PCI Proteins eIF3e and eIF3m Define Distinct Translation Initiation Factor 3 Complexes

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PCI proteins eIF3e and eIF3m define distinct translation initiation factor 3 complexes

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Background: PCI/MPN domain protein complexes comprise the 19S proteasome lid, the COP9 signalosome (CSN), and eukaryotic translation initiation factor 3 (eIF3). The eIF3 complex is thought to be composed of essential core subunits required for global protein synthesis and non-essential subunits that may modulate mRNA specificity. Interactions of unclear significance were reported between eIF3 subunits and PCI proteins contained in the CSN.

Results: Here, we report the unexpected finding that fission yeast has two distinct eIF3 complexes sharing common core subunits, but distinguished by the PCI proteins eIF3e and the novel eIF3m, which was previously annotated as a putative CSN subunit. Whereas neither eIF3e nor eIF3m contribute to the non-essential activities of CSN in cullin-RING ubiquitin ligase control, eIF3m, unlike eIF3e, is an essential gene required for global cellular protein synthesis and polysome formation. Using a ribonomic approach, this phenotypic distinction was correlated with a different set of mRNAs associated with the eIF3e and eIF3m complexes. Whereas the eIF3m complex appears to associate with the bulk of cellular mRNAs, the eIF3e complex associates with a far more restricted set. The microarray findings were independently corroborated for a random set of 14 mRNAs by RT-PCR analysis.

Conclusion: We propose that the PCI proteins eIF3e and eIF3m define distinct eIF3 complexes that may assist in the translation of different sets of mRNAs.
eight subunit lid complex, which cleaves ubiquitin from substrates, thus apparently facilitating the entry of sub-
strates into the catalytic proteasome barrel [4,5].

In higher eukaryotes, the subunits of the 19S lid show
pair-wise similarity to the eight subunits of the CSN [6-9].
In vivo, CSN promotes the activity of cullin-RING ubiqui-
tin ligases [10-16], multiprotein complexes containing cullins, the RING protein Rbx1, and one of several hun-
dred substrate-specific adaptors [17-22]. The MPN
domain containing CSN subunit 5 harbors a protease
motif [23] that cleaves the ubiquitin-related peptide
Nedd8 from cullins [24,25]. This activity, acting in con-
cert with the CSN-associated deubiquitylase enzyme
Ubp12, was proposed to promote cullin function by facil-
ilitating the recruitment of labile substrate adaptors
[11,16,26,27].

The third PCI/MPN complex, eIF3, is more distantly
related to CSN and the 19S lid (reviewed in [28]).
Whereas human eIF3 consists of up to 13 subunits, con-
secutively named eIF3a – 1 and GA17 [29,30], budding
yeast contains only six to eight subunits (depending on
purification conditions). Five of these subunits are
orthologs of human eIF3a, b, c, g, and eIF3i [31,32] and
appear to constitute a conserved core complex [31,33].
Fission yeast contains the same five core subunits, in addi-
tion to the non-core subunits eIF3d/Moe1p, eIF3e/Int6p,
and eIF3h [34-36]. A putative eIF3f ortholog was also
identified, but biochemical evidence confirming it as an
authentic eIF3 subunit functioning in protein synthesis is
still outstanding [34,35,37,38].

eIF3 is the most complex translation initiation factor and
plays at least two important roles in protein synthesis.
First, eIF3 binds to the 40S ribosome and facilitates load-
ing of the Met-tRNA/eIF2 · GTP ternary complex to form
the 43S preinitiation complex. Subsequently, eIF3 appar-
ently assists eIF4 in recruiting mRNAs to the 43S complex.
A critical in vivo function of eIF3 core subunits in these
processes was indicated by the lethality of the respective
budding yeast deletion strains [31]. In contrast, in fission
yeast, the non-core subunits eIF3d and eIF3e are not
essential for viability or global protein synthesis
[34,36,38,39]. It was therefore proposed that distinct sub-
classes of eIF3 complexes, containing different combina-
tions of core and non-core subunits, may regulate specific
subsets of mRNAs in fission yeast [34,36,38,39]. Our
study provides the first experimental evidence substanti-
ating this hypothesis by demonstrating that biochemically
distinct eIF3 complexes defined by the PCI domain pro-
teins eIF3e and eIF3m (a novel eIF3 protein) associate
with different sets of mRNAs.

