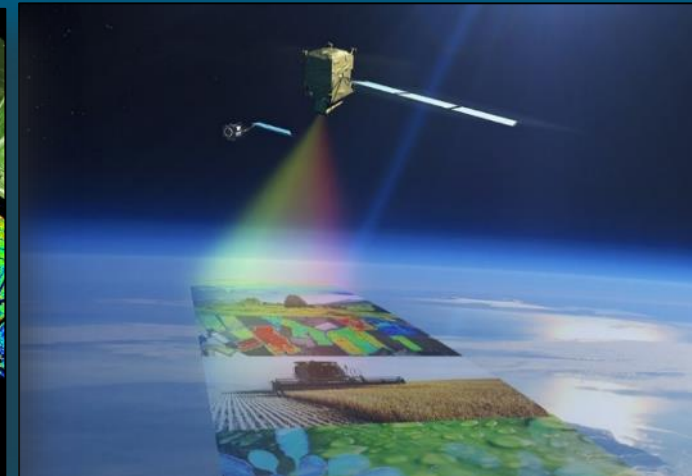
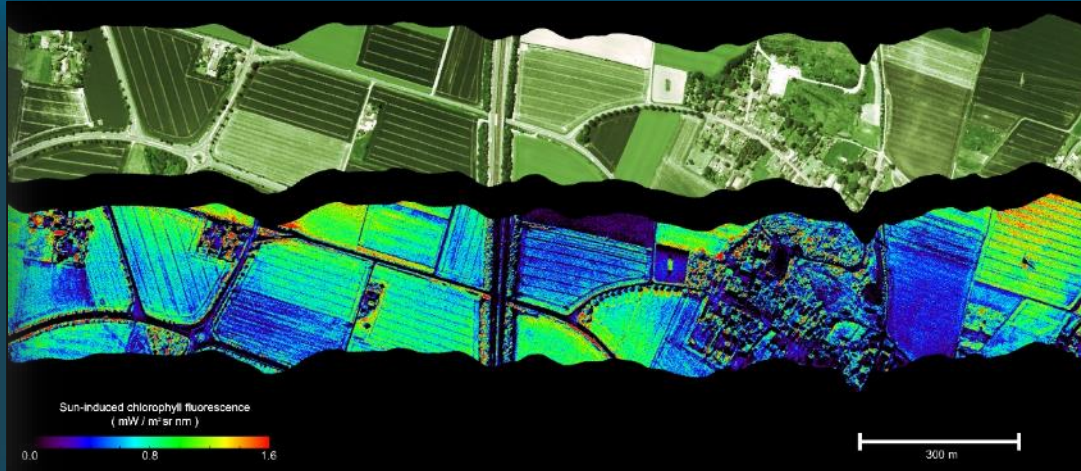
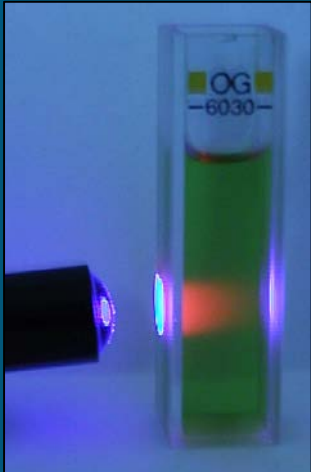


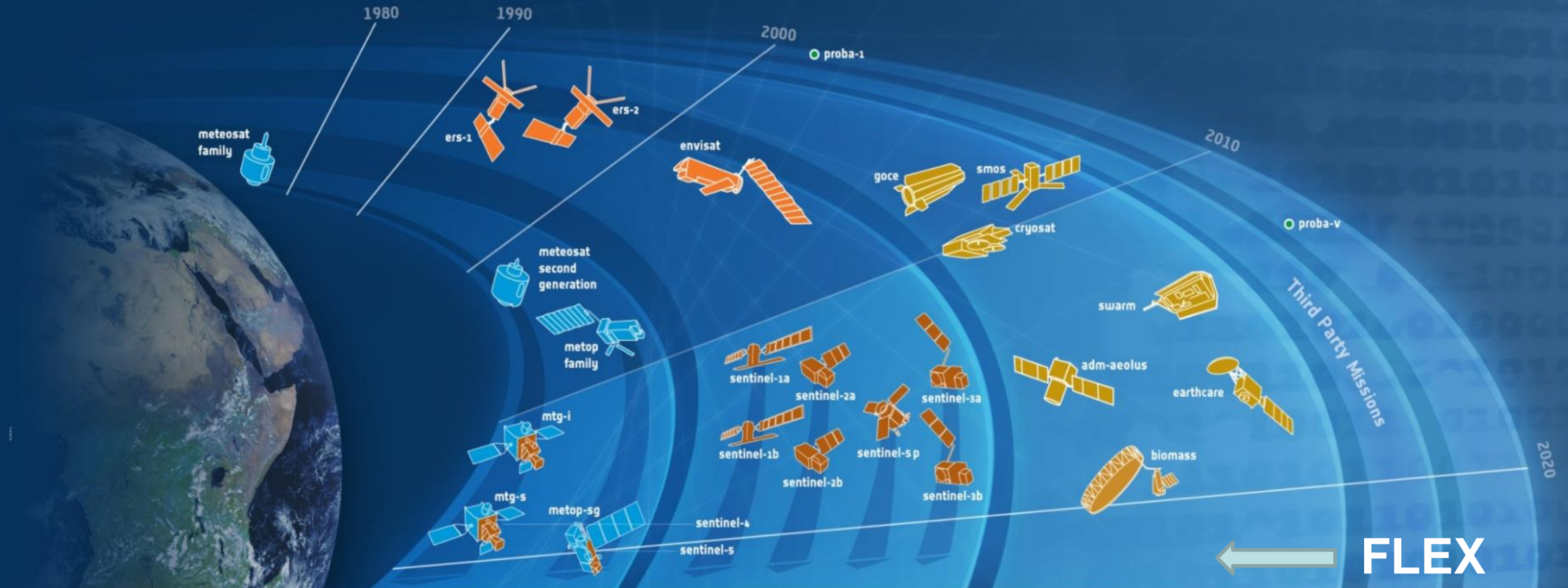
## The airborne sensor *HyPlant* – the history of the first dedicated airborne fluorescence sensor (established 2012)

*Uwe Rascher, Andreas Burkart, Maria-Pilar Cendrero, Maria Matveeva, Anke Schickling, Luis Alonso, Sergio Cogliati, Roberto Colombo, Alexander Damm, Matthias Drusch, Yves Goulas, Jan Hanus, Andreas Huth, Elizabeth Middleton, Franco Miglietta, Gina Mohammed, Micol Rossini, Dirk Schüttemeyer, Christiaan van der Tol, Wout Verhoef, Frantizek Zemek*

\* Forschungszentrum Jülich, Institute of Bio- and Geosciences, IBG-2: Plant Sciences, Germany



# ESA's Earth Observation satellites



## Meteorological Missions

driven mainly by Weather forecasting and Climate monitoring needs. These missions developed in partnership with EUMETSAT include the Meteorological Operational satellite programme (MetOp), forming the space segment of EUMETSAT's Polar System (EPS), and the new generation of Geostationary Meteorosol satellites (MSG & MTG satellites).

## Copernicus Sentinel Missions

driven by Users needs to contribute to the European Global Monitoring of Environment & Security (GMES) initiative. These satellite missions developed in partnership with the EU include C-band imaging radar (Sentinel-1), high-resolution optical (Sentinel-2), optical and infrared radiometer (Sentinel-3) and atmospheric composition monitoring capability [Sentinel-4 & Sentinel-5 on board Met missions MTG and EPS-SG respectively].

## Earth Explorer Missions

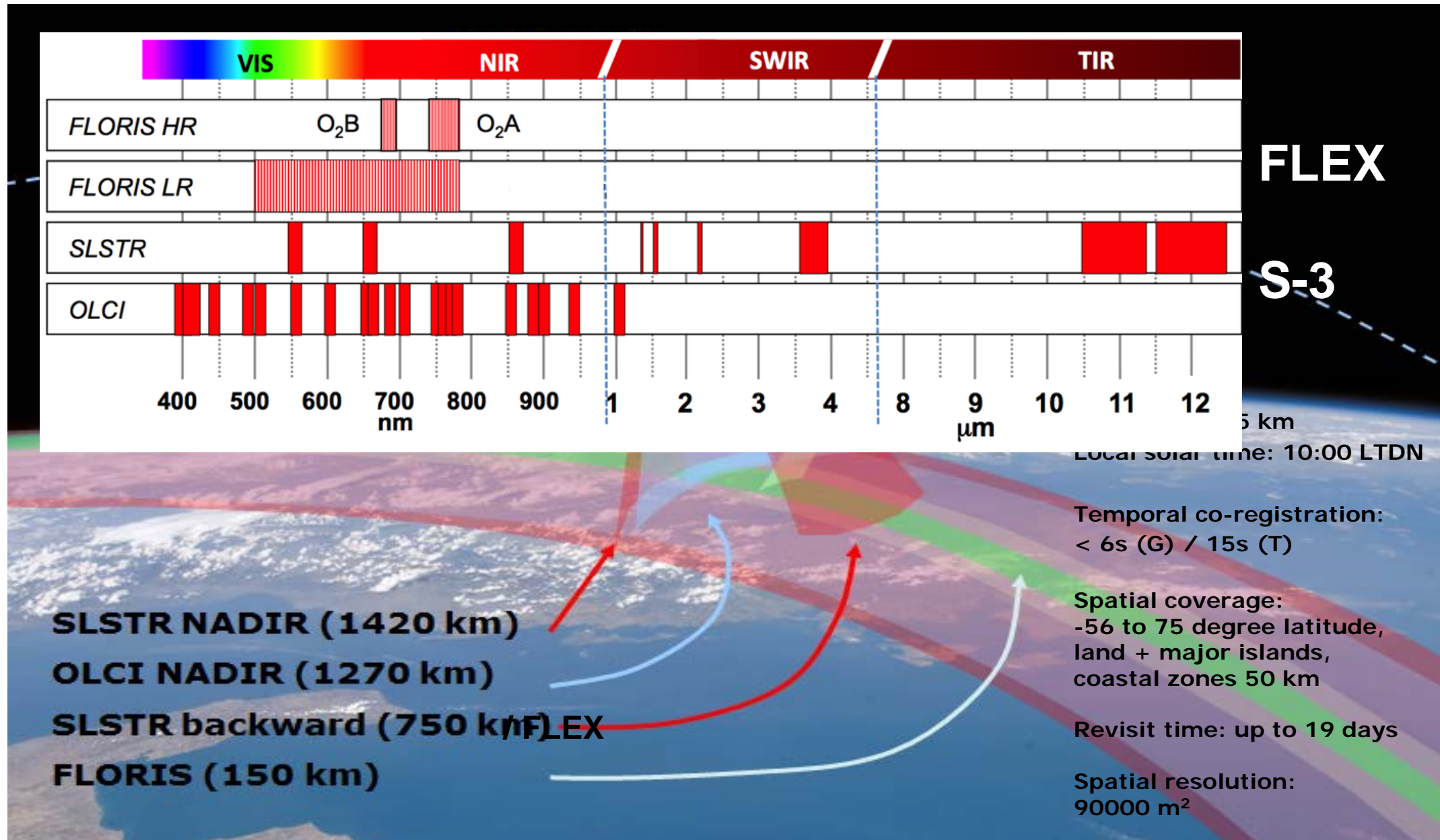
driven by Scientific needs to advance our understanding of how the ocean, atmosphere, hydrosphere, cryosphere and Earth's interior operate and interact as part of an interconnected system. These Research missions, exploiting Europe's excellence in technological innovation, pave the way towards new development of future EO applications.

Missions  
With  
Partners

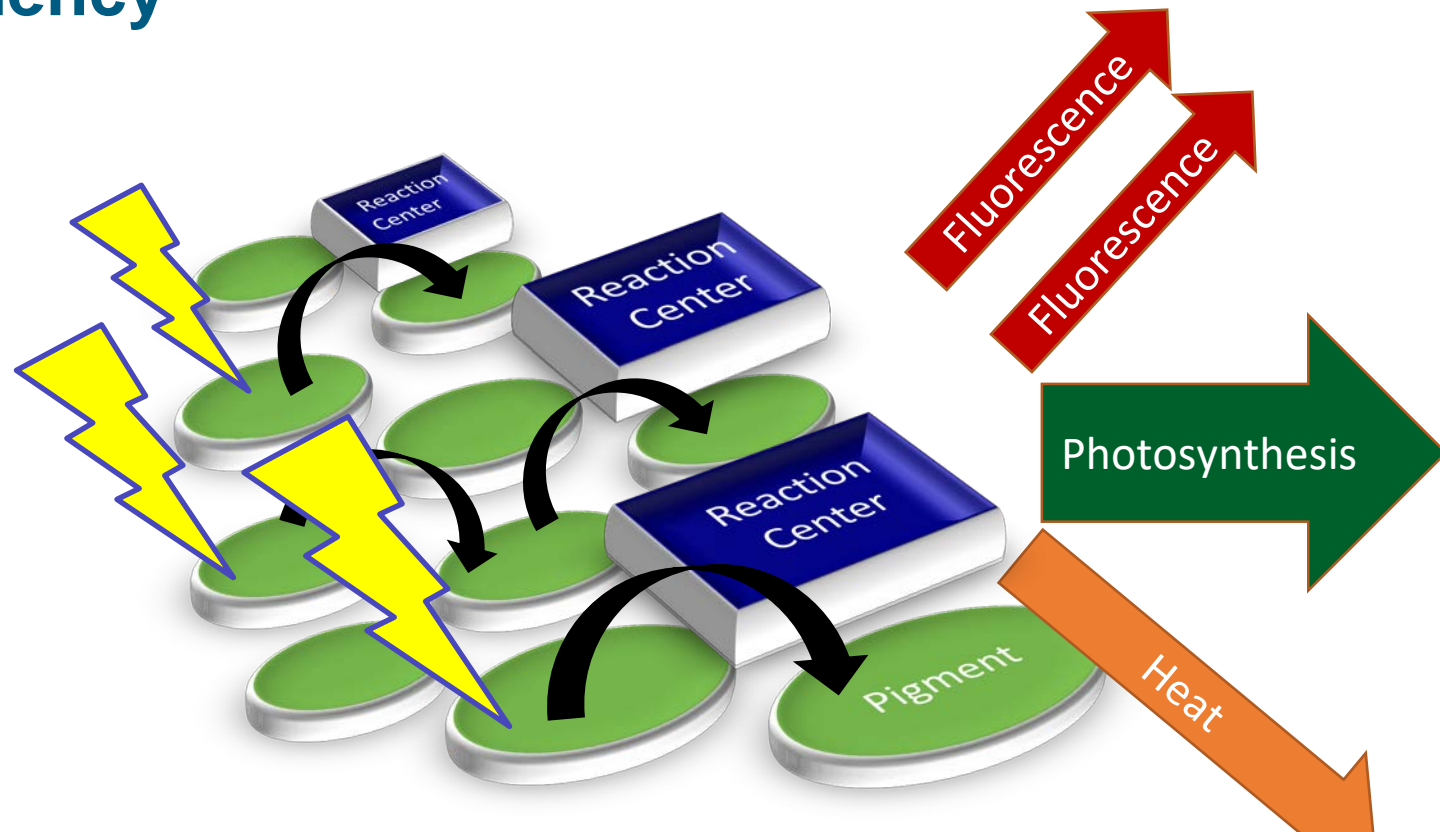
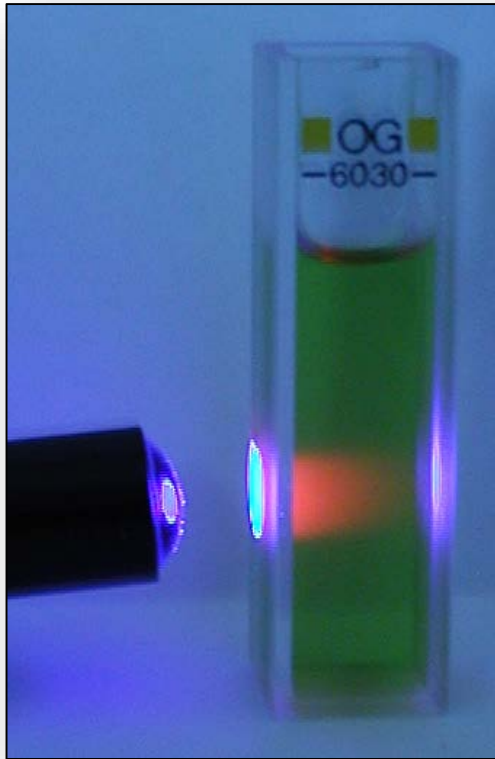
EDP  
Operated  
Missions



