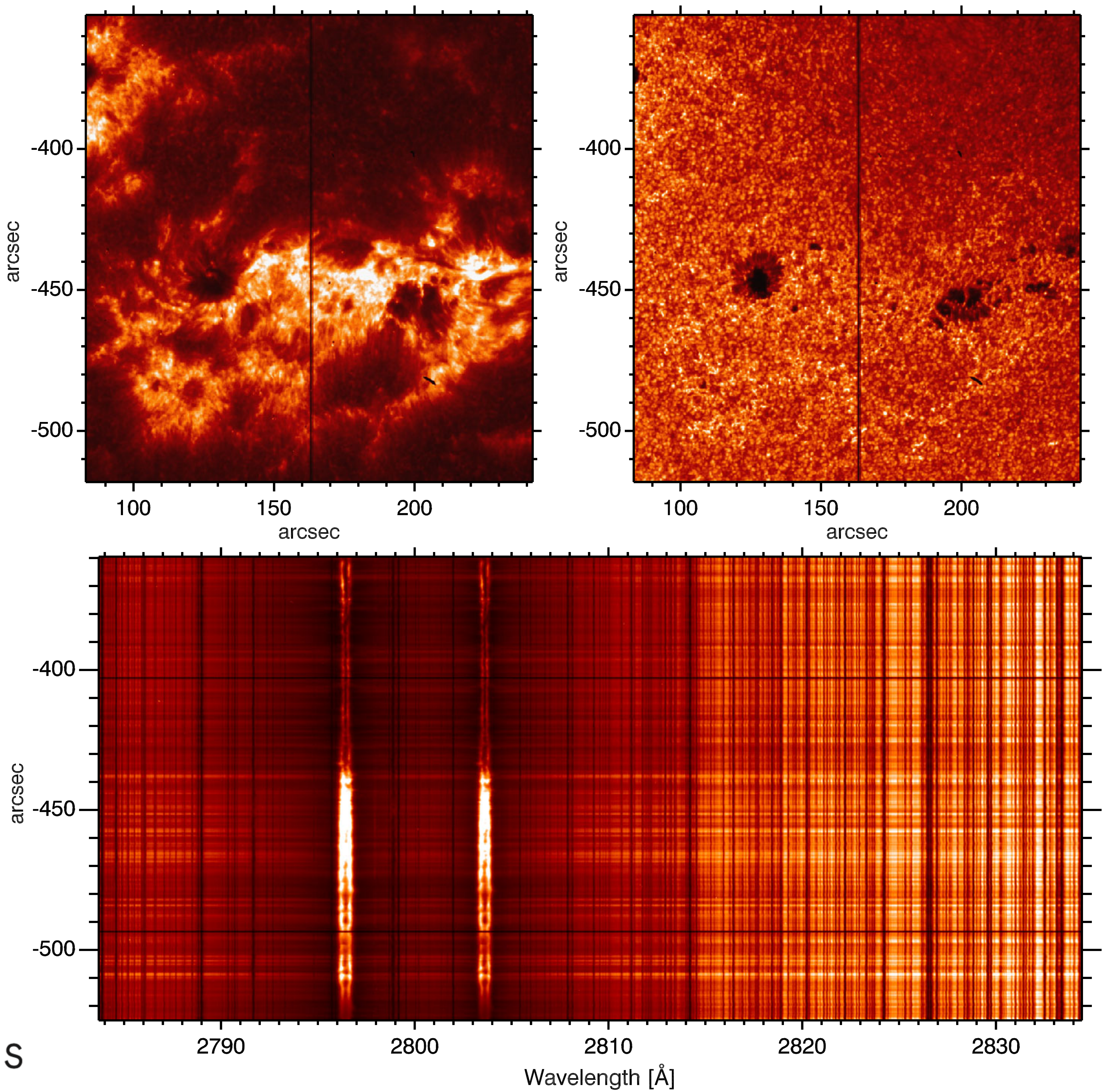
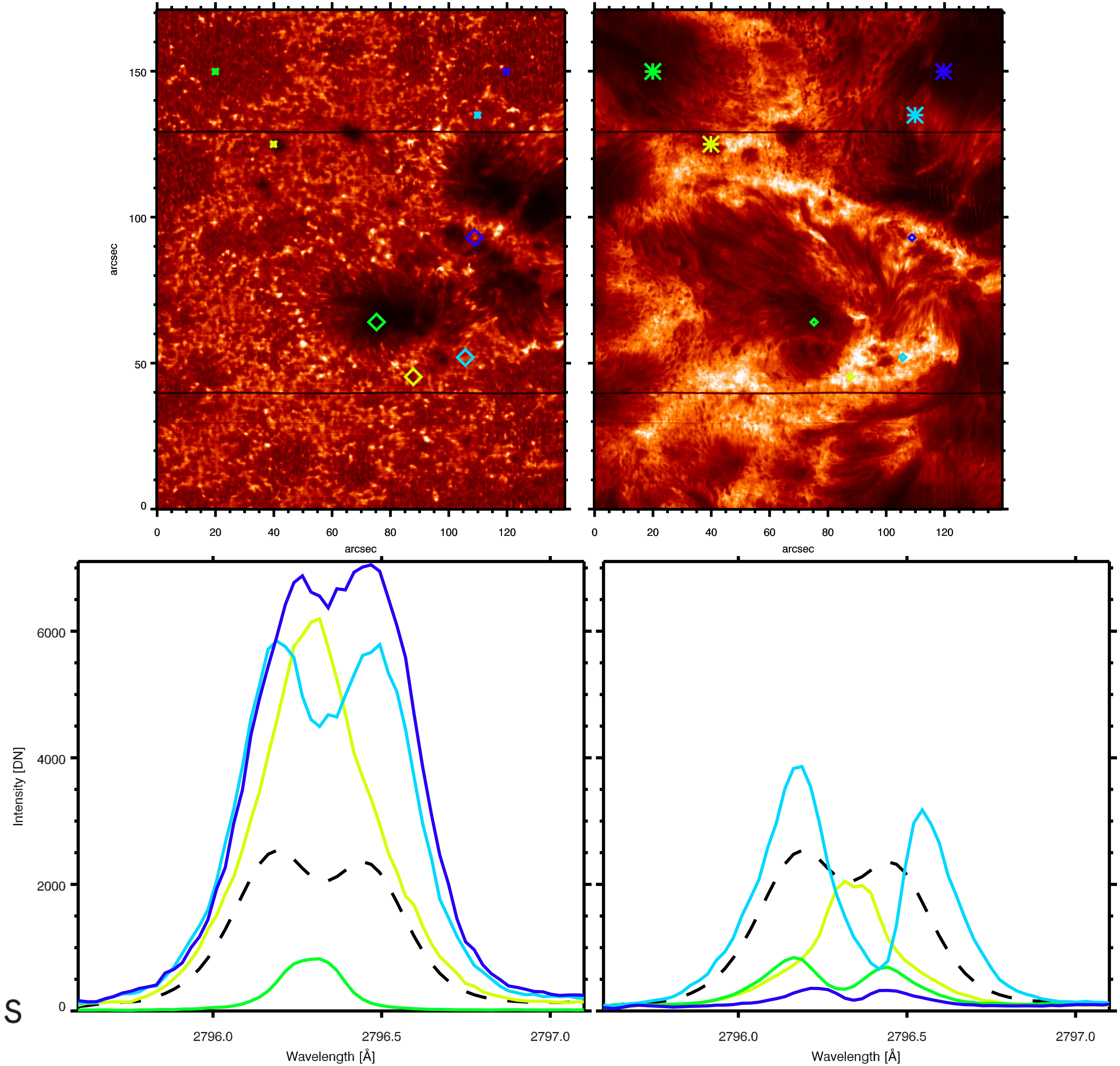
Rosseland
Centre
for Solar
Physics

Optically thick diagnostics

Mats Carlsson
Rosseland Centre for Solar Physics, Univ Oslo
Göttingen, June 25 2018


-400
-450
-500
arcsec
100
150
200
arcsec
-400
-450
-500
arcsec
100
150
200
arcsec
-400
-450
-500
arcsec
2790
2800
2810
2820
2830
Wavelength [Å]

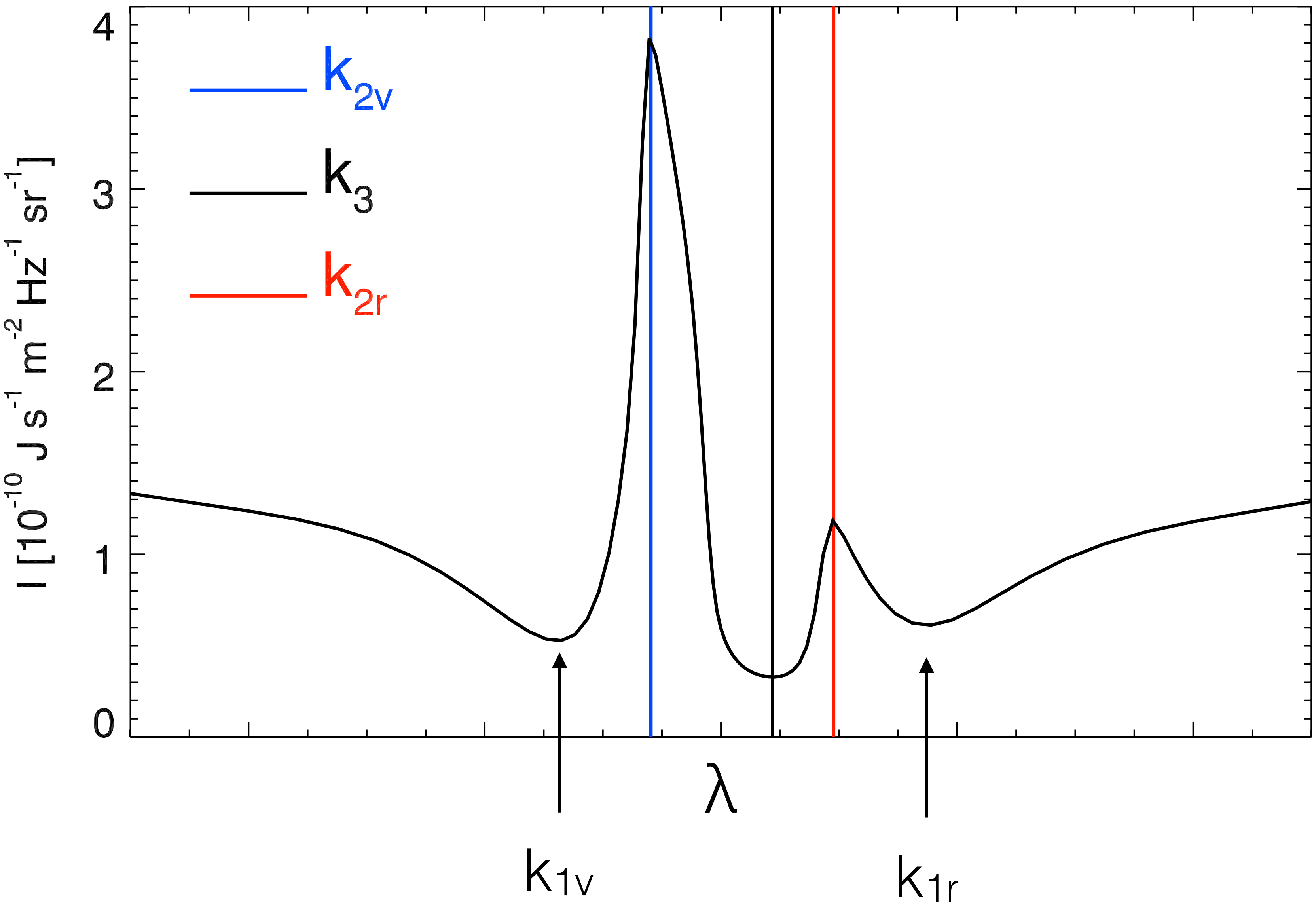
R C S



150
100
50
0
arcsec
0
20
40
60
80
100
120
arcsec
0
20
40
60
80
100
120
arcsec
6000
4000
2000
0
Intensity [DN]
2796.0
2796.5
2797.0
Wavelength [Å]
2796.0
2796.5
2797.0
Wavelength [Å]

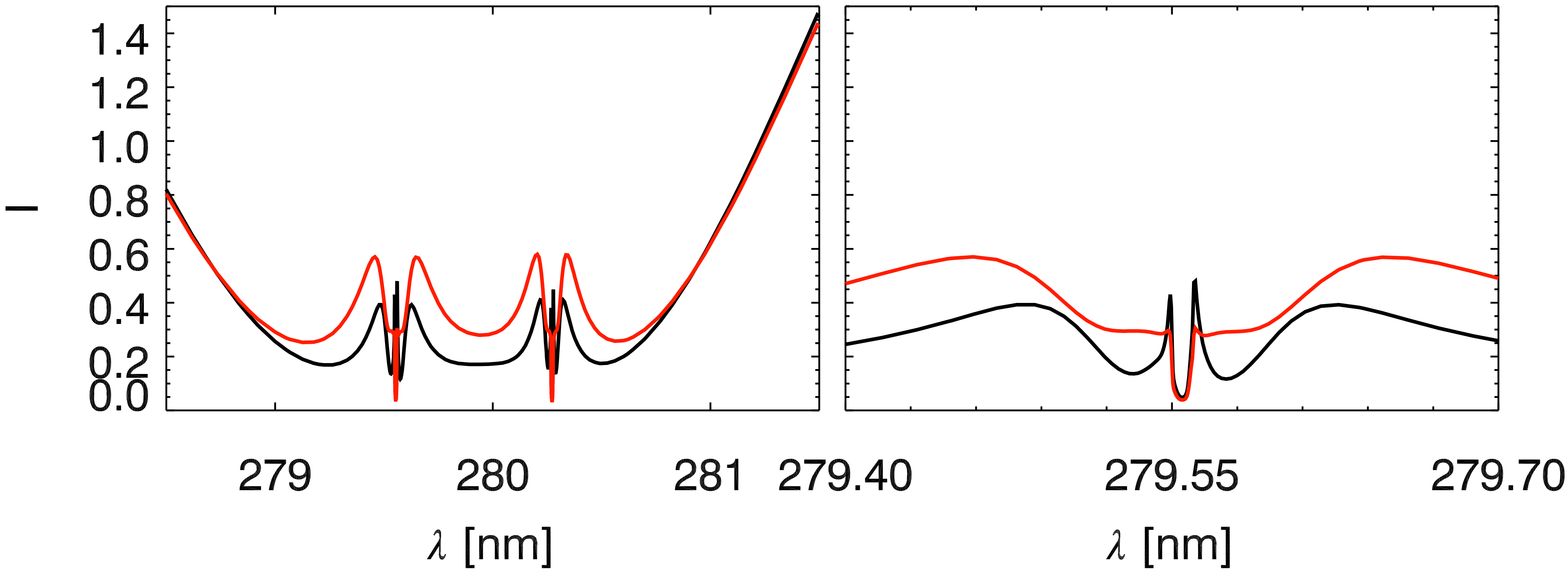
R C S

Mg II h&k jargon



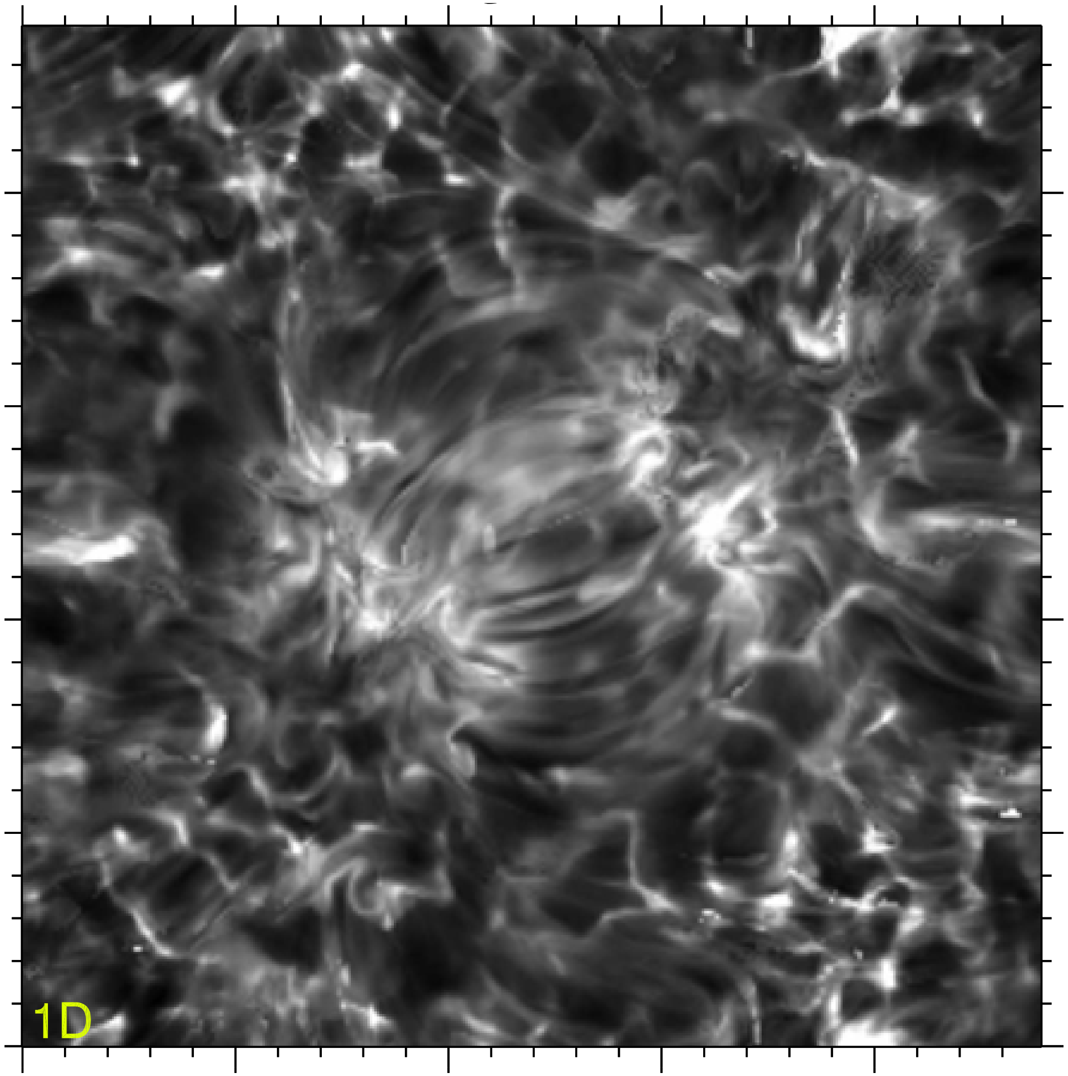
R C S

Additional complication 1: partial redistribution



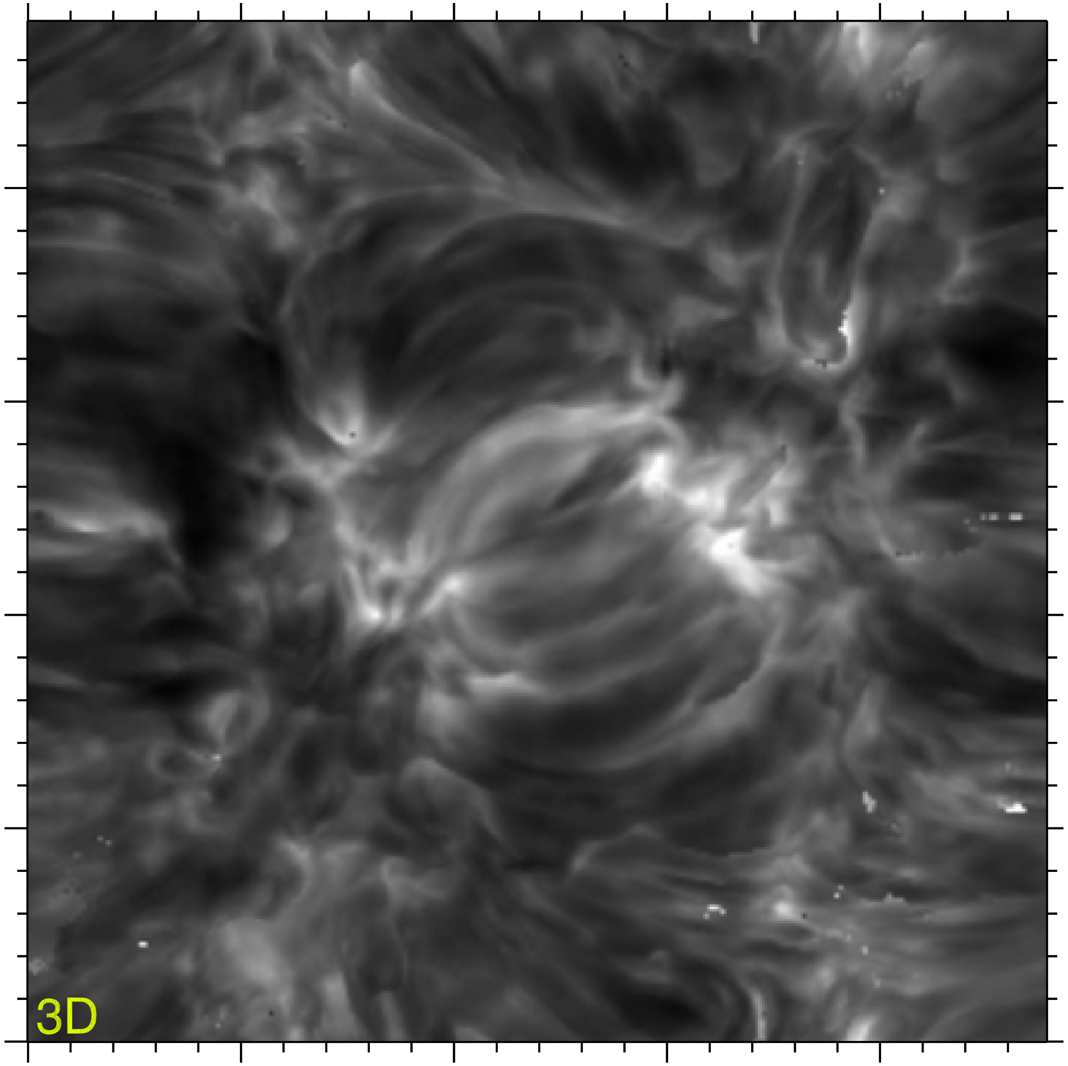
R C S

Additional complication 2: 3D effects in h3 & k3



R C S

Additional complication 2: 3D effects in h3 & k3



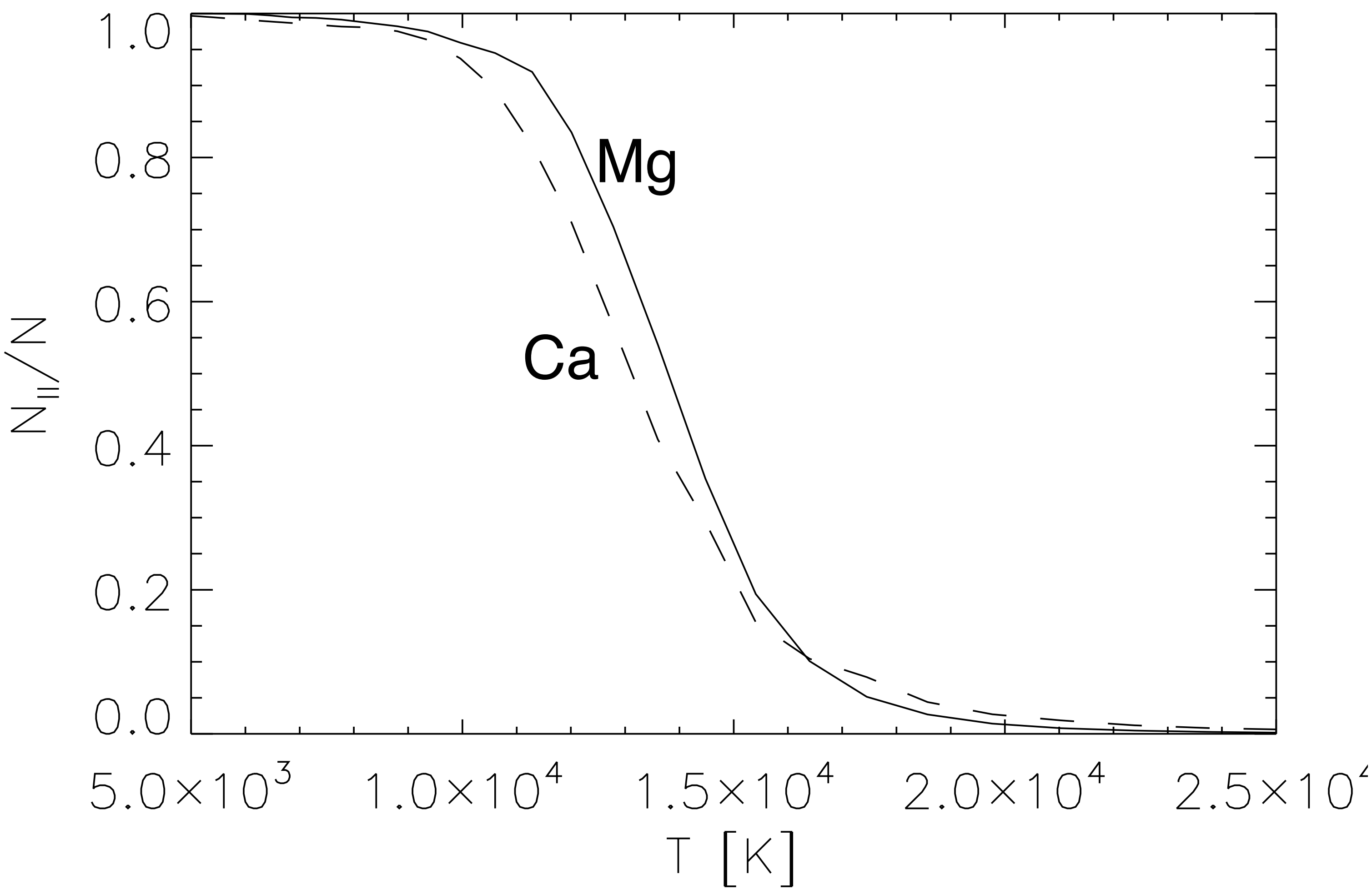
Basic properties of Mg compared to Ca

	Ca	Mg
Abundance (Asplund et al. 2009)	6.34±0.04	7.60±0.04
Atomic weight	40.1 u	24.3 u
Ionization potential I⇒II	6.11 eV	7.6 eV
Ionization potential II⇒III	11.87 eV	15.04 eV

Abundance

- Mg is 18.2 times more abundant.
- Mg II h&k form 2.9 scale heights higher than Ca II H&K, if all else equal
- 2.9 scale heights $\approx$ 500-900 km

