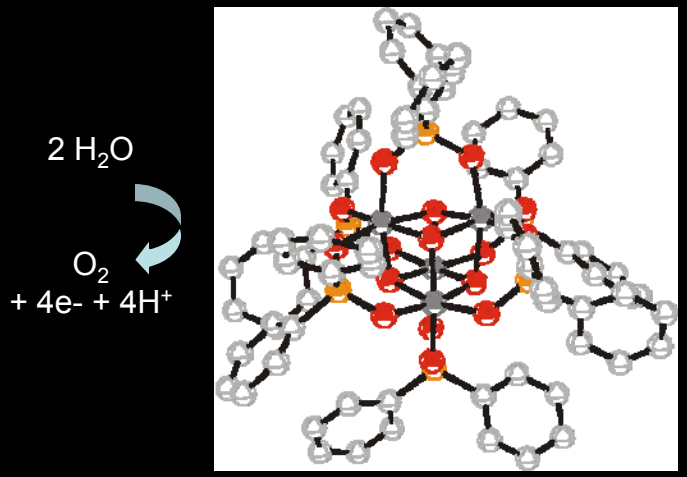
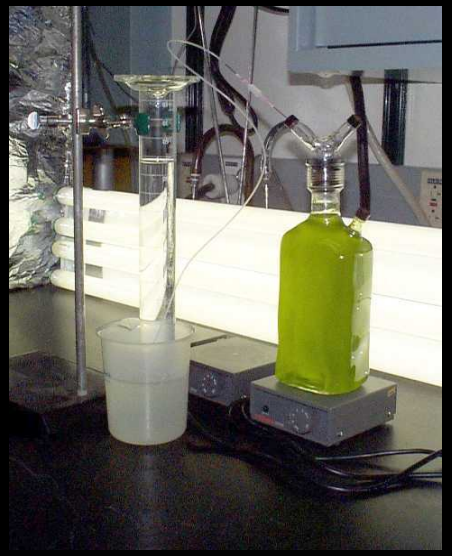
Nature's Renewable Energy Blueprint: Bio-Solar Hydrogen via Photosynthesis and Biomimics

$H_2O \rightarrow O_2 + H_2 (H^+/e^+)$

Bio-Inspired Abiotic Catalysts



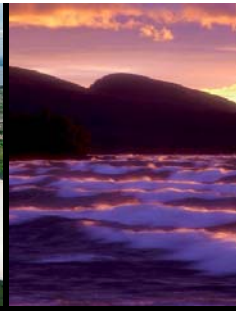
Direct Bio-Solar H_2 Production











WAVE WIND PV BIOMASS SOLAR TOWER HYDROELECTRIC TIDAL POWER

RENEWABLE ENERGY SOURCE SIZE (TW-YR)	ANNUAL ENERGY RESOURCE DEMAND	x GLOBAL ENERGY @ 46 TW-YR
SOLAR	178,000	3869x
GEOTHERMAL	92,063	2001x
WIND	194	420x
OCEAN THERMAL	10	
WAVE	2	
HYDROELECTRIC	1.6	
TIDAL	0.1	
TOTAL	270,271	5875x

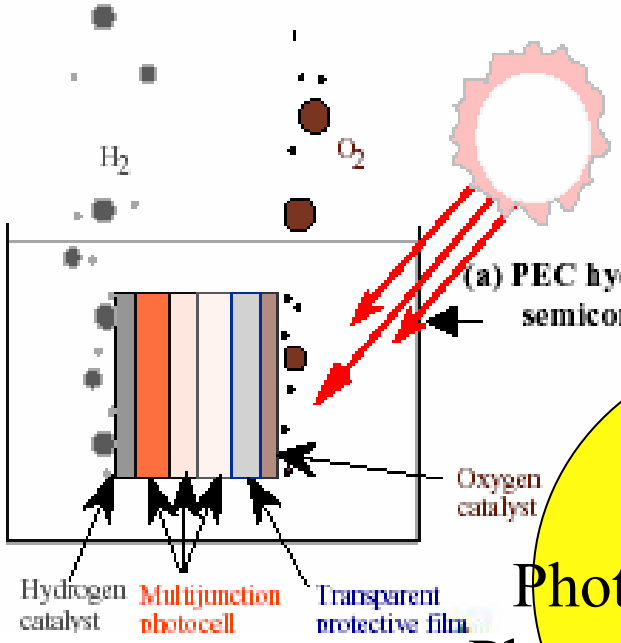
13TW-YR

- ALMOST ALL CLEAN ENERGY TECHNOLOGIES GENERATE ELECTRICITY
- GLOBAL ENERGY USE: 33% ELECTRICITY: 67% FUELS (eg OIL, COAL, GAS)

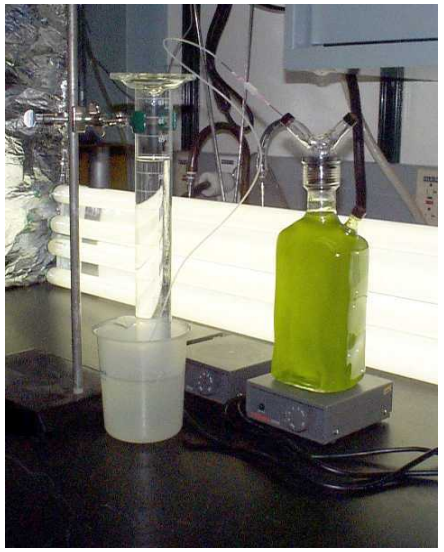
FUTURE TECHNOLOGY ASSESSMENT → SOLAR H_2 FROM H_2O

IEA source

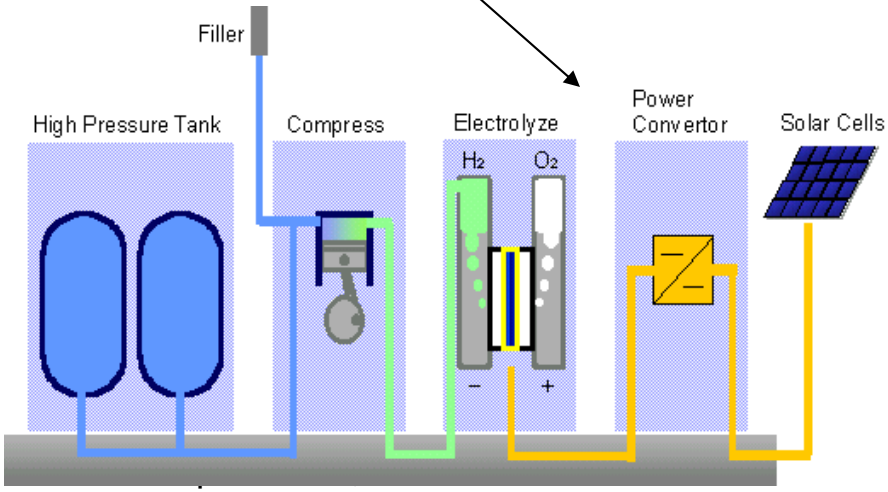
Direct Solar Methods



Biological
Photoelectrochemical
Photovoltaic/Electrolysis



http://www.nrel.gov/st.html



Part II

BioSolarH_2 →

Renewable Bio-solar H_2 Production from Water via Robust Oxygenic Phototrophs

June 2005 launch

PRINCETON PENNSTATE HAWAII

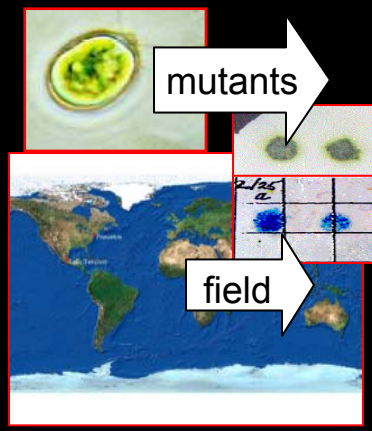
Air Force Office of Scientific Research
The Basic Research Manager of the Air Force

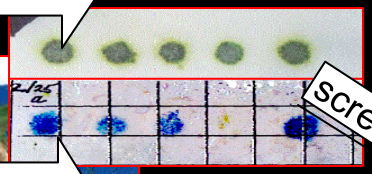
Renewable Bio-solar Hydrogen Production from Robust Oxygenic Phototrophs

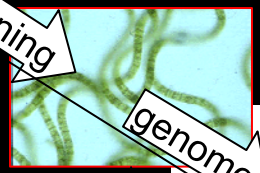
BioSolarH_2→ Team

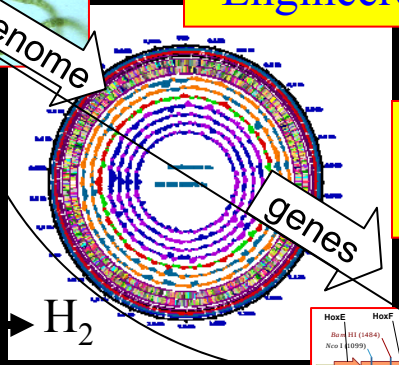
G. Charles Dismukes	PU	photosynthesis/engineering
Edward I. Stiefel	PU	enzymology/inorganic
Donald A. Bryant	PSU	genetics/mol biology cyanos
Matthew Posewitz	CSM	genetics/mol biology algae
Eric Hegg	UU	enzymology/inorganic
Robert Bidigare	UH	microbial physiology/ecology

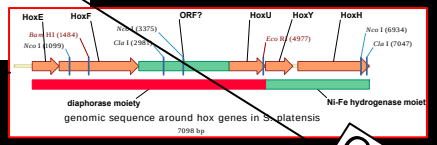
Renewable Bio-solar H_2 Production from Robust Oxygenic Phototrophs

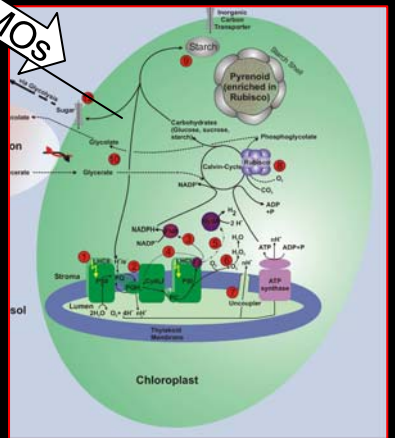












Oxygenic Photosynthesis

Achievements June 2005

- Identified novel H_2 photoproducers
- Developed high throughput screen for H_2
- Built ultra-sensitive H_2 detection instruments
- Engineered mutants in a green alga

