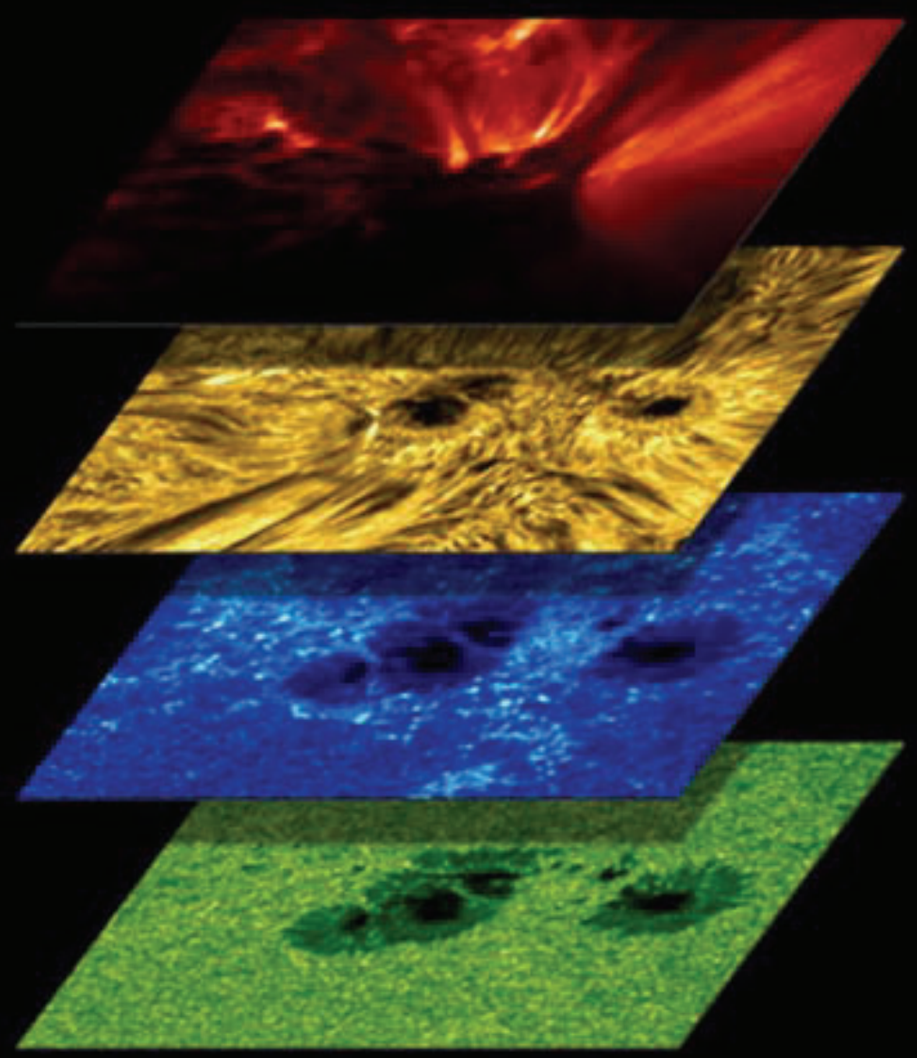
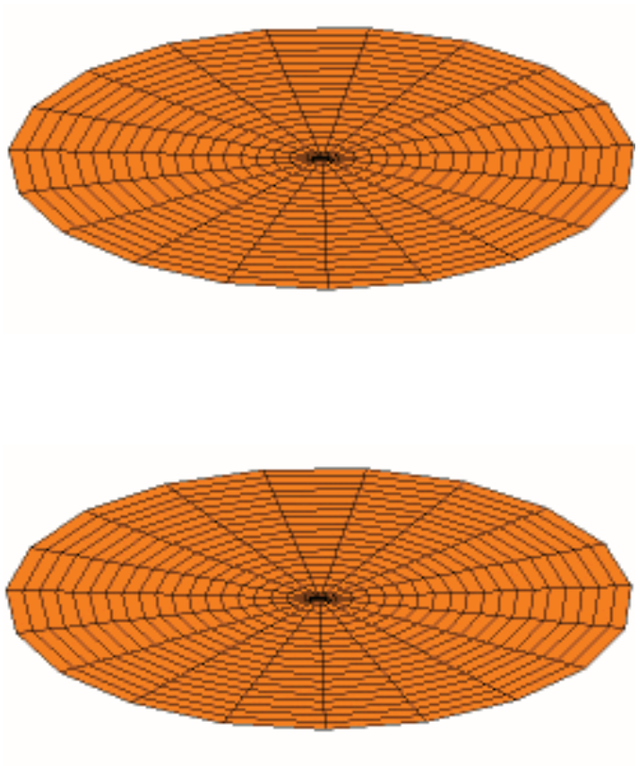
Response of solar irradiance to sunspot emergence: how instantaneous is it ?



T. Dudok de Wit

with contributions from Greg Kopp, Sasha Shapiro, Matthieu Kretzschmar, Veronica Witzke, Cécile Louchet
+ Biggus Dickus

Drums



These vibrations tell us

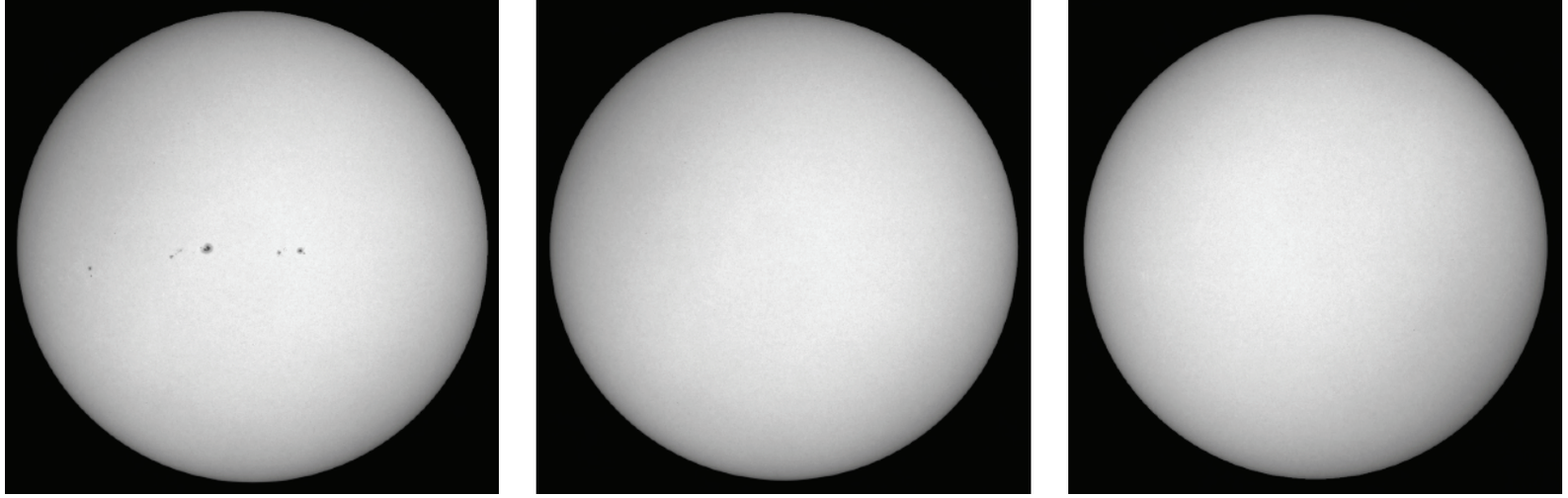
- how the drum was hit
- what the mechanical properties of the membrane are

Solar analogy :

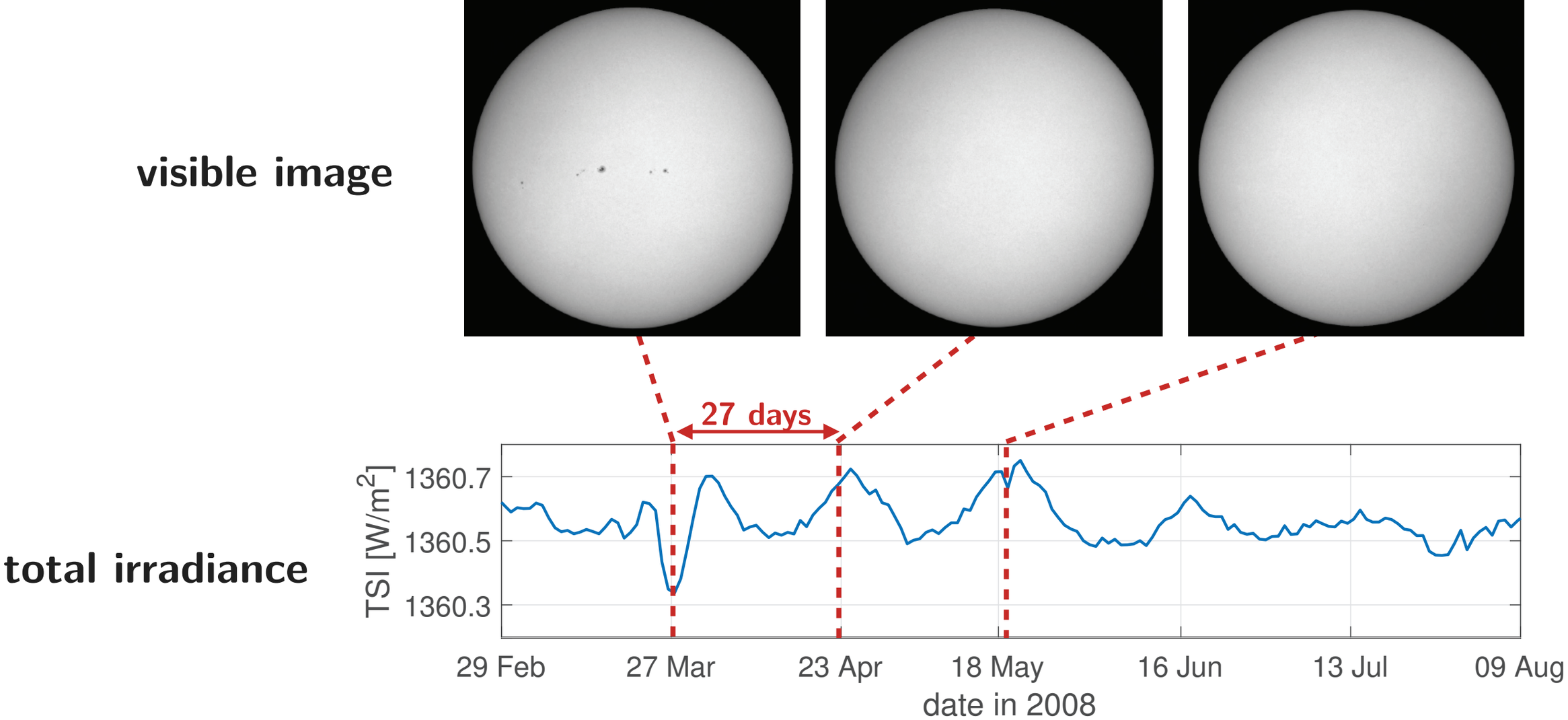
drum sticks = sunspot emergence (trigger)

