

# Mechanical force of uterine occupation enables large vesicle extrusion from proteostressed maternal neurons

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## Abstract

Large vesicle extrusion from neurons may contribute to spreading pathogenic protein aggregates and promoting inflammatory responses, two mechanisms leading to neurodegenerative disease. Factors that regulate extrusion of large vesicles, such as exophers produced by proteostressed *C. elegans* touch neurons, are poorly understood. Here we document that mechanical force can significantly potentiate exopher extrusion from proteostressed neurons. Exopher production from the *C. elegans* ALMR neuron peaks at adult day 2 or 3, coinciding with the *C. elegans* reproductive peak. Genetic disruption of *C. elegans* germline, sperm, oocytes, or egg/early embryo production can strongly suppress exopher extrusion from the ALMR neurons during the peak period. Conversely, restoring egg production at the late reproductive phase through mating with males or inducing egg retention via genetic interventions that block egg-laying can strongly increase ALMR exopher production. Overall, genetic interventions that promote ALMR exopher production are associated with expanded uterus lengths and genetic interventions that suppress ALMR exopher production are associated with shorter uterus lengths. In addition to the impact of fertilized eggs, ALMR exopher production can be enhanced by filling the uterus with oocytes, dead eggs, or even fluid, supporting that distention consequences, rather than the presence of fertilized eggs, constitute the exopher-inducing stimulus. We conclude that the mechanical force of uterine occupation potentiates exopher extrusion from proximal proteostressed maternal neurons. Our observations draw attention to the potential importance of mechanical signaling in extracellular vesicle production and in aggregate spreading mechanisms, making a case for enhanced attention to mechanobiology in neurodegenerative disease.

### eLife assessment

This **important** study explores the potential influence of physiologically relevant mechanical forces on the extrusion of vesicles from *C. elegans* neurons. The authors provide **compelling** evidence to support the idea that uterine distension per se can induce vesicular extrusion from adjacent neurons. Overall, this work will be of interest to neuroscientists and investigators in the extracellular vesicle and proteostasis fields.

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## Introduction

In neurodegenerative disease, prions and protein aggregates can transfer among cells of the nervous system to promote pathology spread <sup>1,2</sup>. Determination of the factors that enhance or deter pathological transfer is therefore a central goal in the effort to clinically address neurodegenerative disease. Study of aggregate transfer in the context of the mammalian brain is a major experimental challenge as events are rare, sporadic and transiently apparent, and tissue is not easily accessible for *in vivo* observation. We model aggregate transfer by proteostressed ALMR touch receptor neurons in the living *C. elegans* nervous system <sup>3–5</sup>, an experimental system that enables molecular and genetic manipulation and evaluation in physiological context, directly through the transparent cuticle <sup>6</sup>.

More specifically, *C. elegans* adult neurons can extrude large vesicles called exophers (~5µm, 100X larger than exosomes) that carry potentially deleterious proteins and organelles out of the neuron <sup>3–5</sup>. Disrupting proteostasis via diminished chaperone expression, autophagy, proteasome activity, or over-expressing aggregating proteins like human Alzheimer's disease associated fragment Aβ<sub>1-42</sub>, expanded polyglutamine Q128 protein, or high concentration mCherry fluorophore, increases exopher production from the affected neurons. Neurons that express proteotoxic transgenes maintain higher functionality if those neurons produce exophers as compared to those that do not, suggesting that exopher-genesis can be neuroprotective, at least in young adult neurons. Extruded exopher contents can be transferred to neighboring glial-like hypodermal cell for content degradation in the lysosomal network <sup>7</sup>. Several mammalian models feature similar biology <sup>8–12</sup>, and thus we speculate that the basic transfer biology represents a conserved process that can be recruited for animal-wide proteostasis balance.

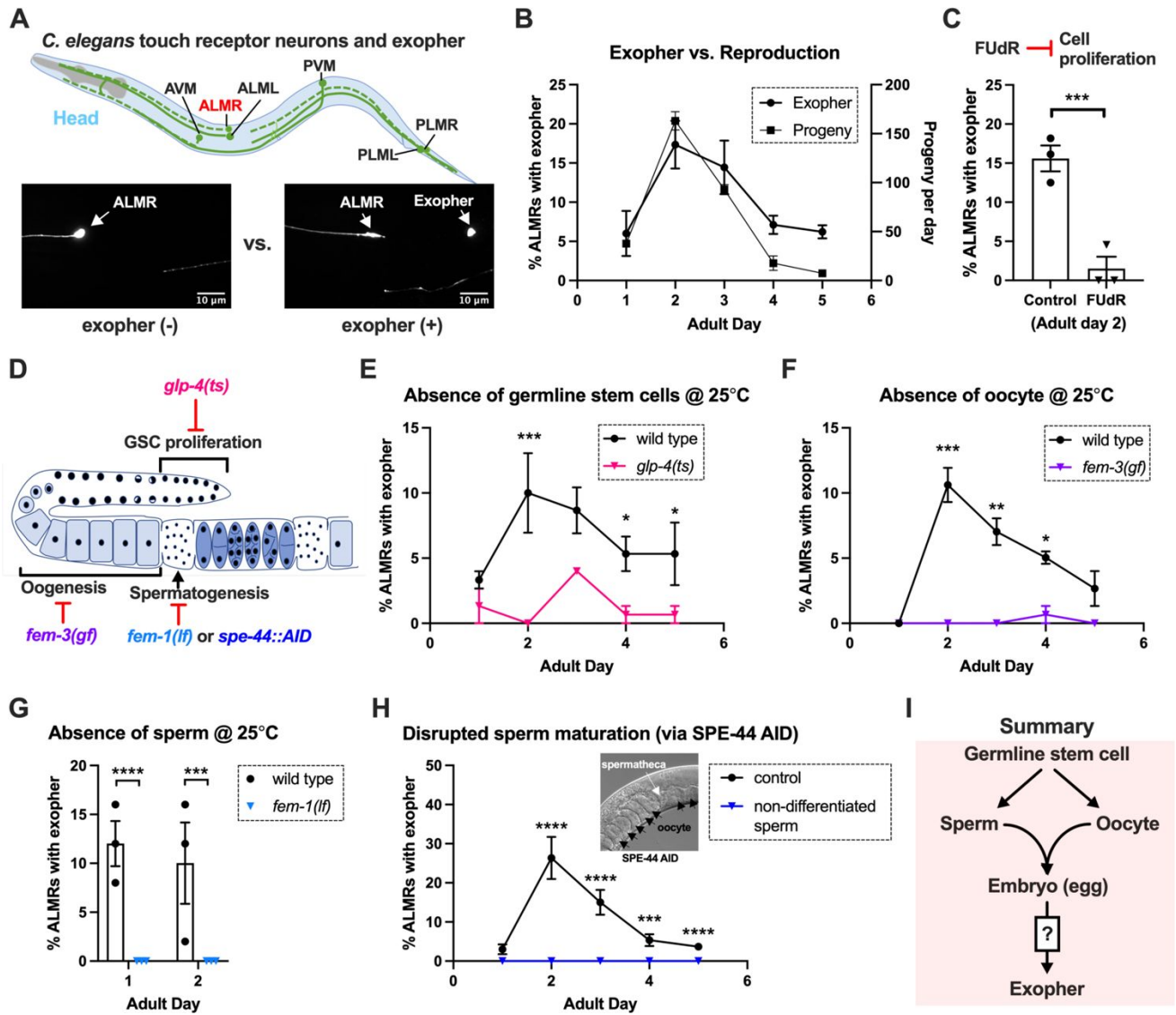
Neuronal exophers are generated only in adult animals, with an unexpected pattern of a peak at young adult days 2-3 and then later in age with more variable onset <sup>3</sup>. While using chemical reagent 5-fluoro-2'-deoxyuridine (FUdR) to block progeny production for aging studies, we found that blocking reproduction strongly limited the early adult peak of exopher production. Here we report data that support that early adult exopher production is sensitive to the load of eggs in the reproductive tract. We document that uterine expansion, rather than chemical signals emanating from fertilized eggs, correlates strongly with level of exopher production and suggest a model in which mechanical signaling, normally induced across generations from egg to parent via uterine stretch, is a license for proteostressed neurons to release potentially toxic materials in large extracellular vesicles.

Mechanical signaling exerts a profound impact on virtually all cell types, and has been implicated in traumatic brain injury and neurodegenerative disease, yet remains poorly understood <sup>13</sup>. Our observations direct enhanced experimental attention to studies on how mechanical force can

influence extracellular vesicle formation and aggregate transfer in the living brain and in neurodegenerative disease.

## Results

The six *C. elegans* gentle touch receptor neurons (AVM, ALML and ALMR located in the anterior body and PVM, PLML and PLMR located in the posterior body) can be readily visualized *in vivo* by expression of fluorescent proteins under the control of the touch neuron-specific *mec-4* promoter (Fig. 1A). We commonly monitor exophers extruded by the ALMR neuron, which typically produces more exophers than the other touch neurons<sup>3,14</sup>, using a strain in which fluorophore mCherry is highly expressed in touch neurons and is avidly eliminated (strain ZB4065 *bzIs166[P<sub>mec-4</sub>::mCherry]*, hereafter referred to as mCherryAg2 for simplicity). ALMR exopher production occurs with a distinctive temporal profile, such that at the L4 larval stage ALMR rarely, if ever, produces an exopher, but in early adult life, the frequency of exopher events increases, typically reaching a peak of 5-20% of ALMR neurons scored at adult day 2 (Ad2); exopher detection then falls to a low baseline level after Ad3<sup>3,14</sup>, a pattern that parallels adult reproduction (Fig. 1B). Late in life, exophers can reappear with variable frequency, but here we focus on young adult exopher generation.



**Figure 1.**

Exophergogenesis is dependent on the presence of the germline, oocytes and sperm. **A. Exophers produced by ALMR are readily visualized in living *C. elegans*.** Top, positions of the six *C. elegans* touch receptor neurons: AVM (Anterior Ventral Microtubule cell), ALMR (Anterior Lateral Microtubule cell, Right), ALML (Anterior Lateral Microtubule cell, Left), PVM (Posterior Ventral Microtubule cell, Right), PLMR (Posterior Lateral Microtubule cell, Right) and PLML (Posterior Lateral Microtubule cell, Left). Bottom panels are representative pictures of an ALMR neuron without (lower left) or with (lower right) exopher production from strain ZB4065 *bzIs166*[*P<sub>mec-4</sub>::mCherry*], which expresses elevated mCherry in the touch receptor neurons. Over-expression of mCherry in *bzIs166* is associated with enlargement of lysosomes and formation of large mCherry foci that often correspond to LAMP::GFP-positive structures; ultrastructure studies reveal considerable intracellular not seen in low reporter-expression neurons; polyQ74, polyQ128, A $\beta$ <sub>1-42</sub> over-expression all increase exophers<sup>3,4,5</sup>. Most genetic compromise of different proteostasis branches—heat shock chaperones, proteasome and autophagy—enhance exophergogenesis, supporting exophergogenesis as a response to proteostress. **B. Both exopher production and reproduction typically peak around Ad2 in the *P<sub>mec-4</sub>::mCherry* strain.** Left axis: the frequency of exopher events in the adult hermaphrodite *C. elegans* strain ZB4065 at 20°C; Mean  $\pm$  SEM of 9 independent trials (~50 animals in each trial). Right axis: daily progeny count (Mean  $\pm$  SEM) from 10 wild type N2 hermaphrodites. **C. FUDR, which inhibits progeny production, suppresses early adult exopher production.** Data are the percentage of ALMR exopher events among >50 Ad2 hermaphrodites in each trial (total of 3 independent trials) for strain ZB4065 at 20°C in absence (control) or presence of 51  $\mu$ M FUDR. \*\*\*  $p < 0.001$  in Cochran–Mantel–Haenszel test. **D. Illustration of the roles of germline development genes tested for impact on exophers.** The *C. elegans* reproductive system comprises a biolobed gonad in which germ cells (light blue, dark nuclei) develop into mature oocytes, which are fertilized in the spermatheca (sperm indicated as dark dots) and held in the uterus until about the 30 cell gastrulation stage, at which point eggs (dark blue) are laid. Indicated are the steps impaired by germline developmental mutations we tested. **E. Germline stem cells are required for efficient exopher production.** Data show the percentage of ALMR exopher events (Mean  $\pm$  SEM) among 50 adult hermaphrodite *C. elegans* that express the wild type GLP-4 protein or the GLP-4(ts) protein encoded by *glp-4(bn2)* at 25°C. All animals express *P<sub>mec-4</sub>::mCherryAg2*, and the *glp-4(ts)* mutants lack a germline when reared at the restrictive temperature (25°C). Eggs collected from both wild type and the *glp-4(ts)* mutants were grown at 15°C for 24 hours before being shifted to 25°C (at L1 stage) to enable development under restrictive conditions; 3 independent trials of 50 animals represented by each dot; \*\*\*  $p < 0.001$  or \*  $p < 0.05$  in Cochran–Mantel–Haenszel test. Note that in WT, temperature shift normally induces a modest elevation in exopher numbers (typically a few % increase, supplemental data in ref. 4) and is thus not itself a factor in exopher production levels. **F. Oogenesis is required for efficient exopher production.** Spermatogenesis occurs but oogenesis is blocked when *fem-3(gf)* mutant hermaphrodites are cultured at 25°C. Data show the percentage of ALMR exopher events (Mean  $\pm$  SEM) in hermaphrodite *C. elegans* that express the wild type FEM-3 protein or the temperature-dependent gain-of-function (*gf*) FEM-3 protein (25°C; 3 independent trials, n=50/trial), \*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$  or \*  $p < 0.05$  in the Cochran–Mantel–Haenszel test. **G. Spermatogenesis is required for efficient exopher production.** There is no spermatogenesis in *fem-1(lf)* at the restrictive temperature of 25°C, while oogenesis is normal in the hermaphrodite. Shown is the percentage of ALMR exopher events (Mean  $\pm$  SEM) in adult hermaphrodites that express the wild type FEM-1 protein or the temperature-dependent loss of function (*lf*) FEM-1 protein (@25°C; 3 independent trials, 50 animals/trial). \*\*\*\*  $p < 0.0001$  or \*\*\*  $p < 0.001$  in Cochran–Mantel–Haenszel test. **H. Spermatogenesis is required for efficient exopher production.** Data show the percentage of ALMR exopher events (Mean  $\pm$  SEM) in hermaphrodite *C. elegans* that express the express the SPE-44::degron fusion. SPE-44 is a critical transcription factor for spermatogenesis<sup>25</sup>, and is tagged with a degron sequence that enables targeted degradation in the presence of auxin in line ZB4749. In the AID system, auxin is added to the plates in 0.25% ethanol, so “control” is treated with 0.25% ethanol and “no sperm” is treated with 1 mM auxin applied to plates in 0.25% ethanol from egg to adult day 1; 4-6 independent trials of 50 animals per trial. \*\*\*\*  $p < 0.0001$  or \*\*\*  $p < 0.001$  in Cochran–Mantel–Haenszel test. Note that under no sperm or non-functional sperm production, oocytes still transit through the spermatheca and enter the uterus (as shown by the DIC picture); unfertilized oocytes can be laid if the egg laying apparatus is intact. **I. Summary: Genetic interventions that block major steps of germ cell development strongly block ALMR exophergogenesis in the adult hermaphrodite. The dual requirement for sperm and oocytes suggests that fertilization and embryogenesis are required events for inducing ALMR exophergogenesis.**

## Sterility-inducing drug FUDR suppresses ALMR exophgergenesis

In experiments originally designed to study exopher events in aging animals, we sought to generate age-synchronized populations by blocking progeny production from early adult stages using DNA synthesis inhibitor 5-fluoro-2'-deoxyuridine (FUDR). Unexpectedly, we found that 51μM FUDR strongly suppressed exopher events as quantitated at Ad2 (**Fig. 1C**). FUDR is commonly used in *C. elegans* to inhibit the proliferation of germline stem cells and developing embryos, but has also been noted to impair RNA metabolism<sup>15</sup> and improve adult proteostasis<sup>16</sup>. To probe which FUDR outcome might confer exopher suppression, we first addressed whether disruption of progeny production by alternative genetic means might suppress exophgergenesis, which would implicate a viable germline as a factor in exopher modulation.

## Germline elimination and germline tumors suppress ALMR exopher production

In the assembly line-like hermaphrodite *C. elegans* gonad, germline stem cells close to the signaling distal tip cell (DTC) proliferate by mitosis (cartoon of *C. elegans* gonad and germ cell development in **Fig. 1D**). We disrupted germ cell production using the *glp-4(bn2ts)* valyl-tRNA synthetase 1 mutant. At the restrictive temperature (25°C), *glp-4(bn2ts)* causes germ cell arrest during the initial mitotic germ cell divisions, effectively eliminating the germline<sup>17</sup>. We constructed an mCherryAg2; *glp-4(bn2ts)* strain and quantitated ALMR exopher production in animals grown at the restrictive temperature, scoring exophers during early adulthood (**Fig. 1E**). ALMR neurons in the germline-less *glp-4* mutant produced significantly fewer exophers on Ad1-4 as compared to age- and temperature-matched controls.

