Communautés microbiennes complexes et défi de l’adaptation à l’environnement : l’union fait la force

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http://www.ese.u-psud.fr/rubrique7.html?lang=en; puri.lopez@u-psud.fr

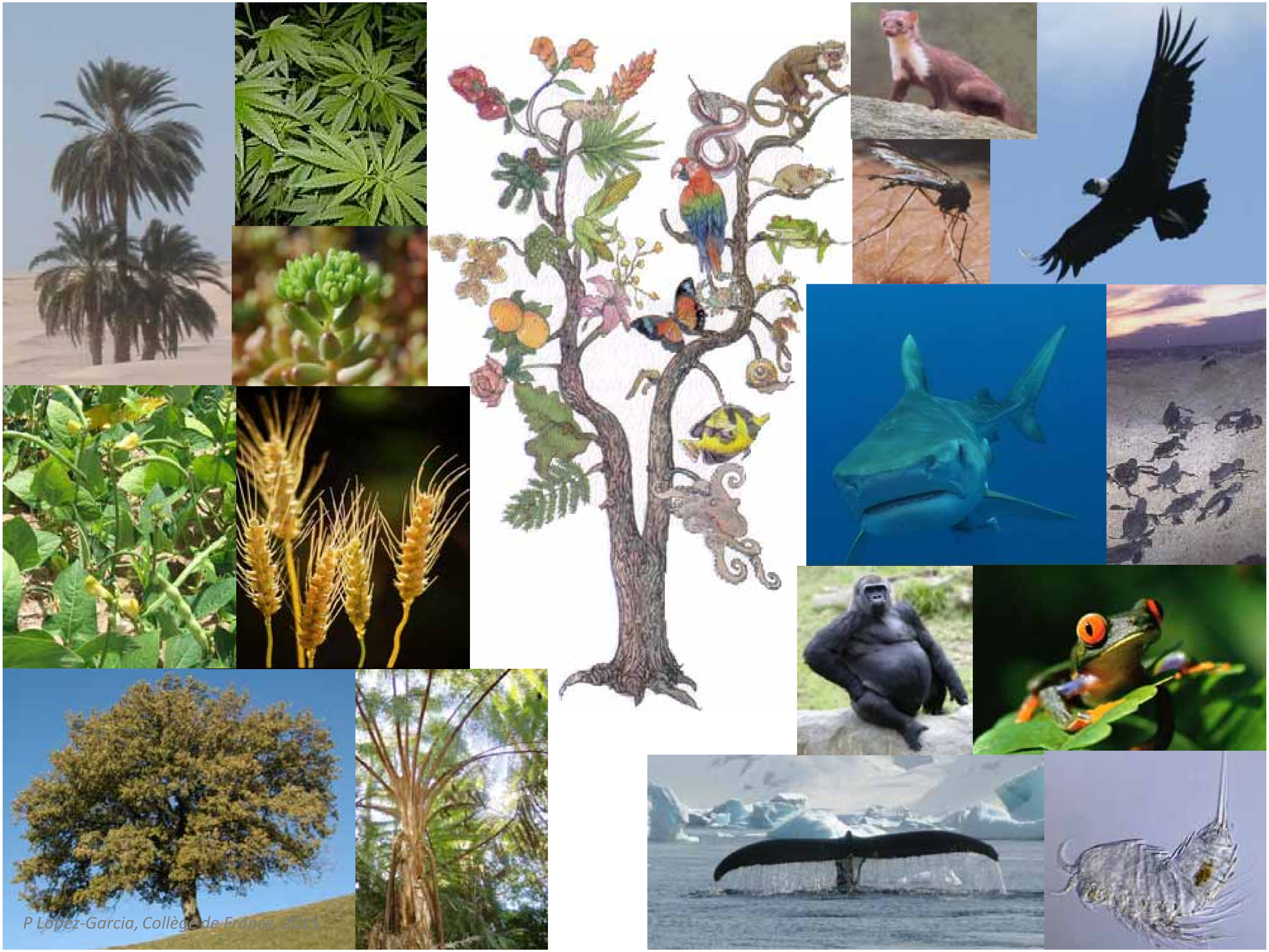
1. La diversité microbienne et la vie en communauté

2. Symbioses : conséquences écologiques et évolutives

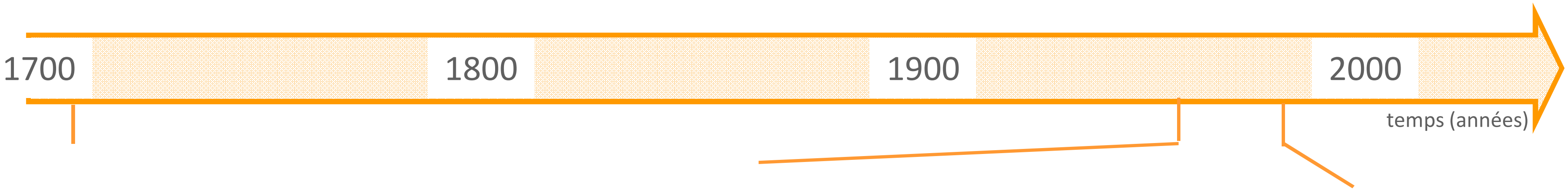
    Symbioses micro / macroorganismes

    Symbioses microbiennes

    L'origine des organites / cellule eucaryote


P Lopez-Garcia, Collège de France, 2015

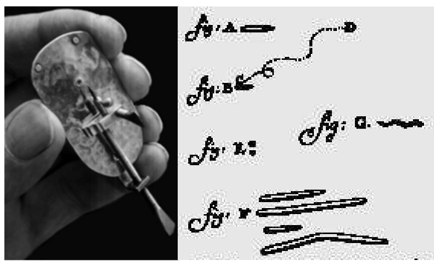
Notre perception du monde microbien



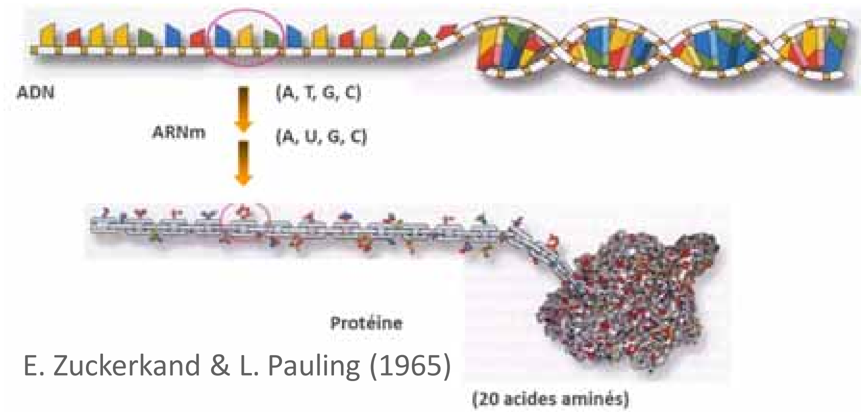
Vie microbienne

Phylogénie moléculaire et classification naturelle

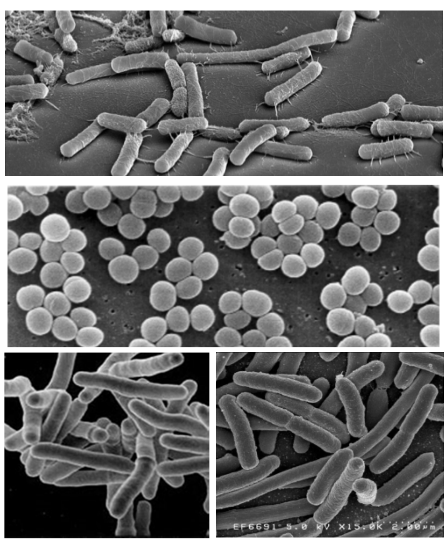
Microbiologie environnementale



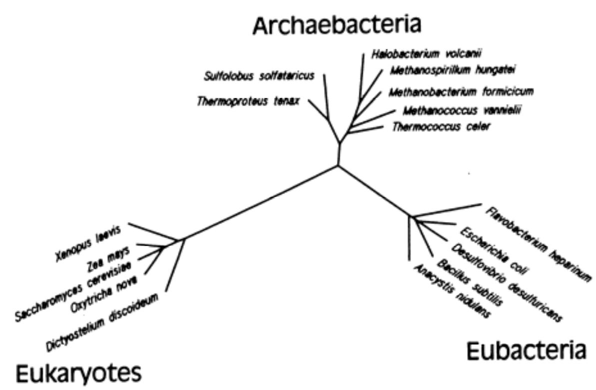
A. van Leeuwenhoek (1632-1723)



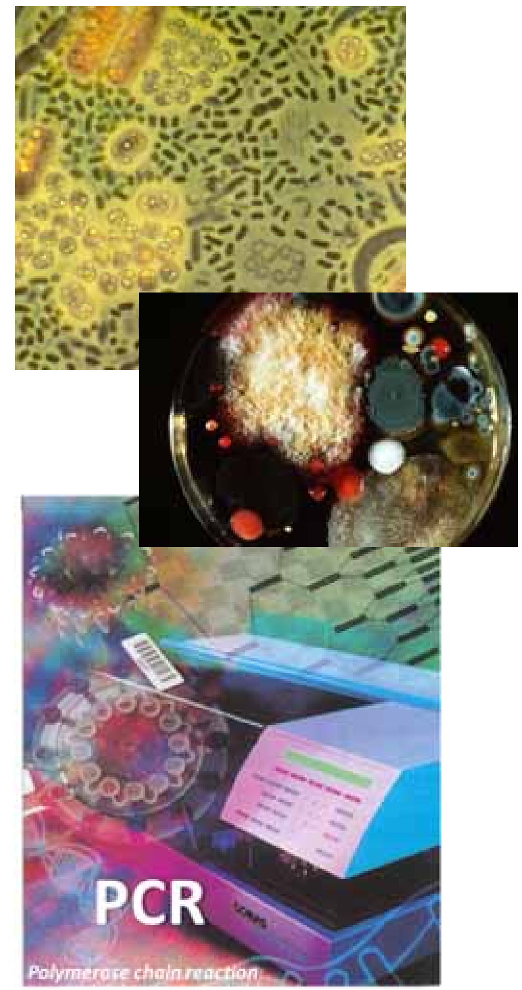
E. Zuckerkand & L. Pauling (1965)



SSU rRNA
(small subunit rRNA)



Woese et al. (1977, 1990)



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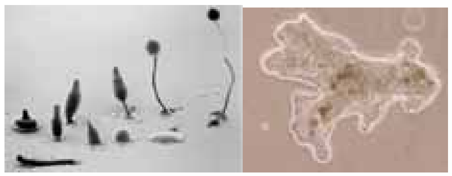
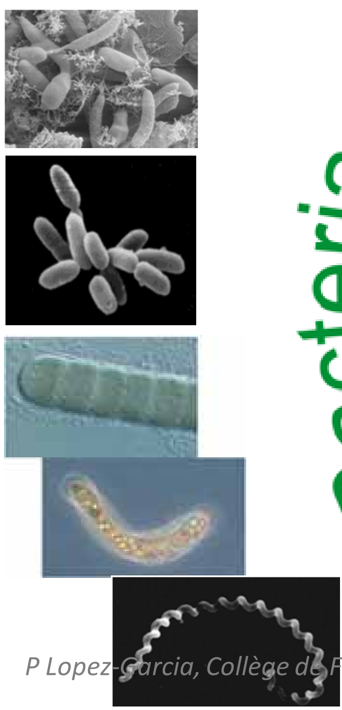
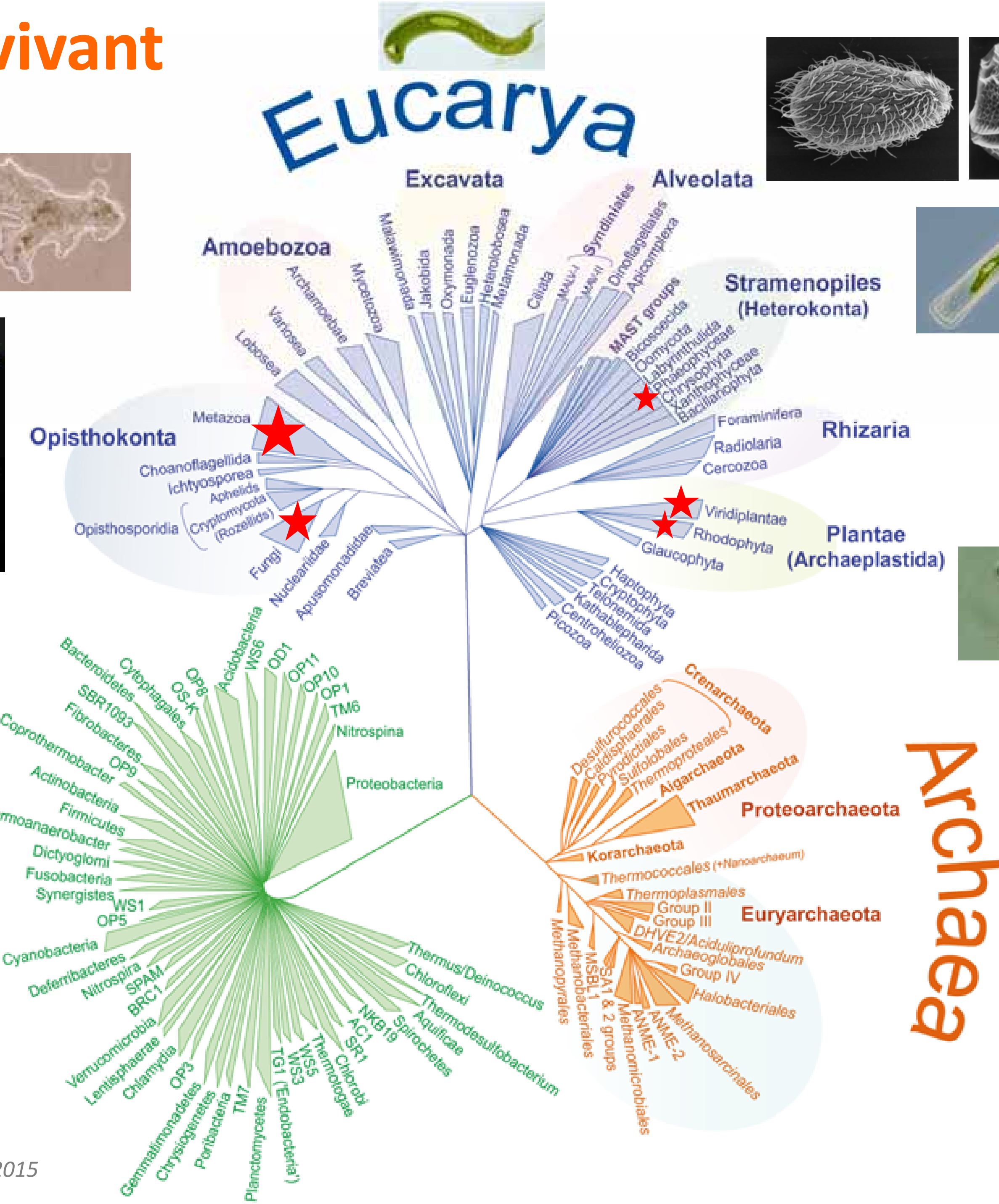
L'arbre du vivant

(16S/18S rRNA)







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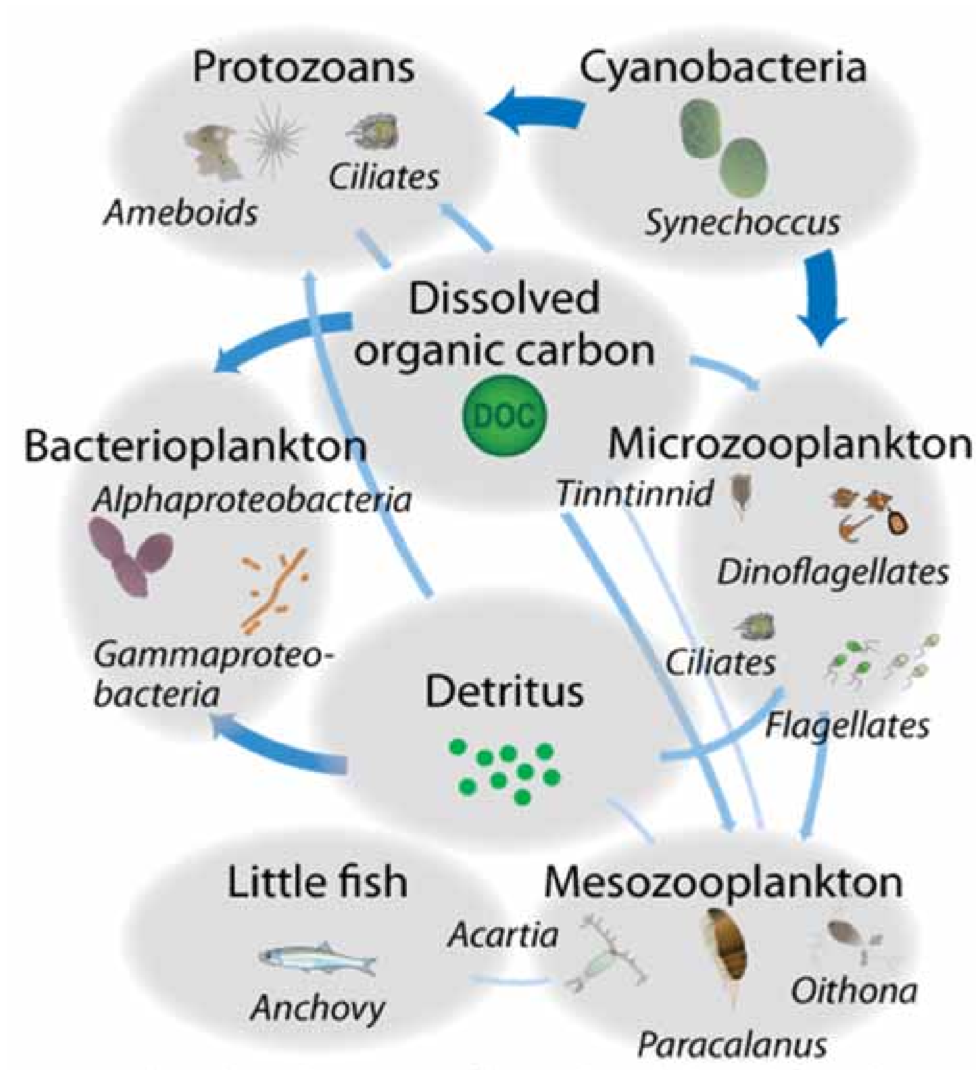
Interactions