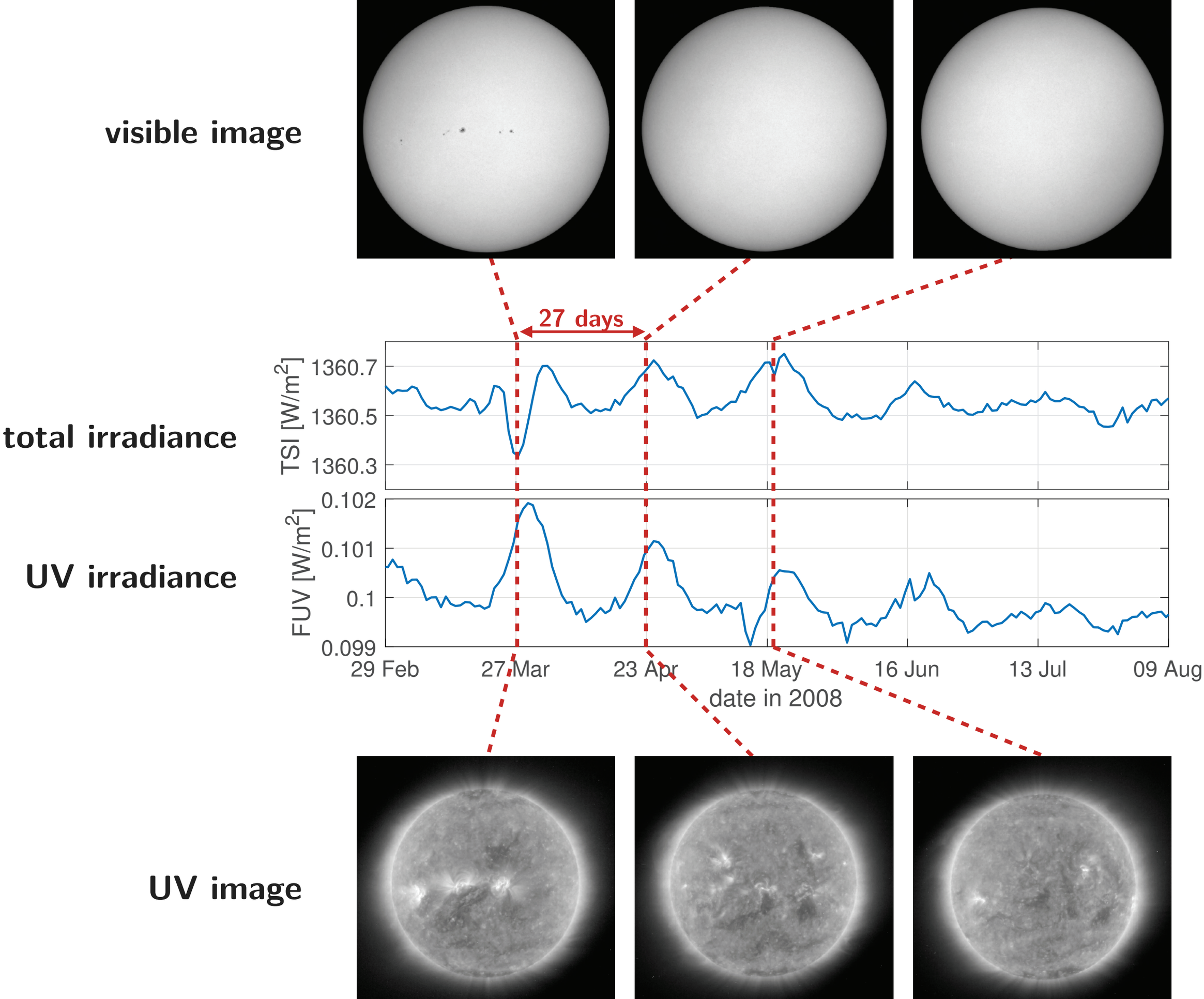
drum surface = solar irradiance (response)

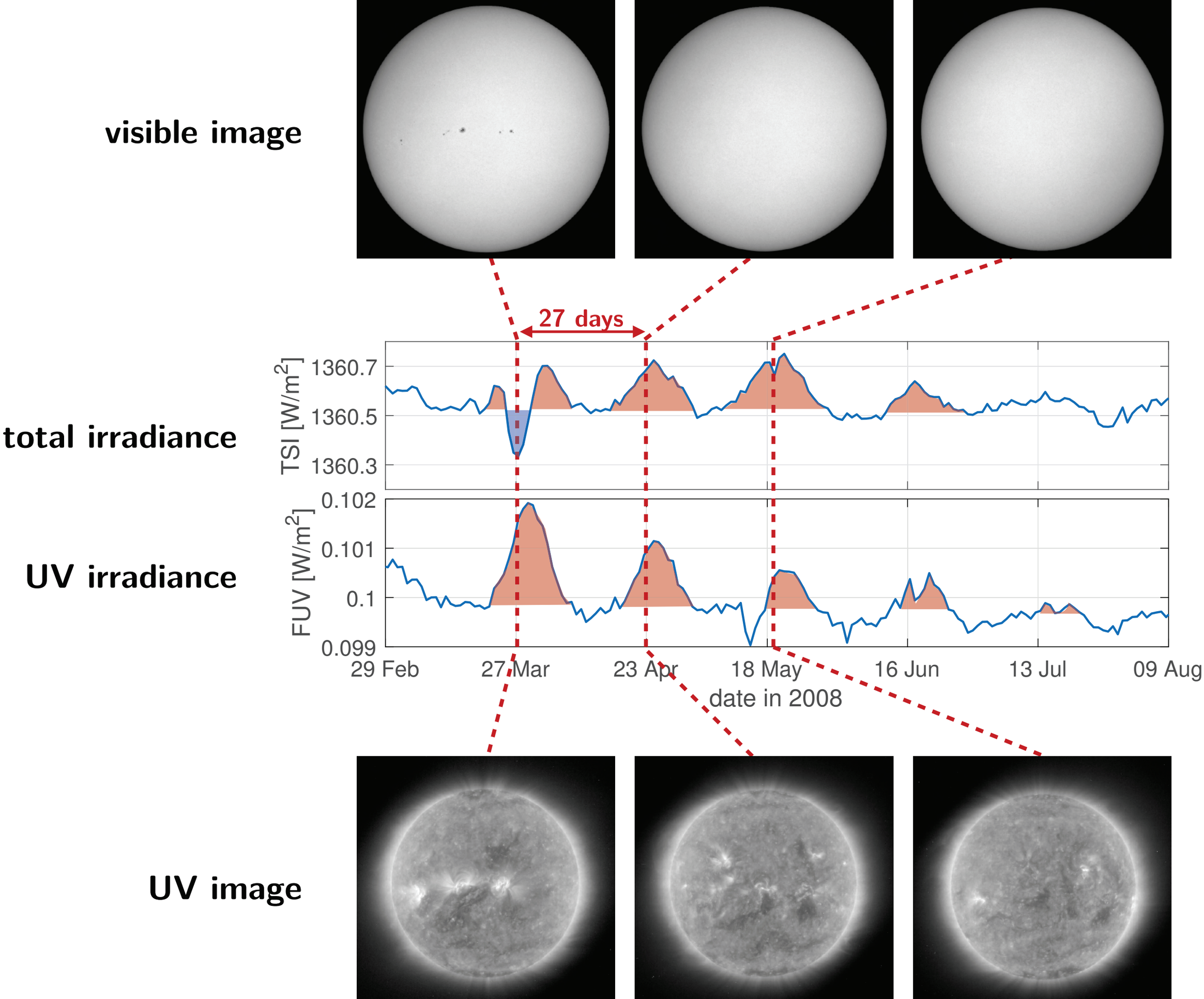
visible image



27 March 2008 | 27 days later | 54 days later


visible image
total irradiance
27 days
TSI [W/m2]
1360.7
1360.5
1360.3
29 Feb
27 Mar
23 Apr
18 May
16 Jun
13 Jul
09 Aug
date in 2008


visible image
27 days
total irradiance
TSI [W/m2]
1360.7
1360.5
1360.3
UV irradiance
FUV [W/m2]
0.102
0.101
0.1
0.099
29 Feb
27 Mar
23 Apr
18 May
16 Jun
13 Jul
09 Aug
date in 2008
UV image

