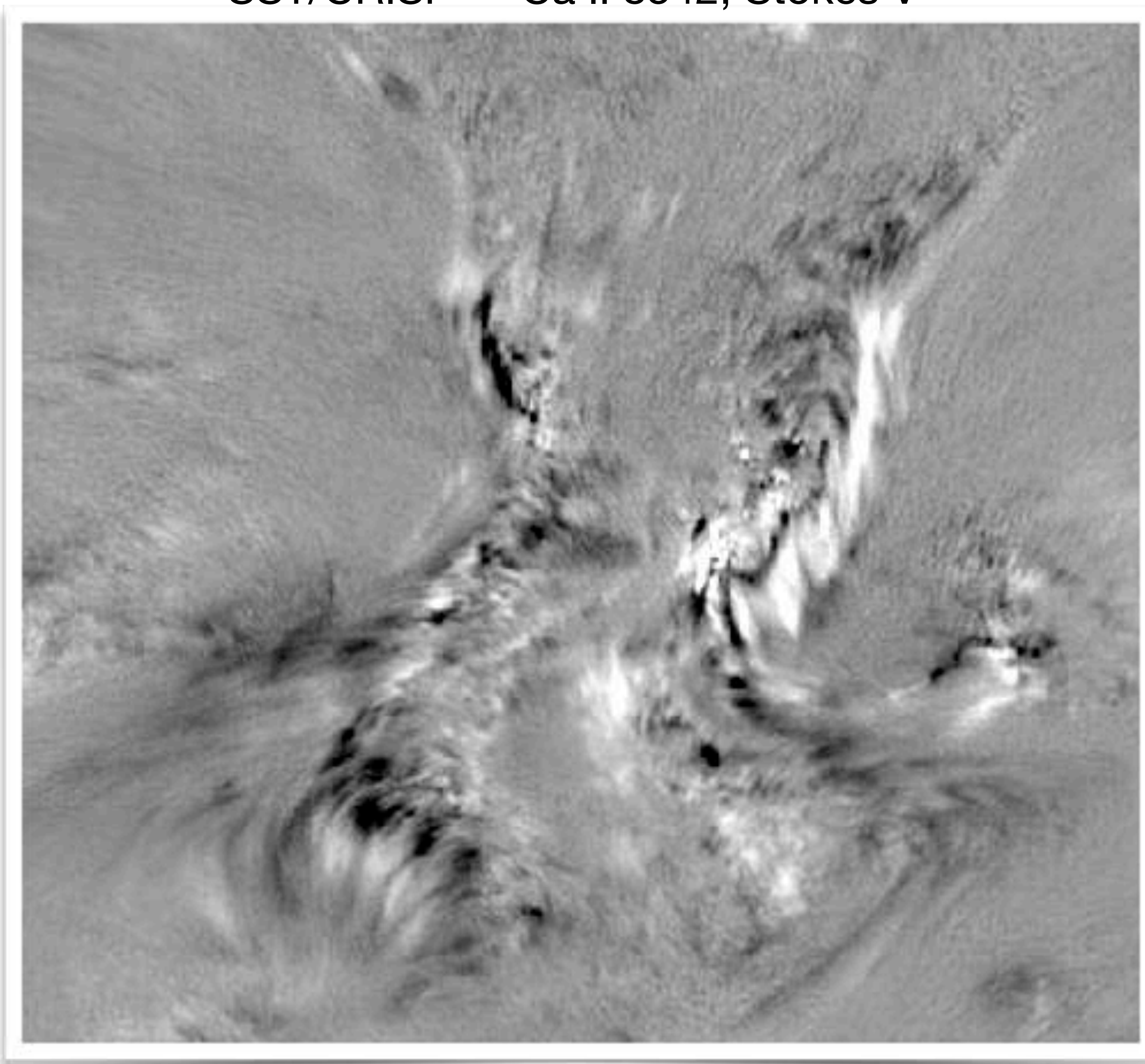
STiC —The Stockholm inversion COde: *why/where/when*

SST/CRISP — Ca II 8542, Stokes V



Jaime de la Cruz Rodríguez

The Institute for Solar Physics — Stockholm University

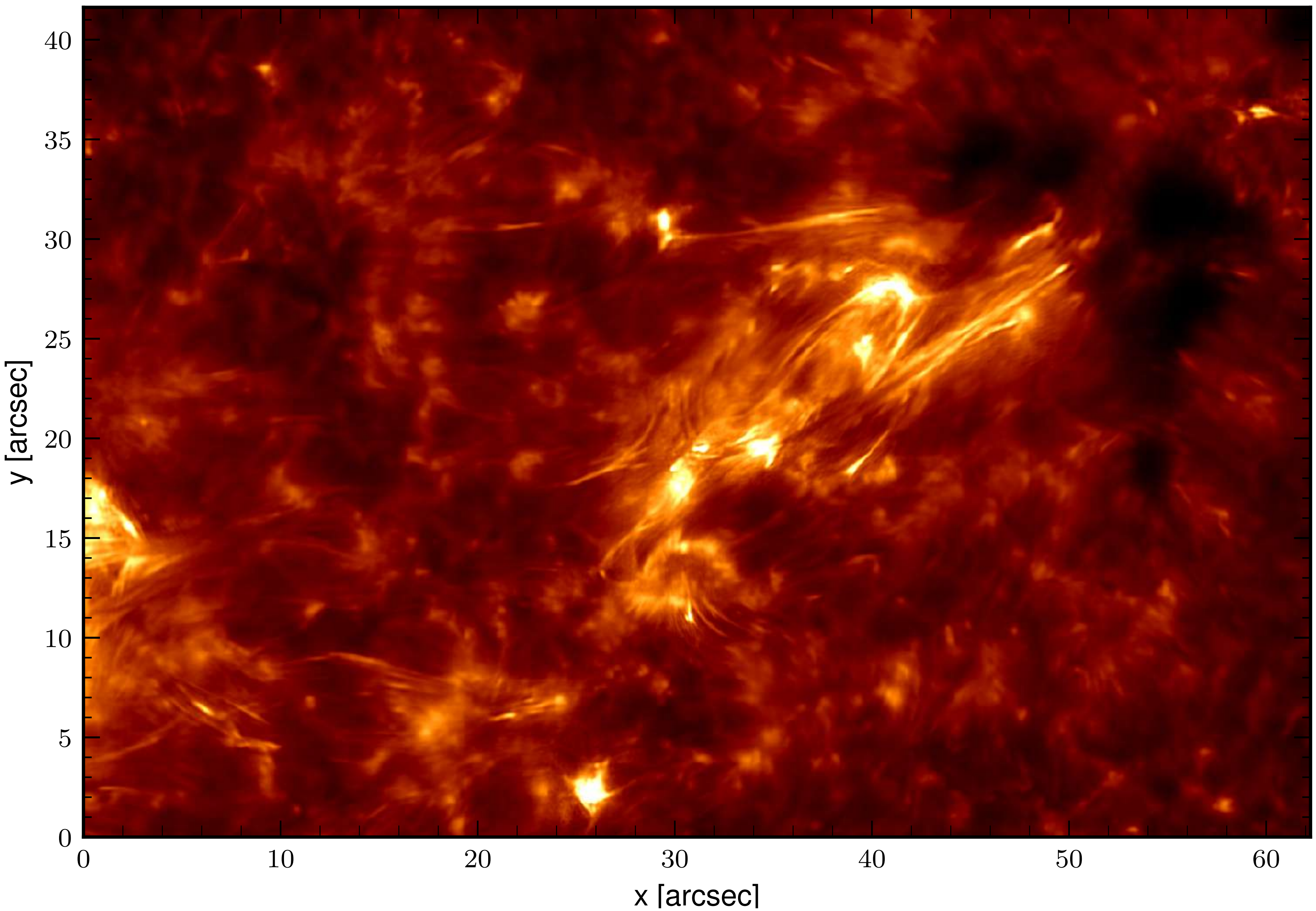
European Research Council

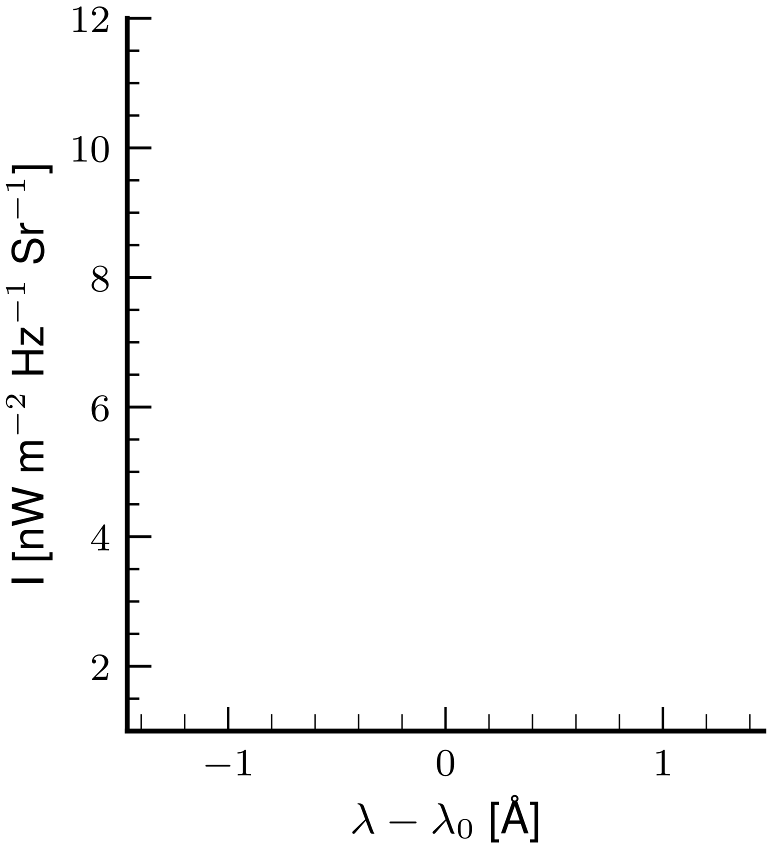
Established by the European Commission

What is an *inversion*?

The atmosphere leaves an imprint in the line profiles

SST/CHROMIS Ca II K (wing)





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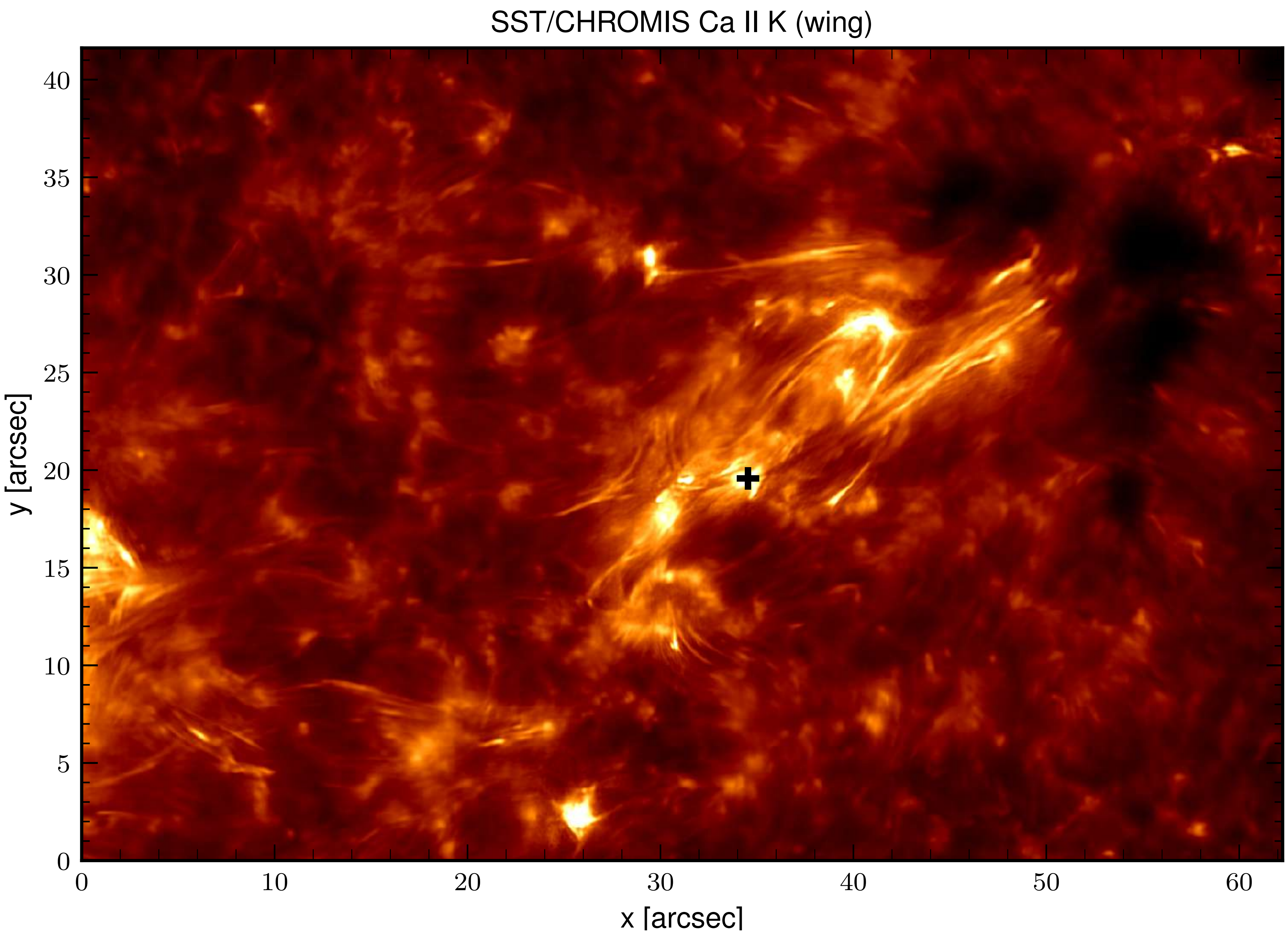

