A team of heterochromatin factors collaborates with small RNA pathways to combat repetitive elements and germline stress

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Abstract

Repetitive sequences derived from transposons make up a large fraction of eukaryotic genomes and must be silenced to protect genome integrity. Repetitive elements are often found in heterochromatin; however, the roles and interactions of heterochromatin proteins in repeat regulation are poorly understood. Here we show that a diverse set of *C. elegans* heterochromatin proteins act together with the piRNA and nuclear RNAi pathways to silence repetitive elements and prevent genotoxic stress in the germ line. Mutants in genes encoding HPL-2/HP1, LIN-13, LIN-61, LET-418/Mi-2, and H3K9me2 histone methyltransferase MET-2/SETDB1 also show functionally redundant sterility, increased germline apoptosis, DNA repair defects, and interactions with small RNA pathways. Remarkably, fertility of heterochromatin mutants could be partially restored by inhibiting *cep-1/p53*, endogenous meiotic double strand breaks, or the expression of MIRAGE1 DNA transposons. Functional redundancy among these factors and pathways underlies the importance of safeguarding the genome through multiple means.
Introduction

Heterochromatin, the more tightly packed form of chromatin, plays important roles in maintaining the structural and functional integrity of the genome (1). It is less transcriptionally active than euchromatin and highly enriched for repetitive elements such as transposons and satellite repeats, which are kept silent to maintain genome integrity. The heterochromatin state is stable and heritable across generations highlighting the importance of keeping certain regions of the genome repressed.

Histones in heterochromatin are marked with modifications associated with transcriptional repression such as H3K9 methylation. In organisms with point centromeres, heterochromatin is typically found in large domains adjacent to centromeres and telomeres (1). In C. elegans, heterochromatin associated histone methylations H3K9me2 and H3K9me3 are instead mostly found in many small domains on the distal arm regions of autosomal chromosomes (2). This pattern is likely to be related to the holocentric nature of C. elegans chromosomes, which have distributed centromeres rather than a single point centromere. Two histone methyltransferases carry out all H3K9 methylation (3). The SETDB1 homolog MET-2 carries out mono- and di-methylation of H3K9. SET-25 primarily carries out tri-methylation of H3K9, but it can generate all three methylated forms of H3K9. In the absence of both proteins, H3K9 methylation is undetectable, heterochromatic distal arm regions show reduced association with the nuclear lamina, and heterochromatic transgenes are desilenced (3).

A hallmark of heterochromatin is heterochromatin protein 1 (HP1), the first heterochromatin protein to be discovered through work in Drosophila (4, 5). HP1 contains a chromodomain that binds to methylated H3K9, and it is essential for
heterochromatin maintenance (4). In addition to HP1, a large and diverse array of
proteins is associated with heterochromatin, including nucleosome remodelers,
histone modifying enzymes, histone binding proteins, and DNA binding proteins (6,
7). However the functions and interactions of heterochromatin proteins are not well
understood.

Many C. elegans proteins that have predicted functions in heterochromatin or
transcriptional repression are important for development. These include MET-
2/SETDB1, HPL-2/HP1, LIN-61, LIN-13, and LET-418/Mi-2 (8-13). HPL-2 is a C.
elegans ortholog of heterochromatin HP1, and LIN-61 is a protein containing MBT
(malignant brain tumor) repeats. Both HPL-2 and LIN-61 can bind to all methylated
forms of H3K9 in vitro (12, 14, 15), and both can repress a heterochromatic reporter
(3, 8, 16). LIN-13 is a multi-zinc finger protein (10). A complex containing LIN-13,
HPL-2, and LIN-61 has been detected in vivo, and LIN-13 is required for the
formation of HPL-2::GFP nuclear foci (13, 17). LET-418 is an ortholog of Mi-2, an
ATP-dependent nucleosome remodelling component of the repressive NuRD and Mec
complexes (9, 18, 19).

Mutants of hpl-2, lin-61, lin-13, met-2, and let-418 display both germ line and
somatic defects. let-418 and lin-13 null mutants are sterile (9, 10), hpl-2 null mutants
show temperature sensitive sterility (11), and lin-61 and met-2 null mutants have
slightly reduced brood sizes (12). The underlying cause of the fertility defects is not
known, but hpl-2 mutants have been shown to produce abnormal oocytes, suggesting
defective gametogenesis (8). Somatic defects are pleiotropic and show similarities
among mutants, with most showing slow growth, somatic expression of germ line
genes, synthetic vulval development defects, and larval arrest (some only at high
temperature) (10, 11, 13, 16-18, 20-23). Additionally, genetic interactions have been
observed between some of the mutants, suggesting partially redundant functions, and that defects may result from alteration of a shared heterochromatin-linked process (12, 17, 24).

The genomic distribution of only one of the above heterochromatin proteins has been studied. An HPL-2 ChIP-chip study in early embryos showed that most binding was on the distal arm regions of autosomes in a pattern of similar to H3K9me1 and H3K9me2; interestingly, binding to chromatin was not dependent on H3K9 methylation (14). HPL-2 was observed to be broadly genic, with additional association at promoters in central chromosome regions and at repeats on distal arm regions; however, no clear relationship between HPL-2 binding and gene expression changes was observed (14). Systematic and comparative analyses of heterochromatin factors are needed to understand their functions.

The genomic binding patterns of orthologs of some of the above factors suggest roles in the regulation of mobile elements. SETDB1 binds to promoters of developmentally regulated genes in mammalian embryonic stem cells, 40% of which are found next to or overlapping endogenous retroviruses (25-27). In addition, retrotransposons are derepressed in Setdb1 knockout mouse ES cell lines and primordial germ cells (26, 28). Retrotransposons are also repressed by HP1α and HP1β in mESCs, but it is a different set of retrotransposons than is targeted by SETDB1 (29). Drosophila HP1 binds to genes and to transposable elements, particularly in pericentric chromosomal regions, but transposable element expression in mutants has not been assessed (30, 31). A recent study showed that Mi-2 could bind to a LINE1 retrotransposon promoter and repress a LINE1 reporter in human and mouse cell lines (32). The genomic distribution of Mi-2 is unclear as different genome-wide binding studies in human ES cells have yielded conflicting results (33).
The expression of repetitive elements can be detrimental to genome stability due to the negative effects of homologous recombination and transposon-induced breaks. Because the germline produces the gametes that transmit genetic information across generations, silencing of repetitive elements is an absolute requirement for germline health. A small RNA pathway called the piRNA pathway, present in most animals, plays a role in transposon silencing in the germline (34). Recent work in *C. elegans* implicated HPL-2/HPI and the H3K9me3 histone methyltransferase SET-25 in piRNA pathway function, indicating a connection between heterochromatin and small RNA silencing of piRNA targets (35).

In the *C. elegans* germline, the piRNA pathway involves generation of 21nt piRNAs that bind to the Piwi argonaute protein PRG-1 (36-38). This triggers generation of secondary 22G siRNAs that mediate silencing either in the cytoplasm or nucleus (35, 37, 39-47). Cytoplasmic silencing mechanisms are not well understood, but recent advances have been made in the understanding of transcriptional silencing. In the nucleus, the piRNA pathway engages a second small RNA pathway called the nuclear RNAi pathway, which orchestrates H3K9 and H3K27 methylation and inhibition of RNA Pol II (42, 46, 48, 49). Although the nrde pathway can be triggered by the piRNA pathway in the germline, it is also active in the soma, with dedicated Argonaute proteins for germline (HRDE-1) and soma (NRDE-3) (42, 46, 47, 50).

Regions transcriptionally upregulated in *hrde-1* mutants were found to be enriched for retrotransposons, suggesting that repetitive elements may be endogenous targets in the germline (51).

In addition to silencing transcription and maintaining the structural and functional integrity of the genome, heterochromatin also plays an important role in DNA repair. Heterochromatic compaction protects DNA from damage, and regulated
decondensation is important for damage repair (52). Additionally, in mammals, transient formation of heterochromatin occurs at the edges of double strand breaks, which involves recruitment of heterochromatin-associated proteins HP1 and nucleosome remodeller Mi-2, as well as methylation of H3K9 (53). This is thought to aid in damage repair by keeping the broken strands in proximity and inhibiting local transcription.

Here, through systematic genetic and genomic analyses, we investigate interactions and functions of five heterochromatin proteins (HPL-2/HP1, LIN-13, LIN-61, LET-418/Mi-2 and MET-2/SETDB1) and relationships with the piRNA and nuclear RNAi pathways. Our results reveal a nexus of factors that cooperate to prevent expression of repetitive elements and protect the germ line from endogenous damage.
Results

Heterochromatin factors show partially redundant functions for fertility

The five genes we study here (hpl-2/HP1, lin-13, lin-61, let-418/Mi-2, and met-2) are needed for normal fertility ([9-12, 54, 55]; Supplementary file 1). Previous analyses uncovered genetic interactions in fertility between three pairs of genes (hpl-2 and lin-13, lin-61 and hpl-2, lin-61 and met-2; [12, 17, 24]; however, the remaining six combinations were untested. Using RNAi in mutant backgrounds, we found that double loss of function of each of the uninvestigated pairs also caused synthetic sterility, which we also observed for three tested double mutant combinations (Figures 1A-C). The single mutants show complex and pleiotropic germ line defects, but they all showed a high occurrence of abnormal oocytes, suggesting that sterility may be due in part to abnormal oogenesis (Figure 1-figure supplement 1). The fertility defects of single mutants and the enhancement in double loss of function combinations indicate that the five heterochromatin factors each have unique and partially redundant germ line roles. The genetic interactions suggest that the five factors may cooperate in a germ line process required for fertility.

HPL-2, LIN-13, LIN-61, LET-418, and MET-2 are enriched at repetitive elements and show extensive co-binding

To begin to investigate the roles of HPL-2, LIN-13, LIN-61, LET-418, and MET-2 in genome regulation, we mapped their binding locations using ChIP-seq analyses in young adults and compared the patterns to each other and to those of H3K9me2 and H3K9me3. Binding of each of the five factors is enriched on the distal arm regions of
the autosomes (Figure 2A; Figure 2-figure supplement 1A), as previously seen for H3K9me2, H3K9me3, and HPL-2 (2, 14, 56). Examination of ChIP-seq signals at a more local level revealed similar binding patterns for the five heterochromatin proteins (Figure 2B). Indeed, genome-wide correlation analyses showed significant positive correlations in signal between all datasets (Figure 2-figure supplement 1B). In addition, signals for each of the five heterochromatin factors showed high correlation with H3K9me2 but not with H3K9me3 (Figure 2B, Figure 2-figure supplement 1B).

To further investigate patterns of binding, we identified regions of peak enrichment for each dataset (Figure 2-figure supplement 1C, Figure 2-source data 1; 12449 to 19313 peaks per factor). For each factor, peaks are enriched on the distal chromosomal regions of autosomes; most peaks are intergenic or located in introns, with enrichment for intergenic binding in central chromosomal regions and enrichment for intronic binding in distal arm regions (Figure 2-figure supplement 1A).

