Multi-wavelength radio observations as proxies for upper atmosphere modeling

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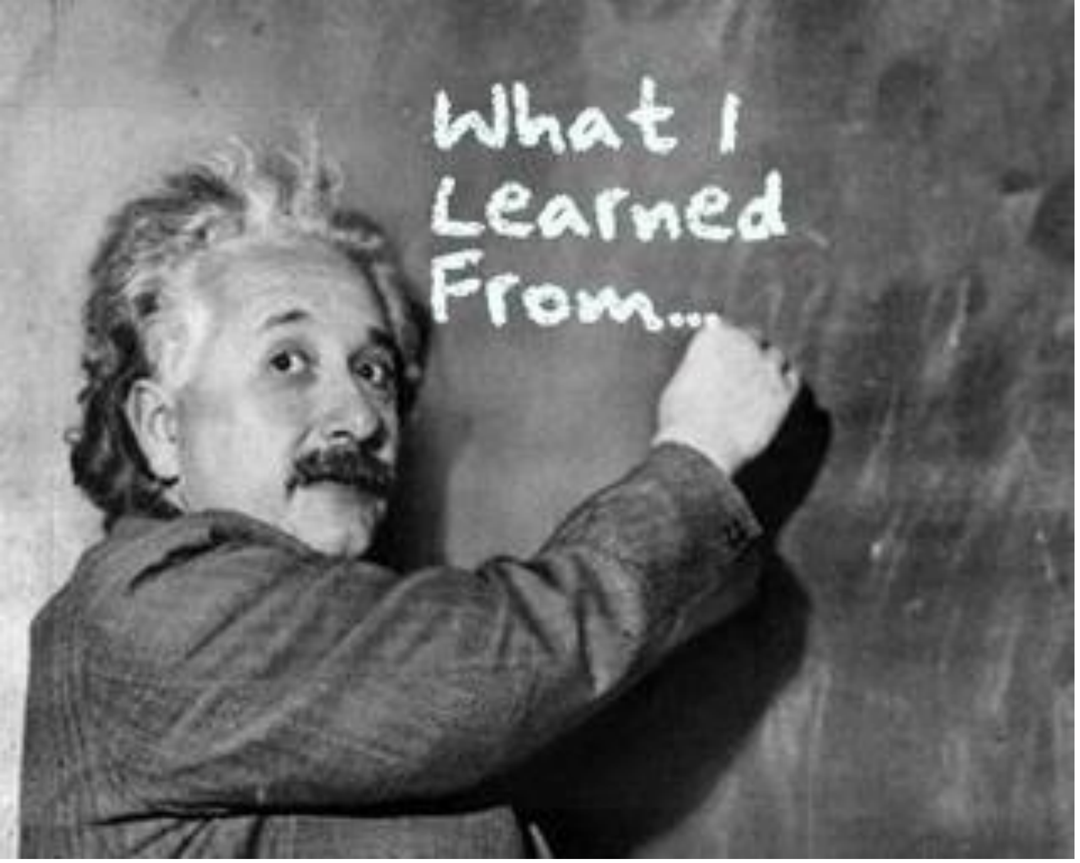
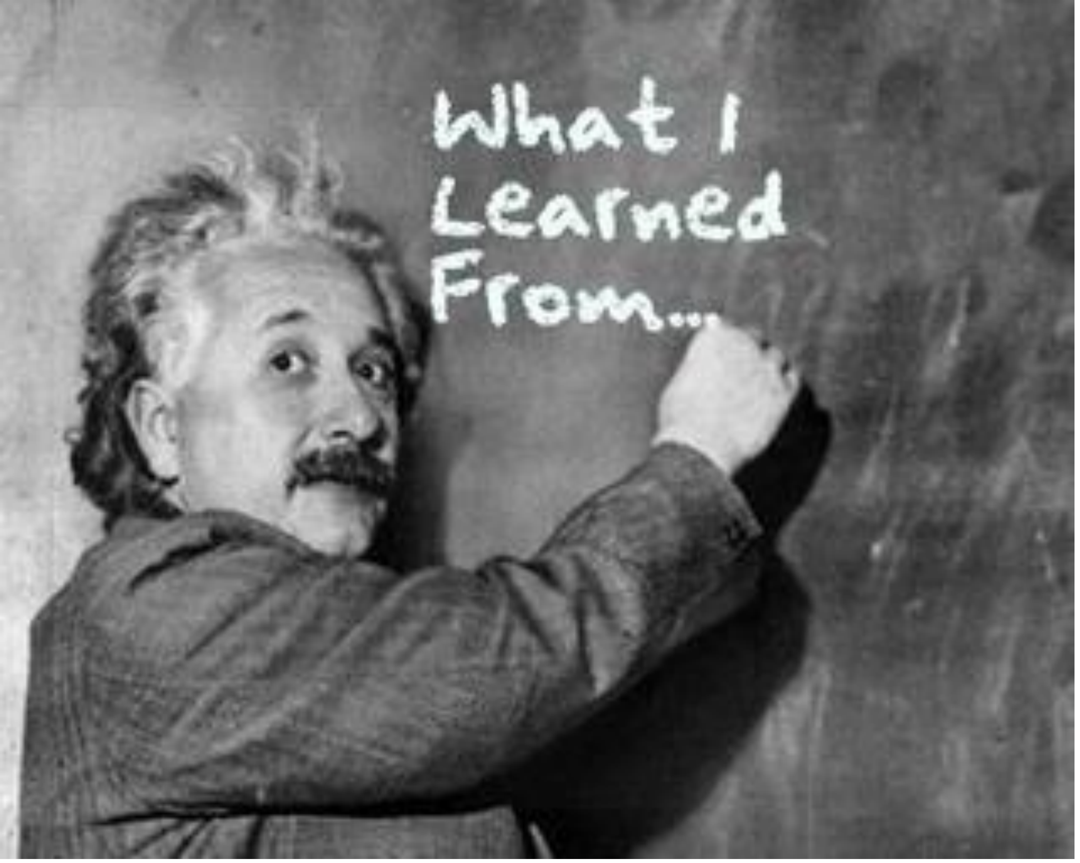
With special thanks to the instrument teams: Penticton, Nobeyama, SORCE, TIMED, Greenwich Observatory, …

f10.7

...on the shoulders of giants



Take home message 1

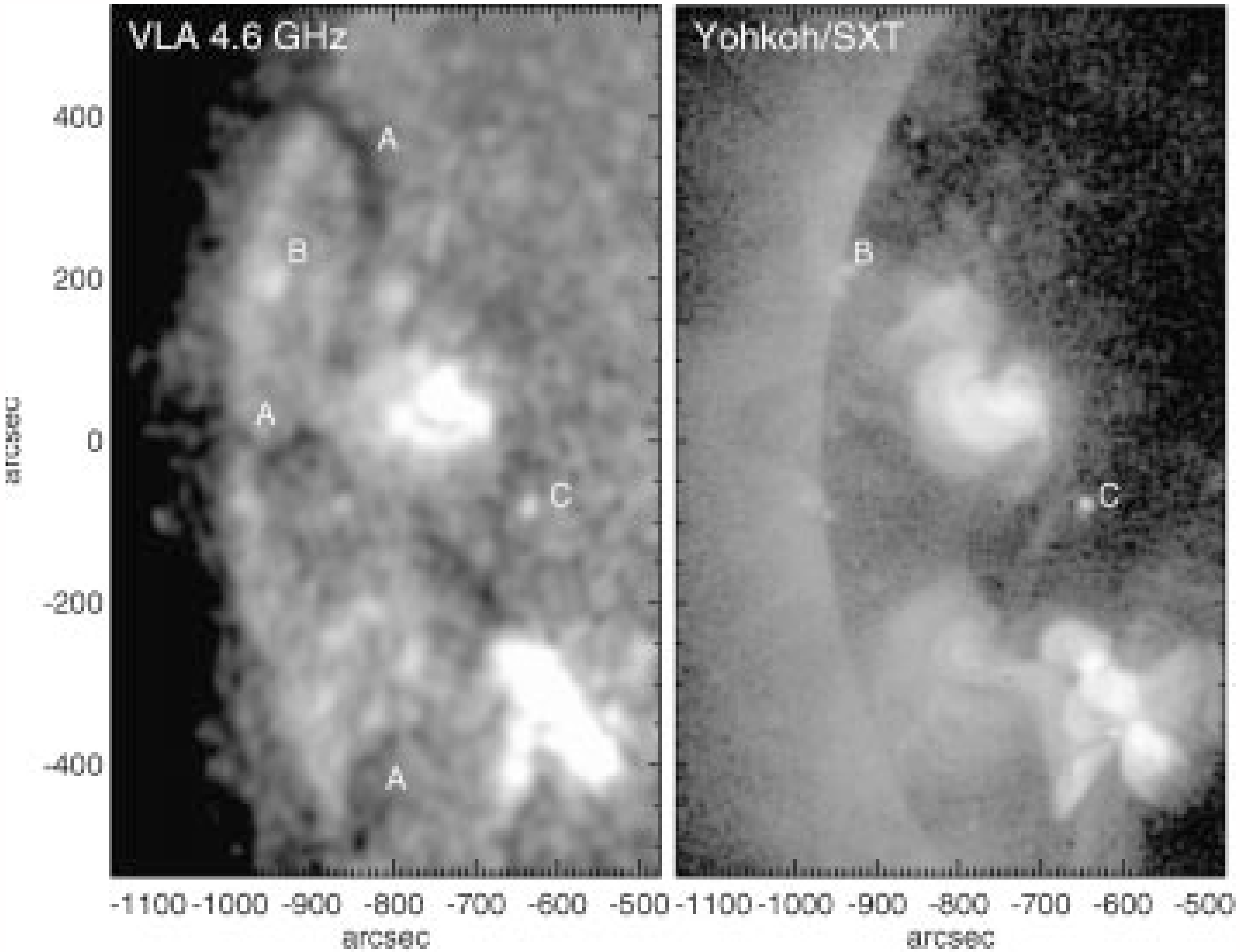


Take home message 1

Do not disrupt these historic observations
Look at what former generations have done...

Radio vs UV observations

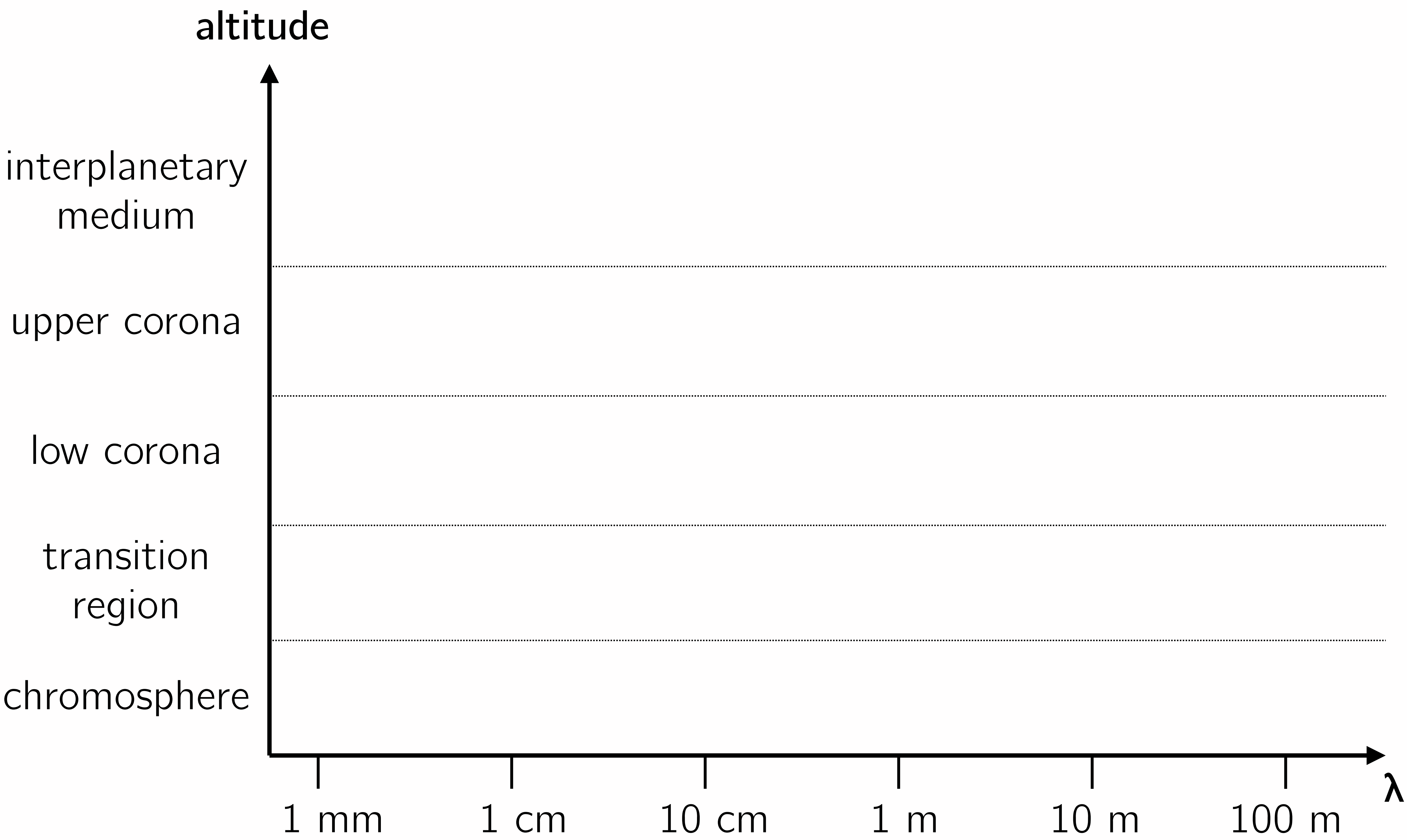
- There is an intimate connection between solar irradiance in the UV and in centimetric radio emissions...



6 cm (VLA) **soft X-ray (Yohkoh)**

S. White (1999)

The radio spectrum in a nutshell



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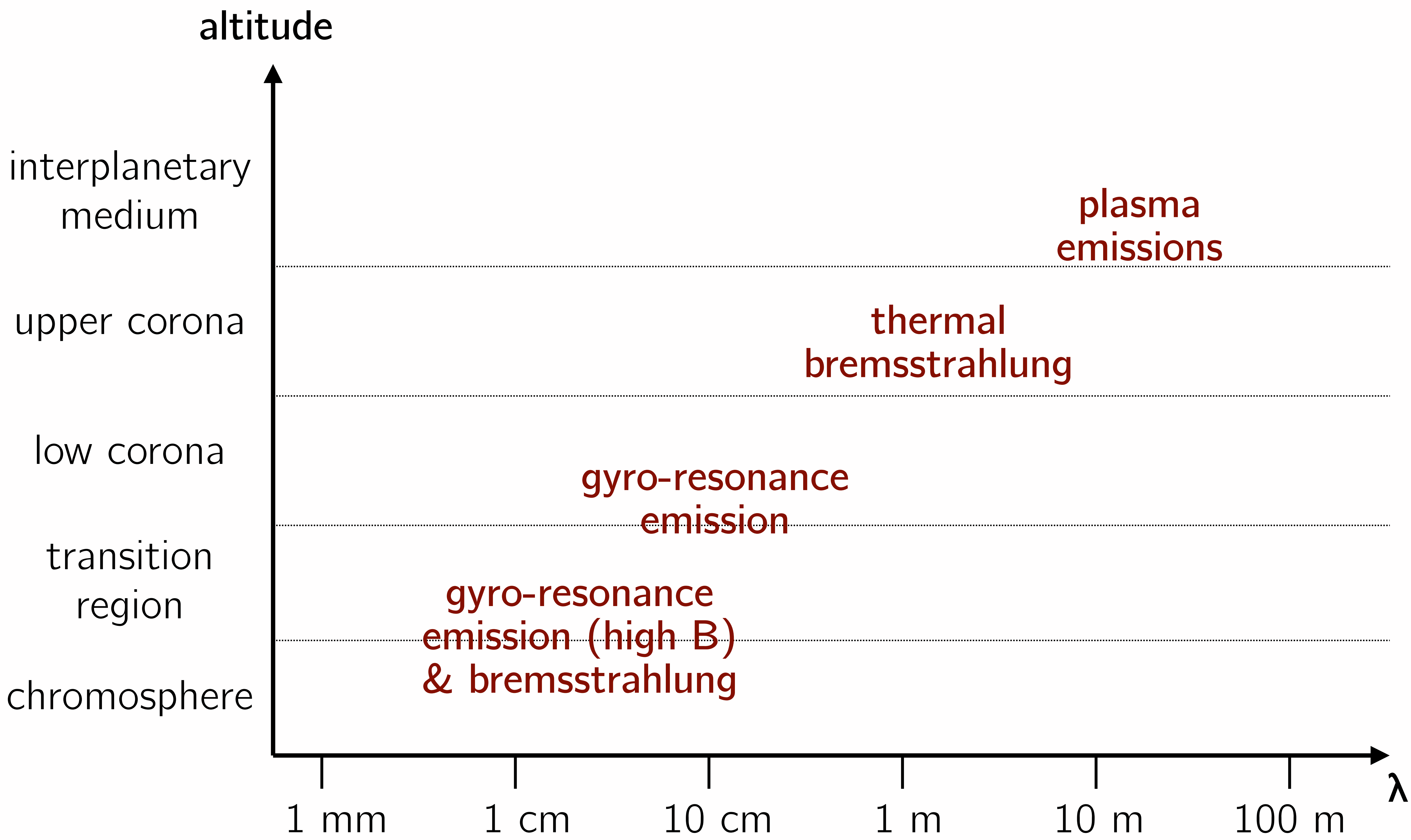

