tudor-domain containing protein 5-prime promotes male sexual identity in the *Drosophila* germline and is repressed in females by *Sex lethal*

Shekerah Primus¹, Caitlin Pozmanter¹, Kelly Baxter¹, and Mark Van Doren¹*

¹Department of Biology, Johns Hopkins University, Baltimore, Maryland, United States of America

*Corresponding author

E-mail: vandoren@jhu.edu (MVD)

Short title: Tdrd5p promotes male germline identity
Abstract

For sexually reproducing organisms, production of male or female gametes depends on specifying the correct sexual identity in the germline. In *D. melanogaster*, *Sex lethal* (*Sxl*) is the key gene that controls sex determination in both the soma and the germline, but how it does so in the germline is unknown, other than that it is different than in the soma. We conducted an RNA expression profiling experiment to identify direct and indirect germline targets of Sxl specifically in the undifferentiated germline. We find that, in these cells, Sxl loss does not lead to a global masculinization observed at the whole-genome level. In contrast, Sxl appears to affect a discrete set of genes required in the male germline, such as *Phf7*. We also identify *tudor domain containing protein 5-prime* (*tdrd5p*) as a target for Sxl regulation that is important for male germline identity. *tdrd5p* is repressed by Sxl in female germ cells, but is highly expressed in male germ cells where it promotes proper male fertility and germline differentiation. Additionally, *Tdrd5p* localizes to cytoplasmic granules with some characteristics of RNA Processing (P-) Bodies, suggesting that it promotes male identity in the germline by regulating post-transcriptional gene expression.
Author summary

Like humans, all sexually reproducing organisms require gametes to reproduce. Gametes are made by specialized cells called germ cells, which must have the correct sexual identity information to properly make sperm or eggs. In fruit flies, germ cell sexual identity is controlled by the RNA-binding protein Sxl, which is expressed only in females. To better understand how Sxl promotes female identity, we conducted an RNA expression profiling experiment to identify genes whose expression changes in response to the loss of Sxl from germ cells. Here, we identify tudor domain containing protein 5-prime (tdrd5p), which is expressed 17-fold higher in ovaries lacking Sxl compared to control ovaries. Additionally, tdrd5p plays an important role in males as male flies that are mutant for this gene cannot make sperm properly and thus are less fertile. Moreover, we find that tdrd5p promotes male identity in the germline, as several experiments show that it can shift the germ cell developmental program from female to male. This study tells us that Sxl promotes female identity in germ cells by repressing genes, like tdrd5p, that promote male identity. Future studies into the function of tdrd5p will provide mechanistic insight into how this gene promotes male identity.
Introduction

Sex determination is an essential process in sexually reproducing species, as the production of eggs and sperm depends on the sexual identity of the germ cells and somatic cells of the gonad. In some animals, such as the medaka fish and the house fly, the sexual identity of the soma determines the sexual identity of the germline. But in other animals, such as fruit flies and mammals, the intrinsic sex chromosome constitution (XX vs. XY) of the germ cells is also important for proper gametogenesis (reviewed in [1]). In such cases, the “sex” of the germ cells must match the “sex” of the soma in order for proper gametogenesis to occur. While studies have revealed a great deal about how sex is determined in the soma, how germline sexual identity is determined by a combination of somatic signals and germline intrinsic properties is much less well understood.

In Drosophila, somatic sexual identity is determined by the X chromosome number [2], [reviewed in 3], with two X’s activating expression of the key sex determination gene Sex lethal (Sxl), promoting female identity. The Sxl RNA-binding protein initiates an alternative RNA splicing cascade to allow female-specific splicing of transformer (tra) and, subsequently, doublesex (dsx) and fruitless (fru). dsx and fru encode transcription factors that control somatic sexual identity [reviewed in 4]. Sxl is also the key sex determination gene in the germline, as Sxl is expressed in the germline in females, and loss of Sxl causes female (XX) germ cells to develop as germline ovarian
tumors [5], similar to male (XY) germ cells transplanted into a female soma [6–8].

Further, expression of Sxl is sufficient to allow XY germ cells to make eggs when transplanted into a female soma [9]. However, how Sxl is activated in the female germline and how it regulates female germline identity remain unknown, except for the fact that both are different than in the soma [6,10–16]. To understand how Sxl promotes female germ cell identity, it is essential to discover its targets in the germline.

In this work, we report an RNA expression profiling (RNA-seq) experiment conducted to identify genes regulated downstream of Sxl in the germline. We found that a previously uncharacterized tudor domain containing protein, *tudor domain protein 5-prime* (*tdrd5p*), is a target of Sxl in the germline. *tdrd5p* is strongly expressed in the *Drosophila* early male germline and is repressed by Sxl activity in the early female germline. It promotes male identity in the germline, and its loss results in germline maintenance and differentiation defects in males, thus reducing their fertility. Tdrd5p protein localizes to cytoplasmic granules related to RNA Processing (P-) Bodies, suggestive of a function in post-transcriptional regulation of gene expression.

**Results**

**Analysis of Sxl-dependent gene expression changes in the germline**

To investigate how Sxl acts to promote female identity in germ cells, we conducted an RNA-seq experiment comparing ovaries with and without Sxl function in
the germline. To exclude the major gene expression changes that occur during the later stages of gametogenesis, the RNA-seq experiment was done in the bag of marbles (bam) mutant background. bam is essential for germline differentiation in both males and females; therefore, by using bam mutants we focus our experiment on gene expression changes in the early germline, where Sxl is expressed most robustly, instead of later stages of gametogenesis (Fig 1A, B). The use of bam mutants also gives us the ability to compare similar tissue samples, since ovarian tumors from bam mutants and bam, Sxl double mutants are very similar [17]. Thus, the two genotypes used for the RNA-seq experiment are both in the bam-mutant background, with the experimental genotype knocking down Sxl in the germline using RNAi (nanos-Gal4, UAS-SxlRNAi, bam), and a control genotype expressing a control RNAi (nanos-Gal4, UAS-mCherryRNAi, bam). Sxl protein in the germline was dramatically reduced in the Sxl RNAi samples relative to controls (Fig 1B, C). Additionally, we conducted RNA-seq on bam mutant males compared to females, similar to what has been done previously [18] in order to identify male-enriched vs. female-enriched RNAs in the undifferentiated germline. Libraries were prepared from three biological replicates of each genotype and sequenced with 100bp paired-end reads. The raw reads for all libraries were of very high quality—over 95% of the raw reads received a high quality score. In addition, for each library more than 85% of reads were uniquely mapped to the Drosophila genome, and all replicates had high replicate correlation.
As Sxl can regulate alternative splicing in the soma, we analyzed our RNA-seq data for changes in exon usage using DEXSeq [19]. We filtered these results for statistical significance (padj < 0.05) and for changes in exon expression that were 2-fold or greater (all DEXSeq data is presented in S1 Table). This identified 44 exons from 34 independent genes. A similar number of exons were upregulated in Sxl- (20, 45%) vs. downregulated (24, 55%). However, manual curation of these data did not reveal strong candidates for relevant biological regulation of alternative splicing by Sxl. The main exception was the Sxl RNA itself, which in Sxl RNAi samples exhibited the characteristic inclusion of the male-specific exon that requires Sxl protein in order to be excluded in the female soma. Thus, the residual Sxl RNA present after germline Sxl RNAi must be insufficient to produce enough Sxl protein for Sxl autoregulation, further reducing Sxl function in the germline and demonstrating the effectiveness of the germline Sxl RNAi approach. This analysis also identified the alternative, testis-specific promoter for the male germline sex determination factor Plant homeodomain containing protein 7 (Phf7, [20] as being regulated downstream of Sxl, as has previously been described [21]. However, based on this analysis, it does not appear that regulation of alternative splicing is a primary mechanism for Sxl regulation of gene expression in the germline.