## Both oogenesis and spermatogenesis are critical for early adult exopher production

Given that lack of functional germ cells impaired neuronal exopher production, we sought to test whether oocytes or sperm might be specifically required for exophgergenesis, taking advantage of *C. elegans* genetic reagents available for the manipulation of gamete development.

## Oogenesis is required for the peak of early adult exophgergenesis

In the *C. elegans* hermaphrodite, the differentiation of germline stem cells begins during the L4 larval stage with spermatogenesis, after which sperm production is shut down and oogenesis begins<sup>18</sup>. Genetic mutants that produce only sperm or only oocytes have been well characterized. To test a mutant that produces sperm but no oocytes, we employed *fem-3(q20ts)*, a temperature sensitive gain-of-function mutant that causes germ cells to exclusively differentiate into sperm<sup>19,20</sup>. We constructed an mCherryAg2; *fem-3(q20ts)* line, reared animals at non-permissive temperature 25°C, and scored ALMR exophers in mutant and control animals during early adulthood. In the sperm-only, oocyte-deficient *fem-3(q20ts)* background, exophgergenesis is mostly diminished over the first five days of adulthood (**Fig. 1F**). We infer that oocytes must be present for early adult ALMR exopher production and conclude that sperm alone are not sufficient to drive exopher elevation.

## Spermatogenesis is required for the peak of early adult exophgergenesis

The presence of functional sperm can stimulate ovulation to trigger oocyte maturation. To assess neuronal exopher production in the reciprocal reproductive configuration in which animals have oocytes but no sperm, we disrupted spermatogenesis using two approaches. First, we used a temperature sensitive *fem-1* mutation to produce animals with oocytes but no sperm<sup>21</sup>. We

crossed *fem-1(fc17ts)* into the mCherryAg2 strain and examined exopher production from ALMR neurons in hermaphrodites at the restrictive temperature of 25°C. We found that ALMR exopher production in *fem-1(fc17)* mutants was suppressed at 25°C (**Fig. 1G** [↗](#)).

Second, we used the auxin-inducible degron system (AID [22](#) [↗](#), [23](#) [↗](#)) to degrade SPE-44, an essential protein required for spermatid differentiation [24](#) [↗](#), [25](#) [↗](#). In the AID system, addition of auxin to the culture induces rapid degradation of proteins genetically tagged with a specific auxin-dependent degron sequence. AID targeting of SPE-44-degron is highly effective in disrupting sperm maturation [24](#) [↗](#). We treated strain ZB4749 (fxIs1[P<sub>pie-1</sub>::TIR1::mRuby] zdIs5[P<sub>mec-4</sub>::GFP]; bzIs166[P<sub>mec-4</sub>::mCherry]; *spe-44*(fx110[*spe-44*::degron])) with auxin during larval developmental stages to block sperm maturation and then transferred Ad1 animals to NGM plates without auxin, a condition that disrupted sperm maturation but allowed oocyte generation. We find that blocking sperm maturation by targeting SPE-44 for degradation abolished ALMR exopher production (**Fig. 1H** [↗](#)) even though oogenesis is not significantly impacted [24](#) [↗](#).

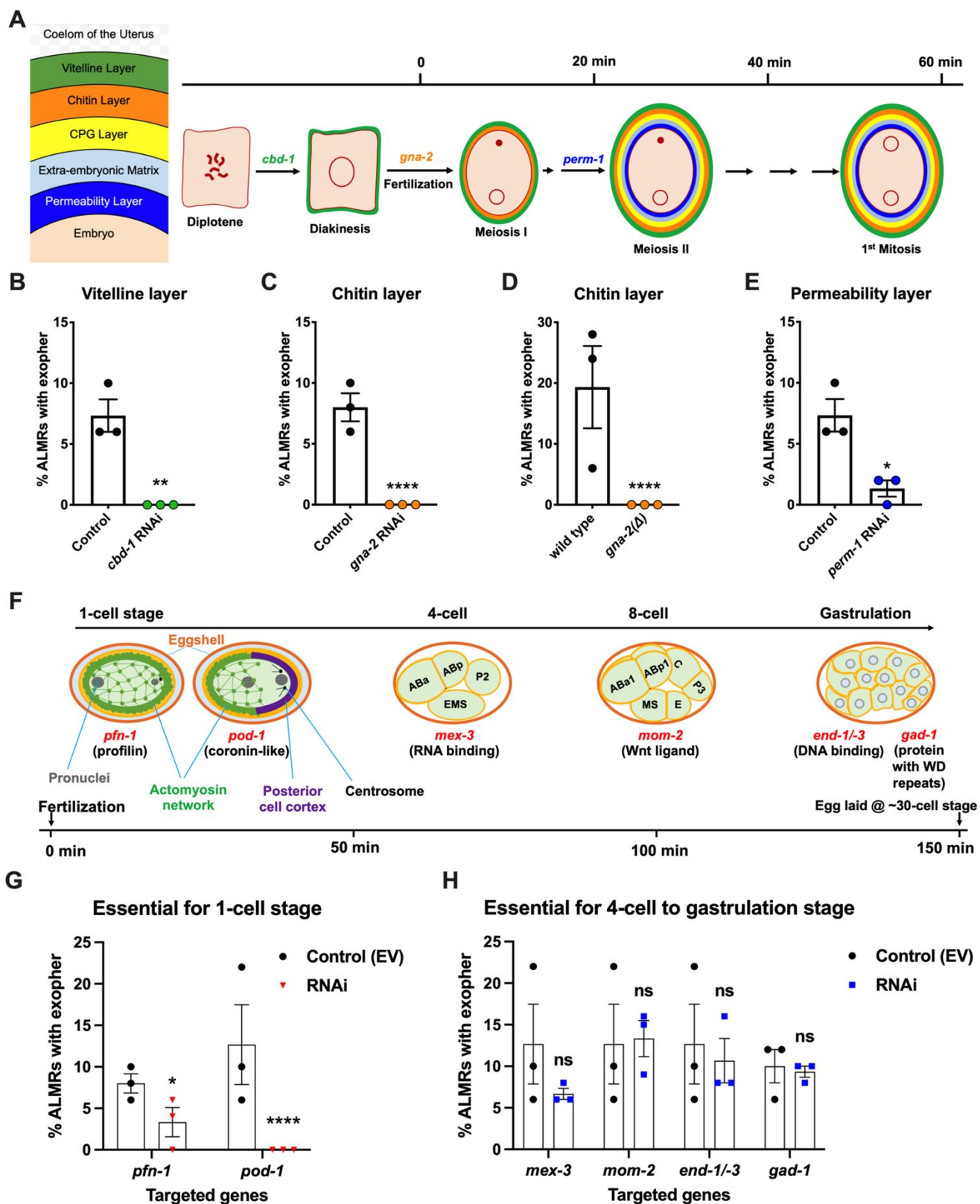
We infer that functional sperm must be present for early adult ALMR exopher production and conclude that oogenesis alone is not sufficient to drive exopher elevation in early adult life.

## Fertilization and early embryonic divisions are required for the early adult exophogenesis peak

The requirement of sperm and oocytes for neuronal exopher production raises the obvious question as to whether fertilized eggs/embryos are required for ALMR exophogenesis (**Fig. 1I** [↗](#)). *C. elegans* genes impacting fertilization and embryonic development have been studied in exquisite detail [26](#) [↗](#)–[29](#) [↗](#). We tested embryonic development genes known for roles at particular stages for impact on neuronal exopher levels using RNAi knockdown approaches.

In *C. elegans* fertilization, as the mature oocyte encounters the sperm-filled spermatheca, a single sperm enters the mature ovulated oocyte (fertilization time 0), triggering the rapid events of egg activation, which include polyspermy block, eggshell formation, completion of meiotic divisions and extrusion of polar bodies. The multi-step eggshell formation (**Fig. 2A** [↗](#)) is completed within 5 minutes of sperm entry, by which time the zygote has been passed into the uterus, where the maternal chromosomes execute both meiotic divisions (meiosis accomplished by ~20 minutes after fertilization). After establishment of egg polarity cues, the first mitotic cell division occurs ~40 minutes after fertilization [27](#) [↗](#), [29](#) [↗](#). Eggs are held in the mother's uterus until they are laid at the ~30 cell stage (gastrulation). In wild type, ~8 fertilized eggs occupy the uterus when egg laying begins at ~6 hours of adult life [30](#) [↗](#).







## Figure 2

Events required for Ad2 elevation of exopher production occur during the earliest stages consequent to fertilization and are largely completed by the 4 cell stage. A. **Diagram of eggshell layers, post-fertilization timeline for layer formation, and indication of steps at which RNAi disrupts eggshell biogenesis.** The formation of the multilayered eggshell is accomplished via a hierarchical assembly process from outside to inside, with outer layers required for later formation of inner layers. The outmost vitelline layer assembles in part prior to fertilization, dependent on Chitin-Binding Domain protein (CBD-1) <sup>31</sup>. The next eggshell layer is made up of chitin, which confers eggshell stiffness and requires the *gna-2*-encoded enzyme glucosamine-6-phosphate N-acetyltransferase (GNPNAT1) for precursor biosynthesis<sup>32</sup>. The innermost lipid layer of eggshell is called the permeability layer, which is lipid-rich and is needed to maintain osmotic integrity of the embryo. PERM-1 <sup>33</sup> (among others, including FASN-1 <sup>36</sup>, POD-1 <sup>35</sup> and EMB-8 <sup>37</sup>) is required for permeability barrier formation <sup>27,39</sup>. Note that eggshell biogenesis is critical for polyspermy barrier, spermathecal exit, meiotic chromosome segregation, polar body extrusion, AP polarization and internalization of membrane and cytoplasmic proteins, and correct first cell divisions <sup>39</sup>, so genetic separation of eggshell malformation from the earliest embryonic formation is not possible. B. ***cbd-1*, a gene encoding an essential component of the eggshell vitelline layer, is critical for Ad2 exopher elevation.** Exopher scores in Ad2 animals (strain ZB4757: bzIs166[P<sub>*mec-4*</sub>::mCherry] II) that were treated with RNAi against *cbd-1*, total of 3 trials (50 hermaphrodites per trial), \*\*  $p < 0.01$  in Cochran-Mantel-Haenszel test, as compared to the empty vector (EV) control. C. ***gna-2*, a gene required for chitin precursor biosynthesis and chitin layer formation, is critical for Ad2 exopher elevation.** C. Exopher scores in Ad2 animals treated from the L1 stage with RNAi against *gna-2*. The *gna-2* gene encodes enzyme glucosamine-6-phosphate N-acetyltransferase (GNPNAT1) required for chitin precursor biosynthesis. D. Exopher scores in Ad2 animals harboring a null mutation in the essential *gna-2* gene. *gna-2* homozygous null worms are GFP negative progeny of strain ZB4941: bzIs166[P<sub>*mec-4*</sub>::mCherry]; *gna-2(gk308)* I/ht2 [bli-4(e937) let-?(q782) qIs48[P<sub>*myo-2*</sub>::GFP; P<sub>*pes-10*</sub>::GFP; P<sub>*ges-1*</sub>::GFP] (I;III). Data represent a total of 3 trials (50 hermaphrodites per trial), \*\*\*\*  $p < 0.0001$  in Cochran-Mantel-Haenszel test, as compared to wild type animals. E. ***perm-1*, a gene required for permeability barrier synthesis, is critical for Ad2 exopher elevation.** Exopher scores in Ad2 animals treated with RNAi against *perm-1*, which encodes a sugar modification enzyme that acts in the synthesis of CDP-ascarylose. Data represent a total of 3 trials (50 hermaphrodites per trial), \*  $p < 0.05$  in Cochran-Mantel-Haenszel test, as compared to the empty vector (EV) control. Note that previously characterized strong exopher suppressors *pod-1*, *emb-8*, and *fasn-1* <sup>4</sup> are also needed for egg shell permeability barrier layer formation <sup>35,37</sup>. F. **Diagram of select genes required for specific stages of embryonic development.** *pfn-1(RNAi)* (arrest at the one-cell stage <sup>40</sup>); *pod-1(RNAi)* (arrest at the two-cell stage <sup>41</sup>); arrest stage phenotype for other genes is not precisely documented, but these genes play significant roles at the indicated stages; images annotated according to WormAtlas doi:10.3908/wormatlas.4.1). G. **RNAi targeting of early acting embryonic development genes lowers exopher production.** Exopher scores from Ad2 animals that were treated with RNAi against genes characterized to be essential for 1-cell to 2-cell stage embryonic development. Total of 3 trials (50 hermaphrodites per trial). \*  $p < 0.05$  or \*\*\*\*  $p < 0.0001$  in Cochran-Mantel-Haenszel test, as compared to the empty vector control. Strong exopher suppressor *pod-1* has been previously reported <sup>4</sup>. We found RNAi directed against gene *emb-8* (as early as 2 cell arrest, but arrest at the 1- to 50-cell stage reported <sup>42</sup>) to be more variable in outcome (not shown). H. **RNAi targeting of genes that disrupt 4-cell stage and later embryonic development does not alter exopher production levels.** Exopher scores in Ad2 animals that were treated with RNAi against genes that are essential for 4-cell to gastrulation stages of embryonic development. Total of 3 trials (50 hermaphrodites per trial). ns, not significant in Cochran-Mantel-Haenszel test, as compared to the empty vector control.

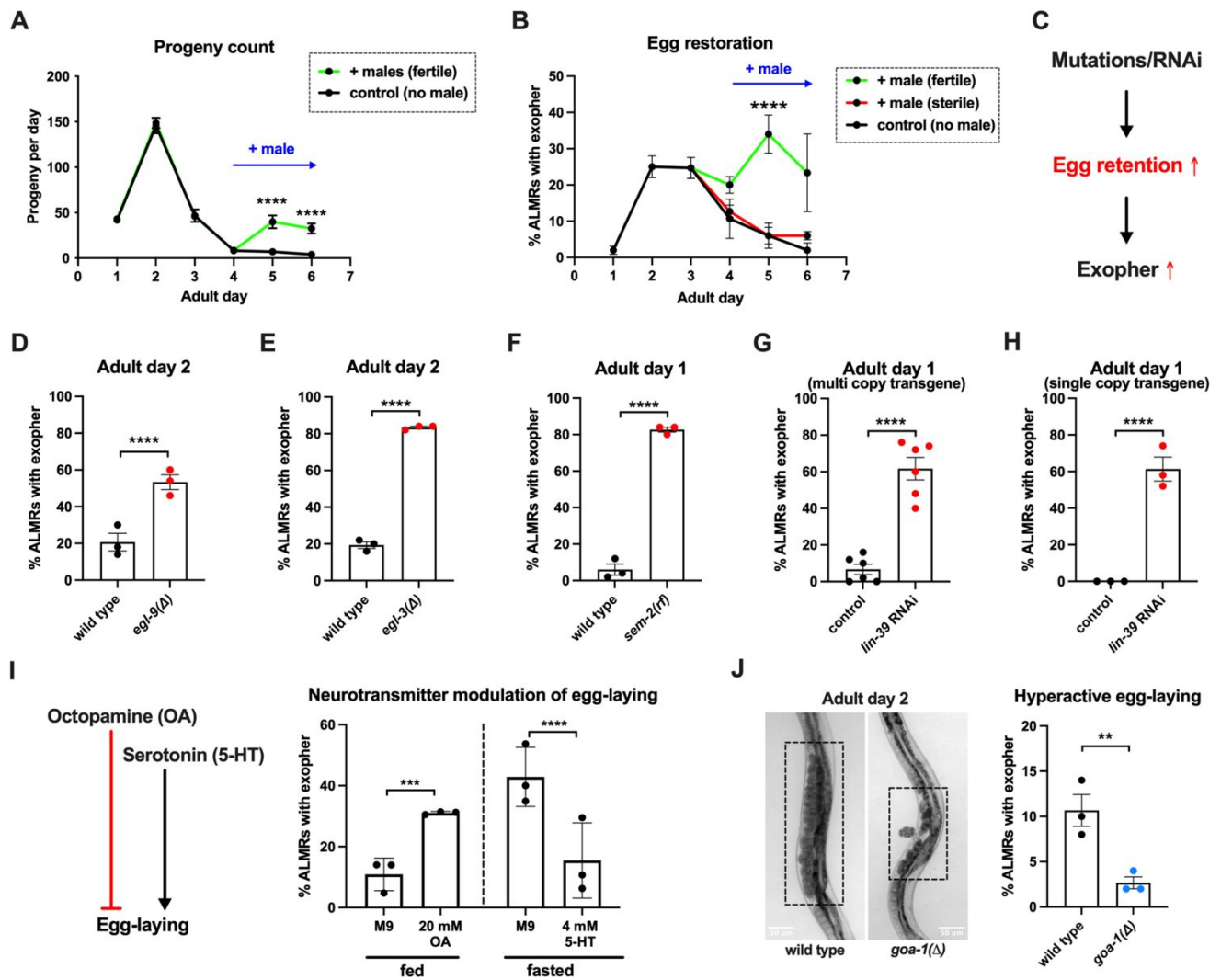
Our data revealed an unexpected theme: we found that disruption of tested early-acting genes essential for eggshell assembly (chitin binding domain protein *cbd-1* <sup>31</sup> (Fig. 2B), chitin precursor synthesis gene *gna-2* <sup>32</sup> (Fig. 2C, D), permeability barrier-required CDP-ascarylose synthesis gene *perm-1* <sup>33</sup> (Fig. 2E)), and/or needed for the progression through the 1-cell or 2-cell stages of embryonic development <sup>34-37</sup> (profilin *pfn-1* and coronin-related *pod-1* (Fig. 2F)), cause potent suppression of ALMR exopherogenesis (Fig. 2G). In contrast, RNAi knockdowns of genes playing important roles for later stage embryonic development (4 cell to 8 cell stages *mex-3*, *mom-2*, gastrulation genes *end-1/3* or *gad-1*) (Fig. 2F) confer negligible impact

on ALMR exophergenesis (**Fig. 2H** [↗](#)). Our data support a fertilization requirement for neuronal exopher stimulation and suggest that the exophergenesis signal/condition that promotes the early adult wave of exophergenesis is associated with the very earliest stages of embryonic development. Of note, disruption of eggshell biosynthesis has the immediate downstream consequence of disruption of early polarity establishment and first divisions, such that genetic separation of eggshell production from first division proficiency is not possible, for example, *pod-1* RNAi has been reported to be associated with eggshell deficits <sup>35</sup> [↗](#), although no eggshell deficits are observed for *pfn-1* RNAi <sup>38</sup> [↗](#). We thus conclude that either eggshell integrity or biochemical events associated with the first embryonic cell divisions are required for neuronal exophergenesis.

