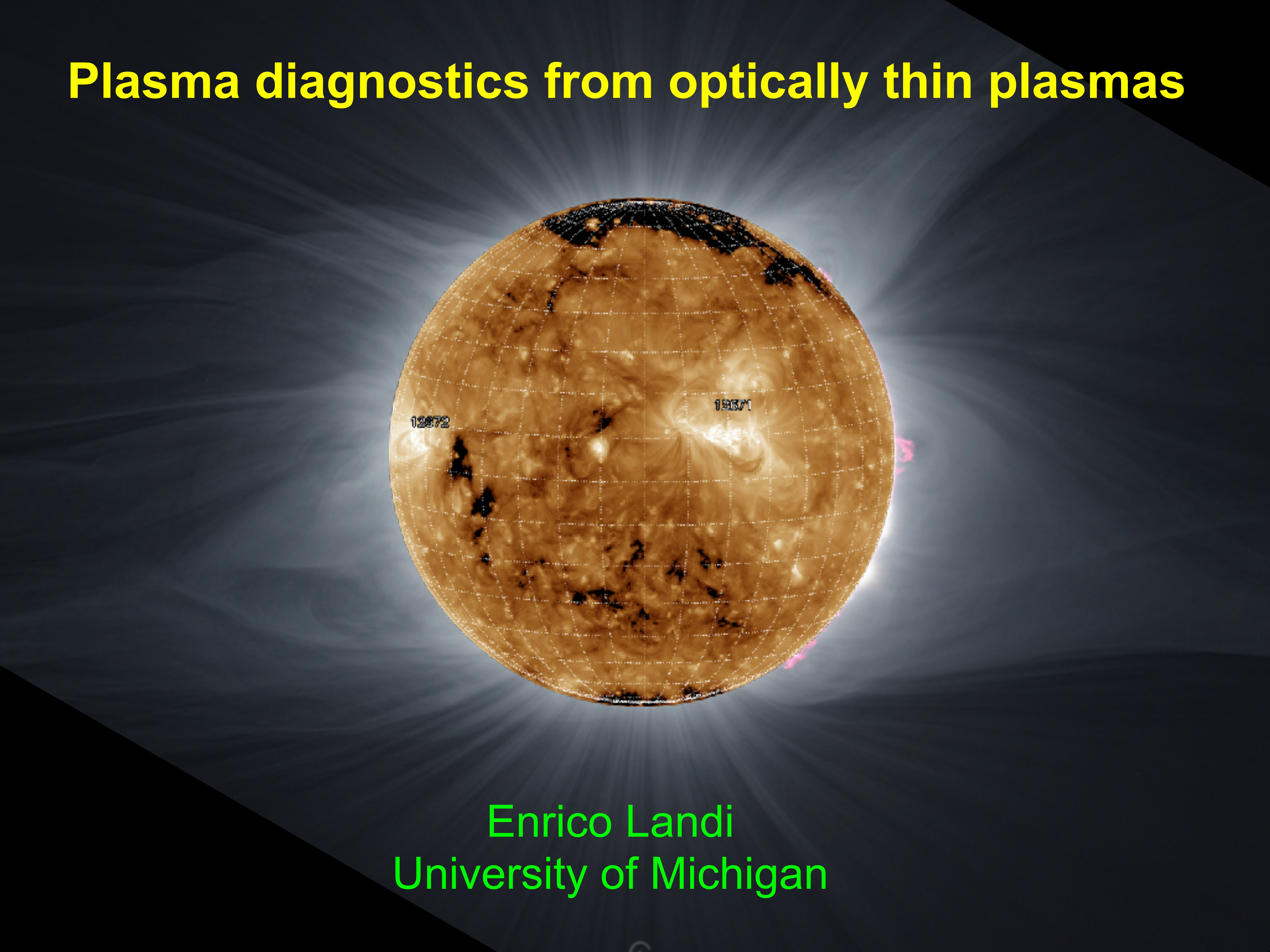
Plasma diagnostics from optically thin plasmas



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Plasma diagnostics: what we want to know

Anything we can

- Thermal status
  - Electron density
  - Ion and electron temperatures
  - Plasma thermal distribution
- Dynamics
  - Bulk motions
  - Non-thermal motions
- Composition
  - Elemental abundances
  - Ion abundances
- Magnetic field

Plan of the lecture

Focus on *EUV spectral line diagnostics only*

Topics:

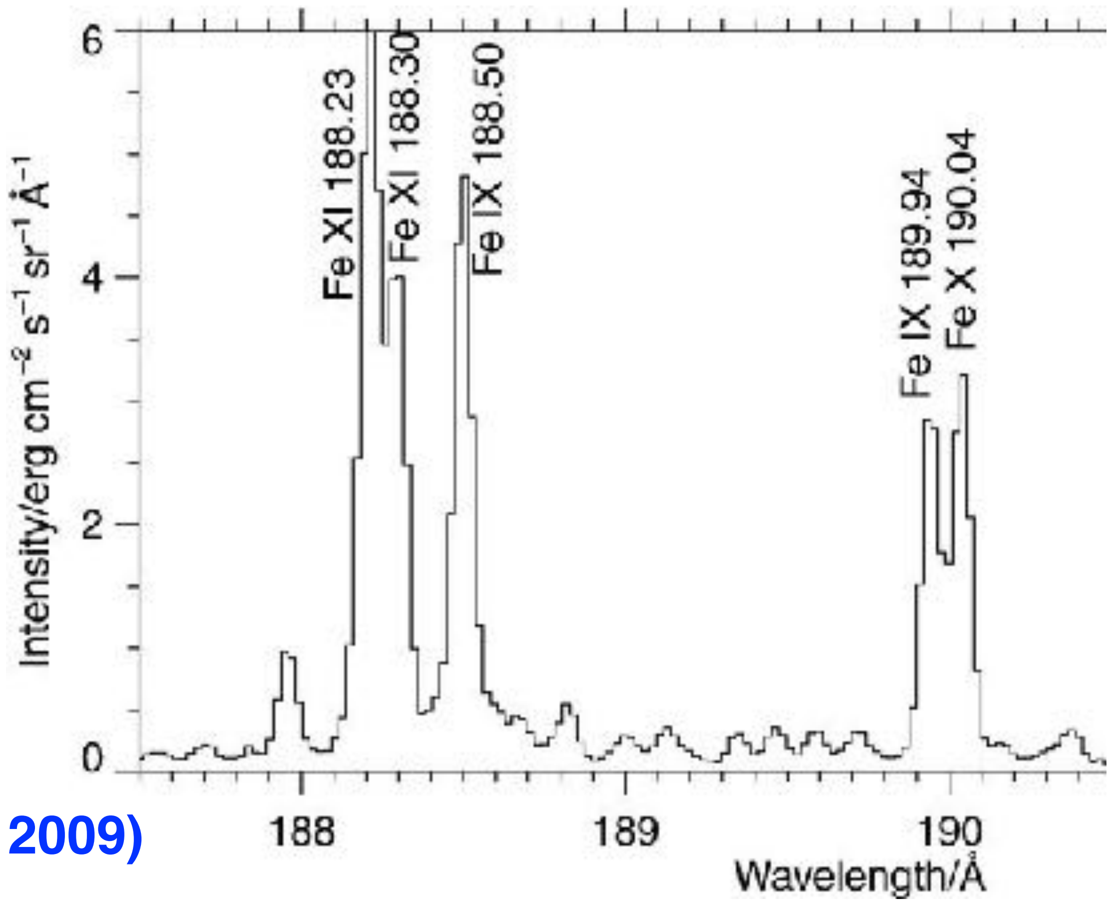
1 - Basics of line formation mechanisms

2 - Plasma diagnostics techniques

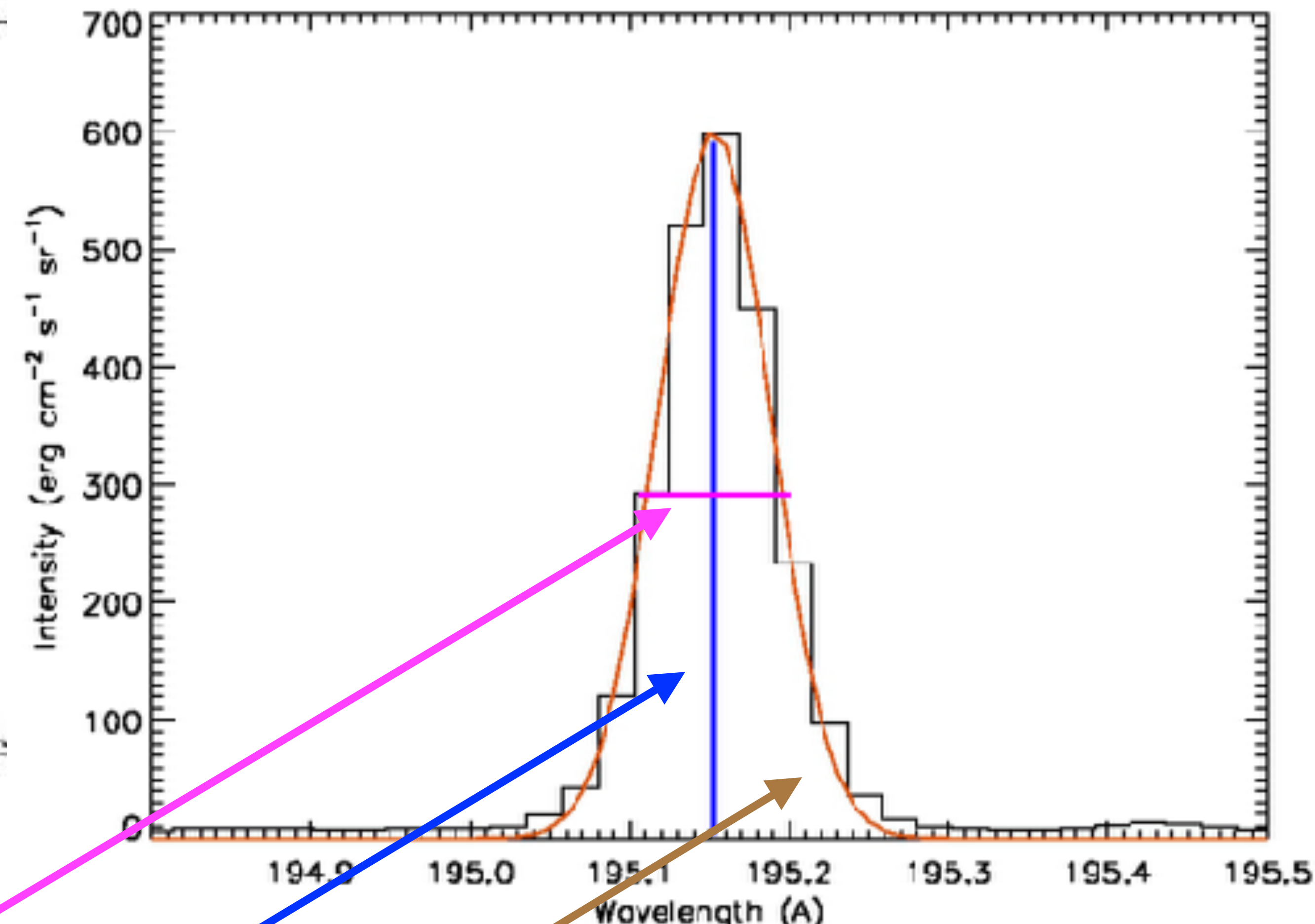
A. Intensity ratios
B. Thermal structure
C. Line width
D. Ion temperatures
E. Wind speed