We also analyzed changes in overall gene expression levels in the presence of absence of Sxl function (DE-Seq [22]). 94 genes were differentially expressed between
the two samples (with padj < 0.05), with 40 being upregulated (43%) and 54 being
downregulated (57%) in the Sxl RNAi samples (S2 Table). 24 of these genes differed 4-
fold or more between the two samples (6 upregulated in Sxl RNAi, 18 downregulated).
We also observed a bias toward X chromosome localization for the differentially
expressed genes, with 31.9% being present on the X chromosome compared to only
15.1% of all genes surveyed having X chromosome localization.

We next asked whether Sxl acts as a global regulator of X chromosome gene
expression/dosage compensation in the germline, as it does in the soma. Despite the X
chromosome bias for differentially expressed genes, relatively few X chromosome genes
overall (30 genes or 1.2% of X chromosome loci surveyed) were called as differentially
expressed in our analysis. Further, if Sxl was a global regulator of X chromosome gene
expression, we would expect that the overall level of X chromosome gene expression,
relative to autosomal gene expression, would be altered in Sxl loss of function.
However, the overall ratio of average gene expression between the X chromosome and
autosomes was little changed between control and Sxl RNAi samples (X:A of 1.19 for
controls and 1.24 for Sxl RNAi). We conclude that Sxl is not a global regulator of X
chromosome gene expression in the germline.

Lastly, we evaluated the extent to which loss of Sxl in the undifferentiated (bam-
mutant) female germline leads to masculinization of these cells. We conducted principle
component analysis on the individual replicates of all four of our experimental
conditions (Fig 1D). We find that bam Sxl-RNAi female samples are much more similar to bam female samples and control bam mCherry-RNAi samples than they are to bam male samples. Thus, this analysis does not support a strong masculinization of the bam-mutant female germline in the absence of Sxl. However, it is also known that bam does not affect males and females in exactly the same manner [23] and, in addition, the bam male samples also contain male somatic cells while the other samples contain female somatic cells. Both of these factors may contribute to the segregation of the bam male sample away from the others. To circumvent this problem, we analyzed the 94 genes differentially expressed between bam Sxl-RNAi and control samples to determine whether there was a “male” signature. We determined whether genes differentially expressed in Sxl-RNAi compared to controls were also differentially expressed in bam males compared to bam females. Of the 94 genes differentially expressed in Sxl RNAi, a high fraction (44 genes) were also differentially expressed between bam male vs. female samples (47%, which is considerably higher than the fraction of total genes in the genome called as different between bam male and female, 13%). However, these genes did not always change in the expected direction; only 61% of genes altered in both Sxl RNAi and bam males changed in the same direction in both, while 39% changed in the opposite direction (Fig 1E). Thus, the Sxl-RNAi sample does not appear globally “masculinized” relative to controls and it may be that Sxl’s role in repressing male
identity in the early germline is restricted to a few specific targets that are important for
the male germline.

One such candidate is a previously uncharacterized gene, CG15930, that was
strongly upregulated in Sxl-RNAi ovaries and is normally enriched in testes. CG15930
exhibits strong homology to mouse Tdrd5 [24], which is essential for male germ cell
development and spermatogenesis in mice [25]. However, since CG15930 is not as
similar to Tdrd5 as Drosophila tejas [26], and therefore not a paralog of Tdrd5, we named
this gene tudor domain containing protein 5- prime (tdrd5p). We chose this gene for further
study.

trd5p is expressed in a sexually dimorphic manner

The RNA-seq expression profiles show that trd5p has a dynamic expression
pattern characteristic of genes with sex-specific functions. trd5p is 18-fold enriched in
bam testes compared to bam ovaries, and is upregulated 17-fold in bam, Sxl-RNAi
ovaries relative to bam, control-RNAi ovaries (Fig 2A), and is clearly enriched in bam,
Sxl-RNAi ovaries by RT-PCR (Fig 2B). This is in contrast to nanos, which is expressed at
similar levels in all of the genotypes in our RNA-seq experiment (Fig 2A), consistent
with its role in the germline of both sexes. Changes in trd5p expression were restricted
to total RNA levels, and no change in exon usage was detected. In situ hybridization to
wild-type gonads revealed that trd5p expression is highly enriched in the testis,
particularly at the apical tip of the testis where the germline stem cells and proliferating
gonial cells reside (Fig 2C-D). The finding that \textit{tdrd5p} is expressed at high levels in testes
relative to ovaries, and is repressed by \textit{Sxl} in the ovary, suggests that it plays a role in
male germline development or function.

To determine the expression pattern of Tdrd5p protein, we generated a genomic
transgene that includes a hemagglutinin (HA) epitope tag at the N-terminus of the
Tdrd5p protein. The tag was inserted immediately following the start codon of the gene
within a 20kb BAC that extends well upstream and downstream of the genes
neighboring \textit{tdrd5p} (S1 Fig), and is therefore likely to recapitulate endogenous
expression. Anti-HA immunostaining shows that Tdrd5p protein is expressed in the
germline of the testis, and is also present in the ovary at lower levels (Fig 2E, F).

HA:Tdrd5p is observed in male germline stem cells, spermatogonia and spermatocytes.
The protein is seen in distinct foci that are smaller and more numerous in germline stem
cells (Fig 2G, arrows), but appear larger in spermatocytes (Fig 2E arrows). The foci are
predominantly cytoplasmic, with many abutting a perinuclear germline structure called
the nuage. The accumulation of Tdrd5p into cytoplasmic punctae is characteristic of
ribonucleoprotein complexes ("RNA bodies") [reviewed in 27], and suggests that it may
be involved in mRNA decay or translational repression. Interestingly, HA:Tdrd5p co-
localizes with \textit{decapping protein 1}, (YFP-DCP1, Fig 2H, arrows), which plays a major role
in mRNA degradation, and is also required for \textit{osk} mRNA localization to the posterior
of the oocyte [28]. [reviewed in 29]. As DCP-1 is localized to “Processing bodies” (P-bodies), Tdrd5p appears to be present in a subset of these structures.

