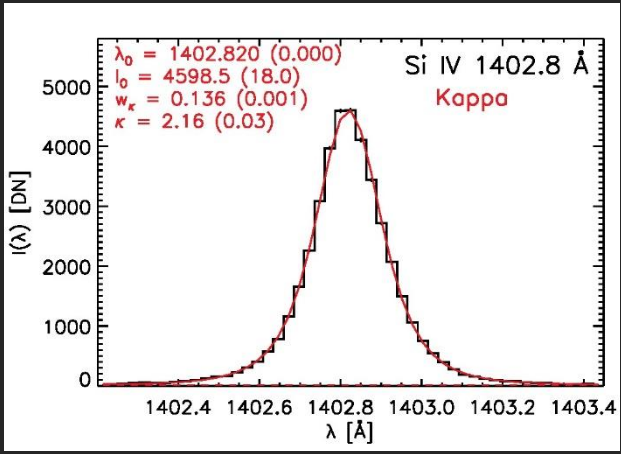

Non-Maxwellian analysis of *IRIS* TR lines

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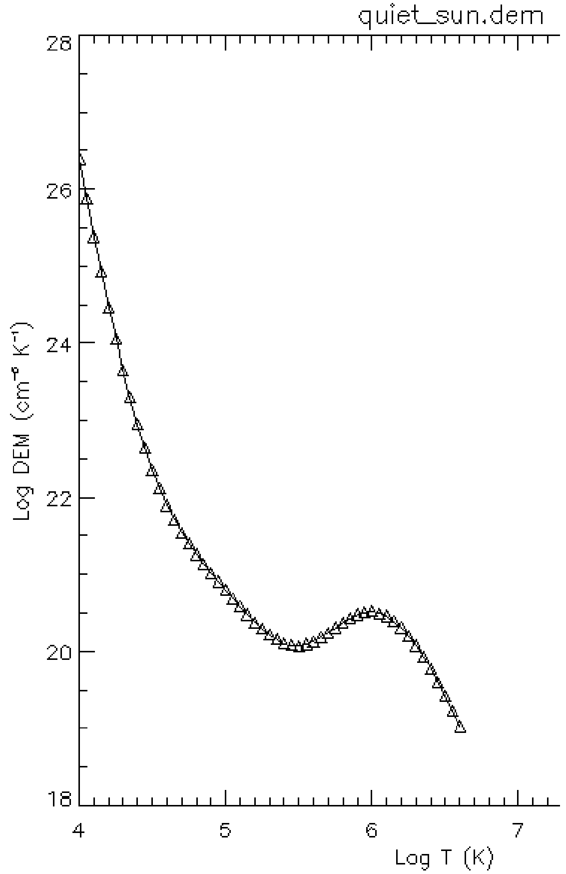
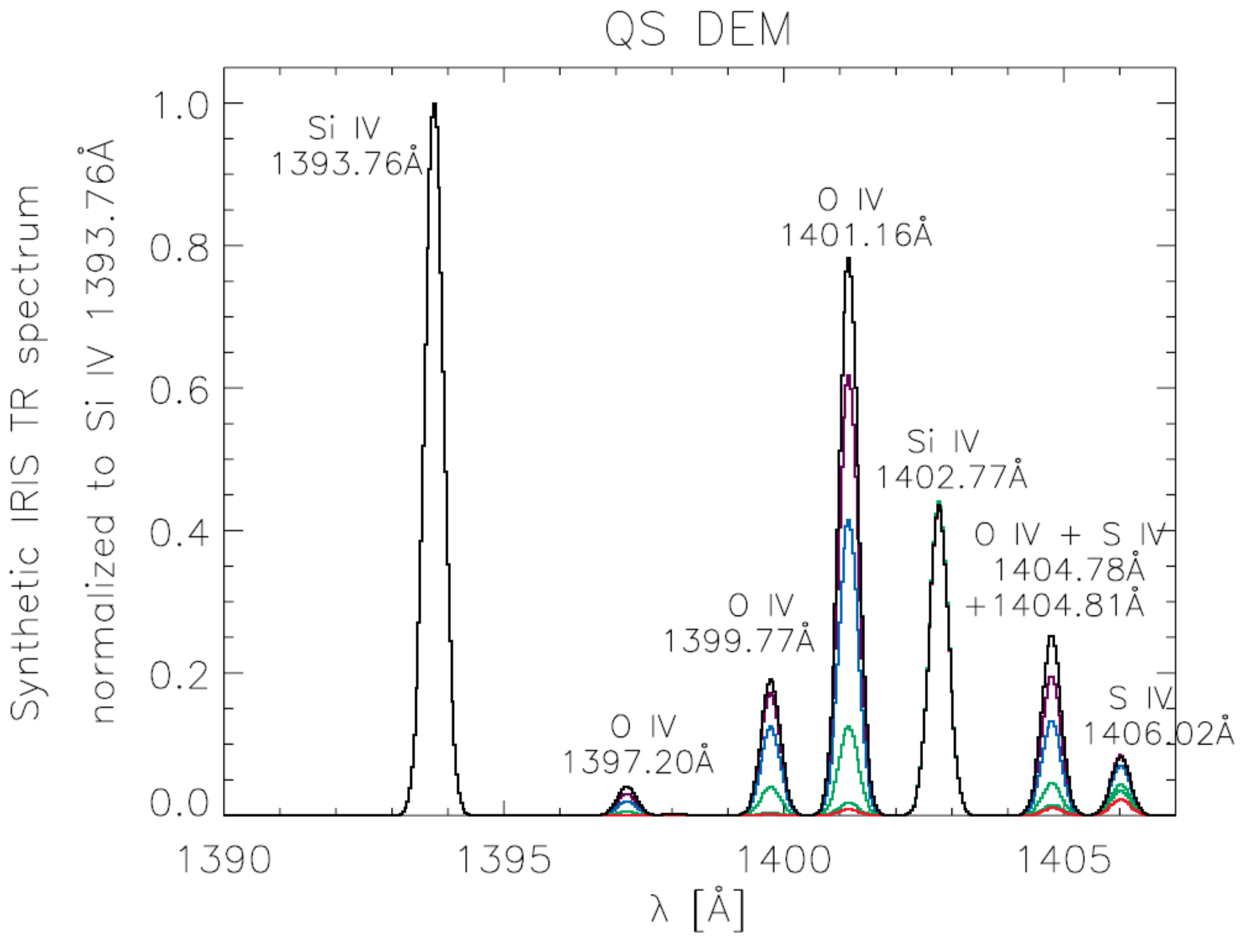
Elena Dzifčáková, Giulio Del Zanna, and Paola Testa

Astronomical Institute of the Czech Academy of Sciences
UNIVERSITY OF CAMBRIDGE
CfA

Coronal Loops Workshop 8, Palermo
2017 June 30

Synthetic *IRIS* TR spectrum

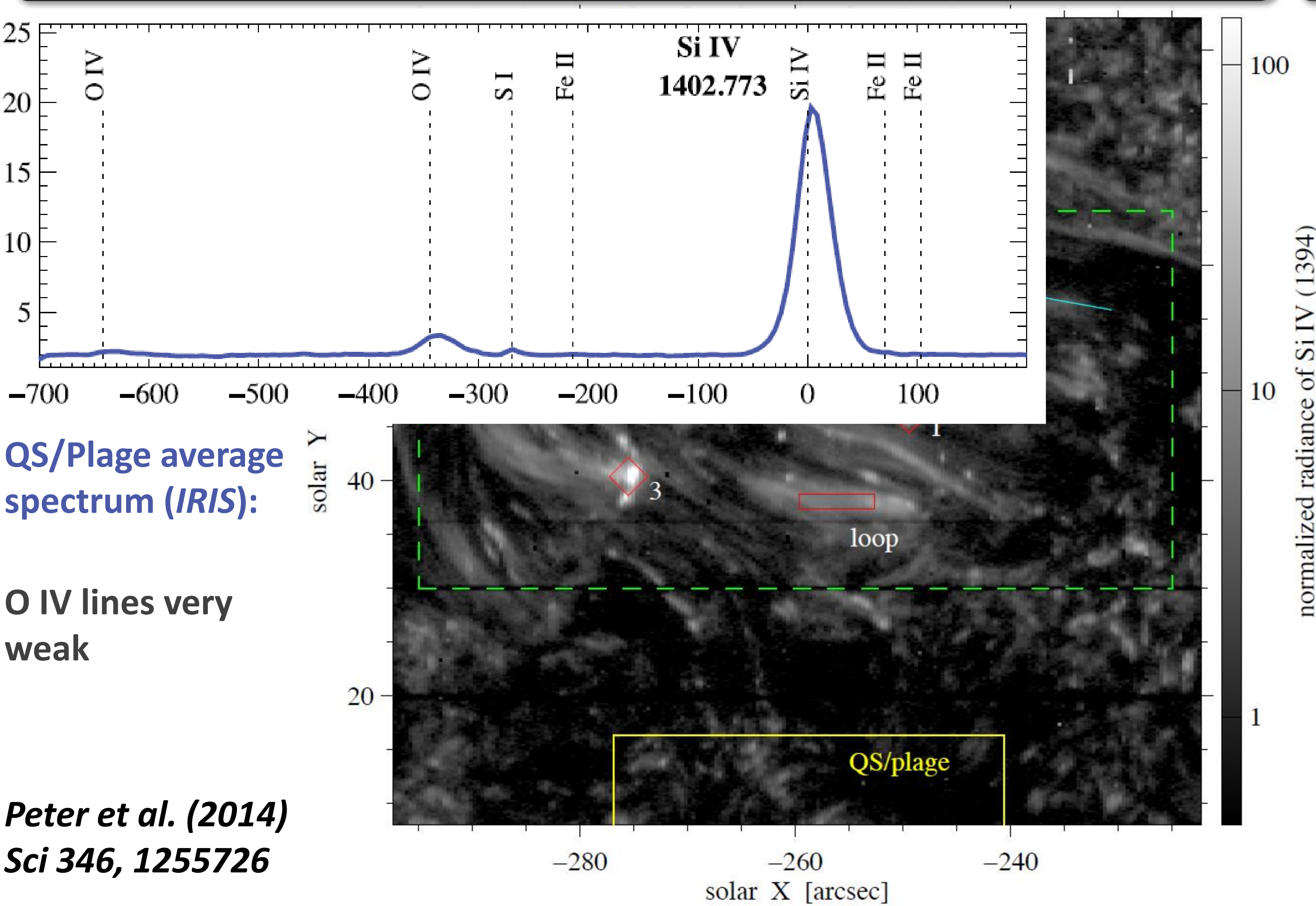




Dudík et al. (2014), ApJ 780, L12

- **Predicted *IRIS* FUV2 spectrum for a typical quiet Sun DEM:**
  O IV 1401.2 Å line stronger than the Si IV 1402.8 Å
- **For AR, with steeper DEM slope, O IV > Si IV also**

TR Lines: Challenges

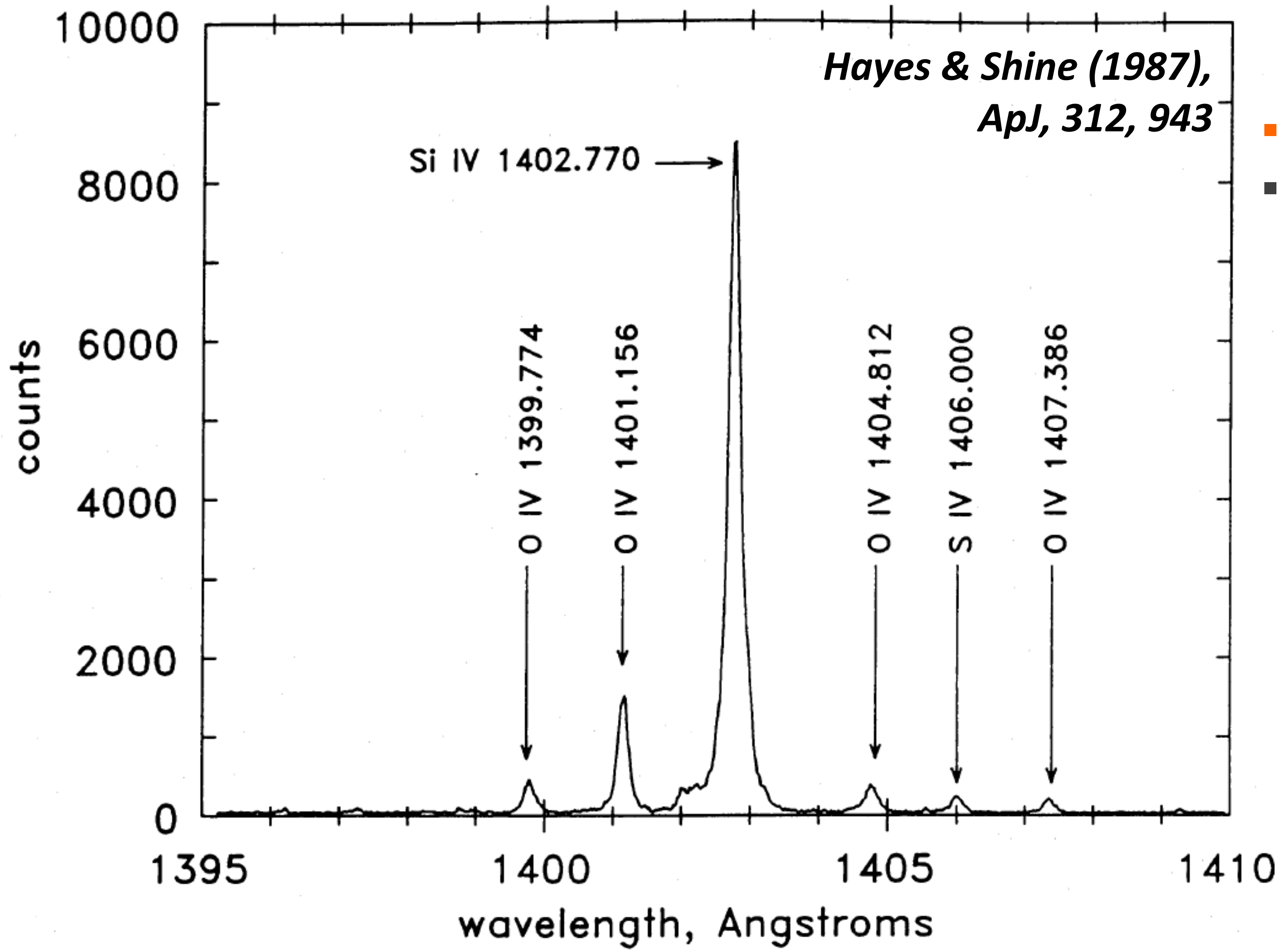


QS/Plage average spectrum (*IRIS*):

O IV lines very weak

Peter et al. (2014) Sci 346, 1255726

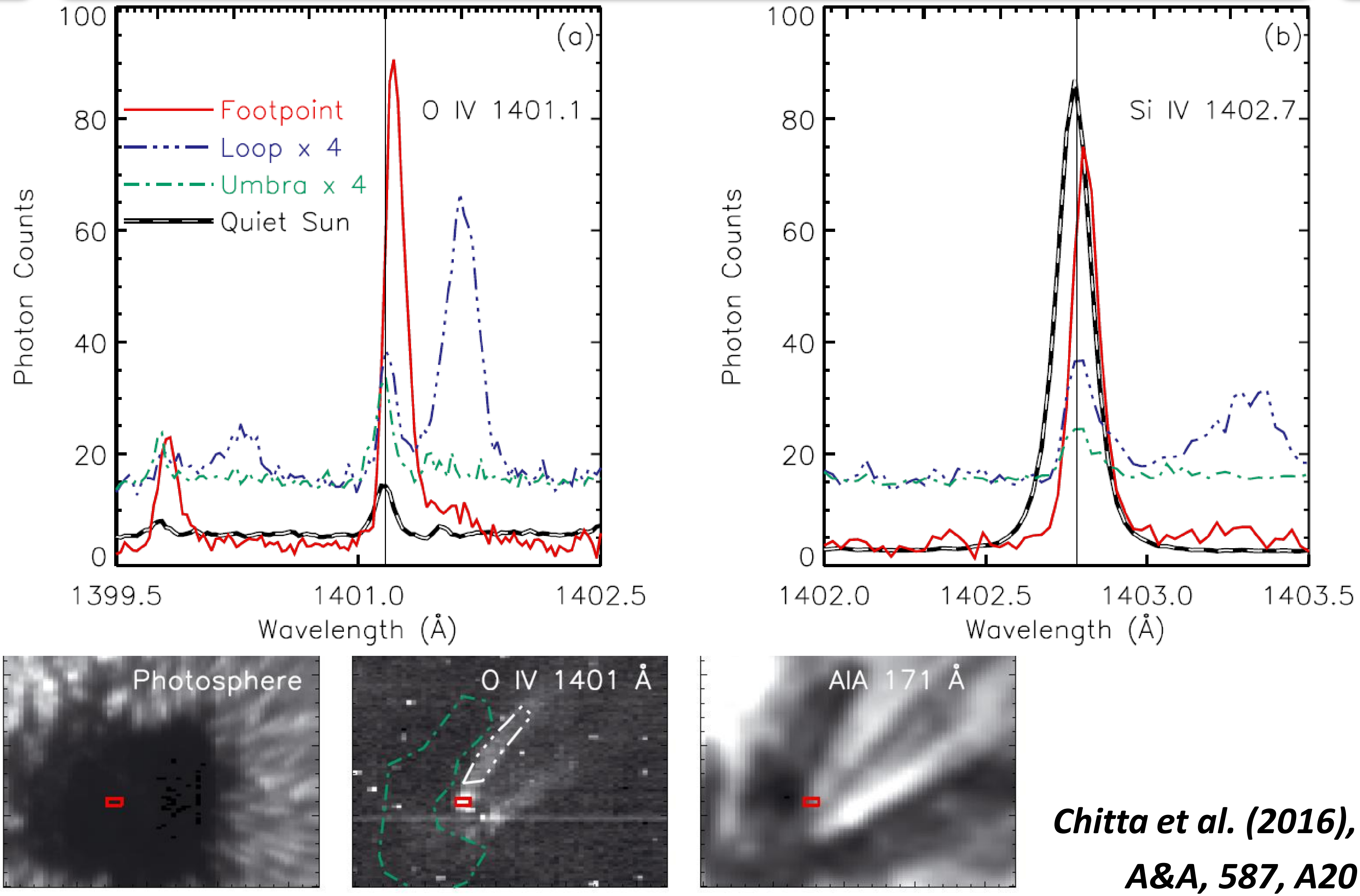
TR Lines: Challenges



- **Typical TR spectrum**
- **Seen with many instruments (*SMM*/UVSP, *SOHO*/SUMER, *IRIS*)**