Results

Both csn6 and csn7b are essential genes

CSN complexes of higher eukaryotes typically contain
eight distinct subunits (two MPN and six PCI proteins).
However, in fission yeast only six subunits are known
(Csn1p, 2p, 3p, 4p, 5p, 7p; Ref. [13]), none of which are
essential for viability [40-42]. We noticed two genes in the
Schizosaccharomyces pombe genome database, originally
annotated as csn6 (SPBC4C3.07) and csn7b (SPAC1751.03),
which encode MPN and PCI domain
containing proteins with considerable similarity to meta-
zoan CSN6 and CSN7B, respectively (data not shown).
In order to determine whether these genes might function in
the known biochemical pathways regulated by CSN, cullin
deneddylation and Ubp12p-mediated deubiquityla-
tion [24,26], we deleted csn6 and csn7b in wild-type
diploid cells. Upon sporulation and tetrad analysis, only
two viable spores could be recovered in each case, both of
which were uracil auxotroph (Fig. 1A, and data not
shown). Thus, unlike the genes encoding the six known
subunits of the fission yeast CSN [41,42], csn6 and csn7b
are essential.

csn6p and Csn7Bp associate with eIF3 components

To elucidate the essential functions of Csn6p and Csn7Bp,
we sought to identify their interacting proteins. To this
end, we attempted to modify csn6 and csn7b at their
endogenous genomic loci with five consecutive protein A
epitope tags (proA). The C-terminal tag also contained a
cleavage site for Tobacco Etch Virus (TEV) protease
upstream of the protein A moieties. Diploid analysis indi-
cated that C-terminal tagging destroyed the essential func-
tion of csn6 (data not shown). In contrast, a csn7b-proA
haploid strain was viable and did not display any obvious
phenotypes (data not shown). This indicated that the
tagged allele was functional. Total protein lysate from the

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Figure 1
Analysis of \textit{c}sn6 and \textit{c}sn7b genes and proteins. (A) The \textit{c}sn6 and \textit{c}sn7b genes were disrupted in diploid \textit{S. pombe} cells by inserting the \textit{ura4} marker. Diploids were sporulated and spore viability was examined by tetrad analysis. Only two spores were viable, indicating that \textit{c}sn6 and \textit{c}sn7b are essential. (B) Cell lysate from a strain carrying \textit{c}sn7b modified with five C-terminal pro-A tags and a TEV cleavage site at the endogenous genomic locus was absorbed to IgG resin, followed by elution of bound proteins with TEV protease (left panel) or SDS (right panel). Gels were stained with Coomassie Brilliant Blue, and proteins were identified by MALDI-TOF mass spectrometry. The asterisks denote degradation products of elf3c.

Table 1: Summary of elf3 subunits in various eukaryotes

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<tr>
<th>Unified Nomenclature</th>
<th>Domain</th>
<th>Human</th>
<th>\textit{S. cerevisiae} (Core subunits)</th>
<th>\textit{S. pombe Csn7Bp complex}</th>
<th>\textit{S. pombe Int6p complex}</th>
<th>\textit{S. pombe elf3b complex}</th>
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were consistently absent from the Csn7Bp complex when analyzed either by MALDI-TOF or by LC-MS/MS (Fig. 1B and 5A).

Notably, no authentic CSN subunits were found in the Csn7Bp complex, consistent with the previous demonstration that S. pombe CSN contains only six non-essential subunits [13]. Structural analysis indicated that Csn6p is not only related to human CSN6, but shows a slightly greater overall similarity to human eIF3f (data not shown). Based on the functional characterization described below (Fig. 2), fission yeast Csn6p therefore appears to be the ortholog of human eIF3f.

A Csn7Bp ortholog is not known in the human elf3, although the recently identified subunit GA17 [30] shows considerable similarity to Csn7Bp (K. Hofmann, personal communication). In addition, interactions of metazoan CSN7 with elf3 subunits have previously been observed [43,44]. With regards to the unified nomenclature of elf3 subunits [29], we propose elf3m as a more appropriate name for the novel fission yeast elf3 subunit encoded by csn7b (see Table 1). Throughout this manuscript, we will use this novel name for the elf3f and elf3m genes and their products. The original annotations have recently been revised by the curator of the S. pombe genome database, in order to reflect the findings presented here.

The elf3f and elf3m proteins are primarily cytoplasmic

The evidence presented above suggested that elf3f and elf3m are essential subunits of S. pombe elf3. To substantiate this possibility, we determined the subcellular localization of elf3f and elf3m. If these proteins were authentic elf3 subunits involved in protein synthesis, they should assume a subcellular localization similar to known elf3 subunits. We therefore prepared three strains expressing C-terminal GFP-tagged alleles of elf3b, elf3e, and elf3m integrated into their respective genomic loci. In addition, since C-terminal GFP-tagging destroyed the essential function of the small elf3f protein, we prepared a strain mildly overexpressing N-terminally GFP-tagged elf3f from a pREP81 plasmid. Fluorescence microscopy of live cells revealed that all four proteins were primarily localized in the cytoplasm (Fig. 2A), which would be consistent with a function in protein translation. In contrast, CSN subunits are largely nuclear in fission yeast ([41], and our own unpublished observation).

elf3f and elf3m are required for global protein synthesis

To directly assess the potential role of elf3f and elf3m in protein synthesis, we prepared haploid elf3f and elf3m deletion strains maintained viable by plasmids driving the regulated expression of elf3f and elf3m, respectively. Expression from these plasmids could be turned off by the addition of thiamin to the growth media, resulting in a strong reduction in protein levels within 20 to 32 hours (Fig. 2B). Coincident with shut-off of elf3f and elf3m expression, global cellular protein synthesis was diminished by ~80%, as determined by metabolic labeling with 35S-methionine (Fig. 2C).

