Astrophysical Plasmas

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Introduction

The atomic processes involved in X-ray emitting plasmas:

- Particle collisions (usually electrons, sometimes protons)
    - Excitation / de-excitation
    - Ionization / recombination
- Photon interactions
    - Excitation
    - Ionization
    - Radiative decay (line emission)
    - Absorption

Introduction

So, X-ray emitting plasmas come in two types: collisional and photoionized.

- Collisional: $k_B T_e \sim$ ionization energy of the ions in the plasma
- Photoionized: $k_B T_e \ll$ ionization energy of the ions in the plasma

Collisional plasmas

There are two types of astrophysical **collisional** plasmas: Coronal/Nebular and Collisional-Radiative.

- **Coronal/Nebular**: $N_e < 10^{14} - 10^{16}$ cm^{-3}
  - aka "ground state" approximation, since ions assumed to be ground state when collisions happen
  - more common than CR
  - collisions excite ions, but rarely de-excite them
  - any decay is radiative

Collisional plasmas

There are two types of astrophysical **collisional** plasmas: Coronal/Nebular and Collisional-Radiative.

- **Collisional-Radiative**: 10^{14} cm^{-3} < N_e < 10^{27} cm^{-3}
  - Collisions compete with photons in de-exciting levels
  - A level with small transtion rate (oscillator strength) may be collisionally de-excited before it can radiate.

Collisional plasmas

Collisional plasmas can be in ionization equilibrium. This happens when $\Sigma I_{rate}(I) = \Sigma R_{rate}(I)$

They can also not be in eqilibrium, in which case the plasma is either ionizing [$\Sigma I_{rate}(I) > \Sigma R_{rate}(I)$] or recombining [$\Sigma I_{rate}(I) < \Sigma R_{rate}(I)$].

Collisional plasmas

In collisional plasmas, there are three ion types worth noting.

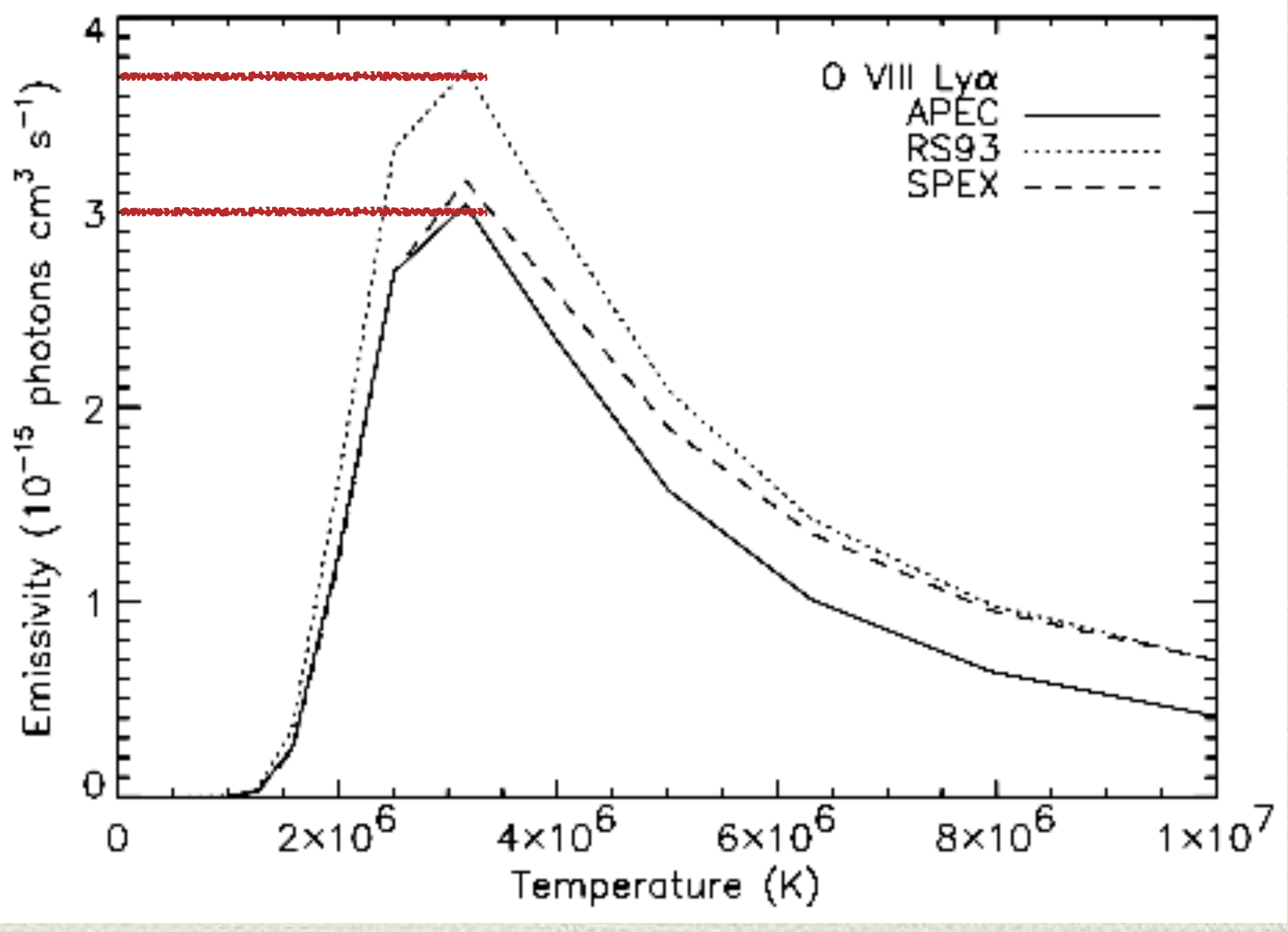
1) H-like: All transitions from C to Ni are in X-ray band. Lyα/Lyβ is a good temperature indicator. And Lyα is bright.