To facilitate comparisons between datasets, we merged peak calls from all factors into a superset termed Any5 (n=33,301), then annotated each region in the Any5 set for the factors bound (Figure 2-source data 1). There is a high degree of peak overlap among the five factors, with 58% of sites in the Any5 set being bound by >1 factor (Figure 2C). Sites uniquely bound by only one factor are in the minority within each dataset (3.4%–27.4%, Figure 2C and Figure 2-figure supplement 1C). Strikingly, the largest binding group contains all five factors (termed “All5”; Figure 2C). Enrichments for H3K9me2 and H3K9me3 vary between binding classes, with the All5 class showing high enrichment for H3K9me2 (Figure 2C). These results show that HPL-2, LET-418, LIN-13, LIN-61, and MET-2 extensively overlap in binding genome-wide.
The previous HPL-2 ChIP-chip study in embryos noted binding at repetitive elements, which are concentrated on the distal arm regions of autosomes (14). Repeat-rich heterochromatin in *C. elegans* is distributed in small domains rather than being concentrated in large regions as in mammals or Drosophila; therefore, the sequences of most repetitive regions have been determined. To investigate the association of heterochromatin factor binding at repetitive DNA, we used the recent Dfam2.0 annotation, which classified 62,331 individual repetitive elements in *C. elegans* into 184 repeat families, which were further classified by type (e.g., DNA transposon, retrotransposon, satellite, or unknown (57)).

We observed that HPL-2, LIN-13, LIN-61, LET-418, and MET-2 are all strongly associated with repetitive DNA elements (Figure 2C). A large proportion of each factor’s peaks overlaps a repeat sequence (46.3% - 71.0%), and regions with all five factors have particularly strong repeat association (76.6%, Figure 2C, Figure 2-figure supplement 1C). Furthermore, of the total set of 62331 annotated repetitive elements, nearly half (46%) overlap a peak of at least one factor, and 8002 (13%) by all five factors (Figure 2-figure supplement 1D). All repeat types and 180 of 184 repeat families are associated with a heterochromatin factor peak; of these, 105 repeat families are enriched for binding by at least one factor (Figure 2-source data 2). HPL-2, LIN-13, LIN-61, MET-2, and H3K9me2 have a particularly strong association with Helitron families; LET-418 shows generally lower enrichment on repeat families than the other factors (Figure 2D; Figure 2-figure supplements 2-6).

H3K9me2 and H3K9me3 show different patterns of repeat enrichment. H3K9me2 is more associated with DNA transposons and satellite repeats, similar to the heterochromatin factors, whereas H3K9me3 is particularly associated with retrotransposon families, especially LINE and SINE elements (Figure 2D; Figure 2-
We also observed that H3K9me2 and all heterochromatin factors are enriched at telomeres, whereas H3K9me3 is not (Figure 2-figure supplement 1E). The binding and co-association of HPL-2, LET-418, LIN-13, LIN-61, and MET-2 at repetitive elements suggests roles in the regulation of these sequences.

Repetitive elements are desilenced in hpl-2, lin-13, lin-61, let-418, and met-2 set-25 mutants

Because silencing of repetitive DNA elements is important for germ line function, we considered that the heterochromatin factors might function in preventing repeat expression. To investigate this possibility, we generated and analysed RNA sequence expression data for wild-type and heterochromatin mutant adults. MET-2 deposits H3K9me1 and H3K9me2, but all three methylation states of H3K9 are still present in met-2 mutants (at lower levels) due to the action of SET-25 (3). Therefore we assayed a met-2 set-25 double mutant, in which H3K9 methylation was not detectable (3). For each strain, we performed two biological replicates and differential expression analyses of the 62,331 Dfam2.0 repeat elements.

We observed upregulation of repetitive elements in every mutant strain (hpl-2, let-418, lin-13, lin-61, and met-2 set-25) (Figures 3A-D, Figure 3-figure supplement 1, Figure 3-source data 1). A total of 71 individual repeat elements representing 29 different families were upregulated in at least one mutant (Figure 3-source data 2; upregulation of 61/71 individual elements was confirmed based on uniquely mapping reads, see Methods). We observed a striking overlap in the sets of repetitive elements regulated by the heterochromatin factors: 41% of elements are upregulated in more
than one mutant (Figure 3A; Figure 3-source data 2). Furthermore, seven repeat
elements are upregulated in all five strains, all of which are MIRAGE1 DNA
transposable elements (Figures 3A, C, D, Figure 3-source data 2). The majority of
repetitive elements upregulated in each heterochromatin mutant strain are DNA
transposons, but retrotransposons are enriched for being upregulated (Figure 3B).
Mutants show variation in the classes of repeats regulated; for example, SINE
retrotransposons are particularly affected in let-418 mutants, while many Helitron
elements are upregulated in lin-13 mutants (Figure 3B).

Overall, the total number of individual repetitive elements found with
significantly altered expression is extremely small (<1%) relative to the >30,000 with
factor binding, indicating that binding does not generally regulate repeat transcription.
There are many types of repetitive elements, and only a small fraction would be
expected to have potential for RNA expression. For example, 67% of repetitive
elements are predicted to be non-autonomous DNA transposons, which would be
mobilised in trans by a transposase encoded by another repetitive element, and many
annotated elements are small fragments of larger elements. We therefore wondered
whether the upregulation of repetitive element expression in heterochromatin mutants
might be particularly associated with transposases or retrotransposons. Of 62331
Dfam2.0 elements, 221 overlap a predicted transposase ORF, and 1085 are annotated
as LTR retrotransposons. We found that elements upregulated in any heterochromatin
factor mutant are 83-fold enriched for containing a transposase (21 of 71) and 10-fold
enriched for LTR retrotransposons (13 of 71), together accounting for nearly half of
upregulated repeats. Therefore, a key role of heterochromatin factors is to suppress
expression of repetitive element transposases. The widespread binding of
heterochromatin factors to non-expressed repetitive elements is likely to play roles
other than in the regulation of transcription. These could include preventing the cutting, copying, or movement of elements, or maintaining genome integrity by suppressing homologous recombination between repetitive elements (58, 59).

We also analysed alterations in protein coding gene expression in the heterochromatin mutants. Consistent with roles in repression, we identified three to five times more genes with upregulated expression in each mutant strain compared to those with reduced expression (267-513 upregulated genes per mutant; Figure 3-source data 3). Additionally, there is a high degree of overlap among the upregulated genes; of the total set of 1155 genes upregulated in any of the five mutant strains, 404 are upregulated in more than one (Figure 3-source data 3). Heterochromatin factors are enriched at upregulated genes, but not downregulated genes (except for genes misregulated in let-418 mutants); additionally, both H3K9me2 and H3K9me3 are enriched at upregulated genes in all mutant strains (Figure 3-figure supplement 2). Enrichment for all factors and H3K9 methylation is particularly strong at genes upregulated in met-2 set-25 mutants (Figure 3-figure supplement 2). These associations suggest direct roles in repression.

Repression of desilenced MIRAGE1 elements partially restores fertility of heterochromatin mutants.

The silencing of repetitive elements is a universal conserved feature of germ line function. The prominent upregulation of MIRAGE1 elements in all heterochromatin mutants prompted us to ask whether expression of this element might play a role in their reduced fertility. MIRAGE1 is an autonomous DNA transposable element that has two open reading frames. Of 69 MIRAGE1 element annotations in Dfam2.0, only...
six are full length. These six, plus an additional six partial MIRAGE1 elements are upregulated in at least one heterochromatin mutant, and both ORFs show upregulation.

We first examined the tissue distribution of MIRAGE RNA using RNA-FISH (60). As expected from the RNA-seq results, wild-type adults had very low levels of MIRAGE1 RNA-FISH signal in germ line and soma (Figure 3E and Figure 3-figure supplement 3). In three tested heterochromatin mutants (hpl-2, let-418, and lin-13), we observed abundant germ line localized MIRAGE1 RNA whereas somatic expression remained low (Figure 3E and Figure 3-figure supplement 3). Therefore, hpl-2, let-418, and lin-13 are important for repression of MIRAGE1 in the germ line.

To test whether upregulation of MIRAGE1 contributes to sterility, we used two sets of RNAi clones to simultaneously knockdown ORF1 and ORF2 (sets termed mirage-A and mirage-B). mirage-A and mirage-B target 16 different MIRAGE1 elements, including all full length elements and most of the MIRAGE1 elements upregulated in each of these mutants (8/8 for let-418, 7/8 for lin-13, and 10/11 for hpl-2). To assess an effect on fertility, we grew hpl-2, lin-13, and let-418 mutants at 25°C, a condition under which they are nearly sterile, and tested for an increase in brood size after RNAi knockdown. Remarkably, RNAi of MIRAGE1 using mirage-A or mirage-B sets of RNAi clones led to a small but significant increase in fertility of all three mutants, showing that inappropriate MIRAGE1 expression contributes to their sterility (Figure 4A). We also observed that MIRAGE1 RNAi resulted in amelioration of somatic growth defects (not shown). These results indicate that one mechanism by which heterochromatin proteins promote normal germ line function is via the repression of repetitive elements, in particular those encoding transposases.
Heterochromatin mutants display DNA repair defects, increased germ line apoptosis and fertility dependence on CEP-1/p53

Desilencing of repetitive elements has been reported to cause DNA damage in other organisms (61); therefore, repeat expression in heterochromatin mutants might lead to genotoxic stress and genome instability in the germ line. Consistent with this, loss of \textit{lin-61} leads to replication stress and genome instability, with increased germ line and somatic mutation frequency (62, 63). \textit{lin-61} mutants also have defects in DNA repair (62, 63). A previous study reported that an \textit{hpl-2}(tm1489) null mutant strain was hypersensitive to ionizing radiation (IR) (64); however, we found that this strain also harboured a deletion in the \textit{polq-1} gene, which encodes DNA polymerase theta.

Because \textit{polq-1} mutants are reported to have increased sensitivity to DNA damaging agents and display genome instability (65), it was unclear if the defects observed were due to \textit{hpl-2} (see Methods).

To determine whether \textit{hpl-2} has a role in DNA repair, we tested the response of the isolated \textit{hpl-2}(tm1489) mutant to IR induced DNA damage. Following IR, we observed that \textit{hpl-2} mutants show higher levels of oocyte fragmentation compared to wild type, suggesting that they are defective in DNA repair (Figure 5-figure supplement 1). Additionally, \textit{hpl-2} mutant germ lines are hypersensitive to induction of phosphorylation of the DNA damage checkpoint kinase CHK-1 (Figure 5-figure supplement 1). The hypersensitivity of \textit{hpl-2} and \textit{lin-61} mutants to exogenous DNA damage are consistent with increased genotoxic stress in the germ line.

