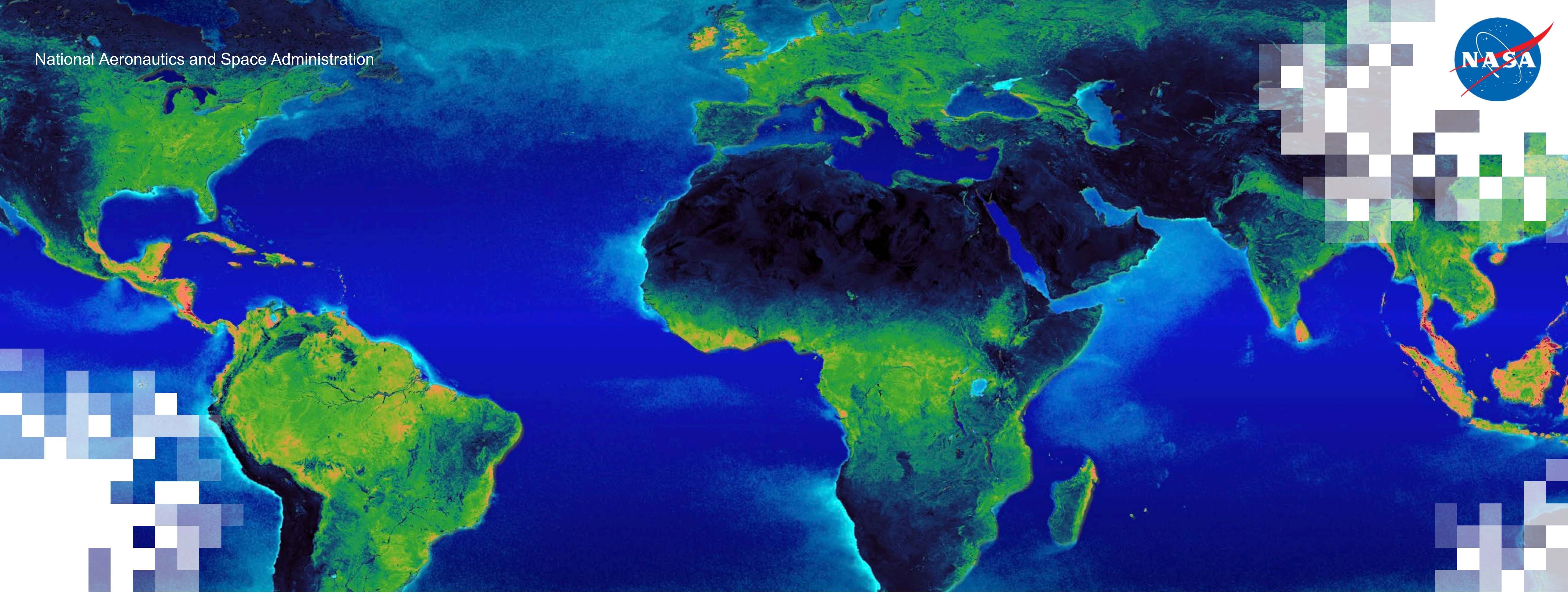


APPLIED REMOTE SENSING TRAINING PROGRAM
TRAIN - EMPOWER - ADVANCE

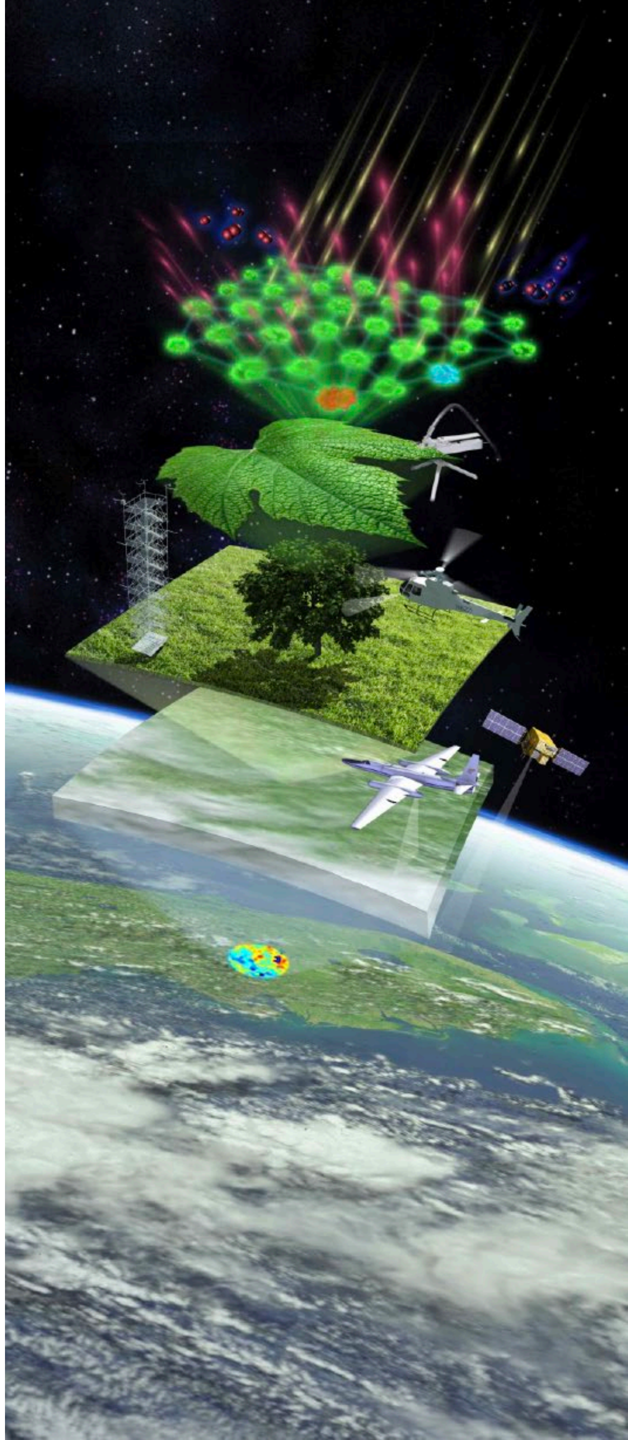
Use of Solar Induced Fluorescence to Assess Vegetation Photosynthesis

Christian Frankenberg, Philipp Köhler

Webinar Agenda

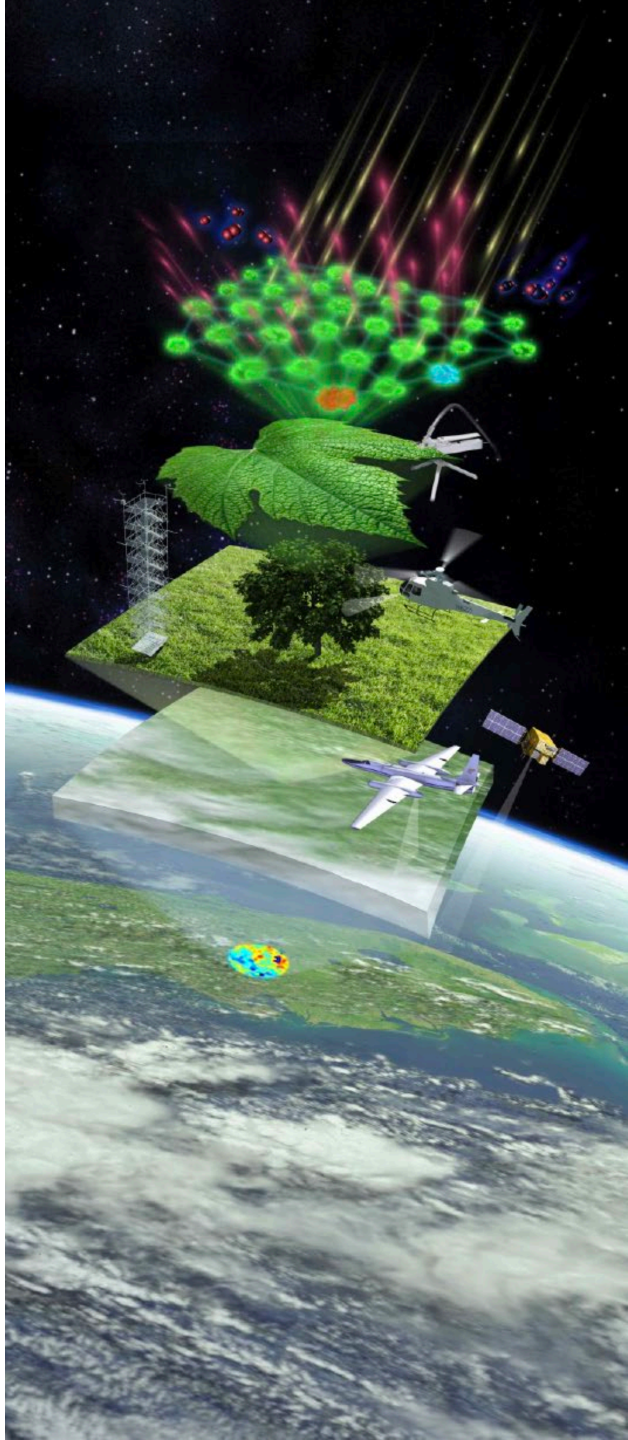
- Here: A primer into Solar Induced Chlorophyll Fluorescence

- Later:
- Overview of different satellite-derived SIF datasets
- Their characteristics
- Where they can be accessed
- Demo with OCO-2 data showing participants how to open, interpret, and analyze the data to identify vegetation stress
- Q&A session



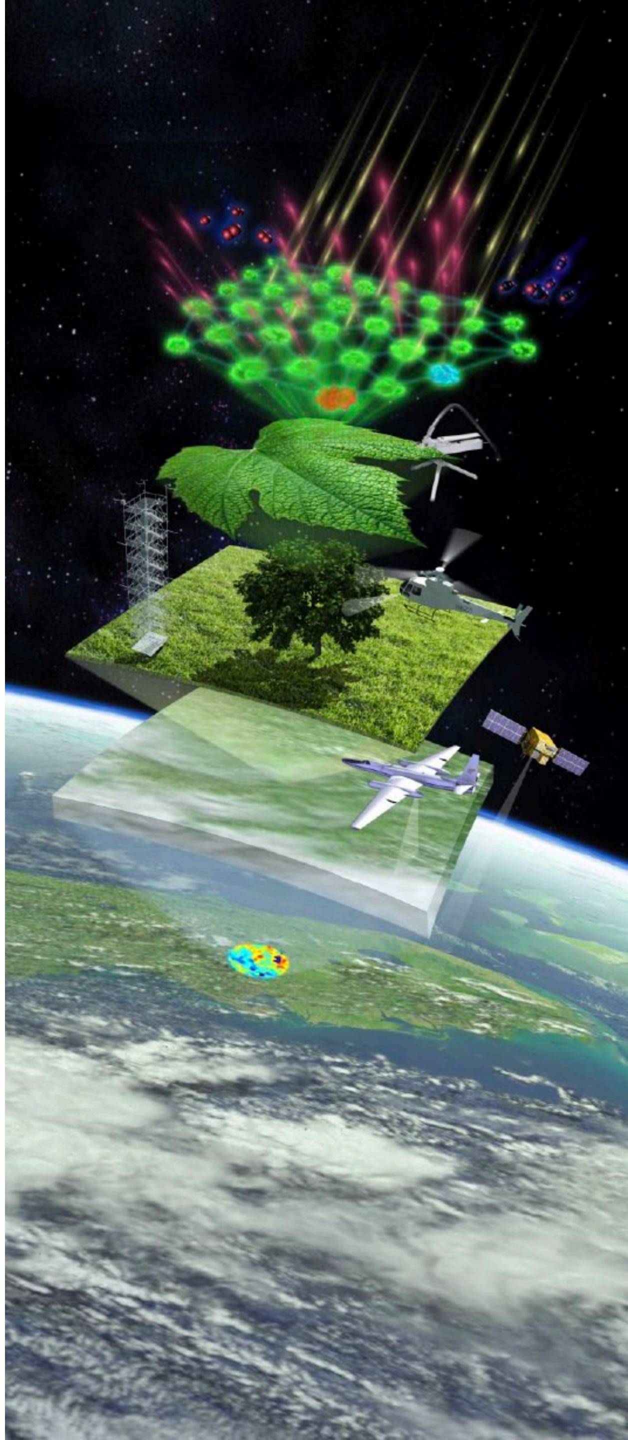
Part 1

- Introduction to SIF
- Active Fluorometry and solar induced fluorescence
- How do we measure fluorescence?
- Limitations of using SIF



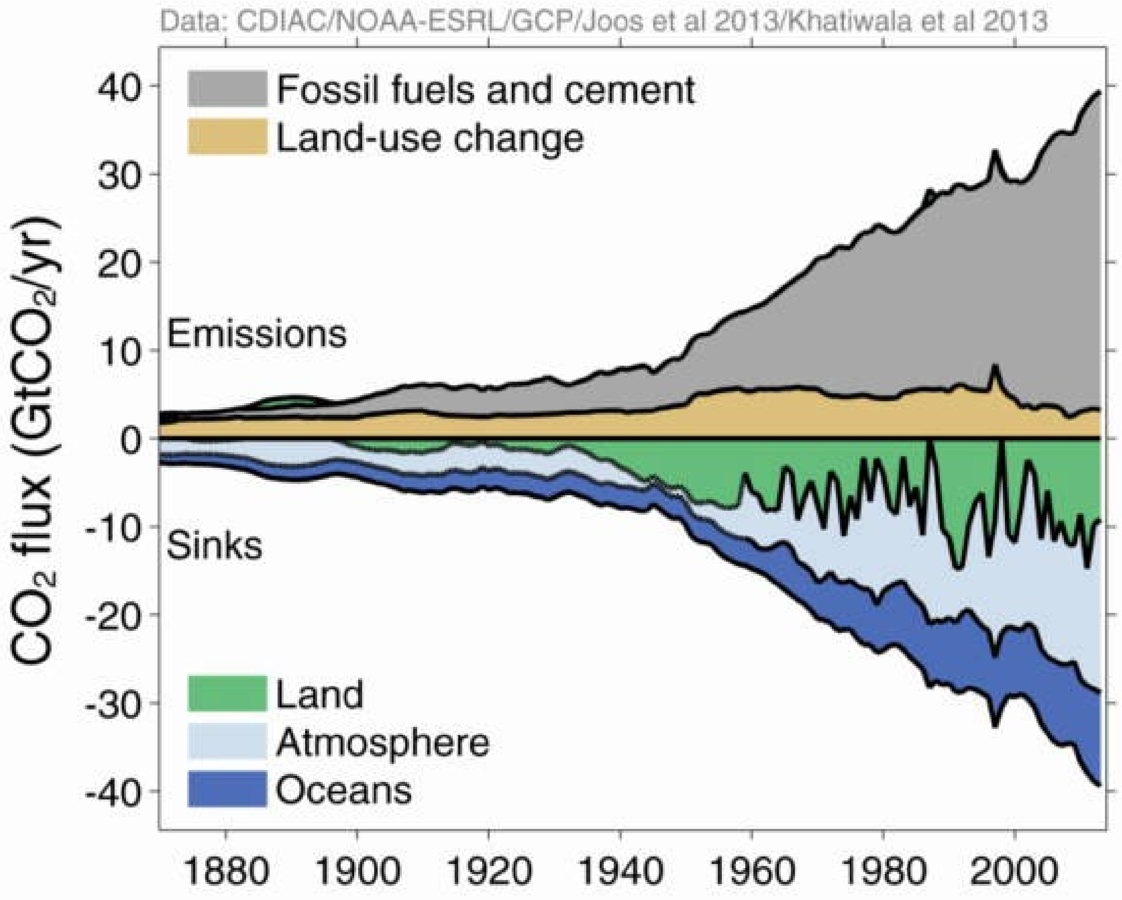
Learning Objectives

- Understand the basic concepts of SIF
- How is SIF related to photosynthesis and electron transport?
- What is the difference between PAM fluorescence and SIF?
- Know how to interpret the measurements and apply them
- Be able to access, open, and analyze SIF data



Motivation

- The Global Carbon Cycle
- Photosynthesis (gross CO_2 uptake) is the largest sink for Carbon in the Earth's atmosphere. Its future will determine whether plants will continue to do us a favor by taking up CO_2.



Introduction to Solar Induced Chlorophyll Fluorescence

- A small fraction of the absorbed light is being re-emitted as fluorescence (>700nm, just tiny overlap with the visible spectral range).
- This happens even for dissolved chlorophyll solution (e.g., in alcohol). See figure on the right.

Introduction to Solar Induced Chlorophyll Fluorescence

- During photosynthesis, a small fraction of energy is reemitted as light (fluorescence).
- Remote sensing instruments include a measurement region that reveals this signal.
- This measurement is more directly tied to plant health and activity than traditional measurements like greenness.

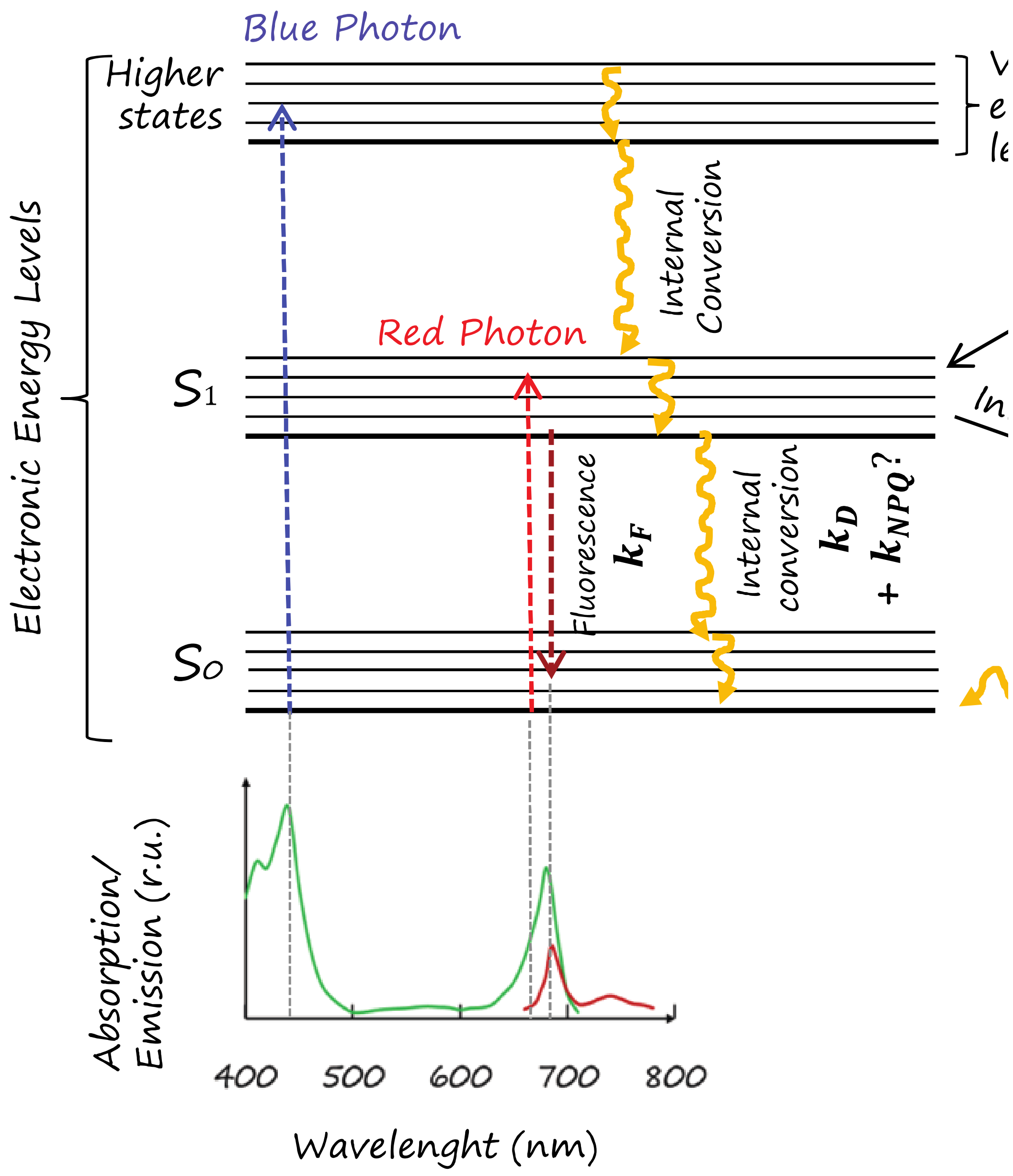


Fig. 3. Idealized Jablonski diagram illustrating the energy partitioning of absorbed blue light, an electron from the ground state is raised to a higher energy state. The

Porcar-Castell et al 2014, review initiated at KISS

Introduction to Solar Induced Chlorophyll Fluorescence

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- Remote sensing instruments include a measurement region that reveals this signal.
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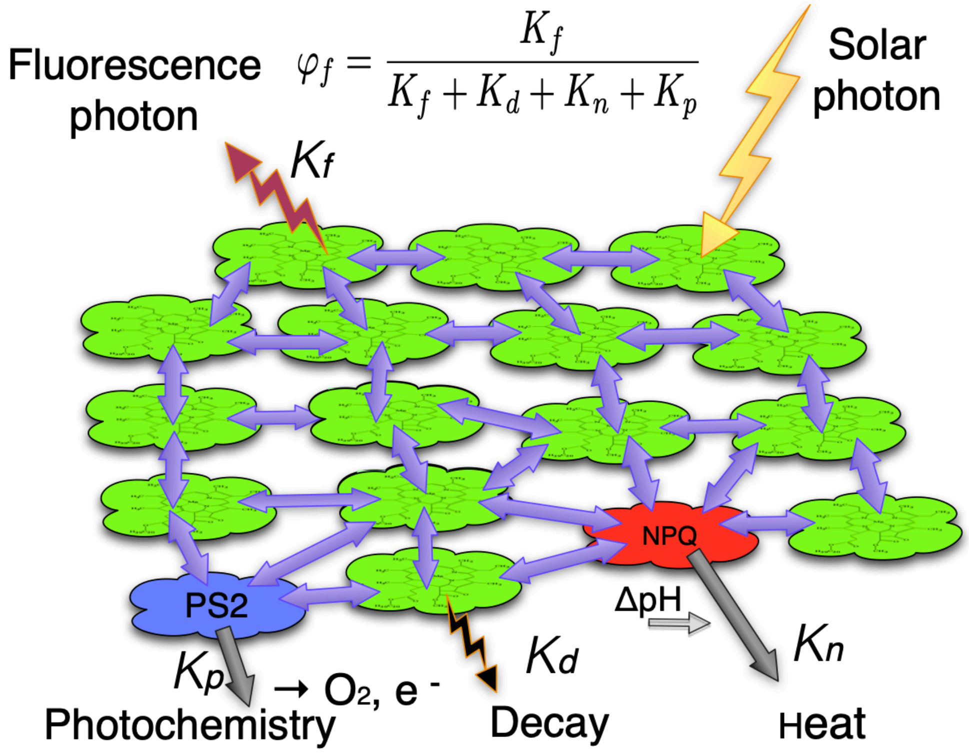