HA:Tdrd5p protein expression is upregulated in ovaries that are mutant for Sxl function in the germline (Fig 3A-B). Note that the punctae seen in males are also present in Sxl RNAi ovaries, though they are fewer in number (Fig 3D, arrows). Thus, the de-repression of tdrd5p in Sxl RNAi ovaries is also detected at the protein level.

Interestingly, the tdrd5p mRNA has 2 putative Sxl binding sites [30,31], one within the 3rd intron and the other in the 3’ UTR (S1 Fig). This suggests that Sxl may directly regulate tdrd5p expression by binding to one or both of these sites and influencing tdrd5p RNA processing in the nucleus or translation in the cytoplasm. To assess Sxl’s direct regulation of tdrd5p, we mutated both Sxl binding sites in the a HA:tdrd5p transgene (HA:tdrd5p<sup>ddel</sup>). We found HA:tdrd5p<sup>ddel</sup> flies show upregulation of HA:Tdrd5p in the female germline (Fig 3C, E), similar to the upregulation caused by loss of Sxl from the germline. Quantification of this difference by western blot showed that HA:Tdrd5p is 3-fold upregulated in the female germline of HA:tdrd5p<sup>ddel</sup> flies.

However, quantitative RT-PCR analysis specific for the HA-tagged transgenes showed no significant difference in RNA expression between ovaries of HA:tdrd5p flies compared to HA:tdrd5p<sup>ddel</sup> flies (data not shown). This suggests that Sxl directly regulates the expression of Tdrd5p protein in the female germline by repressing
translation. The basis for the changes we observed in tdrd5p RNA levels in Sxl RNAi ovaries by RNA-seq remains unknown.

tdrd5p is required for proper male fertility & germline differentiation

The male-biased expression pattern of tdrd5p suggests it may have an important function in the male germline. Knocking down tdrd5p function in the germline by RNAi, however, produced no observable phenotype. To conduct a more comprehensive study of tdrd5p function we generated tdrd5p mutant alleles using CRISPR-Cas9 genome editing. We generated several independent predicted null alleles of tdrd5p (S1 Fig), and analyzed male fertility and testis morphology of both young males and aged males. We determined that young (5 days old) tdrd5p mutant males have a 50% reduction in fecundity compared to controls (Fig 4F), suggesting that tdrd5p is required for proper male fertility.

To characterize the germ cell defects that may lead to decreased fecundity, we evaluated several aspects of germ cell differentiation in young and aged mutant males. While testes of newly eclosed males appeared similar to wild-type, testes of older males (15-20 days old) exhibited a dystrophic “skinny testis” phenotype with a dramatic reduction in the germline (Fig 4A-C). This was observed in 7% of animals raised at 25°C and 18% of animals raised at 29°C. Additionally, 15% of males exhibited a displaced hub phenotype (Fig 4E arrow), where the hub is no longer located at the apical tip of the
testis as seen in wild-type (Fig 4D arrow). These combined phenotypes suggest a defect in proper germline differentiation and maintenance. Analyzing the expression of critical germ cell differentiation genes such as *bam* and *spermatocyte arrest* (required for meiotic cell cycle progression) [32] did not shed further light on the germ cell defect. Therefore, while the morphological defects present at a low penetrance, their overall effects culminate into a substantial reduction in fecundity; a phenotype which supports *tdrd5p* importance in male germline development.

Tudor domain-containing proteins have well known functions in small RNA pathways, transcriptional regulation, and the assembly of snRNPs [reviewed in 33]. The closest *Drosophila* homolog to *tdrd5p* is *tejas*, and the closest mammalian homolog to *tdrd5p* is mouse TDRD5. Both *tejas* and TDRD5 have been shown to function in the piRNA pathway and to repress the expression of transposons in the germline [25,26,34]. Interestingly, we found no changes in transposon expression in *tdrd5p* mutants in our RNA-seq analysis (data not shown). We also analyzed the expression of a wide variety of transposons by quantitative rtPCR and found little to no difference between wt and *tdrd5p*-mutant testes (data not shown). Defects in the piRNA pathway can also lead to increased accumulation of the Stellate protein in the male germline [35,36]. We examined the expression of Stellate in *tdrd5p* mutant males, as well as in *tdrd5p* mutant males also heterozygous for mutant alleles of *tejas*, *ago3* or *aubergine* (two PIWI proteins with key functions in the piRNA pathway). None of these testes showed the increased...
Stellate expression observed in tejas homozygous mutant testes (S2 Fig, [26]). Therefore, while tdrd5p’s activity is important for the proper development of the male germline, it has a distinct function from regulation of transposon expression.

**tdrd5p promotes male identity in the germline**

The sex-specific nature of tdrd5p’s expression and mutant phenotype suggests it may play a role in promoting male germline sexual identity. However, unlike the male-specific Phf7 gene [20], expression of UAS-tdrd5p in the female germline did not, by itself, result in defects in the female germline (data not shown). To further investigate tdrd5p’s role in sexual identity, we decided to conduct our experiments using the sensitized genetic backgrounds frequently used for the investigation of genes involved in sexual identity. Females mutant for transformer (tra)—a key player in the somatic sex determination pathway—undergo a transformation so that the somatic gonad of XX tra mutants develops as male instead of female. However, because the germline is XX, and therefore incompatible with spermatogenesis, the germline of these testes is highly undeveloped, causing these animals to be sterile (Fig 5B). A strong test of a gene’s ability to promote male identity in the germline is to determine whether it is sufficient to induce XX germ cells to enter spermatogenesis in these animals. Indeed, expression of tdrd5p in the germline of XX tra mutants resulted in a robust rescue of spermatogenesis. 18% of these animals had highly developed testes that were wild type.
in size, containing all of the stages of germ cell differentiation up to spermatocytes (Fig 5C, note: since these animals lack a Y chromosome and the spermatogenesis genes located there, they were not expected to be fertile). This is strong evidence signifying that tdrd5p promotes male identity in the germline.