# FLEX Satellite Mission – a tandem concept with Sentinel-3

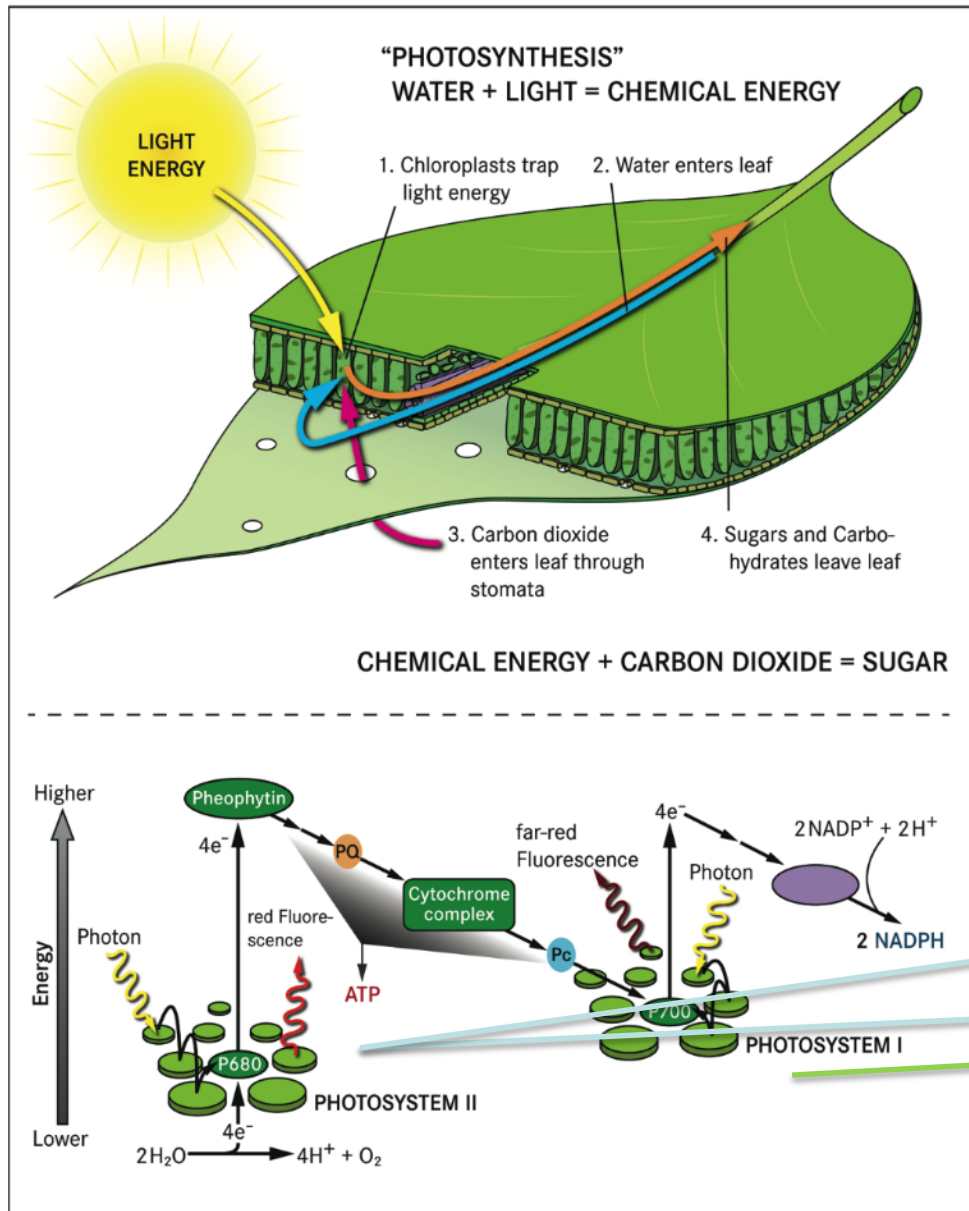


# The origin of fluorescence – an indicator for photosynthetic efficiency

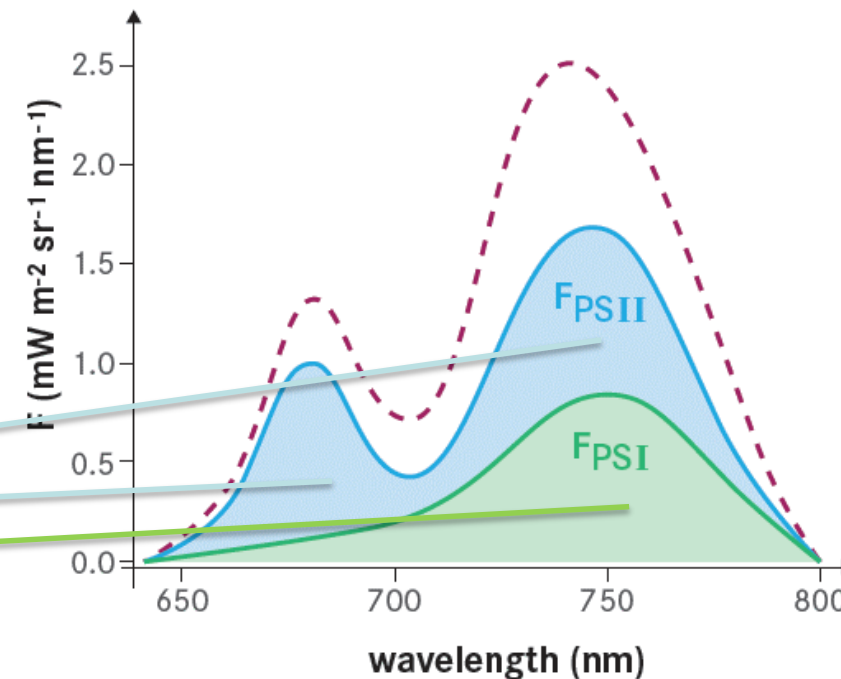


1. Chlorophyll molecules emit fluorescence. The intensity of the fluorescence signal depends on light intensity, the concentration of chlorophyll (LAI) and the functional status of photosynthesis
2. The fluorescence signal is rather weak (2-5 % of intensity of reflected light in this spectral region)

# The origin of fluorescence – an indicator for photosynthetic efficiency

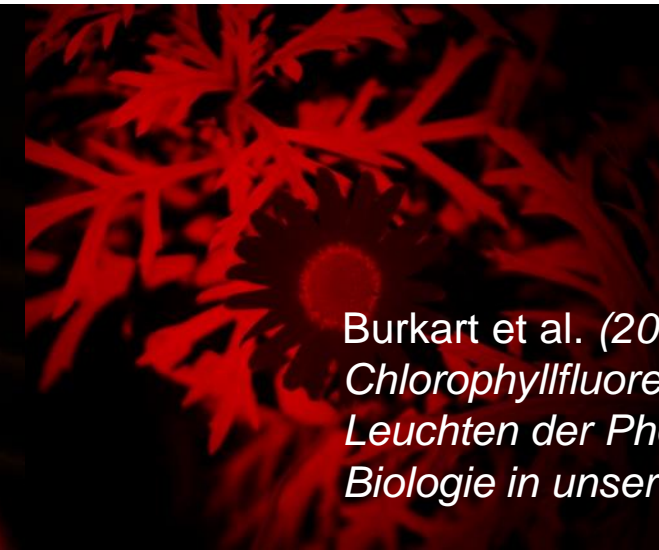
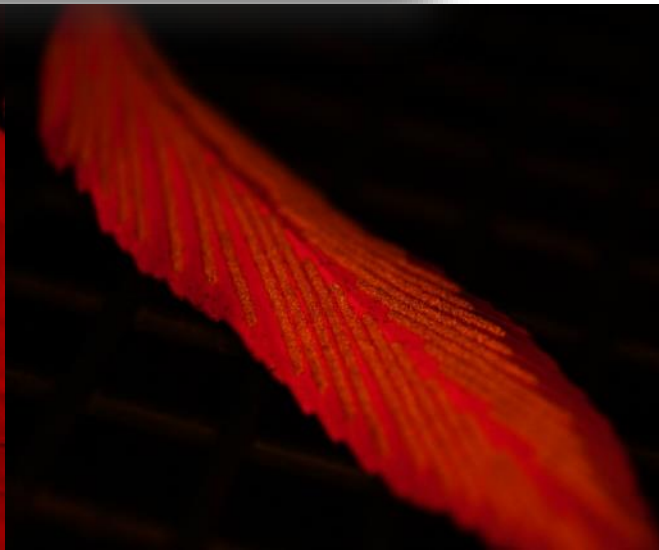
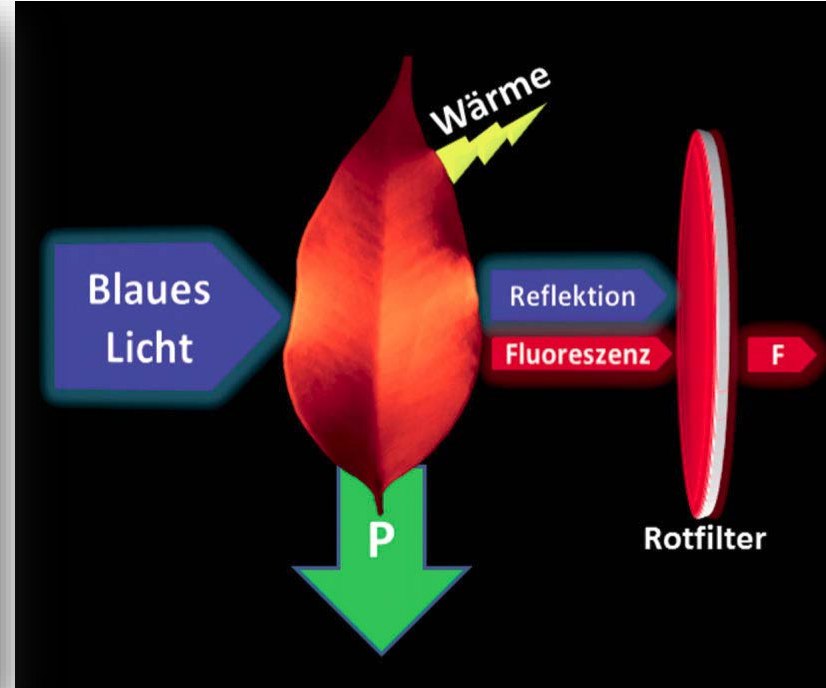
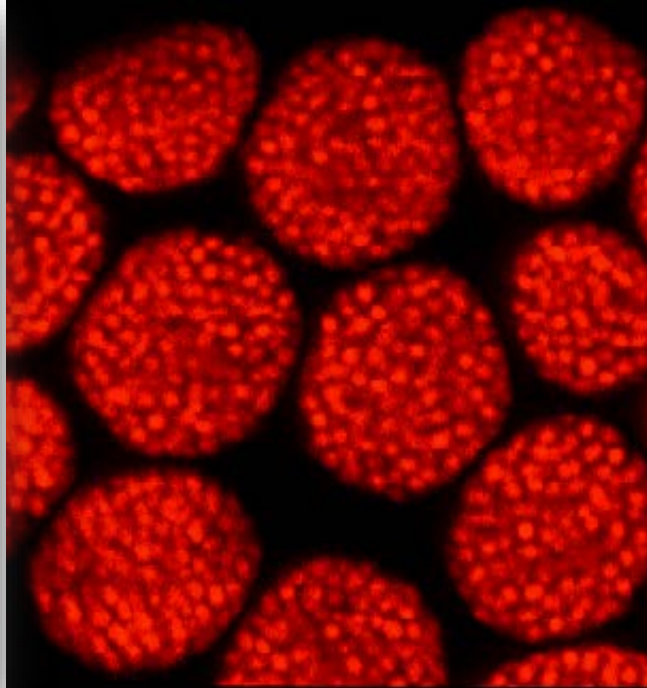


- Photosynthesis is a highly regulated process that involves a cascade of electron transfers (*Light reaction*) to fuel carbon fixation (*Calvin cycle*)
- Fluorescence is emitted from the cores of the photosynthetic machinery: Photosystems I and II
- Two-peak feature of fluorescence



