

1 RESEARCH ARTICLE

2 **Compositionally distinct nuclear pore complexes of functionally**
3 **distinct dimorphic nuclei in ciliate *Tetrahymena***

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18 **RUNNING TITLE:** *Tetrahymena* nuclear pore complex

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20 **KEY WORDS:** FG-Nup, Nuclear dimorphism, Nuclear envelope, Nucleoporin,
21 Y-complex

22

23 **SUMMARY STATEMENT:** Our study demonstrates compositional and structural
24 differences of the nuclear pore complex between the functionally differentiated
25 macronucleus and micronucleus within a single cytoplasm of ciliated protozoa.

26 **ABSTRACT**

27 The nuclear pore complex (NPC), a gateway for nucleocytoplasmic trafficking, is
28 composed of about 30 different proteins called nucleoporins. It remains unknown
29 whether the NPCs within a species are homogeneous or vary depending on the cell type,
30 or physiological condition. Here, we present evidence for compositionally distinct NPCs
31 that form within a single cell in a binucleated ciliate. In *Tetrahymena thermophila*, each
32 cell contains both a transcriptionally-active macronucleus (MAC) and a germline
33 micronucleus (MIC). By combining *in silico* analysis, mass spectrometry analysis for
34 immuno-isolated proteins, and subcellular localization analysis of GFP fused proteins,
35 we identified numerous novel components of MAC and MIC NPCs. Core members of the
36 Nup107-160 scaffold complex were enriched in MIC NPCs. Strikingly, two paralogs of
37 Nup214 and of Nup153 localized exclusively to either MAC or MIC NPCs. Furthermore,
38 the transmembrane components Pom121 and Pom82 localize exclusively to MAC and
39 MIC NPCs, respectively. Our results argue that functional nuclear dimorphism in ciliates
40 is likely to depend on compositional and structural specificity of NPCs.

41 INTRODUCTION

42 Ciliated protozoa maintain two distinct nuclei within the same cytoplasm: a somatic
43 macronucleus (MAC) and a germline micronucleus (MIC) (Fig. 1A) (Eisen et al., 2006;
44 Orias et al., 2011; Karrer, 2012). The polyploid MAC is transcriptionally active, and its
45 acentromeric chromosomes segregate during cell division by a spindle-independent
46 amitotic process. In contrast, the diploid MIC has transcriptionally inert, centromeric
47 chromosomes that segregate by canonical mitosis. In *Tetrahymena thermophila*, DNA
48 replication in the MIC and MAC occurs during non-overlapping periods in the cell cycle.
49 Thus, nuclear dimorphism in ciliates involves non-equivalent regulation of multiple
50 activities in two distinct nuclei (Orias, 2000; Goldfarb and Gorovsky, 2009). This is
51 likely to require targeted transport of components to the MIC vs. MAC, for which
52 differences in the NPCs may be important determinants.

53 Previously, we analyzed 13 *Tetrahymena* nucleoporins (Nups), and discovered that
54 four paralogs of Nup98 were differentially localized to the MAC and MIC (Iwamoto et al.,
55 2009). The MAC- and MIC-specific Nup98s are characterized by Gly-Leu-Phe-Gly
56 (GLFG) and Asn-Ile-Phe-Asn (NIFN) repeats, respectively, and this difference is
57 important for the nucleus-specific import of linker histones (Iwamoto et al., 2009). The
58 full extent of compositional differentiation of MAC and MIC NPCs could not, however,
59 be assessed, since only a small subset of the expected NPC components were detected.

60 NPCs have been studied in eukaryotes including rat (Cronshaw et al., 2002),
61 *Saccharomyces cerevisiae* (Rout et al., 2000), *Aspergillus nidulans* (Osmani et al., 2006),
62 *Schizosaccharomyces pombe* (Asakawa et al., 2014), *Arabidopsis thaliana* (Tamura et al.,
63 2010), and *Trypanosoma brucei* (Degrasse et al., 2009; Obado et al., 2016) (Table S1).
64 The NPC structure has an 8-fold rotational symmetry, and is made up of roughly 30
65 known Nups organized into subcomplexes (Alber et al., 2007; Bui et al., 2013) (Fig. S1).
66 The Nup93 complex in mammalian cells (Nic96 in *S. cerevisiae*) forms a stable scaffold
67 composed of Nup93^{ScNic96}, Nup205^{ScNup192}, Nup188^{ScNup188}, Nup155^{ScNup170 or ScNup157}, and
68 Nup53/Nup35/MP-44^{ScNup53 or ScNup59} (Grandi et al., 1997; Hawryluk-Gara et al., 2005;
69 Amlacher et al., 2011). A second stable scaffold in mammals, the Nup107-160 complex
70 (called the Y-complex or Nup84 complex in *S. cerevisiae*) is composed of conserved
71 subunits Nup107^{ScNup84}, Nup160^{ScNup120}, Nup133^{ScNup133}, Nup96^{ScNup145C}, Nup85^{ScNup85},
72 Seh1, and Sec13, together with species-specific subunits (Siniosoglou et al., 1996;

73 Lutzmann et al., 2002; Loiodice et al., 2004). Peripheral to the scaffolds are Phe-Gly (FG)
74 repeat-bearing Nups, whose disordered FG-repeat regions constitute the central channel,
75 with FG repeats interacting with nuclear transport receptors (Terry and Wentle, 2009).
76 Three transmembrane (TM) Nups anchoring the NPC to the mammalian nuclear
77 membrane are NDC1, gp210, and POM121 (Greber et al., 1990; Hallberg et al., 1993;
78 Stavru et al., 2006) (in yeast: Ndc1, Pom152, and Pom34 (Winey et al., 1993; Wozniak et
79 al., 1994; Miao et al., 2006)). A distinct nucleoplasmic basket is formed with
80 Tpr^{ScMip1/Mip2} (Cordes et al., 1997; Strambio-de-Castillia et al., 1999).

81 Based on prior analysis, *T. thermophila* appeared to lack homologs of many widely
82 conserved NPC components. These included scaffold Nups (mammalian Nup205, 188,
83 160, 133, 107, 85, and 53, among others) from the Nup93 and Y-complexes. Similarly,
84 homologs of FG-Nups Nup214, 153, 62, and 58 were also not detected, as were TM Nups
85 except for gp210. These NPC components may have evaded homology-based searches
86 due to extensive sequence divergence, given the large evolutionary distance between
87 ciliates and animals, fungi, and plants.

88 To address these ambiguities and to better understand NPC differentiation in *T.*
89 *thermophila*, we attempted comprehensive identification of Nups. First, we analyzed
90 proteins affinity-captured with known Nups. Furthermore, we mined updated genome
91 and protein databases for characteristic Nup sequences or conserved domains, using *in*
92 *silico* structure prediction. The resulting expanded catalog of *Tetrahymena* Nups,
93 combined with localization data, sheds new light on the extent to which NPC architecture
94 can vary within a single species, and even in a single cytoplasm.

95

96 **RESULTS**

97 **The Nup93 complex includes a unique Nup205 ortholog and a novel central** 98 **channel FG-Nup**

99 In mammalian cells, the Nup93 complex (Fig. 1B) is composed of Nup93, Nup205,
100 Nup188, Nup155, and Nup53 (Fig. S1) (Grandi et al., 1997; Hawryluk-Gara et al., 2005).
101 In *Tetrahymena*, we previously identified homologs for Nup93 (*TtNup93*; Gene Model
102 identifier TTHERM_00622800) and Nup155 (*TtNup155*; TTHERM_00760460), and
103 found them distributed to MAC and MIC NPCs (Iwamoto et al., 2009). To identify other
104 Nup93 complex components, we used mass spectrometry to analyze anti-GFP

105 immunoprecipitates from *Tetrahymena* expressing GFP-*Tt*Nup93 (Fig. 1C). All of the
106 proteins listed in Table S2 as ‘hypothetical protein’ were examined by Blast search for
107 similarities to known Nups of other species. In addition, all of the ‘hypothetical proteins’
108 were examined by expression profile analysis in the *Tetrahymena* Functional Genomics
109 Database (TetraFGD) web site (<http://tfgd.ihb.ac.cn/>) (for details see the “Microarray”
110 page of the TetraFGD: <http://tfgd.ihb.ac.cn/tool/exp> (Miao et al., 2009)) (also see
111 Materials and Methods). When either the Blast search or the expression profile analysis
112 (details described below) found similarities to any known Nups, we examined its
113 subcellular localization in *T. thermophila* by ectopically expressing GFP fused proteins.
114 By these analyses we found Nup308 (TTHERM_00091620) and the novel protein
115 TTHERM_00194800 (*Tt*Nup58: Nup58 in Fig. 1D and Table S2).

116 Nup308, a protein of 2675 amino acid residues, was previously identified as a
117 *Tetrahymena*-specific Nup, but it was not assigned to a subcomplex (Iwamoto et al.,
118 2009). Based on PSIPRED analysis, Nup308 is composed of GLFG repeats forming an
119 N-terminal disordered structure (residues 1–570), followed by a large C-terminal
120 α -helix-rich region (residues 571–2675) (Fig. 2). To identify potential Nup308
121 counterparts, we looked for Nups in other species with similar distributions of secondary
122 structures. Interestingly, a large α -solenoid domain is a predicted feature of both Nup205
123 and Nup188, conserved core members of the Nup93 complex (Kosova et al., 1999;
124 Andersen et al., 2013), although these proteins do not have FG repeats.