Similarly, if tdrd5p promotes male identity in the germline, we would expect that it would be able to enhance the ability of other mutations to masculinize the female germline. Homozygous mutants of ovarian tumor (otu) and sans fille (snf) have been shown to masculinize the female germline and cause germline tumors in ovaries, similar to Sxl-RNAi [37–40], while females heterozygous for mutant alleles of otu and snf are fully fertile and have normal ovary morphology. However, ectopic expression of tdrd5p in the germline of females heterozygous for otu or snf resulted in the formation of ovarian tumors. 25% of snf/+; nos > tdrd5p ovaries have large, pervasive germline tumors similar to the homozygous snf mutants (Fig 5D-F). Another 25% of these ovaries show a complete loss of the germline (Fig 5G), which phenocopies strong sex determination mutants [37,41]. Additionally, 40% of otu/+; nos > tdrd5p ovaries exhibit either ovarian tumors or complete loss of germline. This evidence supports tdrd5p as a male-promoting factor in the germline. We therefore conclude that tdrd5p functions in germline sexual identity; it promotes male identity in the germline and is repressed by Sxl in the female germline.
Discussion

The role of Sxl in the germline

It has been known for many years that Sxl is necessary for female germline identity [7,8], and Sxl has also been shown to be sufficient to allow XY germ cells to undergo oogenesis [9]. It is likely that Sxl plays multiple roles in the germline, both to promote female identity in the early germline, perhaps as early as in the embryonic germline [9], and in regulating the differentiation of the germline during oogenesis [42].

Here we examined the role of Sxl more specifically in the undifferentiated germline through the use of bam mutants. Principle component analysis indicated that, under these conditions, samples with Sxl function reduced in the germline clustered close to control female samples, and far from male samples. While some of the male/female differences may be contributed by the somatic cells present in these samples, we conclude that reducing Sxl function in the undifferentiated germline does not lead to a dramatic masculinization at the whole-genome level. In contrast, we propose that the role for Sxl in the early germline may be restricted to a relatively small number of changes in sex-specific germline gene expression that are important for female vs. male germline function.

Recently, a genomic analysis of ovaries mutant for the RNA splicing factor sans fille (snf) was conducted [21]. This is considered to also be a Sxl germline loss-of-function condition as one important change in snf-mutant ovaries is a loss of Sxl
expression and an ovarian tumor phenotype that can be rescued by Sxl expression [17,42,43]. In contrast to our results, an increased expression of spermatogenesis genes was observed in snf tumorous ovaries compared to wild type ovaries. It is likely that changes in these “differentiation” genes were not observed in our bam-mutant samples since germline differentiation is arrested at an earlier stage in bam mutants, allowing us to focus on the undifferentiated germline. Thus, these two analyses can help separate the role of Sxl in regulating early germline sexual identity vs. later aspects of sex-specific germline differentiation. Interestingly, one “differentiation” gene was identified in both RNA-seq analyses: the testis-specific basal transcription factor TATA Protein Associated Factor 12L (Taf12L or rye). This may indicate that Taf12L could play a role in the undifferentiated germline as well as the later stages of spermatocyte differentiation. In addition, both analyses found evidence for differential regulation of the important male germline identity factor Phf7 [20], where an upstream promoter is utilized preferentially in the male germline and is repressed downstream of Sxl in females [21 and data not shown]. This indicates a role for Phf7 in both the early and differentiating germline. Finally, we did not observe strong candidates for targets of alternative RNA splicing regulated by Sxl. The only strong candidate for alternative RNA splicing was the Sxl RNA itself, where the male-specific exon was retained in the residual Sxl RNA from the Sxl RNAi samples. This provides further evidence that Sxl autoregulation occurs in the germline as it does in the soma, as has previously been proposed [44]. It is
likely that Sxl may also act at the level of translational control in the germline, as our
evidence indicates here for regulation of Tdrd5p. Future experiments to identify Sxl-
associated germline RNAs will be important for investigating this mechanism of action,
as has recently been conducted [9].

In addition to its role in sex determination in the soma, Sxl also acts to initiate
global X chromosome gene regulation and dosage compensation through translational
control of male-specific lethal-2 [45], and it is possible that Sxl plays a similar role in the
germline. Whether or not the germline even undergoes dosage compensation is
controversial, and thoughtful work has led to opposite conclusions [46,47]. Further, if
dosage compensation does exist in the germline, it must utilize a separate mechanism
from the soma, as the somatic dosage compensation complex members msl1 and msl2
are not required in the germline [48,49]. However, Sxl could retain an msl-independent
role to regulate global X chromosome gene expression in the germline. We did not
observe evidence for this. First, few X chromosome genes were differentially expressed
between Sxl- and control samples (30 genes or 1.2% of X chromosome genes tested).
Second, the ratio of average gene expression between X chromosome genes and
autosomes was very similar in Sxl- females compared to control females (X/A for
controls: 1.24, Sxl-: 1.19) and this was similar when considering only genes in particular
expression categories (e.g. all genes with some expression in both samples). Thus, it
appears likely that Sxl’s role in the germline is distinct from that in the soma; it acts to
control sex-specific gene regulation and sexual identity in both the germline and the soma, but acts as a general regulator of X chromosome gene expression and dosage compensation only in the soma.

\textit{tdrd5p} promotes male germline identity.

We show here that \textit{tdrd5p} is both a target for \textit{Sxl} regulation and is important for male germline identity and spermatogenesis. \textit{tdrd5p} expression is highly male-biased, both at the RNA and protein levels (Fig 2). When female germ cells are sensitized by partial loss of female sex determination genes, expression of \textit{tdrd5p} exacerbates the masculinized phenotype in these germ cells (Fig 5). Significantly, expression of \textit{tdrd5p} is sufficient to promote spermatogenesis in XX germ cells present in a male soma (XX \textit{tra-mutant testes}, Fig 5). Thus, \textit{tdrd5p} clearly has a role in promoting male germline identity.

Loss of \textit{tdrd5p} also has a strong effect on male fecundity, even though it is not absolutely required for spermatogenesis. The 50\% reduction in fecundity is a strong effect and indicates that \textit{tdrd5p} plays an important role in the male germline. However, the fact that some spermatogenesis still proceeds suggests that other factors act in combination with \textit{tdrd5p} to control this process. One good candidate is \textit{Phf7} which we have previously demonstrated to have a similarly important, but not absolute, requirement for spermatogenesis [20]. However, our analyses of \textit{tdrd5p, Phf7} double
mutants did not reveal any synergistic effect on male germline development or
fecundity (data not shown). This suggests that other important players in promoting
male germline identity remain to be identified.