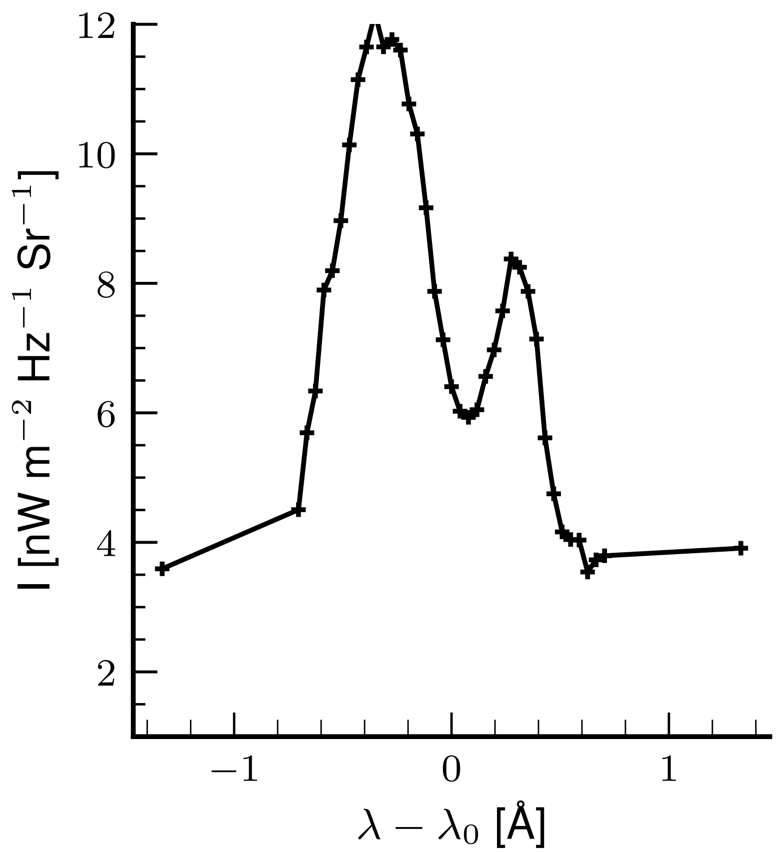

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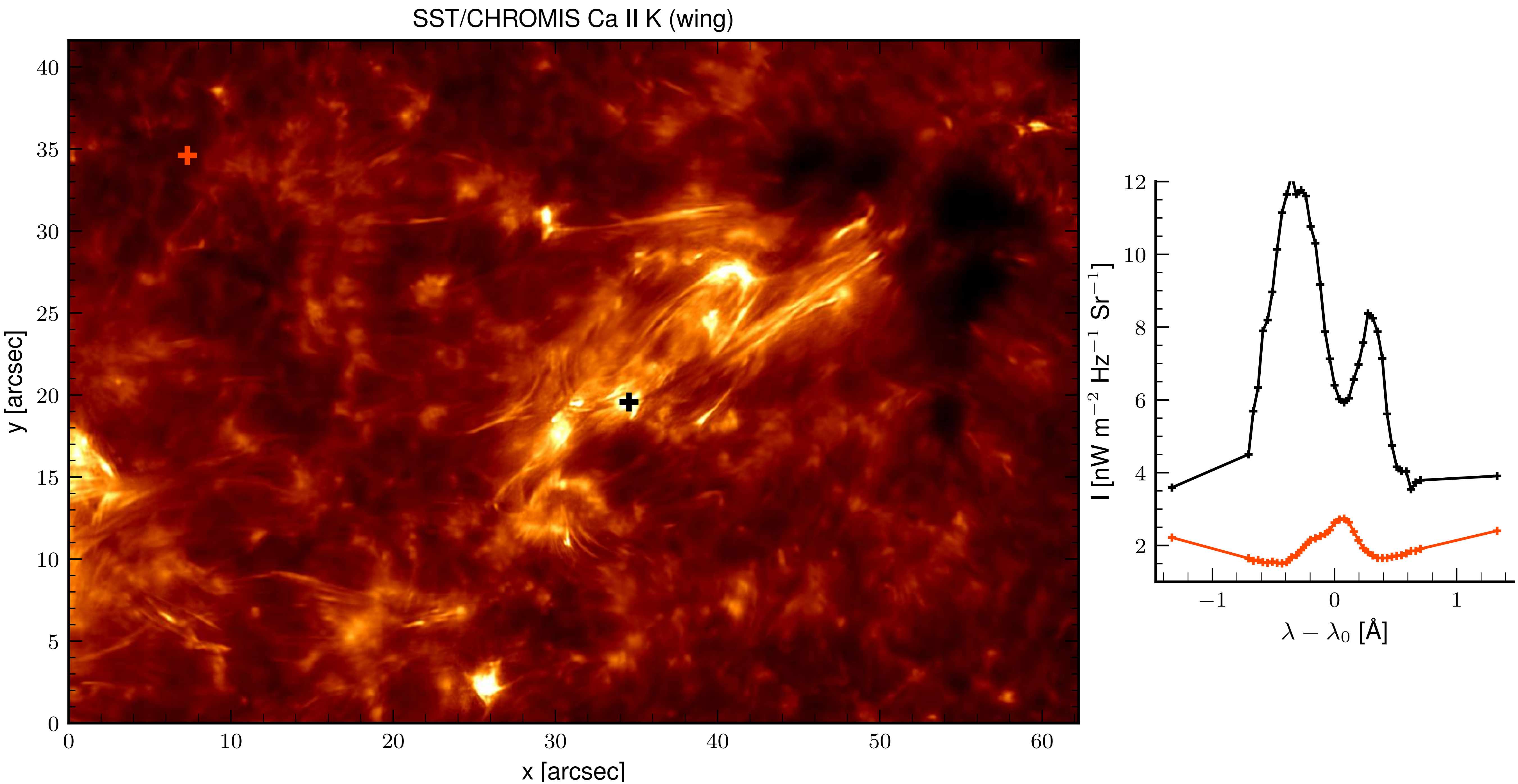

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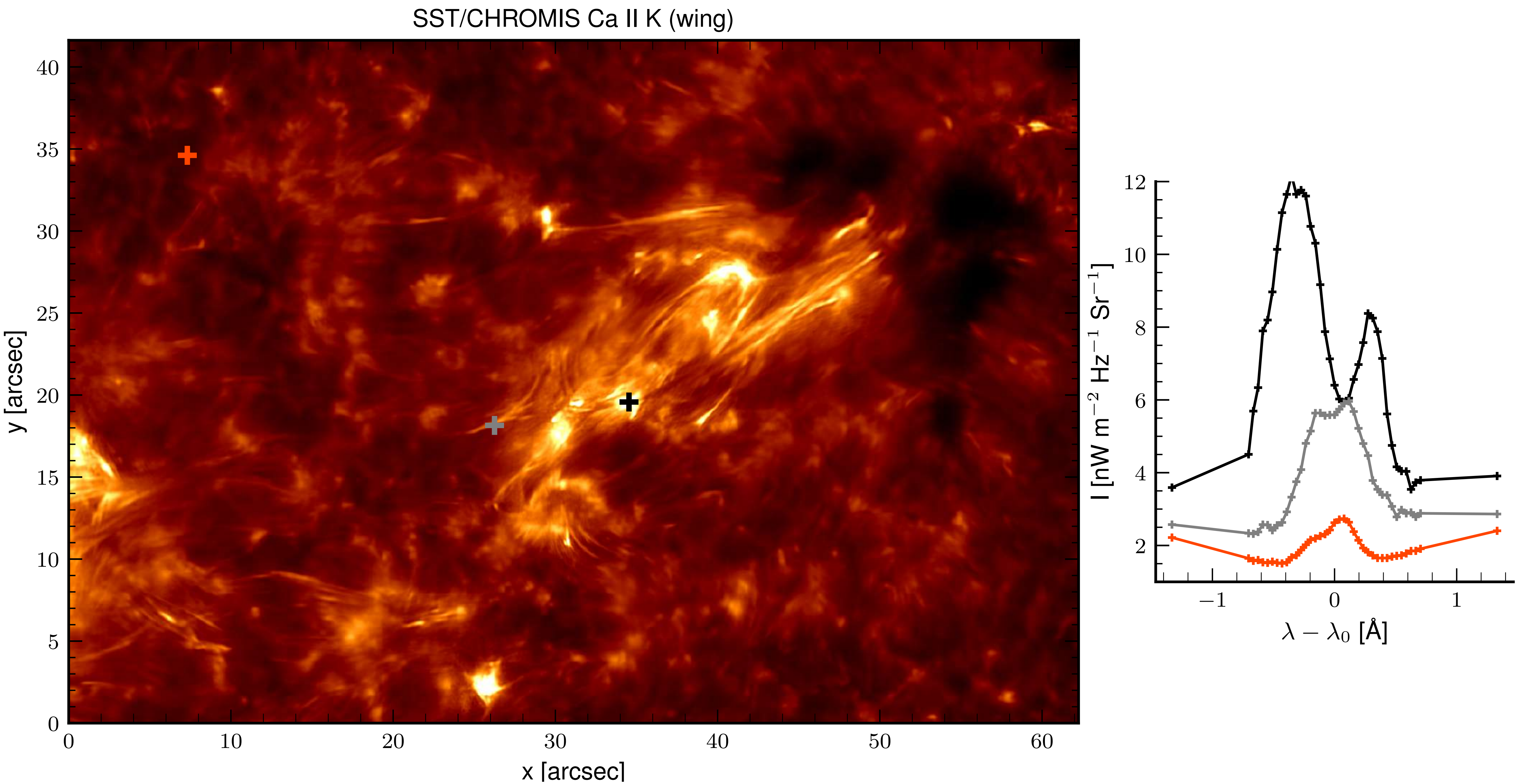

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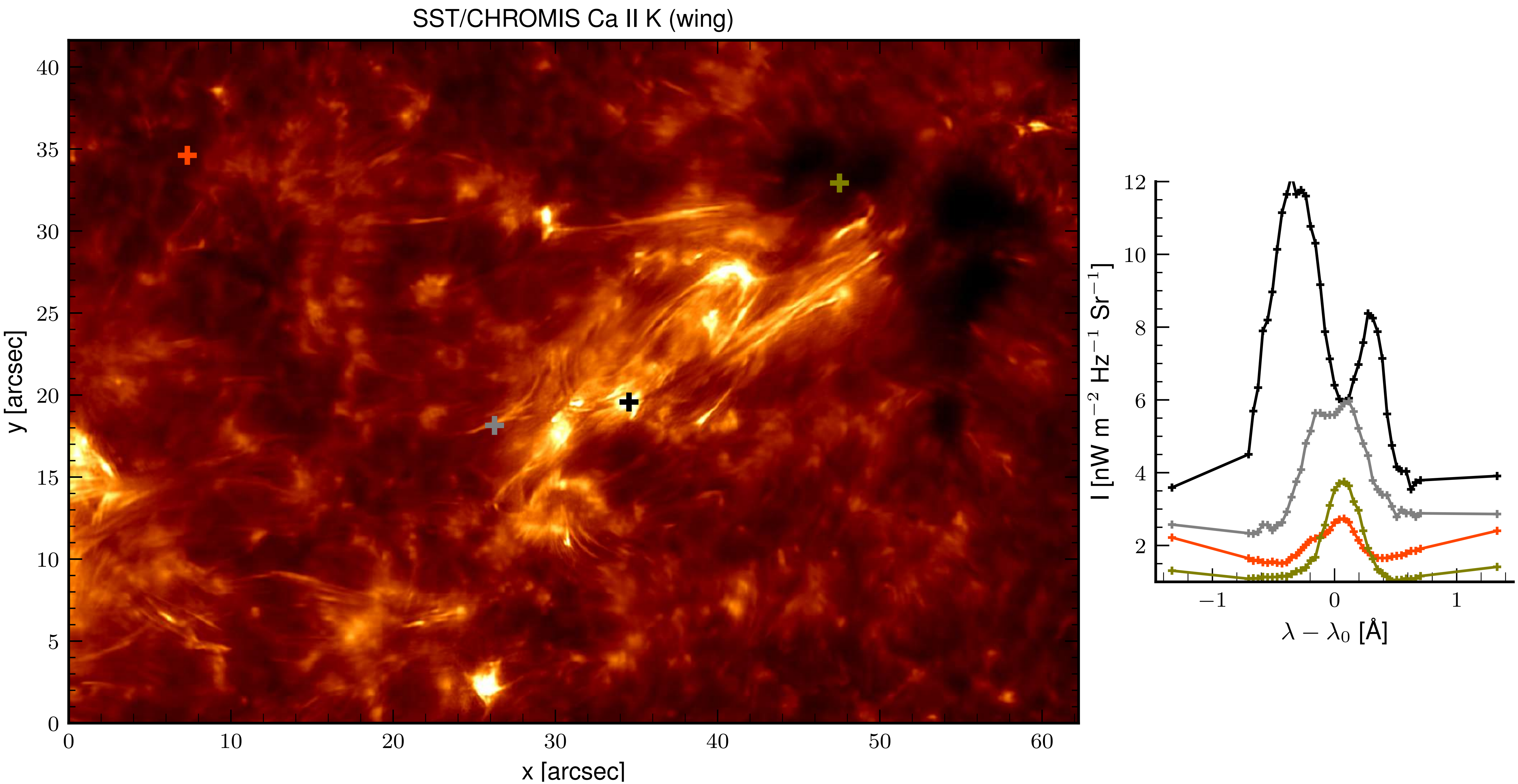

What is an *inversion*?

It is a non-linear least squares fit

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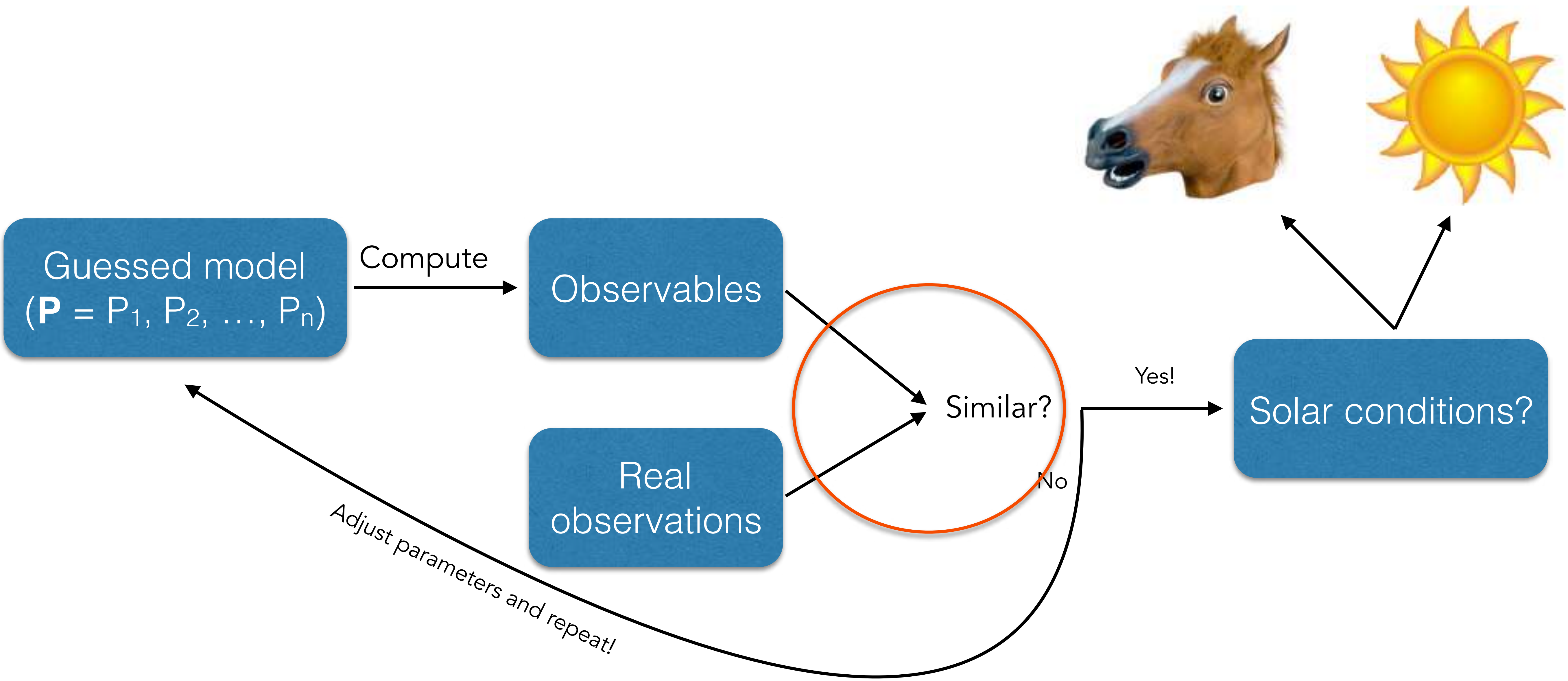

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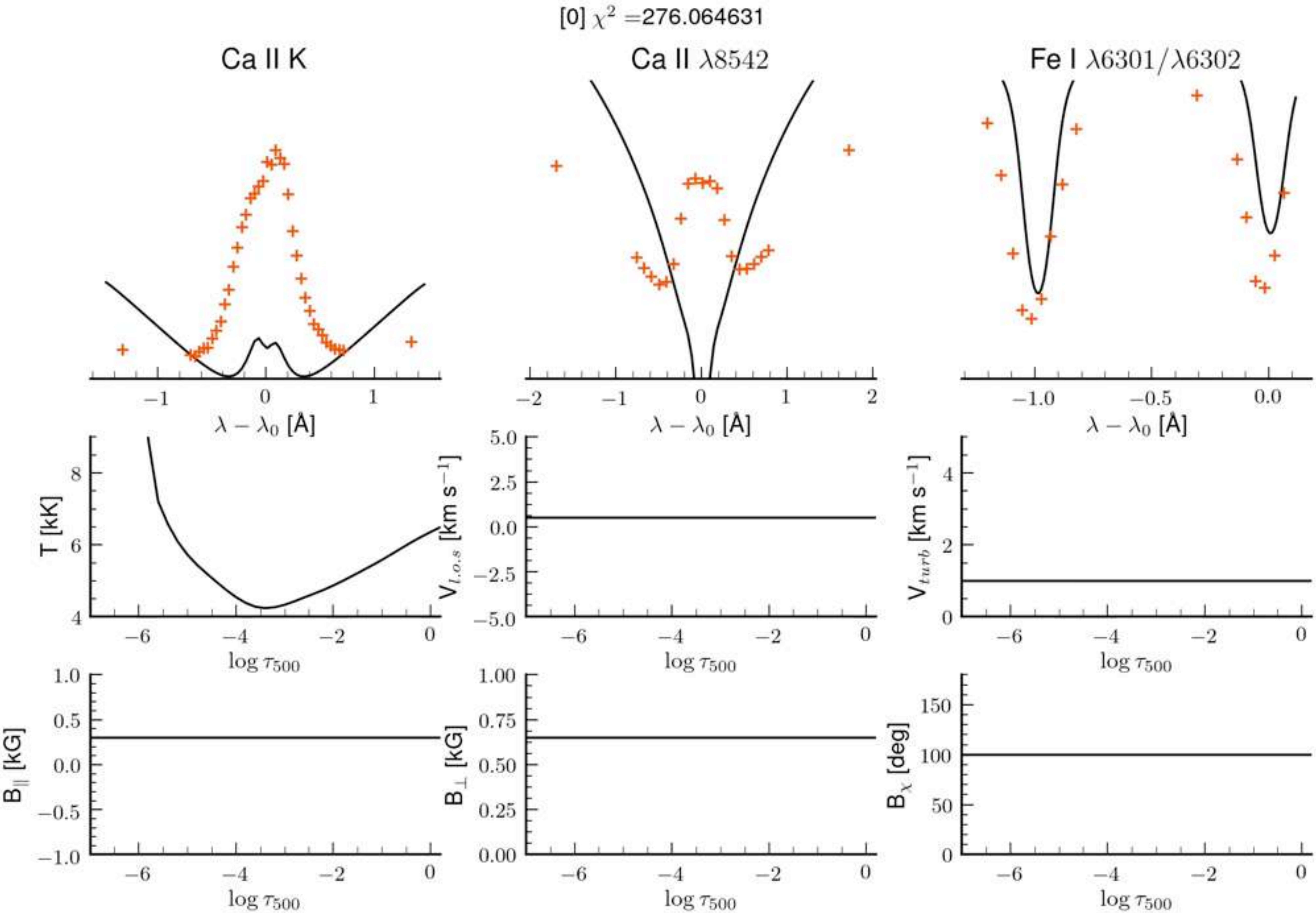
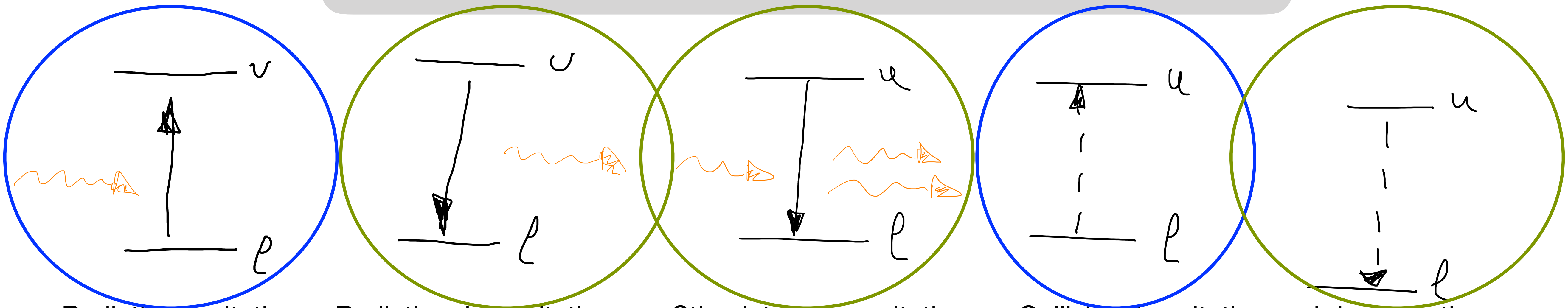


LTE vs NLTE

NLTE is a very vague term!

