Calibration and Spectra of Photoionized Sources

T. Kallman NASA/GSFC

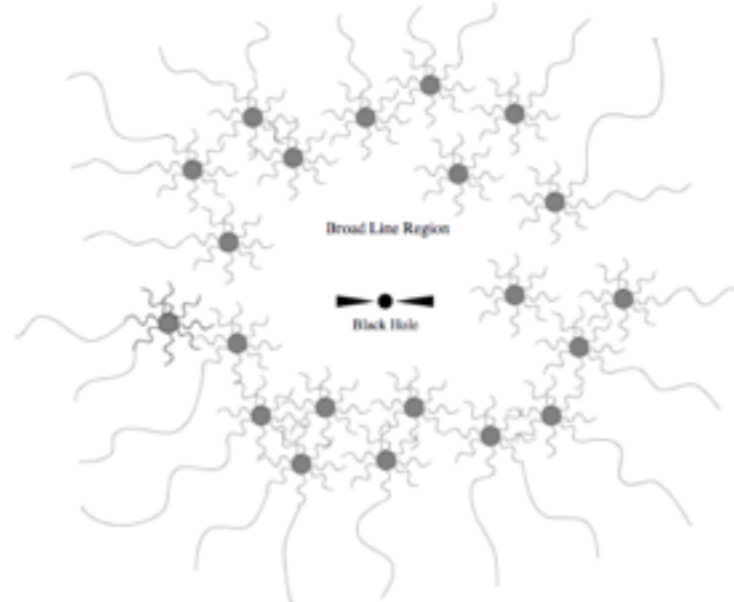
Outline:
disclaimer
Background
Examples
Photoionized sources as calibrators?

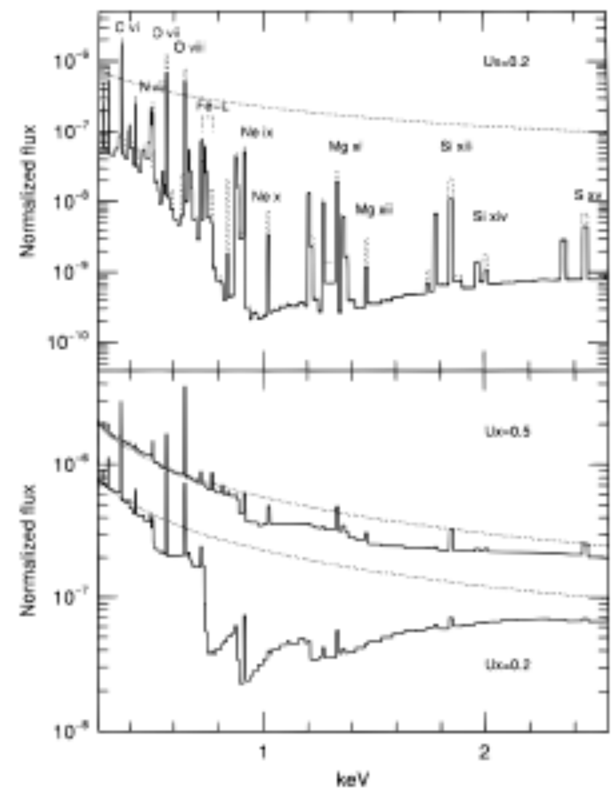
What is ‘photoionization’?

- When dominant excitation/ionization is from photons (vs. electrons)
  - Also: spectral signatures due to photoabsorption
  - Also could include: any signatures of bound-free
- context?
  - Compact objects (agn, x-ray binaries, cv’s…)
  - Also ism/igm
- What do we expect to see?
  - Signature of absorption and reprocessing
  - Atomic features
    - Interesting since $T_{rad} >> T_{gas}$
  - Signs of geometry
  - Indicators of dynamics

A Historical note

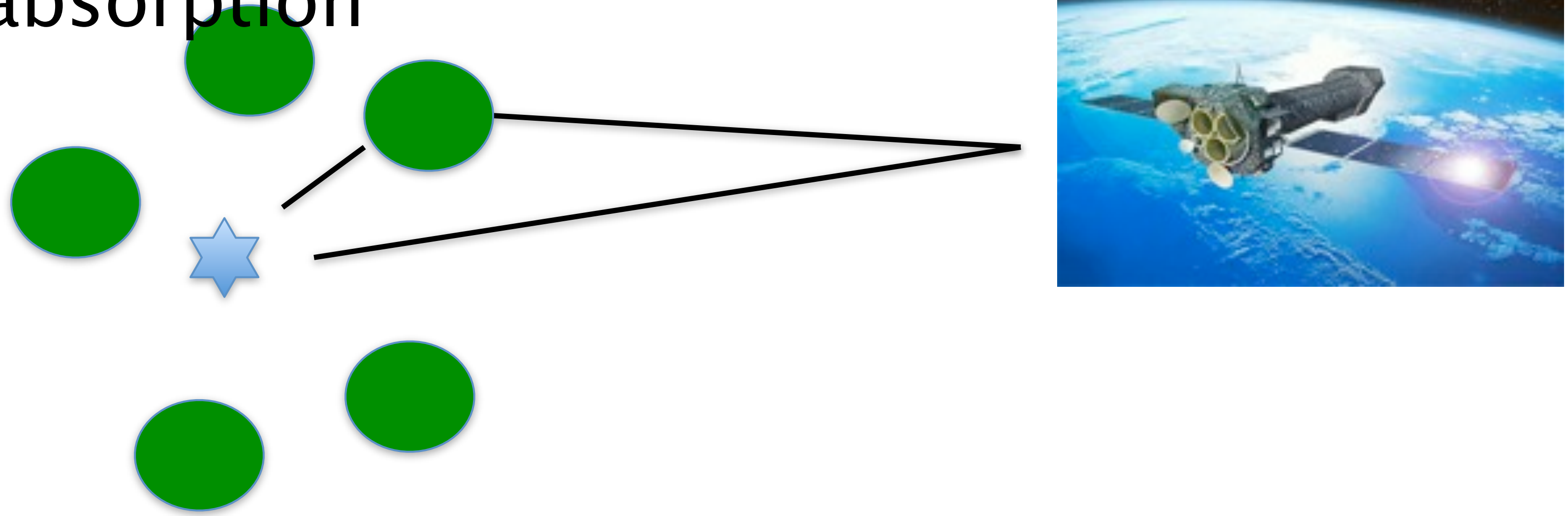
- Prior to chandra, focus was on emission
  - Analogy with nebular lines
  - Notwithstanding asca detection of agn warm absorbers

