Photosynthetic Energy Capture, Conversion, and Storage: From Fundamental Mechanisms to Modular Engineering

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MICHIGAN STATE UNIVERSITY | Department of Energy Plant Research Laboratory

About

- Over 55 years of collaboration between PRL and DOE
- Top notch fundamental research
- Educating future scientists to face 21st century global challenges
- Cutting edge technologies for long-term ‘green’ solutions (food, energy)

PRL // 56 Year History

- Contract between AEC and MSU on March 6, 1964:

  "…to conduct a **comprehensive, interdisciplinary research and related education and training program in plant sciences** with the principal emphasis being the development of an understanding of **how higher plants function as whole organisms, both as individuals and as populations in an environment**…"

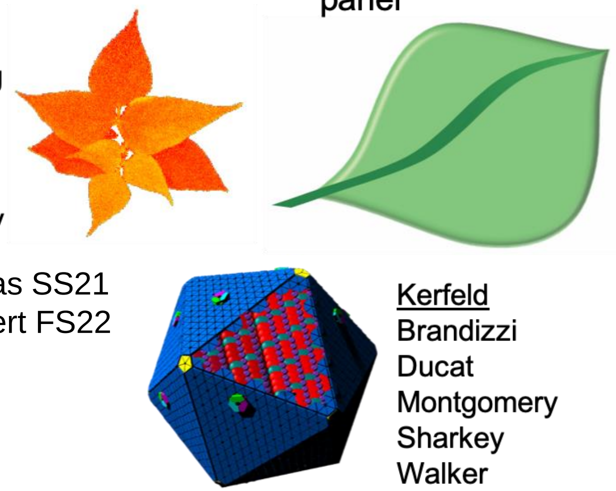
PRL // Structure

Faculty

- Annual appointments
- 12 tenure track positions
- Appointments in tenure granting academic departments
- 12-month salaries covered by MSU (exception, director)

Project Structure

- Three Subprojects
- Cross-pollination of expertise and labs

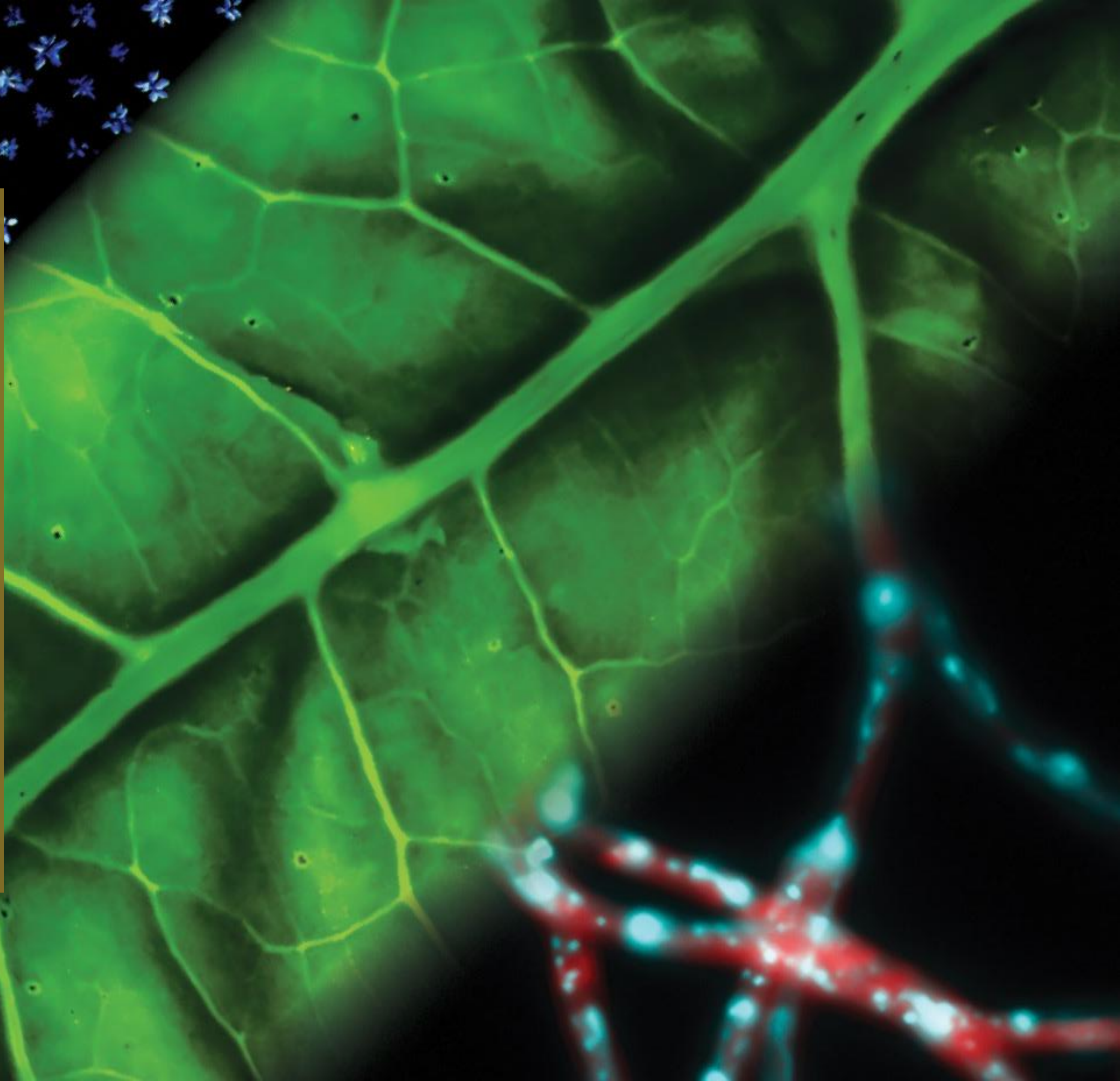


Goals and Expected Outcomes

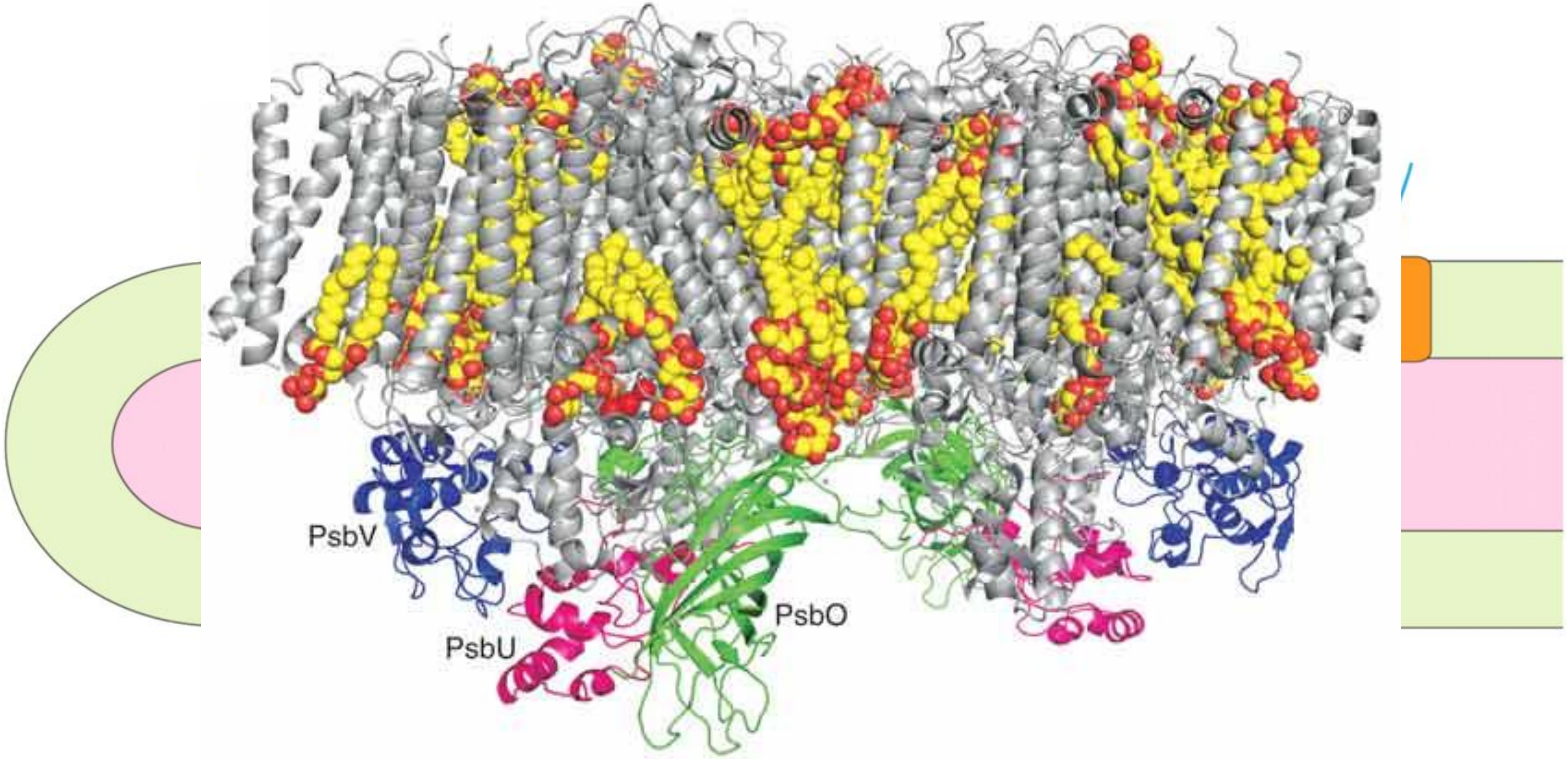
- Explore **photosynthetic processes at multiple scales** of biological organization
- Gain a comprehensive **understanding of "real life photosynthesis,"** i.e., its limitation and regulation under stochastic conditions in the natural environment and in response to environmental challenges
- Long term goal to **explore basic mechanisms of energy storage by oxygenic photosynthesis**, its use in the fixation of carbon, and directing it into energy storage and the building and maintenance of the biological solar panels themselves in cyanobacteria, algae, and plants

