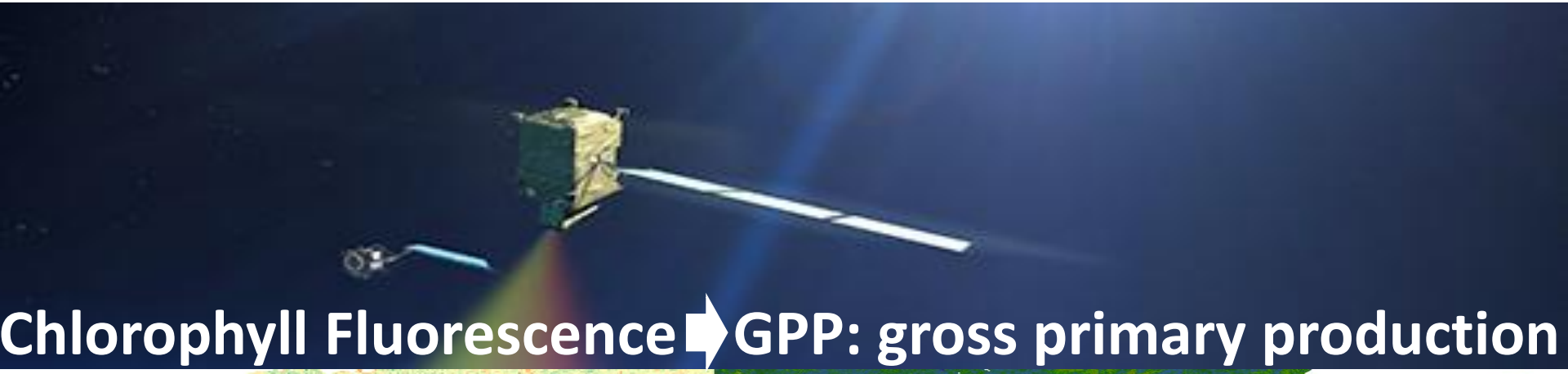
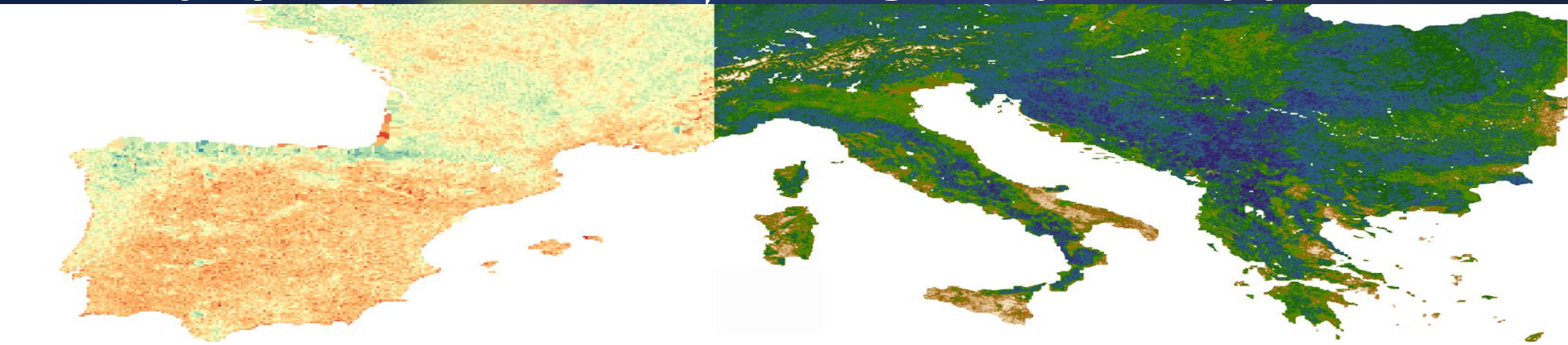
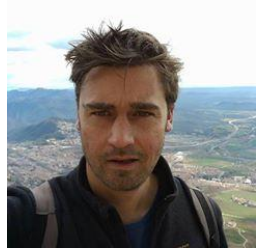
Fluorescence Spectrometry and Radiative Transfer Modelling of Vegetation



Chlorophyll Fluorescence ➡ GPP: gross primary production

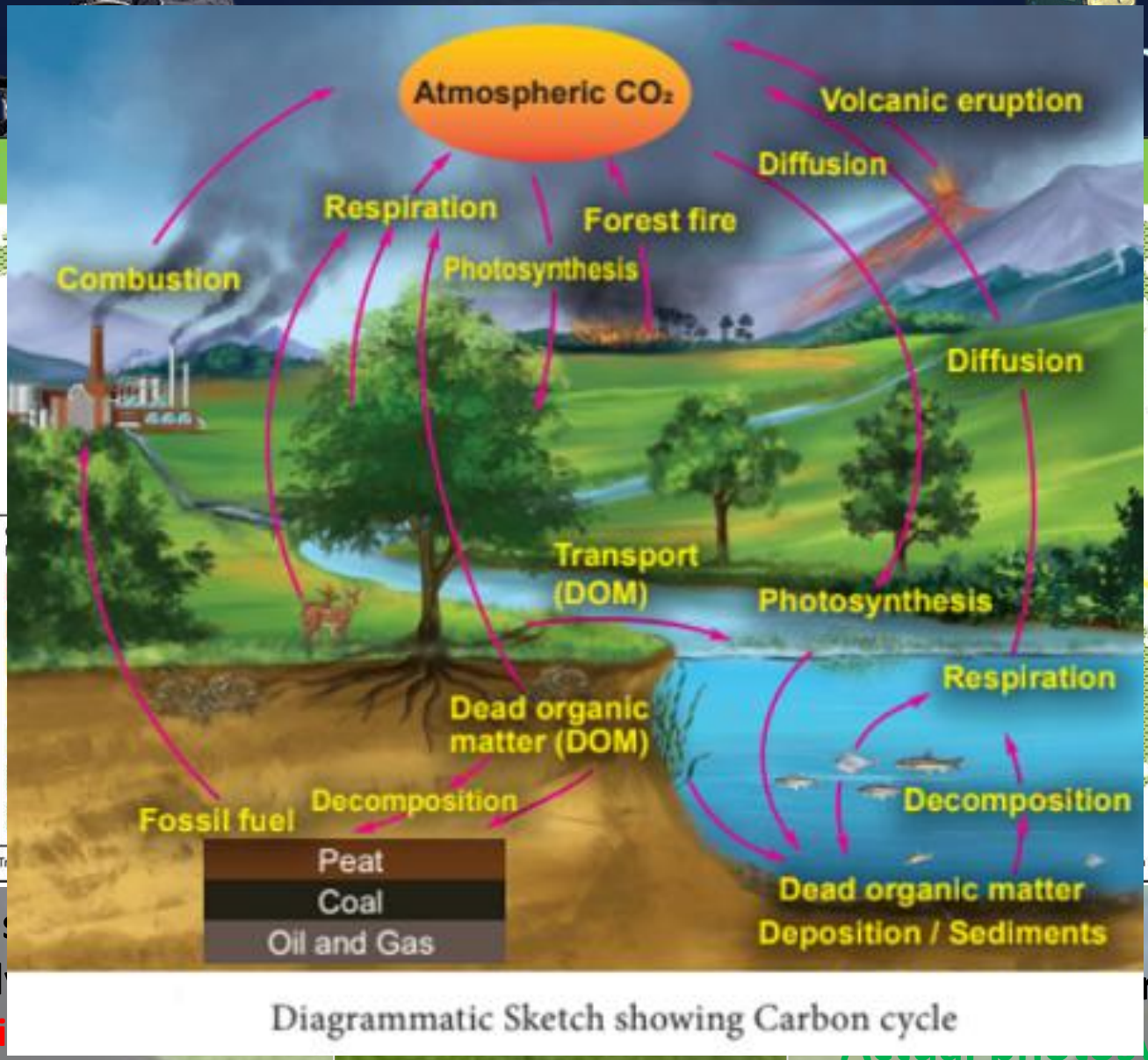


Jochem Verrelst, PhD in Remote Sensing, jochem.verrelst@uv.es
Postdoc Researcher at the **Laboratory of Earth Observation**
University of Valencia, Spain



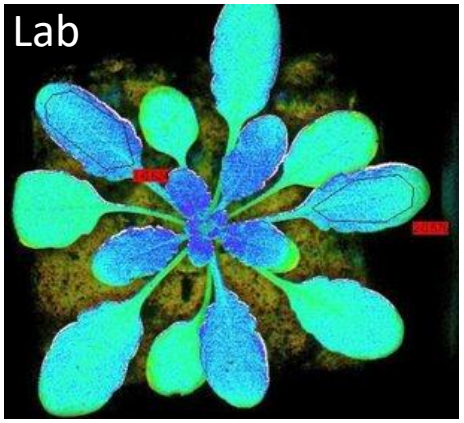
ESA's Earth Observation fleet

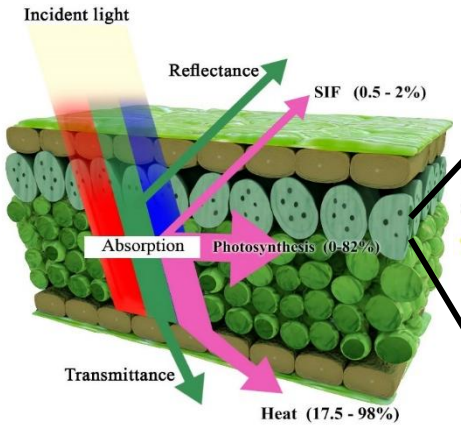
How to quantify terrestrial photosynthetic activity?