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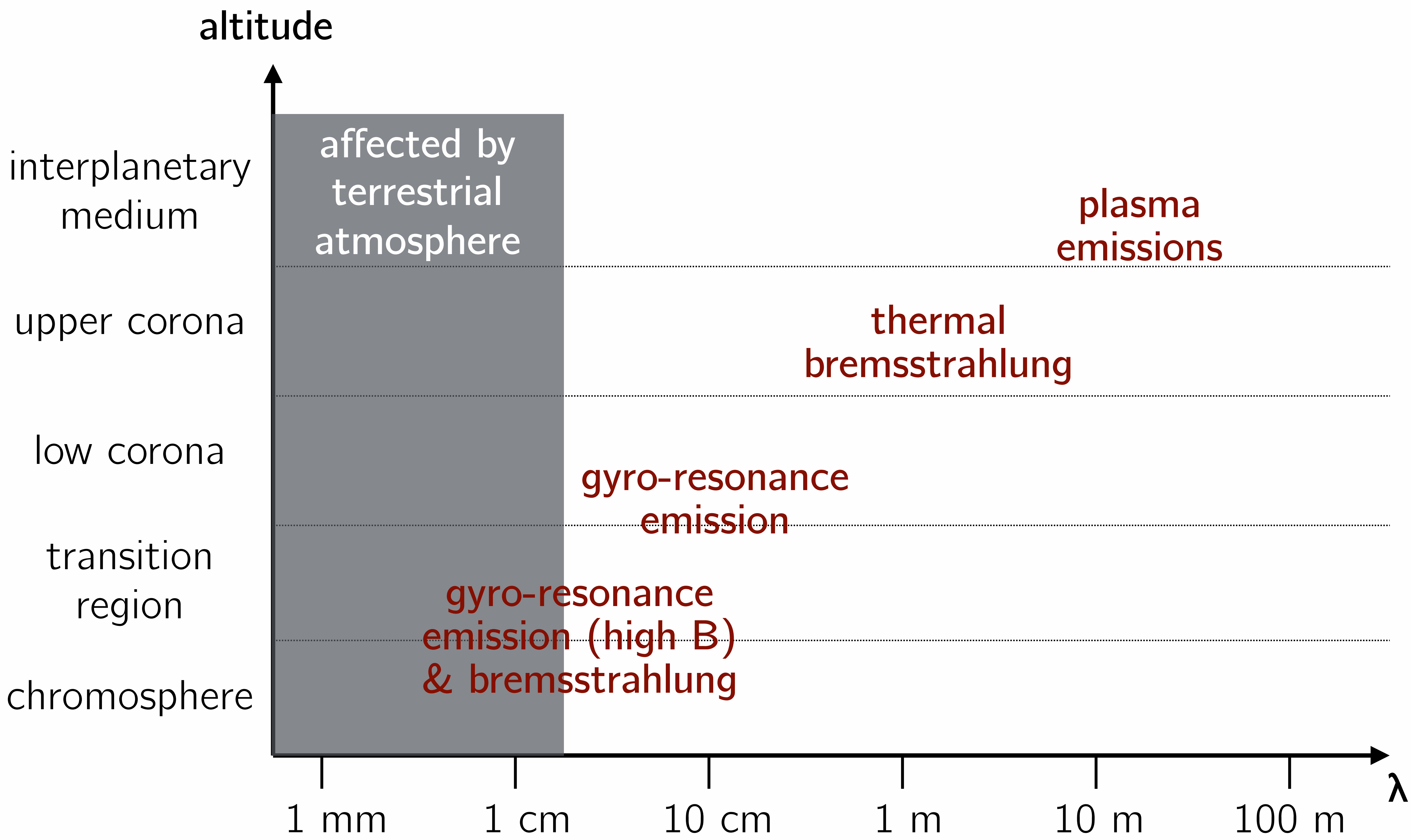

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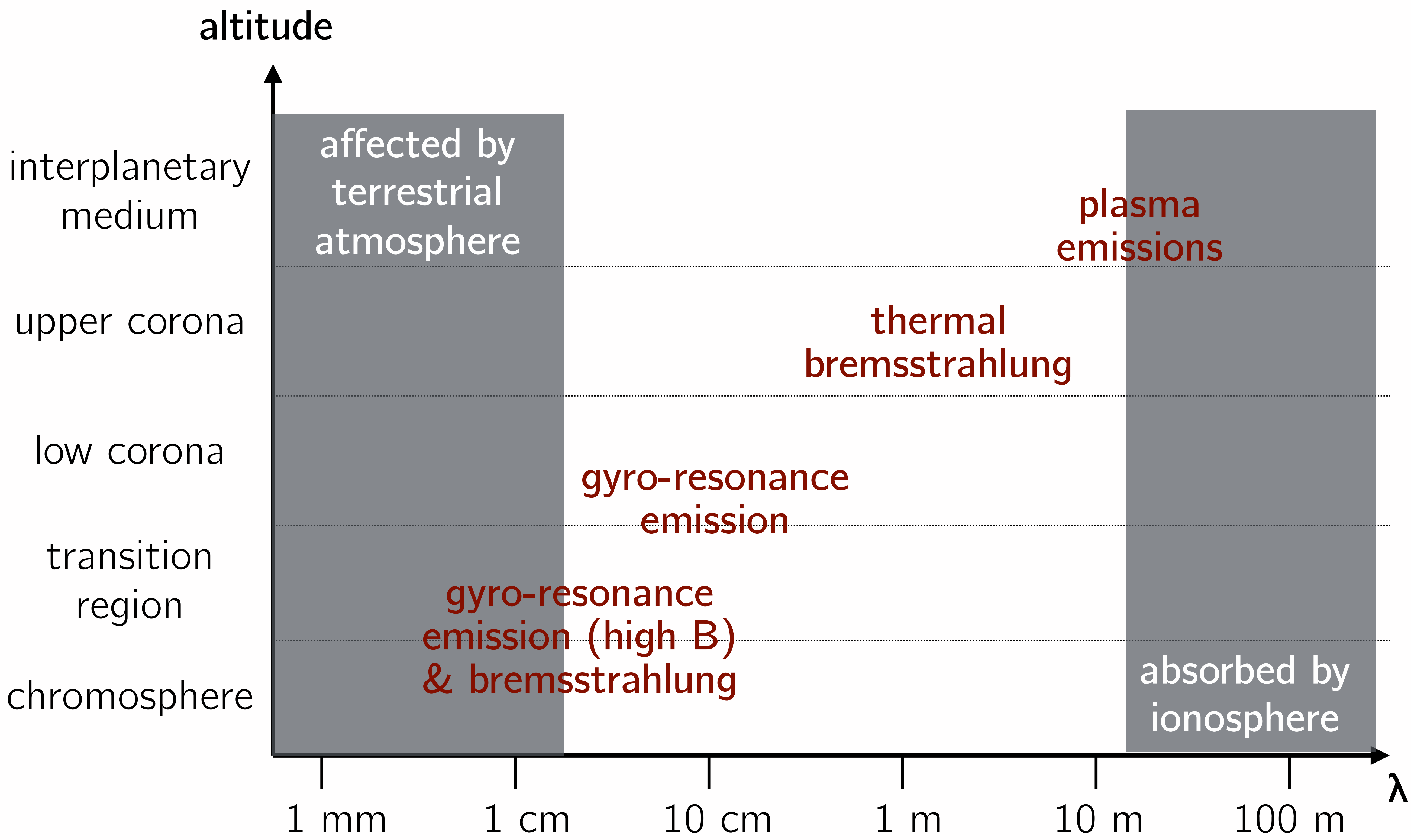

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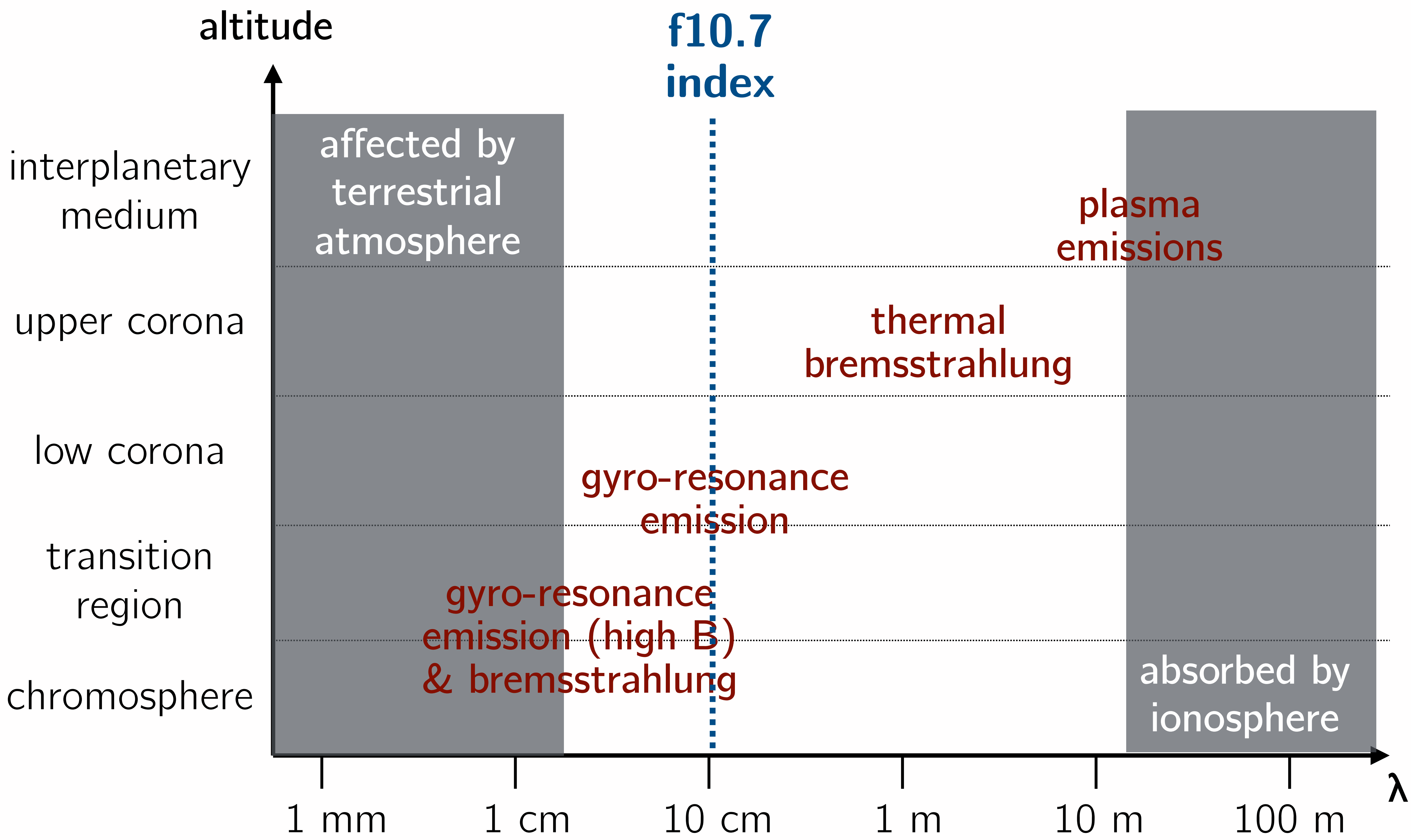

Physical picture

- Simplified picture
  - gyroresonance ≈ essentially sunspots
  - bremsstrahlung ≈ quiet Sun + plages, faculae, ...
- The relative contribution of gyroresonance/ bremsstrahlung is wavelength-dependent

Physical picture

- Simplified picture
  - gyroresonance $\approx$ essentially sunspots
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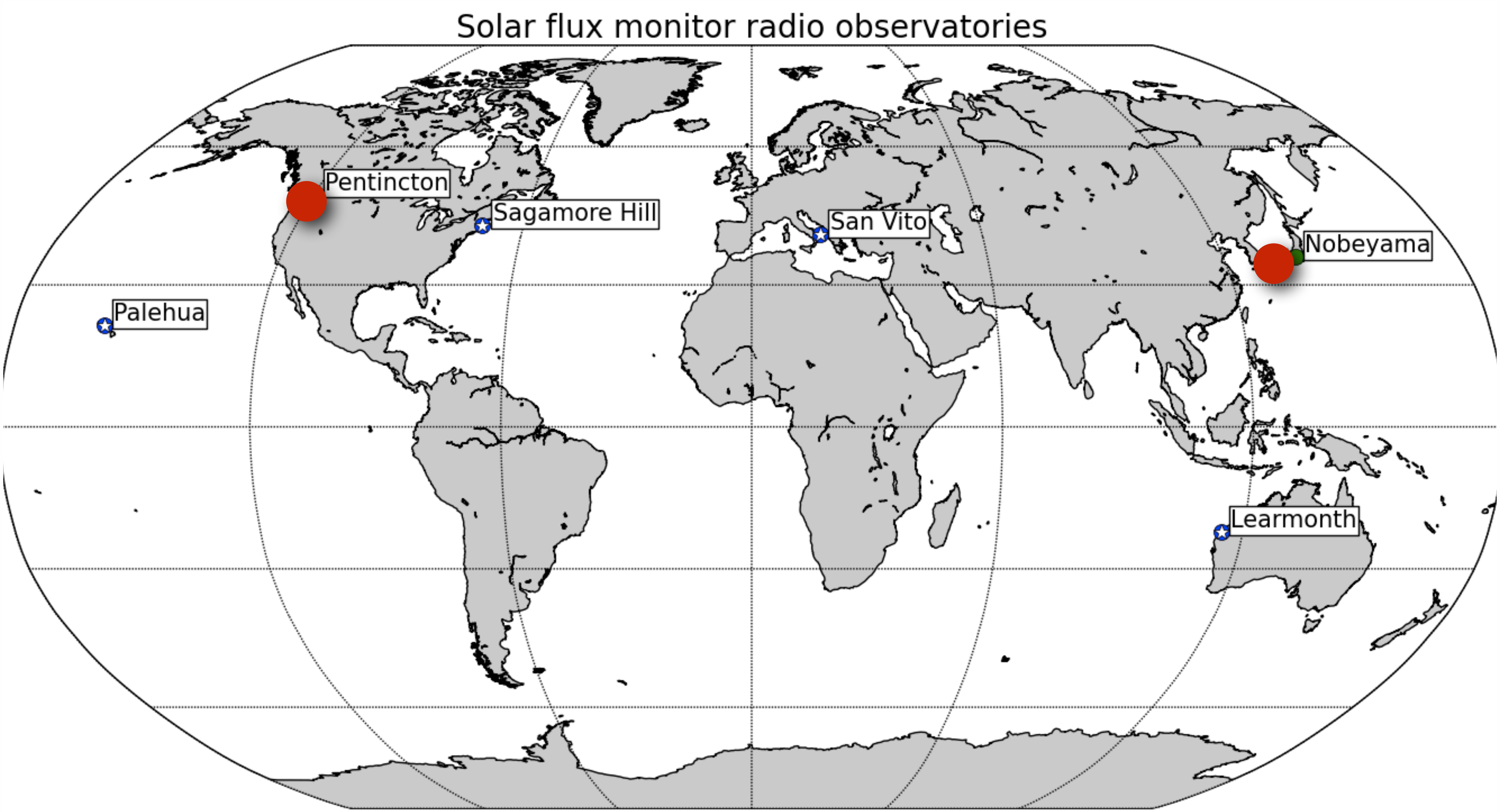
Could synoptic radio observations inform us about the filling factors of different solar features? ...and help reconstruct/constrain the SSI?