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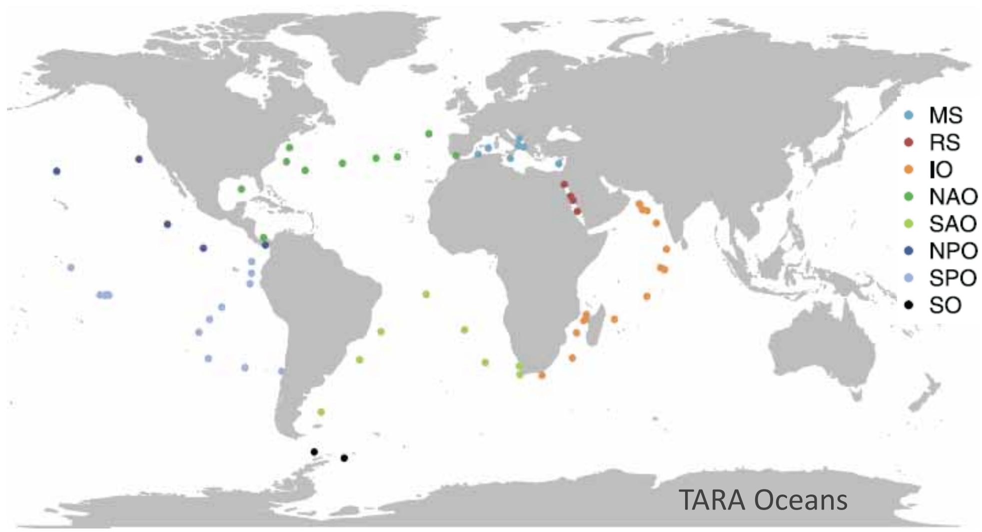
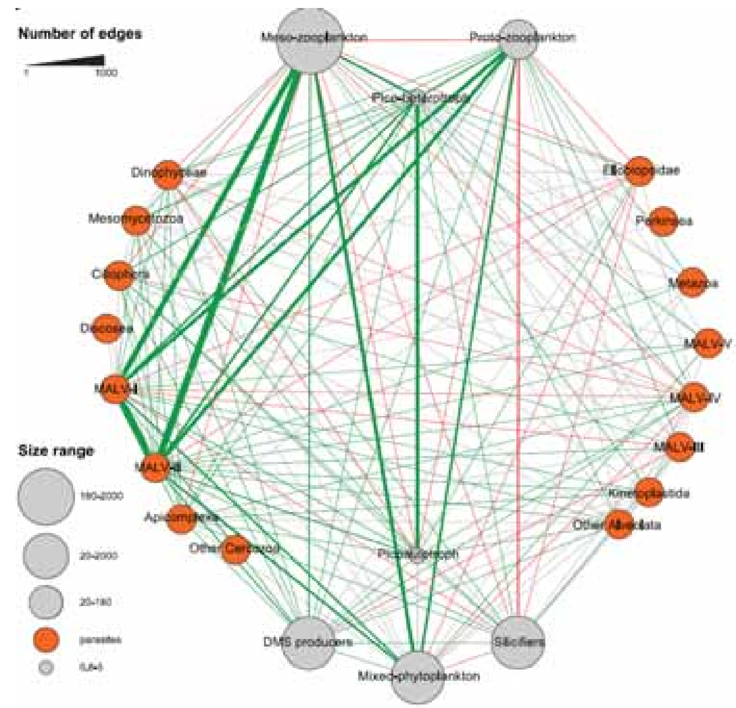
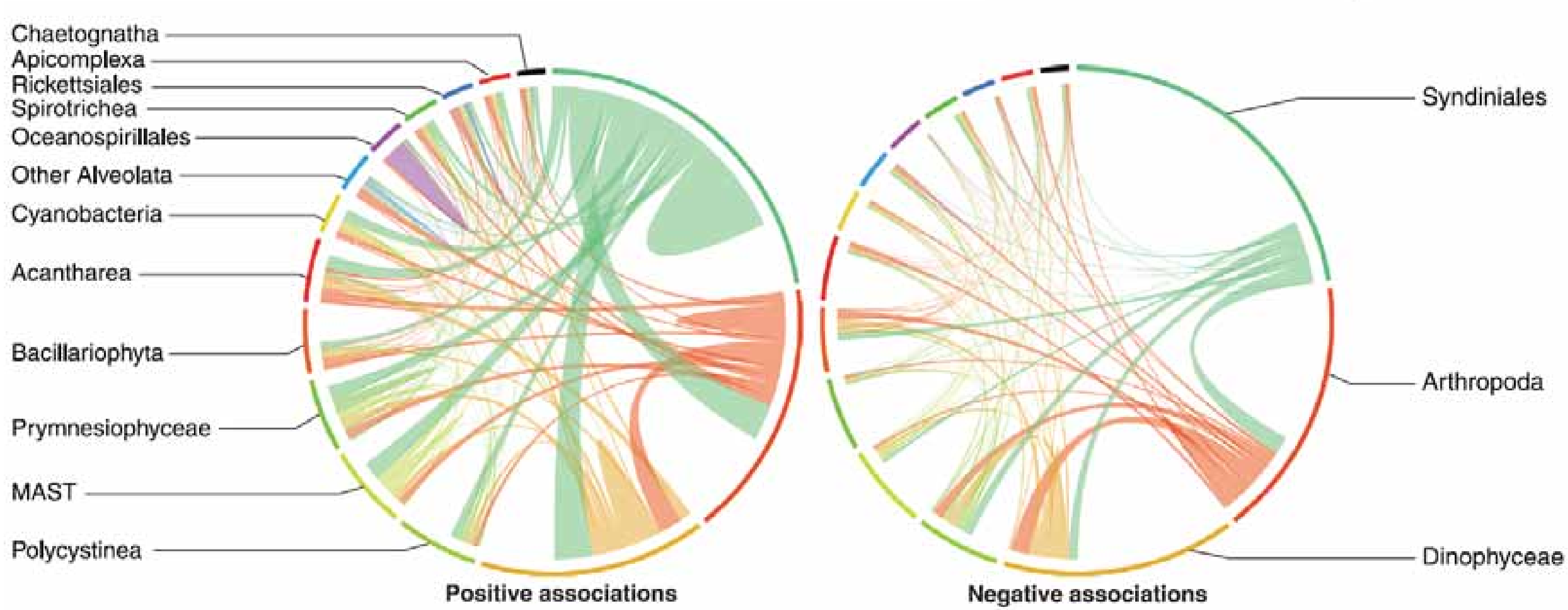
Interactions

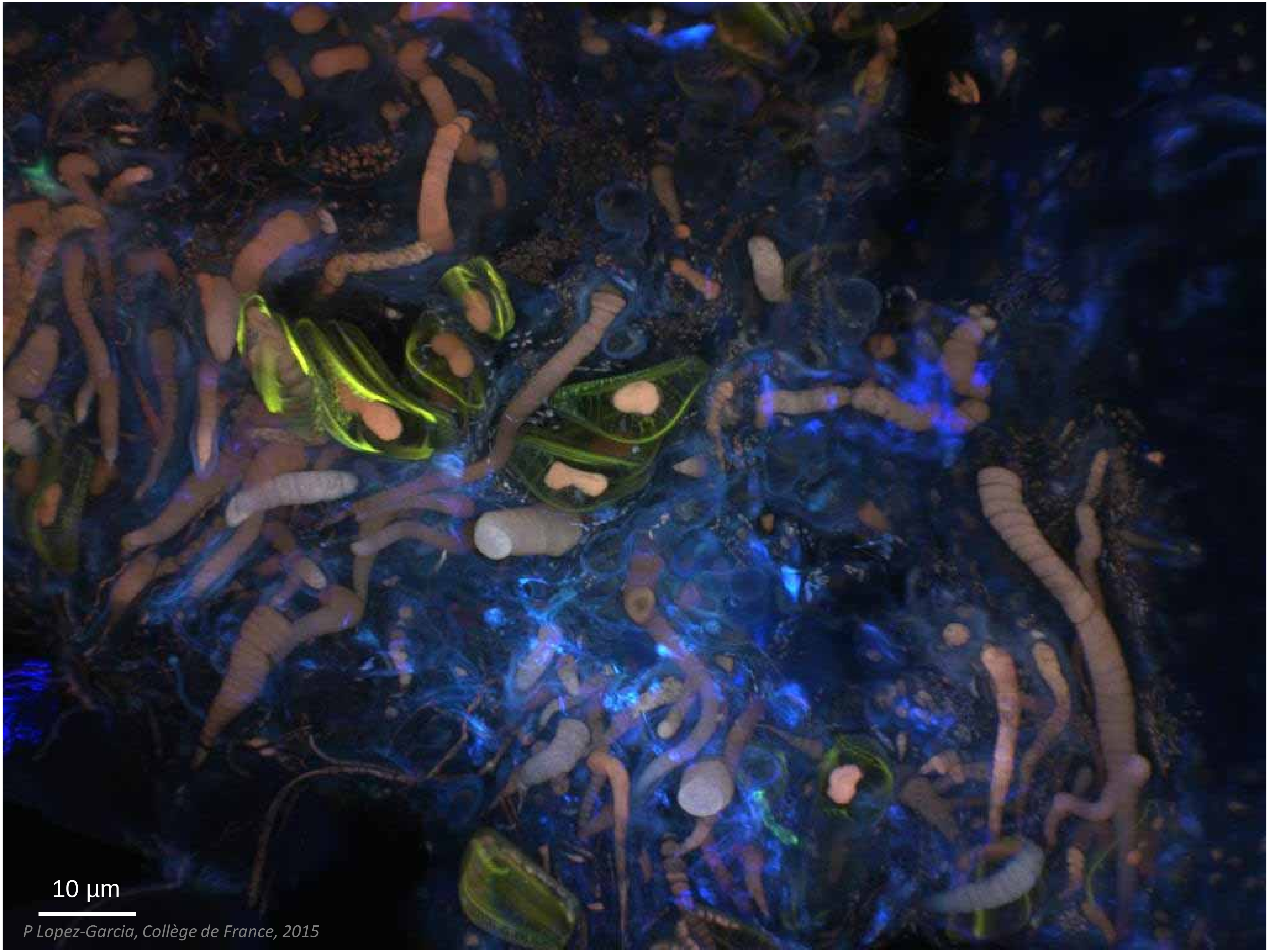




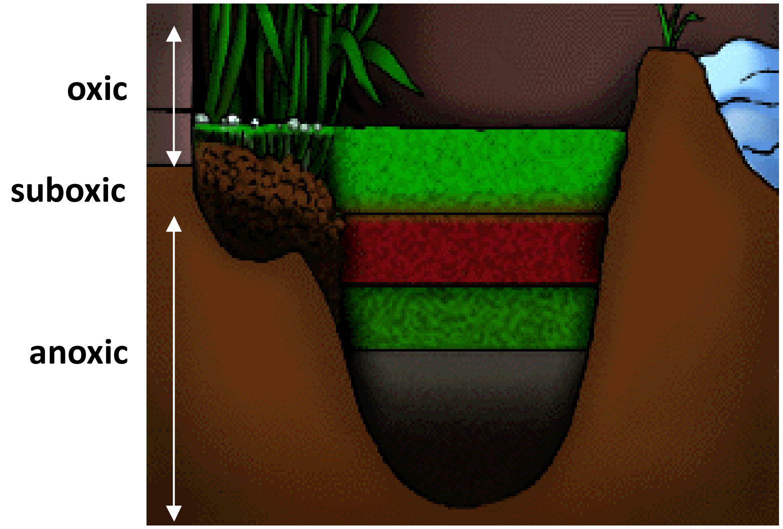


P Lopez-Garcia, Collège de France, 2015

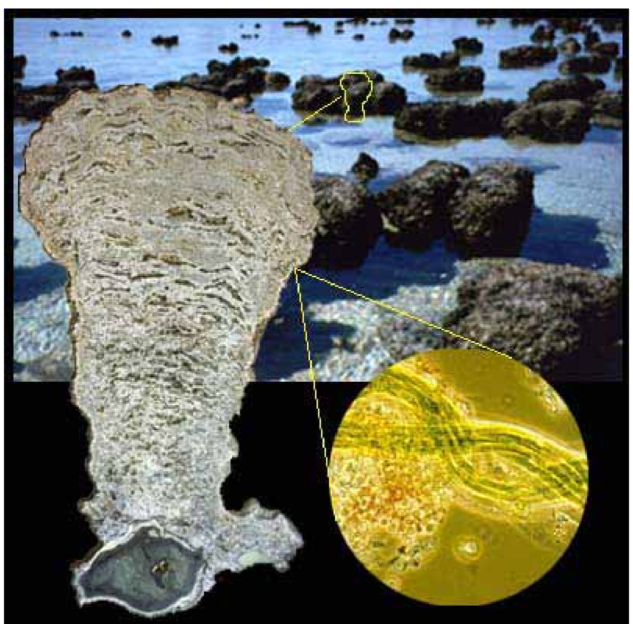
Lima-Mendez et al, Science (2015)


10 µm
P Lopez-Garcia, Collège de France, 2015

Biofilms et tapis microbiens

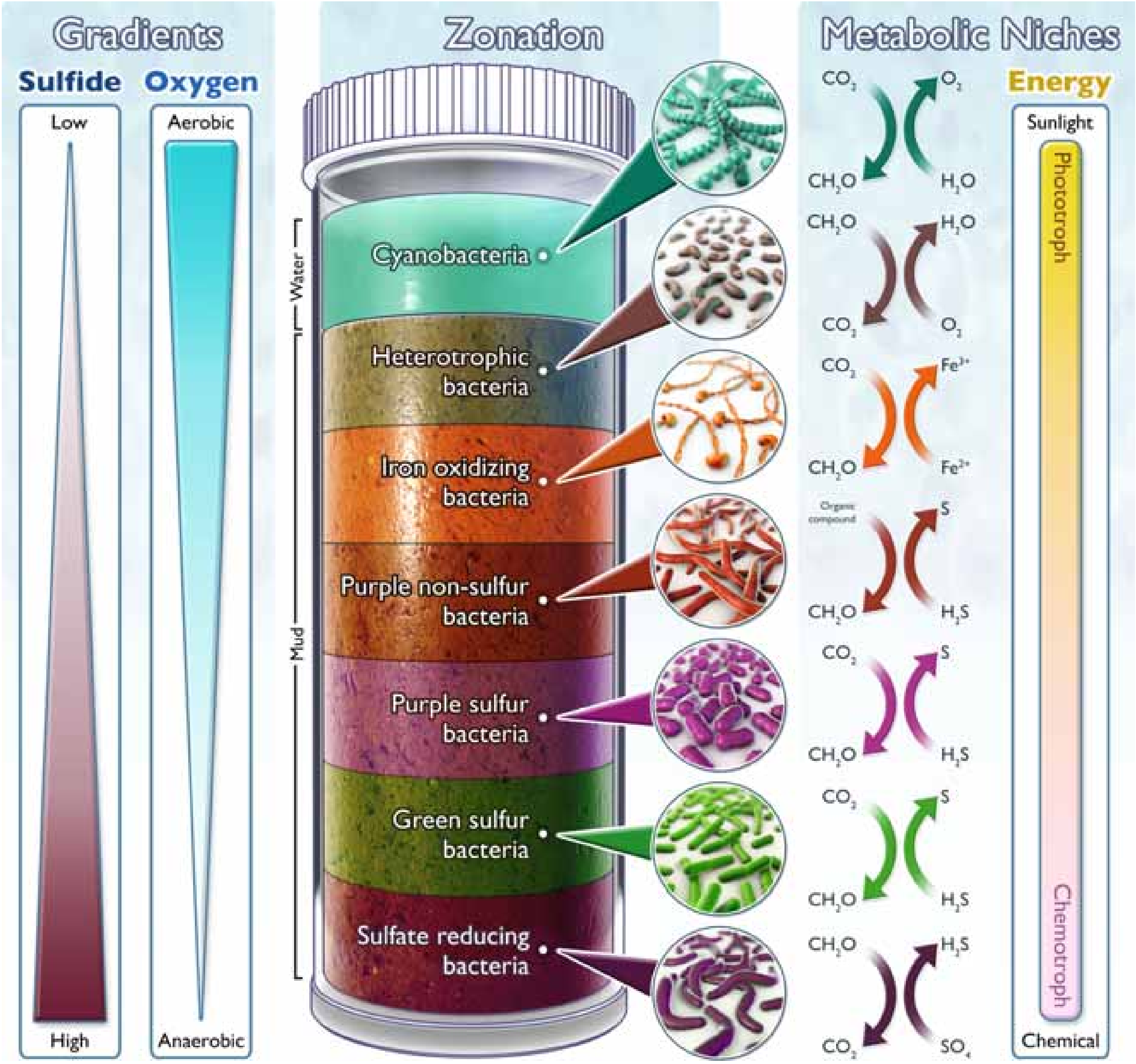


Strict anaerobes



P Lopez-Garcia, Collège de France, 2015

Interactions métaboliques



P Lopez-Garcia, Collège de France, 2015

Symbiose

From Greek "sym" (with) and "biosis" (living)
Heinrich Anton de Bary, 1879

- **Selon l'effet dans la fitness du partenaire**

  Mutualisme

  Parasitisme

  Comensalisme

- **Selon le niveau d'interdépendance entre partenaires**

  Facultative

  Obligatoire

- **Selon la localisation du symbiont / hôte**

  Ectosymbiose

  Endosymbiose

Lichens

P Lopez-Garcia, Collège de France, 2015

Symbioses micro / macroorganismes

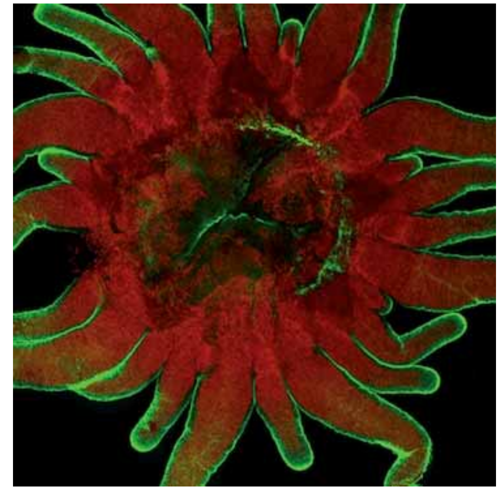
1. Phototrophes

2. Hétérotrophes

3. Chimiotrophes

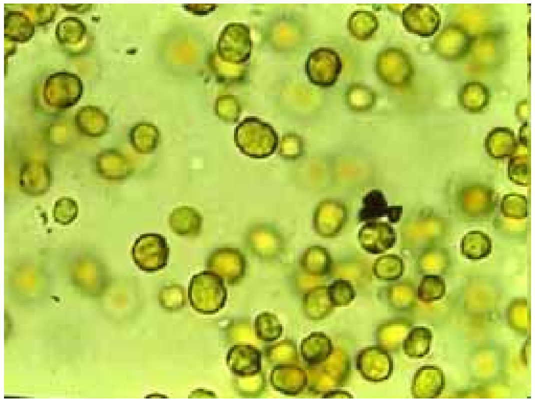
Symbioses phototrophes

Anemones



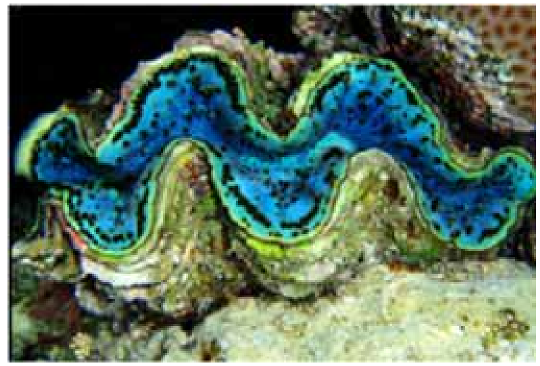
Symbiodinium *(red autofluorescence)*
Aiptasia pallida *(microtubules stained green)*

Zooxanthella



Dinoflagellates (*Symbiodinium*)

Bivalves



Tridacna-Symbiodinium

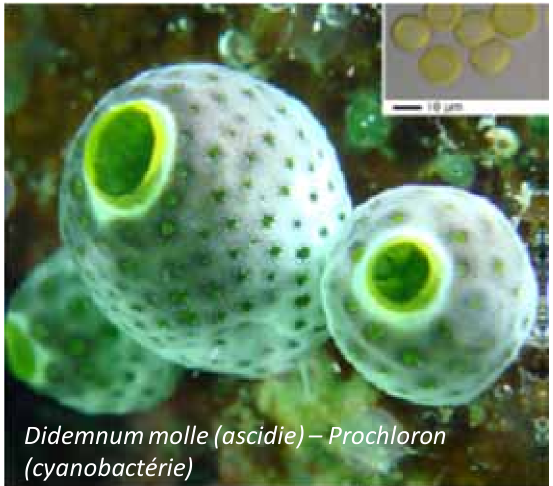
Corals

X

symbiont loss

"*Coral bleaching*"

P Lopez-Garcia, Collège de France, 2015



Didemnum molle (ascidie) – Prochloron (cyanobactérie)

Mollusques – algues vertes

Hydra (Cnidaria) – Chlorella (algue verte)

(*Ambystoma maculatum*)

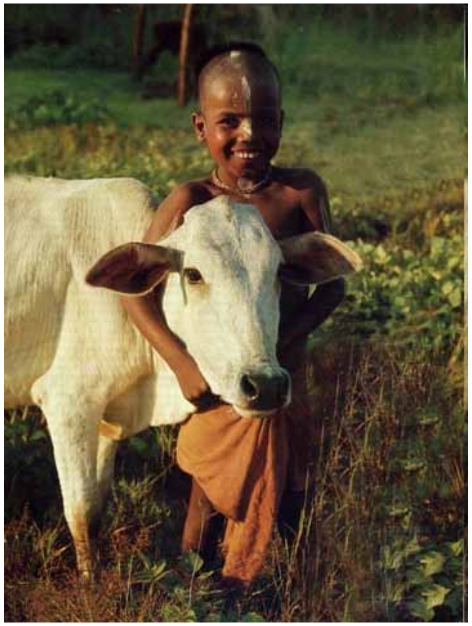
Algae cohabit with salamander embryos in their eggs — and inside their cells.

