Dielectronic Satellite Lines and Double-Layers in Solar Flares

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Atomic Physics and Plasma Spectroscopy:
Celebrating the Achievements of Alan Gabriel

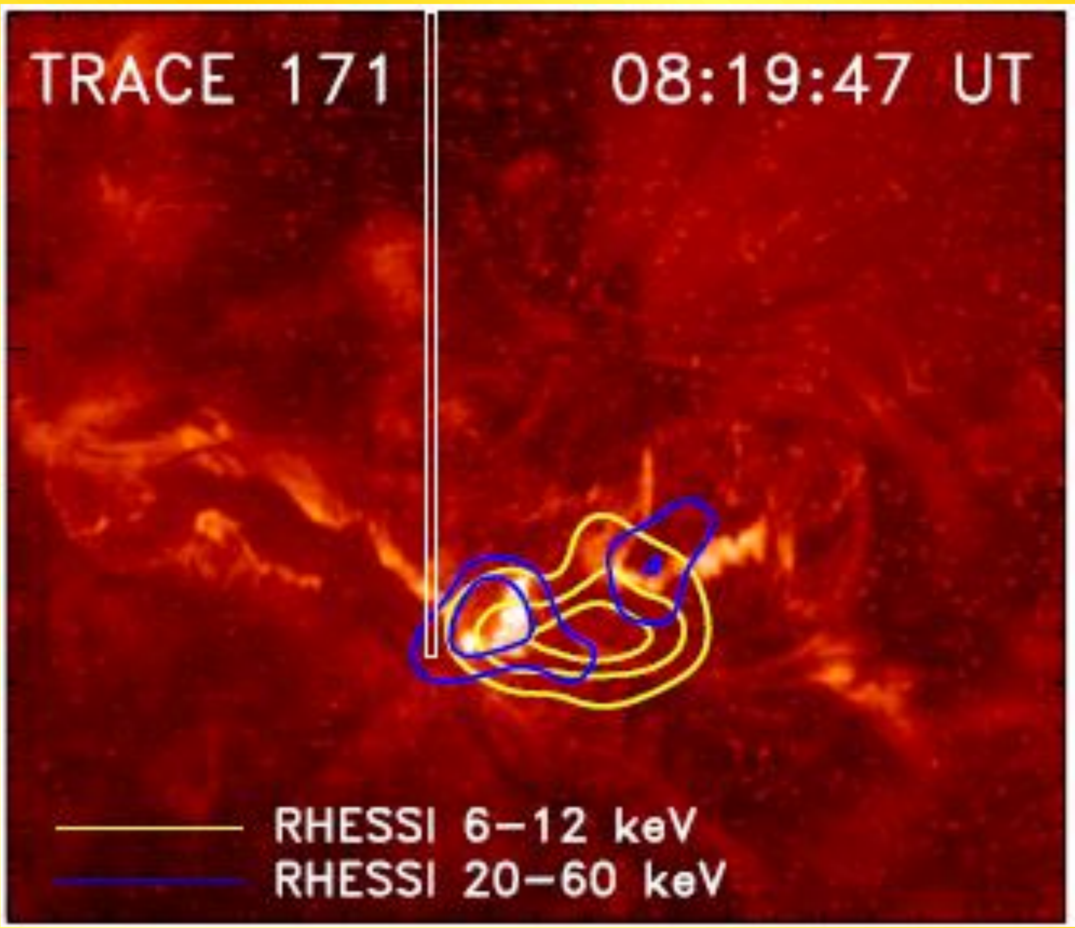
Outline

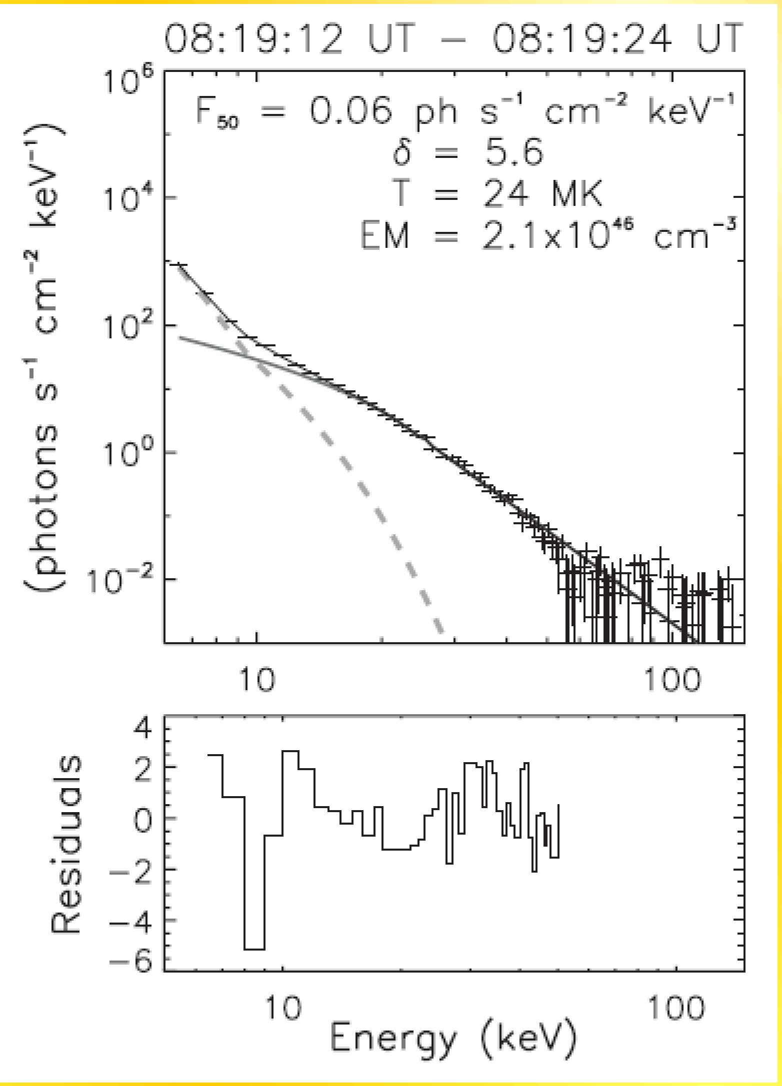
I. **The power-law distributions (nonthermal tails)**
   Motivation: RHESSI flare observations

II. **The *κ*-distributions**
   Definition and properties, physical background
   Ionization equilibrium and spectra
   Radiative losses, EUV and X-ray filter responses
   Diagnostic methods

III. **The *n*-distributions and the like**
   Flare plasma diagnostics
   Types of distributions: Moving-Maxwellian and Double Layers
   Physical background

I. The nonthermal tails





Veronig et al. (2010), ApJ 719, 655

The nonthermal tails

Gabriel & Phillips (1979), MNRAS 189, 319:

Effect on the Fe XXIVd / Fe XXV satellite/allowed line ratios

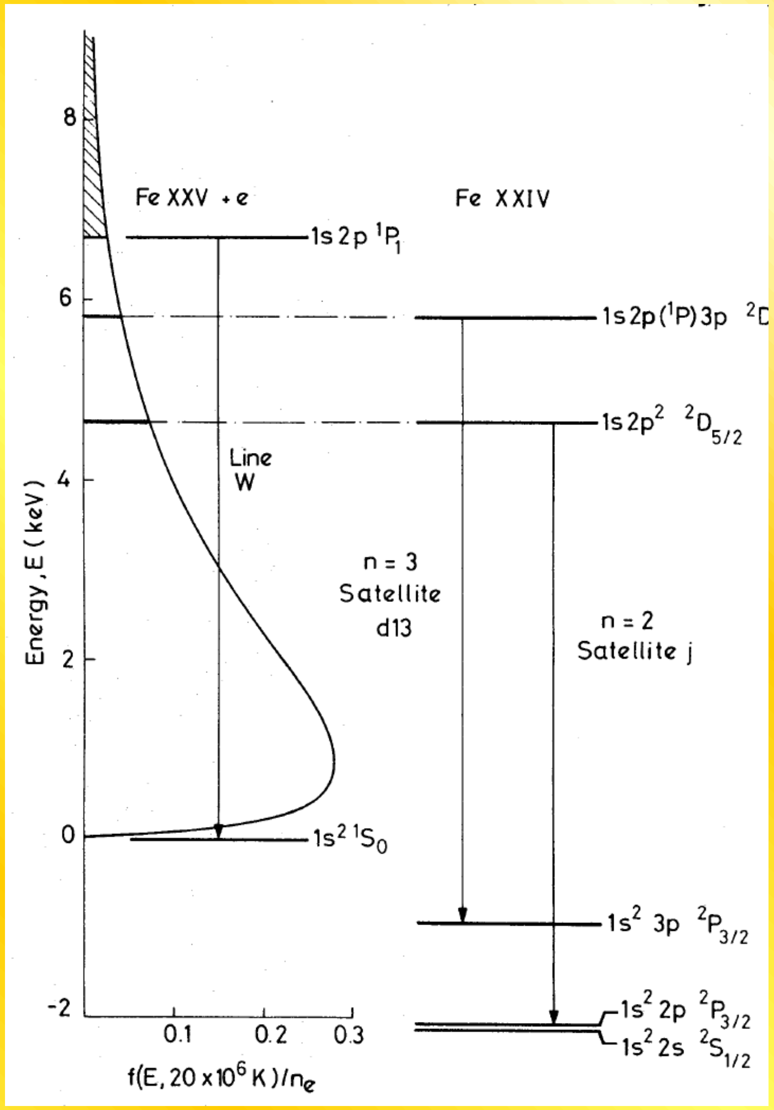
- excess excitation of the Fe XXV line
- decrease of the ratio by up to 40%