125 To investigate whether this structural similarity between *Tetrahymena* Nup308 and
126 Nup205 and Nup188 homologs in other species reflected shared evolutionary origins, we
127 performed a phylogenetic analysis. Nup308 formed a clade with Nup205 orthologs,
128 supported by a bootstrap probability of 72%, but not with Nup188 orthologs (Fig. S2).
129 Nup188 appears absent in *Tetrahymena*, since we failed to find any candidates in either
130 the database or in our mass spectrometry data. Taken together, our results strongly
131 suggest that Nup308 belongs to the Nup93 complex and is orthologous to human Nup205,
132 but has acquired an unusual GLFG repeat domain. Consistent with this assignment,
133 GFP-Nup308 localized similarly to GFP-*Tt*Nup93, being equally distributed between
134 MAC and MIC NPCs (Iwamoto et al., 2009).

135 The second Nup candidate identified in *Tt*Nup93 pulldowns was
136 TTHERM_00194800. This small protein (45 kDa deduced molecular weight) is

137 composed of an N-terminal FG-repeat region and a C-terminal coiled-coil region (Fig. 2),
138 which are characteristics of central channel FG-Nups that are tethered by Nup93 (Chug et
139 al., 2015). The secondary structure characteristics of the novel *Tetrahymena* Nup are
140 highly similar to those of Nup62 and Nup58, central channel proteins in yeast and
141 vertebrates that interact with Nup93 (Grandi et al., 1993, 1997). Because another protein
142 was found as an Nup62 ortholog (described below), this protein is the likely *Tetrahymena*
143 ortholog of Nup58; therefore, we named it *TtNup58* (Nup58 in Fig. 1D,E).

144

145 **Newly identified members of the Y-complex are likely homologs of** 146 **conserved Nups**

147 The vertebrate's Y-complex (Fig. 3A) contains 10 distinct proteins (Orjalo et al., 2006;
148 Mishra et al., 2010), of which 3 had identified homologs in *Tetrahymena* (*TtSeh1*,
149 *TtSec13*, *TtNup96*) (Iwamoto et al, 2009). To investigate whether the remaining seven
150 are present in *Tetrahymena* but had been overlooked due to sequence divergence, we
151 carried out mass spectrometric analysis of anti-GFP immunoprecipitates from cells
152 expressing the known Y-complex GFP-tagged Nups described below.

153 First, in precipitates of GFP-*TtSeh1*, we identified an 86 kDa protein orthologous to
154 Nup85 (Table S3) with a short stretch of four predicted β -strand blades at the N-terminus
155 followed by an α -solenoid domain (Fig. 2). That architecture is typical of Nup85
156 orthologs that are Y-complex components in other organisms (Brohawn et al., 2008). We
157 therefore tentatively named the *Tetrahymena* protein *TtNup85*. GFP-*TtNup85* localized
158 to NPCs in both the MAC and MIC (Figs 3B and S3A).

159 We then immunoprecipitated GFP-*TtNup85*, and identified two novel candidate
160 Y-complex core members. Both proteins are composed of a β -strand-rich N-terminal half
161 and an α -helical-rich C-terminal half. This domain architecture is characteristic of the
162 Y-complex components Nup160 and Nup133 (Berke et al., 2004; Devos et al., 2004), and
163 we tentatively named the *Tetrahymena* proteins *TtNup160* and *TtNup133* (Fig. 2 and
164 Table S4). GFP-*TtNup160* and GFP-*TtNup133* localized to NPCs in both nuclei, like
165 other Y-complex components (Figs 3B and S3A).

166 Another conserved Y-complex component is Nup107, which interacts with Nup96.
167 To search for the *Tetrahymena* homolog we used GFP-*TtNup96* as bait and identified a

168 109 kDa protein (Table S5) that is rich in predicted α -helices like human Nup107 (Fig. 2).
169 The protein, tentatively named *TiNup107*, localized as a GFP-tagged construct to NPCs
170 of both nuclei (Figs 3B and S3A).

171 The genes encoding all members of the Y-complex except for Nup96 are
172 co-expressed and exhibit sharp expression peaks at 2 h (C-2) after two cell strains with
173 different mating-types were mixed for conjugation (for details see the “Microarray” page
174 of the TetraFGD: <http://tfgd.ihb.ac.cn/tool/exp> (Miao et al., 2009)) (Fig. 3C). In contrast,
175 *TiNup96* exhibits an expression peak at 4 h (C-4). This difference in the timing of
176 expression between *TiNup96* and the other Y-complex components may be related to a
177 unique aspect of *TiNup96* gene structure: *TiNup96* is expressed as part of a single
178 transcription unit together with *MicNup98B*, under the promoter of the *MicNup98B* gene
179 (Iwamoto et al., 2009).

180 Three other components of the human Y-complex were not detected in our studies:
181 Nup43, Nup37, and ELYS. These components may be species-specific (Bilokapic and
182 Schwartz, 2012; Rothballer and Kutay, 2012), and genuinely absent from *Tetrahymena*.
183 They are also absent from *S. cerevisiae* (Alber et al., 2007) (see Table S1), supporting this
184 idea.

185

186 **Y-complex components show biased localization to the MIC**

187 As previously reported, GFP-tagged Nup93 complex members and some of the central
188 channel Nups (*TiNup93*, *TiNup308*, and *TiNup54*) were distributed equally between
189 MAC and MIC NPCs, judging by fluorescence intensities (Iwamoto et al., 2009). In
190 striking contrast, all Y-complex components so far identified exhibit distinctively biased
191 localization to the MIC nuclear envelope (NE) compared to the MAC NE (Fig. 3B).
192 Fluorescence intensities in the MIC were 2.69–3.96 times higher than those in the MAC
193 (Fig. 3B). This biased localization of Y-complex components may be caused by
194 overexpression of the components due to ectopically expressing the GFP-tagged proteins
195 in addition to the expression of endogenously untagged ones. To address this issue, we
196 examined the localization of Nup160-GFP, Nup133-GFP, and Seh1-mCherry expressed
197 from endogenous loci under the control of their native promoters, and therefore expressed
198 at physiological levels. All three proteins showed biased localization, as found for the
199 overexpressed GFP-tagged proteins (compare the images in Fig. 3B and Fig. S3B),

200 suggesting that the biased localization is not caused by overexpression of the tagged
201 proteins. Because the NPC density is similar in the MAC and MIC (Fig. S1 in Iwamoto et
202 al. (2009)), the relative concentration of Y-complex components in the MIC NE suggests
203 that the Y-complex is present at higher copy number per NPC in the MIC compared to the
204 MAC (Fig. 3D).

205

206 **Newly-detected FG-Nups include nucleus-specific and common** 207 **components**

208 FG-Nups were originally characterized as nucleoporins with domains containing
209 extensive repeats of phenylalanine-glycine (FG) that function in nucleocytoplasmic
210 transport. More recently, we reported a remarkable difference in MAC and MIC NPCs
211 regarding the repeat signature present in four Nup98 paralogs. The repeat signature of
212 MacNup98A and -B is mostly GLFG, while that of MicNup98A and -B is mostly NIFN
213 (Fig. 2) (Iwamoto et al., 2009; 2010; 2015). We have now taken advantage of the recently
214 improved annotation of the *Tetrahymena* Genome Database Wiki
215 (<http://ciliate.org/index.php/home/welcome>), to search for sequences bearing repeats that
216 are similar to those of FG-Nups in other species. We found five candidate FG-Nups.
217 Based on the molecular size and the positions of predicted α -helices, β -strands, and
218 FG-repeat regions, we designated four of these proteins as MicNup214
219 (TTHERM_00992810), MacNup214 (TTHERM_00755929), MicNup153
220 (TTHERM_00647510), and MacNup153 (TTHERM_00379010): GFP-fusions of
221 MicNup214 and MacNup214 were exclusively localized to the MIC and MAC,
222 respectively (Fig. 4A,B). Fluorescent protein (GFP or mNeon)-fusions of MicNup153
223 were mostly localized to the MIC and secondarily to the MAC in most growing cells (Fig.
224 4A), although it was exclusively localized to the MIC in some cells (Fig. S3C).
225 GFP-fusions of MacNup153 were exclusively localized to the MAC (Fig. 4B). The
226 localization of the fifth candidate FG-Nup (*Tt*Nup62: Nup62 in Fig. 4C), like the novel
227 nucleoporin *Tt*Nup58 (Nup58 in Fig. 4C) identified as a central channel protein
228 (discussed above), was less specific.

229 A striking feature of the Nup214 paralogs is that they contain the same
230 nucleus-specific repeat motifs described earlier for *Tt*Nup98 paralogs. Like the
231 MIC-specific Nup98 paralogs, MicNup214 contains NIFN repeats (the last N is mostly Q

232 in this protein), while MacNup214 contains FG repeats (Fig. 2). This difference may be
233 an important determinant for selective protein transport to the MAC and MIC, as
234 previously shown for *TtNup98s* (Iwamoto et al., 2009). We note that MacNup214 lacks a
235 β -strand-rich N-terminal region that is found in other Nup214 orthologs (Weirich et al.,
236 2004; Napetschnig et al., 2007) (Fig. 2).

237 In contrast, MicNup153 and MacNup153 do not differ markedly from one another in
238 their molecular features (Fig. 2). Because the N-terminus domain of human Nup153 is
239 involved in its NPC localization (Enarson et al., 1998), we speculate that the N-terminal
240 domains of MicNup153 and MacNup153 may also be involved in their nucleus-specific
241 localization in *Tetrahymena*. Further study is required to elucidate their nucleus-specific
242 localization.