Will neglect: *magnetic field (DKIST, UCoMP)*

What we measure



(Young 2009)



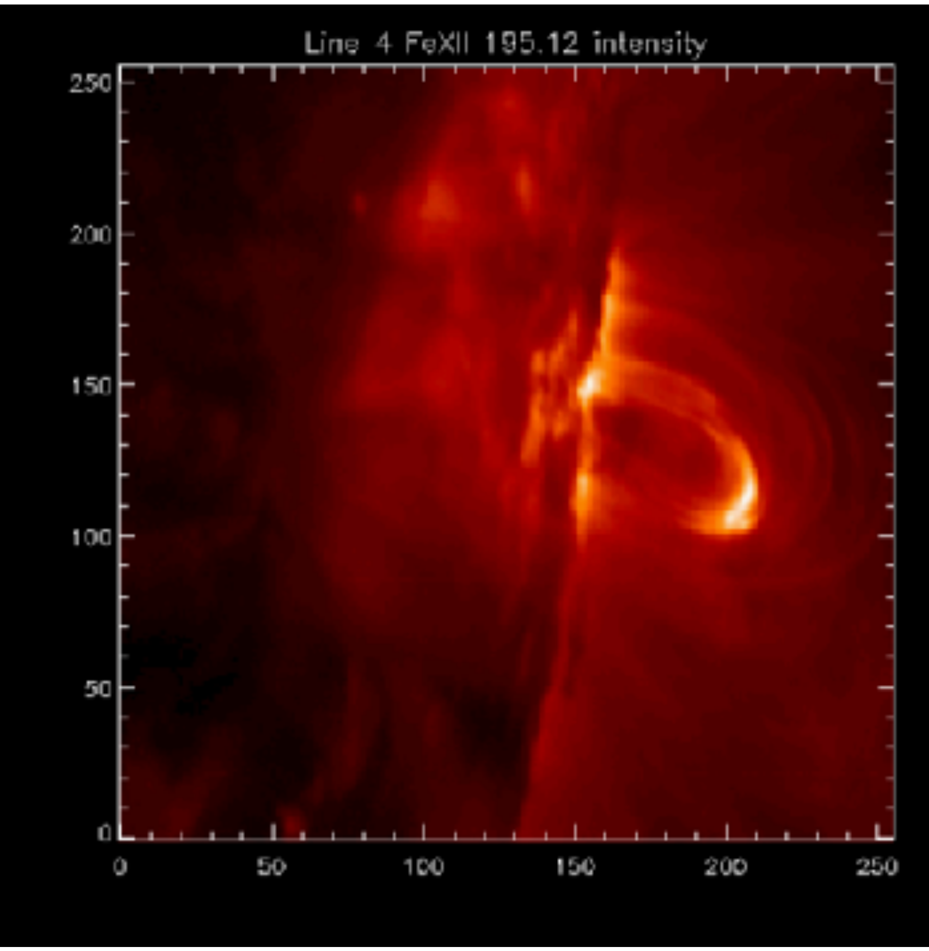
Spectral lines

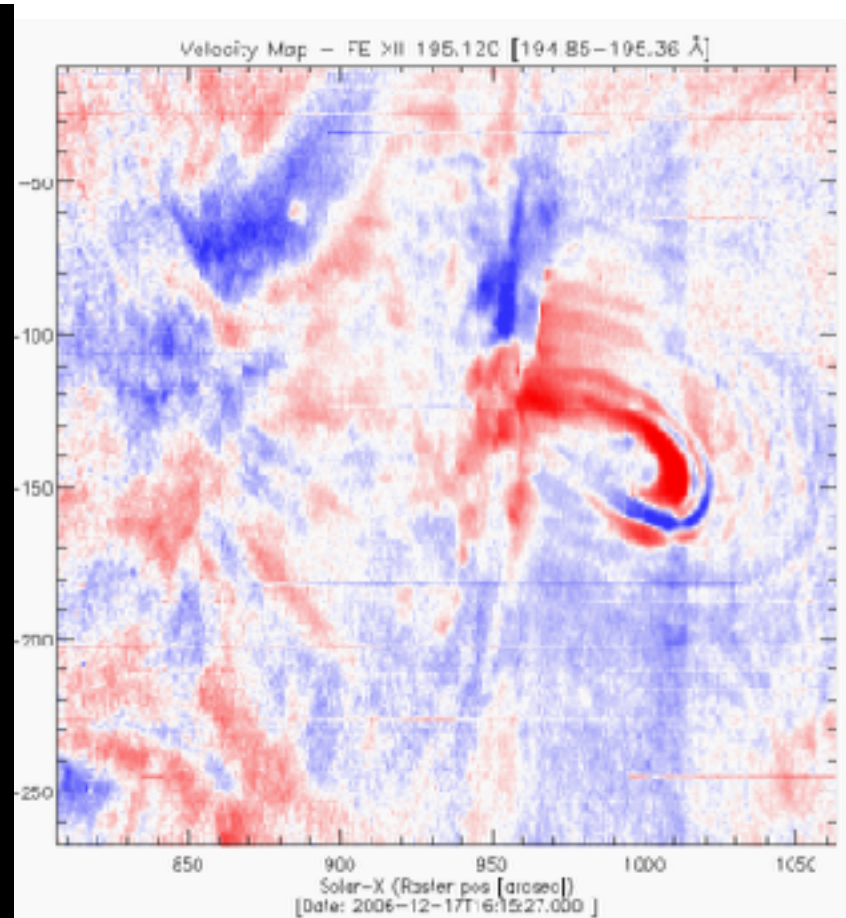
- Line width
- Line centroid
- Line flux or intensity (the area)

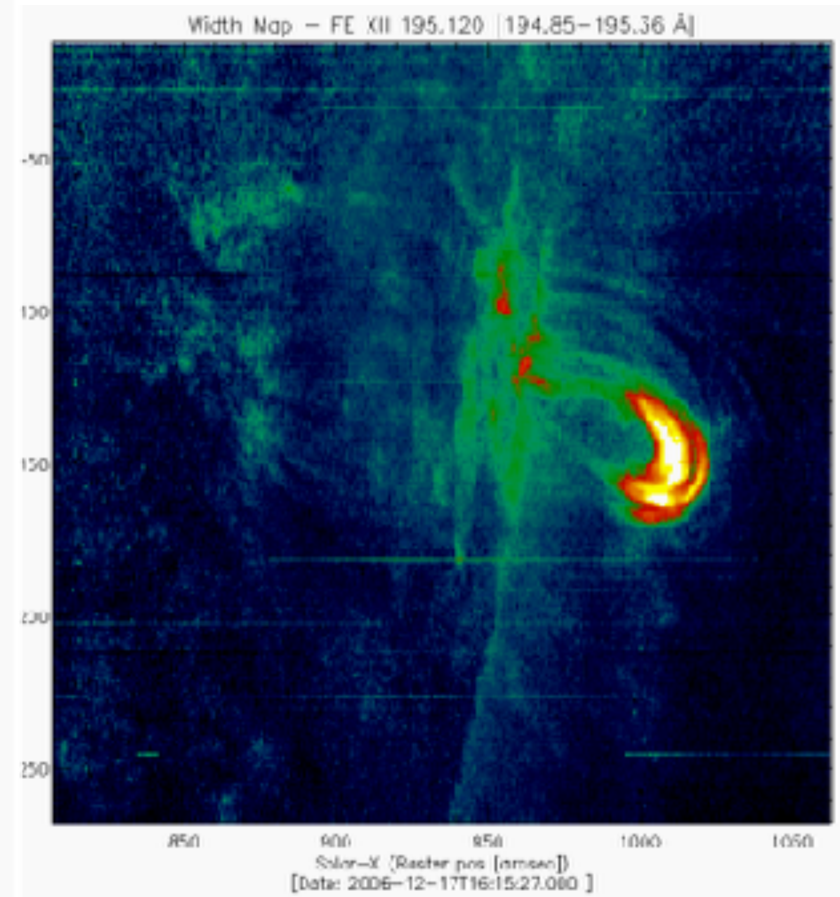
How: Gaussian fitting of observed lines

How to use the measurements

(Courtesy Hinode/EIS team)







Line intensity

Many plasma parameters

Line centroid

Line-of-sight bulk speed

Line width (FWHM)

Non-thermal dynamics

Ion temperatures

$$\frac{\lambda - \lambda_{ij}}{\lambda_{ij}} = \frac{\mathrm{v}}{c}$$

$$FWHM = \frac{\lambda_{ji}}{c}\sqrt{4\ln 2\left(\frac{2k_B T_{ion}}{M} + \mathrm{v}_{nth}^2\right)}$$

How to use the line intensity

Line intensities

- Electron density and temperature
- Plasma thermal structure
- Element abundances

Line polarization

- Magnetic field

Exotic techniques

- Absorption
- Techniques for simultaneous diagnostics
- Empirical modeling

The solar coronal spectrum

The ingredients — individual volume dV

$$dW_{ji} = N_j\left(X^{+m}\right)A_{ji}h\nu_{ji}dV \qquad erg\ s^{-1}$$ Emitted power

$$h\nu_{ji} = E_j - E_i$$ Transition energy

$$A_{ji}$$ Einstein coefficient

$$N_j\left(X^{+m}\right)$$ Number density of emitters

$$dV = S\ dx$$ Emitting volume

The optically thin assumption

$$F = \frac{S}{4\pi d^2}\int_{-\infty}^{+\infty} N_j\left(X^{+m}\right)A_{ji}h\nu_{ji}\,dx$$