Produced in solar flares as a result of particle acceleration

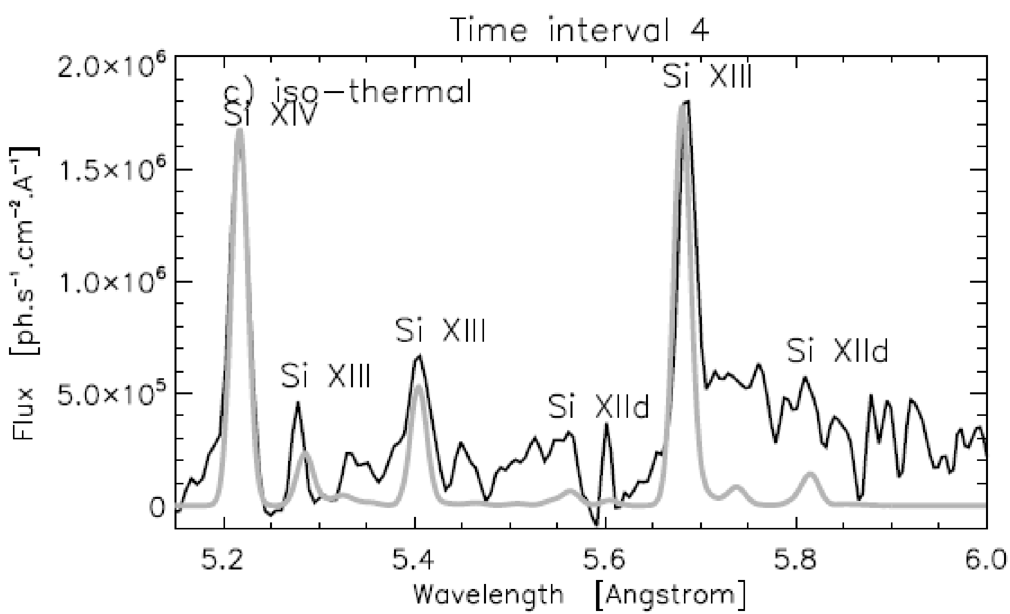
Fletcher et al. (2011), SSRv, 159, 19

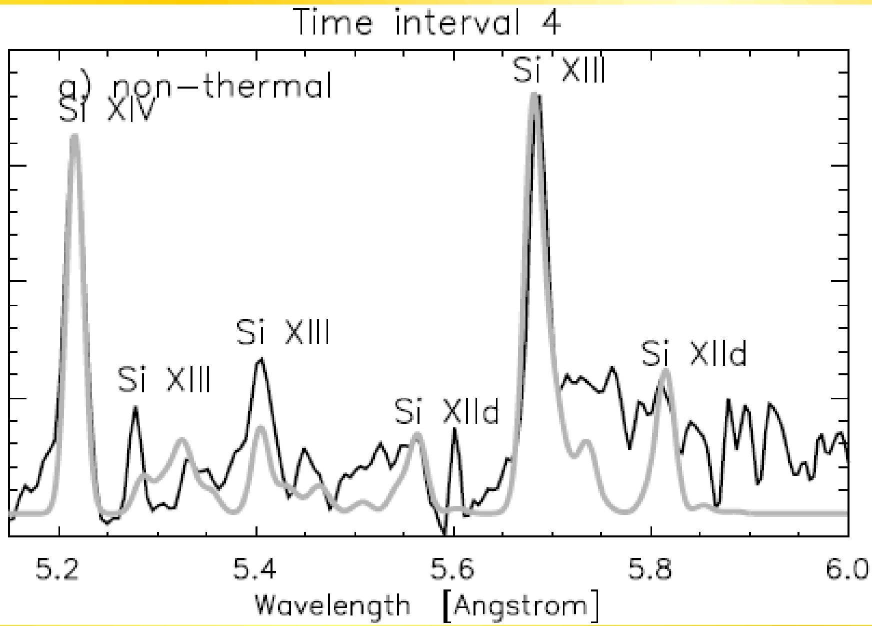
Zharkova et al. (2011), SSRv, 159, 357

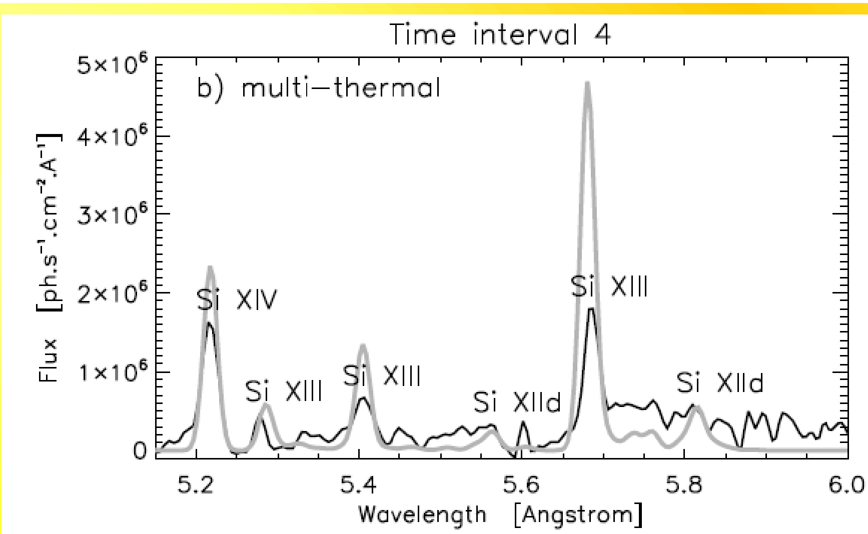
Petkaki & MacKinnon (2007, 2011)



Observed spectra - RESIK



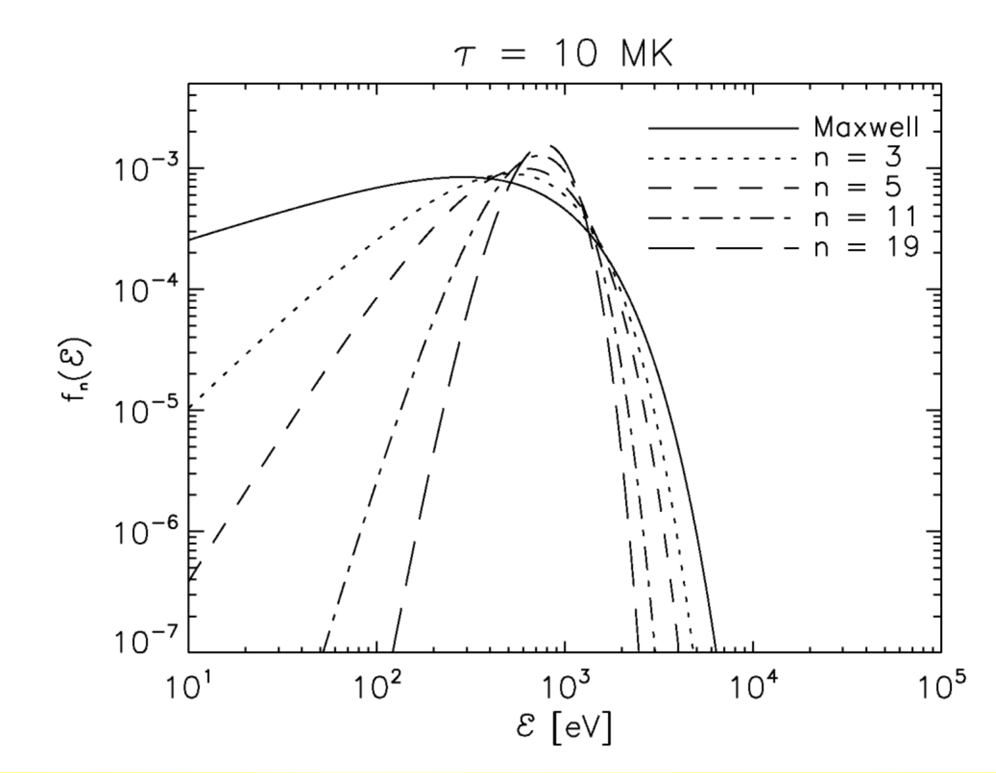




Dzifčáková et al. (2008), AA 488, 311

III. The *n*-distributions

$$f_n(E)dE = B_n \frac{2E^{1/2}}{\sqrt{\pi}\left(k_\mathrm{B}T\right)^{3/2}}\left(\frac{E}{k_\mathrm{B}T}\right)^{\frac{n-1}{2}} \mathrm{e}^{-E/k_\mathrm{B}T}dE$$