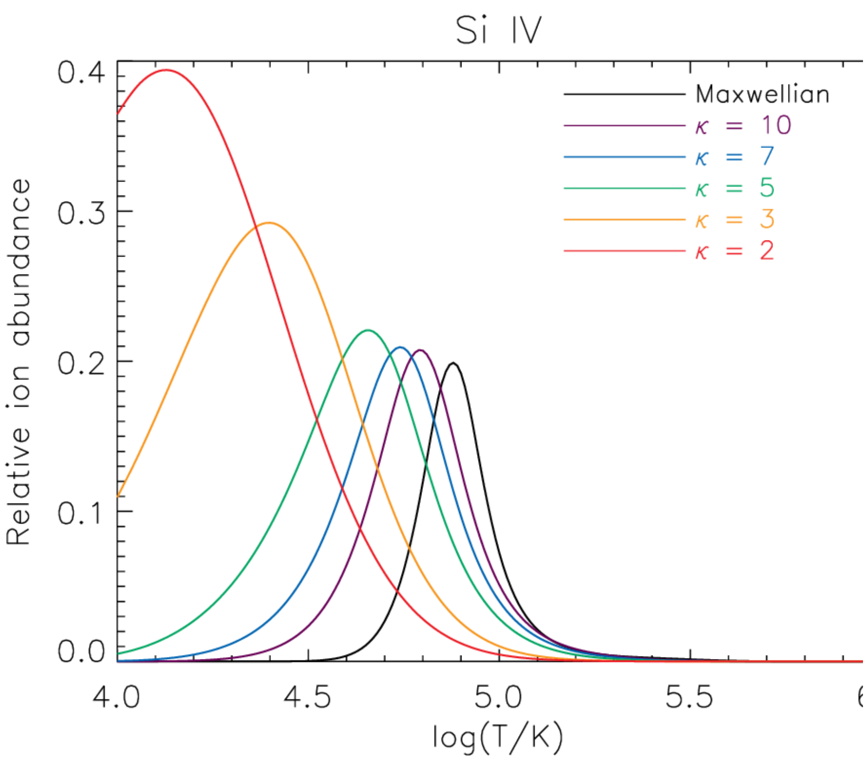
Doyle & Raymond (1984)
Judge et al. (1995)
Curdt et al. (2001)
Doschek & Mariska (2001)
Del Zanna et al. (2002)
Peter et al. (2014)
Polito et al. (2016)
Doschek et al. (2016)

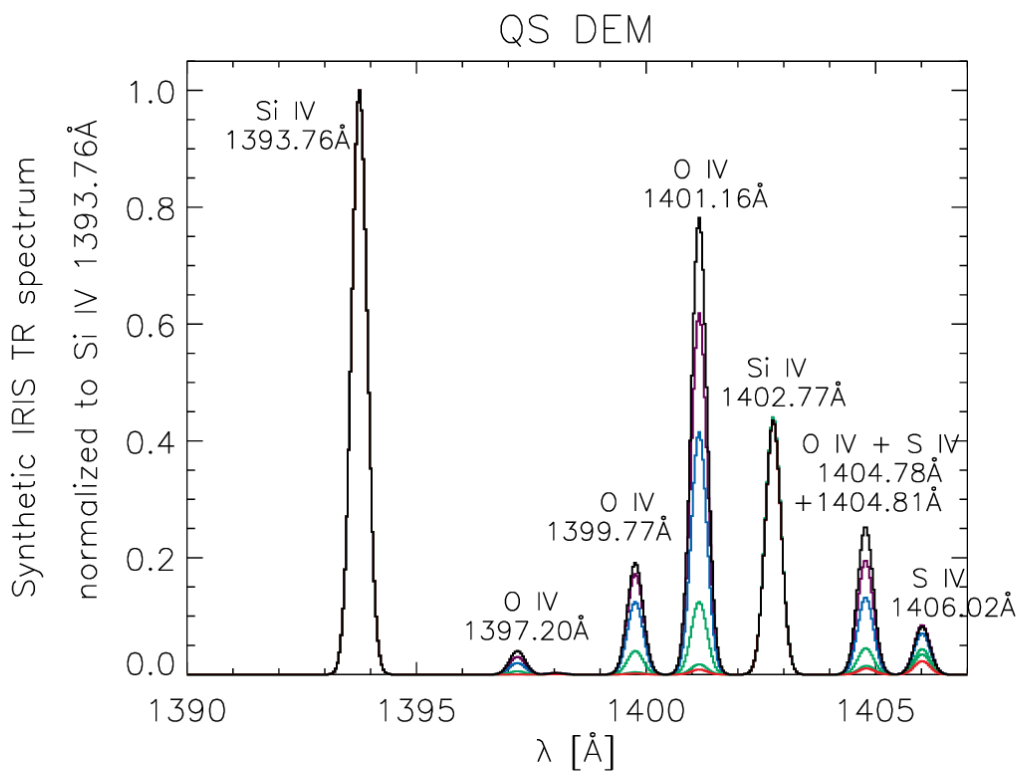
O IV > Si IV ? : Single Solar Case



Chitta et al. (2016), A&A, 587, A20

The κ-distributions and TR lines

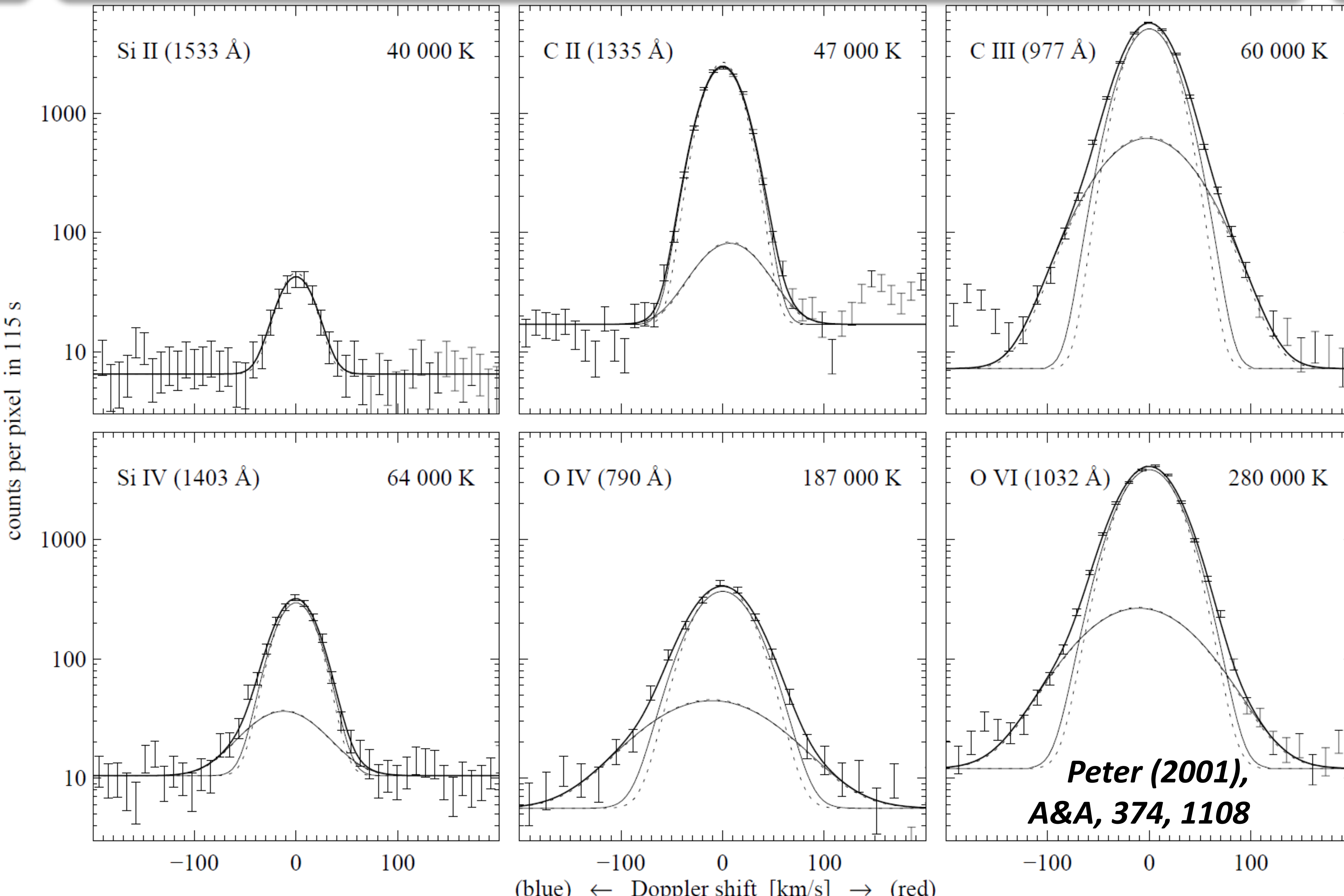




Dzifčáková & Dudík (2013), ApJS, 206, 6
Dudík et al. (2014), ApJL, 780, L12
Dzifčáková et al. (2017), A&A, in press

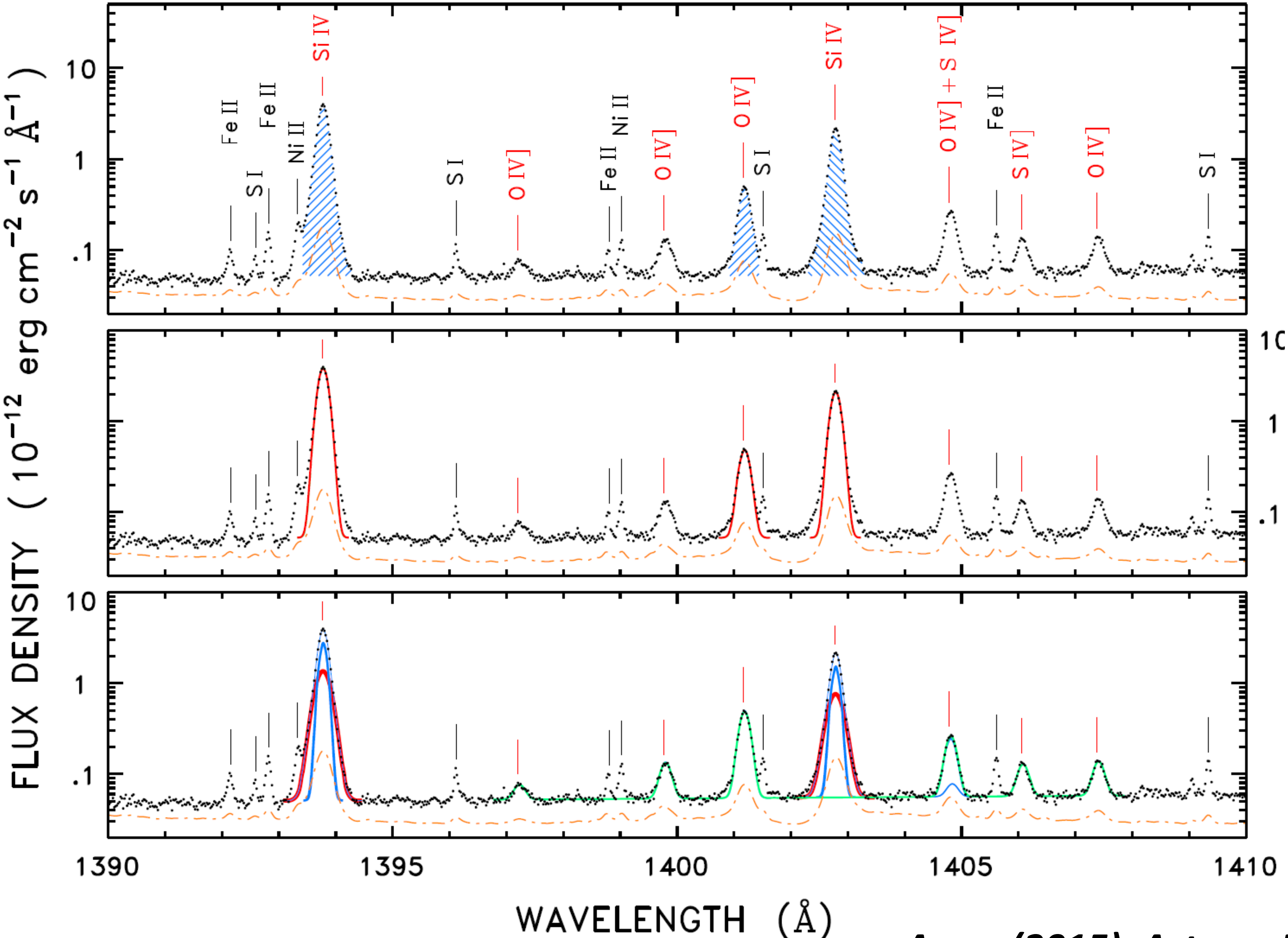
- **For TR lines, ion abundance peaks are shifted to lower *T***
- **High-energy tail: ionization rate enhanced by orders of magnitude**
- **Recombination enhanced by a factor of < 2**

Non-Gaussian Line Profiles



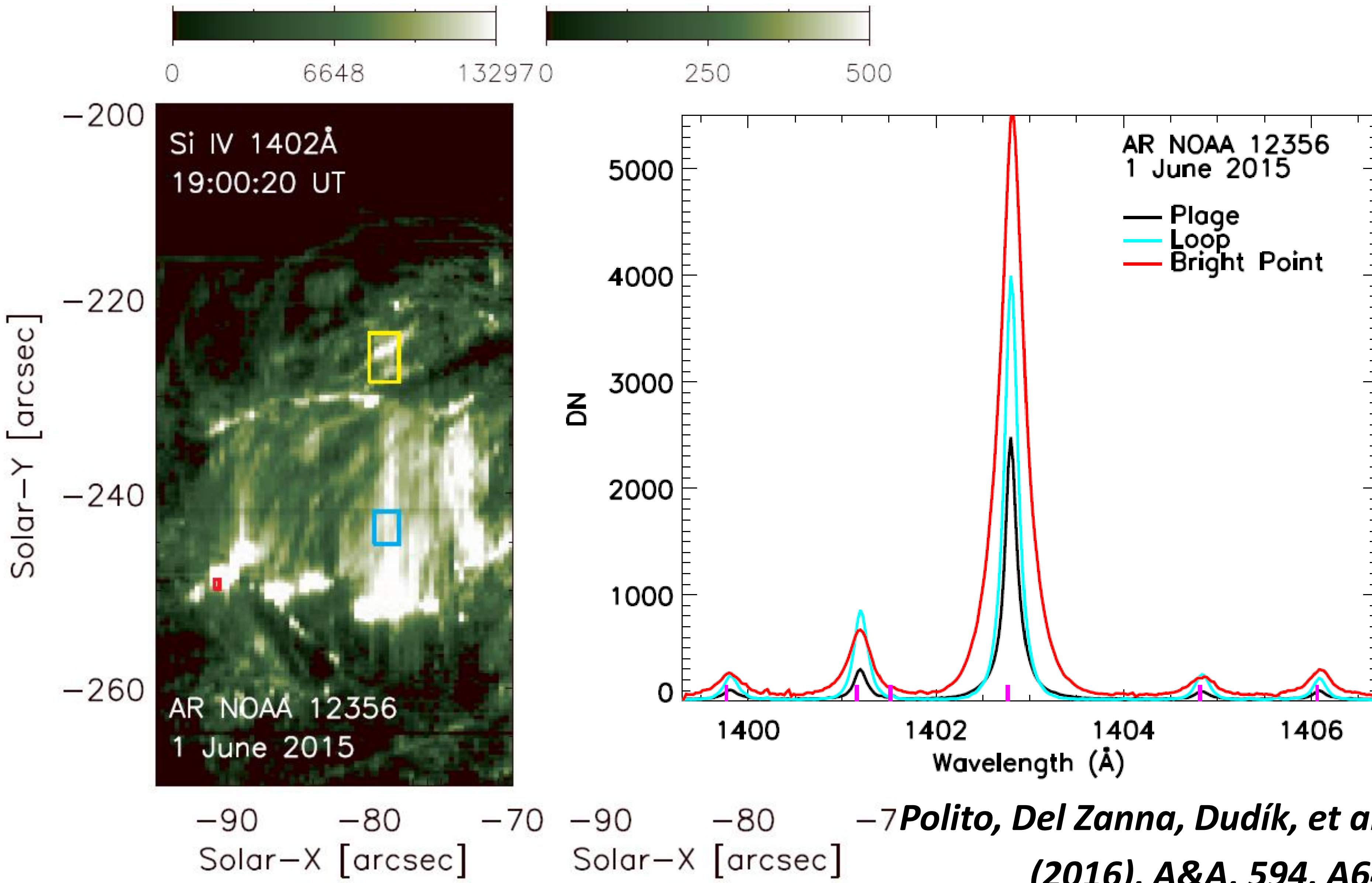
Peter (2001), A&A, 374, 1108

α Centauri A+B



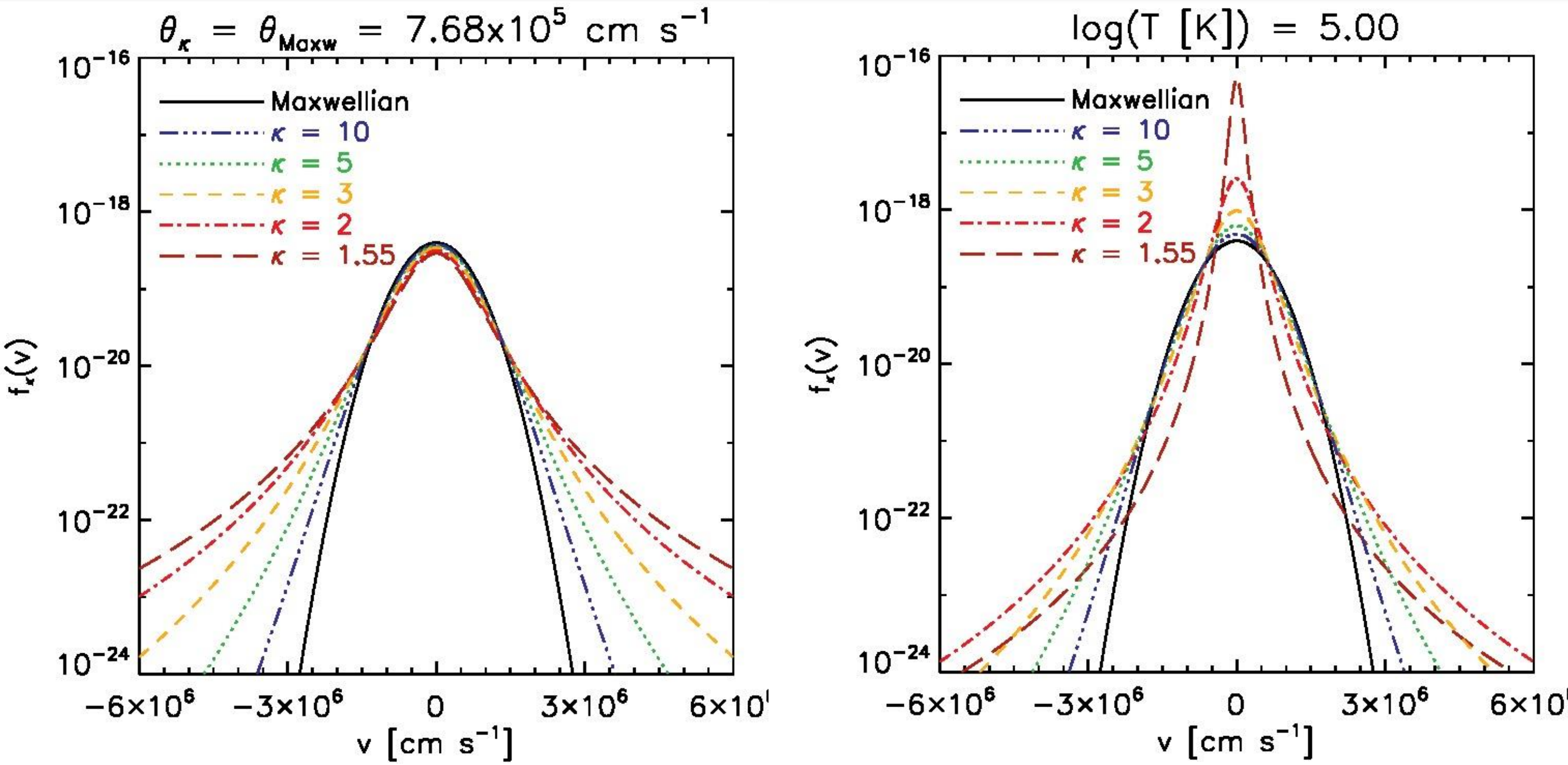
Ayres (2015), Astron. J., 149, 58

Non-Gaussian Line Profiles: *IRIS*



Polito, Del Zanna, Dudík, et al. (2016), A&A, 594, A64

The κ-distributions



$$f_\kappa(v)\mathrm{d}v = \frac{C_\kappa}{(\pi(\kappa-3/2)\theta^2)^{3/2}} \frac{\mathrm{d}v}{\left(1+\frac{v^2}{(\kappa-3/2)\theta^2}\right)^{\kappa+1}}$$

$$T = \frac{m}{k_\mathrm{B}} \int v^2 f_\kappa(v) \mathrm{d}^3\vec{v} = \frac{m}{2k_\mathrm{B}} \frac{2\kappa}{2\kappa-3} \theta_\kappa^2$$

