Practical limits of bio-energy production and CO_2 sequestration by algae or cyanobacteria.

Photobioreactors for precision cultivation of cyanobacteria and for high content analysis of suspension dynamics:

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History

- *1940's diatoms for fuel (Germany)*
- *1950-60's algae for food (Japan, Taiwan, CZ, Israel…)*
- *1970-80's wastewater, atmosphere regeneration (worldwide)*
- *1980-90's microalgae for biofuels (DOE/SERI, USA)*
- *1990-2000's CO2 bioremediation (RITE, Japan)*

- *2007: BP funding to UC Berkeley and Lawrence Berkeley National Laboratory and University of Illinois (higher plants, 500M$)*
- *Greenfuel and many others … surge in interest from industry (and politicians)*

- ***future success or failure ?***

Historical perspective

1981-85
MBÚ Třeboň: Chlorella I and Chlorella II Interkosmos experiments
& radioactively labeled products

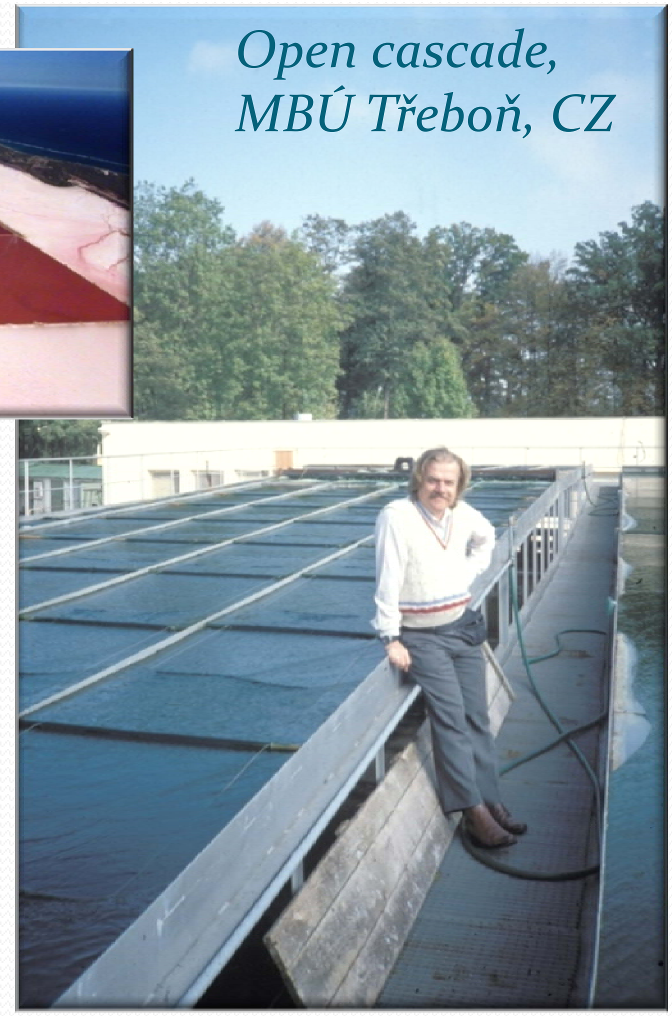
1993 – present: instruments and techniques for photosynthesis research

1997 – "high content" photobioreactor

*2007 – **"How much space do we need to fix CO2 from 1 GW coal power plant?"***

How much space do we need to fix CO_2 from 0.8 GW coal power plant? Is it feasible to use cyanobacteria or algae for the job?

ca. 10x10 km



Why "Bioenergy"?

- *Limited known reserves: oil supply for 41 years, gas for 64 years, coal 155 years*

- *Dependence on oil imports from politically unstable regions*

- *Problems of the new renewables: high cost, low capacity*

Why "CO2 sequestration"?

- *Environmental concerns*

Why Bio-Energy from Algae and Cyanobacteria?

Existing biodiesel sources compared with potential of microalgae

CROP	***Corn***	***Soybean***	***Canola***	***Jatropha***	***Coconut***	***Oil palm***	***Microalgae***	***Microalgae***
OIL YIELD (l/ha)	*172*	*446*	*1190*	*1892*	*2689*	*5950*	*136900*	*58700*

70% and 30% oil in wet biomass

(from Y.Chisti (2007) Biodiesel from microalgae. Biotechnology Advances 25: 294-306)

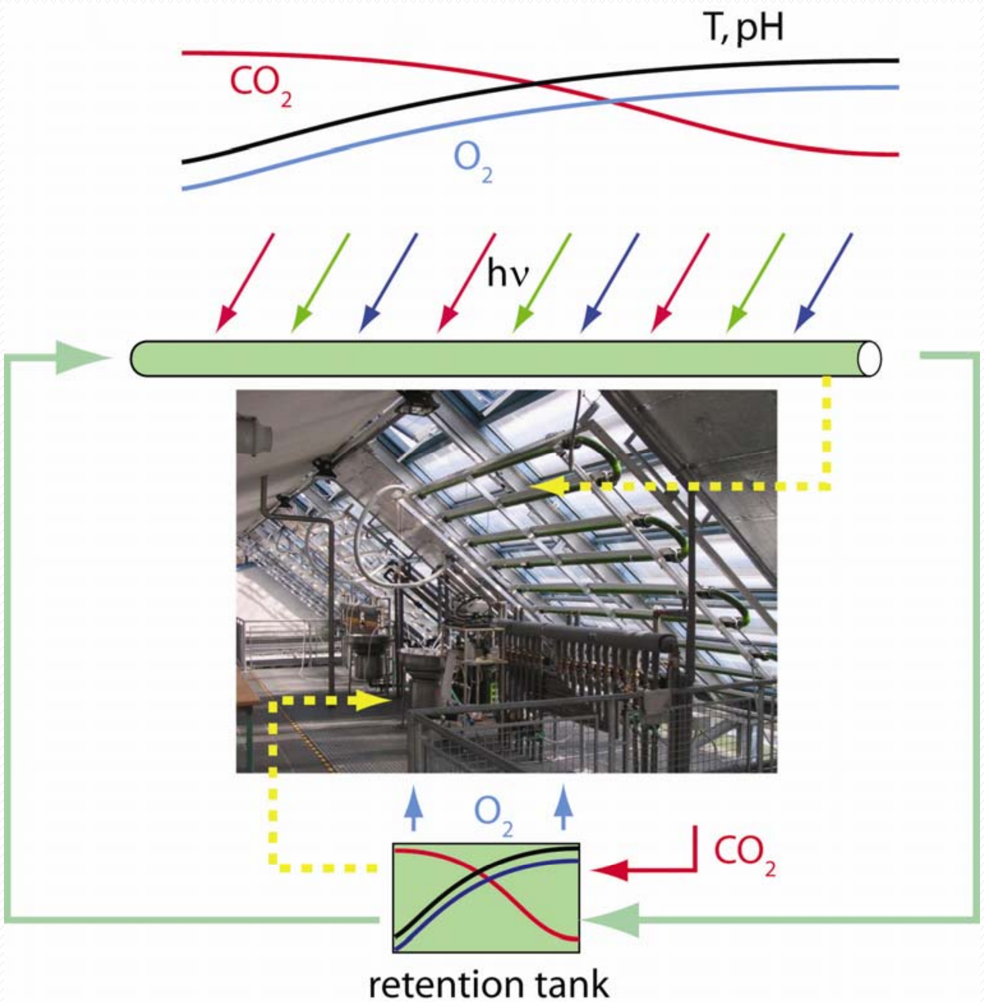
Which Organisms? Some Candidates:

Alga	Oil content (% DW)
Botryococcus braunii	25-75
Chlorella sp.	28-32
Cryptocodinium cohnii	20
Cylindrotheca sp.	16-37
Dunaliella primolecta	23
Isochrysis sp.	25-33
Monallanthus salina	>20
Nannochloris sp.	20-35
Nannochloropsis sp.	31-68
Neochloris oleoabundans	35-54
Nitzschia sp.	45-47
Phaeodactylum tricornutum	20-30
Schizochytrium sp.	50-77
Tetraselmis sueica	15-23

Present closed-system technologies

Tubular bioreactor, Centre of biological technologies UFB JčU
Nové Hrady, CZ

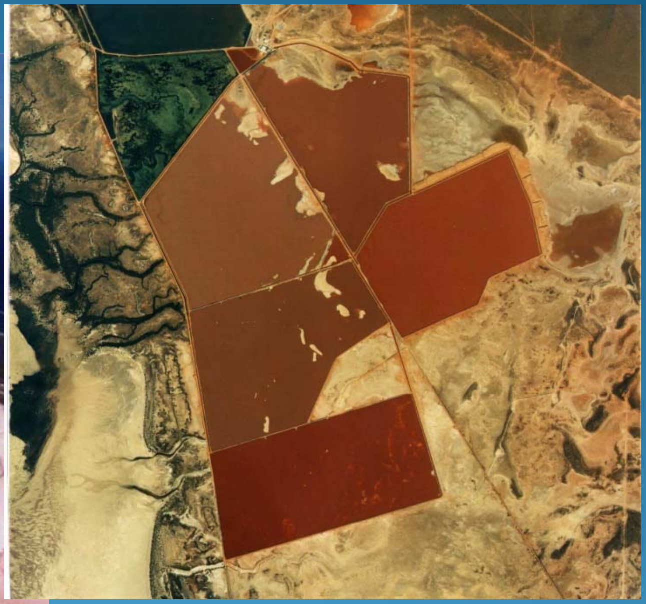
Closed Photobioreactor Features



+ clean culture
+ low evaporation
+ low CO2 escape
+ high density / low harvesting cost

- high capital cost
- high cleaning cost
- up T, up O_2

Present open-system technologies



Geography

Region	SW USA		NE USA		UK	
Lipid content	0.5	0.33	0.5	0.33	0.5	0.33
Biodiesel, gal/m^2/year	1.24	0.82	1.06	0.71	0.77	0.52

With yields ≈ 1-2 gal(oil) / m^2 / year and oil price < \$3 / gal:
the capital cost depreciation < several \$ / year

Open system	*Closed system*
- contamination	*+ clean culture*
- high evaporation	*+ low evaporation*
- CO_2 escape	*+ low CO_2 escape*
- low density / high harvesting cost	*+ high density / low harvesting cost*
+ low capital cost	*- high capital cost*
+ low cleaning cost	*- cleaning cost*
+ T, O_2 conservative	*- up T, up O_2*

YIELD LIMITS (€, kg, l / m^2· year) ??

Yields

Arguments, estimates:

- *{8 mol photons / 1 mol CO_2 fixed to (CH_2O); 1 mol CH_2O … 468 kJ; 1 mol mean PAR photons … 217 kJ}* → $\mathbf{Q_{theor}=0.27}$
- *Correction for photosynthetic efficiency, saturation & photoinhibition:* $\mathbf{Q_{ps\text{-}eff}=0.9}$ *(heat & fluorescence dissipation)*
- *Correction for photon reflection/scattering within the suspension:* $\mathbf{Q_{abs}=0.85}$
- *Correction for energy used to support essential cell functionalities, maintenance of cells:* $\mathbf{Q_{life}=0.85}$
- *Correction for bioreactor wall transmission:* $\mathbf{Q_{tr}=0.9}$
- *Correction for bioreactor wall reduced cleanliness:* $\mathbf{Q_{clean}=0.95}$
- *Correction for bioreactor selfshading:* $\mathbf{Q_{shade}=0.93}$
- *Correction for reflectance at various bioreactor-sunlight incident angles:* $\mathbf{Q_{refl}=0.88}$
- *Correction for bio-fuel harvesting and extraction:* $\mathbf{Q_{process}=0.98}$
- *Correction for bioreactor availability (-maintenance, defects):* $\mathbf{Q_{av}=0.98}$
- *Correction for technological execution (reliability, reproducibility…):* $\mathbf{Q_{tech}=1}$

Optimistic estimates …

Estimated total maximum efficiency: $\mathbf{Q_{total} = \prod Q_x \approx 0.1}$

Fraction of theoretical efficiency: $\mathbf{F = Q_{total} / Q_{theor} \approx 0.37}$

- $E_{biomass} = PAR \times Q_{total}$
- *PAR mean in USA: 80 - 90 W/m²*
- $E_{biomass} = 6.5 - 10.5\ W/m^2$ *… in the best locations*
- *Energy available for biodiesel production (lipid content): 0.33 – 0.5 on energy basis (0.15-0.25 on weight basis)*
- *For sugarcane* $F = Q_{total} / Q_{theor} \approx 0.037$ *(ten times less than the optimistic estimate for algae!)*
- *Terrestrial higher plants range max. 0.3-1* W/m^2