The solar coronal spectrum

The interesting physics is in the number density of emitters

$$N_j\left(X^{+m}\right)=\frac{N_j\left(X^{+m}\right)}{N\left(X^{+m}\right)}\frac{N\left(X^{+m}\right)}{N\left(X\right)}\frac{N\left(X\right)}{N\left(H\right)}\frac{N\left(H\right)}{N_e}N_e$$

Level population

Ion population
(the charge state composition)

Element abundance

Free electron/hydrogen ratio

Electron density

Absolute abundance = abundance relative to H

The solar coronal spectrum

Each of these terms is our gateway to plasma properties

$$\frac{N_j\left(X^{+m}\right)}{N\left(X^{+m}\right)} = f\left(T_e, N_e\right)$$

Used for electron density and temperature diagnostics

$$\frac{N\left(X^{+m}\right)}{N\left(X\right)} = f\left(T_e\right)$$

Used for thermal structure diagnostics

$$\frac{N\left(X\right)}{N\left(H\right)}$$

Used for element abundance diagnostics

$$\frac{N\left(H\right)}{N_e} = f\left(T_e\right)$$

T-sensitive below 100,000K

$$N_e$$

Denser plasmas will emit more

The level population

$$N_j\left(X^{+m}\right)=\frac{N_j\left(X^{+m}\right)}{N\left(X^{+m}\right)}\frac{N\left(X^{+m}\right)}{N\left(X\right)}\frac{N\left(X\right)}{N\left(H\right)}\frac{N\left(H\right)}{N_e}N_e$$

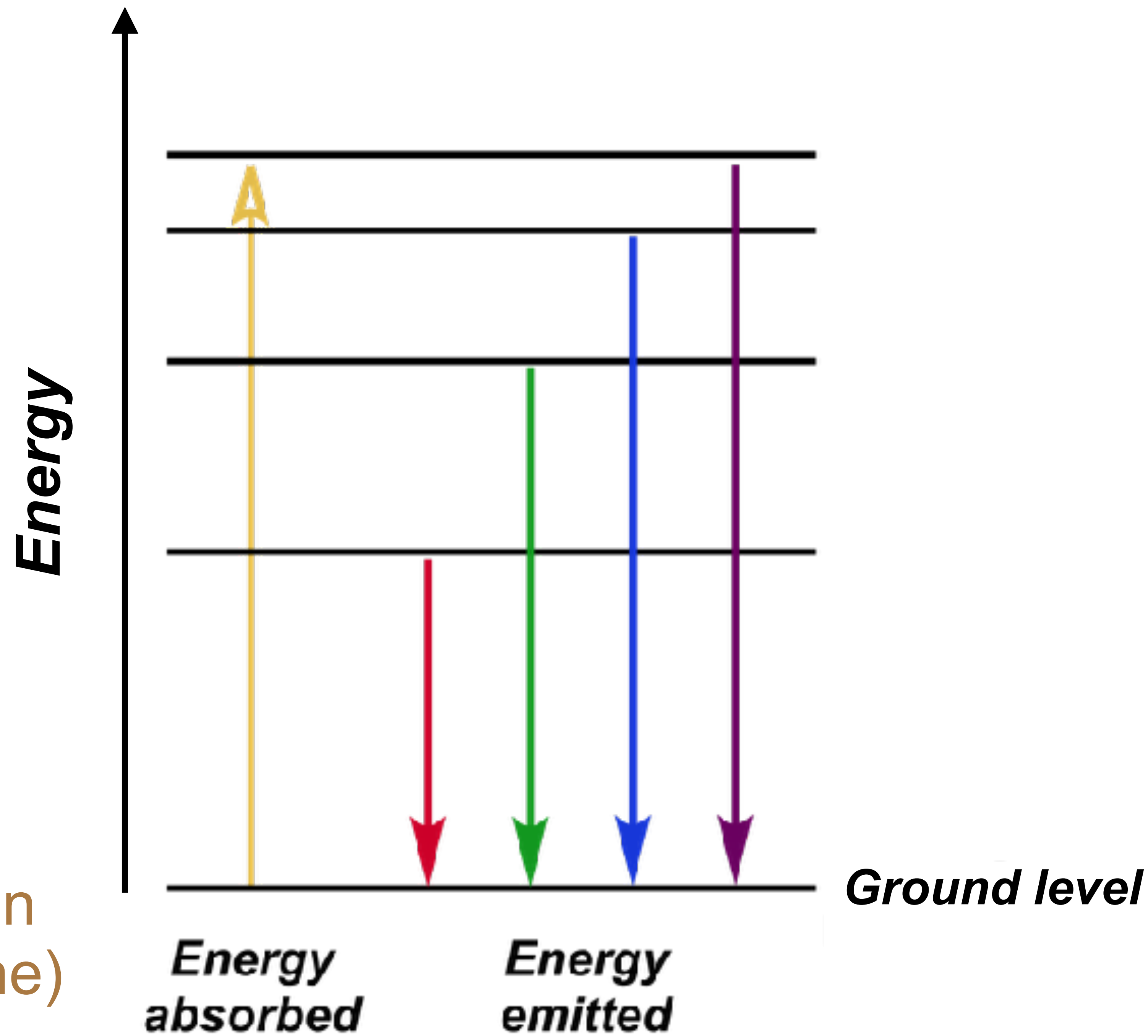
Level population is the key for single ion emission

Ion in excited state decays to a lower energy, emitting a photon

How do I get the ion in and out an excited state?

1 - Electron-ion collision

2 - Photo-excitation (neglect this one)



The level population

$$N_j(X^{+m}) = \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)} \frac{N(X)}{N(H)} \frac{N(H)}{N_e} N_e$$

Statistical equilibrium - multi-level atom

$$\sum_{j>i} N_j N_e C^{\mathrm{d}}_{ji} + \sum_{j<i} N_j N_e C^{\mathrm{e}}_{ji} + \sum_{j>i} N_j A_{ji} =$$

In

Collisional de-excitation from higher levels

Collisional excitation from lower levels

Cascades from higher levels

$$N_i \left(\sum_{j<i} N_e C^{\mathrm{d}}_{ij} + \sum_{j>i} N_e C^{\mathrm{e}}_{ij} + \sum_{j<i} A_{ij} \right)$$

Out

Collisional de-excitation to lower levels

Collisional excitation to higher levels

Cascades to lower levels

$$\sum_i N_i = 1$$

Normalization condition

1 - Density determines # of electron-ion collisions

2 - Temperature determines collision rates C^d, C^e

The ion population

$$N_j\left(X^{+m}\right) = \frac{N_j\left(X^{+m}\right)}{N\left(X^{+m}\right)} \frac{N\left(X^{+m}\right)}{N(X)} \frac{N(X)}{N(H)} \frac{N(H)}{N_e} N_e$$

The fundamental equation

1 - Electron-ion collisions

2 - Photo-ionization

Creation of ion N_i

$$\frac{dN_i}{dt} = N_e\left[N_{i-1}\left(\alpha^{ci} + \alpha^{ea}\right) + N_{i+i}\left(\alpha^{rr} + \alpha^{dr}\right)\right] + N_{i-1}P_{i-1} -$$

$$- N_i\left[N_e\left(\alpha^{ci} + \alpha^{ea} + \alpha^{rr} + \alpha^{dr}\right) + P_i\right]$$

Distruction of ion N_i

$$\sum_{i=1}^{N} N_i = 1$$

Normalization condition

This system of equations is used to calculate the charge state evolution of solar wind, flares etc…

The ion population

$$N_j\left(X^{+m}\right)=\frac{N_j\left(X^{+m}\right)}{N\left(X^{+m}\right)}\frac{N\left(X^{+m}\right)}{N\left(X\right)}\frac{N\left(X\right)}{N\left(H\right)}\frac{N\left(H\right)}{N_e}N_e$$

The approximations: Ionization equilibrium
No photoionization

$$0=N_e\left[N_{i-1}\left(\alpha^{ci}+\alpha^{ea}\right)+N_{i+i}\left(\alpha^{rr}+\alpha^{dr}\right)\right]-$$
$$-N_eN_i\left[\alpha^{ci}+\alpha^{ea}+\alpha^{rr}+\alpha^{dr}\right]$$

$$\sum_{i=1}^{N}N_i=1$$

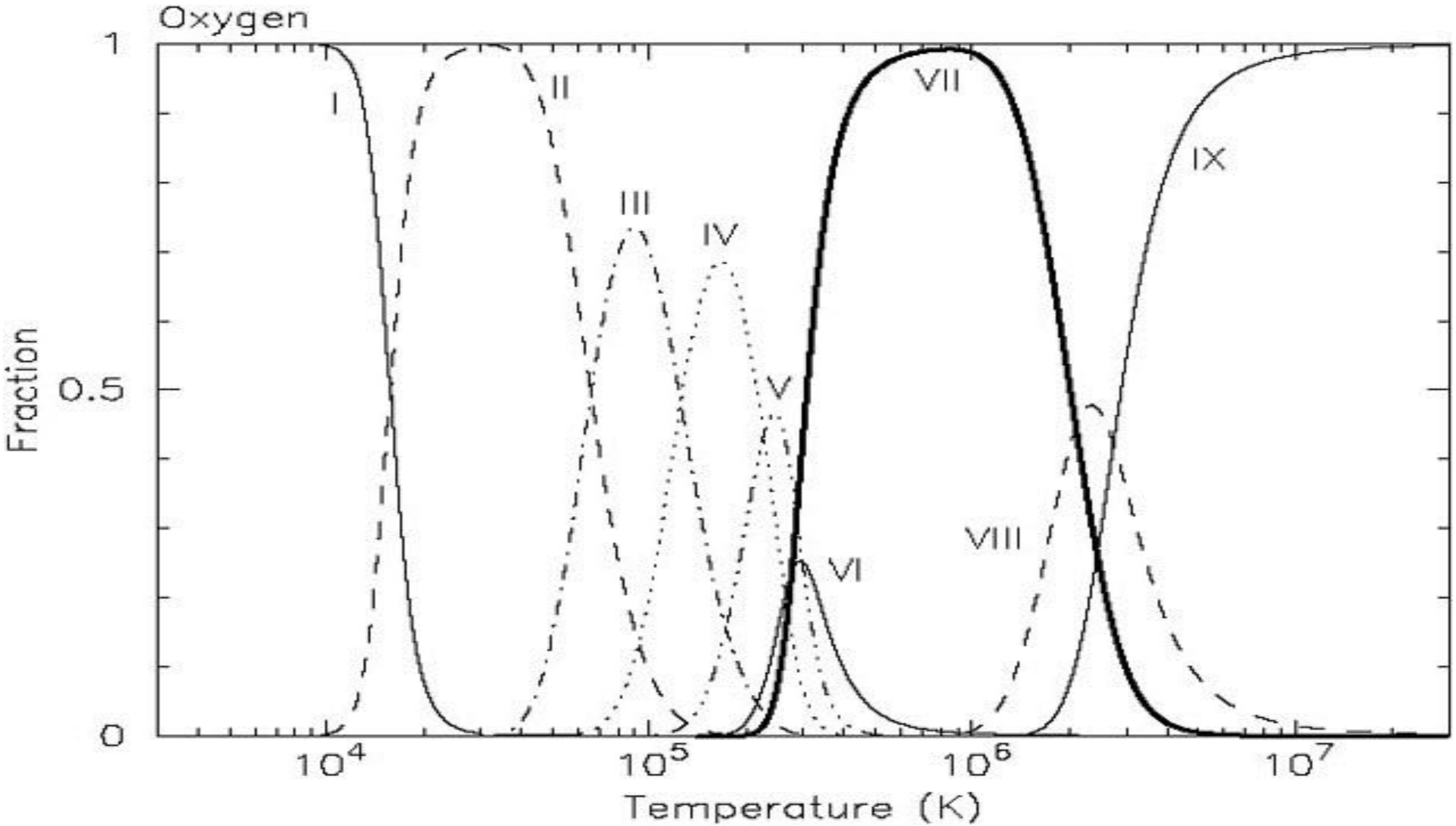
1 - No more dependence on electron density!