We considered that the repeat desilencing and DNA repair defects of heterochromatin mutants might lead to increased germ line apoptosis, and thereby contribute to germ line and fertility defects. In wild-type animals, physiological
apoptosis occurs in the pachytene region of the gonad, with around half of the initially produced germ cells eliminated by apoptosis as a quality control mechanism (66). DNA damage causes increased apoptosis over physiological levels, and this increase is dependent on cep-1/p53 (67, 68). To assess germ line cell death in the heterochromatin mutants we used a CED-1::GFP reporter, which allows visualization of apoptotic germ cells in adult animals (69). We observed that hpl-2, lin-13, lin-61, and set-25 met-2 mutants all displayed increased germ line apoptosis (Figure 5; let-418 was not assayed because the apoptosis reporter used is genetically linked). Thus, heterochromatin factor mutants have increased germ cell death.

p53 is important for transduction of the DNA damage response and other stresses, and C. elegans cep-1/p53 is required for damage induced cell death (67, 68). We used RNAi to test whether activation of p53 dependent pathways played a role in heterochromatin mutant sterility. Following RNAi of cep-1/p53, we found that the brood sizes of hpl-2, lin-13, and let-418 mutants grown at 25°C were modestly increased (Figure 4A). We further tested the effect of loss of cep-1 by making double mutants with cep-1(lg12501). Similar to the RNAi results, we observed that mutation of cep-1 increased the fertility of lin-13, let-418 and hpl-2 mutants (Figure 4B). This increase is not due to a general effect of cep-1 on fertility, as cep-1 mutants have a slightly reduced brood size compared to wild-type animals (Figure 4B). We also observed that cep-1 loss partially rescued the slow growth phenotype of the mutants (Figure 4C). These results suggest that genotoxic stress and DNA damage signalling in heterochromatin mutants activates p53, which contributes to sterility and slow growth. The increase in fertility upon cep-1/p53 inhibition may be a direct consequence of reduced germ line apoptosis, or alternatively the effect may be indirect, by preventing DNA damage signalling or improving growth rate. We also
note that although fertility of heterochromatin mutants is increased when *cep-1/p53* is inhibited, it is not restored to wild-type levels indicating that other mechanisms contribute to sterility.

*SPO-11 induced endogenous DNA damage contributes to heterochromatin mutant sterility*

We next investigated whether endogenous physiological DNA damage may also contribute to heterochromatin mutant sterility. During meiosis, double strand breaks are induced by the topoisomerase-like protein SPO-11 to facilitate crossover formation and meiotic recombination (70). Similar to inhibition of damage induced cell death or MIRAGE1 expression, we found that inhibiting meiotic double strand breaks by RNAi of *spo-11* increased the brood size of *hpl-2, lin-13,* and *let-418* mutants (Figure 4A), suggesting that defects in repair of meiotic double strand breaks contributes to sterility.

The *piRNA* pathway shows similarity in repeat regulation and functional connections to heterochromatin factors

The *piRNA* pathway has a well-known role in preventing the activity of transposons in the germ line (34). In *C. elegans*, the *piRNA* pathway operates through the Piwi Argonaut protein PRG-1. Silencing occurs both transcriptionally, through engagement of the nuclear RNAi pathway, and post-transcriptionally, through a poorly understood mechanism. Interestingly, *prg-1* mutants have fertility defects, displaying a low brood size and a mortal germline phenotype that is more pronounced
at elevated temperatures (37, 38). The observation that heterochromatin mutants
desilence repetitive elements together with the finding that HPL-2 and H3K9
methyltransferase SET-25 are needed for piRNA pathway function in conjunction with
the nuclear RNAi pathway (35) prompted us to further investigate connections
between these factors.

We first assayed the expression of repetitive DNA in \textit{prg-1} mutant adults
because genome-wide profiling had not previously been done. We detected
upregulation of 18 repetitive elements in \textit{prg-1} mutants, 14 of which are also
upregulated in at least one of the heterochromatin mutants, including MIRAGE1
elements (Figure 6A, Figure 3-source data 1 and 2). RNA FISH experiments showed
that MIRAGE1 RNA is increased in \textit{prg-1} mutant germ lines, similar to observations
in heterochromatin mutants described above (Figure 3E and Figure 3-figure
supplement 3). Given this overlap in targets and the fertility defects of \textit{prg-1} mutants,
we assessed whether they also showed increased germ line apoptosis as seen in
heterochromatin factor mutants. Indeed, we observed significantly increased germ
cell death in \textit{prg-1} mutant adults (Figure 6B). Therefore, the piRNA pathway and
heterochromatin factors have shared targets and phenotypes, and likely collaborate in
maintaining genomic integrity of the developing germline.

We next used a piRNA activity sensor to test whether heterochromatin factors
other than \textit{hpl-2} are needed for piRNA pathway function. Similar to \textit{hpl-2} and \textit{set-25},
we found that \textit{lin-61} and \textit{let-418} mutants derepress the piRNA sensor reporter (Figure
6C, D). We also observed weak desilencing in a fraction of \textit{met-2} mutants (Figure 6D),
which was not observed in a previous assay (35). However, the piRNA sensor was
not desilenced in \textit{lin-13} mutants. It is possible that the lack of desilencing is due to
the lin-13(n770) allele being non-null, however this mutant does show defects such as upregulation of repetitive elements and increased apoptosis.

A previous study profiling small RNAs in hpl-2 mutants in a piRNA sensor background showed that piRNAs targeting the sensor or a few endogenous targets were not altered in abundance, suggesting that hpl-2 acts downstream of piRNA production (35). To investigate this further, we compared the global abundance of piRNAs in hpl-2 and wild-type adults. Similar to the above results, we found that hpl-2 mutants make normal levels of piRNAs (Figure 6-figure supplement 1). We also investigated the production of secondary 22G siRNAs in hpl-2 mutants. We detected a decrease in 22G RNAs mapping near predicted piRNA target sites in prg-1 mutants as previously observed (41), but levels were normal in hpl-2 mutants (Figure 6-figure supplement 1). hpl-2 mutants also showed normal levels of 22Gs at repeat elements. (Figure 6-figure supplement 1). Therefore, at least for hpl-2, the role in the piRNA pathway appears to be downstream of piRNA and subsequent 22G RNA synthesis.

To summarize, hpl-2, lin-61, let-418, set-25, and met-2 are important for piRNA pathway function. Nevertheless, the widespread binding sites and desilencing of additional targets relative to prg-1 indicate that heterochromatin proteins also mediate repression that is not piRNA-induced.

Partial redundancy between let-418/Mi-2 and the nuclear RNAi pathway

The C. elegans nuclear RNAi pathway (called the nrde pathway) mediates transcriptional repression and directs H3K9me3 methylation to its targets (42, 44-47, 50). The nrde pathway also functions in repression of piRNA targets (35). To
investigate the relationship between the nrde pathway, the piRNA pathway, and heterochromatin factors in repetitive element regulation, we carried out RNA-seq on \textit{nrde-2\texttrademark gg91}, a putative null mutant, and compared results to those of heterochromatin and \textit{prg-1} mutants. We observed that \textit{nrde-2} mutants showed a larger and different spectrum of repetitive element desilencing compared to \textit{prg-1} or any of the heterochromatin mutants (Figure 7-figure supplement 1, Figure 3-source data 1 and 2). Of 71 elements desilenced in \textit{nrde-2} mutants, only seven overlap a repeat desilenced in one of the heterochromatin mutant strains (Figure 7-figure supplement 1). Notably MIRAGE1 elements, prominently upregulated in heterochromatin and \textit{prg-1} mutants, are not desilenced in \textit{nrde-2} mutants (Figure 3-source data 1 and 2; Figure 7-figure supplement 1). Retrotransposons are highly enriched among \textit{nrde-2} targets (45/71) whereas heterochromatin factors and \textit{prg-1} are more associated with DNA transposon misregulation (Figure 3B). Therefore, although the nrde pathway is required for aspects of piRNA function, repetitive element targets largely differ.

Notably, the finding that elements derepressed in \textit{nrde-2} mutants differ from those in \textit{met-2 set-25} mutants, which lack detectable H3K9 methylation, suggests that H3K9 methylation may not be required for nrde dependent repression.

Like the heterochromatin factor and \textit{prg-1} mutants, \textit{nrde-2} mutants also show a temperature sensitive decrease in fertility (42). To test whether the \textit{nrde-2} fertility function had functional overlap with heterochromatin factors, we constructed double mutants between \textit{nrde-2} and three mutants (\textit{hpl-2}, \textit{lin-61}, and \textit{let-418}). We observed no reduction in fertility for \textit{nrde-2; hpl-2}, and a weak but non-significant reduction for \textit{nrde-2; lin-61} double mutants (Figure 7A). However, \textit{nrde-2; let-418}, double mutants showed a significantly smaller brood size than expected compared to the single mutants, indicating partial functional redundancy between \textit{let-418} and the \textit{nrde}
pathway (Figure 7A). We also observed that all three double mutants showed significantly increased embryo lethality compared to the single mutants (Figure 7B).

To further investigate the genetic interaction between \textit{nrde-2} and \textit{let-418}, we carried out RNA-seq of \textit{nrde-2; let-418} adults to test for redundancy in repeat element repression. We found that more repeats are upregulated in \textit{nrde-2; let-418} double mutants compared to \textit{nrde-2} or \textit{let-418} single mutants (Figure 7B). Most of the repeat elements upregulated only in the \textit{nrde-2; let-418} double mutant are retrotransposons (27/46; Figure 7B and Figure 3-source data 2). We conclude that NRDE-2 and LET-418 have unique and redundant roles in the repression of repetitive DNA elements.

Because a key output of the \textit{nrde} pathway is the deposition of H3K9me3, the observed redundancy between NRDE-2 and LET-418 prompted us to investigate whether the \textit{nrde} pathway might control H3K9me3 levels at heterochromatin regulated loci. To this end, we used published H3K9me3 ChIP-seq datasets in four different \textit{nrde} mutants (\textit{hrde-1}, \textit{nrde-2}, \textit{nrde-3}, and \textit{nrde-4}; 44, 47, 51). and analysed levels at genes and repeats upregulated in \textit{nrde-2} mutants or only in heterochromatin mutants. The \textit{nrde} pathway acts in the germ line and soma: HRDE-1 and NRDE-3 are argonautes specific for germ line or soma, respectively, whereas NRDE-2 and NRDE-4 act in all tissues (42, 46, 47, 50). We observed that repeat elements and genes upregulated in \textit{nrde-2} mutants also have reduced H3K9me3 levels, supporting the link between H3K9me3 methylation and repression of endogenous targets (Figure 7-figure supplements 2 and 3). H3K9me3 was also reduced on \textit{nrde-2} upregulated elements in mutants of other \textit{nrde} genes that act in the germ line (\textit{hrde-1} and \textit{nrde-4}), but not in the soma specific argonaute mutant \textit{nrde-3} (Figure 7-figure supplements 2 and 3). This suggests that the transcriptional upregulation observed in \textit{nrde-2} mutants occurs largely in the germ line.
We next analysed H3K9me3 levels in sets of genes and repeats upregulated in heterochromatin mutant strains but not in \textit{nrde}-2 mutants to ask if these elements were also under \textit{nrde} control. Indeed, genes upregulated in any of the five heterochromatin factor mutant strains (\textit{hpl-2, lin-13, let-418, lin-61, met-2 set-25}) but not in \textit{nrde}-2 mutants also showed reduced H3K9me3 in germ line \textit{nrde} mutants, though the reduction was weaker than for \textit{nrde}-2 regulated genes (Figure 7-figure supplement 3). Repeats upregulated only in heterochromatin factor mutants showed a trend of reduced H3K9me3 (Figure 7-figure supplement 2). Therefore, the germ line nuclear RNAi pathway partially controls H3K9me3 levels at loci regulated by heterochromatin factors. Because these elements are not upregulated in \textit{nrde}-2 mutants, this indicates that the observed reduction of H3K9me3 is not sufficient for derepression and supports partial redundancy between the \textit{nrde} pathway and heterochromatin factors in repeat silencing.
Discussion

All animal genomes contain abundant repetitive elements, which are subject to silencing control. This study expands our knowledge of repetitive element silencing by showing that a diverse set of heterochromatin factors (HPL-2/HP1, LIN-61, LET-418/Mi-2, LIN-13, and MET-2) work together with the piRNA and nuclear RNAi pathways to silence repetitive elements such as DNA transposons and retrotransposons. The systematic analyses of multiple factors, most of which are conserved, uncovered a network of functional interactions between them. We suggest that the interactions we identify here are likely to be relevant to the control of repetitive elements in other animals.