Geography constraints

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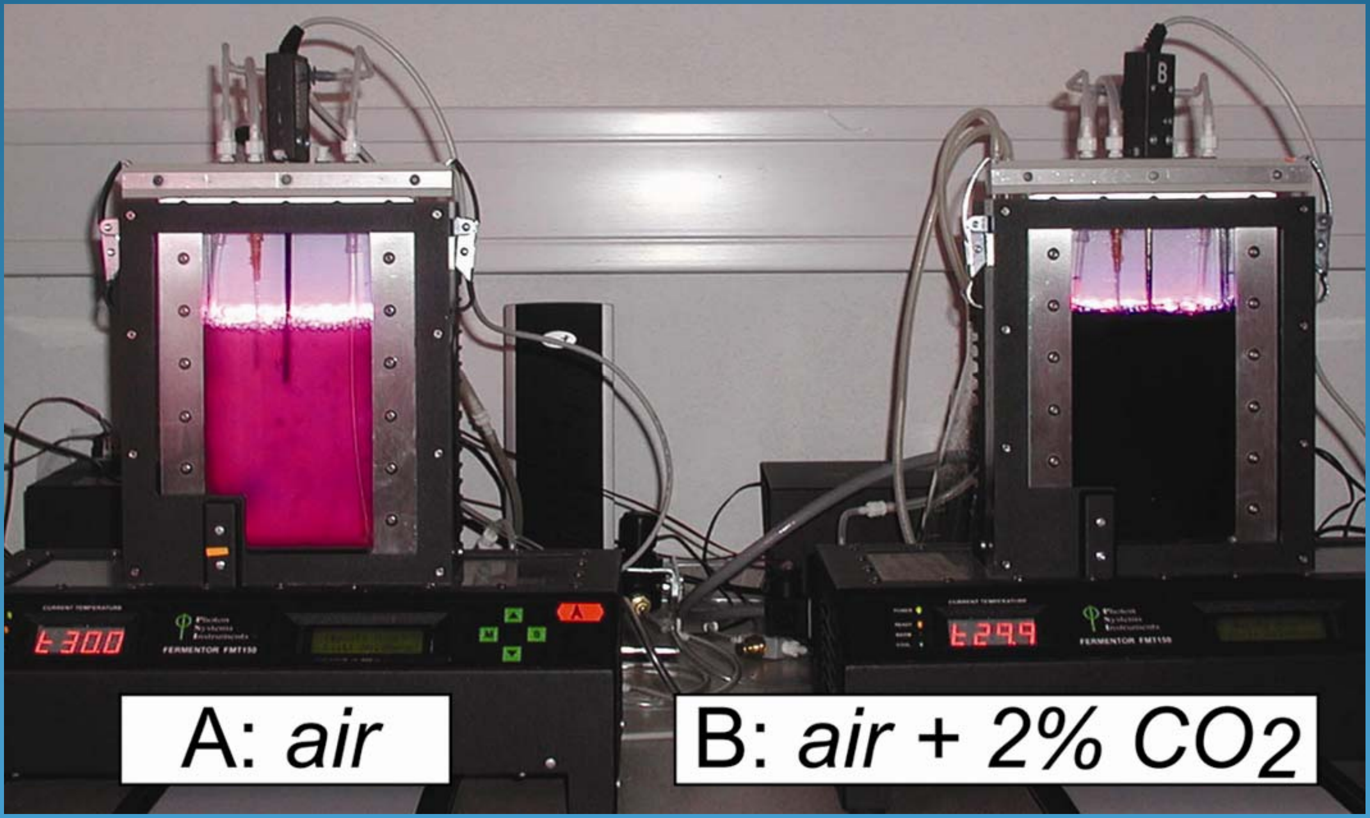
How to proceed?

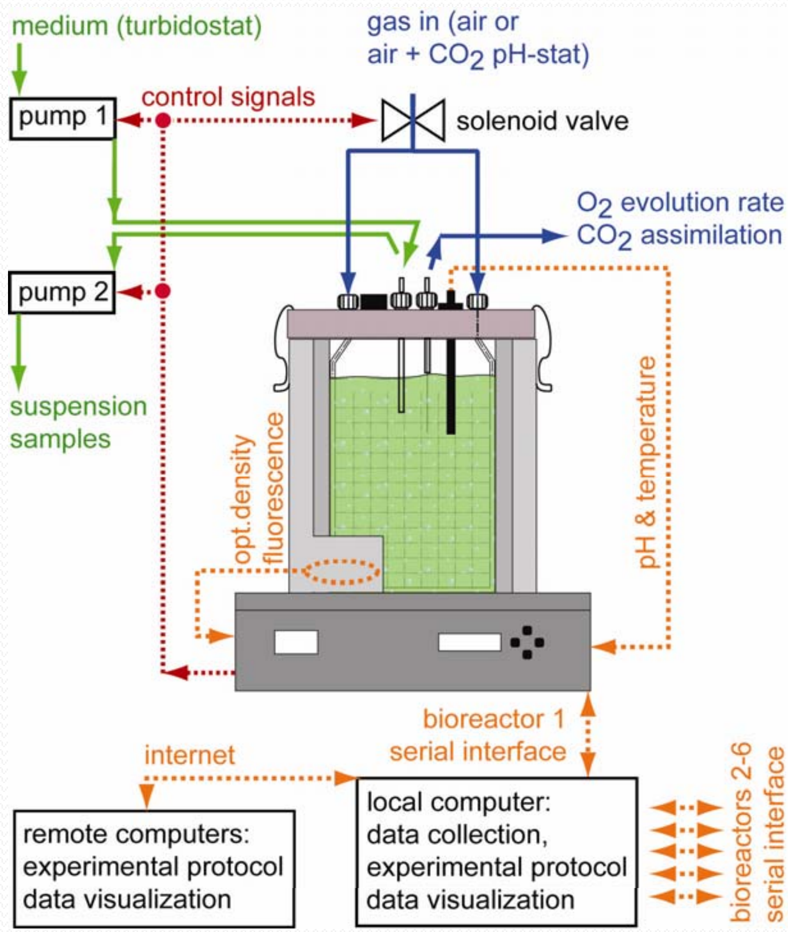
Talk with industry,
promise
Mbarrels of oil / year
… go (… for how long?)

Talk with smart industry,
identify bottlenecks,
ask and answer questions:
What organism?
What product?
What are the practical limits on yields?
What instruments do we need?
What models do we need?
… many other … work for success
coming earlier than your investor
becomes disappointed …