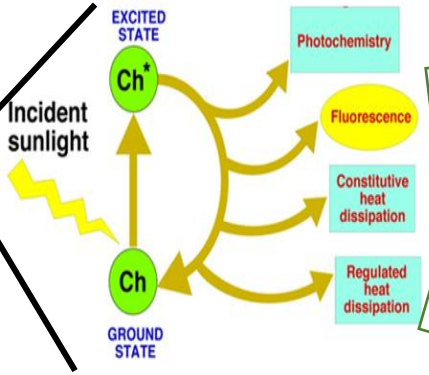


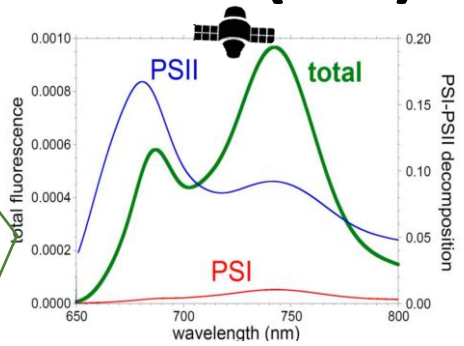
Diagrammatic Sketch showing Carbon cycle

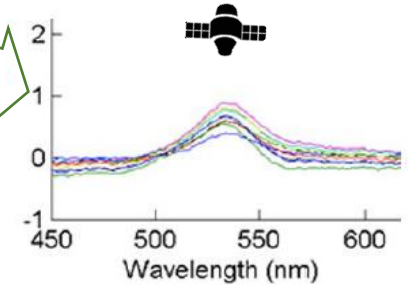
What is sun-induced chlorophyll fluorescence (SIF)?