Let’s assume a bound-bound transition in a 2 level atom



Radiative excitation Radiative de-excitation Stimulated de-excitation Collisional excitation and de-excitation

The rate equation for this atom is:

$$\frac{n_u}{n_l} = \frac{\bar{J}B_{lu} + C_{lu}}{A_{ul} + \bar{J}B_{ul} + C_{ul}}$$

Note the dependence with J (the mean intensity) -> non-locality

When should/can I use STiC

With observations of non-LTE lines*

Zeeman induced polarization

Hydrostatic equilibrium

Line	PRD/SE	Polarization	Max. formation
Na I D1	SE	Zeeman	Upper photosphere
Mg I 517 nm	SE	Zeeman	Upper photosphere
Ca II IR triplet	SE	Zeeman + Scatt.	Lower chromosphere
H I 656 nm	SE	Zeeman + Scatt.	Middle chromosphere
He I D3	SE	Zeeman + Scatt.	Mid/up chromosphere
He I 1083 nm	SE	Zeeman + Scatt.	Mid/up chromosphere
Ca II H & K	PRD	Zeeman + Scatt.	Upper chromosphere
Mg II h & k	PRD	Zeeman + Scatt.	Upper chromosphere

What is STiC?

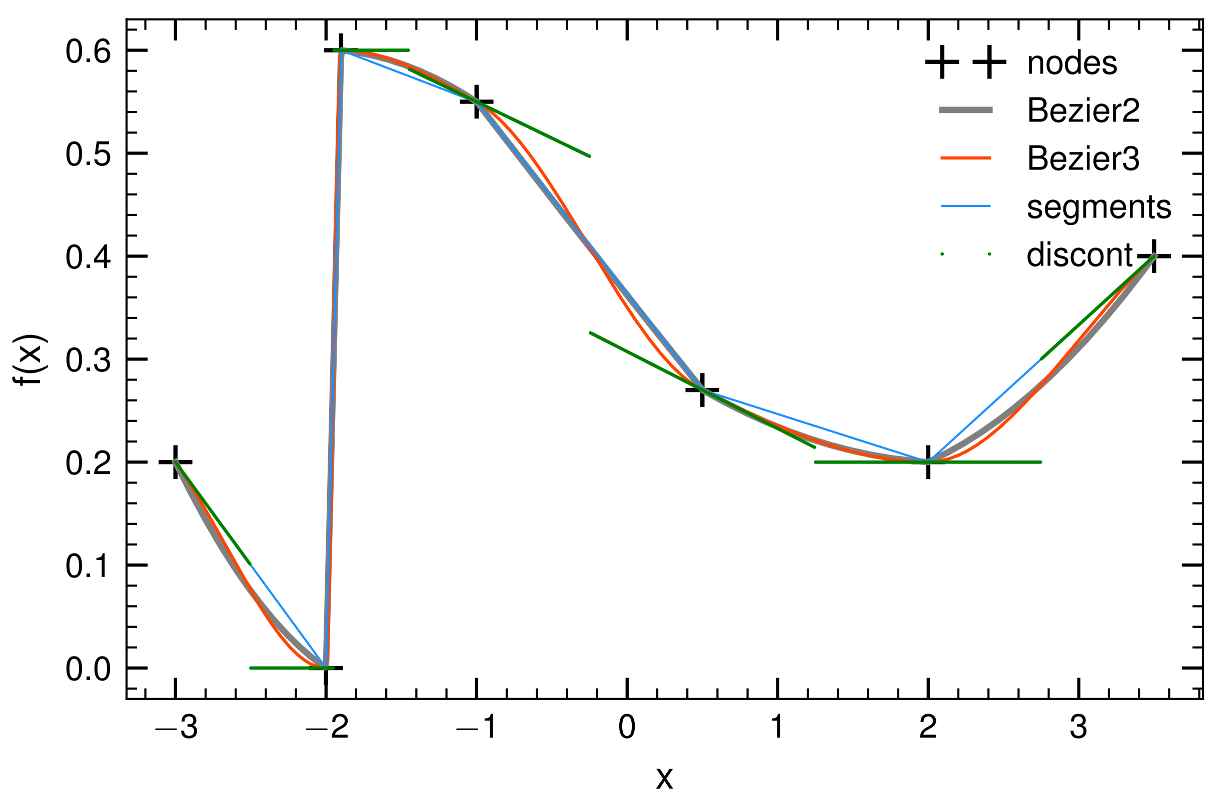
It is a nLTE code based on the excellent RH code

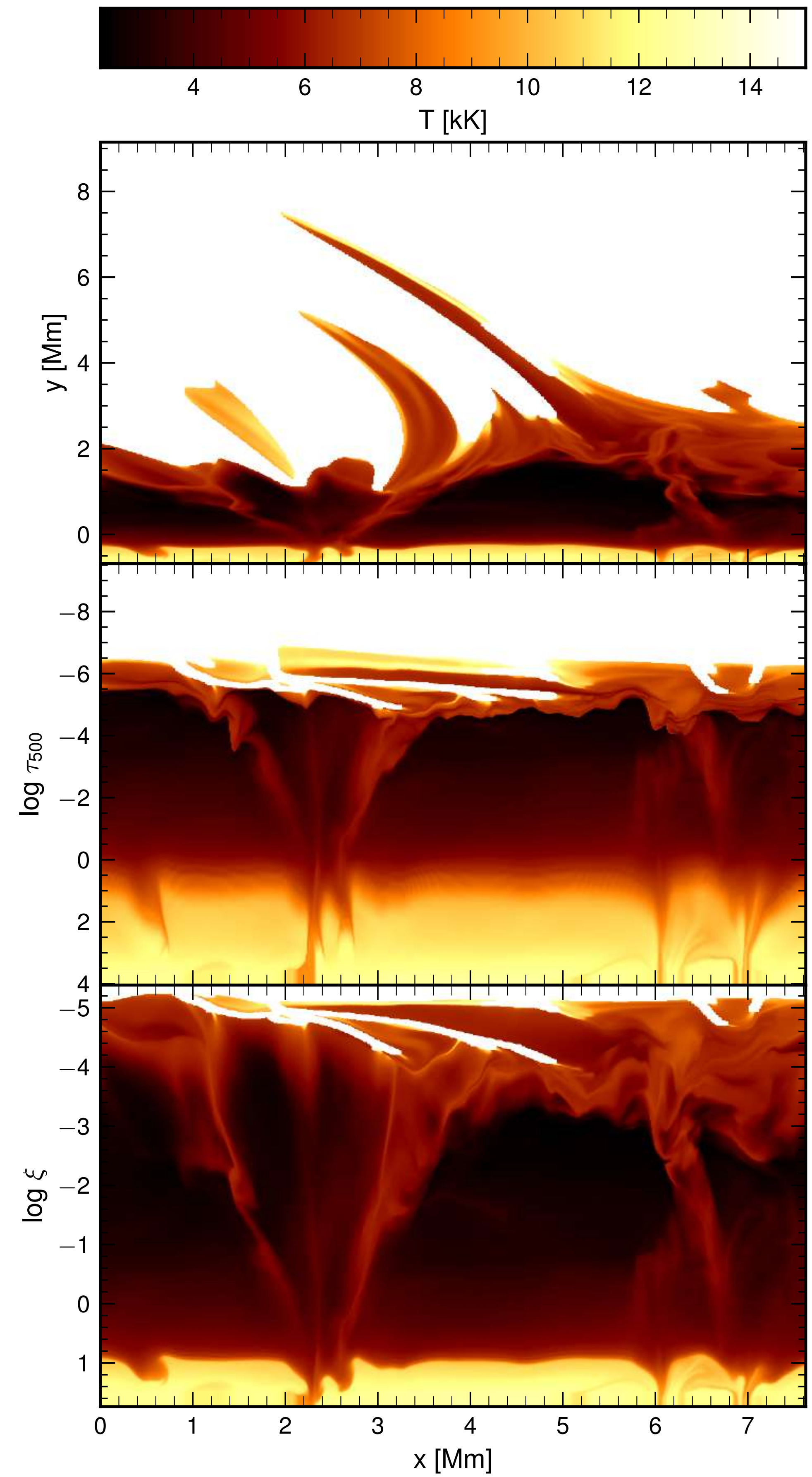
It allows reconstructing the stratification of a model atmosphere

Allows including lines from different species including PRD

Regularization of the model parameters

Inversions in column mass or optical depth using nodes



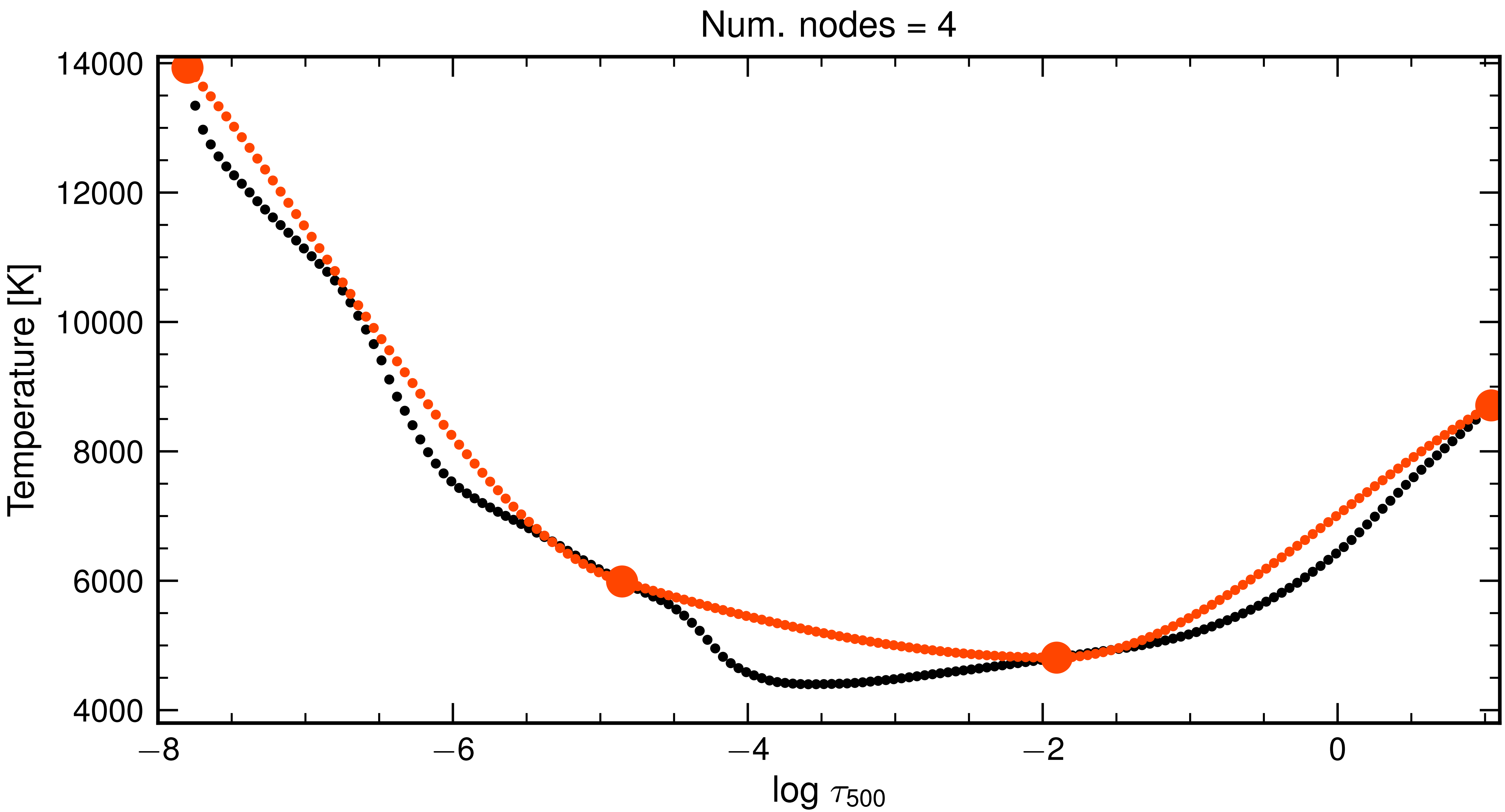


Simulation by Martinez-Sykora et al. (2017)

The concept of nodes (degrees of freedom)

We need a fine grid of depth points to solve the transfer equation

We cannot operate over all those individual grid points: not well constrained



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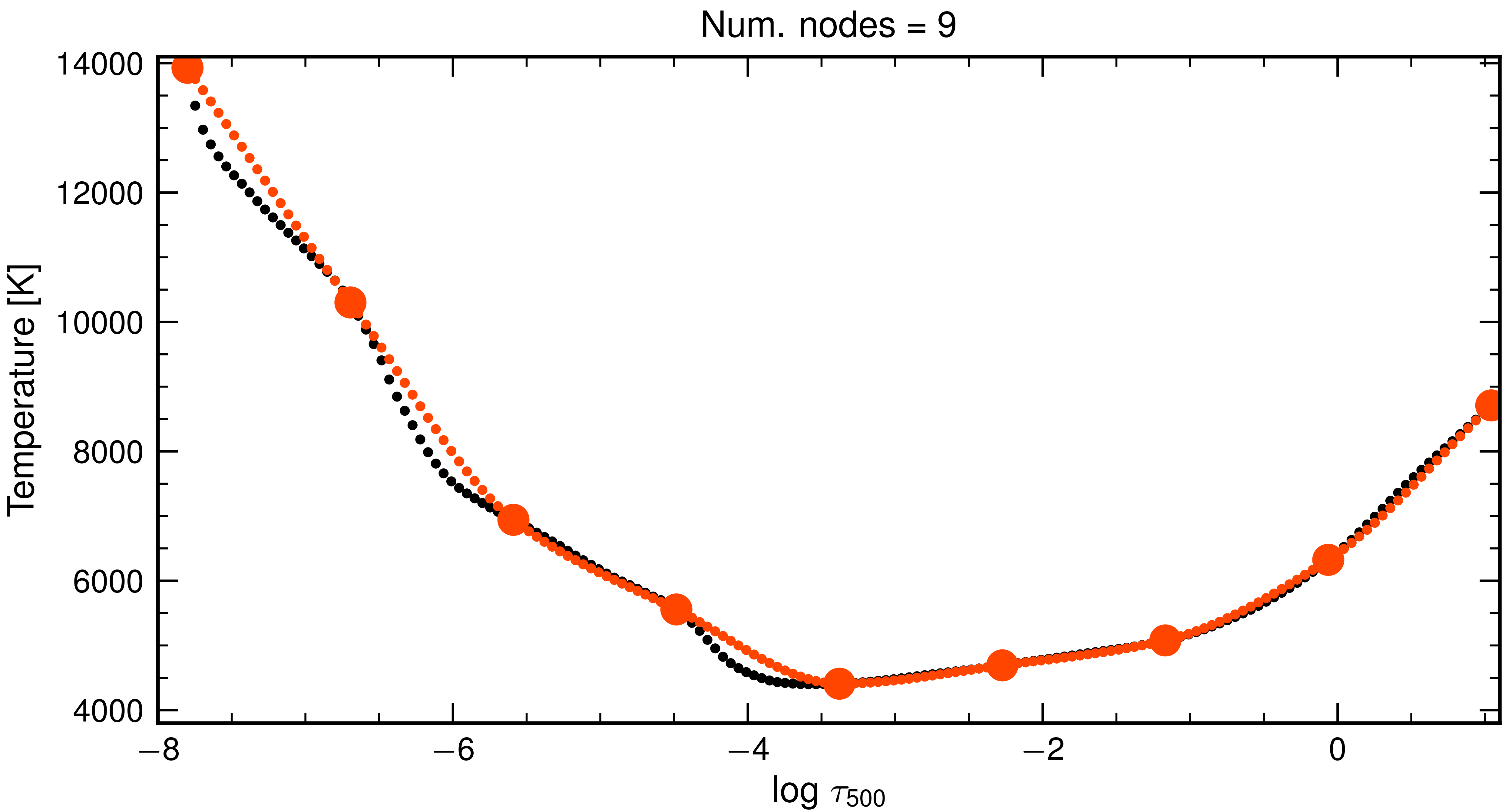