Experimental Tools

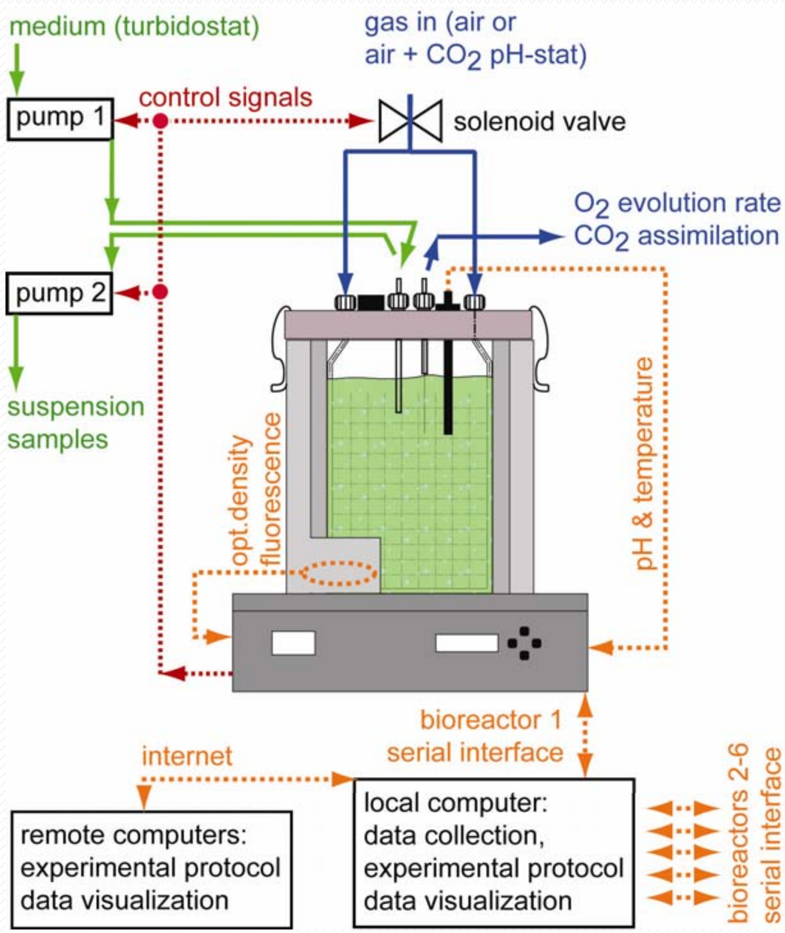


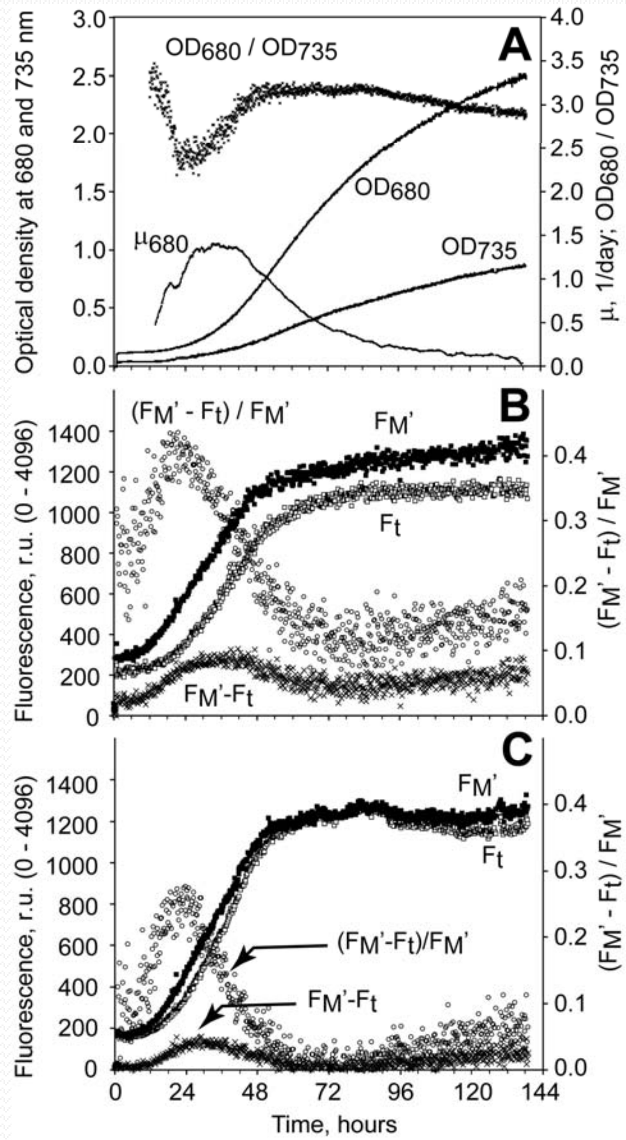
Screening / optimizing in a battery of small bioreactors



Nedbal et al. (2008) Biotech.Bioeng. DOI 10.1002/bit.21833

Some of the output signals





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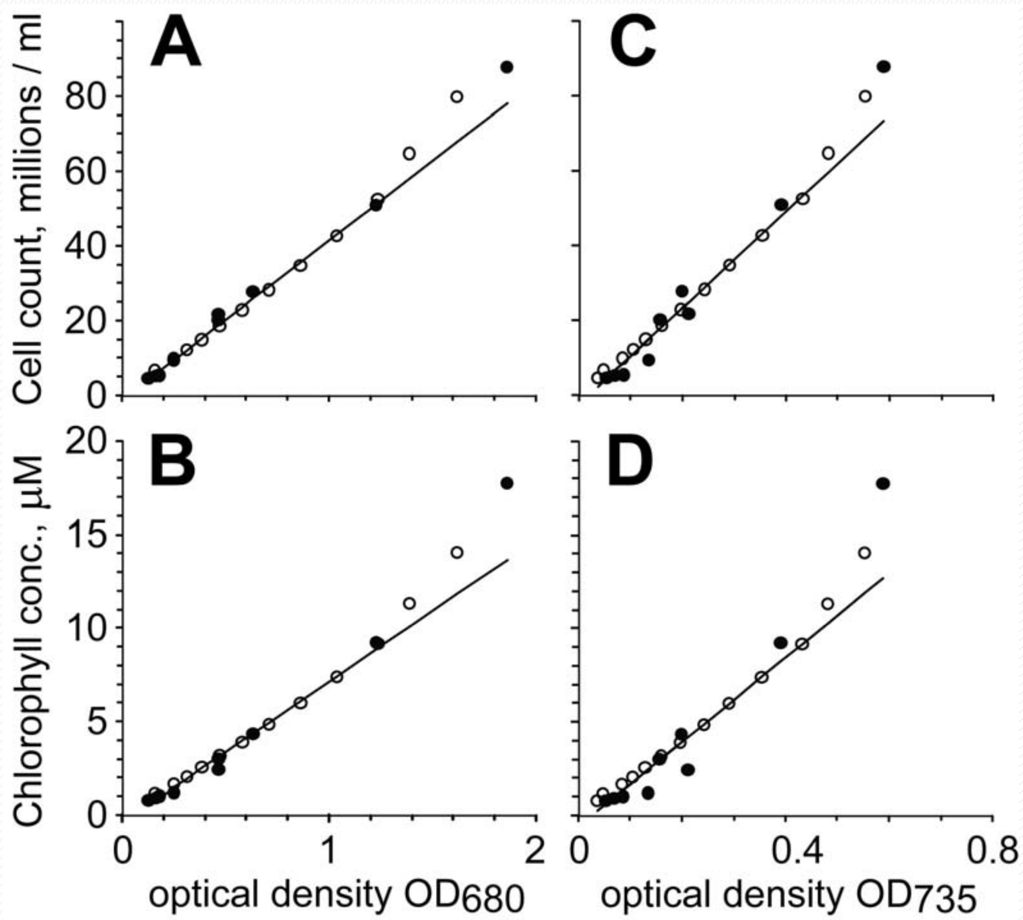
Linearity



