Evolution of eukaryotic cell
genomics, phylogenomics & biology

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about me

taxonomy & phylogeny of protists, reductive evolution of mitochondria and plastids, eukaryotic cell evolution, microbial eukaryotes genomics & transcriptomics, evolution of phototrophy in eukaryotes

PhD 2011
Post-doc 2013
Post-doc 2016
Assistant Professor 2017
Group Leader 2019

Workshop on genomics student
Workshop on molecular evolution student
Workshop on genomics TA
Workshop on phylogenomics Co-director
Eukaryotic microbes aka protists

“These animacules had diverse colours...others again were green in the middle, and before and behind white...”
Ernst Haeckel’s classification of life
Protista “kingdom of primitive forms”
Protists constitute the majority of lineages across the eukaryotic tree of life

Warden et al. 2015
Doolittle, 1999
Lokiarcheota – missing link?

„Our results provide strong support for hypotheses in which the eukaryotic host evolved from a bona fide archaeon”

Lokiarcheota phylogenomics

Lokiarcheota genomes contain expanded repertoire of eukaryotic signature proteins that are suggestive of sophisticated membrane remodelling capabilities

Pipeline for ASGARD study

endosymbiosis
understanding origin and fate of organelles
What are the initial steps of the enslavement of endosymbiont?

What is the order of events in this phase of transition from prey to endosymbiont?

Are there any universal patterns during the loss of organellar functions?

What are the indispensable functions of the vestigial organelles?
Origin of chloroplasts

**primary endosymbiosis**

Heterotrophic eukaryote → Engulfment of cyanobacterium

- Green plants
- Red algae
- Glaucophyta

**Origin of chloroplasts**

**Primary endosymbiosis**
Plastids and cyanobacteria are recovered repeatedly as a monophyletic group.
Cyanobacteria which became a chloroplast

- *Gloeomargarita lithophora* is the closest extant cyanobacteria to plastids
- old cyanobacterial lineage
- freshwater cyanobacteria

Ponce-Toledo et al., 2017
Secondary endosymbioses in several lineages of microbial eukaryotes

Phylogenomics of plastids

secondary „red” endosymbionts

Sevcikova et al. 2015
Phylogenomics of eukaryotes
based on nuclear genes

Burki et al. 2016
Cryptic serial endosymbiosis

Burki et al. 2016
organelle enslavement

origin of plastids via kleptoplastidity

**kleptoplasty**

transient association between host and endosymbiont, which might resemble the initial steps of the establishing endosymbiosis
photosynthetic euglenids - the only Excavates with secondary plastids

Burki et al. 2014
Rapaza viridis – mixotrophic euglenid

feeds on a specific strain of green algae, *Tetraselmis* sp.

*Rapaza viridis*

*Tetraselmis* chloroplast

*Rapaza* chloroplast

Yamaguchi, Yubuki & Leander (2013)
Autotrophs

Loss of phagotrophy

Plastid

Phototrophs

Mixotrophs

Rapaza viridis

Eukaryotrophy

Eukaryotrophs

Heterotrophs

Bacteriotrophs
Tetraselmis
‘core’ chlorophytes

Pyramimonas
Prasinophytes
Rapaza posses only *Tetraselmis*-derived plastid but no *Pyramimonas*-like (Euglenophyceae-type)
Genes encoding chloroplast proteins are transferred to nuclear genome via endosymbiotic gene transfer (EGT).

Plastid proteins encoded in nuclear genome are targeted to the plastids.
Which comes first, gene transfer or cellular fixation?

A targeting-ratchet model for the endosymbiotic origin of plastids
Keeling, 2013
Are there any plastid proteins encoded in nuclear genome of *Rapaza* targeted to kleptochloroplasts?
What is the origin of plastid-targeted proteins?
Feeding on various algae

transfer of genes encoding plastid proteins to the nuclear genome

targeting of plastid proteins to the kleptoplast

origin of plastids via kleptoplastidity
Which comes first, gene transfer or cellular fixation?

Heterotrophic euglenid

Feeding on various algae

Mixotrophic euglenid

Phototrophic euglenid

Yubuki, Karnkowska, et al. unpublished
Which Comes First, Gene Transfer or Cellular Fixation?