All factors and pathways studied are individually important for germ line function, as evidenced by reduced fertility or sterility of single mutants, and all are individually necessary for repetitive element silencing. Importantly, functional redundancy among the factors and pathways demonstrates widespread safeguards for ensuring germ line health and fertility. Our results show that there are interacting and overlapping mechanisms of repeat element silencing (Figure 8A).

Heterochromatin factors and small RNA pathways

Connections between heterochromatin formation and transcriptional silencing via RNAi mechanisms involving small RNAs have been observed in a variety of organisms (71, 72). For instance, RNAi machinery directs silencing at repetitive centromeric regions in S. pombe in a process that involves H3K9 methylation and chromodomain proteins that are similar to HP1. Likewise, in Arabidopsis and other
eukaryotes, repetitive elements have been shown to be repressed in chromatin by the
action of nuclear pathways involving small RNAs and the targeting of H3K9
methylation. These pathways have also been implicated in gene silencing. However
the mechanisms linking these silencing pathways are not fully understood and it is
clear that factors involved in heterochromatin formation and function remain to be
identified. For example a recent study of HP1a interactors in Drosophila identified
many new factors needed for gene silencing and/or heterochromatin organization (73)

Previous studies in *C. elegans* have also uncovered connections between
heterochromatin factors and small RNA pathways. The piRNA pathway is a small
RNA pathway active in the germ line that silences transposons and genes through
cytoplasmic and nuclear mechanisms (34). In the nucleus, the piRNA pathway
engages the nrde pathway and heterochromatin factors for transcriptional repression:
HPL-2, the H3K9me3 histone methyltransferase SET-25, and nuclear RNAi factors
are necessary for silencing a piRNA pathway sensor (35). The nrde pathway directs
H3K9me3 both endogenously and in response to exogenous dsRNA and effects
transcriptional repression in both the germ line and soma (42, 44, 46, 50).
Endogenous germ line nrde targets have been suggested to include retrotransposons
based on their enrichment at genomic intervals with increased expression and
decreased H3K9me3 levels in germ line nuclear RNAi mutants (51). Here, through
genetic and profiling analyses, we have established additional connections between
heterochromatin factors and small RNA pathways, linking them to repetitive element
repression, uncovering functional redundancy, and expanding understanding of their
relationships.

**Heterochromatin factors associate with and repress repetitive elements**
We found that the genome-wide distributions of each of the five heterochromatin factors studied here (HPL-2/HP1, LIN-13, LIN-61, LET-418/Mi-2, and MET-2/SETDB1) are highly correlated with each other and strongly associated with repetitive elements. These patterns are correlated with H3K9me2, but not with H3K9me3, as previously seen for HPL-2 in embryos (14). H3K9me2 and H3K9me3 modifications largely do not overlap (this study and (2)), but both are associated with repetitive elements. We further found that H3K9me2, but not H3K9me3 is enriched at telomeres. These patterns support functional differences between H3K9me2 and H3K9me3.

In addition to the similarity in binding profiles, we found that hpl-2, lin-13, lin-61, let-418, and met-2 set-25 mutant strains all showed derepression of repetitive elements and genes. While this paper was under review, Zeller et al reported that met-2 set-25 mutants derepressed transposable element expression in embryos and gonads, similar to the results presented here for met-2 set-25 young adults (74). The global loss of H3K9 methylation also leads to transposon derepression and mobilization in Drosophila (75). The patterns of upregulated repetitive elements and genes among the five heterochromatin mutant strains are strikingly similar, indicating shared targets. However, although binding profiles and consequences of loss are similar, the factors also have unique roles. Furthermore, genetic interactions between all pairs show that they have partially redundant functions. To understand these relationships, it will be important to investigate their interdependencies and the consequences of inactivating multiple factors together.

Relationships between heterochromatin factors and small RNA pathways
Comparing expression profiles of heterochromatin mutants to those of prg-1 (piRNA pathway) and nrde-2 (nuclear RNAi pathway) mutants, we observed that repeat elements and genes have similar patterns of derepression in heterochromatin factor and prg-1 mutants, but these largely differ from those in nrde-2 mutants. Consistent with a functional link between the heterochromatin factors and the piRNA pathway, a previous study showed that HPL-2 and SET-25 are needed for piRNA pathway function (35). Here we further found that LIN-61, LET-418, and MET-2 (weakly) are also important. It appears that heterochromatin proteins act as downstream effectors of the piRNA pathway rather than having a role in small RNA biogenesis or stability since levels of piRNAs and their secondary 22G RNAs are normal in hpl-2 mutants (35) (and this study). Investigating whether small RNA populations are altered in other heterochromatin mutants will be needed to confirm this hypothesis. This mechanism appears to differ from the situation in S. pombe, where H3K9 methylation and chromodomain proteins are required for association of silencing complexes that generate siRNAs (72, 76, 77). However, it is possible that redundancy between heterochromatin factors in C. elegans may have masked involvement in small RNA production.

Many more elements are desilenced in nrde-2 mutants than in prg-1 mutants, with little overlap between the two. The elements derepressed in nrde-2 mutants are mostly LTR retrotransposons, in line with a study finding transcriptionally upregulated genomic intervals in hrde-1 mutants to be enriched for LTRs and unaffected in prg-1 mutants (51). The apparent difference in targets between NRDE-2 and PRG-1 could be due to the requirement for PRG-1 in initiation but not maintenance of silencing. Once silencing is established by PRG-1, nuclear RNAi maintains silencing in a process termed RNAe that depends on continued generation
of secondary siRNAs by mutator proteins, the presence of secondary siRNA-
associated argonautes (including \textit{nrde-2}), and maintenance of the established
chromatin state by heterochromatin factors (35, 39-41, 78).

Our study also uncovered interactions between heterochromatin factors and
the nuclear RNAi pathway. We found that \textit{let-418; nrde-2} double mutants show a
strongly enhanced fertility defect compared to the single mutants, and that they
desilence a larger set and a wider spectrum of repetitive elements. Therefore, for some
elements, either LET-418 or NRDE-2 is sufficient for silencing, demonstrating
redundancy in repetitive element silencing. These interactions further emphasize the
overlapping safeguards that function to effectively repress repetitive elements. The
increased embryo lethality seen in double mutants between \textit{nrde-2} and three tested
heterochromatin factors (\textit{hpl-2}, \textit{lin-61}, or \textit{let-418}) suggest additional as yet
unexplored redundancy between the nuclear RNAi pathway and heterochromatin
factors. That a substantial number of repetitive elements are desilenced in
heterochromatin factor mutants but not in \textit{prg-1} or \textit{nrde-2} mutants suggests that
heterochromatin factors can also act as independent agents, silencing repetitive
elements independently of small RNA pathways.

Interestingly, genes and repeats upregulated in \textit{nrde-2} mutants more often
have high levels of H3K9me3 than H3K9me2 whereas those upregulated in \textit{met-2 set-}
25 mutants (which lack all H3K9 methylation) show the opposite pattern and more
often have high H3K9me2 marking (Figure 3-figure supplement 2). The association
between H3K9me3 and \textit{nrde-2} upregulated genes suggests that the nuclear RNAi
pathway may specifically engage this modification. Consistent with this, repeats and
genes upregulated in \textit{nrde-2} mutants have strongly reduced H3K9me3 levels in germ
line nuclear RNAi pathway mutants. However, the difference in elements desilenced
in *nrde-2* and *met-2 set-25* mutants (which lack H3K9 methylation) argues against an 
essential requirement for H3K9 methylation in *nrde* mediated repression. We 
observed that H3K9me3 levels in *nrde-2* and other germline nuclear RNAi mutants 
are also weakly reduced at genes and repeats repressed by heterochromatin pathway 
factors, even though these elements are not upregulated in *nrde-2* mutants. This 
suggests that the heterochromatin factors and the nuclear RNAi pathway may regulate 
many common elements, but that heterochromatin factors can still effectively silence 
them in the absence of the nuclear RNAi pathway. Future analyses in mutants 
compromised for both nuclear RNAi and heterochromatin factors will be needed to 
address the mechanisms of this redundancy.

**Heterochromatin factors may act locally within euchromatic domains**

We speculate that in many cases, repetitive element regulation involves a local 
mechanism rather than the spreading of large heterochromatin domains. First, we 
observe that heterochromatin factor binding is often closely associated with repetitive 
elements and does not extend to adjacent genes. Second, genes containing repetitive 
elements bound by heterochromatin factors (usually within introns) are often 
expressed. Indeed, one fourth of genes contain a repetitive element bound by a 
heterochromatin factor, and of those, 59% (3287/5568) are expressed in the germ line. 
Formation of a large inactive heterochromatin domain would clearly be incompatible 
with such widespread germ line expression.

In *C. elegans*, most H3K9 marking occurs on the distal chromosome arms, 
where small regions of H3K9 are interspersed with chromatin typical of euchromatin 
(2). Many active genes, including those expressed in the germ line, reside in these
arm regions (2). Intriguingly, the repeat- and H3K9-rich chromosome arms are generally associated with the nuclear lamina, a region implicated in transcriptional repression (3, 79). Active genes at the periphery that contain repetitive elements bound by heterochromatin factors may be subject to special mechanisms for their expression.

Heterochromatin factors and DNA repair

In addition to functioning in repetitive element repression, some of the heterochromatin factors we studied here are implicated in DNA repair or genome stability. We found that hpl-2 mutant germ lines show reduced repair and increased activation of DNA damage signaling in response to ionizing radiation. LIN-61 is needed for DNA repair in the germ line and its loss causes an increase in the germ line mutation rate (62, 63). Additionally, both lin-61 and set-25 were identified in a genome-wide RNAi screen for genes needed for genome stability in the soma (63). Furthermore, met-2 set-25 mutants, which lack all H3K9methylation, were recently shown to have increased sensitivity to replication stress and increased rates of repeat associated mutations and R loops (74). In mammalian cells, orthologs of LET-418 (Mi-2), HPL-2 (HP1), and MET-2 (SETDB1), have documented roles in DNA repair (80-82). Mi-2 is needed for recruitment of DNA repair proteins to sites of DSBs, and loss of Mi-2 from human fibroblast cell lines leads to apoptosis and sensitivity to ionizing radiation (83-85). HP1 accumulates at DSBs and its depletion causes abnormal recruitment of repair factors (86). Additionally, DNA damage repair defects caused by depletion of SETDB1 are similar to those seen upon loss of HP1 (80). Defects in repair of DNA lesions are likely to cause germ line stress and to contribute
to the germ line instability, germ line development defects, and increased germ line apoptosis seen in heterochromatin factor mutants. Such processes might also underlie the reduced fertility and increased germ line apoptosis seen in prg-1 mutants.