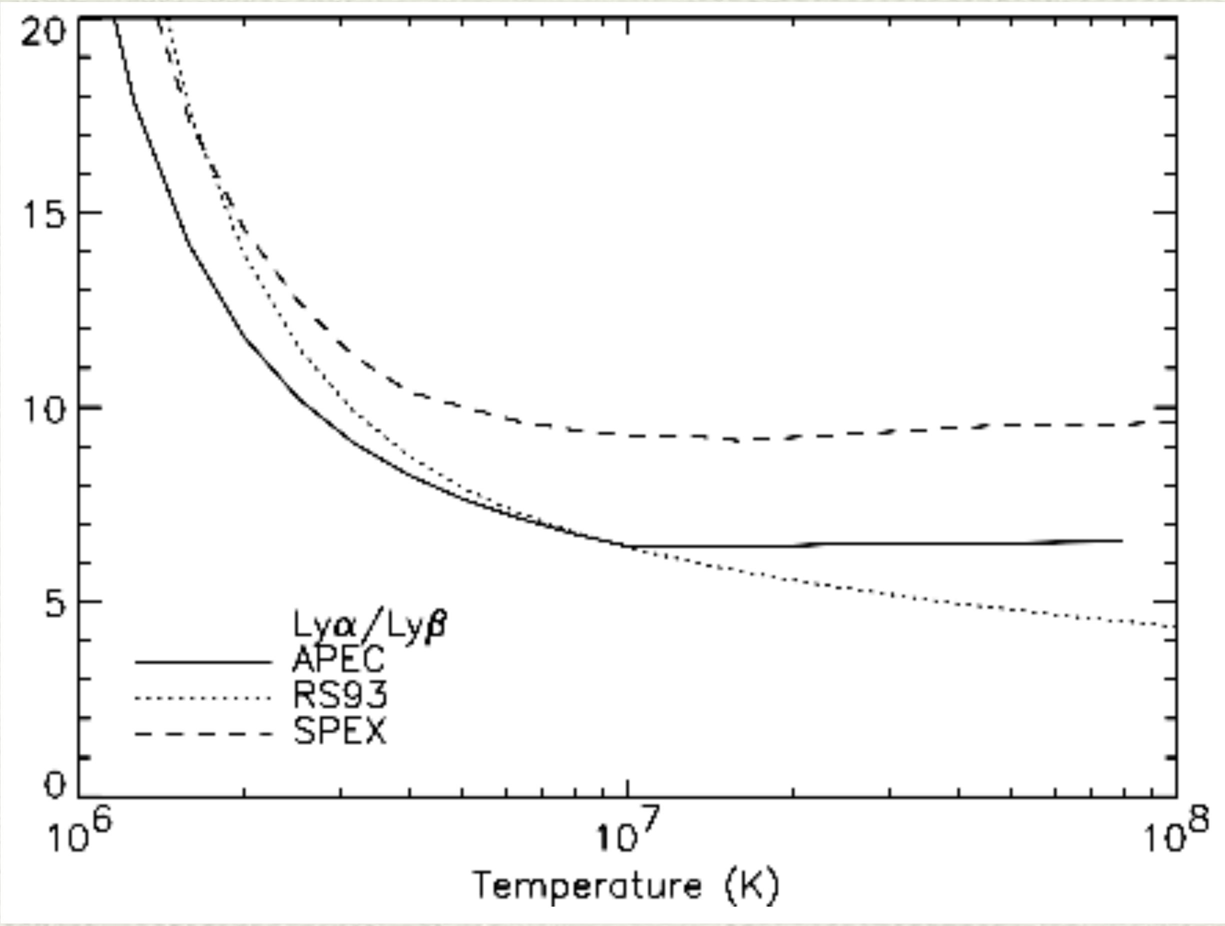
2) He-like: Transitions with $\Delta n \geq 1$ are bright and in X-ray band. $n=2 \rightarrow 1$ transitions have 4 transitions that are useful diagnostics, but need R=300 to separate them.

3) Ne-like: Primarily Fe XVII. Useful for density diagnostic.

Collisional plasmas, H-like

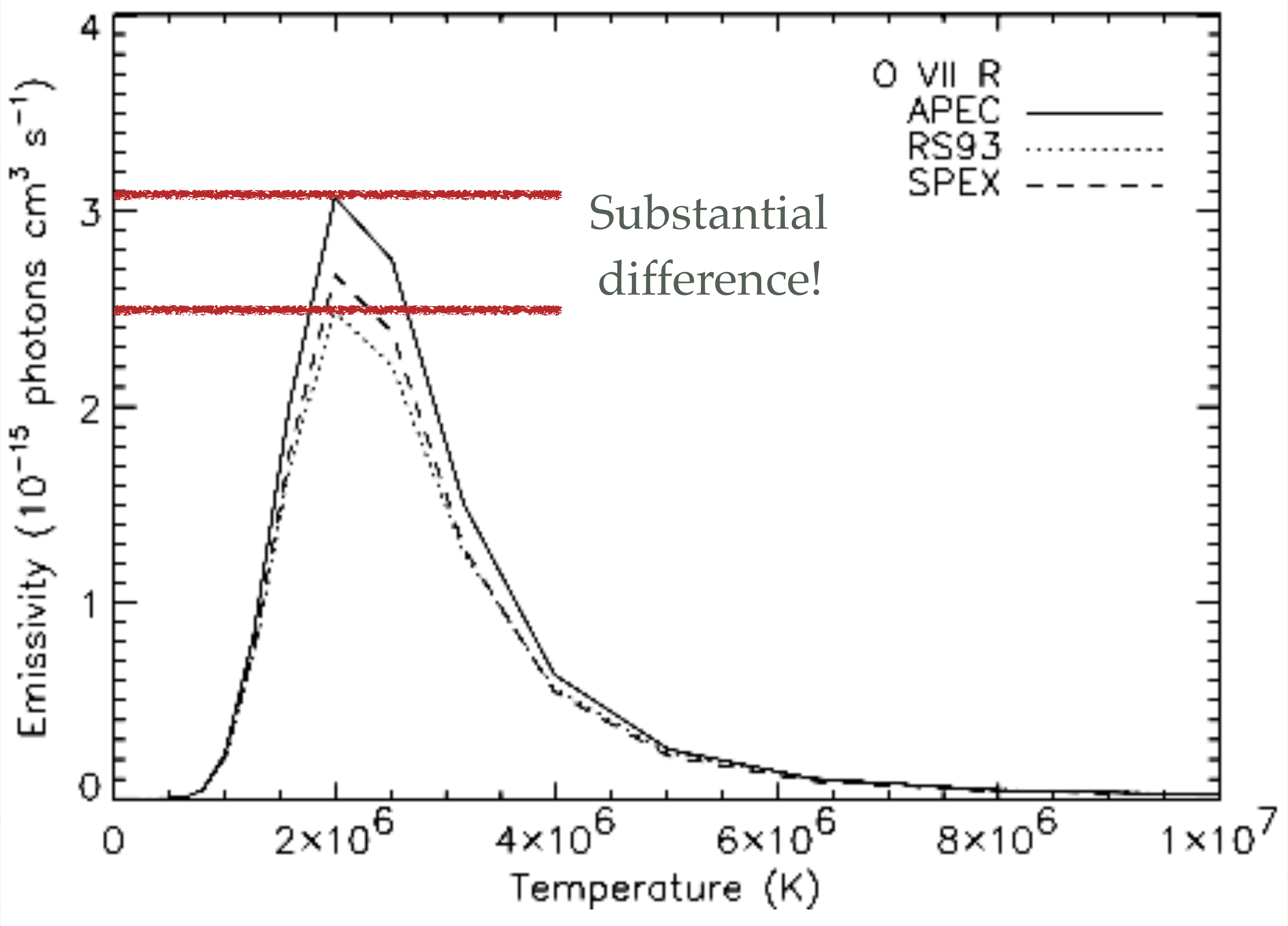
How well can we model H-like lines? Three calculations of the O VIII Lyα line as a function of temperature, and three calculations of O VIII Lyα/Lyβ as function of temperature. (APEC agreed with measurements.)





Collisional plasmas, He-like

- Same question, different ion. O VII as functition of temp for 3 models.

