Setting observational constraints on the chromospheric heating problem

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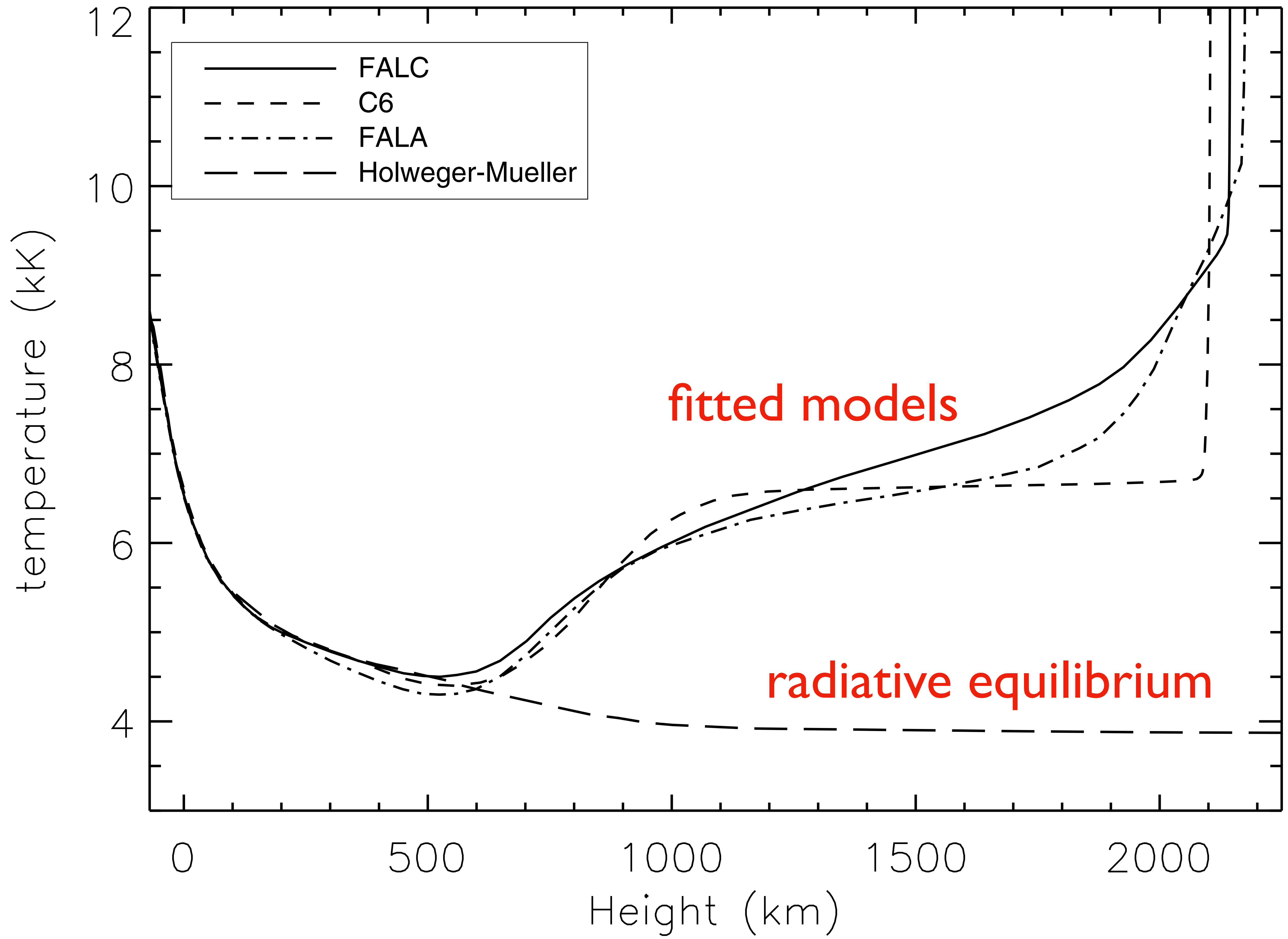
We would like you to cover the following topics:

"What are the observational constraints on the physical mechanisms that are responsible for heating in the chromosphere?

Given the observational clues/constraints, which mechanisms seem likely to play a role?"

The chromospheric heating problem



Adapted from Rezaei et al. (2008)

Sustained ***chromospheric*** radiative losses of:

- 4 kW m^{-2} in quiet Sun
- 20 kW m^{-2} in active regions

↓

No information about the heating processes!

What might heat the chromosphere?

Many heating and energy transport mechanisms have been proposed from theoretical studies:

Magneto-acoustic waves and shocks	Ohmic current dissipation	Ambipolar diffusion
Magnetic reconnection	Viscous heating	Turbulent Alfvén wave cascade

The question is:
In which <u>proportion</u> are they contributing in different chromospheric conditions?

What might heat the chromosphere?

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- Ohmic current dissipation
- Ambipolar diffusion
- Magnetic reconnection
- Turbulent Alfvén wave cascade

Estimating these heating terms require **knowledge** of the **magnetic field** or the **electric current** vectors