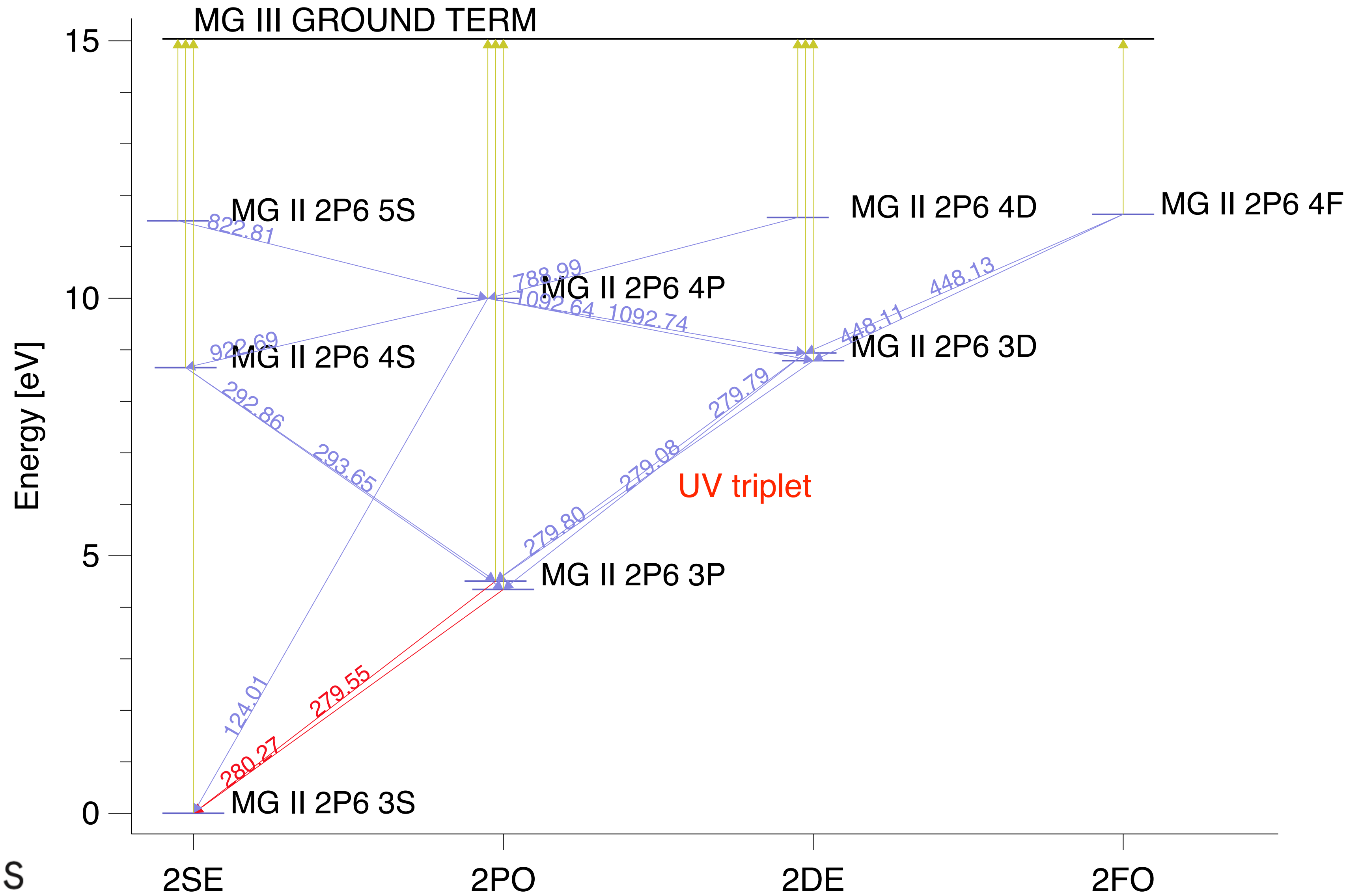
Ionization



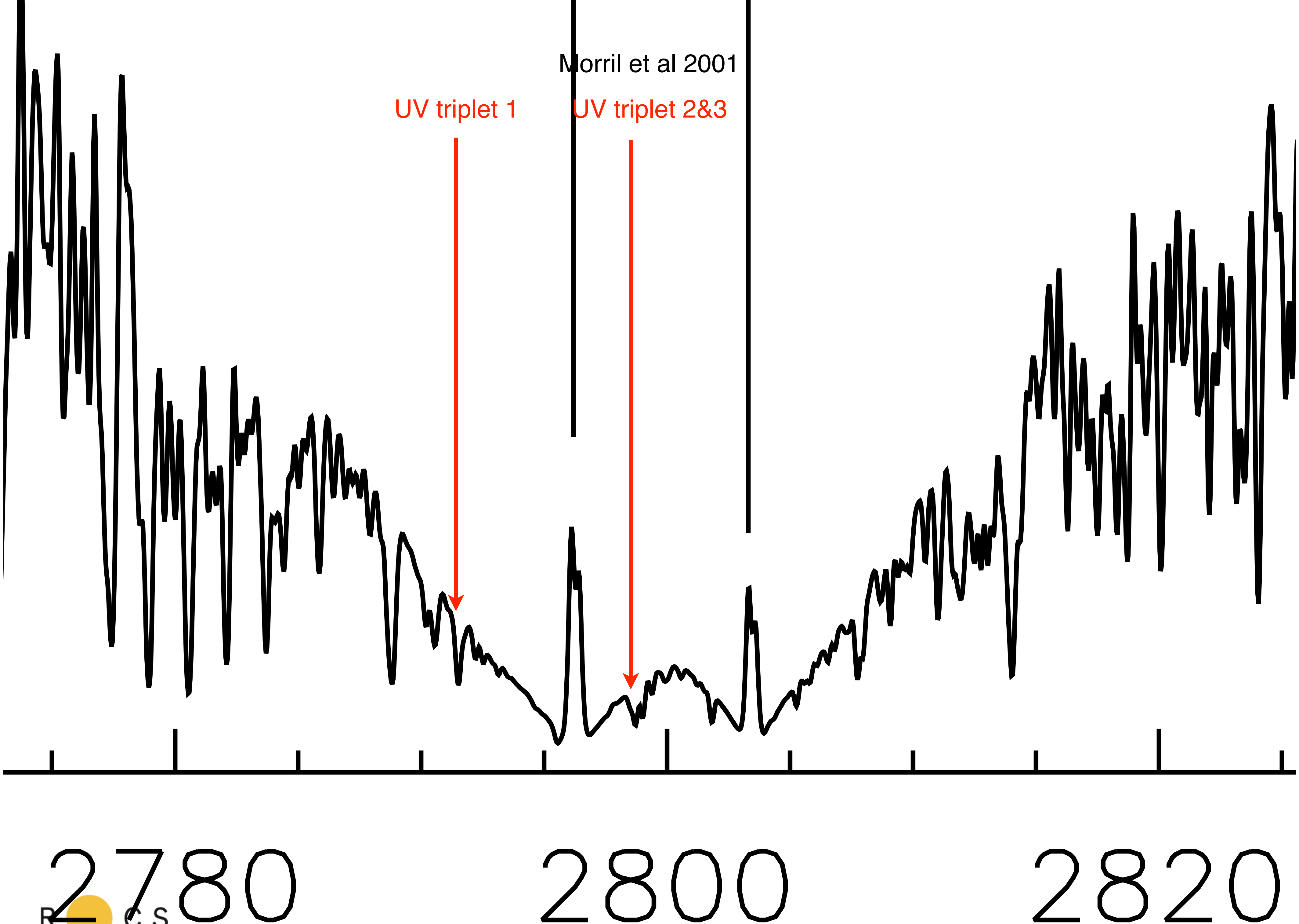
R C S

Carlsson & Leenaarts 2012

Mg II term diagram



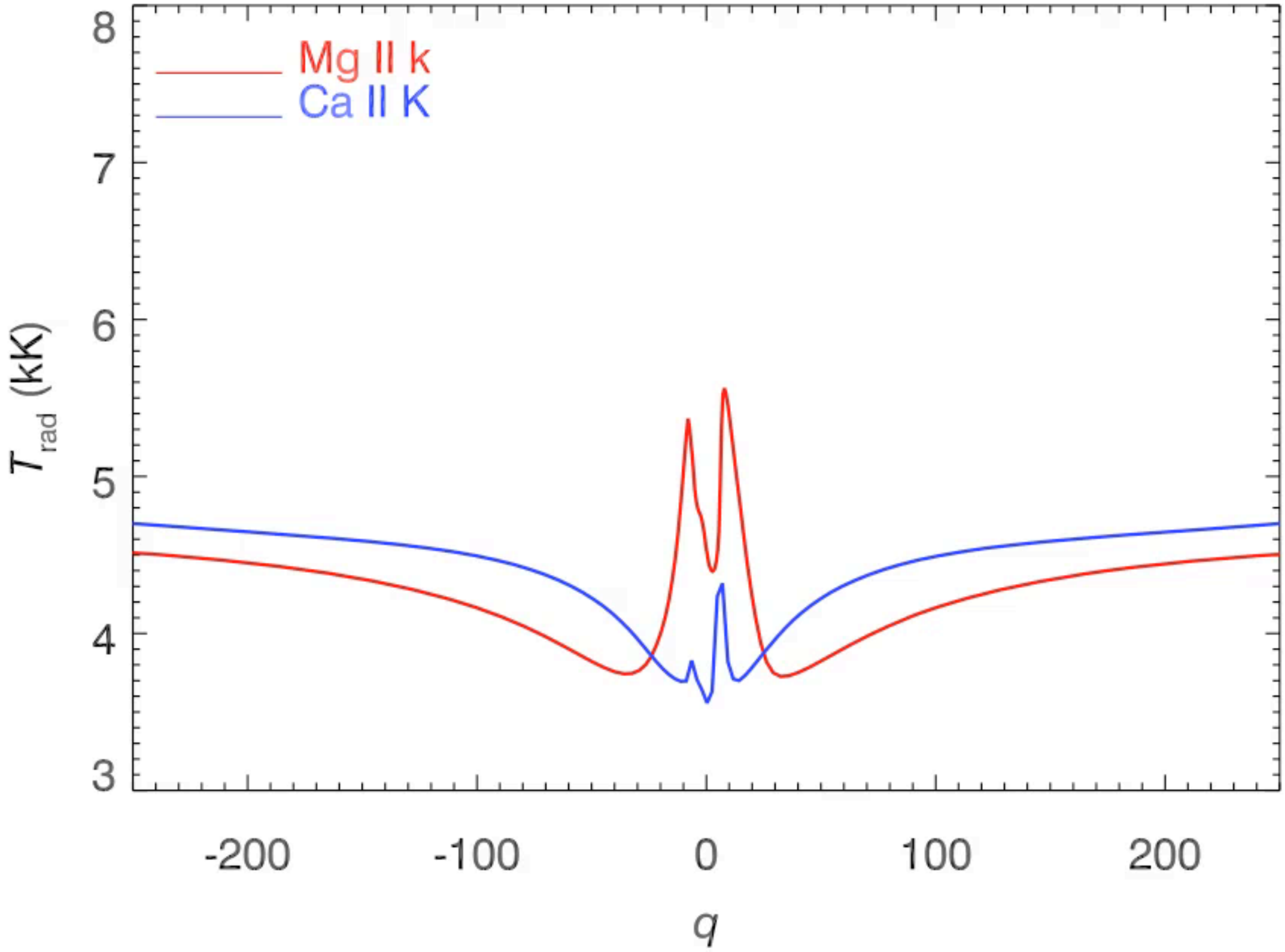
R C S


Morril et al 2001
UV triplet 1
UV triplet 2&3
2780
2800
2820

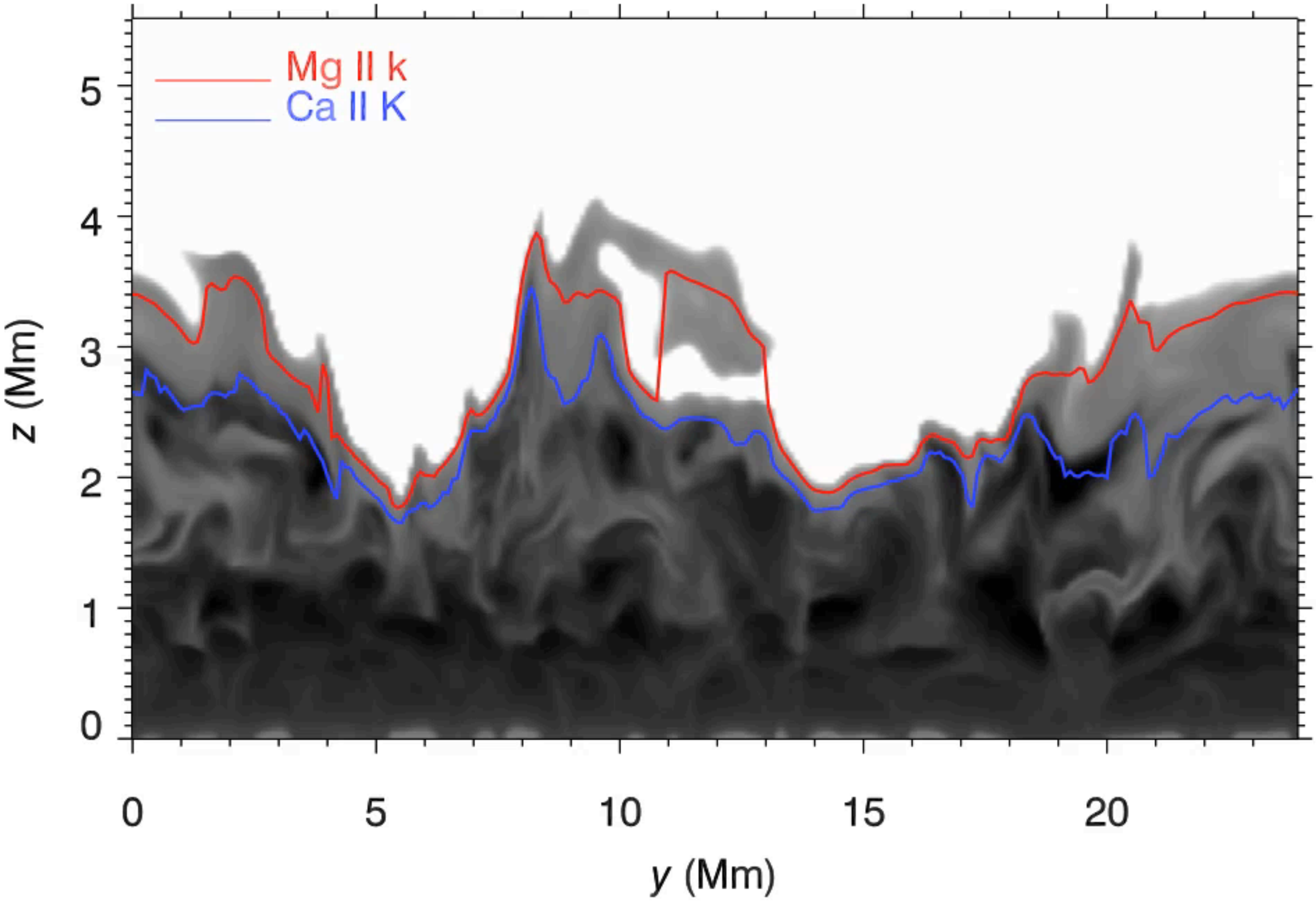
Comparison of Mg II k and Ca II K profiles

- convert I to T_{rad}
  - take out wavelength sensitivity of the Planck function
- convert wavelength to $q = \dfrac{\lambda - \lambda_0}{\Delta\lambda_{\mathrm{D}}}$
  - take out difference in thermal width

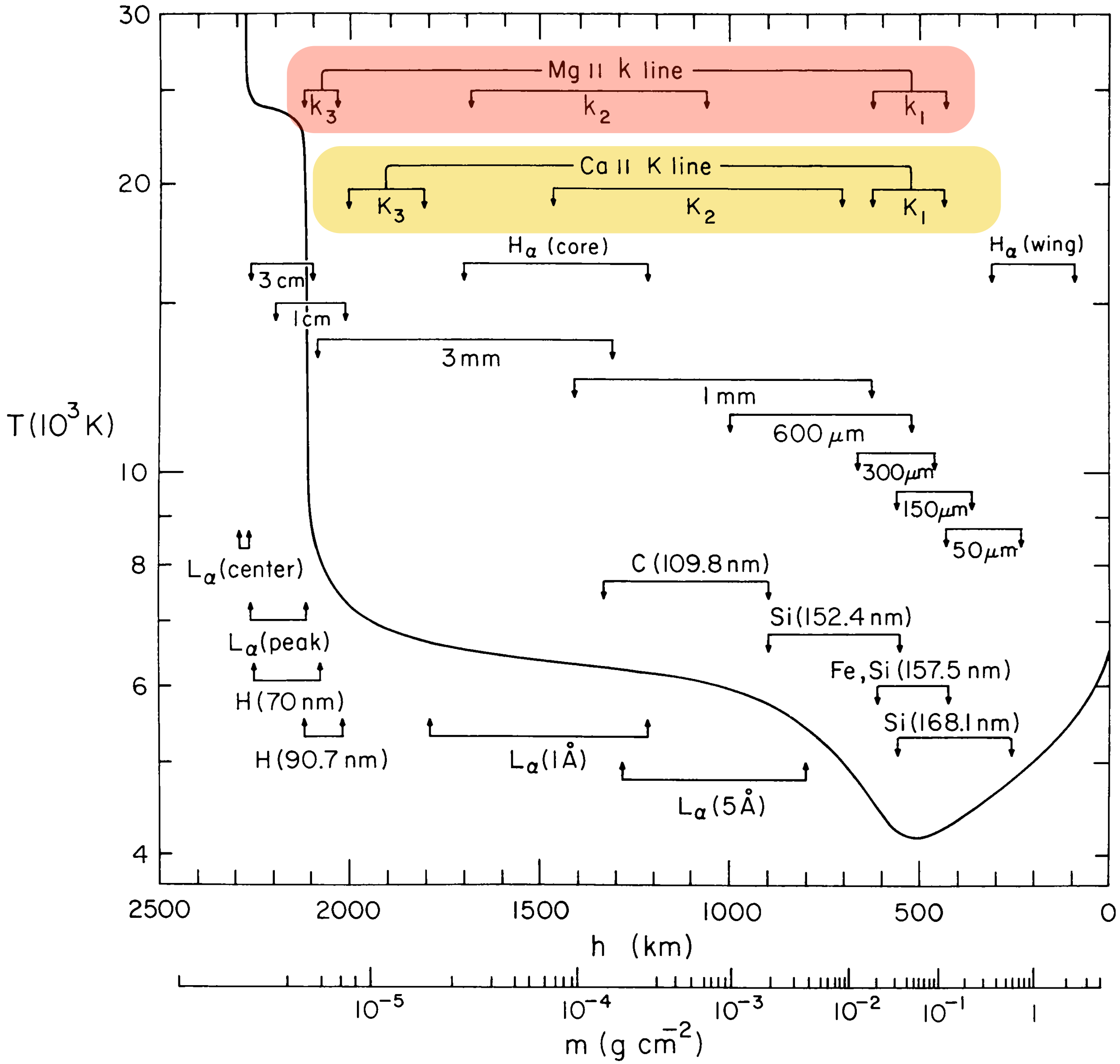
R C S


Mg II k
Ca II K
8
7
6
5
4
3
T_{rad} (kK)
-200
-100
0
100
200
q

Compare largest k_3 $\tau=1$ heights



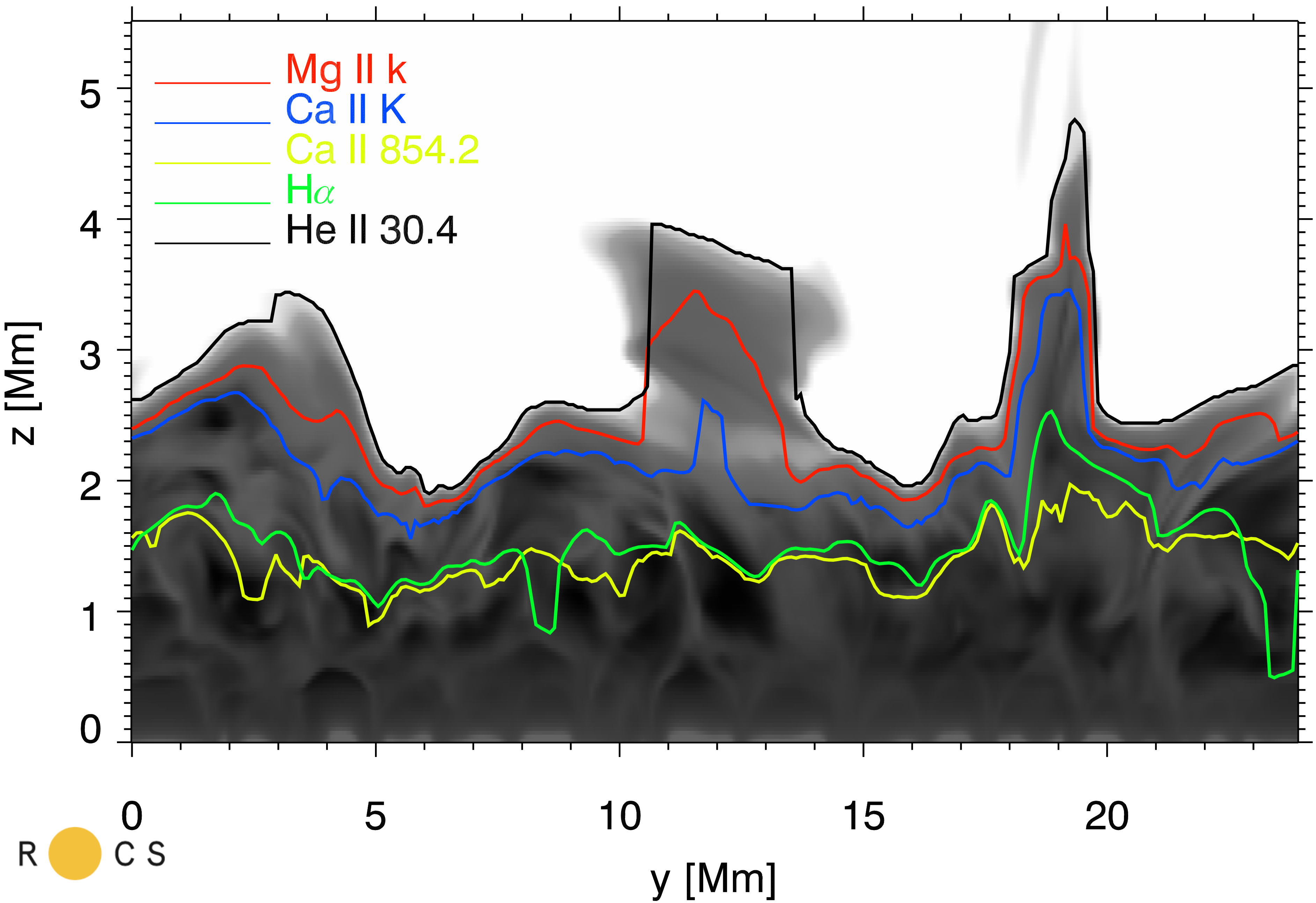
Mg II h&k sample the whole chromosphere, and reach higher than Ca II H&K



Vernazza et al. 1981

R C S

h&k line cores are unique:

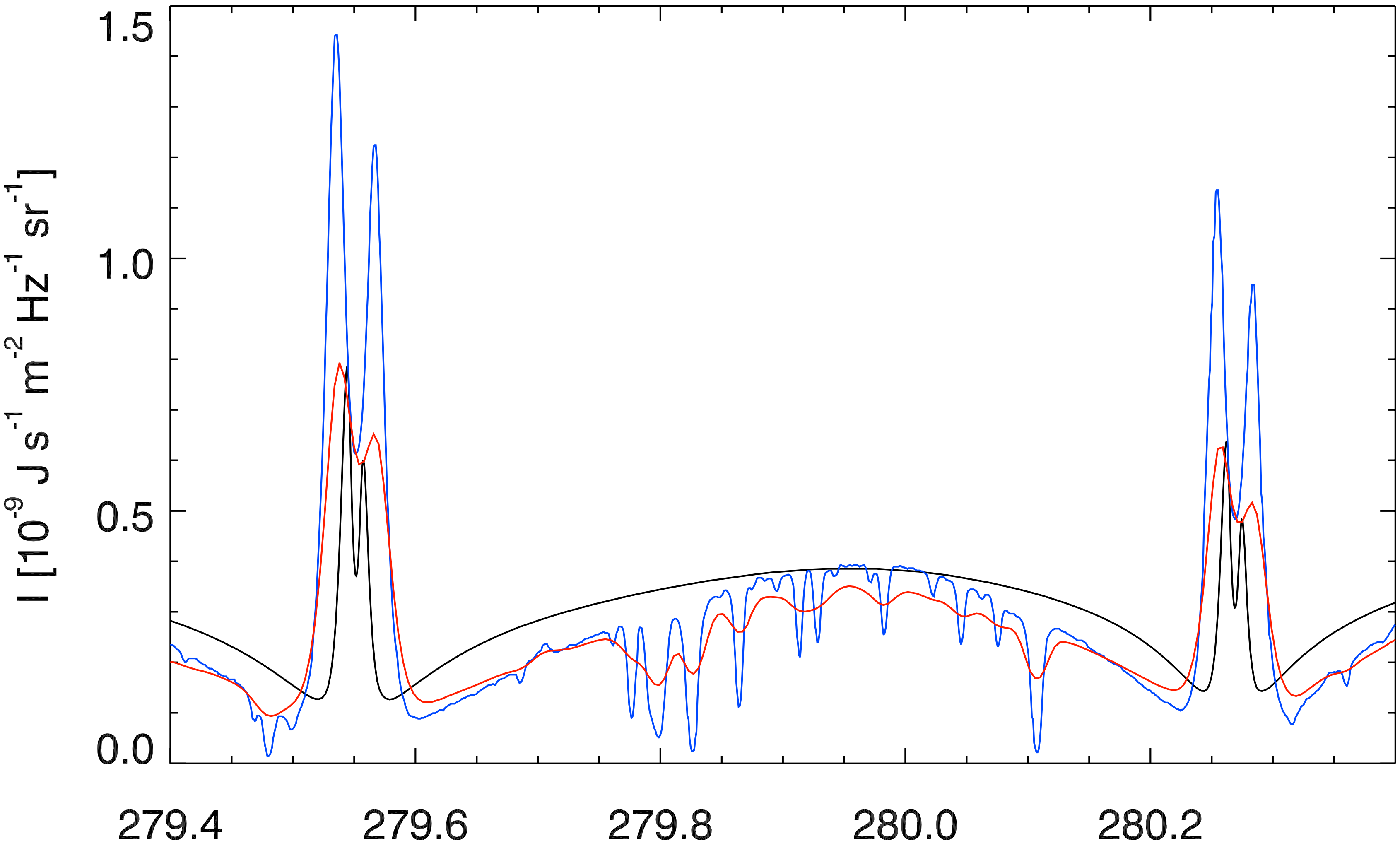


R C S

Hybrid approach
Synthetic Mg II h&k observations

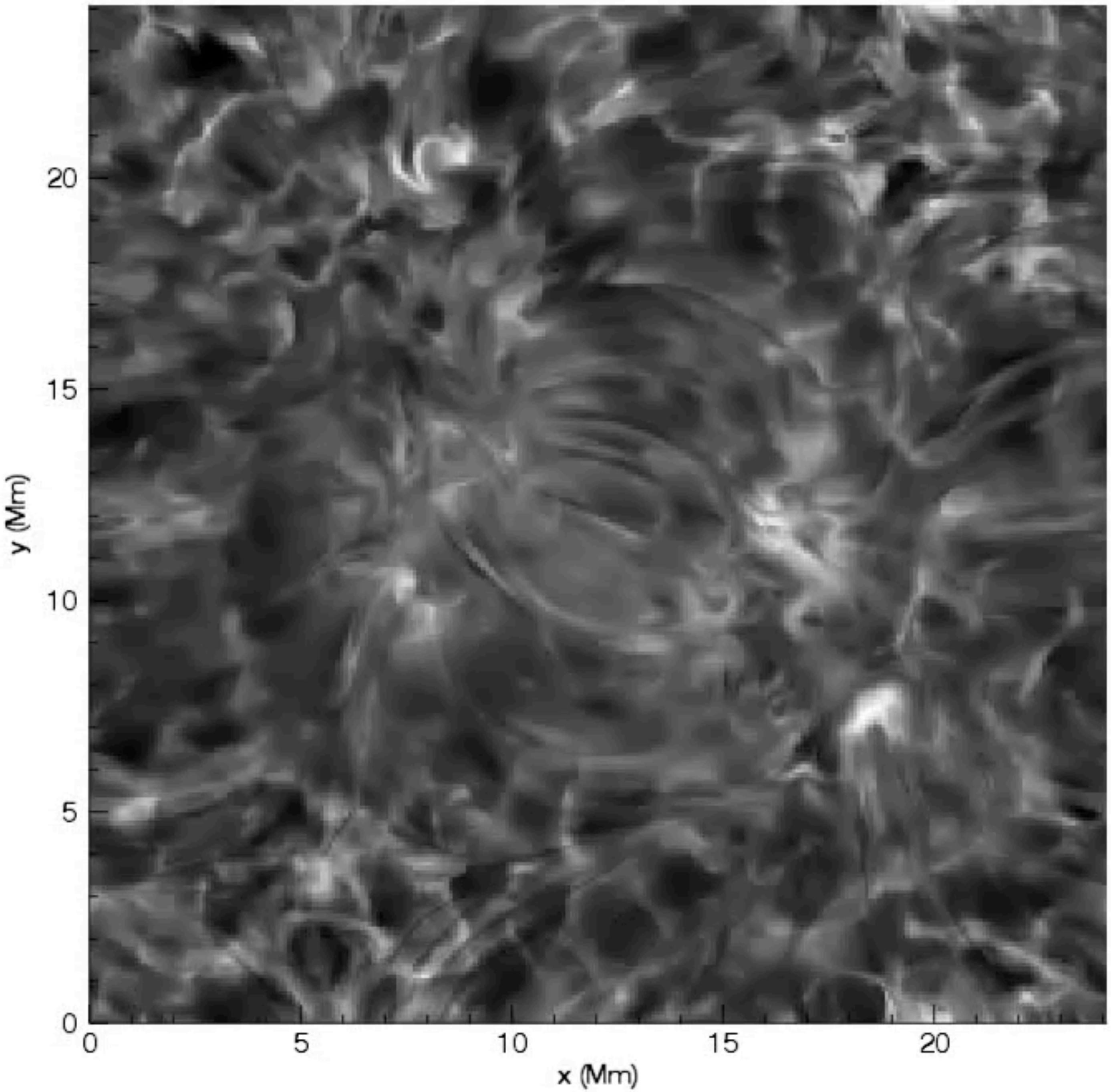
- Based on the 24x24x14 Mm simulation of “enhanced network”
  - **samples a limited range of solar conditions**
- available for download at;
  - http://iris.lmsal.com/modeling.html
  - http://sdc.uio.no/search/simulations
- description of methods and use in
  - Carlsson et al 2016, A&A 585, A4
  - The Formation of IRIS Diagnostics I - II - III
    - Leenaarts et al.: 2013a, ApJ, 772, 89
    - Leenaarts et al.: 2013b, ApJ, 772, 90
    - Pereira et al.: 2013, ApJ, 778, 143