243 While the expression of this set of FG-Nups is upregulated during conjugation (Fig.
244 4D), the MIC-specific components tend to be expressed 2 h earlier than MAC-specific
245 ones. For example, MicNup214 expression peaks at 2 h in conjugation (C-2) vs.
246 MacNup214 at C-4; similarly, MicNup153 peaks at C-6 vs. MacNup153 at C-8 (Fig. 4D).
247 The earlier expression of MIC-specific components compared with MAC-specific ones
248 may reflect a selective requirement for MIC-specific NPCs during early stages of
249 conjugation, such as the crescent stage (Sugai and Hiwatashi, 1974). In contrast, the later
250 expression of MAC-specific components probably reflects formation of the new MACs
251 that occurs in the later stages of conjugation.

252 The fifth candidate FG-Nup identified by this screen was a 39 kDa protein
253 (TTHERM_01122680). This protein is composed of an N-terminal FG-repeat region and
254 a C-terminal coiled-coil region with the characteristics of central channel FG-Nups and is
255 assigned as a Nucleoporin NSP1/NUP62 family protein (IPR026010) (Fig. 2).
256 Consequently, this protein is the likely *Tetrahymena* ortholog of Nup62; therefore, we
257 named it *TtNup62*. The GFP-tagged protein was distributed to both nuclei (Nup62 in Fig.
258 4C), similarly to the central channel Nups *TtNup58* (Figs 1E and 4C) and *TtNup54*
259 (Iwamoto et al., 2009), although *TtNup62* was slightly enriched in the MAC NE, whereas
260 *TtNup58* was slightly enriched in the MIC NE. The expression profile of *TtNup62* was
261 similar to that of *TtNup58*, with an expression peak after 4 h of conjugation (C-4) (Fig.
262 4D).

263 *Ti*Nup62 has relatively few repeats in its FG motif compared with homologs such as
264 human Nup62 and *S. cerevisiae* Nsp1 (Fig. 2), although it has several FX repeats (X=N,
265 Q, A or T in the case of this protein). A feature unique to *Tetrahymena* is the presence of
266 GLFG repeats in Nup308, an ortholog of Nup205. The Nup93 complex containing
267 Nup205 anchors Nup62 (Vollmer and Antonin, 2014), and it is likely that the
268 *Tetrahymena* Nup93 complex containing Nup308 anchors *Ti*Nup62. Thus, we
269 hypothesize that the GLFG repeats present in Nup308 compensate for the low number of
270 FG repeats of *Ti*Nup62 presents in the central channel.

271

272 **Nup88, Nup185, and Tpr**

273 We used a variety of strategies to identify additional Nups. Homology searches against
274 InterPro (<http://www.ebi.ac.uk/interpro/>) revealed a gene (TTHERM_00455610) with a
275 conserved Nup88 domain “*Ti*Nup88 (PTHR13257:SF0)” (Fig. 2) and an expression
276 profile similar to those of some other *Tetrahymena* Nups (Fig. 5A). Localization of a
277 GFP-fusion to NPCs was highly biased, albeit not exclusive, to the MAC (Fig. 5C). We
278 therefore named this protein *Ti*Nup88, which is known to localize to the cytoplasmic side
279 of the NPC in other species (Fig. 5B). As Nup88 in other species is known to interact with
280 Nup214 and Nup98 (Fornerod et al., 1997), *Ti*Nup88 may contribute to the
281 nucleus-specific localization of Nup214 and Nup98 paralogs.

282 TTHERM_00755920 (encoding a 185 kDa protein), which lies adjacent to the open
283 reading frame (ORF) of MacNup214, attracted our interest because its predicted
284 molecular structure resembled those of large scaffold Nups such as Nup160, Nup155, and
285 Nup133, and because its expression profile is similar to those of some other *Tetrahymena*
286 Nups (Fig. 5A). A GFP-fusion localized to NPCs, with a bias to the MAC (Fig. 5D).
287 Based on its predicted molecular weight, we named this protein Nup185. Nup185
288 contains a conserved domain ‘Nucleoporin (SSF117289)’ (Fig. 2), which is generally
289 found near the N-terminal regions of Nup155 and Nup133 homologs. The expression
290 peak of Nup185 appeared at C-6 (Fig. 5A).

291 To assess the location of Nup185 within the NPC architecture, we identified
292 interacting proteins by immunoprecipitating GFP–Nup185. One interacting protein was
293 TTHERM_00268040, which bears predicted coiled-coil motifs throughout its entire
294 sequence (Fig. 2) and is thus similar to the nuclear basket component, Tpr (Fig. 5B).

295 THERM_00268040 fused with GFP localized equivalently to MAC and MIC NPCs
296 (Fig. 5E). This protein is a likely ortholog of human Tpr; therefore, we named it *TtTpr*.
297 Nup185 did not interact with any members of the Y- or Nup93 complexes (Table S6).

298

299 **The transmembrane Nups Pom121 and Pom82 show nucleus-specific** 300 **localization**

301 Some but not all of the transmembrane (TM) Nups are conserved between vertebrates and
302 yeasts: the former have POM121, gp210, and NDC1 (Cronshaw et al, 2002; Stavru et al,
303 2006), while the latter have Pom34, Pom152, and Ndc1 (Rout et al, 2000; Asakawa et al,
304 2014). The only reported TM Nup in *T. thermophila* is gp210 (Iwamoto et al., 2009).
305 Because all *Tetrahymena* Nups identified so far have a similar expression pattern, in
306 which a large expression peak appears during early conjugation stage (Figs 3C, 4C and
307 5A), we used expression profiling and TM domain search to identify possible TM Nups
308 in the updated TetraFGD and the TMHMM Server
309 (<http://www.cbs.dtu.dk/services/TMHMM-2.0/>), respectively. Using this approach, we
310 found two candidate TM Nups. Each has one TM domain and an FG-repeat region
311 (“*TtPom121*” and “*TtPom82*” in Fig. 6A). Their expression profiles are shown in Fig. 6B.

312 One of the TM Nup candidates (THERM_00312730; *TtPom121*) has an
313 N-terminal TM domain and C-terminal FG repeats (Fig. 6A, middle) with a deduced
314 molecular weight of 129 kDa. These attributes are very similar to those of vertebrate
315 POM121 (compare top and middle parts of Fig. 6A) (Rothballer and Kutay, 2012).
316 *TtPom121* fused with GFP at its C-terminus (*TtPom121*–GFP) localized specifically to
317 MAC NPCs (Fig. 6C, upper). Consequently, this protein is the likely *Tetrahymena*
318 ortholog to human POM121; therefore, we named it *TtPom121*.

319 Notably, when GFP was fused with the N-terminus of *TtPom121* at a region close to
320 the TM domain (GFP–*TtPom121*), the tagged protein localized in the MAC nucleoplasm,
321 but not in MAC NPCs or the MIC nucleoplasm (Fig. 6C, lower). This result suggests that
322 *TtPom121* bears a MAC-specific nuclear localization signal (NLS) in its N-terminal
323 region. Similarly, POM121 homologs in vertebrates have NLS sequences in the
324 N-terminal region (Yavuz et al., 2010; Funakoshi et al., 2011).

325 In contrast, the other TM Nup candidate (THERM_00375160; *TtPom82*) localized
326 exclusively to MIC NPCs (Fig. 6D, upper). This protein has predicted molecular features

327 that have not been reported in Nups from any other organism: a TM domain near the
328 C-terminus, central coiled-coil, and N-terminal FG repeats (Fig. 6A, bottom). We named
329 this protein *TiPom82* according to its predicted molecular weight (82 kDa). A construct
330 lacking the TM domain showed diffuse cytoplasmic localization (Fig. 6D, lower),
331 suggesting that MIC NPC-specific localization of *TiPom82* does not depend on the
332 MIC-specific nuclear transport of *TiPom82*. This result suggests that *TiPom121* and
333 *TiPom82* use different mechanisms to target to the MAC and MIC NPCs.

334 Next, we performed immuno-electron microscopy (iEM) for the Pom proteins using
335 anti-GFP antibody in order to know their sub-NPC localization. Intriguingly, their
336 sub-NPC localizations were opposite; Pom121 was exclusively localized to the nuclear
337 side of the MAC NPC (Fig. 6E), whereas Pom82 was exclusively localized to the
338 cytoplasmic side of the MIC NPC (Fig. 6F).

339 Given the difference in molecular features, their behaviors when the TM domain
340 function was disrupted, and their sub-NPC localizations, Pom121 and Pom82 are
341 unlikely to be functional homologs of each other. Taken together, these findings lead to
342 the conclusion that MAC and MIC NPCs contain distinct TM components (Fig. 6G,H).
343 The protein components of MAC and MIC NPCs are summarized in Fig. 7.

344 One TM Nup, found in both fungi and animals but missing from our *Tetrahymena*
345 catalog, is Ndc1. We identified a potential Ndc1 homolog in THERM_00572170, a
346 protein with six predicted TM domains that is co-transcribed with other Nups (see
347 http://tfgd.ihb.ac.cn/search/detail/gene/THERM_00572170). However, neither N- nor
348 C-terminal GFP fusions of this protein localized to NPCs (Fig. S3D). Therefore,
349 *Tetrahymena* NPCs may lack Ndc1. Similarly, Ndc1 has not been detected in
350 *Trypanosoma* NPCs (Obado et al., 2016).