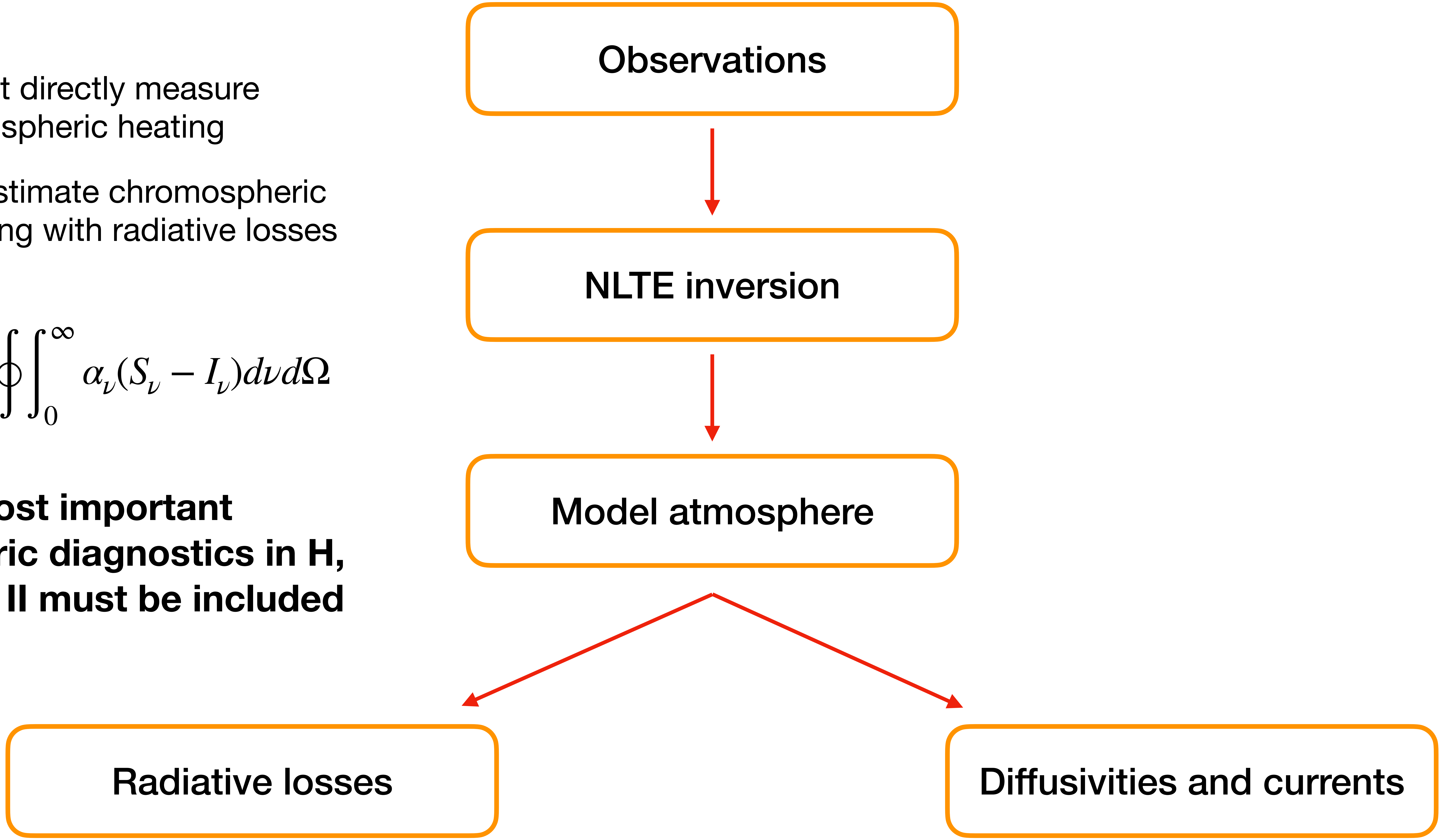
Radiative losses: the energy budget

We cannot directly measure chromospheric heating

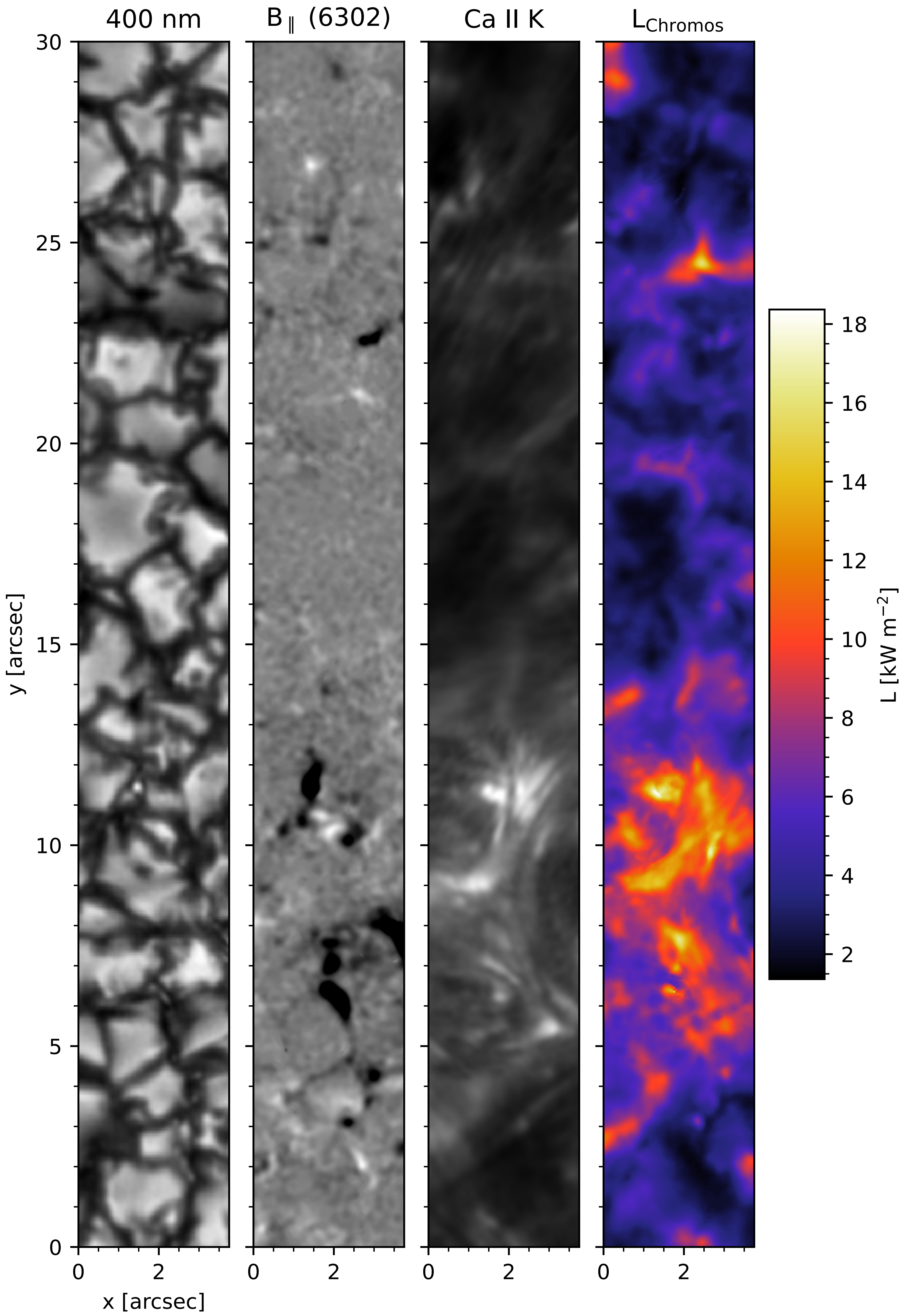
But we can estimate chromospheric heating / cooling with radiative losses

$$Q = \nabla \cdot \boldsymbol{F} = \oint \int_0^\infty \alpha_\nu (S_\nu - I_\nu) d\nu d\Omega$$

The most important chromospheric diagnostics in H, Ca II and Mg II must be included