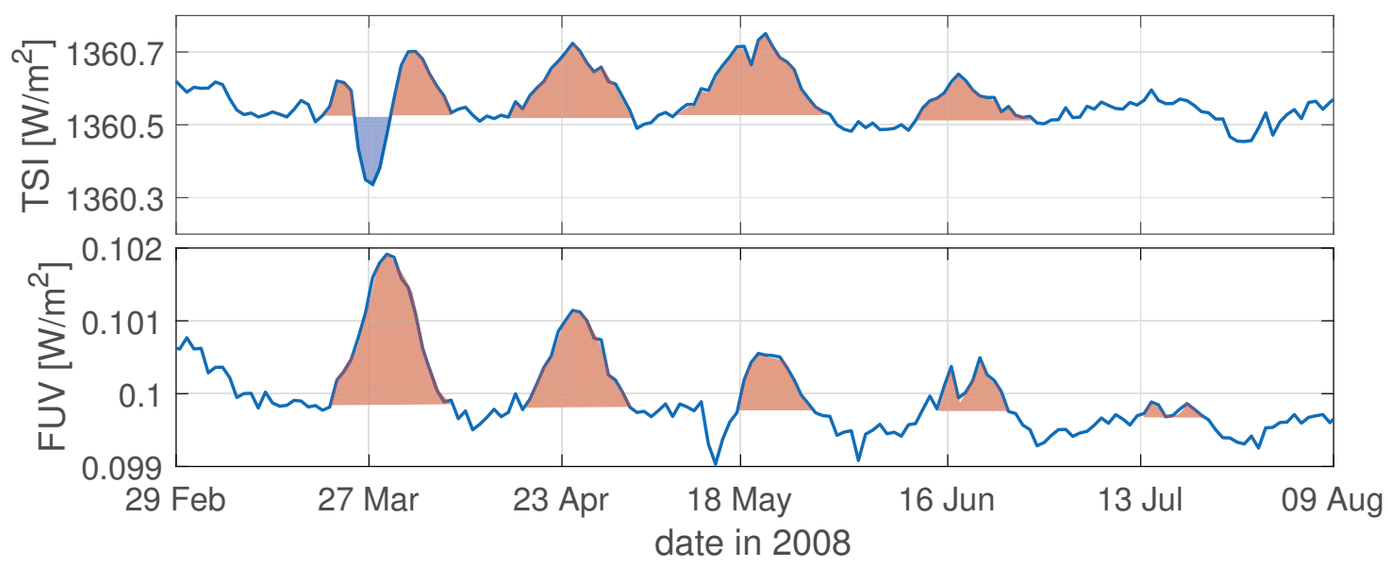

visible image
27 days
total irradiance
TSI [W/m2]
1360.7
1360.5
1360.3
UV irradiance
FUV [W/m2]
0.102
0.101
0.1
0.099
29 Feb
27 Mar
23 Apr
18 May
16 Jun
13 Jul
09 Aug
date in 2008
UV image

Questions

- Q1: How instantaneous is the response of the Solar Spectral Irradiance (SSI) ?
- Q2: What is the total energy budget at each wavelength ?
- Q3: Can these short-term imbalances explain the solar cycle modulation ?
- Q4: Can this help up better reconstruct SSI from proxy data ?

total irradiance

UV irradiance



Question 1

How instantaneous is the response of the SSI ?

Q1: Instantaneity of the response

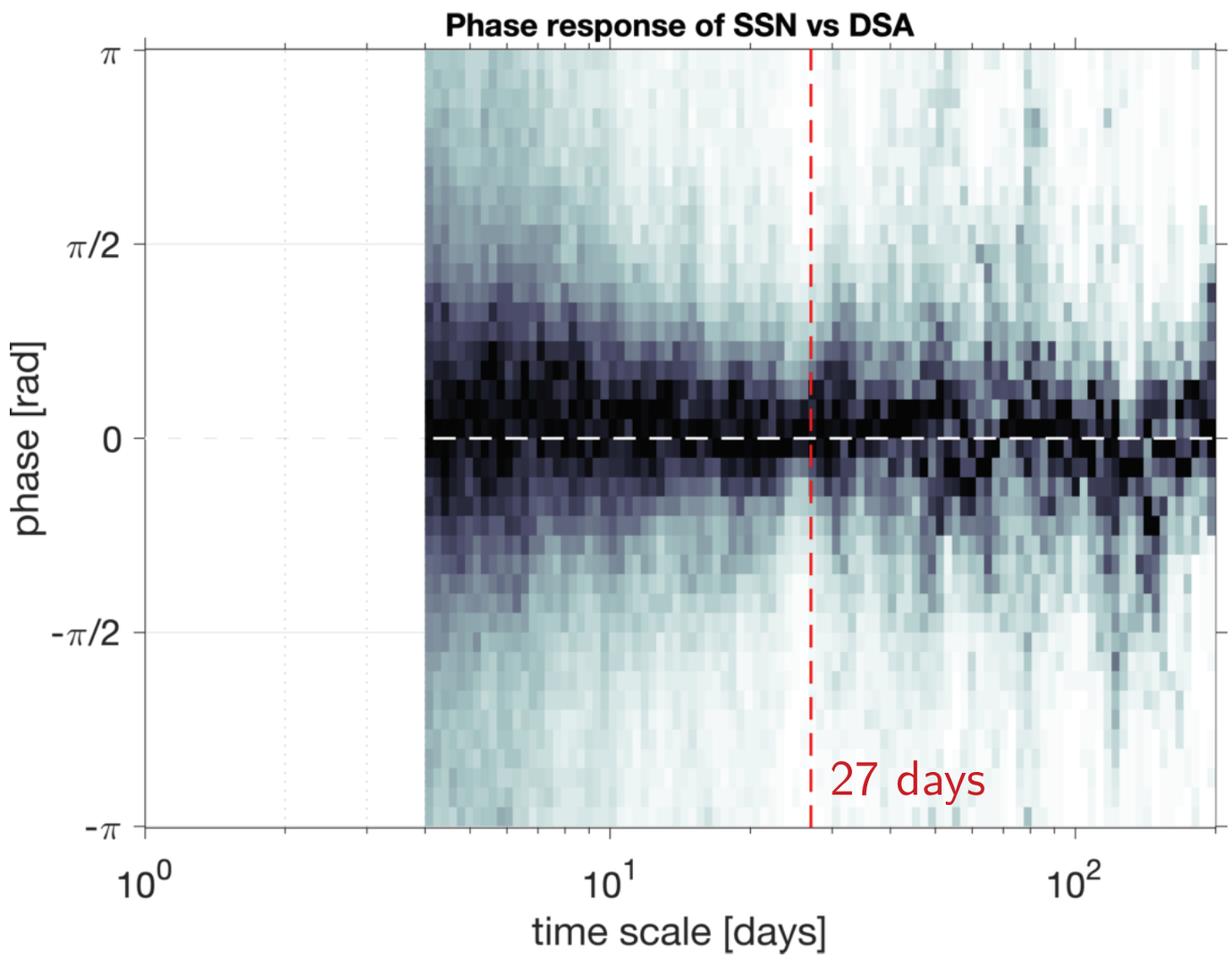
- The main trigger of SSI variability is magnetic flux emergence :

  our best proxy for spot emergence is the **daily sunspot area** (DSA)

- Method
  - compute complex wavelet transform of each proxy
  - for each scale, determine phase lag vs DSA

