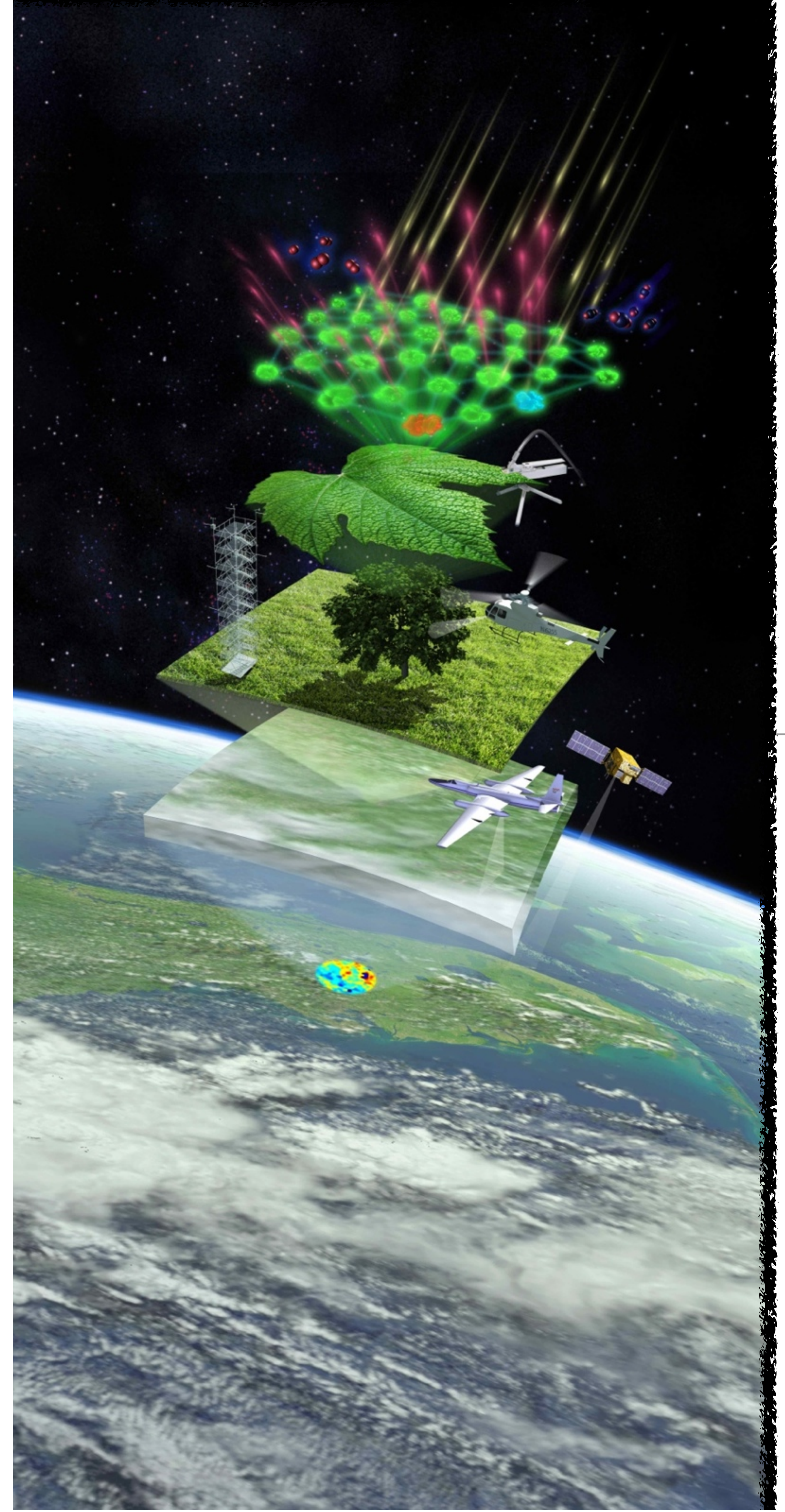
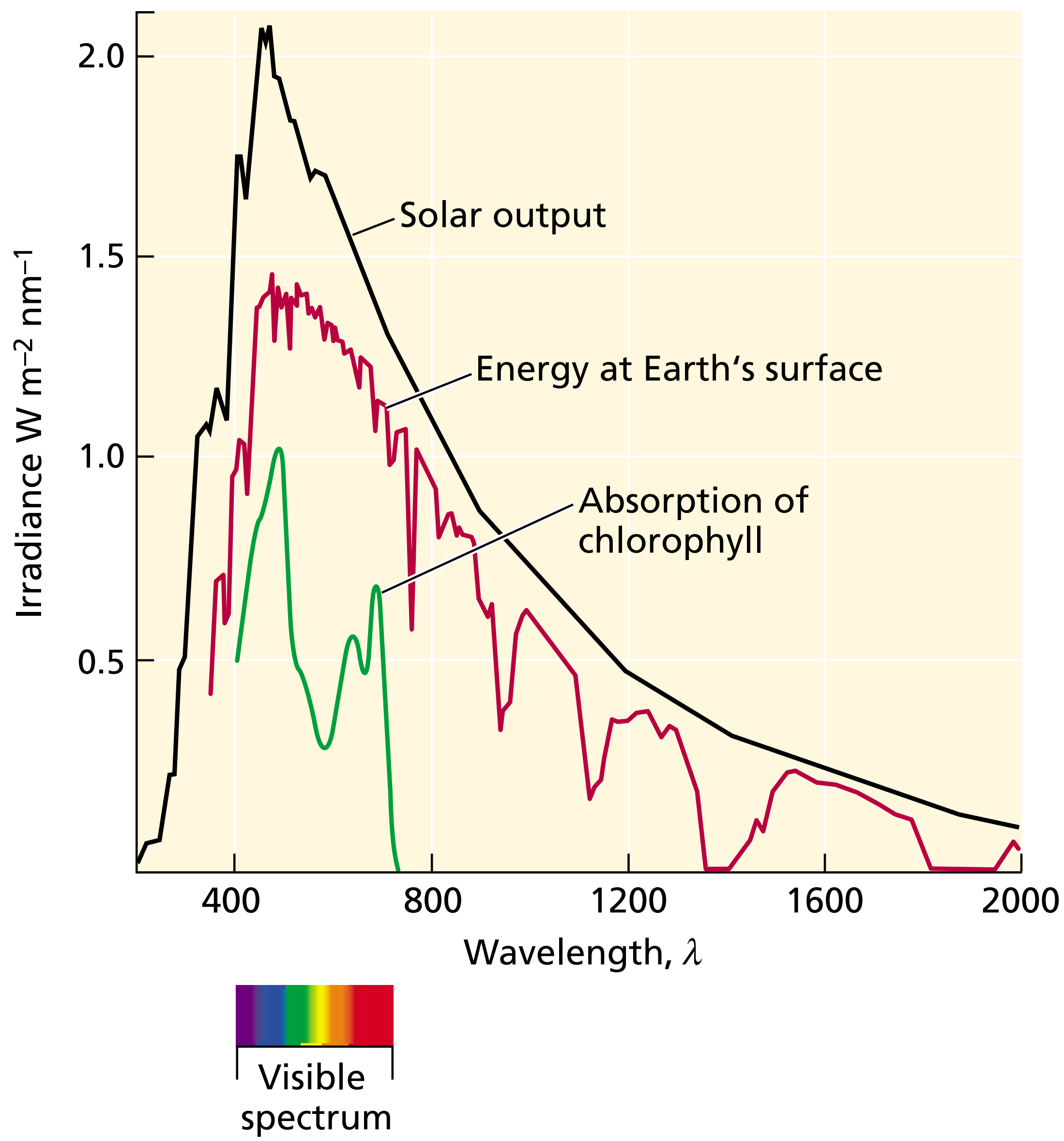
Remote Sensing of Solar Induced Chlorophyll Fluorescence

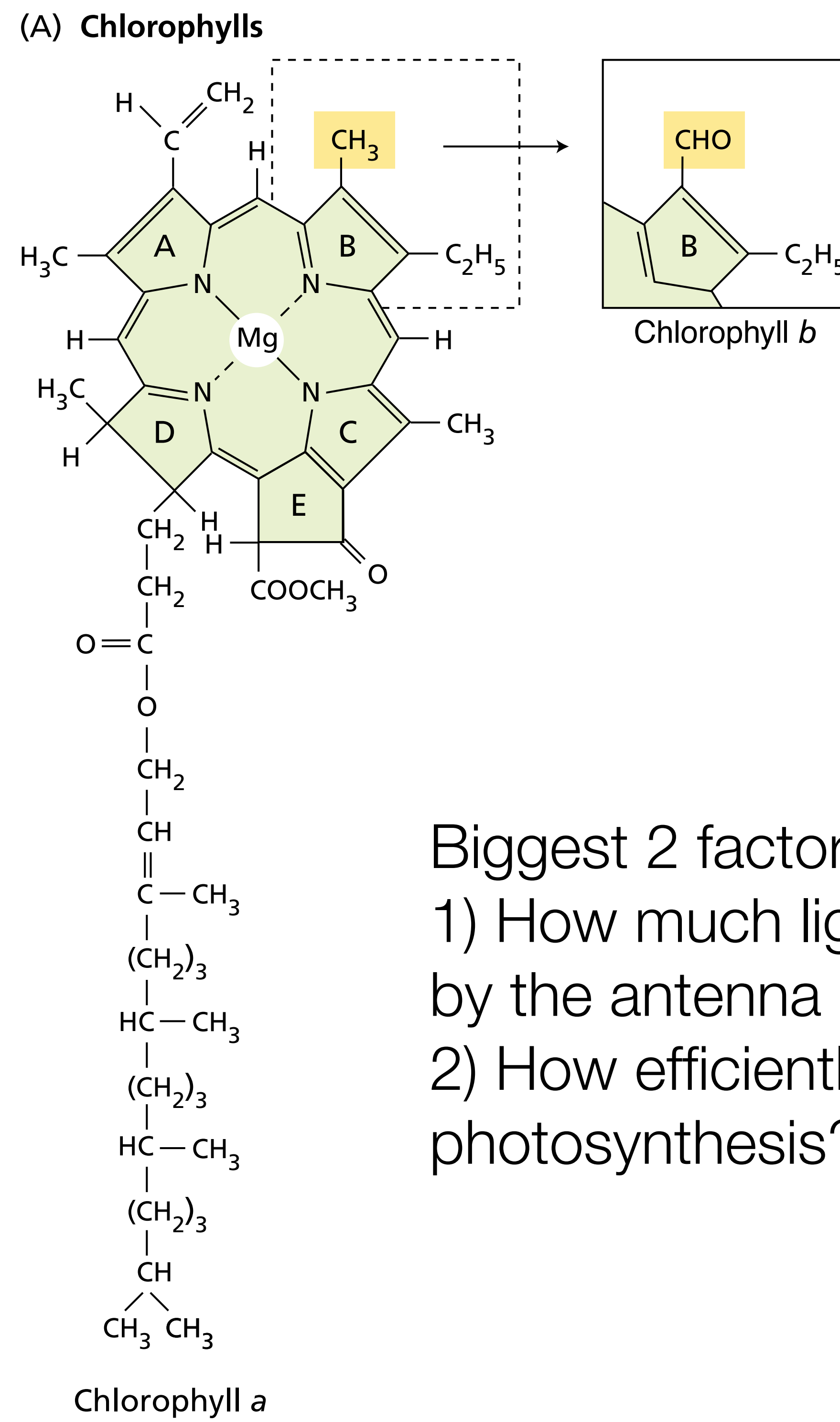
The past, the present and the future

Christian Frankenberg[1,2]
(1) California Institute of Technology, Pasadena, CA, United States
(2) Jet Propulsion Laboratory / Caltech, Pasadena, CA, United States



Absorption of sunlight drives it all.

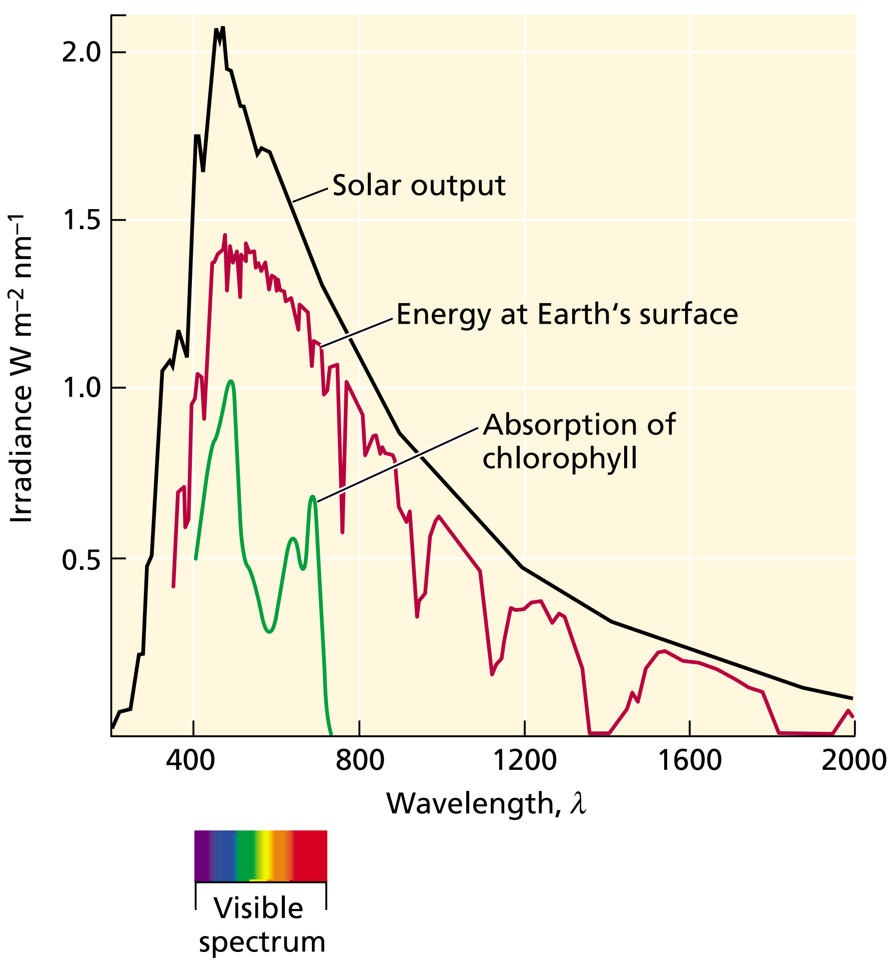




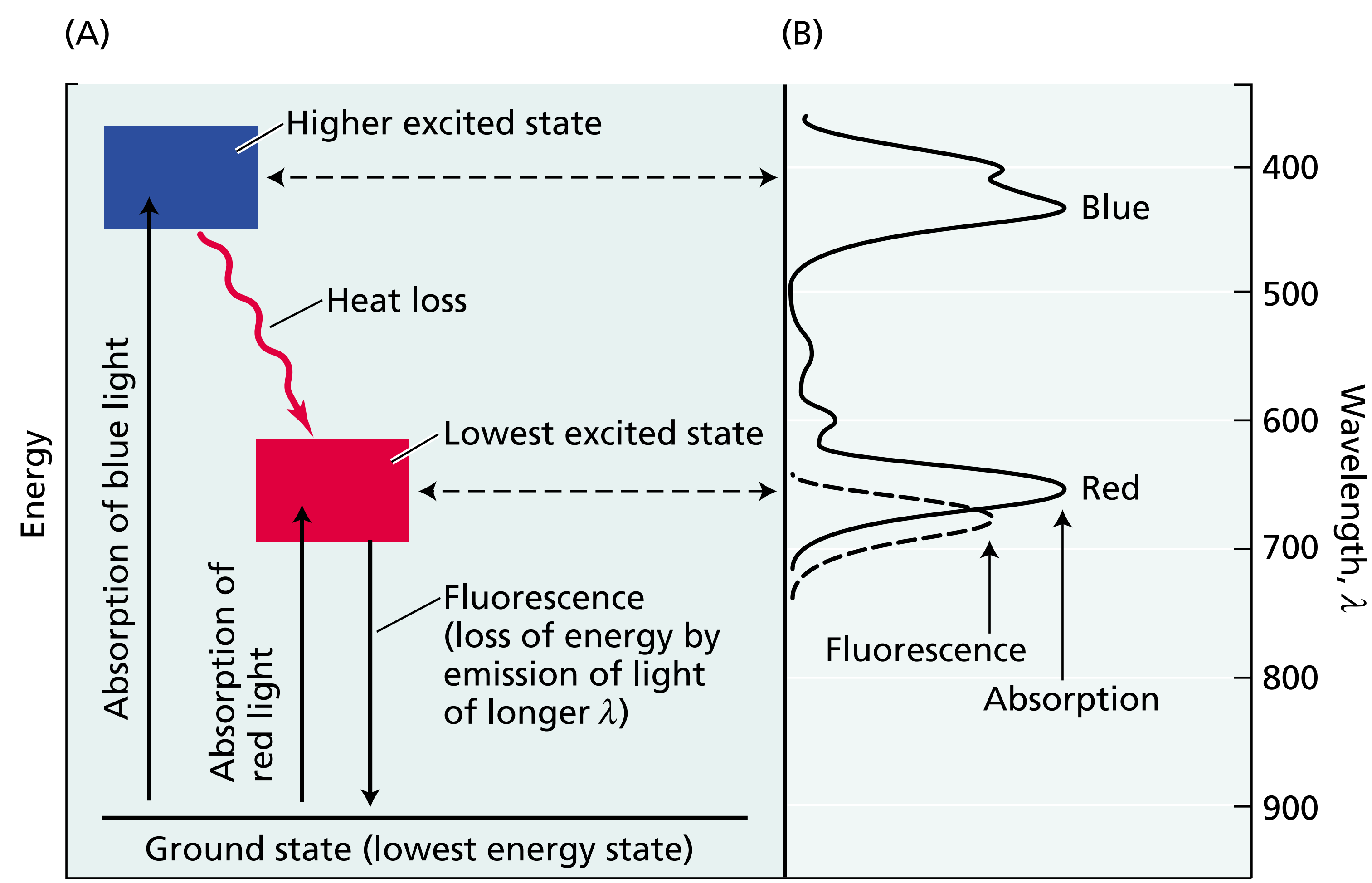
Biggest 2 factors:
1) How much light is absorbed by the antenna system?
2) How efficiently is this light used for photosynthesis?

Taiz and Zeiger, "Plant Physiology", 2010.

The light reactions



$$Chl + h\nu \rightarrow Chl^*$$



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The light reactions

Unstable higher state, very fast transition to lower state

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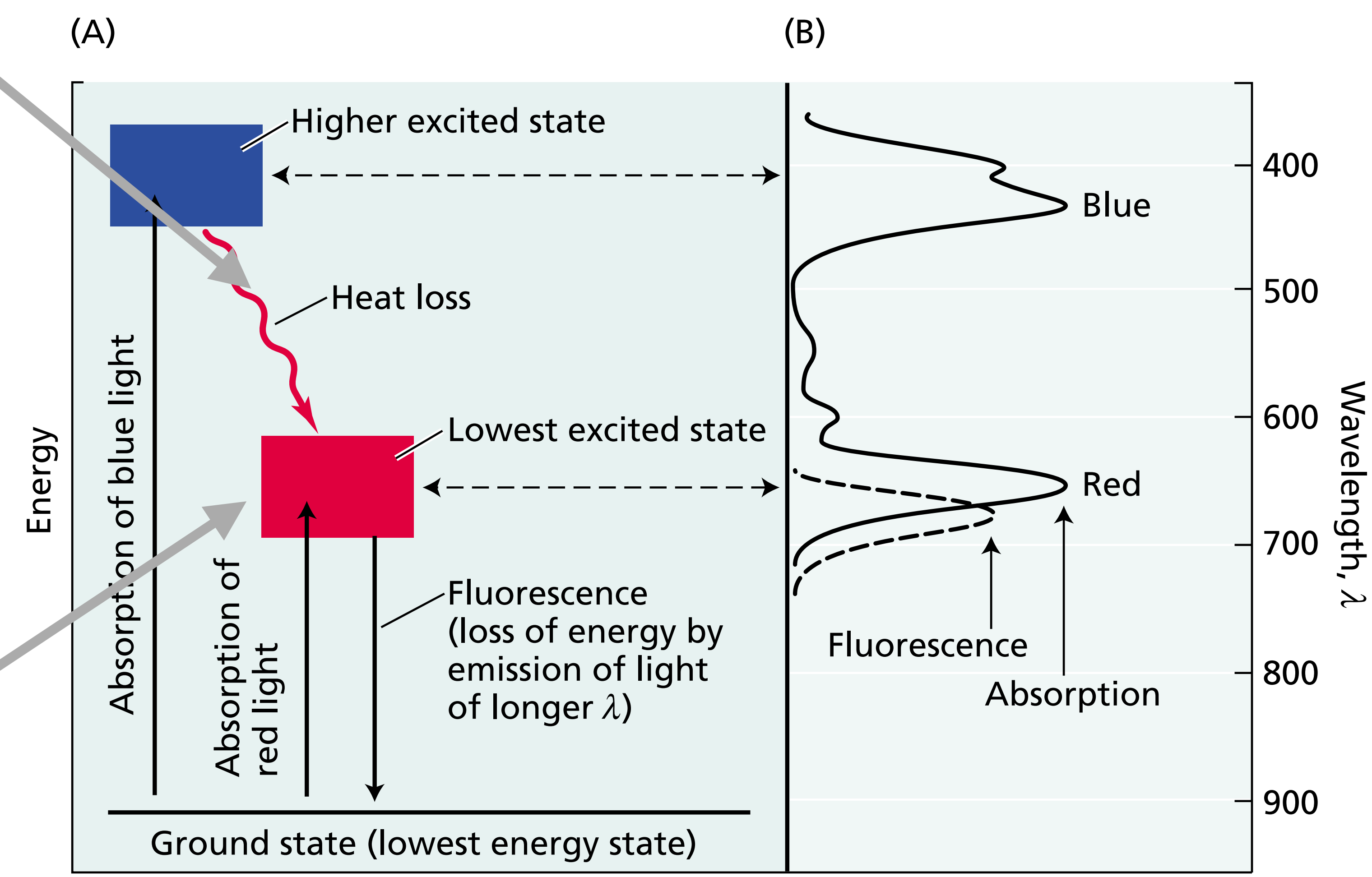

Lowest excited state "somewhat" stable (lifetime of a few nanoseconds)

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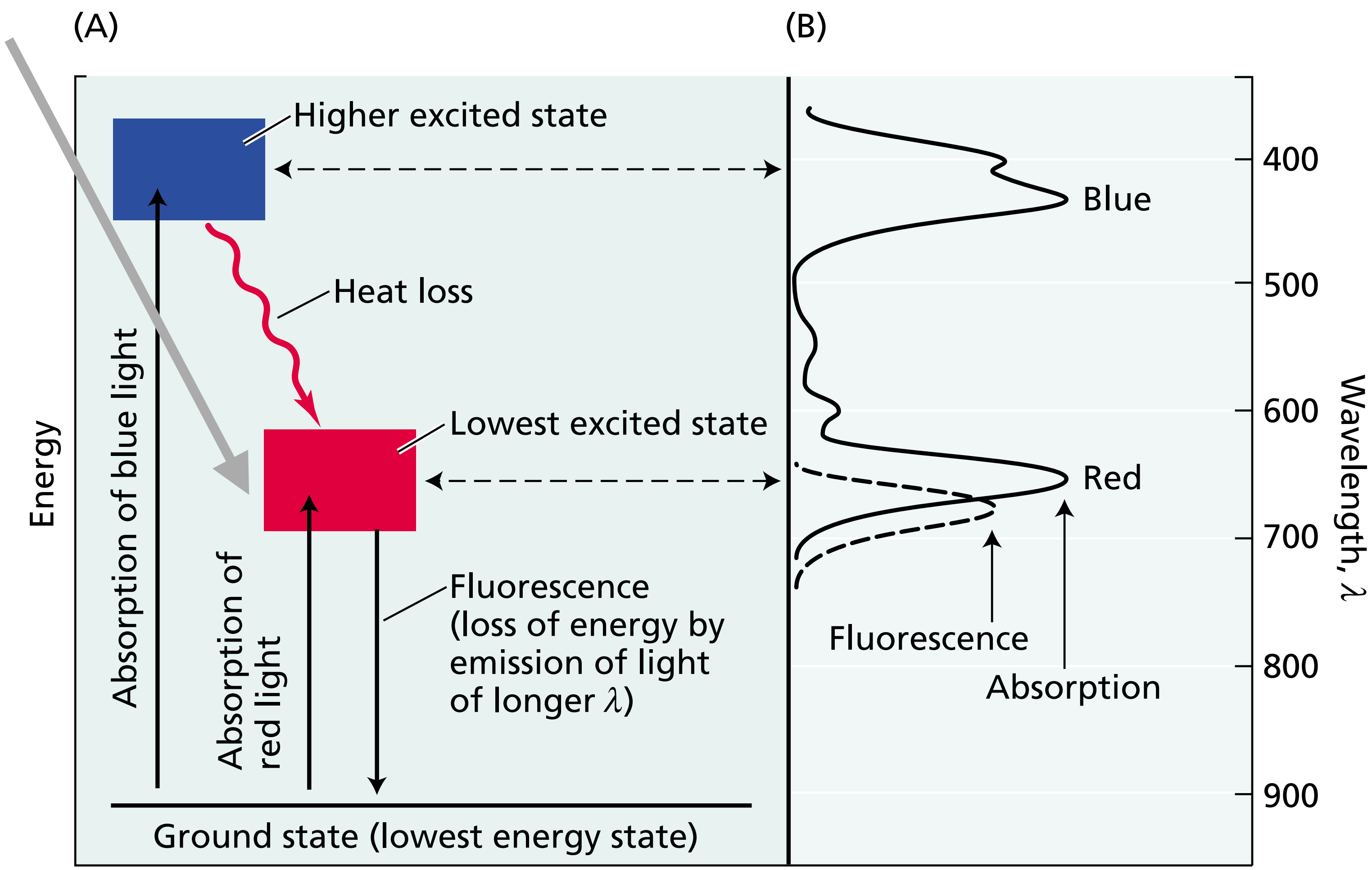

Can do:

1. Re-emit a photon (fluorescence)
2. Fall back to ground level (release heat)
3. Transfer energy to another chlorophyll
4. Perform photochemistry, causing chemical reactions