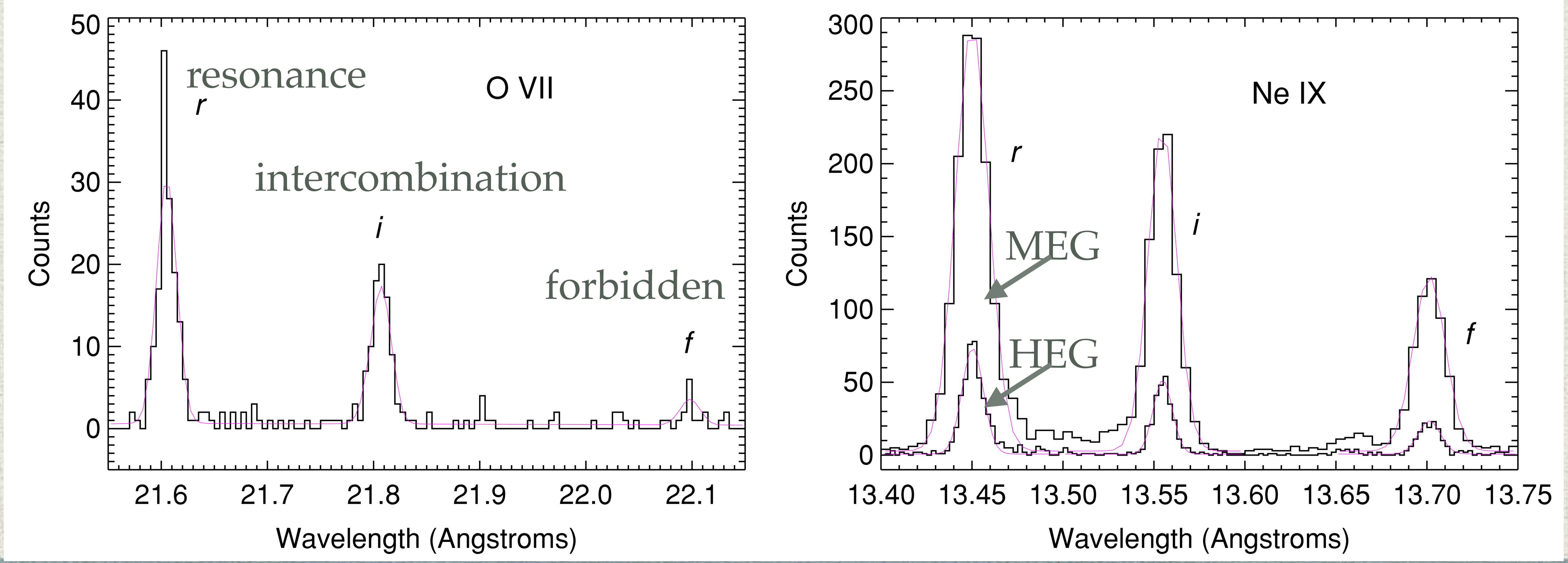


Collisional plasmas, He-like

An example of He-like lines O VII and Ne IX in TW Hydrae (Brickhouse et al. 2010). The flux ratios of the lines indicate the temperature and density of the plasma.

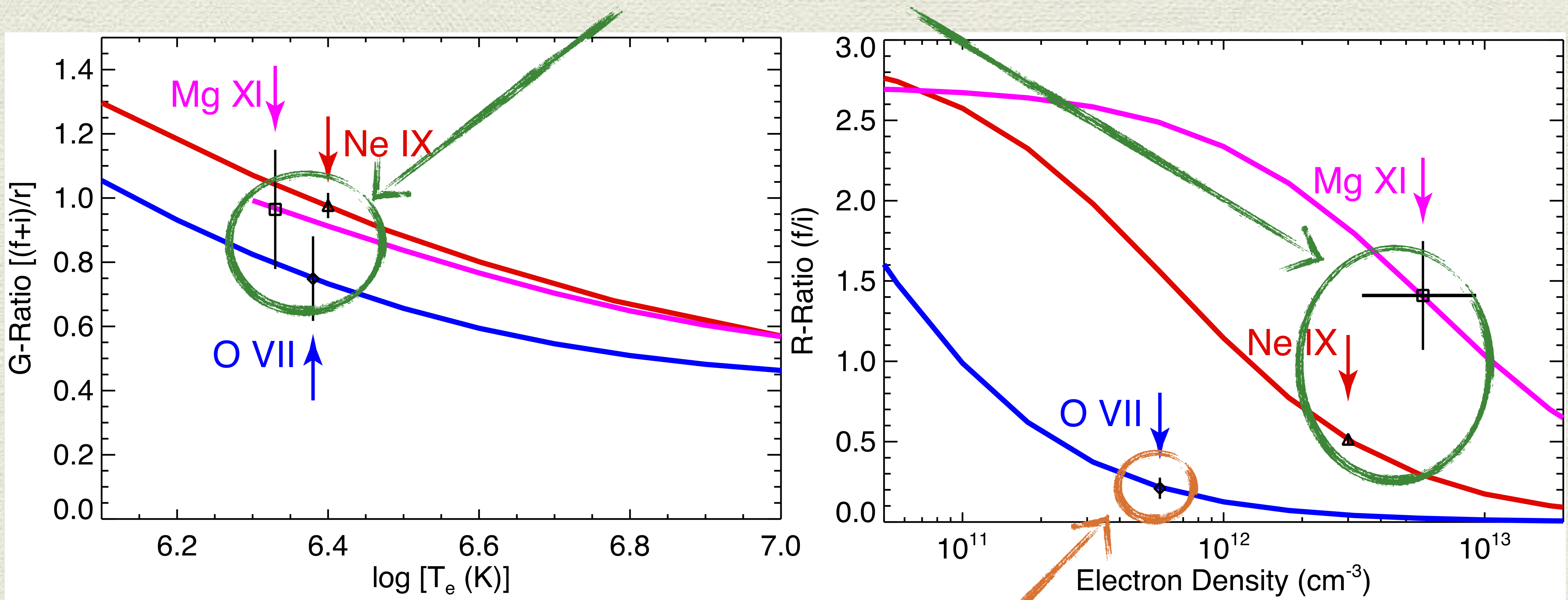
- G ratio = (f+i)/r; diagnostic of T_e
- R ratio = f/i; diagnostic of N_e

Use multiple ions to determine characteristics of gas.



The model curves below are from APEC model and various literature sources.

Pretty good agreement!



Brickhouse et al. 2010

Except for this…

These ions are formed at similar temperature, but very different densities.

Collisional plasmas, He-like

Why is the G ratio [(f+i)/r] sensitive to T_e, and R ratio (f/i) to N_e?