Q1: Instantaneity of the response

- Phase lag of sunspot number vs DSA

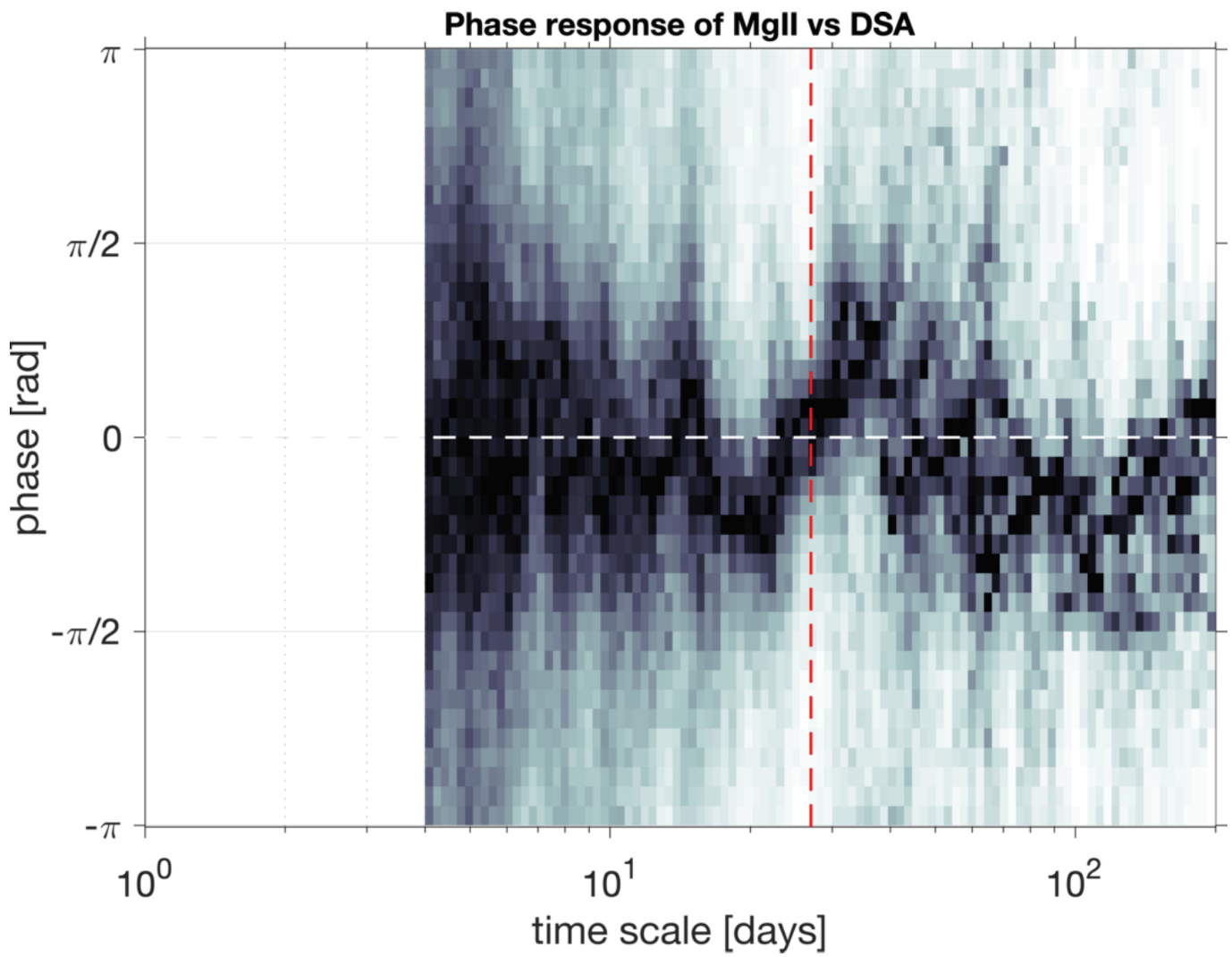


Phase lag > 0
Sunspot number is ahead

Phase lag < 0
Sunspot number lags DSA

Q1: Instantaneity of the response

- Phase lag of MgII index vs DSA

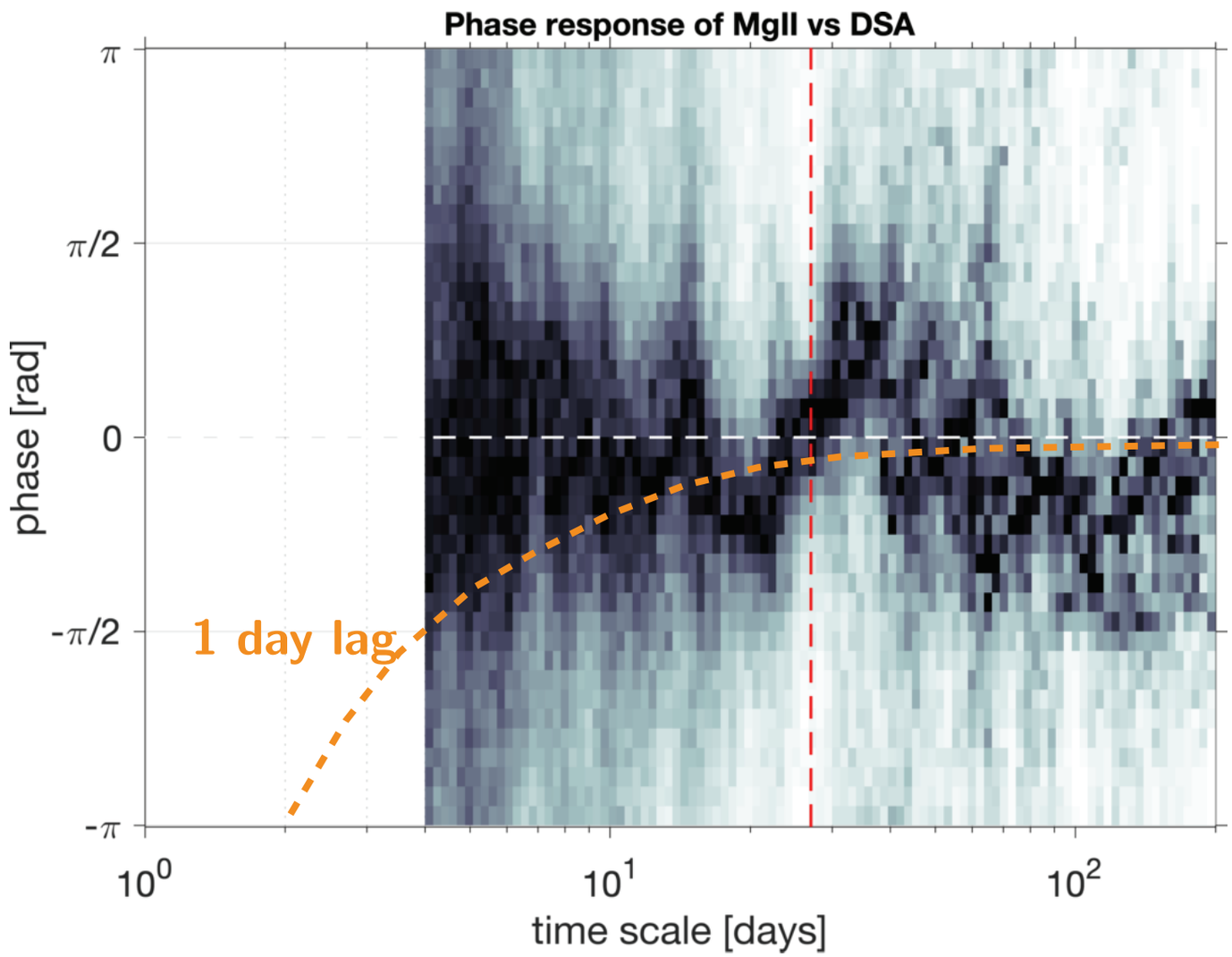


Phase lag > 0
MgII is ahead

Phase lag < 0
MgII lags DSA

Q1: Instantaneity of the response

- Phase lag of MgII index vs DSA

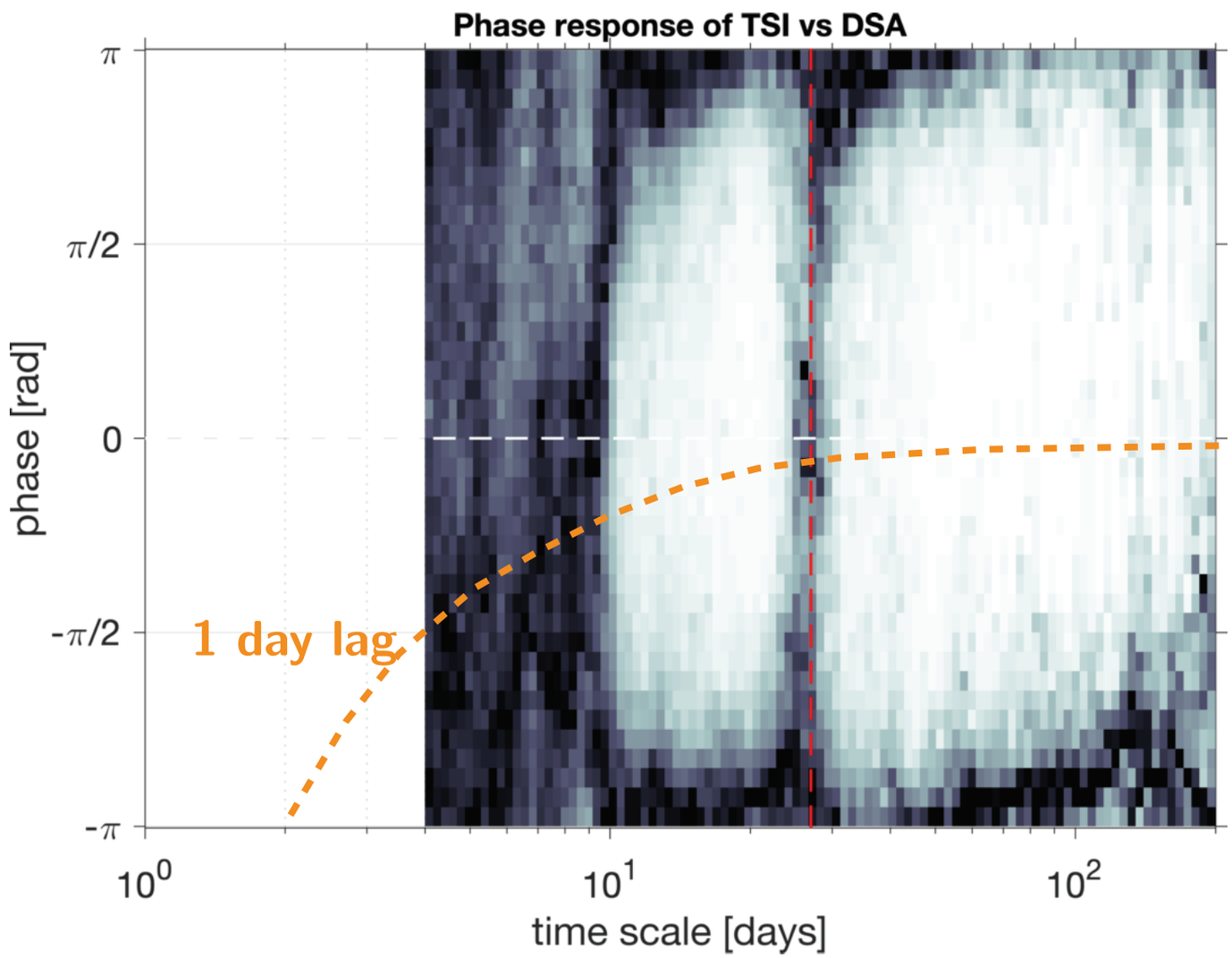


Phase lag > 0
MgII is ahead

Phase lag < 0
MgII lags DSA

Q1: Instantaneity of the response

- Phase lag of the Total Solar Irradiance (TSI) index vs DSA



Phase lag > 0
TSI is ahead

Phase lag < 0
TSI lags DSA

Conclusion 1

- The SSI and most proxies do NOT respond instantaneously to changes in the daily sunspot area
- Reconstruction models involving instantaneous combinations of proxies will miss some of the variability of the SSI

Question 2

How to model this non-instantaneous response ?

Q2: Transfer function approach

$u(t)$

input:
magnetic flux
emergence
(sunspot area)

$U(\omega)$

linear system
active regions,
plages, faculae,
etc.