Gaining Multiscale Photosynthetic Knowledge Will Help:

- Improve photosynthetic efficiency and plant productivity
- Develop photosynthetic modules that can be recombined in novel ways to expand the production of photosynthesis-based bioproducts
- Develop more resilient plants to address climate change

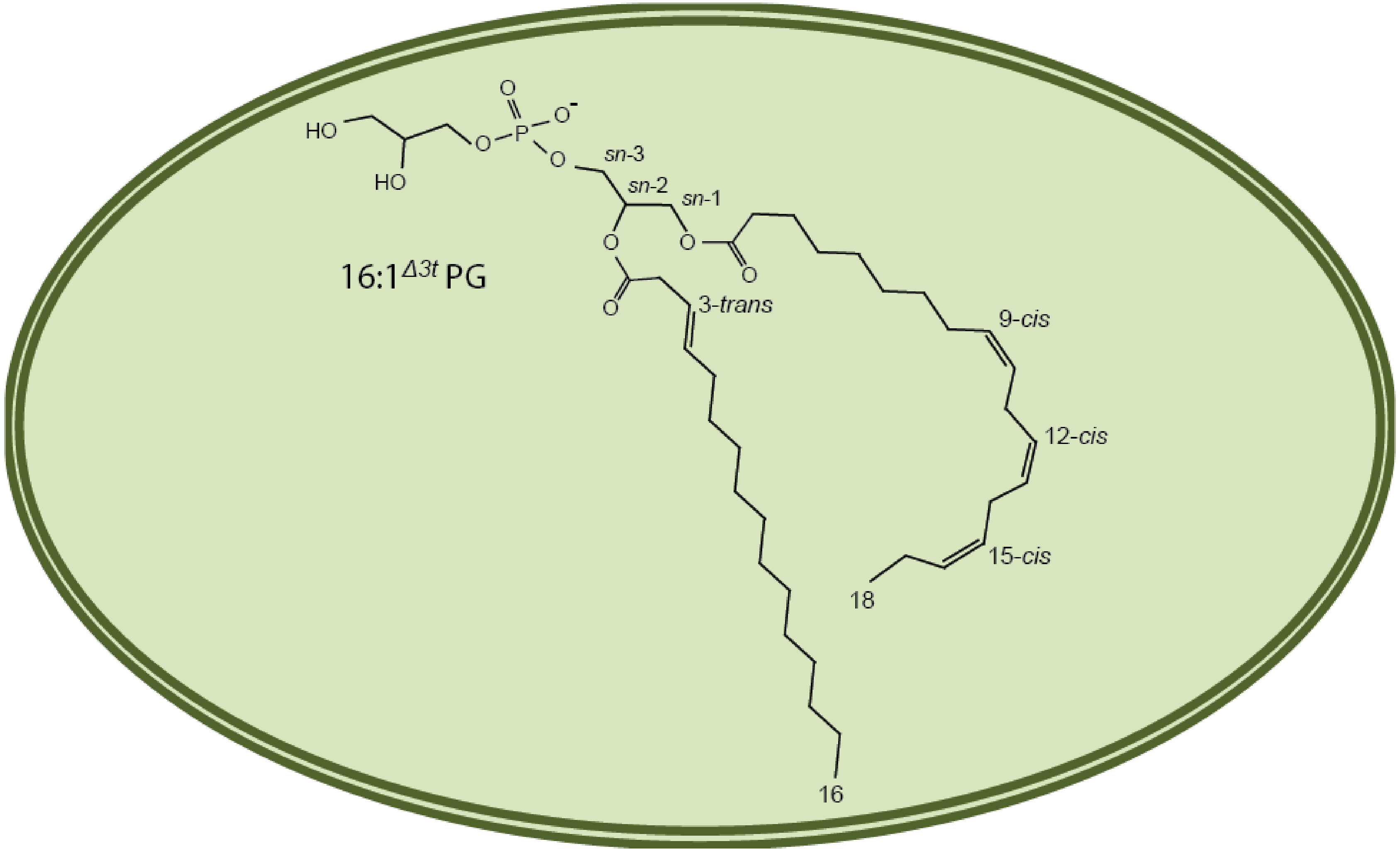


Example 1: The function of thylakoid lipids in photosynthesis under dynamic conditions

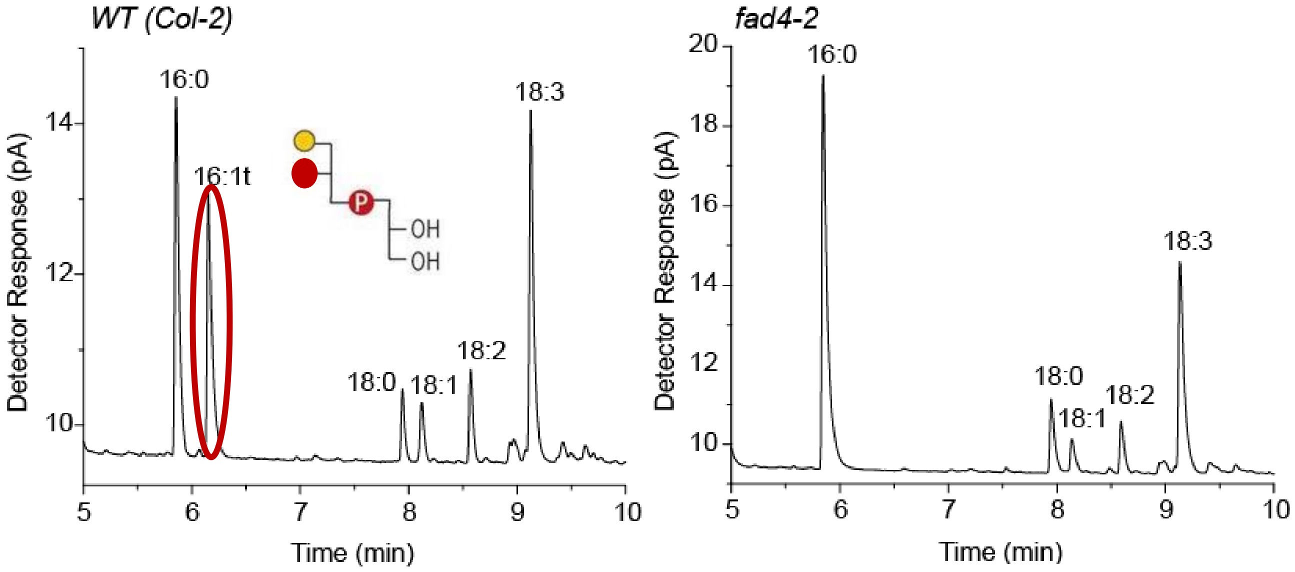


Guskov et. al. (2009) Nat. Struc. Mol. Biol. 16: 334-342

A phosphatidylglycerol (PG) specific to photosynthetic membranes: 16:1$^{\Delta 3t}$ PG



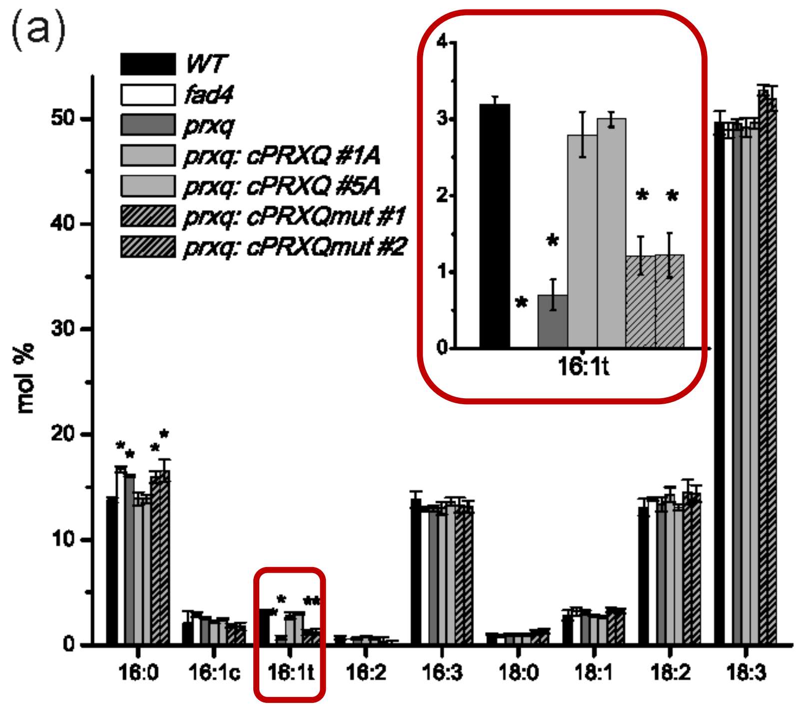
FAD4 is responsible for $16:1^{\Delta 3t}$ PG