The activation of MIRAGE1 DNA transposases in all heterochromatin factor mutant strains and prg-1 mutants would be expected to cause double strand breaks and/or replication stress. We show that this abnormal expression contributes to sterility because fertility was partially restored in hpl-2, let-418, and lin-13 mutants when MIRAGE1 transcripts were knocked down via RNAi. Similarly, inhibiting endogenous meiotic double strand breaks by knockdown of spo-11 also partially restored fertility. These results suggest that heterochromatin factors act to combat different types of genotoxic insults, both through silencing repetitive elements and facilitating repair. If not dealt with, these insults cause sterility (Figure 8B).

We also observed that loss of cep-1/p53 suppressed heterochromatin factor defects. p53 is important for mediating DNA damage signaling (87). In C. elegans, p53/cep-1 is required for damage induced germ cell death (67, 68). In the soma, DNA damage signaling does not lead to p53/CEP-1-mediated apoptosis; however, CEP-1 does play a role in DNA repair in the soma, and it slows larval development in response to loss of CLK-2/TEL2 DNA damage signaling (88, 89). Our findings that loss of cep-1 partially suppresses the sterility and slow growth phenotypes of hpl-2, lin-13, and let-418 suggests that activation of damage signaling and cep-1/p53 underlies these defects.

Interestingly, none of the heterochromatin mutant strains studied here display hallmarks of mutators such as high embryo lethality or the frequent production of progeny with visible mutant phenotypes. We propose that quality control mechanisms
in the germ lines of heterochromatin factor mutants largely prevent improperly repaired meiotic germ cells from becoming mature gametes, either through apoptosis or the arrest of gametogenesis, to ensure that mutation rates are low.

Conclusions

This study indicates a complex orchestration of fertility protection by HPL-2/HP1, LIN-13, LIN-61, MET-2, and LET-418/Mi-2 together with the piRNA and nuclear RNAi pathways. Repression of repetitive elements may prevent replication stress and DNA damage, but when damage does occur, these heterochromatin proteins participate in repair pathways to maintain genome integrity. Further work will be required to untangle the mechanisms and individual roles in DNA repair pathways and repetitive element repression.
Methods

Worm culture and strains

Strains were cultured using standard methods (Brenner, 1974). Strains used in the paper are given in Supplementary file 2. Whole genome sequencing of PFR40 hpl-2(tm1489) identified an 882bp deletion in the polq-1 gene at chrIII:5792238-5793119. The underlined T residue marks the junction of the deletion and matches the flanking sequence of both sides of the deletion:

TAAATCTCTATCCGATGTGAT

We have named this lesion polq-1(we100). The JA1902 strain harboring hpl-2(tm1489) but lacking polq-1(we100) was derived by outcrossing MT15062 hpl-2(tm1489);hpl-1(n4317), which does not contain polq-1(we100).

ChIP-seq

Wild-type young adults (YA) were prepared by growing synchronized L1s in liquid culture using standard S-basal medium with HB101 E. coli for 60 hours at 20°C. Adults were sucrose floated, washed in PBS, and flash frozen in liquid nitrogen. Extract preparation and chromatin immunoprecipitation were performed as in (90) with the following modifications: tissue was fixed for 10 minutes in 1.5 mM EGS (Pierce 21565) then formaldehyde added to 1% for a further 10 minutes before quenching with 0.125M glycine and washing 2X with PBS plus protease inhibitors. Pellets were washed once in FA buffer, then resuspended in 1ml FA buffer per 1 mL of ground worm powder and the extract sonicated to an average size of 250 base pairs with a Diagenode Bioruptor or Bioruptor Pico for 28 pulses of 30 seconds followed
by 30 seconds pause. Antibodies used for ChIP are given in Supplementary file 3.

Following ChIP and DNA purification, libraries were prepared using the Illumina TruSeq kit. Fragments in the 250-300 base pair range were selected using Agencourt AMPure XP beads. Two biological replicate ChIPs were conducted for each factor.

**RNA-seq**

Synchronized, starved L1 stage worms were grown on NGM plates at either 15°C (lin-13, prg-1, nrde-2, nrde-2; let-418, and N2) or 20°C (hpl-2, let-418, lin-61, met-2 set-25, and N2) until the L4 stage and then shifted to 25°C for 15-18 hours until they reached young adult stage. Worms were washed off plates at the young adult stage, flash frozen in liquid nitrogen, and stored at -80°C until use. RNA was extracted from frozen worms using TriPure (Roche). RNA was purified with Zymo Research RNA Clean and Concentrator-5 (Cambridge Bioscience) following DNAse I digestion. Ribosomal RNA was depleted using Ribo-Zero rRNA Removal Kit (Human/Mouse/Rat) (Illumina). Libraries were prepared using the NEBNext Ultra Directional RNA Library Prep Kit for Illumina (New England Biolabs). Two biological replicates were prepared for each strain.

**Data Processing**

ChIP-seq and RNA-seq libraries were sequenced using Illumina HiSeq. Reads were aligned to the WS220/ce10 assembly of the *C. elegans* genome using BWA v. 0.7.7 (91) with default settings (BWA-backtrack algorithm). The SAMtools v. 0.1.19 'view' utility was used to convert the alignments to BAM format. To be able to investigate
binding and expression at repetitive elements, we used all aligned reads (mapq0) to
generate pileup and normalised tracks. Normalized ChIP-seq coverage tracks were
generated using the BEADS algorithm (92) without the mappability correction step.
ChIP-seq and RNA-seq library read numbers and alignment statistics are given in
Figure 2-source data 3.

Peak calls

Broad and sharp ChIP-seq peaks were generated as follows. Initial ChIP-seq peaks
were called using MACS v. 2.1.1 (93) with a permissive 0.7 q-value cutoff and
fragment size of 150bp against a summed ChIP-seq input. These were used in
conjunction with a modified IDR procedure to generate broad peak calls ((94);
https://www.encodeproject.org/software/idr/) with an IDR threshold of 0.05 to
combine replicates. These broad peaks are termed “IDR peaks” (Figure 2-source data
1). The pipeline for generating IDR peaks is available here:
https://github.com/Przemol/biokludge/blob/master/macs2_idr/macs2_idr.ipy. To
generate sharp peak calls, the IDR calls were further refined using an adhoc post-
processing step, as visually distinct peaks close to each other were often contained
within single broad peaks. We identified concave regions within the IDR peaks using
the smoothed second derivative of the mapq0 pileup coverage signal with 250bp
kernel
We empirically found the minimum of the second derivative within a concave region
to be a good indicator of a visually compelling peak, and used concave regions
(within IDR peaks) with a threshold of lower than -500 curvature index. Next, we
discarded peaks with MASC2 score lower than 100 and peak width lower than 100bp.
The resulting peaks were filtered against combined ENCODE
(http://www.broadinstitute.org/~anshul/projects/worm/blacklist/ce10-blacklist.bed.gz)
and in-house blacklist
(https://gist.github.com/przemol/8a712a2e840f95237f4a4f322f65bee1) to generate
our final sharp peak calls, described as “concave peaks.” We created a summary peak
call super set by creating a union of the five heterochromatin factor concave peak
calls. We termed this set “Any5” (n=33301; Figure 2-source data 1). Each Any5
region was then annotated for overlap with each factor. Venn diagrams were plotted
using VennDiagram R package (95), and UpSet plots were generated as described in
(96). For determination of factors bound to repeats, we used broad IDR peak calls
since repeats usually display a pattern of broad factor binding. Broad IDR peaks were
used in Figure 3-figure supplement 2.

Differential expression analyses of genes

We built an exon model based on Ensembl Gene 77 (Nov 2014) database gene
annotation lifted over to ce10/WS220. Tag counts for each gene were extracted from
BAM alignment files using HTSeq method working in union mode and implemented
in R. These values were used to build an expression matrix. Differential gene
expression between N2 and mutant backgrounds was tested using DESeq2; mutants
were compared to their temperature matched control N2 replicates (97). Reads per
kilobase of exon model per million mapped reads (RPKM) normalized expression
values were generated using the median ratio method (Equation 5 in Anders and
Huber, 2010). RPKM values, maximum posterior estimates of log2 FC (LFC) and
statistical significance estimates for each gene is in Figure 3-source data 3. We used a false discovery rate (FDR) < 0.01 and LFC > 1 to call genes up-regulated, and FDR < 0.01 and LFC < -1 to call genes down-regulated. To avoid small differences in developmental stages from contributing to apparent gene expression differences, we also excluded genes whose wild-type expression oscillates repeatedly during development (Supplemental Table S7 in(98)).

Differential expression analyses of repeats

We built a repeat element model based on Dfam 2.0 ((57), downloaded Sept 2015 from http://dfam.org/). The model contained 62331 individual repeats divided into 184 families. Since individual repeats did not had unique identifiers (UID), we named them based on genomic position in “chromosome:start-end” convention, e.g. “chrI:10773-11032”. Tag counts for each repeat were extracted from BAM alignment files using HTSeq method working in union mode and implemented in R. These values were used to build expression matrixes. Differential repeat expression between N2 and mutant backgrounds was tested using DESeq2 as described above for genes. A table containing RPKM values, maximum posterior estimates of log2 FC (LFC) and statistical significance estimates for each repeat is available in Figure 3-source data 1. Upregulated repeats were defined as those with a false discovery rate (FDR) < 0.01, and LFC > 0. In addition, repeats that overlapped a gene upregulated in the matched mutant background were filtered out. For purpose of filtering, differentially expressed genes were defined with more permissive cutoffs: FDR < 0.05 and LFC > 0.
To assess expression of individual repeats scored as upregulated above, we counted uniquely mapping reads, defined as having a BWA mapping quality over 10. Elements with >10 unique reads and fold-change >1.5 were considered upregulated, which applied to 61 of 71 elements upregulated in any of the heterochromatin factor mutant strains. The remaining 10 elements had insufficient uniquely mapping reads for assessment.