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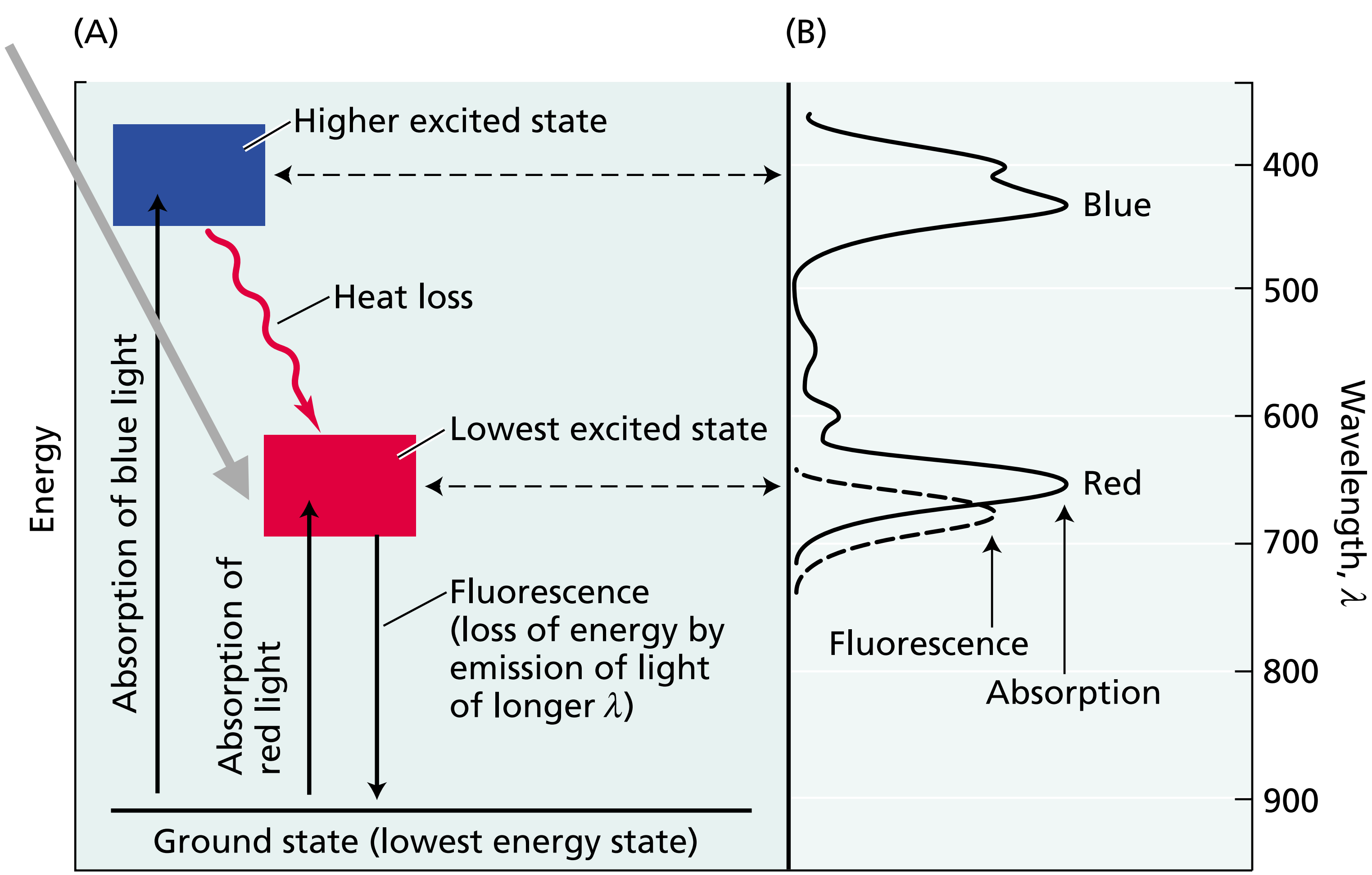
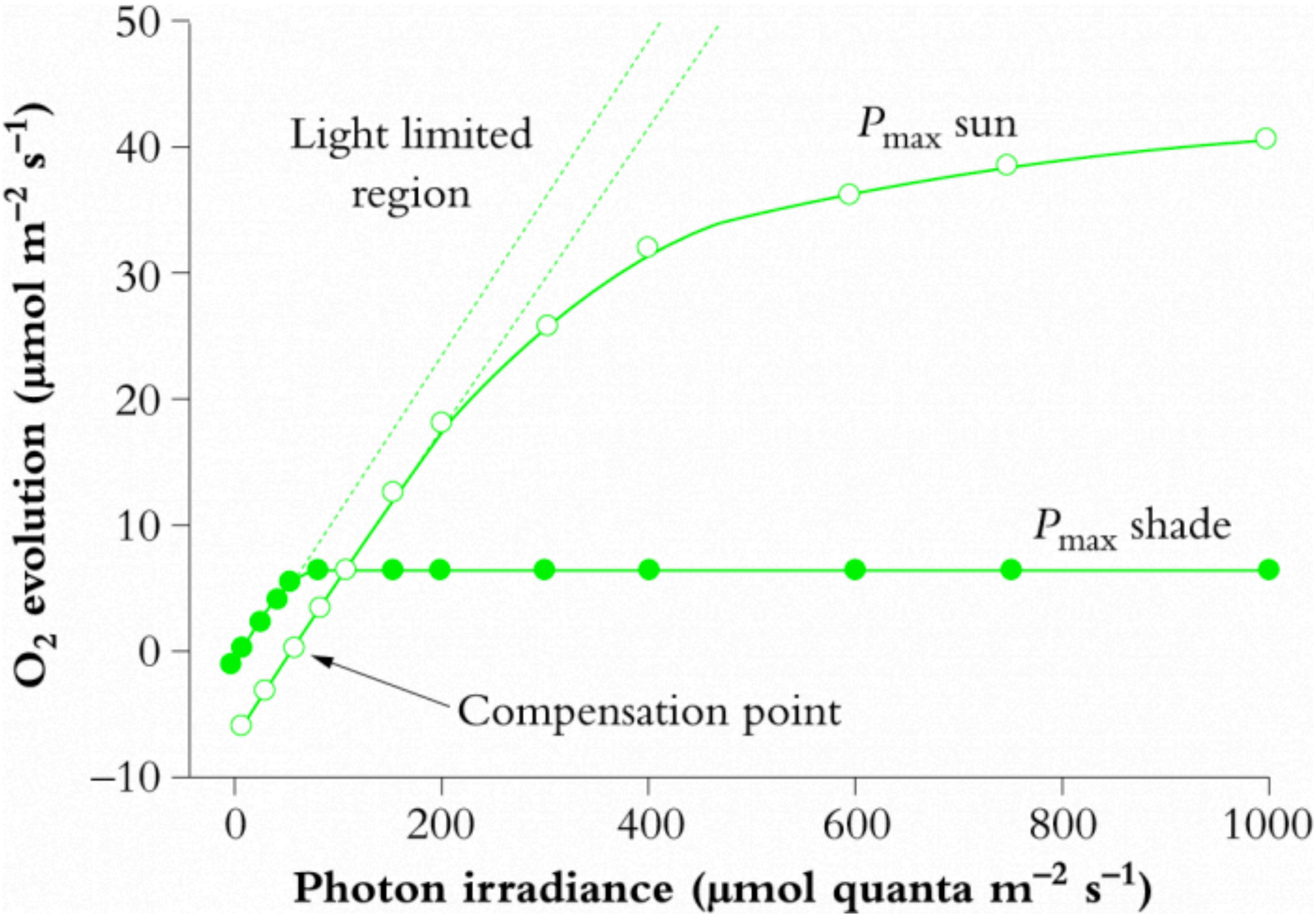


Lifetime is actually the best metric for fluorescence yield

Plants are not only light limited

— what happens to excess light?



http://plantsinaction.science.uq.edu.au/

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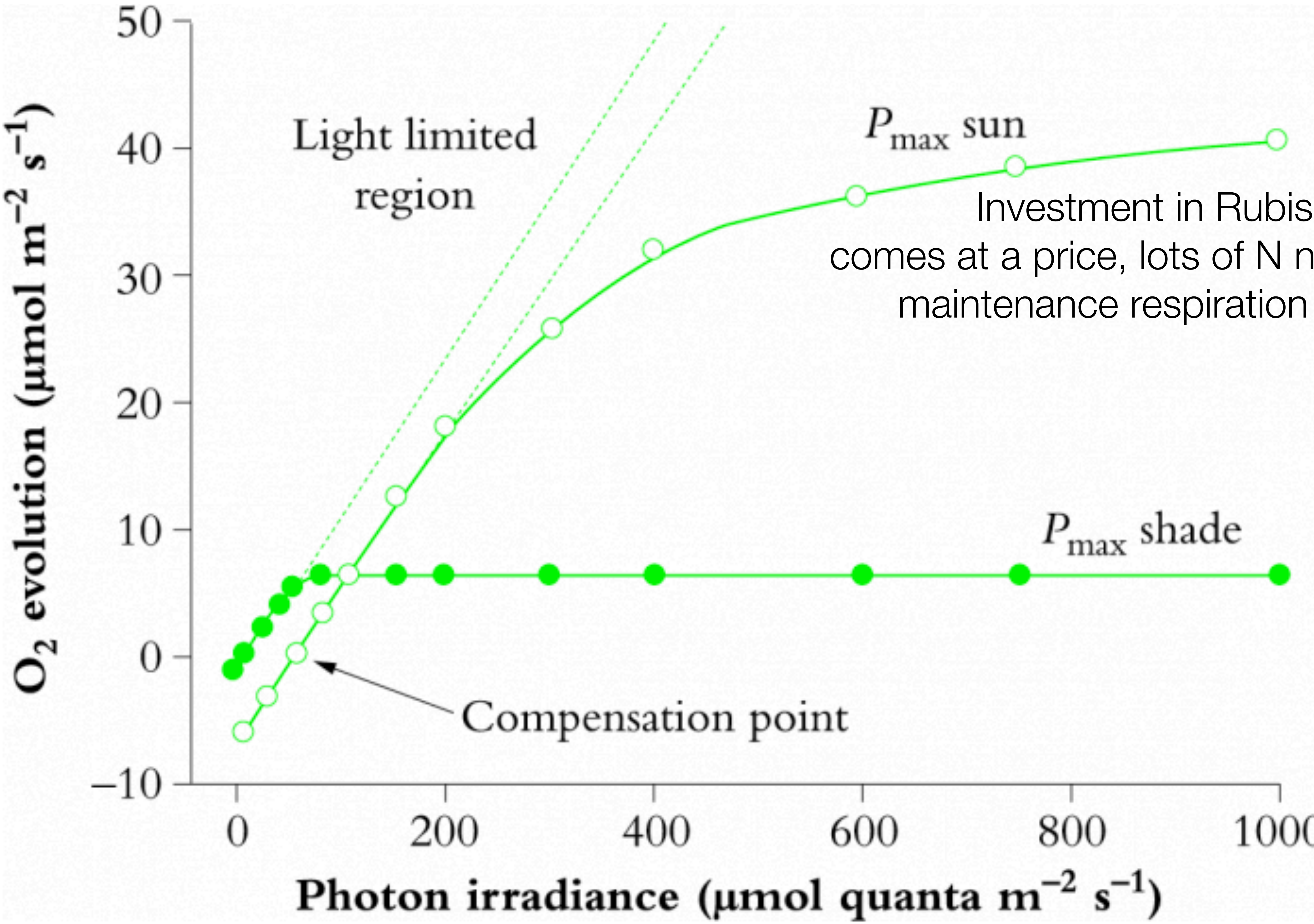

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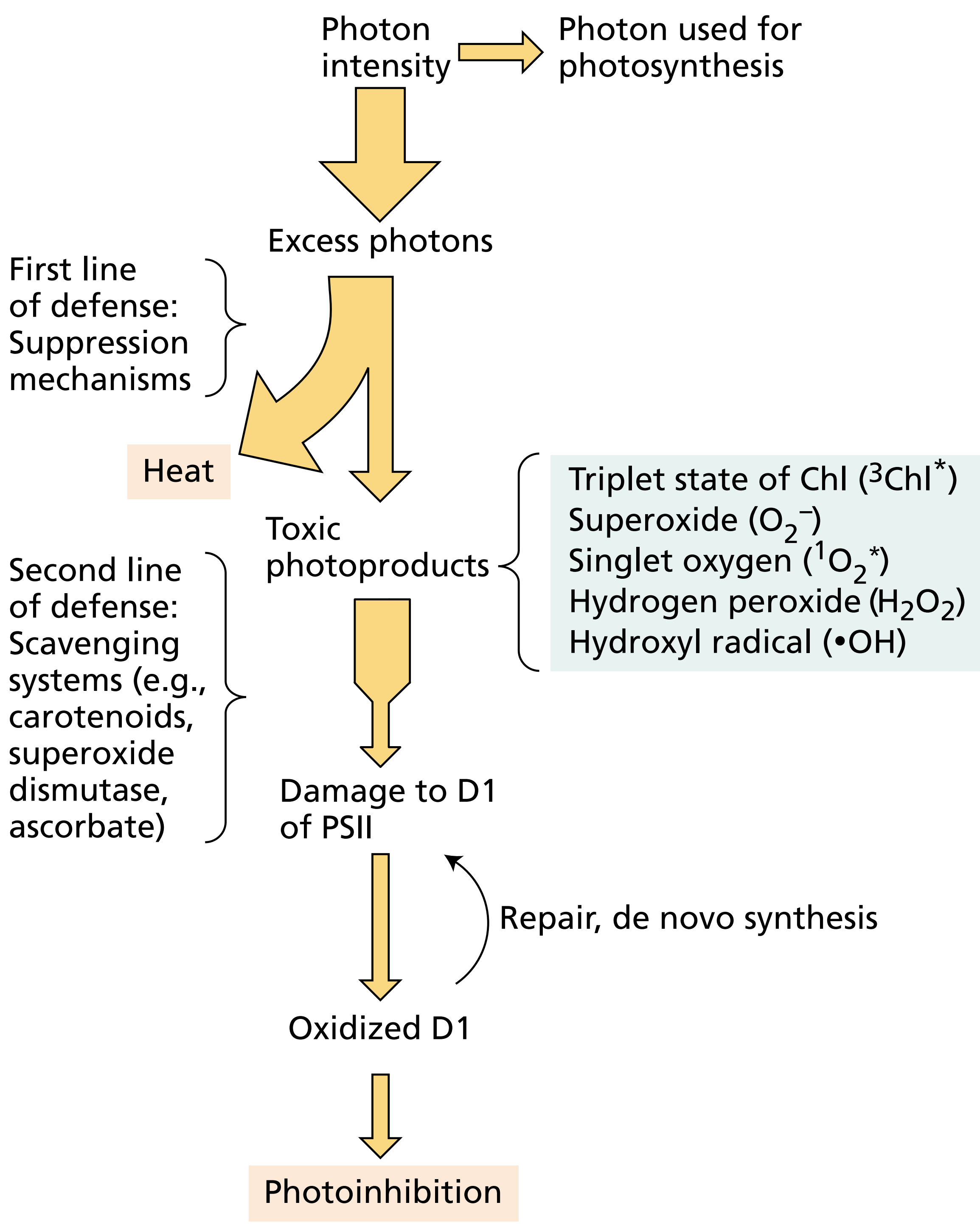
Light absorption can be dangerous!



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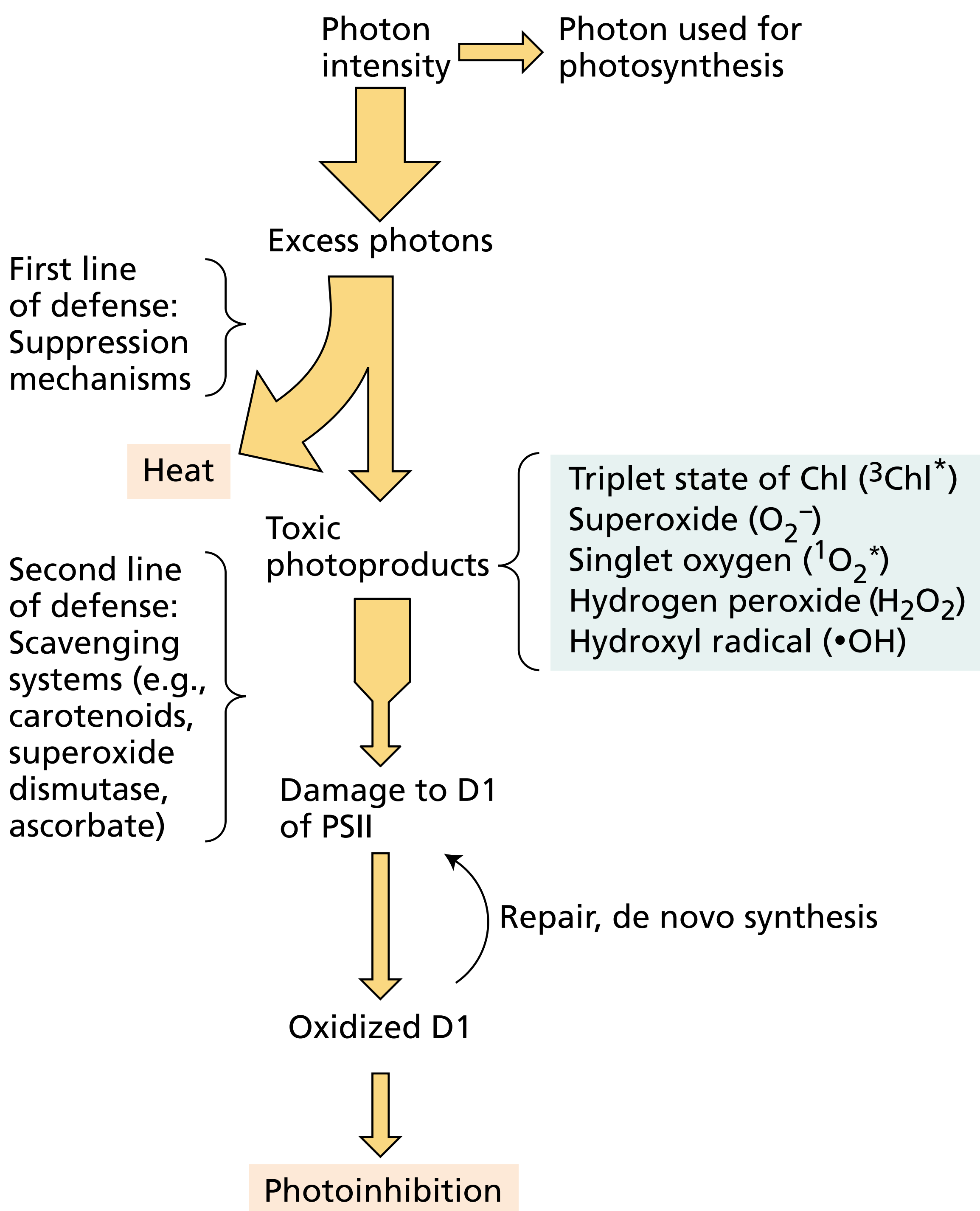

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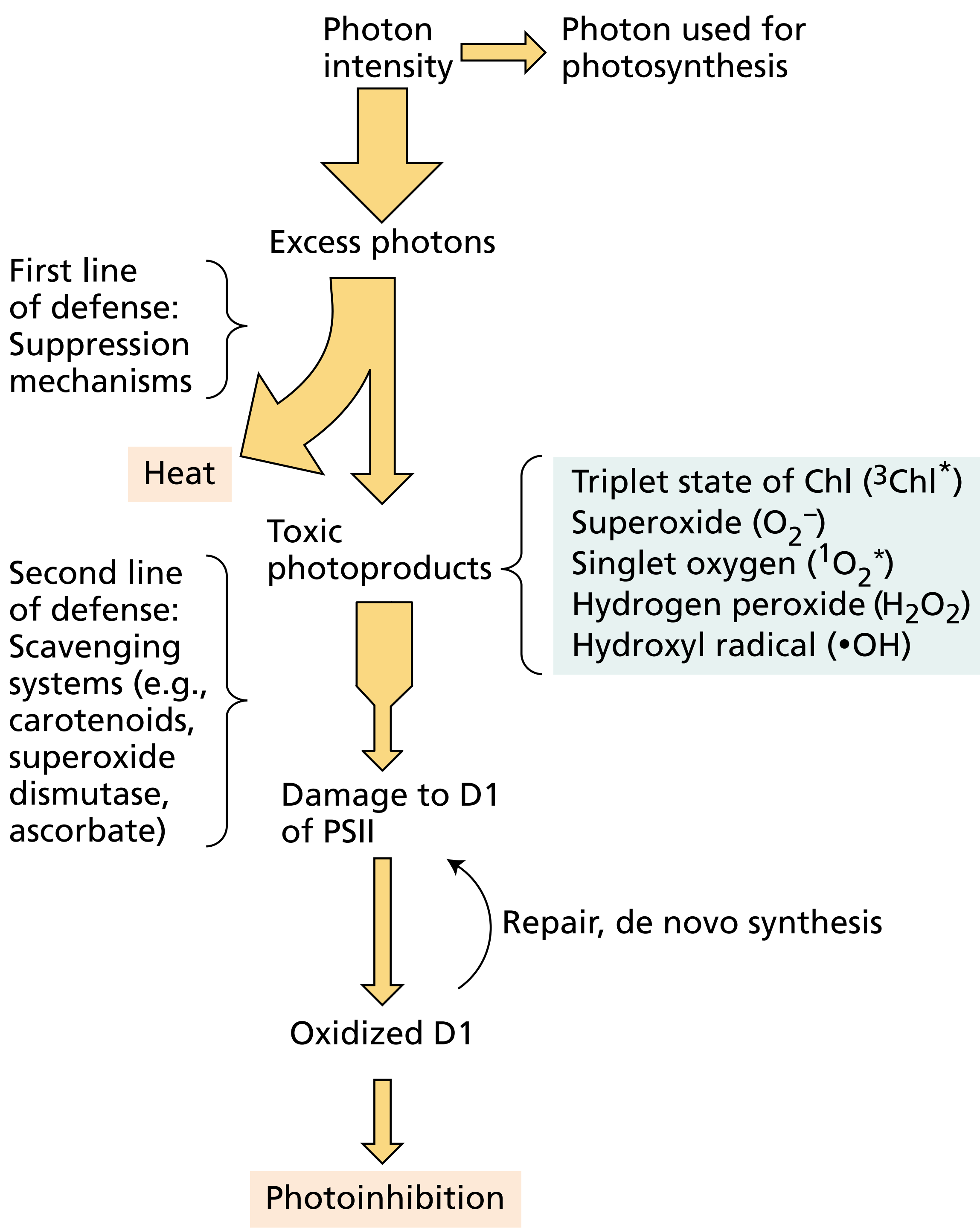

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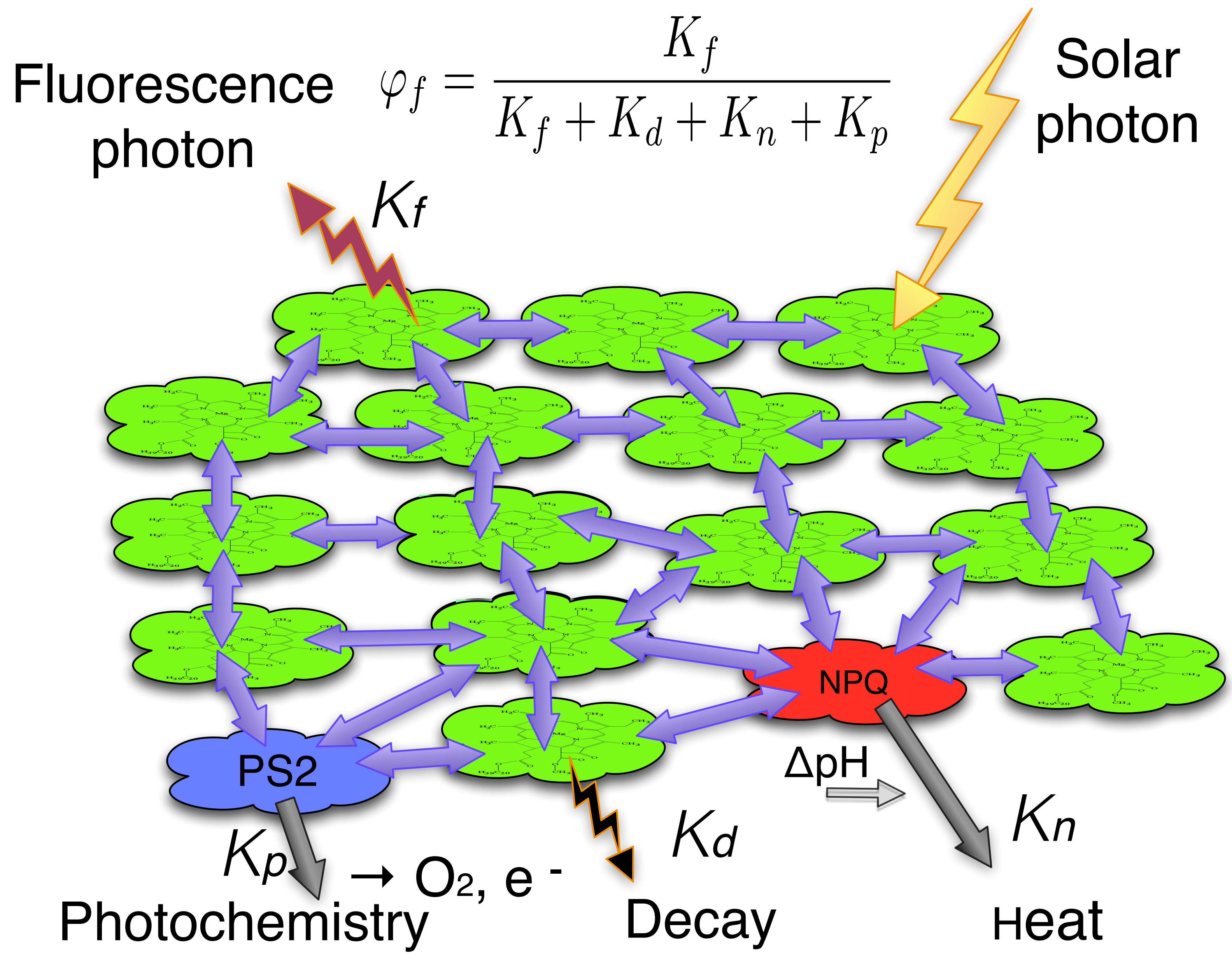
Need more pathways to quench absorbed energy

Fate of absorbed photons in antenna system



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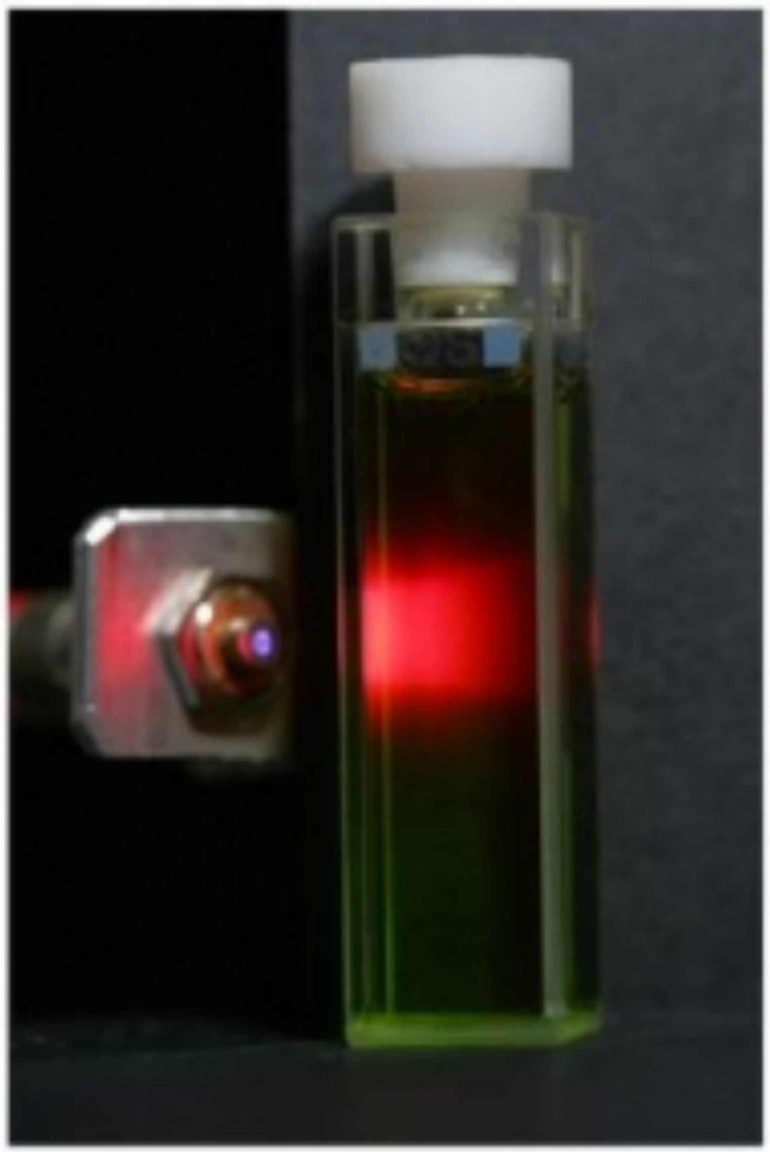
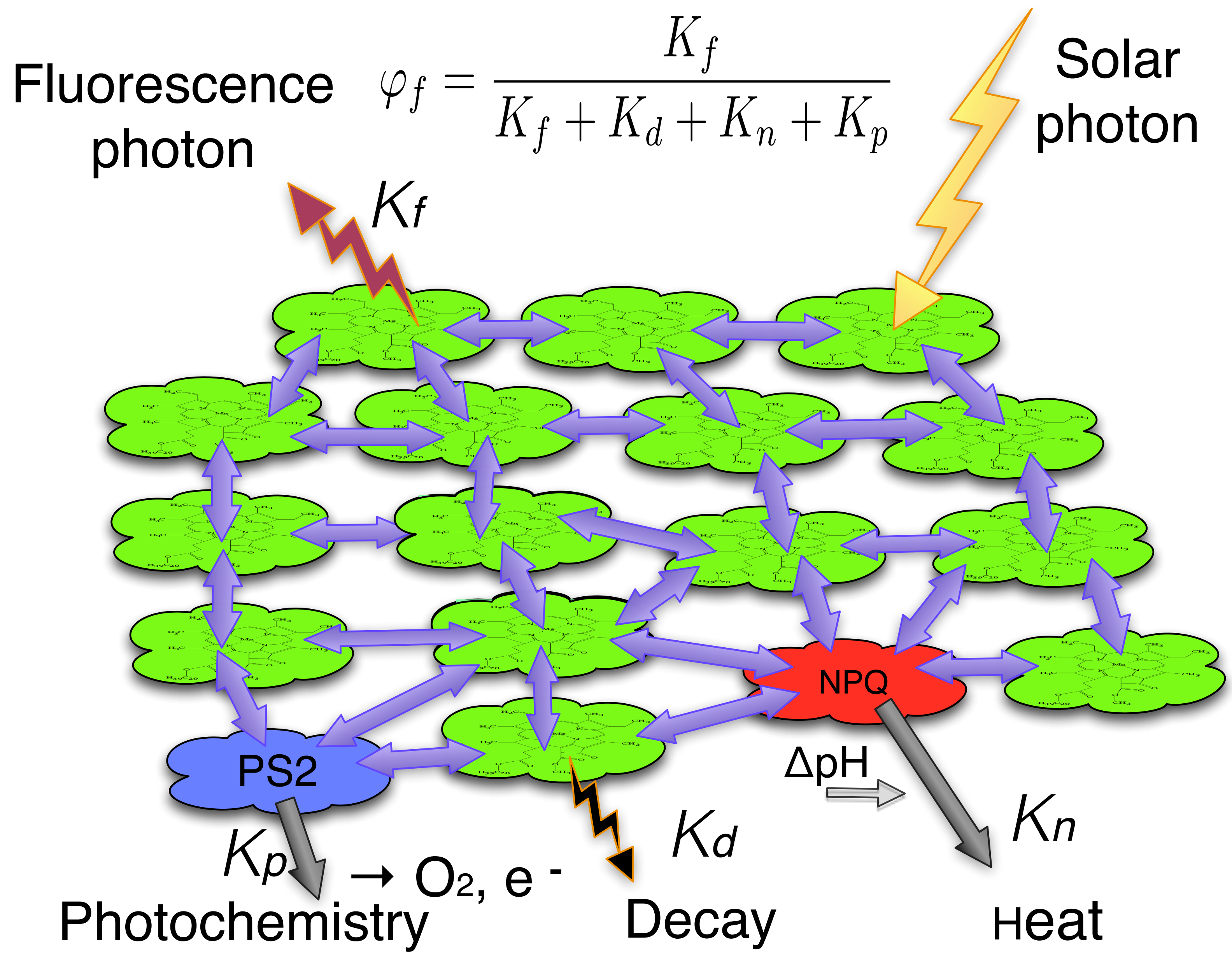


