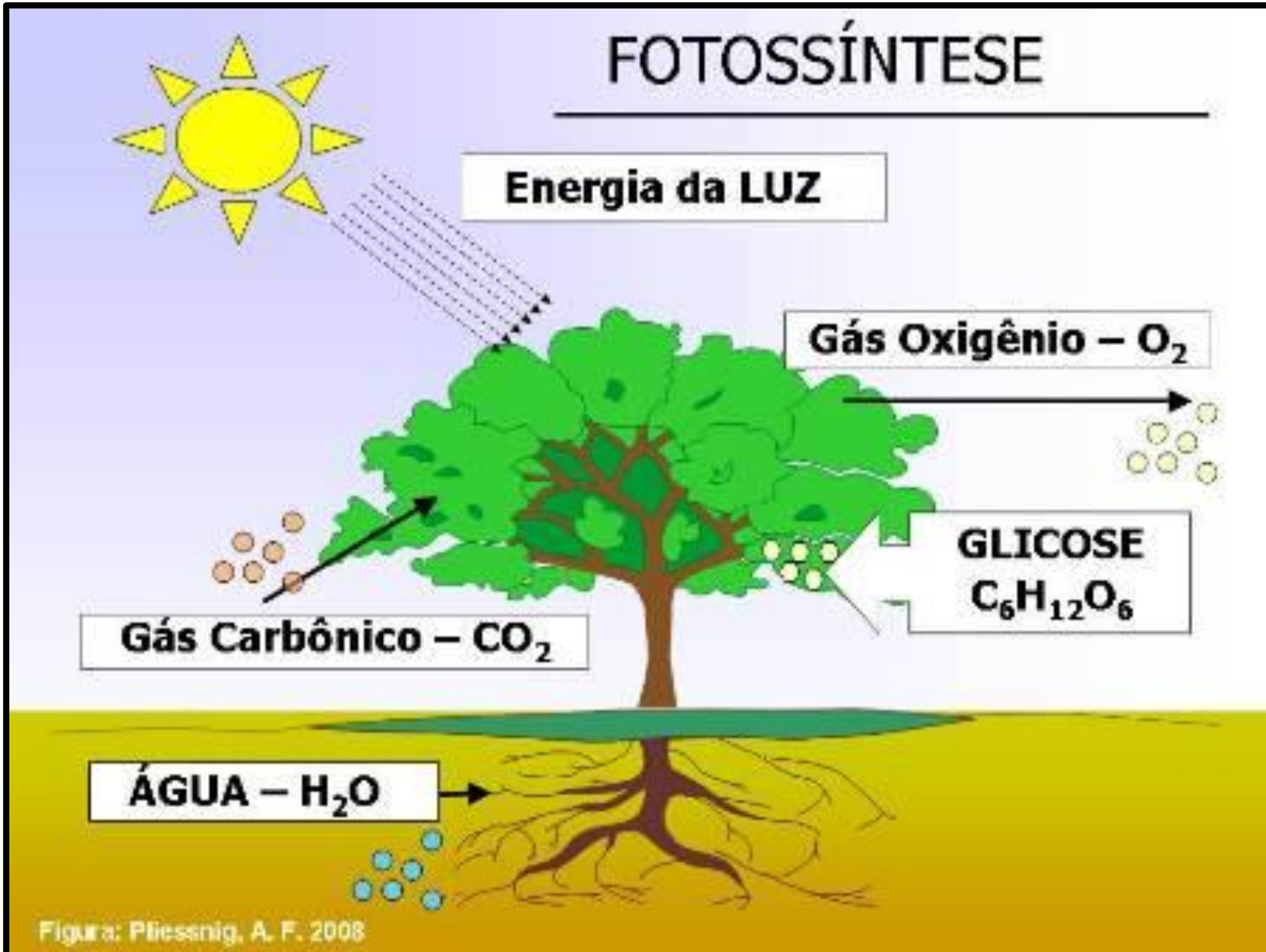
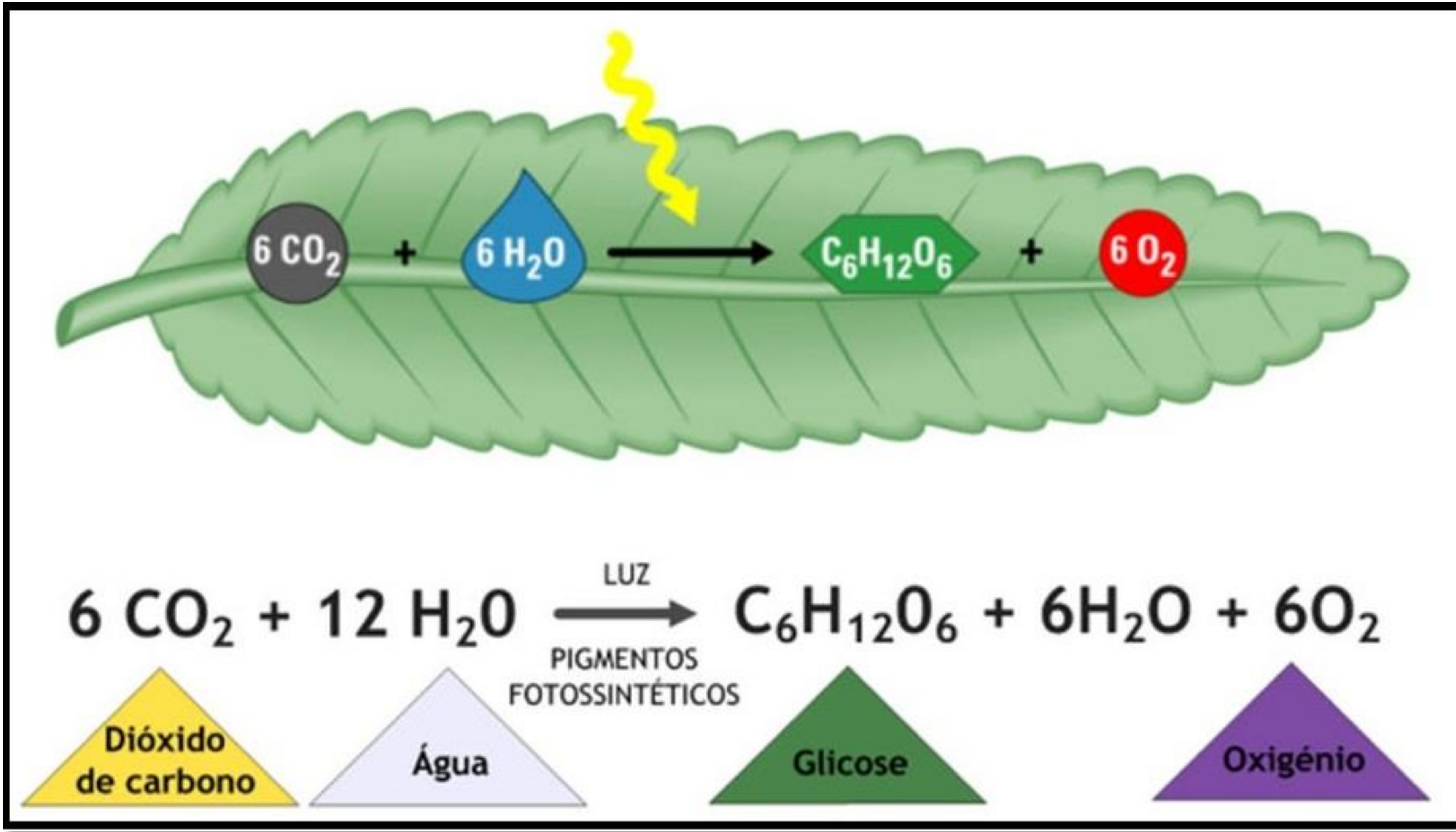
Fotossíntese

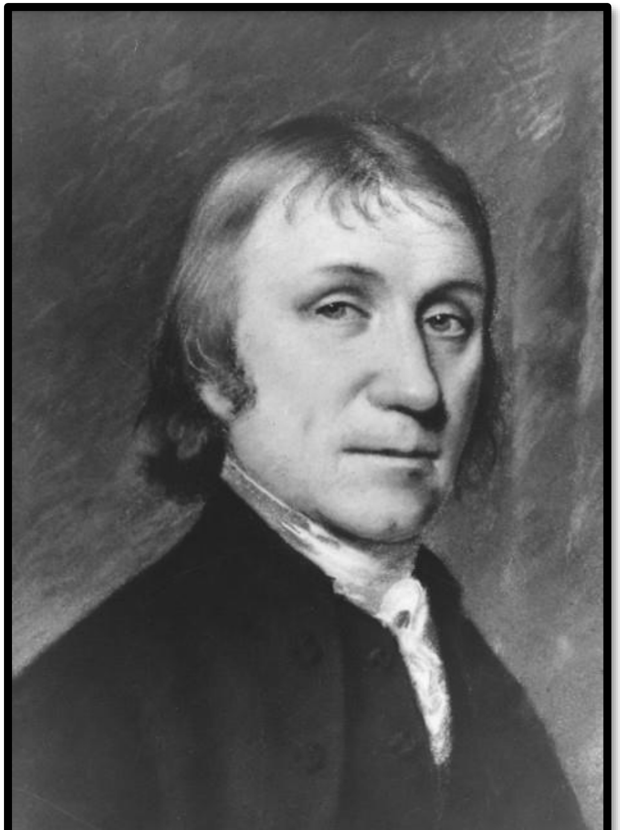

FOTOSSÍNTESE
Energia da LUZ
Gás Oxigênio – O_2
GLICOSE
$C_6H_{12}O_6$
Gás Carbônico – CO_2
ÁGUA – H_2O
Figura: Pliessnig, A. F. 2008


6 CO2
+
6 H2O
C6H12O6
+
6 O2
LUZ
6 CO2 + 12 H2O → C6H12O6 + 6H2O + 6O2
PIGMENTOS
FOTOSSINTÉTICOS
Dióxido
de carbono
Água
Glicose
Oxigénio

1- História da fotossíntese

2- Evolução da fotossíntese

1- História da fotossíntese



Joseph Priestley
(1733-1804)

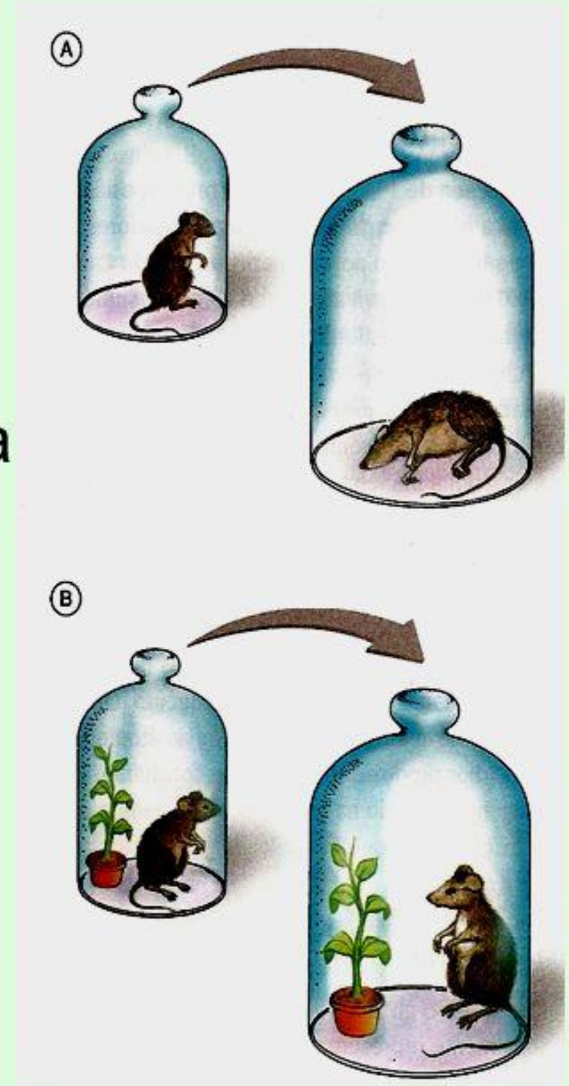
1772: A descoberta do oxigênio

<u>**Descoberta de Joseph Priestley:**</u>

“Fiquei muito feliz em encontrar acidentalmente um método de restaurar o ar injuriado pela queima das velas e descobrir pelos menos um dos restauradores que a natureza emprega para essa finalidade:a vegetação”

→1772

Ar "esgotado" (irrespirável) —PLANTAS→ Ar "puro" (respirável)



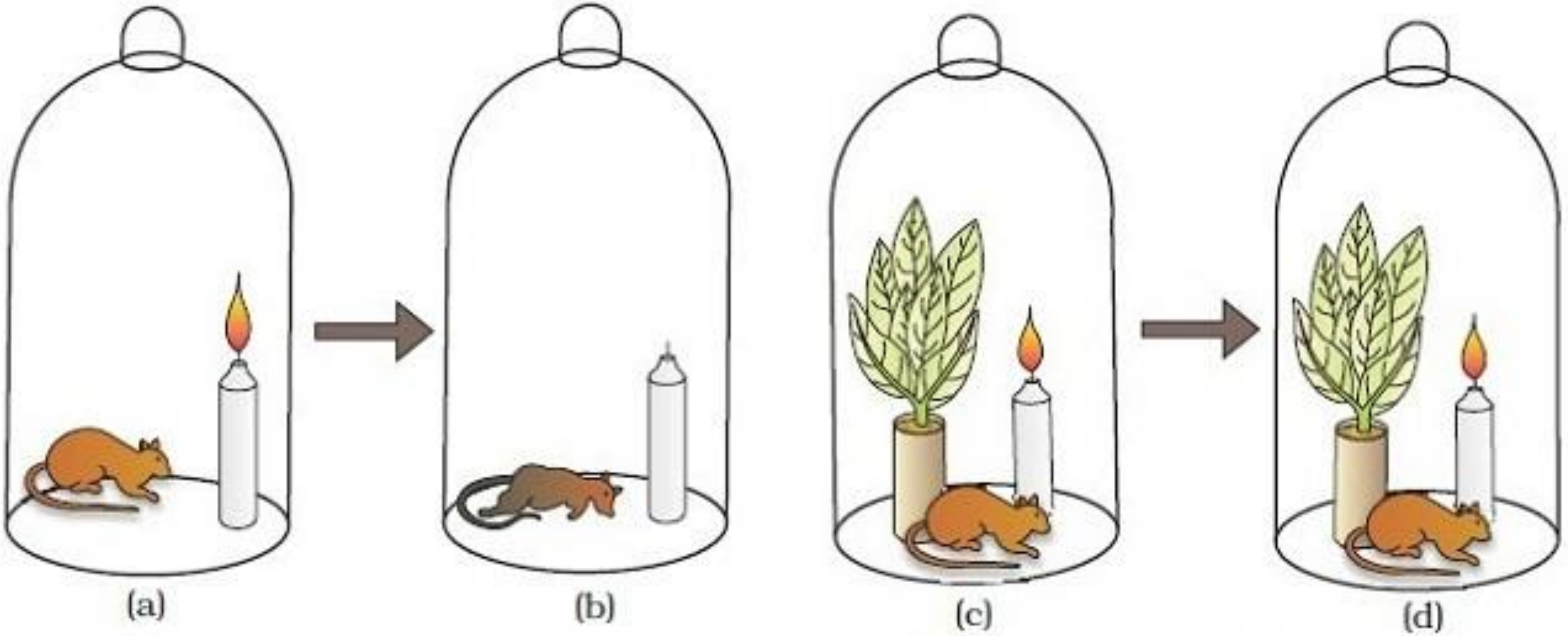
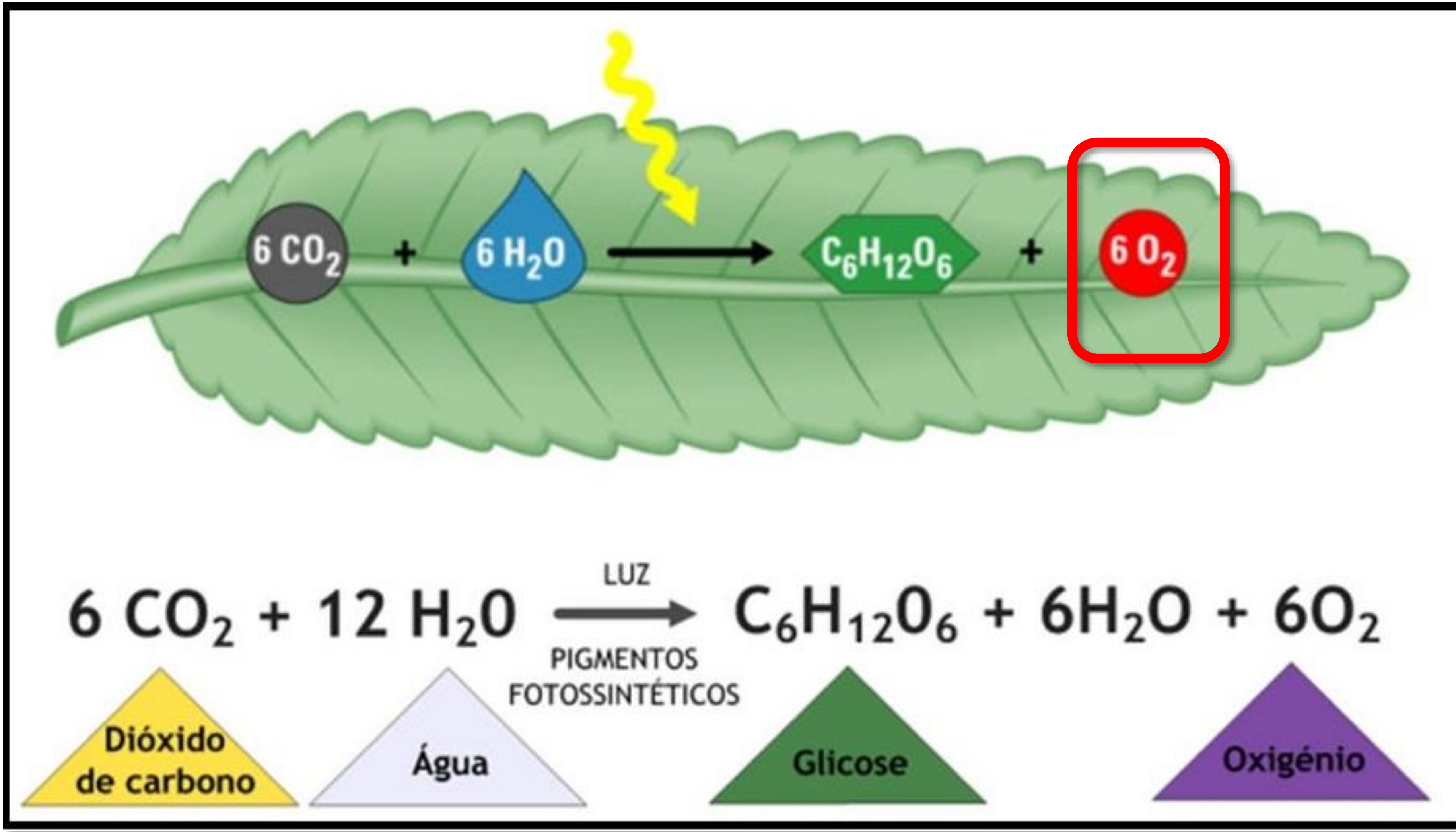


Figure 1. Priestley's experiment

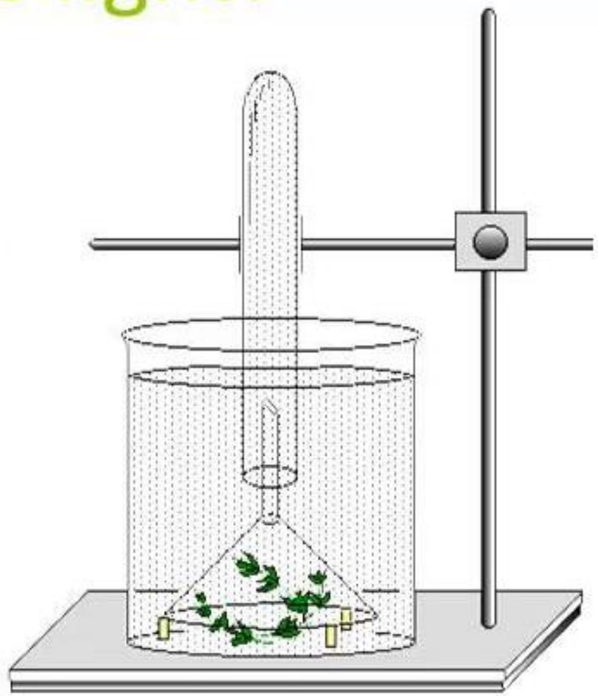

6 CO2
+
6 H2O
C6H12O6
+
6 O2
6 CO2 + 12 H2O → C6H12O6 + 6H2O + 6O2
LUZ
PIGMENTOS FOTOSSINTÉTICOS
Dióxido de carbono
Água
Glicose
Oxigénio

Jan Ingenhousz

(1730-1799)

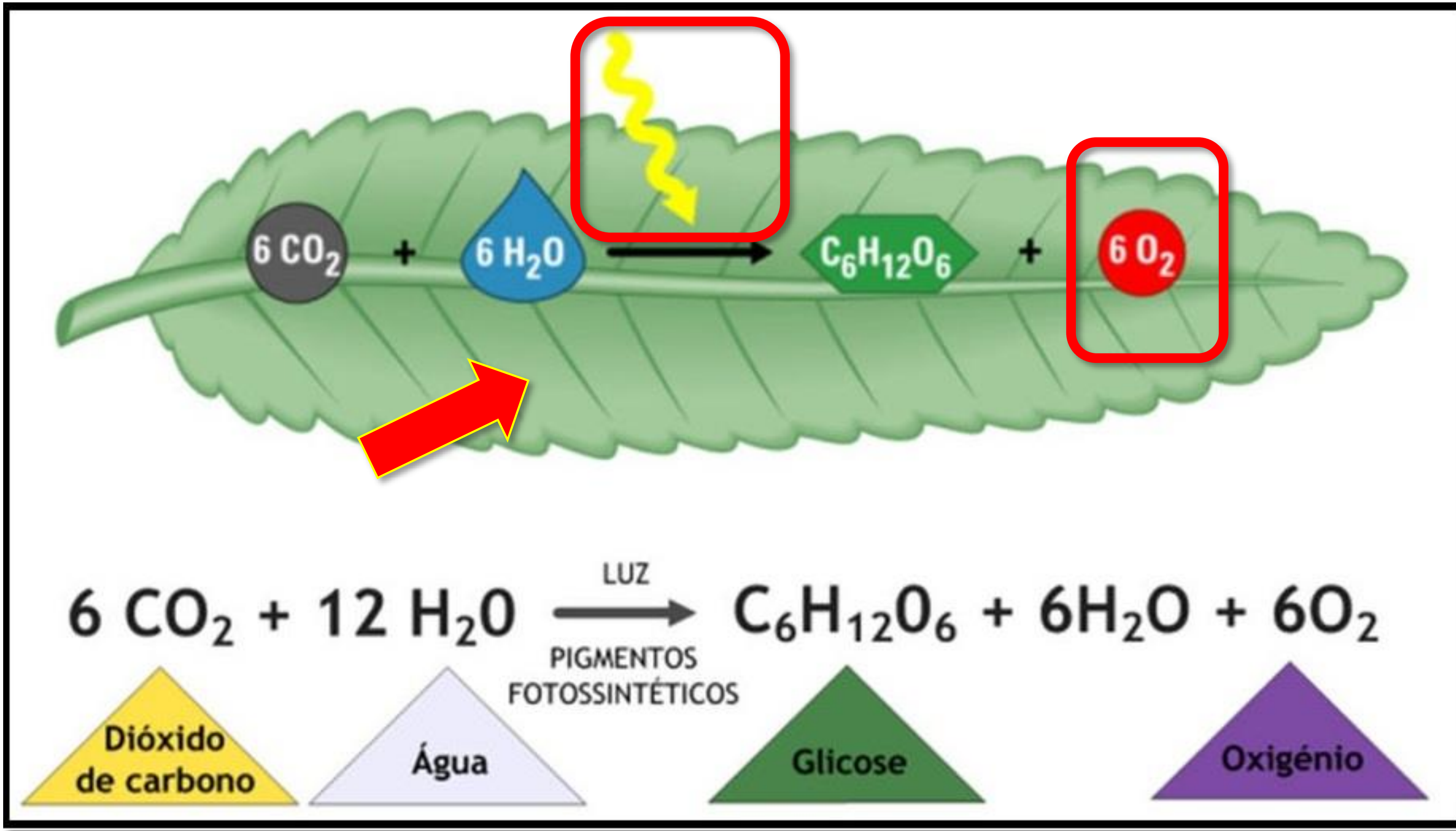
1779: O papel da luz

Let there be light!



Jan Ingenhousz
1730-1799

- Plants give of oxygen in the light
- Plants give off carbon dioxide in the dark
- More oxygen than carbon dioxide
- Only the green parts produce the oxygen


6 CO2
+
6 H2O
C6H12O6
+
6 O2
LUZ
6 CO2 + 12 H2O → C6H12O6 + 6H2O + 6O2
PIGMENTOS
FOTOSSINTÉTICOS
Dióxido
de carbono
Água
Glicose
Oxigénio

Jean Senebier
(1742-1809)

1800: A presença do dióxido de carbono

Recherches sur L'influence de la Lumiere Solaire

- Concluded Senebiers findings:
- Volume of oxygen produced is directly proportional to the light intensity
- Oxygen is solely released when carbon dioxide is being used
- Light is needed for this gas exchange to occur

RECHERCHES

SUR L'INFLUENCE

DE LA

LUMIERE SOLAIRE

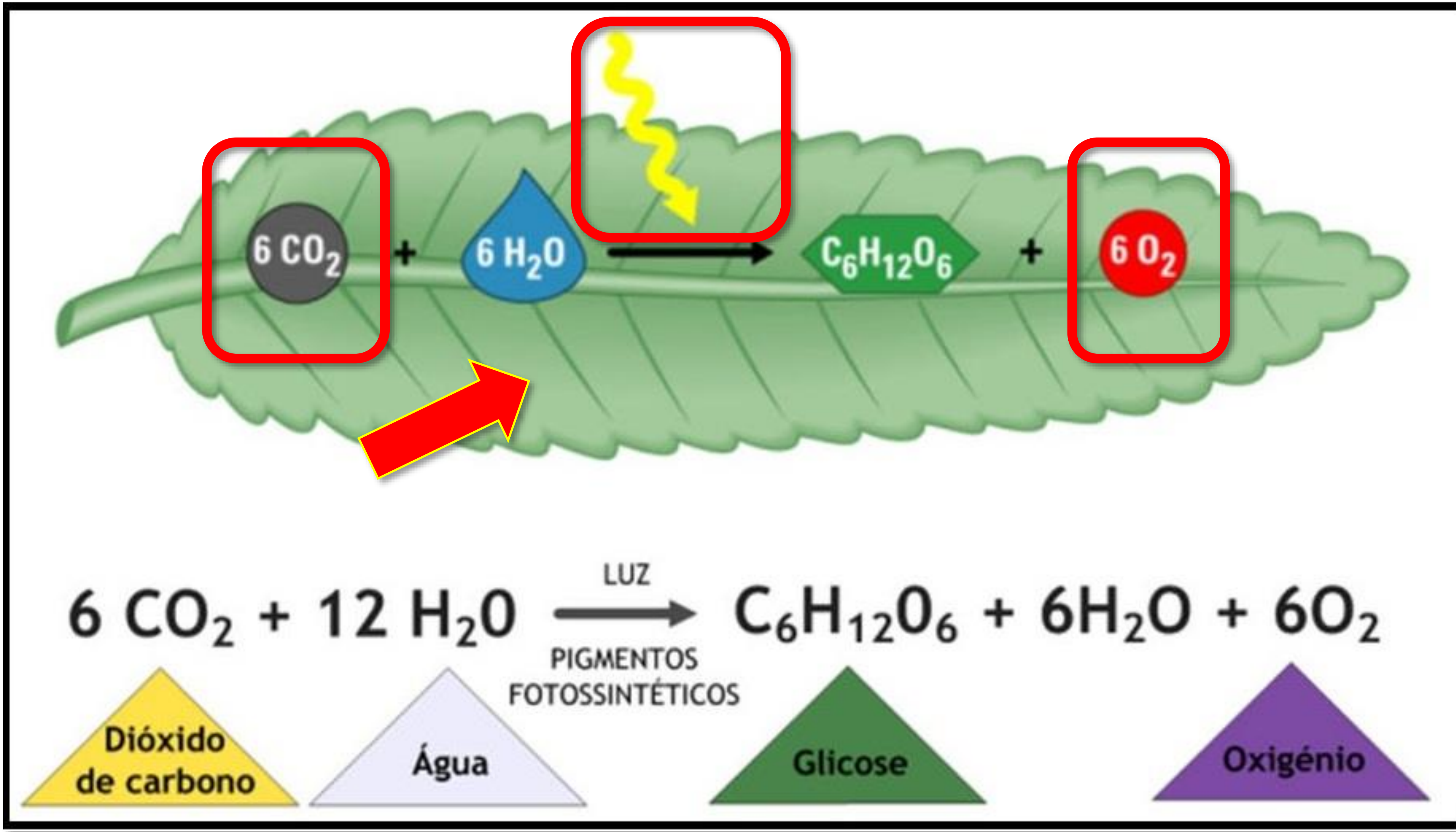
Pour métamorphofer l'air fixe en air pur par la végétation.

PAR JEAN SENEBIER,

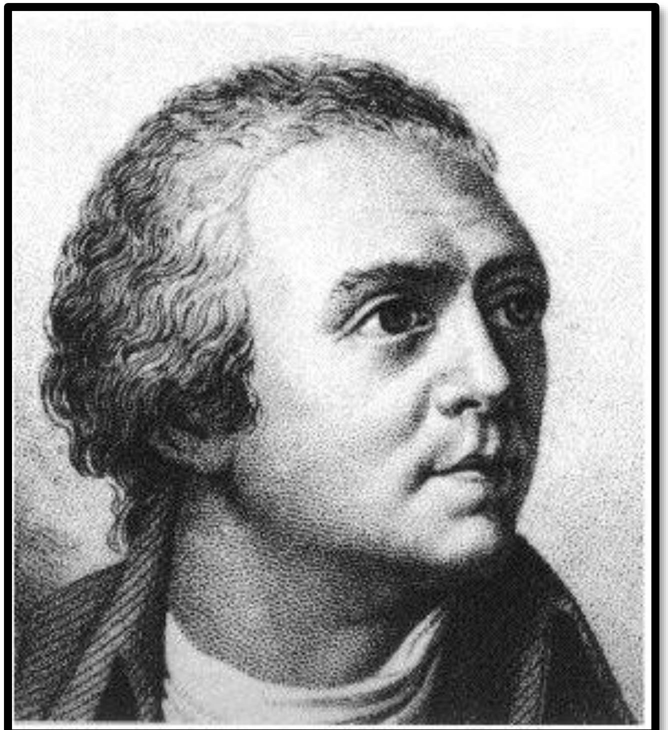
A GENEVE,

Chez BARTHELEMI CHIROL, Libraire.