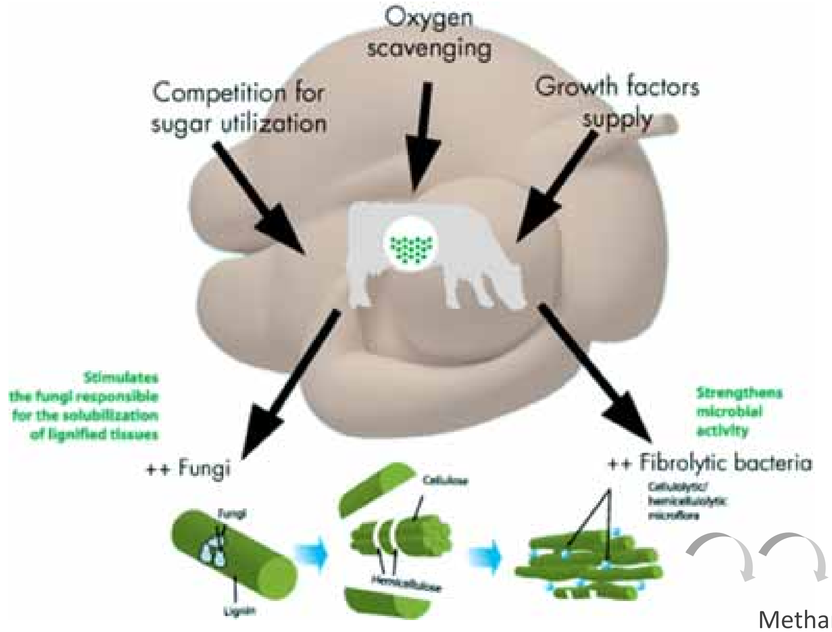
Nature, 2010

Embryons de salamandre : déchets azotés utilisés par les algues
Algues vertes : taux d'oxygène élevé exploité par les embryons

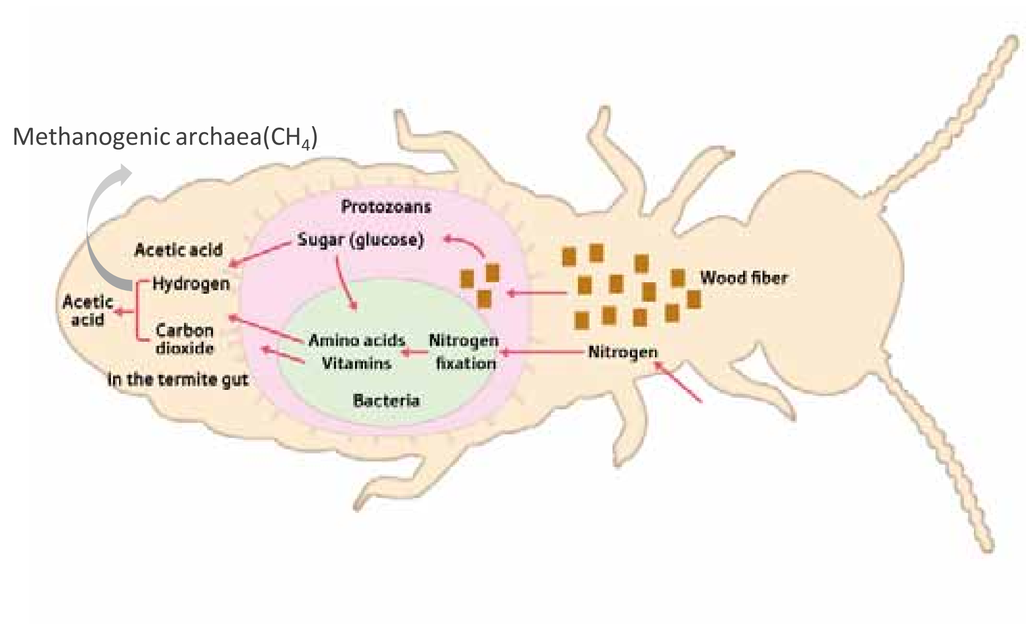
(un cadeau maternel ? les algues sont présentes dans les oviducts)

Symbioses hétérotrophes





Methanogenic archaea (CH_4)



Lignine
Cellulose

⇩ haute efficacité

Sucres simples

⇩

Biocarburant

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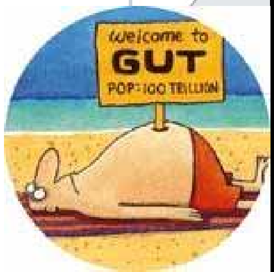
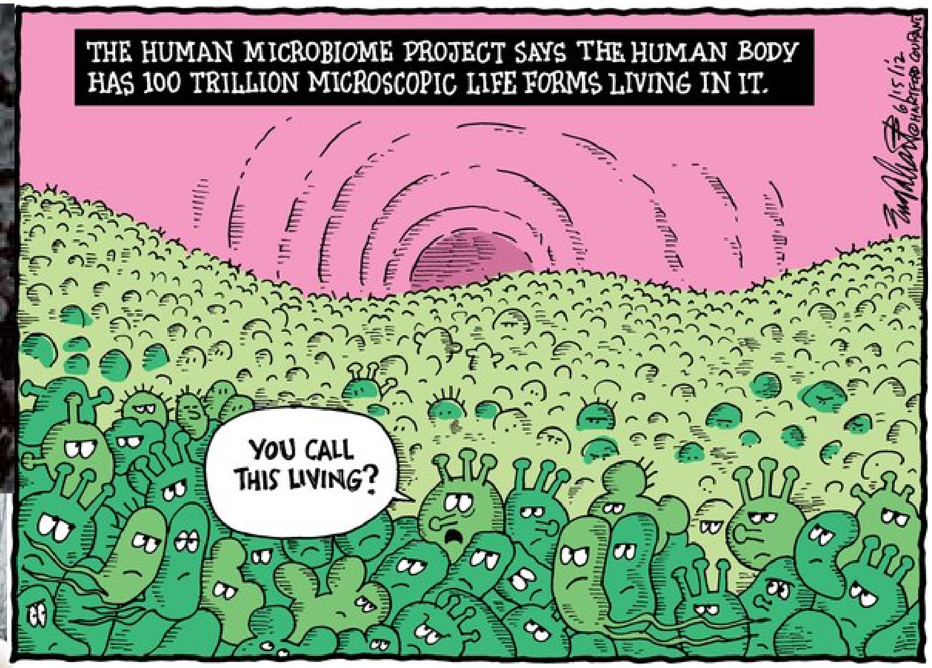
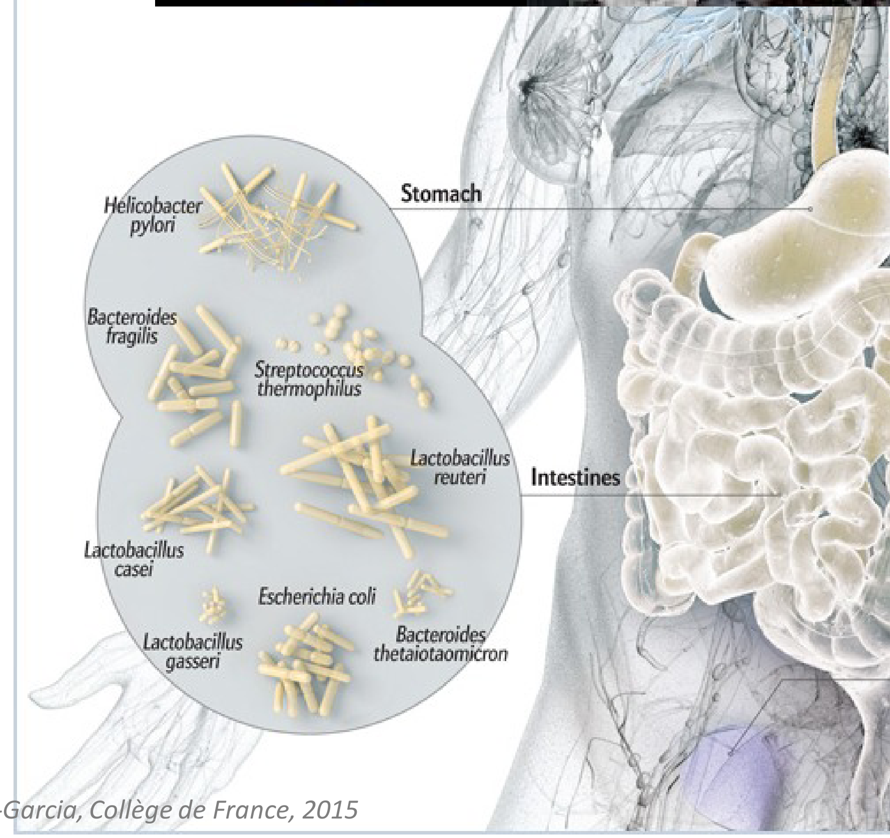
Le(s) microbiome(s) humain







Approches moléculaires et métagénomiques :

- Structure & fonction de l'intestin
- Système immunitaire
- Métabolisme de l'hôte

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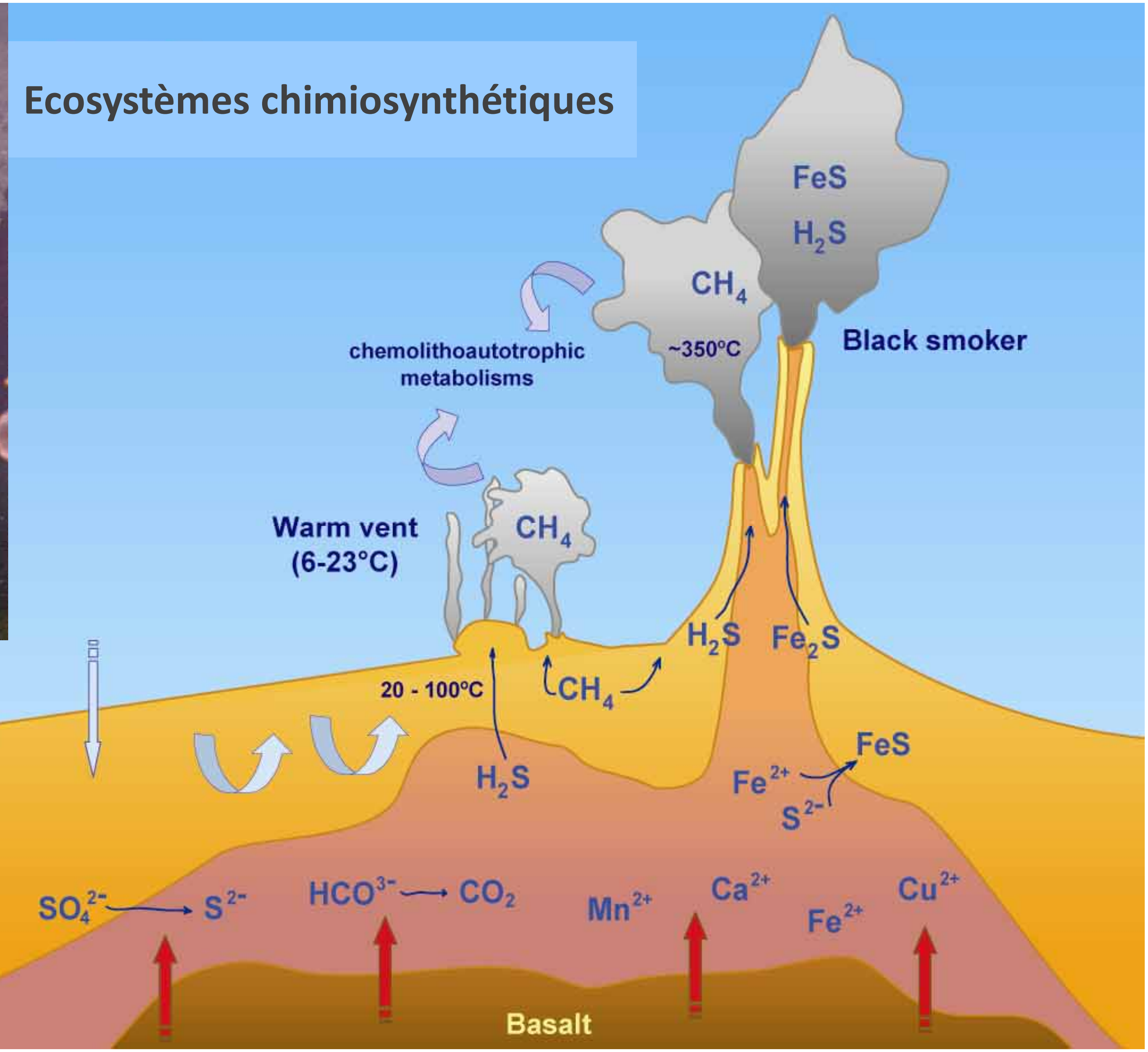
Symbioses chimiotrophes

Ecosystèmes chimiosynthétiques



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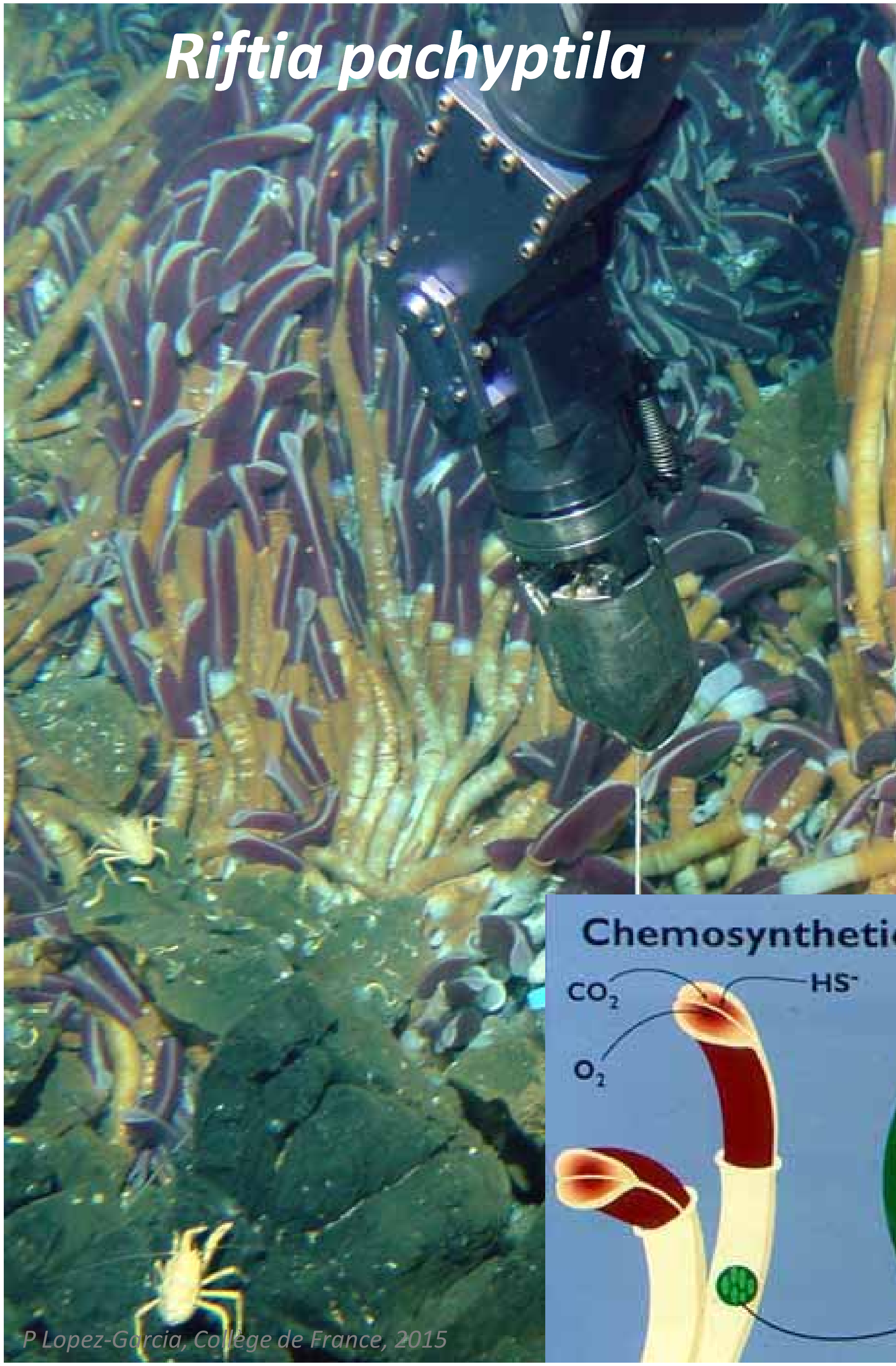
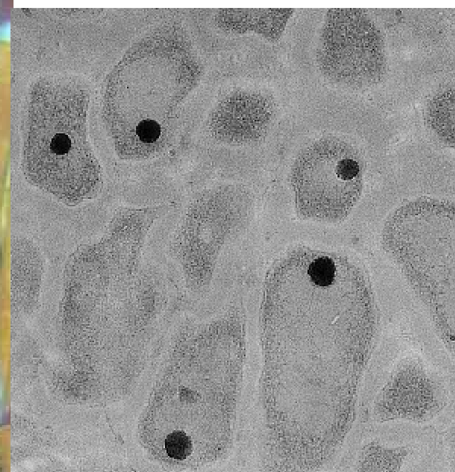
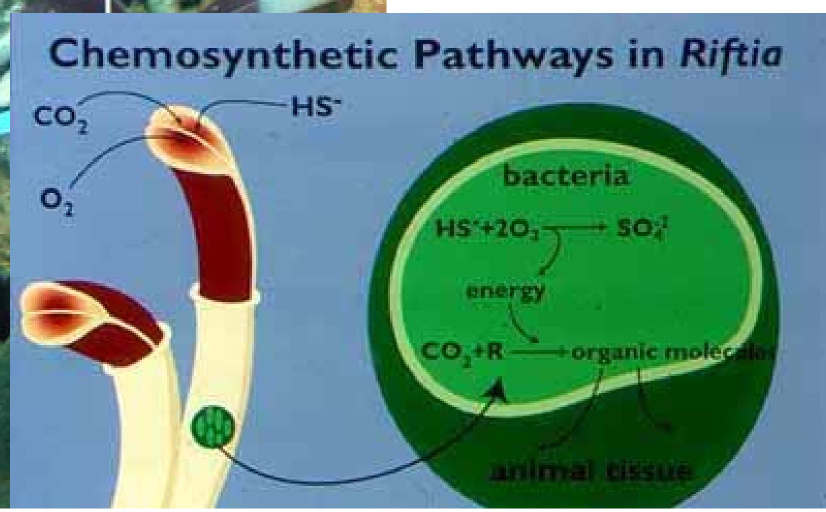


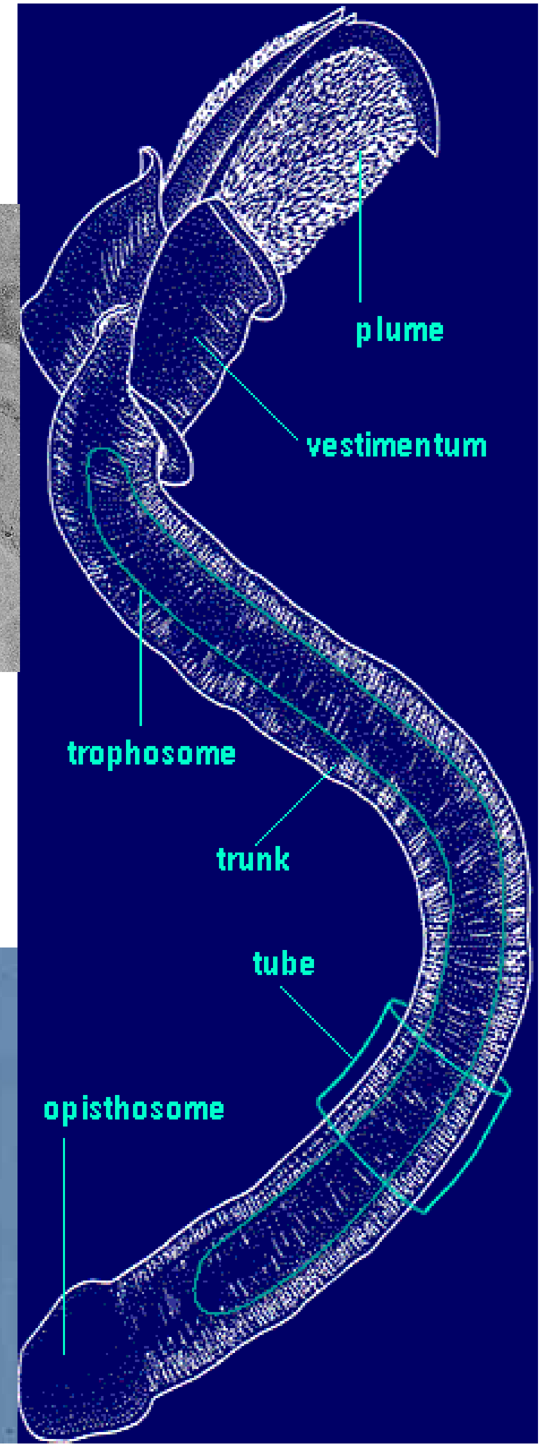
Endosymbiose avec une gammaproteobactérie chimiolithoautotrophe



Hémoglobine modifiée pour le transport de :