Peak narrower than Maxwellian

Very few low-energy electrons

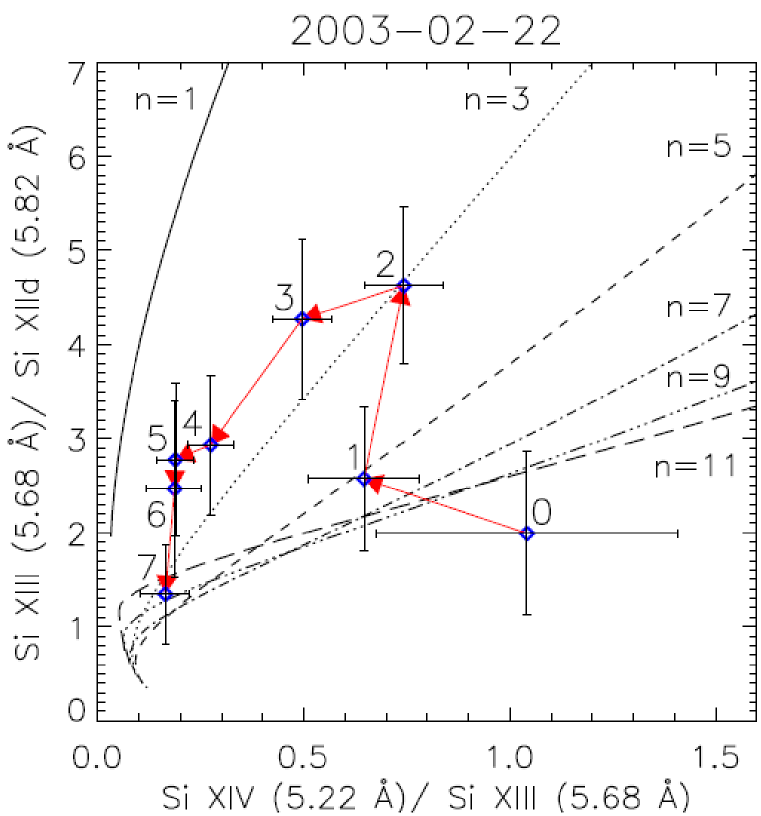
Pseudo-temperature τ:

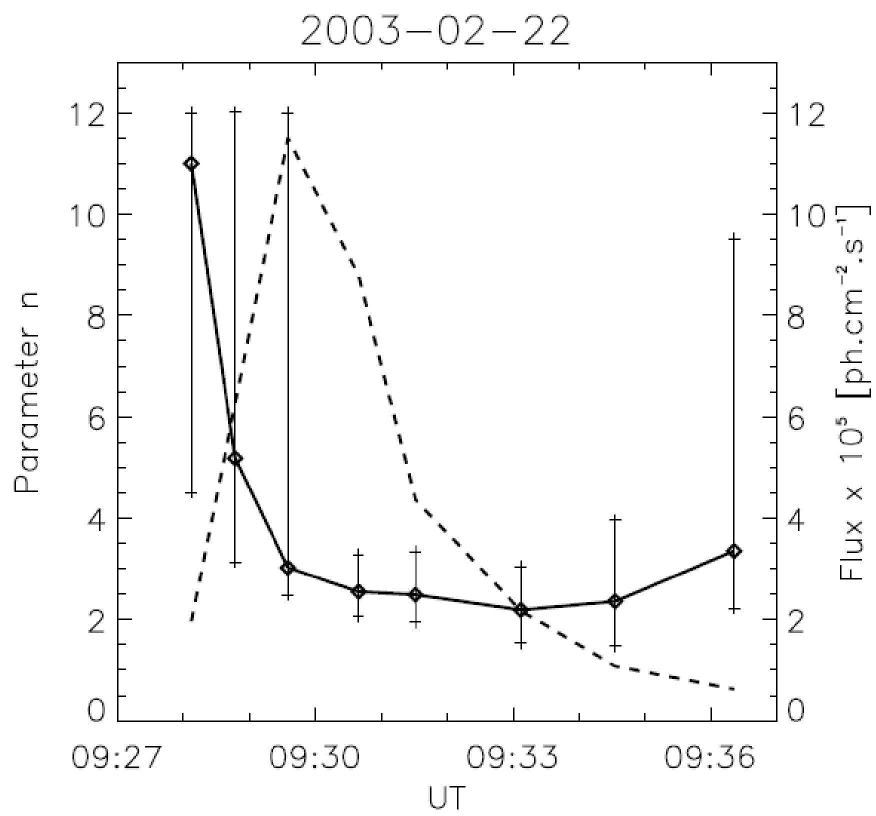
$$\langle E \rangle = \frac{3}{2}k\tau = \left(\frac{n}{2}+1\right)kT$$

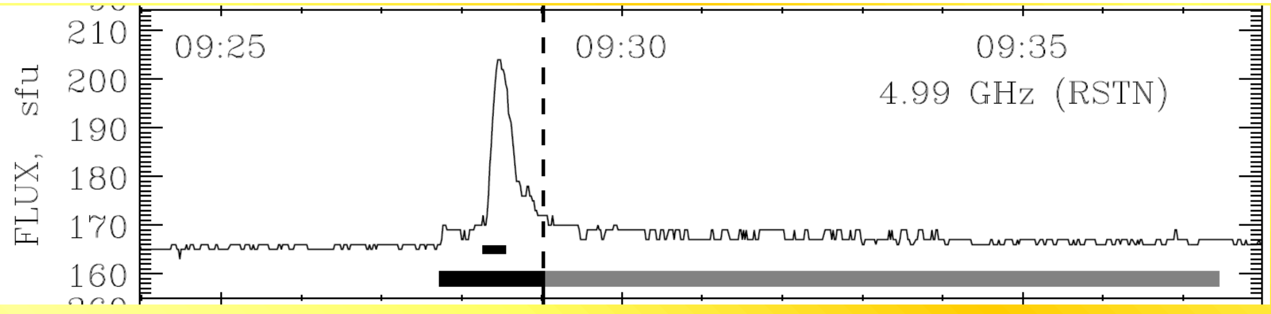
Seely, Feldman & Doschek (1987), ApJ 319, 541