351

352 **The permeability of the nuclear pore differs between MAC and MIC**

353 To better understand the functional consequences of structural differences between MAC
354 and MIC NPCs, we examined the relative pore exclusion sizes by asking whether probes
355 of different sizes could gain access to each nucleoplasm. GFP (approx. 28 kDa) was
356 excluded only from MICs, whereas GFP-GST (more than 100 kDa due to its
357 oligomerization) was excluded from both MACs and MICs (Fig. S4A). In addition,
358 FITC-dextran of 40 kDa could enter MACs, whereas 70-kDa FITC-dextran was

359 completely excluded (Fig. S4B). These results indicate that MAC pores exclude
360 molecules greater than approximately 50 kDa, which is similar to the permeability size
361 limit of nuclear pores in other species (Paine et al., 1975; Gorlich and Mattaj, 1996;
362 Keminer and Peters, 1999). On the other hand, MIC pores impose a much smaller
363 exclusion size, and exclude molecules of even 10–20 kDa (Fig. S4B). This difference in
364 exclusion size may be due to differences between the protein composition and structural
365 arrangement of NPCs of these dimorphic nuclei.

366 **DISCUSSION**

367 We have now identified 28 nucleoporins in the ciliate *T. thermophila*: 15 Nups reported
368 here, and 13 in our previous study (Iwamoto et al., 2009). This total comprises 24
369 different Nups for the MAC and MIC: this number includes 18 Nups commonly localized
370 in both nuclei, 4 Nups with nucleus-specific homologues (Nup214, Nup153, Nup98A,
371 and Nup98B), and *TtPom82* and *TtPom121*. This total is somewhat smaller than the
372 roughly 30 Nups known in other eukaryotes, e.g. 34 in human and in *Drosophila*
373 *melanogaster*, 27 in *Caenorhabditis elegans*, 33 in *S. pombe*, and 35 in *S. cerevisiae*
374 (Rothballer and Kutay, 2012; Asakawa et al., 2014). The deficit in *T. thermophila* Nups is
375 due to the absence of homologs for Nup358, GLE1, hCG1/Nup42, Nup43, Nup37,
376 Centrin-2, Nup53, TMEM33, ELYS, and Aladin. Similarly, the protist *Trypanosoma*
377 *brucei* is missing Nup358, GLE1, hCG1/Nup42, Nup37, Centrin-2, TMEM33, and ELYS,
378 and 25 Nups in total have been identified by interactome analysis (DeGrasse et al, 2009;
379 Obado et al., 2016). One conserved Nup identified in *Trypanosoma* but not *Tetrahymena*
380 is Nup53 (*TbNup65* (XP_822630.1)) (Obado et al., 2016). This raises the question of
381 whether a *T. thermophila* Nup53 homolog eluded our search due to sequence or structural
382 divergence. Alternatively, *T. thermophila* may have lost a Nup that is not essential for
383 viability.

384

385 **A role of nucleus-specific Nups**

386 We previously reported that the GLFG-repeat and NIFN-repeat domains in MacNup98s
387 and MicNup98s, respectively, are involved in the nucleus-specific transport of linker
388 histones (histone H1 and MLH, respectively), arguing that these nucleus-specific Nups
389 are determinants of nucleus-specific transport (Iwamoto et al., 2009). Importantly, we
390 can now expand this argument, since our expanded catalog shows that all NPC subunits
391 that are nucleus-specific are FG-Nups: Nup214, Nup153, Nup98 and Pom-s. Since the
392 FG-repeats interact with nuclear transport receptors such as importin- β family proteins
393 (Allen et al., 2001; Isgro and Schulten, 2005; Liu and Stewart, 2005; Tetenbaum-Novatt
394 et al., 2012), specificity for the MAC or MIC is likely to be determined in cooperation
395 with importin- β s. This idea is also supported by the presence of nucleus-specific importin
396 family proteins (Malone et al., 2008).

397 It is interesting to note that both MAC- and MIC-specific Nups contain atypical
398 repeat motifs: NIFN, but also more subtle variations on the FG-repeat: FN, FQ, FA, FS
399 and so on (Fig. 2). Because the NIFN-repeat domain of MicNup98A is known to function
400 in blocking misdirected nuclear transport of MAC-specific linker histones (Iwamoto et al.,
401 2009), the atypical FG-repeats may similarly be involved in controlling nucleus-specific
402 transport of particular proteins. However, importin- β s that preferentially interact with the
403 NIFN-repeat and their cargos have not been found, and thus the complete role of the
404 NIFN-repeat motif in nucleus-specific transport remains to be elucidated.

405

406 **A role of biased Nups to build different NPC structures**

407 The nucleus-specific Nups generate obvious structural differences between MAC and
408 MIC NPCs. However, these different components have to be integrated into two NPC
409 scaffold structures that are constructed of the same components. One way to make
410 different structures from the same components may be to incorporate different amounts
411 of these components, leading to different structures that allow biased
412 localization/assembly of nucleus-specific components. The localization of the
413 Y-complex (Fig. 3B) and Nup88 (Fig. 5C) was highly biased to either MICs or MACs,
414 respectively. Thus, these biased components may be critical for directing assembly of
415 MAC- or MIC-type NPCs. Consistent with this idea, Nup98 homologs in vertebrates
416 interact with the Y-complex components Nup96 (Hodel et al., 2002) and Nup88 (Griffis
417 et al., 2003). This model raises the question of how structurally similar paralogs in
418 *Tetrahymena* can differentially recruit nucleus-specific FG-Nups.

419 The copy number of the Y-complex within individual NPCs differs between the
420 MAC and MIC (Fig. 3B,D), indicating that at least two NPC structures with different
421 Y-complex stoichiometries can form in ciliates. This quantitative difference in
422 Y-complex incorporation may be directed by membrane Nups. The nucleus-specific TM
423 Nups, Pom121 and Pom82, are currently strong candidates for initiating NPC assembly
424 on the nuclear membrane. In vertebrates, Pom121 binds the Y-complex through a
425 Nup160 homolog (Mitchell et al., 2010). In *Tetrahymena*, *TrPom121* and *TrPom82* may
426 differentially affect Y-complex integration into MAC or MIC NPCs. This model can be
427 extended to biased integration of Nup98 paralogs, since Pom121 has been shown to
428 directly bind Nup98 (Mitchell et al., 2010), supporting our idea that biased Nups and

429 nucleus-specific Nup98 paralogs cooperate to build two distinct NPCs. In this model, the
430 acquisition of specialized Pom proteins might have been one of the most crucial
431 evolutionary events for generating nuclear dimorphism in ciliates. Taken overall, our
432 study contributes to understanding the diversity of NPC architectures in eukaryotes,
433 including potential functional and evolutionary aspects.

434 MATERIALS AND METHODS

435 *In silico* genomic database analysis and secondary structure prediction

436 We searched for candidates Nups using protein BLAST on the NCBI website and
437 *Tetrahymena* Genome Database Wiki (<http://ciliate.org/index.php/home/welcome>)
438 (Eisen et al., 2006; Stover et al., 2012). Expression profiles based on microarray data
439 (<http://tfgd.ihb.ac.cn/tool/exp>) were obtained from the TetraFGD (<http://tfgd.ihb.ac.cn/>)
440 (Miao et al., 2009). We identified the candidate proteins as Nups when the expression
441 profile satisfied two conditions: First, the amount of expression is lower in vegetative
442 stages than in conjugation stages. Second, expression peaks appear in between C-2 and
443 C-8 stages of conjugation. Secondary structures and transmembrane domains were
444 predicted by PSIPRED (<http://bioinf.cs.ucl.ac.uk/psipred/>) and the TMHMM Server
445 (<http://www.cbs.dtu.dk/services/TMHMM-2.0/>), respectively. Coiled-coil regions were
446 predicted by PBIL Coiled-Coils prediction
447 (https://npsa-prabi.ibcp.fr/cgi-bin/npsa_automat.pl?page=npsa_lupas.html) or SIB
448 COILS (http://embnet.vital-it.ch/software/COILS_form.html). Conserved domains were
449 searched for using InterPro (<http://www.ebi.ac.uk/interpro/>).

450

451 DNA construction

452 cDNAs were amplified by PrimeSTAR reagent (Takara, Kyoto, Japan) from the reverse
453 transcripts prepared from the total RNA fraction of vegetative or conjugating cells as
454 described previously (Iwamoto et al., 2009). The cDNAs were digested with *Xho*I and
455 *Apa*I, and cloned into the pIGF1 vector to ectopically express them as N-terminal
456 GFP-tagged proteins (Malone et al., 2005). The pIGF1C vector with the multi-cloning
457 site at the 5' site of the GFP-coding sequence was generated by modifying the pIGF1
458 vector, and used to ectopically express GFP-tagged Nup58 and Pom121 as C-terminal
459 GFP-tagged proteins: the cDNAs of these Nups were cloned into the pIGF1C vector
460 using the *Xho*I and *Kpn*I sites. To endogenously express Nups tagged with a fluorescent
461 protein at the C-termini of the macronuclear ORFs, MicNup214, Nup160, and Nup133
462 were tagged with GFP using a pEGFP-neo4 vector (Mochizuki, 2008) (a kind gift from
463 Dr. K. Mochizuki, IMBA), MicNup153 was tagged with mNeon using a
464 p2xmNeon_6xmyc_Neo4 vector (a kind gift from Dr. Turkewitz, Univ. of Chicago), and

465 Seh1 was tagged with mCherry using a pmCherry-pur4 vector (Iwamoto et al., 2014).

466 Primers used in this study are listed in Table S7.

467

468 **Expression of GFP–Nups in *Tetrahymena* cells**

469 Conjugating cells were subjected to transfection by electroporation using a Gene Pulser II

470 (Bio-Rad, Hercules, CA) as described previously (Iwamoto et al., 2014; 2015). The

471 resulting cell suspension was cultivated for 18 h and then treated with selection drugs,

472 paromomycin sulfate (Sigma-Aldrich, St. Louis, MO) at 120 µg/ml when using pIGF1,

473 pIGF1C, pEGFP-neo4, and p2xmNeon_6xmyc_Neo4 vectors, or puromycin

474 dihydrochloride (Fermentek, Jerusalem, Israel) at 200 µg/ml when using a

475 pmCherry-pur4 vector. Cadmium chloride was also added at 0.5 µg/ml to induce the

476 expression of drug resistant genes for pEGFP-neo4, p2xmNeon_6xmyc_Neo4, and

477 pmCherry-pur4 vectors. Resistant cells usually appeared within a few days after the drug

478 was added. We checked that at least 5 independent clones (*i.e.*, grown in 5 different wells)

479 exhibited the same intracellular localization of each GFP–Nup.