Payoff

Clean H_2 from non-fossil source

Objectives

- Screening for the right organisms, photosystems & hydrogenases
- Down-regulation of competing biochemical pathways
- Random & specific mutagenesis for higher H_2 production
- Genetically combining host phototrophs with optimal hydrogenases

H_2ase-dependent Solar Biological Hydrogen from Water

Microalgae

Direct H_2, 2 quanta/e^-, 1 stage, no gas separation

$$H_2O \rightarrow H_2 + \tfrac{1}{2} O_2$$

(NREL, ORNL, UCB) Indirect H_2 via biomass, 4 quanta/e^-, 2 temporally resolved stages

$$2\,H_2O + CO_2 \xrightarrow{light} O_2 + [CH_2O] + H_2O \qquad \text{PS}$$

$$2\,H_2O + [CH_2O] \xrightarrow{\text{anaeorbic } \cancel{PSII}} \xrightarrow{light} 2\,H_2 + CO_2 + H_2O \qquad \text{Resp + low \% PS}$$

Cyanobacteria

Indirect H_2 via biomass, 2 quanta/e-, 2 temporally resolved stages

$$2\,H_2O + CO_2 \xrightarrow{light} [CH_2O] + O_2 + H_2O \qquad \text{PS}$$

$$[CH_2O] + H_2O \xrightarrow{anaeorbic + dark} 2\,H_2 + CO_2 \qquad \text{Fermentation}$$

H_2 efficiency* losses occur at max solar flux & from competing pathways for e^-/H^+

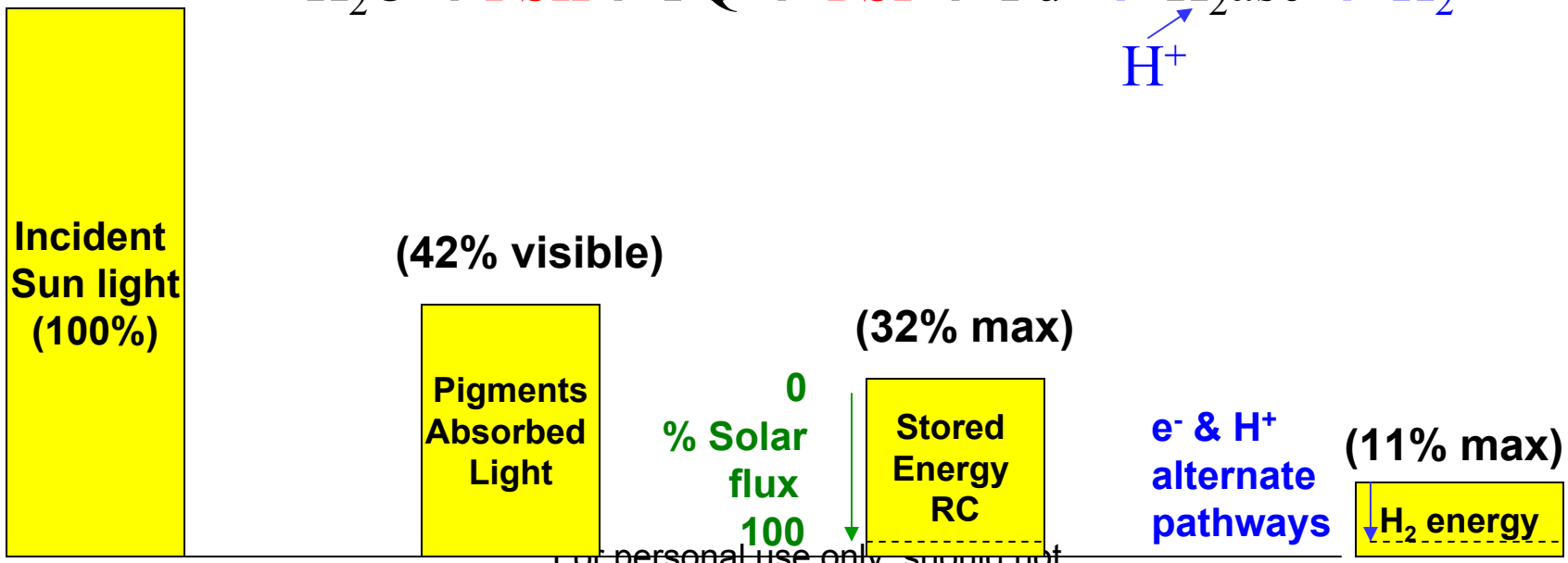
$$QY(H_2) = \Lambda_i\,(1-\Lambda_{NPQ})\,(1-\Omega_2)\,\Phi_1\Phi_2\,(1-X_C)(1-X_A)(1-X_N)(1-X_O)$$

light energy capture

e^- & H^+ competing pathways

$H_2O \rightarrow PSII \rightarrow PQ \rightarrow PSI \rightarrow Fd \rightarrow H_2ase \rightarrow H_2$

H^+



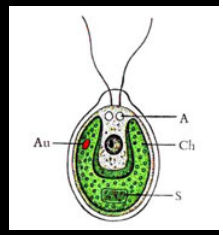
* Kruse et al. (2005) *Photochem. Photobiol. Science VOL.4,*

Solar Bio-H_2 Goals: Economic viability[4]

- ~10% efficiency at ambient light levels (eg., antenna deletion mutants)
- Requires strict temporal or sptial separation of H_2 and O_2
- Achieve current cost estimates for large scale bioreactors

4. Independent predictions by NREL and Thiess Engineering

Solar Bio-H_2 Current Status

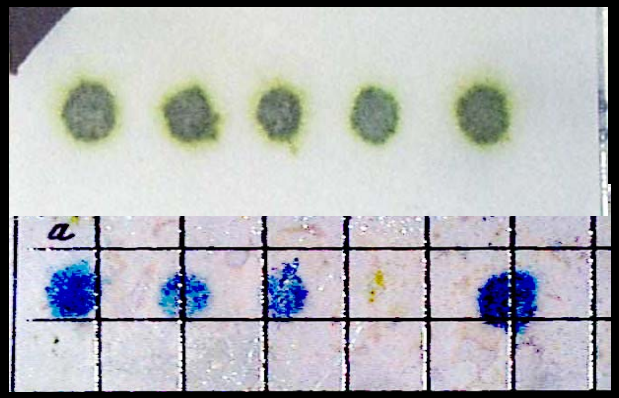


Chlamydomonas reinhardtii: two stage light + dark + S deprivation

Strain	IncidentPhoton Conv. Eff.	H_2 rate ml (liter culture)$^{-1}$ hr^{-1}
• WT [1]	~ 0.1%	1.5
• LHC insertion mutant [2]		0 (expected 3-4 x)
• stm6 mutant [3]	~1.5%	(5 -13 x)