Further biochemical analysis by sucrose gradient velocity centrifugation revealed a strong reduction in the formation of polysomes in elf3f and elf3m mutants following promoter shut-off (Fig. 2D). In contrast, as described previously [34,36,38,39], elf3e mutants showed only a minor reduction in total protein synthesis (data not shown) and essentially normal polysomes (Fig. 2D).

The conserved cullin deneddylation function of CSN was not impaired either in elf3f and elf3m mutants or in elf3e mutants, since cullin 1 (Cul1p) did not accumulate exclusively in the deneddylated form as it does in csn5 mutants (Fig. 2E). Similarly, unlike in csn5 mutants (Fig. 2E; [26]), CSN/Ubp12p-mediated inhibition of Cul1p in vitro ubiquitin ligase activity was not impaired upon shut-off of either elf3f or elf3m expression. Cul1p neddylation and activity were also unaffected in elf3e mutants (Fig. 2E). These data suggested that elf3f and elf3m are bona fide subunits of fission yeast elf3 but not CSN, performing essential functions in protein synthesis similar to elf3 core subunits.

The elf3f and elf3e proteins define distinct elf3 complexes

Although the purification of the elf3m complex robustly retrieved roughly stoichiometric amounts of known elf3 subunits, two subunits, elf3d and elf3e, were conspicuously absent (Fig. 1B, Table 1). To exclude the possibility that we had overlooked these subunits because they were obscured by the IgG bands, we affinity-purified elf3e-associated proteins from an elf3e-proA strain. The retrieved proteins were identified using MALDI-TOF mass spectrometry as before.

Like the elf3m complex, the elf3e complex contained roughly stoichiometric amounts of the elf3 core subunits a, b, c, g, and i (Fig. 3A, Table 1). In addition, elf3f was present while, unexpectedly, elf3m and elf3h were missing. We did not detect the proteasome lid subunit Rpn5p, which previously had been shown to associate with elf3e and elf3d [45]. This observation indicated that the described elf3d/elf3e/Rpn5p interaction is either unstable under our purification conditions or contains only a minor fraction of the total elf3e engaged in protein interactions.

These results raised the intriguing possibility that fission yeast contains two distinct elf3 complexes that comprise an overlapping set of core subunits, but are distinguished
Figure 2

Roles of *eif3e* and *eif3m* in protein synthesis. (A) Subcellular localization. Live cells expressing GFP-tagged alleles of *eif3b*, *eif3e*, and *eif3m* at the endogenous genomic loci were examined by fluorescence microscopy. N-terminally GFP-tagged *eif3f* was expressed at low levels from the pREP81 plasmid. (B) Shut-off strains. Diploid heterozygous *eif3f* and *eif3m* deletion strains were transformed with pREP81 plasmids driving the thiamin-repressible expression of Myc-tagged eIF3f and eIF3m, respectively. Diploids were sporoated and homozygous disruptants carrying the *eif3f* and *eif3m* plasmids were selected. Cells were grown in liquid medium to an OD595 of 0.3 in the absence of thiamin, followed by promoter shut-off by the addition of thiamin. Samples were taken at the indicated time points after promoter shut-off and analyzed for the expression of plasmid borne eIF3f and eIF3m by immunoblotting with anti-Myc antibodies. (C) Effect on total protein synthesis. The *eif3f* and *eif3m* shut-off strains were maintained in the absence or presence of thiamin as indicated. Strains transformed with empty pREP81 plasmid were included as control. Cells were metabolically labeled with 35S-methionine, and aliquots of total cellular proteins were separated by SDS-PAGE and analyzed by autoradiography. The Coomassie Blue stained gel is shown to document equal protein loading. Data were quantified by PhosphorImager analysis and results are displayed in a bar graph. (D) Effect on polysomes. Polysome profiles were determined for the indicated strains as described in the Methods section. An *eif3e* deletion strain is shown for reference. (E) Effect on CSN-mediated regulation of cullin-RING ubiquitin ligases. Cul1p complexes were immunopurified from the indicated strains and employed in substrate-independent in vitro ubiquitylation reactions with purified E1, the E2 Cdc34p, ubiquitin, and ATP [26]. Polyubiquitin chains formed in the reaction are indicated (top panel). In contrast to csn5 mutants, derepression of Cul1p activity is not observed in cells lacking *eif3f*, *eif3m*, or *eif3e*. The neddylation state of Cul1p was determined by immunoblotting (middle panel). Hyperneddylated Cul1p only accumulates in csn5 mutants. Shut-off of *eif3f* and *eif3m* expression was verified by immunoblotting with anti-Myc antibodies (lower panel).
Figure 3
Distinct elf3 complexes. (A) elf3 complexes associated with elf3e and elf3m were affinity-purified by absorption of the respective pro-A-tagged proteins to IgG beads. Bound proteins were eluted by cleavage with SDS (elf3e) or TEV protease (elf3m). (B) The eluates described in (A) were analyzed by immunoblotting with elf3d antibodies. The asterisk refers to cross-reactivity of the secondary antibody with Ig light chains. (C) Lysates from cells expressing Myc-tagged Csn5p, elf3e, and elf3m from their endogenous genomic loci were immunoprecipitated with anti-elf3d antisera. Coprecipitated proteins were identified by immunoblotting as indicated. Total cell lysates are shown to document expression levels of the endogenously tagged proteins. (D) Protein lysate from cells expressing protein A-tagged elf3b from the endogenous promoter was absorbed to IgG beads, and specifically retained proteins were identified by LC-MS/MS.
by the presence of either the essential PCI protein elf3m and the MPN domain protein elf3h or the non-essential PCI protein elf3e and its binding partner elf3d. To exclude the possibility that our mass spectrometry analysis missed substoichiometric amounts of elf3d in the elf3m complex, we analyzed elf3m complexes by immunoblotting with elf3d antisera. Whereas elf3d was readily detectable in the elf3e complex, it was undetectable in the elf3m complex (Fig. 3B). In the reciprocal experiment, elf3d antibodies co-immunoprecipitated elf3e-13Myc, but not elf3m-13Myc or Csn5p-13Myc (Fig. 3C).