2 - Ion population only depends on T_e

3 - Rates are STRONGLY temperature dependent

The ionization balance

An ion can be associated to a temperature range



The other parameters

$$N_j\left(X^{+m}\right)=\frac{N_j\left(X^{+m}\right)}{N\left(X^{+m}\right)}\frac{N\left(X^{+m}\right)}{N(X)}\frac{N(X)}{N(H)}\frac{N(H)}{N_e}N_e$$

Element abundance

- Fixed for a given plasma
- May change along LOS

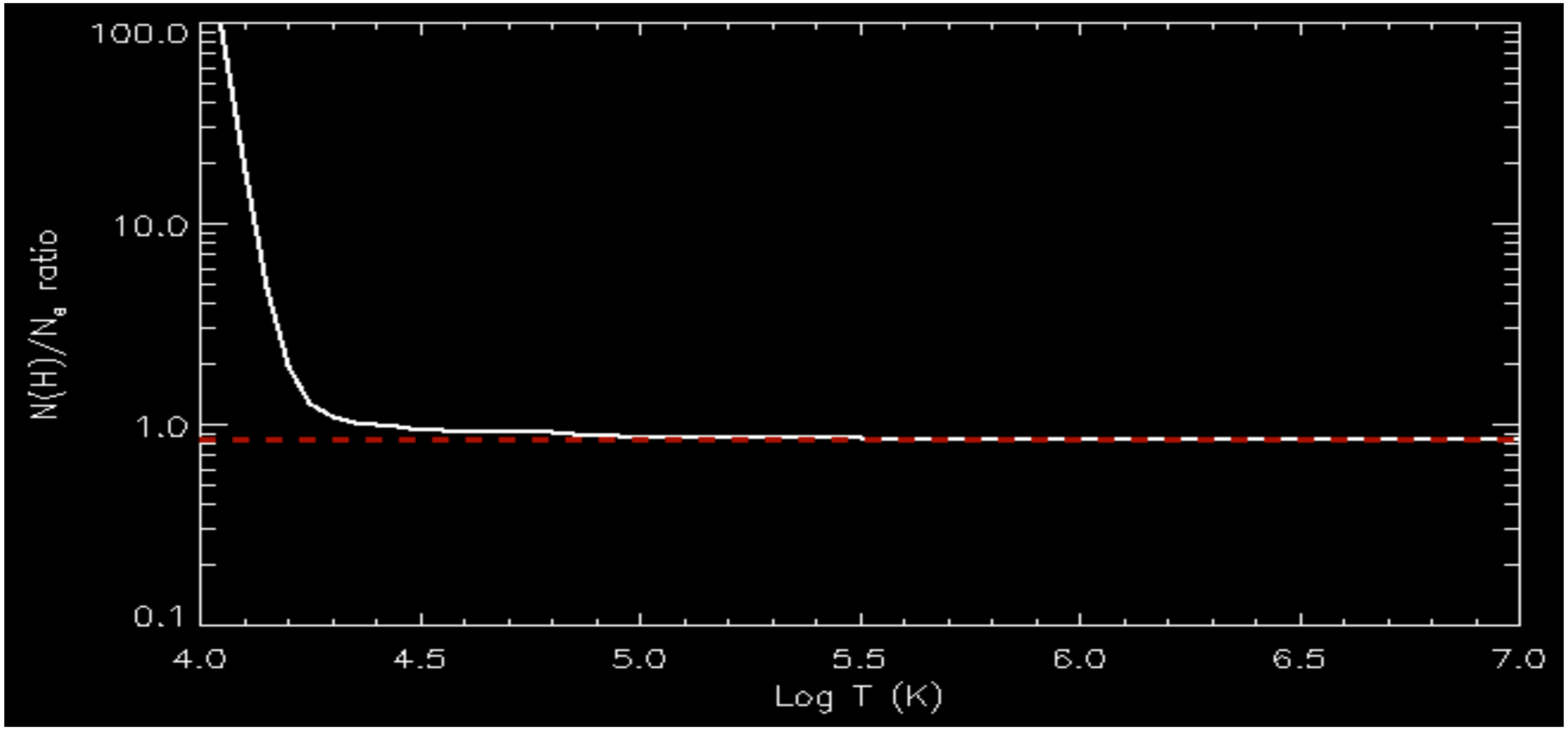
- Photosphere and corona have different composition — *the FIP effect*

The other parameters

$$N_j\left(X^{+m}\right)=\frac{N_j\left(X^{+m}\right)}{N\left(X^{+m}\right)}\frac{N\left(X^{+m}\right)}{N(X)}\frac{N(X)}{N(H)}\frac{N(H)}{N_e}N_e$$

Hydrogen-electron ratio

Determined by H, He ionization



The final line flux

Define new quantities:

$$G(N_e,T_e)=\frac{N_j(X^{+m})}{N(X^{+m})}\frac{N(X^{+m})}{N(X)}\frac{N(X)}{N(H)}\frac{N(H)}{N_e}\frac{A_{ji}}{N_e}h\nu_{ji}$$

Contribution Function

$$\varphi(T_e)=N_e^2\frac{dV}{dT_e}$$

Differential Emission Measure

$$\longrightarrow \quad F=\frac{1}{4\pi d^2}\int_T G(N_e,T_e)\varphi(T_e)\,dT_e$$

1 — $G(T_e,N_e)$ describes atomic physics

(can calculate it beforehand with CHIANTI)

2 — DEM describes plasma properties

3 — LOS integration is now over temperature

I - Line intensity ratios

Most popular technique
Fast and easy!

$$R = \frac{F_1}{F_2} = \frac{\int_0^\infty G_1(T_e, N_e)\varphi(T)\,dT}{\int_0^\infty G_2(T_e, N_e)\varphi(T)\,dT} \sim \frac{G_1(T_e, N_e)}{G_2(T_e, N_e)}$$

Lines from the same ion:

$$R_{same} \sim \frac{\left[\frac{N_i(X^{+m})}{N(X^{+m})}\right]}{\left[\frac{N_j(X^{+m})}{N(X^{+m})}\right]}$$

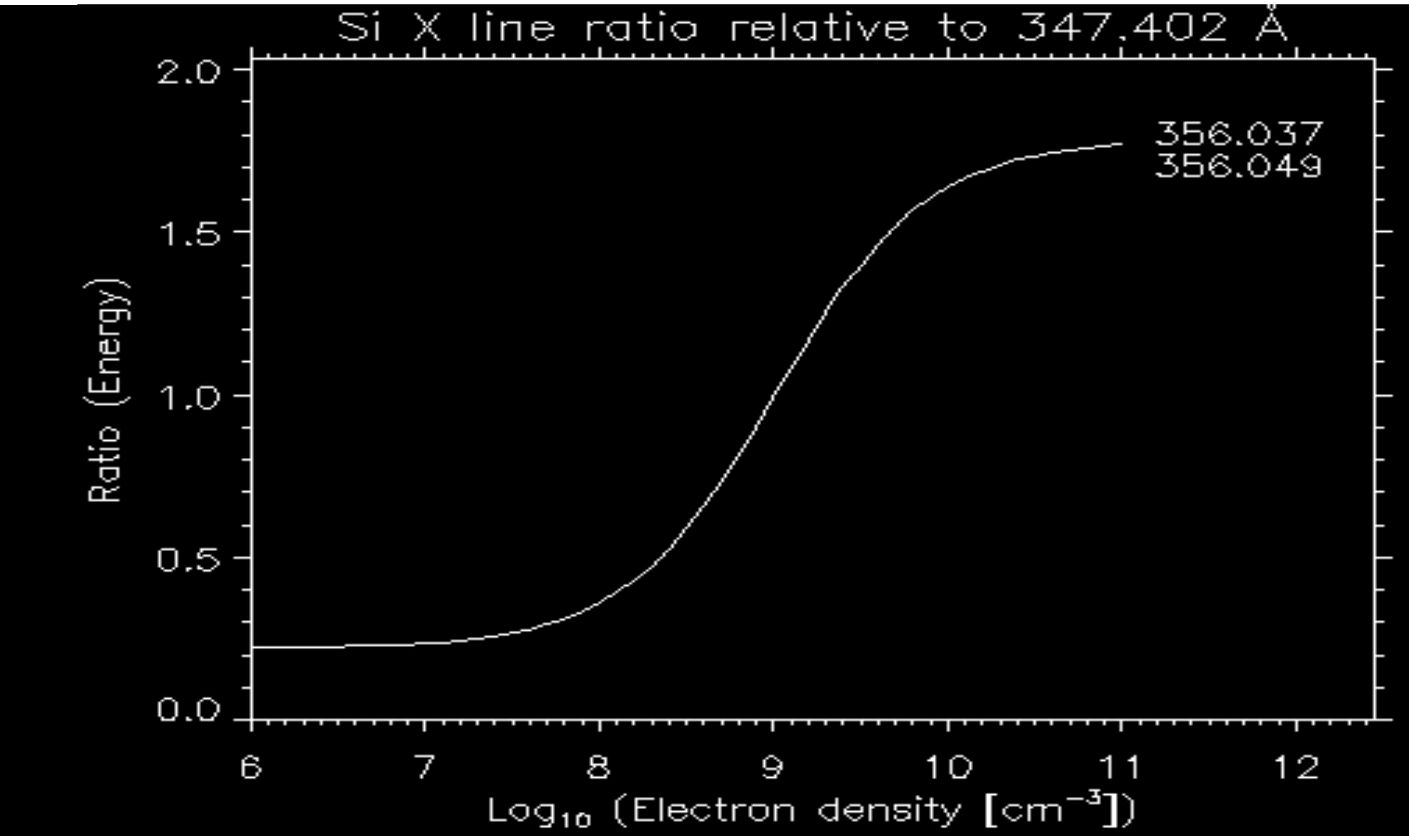
Lines from different ions
of the same element:

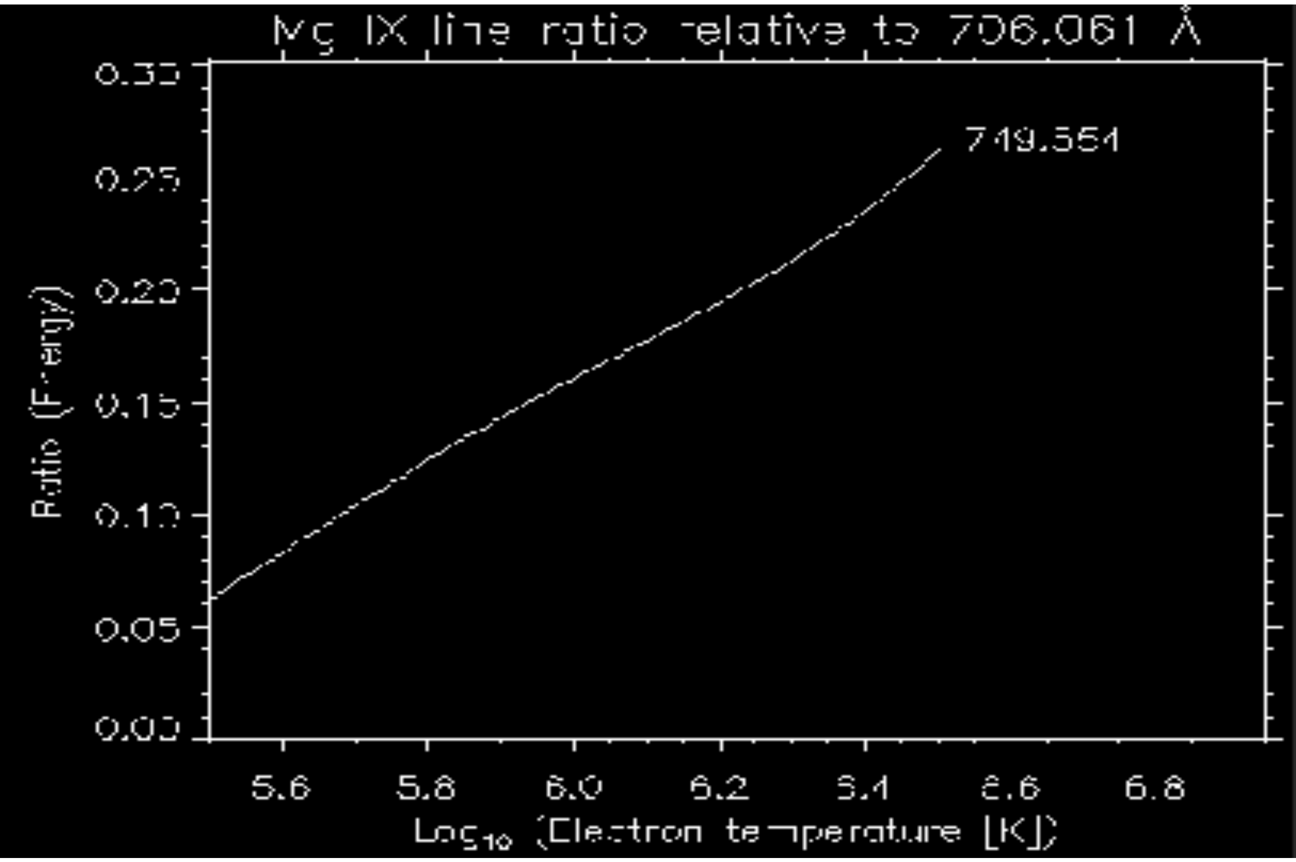
$$R_{diff} \sim R_{same} \frac{\left[\frac{N(X^{+m})}{N(X)}\right]}{\left[\frac{N(X^{+n})}{N(X)}\right]}$$

Lines from different elements:

$$R \sim R_{diff} \frac{N(X_1)}{N(X_2)}$$

I - Line intensity ratios - same ion

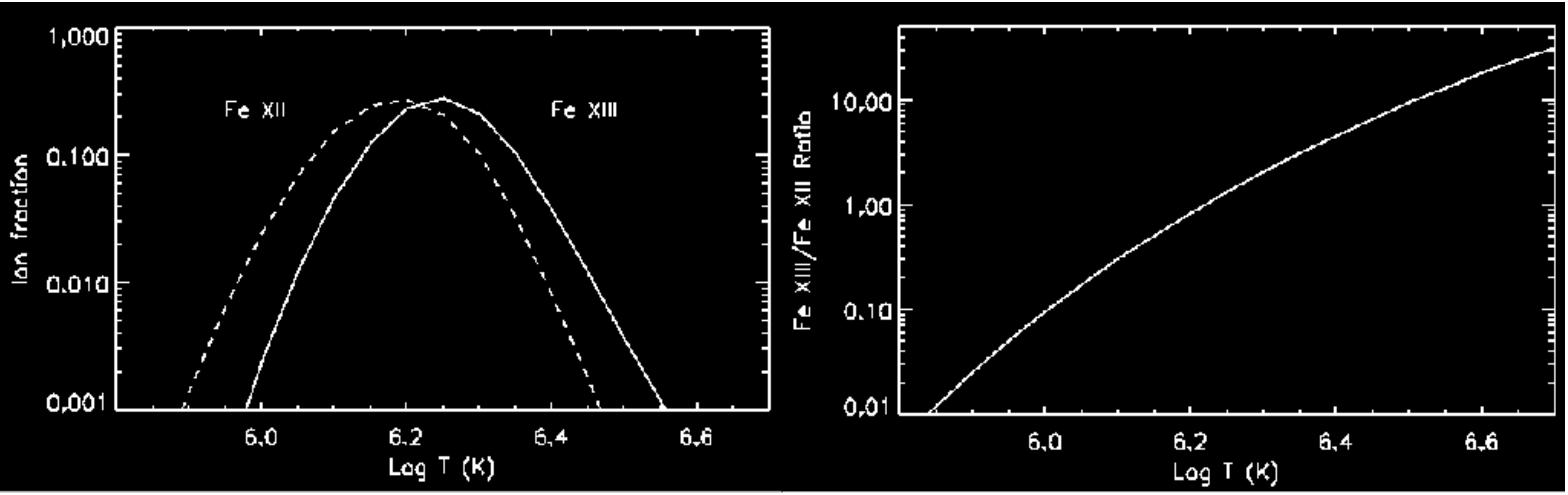




Lines from the same ion - pros:

- *Ratio can be used for temperature and density diagnostics, or both*
- Ratio is independent of ion and element abundances
- Often there are many lines to choose from

I - Line intensity ratios - different ions



Lines from different ions

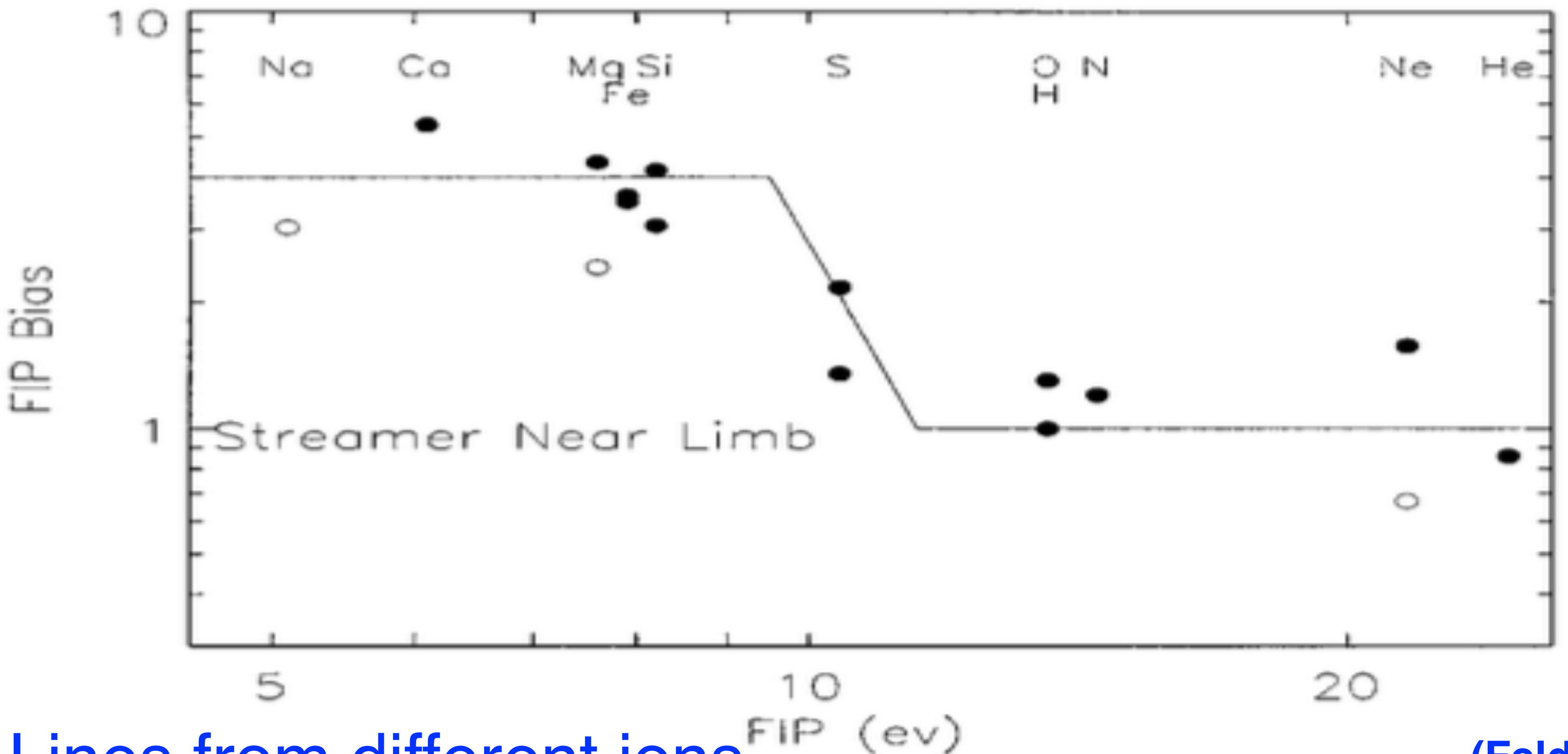
Pros:

- *Consecutive ions provide excellent T diagnostics*
- Element abundance is not a problem

Cons:

- Add ionization/recombination rate uncertainties
- They might be emitted by different plasmas

I - Line intensity ratios - different elements



$$FIP = \frac{\left[\frac{N(X)}{N(H)}\right]_{corona}}{\left[\frac{N(X)}{N(H)}\right]_{photos.}}$$

Lines from different ions

(Feldman et al. 1998)

Pros:

- *Study relative abundances, FIP effect*

Cons:

- Need to know plasma T, N_e beforehand
- Need ions formed at the same temperature

II - Thermal structure diagnostics

(Landi et al. 2002)

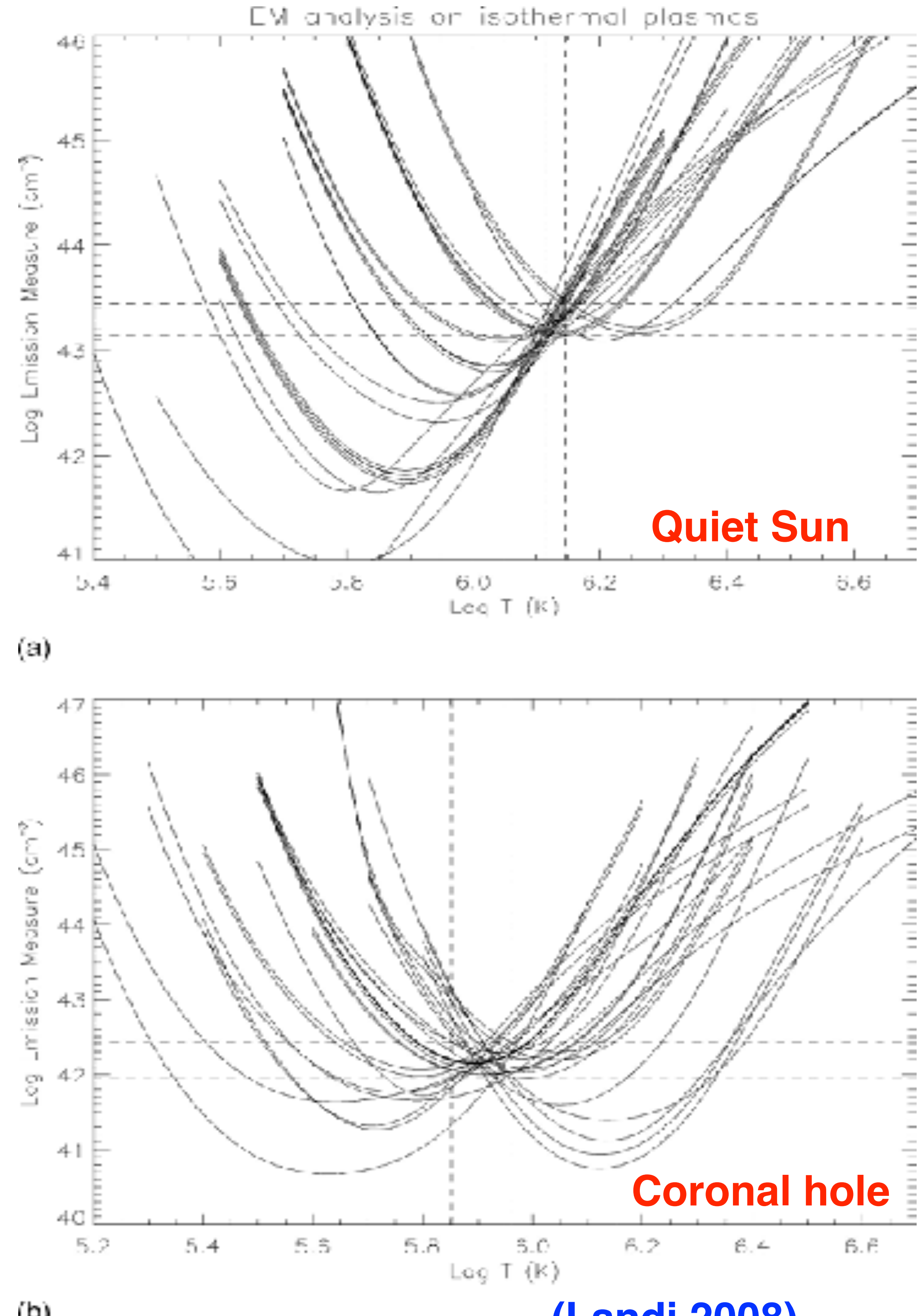
Isothermal plasma:

$$\begin{cases} F = \dfrac{1}{4\pi d^2}\displaystyle\int G(N_e,T_e)\,N_e^2\,dV \\ EM = N_e^2 V \end{cases}$$

$$\rightarrow F = \frac{G\left(N_e,T_e^{pl}\right)}{4\pi d^2}EM$$

Can determine the EM (maybe N_e) and T_e from density-insensitive lines of different ions:

$$EM(T_e) = 4\pi d^2 \frac{F}{G(N_e,T_e)} = EM\,\frac{G\left(N_e,T_e^{pl}\right)}{G(N_e,T_e)}$$



(Landi 2008)

II - Thermal structure diagnostics

Multithermal plasma:

$$F = \frac{1}{4\pi d^2} \int G(N_e, T_e) \varphi(T_e) dT$$

Need to determine $\varphi(T_e)$

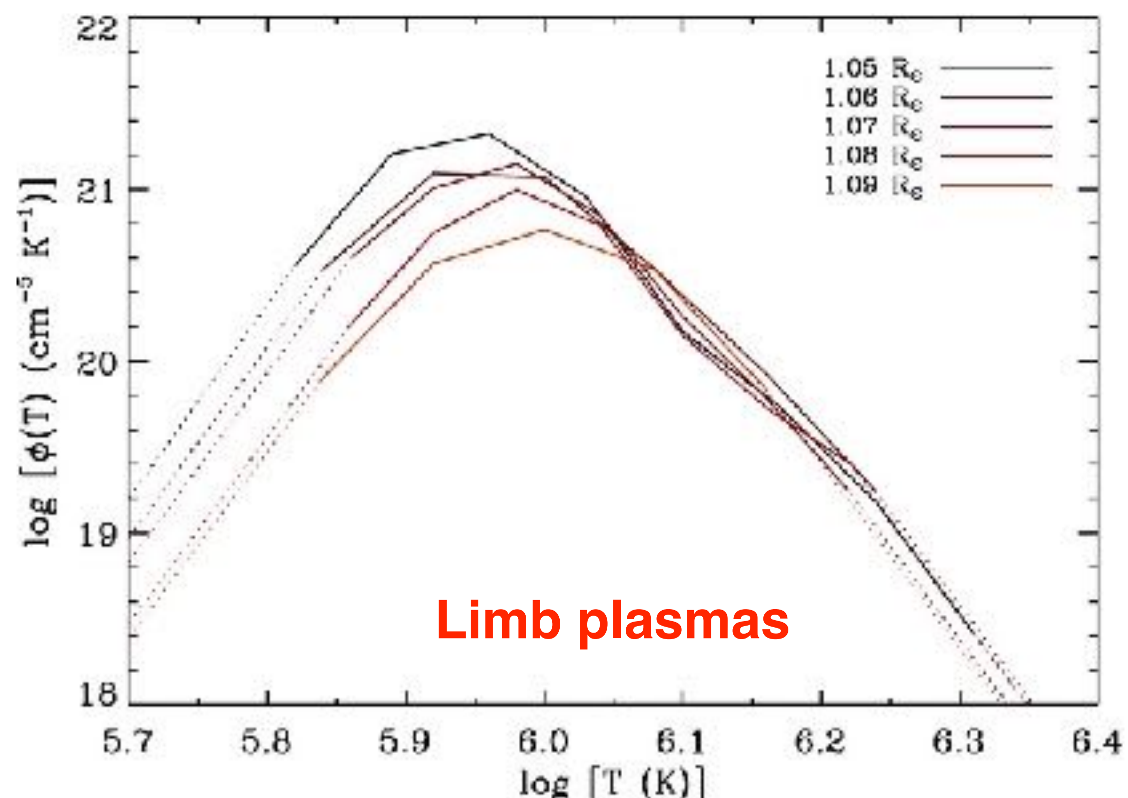
Three main methods:

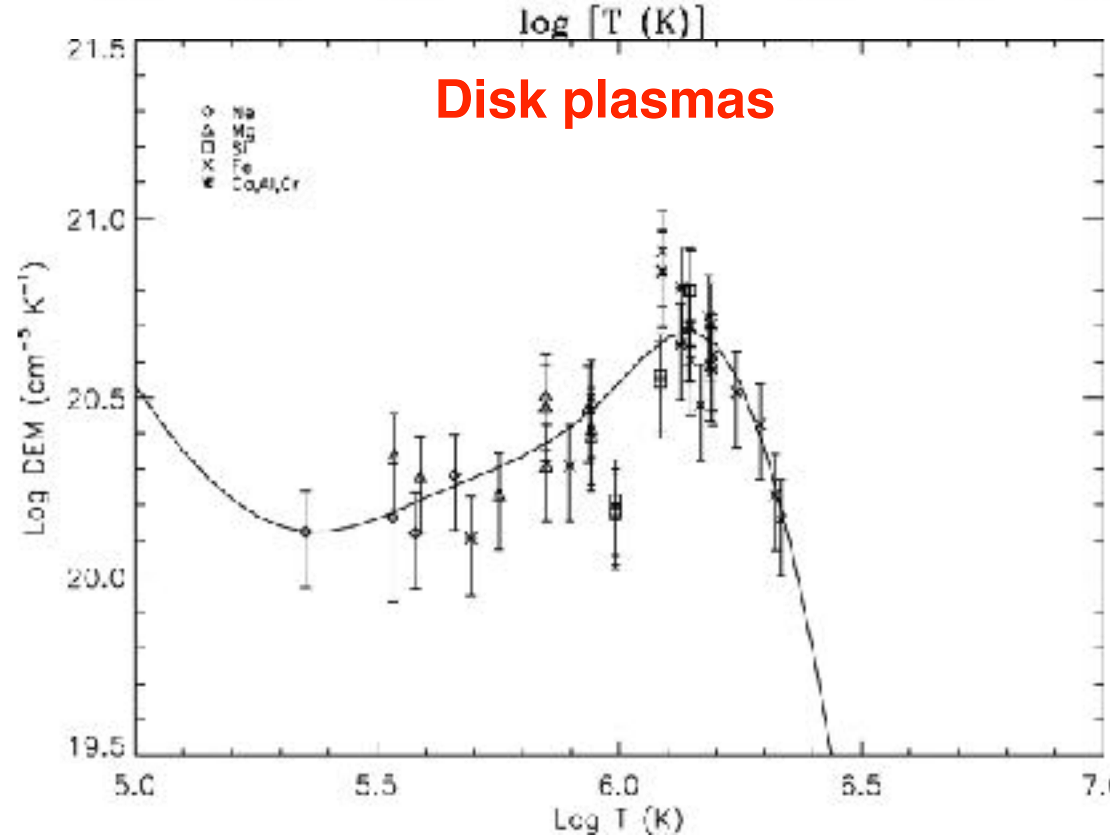
- Iterative techniques
- Inversion techniques
- Monte Carlo techniques