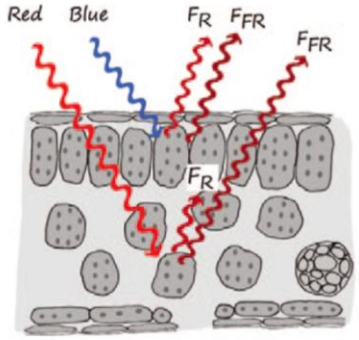




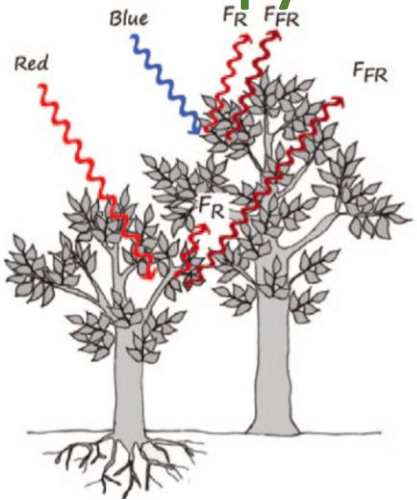


(re-)absorption and scattering mechanisms

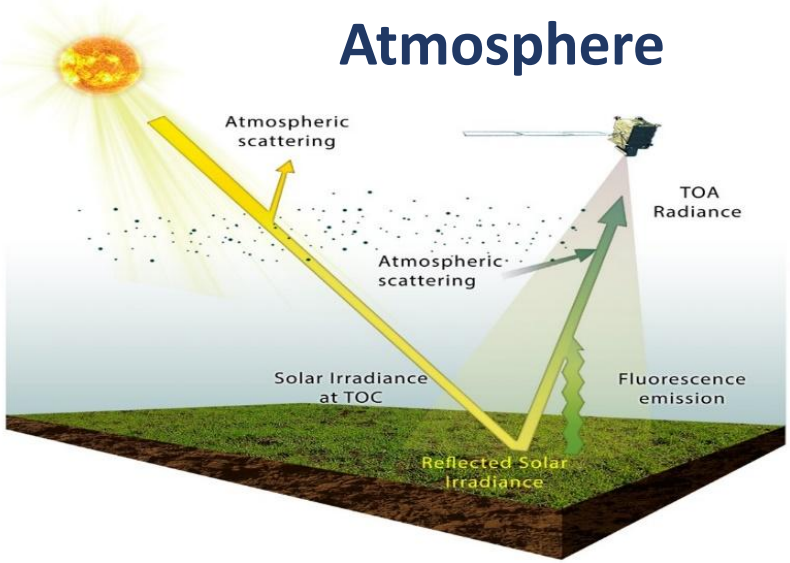
Leaf



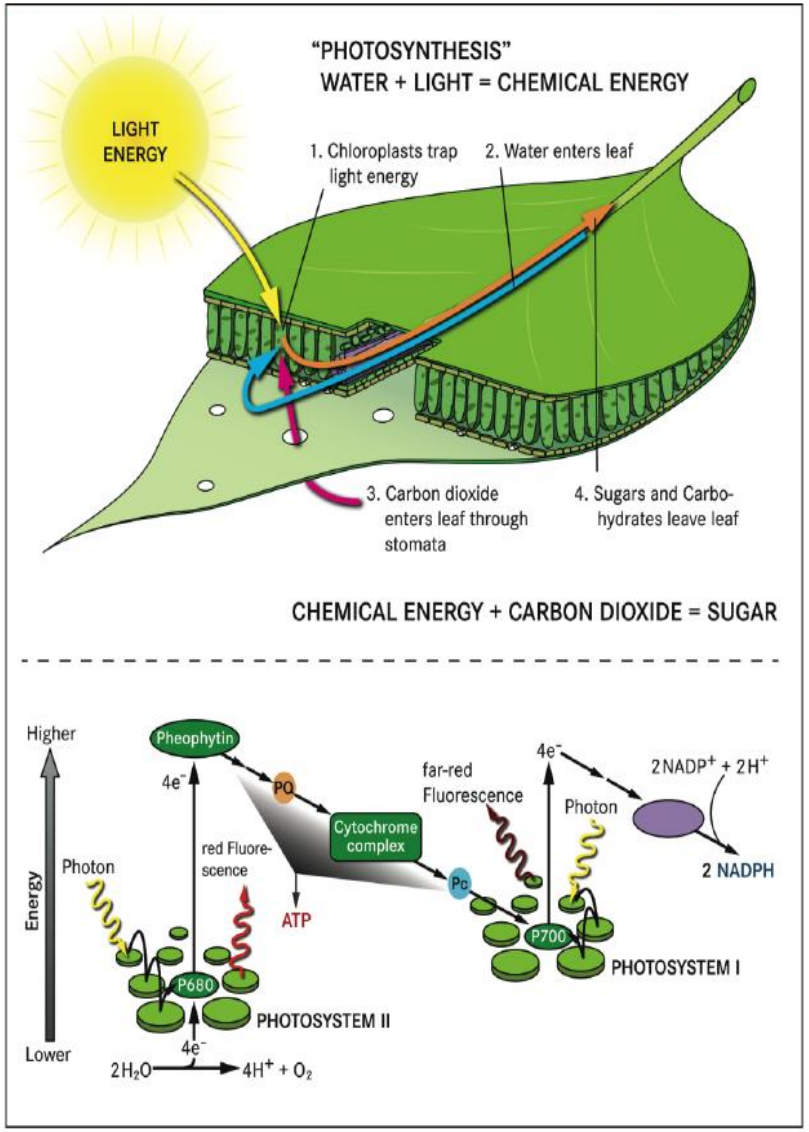
Canopy



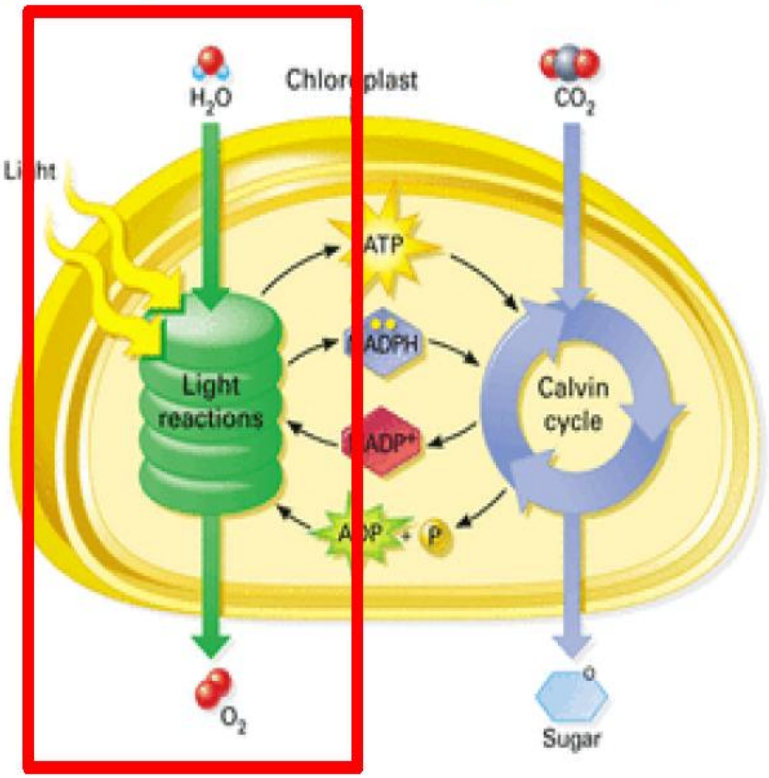
Atmosphere



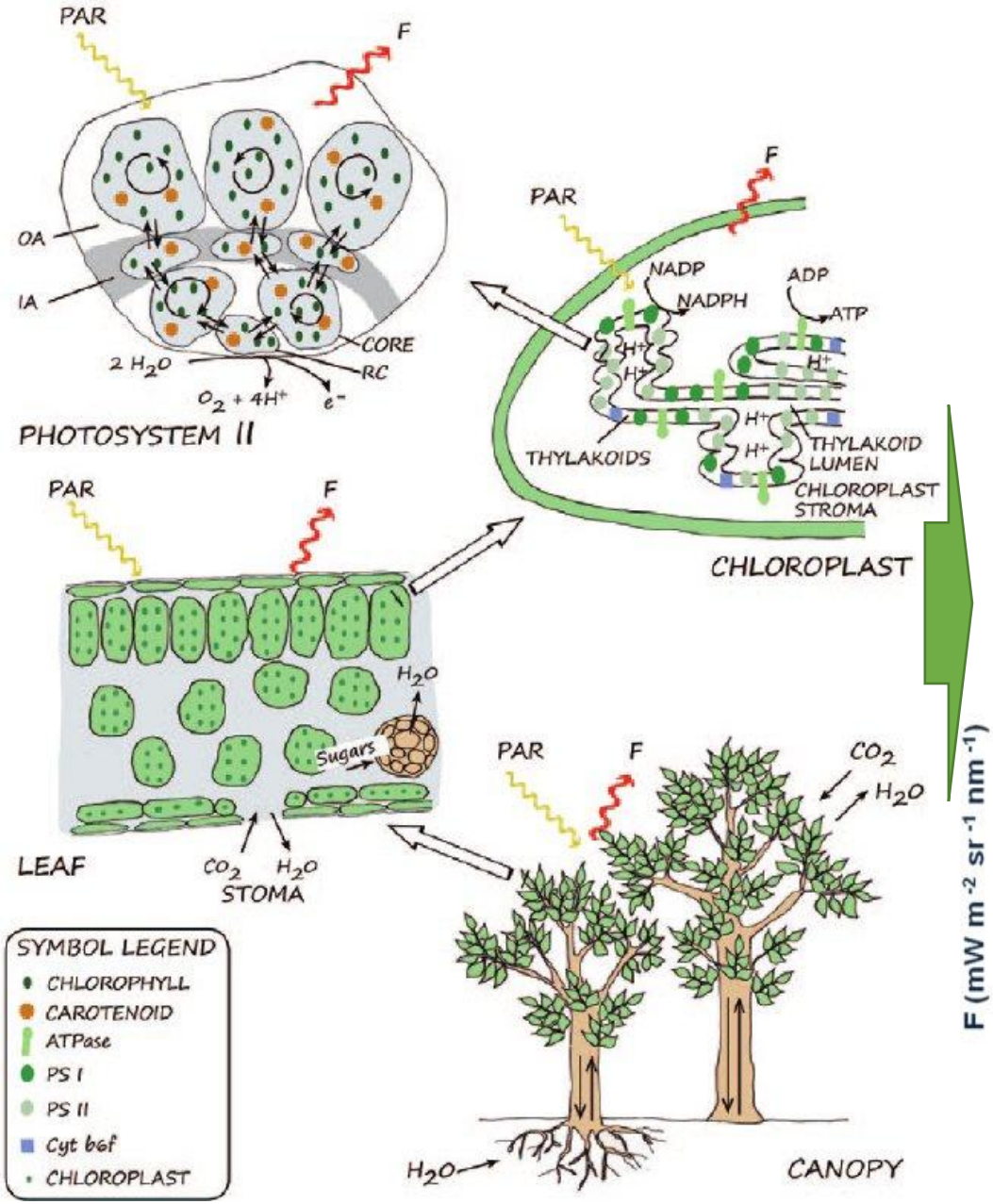
Photosynthesis & sun-induced Chl fluorescence (SIF)



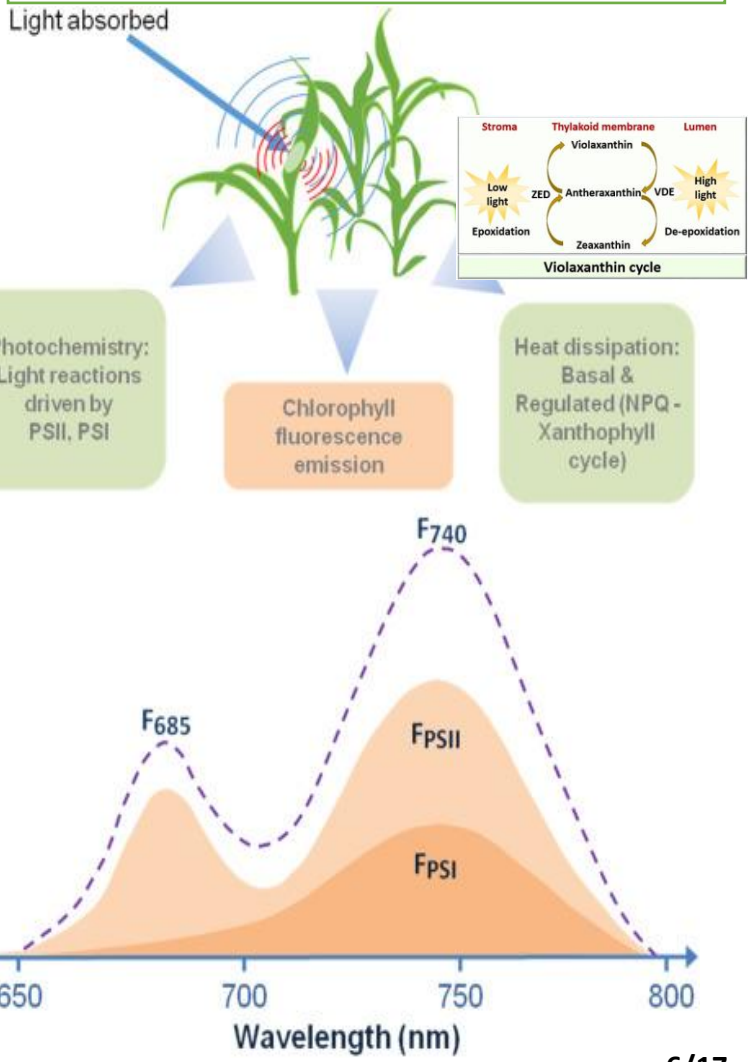
- Photosynthesis is a highly regulated process that involves a cascade of electron transfers (*Light reaction*) to fuel carbon fixation (*Calvin cycle*)
- Fluorescence is emitted from the cores of the photosynthetic machinery: Photosystems I and II



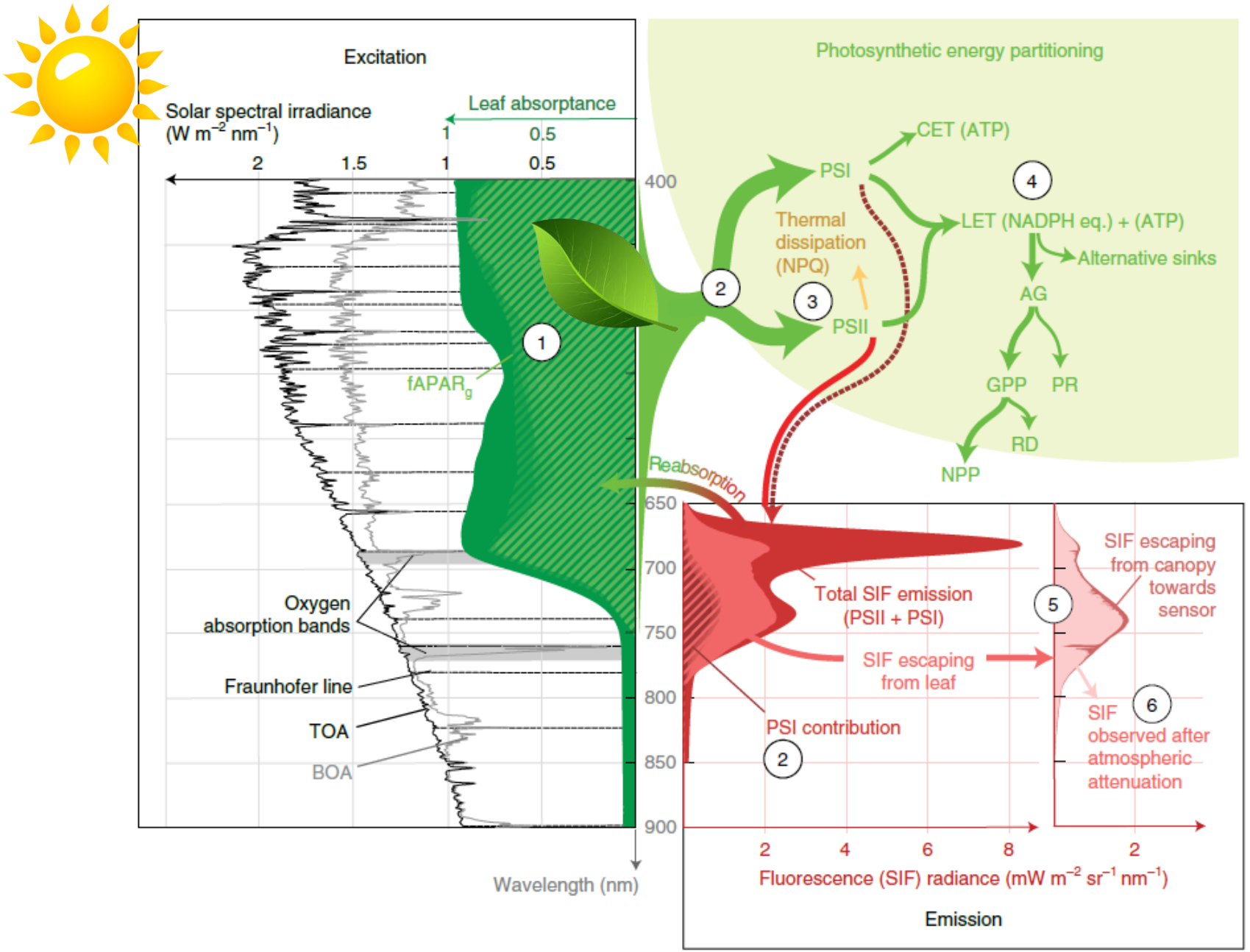
A closer look to SIF – photosynthesis dynamics



Photosynthesis: 3 main dynamics, 2 can be measured by imaging spectroscopy: SIF & NPQ