480

481 **Immunoprecipitation**

482 For immunoprecipitation, GFP–Nup-expressing cells in logarithmic growth were
483 pretreated with 0.5 mM PMSF for 30 min at 30°C and then collected by centrifugation.

484 The cells were resuspended at 2.5×10^6 cells/ml in homogenization buffer composed of

485 150 mM NaCl, 1% Triton X-100, 2 mM PMSF, and Complete Protease Inhibitor Cocktail

486 (Roche Diagnostics, Mannheim, Germany), and then homogenized with sonication on ice.

487 The supernatant obtained after centrifugation at 10,000×g for 15 min was pretreated with

488 Protein A Sepharose to absorb non-specifically bound proteins. After removal of the

489 beads by low-speed centrifugation, the supernatant was incubated with 50 µg anti-GFP

490 rabbit polyclonal antibody (#600-401-215, Rockland Immunochemicals, Limerick, PA)

491 for 2 h at 4°C. To collect immunoprecipitated target proteins of interest, fresh Protein A

492 Sepharose was added, incubated for another 2 h at 4°C, and then collected by

493 centrifugation. After brief washing with homogenization buffer, the Sepharose beads

494 were incubated with NuPAGE sample buffer (Thermo Fisher Scientific, Waltham, MA)

495 to elute bound proteins. The proteins were separated by SDS-PAGE.

496

497 **Mass-spectrometry analysis**

498 The gel sample lane was cut into several pieces, and each treated with trypsin. The
499 trypsinized peptide sample was subjected to liquid chromatography/tandem mass
500 spectrometry (LC/MS/MS) using the LXQ linear ion trap (Thermo Finnigan, San Jose,
501 CA) equipped with a Magic2002 and nanospray electrospray ionization device (Michrom
502 BioResources, Auburn, CA and AMR, Tokyo, Japan), as described previously (Obuse et
503 al., 2004). The LC-MS/MS data were searched by Mascot (Matrix Science, London, UK)
504 with a non-redundant *T. thermophila* specific database (25,131 sequences) constructed
505 from the nr NCBI database. The resulting files were loaded into Scaffold software
506 (Proteome Software, Portland, OR) for comparing identified proteins between samples.

507

508 **Microscopic observation**

509 Intracellular localizations of GFP-tagged Nups were observed by fluorescence
510 microscopy (IX-70; Olympus, Tokyo, Japan). Images were taken using the DeltaVision
511 microscope system (GE Healthcare, Issaquah, WA) with oil-immersion objective lens
512 UApo40 (NA=1.35) (Olympus). Line profiles of fluorescence intensity were obtained
513 using a measurement tool included in the DeltaVision system. Background fluorescence
514 measured cytoplasm as an averaged value of 5×5 pixels was subtracted from the peak
515 values of fluorescence on the NE.

516

517 **Indirect Immunofluorescence staining**

518 *Tetrahymena* cells expressing GFP-tagged Nups were first fixed with cold methanol for
519 20 min, and then additionally fixed with 4% formaldehyde in PBS for 20 min. After
520 treated with 1% bovine serum albumin (BSA), cells were treated with 5 µg/ml anti-GLFG
521 monoclonal antibody 21A10 for 2-3 hrs (Iwamoto et al., 2013). After washing with PBS,
522 cells were treated with Alexa Fluor 594-conjugated goat anti-mouse IgG at 1/1000
523 dilution for 1 h (Thermo Fisher Scientific). Images of forty z-sections with a 0.2-µm
524 interval were taken for cells using the DeltaVision microscope system with
525 oil-immersion objective lens PlanApoN60OSC (NA=1.4) (Olympus), and were
526 processed by deconvolution using SoftWoRx software equipped with the microscope.

527

528 **Immuno-electron microscopy**

529 *Tetrahymena* cells expressing GFP-tagged Nups were fixed with 4% formaldehyde for 30
530 min. After washing 3 times with PBS, they were permeabilized with 0.1% saponin for 15
531 min at room temperature. After treatment with 1% BSA, cells were incubated with
532 anti-GFP polyclonal antibody (Rockland Immunochemicals) at 1/200 dilution for 2 hrs,
533 washed three times with PBS, then incubated with FluoroNanogold-anti rabbit Fab'
534 Alexa Fluor 594 (Nanoprobes, Yaphank, NY) at 1/400 dilution for 1 h. The
535 immunolabelled cells were fixed with 2.5% (w/v) glutaraldehyde (Nacalai tesque, Kyoto,
536 Japan) for 1 h. After washing with 50 mM HEPES (pH 5.8) they were incubated with
537 silver enhancement reagent (Tange et al., 2016) for 7 min. The reaction was stopped by
538 washing three times with distilled water. Then the cells were post-fixed with 1% OsO₄ for
539 15 min, electron stained with 2% uranyl acetate for 1 h, dehydrated with sequentially
540 increased concentrations of ethanol, and embedded in epoxy resin (Epon812). The
541 ultrathin sections sliced from the resin block were stained with 4% uranyl acetate for 15
542 min and lead citrate (Sigma-Aldrich) for 1 min, and observed by a transmission electron
543 microscope JEM-1400 (JEOL, Tokyo, Japan) with an acceleration voltage of 80 kV.

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551

552 **Competing interests**

553 No competing interests declared.

554

555 **Author contributions**

556 MI, HO, CM, YF, and KN performed the experiments. MI, KN, CO, YH and TH
557 designed the experiments. All authors examined and discussed the data, and MI, CO, YH,
558 and TH wrote the manuscript.

559

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773 **Figure legends**

774 **Fig. 1. Immunoprecipitation and mass spectrometry analysis to identify Nup93**
775 **complex members.** (A) A *T. thermophila* cell fixed with methanol and stained with
776 DAPI. Bar, 20 μ m. (B) The position of the Nup93 complex within the NPC architecture.
777 See also Fig. S1. (C) Simplified procedure of immunoprecipitation and mass
778 spectrometry for GFP-*Tt*Nup93-expressing cells used for immunoprecipitation. (D)
779 Mass spectrometric identification of the proteins co-precipitated with GFP-*Tt*Nup93.
780 The top seven proteins are listed among other identified proteins (Table S2). (E) Physical
781 interaction map of Nup93 based on the mass spectrometry results.

782

783 **Fig. 2. Distributions of secondary structures and conserved domains in *Tetrahymena***
784 **nucleoporins.** Each Nup is shown as the protein name on the left. Blue, red, and black
785 letters mean MIC-specific, MAC-specific, and shared components, respectively.
786 Asterisks on the left shoulder of the protein names indicate Nups newly identified in this
787 study. The colored components in the illustration are as follows: orange boxes/bars,
788 α -helix; green boxes/bars, β -strand; red slanting lines, FG repeats; blue slanting lines, FX
789 repeats (X means any residue, but the majority are N and Q); and purple ellipse, predicted
790 TM domain. Conserved domains are indicated by differently colored bars with standard
791 domain names.

792

793 **Fig. 3. Y-complex components localize to both nuclei but are biased to MICs.** (A)
794 The position of the Y-complex within the NPC architecture. (B) Fluorescent micrographs
795 of GFP-Nups ectopically expressed in *Tetrahymena* cells. White broken lines represent
796 the borders of cells. The inset in each panel shows a deconvoluted image focused on the
797 MAC surface. Arrows indicate the position of the MIC. Bars, 20 μ m. A line profile of
798 fluorescence intensity along the thin green broken line is presented under each image
799 panel. Blue and red arrowheads indicate the points corresponding to MIC and MAC
800 envelopes, respectively. An asterisk marks the point at which the borders of the two
801 nuclei overlap, and where the intensity is measured as the sum of both NEs. Below the
802 line profile, the fluorescence intensities of MAC and MIC NEs from 50 cells are plotted.
803 The vertical axis of the graph is shown in arbitrary units. Broken lines connect the plots of
804 MAC and MIC within the same cell. Average values are presented by red and blue bars

805 for MAC and MIC, respectively. The numbers upon the MIC plots indicate fold increase
806 of fluorescence in MIC from MAC. All differences are significant ($P < 10^{-20}$ by Student's
807 *t*-test). (C) Expression profiles of the Y-complex members extracted from the TetraFGD
808 (<http://tfgd.ihb.ac.cn/>). Plots are the average of two values presented in the database. The
809 horizontal axis represents successive stages of culture growth and therefore different
810 physiological conditions. For the logarithmic growth stage, L-l, L-m, and L-h represent
811 low, medium, and high cell concentrations, respectively. For starvation and conjugation
812 stages, numbers represent hours after the transfer of the cells to each condition. The
813 vertical axis represents relative values of mRNA expression. For details, visit the
814 database website. (D) A simple representation of the deduced composition of MAC and
815 MIC NPCs with different numbers of Y-complexes.