1. NREL team 2004
2. UCB team, Melis et al.
3. Univ. Bielfeld & Univ Queensland: Kruse & Hankamer, JBC (2005)

Colonies on agar plate

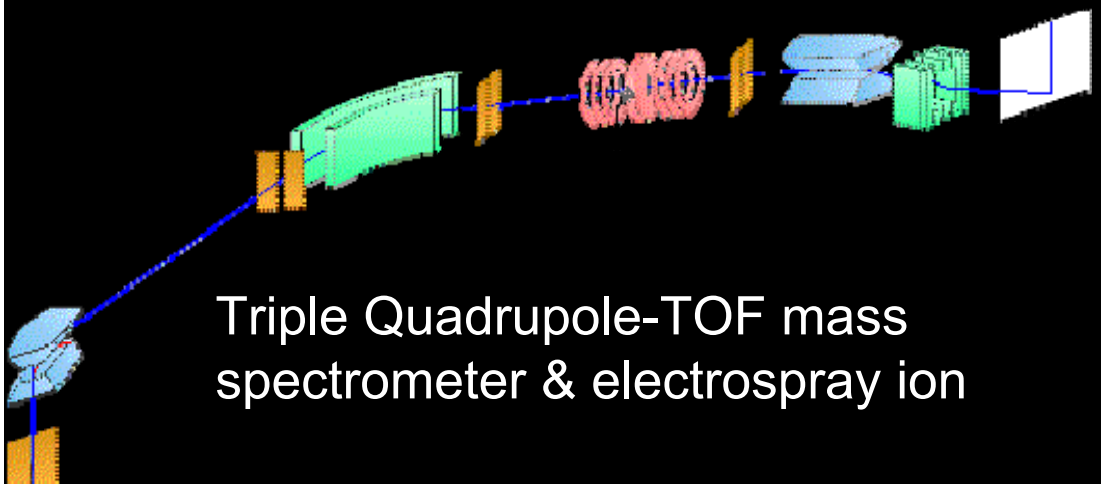


NREL WO_3 H_2 gas sensor

Fast repetition rate fluorimeter
PSII Quantum Efficiency

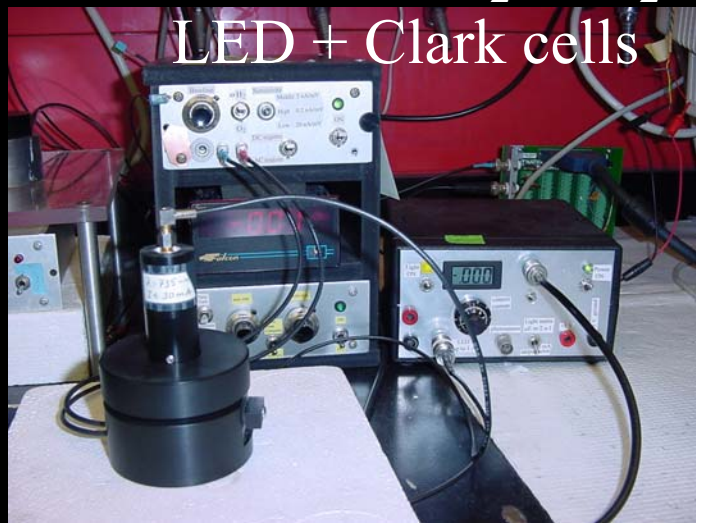
BioSolarH_2 Instrumentation Development

Metabolomics & Proteomics

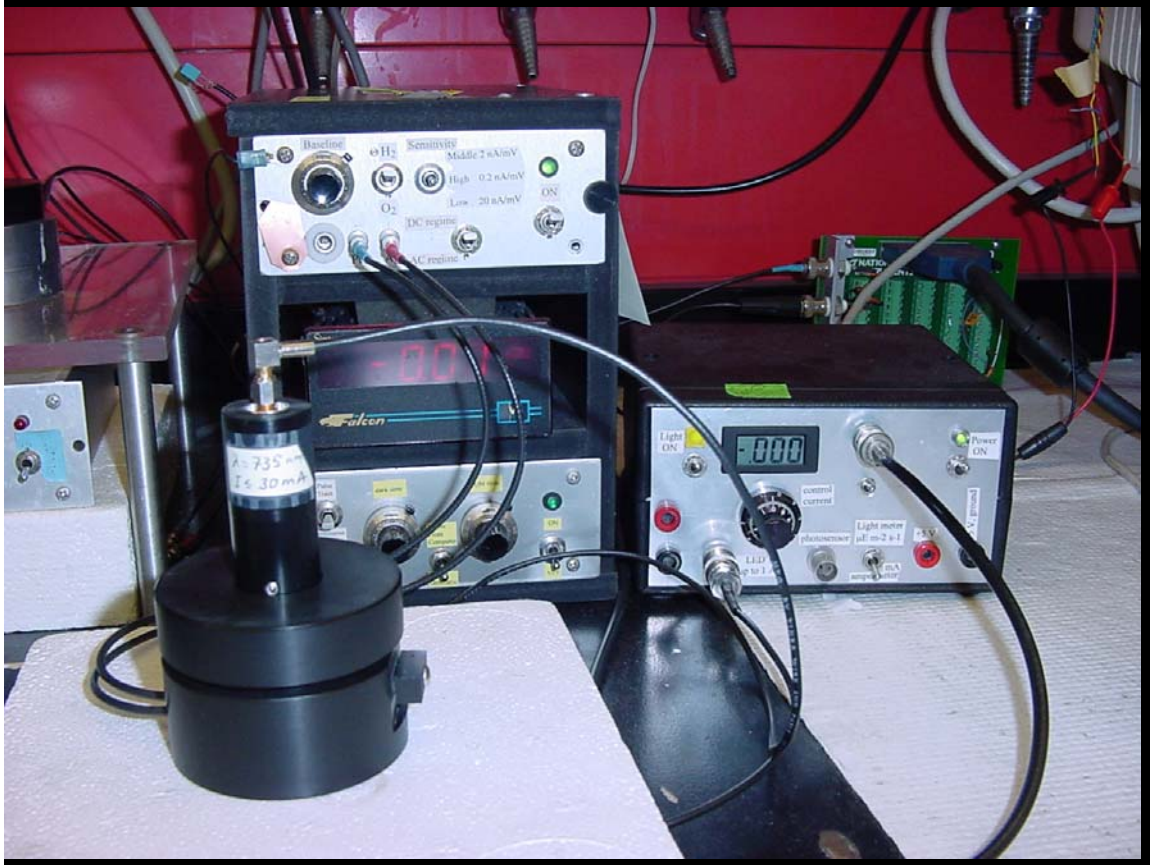


Triple Quadrupole-TOF mass spectrometer & electrospray ion

Dissolved H_2 & O_2
LED + Clark cells



Ultrasensitive cells for dissolved H_2 & O_2 with multi-wavelength light-emitting diode illuminator

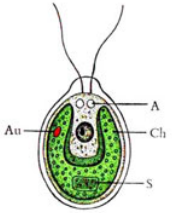


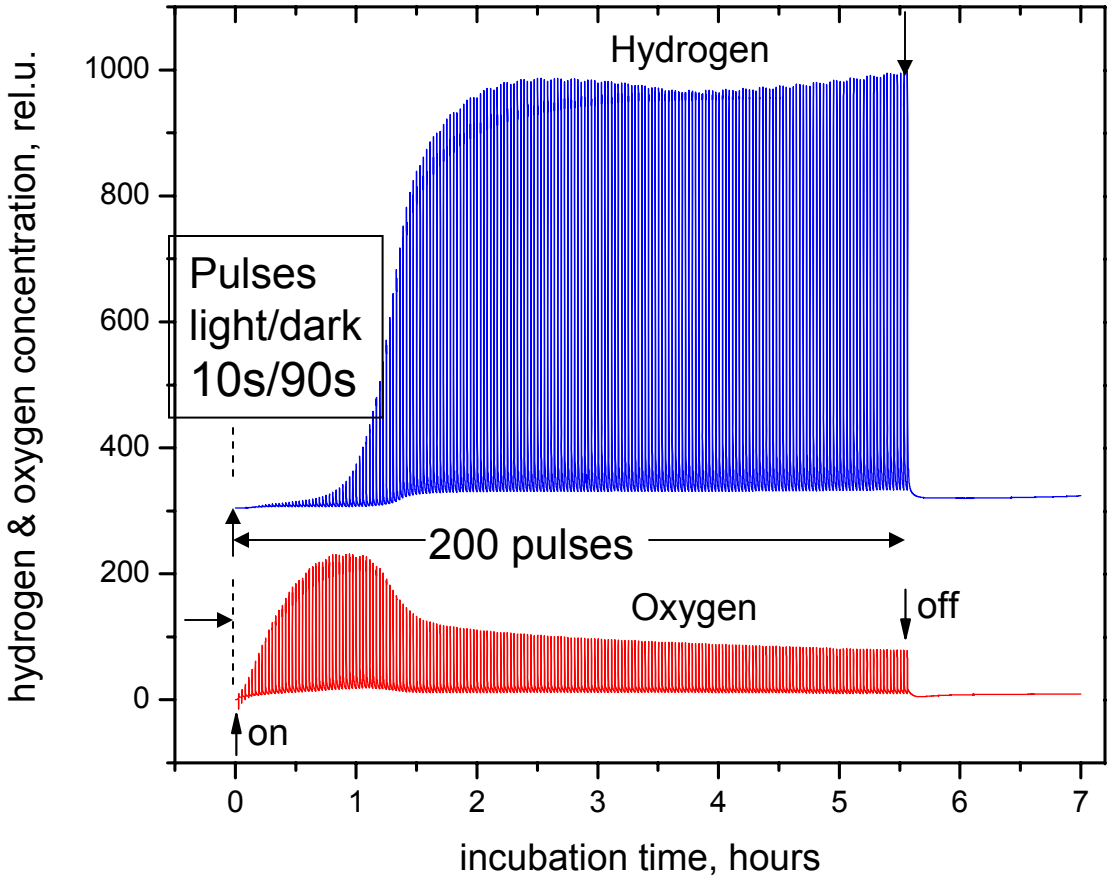
Clark type Cells for dissolved O_2 & H_2

10^{-8} Molar H_2 or O_2
5 µL volume
Sensitivity 50 femtomoles
0.1 sec response time

Wavelength selective illumination via LEDs: blue, orange, red, infrared, white

Photo-H_2 and –O_2 in WT *Chlamydomonas reinhardtii* CC124





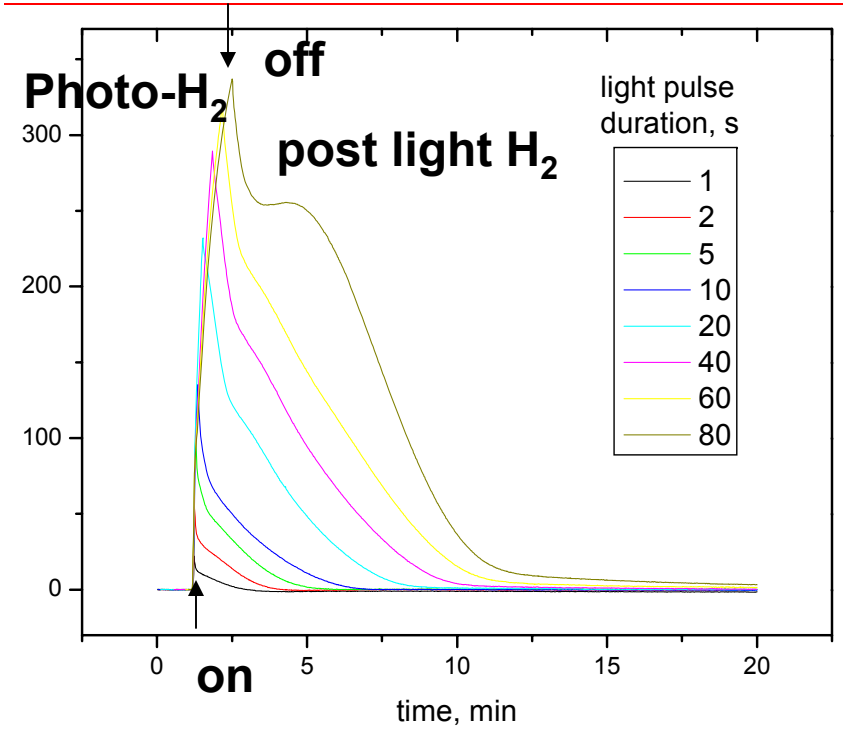
Conclusions

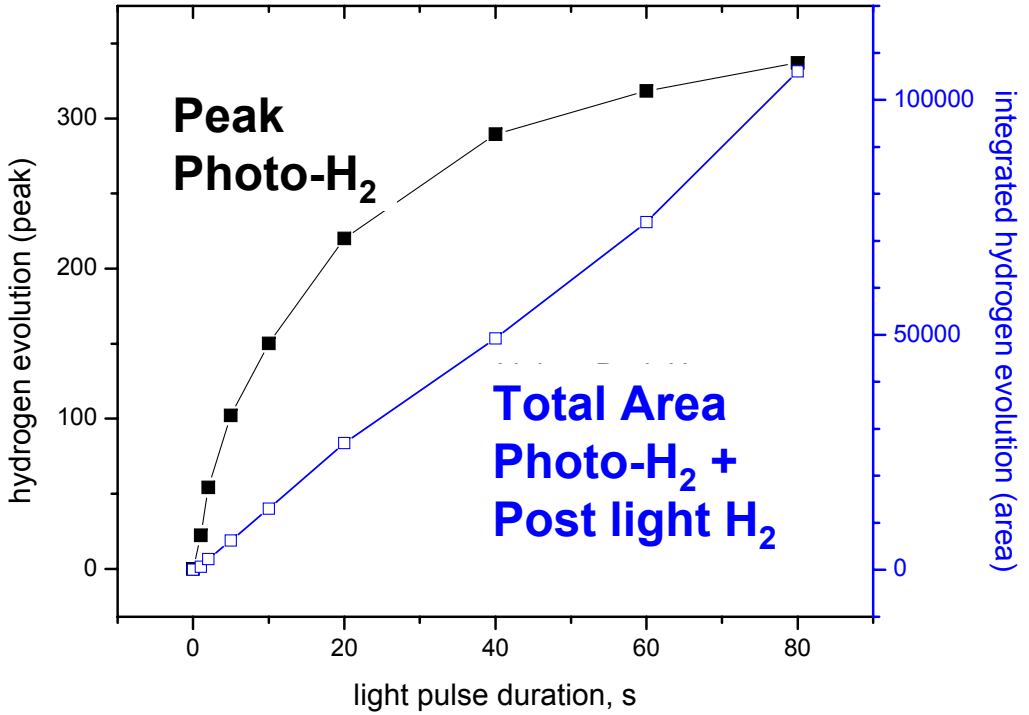
- **Major Photo-H_2**
- **Minimal dark-H_2**
- **Co-production of H_2 and O_2**
- **H_2 yield is O_2 limited**

