Photosynthesis for Hydrogen and Fuels Production

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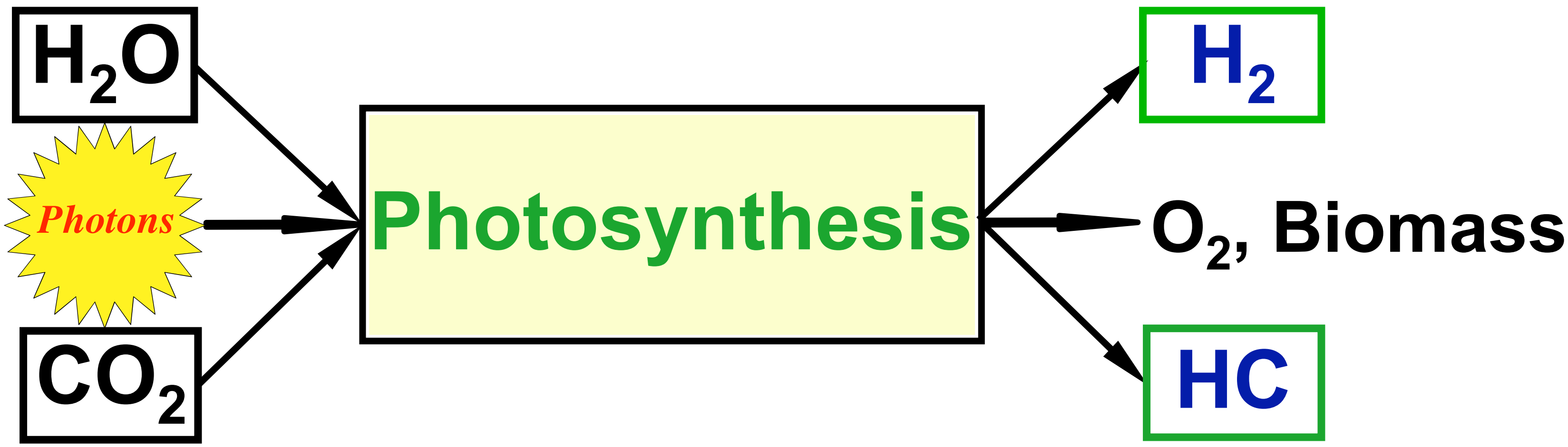
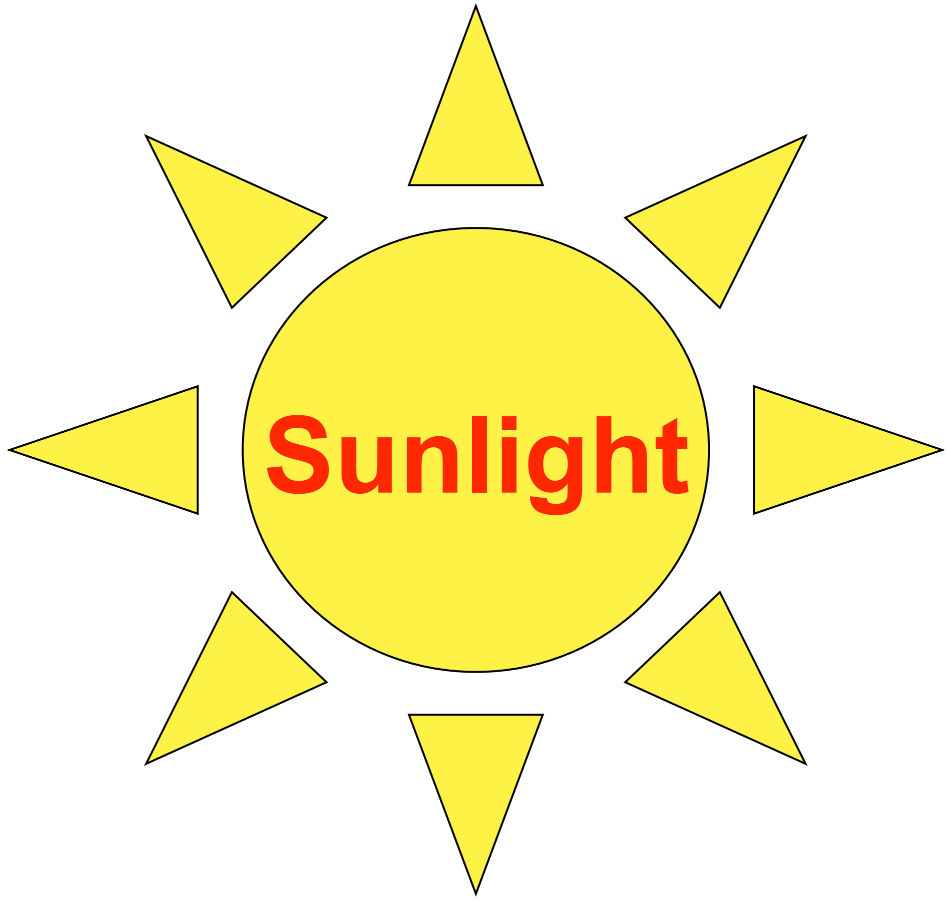
UC Berkeley

24-Jan-2011

Feedstock and products



Process offers a renewable fuels supply and mitigation of climate change.



Average US Solar insolation = 5 kWh m^{-2} d^{-1}

CA household electricity consumption = 15 kWh d^{-1}

The relevant literature

Plant, Cell and Environment (2006) **29**, 315–330

doi: 10.1111/j.1365-3040.2005.01493.x

Can improvement in photosynthesis increase crop yields?

STEPHEN P. LONG[1], XIN-GUANG ZHU[1], SHAWNA L. NAIDU[1] & DONALD R. ORT[2]

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“Six potential routes of increasing epsilon(c) by improving photosynthetic efficiency were explored, ranging from altered canopy architecture to improved regeneration of the acceptor molecule for CO_2. Collectively, these changes could improve epsilon(c) and, therefore, Y-p by c. 50%.”

Gains upon improving the carbon reactions of photosynthesis: up to 50%

The relevant literature

Plant Science 177 (2009) 272–280

Contents lists available at ScienceDirect

Plant Science

journal homepage: www.elsevier.com/locate/plantsci

Review

Solar energy conversion efficiencies in photosynthesis: Minimizing the chlorophyll antennae to maximize efficiency

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Gains upon improving sunlight conversion efficiency: up to 300%

DOE Hydrogen Program

Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures

R&D project funded by the DOE-EERE Hydrogen Program

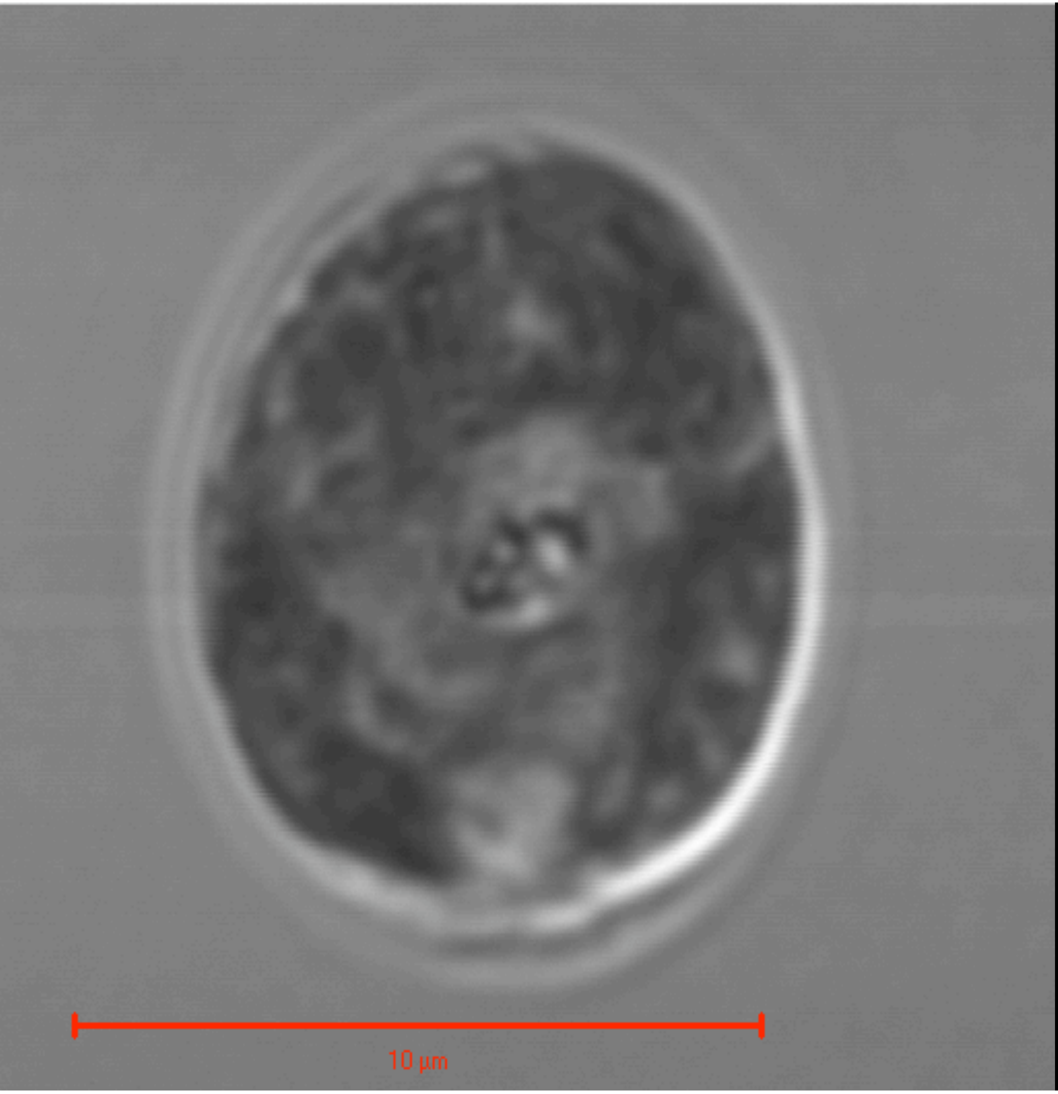
This presentation does not contain any proprietary, confidential, or otherwise restricted information