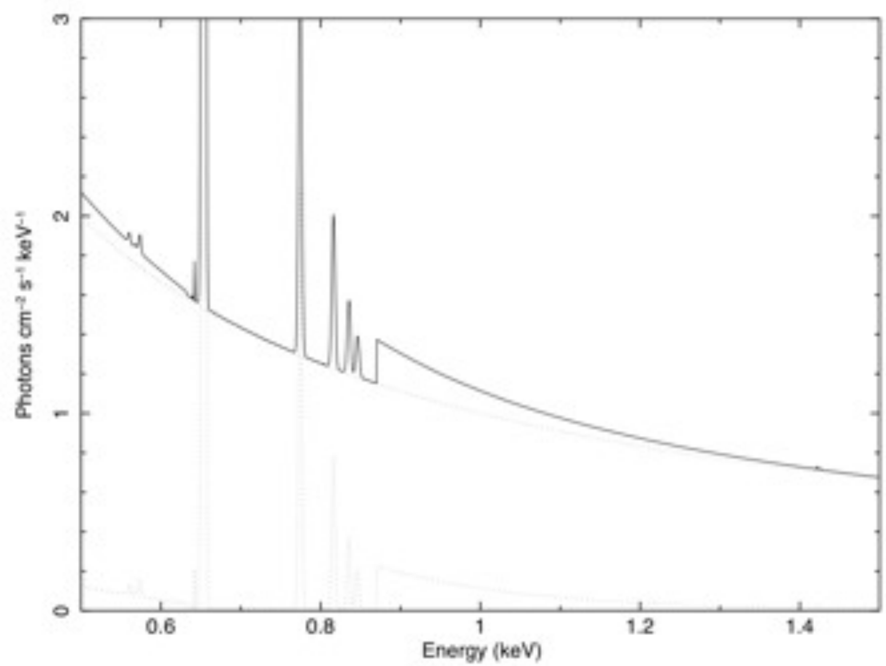




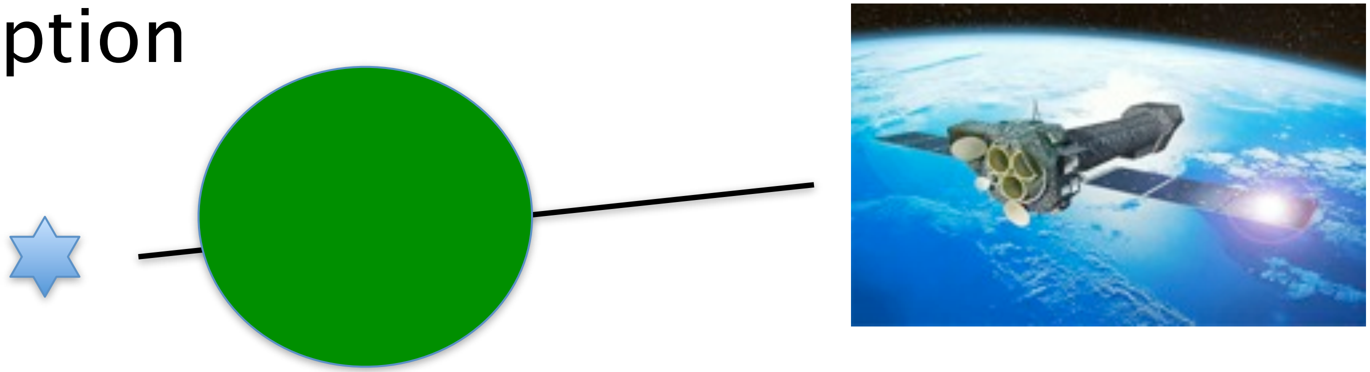
(Netzer 1996)

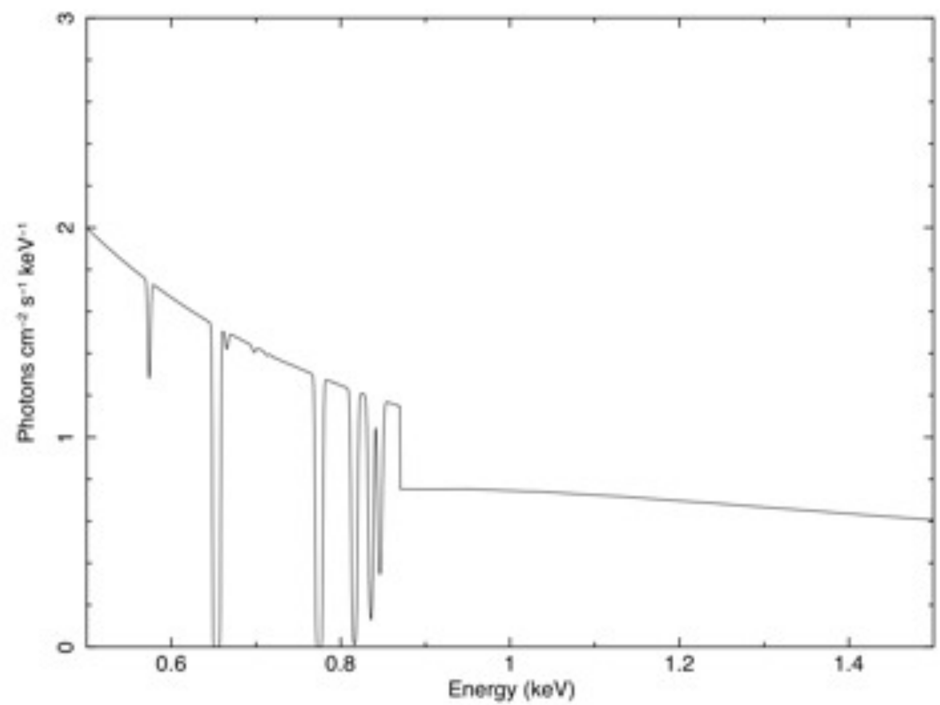
Small clouds, covering <<1: Emission, no absorption