Cells from Petri dish resuspended in TAP liquid medium.
Anaerobic pre-incubation time 12 min →
Pulse illumination via white LED at 130 μE m^{-2} s^{-1}

G. Ananyev

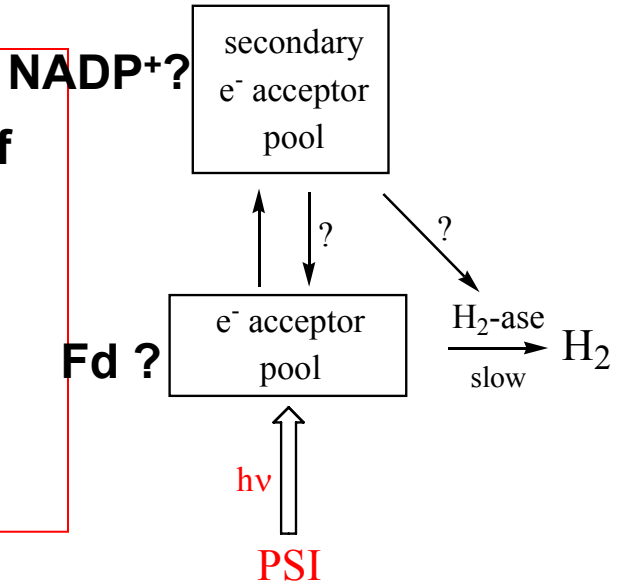
Light pulses produce two kinetic phases of photo-H_2 in *C. reinhardtii* WT



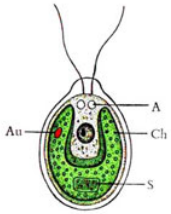


Conclusion:

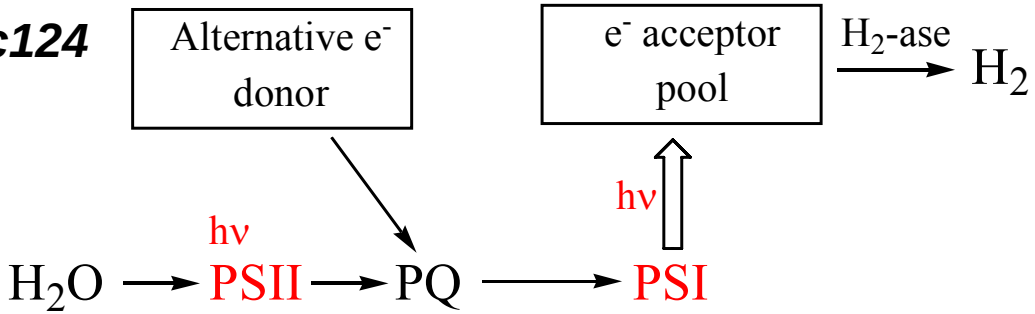
- **Two pools of photo-electron acceptors in PSI capable of light-induced H_2 production**
- **Integrated H_2 yield is linear with pulse duration → competing pathways for e^-/H^+ consumption are either fixed or not present**



G. Ananyev

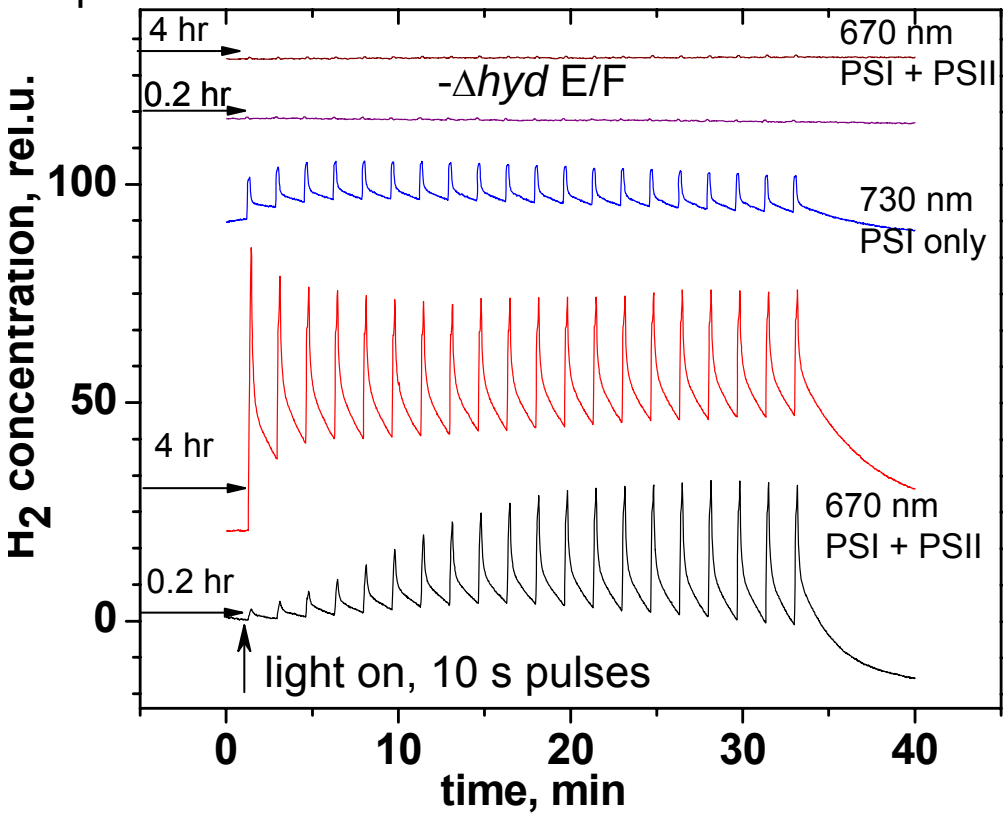


Chlamydomonas reinhardtii cc124



Anaerobic -O_2

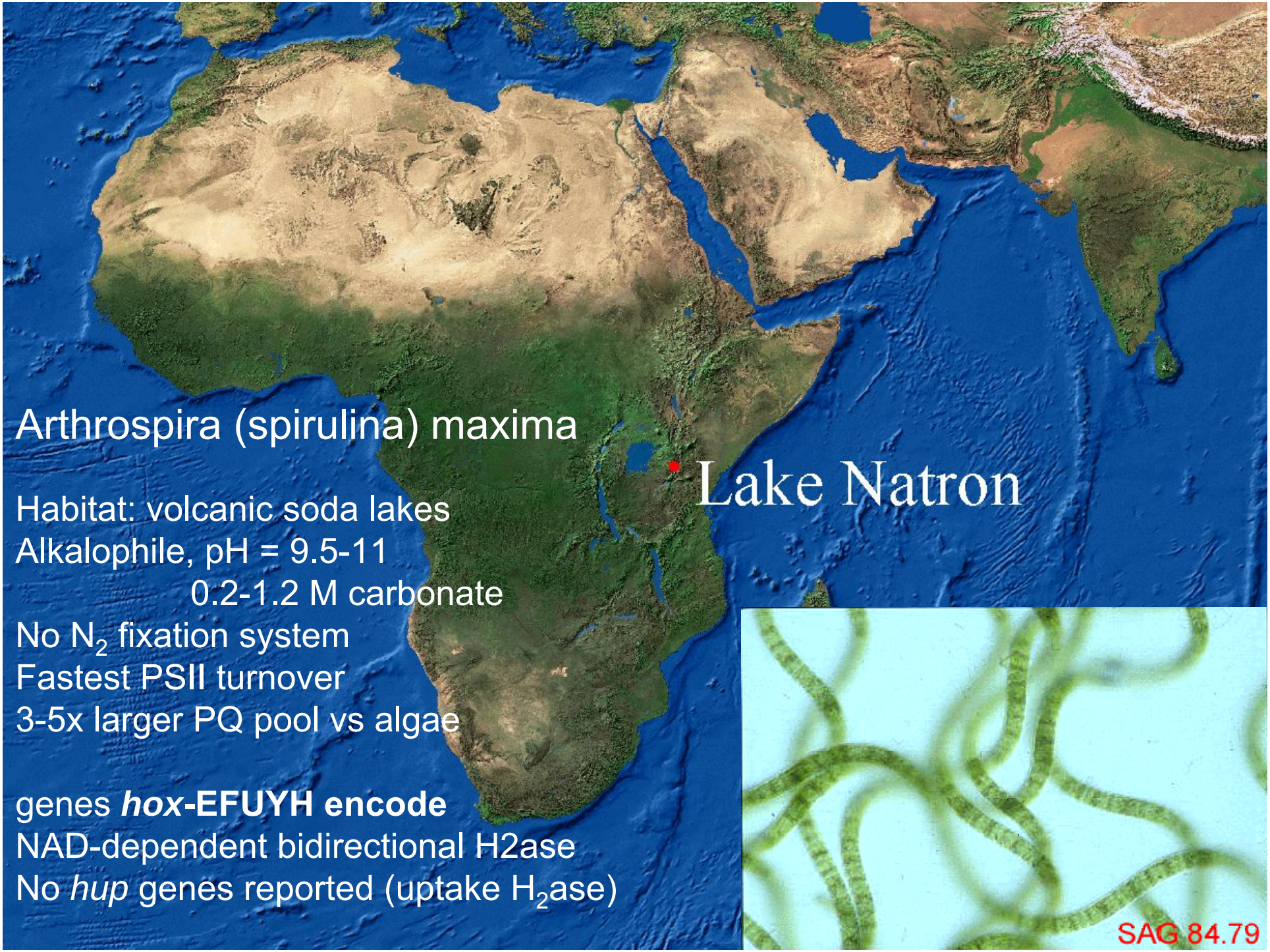
pre-incubation



Conclusions:

- **Photo-H_2 & dark-H_2 requires H_2ase genes hyd E/F**
- **Maximum photo-H2 production requires illumination of both PSI and PSII**
- **The major source of reductant required for photo-H2 comes from water via PSII turnover**
- **The minor PSI only pathway presumably involves PQ/other donor**

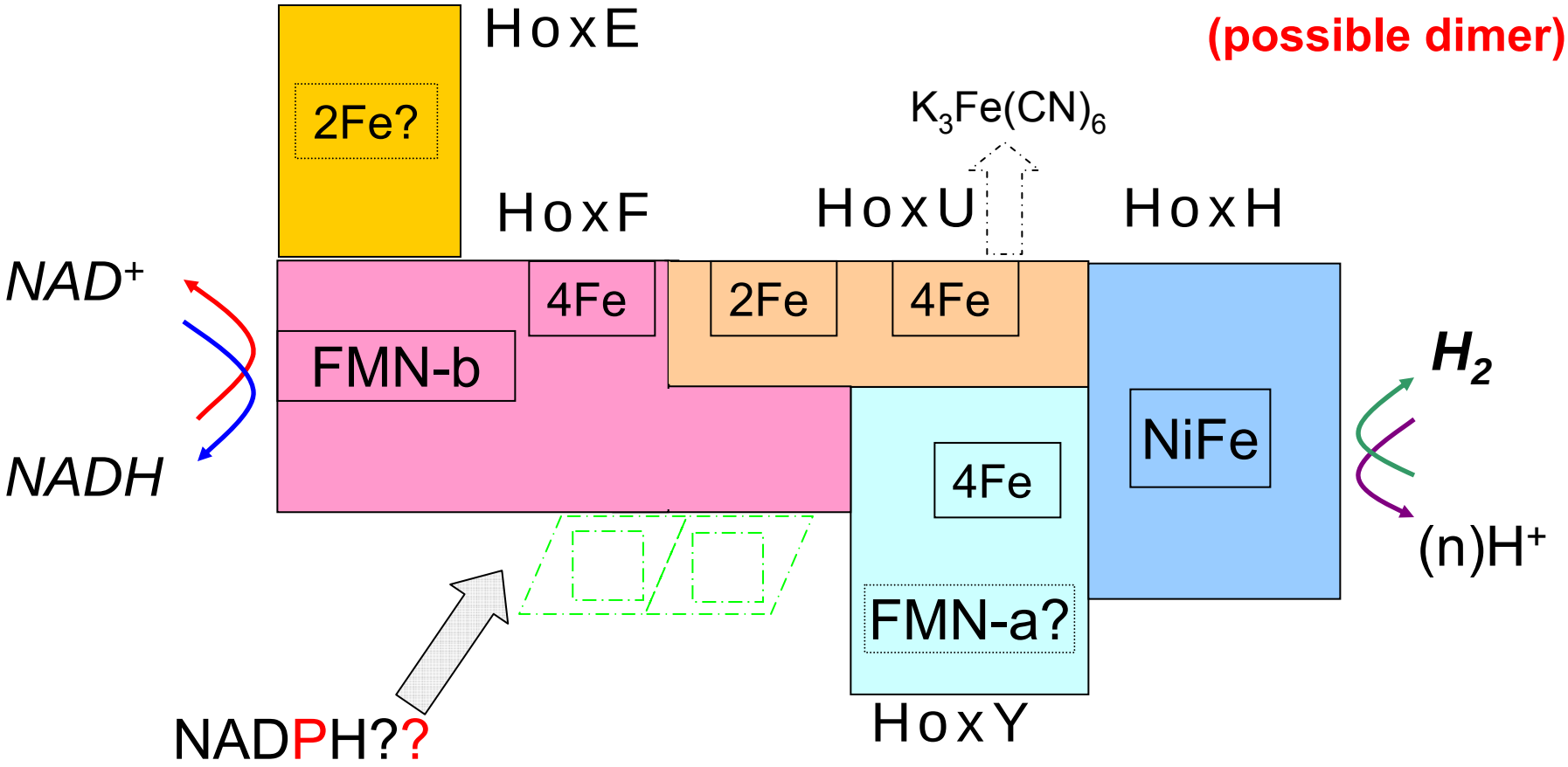
G. Ananyev & M. Posewitz


Arthrospira (spirulina) maxima
Lake Natron
Habitat: volcanic soda lakes
Alkalophile, pH = 9.5-11
0.2-1.2 M carbonate
No N_2 fixation system
Fastest PSII turnover
3-5x larger PQ pool vs algae
genes ***hox*-EFUYH encode**
NAD-dependent bidirectional H2ase
No *hup* genes reported (uptake H_2ase)
SAG 84.79

Reversible NAD-dependent NiFe-hydrogenase (***cyanobacteria***)

e.g. Synechocystis sp. 6803, *Synechococcus* sp. 6301, *Arthrospira maxima*

HoxEFUYH
(possible dimer)

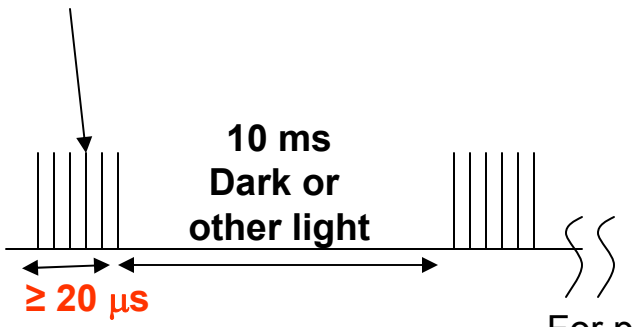


HoxE described in Schmitz *et al, 2002*

Princeton: Fast Repetition Rate Laser Fluorometer

- ≥50 ns pulses 0.5 W; 660 nm laser
- ≥20 µs duration pulse train at full light saturation
- Programmable pulse flexibility
- Fast sampling, 20 mHZ detection
- Chlorophyll Fo, Fv, Fm,
- cross section of PSII
- Q_A^- oxidation kinetics

STF – single turnover laser flash train



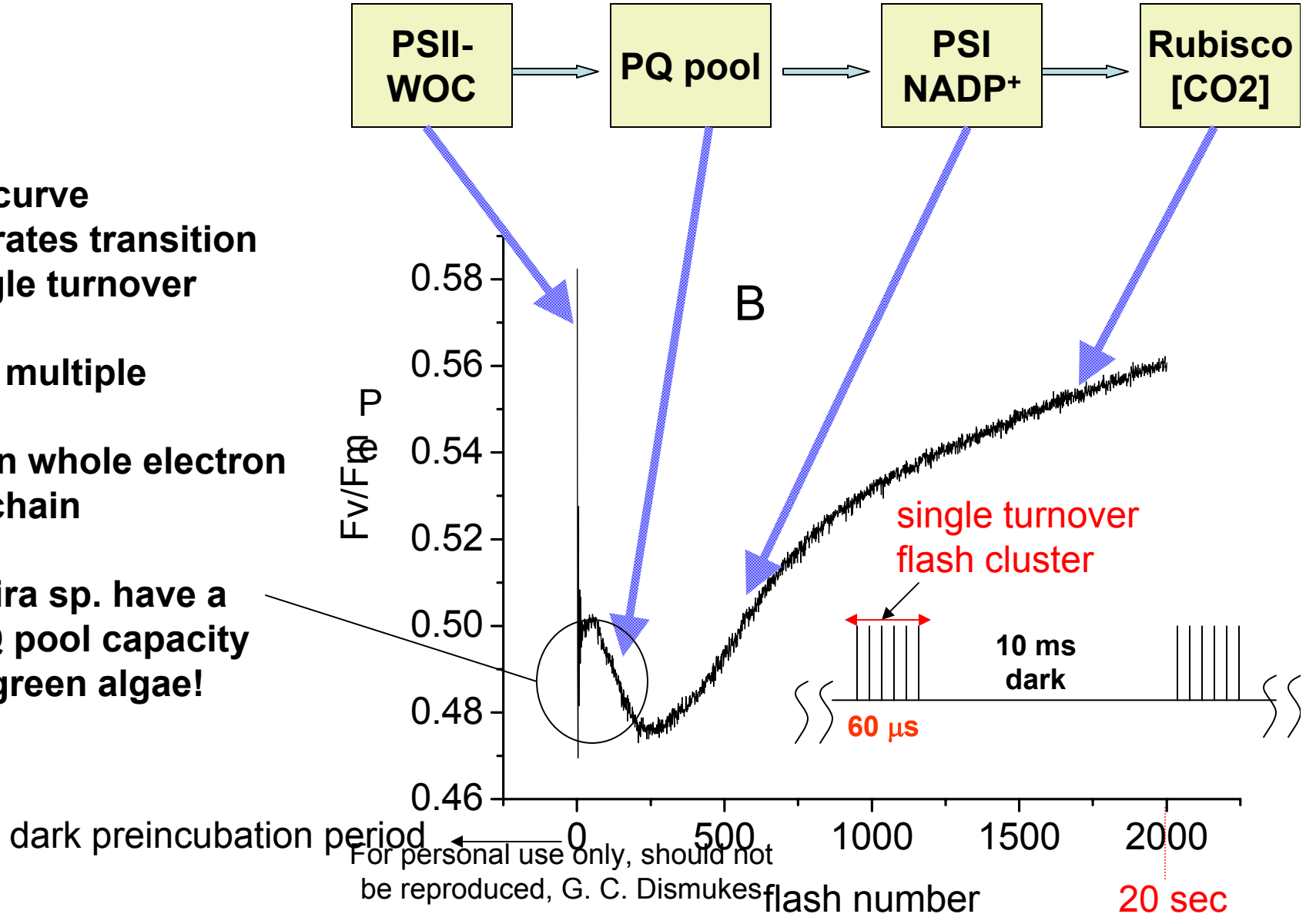
Variables to be measured:
- **Fv/Fm = PSII quantum efficiency H_2O → PQ**
- **PQ pool size**

Ananyev & Dismukes, Photosyn Res. (2005)