816

817 **Fig. 4. Newly identified FG-Nups of *Tetrahymena*.** (A) MIC-specific paralogs of
818 Nup214 and Nup153. The upper figure indicates the predicted positions of these Nups
819 within the MIC NPC. Fluorescence micrographs show the subcellular localization of
820 fluorescent protein-tagged Nups; MicNup214 and MicNup153 were endogenously
821 tagged with GFP and mNeon at the C-termini of their ORFs, respectively. Arrows
822 indicate the position of the MIC. Other fluorescent bodies dispersed in the cytoplasm are
823 phagosomes taking in materials derived from the culture medium. (B) MAC-specific
824 paralogs of Nup214 and Nup153. The upper figure indicates the predicted positions of
825 these Nups within the MAC NPC. Fluorescence micrographs show the subcellular
826 localizations of ectopically expressed GFP-Nups. The left panels show a whole cell, and
827 each nuclear region is enlarged in the right panels. White broken lines represent the
828 borders of cells. Insets in the left panels show deconvoluted images focused on the MAC
829 surface. Arrows indicate the position of MICs. Bars indicate 20 μm for the left panels and
830 5 μm for the right panels. (C) *Tt*Nup62 and *Tt*Nup58 localized in both nuclei. The upper
831 illustration indicates the predicted position of these Nups, which constitute the Nup62
832 complex. Fluorescent micrographs show the subcellular localizations of ectopically
833 expressed GFP-*Tt*Nup62 and *Tt*Nup58-GFP. Bars, 20 μm . Line profiles and plots of
834 fluorescence intensity are shown under each image panel in the same manner as in Fig.
835 3B. Both differences are significant ($P < 10^{-16}$ by Student's *t*-test). (D) Expression

836 profiles of FG-Nups, as in Fig. 3C.

837

838 **Fig. 5. Nuclear localization and expression profiles of Nup88, Nup185, and Tpr.** (A)
839 Expression profiles. (B) The predicted positions of *Tt*Nup88 and *Tt*Tpr. The position of
840 Nup185 is unknown. (C) The subcellular localization of ectopically expressed
841 GFP-*Tt*Nup88. The left panel shows a whole cell, and its nuclear region is enlarged in the
842 right panel. White broken lines represent the borders of cells. Inset in the left panel shows
843 the deconvoluted image focused on the MAC surface. Arrows indicate the position of the
844 MICs. Bars indicate 20 μm for the left panel and 5 μm for the right panel. A line profile
845 and plots of fluorescence intensity are shown under each image panel, as in Fig. 3B. The
846 fluorescence intensity of the MIC NE is significantly lower than that of the MAC NE ($P <$
847 10^{-39}). (D) Subcellular localization of ectopically expressed GFP-Nup185. The
848 fluorescence intensity of the MIC NE is significantly lower than that of the MAC NE ($P <$
849 10^{-30}). (E) Subcellular localization of ectopically expressed GFP-*Tt*Tpr. The
850 fluorescence intensity of the MIC NE is slightly lower than that of the MAC NE ($P =$
851 0.0024, by Student's *t*-test).

852

853 **Fig. 6. Two novel pore membrane proteins show nuclear specificity.** (A) Illustration
854 of molecular profiles. The frequency and positions of FG repeats are compared between *T.*
855 *thermophila* Pom proteins and human POM121C (accession: A8CG34). Red and blue
856 slanting lines represent FG and FX (X means any amino acid residue, but the majority are
857 N, Q, and S), respectively. Orange and green boxes represent α -helices and β -strands,
858 respectively. Purple ellipses represent predicted TM domains. (B) The expression profiles
859 of nucleus-specific Pom-s and shared *Tt*gp210, as in Fig. 3C. (C) Fluorescence
860 micrographs show ectopically expressed GFP-tagged *Tt*Pom121. Left panels show whole
861 cells, and the right panels show enlarged images of the nuclear regions. White broken
862 lines represent the borders of cells. Arrows indicate the position of MICs. Bars indicate
863 20 μm for the left panels and 5 μm for the right panels. (D) Fluorescence micrographs
864 show GFP-tagged Pom82 (full length, 1–699 aa) and GFP-Pom82 Δ TM (transmembrane
865 domain-deletion mutant, 1–678 aa) both ectopically expressed. Arrows indicate the
866 position of the MICs. Other fluorescent bodies dispersed in the cytoplasm are

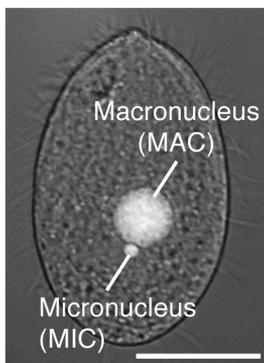
867 phagosomes taking in materials derived from the culture medium. (E, F) iEM for
868 Pom121-GFP localizing to the MAC NPC (E) and GFP-Pom82 localizing to the MIC
869 NPC (F) using anti-GFP antibody. (a) Immuno-electron micrographs for a single NPC.
870 Dark dots represent signals of gold particles. Bars, 100 nm. (b) Images present a
871 projection image of 20 immuno-electron micrographs of NPCs decorated with gold
872 particles. (c) The positions of individual gold particles in (b) are plotted. Broken lines
873 trace nuclear envelope, and upper and lower sides are cytoplasm and nucleoplasm,
874 respectively. (G) The position of *Tt*Pom121 within the MAC NPC architecture. (H) The
875 position of *Tt*Pom82 within the MIC NPC architecture.

876

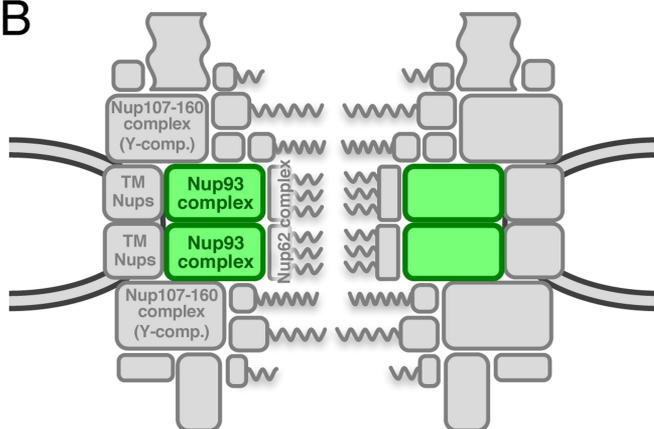
877 **Fig. 7. Schematic models of MAC and MIC NPCs.** (A) Deduced composition of the
878 MAC NPC. (B) Deduced composition of the MIC NPC. Boxes colored in red and blue
879 represent MAC-specific and MIC-specific components, respectively: Pom121 (P121),
880 Pom82 (P82), Nup98 paralogs (98), Nup214 (214), and Nup153 (153). Green boxes
881 represent shared components including the nuclear basket structure Tpr and its associated
882 Nup50 (50). *Tt*Nup50 is distributed mostly in the nucleoplasm in MACs, whereas it
883 localizes to the NPC in MICs (Malone et al., 2008; Iwamoto et al., 2009). Yellow boxes
884 are MIC-biased Y-complexes, and purple boxes are MAC-biased *Tt*Nup88 (88). The
885 number of duplications of yellow and purple boxes does not reflect the actual quantity of
886 those components *in vivo*. Homologs of Nup358 (358), hCG1 (CG), ALADIN (AL), and
887 ELYS constituting the cytoplasmic structure, were not found in *T. thermophila*.

888

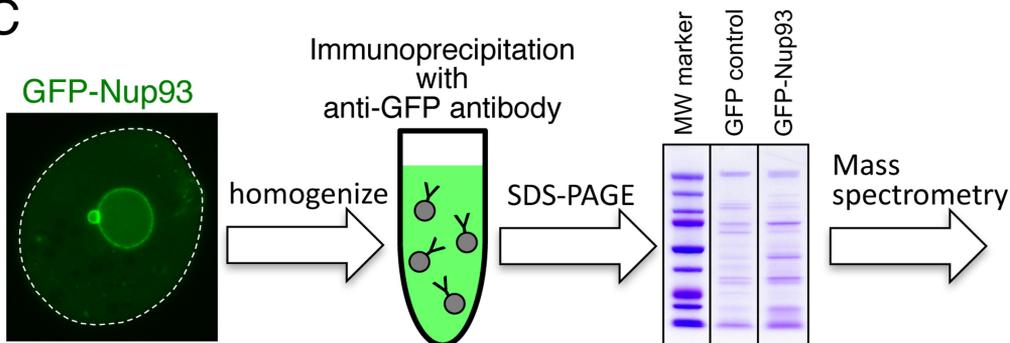
A



B



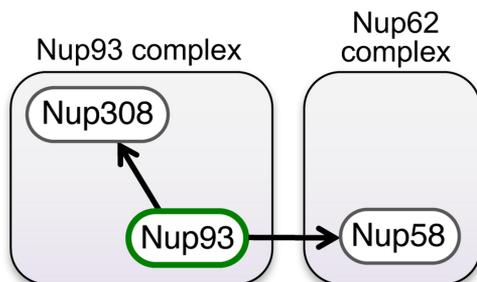
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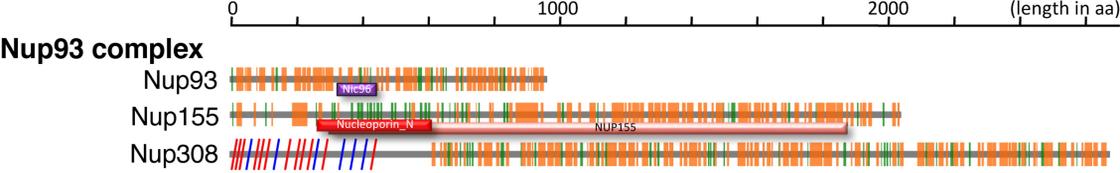