To exclude the possibility that our cell lysis or affinity purification conditions led to uncontrolled release of elf3 subunits, thus mimicking the existence of distinct subcomplexes, we performed a purification using the protein A-tagged elf3b core subunit as bait. As determined by LC-MS/MS performed on excised bands detected in the complex upon PAGE separation, the elf3b complex contained all known elf3 core components as well as elf3f and elf3m (Fig. 3D). The elf3e and elf3d proteins were also present, albeit in clearly substoichiometric amounts. These findings indicate that purification of elf3b resulted in the copurification of the distinct elf3m- and elf3e-containing complexes. Taken together, these data strongly suggested the existence of two distinct elf3 complexes defined by the PCI proteins elf3m and elf3e.

The elf3m and elf3e proteins associate with distinct sets of mRNAs

The finding that elf3m is essential, whereas elf3e is dispensable, suggested the possibility that the different elf3 complexes they define regulate different subsets of mRNAs. To approach this, we sought to identify mRNAs specifically associated with the elf3m and elf3e complexes. The complexes were affinity-purified as described above in the presence of RNase inhibitors, and the associated RNA was extracted, amplified, and converted to Cy3-labeled cDNA as described in the Methods section. The Cy3-labeled cDNA was hybridized competitively with Cy5-labeled cDNA prepared from total RNA onto microarrays representing all 4988 predicted S. pombe cDNA to determine the relative expression rank of each mRNA. A plot of expression rank vs. factor of enrichment of the 106 mRNAs most enriched in the elf3e complex was enriched for rare mRNAs (~65% of elf3e-associated mRNAs had an expression rank > 4000; see Fig. 4C). The lack of a linear correlation between mRNA expression level and enrichment in the elf3e and elf3m complexes argues against unspecific copurification of abundant mRNAs.

Specific association of mRNAs with elf3m and elf3e complexes

To validate the results from the microarray hybridizations, we chose several mRNAs at random from each list of 106 and used RT-PCR to confirm their interactions with the
Figure 4

Association of mRNAs with eIF3 complexes. (A) Messenger RNAs associated with eIF3e and eIF3m complexes were identified by microarray hybridization as described in the Methods section. The graph indicates the numbers of mRNAs enriched more than three-fold over mock in both complexes. (B) Classification into functional groups of the 106 mRNAs most highly and uniquely enriched in complexes with eIF3e or eIF3m. (C) The relative expression ranks of the 106 most highly and uniquely enriched mRNAs in the eIF3e and eIF3m complexes were determined using the relative hybridization signals obtained with total S. pombe cDNA ([see additional file 1]). The expression ranks were plotted against the factor of enrichment of each mRNA in the eIF3 complexes. No correlation between expression rank and enrichment is apparent, indicating that highly expressed mRNAs were not unspecifically enriched in eIF3 complexes. The 5407 individual features on the microarray slides represent the 4988 ORFs and transcripts predicted in the Sanger Centre S. pombe genome database and various controls. To simplify the analysis, expression ranks were also assigned to these control spots, thus resulting in expression ranks for some ORFs higher than the theoretically possible number of 4988.
respective eIF3 complexes. eIF3e-proA- and eIF3m-proA-associated complexes were affinity-purified as before and separated by PAGE. Both complexes showed the same differential subunit composition as described above (Fig. 5A). The associated RNA was purified, split into equal portions, and employed in RT-PCR reactions.