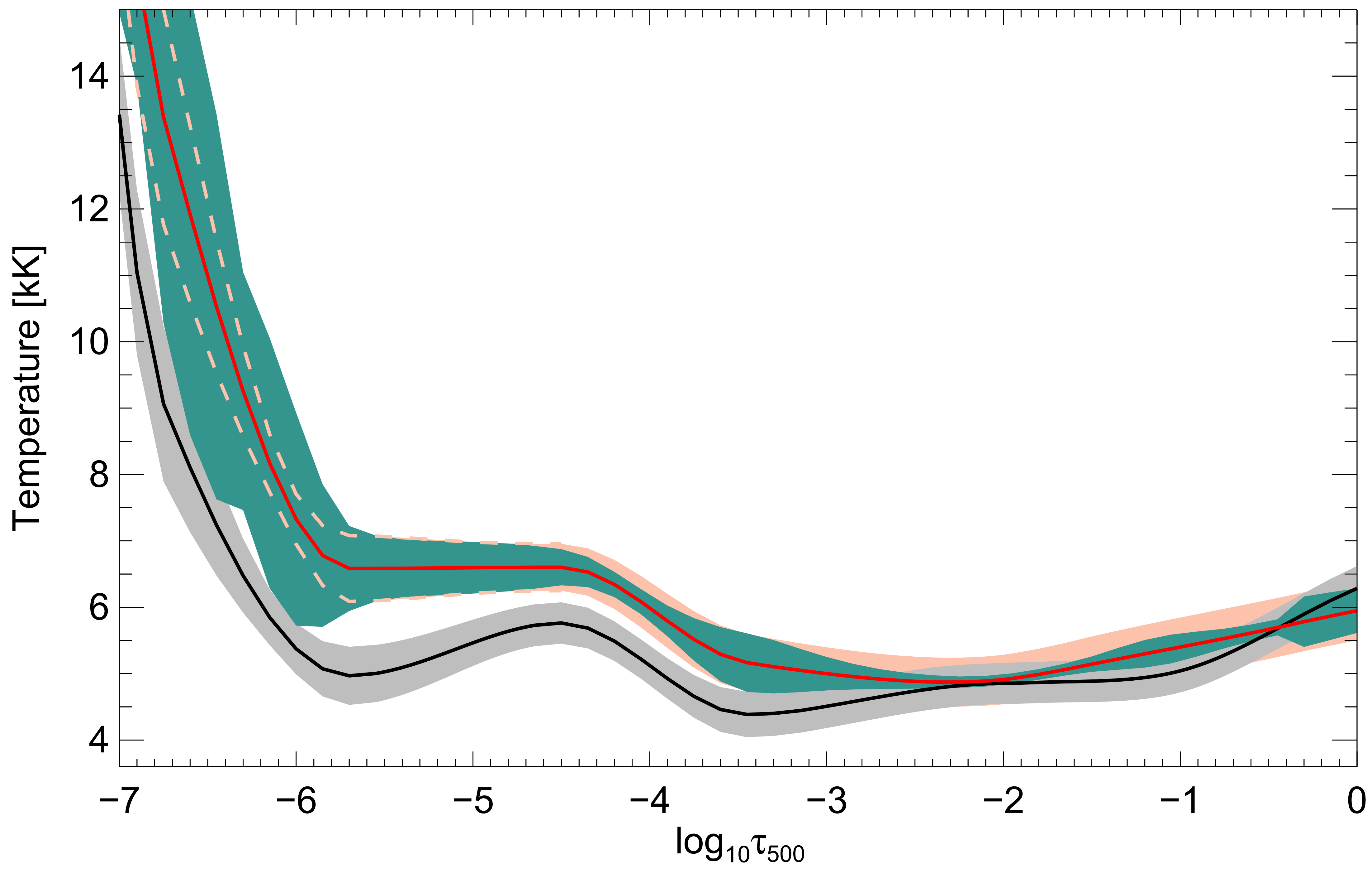


Radiative losses: QS / inter-network

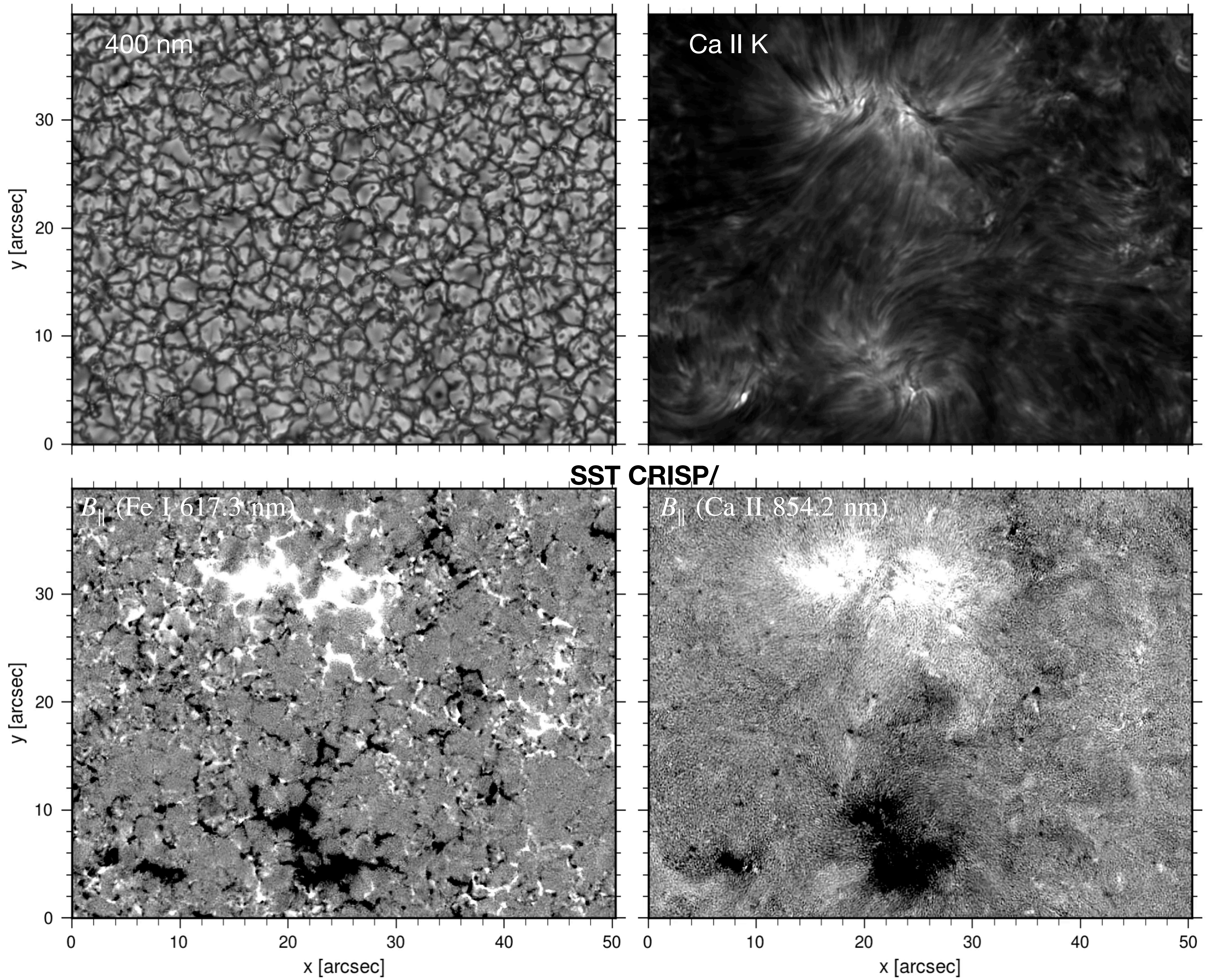


de la Cruz Rodriguez & Leenaarts (in prep.)

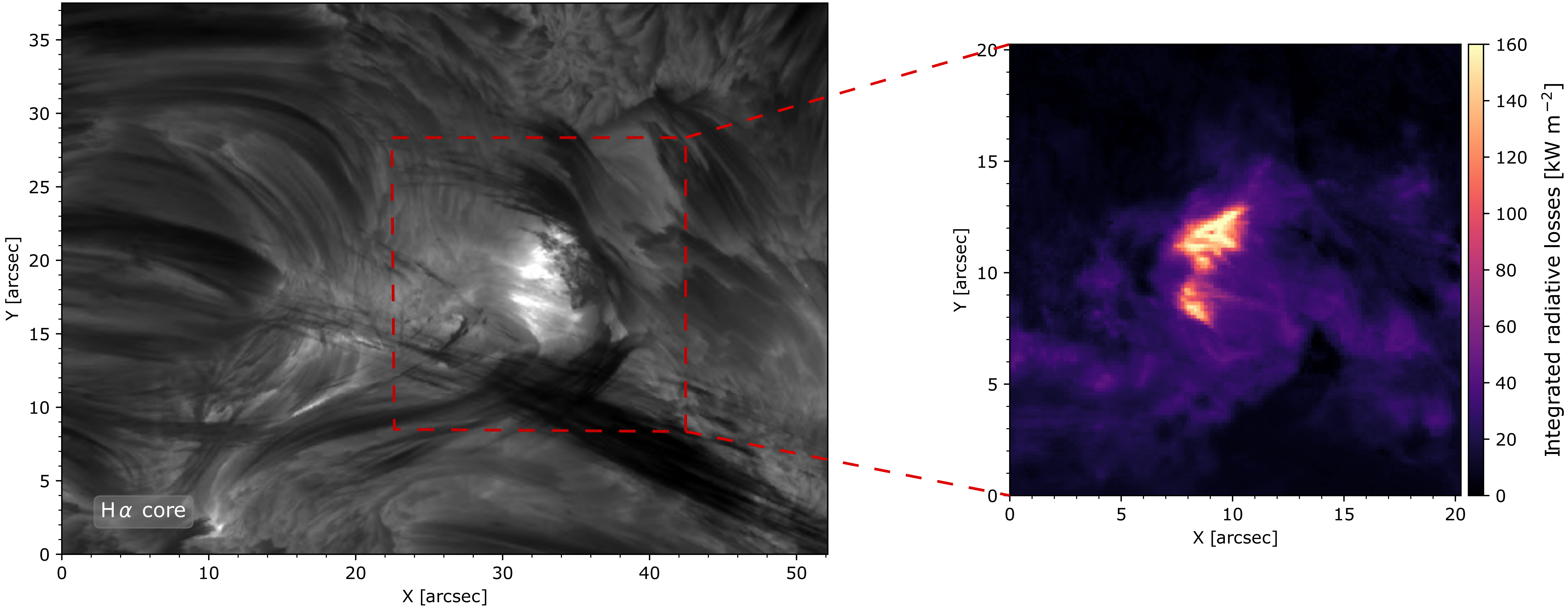
Radiative losses: QS / inter-network



Gosic et al. (2018)