Dzifčáková (1998), SoPh 187, 317

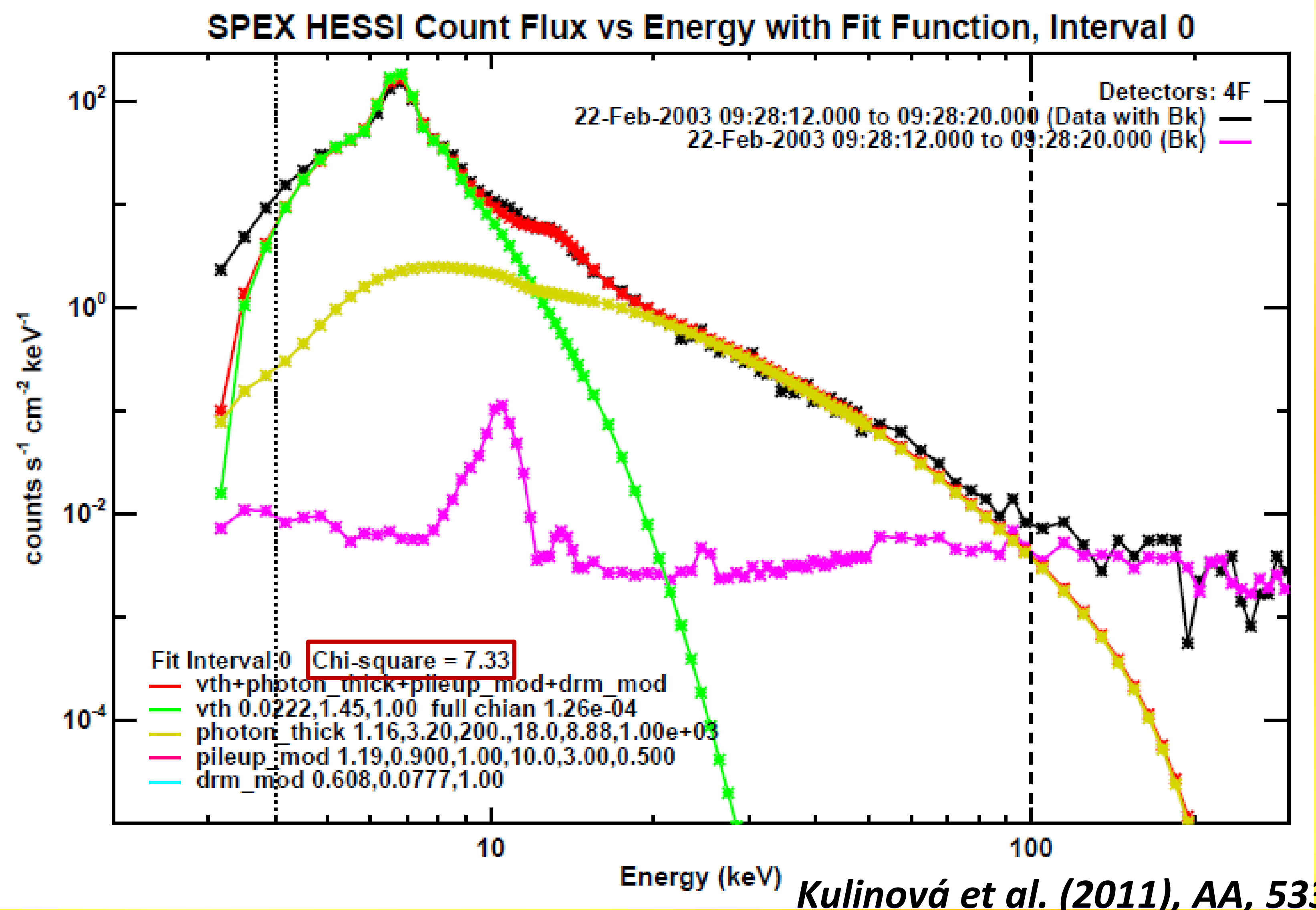
Diagnostics - results





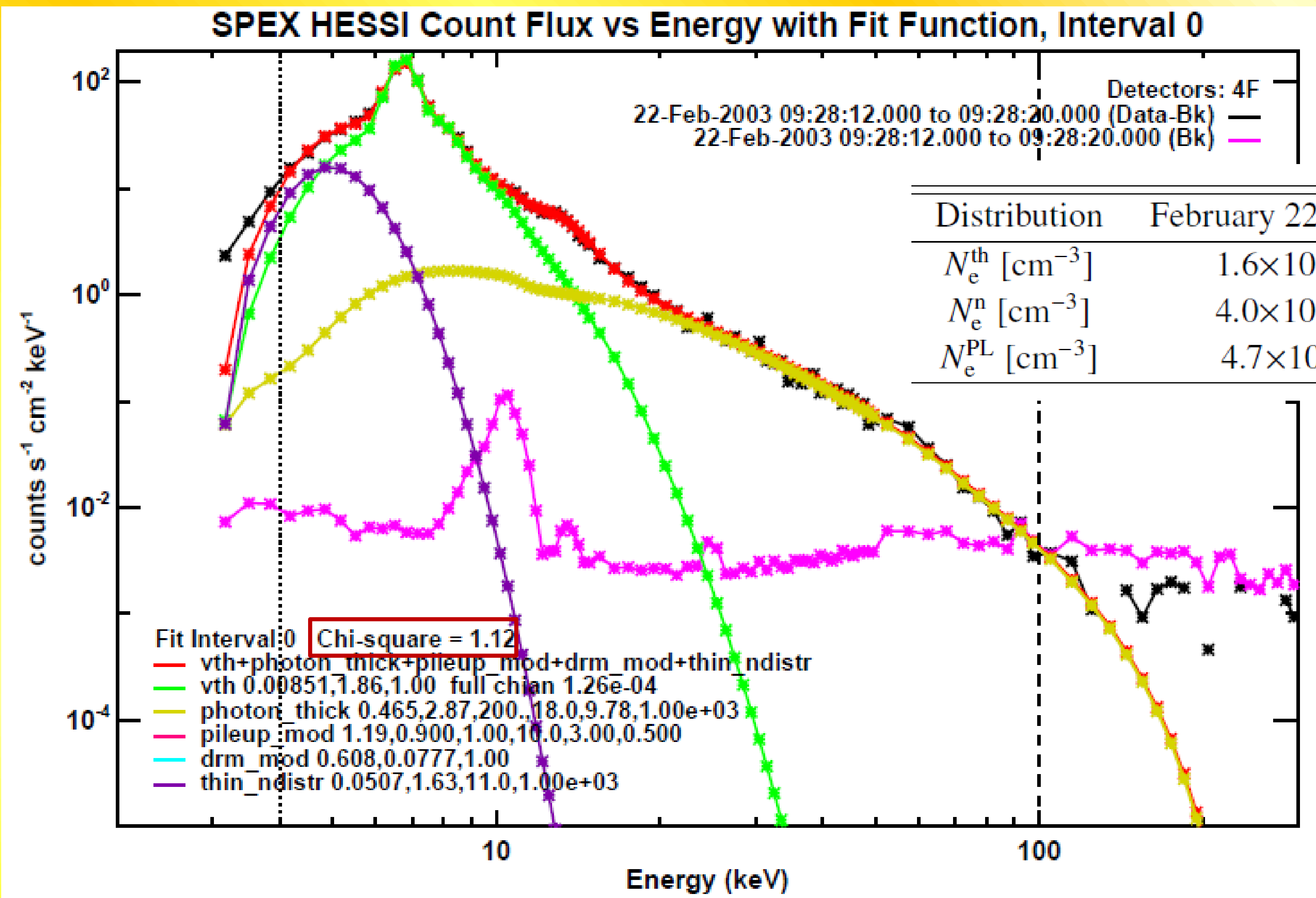


Diagnostics - RHESSI



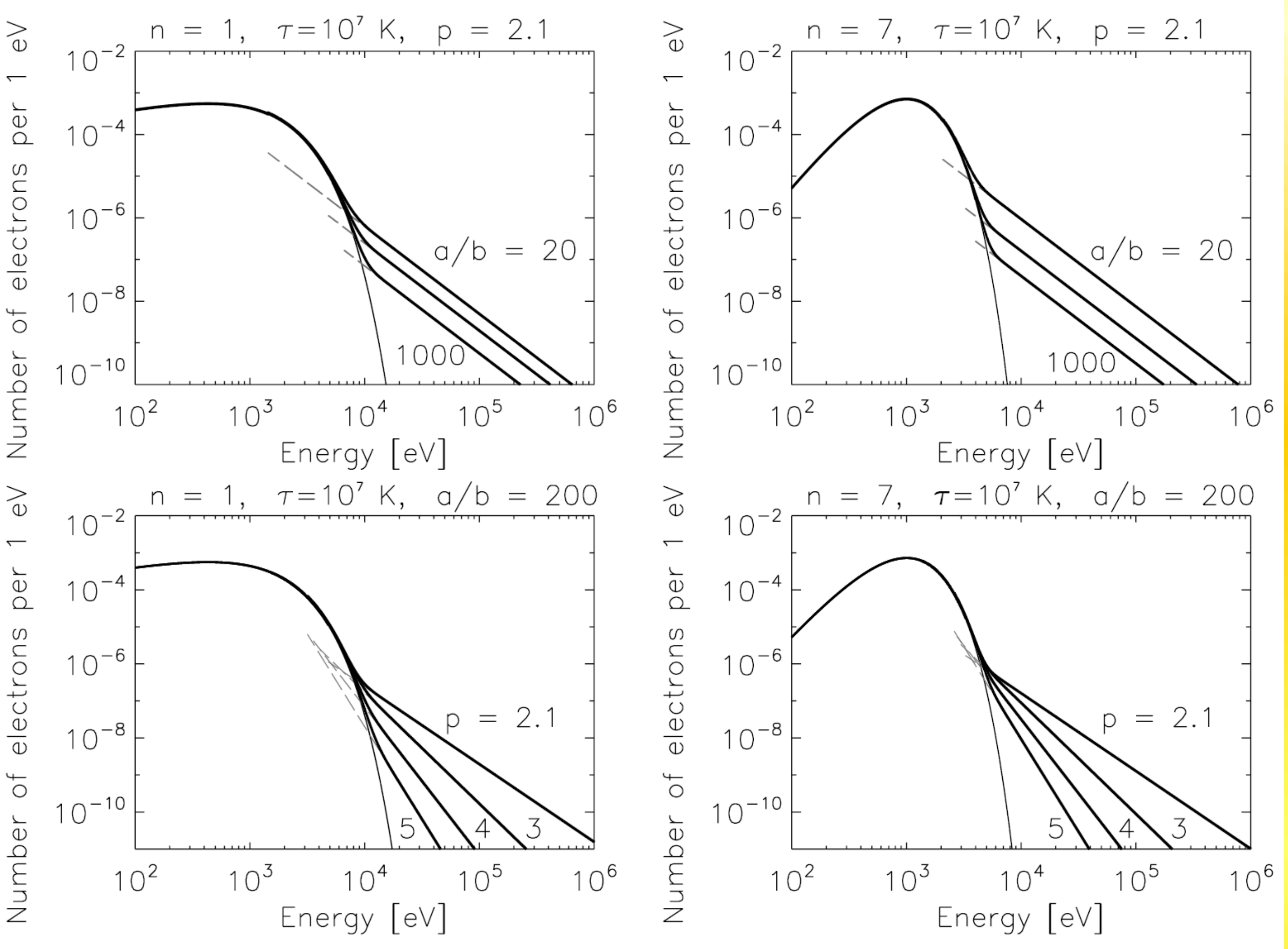
Kulinová et al. (2011), AA, 533, A81

Diagnostics - RHESSI

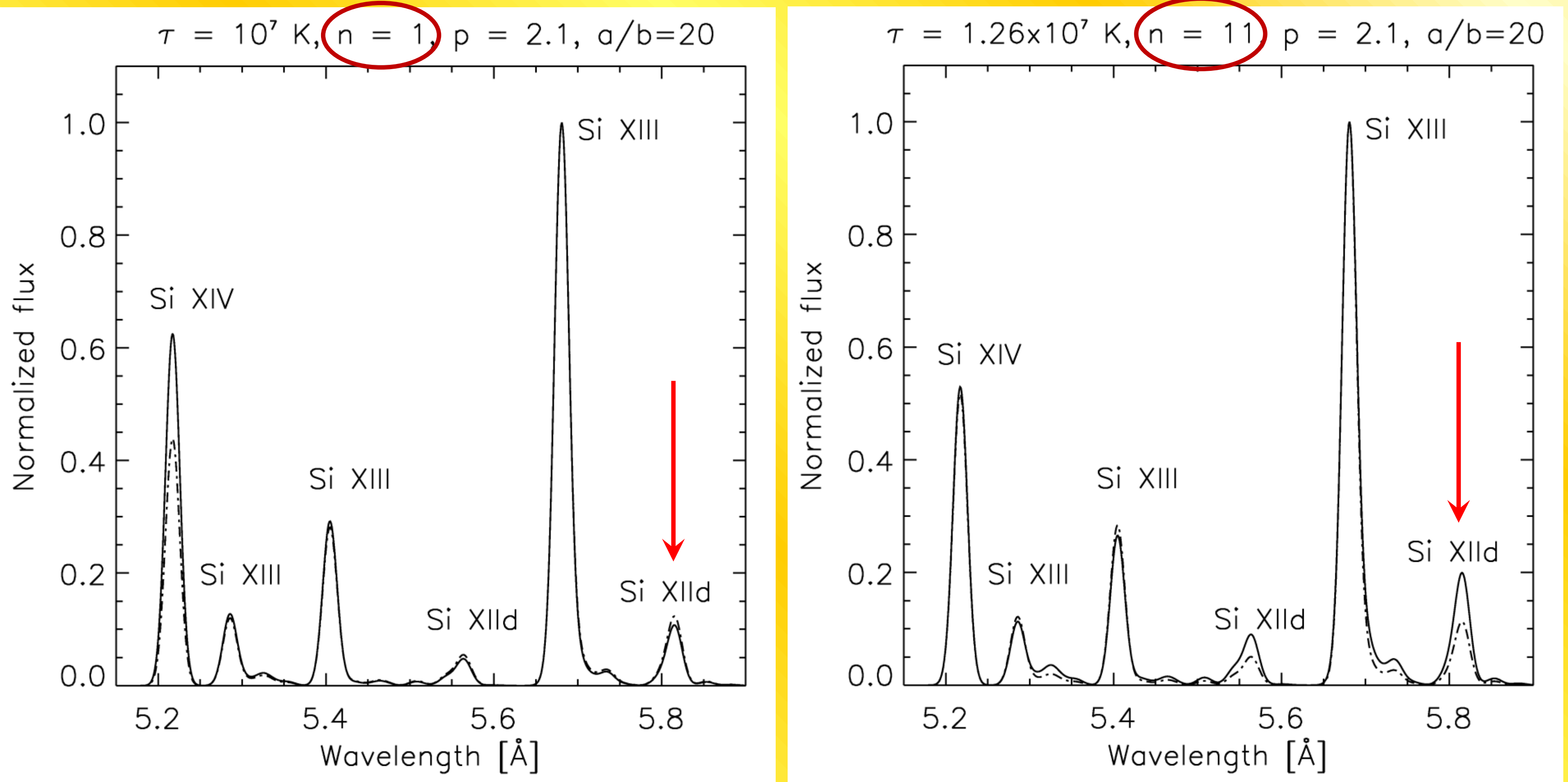


Distribution	February 22, 2003
N_e^{th} [cm^{-3}]	1.6×10^{10}
N_e^{n} [cm^{-3}]	4.0×10^{10}
N_e^{PL} [cm^{-3}]	4.7×10^{6}

Composed *np*-distribution



Si XIId: *tail* vs. *bulk*



Dzifčáková, Homola & Dudík (2011), AA 531, A111

Physical background - drifts

Karlický, Dzifčáková & Dudík (2012), Astron. Astrophys., 537, A36

„Moving Maxwellian“ (Maxwellian with a drift velocity v_0)

$$f(v_x, v_y, v_z) = C \exp\left[-\frac{(v_x - v_0)^2 + v_y^2 + v_z^2}{v_T^2}\right],$$

can be written as

$$f(E, v_0)\mathrm{d}E = C_1 \frac{\sinh\left[2\frac{v_0}{v_T}\sqrt{\frac{E}{k_B T}}\right]}{\frac{v_0}{v_T}} \exp\left[-\frac{E}{k_B T}\right] \mathrm{d}E,$$

With the $f(E,v_0)$ having the same gradient as the *n*-distribution.