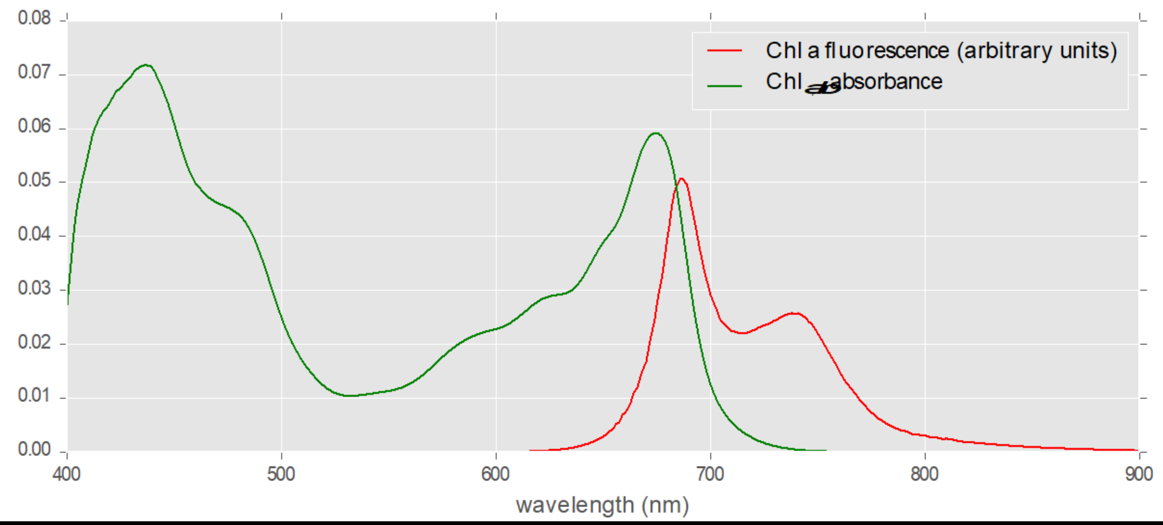
from Frankenberg, Berry, Guanter, Joiner (2012)

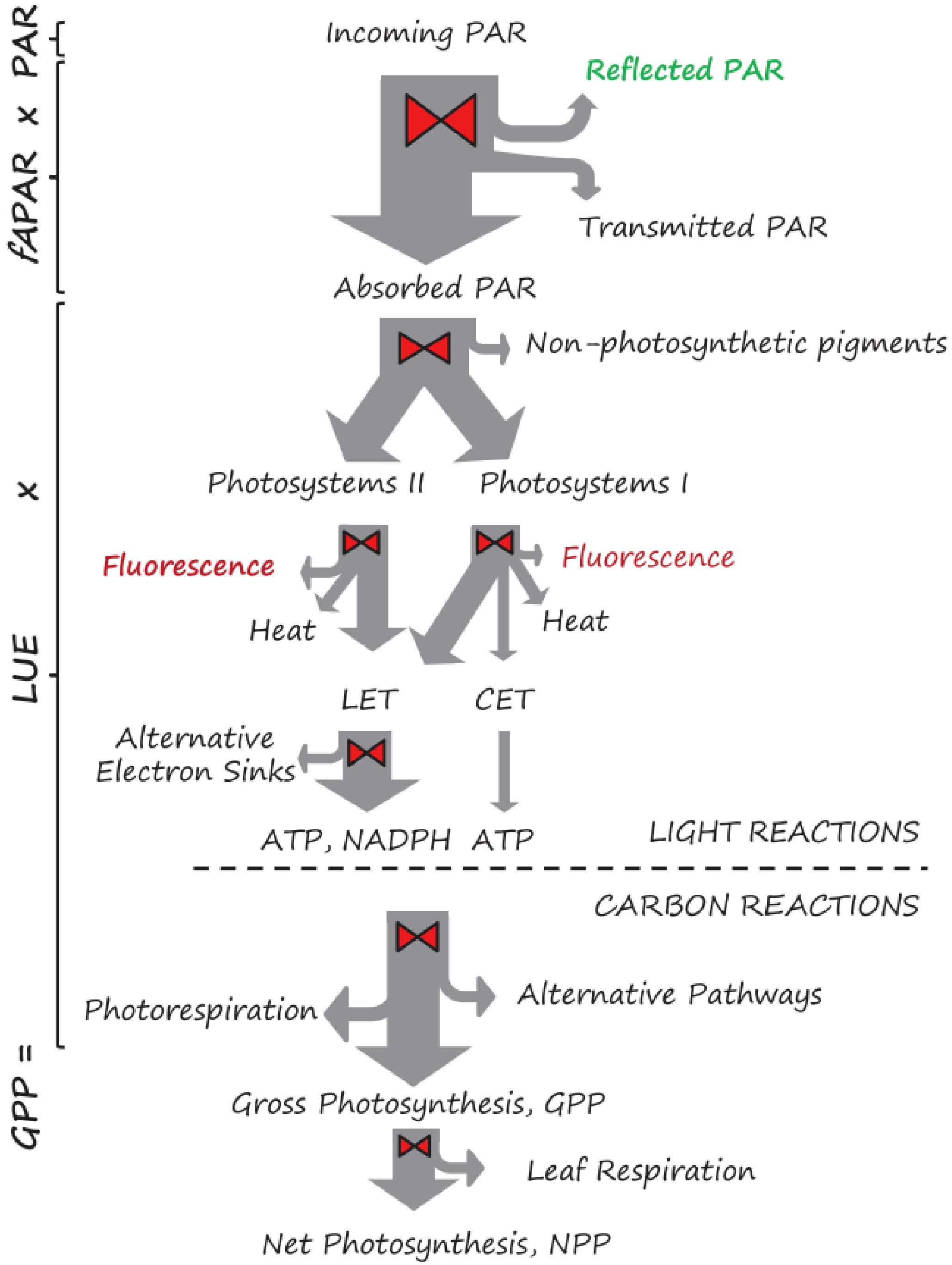
Journal of Experimental Botany, Vol. 65, No. 15, pp. 4065–4095, 2014
doi:10.1093/jxb/eru191 Advance Access publication 27 May, 2014

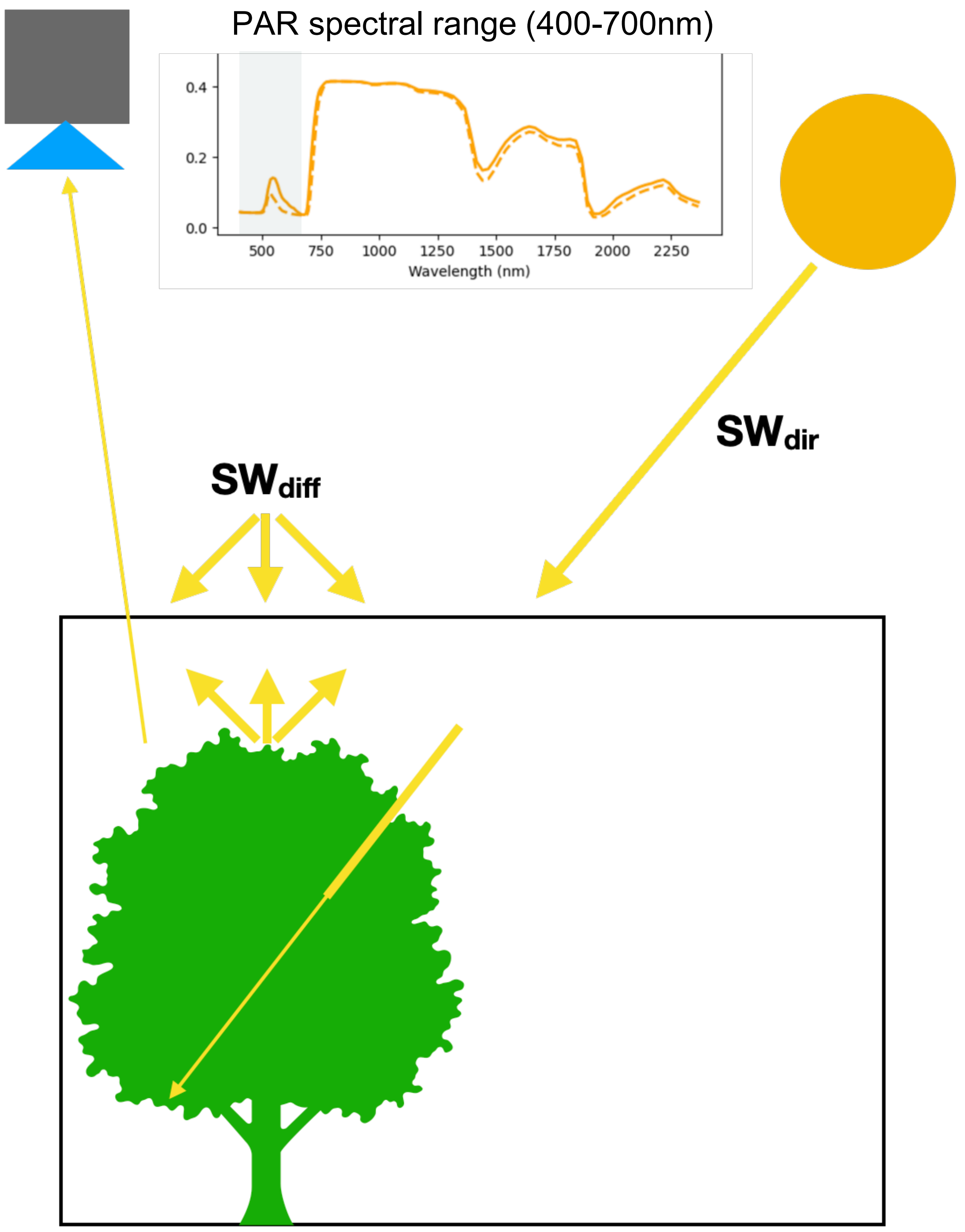
DARWIN REVIEW

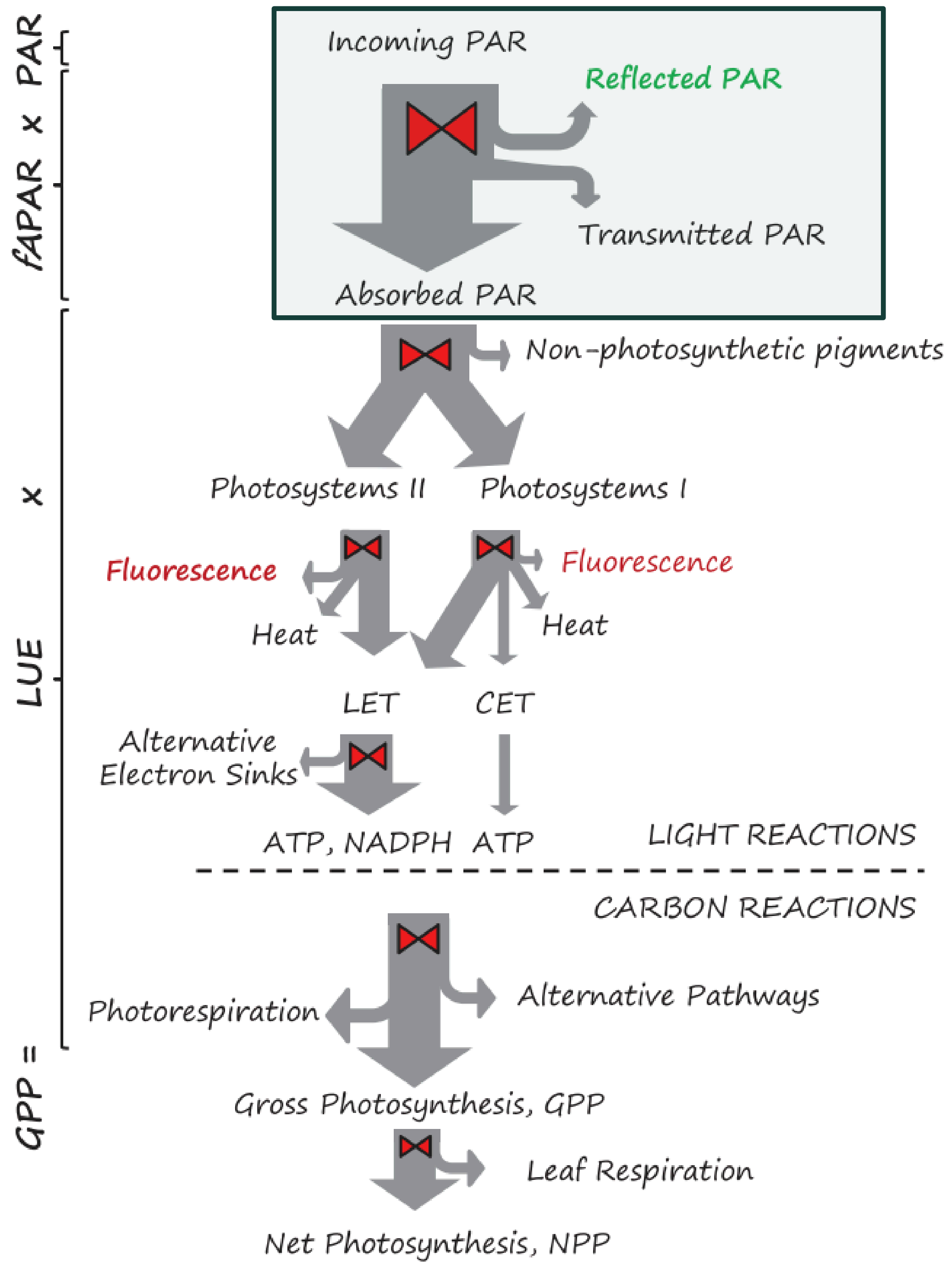
Linking chlorophyll *a* fluorescence to photosynthesis for remote sensing applications: mechanisms and challenges

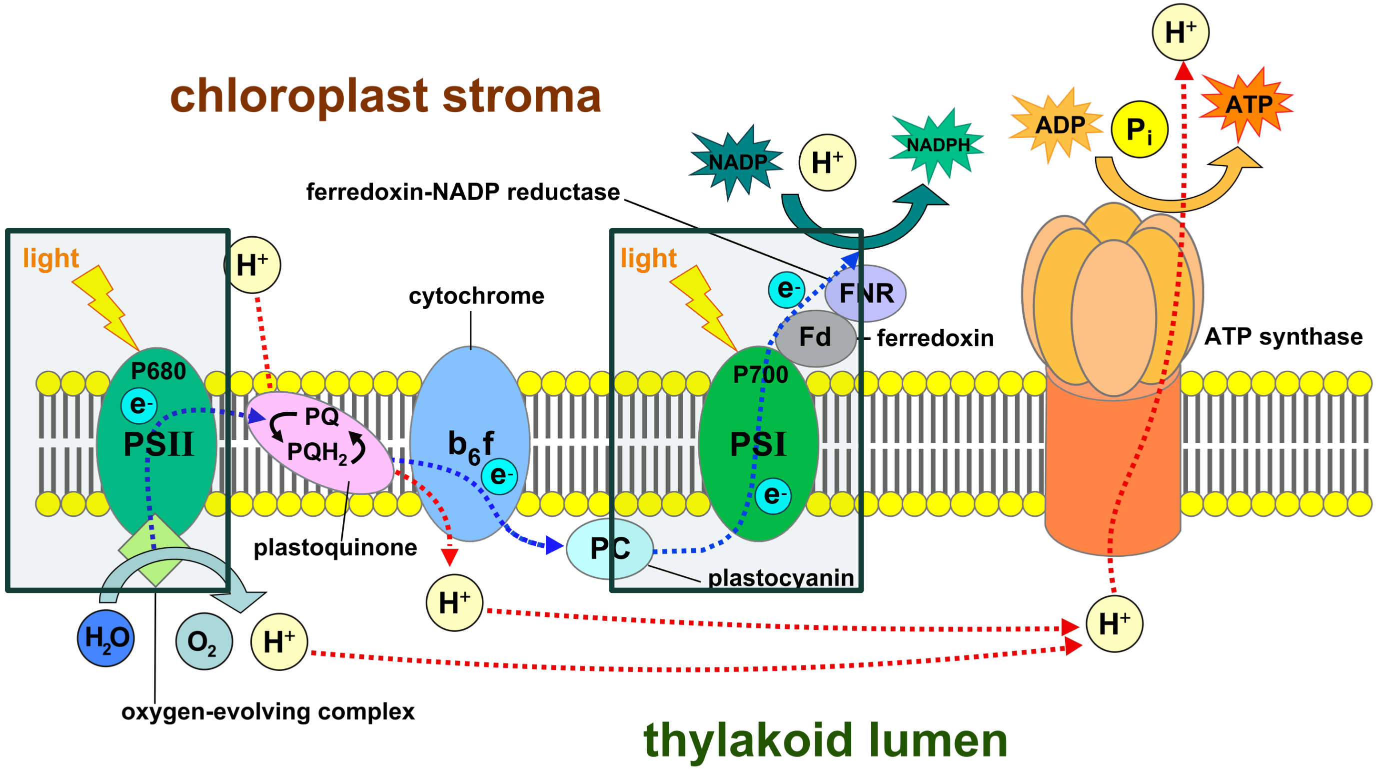
Albert Porcar-Castell[1,*], Esa Tyystjärvi[2], Jon Atherton[1], Christiaan van der Tol[3], Jaume Flexas[4], Erhard E. Pfündel[5], Jose Moreno[6], Christian Frankenberg[7] and Joseph A. Berry[8]

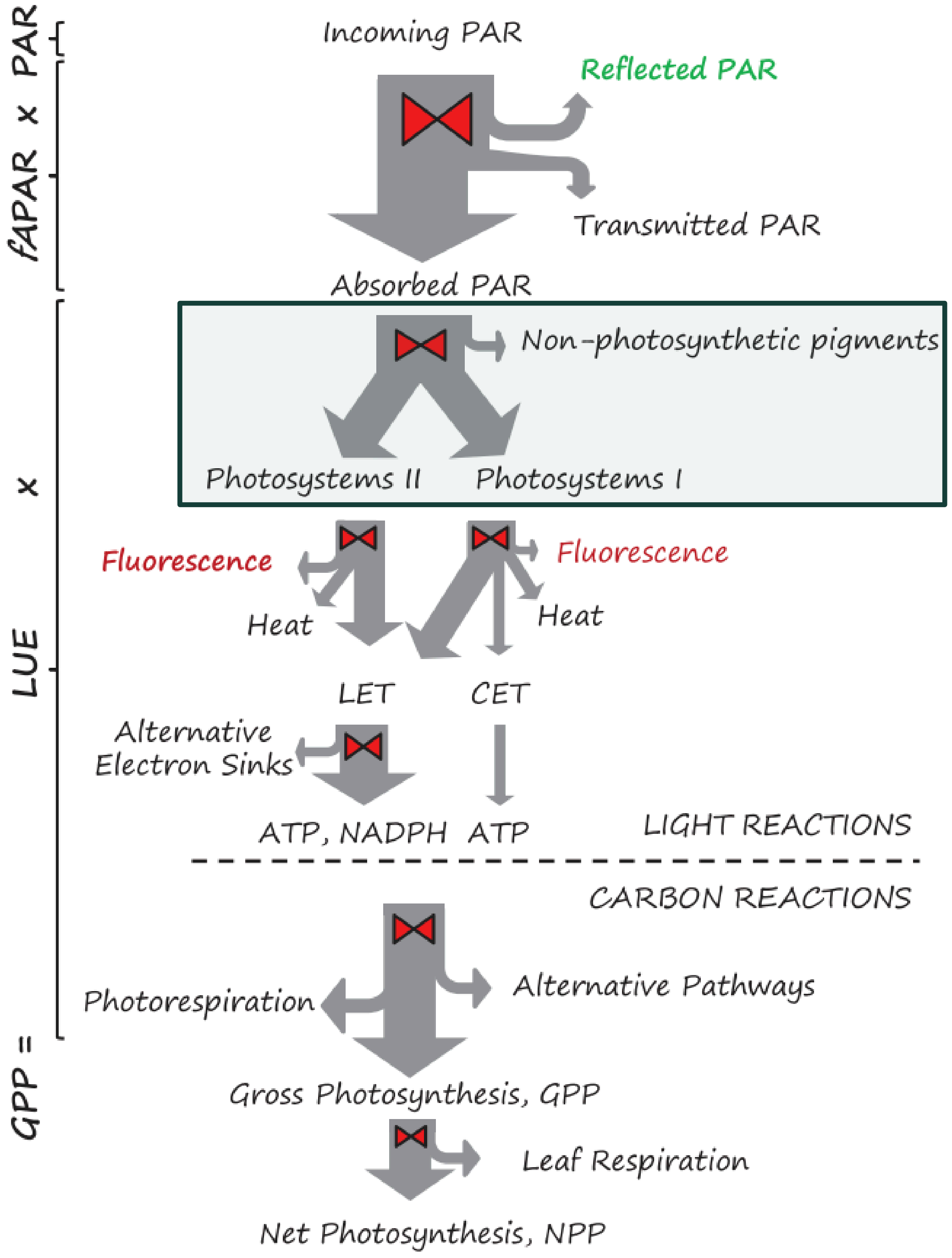




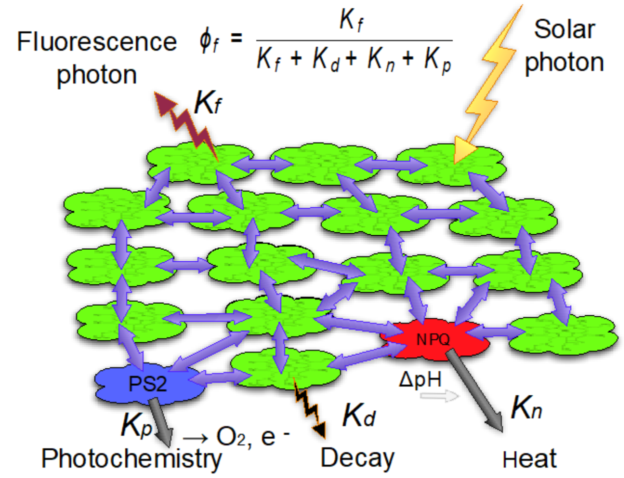

PAR spectral range (400-700nm)
0.4
0.2
0.0
500 750 1000 1250 1500 1750 2000 2250
Wavelength (nm)
SWdir
SWdiff