Simulations do not match the line width and height



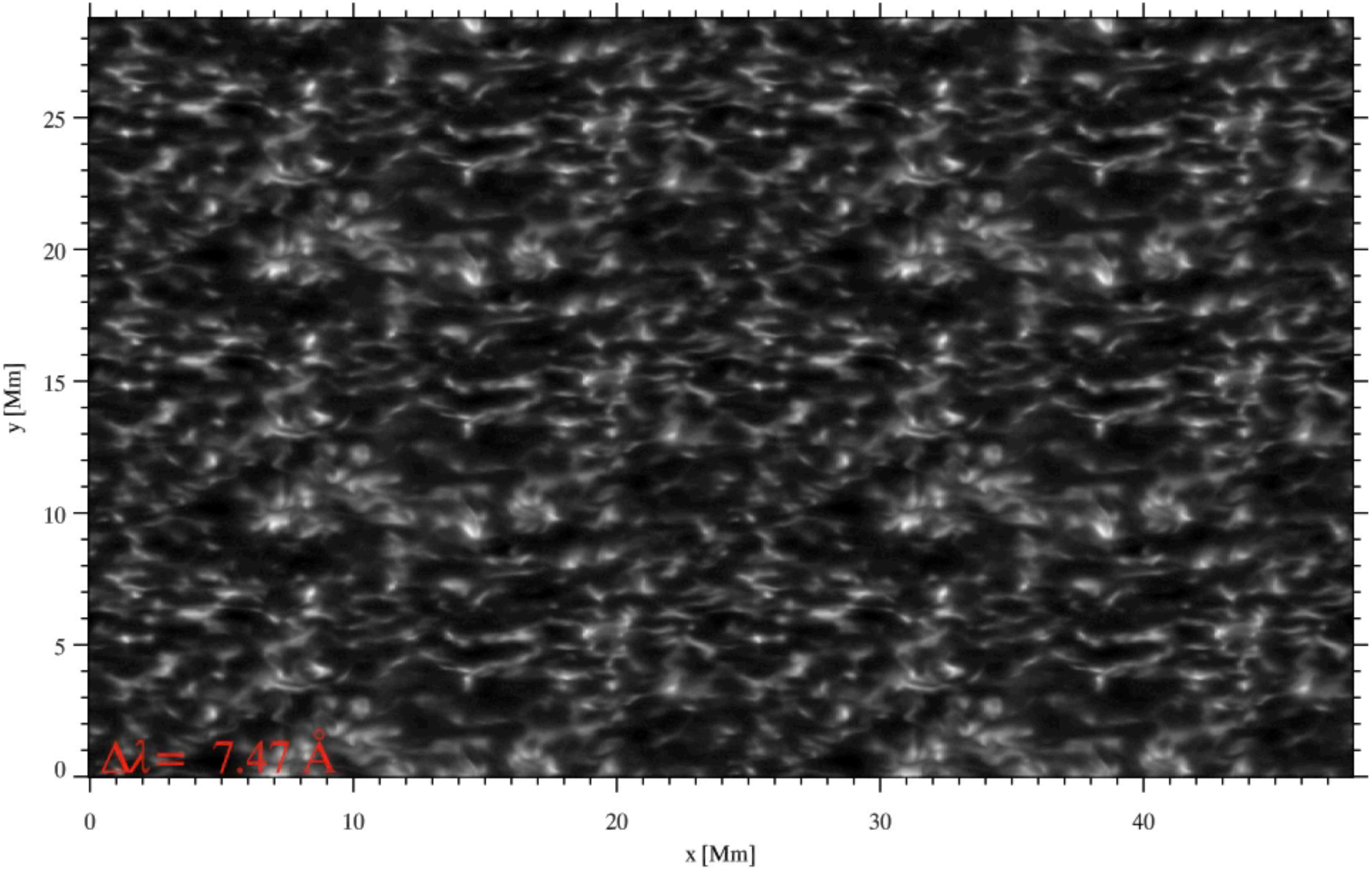
R C S

disk-center: μ=1



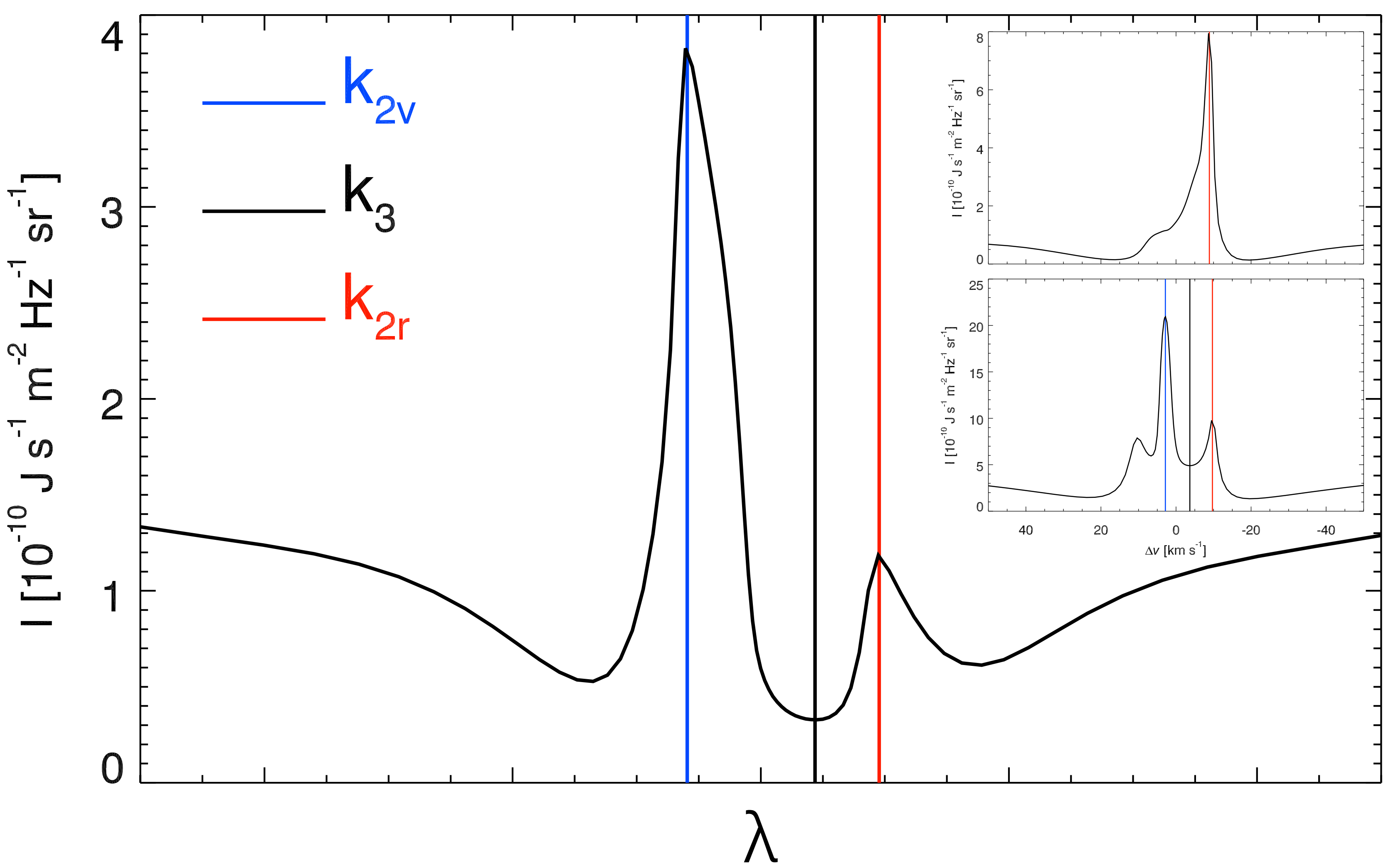
R C S

limbward: μ=0.4



R C S

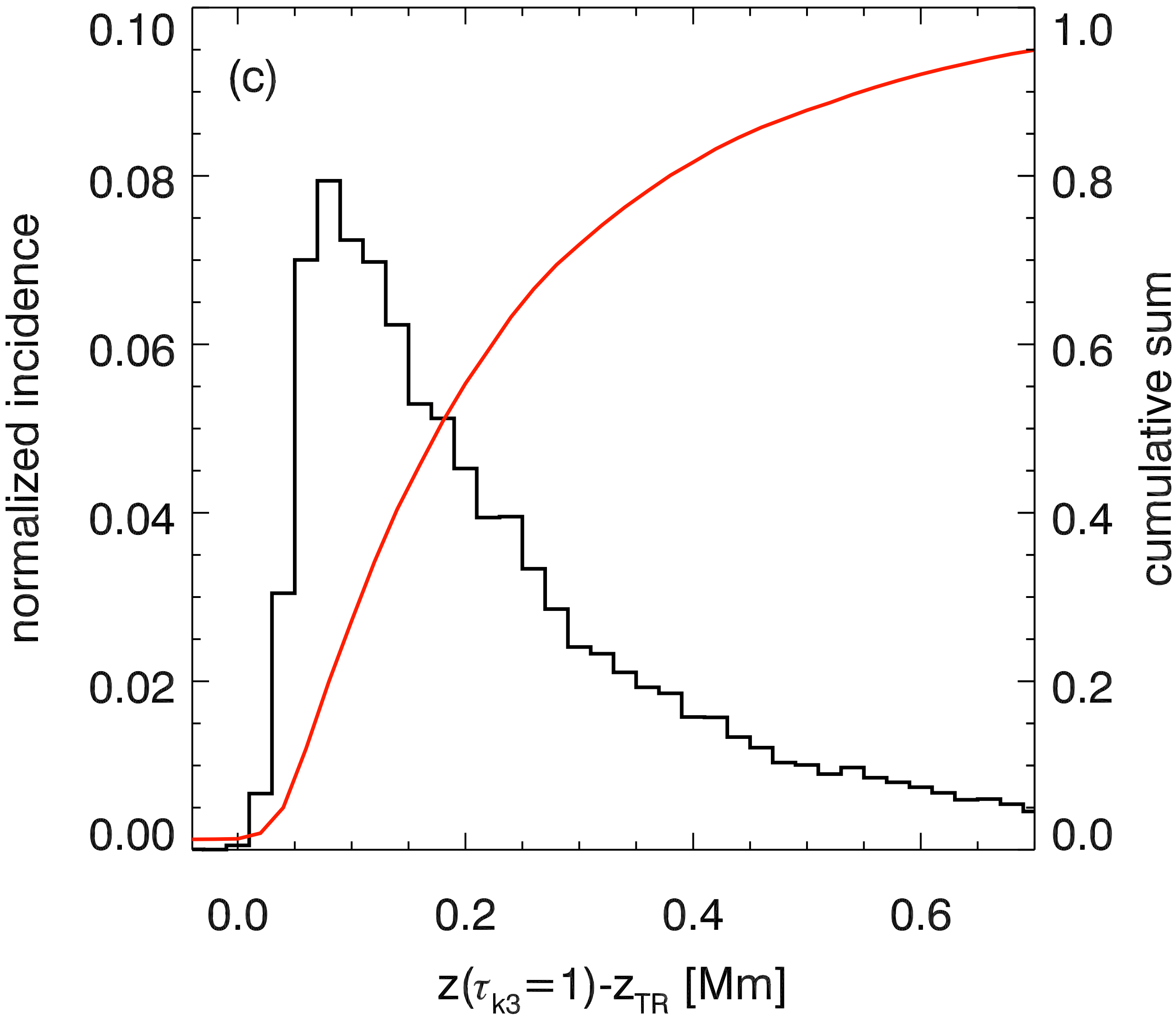
Observables: intensity and Doppler-shift of features

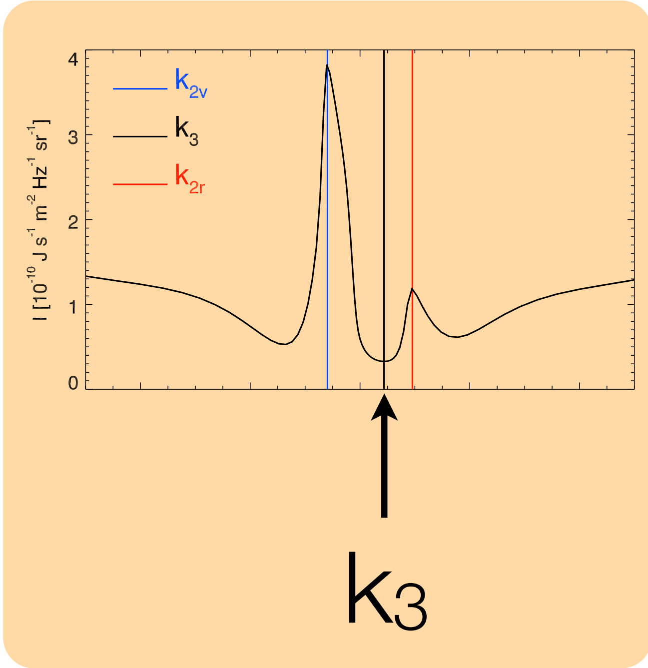


- Automated detection routine in Solarsoft
- Another possibility is double Gaussian fitting, also in Solarsoft.

R C S

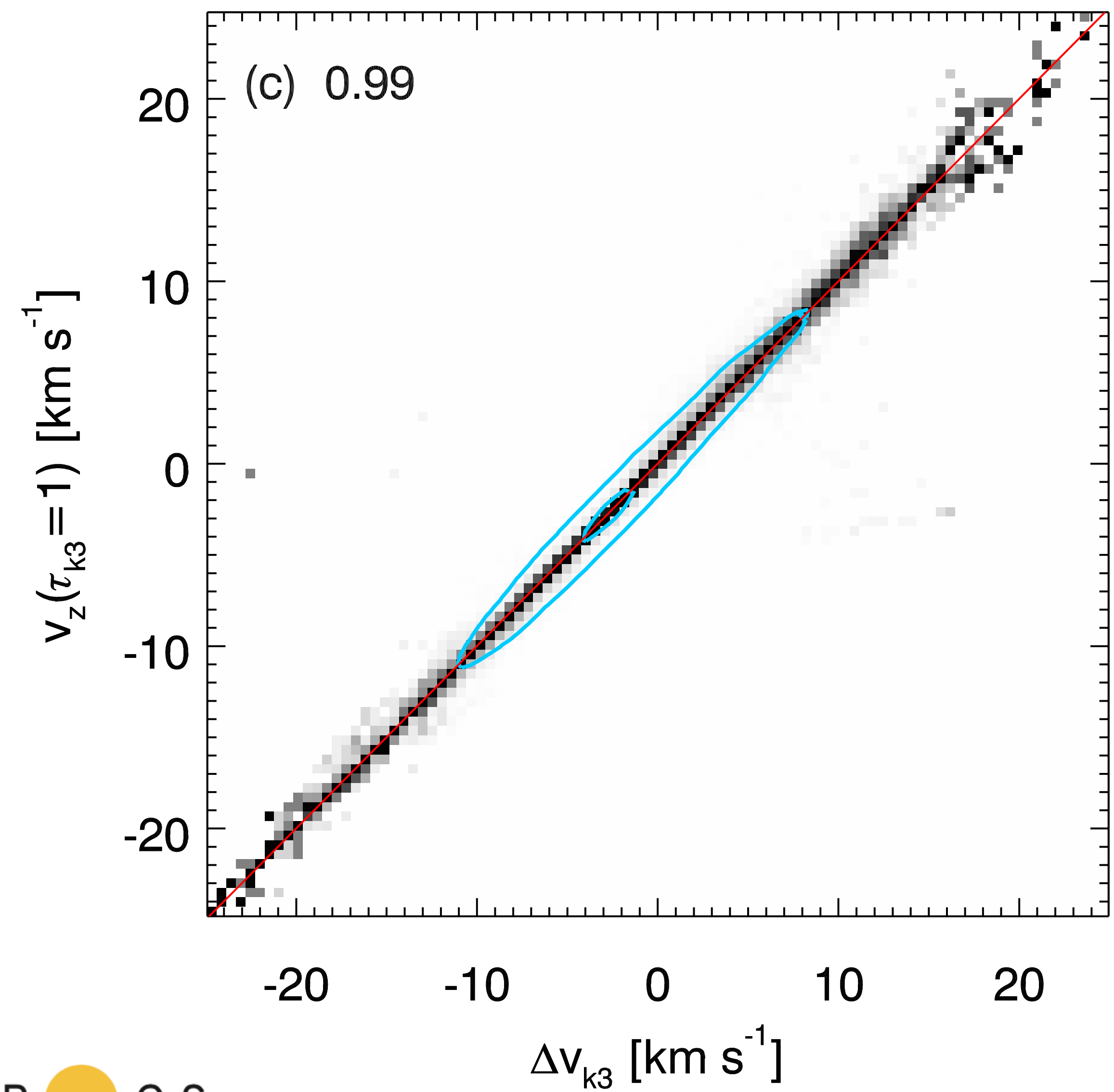
h_3 & k_3 form 200 km below the TR

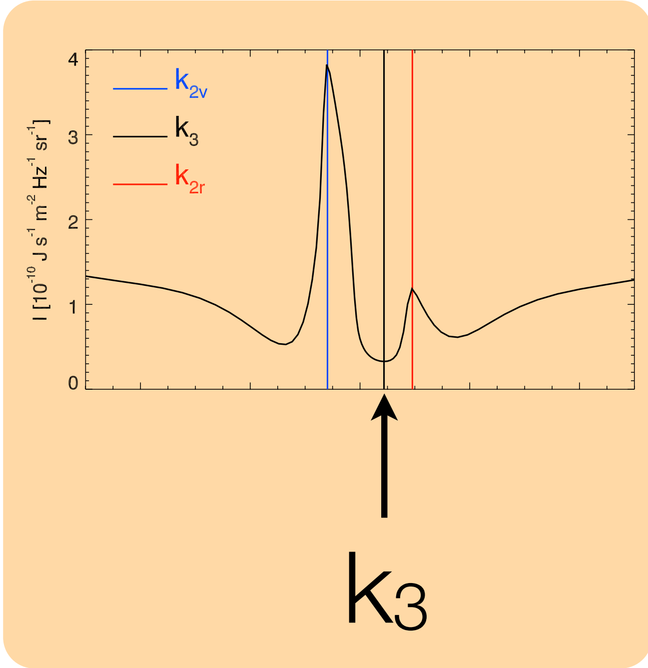




R C S

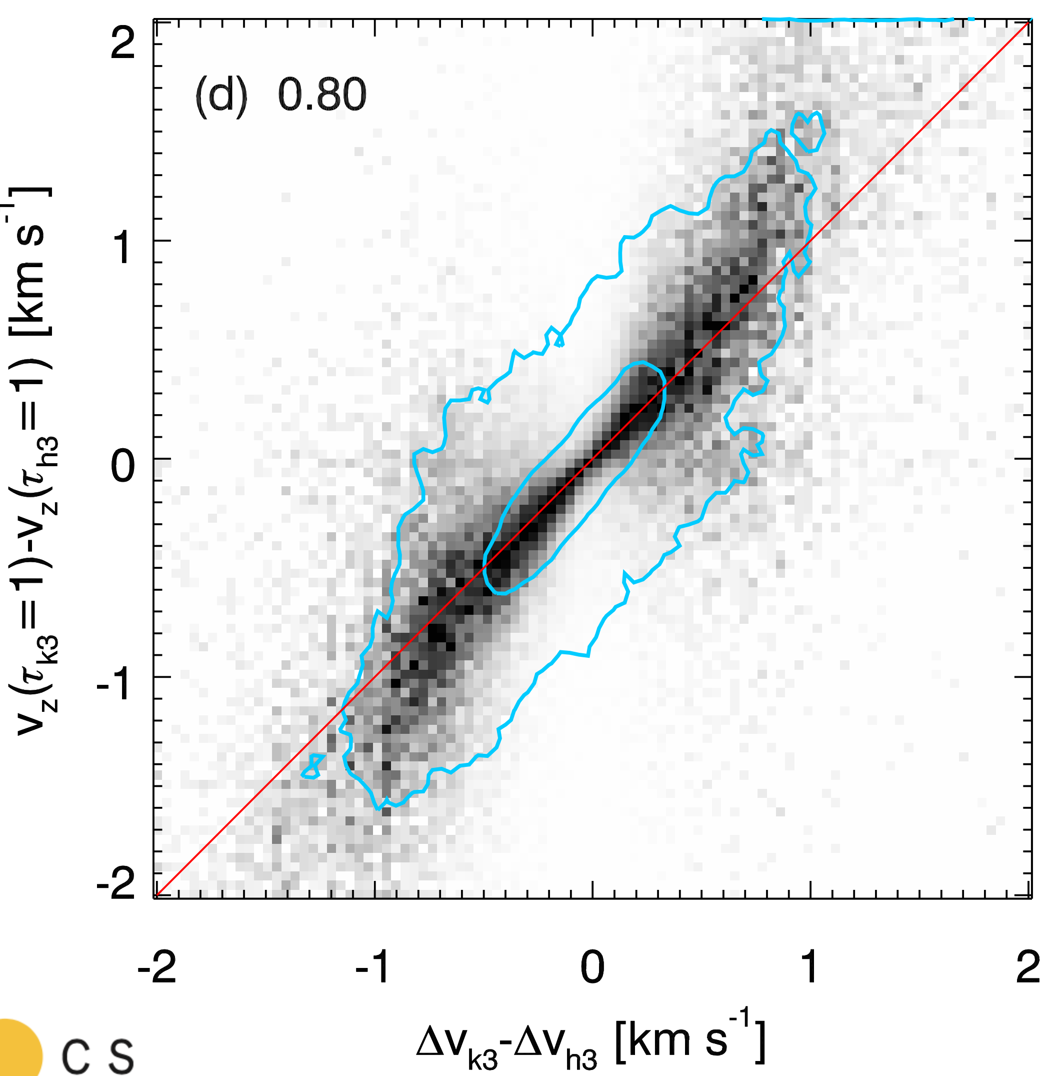
h_3 & k_3: Doppler shift measures $v_z(\tau=1)$

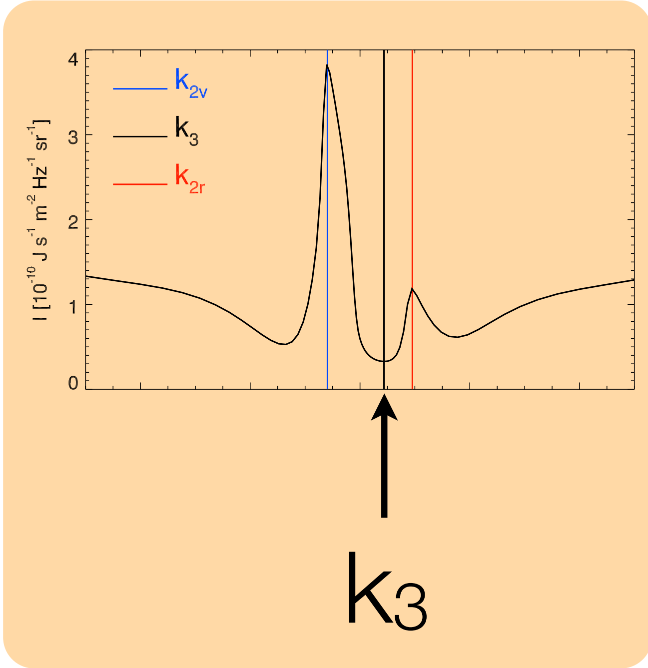




R C S

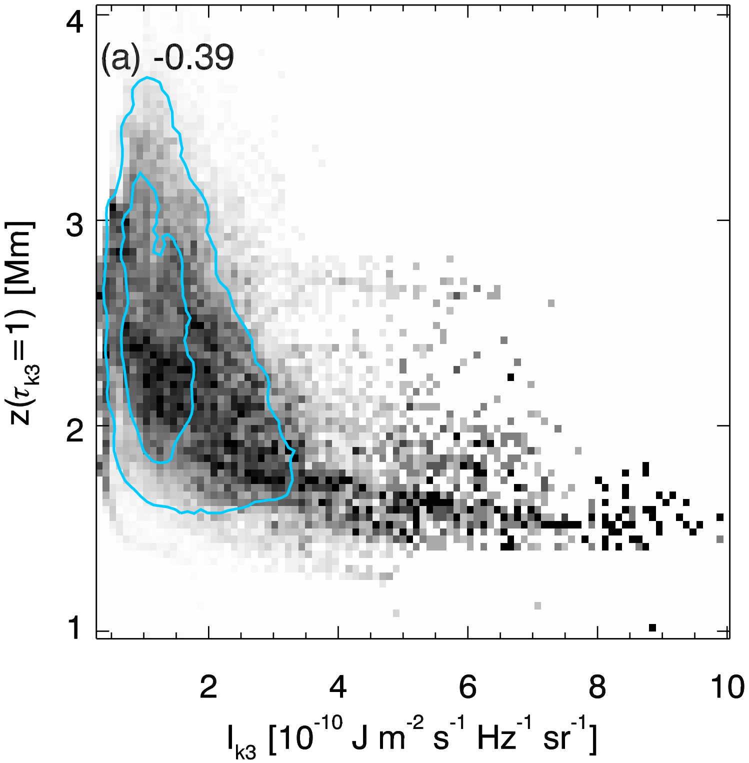
h_3-k_3 Doppler shift measures velocity gradient





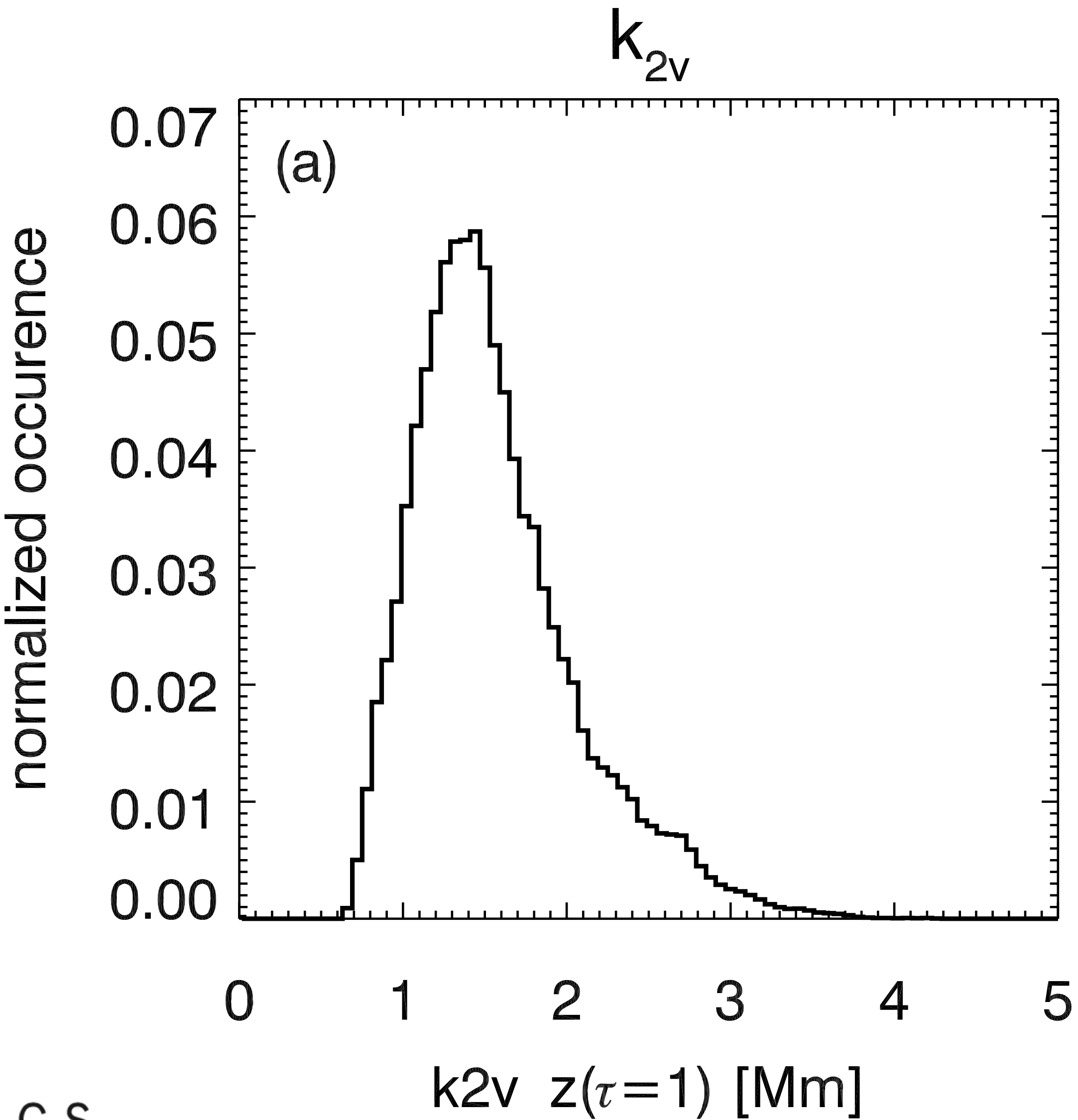
R C S

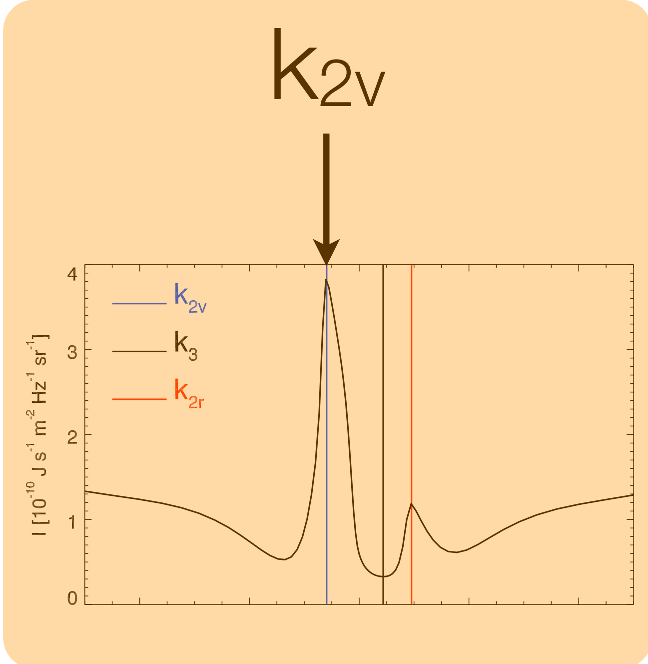
What about h_3-k_3 intensity?
It's complicated…



- **internetwork:** weak correlation between τ=1 height and intensity: density diagnostic
- **network:** temperature, but not from τ=1?
- **plage:** diagnostic of coronal density and temperature?

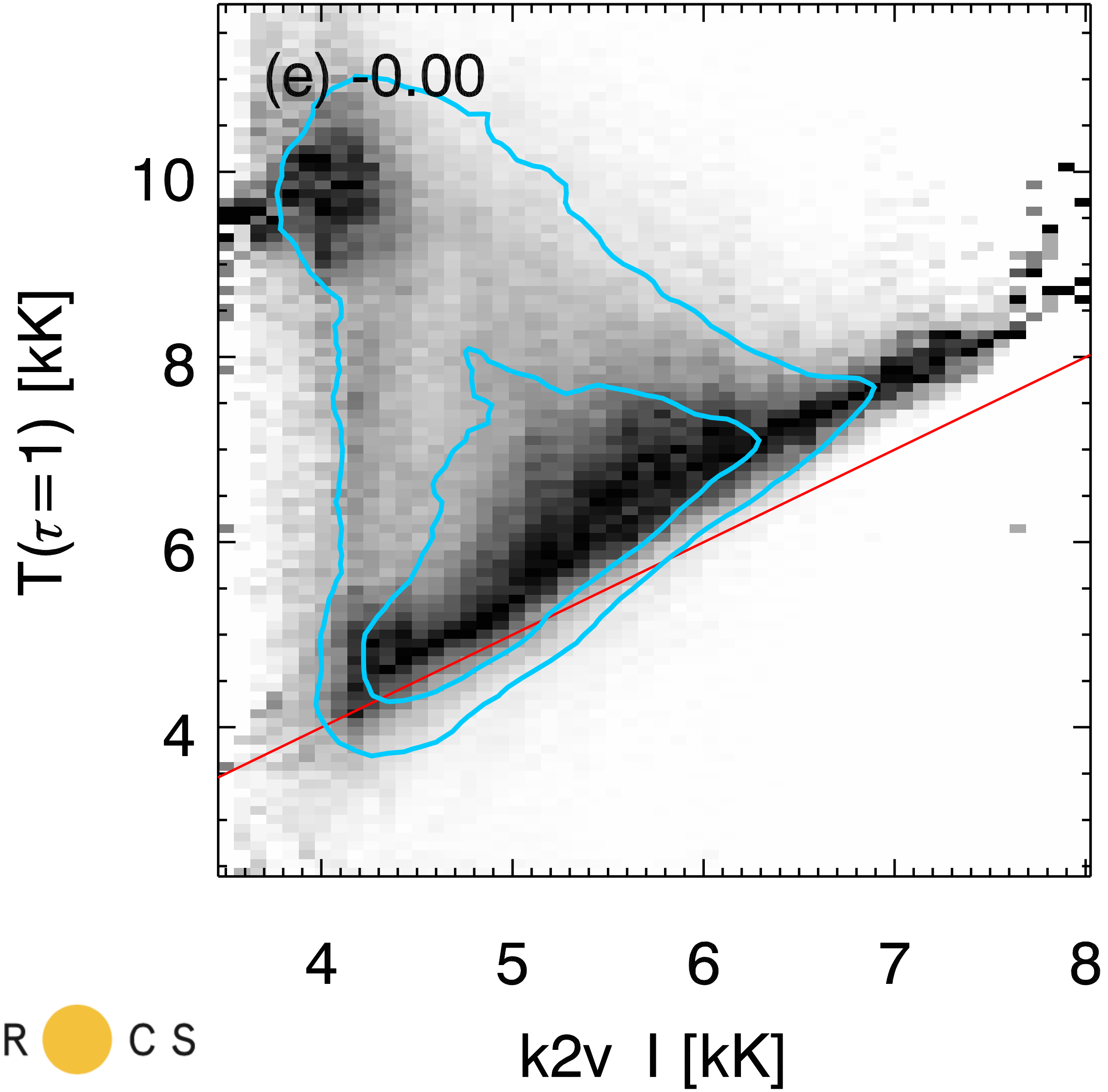
h_{2v} & k_{2v} peak form in mid chromosphere