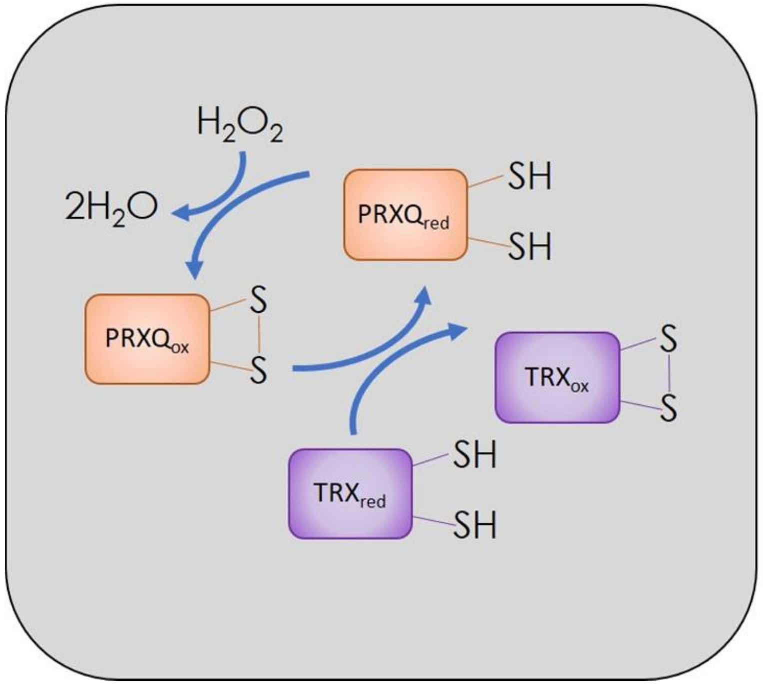


Patrick Horn

Browse J, McCourt P, Somerville CR. Science (1985) 227:763-5
Gao J, Ajjawi I, Manoli A, Sawin A, Xu C, Froehlich JE, Last RL, Benning C. Plant J. (2009). 60:832-9

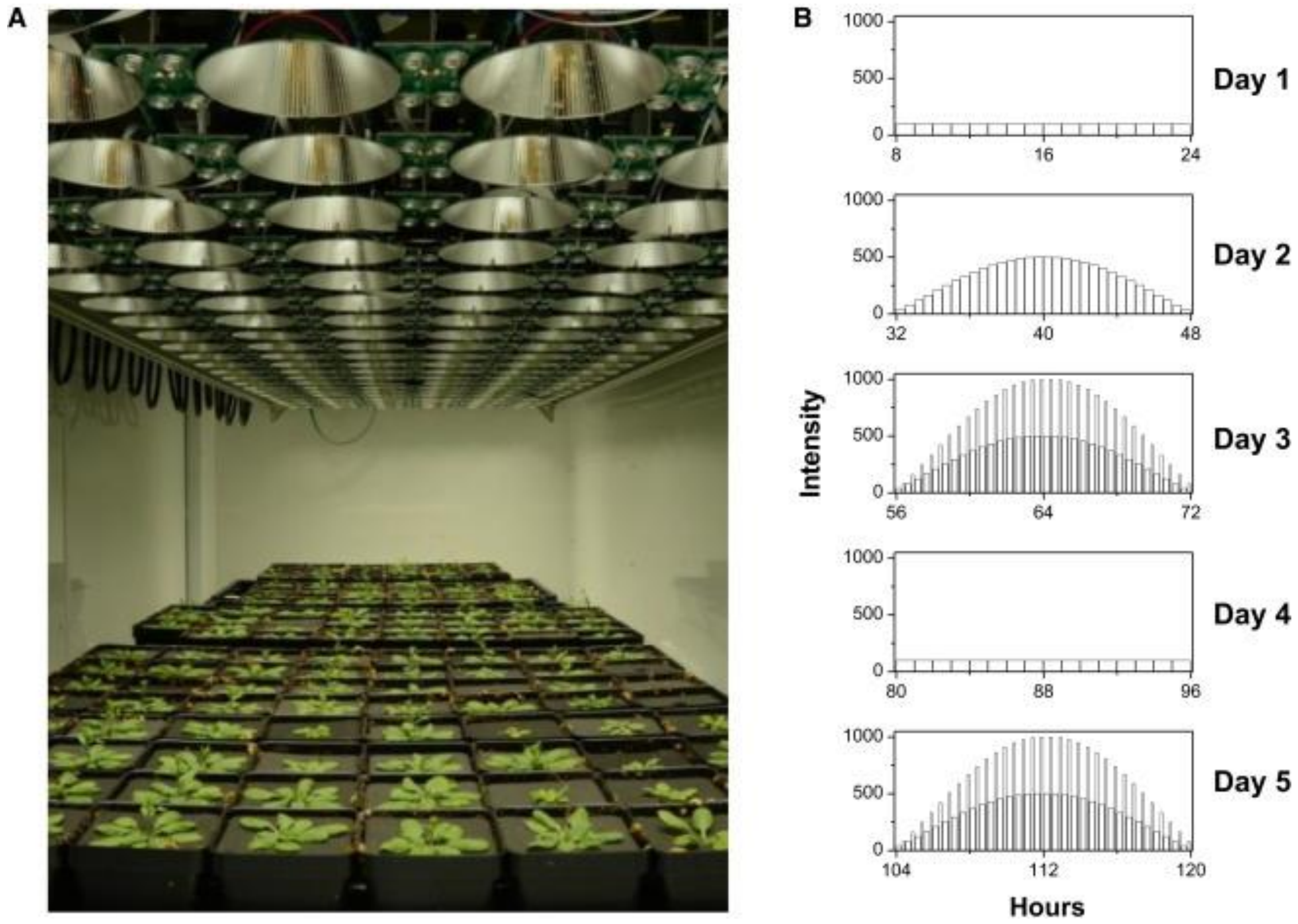
FAD4 requires a specific, redox active peroxiredoxin, PRXQ, for 16:1$^{\Delta 3t}$ PG synthesis





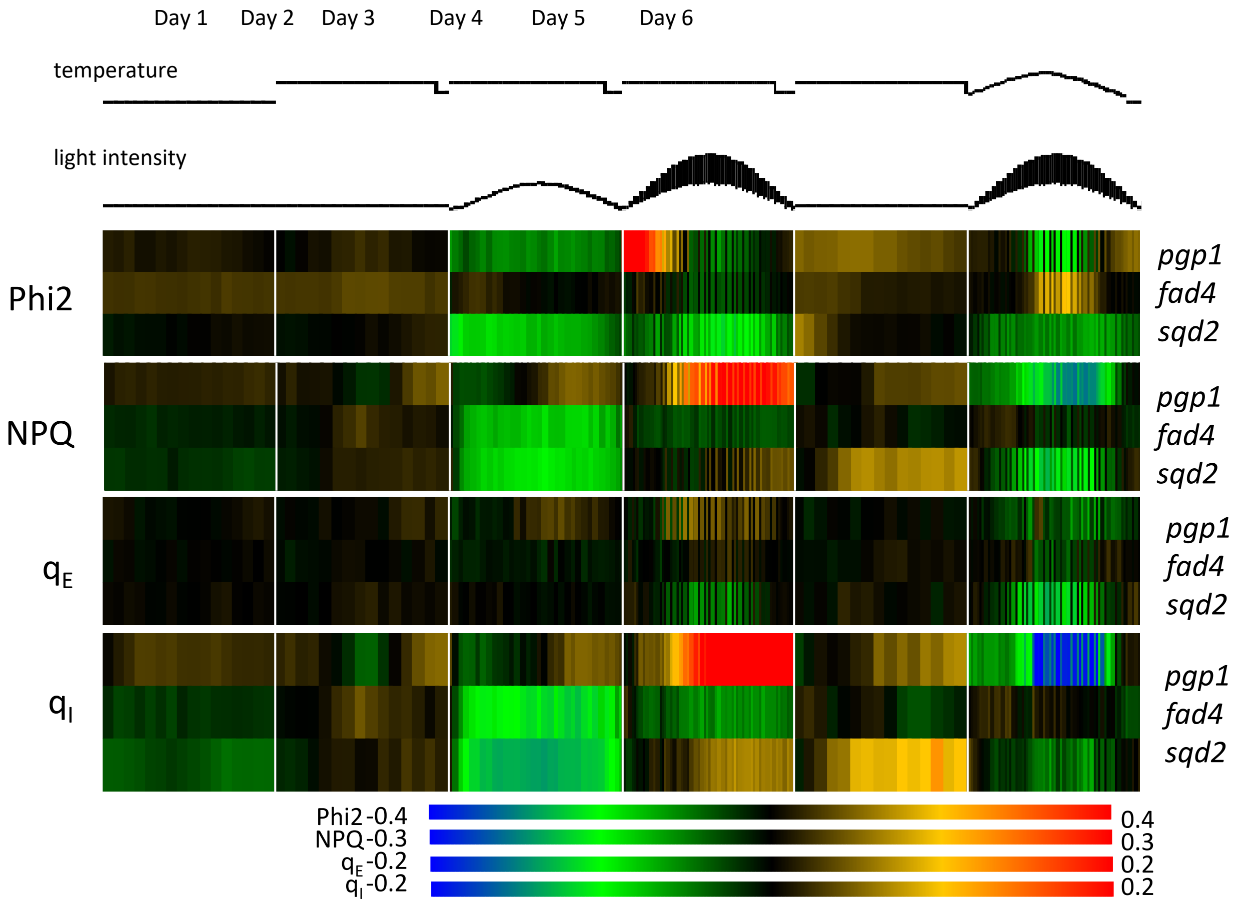
Patrick J. Horn, Montgomery D. Smith, Tessa R. Clark, John E. Froehlich, Christoph Benning (2019). Plant J. DOI: (10.1111/tpj.14657)

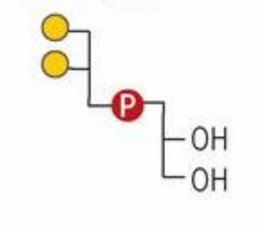
Probing the Function of Lipids in Photosynthesis through Phenomics



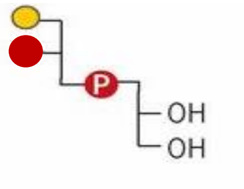
Cruz JA, Savage LJ, Zegarac R, Hall CC, Satoh-Cruz M, Davis GA, Kovac WK, Chen J, Kramer DM. Cell Syst. 2016, 2:365-77. doi: 10.1016/j.cels.2016.06.001.