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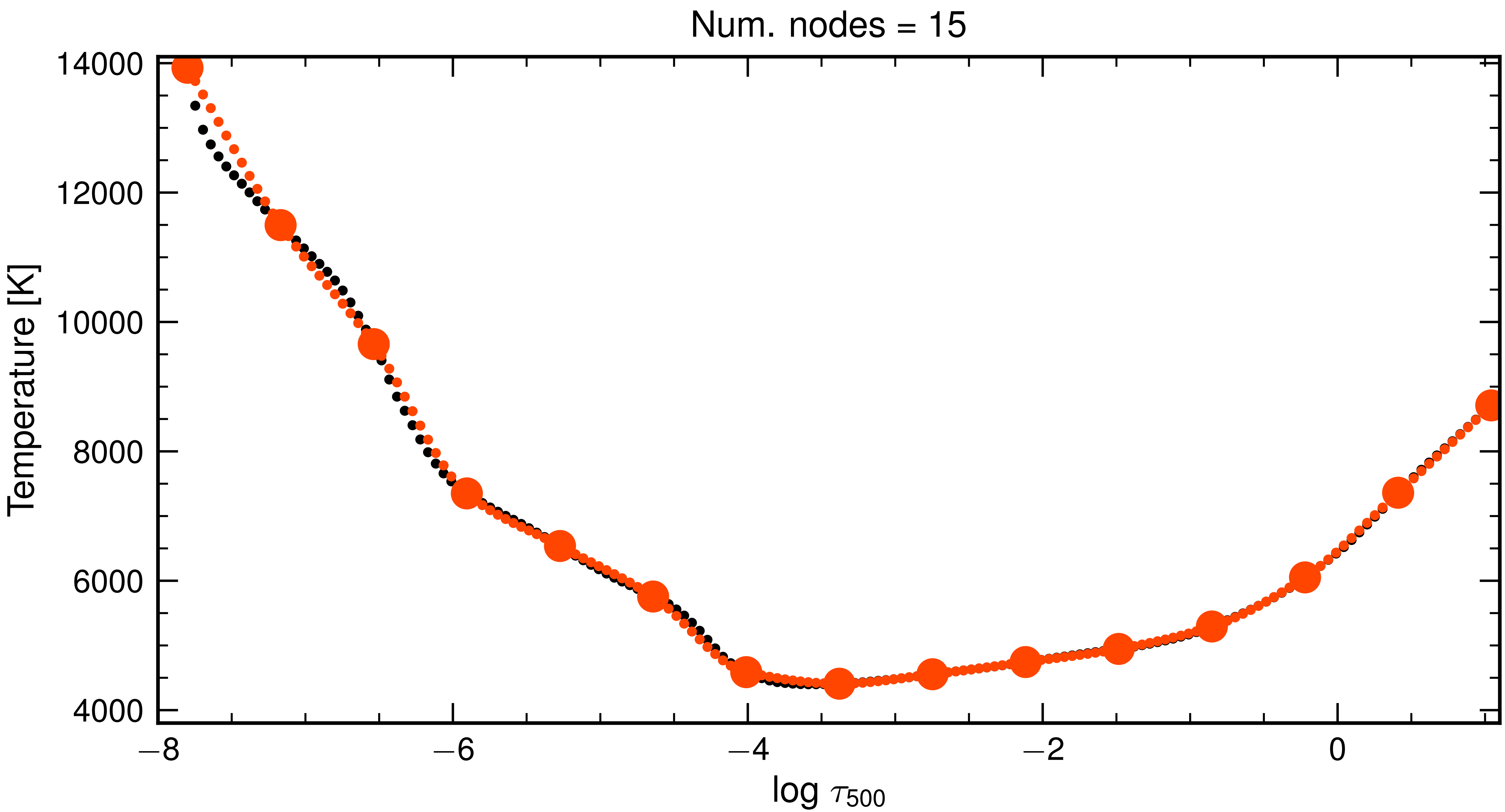


Free parameters in STiC

Works in CGS units [not SI!]

You can place nodes individually in:

- Temperature [K]
- V_{los} [cm s^{-1}]
- V_{turb} [cm s^{-1}]
- B_{long} [G]
- $|B_{trans}|$ [G]
- B_{χ} [rad]

The number of nodes in each parameter can be different!

STiC: The value of the node is the value of the variable

SIR, NICOLE: The value of the node is the value of a correction to the variable

Improving the inversion engine with regularization

de la Cruz Rodriguez, Leenaarts, Danilovic & Uitenbroek (to be submitted)

We can write the merit function with an extra regularization term:

$$\chi^2(\boldsymbol{p}, \boldsymbol{x}) = \frac{1}{N_{dat}} \sum_{i=1}^{N_{dat}} \left[\frac{o_i - s_i(\boldsymbol{p}, x_i)}{\sigma_i} \right]^2 + \sum_{j=1}^{N_{par}} \alpha_j r_j(\boldsymbol{p})^2.$$

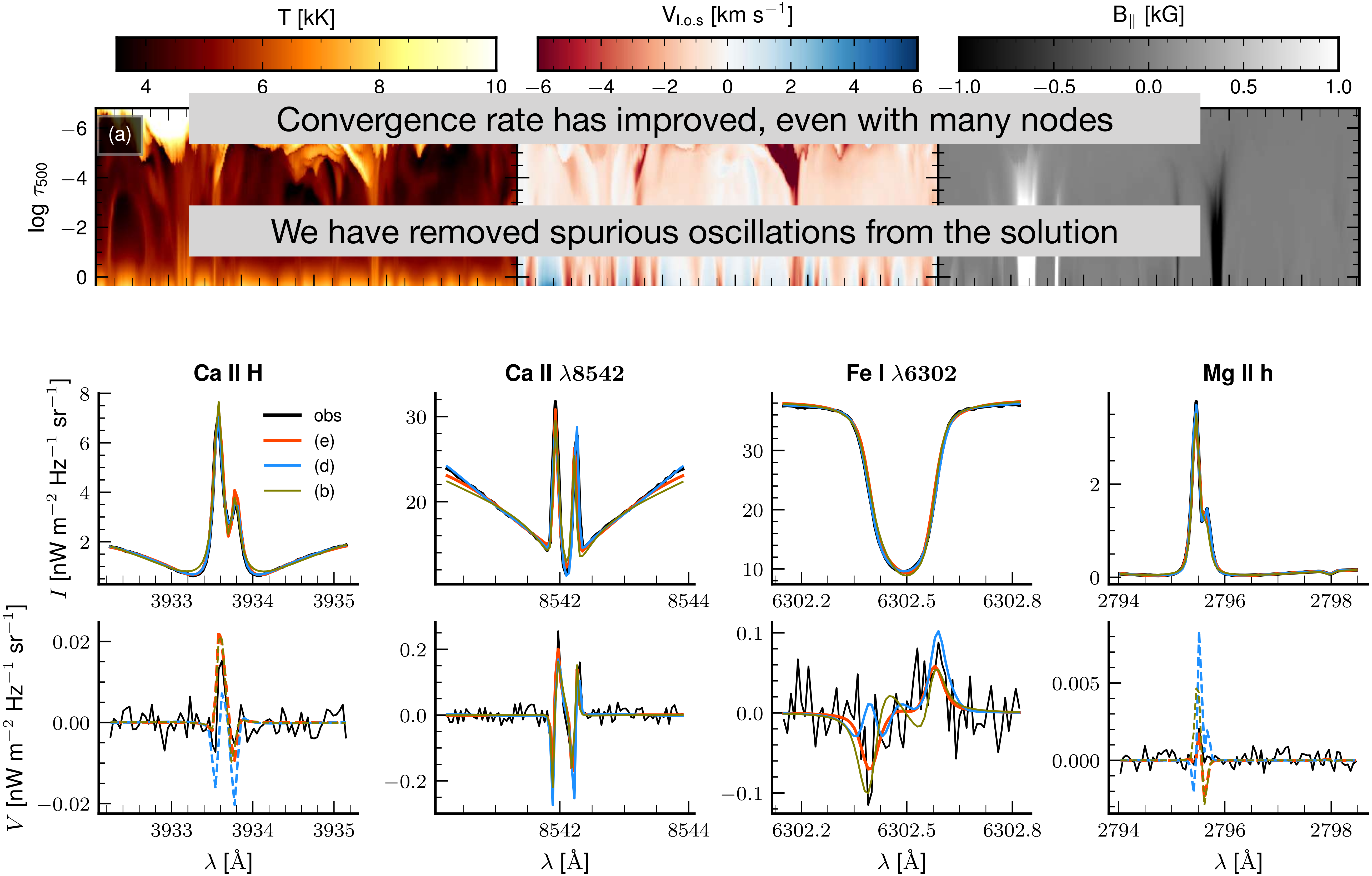
Then we linearize these equation so *Δp* are corrections to our parameters that minimise the merit function:

$$\chi^2(\boldsymbol{p} + \boldsymbol{\Delta p}, \boldsymbol{x}) = \frac{1}{N_{dat}} \sum_{i=1}^{N_{dat}} \left[\frac{o_i - s_i(\boldsymbol{p}, x_i) - \boldsymbol{j}_i^T \boldsymbol{\Delta p}}{\sigma_i} \right]^2 + \sum_{j=1}^{N_{par}} \left[\alpha_j r_j(\boldsymbol{p}) + \boldsymbol{h}^T \boldsymbol{\Delta p} \right]^2.$$

If we take the derivative respect to *Δp* and do some algebra, we derive the Levenberg-Marquardt algorithm, but this time including regularization terms:

Regularization functions:

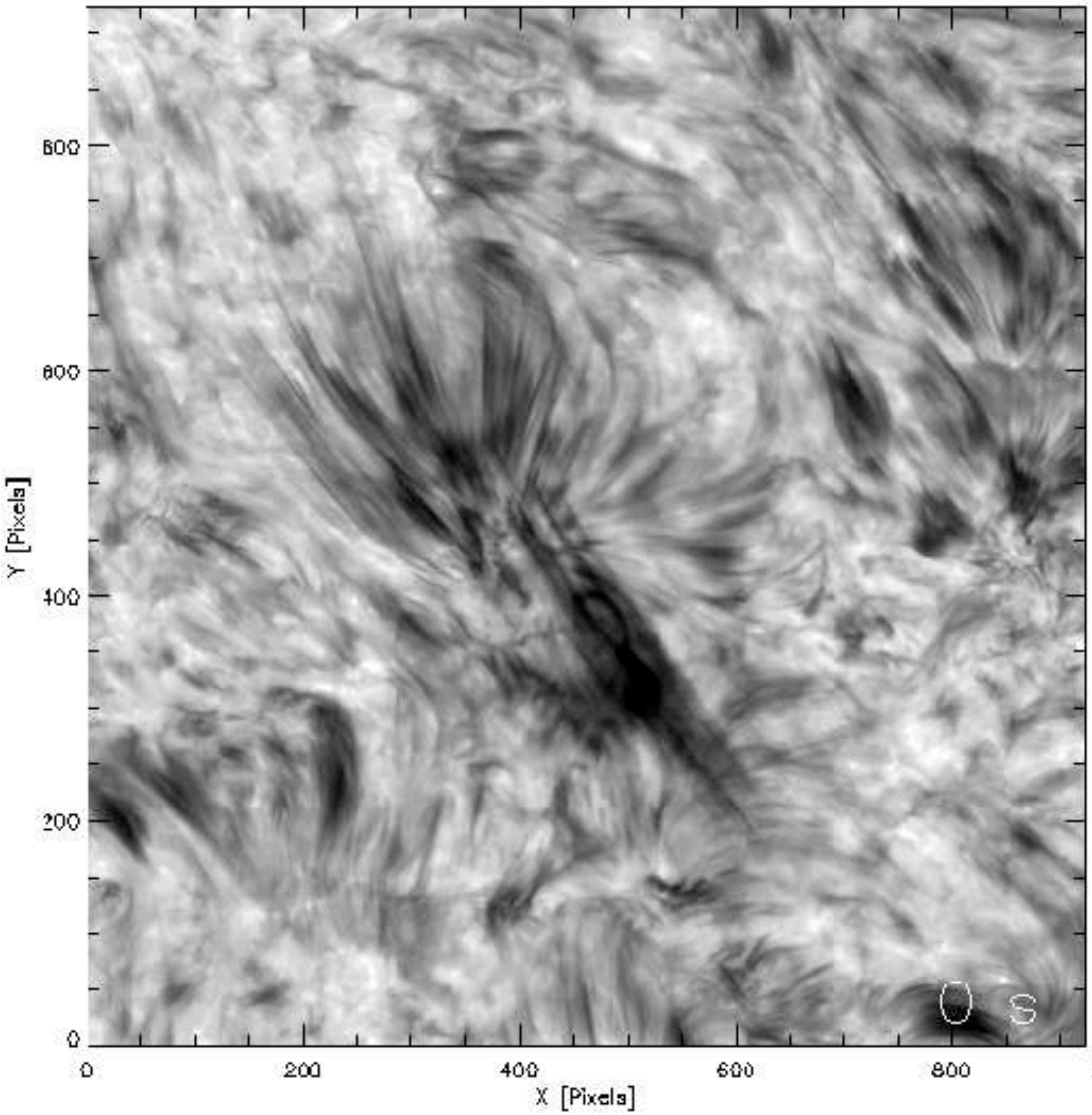
- Tikhonov first derivative: penalises gradients in the solution (p_k - p_{k-1})
- Tikhonov low norm: penalises deviation from an expected value (p_k - v)
- Second derivative: penalises changes in the gradient (p_{k+1} - 2p_k + p_{k-1}) / (2 dx)

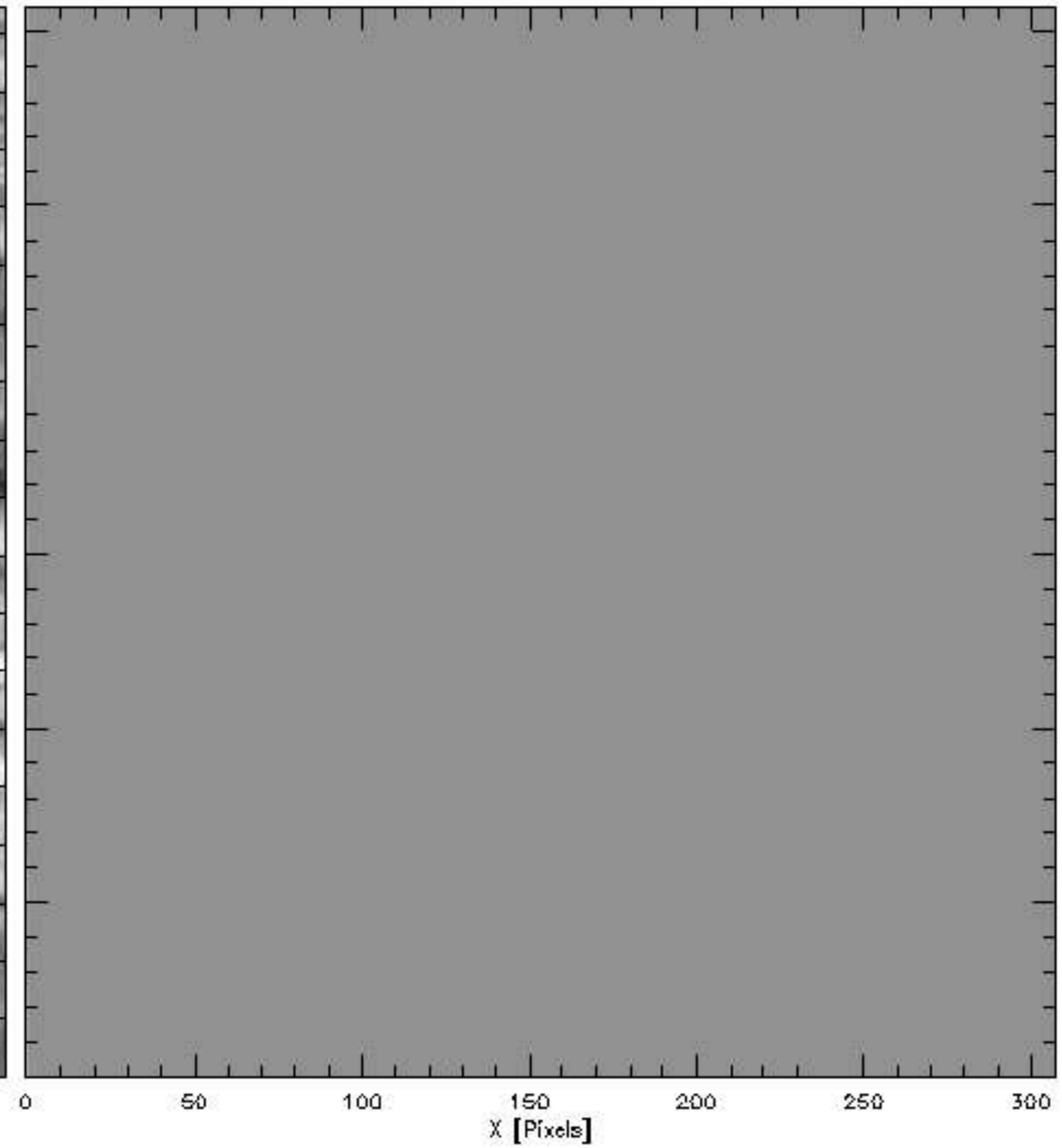

Convergence rate has improved, even with many nodes
We have removed spurious oscillations from the solution
T [kK]
$V_{l.o.s}$ [km s^{-1}]
$B_{||}$ [kG]
(a)
log τ_{500}
Ca II H
Ca II λ8542
Fe I λ6302
Mg II h
obs
(e)
(d)
(b)
I [nW m^{-2} Hz^{-1} sr^{-1}]
V [nW m^{-2} Hz^{-1} sr^{-1}]
λ [Å]