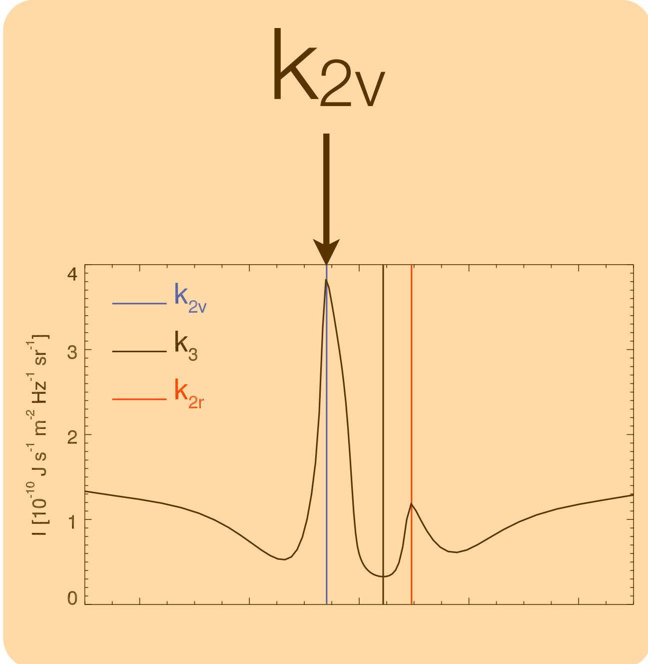




R C S

h_{2v} & k_{2v} peak intensity measures temperature

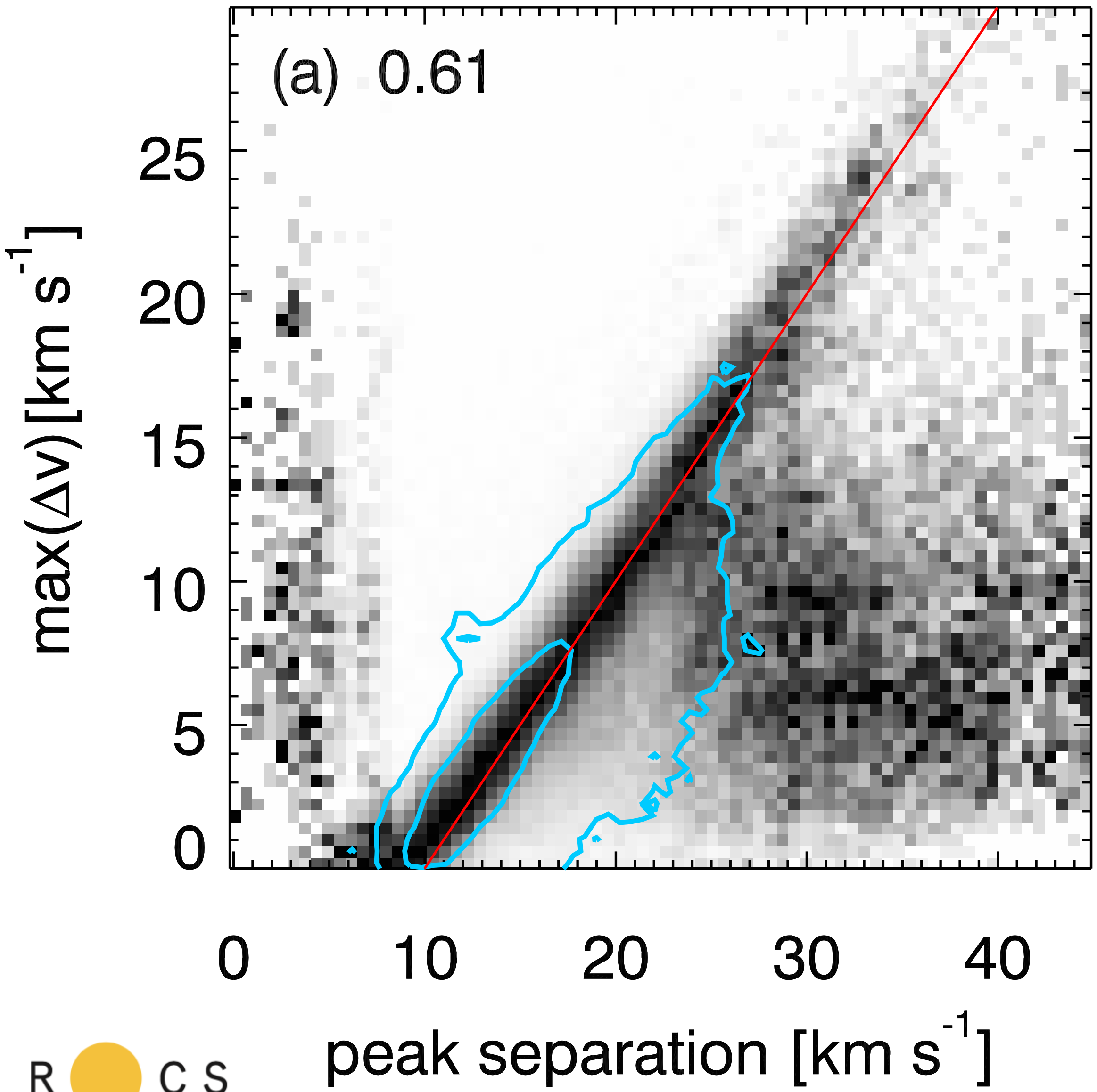


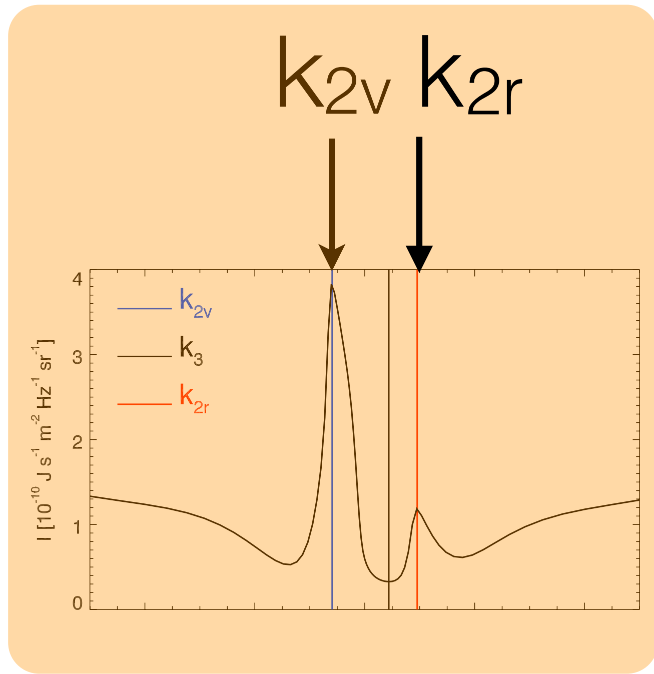


There is a radiometric calibration, so DN to T conversion is possible

R C S

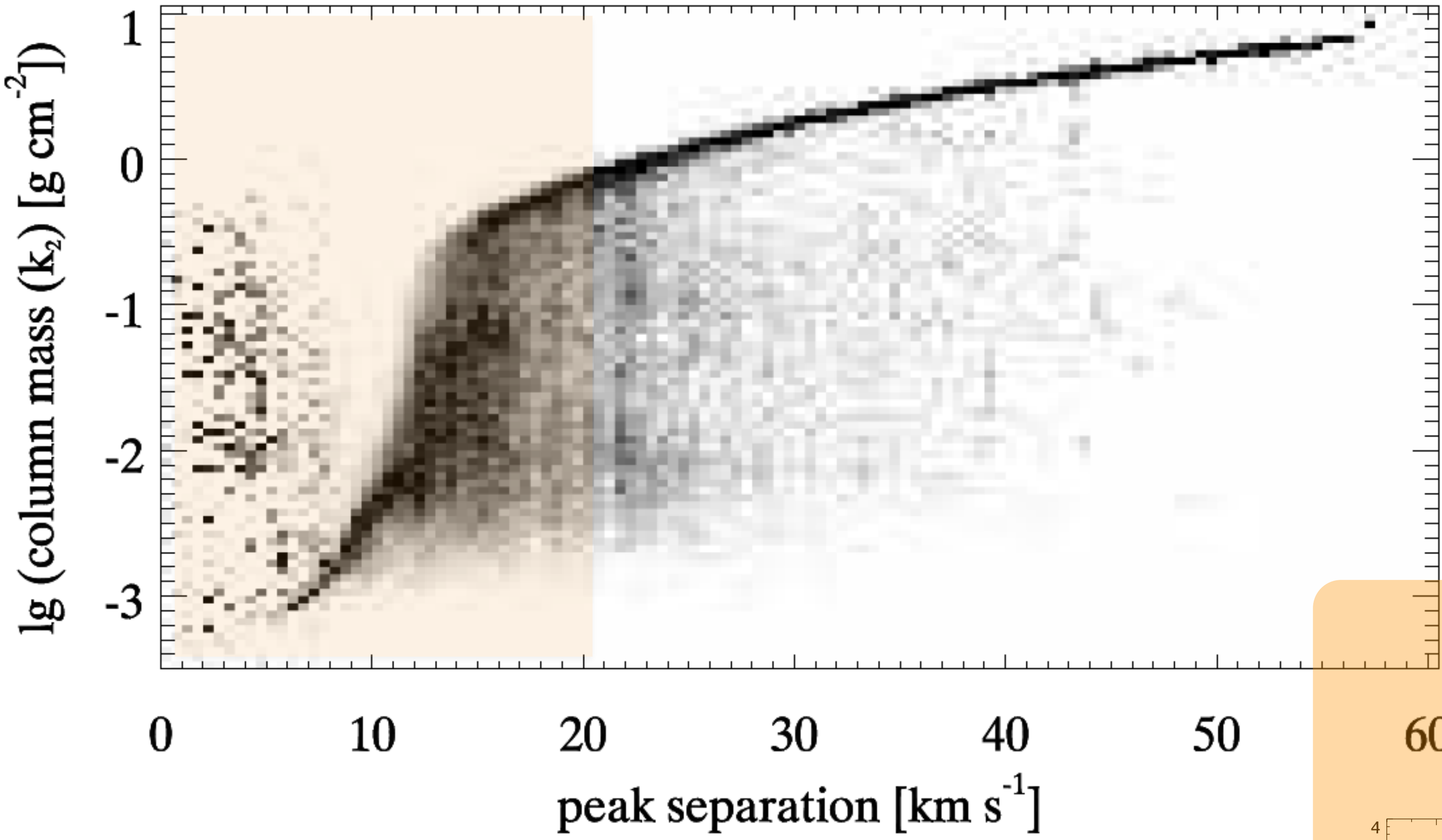
h_{2v} & k_{2v} peak separation measures velocity gradients in the chromosphere

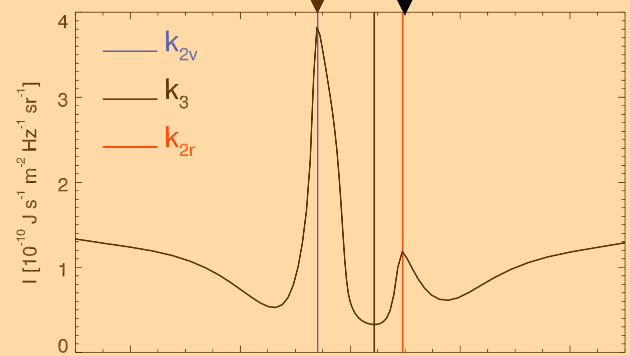




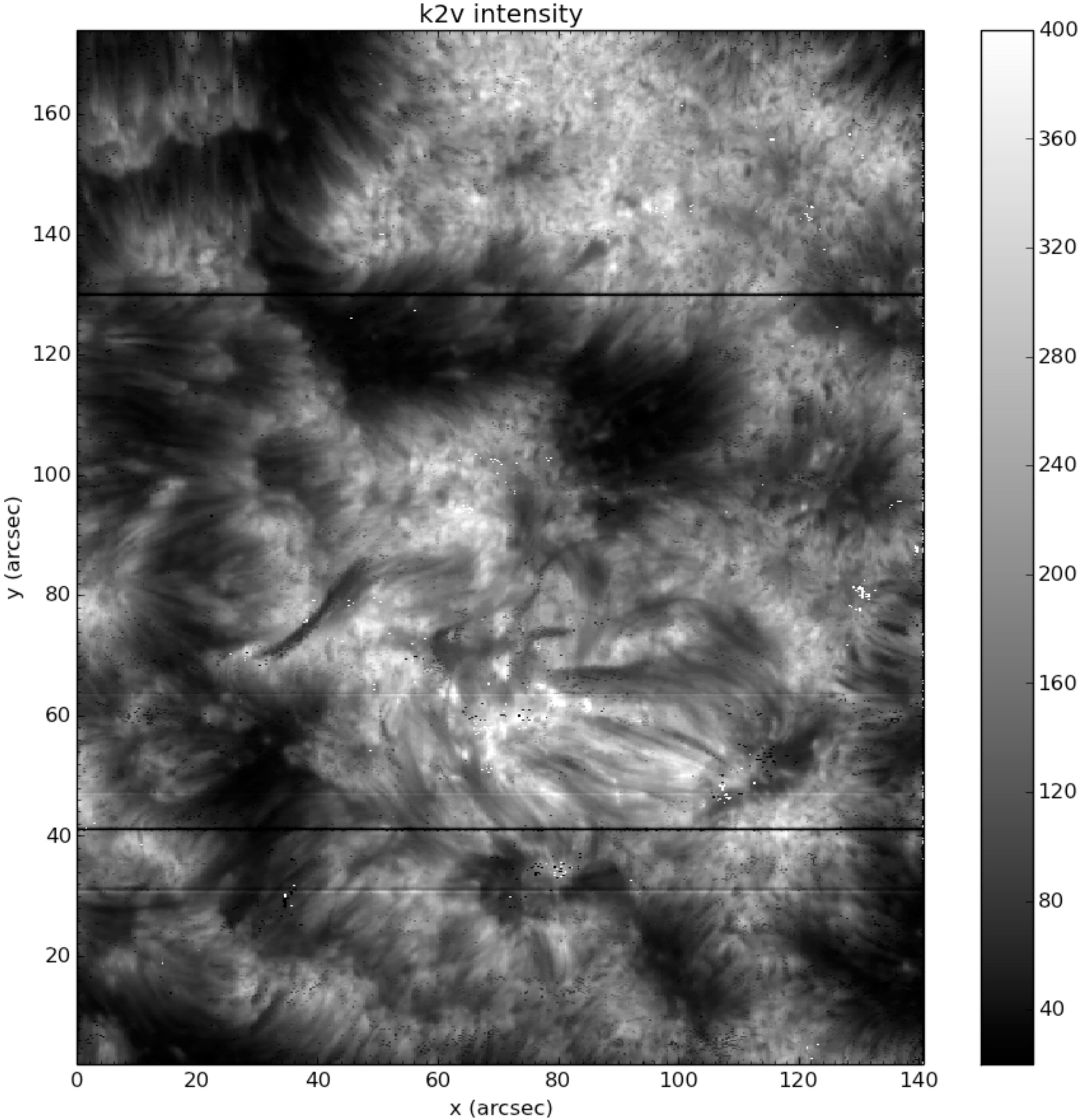
$$\frac{\lambda(\mathrm{k}_{2R})-\lambda(\mathrm{k}_{2V})}{\lambda_0}c$$

very wide k2 separation is a measure of deep chromospheric temperature rise





R C S

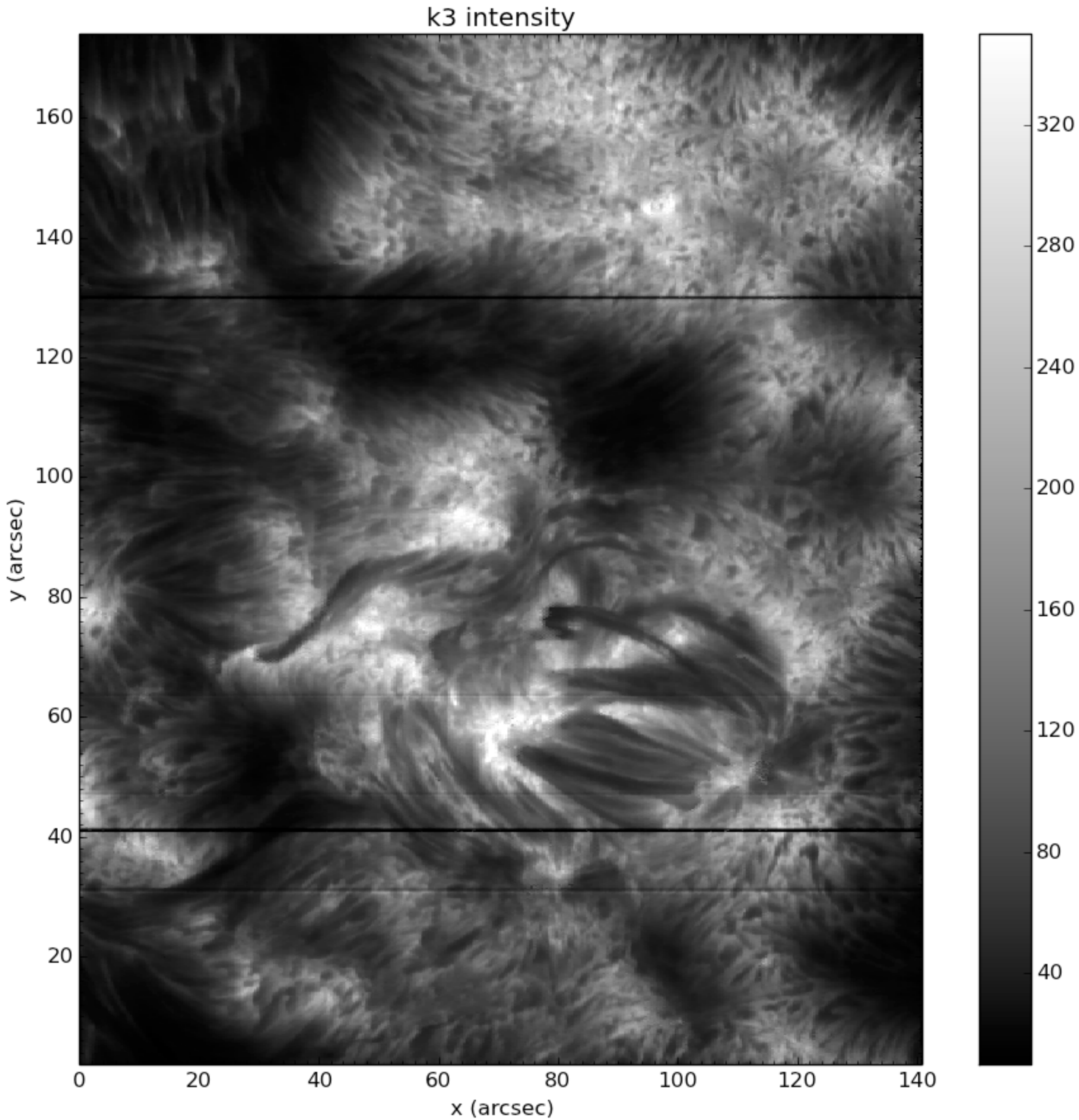


Emerging flux region

k2v intensity
=
temperature proxy

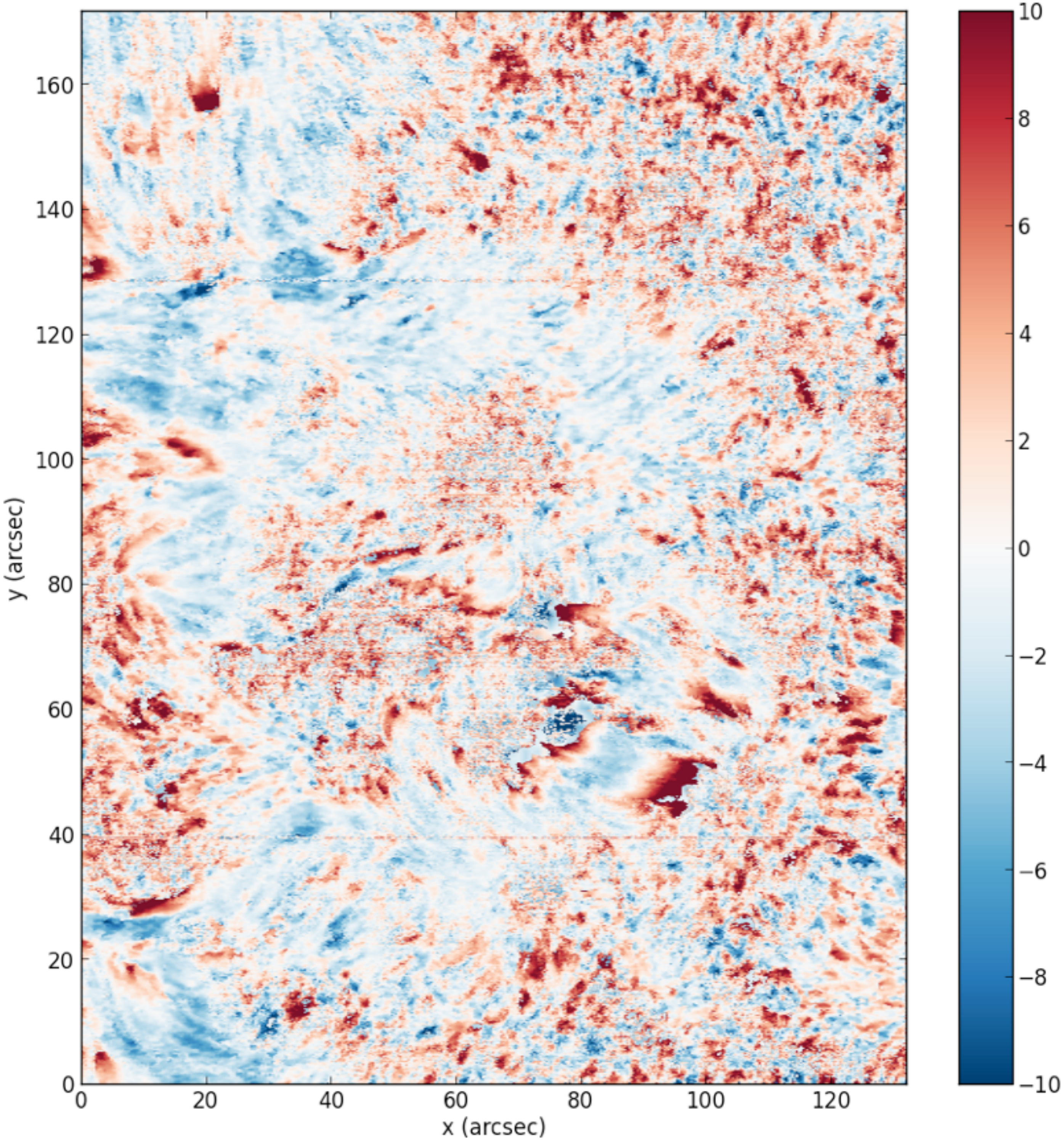
Emerging flux region

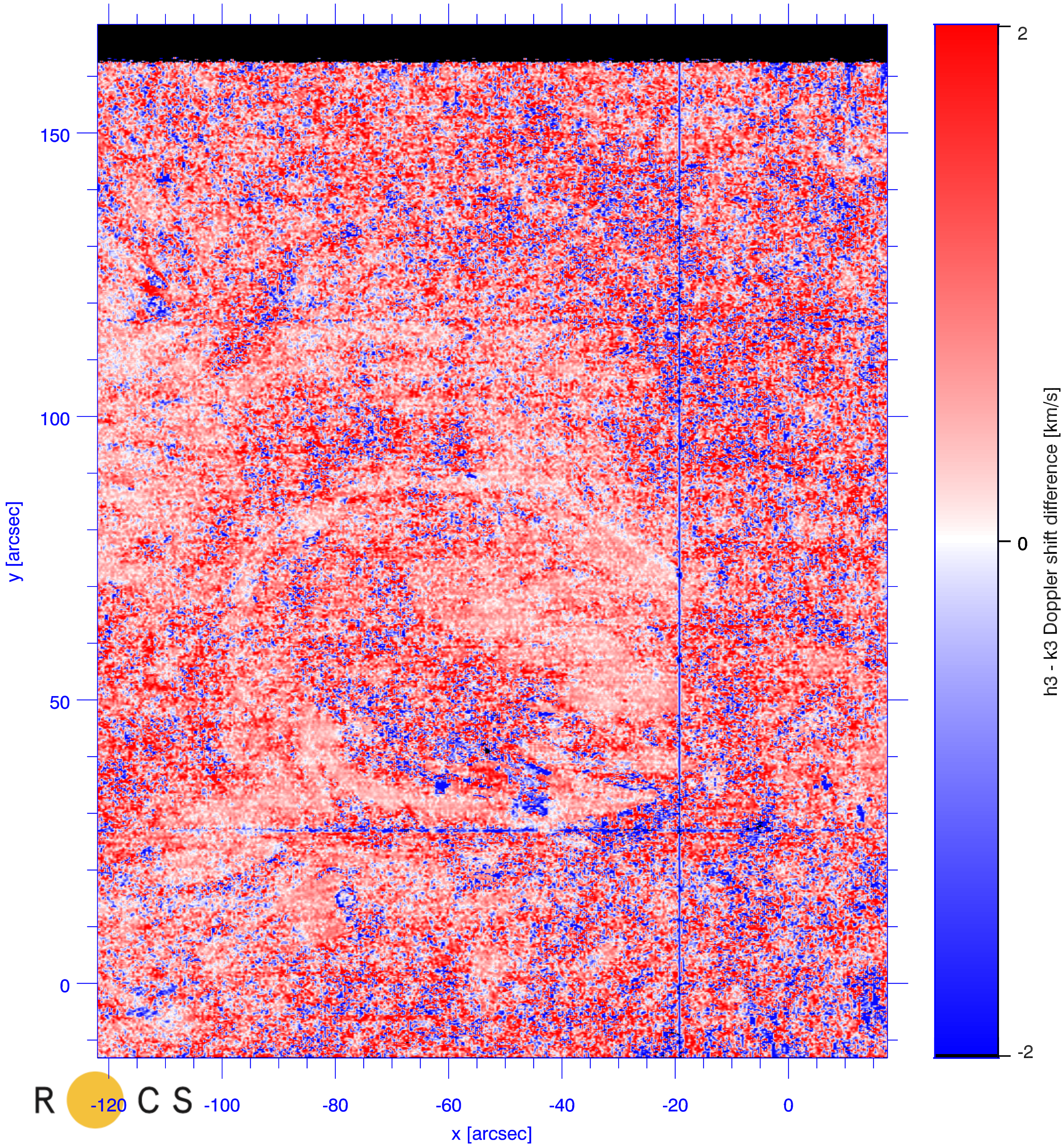
k3 intensity



Emerging flux region

k3 Doppler shift
=
velocity just below TR





Emerging flux region

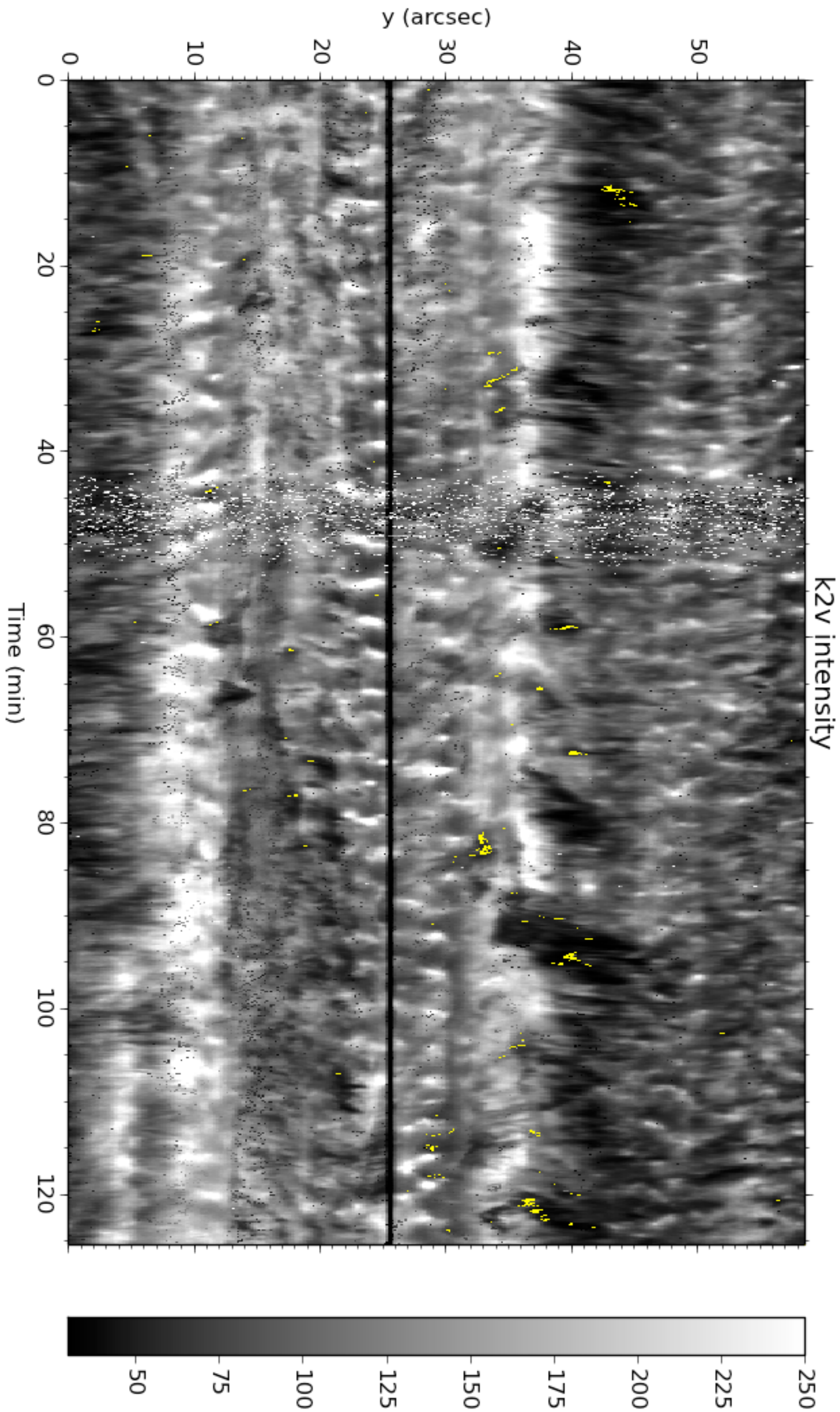
h3-k3 Doppler shift
=
vertical velocity gradient