## Restoring fertilized eggs later in life can extend ALMR exophergenesis

Having found that fertilized eggs are necessary for the early adult elevation in exopher production, we asked whether the presence of eggs is sufficient for stimulation of exopher production by introducing fertilized eggs later in adult life when they are not normally present. In *C. elegans*, sperm are made in the L4 stage and are stored in the spermatheca to fertilize oocytes that mature in the adult. Sperm are limiting for hermaphrodite self-fertilization, with more oocytes made than can be fertilized by self-derived sperm.

Unmated hermaphrodites thus cease egg laying around adult day 4 because they run out of self-supplied sperm. However, if males mate with hermaphrodites, increased progeny numbers can be produced due to increased sperm availability. More germane to our experiment, if males are mated to the reproductively senescing hermaphrodite to replenish sperm, hermaphrodites can produce fertilized eggs for a few additional days (**Fig. 3A** [↗](#)).



### Figure 3

ALMR exophogenesis levels are markedly influenced by the number of fertilized eggs retained in the uterus. **A. Later life mating extends the *C. elegans* reproductive period.** Progeny count for each wild type hermaphrodite in the presence (green) or absence (black) of males (1 hermaphrodite +/- 5 males) from Ad1 to Ad6. Males are present from Ad4 to Ad6. Total of 12 wild type hermaphrodites scored for each condition. Data shown are mean  $\pm$  SEM. \*\*\*\*  $p < 0.0001$  in 2way ANOVA with Šidák's multiple comparisons test. **B. Introducing fertilized eggs in late adulthood extends the period of elevated exophogenesis.** Males carrying functional (green) or nonfunctional (red) sperm (*spe-45(tm3715)*) were added to plates housing hermaphrodites as endogenous stores of sperm are depleted at Ad3. Data shown are mean  $\pm$  SEM of percentage hermaphrodite ALMR neurons exhibiting an exopher event on days indicated. Total of 3 trials, and 50 hermaphrodites for each treatment at a single time point. \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test, as compared to the sterile male group or no male control. **C. Hypothesis:** Genetic interventions (mutations/RNAi) that increase egg retention will increase ALMR exophogenesis. **D. Genetic interventions that induce egg retention elevate exopher levels. *egl-9(sa307)*.** ALMR exopher scores Ad2. Strain ZB4757: bzIs166[*P<sub>mec-4</sub>::mCherry*] II vs. strain ZB4772: bzIs166[*P<sub>mec-4</sub>::mCherry*] II; *egl-9(sa307)* V. Total of three trials (50 worms per trial, each trial one dot); \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test, as compared to the wild type control. **E. Genetic interventions that induce egg retention elevate exopher levels. *egl-3(gk238)*.** ALMR exopher scores Ad1. Strain ZB4757: bzIs166[*P<sub>mec-4</sub>::mCherry*] II vs. strain ZB4904: bzIs166[*P<sub>mec-4</sub>::mCherry*] II; *egl-3(gk238)* V. Total of three trials (50 worms per trial, each trial one dot); \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test, as compared to the wild type control. **F. Genetic interventions that induce egg retention elevate exopher levels. *sem-2(n1343)*.** ALMR exopher scores Ad1. Strain ZB4757: bzIs166[*P<sub>mec-4</sub>::mCherry*] II vs. strain ZB4902: *sem-2(n1343)* I; bzIs166[*P<sub>mec-4</sub>::mCherry*] II. Exophers were scored on Ad1 because of the damaging excessive bagging that ensues in this background. Total of three trials (50 worms per trial, each trial one dot); \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test, as compared to the wild type control. **G. Genetic interventions that induce egg retention elevate exopher levels. *lin-39(RNAi)* on a multi copy transgenic strain.** ALMR exopher scores Ad2. Strain ZB4757: bzIs166[*P<sub>mec-4</sub>::mCherry*] II treated with RNAi against *lin-39*. Total of six trials (50 worms per trial, each trial one dot); \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test, as compared to the wild type control. **H. Genetic interventions that induce egg retention elevate exopher levels. *lin-39(RNAi)* on a single copy transgenic strain.** ALMR exopher scores Ad2. Strain OD2984: ltsi953 [*P<sub>mec-18</sub>::vhhGFP4::zif-1::operon-linker::mKate::tbb-2* "UTR + *Cbr-unc-119(+)*] II; *unc-119(et3)* III treated with RNAi against *lin-39*. Total of three trials (50 worms per trial, each trial one dot); \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test, as compared to the wild type control. **I. Egg-laying modulating neurotransmitters octopamine (OA) and serotonin (5-HT) influence ALMR exophogenesis levels.** Data show the mean  $\pm$  SEM of percentage hermaphrodite ALMR neurons exhibiting an exopher event at Ad2 after 48 hours of treatment with 20mM octopamine (OA) or 4mM serotonin (5-HT) on OP50 bacteria seeded NGM plates. Because 5-HT (which increases egg laying) was hypothesized to suppress exopher production, we assayed under conditions of six hour food limitation, which markedly raises the exopher production baseline, enabling easier quantitation of suppression effects<sup>4</sup>. Total of 3 trials and 50 hermaphrodites per trial for each condition. \*\*\*  $p < 0.001$  or \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test, as compared to the control group treated with M9 buffer (solvent for OA or 5-HT). **J. Mutant *goa-1(n1134)*, with hyperactive egg-laying and low egg retention in the uterus** (pictures on the left, representative of 20), has low exopher scores at Ad2. **Strain ZB4757:** bzIs166[*P<sub>mec-4</sub>::mCherry*] II vs. strain ZB5352: *goa-1(n1134)* I; bzIs166[*P<sub>mec-4</sub>::mCherry*] II. Boxes highlight egg zone. \*\*  $p < 0.01$  in Cochran–Mantel–Haenszel test.

To determine if the presence of eggs might be sufficient to drive exopher production after Ad3, we mated males to Ad3 reproductively senescing hermaphrodites. We found that restored egg production is associated with increased and extended exopher production, provided that hermaphrodites were mated to fertilization-proficient males (Fig. 3B). We conclude that adult ALMR exophogenesis is driven by the presence of fertilized eggs and that the older age decrease in exopher production (~Ad4) under standard culture conditions is more likely attributed to the lack of fertilized egg accumulation at this lifestage, rather than to the existence of a chronological limit on the biochemical capacity to elevate exopher levels at older ages.

## Genetically induced egg retention elevates ALMR exopher production

Fertilized eggs might release a signal or create a condition that stimulates exophogenesis. If such an influence were limiting, increasing the egg concentration in the body might increase exopher numbers. To address whether elevating the young adult egg load can increase exophers, we took multiple distinctly-acting genetic approaches to limit egg laying and promote egg retention in the body (**Fig. 3C**). We tested four genetic conditions that lower or block egg-laying: a null mutation of prolyl hydroxylase *egl-9*, for which disruption induces a mild egg laying defect<sup>43</sup>; a null allele of proprotein convertase subtilisin/kexin type 2 *egl-3*<sup>44</sup> that perturbs neuropeptide processing and confers a severe egg-laying defective phenotype<sup>43</sup>; a reduction-of-function mutation in SOX transcription factor SEM-2 (*sem-2(n1343)*) that eliminates production of the sex myoblasts needed to generate egg laying muscle; and RNAi directed against the *lin-39* homeobox transcription factor HOXA5 ortholog required for vulval cell fate specification<sup>45,46</sup>.

We found that the associated massive egg retention correlated with a dramatic elevation of exopher numbers for each genetic impediment to egg laying (*egl-9* (**Fig. 3D**); *egl-3* (**Fig. 3E**); *sem-2* (**Fig. 3F**), *lin-39*(RNAi) (**Fig. 3G**)). For example, under the treatment of *lin-39*(RNAi), ~60% of the wild type strain expressing mCherry in ALMR by a multi-copy transgene produced ALMR exophers on Ad1, compared to only ~7% of the same strain treated with empty vector (EV) control (**Fig. 3G**). We conclude that regardless of the genetic strategy employed to trap eggs in the body, egg retention can lead to high ALMR exopher production.

In complementary studies, we examined the impact of egg retention on ALMR exophogenesis when we expressed fluorescent protein mKate from a single copy transgene (*i.e.*, in the absence of an over-expressed reporter). We found that the empty vector control treatment without induction of egg retention is associated with no ALMR exophogenesis in the single copy mKate transgenic strain (0% in all three trials). However, when we treated with *lin-39*(RNAi) to induce egg retention, we measured ~60% exophogenesis. Thus regardless of the expression levels of exogenous proteins in the ALMR neuron, the egg retention condition can induce high exopher production.

## Hyperactive egg-laying and consequent low egg retention is associated with low exopher production

Neurotransmitters octopamine (OA) and serotonin (5-HT) have been well documented to play opposing roles in *C. elegans* egg-laying behavior<sup>47</sup>. Feeding *C. elegans* octopamine strongly suppresses egg-laying to induce egg retention, while supplementing with 5-HT causes hyperactive egg-laying<sup>48</sup>. Consistent with outcomes in animals physically blocked for egg-laying, treatment with egg retention-promoting OA enhanced ALMR exophogenesis (**Fig. 3I**).

To test the outcome of 5-HT-induced enhanced egg laying, we measured the impact of 5-HT consequent to 6 hour food withdrawal, a condition that we previously found markedly enhances ALMR exophogenesis<sup>48</sup>, and therefore is expected to increase the dynamic range for scoring exopher suppression. We find that 5-HT treatment, which lowers egg retention, strongly suppresses fasting-associated ALMR exophogenesis (**Fig. 3I**). Although perturbing neuronal signaling holds complex consequences for whole-animal physiology, our findings are consistent with a model in which high egg load increases neuronal exophogenesis, and low egg retention decreases exophogenesis.

The egg laying circuit is controlled in part by Goa inhibition—null allele *goa-1(n1134)* removes this inhibition such that eggs are often laid at very early developmental stages (2-4 cell stage) rather than being retained in the uterus until gastrulation (~30 cell stage)<sup>49</sup>. We introduced *goa-*

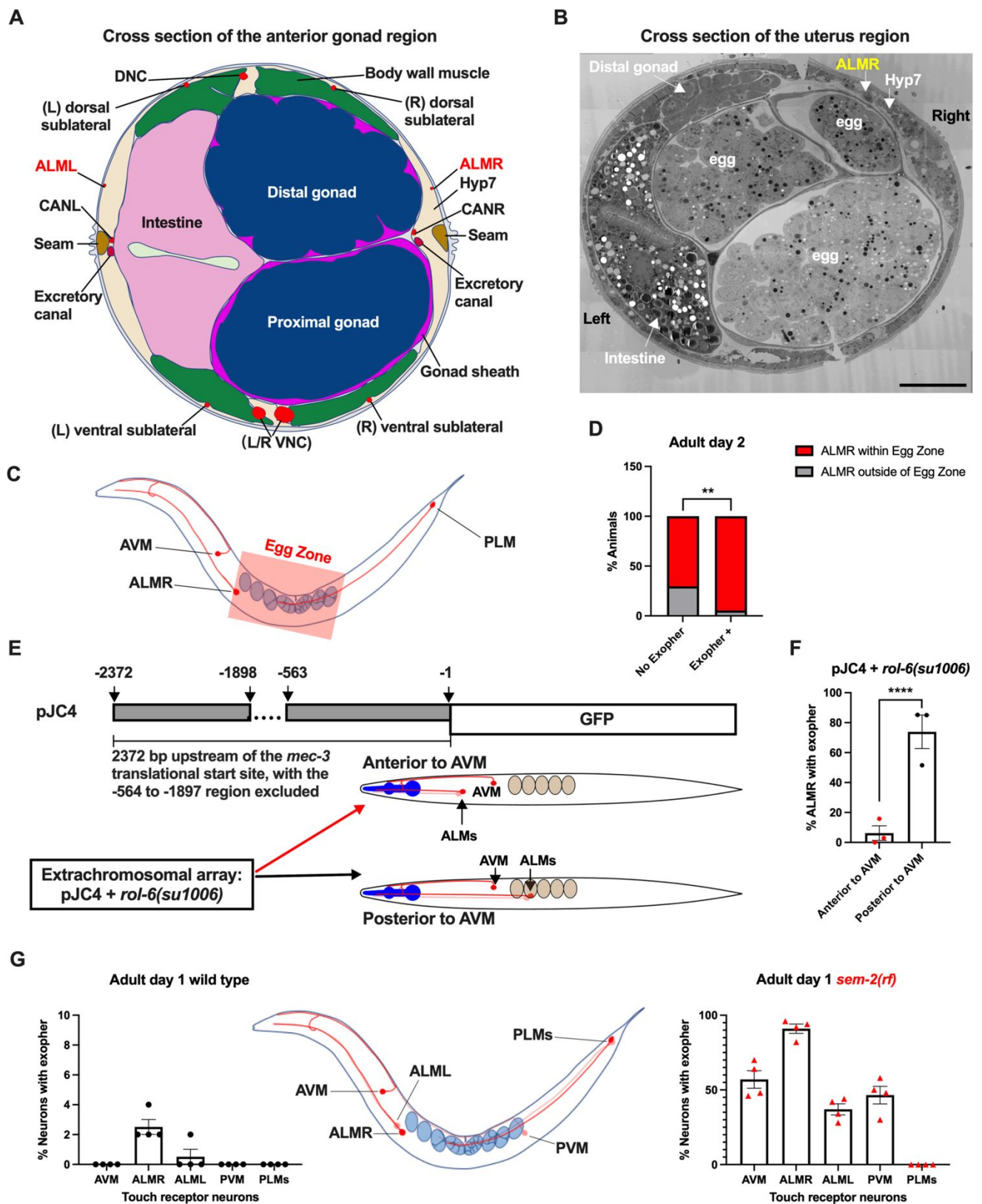
*1(n1134)* into the mCherryAg2 background and scored ALMR exopher events at Ad2. We confirmed that *goa-1(n1134)* retains few eggs in the uterus and is associated with a significantly lower number of ALMR exopher events as compared to the age-matched wild type control (**Fig. 3J** [↗](#)).

In sum, manipulation of uterine egg occupancy is strongly correlated with the extent of ALMR neuronal exophogenesis—high egg retention promotes high exophogenesis and low egg retention is associated with low exophogenesis.

## ALMR neuron proximity to the egg zone correlates with exophogenesis frequency

The ALML and ALMR anterior touch neurons share developmental, morphological and functional similarities <sup>50</sup>[↗](#), yet paradoxically, ALMR consistently produces exophers at higher levels than ALML <sup>3</sup>[↗](#) (also **Fig. 4G** [↗](#)). The ALM neurons are embedded within the *C. elegans* hypodermis, but the ALMR soma is situated in vicinity of the gonad and its resident eggs, whereas the ALML soma, on the opposite side of the animal, is positioned closer to the intestine (**Fig. 4A** [↗](#), 4B) <sup>51</sup>[↗](#).