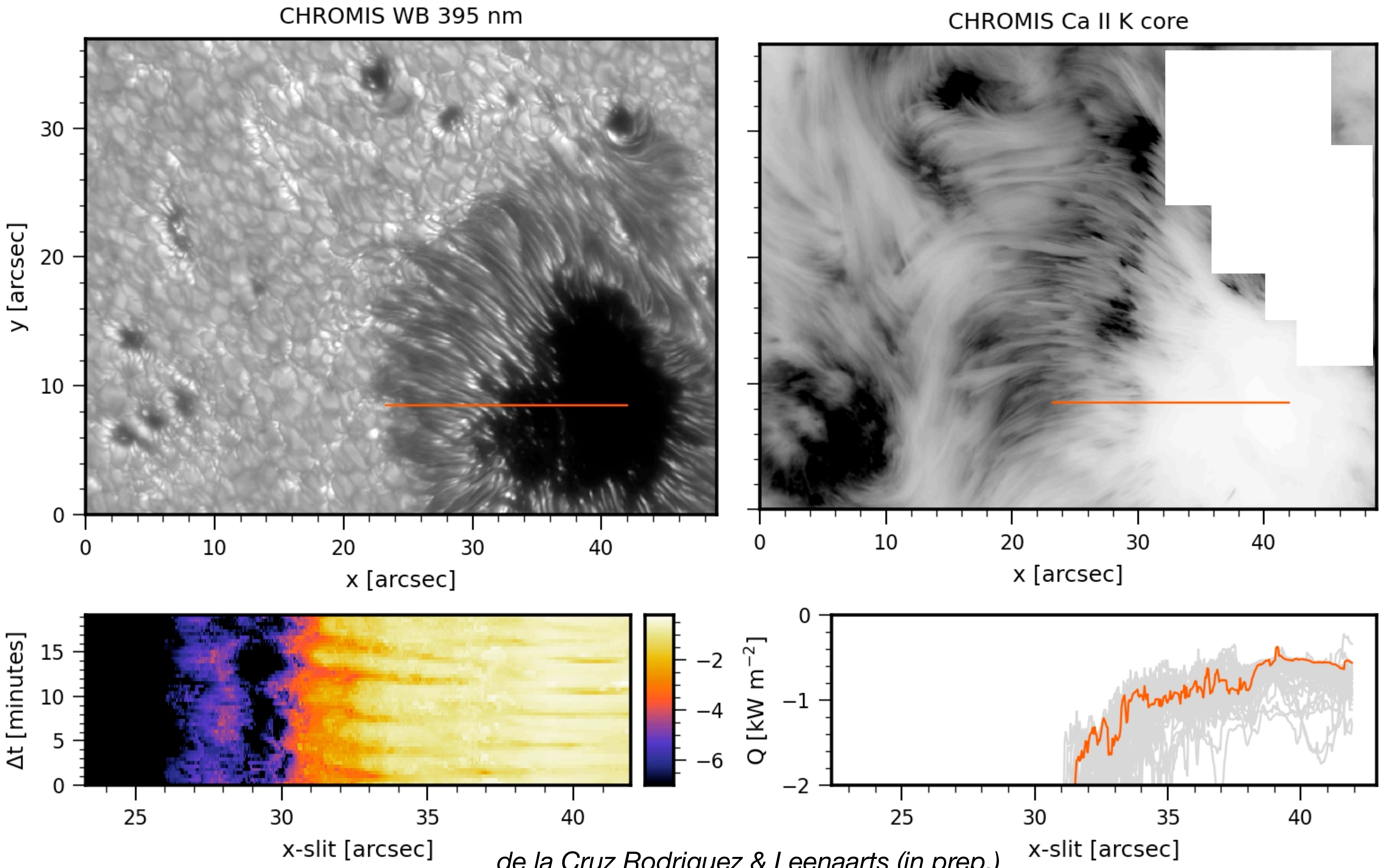


Radiative losses: magnetic reconnection



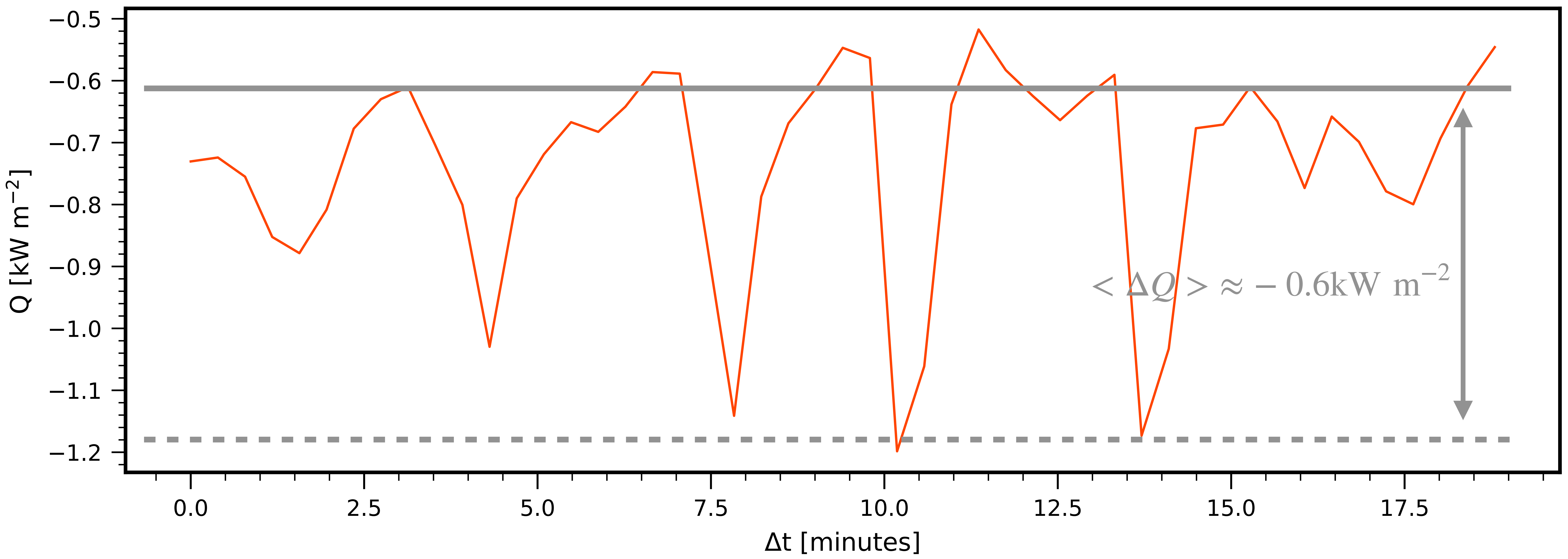
Diaz Baso, de la Cruz Rodriguez & Leenaarts (2020)

Radiative losses: umbral flashes



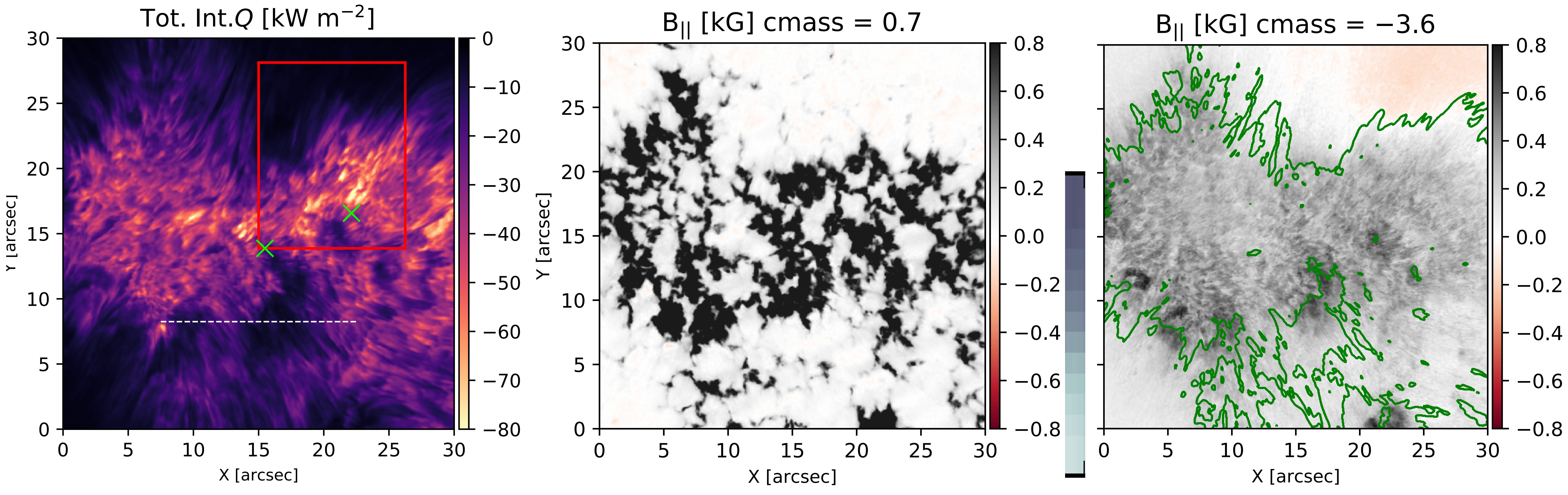
de la Cruz Rodriguez & Leenaarts (in prep.)

Radiative losses: umbral flashes



de la Cruz Rodriguez & Leenaarts (in prep.)