This picture may be too simple

- Beware: the radio spectral variability is far more complex
  - low altitude emissions may be absorbed higher up in the corona
  - optically thick vs optically thin emissions
  - non-thermal emissions (e.g. flares) are even more complex

What measurements are there ?



from C. Marqué (2013)

Synoptic observations

- Observations from Ottawa/Penticton and Toyokawa/Nobeyama are exceptionally good
  - daily calibration, same instruments = excellent **stability**
  - daily values without flares (mostly) = excellent **continuity**

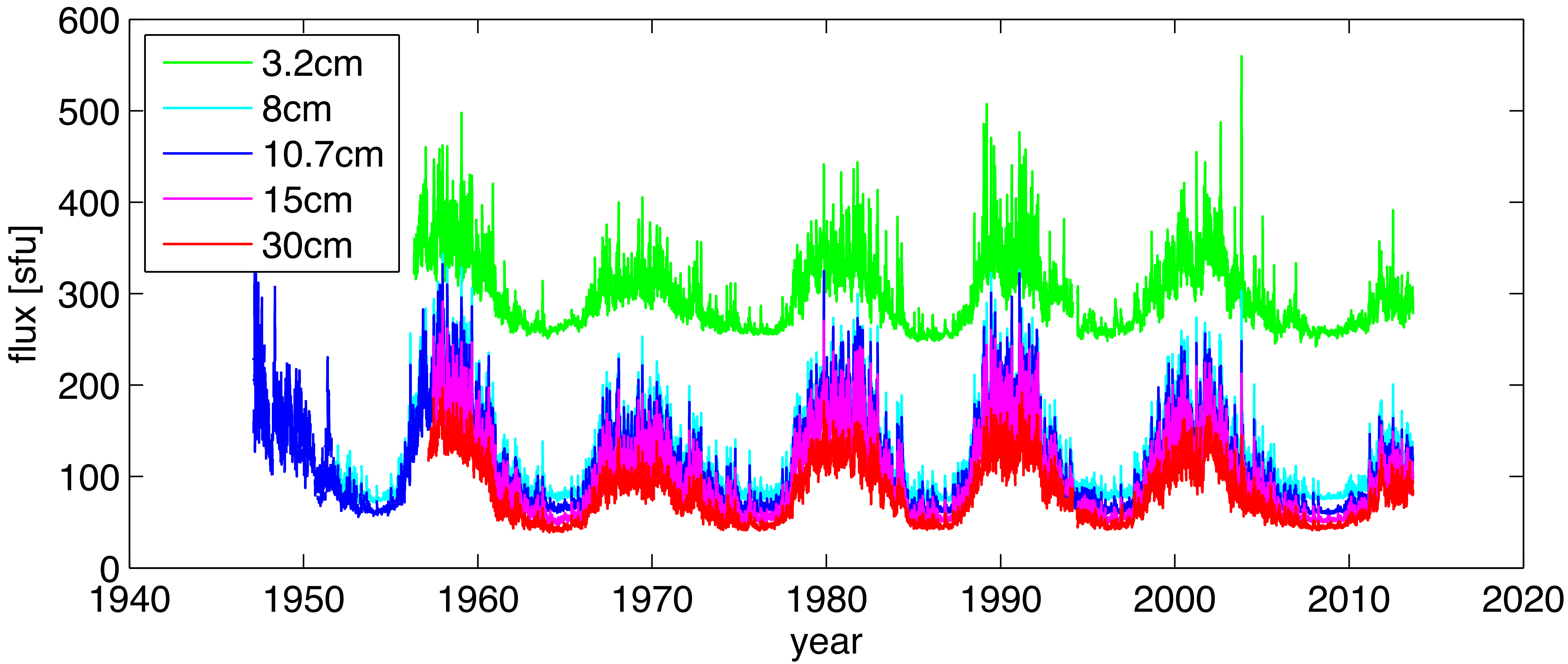
wavelength [cm]	frequency [GHz]	origin of observations	beginning of measurements	number of gaps since beginning
3.2	9.4	Toyokawa/Nobeyama	May 1, 1956	195
8.0	3.75	Toyokawa/Nobeyama	Nov. 6, 1951	203
10.7	2.8	Ottawa/Penticton	Feb. 14, 1947	311
15.0	2.0	Toyokawa/Nobeyama	June 1, 1957	231
30.0	1.0	Toyokawa/Nobeyama	March 1, 1957	163

A new dataset

- We now have a **homogeneous dataset** with
  - **daily values** from 6 November 1957 till today
  - **5 wavelengths**: 3.2, 8, 10.7, 15 and 30 cm
  - all values regridded to noon UT
  - without flares, data gaps filled in by expectation-maximization
  - one month latency (can be reduced to < 24 hrs)

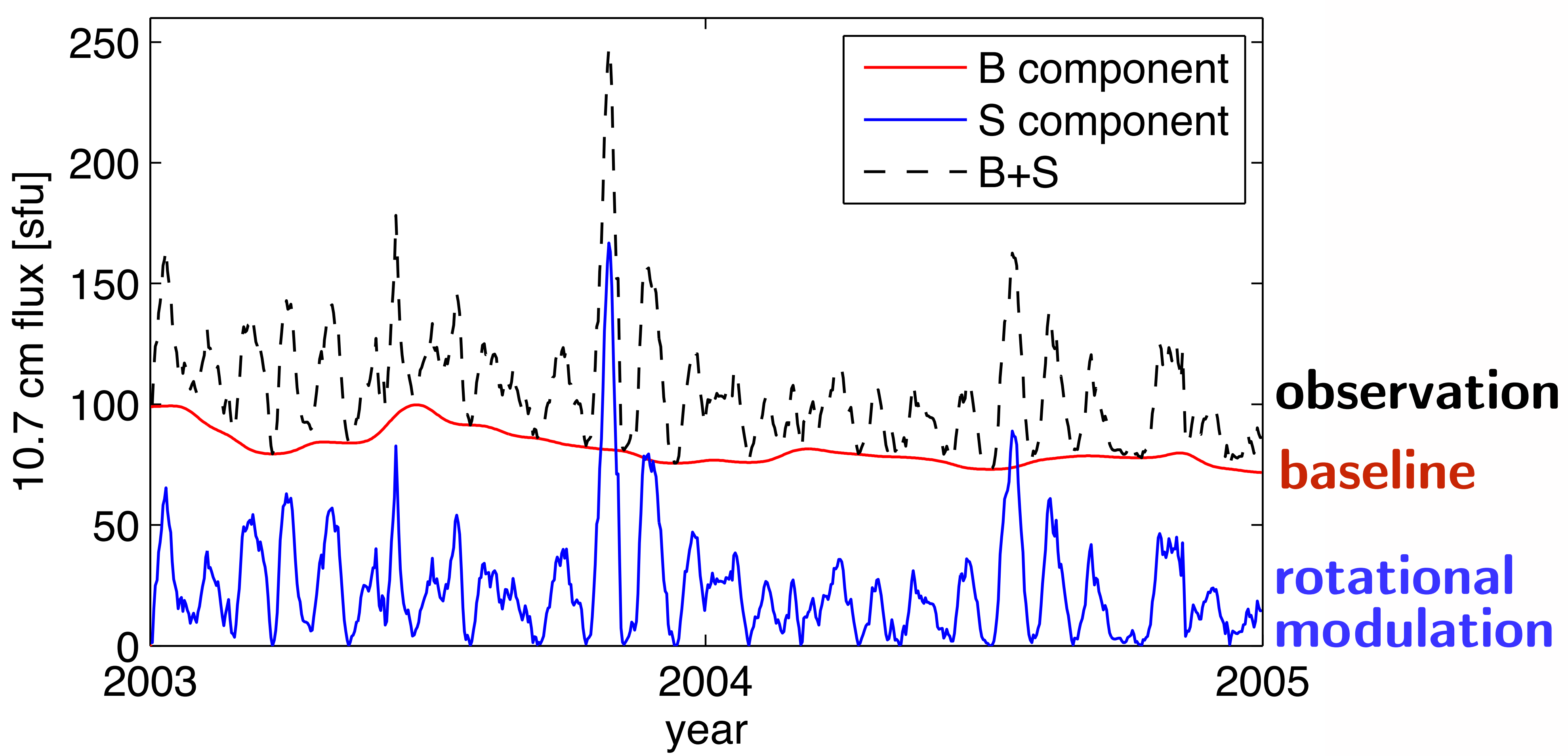
- Download from http://projects.pmodwrc.ch/solid/

The observations



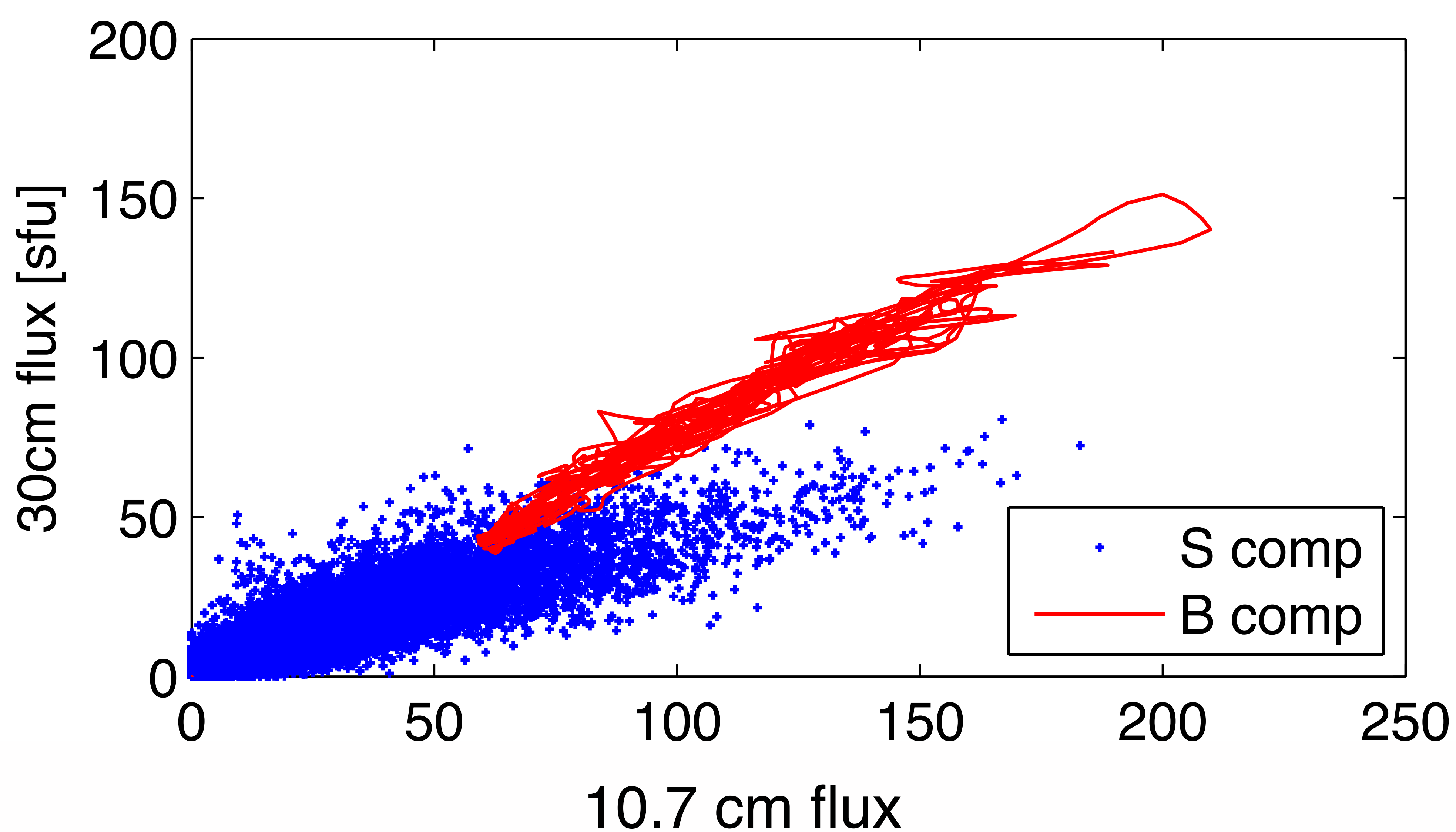
Analysis procedure

- Decompose the radio fluxes into [Kundu, 1965]
  - a baseline component (B)
  - a rotationally modulated component (S, or SVC)



Two components

- Different wavelengths show different slopes
  = driven by different physical processes



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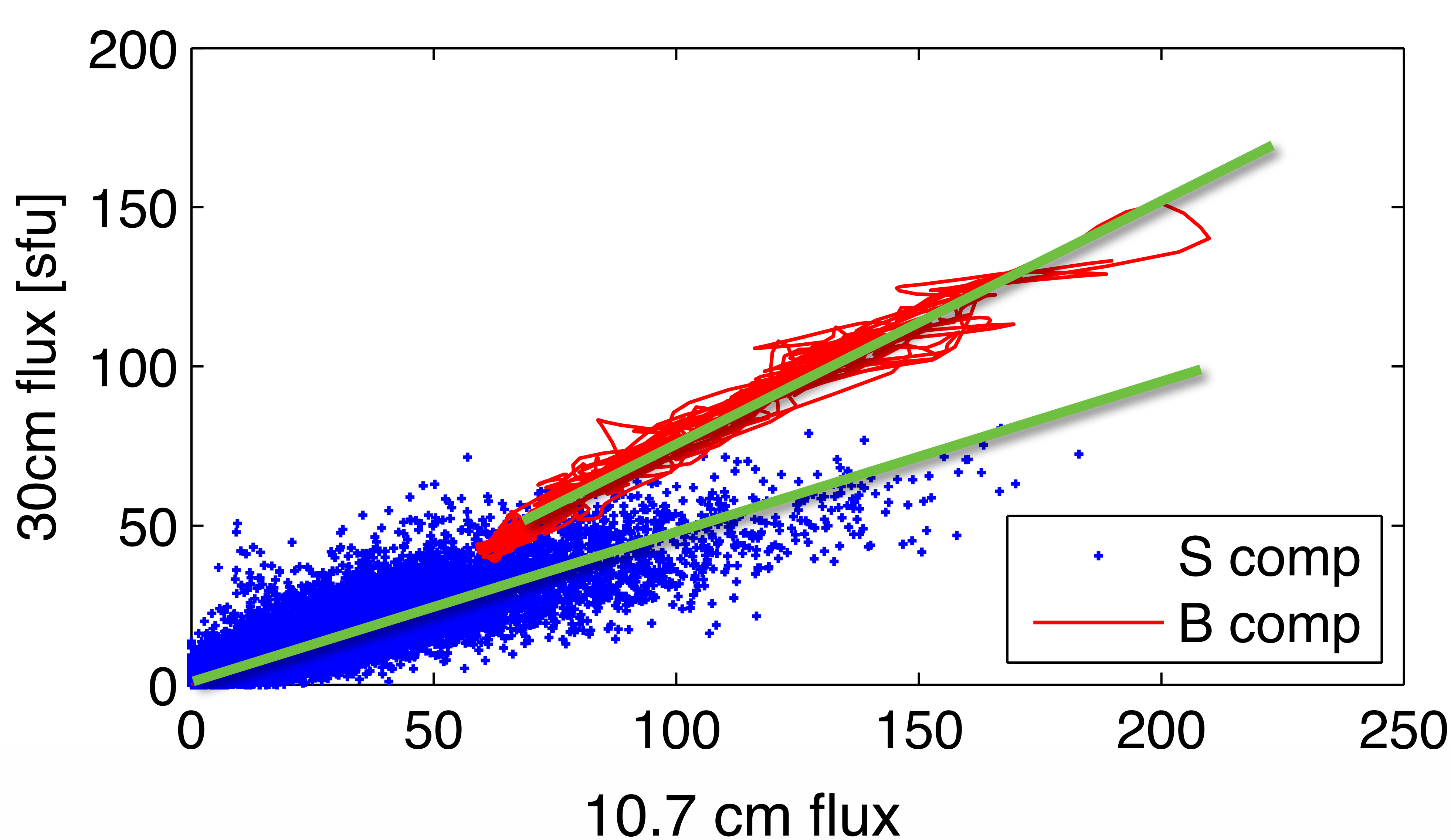
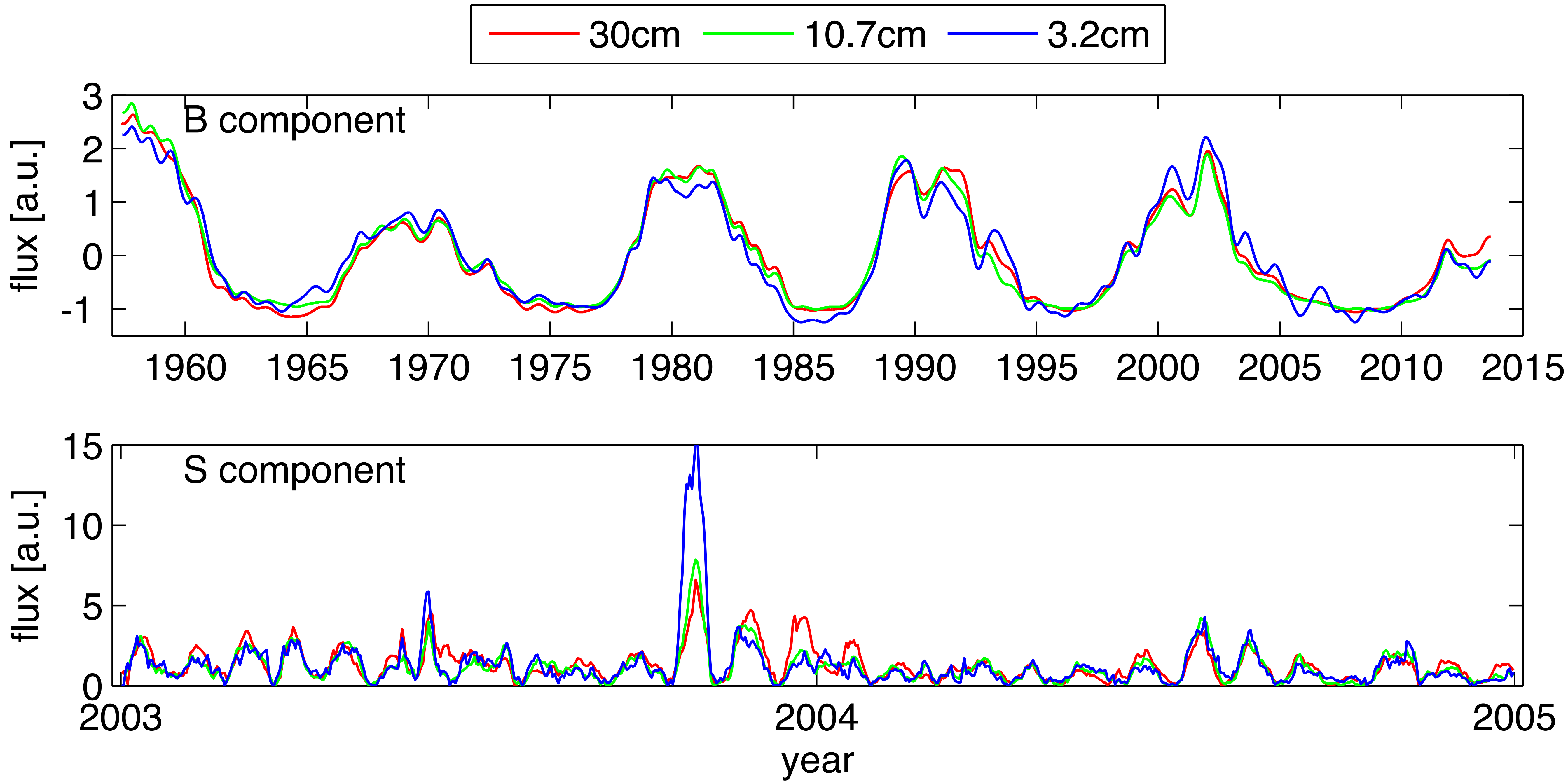