Diagnostics

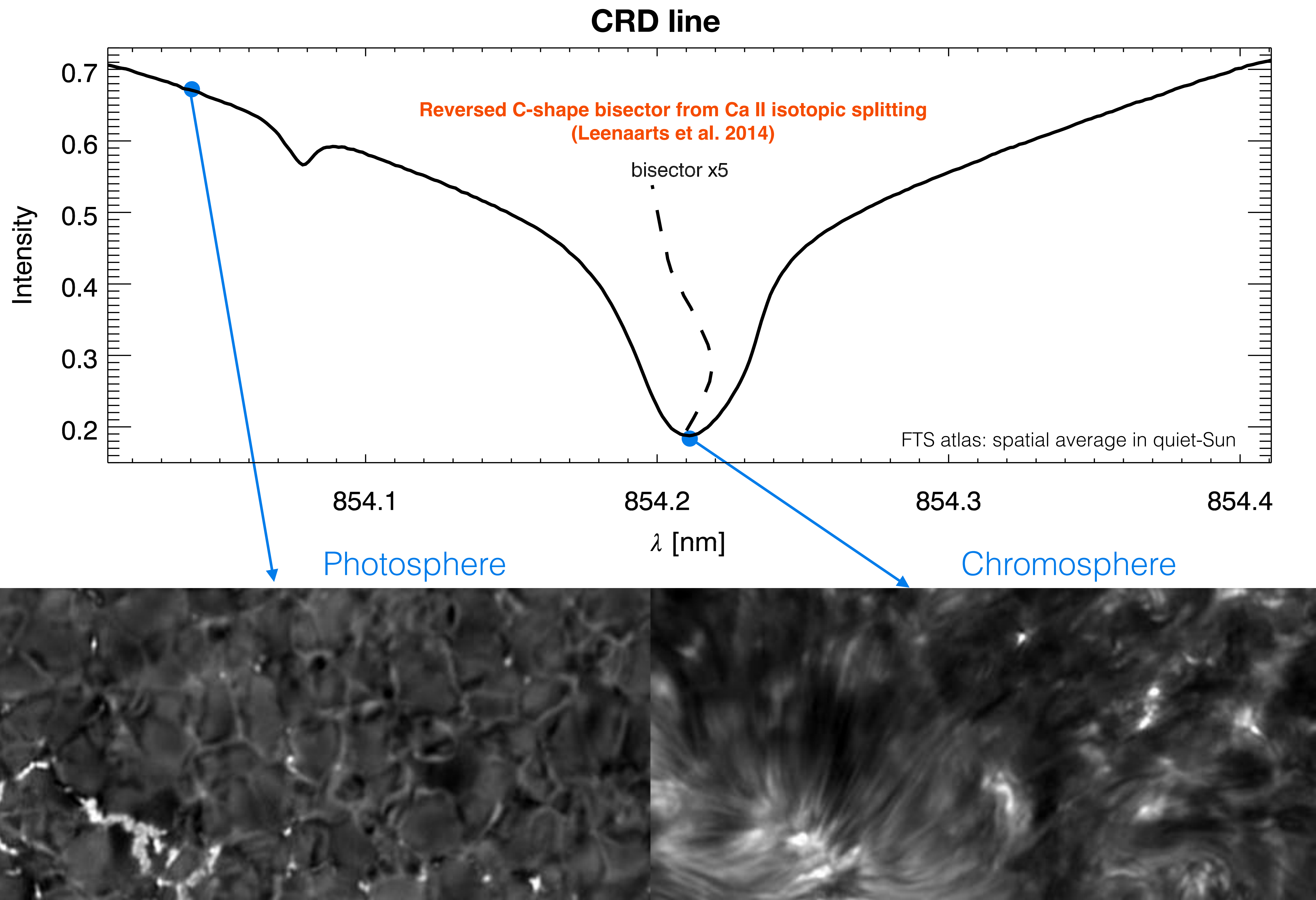
Choose your instrument wisely

E.g., FPI vs slit-spectrograph

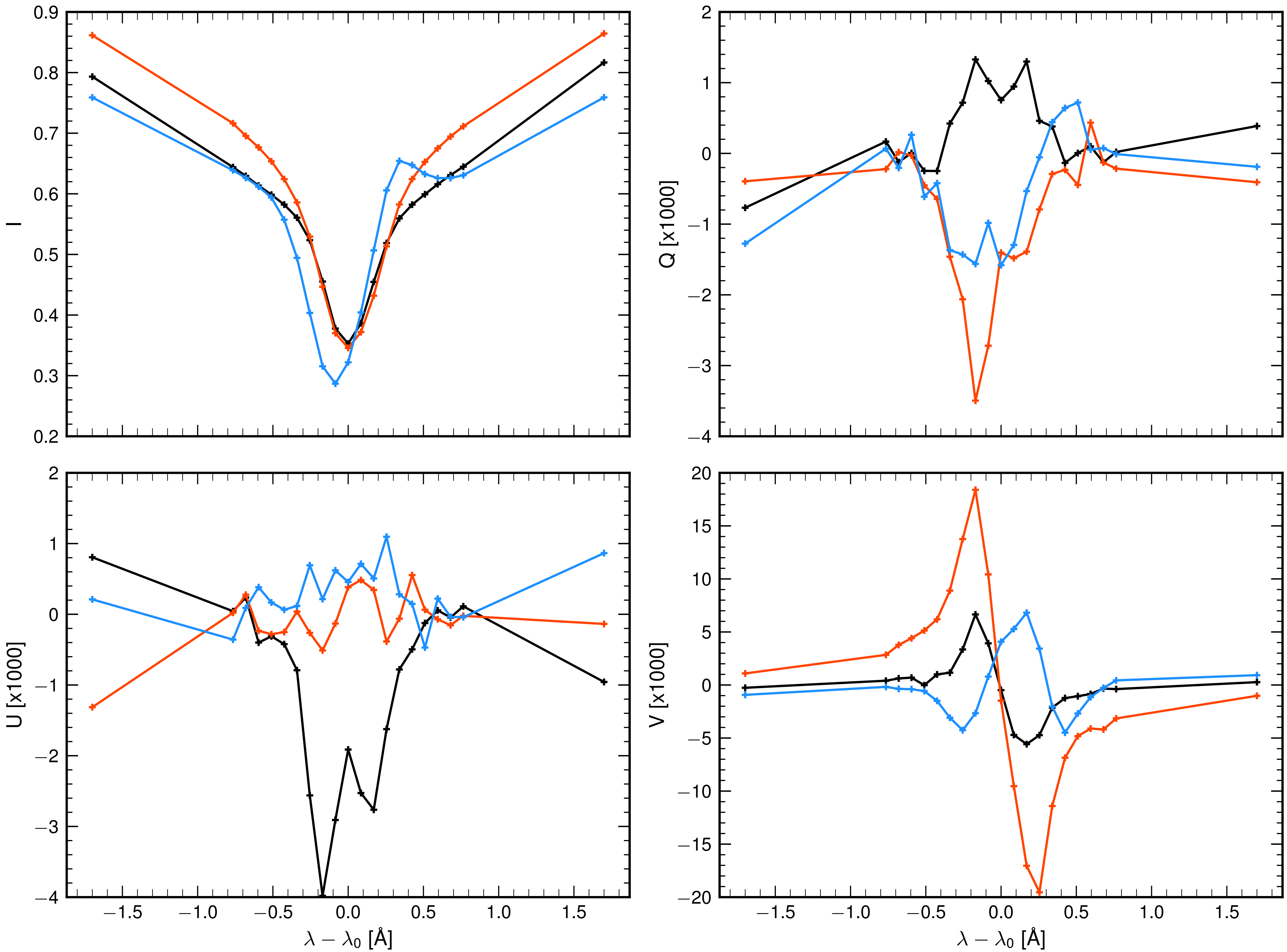




Ca II 8542


CRD line
Reversed C-shape bisector from Ca II isotopic splitting
(Leenaarts et al. 2014)
bisector x5
FTS atlas: spatial average in quiet-Sun
Intensity
0.7
0.6
0.5
0.4
0.3
0.2
854.1
854.2
854.3
854.4
λ [nm]
Photosphere
Chromosphere

Ca II 8542



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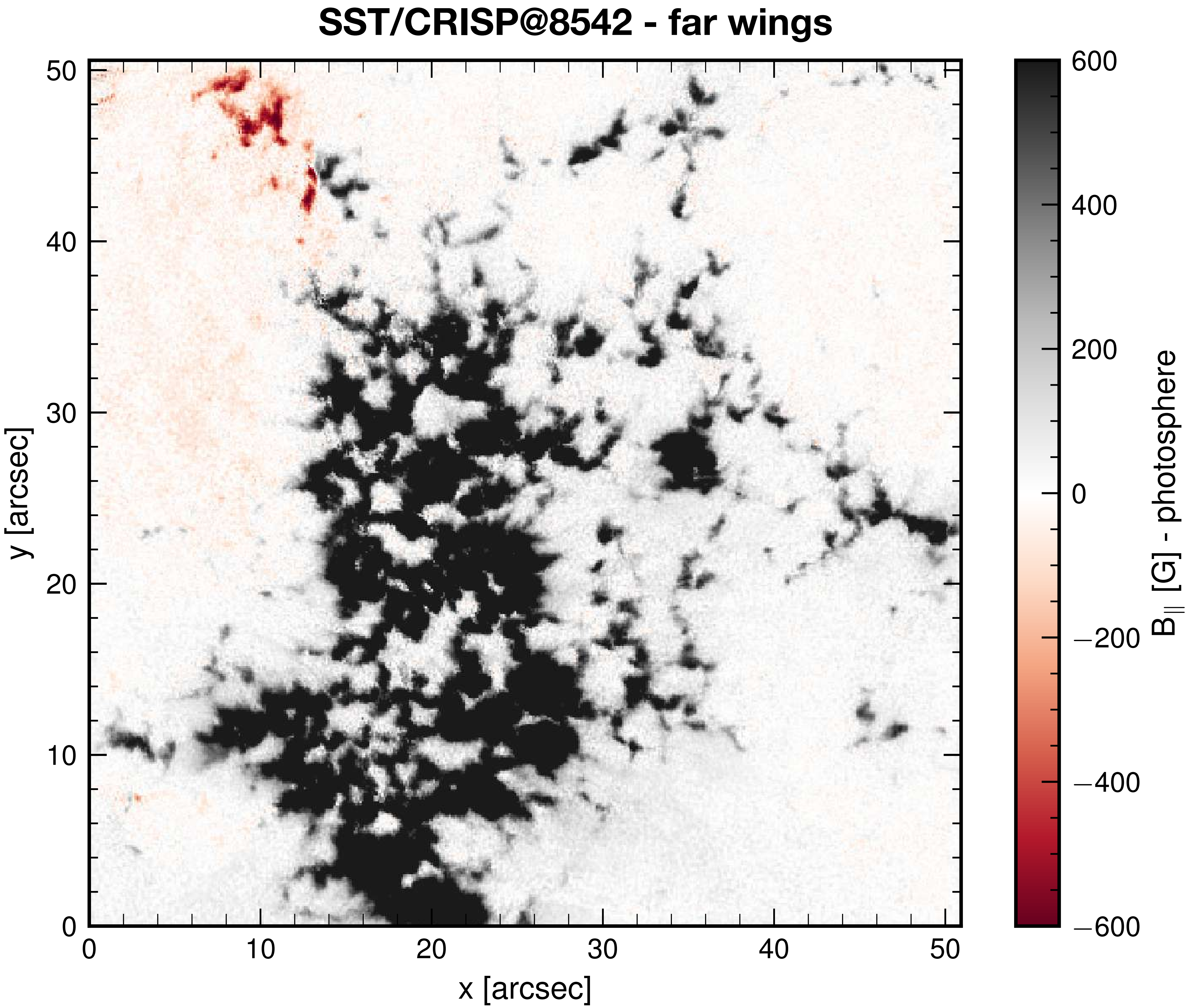
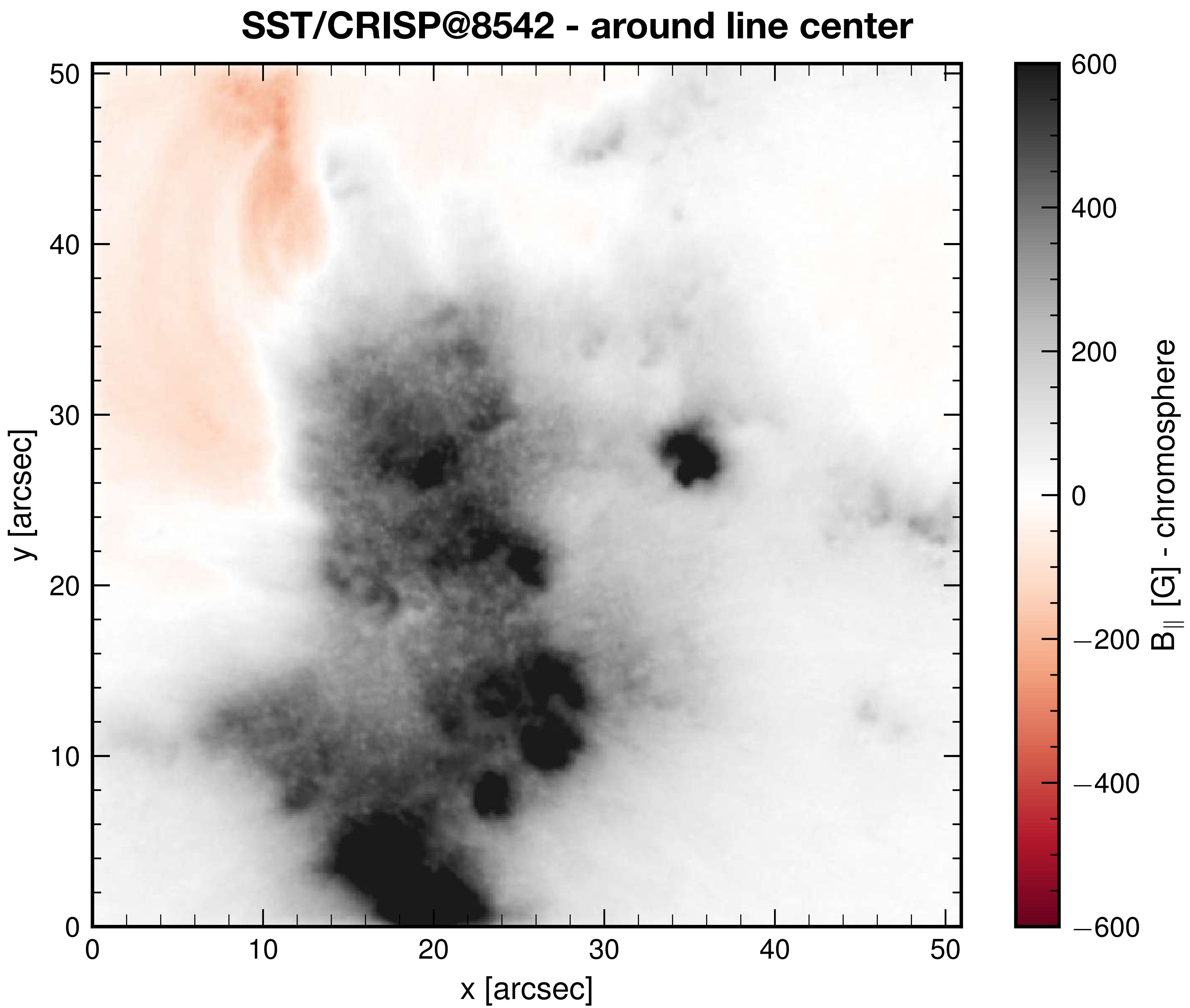


de la Cruz Rodriguez et al. (in prep.)