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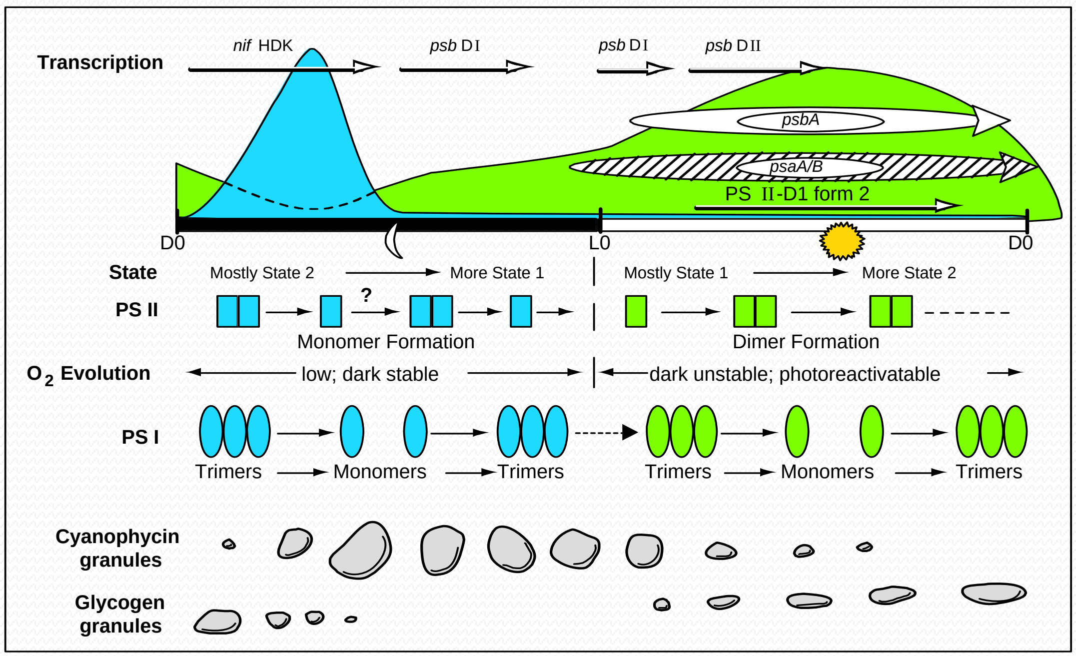
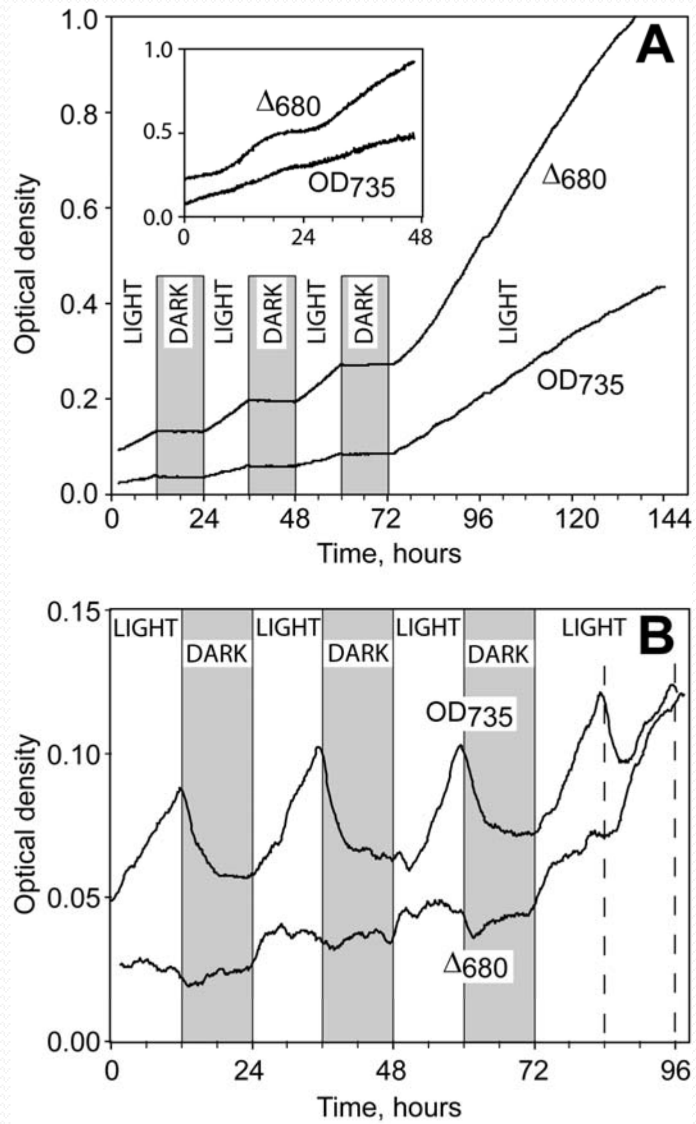
Sensitivity