$H(\omega)$

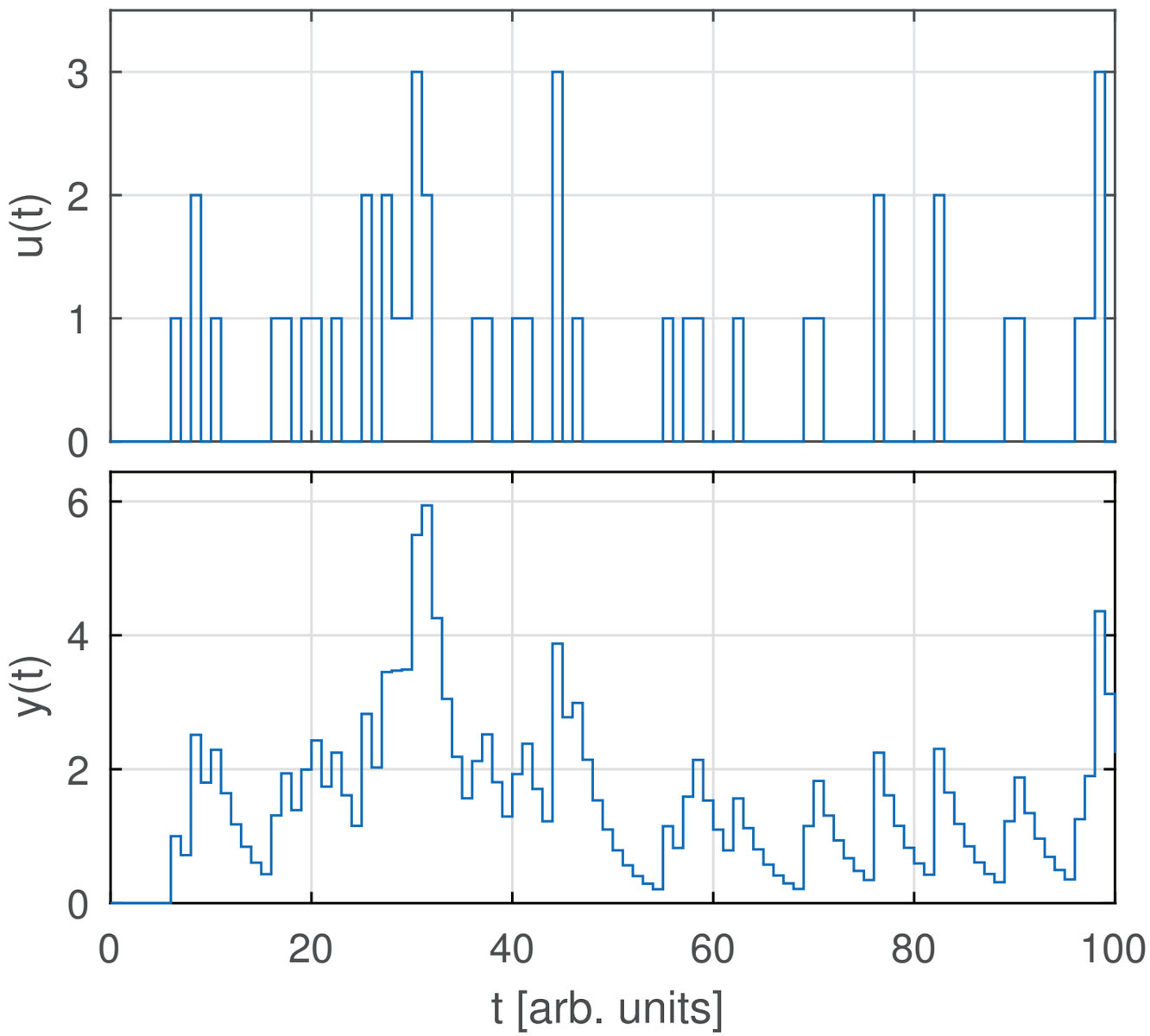
output:
irradiance

$Y(\omega) = H(\omega)U(\omega)$

Q2: Transfer function : example

- Example : differential equation

$$\frac{\mathrm{d}}{\mathrm{d}t}y(t) = u(t) - \frac{y(t)}{\tau}$$

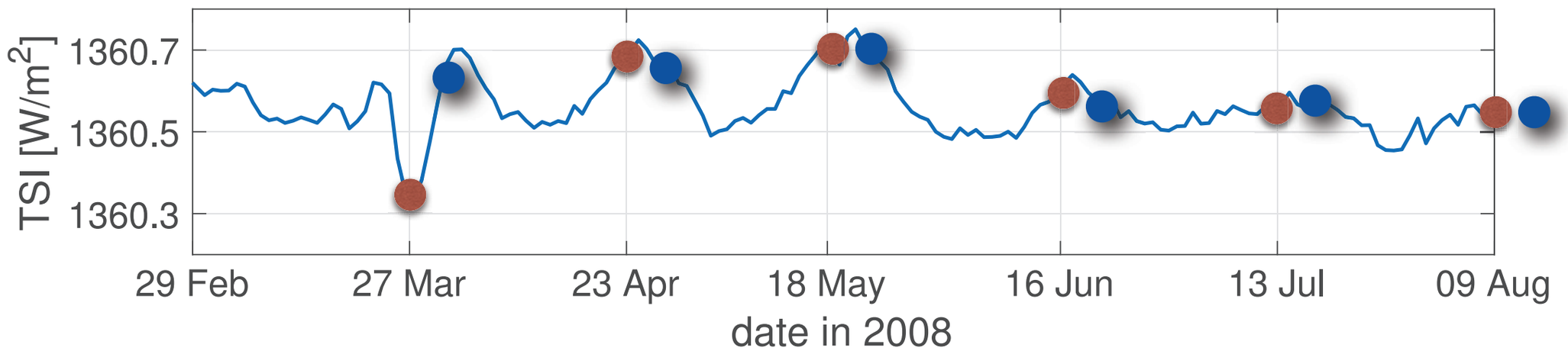


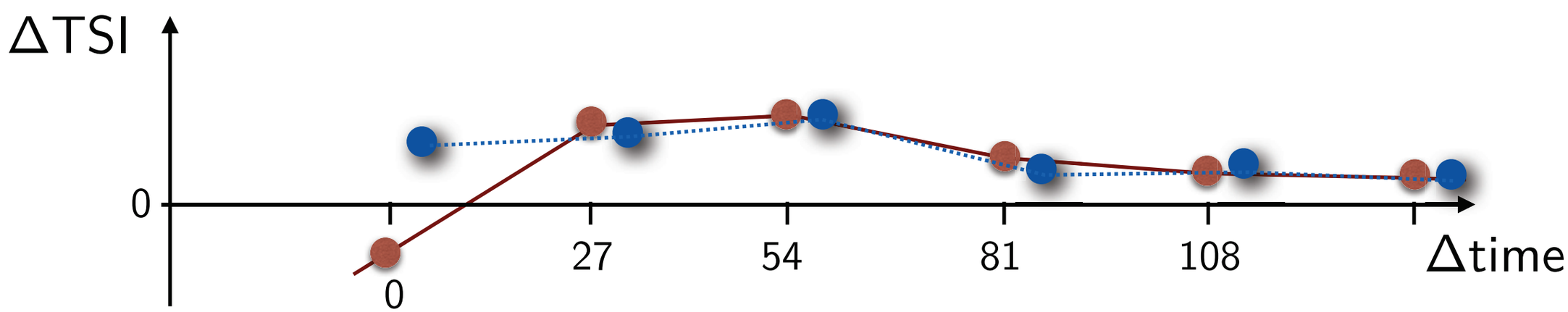
input u(t)

output y(t)

Q2: Stroboscope

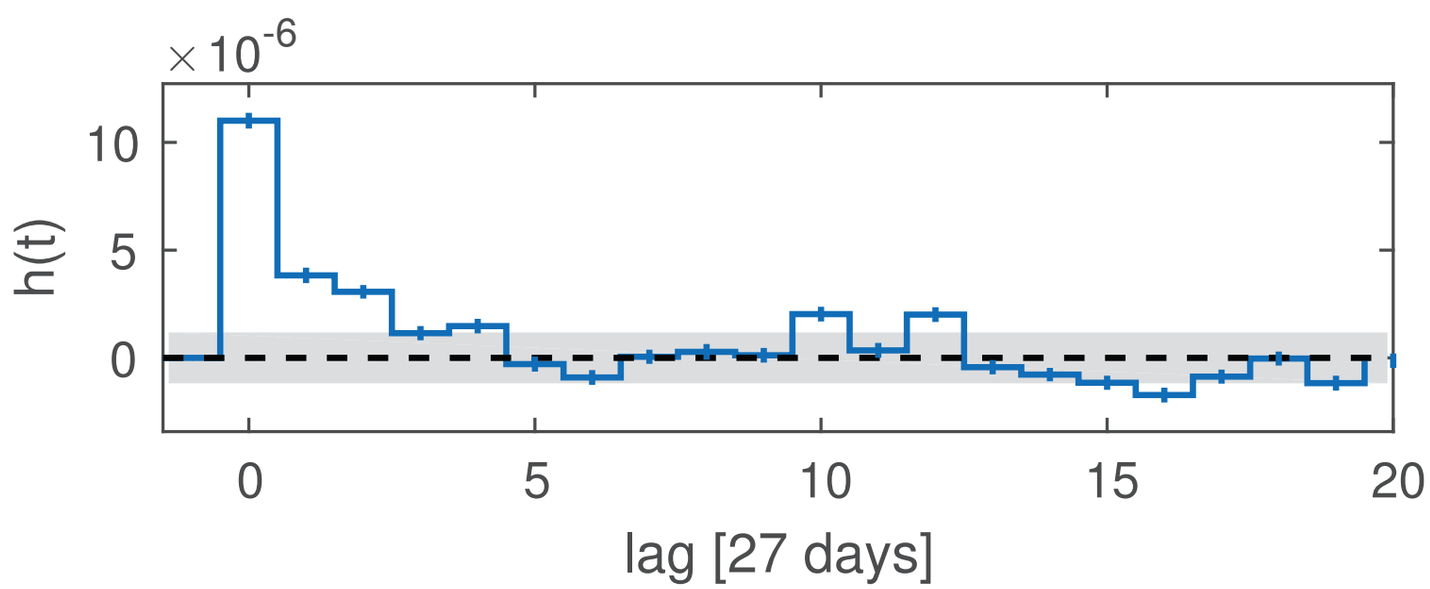
- Problem: disentangle solar rotation & natural evolution of sunspots
  - solution: take one snapshot every solar rotation (every 27 days)
  - constraint: cannot resolve variations < solar rotation
    (+ Nyquist criterion is not fulfilled)





