# INVERSION OF THE IRIS Mg II h&k SPECTRAL DATA USING MACHINE LEARNING TECHNIQUES

A. Sainz Dalda
J. de la Cruz Rodríguez,
A. Agrawal
B. De Pontieu

1. BAERI - LMSAL 2. Univeristy of Stockholm
3. LMSAL 4. Henry M. Gunn High School

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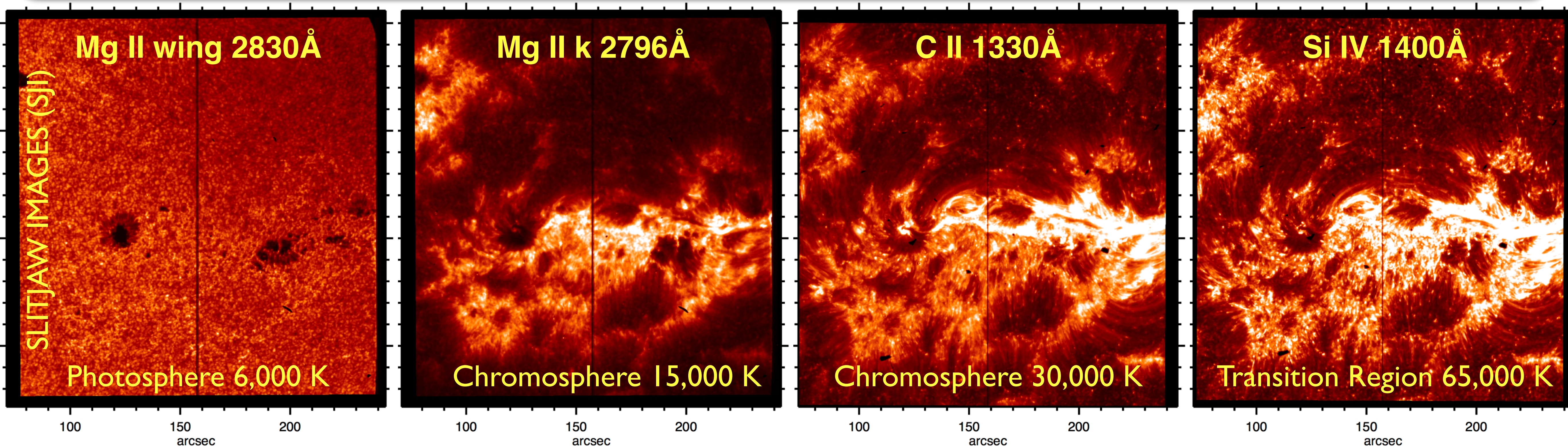
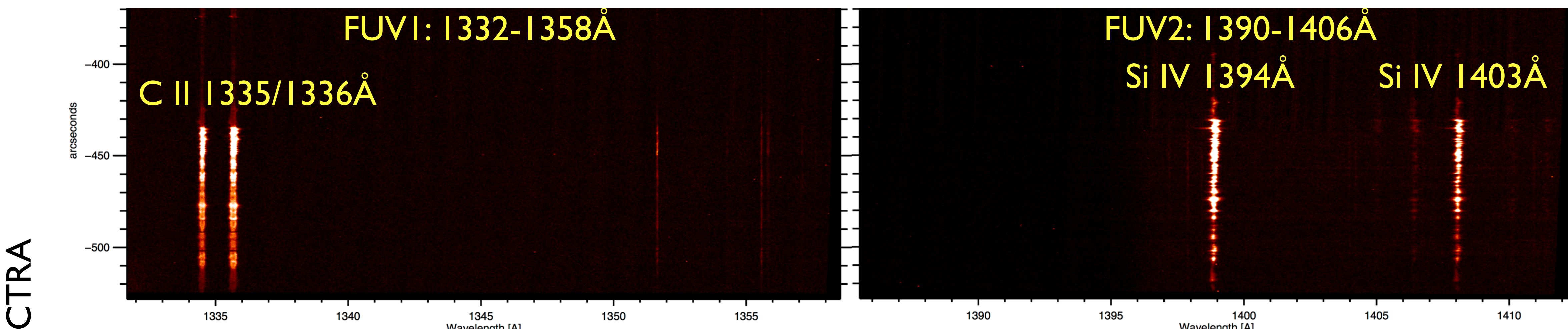
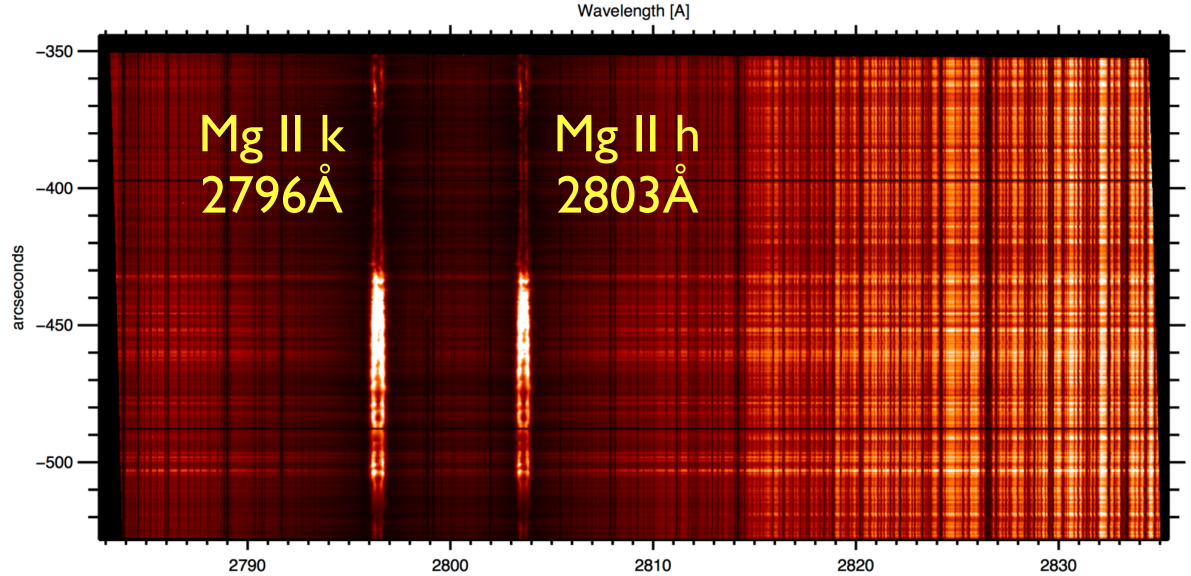
# Interface Region Imaging Spectrograph (IRIS)




high spatial (~0.33"),
temporal (down to ~1s) and
spectral resolution ($\Delta\lambda$ ~ 0.0125-0.025Å)

# Mg II h&k IRIS Observations

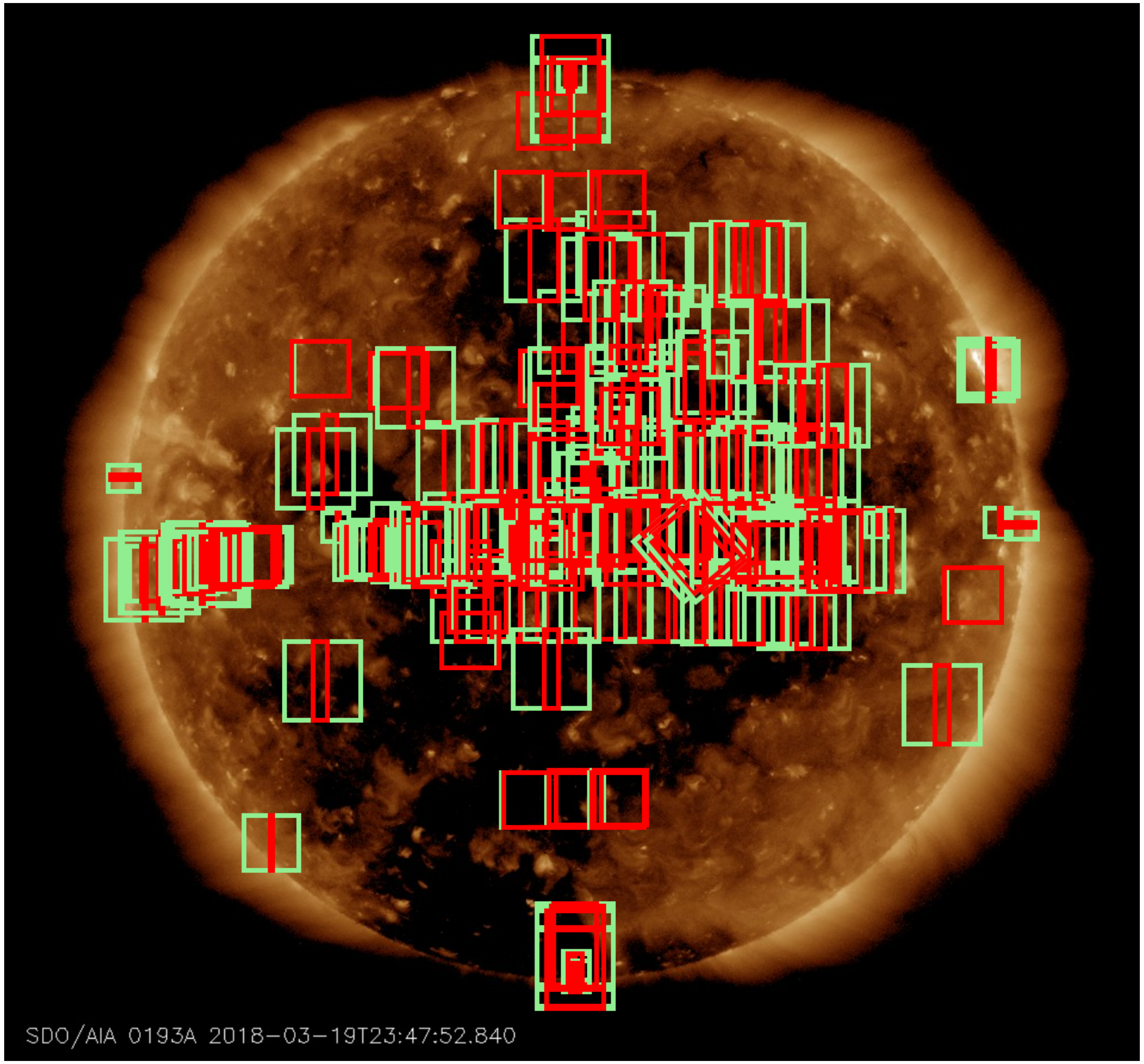
## ~44,800 data sets from 2013-07-20

Sit & Stare

Small raster

Large Sparse 4-step raster

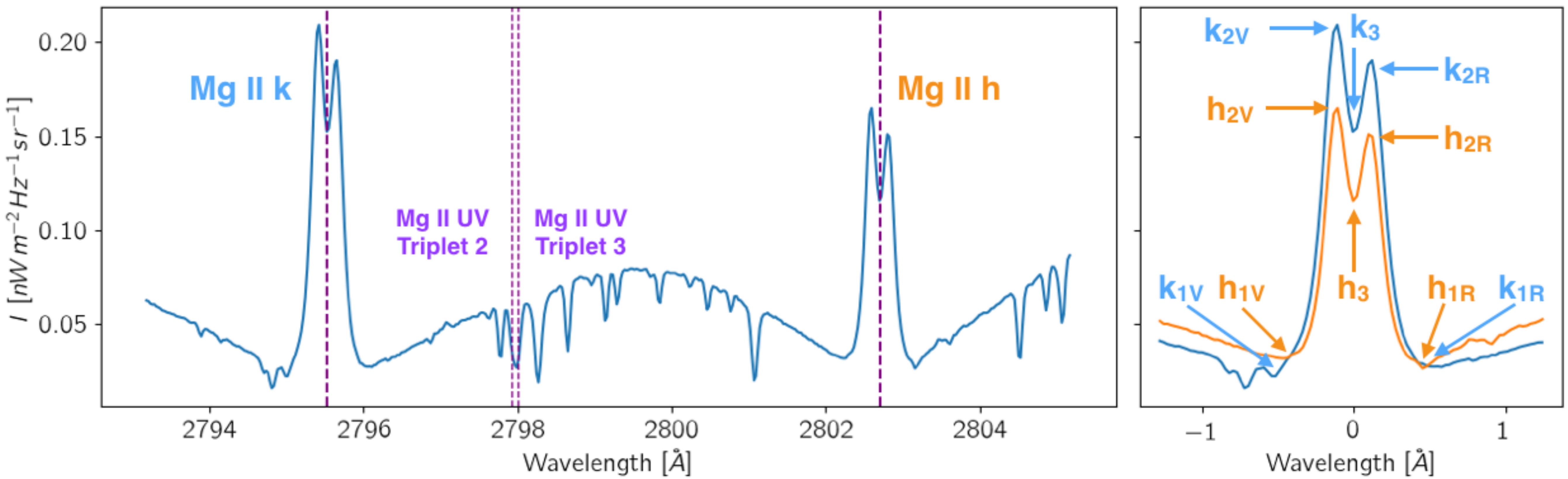
Medium dense 16/32-step raster




Large Sparse 64-step raster

Large dense 320-step raster

# Proxies based on Mg II h&k Profile Features




## Profile Features
$k_3$, $k_{2V}$ & $k_{2R}$

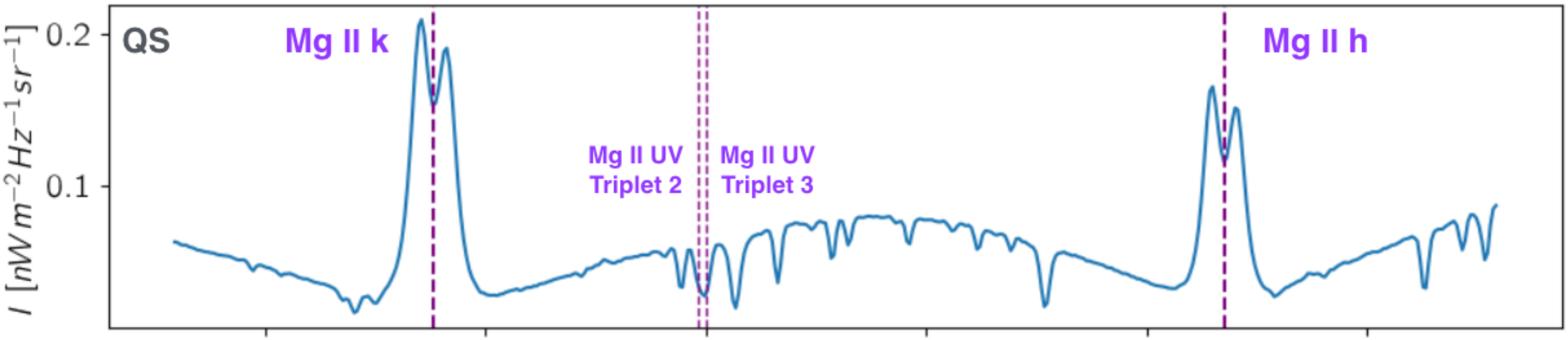
Correlation between Mg II Features and Atmospheric Properties