GPP = fAPAR x PAR x LUE
Incoming PAR
Reflected PAR
Transmitted PAR
Absorbed PAR
Non-photosynthetic pigments
Photosystems II
Photosystems I
Fluorescence
Heat
Fluorescence
Heat
LET
CET
Alternative Electron Sinks
ATP, NADPH
ATP
LIGHT REACTIONS
CARBON REACTIONS
Photorespiration
Alternative Pathways
Gross Photosynthesis, GPP
Leaf Respiration
Net Photosynthesis, NPP





https://en.wikipedia.org/wiki/Photosystem#/media/File:Thylakoid_membrane_3.svg

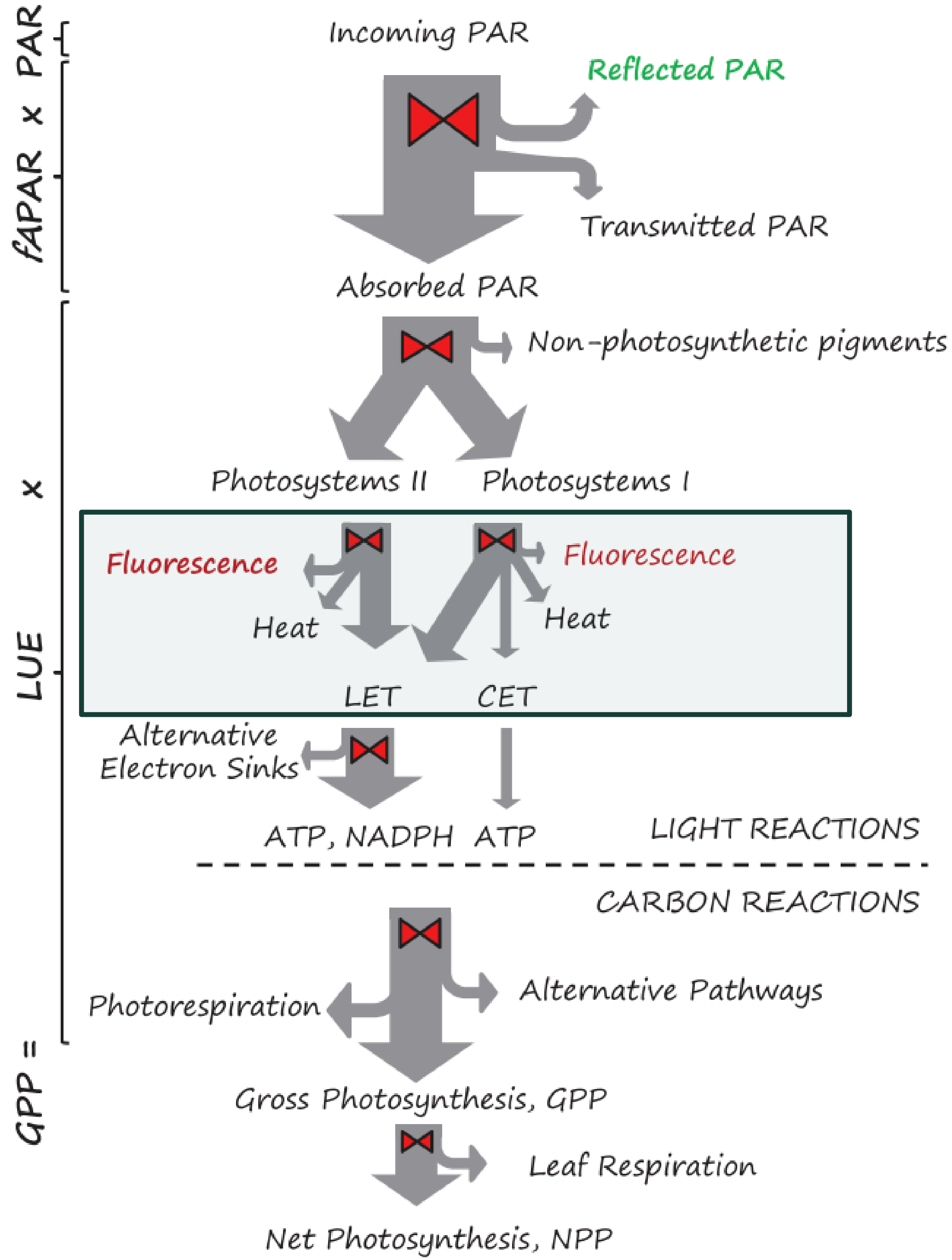


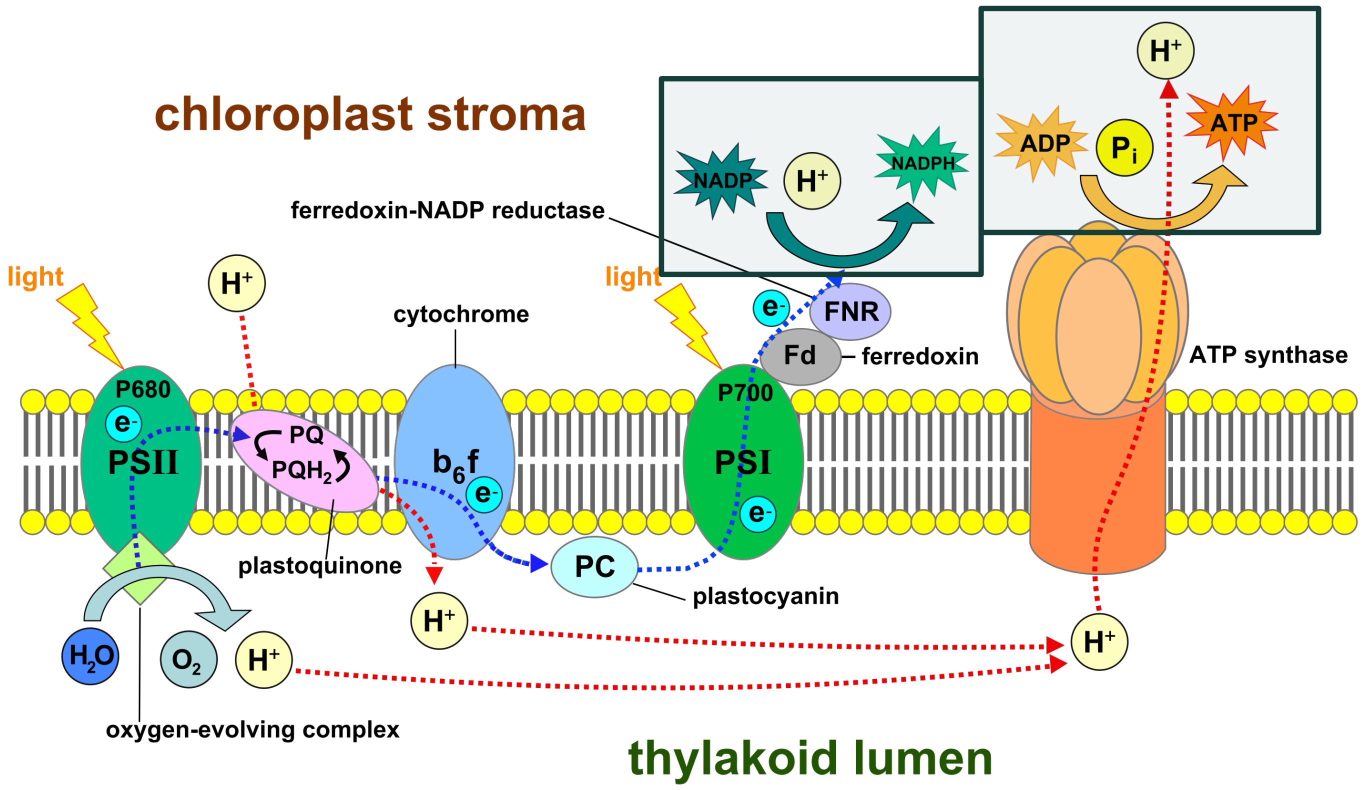
from Frankenberg, Berry, Guanter, Joiner (2012)

- Fluorescence yield

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

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





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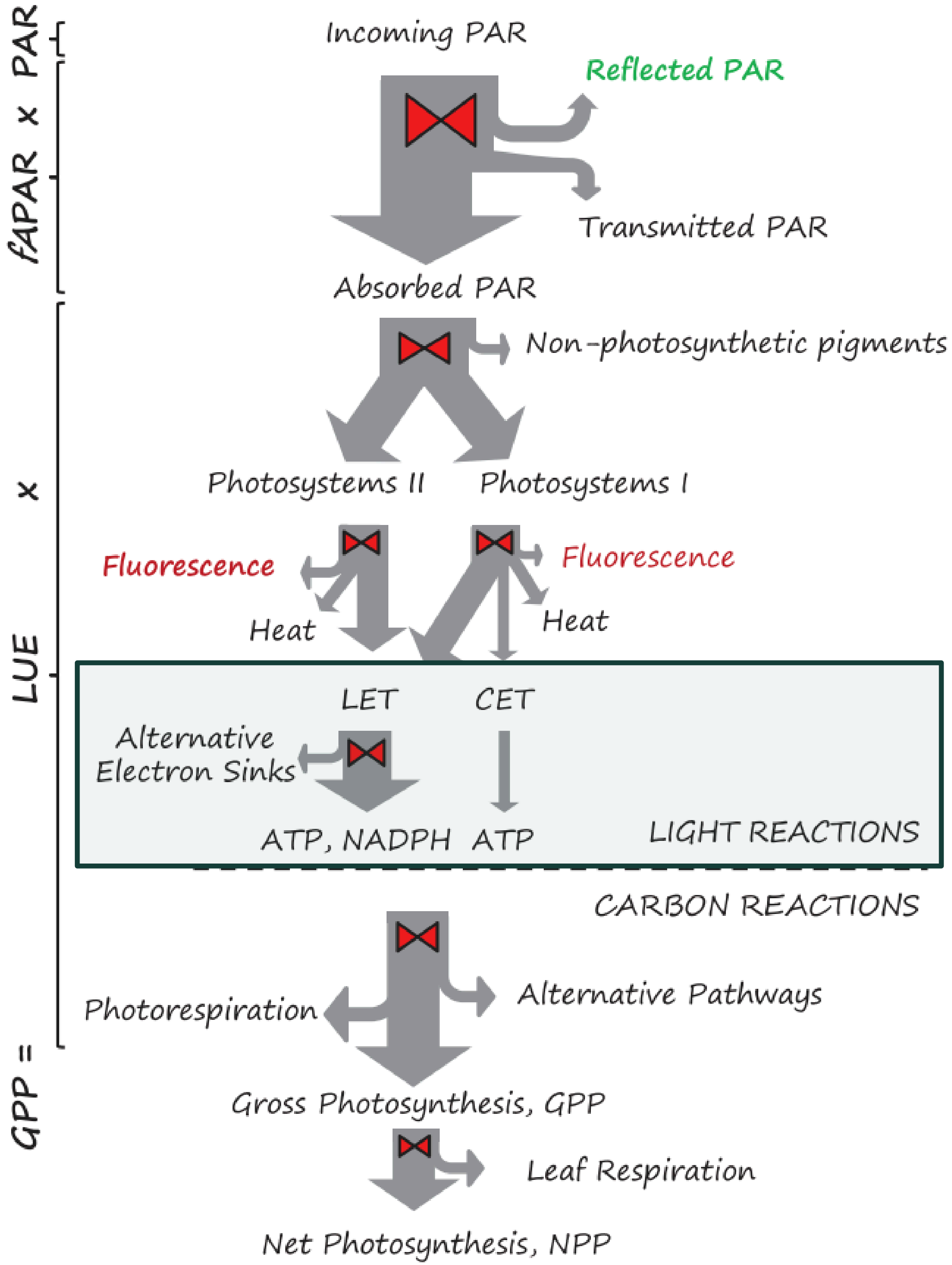
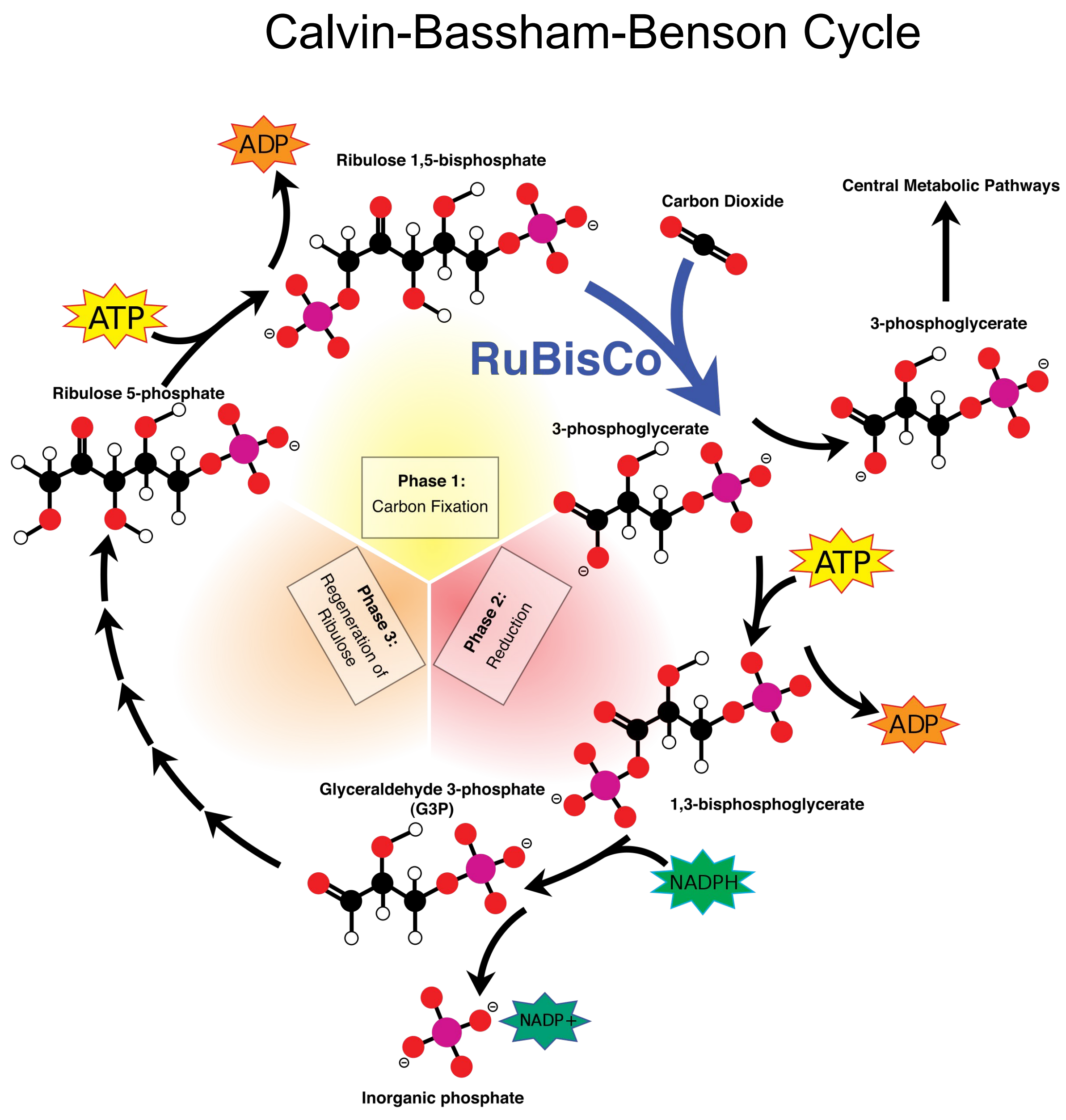
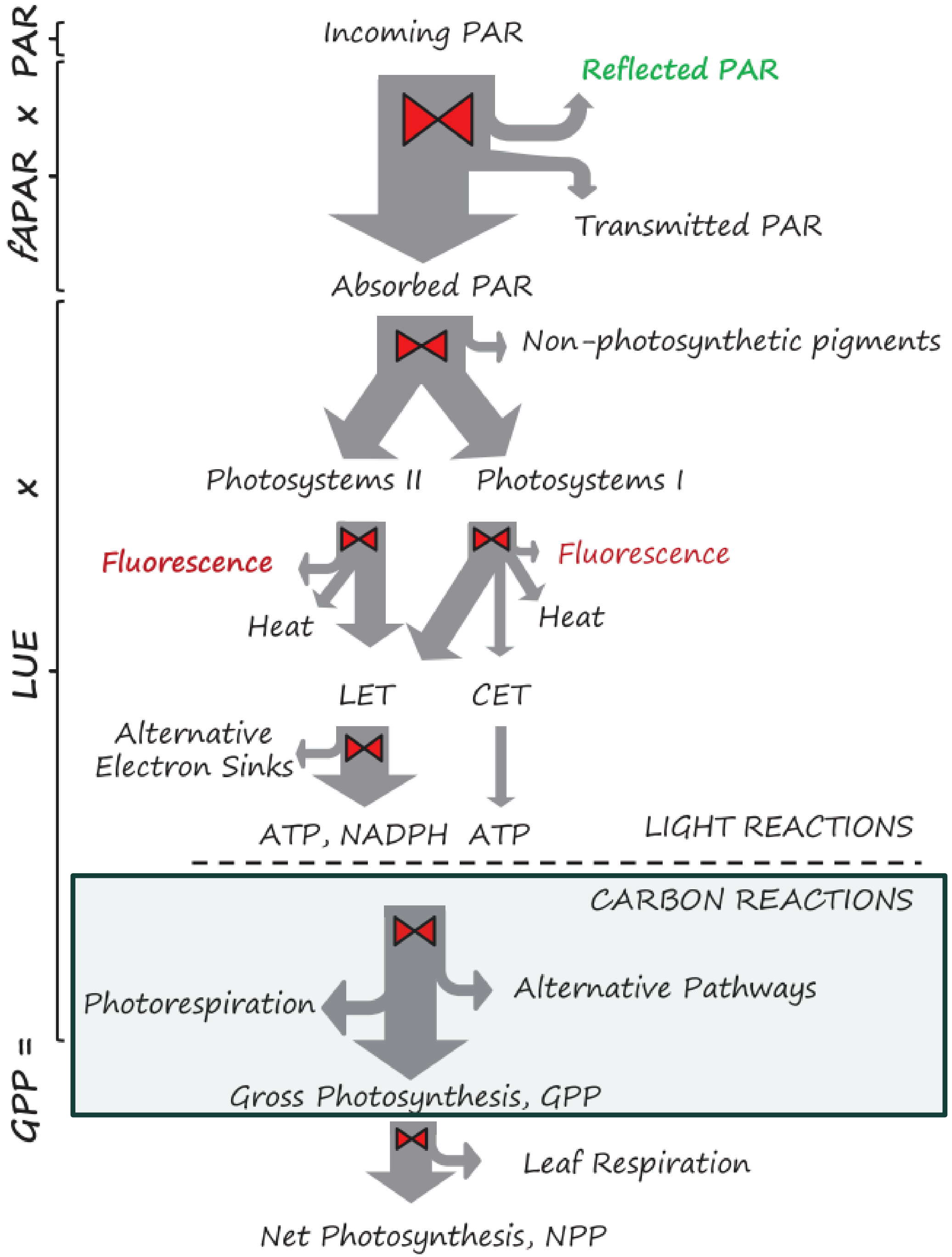
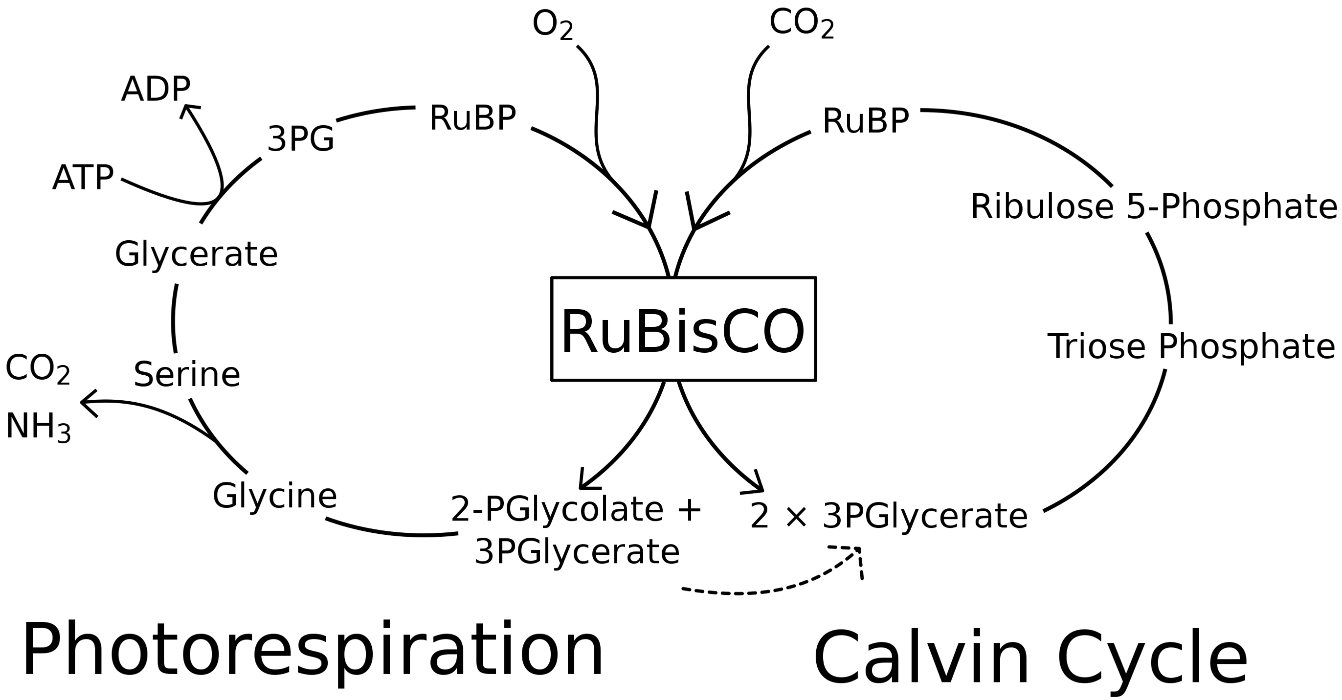