What is the function of 16:1$^{\Delta 3t}$ PG in the photosynthetic membrane?

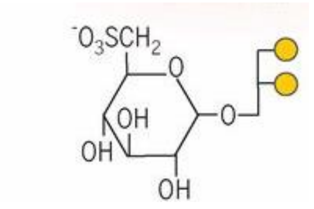




pgp1



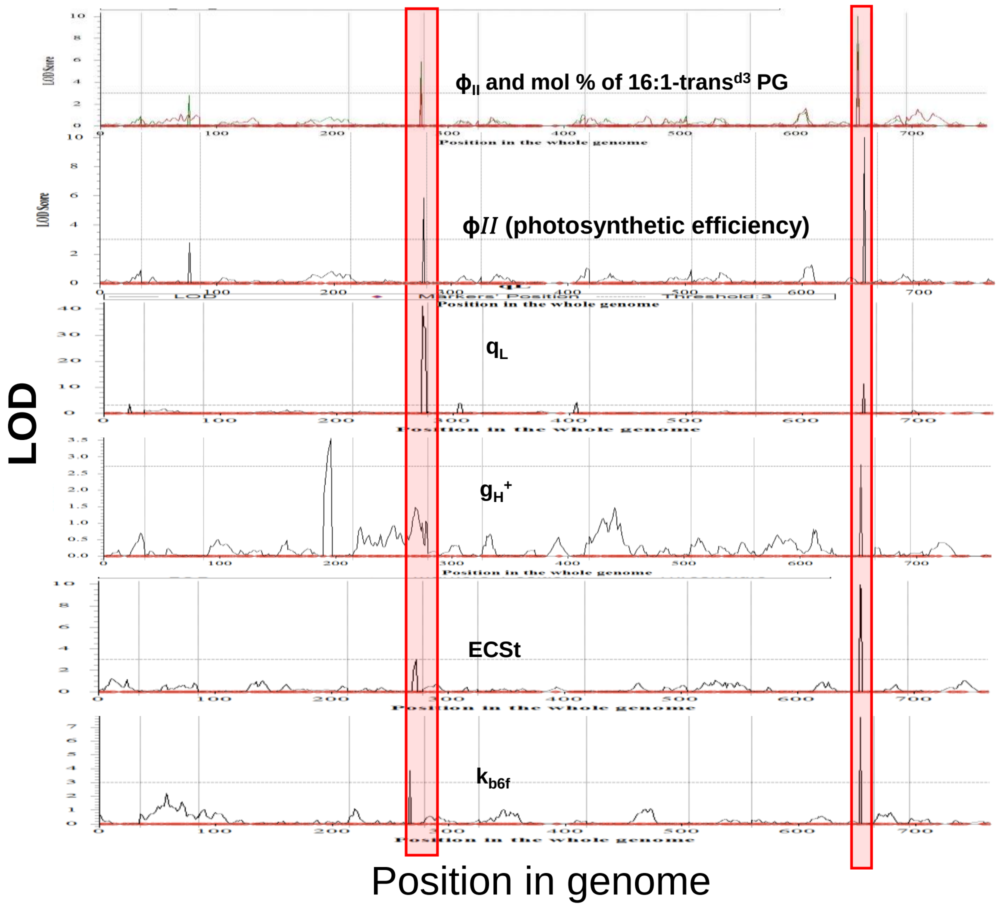
fad4



sqd2

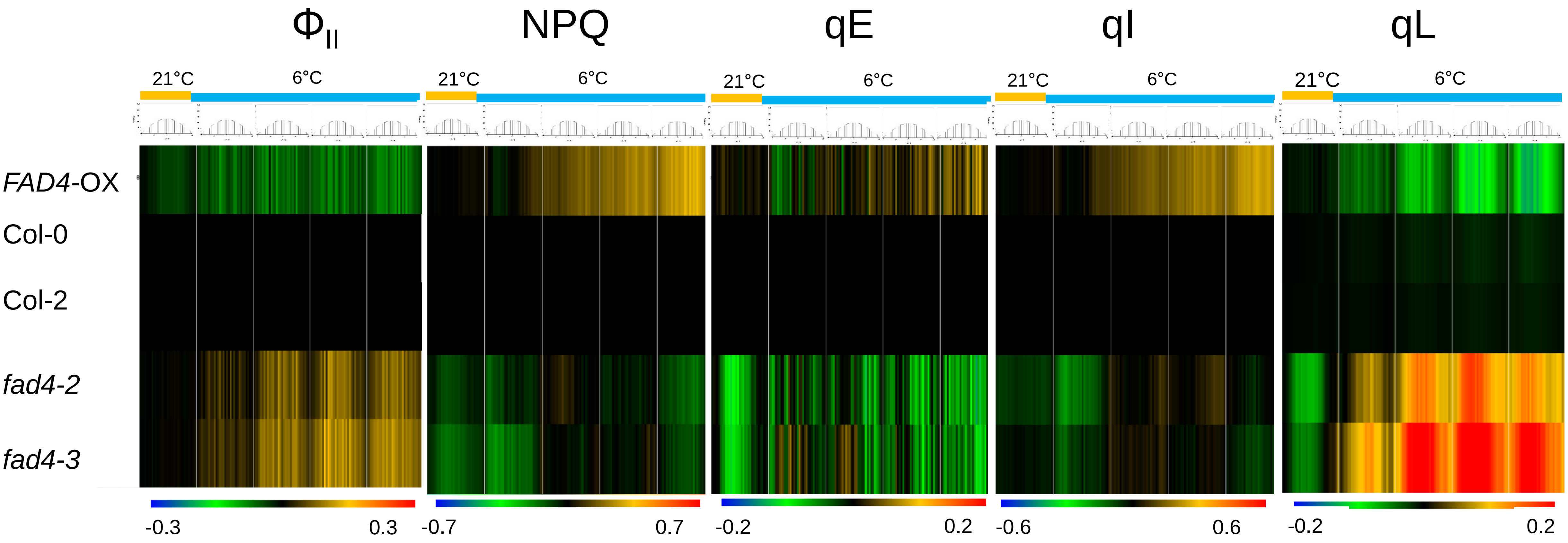
Lina Yin, Linda Savage, Jeff Cruz, Dave Kramer

Genetic linkage between a specific thylakoid lipid 16:1$^{\Delta 3t}$ PG and photosynthetic QTLs in Cow Pea RILs under low temperature



Donghee Hoh, Patrick J. Horn, Atsuko Kanazawa, John Froehilch, Jeffrey Cruz, Oliver L Tessmer, David Hall, Lina Yin, Christoph Benning and David M. Kramer

In the cold (6°C) 16:1$^{\Delta 3t}$ PG levels are inversely correlated with photosynthetic performance



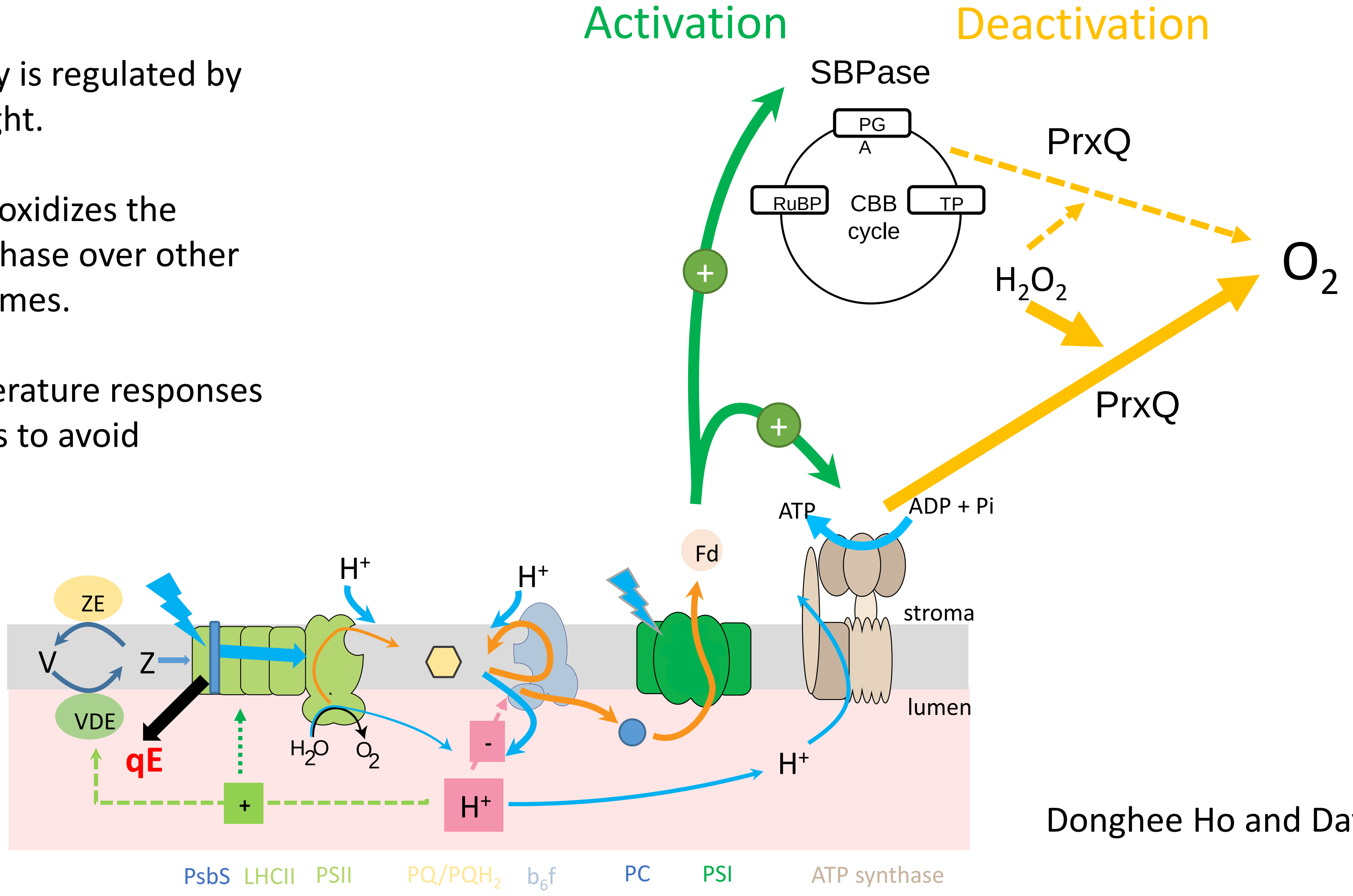
Donghee Hoh, Patrick J. Horn, Atsuko Kanazawa, John Froehilch, Jeffrey Cruz, Oliver L Tessmer, David Hall, Lina Yin, Christoph Benning and David M. Kramer

Redox Regulation of ATPC1ase subunit by PRXQ

ATP synthase activity is regulated by redox state in the light.