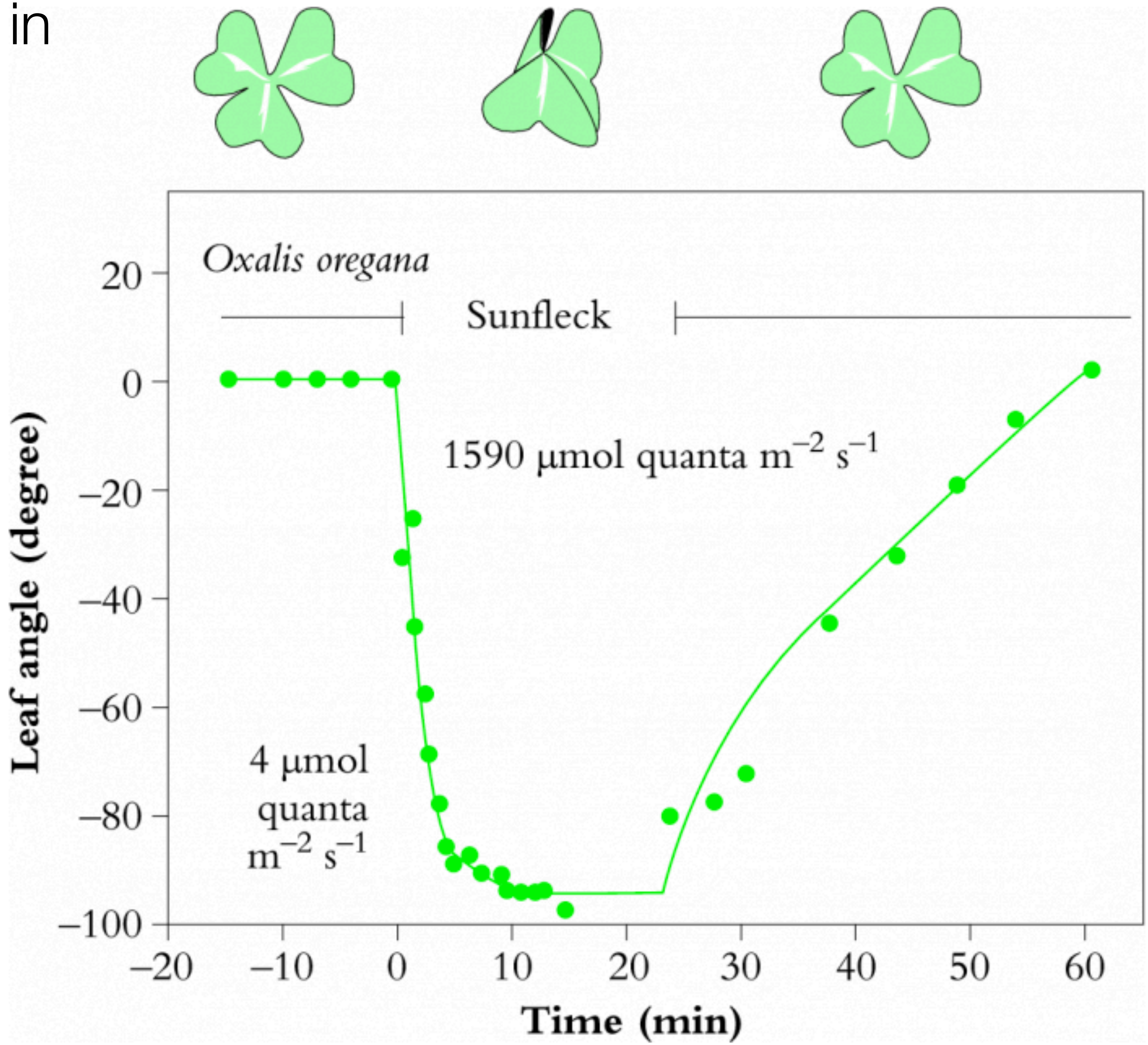


Pure Chlorophyll Solution —> Kp and Kn=0, fluorescence yield around 1
higher fluorescence from Chl solution than leaf already found in 1874 (Mueller)

Taiz and Zeiger, "Plant Physiology", 2010.

Alternative method: Avoid absorption in the first place

— Leaf orientation



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Alternative method: Avoid absorption in the first place

— Chloroplast movements

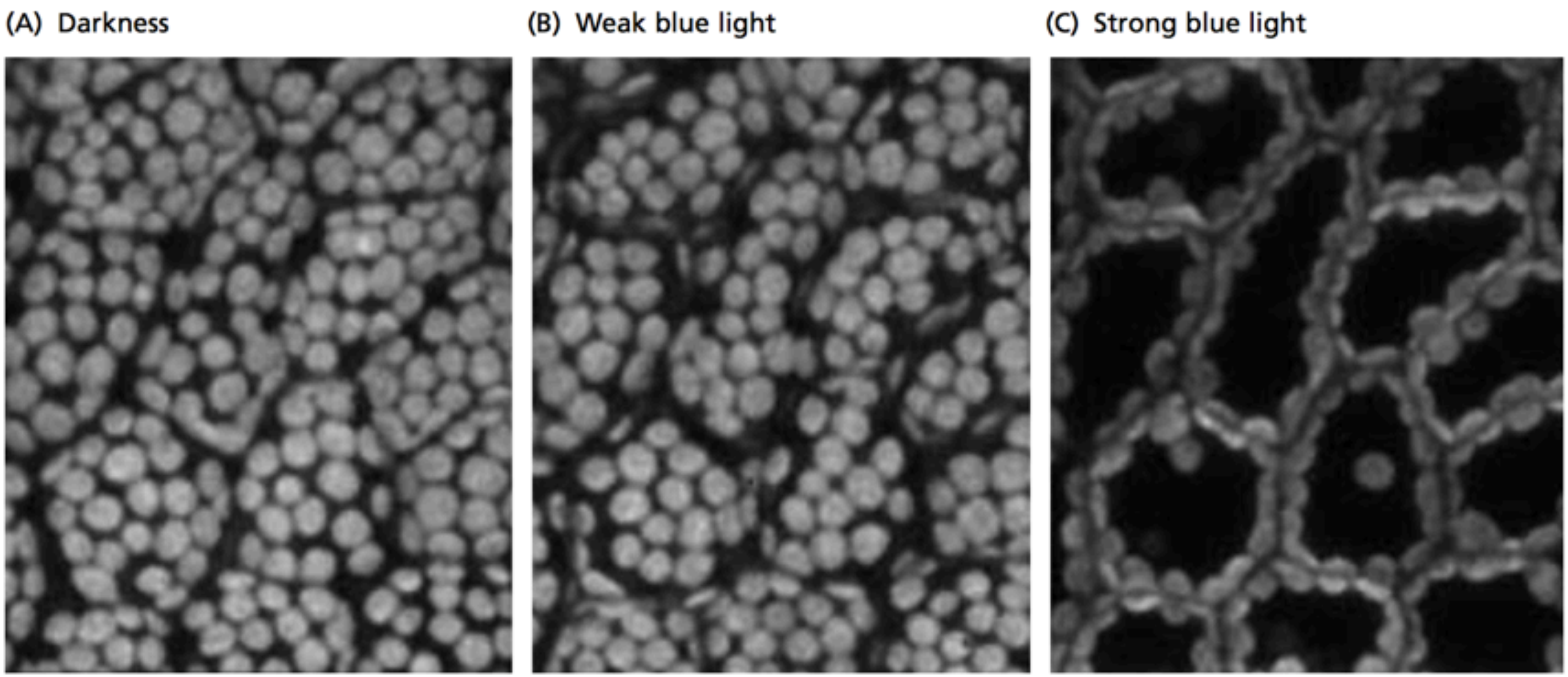
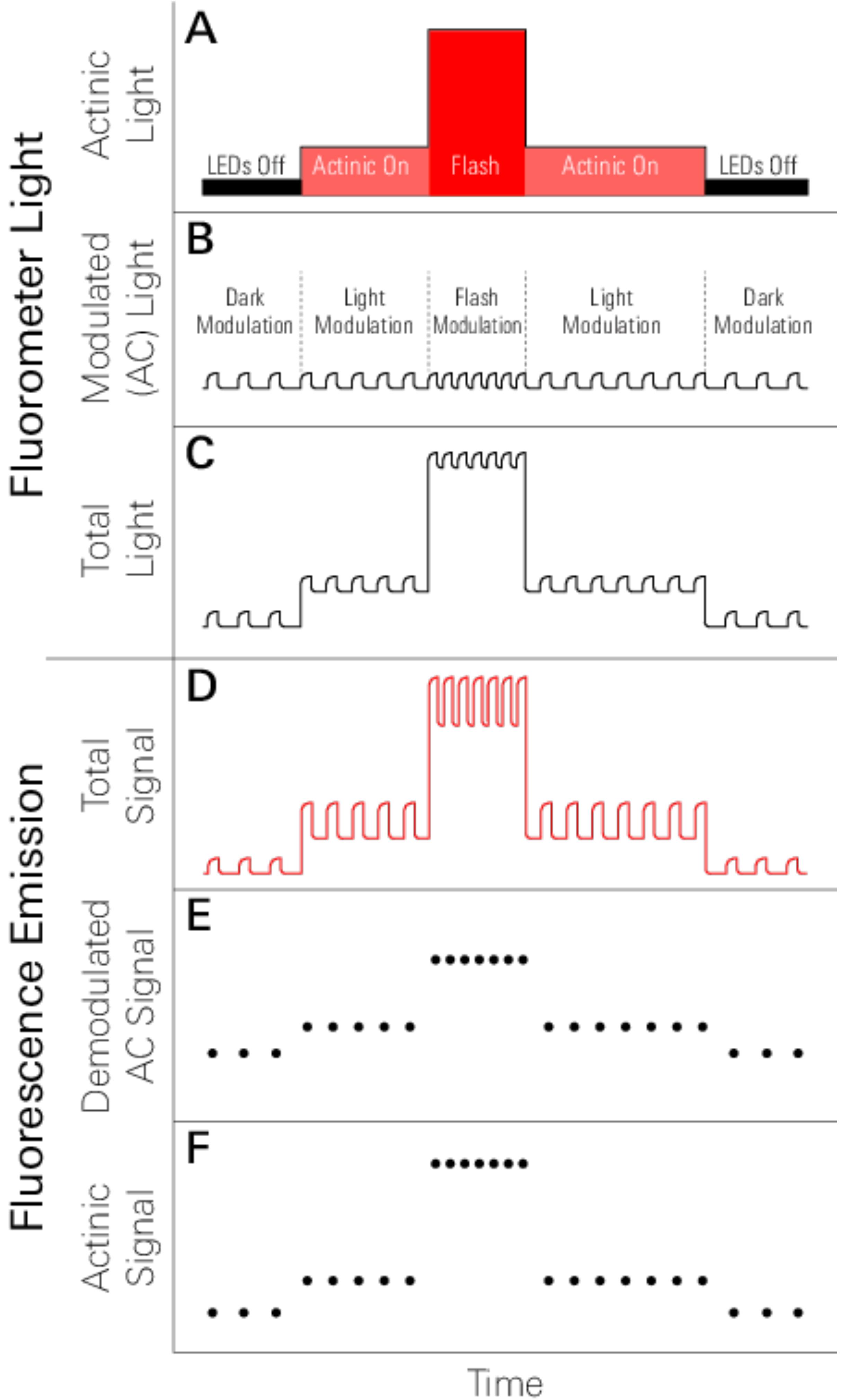


FIGURE 9.5 Chloroplast distribution in photosynthesizing cells of the duckweed *Lemna*. These surface views show the same cells under three conditions: (A) darkness, (B) weak blue light, and (C) strong blue light. In A and B, chloroplasts are positioned near the upper surface of the cells, where they can absorb maximum amounts of light. When the cells were irradiated with strong blue light (C), the chloroplasts move to the side walls, where they shade each other, thus minimizing the absorption of excess light. (Micrographs courtesy of M. Tlalka and M. D. Fricker.)

Taiz and Zeiger, "Plant Physiology", 2010.

Pulse Amplitude Modulated (PAM) fluorometry



F_s (dSIF/dAPAR)

SIF

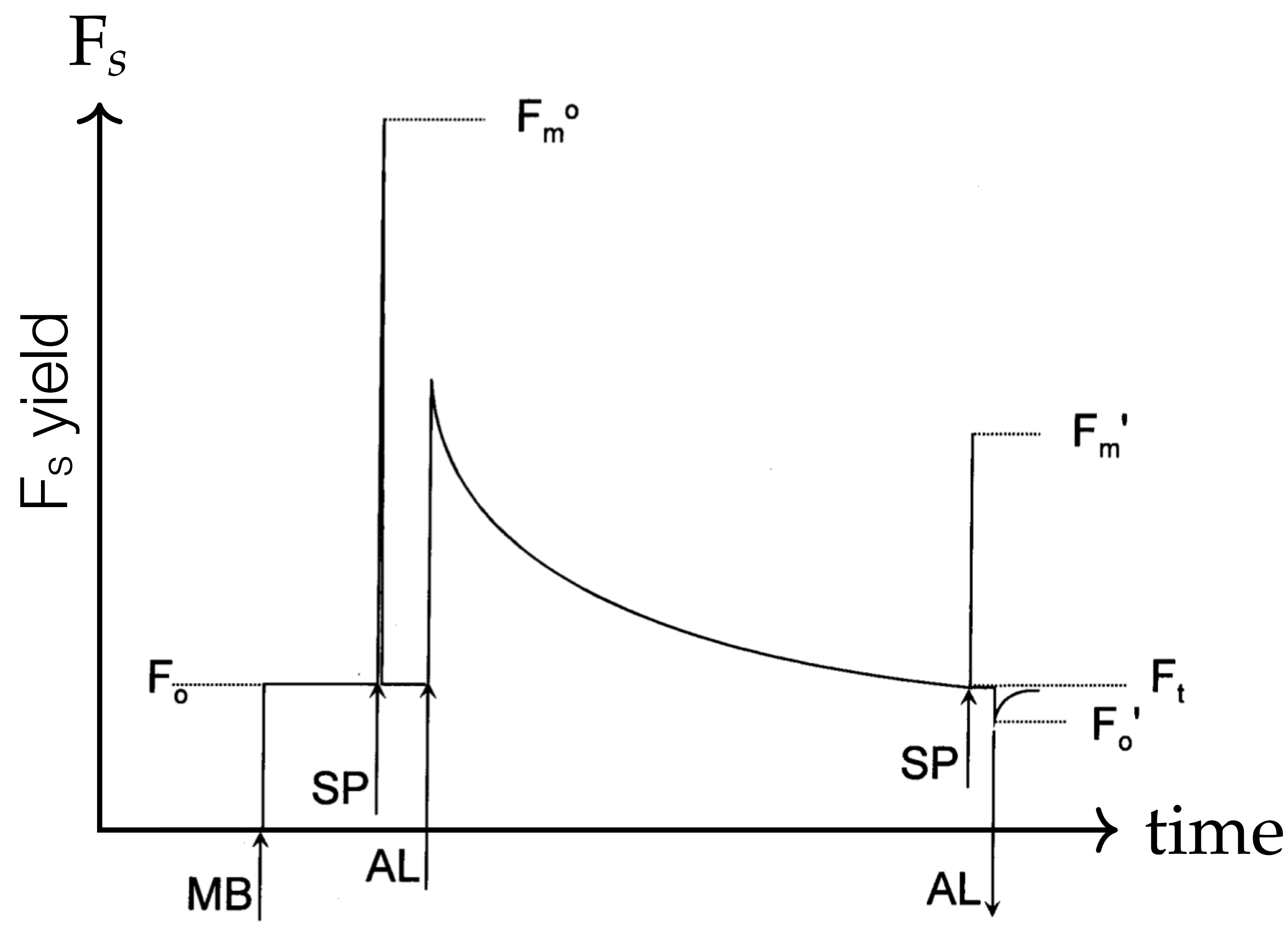
https://www.licor.com/env/help/6800/Content/theory.html

The leaf scale — Active Fluorometry

- Fluorescence yield

$$\Phi_f = \frac{K_f}{K_f + K_p + K_n}$$

- Rates for:
- Fluorescence
- Photosynthesis
- Heat quenching (NPQ)



from Maxwell & Johnson 2000

AL=Actinic Light (moderate light was turned on ↑ and off ↓)

SP = Saturating Pulse (strong pulsed light at each ↑)

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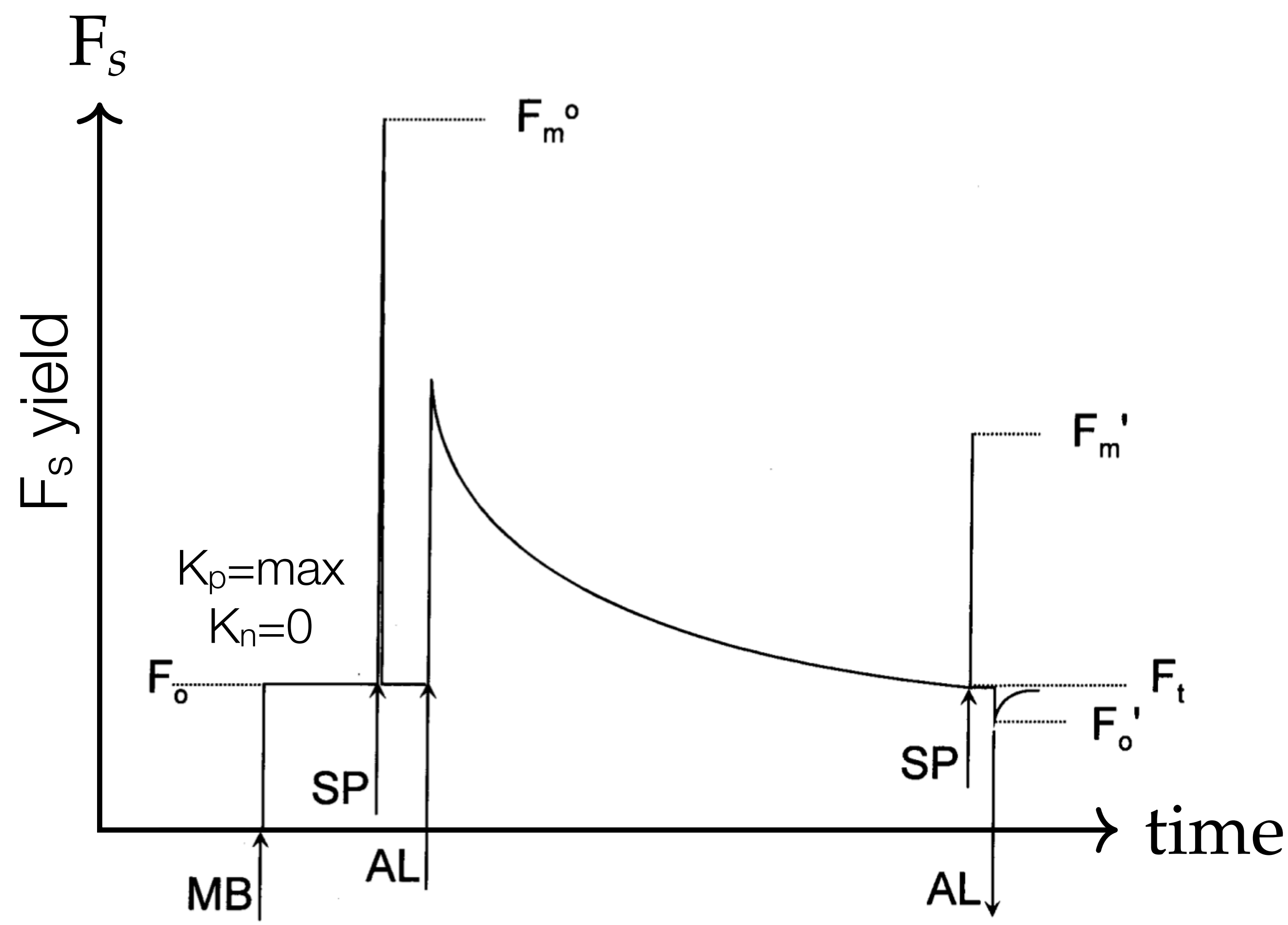

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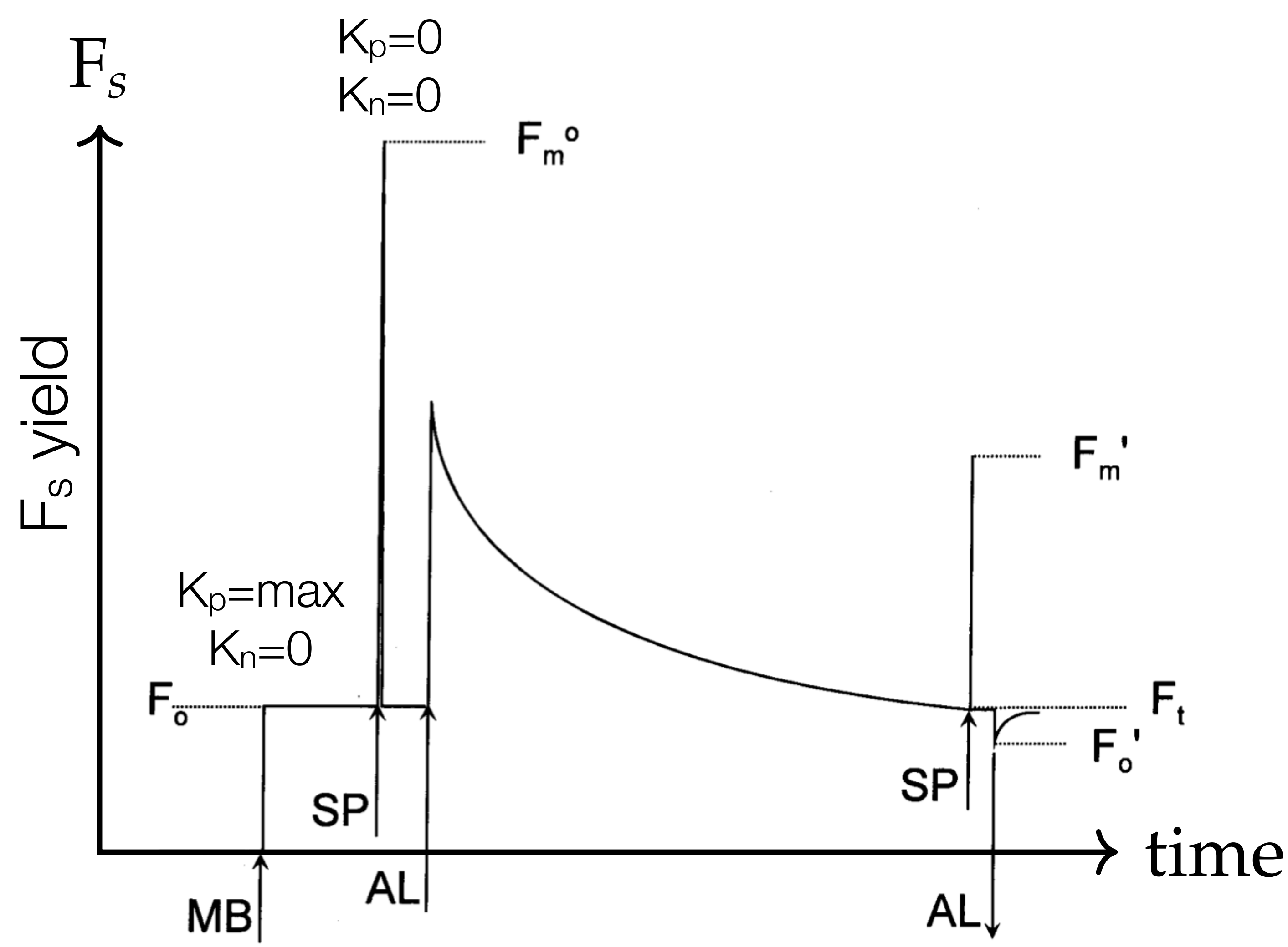

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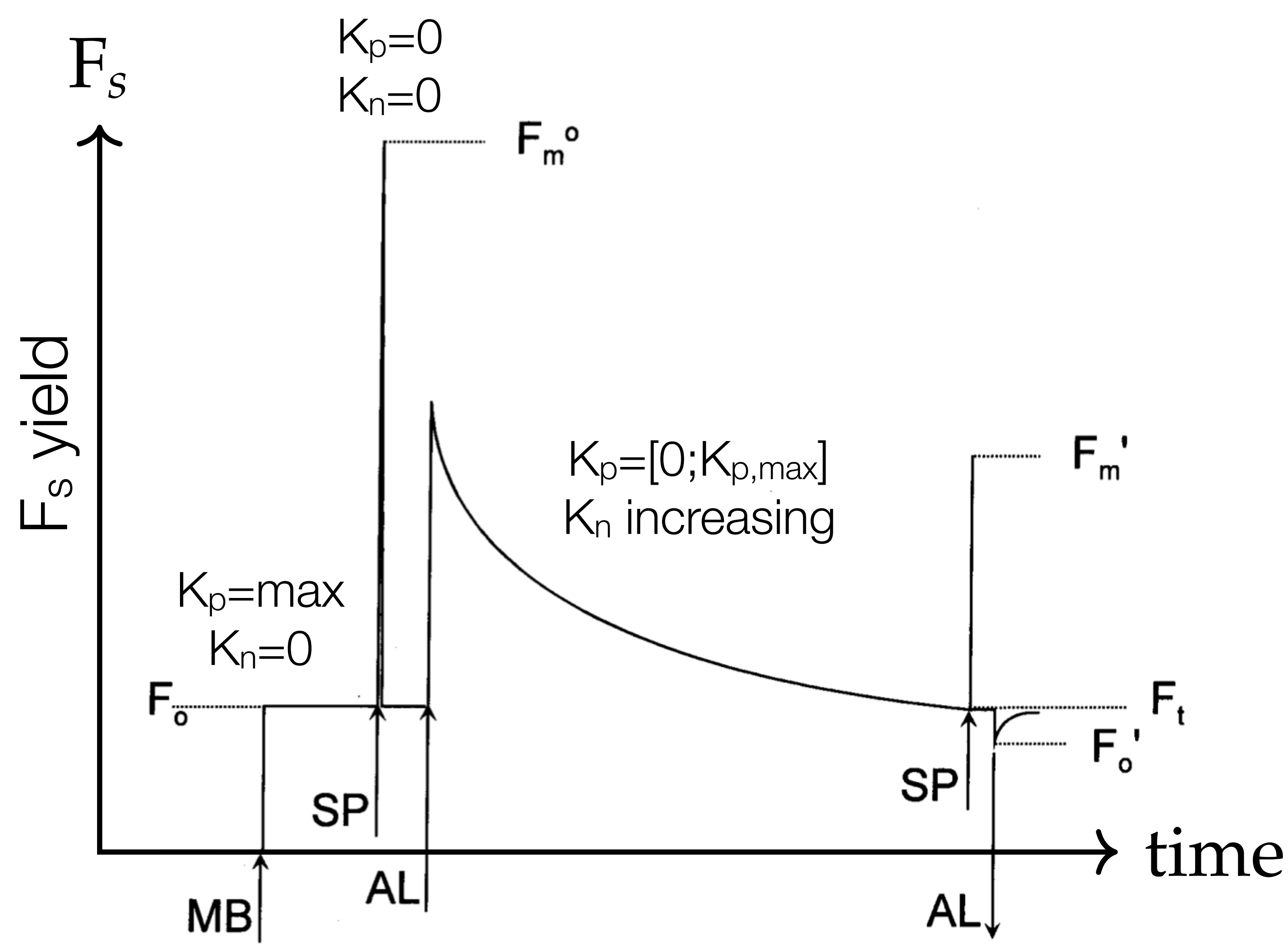