| Spectral Observable | Atmospheric Property |
|---|---|
| $\Delta v_{k3}$ or $\Delta v_{h3}$ | Upper chromospheric velocity |
| $\Delta v_{k2}$ or $\Delta v_{h2}$ | Mid chromospheric velocity |
| $\Delta v_{k3} - \Delta v_{h3}$ | Upper chromospheric velocity gradient |
| k or h peak separation | Mid chromospheric velocity gradient |
| $k_2$ or $h_2$ peak intensities | Chromospheric temperature |
| $(I_{k2v} - I_{k2r})/(I_{k2v} + I_{k2r})$ | Sign of velocity above $z(\tau = 1)$ of $k_2$[a] |

**Notes.** This is a simplified view and all correlations above have scatter.
[a] Likewise for the $h_2$peaks.

Pereira et al., 2013, ApJ, 778,143

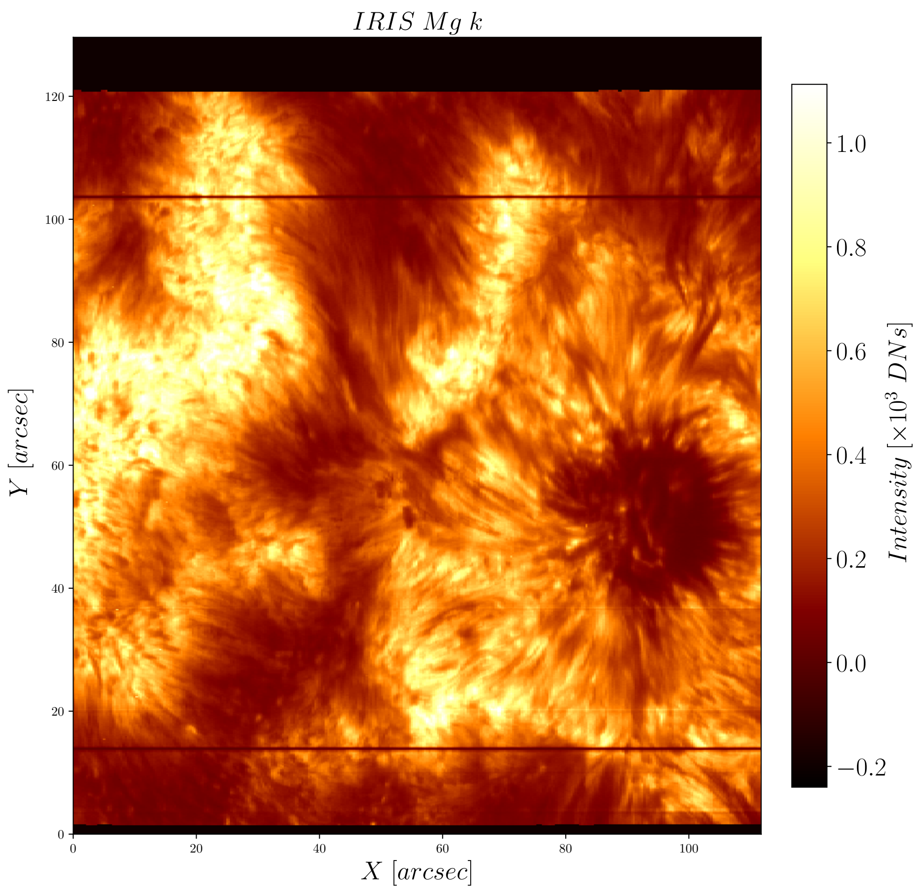
# Proxies based on Mg II h&k Profile Features



# Inversion of the Full data by STiC

**de la Cruz Rodríguez et al. 2016, ApJ, 830, 30D**

**Inversion performance**: **1 px / 2 CPU-hour** (non-LTE + PRD)
**Setup:** inversions of only-Intensity profiles with 473 spectral points, model atmosphere in **39 optical depth heights**, 2 cycles, 7 nodes in T, and 4 nodes both in $v_{los}$ and $v_{turb}$.




### Data Information

- Location: (X,Y) = (559”, 121”), $\mu$ = 0.81
- Spatial scale in X, Y: 0”.35, 0”.16
- Spectral scale: 0.025 mÅ
- Analyzed spectral range: Mg II k&h
- Exposure Time: 8s
- FoV size: 112” x 119”
- Pixels in the FoV: **228941**

**Estimated time mid-large raster:**
**228941px / (1px/2 CPU-hour)**
**~ 460000 CPU-hour**

**Estimated time ALL IRIS data:**
**44,800x50,000px/(1px/2 CPU-hour)**
**~ 4.5x10$^9$ CPU-hour~ 512,000 CPU-yr**

# What is IRIS$^2$?

**IRIS**

**I**nversion based on

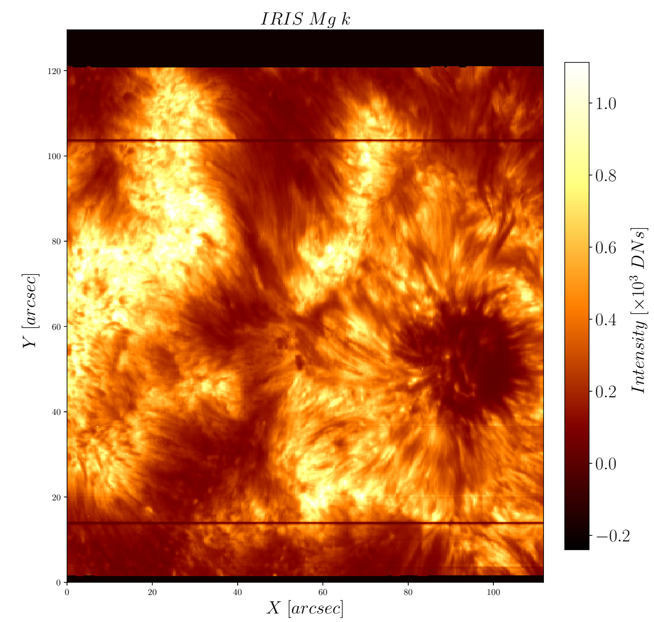
**R**epresentative profiles

**I**nverted by

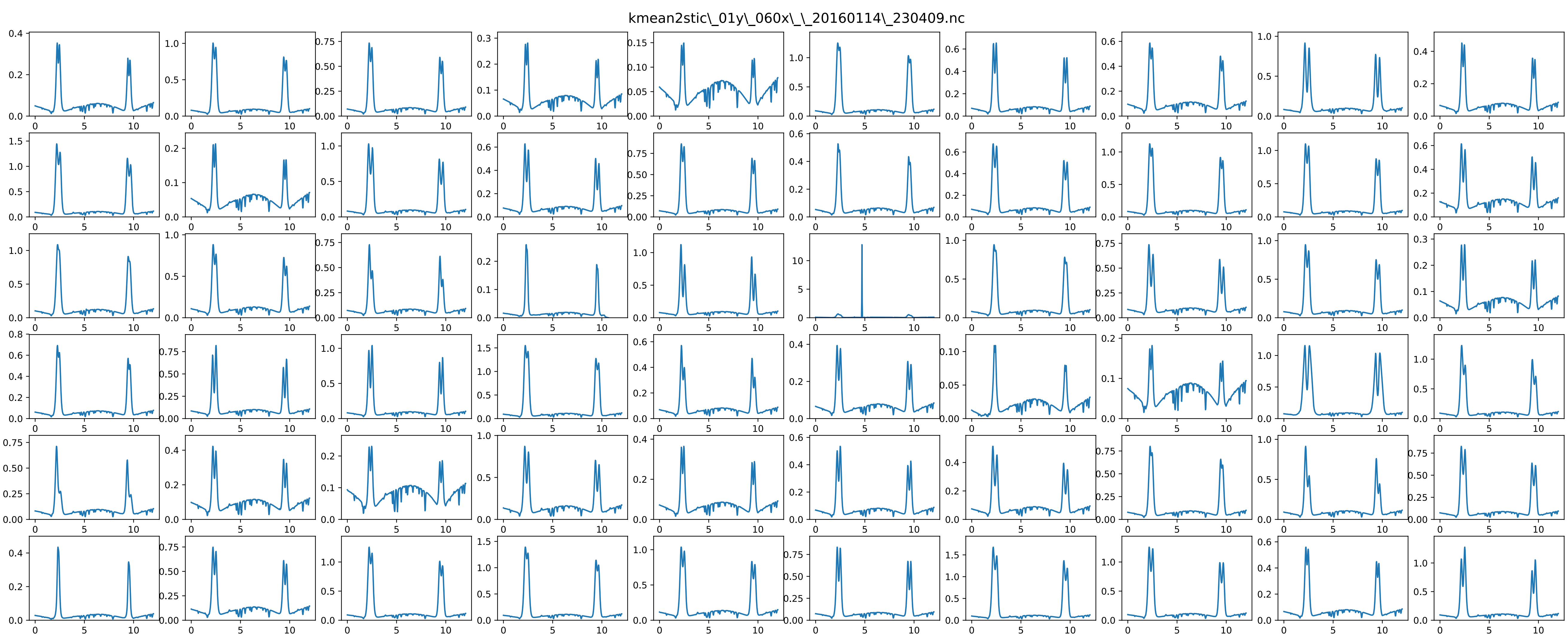
**S**TiC

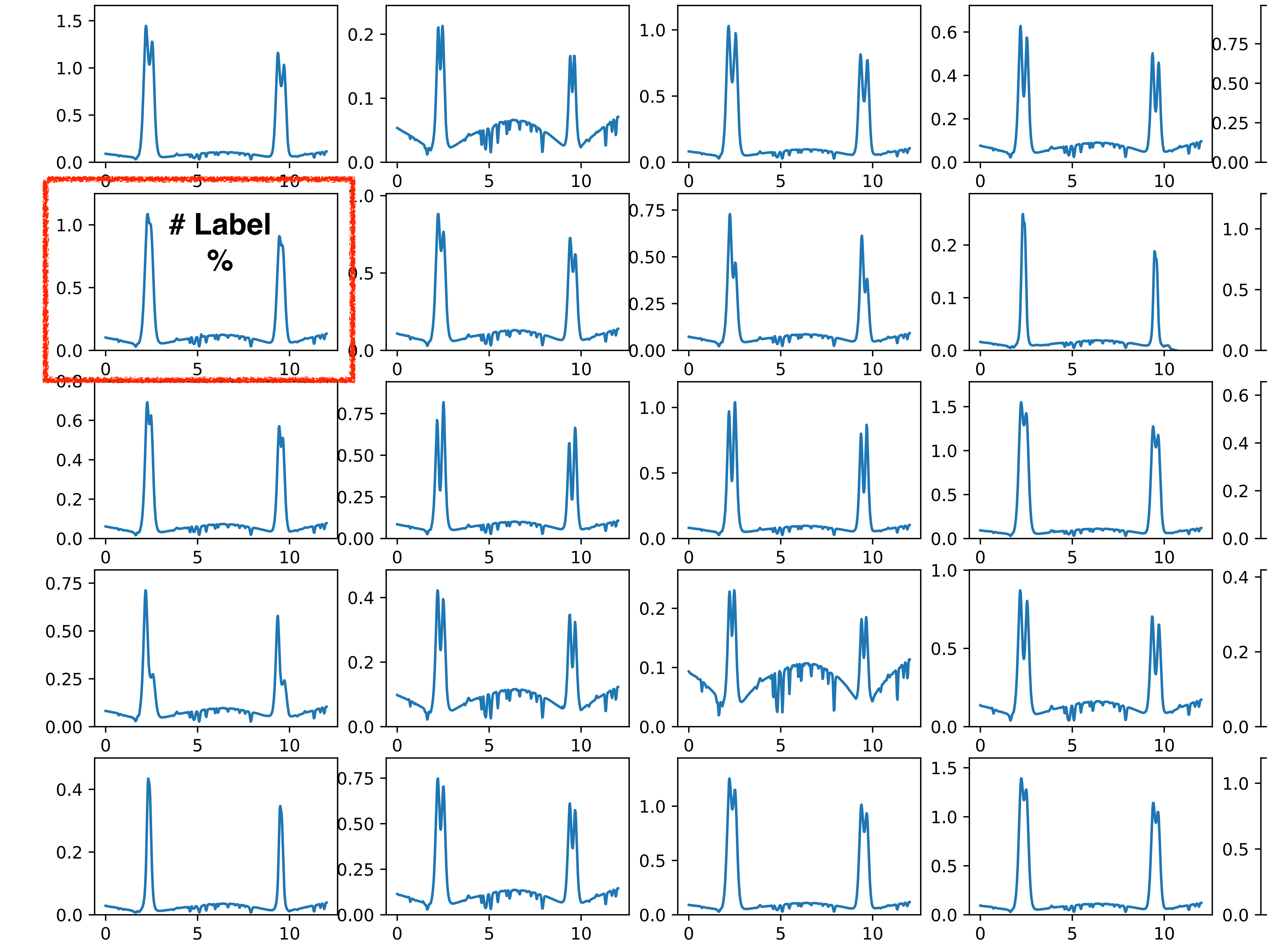
**Goal:** **To recover the depth-stratified thermodynamics in the chromosphere and high photosphere from IRIS Mg II h&k lines in an easy-to-use, fast way while keeping a similar quality in the results to that provided by STiC.**