- O_2
- H_2S
- NO_3^-





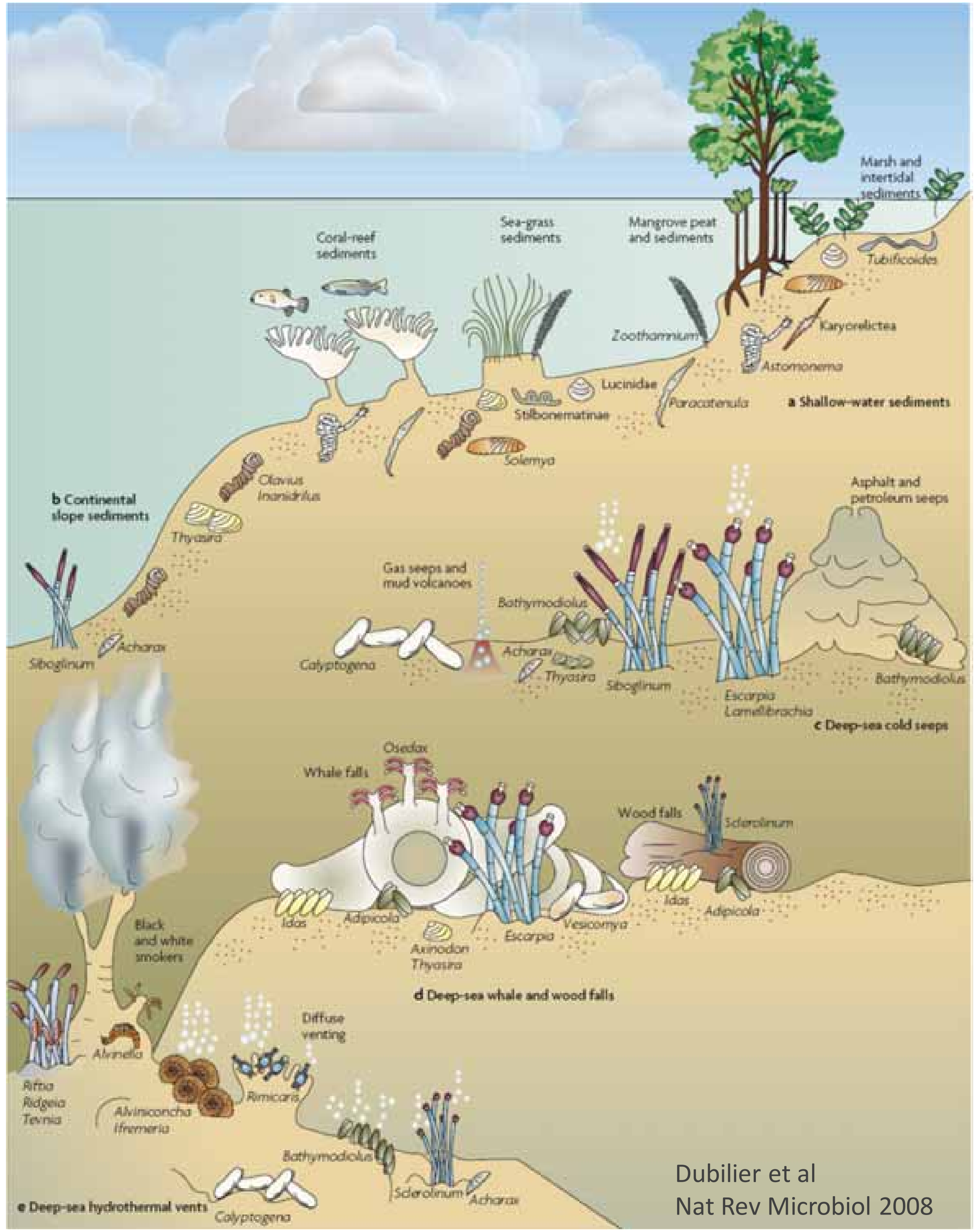
L'étendu des symbioses chimiotrophes

- **Bactéries H_2S-oxydantes**
  - **Gammaproteobacteria**
  - **Epsilonproteobacteria**
- **Bactéries méthanotrophes**
  - **Gammaproteobacteria**
- **Certaines bactéries sulfato-réductrices**
  - **Deltaproteobacteria**

Ectosymbionts

Endosymbionts

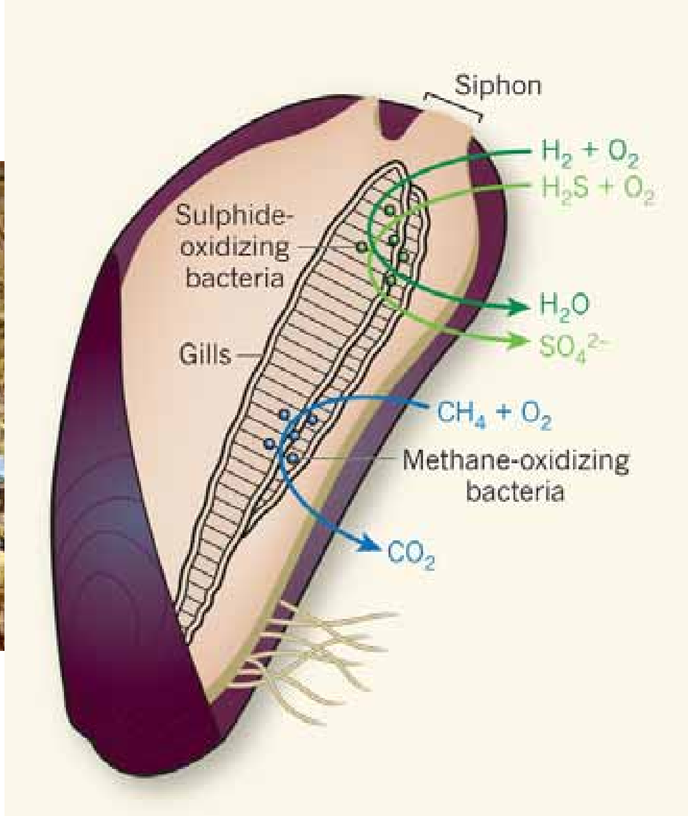
Haute spécificité hôte-symbiont

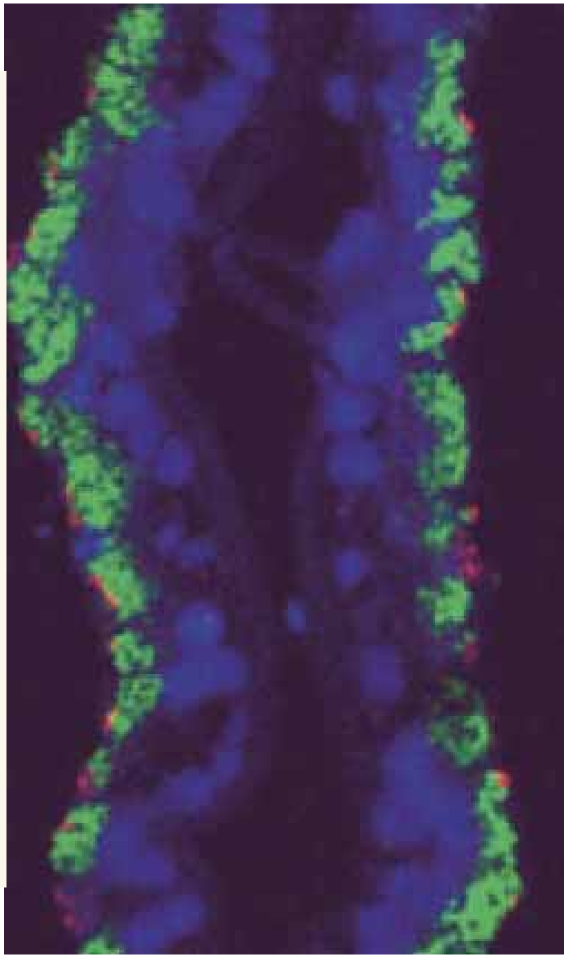


Dubilier et al
Nat Rev Microbiol 2008

Symbioses multiples

Bathymodiolus spp.

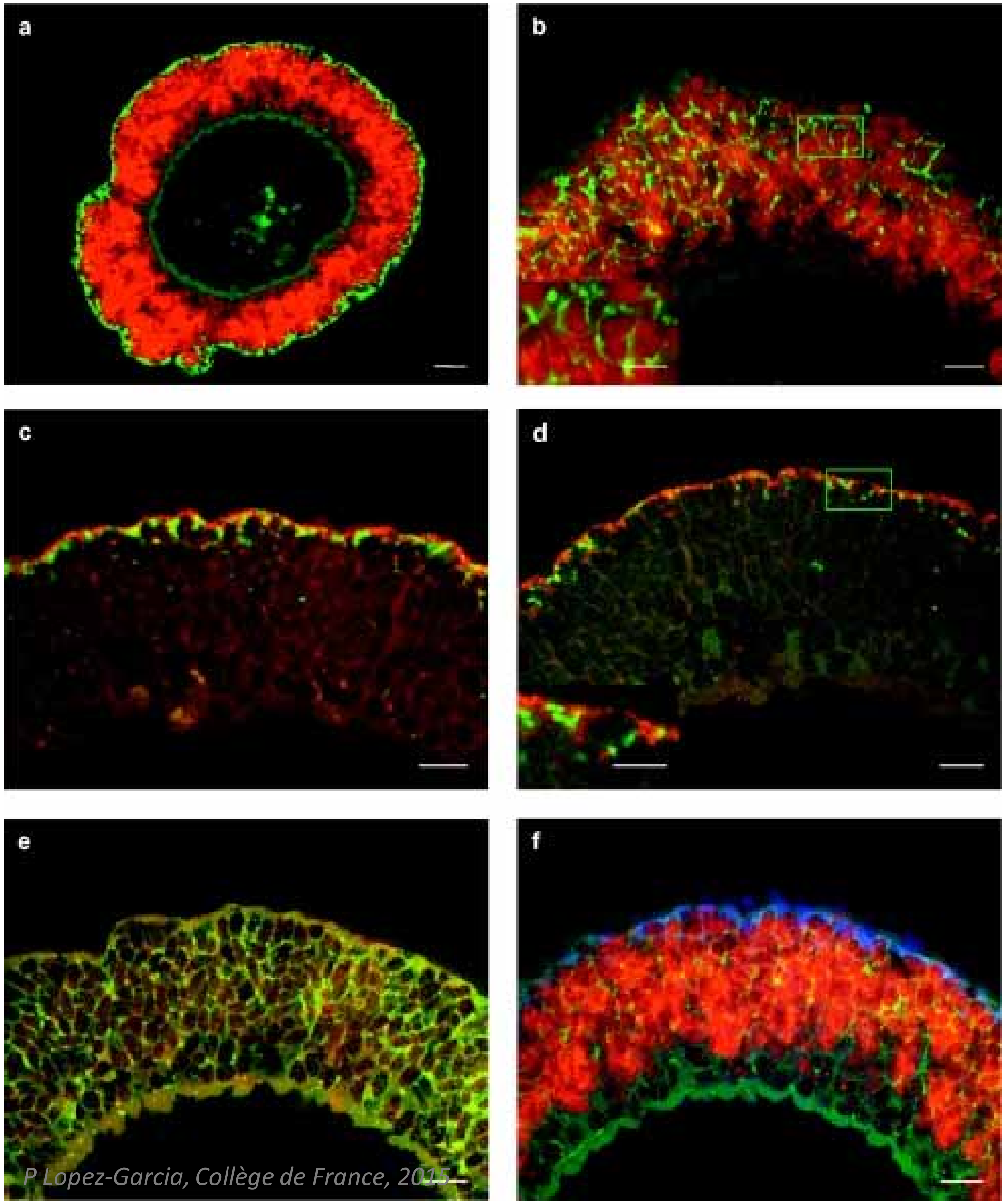




sulfur-oxidizing chemoautotroph (green)
and methane-oxidizer (red) gammaproteobacterium

Duperron et al. 2007

Coexistence of Bacterial Sulfide Oxidizers, Sulfate Reducers, and Spirochetes in a Gutless Worm (Oligochaeta) from the Peru Margin



Olavius algarvensis,

2 Gammaprotéobactéries symbiotiques (rouge)

2 Deltaprotéobactéries symbiotiques (vert)

1 Spirochète

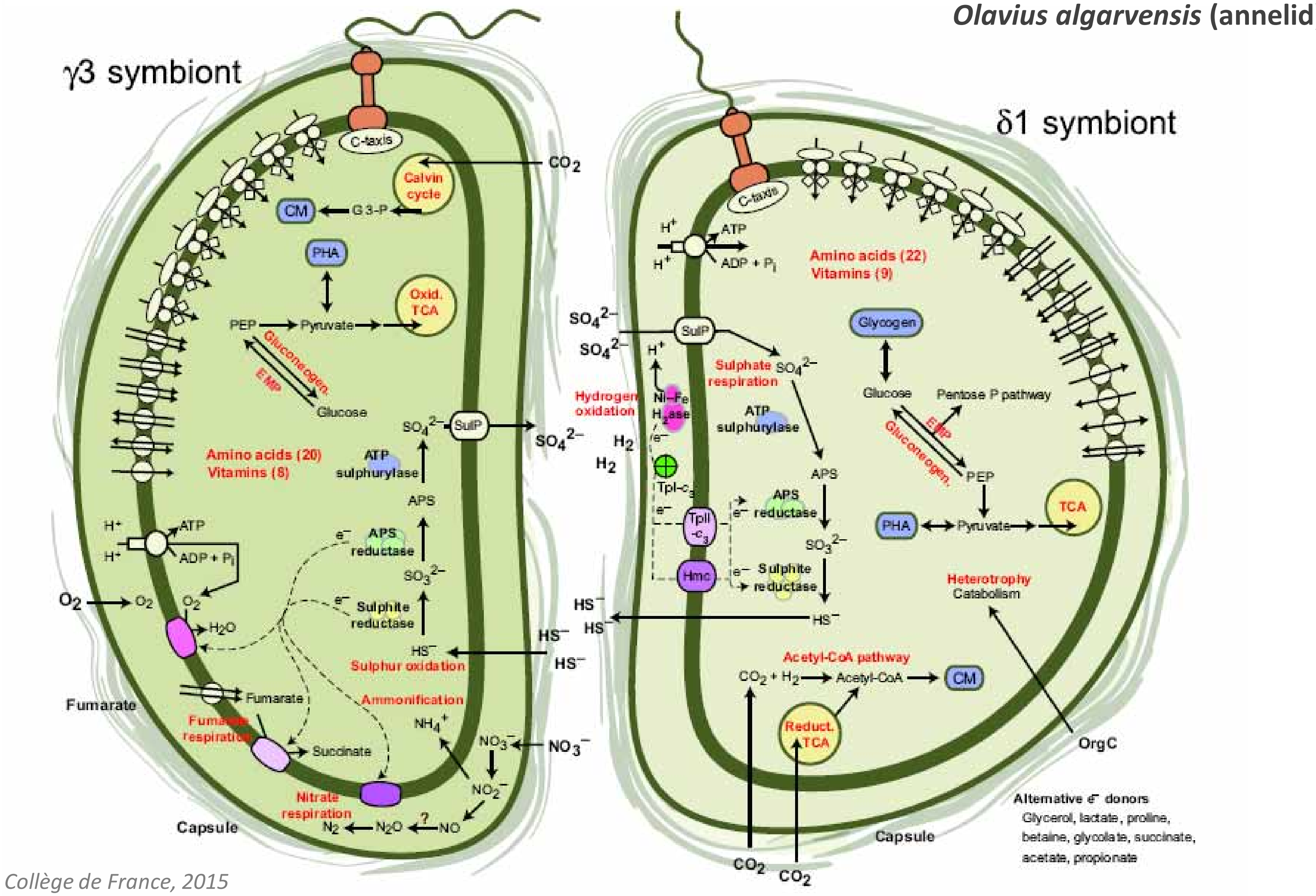
Blazejak et al, AEM 2005

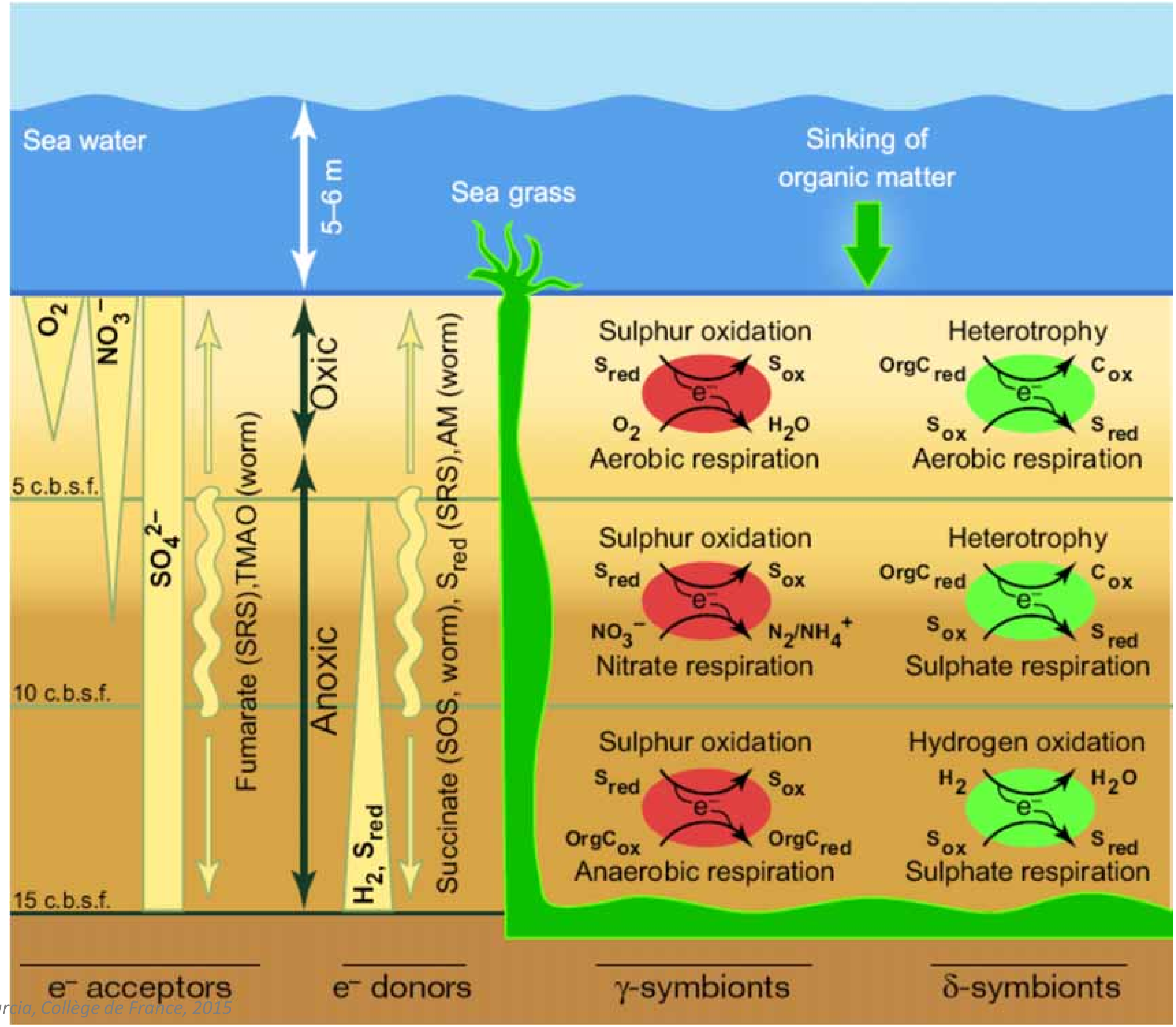
Symbiosis insights through metagenomic analysis of a microbial consortium

Nature 2006

Tanja Woyke[1,2], Hanno Teeling[3], Natalia N. Ivanova[1], Marcel Hunteman[3], Michael Richter[3], Frank Oliver Gloeckner[3,4], Dario Boffelli[1,2], Iain J. Anderson[1], Kerrie W. Barry[1], Harris J. Shapiro[1], Ernest Szeto[1], Nikos C. Kyrpides[1], Marc Mussmann[3], Rudolf Amann[3], Claudia Bergin[3], Caroline Ruehland[3], Edward M. Rubin[1,2] & Nicole Dubilier[3]

***Olavius algarvensis* (annelid)**





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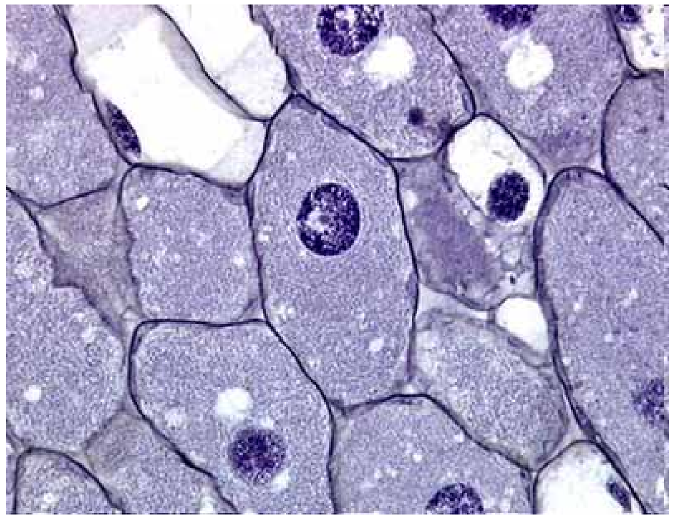
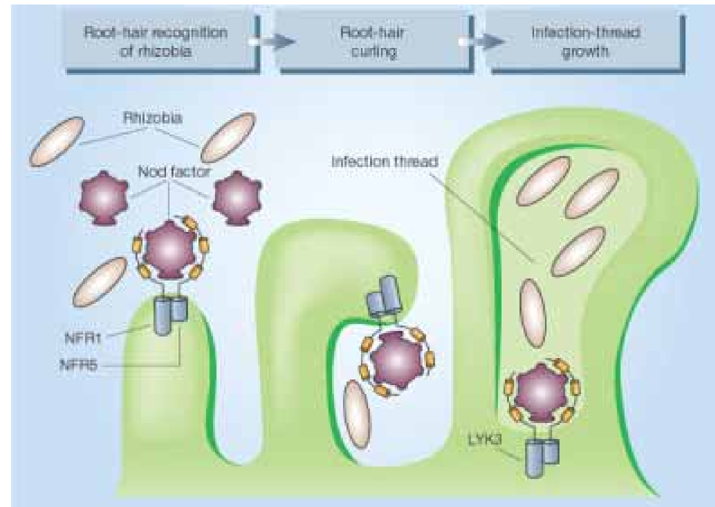
Symbioses plantes - microorganismes