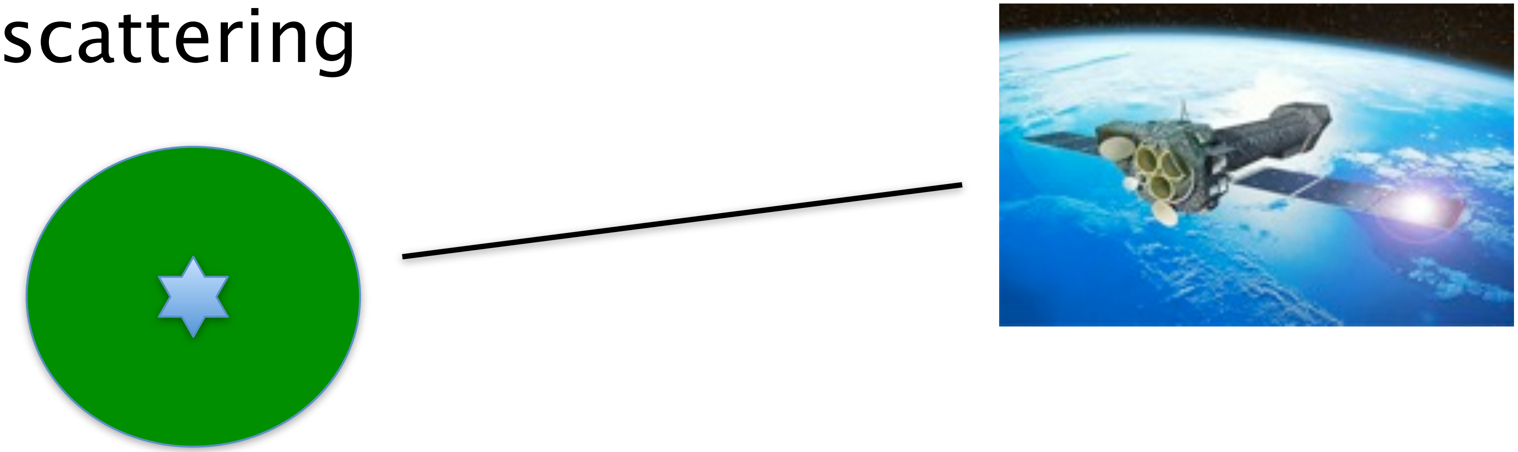


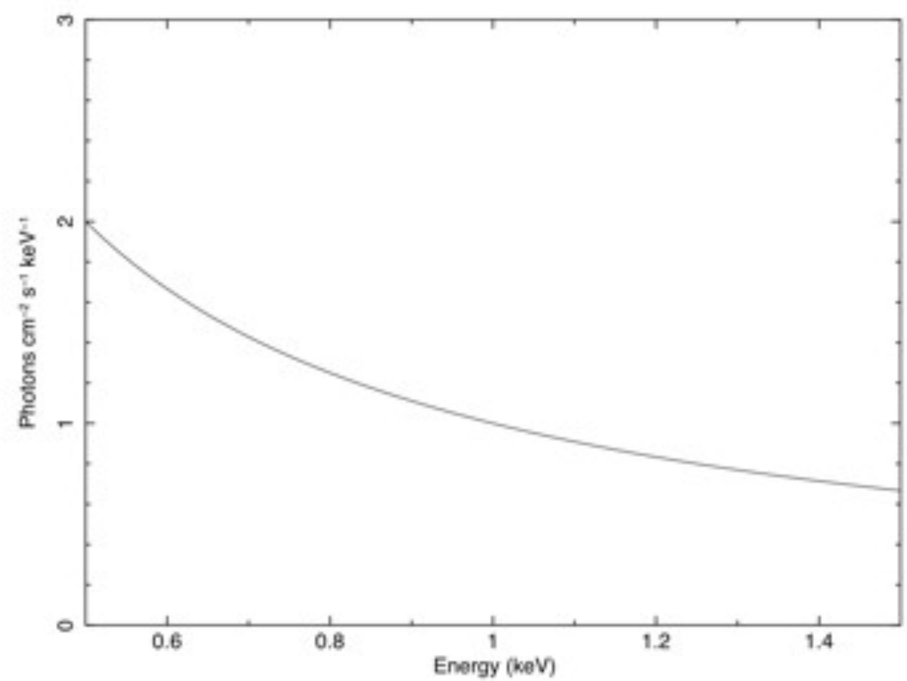
If the gas is in the line of sight only, pure absorption



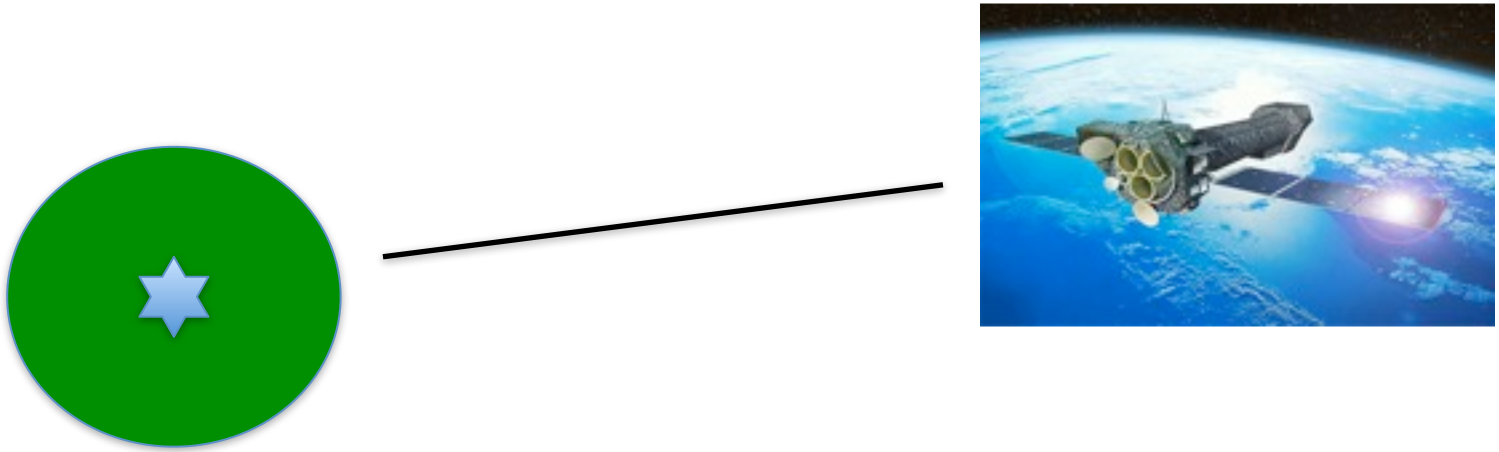


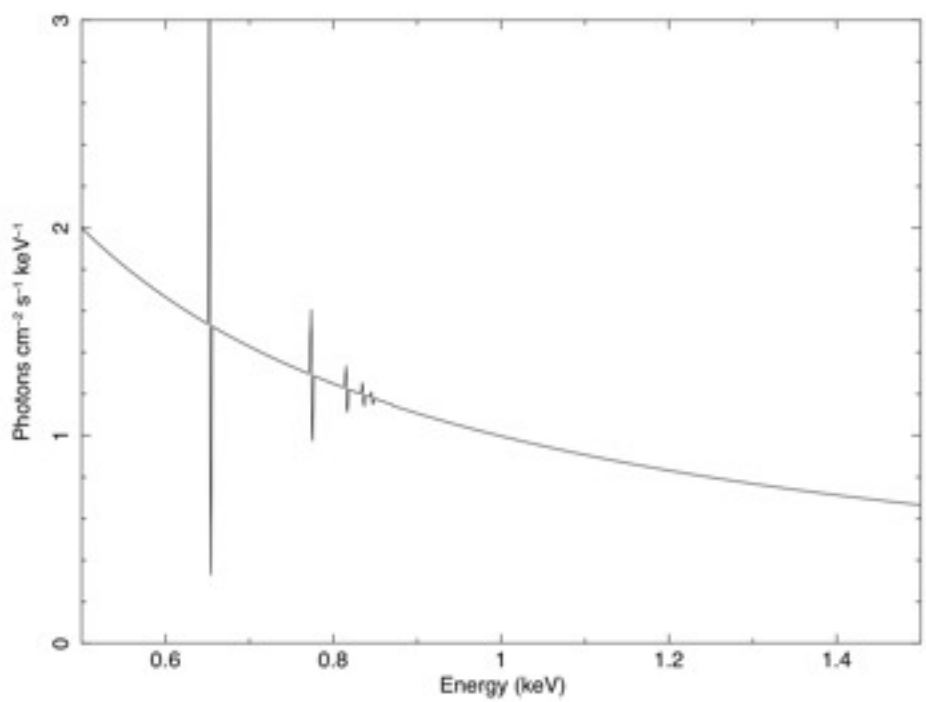
if C~1, expect no signature for elastic scattering