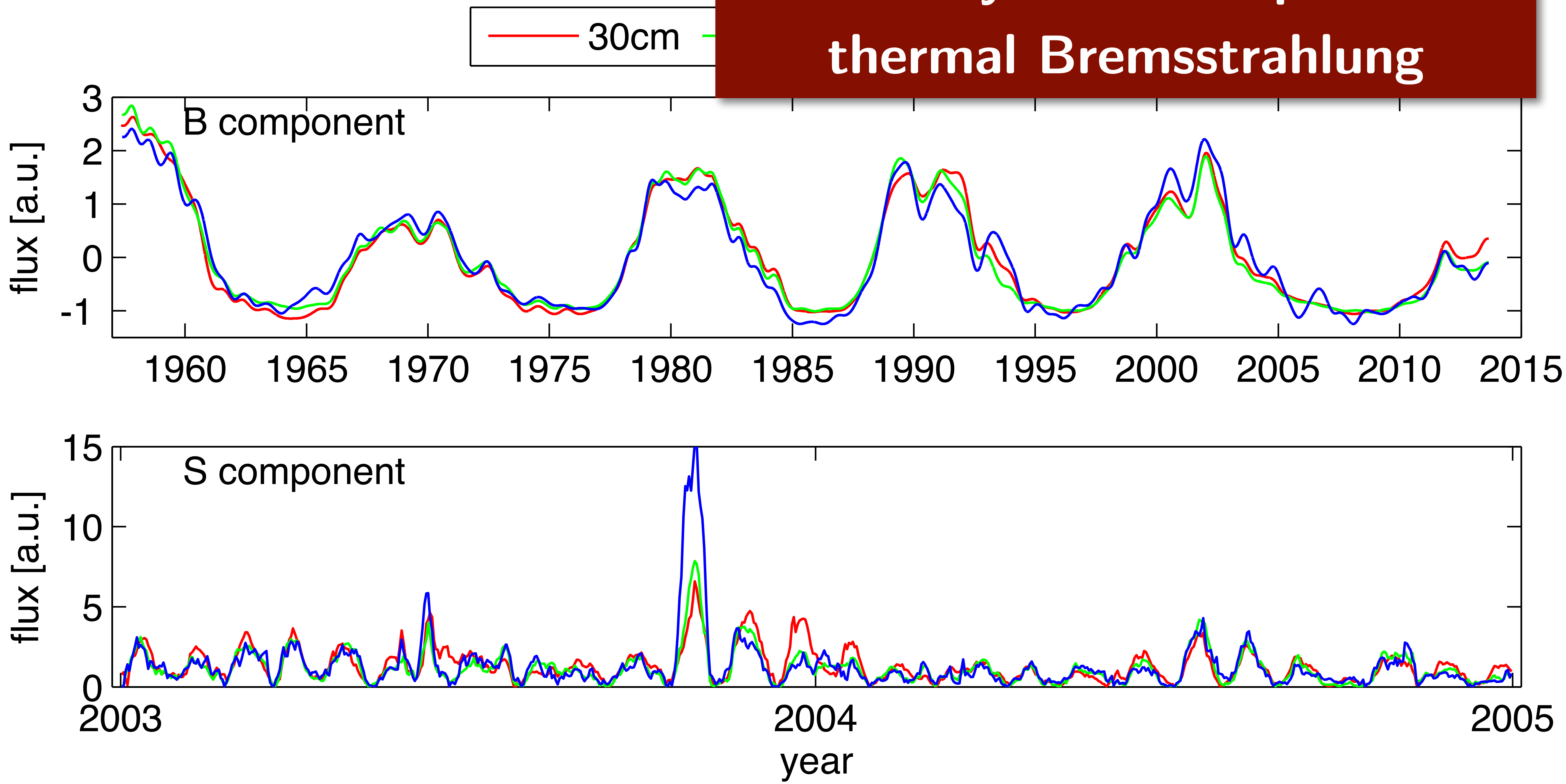
Synoptic observations



All quantities have been rescaled

Synoptic observations

Long-term variability is mostly driven by the same process: thermal Bremsstrahlung



All quantities have been rescaled

Intermediate conclusion

- Very similar variations at all wavelengths
  → a few contributions may explain most of the variability

- Linear combinations of different wavelengths may be used to reconstruct the SSI
  e.g. [Schmahl & Kundu, 1995].

Part I

Can we isolate the different physical contributions to these synoptic radio fluxes?

Blind source separation

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  - linear mixing
  - the sources are mostly independent in time
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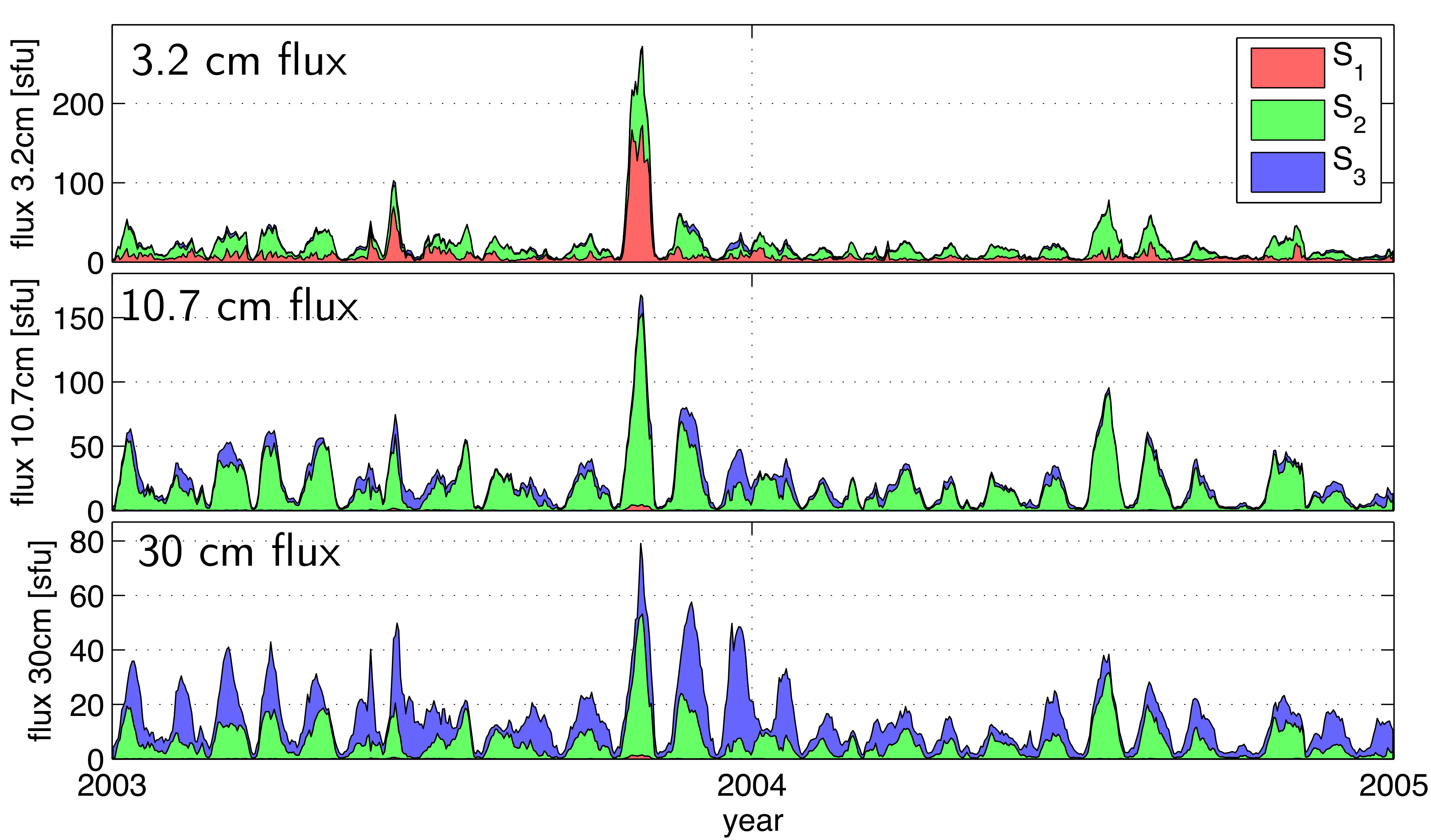
- **Objective** : extract the original constituents ("sources") that appear mixed in the radio fluxes
- **Assumptions**
  - linear mixing
  - the sources are mostly independent in time
  - positivity: the sources and their concentrations must be ≥ 0
- **Solution**: use blind source separation
  - used recently in acoustics, chemometry, cosmology, ...
  - consider Bayesian Positive Source Separation [Moussaoui et al., 2003]

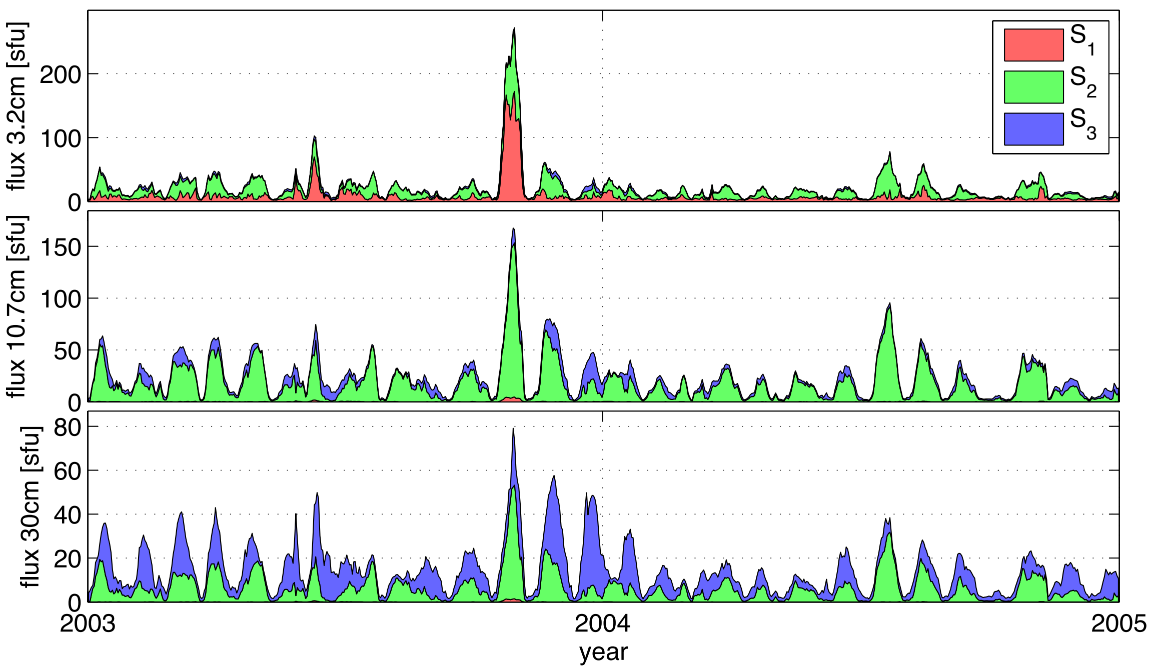
How many sources are there ?

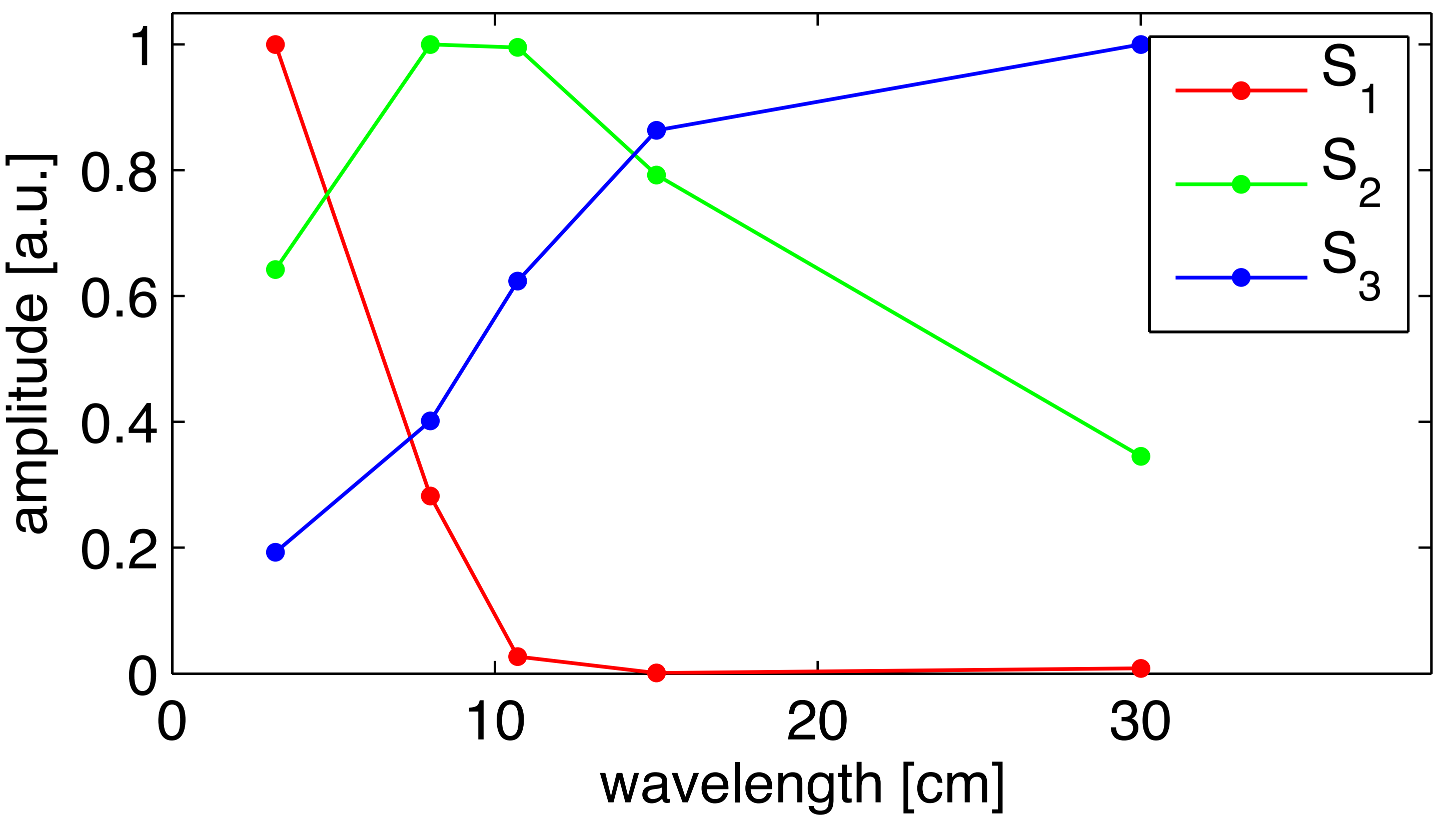
- With 5 wavelengths we can identify at most 5 sources
- Various criteria all show that we have 3 sources

What do the sources look like ?