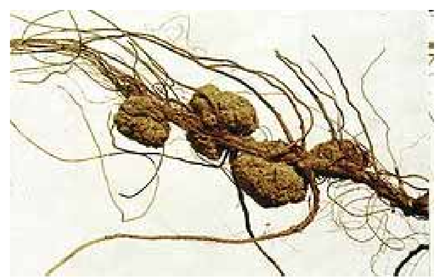
Rhizobium **et genres apparentés (Alphaproteobacteria)**

Fixation N_2





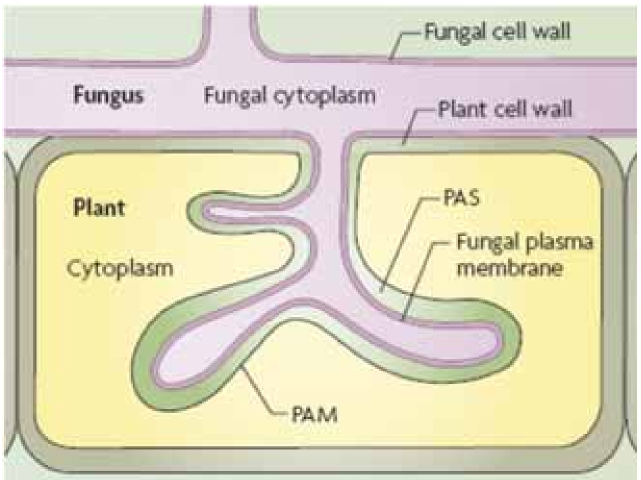
Agrobacterium **spp.**
(Alphaproteobacteria)
parasite/pathogène



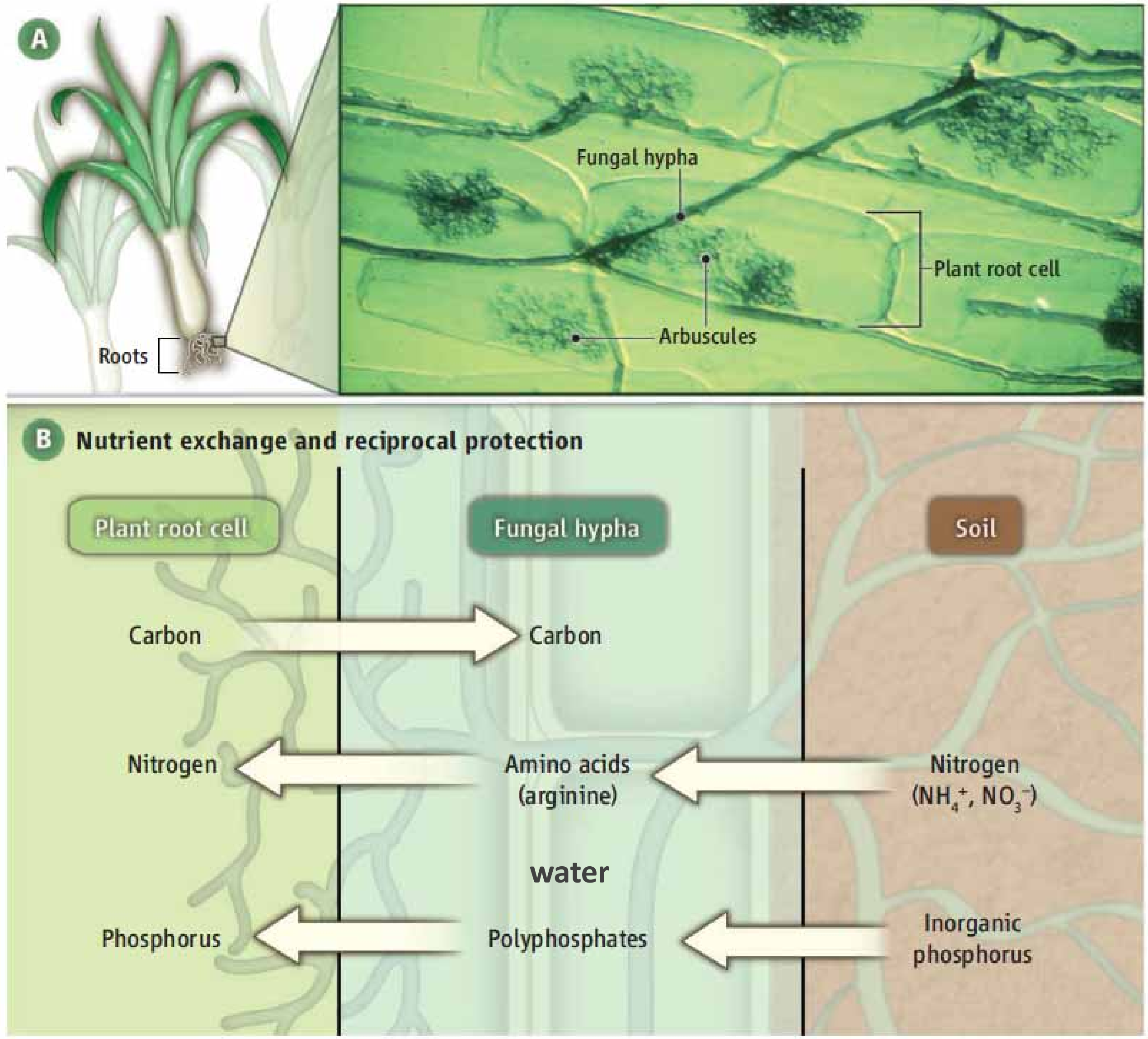
Mycorhizes

> 80% plantes terrestres – symbioses avec des champignons filamenteux (notamment Glomeromycota)

Arbuscular mycorrhiza



PAM periarbuscular space - exchanges



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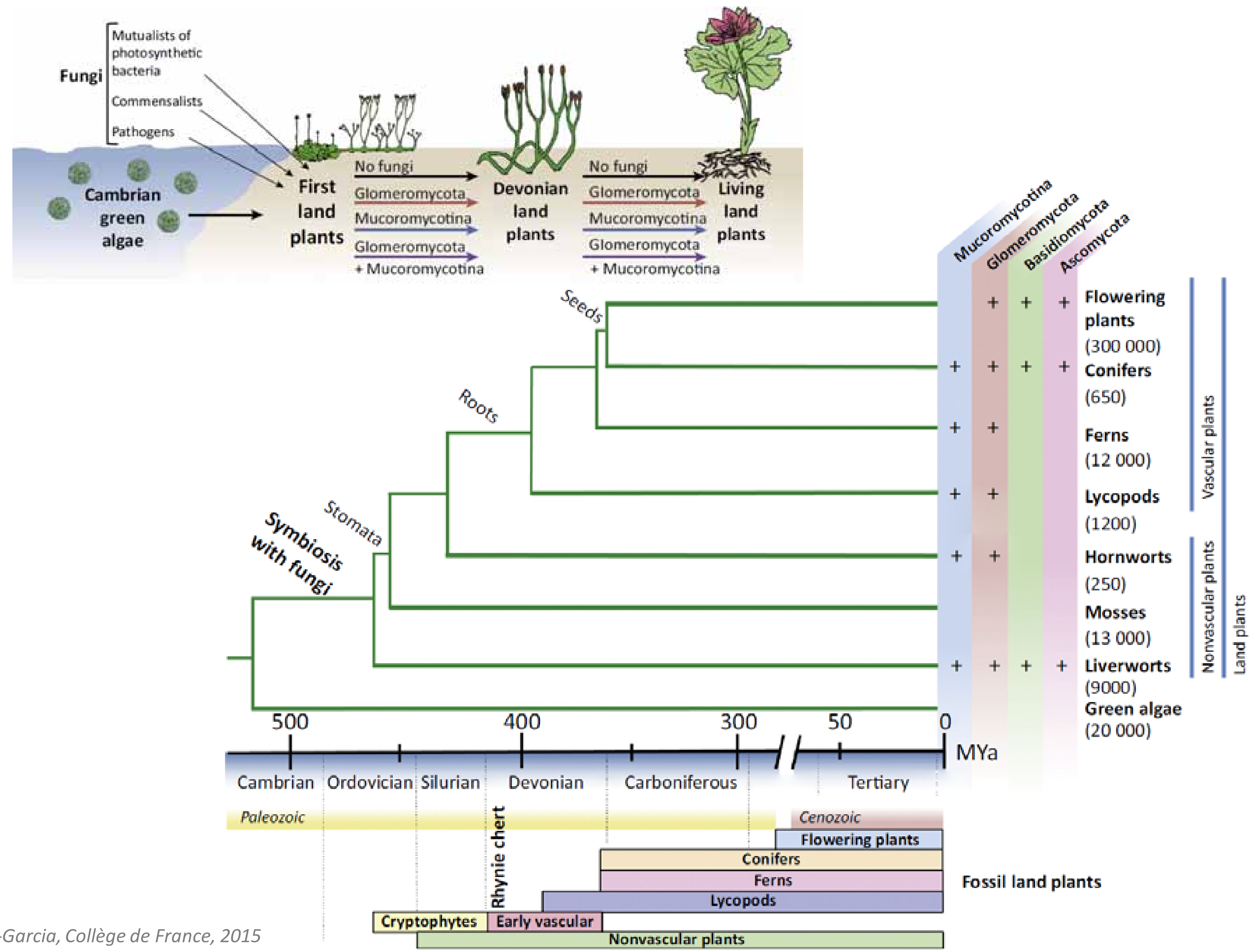
Mycorhizes et évolution des plantes terrestres



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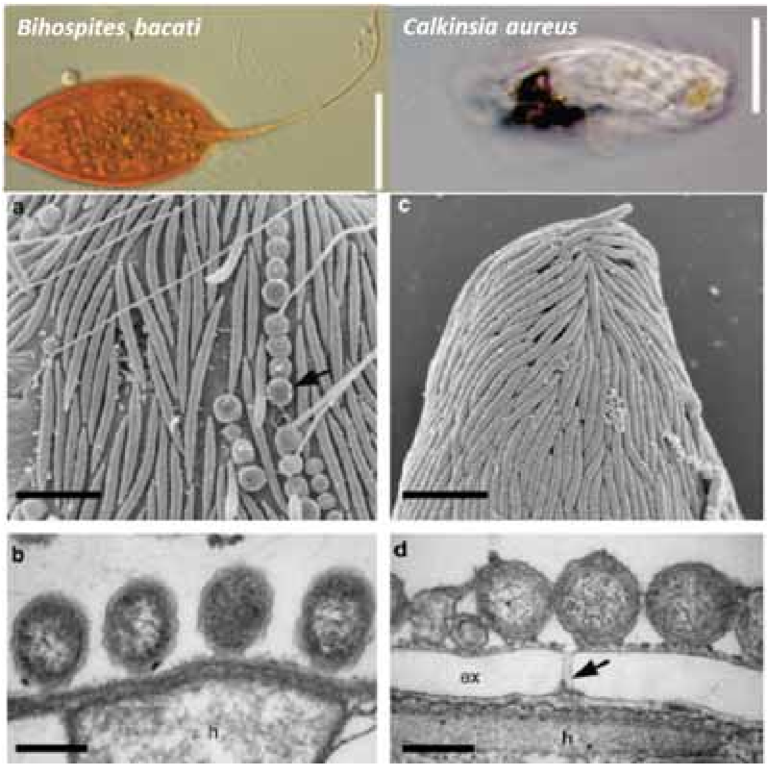
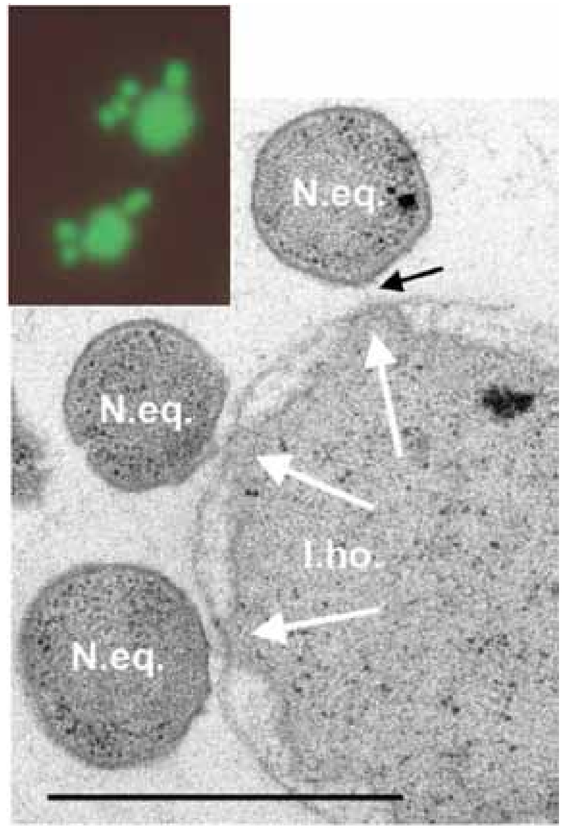
Symbioses microbiennes

eucaryote - bactérie



Symbiontida (Euglenozoa)
Epsilonproteobactérie (H_2S ou S-oxydante)

archée - archée



Ignicoccus hospitalis
Nanoarchaeum equitans
(hyperthermophiles)

bactérie - bactérie

Phototrophic consortia:
"Chlorochromatium aggregatum"

- Bactérie verte du soufre (Chlorobi): photosynthèse anoxigénique avec H_2S
- Bétaprotéobactérie hétérotrophe : mobilité ?

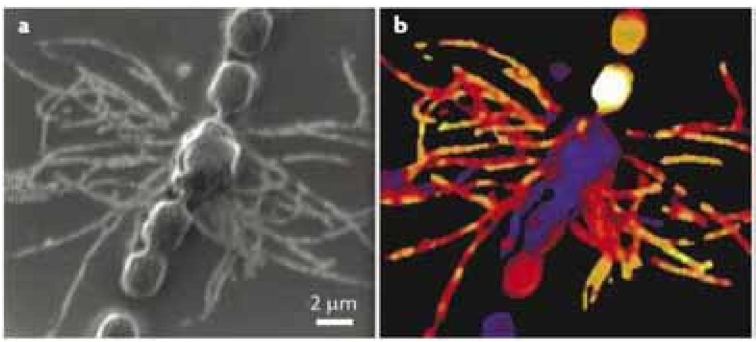
P Lopez-Garcia, Collège de France, 2015

Syntrophies : symbioses métaboliques

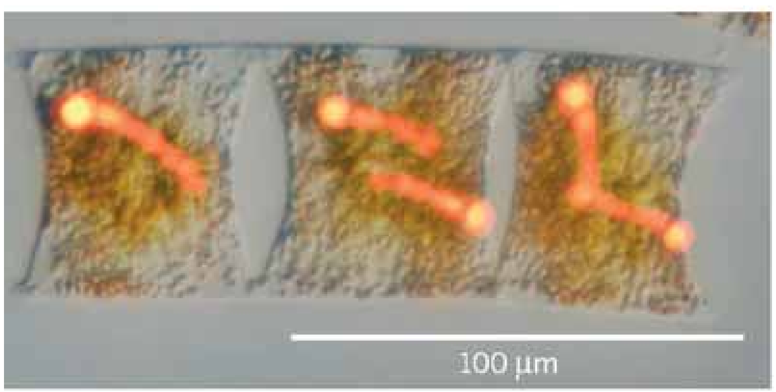
Symbioses basées sur le transfer d'azote

FISH et Nano SIMS (nano) secondary-ion mass spectrometry

Anabaena (Cyanobacteria) – *Rhizobium* fixateur de N_2 (Alphaproteobacteria)



Diatomée marine – cyanobactérie filamenteuse fixatrice de N_2 (hétérocystes)



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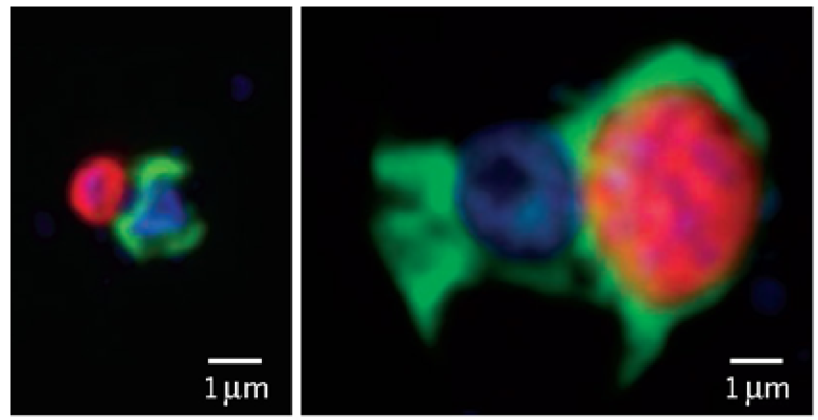
UCYN-A1 UCYN-A2



Cyanobactéries UCYN-A (rouge)

Prymnesiophyte (Haptophyta) *Braarudosphaera bigelowii* (vert)

Metabolic streamlining in an open-ocean nitrogen-fixing cyanobacterium

Nature 2010

H. James Tripp[1], Shellie R. Bench[1], Kendra A. Turk[1], Rachel A. Foster[1], Brian A. Desany[2], Faheem Niazi[2], Jason P. Affourtit[2] & Jonathan P. Zehr[1]

UCYN-A: *Candidatus* Atelocyanobacterium thalassa

Thompson et al 2012

Petite cyanobactérie marine non-cultivable et très abondante

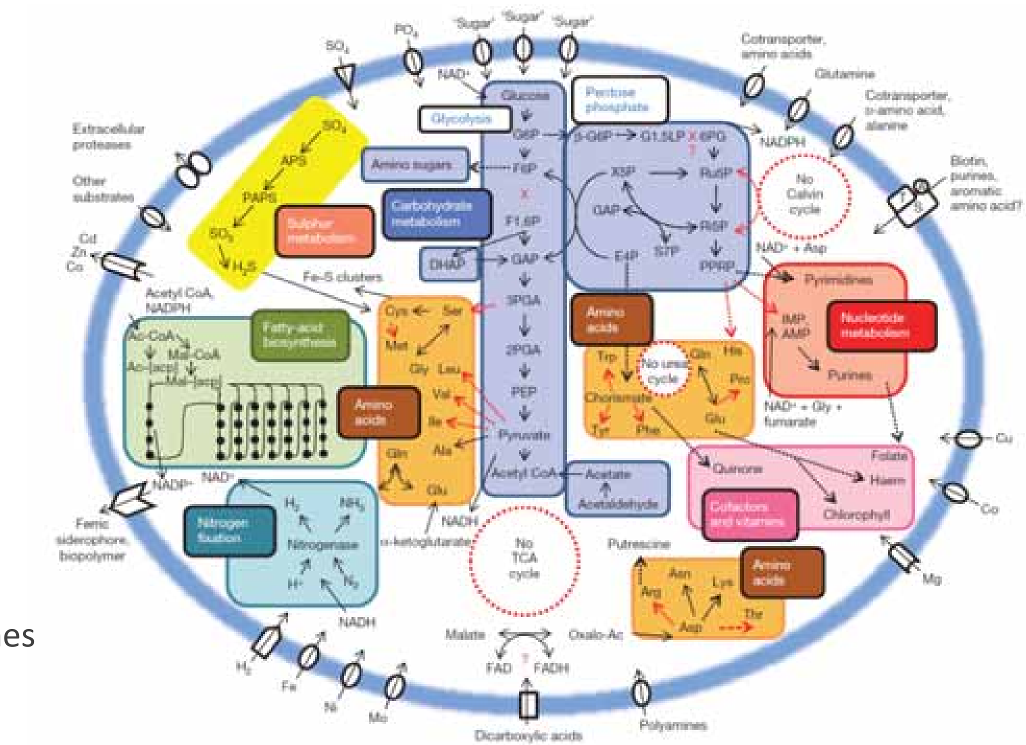
⬇

Cellules triées par FACS (*fluorescence activated cell sorting*)

⬇

Génome :

- Génome réduit : 1,44 Mbp
- Fixatrice de N_2
- Pas de gènes du photosystème II ni de RuBisCO (pas de photosynthèse)
- Plusieurs voies de synthèse d'acides aminés et purines



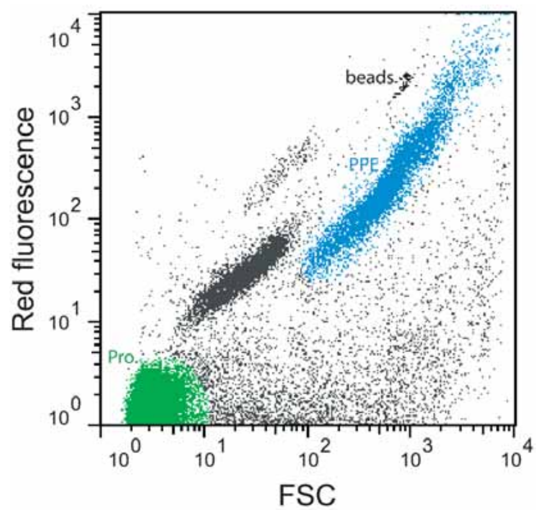
Symbiose ?