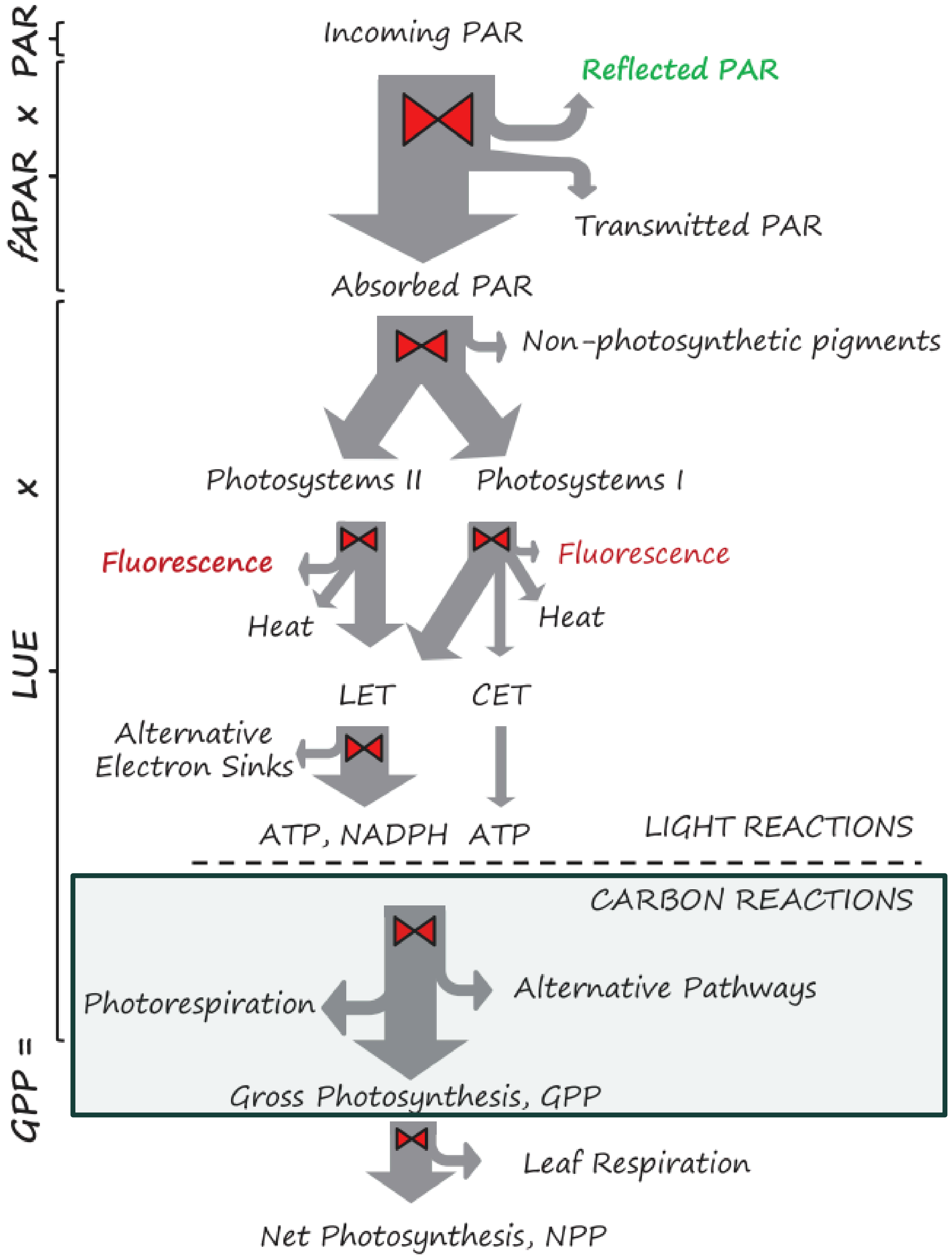


https://en.wikipedia.org/wiki/Calvin_cycle#/media/File:Calvin-cycle4.svg



Loss through Photorespiration





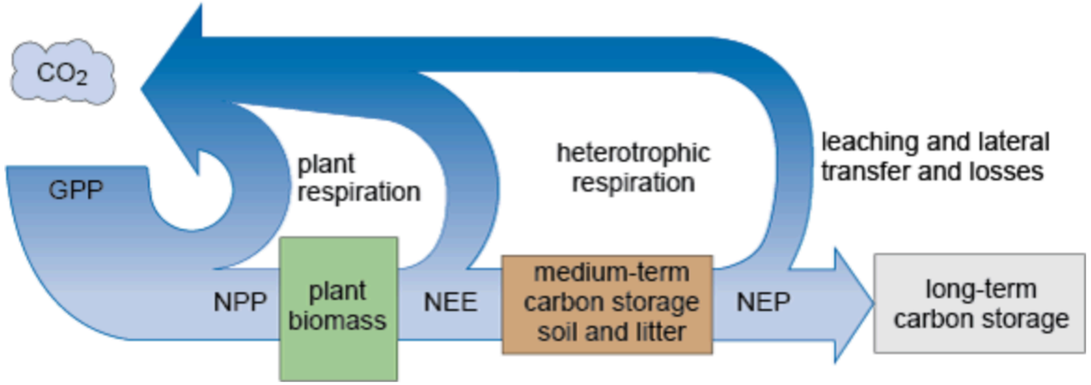
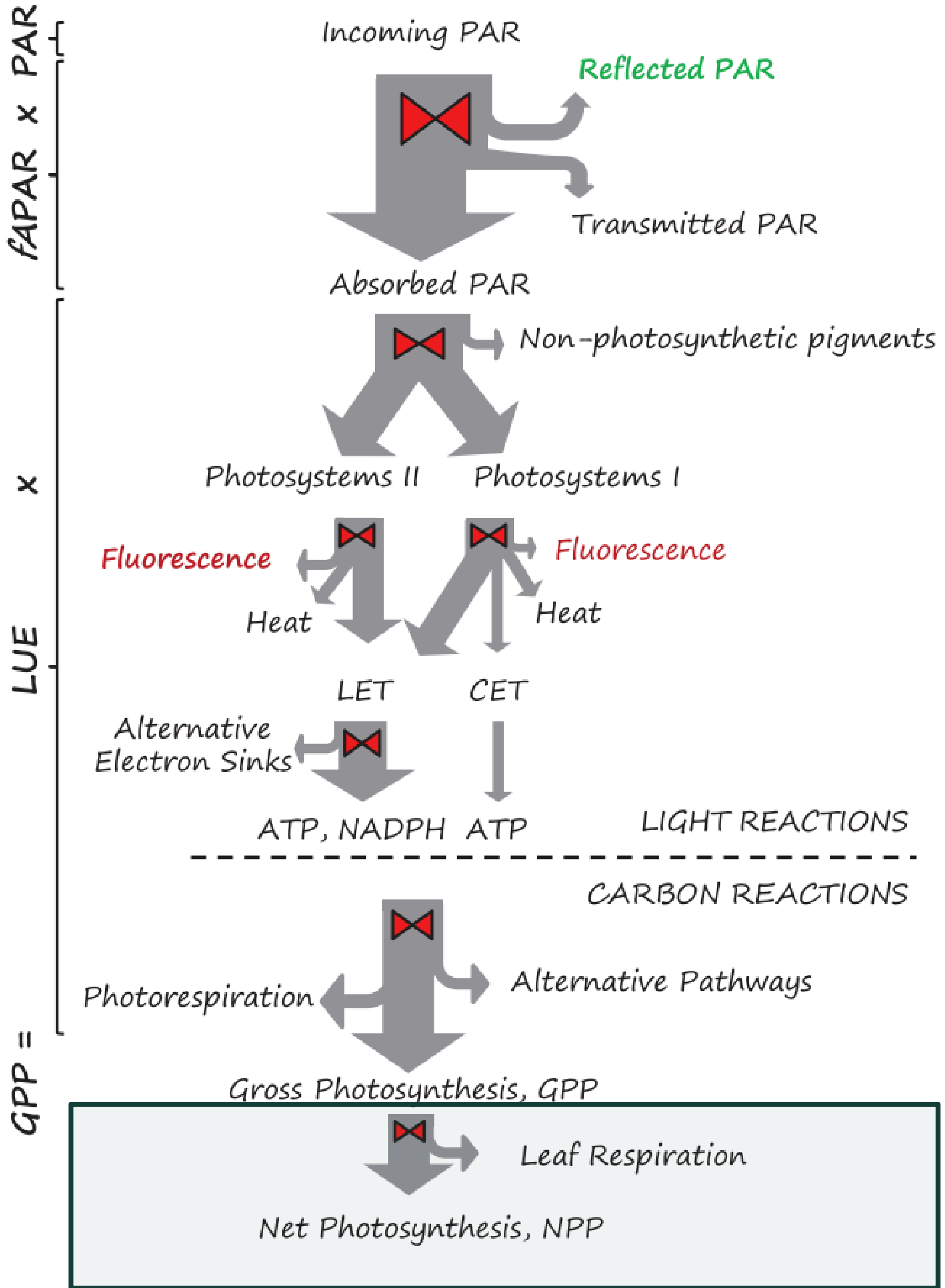
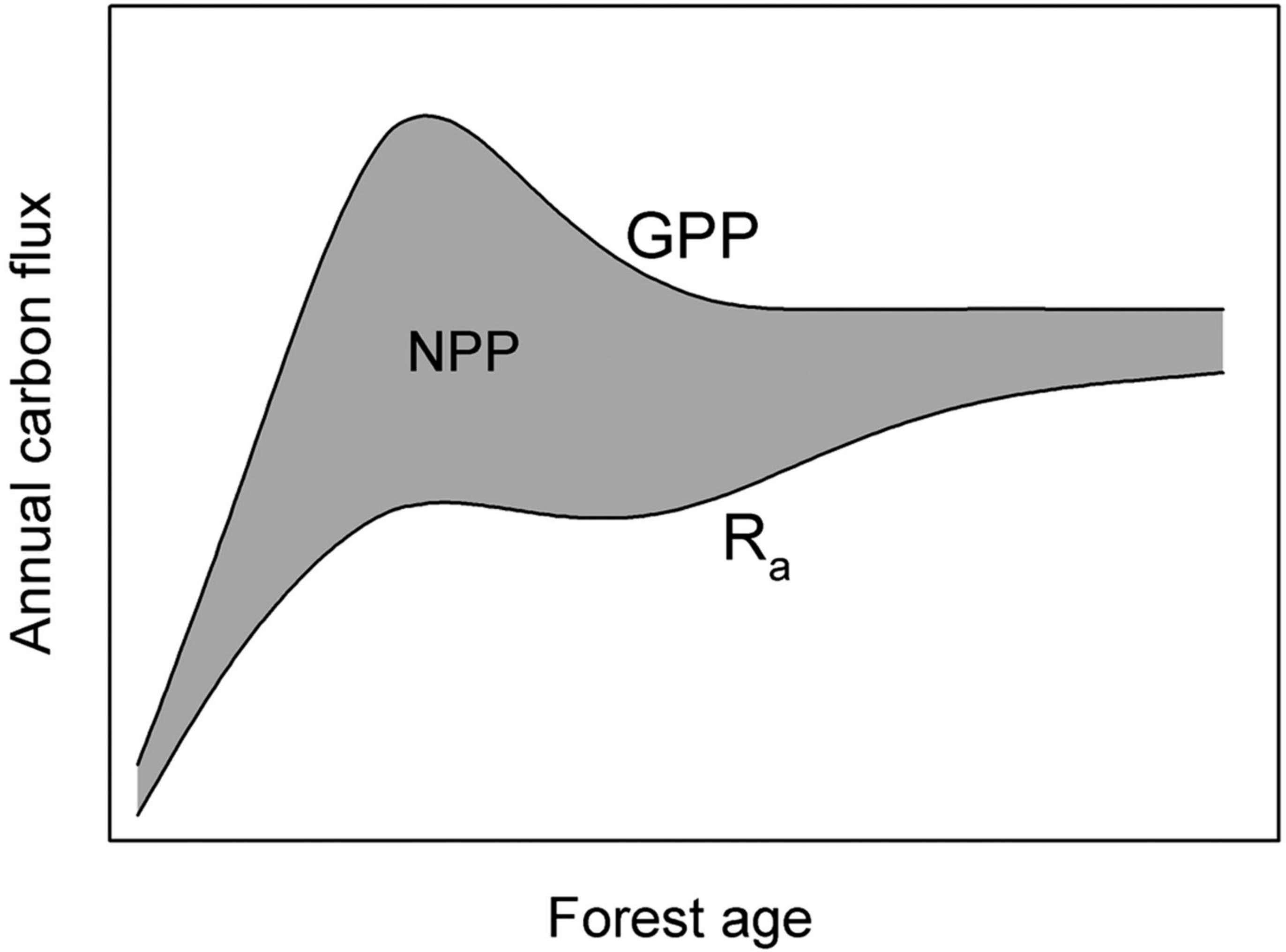
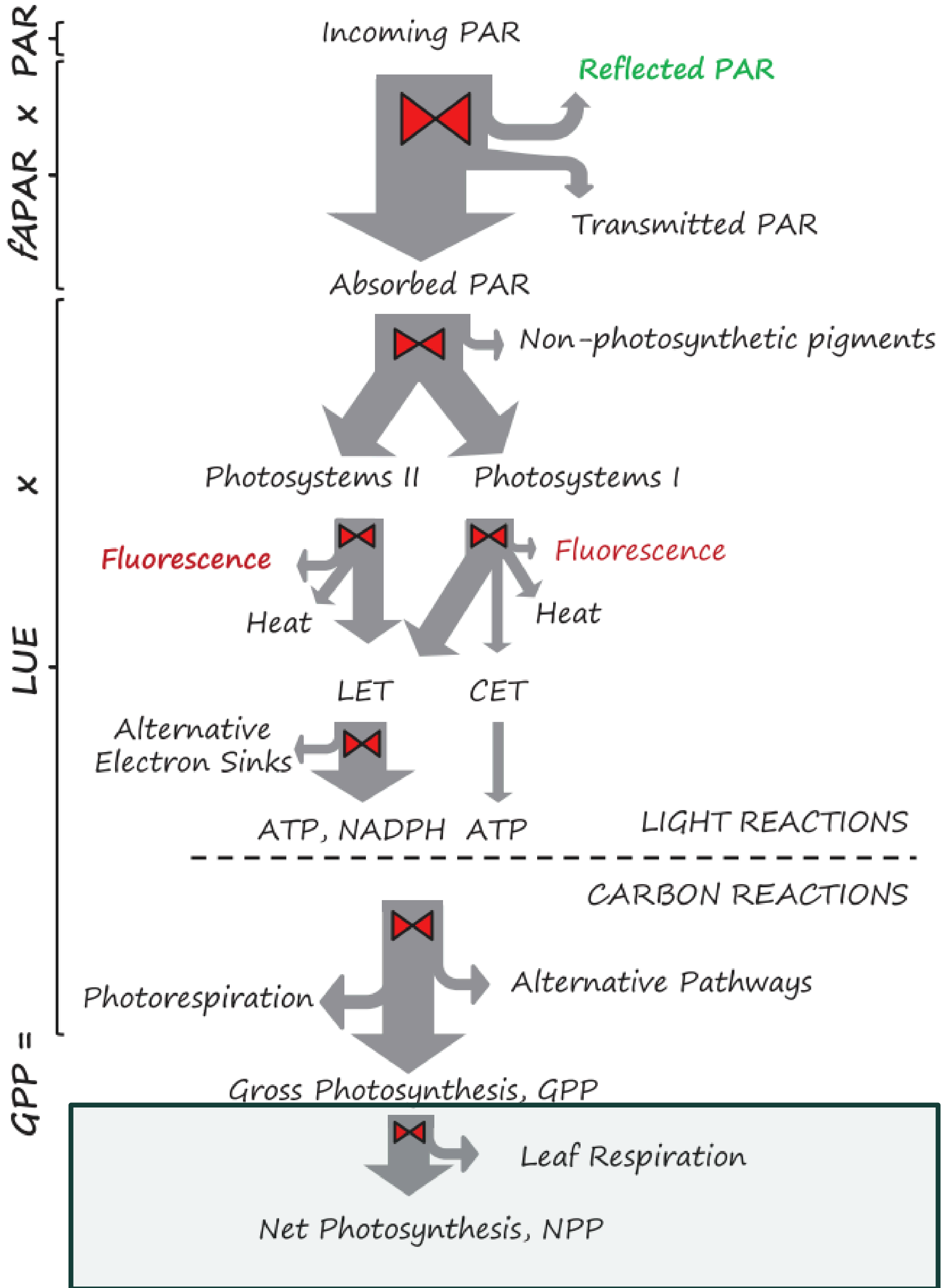


Figure 2.2.21 Net ecosystem production (NEP) is equal to net ecosystem exchange (NEE) minus losses from leaching and including any losses or gains from lateral carbon transfers. NEP is equivalent to the amount of carbon accumulated in ecosystem organic matter (alive and dead) over the period of time in question (normally 1 year).

https://biology.stackexchange.com/questions/81773/what-does-the-difference-between-gpp-npp-represent





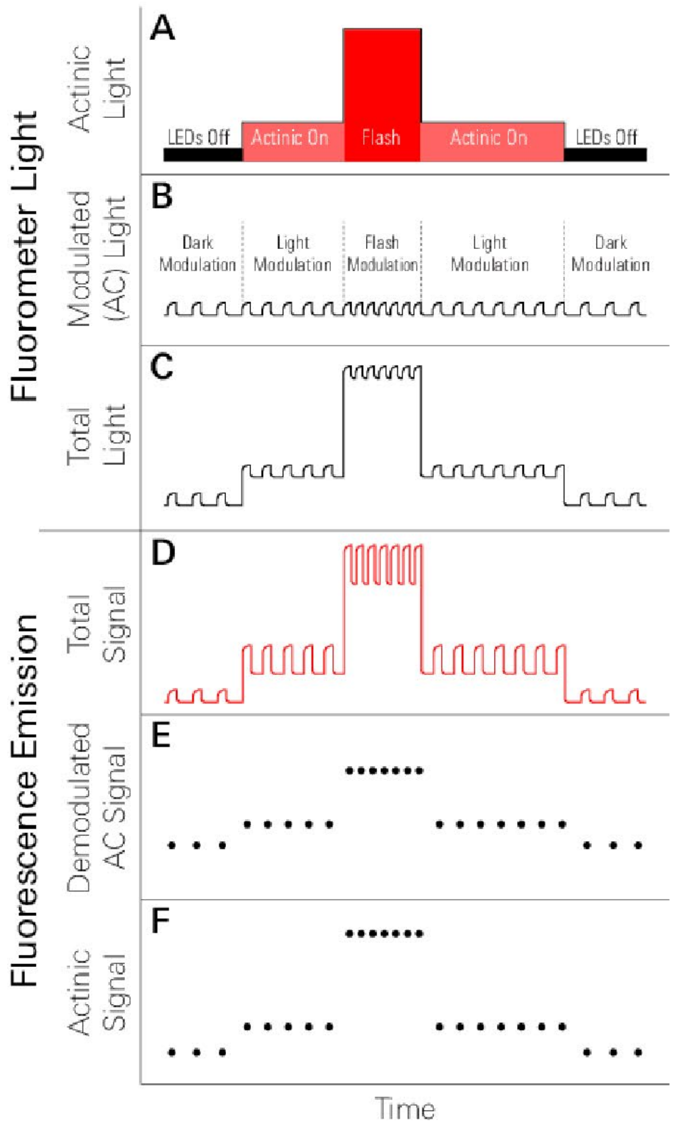


https://www.pnas.org/content/111/24/8856

So, what can fluorescence teach us about photosynthesis?

- Let’s start with active methods that have been used for decades
- … and then move on to solar-induced fluorescence and what we can learn from that (and what the difference is to active methods)

Active Fluorometry (Decades of Research)



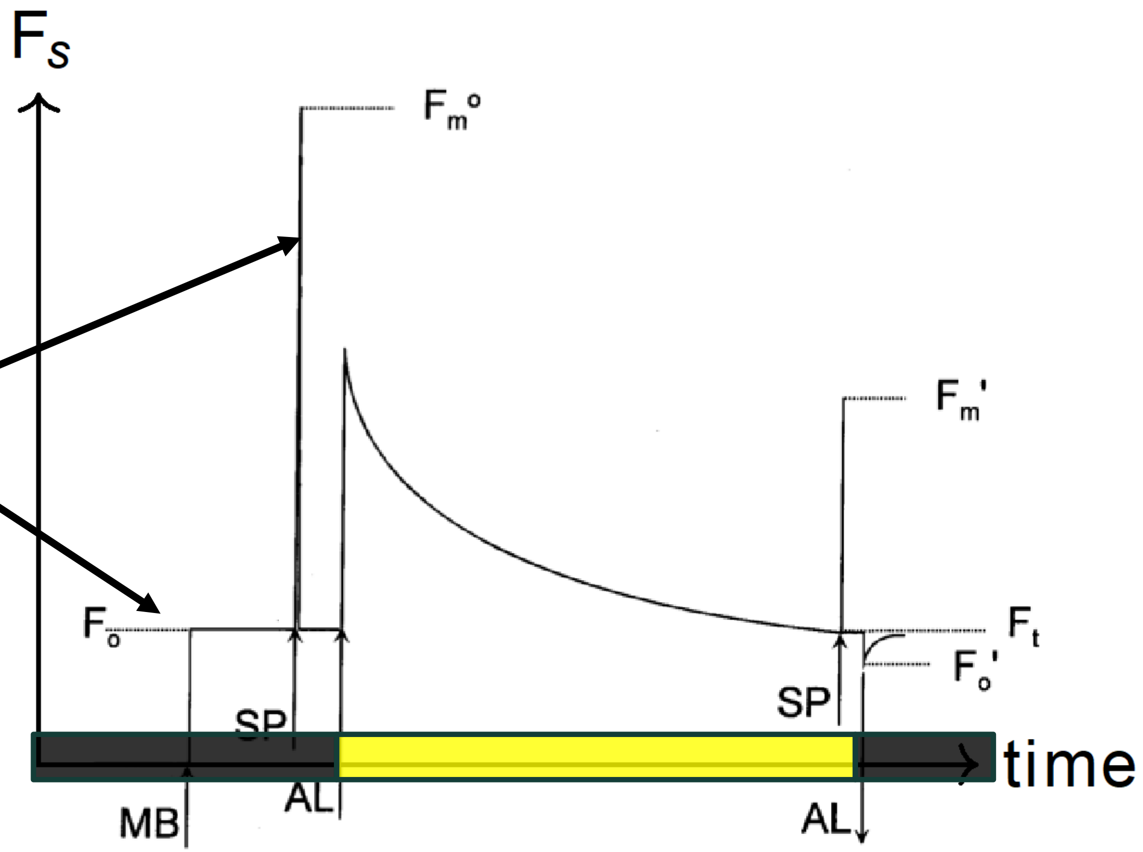
Graphics from Licor and Walz

The Power of 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 ″)

The Power of Active Fluorometry

- Fluorescence yield

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

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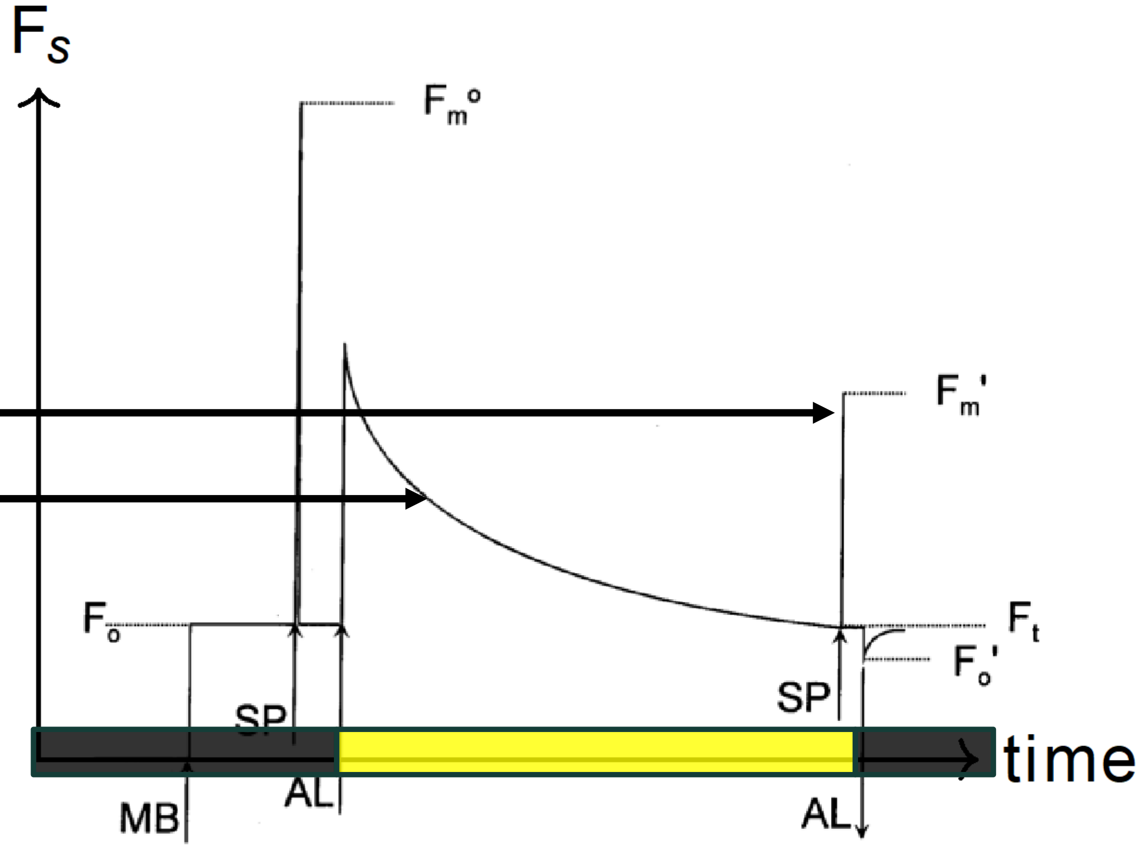