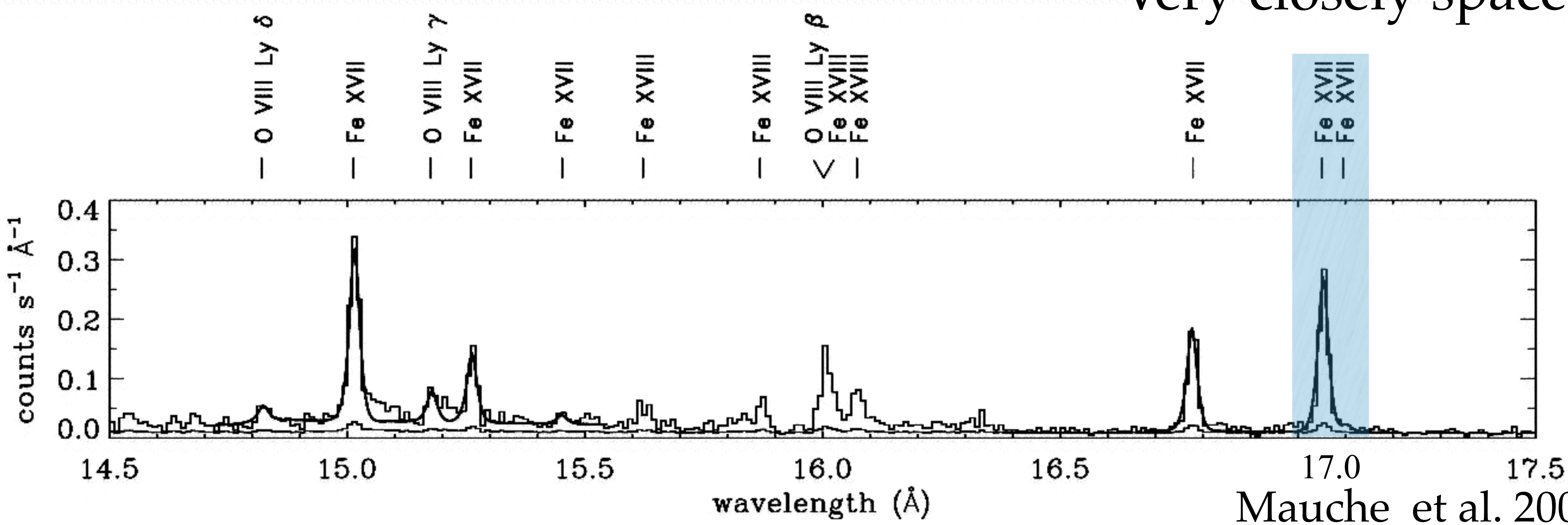
- The **r line** is excited by collisions, which are **temperature-dependent**, while the f and i lines are excited by recombination and other processes.
- The **f line is dependent on density,** because if N_e is big enough, collisions move electrons from the f to the i and r levels.

Collisional plasmas, Ne-like

Fe XVII is the most prominent Ne-like ion; Ni XIX is 10x weaker simply due to relative abundances. There are many diagnostic features, as seen in this grating spectrum of this white dwarf, EX Hya.

The Fe XVII lines shown below are used for density diagnostic or UV flux diagnostic. Note the blended lines!

Very closely spaced!



Mauche et al. 2001

Collisional plasmas - models

If we want to understand a collisional plasma, we need a collisional plasma model.

- If a collisional plasma is in equilibrium, it is often modeled as
  - Raymond-Smith; Mekal; APEC; CIE (Coronal Ionization Equilibrium, even if it isn't a corona)
- If a collisional plasma is not in equilibrium, it is often modeled as
  - NEI or NIE; Ionizing; Recombining; Thermal + power law tail

Collisional plasmas - models

- These models are included in standard analysis software packages. The following are in XSpec and Sherpa:

apec	**AtomDB code; good for high res data**
raymond	**Updated (1993) R-S (1977) code**
meka	**Original Mewe-Kaastra (1985) code; outdated**
mekal	**Mewe-Kaastr-Liedahl code (1992); new Fe L lines**
c6mekal	**mekal with a polynomial EM distribution**
equil	**Borkowski upate of Hamilton et al. (1983)**
nei	**ionizing plasma version of equil**
sedov	**Sedov (SNR) version of equil**
pshock	**plane parallel shock version of equil**

- Variable abundance versions of these are also available.

Fitting your collisional plasma spectrum

High resolution spectra are ideal. But sometimes all we have is low resolution, so we fit what we have.

If you think your spectrum is dominated by collisional equilibrium plasma, you can fit an appropriate model (like apec, mekal, etc.)

Be default, the only parameters are temperature and emission measure. If you get a bad fit, you can add more parameters (abundance relative to solar, redshift).

If you still get a bad fit, the abundances can be varied independently, or the equilibrium assumption can be relaxed.

Fitting your collisional plasma spectrum

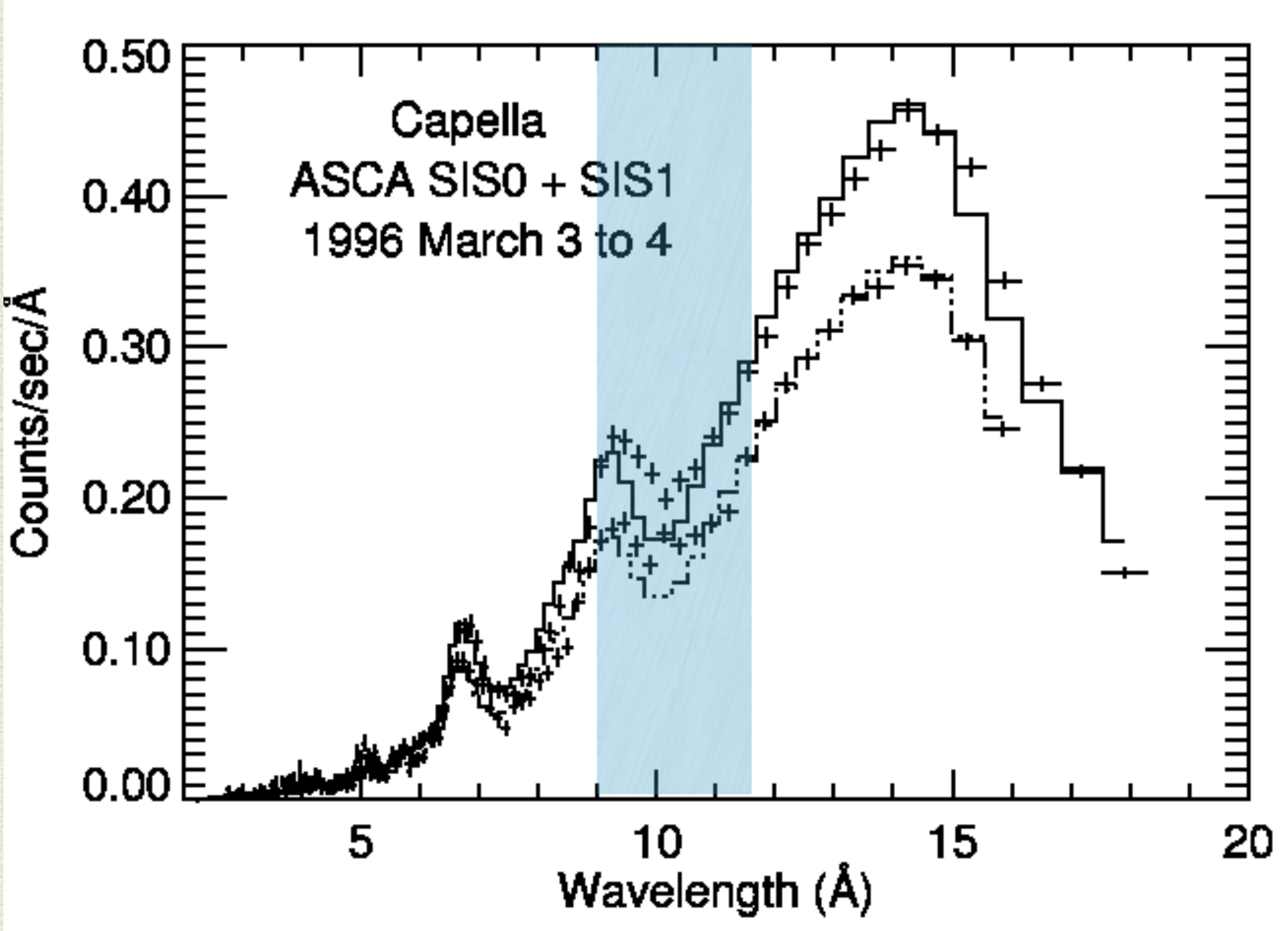
Things to be aware of:

1) If the underlying model is inadequate, your results may be, too.