noisy but not featureless

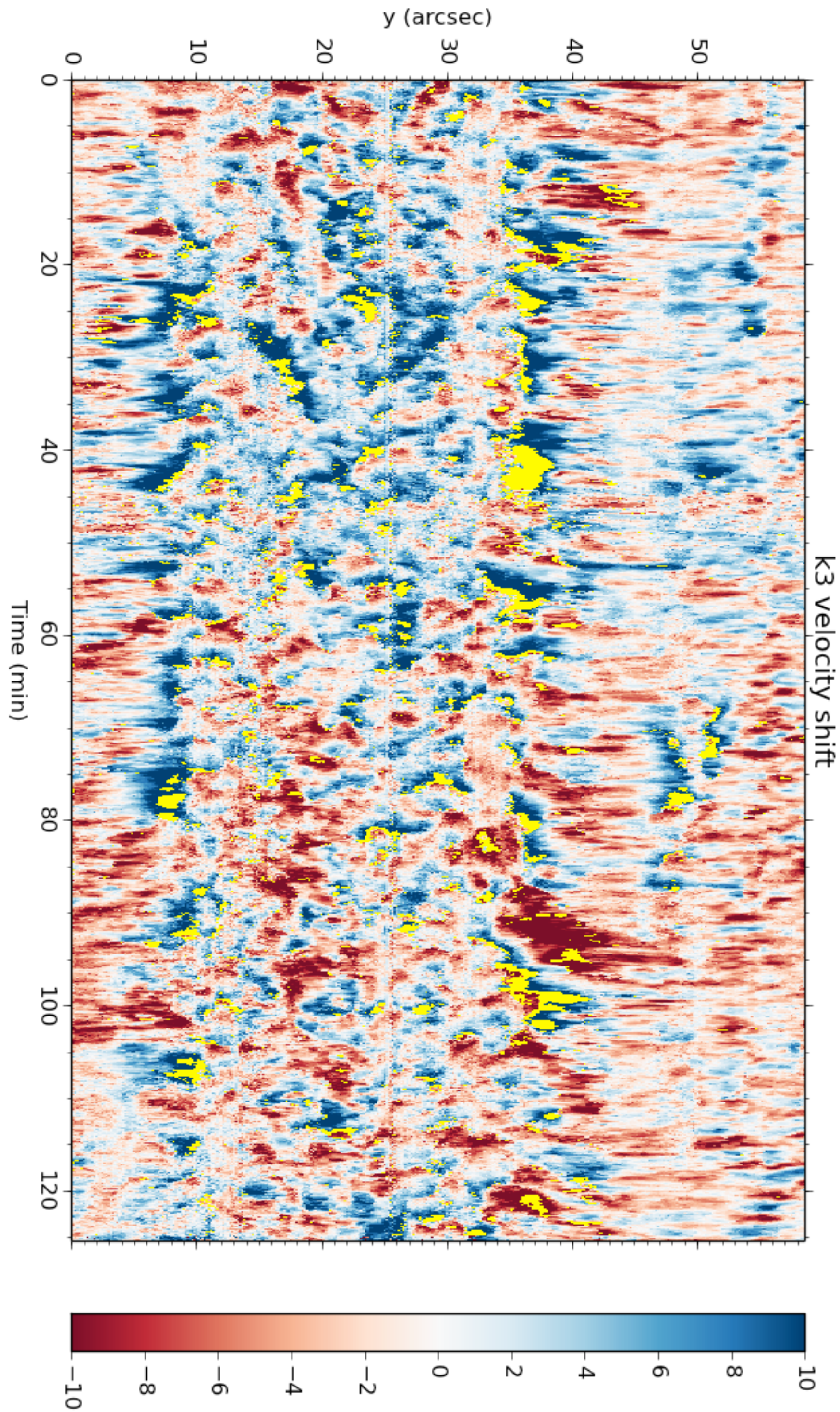
R C S

Quiet sun sit and stare

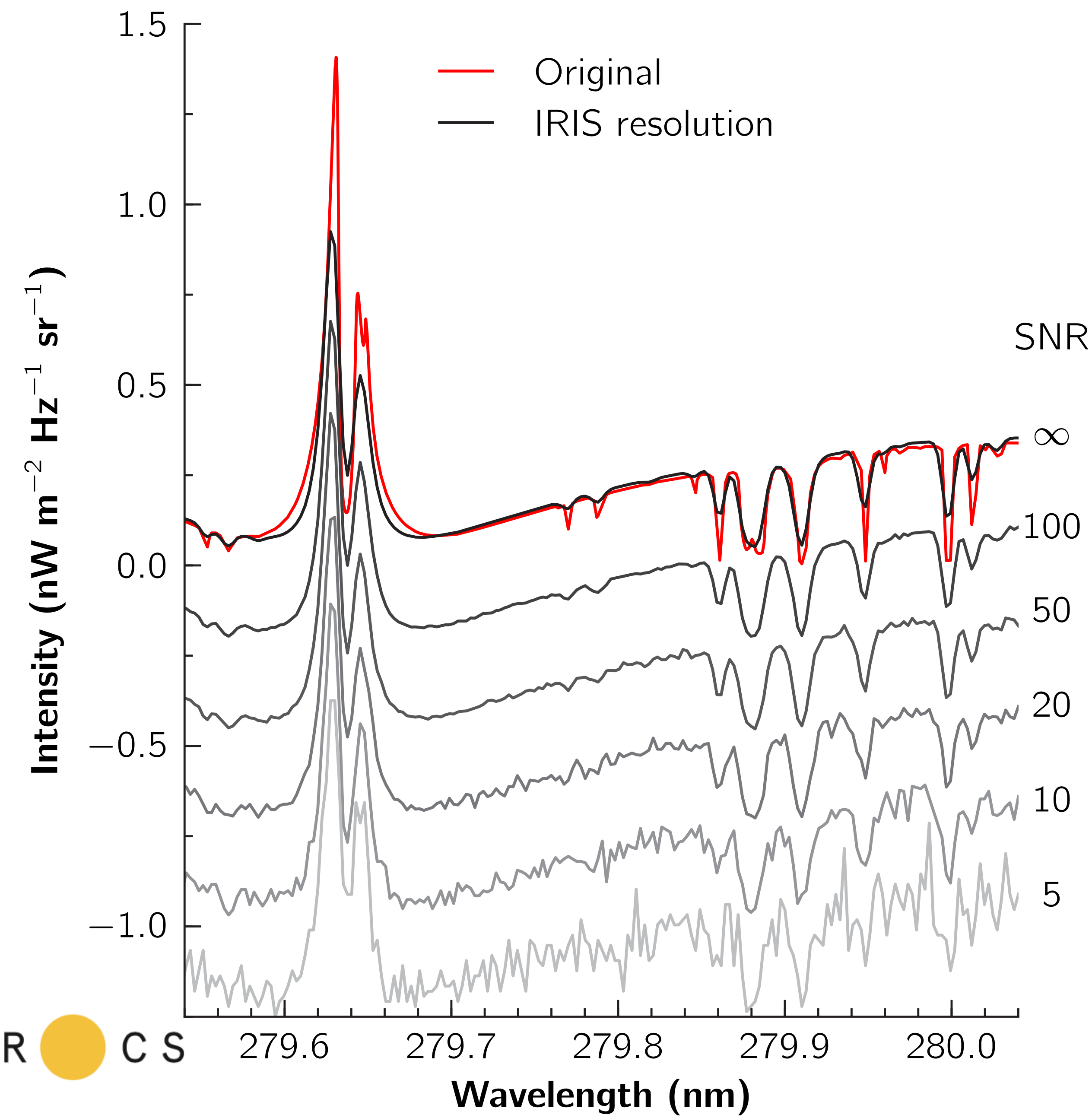
k2v intensity



k3 Doppler shift

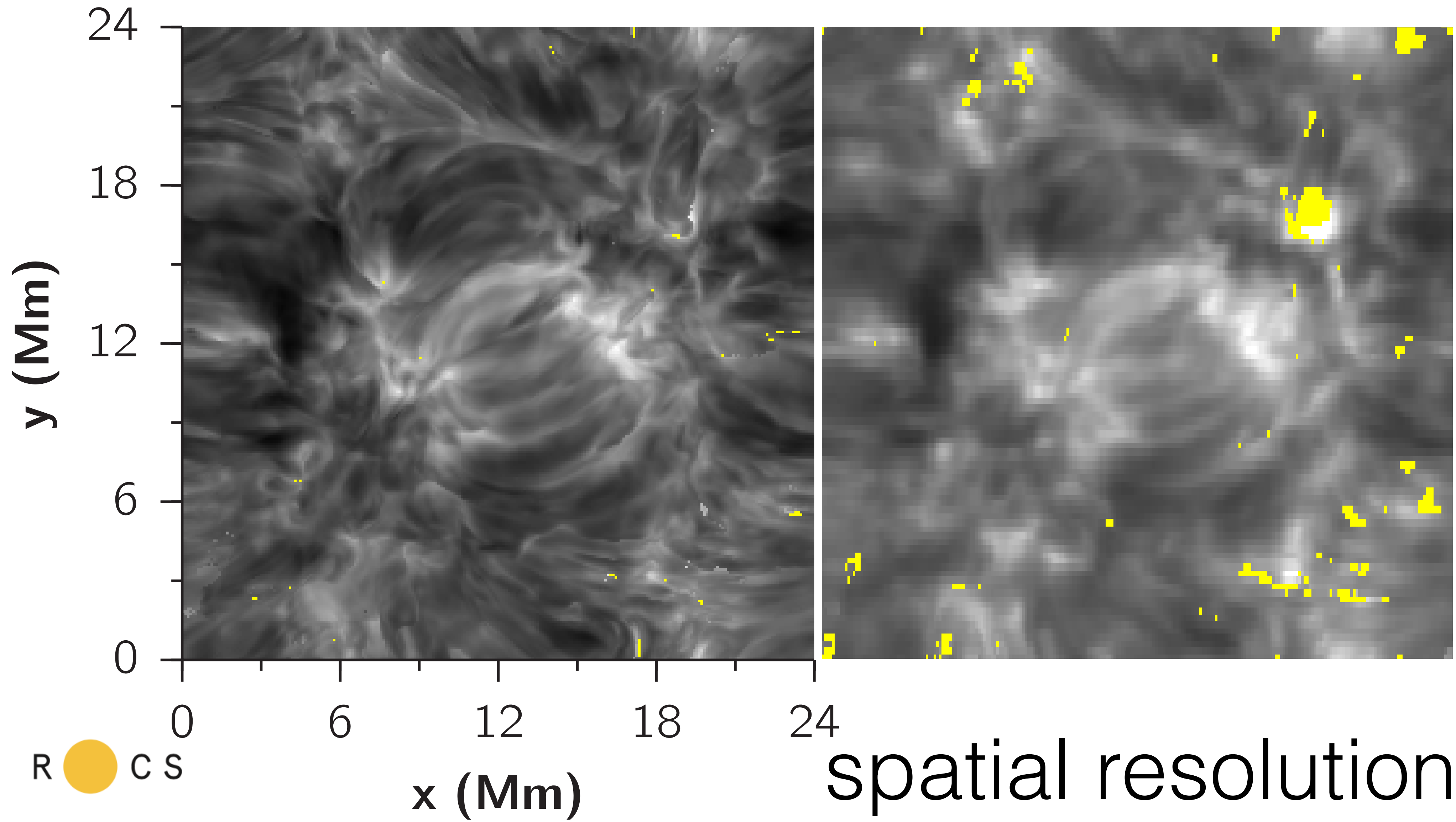


What remains at IRIS resolution?



S/N ratio

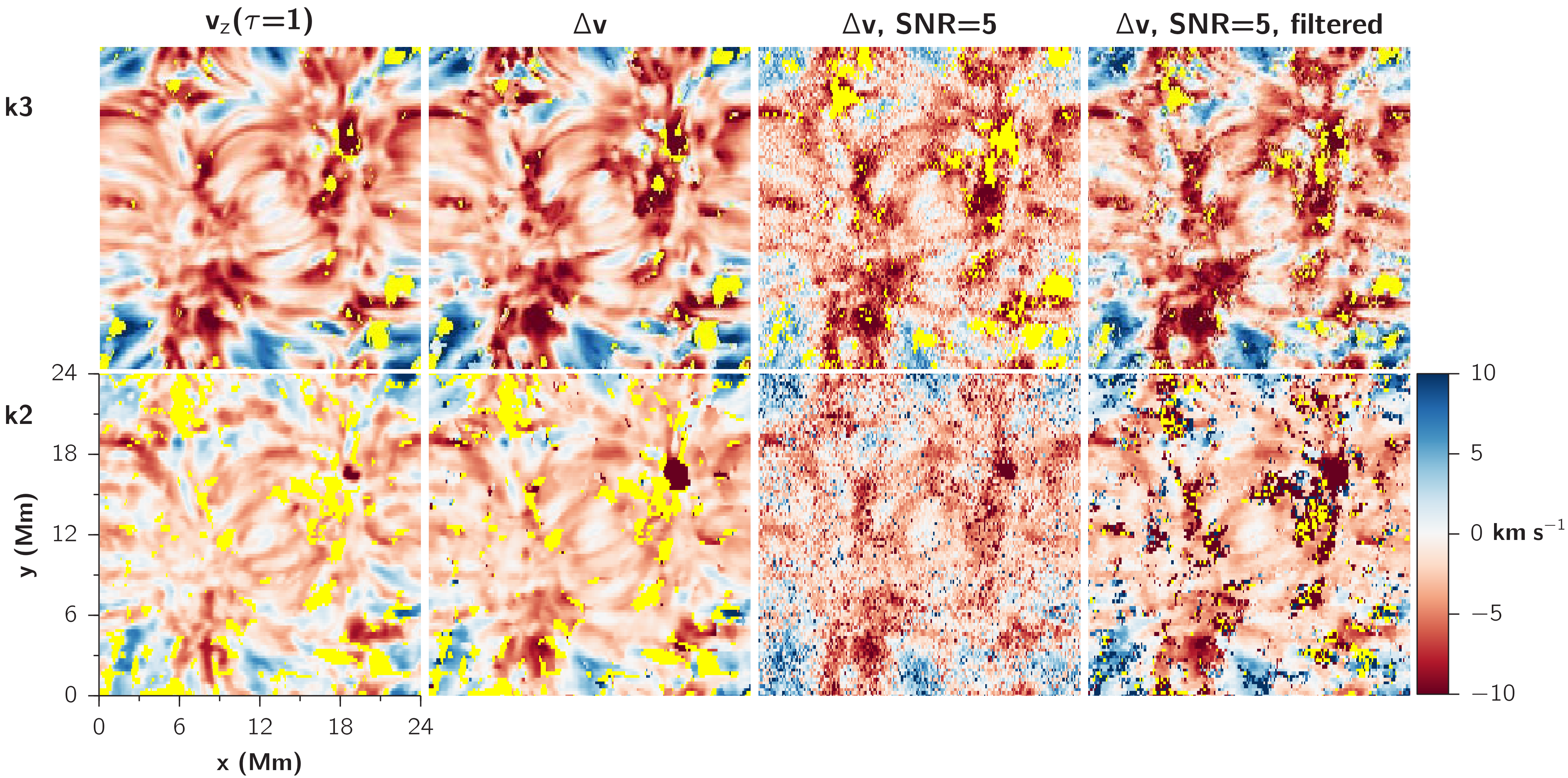
What remains at IRIS resolution?



R C S

spatial resolution

What remains at IRIS resolution?

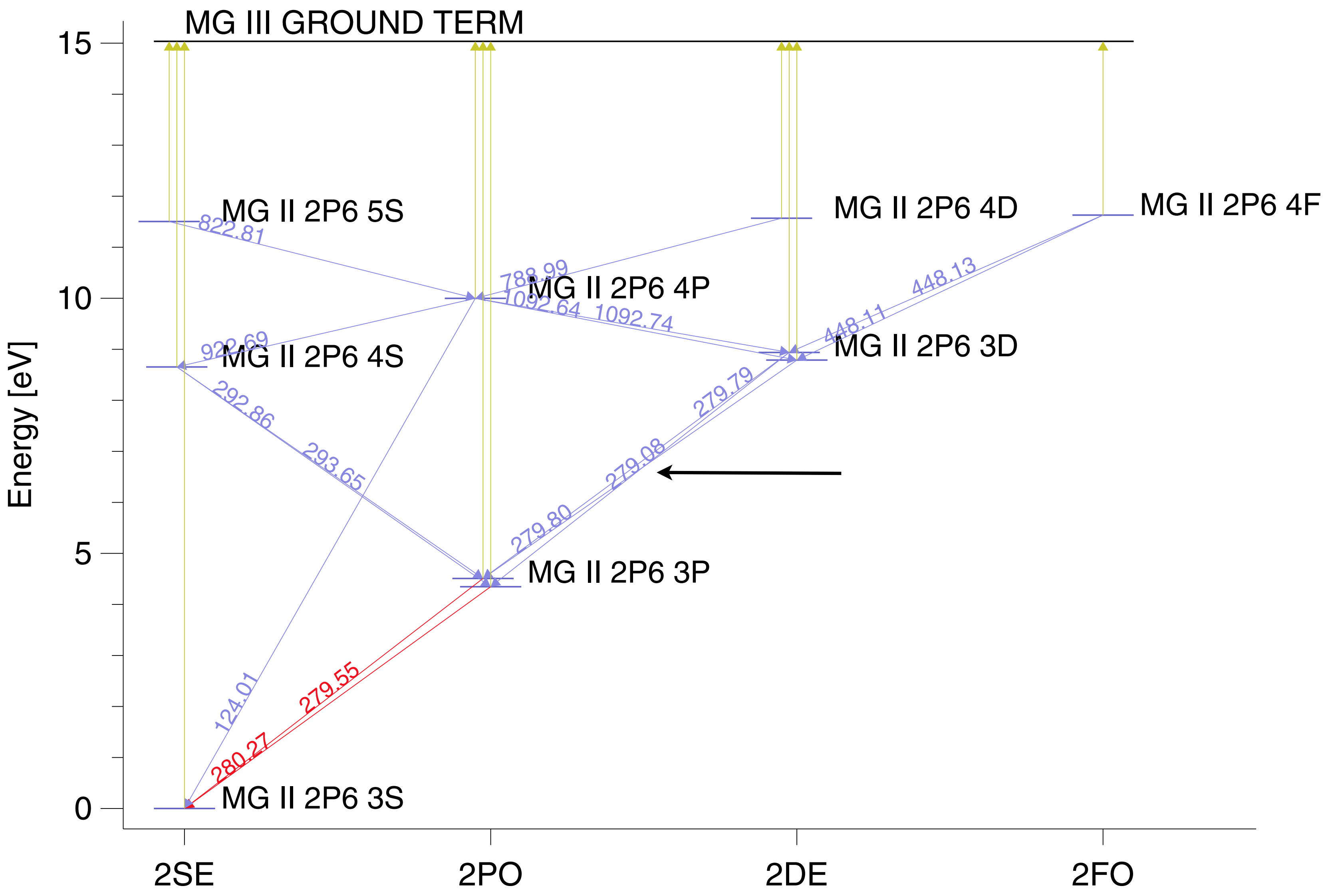


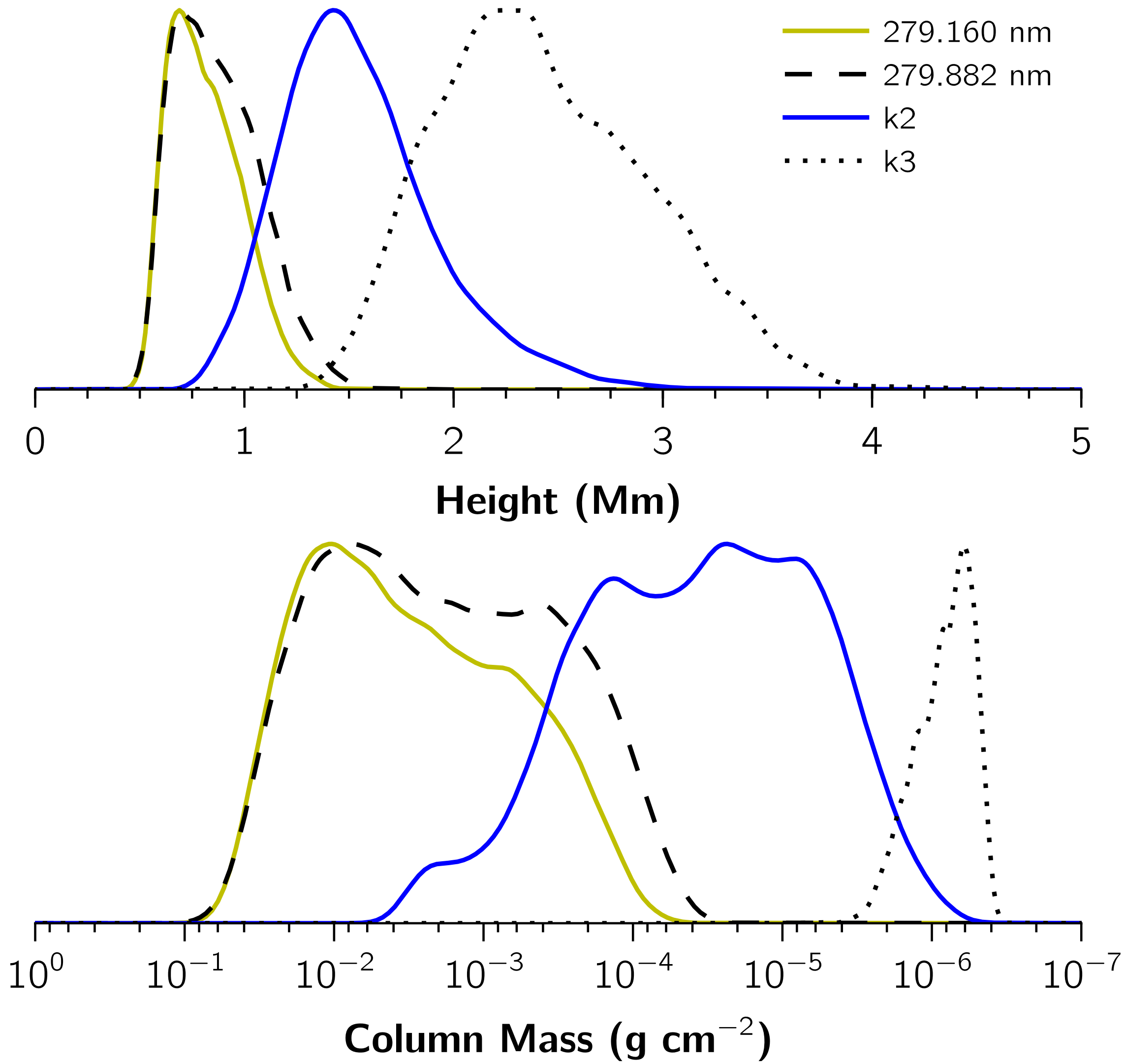
R C S

velocity diagnostic

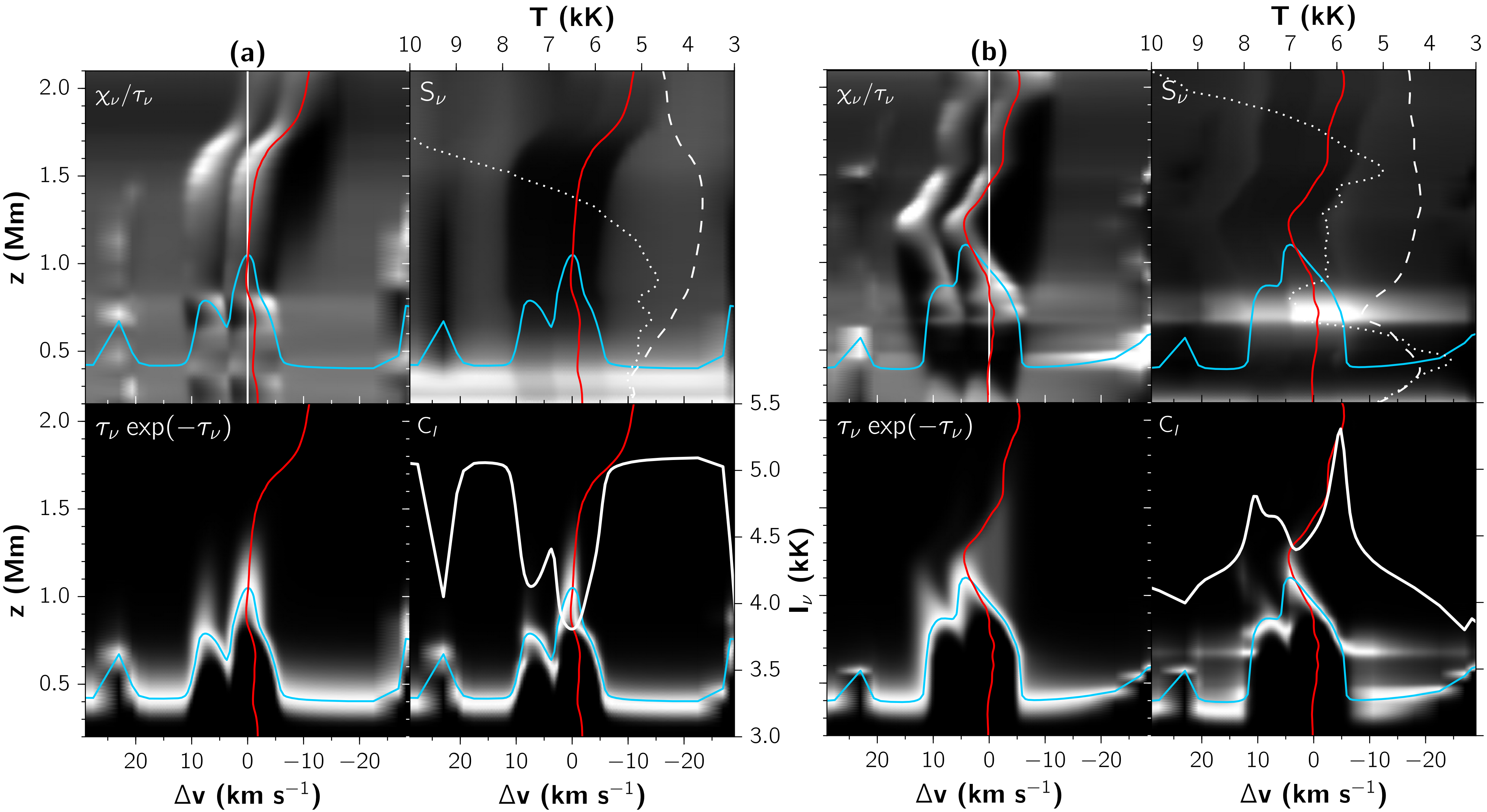
- Line core forms ~200 km below transition region
- Line core is an excellent velocity diagnostic
- h&k combined measure velocity gradients: short-wavelength oscillations?
- peaks measure mid-chromospheric temperatures
- additional diagnostics:
  - chromospheric velocity extremes
  - mid-chromospheric velocity

Remember:
All based on simulations. We believe most results are robust, but do not blindly apply the results to your data.

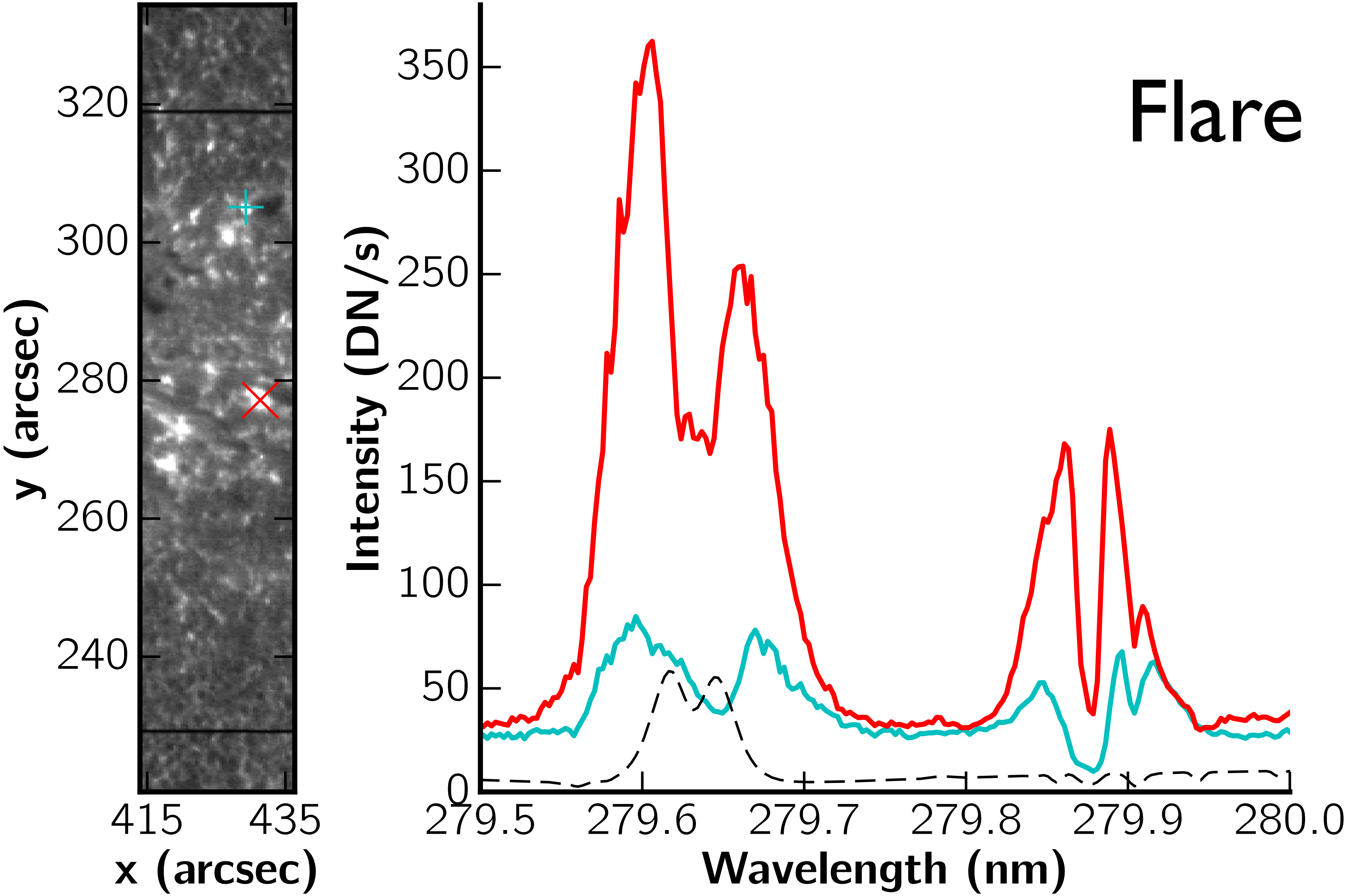

MG III GROUND TERM
Energy [eV]
15
10
5
0
MG II 2P6 5S
MG II 2P6 4D
MG II 2P6 4F
MG II 2P6 4P
MG II 2P6 4S
MG II 2P6 3D
MG II 2P6 3P
MG II 2P6 3S
822.81
788.99
1092.64
1092.74
922.69
448.13
448.11
292.86
293.65
279.79
279.08
279.80
124.01
279.55
280.27
2SE
2PO
2DE
2FO

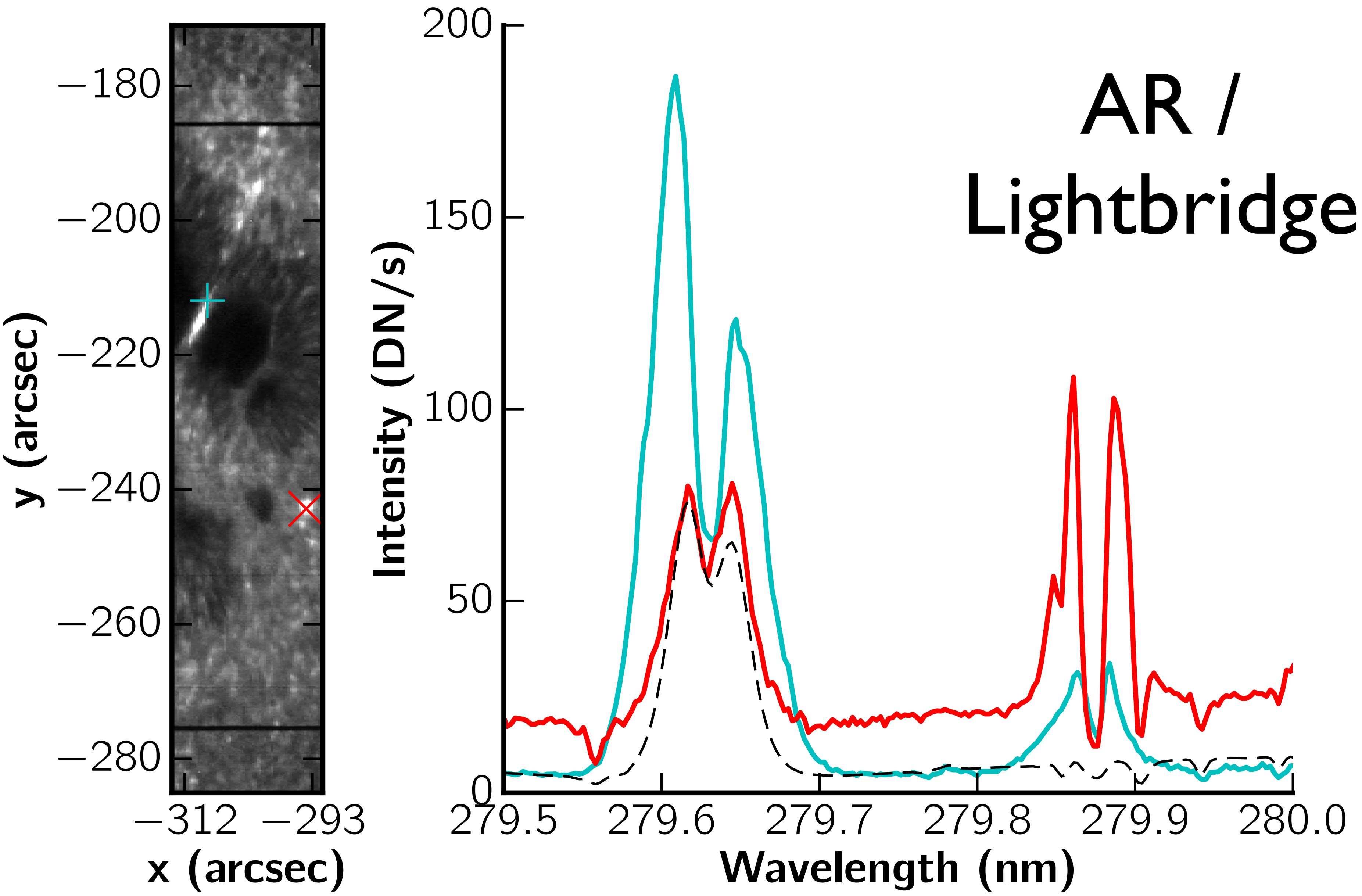

279.160 nm
279.882 nm
k2
k3
0
1
2
3
4
5
Height (Mm)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Column Mass (g cm^{-2})

R C S

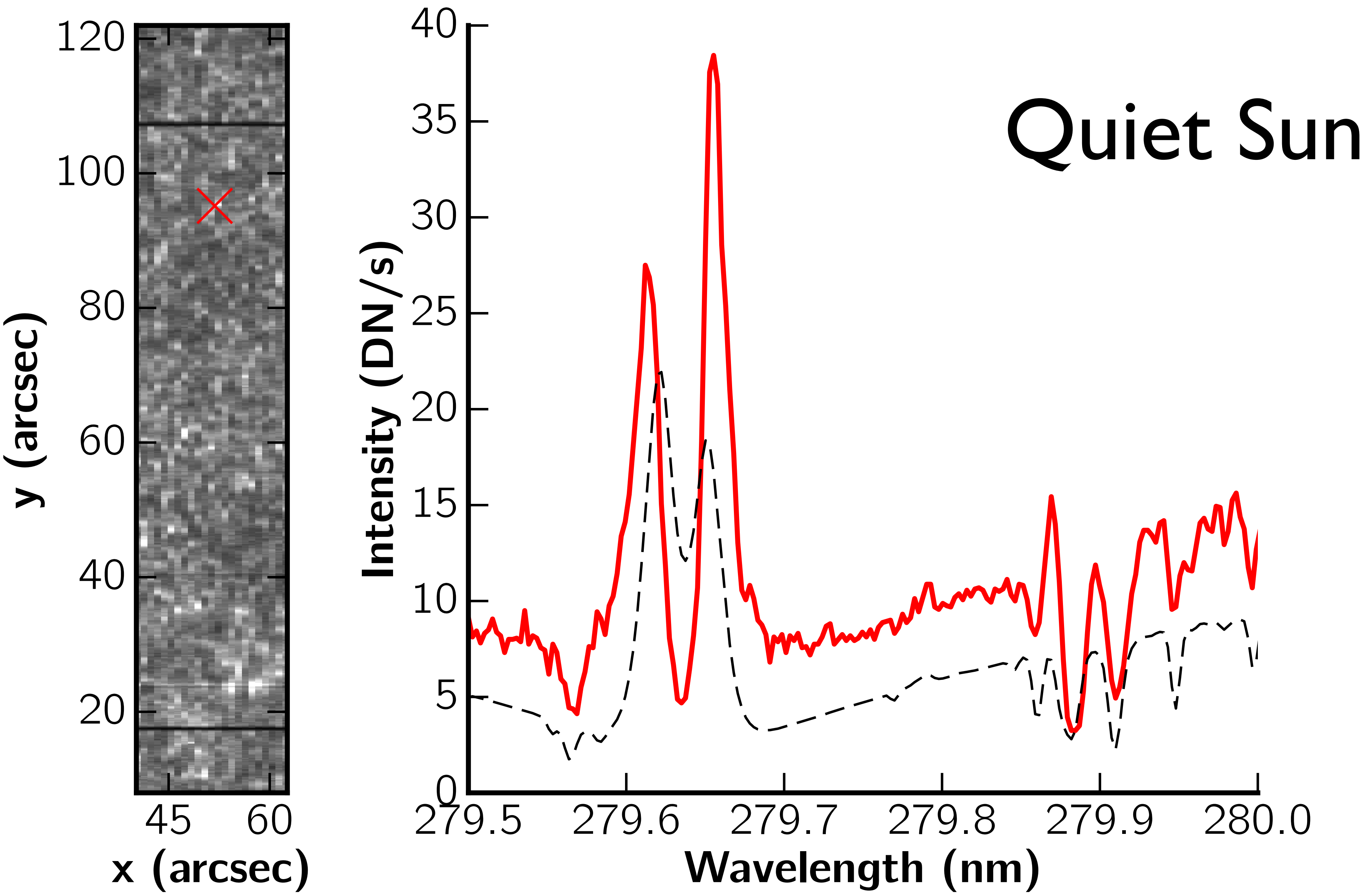

(a)
(b)
T (kK)
10 9 8 7 6 5 4 3
χ_ν/τ_ν
S_ν
$\tau_\nu \exp(-\tau_\nu)$
C_I
z (Mm)
2.0 1.5 1.0 0.5
I_ν (kK)
5.5 5.0 4.5 4.0 3.5 3.0
20 10 0 −10 −20
Δv (km s^{-1})