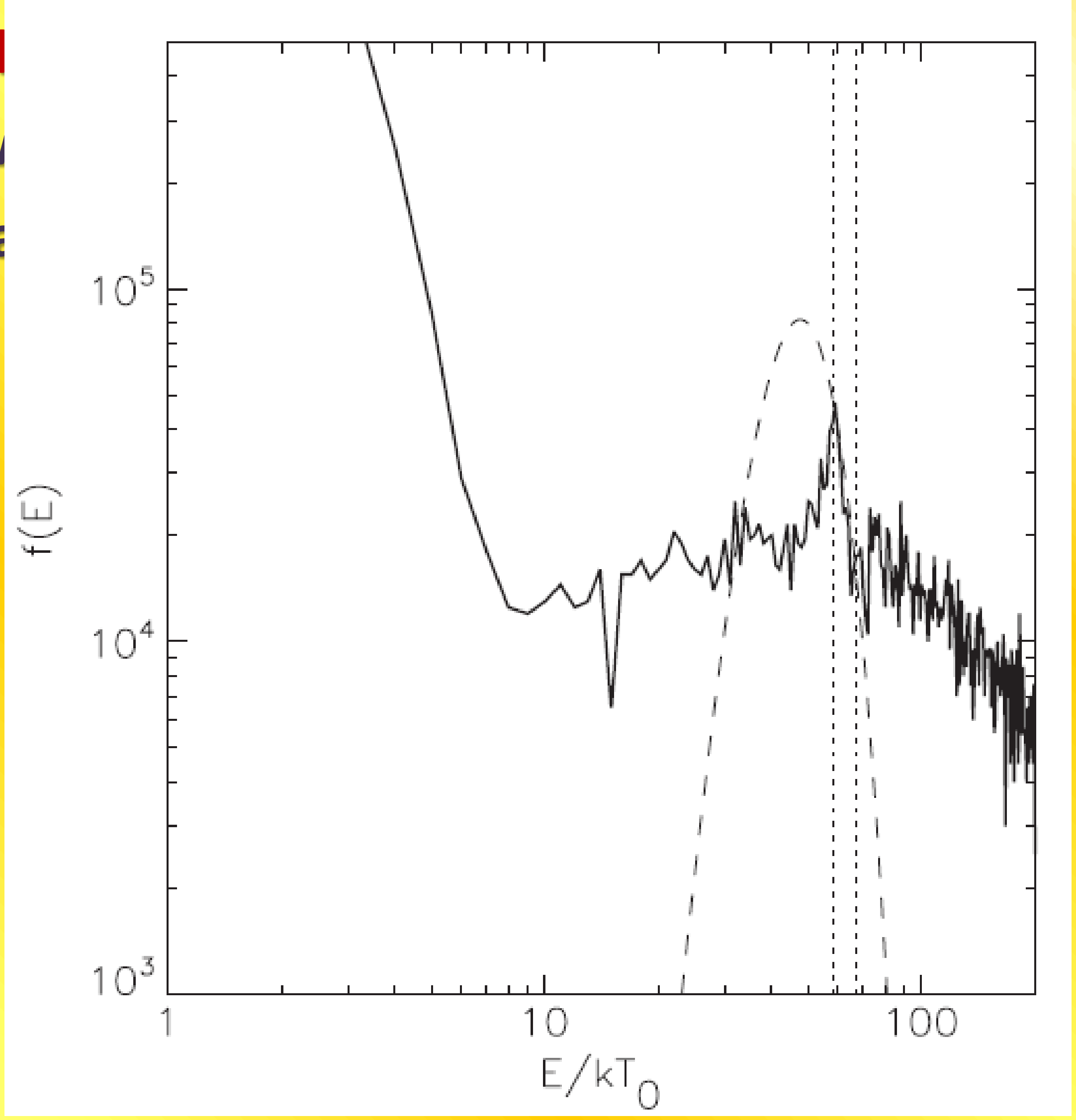
Double Layers

Moving Maxwellian is unstal

Double layers – structures w

– can lead to a

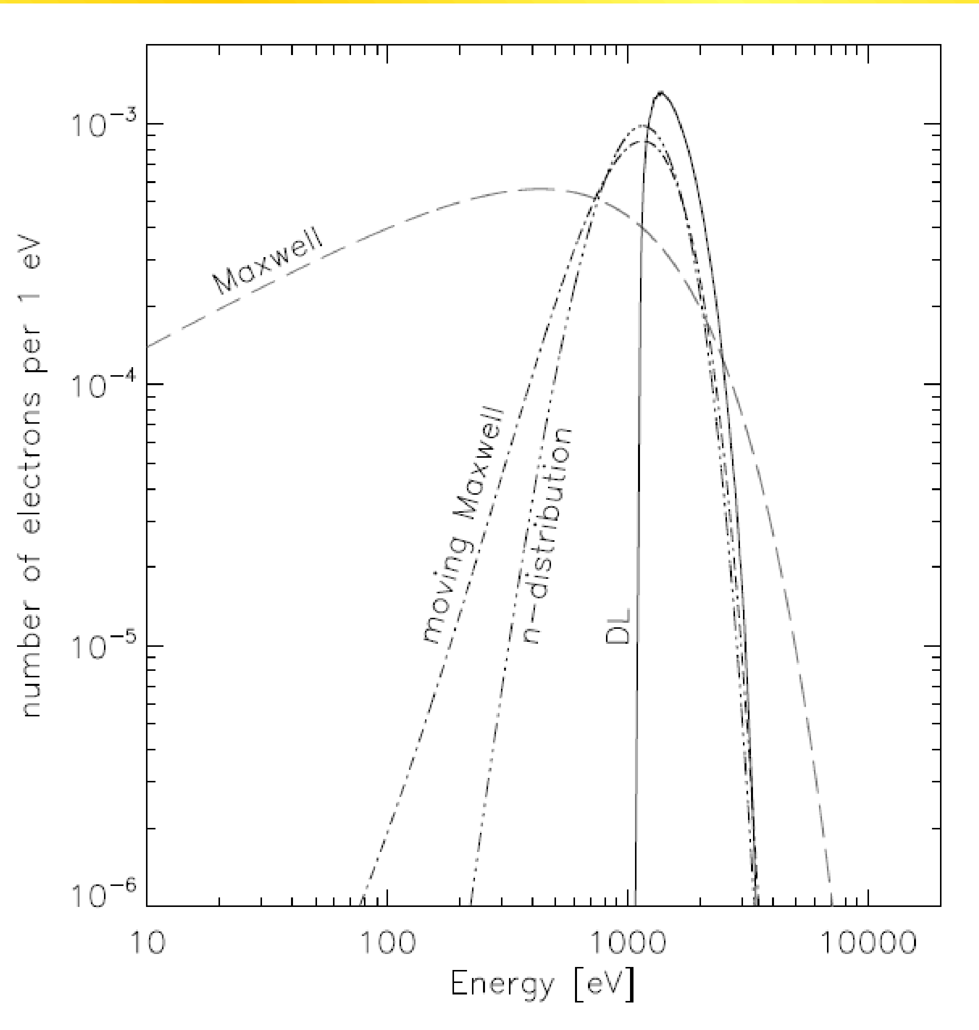
– observed in

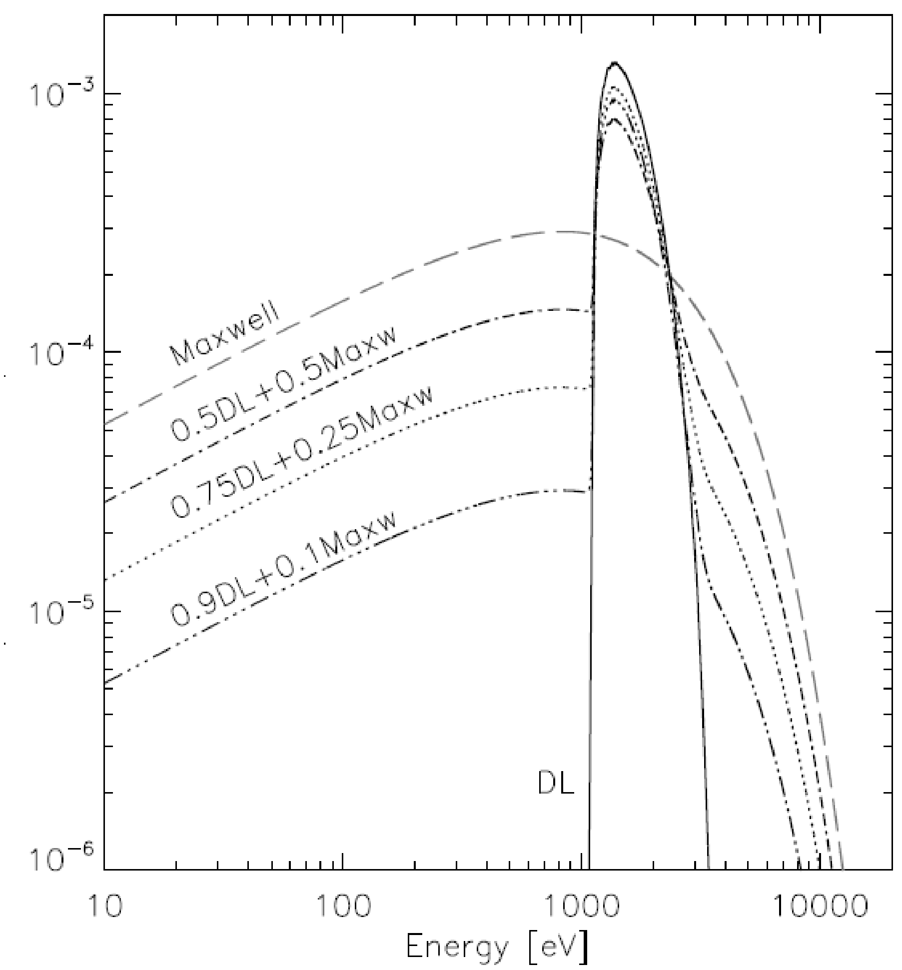


Karlický (2012), ApJ 750:49

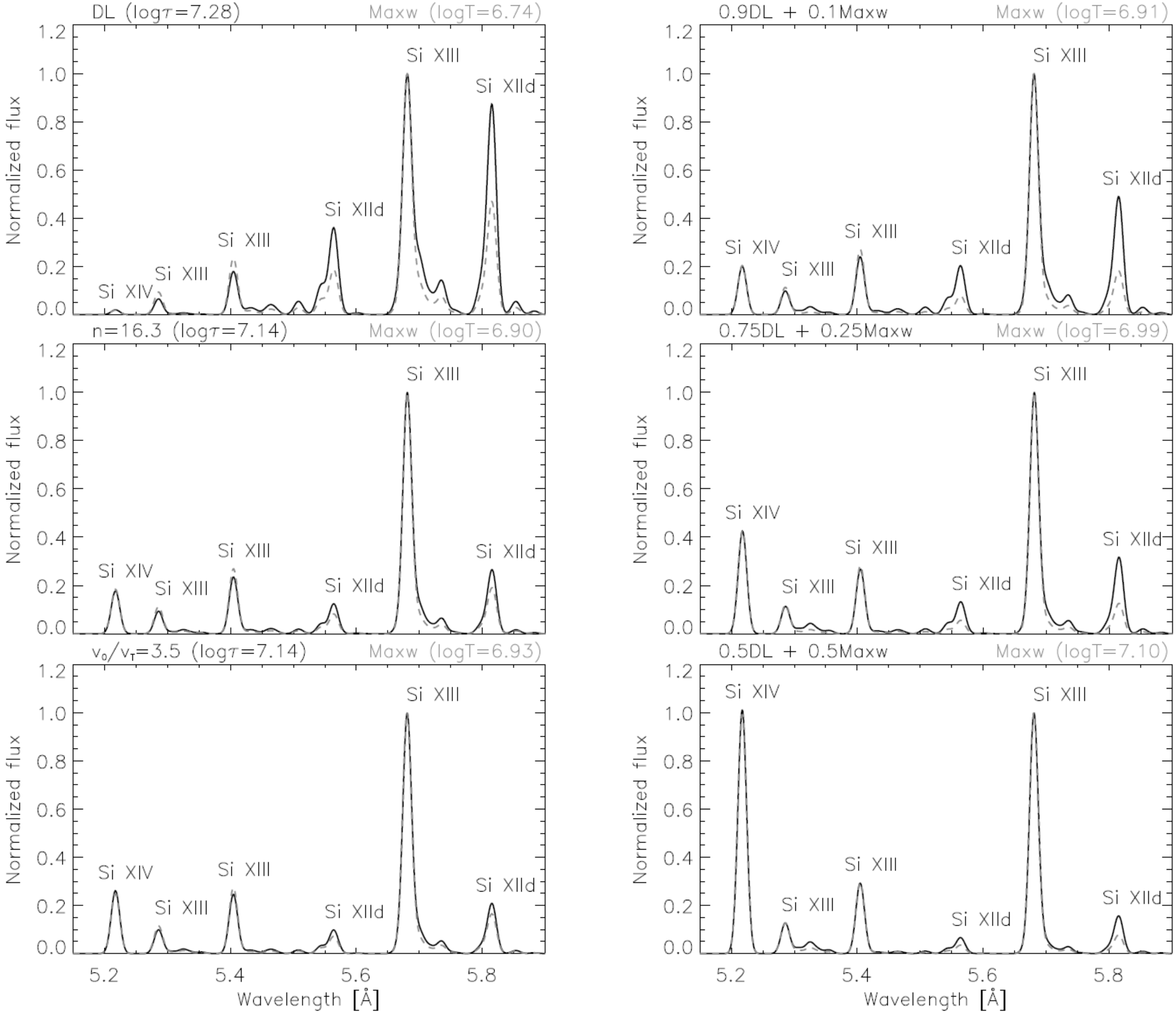
- simulation of DL using PIC code
- accelerated electrons
- return current
- reflected beam electrons