2) Cross-check your results any way possible. Example: the emission measure is related to denisty and emitting volume. Are they reasonable?

3) If you can't get a good fit in a certain region, the model may be the problem, not the data.

For example, this spectrum of Capella was fit with a collisional plasma model that largely provides a good fit — except for between 9-12 Å, due to missing Fe lines in the model.



Final thoughts on plasmas

Some things you should keep in mind when fitting a plasma spectrum:

- Use high resolution data if you have it.
- Only the strongest lines will be visible.
- They may be blended.
- Plasma codes have (at least) 10% errors on line strength.
- To paraphrase Keith Arnaud, the goal is understanding, not perfect fit.

Bonus!

Absorption + Scattering from ISM

X-rays can be absorbed or scattered by IS gas and dust grains, which are semi-transparent to X-rays. Observed spectra need to be corrected for the effects to recover a source's intrinsic spectral energy distribution.

Particularly important for O, Fe, Si, Mg, Si, C, N, Ne, since these have their K or L shell absorption edges in soft X-ray band.

Absorption from ISM

- Important things to consider: photoionization cross section of ISM, abundances

$$\sigma_{\rm ISM} = \sigma_{\rm gas} + \sigma_{\rm molecules} + \sigma_{\rm grains}$$

- For $\sigma_{\rm gas}$, sum the photoionization cross sections of individual atoms and ions in warm phase ISM, *weighting their contributions by their abundances*. For $\sigma_{\rm molecule}$, only worry about H! For $\sigma_{\rm grains}$, it gets complicated…

Absorption from ISM

- In “large” grains ($a \sim 0.25\ \mu$m), optical depth can be such that most X-ray absorption happens on surface, so contribution of material “inside” grain is small
- This shielding means that presence of large grains actually *reduces* the absorptivity of ISM relative to absorptivity in pure gaseous medium.

Absorption from ISM

Optical depth of grains with a given grain size distribution $dn_{gr}(a)/da$ is shown; it assumes that the grains are chemically homogeneous with an average photoabsorption cross section $<\sigma>$ (not the same as the geometric $\sigma=\pi a^2$ because grains are partly transparent to X-rays) that can be approximated with spheres of radius $<a>$ and an average column density <N>, number of grains along sight line is ξ_g.

$$\begin{aligned}\tau_{\mathbf{grains}} &= \sigma_{\mathbf{grains}} N_{\mathbf{H}} \\ &= N_{\mathbf{H}}\, \xi_g \int_0^\infty \frac{dn_{\mathbf{gr}}(a)}{da}\, \sigma_{\mathbf{geom}} \\ &\quad \times [1 - \exp(-\langle\sigma\rangle\langle N\rangle)]da\end{aligned}$$

Absorption from ISM

- Assumed elemental abundances are crucial to computing the total ISM aborption. Gas phase ISM abundances are well known, but not the total. Solar (photosphere or meterorites) is usually used.
    - The solar values of some major elements are not well known and have changed a lot in last 30 years.
    - Comparison between solar and what ISM abundances we do have show large differences in dust-forming elements. (Though more modern solar abundances are better.)
    - Why would 4.5 Gyr old star accurately reflect ISM today?

Absorption from ISM

- Some commonly used abundances in Xspec and Sherpa.

wilm	ISM; based on analyses of UV derived abunds, tweaked modern solar
lodd	Solar photosphere (her paper also has proto-solar and meteorites). Lodders 2003
aspl	Solar photosphere; Asplund et al 2009
feld	Solar photosphere; Feldman 1992
aneb	Meteorites. Anders & Ebihara 1982
grsa	Solar photosphere; Grevesse et al. updated angr in 1998
angr	Solar photosphere; old. Anders & Grevesse 1989

Absorption from ISM

- Some commonly used absorption models and cross sections in Xspec and Sherpa. The absorption models have variants that allow variable abundances.

tbabs, etc.	suite of models that takes gas, molecules, grains into account. Uses updated cross sections. 2000-2016
wabs	photoelectric absorption using cross sections from Morrision & McCammon 1983; old
phabs	photoelectric absorption using cross sections set by user.
vern	cross sections from Verner et al. 1996
bcmc	cross sections from Balucinska-Church & McCammon 1992; new He cross sections as of 1998

Absorption from ISM

The standard grain size distribution disclaimer…

- To find the attenuation, we also need to know the grain size distribution, which is given by a grain model. Typically, people use MRN (Mathis et al. 1977) or modified version, or WD.

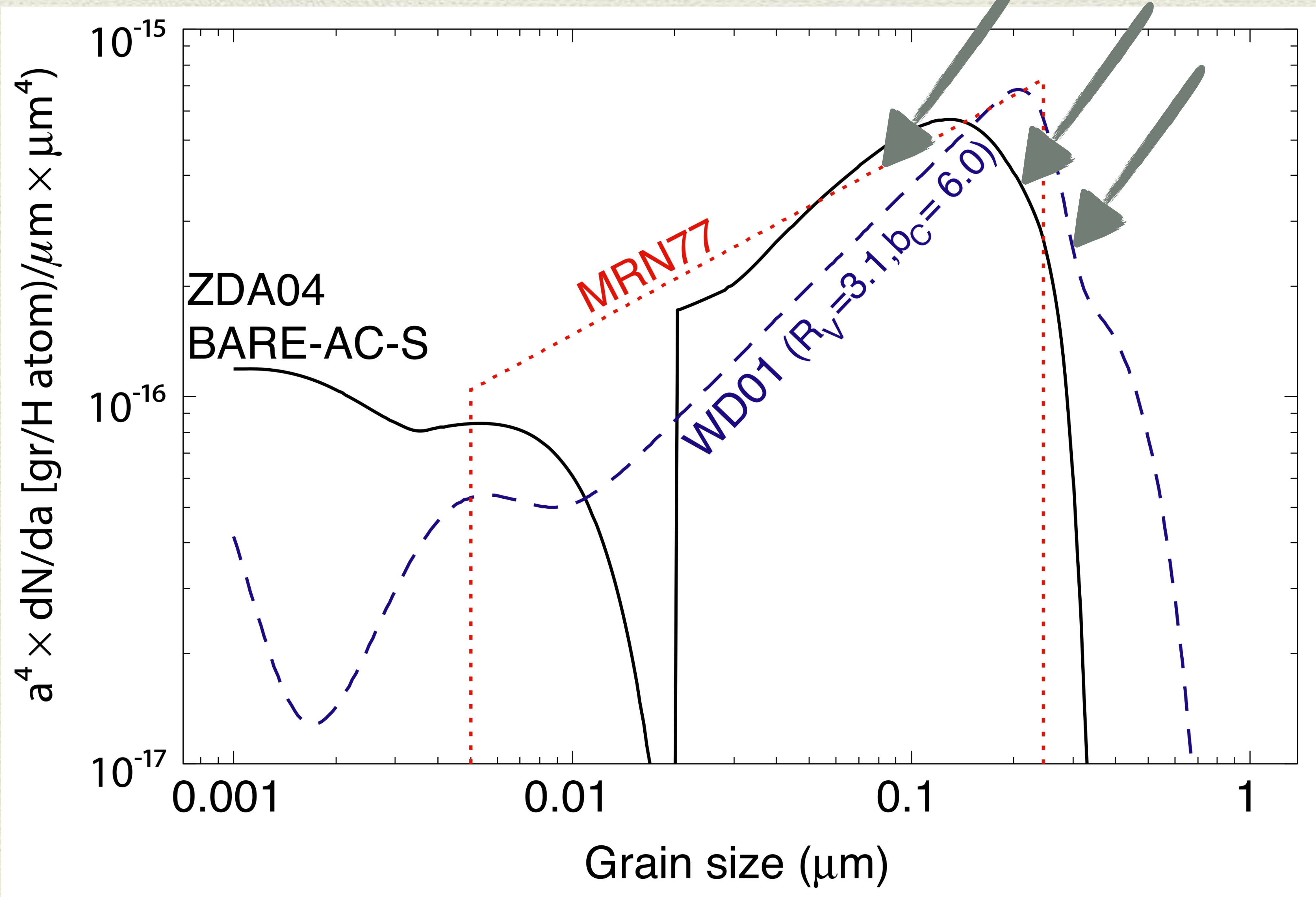
- Almost all models assume "standard diffuse ISM" R_V=3.1… (in Galaxy, R_V=2.5-5.5; diffuse vs. dense; grain sizes) a lot of sightlines are not "standard".