**Figure 4.**

ALMR exophogenesis levels correlate with proximity to the egg zone. **A.** ALMR is positioned close to the uterus and ALML is situated on the opposite side, close to the intestine. A diagram of ALMR and ALML positions relative to major body organs in cross section that is anterior to the “egg zone”. Image drawing based on the EM pictures of adult hermaphrodite slice #273 of WormAtlas. DNC: dorsal nerve cord; VNC: ventral nerve cord; Hyp7: hypodermal cell 7; CAN(L/R): canal associated neurons (left/right); neurons in red. **B.** Electron microscopy cross section image of the uterus region indicating ALMR soma and eggs within the adult uterus. Note ALMR is close to the egg-filled uterus, ALML is on the opposite side closer to the intestine. The ALML soma is not evident in this cross section. Scale bar = 10  $\mu$ m. **C.** Illustration of the egg zone definition, distance between outermost eggs. The measure of this distance corresponds to uterine length. **D. ALMRs positioned close to the filled gonad produce exophers more frequently than ALMRs that are positioned a bit more distally.** We selected Ad2 mCherry animals at random, then identified whether or not ALMR had produced an exopher, and subsequently determined whether ALMR was positioned within the egg zone or outside the egg zone as indicated (neuronal soma positioning differences are a consequence of developmental variation). Neurons with somas positioned further from the egg area produced fewer exophers than neurons within the egg zone indicated; total of 91 worms for the “No Exopher” group and 37 for the “Exopher +” group; \*\*  $p < 0.01$  in Chi-Square test. **E.** The Aamodt group<sup>53</sup> previously reported that high copy numbers of plasmid pJC4 containing the *mec-3* promoter region (–1 to –563, and –1898 to –2372 of the *mec-3* translational start) exhibited increased abnormal positioning of ALM neurons anterior to AVM. We introduced plasmid pJC4 along with transformation reporter *prf4 rol-6(su1006)* in the background of mCherryAg2 (note this revealed that *rol-6(su1006)* is a strong exopher enhancer) and identified neurons that were positioned posterior to AVM (normal, close to the uterus) and those that were positioned anterior to AVM (further away from the uterus). **F. ALMR neurons genetically induced to adopt positions further away from the uterus generate fewer exophers than those close to the uterus.** We counted numbers of exophers produced in Ad2 Rol hermaphrodites for each position type. Strain ZB5046: Ex [(pJC4) *P<sub>mec-3</sub>::GFP + prf4*]; *bzIs166[P<sub>mec-4</sub>::mCherry]* II. Total of three trials (61 (34a + 27p); 39(19a + 20p); 51(20a + 31p) animals per trial); \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test. **G.** When eggs cannot be laid in the *sem-2(rf)* mutant, the eggs that accumulate in the body are brought in closer proximity to ALML, AVM and PVM touch neurons with a resulting increase in their exopher production. Strain ZB4757: *bzIs166[P<sub>mec-4</sub>::mCherry]* II vs. strain ZB4902: *sem-2(n1343)* I; *bzIs166[P<sub>mec-4</sub>::mCherry]* II. Left, Exopher scoring (Mean  $\pm$  SEM) of all six touch receptor neurons in Ad1 wild type hermaphrodite; Right, Exopher scoring (Mean  $\pm$  SEM) of all six touch receptor neurons in Ad1 *sem-2(rf)* hermaphrodite. Total of 4 trials (50 worms per trial) for each. Wild type, egg laying proficient animals on Ad1 exhibit low exopher levels, but when eggs accumulate early in the *sem-2* mutant, exophers markedly increase in ALMR and other touch neurons that are in the vicinity of an expanded uterus. PLM neurons are situated posterior to the anus and are not subject to uterine squeezing effects.

To ask if proximity to the gonad is correlated with exopher production, we randomly selected 128 Ad2 hermaphrodites that expressed mCherry in the touch receptor neurons, imaged in brightfield to visualize the egg zone of each animal, and imaged again in the red channel to visualize the touch neuron, recording the relative positions of ALMR and the egg zone (Fig. 4C). We also assessed whether the ALMR neuron had produced an exopher or not.

We found that 37/128 ALMRs examined had produced an exopher (Exopher+), and that 36/37 (95%) of the Exopher+ ALMR neuronal somas that had produced exophers were positioned within the visualized egg zone (Fig. 4D). For the Exopher-ALMRs that had not produced exophers, 63/91 (70%) had neuronal somas located in the egg zone. Thus, although ALMR soma positioning in the egg zone does not guarantee exophogenesis in the mCherryAg2 strain, the neurons that did make exophers were nearly always in the egg zone ( $p < 0.01$  in Chi-Square test, Fig. 4D).

To further test for association of egg zone proximity to ALMR and exopher production, we genetically shifted ALM position. During development, the ALM neurons migrate posteriorly to near the mid-body<sup>52</sup> and most commonly, ALM somas are situated posterior to AVM. ALM soma positions, however, can be influenced by migration and specification cues. In particular,

transgenic introduction of a *mec-3* promoter fragment bearing an internal deletion (fusion of the -1 to -563 sequences to the -1898 to -2372 *mec-3* promoter fragment, plasmid pJC4) can induce anterior ALM migration during development, sometimes resulting in final ALM positions anterior to AVM <sup>53</sup> (Fig. 4E). We took advantage of the partially deleted *mec-3* promoter sequences in pJC4 to manipulate ALM position. In these studies we introduced pJC4 with the co-transformation marker pRF4 (*rol-6(su1006)*) that disrupts the cuticle to induce rolling of transgenic animals into the  $P_{mec-4}::mCherry$  background. Rol hermaphrodites have a strikingly high baseline of ALMR exophogenesis (~40% exophers in rollers vs. ~20% in the wild type). Strikingly, we found that when ALMs are situated anterior to AVM, ALMR exophogenesis drops to ~5% (4/73) vs. 71% for posterior position (55/78) (Fig. 4F). Although we cannot exclude that physiological changes in differently-positioned touch neurons underlie reduced exophogenesis, data are consistent with a model in which proximity to the egg zone correlates with exophogenesis.

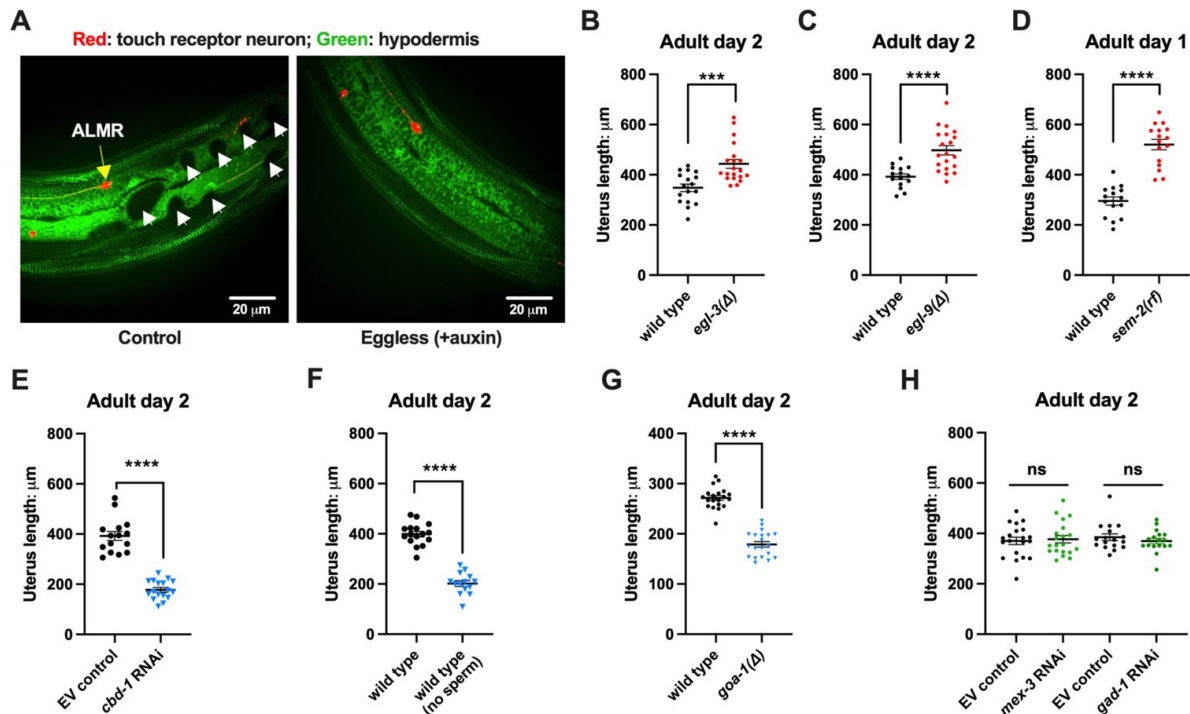
Another way to increase egg proximity to ALMR is to disrupt egg laying capacity, which confers egg retention and uterine expansion. We hypothesized that in the *sem-2(rf)* mutant, which is associated with considerable internal egg accumulation, additional touch neurons should experience increased proximity to eggs in the blocked uterus. Indeed, we find that in the *sem-2(rf)* background, every touch neuron that is positioned in the general region of the expanded uterus (ALML, AVM, PVM) increases exopher production, but the posterior PLM neurons, which cannot be approached by the gonad, do not produce exophers (Fig. 4G). Thus, touch neurons can be stimulated to produce exophers if the egg domain is artificially brought closer to them. Data are consistent with a model in which ALMR normally makes most exophers because of its closest natural positioning near the egg-filled uterus. Possibilities are that a diffusible signal may emanate from the filled uterus or that mechanical pressure associated with a filled uterus might signal enhanced exophogenesis.

## Uterine expansion associated with high egg load correlates with high exophogenesis

How might the presence of eggs signal to the maternal neurons to induce exophers? We consider two main possibilities: 1) eggs filling the uterus might exert physical pressure that activates essential stretch-signaling for young adult neuronal exopher release. This mechanical stretch signal might act directly (for example introducing chronic and/or dynamic pressure on the touch neurons), or indirectly (possibly inducing the stretched uterus/somatic gonad to release chemical signals that promote neuronal exopher formation); 2) early fertilized eggs might release a short-range chemical signal that contributes to young adult proteostasis reorganization <sup>54,55</sup> to promote exophogenesis.

To begin to dissect the role of egg pressure in promoting exophogenesis, we analysed the physical relationships of neurons, eggs and uterine shape. Eggs can readily be observed to distort tissue structure in young adult *C. elegans*. For example, in a strain that expresses GFP to label the hypodermis and expresses mCherry to label the touch neurons, the distortion of the hypodermis by eggs can be easily visualized as dark non-fluorescent eggs project through the observation plane of the hypodermis (Fig. 5A). Thus, the uterus can approach and pressure surrounding tissue, including touch neurons.

We quantitated the absolute uterine length as an indicator for stretch in relation to exopher production levels under representative condition of high and low exophogenesis. We found that egg retention mutants that exhibit high exophogenesis, *egl-3(tl)* (Fig. 5B), *egl-9(tl)* (Fig. 5C), and *sem-2(rf)* (Fig. 5D), had significantly longer egg zones (i.e., uterus length) as compared to wild type. In contrast, *cbd-1(RNAi)* (Fig. 5E), sperm-less induction with SPE-44 AID (Fig. 5F), and hyperactive egg-laying mutant *goa-1(tl)* (Fig. 5G), which we find to be strong exophogenesis suppressors, are all associated with short uterine egg zones. Knocking down either



**Figure 5.**

Uterine length measures for egg-laying defective and gastrulation defective mutants support the correlation of high exopher production and uterine expansion A. **Eggs can distort tissues in their vicinity.** Shown is strain ZB4942: *fxIs1[Ppie-1::TIR1::mRuby]* I; *bzIs166[P<sub>mec-4</sub>::mCherry]* II; *spe-44(fx110[*spe-44::degron*])* IV; *pwsI93[Phyp7::oxGFP::lgg-1]*, with touch neurons expressing mCherry (red); and the hypodermis expressing GFP. Dark round areas (white arrows) are eggs that press into the hypodermis when viewed in this focal plane. On the right, slit-like dark regions correspond to hypodermal seam cells.

B. Uterus length of WT vs. *egl-3(Δ)*; strain ZB4757: *bzIs166[P<sub>mec-4</sub>::mCherry]* II vs. ZB4904: *bzIs166[P<sub>mec-4</sub>::mCherry]* II; *egl-3(gk238)* V.  $n = \sim 20$  hermaphrodites from one trial. \*\*\*  $p < 0.001$  in two-tailed  $t$  test. Note that we did not normalize uterine length to body length in B-E. C. Uterus length of WT vs. *egl-9(Δ)* ZB4757: *bzIs166[P<sub>mec-4</sub>::mCherry]* II vs. ZB4772: *bzIs166[P<sub>mec-4</sub>::mCherry]* II; *egl-9(sa307)* V.  $n = \sim 20$  hermaphrodites from one trial. \*\*\*\*  $p < 0.0001$  in two-tailed  $t$  test. D. Uterus length of WT vs. *sem-2(rf)*; strain ZB4757: *bzIs166[P<sub>mec-4</sub>::mCherry]* II vs. ZB4902: *sem-2(n1343)* I; *bzIs166[P<sub>mec-4</sub>::mCherry]* II.  $n = \sim 20$  hermaphrodites from one trial. \*\*\*\*  $p < 0.0001$  in two-tailed  $t$  test. E. **Uterine length is short under *cbd-1*(RNAi) compared to WT + empty vector RNAi.** Uterus length of strain ZB4757: *bzIs166[P<sub>mec-4</sub>::mCherry]* treated with RNAi against *cbd-1* or control empty vector feeding RNAi.  $n = \sim 20$  hermaphrodites from one trial. \*\*\*\*  $p < 0.0001$  in two-tailed  $t$  test. F. **When sperm maturation is blocked in egg laying competent animals, leaving oocytes to occupy reproductive structures, the uterus length is short.** Uterus length of strain ZB4749: *fxIs1[P<sub>pie-1</sub>::TIR1::mRuby]* *zIs5[P<sub>mec-4</sub>::GFP]* I; *bzIs166[P<sub>mec-4</sub>::mCherry]* II; *spe-44(fx110[*spe-44::degron*])* IV. 1 mM auxin treatment induces the no sperm status.  $n = \sim 20$  hermaphrodites from one trial. \*\*\*\*  $p < 0.0001$  in two-tailed  $t$  test. G. **Uterine length is short in the hyperactive egg-laying mutant which has low occupancy of eggs in the uterus.** Uterus length of strain N2: wild type vs. strain MT2426: *goa-1(n1134)* I.  $n = 20$  hermaphrodites from one trial. \*\*\*\*  $p < 0.0001$  in two-tailed  $t$  test. H. **Knocking down the 4-cell stage gene *mex-3* or the gastrulation gene *gad-1* has normal uterine length.** Uterus length of strain ZB4757: *bzIs166[P<sub>mec-4</sub>::mCherry]* treated with RNAi against the *mex-3* or *gad-1* gene. *mex-3* RNAi disrupts embryonic development at the 4-cell stage, while *gad-1* RNAi disrupts gastrulation at the stage at which eggs are normally laid and perturbs later development but not egg shell formation and egg laying.  $n = \sim 20$  hermaphrodites from one trial. Not significant (ns) in two-tailed  $t$  test as compared to the empty vector control.

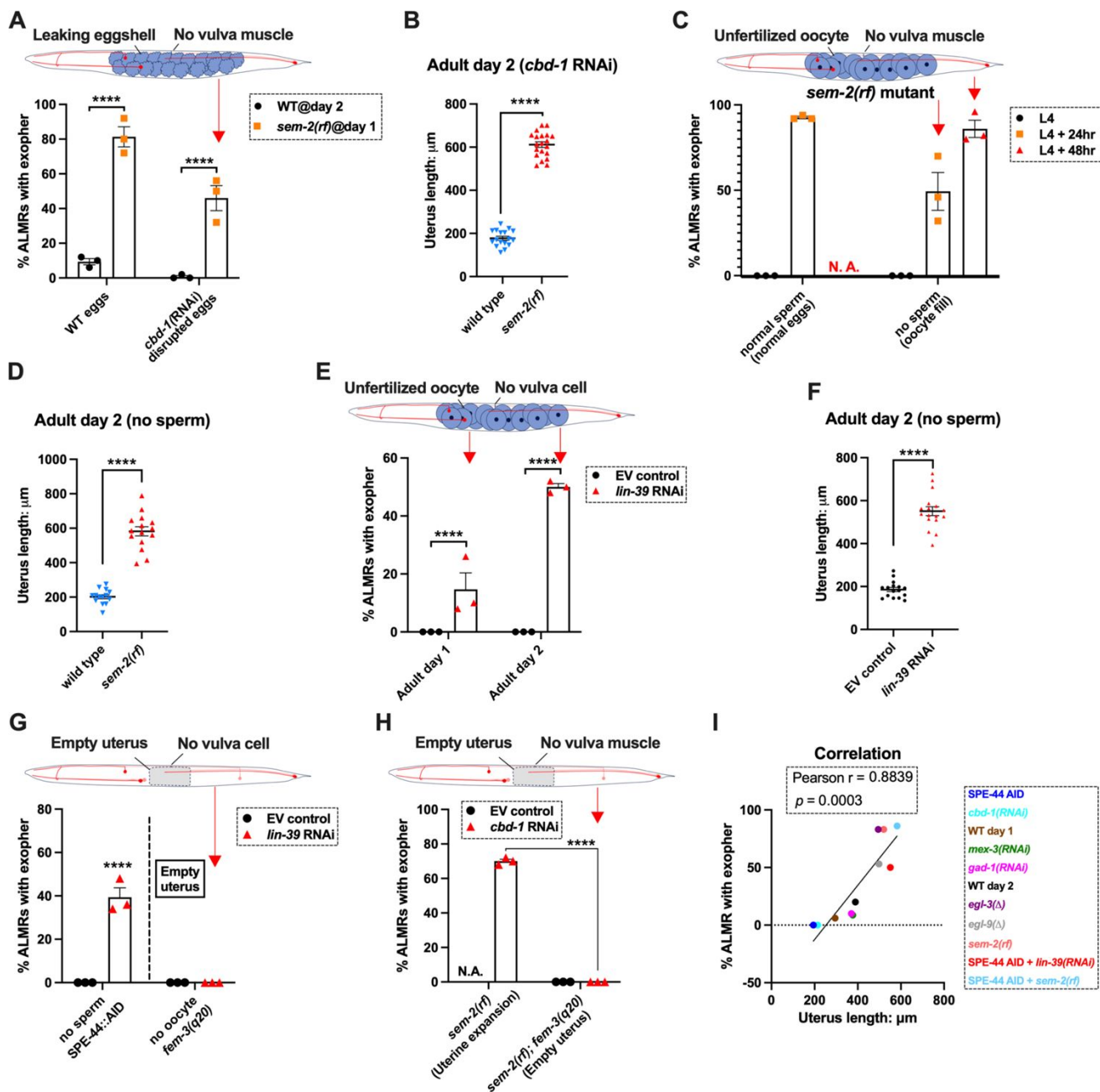
the 4-cell stage gene *mex-3* or the gastrulation gene *gad-1*, which are associated with neither egg retention nor exopher elevation, does not have an extended egg zone/uterine length (**Fig. 5H** [↗](#)), so not all developmental compromises are associated with uterine extension.