Our data indicate that Tdrd5p regulates male germline identity by influencing
post-transcriptional gene regulation. Other tudor-domain containing proteins have been
shown to act in RNA-protein bodies to influence RNA stability and translational
regulation [reviewed in 33]. Further, Tdrd5p localizes to cytoplasmic punctae,
specifically a subset of the punctae that also contain Decapping Protein1 (DCP-1),
suggesting that these bodies are related to Processing bodies (P-bodies) that are known
to control post-transcriptional gene regulation [28,50], [reviewed in 29]. Interestingly,
Tdrd5p’s closest homologs, Tejas in flies and TDRD5 in mice, have been shown to
regulate piRNA production and transposon regulation [25,26]. Further, their
localization to VASA-containing nuage is thought to influence transposon control
[26,51]. However, we observe no changes in transposon expression regulated by tdrd5p,
and Tdrd5p does not co-localize with VASA in nuage. We have also not observed any
genetic interaction between tejas and tdrd5p (data not shown). Thus, we propose that
Tdrd5p plays a distinct role in regulating male germline identity and spermatogenesis,
and this may be in the regulation of mRNAs rather than transposons. One possibility is
that the role of mouse TDRD5 in transposon regulation and spermatogenesis has been
separated into the roles of Tejas in transposon regulation and Tdrd5p in regulating male
identity and spermatogenesis in flies. It is widely known that regulation of germline identity is dependent on post-transcriptional mechanisms involving tudor-domain proteins such as the original Tudor protein [52], which helps define the germ plasm, an RNA body that regulates germline identity [reviewed in 53]. Further, the regulation of sex-specific gametogenesis is also dependent on RNA bodies and their requisite tudor-domain proteins, such as TDRD5 in mouse [54], [reviewed in 27]. Our studies indicate that initial germline sexual identity is similarly regulated by post-transcriptional mechanisms, including RNA bodies containing other, distinct, TUDOR-domain proteins such as Tdrd5p.

Materials and methods

Library Generation and sequencing

Gonads were dissected from 1-3 day old flies raised at 25°C. Ovaries were dissected from virgin females. 3 biological replicates were dissected for each genotype. Total RNA was isolated from all genotypes using RNA-bee (Tel-Test). Contaminating DNA was removed from the RNA using Turbo-DNA-free (Ambion). 200ng of RNA was used to prepare each library using the illumina TruSeq RNA Library Prep kit v2. 100bp paired-end read sequencing was done by the Johns Hopkins Genetic Resources Core Facility. The bam mutant male and female libraries were sequenced in one lane and the Sxl-RNAi, control-RNAi libraries were sequenced in separate lane, therefore having 6
libraries per lane.

Read mapping, quality, and differential expression analysis

Quality of raw reads was assessed using the fastQC kit (Babraham Institute). RNA-Seq reads were mapped to the Drosophila genome using Ensembl BDGP6 release 85, and Bowtie 2.2.9, TopHat 2.1.1, and HTSeq 0.9.1 [55–57]. Differential gene expression analysis was done using DESeq using ensemble annotation BDGP6 [22]. Adjusted P value of 0.05 used for significance cutoff. Differential exon analysis was done using DEXSeq [19].

Fly stocks and Fecundity Tests

The fly stocks used were obtained from Bloomington Stock Center unless otherwise indicated. bam\textsuperscript{1} [58], bam\textsuperscript{Δ86} (BDSC# 5427), nos-Gal4 [59], the control RNAi used was p\{VALIUM20-mCherry\}attP2 (BDSC# 35785), uas-\textit{Sxl-RNAi}=TRiP.HMS00609 (BDSC# 34393), uas-CG15930-RNAi=TRiP. GL01046 (BDSC# 36882), \textit{Snf}^{148}, \textit{otu}^{17}, \textit{tej}^{48-5}, attP40\{\textit{nos-Cas9}\} (NIG-FLY# CAS-0001), YFP:dDCP1 (a kind gift from Ming-Der Lin, [28]).

Fecundity tests were carried out by setting up crosses with one \textit{tdrd5p} mutant male and 15 virgin females of the control stock. The control stock used is \textit{nos-Cas9} isogenized to FM7KrGFP fly stock to reproduce the treatment of the \textit{tdrd5p} mutant fly lines while screening for transformants. Each male was mated with virgin females for 4 days. Females were then discarded and each male was placed with another 15 virgin females in a new bottle. This was repeated twice more for a total of four mating bottles per male.
All offspring were counted by day 18. Total offspring per male was calculated by averaging the number of offspring from each of the four mating bottles for each male.

**Immunofluorescence**

Adult ovaries and testes were fixed, blocked and stained as previously described [60]. All images were taken with a Zeiss LSM 510 confocal microscope.

Primary antibodies and the concentrations used are as follows: chicken anti-Vasa 1:10,000 (K. Howard); rabbit anti-Vasa 1:10,000 (R. Lehmann); mouse anti-Sxl 1:8 (M18, DSHB); mouse anti-Armadillo 1:100 (N2 7A1, DSHB); rat anti-HA 1:100 (3F10, Roche); guinea pig α-TJ (1:1,000; generated by J. Jemc using the same epitope as previously described [61]); mouse anti-HTS 1:4 (1B1, DSHB). DSHB: Developmental Studies Hybridoma Bank. Secondary antibodies were used at 1:500 (Alexa-fluor). Samples were mounted in vectashield mounting solution with DAPI (vector Industries).

**RT-PCR, quantitative RT-PCR & In-situ hybridization**

For RT-PCR and qRT-PCR, total RNA was isolated from ovaries and testes using RNA-bee (Tel-Test). Contaminating DNA was removed from the RNA using Turbo-DNA-free (Ambion). RNA was converted to cDNA using Superscript II (Invitrogen). qRT-PCR was done using 2 biological replicates and in technical triplicate, using SYBR green detection. In-situ hybridization was carried out as previously described [62]. DIG-
labelled sense and antisense probes were synthesized by in vitro transcription of PCR product generated from RP98-1M22 BAC (BACPAC Resources Center).

**Mutagenesis and BAC-tagging**

Mutant alleles of *tdrd5p* were created using CRISPR-Cas9 mediated genome editing. Small guide RNA (sgRNA) was designed and cloned following the Perrimon lab protocol [63], using the U6b-sgRNA-short vector described therein. The sgRNA was injected by Best Gene inc into *nos*-Cas9(II-attP40) flies. The HA:*Tdrd5p* transgenic flies were generated by BAC recombineering [64,65], using the CH322-188C18 BAC obtained from the BACPAC Resources Center. A 3xHA epitope tag was added to the N-terminus of the gene (S1 Fig). This construct was also modified to delete the Sxl binding sites in the intron and the 3’UTR. The Sxl binding site in *tdrd5p* 3’UTR was deleted using QuickChange II site-directed mutagenesis kit (agilent). The intronic binding site was removed by deleting the entire intron.

**Acknowledgements**

We thank the fly community for providing stocks and reagents, either directly as specified in the materials and methods or through their contributions to the Bloomington Stock Center, the Developmental Studies Hybridoma Bank, and BACPAC Resources. We would also like to thank David Mohr and the Johns Hopkins Sequencing
facility for technical expertise on high throughput RNA sequencing, Dr. Frederick Tan
and other members of the Johns Hopkins Community for technical expertise on
Bioinformatics and sequencing analysis, as well as members of the Chen, Johnston and
Van Doren laboratories for helpful discussions. Imaging was performed at the
Integrated Imaging Center at the John Hopkins University.

References

1. Murray SM, Yang SY, Van Doren M. Germ cell sex determination: A
collaboration between soma and germline. Curr Opin Cell Biol. 2010;22(6):722–9.