M. DCC. LXXXIII.



6 CO2
+
6 H2O
C6H12O6
+
6 O2
LUZ
6 CO2 + 12 H2O → C6H12O6 + 6H2O + 6O2
PIGMENTOS
FOTOSSINTÉTICOS
Dióxido
de carbono
Água
Glicose
Oxigénio



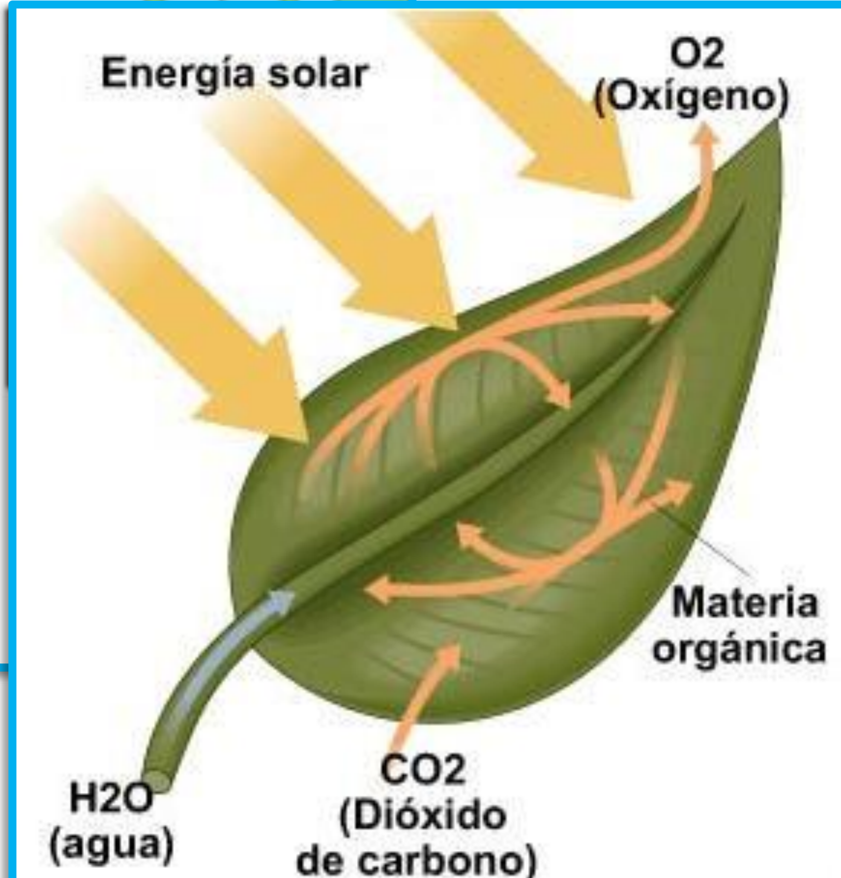
Nicholas Théodore de Saussure (1767–1845)

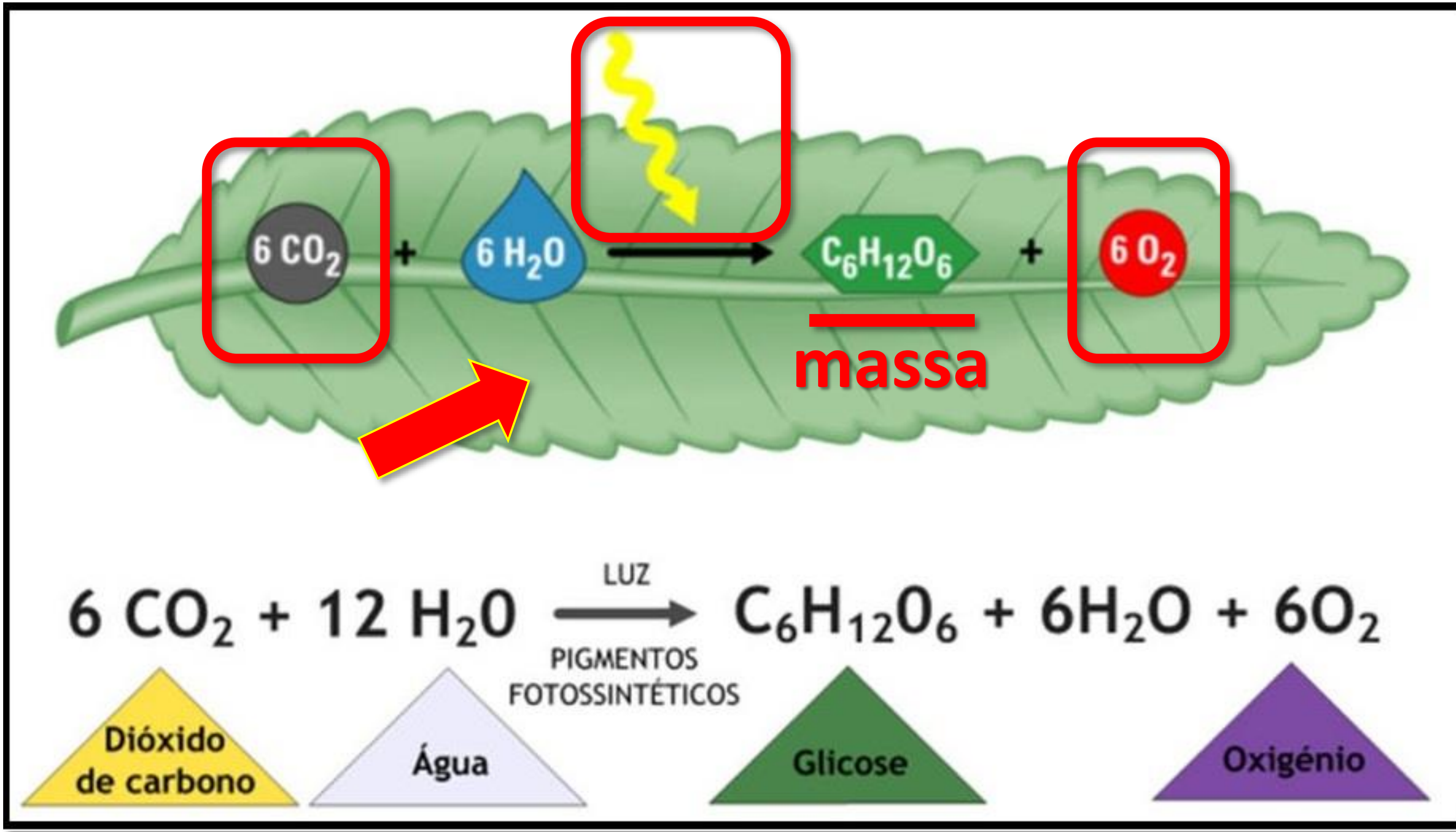
1804: O dióxido de carbono é incorporado pela planta

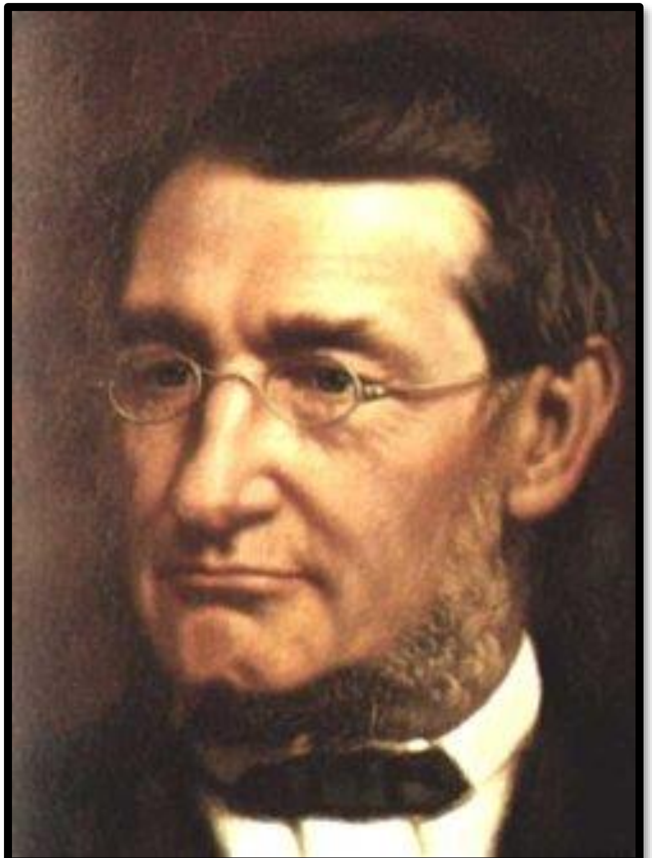
It's not ALL water…

Nicolas-Théodore de Saussure (1767-1845)

- **Step 1:** Puts plant in a closed container
- **Step 2:** measure the weight of CO_2 and weight of plant at the start
- **Step 3:** Sun!
- **Step 4:** Measure the weight again
- **Results:** CO_2 goes down, but not as much as plant goes up. The rest must be water!




6 CO2
6 H2O
C6H12O6
6 O2
massa
LUZ
6 CO2 + 12 H2O → C6H12O6 + 6H2O + 6O2
PIGMENTOS FOTOSSINTÉTICOS
Dióxido de carbono
Água
Glicose
Oxigénio



Julius Robert von Mayer
(1814–1878)

1845: A fotossíntese é uma transformação da energia luminosa em química

Julius Robert von Mayer

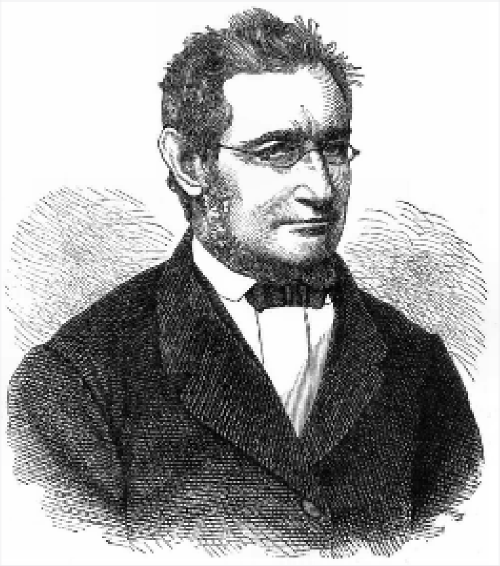


Image obtained from:
http://www.museon.nl/files/Julius_Robert_von_Mayer.jpg

-Proposed the idea that plants convert the energy emitted by the Sun into chemical energy known as photosynthesis. [6]

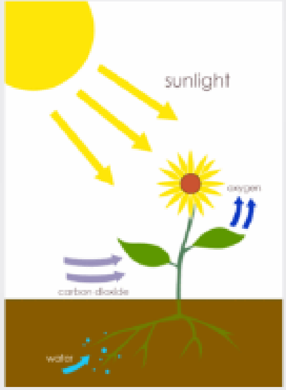
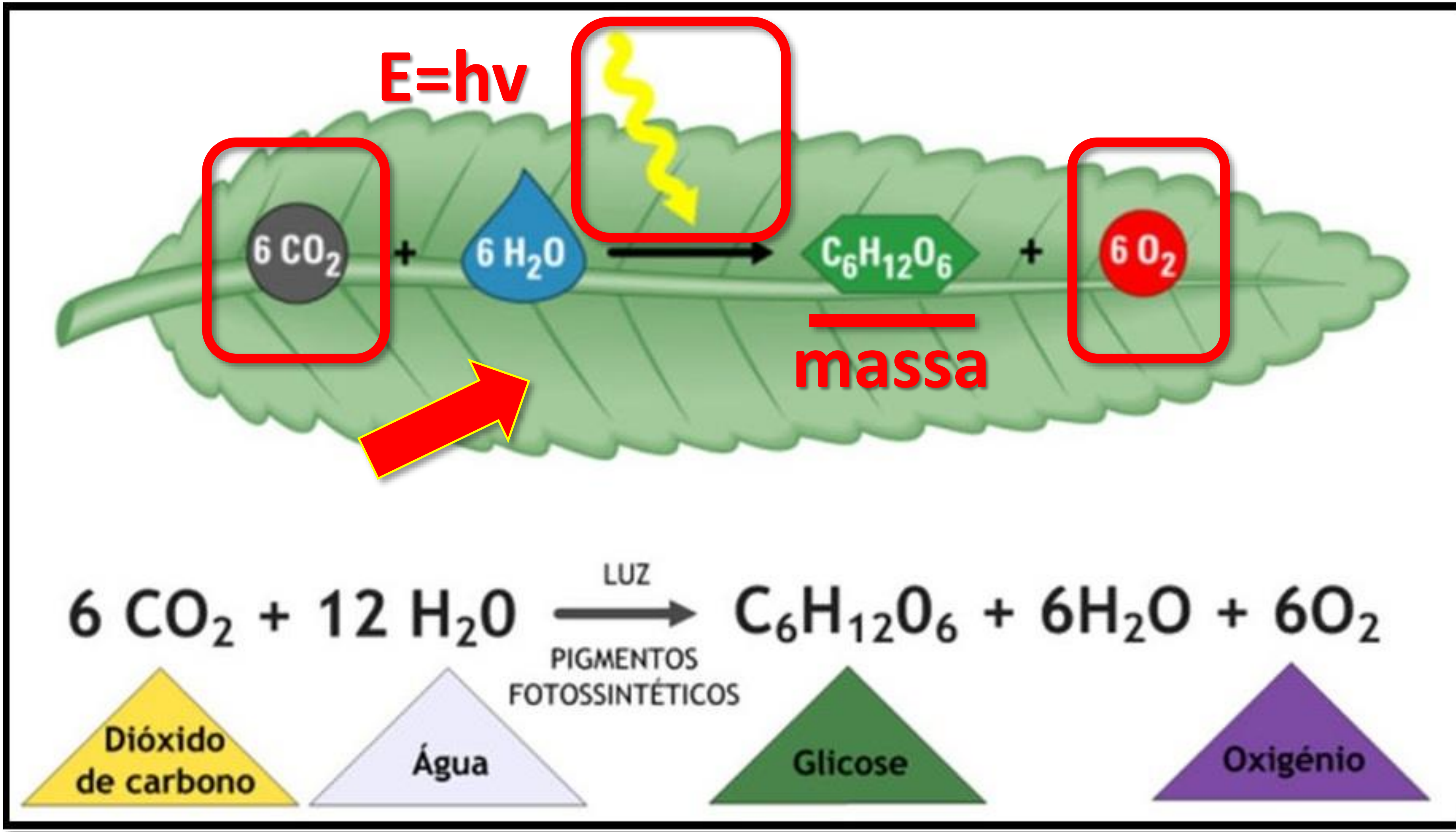


Image obtained from:
http://upload.wikimedia.org/wikipedia/commons/thumb/d/db/Photosynthesis.gif/220px-Photosynthesis.gif

von Mayer was able to compile a series of ideas from previous scientists to come up with his theory


E=hv
6 CO2
6 H2O
C6H12O6
6 O2
massa
LUZ
6 CO2 + 12 H2O → C6H12O6 + 6H2O + 6O2
PIGMENTOS FOTOSSINTÉTICOS
Dióxido de carbono
Água
Glicose
Oxigénio

Julius von Sachs
(1832–1897)

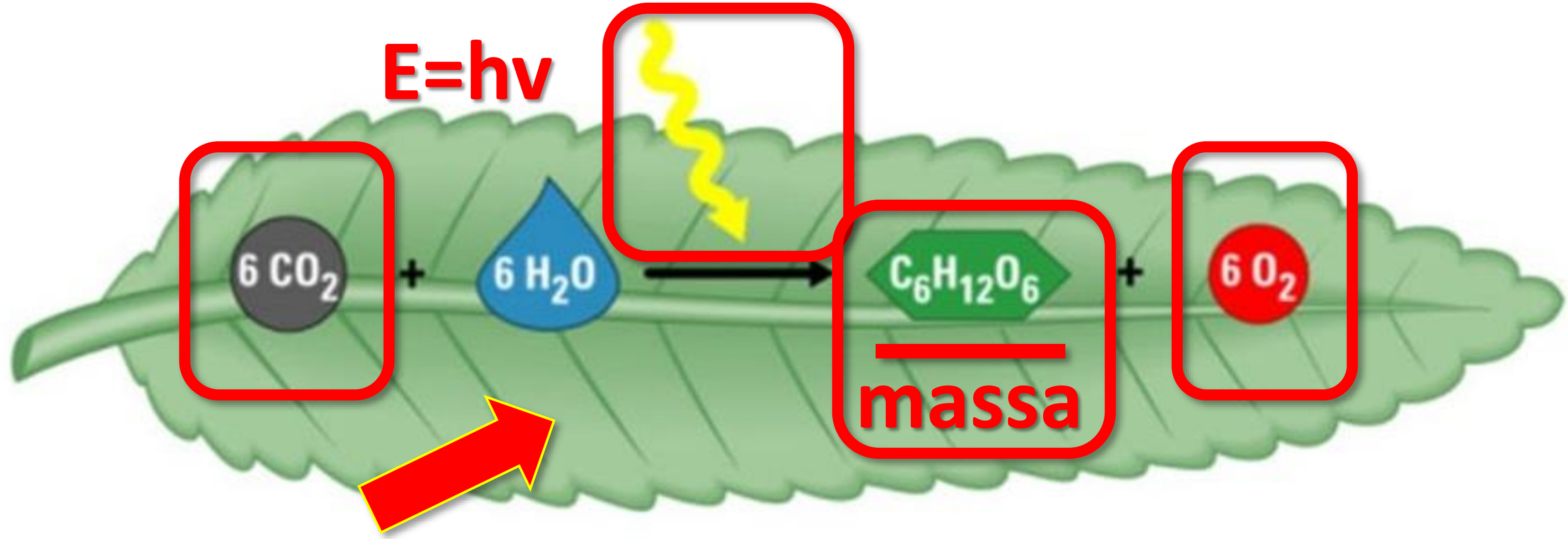
1862-64: O amido é formado na luz e consumido ou estocado no escuro

Mmmmm… sugar

- Plants in the light… make starch!
- Plants in the dark… starch disappears!

Julius von Sachs
(1832-1897)

Where did the starch come from? Photosynthesis, yo.



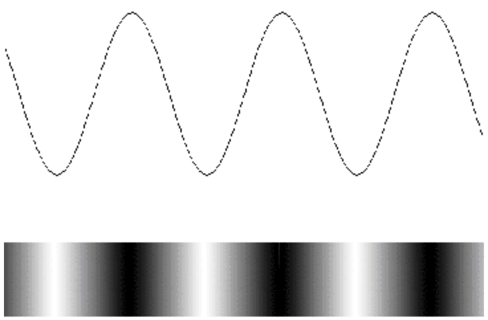
$$6\ CO_2 + 12\ H_2O \xrightarrow[\text{PIGMENTOS FOTOSSINTÉTICOS}]{\text{LUZ}} C_6H_{12}O_6 + 6H_2O + 6O_2$$

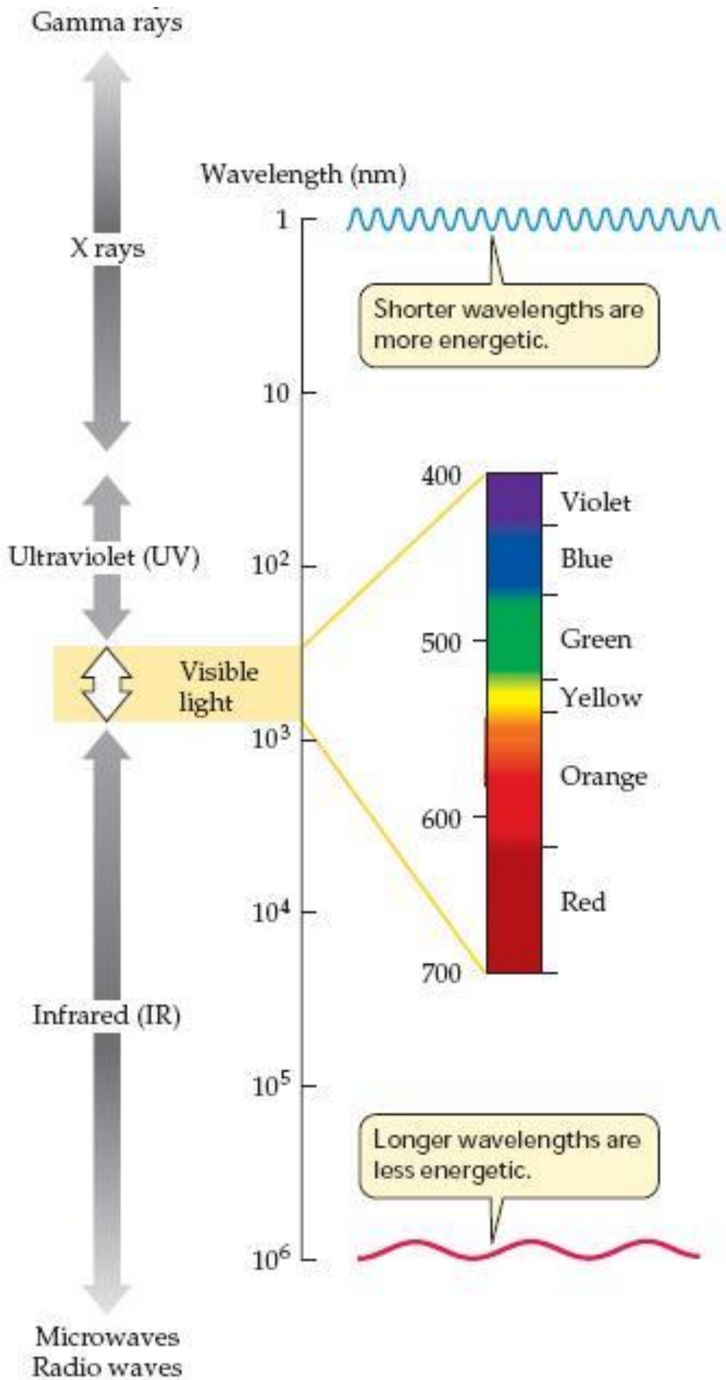
Theodor Wilhelm Engelmann (1843–1909)

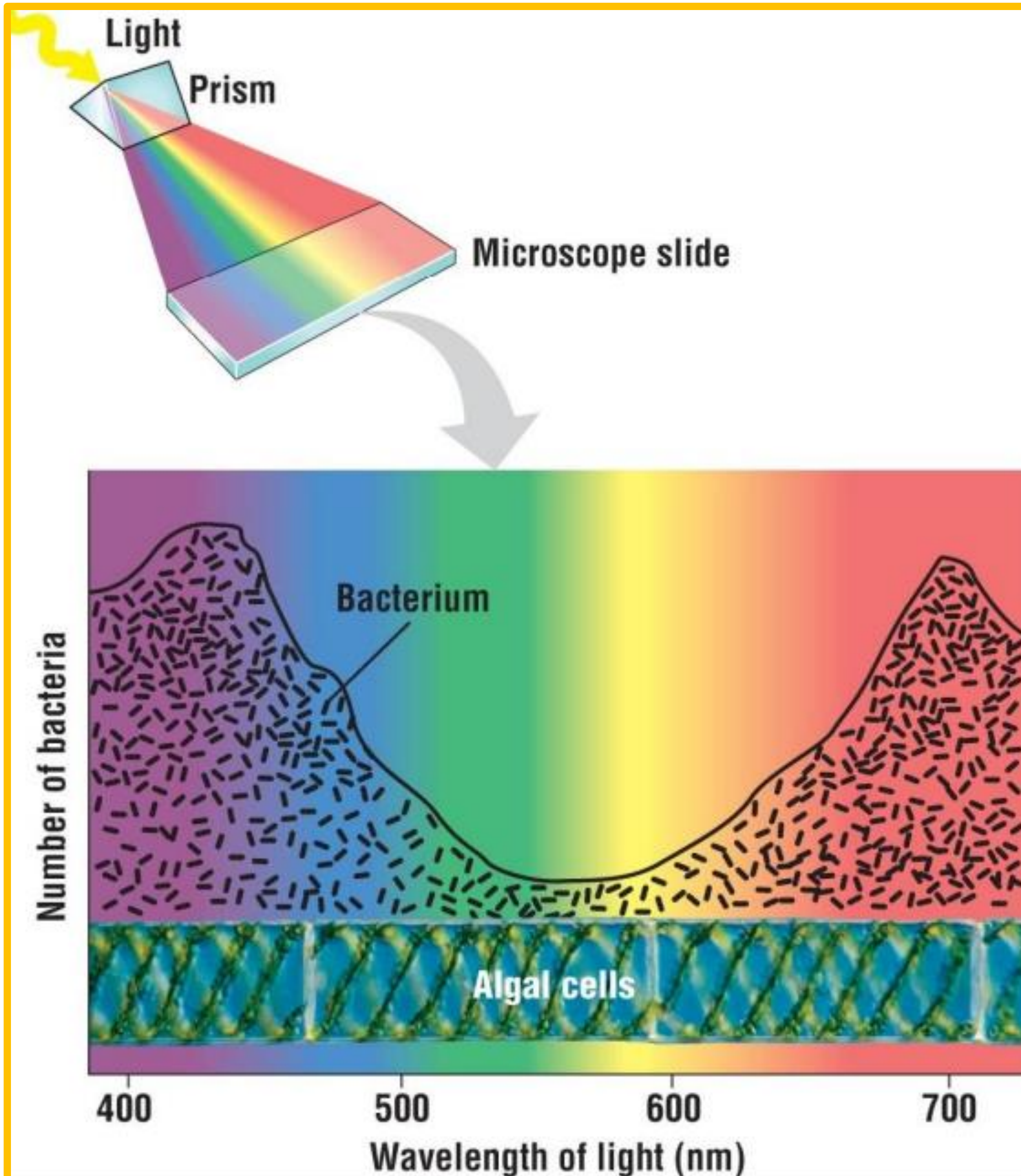
1883: O Espectro de absorção de luz na fotossíntese é semelhante ao espectro de absorção das clorofilas

As propriedades da luz

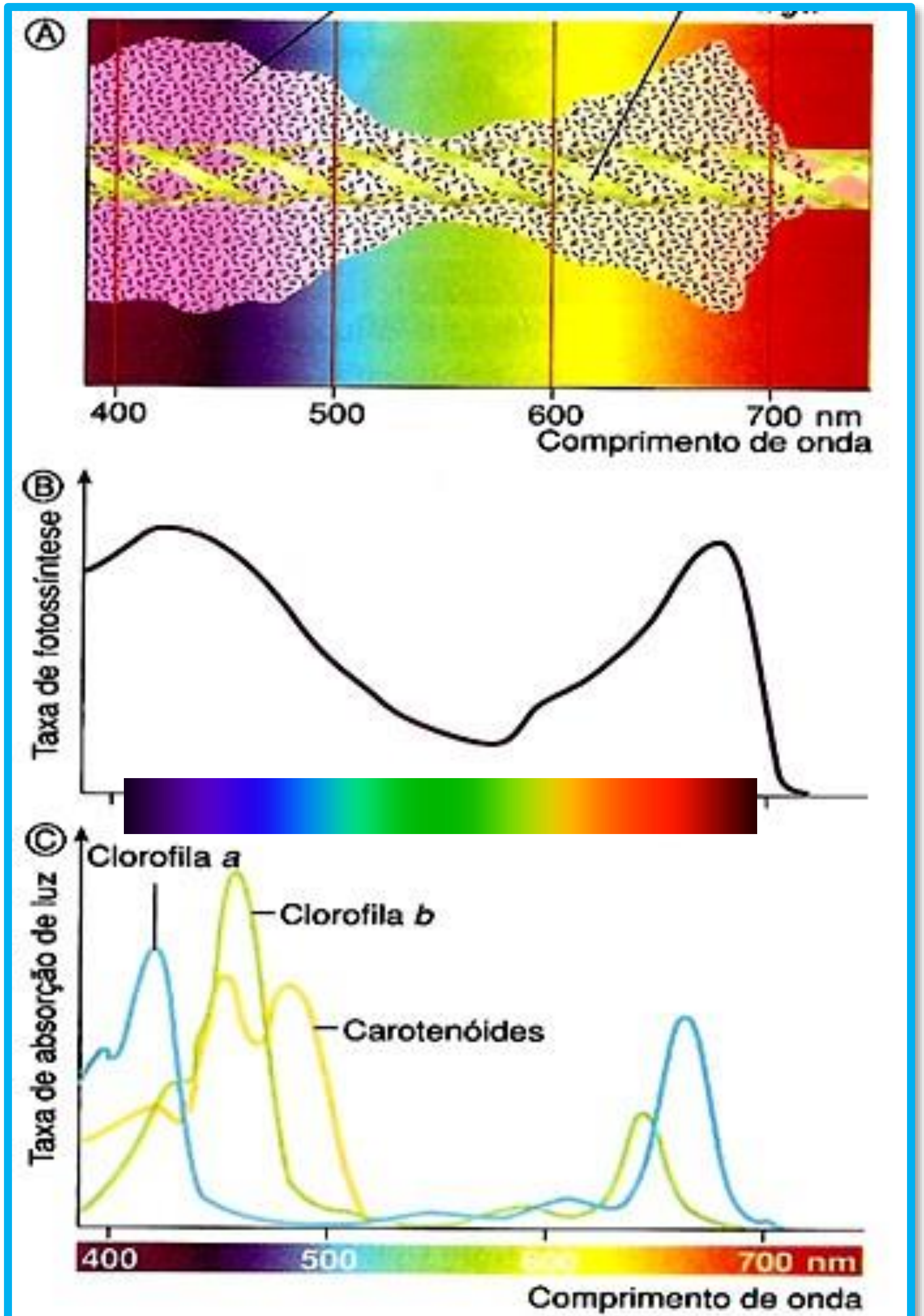
1. Luz: Radiação eletromagnética que se propaga em ondas.
2. A luz transporta “pacotes” de energia denominados **Fótons.**
3. A luz visível corresponde a uma pequena parte do espectro eletromagnético (400 a 700 nm) – luz violeta até vermelha.
4. A energia contida em cada fóton é inversamente proporcional ao comprimento de onda.

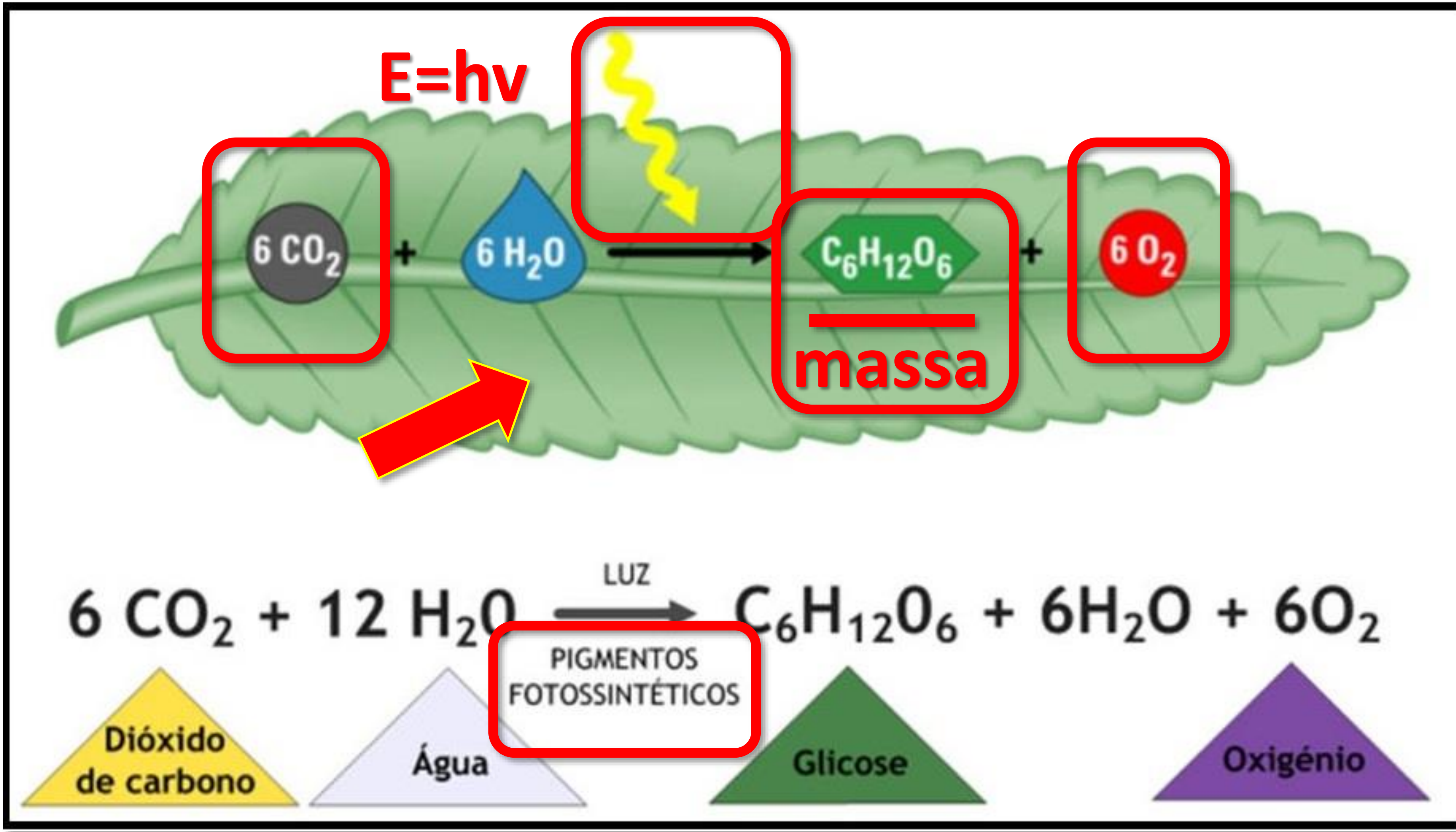



Gamma rays
Wavelength (nm)
1
X rays
Shorter wavelengths are more energetic.
10
400
Violet
Blue
Ultraviolet (UV)
10^2
500
Green
Visible light
Yellow
10^3
Orange
600
Red
10^4
700
Infrared (IR)
10^5
Longer wavelengths are less energetic.
10^6
Microwaves
Radio waves



Light
Prism
Microscope slide
Bacterium
Number of bacteria
Algal cells
400
500
600
700
Wavelength of light (nm)


A
400
500
600
700 nm
Comprimento de onda
B
Taxa de fotossíntese
C
Clorofila a
Clorofila b
Carotenóides
Taxa de absorção de luz
400
500
700 nm
Comprimento de onda


E=hv
$6\,CO_2$ + $6\,H_2O$ → $C_6H_{12}O_6$ + $6\,O_2$
massa
LUZ
$6\,CO_2 + 12\,H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$
PIGMENTOS FOTOSSINTÉTICOS
Dióxido de carbono
Água
Glicose
Oxigénio