## Even when eggshell production and early embryonic divisions are disrupted, forced uterine expansion can elevate exopher levels

Our initial studies suggest extended uterine length is correlated with high exopher levels, but high egg retention is also a feature of an extended uterus. To begin test a requirement for fertilized eggs *per se* in the exopher influence, we asked whether egg viability is essential for promoting early adult exopherogenesis. We manipulated egg integrity/uterine contents in egg retention mutants by egg/embryo perturbation, testing for impact on exopherogenesis.

Under conditions of *cbd-1(RNAi)*, eggshell development and embryonic development are blocked; eggs that form are fragile and can be malformed consequent to passing through the spermatheca into the uterus; embryonic development does not proceed and egg remnants tend to be sticky <sup>56</sup> [↗](#). As shown in **Fig. 2B** [↗](#) (and again in **Fig. 6A** [↗](#)), treating WT reproductive animals (that have functional egg laying capacity) with *cbd-1(RNAi)* to kill embryos exerts a potent block on ALMR exopherogenesis. We proceeded to test the consequence of *cbd-1(RNAi)* in mutants that cannot extrude eggs or their remnants, and therefore would retain defective eggshell/dead embryos in the uterus.





**Figure 6.**

Uterine expansion correlates strongly with ALMR exophogenesis regardless of whether eggs, oocytes, or debris are retained. A. Despite *cbd-1(RNAi)* mediated disruption of eggshell formation and earliest embryonic cell divisions, exopher levels are high in the *sem-2(rf)* egg retention background. The percentage of ALMR exopher events among 50 Ad2 wild type (left) or Ad1 *sem-2(rf)* hermaphrodite *C. elegans* that are treated with either empty vector control RNAi or RNAi targeting *cbd-1* in each trial (total of 3 independent trials). *sem-2* mutants bag extensively at Ad2 and cannot be tested. Cartoon indicates uterine filling status of test *sem-2(rf); cbd-1(RNAi)*. Strain ZB4757: bzIs166[P<sub>mec-4</sub>::mCherry] II vs. strain ZB4902: *sem-2(n1343)* I; bzIs166[P<sub>mec-4</sub>::mCherry] II. \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test. B. **Uterine length remains long in the egg-laying defective *sem-2(rf)* + *cbd-1(RNAi)*.** Uterus length of strain ZB4757: bzIs166[P<sub>mec-4</sub>::mCherry] II vs. ZB4902: *sem-2(n1343)* I; bzIs166[P<sub>mec-4</sub>::mCherry] II treated with RNAi against *cbd-1*.  $n = \sim 20$  hermaphrodites from one trial, Ad2, \*\*\*\*  $p < 0.0001$  in two-tail unpaired *t*-test. C. Blocking sperm maturation in a *sem-2(rf)* mutant, which fills the uterine space with oocytes, induces exophers in the absence of eggs. The percentage of ALMR exopher events among 50 *sem-2(rf)* hermaphrodite *C. elegans* that express the SPE-44 AID system (“control” is treated with 0.25% ethanol vehicle and “no sperm” is treated with 1mM auxin in 0.25% ethanol from egg to adult day 2) in each trial (total of 3 independent trials). L4 stage is the last larval stage before adult. Cartoon indicates uterine oocyte filling status of test *sem-2(rf); spe-44 AID*. Strain ZB4953: *sem-2(n1343)* fxIs1[P<sub>pie-1</sub>::TIR1::mRuby] I; bzIs166[P<sub>mec-4</sub>::mCherry] II; *spe-44(fx110[spe-44::degron])* IV. D. **When sperm maturation is disrupted in mutants blocked for egg laying, leaving oocytes to occupy reproductive structures, the uterus expands as oocytes accumulate.** Uterus length of strain ZB4749: fxIs1[P<sub>pie-1</sub>::TIR1::mRuby] zdIs5[P<sub>mec-4</sub>::GFP] I; bzIs166[P<sub>mec-4</sub>::mCherry] II; *spe-44(fx110[spe-44::degron])* IV vs. ZB4953: *sem-2(n1343)* fxIs1[P<sub>pie-1</sub>::TIR1::mRuby] I; bzIs166[P<sub>mec-4</sub>::mCherry] II; *spe-44(fx110[spe-44::degron])* IV. 1 mM auxin treatment induces the no sperm status to both strains.  $n = \sim 20$  hermaphrodites from one trial, Ad2. \*\*\*\*  $p < 0.0001$  in two-tail unpaired *t*-test. E. Disrupting sperm maturation in *lin-39(RNAi)* animals blocked for egg-laying fills the uterine space with oocytes, and induces exophers in the absence of eggs. The percentage of ALMR exopher events among 50 adult day 1 or 2 SPE-44 AID no sperm hermaphrodite *C. elegans* treated with either control RNAi or *lin-39* RNAi in each trial (total of 3 independent trials). Cartoon indicates uterine oocyte filling status of test *lin-39(RNAi); spe-44 AID*. ZB4749: fxIs1[P<sub>pie-1</sub>::TIR1::mRuby] zdIs5[P<sub>mec-4</sub>::GFP] I; bzIs166[P<sub>mec-4</sub>::mCherry] II; *spe-44(fx110[spe-44::degron])* IV. \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test. F. When sperm maturation is blocked, leaving oocytes to occupy reproductive structures, the uterus length is short; but if oocytes cannot be laid in the *lin-39(RNAi)* background, the uterus expands as oocytes accumulate. Uterus length of strain ZB4749: fxIs1[P<sub>pie-1</sub>::TIR1::mRuby] zdIs5[P<sub>mec-4</sub>::GFP] I; bzIs166[P<sub>mec-4</sub>::mCherry] II; *spe-44(fx110[spe-44::degron])* IV + 1 mM auxin treatment to eliminate sperm maturation.  $n = \sim 20$  hermaphrodites. \*\*\*\*  $p < 0.0001$  in two-tail unpaired *t*-test. G. Blocking oocyte production in the background of *lin-39(RNAi)*-mediated disruption of the egg-laying apparatus eliminates early adult exophogenesis. We used *spe-44 AID* to block sperm maturation and *fem-3(q20)* to prevent oocyte production; *lin-39(RNAi)* to disrupt egg-laying capacity. Cartoon indicates empty uterus status of test *fem-3(q20); spe-44 AID; lin-39(RNAi)* strain. Exopher scoring of Ad2 ZB4749: fxIs1[P<sub>pie-1</sub>::TIR1::mRuby] zdIs5[P<sub>mec-4</sub>::GFP] I; bzIs166[P<sub>mec-4</sub>::mCherry] II; *spe-44(fx110[spe-44::degron])* IV + 1 mM auxin or ZB5042: bzIs166[P<sub>mec-4</sub>::mCherry] II; *fem-3(q20)*ts IV, treated with either control empty vector (EV) RNAi or *lin-39* RNAi at 25°C. Total of three trials (50 worms per trial). \*\*\*\*  $p < 0.0001$  in Cochran–Mantel–Haenszel test. H. Blocking oocyte production in the background of *sem-2(rf)*-mediated disruption of the egg-laying apparatus eliminates early adult exophogenesis. We used *cbd-1(RNAi)* to disrupt eggshell and *fem-3(q20)* to prevent oocyte production; *sem-2(n1343)* to disrupt egg-laying capacity. Exopher scoring of adult day 2 hermaphrodites, treated with either control empty vector (EV) RNAi or *cbd-1* RNAi at 25°C. Total of three trials (50 worms per trial). Cartoon indicates empty uterus status of test *fem-3(q20); cbd-1(RNAi); sem-2(rf)* strain. I. **The uterus length is correlated with ALMR exophogenesis.** Data shown are the mean of uterus length (X axis) and percentage ALMRs with exopher (Y axis) for different genotypes/treatments measured in this study. The correlation line is based a linear fit model and the Pearson *r* and *p* value is based on the correlation assay. Uterus length from short to long: SPE-44::AID; *cbd-1(RNAi)*; wild type (adult day 1); *mex-3(RNAi)*; *gad-1(RNAi)*; wild type (adult day 2); *egl-3(11)*; *egl-9(11)*; *sem-2(rf)*; SPE-44::AID + *lin-39(RNAi)*; SPE-44::AID + *sem-2(rf)*.



We subjected the *sem-2(rf)* egg-laying defective mutant to *cbd-1(RNAi)* so that the uterus would fill with eggshell/dead embryo remains. Strikingly, we found that *cbd-1(RNAi)*/dead embryo retention in the *sem-2(rf)* background is still associated with significantly elevated levels of ALMR exophogenesis (~45%), while in egg-laying proficient wild type, barely any ALMR exophogenesis is observed under *cbd-1(RNAi)* conditions (<1%) (69/150 for *sem-2* egg-laying blocked *cbd-1(RNAi)* vs. 1/150 for egg-laying proficient *cbd-1(RNAi)*, **Fig. 6A** [↗](#)).

Importantly, under conditions of defective eggshell/dead embryo retention associated with *cbd-1(RNAi)*; *sem-2(rf)*, the uterine egg zone is expanded (**Fig. 6B** [↗](#)), extending the correlation of exopher production with uterine length. We conclude that intact eggshells and earliest embryonic divisions are not required for the boost in exopher production observed when uterine contents are forced to accumulate—uterine retention of dead eggs and egg remnants is sufficient for exopher elevation if the egg laying apparatus is defective. Expansion of the uterine compartment, rather than eggshell/embryo integrity, tracks with exopher elevation.

## Forced uterine expansion via oocyte accumulation can elevate exopher levels

Although uterine retention of malformed inviable embryos is sufficient to elevate neuronal exophers when egg laying is blocked, the defective *cbd-1* embryos or debris might still release egg-associated chemical signals. To test for a requirement of any fertilization-dependent egg signals in the egg-laying compromised mutants, we asked whether uterine filling with only oocytes can suffice to promote neuronal exopher elevation. Unfertilized oocytes cannot initiate embryonic development or egg-shell biosynthesis; nor can oocytes elevate ALMR exophogenesis in hermaphrodites that are proficient at egg-laying (**Fig. 1G** [↗](#) & **H**).

We tested two distinct uterine retention conditions—*sem-2(rf)* and *lin-39(RNAi)*—in which we used the auxin inducible degron system to disrupt sperm maturation such that only oocytes filled the gonad. Note that in the absence of sperm, oocytes do not mature but are “ovulated” at a much reduced rate; oogenesis continues such that ~25 oocytes are typically found stacked in the gonad (**Fig. S6** [↗](#)). For both genetic retention strategies, we found that build-up of retained oocytes in egg-laying blocked animals was sufficient to elevate exophers (**Fig. 6C** [↗](#) & **E**) and expand the uterus (**Fig. 6D** [↗](#) & **F**; **Fig. S6**).

Moreover, the oocyte retention was similarly efficacious in elevating exopher production to egg retention, increasing ALMR exophogenesis to approximately 80% in the *sem-2(rf)* mutant (**Fig. 6C** [↗](#)). We conclude that fertilization, egg shells and egg remnants are not essential for the early adult exopher peak. Expansion of the uterus with unfertilized oocytes can suffice to elevate neuronal exopher formation.

## Lack of a functional egg-laying apparatus does not induce exopher elevation when the uterus is not filled

The above-described experiments left open the possibility that the lack of a functional egg-laying apparatus itself might be causative in the elevation of exopher production. To address this possibility, we compared disruption of sperm (permissive for oocyte accumulation) to disruption of oogenesis (effectively empties the uterus) when egg-laying capacity was compromised by *lin-39(RNAi)* (**Fig. 6G** [↗](#)). *lin-39(RNAi)* + oocyte retention promotes exopher formation, but eliminating oocytes (*fem-3(gf)*) eliminates exopher elevation even when egg-laying is blocked by *lin-39(RNAi)*. That is to say, although oocyte accumulation with uterine expansion suffices to elevate exophers, removing the oocytes and uterus occupancy eliminates the exopher boost. We observe the same outcome of suppressed exopher formation when *cbd-1(RNAi)*-induced dead embryo retention in

the *sem-2(rf)* egg-laying defective mutant (which is exopher-inducing) is prevented from oocyte production by *fem-3(gf)* (Fig. 6H). Thus, disruption of egg laying on its own is not the driving factor in high exopherogenesis; rather, uterine filling is required.

We revisited the relationship of uterine length and exopher level by adding data from the studies with oocyte retention to reinforce the conclusion that ALMR exopherogenesis is strongly correlated with the level of uterus stretching caused by the accumulation of uterine contents (Fig. 6I).

## Sustained physical distortion of the gonad by fluid injection can rapidly elevate exopher production

To independently test for a role for physical stretch/filling of the uterus in exopher induction, we distorted the gonad compartment by injecting dye-containing M9 buffer into a very young adult. The animal subjects we tested were vulva-less (*lin-39(RNAi)*) and also subjected to *spe-44* AID to block sperm production. These vulva-less + sperm-less hermaphrodites normally exhibit high ALMR exopherogenesis at late Ad1 and Ad2 (Fig. 6C&D) due to oocyte accumulation. To avoid oocyte influence, we conducted our physical expansion studies just as animals reach Ad1, a time when ALMR exopherogenesis is typically not observed (Fig. 7A).

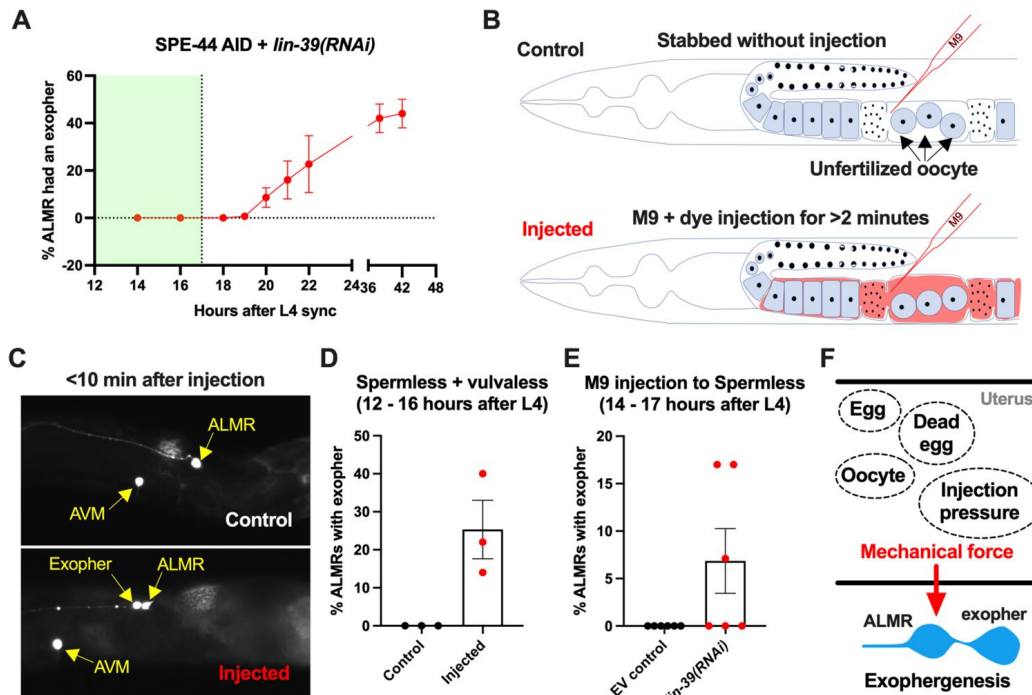
We picked the L4 stage vulva-less (*lin-39(RNAi)*) + sperm-less (SPE-44 AID) hermaphrodites for age synchronization (20°C, grown for 12 hours after L4 selection) and then injected dye containing M9 buffer into the uteri of these very young adult day 1 hermaphrodites, scoring for exopher production ~10 minutes after the injection (Fig. 7B).

Control animals (mock injected animals that were stabbed without fluid delivery) exhibited no ALMR exophers. By contrast, we found that when we held injection pressure continuous for 2 or more minutes, ~20% of the ALMs scored exhibited an exopher event shortly after injection (Fig. 7C&D). Injection experiments using animals with functional vulvae (in which injected material is rapidly extruded through the vulval opening) failed to induce ALMR exophers (Fig. 7E), supporting that ALMR exopherogenesis caused by 2-minute injection of dye-containing M9 is due to the physical distortion of gonad rather than the chemical impact of the dye-containing M9.