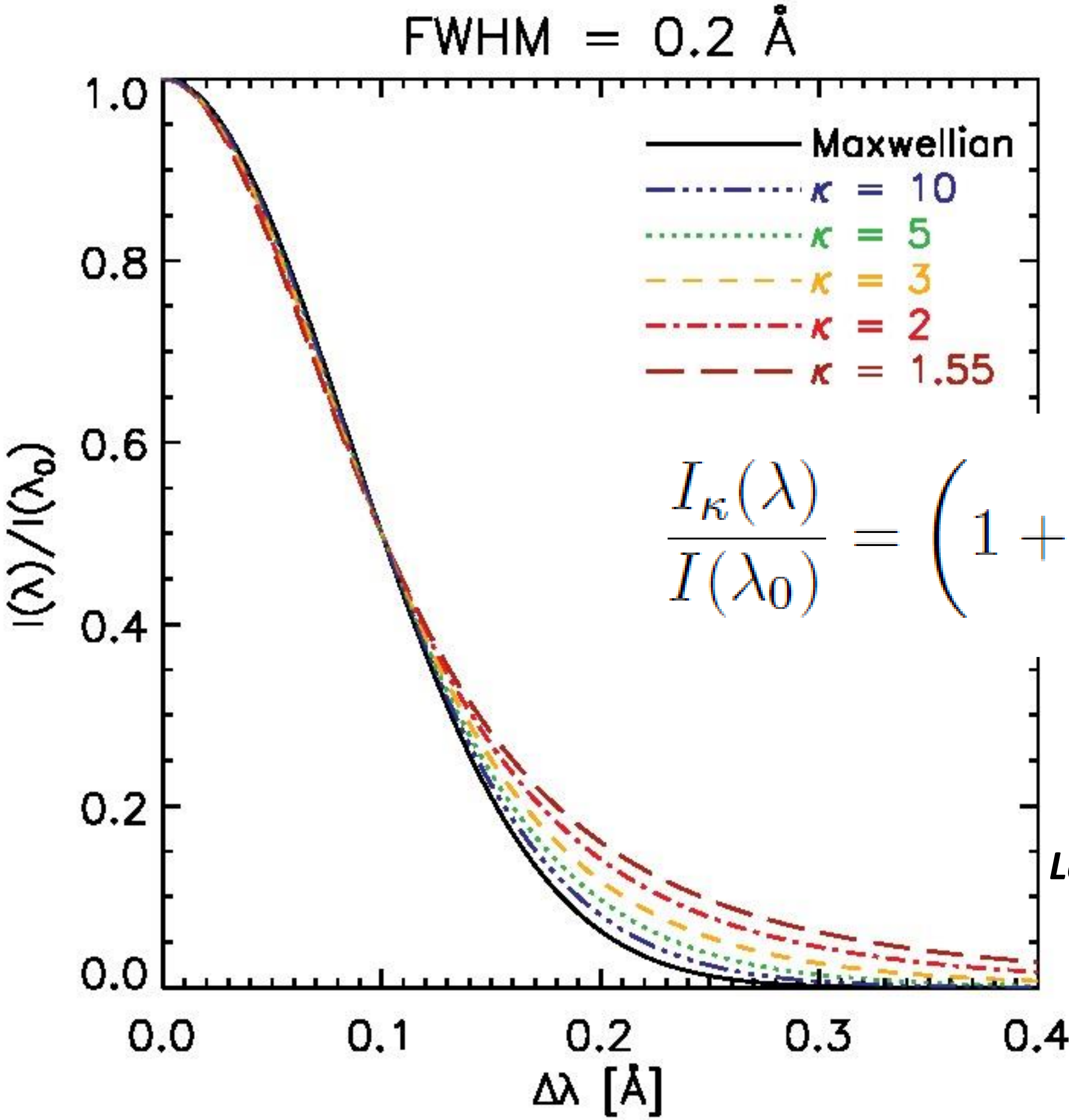
Olbert (1968)

Vasilyunas (1968)

Livadiotis (2015)

Lazar et al. (2016)

κ-Distributions and Line Profiles



$$\Delta\lambda/\lambda_0 = v_{\|}/c$$

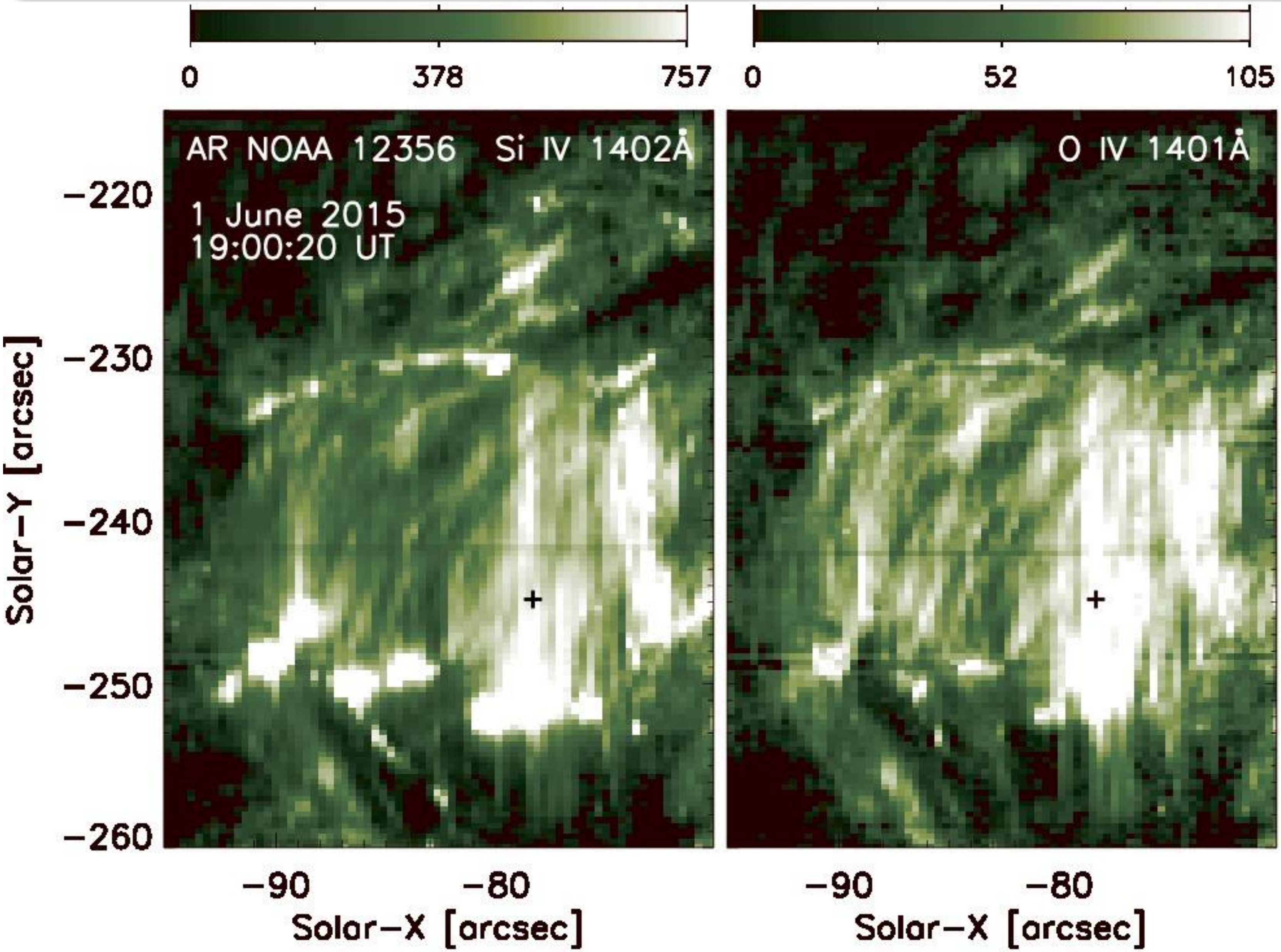
↓

$$\frac{I_\kappa(\lambda)}{I(\lambda_0)} = \left(1 + \frac{mc^2(\lambda-\lambda_0)^2}{2k_\mathrm{B}T(\kappa-3/2)\lambda_0^2}\right)^{-\kappa}$$

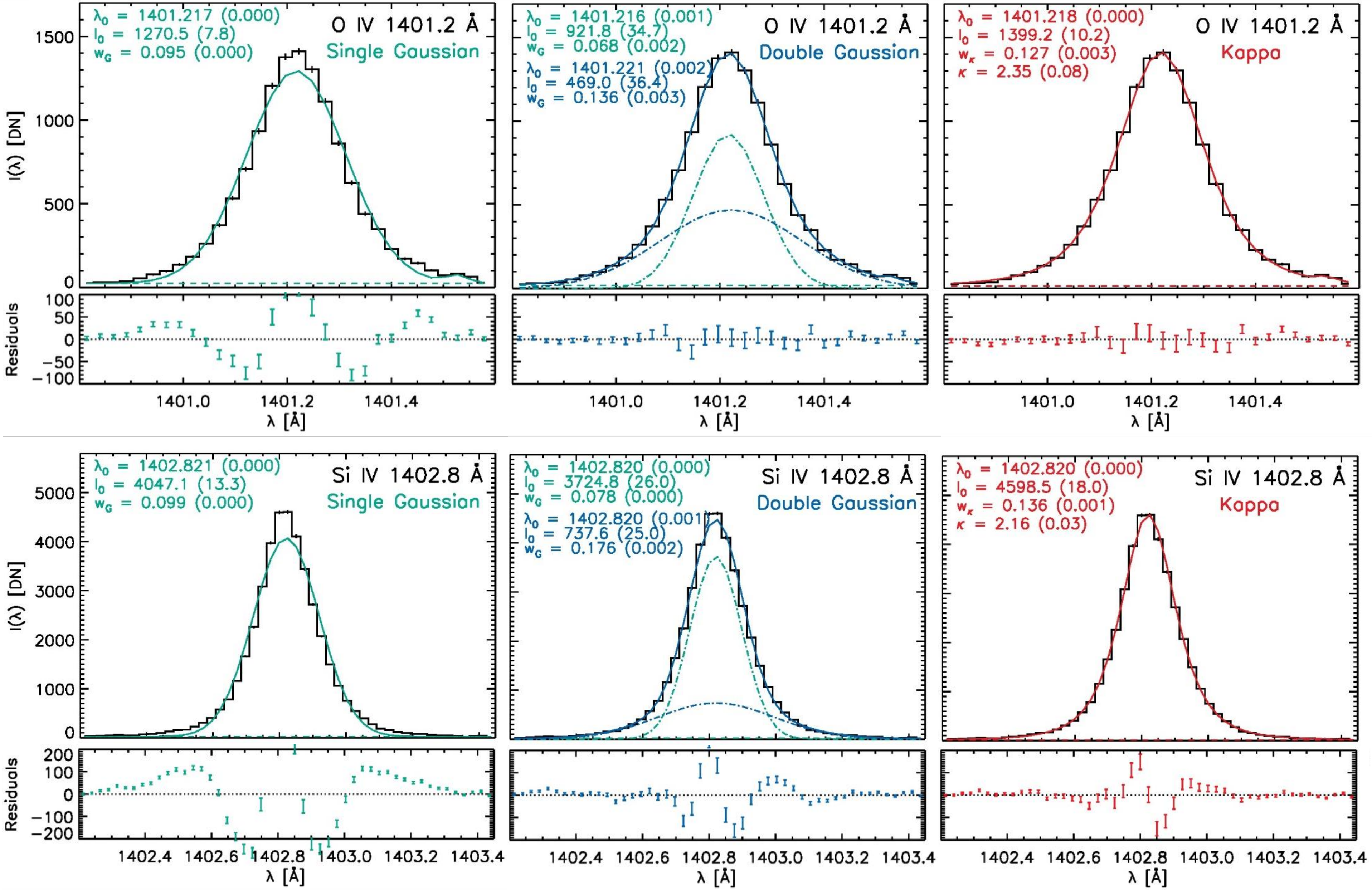
Dzifčáková (1998), PhD Thesis
Lee, Williams & Lapenta (2013), unpubl.
Jeffrey et al. (2016), A&A, 590, A99
Jeffrey et al. (2017), ApJ, 836, 35