21 SEPTEMBER 2012 VOL 337 SCIENCE

Unicellular Cyanobacterium Symbiotic with a Single-Celled Eukaryotic Alga

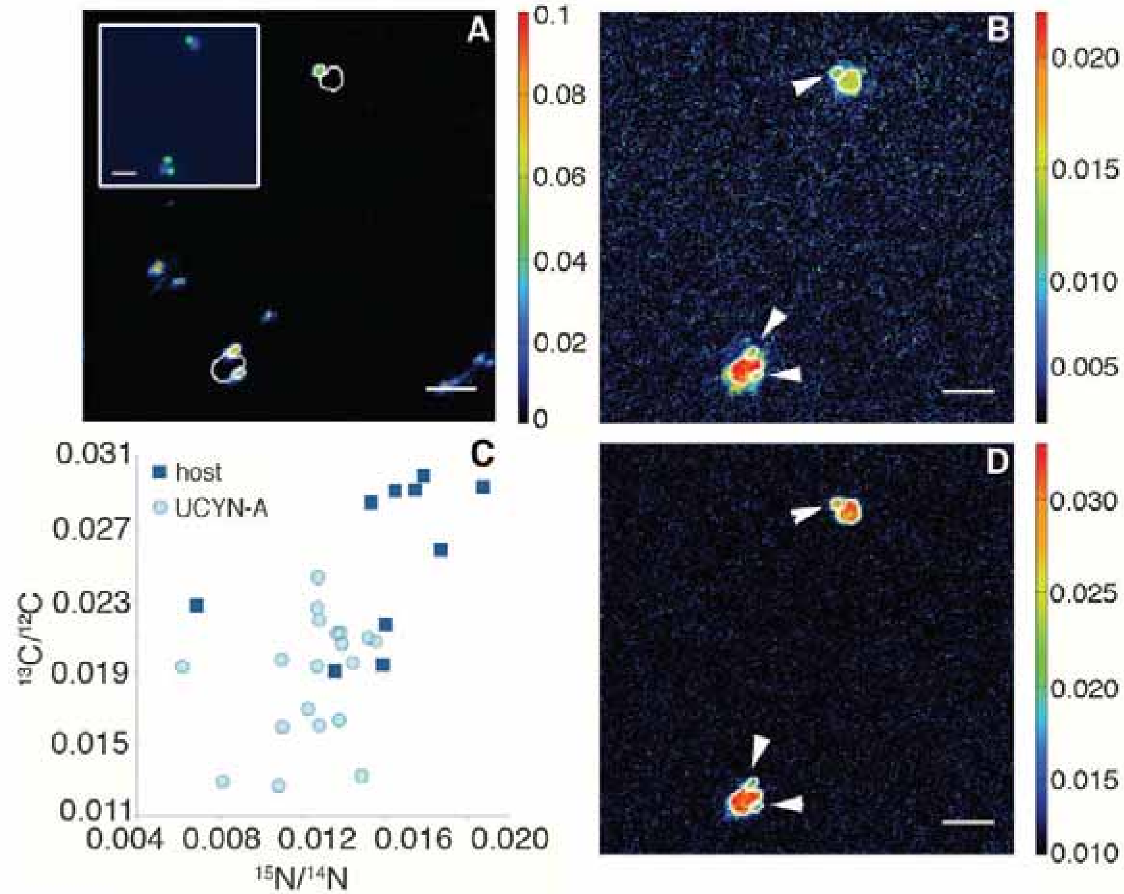
Anne W. Thompson,[1*] Rachel A. Foster,[2*] Andreas Krupke,[2] Brandon J. Carter,[1] Niculina Musat,[2†] Daniel Vaulot,[3] Marcel M. M. Kuypers,[2] Jonathan P. Zehr[1‡]

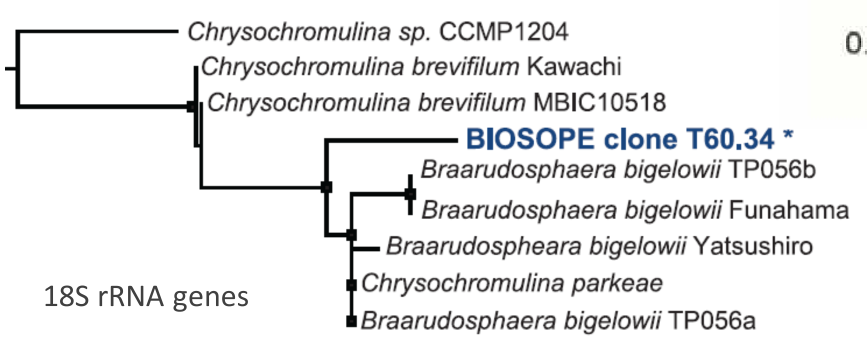
FACS (fluorescent activated cell sorting)



PPE, picoplanktonic photosynthetic eukaryotes

HISH-SIMS
halogenated in situ hybridization
(nano) secondary-ion mass spectrometry





18S rRNA genes

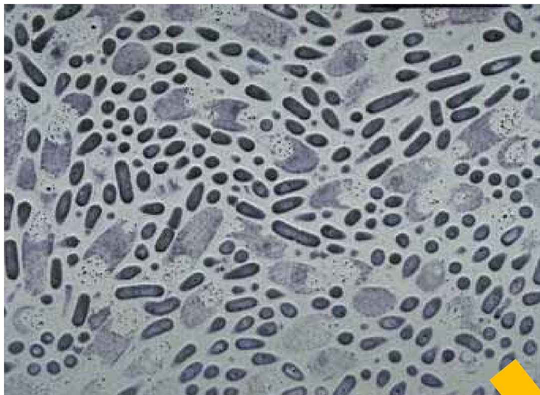
Hôte : picoalgue (Prymnesiophyta, Haptophyta)

Echange : N organique à l'algue, C à la cyanobactérie

Syntrophies : symbioses métaboliques

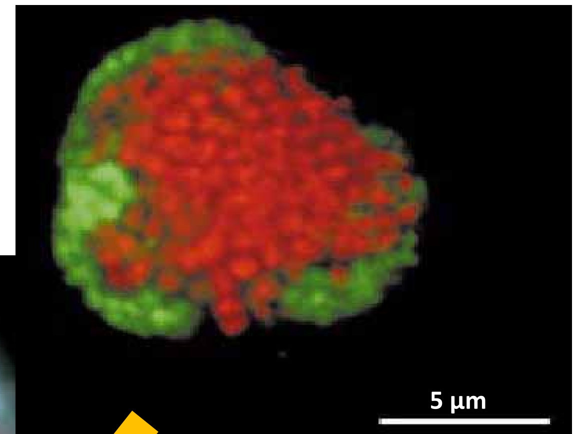
Transfer interspécifique d'hydrogène

Archées méthanogènes
Bactéries fermentatrices

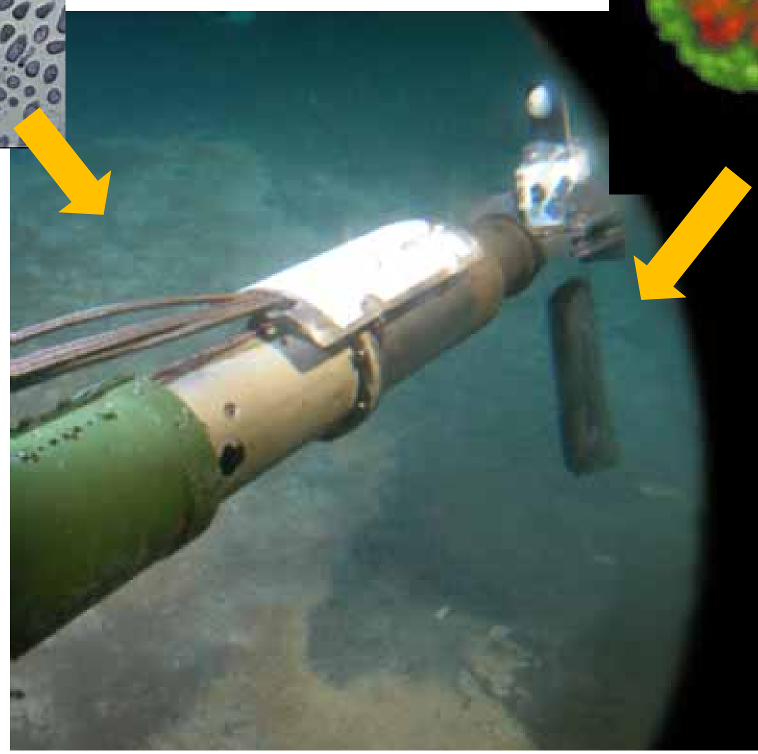


Sédiments anoxiques

Oxidation anaérobie du méthane (CH_4) :
Archées méthanotrophes (ANME)
+ bactéries sulfato-réductrices



Suintements froids



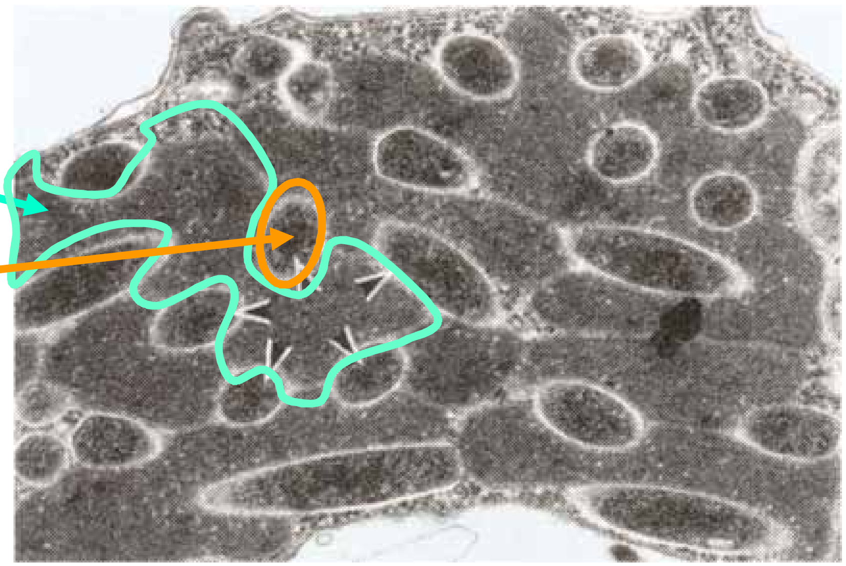
P Lopez-Garcia, Collège de France, 2015

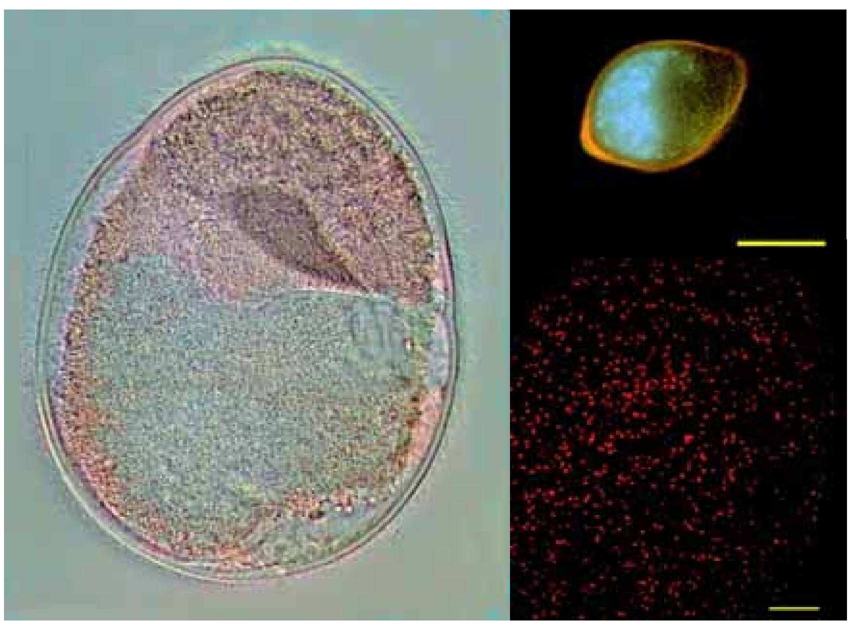
Endosymbioses

Methanogenic archaea and Hydrogenosomes
(H_2-producing organelles in anaerobic protists)

composés organiques → H_2 + CO_2

H_2 + CO_2 → CH_4





archées méthanogènes dans le cilié anaérobie *Nyctotherus ovalis*

P Lopez-Garcia, Collège de France, 2015

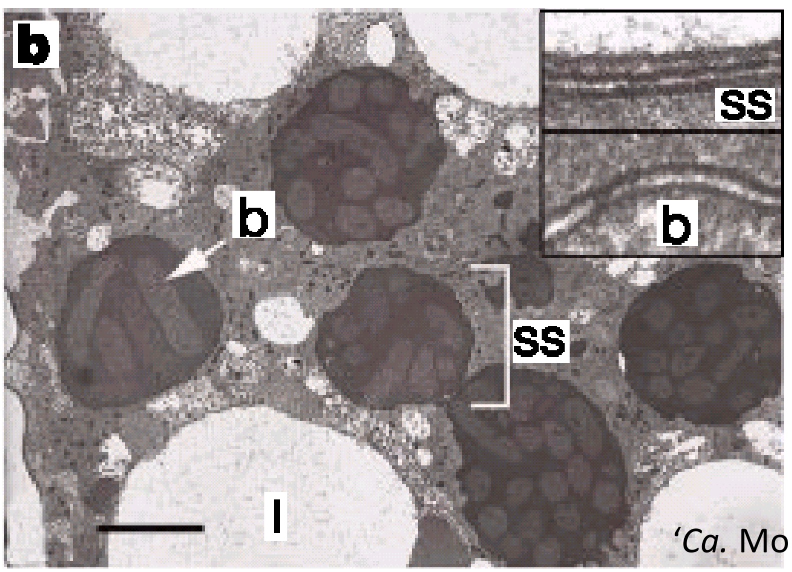
Endosymbiose chez les procaryotes

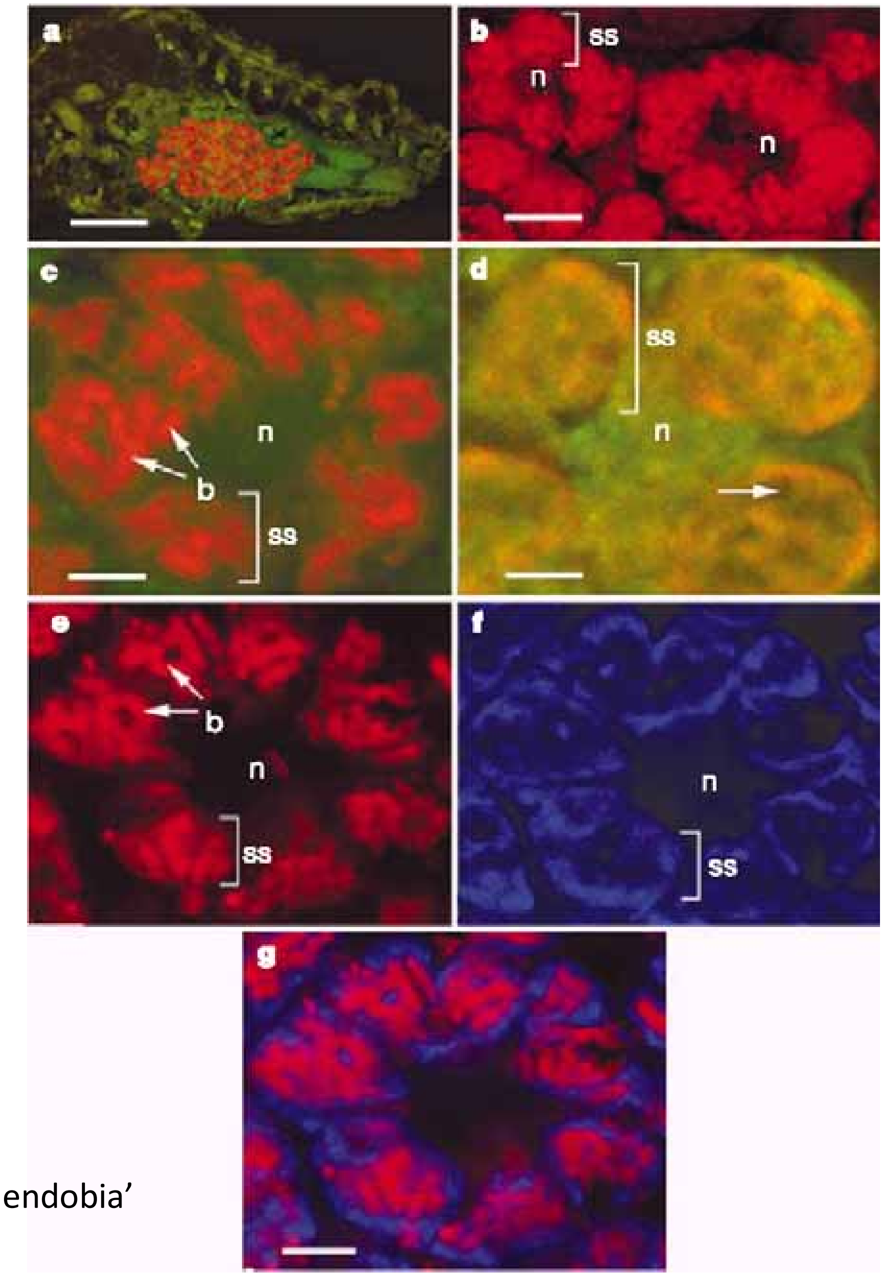
NATURE | VOL 412 | 26 JULY 2001 | www.nature.com

Mealybug β-proteobacterial endosymbionts contain γ-proteobacterial symbionts

Carol D. von Dohlen, Shawn Kohler*, Skylar T. Alsop & William R. McManus

Department of Biology, 5305 Old Main Hill, Utah State University, Logan, Utah 84322, USA



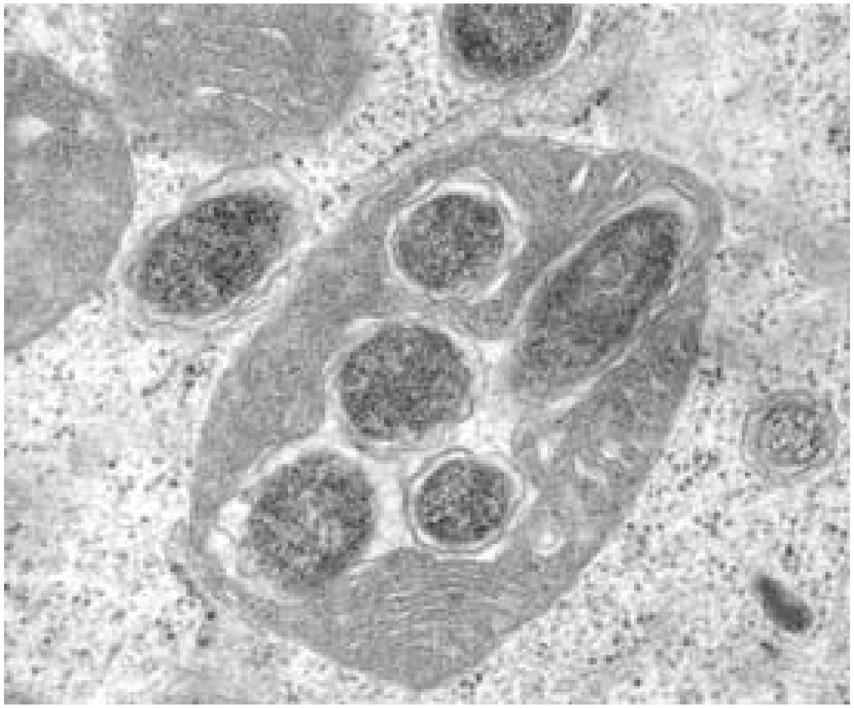


‘*Ca.* Moranella endobia’

Endosymbiose chez la mitochondrie !