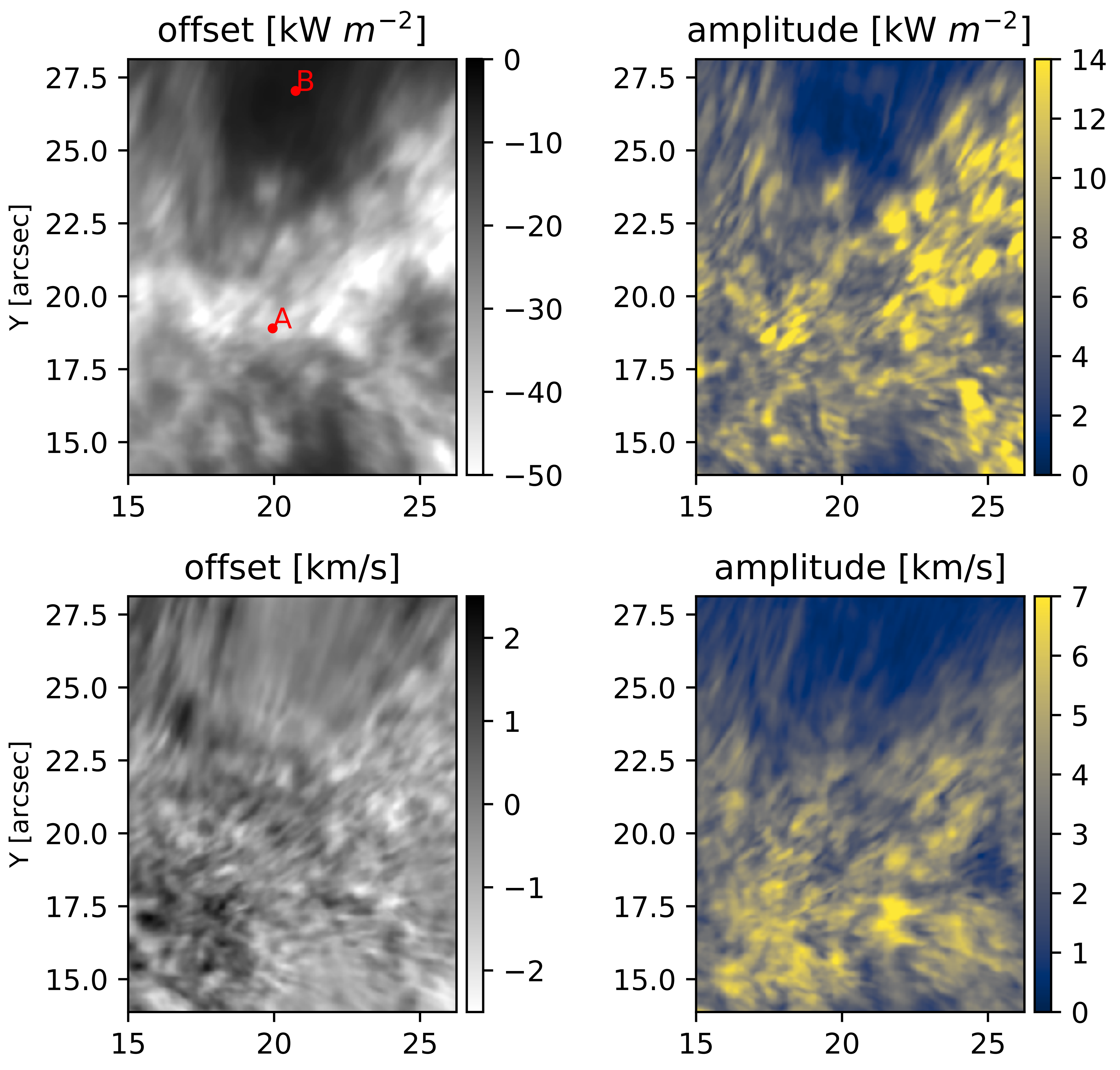
Radiative losses: plage



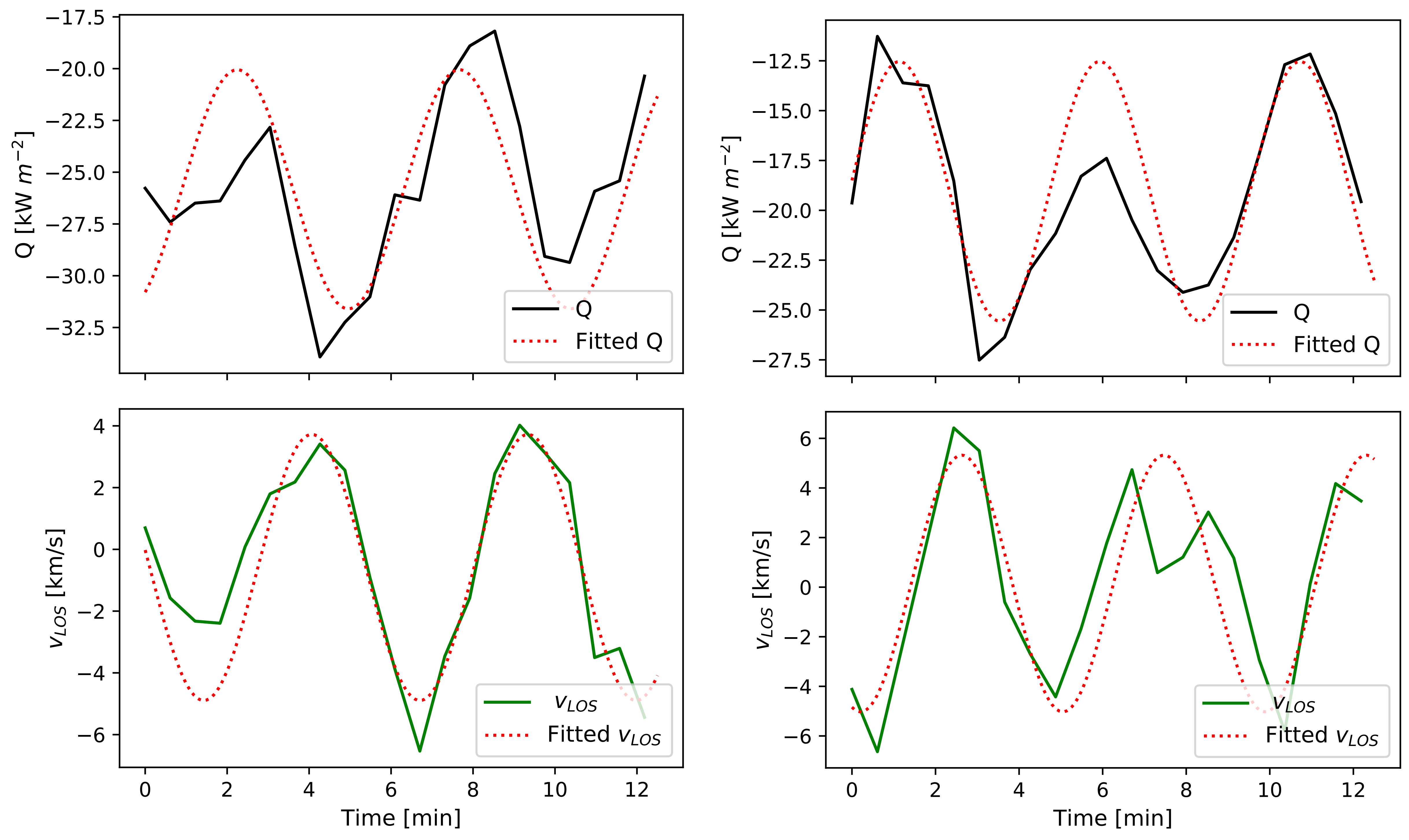
Morosin et al. (2022)

- ***Upper photosphere*:** radiative losses dominate between footpoints (canopy effect)
- ***Chromosphere***: Radiative losses are room filling over the photospheric footpoints

Radiative losses: plage



Temporal evolution of $Q_{\rm rad}$ and $v_{\rm l.o.s}$



Morosin et al. (2022)

“Radiative losses allow us to estimate the total energy budget and we can look at correlations with other parameters"

“Can we do (observationally) better?“

Can we separate the contribution from different heating terms?