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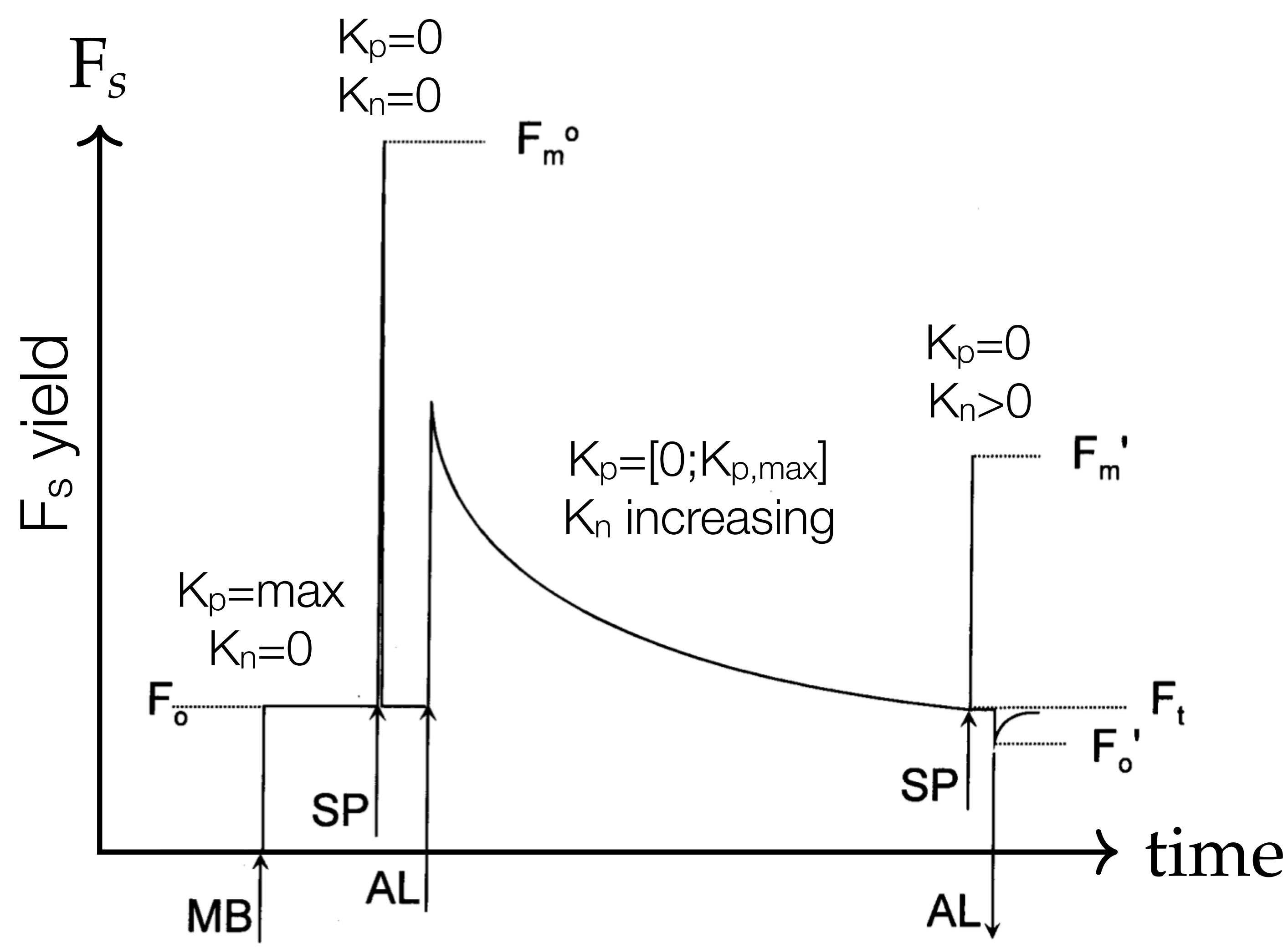

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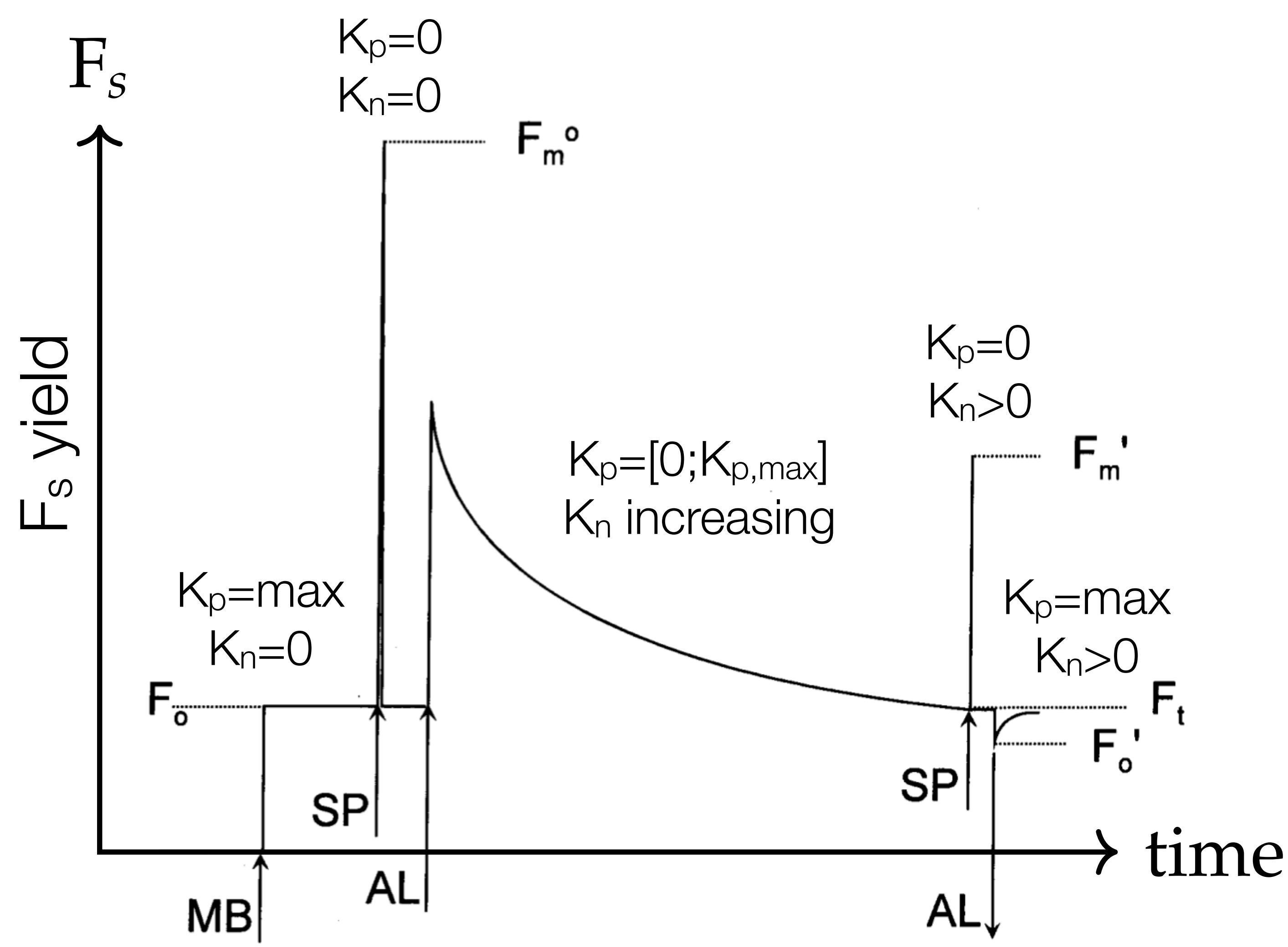

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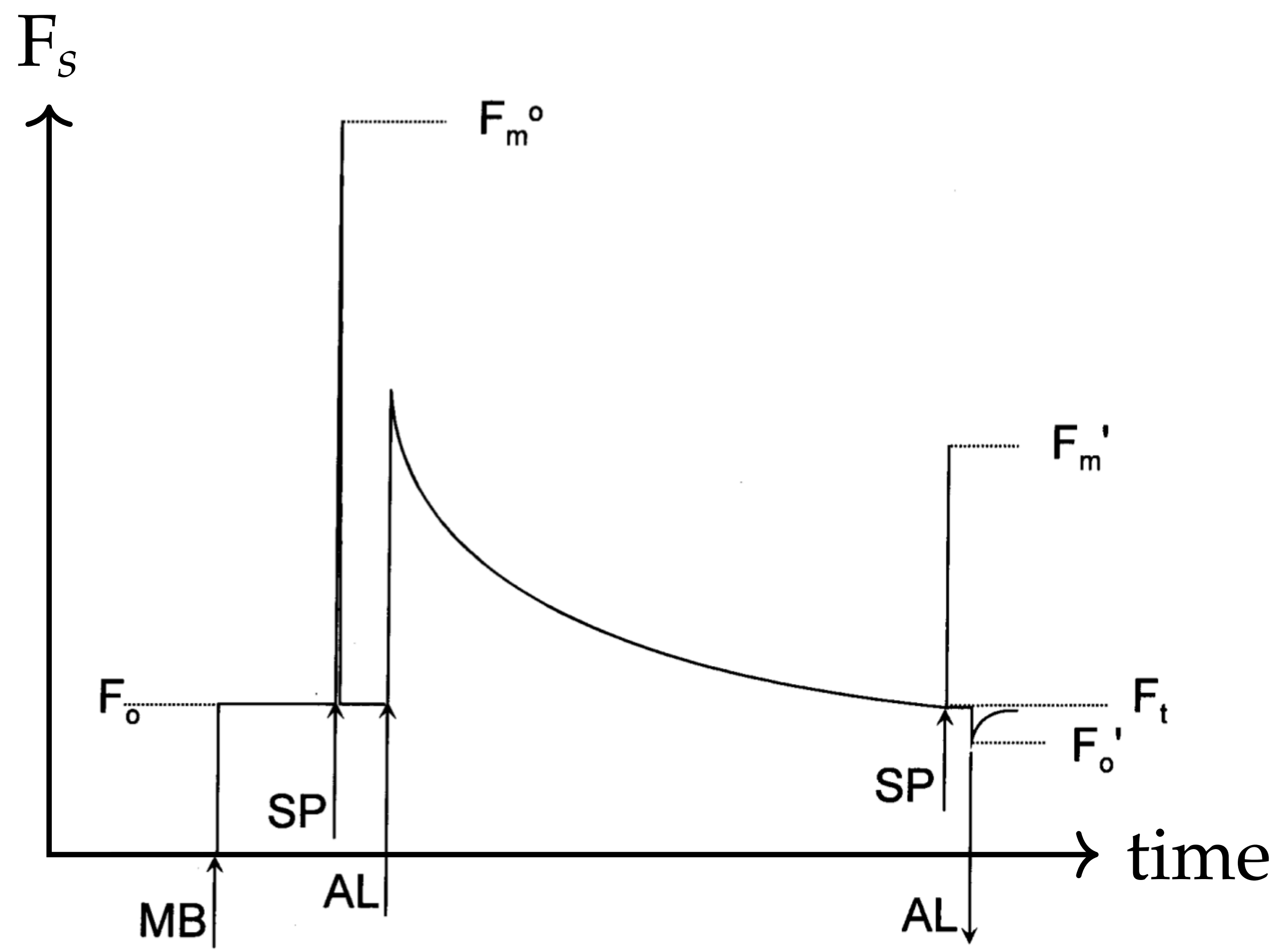
THE POWER OF ACTIVE FLUOROMETRY



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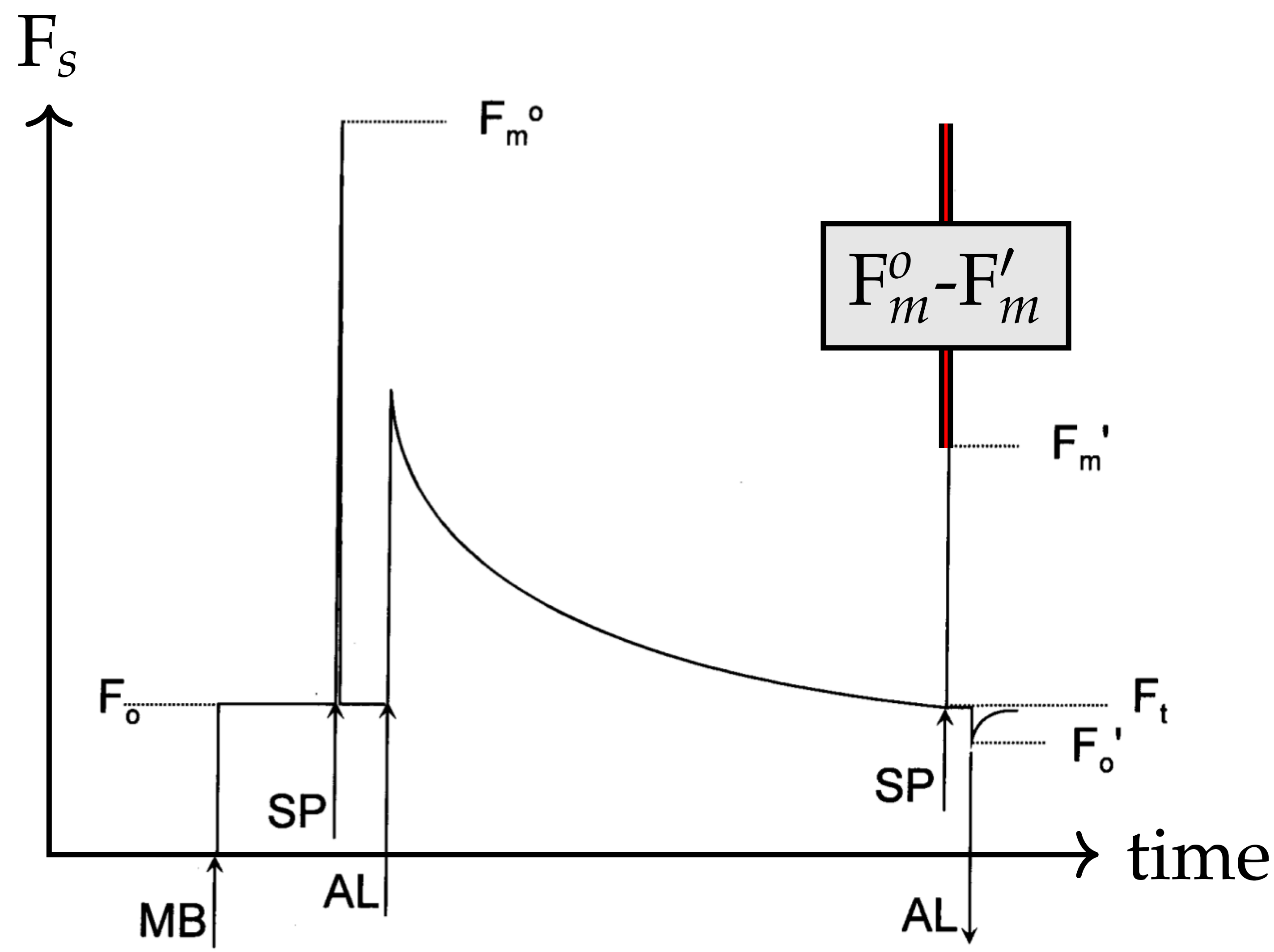
- NPQ = $(F_m^o - F_m')/F_m'$



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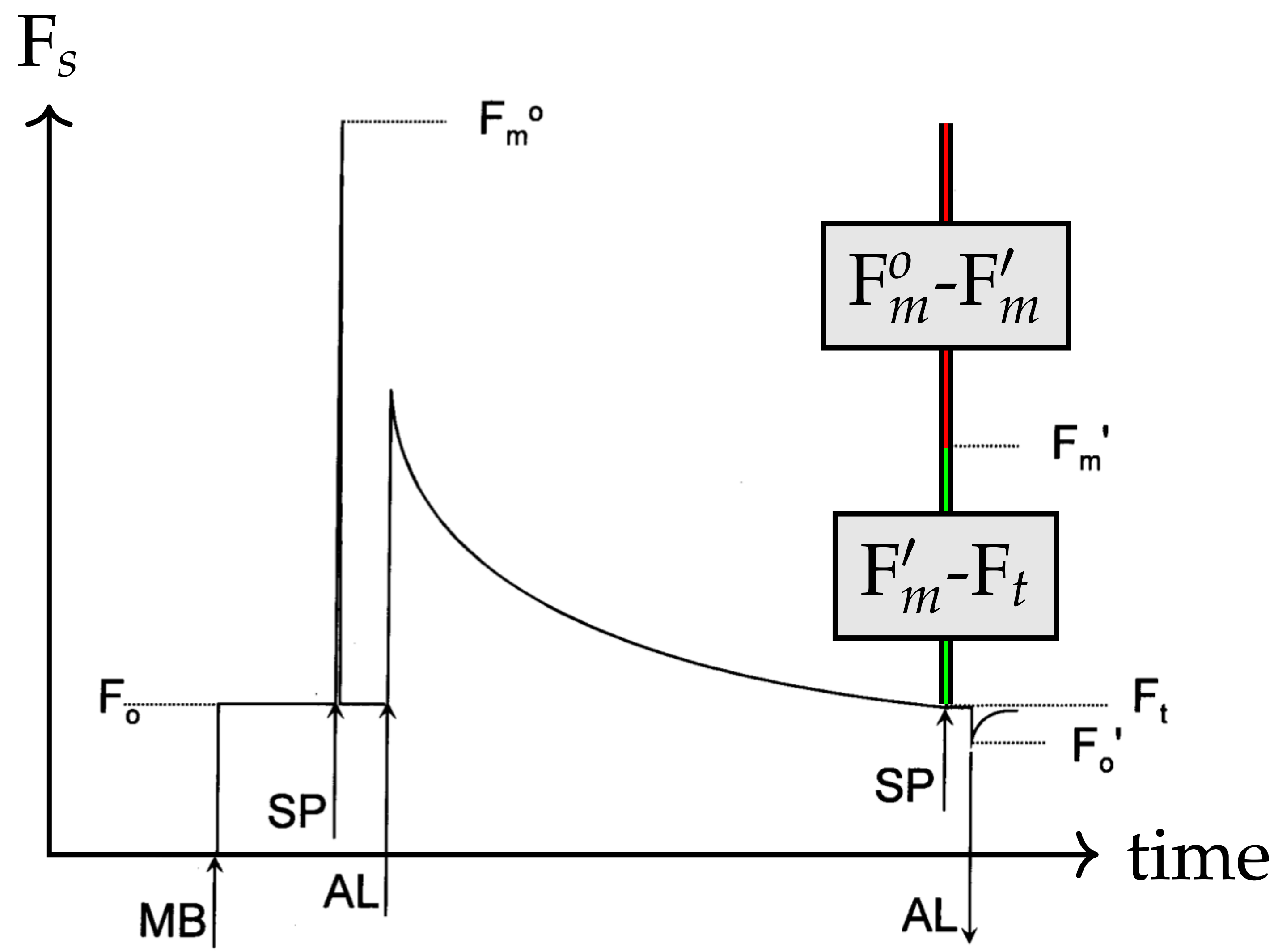
- NPQ = $(F_m^o - F_m')/F_m'$
- $\Phi_{PSII} = (F_m' - F_t)/F_m'$

Genty, Briantais, Baker (1988), >5000 citations



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THE POWER OF ACTIVE FLUOROMETRY

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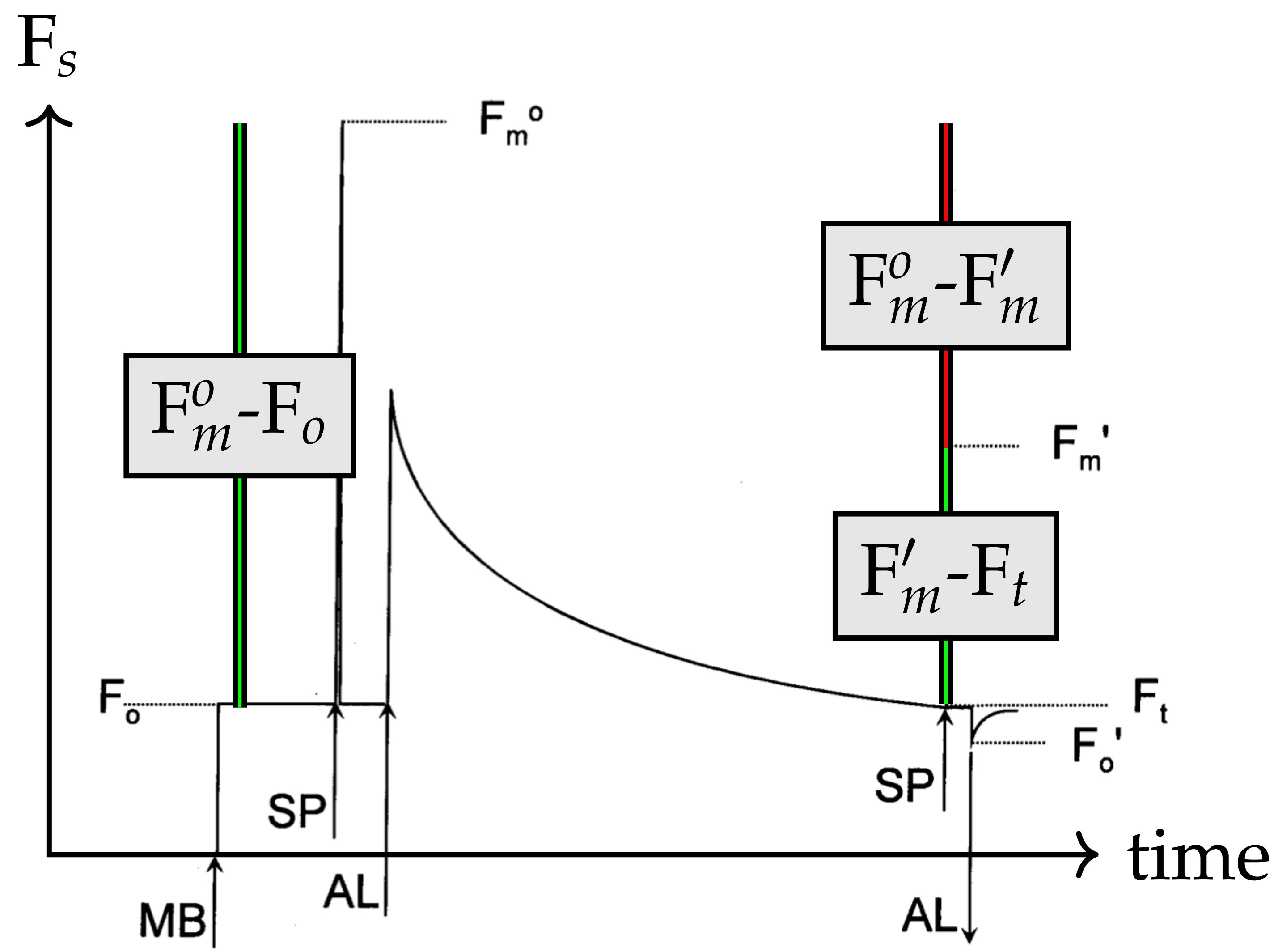
  Genty, Briantais, Baker (1988), >5000 citations
- maximum PSII yield $= (F_m - F_o)/F_m$



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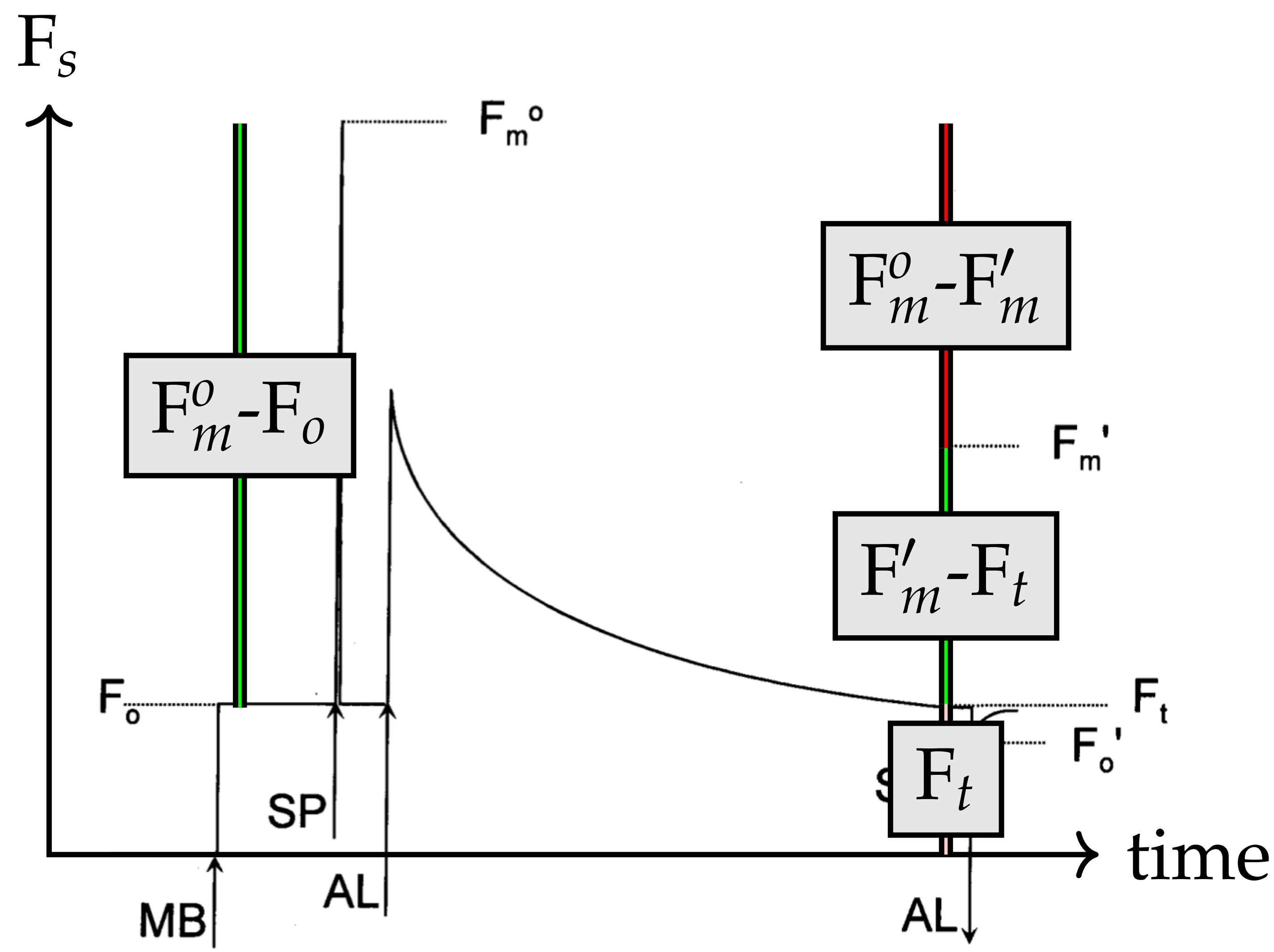
  Genty, Briantais, Baker (1988), >5000 citations
- maximum PSII yield $= (F_m - F_o)/F_m$
- steady state fluorescence F_t
- F_t * APAR is the only thing we can measure from space