2. Erickson JW, Quintero JJ. Indirect effects of ploidy suggest X chromosome
dose, not the X:A ratio, signals sex in Drosophila. PLoS Biol. 2007
Dec;5(12):e332.

3. Salz HK, Erickson JW. Sex determination in Drosophila: The view from the
top. Fly (Austin). 2010 Jan;4(1):60–70.

4. Camara N, Whitworth C, Van Doren M. The Creation of Sexual
Dimorphism in the Drosophila Soma. Vol. 83, Current Topics in
Developmental Biology. Elsevier Inc.; 2008. 65-107 p.
5. Salz HK, Cline TW, Schedl P. Functional changes associated with structural alterations induced by mobilization of a P element inserted in the Sex-lethal gene of Drosophila. Genetics. 1987;117(2):221.

6. Schupbach T. Autosomal Mutations That Interfere with Sex Determination in Somatic Cells of Drosophila Have No Direct Effect on the Germline. Dev Biol. 1982;189(1):117–27.

7. Schupbach T. Normal Female Germ Cell Differentiation requires the female X chromosome to Autosome Ratio and Expression of Sex-Lethal in Drosophila melanogaster. Genetics. 1985;109(3):529–48.

8. Steinmann-Zwicky M, Schmidt H, Nothiger R. Cell autonomous and inductive signals can determine the sex of the germline of Drosophila melanogaster by regulating sex-lethal. Cell. 1989;57:157–166.

9. Hashiyama K, Hayashi Y, Kobayashi S. Drosophila Sex lethal Gene Initiates Female Development in Germline Progenitors. Science. 2011 Jul 7;333(6044):885–8.

10. Marsh JL, Wieschaus E. Is sex determination in germ line and soma controlled by separate genetic mechanisms? Nature. 1978;272(5650):249–51.
11. Torres M, Sánchez L. The scute (T4) gene acts as a numerator element of the X:A signal that determines the state of activity of sex-lethal in Drosophila. EMBO J. 1989;8(10):3079–86.

12. Bell LR, Horabin JI, Schedl P, Cline TW. Positive autoregulation of Sex-lethal by alternative splicing maintains the female determined state in Drosophila. Cell. 1991;65(2):229–39.

13. Duffy JB, Gergen JP. The Drosophila segmentation gene runt acts as a position-specific numerator element necessary for the uniform expression of the sex-determining gene Sex-lethal. Genes Dev. 1991;5(12 A):2176–87.

14. Granadino B, Santamaria P, Sánchez L. Sex determination in the germ line of Drosophila melanogaster: activation of the gene Sex-lethal. Development. 1993 Jul;118(3):813–6.

15. Hoshijima K, Kohyama A, Watakabe I, Inoue K, Sakamoto H, Shimura Y. Transcriptional regulation of the Sex-lethal gene by helix-loop-helix proteins. Nucleic Acids Res. 1995;23(17):3441–8.

16. Kramer SG, Jinks TM, Schedl P, Gergen JP. Direct activation of Sex-lethal transcription by the Drosophila runt protein. Development.
17. Chau J, Kulnane LS, Salz HK. Sex-lethal Facilitates the Transition From Germline Stem Cell to Committed Daughter Cell in the Drosophila Ovary. Genetics. 2009 Feb;182(1):121–32.

18. Gan Q, Chepelev I, Wei G, Tarayrah L, Cui K, Zhao K, et al. Dynamic regulation of alternative splicing and chromatin structure in Drosophila gonads revealed by RNA-seq. Cell Res. 2010 Jul;20(7):763–83.

19. Anders S, Reyes a, Huber W. Detecting differential usage of exons from RNA-seq data. Genome Res. 2012;22(10):2008–17.

20. Yang SY, Baxter EM, Van Doren M. Phf7 controls male sex determination in the Drosophila germline. Dev Cell. 2012 May 15;22(5):1041–51.

21. Shapiro-Kulnane L, Smolko AE, Salz HK. Maintenance of Drosophila germline stem cell sexual identity in oogenesis and tumorigenesis. Dev. 2015;142(6):1073–82.

22. Anders S, Huber W. Differential expression analysis for sequence count data. Genome Biol. 2010 Oct;11(10):R106.

23. Ohlstein B, McKearin D. Ectopic expression of the Drosophila Bam protein
eliminates oogenic germline stem cells. Development. 1997;124(18):3651–62.

24. Smith JM, Bowles J, Wilson M, Teasdale RD, Koopman P. Expression of the Tudor-related gene Tdrd5 during development of the male germline in mice. Gene Expr Patterns. 2004;4(6):701–5.

25. Yabuta Y, Ohta H, Abe T, Kurimoto K, Chuma S, Saitou M. TDRD5 is required for retrotransposon silencing, chromatoid body assembly, and spermiogenesis in mice. J Cell Biol. 2011;192(5):781–95.

26. Patil VS, Kai T. Repression of Retroelements in Drosophila Germline via piRNA Pathway by the Tudor Domain Protein Tejas. Curr Biol. 2010;20(8):724–30.

27. Voronina E, Seydoux G, Sassone-Corsi P, Nagamori I. RNA granules in germ cells. Cold Spring Harb Perspect Biol. 2011;3(12).

28. Lin M Der, Fan SJ, Hsu WS, Chou T Bin. Drosophila Decapping Protein 1, dDcp1, Is a Component of the oskar mRNP Complex and Directs Its Posterior Localization in the Oocyte. Dev Cell. 2006;10(5):601–13.

29. Ling SHM, Qamra R, Song H. Structural and functional insights into eukaryotic mRNA decapping. Wiley Interdiscip Rev RNA. 2011;2(2):193–
30. Sakashita E, Sakamoto H. Characterization of RNA binding specificity of the *Drosophila* Sex-lethal protein by in vitro ligand selection. Nucleic Acids Res. 1994;22(20):4082–6.

31. Samuels ME, Bopp D, Colvin RA, Roscigno RF, Garcia-Blanco MA, Schedl P. RNA binding by Sxl proteins in vitro and in vivo. Mol Cell Biol. 1994;14(7):4975–90.

32. Lin T, Viswanathan S, Wood C, Wilson PG, Wolf N, Fuller MT. Coordinate developmental control of the meiotic cell cycle and spermatid differentiation in *Drosophila* males. Development. 1996;122:1331–41.

33. Pek JW, Anand a., Kai T. Tudor domain proteins in development. Development. 2012;139(13):2255–66.

34. Ding D, Liu J, Midic U, Wu Y, Dong K, Melnick A, et al. TDRD5 binds piRNA precursors and selectively enhances pachytene piRNA processing in mice. Nat Commun. 2018;9(1):127.

35. Bozzetti MP, Massari S, Finelli P, Meggio F, Pinna L a, Boldyreff B, et al. The Ste locus, a component of the parasitic cry-Ste system of *Drosophila*...
melanogaster, encodes a protein that forms crystals in primary spermatocytes and mimics properties of the beta subunit of casein kinase 2. Proc Natl Acad Sci U S A. 1995;92(13):6067–71.