The RT-PCR analysis of a total of fourteen mRNAs included eight mRNAs identified in the eIF3e complex, five mRNAs identified in the eIF3m complex, and one mRNA found to be associated with both complexes with similar enrichment factors. These mRNAs varied widely in their factors of enrichment and their enrichment ranks as indicated in Fig. 5B. Without exception, all eight mRNAs found to be enriched in the eIF3e complex by microarray analysis were also found preferentially associated with this complex by RT-PCR (Fig. 5B). Based on this result, we calculate a false positive rate of less than 0.11 with a 95% confidence interval of 0.00 – 0.31. Whereas mRNAs with a high enrichment factor (>10, [see additional file 2]) appeared to be exclusively associated with eIF3e-proA (within the limit of detection), those with a lower enrichment factor (<10) also displayed a low amount of association with the eIF3m complex (Fig. 5B). Conversely, all five mRNAs highly enriched in the eIF3m complex as determined by microarray analysis ([see additional file 2]) were almost exclusively bound to this complex when analyzed by RT-PCR (Fig. 5B).

Figure 5
Specific association of mRNAs with the eIF3e and eIF3m complexes. (A) The eIF3 complexes shown were affinity-purified as described in the Methods section, and separated by SDS-PAGE followed by staining with Coomassie Brilliant Blue. The labeled bands were identified by LC-MS/MS. eIF3f* refers to a band in the eIF3m complex that was not identified by mass spectrometry in this experiment, and is therefore assigned based on its comigration with eIF3f identified in the eIF3e complex (right lane). eIF3f was positively identified by MALDI-TOF mass spectrometry as a subunit of the eIF3m complex in Fig. 1B. (B) The indicated eIF3e- and eIF3m-associated mRNAs were extracted from the purified complexes and employed in RT-PCR reactions using primers specific for each mRNA (see Table 3). PCR products obtained with total S. pombe RNA are shown for reference in the left panel. The factor of enrichment of each mRNA in the respective eIF3 complex and the enrichment rank (out of all 106 mRNAs enriched in either complex) are indicated below the gels.
Notably, the mRNA encoding the proteasome subunit Rpn5p, which was found in both complexes by microarray analysis with similar enrichment factors (eIF3e = 5.1; eIF3m = 8.1) was also confirmed as being associated with both eIF3 complexes by RT-PCR (Fig. 5B). These results strongly suggest that the eIF3m and eIF3e complexes specifically associate with distinct sets of mRNAs.

Discussion

**PCI proteins define distinct eIF3 complexes**

Our results show that Csn6p and Csn7Bp are subunits of fission yeast eIF3. Csn6p was shown to be the eIF3f subunit conserved in all eukaryotes except budding yeast. Consistent with this finding, eIF3f has previously been found to be associated with eIF3g, although the role of eIF3f in protein synthesis had not been examined [34]. Our study further identified two distinct eIF3 complexes defined by the PCI proteins eIF3e and eIF3m (Fig. 3A). No direct equivalent of eIF3m is apparent in eIF3 preparations from other eukaryotes. Considering the essential function of eIF3m in protein synthesis in fission yeast, it is possible that other PCI proteins substitute for eIF3m in other organisms.

Consistent with this idea is the finding that the PCI domain containing GA17, a recently identified protein copurifying with human eIF3 [30], shows more similarity to eIF3m than to any other PCI protein (K. Hofmann, personal communication). In addition, the PCI domain containing CSN subunits 1, 3, 7, and 8 were found to interact with eIF3 subunits in Arabidopsis thaliana and in human cells [43,44,46]. In addition, Pci8p/Csn11p, a non-essential PCI subunit of the budding yeast CSN [47,48], copurifies with essential eIF3 core subunits [49]. Although the functional significance of these interactions is still unclear, our findings raise the intriguing possibility that they define multiple subclasses of distinct eIF3 complexes. Whereas fission yeast appears to rely on an essential eIF3 complex classified by eIF3m and a non-essential complex specified by eIF3e, higher eukaryotes may divide the task of mRNA translation among a multitude of eIF3 complexes. Since the individual PCI proteins defining these subcomplexes are expected to be present in substoichiometric amounts relative to core components, as is eIF3e in the S. pombe core complex, they may have escaped detection in bulk eIF3 preparations from higher eukaryotes.