Dudík et al. (2017), ApJ, 842, 19

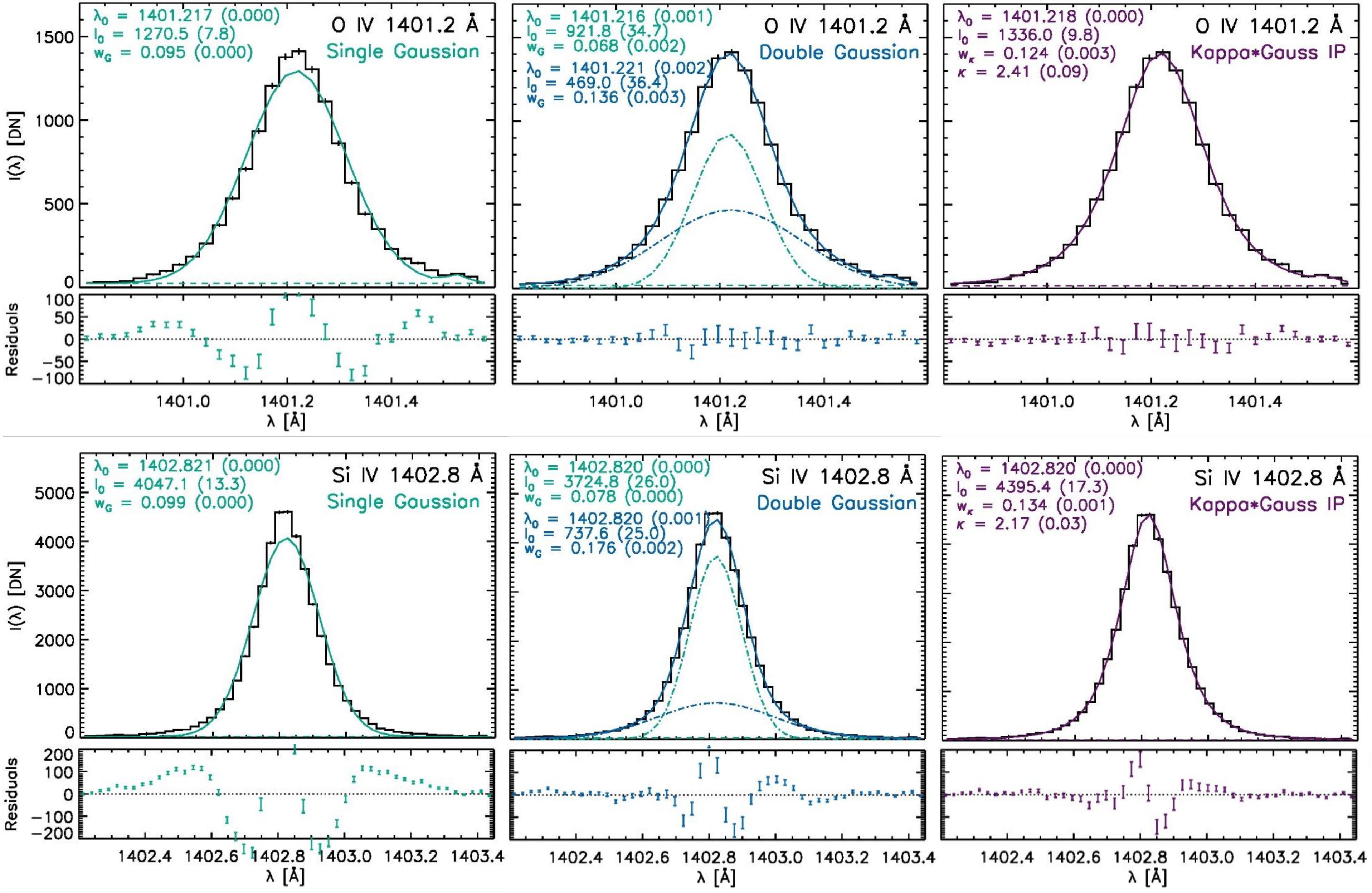
IRIS Example Spectrum



IRIS Example Spectrum: Fitting



IRIS Example Spectrum: Fitting



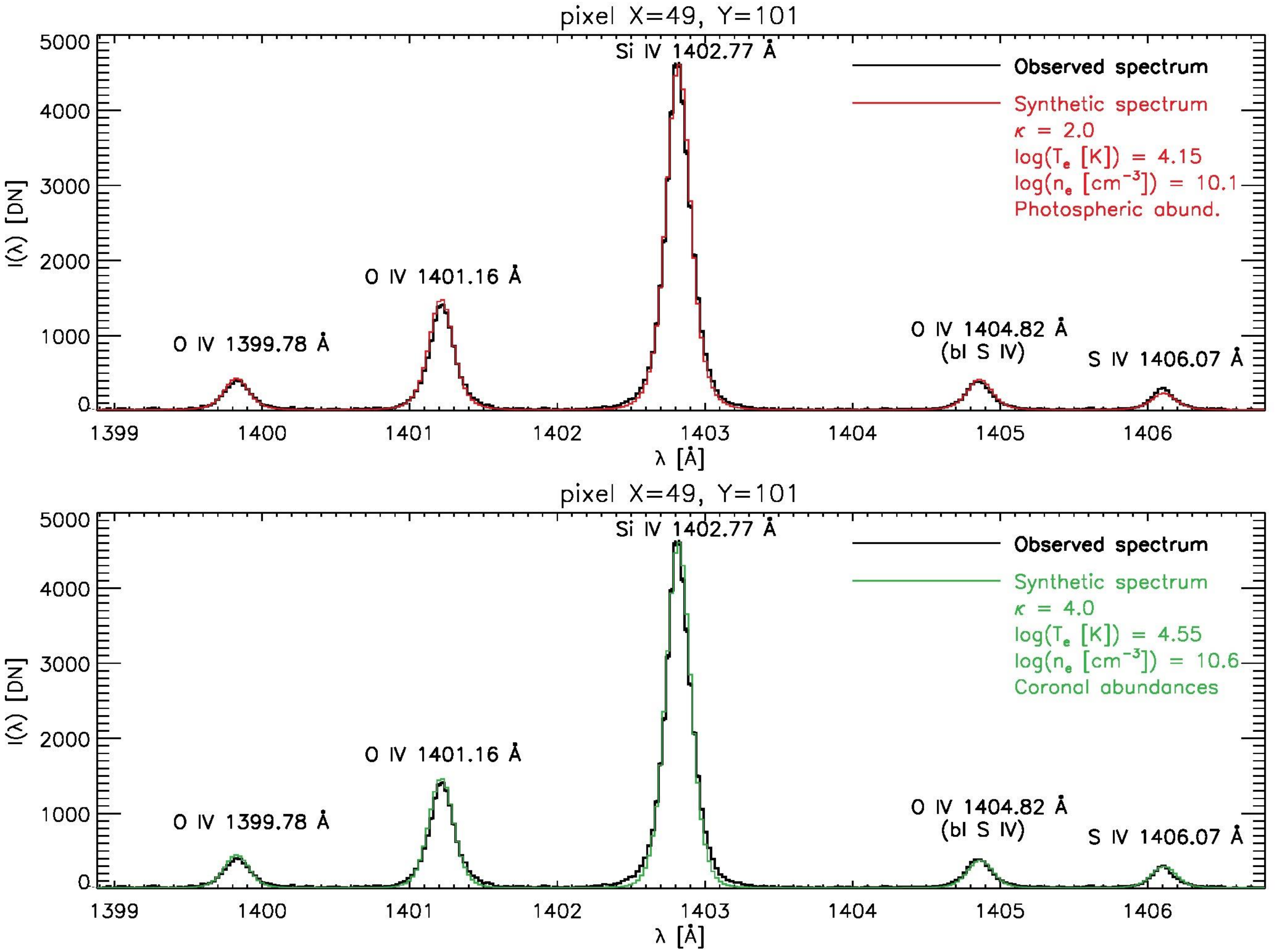
IRIS Example Spectrum: Fitting

Line	λ_0 [Å]	I_0 [DN]	w_κ [Å]	κ	FWHM_κ [Å]	T_i [MK]
O IV 1399.78 Å	1399.831 ± 0.001	385 ± 6	0.143 ± 0.010	2.16 ± 0.17	0.20 ± 0.08	1.81 ± 0.26
O IV 1401.16 Å	1401.218 ± 0.000	1399 ± 10	0.127 ± 0.003	2.35 ± 0.08	0.20 ± 0.05	1.43 ± 0.06
Si IV 1402.77 Å	1402.820 ± 0.000	4598 ± 18	0.136 ± 0.001	2.16 ± 0.03	0.19 ± 0.02	2.86 ± 0.06
O IV 1404.82 Å (bl S IV)	1404.855 ± 0.001	383 ± 6	0.163 ± 0.018	1.90 ± 0.13	0.19 ± 0.13	2.35 ± 0.52
S IV 1406.06 Å	1406.103 ± 0.001	282 ± 5	0.144 ± 0.021	1.91 ± 0.18	0.17 ± 0.17	3.64 ± 1.08

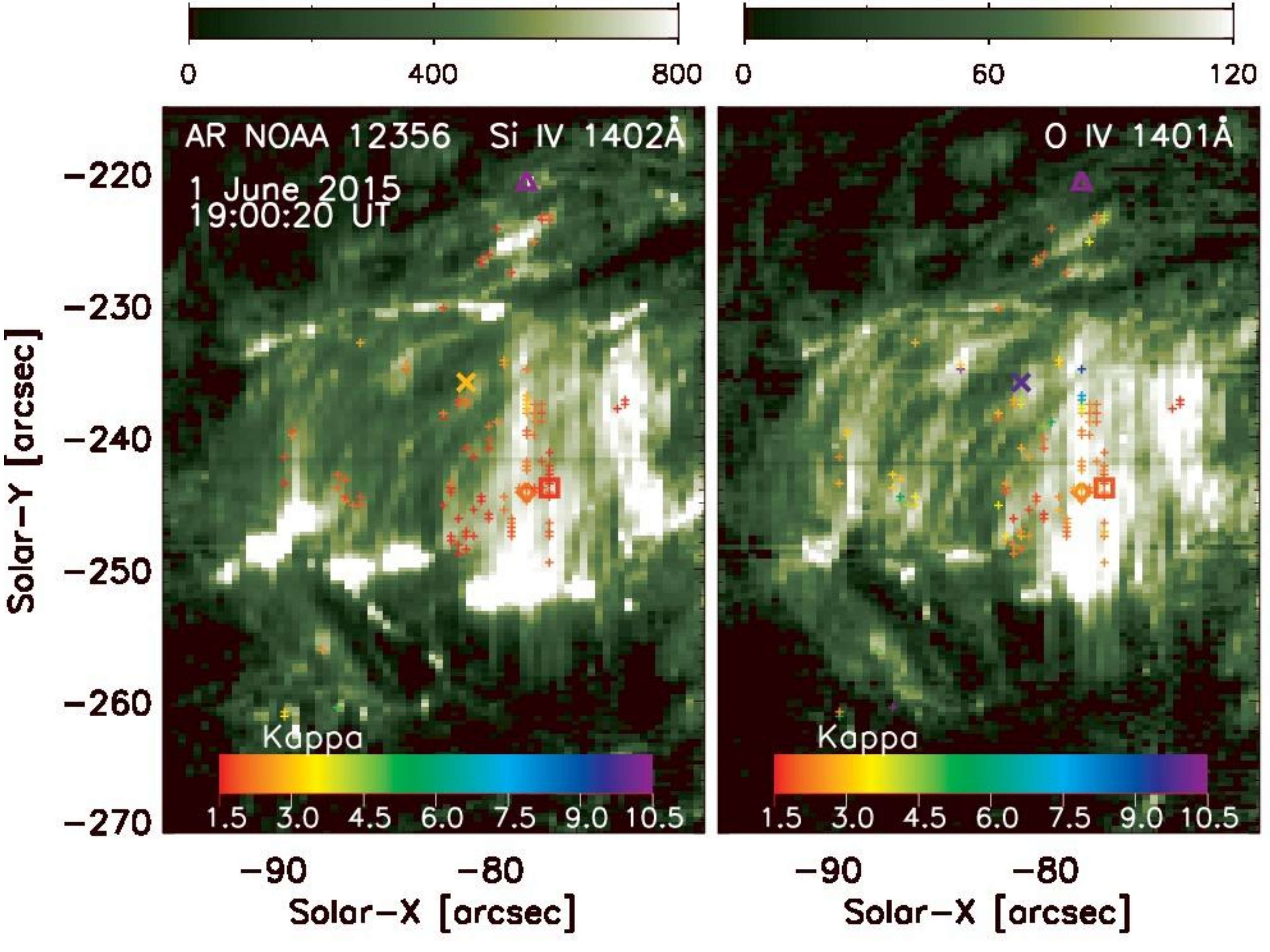
- (Almost) consistent κ values derived from all five TR lines
- **All five lines have the same FWHM**
- Significant non-thermal widths

$$w_\kappa^2 = \frac{1}{2}\frac{\lambda_0^2}{c^2}\left(\theta^2 + (\theta^{(\mathrm{nth})})^2\right) = (w_\kappa^{(\mathrm{th})})^2 + (w_\kappa^{(\mathrm{nth})})^2$$

Line	w_κ [Å]	$\log(T_{\mathrm{max,Maxw}}$ [K])	$w_{\mathrm{Maxw}}^{(\mathrm{th})}$	$w_{\mathrm{Maxw}}^{(\mathrm{nth})}$	$\log(T_{\mathrm{max},\kappa=2}$ [K])	$w_{\kappa=2}^{(\mathrm{th})}$	$w_{\kappa=2}^{(\mathrm{nth})}$
O IV 1399.78 Å	0.143 ± 0.010	5.15	0.040	0.137	4.45	0.018	0.141
O IV 1401.16 Å	0.127 ± 0.003	5.15	0.040	0.121	4.45	0.018	0.126
Si IV 1402.77 Å	0.136 ± 0.001	4.90	0.023	0.134	4.10	0.009	0.136
O IV 1404.82 Å (bl S IV)	0.163 ± 0.018	5.15	0.040	0.158	4.45	0.018	0.162
S IV 1406.06 Å	0.144 ± 0.021	5.05	0.025	0.141	4.20	0.009	0.143

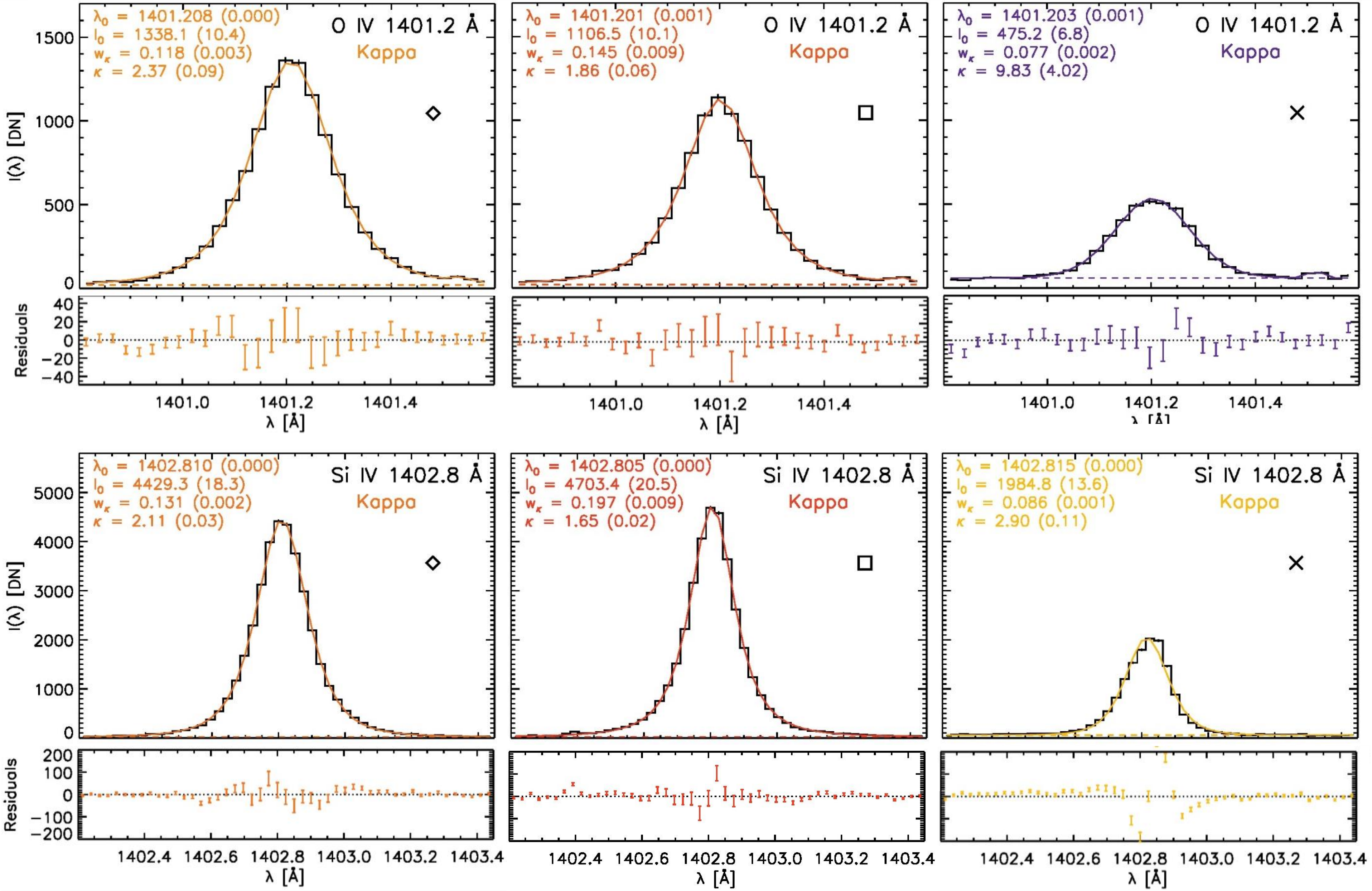


pixel X=49, Y=101
Si IV 1402.77 Å
O IV 1401.16 Å
O IV 1399.78 Å
O IV 1404.82 Å
(bl S IV)
S IV 1406.07 Å
Observed spectrum
Synthetic spectrum
κ = 2.0
log(T_e [K]) = 4.15
log(n_e [cm^-3]) = 10.1
Photospheric abund.
I(λ) [DN]
λ [Å]
pixel X=49, Y=101
Si IV 1402.77 Å
O IV 1401.16 Å
O IV 1399.78 Å
O IV 1404.82 Å
(bl S IV)
S IV 1406.07 Å
Observed spectrum
Synthetic spectrum
κ = 4.0
log(T_e [K]) = 4.55
log(n_e [cm^-3]) = 10.6
Coronal abundances
I(λ) [DN]
λ [Å]

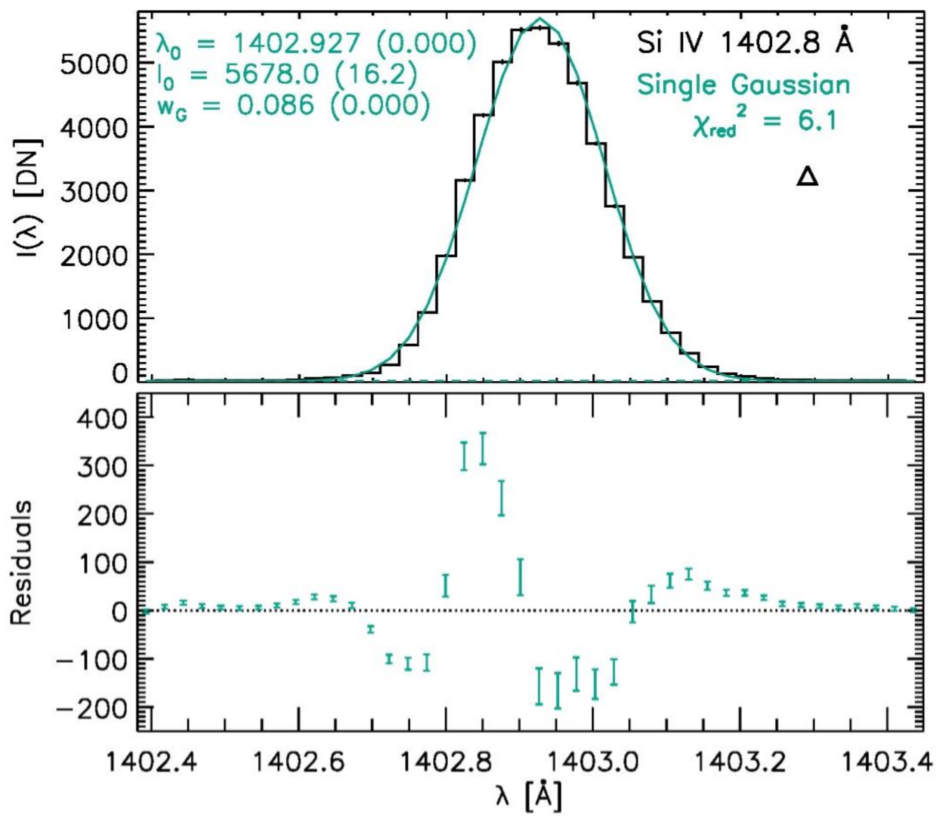


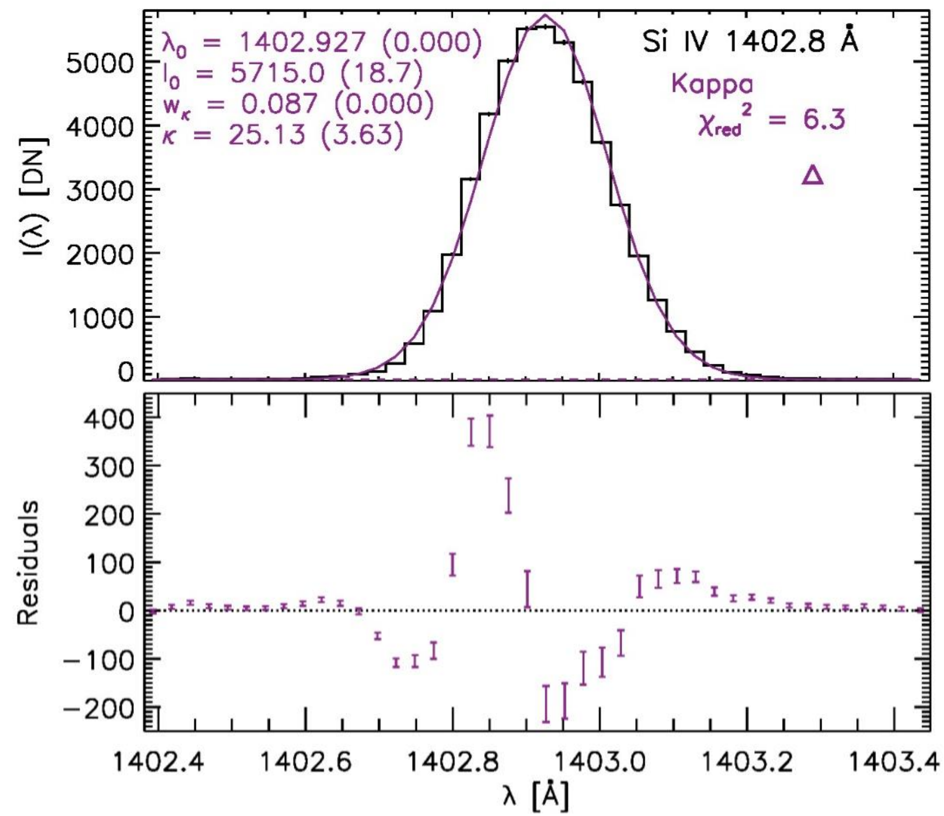
0
400
800
0
60
120
AR NOAA 12356
Si IV 1402Å
1 June 2015
19:00:20 UT
O IV 1401Å
−220
−230
−240
−250
−260
−270
Solar−Y [arcsec]
Kappa
1.5
3.0
4.5
6.0
7.5
9.0
10.5
−90
−80
Solar−X [arcsec]

More cases…


λ0 = 1401.208 (0.000)
I0 = 1338.1 (10.4)
wκ = 0.118 (0.003)
κ = 2.37 (0.09)
O IV 1401.2 Å
Kappa
λ0 = 1401.201 (0.001)
I0 = 1106.5 (10.1)
wκ = 0.145 (0.009)
κ = 1.86 (0.06)
O IV 1401.2 Å
Kappa
λ0 = 1401.203 (0.001)
I0 = 475.2 (6.8)
wκ = 0.077 (0.002)
κ = 9.83 (4.02)
O IV 1401.2 Å
Kappa
I(λ) [DN]
Residuals
λ [Å]
λ0 = 1402.810 (0.000)
I0 = 4429.3 (18.3)
wκ = 0.131 (0.002)
κ = 2.11 (0.03)
Si IV 1402.8 Å
Kappa
λ0 = 1402.805 (0.000)
I0 = 4703.4 (20.5)
wκ = 0.197 (0.009)
κ = 1.65 (0.02)
Si IV 1402.8 Å
Kappa
λ0 = 1402.815 (0.000)
I0 = 1984.8 (13.6)
wκ = 0.086 (0.001)
κ = 2.90 (0.11)
Si IV 1402.8 Å
Kappa
I(λ) [DN]
Residuals
λ [Å]