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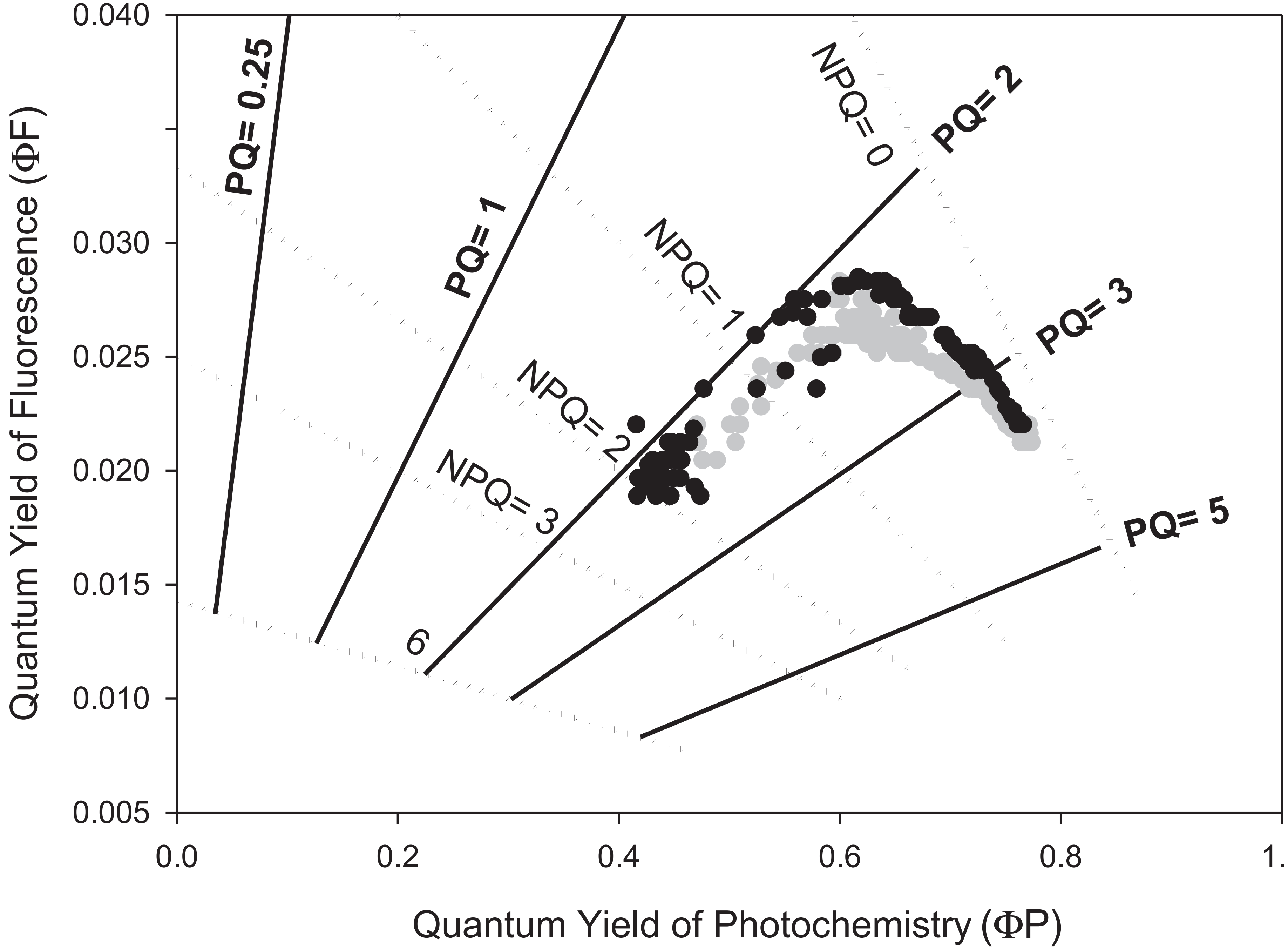
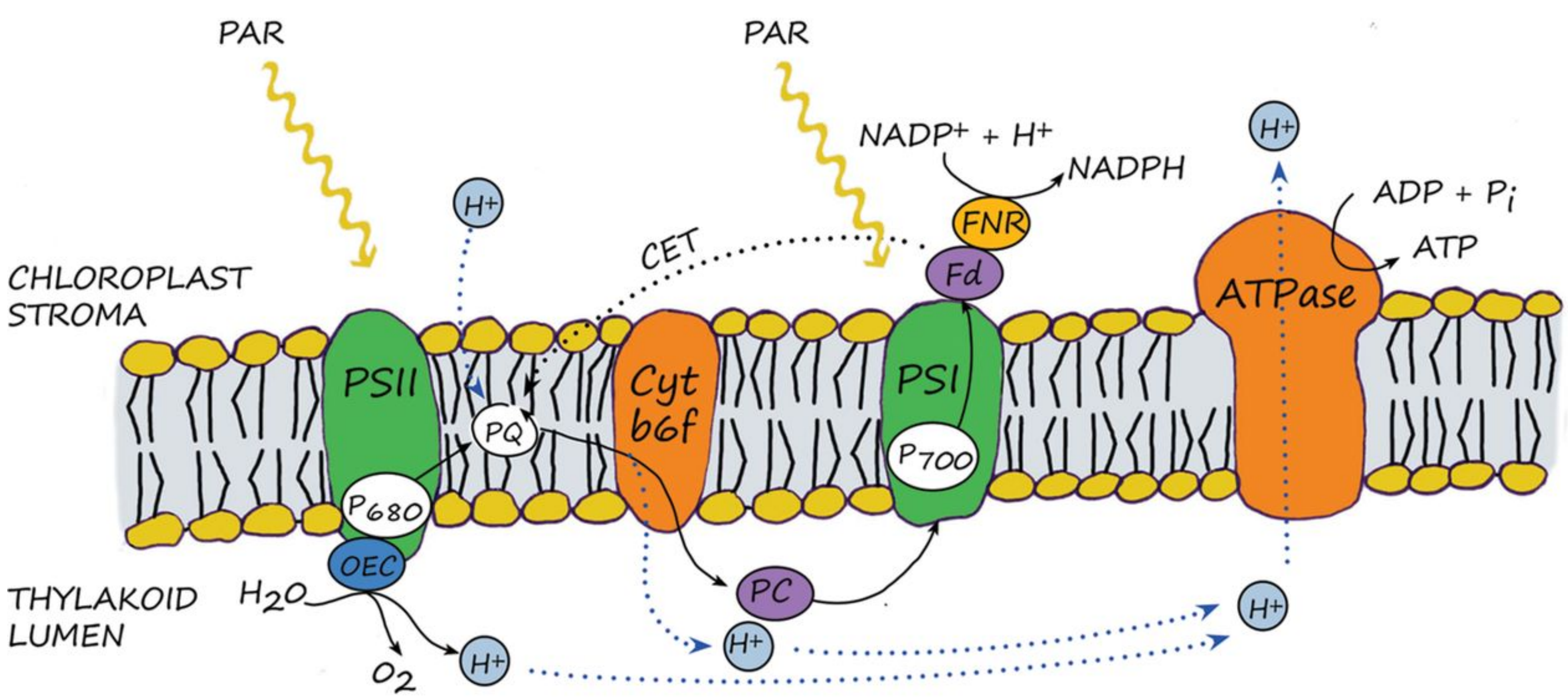
General yield relationship



from Porcar-Castell et al (2014)

The leaf scale (why interested in SIF spectra?)



Porcar-Castell et al- Review paper

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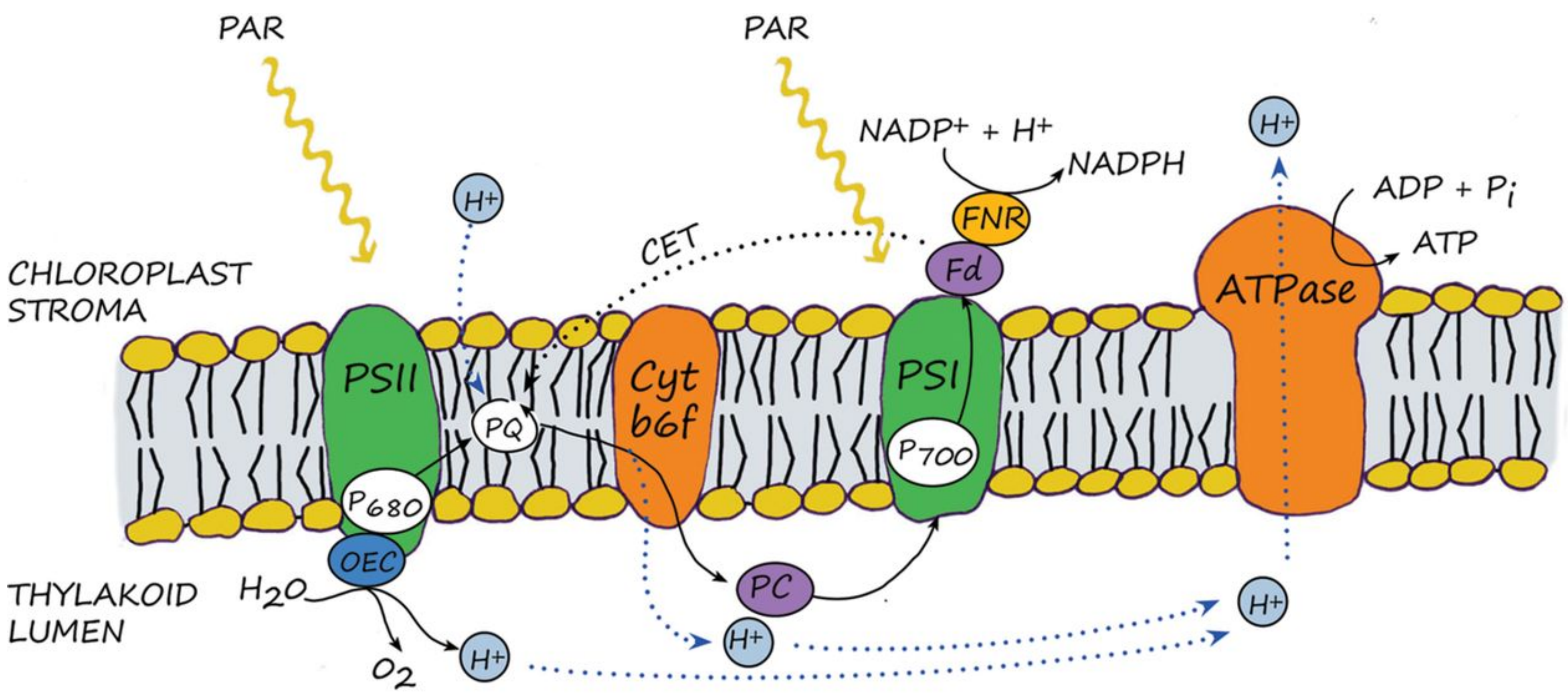

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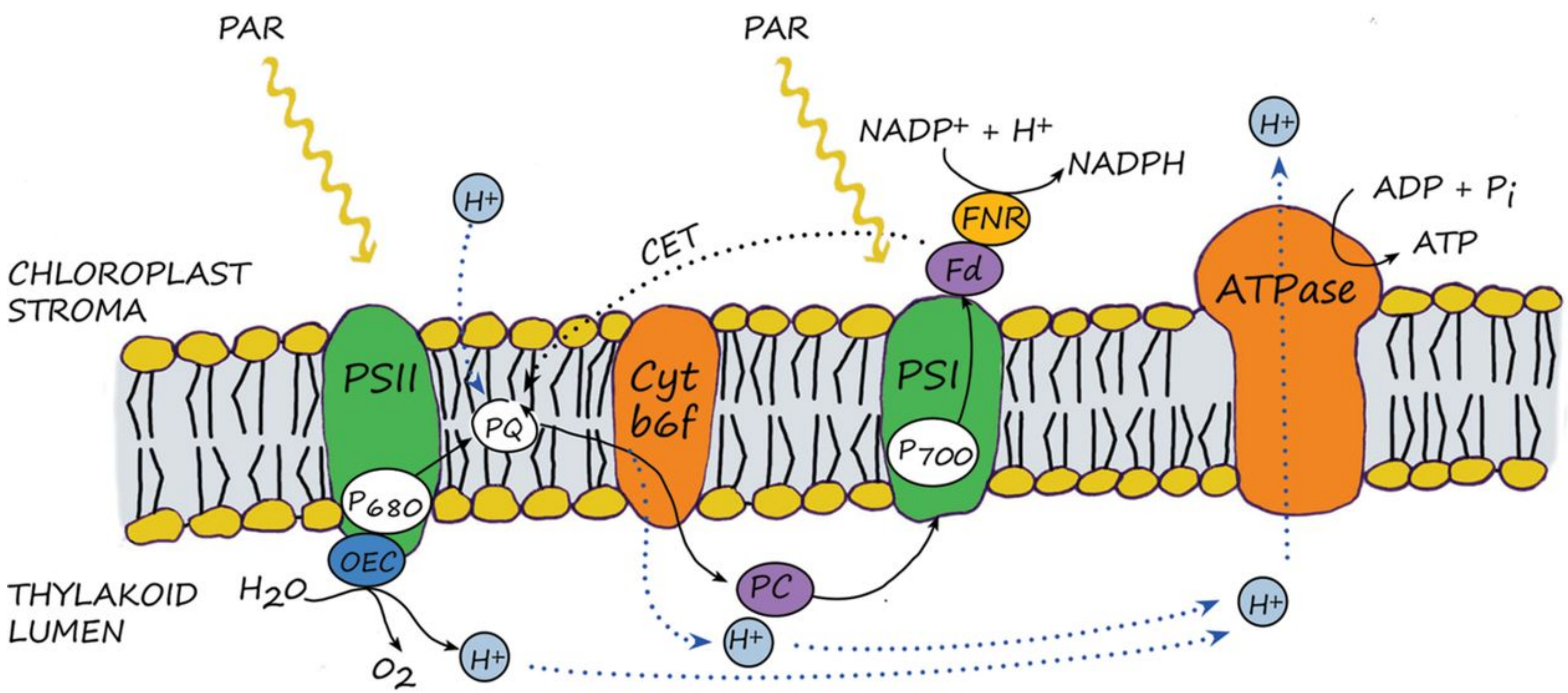

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K_p is variable

back transfer of excitation at too high ETR

K_p constant

steeper redox gradient, $P700^+$ itself a quencher

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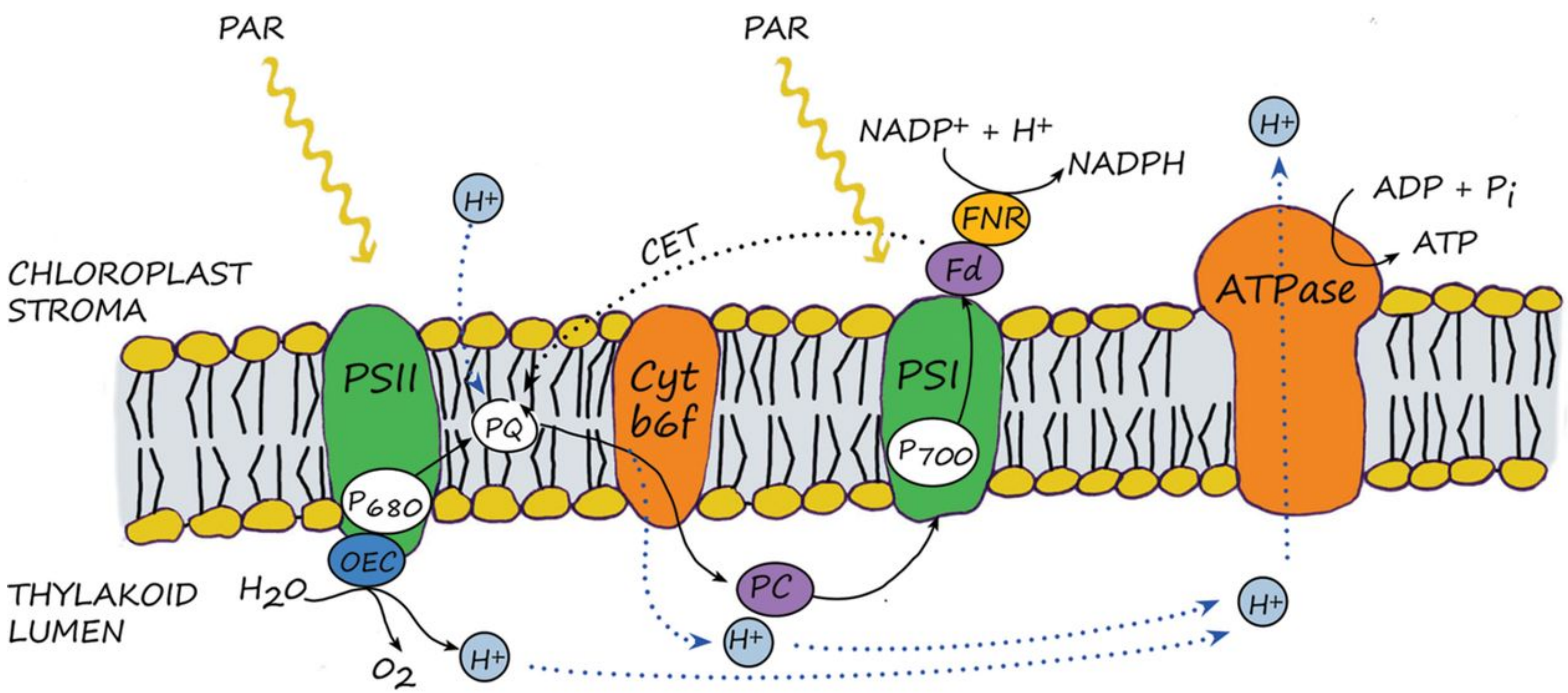

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K_n is variable

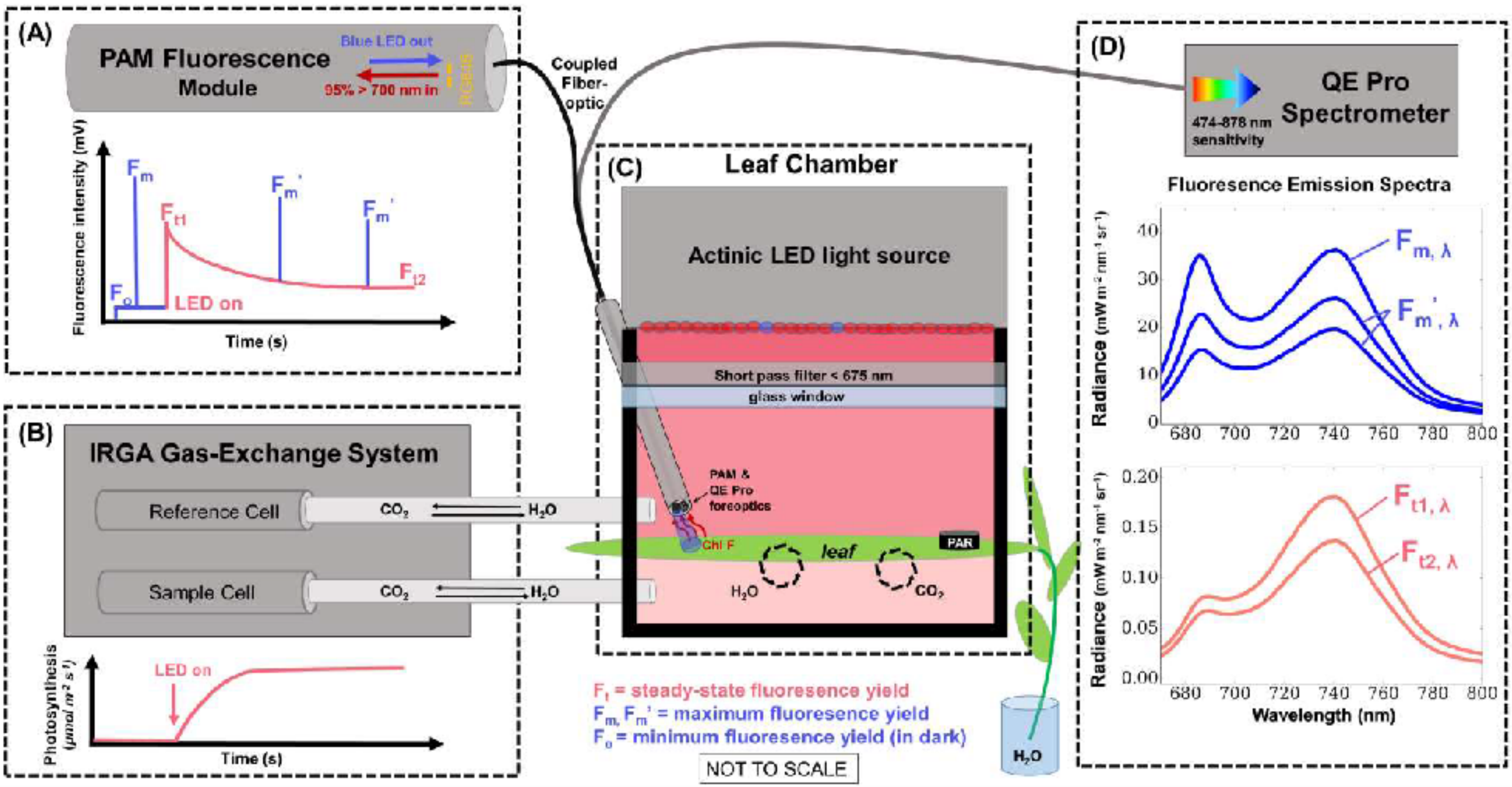
Quenching in antenna system

K_n ??

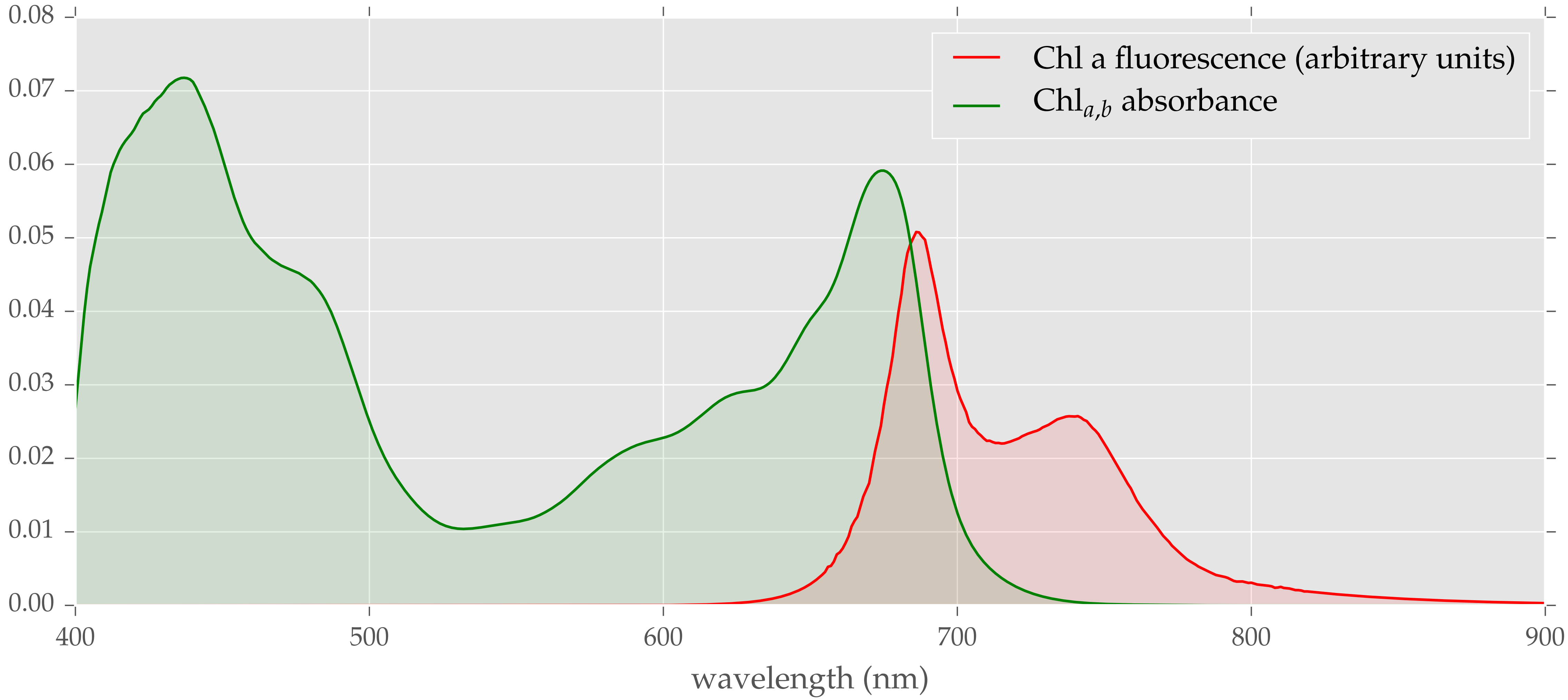
assumed constant

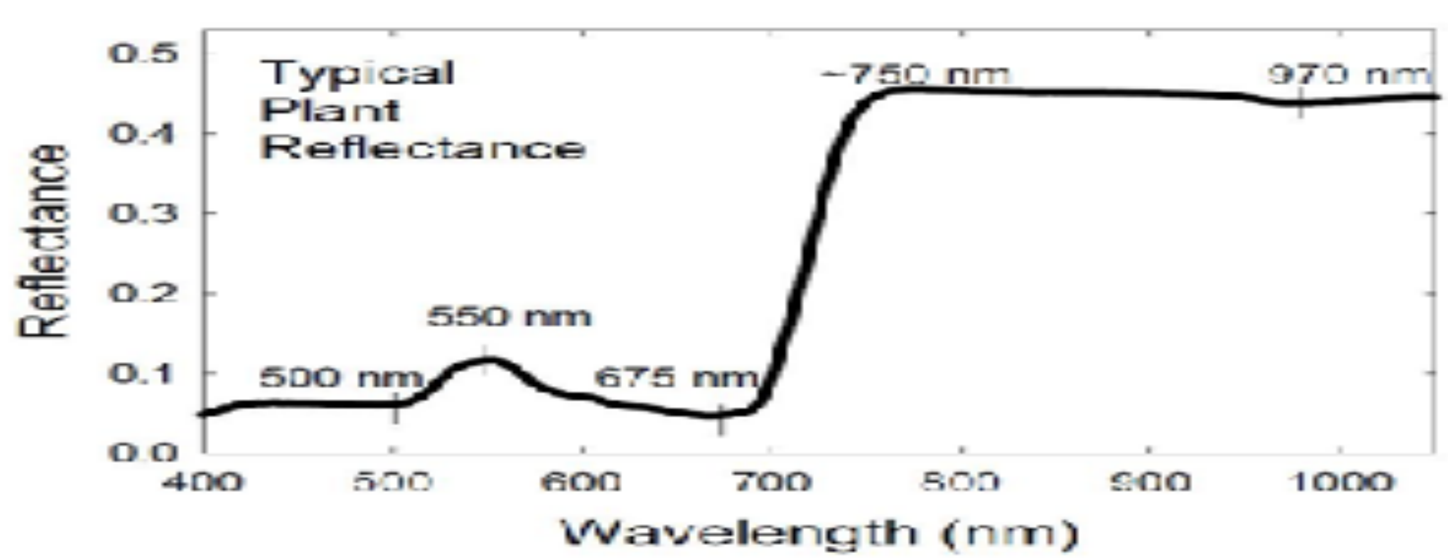
Combine PAM with SIF spectral shape measurements
A modified WALZ GFS-3000 system

Magney, Frankenberg et al, **New Phytologist 2017**



Remote Sensing of vegetation and SIF

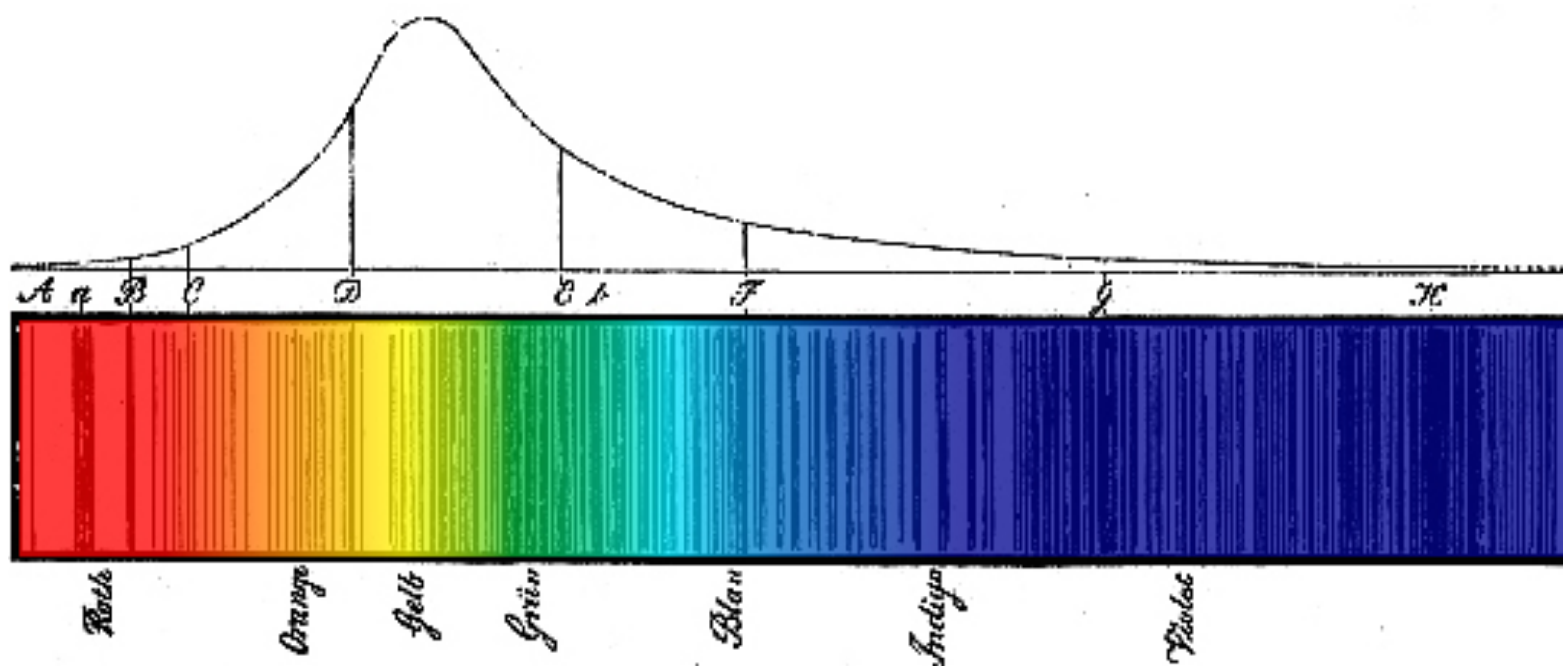


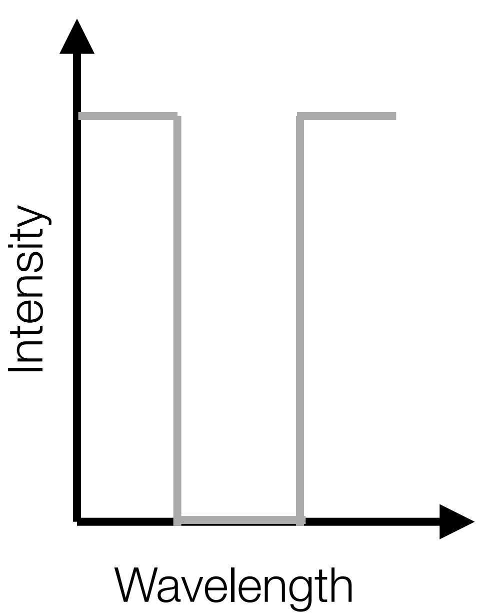


KISS director has a relevant hobby

Land Surface Remote Sensing (©NIR photography picture from Tom Prince, Caltech)

How to measure an additive signal?