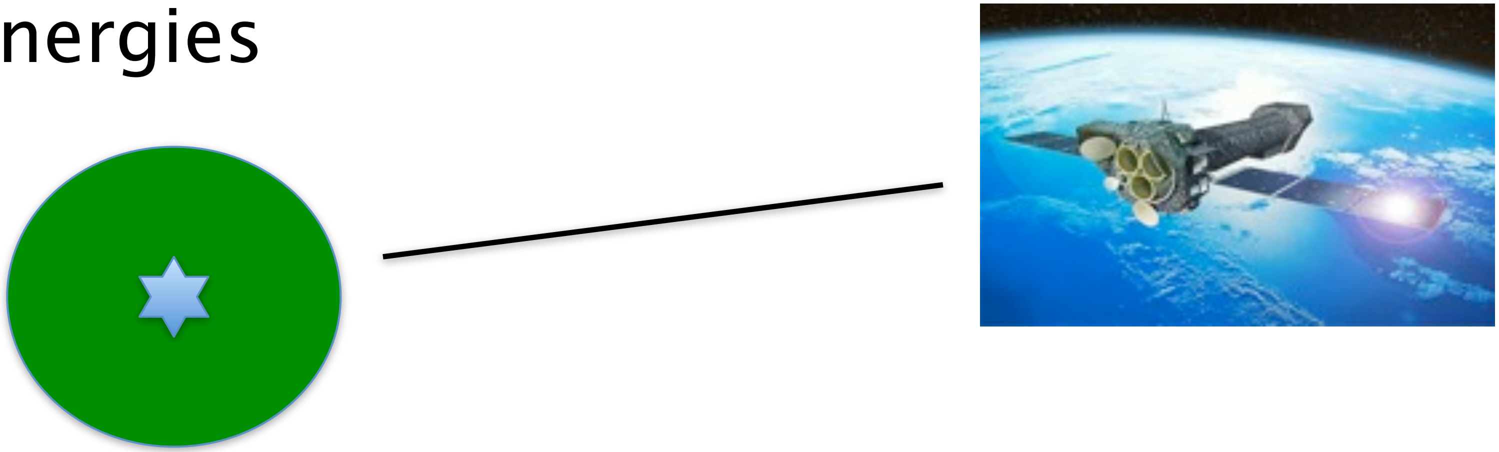


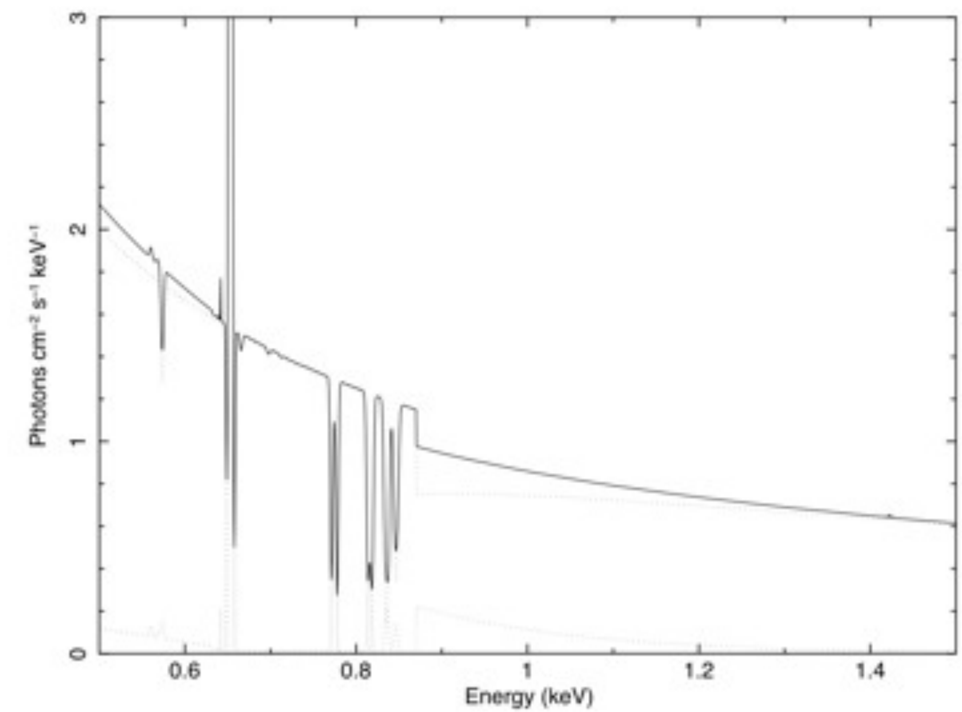
If the gas is expanding, get P-Cygni profiles





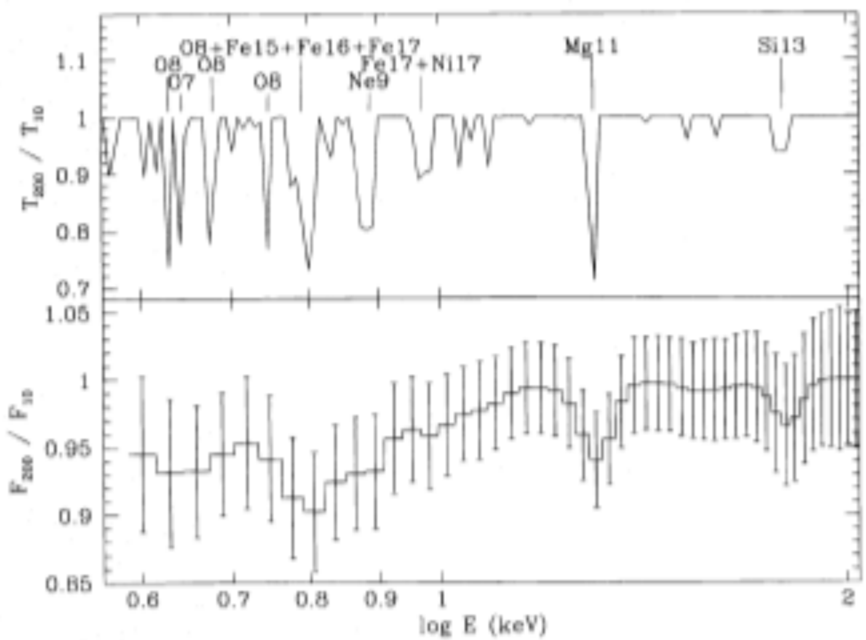
atomic processes redistribute the photon energies





A Historical note

- Discovery of line absorption took many people by surprise (cf. Kriss et al. 1996)
- Absorption lines imply non-spherical geometry
- Blueshift indicates outflow