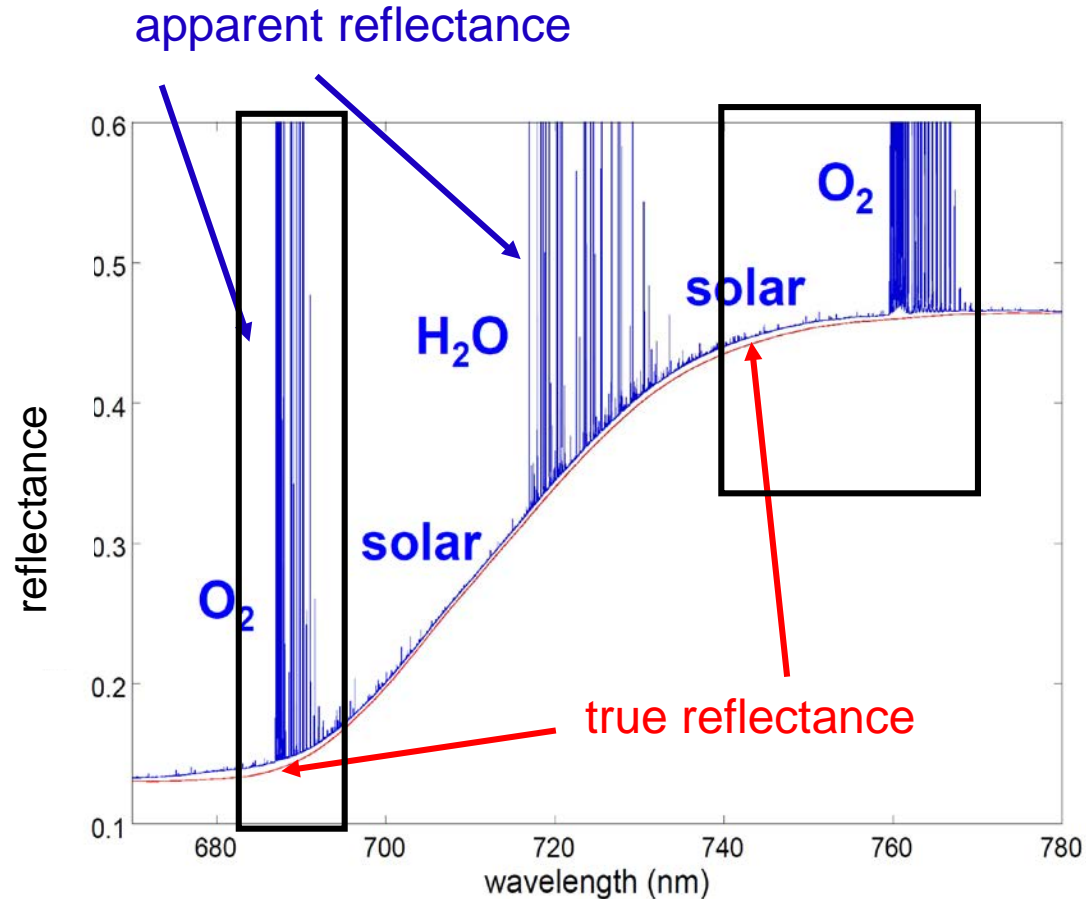


# Pigments, photosystems and photosynthesis: a highly structured biological 'super-complex' that emits fluorescence

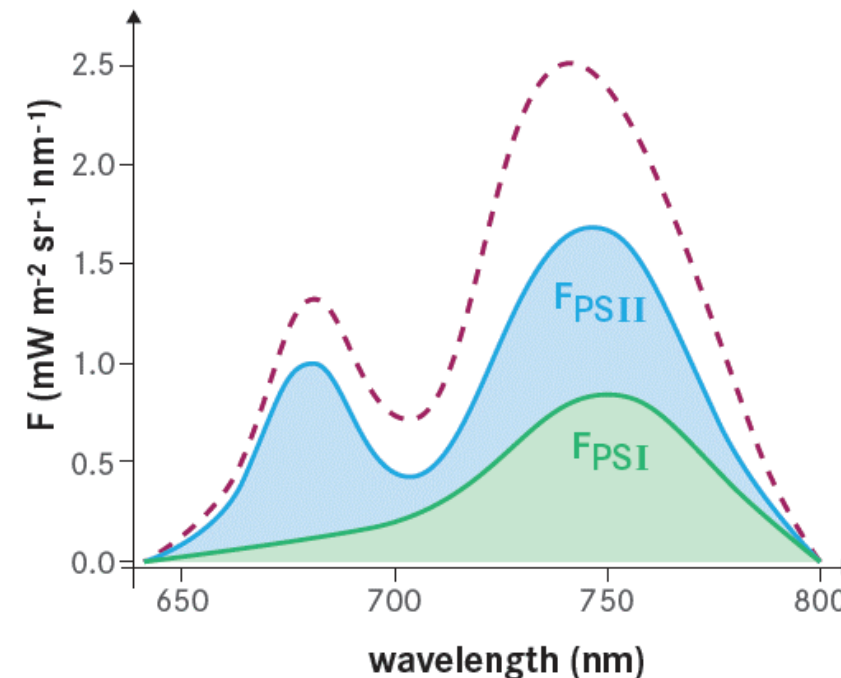


Burkart et al. (2014) *Einblicke in die Chlorophyllfluoreszenz - Das Leuchten der Photosynthese. Biologie in unserer Zeit*, 44, 182-186.

# Sun-induced fluorescence can be measured in the solar and atmospheric absorption lines



Atmospheric oxygen and solar absorption lines can be used to retrieve the fluorescence signal from the surface reflectance (under



Plascyk (1975) *Optical Engineering* 14, 339–346

Carter et al. (1996) *Remote Sensing of Environment* 55, 89–92

Moya et al. (2004) *Remote Sensing of Environment* 91, 186–197

Meroni et al. (2009) *Remote Sensing of Environment*, 113, 2037–2051

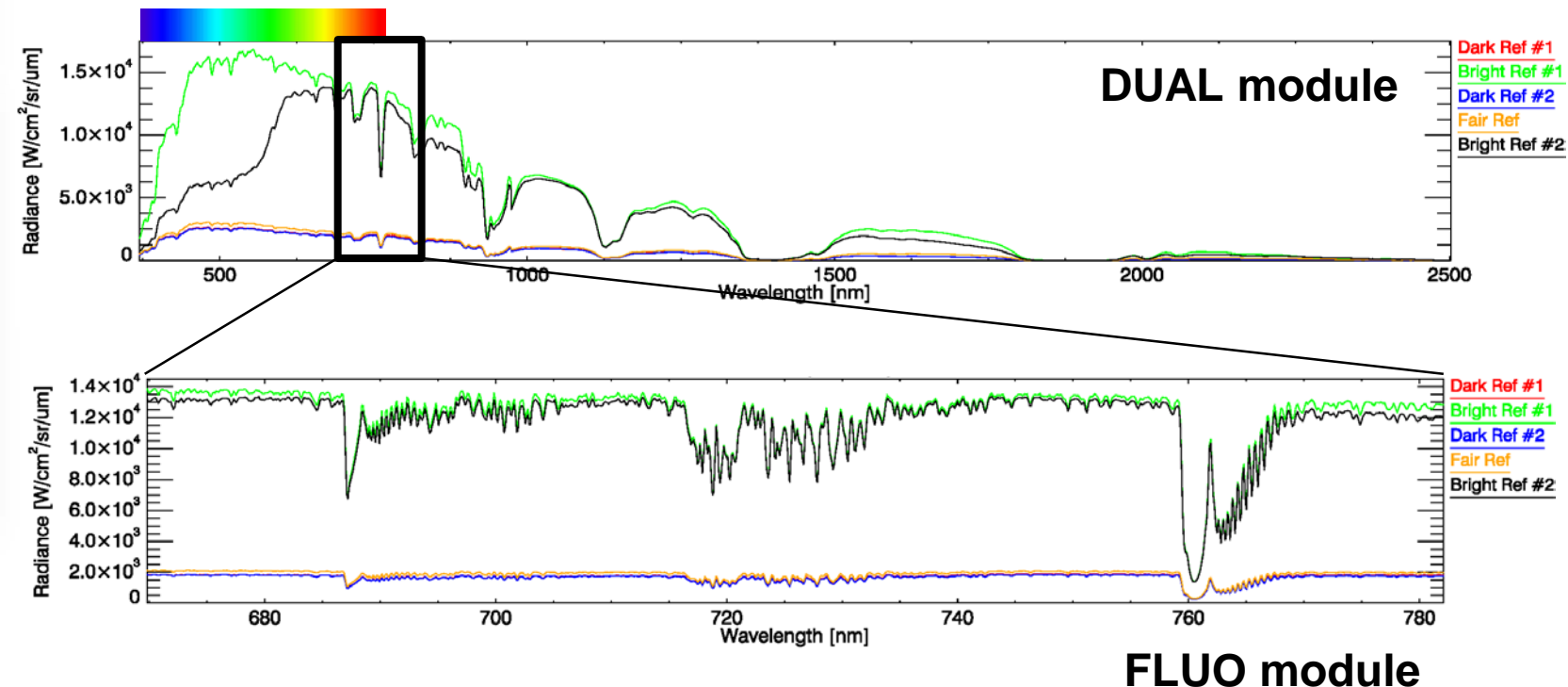


# HyPlant: A high-resolution airborne imaging spectrometer with FLEX like measurement characteristics



Rascher et al. (2015) *Global Change Biology*, 21, 4673–4684

- **DUAL module** (380 – 2500 nm)  
VIS/NIR: 3-4 nm FWHM, 1.7 nm SSI, SNR 510  
SWIR: 13 nm FWHM, 5.5 nm SSI, SNR 1100
- **FLUO module** (670 – 780 nm)  
0.25 nm FWHM, 0.11 nm SSI, SNR 210





# HyPlant: modelling the importance of sensor characteristics

Remote Sensing of Environment 115 (2011) 1882–1892



Contents lists available at ScienceDirect

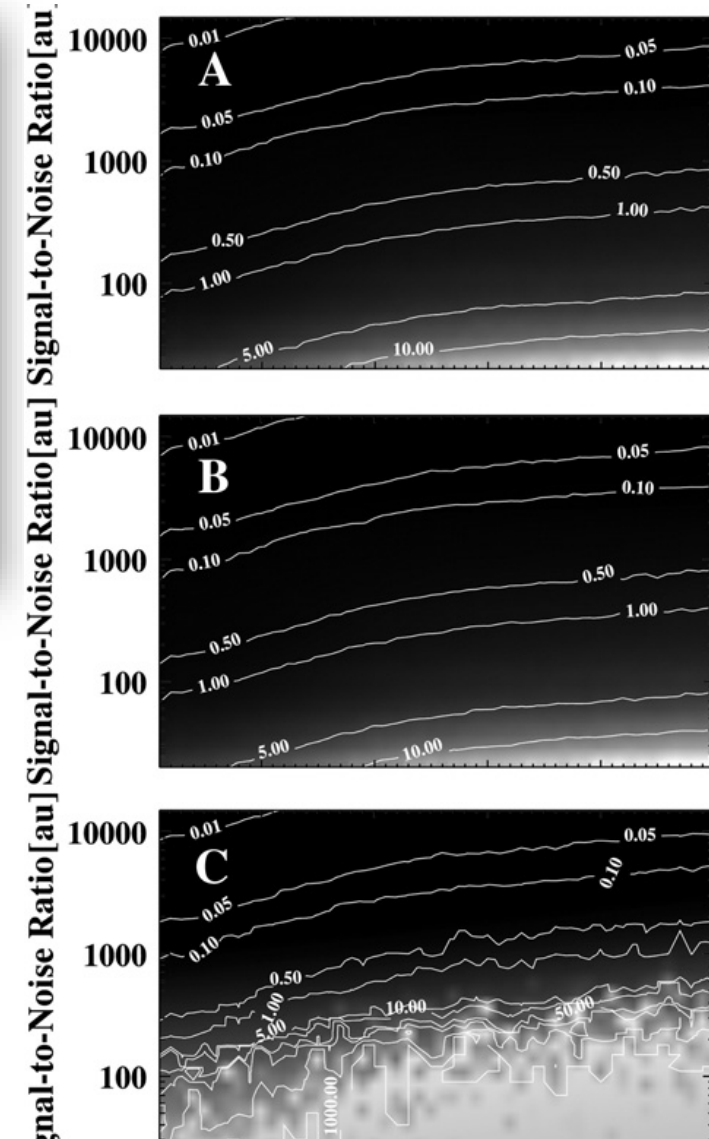
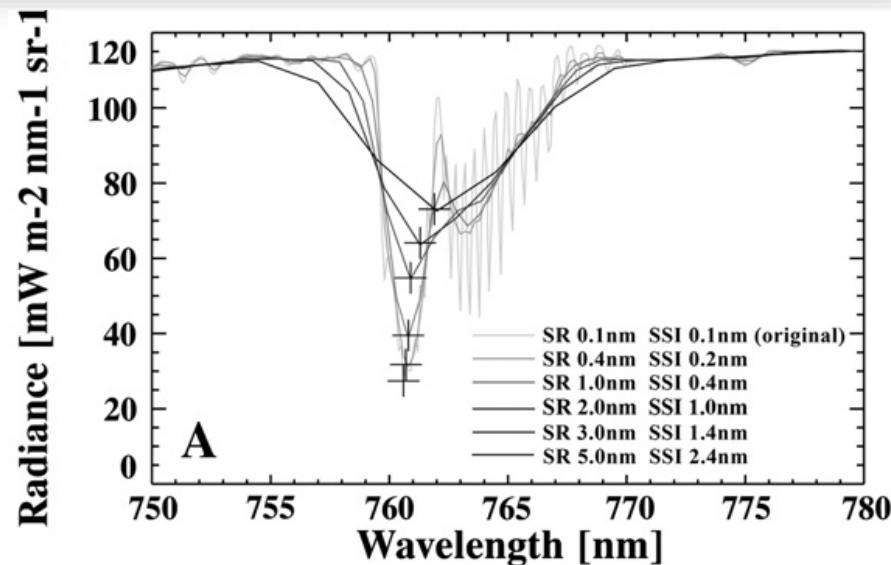
Remote Sensing of Environment

journal homepage: [www.elsevier.com/locate/rse](http://www.elsevier.com/locate/rse)