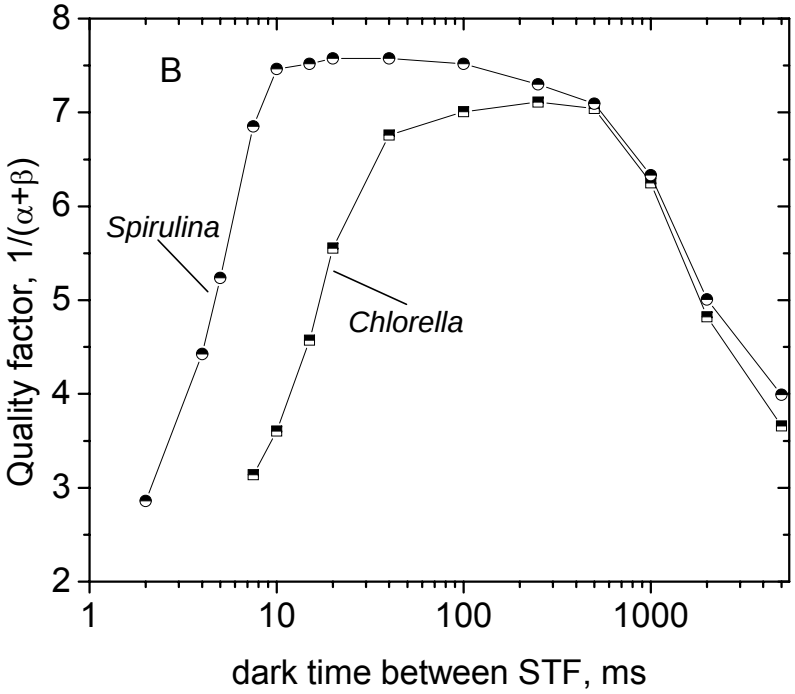
PSII Variable Fluorescence at 100Hz flash repetition rate; *Arthrospira p. whole cells*

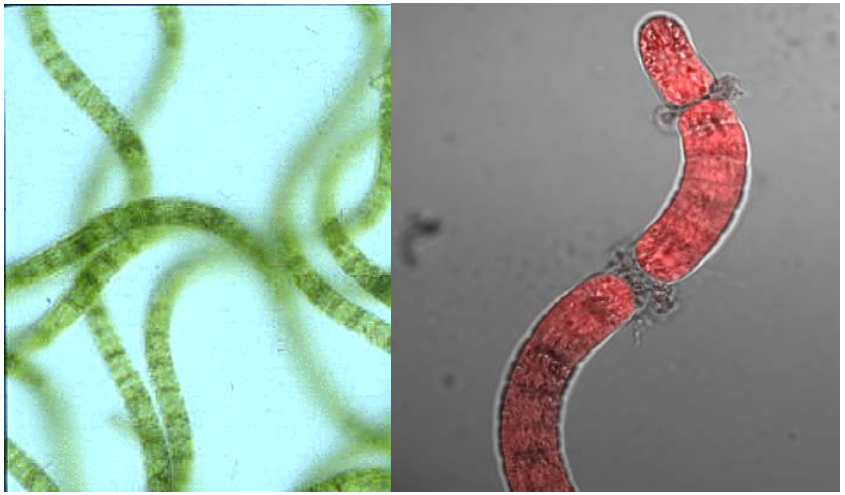
Kautsky curve demonstrates transition from single turnover events in PSII to multiple electron transfer in whole electron transfer chain

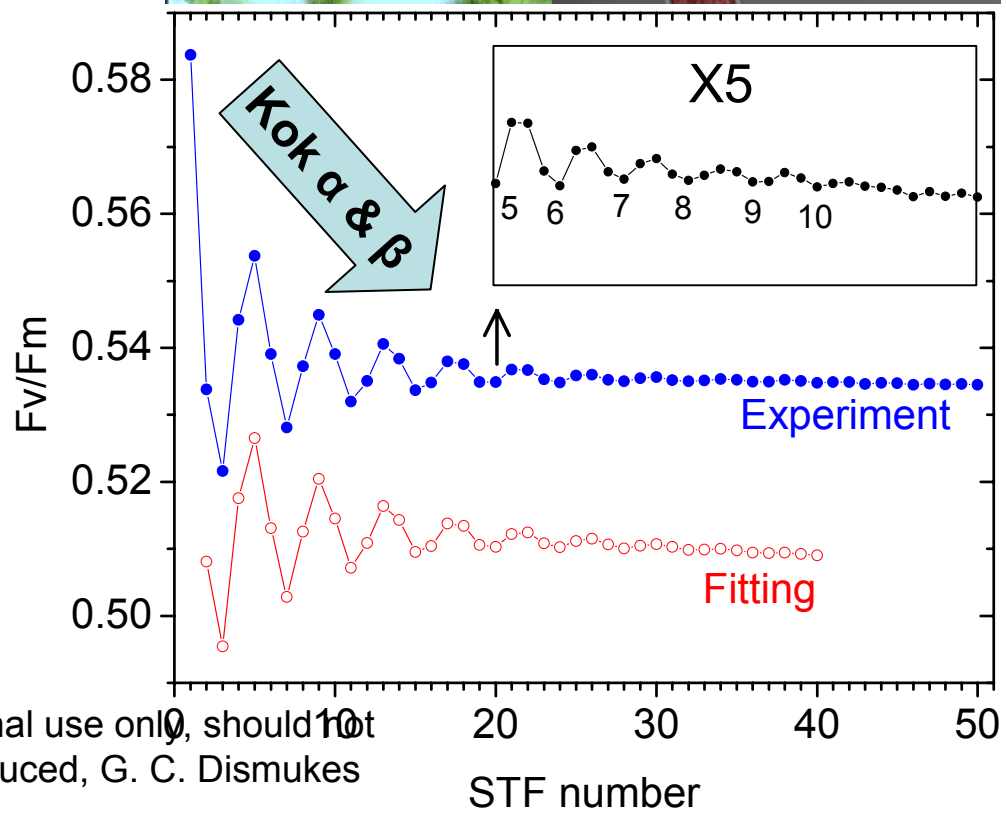
Arthrospira sp. have a larger PQ pool capacity 3-5X vs. green algae!



Turnover Frequency of PSII is highest by 5x for *Arthrospira maxima*





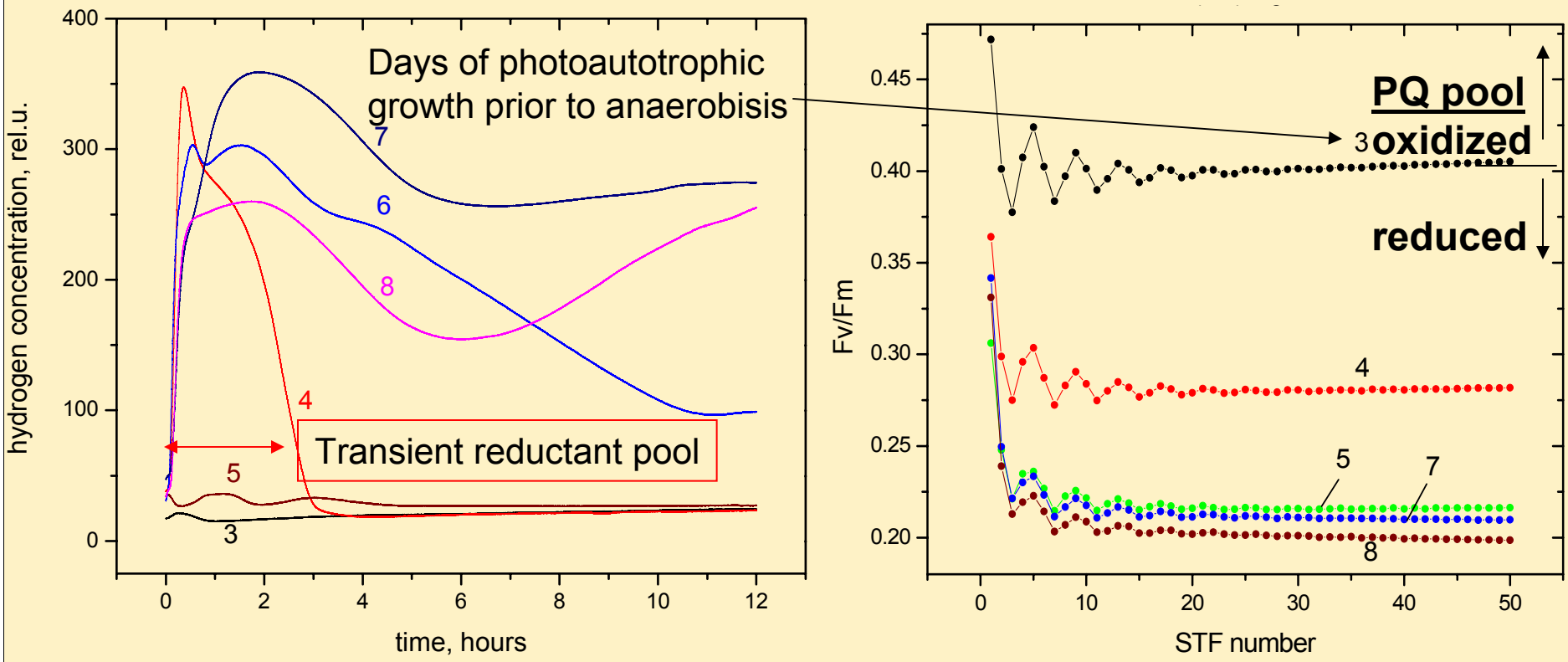


Kok parameters:
photochemical misses (α)
& double hit/misses (β)