Chlorophyll *a*

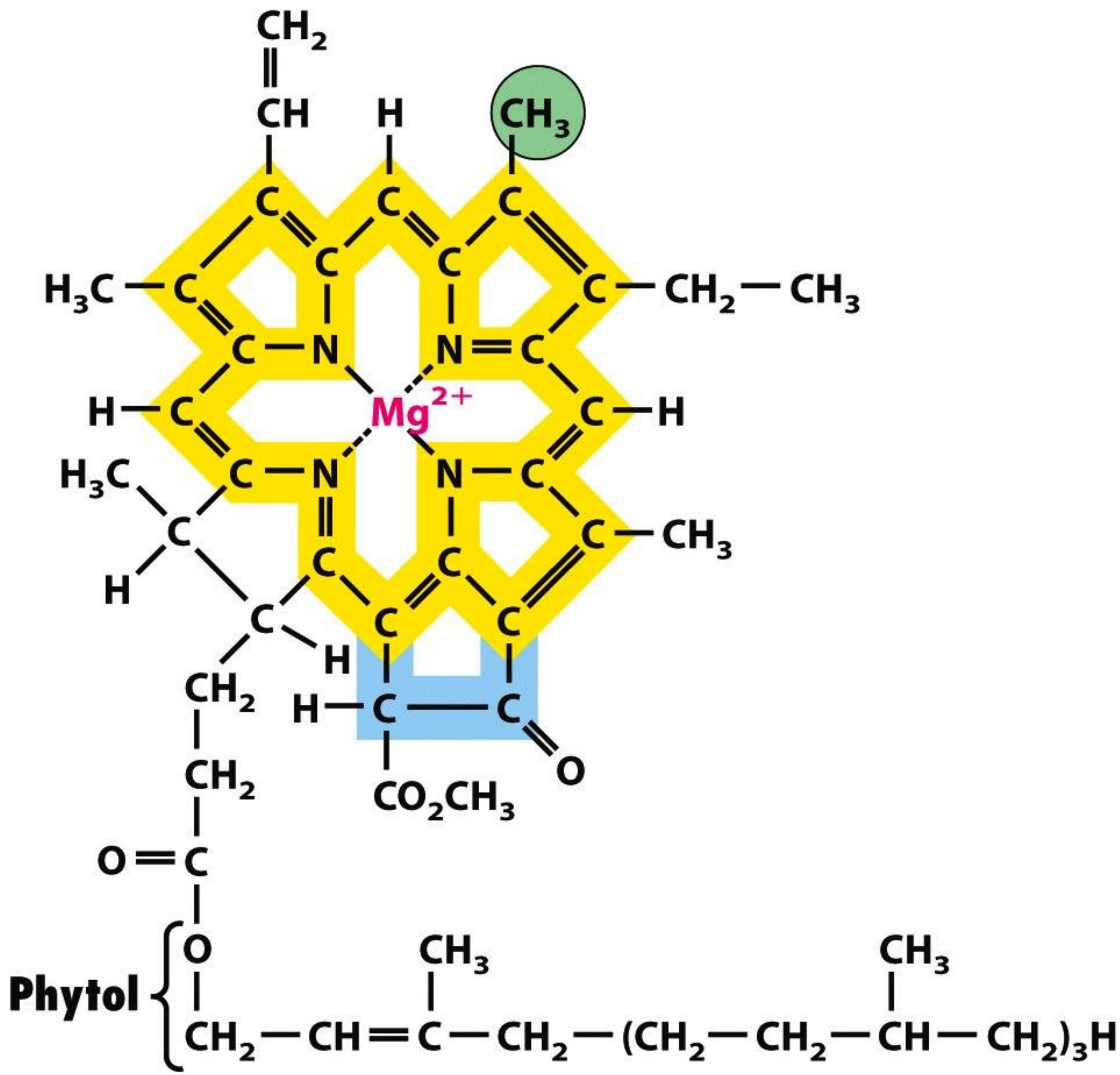
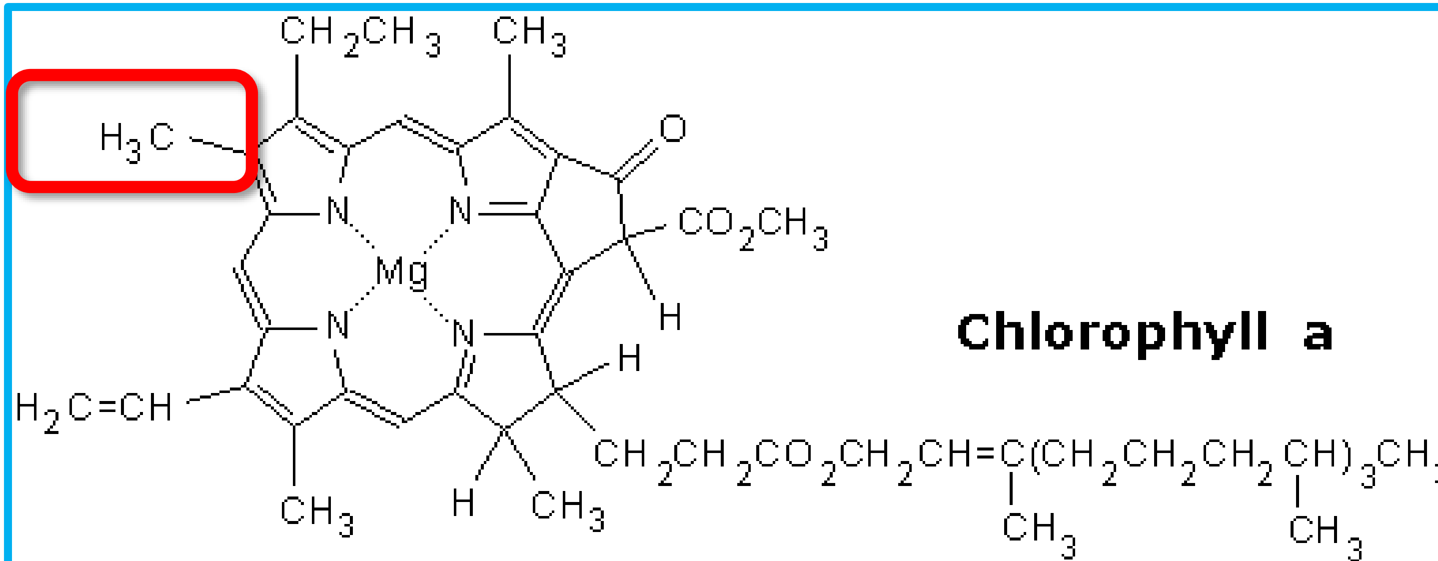
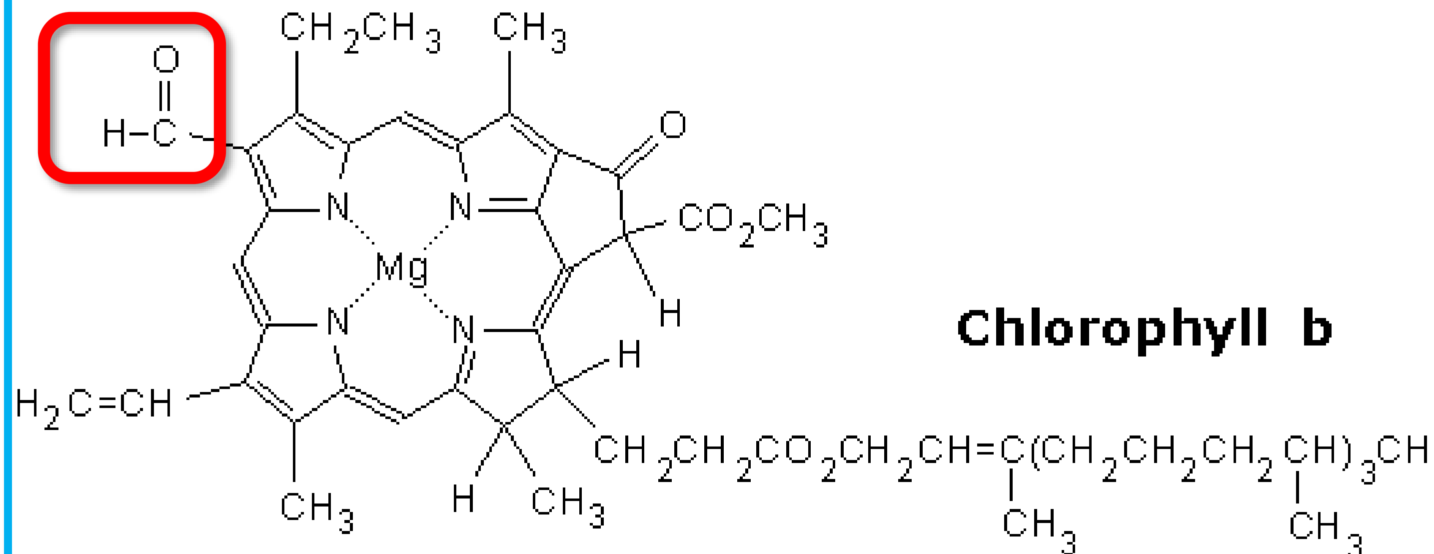


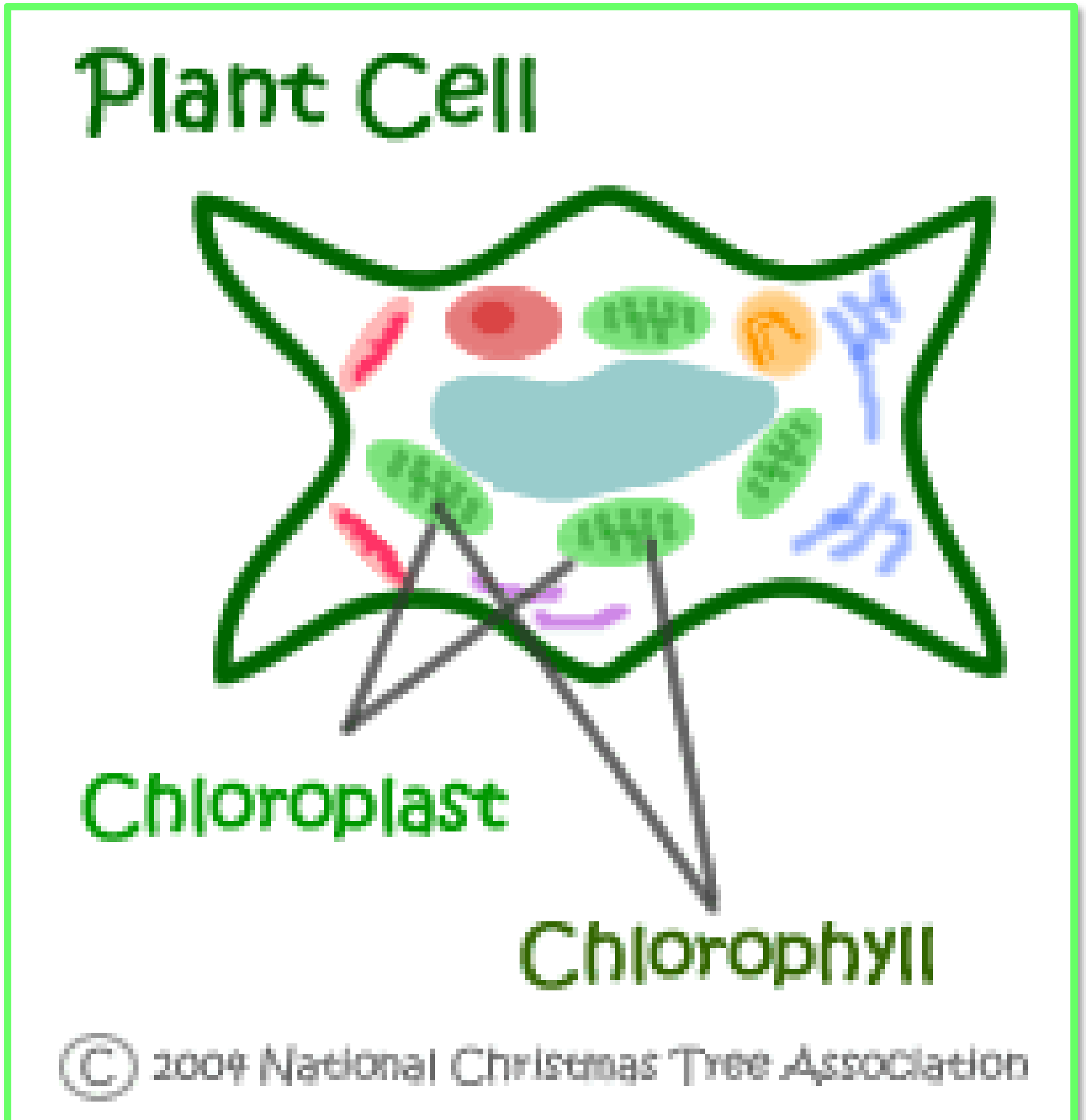
Figure 12-31
Molecular Cell Biology, Sixth Edition



Chlorophyll a



Chlorophyll b

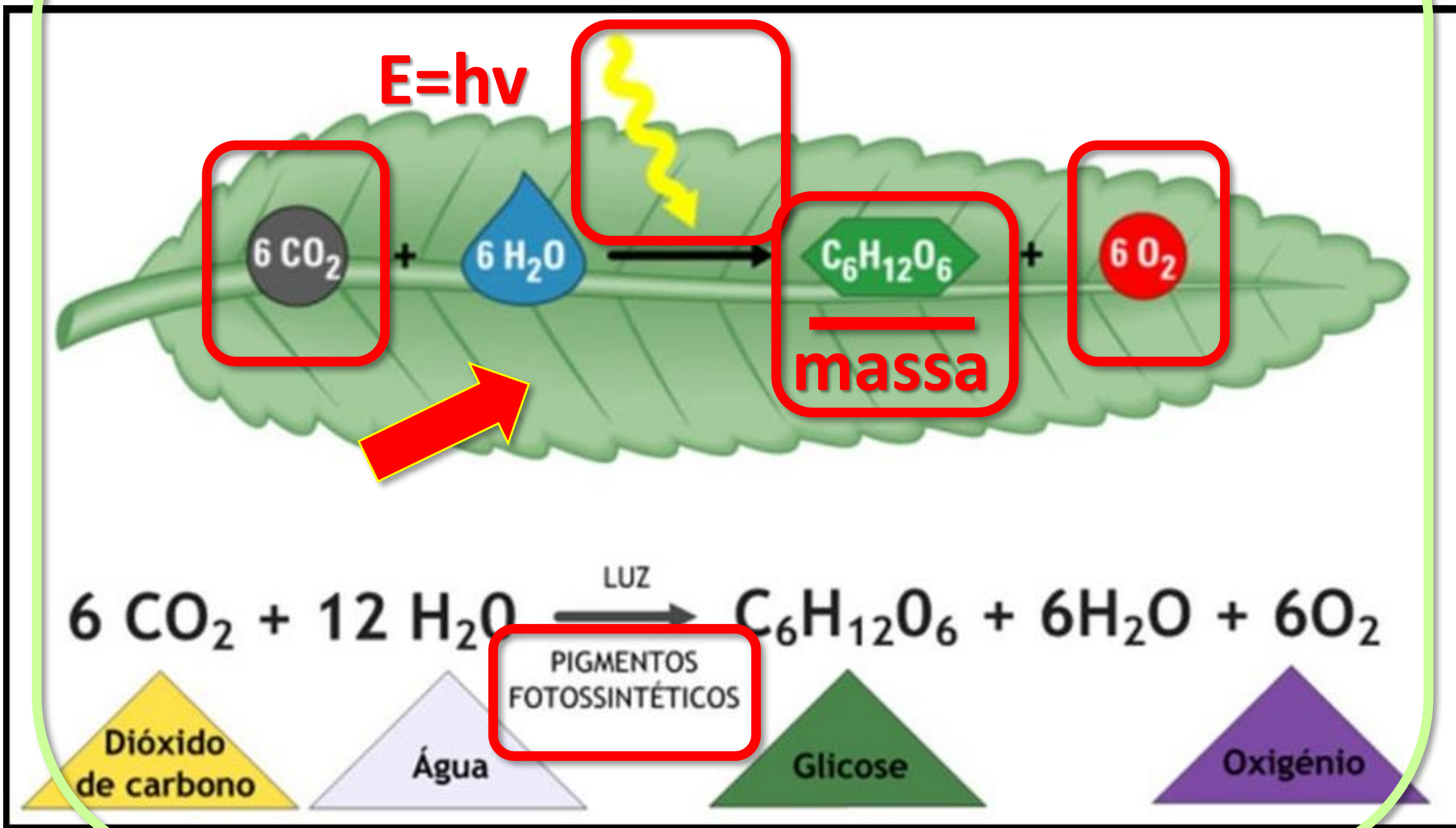

Plant Cell
Chloroplast
Chlorophyll
© 2004 National Christmas Tree Association

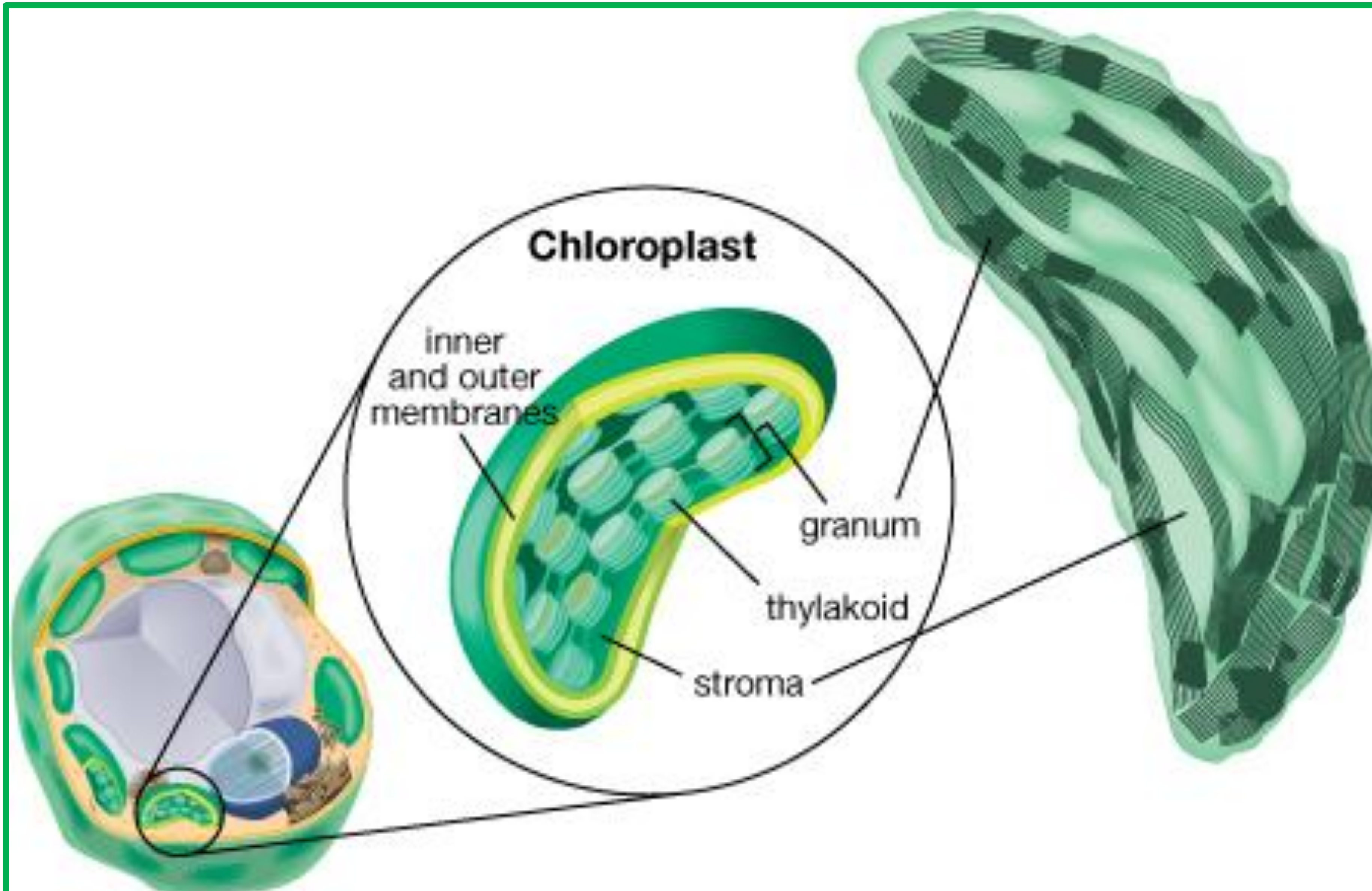
Julius von Sachs
(1832–1897)

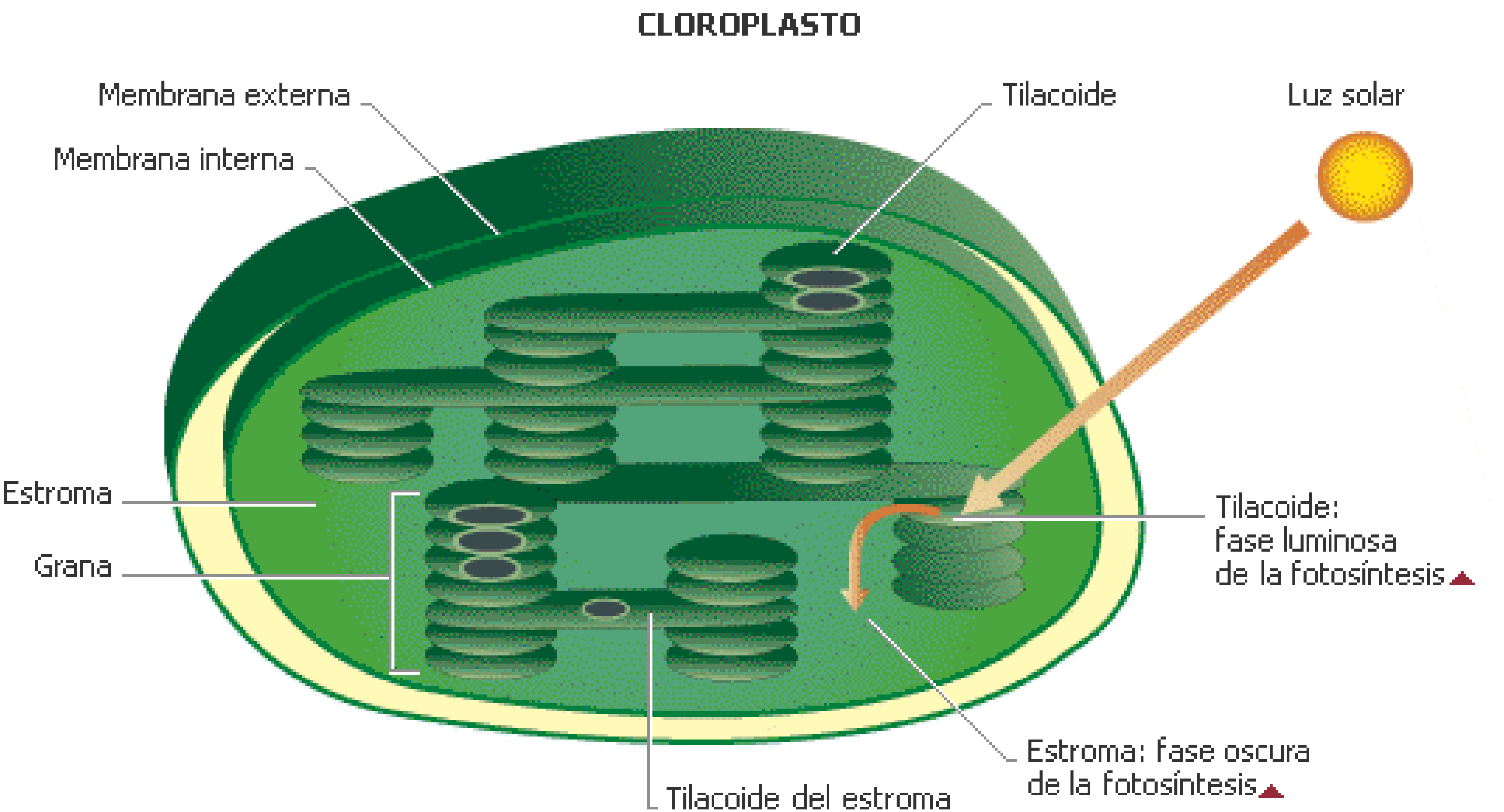
Em 1887:

"A prova mais definitiva de que os corpos de clorofila (cloroplastos) assimilam o gás carbônico é fornecida pelo fato de que o primeiro produto desta assimilação (amido) aparece justamente nos corpos de clorofila e não em outro lugar da célula vegetal"

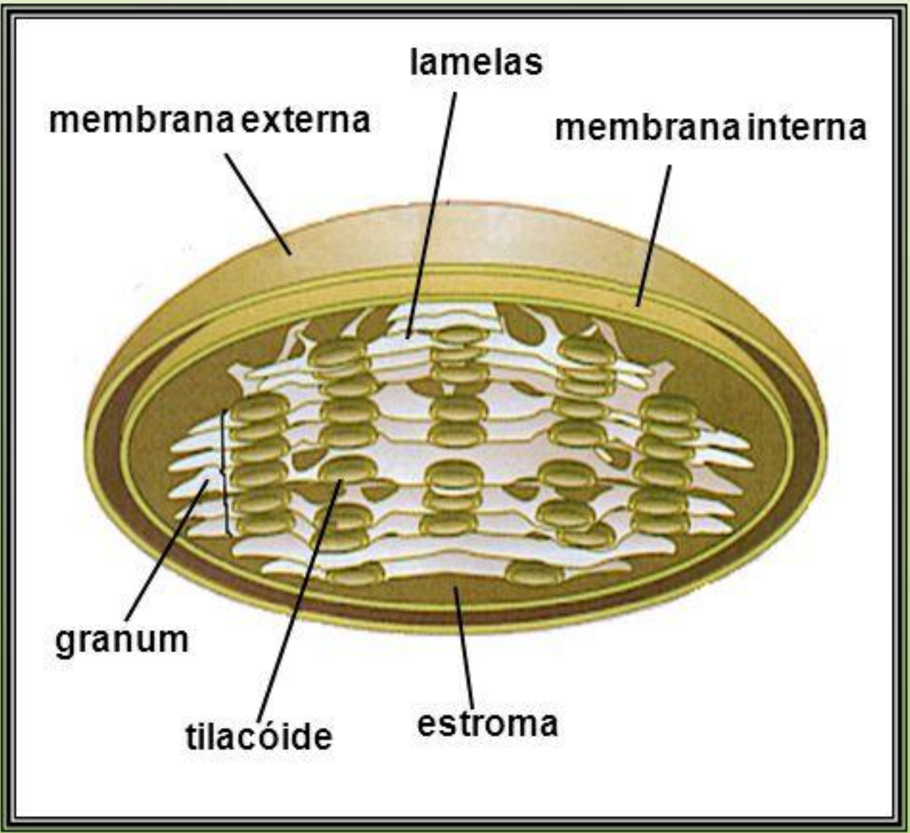
cloroplastos




Chloroplast
inner
and outer
membranes
granum
thylakoid
stroma


CLOROPLASTO
Membrana externa
Membrana interna
Tilacoide
Luz solar
Estroma
Grana
Tilacoide: fase luminosa de la fotosíntesis
Estroma: fase oscura de la fotosíntesis
Tilacoide del estroma

Cloroplastos



CARACTERÍSTICAS

Possuem DNA e ribossomos

Função: armazenamento de substâncias de reserva e pigmentos

Os cloroplastos são os principais responsáveis pela fotossíntese.

Célula Vegetal

Plastídios:

Funções dos plastídeos:

envolvidos na fotossíntese

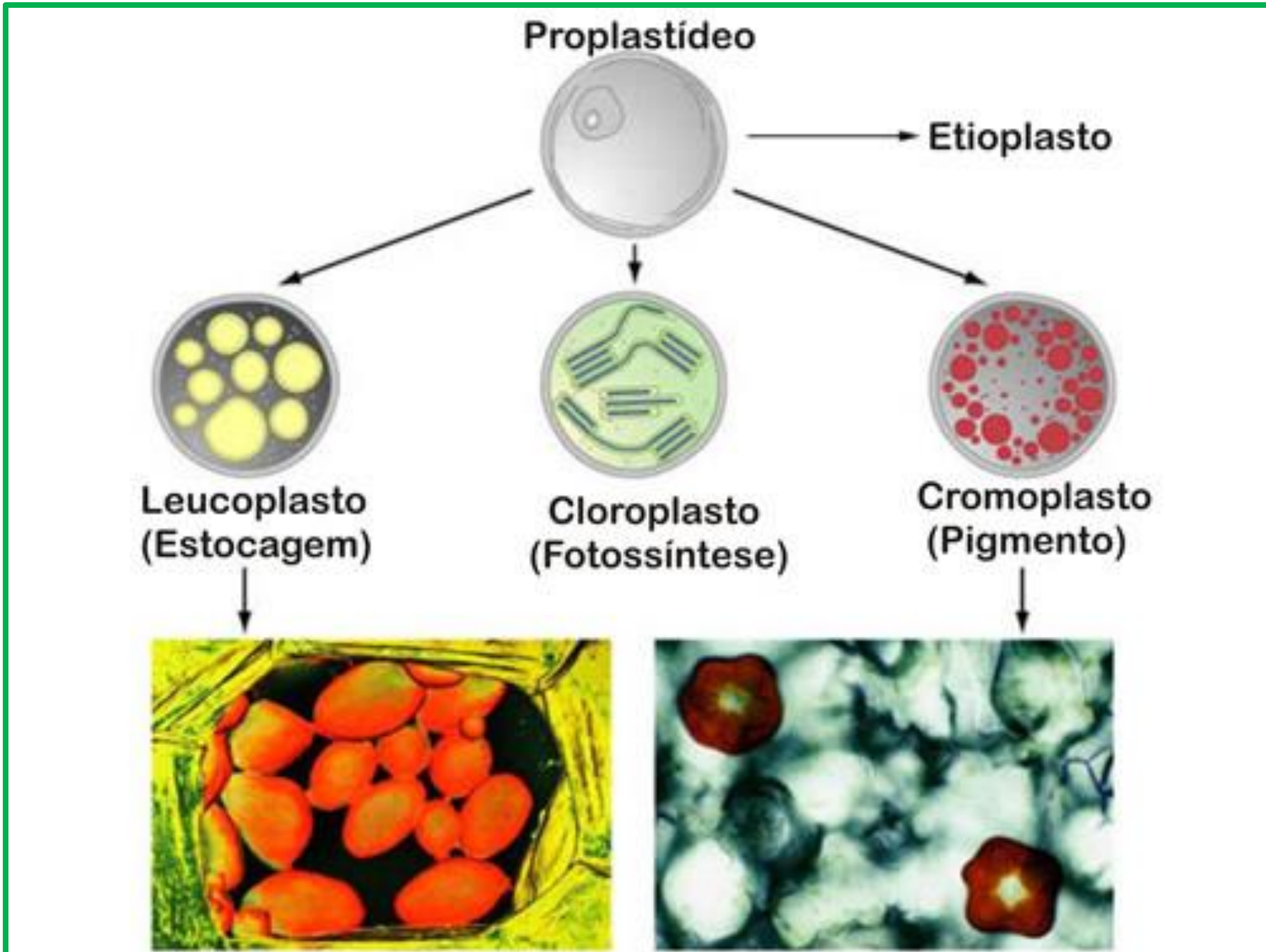
síntese de aminoácidos e ácidos graxos

onde ocorre a assimilação do Nitrogênio e Enxofre

armazenamento de amido, proteínas e lipídeos

presença de pigmentos como clorofila e carotenóides

carotenóides estão envolvidos na atração de polinizadores



Proplastídeo
Etioplasto
Leucoplasto
(Estocagem)
Cloroplasto
(Fotossíntese)
Cromoplasto
(Pigmento)

Plastídeos:

Abundantes nos vegetais superiores, são delimitados por uma membrana e contêm no interior pigmentos (<u>cromo</u>plastídeos) ou não (<u>leuco</u>plastídeos)

Grego *chloro* = verde

***erythrós* = vermelho**

***kyano* = azul**

***xanthós* = amarelo**

Em folhas, alguns caules, cascas de frutos e de alguns tubérculos (cenoura, beterraba, etc)

Grego *leukós* = branco

Parênquimas de armazenamento de raízes, caules e frutos, devido acúmulo de amido, lipídeos e proteínas.