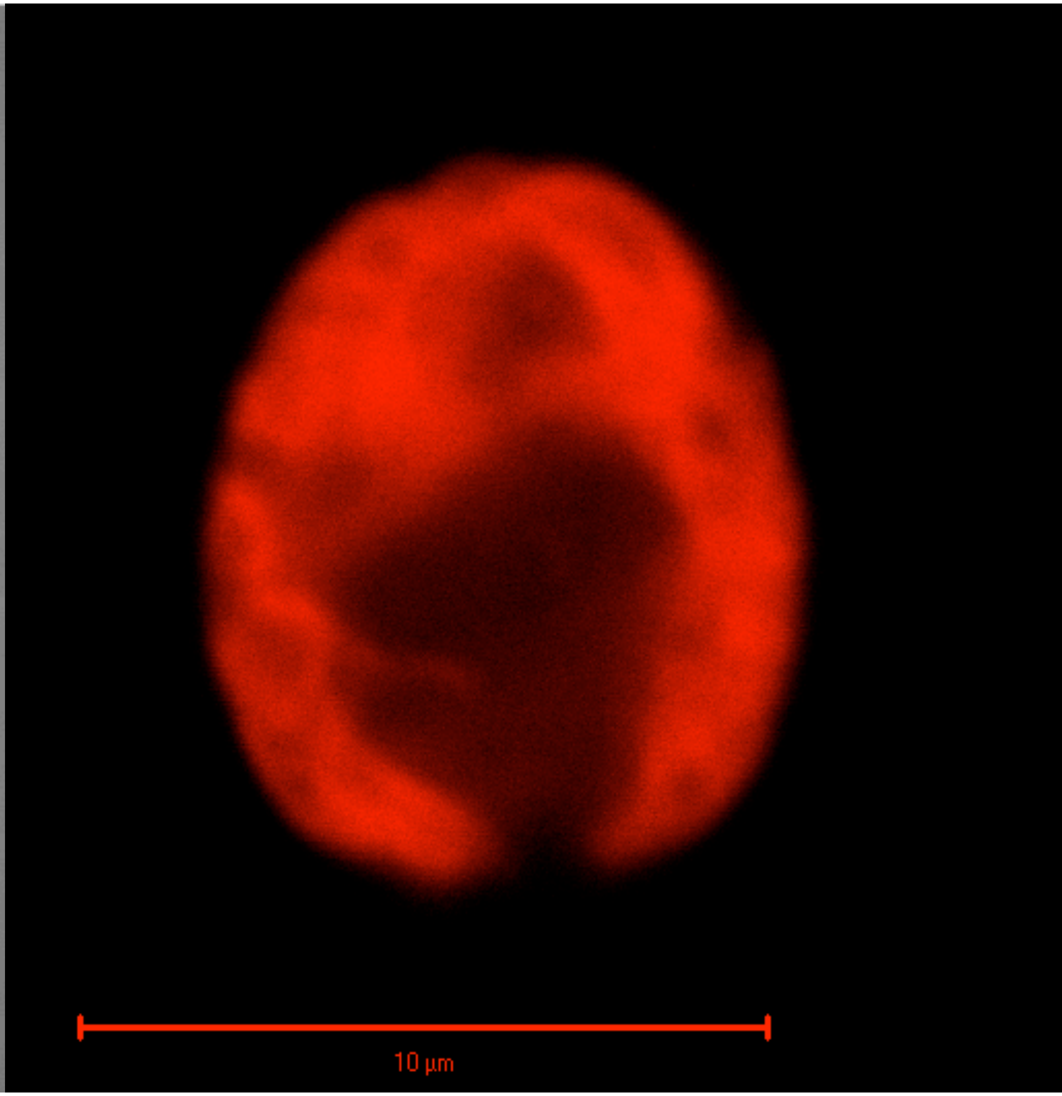
View of a microalga cross-section

The unicellular green alga
Chlamydomonas reinhardtii

Self-repairing and replicating microstructure

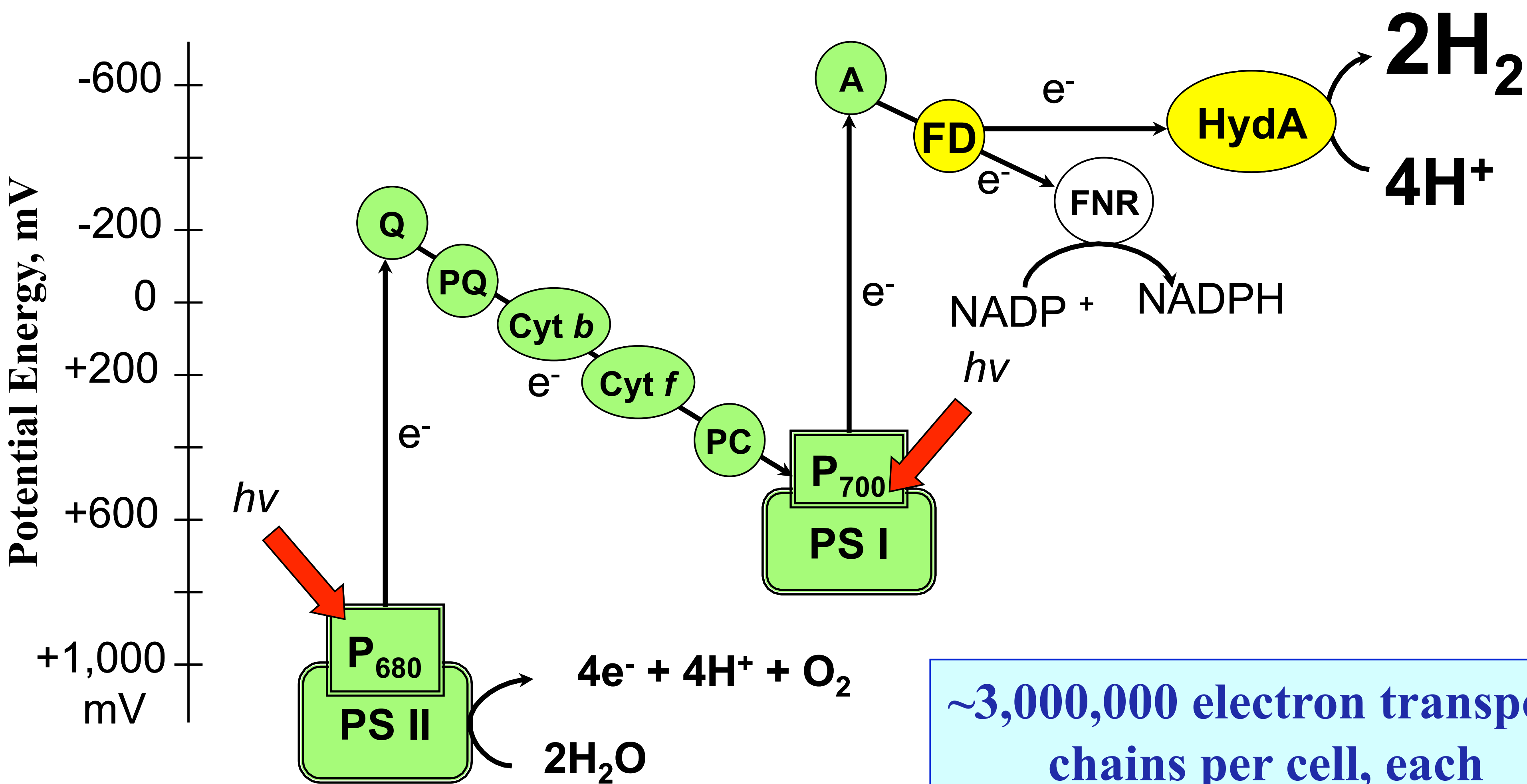
The green microalga *Chlamydomonas reinhardtii*