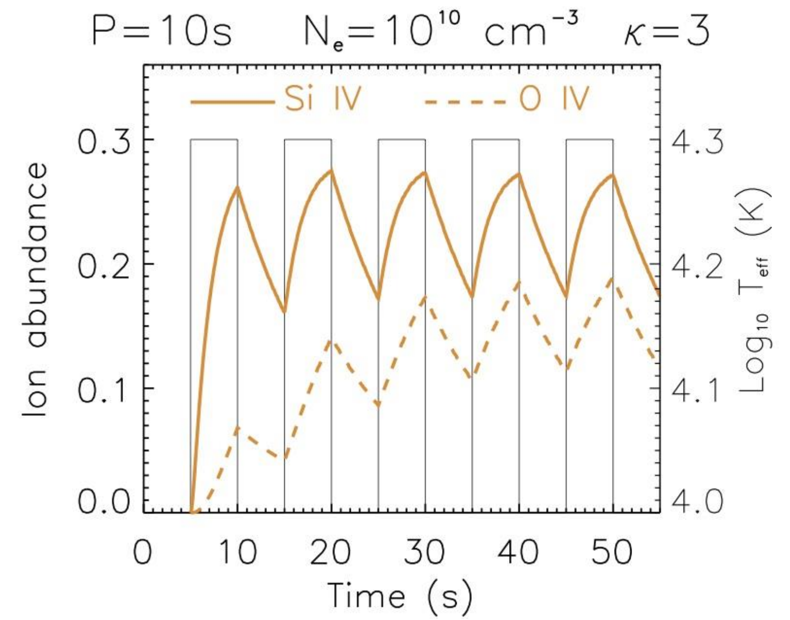
Si IV: Case of a Gaussian Profile

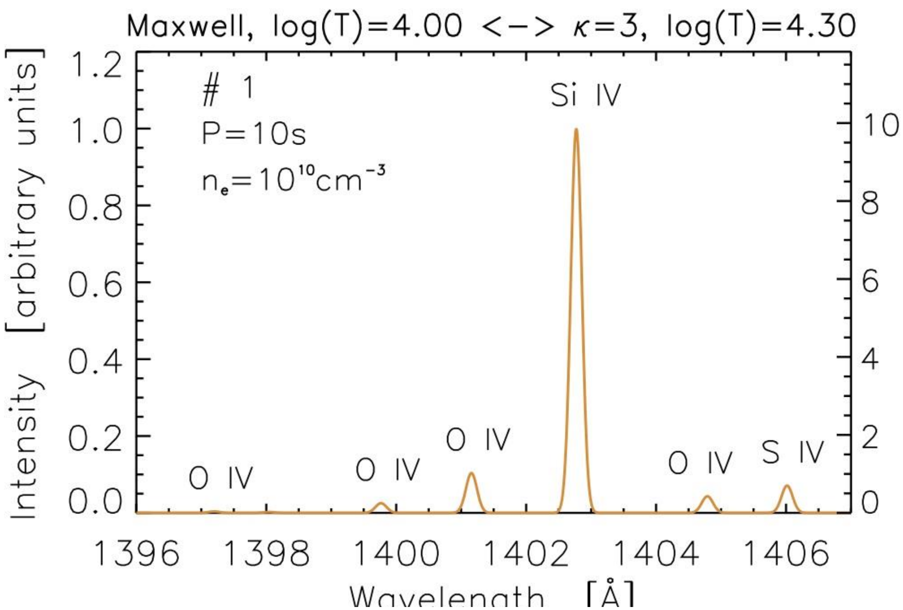


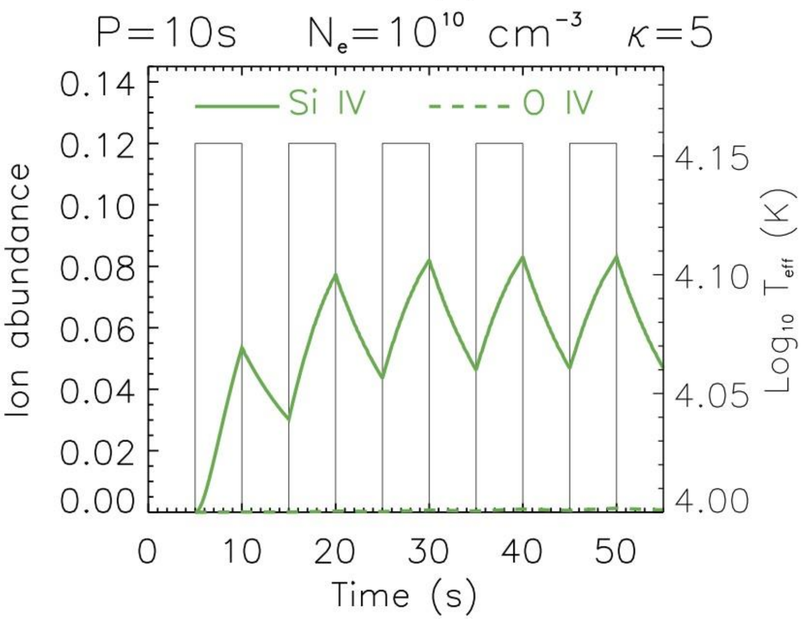


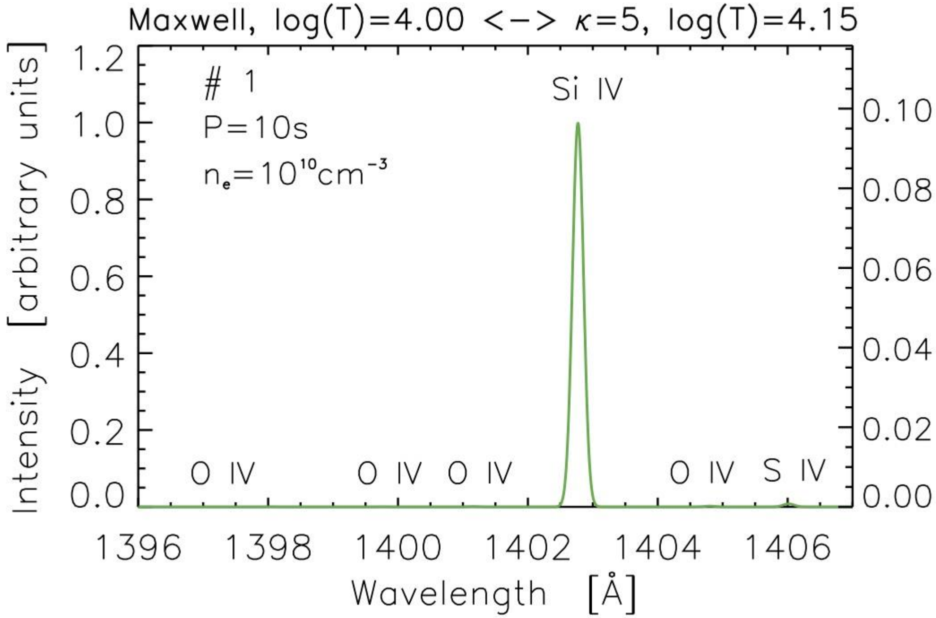
- **Detection of a single, very bright Gaussian pixel**
- **Third brightest pixel with symmetric profiles**
- **The non- Gaussian profiles are *not* caused by instrumental effects**
- **Larger / asymmetric residuals: Possibly 2 Gaussian components**

Tails too strong? : κ + NEI



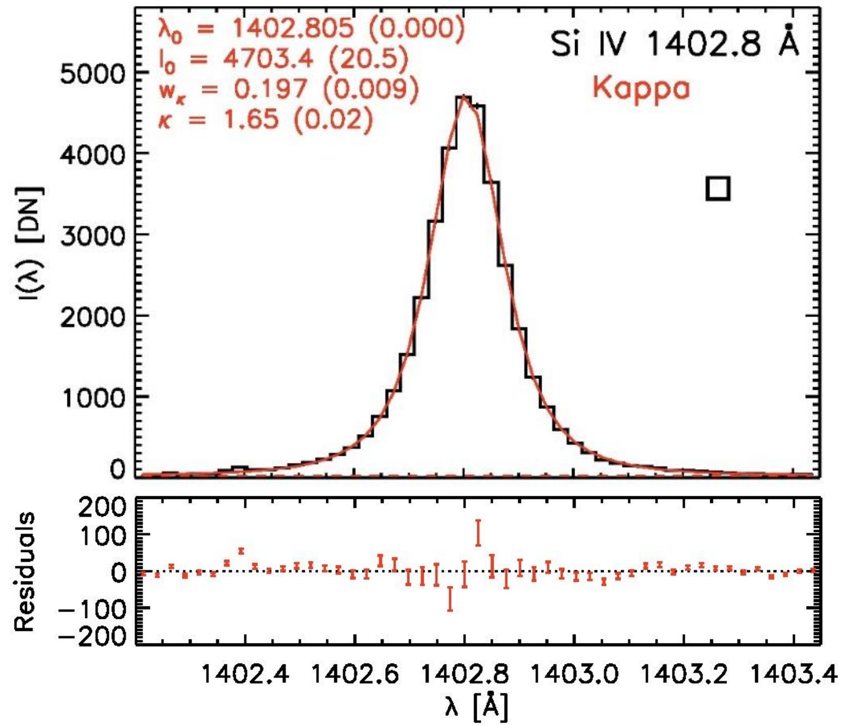






Summary

- Detected non-Gaussian, highly symmetric profiles of TR lines in 120 pixels
- Typical κ values found from profiles are $\kappa \approx 1.7 - 2.5$
- This is not an instrumental effect – we detected a Gaussian pixel
- Typical κ values found from fitting of relative intensities are $\kappa \approx 2 - 3$ (but sensitive to abundances)
- The Si IV 1402.8 Å line is optically thin

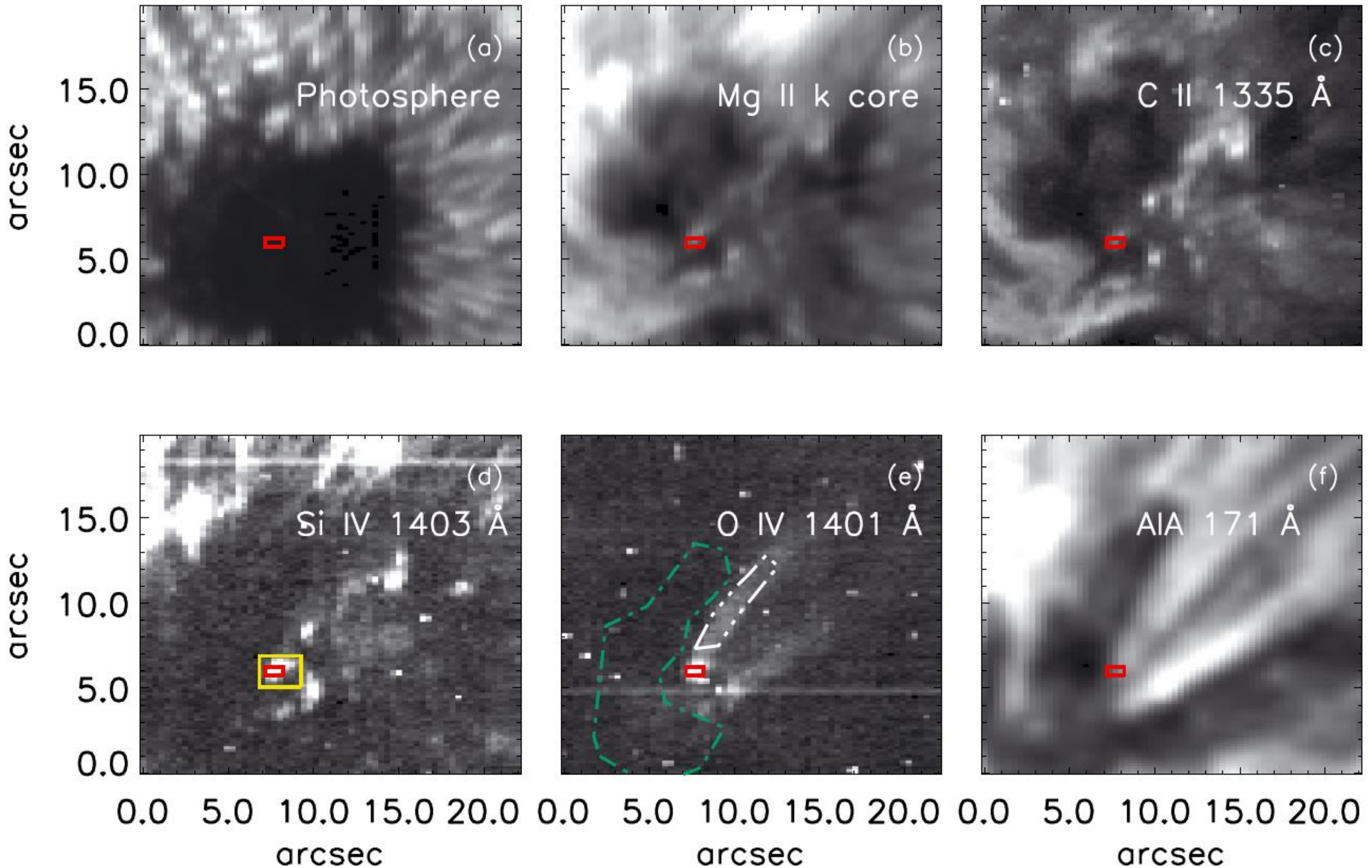


Dudík et al. (2017), ApJ, 842, 19

Review on non-Maxwellians and non-equilibrium ionization:

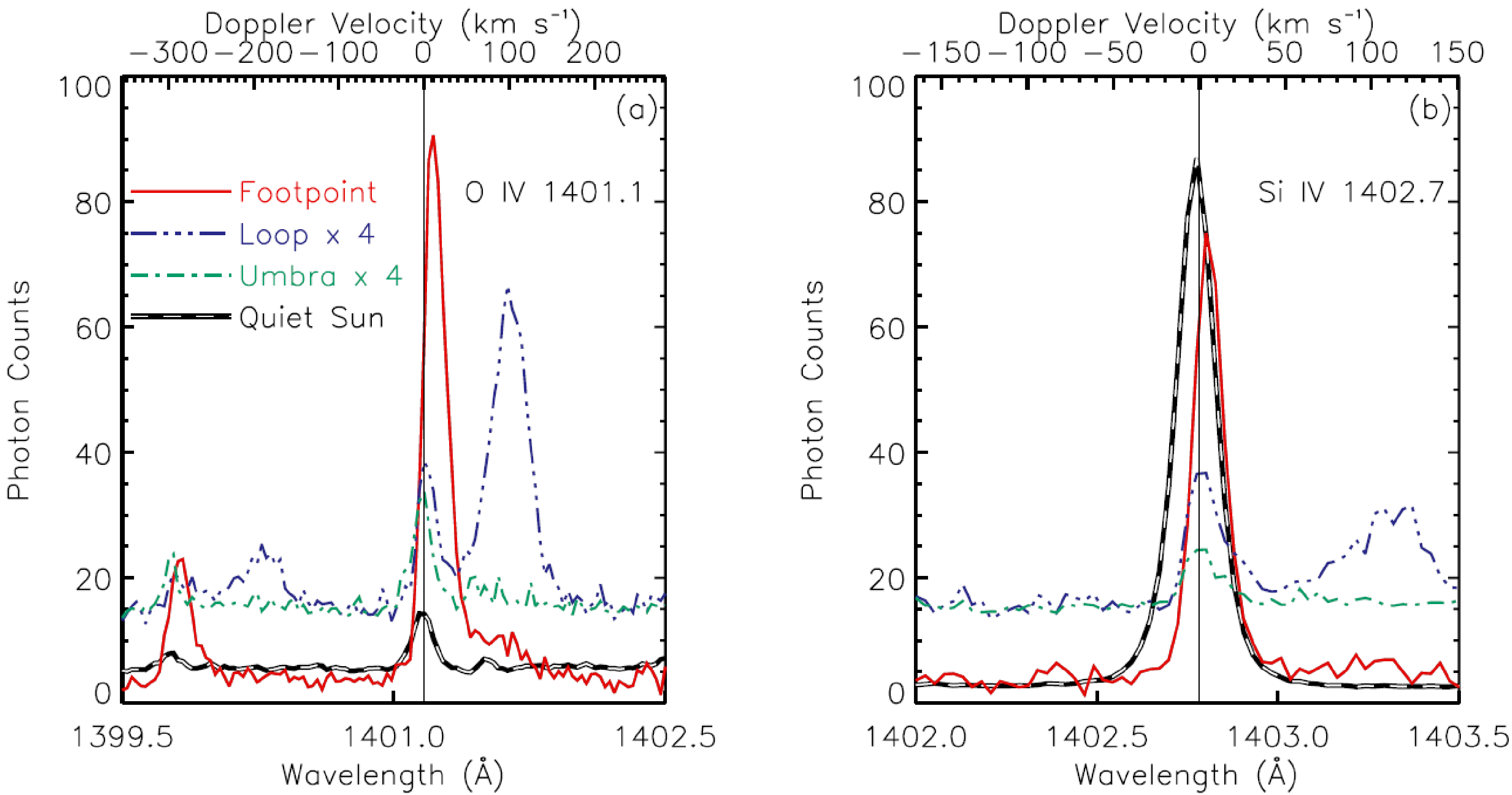
Dudík et al. (2017), Solar Phys., accepted