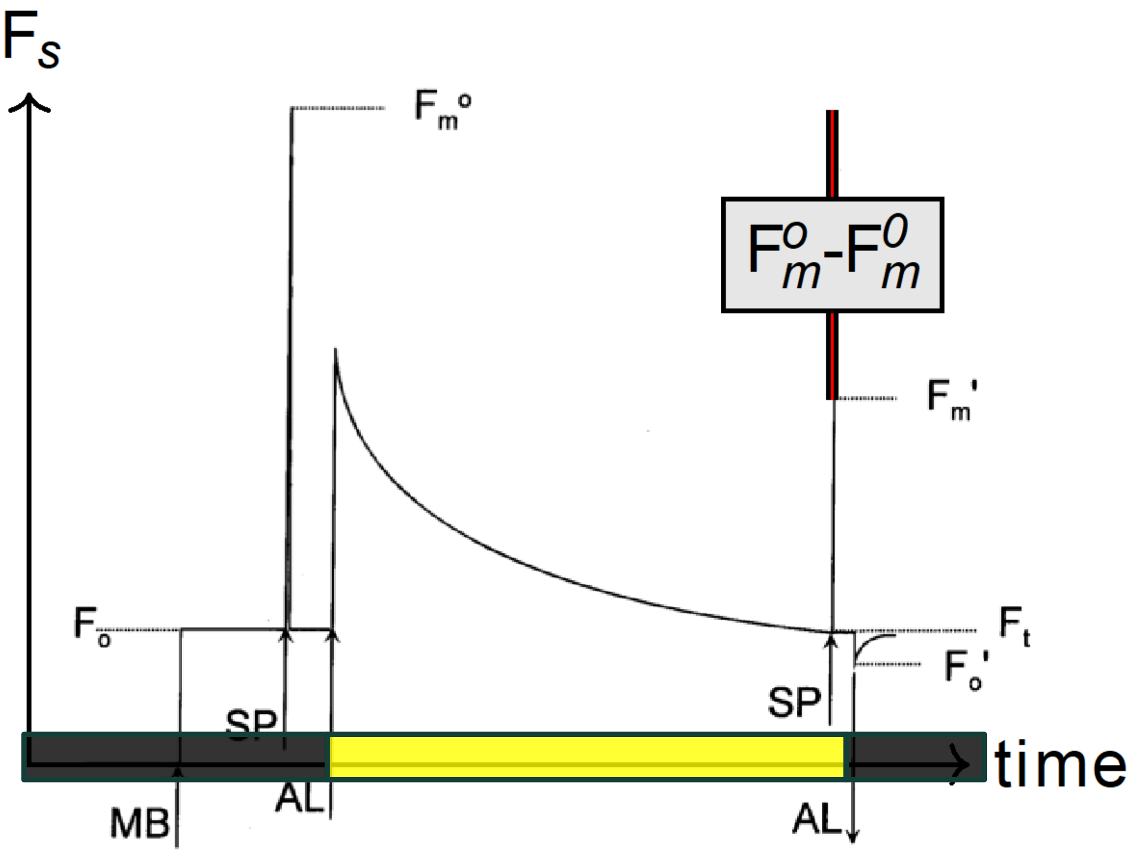
from Maxwell & Johnson 2000

AL=Actinic Light (moderate light was turned on ″ and off #)

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

The Power of Active Fluorometry

- $NPQ = (F_m^o - F_m^0)/F_m^0$



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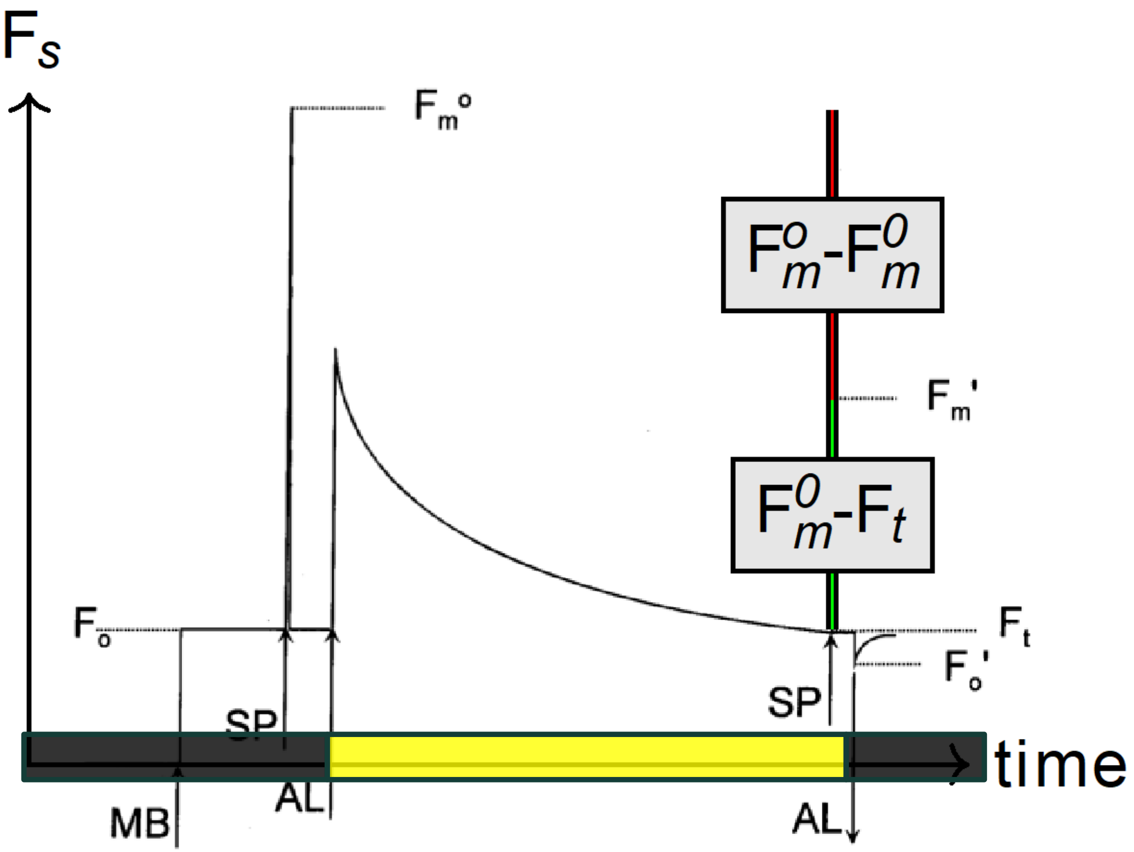
The Power of Active Fluorometry

- $NPQ = (F_m^o - F_m^0)/F_m^0$
- $\Phi_{PSII} = (F_m^0 - F_t)/F_m^0$

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



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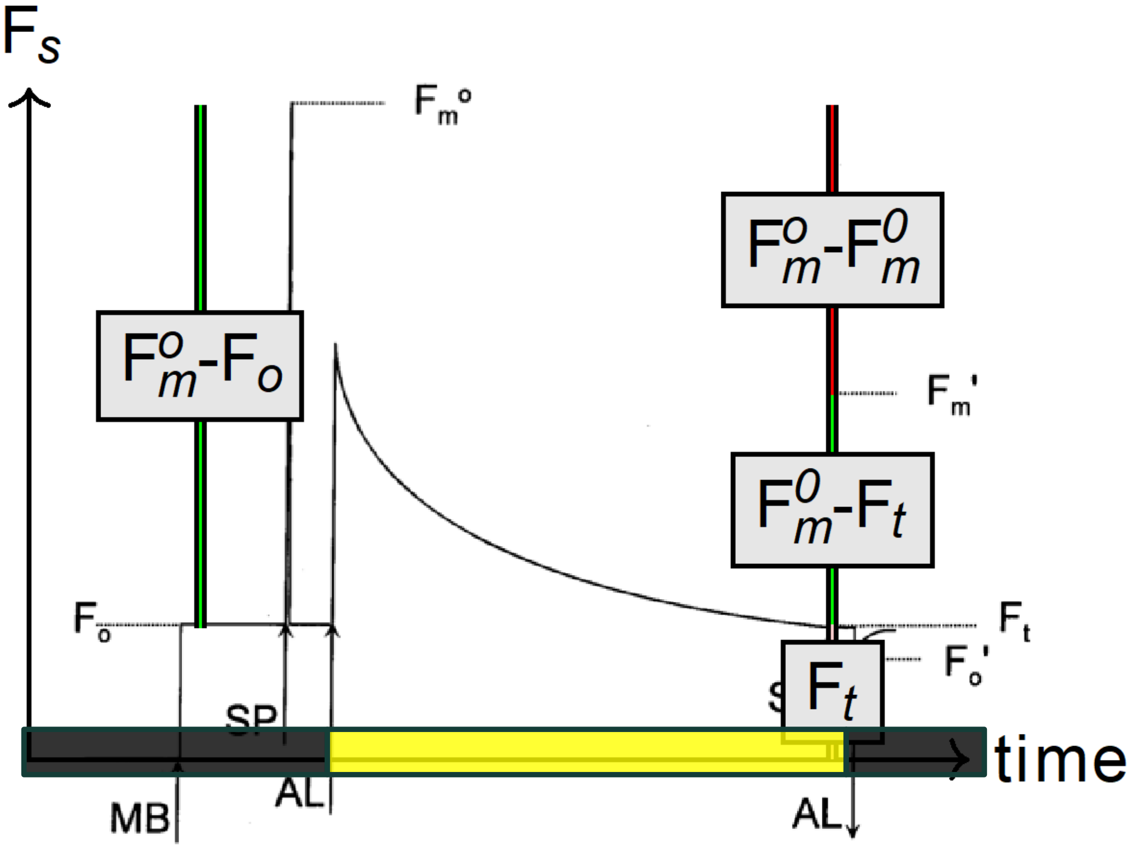
  Genty, Briantais, Baker (1988), > 5000 citations

- maximum PSII yield $= (F_m - F_o)/F_m$



from Maxwell & Johnson 2000

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

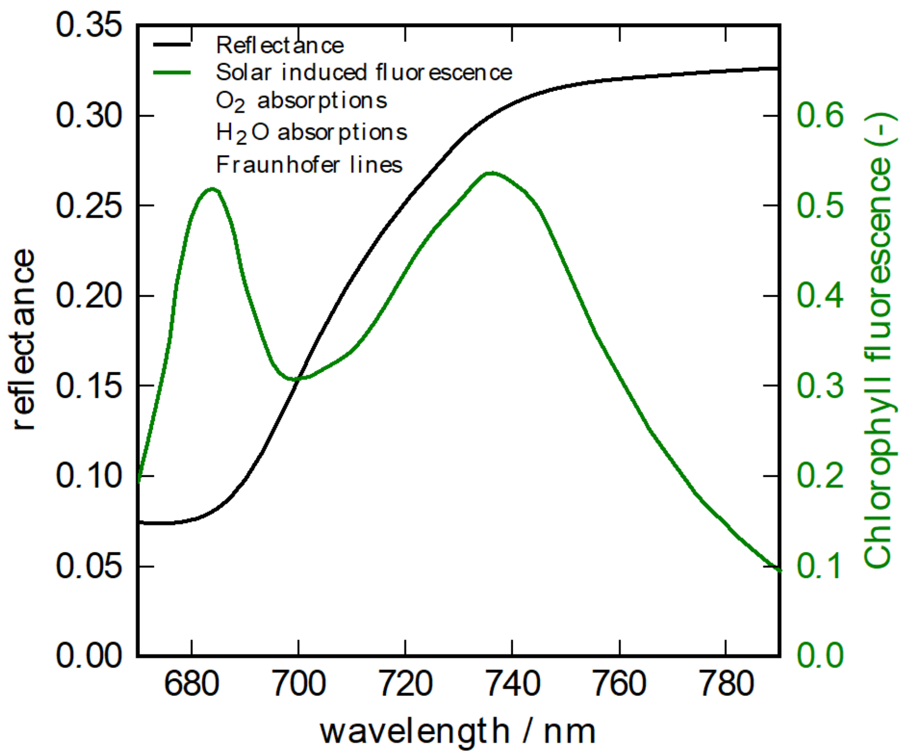
The Power of Active Fluorometry

With active fluorescence, the efficiency of PSII and hence electron transport can be directly calculated with

$$J = \Phi_{PSII} * APAR * \beta$$

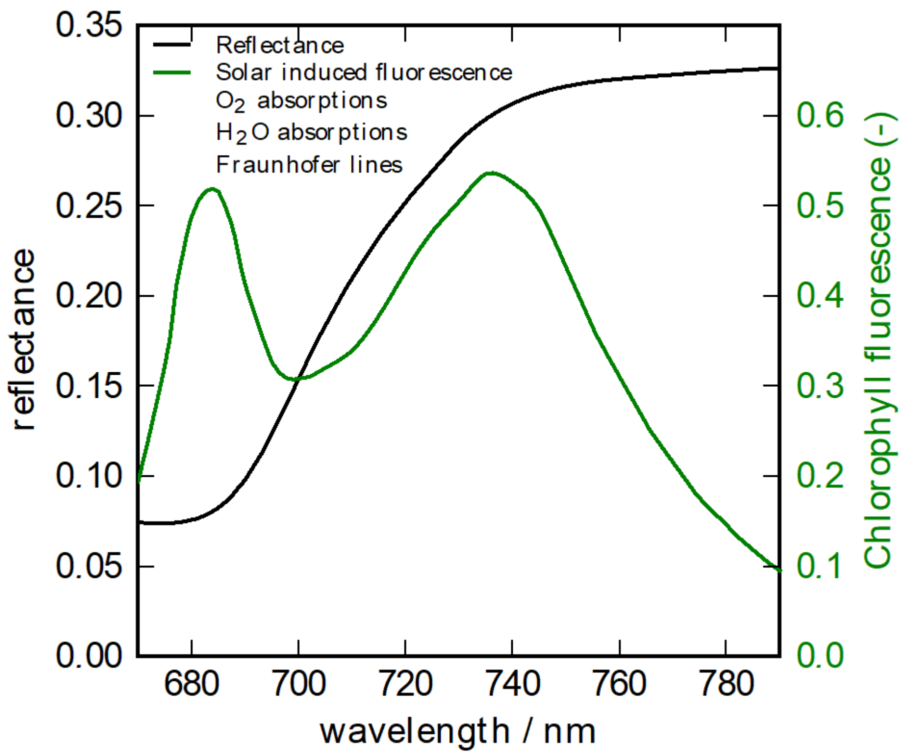
with β being the fraction of light absorbed by PSII (re PSI, often just assumed to be 0.5 on average)

Solar Induced Fluorescence (absolute)



$$SIF = PAR \cdot fPAR \cdot \Phi_f$$

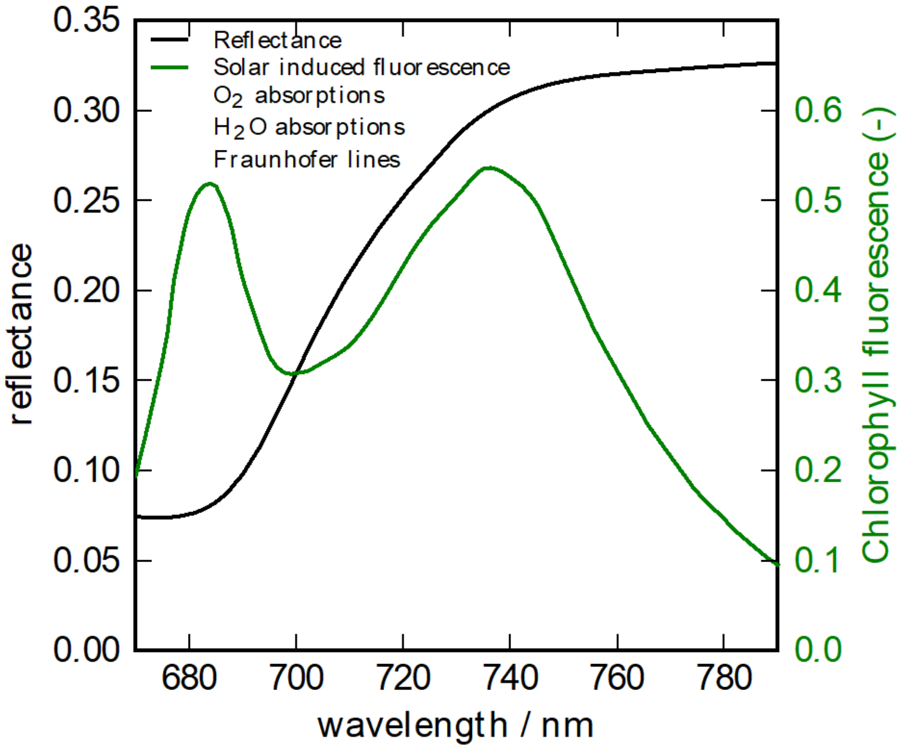
SOLAR INDUCED FLUORESCENCE (ABSOLUTE)



- Photosynthetically Active Radiation

$$SIF = PAR \cdot fPAR \cdot \Phi_f$$

SOLAR INDUCED FLUORESCENCE (ABSOLUTE)

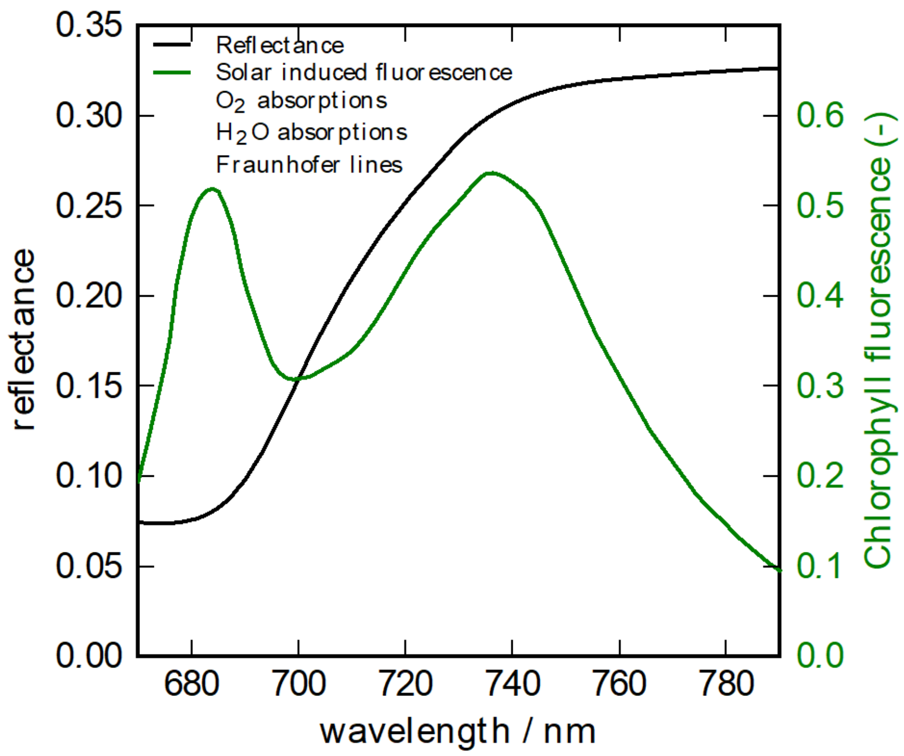


- Photosynthetically Active Radiation

$$SIF = PAR \cdot fPAR \cdot \Phi_f$$

- Fraction of PAR absorbed

Solar Induced Fluorescence (absolute)



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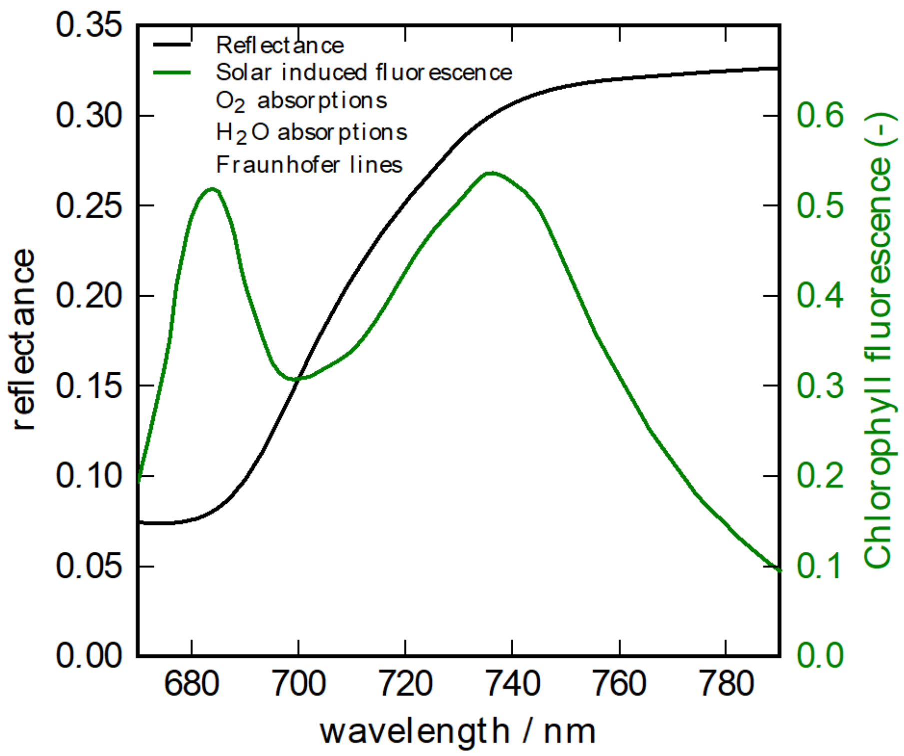
- fPAR can be estimated from NDVI (with some caveats!)