A targeting-ratchet model for the endosymbiotic origin of plastids
Keeling, 2013
mitochondria
The genome sequence of *Rickettsia prowazekii* and the origin of mitochondria

Andersson (1998), Nature
Deep mitochondrial origin outside the sampled alphaproteobacteria

Martijn et al. (2018) Nature
“mitochondria did not evolve from Rickettsiales or any other currently recognized alphaproteobacterial lineage. Rather, our analyses indicate that mitochondria evolved from a proteobacterial lineage that branched off before the divergence of all sampled alphaproteobacteria.”
Which came first nucleus or mitochondrion?
Archezoa hypothesis

Cavalier-Smith, 1989

Archezoa

• early branching eukaryotes
• lack of introns
• no sexual reproduction
• lack of peroxisomes
• lack of Golgi apparatus
• lack of mitochondria

Trichomonas  Giardia  Microsporidia  Archamoebae
mitochondria related organelles (MROs) in eukaryotic microbes
Hydrogen producing mitochondria

Hydrogenosomes

Mitosomes

metabolic diversity of MROs
common origin of mitochondria and MROs

- mitochondrial chaperonins
- ATP transporters
- mitochondrial membrane transport proteins
- Fe-S cluster assembly proteins
Archezoa hypothesis rejected

• All “archezoa” possess:
  - mitochondrial genes in nuclear genomes
  - degenerate derivatives of mitochondria
  - they do not group together on the modern tree of life

Common ancestor of all eukaryotes possessed mitochondria
Does amitochondriate eukaryote exist?
cryptic mitochondria

Keeling, 2007
mitochondria in Excavata

Oxymonadida

Trimastix

Parabasalia

Chilomastix

Dysnectes

Diplomonadida

Euglenozoa

Carpediemonas

Malawimonas

Dysnectes

Heterolobosea

Tsukubamonas

Oxymonads

Malawimonas

Jakobida
Metamonada
Parabasalia (*Trichomonas*)
Fornicata (*Giardia*)
Preaxostyla
Trimastix
*oxymonads*

- found in the intestinal tracts of termites, insects, and vertebrates
- sexual reproduction debatable
- no peroxisomes
- no Golgi apparatus
- no mitochondria
Monocercomonoides microaerophilic, commensal of animals

**Genome analysis**

- intron rich
- meiotic toolkit present
- no stacked Golgi, but most of the proteins present
- lack peroxisomes
- genome exhibit most of the typical eukaryotic features

Karnkowska et al. (2016) Curr Biol
Monocercomonoides is less divergent than Parabasalids and Diplomonads

Karnowska et al. (2016) Curr Biol
Searching for mitochondrial proteins

Mitochondrial outer membrane targeted proteins (TA)
Proteins with mitochondrial localization signal
β-barrel mitochondrial outer membrane proteins
mitochondrial membrane transport proteins

yeast
mitochondrial membrane transport proteins
mitochondrial membrane transport proteins
Fe-S cluster assembly
the most conserved mitochondrial process

- Fe/S proteins are essential for viability
- they are involved in: DNA repair, DNA replication, ribosome assembly
Fe-S cluster assembly systems in eukaryotes

- CIA
- SUF
- ISC

nuclear Fe-S proteins

cytosolic Fe-S proteins
Fe-S cluster assembly systems in *Monocercomonoides*

- CIA
- SufS
- SufU
- SufB
- SufC
- SufD
- FADH$_2$
- ADP+Pi
- ATP
- Fe
- nuclear Fe-S proteins
- cytosolic Fe-S proteins
Lateral gene transfer (LGT) of SUF system

Karnkowska et al. (2016) Curr Biol
SUF system is widespread in Preaxostyla

Vacek et al. (2018) MBE
Loss of oxidative phosphorylation

An anaerobic eukaryote with mitochondrion related organelles (MRO)

Mitochondrial Fe-S cluster assembly (ISC) system

Loss of MRO

Monocercomonoides sp.
an amitochondriate eukaryote

Bacterial sulfur mobilization (SUF) pathway
loss of a mitochondrial organelle

LGT of SUF system resulted in relocation of the pathway to the cytosol

Endosymbiosis can be undone!

Karnkowska et al. (2016) Curr Biol
Which came first nucleus or mitochondrion?
Late acquisition of mitochondria

LECA protein families of alphaproteobacterial ancestry and of mitochondrial localization show the shortest phylogenetic distances to their closest prokaryotic relatives, compared with proteins of different prokaryotic origin or cellular localization.

Stem length analysis

Pittis and Gabaldon (2016) Nature
The great advances in our understanding of the evolution of eukaryotic cell are coming from the species discovery and biological observations.

Genomics and phylogenomics are very powerful methods, which help to understand the evolution of eukaryotes.
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