Two main problems:

- Non-unique solution
- Need lines from many ions

(Hahn et al. 2011)





(Brosius et al. 2008)

III - Line width diagnostics

Line profile - key facts:

$$FWHM = \frac{\nu_{ji}}{c}\sqrt{4\ln 2\left(\frac{2k_B T_{ion}}{M_{ion}} + V_{nth}^2\right)}$$

Thermal motions
(ion temperature)

Non-thermal motions

Rotation
Oscillations
Turbulence
Explosive motions

Problem:

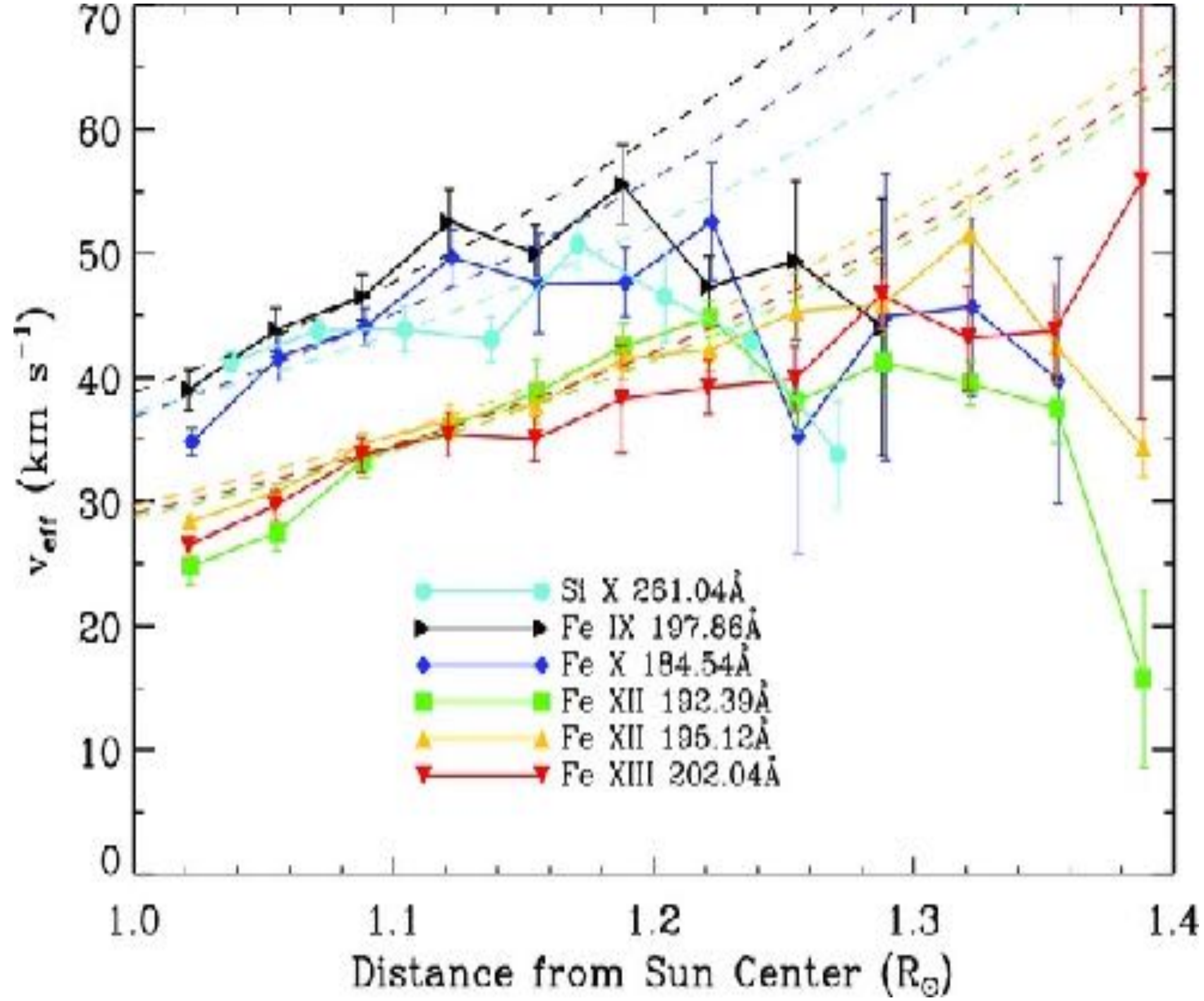
You have two unknowns in one observable

III - Line width diagnostics

(Hahn et al. 2012)

Dealing with FWHM:

$$FWHM = \frac{\lambda_{ji}}{c}\sqrt{4\ln 2\left(\frac{2k_B T_{ion}}{M} + v_{nth}^2\right)}$$



1 - Measure *Effective Velocity*

$$v_{eff}^2 = \frac{2k_B T_{ion}}{M} + v_{nth}^2$$

2 - Common assumptions

Assume $T_{ion}=T_e$ Get v_{nth}

Assume v_{nth} Get T_{ion}

These assumptions are not always justified

IV - Ion temperature

Dealing with FWHM:

$$FWHM = \frac{\lambda_{ji}}{c}\sqrt{4\ln 2\left(\frac{2k_B T_{ion}}{M} + \mathrm{v}_{nth}^2\right)}$$

3 - If you consider many lines *(Tu et al. 1998)*

Step 1: Simply determine upper limits to T_{ion} and v_{nth}

$$T_{ion} < T_{ion}^{\max} \qquad \mathrm{v}_{nth} < \mathrm{v}_{nth}^{\max}$$

Step 2: Assume v_{nth} is the same for all

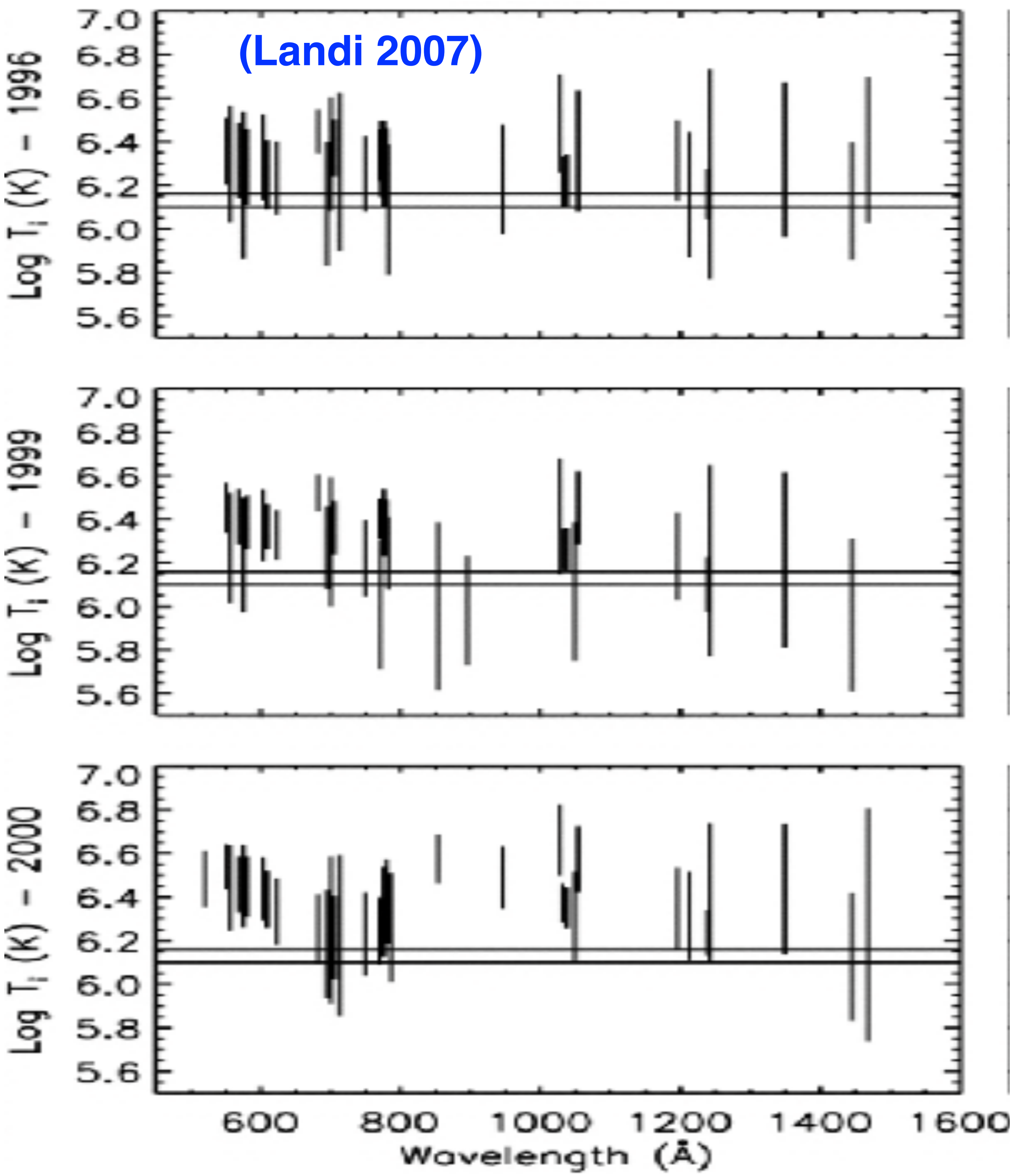
Determine maximum v_{nth} value among all lines

$$\mathrm{v}_{nth} < \min\left(\mathrm{v}_{nth}^{\max}\right) = \mathrm{v}_{\min} \longrightarrow T_{ion} > T_{ion}\left(\mathrm{v}_{\min}\right)$$