# From 22894 profiles…



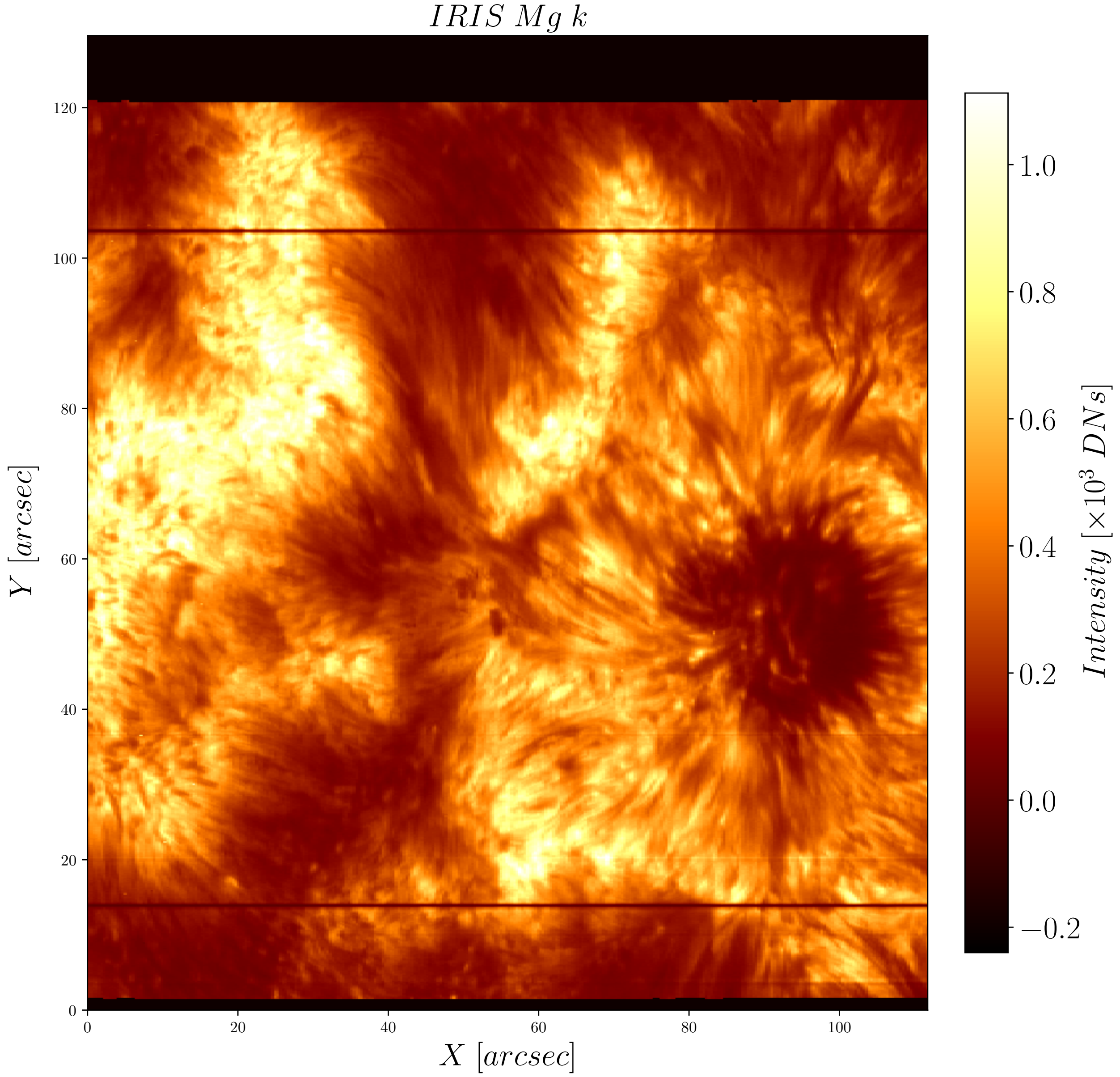

# …to 60 Mg II h&k Representative Profiles (RPs)

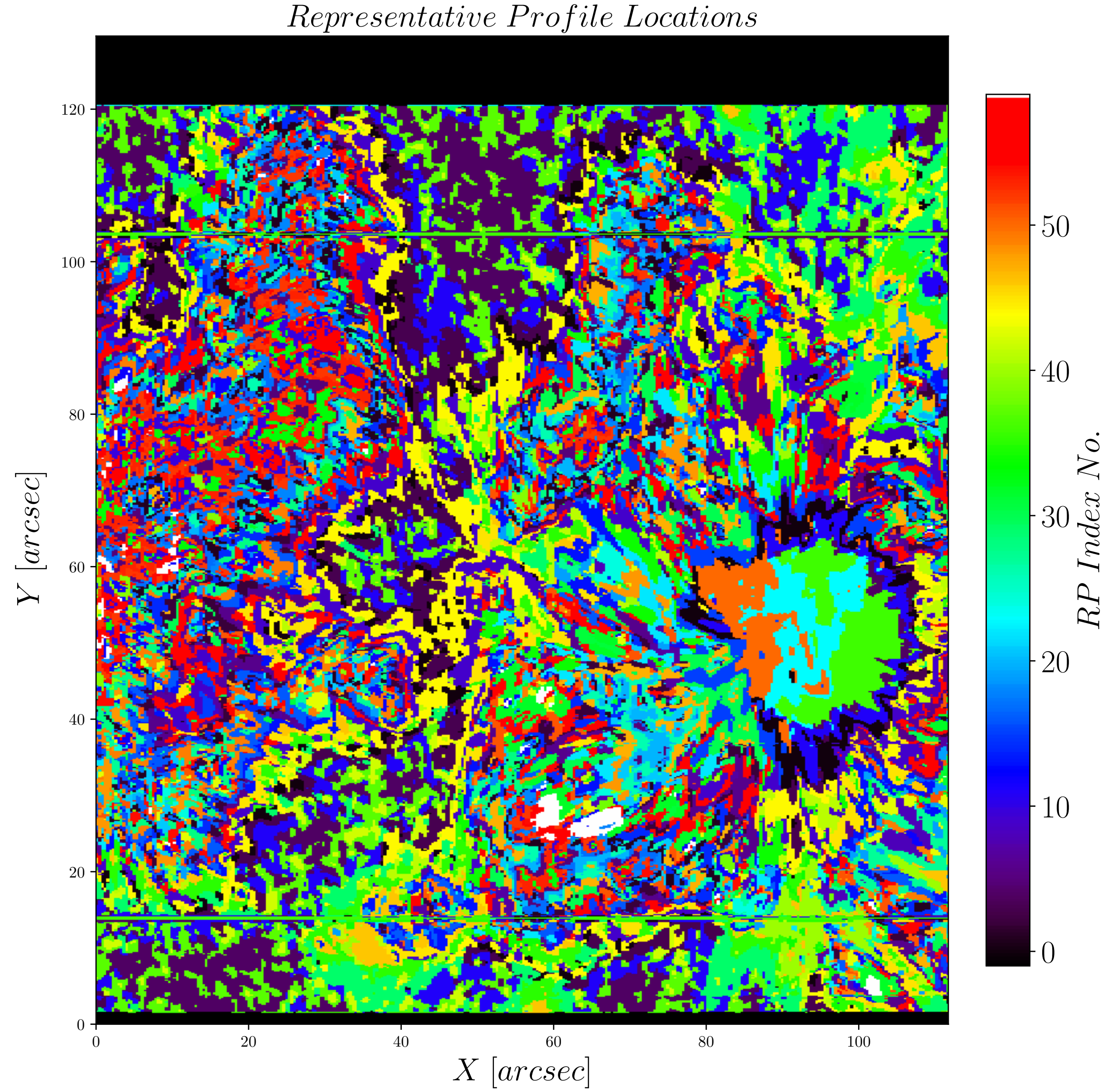




# Label
%

# Spatial Distribution of the Representative Profiles




- **The Representative Profiles (RPs) are *clustered* in a similar way that the solar features are in the solar atmosphere.**

- **The RPs are the signature of different, spatially coherent conditions in the solar atmosphere, i.e., of Representative Model Atmospheres (RMAs)**