Metabolic Rhythms in *Cyanothece* 51142





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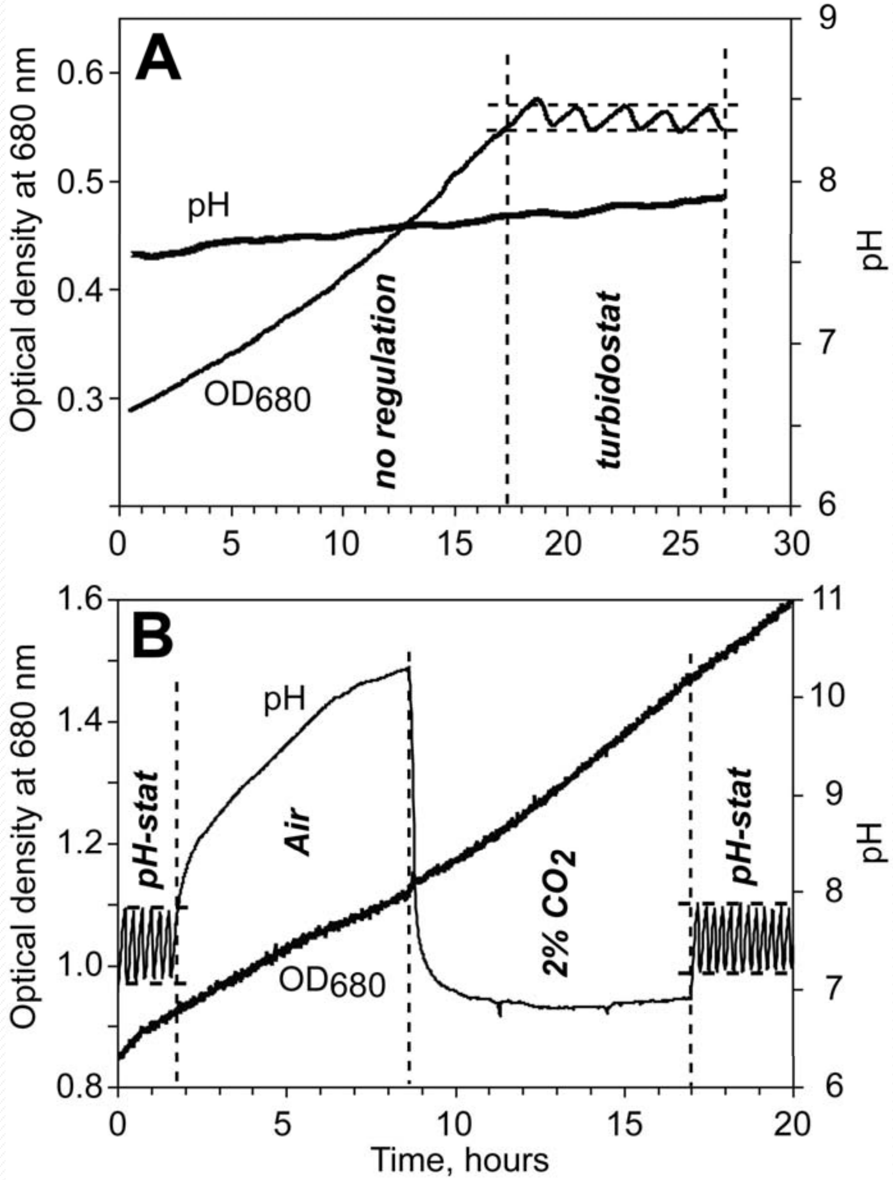
Turbidostat & pH stat