PSII quantum efficiency ~54%

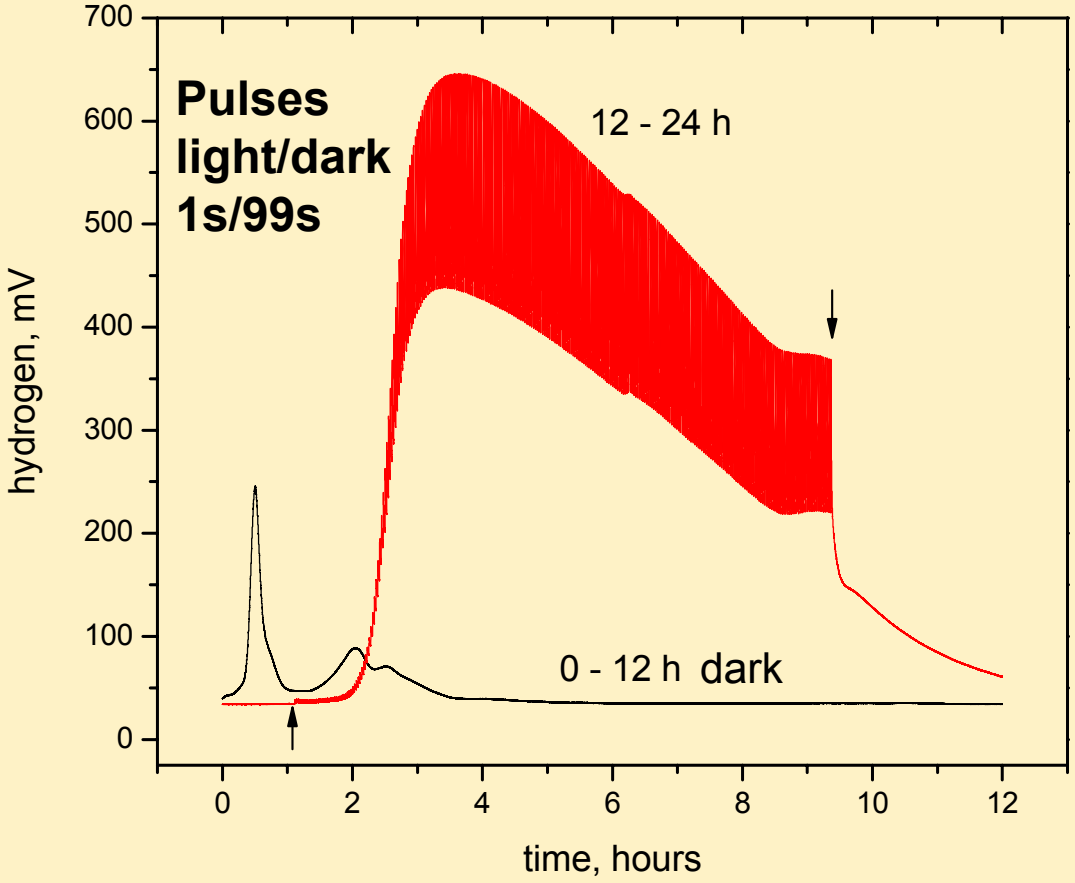
* Ananyev & Dismukes, Photosyn Res. (2005)

Induction of dark H_2 ↑(Left) & PSII quantum efficiency (Right) during photoautotrophic growth at 1.7 μM Ni^{2+} of *A. maxima*



- Ni^{2+} addition to standard cyanobacteria growth media (Zarrouk) is essential for H_2ase↑
- 3-4 days lag to fermentative H_2 , yields transient reductant pool (2 or 3 peaks)
- Second lag phase 1-2 days later, oscillations in H_2
- Culture survives for 10-11 days in batch culturing no additives
- Microscopy shows that most active dark-H_2 producing cells have no gas vacuoles

PSI + PSII Illumination by 640 nm red light produces additional H_2



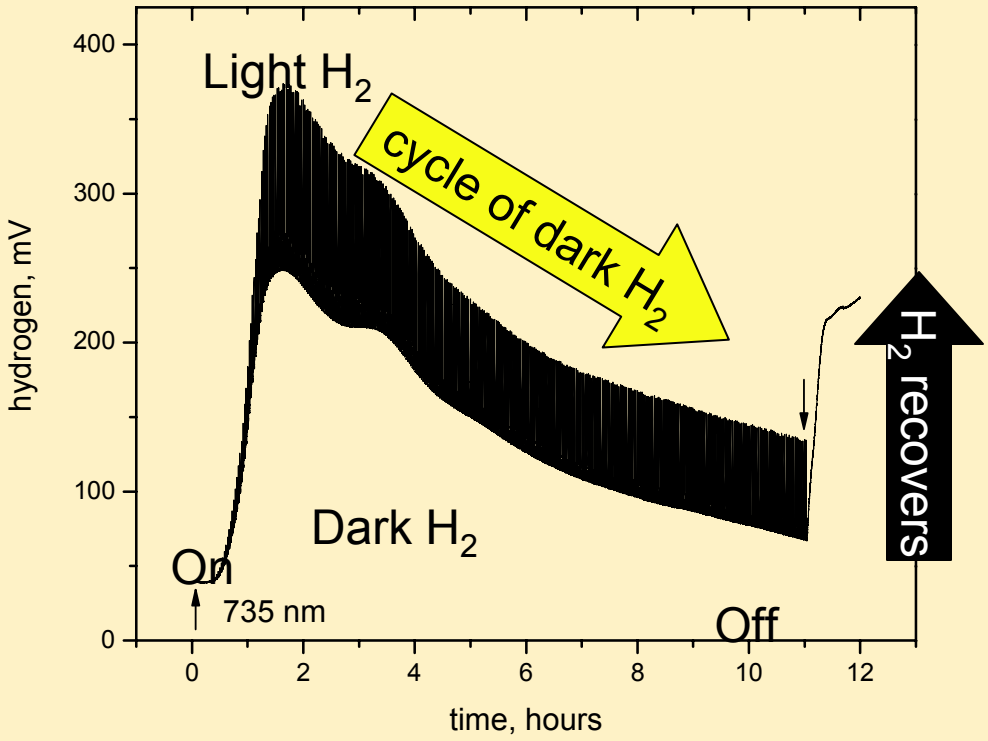
Conclusions

•Dark (fermentative) and a light-induced pathways to H_2 are present

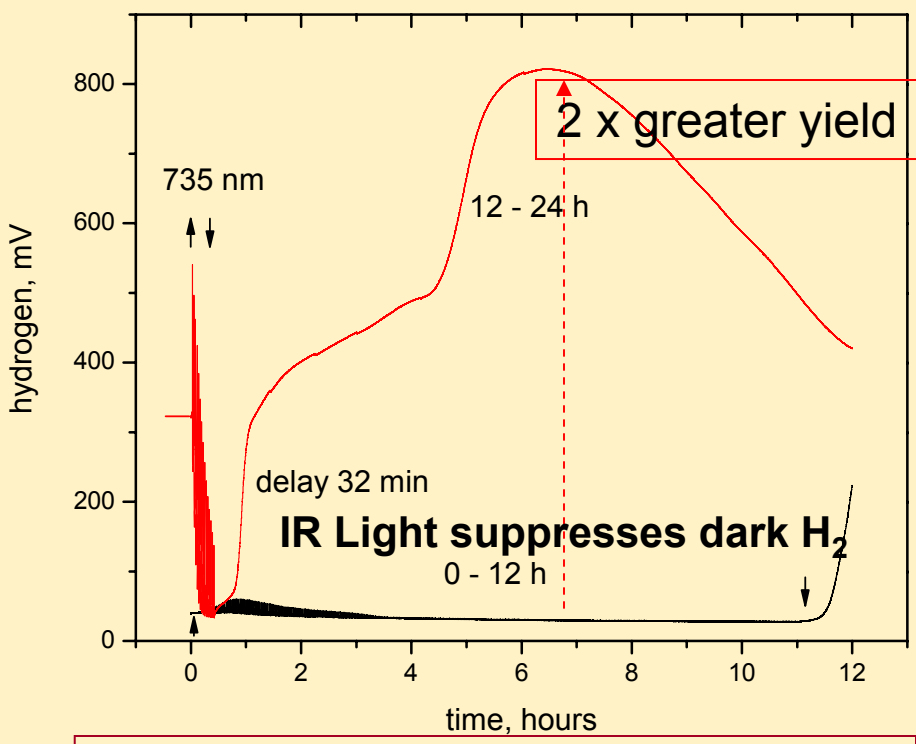
These pathways share a common intermediate that is precursor to H_2