# IRIS Inversion based on the RPs Inverted by STiC

## IRIS²

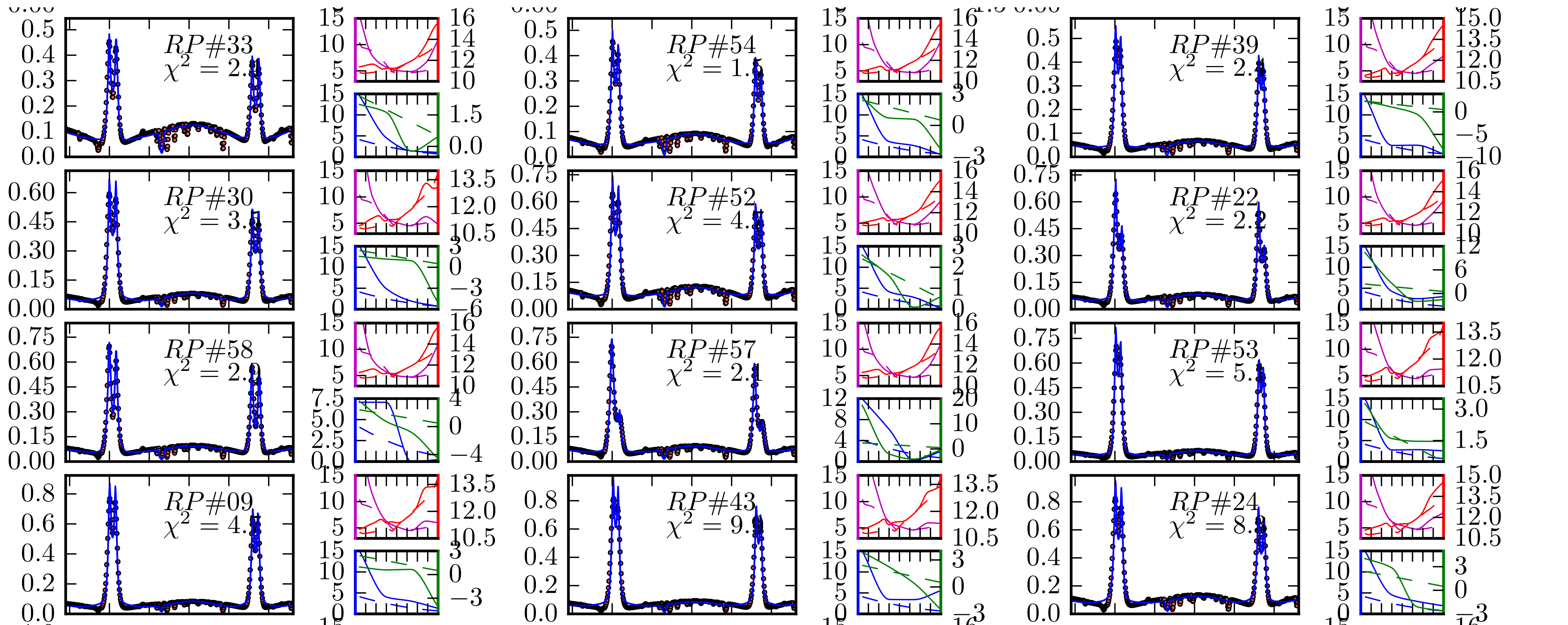
Sainz Dalda et al. 2019, ApJ

de la Cruz Rodríguez et al. 2016, 2019

**60 RPs**
**I @ 473 λs**

**STiC** →

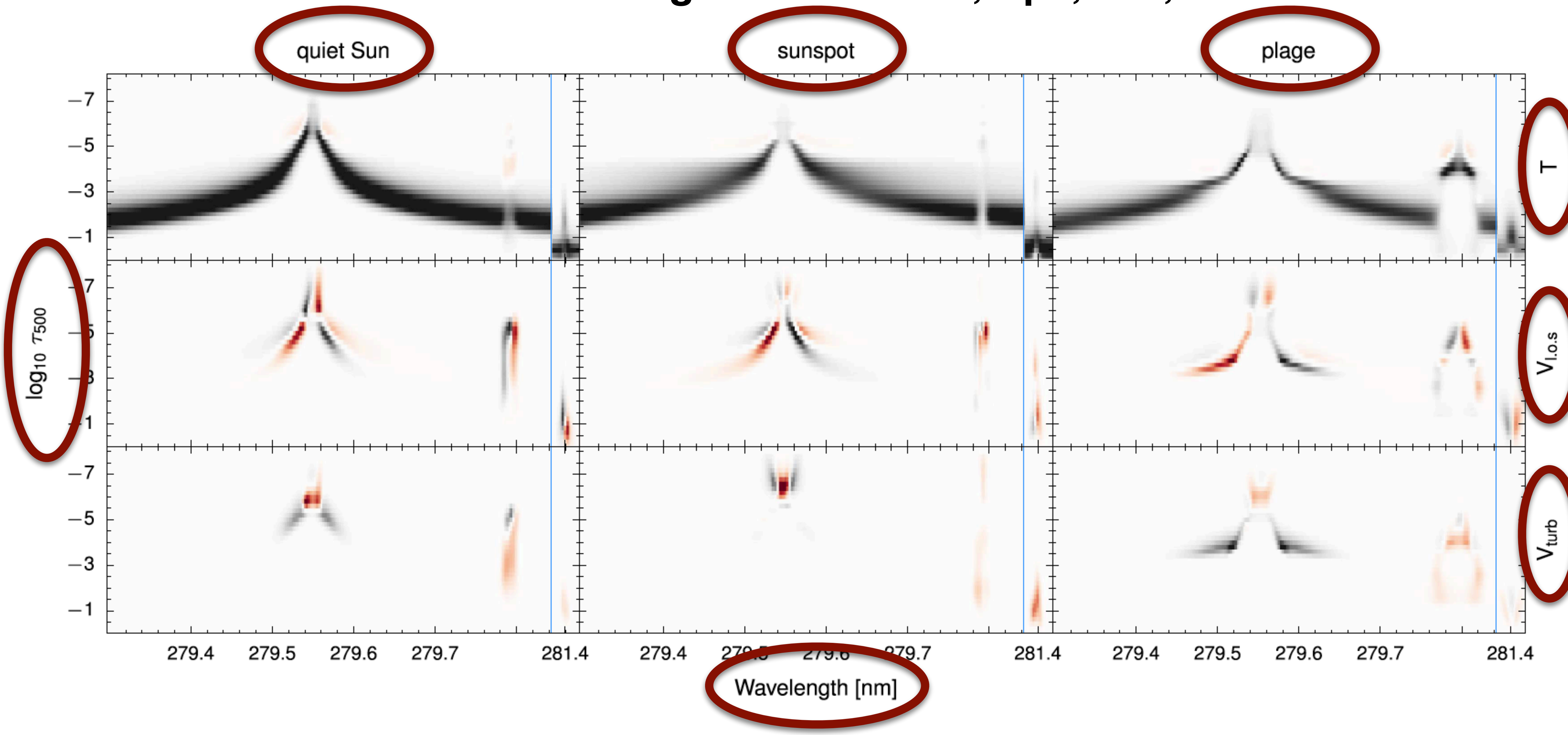
**60 SynRPs & 60 RMAs**
**T, vlos, vturb, & $n_e$ @**
**39 opt. depth**



# RPs Inverted by STiC

## Response Functions

### de la Cruz Rodríguez et al. 2016, ApJ, 830, 30D




**Uncertainty in a physical parameter m**

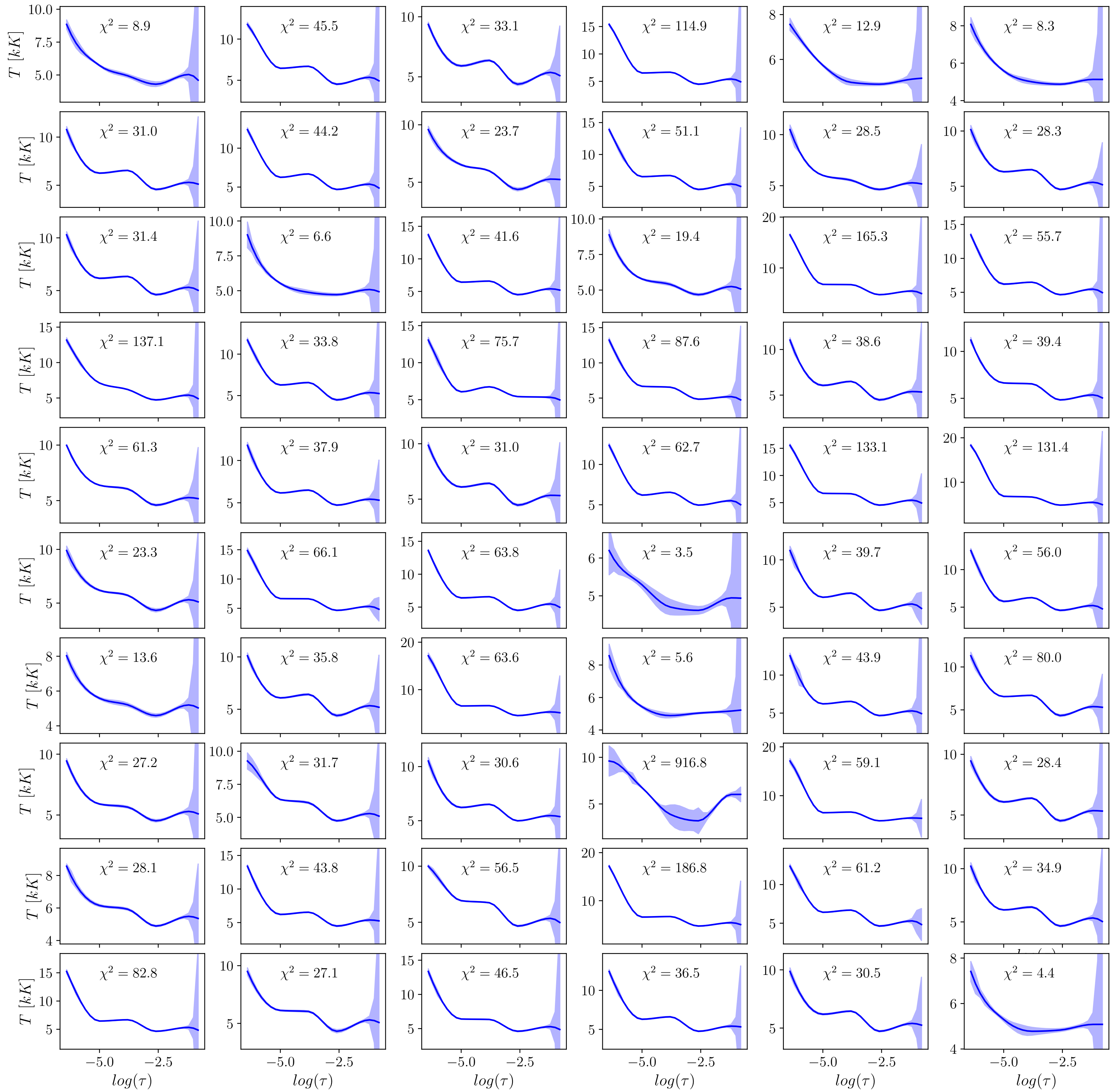
$$\sigma_m^2 \simeq \frac{2}{np+r} \frac{\sum_{s=0}^{3} \sum_{i=1}^{q} \left[ I_s^{\mathrm{obs}}(\lambda_i) - I_s^{\mathrm{syn}}(\lambda_i; \boldsymbol{x}) \right]^2 w_{s,i}^2}{\sum_{s=0}^{3} \sum_{i=1}^{q} R_{m,s}^2(\lambda_i) w_{s,i}^2}.$$

# RPs Inverted by STiC

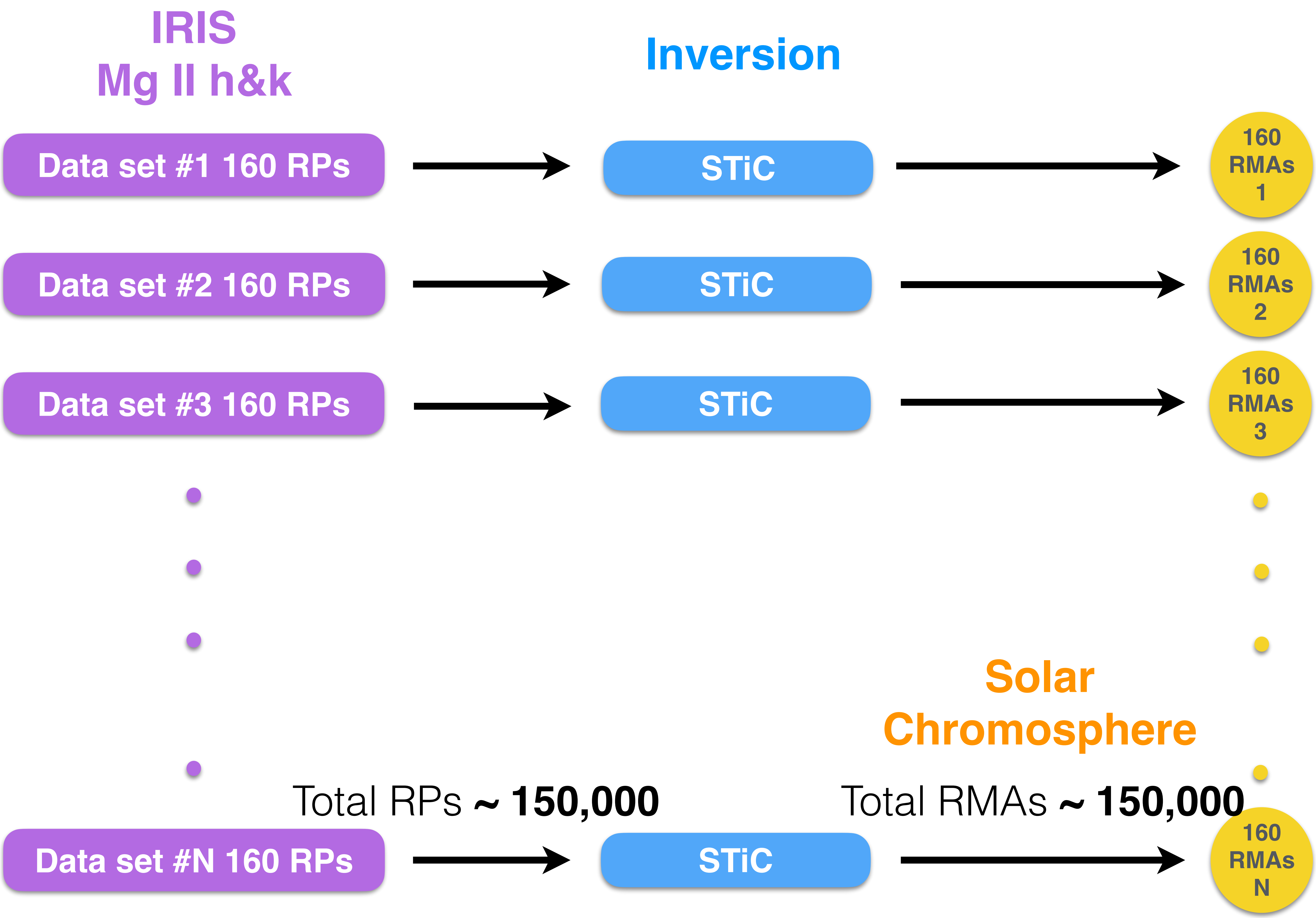
STiC

60 RMAs

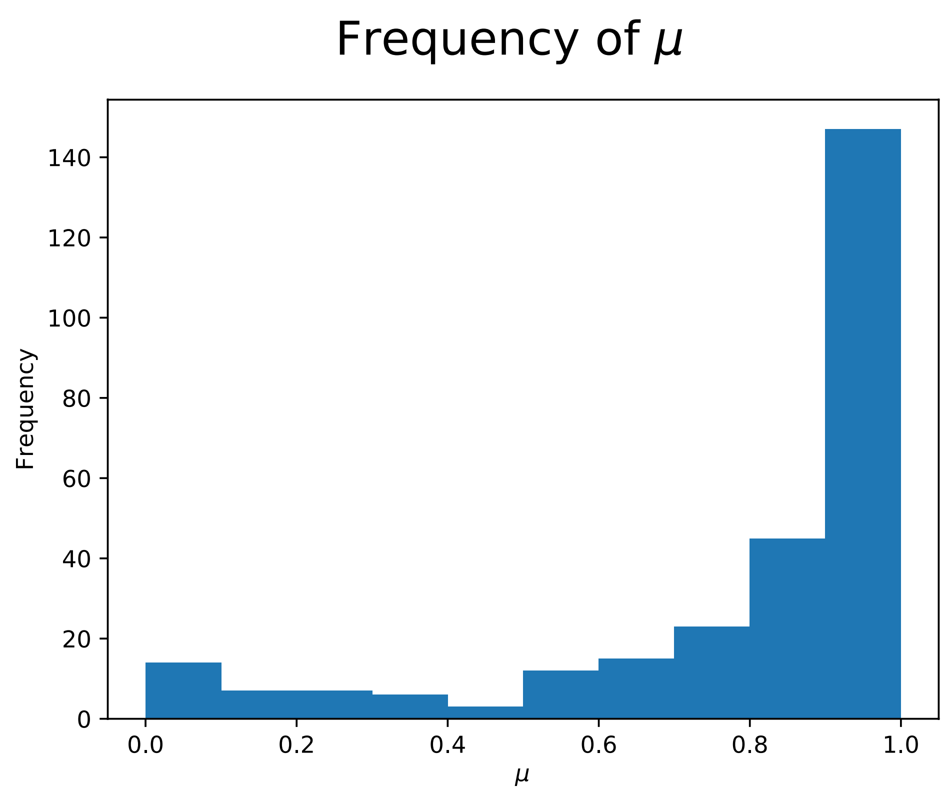
Temperature [kK]