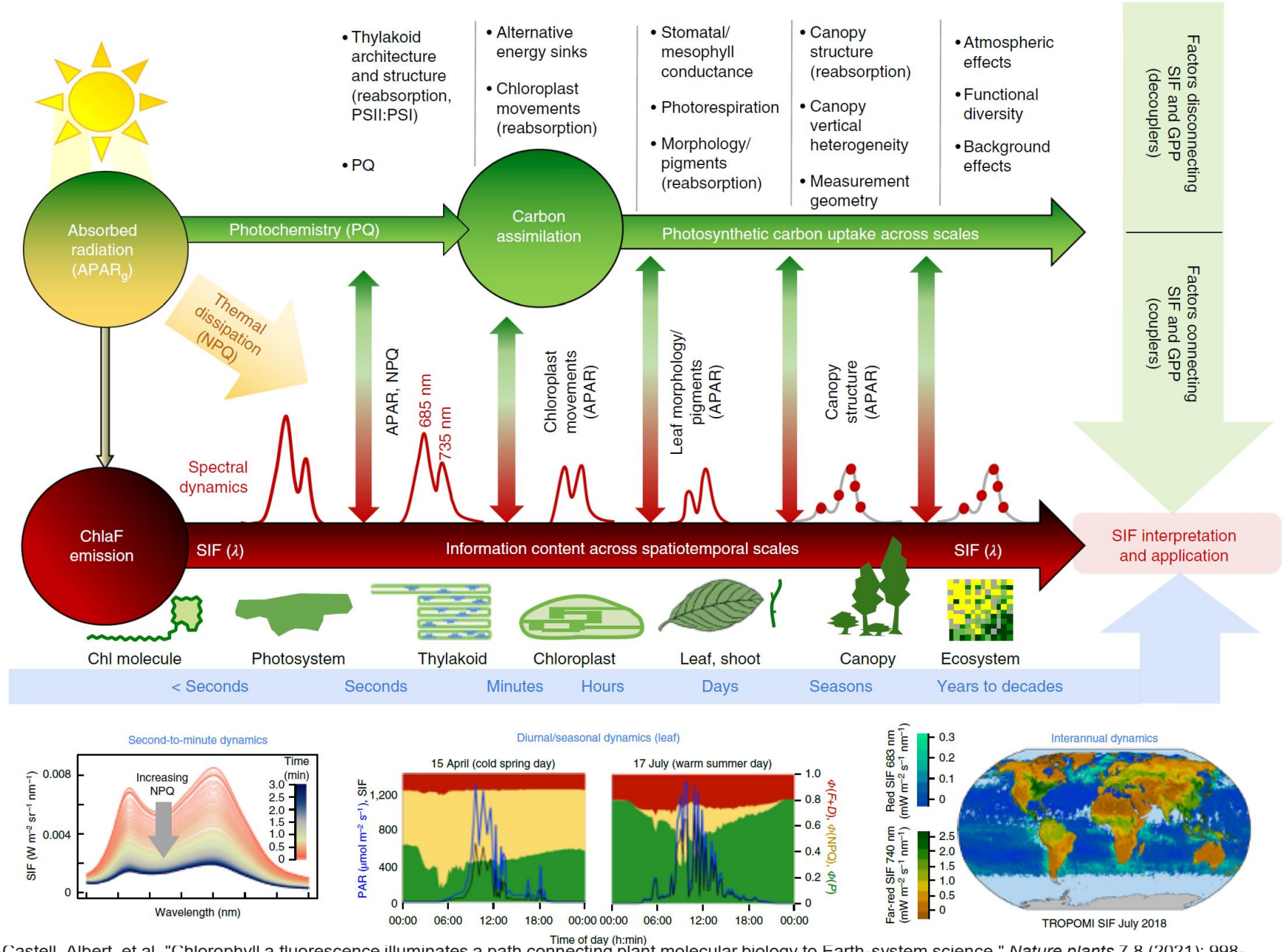


Energy transport: irradiance, absorptance & SIF emission

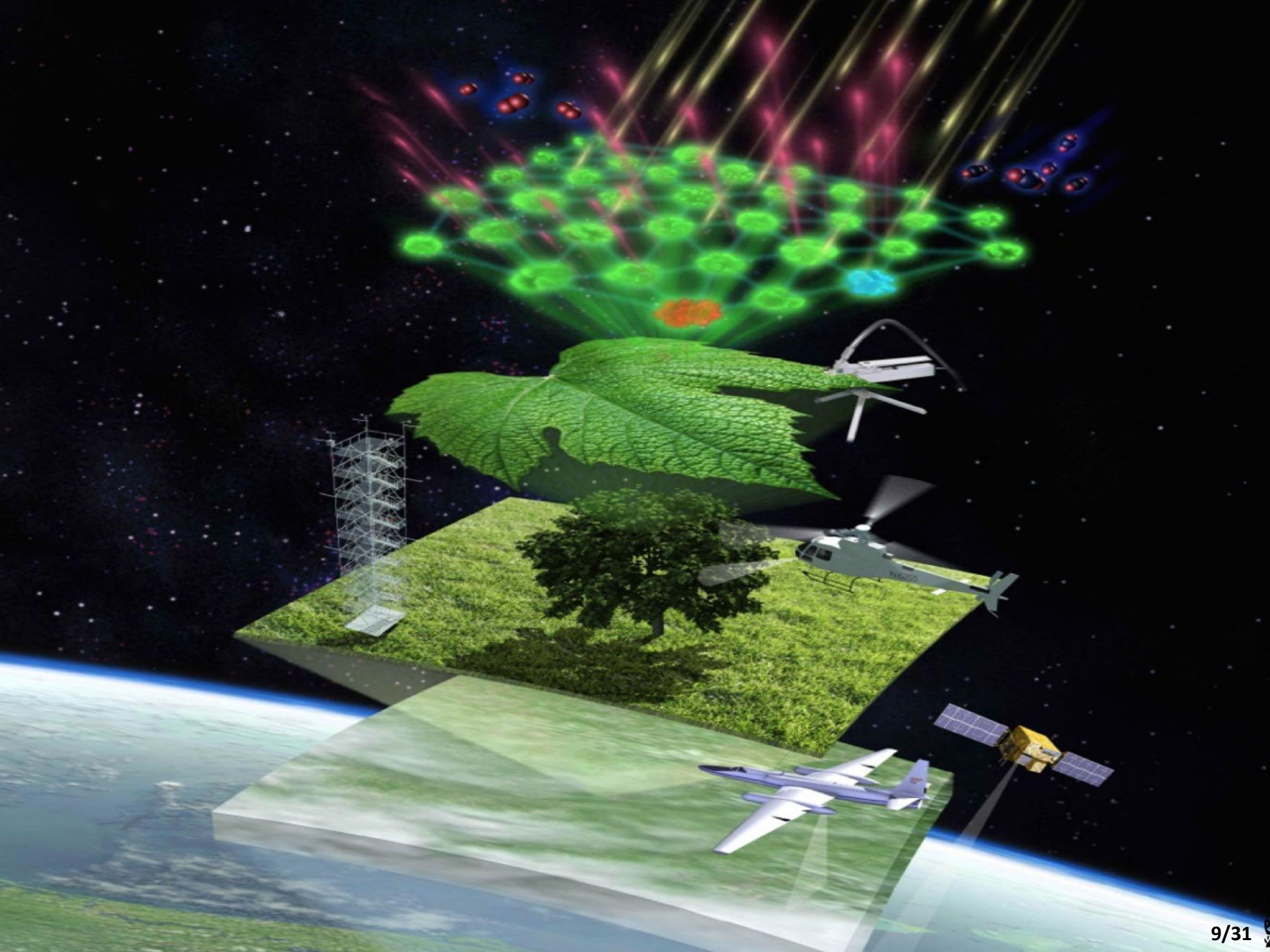


Porcar-Castell, Albert, et al. "Chlorophyll a fluorescence illuminates a path connecting plant molecular biology to Earth-system science." *Nature plants* 7.8 (2021): 998-1009.