PSI Illumination by IR 735 nm stops fermentative H_2↑ & stores H_2 precursor

1 s light/ 99 s dark



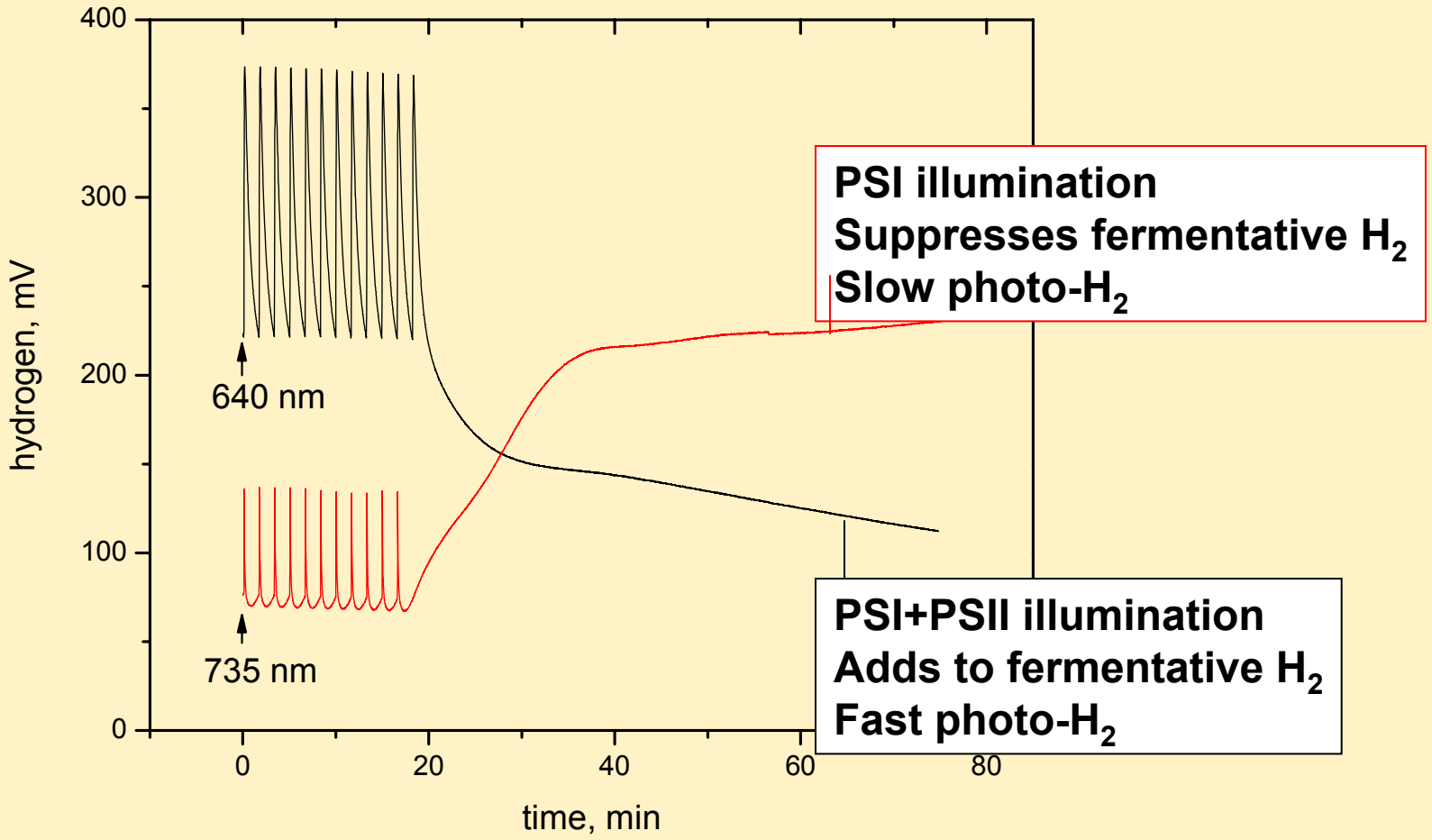
5 s light/95 s dark



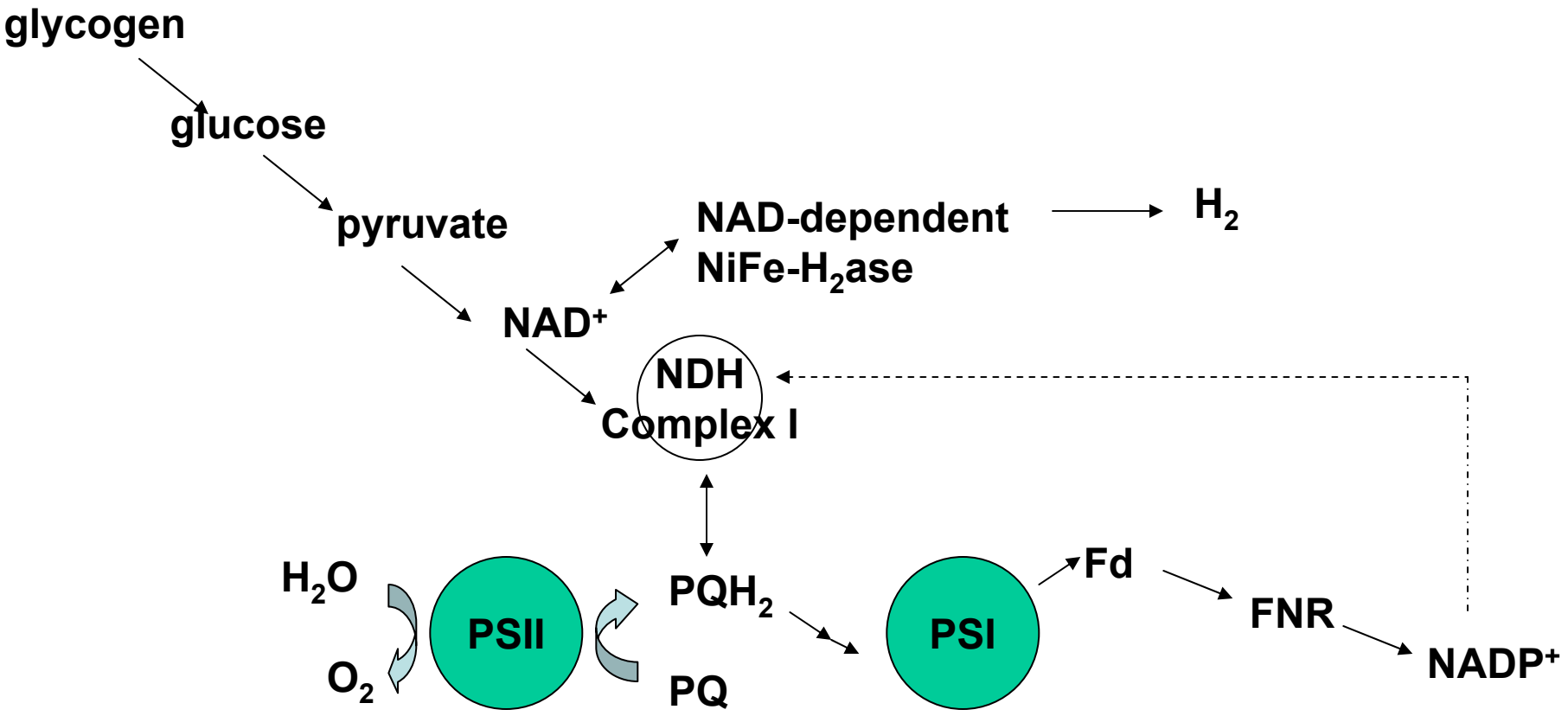
Dark H_2 reductant is stored under IR illumination

Fermentative H_2 restored in dark after IR light stopped at 2x higher rate

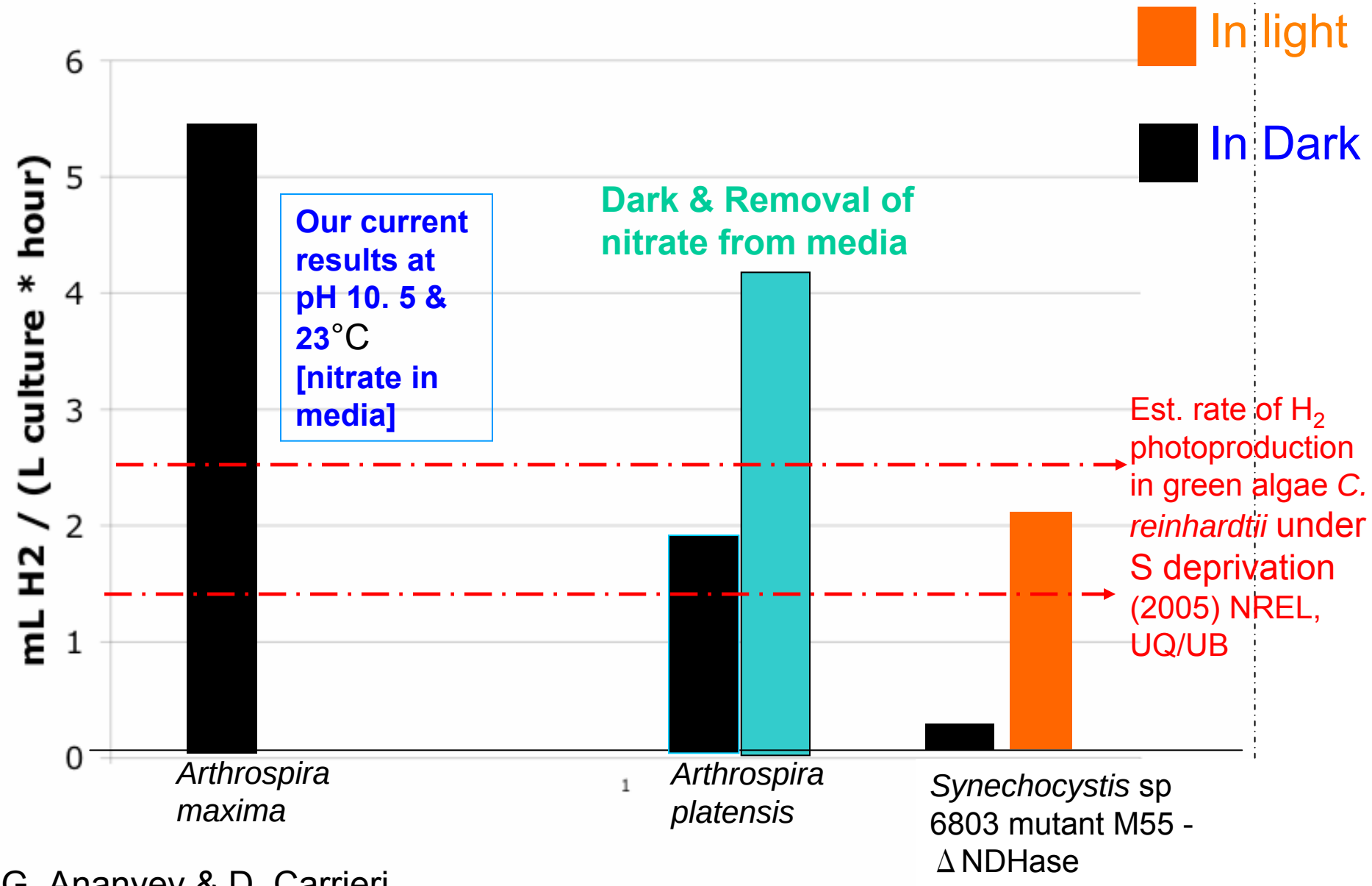
A. maxima


400
300
200
100
0
hydrogen, mV
640 nm
735 nm
0
20
40
60
80
time, min
PSI illumination
Suppresses fermentative H2
Slow photo-H2
PSI+PSII illumination
Adds to fermentative H2
Fast photo-H2

Model for Dark and Light H_2 production by *Arthrospira m.*



Sustained H_2 production rates via hydrogenase : representative reports of cyanobacteria using water as electron donor



G. Ananyev & D. Carrieri

Factors that increase H2 production by *A. maxima*

- Increasing temperature from 23 to 35 ^{o}C;
- Conditions for Glycogen accumulation (high light, high [CO2]);
- Micronutrients: Ni2+ (20x H2) & Fe3+(4x H2)
- Low pH (10.5→ 6) for H2 evolution (2-3x)

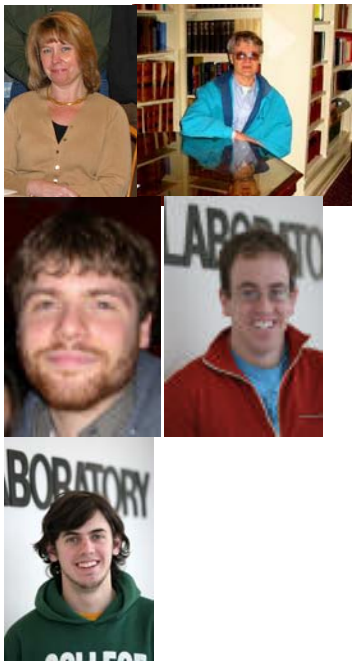
Conclusions

- New tools for measuring H_2, O_2 and redox status provide reliable quantitative data on concentrations and fluxes

- greatly simplify and clarify the fundamental mechanisms of H_2 production in microalgae and cyanobacteria

- Cyanobacteria & microalgae have different pathways to H_2

- Ideal temporal separation of H_2 and O_2 production in cyanobacteria solves gas separation problem



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