Spectral profile





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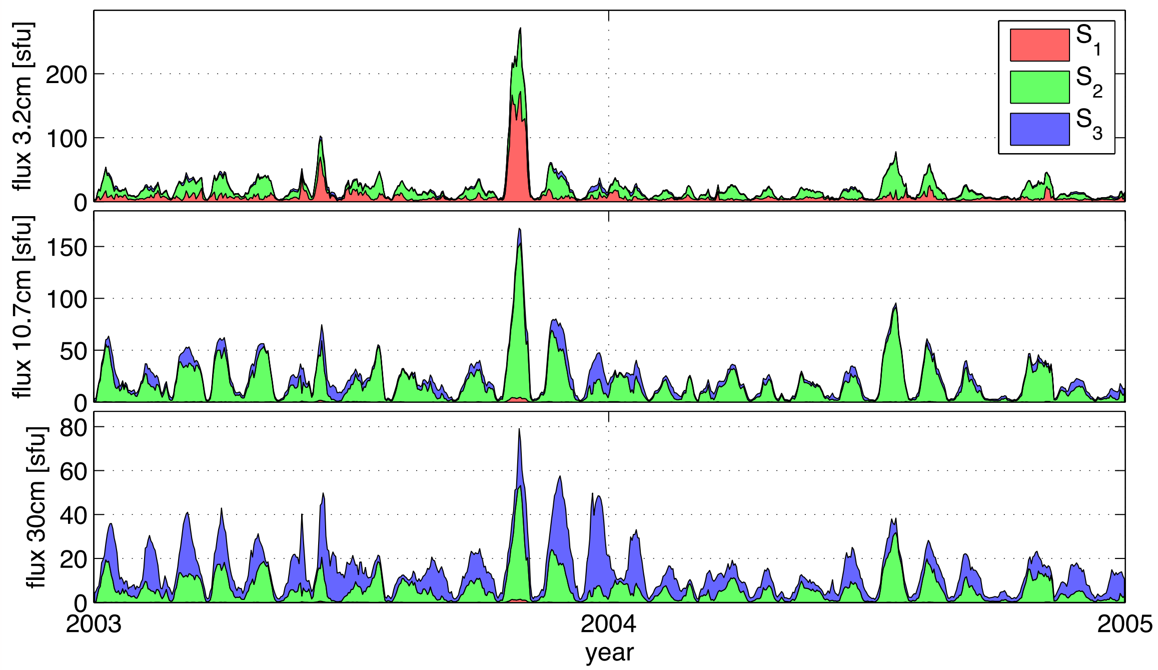
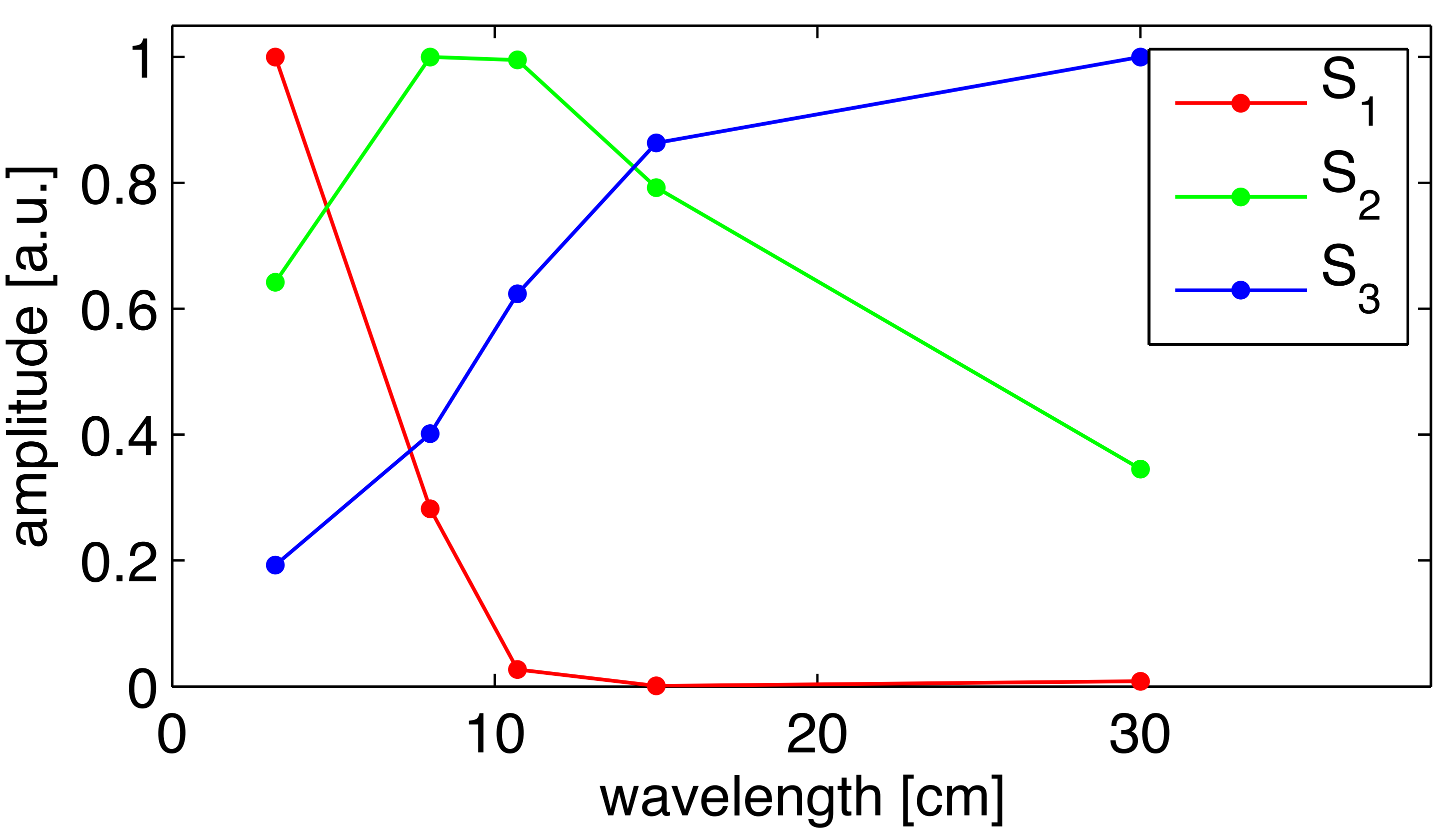


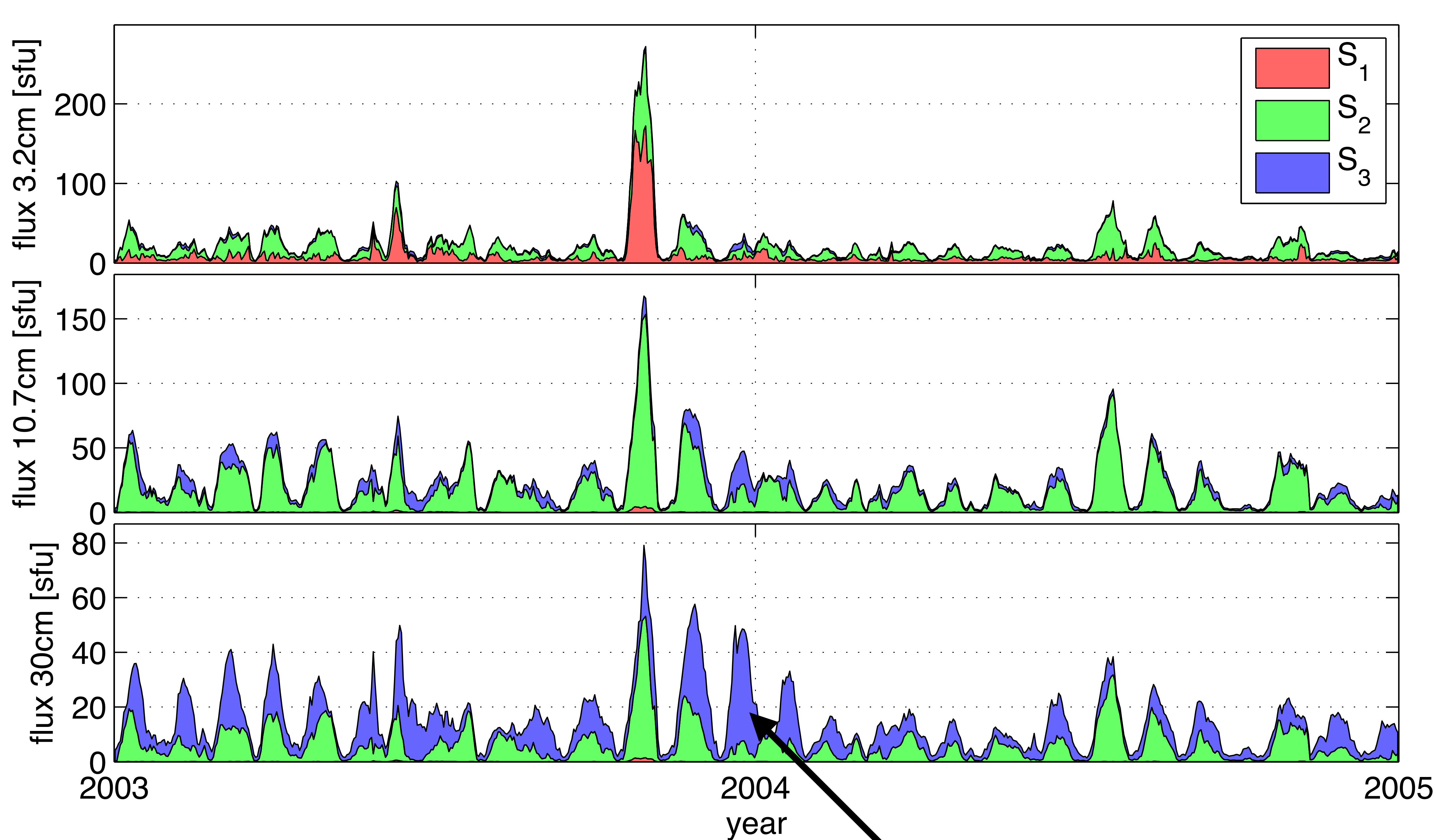


Source 1: only during active Sun
= gyroresonance emissions from active regions with high B

Source 2: only with sunspots
= gyroresonance emissions

Source 3: only with plages/faculae
= Bremsstrahlung emissions

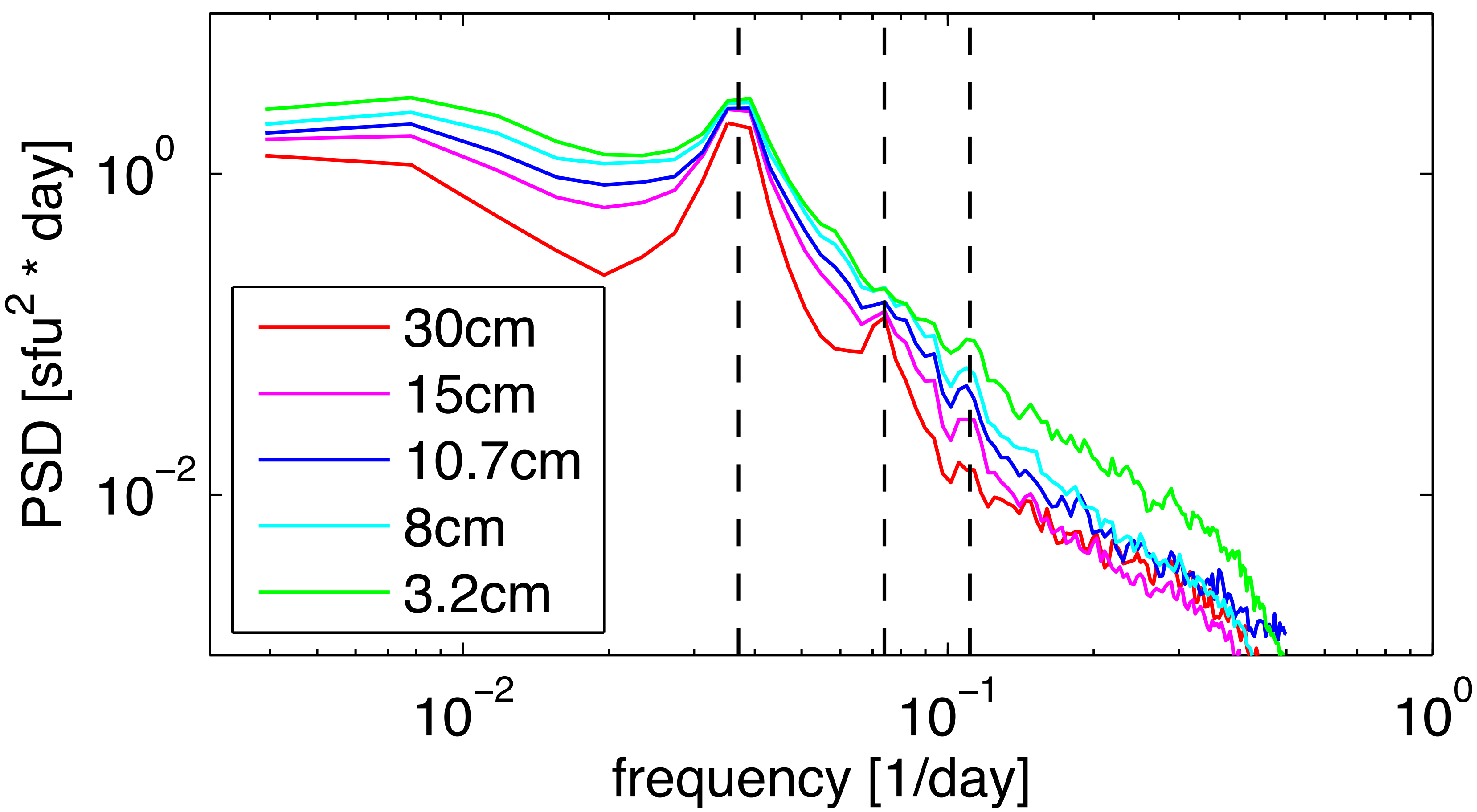
Spectral profile



Source 3 = Bremsstrahlung proxy

Power spectral density

- Power spectral density (periodogram)