Calculate ionization balance according to…

$$\frac{dn_i}{dt} = \Sigma_j \left(n_j R_{ji}(T, F, n..) - n_i R_{ij}(T, F, n...)\right)$$

- neglect time dependence
- The rate coefficients R_{ij} divide:
  - Coronal: excitation due primarily to electron collisions
    - Appropriate for mechanically heated gas: stellar coronae, virial flows
  - Photoionization: excitation due primarily to recombination following photoionization
    - Appropriate for gas exposed to strong radiation field, such as may occur near a black hole or neutron star which radiates a strong continuum

Calculate ionization balance according to…

$$\frac{dn_i}{dt} = \Sigma_j \left(n_j R_{ji}(T, F, n..) - n_i R_{ij}(T, F, n...)\right)$$

- neglect time dependence
- The rate coefficients R_{ij} divide:
  - Coronal: excitation due primarily to electron collisions
    - Appropriate for mechanically heated gas: stellar coronae, virial flows
  - Photoionization: excitation due primarily to recombination following photoionization
    - Appropriate for gas exposed to strong radiation field, such as may occur near a black hole or neutron star which radiates a strong continuum

photoionization models couple to the temperature

$$\frac{d}{dt}\left(\frac{3}{2}nkT\right) = H(T,F,n..) - C(T,F,n..)$$

Heating rate — Cooling rate

- Heating is due to slowing down of photoelectrons (plus Compton scattering)
- Cooling is due to electron collisions: excitation, ionization, recombination (plus Compton scattering)
- => the temperature is not a free parameter
- Both temperature and ionization balance depend on the 'ionization parameter', the ratio

$$\frac{\text{radiation flux}}{\text{gas density}} \equiv \frac{F}{n} \equiv \frac{\xi}{4\pi}$$

photoionization models couple to the temperature

$$\frac{d}{dt}\left(\frac{3}{2}nkT\right) = H(T, F, n..) - C(T, F, n..)$$

Heating rate

Cooling rate

- Heating is due to slowing down of photoelectrons (plus Compton scattering)
- Cooling is due to electron collisions: excitation, ionization, recombination (plus Compton scattering)
- => the temperature is not a free parameter
- Both temperature and ionization balance depend on the ‘ionization parameter’, the ratio

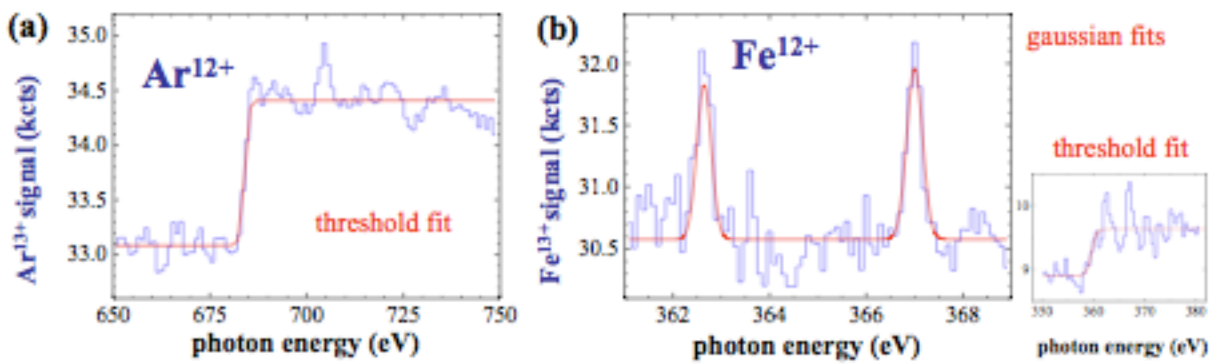
$$\frac{\text{radiation flux}}{\text{gas density}} \equiv \frac{F}{n} \equiv \frac{\xi}{4\pi}$$

Ingredients of photoionization models

– Photoionization equilibrium → ion fractions
    - Most now explicitly calculate excited level populations
– Thermal equilibrium → temperature
– Spectrum synthesis → 'xspec' models
    - Either 'tables' or 'analytic'
– Radiation transfer (major variations on this)
    - Transfer of ionizing continuum into the gas
    - Transfer of cooling radiation out of the gas
    - 'formal solution' to equation of transfer → synthetic spectrum
– All together → 'full global model'

Atomic data: recent

- Photoionization experiment:
  - Ebit+3rd generation light source
  - Measure fluorescence emission following photoexcitation or photoionization
- Dr experiments pushing to end of iron



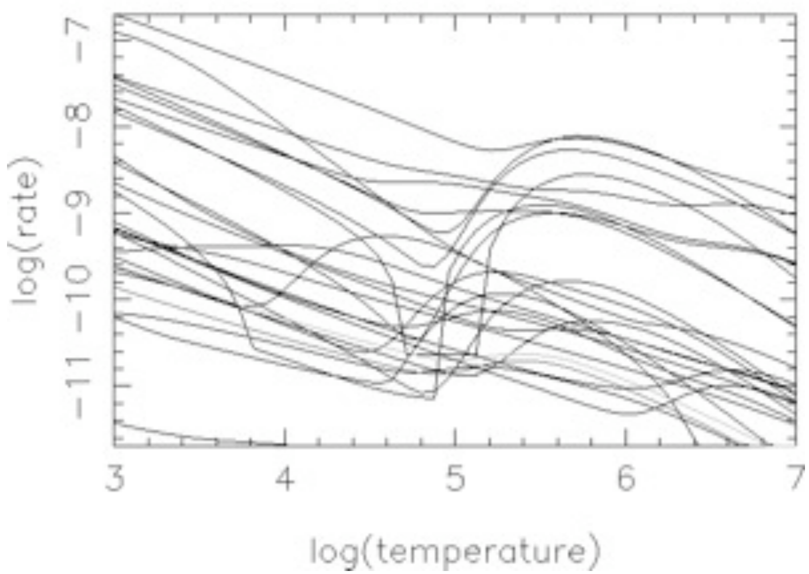
What atomic data goes into models?

process	status
recombination	x
ionization	Reciprocal with rec.
Electron impact excitation	linear
Charge transfer	N/a
Inner shell fluorescence/auger	x

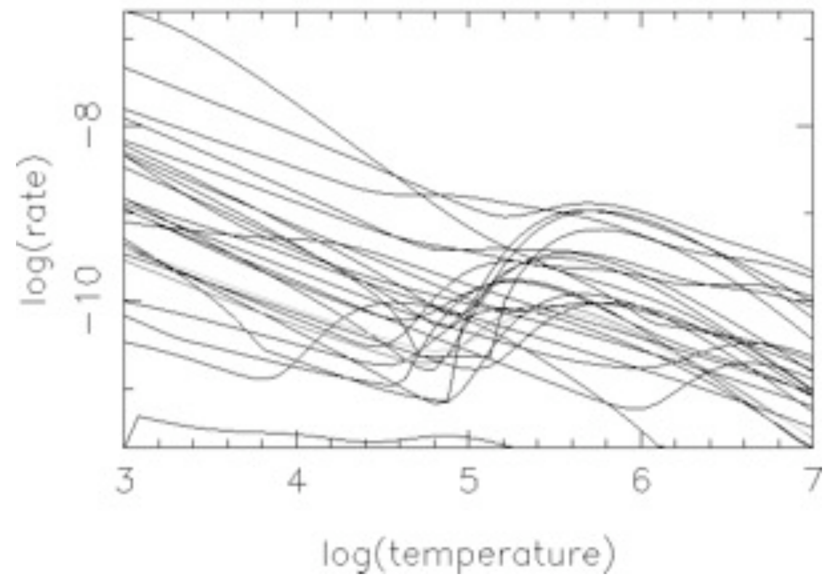
how do model/astrophysical results depend on atomic data?