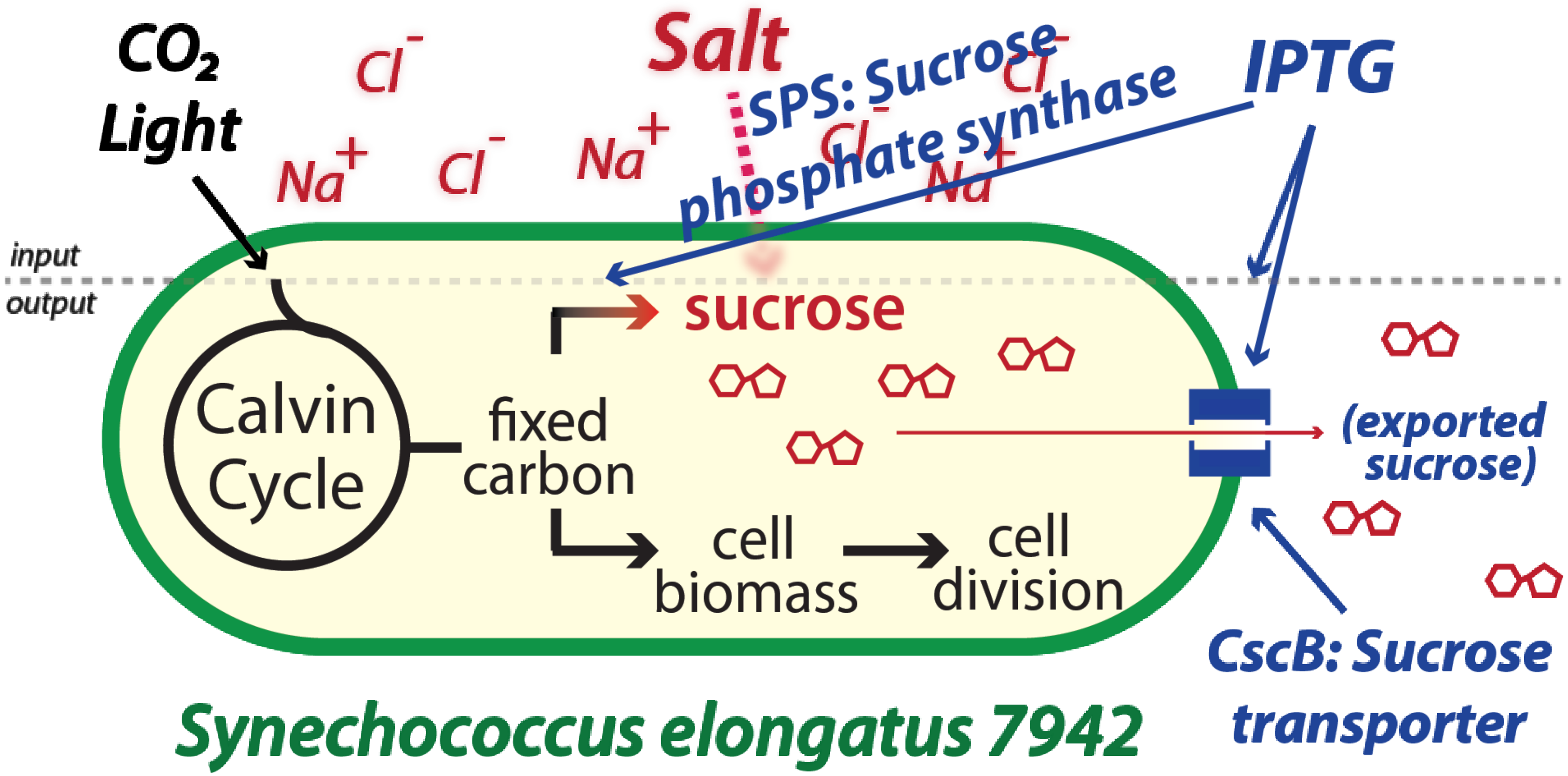
PRXQ preferentially oxidizes the chloroplast ATP synthase over other thiol-regulated enzymes.

Important for temperature responses of the light reactions to avoid photodamage.



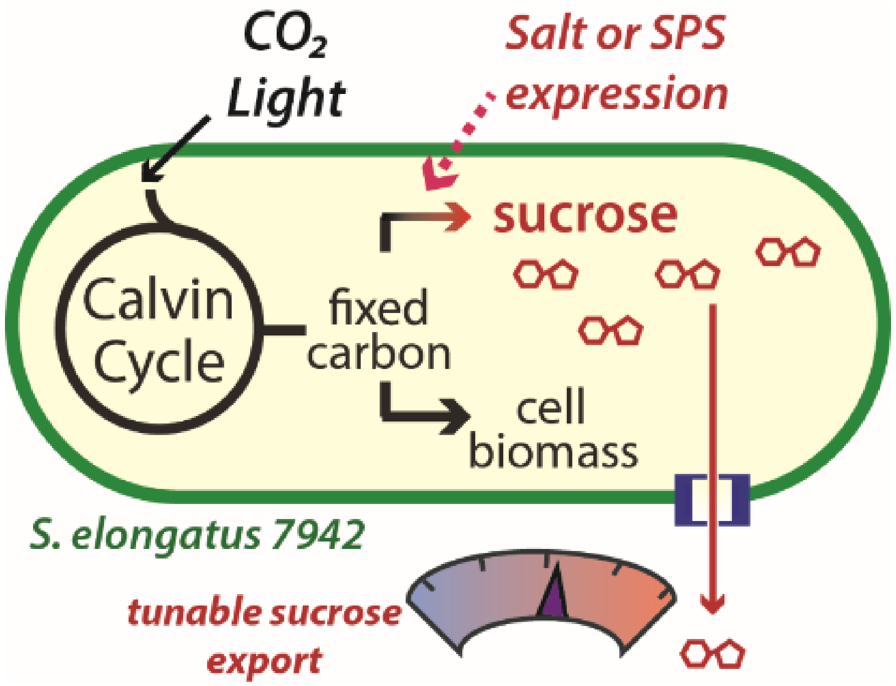
Donghee Ho and David Kramer

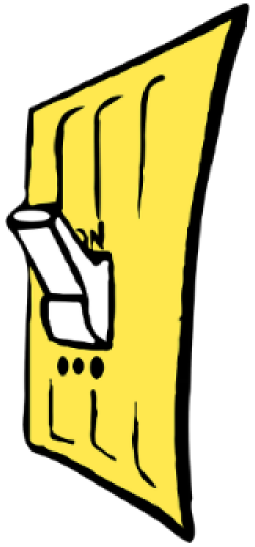
Example 2: Cyanobacterial model to study the effect of carbon partitioning on photosynthetic performance



Ducat, DC., et al. *Applied and environmental microbiology* 78.8 (2012).
Abramson BW, et al. *Plant Cell Phys*. (2016)