**Distinct eIF3 complexes and translational specificity**

Although our finding of distinct eIF3 complexes that associate with different sets of mRNAs was surprising, circumstantial evidence pointing to their existence was provided in previous studies. For example, fission yeast eIF3e copurifies with eIF3 core subunits, and yet, unlike core subunits, eIF3e is not required for global protein synthesis or viability. Two competing models were proposed to explain the pleiotropic phenotype of eIF3e deletion mutants, which includes slow growth in minimal media and meiotic defects [34,36,38,39,50,51]. In the first model, eIF3e regulates the translation of all transcripts, but rare mRNAs may be more affected by a fractional reduction in translation efficiency and thus give rise to distinct phenotypes. In the second model, eIF3e regulates the translation of a specific subset of mRNAs encoding proteins whose deletion leads to distinct phenotypes but not lethality. The findings presented here strongly favor the second model.

Our microarray analysis revealed 106 mRNAs uniquely enriched in the eIF3e complex, many being rare, whereas 2050 transcripts were uniquely enriched in the eIF3m complex. The latter finding is consistent with the severe protein synthesis defect and lethality of eIF3m deletion mutants. Whereas these mRNA lists were based on an arbitrary cut-off value of three-fold enrichment over mock, this criterion proved stringent enough to confirm specific association with their respective eIF3 complexes of all 14 mRNAs retested by RT-PCR. Thus, since we calculate the false positive rate to be less than 0.11 with 95% confidence interval 0.00 – 0.31, the maximum number of mRNAs listed potentially false positively as enriched in the eIF3e complex would be 33 out of 106 (with 95% confidence).

However, we consider it unlikely that all mRNAs found enriched in the eIF3e complex are exclusive translational targets of this complex, because the cellular phenotypes of eIF3e mutants are rather discrete. Although many of the eIF3e-associated mRNAs encode essential proteins, viability, global protein synthesis, and polysome formation are not affected in these mutants when they are grown in rich media (Fig. 2D, and data not shown). It is therefore likely that eIF3m or other PCI domain proteins can deputize for eIF3e in many cases. In fact, our microarray study revealed that a substantial portion of eIF3e-associated mRNAs was also recovered in the eIF3m complex (Fig. 4A). Nonetheless, we strongly suspect that inefficient translation of a limited set of eIF3e-associated mRNAs contributes to distinct cellular phenotypes found in eIF3e mutants (see below).

**The eIF3e protein and translational control during stress response**

The eIF3e mutants display marked sensitivity to a wide variety of cellular stresses, such as osmotic stress, nutrient starvation, and low temperature [34,38,39,50,52] In addition, eIF3e mutants show synthetic lethality with proteasome mutants, which are presumed to accumulate a large load of misfolded proteins [45]. Conversely, overexpression of eIF3e confers resistance to a broad spectrum of
unrelated drugs, whose only commonality appears to be that they induce cellular stress [38]. Overexpression of elf3e also activates genes involved in stress defense, such as thioredoxin [38]. Interestingly, the mRNA encoding thioredoxin was also identified as a putative translational target of elf3e (see additional file 2]). Finally, elf3e undergoes relocalization into cytoplasmic foci in response to heat and osmotic stress, thus implicating it in stress regulation [35].

Global protein synthesis is actively switched off in response to cellular stress and nutrient deprivation (reviewed in Refs. [53,54]). This shut-off protects cells from proteotoxicity by relieving chaperones of their load of unfolded client proteins, conserving amino acids for other essential functions, and attenuating the metabolic consequences of protein synthesis. However, long-term adaptation to stress conditions, repair and recovery require synthesis of new stress-induced proteins. During the stress response, some mRNAs must be translated in the presence of a repressed general translation machinery, suggesting that select elfs can escape the global repression. Our studies raise the intriguing possibility that the elf3e complex has such a specialized function during stress response. Lack of elf3e may prevent stress-induced synthesis of its critical translational targets, thus leading to the known stress sensitivity of the mutant. Substantial additional work will be required to address this possibility.

Potential mechanisms underlying mRNA discrimination by elf3 complexes
Several lines of evidence have begun to implicate other general translation factors, including elf2 and elf4, in translational specificity [55]. Importantly, these factors are downstream of important signaling cascades, including the nutrient-sensing TOR pathway and a variety of stress-induced kinases (reviewed in Refs. [55,56]). Although the details of these regulatory mechanisms are beginning to emerge, it is still unclear exactly how elf2 and elf4 contribute to mRNA specificity.

Since elf3 cooperates with the cap-binding elf4 complex in directing the 5’ end of mRNAs to the 40S ribosome, and several elf3 subunits contain RNA binding motifs, our data is consistent with a model in which elf3 complexes defined by distinct PCI proteins recognize determining features of mRNAs presented to the 40S subunit in concert with elf4. In agreement with this idea is the recent finding that the human PCI protein elf3a specifically facilitates the translation of the mRNA encoding ribonucleotide reductase M2 [57]. In addition, A. thaliana elf3h, a non-core subunit, was recently shown to be specifically required for efficient translation of the transcription factor ATB2 [46].