Solar Induced Fluorescence (absolute)

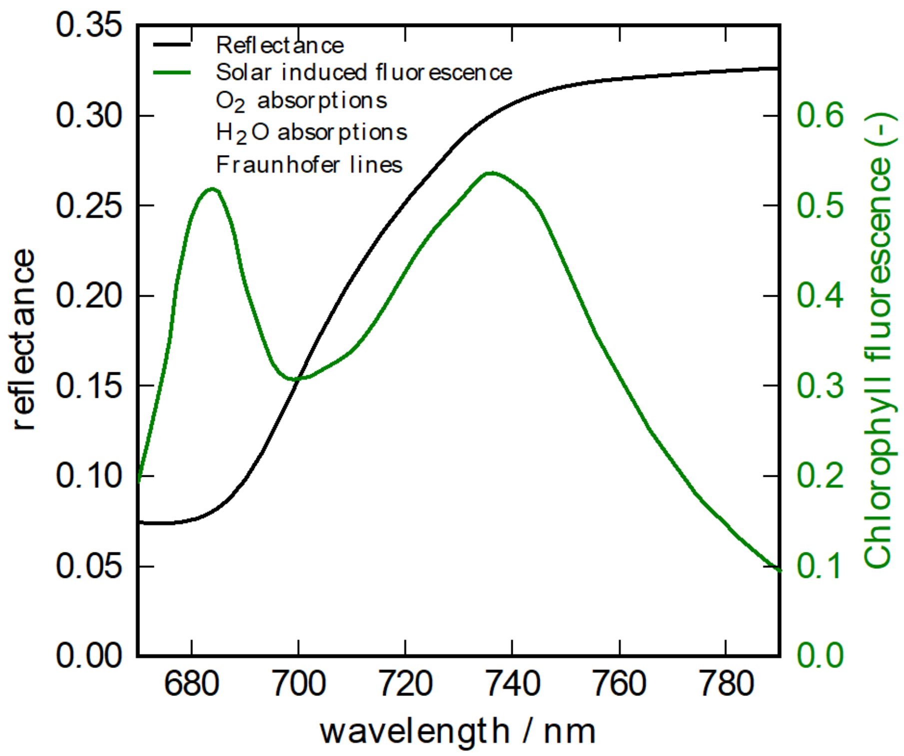


- Photosynthetically Active Radiation

$$SIF = PAR \cdot fPAR \cdot \Phi_f$$

- Fraction of PAR absorbed
- fPAR can be estimated from NDVI (with some caveats!)
- $GPP = PAR \cdot fPAR \cdot \Phi_p$

SOLAR INDUCED FLUORESCENCE (ABSOLUTE)

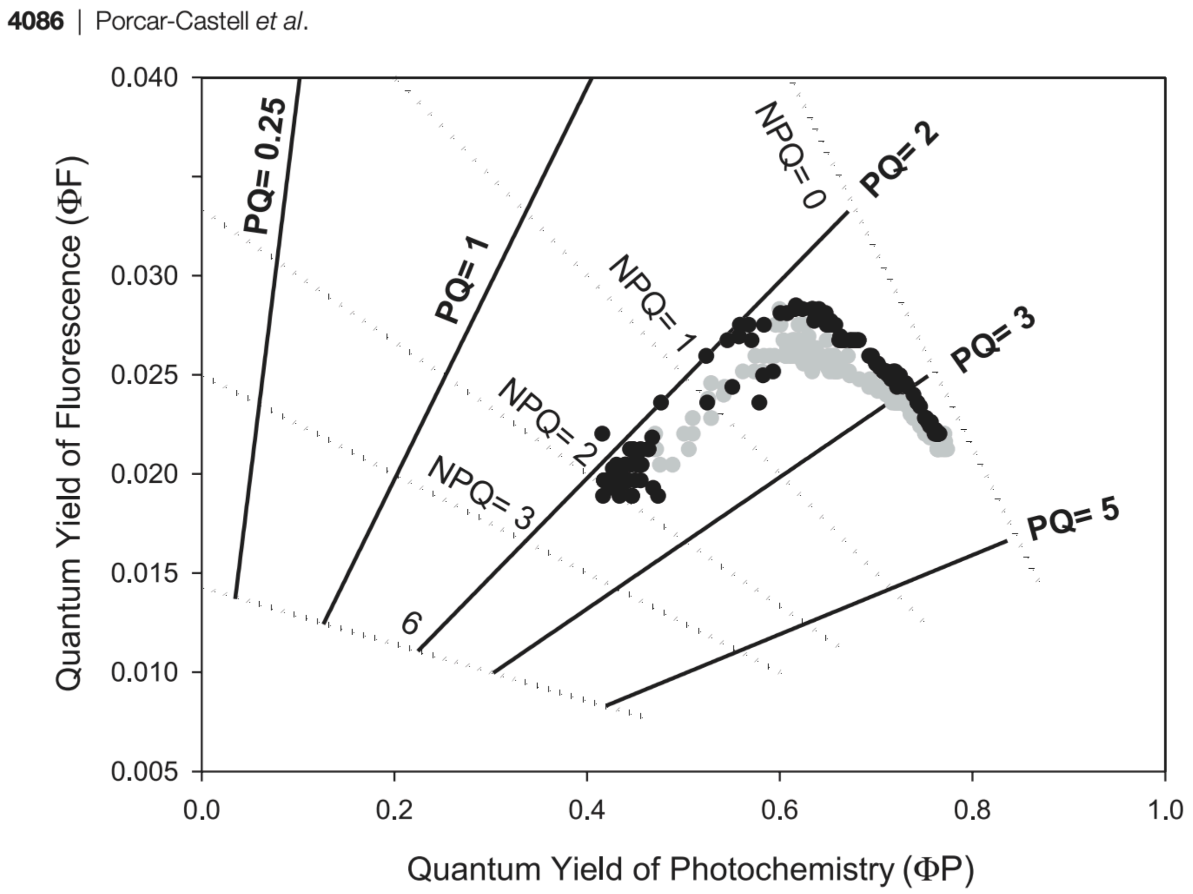


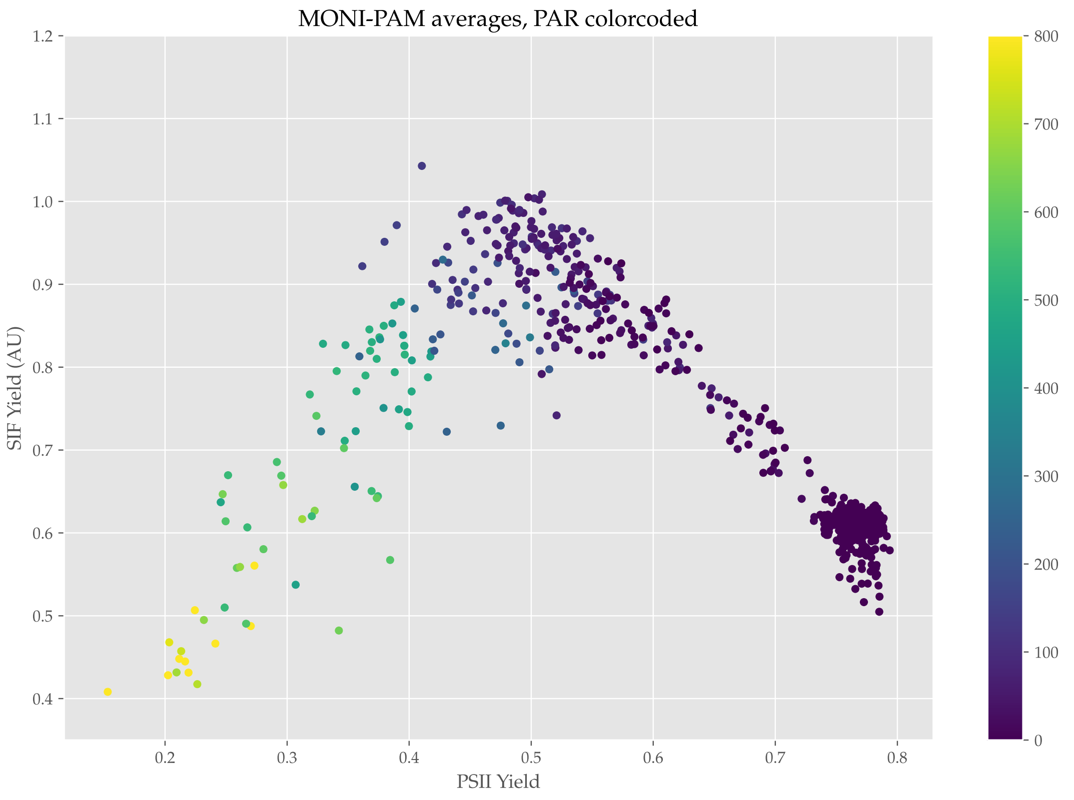
- Photosynthetically Active Radiation

$$SIF = PAR \cdot fPAR \cdot \Phi_f$$

- Fraction of PAR absorbed
- fPAR can be estimated from NDVI (with some caveats!)
- $GPP = PAR \cdot fPAR \cdot \Phi_p$
- $GPP = SIF \cdot \Phi_p / \Phi_f$

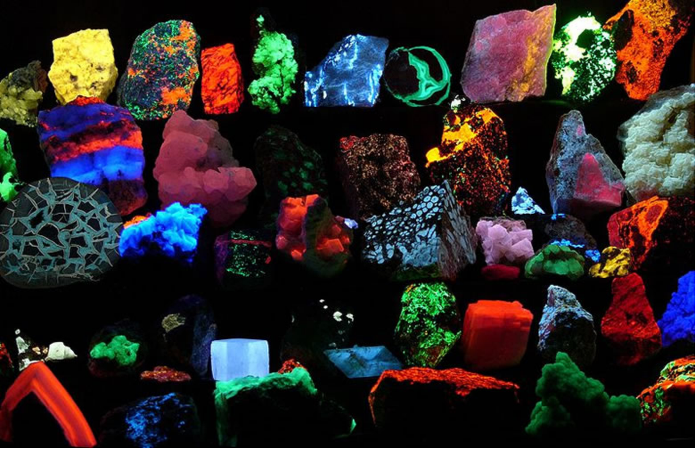
The Relationship Between Fluorescence and Photosynthesis Yields





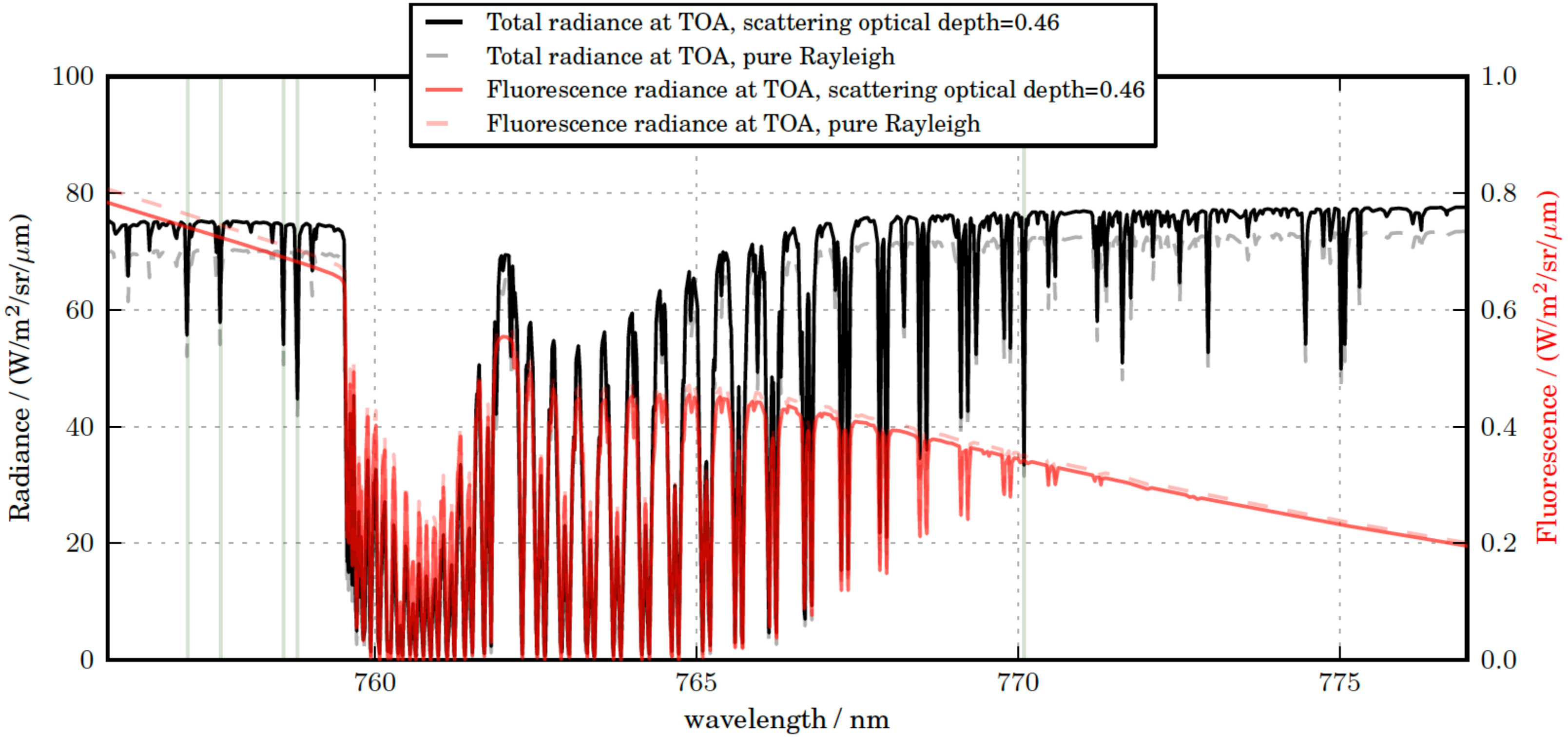
How do we measure SIF?

- From the theory of what SIF means to the means of measuring it

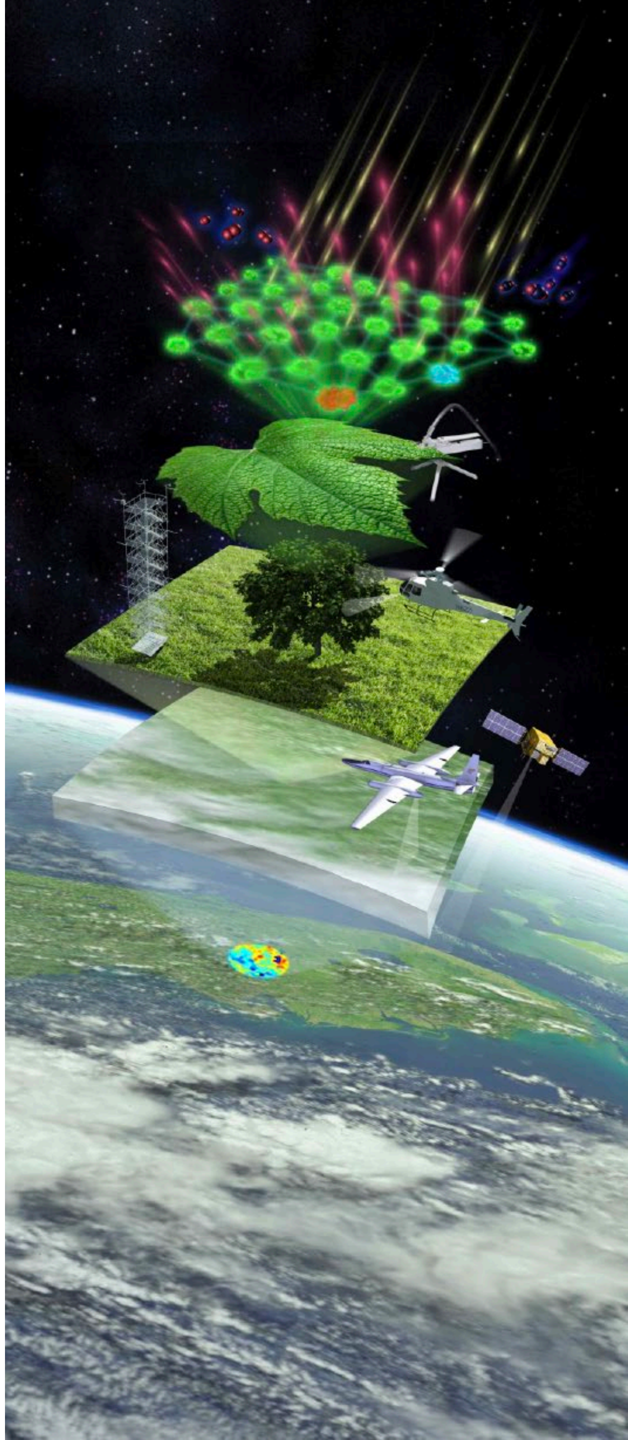


How do you measure this faint glow remotely?

(It adds just about 1% to the total signal. Think of it like turning on a lightbulb in a sunny room.)



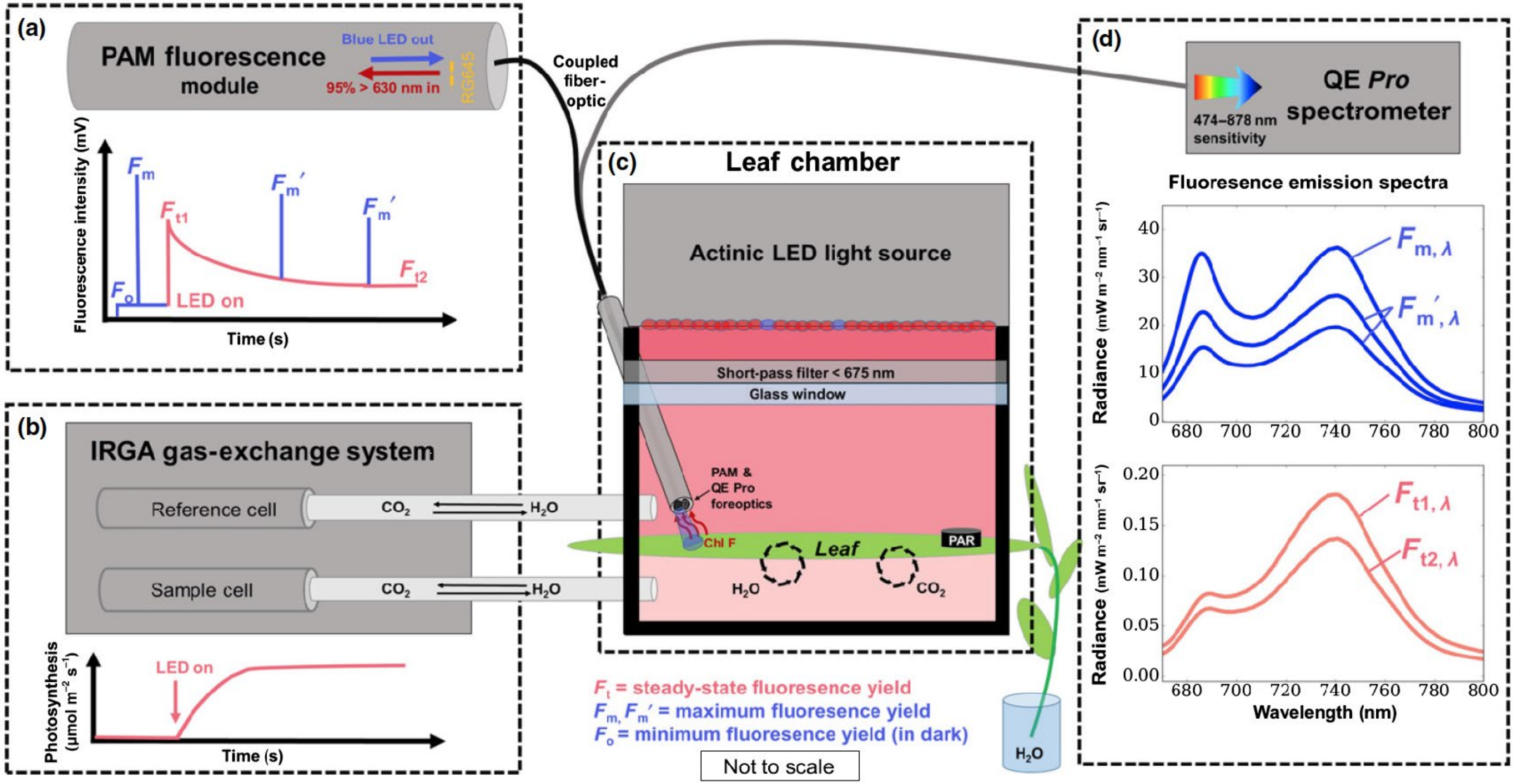
Frankenberg et al, AMT (2012)



Methods

Connecting active to passive fluorescence with photosynthesis: a method for evaluating remote sensing measurements of Chl fluorescence

Troy S. Magney[1], Christian Frankenberg[1,2], Joshua B. Fisher[1], Ying Sun[1,3], Gretchen B. North[4], Thomas S. Davis[5], Ari Kornfeld[6] and Katharina Siebke[7]



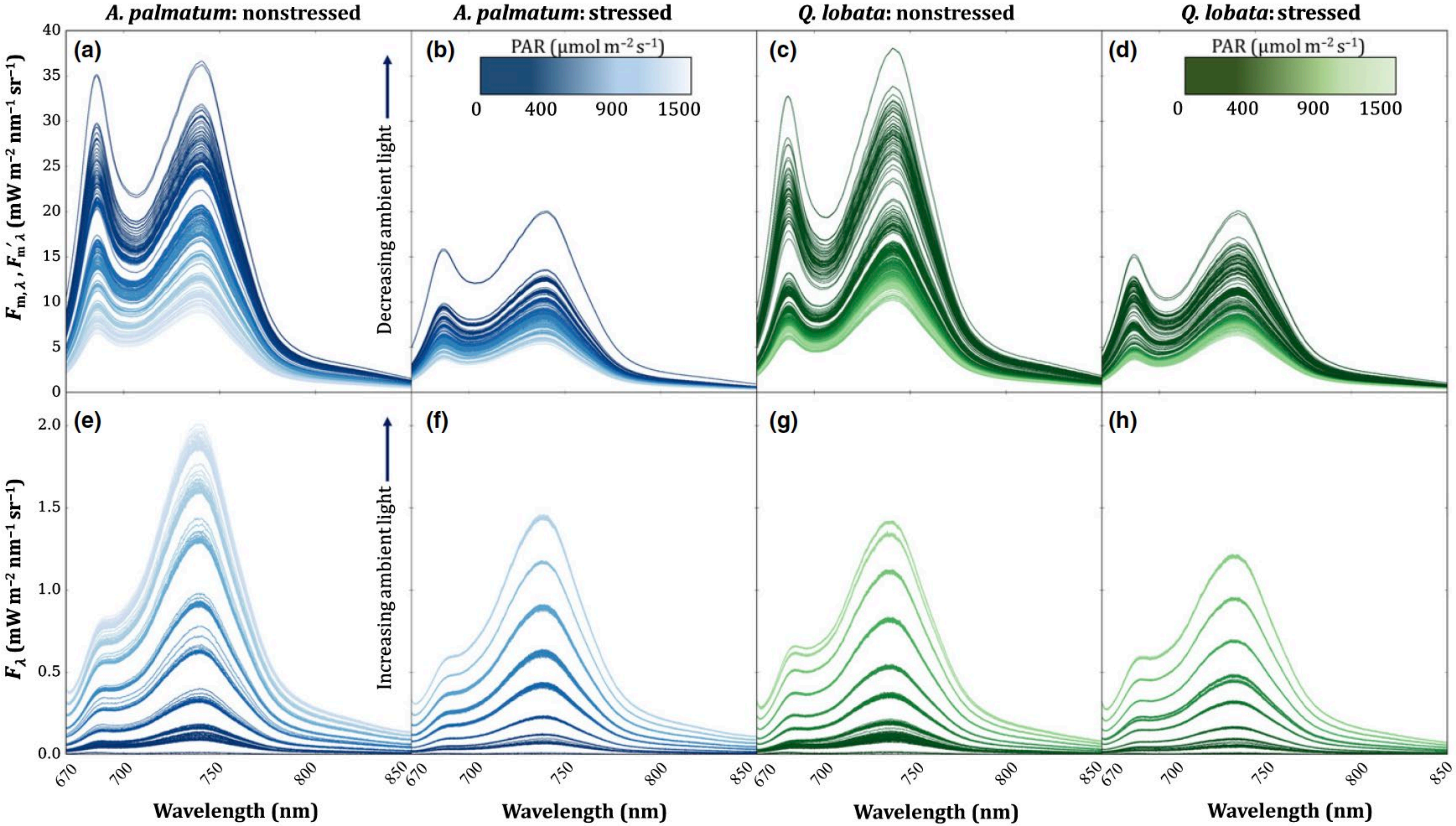
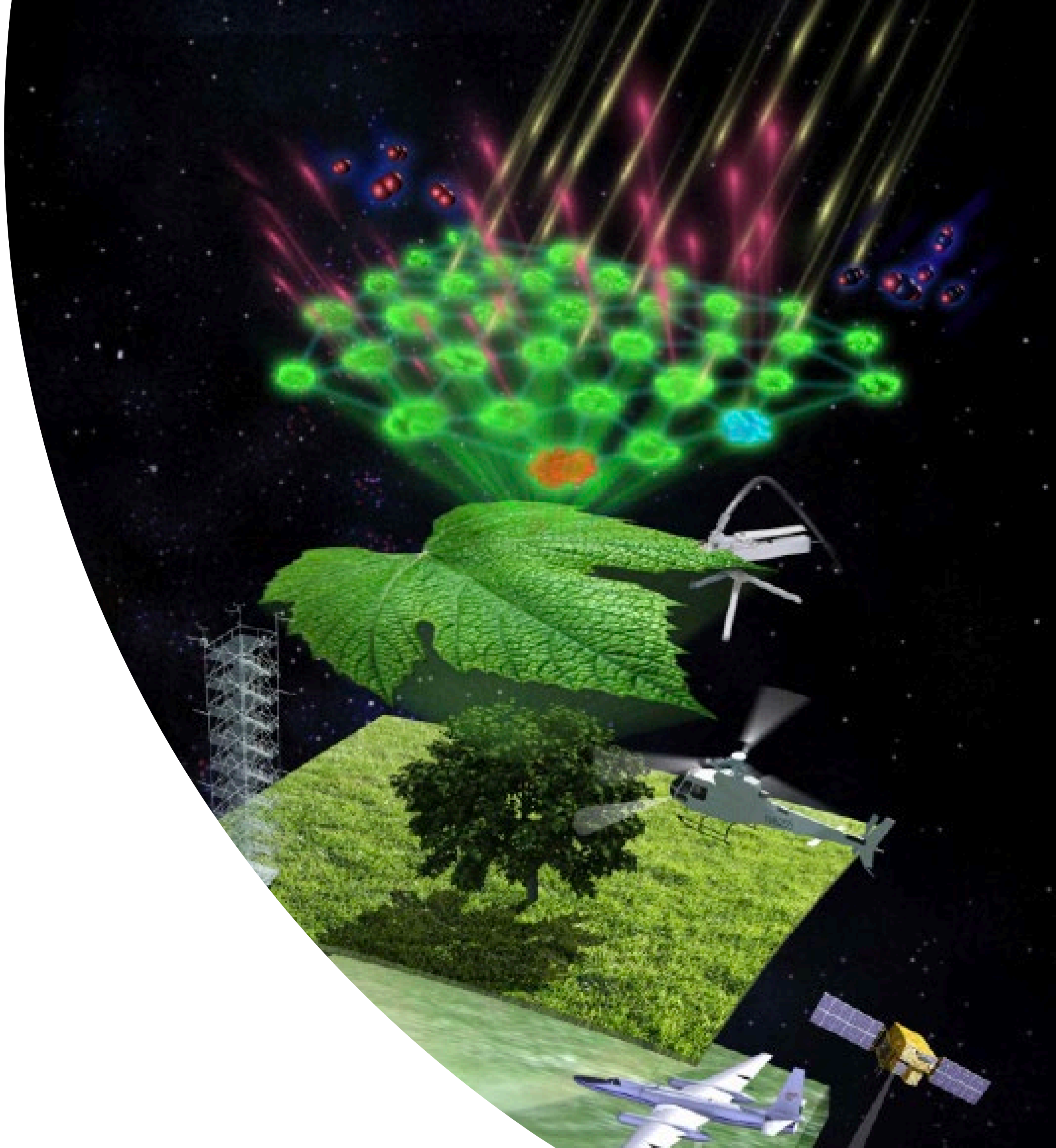
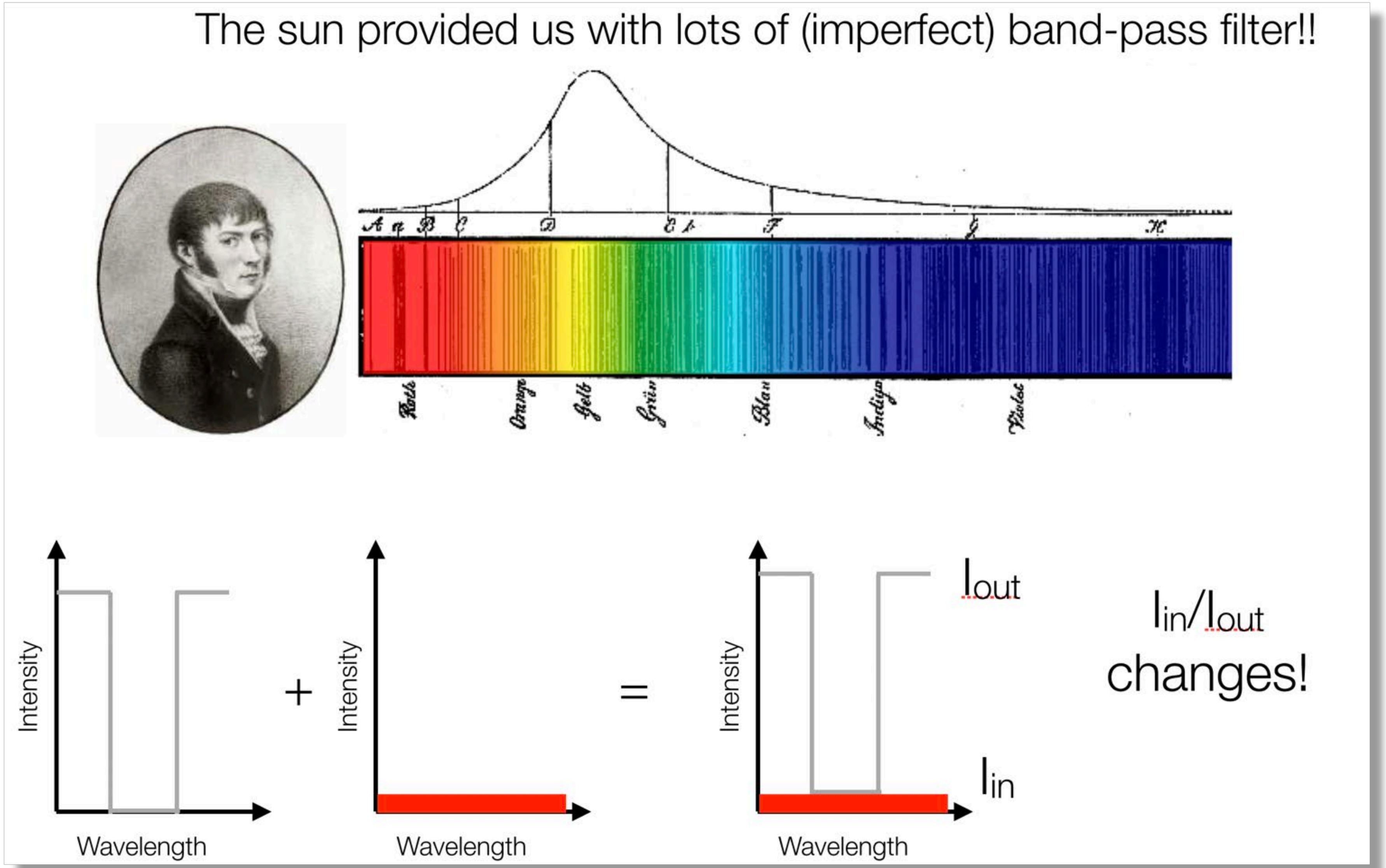