Telomere enrichment

Telomere enrichment for ChIP-seq factors were determined by counting reads with the telomere sequence “GCCTAA”. Reads were extracted from BAM files (including non- aligned reads) and trimmed to 36bp. Then the number of “GCCTAA” motifs was counted for each read using Biostrings R package. Telomeric reads were defined as those having 5 or 6 “GCCTAA” motifs in 36bp. To assess the statistical significance of enrichment we used one sided Mann–Whitney U test (2 replicates for each factor vs. input background of 129 experiments) and reported the p-values.

small RNA analyses

The following small RNA datasets from (35) were used: prg-I (GSM708661), WT matching prg-I (GSM708660), hpl-2 (GSM950181), WT matching hpl-2 (GSM950180), nrde-2 (GSM950179), WT matching nrde-2 (GSM950178). Uniquely matching positions in each dataset were determined and the smallest number (530039, in the prg-I dataset) subsampled from each. piRNA number was then determined by calculating the number matching the piRNAs annotated in (38) or (34) (n=27884
piRNAs). piRNA targets were determined as in (41), requiring a perfect match and no more than one G:U pair in the seed region (nt 2–8), and allowing up to two mismatches and an additional G:U pair outside of the seed region, excluding self hits (n=391173). piRNA dependent 22Gs were also defined as in (41), as 22G RNAs that mapped in 100bp windows centered at piRNA target sites, allowing zero or one mismatch.

H3K9me3 levels in nrde mutants

The following H3K9me3 ChIP seq datasets were used: nrde-2 (GSM855086), nrde-3 (GSM932875), nrde-4 (GSM932876), WT for nrde-2, -3, -4 (GSM855085), hrde-1 (GSM1399632), and WT for hrde-1 (GSM1399631) from (44, 47, 51). Datasets were processed as described in the data processing section above. The average signal in each region of interest was calculated and the H3K9me3 fold change was calculated relative to the matched wild-type dataset. Control repeats (n=612) have >1.5-fold H3K9me3 levels relative to the genome average, have <1-fold signal for each of the five heterochromatin factors (HPL-2, LIN-13, LIN-61, LET-418 and MET-2) relative to the genome average, and are not upregulated in any of the five mutant strains. A reduction of H3K9me3 at gene and repeat sets of interest was assessed by comparing to all genes or all repeats using a single-sided Mann-Whitney U test.

Detection of phospho-CHK-1

N2 and hpl-2 adults grown at 25°C were irradiated at 0, 20, and 100 Gy and recovered for one hour at 25°C. One hour post irradiation, gonads were dissected in 8 µL M9 on slides and freeze-cracked. Gonads were fixed four minutes in 100 % methanol.
followed by twenty minutes in 4% formaldehyde in 1X PBS. After fixation, gonads were washed two times for ten minutes in 1X PBS + 0.2% Tween-20 (PBST), blocked for one hour at room temperature in 1% milk in PBST, washed two times for ten minutes in PBST, incubated overnight at 4°C in primary antibody diluted in PBST (1:50 rabbit monoclonal α-phospho-CHK-1, Ser345, 133D, Cell Signalling Technologies, catalogue #2348), washed two times for ten minutes in PBST, incubated 2 hr with secondary antibody (Molecular Probes) and DAPI. Gonads were scored for the presence of phospho-CHK-1 staining using a Zeiss 510 Meta scanning-laser confocal microscope. Counts from individual experiments were pooled to give overall totals, and a two-tailed proportions Z test was used to determine whether there was a difference between N2 and hpl-2 worms at a specific condition.

Oocyte Chromatin Fragmentation Assay

L4 N2 and hpl-2(tm1489) grown at 20°C were irradiated at 0, 50, and 100 Gy, recovered for 24 hours at 20°C, then fixed in MeOH and DAPI stained. Slides were scored for the number of DAPI bodies in diakinesis oocytes. Oocytes with six DAPI bodies, representing the six bivalent chromosomes, were considered normal; oocytes with other numbers of DAPI bodies, representing chromosome fracturing or clumping, were considered fractured. To determine whether the proportion of oocytes with fractured chromosomes was different between N2 and hpl-2(tm1489) worms at a particular condition, a two-tailed proportions Z test was used. Two-tailed P values were calculated using a Z score table.

Germ line apoptosis measurements
bcIs39 (Plim7::ced-1::GFP) expressed in gonadal sheath cells, was used to count engulfed germ line corpses (69). Strains containing bcIs39 in wild type and mutant backgrounds were maintained at 20°C. L4s of each genotype were picked and 48 hours later scored for the number of engulfed apoptotic cells in the gonad. A minimum of 25 gonads per experiment were scored in three independent experiments. The number of apoptotic cells in the germ line observed with the ced-1::GFP is higher than the number stained by vital dye or visualized by Nomarski optics because the reporter also marks cells at earlier stages of apoptosis than can be detected by other methods (99, 100). In lin-13, hpl-2, and met-2 set-25 strains, full or partial silencing of the GFP transgene reporter occurred in some individuals. These animals were excluded because it was not possible to count cell deaths. Statistical significance was scored using a Mann-Whitney non-parametric test over all the datapoints combined.

Assessment of abnormal oogenesis

Strains were maintained at 20°C and shifted to 25°C at the L4 stage. Adult germlines were imaged 48 hours later by mounting animals on 3% agarose pads in 5 mM Tetramisole, using a Zeiss widefield upright microscope using Nomarski optics. Oogenesis was deemed ‘abnormal’ if oocytes appeared small and rounded, if they were disorganized, or if their cytoplasm had taken on a pronounced curdled texture. Germlines which had mostly or fully disintegrated, and lacked detectable oocytes, were also quantified.

Sterility interaction tests
Fertility interactions among heterochromatin factors were tested as follows: N2, let-418(n3536), and lin-13(n770) were maintained at 20°C. Worms were fed at 20°C from the L4 stage for the following RNAi clones from (101): hpl-2 (K01G5.2), met-2 (R05D3.11), and lin-61 (R06C7.7) or from starved L1s for lin-13 (sij2_C03B8.4). RNAi plates were prepared as in (102). Progeny of fed L4s or the fed L1 were singled out onto fresh RNAi plates as L4s and total broods assessed by transferring the worms to new plates every day until they stopped laying eggs. Two independent experiments were conducted, with 3-8 total broods counted for each strain/RNAi combination.

Three double mutant combinations were also constructed and tested: lin-61(tm2649); lin-13(n770), lin-61(tm2649); hpl-2(tm1489), and hpl-2(tm1489); let-418(n3536).

Wild-type N2, single mutants, and double mutant strains were maintained at 20°C and total broods counted.

Fertility interactions between nrde-2 and let-418, hpl-2, or lin-61 were tested as follows. Wild-type, single mutants, and double mutants were grown at 15°C from starved L1 until the L3 stage, then transferred to 25°C. Total brood size per worm was determined for 12-24 worms per strain across two independent experiments.

Genotypes of strains are given in Supplementary file 2.

Statistical tests for the above genetic interactions were conducted as follows:

Under the null hypothesis that the two genes do not interact to affect fertility, the expected brood size of double mutant (or RNAi knockdown in a single mutant background) is the product of those of the single mutants (or that of the single mutant and the RNAi knockdown in a wild type background) divided by the brood size of the wild-type (or of the wild-type strain grown on control (empty vector) RNAi plates).

Similar to (103), a t-test was used to test if the observed brood size of double mutants
(or RNAi knockdown in a single mutant background) equals the expected brood size under the null hypothesis.

Tests for suppression of sterility of hpl-2(m1489), lin-13(n770), and let-418(n3536) mutants were conducted mutants as follows. The three strains show temperature sensitive sterility. Strains were maintained at 20°C, a temperature at which they are fertile, and starved L1s prepared by bleaching adults to collect embryos and hatching them in M9 buffer for 24 hrs at 20°C. Starved L1s were spotted onto RNAi plates prepared as in (102). They were then grown under conditions at which the mutant strain is nearly sterile: hpl-2 was incubated at 24°C or 25°C, lin-13 was incubated at 24°C, and let-418 was incubated for 7.5hrs at 20°C, then shifted to 24°C. After three days, the number of progeny produced by these L1s was counted. RNAi plates were prepared as in (102). The following RNAi clones were from (101): cep-1 (F52B5.5), spo-11 (T05E11.4), mirage-A (K02E7.2 + K02E7.3), mirage-B (W03G1.3 + W03G1.4). For each combination of mutant strain and target gene to knockdown, a paired t-test was used to compare the average number of progeny per parent from gene-targeting RNAi plates and matched empty vector plates incubated under the same condition.

Brood sizes of cep-1(lg12501); hpl-2(tm1489), cep-1(lg12501);let-418(n3536) and cep-1(lg12501);lin-13(n770) double mutants were compared to wild-type and single mutants. Adults raised at 15°C were bleached to obtain embryos and left at 20°C to hatch without food to obtain starved L1s. The starved L1s were fed with OP50 bacteria and immediately shifted to 25°C (for hpl-2 tests) or fed at 20°C for 7.5 hrs before shifting to 25°C (for let-418 and lin-13 tests). Experiments were repeated at least twice and total brood sizes were determined for 8 to 40 worms per strain. L1s prepared in the same way were used for growth rate tests, counting the number of
adults, L4s, or worms younger than L4 (indicated <L4) after approximately 48 hrs post feeding. A single sided t-test was used to test whether the brood size of the cep-1 double mutant is larger than that of the single heterochromatin mutant.

**piRNA sensor expression**

mjls144 [mex-5p::HIS-58::GFP::piRNA(21UR-1)::tbb-2-3′UTR] was used to assess piRNA pathway function (35). Synchronized larvae containing mjls144 in wild type or mutant backgrounds were maintained at 20°C, and scored for germ line expression 24 hours post-L4 stage. Four experiments were conducted per strain, with a minimum of 25 worms per experiment. GFP was scored using a Zeiss Axioplan 2 upright widefield microscope, where the level of GFP expression was assessed (none, low, moderate). Moderate expression was scored when GFP was easily detectible in oocytes and pachytene nuclei. Low expression was scored when GFP was just visible in oocyte and pachytene nuclei. In Figure 6, silenced represent gonads with no expression and Expressed - GFP(+) represent moderate or low expression. In the case of met-2, all expression was in the low category.

**RNA FISH**

N2, hpl-2, lin-13, let-418, and prg-1 young adults were fixed and stained by RNA FISH as described (60). Stellaris® FISH probes targeting MIRAGE1 and sqv-1 (as an internal control) were obtained from Bioresearch Technologies (Novato, CA). CAL Fluor Red610 was used for MIRAGE1 and Quasar 570 was used for sqv-1. From 11-22 individuals per strain were scored.
Datasets

Datasets generated in this paper are available at GEO accession GSE87524.
Acknowledgements

We are grateful to A. Akay for helpful comments on the manuscript. This work was supported by Wellcome Trust Senior Research Fellowships to JA (054523 and 101863). AM was supported by a fellowship from the Canadian Institutes of Health Research, DA by a Darwin Trust scholarship, and AS by an HFSP postdoctoral fellowship. EM was supported by grants from the Wellcome Trust (104640/Z/14/Z) and Cancer Research UK (C13474/A18583). JA and EM also acknowledge support by core funding from the Wellcome Trust (092096) and Cancer Research UK (C6946/A14492).
References


Figure legends

Figure 1. Heterochromatin proteins have redundant roles in fertility.