Scattering from ISM

- Small angle scattering of X-rays off dust also scatters X-rays out of line of sight, significantly and systematically affecting the measured source spectrum, even in lightly absorbed sources.
- To measure this, grain scattering cross section must be combined with a model that specifies the grain size distribution and composition.

Size Distributions from Some Commonly Used Models for Standard Diffuse ISM (R_V=3.1).

All of them fit the observables (optical/UV extinction, IR emission, polarization…) reasonably well.



Comparison of contributing fluxes in the spectrum of GRS 1758-258 (disk bb + pl; N_H~7e21 cm^{-2}) assuming scattering from different models.

F_x(10^{-10} erg/cm^2/s)	No scattering	Mathis et al. 1977	WD 2001	Zubko et al. 2004 (BAS)
Disk blackbody	8.38±0.10	9.04±0.11	9.31±0.11	8.88±0.10
Power law	1.20±0.03	1.24±0.03	1.23±0.03	1.23±0.03

Because scattering is heavily dependent on large grains, different grain models produce different scattering, even for the same ISM phase (R_v=3.1).

Absorption from ISM - Final Thoughts

- Choose your abundances and absorption model carefully. This is especially important if your target is in LMC, SMC which have different abundances than Galaxy.
- Be aware of the limitations of grain models.
- Keep an eye on scattering, which can be significant particularly if the column density is high. There is a model in Xspec ("xscat") to correct for it.

Back ups

Photoionized plasmas

In a photoionized gas, the temperature is not a free parameter.

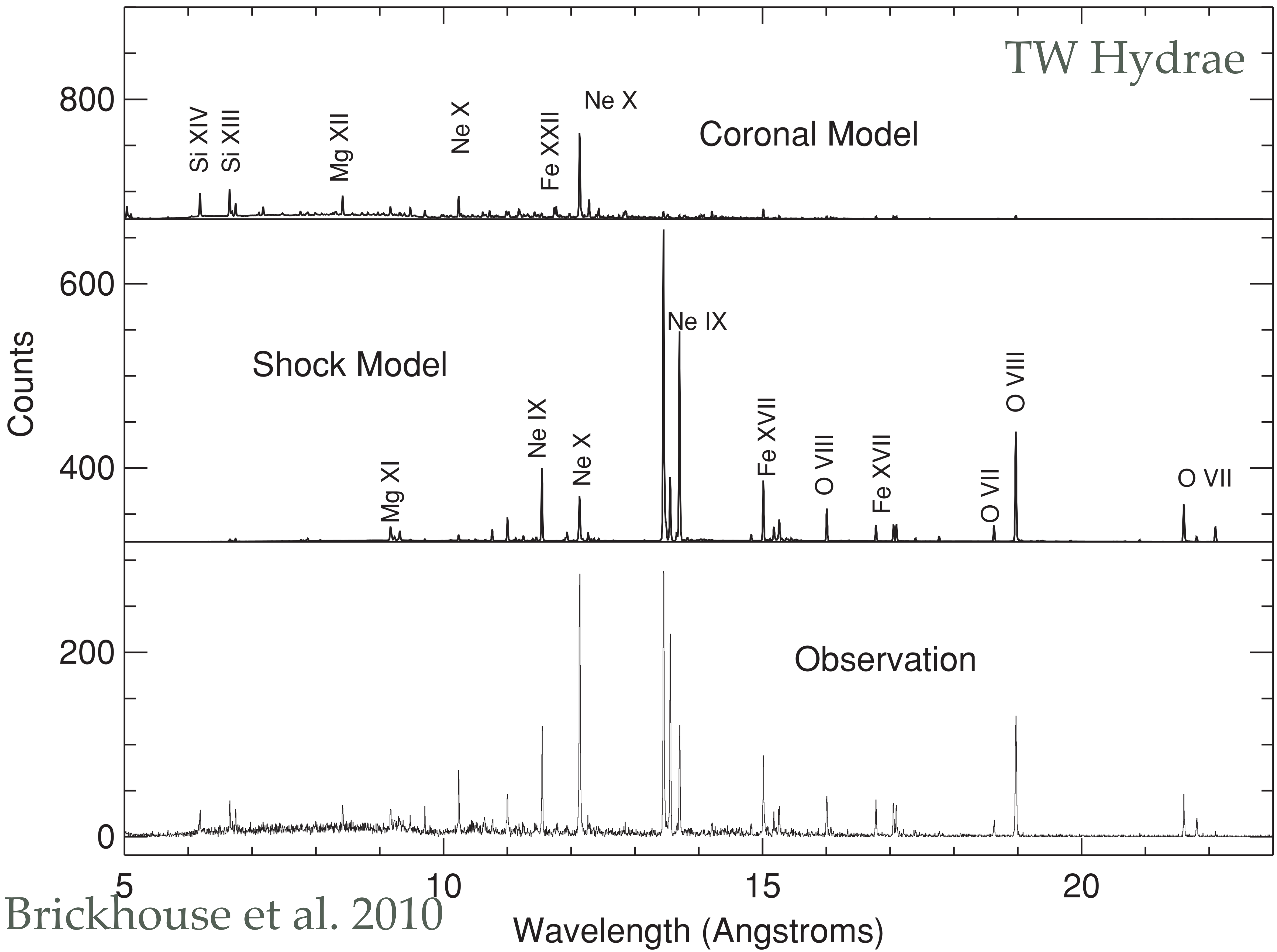
The ionization balance is determined by the shape and strength of the radiation field.

Photoionized plasmas

Due to the democratic ionization balance, it is more likely that diverse ions like N VII, O VIII, Si XIV can coexist and emit efficiently than it would be in a coronal gas.