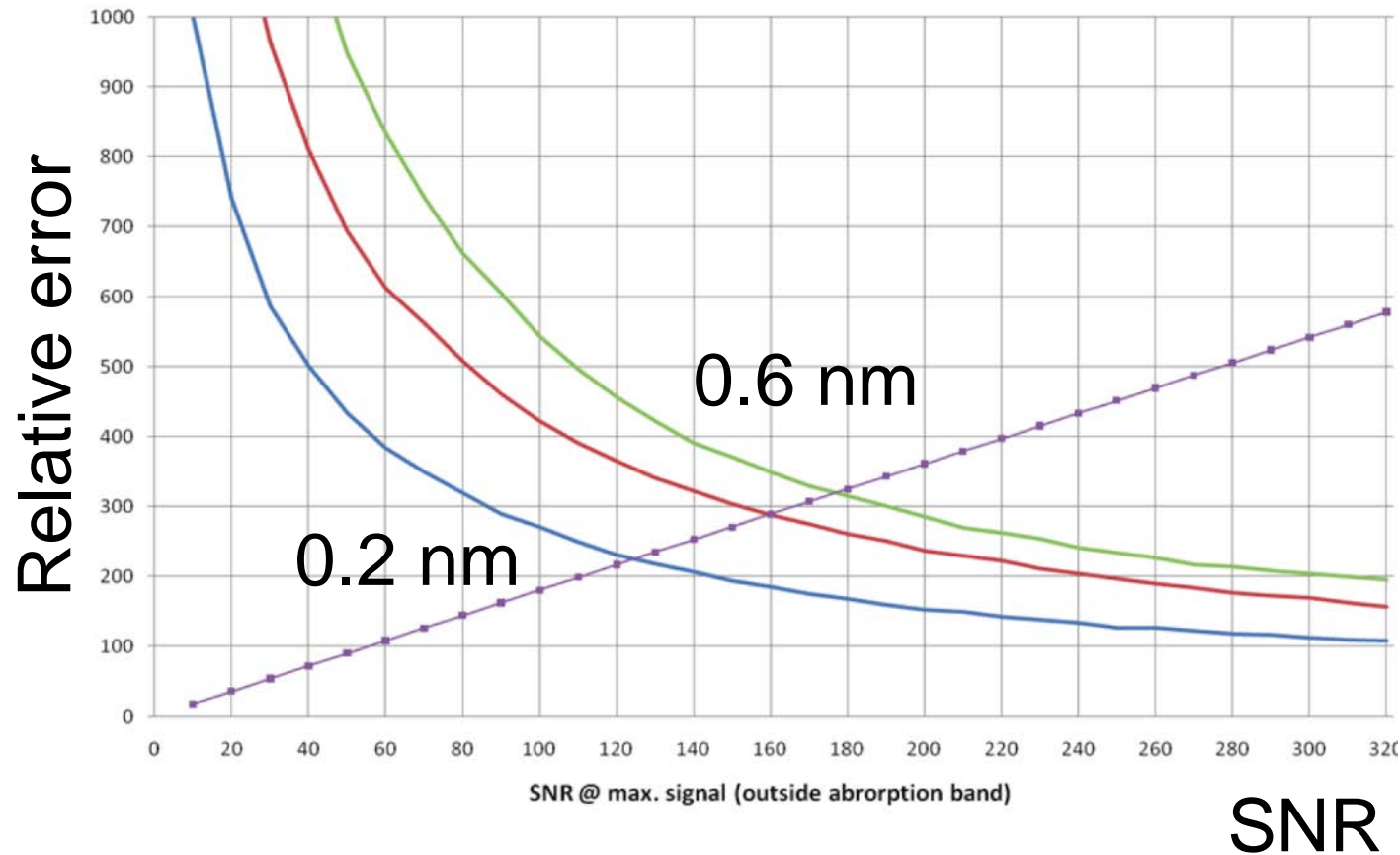


Modeling the impact of spectral sensor configurations on the FLD retrieval accuracy of sun-induced chlorophyll fluorescence

Alexander Damm<sup>a,\*</sup>, André Erler<sup>b</sup>, Walter Hillen<sup>c</sup>, Michele Meroni<sup>d</sup>, Michael E. Schaepman<sup>a</sup>, Wout Verhoef<sup>e</sup>, Uwe Rascher<sup>b</sup>



# HyPlant: modelling the importance of sensor characteristics



- Optimized imaging spectrometer for fluorescence retrieval having
  - High spectral resolution
  - good SNR
  - Low stray light
  - Stable sensor configuration

Damm et al. (2011) *Remote Sensing of Environment*, 115, 1882-1892

Rascher et al. (2015) *Global Change Biology*, 21, 4673-4684



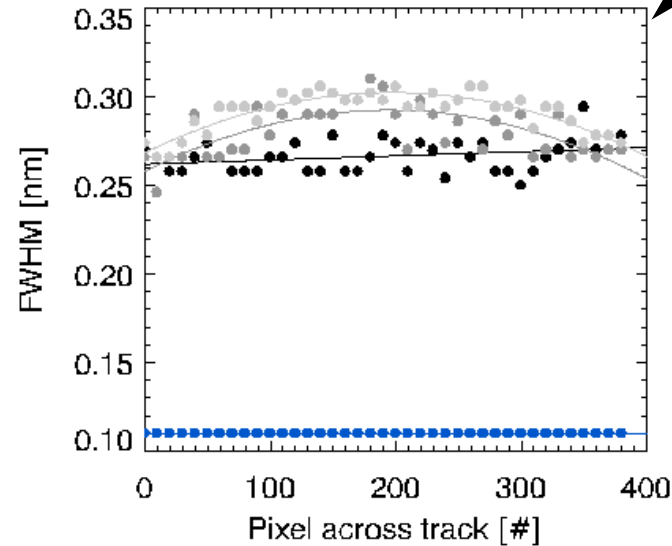
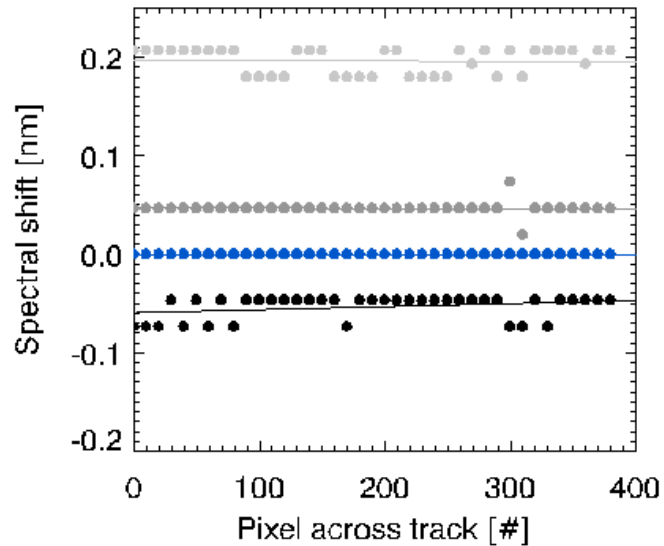
# HyPlant: real sensor characteristics

Sensor	Dual-channel module		Fluorescence module
Spectral performance			
Wavelength range [nm]	380–970	970–2500	670–780
Bands	350	272	1024
Wavelength sampling interval [nm]	1.7	5.5	0.11
Wavelength resolution (FWHM) [nm]	4.0	13.3	0.25 at O <sub>2</sub> -A 0.23 at O <sub>2</sub> -B
Band broadening [nm]	0.2	0.2	0.01 at O <sub>2</sub> -A 0.03 at O <sub>2</sub> -B
Spectral shift [nm]	1.2	2.4	<0.04
Smiling [nm]	0.4	1.2	<0.01 at O <sub>2</sub> -A 0.01 at O <sub>2</sub> -B
Radiometric performance			
SNR with full-scale signal	(510)	(1100)	(240)
Stay light and pixel cross talk [%]			<0.5
Spatial performance			
Spatial pixels	384	384	384
Field of view [deg]	32.3		32.3
Instantaneous field of view [deg]	0.0832		0.0832
Swath [m]	380 at 600 m agl* 1140 at 1780 m agl		380 at 600 m agl 1140 at 1780 m agl
Spatial sampling interval (across track) [m]	0.98 at 600 m agl 2.94 at 1780 m agl		0.98 at 600 m agl 2.94 at 1780 m agl
Sensor type			
Type	CMOS	MCT	sCMOS†
Dynamic range [bit]	12	14	16

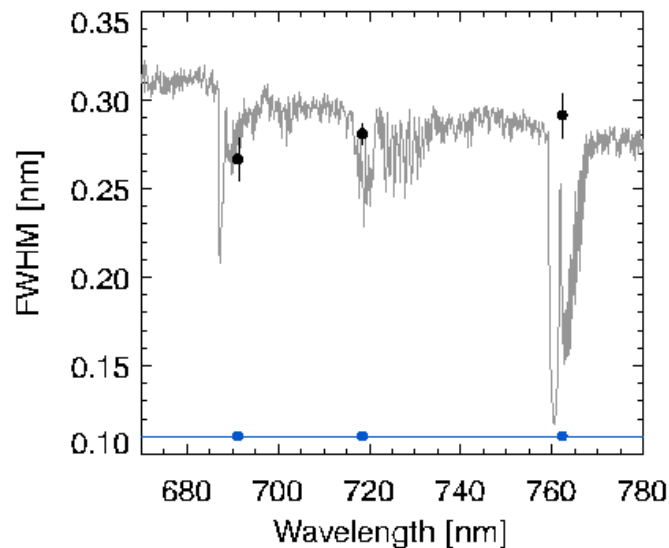
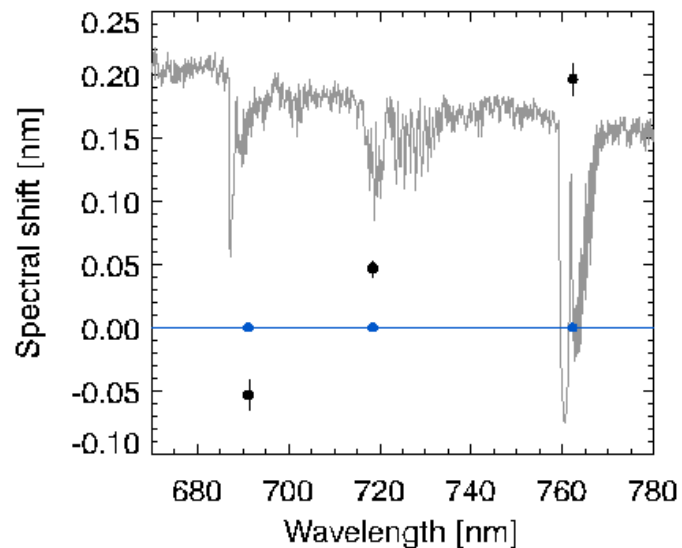
Optimized imaging spectrometer for fluorescence retrieval having

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# HyPlant: real sensor characteristics



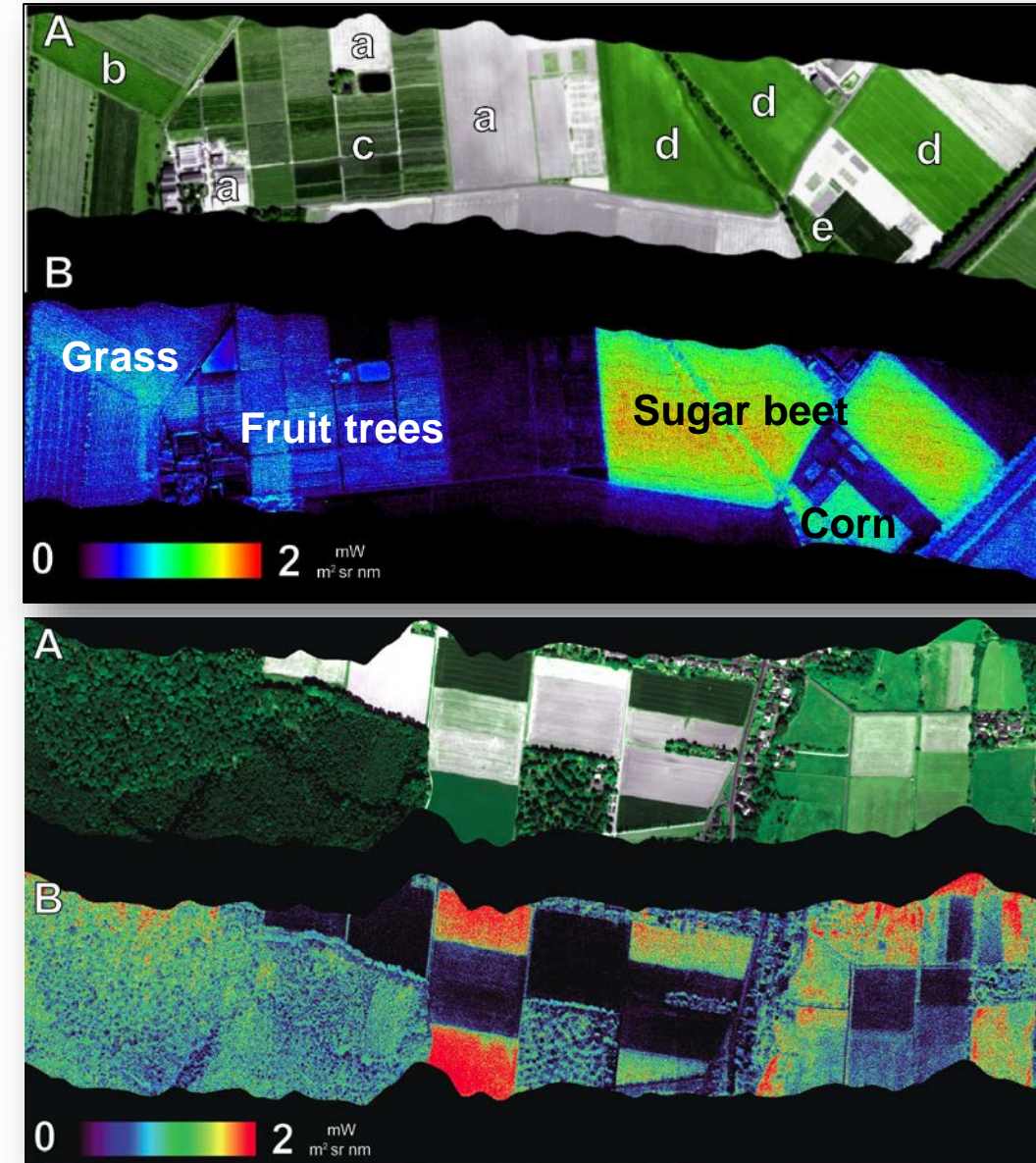
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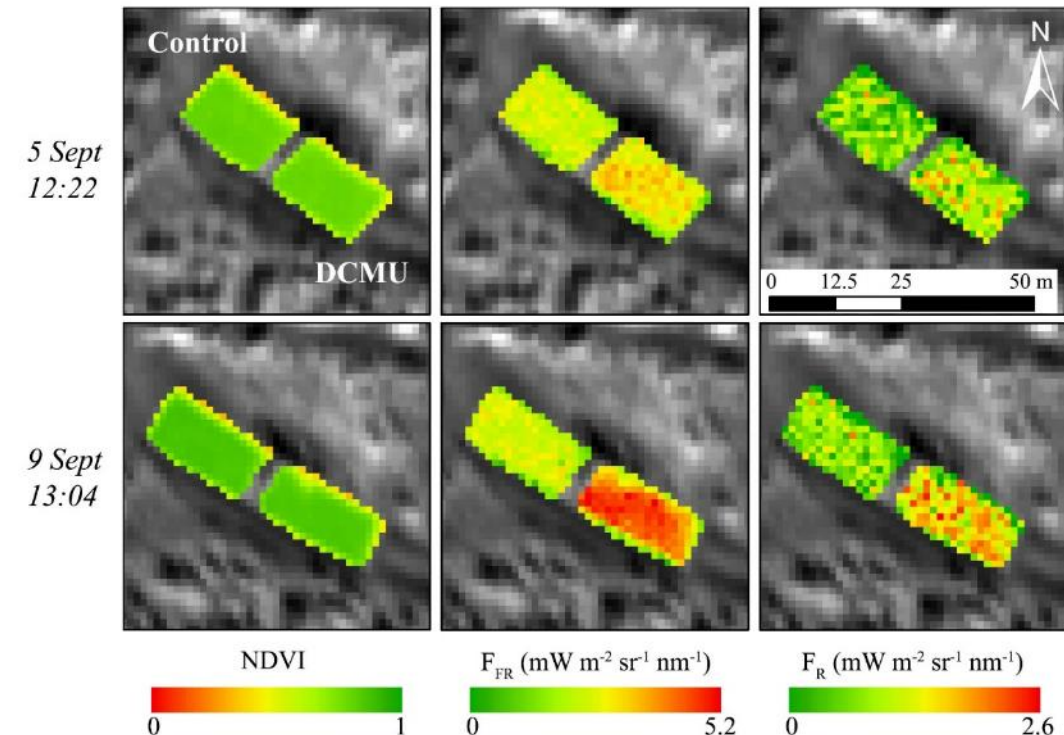
# HyPlant: 2012 campaigns