Impulse response

- **impulse response** h(t)
  describes how the irradiance (integrated over the solar disc)
  reacts to a single spot that would last for 27 days



Q2: Impulse response

- SSI data from SORCE (2003-2016)
- Strong deficit of radiation in the visible, vs enhanced radiation in the UV
- The effect of a spot lasts for 3-5 rotations

extreme-UV (10-120 nm)

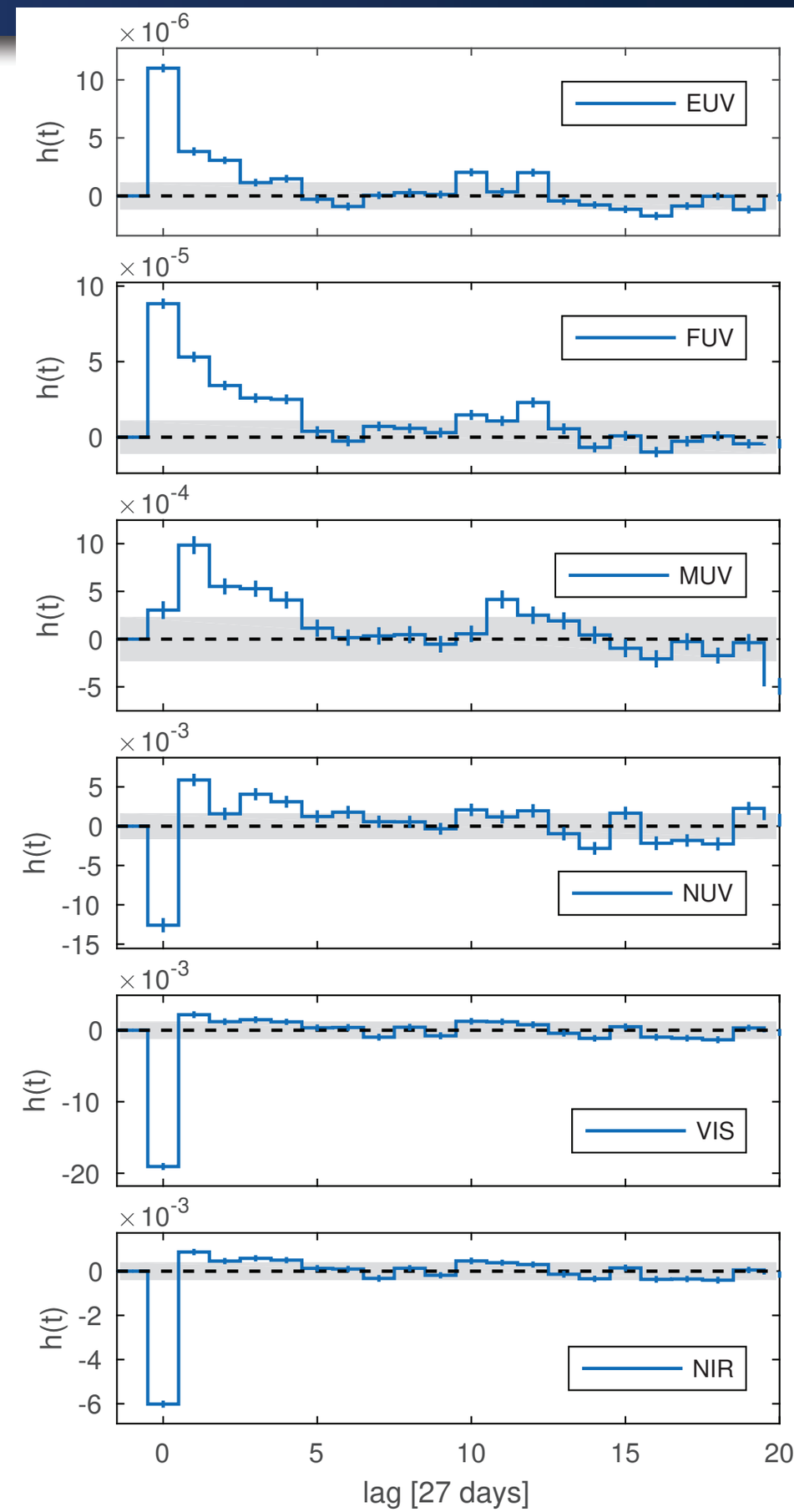
far-UV (120-200 nm)

mid-UV (200-300 nm)

near-UV (300-4000 nm)

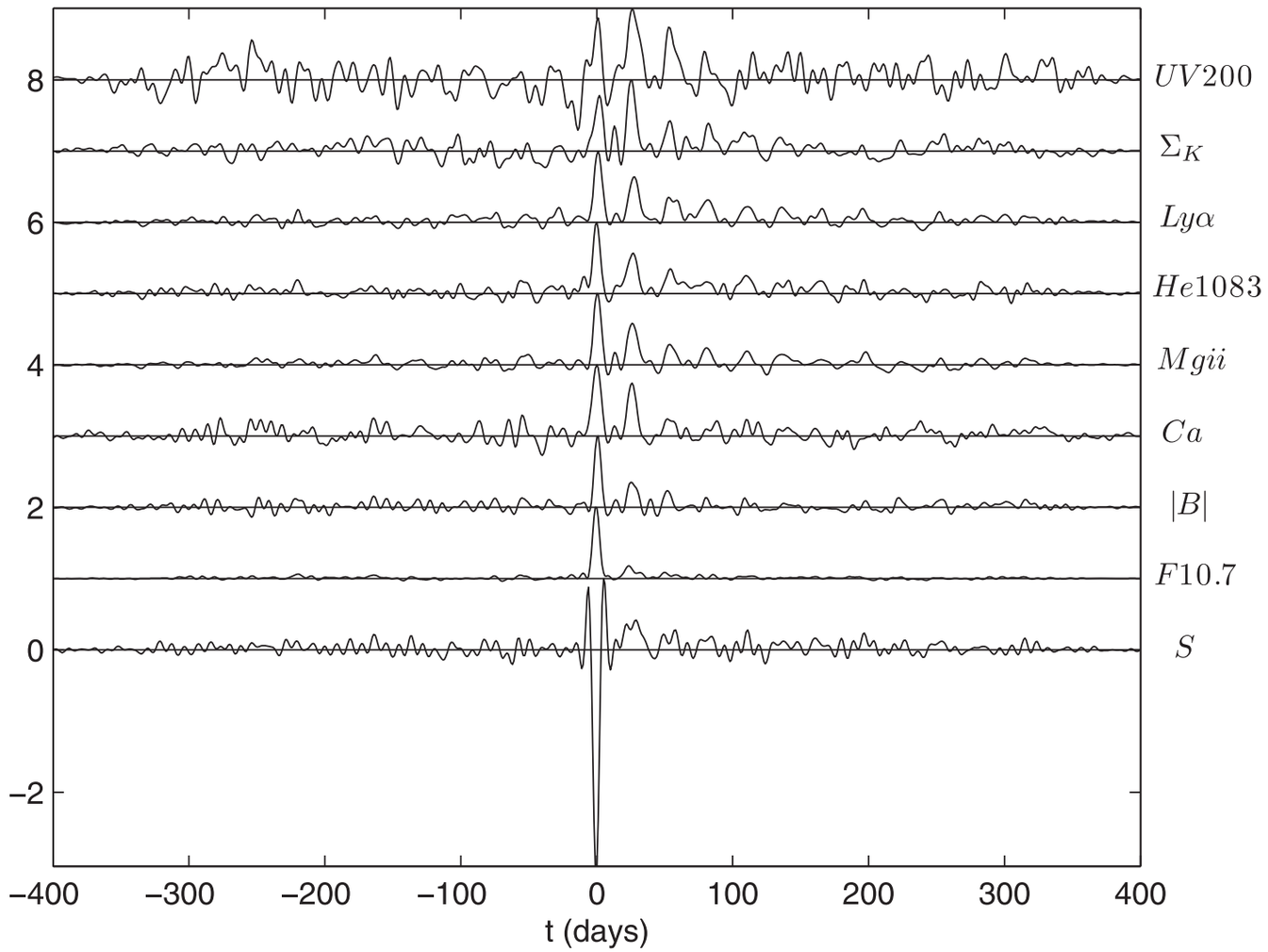
visible (400-600 nm)

near-IR (>600 nm)