In sum, exopher induction by uterine accumulation of eggs, malformed eggs, dead embryos, oocytes, or fluid-induced expansion support a model in which early adult ALMR exopherogenesis is elevated by physical distortion of the uterus that occurs with reproduction (Fig. 7F).

## Discussion

Exopher production by proteo-stressed *C. elegans* touch neurons occurs with a striking temporal pattern that features an early adult peak of exopherogenesis coincident with the period of maximal egg production. Here we report that the early exopherogenesis peak is dependent on uterine occupation, which normally is conferred by fertilized egg accumulation prior to the deposition of eggs. Uterine expansion that is associated with the filling of a blocked uterus with unfertilized oocytes or by fluid alone can also induce high neuronal exopher production, supporting a model in which the physical distention associated with uterine occupancy, rather than chemical signals derived from fertilized eggs *per se*, is a required component of the signaling relay between reproduction and young adult neuronal debris elimination. Trans-tissue cross talk to the maternal nervous system thus appears accomplished via mechanical force transduction. Our findings hold implications for mechano-biology in neuronal proteostasis management.



**Figure 7.**

ALMR exophogenesis can be induced by uterine compartment distortion that accompanies fluid injection **A. Summary of timing of ALMR exophogenesis from age synchronized spermless + vulvaless hermaphrodite.** Total of three trials and 50 hermaphrodites in each trial. Strain ZB4749: *fxIs1[P<sub>pie-1</sub>::TIR1::mRuby]* *zdIs5[P<sub>mec-4</sub>::GFP]* I; *bzIs166[P<sub>mec-4</sub>::mCherry]* II; *spe-44(fx110[*spe-44::degron*])* IV, cultured on the 1 mM auxin treated NGM agar plates seeded with HT115 *E. coli* expressing dsRNA against the *C. elegans lin-39* gene. Eventually, oocytes accumulate in this strain, but at worst very few are evident in the timeframe in which we performed injections. Data shown are mean  $\pm$  SEM at each time point. The data demonstrate that there is no ALMR exophogenesis in this background before the 18<sup>th</sup> hour after L4 sync. Testing the impact of injection on ALMR exophogenesis before the 17<sup>th</sup> hour after L4 thus monitors injection consequences during a timeframe in which no exophers are normally produced. **B. Illustrated experimental design for testing the ALMR exophogenesis response to physically expanding the gonad via 2 minute continuous fluid injection.** We performed 2+ minute duration injections of M9 buffer mixed with food color dye 1:10 or 1.5:10 dye/M9 ratio (to verify successful injection; dye contains water, propylene glycol, FD&C reds 40 and 3, propylparaben) into the uteri of sperm-less only (EV control) or sperm-less + vulvaless (treated with *lin-39* RNAi) animals. Strain: ZB4749 as in panel A, treated with either empty vector (EV) or RNAi against *lin-39* in the presence of 1 mM auxin. *lin-39(RNAi)* disrupts vulval development such that injected fluids are retained to expand the uterus. In injections with animals that have functioning egg laying apparatus, fluids can exit the animal and do not expand the uterus. **C. 2 minute sustained injection into egg-laying blocked, reproduction blocked animals can induce rapid exophogenesis:** representative picture of an ALMR exophogenesis event consequent to injection. **D. 2 minute sustained injection into egg-laying blocked, reproduction blocked animals can induce rapid exophogenesis:** exopher scoring of the control mock injected and 2 minute injected animals. Strain ZB4749: *fxIs1[P<sub>pie-1</sub>::TIR1::mRuby]* *zdIs5[P<sub>mec-4</sub>::GFP]* I; *bzIs166[P<sub>mec-4</sub>::mCherry]* II; *spe-44(fx110[*spe-44::degron*])* IV treated with auxin and *lin-39(RNAi)* to induce the sperm-less and vulva-less status, respectively. Data represent a total of three trials (6 to 10 worms in each trial).  $p < 0.05$  in Cochran-Mantel-Haenszel test, as compared to the no-injection fluid control. **E. 2 minute sustained injection induces rapid ALMR exophogenesis only from vulvaless animals.** Data showing the exopher scoring of the sperm-less EV control (with functional vulva) or sperm-less + vulvaless (treated with *lin-39* RNAi) worms. Strain: ZB4749 (genotype in panel A legend) treated with either empty vector (EV) or RNAi against *lin-39* in the presence of 1 mM auxin to disrupt sperm maturation. Data represent a total of 6 trials (6 to 10 worms in each trial). 3 out of 6 trials showed ALMR exopher induction by M9 injection to the vulvaless worms; while not a single trial produced ALMR exopher induction by M9 injection to animals with WT vulvae. If the vulva is intact, injected fluids are observed to leak out, consistent with the assumption that the gonads of egg-laying proficient animals will not sustain required expansion. **F. Summary.** Eggs, dead egg accumulation, oocyte accumulation, or injection pressure all lead to ALMR exophogenesis. These varied interventions have a similar impact on the uterus, which is the uterine distortion by mechanical forces. We propose that early adult ALMR exophogenesis requires mechanical or stretch-associated force generated by the uterine cargos.

## The mechanical landscape of reproduction that influences neuronal exophogenesis

*C. elegans* reproduction features physical expansion and contraction of multiple tissue/cell types--the gonad houses the expanding germline, the spermatheca expands and retracts vigorously as each mature oocyte enters and exits. The uterus also stretches to house eggs and can contract locally as eggs transit or are expelled via action of the vulval and uterine muscles. The filled reproductive apparatus can thus clearly exert both constitutive and sporadic pressure on surrounding tissues as it enacts its essential functions.

What is the source of the force that promotes exopher production? Elegant work on the egg laying circuit (comprising the somatic gonad, the HSN and VC neurons, and the vulval and uterine muscle) has provided evidence for mechanical signaling within the egg laying circuit that regulates initiation, promotion and termination of egg laying <sup>30,58-60</sup>. Working backward, exopher-promoting force seems unlikely to derive from the vulva or vulval muscle contractions, since when these cells are genetically disrupted in *lin-39(RNAi)* or in *sem-2* mutants, high levels of exophers still are generated. Changes in spermatheca volume, which expands and contracts dramatically as mature oocytes enter via valve opening/closure <sup>61</sup>, might be sensed, but spermatheca contractions are reported to be normal in hyperactive egg laying *goa-1* <sup>62</sup>, which is an exopher-suppressing background. Under no-sperm conditions, oocyte transit rates are lower than for fertilized eggs, and sperm-derived signals influence spermathecal valve opening <sup>57,63,64</sup>, but if the egg laying apparatus is genetically compromised and oocytes accumulate in the absence of sperm, exopher levels are high, suggesting deficits in spermatheca operations or sperm signals *per se* do not drive exophogenesis. Given that under normal reproductive conditions of egg-laying proficiency, correctly shelled eggs are required for the early peak in exopher production, a plausible hypothesis was that fertilized eggs might produce an essential diffusible factor that stimulates neuronal exopher-genesis. However, exophers can be produced abundantly in the absence of fertilized eggs when the vulva is unable to open and release uterine contents, resulting in uterine distention due to debris filling. Thus, the simplest model we envision for the reproductive cues that influence maternal neuronal exophogenesis is that a filled uterus (under normal conditions the consequence of hard-shelled eggs that occupy it) is sensed and required for the early adult peak in exopher production.

## How might force be sensed and transduced?

Mechanotransduction is the sensing of a mechanical signal, such as pressure or stretch, and conversion into a cellular response. Members of several ion channel families have been implicated in sensing of touch, hearing, shear stress, and pressure, including Piezo, TRP, and DEG/ENaC families <sup>65</sup>. These are rational candidates for mechanosensors in neurons, the uterus, or other cells that might act in a relay between the uterus and neuron.

At the same time, classic mechanosensory channels have extremely rapid gating and might not be the best suited candidates for acting in the sustained and locally dynamic forces anticipated for the reproductive uterine environment. Adhesion G-Protein Coupled Receptors, which have extracellular adhesion motifs and 7 transmembrane domains characteristic of the GPCR class (*lat-1*, *lat-2*, *cdh-6* in *C. elegans* <sup>66-68</sup>), or components of the YAP/TAZ transcriptional program <sup>69</sup> may integrate responses to forces transmitted via the cytoskeleton and could be considered as potential players in the required signaling.

Determination of the identity of mechanotransducers and assignment of site of action to the neuron, the uterus, or an intermediate relay cell type remains for future studies. Modeling will also need to incorporate the fact that fluid injections, which required 2 minute long sustained

application of the filling stimulus to induce exophers, could provoke exopher production on a rapid timeframe, typically recorded only 10 minutes after injection period. Thus the proteostressed touch neurons appear poised to eliminate contents upon mechanical stimulation.

## Mechanical signaling in reproduction across species

Uterine stretch may be a more prevalent mechanism for inducing maternal nervous system response than currently appreciated. Distention of the female fly reproductive tract by egg passage through the tract (normal biology) or by artificial means (experimental fluid injection) can induce behavioral attraction of the mother to acetic acid, thought to signal a favorable food environment for offspring<sup>70</sup>. In this case, DEG/ENaC channel family member PPK1 expressed in a subset of mechanosensitive neurons that tile the reproductive tract and respond to its contraction/distention is required. The pathway to the behavioral change remains to be determined. Uterine stretch in mammals has also been reported influence maternal behavior<sup>71</sup>.

## Why link exophers to reproduction?

Turek et al. report that exophers produced by *C. elegans* muscle cells follow a similar time course of highest production at adult day 2, and demonstrated a dependence of the temporal muscle exophogenesis pattern on eggs, and commonly higher close to the uterus<sup>72</sup> (muscle exophers may be released to supply nutrients to developing progeny). Together with our observations, data raise the possibility that the onset of reproduction and the initial filling of the uterus triggers, or generates a “license” for EV/exopher production across tissues. In the case of stressed touch receptor neurons that have been our focus, evidence suggests that deleterious protein aggregates and/or excess proteins and organelles are handed off to neighboring glial-like hypodermal cells for degradation<sup>7</sup>. Clearing the nervous system (and other organs) for optimal function might confer a selective advantage for successful maternal reproduction.

In this regard it is fascinating that the peak exopher production period is coincident with a proteostasis reconfiguration that has been well documented to accompany reproduction onset in young adult *C. elegans*. In brief, during larval development *C. elegans* exhibits high activity of HSF-1 and consequently HSF-1-dependent chaperone expression, but HSF-1 activity is turned down in adult life<sup>54,55,73,74</sup>. At the same time in early adult life, proteasome activity is relatively enhanced (at least as measured in the hypodermis)<sup>75</sup>. These measures may reflect a general proteostasis reorganization (chaperone activity, proteasome activity) that occurs in early adult life in response to reproduction<sup>54,73</sup>. Our observations on neuronal exophers suggest that exopher-mediated content elimination may constitute another co-regulated branch of this proteostasis reconfiguration. Importantly, the HSF-1 turn-down in young adult life is blocked by *cbd-1(RNAi)* (and additional early eggshell/development gene RNAi)<sup>74</sup>. Thus the presence of eggs can signal across tissues to turn-down *hsf-1* proteostasis-related activities in the mother. We speculate that this young adult reconfiguration of proteostasis might reflect a mechanism to optimize successful reproduction, possibly both fine tuning nervous system function and shifting resources balance to favor progeny as suggested by the disposable soma theory of aging proposed by Kirkwood<sup>76</sup>.

Of note, we do not observe exophers in larval stages<sup>3</sup>. We speculate that young adult physiology might be temporally tweaked such that some tissues have optimized capacity to manage/degrade large aggregates and organelles at an early adult developmental “clean up” time, possibly analogous to how a town service for bulky oversized garbage pick-up might be limited to particular times during the year. As exopher production appears generally beneficial for neuronal function and survival<sup>3,77</sup>, the early life extrusion phase appears a positive feature of reproductive life. More broadly, proteome “clean up” phases may be programmed as key steps at specific transitions during development and homeostasis, for example, as occurs in the temporal



lysosome activation that clears aggregate debris in *C. elegans* maturing oocytes <sup>78</sup> or in the maturation of mouse adult neuronal stem cells via vimentin-dependent proteasome activity during quiescence exit <sup>79</sup>.

Across species, production of exopher-like vesicles may also be enhanced by mechanical signals anchored outside of reproduction. For example, mice cardiomyocytes that are constantly under mechanical stress due to contraction activities produce exopher-like vesicles <sup>80</sup>. Mouse kidney proximal tubular epithelia cells (PTEC) under constant mechanical stress due to both fluid shear stresses and absorption-associated osmotic pressure, also release exopher-like vesicles <sup>80</sup>.

## Large vesicle extrusion, mechanobiology and neurodegenerative disease

The impact of mechanical force on *in vivo* production of extracellular vesicles has not been a major focus of the EV field, although a range of studies have considered force consequences (such as fluid shear responses, stretch) in cultured cells. Overall, however, EV biogenesis and uptake appear to be markedly influenced by biomechanical force type, magnitude, and duration <sup>81</sup>. At the same time, the neurodegeneration field has generated myriad studies linking Alzheimer's disease susceptibility and AD pathology signatures such as extracellular accumulation of amyloid- $\beta$  protein and/or intracellular accumulation of tau as outcomes of mechanical stress-based stimuli such as traumatic brain injury, arterial hypertension, and normal pressure hydrocephalus <sup>82,83</sup>. Mechanical stress may trigger or promote protein misfolding, aggregation, and extrusion. Examples of recent implication of mechanical stimuli in AD-related outcomes include that stretch in the brain vascular system can increase APP and B-secretase expression to increase A $\beta$  production <sup>84</sup> and that microglial mechanosensing via the Piezo1 mechanotransducing channel limits progression of A $\beta$  pathology in mouse models <sup>85</sup>. Our study reveals a capacity of mechanical force to influence neuronal release of large vesicles containing neurotoxic species, inviting more serious consideration of the roles of mechanobiology in maintaining proteostasis and influencing aggregate transfer within the context of a living nervous system.

## Methods and materials

### Strains and maintenance

All strains used in this study carry the transgene bzIs166[P<sub>mec-4</sub>::mCherry] to mark the six touch receptor neurons: ALMR, ALML, AVM, PVM, PLMR and PLML. The genotype of *C. elegans* strains used in this study are listed in **Table 1**. We maintained all *C. elegans* strains on nematode growth media (NGM) seeded with OP50-1 *Escherichia coli* in a 20°C or 15°C incubator. We kept all animals on food for at least 10 generations before using them in test.

### Age synchronization

For the majority of experiments, we used a bleaching protocol or an egg-laying protocol for age synchronization, otherwise, we picked L4 animals for synchronization.

### Temperature sensitive mutants

We maintained the age-synchronized temperature sensitive mutations in a 15°C incubator. For either *fem-1* or *fem-3* mutants, we directly placed the isolated eggs into a 25°C incubator in each experimental test. Since the egg-hatching of *glp-4* mutant is out of sync at 25°C, we placed the isolated eggs in a 15°C incubator for 24 hours before transferring them into the 25°C incubator for experimental tests.