- Used to demonstrate the uncoupling of 'greenness' and fluorescence  
[Rascher et al (2015) Global Change Biol., 21, 4673-4684]  
[Simmer et al (2015) BAMS – Bulletin of the American Meteorological Society, 96, 1765-1787]



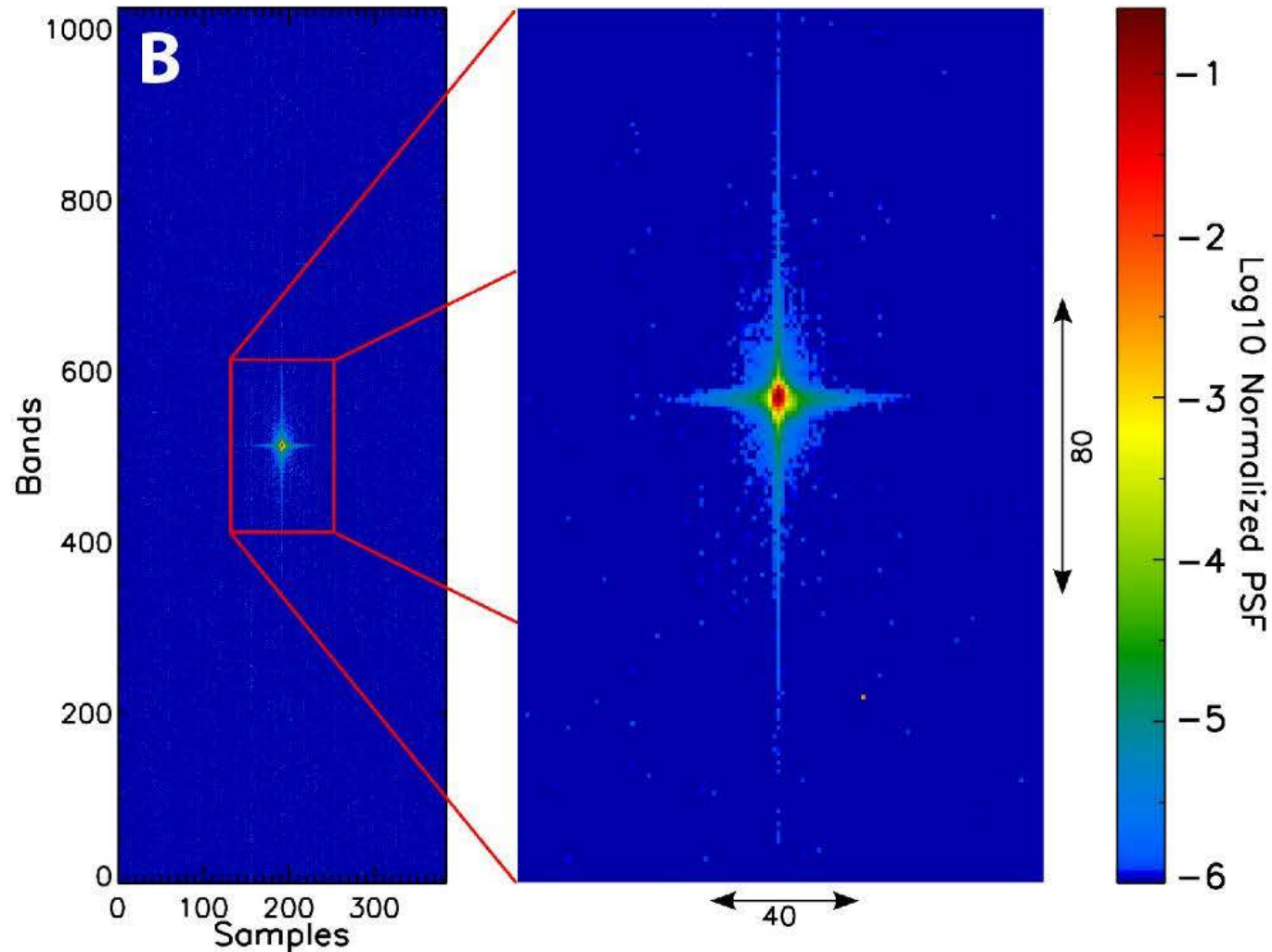
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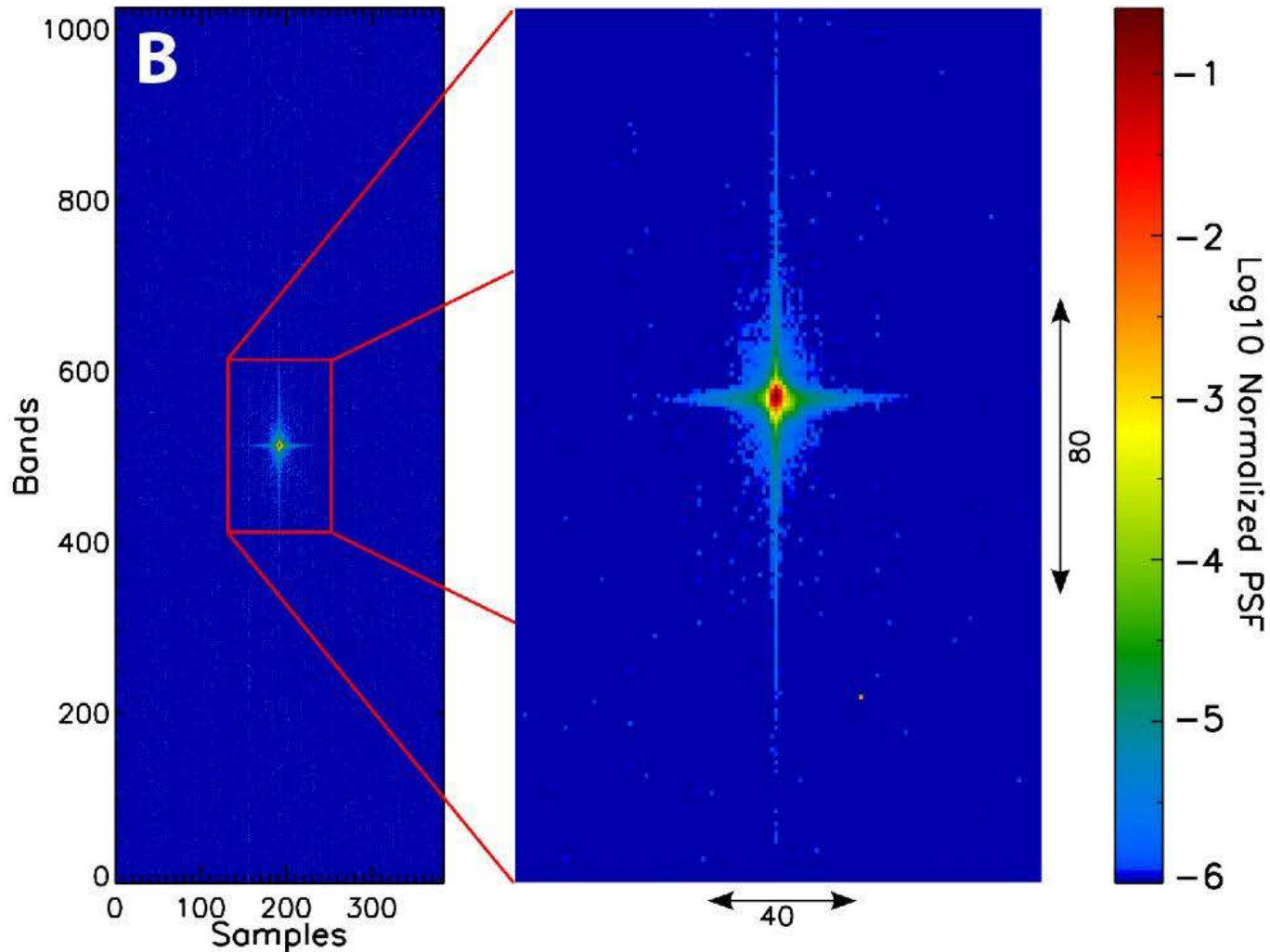
# HyPlant: Having a closer look at radiometric performance. Point spread function and stray light



- Optical path and detector was exchanged / upgraded
  - SNR improved 4 times
  - Point spread function greatly improved

Since 2014

# HyPlant: Having a closer look at radiometric performance. Point spread function and stray light

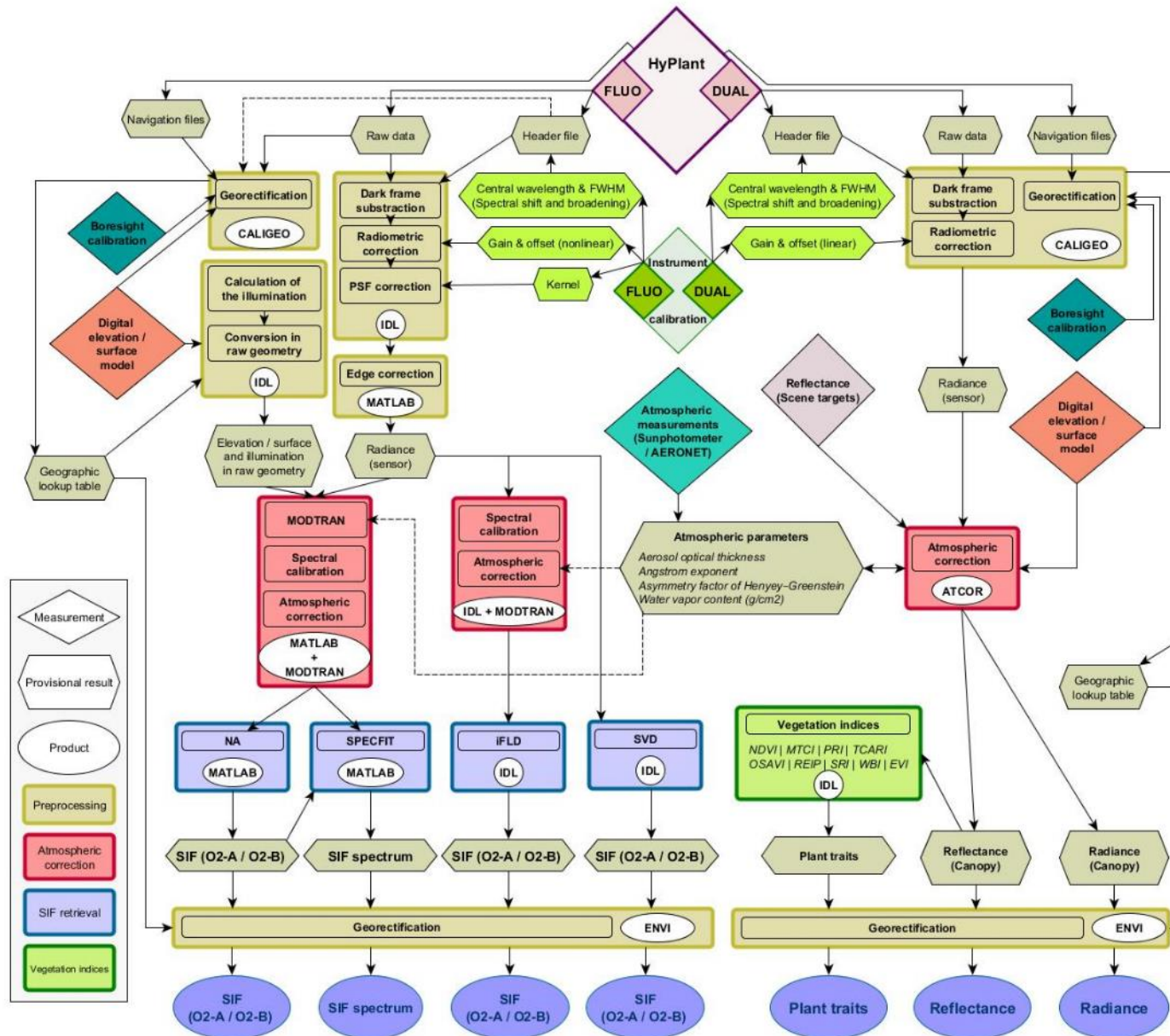


- Optical path and detector was exchanged / upgraded
  - SNR improved 4 times
  - Point spread function greatly improved
- Additional deconvolution algorithm developed and now routinely applied to all flight lines of *HyPlant*