Plastos

- Cromoplastos

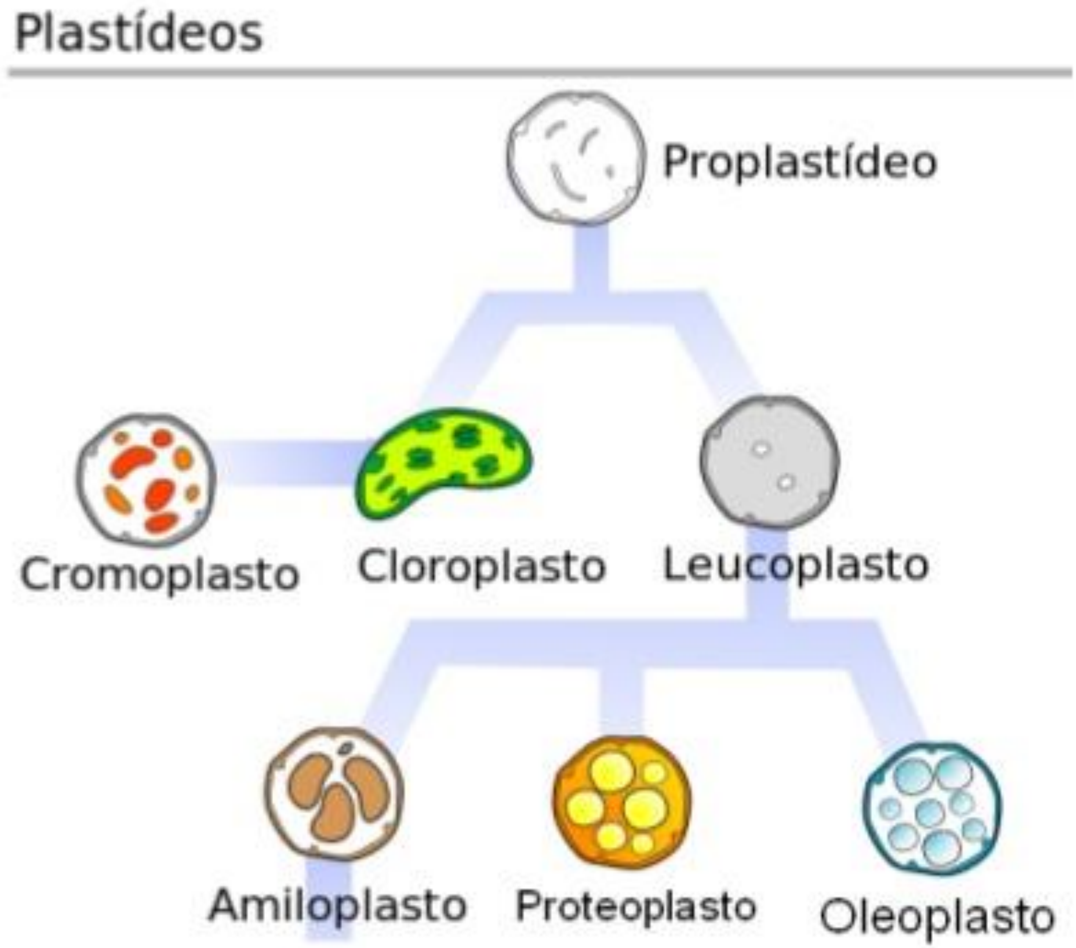
- Pigmentos vermelhos e amarelos

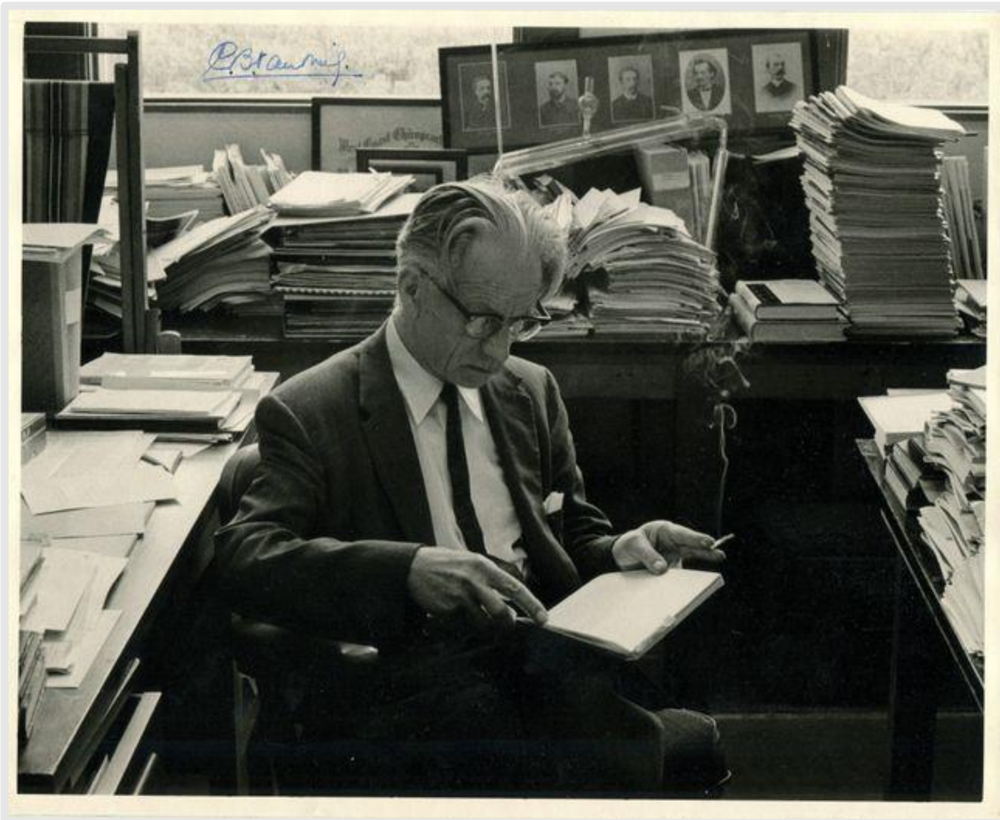
Frutos e flores

- Leucoplastos

- Armazenamento

Amido, óleos, proteínas





Cornelis van Niel

(1897-1985)

1930-41:

O Oxigênio vem da água

Keeping track of the oxygen atom in photosynthesis

Cornelius van Niel (1897-1985)

Standford University

Used radioactive-labeled oxygen in water and unlabeled carbon dioxide in photosynthesis experiments

Found that oxygen gas produced comes from water

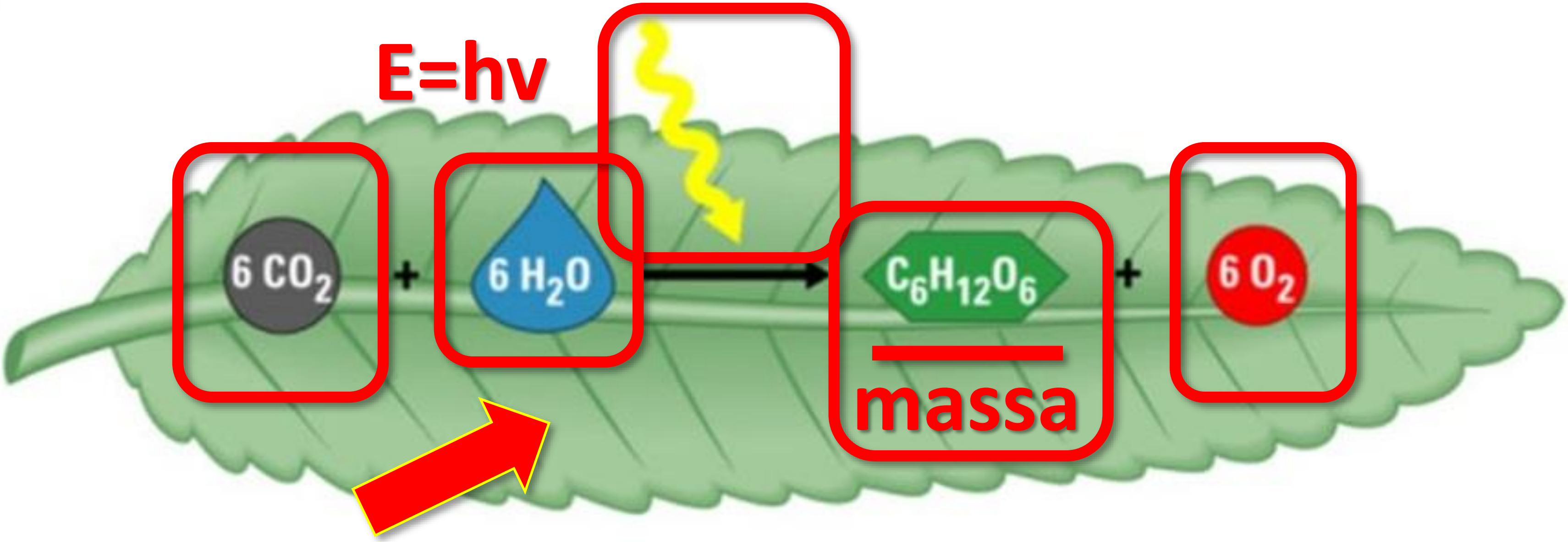
Postulated that the oxygen atom in carbohydrates must be from carbon dioxide

light energy

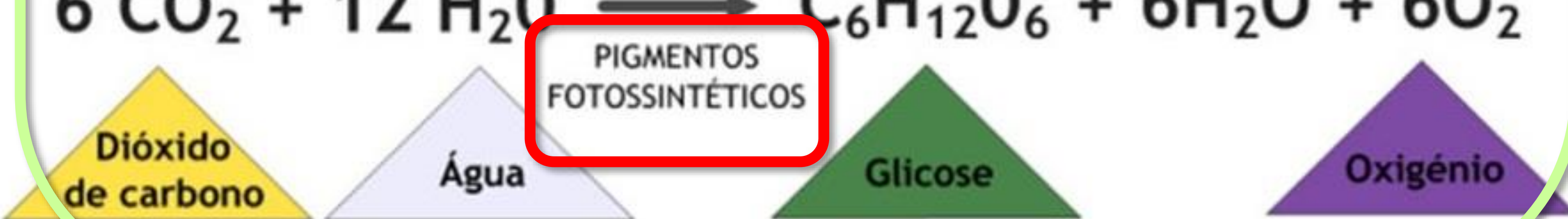
$$CO_2 + H_2O \xrightarrow{\text{light energy}} [CH_2O] + O_2$$

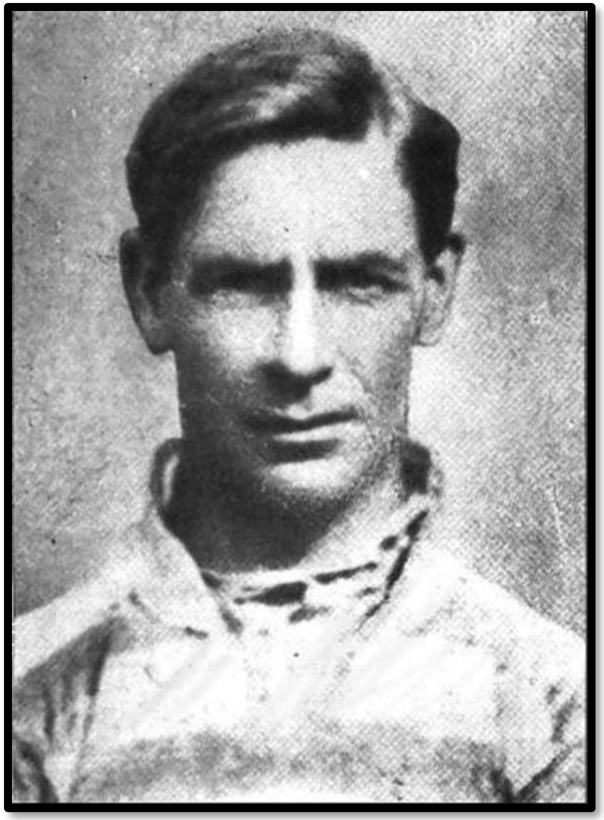
carbon dioxide | water | carbohydrates | oxygen

cloroplastos



$$6\ CO_2 + 12\ H_2O \xrightarrow{LUZ} C_6H_{12}O_6 + 6H_2O + 6O_2$$



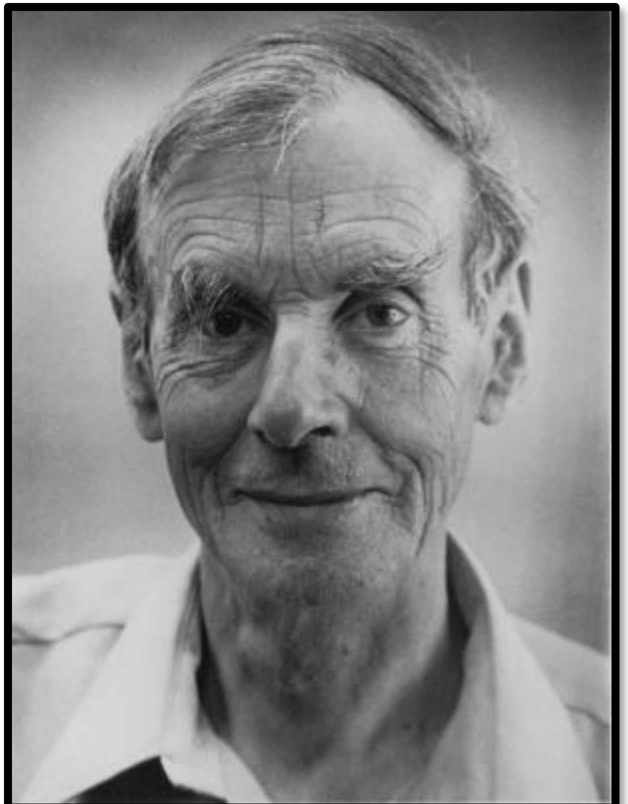


Frederick Frost Blackman

(1866–1947)

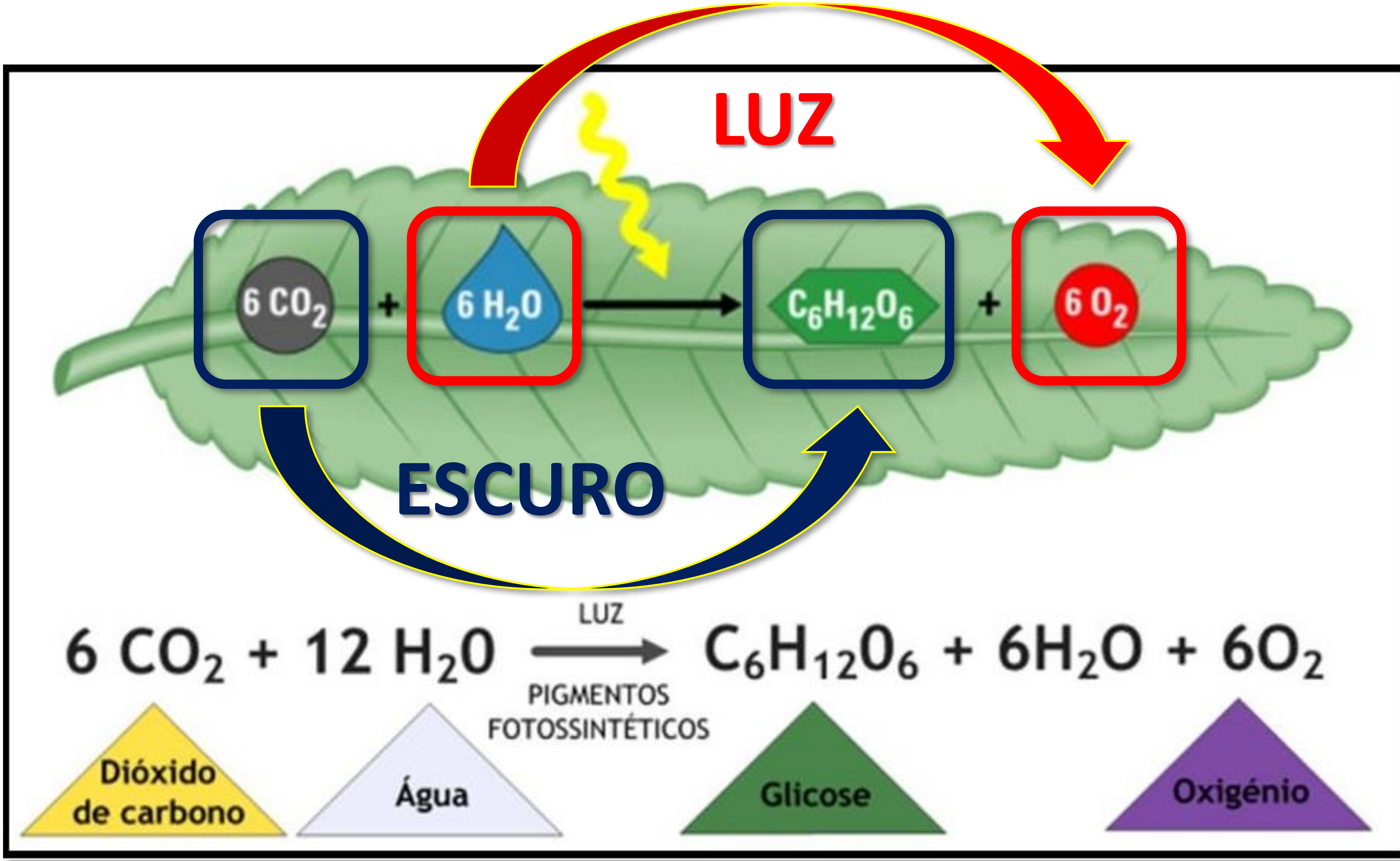
1905:

A Fotossíntese é dividida em duas fases: uma na luz e outra no escuro



Robin Hill
(1899–1991)

1937:
Cloroplastos isolados liberam oxigênio a partir da água (fase com luz)



LUZ
6 CO_2 + 6 H_2O → $C_6H_{12}O_6$ + 6 O_2
ESCURO
$6\ CO_2 + 12\ H_2O \xrightarrow[\text{PIGMENTOS FOTOSSINTÉTICOS}]{\text{LUZ}} C_6H_{12}O_6 + 6H_2O + 6O_2$
Dióxido de carbono
Água
Glicose
Oxigénio

Fotossíntese

Tilacóide

Fases da fotossíntese

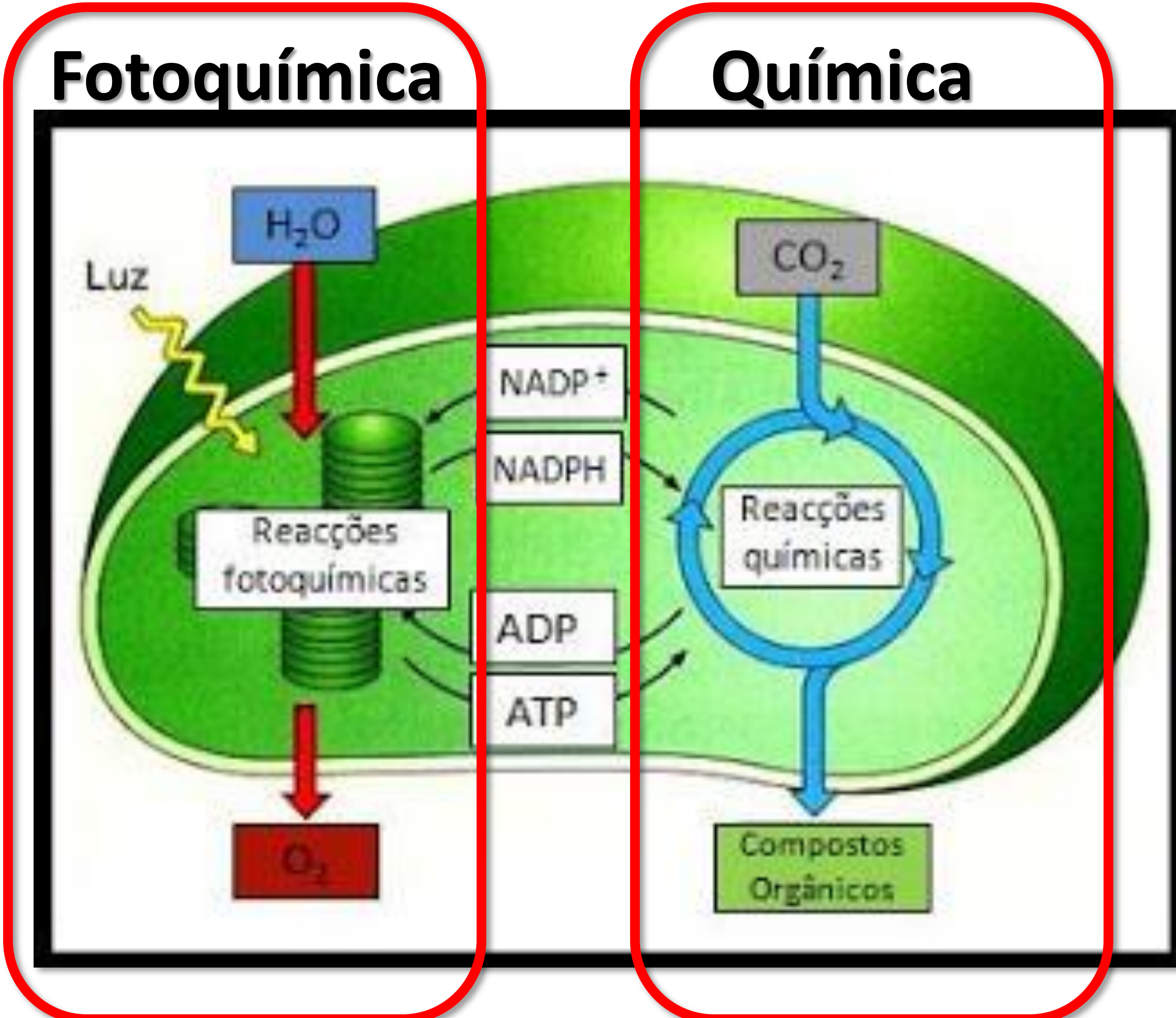
Fase de claro ou fotoquímica

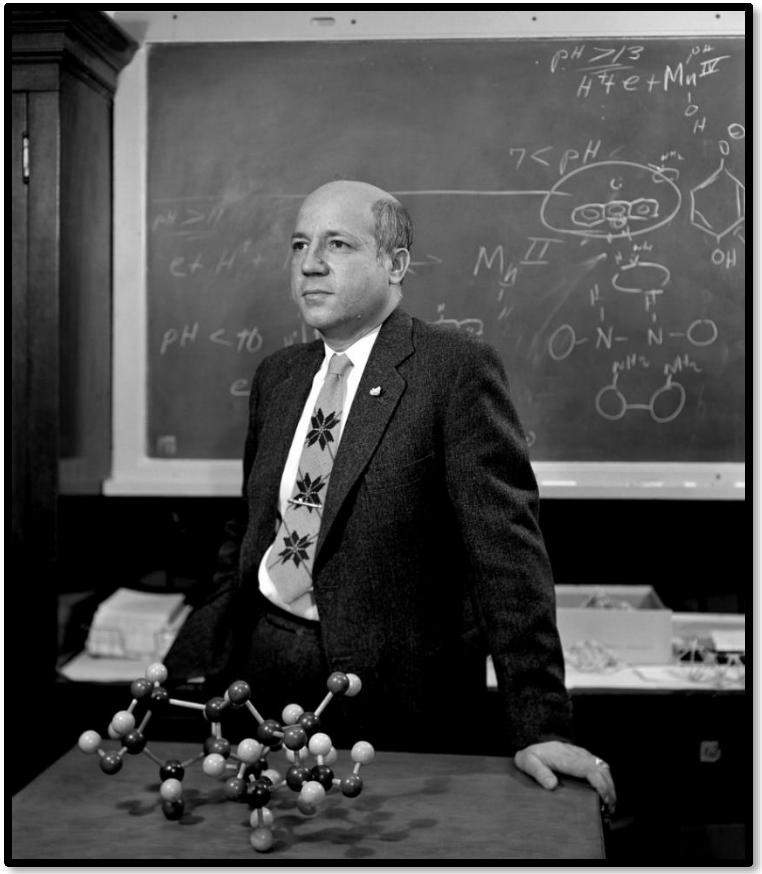
- Absorção da Luz
- Transporte de Elétrons
- Produção de ATP

Fase de escuro ou puramente química

- Fixação do Carbono

Estroma

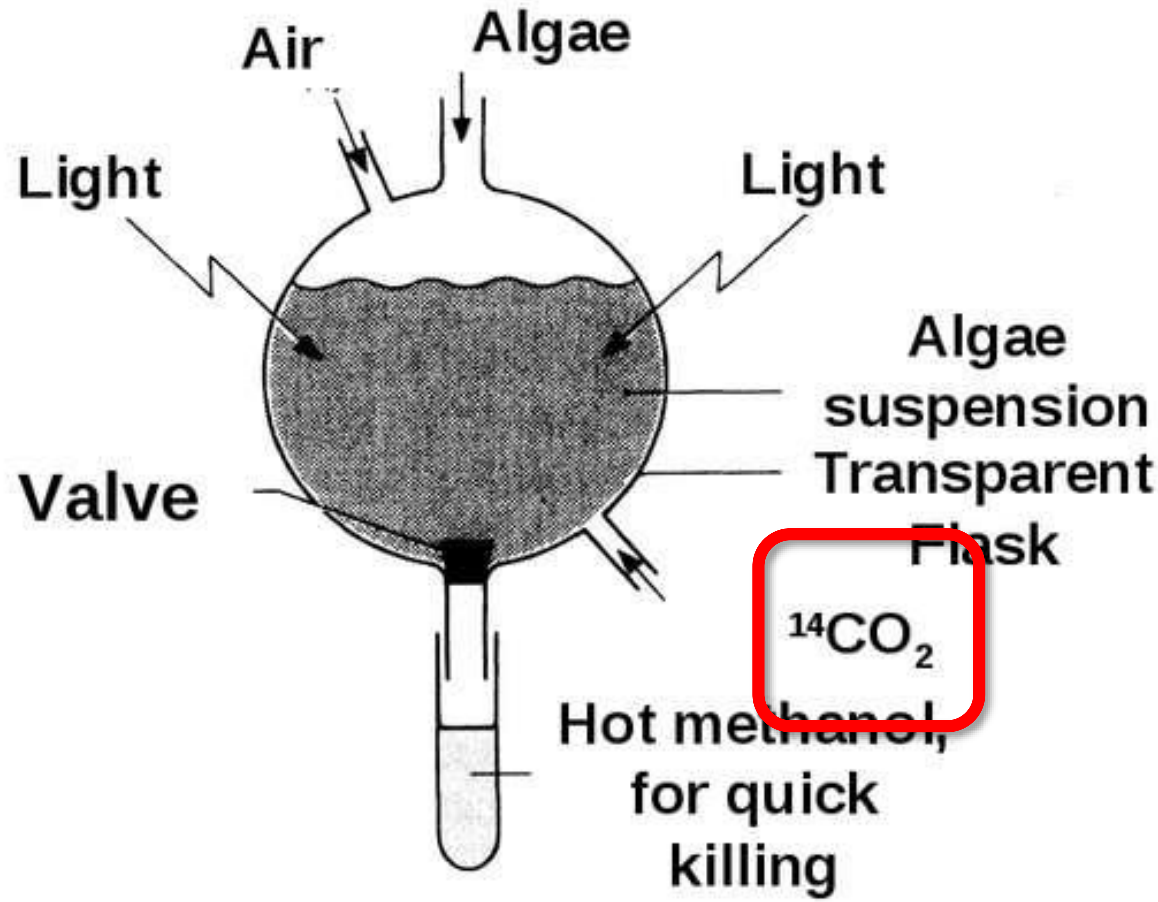

Fotoquímica
Química
H_2O
Luz
CO_2
NADP⁺
NADPH
Reacções fotoquímicas
Reacções químicas
ADP
ATP
O_2
Compostos Orgânicos

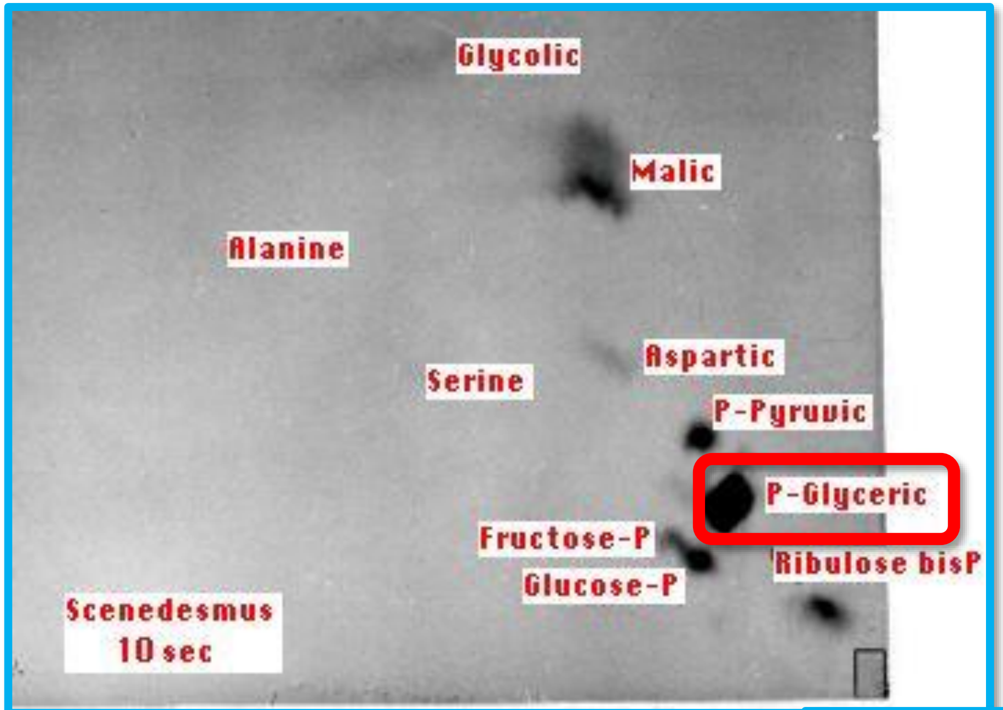


Melvin Ellis Calvin (1911–1997)

1945-57: Elucidação da fixação do dióxido de carbono (fase escura)

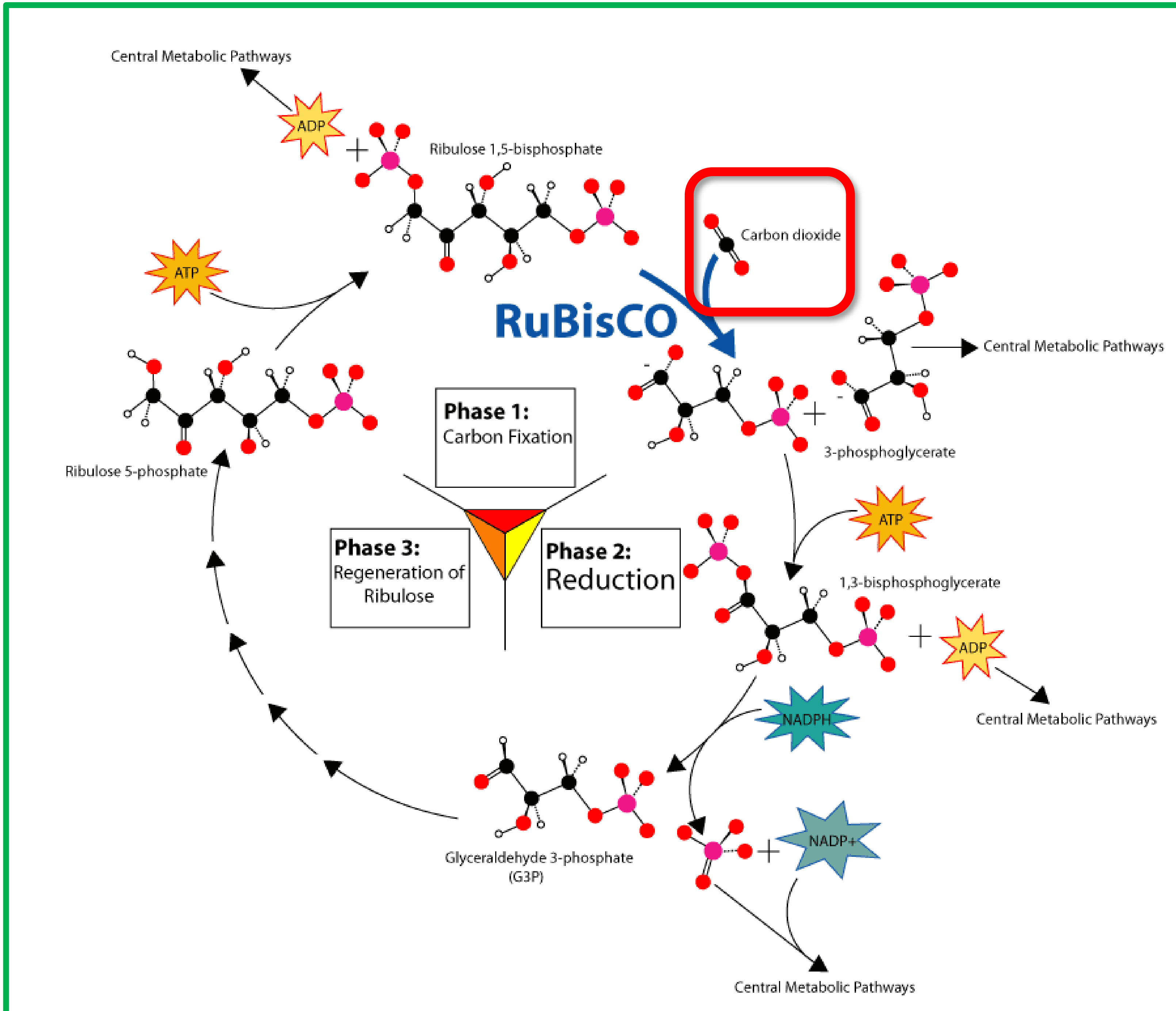
Calvin's experiment





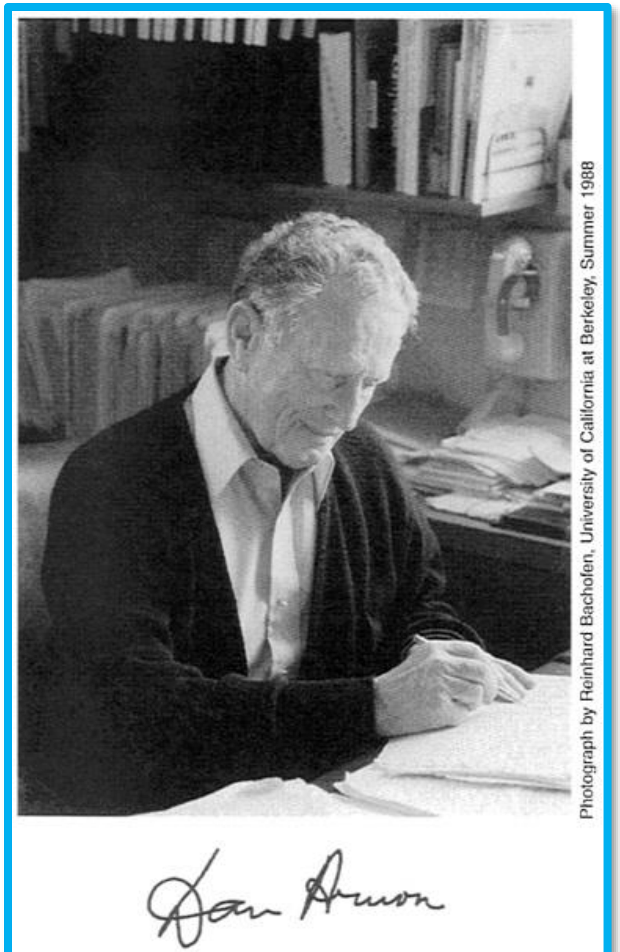
10 segundos

2 minutos


Central Metabolic Pathways
ADP
Ribulose 1,5-bisphosphate
Carbon dioxide
ATP
RuBisCO
Central Metabolic Pathways
3-phosphoglycerate
Ribulose 5-phosphate
Phase 1:
Carbon Fixation
Phase 3:
Regeneration of Ribulose
Phase 2:
Reduction
ATP
1,3-bisphosphoglycerate
ADP
Central Metabolic Pathways
NADPH
NADP+
Glyceraldehyde 3-phosphate (G3P)
Central Metabolic Pathways