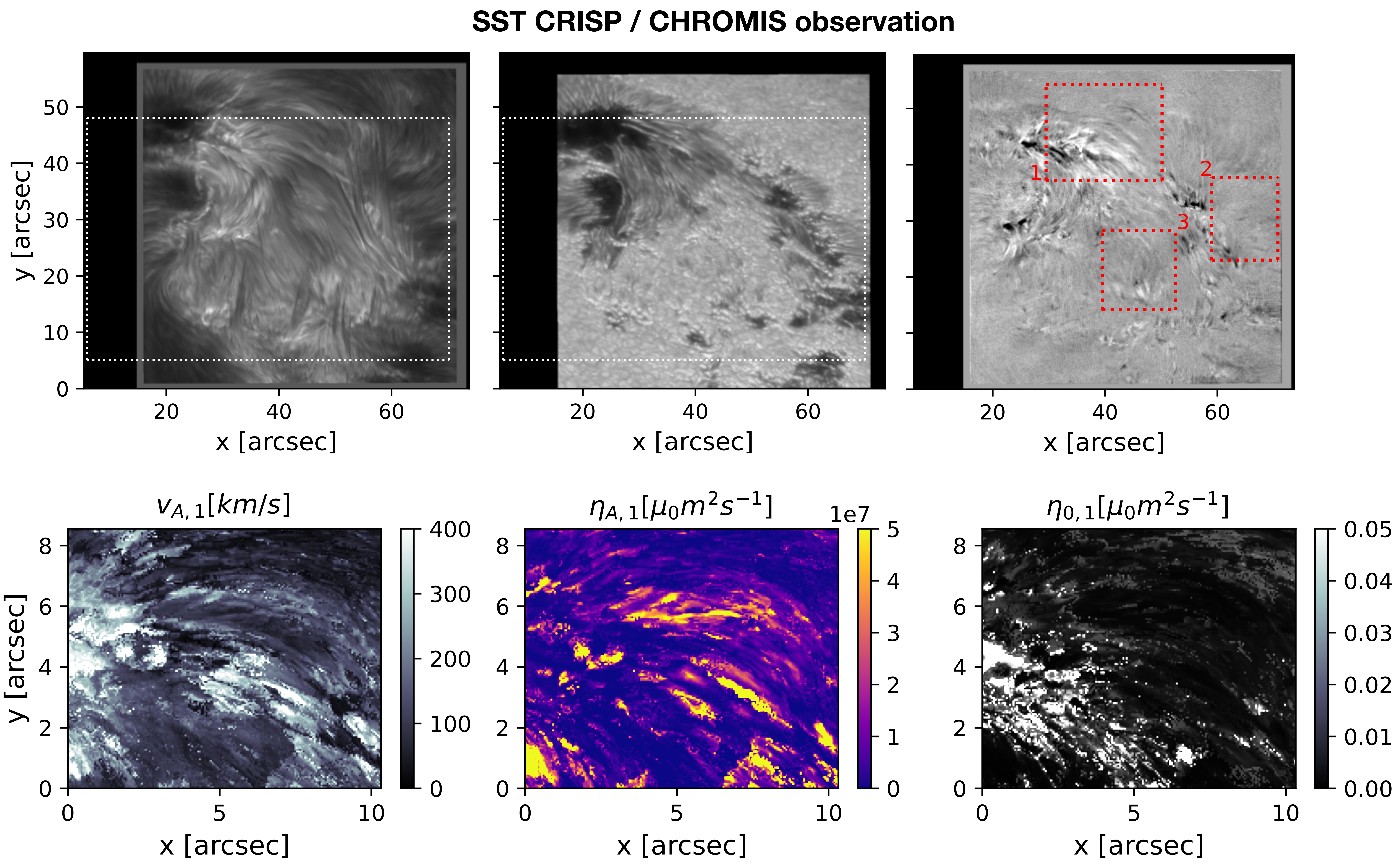
Many contributions are characterized through a diffusivity:

- Ambipolar diffusion: $Q_A = \eta_A J_\perp^2$
- Ohmic dissipation: $Q_O = \eta_O J^2$
- Viscous heating: $H_\nu = \nu_{\rm vis} \left[\frac{1}{2} e_{ij} e_{ij} - \frac{2}{3} (\nabla \cdot \boldsymbol{v})^2 \right]$
- Wave dissipation flux: $E = \rho v_A |v|^2$

The diffusivities can be estimated from the inversion results

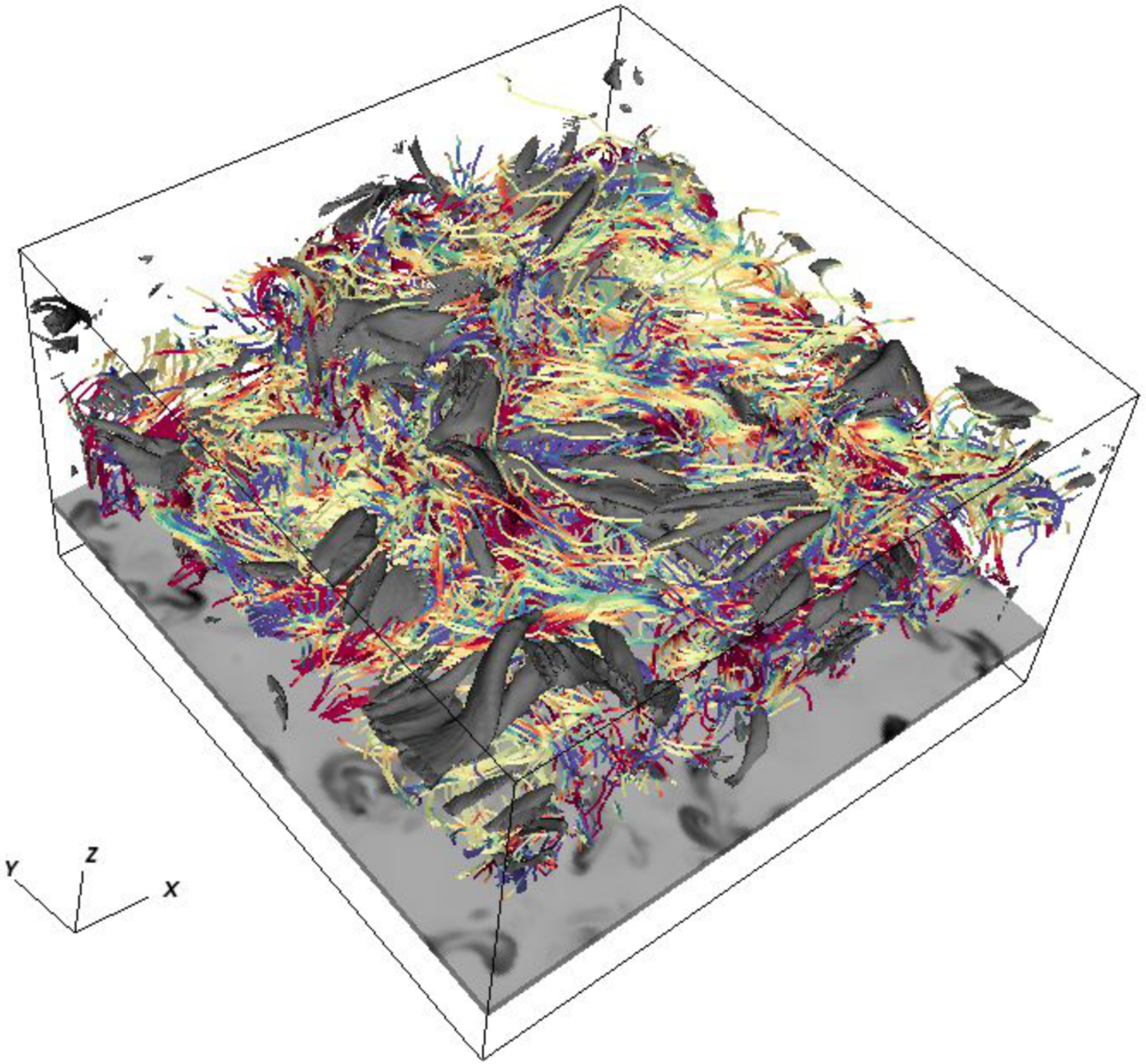
Estimating the current vector and e_{ij} requires *spatial derivatives*

Can we separate the contribution from different heating terms?



Morosin PhD thesis (2022)

Can we separate the contribution from different heating terms?