36. Aravin AA, Natalia M. Naumova AVT, Vasili V. Vagin YMR and VAG. Double-stranded RNA-mediated silencing of genomic tandem repeats and transposable elements in the D. melanogaster germline. Curr Biol. 2001;11(13):1017–27.

37. Storto PD, King RC. Fertile heteroallelic combinations of mutant alleles of the otu Locus of Drosophila Melanogaster. Roux’s Arch Dev Biol. 1987;196(4):210–21.

38. Gans M, Audit C, Masson M. Isolation and characterization of sex-linked female-sterile mutants in Drosophila melanogaster. Genetics. 1975;81(4):683–704.

39. Gollin SM, King RC. Studies of fs(1)1621, a Mutation Producing Ovarian Tumors in Drosophila melanogaster. Dev Genet. 1981;2:203–18.

40. Oliver B, Perrimon N, Mahowald AP. Genetic Evidence That the sans fille Locus Is Involved in Drosophila Sex Determination. Genetics. 1988;120:159–
41. King RC, Mohler D, Riley SF, Storto PD, Nicolazzo PS. Complementation between alleles at the ovarian tumor locus of Drosophila melanogaster. Dev Genet. 1986;7(1):1–20.

42. Chau J, Kulnane LS, Salz HK. Sex-lethal enables germline stem cell differentiation by down-regulating Nanos protein levels during Drosophila oogenesis. Proc Natl Acad Sci U S A. 2012 Jun 12;109(24):9465–70.

43. Nagengast AA, Stitzinger SM, Tseng C-H, Mount SM, Salz HK. Sex-lethal splicing autoregulation in vivo: interactions between Sex-lethal, the U1 snRNP and U2AF underlie male exon skipping. Development. 2003;130:463–71.

44. Hager JH, Cline TW. Induction of female Sex-lethal RNA splicing in male germ cells: implications for Drosophila germline sex determination. Development. 1997 Dec;124(24):5033–48.

45. Bashaw GJ, Baker BS. The msl-2 dosage compensation gene of Drosophila encodes a putative DNA-binding protein whose expression is sex specifically regulated by Sex-lethal. Development. 1995 Oct;121(10):3245–
Gupta V, Parisi M, Sturgill D, Nuttall R, Doctolero M, Dudko O, et al. Global analysis of X-chromosome dosage compensation. J Biol. 2006;5(1):3.

Meiklejohn CD, Landeen EL, Cook JM, Kingan SB, Presgraves DC. Sex chromosome-specific regulation in the drosophila male germline but little evidence for chromosomal dosage compensation or meiotic inactivation. PLoS Biol. 2011;9(8).

Bachiller D, Sánchez L. Mutations affecting dosage compensation in Drosophila melanogaster: Effects in the germline. Dev Biol. 1986;118(2):379–84.

Rastelli L, Kuroda MI. An analysis of maleless and histone H4 acetylation in Drosophila melanogaster spermatogenesis. Mech Dev. 1998;71(1–2):107–17.

Lin M Der, Jiao X, Grima D, Newbury SF, Kiledjian M, Chou T Bin. Drosophila processing bodies in oogenesis. Dev Biol. 2008;322(2):276–88.

Patil VS, Anand A, Chakrabarti A, Kai T. The Tudor domain protein Tapas, a homolog of the vertebrate Tdrd7, functions in the piRNA pathway to
regulate retrotransposons in germline of Drosophila melanogaster. BMC Biol. 2014;12(1):61.

52. Boswell RE, Mahowald AP. tudor, a gene required for assembly of the germ plasm in Drosophila melanogaster. Cell. 1985;43(1):97–104.

53. Mahowald AP. Assembly of the Drosophila Germ Plasm. Int Rev Cytol. 2001;203:187–213.

54. Yabuta Y, Ohta H, Abe T, Kurimoto K, Chuma S, Saitou M. TDRD5 is required for retrotransposon silencing, chromatoid body assembly, and spermiogenesis in mice. J Cell Biol. 2011;192(5):781–95.

55. Kim D, Pertea G, Trapnell C, Pimentel H, Kelley R, Salzberg SL. TopHat2: accurate alignment of transcriptomes in the presence of insertions, deletions and gene fusions. Genome Biol. 2013;14(4):R36.

56. Trapnell C, Roberts A, Goff L, Pertea G, Kim D, Kelley DR, et al. Differential gene and transcript expression analysis of RNA-seq experiments with TopHat and Cufflinks. Nat Protoc. 2012;7(3):562–78.

57. Anders S, Pyl PT, Huber W. HTSeq-A Python framework to work with high-throughput sequencing data. Bioinformatics. 2015;31(2):166–9.
58. McKearin DM, Spradling C. bag-of-marbles: a Drosophila gene required to initiate both male and female gametogenesis. Genes Dev. 1990 Dec;4(12b):2242–51.

59. Van Doren M, Williamson L, Lehmann R. Regulation of zygotic gene expression in Drosophila primordial germ cells. Curr Biol. 1998 Feb 12;8(4):243–6.

60. Gonczy P, Matunis E, DiNardo S, Gönczy P, Matunis E, DiNardo S. bag-of-marbles and benign gonial cell neoplasm act in the germline to restrict proliferation during Drosophila spermatogenesis. Development. 1997;124:4361–71.

61. Li M, Alls JD, Avancini RM, Koo K, Godt D. The large Maf factor Traffic Jam controls gonad morphogenesis in Drosophila. Nat Cell Biol. 2003;5(11):994–1000.

62. Morris C, Benson E, White-Cooper H. Determination of gene expression patterns using in situ hybridization to Drosophila testes. Nat Protoc. 2009;4(12):1807–19.

63. Ren X, Sun J, Housden BE, Hu Y, Roesel C, Lin S, et al. Optimized gene
editing technology for Drosophila melanogaster using germ line-specific Cas9. Proc Natl Acad Sci U S A. 2013;110(47):19012–7.

64. Venken KJT, Kasprowicz J, Kuenen S, Yan J, Hassan BB, Verstreken P. Recombineering-mediated tagging of Drosophila genomic constructs for in vivo localization and acute protein inactivation. Nucleic Acids Res. 2008;36(18):1–9.

65. Venken KJT, Carlson JW, Schulze KL, Pan H, He Y, Spokony R, et al. Versatile P[acman] BAC libraries for transgenesis studies in Drosophila melanogaster. Nat Methods. 2009;6(6):431–4.

Figure legends

Fig 1. Global effects of Sxl loss from the germline.