Ca II 8542



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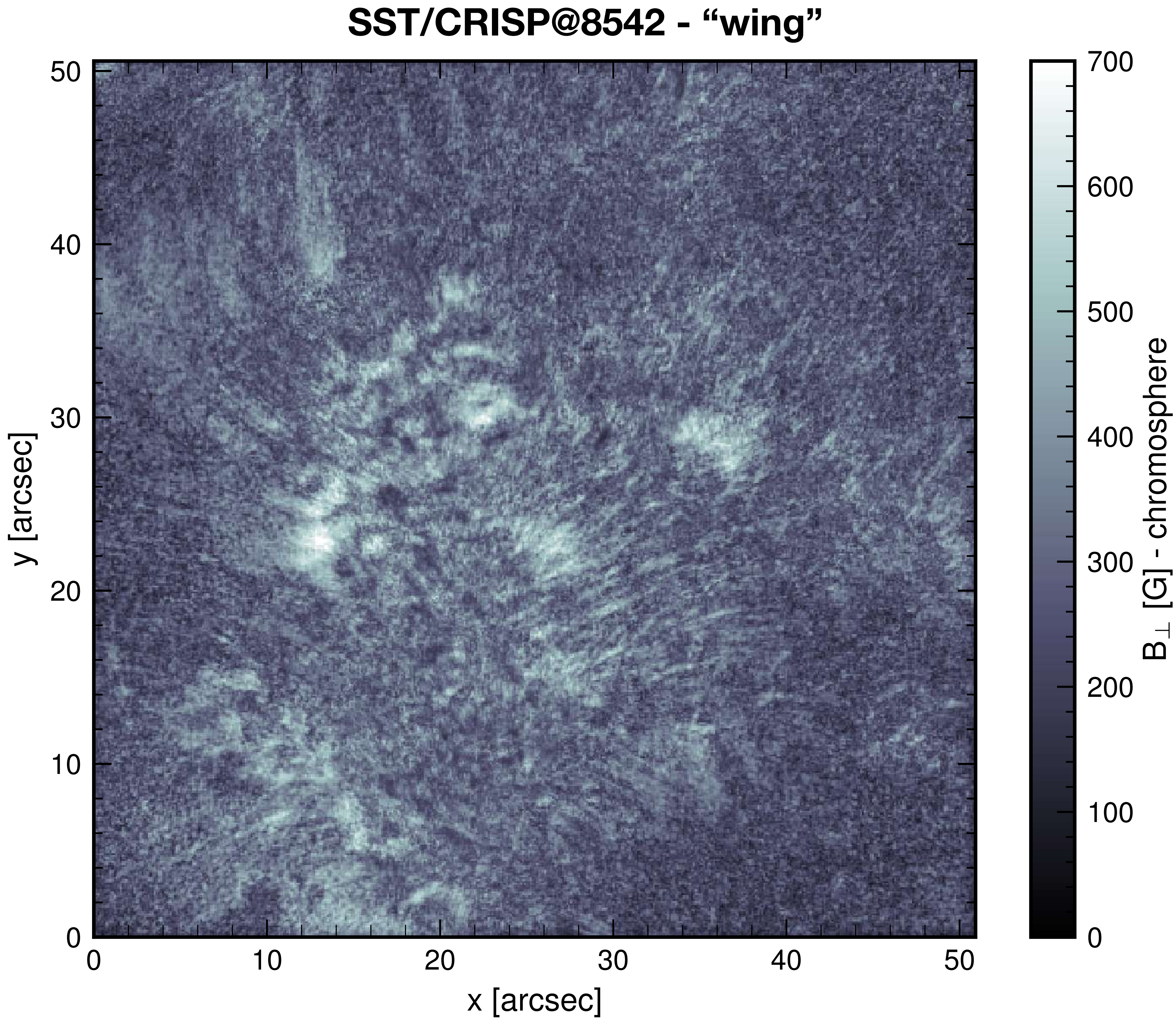
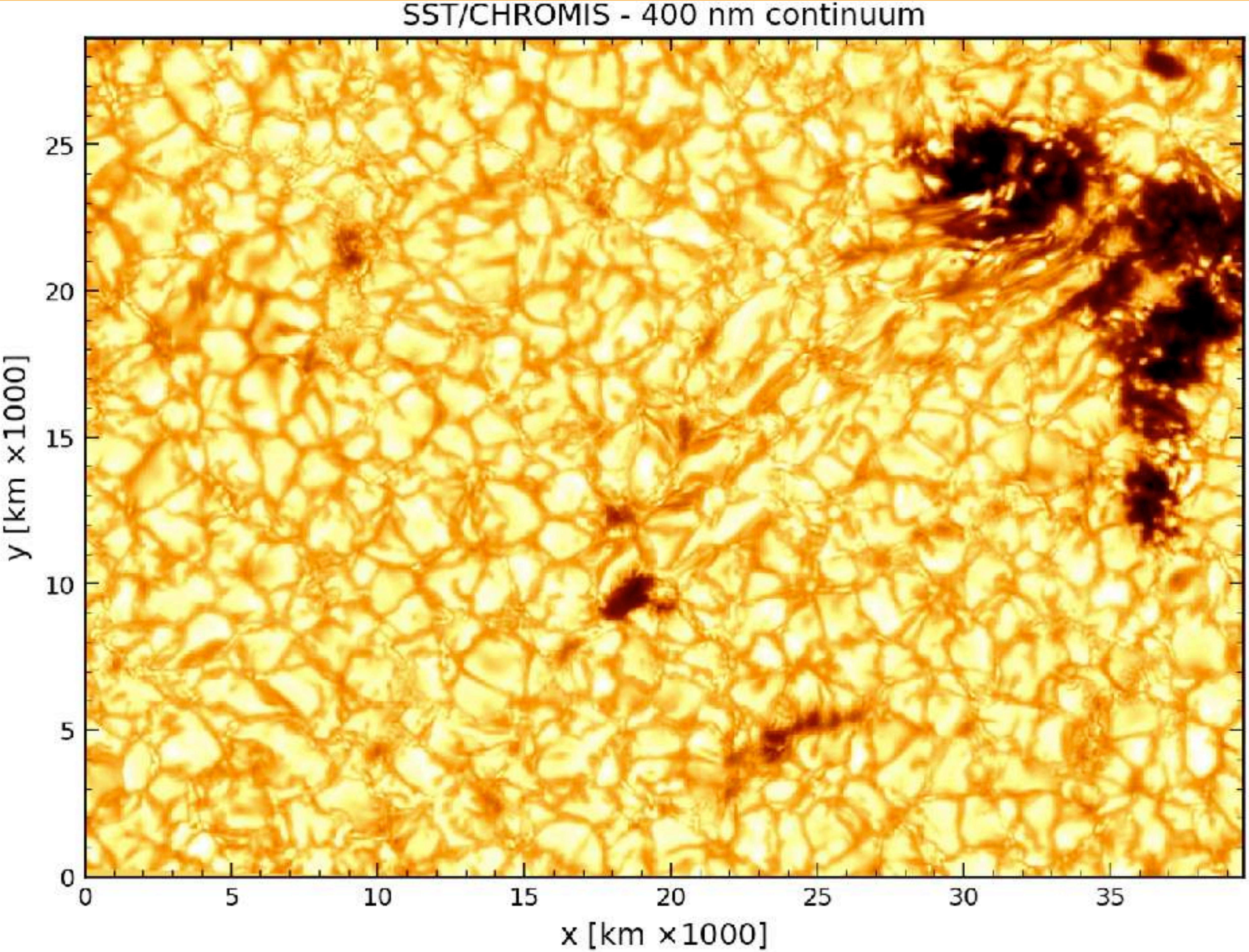
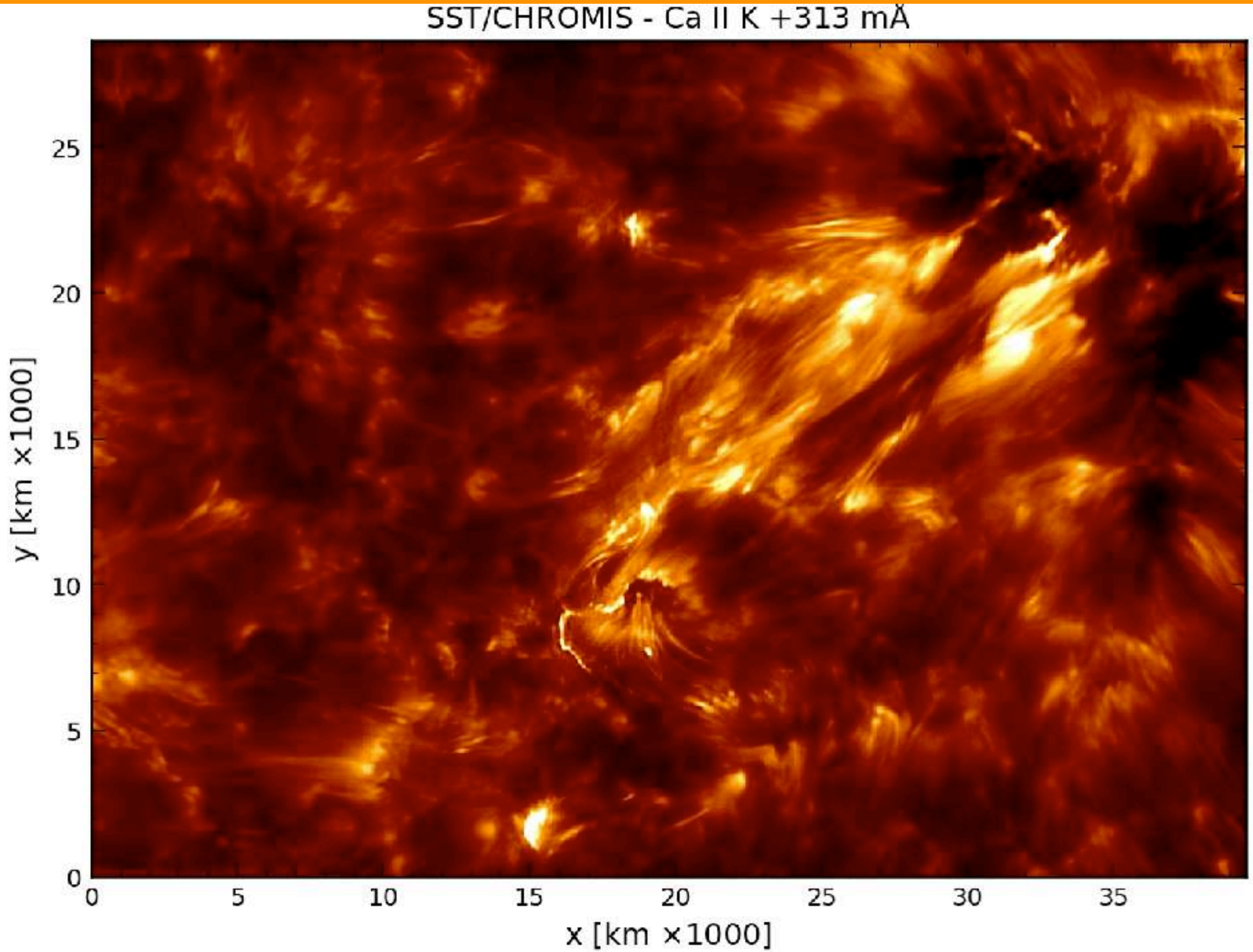


de la Cruz Rodriguez et al. (in prep.)