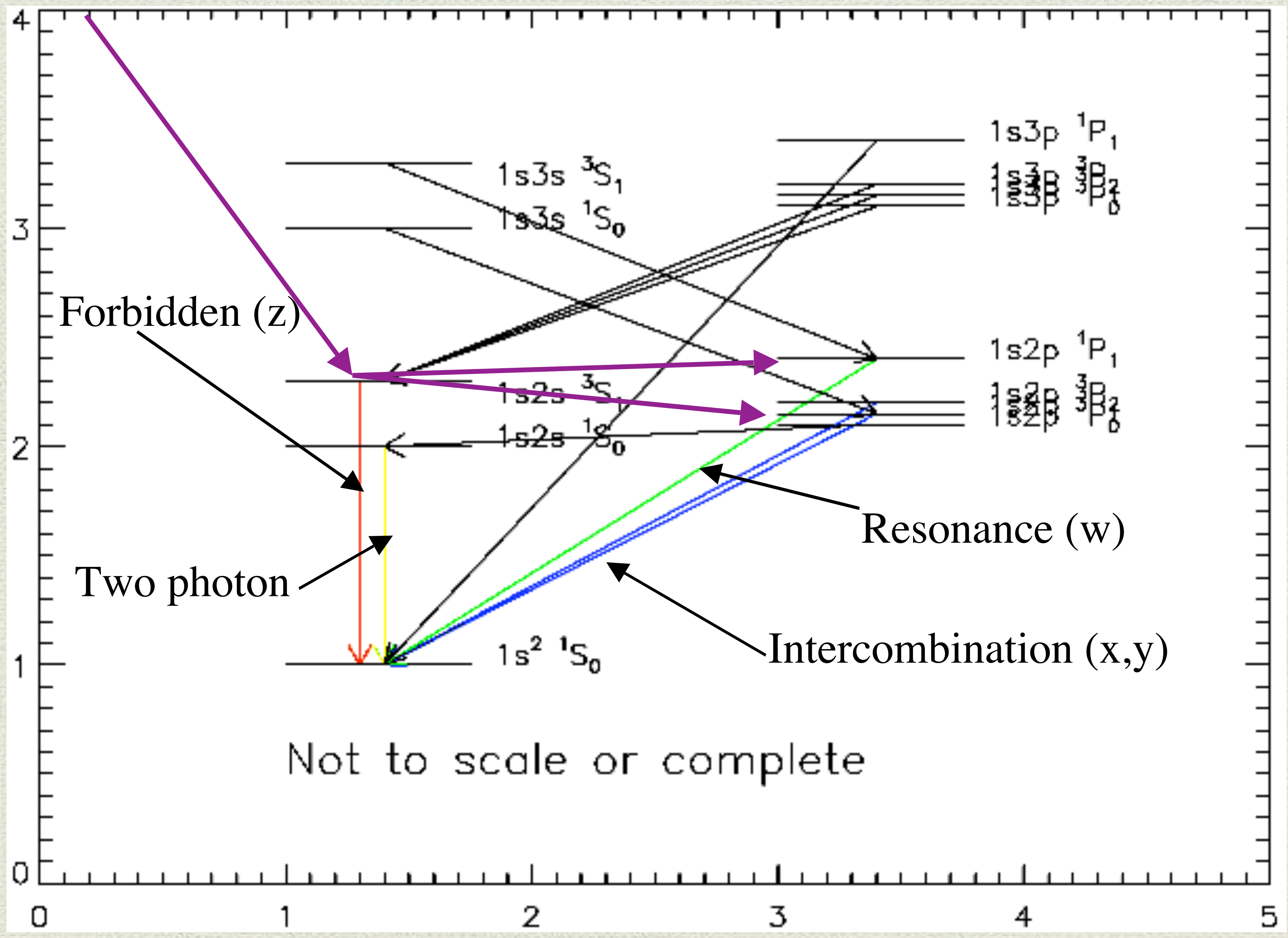
Inner shell ionization and fluorescence is also important in gases where the ionization state is low enough to allow ions with filled shells to exist.

TW Hydrae



Brickhouse et al. 2010

Quick atomic physics interlude



Absorption from ISM - Broadband

- Important things to consider: photoionization cross section of ISM, abundances

$$\sigma_{ISM} = \sigma_{gas} + \sigma_{molecules} + \sigma_{grains}$$

- For σ_{gas}, sum the photoionization cross sections of individual atoms and ions in warm phase ISM, weighting their contributions by their abundanances.

$$\sigma_{gas} = \Sigma_{Z,i}\, N(Z,i)/N(Z) \times N(Z)/N(H) \times (1-\beta_{Z,i}) \times \sigma_{bf}(Z,i)$$

Radiative excitation

Photons can interact with ions, including collisionally ionized plasma.

This can be an important process, but only for allowed transitions. In a collisional plasma, many transitions are forbidden or semi-forbidden.

It can show up as optical depth in allowed lines, weakening them relative to forbidden lines, and can be calculated after modeling a plasma. While this effect is often not important, it should still be checked.