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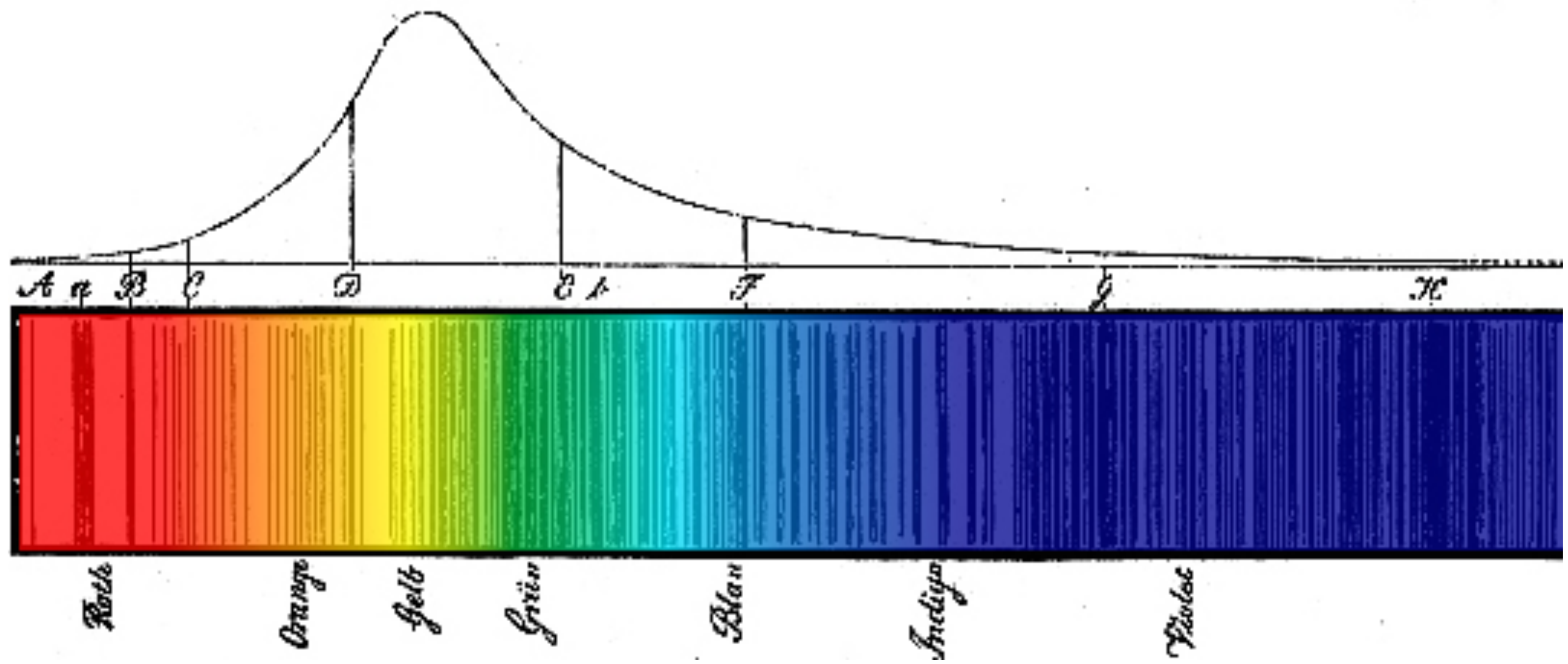

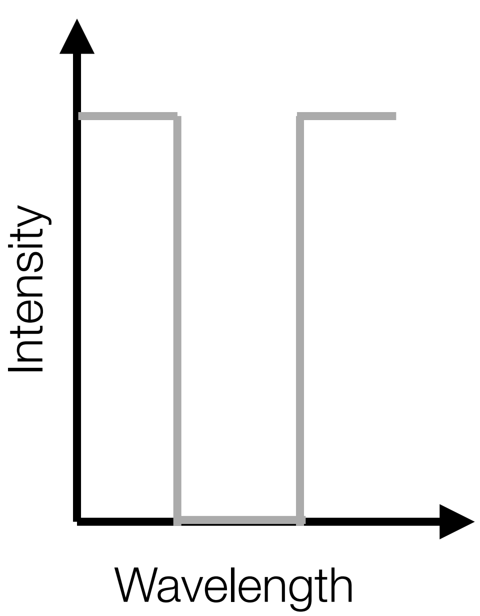

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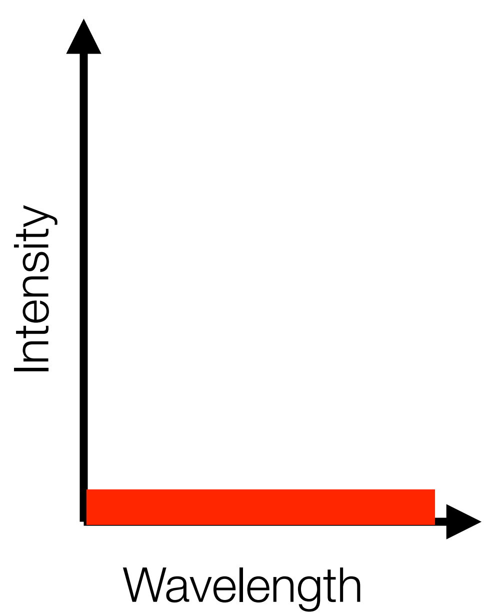

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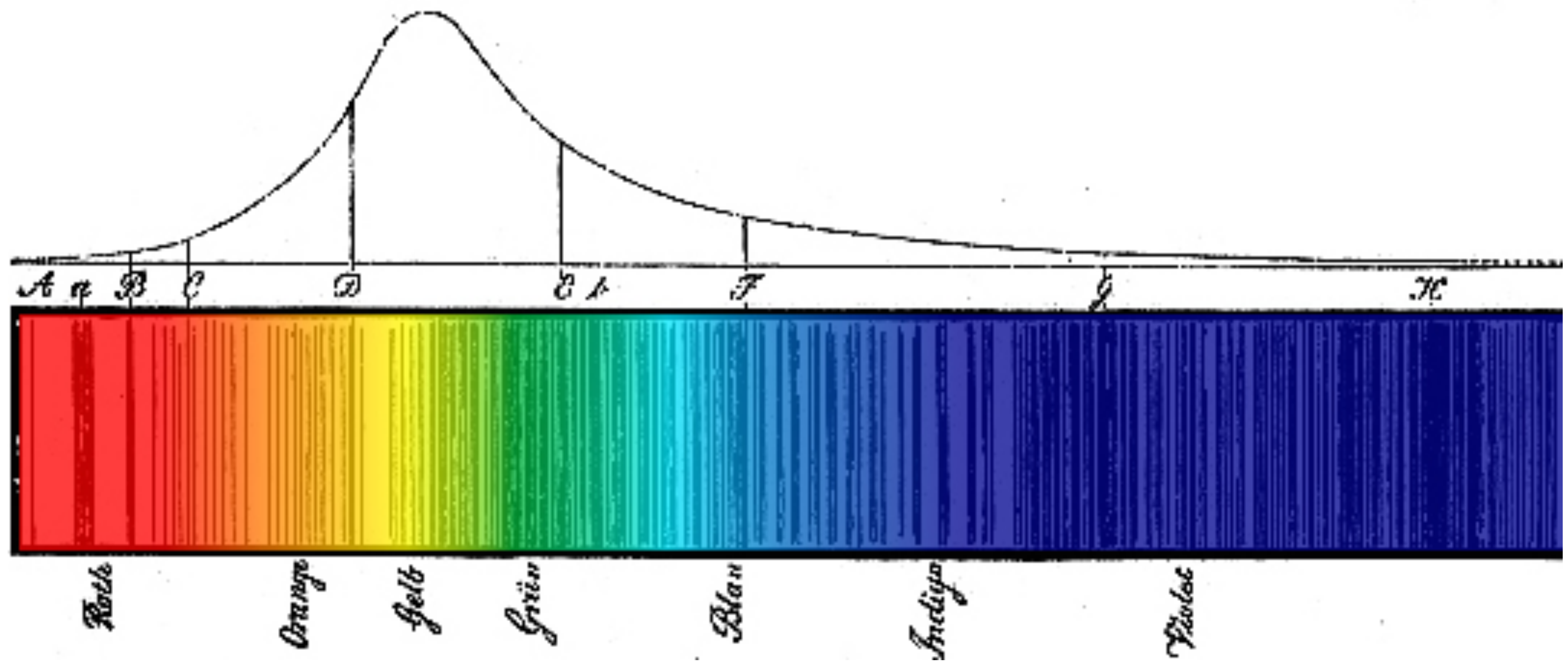

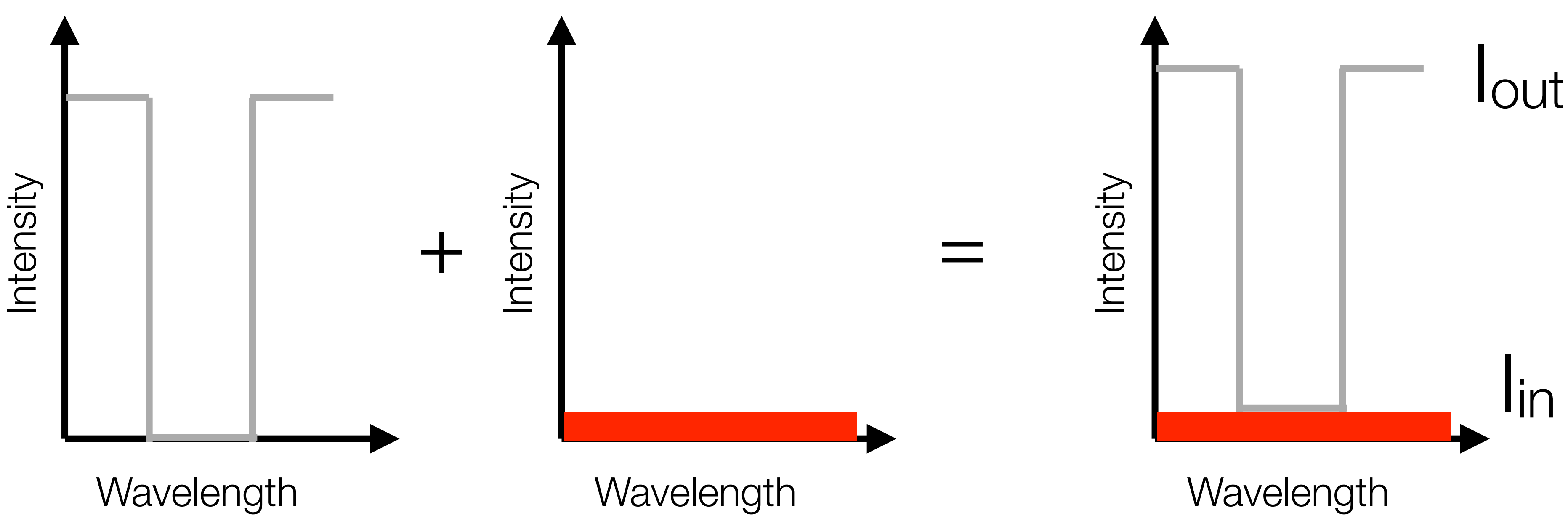

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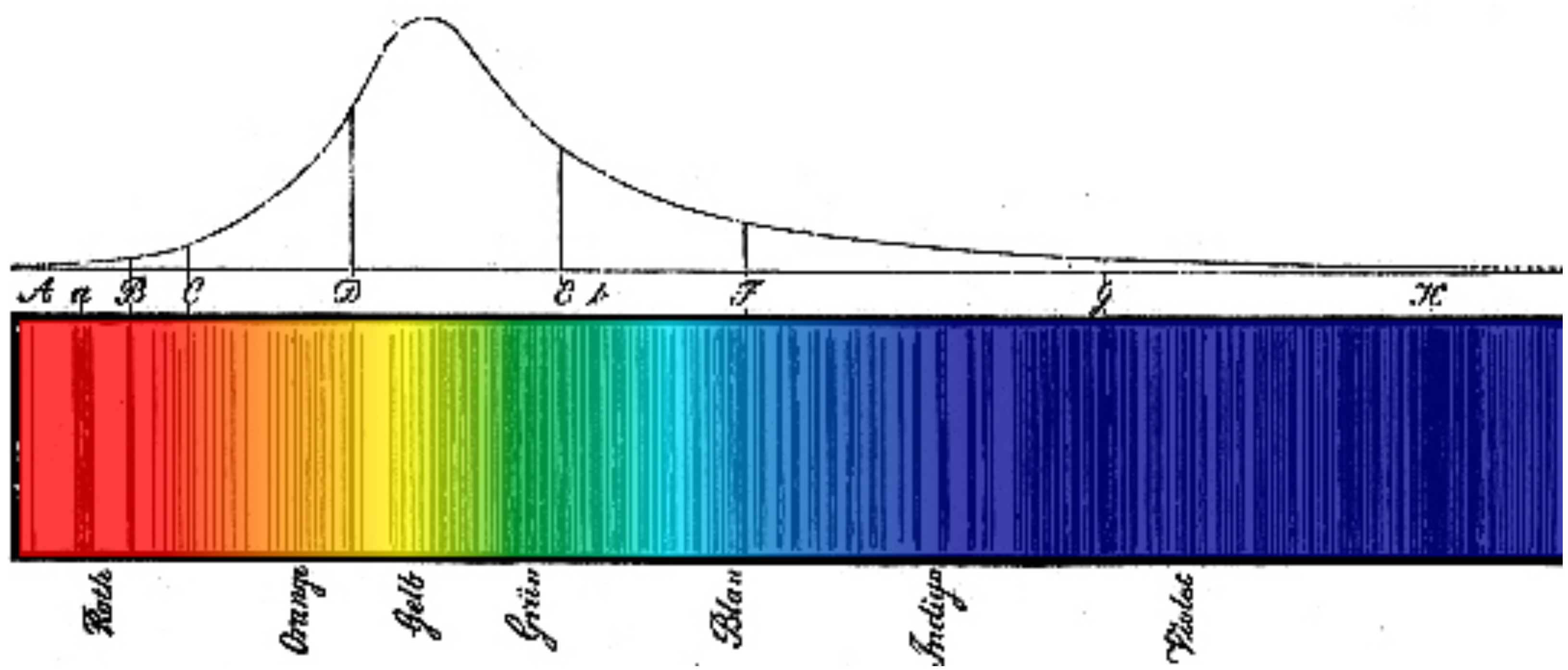

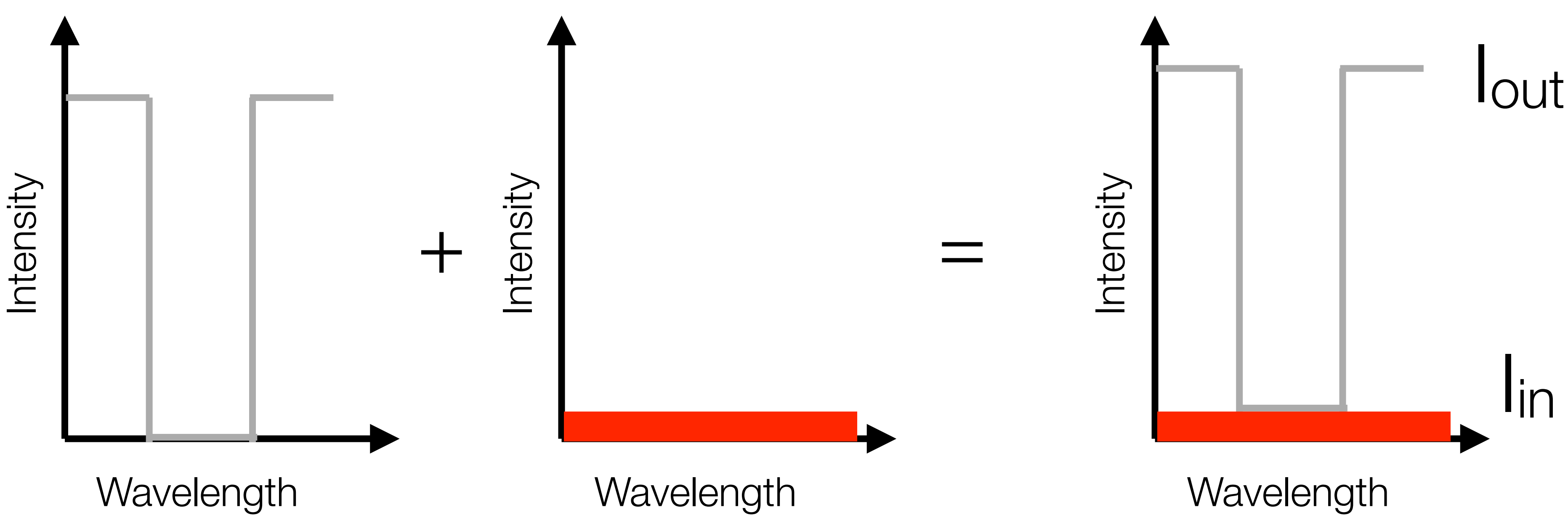

I_{in}/I_{out}

changes!

History of Fraunhofer line in-filling studies

Lunar Luminescence (1950-1960), started with NA Kozyrev in 1956

Luminescence of the Moon and Solar Activity

Zdeněk Kopal

Department of Astronomy, University of Manchester, Manchester, England

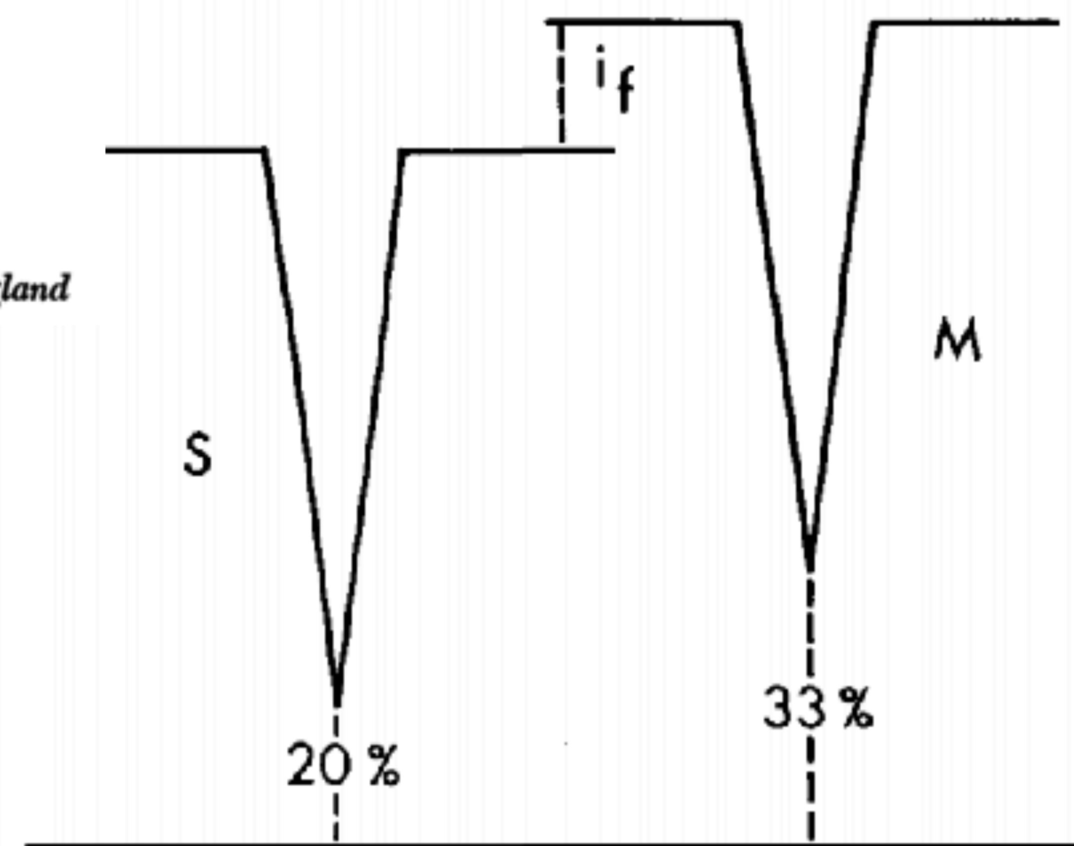

FIGURE 9-2: The line-depth method of detecting luminescence calls for comparing profiles of absorption lines in the spectra A of the sun (*left*) and moon (*right*). An increase in the residual intensity in the case of the moon is a measure of the light (i_F) attributable to lunar luminescence—in this example 16.67 per cent of the total moonlight.

History of Fraunhofer line in-filling studies

Potter et al, 1984 —> unlikely to be a thermal effect (using multiple spectral ranges)

PDF

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Lunar luminescence and the filling-in of Fraunhofer lines in moonlight

A. E. Potter, W. Mendell, T. Morgan

First published: 15 November 1984 Full publication history

DOI: 10.1029/JB089iS01p0C240 View/save citation

History of Fraunhofer line in-filling studies

Grainger and Ring —> Detected Anomalous Fraunhofer Line Profiles in scattered sun-light

Letters to Nature

Nature **193**, 762 (24 February 1962) | doi:10.1038/193762a0

Anomalous Fraunhofer Line Profiles

J. F. GRAINGER & J. RING

1. Department of Astronomy, The University, Manchester.

DURING the spring of 1961 we made observations of the *H* line of Ca(II) in the spectrum of moonlight, with the view of detecting any luminescent radiation which might have been present. The observations were made with the 50-in. reflector of the University of Padua's Observatory at Asiago. [1]

History of Fraunhofer line in-filling studies

Theoretical Explanation by Brinkmann — Rotational Raman Scattering (RRS) in N_2 and O_2

ROTATIONAL RAMAN SCATTERING IN PLANETARY ATMOSPHERES*

R. T. Brinkmann

Division of Geological Sciences, California Institute of Technology, and Jet Propulsion Laboratory, Pasadena, California

Received March 9, 1968; revised May 24, 1968

ABSTRACT

When spectra of deep solar Fraunhofer lines recorded in sunlight scattered by the Earth's atmosphere are compared with similar spectra of direct, unscattered sunlight, it is found that the scattered line profiles are systematically less deep (relative to the continuum) than the direct profiles by a few per cent. This has been taken to indicate the presence of an extra, inelastic component of the scattered radiation field. Its nature has remained unexplained. In this paper it is pointed out that rotational Raman scattering in the atmosphere can be expected to produce just such an extra component. Previous observational work is reviewed and interpreted in light of this explanation. The magnitude of the effect in the atmospheres of other planets is also briefly explored.