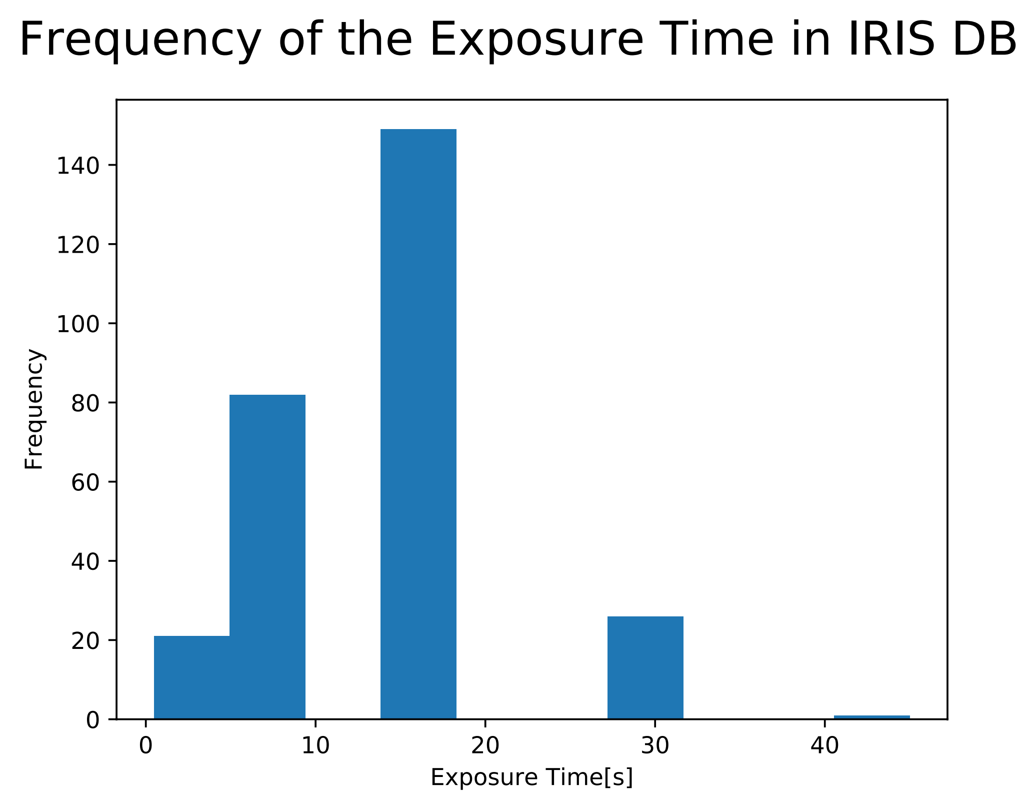


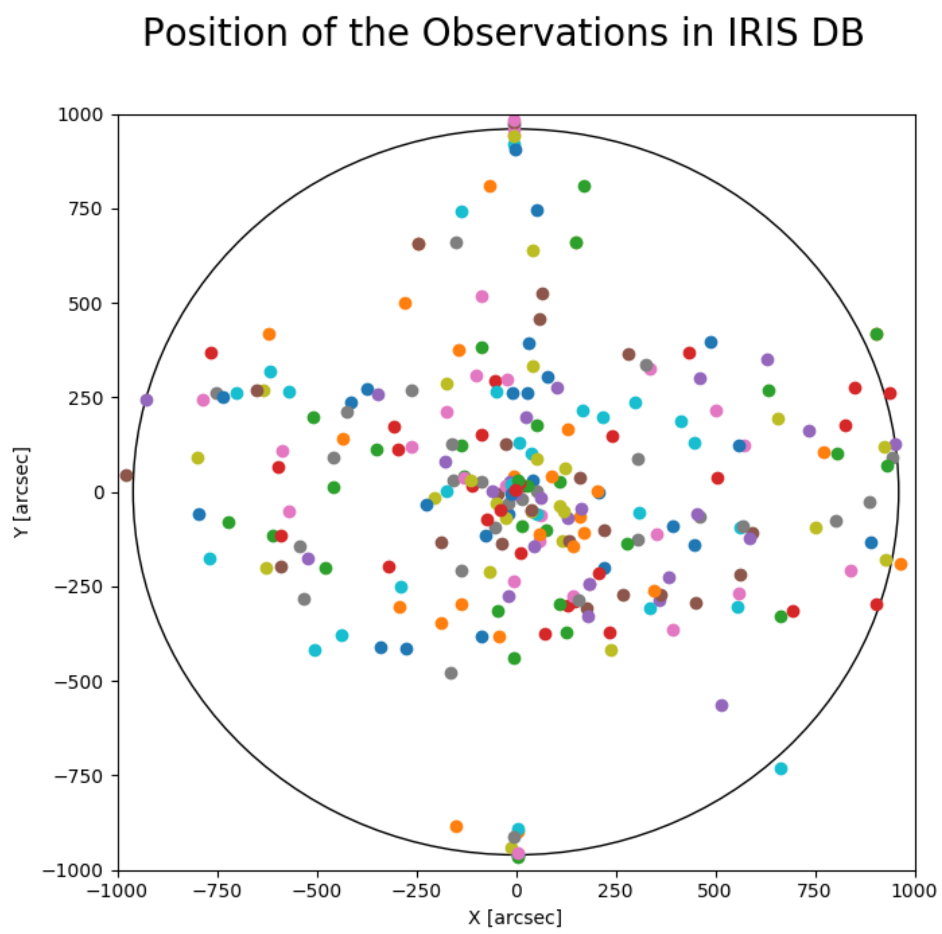
# IRIS Inversion based on the RPs Inverted by STiC