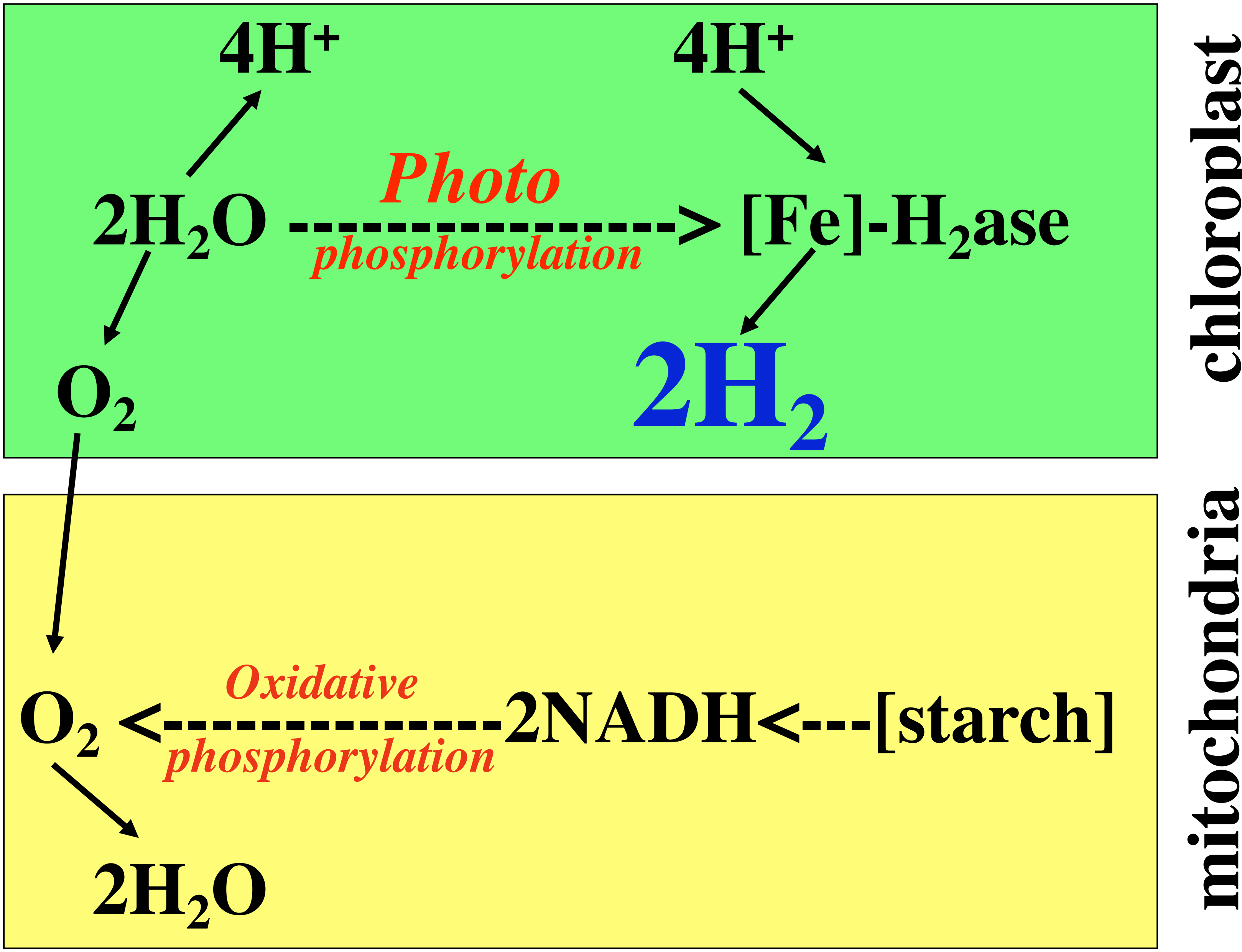
Differential Interference Contrast **Chlorophyll Fluorescence**

Photosynthetic water oxidation and H_2-production



~3,000,000 electron transport chains per cell, each capable of transporting 100 electrons per second