- These issues have been considered previously in the context of solar lines.
  - Gianetti,Landi and Landini (2000)
  - Savin and Laming (2002)
  - Netzer (2004)
- Procedure:
  - We perturb the dielectronic recombination rates coefficients by a constant factor in the log
  - Make trial fits to data with and without perturbed rates

Iron Recombination rate coefficients vs. temperature



Baseline dielectronic recombination (DR) rate (including radiative cascades from n>5) based on Arnaud and Raymond (1992)

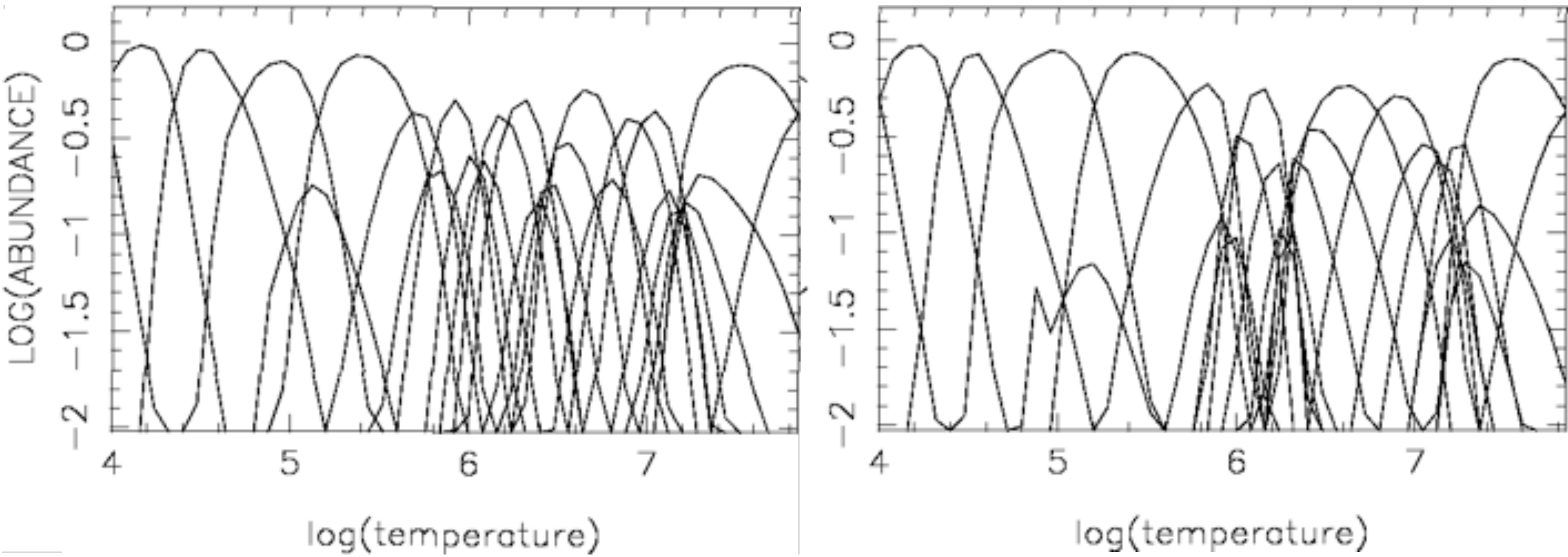


Perturbed DR rates:

log(Rate') =γ log(Rate)