Since 2014

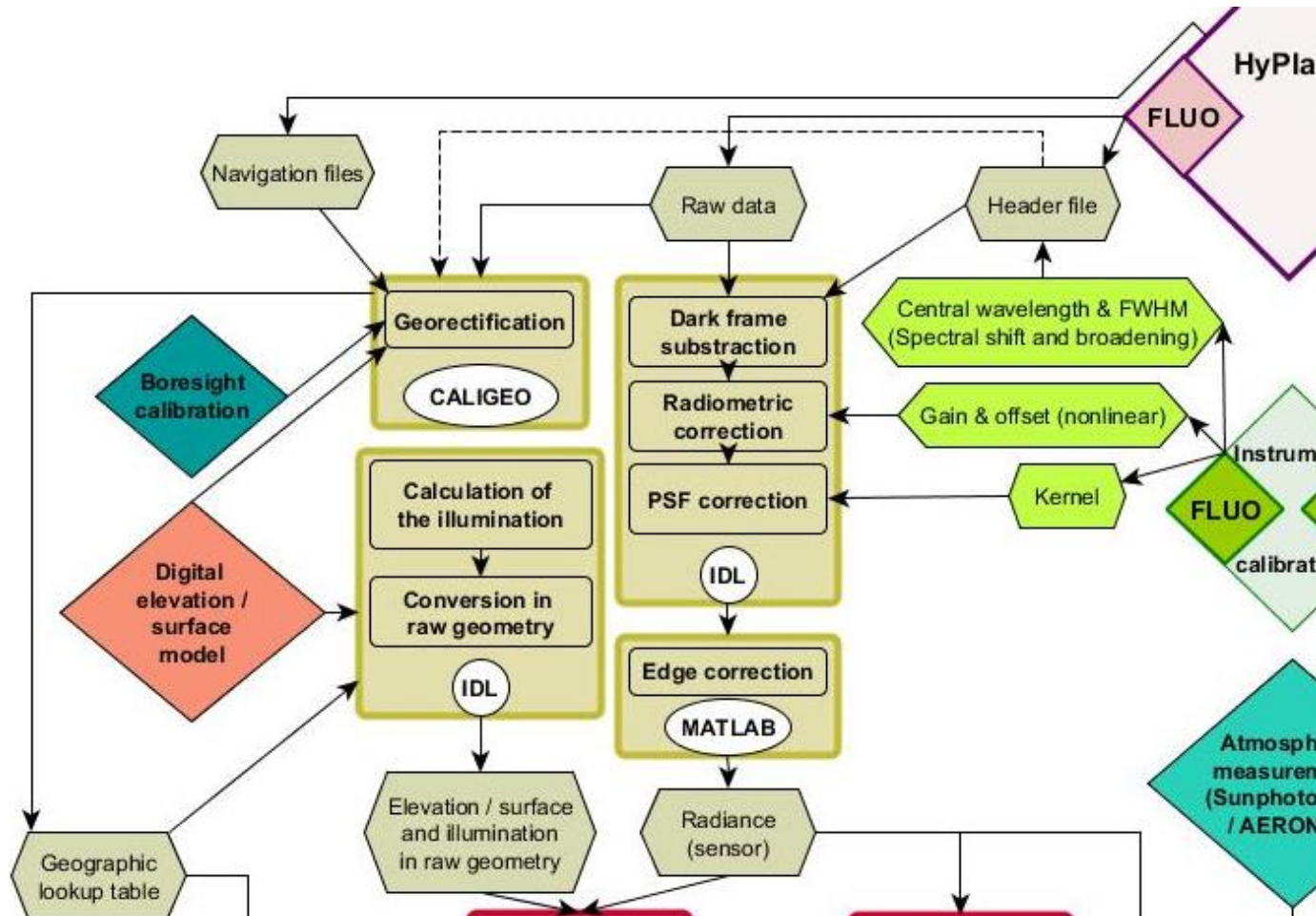


# HyPlant: processing becomes consolidated



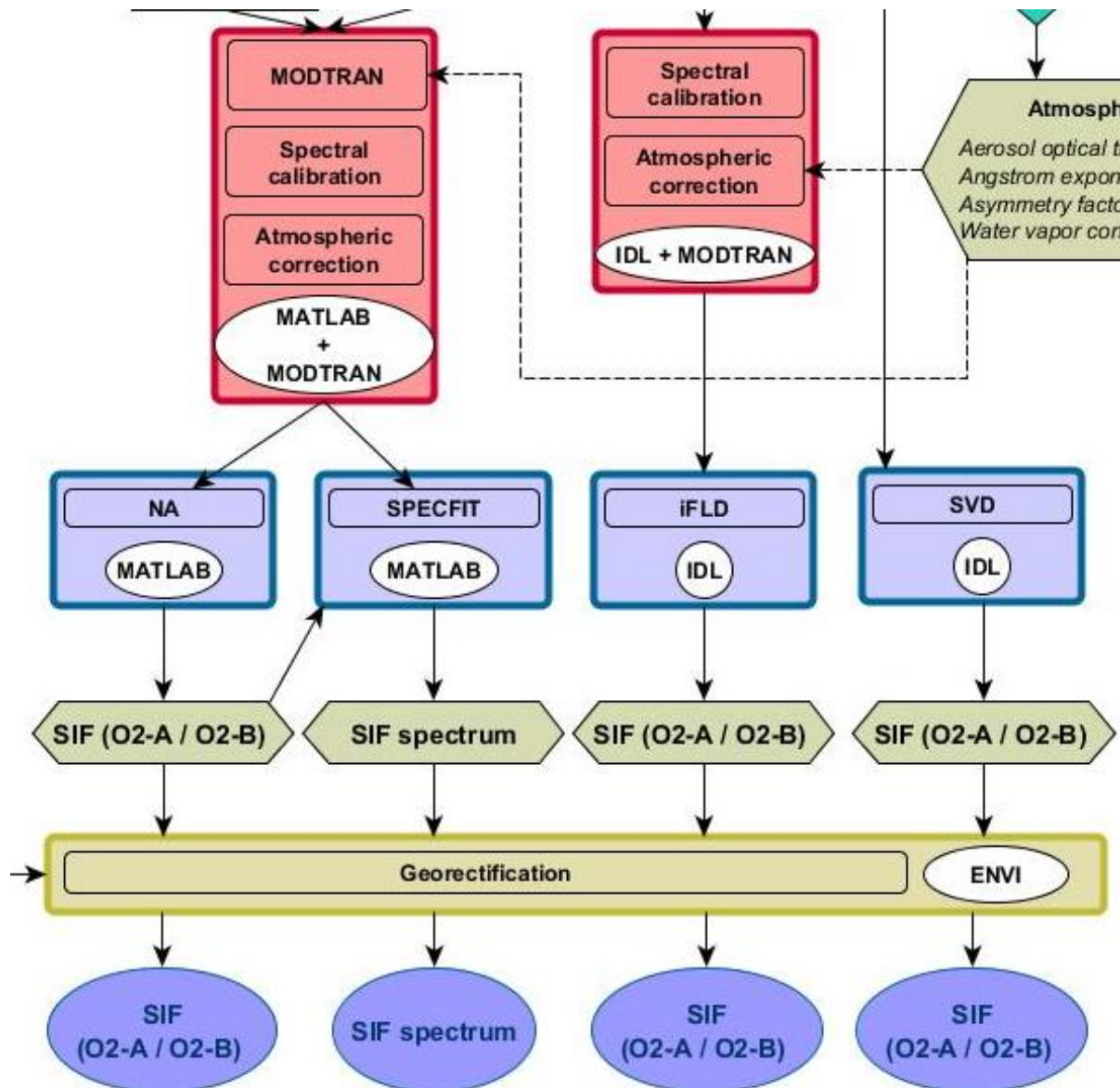
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# HyPlant: processing becomes consolidated



- Optimized imaging spectrometer for fluorescence retrieval
- Processing pipeline developed that includes
  - Advanced and careful pre-processing including deconvolution for point-spread function (PSF)

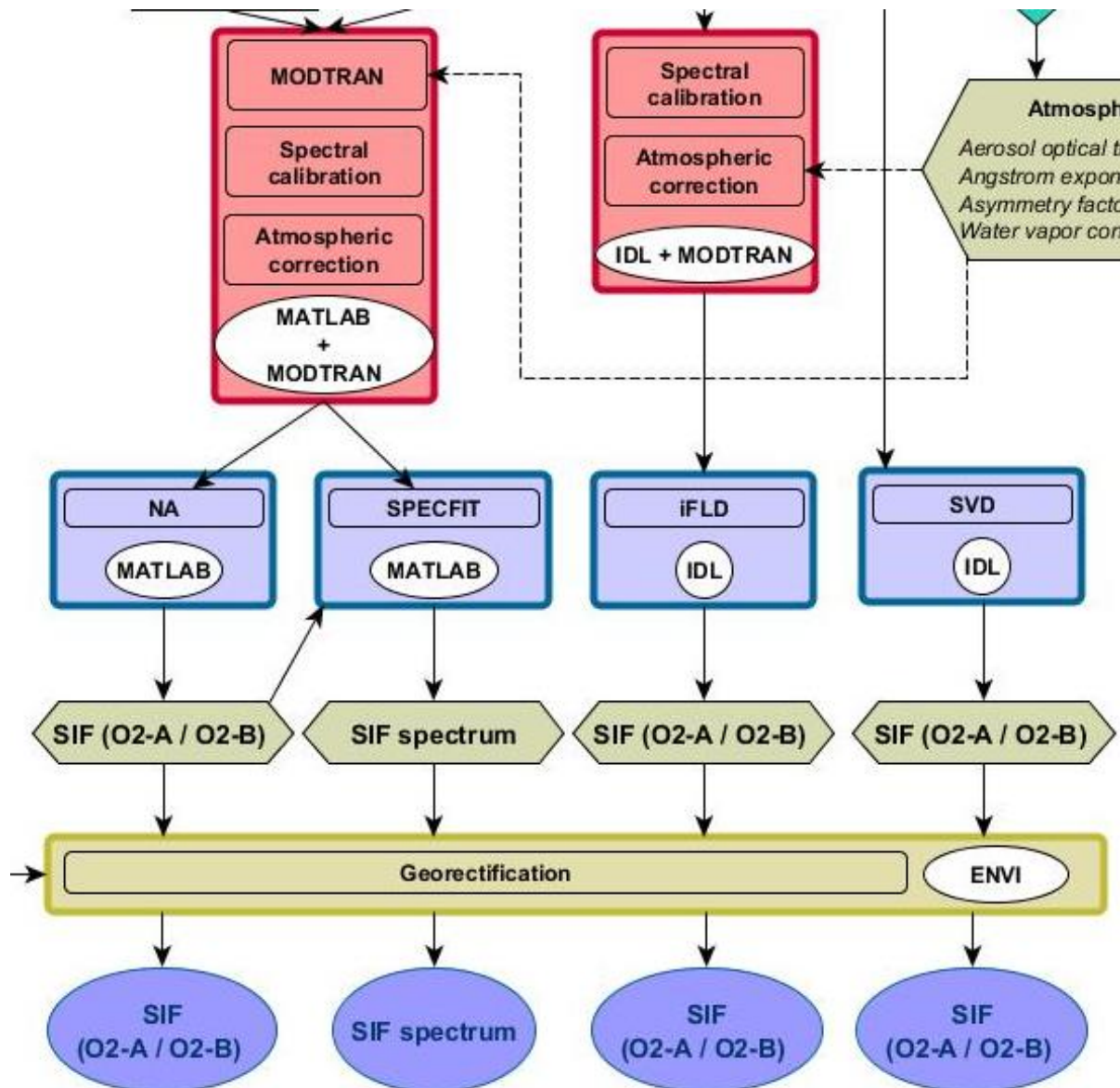
# HyPlant: processing becomes consolidated



- Optimized imaging spectrometer for fluorescence retrieval
- Processing pipeline developed that includes
  - Advanced and careful pre-processing including deconvolution for point-spread function (PSF)
  - Three way to retrieve fluorescence (both peaks and total fluorescence)



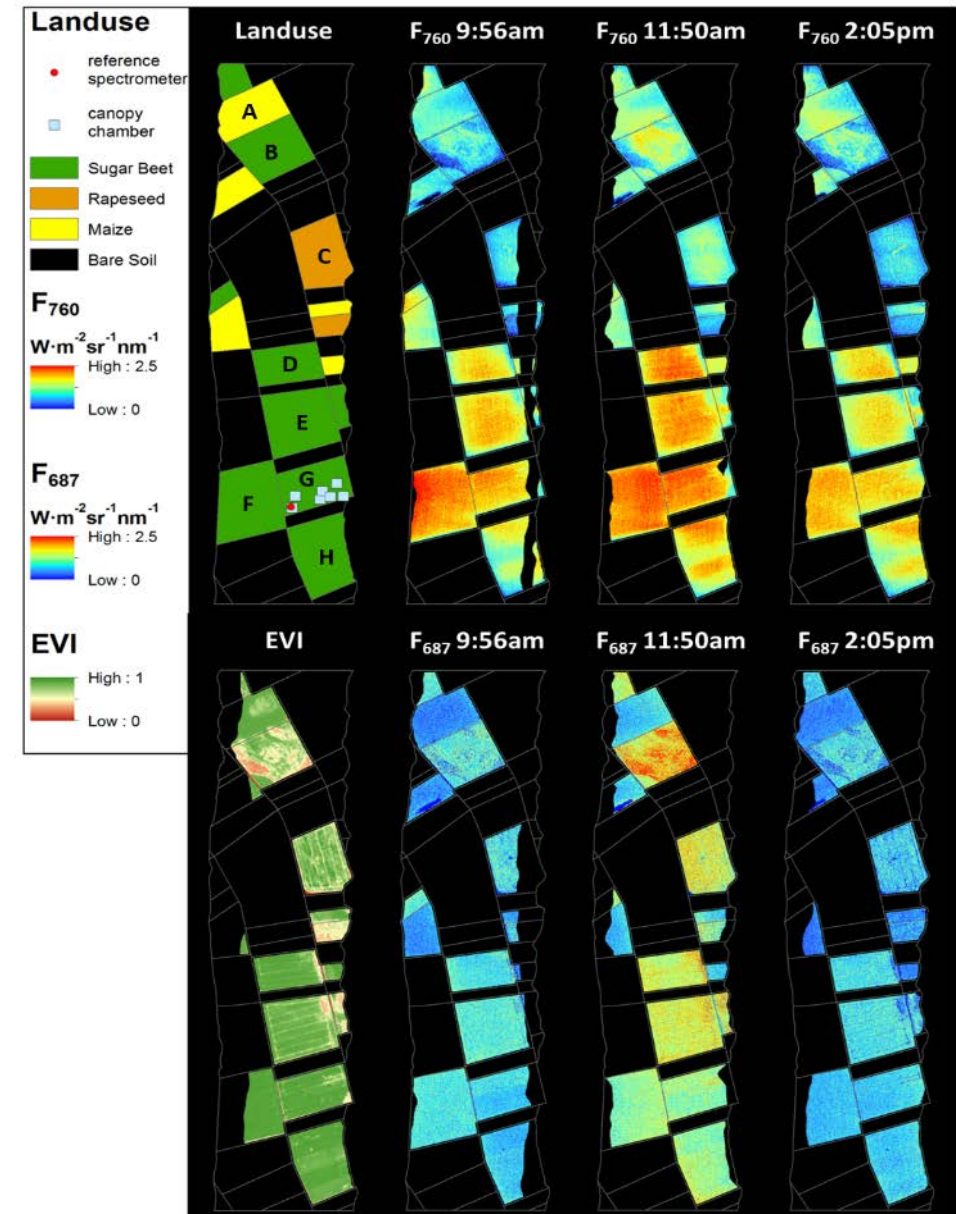
# HyPlant: processing becomes consolidated