| Strain Name | Genotype                                                                                                                                                                                              | Index                                |
|-------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------|
| N2          | wild type                                                                                                                                                                                             | wild type                            |
| ZB4065      | bzIs166[P <sub>mec-4</sub> ::mCherry] II                                                                                                                                                              | wild type                            |
| ZB4757      | bzIs166[P <sub>mec-4</sub> ::mCherry] II (outcrossing ZB4065 to N2 for 6 times)                                                                                                                       | wild type                            |
| ZB4768      | <i>glp-4(bn2)<sup>ts</sup></i> I; bzIs166[P <sub>mec-4</sub> ::mCherry] II                                                                                                                            | <i>glp-4(ts)</i>                     |
| ZB5042      | bzIs166[P <sub>mec-4</sub> ::mCherry] II; <i>fem-3(q20)</i> IV                                                                                                                                        | <i>fem-3(gf)</i>                     |
| ZB4915      | bzIs166[P <sub>mec-4</sub> ::mCherry] II; <i>fem-1(hc17)</i> IV                                                                                                                                       | <i>fem-3(lf)</i>                     |
| ZB4749      | fxIs1[P <sub>pie-1</sub> ::TIR1::mRuby] zdIs5[P <sub>mec-4</sub> ::GFP] I; bzIs166[P <sub>mec-4</sub> ::mCherry] II; <i>spe-44(fx110[spe-44::degron])</i> IV.                                         | SPE-44                               |
| ZB4941      | bzIs166[P <sub>mec-4</sub> ::mCherry]; <i>gna-2(gk308)</i> I/hT2 [ <i>bli-4(e937)</i> <i>let-?(q782)</i> qIs48[P <sub>myo-2</sub> ::GFP; P <sub>pes-10</sub> ::GFP; P <sub>ges-1</sub> ::GFP] (I;III) | <i>gna-2(Δ)</i>                      |
| AD295       | <i>spe-45(tm3715)</i> ; <i>him-5(e1490)</i> ; asEx89 [ <i>spe-45</i> "fosmid 1" mixture + P <sub>myo-3</sub> ::gfp]                                                                                   | <i>spe-45(tm3715)</i>                |
| ZB4772      | bzIs166[P <sub>mec-4</sub> ::mCherry] II; <i>egl-9(sa307)</i> V                                                                                                                                       | <i>egl-9(Δ)</i>                      |
| ZB4904      | bzIs166[P <sub>mec-4</sub> ::mCherry] II; <i>egl-3(gk238)</i> V                                                                                                                                       | <i>egl-3(Δ)</i>                      |
| ZB4902      | <i>sem-2(n1343)</i> I; bzIs166[P <sub>mec-4</sub> ::mCherry] II                                                                                                                                       | <i>sem-2(rf)</i>                     |
| ZB5352      | <i>goa-1(n1134)</i> I; bzIs166[P <sub>mec-4</sub> ::mCherry] II                                                                                                                                       | <i>goa-1(Δ)</i>                      |
| ZB5046      | Ex [(pJC4) P <sub>mec-3</sub> ::gfp + pRF4]; bzIs166[P <sub>mec-4</sub> ::mCherry] II                                                                                                                 | pJC4 + <i>rol-6(su1006)</i>          |
| ZB4942      | fxIs1[P <sub>pie-1</sub> ::TIR1::mRuby] I; bzIs166[P <sub>mec-4</sub> ::mCherry] II; <i>spe-44(fx110[spe-44::degron])</i> IV; pwSi93[P <sub>hyp7</sub> ::oxGFP::lgg-1]                                | Fig, 5A                              |
| ZB4953      | <i>sem-2(n1343)</i> fxIs1[P <sub>pie-1</sub> ::TIR1::mRuby] I; bzIs166[P <sub>mec-4</sub> ::mCherry] II; <i>spe-44(fx110[spe-44::degron])</i> IV                                                      | <i>sem-2(rf)</i>                     |
| ZB5709      | <i>sem-2(n1343)</i> I; bzIs166[P <sub>mec-4</sub> ::mCherry] II; <i>fem-3(q20)</i> IV.                                                                                                                | <i>sem-2(rf)</i> ; <i>fem-3(q20)</i> |
| OD298 4     | ItSi953 [P <sub>mec-18</sub> ::vhhGFP4::zif-1::operon-linker::mKate::tbb-2 3'UTR + <i>Cbr-unc-119(+)</i> ] II; <i>unc-119(ed3)</i> III                                                                | Single-copy transgene                |

**Table 1**

## Strain list

## Auxin inducible degradation

We dissolved auxin (indole-3-acetic acid, 98+%, A10556, Alfa Aesar) in 95% ethanol to make a 400 mM stock, then we prepared a 40 mM auxin solution by diluting the 400mM stock solution in M9 medium (which contains 1mM MgSO<sub>4</sub>) and applied 200 ul of the 40 mM solution on to the NGM-agar plate (which is 60 mm in diameter and contains ~8-9 g medium). We left the plate on an open bench at room temperature for one or two days to dry out the auxin solution, then seeded the plate with 200 ul OP50-1 *E. coli* and waited for another two or three days before storing the plates in a 4°C environmental room. We only used the plates which had been stored in the 4°C environmental room for at least a week, so the concentration of auxin can be equilibrated into 1 mM. We prepared the ethanol control plates under the same procedure, and the final concentration of ethanol in the control plates should be ~0.25%.

To proceed auxin inducible degradation of SPE-44, we placed the isolated eggs on auxin treated plates or the ethanol control plates. After ~72 hours of culture in a 20°C incubator, the animal reached the age of adult day 1 and the auxin treated worms became sterile. Then we transferred the worms into a regular NGM-agar plate without auxin or ethanol.

## Microscopy and image processing

We took the DIC or fluorescent pictures with a Zeiss compound microscope or spinning disc confocal microscope driven by MetaMorph software, then processed the pictures with Fiji ImageJ software.

## Exopher scoring

Exopher numbers vary in experiments between 5-30%, mostly 10-15% range, and typically reach peak at adult day 2 <sup>3</sup>[\[3\]](#). Exphers can remain intact for approximately 2 hours, but the vesicle form of exophers is mostly identifiable in the following 24 hours. Therefore, the exopher count includes both the intact form and the fragmented degraded form, also known as “starry night” <sup>7</sup>[\[7\]](#). We scored the exopher count with the protocol published in JoVE <sup>14</sup>[\[14\]](#). We age-synchronized the animal via egg-laying, bleaching, or L4 picking. Then, we examined at least 50 animals for each genotype or treatment with the FBS10 Fluorescence Biological Microscope (KRAMER scientific), repeated for at least 3 trials.

## RNAi treatment

All RNAi clones used in this study are coming from the Ahringer RNAi library. The NGM-agar RNAi plate contains 1 mM IPTG and 25 µg/ml carbenicillin. The food on top of the medium is HT115 bacteria expressing dsRNA against targeted gene or carrying an empty vector (EV, L4440) as the control. The treatment is from eggs to the last day of each test.

## FUDR treatment

The concentration of FUDR (5-fluorodeoxyuridine) on NGM-agar plate is ~51 mM. The treatment started from adult day 1.

## Male mating experiment

In each trial, we prepared ~2000 age synchronized adult day 1 hermaphrodites and did exopher counting for 50 worms from adult day 1 to day 3. In adult day 3, we divided the worms into three groups (~400 worms in each group, and ~100 worms per plate). Group 1 is the control worms without males. We added ~100 sterile males into group 2 and ~100 normal males into group 3 for each plate.

## Electron microscopy

We prepared mCherry animals for TEM analysis by high pressure freezing and freeze substitution (HPF/FS), and followed a standard to preserve ultrastructure. After HPF in a Baltec HPM-010, we exposed animals to 1% osmium tetroxide, 0.1% uranyl acetate in acetone with 2% water added, held at  $-90^{\circ}\text{C}$  for 4 days before slowly warming back to  $-60^{\circ}\text{C}$ ,  $-30^{\circ}\text{C}$ , and  $0^{\circ}\text{C}$ , over a 2 day period. We rinsed the samples several times in cold acetone and embedded the samples into a plastic resin before curing them at high temperatures for 1–2 days. We collected serial thin sections on plastic-coated slot grids and post-stained them with 2% uranyl acetate and then with 1:10 Reynold's lead citrate, and examined with a JEOL JEM-1400 Plus electron microscope. By observing transverse sections for landmarks such as the 2nd bulb of the pharynx, it was possible to reach the vicinity of the ALM soma before collecting about 1500 serial thin transverse sections.

## The microinjection experiment

We mounted animals on coverslips with dried 2% agarose pads covered in halocarbon 700 oil. We then placed coverslips onto an Axiovert S100 TV Inverted Microscope (Carl Zeiss) and injected animals with capillary needles filled with M9 + 10% red dye under 40 psi of pressure. Needles were pulled from borosil capillary tubing (1.0mm OD, 0.5mm ID; FHC) using a P-97 Micropipette Puller (Sutter Instrument). Puller parameters were as follows: Heat 474 (Ramp-25); Pull 90; Vel 100; Time 180. For the control mock injection, we transiently poked the animal in the uterine region with a needle and then transferred the animal onto an NGM-agar plate. For the injected group, we applied injection pressure for 2 minutes with an estimated flow rate of approximately 25 fL/s and then transferred the animal onto an NGM-agar plate. After each injection or mock injection, we immediately examined the exopher status of the ALMR neuron in less than 10 minutes.

## Statistics

The exopher phenotype (+ or -) for each animal is a nominal variable, so we analyzed the exopher data by Cochran–Mantel–Haenszel test. There is no power analysis for each experiment, but each experiment has at least three independent trials. For analyzing progeny count, we used 2way ANOVA with Šidák's multiple comparisons test. For analyzing the uterus length, we used unpaired two-tail *t*-test.

## Author contributions

GW, RG, SS, EC, AM, AJS, DJ, SS, EF, IM, and KCN did the experiment. GW, RG, SS, EC, AM, AJS, DHH, BDG, and MD designed the experiment. GW, RG, SS, DHH, BDG, and MD wrote the manuscript.

## Declaration of interests

The authors declare no competing interests.

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## Editors

Reviewing Editor

**Patrick Hu**

Vanderbilt University Medical Center, Nashville, United States of America

Senior Editor

**Claude Desplan**

New York University, New York, United States of America

### Reviewer #1 (Public Review):

Summary:

The authors sought to understand the stage-dependent regulation of exophogenesis, a process thought to contribute to promoting neuronal proteostasis in *C. elegans*. Focusing on the ALMR neuron, they show that the frequency of exopher production correlates with the timing of reproduction. Using many genetic tools, they dissect the requirements of this pathway to eventually find that occupancy of the uterus acts as a signal to induce exophogenesis. Interestingly, the physical proximity of neurons to the egg zone correlates with exophogenesis frequency. The authors conclude that communication between the uterus and proximal neurons occurs through the sensing of mechanic forces of expansion normally provided by egg occupancy to coordinate exophogenesis with reproduction.

Strengths:

The genetic data presented is thorough and solid, and the observation is novel.

Weaknesses:

The authors have addressed the main weakness of the study in the revised manuscript, by providing data showing stimulation of exopher production in a single-copy transgenic line. Whether this process is related to the extrusion of cellular damage by the neurons in relatively young day 2 animals should be addressed in future studies.

<https://doi.org/10.7554/eLife.95443.2.sa3>

### Reviewer #2 (Public Review):

Summary:

This paper reports that mechanical stress from egg accumulation is a biological stimulus that drives the formation of extruded vesicles from the neurons of *C. elegans* ALMR touch neurons. Using powerful genetic experiments only readily available in the *C. elegans* system, the authors manipulate oocyte production, fertilization, embryo accumulation, and egg-

laying behavior, providing convincing evidence that exopher production is driven by stretch-dependent feedback of fertilized, intact eggs in the adult uterus. Shifting the timing of egg production and egg laying alters the onset of observed exophers. Pharmacological manipulation of egg laying has the predicted effects, with animals retaining fewer eggs having fewer exophers and animals with increased egg accumulation having more. The authors show that egg production and accumulation have dramatic consequences to the viscera, and moving the ALMR process away from eggs prevents the formation of exophers. This effect is not unique to ALMR but is also observed in other touch neurons, with a clear bias toward neurons whose cell bodies are adjacent to the filled uterus. Embryos lacking an intact eggshell with reduced rigidity have impaired exopher production. Acute injection into the uterus to mimic the stretch that accompanies egg production causes a similar induction of exopher release. Together these results are consistent with a model where stretch caused by fertilized embryo accumulation, and not chemical signals from the eggs themselves or egg release, underlies ALMR exopher production seen in adult animals.

#### Strengths:

Overall, the experiments are very convincing, using a battery of RNAi and mutant approaches to distinguish direct from indirect effects. Indeed, these experiments provide a model generally for how one would methodically test different models for exopher production. The source and factors influencing exopher production had previously been unclear. This study addresses how and when they form in the animal using physiologically meaningful manipulations. The stage is now set to address at a cellular level how exophers like these are made and what their functions are.

#### Weaknesses:

Not many. The experiments are about as good as could be done. Some of the n's on the more difficult to work strains or experiments are comparatively low, but this is not a significant concern because the number of different, complementary approaches used. The microinjection experiment is very interesting, and the authors have added additional details on how these experiments were conducted in the revised manuscript. The authors have now included data from strains bearing a single-copy transgene that expresses mKate2 in the same neurons, showing that induced egg accumulation drives a similar degree of exopher production. This indicates that exophers seen are generated in response to specific biological conditions and not merely an artifact of mCherry protein over-expression.

<https://doi.org/10.7554/eLife.95443.2.sa2>

#### Reviewer #3 (Public Review):

##### Summary:

In this paper, the authors use the *C. elegans* system to explore how already-stressed neurons respond to additional mechanical stress. Exophers are large extracellular vesicles secreted by cells, which can contain protein aggregates and organelles. These can be a way of getting rid of cellular debris, but as they are endocytosed by other cells can also pass protein, lipid, and RNA to recipient cells. The authors find that when the uterus fills with eggs or otherwise expands, a nearby neuron (ALMR) is far more likely to secrete exophers. This paper highlights the importance of the mechanical environment in the behavior of neurons and may be relevant to the response of neurons exposed to traumatic injury.

##### Strengths:

The paper has a logical flow and a compelling narrative supported by crisp and clear figures.



The evidence that egg accumulation leads to exopher production is strong. The authors use a variety of genetic and pharmacological methods to show that increasing pressure leads to more exopher production, and reducing pressure leads to lower exopher production. For example, egg-laying defective animals, which retain eggs in the uterus, produce many more exophers, and hyperactive egg-laying is accompanied by low exopher production. The authors even inject fluid into the uterus and observe the production of exophers.

#### Weaknesses:

The main weakness of the paper is that it does not explore the molecular mechanism by which the mechanical signals are received or responded to by the neuron. The authors are currently addressing this in their follow-up studies.

<https://doi.org/10.7554/eLife.95443.2.sa1>

#### Author response:

The following is the authors' response to the original reviews.

##### **eLife assessment**

*This important study explores the potential influence of physiologically relevant mechanical forces on the extrusion of vesicles from *C. elegans* neurons. The authors provide compelling evidence to support the idea that uterine distension can induce vesicular extrusion from adjacent neurons. The work would be strengthened by using an additional construct (preferably single-copy) to demonstrate that the observed phenotypes are not unique to a single transgenic reporter. Overall, this work will be of interest to neuroscientists and investigators in the extracellular vesicle and proteostasis fields.*

We now include supporting data using a single copy alternate fluorescent reporter expressed in touch neurons (Fig. 3H).

In brief, we examined the induction of exophogenesis in an alternative single-copy transgene strain that expresses mKate fluorescent protein specifically in touch receptor neurons. As compared to the multi-copy transgene that is broadly used in this study and expresses mCherry fluorescent protein specifically in touch receptor neurons, the mKate single-copy transgene is associated with a much lower frequency of exophogenesis. However, increasing uterine distension via blocking egg-laying can increase the exophogenesis of the mKate single-copy transgenic line from 0% to approximately 60% on adult day 1, indicating that the observed response is not tied to a single reporter.

##### **Public Reviews:**

##### **Reviewer #1 (Public Review):**

##### *Summary:*

*The authors sought to understand the stage-dependent regulation of exophogenesis, a process thought to contribute to promoting neuronal proteostasis in *C. elegans*. Focusing on the ALMR neuron, they show that the frequency of exopher production correlates with the timing of reproduction. Using many genetic tools, they dissect the requirements of this pathway to eventually find that occupancy of the uterus acts as a signal to induce exophogenesis. Interestingly, the physical proximity of neurons to the egg zone correlates with exophogenesis frequency. The authors conclude that*

*communication between the uterus and proximal neurons occurs through the sensing of mechanic forces of expansion normally provided by egg occupancy to coordinate exophogenesis with reproduction.*

**Strengths:**

*The genetic data presented is thorough and solid, and the observation is novel.*

**Weaknesses:**

*The main weakness of the study is that the detection of exophers is based on the overexpression of a fluorescent protein in touch neurons, and it is not clear whether this process is actually stimulated in wild-type animals, or if neurons have accumulated damaged proteins in relatively young day 2 animals.*

We now include data using a single copy alternate fluorescent reporter expressed in touch neurons. Although baseline exopher levels are low in this strain, we demonstrate that inducing egg retention in this background markedly increases exopher generation from a baseline of near zero to ~60% (new Fig. 3H), supporting that uterine distention, rather than reporter identity, is associated with early life exopher elevation. Data also add to our observations indicating that high protein-expressing strains generally produce higher baseline levels of exophers in early adulthood (for example, Melentijevic et al. (PMID 28178240) documented that mCherry RNAi knockdown in the strain primarily studied here can lower exopher levels).

The second point raised here, regarding the occurrence and physiological role of early-adult exophers in “native” non-stressed neurons is a fascinating question that we are beginning to address in continuing experiments. Readers will appreciate that quantifying relatively rare, “invisible” touch receptor neuron exophogenesis accurately without expressing a fluorescent reporter is technically challenging. Our speculation, outlined now a bit more clearly in the Discussion here, is that certain molecular and organelle debris that cannot readily be degraded in cells during larval development may be stored until release to more capable degradative neighbors or to the coelomocytes for later management, as one component of the early adult transition in proteostasis (see J. Labbadia and R. I. Morimoto, PMID 24592319). Receiving cells may be primed for this at a particular timepoint, possibly analogous to the “bulky garbage” collection of over-sized difficult-to-dispose-of household items that a town will address with specialized action only at specific times. The prediction is that we should be able to detect some mass protein aggregation through early development, and at least partial elimination by adult day 3; this elimination should be impaired when eggs are eliminated. Initial testing is underway.

**Reviewer #2 (Public Review):**

**Summary:**

*This paper reports that mechanical stress from egg accumulation is a biological stimulus that drives the formation of extruded vesicles from the neurons of C. elegans ALMR touch neurons. Using powerful genetic experiments only readily available in the C. elegans system, the authors manipulate oocyte production, fertilization, embryo accumulation, and egg-laying behavior, providing convincing evidence that exopher production is driven by stretch-dependent feedback of fertilized, intact eggs in the adult uterus. Shifting the timing of egg production and egg laying alters the onset of observed exophers. Pharmacological manipulation of egg laying has the predicted effects, with animals retaining fewer eggs having fewer exophers and animals with increased egg accumulation having more. The authors show that egg production and accumulation have dramatic consequences for the viscera, and moving the ALMR process away from*

eggs prevents the formation of exophers. This effect is not unique to ALMR but is also observed in other touch neurons, with a clear bias toward neurons whose cell bodies are adjacent to the filled uterus. Embryos lacking an intact eggshell with reduced rigidity have impaired exopher production. Acute injection into the uterus to mimic the stretch that accompanies egg production causes a similar induction of exopher release. Together these results are consistent with a model where stretch caused by fertilized embryo accumulation, and not chemical signals from the eggs themselves or egg release, underlies ALMR exopher production seen in adult animals.