0.9 <γ<1.1

Coronal ionization balance

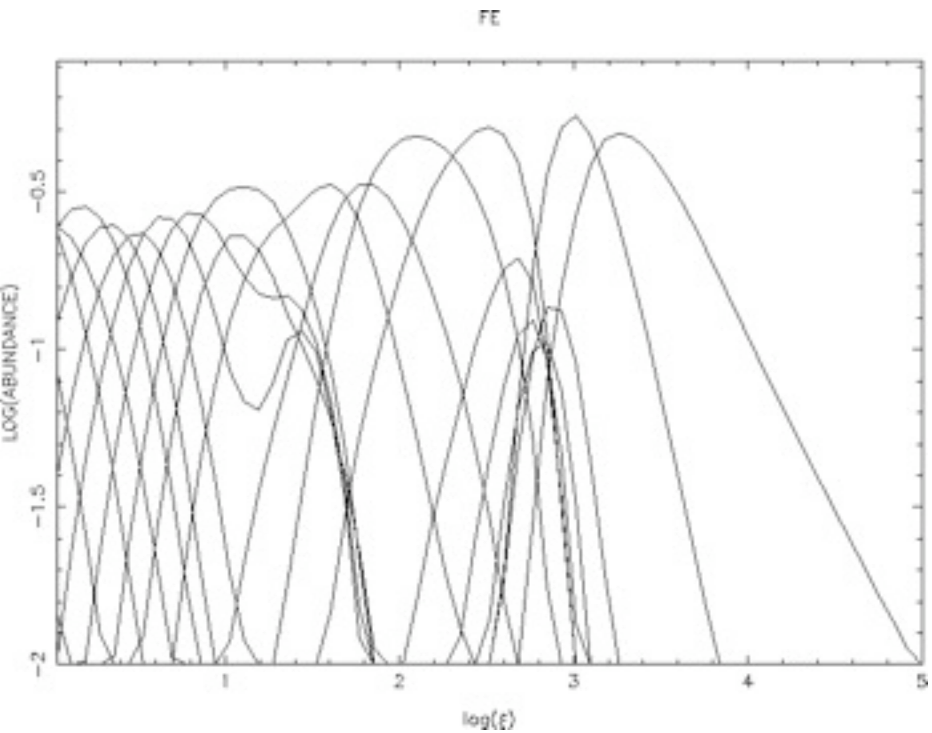


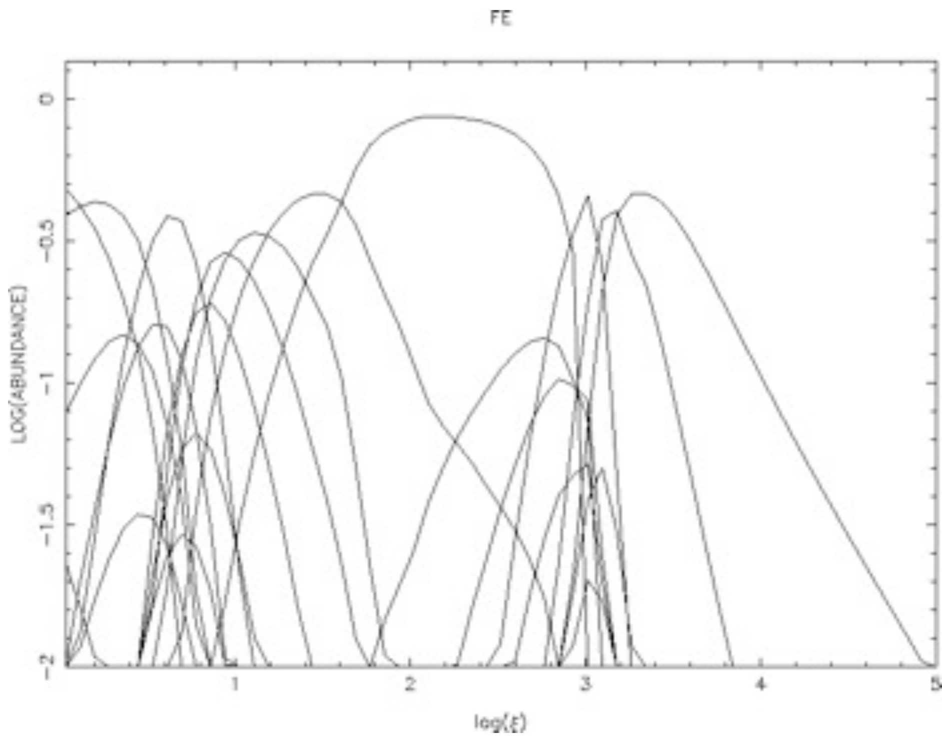
baseline

Perturbed DR

--> Δlog(T)=0.1

Photoionization equilibrium for iron





ξ=4π Flux/density

baseline

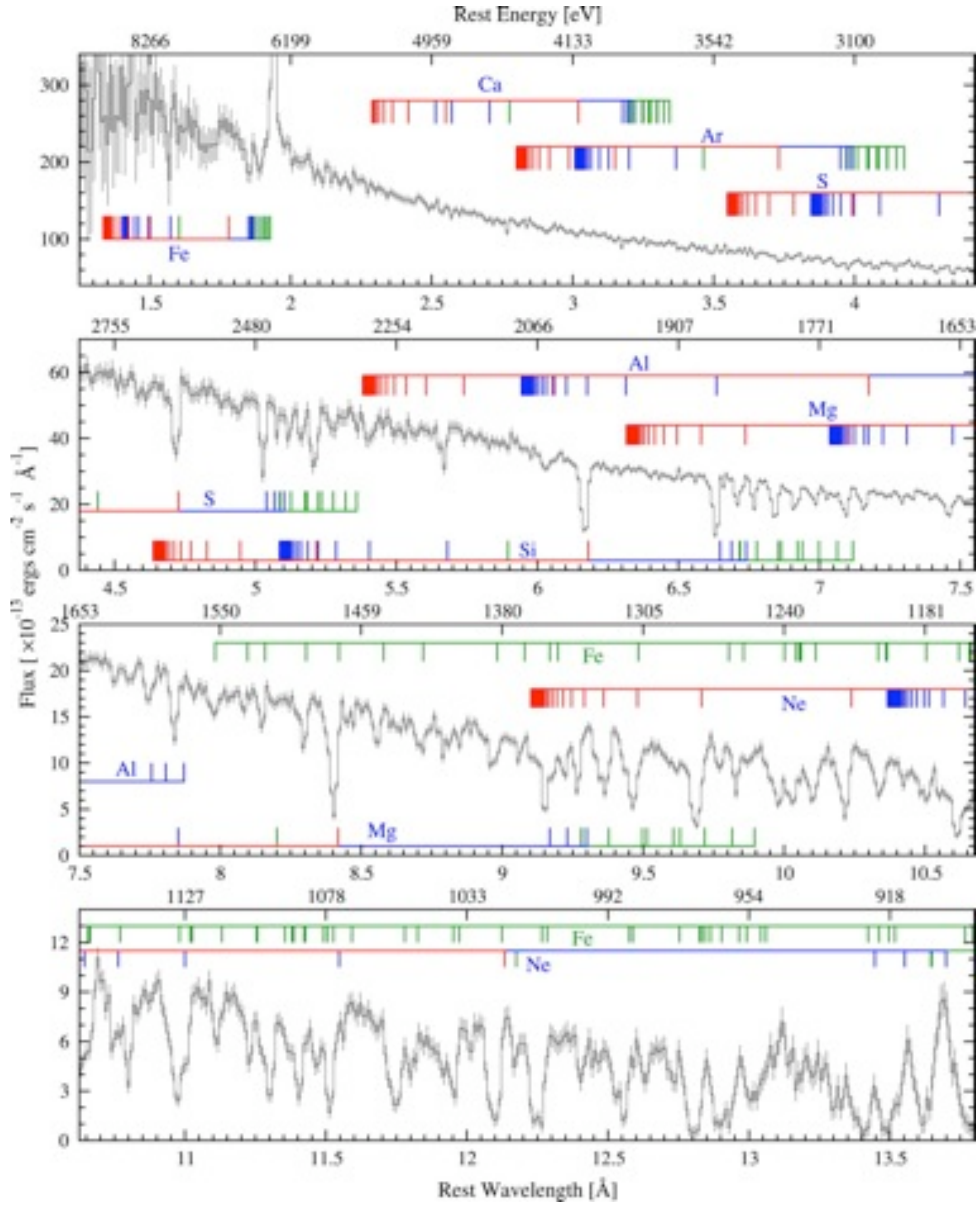
Perturbed DR

--> Δlog(ξ)=0.2 or greater

an astrophysical example: NGC3783

- 900 ksec Chandra HETG observation
- >100 absorption features
- blueshifted, v~800 km/s
- broadened, vturb~300 km/s
- emission in some components
- fit to 2 photoionization model components