- SVD: good first estimate that works in about 70% of the cases
- 3-FLD: not usable because of strong dependency of surface reflectance
- iFLD: 'working retrieval' as long as we have non-vegetated reference targets in the scene
- Spectral fitting: method of choice that was recently adapted also for *HyPlant*. (need for good characterization of atmospheric parameters)

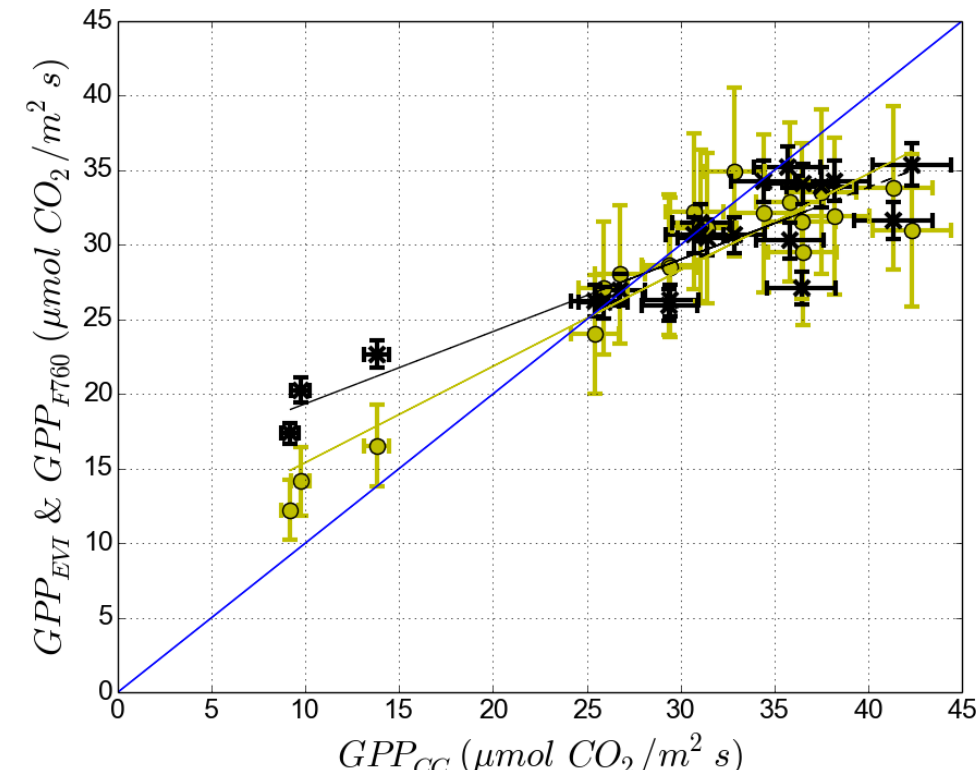
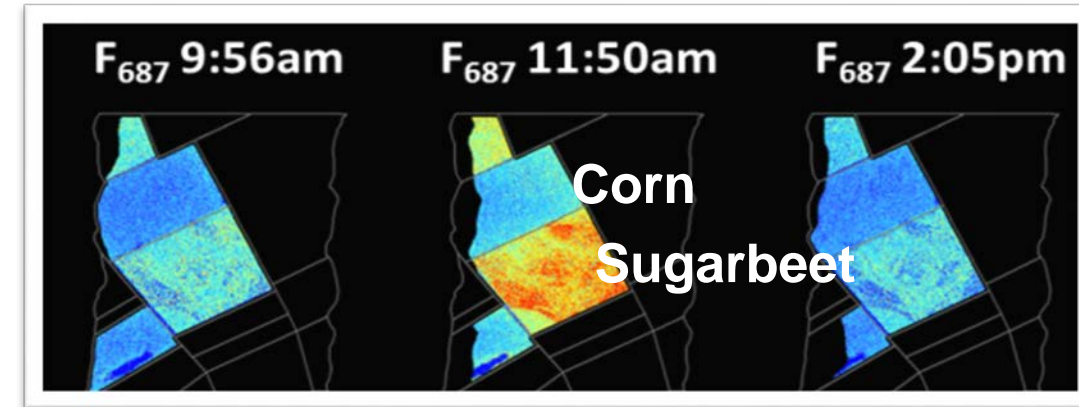
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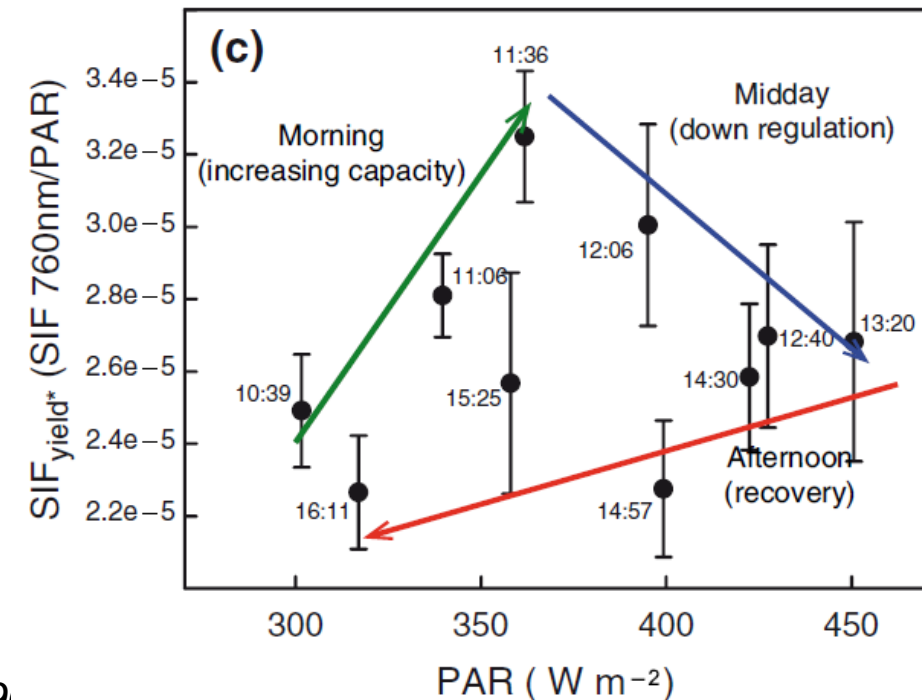
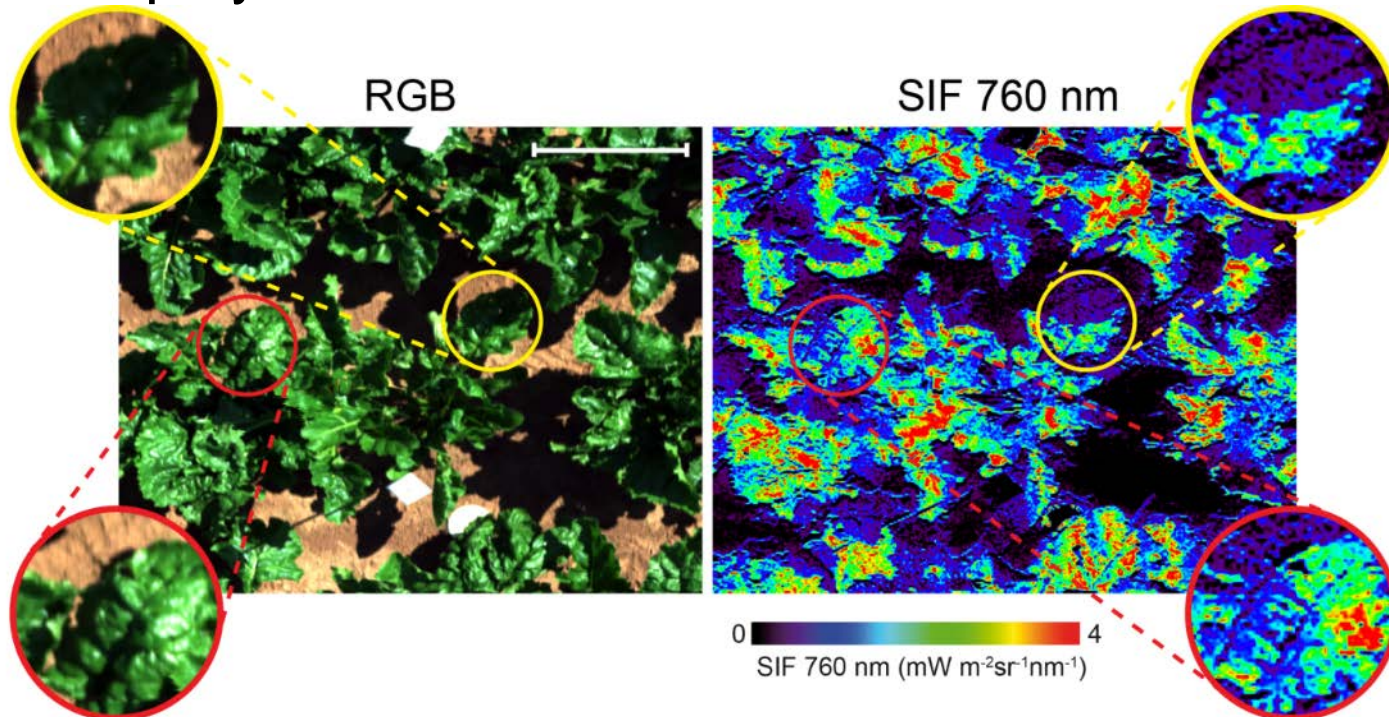
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# What are we doing to complement airborne mapping of fluorescence?

- Mapping of sun-induced fluorescence on the ground to understand interplay of the variations of light intensity within natural canopies and the three dimensional leaf display



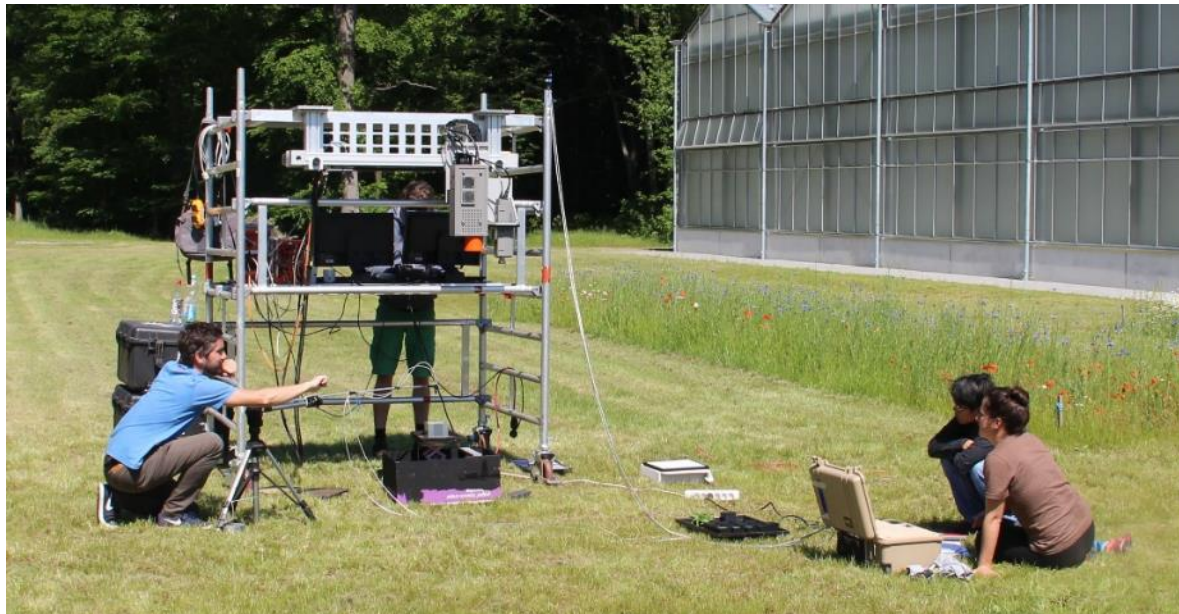
Pinto et al. (2016) *Plant, Cell and Environment*, 39, 1500–1512