History of Fraunhofer line in-filling studies

In-depth study by Kattawar et al in 1980, RRS henceforth called “Ring” effect

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INELASTIC SCATTERING IN PLANETARY ATMOSPHERES. I. THE RING EFFECT, WITHOUT AEROSOLS

GEORGE W. KATTAWAR, ANDREW T. YOUNG, AND TERRY J. HUMPHREYS
Texas A & M University

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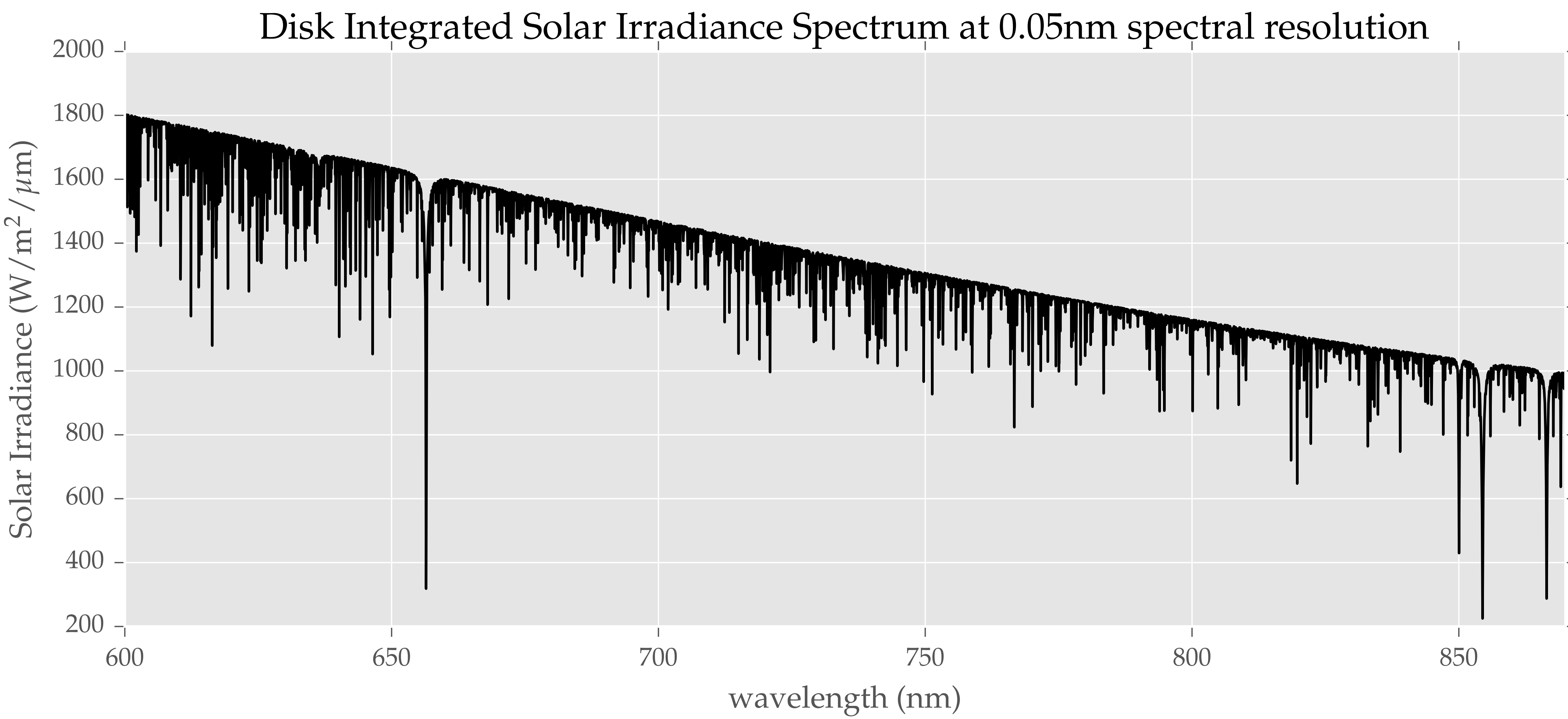
ABSTRACT

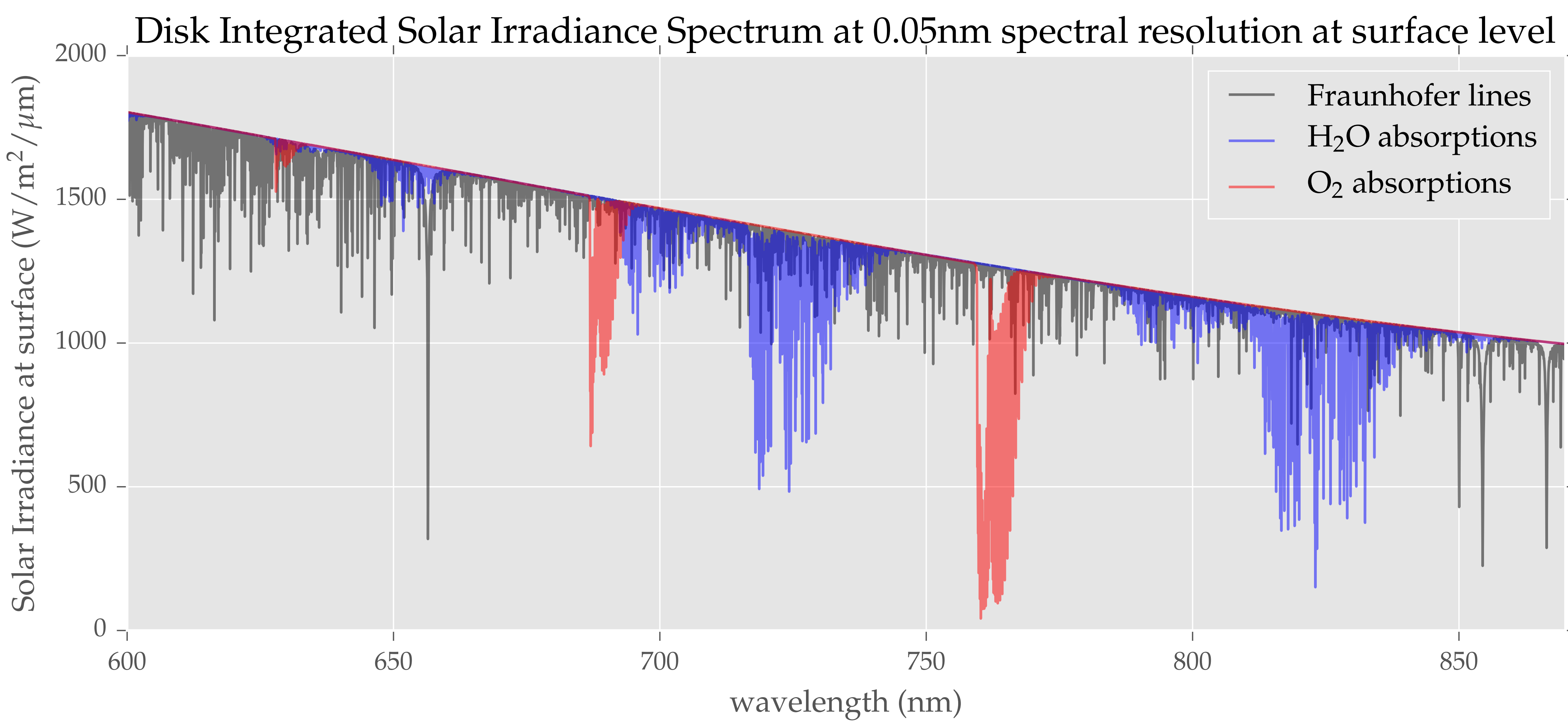
We have investigated the contribution of inelastic molecular scattering (Rayleigh-Brillouin and rotational Raman scattering) to the filling-in of Fraunhofer lines in the light of the blue sky. Aerosol fluorescence is shown to be negligible, and aerosol scattering is ignored in this paper. We discuss the angular and polarization dependences of the filling-in detail for single scattering. An approximate treatment of multiple scattering, using a backward Monte Carlo technique, allows us to investigate the effects of the ground albedo. As the molecular scatterings alone produce more line-filling than is observed, it seems likely that aerosols dilute the effect by contributing unaltered sunlight to the observed spectra.

Subject headings: planets: atmospheres — polarization — radiative transfer

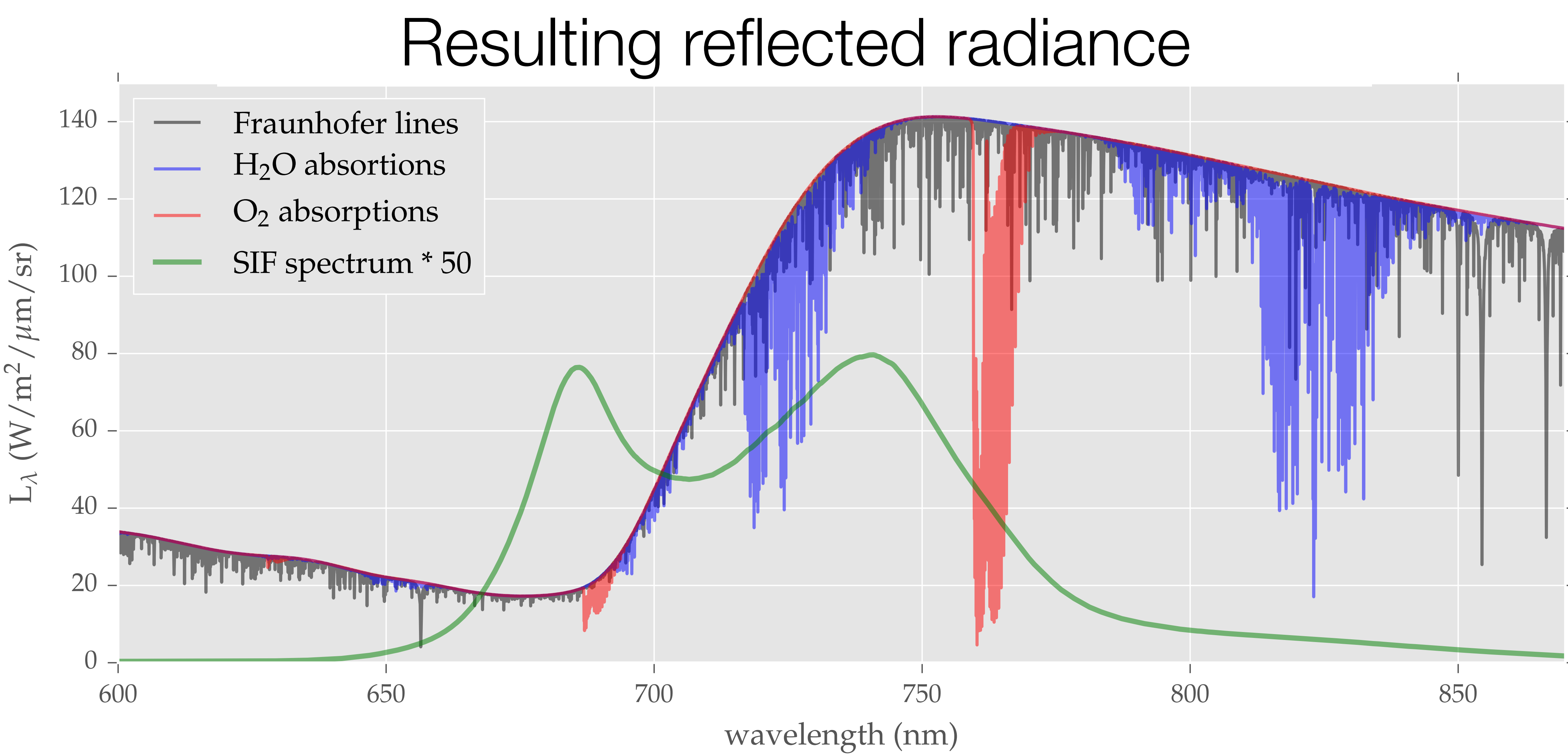
Need absorption features that are only un-changed in the atmosphere —> Fraunhofer lines are ideal



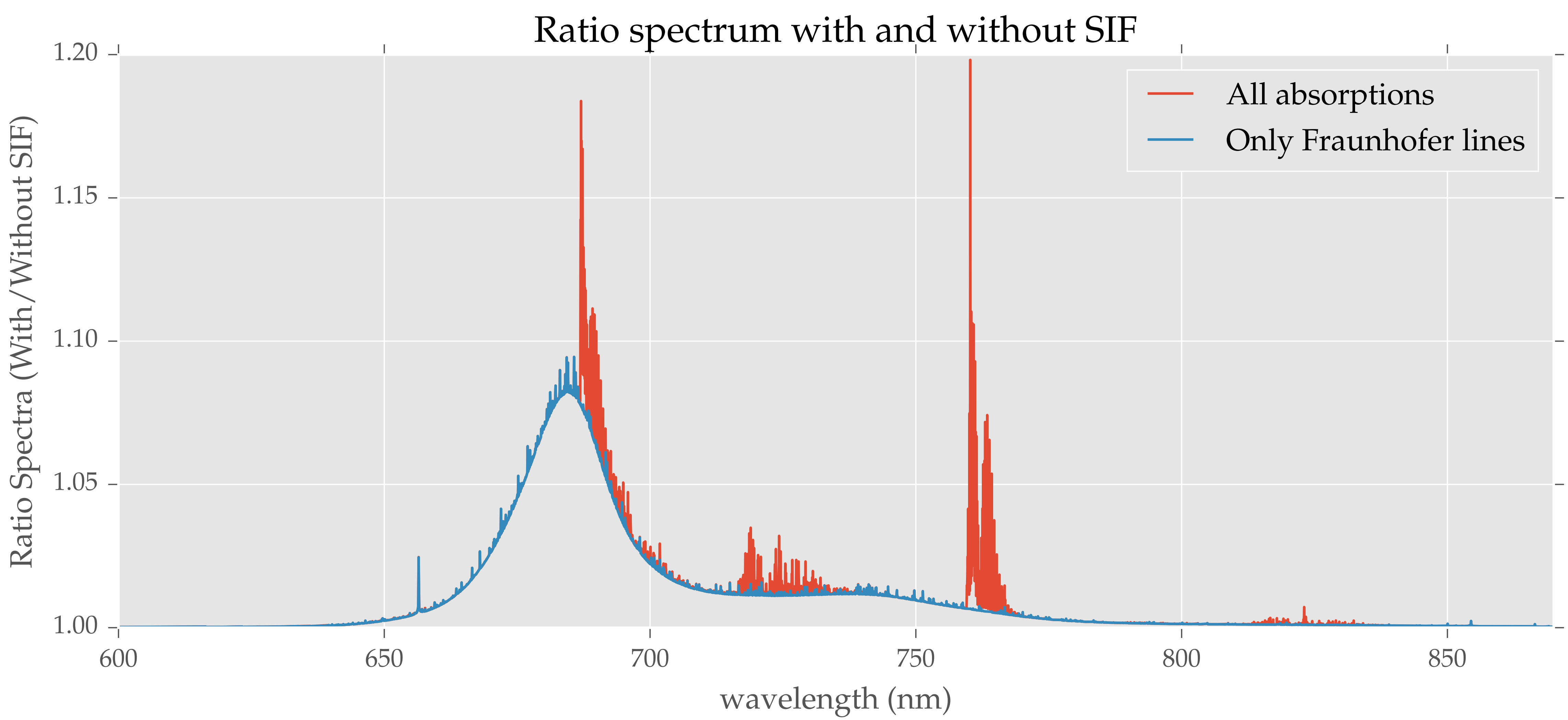
Incoming at the surface



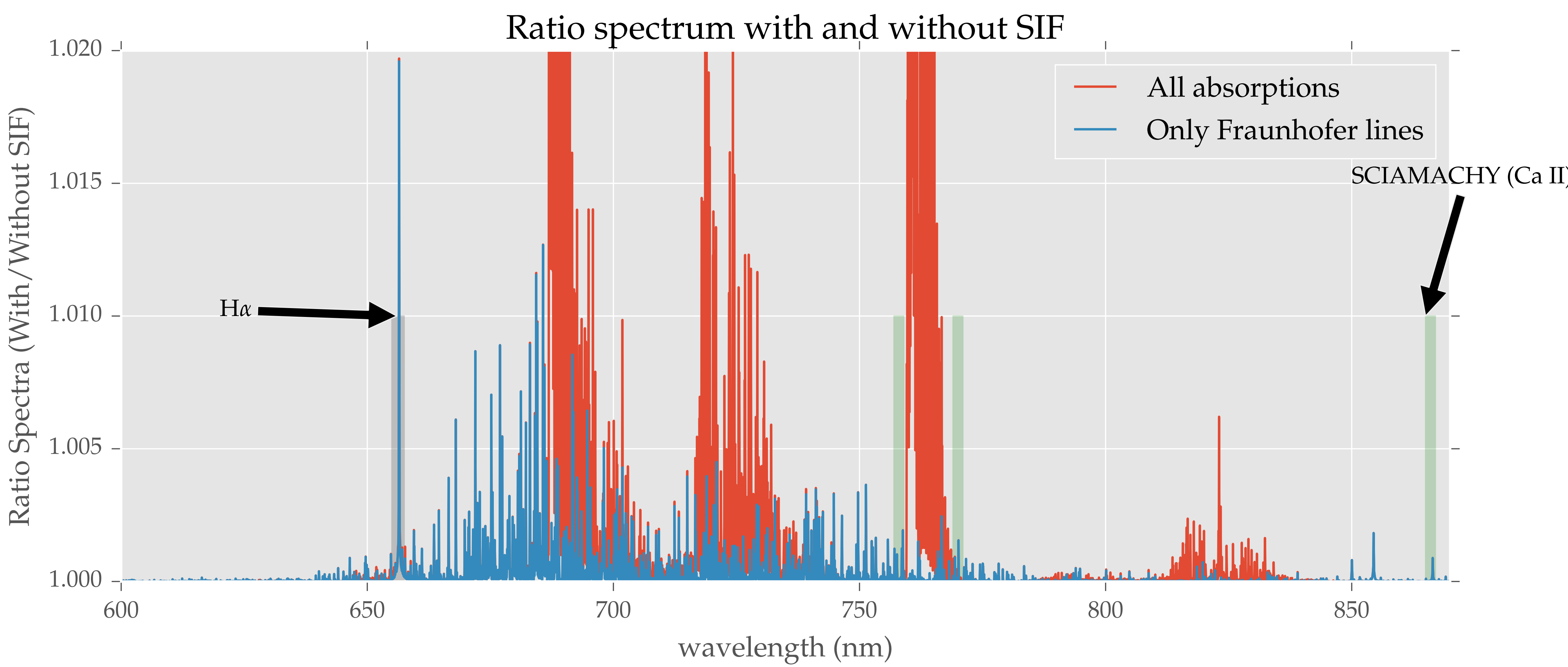
After reflection from canopy



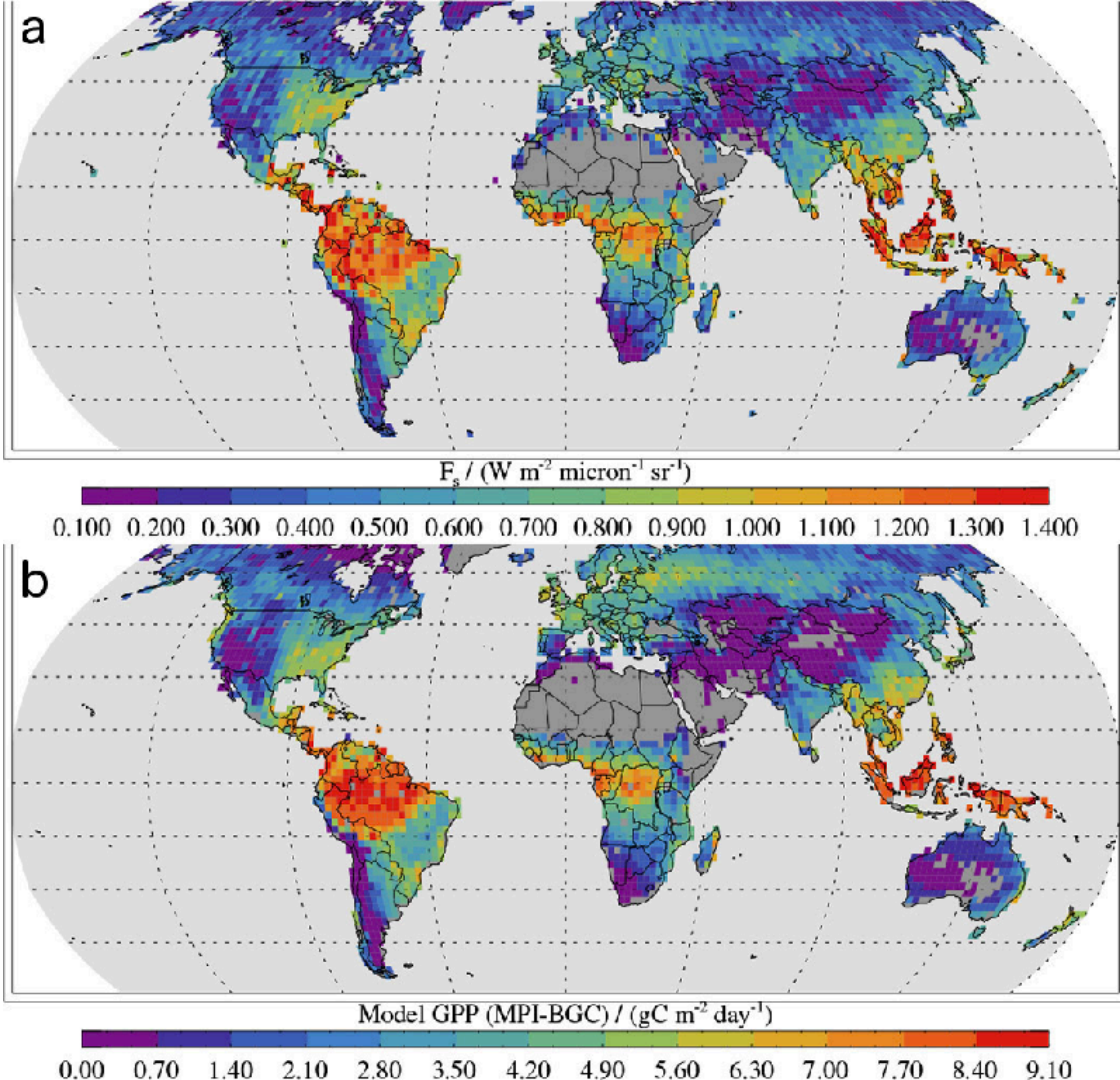
Ratio Spectrum (with/without SIF)



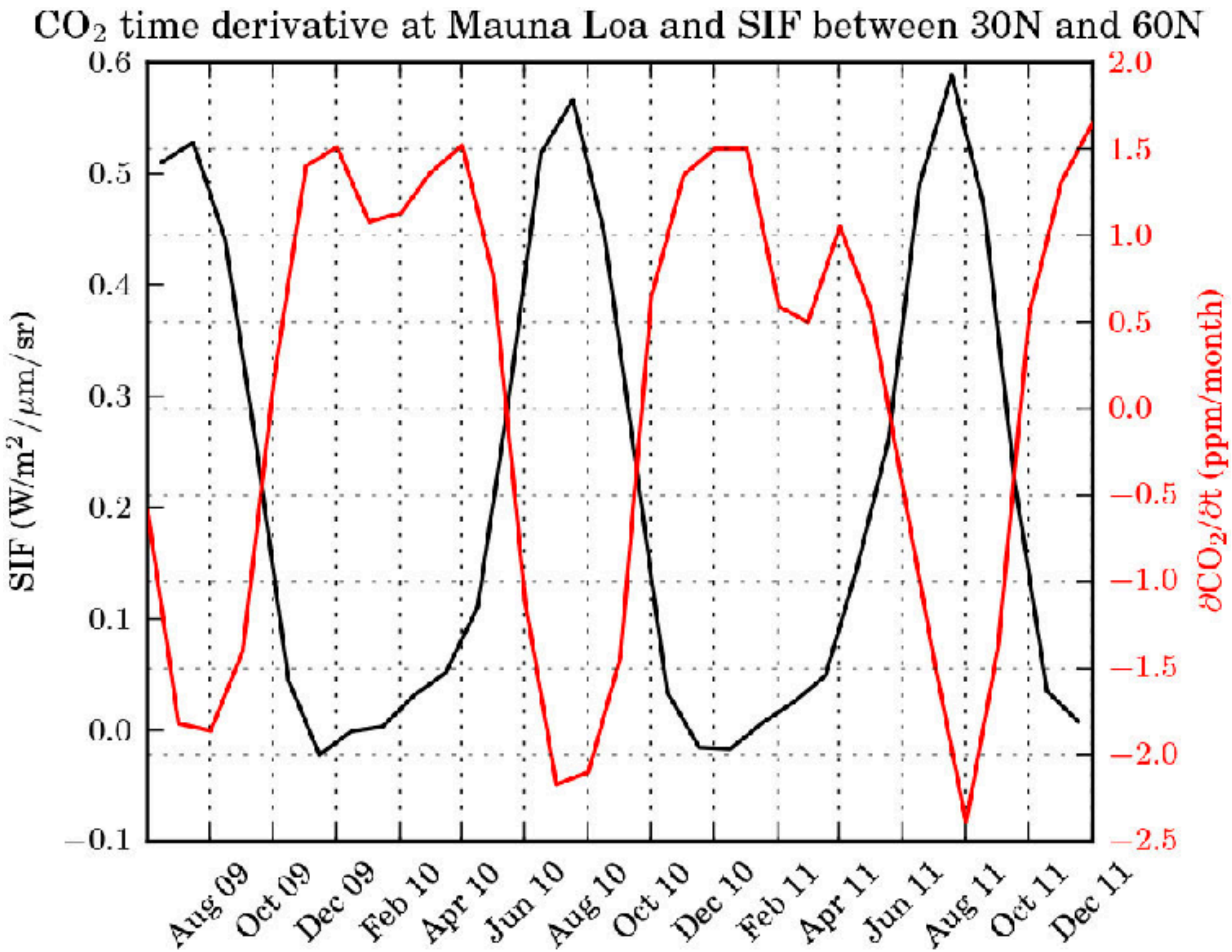
Ratio Spectrum (with/without SIF)



Earliest work with GOSAT

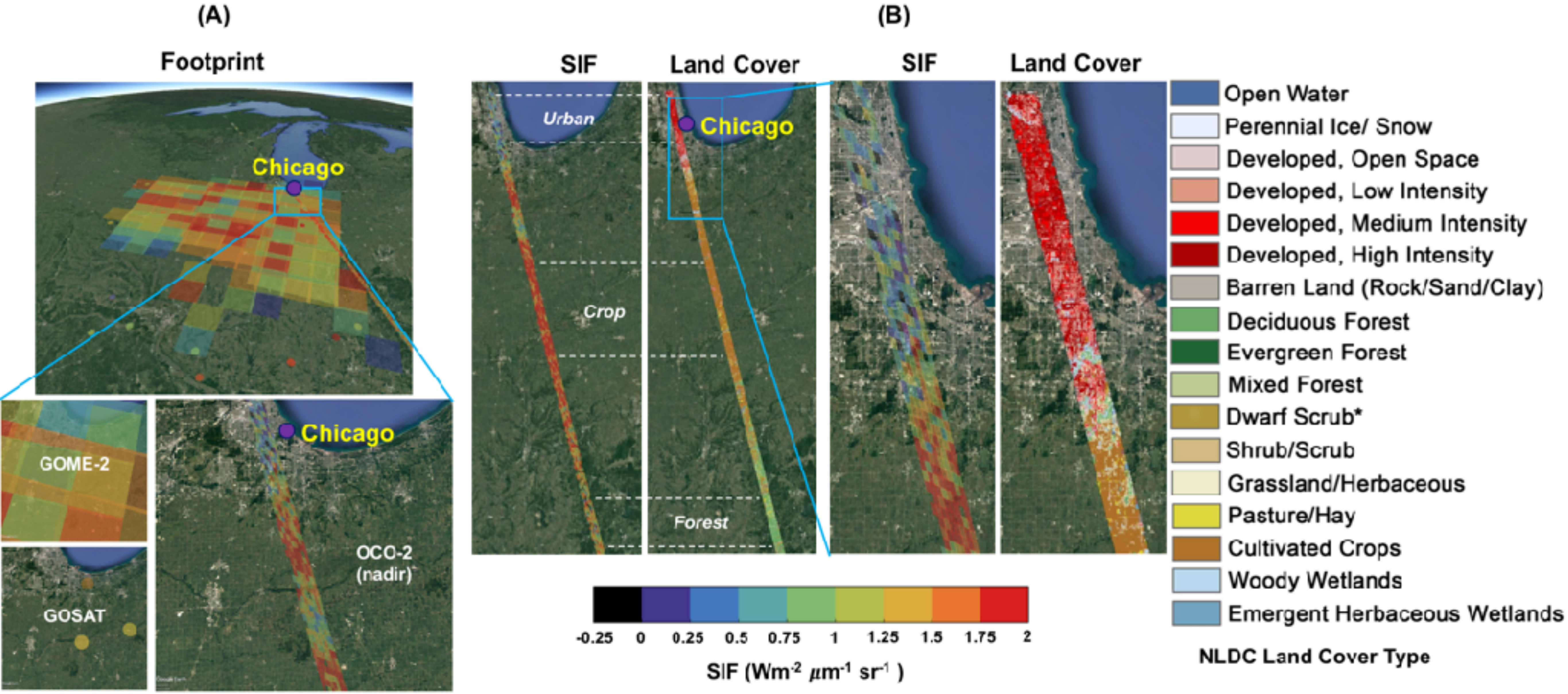


Hemispheric-scale CO_2 derivatives and SIF



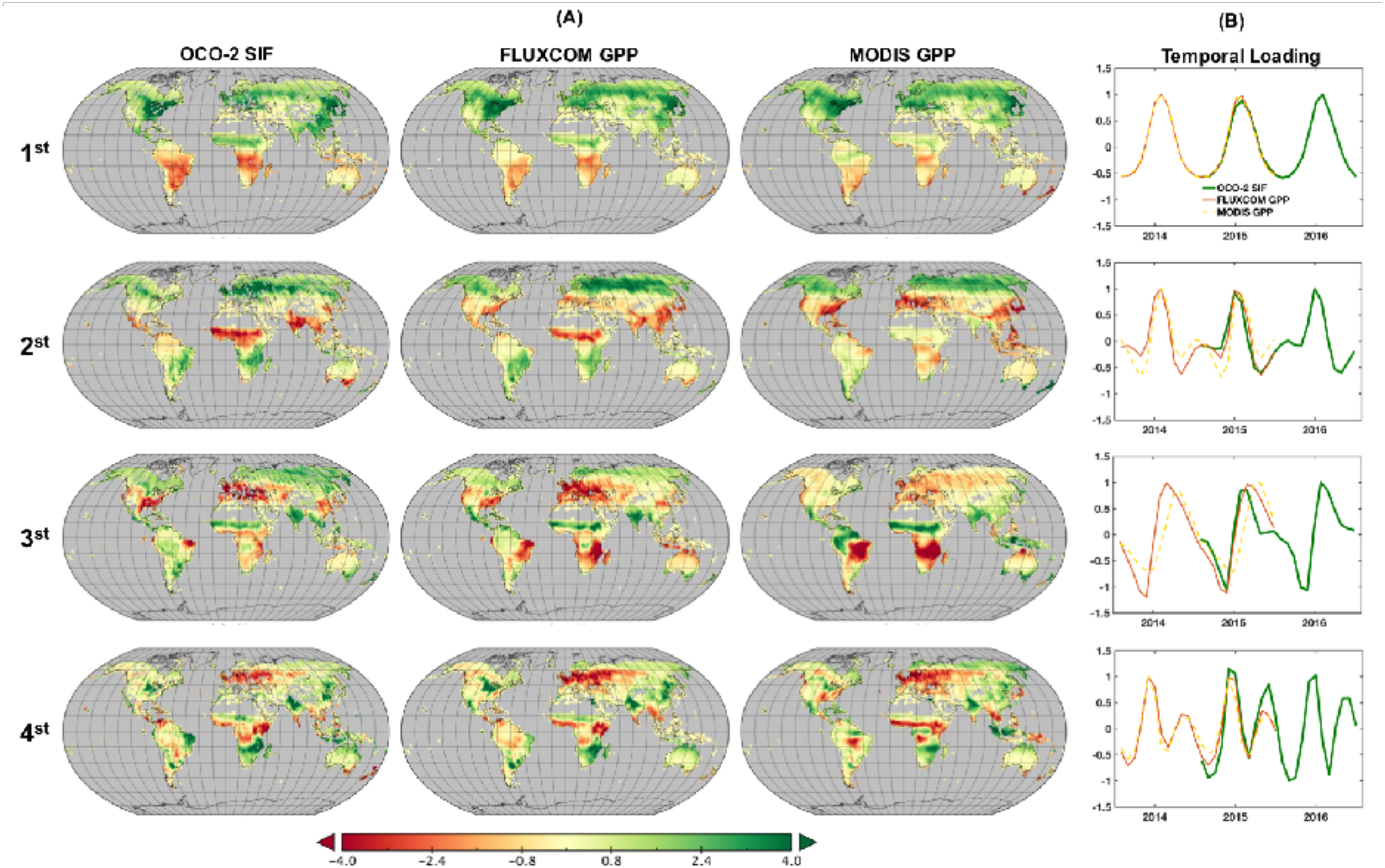
The view from space: Now OCO-2

Sun et al, Solar-induced chlorophyll fluorescence from the Orbiting Carbon Observatory-2: Overview of the retrieval and biophysical performance



Primary Modes of GPP

Sun, Frankenberg et al, to be published end of Sept.