R C S


Flare
y (arcsec)
320
300
280
260
240
415
435
x (arcsec)
Intensity (DN/s)
350
300
250
200
150
100
50
0
279.5
279.6
279.7
279.8
279.9
280.0
Wavelength (nm)

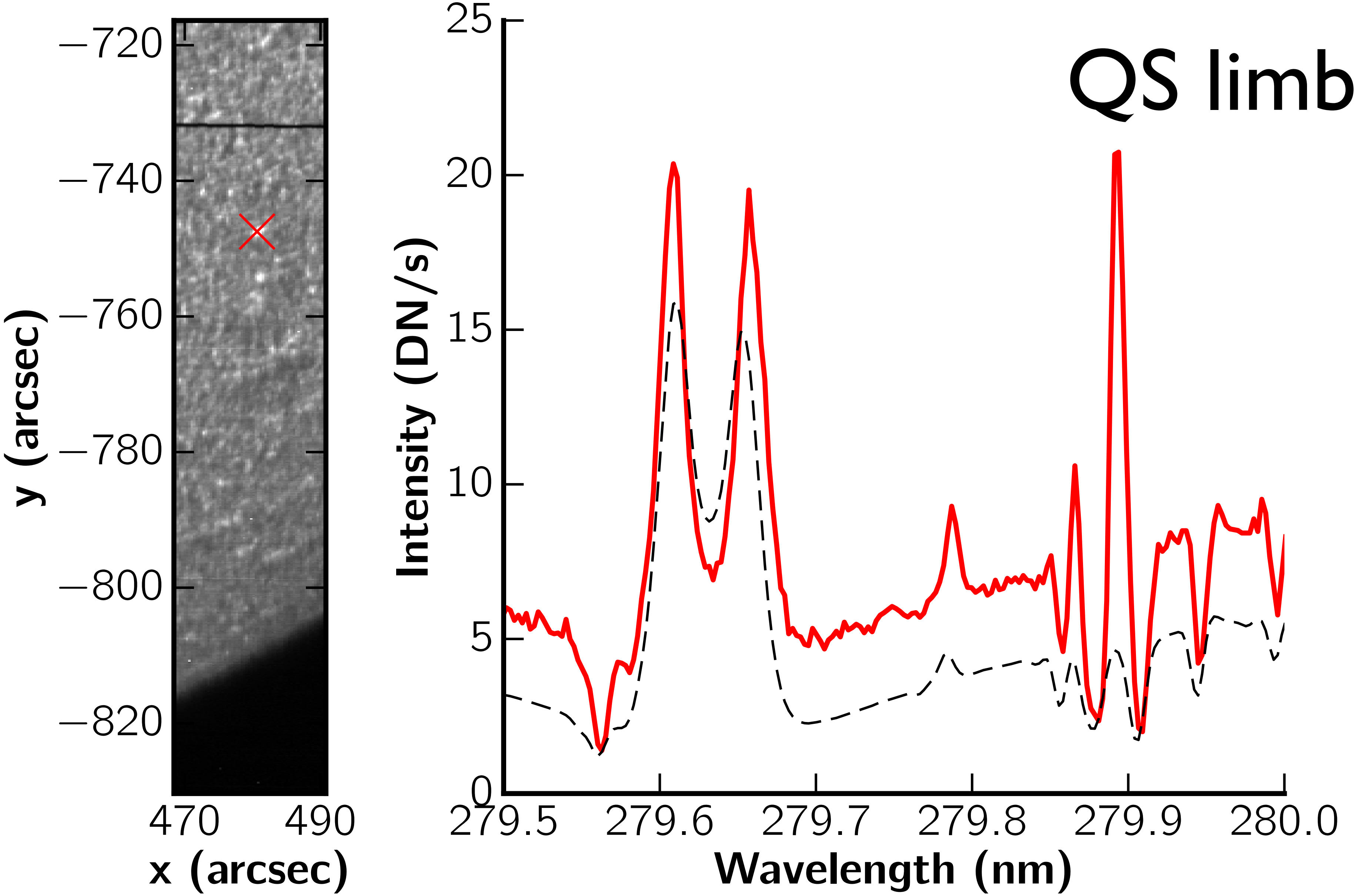


AR /
Lightbridge
−180
−200
−220
−240
−260
−280
y (arcsec)
−312
−293
x (arcsec)
200
150
100
50
0
Intensity (DN/s)
279.5
279.6
279.7
279.8
279.9
280.0
Wavelength (nm)



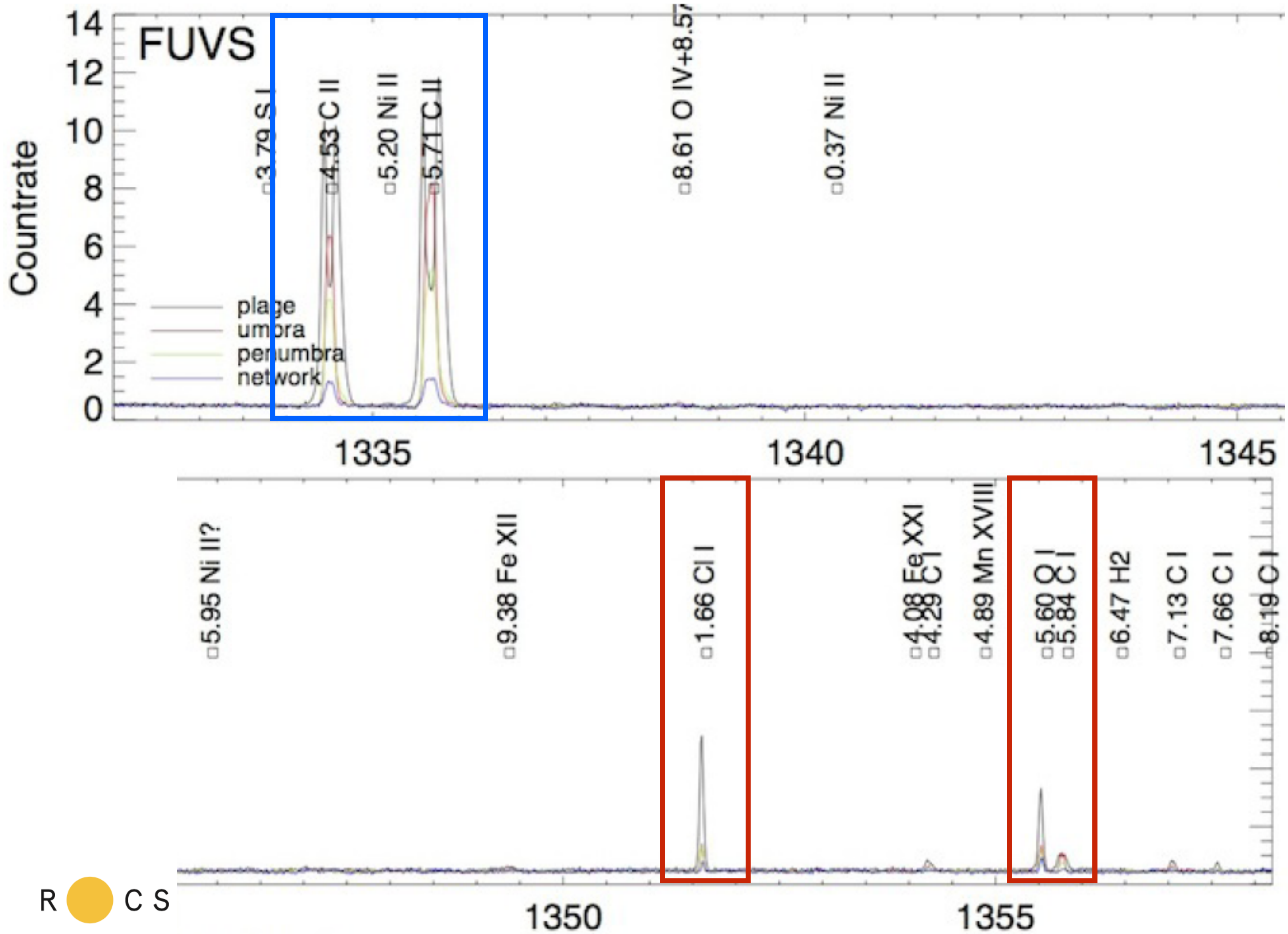
Quiet Sun
y (arcsec)
120
100
80
60
40
20
45
60
x (arcsec)
Intensity (DN/s)
40
35
30
25
20
15
10
5
0
279.5
279.6
279.7
279.8
279.9
280.0
Wavelength (nm)

R C S

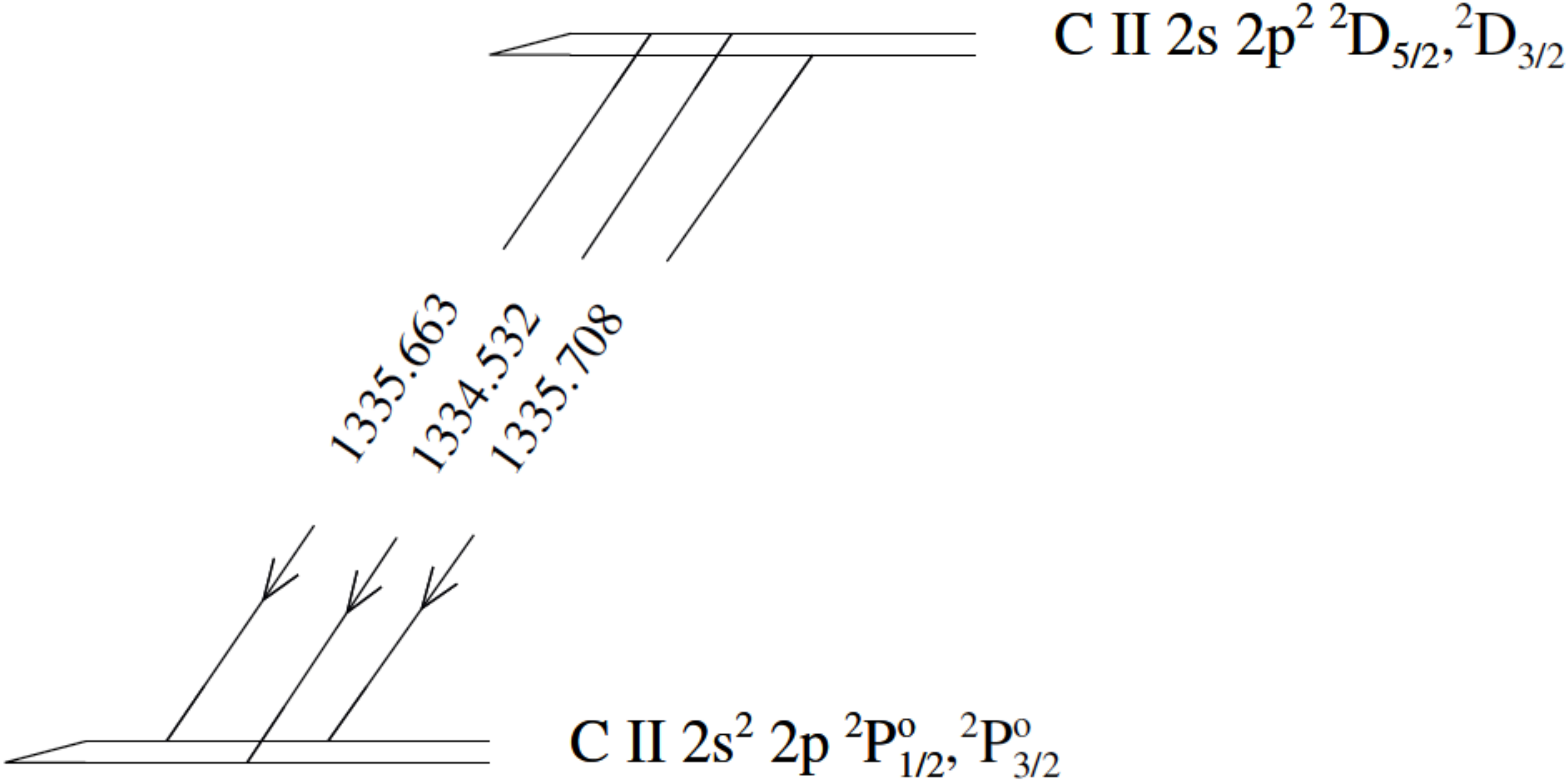


QS limb
−720
−740
−760
−780
−800
−820
y (arcsec)
470
490
x (arcsec)
25
20
15
10
5
0
Intensity (DN/s)
279.5
279.6
279.7
279.8
279.9
280.0
Wavelength (nm)

R C S


FUVS
Countrate
plage
umbra
penumbra
network
3.79 S I
4.53 C II
5.20 Ni II
5.71 C II
8.61 O IV+8.57
0.37 Ni II
1335
1340
1345
5.95 Ni II?
9.38 Fe XII
1.66 Cl I
4.08 Fe XXI
4.29 C I
4.89 Mn XVIII
5.60 O I
5.84 C I
6.47 H2
7.13 C I
7.66 C I
8.19 C I
1350
1355

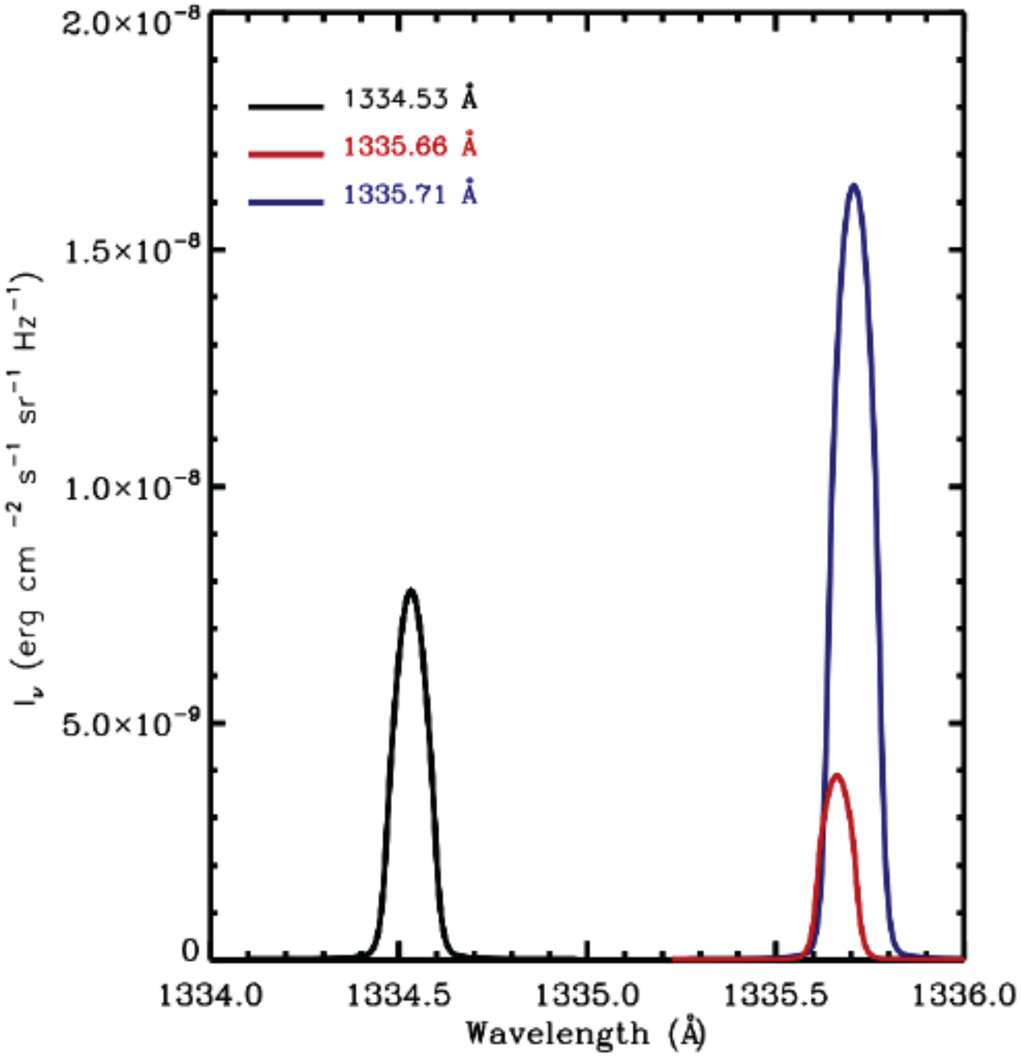
C II lines at 1334-1336



R C S

Rathore & Carlsson 2015
Rathore et al 2015

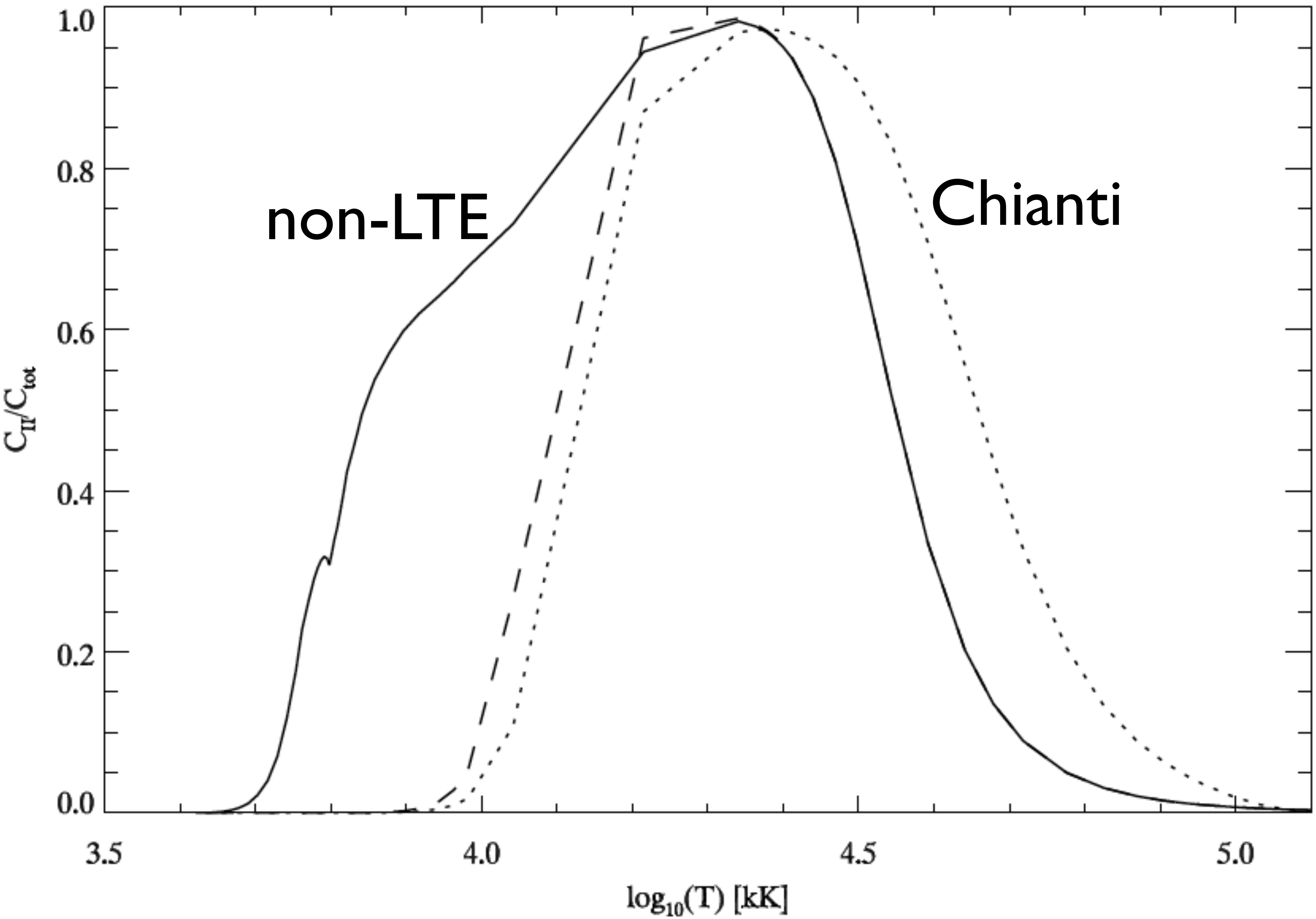
C II 1335 multiplet



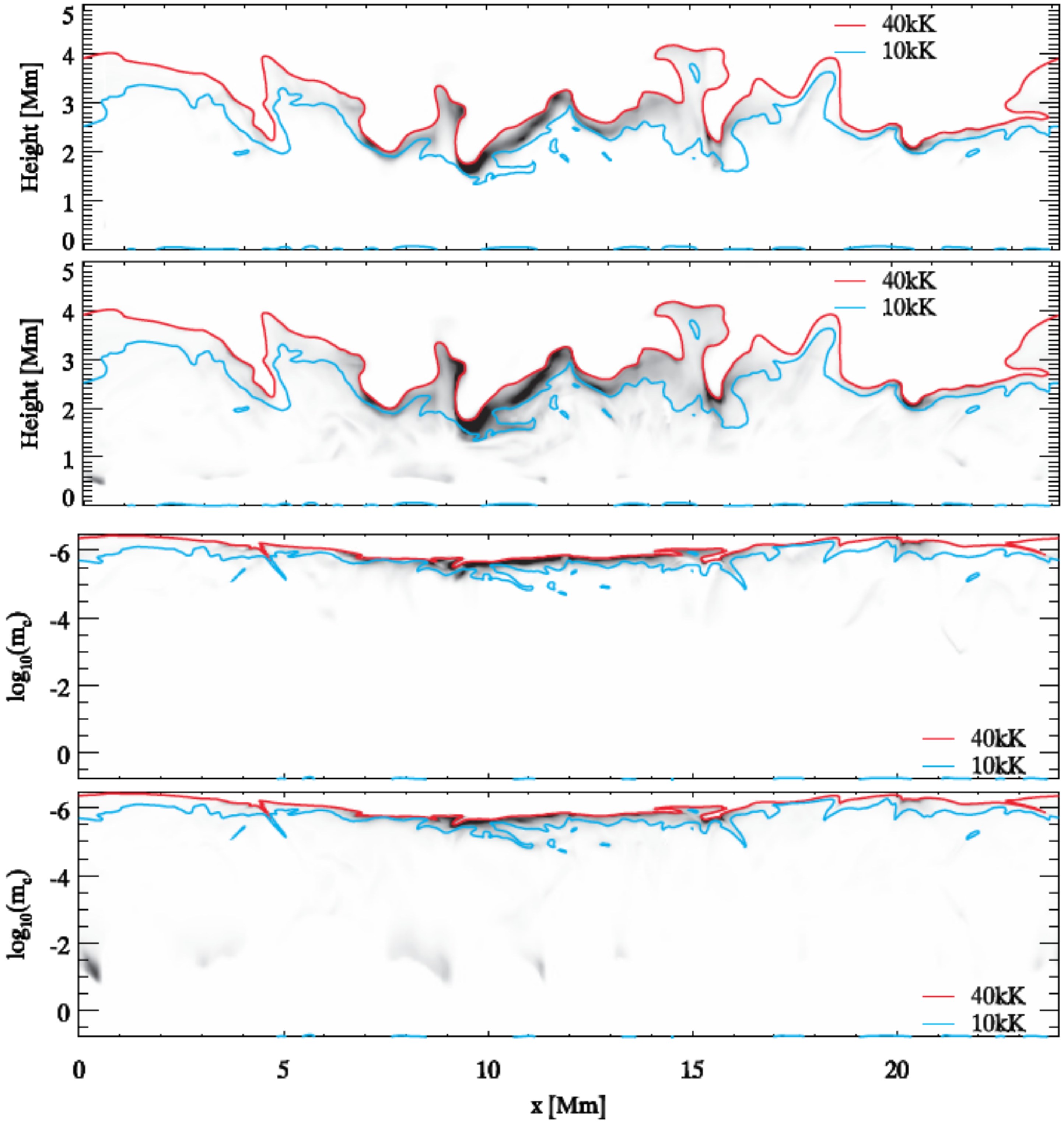
Wavelength (Å)	J_u	J_l	gf
1334.5323	3/2	1/2	0.257
1335.6625	3/2	3/2	0.0512
1335.7077	5/2	3/2	0.464