SIF emission upscaling & dynamics

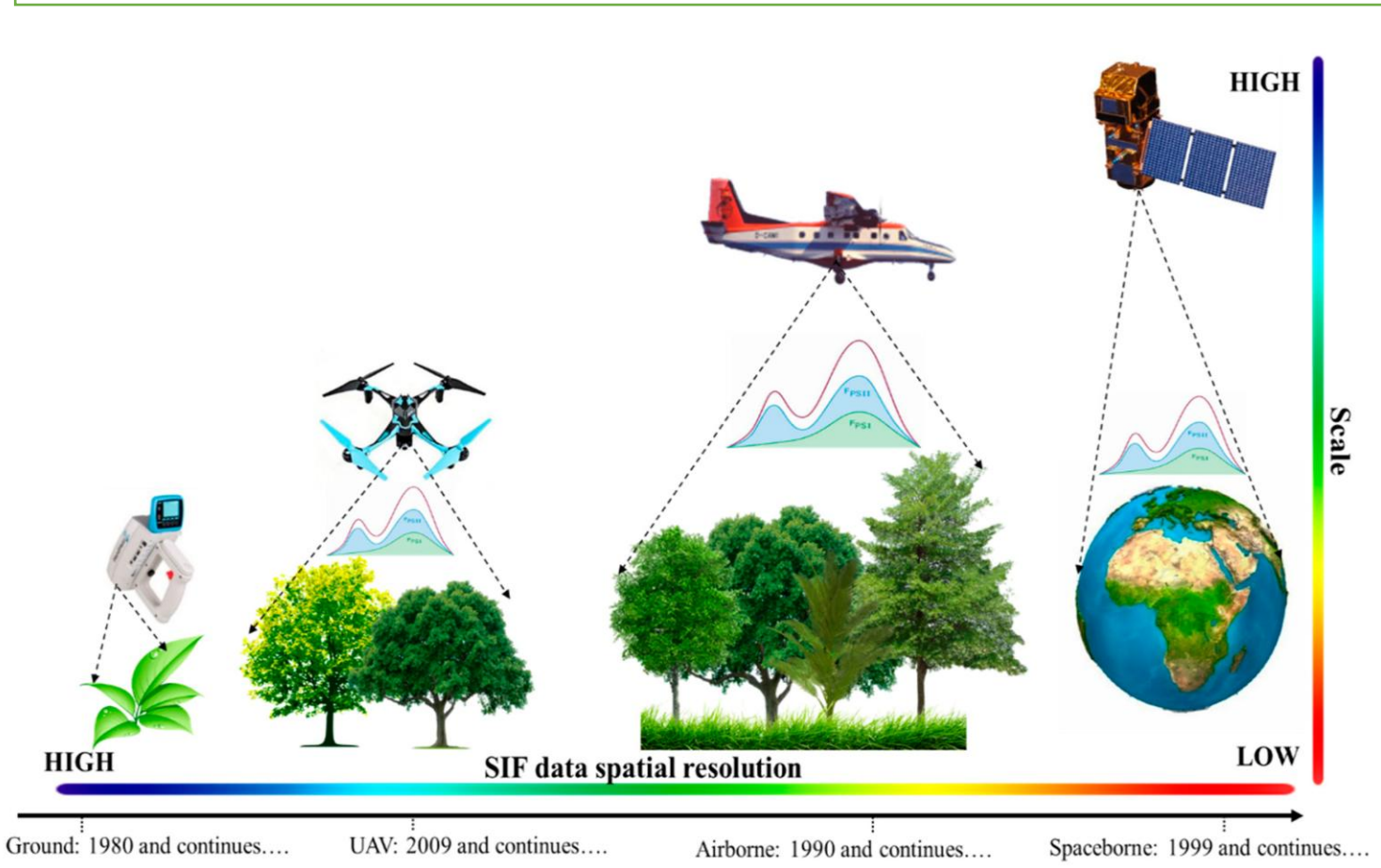


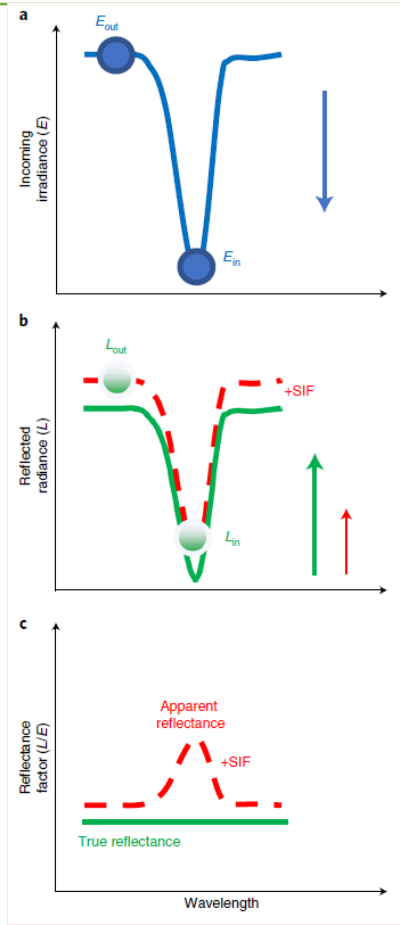
Porcar-Castell, Albert, et al. "Chlorophyll a fluorescence illuminates a path connecting plant molecular biology to Earth-system science." *Nature plants* 7.8 (2021): 998-1009.



Measuring SIF from leaf to space

Unlike in the lab, **for SIF retrieval we cannot make use of filters**. Instead use is made of “natural” filters, so called Atmospheric Windows. Particulaly Fraunhofer lines and oxygen absorption Windows block incoming irradiance. Based on differences in reflected radiance and reflectance factor SIF can be derived.



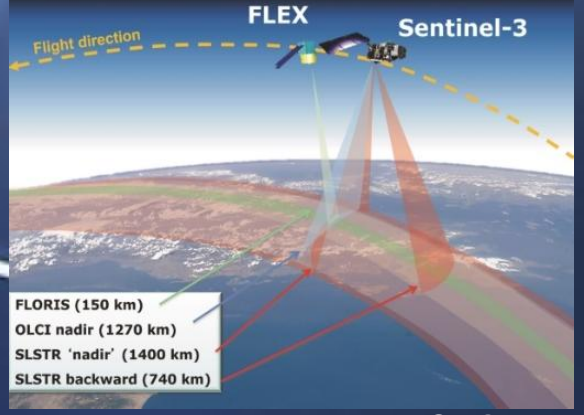


Bandopadhyay, S.; Rastogi, A.; Juszczak, R. **Review of Top-of-Canopy Sun-Induced Fluorescence (SIF) Studies from Ground, UAV, Airborne to Spaceborne Observations**. *Sensors* 2020, *20*, 1144. https://doi.org/10.3390/s20041144
See also for an **overview of SIF retrieval methods**

Porcar-Castell, Albert, et al. "Chlorophyll a fluorescence illuminates a path connecting plant molecular biology to Earth-system science." *Nature plants* 7.8 (2021): 998-1009.

FLEX

Sentinel-3



FLEX aims to quantify **actual photosynthetic activity** of terrestrial ecosystems from space, accounting for **vegetation health** status and **stress** conditions.

While **ESA** aims to deliver up to (L2) SIF products, it is for the **scientists** to process, interpret & develop applications: **to push for cutting-edge science**

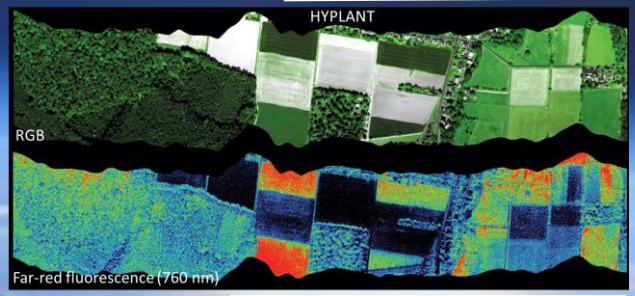
Space

Launch: 2025

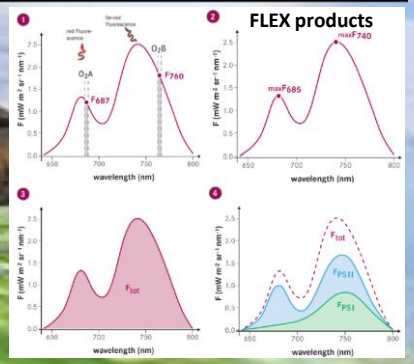
?

State of the art

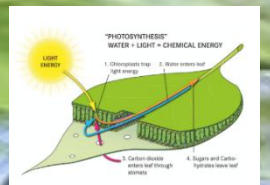
Airborne



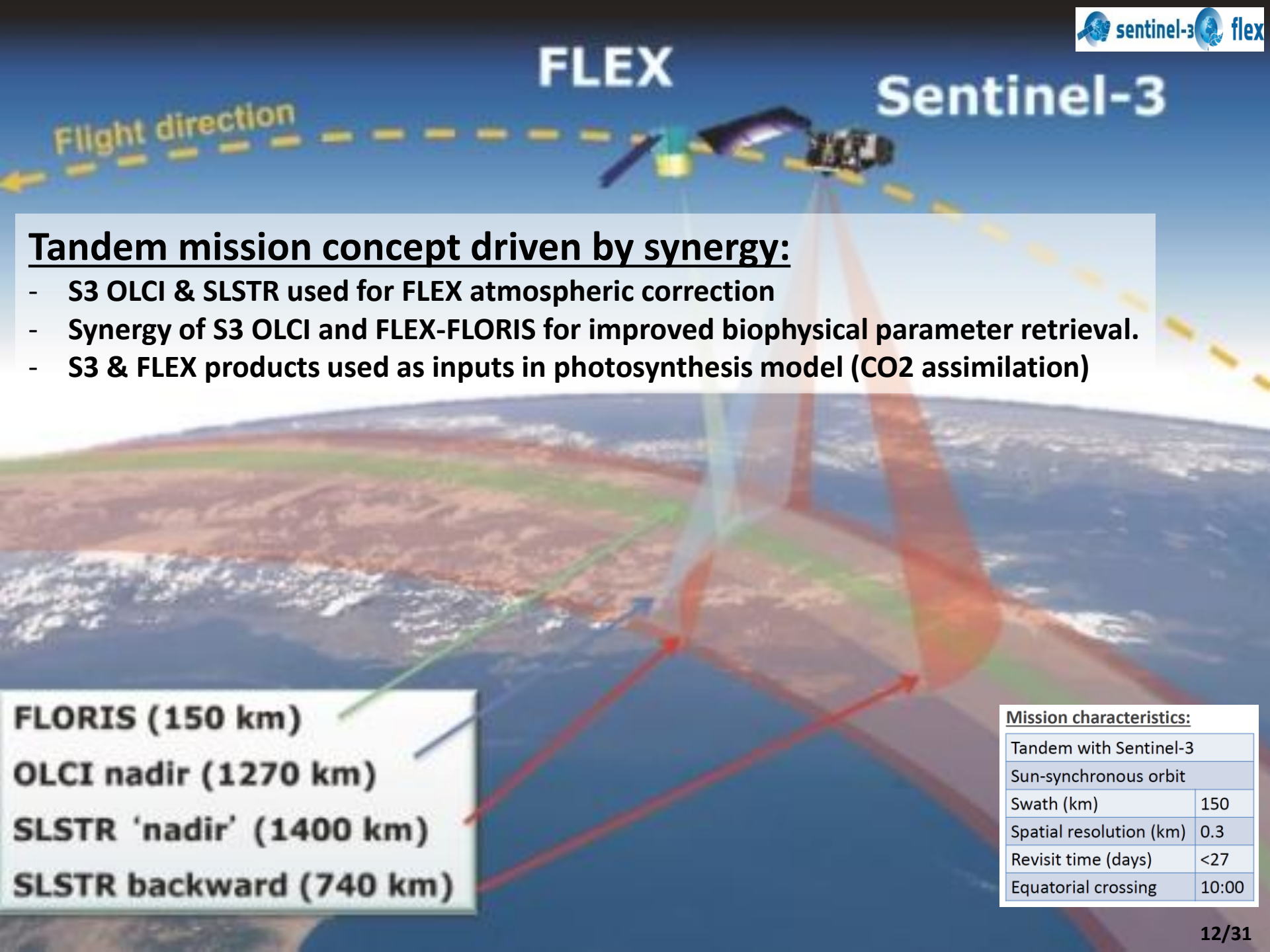
Canopy



Leaf



Cell



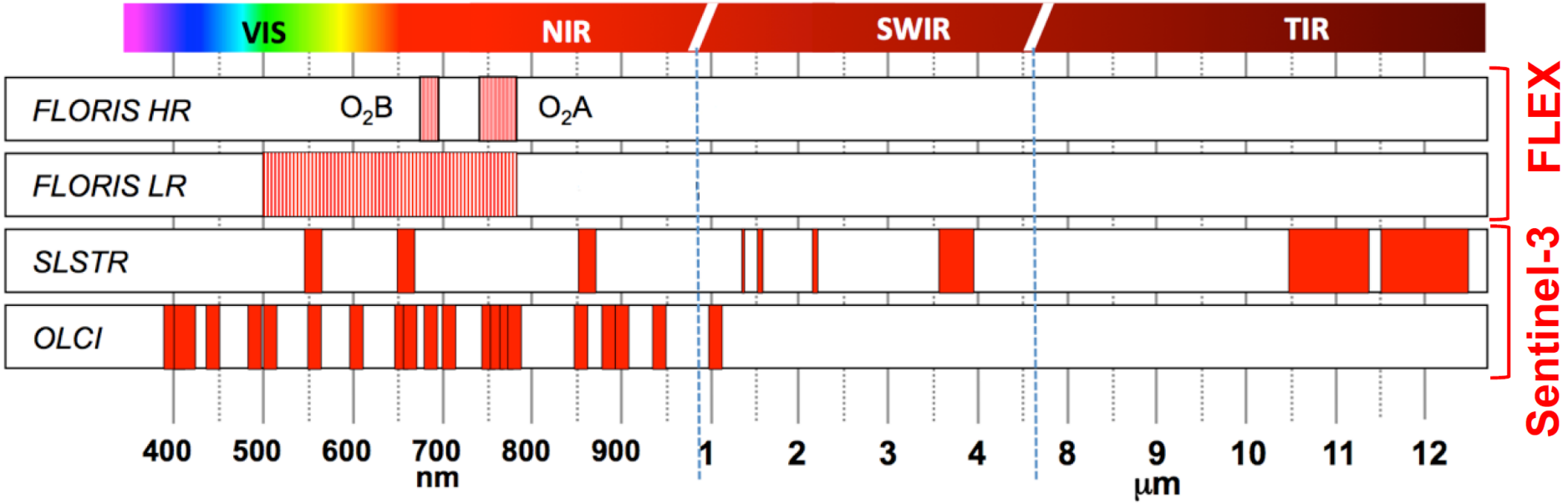
Tandem mission concept driven by synergy:

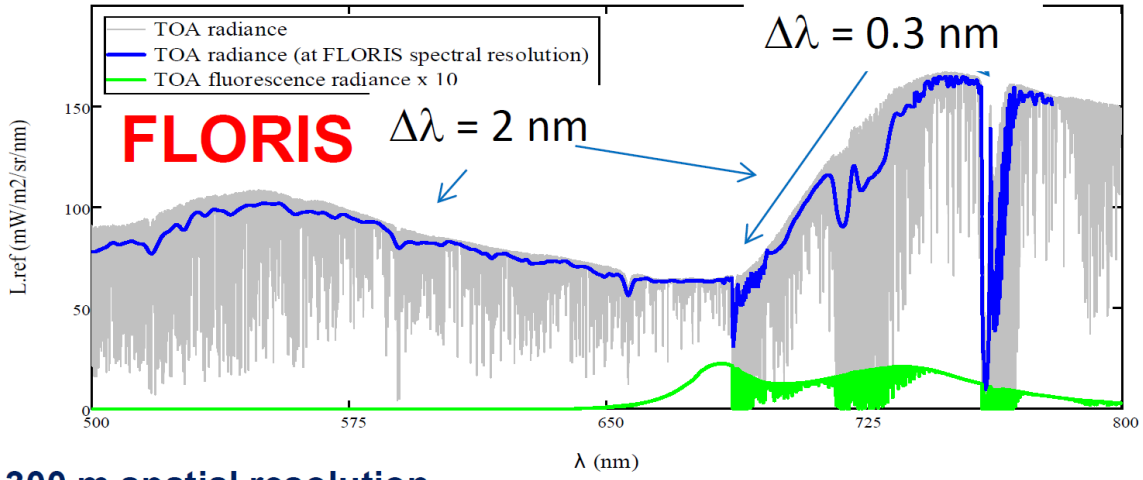
- S3 OLCI & SLSTR used for FLEX atmospheric correction
- Synergy of S3 OLCI and FLEX-FLORIS for improved biophysical parameter retrieval.
- S3 & FLEX products used as inputs in photosynthesis model (CO_2 assimilation)

Mission characteristics:

Tandem with Sentinel-3	
Sun-synchronous orbit	
Swath (km)	150
Spatial resolution (km)	0.3
Revisit time (days)	<27
Equatorial crossing	10:00