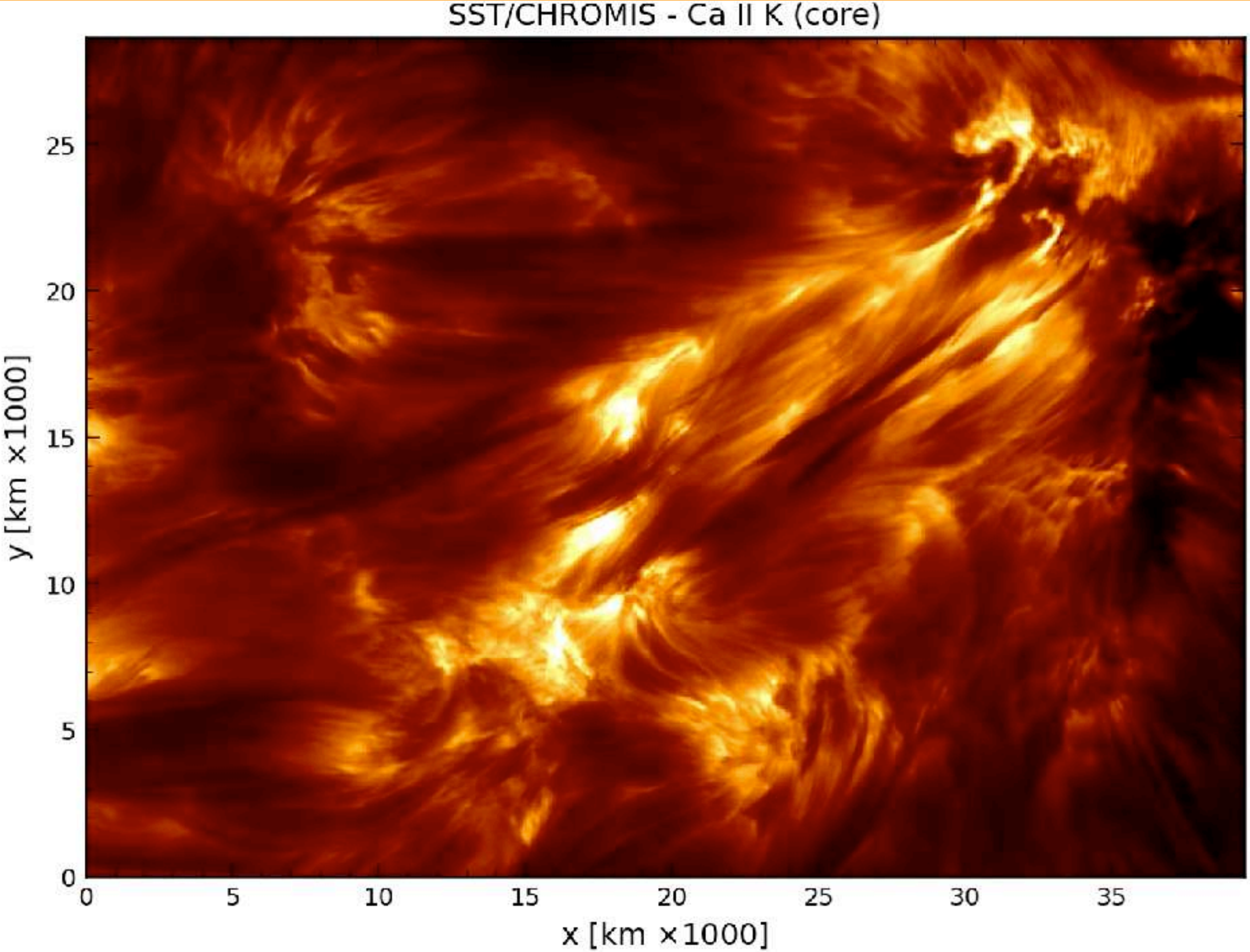
Ca II K


SST/CHROMIS - 400 nm continuum
y [km ×1000]
x [km ×1000]
0
5
10
15
20
25
30
35

Ca II K

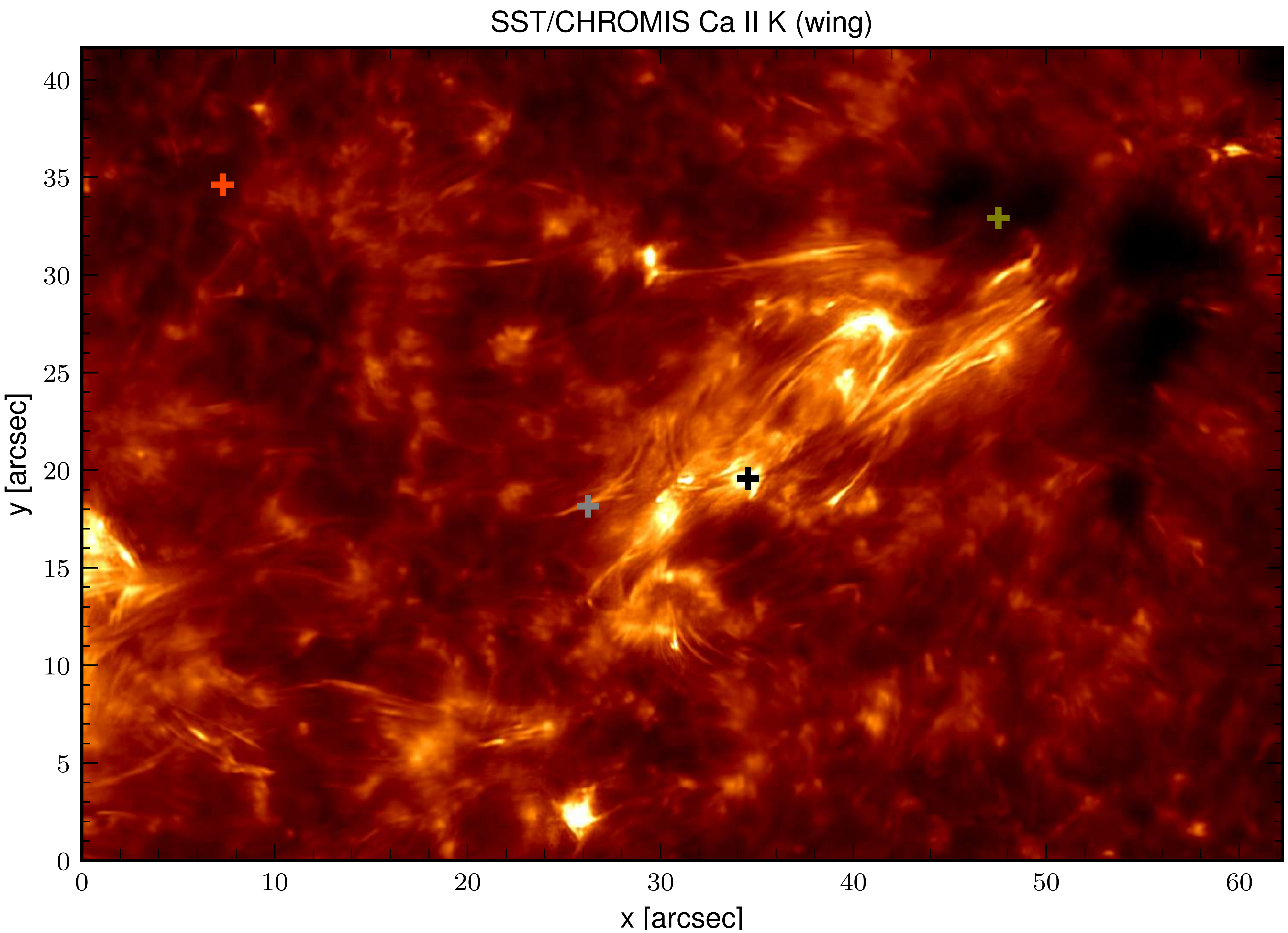


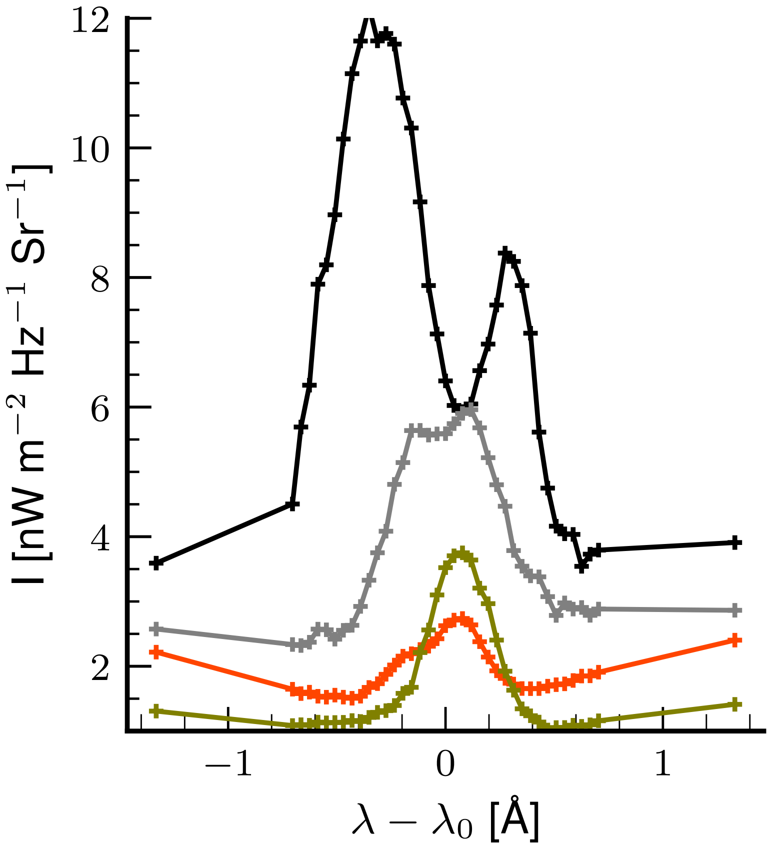
Ca II K



Ca II K

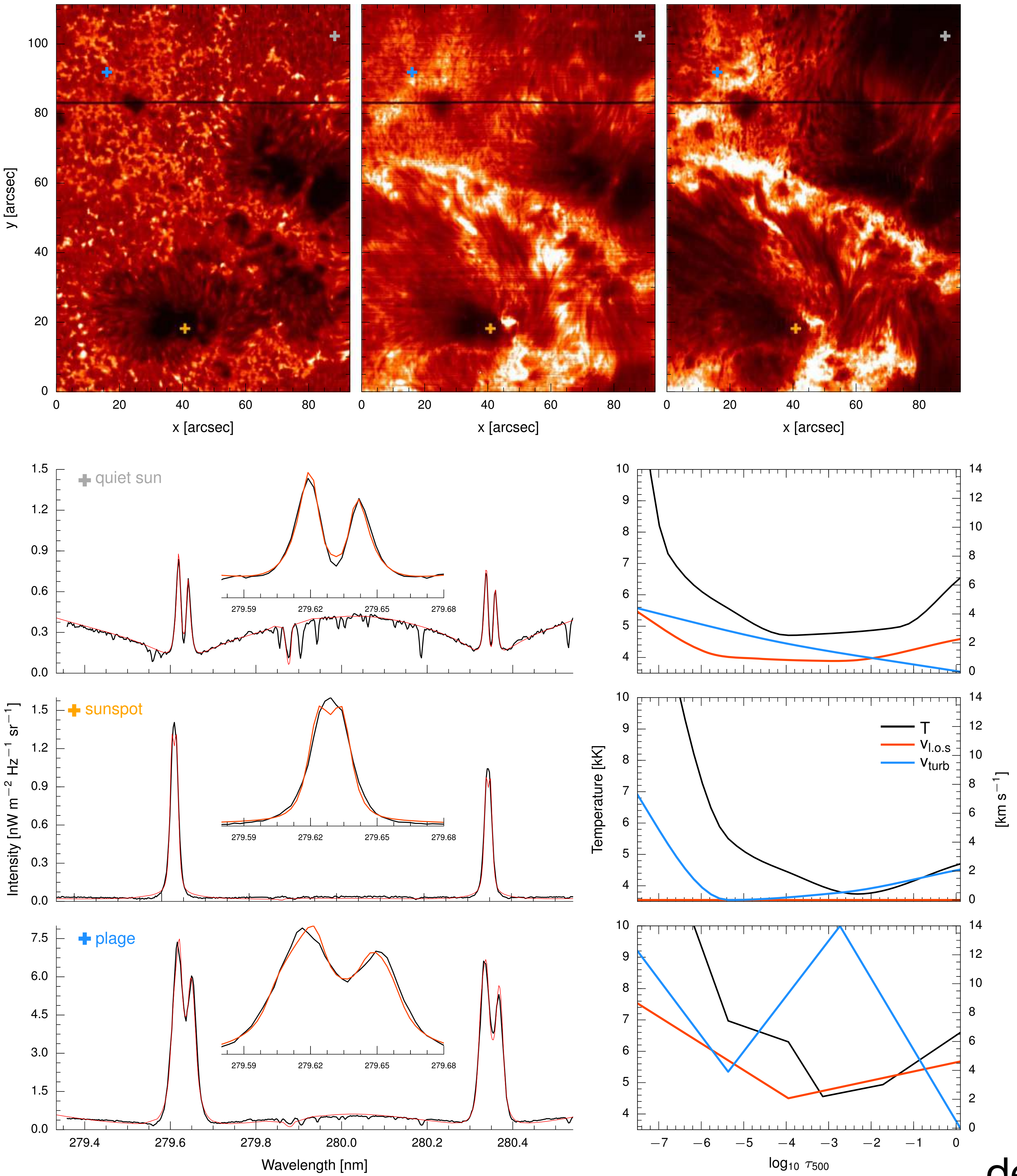
PRD line





Mg II h&k

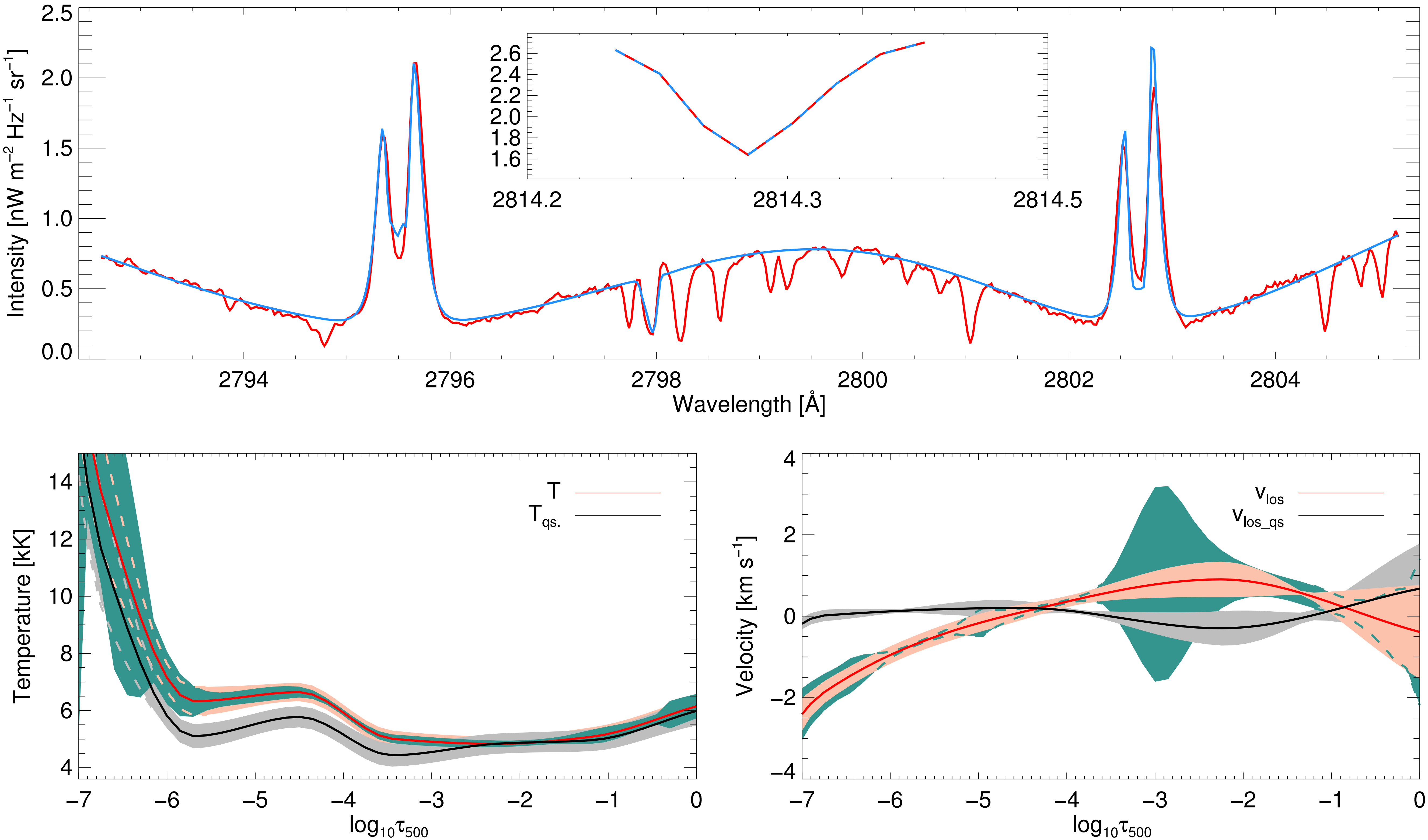
PRD lines



de la Cruz Rodriguez et al. (2016)

Mg II h&k

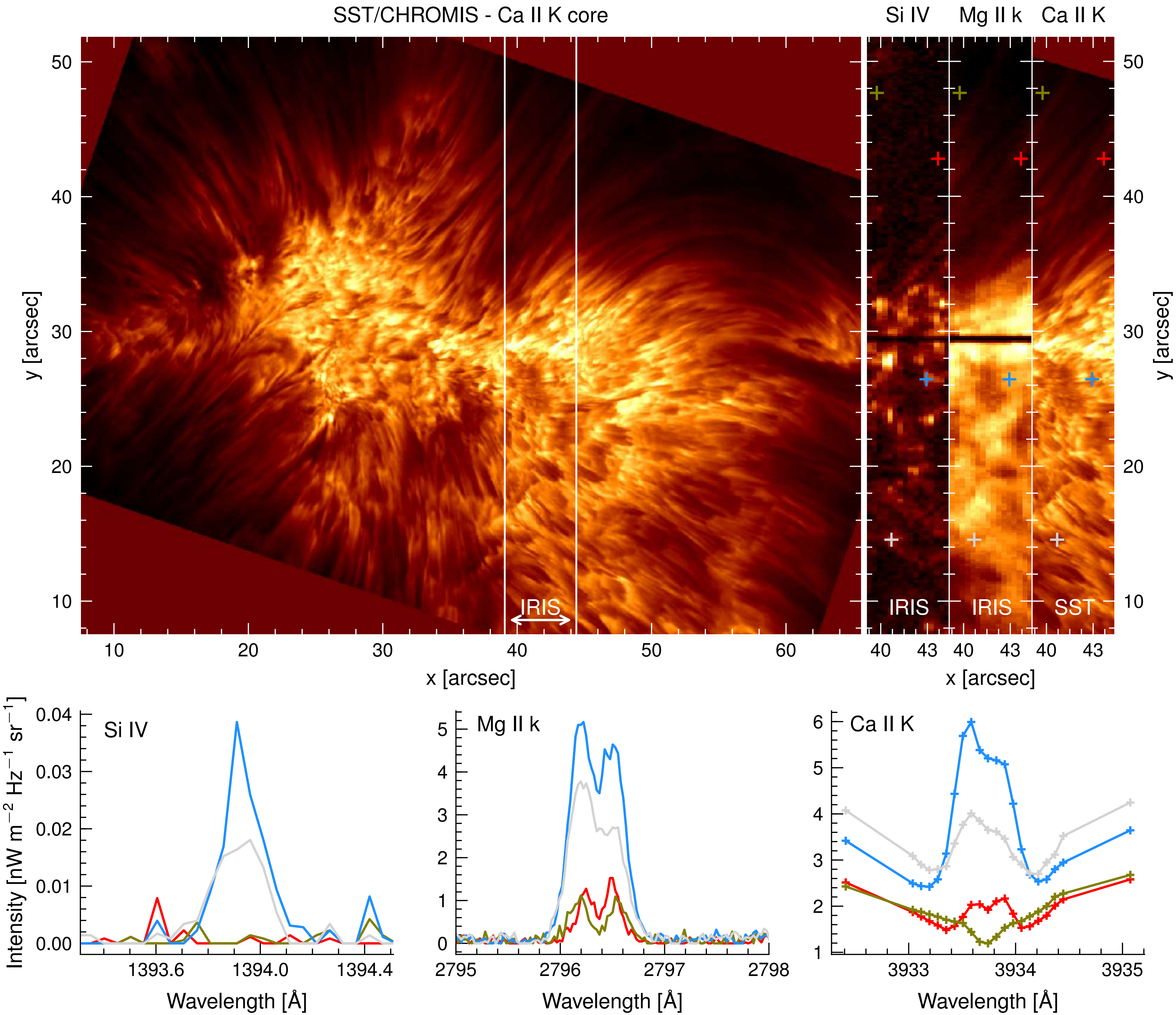
PRD lines



Gosic et al. (2018)