Fixação do dióxido de carbono no escuro (ciclo de Calvim)

$$6\ CO_2 + 12\ NADPH + 12\ H_2O + 18\ ATP \longrightarrow C_6H_{12}O_6 + 12\ NADP^+ + 18\ ADP + 18\ Pi$$



Daniel Arnon

(1910-1994)

1954: Demonstrou a fotofosforilação (produção de ATP a partir da luz)

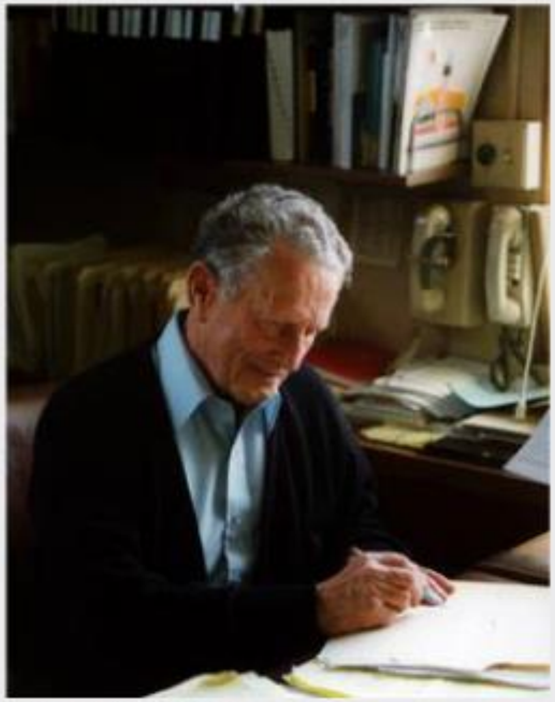


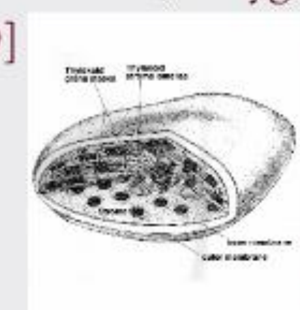
Image obtained from:
http://www.nap.edu/html/biomems/photo/darnon.JPG

Daniel Arnon

-Was the first to come up with the idea of and test the idea of photophosphorylation

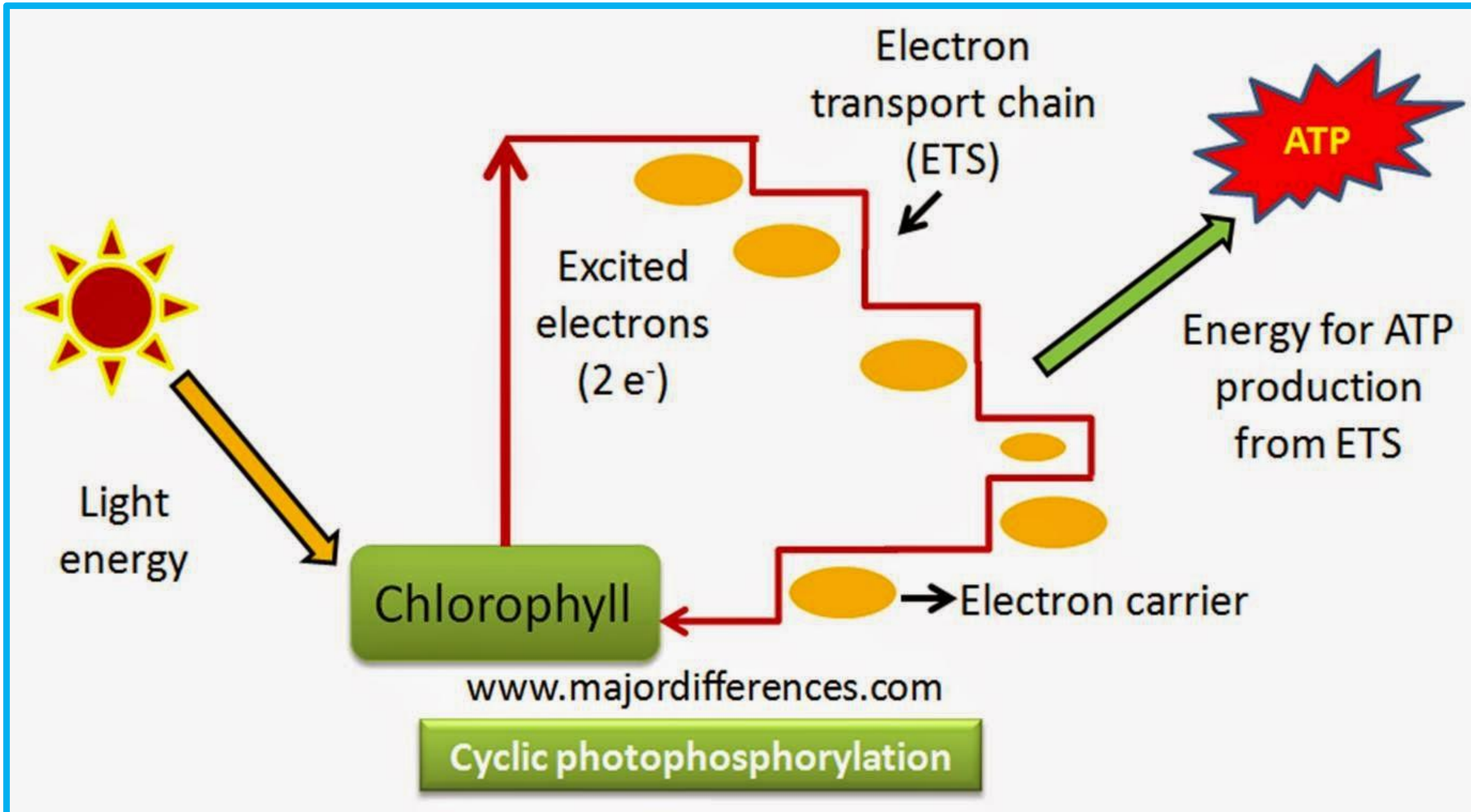
-He isolated chloroplast and studied how light energy was converted into chemical energy

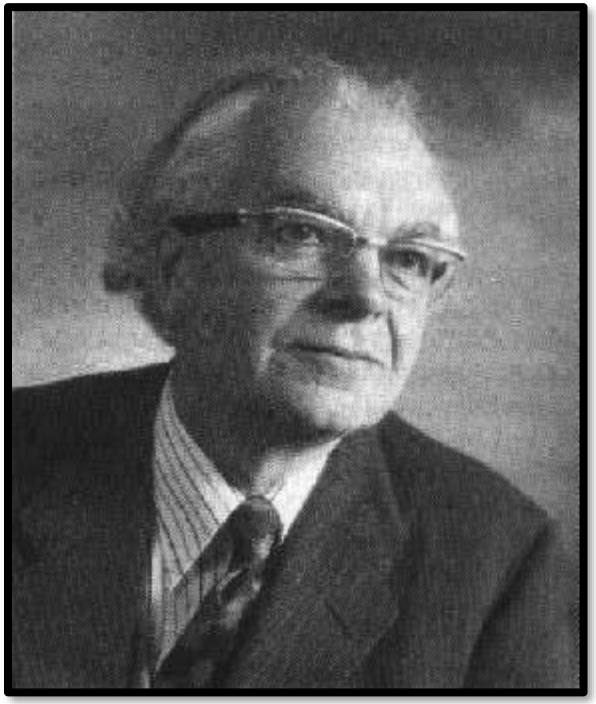
-He found that 1) ATP formed in the lamellae. 2) Only photons (light energy) was used. 3) Oxygen was neither produced or consumed. [9]



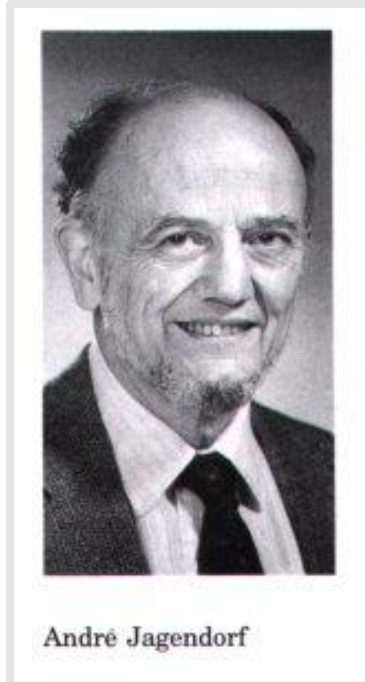
A cross-section picture of a chloroplast

Image obtained from:
http://www.life.illinois.edu/govindjee/paper/fig2.gif


Electron
transport chain
(ETS)
ATP
Excited
electrons
(2 e-)
Energy for ATP
production
from ETS
Light
energy
Chlorophyll
Electron carrier
www.majordifferences.com
Cyclic photophosphorylation



Peter Mitchell (1920-1992)

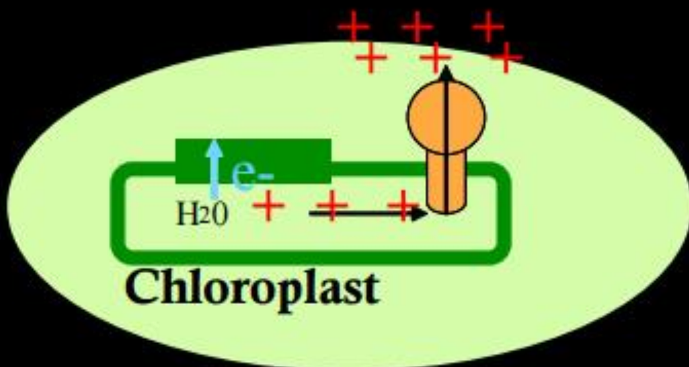


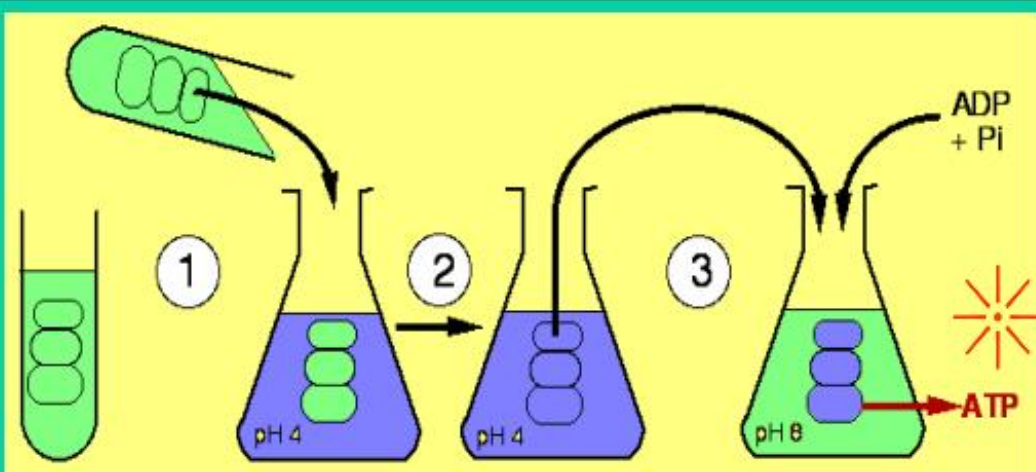
André Jagendorf (1926-)

1966: Hipótese quimiosmótica para produção de ATP também se aplica à fotossíntese

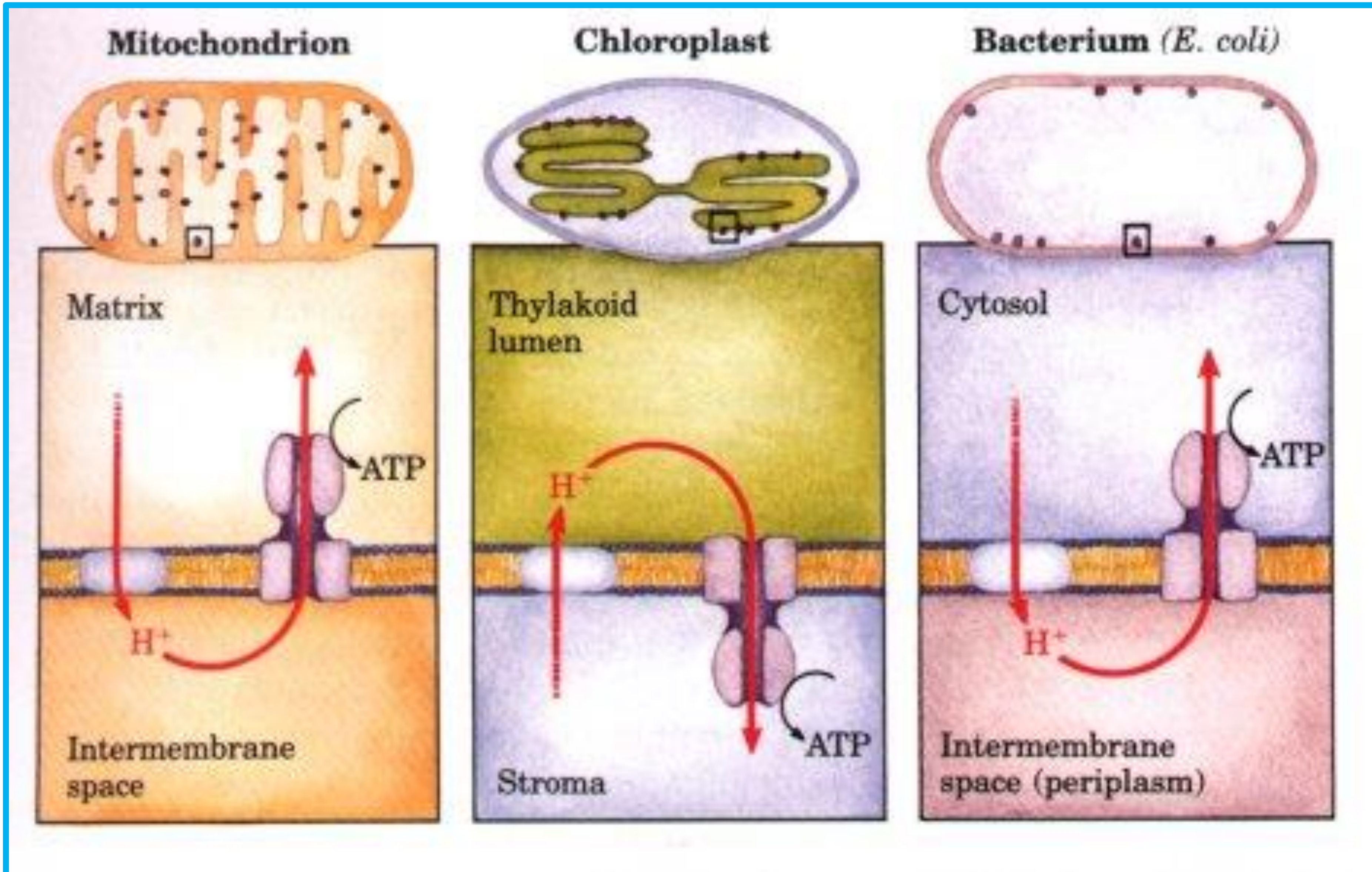
Chemiosmotic Mechanism for ATP Synthesis

Jagendorf's chloroplast work provided powerful support for Peter Mitchell's theory for ATP generation



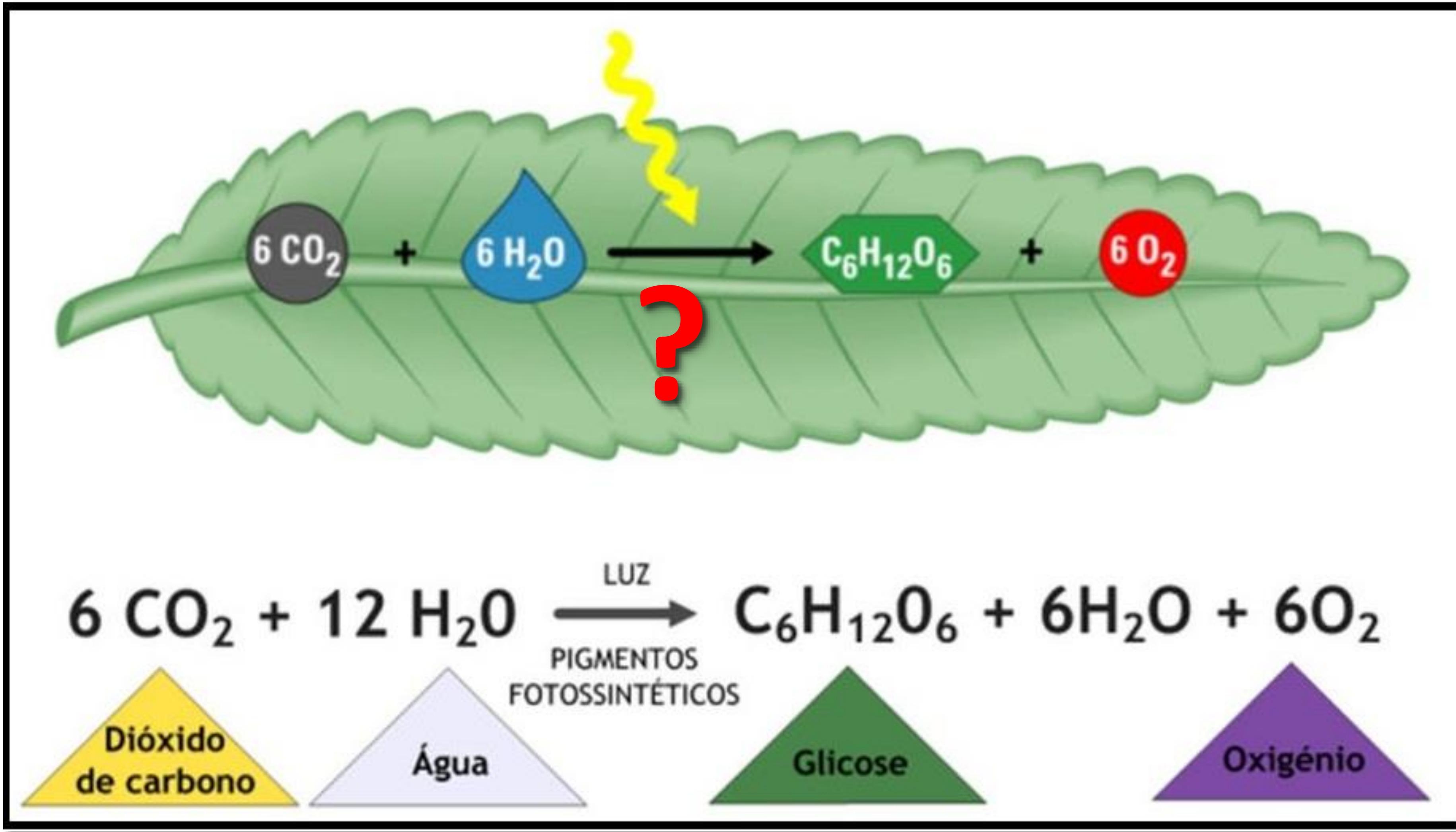


Andre T. Jagendorf



Mitochondrion
Chloroplast
Bacterium (E. coli)
Matrix
ATP
H+
Intermembrane space
Thylakoid lumen
H+
ATP
Stroma
Cytosol
ATP
H+
Intermembrane space (periplasm)

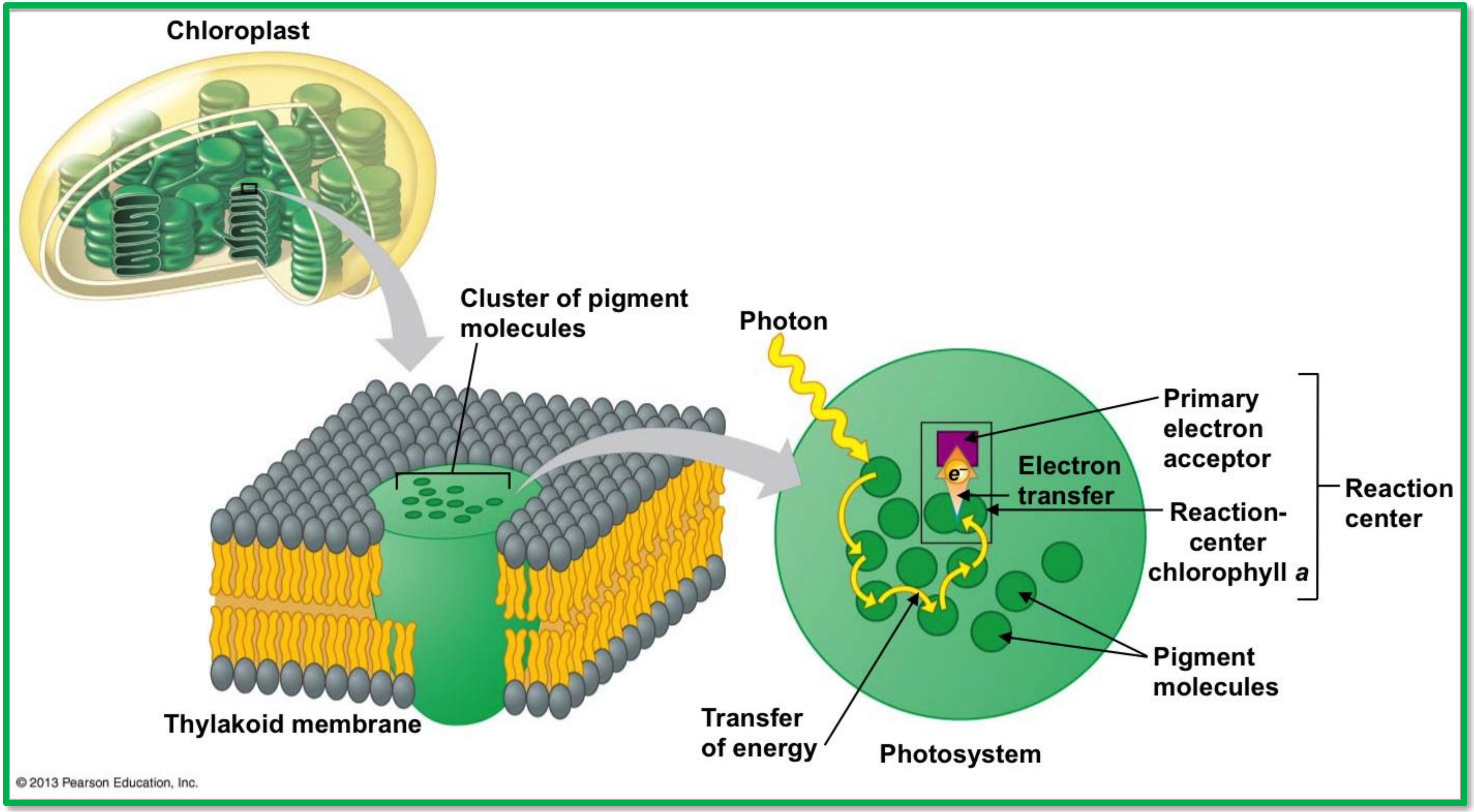
Componentes moleculares?



Robert Emerson (1902-1959)

1957: Dois fotossistemas (centros de reação) operando sinergicamente nas membranas tilacóides

Centro de reação



Fundamental theories of Photochemistry

❖ Selection rules:

1. Radiation transitions (Absorption, fluorescence)
   Allowed transitions: g ⟷ u, e.g.: S_0 ⟷ S_1 and T_1 ⟷ S_0
   Forbidden transitions: g ⟷ g, u ⟷ u, e.g.: S_1 ⟷ T_1
2. Radiationless transitions (vibration relaxation, Internal conversion, Intersystem crossing)
   Allowed transitions: g ⟷ g, u ⟷ u, e.g.: S_1 ⟷ T_1
   Forbidden transitions: g ⟷ u, e.g.: S_0 ⟷ S_1 and T_1 ⟷ S_0

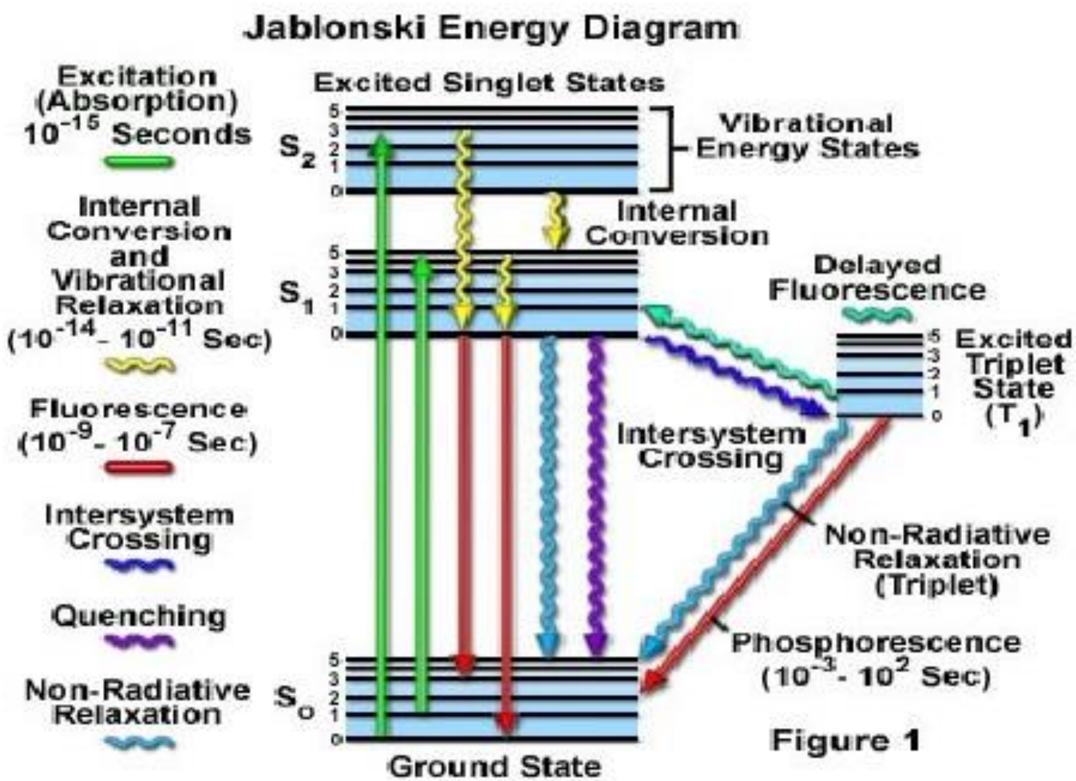
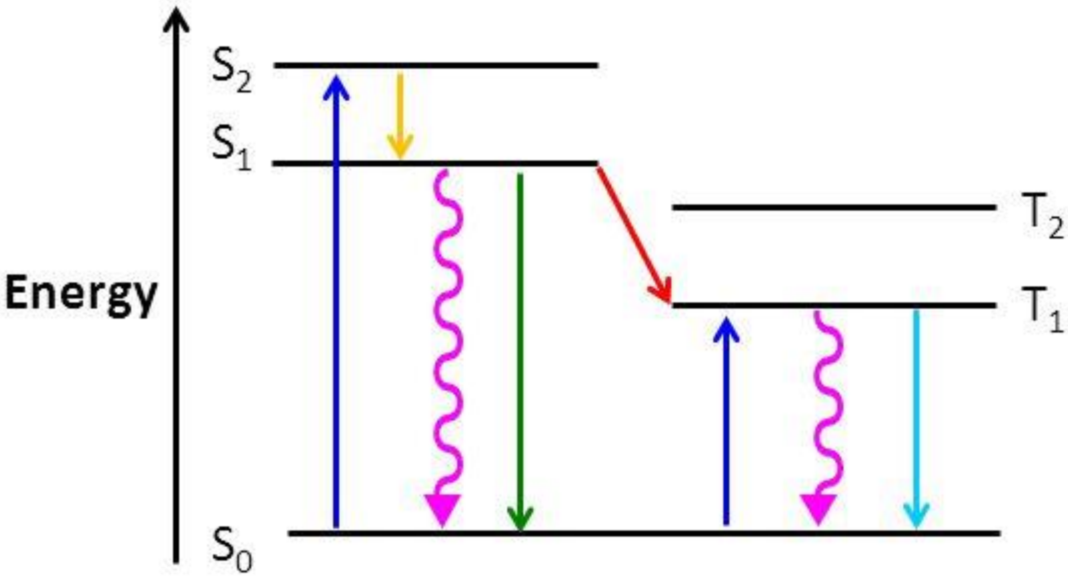