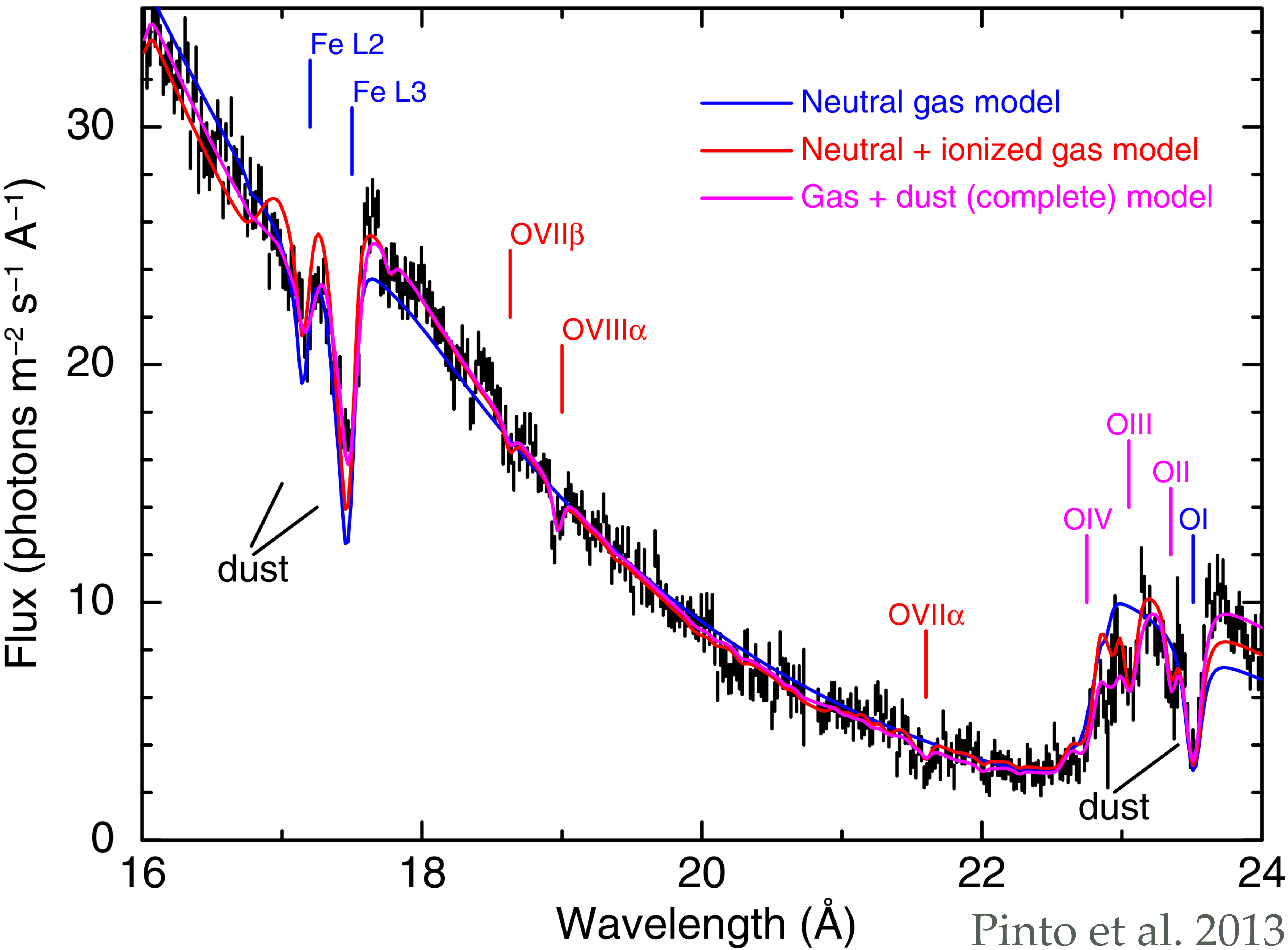
Plasmas

	Photoionized	Coronal
Dominant mechanism	photoionization	electron impact
Examples	AGN, binaries, H II regions	Stellar coronae, SNR, galaxy clusters
Spectral Signature	Absorption, bound-free, bound-bound; Emission: recombination	Emission lines; $\Delta n=0,1,2$ favored

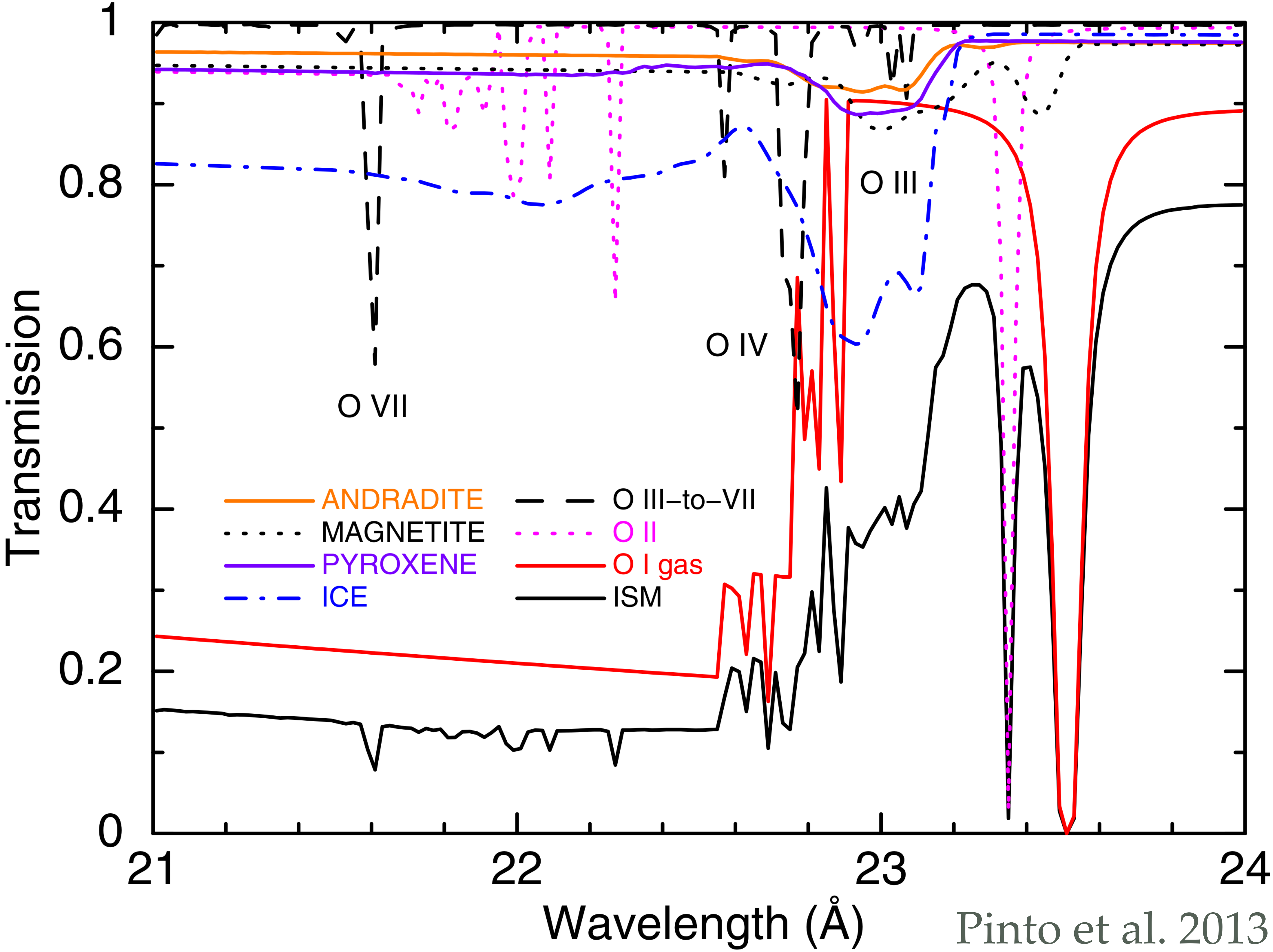
Absorption from ISM - High Resolution

- Grain compositions/structures are still unknown, after decades of study. X-ray absorption fine structure near edges gives ionization states; comparison with dust analogs in lab gives grain compositions.

- Both dense and diffuse media (i.e., all values of $R_{V;}$ phases of life) can be examine with X-rays (as opposed to UV, which is limited to diffuse media, and IR, which is limited to dense media). A total census of the ISM!



Pinto et al. 2013



Pinto et al. 2013

Introduction

Plasmas can also be in Local Thermodynamic Equilibrium. This happens when

$$N_e > 1.3e14\ T_e \Delta E_{ij}^3\ \mathrm{cm}^{-3}$$

For $T_e = 10^7$ K and H-like Fe, $N_e > 2e27\ \mathrm{cm}^{-3}$

For $T_e = 10^5$ K and H-like O, $N_e > 1e24\ \mathrm{cm}^{-3}$

Extremely high densities! Not seen outside stars…

Photoionized plasmas

In a coronal gas, need $kT_e \sim \Delta E$ to collisionally excite lines.

In a photoionized gas, there are fewer lines which satisfy this condition, so excitation is often by recombination cascade.

Also get recombination continua from recombination by cold electrons directly to the ground state. These features' widths is directly proportional to the temperature.

Photoionized plasmas

What happens when an photon source illuminates the gas?

- The photons ionize the atoms in the gas.
- The photoelectrons then collide with ambient electrons and heat the gas
- The gas radiates and cools.
- The gas temperature adjusts so that the heating and cooling balance.

Collisional plasmas

Collisional plasmas can be in ionization equilibrium. This happens when

$$\mathbf{I_{rate}(ion) + R_{rate}(ion) = I_{rate}(ion^{-}) + R_{rate}(ion^{+})}$$

They can also not be in eqilibrium, in which case the plasma is either ionizing [$\Sigma I_{rate}(I) > \Sigma R_{rate}(I)$] or recombining [$\Sigma I_{rate}(I) < \Sigma R_{rate}(I)$].