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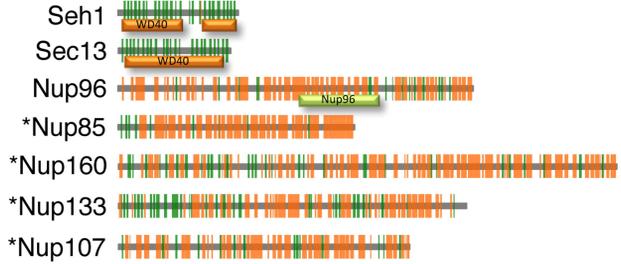
#	Identified Proteins	Gene ID	Predicted MW	Number of assigned spectra	
				GFP control	GFP-Nup93
1	Nup308	TTHERM_00091620	308 kDa	0	54
2	Nup93	TTHERM_00622800	113 kDa	0	14
3	α -tubulin, ATU1	TTHERM_00558620	50 kDa	0	8
4	Nup58	TTHERM_00194800	45 kDa	0	8
5	Translation elongation factor EF-1, subunit α	TTHERM_00655820	48 kDa	0	4
6	Granule lattice, GRL2	TTHERM_00473020	48 kDa	0	4
7	ATP synthase β chain, mitochondrial precursor	TTHERM_00585260	53 kDa	0	4

E

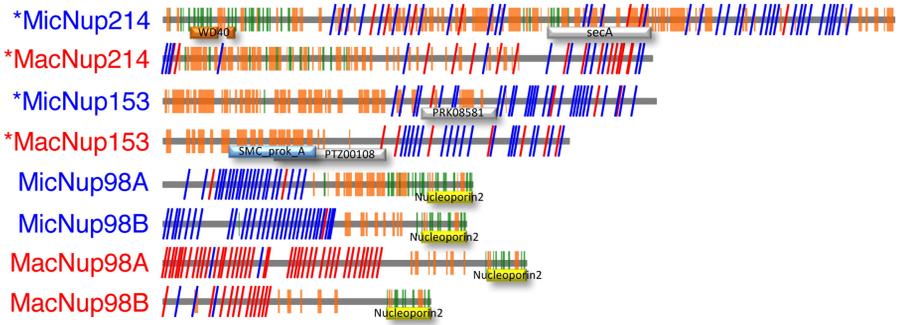




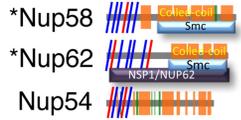
Nup107-160 complex (Y-complex)



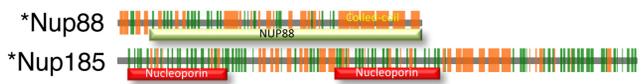
Nucleus-specific FG Nups



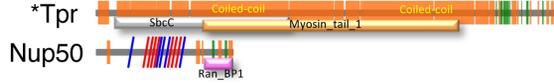
Central channel FG-Nups (Nup62 complex)



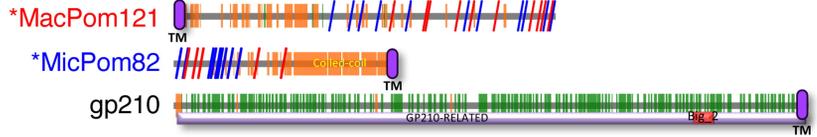
Miscellaneous Nups

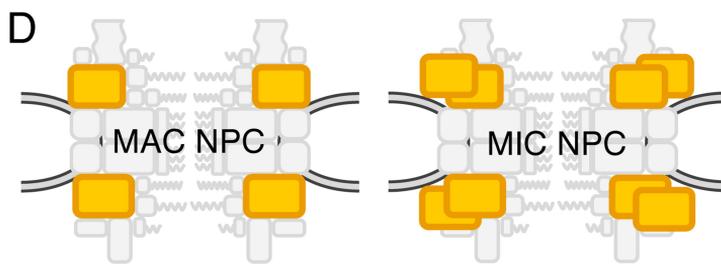
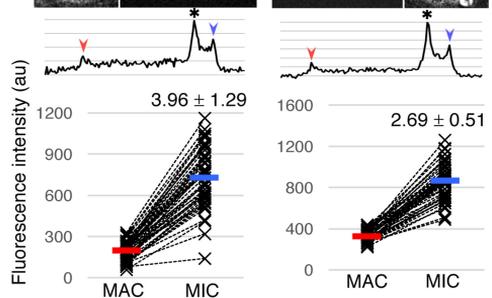
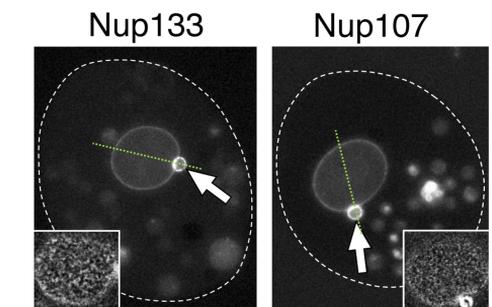
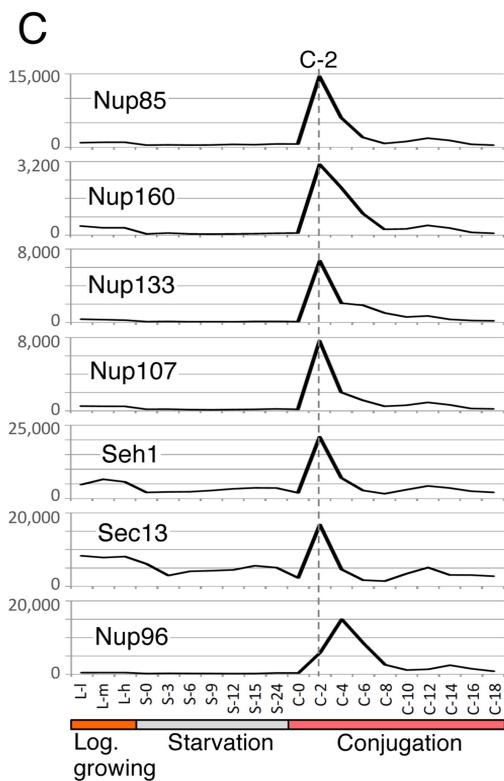
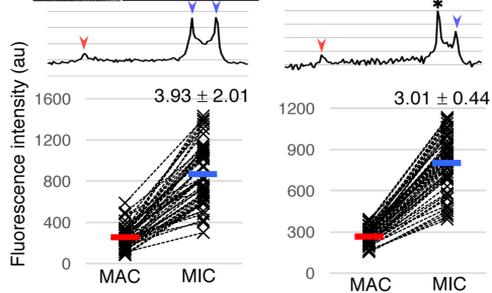
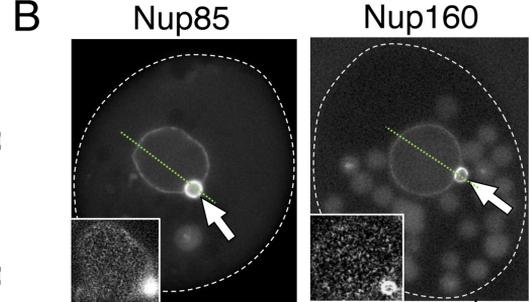
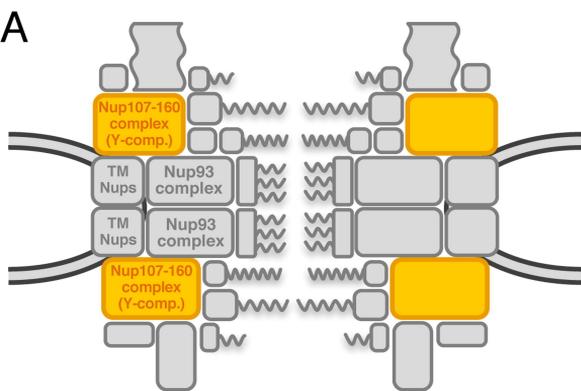