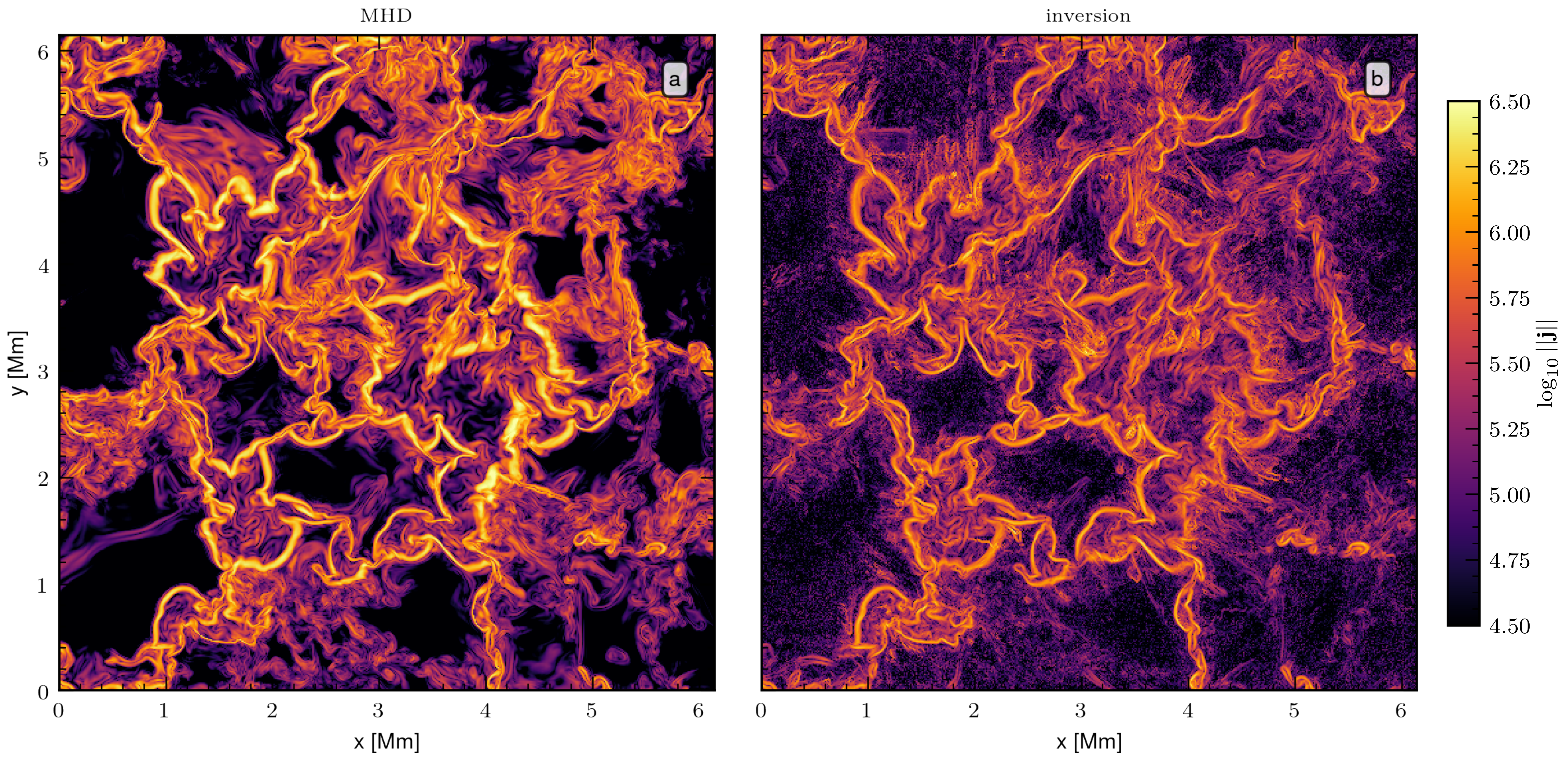


Khomenko et al. (2018)

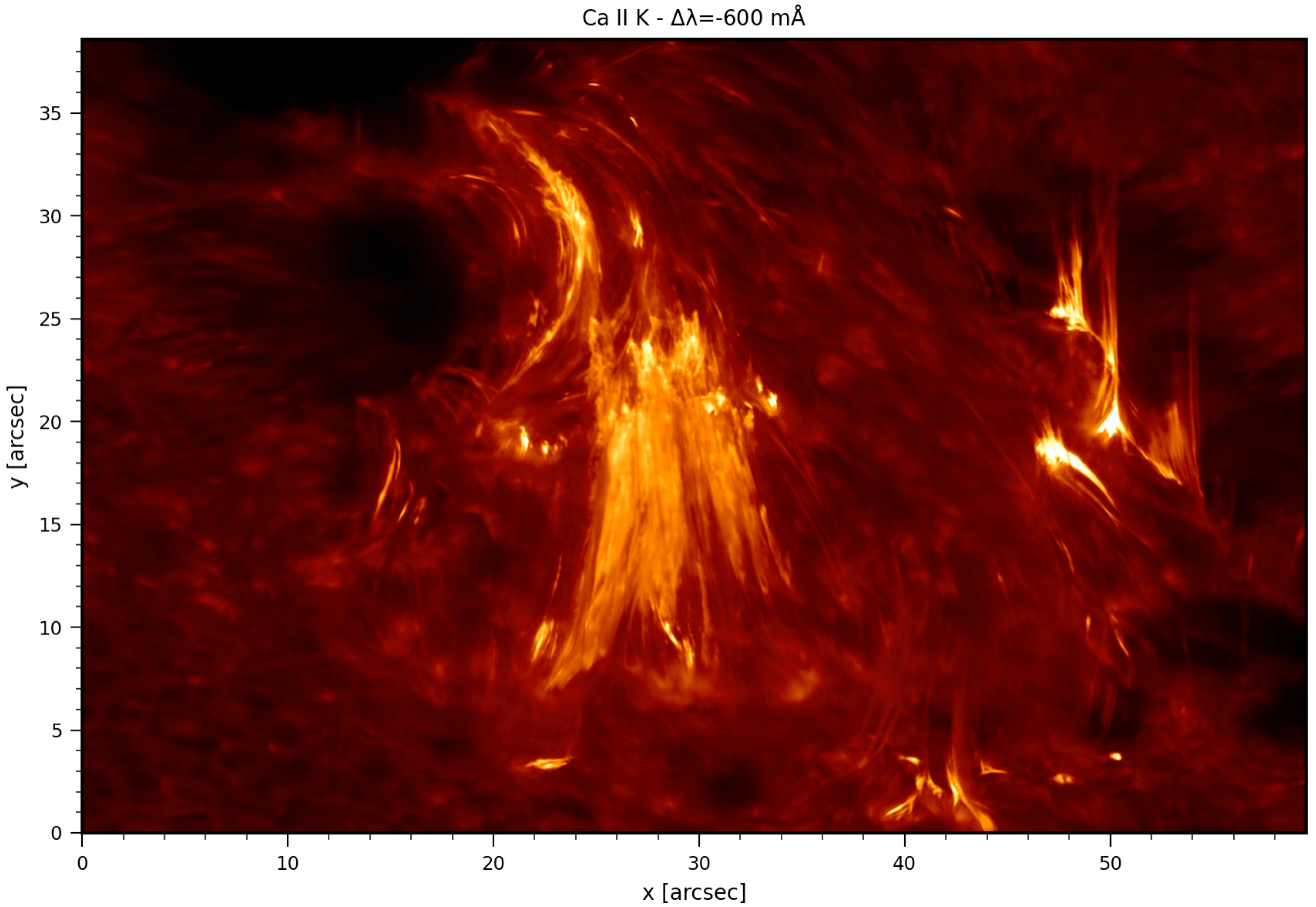
Can we estimate the current vector?

Magneto-hydrostatic (MHS) pressure balance

Derivation of electric currents: $\boldsymbol{j} = \nabla \times \boldsymbol{B}/\mu$



Adapted from Pastor Yabar et al. (2021)


Ca II K - Δλ=-600 mÅ
y [arcsec]
x [arcsec]
0
5
10
15
20
25
30
35
0
10
20
30
40
50

What observations do we need?

Many diagnostics
(lines, continua, polarization, et al.)