CFIS — Chlorophyll Fluorescence Imaging Spectrometer

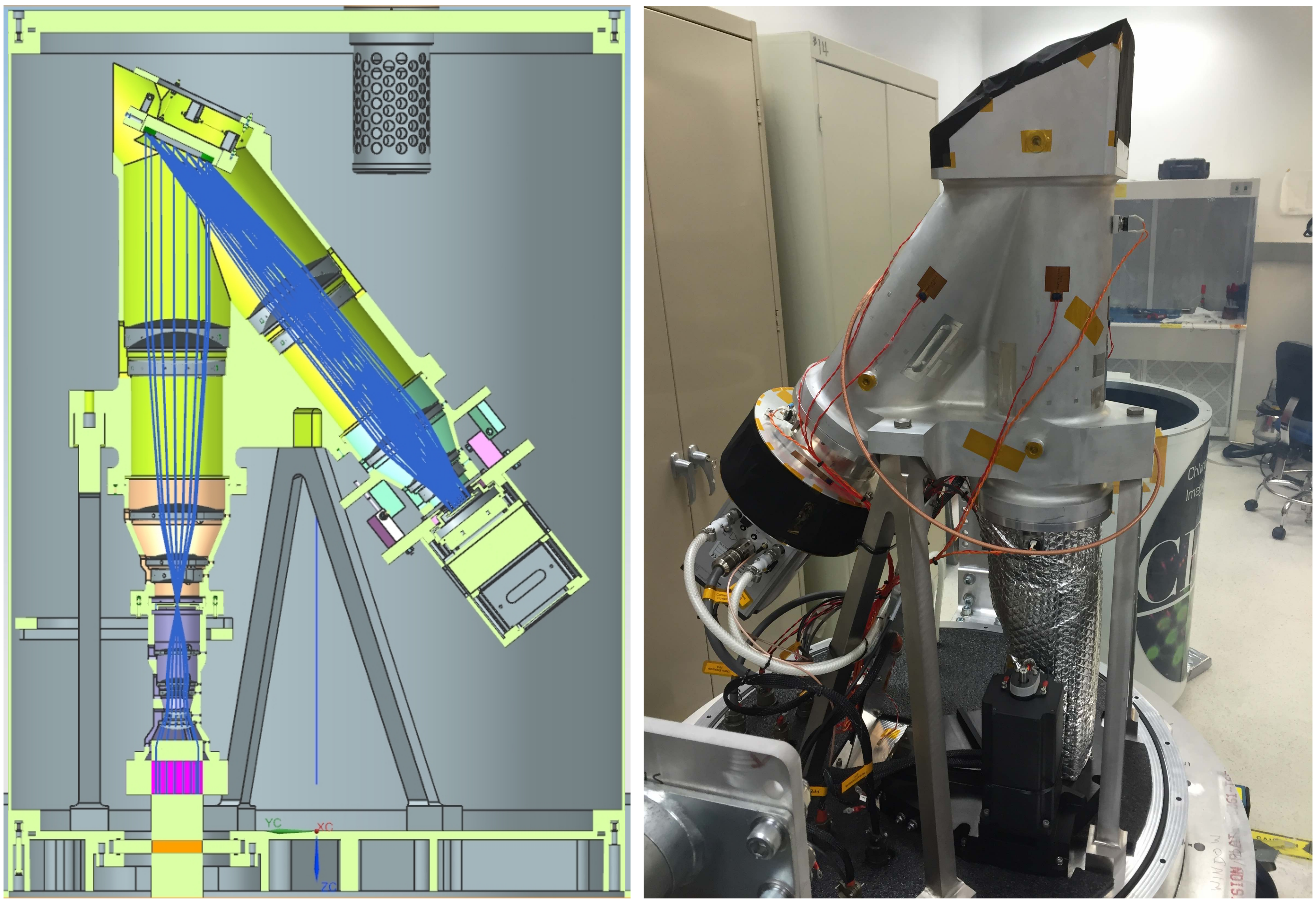
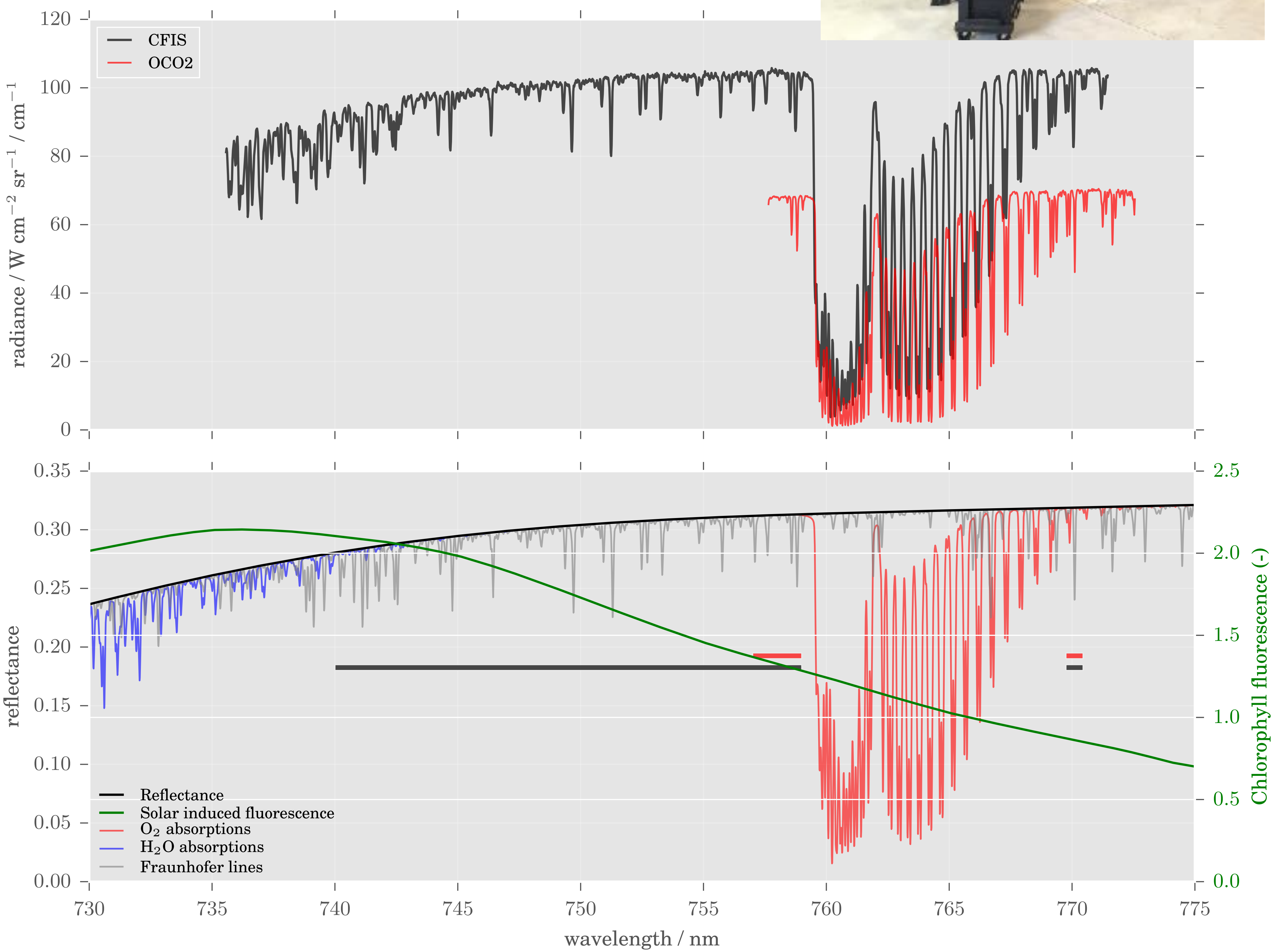
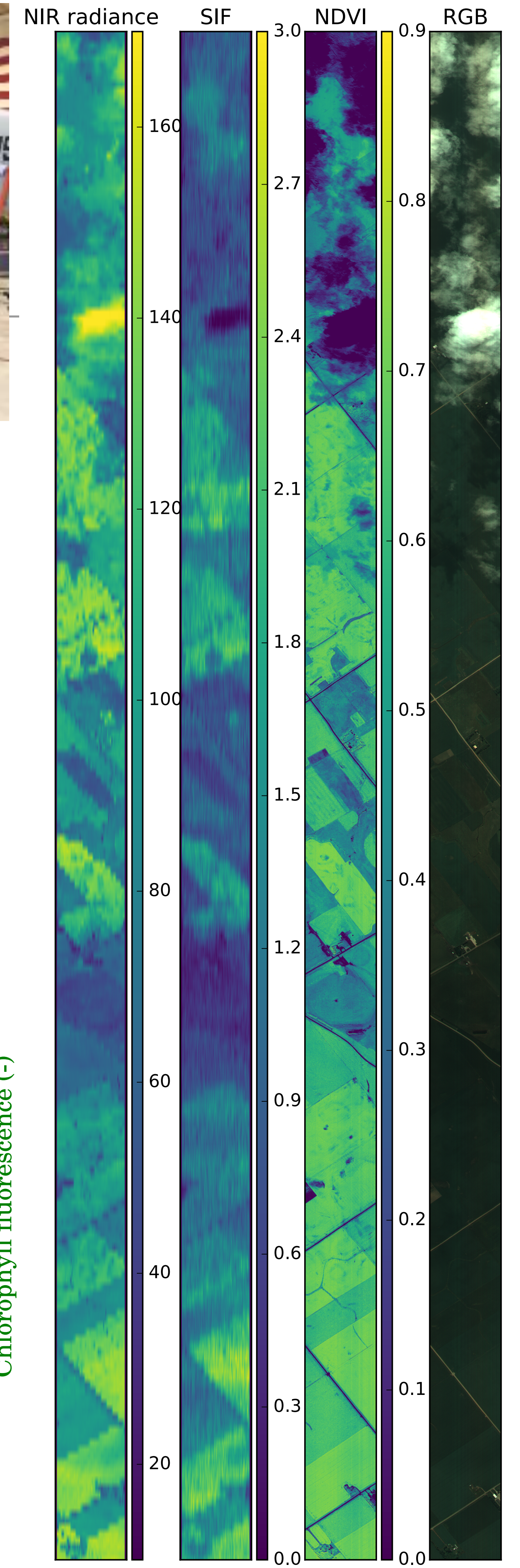


Figure 2: Left: CFIS computer-aided design model, showing the mechanical and optical layout. Right: Picture of CFIS without housing can in the laboratory.

Airborne (CFIS)

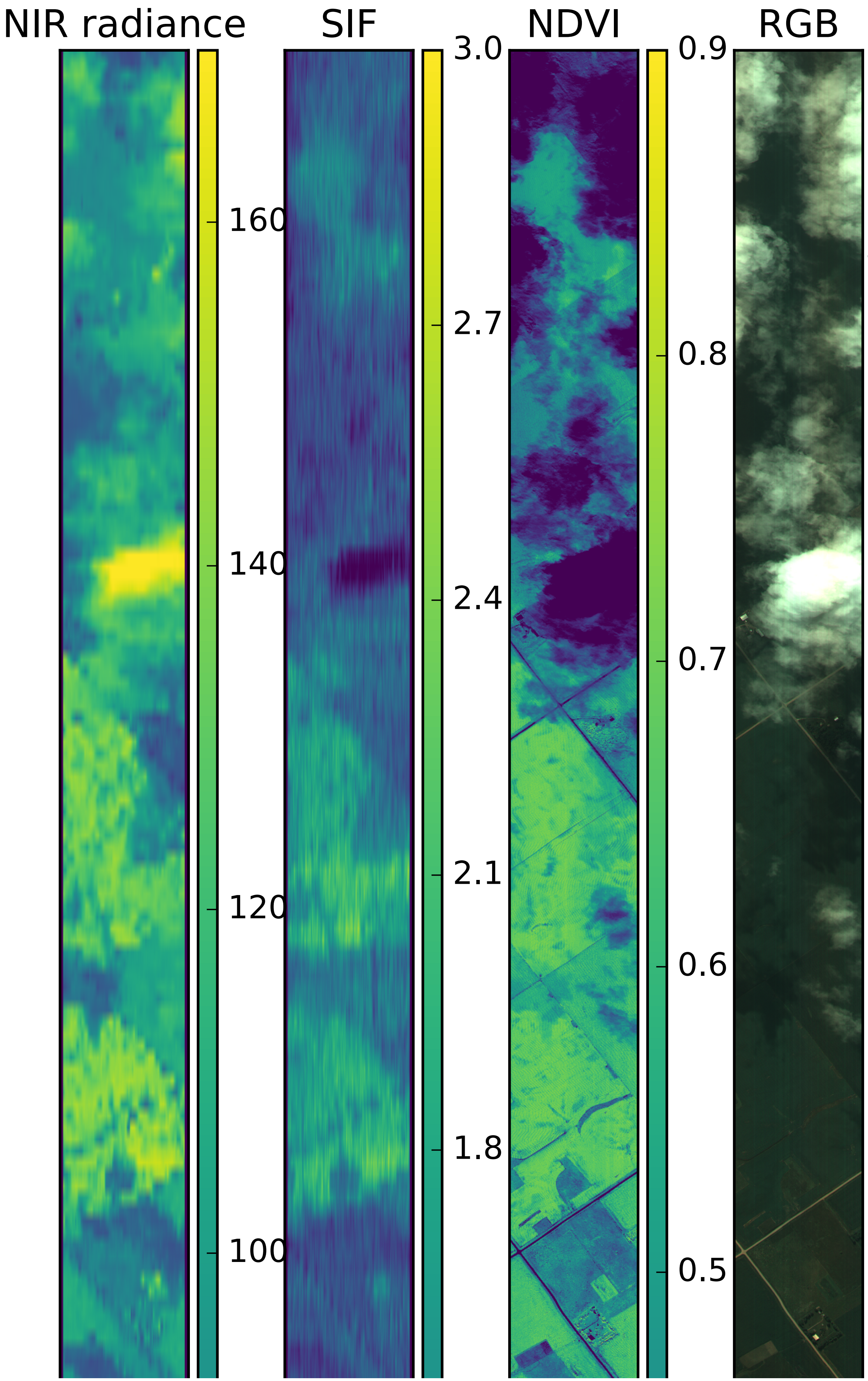
Frankenberg et al, paper in prep



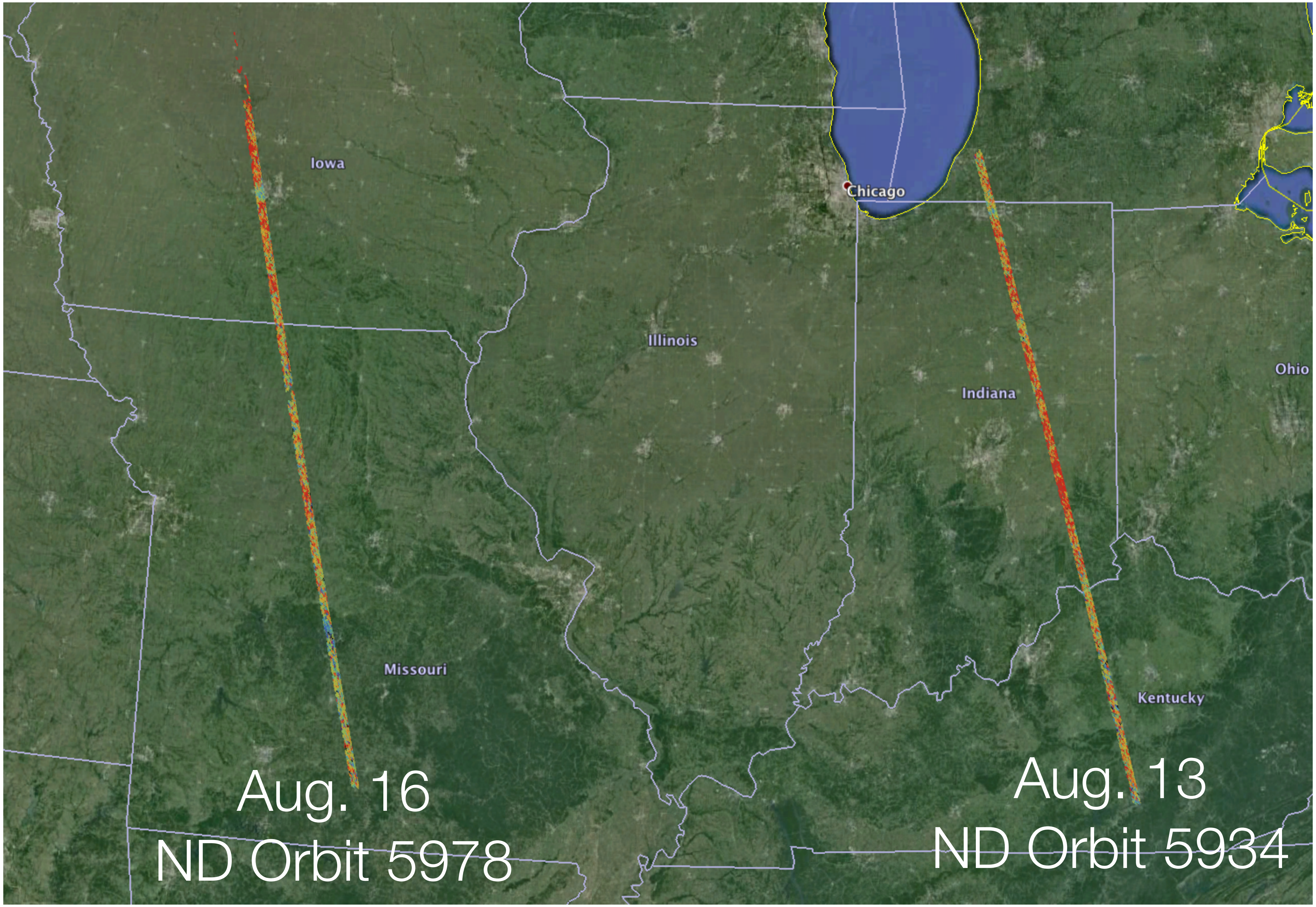


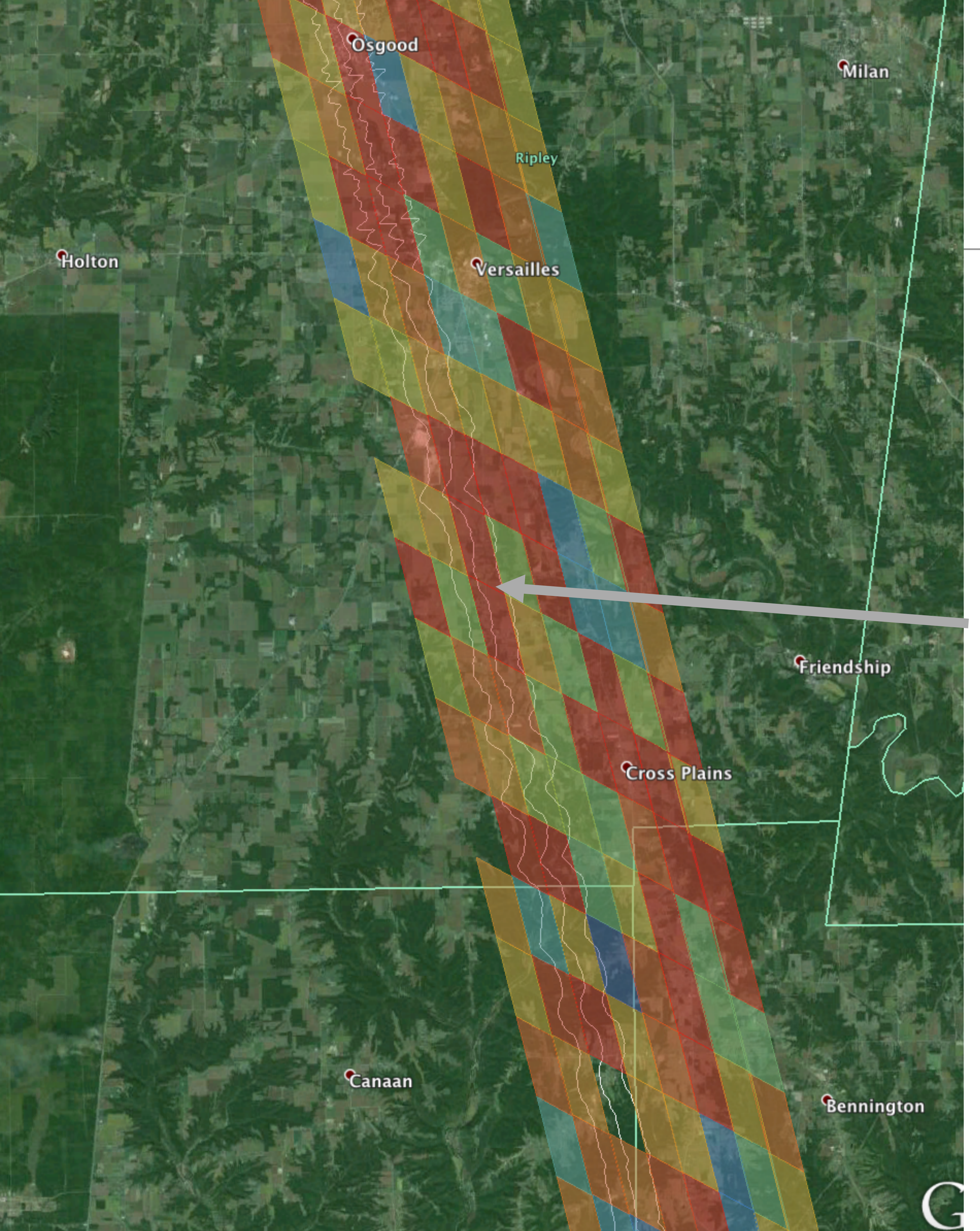
Airborne (CFIS)

Frankenberg et al, paper in prep



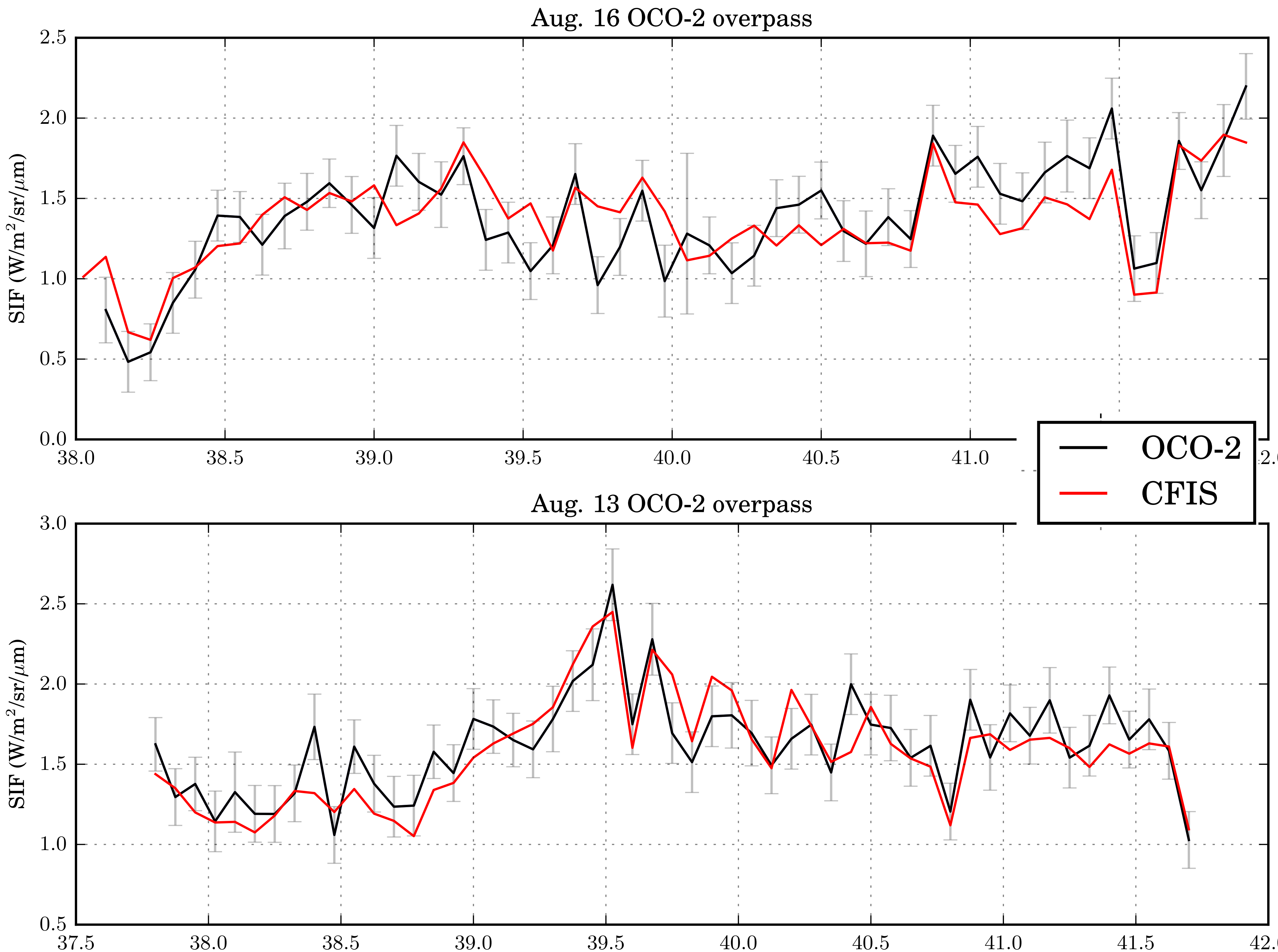
OCO-2 underpasses — OCO2 SIF





White lines indicate edges and center of CFIS swath

OCO-2 SIF validation (via CFIS)



Ground-based measurements (enabled by KISS)

Ground-based measurements
PhotoSpec systems, enable by KISS

Ground-based measurements
PhotoSpec systems, enable by KISS

The future from space

- TROPOMI (will be launched soon, fingers crossed)
- FLEX (chosen by ESA as Earth Explorer 8)
- GeoCARB (Geostationary, SIF no primary focus though)
- Sentinel 3?