(A) Genetic interactions in fertility assayed using RNAi. Indicated RNAi of wild-type, let-418(n3536), or lin-13(n770) was conducted by feeding at 20°C as described in the methods. Results are a combination of two independent experiments with the progeny of 3-8 total broods counted for each strain/RNAi combination. A one-sided t-test was used to determine whether the mutant/RNAi combination had a lower brood size than expected under a multiplicative model of interaction when compared to the mutant grown on empty vector RNAi and the individual RNAi knockdowns in wild-type animals. Brood size is significantly lower than expected for all RNAi/mutant combinations at p<0.05. (B) Indicated double mutants were constructed and their brood sizes compared to that of the individual signal mutants raised at 20°C. Statistical testing was as in (A), with brood sizes of the three double mutants significantly lower than expected at p<0.05 in a one-sided t-test. (C) All pairs of hpl-2, lin-13, lin-61, let-418, and met-2 show genetic interactions in fertility, as determined in this study or previous studies. ref 1. Coustam et al, Dev Biol. 2006. ref 2. Koester-Eiserfunke and Fischle, PLoS Genet. 2011. ref 3. Simonet et al, Dev Biol. 2007. Supplementary file 1 shows previously reported sterility phenotypes. Figure 1 – figure supplement 1 shows examples and quantification of abnormal oogenesis in heterochromatin mutants.

Figure 2. HPL-2, LET-418, LIN-13, LIN-61, and MET-2 show extensive co-binding and are enriched at repetitive elements.

(A) Distribution of the indicated proteins and histone modifications over each C. elegans chromosome. z-scored ChIP-seq tracks are shown for HPL-2 (red), LET-418 (blue), LIN-13 (green), LIN-61 (orange), MET-2 (pink), H3K9me2 (grey) and H3K9me3 (black) on each chromosome, demonstrating enrichment over the autosomal arms. Figure 2-figure supplement 1A shows distributions of peak locations in different chromosome regions. (B) IGV browser screenshot showing similar patterns of the heterochromatin factors and H3K9me2 methylation over a 45 kb region containing multiple repeat elements. z-scored ChIP-seq tracks are as in (A). Any5 peak calls denote combined peak calls for any of the five proteins; repeats are from Dfam2.0 {Hubley, 2016 #4}. Figure 2-figure supplement 1B shows correlations in signal between all datasets. (C) UpSet plot of the association of heterochromatin factors with the 33,301 Any5 peak calls. Dots indicate peak class is bound by the factor. Bars show total number of peaks per class, the orange portion denoting overlap with repeat elements. Below the bar chart relative enrichments for H3K9me2 and H3K9me3 are shown. The peaks that overlap all 5 factors constitute the largest class (n=4810). Figure 2-figure supplement 1 gives total peak numbers per factor, number of peaks overlapping repeats, and number of repeats bound by each factor. Figure 2-source data 1 gives peak calls. (D) Associations of factors and repeat classes. Upper panel: levels of indicated protein or histone modification on families within indicated Dfam 2.0 repeat classes relative to the genome average. Bottom panel: Proportion of families within each repeat class significantly enriched for...
indicated factor or histone modification. Criteria for enrichment are >1.5 fold mean enrichment of family relative to genome, FDR<0.1, considering families with at least 10 members. Number of families with 10 or more members within each class are: Cut and paste (n=89), Helitron (n=7), LTR (n=31), LINE (n=13), SINE (n=3), Satellite (n=16), Unknown (n=7). Figure 2-source data 2 gives enrichment scores for repeat family factor binding.

Figure 3. Repetitive elements are upregulated in hpl-2, let-418, lin-13, lin-61, met-2 set-25, prg-1, nrde-2, and nrde-2; let-418 mutants.
(A) Venn diagram of elements upregulated in hpl-2, let-418, lin-13, lin-61, and met-2 set-25 mutants. The seven elements upregulated in all five strains are MIRAGE1 elements. (B) Distribution of Dfam 2.0 repeat classes upregulated in each strain. (C) Repeat families with members upregulated in at least one of hpl-2, let-418, lin-13, lin-61, or met-2 set-25 mutant strains. (D) IGV browser screenshot of a MIRAGE1 element that is upregulated in all mutant strains. Tracks are reads per million of two combined replicates. Figure 3-figure supplement 1 gives further examples of elements upregulated in different strains. (E) Single molecule RNA-FISH signals of MIRAGE 1 element RNA in the adult germ line (white dots). Signal is not detectable in wild-type but is abundant in the indicated mutant backgrounds. Figure 3 – figure supplement 3 shows additional images of MIRAGE1 and sqv-1 control RNA FISH in germline and somatic tissues. Figure 3-figure supplement 2 shows enrichment of heterochromatin factors, H3K9me2, and H3K9me3 on regulated genes and repeats.

Figure 4. Phenotypic suppression of hpl-2, let-418 and lin-13 by inhibition of MIRAGE1, cep-1/p53, or spo-11
(A) RNAi of MIRAGE1, cep-1/p53 or spo-11 partially suppresses sterility of hpl-2, let-418, and lin-13. Average number of progeny per worm for control empty vector RNAi (EV) or the indicated RNAi treatments in hpl-2(tm1489), let-418(n3536), or lin-13(n770) (averages of 5-11 experiments). Experiments were done under conditions where the mutant strain was nearly sterile to detect an increase in fertility (see Methods). Control progeny numbers vary by experiment, but were always paired with experimental RNAi. Stars indicate statistical significance assessed using paired t-tests, comparing experimental to control RNAi (p<0.05, one star; p<0.01, two stars; p<0.001, three stars). Two sets of RNAi clones were used to target MIRAGE1 elements (termed mirage-A and mirage-B). RNAi clones used are given in the methods. (B) Mutation of cep-1/p53 partially suppresses sterility of hpl-2, let-418, and lin-13 mutants at 25°C. Statistical significance was assessed using single sided t-tests, asking if cep-1; hpl-2, cep-1; let-418, and cep-1; lin-13 double mutants had larger broods than the corresponding heterochromatin single mutants. See methods for growth conditions. (C) Loss of cep-1 partially rescues growth delay defect of heterochromatin mutants at 25°C. Developmental stage of worms grown from L1 at 25°C for approximately 48 hrs was assessed (adult, L4, younger than L4).
representative experiment out of three replicates is shown, assaying between 95 and 213 worms in each. See methods for growth conditions.

Figure 5. Heterochromatin mutants have increased germline apoptosis.

CED-1::GFP (bcIs39 [Plim-7::ced-1::gfp]), expressed in gonad sheath cells, marks engulfed apoptotic cells in the pachytene region of the adult gonad. (A) CED-1::GFP images for wild type, hpl-2, and met-2 set-25 mutant gonads. Arrows point to engulfed apoptotic cells; scale bar = 16 um. (B) Number of apoptotic cells per gonad arm for wild-type (bcIs39), hpl-2(tm1489); bcIs39, lin-13(n770); bcIs39, and met-2(n4256) set-25(n5021); bcIs39. Shown are the combined data points of at least 3 independent replicates; each dot represents an individual gonad arm count. Bars denote mean and SD. Mann-whitney non-parametric tests were performed on mutant versus control. (p-values for hpl-2, lin-61, met-2 set-25 are <0.0001; p-value for lin-13 is 0.009). Strains were cultured at 20°C and scored 48 hrs after the L4 stage. Figure 5 –figure supplement 1 shows increased sensitivity of hpl-2 to IR-induced DNA damage.

Figure 6. Heterochromatin factors interact with the piRNA pathway.

(A) Venn diagram showing extent of overlap between repeats upregulated in prg-1 mutants and repeats upregulated in any of the five heterochromatin factor mutant strains (hpl-2, let-418, lin-13, lin-61, or met-2 set-25). Listed in the Venn are the numbers of repeats and repeat families common or unique to prg-1. (B) prg-1 mutant germ lines show increased germ cell death. Shown are the number of apoptotic cells per gonad arm for bcIs39 (CED-1::GFP) and prg-1; bcIs39 (CED-1::GFP). Each dot represents an individual gonad arm count. Bars denote mean and SD. A minimum of 25 gonads were scored per experiment and shown are the combined datapoints of at least 3 independent replicates. Mann-whitney non-parametric tests were performed on mutant versus control (P-value <0.0001). Strains were cultured at 20°C until L4 stage, then shifted to 25°C for 48 hrs before scoring. (C, D) Heterochromatin mutants desilence a piRNA sensor. piRNA sensor expression (mjIs144 [mex-5p::HIS-58::GFP::piRNA(21UR-1)::tbb-2-3'UTR]) was quantified in one day old wild-type and heterochromatin mutants cultured at 20°C. (C) Representative GFP and DIC microscope images of adult germ lines in which the reporter is silent (WT, lin-13) or expressed (lin-61). (D) Quantification of piRNA sensor expression in wild type and heterochromatin mutants. Shown are the means and standard error of the percentage of worms which at least weakly desilenced the GFP reporter in oocytes and pachytene regions. A minimum of 100 worms for each strain was assessed over four independent experiments. Fishers exact tests were performed on the combined datapoints to address significance, with let-418 (p-value <0.0001), lin-61 (p-value <0.0001) and set-25 (p-value <0.0001) all displaying increased frequency of expression of the piRNA sensor reporter, while sensor expression in lin-13 is
not significantly different from wild type (p-value 0.4419). met-2 mutants weakly desilence the sensor in a small subset of adults scored (p-value 0.0215).

**Figure 7.** *nrde-2* and *let-418* show functional redundancy.

(A) *nrde-2* and *let-418* mutants show genetic interaction in fertility. Brood sizes of *nrde-2; hpl-2, nrde-2; let-418, and nrde-2; lin-61* double mutants were compared to those of single mutants. Synchronized single or double mutant strains of the indicated genotype were grown at 15°C until the L3 stage and then transferred to 25°C, and total progeny including dead embryos determined for 12-24 mothers across two independent experiments. A single-sided Mann-Whitney U test was used to determine whether the double mutant had a lower brood size than expected under a multiplicative model of interaction when compared to the individual single mutants. Brood size is significantly lower than expected for *nrde-2; let-418* (p =9.21E-11) but not *lin-61; nrde-2* (p=0.20) or *nrde-2; hpl-2* (p=98). (B) *nrde-2; hpl-2, nrde-2;let-418* and *lin-61;nrde-2* double mutants show increased proportion of dead embryos within their broods compared to single mutants. Total number of dead embryos was determined as a proportion relative to their total brood size for the experiment in (A). Mann-Whitney U tests were performed to compare the proportion of unhatched eggs in double mutants relative to *nrde-2* single mutants, and were all found to be significant at p<0.05. (C) Repeat families with members upregulated in *let-418, nrde-2, and nrde-2; let-418* young adult worms. Figure 7-figure supplement 1A compares repeat families upregulated in *nrde-2, prg-1*, or any of the five heterochromatin mutants (D) Example of repeats upregulated in *nrde-2; let-418*, but not the single mutants. Tracks are RNA-seq reads per million of two combined replicates. Figure 7-figure supplement 1B shows lack of MIRAGE1 expression in the *nrde-2* mutant background.