O IV *can* be stronger than Si IV



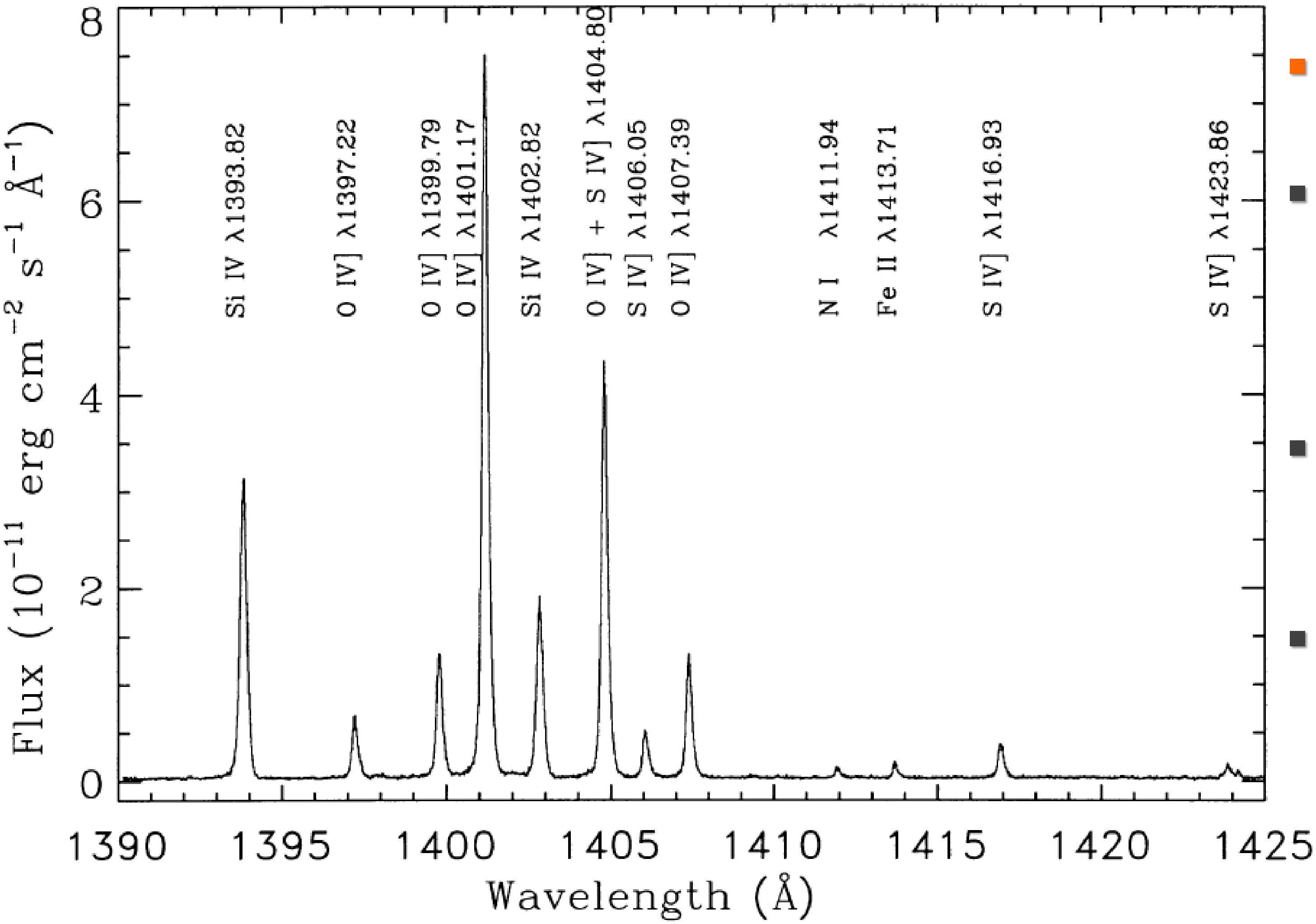
Chitta et al. (2016), A&A, 587, A20

O IV *can* be stronger than Si IV



Chitta et al. (2016), A&A, 587, A20

Case of RR Telescopii Nebula



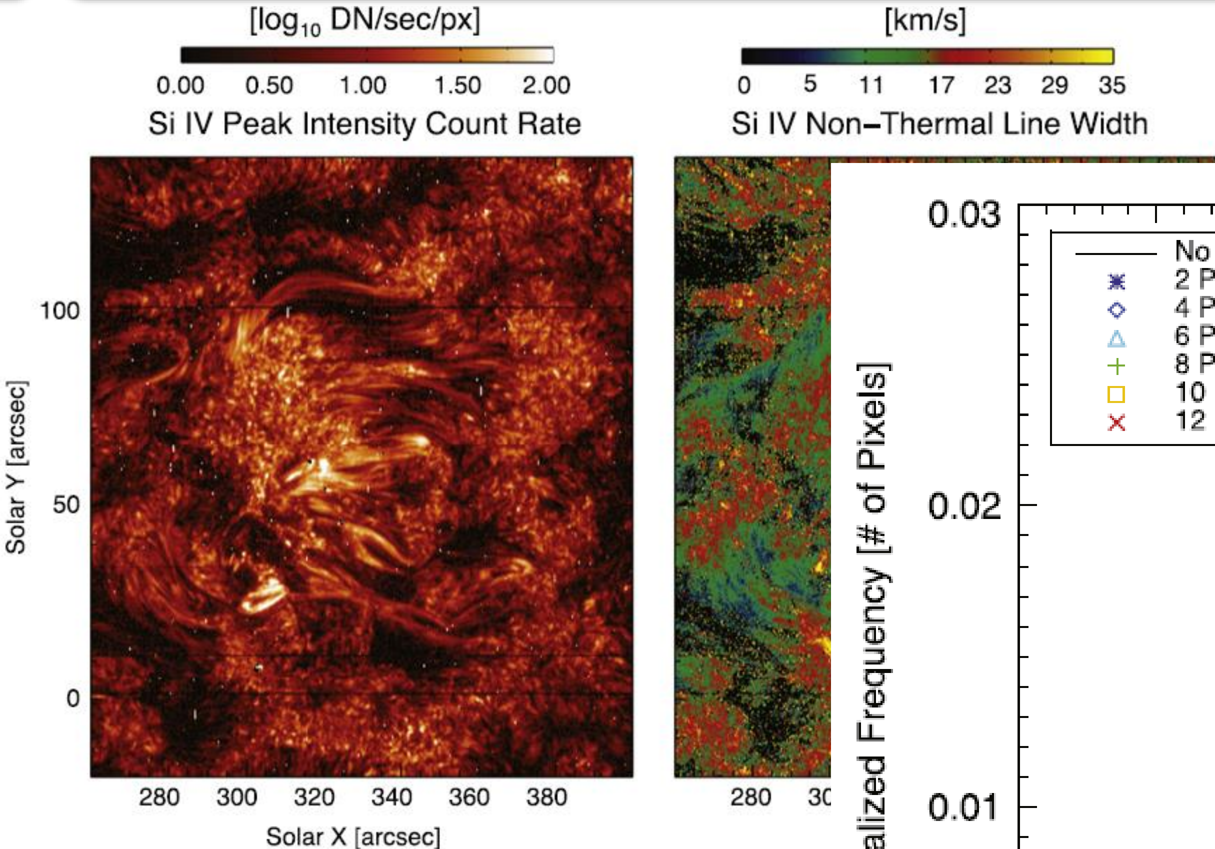
- **Symbiotic nova**
- **Mira-type giant and a white dwarf**
- **Last outburst in July 1948**
- **Observed by Hubble/GHRS**

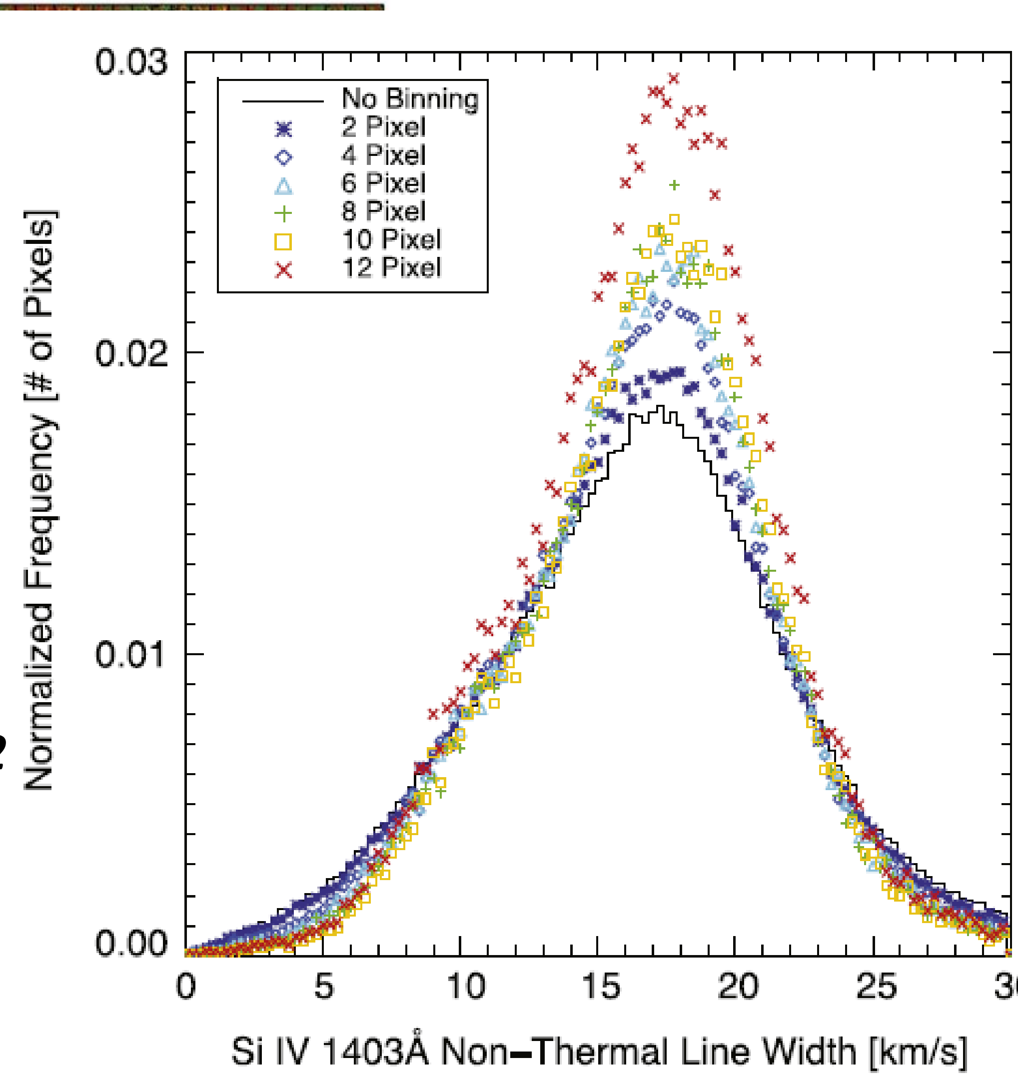
Harper et al. (1999), MNRAS, 303, L41

See also Keenan et al. (2002), MNRAS, 337, 901

Del Zanna et al. (2002), A&A, 385, 968

Non-thermal widths





De Pontieu et al. (2015), ApJ, 799, L12

- **Typical Si IV non-thermal widths are 15 – 20 km s^{-1}**
- **Independent of spatial resolution**

Non-Equilibrium Ionization (NEI)

$$\frac{\partial Y_i}{\partial t} + \frac{\partial}{\partial s}(Y_i v) = n_{\rm e}(I_{i-1}Y_{i-1} + R_i Y_{i+1} - I_i Y_i - R_{i-1} Y_i \;\; + \cdots)$$

e.g., Bradshaw & Mason (2003), A&A 401, 699

where

Y_i – population of ion +*i*

v – plasma velocity along *s* (loop)

I_i – total ionization rate of ion +*i*

R_i – total recombination rate of ion

If v = 0:

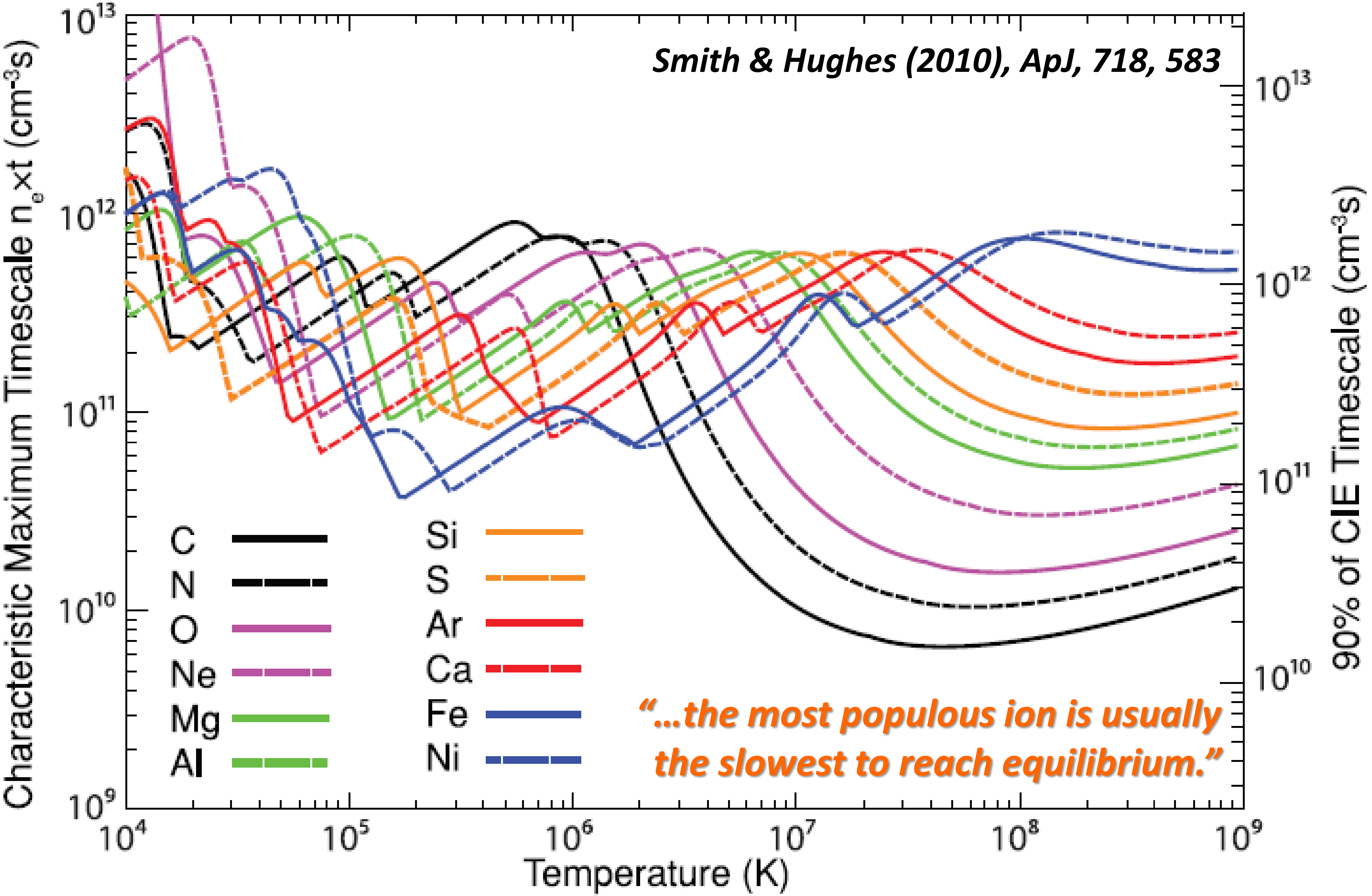
- **Coupled set of Z+1 first-order differential equations for Y_i**
- **Can be re-cast as Z uncoupled first-order diff eqs using eigenvector basis**
- **Solution is a set of Z separate exponential functions**
- **Ionization equilibration timescale is given by the smallest eigenvalue λ_j**

$$Y_i(t, T_e) - Y_{i,\rm eq}(T_e) = \sum_j W_{ji}(T_e) c_j \exp\left(-n_{\rm e}\lambda_j t\right)$$

Smith & Hughes (2010), ApJ, 718, 583

see also Golub et al. (1989), SoPh 122, 145; Reale & Orlando (2008), ApJ 684, 715

NEI: Timescales

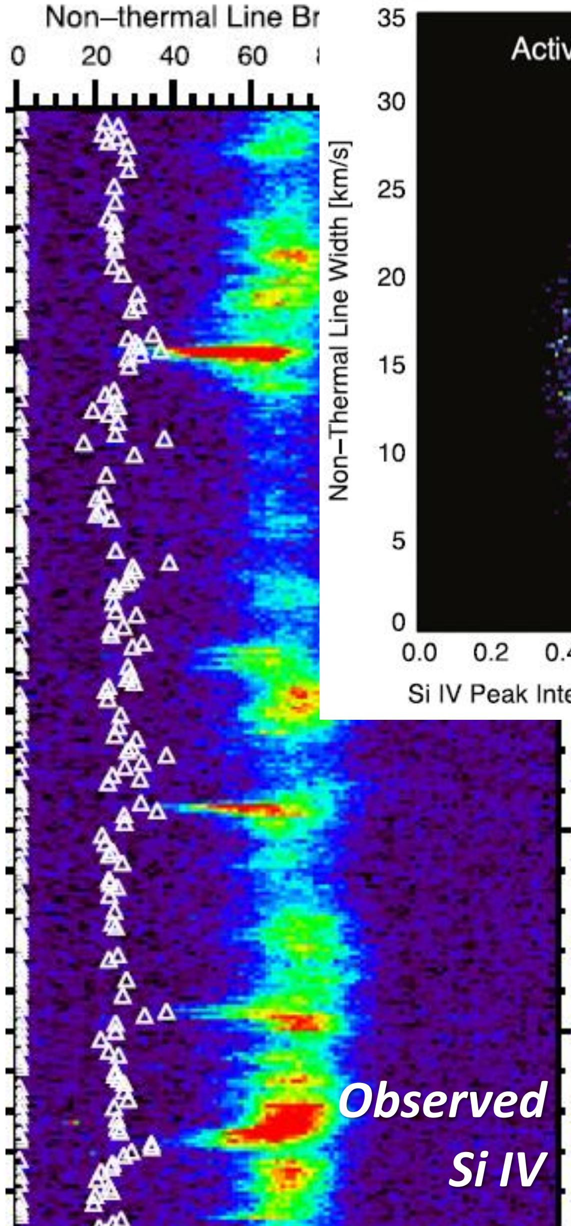


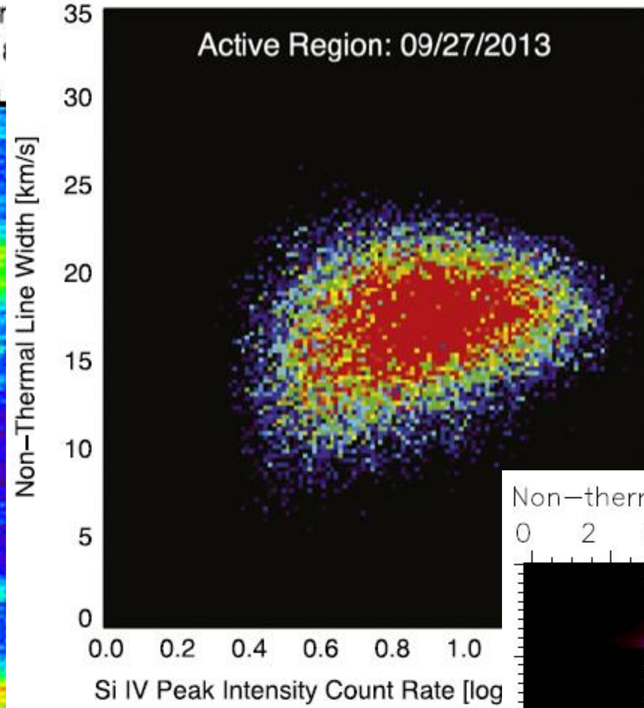
"…the most populous ion is usually the slowest to reach equilibrium."