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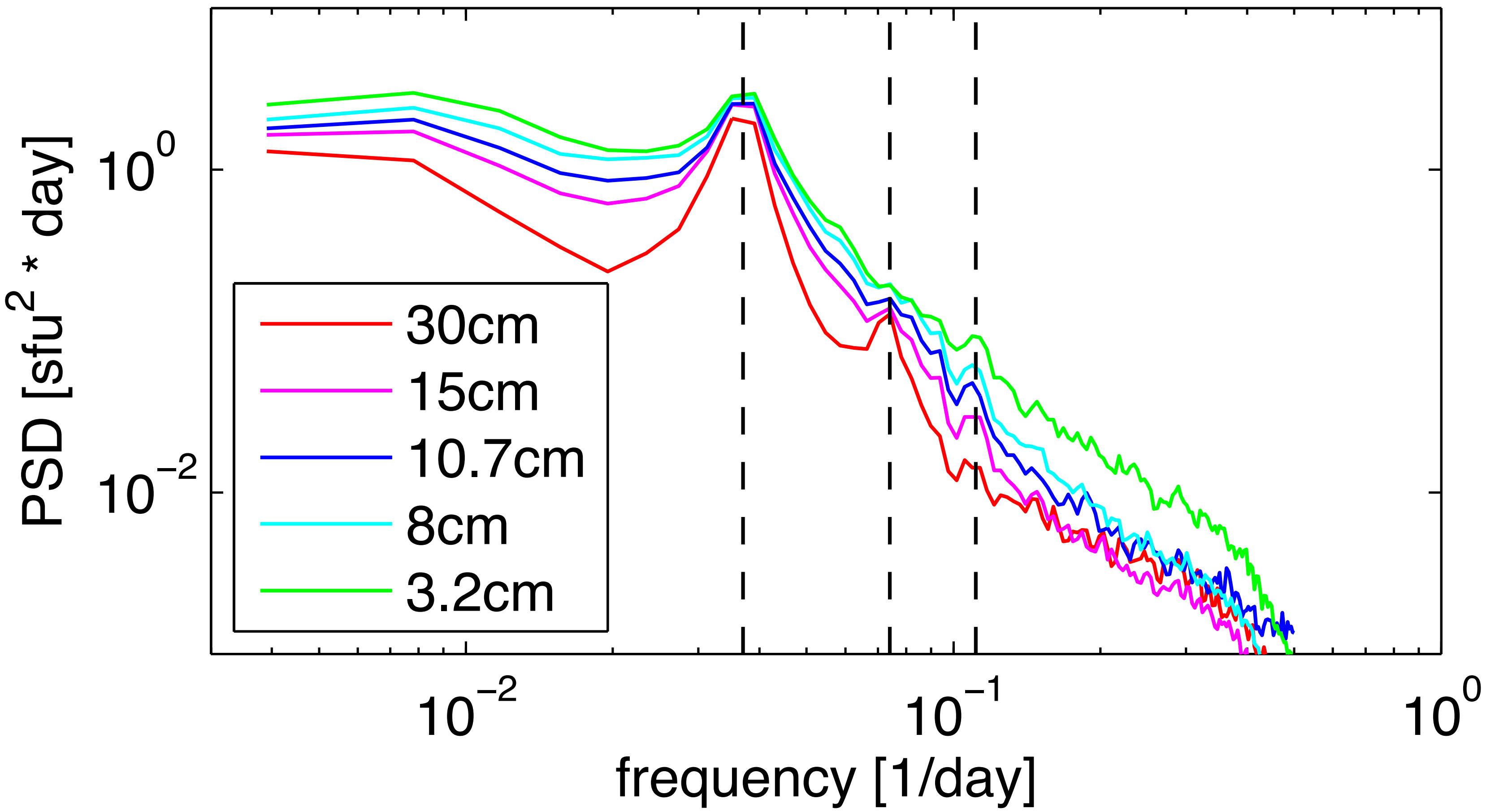
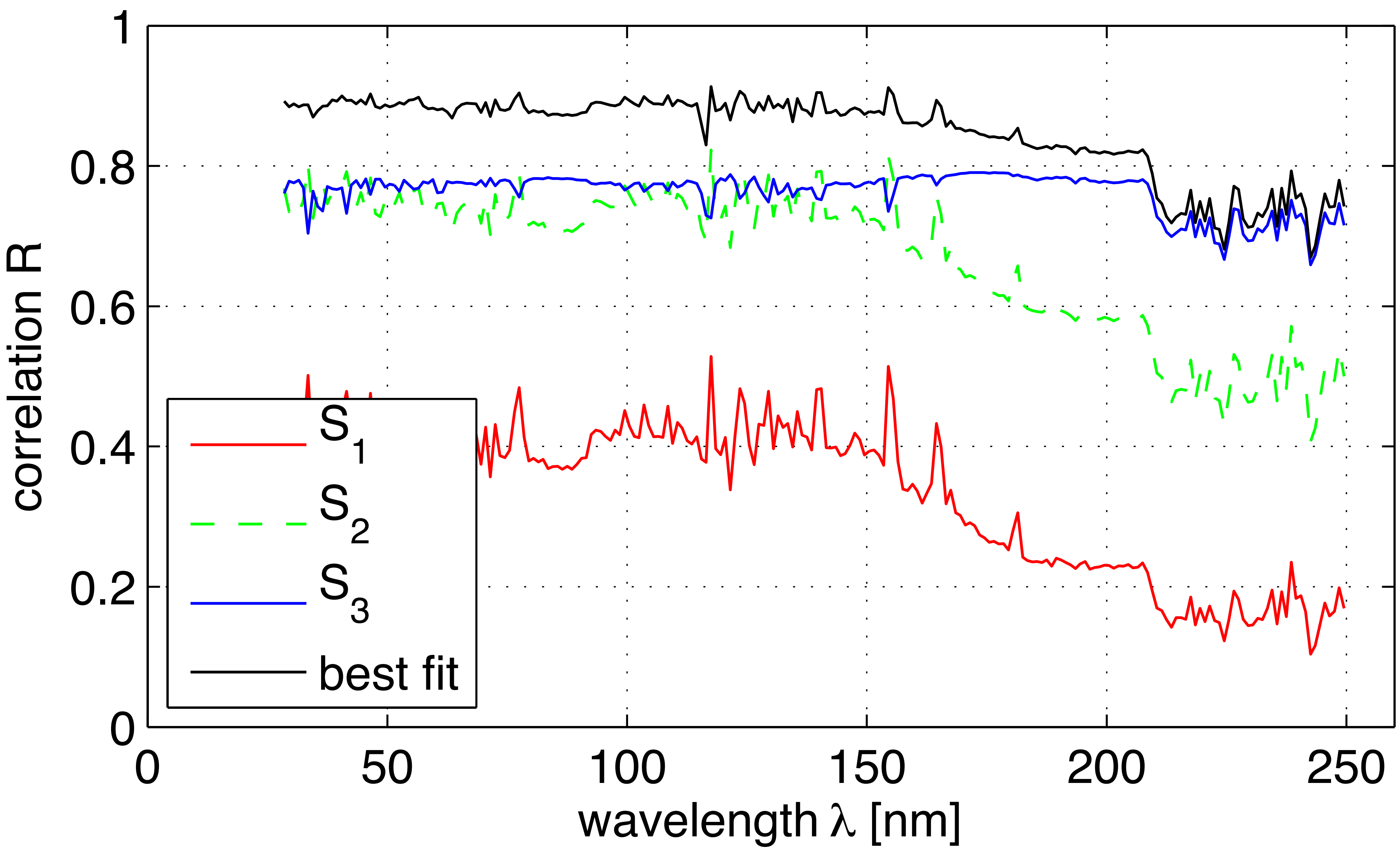


Stronger harmonics at 30cm are not due to center-to-limb effects but to longer lifetime of emitting solar structures [Donnelly et al., 1982]

A Bremsstrahlung proxy ?

- How do our sources correlate with the SSI ?

  Data from TIMED & SORCE, 2003-2010



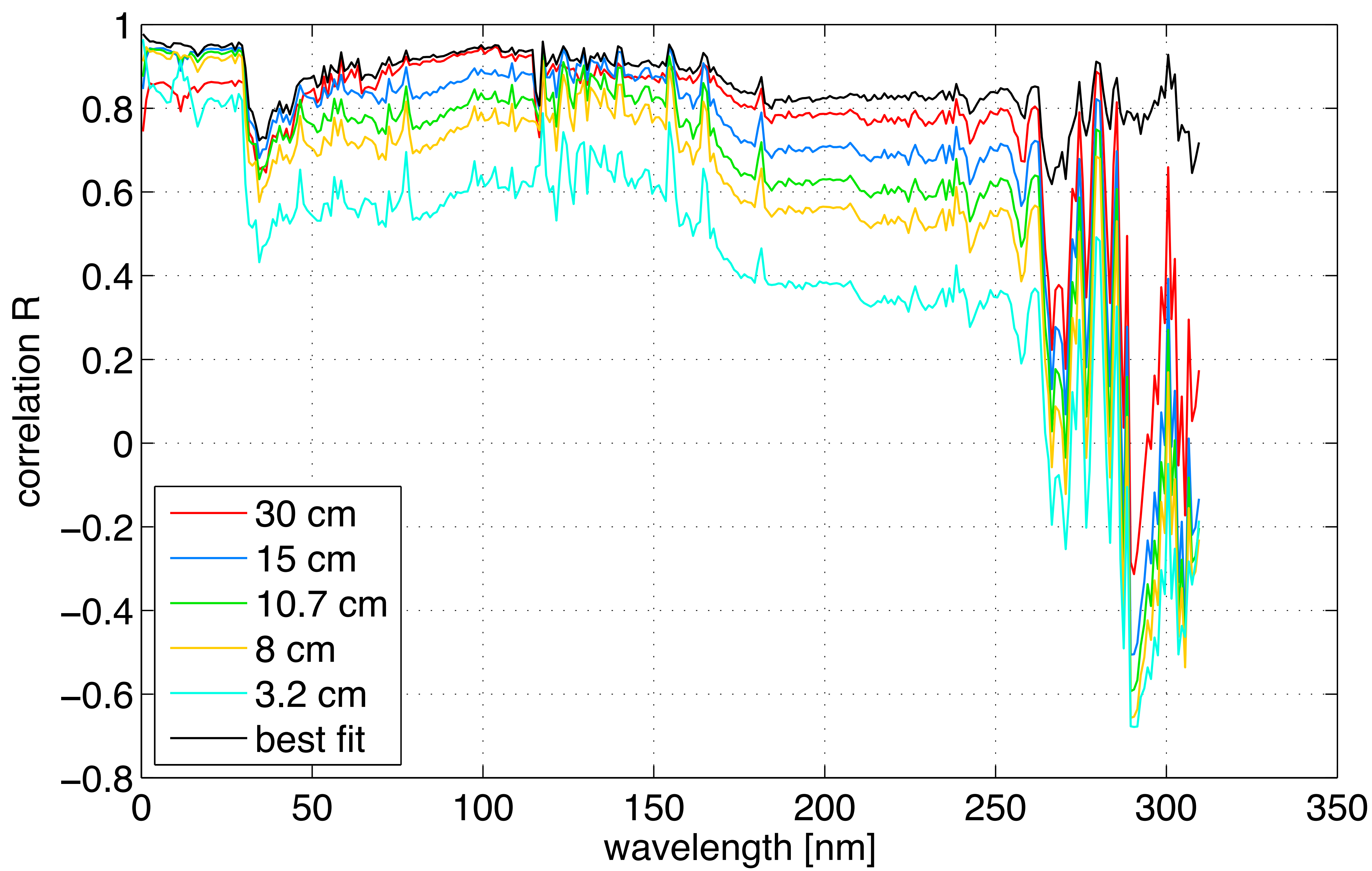
Source 3: Bremsstrahlung

Source 2: gyroresonance

Source 1: gyroresonance (active Sun)

A Bremsstrahlung proxy ?

- How do different wavelengths correlate with the SSI ?
  Data from TIMED & SORCE, 2003-2010



Intermediate conclusions

- We have a **new Bremsstrahlung proxy** that is indeed highly correlated with the MUV-NUV bands
- **Use the 30 cm flux** if you want a better correlation with the SSI
  - because it has a higher Bremsstrahlung content
- Gyroresonance emissions account for over 85% (50%) of the rotational variability at 10.7 cm (30 cm)

Intermediate conclusions

Should we consider wavelengths longward of 30 cm ?

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yes, 42 cm

Part II

Reconstruction of the SSI

Reconstruction of the SSI

The SSI can be reconstructed in various ways

- Simple empirical linear regression

$$I(\lambda, t) = \sum_{k=1}^{5} \alpha_k \; \phi(\lambda_k, t)$$

SSI ***radio flux***

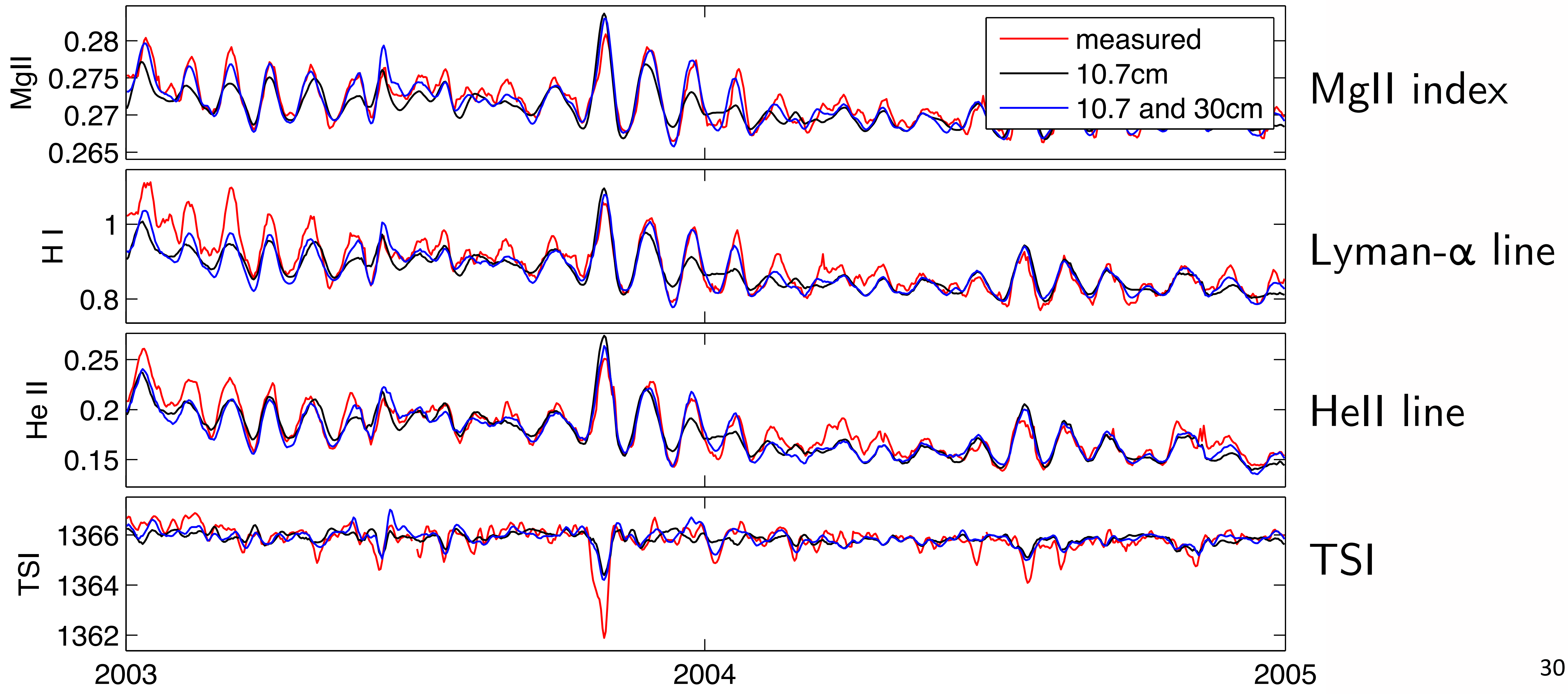
- Linear regression after decomposing into different scales (much better)

$$I(\lambda, t) = \sum_{\tau} \sum_{k=1}^{5} \alpha_{k,\tau} \; W_\tau \phi(\lambda_k, t)$$

wavelet transform

Reconstruction of the SSI

- Excerpt: various reconstructions
  (model has been trained on a different interval)



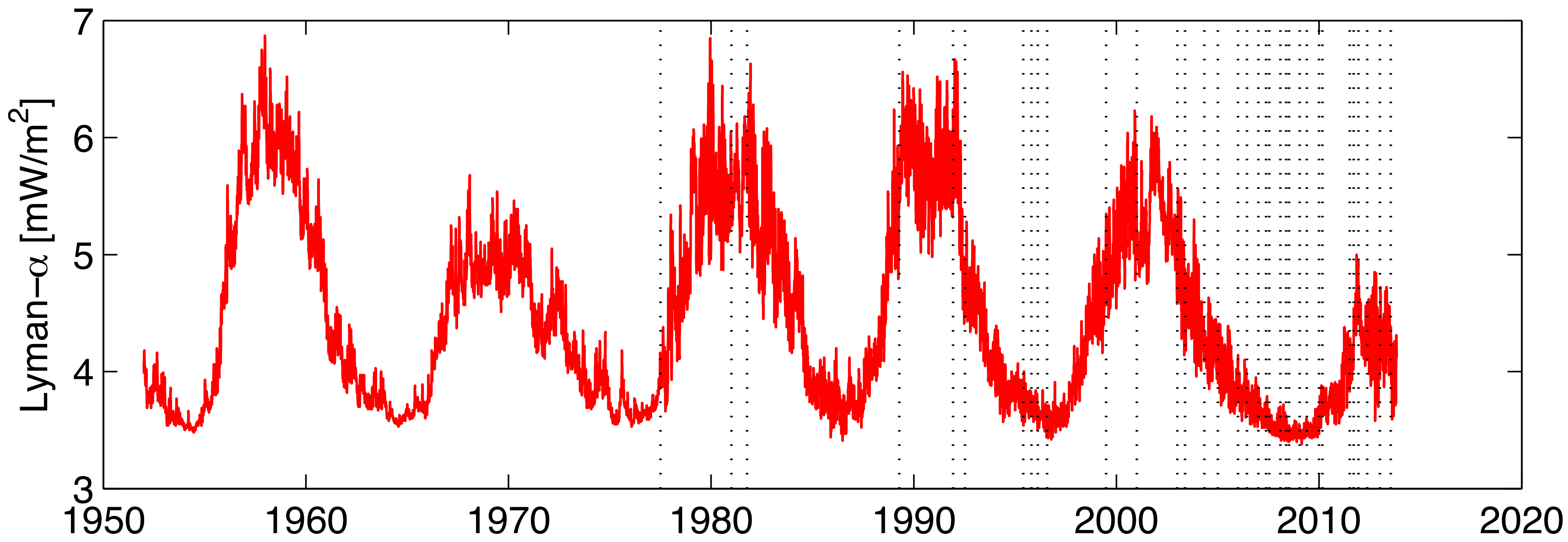
What can we reconstruct ?