#### Strengths:

Overall, the experiments are very convincing, using a battery of RNAi and mutant approaches to distinguish direct from indirect effects. Indeed, these experiments provide a model generally for how one would methodically test different models for exopher production. The paper is well-written and easy to understand. I had been skeptical of the origin and purpose of exophers, concerned they were an artefact of imaging conditions, caused by deranged calcium activity under stressful conditions, or as evidence for impaired animal health overall. As this study addresses how and when they form in the animal using otherwise physiologically meaningful manipulations, the stage is now set to address at a cellular level how exophers like these are made and what their functions are.

#### Weaknesses:

Not many. The experiments are about as good as could be done. Some of the n's on the more difficult-to-work strains or experiments are comparatively low, but this is not a significant concern because of the number of different, complementary approaches used. The microinjection experiment in Figure 7 is very interesting, there are missing details that would confirm whether this is a sound experiment.

We expanded description of details for the microinjection experiment in both the figure legend and the methods section, to enhance clarity and substantiate approach.

#### Reviewer #3 (Public Review):

##### Summary:

In this paper, the authors use the *C. elegans* system to explore how already-stressed neurons respond to additional mechanical stress. Exophers are large extracellular vesicles secreted by cells, which can contain protein aggregates and organelles. These can be a way of getting rid of cellular debris, but as they are endocytosed by other cells can also pass protein, lipid, and RNA to recipient cells. The authors find that when the uterus fills with eggs or otherwise expands, a nearby neuron (ALMR) is far more likely to secrete exophers. This paper highlights the importance of the mechanical environment in the behavior of neurons and may be relevant to the response of neurons exposed to traumatic injury.

##### Strengths:

The paper has a logical flow and a compelling narrative supported by crisp and clear figures.

The evidence that egg accumulation leads to exopher production is strong. The authors use a variety of genetic and pharmacological methods to show that increasing pressure leads to more exopher production, and reducing pressure leads to lower exopher production. For example, egg-laying defective animals, which retain eggs in the uterus, produce many more exophers, and hyperactive egg-laying is accompanied by low

*exopher production. The authors even inject fluid into the uterus and observe the production of exophers.*

*Weaknesses:*

*The main weakness of the paper is that it does not explore the molecular mechanism by which the mechanical signals are received or responded to by the neuron, but this could easily be the subject of a follow-up study.*

We agree that the molecular mechanisms operative are of considerable interest, and our initial pursuit suggests that a comprehensive study will be required for satisfactory elaboration of how mechanical signals are received or responded to by the neuron.

*I was intrigued by this paper, and have many questions. I list a few below, which could be addressed in this paper or which could be the subject of follow-up studies.*

*- Why do such a low percentage of ALMR neurons produce exophers (5-20%)? Does it have to do with the variability of the proteostress?*

We do not yet understand why some ALMR neurons within a same genotype will produce exophers and some will not. We know that in addition to the uterine occupation we report here, proteostasis compromise, feeding status, oxidative stress, and osmotic stress can elevate exopher numbers (PMID 34475208); cell autonomous influences on exopher levels include aggresome-associated biology (PMID 37488107) and expression levels of the mCherry protein (PMID 28178240). Turek reports that social interaction on plates can influence muscle exopher levels (PMID 34288362). Thus, although variable proteostress experienced by neurons is likely a factor, we have not yet experimentally defined specific trigger rules. We suspect the summation of internal proteostasis crisis and environmental conditions, including particular force vectors/frequency will underlie the variable exopher production phenomenon.

*- Why does the production of exophers lag the peak in progeny production by 24-48 hours? Especially when the injection method produces exophers right away?*

The progeny production can track well with exopher production (Fig. 1B), although the nature of egg counts (permanent, one time events) vs. exophers (which are slowly degraded) can skew the peak scores apart. We synchronized animals at the L4 stage. 24 hours later was adult day 1, and we measured then and every subsequent 24 hours. The daily progeny count reflects the total number of progeny produced every 24 hours; exopher events were scored once a day, but exophers can persist such that the daily exopher count can partially reflect slow degradation, with some exophers being counted on two days. We now explain our scoring details better in the Methods section.

The rapid appearance of exophers, as early as about ~10 minutes after sustained injection, is fascinating and probably holds mechanistic implications for exopher biology. For one thing, we can infer that in the mCherry Ag2 background, touch neurons can be poised to extrude exophers, but that the pressure/push acts to trigger or license final expulsion. It is interesting that we found we needed to administer sustained injection of two minutes to find exopher increase (now better emphasized in the expanded Methods section). We speculate that a multiple pressure events, or sustained force vector might be critical (like an egg slowly passing through?). Minimally, this assay may help us assign molecular roles to pathway components as we identify them moving forward.

*- As mentioned in the discussion, it would be interesting to know if PEZO-1/PIEZO is required for uterine stretching to activate exopherogenesis. pezo-1 animals accumulate*

*crushed oocytes in the uterus.*

We have begun to test the hypothesis that PEZO-1 is a signaling component for ALMR exophogenesis, initially using the N and C terminal pezo-1 deletion mutants as in Bai et al. (PMID 32490809). These pezo-1 mutants have a mild decrease in ALMR exophogenesis under normal conditions. However, vulva-less conditions in pezo-1N and piezo-1C increased ALMR exophogenesis from approximately 10% to 60%, similar to the response of wild-type worms to high mechanical stress, data that suggest PEZO-1 is not a required player in mediating mechanical force-induced ALMR exophogenesis. We are currently testing genetic requirements for other known mechanosensors. We intend comprehensive investigation of the molecular mechanisms of mechanical signaling in a future study.

#### **Recommendations for the authors:**

##### **Reviewer #1 (Recommendations For The Authors):**

*-The study would be significantly strengthened by the addition of data detecting regulation of exophogenesis by uterine forces in a more physiological context, in the absence of overexpression of a toxic protein. In other words, is this a process that occurs naturally during reproduction, or is it specific to proteotoxic stress induced by overexpression? Perhaps the authors could repeat key experiments using a single copy transgene, and challenge the animals with exogenous proteotoxic stress if necessary.*

We now include data using a single copy alternate fluorescent reporter expressed in touch neurons. Although baseline exopher levels are low in this strain, we demonstrate that inducing egg retention in this background markedly increases exopher generation from a baseline of near zero to ~60% (Fig. 3H), supporting that uterine distention, rather than reporter identity or over-expression alone drives early life exopher elevation.

Also noteworthy is that we find exophogenesis in the single-copy transgenic line is only approximately 0.3% on adult day 2 (average in three trials, data not shown), which is much lower than the 5-20% exophogenesis rate typically observed in the multi-copy high expression mCherry transgenic line. Therefore, consequences of overexpression of mCherry likely potentiate exophogenesis.

*-The authors mention that exophogenesis has been described in muscle cells. Is this also dependent on the proximity to the uterus? It would have been interesting to include data on other cell types in the vicinity of the reproductive system.*

Yes, in interesting work on exophers produced by muscle, Turek et al. reported that muscle exopher events are mostly located in a region proximal to the uterus. Moreover, this work also documented that sterile hermaphrodites are associated with approximately 0% muscle exophogenesis, and egg retention in the uterus strongly increases muscle exophogenesis (PMID: 34288362).

*-Is exophogenesis also induced by other forms of mechanical stress? For example, swimming.*

We have looked at crude treatments such as centrifugation or vortexing without observing changes in exopher levels. Our preliminary work indicates that swimming can increase exophogenesis, and this effect depends on the presence of eggs in the uterus. We appreciate the question, and expect to include documentation of alternative pressure screening in our planned future paper on molecular mechanisms.

*-In Figure 1E, the profile of exopher production for the control condition at 25oC is very similar to the profile observed at 20oC in Figure 1B. However, the profile of progeny production at 25oC is known to have an earlier peak of progeny production. Perhaps egg retention is differently correlated with progeny production at this temperature? The authors could easily test this.*

Overall, exophers (which degrade with time) and progeny counts (a fixed number) have slightly different temporal features, anchored in part by how long exophers or their “starry night” debris persist. Most exophers start to degrade within 1-6 hours (PMID: 36861960), but exopher debris can persist for more than 24 hours. An exopher event observed on day 1 may thus also be recorded at the day 2 time point, which leads to a higher frequency of exopher events on day 2 as compared to day 1.

We have previously published on the impact of temperature on exopher number (Supplemental Figure 2 in PMID 34475208). In brief, increasing culture temperature for animals that are raised over constant lifetime temperature modestly increases exopher number; a greater increase in exophers is observed under conditions in which animals were switched to a higher temperature in adult life, suggesting changes in temperature (a mandatory part of the *ts* mutant studies) engages complex biology that modulates exopher production. Our previous data show that in a temperature shift to 25oC, the peak of exophers was at adult day 1. Here, Fig. 1B is constant temperature, 20oC; Fig. 1E has a temperature shift 15-25oC. That egg retention might be temperature-influenced is a plausible hypothesis, but given the complexities of temperature shifts for some mutants, we elected to defer drill-down on the temperature-exopher-egg relationship.

*-It is not clear how to compare panels A and B in Figure 3. In panel A the males are present throughout the adult life of the hermaphrodites whereas in panel B the males are added in later life. Therefore, the effect of later-life mating on progeny production is not shown and the title of panel A in the legend is misleading. The authors need to perform a progeny count in the same conditions of mating presented in Figure 3B to allow direct comparison.*

As Reviewer 1 suggested, we performed a new progeny count now presented in new Fig. 3A, which more appropriately matches the study presented in Fig. 3B; legends adjusted.

*-On page 12, the authors state that the baseline of exophergenesis in rollers is 71%, but then attribute the 71% in Figure 4F to exophergenesis specifically in ALMR that is posterior to AVM. The authors need to clarify this point.*

Good catch on our error. The baseline of exophergenesis in rollers is ~40%, and we corrected the main text.

*-Considering the conclusion of Figure 2 that blocking embryonic events passed the 4-cell stage does not impact exopher production, it would have been interesting to compare the uterine length for *emb-8* and for *mex-3*, since it is quite intriguing that the former suppresses exopher production while the latter has no effect.*

We repeated the *emb-8* and *mex-3* RNAi for these studies and encountered variability in outcome for 2 cell stage disruption via *emb-8* RNAi, which is consistent with the range of published endpoints for *emb-8* RNAi. We elected to include these *emb-8* findings in the figure legend 2G, but removed the RNAi data from the main text figure. *mex-3* uterine measures are added to revised panels 5H, 6I.



**Reviewer #2 (Recommendations For The Authors):**

*-Leaving the worms in halocarbon oil for too long (e.g. 10 min) can desiccate and kill them. Did the authors take them out of the oil before analyzing exopher production? The authors refer to these as 'sustained injections' without much description beyond that. As the worms are very small, the flow rate needed for a sustained injection over 2 minutes must be very low - so low that the needle is in danger of being clogged. Do the authors have an estimate of how much fluid was injected or the overall flow rate? I realize the flow rate measured outside of the worm may not compare directly to that of a pressurized worm, but such estimates would be instructive, particularly if they can be related to the relative volume of the eggs the injection is trying to mimic.*

After injection or mock injection, we removed the animal from the oil and flipped it if necessary to observe the ALMR neuron on the NGM-agar plate. We now expanded description of the experimental details of injection, including the estimated flow rate, in the revised Methods section.

*- The authors describe the ALMR neurons as "proteostressed", but I am not clear on whether these neurons were treated in a unique procedure to induce such a state or if the authors are merely building on other observations that egg-laying adults are dedicating significant resources to egg production, so they must be proteostressed. If they are not inducing a proteostressed state in their experiments, the authors should refrain from describing their neurons and effects as depending on such a state.*

We revised to more explicitly feature published evidence that the ALMR neurons we track with mCherryAg2 bz166 are likely proteostressed. Overexpression of mCherry in bz166 is associated with enlargement of lysosomes and formation of large mCherry foci that often correspond to LAMP::GFP-positive structures in ALMR neurons (PMID: 28178240; PMID: 37488107). Marked changes in ultrastructure reflect TN stress in this background. These cellular features are not seen in wild type animals. We previously published that mCherry, polyQ74, polyQ128, Ab1-42 (which enhance proteostress) over-expression all increase exophers (PMID: 28178240). Likewise most genetic compromise of different proteostasis branches--heat shock chaperones, proteasome and autophagy--promote exophogenesis, supporting exophogenesis as a response to proteostress. In sum, the mCherryAg2 bz166 appear markedly stressed above a non-over expressing line and produce more exophers. RNAi knockdown of the mCherry lowers exopher levels (PMID: 28178240).

In response to reviewer comment, we added a study with a single copy mKate reporter (new data Fig. 3H). We find a very low baseline of exophers in this background. This would support that high autonomous compromise associated with over-expression influences exopher levels. Interestingly, however, we found that ALMR neurons expressing mKate under a single-copy transgene still exhibit excessive exopher production (>60%) under high mechanical stress (Fig. 3H). These data are consistent with ideas that mechanical stresses can enhance exopher production, and may markedly lower the threshold for exophogenesis in close-to-native stress level neurons.

*- The authors should include more details on the source and use of the RNAi, for example, if the clones were from the Ahringer RNAi library, made anew for this study, or both.*

We now add this information in the methods section.

*- I would be curious if the authors would similarly see an induction in exopher production after acute vulval muscle silencing with histamine. I'm not suggesting this experiment,*

*but it may offer a way to induce exophers in a more controlled manner.*

This is a great suggestion that we will try in future studies.

*- I am not sure if Figure 5 needs to be a main figure in the paper or if it would be more appropriate as a supplement.*

We considered this suggestion but we think that the strikingly strong correlation of uterus length and exopher levels is a major point of the story and these data establish a metric that we will use moving forward to distinguish whether an exopher modulation disruption is more likely to act by modulation of reproduction or modulation of touch neuron biology. For this reason we elected to keep Figure 5 in the main text.

**Reviewer #3 (Recommendations For The Authors):**

*-The Statistics section in the methods should be expanded to describe the statistics used in the experiments that aren't nominal, of which there are many.*

We have updated and expanded the statistics section.

*-P.2 Line 49 spelling 'que' should be queue (I remember this by the useless queue of letters lined up after the 'q').*

Corrected

*-The introduction has a bit too much information about oocyte maturation, not relevant to the study.*

We agree that the information about oocyte maturation is not critical for the laying out the related experiments and cut this section to improve focus.

*-p.3 line 22: Some exophers are seen on Day 3, so this should be restated for accuracy.*

Corrected

*-p.3 line 26. Explain here why sperm is necessary (oocytes don't mature or ovulate effectively without sperm).*

We added this clarifying explanation.

*-p.3 line 44 Clarify in the spe-44 the oocytes are in the oviduct (not the uterus). Might be helpful to include a DIC image to accompany the helpful diagram in Figure 1D.*

We added a sentence describing the impact of sperm absence on oocyte maturation, progression into the uterus, and retention in the gonad, with reference to PMID: 17472754. We were able to add a DIC in the tightly packed Figure 1.

In Supplemental Figure 6, we now include a field picture of oocyte retention in the sem-2 mutant and upon treatment of lin-39(RNAi).

*-p.5 line 3 in the Figure 1D legend; recommend delete 'light with' which is confusing and just refer to the sperm as dark dots.*

Corrected

*-p.6 line 22-24 Check for alignment of the statements with Figure 2 (2F is cited, but it should be 2G).*

Corrected

*-p.12 line 13-15; Many ALMRs not in the egg zone (70%) did not produce exophers - this is still quite a lot. It would be good to state this section in a more straightforward way (less leading the reader) and if possible to give a possible explanation.*

We modified the text to be less leading: “Thus, although ALMR soma positioning in the egg zone does not guarantee exophogenesis in the mCherryAg2 strain, the neurons that did make exophers were nearly always in the egg zone.”

*-p.15 paragraph 3 - clarify how uterine length was controlled for the overall body length of the worm.*

We did not systematically measure body length, but rather focused on uterine distention. It would be of interest to determine if length of the body correlates with uterine size, and then address how that relationship translates to exopher production but here our attention came to rest on the striking correlation of uterine length and number of exophers.

*-p.17 line 23-25; Could be stated more simply.*

We adjusted the text: “Moreover, the oocyte retention was similarly efficacious in elevating exopher production to egg retention, increasing ALMR exophogenesis to approximately 80% in the sem-2(rf) mutant (Fig. 6C)”.

*-p.23 Line 4. I think by the time the reader reaches this sentence, the egg-coincident exophogenesis will not be 'puzzling'.*

Agreed, corrected.

*-p.26, Line 22, Male 'mating', not 'matting'.*

Corrected.

*-Throughout, leave space between number and unit (this is not required for degree or percent, but be consistent).*

Corrected.

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