Q2: Impulse response

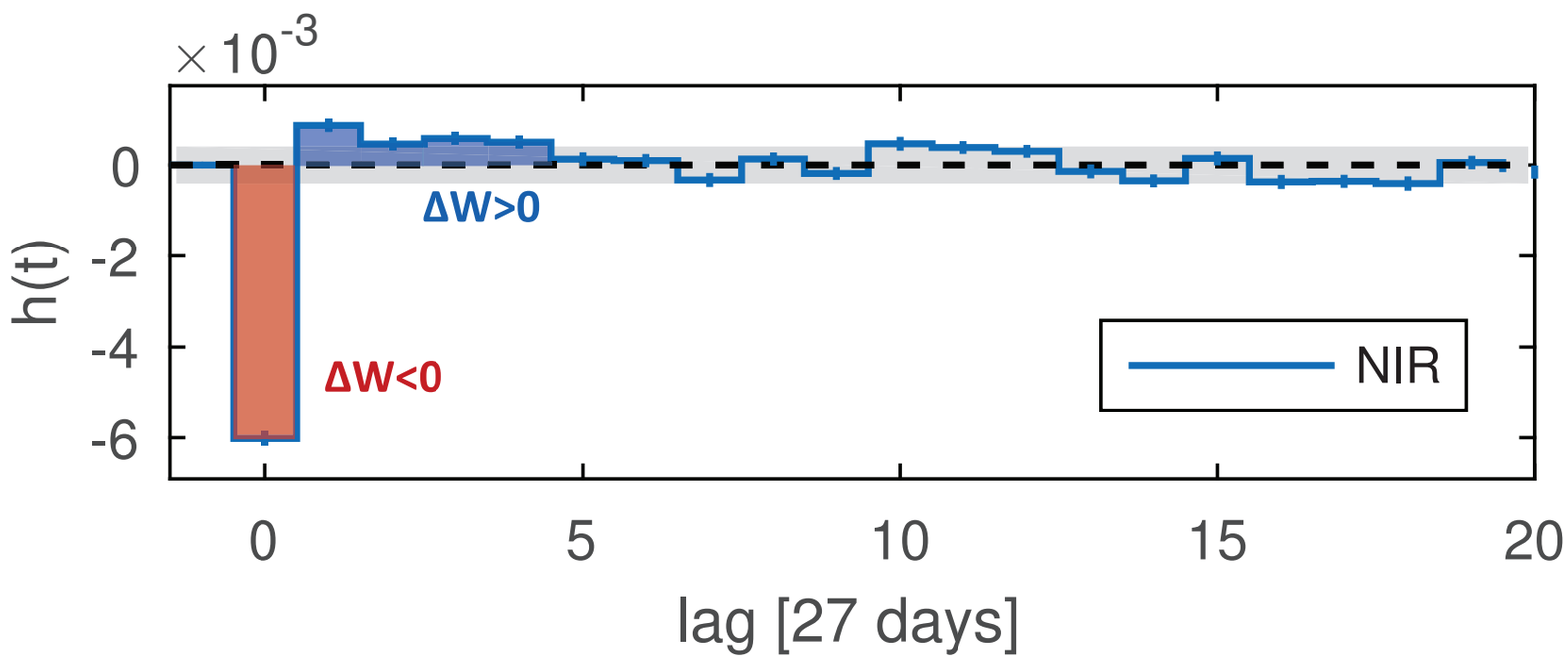
- Preminger and Walton (2007) had used a similar approach but did not disentangle solar rotation and sunspot evolution



Q2: Energy balance

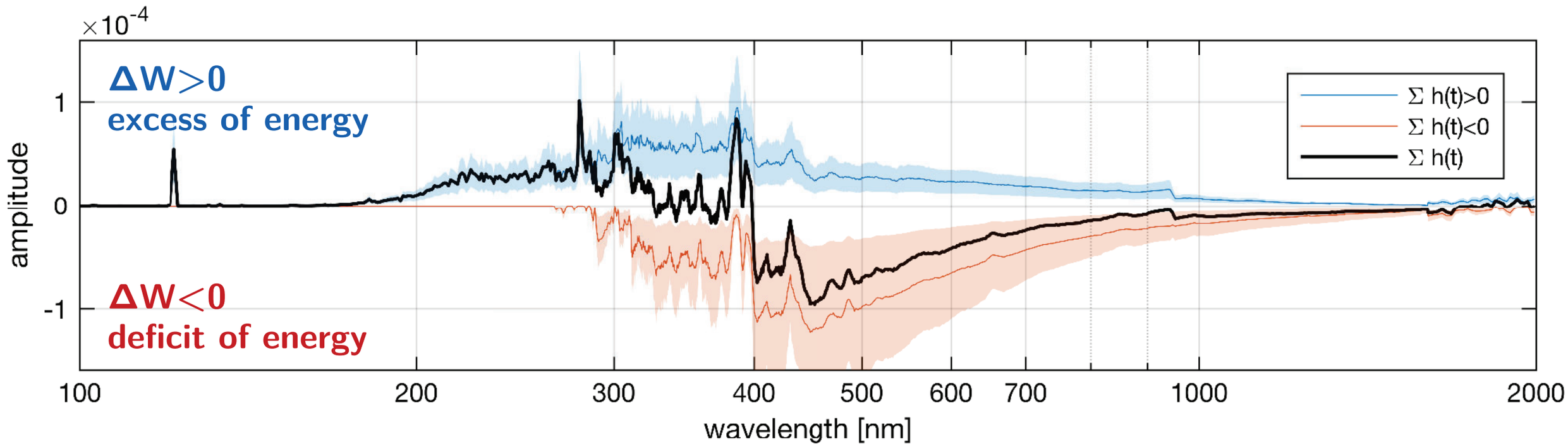
- Does a new sunspot lead to a global excess/deficit of energy of irradiance ?

Example : impulse response h(t) in the near-IR



Q2: Energy balance

- We observe : global excess of energy in the UV, and deficit beyond



Conclusion 2

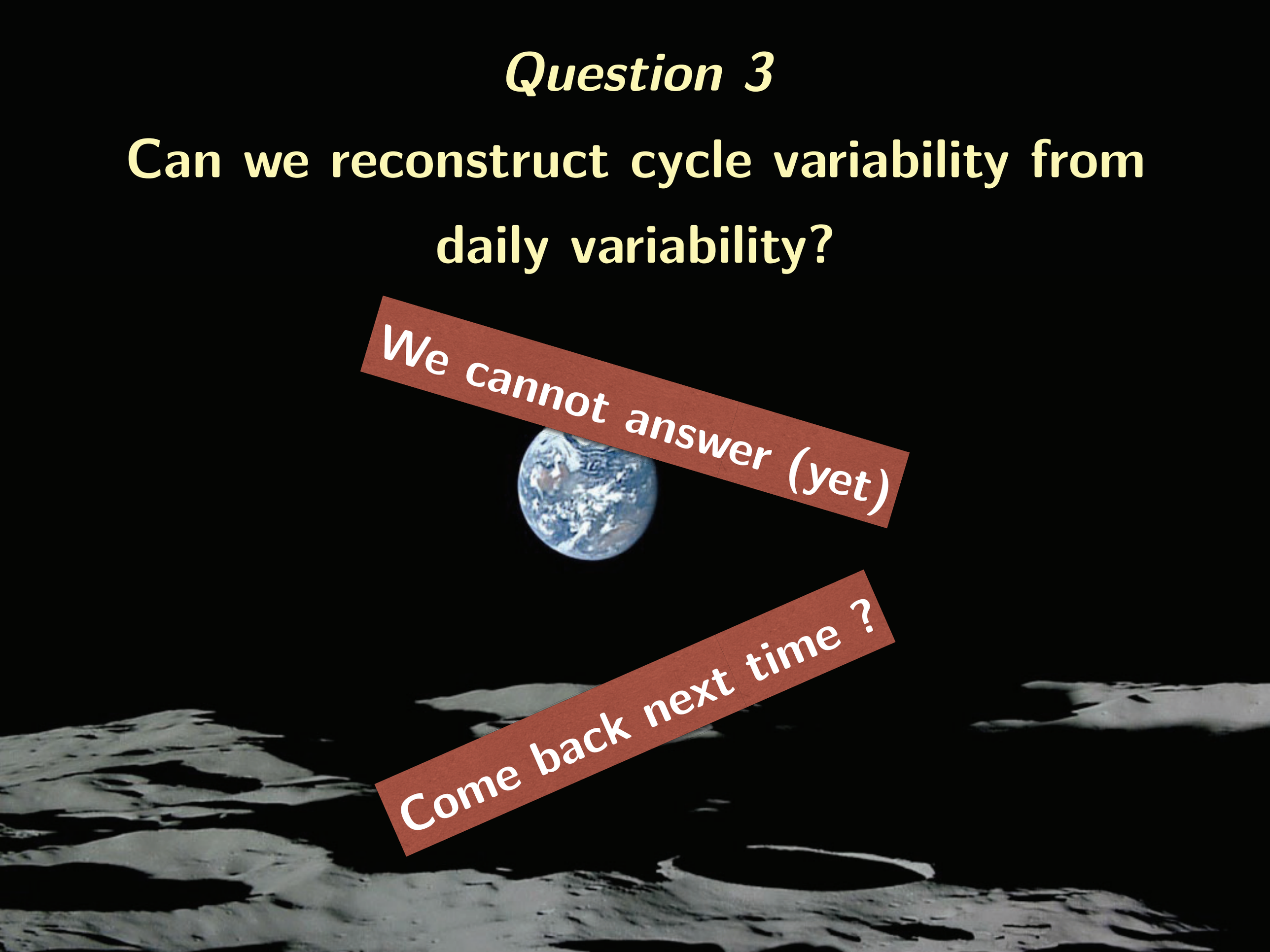
- The impulse response gives deep insight into the response of the SSI to spot emergence
- **But there is a caveat** : the response is not fully linear $\Longrightarrow$ we cannot meaningfully conclude about the energy budget

We find that $$Y(\omega) = H(\omega)U(\omega) + R(\omega)$$

instead of $$Y(\omega) = H(\omega)U(\omega)$$

Question 3

Can we reconstruct cycle variability from daily variability?



Question 4

Can we improve the reconstruction of the SSI that way ?