- Time scales < ~100 days
  - XUV-NUV : excellent
  - VIS-NIR : reasonable

- Time scales > ~100 days
  - too early to assess (SSI data are not stable enough)
  - unlikely to work well: long-term trends may not be the same

Spinoff: stability of composites

- Reconstruction of the Lyman-α composite [LASP]



Composite Lyman-α line

Spinoff: stability of composites

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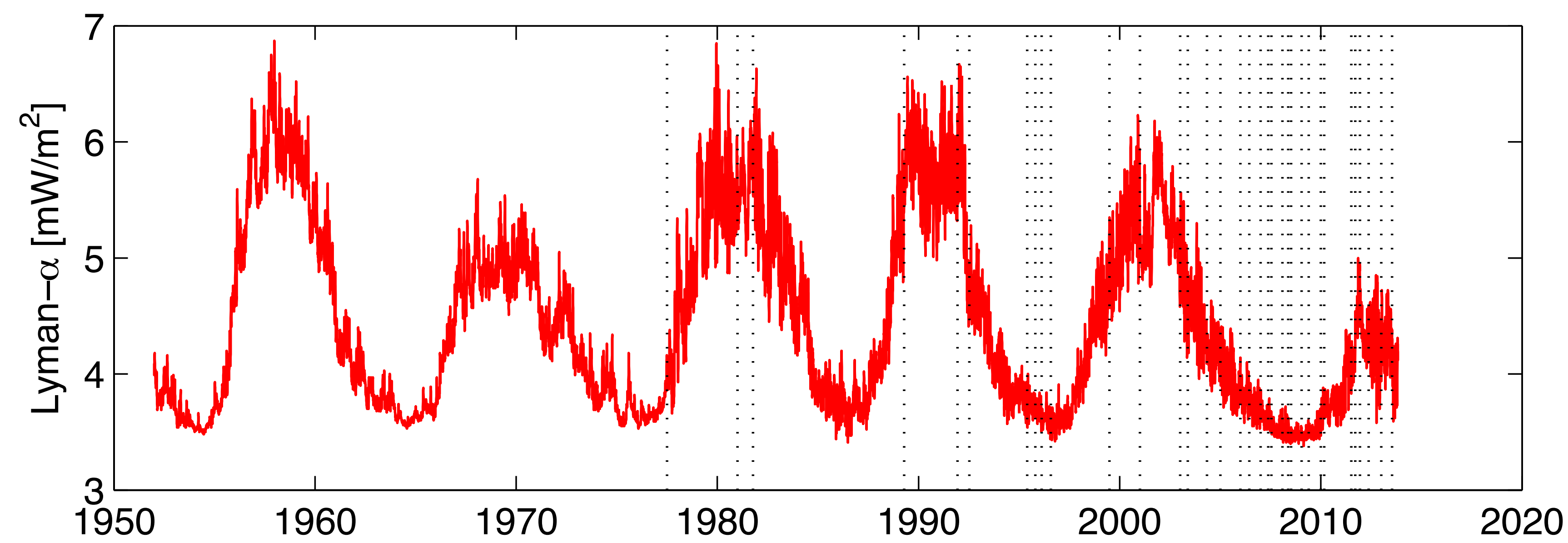

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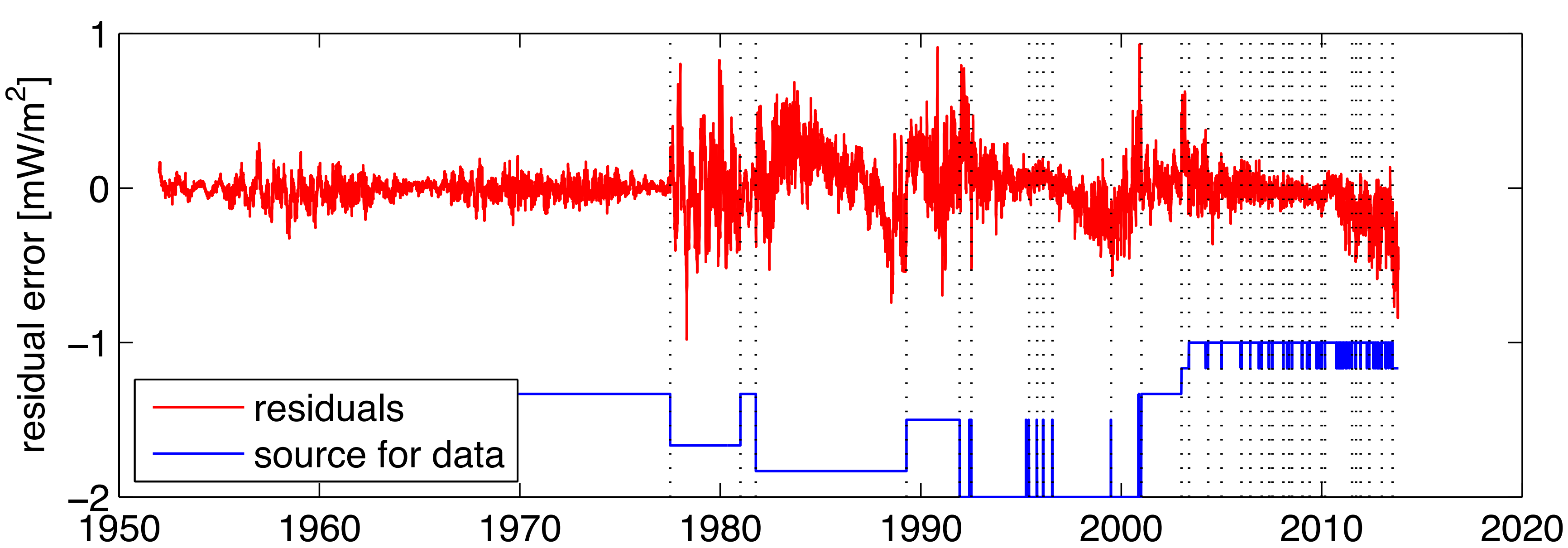


Residual = observations - reconstruction

Part III

Impact on upper atmosphere

Impact on upper atmosphere

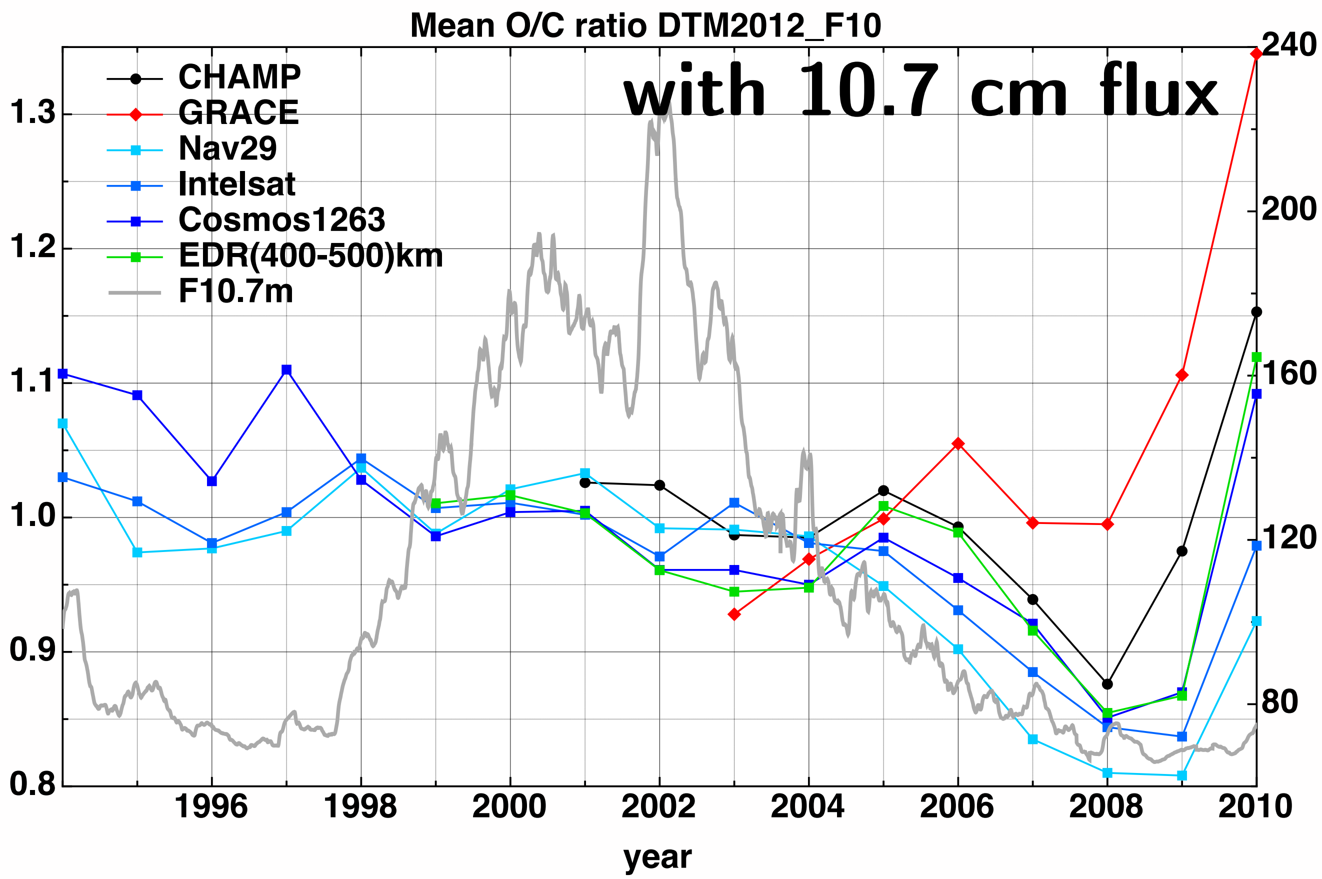
- Evaluate the performance by using these proxies as inputs to a satellite drag model.

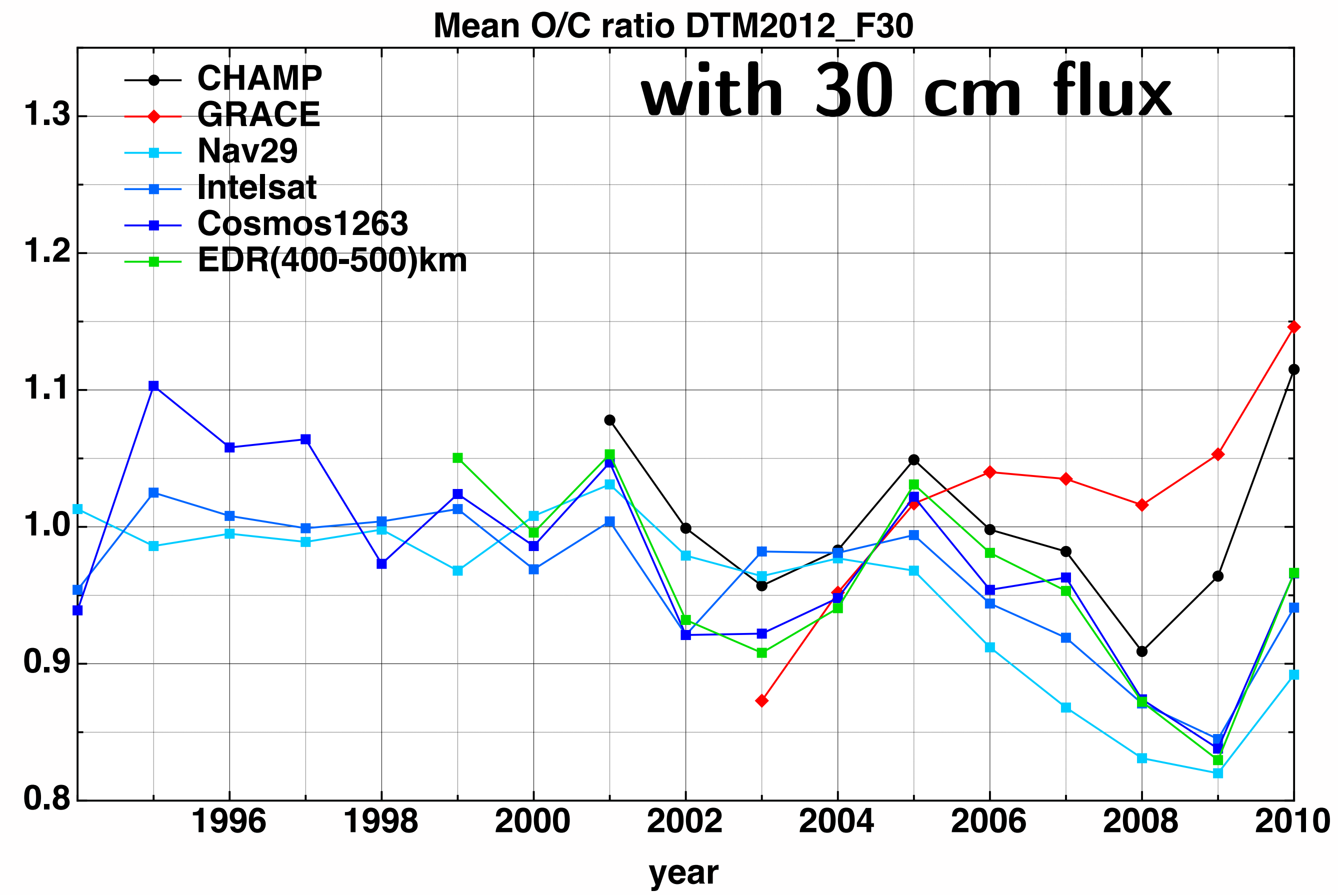
- DTM (Drag Temperature Model) [Bruinsma et al., 2012]
  - predicts temperature and composition as a function of location
  - main inputs are solar and geomagnetic forcing