Double Layers and X-ray spectra



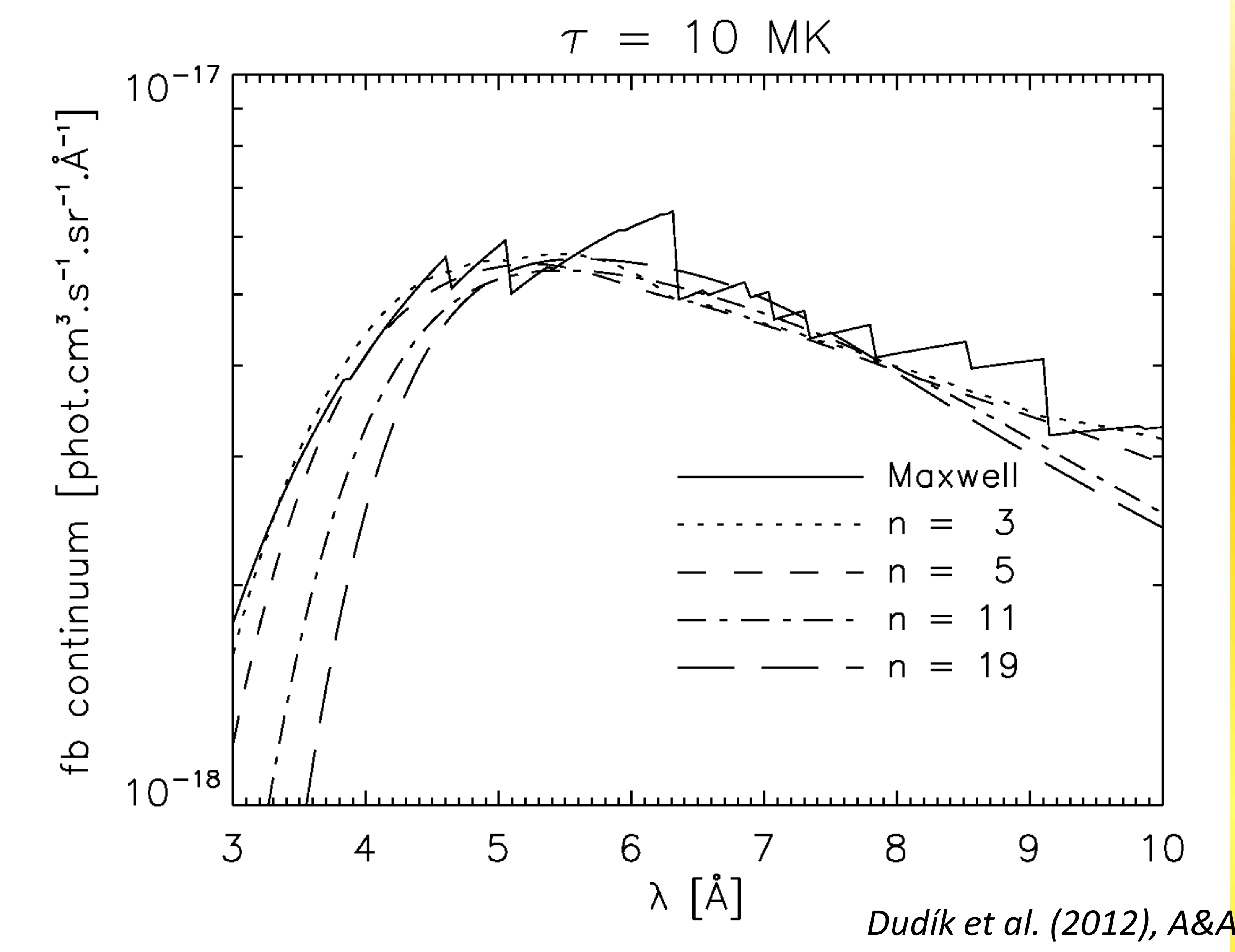


Dzifčáková et al. (2012), A&A, submitted



DL (logτ=7.28)
Maxw (logT=6.74)
0.9DL + 0.1Maxw
Maxw (logT=6.91)
n=16.3 (logτ=7.14)
Maxw (logT=6.90)
0.75DL + 0.25Maxw
Maxw (logT=6.99)
v0/vT=3.5 (logτ=7.14)
Maxw (logT=6.93)
0.5DL + 0.5Maxw
Maxw (logT=7.10)
Si XIV
Si XIII
Si XIId
Normalized flux
Wavelength [Å]

Theoretical f-b continuum



Dudík et al. (2012), A&A, 539, A107

Conclusions

- **H-like, He-like lines and Li-like dielectronic satellites offer important plasma diagnostics**
  - sampling the distribution function at discrete energies

- **Flares: both high-energy tail AND non-Maxwellian bulk**
  - Si XIId lines not sensitive to tail: diagnose distribution core
  - DL + background gives good match to observations

NOTES:

- No X-ray spectrometers. Need a new one.
- Revisit previous observations? (SMM/BCS)
- Use many lines to sample the distribution at various energies
- Energy considerations: radiative cooling affected

Sunset in Ondřejov,
April 1st, 2011

Thank you for your attention

The composed *np*-distributions

Dzifčáková, Homola & Dudík (2011), AA 531, A111:

Composed *np*-distribution: Bulk (*n*) + Tail (*p*)

$$f_n(\mathcal{E} \geq 0)\mathrm{d}\mathcal{E} = \mathcal{B}_n \frac{2}{\sqrt{\pi}(kT)^{3/2}} \left(\frac{\mathcal{E}}{kT}\right)^{\frac{n-1}{2}} \mathcal{E}^{1/2} \exp\left(-\frac{\mathcal{E}}{kT}\right)\mathrm{d}\mathcal{E},$$

$$f_p(\mathcal{E} \geq E_\mathrm{C})\mathrm{d}\mathcal{E} = \frac{(p-1)}{E_\mathrm{C}} \left(\frac{E_\mathrm{C}}{\mathcal{E}}\right)^p \mathrm{d}\mathcal{E},$$

$$f_{np}(\mathcal{E})\mathrm{d}\mathcal{E} = a \cdot f_n(\mathcal{E}) + b \cdot f_p(\mathcal{E})\mathrm{d}\mathcal{E},$$