Hypoxic photosynthesis: O_2 is consumed by mitochondria



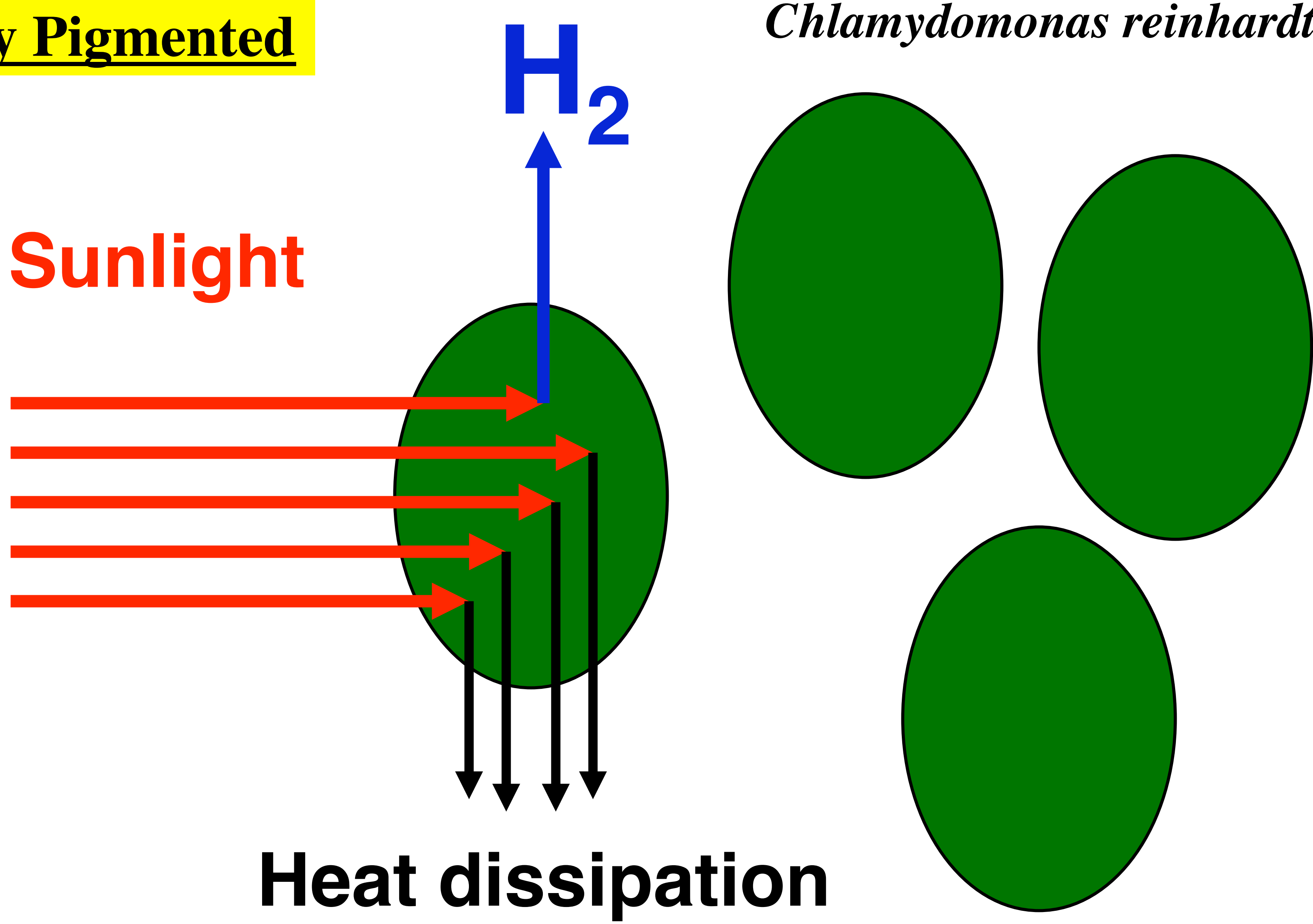
H_2 bubbles

Microalgal H_2-production facility in the laboratory


vent
Hydrogen production
in a backyard
Chlamydomonas reinhardtii mass culture

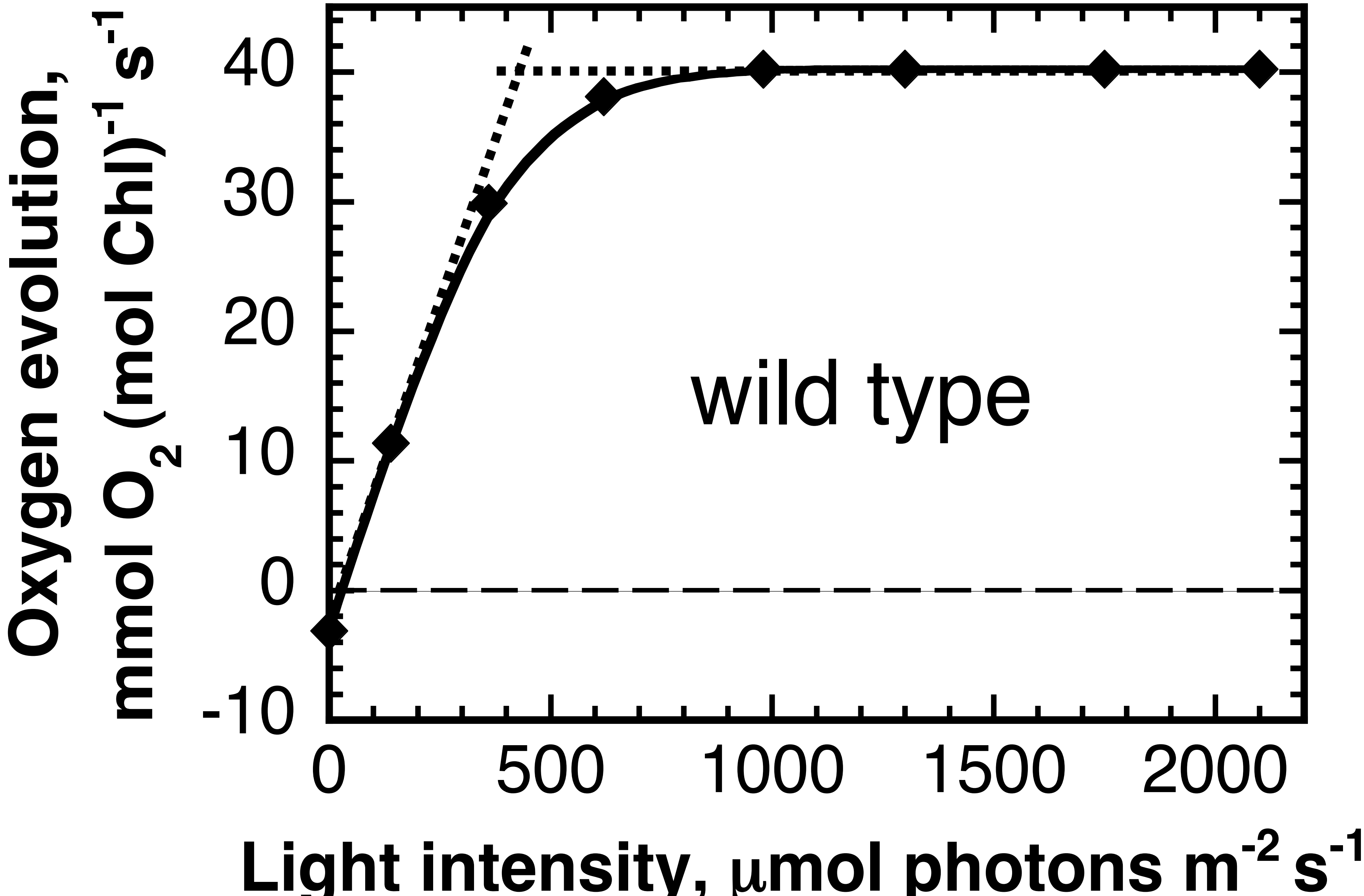
Example: Cells Fully Pigmented

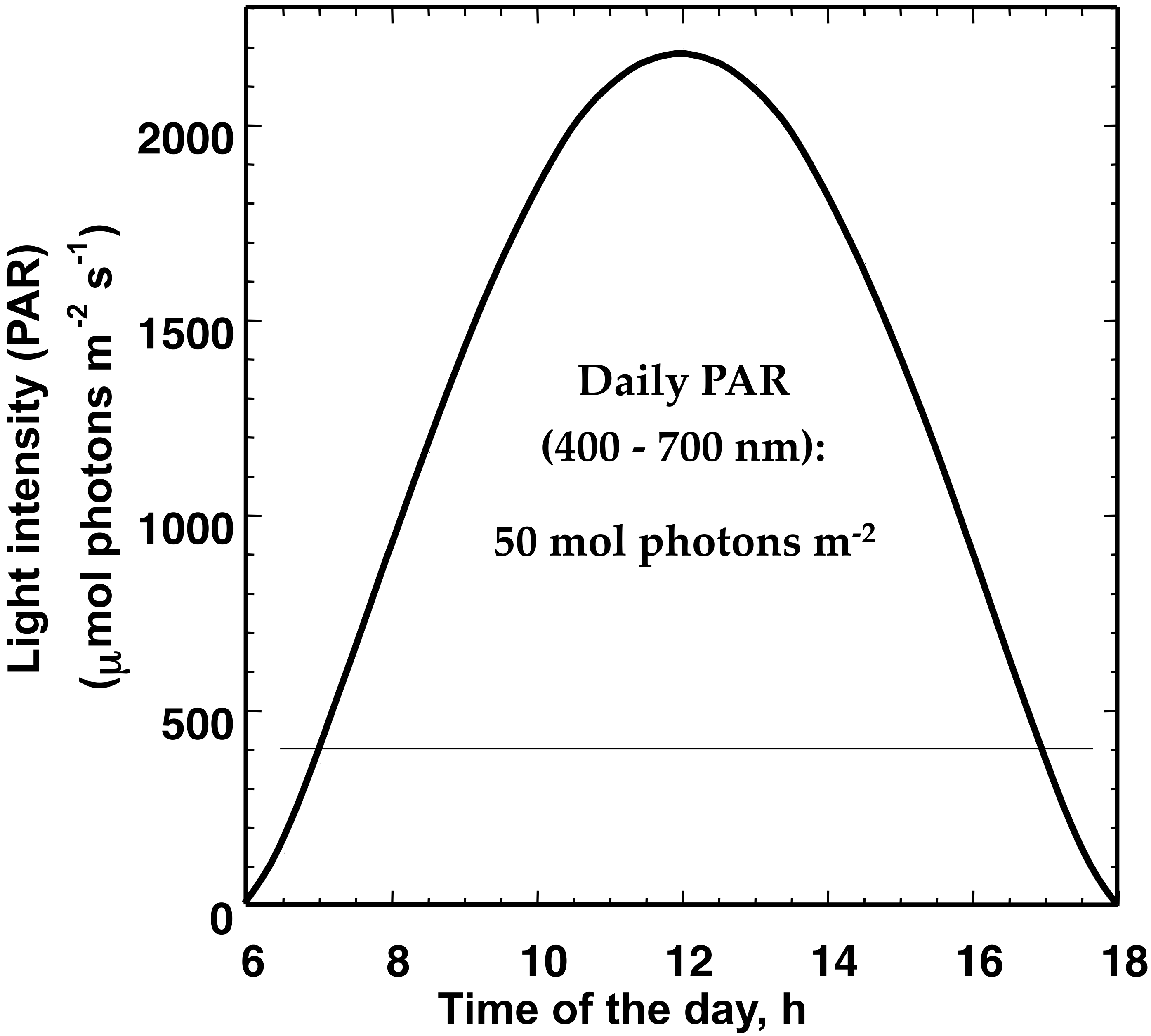
The green algae
Chlamydomonas reinhardtii



Fully pigmented cells over-absorb and wastefully dissipate bright sunlight

The light-saturation curve of photosynthesis




Light intensity (PAR)
(μmol photons m-2 s-1)
2000
1500
1000
500
0
6
8
10
12
14
16
18
Time of the day, h
Daily PAR
(400 - 700 nm):
50 mol photons m-2

The problem of the early light-saturation of photosynthesis

Severe: ***Green and purple bacteria***

Cyanobacteria & red algae

Green & brown algae

Less severe: ***C3 plants & C4 plants***

Photosynthetic Productivities

Theoretical productivity:

~75 g dry weight m^{-2} d^{-1}

(8-10% solar energy conversion efficiency)

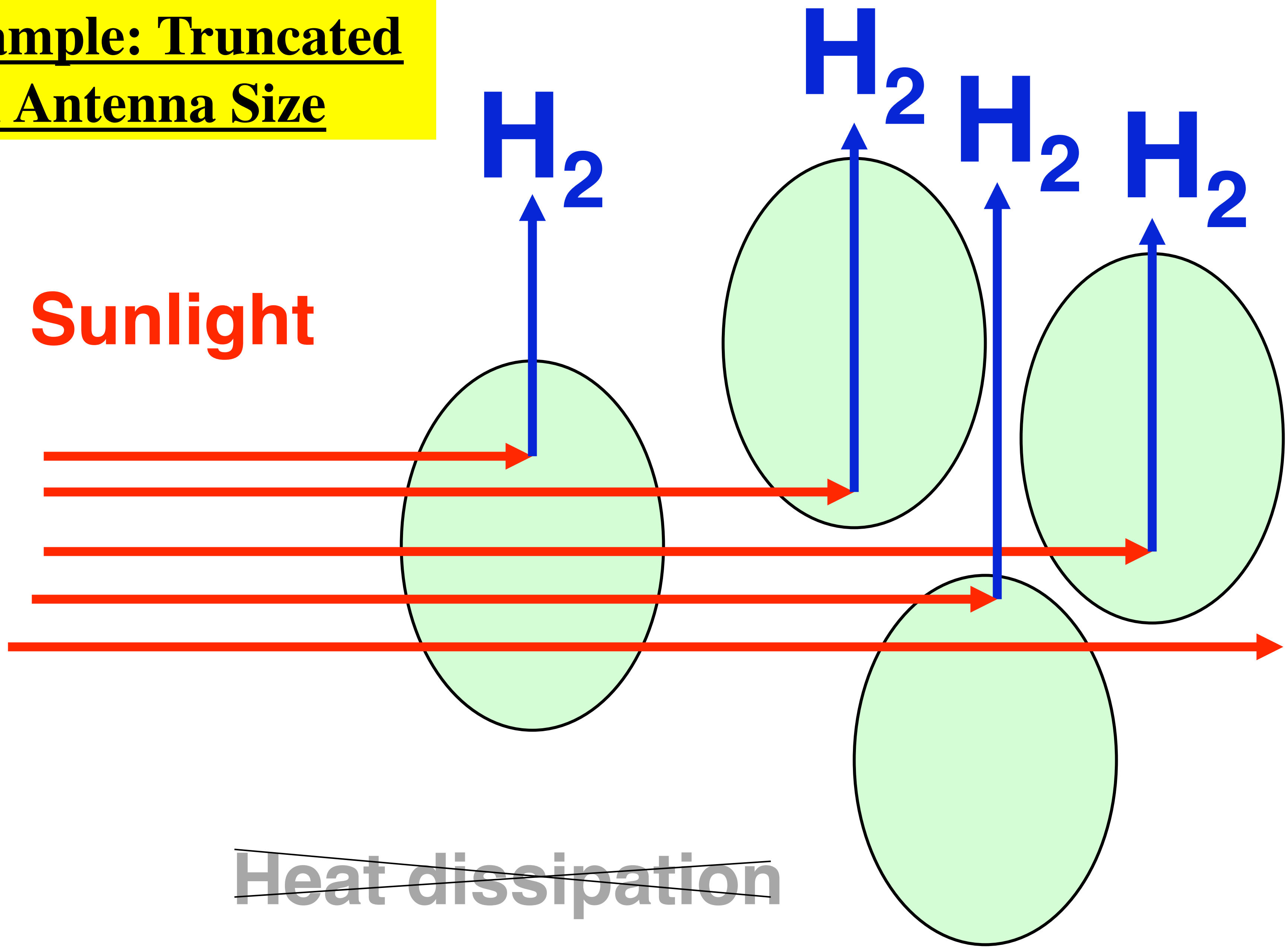
(based on the average US solar insolation = 5 kWh m^{-2} d^{-1})