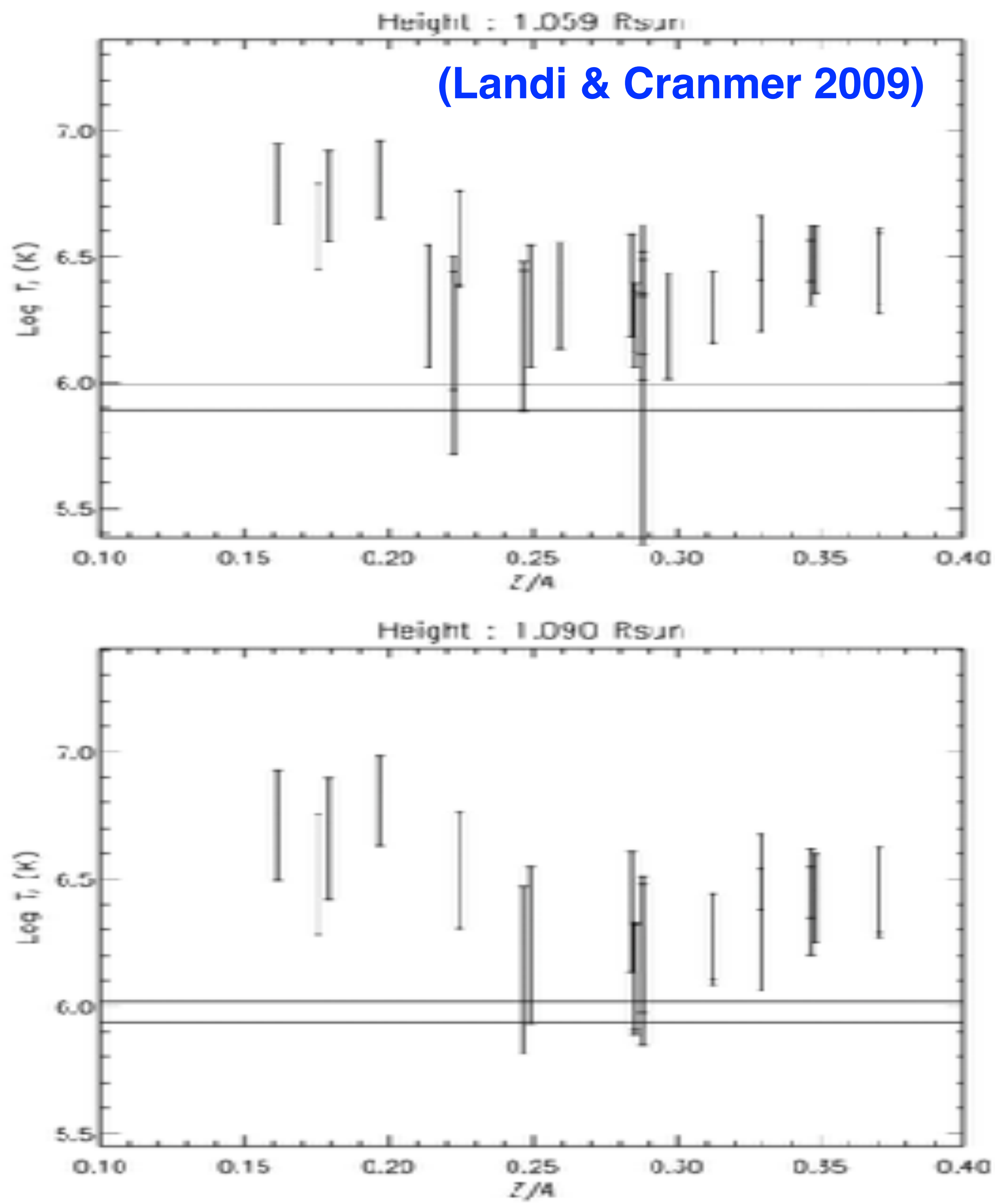
→ *Determine T_{ion} range*

IV - Ion temperature

Off disk streamer

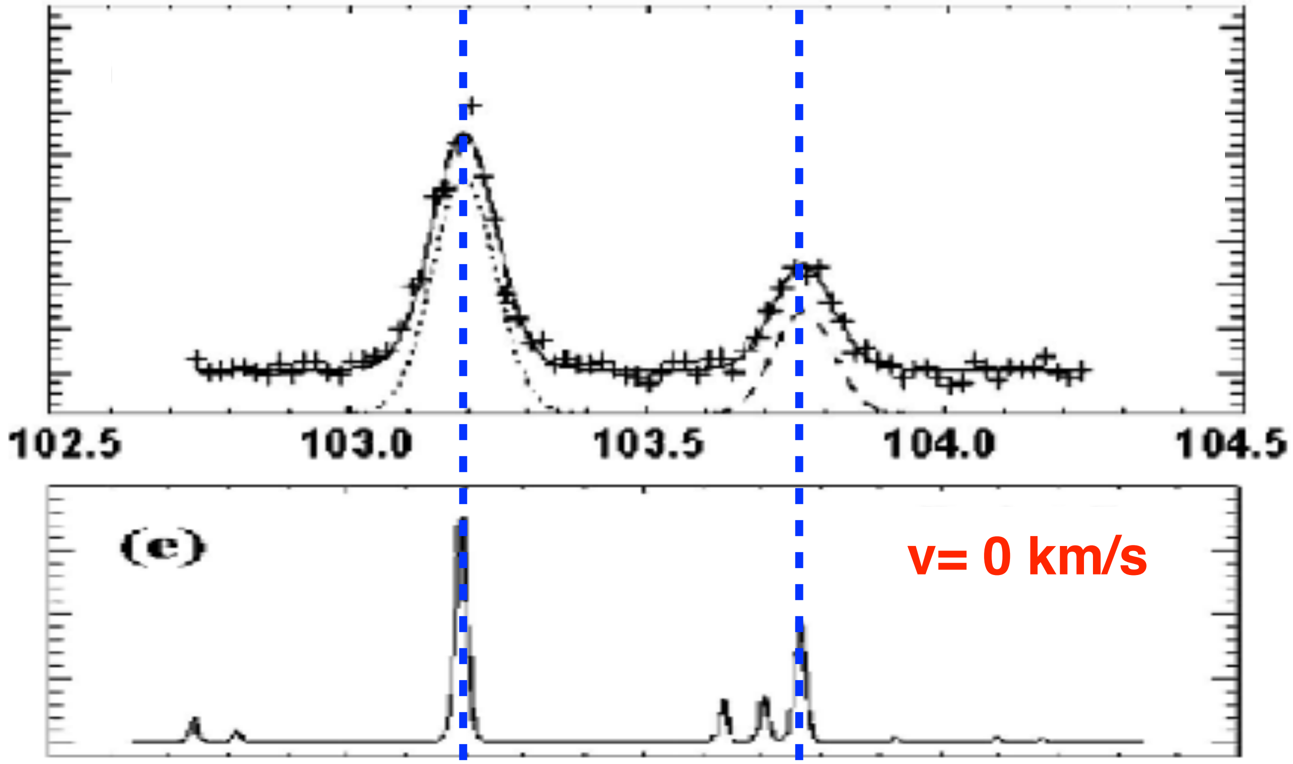


Off disk coronal hole



V - Solar wind speed

(Kohl et al. 2001)

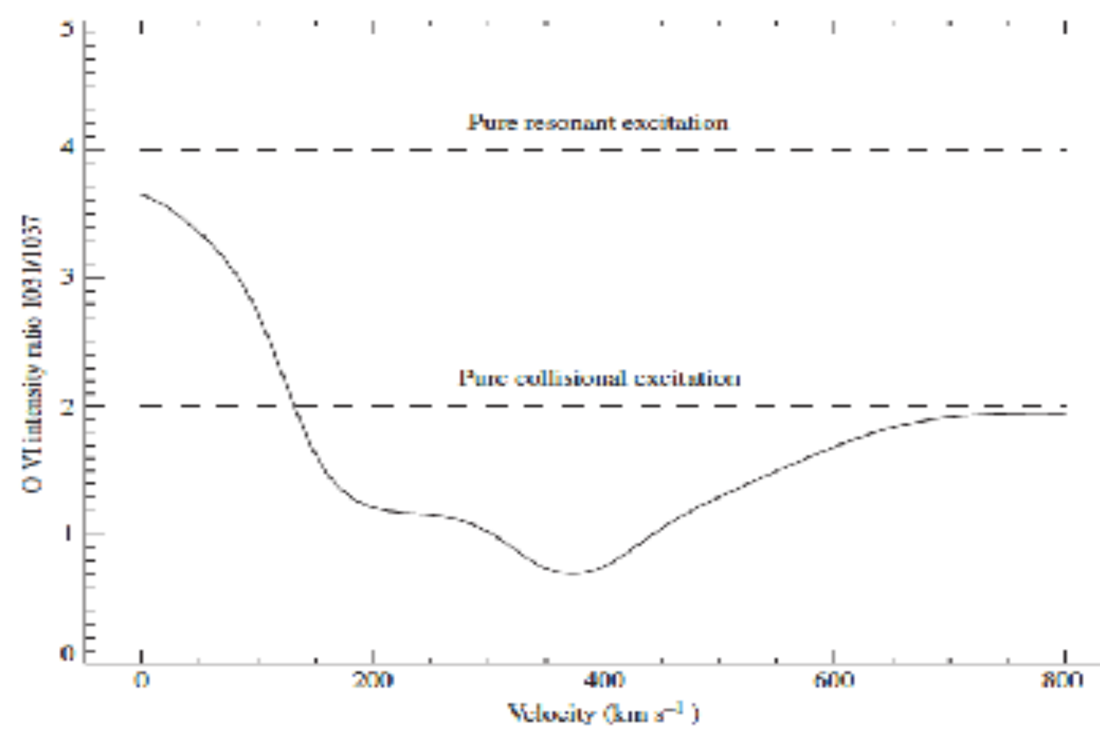


Increasing wind speed changes O VI 1031/1037 ratio

Intensity ratio is constant

Resonant scattering depends on C II lines

Doppler shifts favor the weaker O VI line



(Cranmer et al. 1999)