High spatio-temporal resolution

Large field of view
(full active regions)

Unfortunately, this is what we get:

Few diagnostics with very weak polarization sensitivity

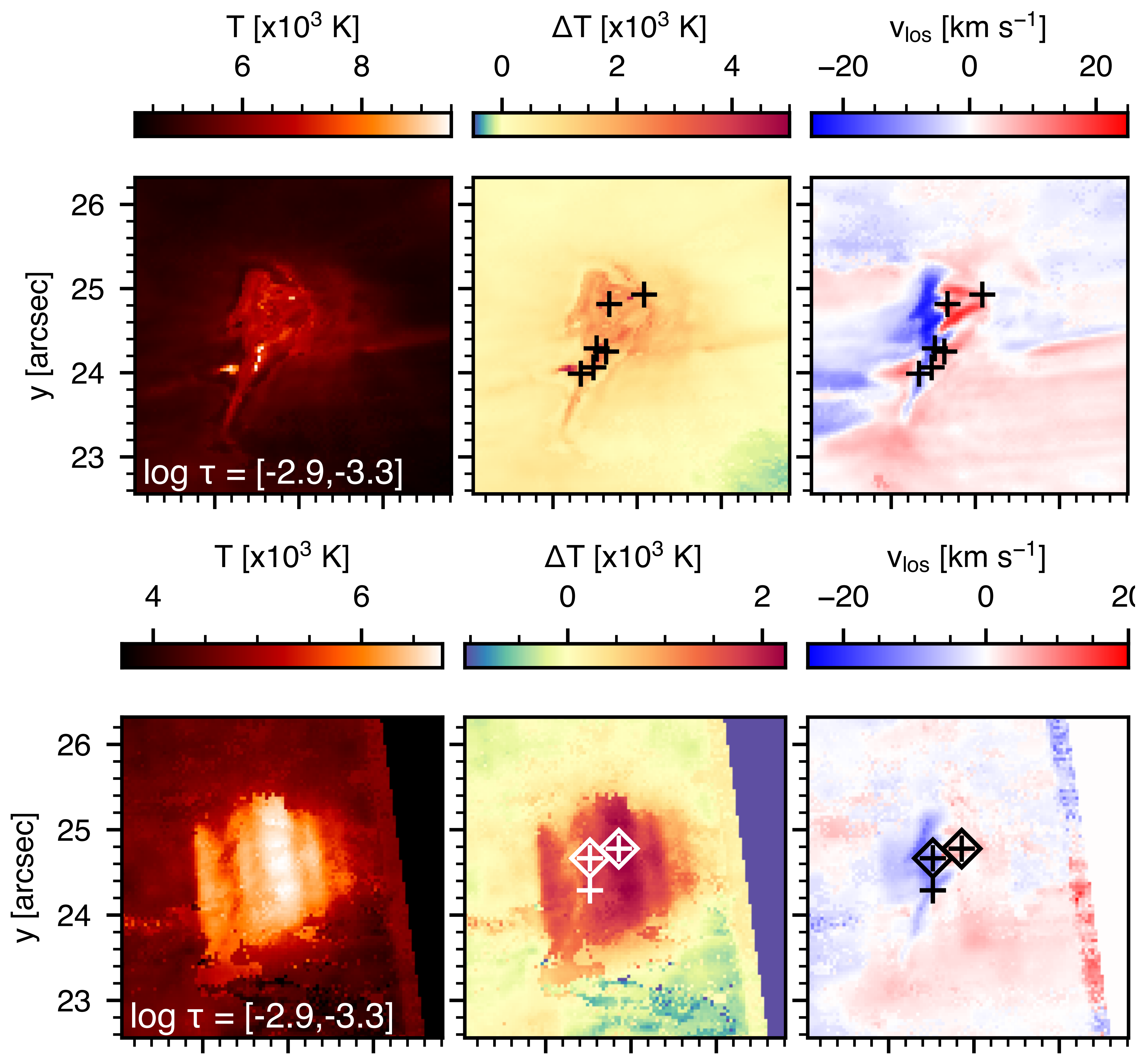
Inhomogeneous spatial resolution and limited temporal cadence

Small FOV
(when spatial resolution is high)

Large spread in wavelength:
Lyman alpha, Si IV lines, Mg II h&k, Ca II H&K, Mg I b, Na I D, Ca II IR triplet, He I 10830, mm-cont

Combining data from different facilities

SST, ALMA, IRIS, DKIST, Sunrise III → very different spatial resolutions



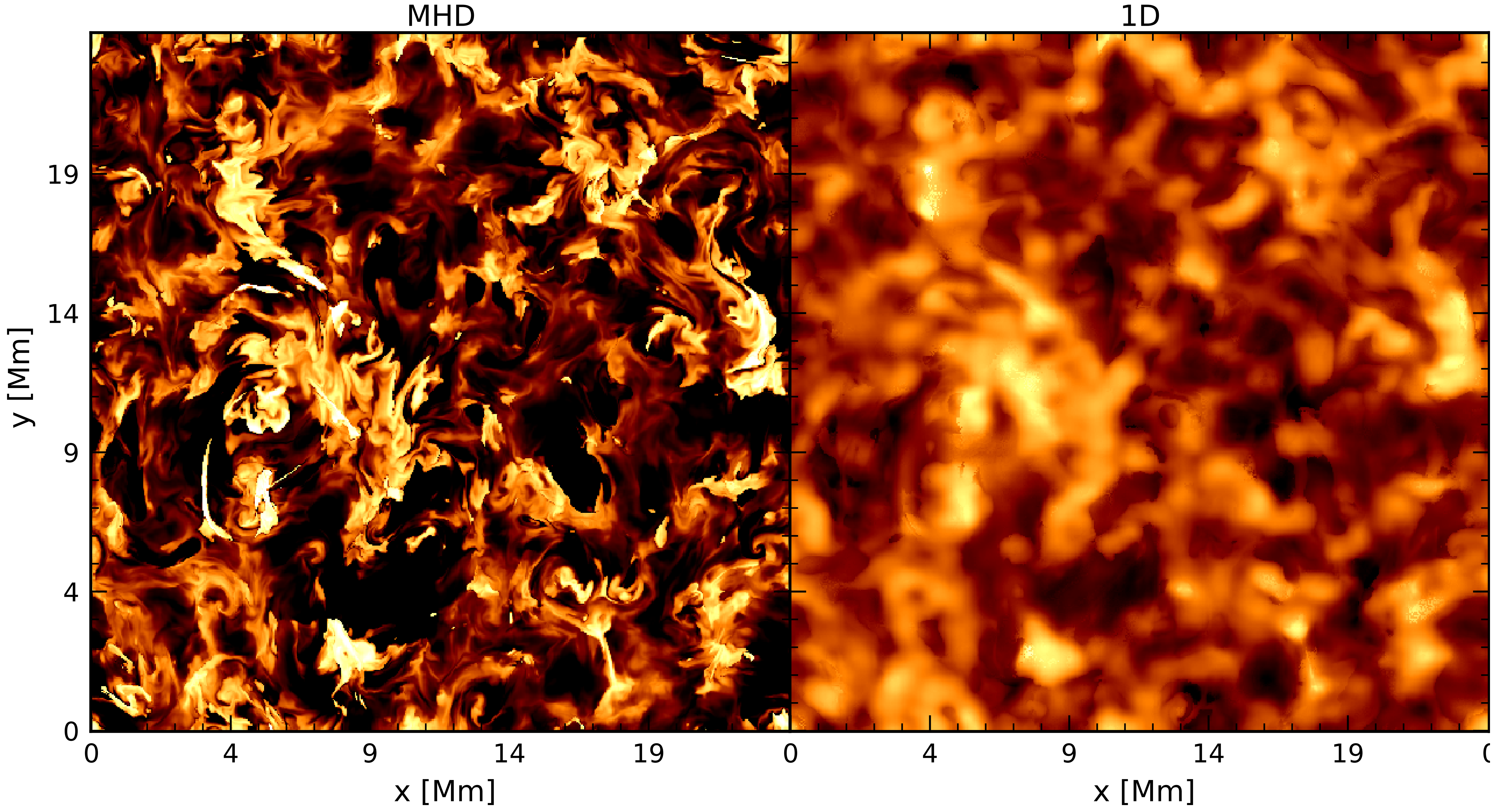
Vissers et al. (2019)

SST CRISP/CHROMIS only

SST CRISP/CHROMIS + NASA's IRIS

Combining data from different facilities

Inversion of a simulated SST/IRIS dataset



Pastor Yabar & de la Cruz Rodríguez in prep.

Combining data from different facilities

Multi-resolution inversion of SST + IRIS data

Ca II K + Ca II 8542 (pol) + Fe I 6173 + Mg II h & k

IRIS obs

Pastor Yabar & de la Cruz Rodríguez in prep.

Conclusion

In my opinion, we can use NLTE inversions to constrain the net radiative losses in the chromosphere and to estimate heating terms, but it is going to be computationally very expensive

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