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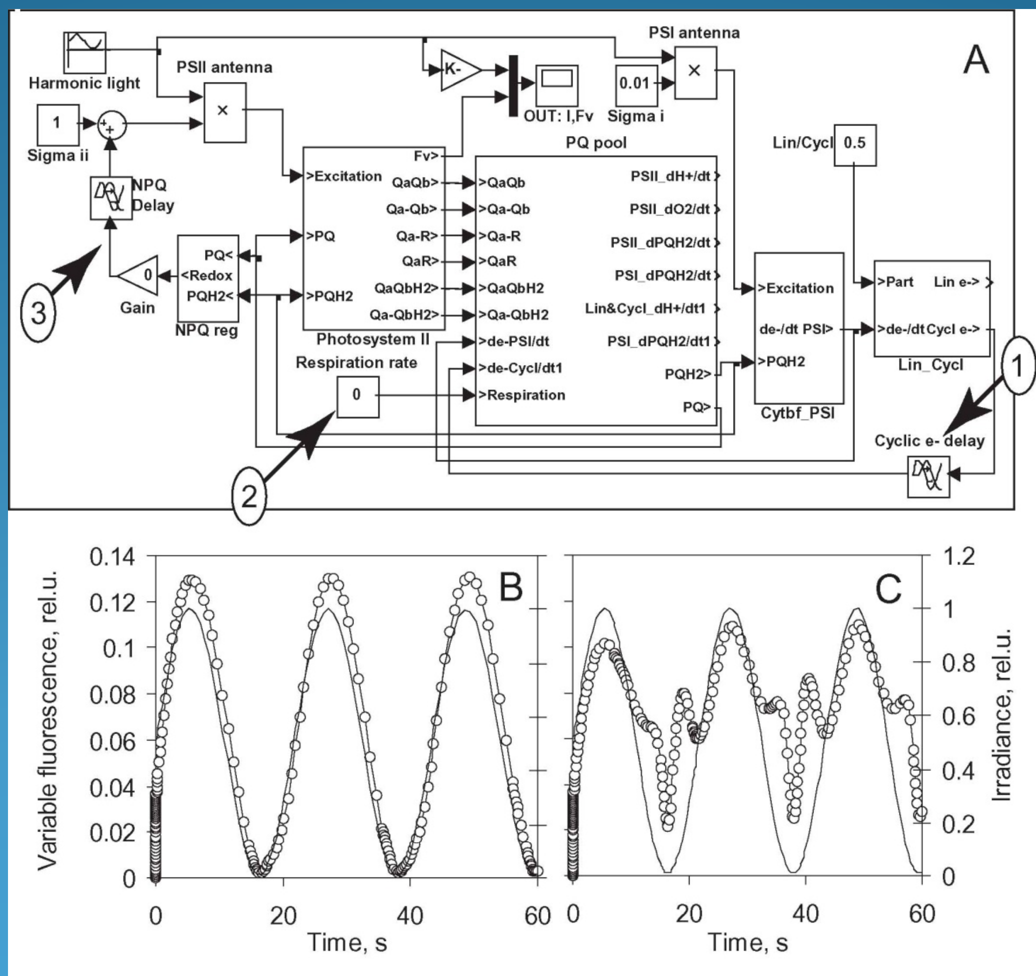
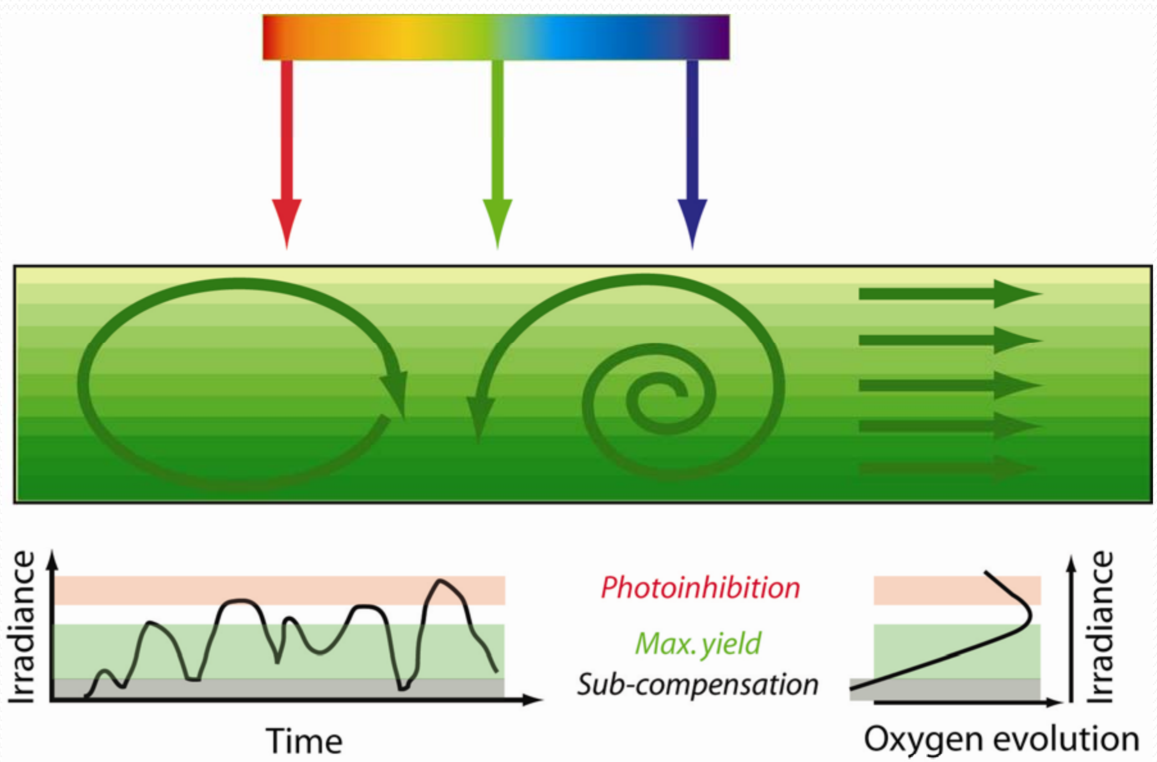
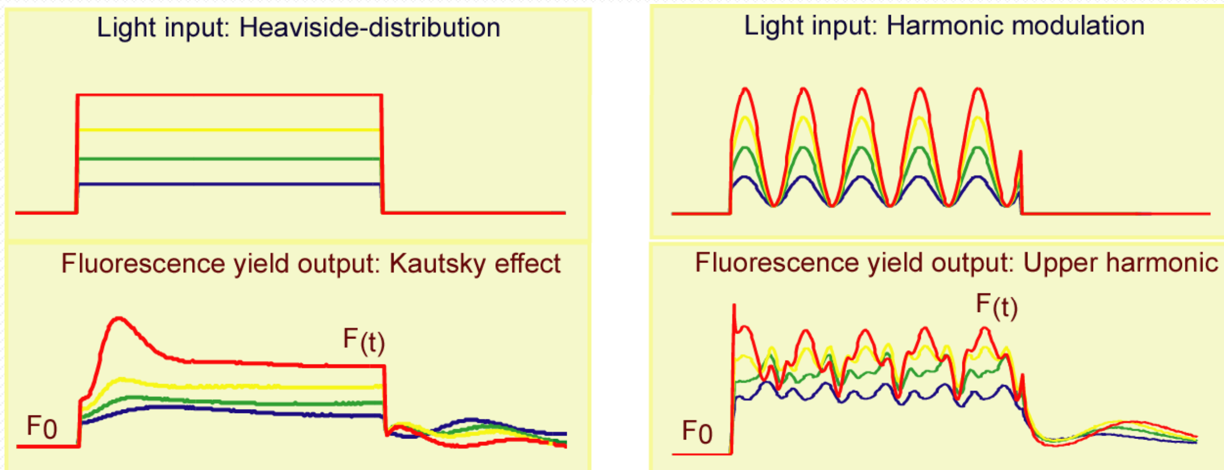
Modeling Tools