Q4: Reconstruct the SSI

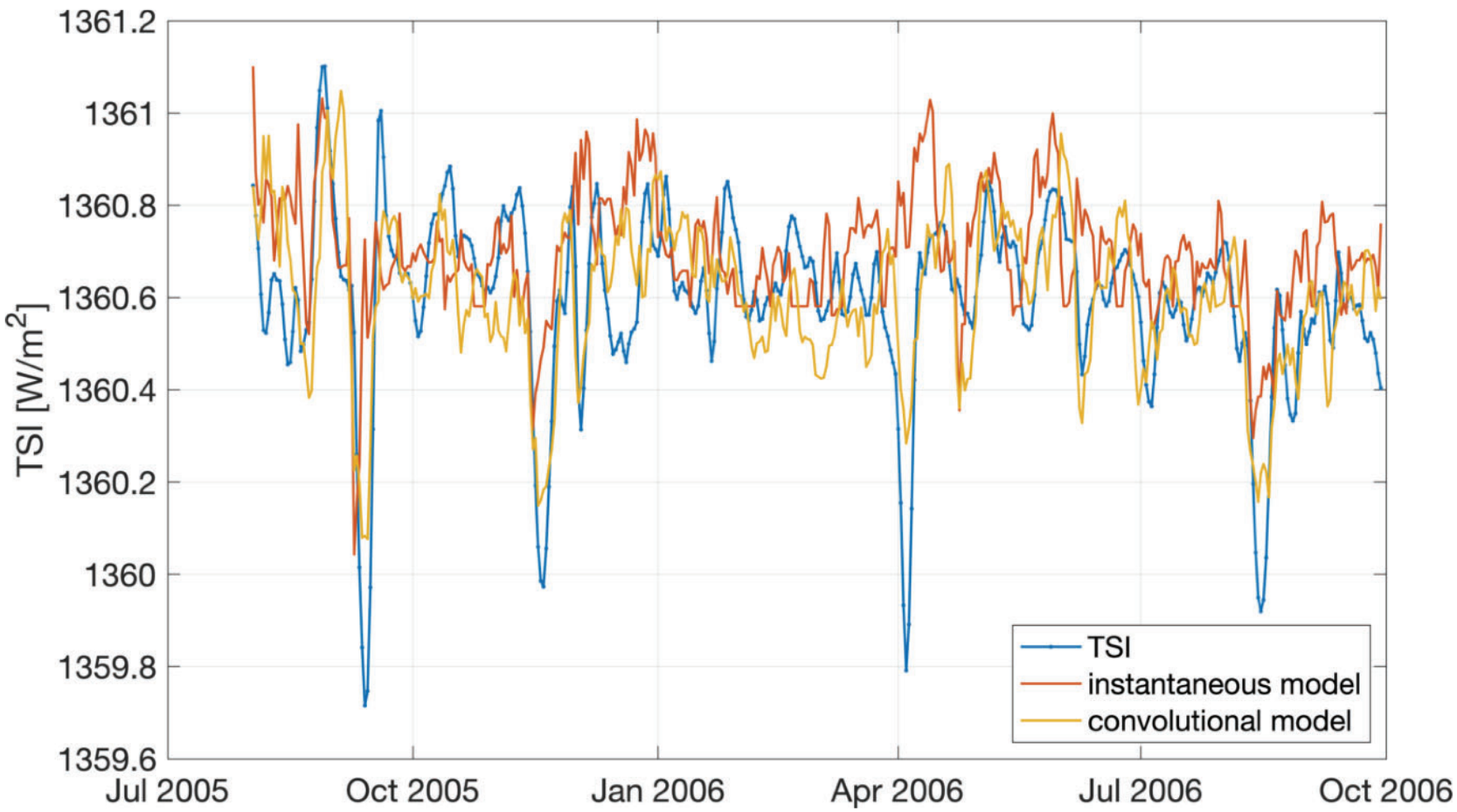
- **Example** : instead of using a model such as

$$\mathrm{TSI}(t) = \mathrm{Constant} + \mathrm{SSN}(t) + \mathrm{DSA}(t)$$

Consider a convolutional (non-instantaneous) model

Q4 : reconstruct the SSI

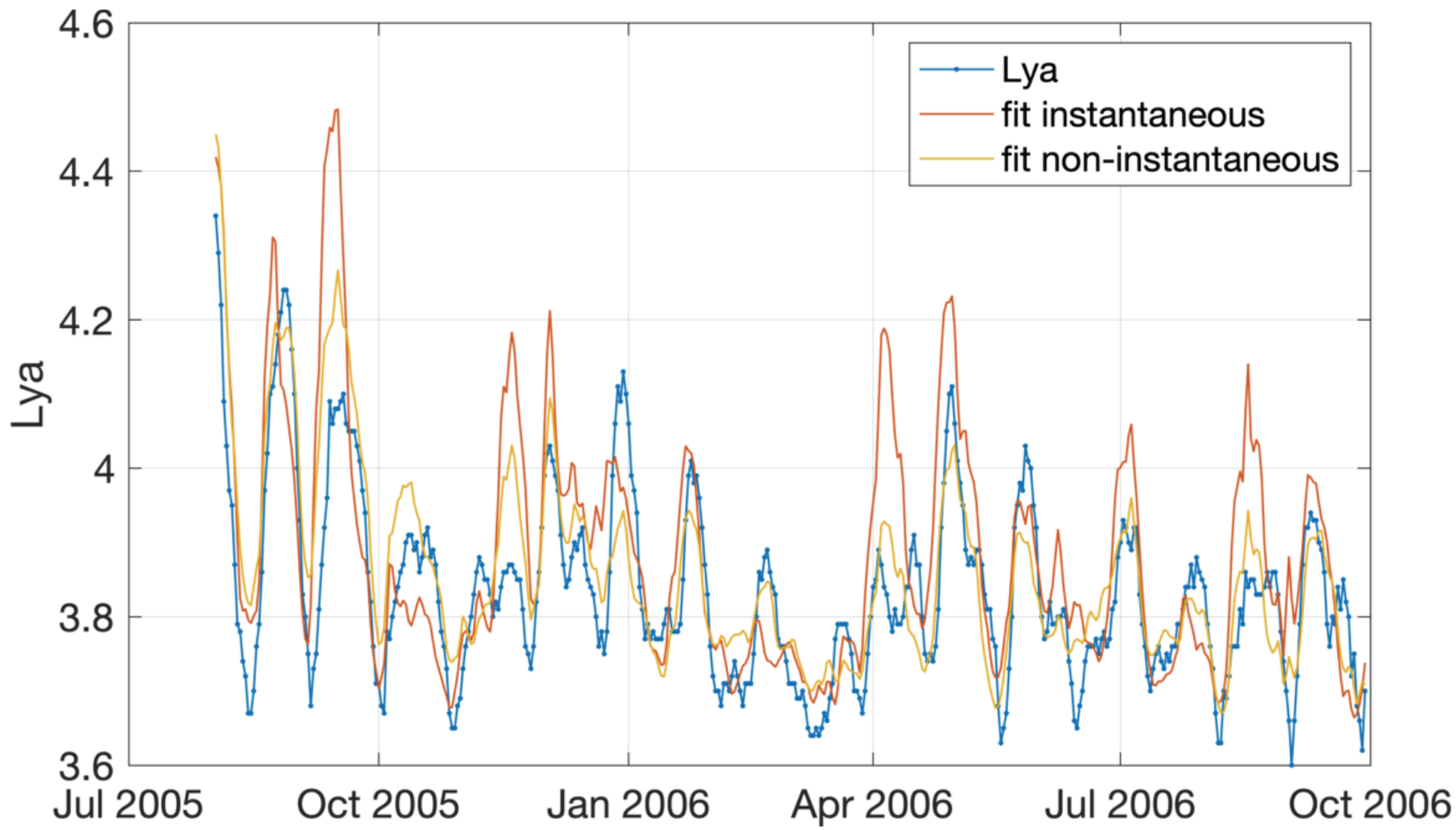
- Example : reconstruction of the TSI from SSN and DSA



Convolutional model = 48% reduction in the reconstruction error

Q4 : reconstruct the SSI

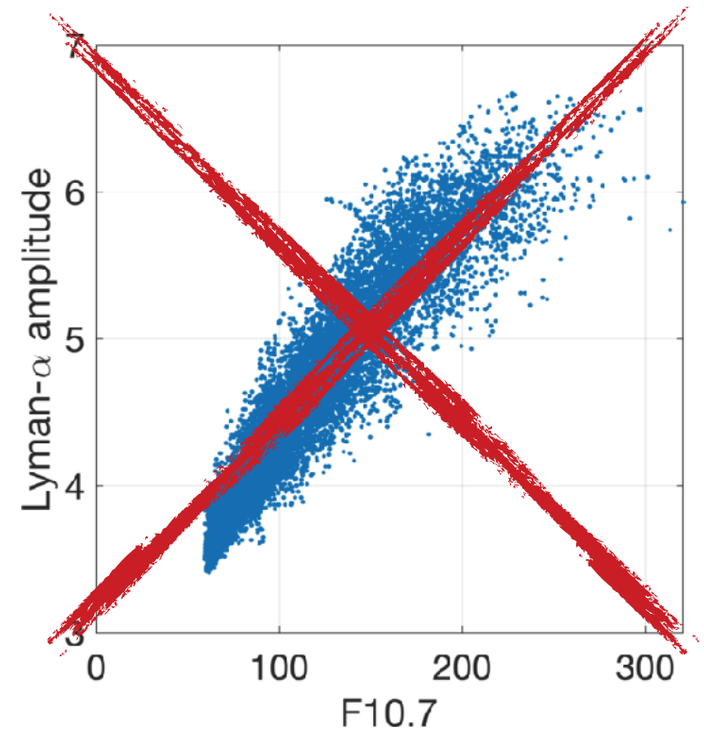
- Example : reconstruction of the Lyman-α line intensity from F10.7



Convolutional model = 51% reduction in the reconstruction error

Final conclusions

- The SSI and solar proxies do **not** respond instantaneously to each other (and to spot emergence)



- Scatter plots are misleading (unless averaged over > month)
- Taking into account this convolutional response is important for
  - better reconstructing the SSI from proxy data
  - understanding how SSI responds to sunspots
- The response of the SSI is weakly nonlinear
  → only a nonlinear model can give an accurate energy budget

more in Dudok de Wit et al. ApJ (2018) 253