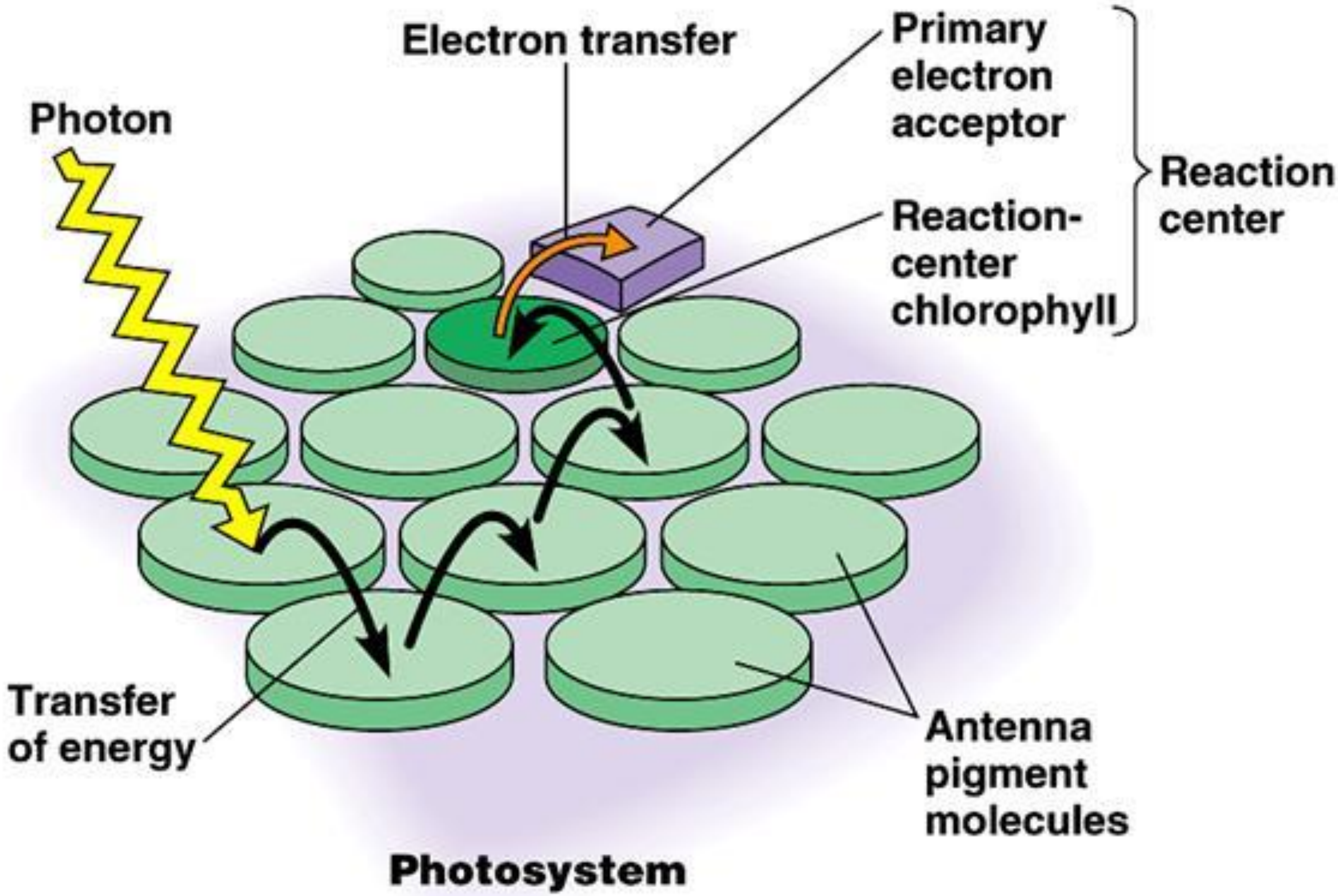
Figure 1

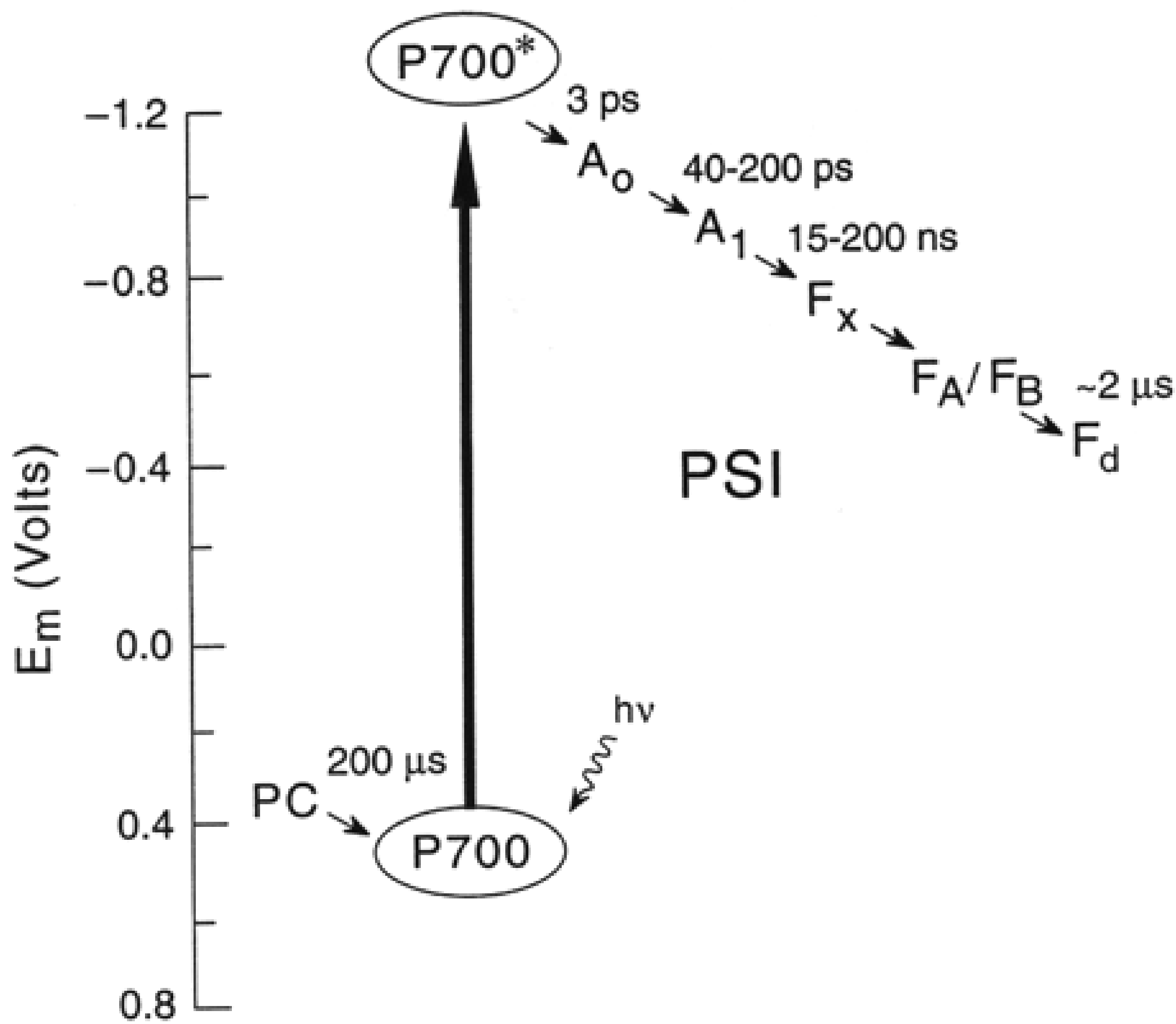
Other Processes



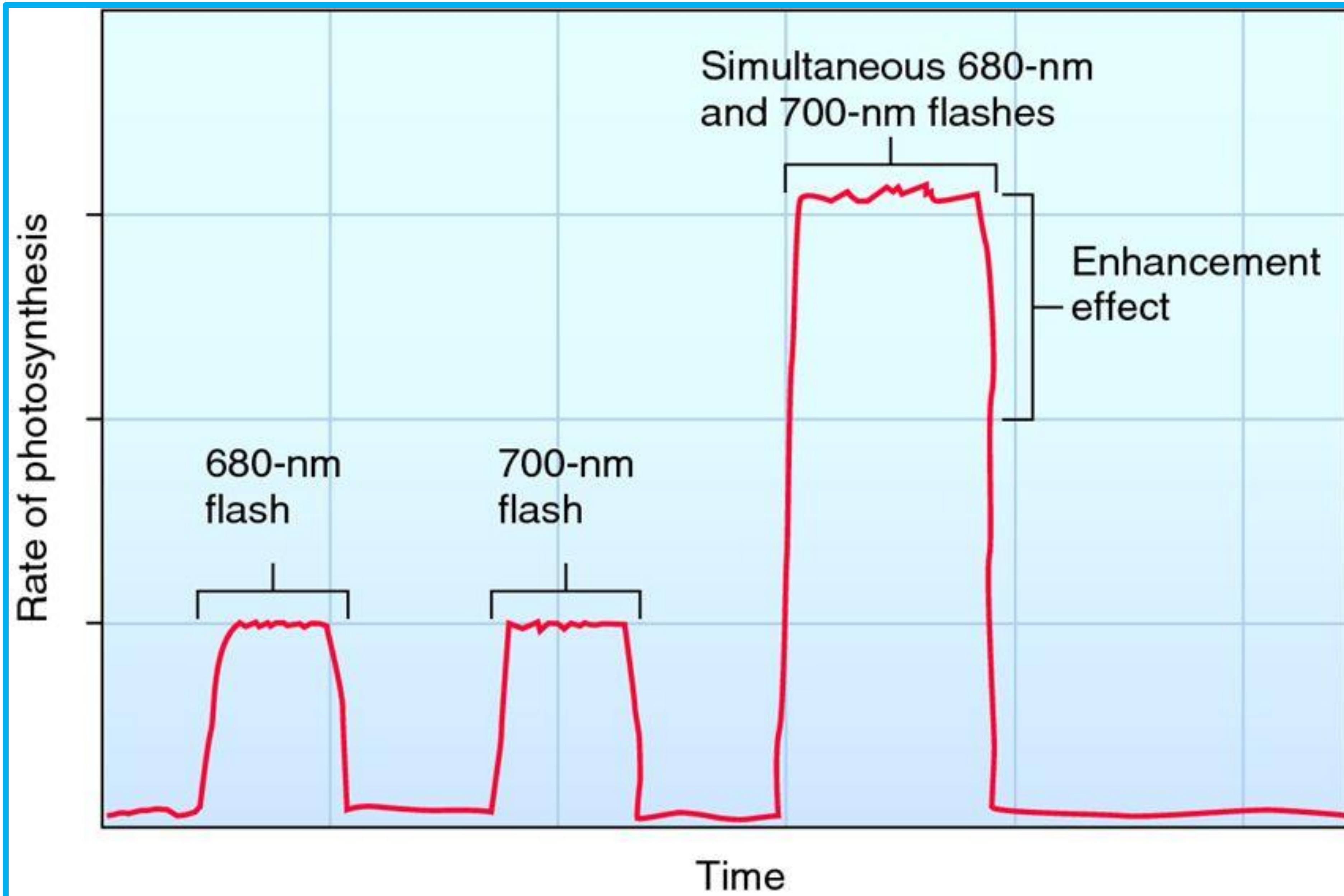
Excitation
Internal Conversion
Fluorescence
Non-radiative decay
Intersystem Crossing
Phosphorescence

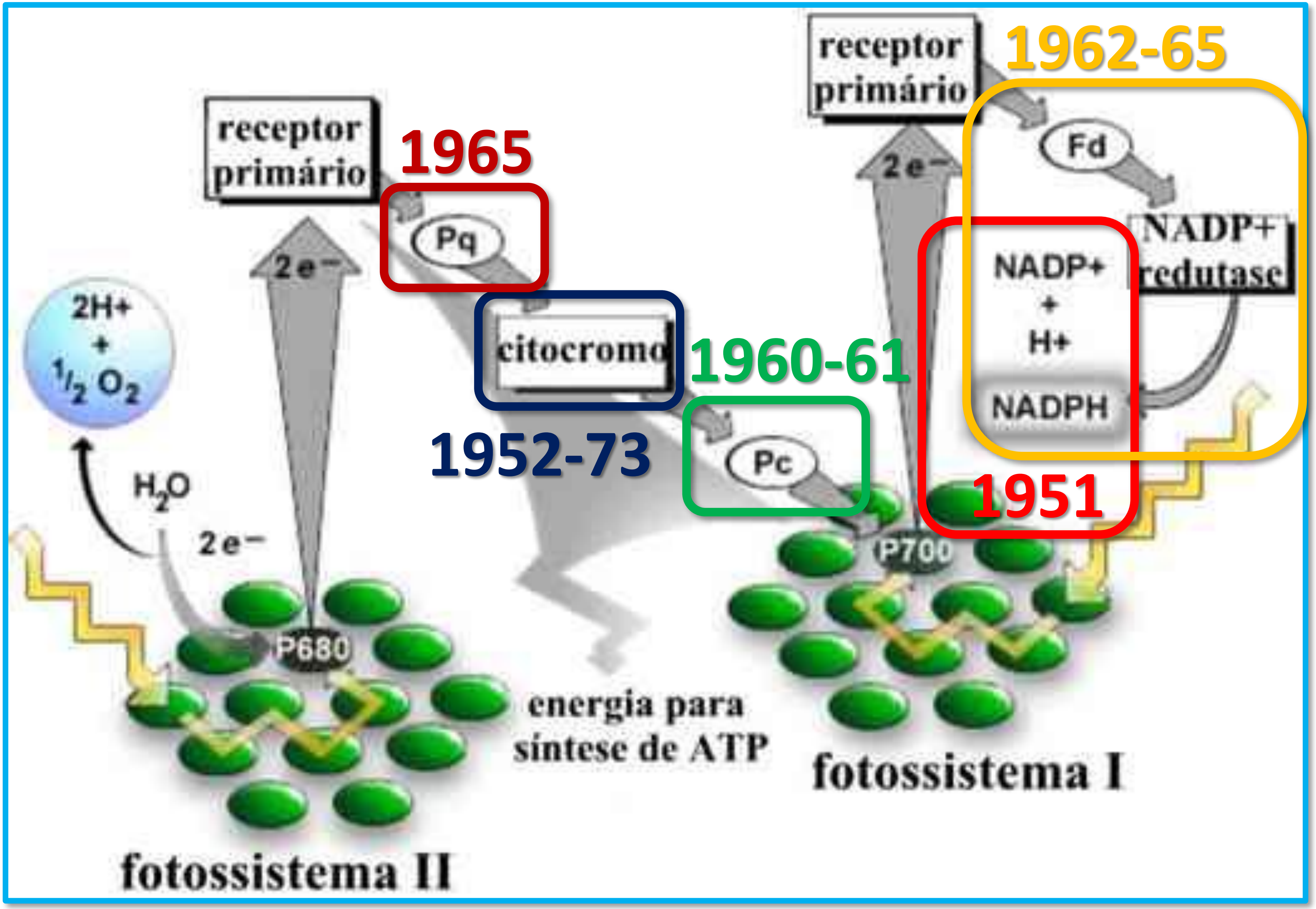
- Electron transfer
- TICT
- ESIPT
- Photochemical Reactions

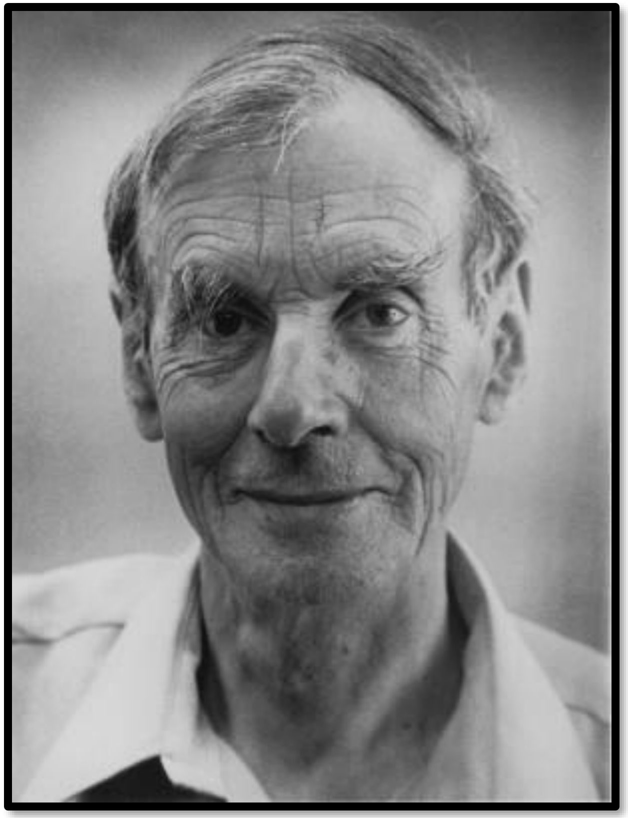

Electron transfer
Primary
electron
acceptor
Reaction
center
Photon
Reaction-
center
chlorophyll
Transfer
of energy
Antenna
pigment
molecules
Photosystem



P700*
3 ps
A0
40-200 ps
A1
15-200 ns
FX
FA/FB
~2 µs
Fd
PSI
Em (Volts)
−1.2
−0.8
−0.4
0.0
0.4
0.8
hν
200 µs
PC
P700

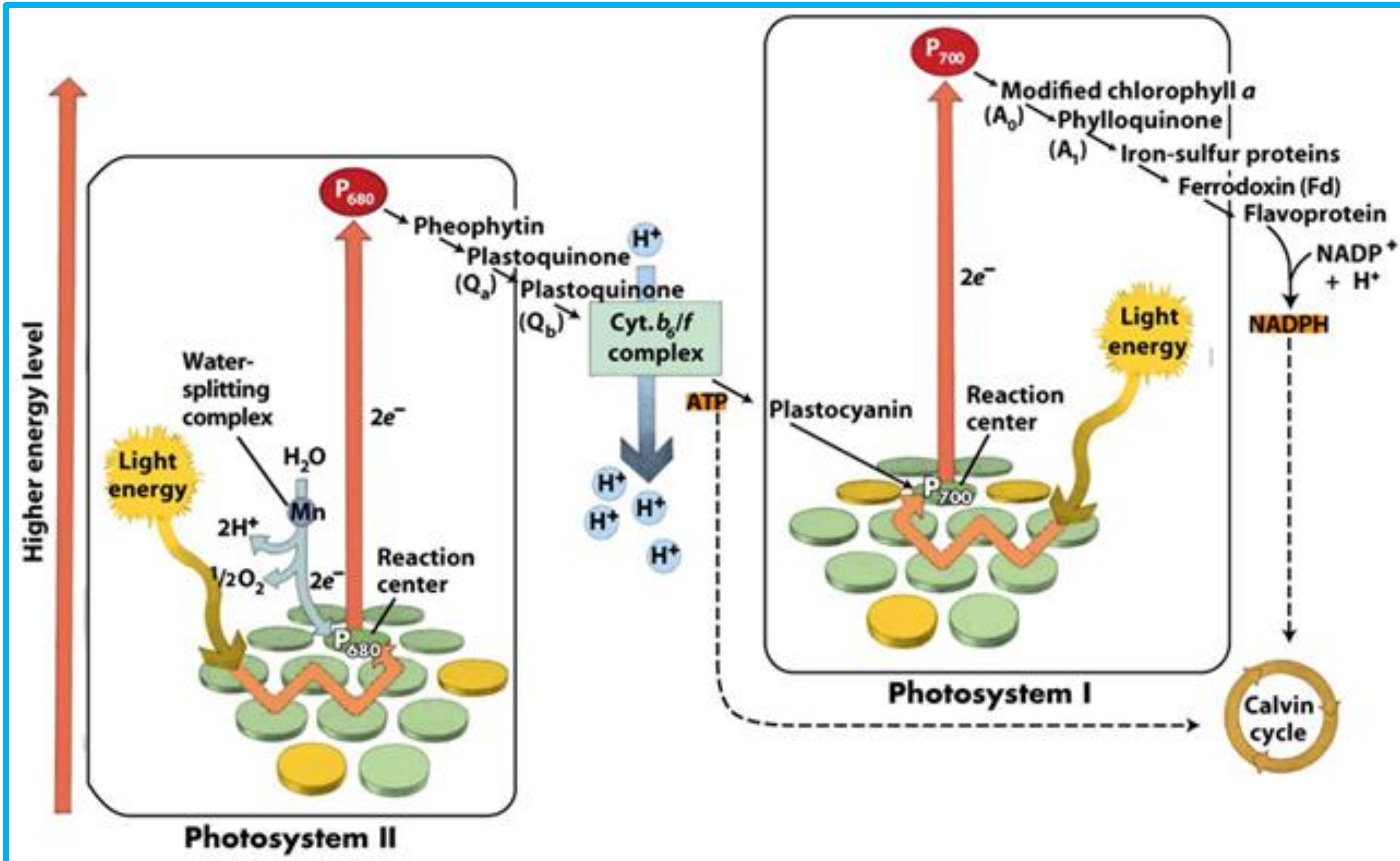

Simultaneous 680-nm
and 700-nm flashes
Enhancement
effect
680-nm
flash
700-nm
flash
Rate of photosynthesis
Time


receptor primário
1965
Pq
citocromo
1952-73
1960-61
Pc
receptor primário
1962-65
Fd
NADP+ redutase
NADP+
+
H+
NADPH
1951
2e⁻
2H+
+
½ O2
H2O
2e⁻
P680
P700
energia para síntese de ATP
fotossistema I
fotossistema II



Robin Hill
(1899–1991)

1960:
Resumindo conhecimento da época propõe o esquema Z da fotossíntese



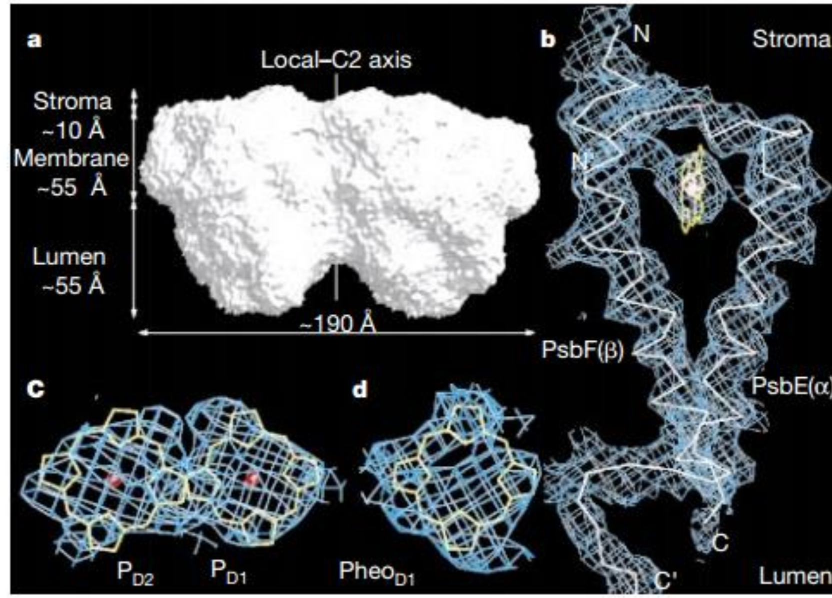
Higher energy level
P_{680}
Pheophytin
Plastoquinone (Q_a)
Plastoquinone (Q_b)
H^+
Cyt. b_6/f complex
H^+
H^+
H^+
H^+
ATP
Water-splitting complex
H_2O
Mn
$2H^+$
$1/2O_2$
$2e^-$
$2e^-$
Light energy
Reaction center
P_{680}
Photosystem II
P_{700}
Modified chlorophyll *a* (A_0)
Phylloquinone (A_1)
Iron-sulfur proteins
Ferrodoxin (Fd)
Flavoprotein
$NADP^+$ + H^+
NADPH
$2e^-$
Light energy
Plastocyanin
Reaction center
P_{700}
Photosystem I
Calvin cycle

Crystal structure of photosystem II from *Synechococcus elongatus* at 3.8 Å resolution

Athina Zouni*, Horst-Tobias Witt*, Jan Kern*, Petra Fromme*, Norbert Krauß†, Wolfram Saenger†, Peter Orth†

**Max-Volmer-Institut für Biophysikalische Chemie und Biochemie, Technische Universität Berlin, Straße des 17, Juni 135, D-10623, Berlin, Germany*
† Institut für Chemie, Kristallographie, Freie Universität Berlin, Takustrasse 6, D-14195 Berlin, Germany

Oxygenic photosynthesis is the principal energy converter on earth. It is driven by photosystems I and II, two large protein–

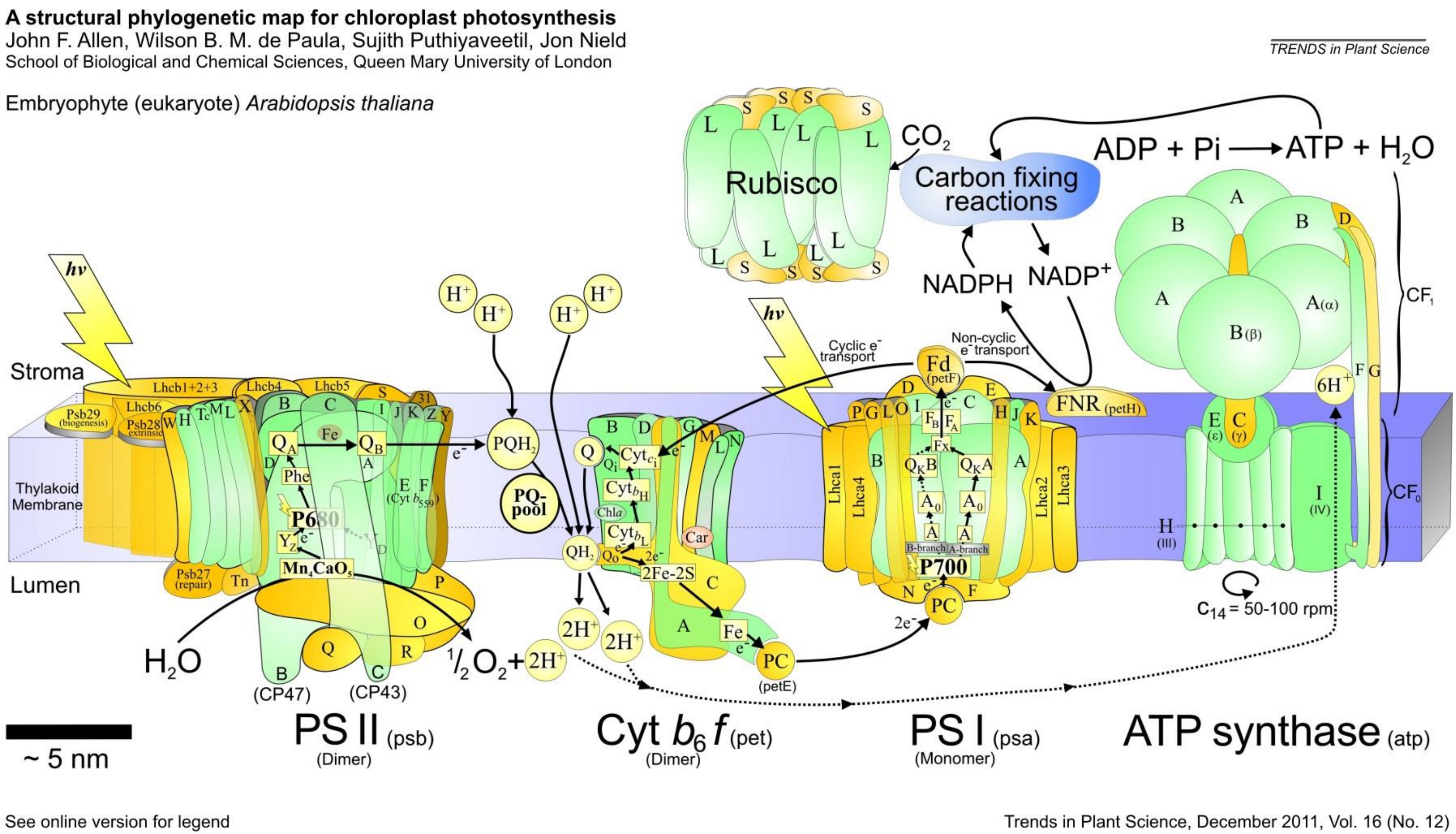


articles

Three-dimensional structure of cyanobacterial photosystem I at 2.5 Å resolution

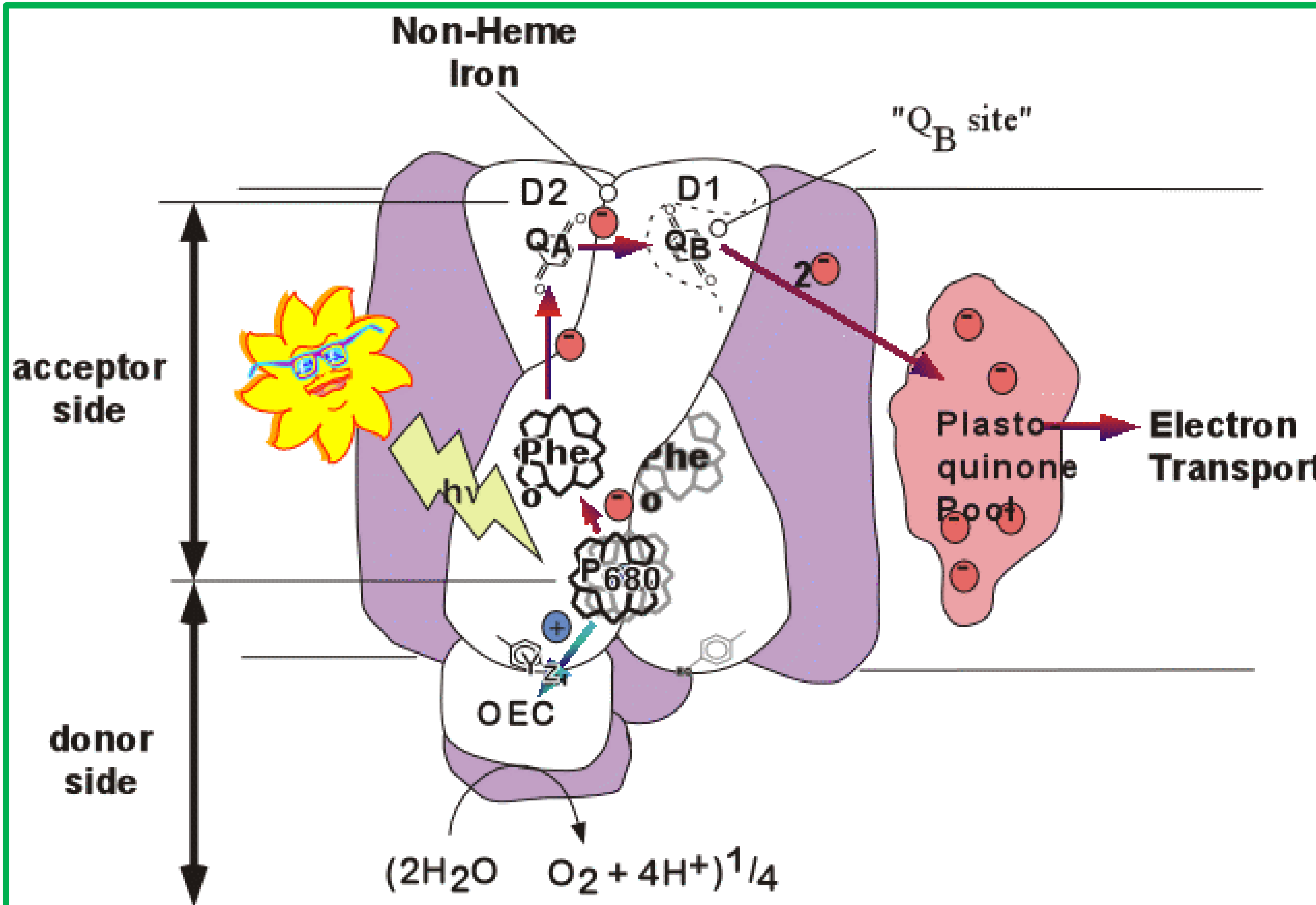
Patrick Jordan*, Petra Fromme†, Horst Tobias Witt†, Olaf Klukas*, Wolfram Saenger* & Norbert Krauß*‡

** Institut für Chemie/Kristallographie, Freie Universität Berlin, D-14195 Berlin, Takustraße 6, Germany*
† Max Volmer Laboratorium für Biophysikalische Chemie, Institut für Chemie, Fakultät 2; Technische Universität Berlin, D-10623 Berlin, Straße des 17. Juni 135, Germany

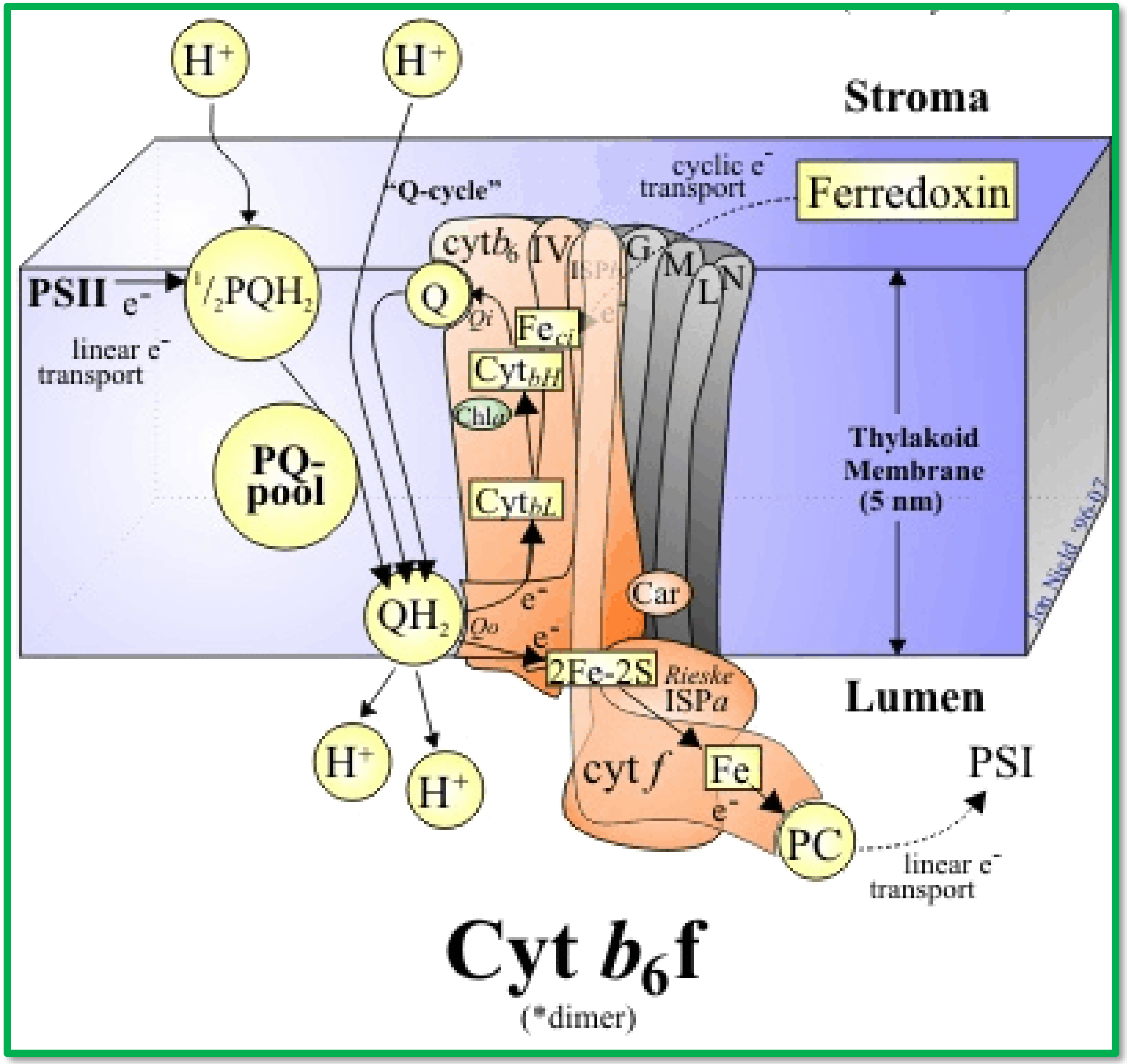


20 subunidades; 99 cofatores	***16 sub.; 7 cofat.***	***11 sub.; 110 cofat.***	***14 subunidades***