FLEX / Sentinel-3 spectral information

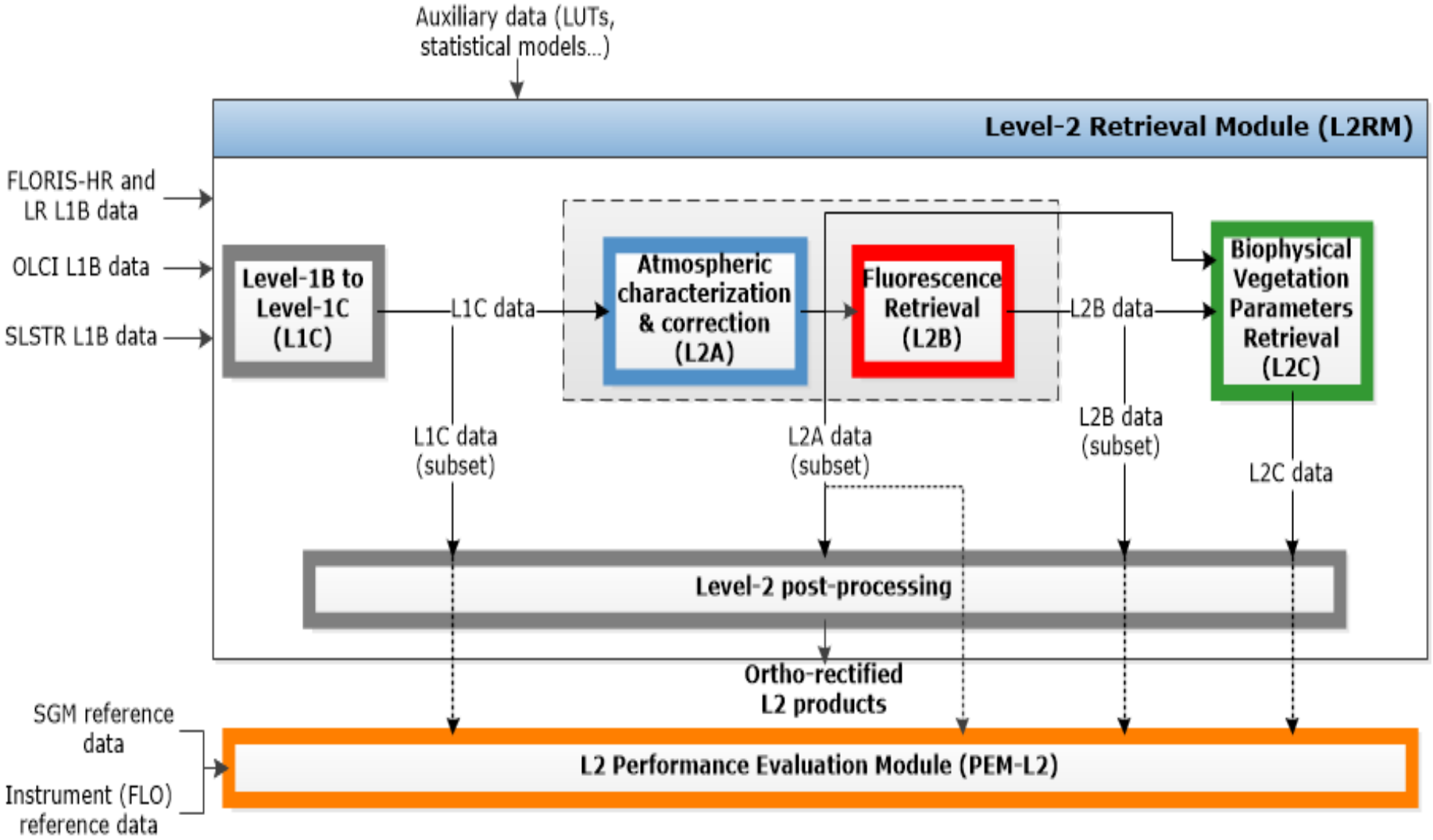




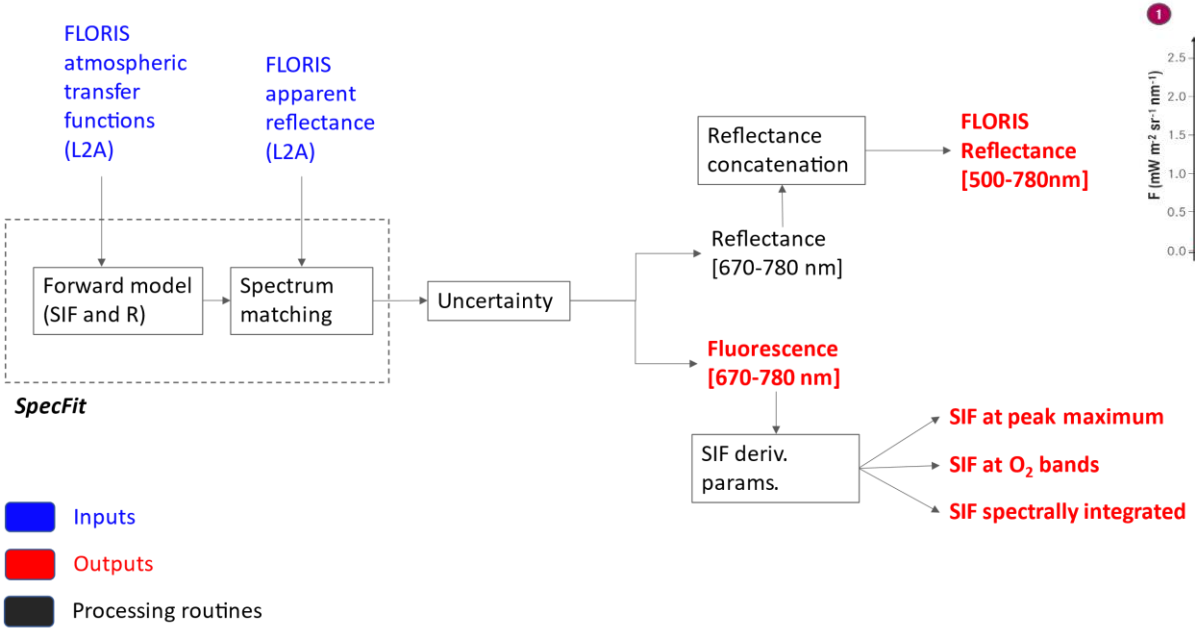
300 m spatial resolution

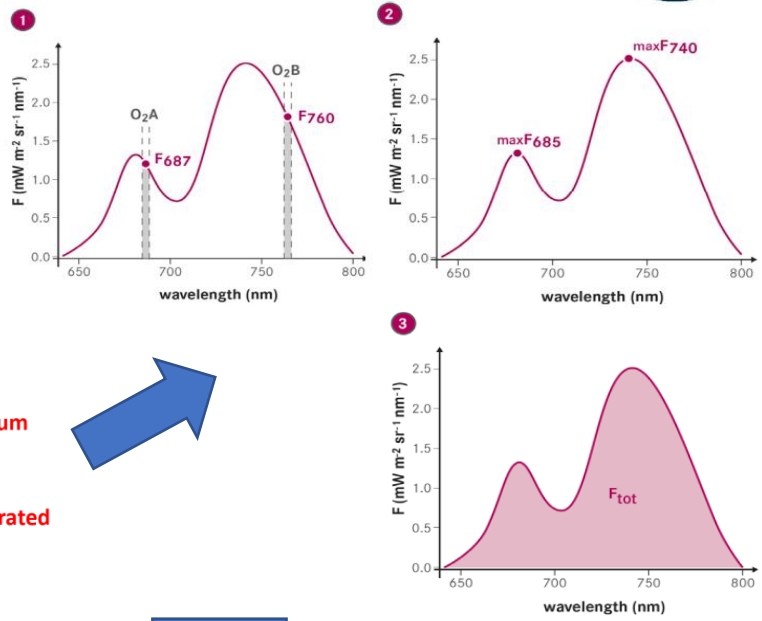
Spectral region	Central Wavelength [nm]	FWHM [nm]	Spectral Sampling [nm]
PRI	500 – 600	3	2
Chl	600 – 677	3	2
O_2-B	677 – 686	0,7	0,5
	686 – 697	0,3	0,1
Red-edge	697 – 740	2	1
	740 – 755	0,7	0,5
O2-A	755 – 759	0,7	0,5
	759 – 762	0,3	0,1
	762 – 769	0,3	0,1
	769 – 780	0,7	0,5

FLEX L2RM processing chain



FLEX L2RM – SIF retrieval



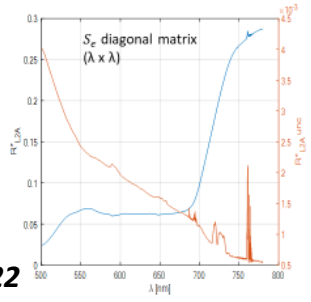


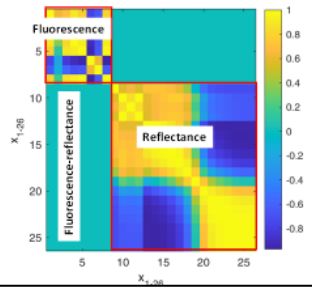
MODEL INVERSION: optimal estimator

Cost function

$$J(\boldsymbol{x}) = (\boldsymbol{y} - \boldsymbol{F}(\boldsymbol{x}))^T \, \boldsymbol{S}_{\boldsymbol{\epsilon}}^{-1} (\boldsymbol{y} - \boldsymbol{F}(\boldsymbol{x})) + \Lambda \, (\mathbf{x} - \mathbf{x_a})^{\mathrm{T}} \mathbf{S}_{\mathbf{a}}^{-1} \, (\mathbf{x} - \mathbf{x_a})$$

- $\boldsymbol{S}_{\boldsymbol{\epsilon}}$: measurement uncertainty covariance matrix
- Λ: scaling parameter for a-priori information (10^{-3})
- $\mathbf{S}_{\mathbf{a}}$: a-priori probability covariance matrix
- $\mathbf{x_a}$: a-priori parameters





S. Cogliati, '22

L2B products:

- **Fluorescence [650-780 nm]**
- **reflectance spectra [500-*780 nm]***
- **F at the O_2 bands *[2 values]***
- **F at peak maximum and wavelength *[2 + 2 values]***
- **F_{int} – spectrally integrated fluorescence *[1 value]***

Application of (global) SIF products

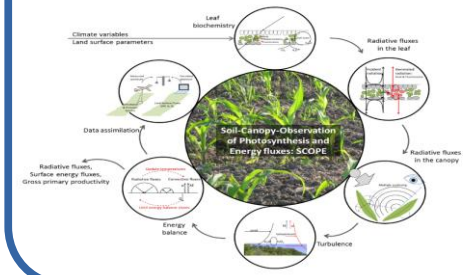
Assimilation

RTM data

EO data (S3, TROPOMI)

field data

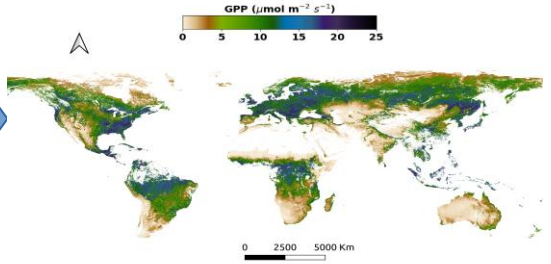
SCOPE



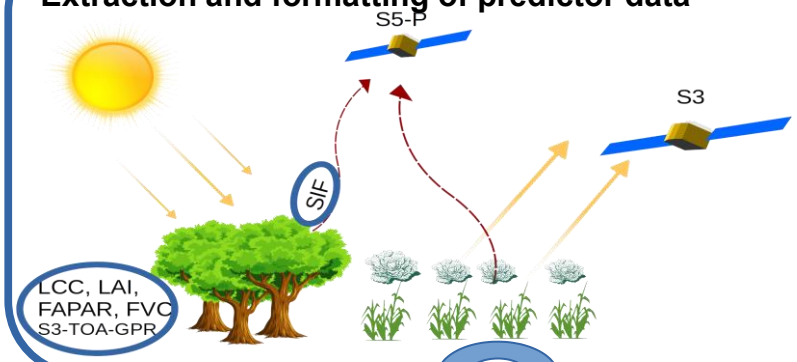
Global scale modelling – training on SCOPE simulations – production through Google Earth Engine

GPP GPR Training

GPP GPR estimation

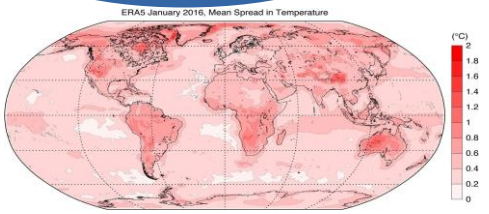


Extraction and formatting of predictor data



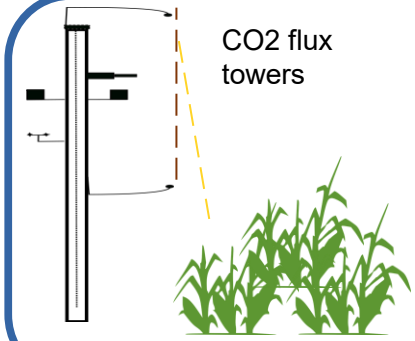
Predictor data joint gridded format

T-air, T-Soil, SWinc, VPD



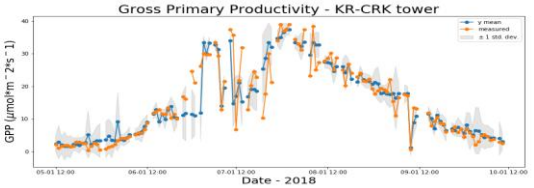
ERA-5 climate Reanalysis

CO2 flux towers



GPP GPR Training

GPP GPR estimation



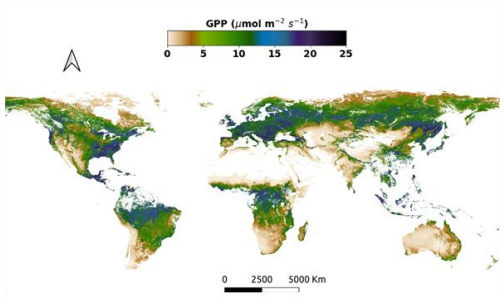
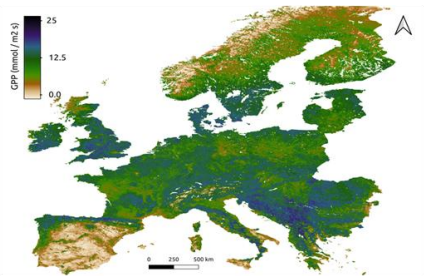
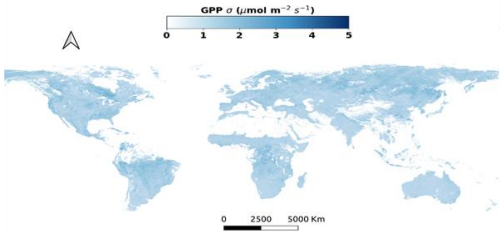
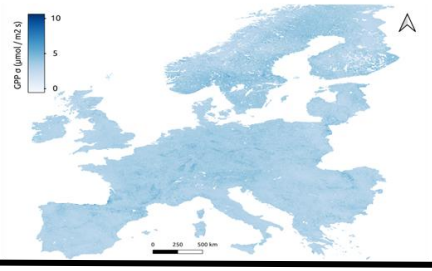
Site point modelling – training on FLUXNET data – production through Skitlearn/GeoPandas

Spatial distribution:

Tropical forests, Taiga and temperate forests reaching peaks of GPP

The best performing model included 8 variables leading to **deviations** (second row) of around **20 % of estimates**

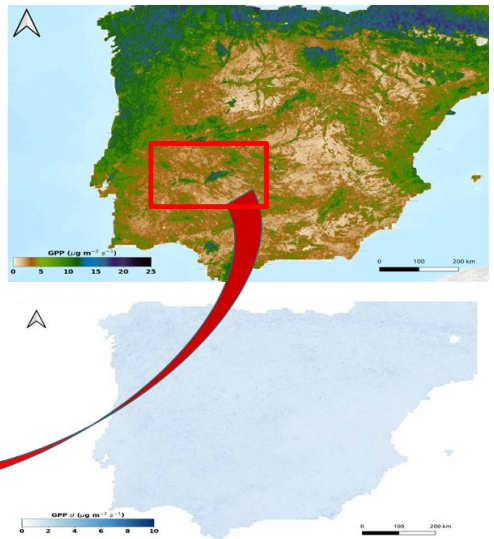
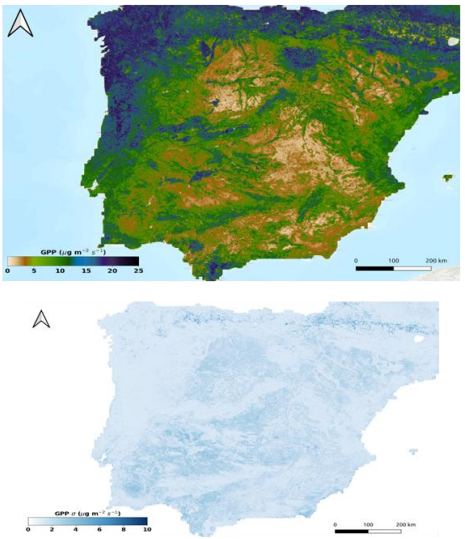
At European scale, peaks of GPP on forest areas: Dinaric Alps.