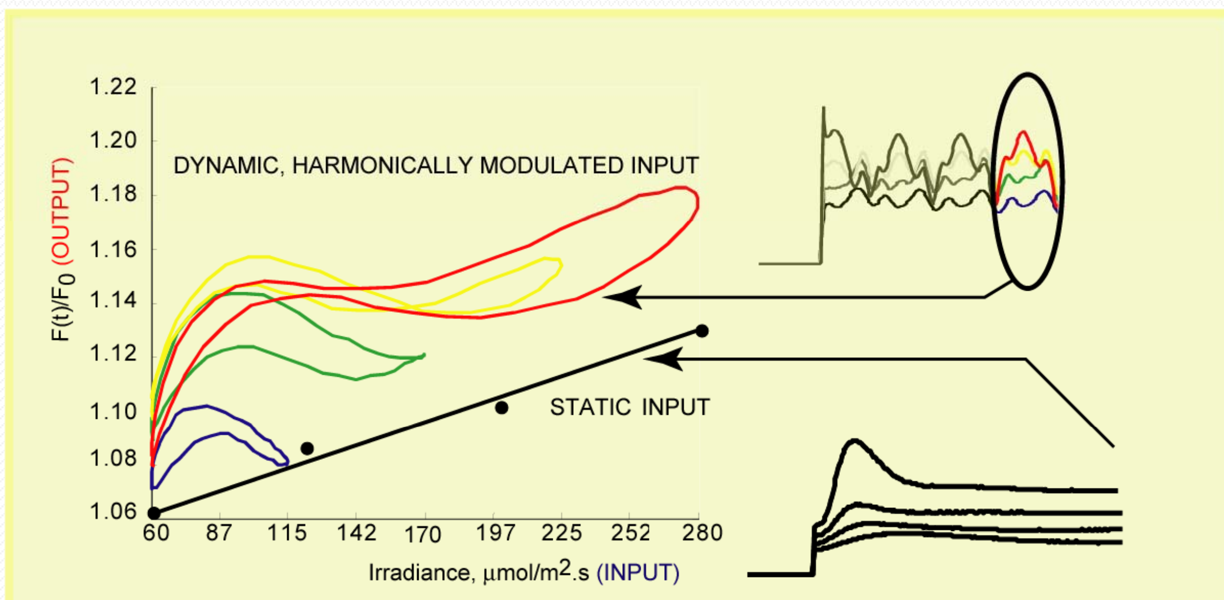


Light Dynamics in Photobioreactors

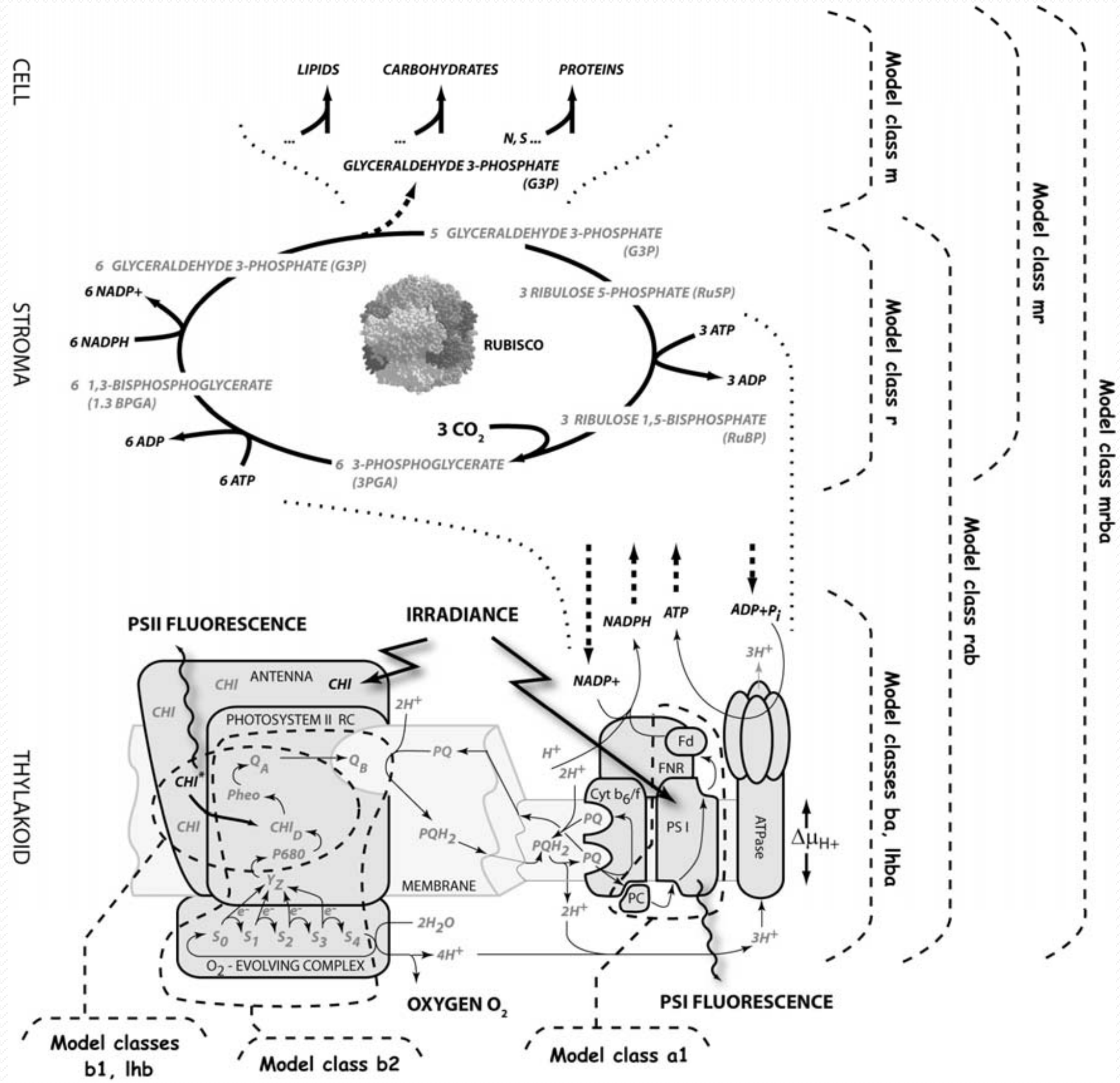


Non-linear response in dynamic light

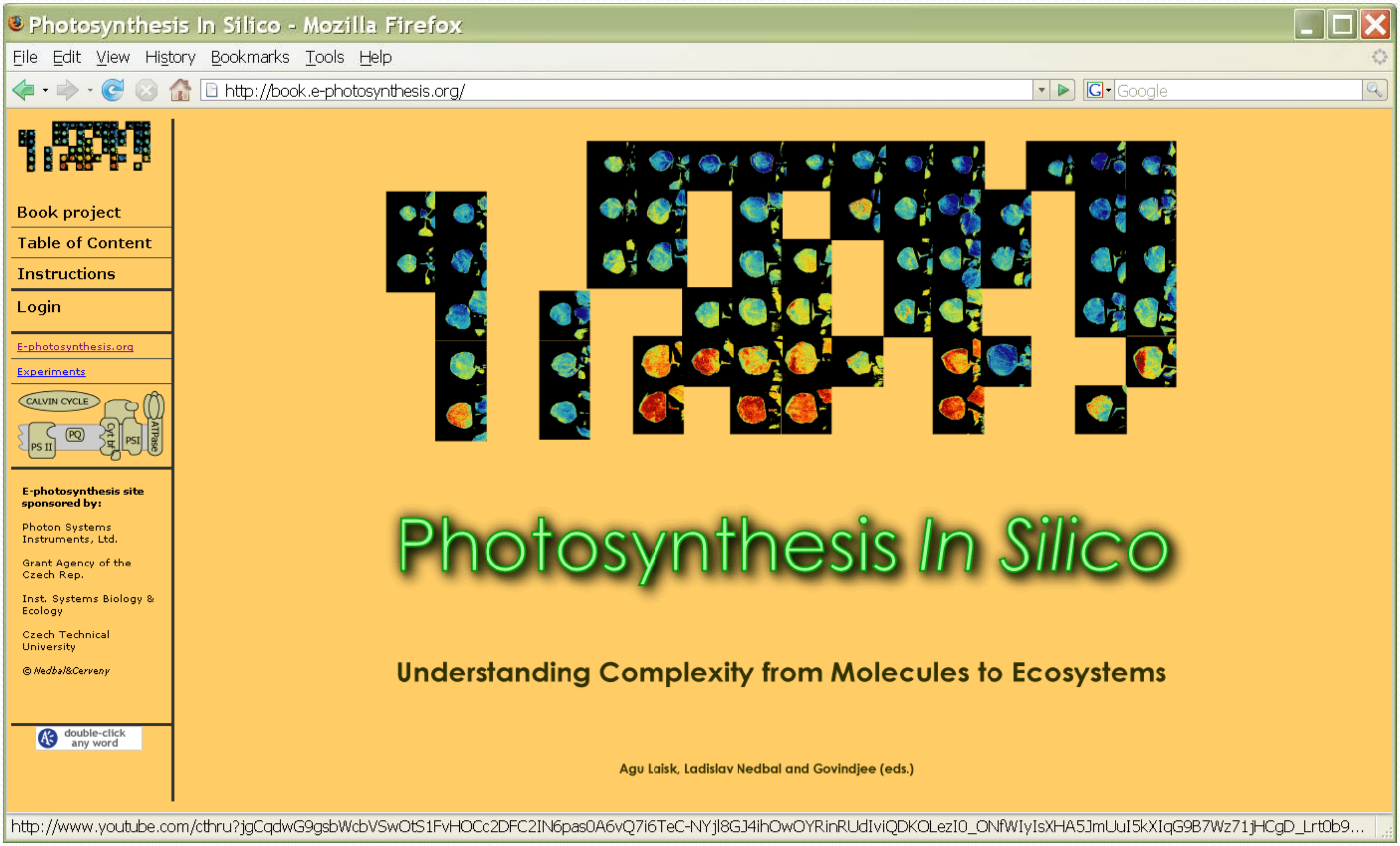




Comprehensive modeling space, SBML, MIRIAM



…. soon to be continued



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and offering external contracts to universities and companies.

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