Photosynthetic Productivities

Theoretical productivity:
~75 g dry weight m^{-2} d^{-1}
(8-10% solar energy conversion E)

Measured productivities:
Less than 25 g dry weight m^{-2} d^{-1}
(3-4% solar energy conversion E)

Example: Truncated Chl Antenna Size



Truncated Chl antenna cells permit greater transmittance of light and overall better solar utilization by the culture

The *Tla* concept
(*Tla* = Truncated light-harvesting antenna)

Minimize the chlorophyll antenna size of photosynthesis to prevent the early light-saturation effect.

Regulation of the Chl antenna size

Large Chl Antenna Size
(600 Chl a and b)

wild type

Genetic determinants

Truncated Chl Antenna Size
(130 Chl a)

tla

Interference with the genetic mechanism for the regulation of the Chl antenna size, to derive a permanently truncated Chl antenna size, is the goal of this R&D.

Approach

- Identify genes that confer a truncated antenna in a model organism.

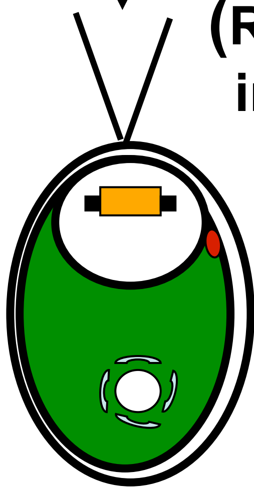
- Apply these genes to other organisms of interest.

- Improve photosynthesis, hydrogen, or fuels production by up to 300%.

DNA insertional mutagenesis and screening

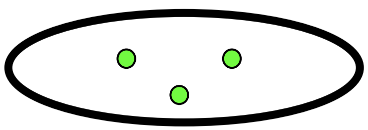
Plasmid DNA

TRANSFORMATION
(Random insertion of plasmid DNA in the nuclear genome)



Chlamydomonas reinhardtii

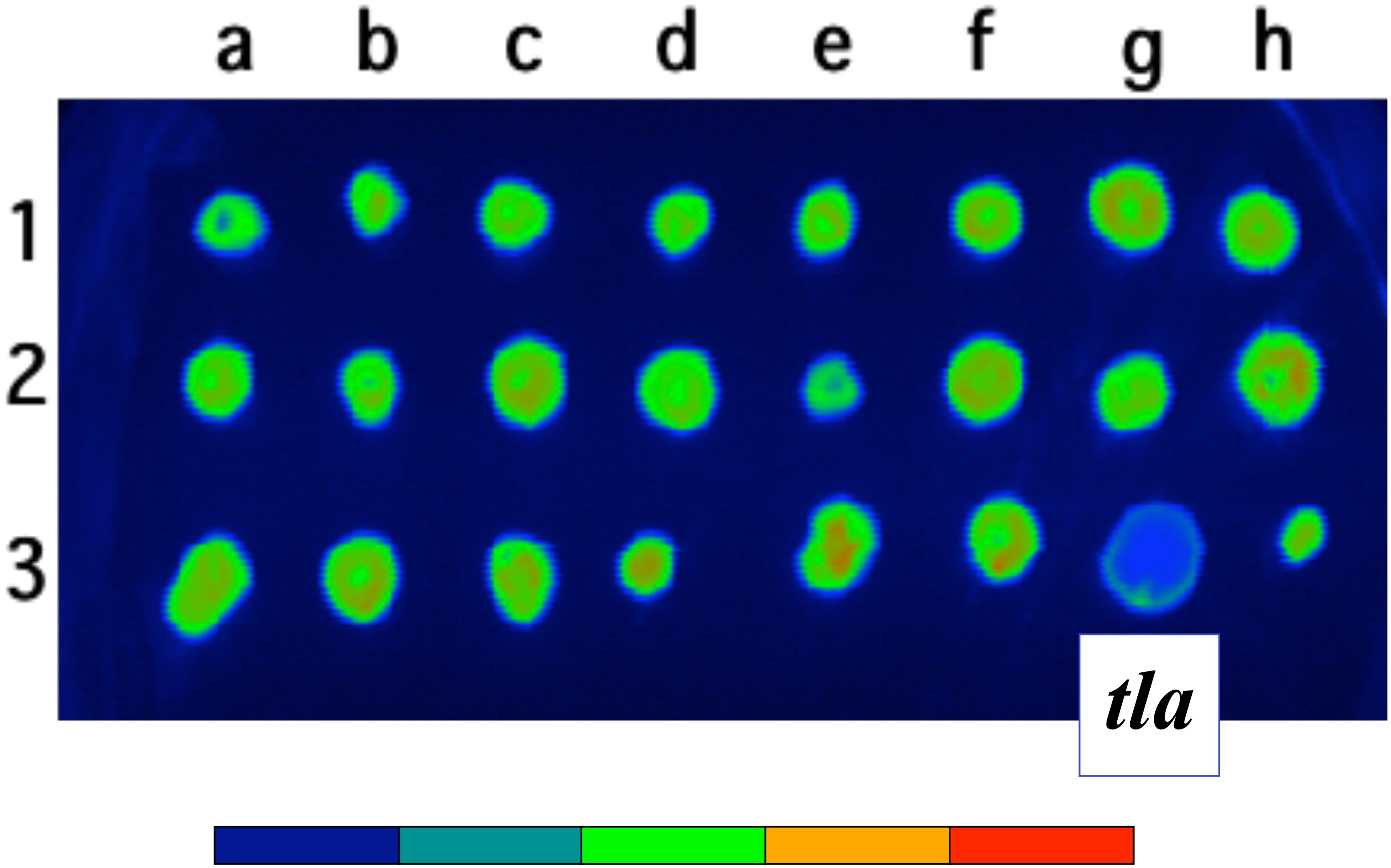
GROW TRANSFORMANTS



SCREEN TRANSFORMANTS

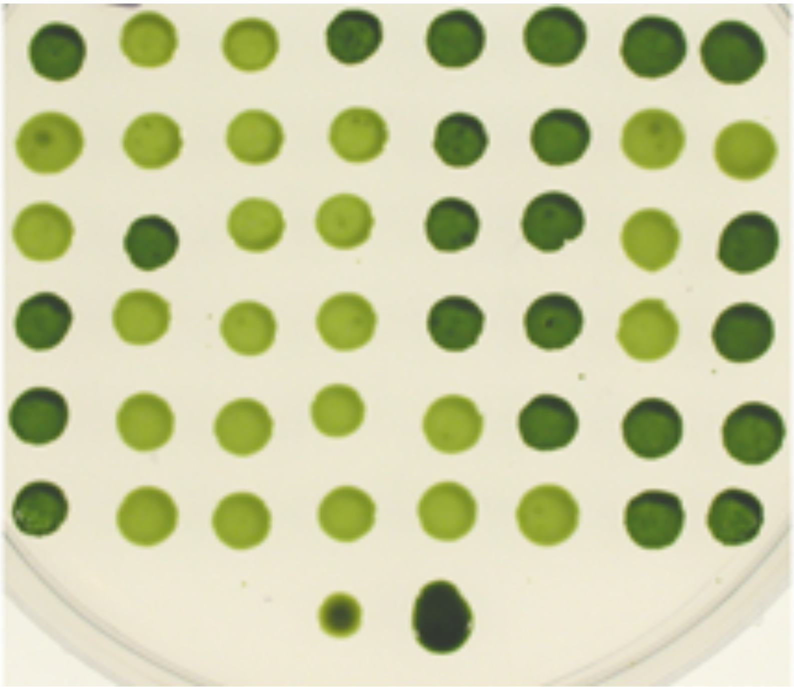
SELECT TRUNCATED ANTENNA STRAINS

DNA insertional mutagenesis and screening



Chlorophyll *a* fluorescence imaging analysis

DNA insertional mutagenesis and screening for *truncated light-harvesting antenna* (*tla*) mutants



Dot-Spot Colonies of
Chlamydomonas reinhardtii

Secondary screening for *tla* mutants

Criteria:

- **Functional photosystem antenna size *smaller than wild type***
- **Number of photosystems per chloroplast should be the *same or greater than wild type***
- **High quantum yield of photosynthesis is maintained**
- **Photosynthesis & productivity per chlorophyll: *inversely proportional to antenna size***

Objective:

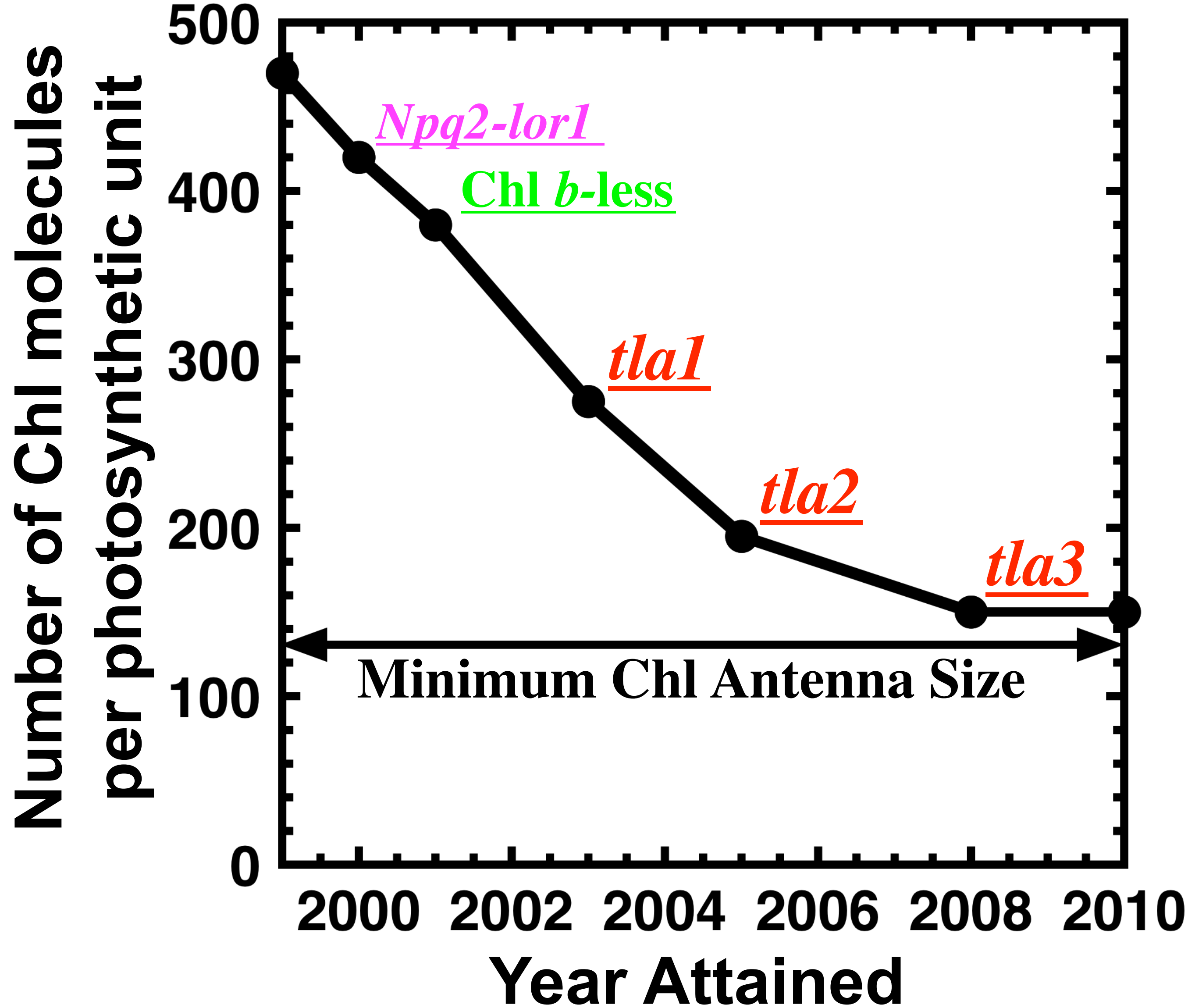
- **Identify "true positive" *tla* mutants with improved sunlight utilization efficiency.**

Progress achieved *vs* targets set

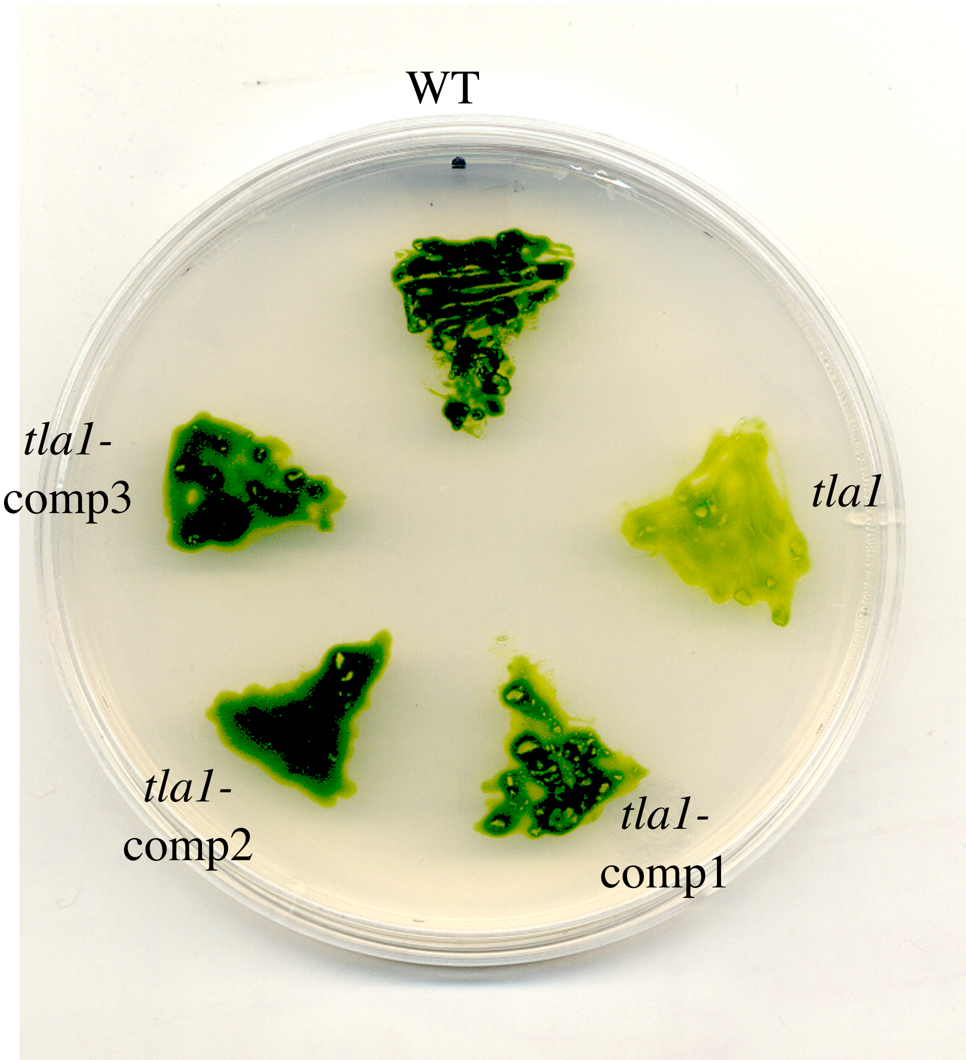
Chlorophyll antenna size in wild type and mutants

	2000	2003	2005	2008	2010	2015
Targets *(Chl Antenna size)*	600 (WT)		300		200	150
Progress Achieved	600 (WT)	275 *tla1*	195 *tla2*	150 *tla3*		

Project Timeline
Chlorophyll Antenna Size in *Chlamydomonas*



Chlamydomonas tla1 mutant phenotype and its complementation



Complemented *tla1* strains with the wild type *Tla1* gene (*tla1*-comp1, *tla1*-comp2, and *tla1*-comp3) recovered the green pigmentation phenotype.