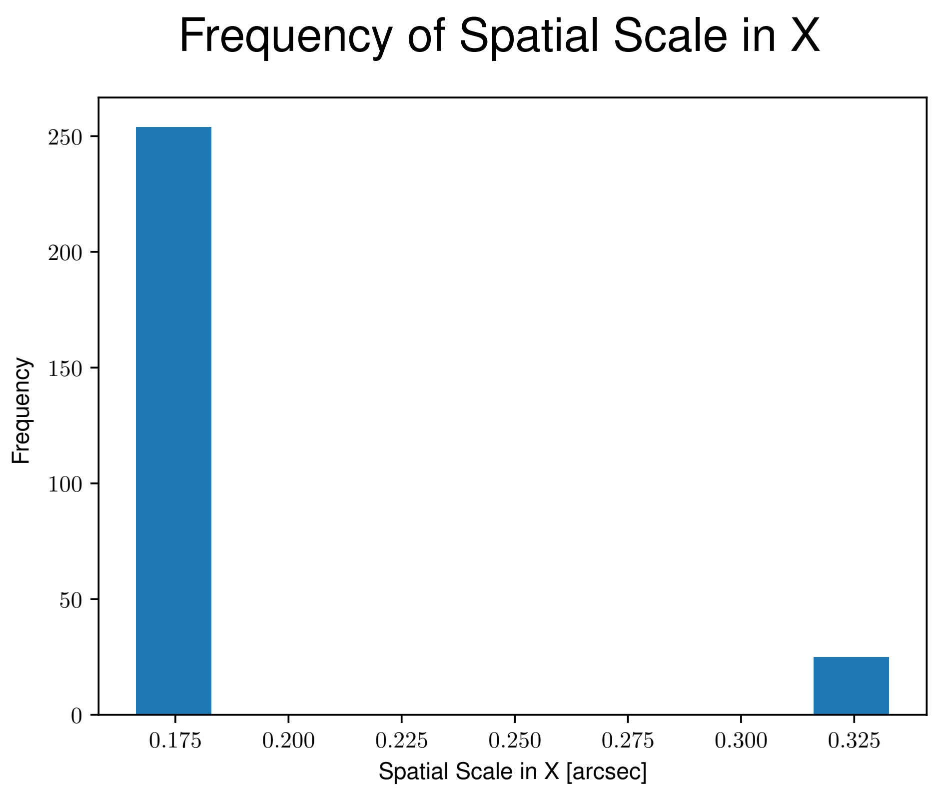


# Building IRIS database



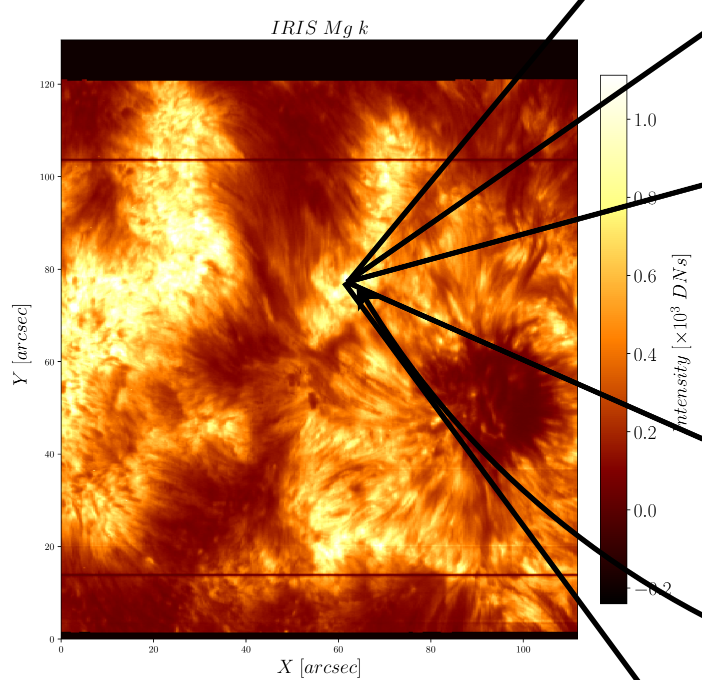



# IRIS Inversion based on the RPs Inverted by STiC

## IRIS²

**Inversion of IRIS profiles:**
Looking for the closest Inverted RP in the IRIS² Database




**Solar Chromosphere**

160 Inverted RPs #1 — 160 RMAs

160 Inverted RPs #2 — 160 RMAs

160 Inverted RPs #3 — 160 RMAs

Observed Profile ≅ Inverted RP — RMA

228941 profiles

30 CPU-minutes

**IRIS² database**

160 Inverted RPs #N — 160 RMAs

Total RPs ~ **150,000**

Total RMAs ~ **150,000**

# IRIS Inversion based on the RPs Inverted by STiC

## IRIS$^2$

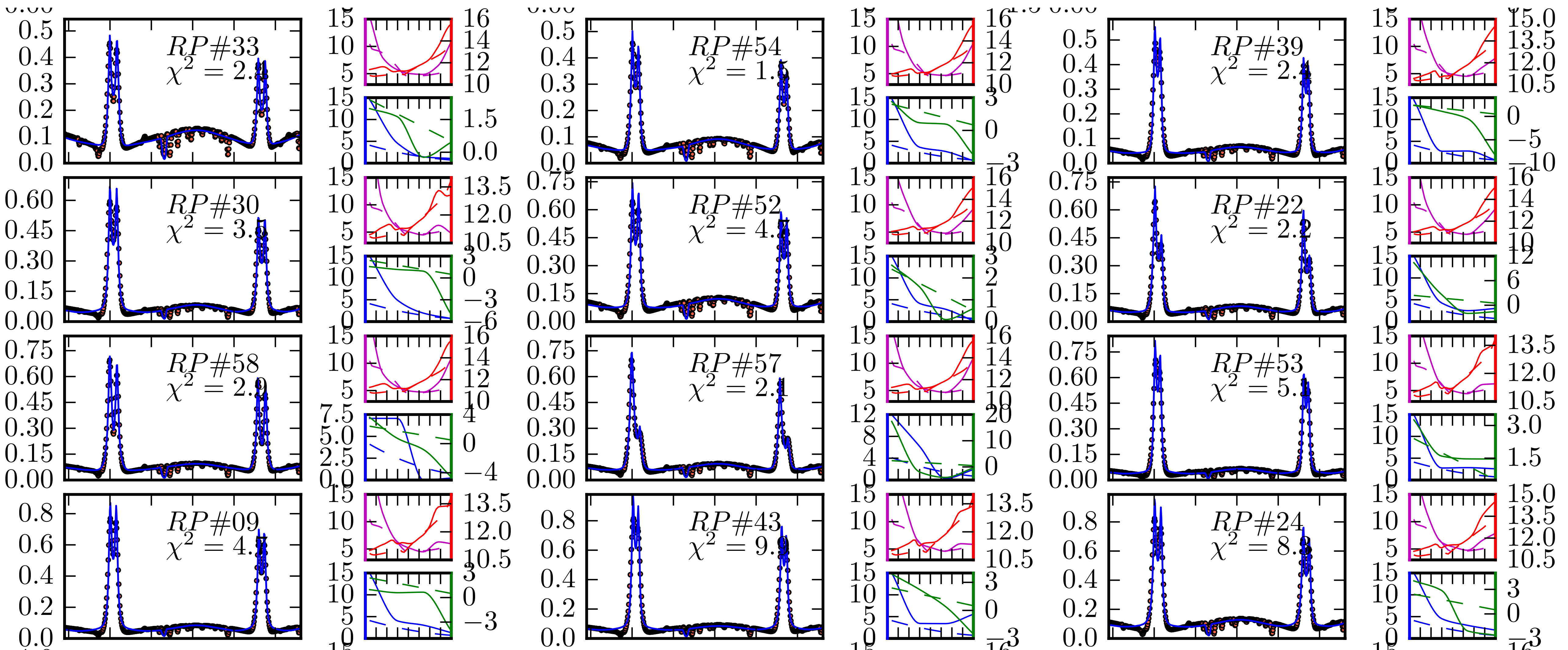
Sainz Dalda et al. 2019, ApJ

de la Cruz Rodríguez et al. 2016, 2019

**150,000 RPs**
**I @ 473 λs**

→ **STiC** →

**150,000 SynRPs & RMAs**
**T, vlos, vturb, & $n_e$ @**
**39 opt. depth**

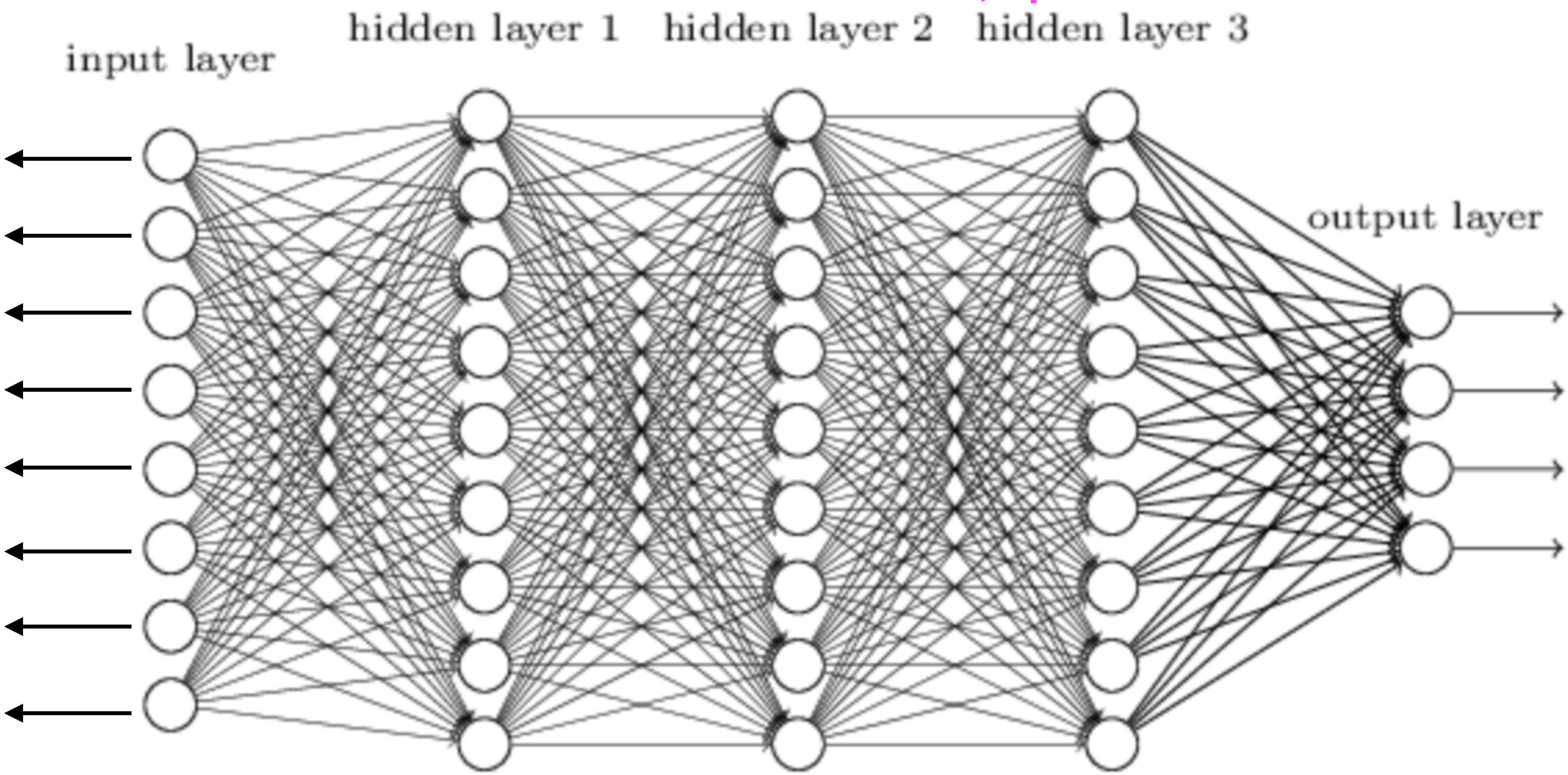


# Deep Learning on IRIS Inversion based on the RPs Inverted by STiC

## deepIRIS²

Sainz Dalda et al. 2019, ApJ

~150,000 SynRPs
I @ 473 λs




~150,000 RMAs
T, vlos, vturb, & ρ @ 39 opt. depth

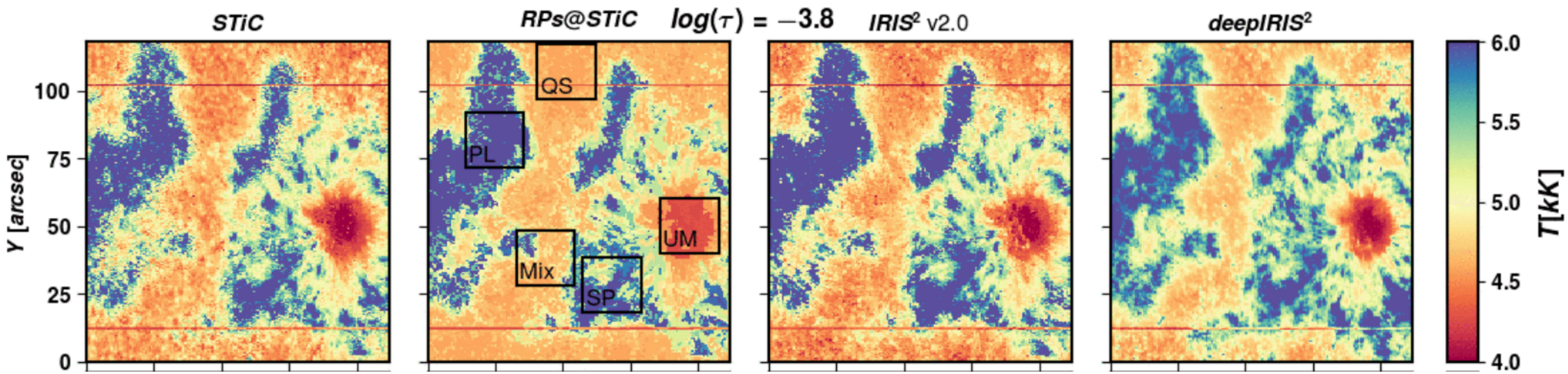
## INNdeepIRIS²

**Invertible Neural Network**

**Predicts the model atmosphere and the observed profile**

Ardizzone et al. 2019
Osborne et al. 2019
Díaz Baso et al. 2022

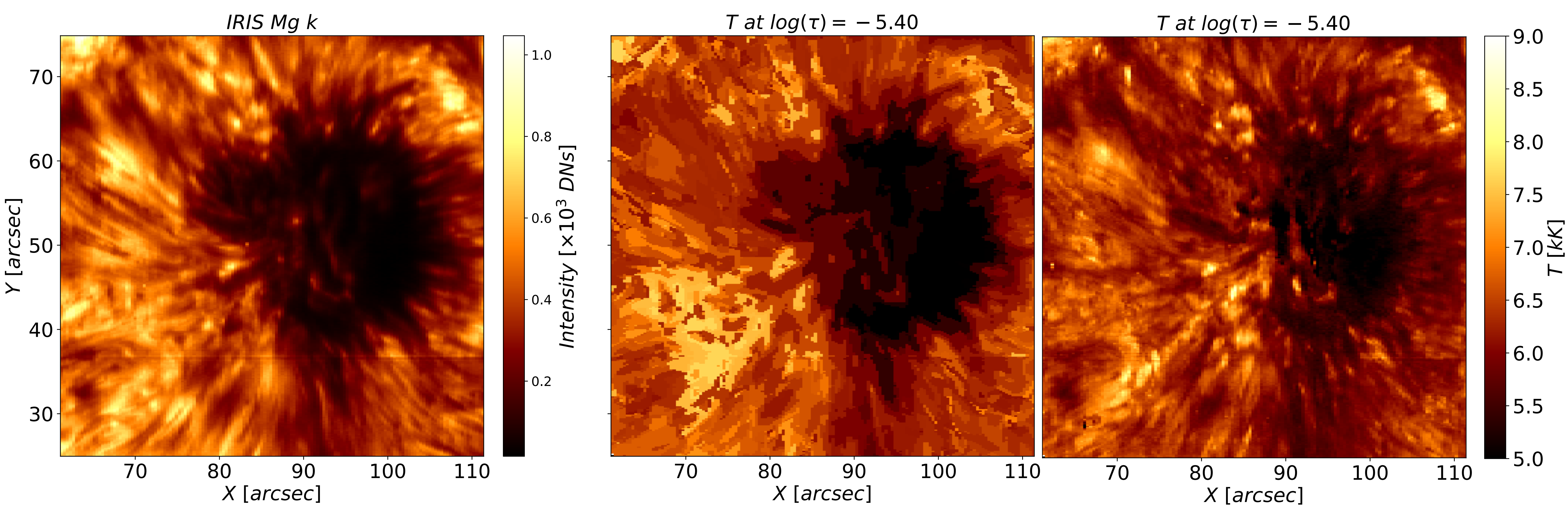
# IRIS² Framework Summary




IRIS Mg II h&k

60 RPs@STIC

deepIRIS²



# Temperature & Microturbulence

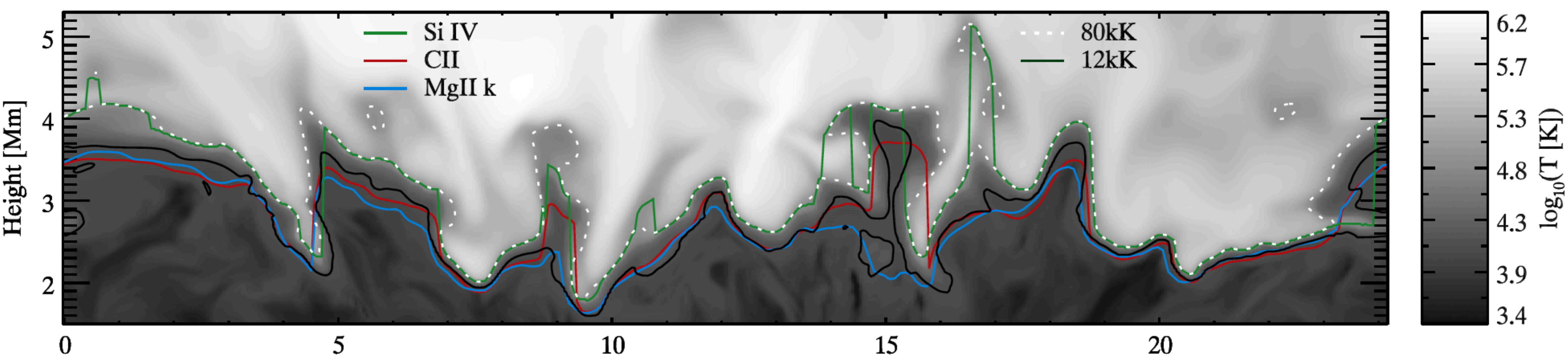
**"Spectral Line formation", Jefferies, J. T., 1968, Blaisdell Publishing Co.**

where $\xi_0$ is a mean random velocity. The velocity broadening accompanying these random motions is superposed on the basic Doppler profile of the absorption coefficient to give an expression of the same form as given in Equation (4.97), but in which the Doppler width is given as

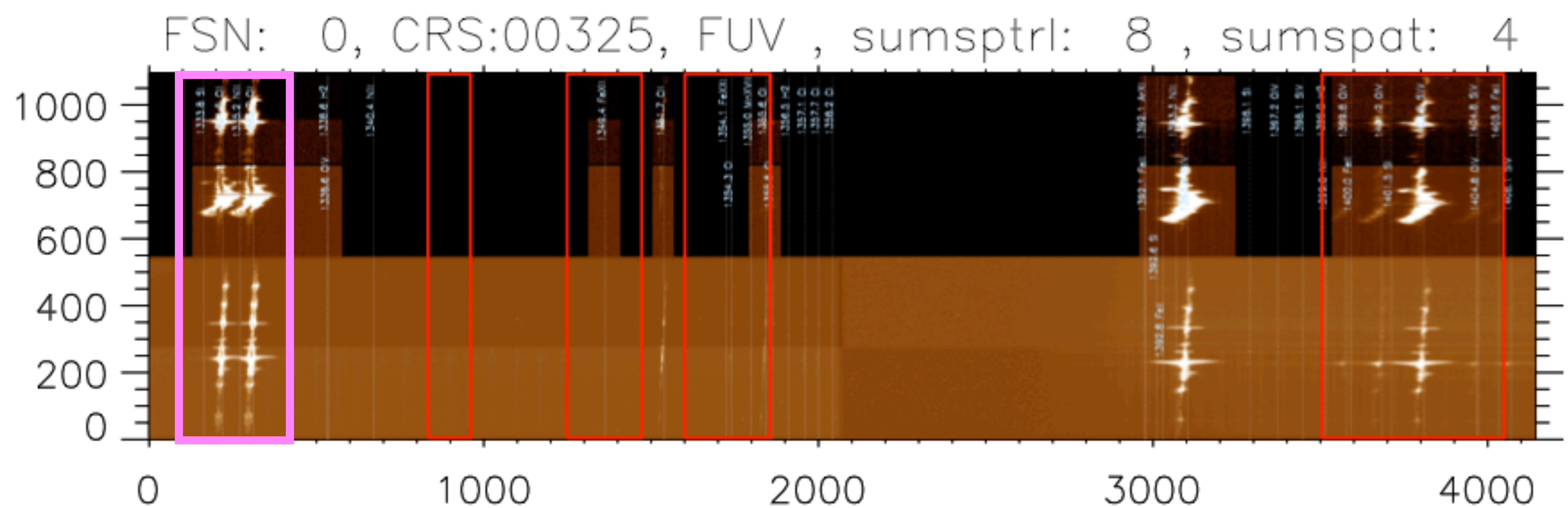
$$\Delta\nu_D = \frac{\nu}{c}\left[\frac{2kT}{m} + \xi_0^2\right]^{1/2}. \tag{4.102}$$

Since $\xi_0$ is presumably the same for all atomic constituents, while $m$ is different, observations of the widths of two line profiles may often be made consistent by a suitable choice of the two parameters $\xi_0$ and $T$. This is, in fact, the reason for the consideration of such random