While we have so far been unsuccessful in identifying common sequence elements within the upstream regions of mRNAs enriched in the elf3e complex (data not shown), this analysis was severely hampered by the fact that 5’UTRs are poorly defined in S. pombe. It is therefore still possible that critical features, including secondary structure determinants, lie within the 5’UTR or other regions of elf3e-associated mRNAs. Substantial additional work will be required to delineate the exact mechanism of how elf3e may contribute to the translation of specific mRNAs and the potential impact of this mechanism on human cancers defective in INT6/elf3e [58,59].

Conclusion
We provide biochemical evidence for the existence of two distinct elf3 complexes in fission yeast. These complexes contain an overlapping set of subunits, but are distinguished by the PCI proteins elf3e and elf3m. Based on the finding that the distinct elf3 complexes associate with different mRNAs, we propose that they have different translational specificities.

Methods
Fission yeast techniques
Preparation of fission yeast cultures, cDNA cloning, yeast transformation, PCR-based genomic epitope tagging and gene deletion, mating, and tetrad analysis were carried out using standard methods as described [26]. The strains used in this study are listed in Table 2.

Affinity purification and mass spectrometry
Epitope-tagged strains (elf3m-proA and elf3e-proA strains) were grown in 12 L yeast extract and supplements (YES) medium to 1.5 optical density (OD) at 595nm wavelength and harvested by centrifugation. Cell lysates were prepared by bead lysis in a lysis buffer containing 50 mM Tris-HCl pH 8.0, 150 mM NaCl, 0.5% Triton X-100, 1 mM dithiothreitol, supplemented with protease inhibitors (10 ug/ml leupeptin, 10 ug/ml pepstatin, 5 ug/ml aprotinin and 1mM phenylmethylsulfonylfluoride). Upon centrifugation at 17,000 rpm for 50 min at 4°C, 300 mg total protein in a volume of 50 ml was absorbed to 100 ul Dyna beads (Dynal Biotech, Oslo, Norway) coupled to whole rabbit IgG (Jackson Immunoochemicals, West Grove, Pennsylvania, USA). Mock purifications were performed in parallel by absorbing lysate from cells lacking any tagged proteins to IgG beads. Beads were collected by a magnetic device and washed five times in 5 ml lysis buffer. TEV protease (Invitrogen, Carlsbad, California, USA) cleavage or elution in 5% SDS solution were used to collect bound proteins. Eluted proteins were separated on tricine gels or by conventional SDS-polyacrylamide gel electrophoresis (SDS-PAGE), and visualized by Coomassie G250 staining. Protein bands were excised from gels, digested with trypsin (Promega Corporation, Madison,
Wisconsin, USA), and subjected to mass spectrometry. The eIF3 complexes were analyzed by MALDI-TOF, and by LC-MS/MS at the Harvard NIEHS Center Proteomics Facility, according to standard procedures.

Protein synthesis and polysome analysis
The eif3f and eif3m conditional shut-off strains were inoculated in 10 ml Edinburgh Minimal Media (EMM) with or without thiamin and cultured at 30°C for 30 hrs. 100 uCi 35S-methionine were added to the cells, which were labeled for 30 min and then harvested by centrifugation. Cell lysates were prepared by bead disruption and equal amounts of the lysates were analyzed by SDS-PAGE. 35S-methionine incorporation was determined by autoradiography and quantified by PhosphorImager analysis (Bio-Rad, Hercules, California, USA).

Polysome analysis was performed exactly as described in Ref. [60]. Briefly, cells were grown in EMM with or without thiamin for 30 hrs. Cycloheximide (100 ug/ml) was added to each culture for 20 min. Cells were harvested and lysed in breaking buffer (20 mM Tris/HCl pH 7.4, 50 mM NaCl, 30 mM MgCl2, 1 mM DTT, 50 ug/ml cycloheximide, 0.2 mg/heparin, 50 U/ml SuperRNasein, and protease inhibitors), followed by centrifugation at 13,000 x g for 5 min. 20 A260 nm units of each supernatant in a volume of 500 ul were fractionated on 5-45 % sucrose gradients for 3 hrs at 30,000 rpm using a SW40-Ti rotor in a Beckman L70 centrifuge. Polysome profiles were obtained by monitoring the absorbance at 254 nm along the gradient using a Bio-Rad fractionator, and the output was recorded using a Bio-Rad UV detector.

RT-PCR
RNAs associated with the eIF3e and eIF3m complexes were purified as described above. Primer design and RT-PCR conditions were according to the manual supplied with the Platinum Quantitative RT-PCR Thermoscript kit (Invitrogen). Primers used for RT-PCR are listed in Table 3. The primer concentration for actin amplification was 0.25 uM. Other primers were used at 1 uM. Total RNA was obtained as described [19].