Photosynthetic unit chlorophyll antenna size of wild type and *tla1* mutant

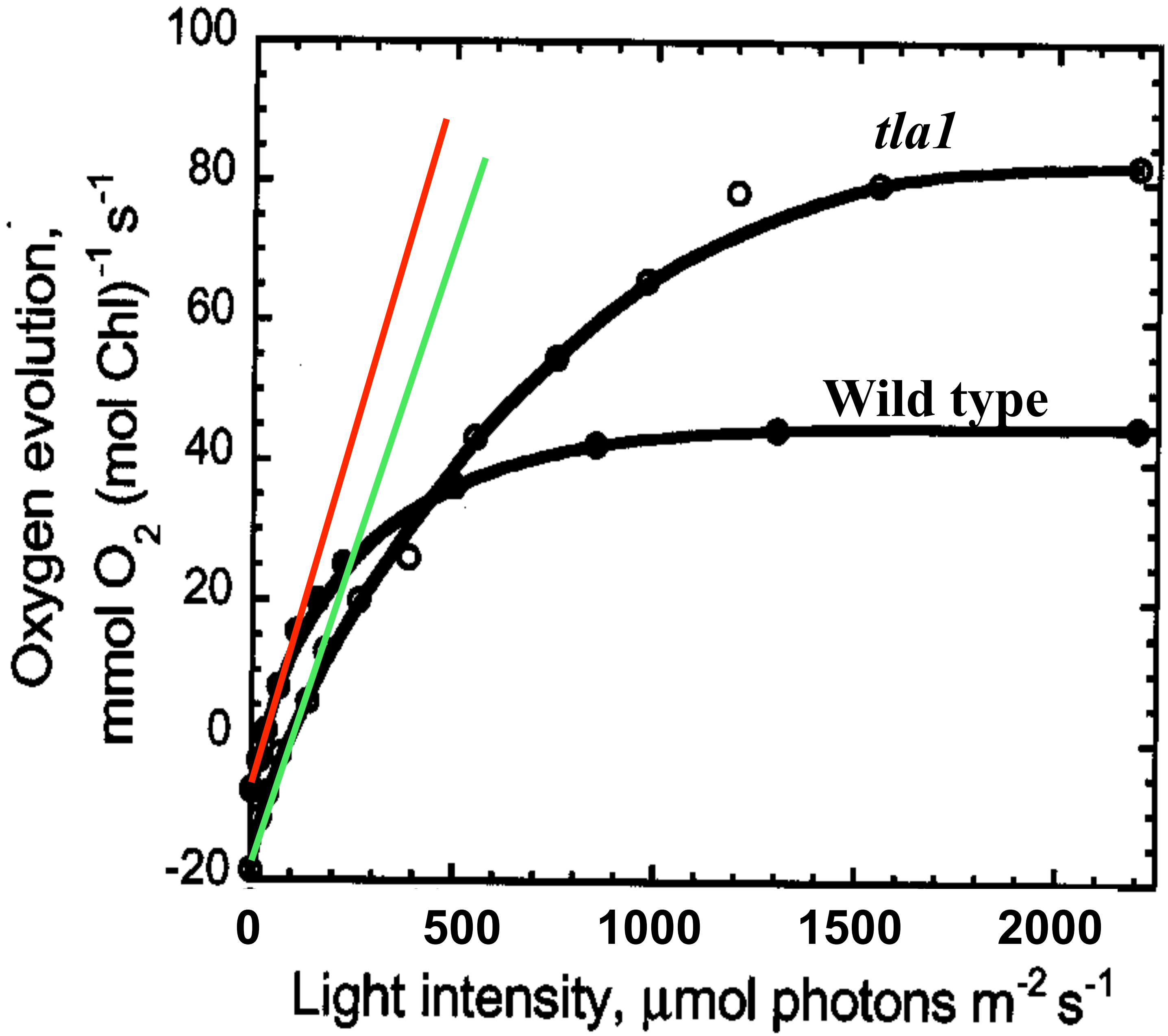
Wild type Chl Antenna Size

- ~ 600 Chl *a* + *b* molecules

tla1 mutant Chl antenna size

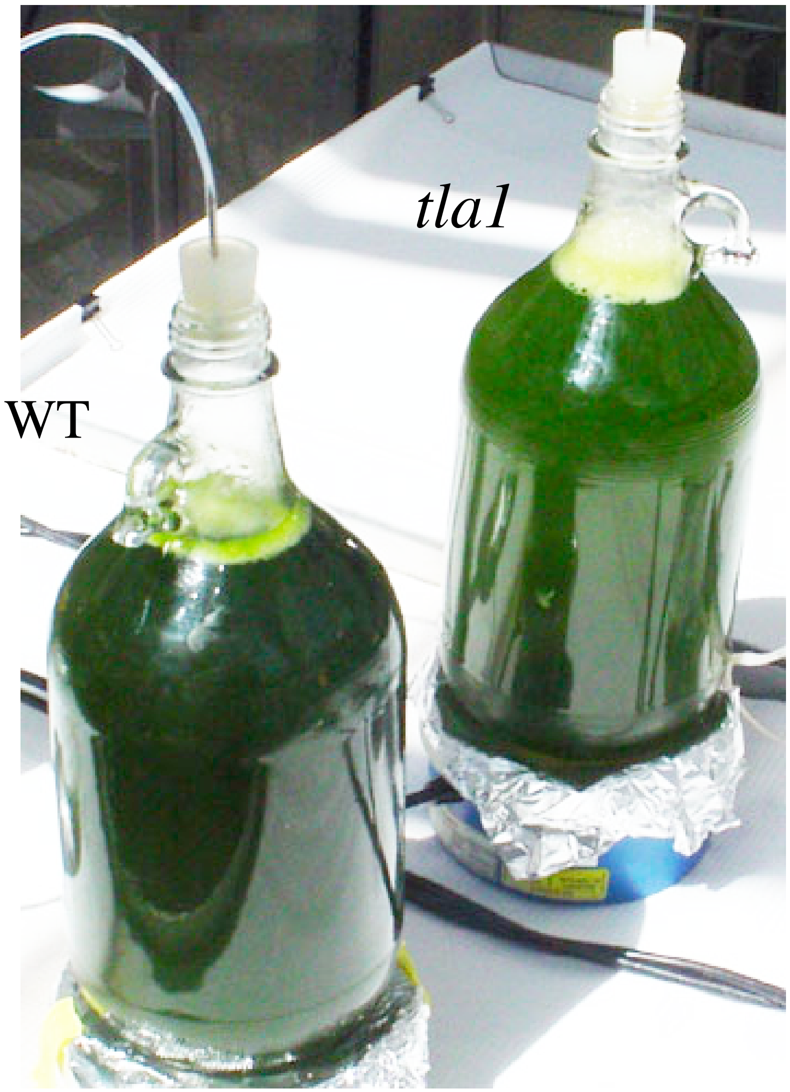
- 300 Chl *a* + *b* molecules

The light-saturation curve of photosynthesis



Productivity in Mass Culture

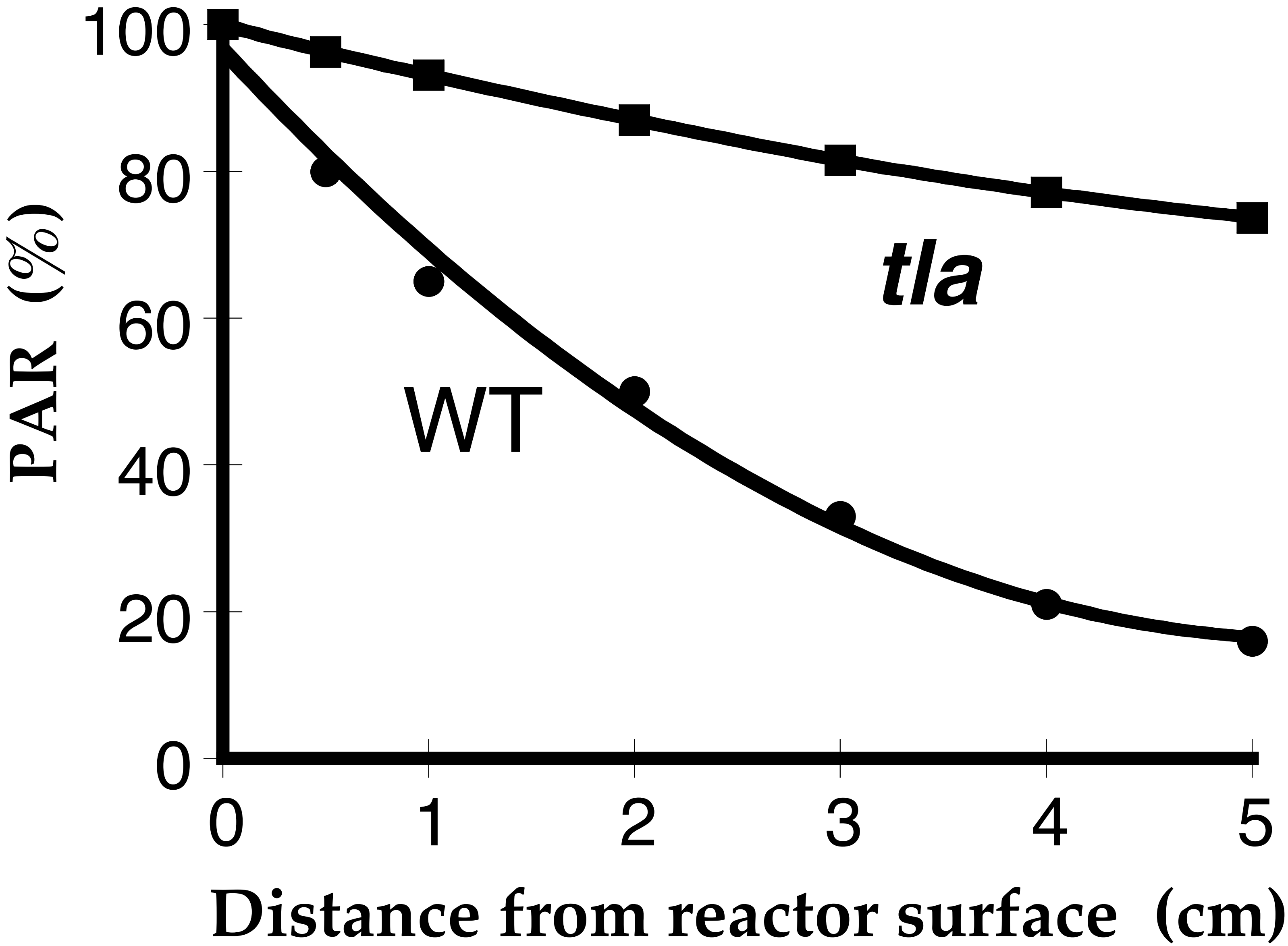
Cultures in the Greenhouse



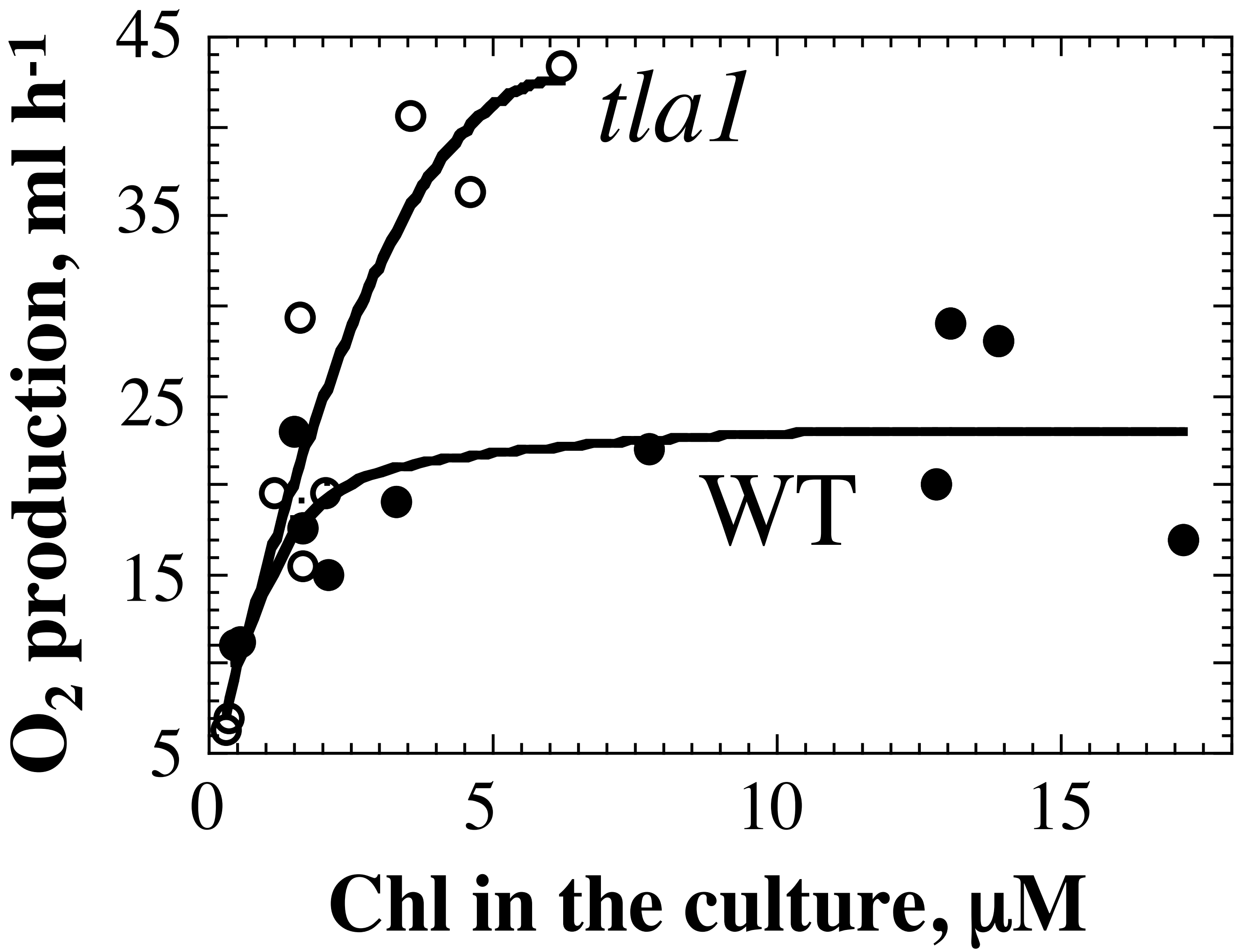
Parameter	WT	*tla1*
Cell/mL ($x10^6$)	6.36	10.0
[Chl] (uM)	25.6	15.4

The *tla1* strain shows greater productivity than the wild type cells under bright sunlight conditions. (Note relative amounts of gas bubbles produced by the two samples.)

Gradient of sunlight penetration through a high density wild type (WT) and *tla* culture



Photosynthetic productivity of wild type (WT) and *tla1* mutant



From Concept to Application

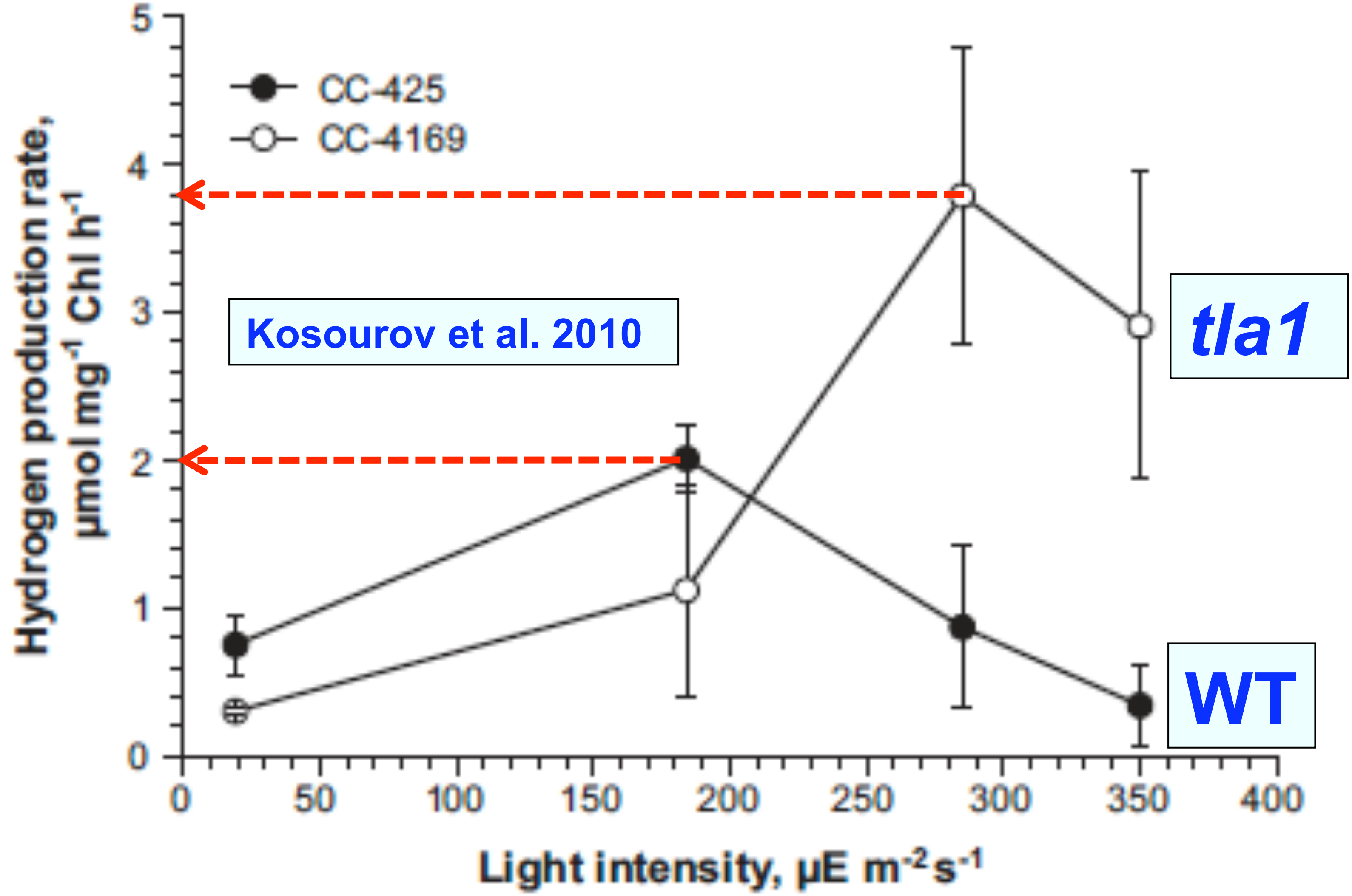
→ The *Tla* concept is commercially applied in green microalgae:

- *Chlamydomonas* for biomass production; and
- *Nannochloropsis* for commercial production of polyunsaturated fatty acids (PUFAs).

→ The *tla1 mutant* strain was requested and acquired by universities (x5), industry (x5), and government labs (x4).