Pinto et al. (2017) *Remote Sensing*, 9, article no. 415, doi: 10.3390/rs9040415



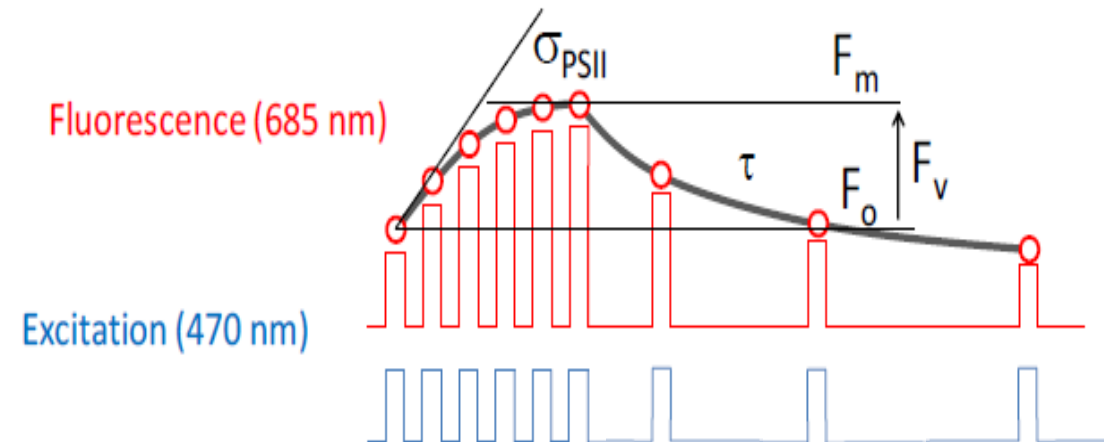
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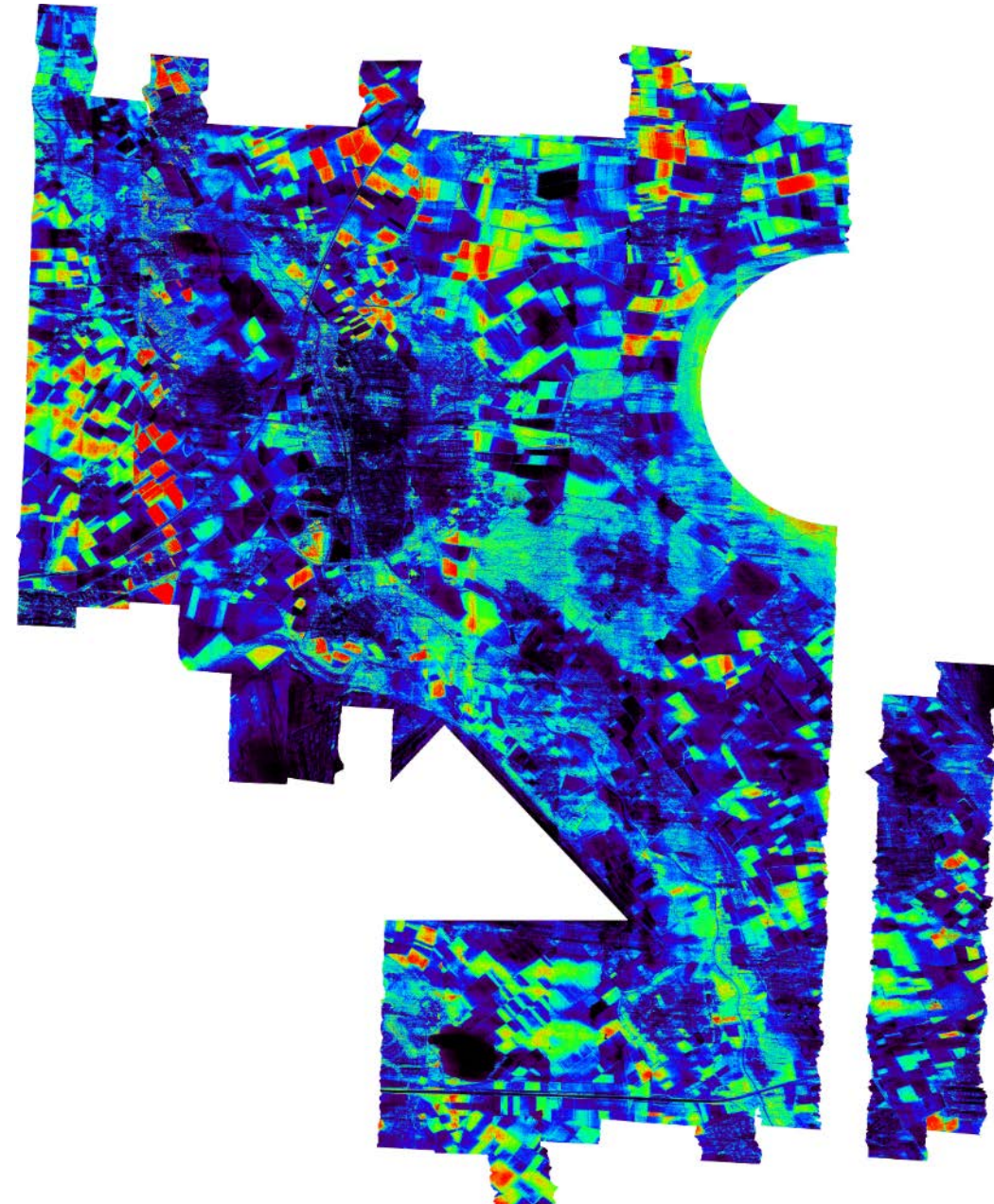
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- Link passive sun-induced fluorescence measurements with active fluorescence approaches that allow deeper insight into the photosynthetic machinery





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- Mapping of sun-induced fluorescence on the ground to understand interplay of the variations of light intensity within natural canopies and the three dimensional leaf display
- New 'HyPlant light' [*HySceen*] is operational
- Link passive sun-induced fluorescence measurements with active fluorescence approaches that allow deeper insight into the photosynthetic machinery
- Aggregate flight lines to produce FLEX like data and understand fluorescence on the 300 x 300 meter pixel





# What are we doing to complement airborne mapping of fluorescence?

- High-resolution point spectrometer developed, optimized and standardized system available
- ~10 systems have been employed and are operational



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**2017**



**2012**



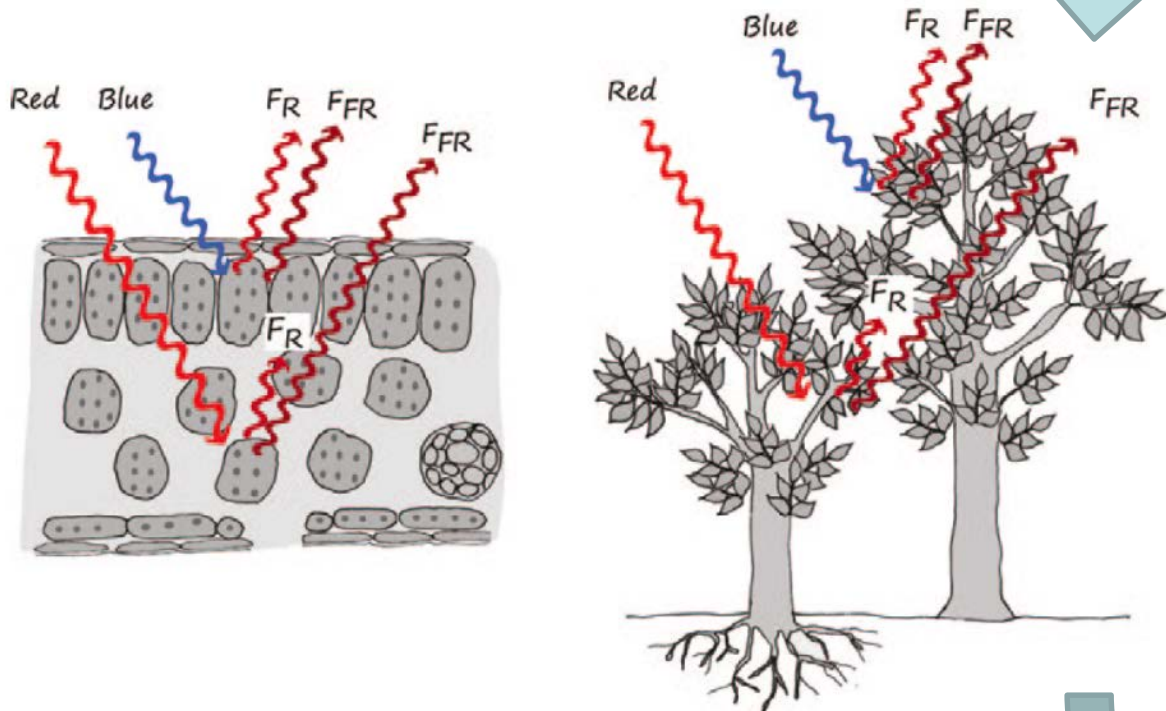
**2016**

Burkart et al. (2015) *IEEE Sensors*, 15, 4603-4611

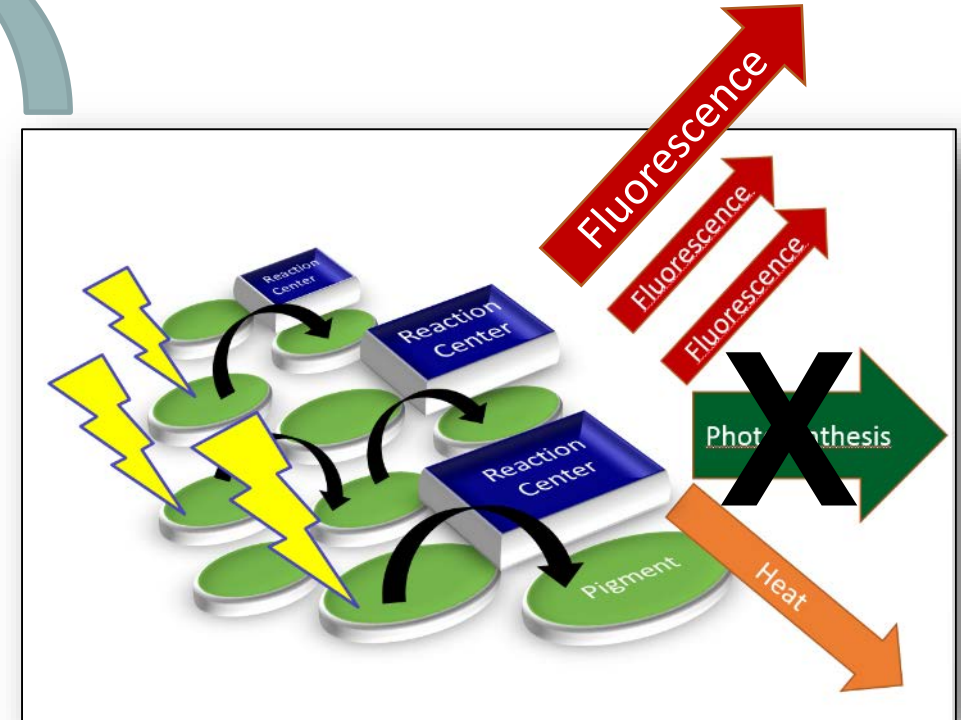
Cogliati et al. (2015) *Remote Sensing of Environment*, 164, 270-281

# Understanding sun-induced fluorescence: A matter to understand Structure / Function Relations

## Structure

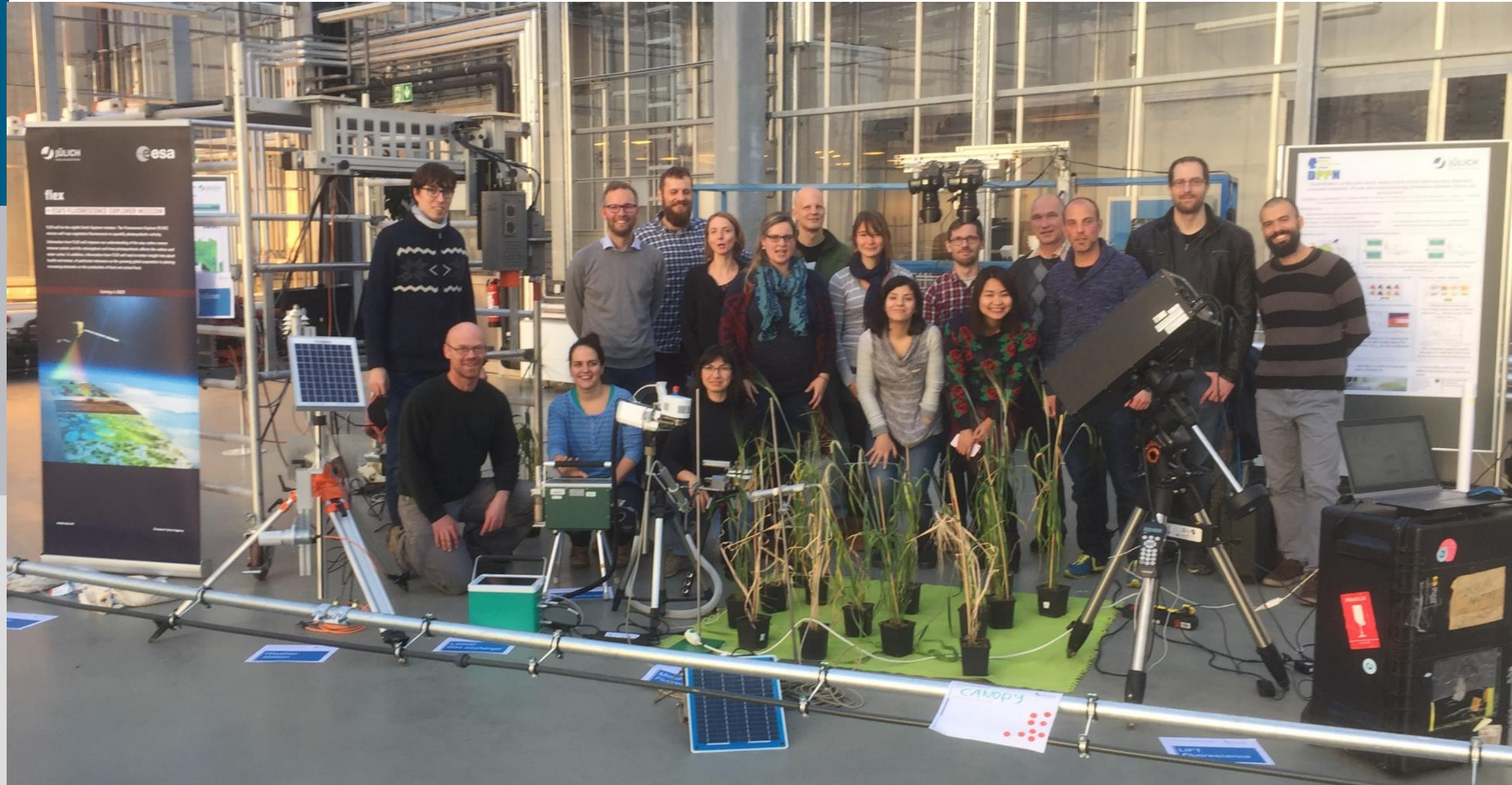


## Function





# Many thanks to my group





# Many thanks to the numerous partners



University of  
Zurich <sup>UZH</sup>



Consiglio  
Nazionale delle  
Ricerche



Centre de Recherche Public  
Gabriel Lippmann



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FORSCHUNGSZENTRUM



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