Alphaproteobactéries appartenant aux Rickettsiales (parasites intracellulaires)

Ixodes ricinus **(tick)**



Sassera et al, 2006

Evolution du génome lors de l'endosymbiose

SymbioGenomes Database

http://symbiogenomesdb.uv.es/

1 056 génomes de symbiotes associés à plus de 200 hôtes

Diminution de la taille du génome

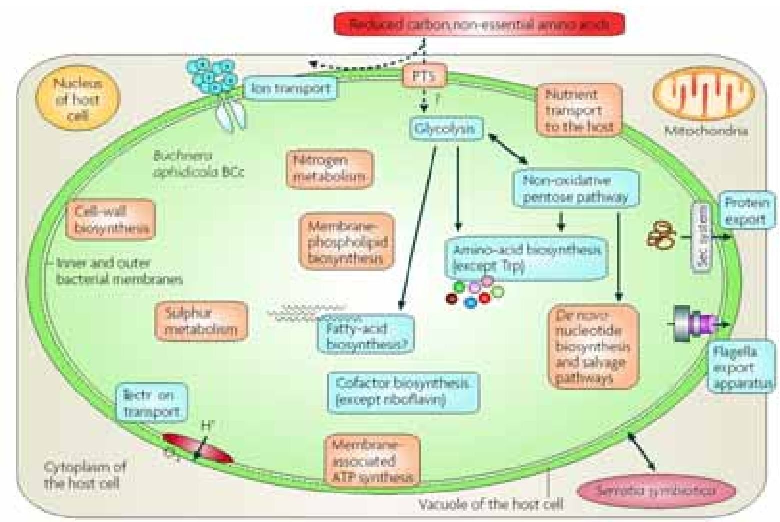
- Inactivation de gènes(pseudogènes) et pertes
- Transfer horizontal de gènes à l'hôte

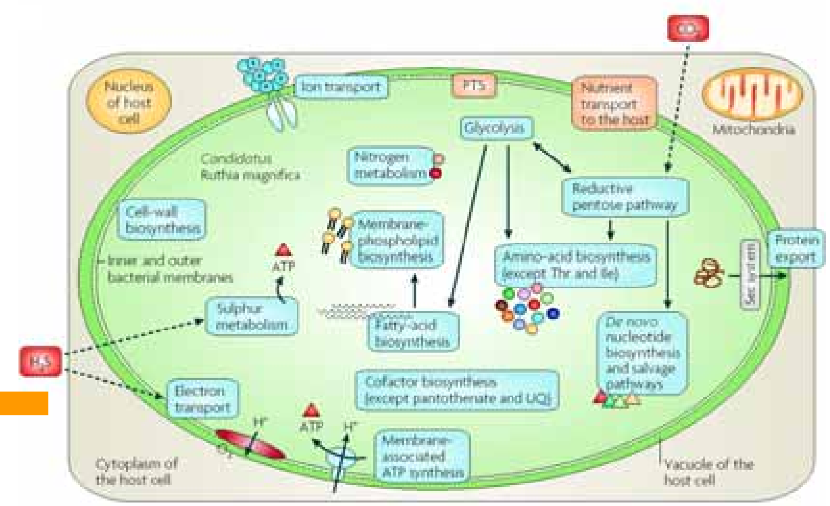
Diminution du contenu en GC

Table 1 | **Genomic data for mutualistic symbionts of animals**

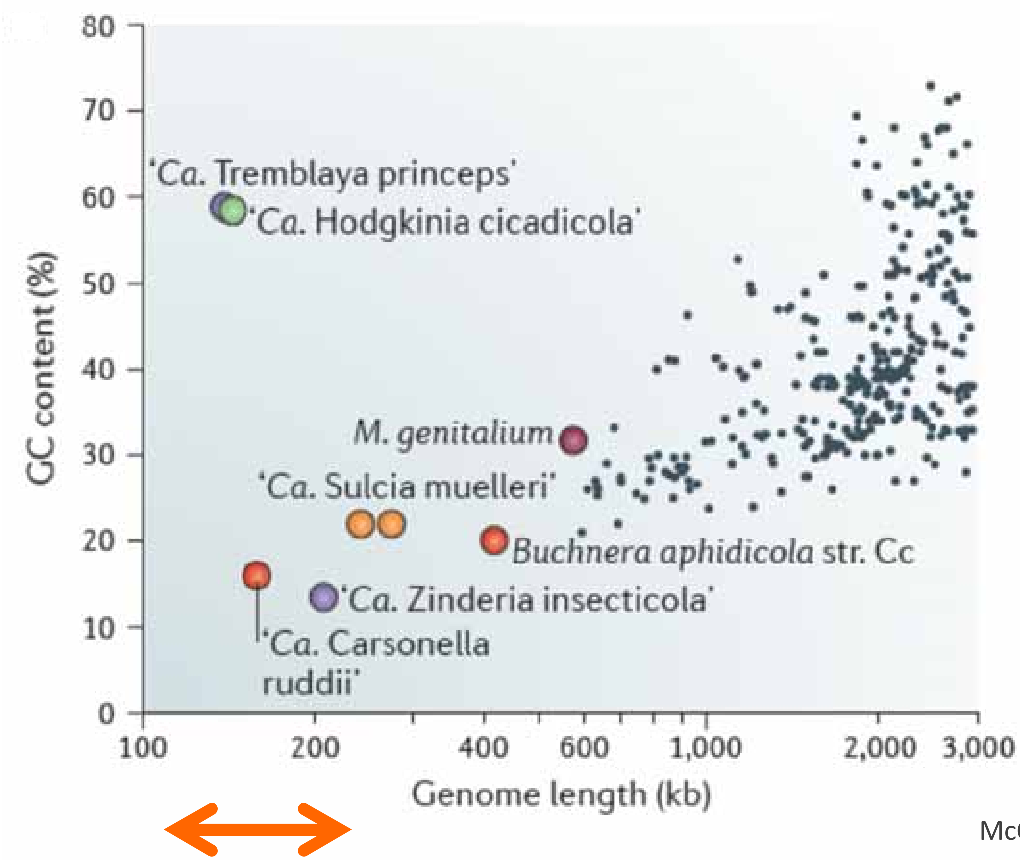
Organism	Host	Metabolic mode	Genome size (kb)	GC content (%)
Buchnera aphidicola BAp*	*Acyrthosiphon pisum* (aphid)[‡]	Heterotroph	652	26.24
Buchnera aphidicola BSg*	*Schizaphis graminum* (aphid)	Heterotroph	653	26.3
Buchnera aphidicola BBp*	*Baizongia pistaciae* (aphid)	Heterotroph	618	25.3
Buchnera aphidicola BCc*	*Cinara cedri* (aphid)	Heterotroph	422	20.2
Blochmannia floridanus[*§]	*Camponotus floridanus* (carpenter ant)	Heterotroph	706	27.4
Blochmannia pennsylvanicus[*§]	*Camponotus pennsylvanicus* (carpenter ant)	Heterotroph	792	29.6
*Wigglesworthia glossinidia**	*Glossina brevipalpis* (tsetse fly)	Heterotroph	698	22.5
*Sodalis glossinidius**	*Glossina morsitans* (tsetse fly)[‡]	Heterotroph (Secondary)	4,171	54.7
Baumannia cicadellinicola[*§]	*Homalodisca coagulata* (sharpshooter)	Heterotroph	686	33.2
Sulcia muelleri[§‖]	*Homalodisca coagulata* (sharpshooter)	Heterotroph	245	22.4
Carsonella ruddii[*§]	*Pachypsylla venusta* (psyllid)	Heterotroph	160	16.6
Wolbachia wBm[¶]	*Brugia malayi* (nematode)[#]	Heterotroph	1,080	34
Ruthia magnifica[*§]	*Calyptogena magnifica* (Deep-sea clam)	Autotroph	1,200	34.0
Vesicomyosocius okutanii[*§]	*Calyptogena okutanii* (Deep-sea clam)	Autotroph	1,000	31.6
Nitratiruptor sp**	Deep-sea-vent animals	Autotroph	1,878	39.7
Sulfurovum sp**	Deep-sea-vent animals	Autotroph	2,563	43.8

Plus petits génomes…





... et génomes enrichis en AT



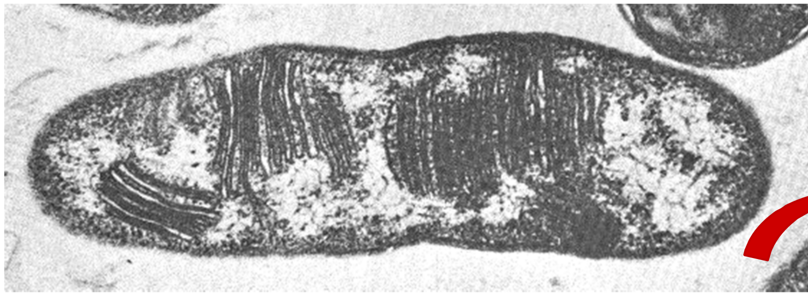
McCutcheon & Moran, NRM 2011

Symbiotes ou organites ?

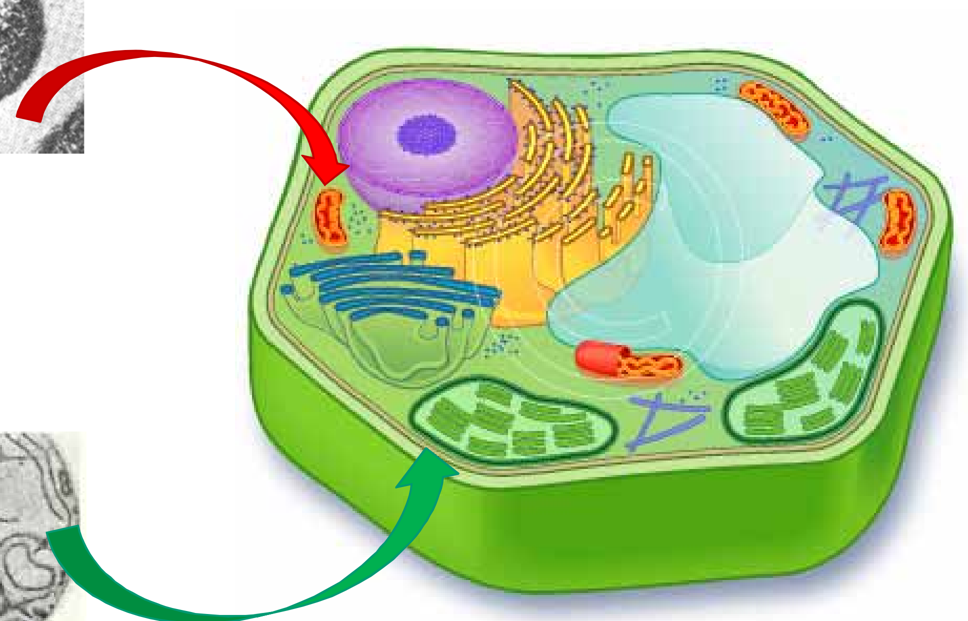
1) **Biais mutationnel universel** (G ou C) vers (A ou T) — Hershberg, 2010

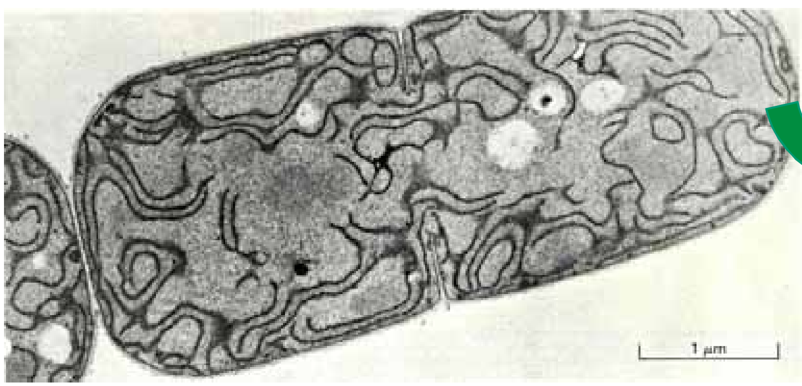
2) **Cliquet de Muller :** en absence de compétition forte, dans des lignées asexuées avec des tailles effectives faibles -> Fixation et accumulation de mutations défavorables

Endosymbiose et origine des organites eucaryotes



Alphaproteobacteria

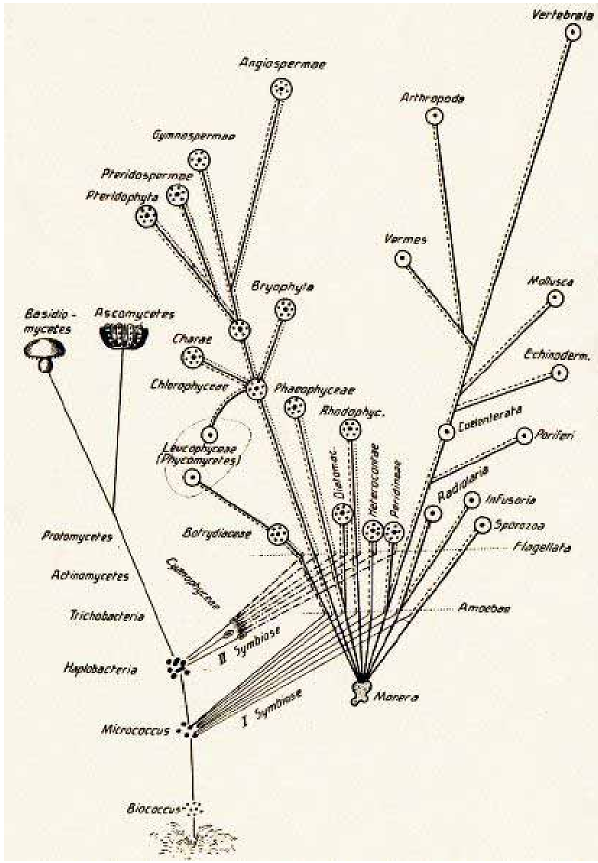




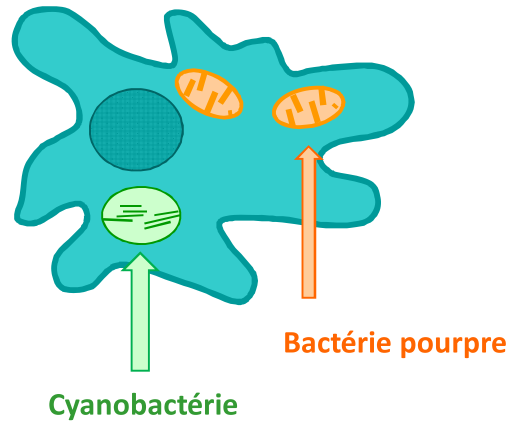
Cyanobacteria

Origine endosymbiotique de mitochondries et plastes

Konstantin Mereschkowsky, 1905



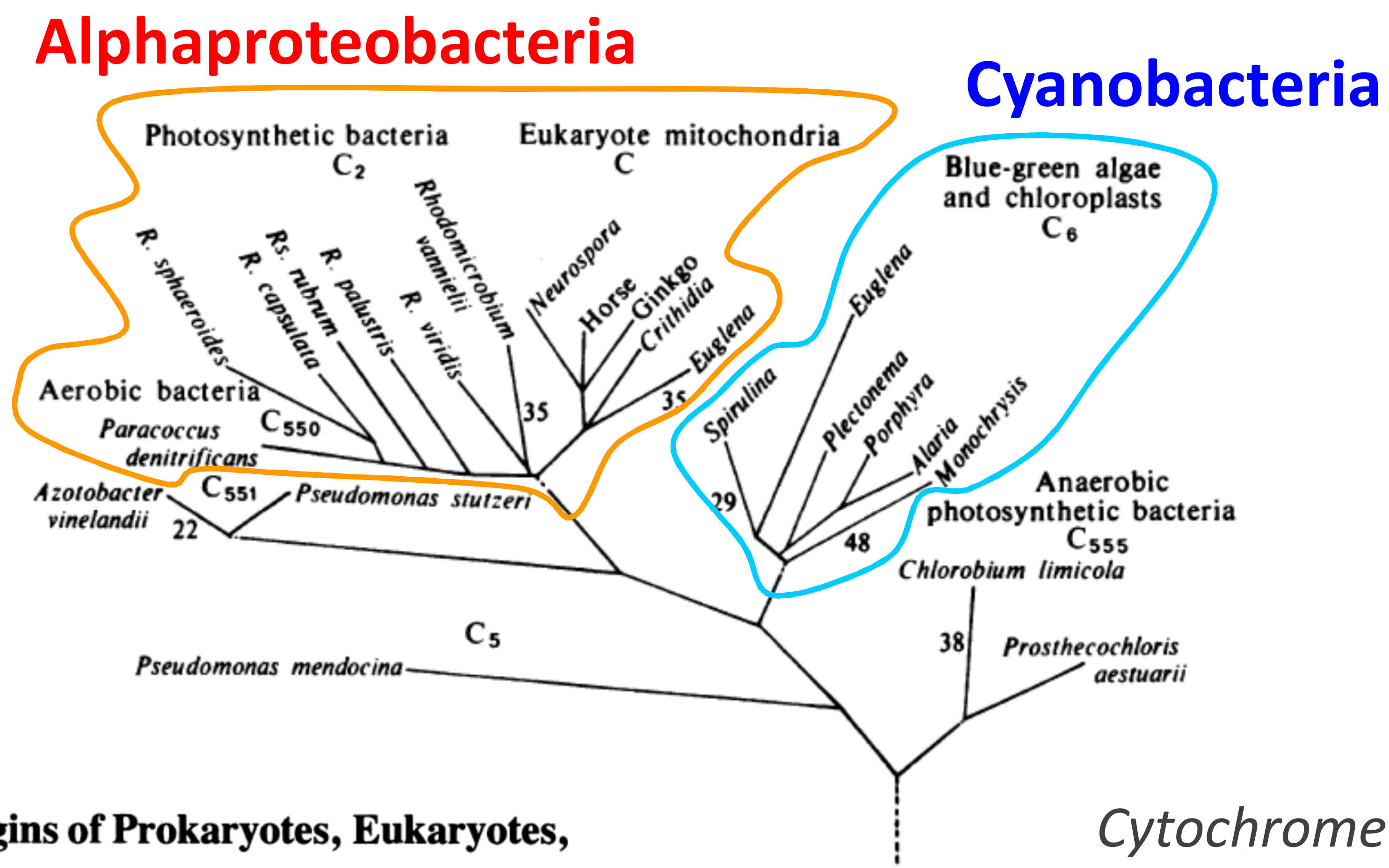
Lynn Margulis (Sagan), 1967



- Mitochondries et chloroplastes dérivent des mitochondries et chloroplastes préexistants
- Organites entourés par une double membrane
- Ribosomes de type bactérien - synthèse de leurs protéines
- Génomes (souvent 1 molécule d'ADN circulaire) … avec des gènes de type procaryote

P Lopez-Garcia, Collège de France, 2015

Origine endosymbiotique de mitochondries et plastes



Cytochrome C

Origins of Prokaryotes, Eukaryotes, Mitochondria, and Chloroplasts

SCIENCE, VOL. 199, 27 JANUARY 1978

Robert M. Schwartz and Margaret O. Dayhoff

L'origine des chloroplastes

Réduction progressive du génome

Cyanobactérie

Free-living

Prochlorococcus spp.	**1.6-1.7** Mbp
Nostoc spp.	**8.2-9.2** Mbp
Scytonema spp.	**12.3** Mbp

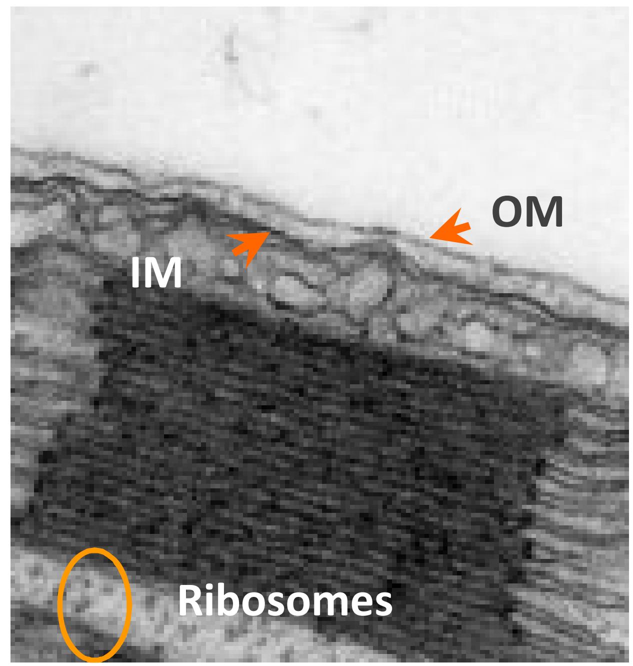
Transfert de gènes vers le noyau :
~15% gènes *Arabidopsis thaliana* d'origine cyanobactérienne

Chloroplaste

Organites avec génome :

Plantes terrestres **110-120** gènes

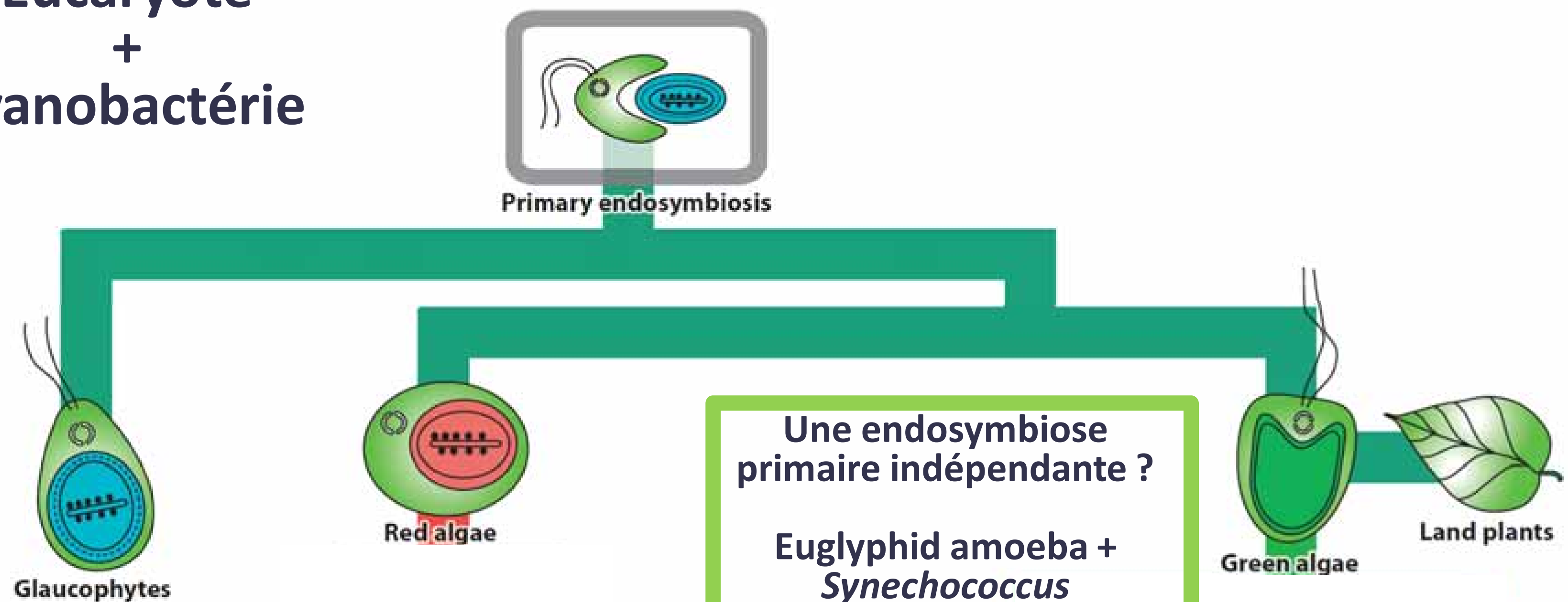
Certaines algues jusqu'à **200** gènes



P Lopez-Garcia, Collège de France, 2015

Endosymbiose primaire

Eucaryote
+
cyanobactérie

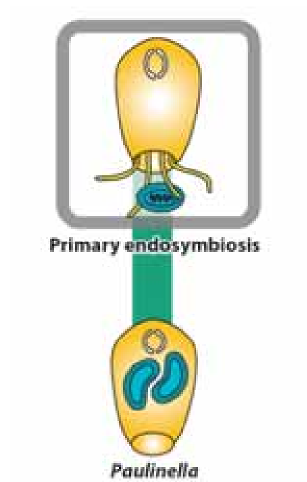


Glaucophytes

Rhodophytes

Une endosymbiose primaire indépendante ?