Key Features of Sucrose-Producing Strains

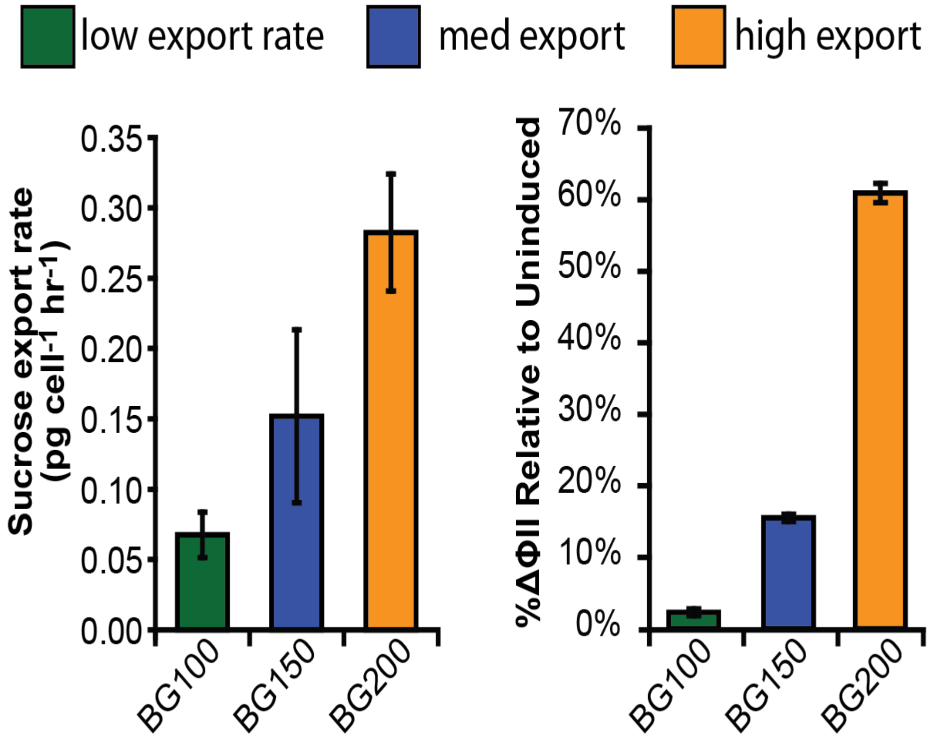




1. Sucrose output is high.

2. Sucrose export can represent a significant redirection of carbon resources away from endogenous metabolic sinks.

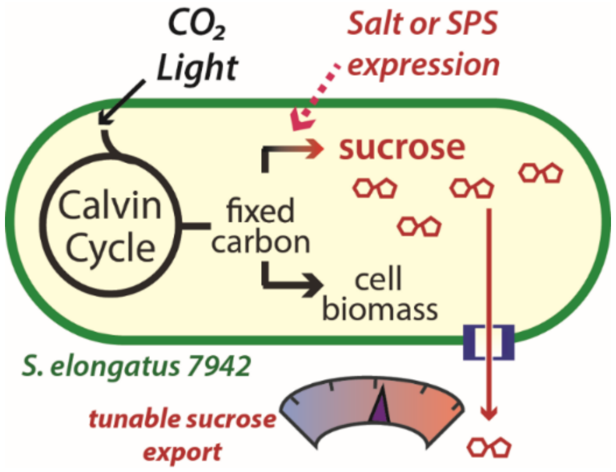
Induction of Sucrose Export

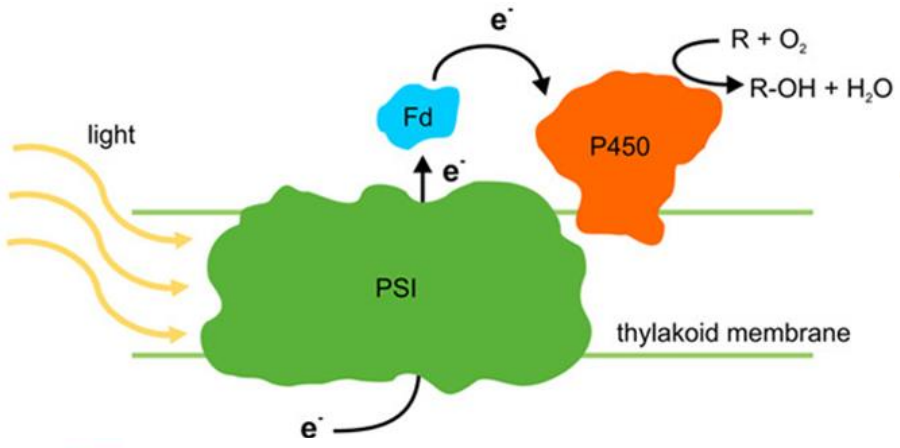


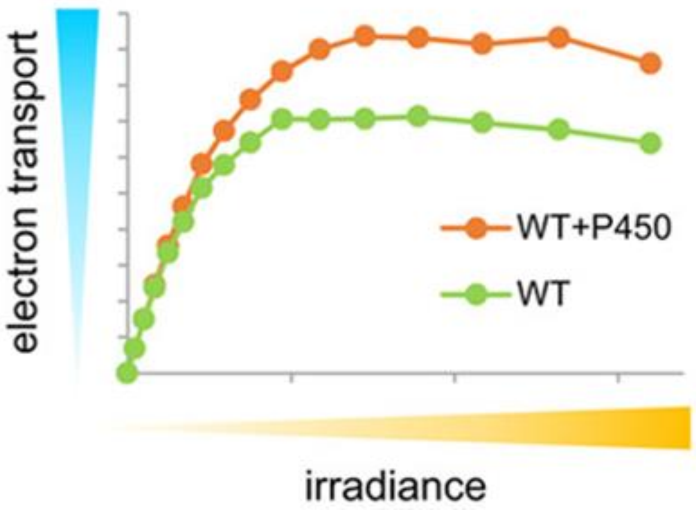
Up to 80% of fixed carbon can be rerouted to sucrose that is secreted.

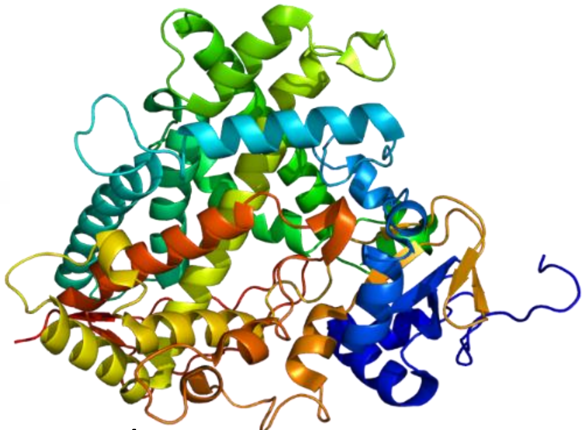
Ducat, DC., et al. *Applied and environmental microbiology* 78.8 (2012).
Xuan, Yuan Hu, et al. *PNAS* 110.39 (2013): E3685-E3694.
Abramson BW, et al. (2016) *Plant Cell Phys*.

Cyanobacteria with Two Engineered Metabolic Sinks Were Used to Examine Dissipative Capacity





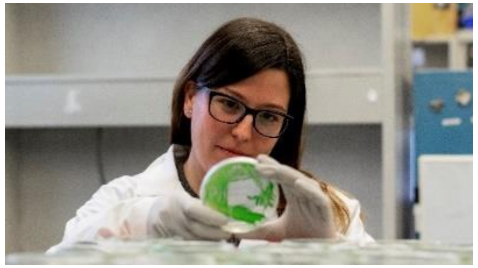




Cytochrome P450 – Cyp1A1

Tom Bibby

David Kramer



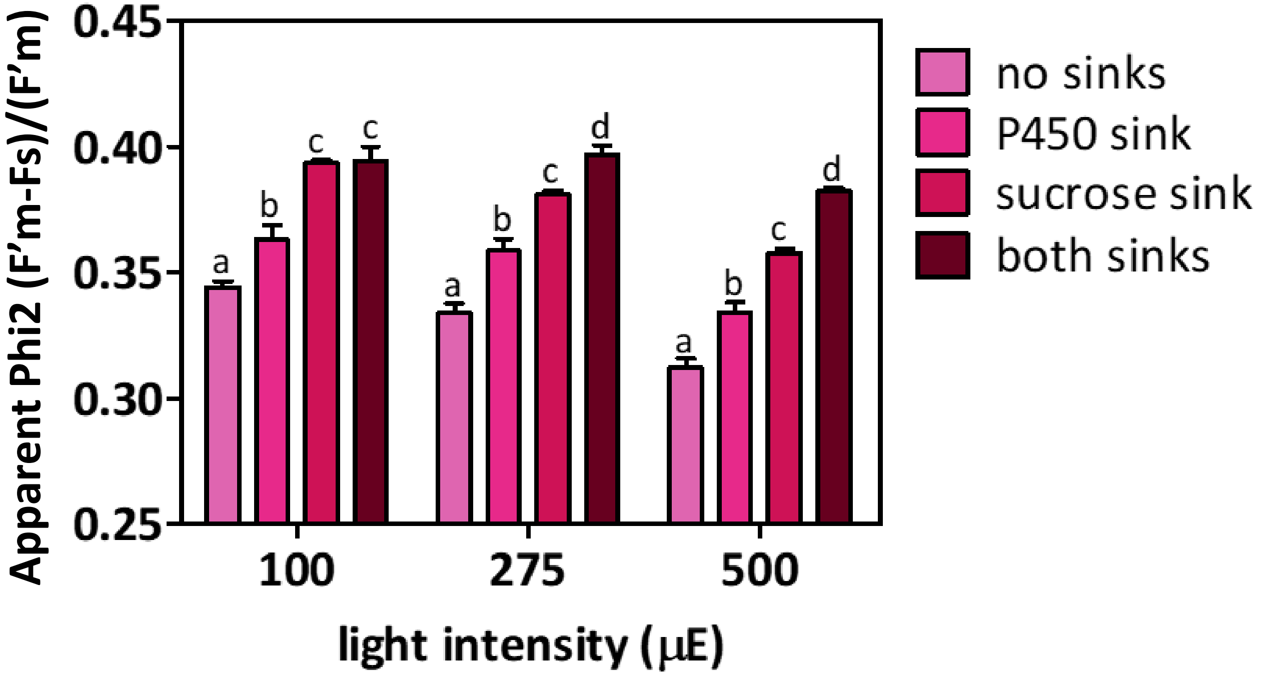
Maria Santos-Merino

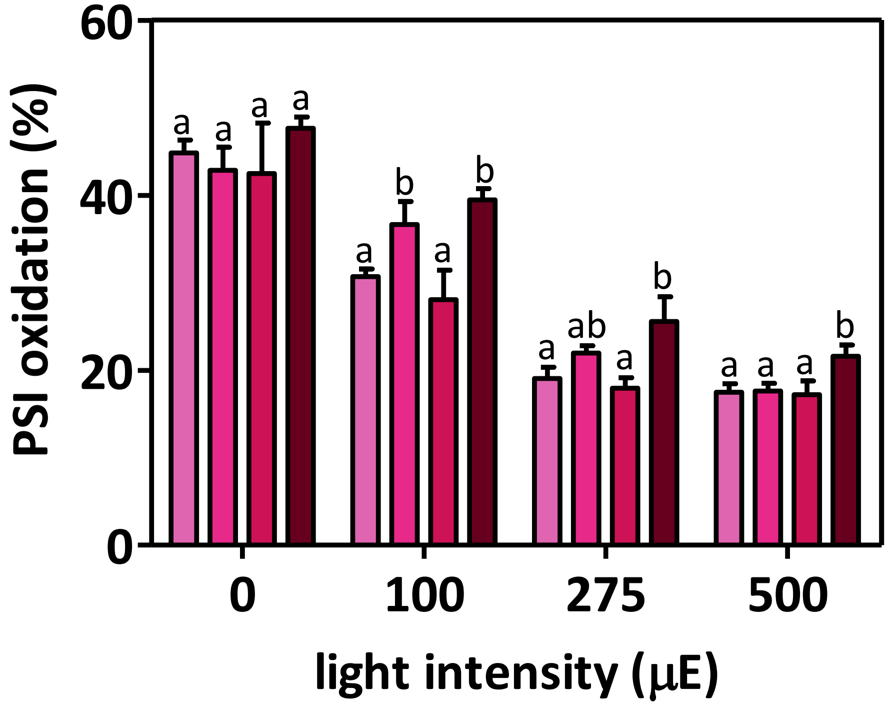
<u>**Driving Questions:**</u>

1) **Are the photosynthetic changes we observe consistent with relaxation of sink limitation?**
2) **Can more than one engineered sink further improve the photosynthetic performance?**

Abramson, BA., et al. *Plant and Cell Physiology* 57.12 (2016): 2451-2460.
Berepiki et al., 2016, *ACS Synth Biol.* 5(12):1369-1375.
Santos-Merino, María, et al. *PNAS* 118.11 (2021).