**Figure 8.** Heterochromatin proteins collaborate with small RNAi pathways to maintain fertility.

(A) Pathways of transposable element silencing in *C. elegans*. Heterochromatin factors participate in repetitive element silencing together with the piRNA and nuclear RNAi pathways, as well as targeting elements independently of these pathways. (B) Derepression of transposable elements and defects in DNA repair likely generate genotoxic stress that leads to germ line defects and infertility in heterochromatin factor mutants.
Legends for Figure Supplements:

Figure 1 – figure supplement 1. Heterochromatin mutants display abnormal oogenesis

(A) Strains of the indicated genotype were shifted to 25°C at the L4 stage and imaged by Nomarksi microscopy 48 hours later. Oocyte quality was determined and deemed ‘abnormal’ when oocytes appeared small, round and gapped, showing the appearance of a curdled cytoplasm, or when they were unaligned and disorganized. Numbers in brackets denote the total number of germlines scored. Disintegrated germline refers to the absence of oocytes and an apparent disintegration of (most of the) gonad arm. Representative images of several of the mutants are shown. Scale bar is 33 μm.

Figure 2-figure supplement 1. Correlation of HPL-2, LET-418, LIN-13, LIN-61, and MET-2 ChIP-seq tracks and enrichment on chromosome arms, repetitive elements, and telomeres.

(A) Distribution of HPL-2, LET-418, LIN-13, LIN-61, MET-2, All5, or Any5 ChIP-seq peaks between chromosome arms and centers (left) and between genes (introns and exons) and intergenic regions on the centers (middle) and arms (right). (B) Pearson correlation coefficients for ChIP-seq track combined replicates in 100 bp windows. (C) Number of peaks for individual data sets within the 33301 Any5 combined peak calls, the numbers unique to each dataset and the numbers of peaks overlapping repetitive elements. (D) Numbers of Dfam 2.0 repetitive elements (n = 62331) that have factors bound based on IDR peak calls (see Methods). (E) Enrichment scores for H3K9 methylation and binding of factors at telomeres.

Figure 3-figure supplement 1. Examples of unique and co-regulated repeat elements in various heterochromatin mutants.

IGV screenshots of repeat elements upregulated in a subset of heterochromatin mutants. (A) HELITRON1 element only upregulated in lin-13 mutants. (B) PALTTAA2 and CELE46B elements only upregulated in hpl-2 mutants. (C) CER16 LTR element upregulated in hpl-2, lin-61, nrde-2 and nrde-2; let-418 mutants. Signal tracks are RPM normalized. Additional tracks show genes, Dfam2.0 repeats, and transposon ORFs.

Figure 3-figure supplement 2. Heterochromatin factors and H3K9 methylation show enriched association with upregulated genes and repeats.

(A) Percent overlap of heterochromatin factor peaks or >1.5 fold enrichment for H3K9me2 or H3K9me3 on upregulated (left) or downregulated (right) genes (-
500 bp to gene end). Parentheses give number of genes with overlap, star indicates FDR<0.01. (B) Enrichment of factors over upregulated repeats in each of the mutant strains.

Figure 3-figure supplement 3. MIRAGE1 RNA is upregulated in the germ lines of hpl-2, lin-13, let-418, and prg-1 mutants.

(A) Single molecule RNA-FISH signals of MIRAGE 1 RNA in the adult germ line (left panels; zoomed in on the right). Middle panels show sqv-1 (positive control) RNA-FISH and DAPI to counterstain nuclei. (B) Single molecule RNA-FISH signals of MIRAGE 1 RNA, showing both germline and somatic tissues. MIRAGE 1 (middle and indicated boxes zoomed in on the right) is increased in mutant germlines but remains low in the soma. Left, DAPI counterstain. Scale bar represents 30 μm.

Figure 5-figure supplement 1. hpl-2 mutants are hypersensitive to ionizing radiation-induced DNA damage.

(A) Phospho-CHK-1 staining of adult germ lines 1 hr post IR treatment. Bars are 10 μm. (B) Quantification of phospho-CHK-1 staining. hpl-2 mutants showed significantly more phospho-CHK-1 positive gonads than wild-type at an intermediate dose of 20 Gy. Strains were grown at 25°C. (C) Images and counts of oocyte chromosomes and fragments following IR. N2 and hpl-2(tm1489) were grown at 20°C, irradiated at 0, 50, and 100 Gy at the L4 stage, and stained with DAPI after 24 hours. Left, representative photographs of N2 and hpl-2 oocytes. Right, counts of DAPI stained fragments in oocytes at the indicated dose of IR. The majority of non-irradiated N2 and hpl-2 oocytes have 6 distinct DAPI bodies, representing the 6 bivalent chromosomes. hpl-2 mutants show more fragmentation of oocyte chromosomes at 50 and 100 Gy, indicating a defect in repair of exogenous DNA damage. Bars are 5 μm. A minimum of 88 oocytes were scored over two to three independent experiments.

Figure 6-figure supplement 1. Quantification of piRNAs and dependent 22G RNAs in prg-1 and hpl-2 mutants

(A) Unique piRNAs, repeat elements targeted by a piRNA, number of unique 22G RNAs mapping near piRNA target sites, and number of repeat elements hit by a piRNA-associated 22G RNA. The number in each class found in 530039 unique small RNA positions subsampled from each dataset (prg-1, hpl-2, and matched wild-types) is shown. (B) log2 ratios of the relative change in abundance of the indicated classes of small RNA or repeats in mutant strains compared to wild-type. Datasets used and the procedure for calculating piRNA and dependent 22G RNA number is given in the Methods.

Figure 7-figure supplement 1. Overlap of nrde-2, prg-1, and heterochromatin targets.

(A) Repeat families with members upregulated in nrde-2, prg-1, and any of the five heterochromatin mutants (let-418, hpl-2, lin-13, lin-61, and met-2 set-25).
Families in bold are specific to a particular overlap. (B) RNA-seq tracks showing MIRAGE element upregulated in heterochromatin factor and *prg-1* mutants but not in *nrde-2* mutants.

**Figure 7-figure supplement 2. H3K9me3 levels on repeats in nrde mutants**

(Top) H3K9me3 log2FC of average signal at indicated regions in *hrde-1*, *nrde-2*, *nrde-4*, and *nrde-3* mutants relative to wild-type. Control repeats have >1.5 fold average signal in wild-type relative to genome average, and no enrichment for any heterochromatin factor. *nrde-2*, all repeats upregulated in *nrde-2* mutants; any5 Heterochromatin, repeats upregulated in any of the 5 heterochromatin mutant strains, but not in *nrde-2* mutants; *prg-1*, repeats upregulated in *prg-1* mutants but not in *nrde-2* mutants. Parentheses show number of elements in each set. A reduction of H3K9me3 at repeat sets of interest was assessed by comparing to all repeats using a single-sided Mann-Whitney U test: one star, p<0.1, two stars, p<0.05; three stars, p<0.001. (Bottom) H3K9me3 levels relative to genome average at indicated regions in each dataset.

**Figure 7-figure supplement 2. H3K9me3 levels on genes in nrde mutants**

(Top) H3K9me3 log2FC of average signal at indicated regions in *hrde-1*, *nrde-2*, *nrde-4*, and *nrde-3* mutants relative to wild-type. *nrde-2*, genes upregulated in *nrde-2* mutants. For each of the other strains, gene sets are those upregulated in the indicated mutant but not upregulated in *nrde-2* mutants. Parentheses show number of genes in each set. A reduction of H3K9me3 at gene sets of interest was assessed by comparing to all genes using a single-sided Mann-Whitney U test: one star, p<0.1, two stars, p<0.05; three stars, p<0.001. (Bottom) H3K9me3 levels relative to genome average at indicated regions in each dataset.
Supplementary files

Supplementary file 1. LET-418, LIN-13, HPL-2, LIN-61, and MET-2 are required for normal fertility.

Supplementary file 2. Strains used in this study.

Supplementary file 3. Antibodies used in this study.

Source data files

Figure 2-source data 1 - Peak calls

Figure 2-source data 2. Enrichment of factors at repeat families

Figure 2-source data 3 - Alignment Statistics for ChIP and RNA sequencing

Figure 3-source data 1 - Analysis of repeats

Figure 3-source data 2 - Repeats upregulated in any mutant strain

Figure 3-source data 3 - Analysis of genes
**Figure 1**

### RNAi Brood size per adult

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### Genotype Brood size per adult

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### Notes

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Figure 2

Enrichment of factors at repeat classes

Proportion of repeat family members enriched for factor

Class

DNA transposons

Satellite

Unknown

Other

HPL-2

LIN-13

LIN-61

MET-2

LET-418

H3K9me2

H3K9me3

Cut and Paste

Helitron

Unknown

DNA transposons

Satellite

Unknown

Class

DNA transposons

Satellite

Unknown

Other

HPL-2

LIN-13

LIN-61

MET-2

LET-418

H3K9me2

H3K9me3

Cut and Paste

Helitron

Unknown

DNA transposons

Satellite

Unknown

Class

DNA transposons

Satellite

Unknown

Other

HPL-2

LIN-13

LIN-61

MET-2

LET-418

H3K9me2

H3K9me3

Cut and Paste

Helitron

Unknown

DNA transposons

Satellite

Unknown

Class

DNA transposons

Satellite

Unknown

Other

HPL-2

LIN-13

LIN-61

MET-2

LET-418

H3K9me2

H3K9me3

Cut and Paste

Helitron

Unknown

DNA transposons

Satellite

Unknown

Class

DNA transposons

Satellite

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Other

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LIN-61

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LET-418

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HPL-2
Figure 4
Figure 5

Adult germline apoptosis

WT

hpl-2 lin-13 lin-61

met-2 set-25

0

10

20

30

40

number of apoptotic cells / gonad

Figure 5
**Figure 6**

**A** Upregulated repeats in the prg-1 germline. Circles indicate the relative abundance of repeats.

**B** Apoptosis in the prg-1 germline. The number of apoptotic cells per gonad is shown.

**C** Images depict GFP expression in WT, lin-13, and lin-61 strains.

**D** Bar chart showing pRNA sensor desilencing. The x-axis represents different conditions, and the y-axis represents the percentage of worms with GFP expression.

The images and data are accompanied by statistical significance markers: **** for highly significant differences, *** for significant differences, and **** for a non-significant difference.
nrde-2; let-418 genes repeats

**Brood sizes**

- Brood size per worm
- WT
- nrde-2
- hpl-2
- let-418
- lin-61
- nrde-2; hpl-2
- let-418
- lin-61
- nrde-2

**Embryonic lethality**

- Proportion dead embryos
- WT
- nrde-2
- hpl-2
- let-418
- lin-61
- nrde-2; hpl-2
- let-418
- lin-61
- nrde-2

**Figure 7**

- Brood sizes
- Embryonic lethality
- Genes
- Transposon ORF
A Pathways of transposable element silencing

- Heterochromatin factors
- Transposable elements
- piRNA pathway
- nuclear RNAi pathway

Other small RNA pathways → nuclear RNAi pathway

post-transcriptional → transcriptional

B Heterochromatin mutants

- TE derepression
- DNA repair defects

Genotoxic stress →

Germ line defects
Infertility

Figure 8