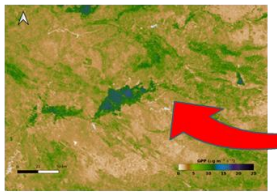
	Estimates and uncertainties on 16-06-2019–13:00:00	Estimates and uncertainties on 16-06-2019–13:00:00
Estimates		
Uncertainties		

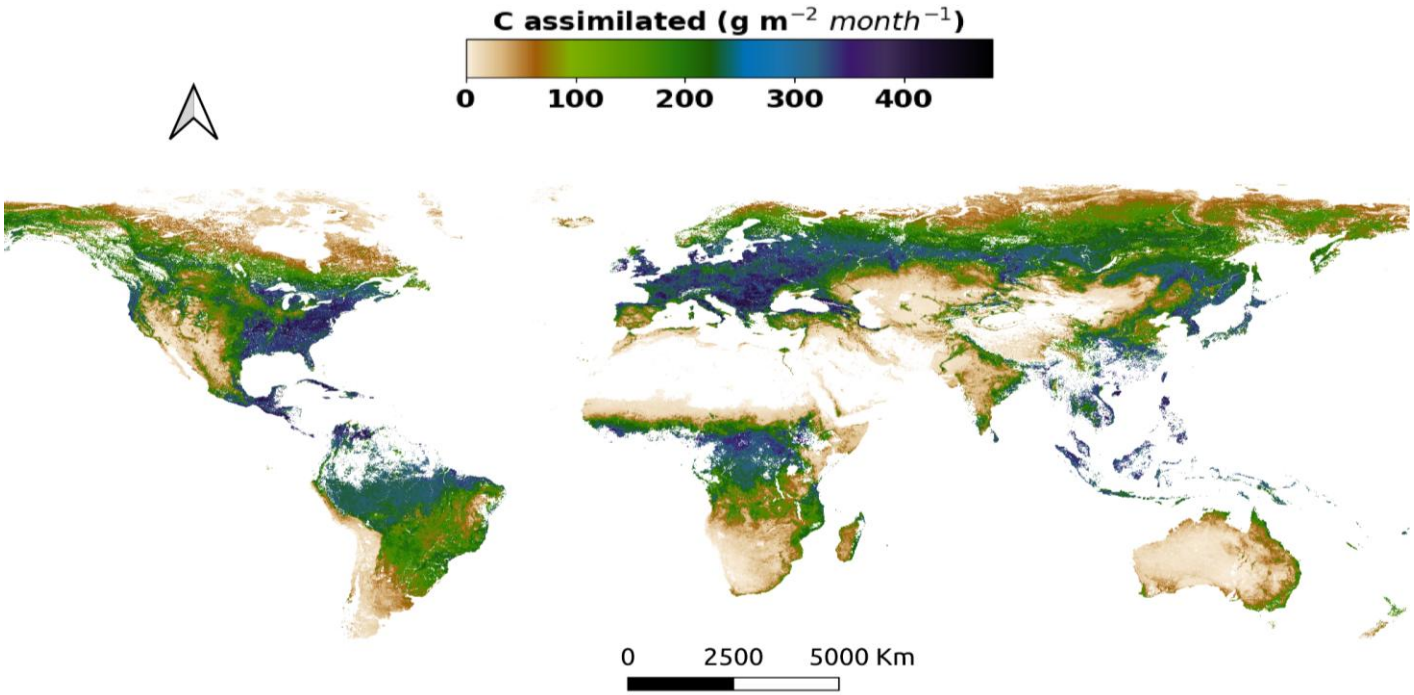
Spatial distribution:

Regional scale map highlighting diverse land cover types, with peak values over forest and agricultural areas.

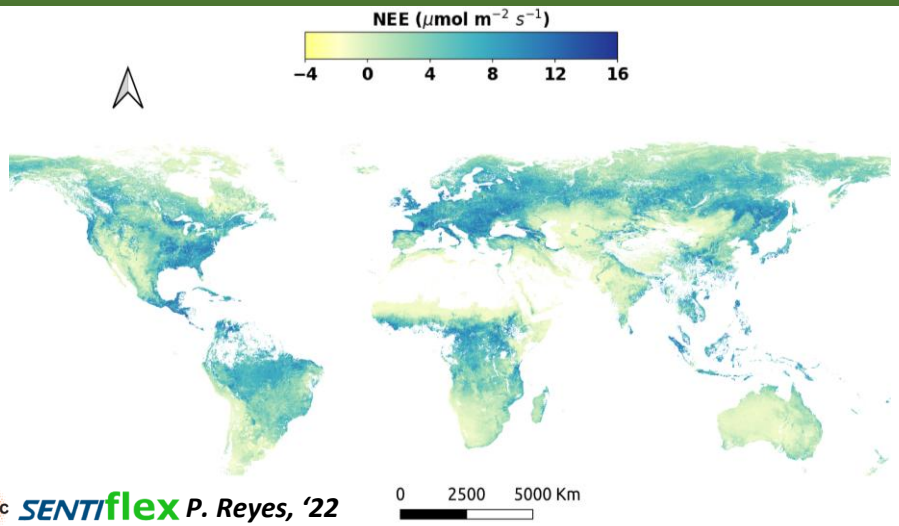
Model including SIF (8 vars) throw most consistent results with lower uncertainties (under 20 %)

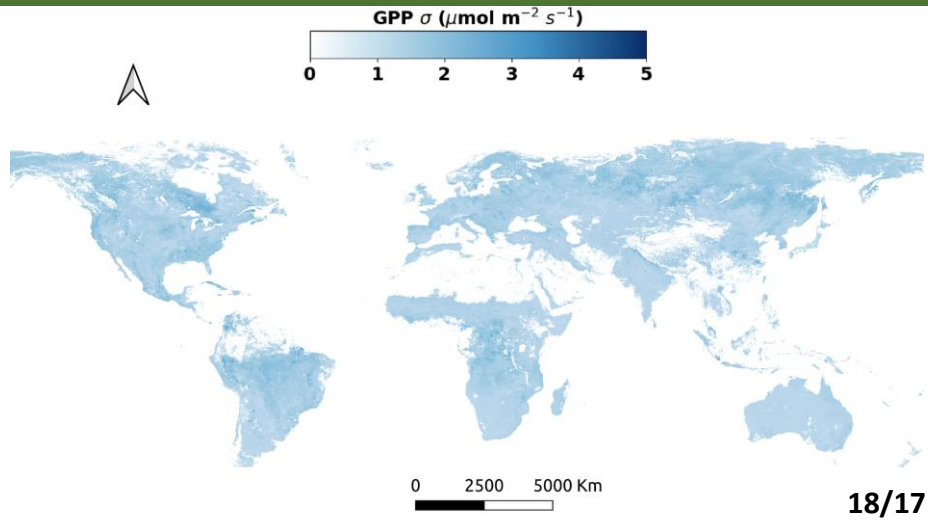
Estimates and uncertainties on 16-06-2019–13:00:00 (**SIF**)	Estimates and uncertainties on 16-06-2019–13:00:00 (**No SIF**)
	



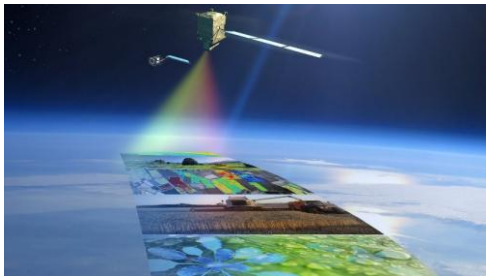


Thanks to inclusion of SIF into data assimilation, terrestrial productivity can be more accurately assessed. With upcoming FLEX, global carbon dynamics can be inferred at higher accuracy and spatial resolution (300 m).

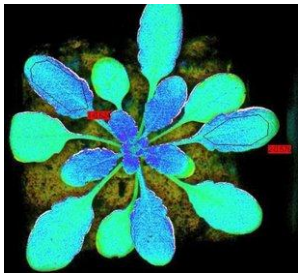




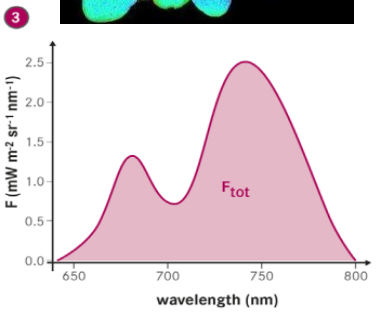
Conclusions



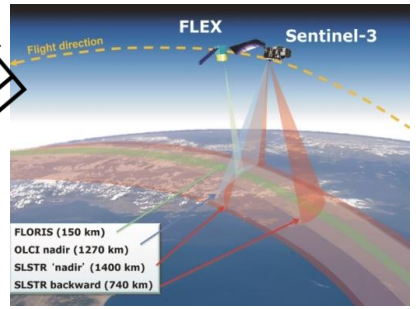
- ESA's Fluorescence Explorer (FLEX) to be launched by 2025



- FLEX will be the first global mission delivering the full 650-800 nm SIF spectra at 300 m resolution



- FLEX will orbit in tandem with Sentinel-3 for key auxiliary information (optical, thermal)



- FLEX is a photosynthesis mission, with applications in: (1) global vegetation dynamics, (2) early stress warning, and (3) improved estimation of carbon balance