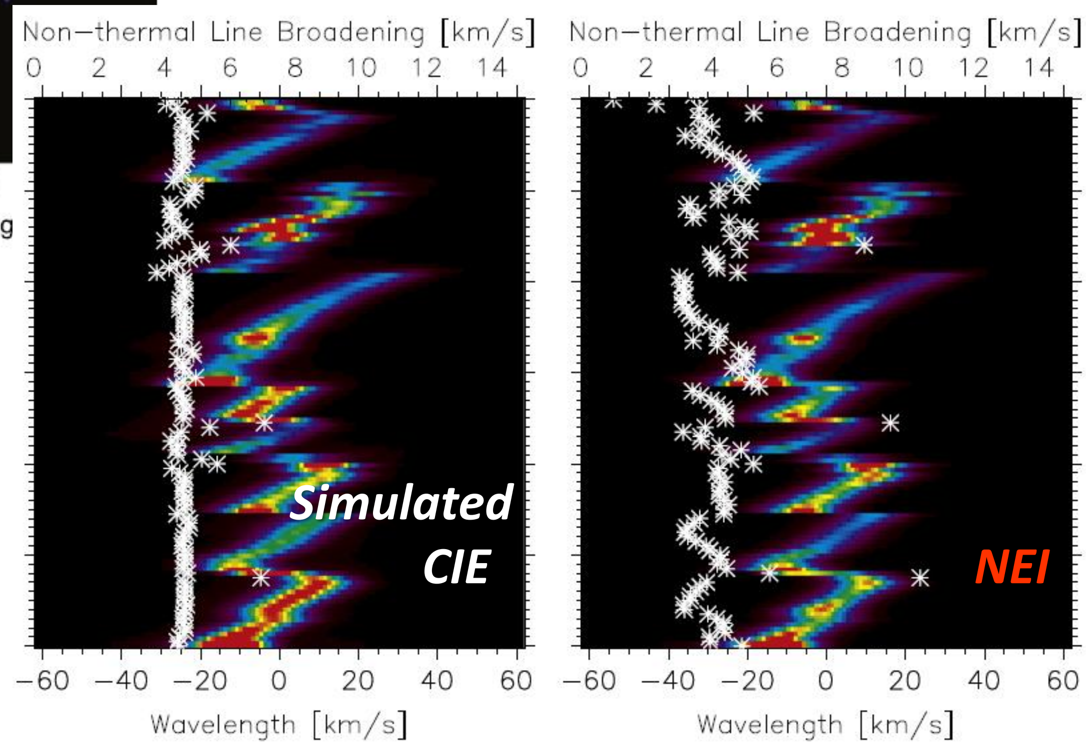
NEI and non-thermal broadening

DePontieu et al. (2015), ApJL 799, L12

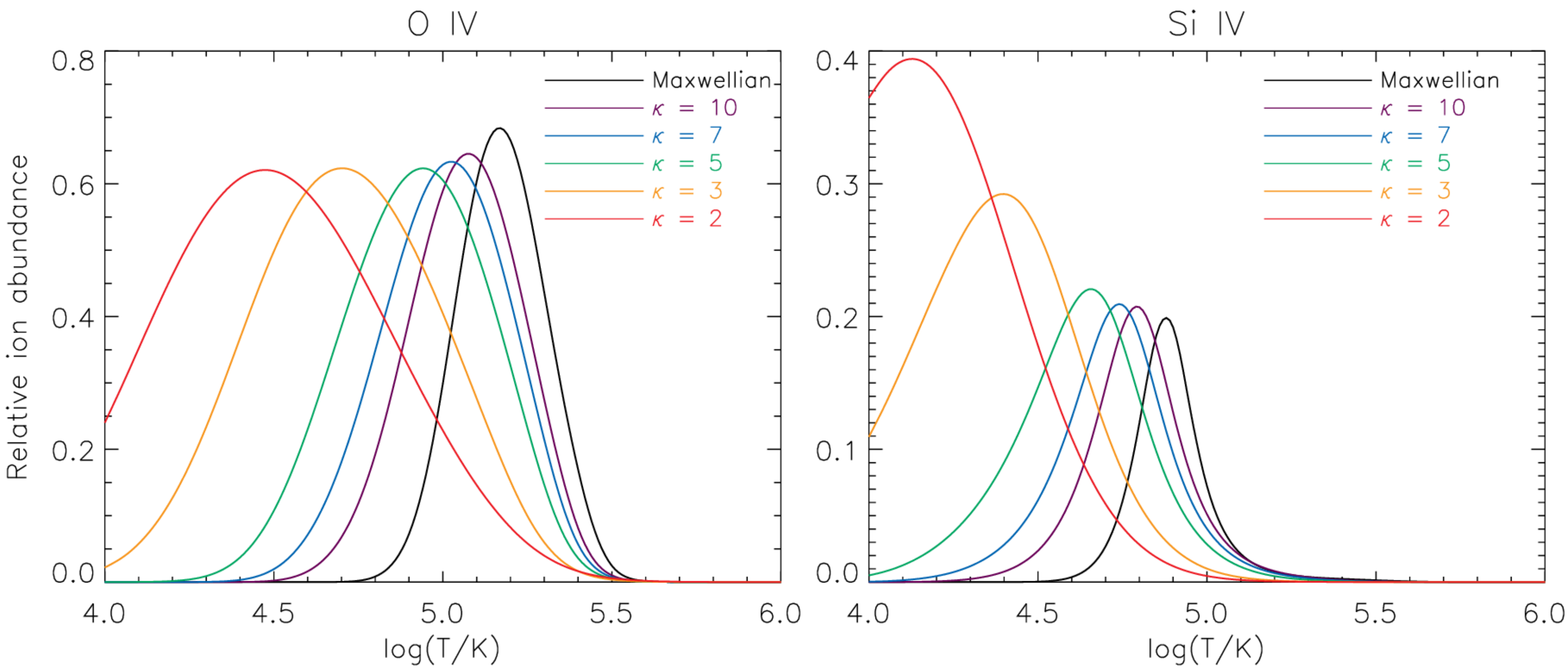
- **Observed: width correlated with intensity, independent of resolution**
- **Slow magnetoacoustic shocks**
- **In simulations, NEI increases the broadening by 2 – 10 km s^{-1} *and produces a correlation***





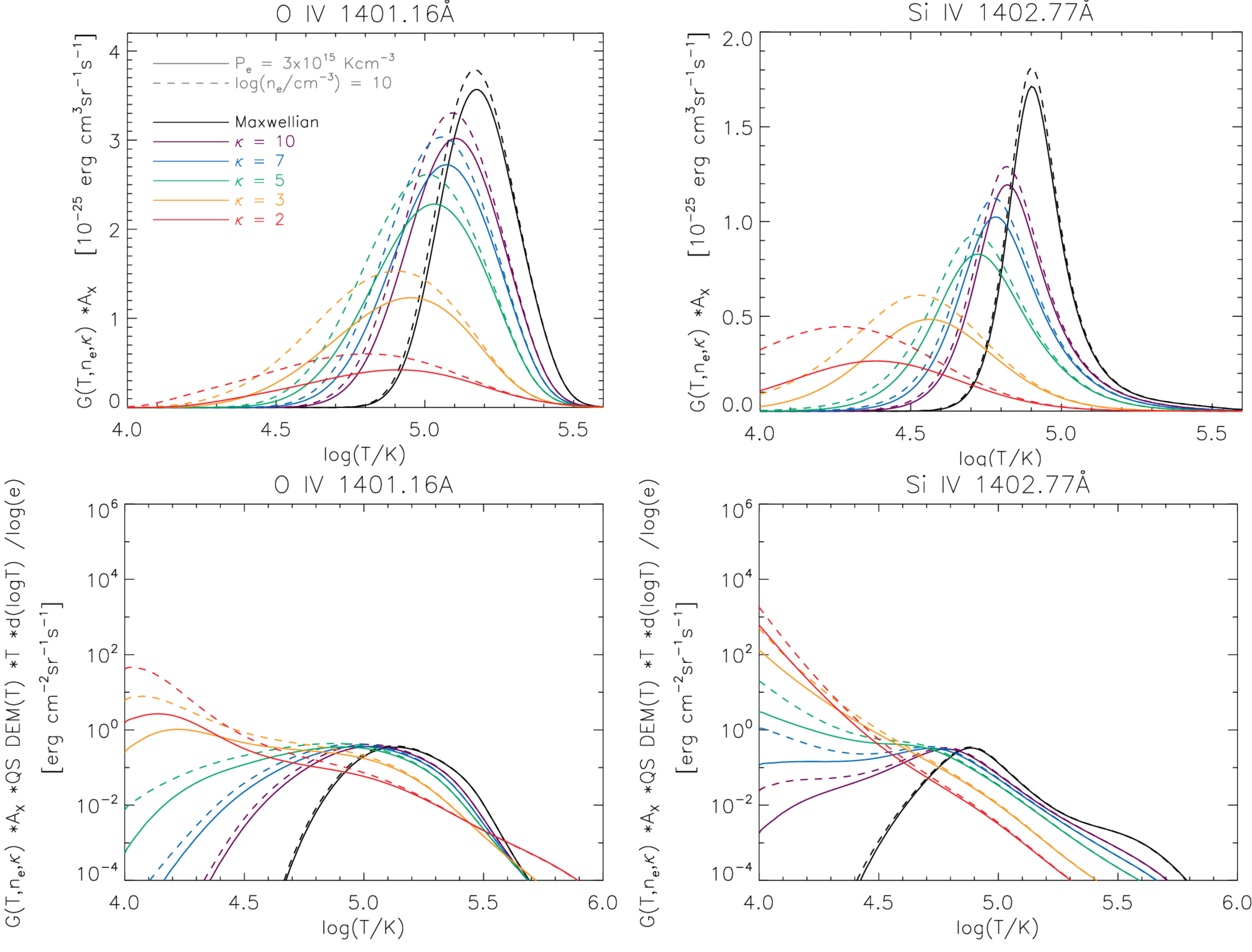


The κ-distributions and TR lines

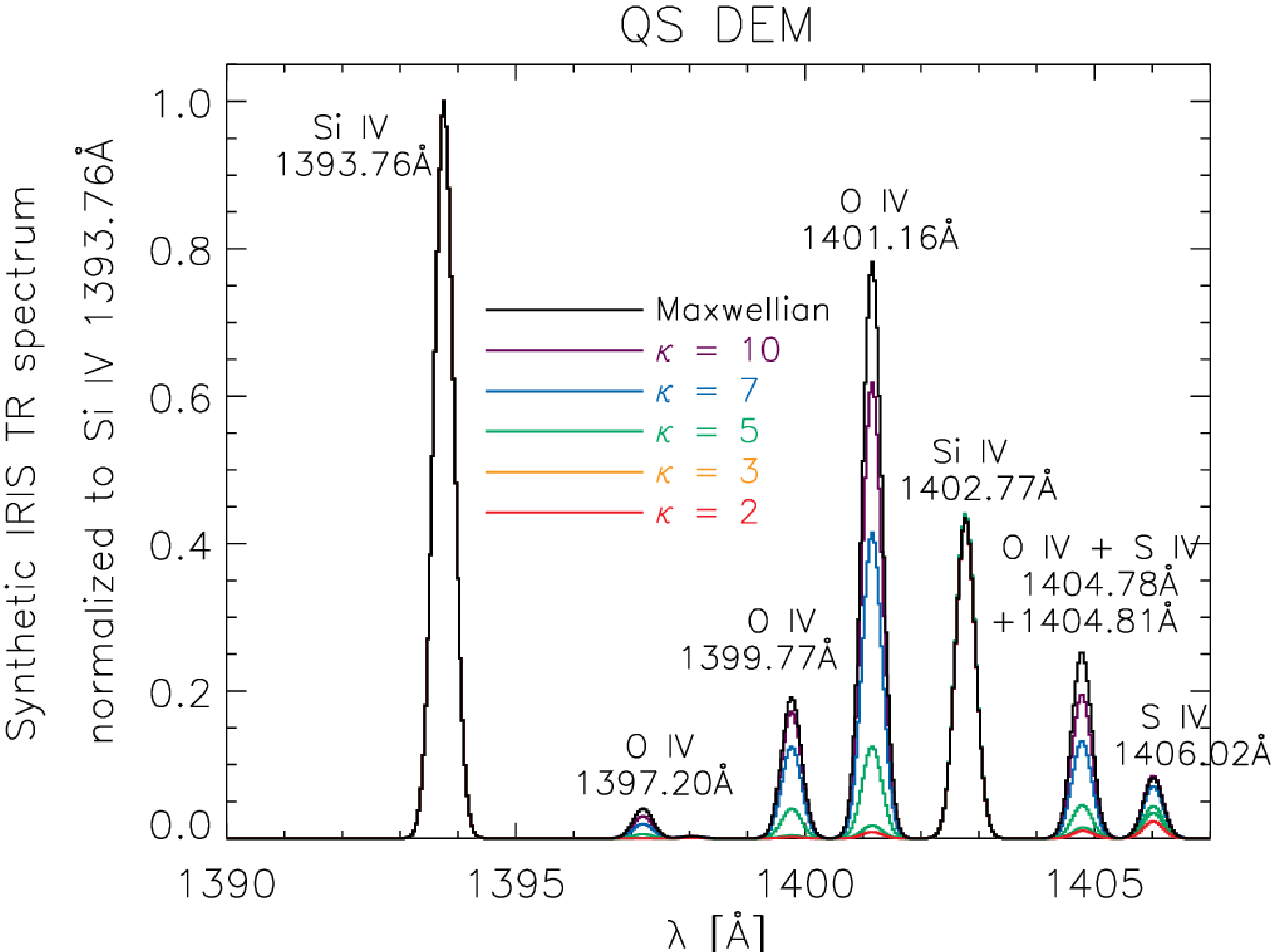


Dzifčáková & Dudík (2013), ApJS, 206, 6
Dudík et al. (2014), ApJL, 780, L12

- **For TR lines, ion abundance peaks are shifted to lower *T***
- **Consequences of high-energy tail: strongly enhanced ionization**
- **Recombination not so strongly enhanced**

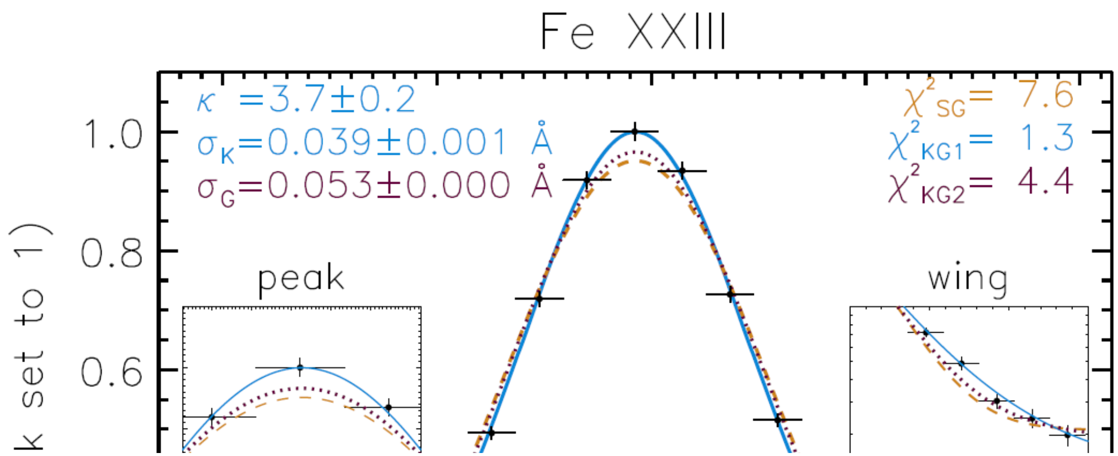


O IV 1401.16Å
Si IV 1402.77Å
Pe = 3x10^15 Kcm^-3
log(ne/cm^-3) = 10
Maxwellian
κ = 10
κ = 7
κ = 5
κ = 3
κ = 2
G(T,ne,κ) *AX [10^-25 erg cm^3 sr^-1 s^-1]
log(T/K)
O IV 1401.16A
Si IV 1402.77Å
G(T,ne,κ) *AX *QS DEM(T) *T *d(logT) /log(e) [erg cm^-2 sr^-1 s^-1]
log(T/K)



QS DEM
Synthetic IRIS TR spectrum
normalized to Si IV 1393.76Å
1.0
0.8
0.6
0.4
0.2
0.0
Si IV
1393.76Å
O IV
1401.16Å
Maxwellian
κ = 10
κ = 7
κ = 5
κ = 3
κ = 2
Si IV
1402.77Å
O IV + S IV
1404.78Å
+1404.81Å
O IV
1399.77Å
O IV
1397.20Å
S IV
1406.02Å
1390
1395
1400
1405
λ [Å]