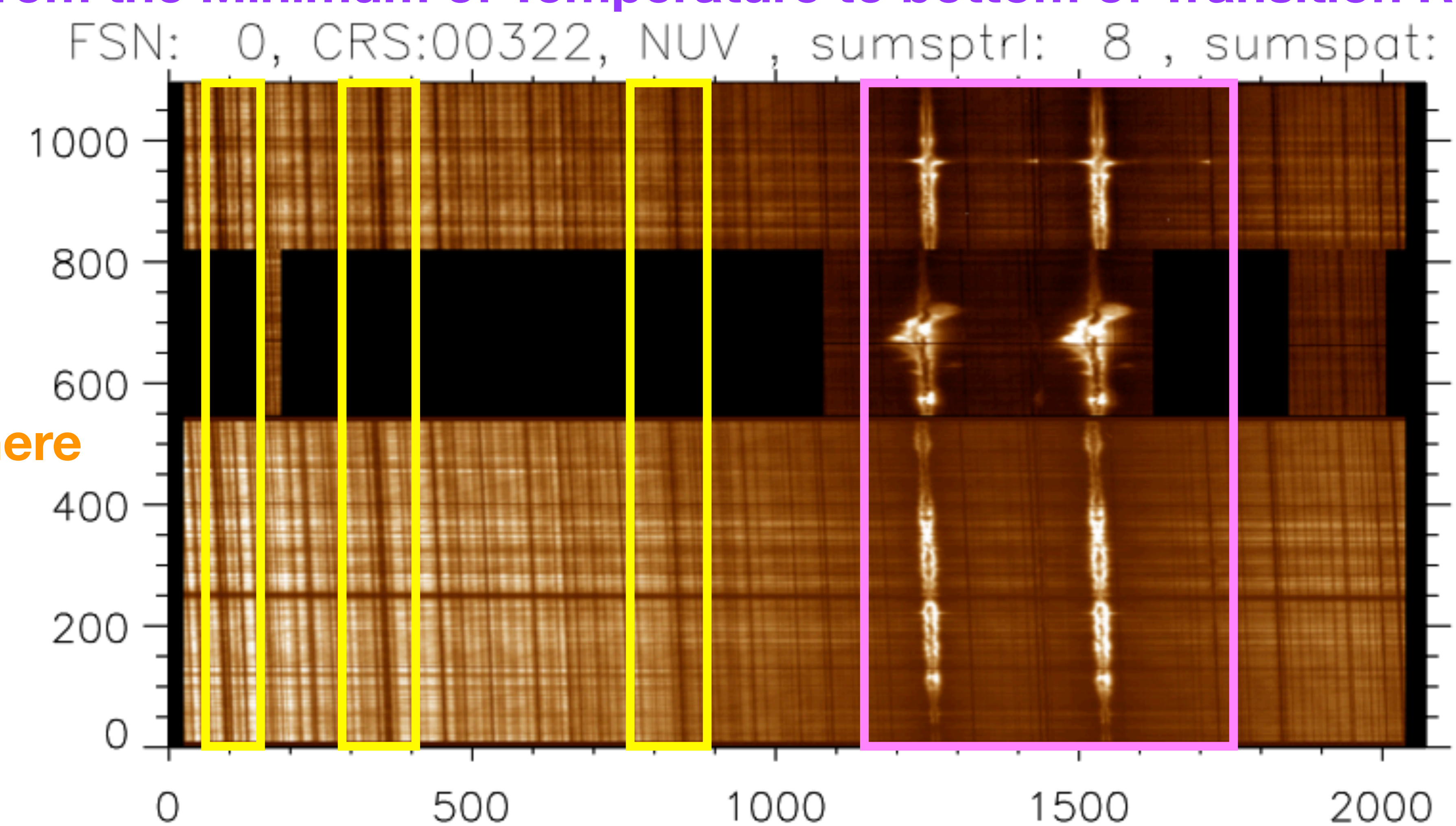
Rathore et al., 2015, ApJ, 811:81



# IRIS MULTI-LINE CAPABILITIES




**From the Minimum of Temperature to bottom of Transition Region**




**Photosphere**

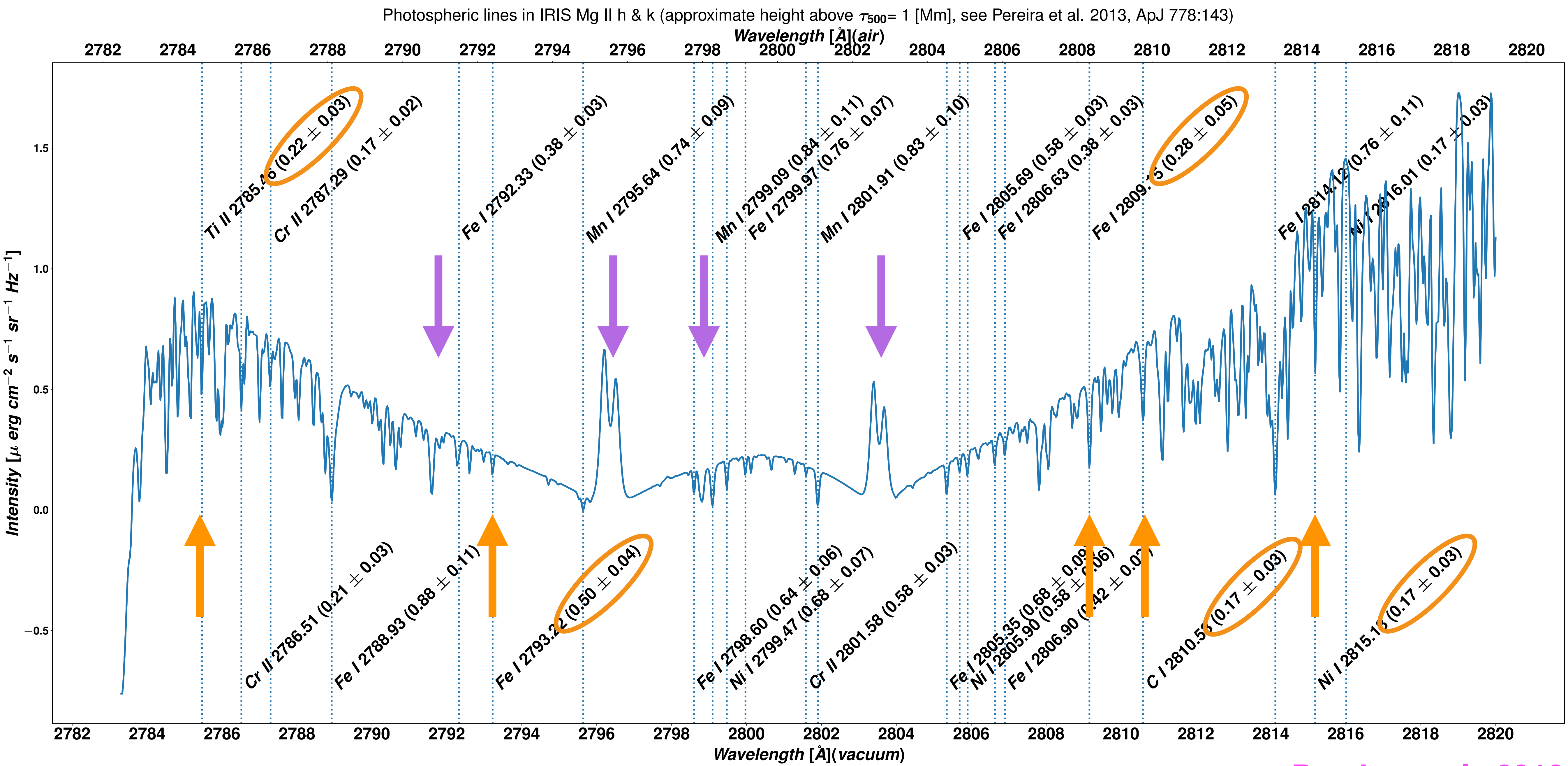
# IRIS$^{2+}$

## Thermodynamics of the chromosphere and photosphere from multi-line IRIS inversions

### C II 1334 & 1335 Å

### Mg II h & k + Mg II UV triplet

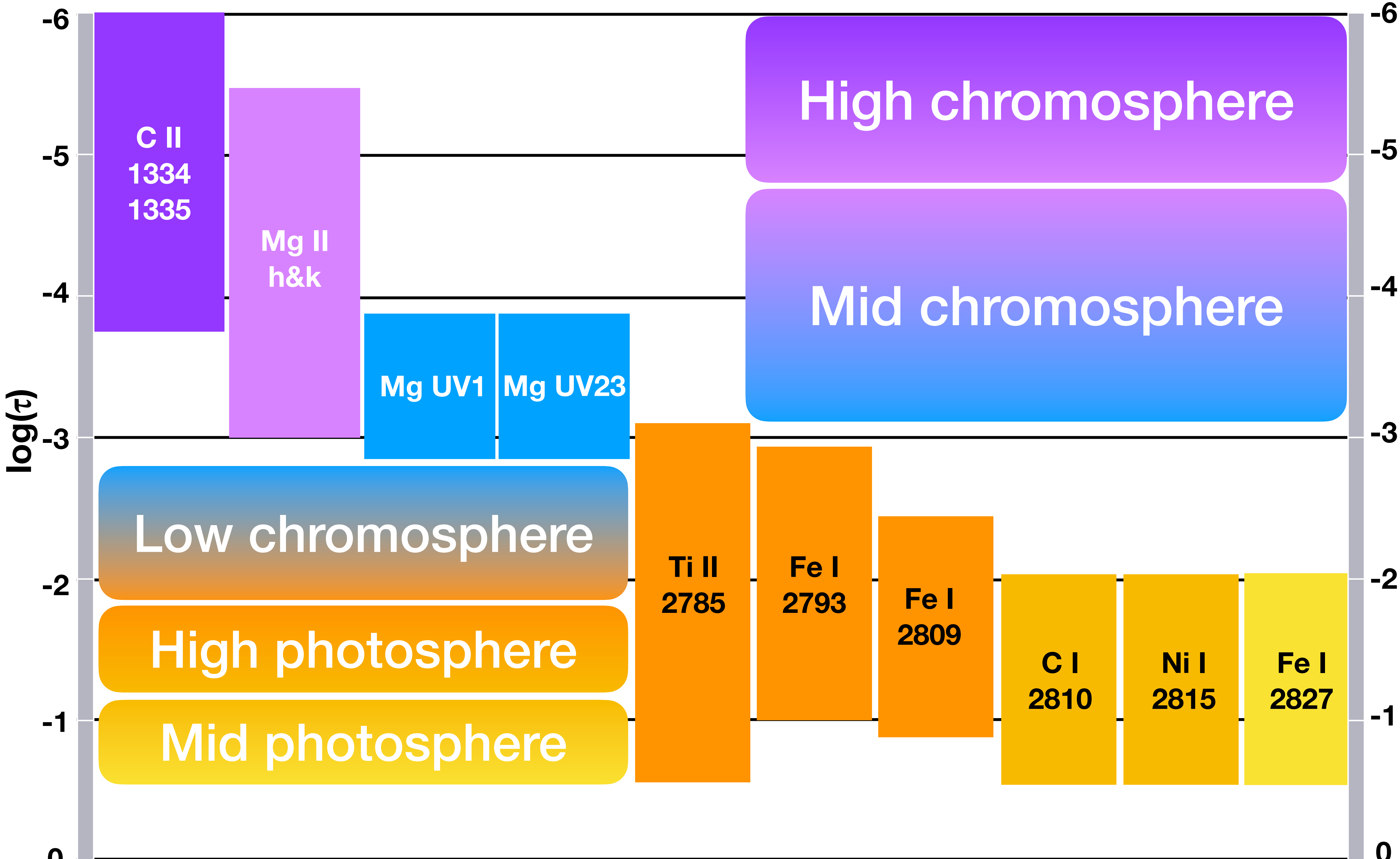
### 6 photospheric lines



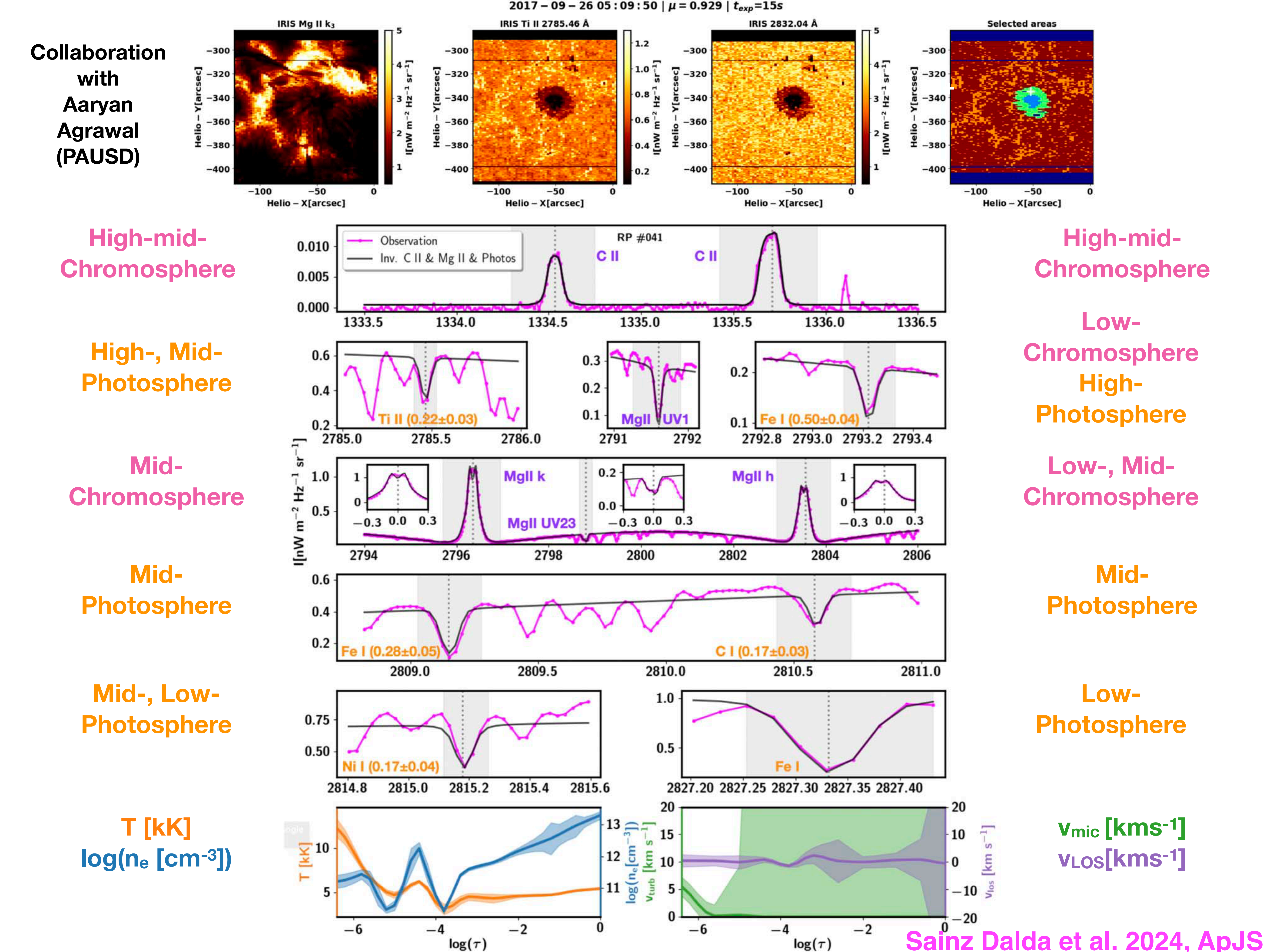

Pereira et al., 2013

# Response Function of the Intensity to the Temperature

**Where the (Intensity) lines are ROUGHLY sensitive to variations of Temperature**




Sainz Dalda et al. 2024, ApJS

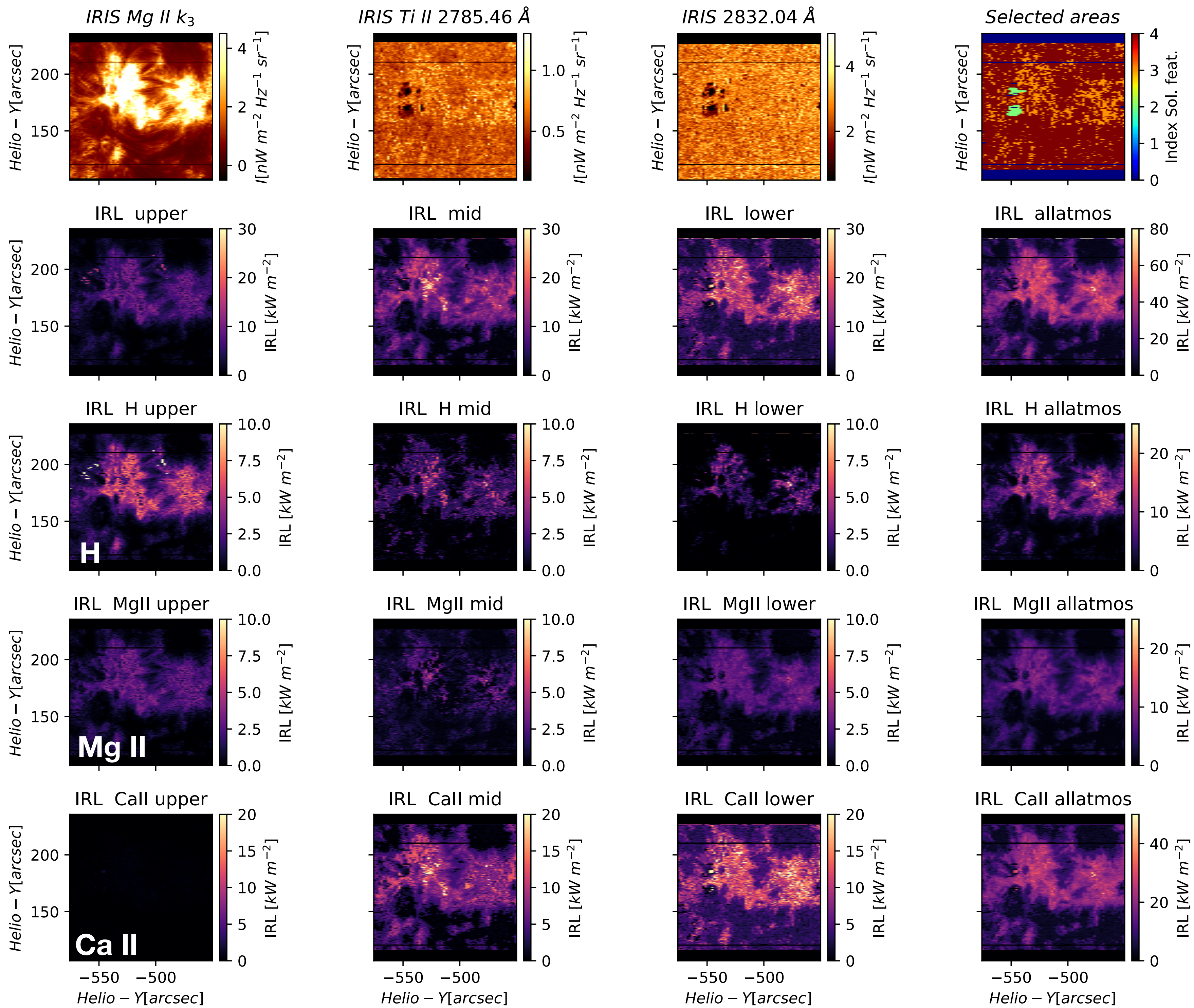


Collaboration with Aaryan Agrawal (PAUSD)
2017 – 09 – 26 05 : 09 : 50 | μ = 0.929 | t_exp=15s
IRIS Mg II k3
IRIS Ti II 2785.46 Å
IRIS 2832.04 Å
Selected areas
Helio – X[arcsec]
Helio – Y[arcsec]
I[nW m-2 Hz-1 sr-1]
High-mid-Chromosphere
High-, Mid-Photosphere
Mid-Chromosphere
Mid-Photosphere
Mid-, Low-Photosphere
T [kK]
log(ne [cm-3])
High-mid-Chromosphere
Low-Chromosphere High-Photosphere
Low-, Mid-Chromosphere
Mid-Photosphere
Low-Photosphere
vmic [kms-1]
vLOS[kms-1]
Observation
Inv. C II & Mg II & Photos
RP #041
C II
C II
Ti II (0.22±0.03)
MgII UV1
Fe I (0.50±0.04)
MgII k
MgII UV23
MgII h
Fe I (0.28±0.05)
C I (0.17±0.03)
Ni I (0.17±0.04)
Fe I
log(τ)
vturb [km s-1]
vlos [km s-1]
Sainz Dalda et al. 2024, ApJS

# IRIS$^{2+}$ v2.0
# The Representative Integrated Radiative Loss (RIRL)

## In collaboration with Jaime de la Cruz Rodríguez

**320 RP-RMA-RIRL per dataset**




**Contributors**

**Lyman-α, H-α, H-β, Lyman cont, Balmer cont**

**MgII h, MgII k, Mg II UV triplet**

**CaII H, CaII K, Ca II IR triplet**

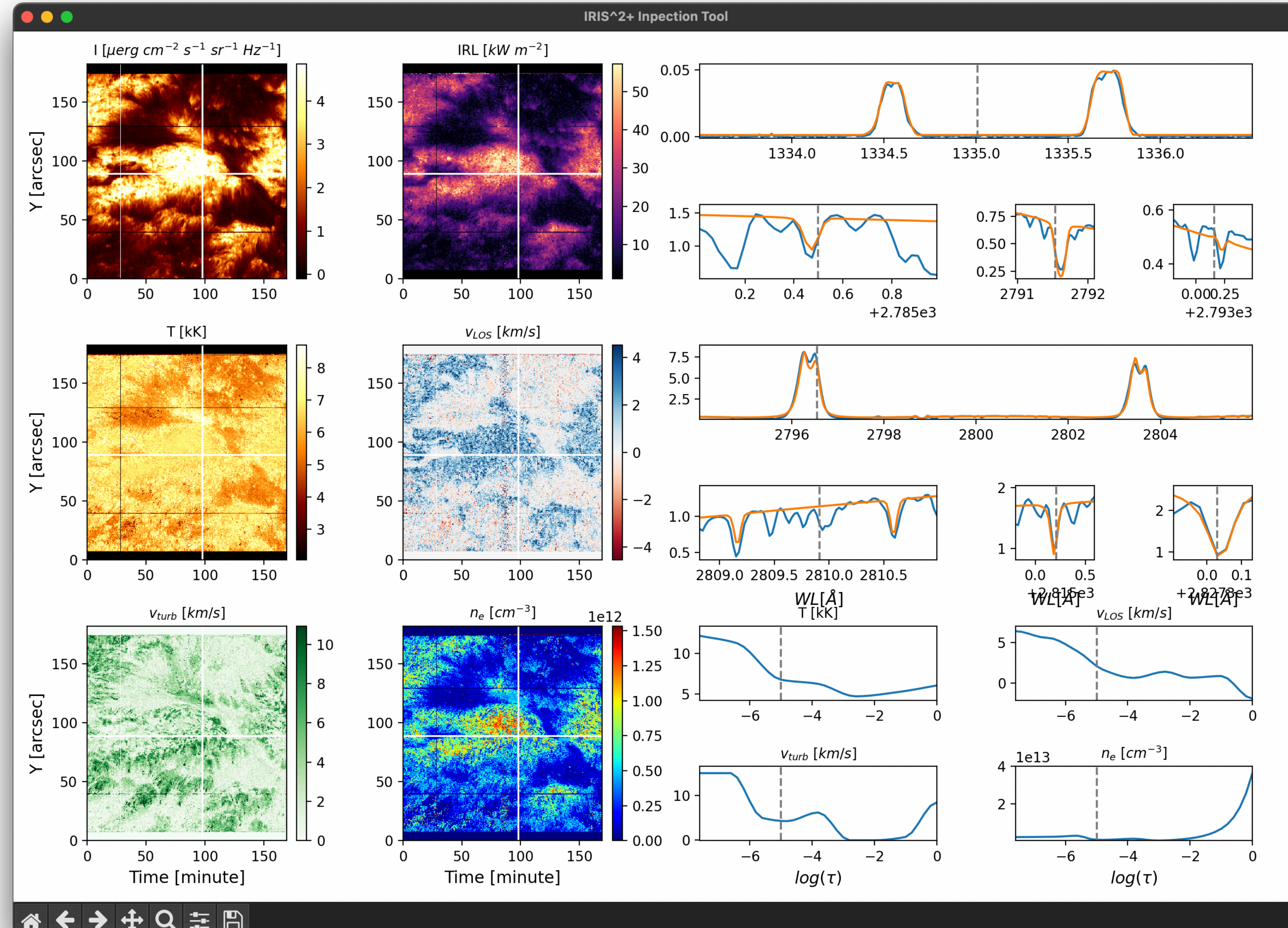