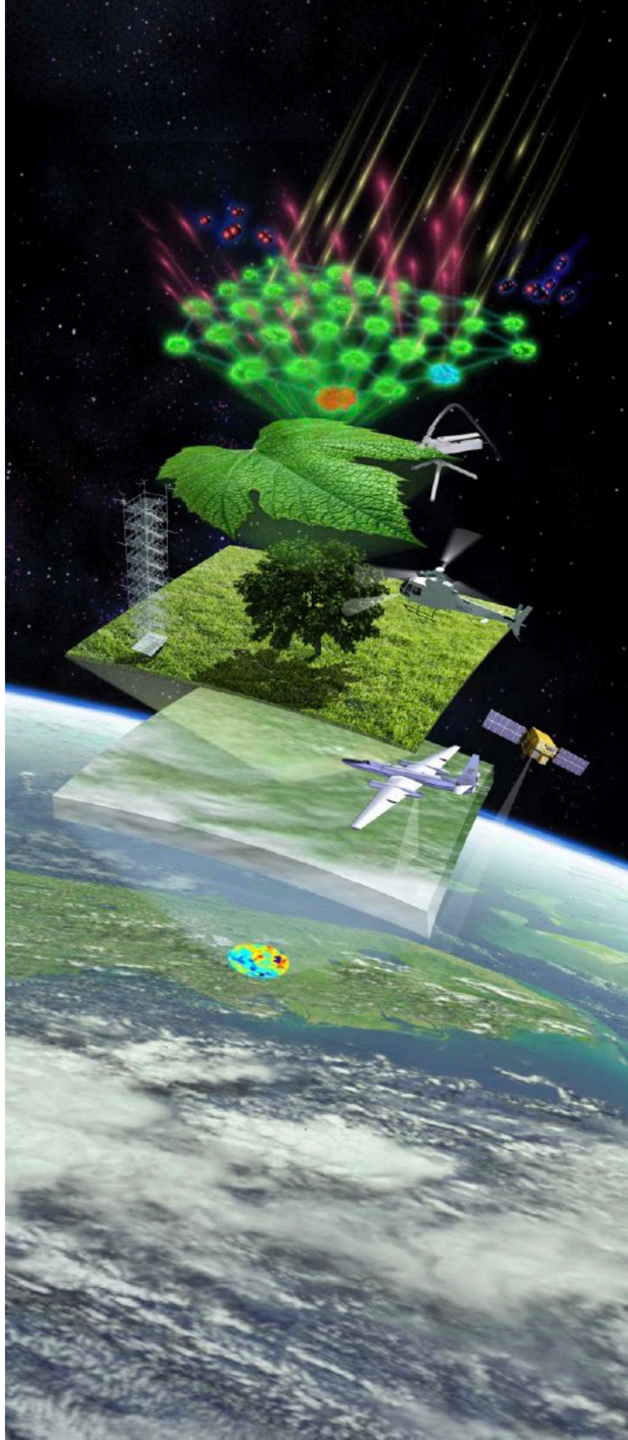
Fig. 4 Maximal fluorescence emission derived from the saturation pulse ($F_{m,\lambda}$ and $F_m{}'_{,\lambda}$) (a–d) and actinic light-induced fluorescence emission (F_λ) (e–h) among *Acer palmatum* (blues) leaves under nonstressed (a, e) and stressed (b, f) conditions; and *Quercus lobata* (greens) leaves under nonstressed (c, g) and stressed (d, h) conditions. Color ramp is indicative of incident photosynthetically active radiation (PAR, μmol m^{-2} s^{-1}) exposure during light response curve – lighter colors indicate greater PAR, and darker colors represent less incident PAR.

We need a curtain!

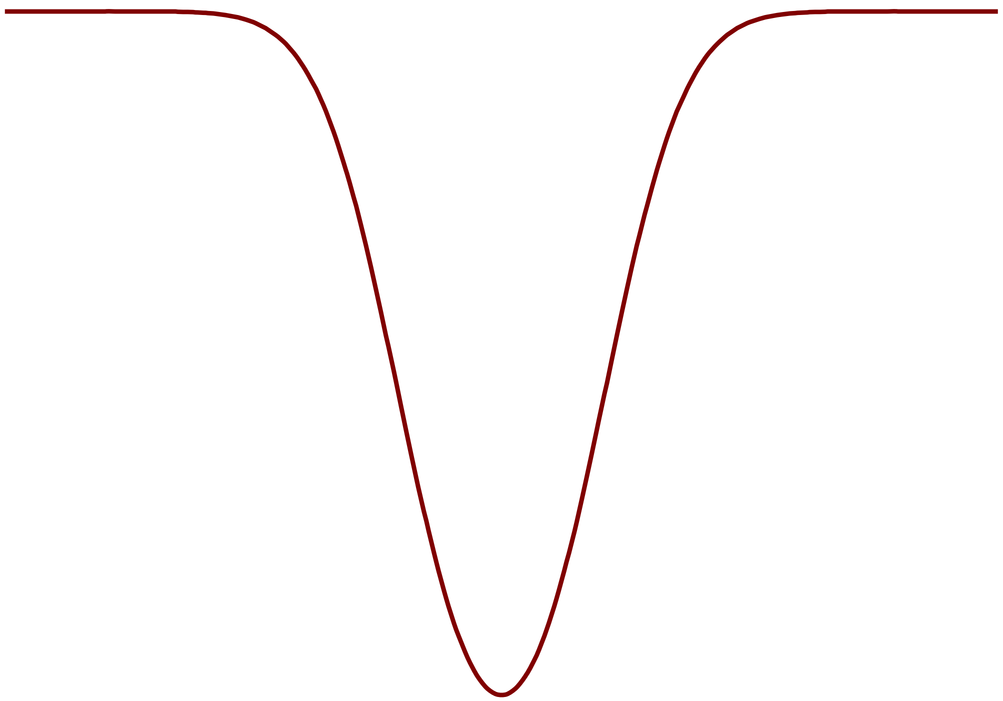


We can use a “dark room” in spectral space!



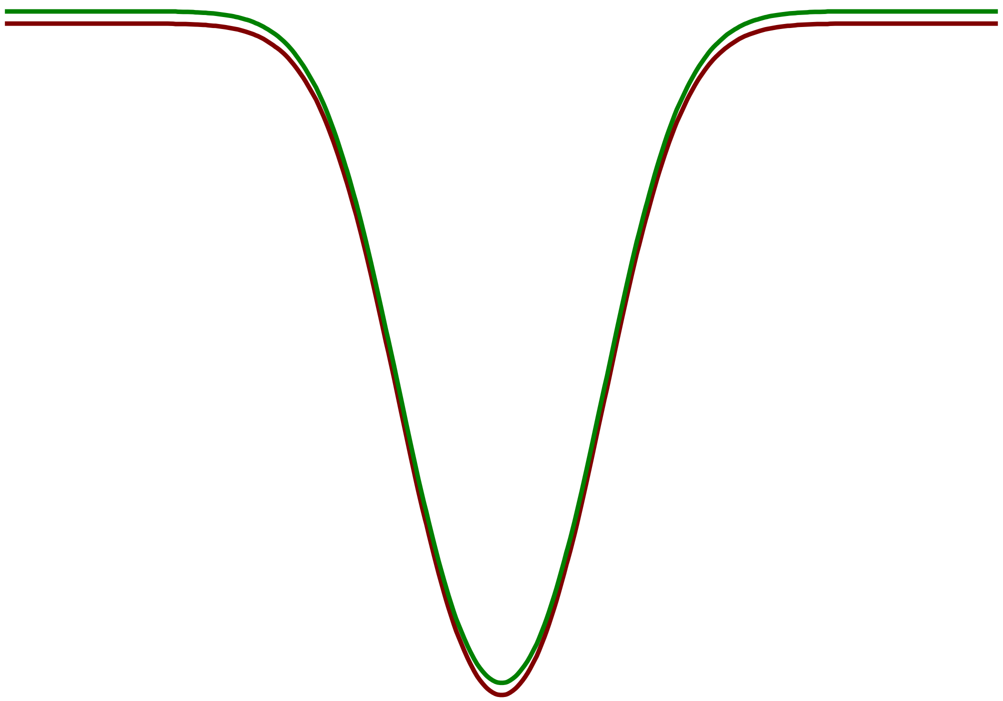


Impact of Fluorescence on Fraunhofer Line



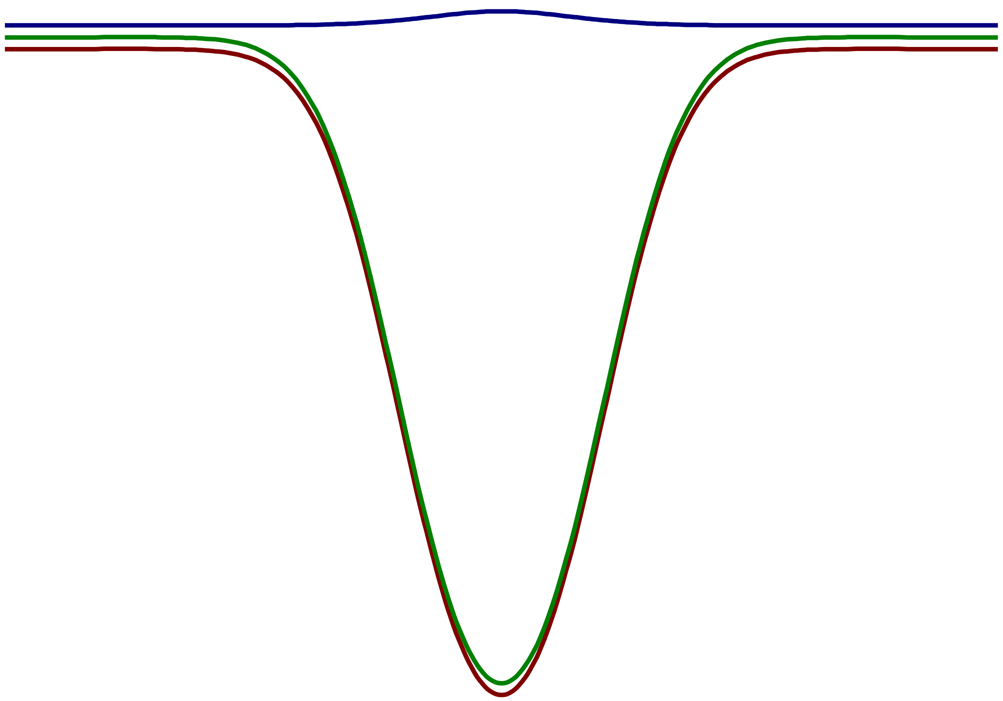
- Made-up Fraunhofer line

Impact of Fluorescence on Fraunhofer Line



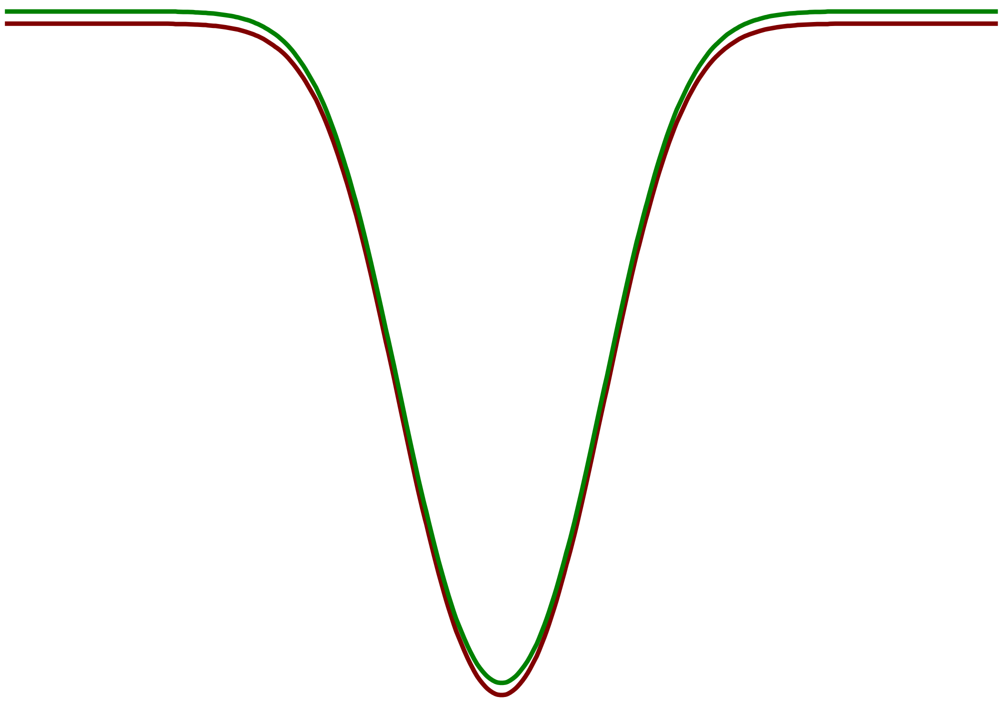
- Made-up Fraunhofer line
- Fluorescence term added

Impact of Fluorescence on Fraunhofer Line



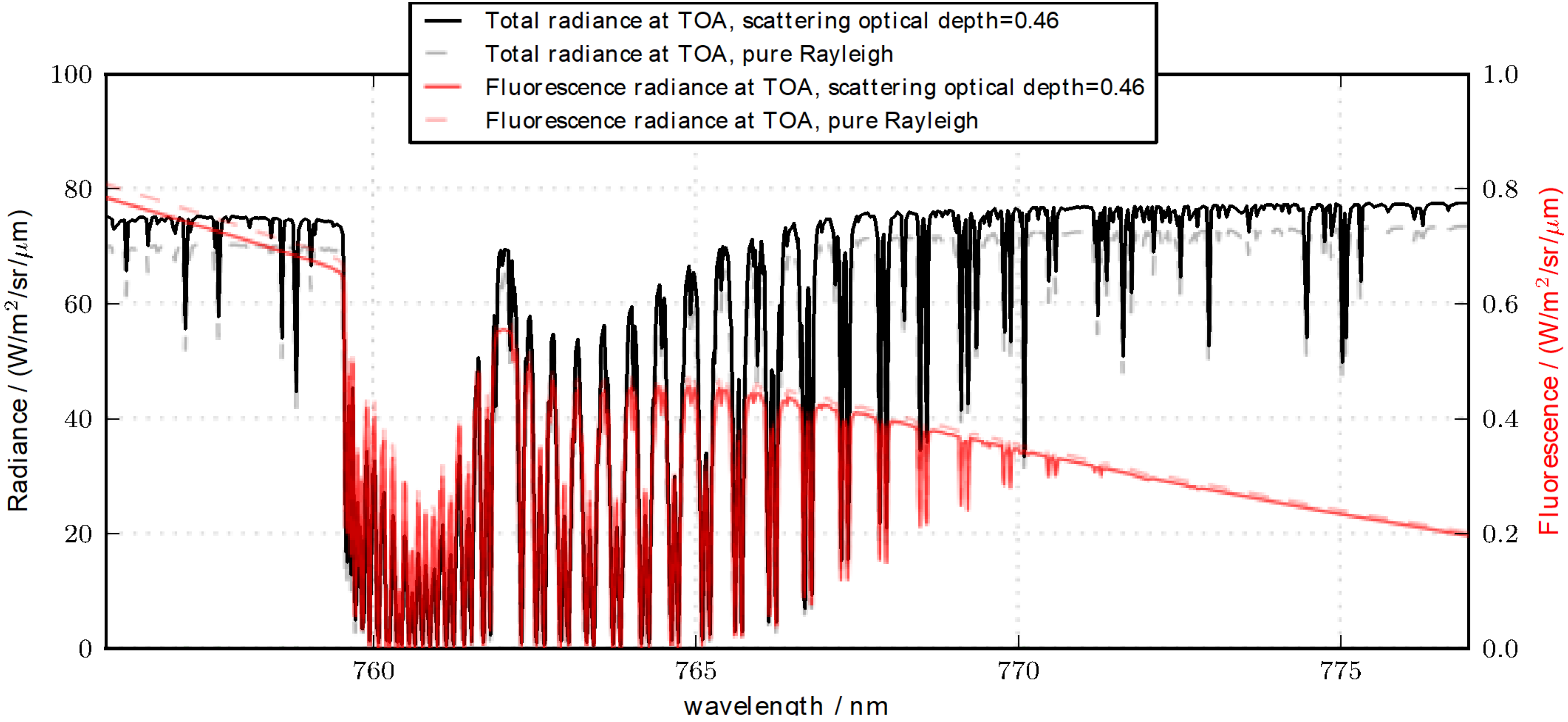
- Made-up Fraunhofer line
- Fluorescence term added
- Ratio of the spectra with and without fluorescence

Impact of Fluorescence on Fraunhofer Line



- Made-up Fraunhofer line
- Fluorescence term added
- Ratio of the spectra with and without fluorescence
- By fitting this *in-filling*, we can derive the fluorescence emission. In principle, it doesn't matter whether we are looking at a leaf, a tree, an ecosystem or a hemisphere, the total emission measurement should be unbiased.