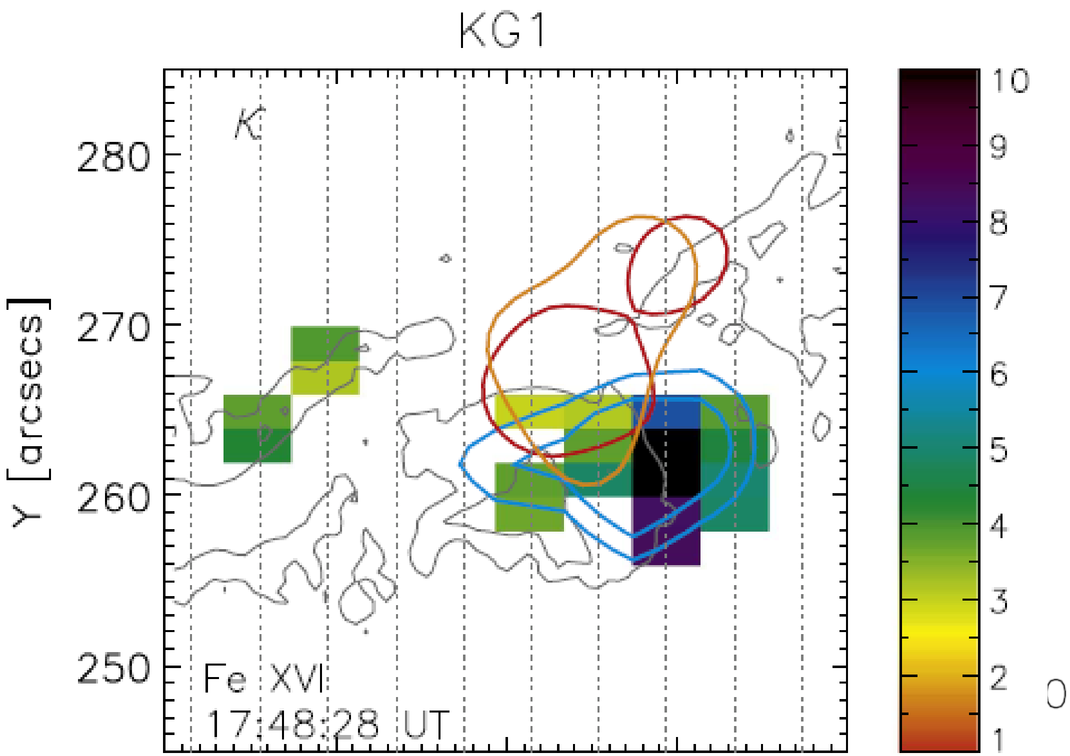
The κ-Profiles in *Hinode*/EIS



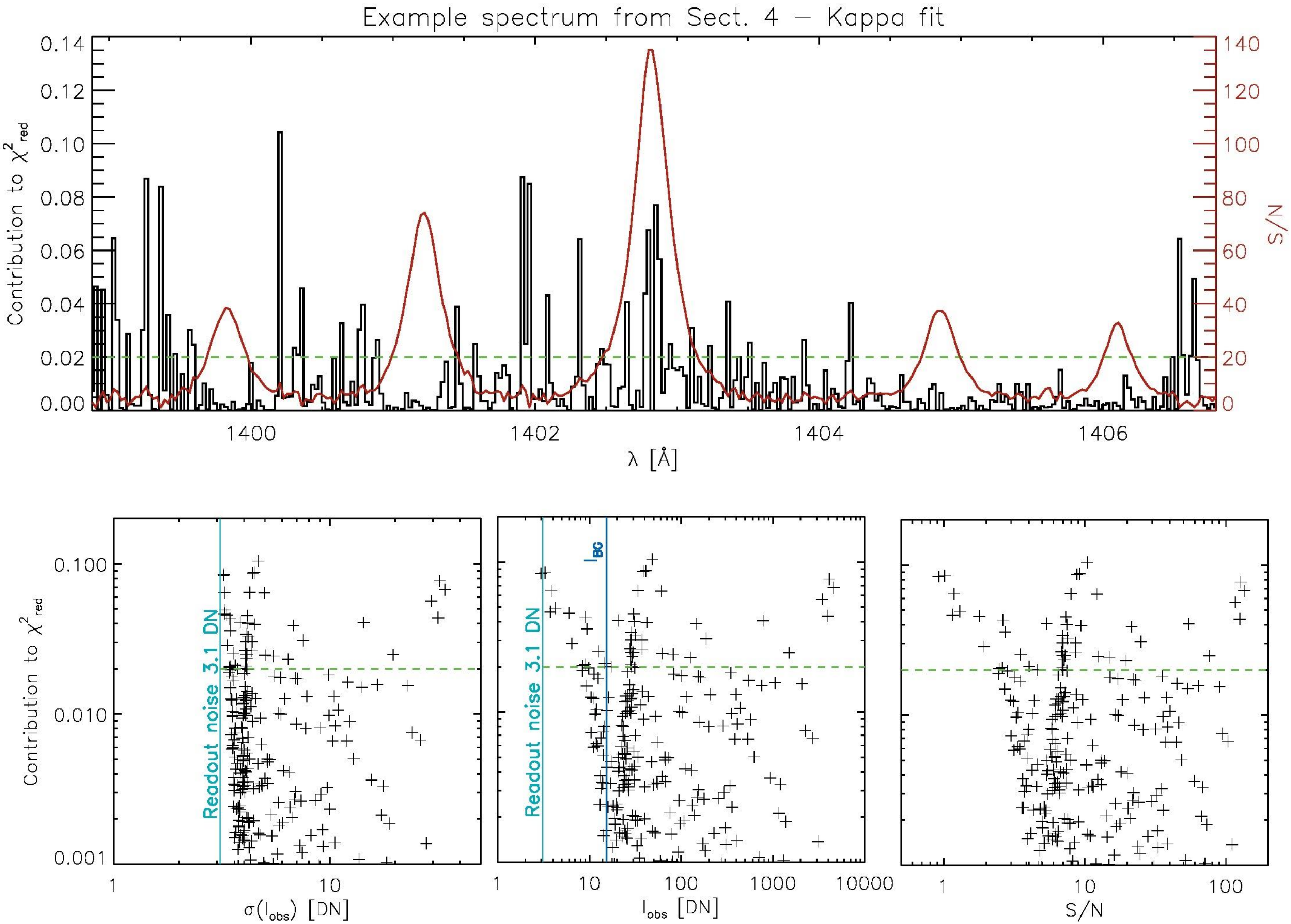
$$\mathcal{W}(\lambda) = \mathcal{G}(\lambda) * \mathcal{K}(\lambda) = A[0] + A[1] \times \sum_{\lambda'} \exp\left(-\frac{(\lambda' - A[2])^2}{2\sigma_I^2}\right) \times \left(1 + \frac{(\lambda - \lambda' - A[2])^2}{2A[3]^2 A[4]}\right)^{-A[4]+1},$$

Jeffrey et al. (2016), A&A, 590, A99

Jeffrey et al. (2017), ApJ, 836, 35

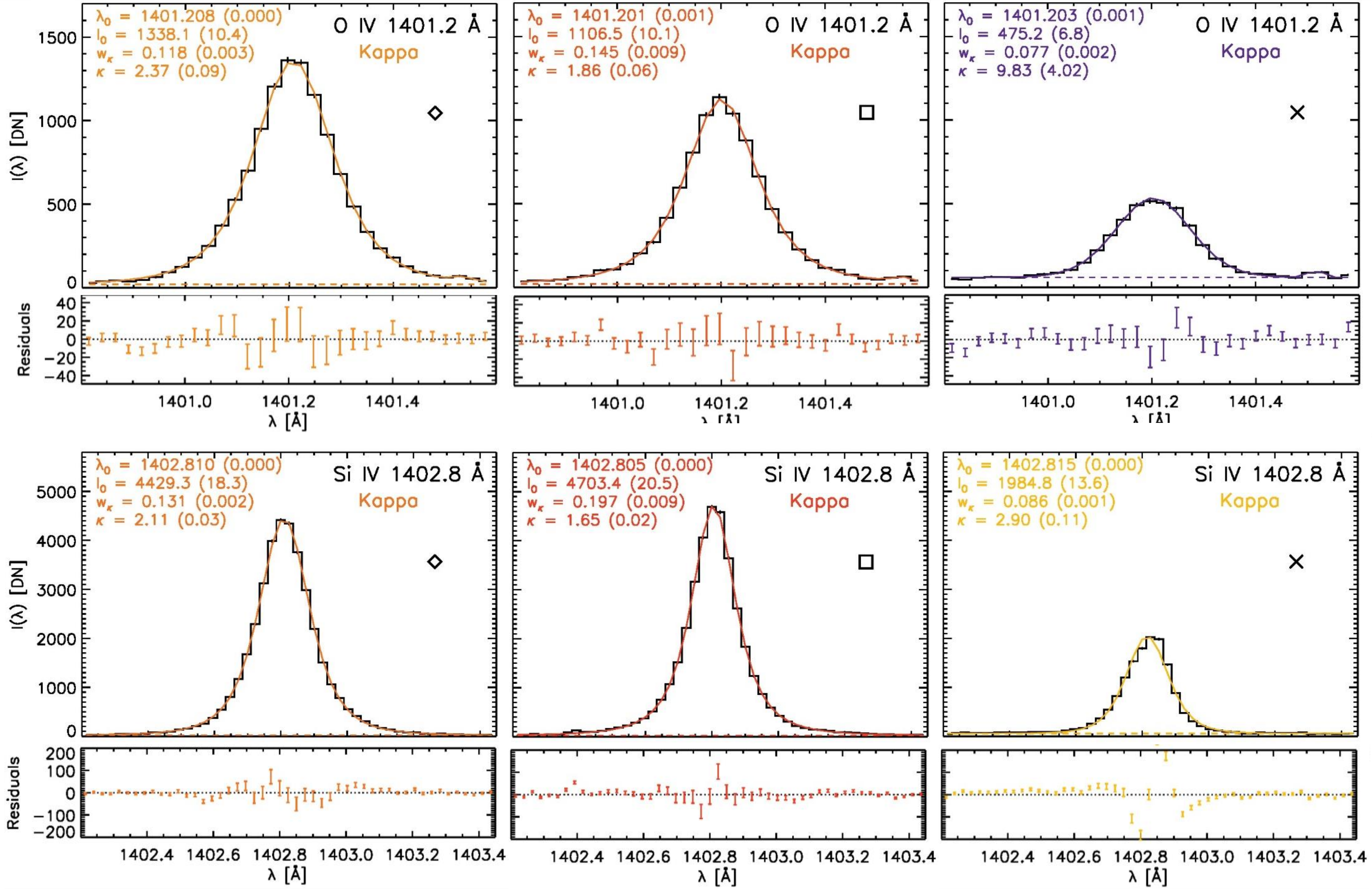


- **Non-Maxwellian fitting of EIS flare lines**
- **Typically find κ ≈ 2 – 3**
- **Convolution with an instrumental profile, taken to be Gaussian**

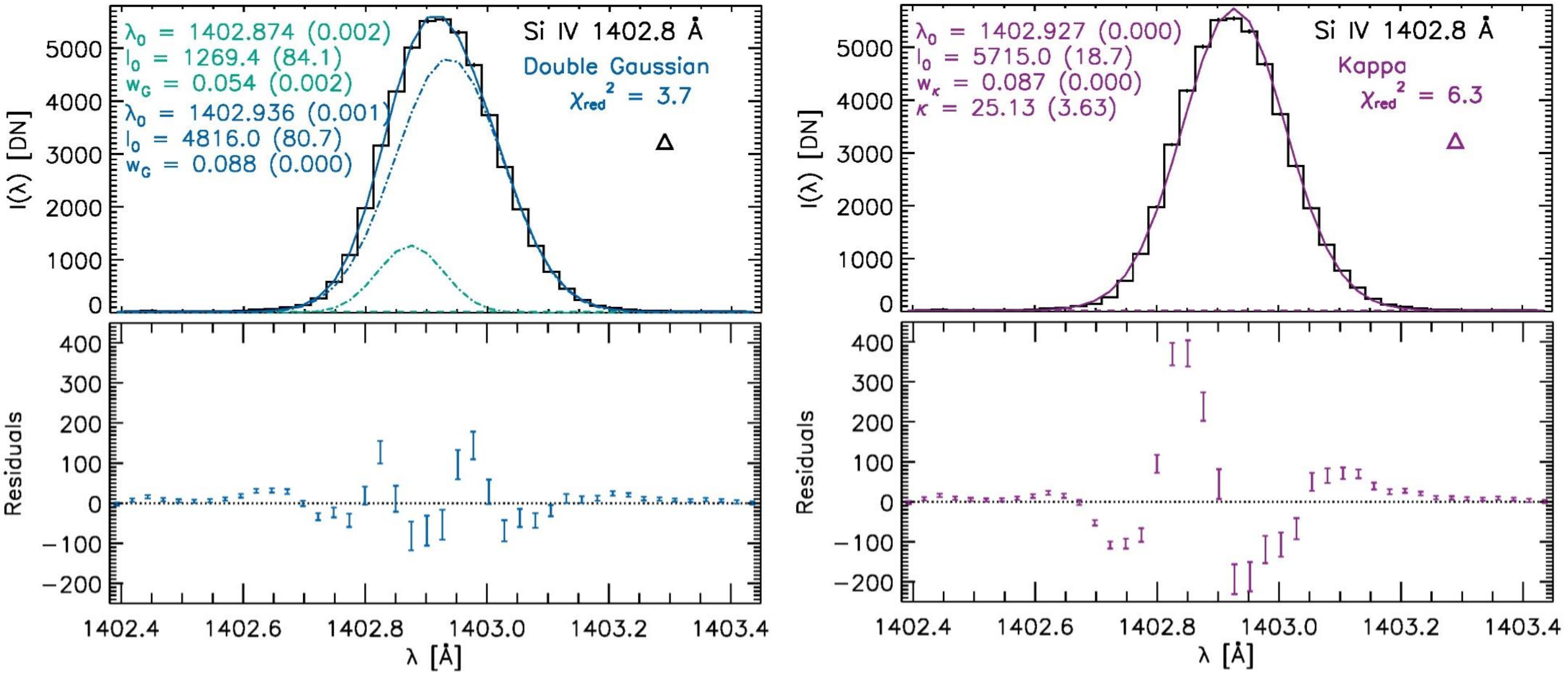


Example spectrum from Sect. 4 – Kappa fit
Contribution to χ^2_{red}
S/N
λ [Å]
Readout noise 3.1 DN
I_{BG}
σ(I_{obs}) [DN]
I_{obs} [DN]
S/N

Selected *IRIS* Spectra



Multi-Component Si IV?



Is the SI IV optically thick?

- The optical thickness is given by (e.g., Buchlin & Vial 2009, A&A, 503, 559):

$$\tau(\lambda) = \tau_0(\lambda_0)\Phi(\lambda) = \frac{\lambda_0^4 A_{ij}\Phi(\lambda)}{4\pi^{3/2}c\Delta\lambda_\mathrm{D}} \frac{N(\mathrm{Si}^{+3})}{N(\mathrm{Si})} A(\mathrm{Si}) \frac{N_\mathrm{H}}{N_\mathrm{e}} \langle N_\mathrm{e}\rangle \Delta s$$

- For Maxwellian and *thermal* width, we get

$$\tau_0 \approx 0.26 f \frac{\langle N_\mathrm{e}\rangle}{10^{10}\ \mathrm{cm}^{-3}}$$

- For κ = 2, the numerical factor is about 1.5
  (due to lower thermal width and higher $N(Si^{+3})$ / N(Si))

- For the ***observed*** width and a Maxwellian, we get

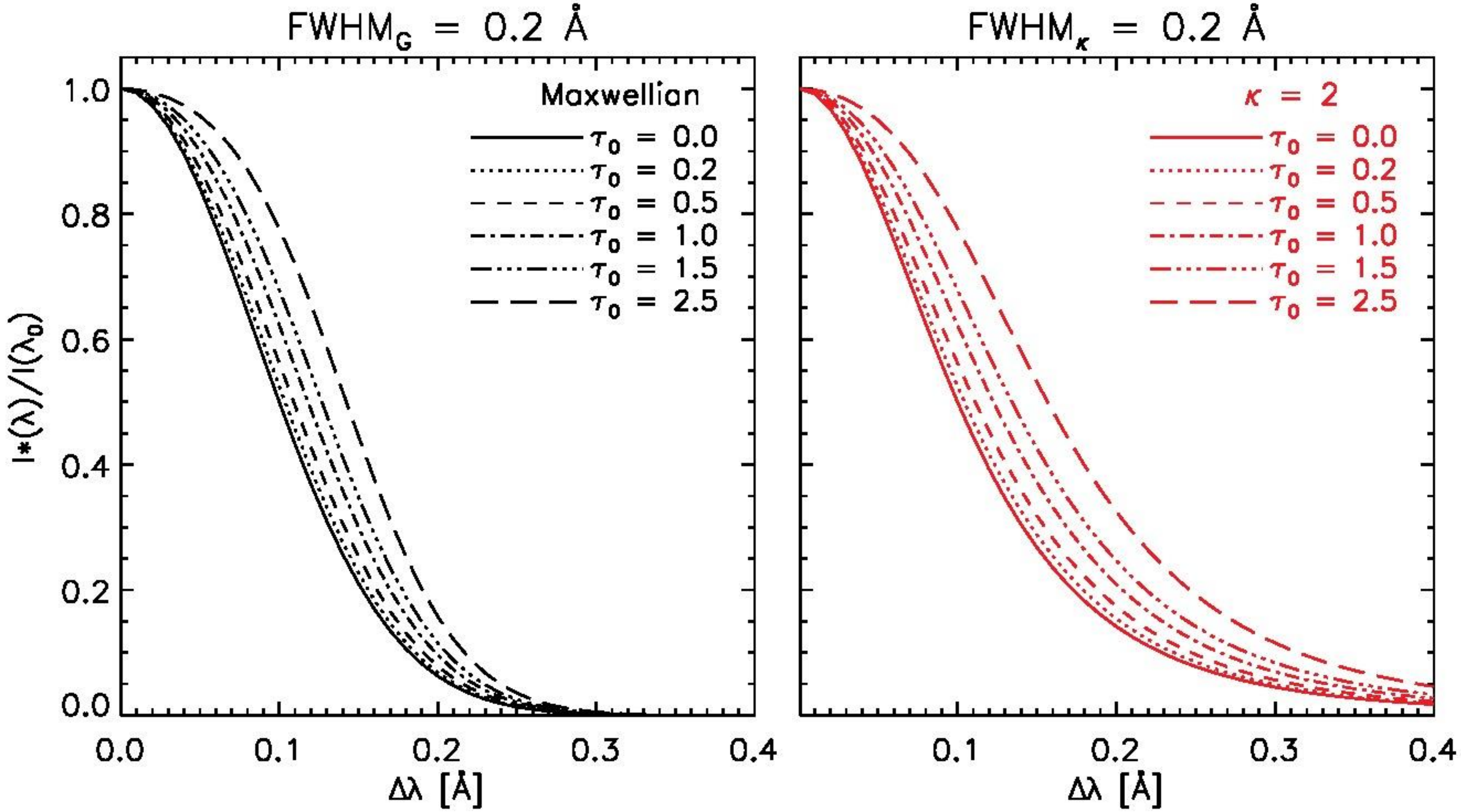
$$\tau_0 \approx 0.02 f \frac{\langle N_\mathrm{e}\rangle}{10^{10}\ \mathrm{cm}^{-3}}$$

- For κ = 2, the numerical factor is about 0.06

Is the SI IV optically thick?

- **If the line is optically thick, then the profile should be (for *S* = const.)**

$$I^*(\lambda) = \int_0^{\tau(\lambda)} S_\lambda \exp\left(-t_\lambda\right) \mathrm{d}t_\lambda = S_\lambda \left[1 - \exp(-\tau(\lambda))\right]$$



Multi-Component Si IV?

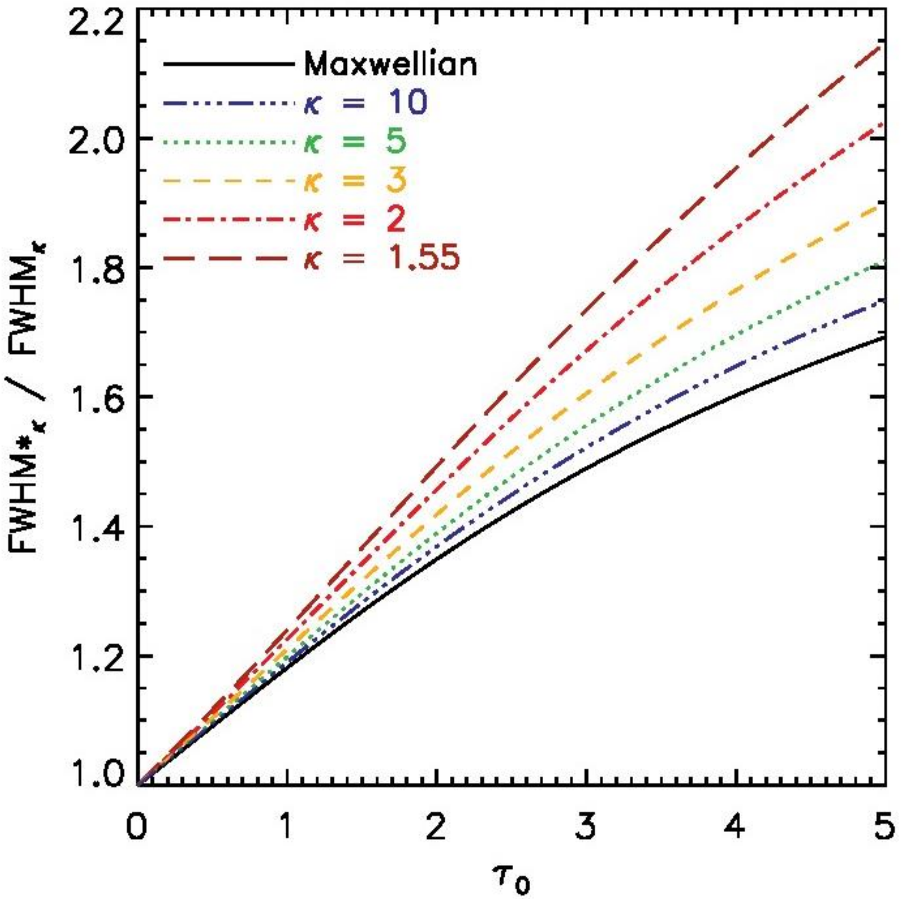
- **The FWHM changes as**

$$\mathrm{FWHM}^*_\kappa(\tau_0)^2 = 8(\kappa - 3/2)w_\kappa^2 \left[\left(\frac{\tau_0}{\ln(2) - \ln(\exp(-\tau_0) + 1)} \right)^{\frac{1}{\kappa}} - 1 \right]$$

- **Recall that the FWHM of the Si IV line is the same as for the O IV and S IV**

- **For solar conditions,**
  O IV lines are always optically thin because of their small A_{ij}

- **⇒ the Si IV is optically *thin***



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