Immunological techniques
Immunoprecipitation, immunoblotting, and in vitro ubiquitination assays were carried out exactly as described previously [26]. Antibodies against protein A and ubiquitin were purchased from Sigma and Genzyme (Cambridge, Massachusetts, USA), respectively. Anti-eIF3d/Moe1p polyclonal antibody was provided by E. Chang (Baylor College of Medicine, Houston, Texas, USA).

Microarray analysis
The eIF3 complexes were affinity-purified as described above, except that 50 U/ml SuperRNasein (Ambion, Austin, Texas, USA) and 5 mM ribonucleoside vanadyl complex (New England Biolab, Beverly, Massachusetts, USA) were added to the lysis buffer. A mock purification was performed under identical conditions with lysate from cells lacking any tagged proteins. The methods for extraction of RNA, cDNA synthesis, RNA amplification, and aminooxylation labeling were adopted from previous publications [61,62]. Briefly, after binding and washing, beads were treated with 3 U/ul DNase I, followed by elution with 5 % SDS, extraction with phenol/chloroform and then ethanol precipitation. The associated RNA was

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reversely transcribed using Superscript II reverse transcriptase (Gibco-BRL Division of Invitrogen) with 1 μM oligo-dT(15)-T7 primer (5’-AAA CGA CGG CCA AAT ACA C 3’) and 1 μM template switch primer (5’-AAG CAG TGG TAT CAA CGC AGA GTA CGG C 3’). Full-length double stranded (ds)-cDNA was synthesized using Advantage Polymerase (Clontech, BD Biosciences, Mountain View, California, USA). Newly synthesized ds-cDNA was passed through Bio-6 columns (Bio-Rad) and dried. RNA amplification was performed with the T7 megascript kit (Ambion). Amplified RNA was purified using the RNeasy kit (Qiagen, Hilden, Germany) and reversely transcribed with Superscript II reverse transcriptase in the presence of aminoallyl-dUTP in reactions primed with oligo-dT (Invitrogen). After RNase H digestion and purification on QIAquick columns (Qiagen), the aminoallyl-cDNA was labeled with Cy3, and purified on QIAquick columns.

Control Cy5-labeled aminoallyl-cDNA was made by oligo dT primed reverse transcription of total S. pombe RNA.

Labeled cDNAs were hybridized onto glass slide microarrays. Microarrays were made by spotting purified ds-PCR products 500 to 1200 bp in length onto glass slides coated with aminopropylsilane (Erie Scientific, Portsmouth, New Hampshire, USA). The PCR products used represented 4988 predicted ORFs and transcripts as annotated by the Sanger Centre [63] and are located at the 3’ end of predicted genes to maximize sensitivity in detecting oligo-dT primed reverse transcription products. Descriptions of primer pairs and the features on the microarrays are available at the Longhorn Array Database [64].

Median pixel intensities for each spot obtained from hybridizations of elf3-associated RNA ([see additional file 1, sheet 1]) were corrected by local background subtraction and divided by the corresponding values obtained from a mock purification. This resulted in the factor of enrichment of mRNAs bound to elf3 complexes over mock. The mRNAs were ranked according to their factor of enrichment ([see additional file 1, sheet 2]). An enrichment factor of three was chosen as an arbitrary threshold. We found 2464 mRNAs were enriched greater than three-fold over mock in the elf3m complex, while we observed 520 mRNAs enriched in the elf3e complex ([see additional file 1, sheet 3]). Comparison of the data sets revealed 414 mRNAs that occurred in both complexes, 2050 mRNAs uniquely enriched in the elf3m complex and 106 mRNAs that were exclusively enriched in the elf3e complex ([see additional file 1, sheet 4; additional file 2]). A corresponding list of the 106 mRNAs most highly and uniquely enriched in the elf3m complex was assembled ([see additional file 2]) and used to select specific mRNAs for RT-PCR analysis.

The competitive Cy5-labeled total cDNA provided clear microarray feature identification and a guide to relative sequence abundance in the pre-purification sample from which the relative expression rank of each mRNA was determined ([see additional file 1, sheet 2]). In this study, data were not adjusted by ratio normalization to total RNA signals or local area normalization functions. The microarray data were deposited with the public ArrayExpress (E-MEXP-208) [65] and GEO [66] databases.

**List of abbreviations**

CSN COP9 signalosome

Cul Cullin

elf Eukaryotic initiation factor

EMM Edinburgh Minimal Media
GFP Green fluorescent protein
IgG Immunoglobulin G
LC/MS/MS Liquid chromatography tandem mass spectrometry
MALDI-TOF Matrix-assisted laser desorption ionization time-of-flight
MPN Mpr1/Pad1 N-terminal
OD Optical density
PAGE Polyacrylamide gel electrophoresis
PCI Proteasome, COP9 Signalosome, eIF3
ProA Protein A
RT-PCR Reverse transcription-polymerase chain reaction
TEV Tobacco etch virus
YES Yeast extract and supplements (growth media)

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