Fotossistema II



Citocromo b6f



Fotos-sistema I

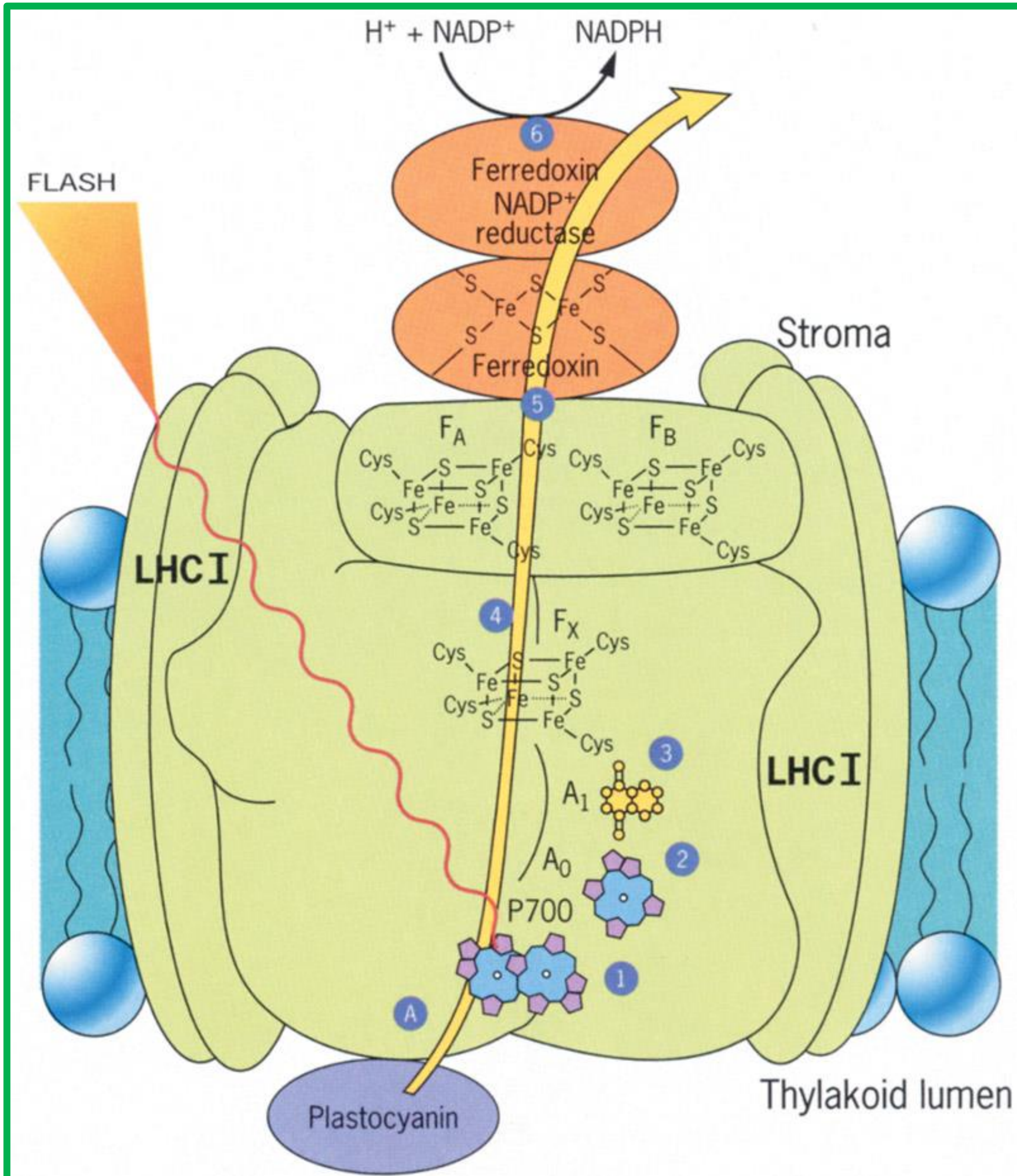
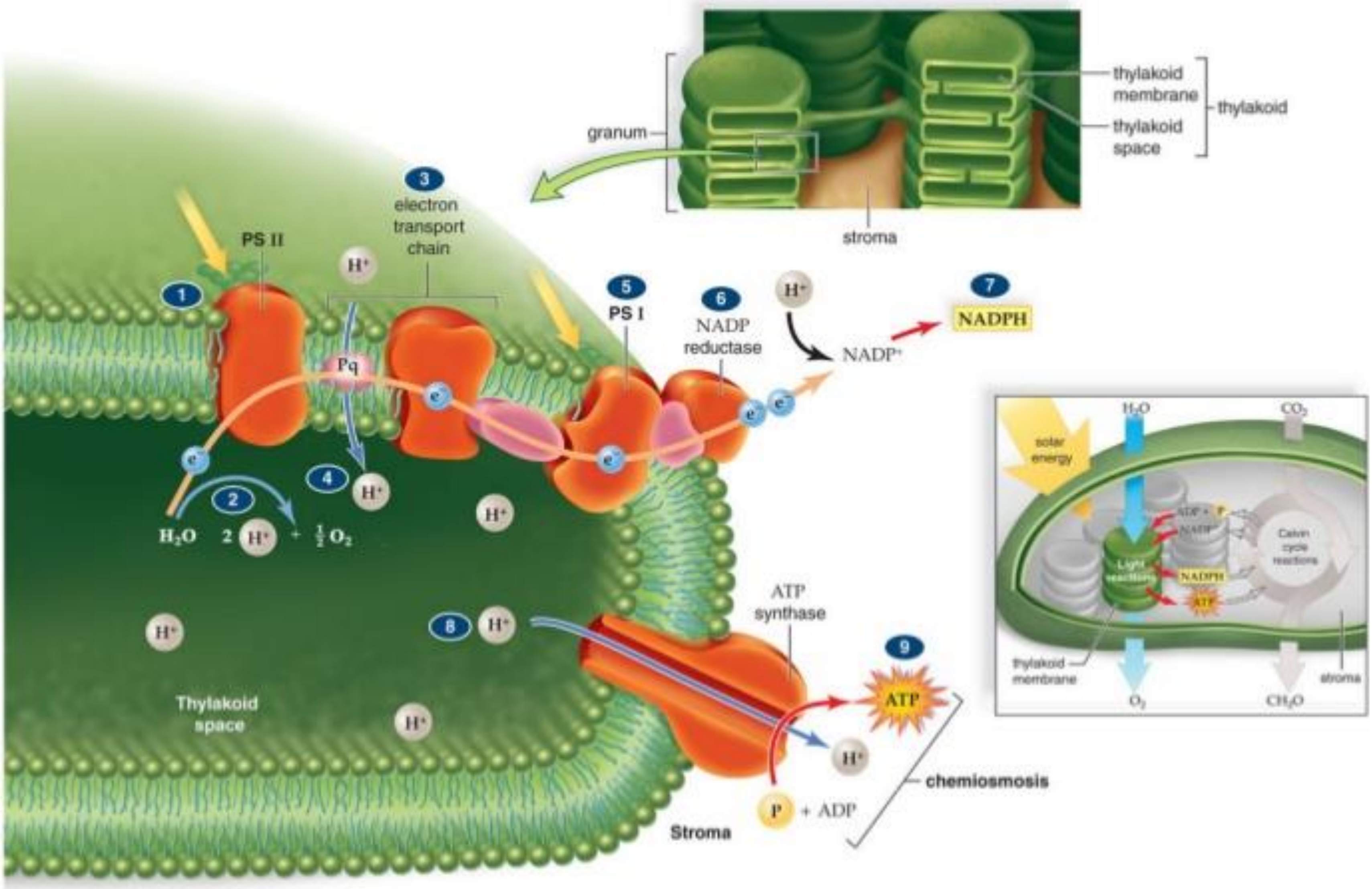
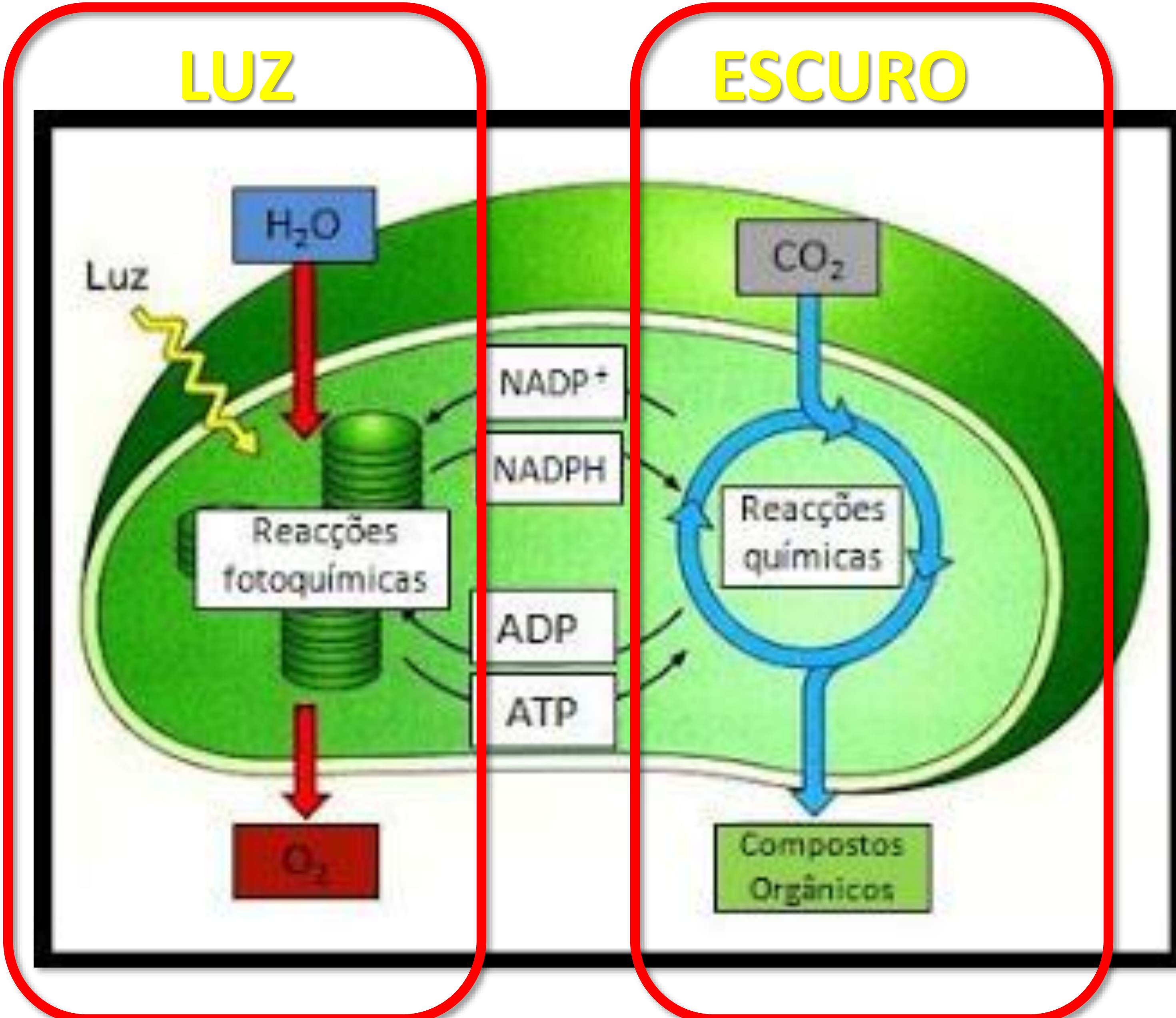


Figure 6.11 Organization of a thylakoid




LUZ
ESCURO
H2O
Luz
CO2
NADP+
NADPH
Reacções fotoquímicas
Reacções químicas
ADP
ATP
Compostos Orgânicos

2- Evolução da fotossíntese

Konstantin Mereschkowski (1855–1921)

Lynn Margulis (1938-2011)

1905, 1967: Cloroplastos derivaram de uma cianobactéria endosimbiótica

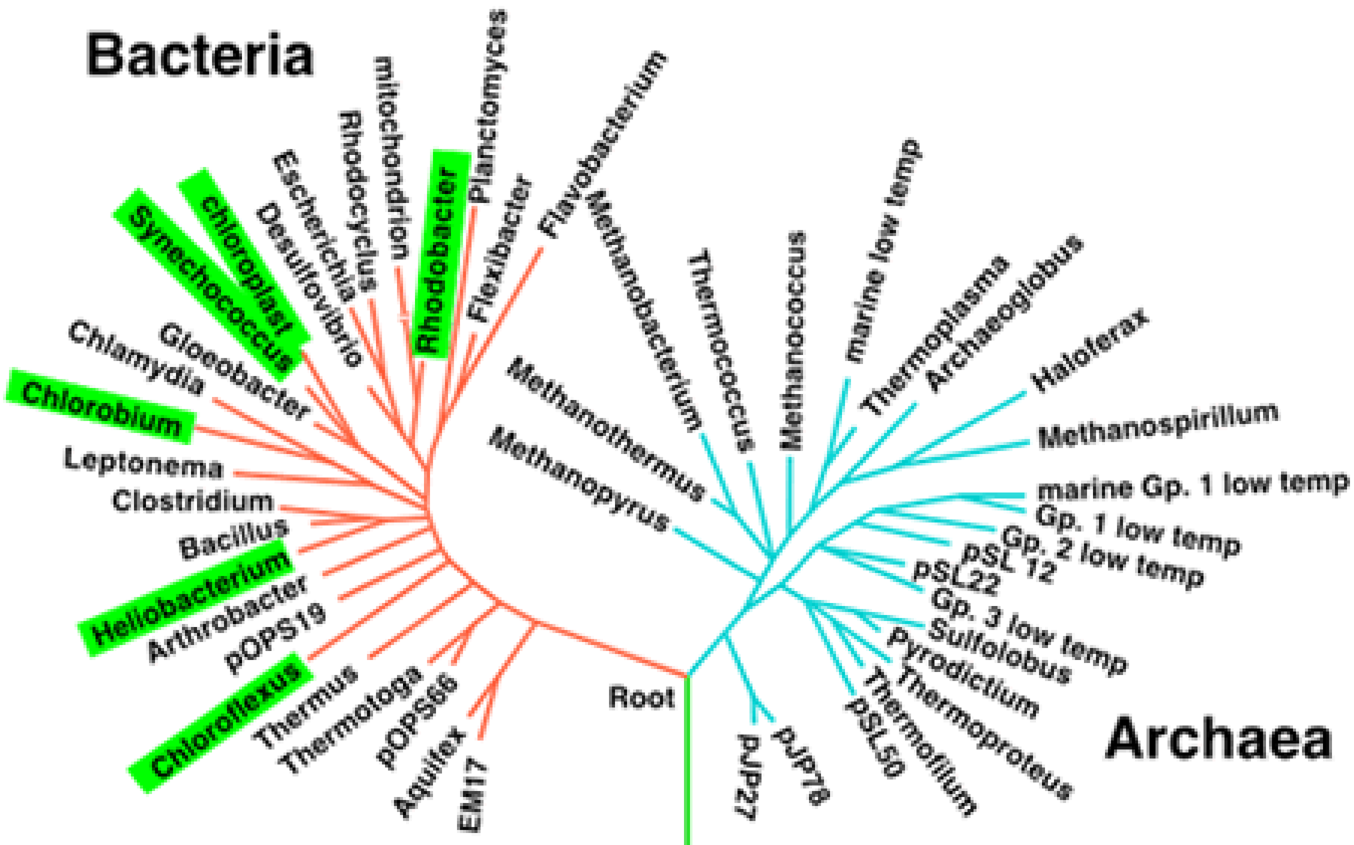


Fig. 2, Phylogenetic analysis of known branches of photosynthetic microorganisms (highlighted in green)

Fotossíntese Bacteriana (Fotorredução)

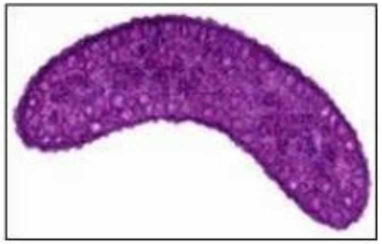
Bactérias Púrpuras do Enxofre (Sulfobactérias)

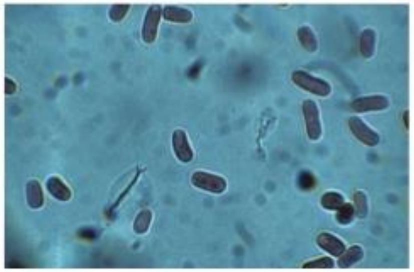
- Realizam um tipo de fotossíntese em que a substância doadora de elétrons não é a água, mas sim o **gás sulfídrico** (H_2S). Neste processo há produção de enxofre e não gás oxigênio.

- São **anaeróbias estritas** pois o O_2 inibe a produção de pigmentos fotossintéticos.

Fonte de Carbono	Fonte de energia	Doador de elétrons
CO_2	**Luz do sol**	**H_2S**

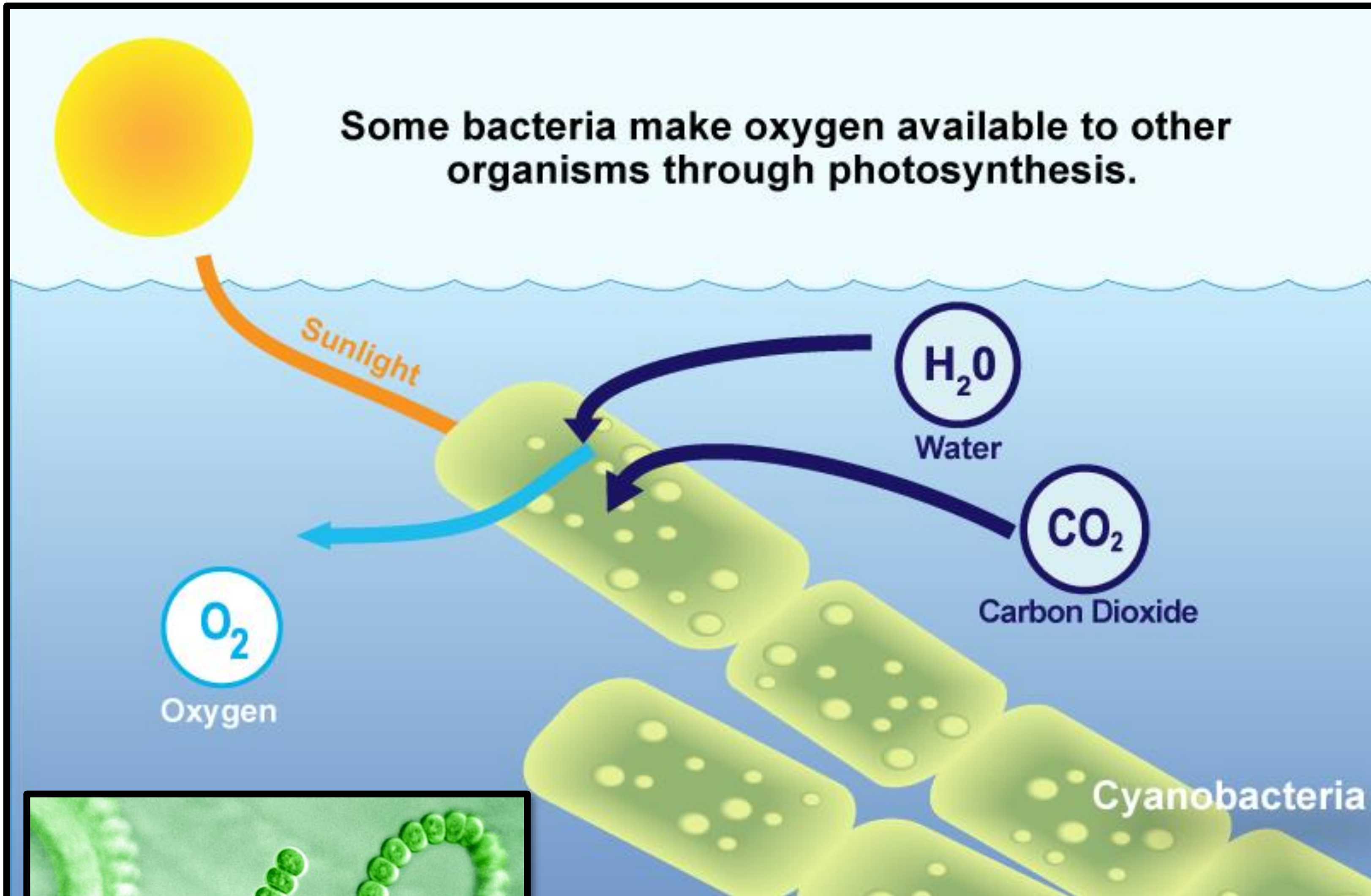
$$CO_2 + 2\,H_2S + Luz \rightarrow CH_2O + 2\,S + H_2O$$

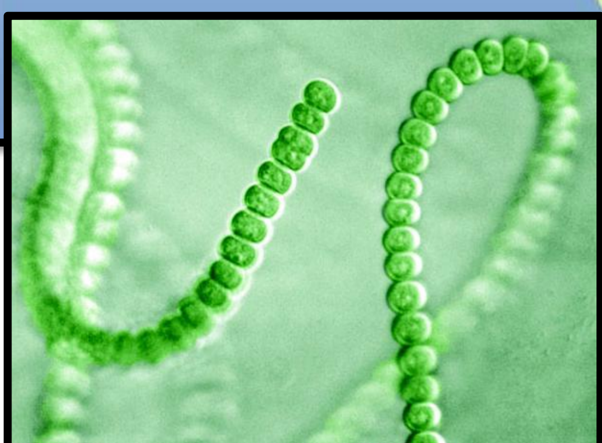




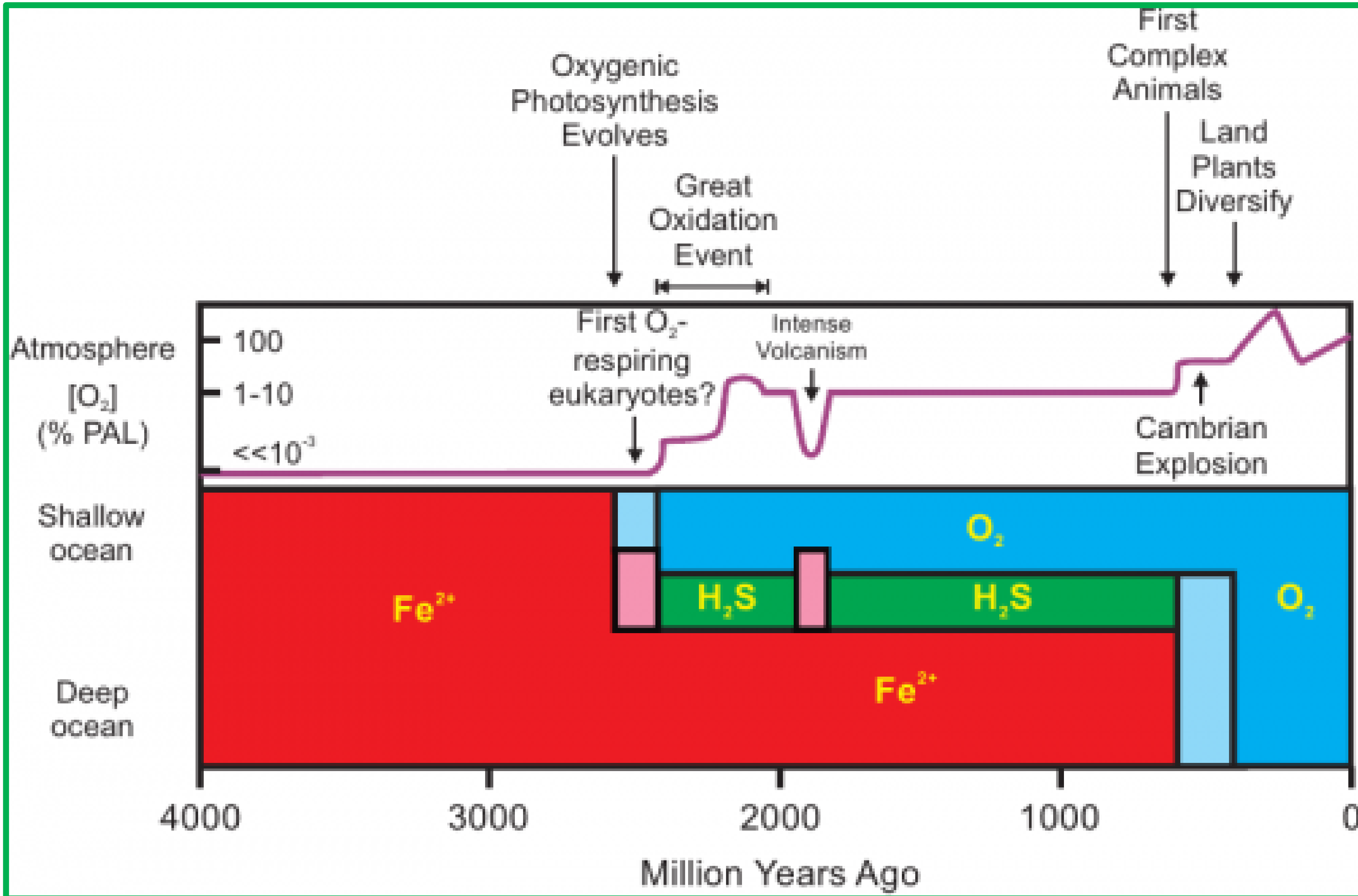
- EX: Bactérias verdes sulfurosas

$$6CO_2 + 12H_2S \xrightarrow[\text{bacterioclorofila}]{\text{luz}} C_6H_{12}O_6 + 12S + 6H_2O$$

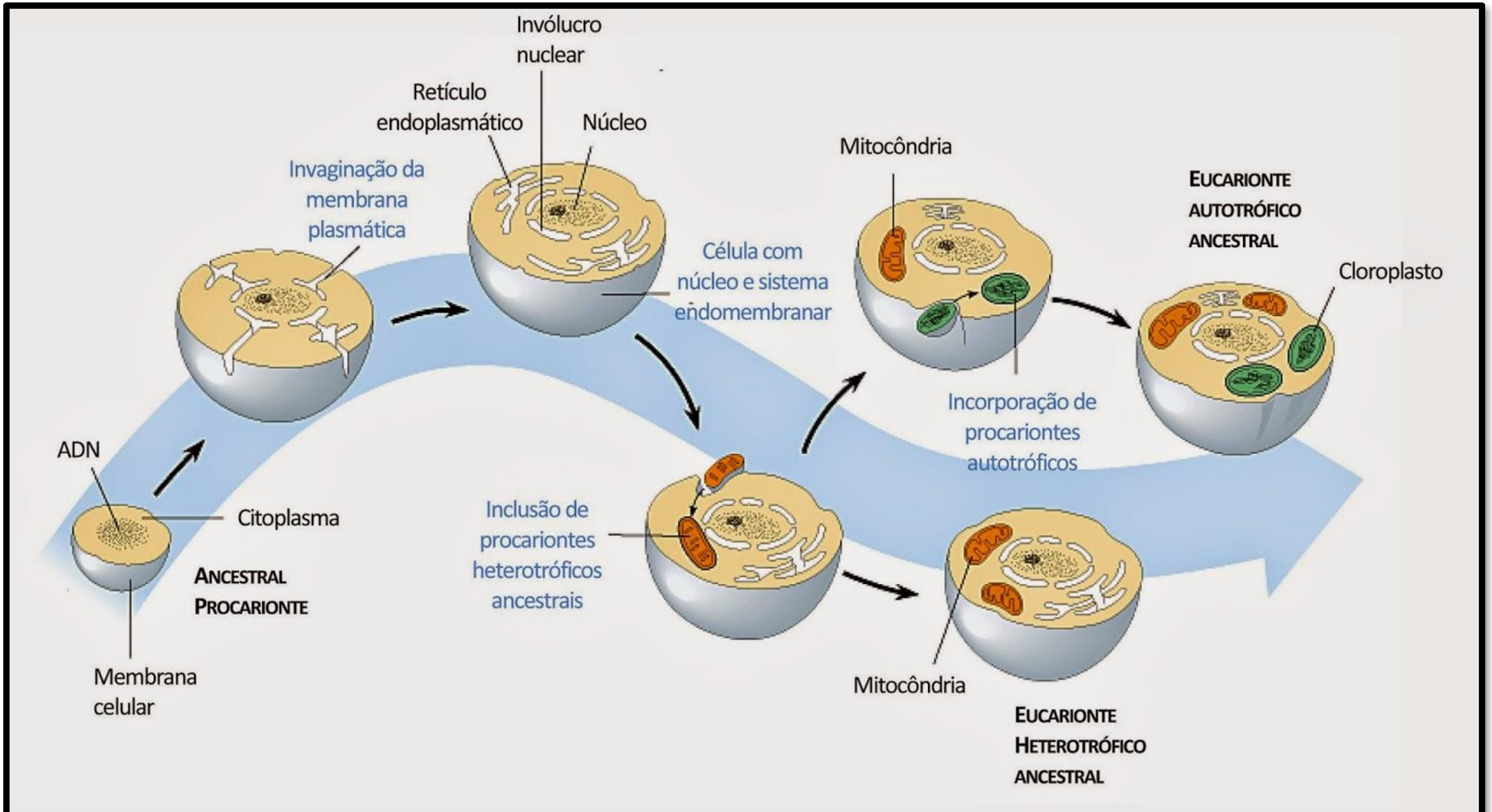


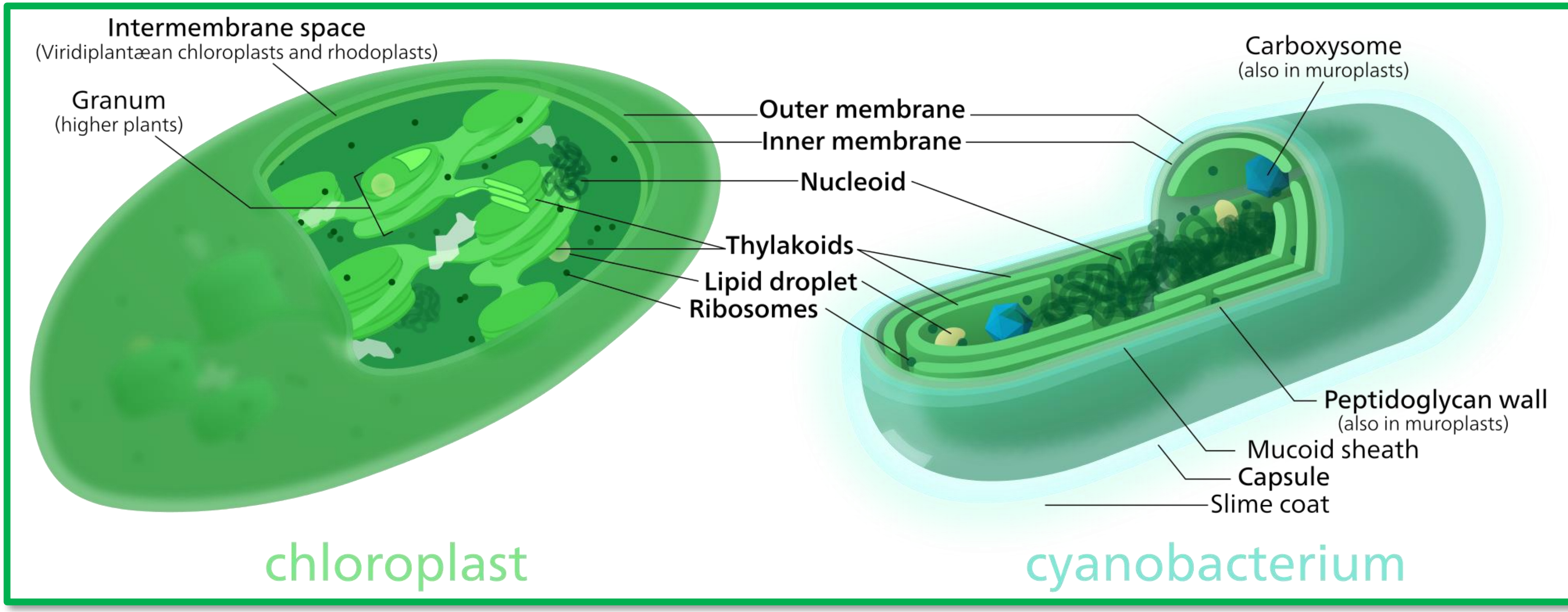


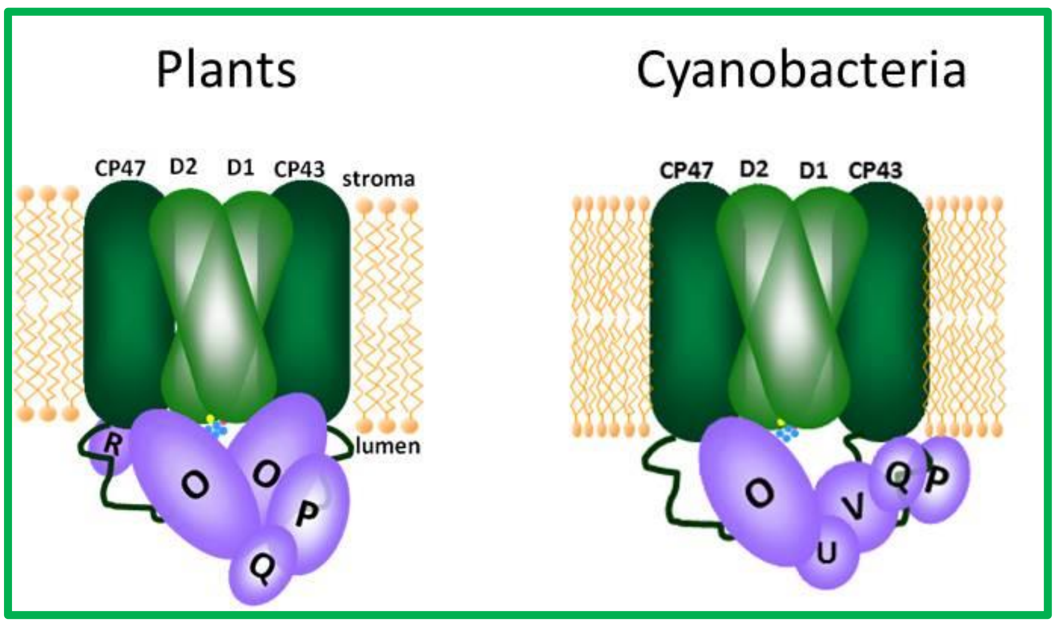
cianobactérias

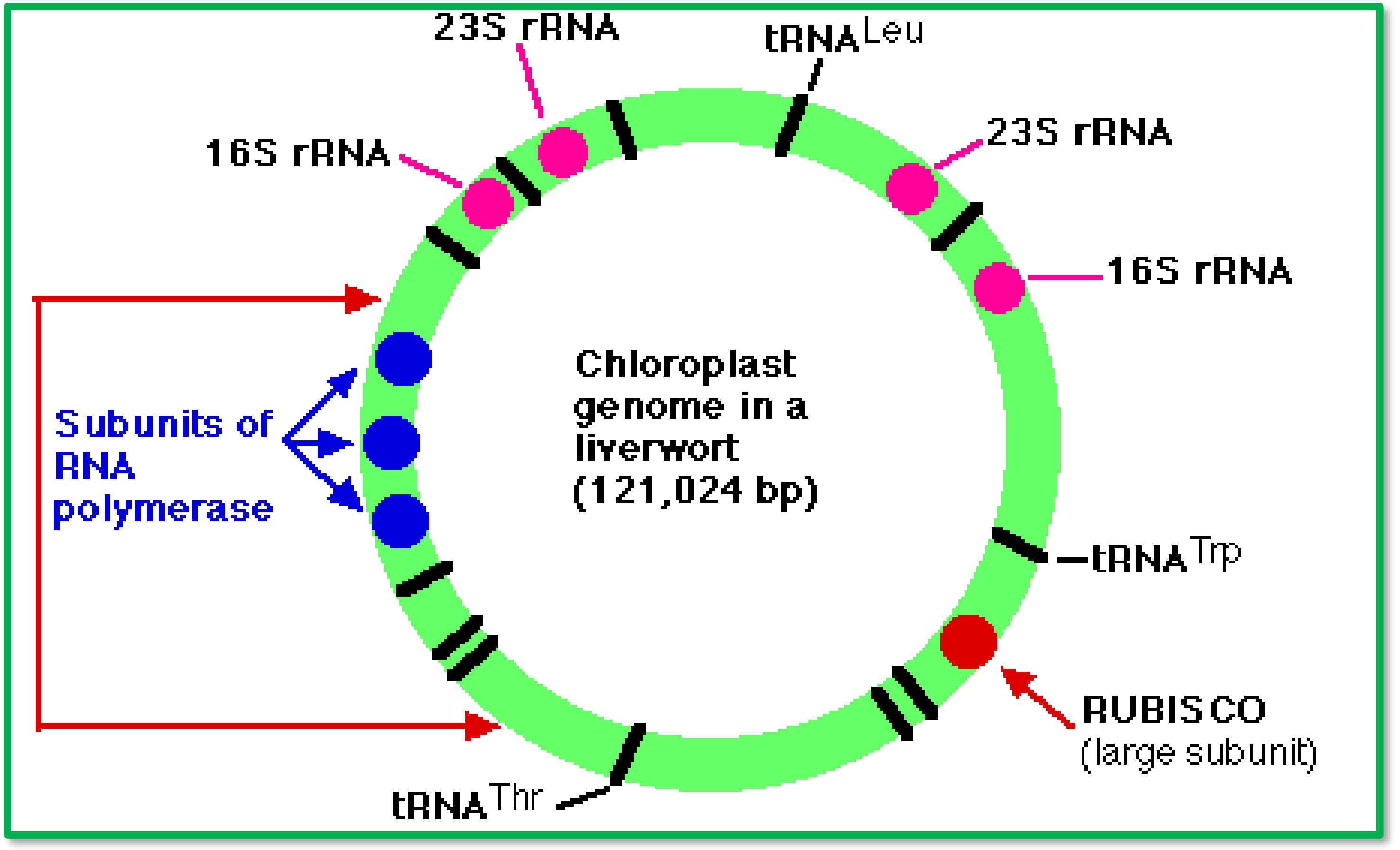

Oxygenic Photosynthesis Evolves
Great Oxidation Event
First Complex Animals
Land Plants Diversify
Atmosphere
[O_2]
(% PAL)
100
1-10
<<10^{-3}
First O_2-respiring eukaryotes?
Intense Volcanism
Cambrian Explosion
Shallow ocean
Deep ocean
Fe^{2+}
O_2
H_2S
H_2S
O_2
Fe^{2+}
4000
3000
2000
1000
0
Million Years Ago