One science example with STiC

The data: SST CRISP & CHROMIS + IRIS



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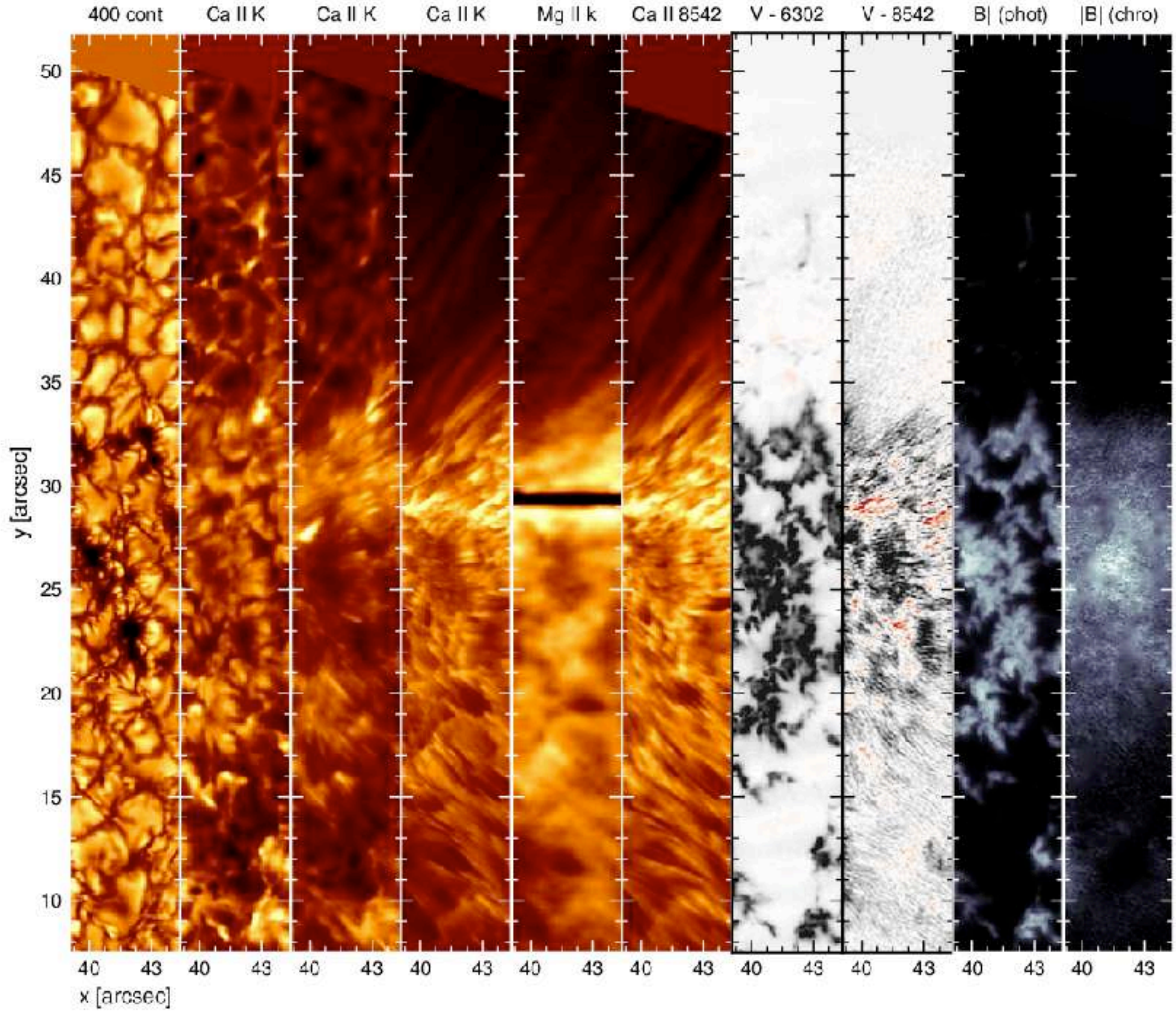
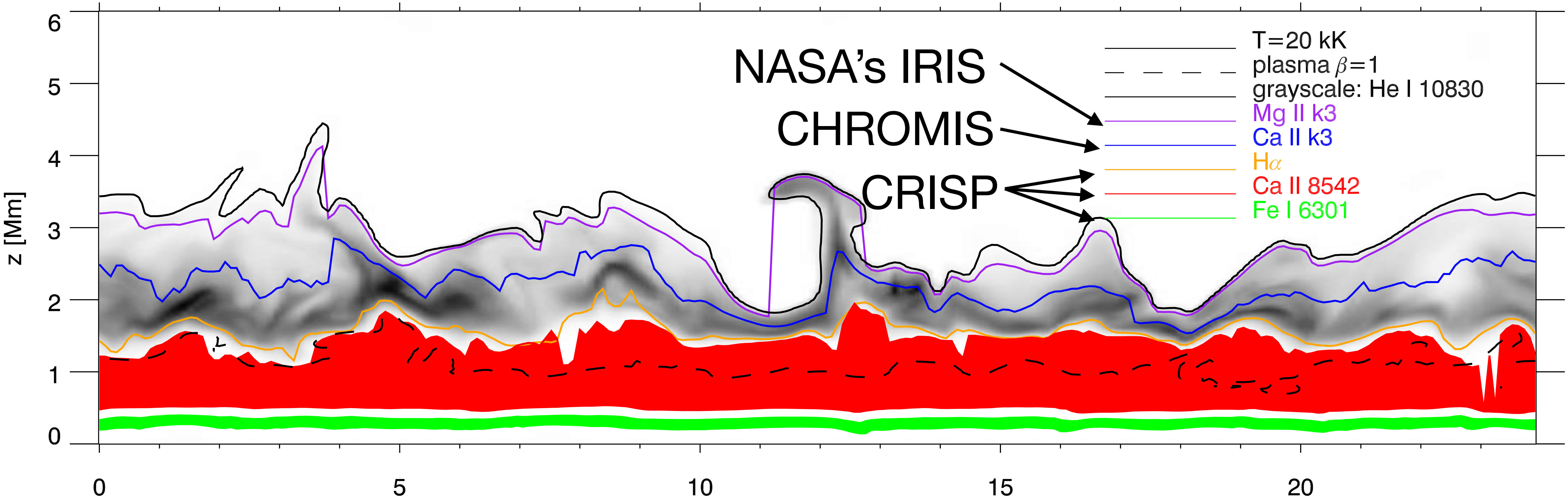


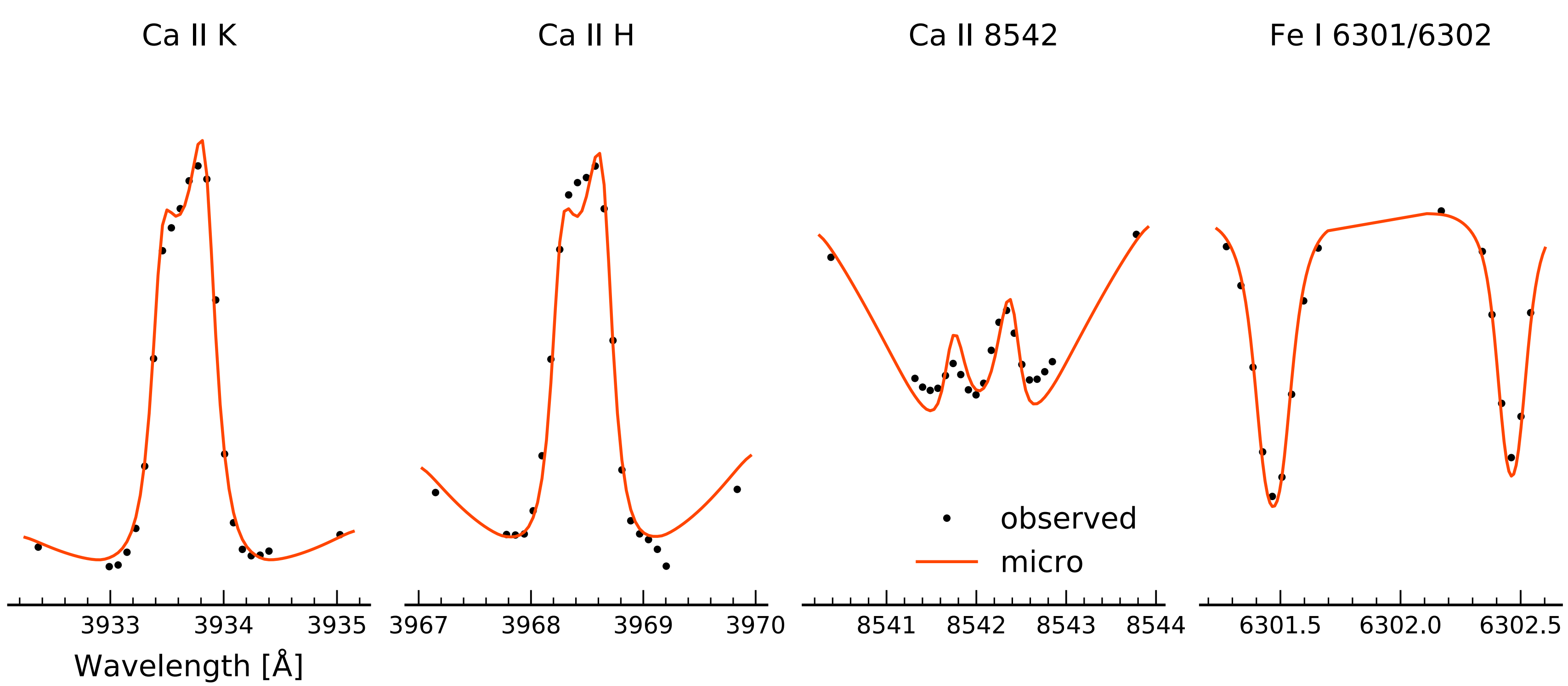
Multi-line non-LTE inversions



Courtesy J. Leenaarts

Coverage up to the upper chromosphere

Excellent redundancy



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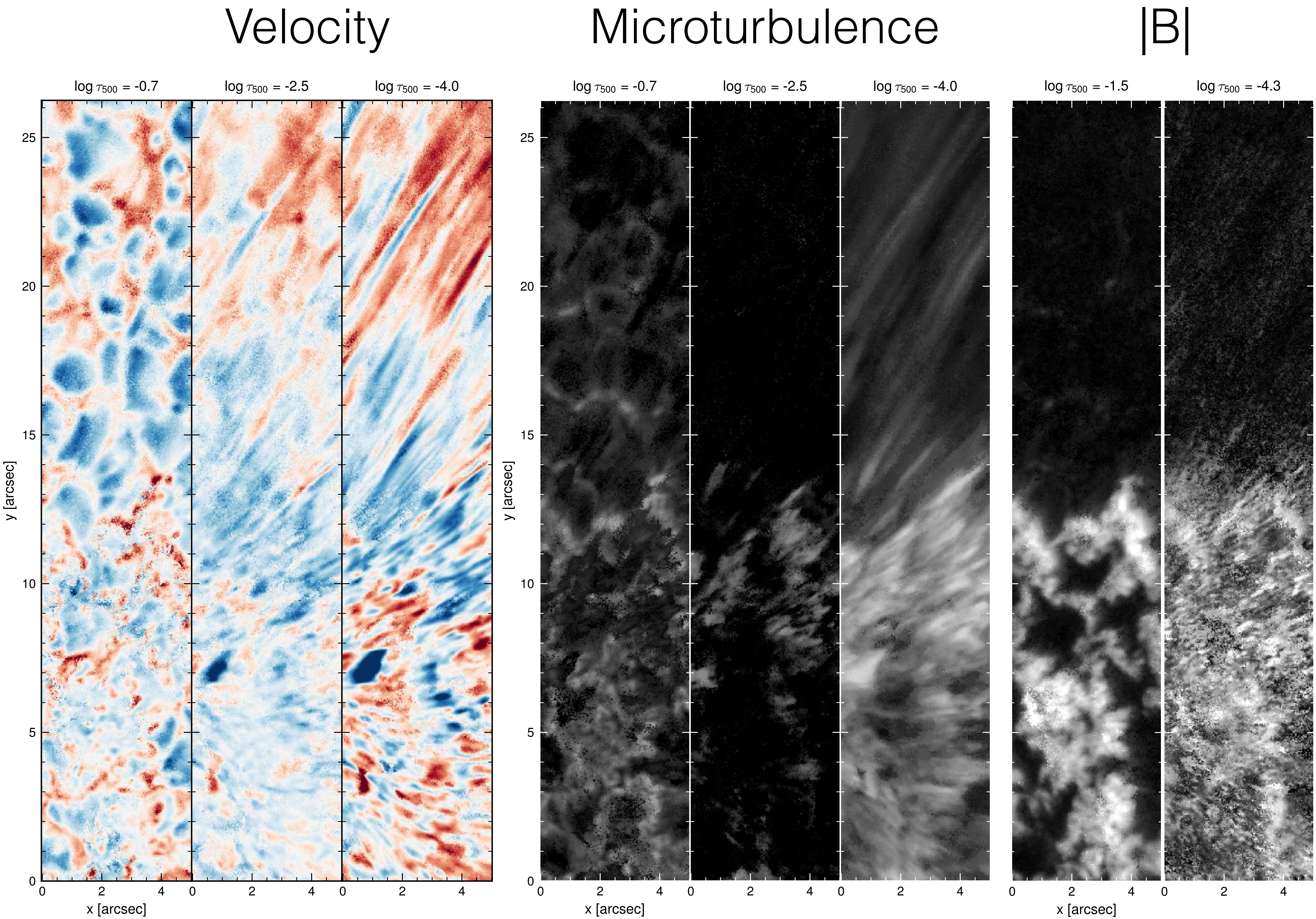
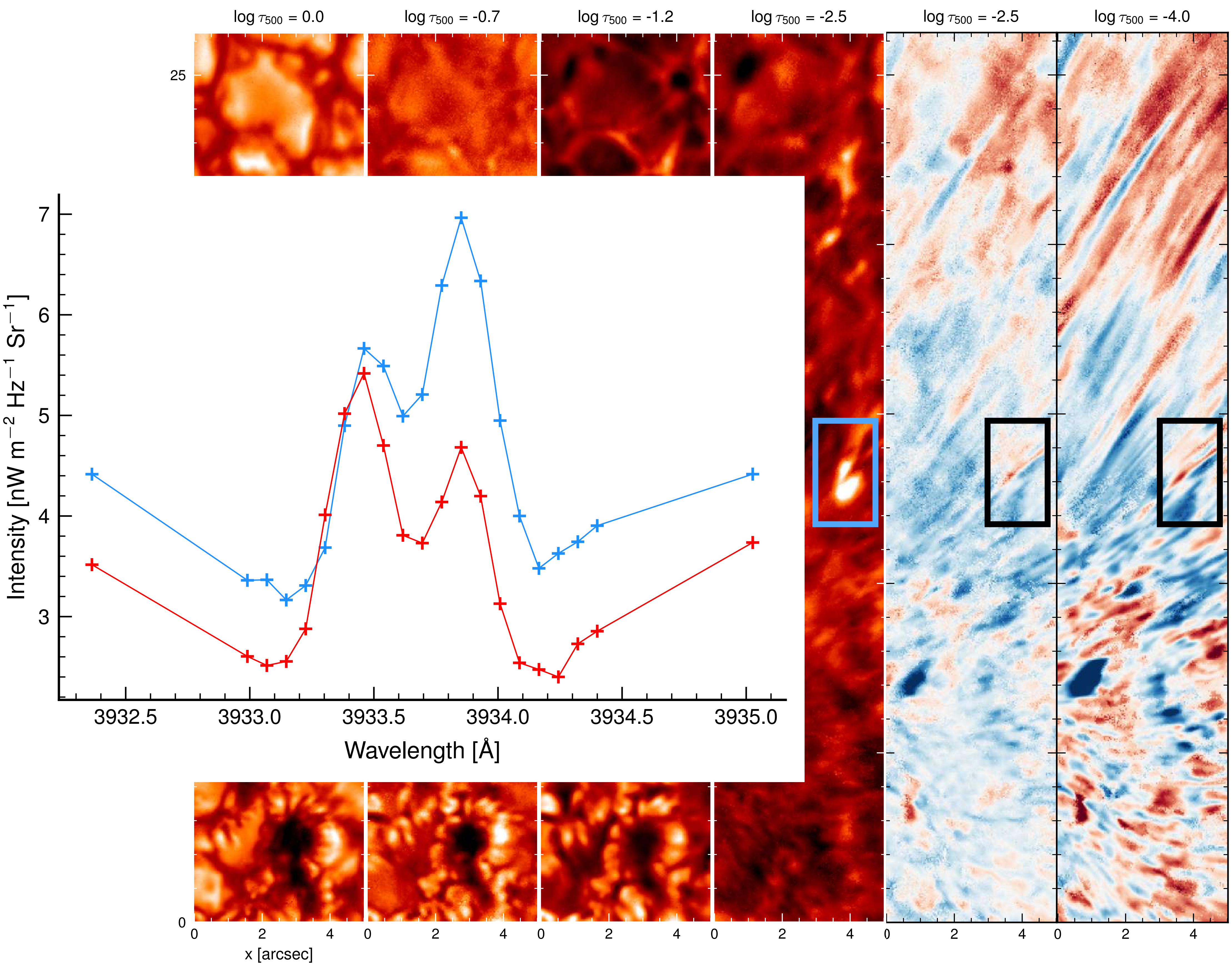


de la Cruz Rodriguez et al. (in prep.)

Multi-line non-LTE inversions

Temperature



de la Cruz Rodriguez et al. (in prep.)

A word of caution

Inversion code always produce a result, which can be easily over-interpreted

Ask yourself the following questions BEFORE you start running the code:

- **What scientific question am I trying to solve?** (find it!)
- **Do I need inversions to solve it?** (if not, don't use inversions!)
- **What aspect of the inversion output can I use to solve my question?** Try to anticipate what part of the output can help you to solve that question.

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement 759548)

Exercises

http://dubshen.astro.su.se/~jaime/2018_HAO_school/exercises_stic.pdf

You will need python to visualise the input/output data:
numpy, matplotlib, netCDF4, scipy, astropy

1. Synthesis of spectra with STiC (RH).
2. Inversion of the spectra from exercise 1.
3. Inversion of a non-LTE/CRD observation of Ca II 8542.
4. Inversion of an observation with LTE/nLTE-CRD/nLTE-PRD lines.
5. Regularization (4b).