A-C) Immunofluorescence of adult ovaries with antibodies as indicated in the figure. A) wild type ovaries, B-C) ovaries used for the RNASeq experiment: bam mutant control RNAi ovaries (B-B’), and bam mutant ovaries with Sxl knocked down in the germline by RNAi (C-C’). Knockdown of Sxl causes a germline tumor phenotype. Note the absence of Sxl from the germline of Sxl-RNAi ovaries and presence in all germ cells of the control RNAi. Dashed lines outline ovarioles. Arrows mark the tips of ovarioles.
Arrowheads mark differentiating egg chambers. Vasa stains germ cells. D) Principle component analysis comparing each replicate of all four genotypes used in the RNAseq experiment E) Pie chart representing the 94 genes with significant changes in expression levels in \( Sxl \) RNAi compared to control RNAi and the corresponding changes in \( bam \) males (bamM) vs. \( bam \) females.

**Fig 2.** \( tdrd5p \) has male-biased expression.

A) Graph showing the RNA-seq expression profiles of genes with important germline functions. B) RT-PCR showing validation of RNA-seq data for \( tdrd5p \) upregulation in \( Sxl \) RNAi. C-D) In-situ hybridization showing expression of \( tdrd5p \) mRNA in wild type testes (C) and ovaries (D). Sense probe produced no signal (not shown). E-F) Confocal images showing expression of the HA tagged Tdrd5p protein in wild type testes (E) and ovaries (F). Asterisk marks the hub. Arrows show HA:Tdrd5p cytoplasmic punctae. G) Higher magnification image showing size and distribution of HA:Tdrd5p punctae in adult testes. H-H') Confocal images showing colocalization of HA:Tdrd5p (arrows) with YFP:DCP1 (arrows) in adult testes. Antibodies used are as shown in the figure: HA stains Tdrd5p, YFP stains DCP1, Vasa stains germ cells, TJ stains somatic cells.

**Fig 3.** Tdrd5p expression is repressed by \( Sxl \) function in the female germline.

Expression of the HA-tagged Tdrd5p protein in A) wild type ovaries, in B) ovaries with \( Sxl \) knocked down in the germline, and in C) ovaries expressing the HA:\( tdrd5p^{ddel} \)
transgene, a construct which lacks the two Sxl binding sites. D) Higher magnification image of Sxl-RNAi ovaries showing increase in HA:Tdrd5p punctae (arrows).

Antibodies used are as described in figure: HA stains HA:Tdrd5p, Vasa stains germ cells, TJ stains somatic cells. E) Immunoblot comparing HA:Tdrd5p expression in HA:Tdrd5p adult ovaries and HA:Tdrd5p<sup>ddel</sup> adult ovaries. Antibody against Sxl is used as a loading control.

**Fig 4. tdrd5p is needed for proper male fertility and germline development.**

A-C′′) Confocal images showing germ cell loss phenotype in testes of aged tdrd5p mutant flies raised at 25°C (n = 29 testes) and 29°C (n = 39 testes). Asterisk marks the hub. D-E) Confocal images showing hub displacement in tdrd5p adult mutant testes. Arrows mark the hub. Vasa stains germ cells, ZFH1 and TJ stain somatic cells, Arm stains membranes, DAPI stains DNA. Antibodies used are as described in the figure. F) Graph showing the total progeny produced per male, comparing tdrd5p mutant males to controls. tdrd5p mutant males have a 50% reduction in fecundity. Data shown represents the average of two independent experiments with 5 males per test.

Significance determined by two-tailed unpaired t test (**P<0.01). See methods for description of control genotype.

**Fig 5. tdrd5p promotes male identity in the germline.**
Confocal images of A) wild type XY adult testes, B) XX \textit{tra} mutant adult testes, and C) XX \textit{tra} mutant adult testes rescued by \textit{tdrd5p} expression in the germline, driven by \textit{nos-gal4-VP16} driver (n=101 testes). D-F') Ectopic expression of \textit{tdrd5p} enhances the \textit{snf} mutant phenotype. Confocal images of D) \textit{snf/+} adult ovaries, E) \textit{snf/+} adult ovaries with ectopic expression of \textit{tdrd5p}, driven in the germline by \textit{nos-gal4-VP16}, and F) \textit{snf/snf} mutant adult ovaries, showing the germline tumor phenotype. Vasa stains germ cells, TJ stains somatic cells, Arm and HTS stain membranes, Dapi stains DNA, antibodies used are as indicated in the figure. G) Quantification of the degree of enhancement of the \textit{snf} and \textit{otu} mutant phenotypes with ectopic \textit{tdrd5p} expression. The number of ovaries scored per genotype is shown in each bar.

\textbf{Supporting Information}

\textbf{S1 Table.} RNAseq analysis\textunderscore changes in exon usage.

\textbf{S2 Table.} RNAseq analysis\textunderscore gene expression changes.

\textbf{S1 Fig.} \textit{tdrd5p} gene model.

\textit{A}) Schematic of the Bacterial Artificial Chromosome used to insert a hemagglutinin (HA) tag in \textit{tdrd5p} by BAC recombineering (not drawn to scale). The \textit{tdrd5p} gene is shown in reference to its closest neighboring genes: \textit{sas10} at its 5' end and \textit{CG4198} at its 3' end, which are both on the opposite strand. \textit{B}) Gene model of \textit{tdrd5p}. The HA tag was
inserted at the N-terminus of $tdrd5p$ immediately after the start codon. Putative Sxl binding sites are located in the 3$^{rd}$ intron and the 3’UTR. Mutant alleles described were generated by CRISPR-Cas9-mediated gene editing in the 1$^{st}$ exon.

**S2 Fig. Stellate transposon is not upregulated in $tdrd5p$ mutants.**

Confocal images showing expression of stellate crystals (arrows) in A) $tej$ mutant testes but not in B) $tdrd5p$ mutant testes. Antibodies used are as indicated in the figure.
A

4.6kb  

CG4198  

tdrd5p  

Sas10  

13.6kb  

B

HA

Tudor Domain

WT AAGAAGCCGAGGATAACAATGATGTGCCGCTCGAT
tdrd5pF1 AAGAAGCCGAGG-ATTGATGTGCCGCTCGAT (-8nt +1nt)
tdrd5pmp3 AAGAAGCCGAGG-TAAACAATGATGTGCCGCTCGAT (-1nt)
tdrd5pmt AAGAAGCCGAGG-TGATGTGCCGCTCGAT (-7nt)
Total=94
up in Sxl and bamM
down in Sxl and bamM
up in Sxl down in bamM
down in Sxl up in bamM
change in Sxl but not bam

Wild Type
A
A'
bam, control RNAi
B
B'
bam, Sxl RNAi
C
C'

D
E

- up in Sxl and bamM
- down in Sxl and bamM
- up in Sxl down in bamM
- down in Sxl up in bamM
- change in Sxl but not bam

Total=94
**Control**

- A
- A''

**tdrd5p mutant**

- B
- B''

- C
- C''

**Total progeny per male**

[F] Graph showing total progeny per male for control and tdrd5p conditions. ** indicates statistical significance.