→ Successful application of the *Tla1* gene at NREL for enhanced H_2-production.

Light intensity-dependent rate of H_2-production by immobilized wild type (CC-425) and *tla1* antenna mutant (CC-4169)



Increased *Tla* awareness in the field

Many labs in several countries are now engaged in *tla* research.

(green microalgae, cyanobacteria, photosynthetic bacteria)

Related DOE workshops

1) Office of Basic Energy Sciences workshop on "What is the Efficiency of Photosynthesis?" May 23-24, 2009

2) ARPA-E workshop, "Applied Biotechnology for Transportation Fuels: Meeting Today's Energy Needs by Maximizing Photon Capture". December 2-3, 2010

Summary and Conclusions

A *Tla* property in mass culture:

- ***Prevents the early light-saturation of photosynthesis.***
- ***Facilitates better sunlight penetration.***
- ***Enhances solar energy conversion efficiency and productivity (up to 300% in green microalgae).***

Future Tla extensions

- ***Development of non-genetic approaches to generating Tla strains.***
- ***Application of Tla technologies for biomass, H_2 and fuels production in cyanobacteria and photosynthetic bacteria.***
- ***Extension of Tla R&D to include generation of cell-fuel* molecules for application in fuel-cells.***

* *cell-fuels* = small-size high-energy bio-products

Thank You for Listening!