- Metric of performance : $O/C =$ ratio of observed-to-computed neutral density

Example of results

- O/C ratio for two different solar inputs





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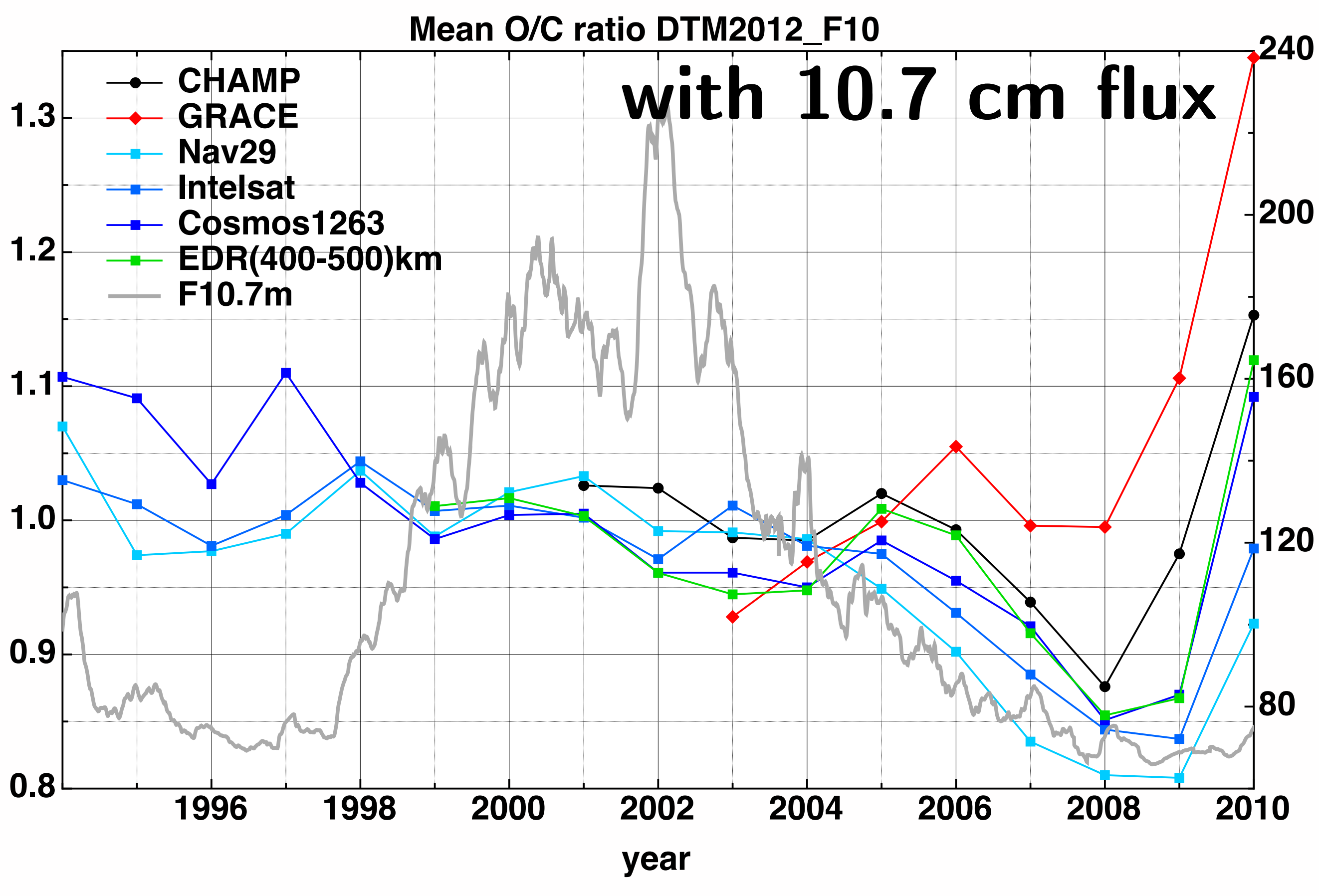
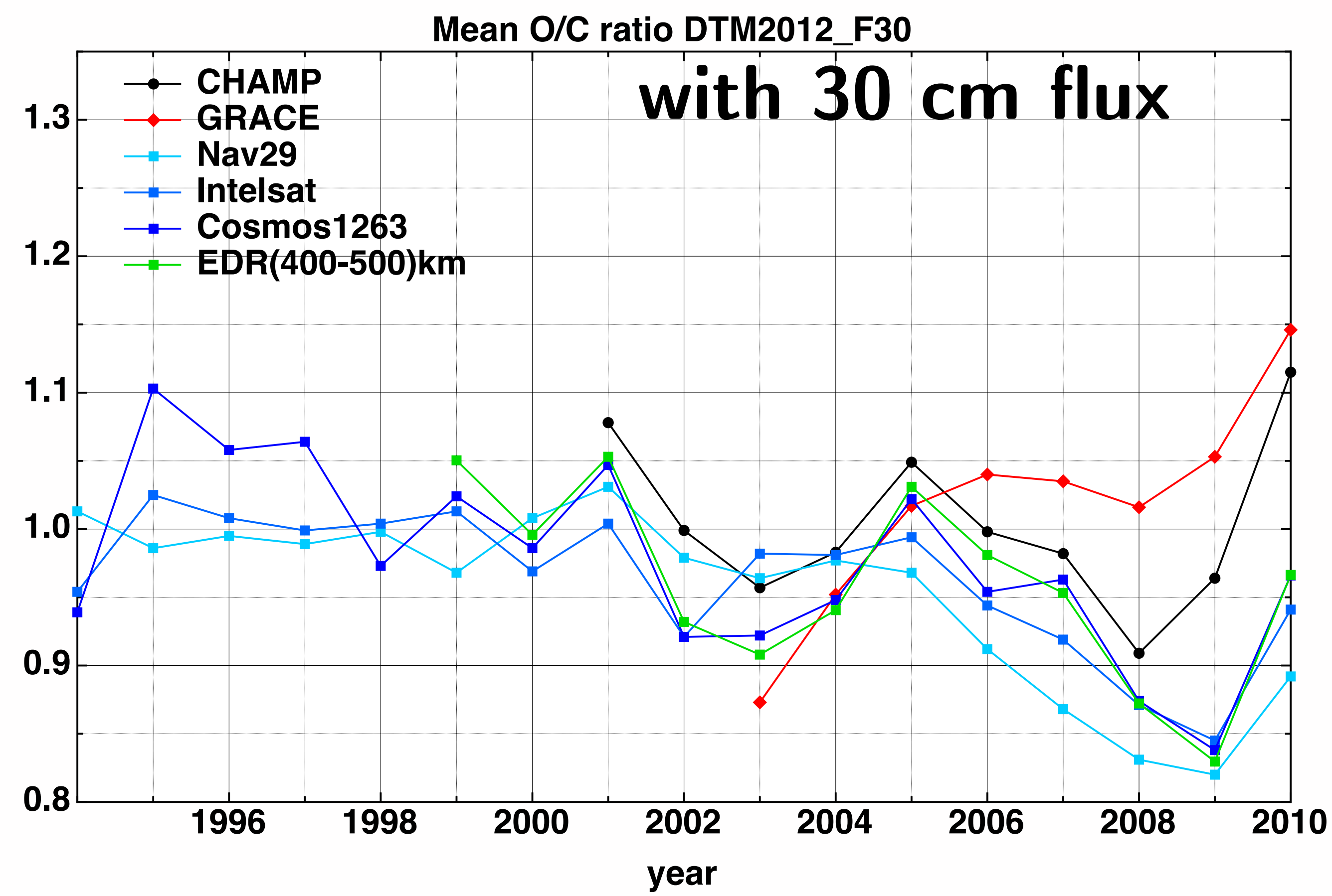
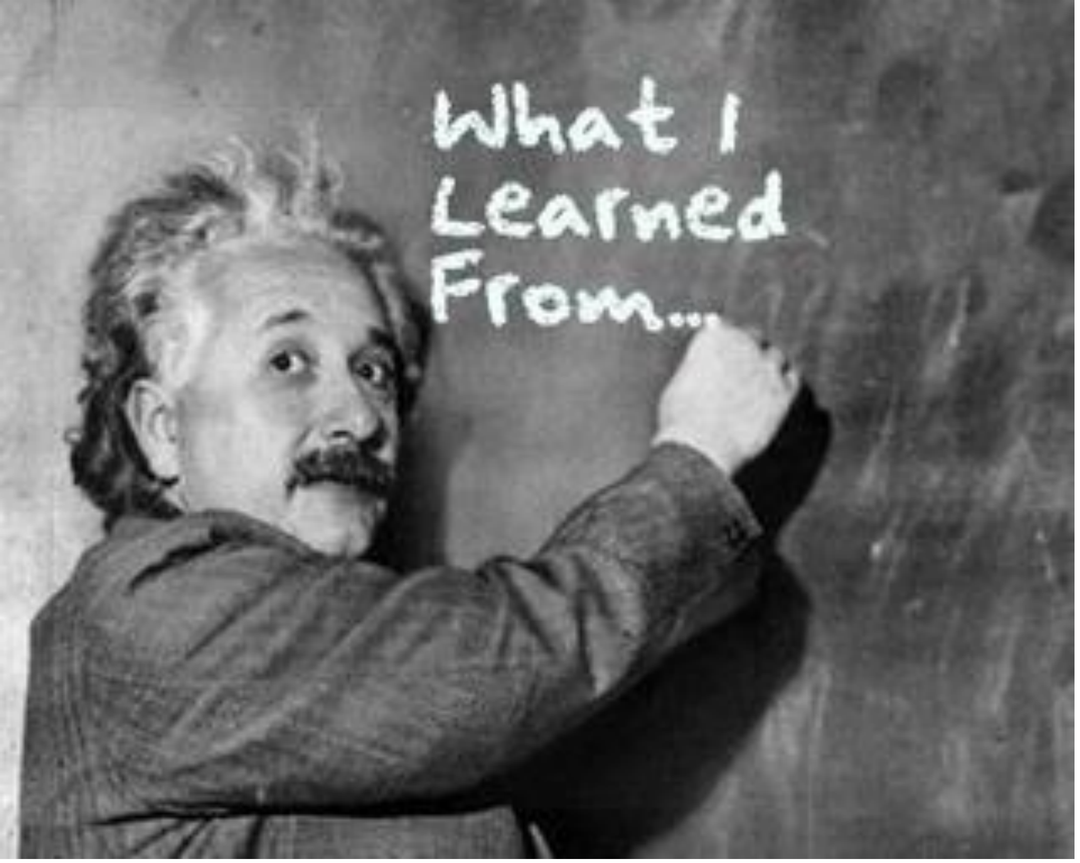




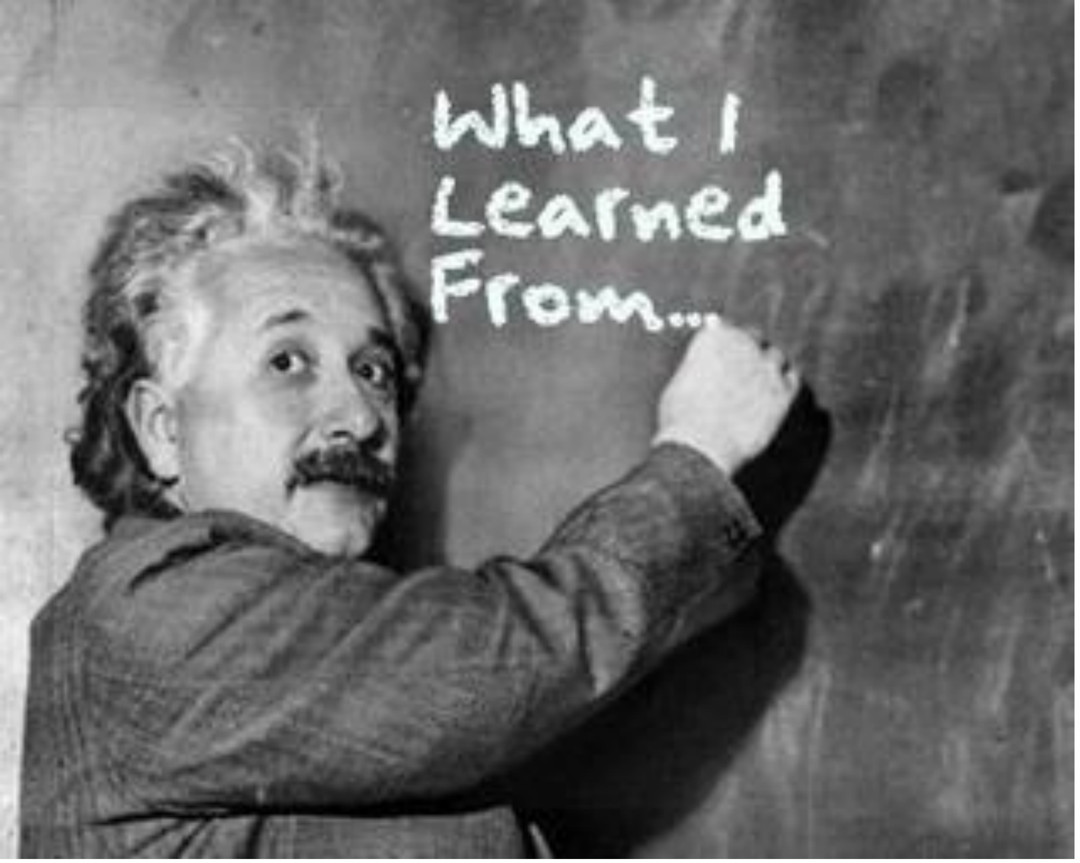
error on O/C is on average 7% lower when 30 cm radio flux is used (instead of 10.7 cm)

Conclusions

- A homogeneous dataset of synoptic radio observations
- By statistical analysis we are able to disentangle contributions associated with Bremsstrahlung & gyroresonance emissions.
- The Bremsstrahlung proxy is excellent for MUV-NUV
- The best single proxy for EUV-NUV is the 30 cm flux
- Caveats
  - daily averages $\neq$ instantaneous snapshots
  - flares are NOT included
  - etc.



Take home message 2

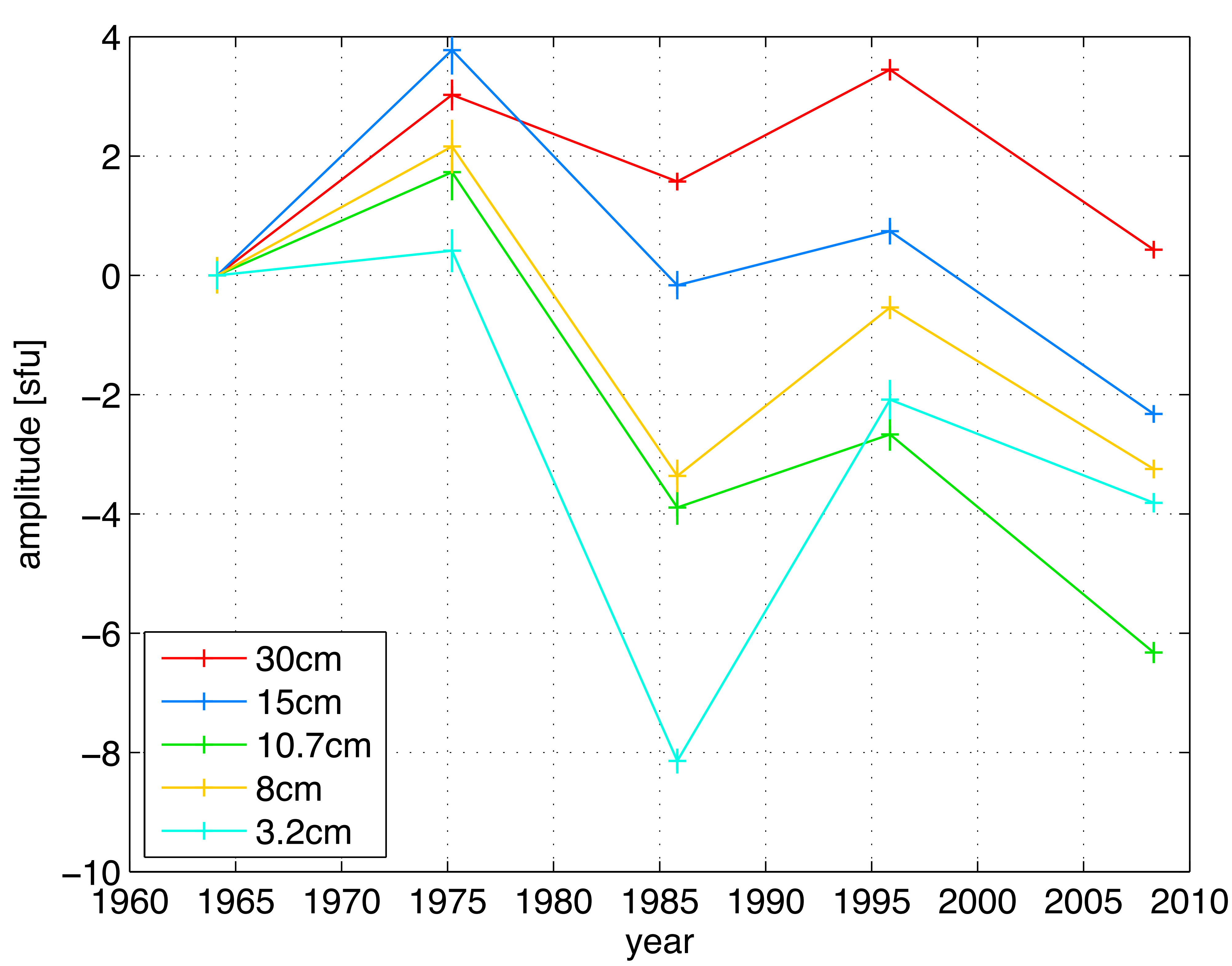


Take home message 2

The spectral information of centimetric radio observations provides considerable added value to the f10.7 index

More…

Long-term trends



Contribution