Euglyphid amoeba + *Synechococcus*

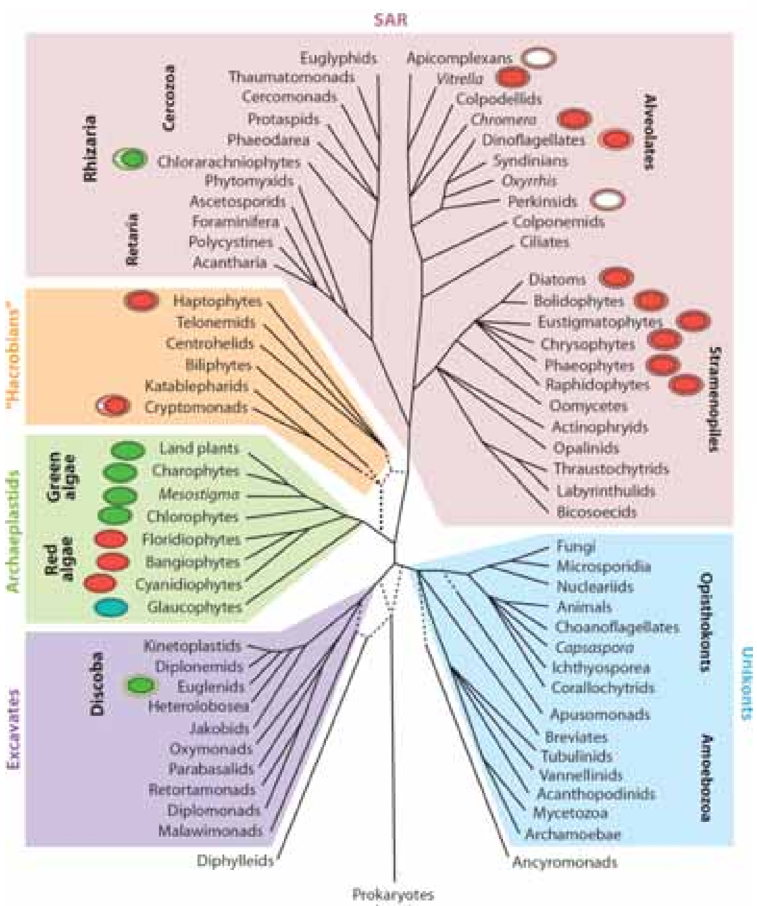


Green plants & algae

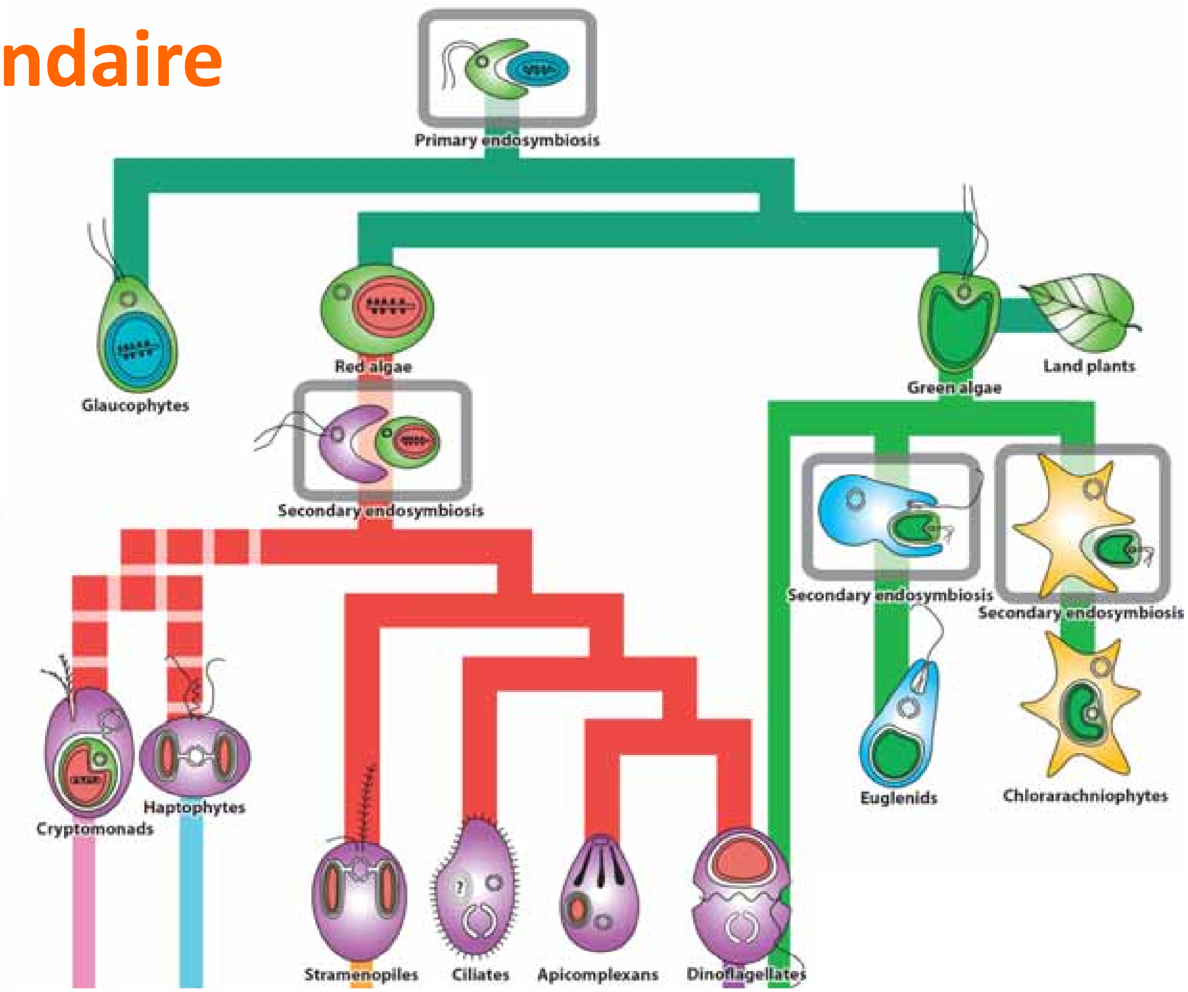
P Lopez-Garcia, Collège de France, 2015

Endosymbiose secondaire

Eucaryote + eucaryote photosynthétique

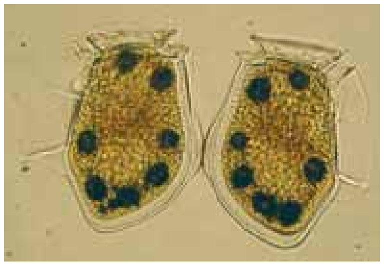


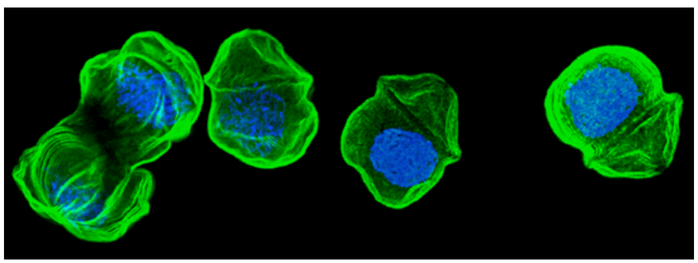
P Lopez-Garcia, Collège de France, 2015

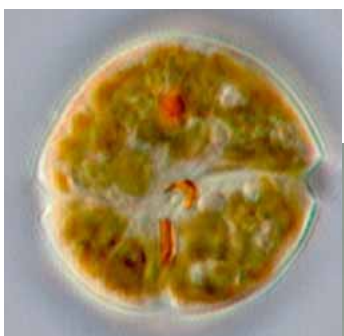


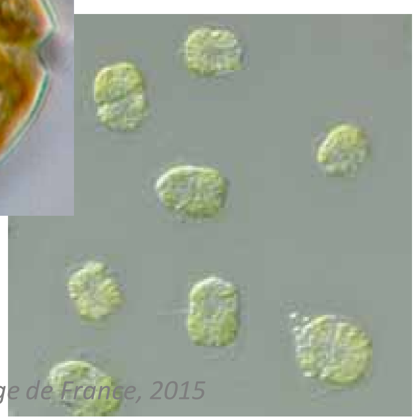
Keeling, 2013

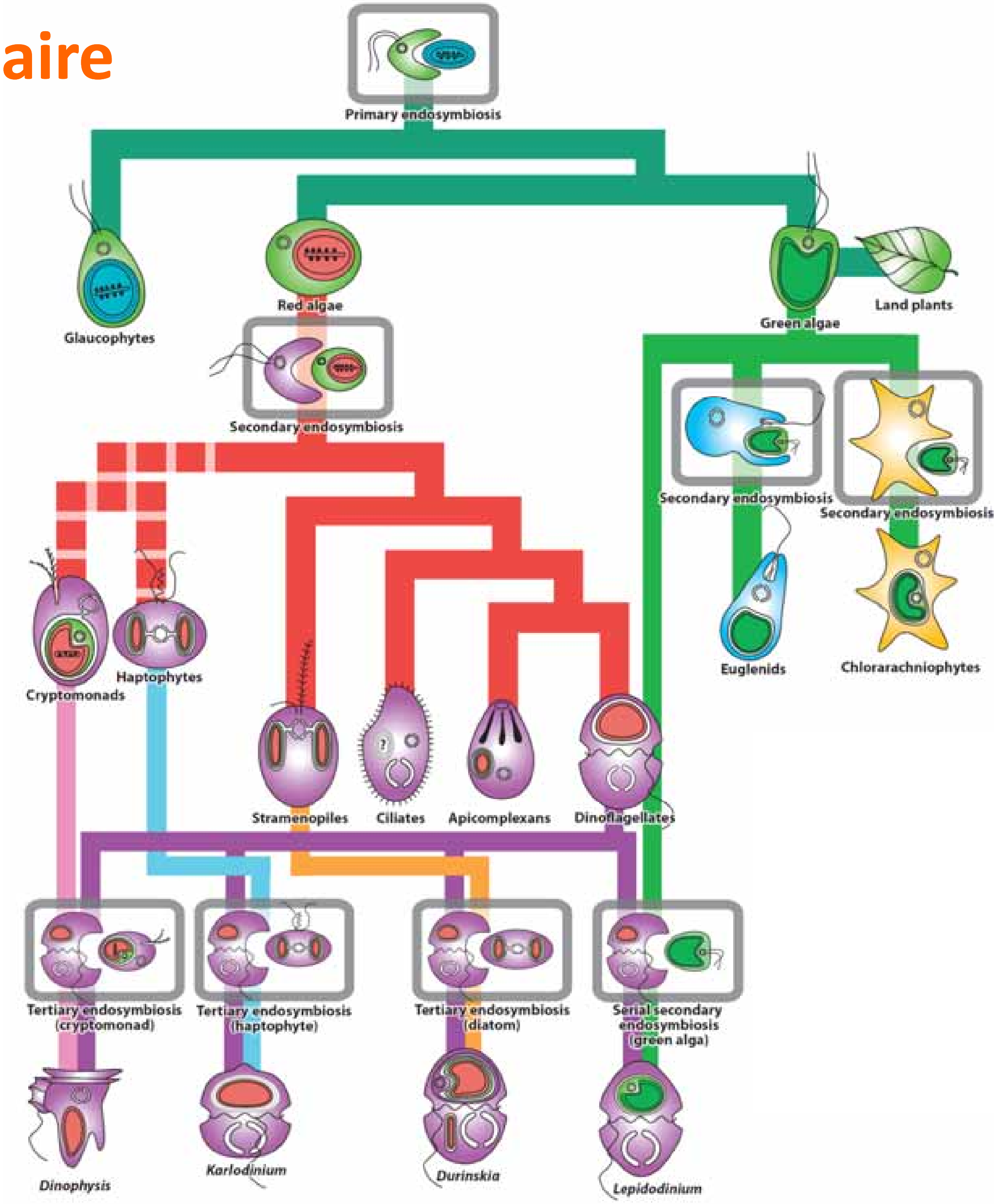
Endosymbiose terciaire
et en série











P Lopez-Garcia, Collège de France, 2015

La symbiose mitochondriale

Réduction progressive du génome

Symbiont facultatif → **Symbiont obligatoire** → **Organite**

Alphaproteobacteria - génomes

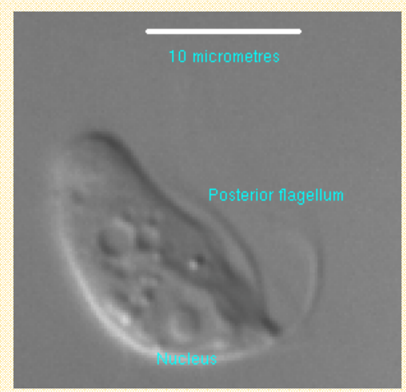
Parasites	
Rickettsia rickettsii	**1.27** Mbp
Free-living	
Rhodospirillum photometricum	**3.88** Mbp
Rhodobacter sphaeroides KD131	**4.71** Mbp
Magnetococcus marinus	**4.72** Mbp
Methylosinus trichosporium	**4.96** Mbp
Rhizobium selenitireducens	**4.97** Mbp
Paracoccus denitrificans PD1222	**5.23** Mbp
Sphingomonas wittichii	**5.9** Mbp
Bradyrhizobium diazoefficiens	**9.11** Mbp

Mitochondries - génomes

3 protein-coding genes (Apicomplexa)

13 protein-coding genes (Mammalia, Metazoa)

~100 gènes (Jakobida, Excavata)



Reclinomonas americana
(*Reclinomonas*-94), 96 genes

Andalucia godoyi
100 genes

P Lopez-Garcia, Collège de France, 2015

La symbiose mitochondriale

Réduction progressive et extinction du génome

Symbiont facultatif

Symbiont obligatoire

Organite

Avec génome — **Sans génome**

Mitochondria

respiration O_2

Hydrogenosomes

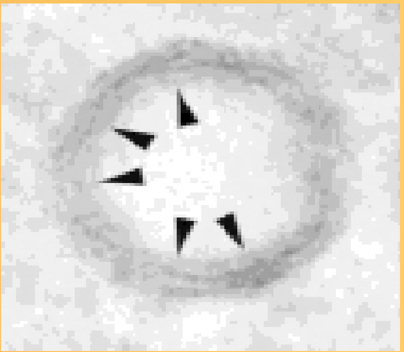
H_2-producing organelles in anaerobic protists

(*Nychtotherus ovalis* hydrogenosome contains a genome)

Akhmanova et al 1998

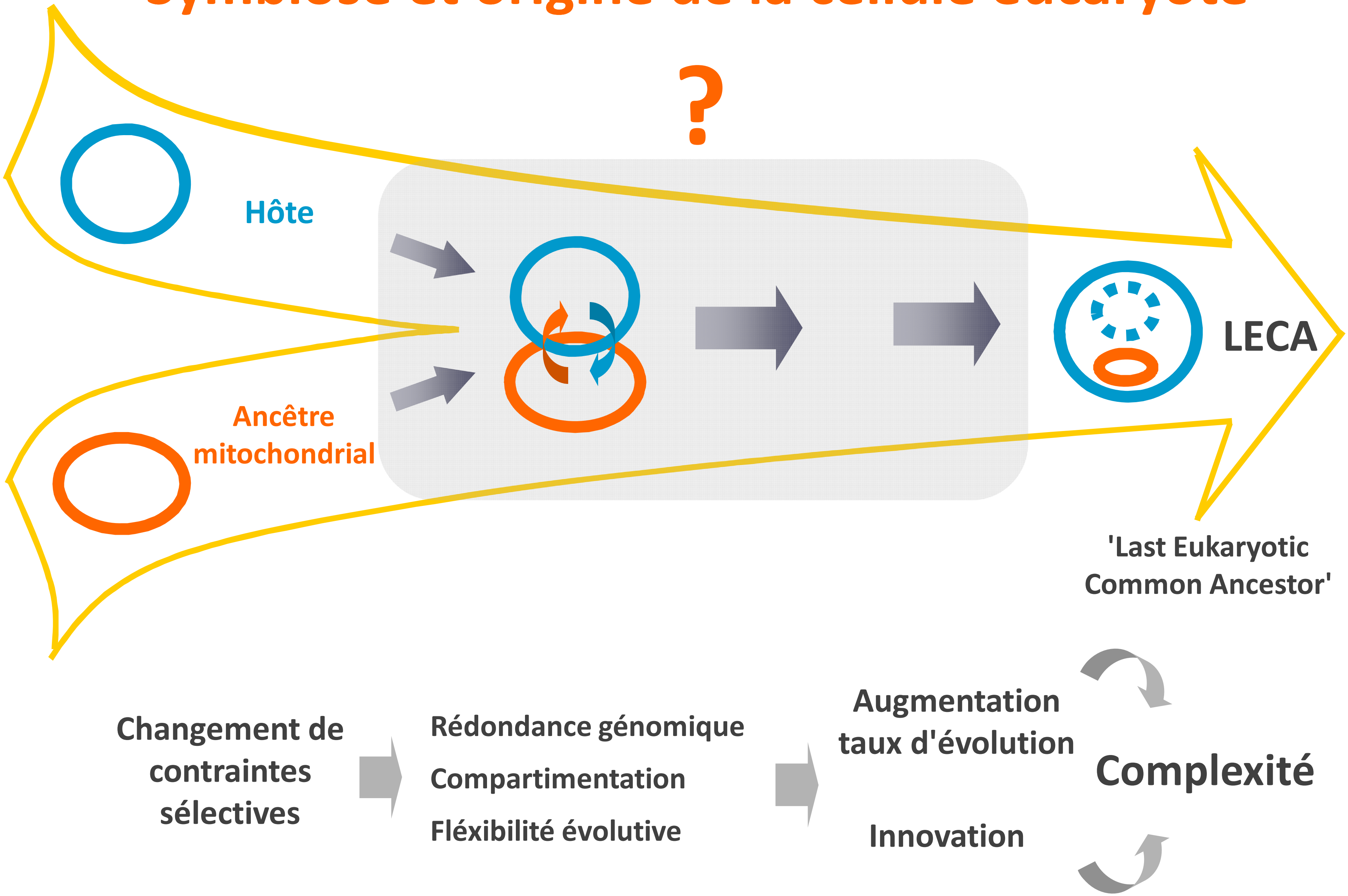
Mitosomes (cryptons)

Fe-S cluster assembly



(Microsporidia)

Symbiose et origine de la cellule eucaryote



P Lopez-Garcia, Collège de France, 2015

Merci !

http://www.ese.u-psud.fr/rubrique7.html?lang=en

puri.lopez@u-psud.fr

P Lopez-Garcia, Collège de France, 2015