R C S

Ionization balance

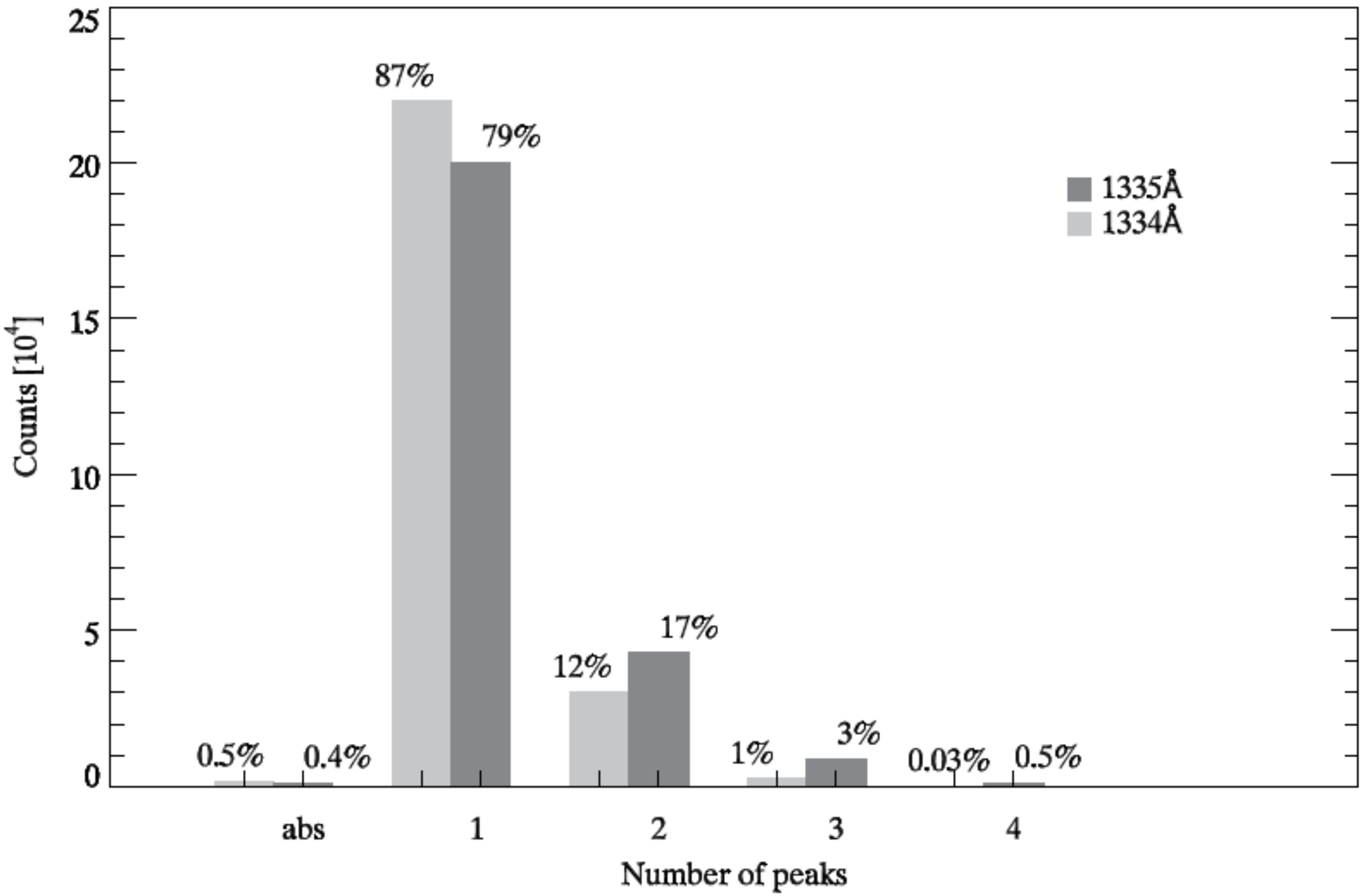


R



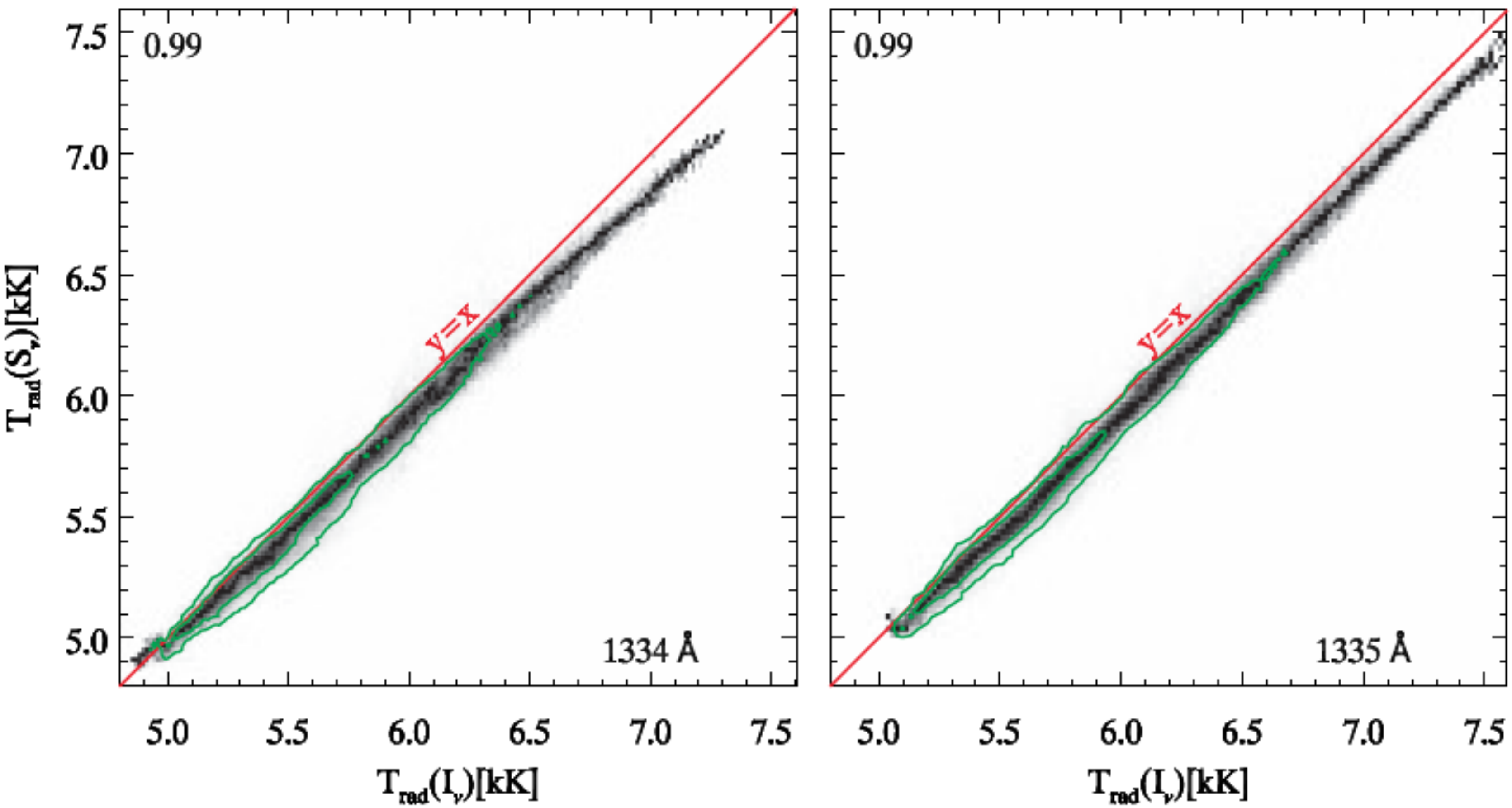
R C S

Number of peaks



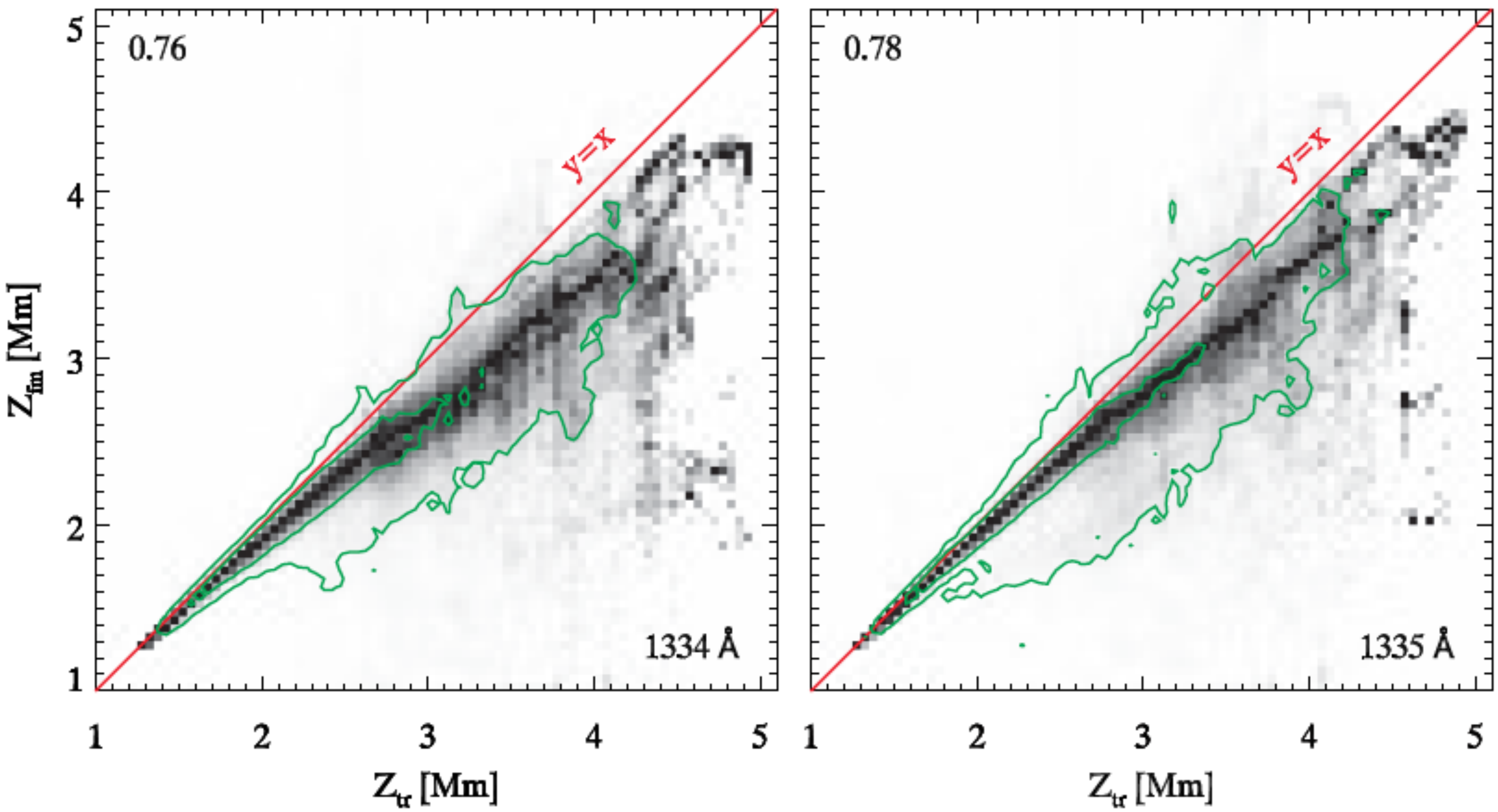
R C S

Eddington Barbier



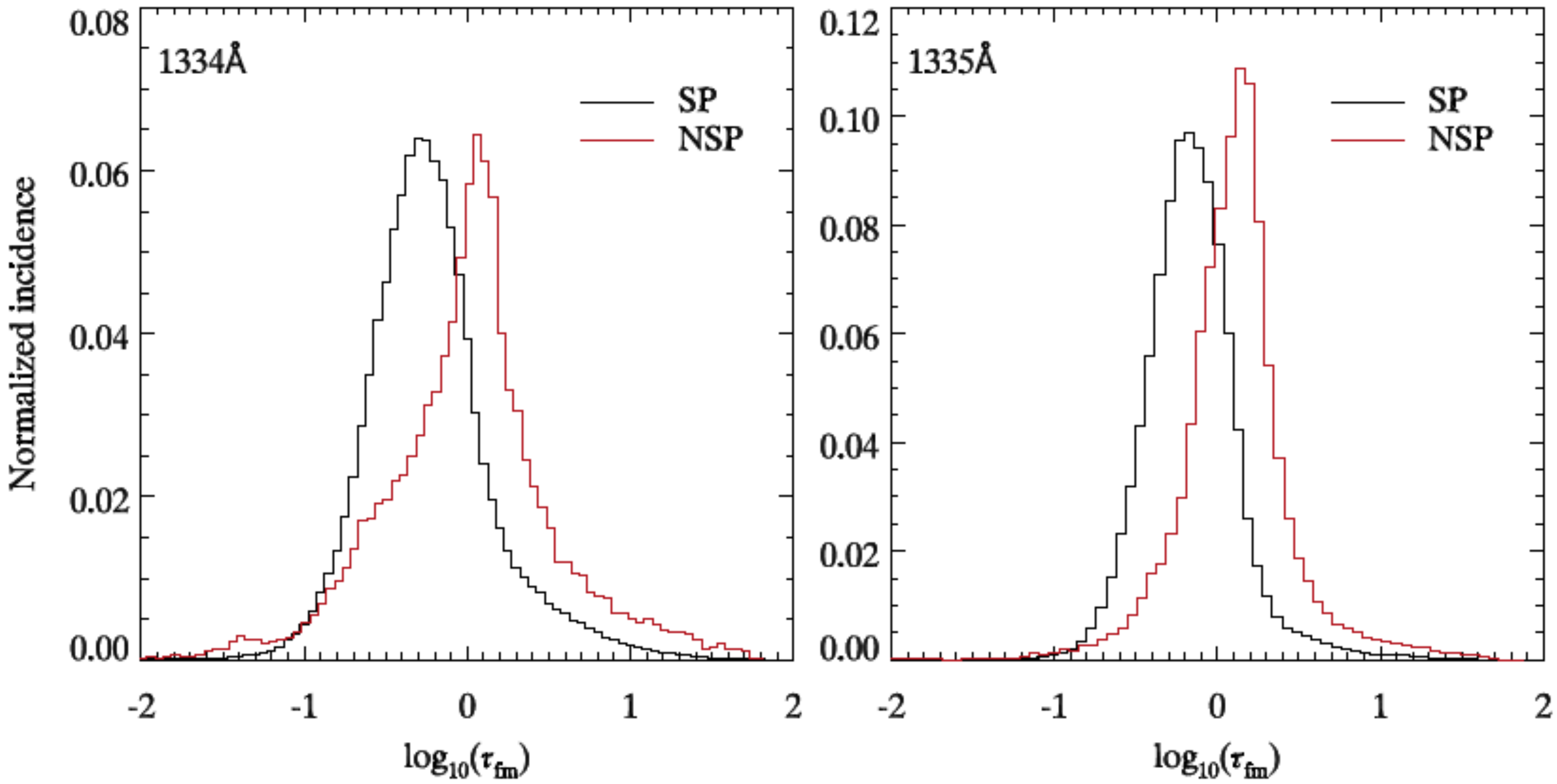
R C S

Height of formation



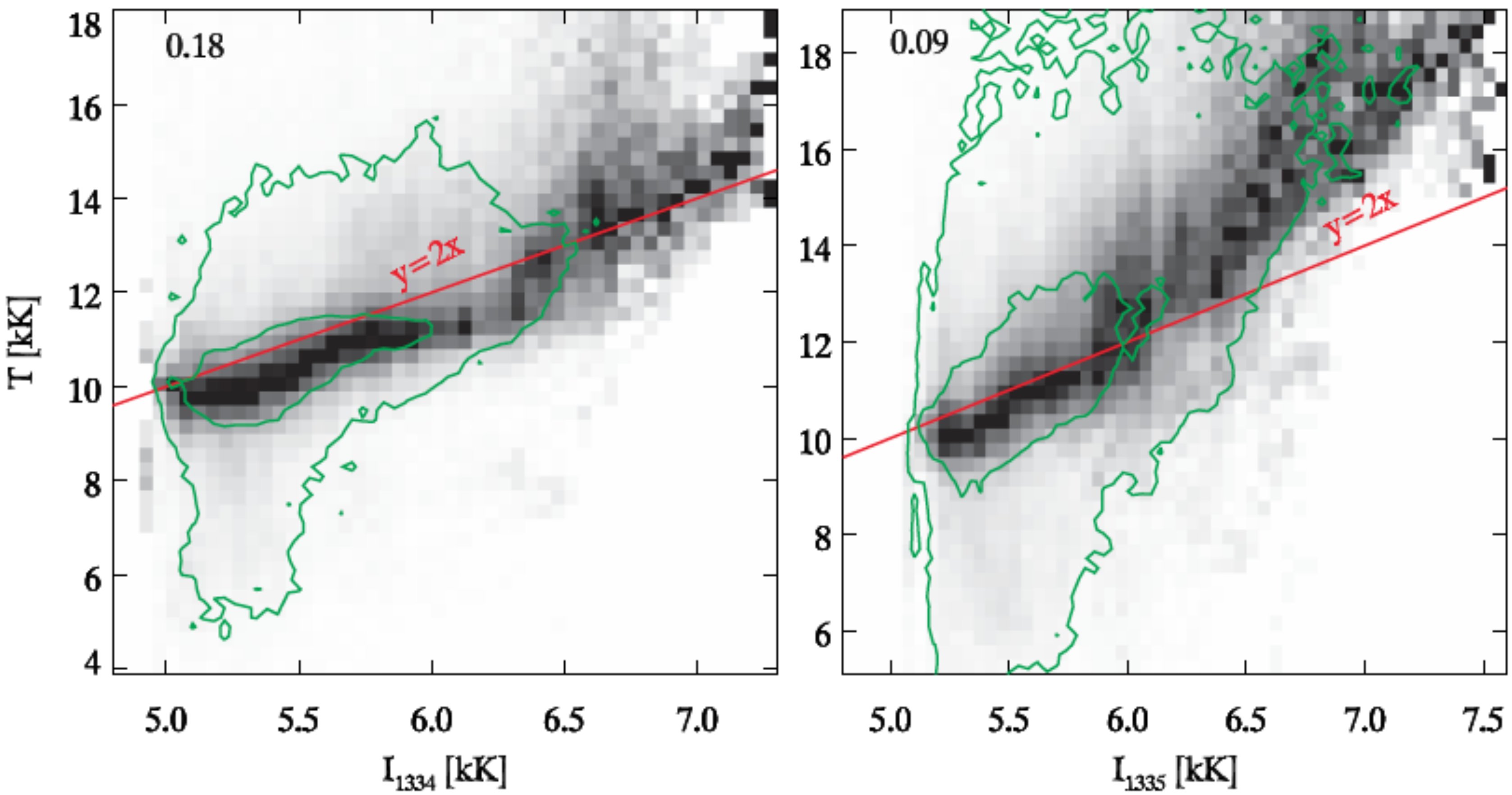
R C S

Height of formation



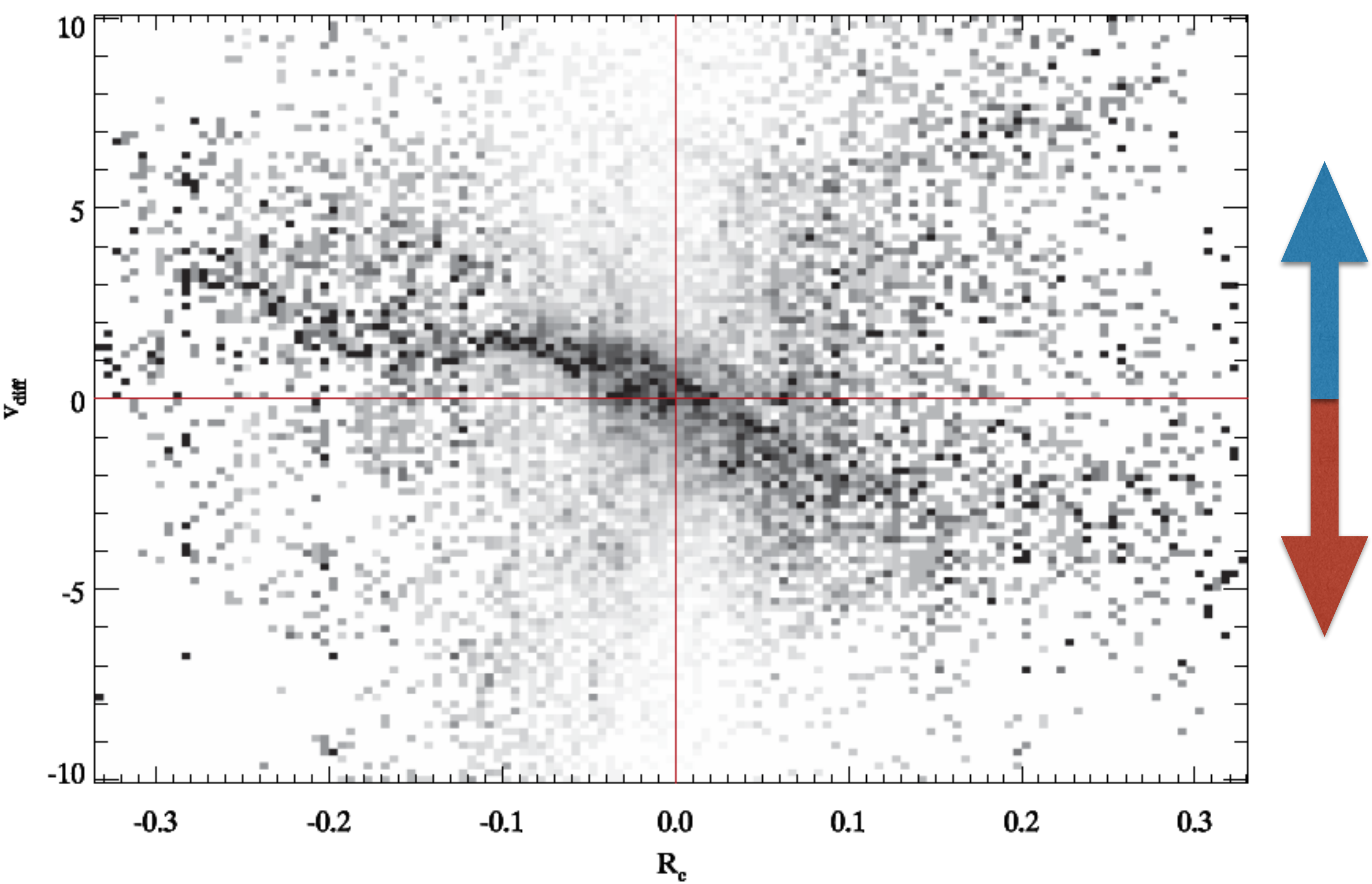
R C S

Intensity as temperature diagnostic



R C S

Line asymmetry

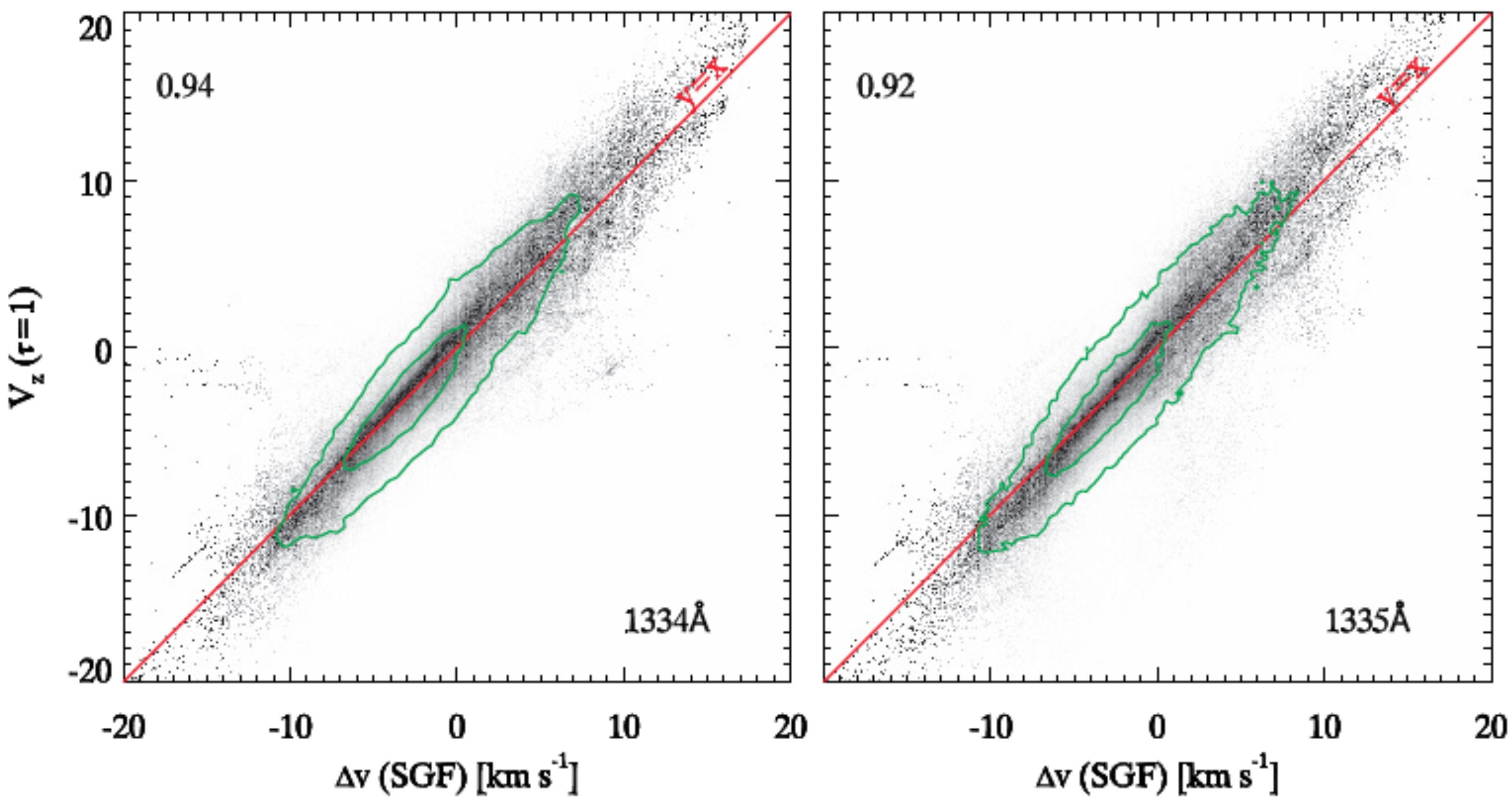


Red peak stronger

Blue peak stronger

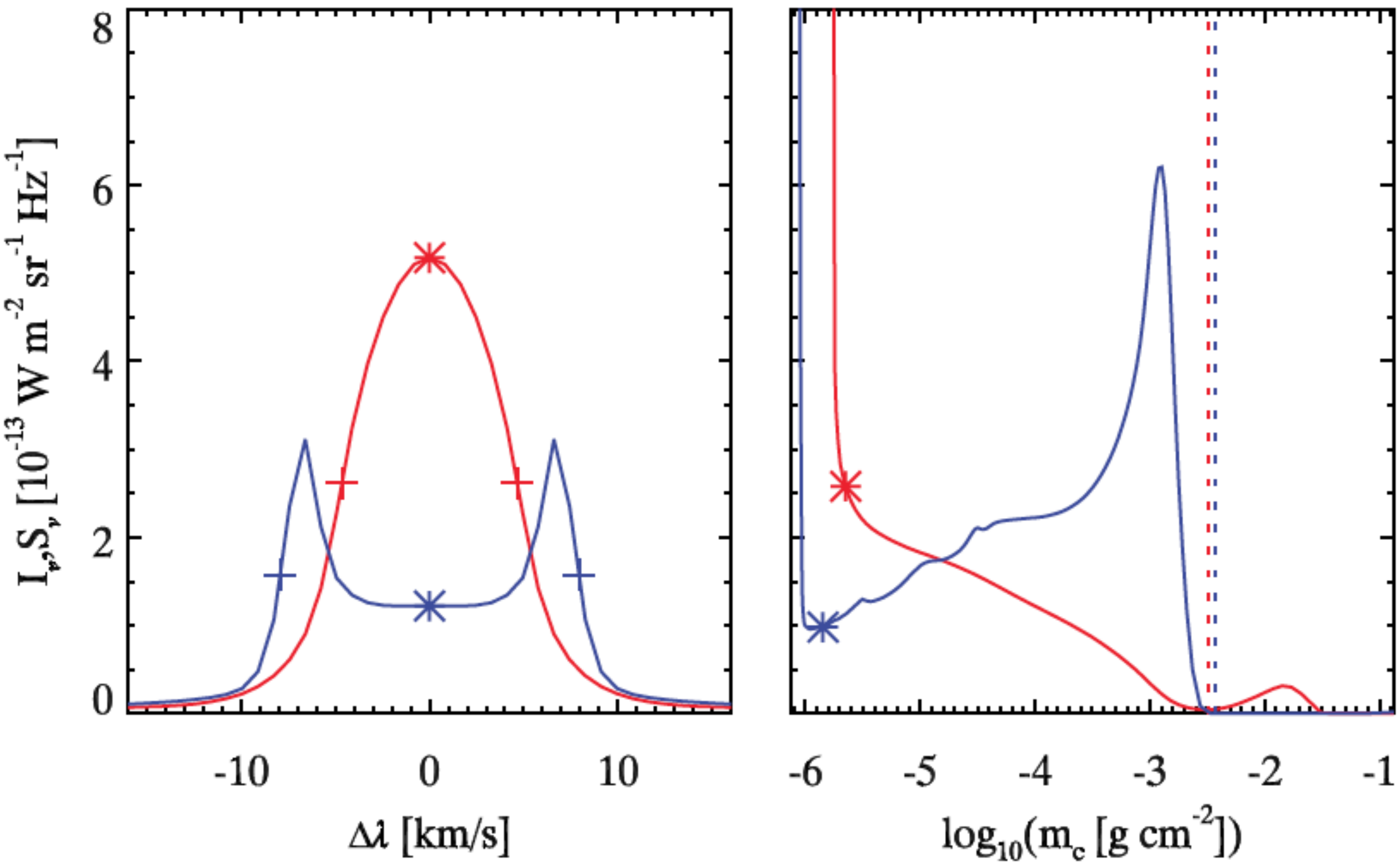
R C S

Doppler shift of single-Gaussian fit

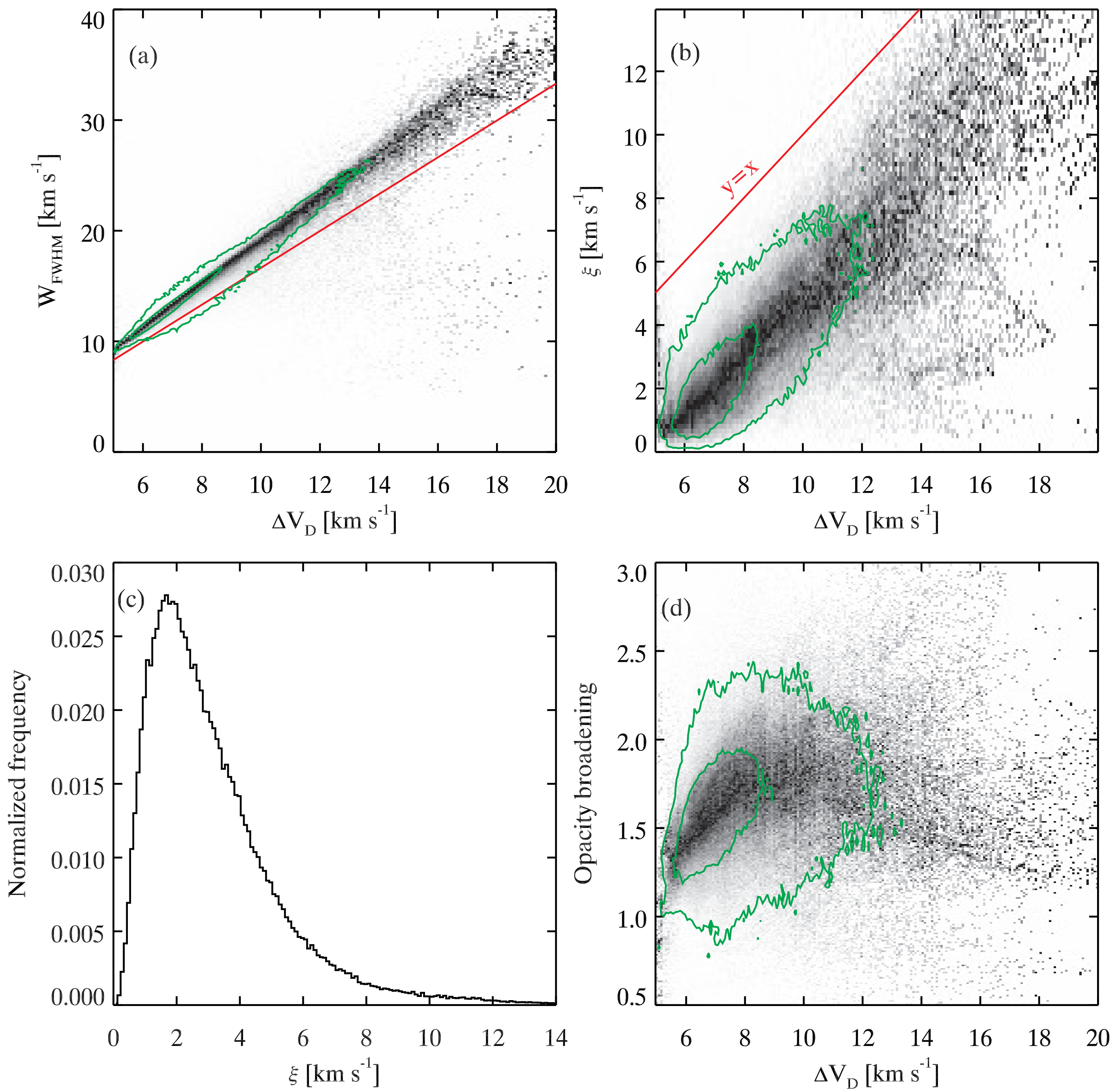


R C S

Line width

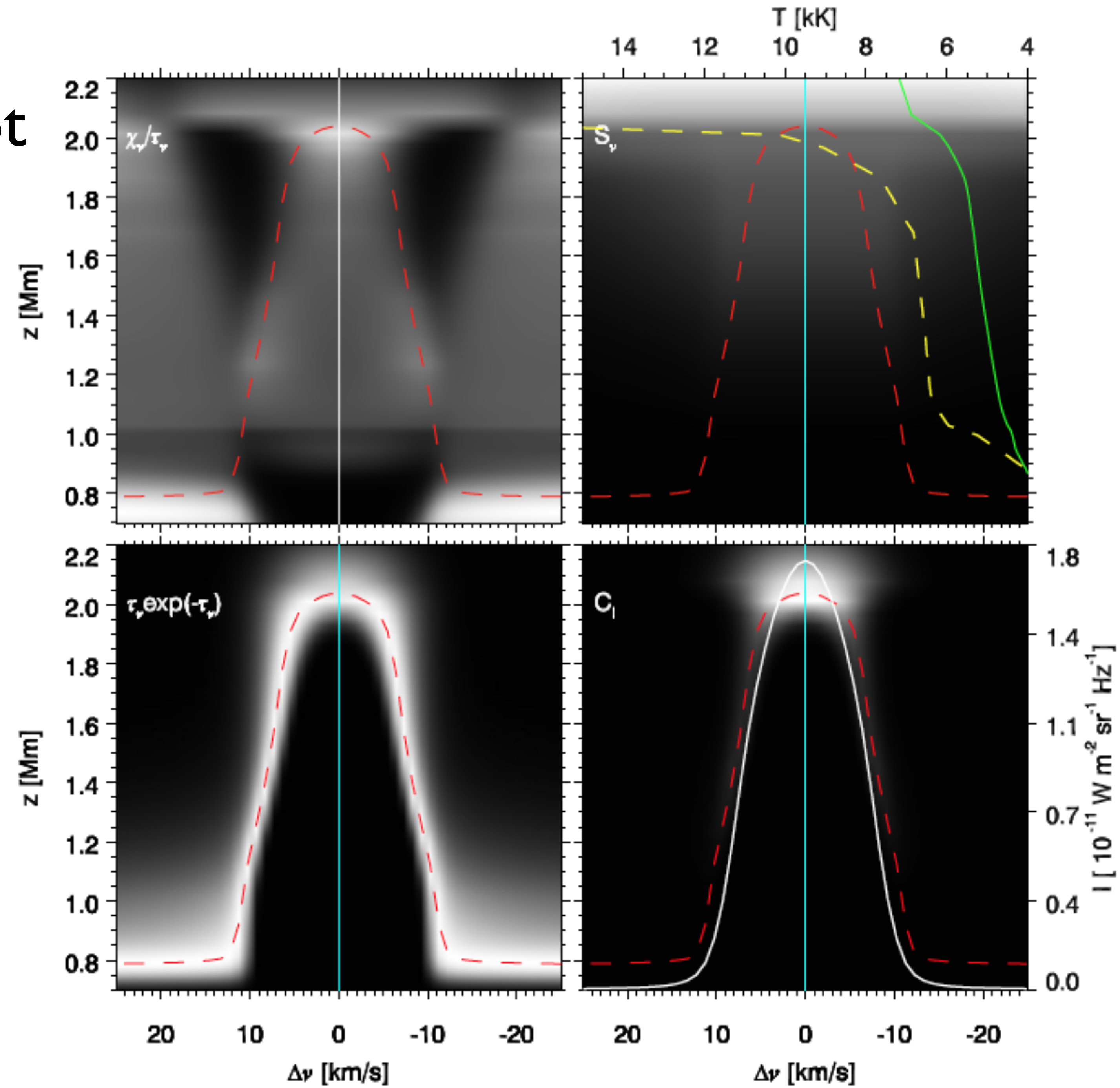


$$\frac{\Delta\nu}{\Delta\nu_D} = \sqrt{\ln\frac{m_c(\Delta\nu)}{m_c(0)}}$$



(a)
W_{FWHM} [km s^{-1}]
ΔV_D [km s^{-1}]
(b)
y=x
ξ [km s^{-1}]
ΔV_D [km s^{-1}]
(c)
Normalized frequency
ξ [km s^{-1}]
(d)
Opacity broadening
ΔV_D [km s^{-1}]