Additive Effects of Simultaneous Activation of Both P450 and Sucrose Metabolic Pathways

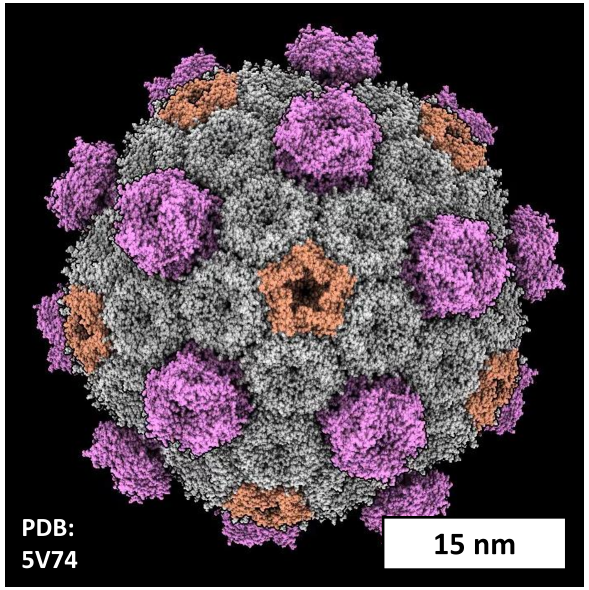




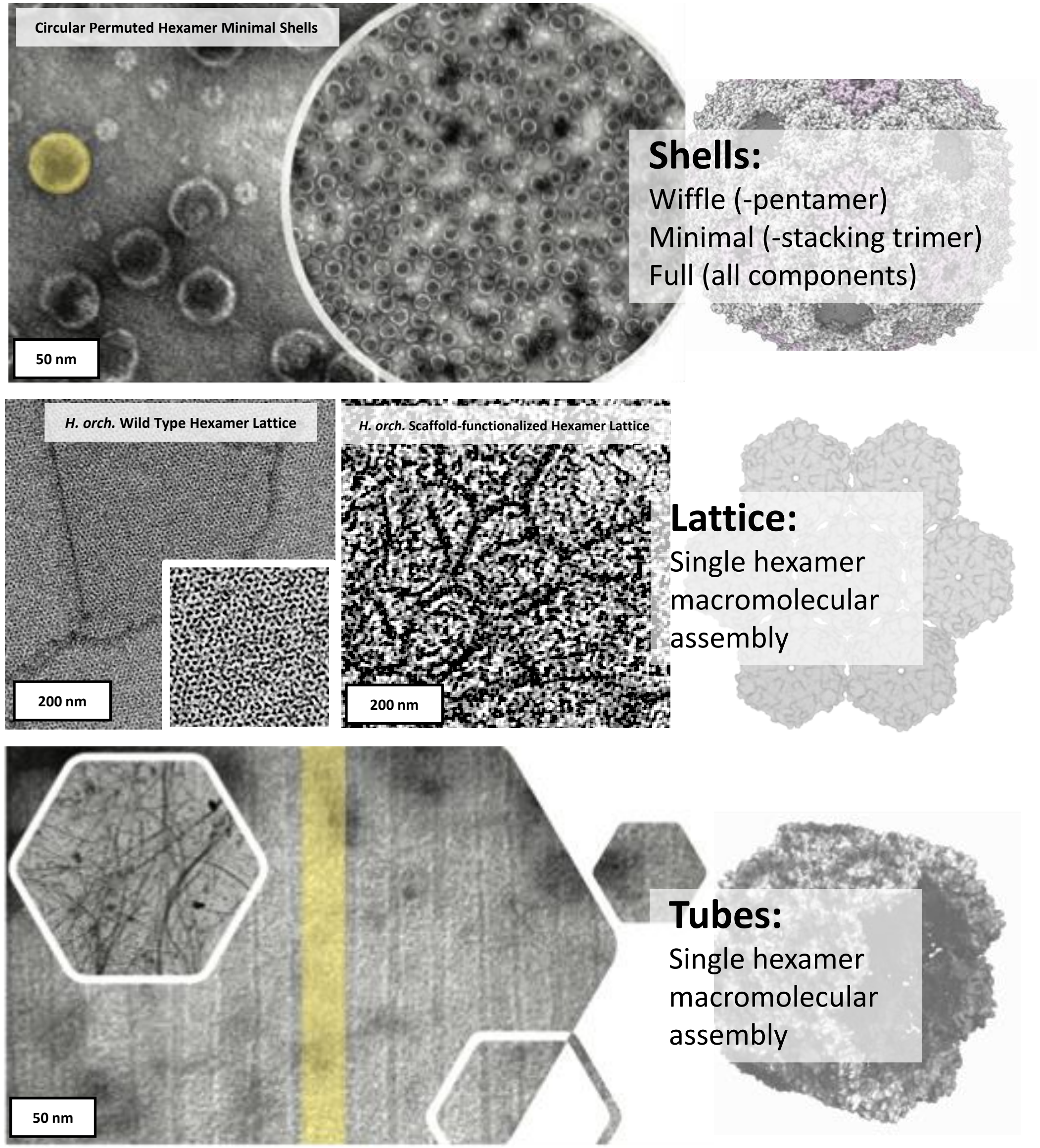
Activation of both sinks has an additive effect on apparent quantum efficiency of PSII (ϕ_{II}) and the relative electron transport rate (rETR).

Santos-Merino, María, et al. *PNAS* 118.11 (2021).

Example 3: Self-assembling Protein Architectures for Plant Synthetic Biology

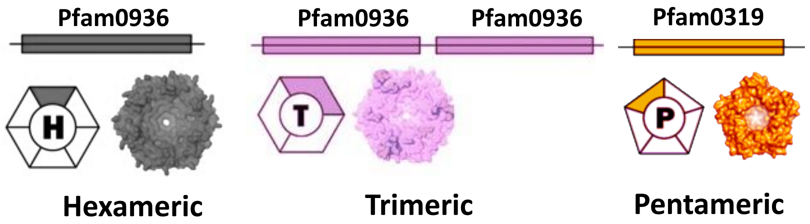


Heterologous Expression And Purification



Bacterial MicroCompartment

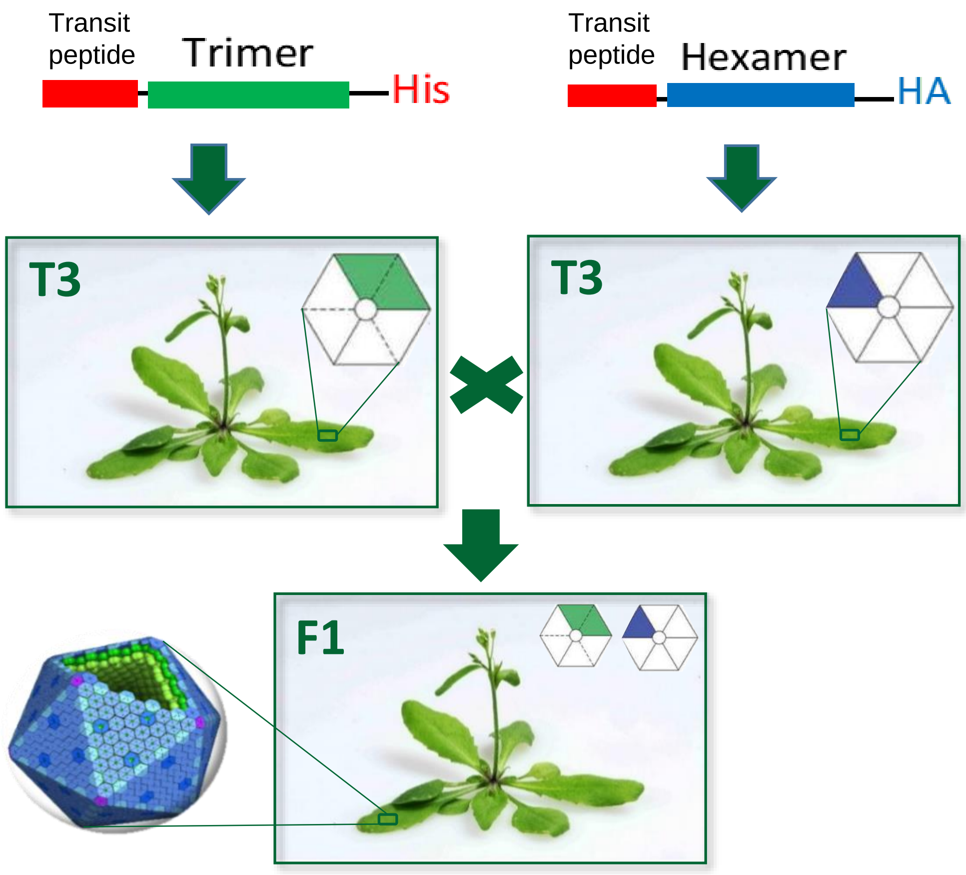
Composed of an outer shell of three protein building blocks:



Sutter et al. *Nano Lett.* 2016 Noel et al. *Adv. Mater. Interfaces.* 2016 Sutter et al. *Science.* 2017 Ferlez et al. *Metab. Eng.* 2019 Young et al. *Nano Lett.* 2019

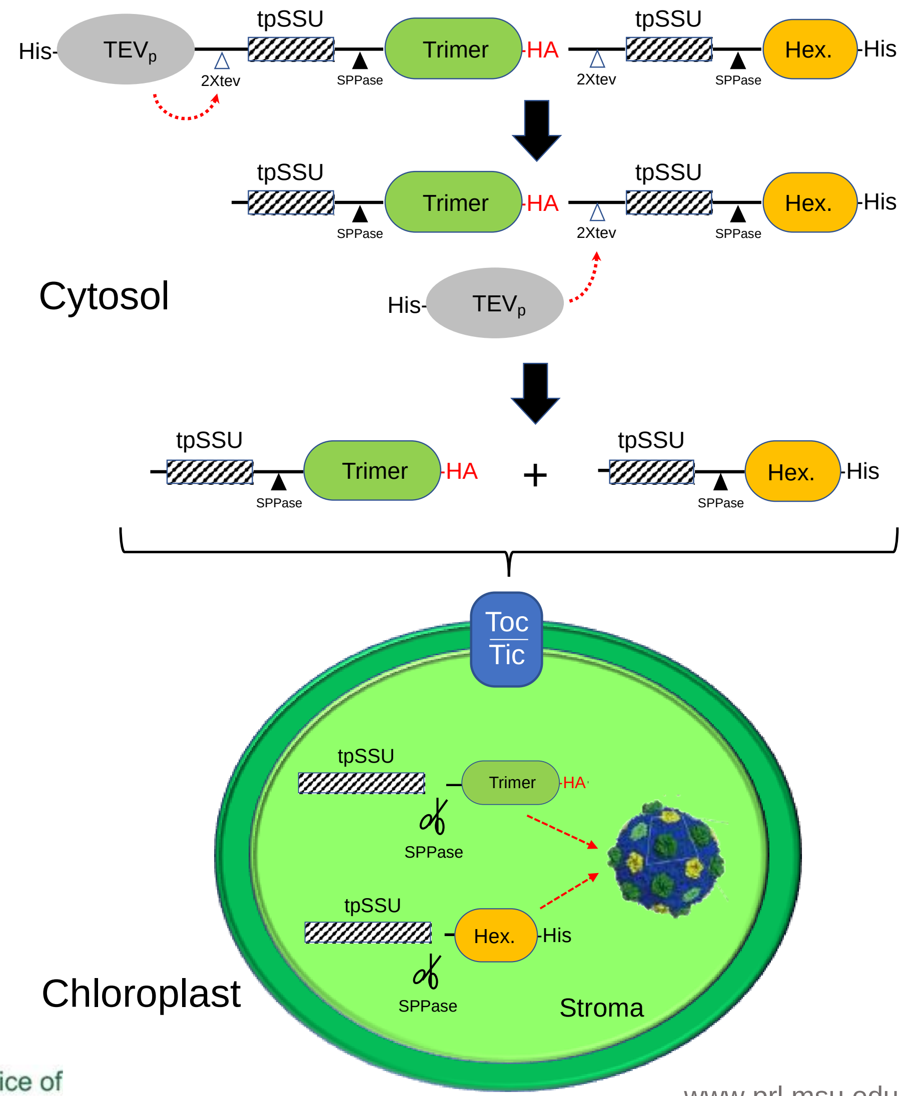
Targeting BMC shell protein components to the Chloroplasts

Classic Genetic Approach



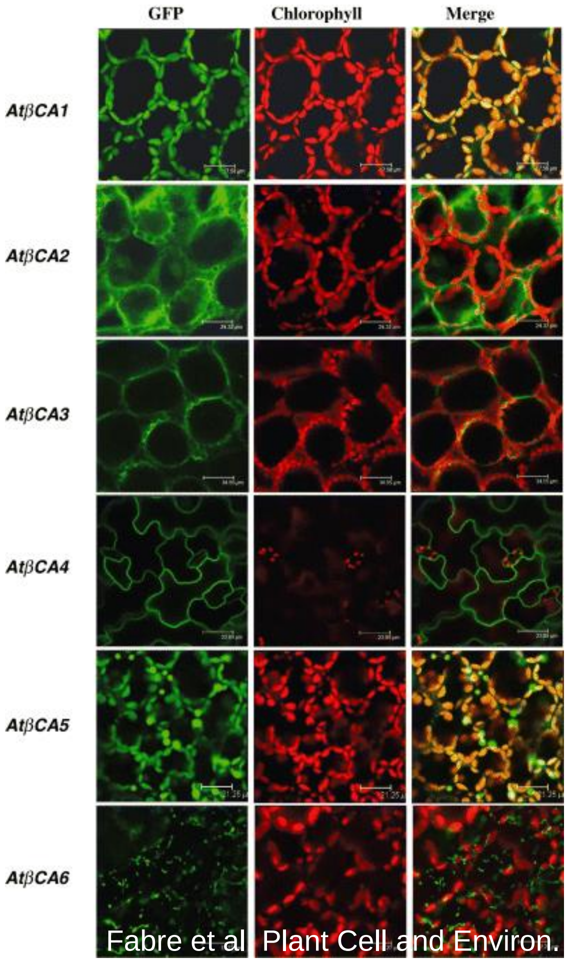
John Froehlich, Drew Mitchel, Linda Danhof, Melissa Borrusch

Shell Train Approach

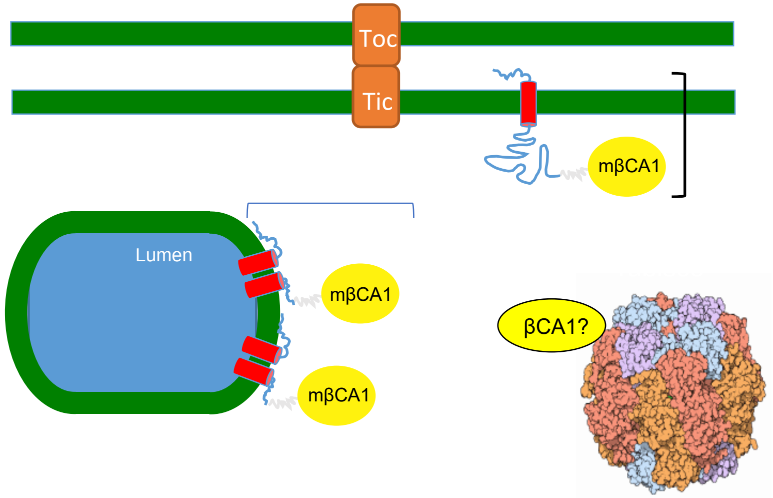


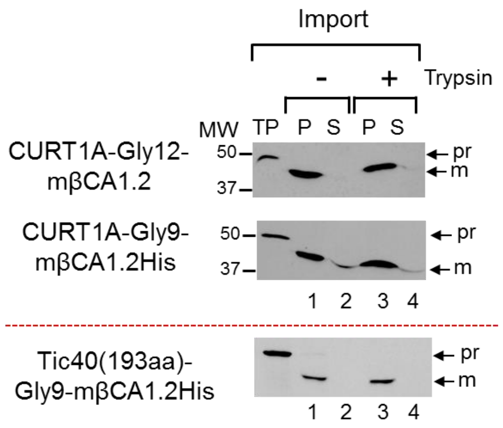
Retargeting and BMC Encapsulation of CAs

Organelle retargeting

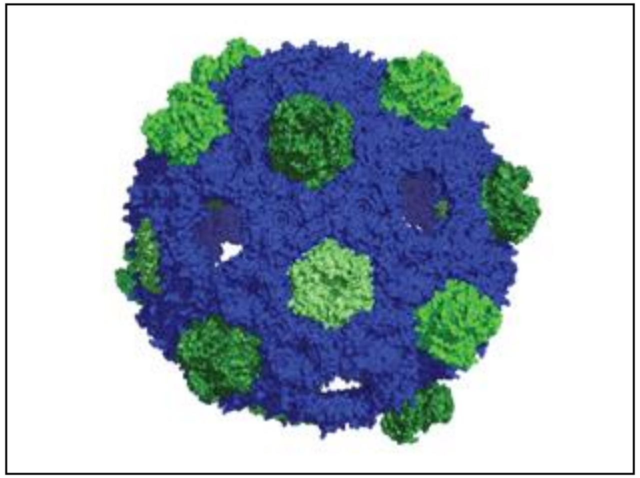


Suborganelle retargeting

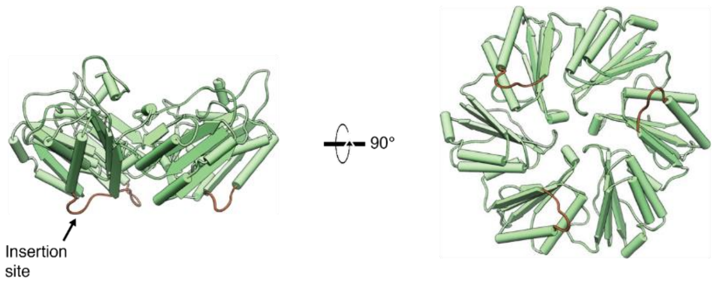




Sequestration into gas-permeable shells



SpyTag-SpyCatcher



Hagen et al. Nat. Commun. 2018

Project Structure

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