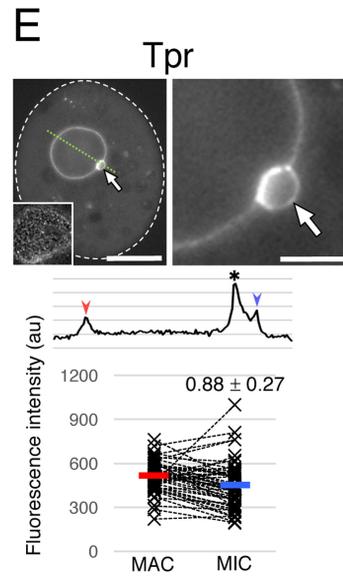
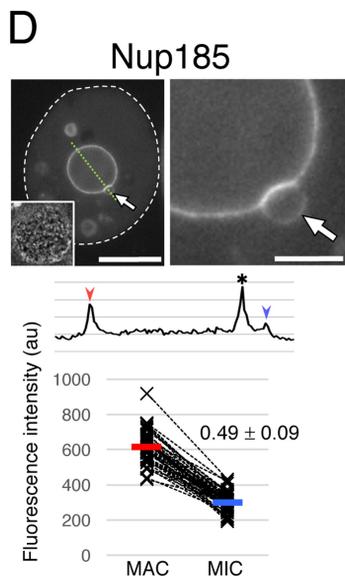
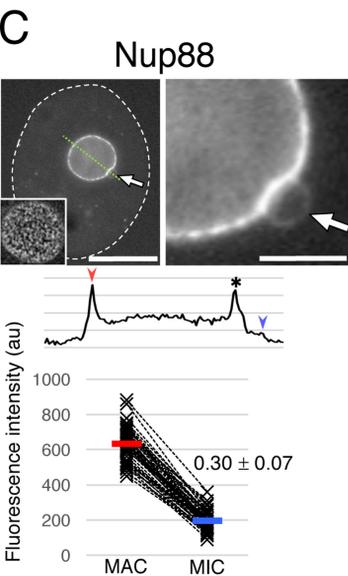
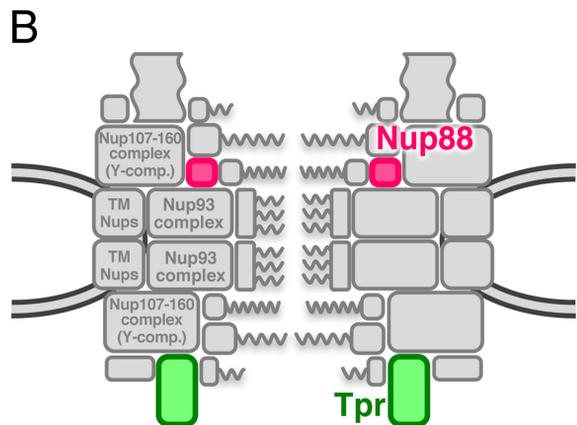
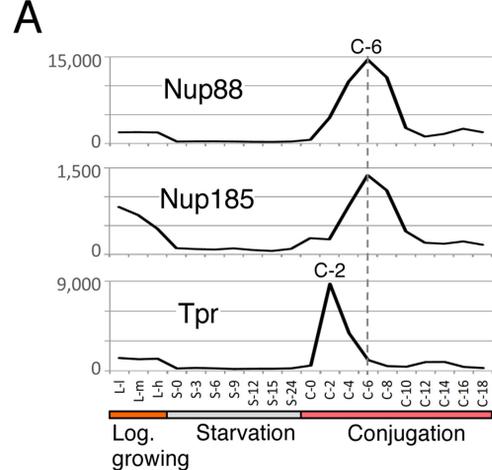
Nuclear basket

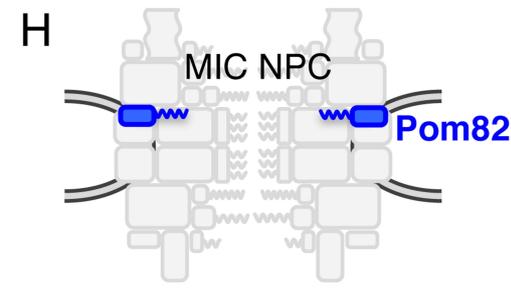
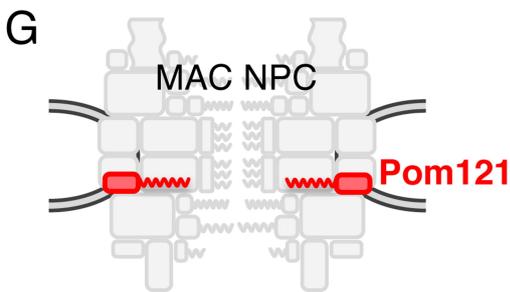
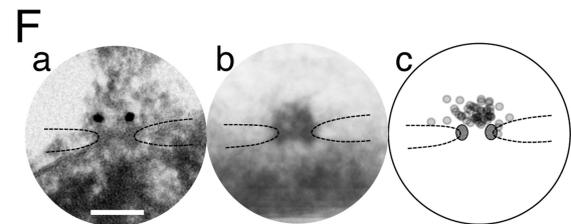
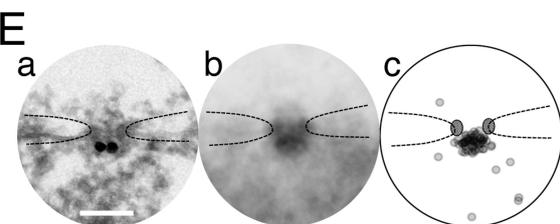
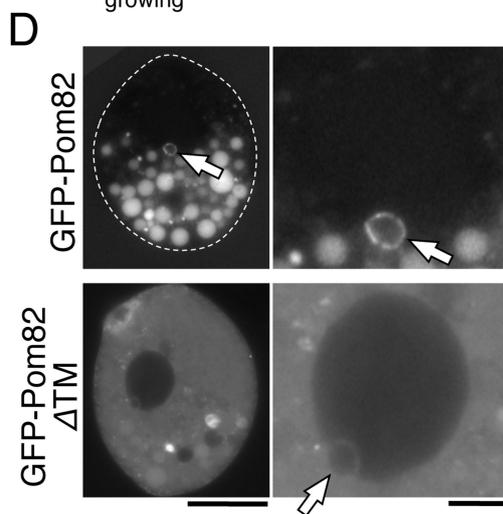
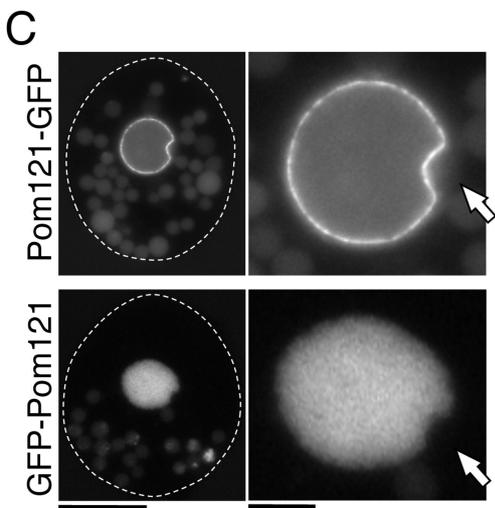
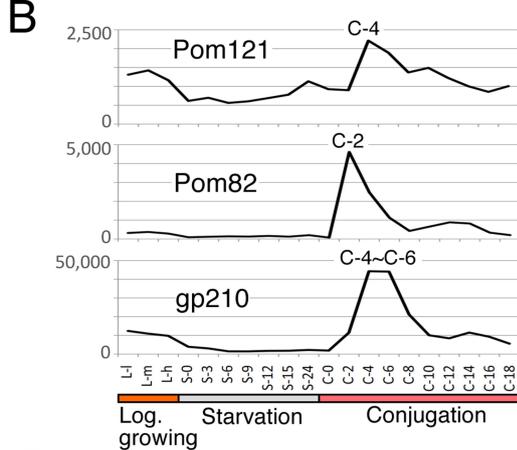
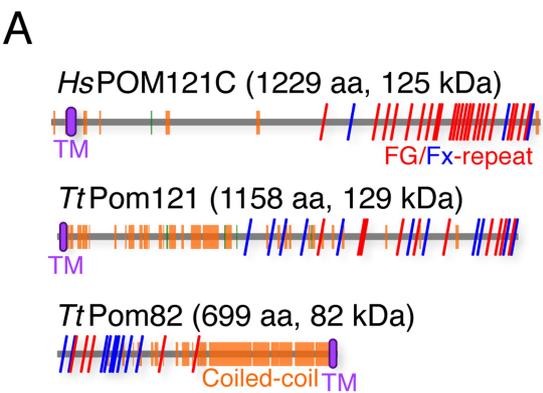


Transmembrane



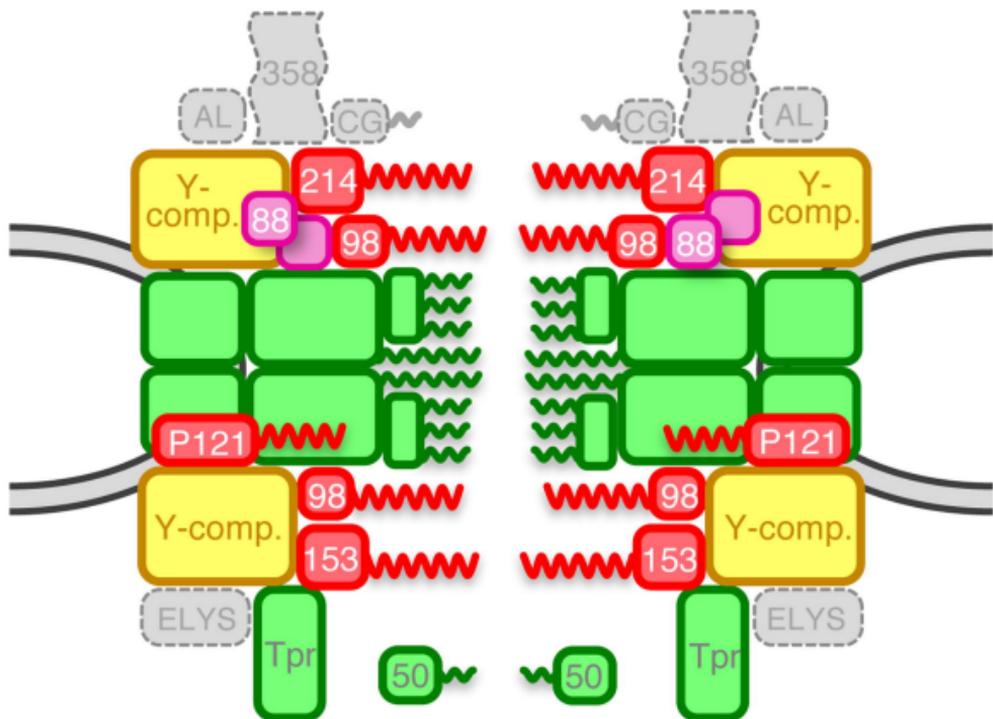






A

MAC NPC



B

MIC NPC