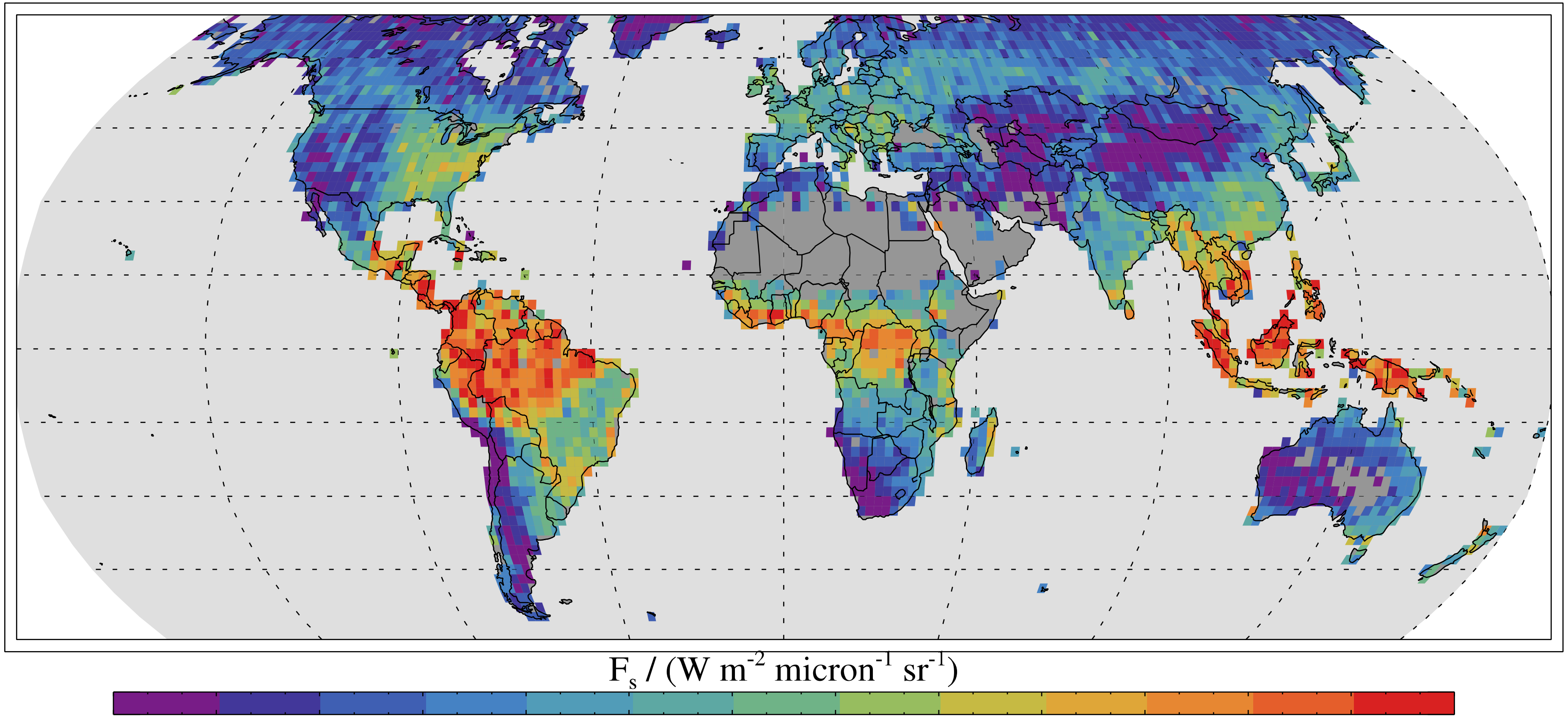
Background: Measuring Fluorescence



Frankenberg, O'Dell, Guanter, et al (2011)
Chlorophyll fluorescence remote sensing from space in scattering atmospheres: Implications for its retrieval and interferences with atmospheric CO_2 retrievals.

History or Evolution of SIF Measurement

Joiner et al, Frankenberg et al

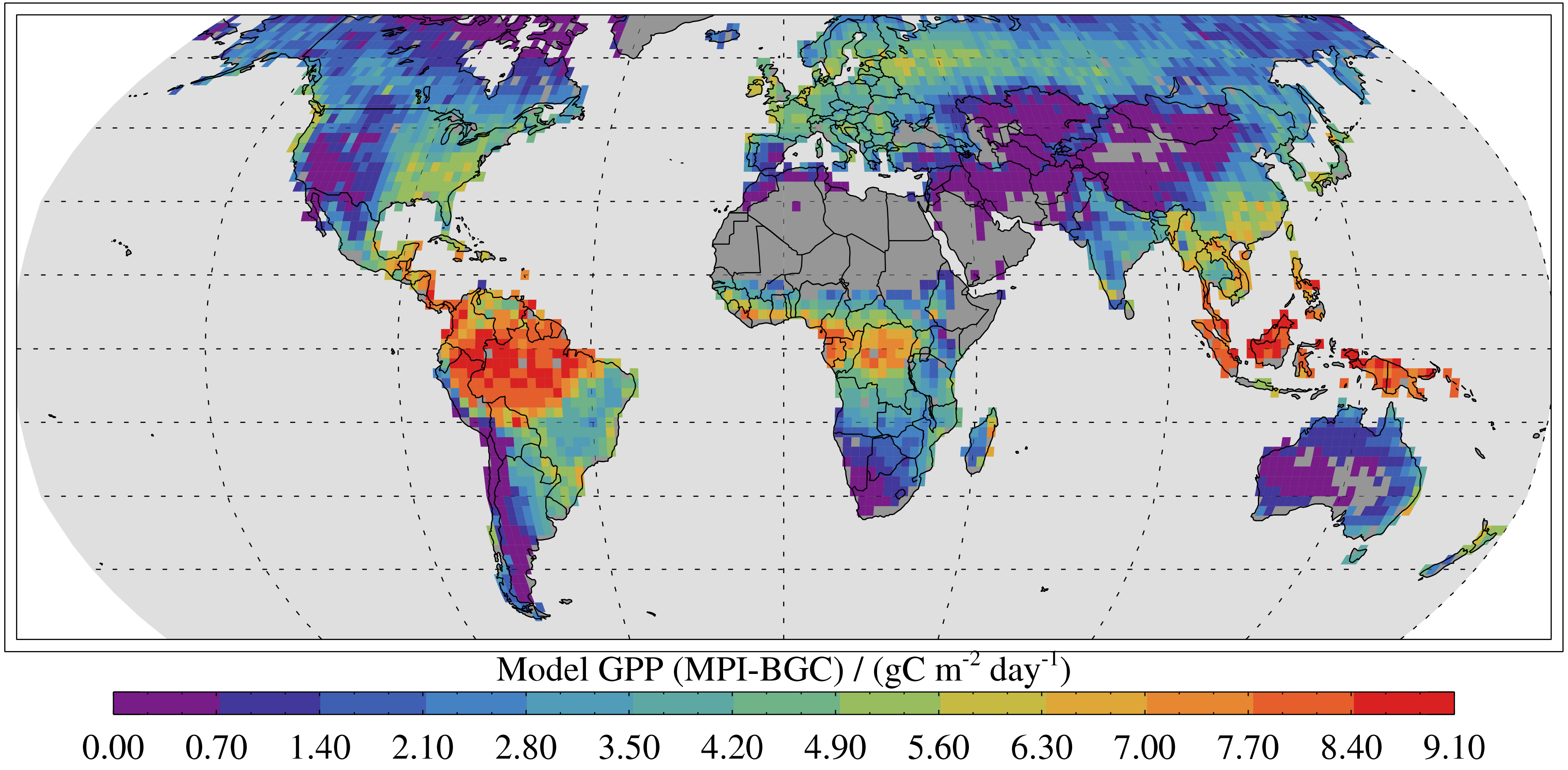


GOSAT

Frankenberg et al, GRL (2011b)

History or Evolution of SIF Measurement

Joiner et al, Frankenberg et al



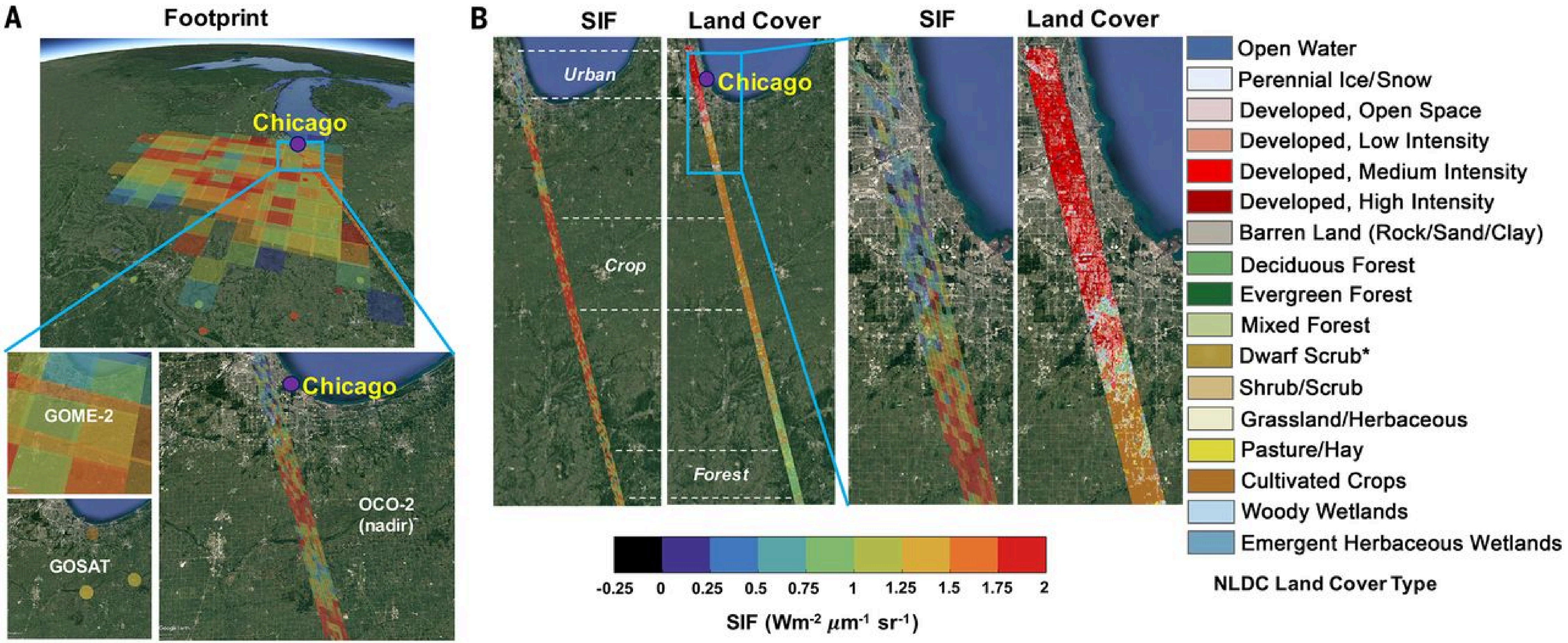
Frankenberg et al, GRL (2011b)

GOSAT

History or Evolution of SIF Measurement

Sun et al

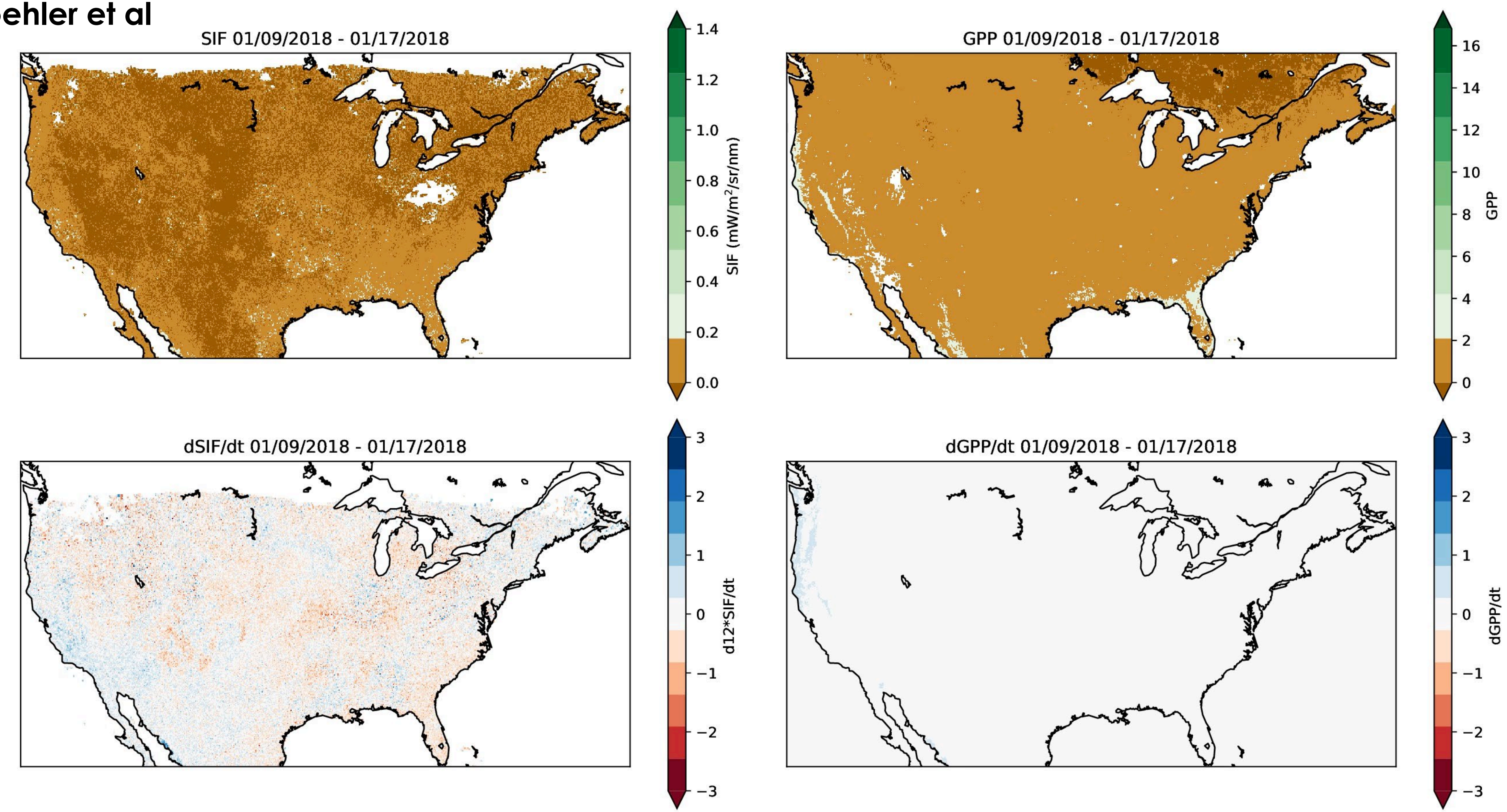
OCO-2



History or Evolution of SIF Measurement

TROPOMI

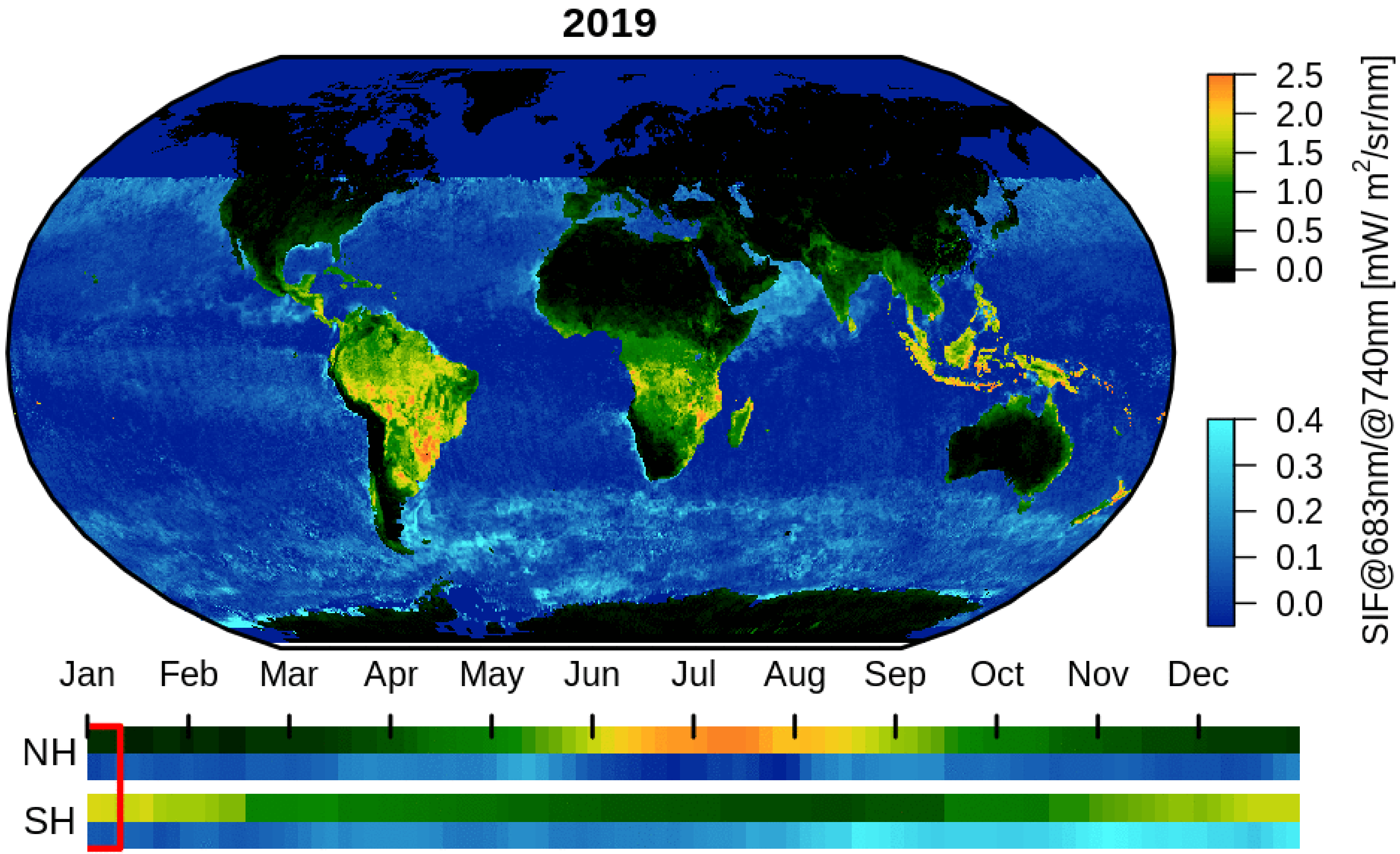
Koehler et al



History or Evolution of SIF Measurement

Koehler et al

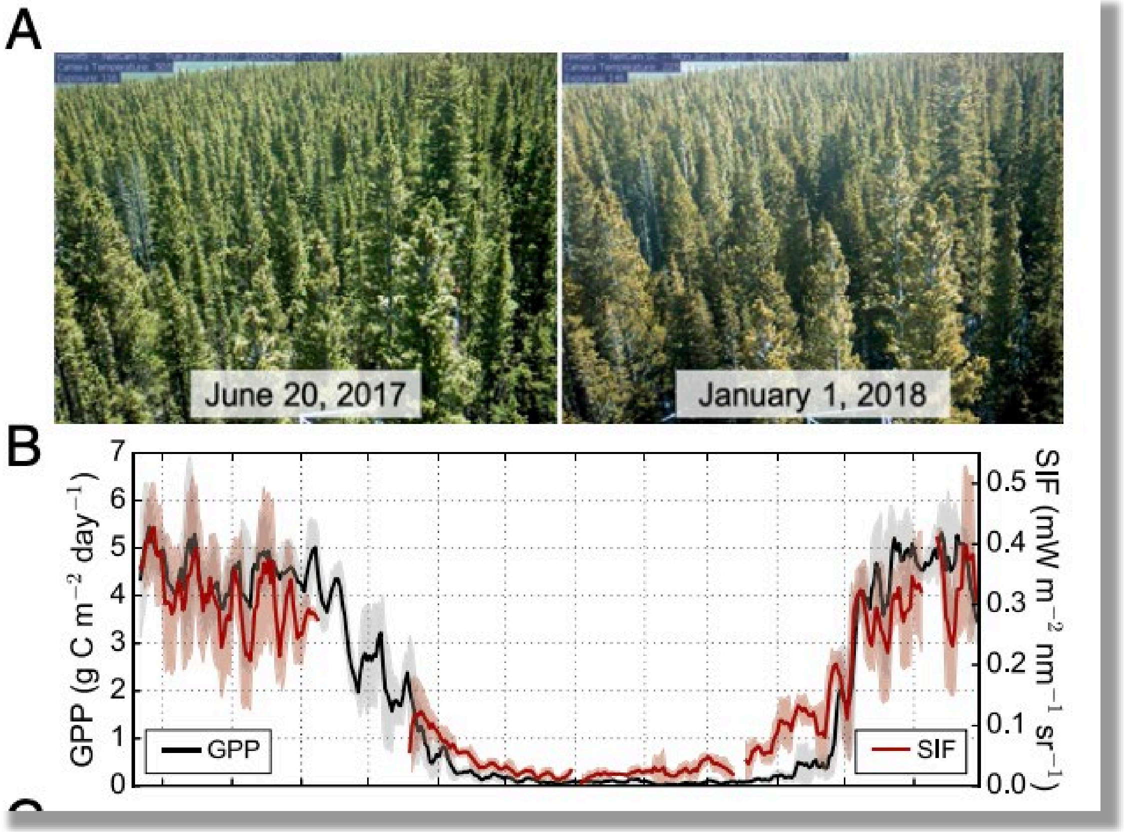
TROPOMI



Now we can measure it from towers as well! (e.g. evergreens)

Mechanistic evidence for tracking the seasonality of photosynthesis with solar-induced fluorescence

Troy S. Magney[a,b,1], David R. Bowling[c], Barry A. Logan[d], Katja Grossmann[e,2], Jochen Stutz[e], Peter D. Blanken[f], Sean P. Burns[f,g], Rui Cheng[a], Maria A. Garcia[c], Philipp Köhler[a], Sophia Lopez[d], Nicholas C. Parazoo[b], Brett Raczka[c], David Schimel[b], and Christian Frankenberg[a,b,1]



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Comprehensive Remote Sensing

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3.10 - Solar Induced Chlorophyll Fluorescence: Origins, Relation to Photosynthesis and Retrieval

C. Frankenberg, J. Berry

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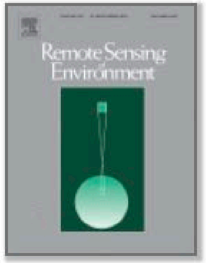

Remote sensing of solar-induced chlorophyll fluorescence (SIF) in vegetation: 50 years of progress

Gina H. Mohammed [a], Roberto Colombo [b], Elizabeth M. Middleton [c], Uwe Rascher [d], Christiaan van der Tol [e], Ladislav Nedbal [d], Yves Goulas [f], Oscar Pérez-Priego [g], Alexander Damm [h, i], Michele Meroni [j], Joanna Joiner [c], Sergio Cogliati [b], Wouter Verhoef [e], Zbyněk Malenovský [k], Jean-Philippe Gastellu-Etchegorry [l], John R. Miller [m], Luis Guanter [n], Jose Moreno [o] … Pablo J. Zarco-Tejada [j, r, s, t]

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First published: 18 March 2019 | https://doi.org/10.1111/nph.15796 | Citations: 36

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On the Covariation of Chlorophyll Fluorescence and Photosynthesis Across Scales

Troy S. Magney, Mallory L. Barnes, Xi Yang

First published: 23 November 2020 | https://doi.org/10.1029/2020GL091098

Limitations and Caveats of using SIF

- Aggregated in time and space, GPP and SIF show surprisingly good linear correlations!
- SIF is not directly measuring GPP, especially on short time-scales (e.g. diurnal cycle) or down-regulation due to stress, the linear relationship can break down
- We still have lots to learn about the relation of PSII and fluorescence yields
- Fluorescence retrievals are no easy and data is noisy! Noise should be handled properly → Beware of the meaning of r^2 in the presence of precision errors!
- We need to understand fully WHY it works so well at coarser spatial and temporal scales.
- Remember, SIF is mostly a proxy for the electron transport rate (as both are driven by absorbed light), how this is used to fix carbon is an entirely different story (i.e. C3 and C4 photosynthetic pathways have a different SIF-GPP relationship.

Next Steps and Future Uses for SIF

- More research needed on SIF-GPP relations from the leaf through the canopy
- Sustained non-photochemical quenching and SIF needs to be properly understood and characterized
- Combine measurements of SIF with other metrics to break the caveats in its analysis (e.g. through measuring transpiration, photochemical reflectance index, etc)
- Towards diurnal cycles from space? What can we learn from SIF at shorter time-scales?
- Use SIF at different spectral positions?
- FLEX, a dedicated Fluorescence mission https://earth.esa.int/eogateway/missions/flex
- Be innovative!