# Analysis and Inspection with IRIS$^2$ & IRIS$^{2+}$

For any [x,y] we need to show:

- 1 < N ≤ 12 observed spectral lines (Nx3D, [x, y, $\lambda^{N}{}_{k}$], in 8 spectral windows with $N_k$ spectral samples)
- 1 < N ≤ 12 best fit spectral lines (Nx3D, [x, y, $\lambda^{N}{}_{k}$], in 8 spectral windows $N_k$ spectral samples)
- 1 monochromatic image at any wavelength of the N observed spectral lines
- 1 monochromatic image at any wavelength of the N fit spectral lines
- T, $v_{los}$, $v_{turb}$, and $n_e$ at any of the 39 sampled optical depth ($-6.8 \leq \log(\tau_{500}) \leq 0$) (4x3D, [x, y, $\log(\tau_{500})$])
- Integrated Radiative Loss (2D, [x,y])
- The thresholds both for the images and plots can be changed either dynamically or manually
- Save relevant data for any selected position
- Working with up to 20x3D + 2D, all sharing the same [x, y] dimensions

# IRIS² & IRIS²⁺ in action

**This is not a figure. It is a highly customizable, interactive visualization and inspection tool.**



# IRIS$^2$ and IRIS$^{2+}$ Framework Summary

- IRIS$^2$ and IRIS$^{2+}$ allows to invert a map (T, $v_{los}$, $v_{turb}$, $p_{gas}$, $n_e$) in a 10-CPU desktop machine in ~ 3 min (PCA+Euclidean distance, IDL) ~1min (PCA+k-NN, Python)

- INNdeepIRIS$^2$ allows to invert a map in a desktop machine in < 1 min (FrEIA, Python)

- Currently, the bottleneck is reading (accessing a disk through the local network) and preparing (radiation calibration, cropping, interpolate (for only-Mg-II-k or only Mg-h-only) the data ~ 5min.

- A visualization tools allows the interactive inspection and analysis of the inversion fit for the observed lines (up to 12), the $\chi^2$ of the fit, the model atmosphere (T, $v_{los}$, $v_{turb}$, and $n_e$), and the integrated radiative loss.

**Thanks for your attention!**

asainz.solarphysics@gmail.com