n – **index *n* describing the bulk**

p – **power-law index of the high-energy tail**

E_C – **low-energy cutoff for the power-law tail**

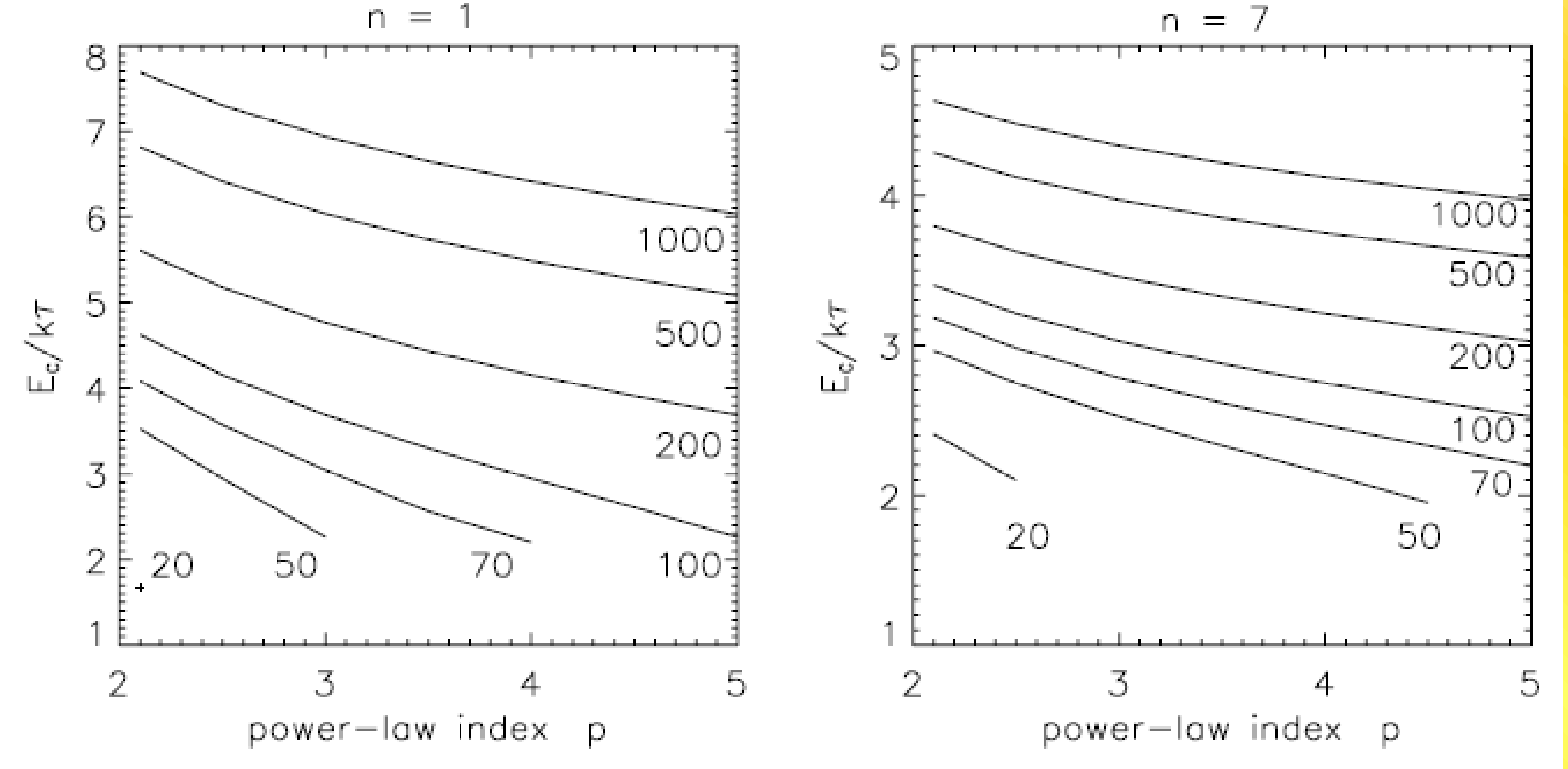
a/b – **bulk/tail ratio, a + b = 1**

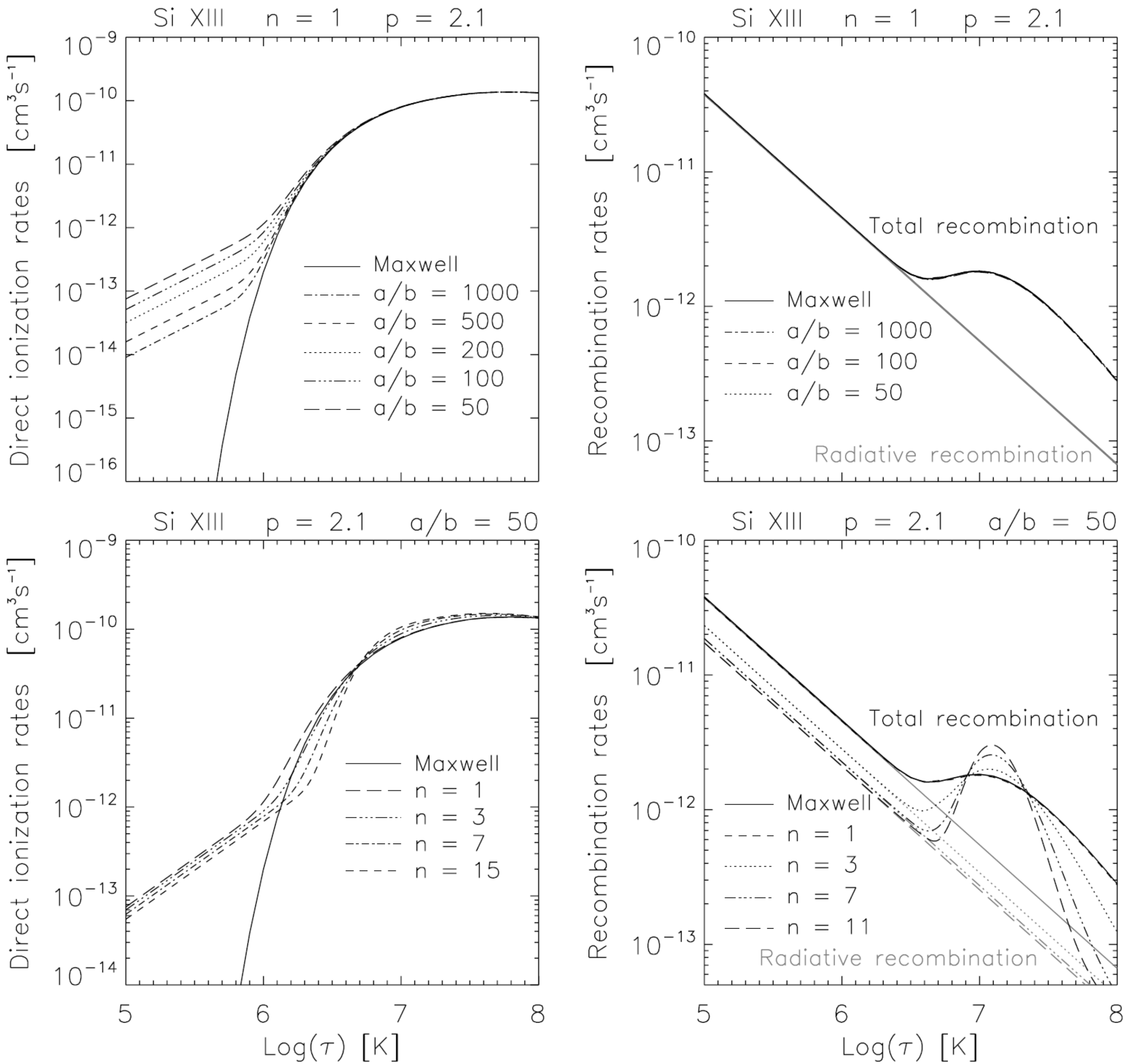
Construction of the distribution

Conditions for E_C :

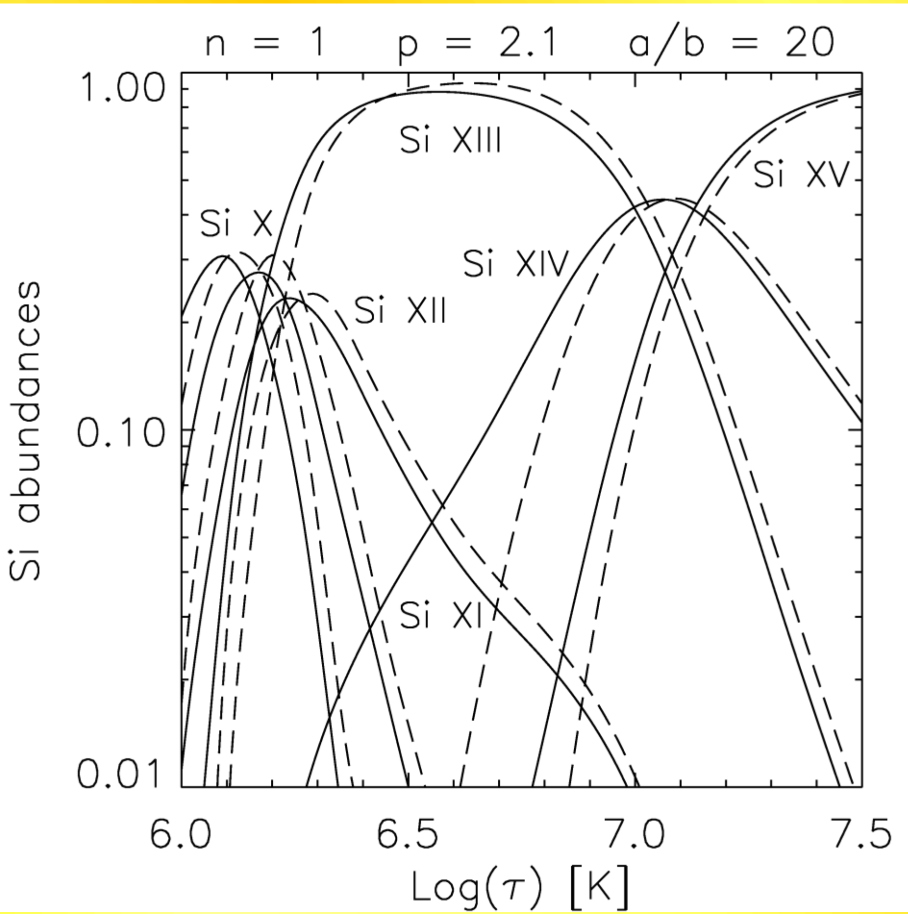
- the power-law tail does not affect the plasma bulk

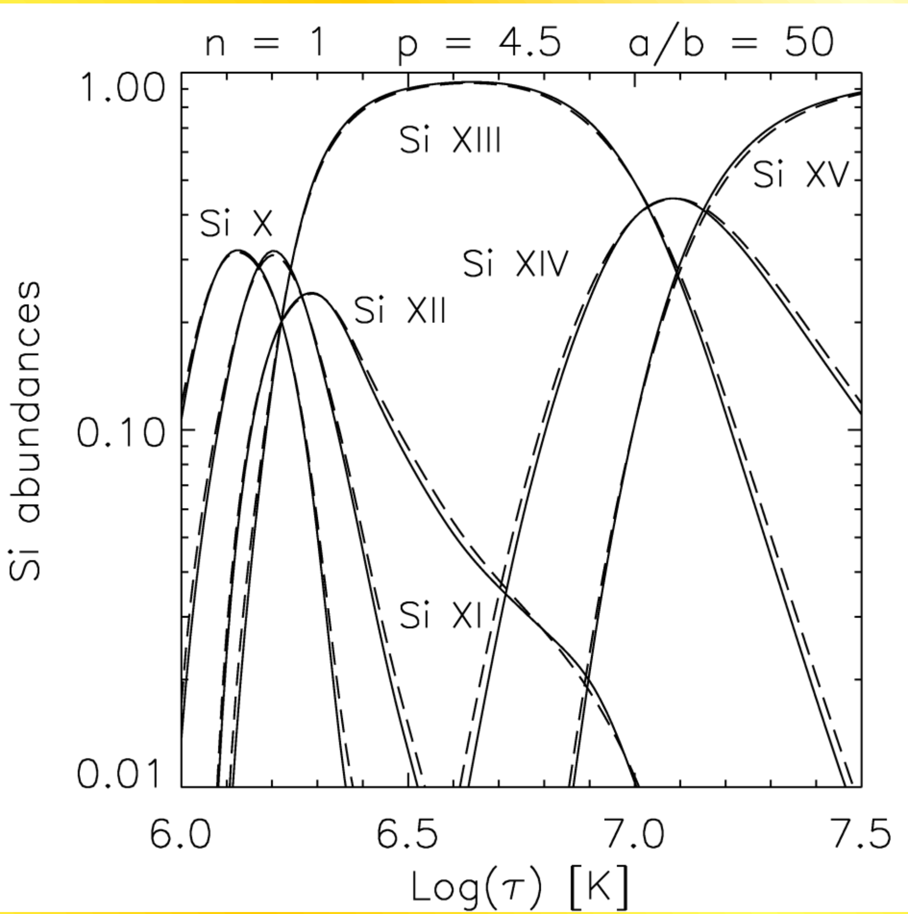
- less than 10% discontinuity at E_C




Si XIII n = 1 p = 2.1
Direct ionization rates [cm^3s^-1]
Maxwell
a/b = 1000
a/b = 500
a/b = 200
a/b = 100
a/b = 50
Si XIII n = 1 p = 2.1
Recombination rates [cm^3s^-1]
Total recombination
Maxwell
a/b = 1000
a/b = 100
a/b = 50
Radiative recombination
Si XIII p = 2.1 a/b = 50
Direct ionization rates [cm^3s^-1]
Maxwell
n = 1
n = 3
n = 7
n = 15
Log(τ) [K]
Si XIII p = 2.1 a/b = 50
Recombination rates [cm^3s^-1]
Total recombination
Maxwell
n = 1
n = 3
n = 7
n = 11
Radiative recombination
Log(τ) [K]

Ionization equilibrium – tail only





Ionization equilibrium – bulk + tail