Sunspot

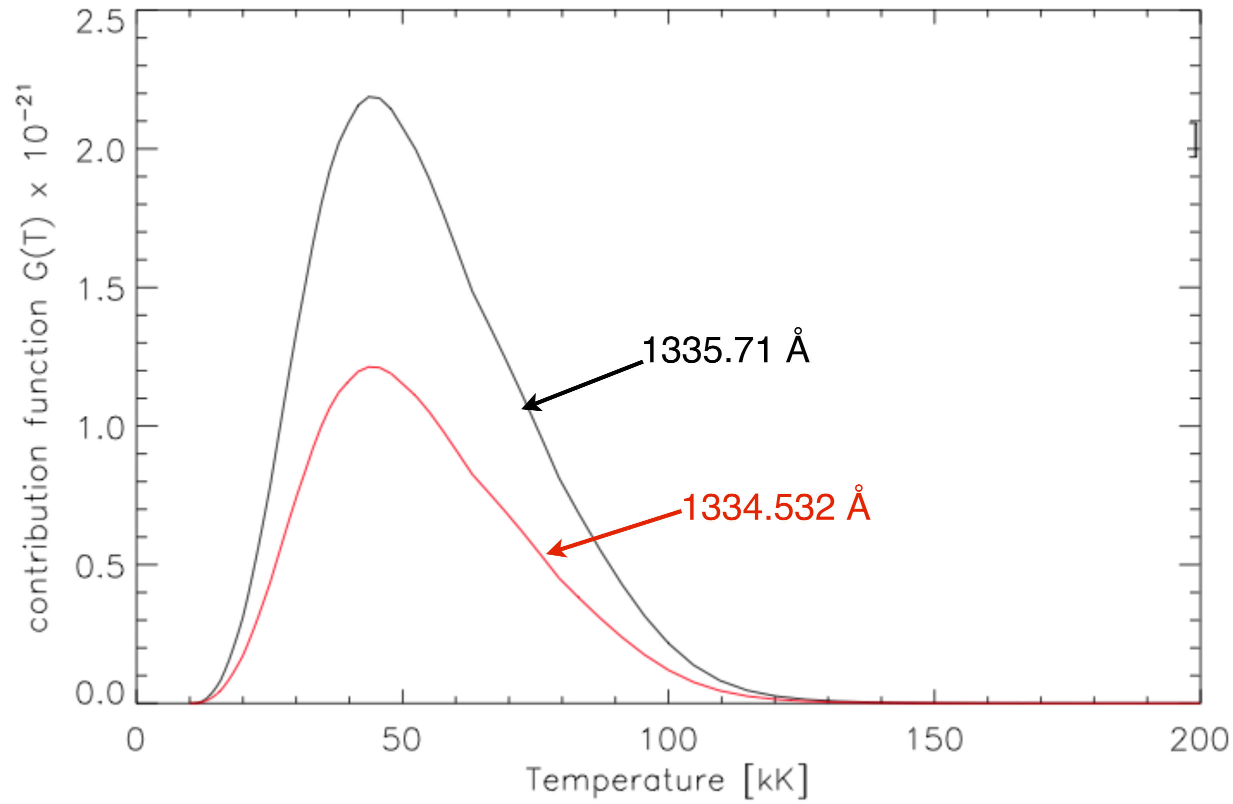


T [kK]
14 12 10 8 6 4
z [Mm]
2.2 2.0 1.8 1.6 1.4 1.2 1.0 0.8
χ_ν/τ_ν
S_ν
$\tau_\nu \exp(-\tau_\nu)$
C_I
1.8 1.4 1.1 0.7 0.4 0.0
I [10^{-11} W m^{-2} sr^{-1} Hz^{-1}]
20 10 0 -10 -20
Δν [km/s]

R C S

Optically thin approximation versus full radiative transfer

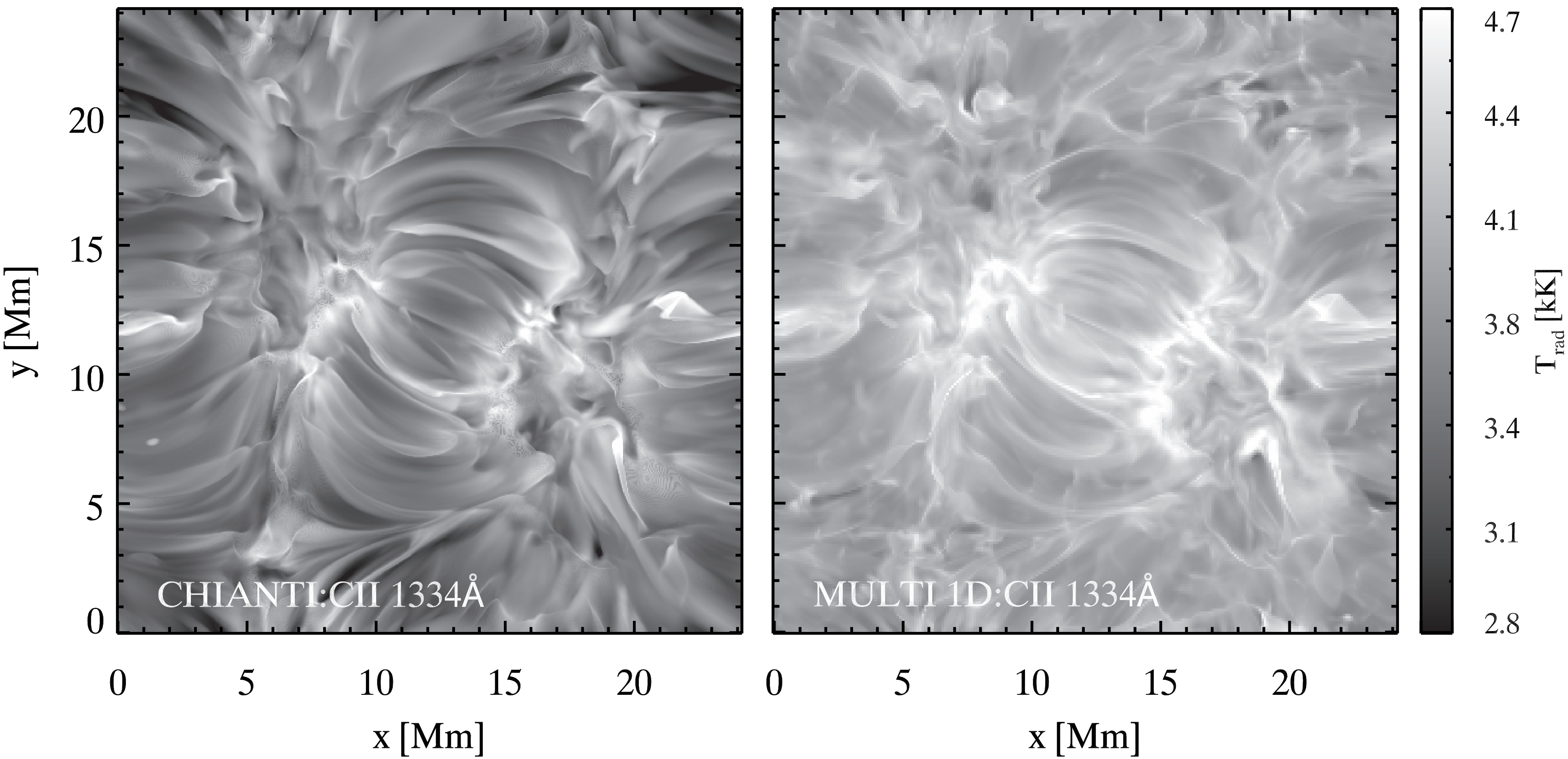
CHIANTI



optically thin ≈ 44 kK
optically thick ≈ 14 kK

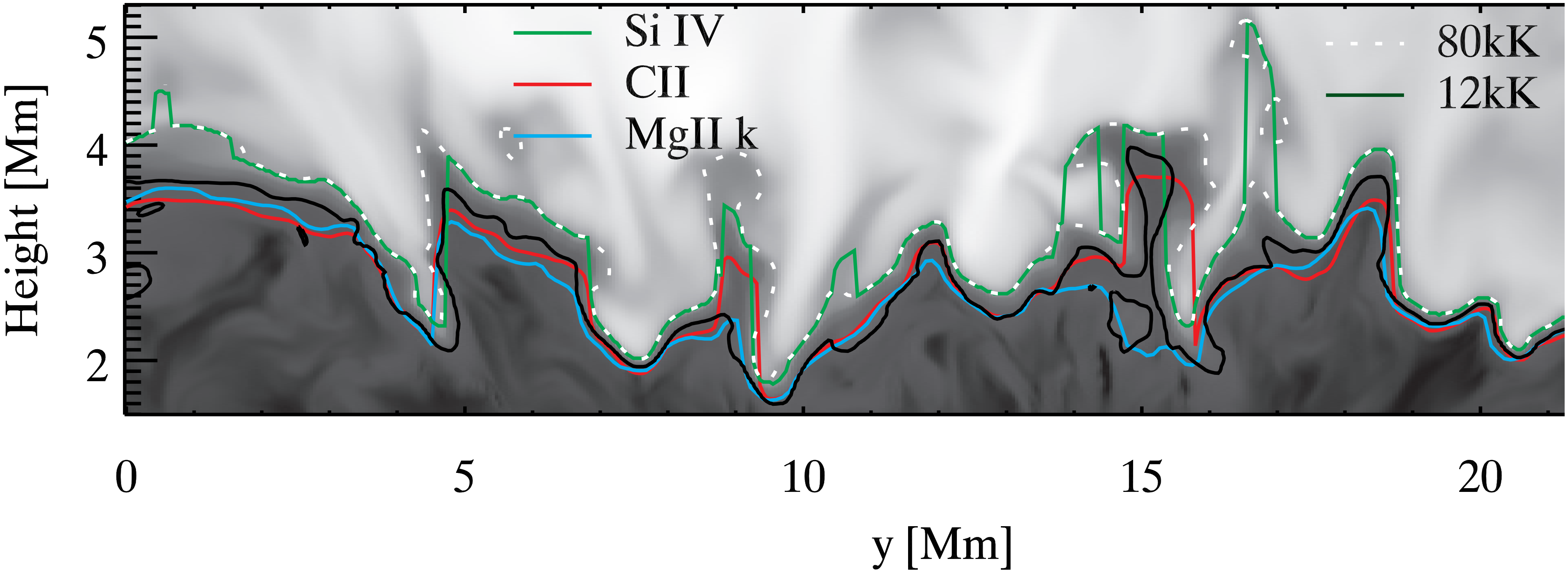
R C S

Optically thin approximation versus full radiative transfer



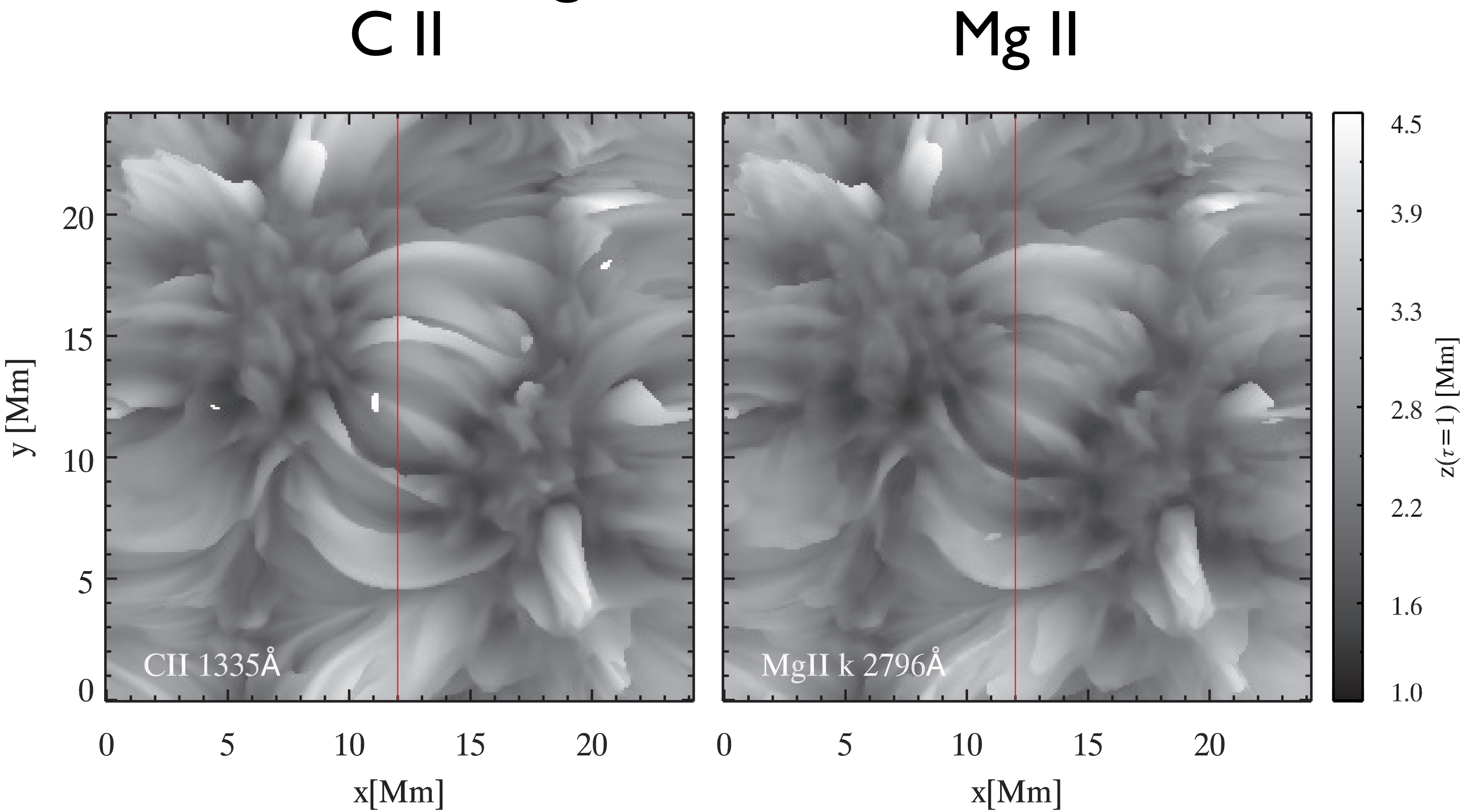
R C S

Si IV - C II - Mg II



R C S

Height of core τ=1

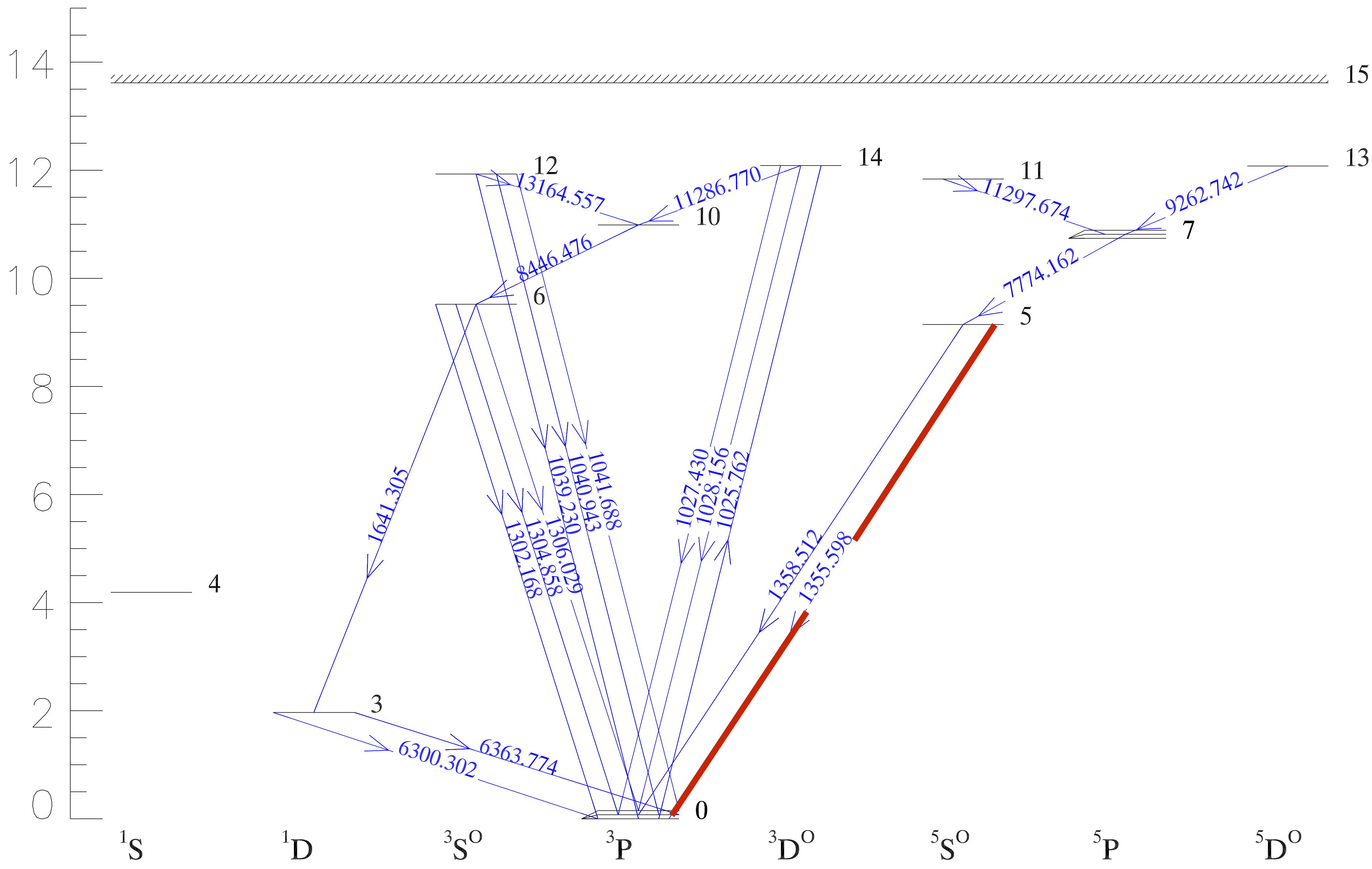


$\kappa_{\nu_0}^{l}$

$$\frac{\mathrm{Mg\,II\,k}}{\mathrm{C\,II\,1335}} = \frac{1}{4/6}\frac{N_{\mathrm{II}}}{N_{\mathrm{el}}}\frac{1}{6.8}\frac{5.2}{1}\frac{2800}{1335}\frac{1}{\Delta V_D} = 2.4(3.4)\frac{N_{\mathrm{II}}}{N_{\mathrm{el}}}$$

R C S

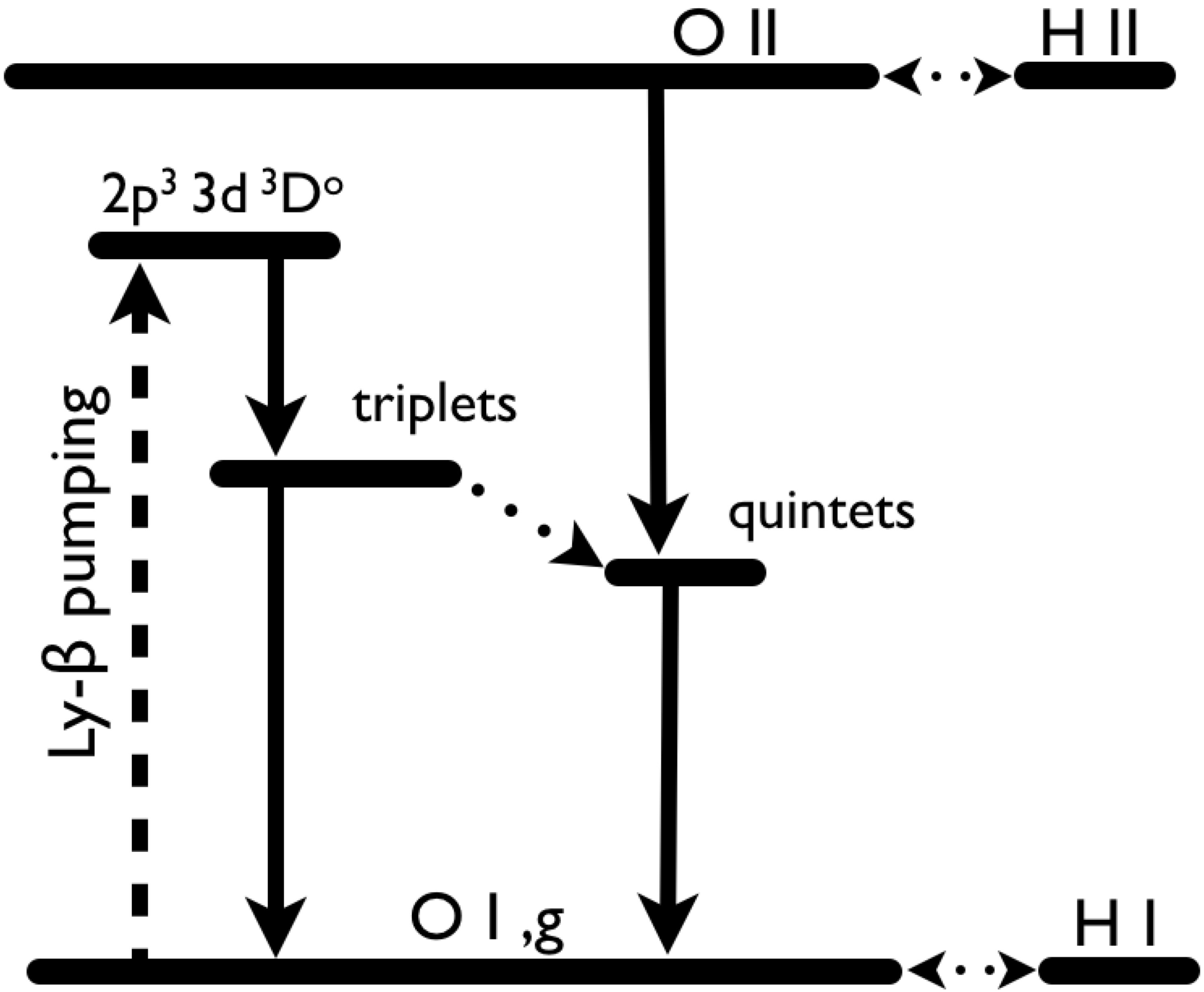
O I 1356



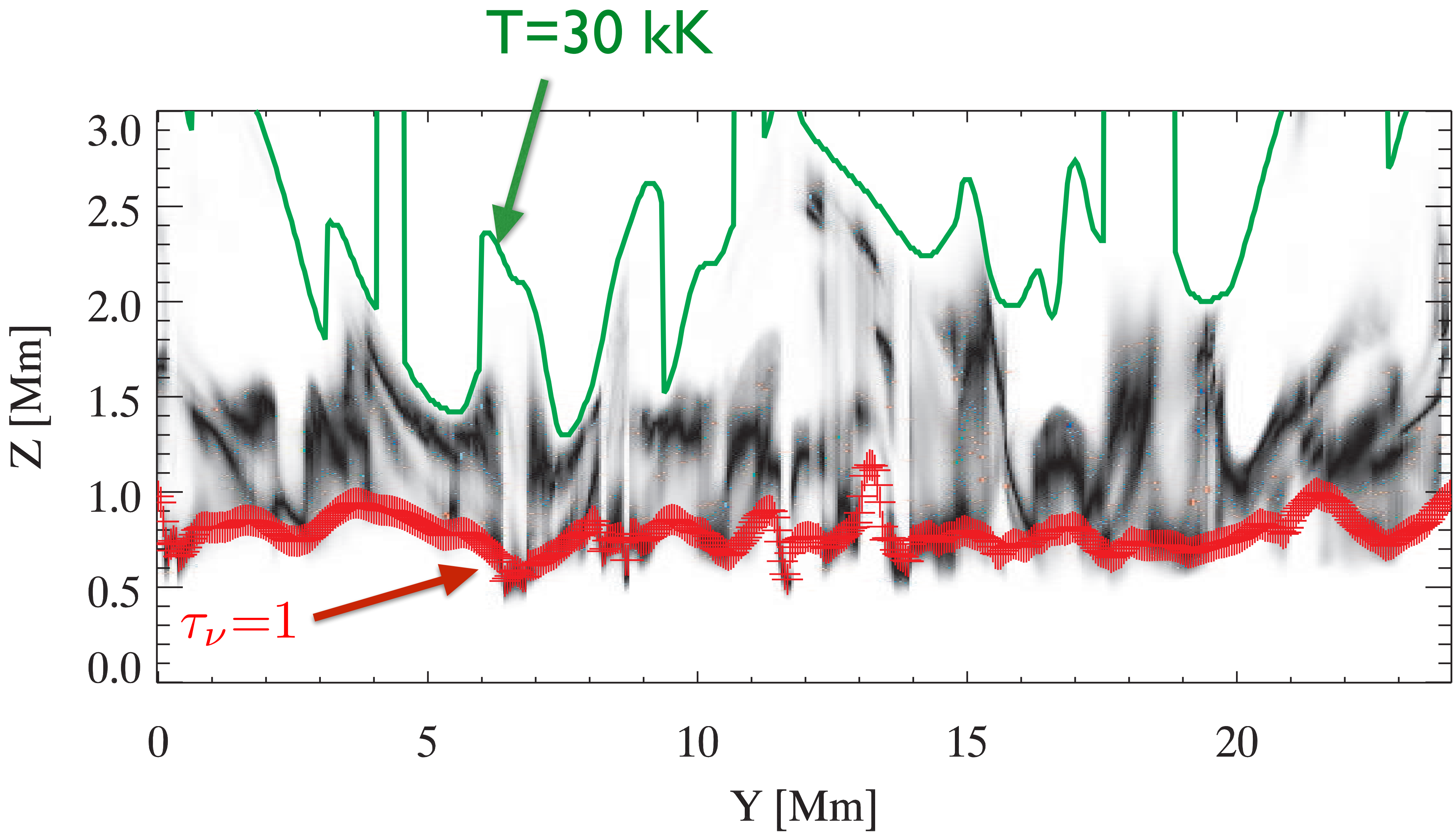
R C S

Lin & Carlsson 2015

Main rates

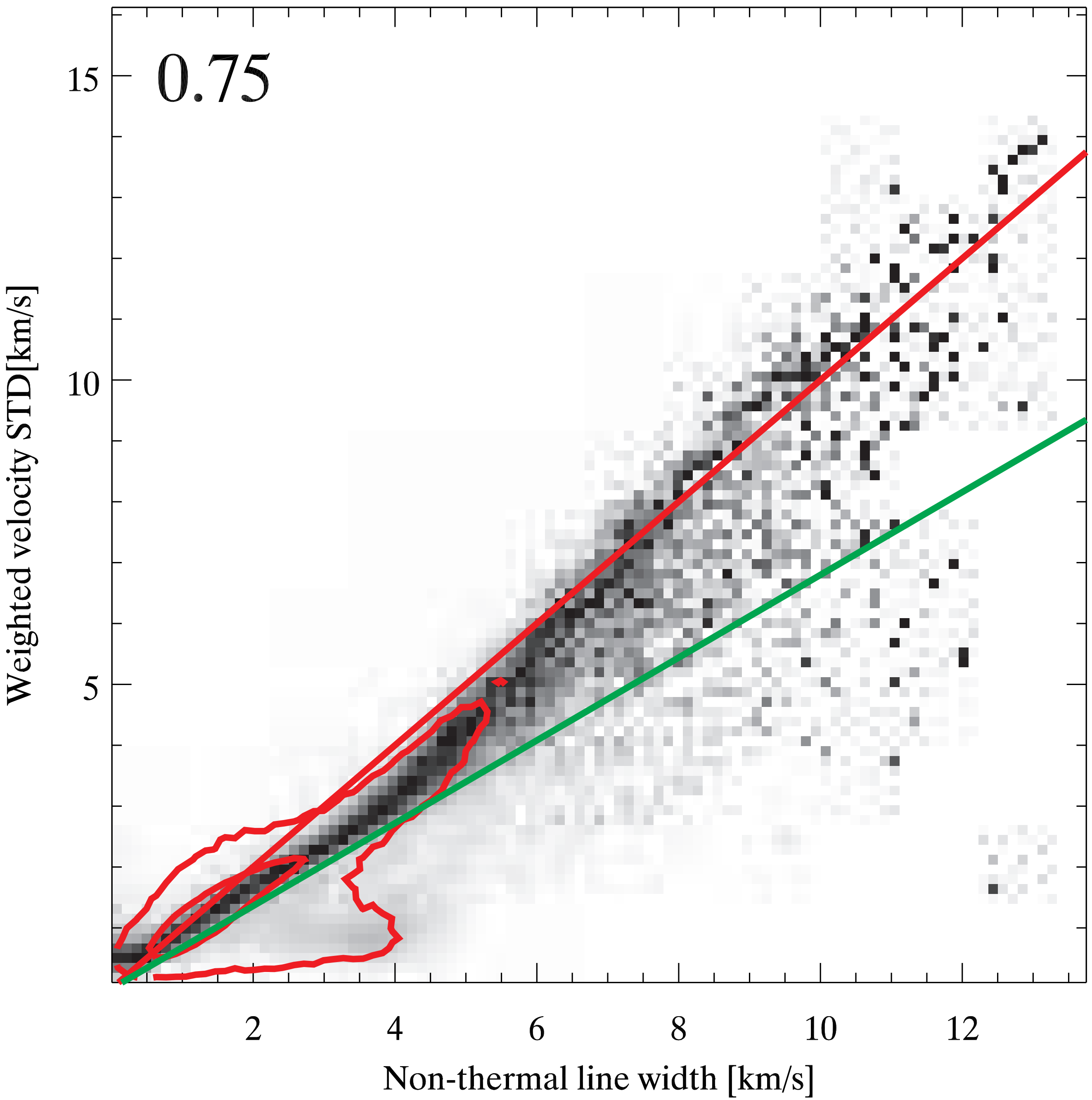


Optically thin formation



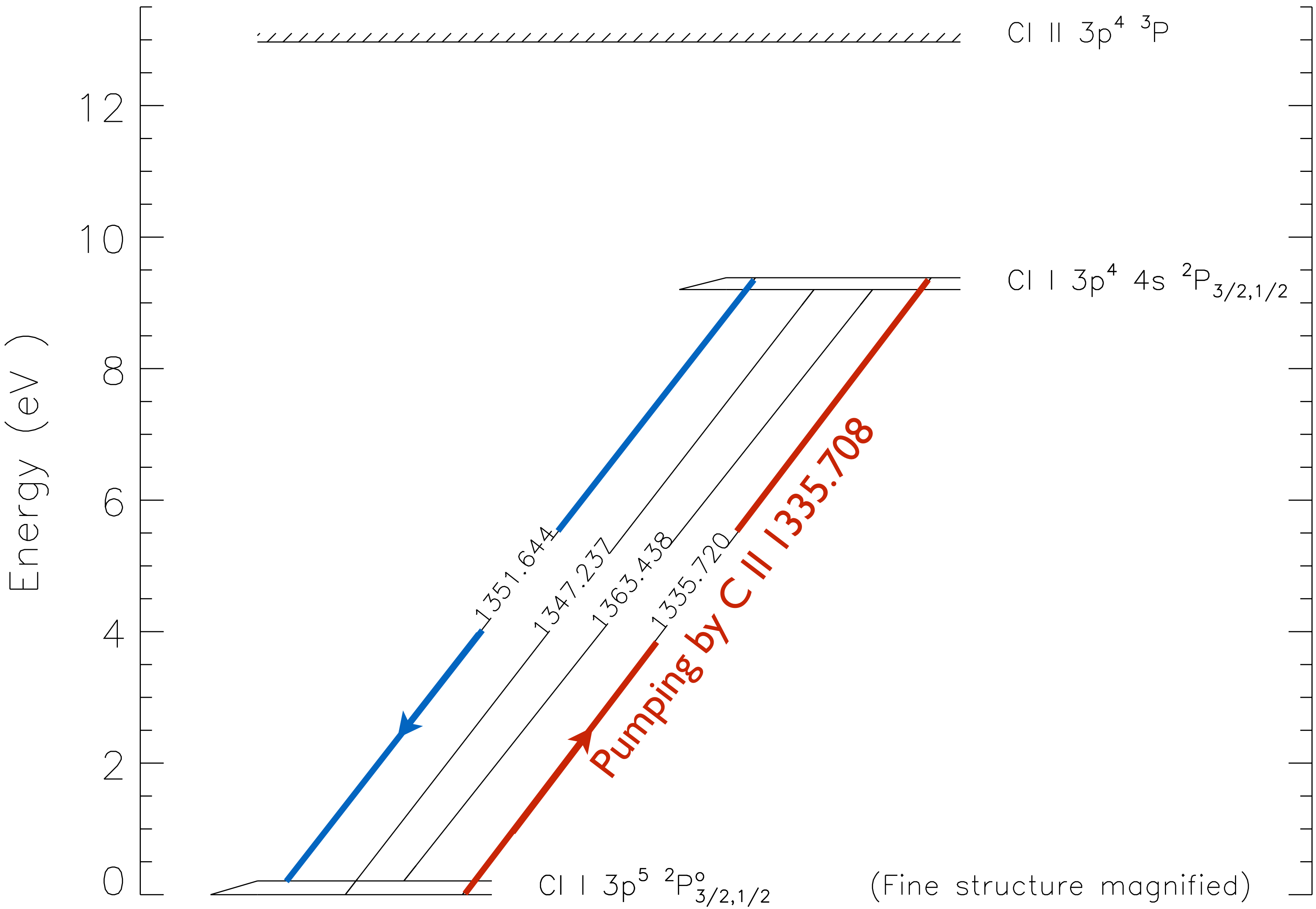
R C S

Line width measure of "turbulence"



R C S

Cl I 1351.7



RCS