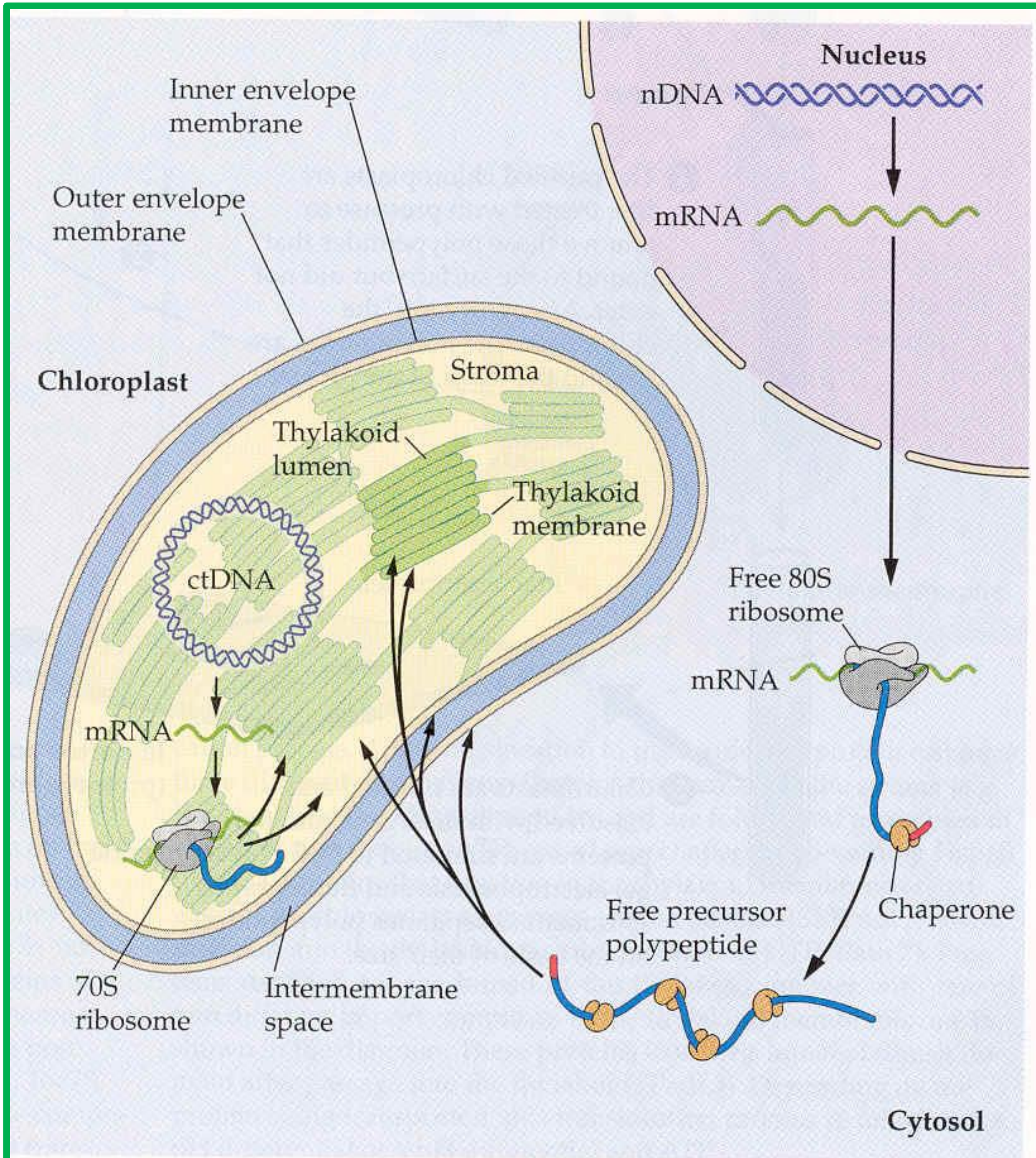
Teoria da Endossimbiose serial



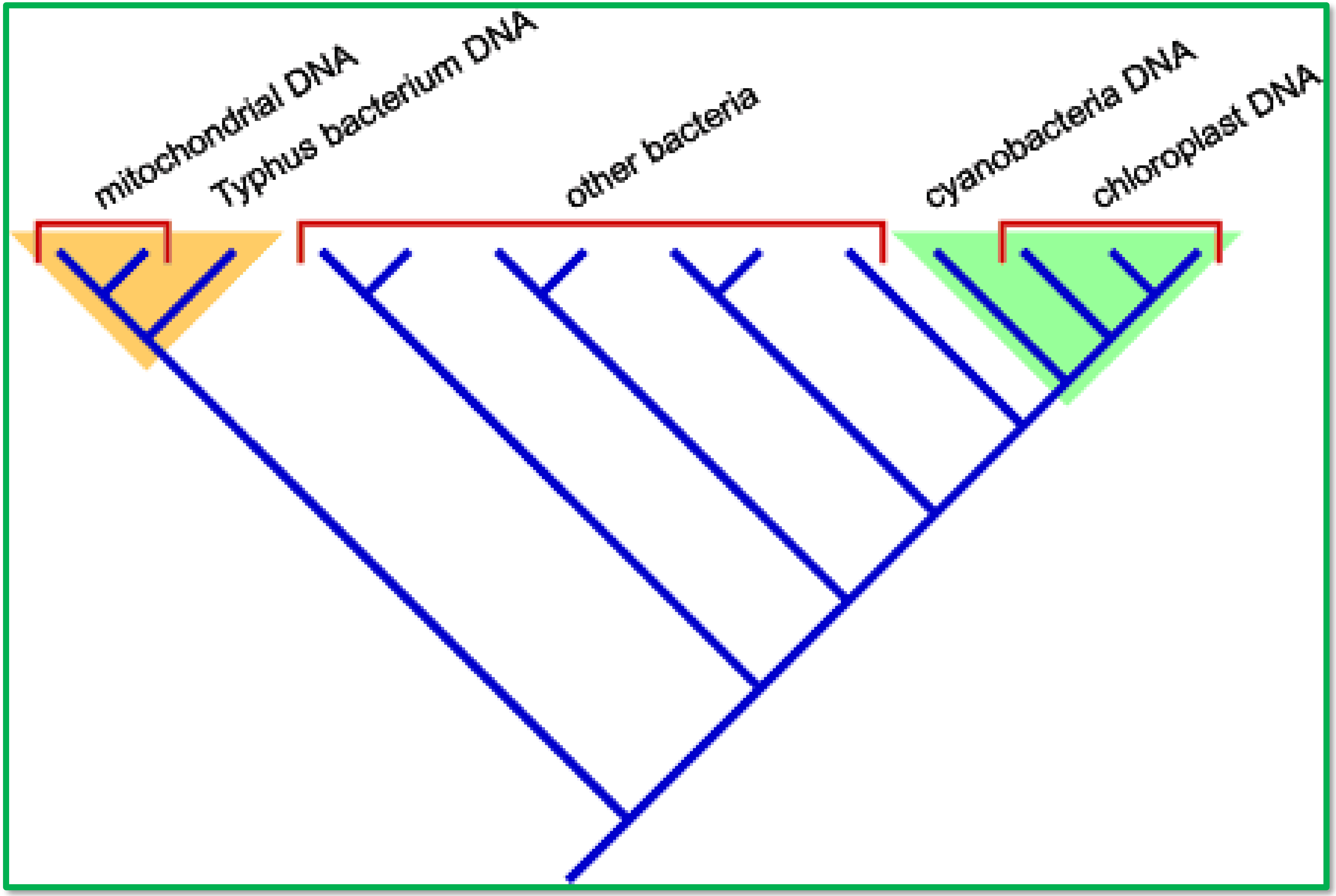

Intermembrane space
(Viridiplantæan chloroplasts and rhodoplasts)
Granum
(higher plants)
Outer membrane
Inner membrane
Nucleoid
Thylakoids
Lipid droplet
Ribosomes
Carboxysome
(also in muroplasts)
Peptidoglycan wall
(also in muroplasts)
Mucoid sheath
Capsule
Slime coat
chloroplast
cyanobacterium

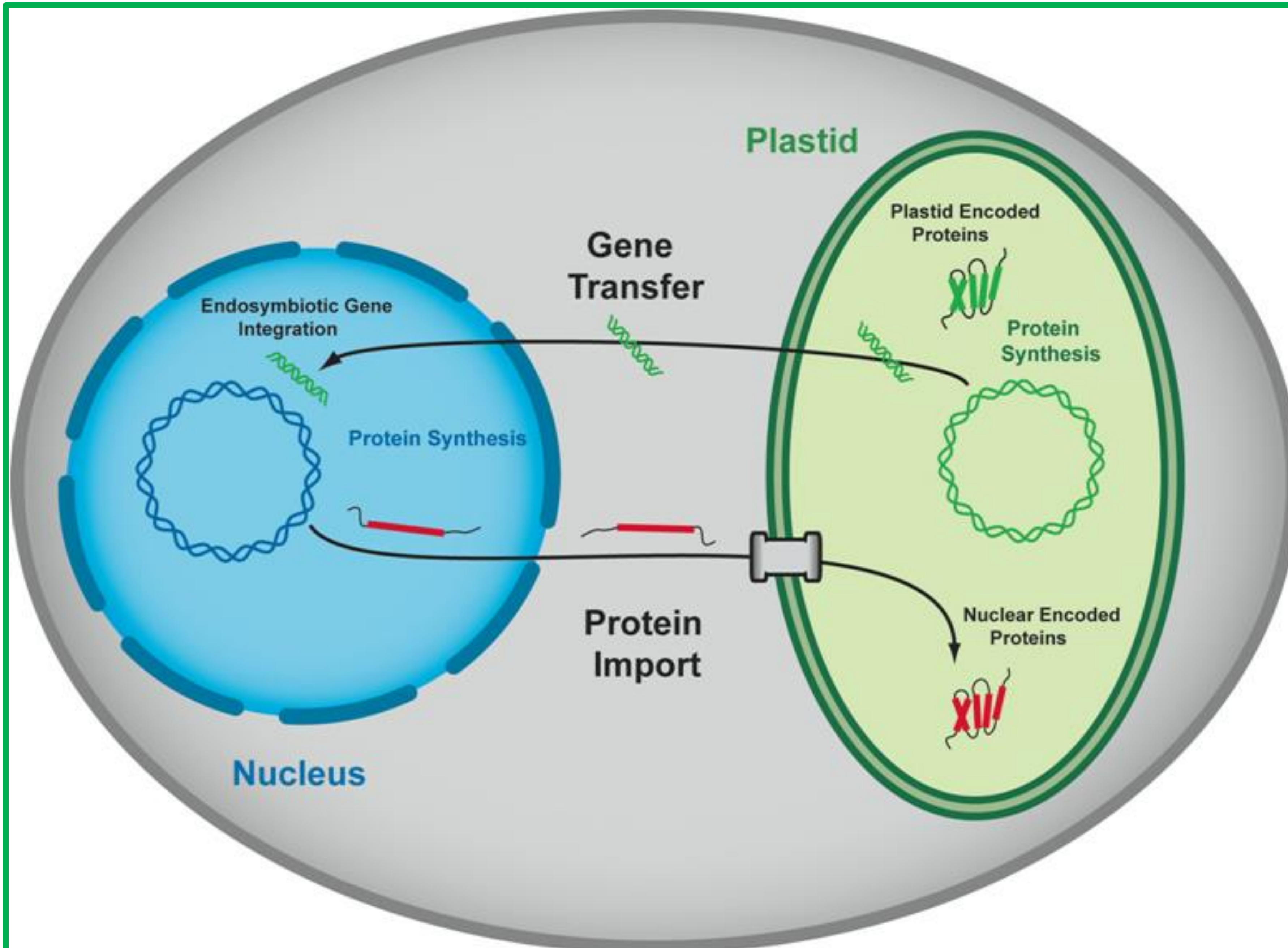

Plants
Cyanobacteria
CP47
D2
D1
CP43
stroma
lumen
R
O
O
P
Q
CP47
D2
D1
CP43
O
U
V
Q
P

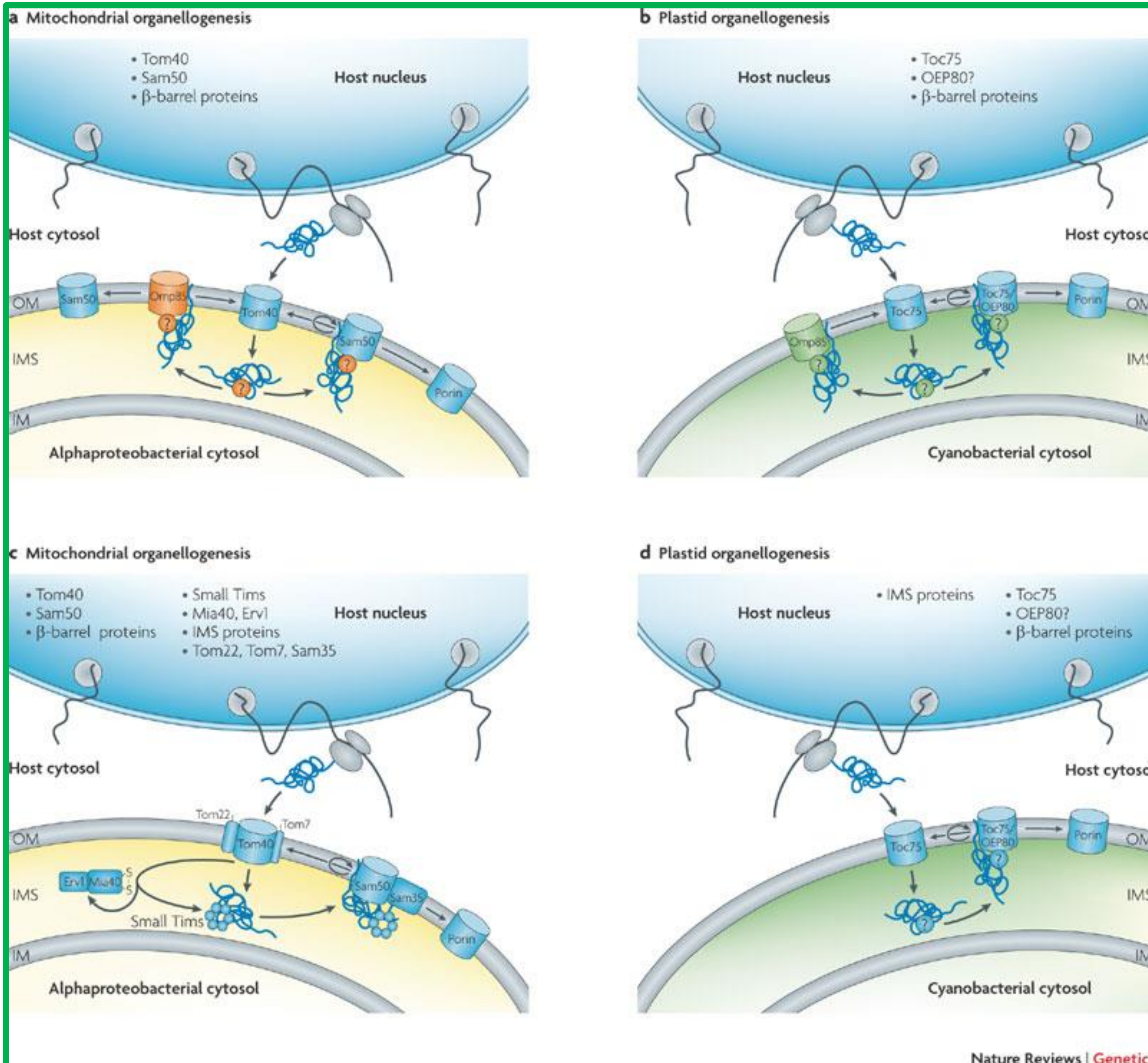

23S rRNA
tRNA Leu
16S rRNA
23S rRNA
16S rRNA
Chloroplast genome in a liverwort (121,024 bp)
Subunits of RNA polymerase
tRNA Trp
RUBISCO
(large subunit)
tRNA Thr

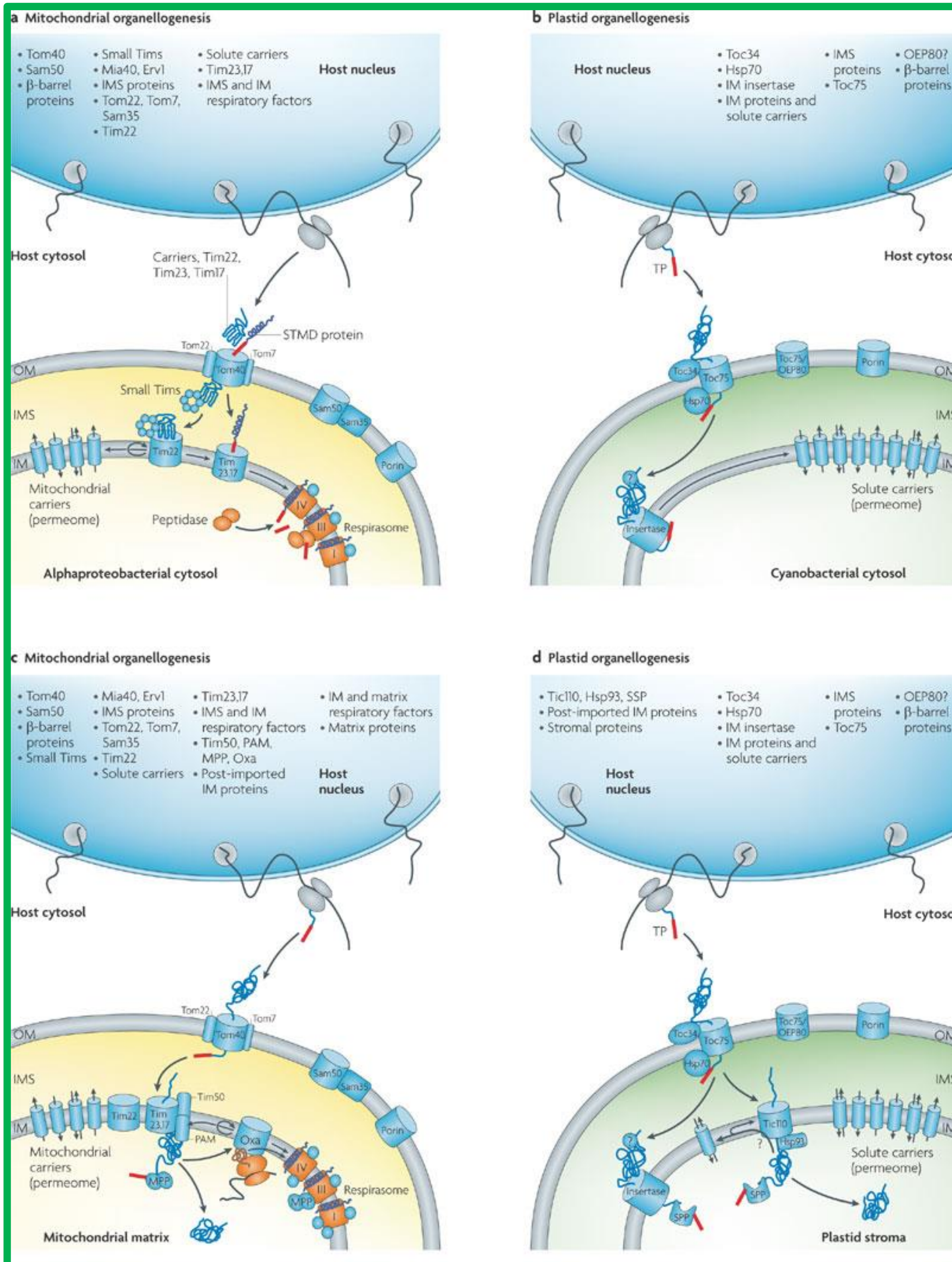


Nucleus
nDNA
mRNA
Inner envelope membrane
Outer envelope membrane
Chloroplast
Stroma
Thylakoid lumen
Thylakoid membrane
ctDNA
mRNA
Free 80S ribosome
mRNA
Chaperone
Free precursor polypeptide
70S ribosome
Intermembrane space
Cytosol

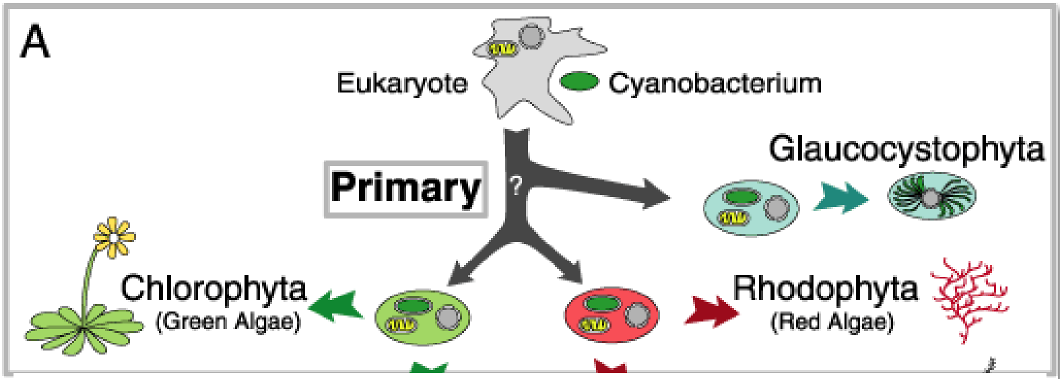

mitochondrial DNA
Typhus bacterium DNA
other bacteria
cyanobacteria DNA
chloroplast DNA

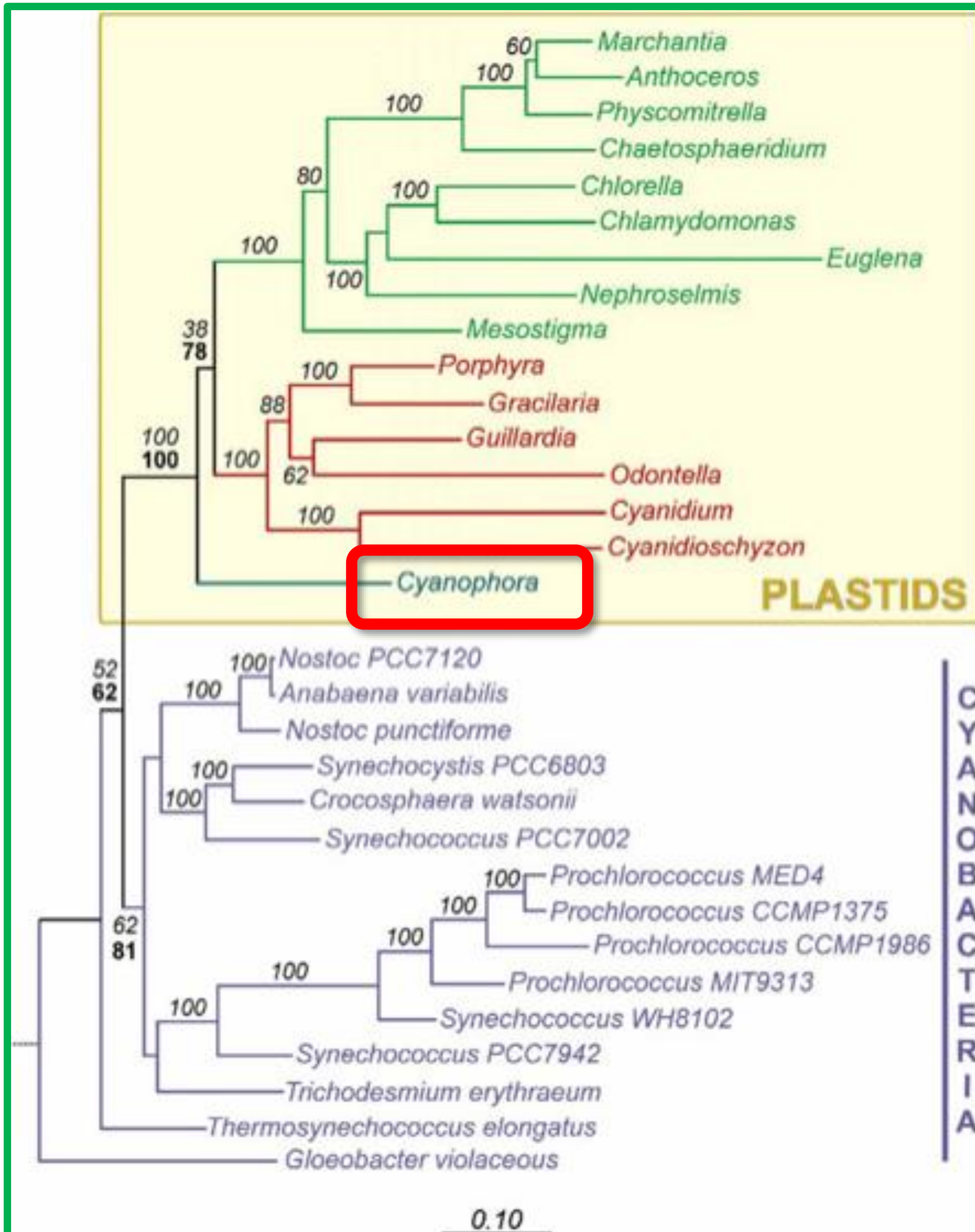

Plastid
Plastid Encoded Proteins
Gene Transfer
Endosymbiotic Gene Integration
Protein Synthesis
Protein Synthesis
Protein Import
Nuclear Encoded Proteins
Nucleus


a Mitochondrial organellogenesis
• Tom40
• Sam50
• β-barrel proteins
Host nucleus
Host cytosol
OM
Sam50
Omp85
Tom40
Sam50
IMS
Porin
IM
Alphaproteobacterial cytosol
b Plastid organellogenesis
Host nucleus
• Toc75
• OEP80?
• β-barrel proteins
Host cytosol
Toc75
Toc75/OEP80
Porin
OM
Omp85
IMS
IM
Cyanobacterial cytosol
c Mitochondrial organellogenesis
• Tom40
• Sam50
• β-barrel proteins
• Small Tims
• Mia40, Erv1
• IMS proteins
• Tom22, Tom7, Sam35
Host nucleus
Host cytosol
Tom22
Tom7
OM
Tom40
Erv1
Mia40
IMS
Small Tims
Sam50
Sam35
Porin
IM
Alphaproteobacterial cytosol
d Plastid organellogenesis
Host nucleus
• IMS proteins
• Toc75
• OEP80?
• β-barrel proteins
Host cytosol
Toc75
Toc75/OEP80
Porin
OM
IMS
IM
Cyanobacterial cytosol
Nature Reviews | Genetics



Nature Reviews | Genetics


A
Eukaryote
Cyanobacterium
Primary
?
Glaucocystophyta
Chlorophyta
(Green Algae)
Rhodophyta
(Red Algae)



Rodriguez-Ezpeleta, N. *et al.*
Curr. Biol. **16**: 1325-1330 (2005)

Figure 1. Phylogeny based on plastid and bacterial protein sequences

The analysis is based on the concatenated dataset of plastid-encoded proteins (50 proteins; 10,334 amino acid positions). The tree has been inferred with BI with the WAG+F+Γ model. Numbers in italics represent support values obtained with 100 bootstrap replicates on the concatenated dataset with PhyML (WAG+F+Γ model), and numbers below (in bold) represent bootstrap values based on 10,000 RELL replicates of the sML analysis (see Experimental Procedures for details).

sharing their kinematic models and GPS data for comparison with the dynamic models, L. Wen for help with using his code, and three anonymous reviewers for their comments that substantially improved the manuscript. We are grateful to UNAVCO, Incorporated Research Institutions for Seismology, NSF-EarthScope, International GNSS Service, NASA, and countless researchers for facilitation and availability of geodetic and seismic data. The codes are available as a zip file as part of the supporting online material.

Supporting Online Material
www.sciencemag.org/cgi/content/full/335/6070/838/DC1
Methods
SOM Text
Figs. S1 and S2
Table S1
References (*29–37*)
Computer Codes

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Cyanophora paradoxa Genome Elucidates Origin of Photosynthesis in Algae and Plants

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The primary endosymbiotic origin of the plastid in eukaryotes more than 1 billion years ago led to the evolution of algae and plants. We analyzed draft genome and transcriptome data from the basally diverging alga *Cyanophora paradoxa* and provide evidence for a single origin of the primary plastid in the eukaryote supergroup Plantae. *C. paradoxa* retains ancestral features of starch biosynthesis, fermentation, and plastid protein translocation common to plants and algae but lacks typical eukaryotic light-harvesting complex proteins. Traces of an ancient link to parasites such as Chlamydiae were found in the genomes of *C. paradoxa* and other Plantae. Apparently, *Chlamydia*-like bacteria donated genes that allow export of photosynthate from the plastid and its polymerization into storage polysaccharide in the cytosol.

reinhardtii (*20*, *21*). Phylogenomic analysis of the predicted *C. paradoxa* proteins showed 274 to be of cyanobacterial provenance (*22*). This constitutes ~6% of proteins in the glaucophyte that have significant BLASTp hits (i.e., 274 out of 4628), as found in other algae (*20*, *21*). BLASTp analysis identified 2029 proteins that are putatively destined for the plastid, of which 293 contain the transit sequence for plastid import [identified by the presence of phenylalanine (F) within the first four amino acids: MF, MAF, MNAF, MSAF, and MAAF] (*23*, *24*) (fig. S4B). Of these 293 proteins, 80% are derived from Cyanobacteria.

Another source of foreign genes in Plantae is horizontal gene transfer (HGT), which is not associated with endosymbiosis. Using 35,126 bacterial sequences as a query, we found 444 noncyanobacterial gene families with a common origin shared amongst Bacteria and Plantae. Among them, 15 genes are present in all three Plantae phyla. An example of a gene derived from Bacteria after an ancient HGT event that is shared by

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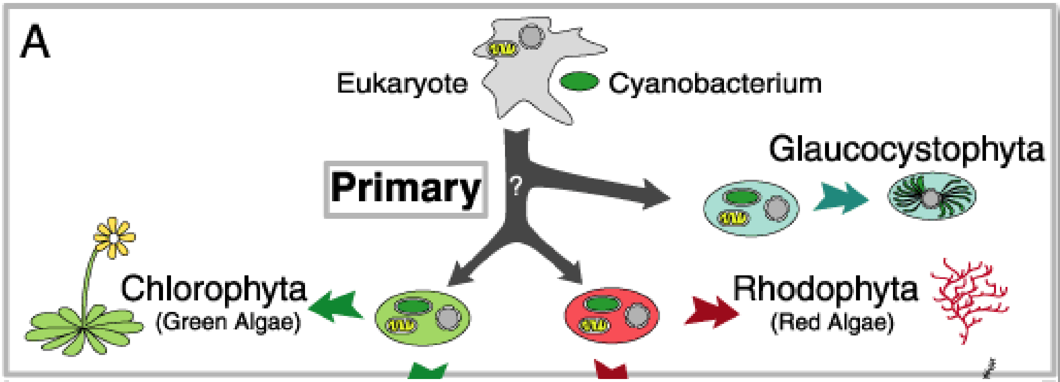
A
Eukaryote
Cyanobacterium
Primary
?
Glaucocystophyta
Chlorophyta
(Green Algae)
Rhodophyta
(Red Algae)