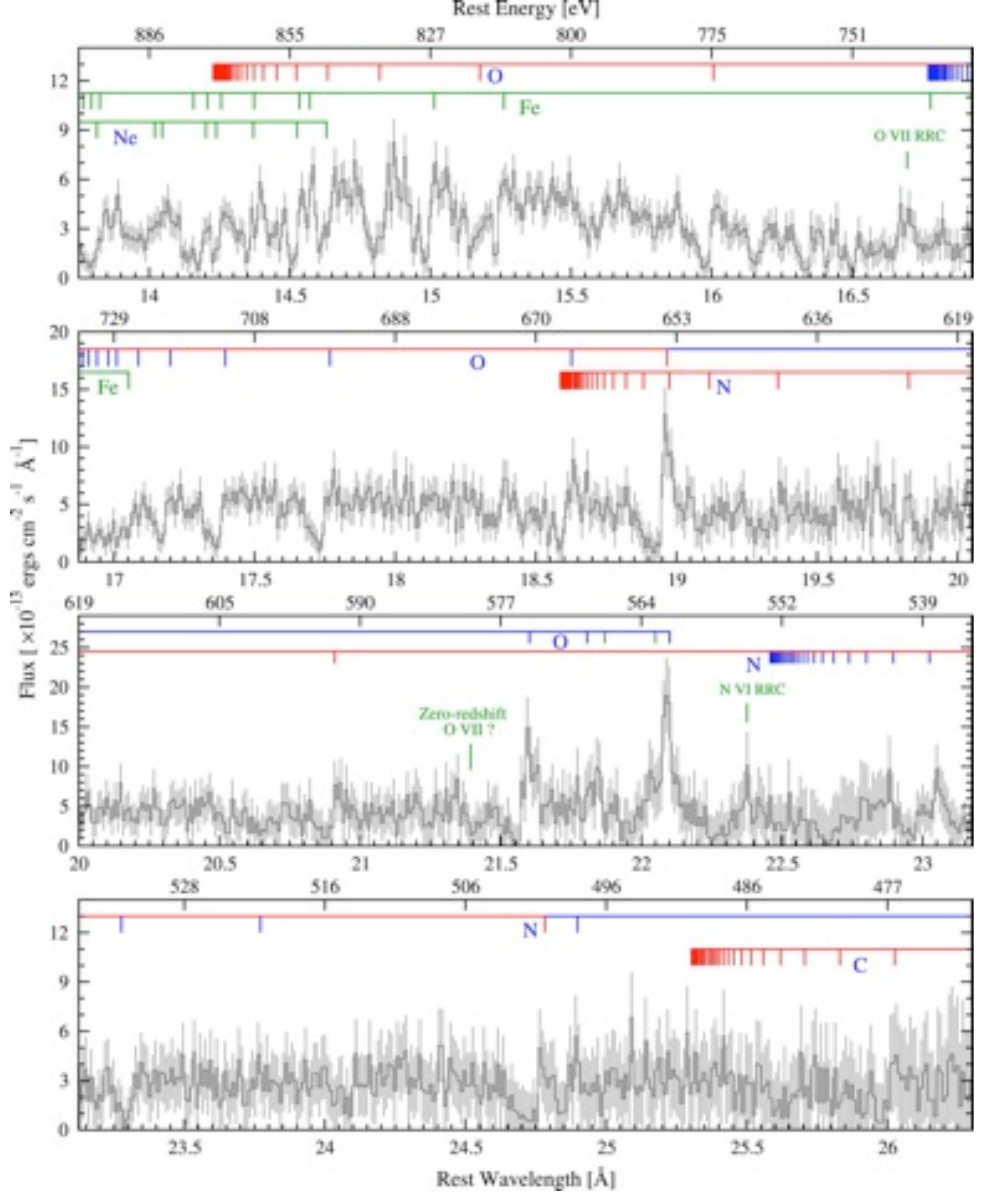
(Kaspi et al 2002)



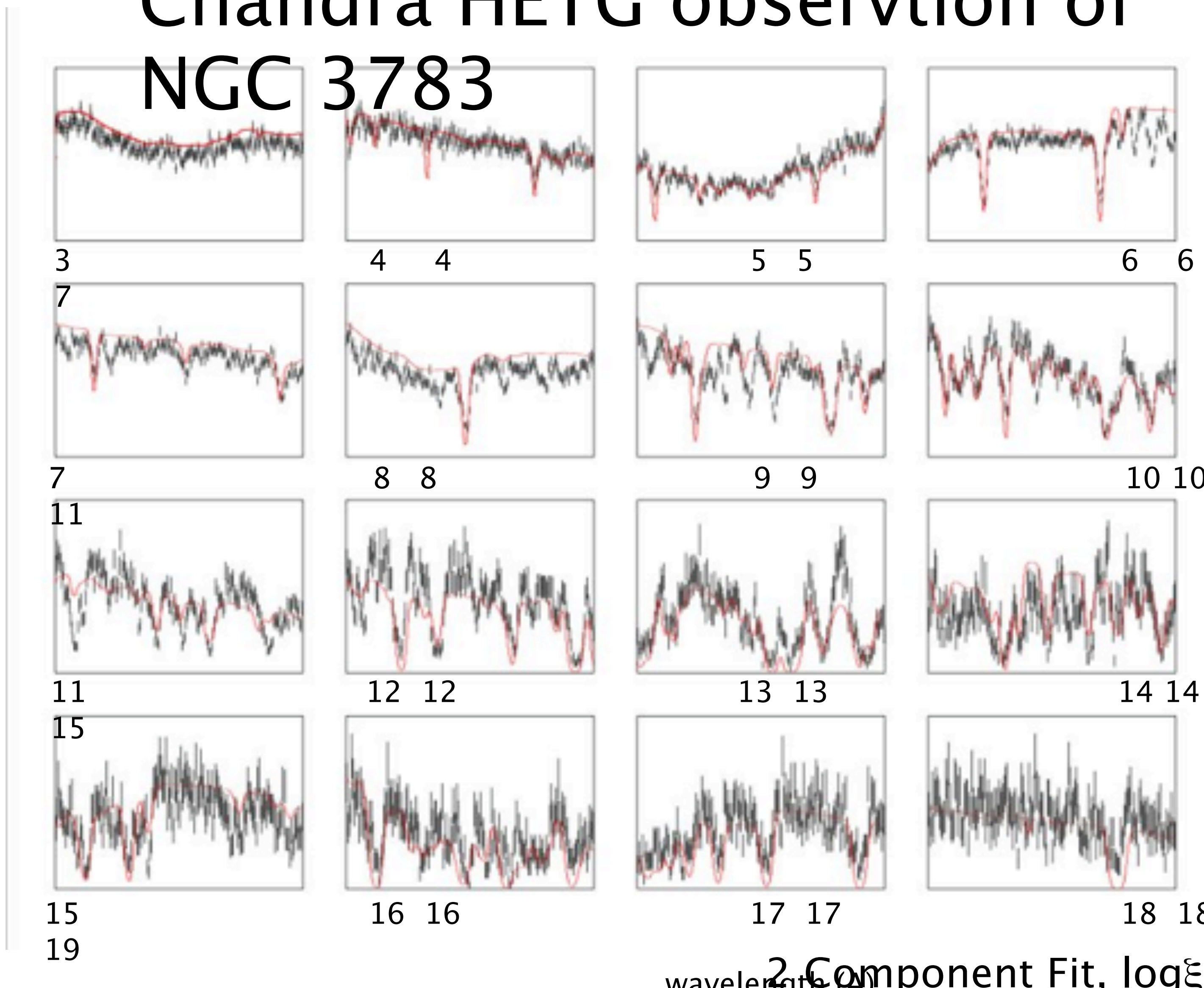
An astrophysical example: NGC3783

- 900 ksec Chandra HETG observation
- >100 absorption features
- blueshifted, v~800 km/s
- broadened, vturb~300 km/s
- emission in some components
- fit to 2 photoionization model components

(Kaspi et al 2002)



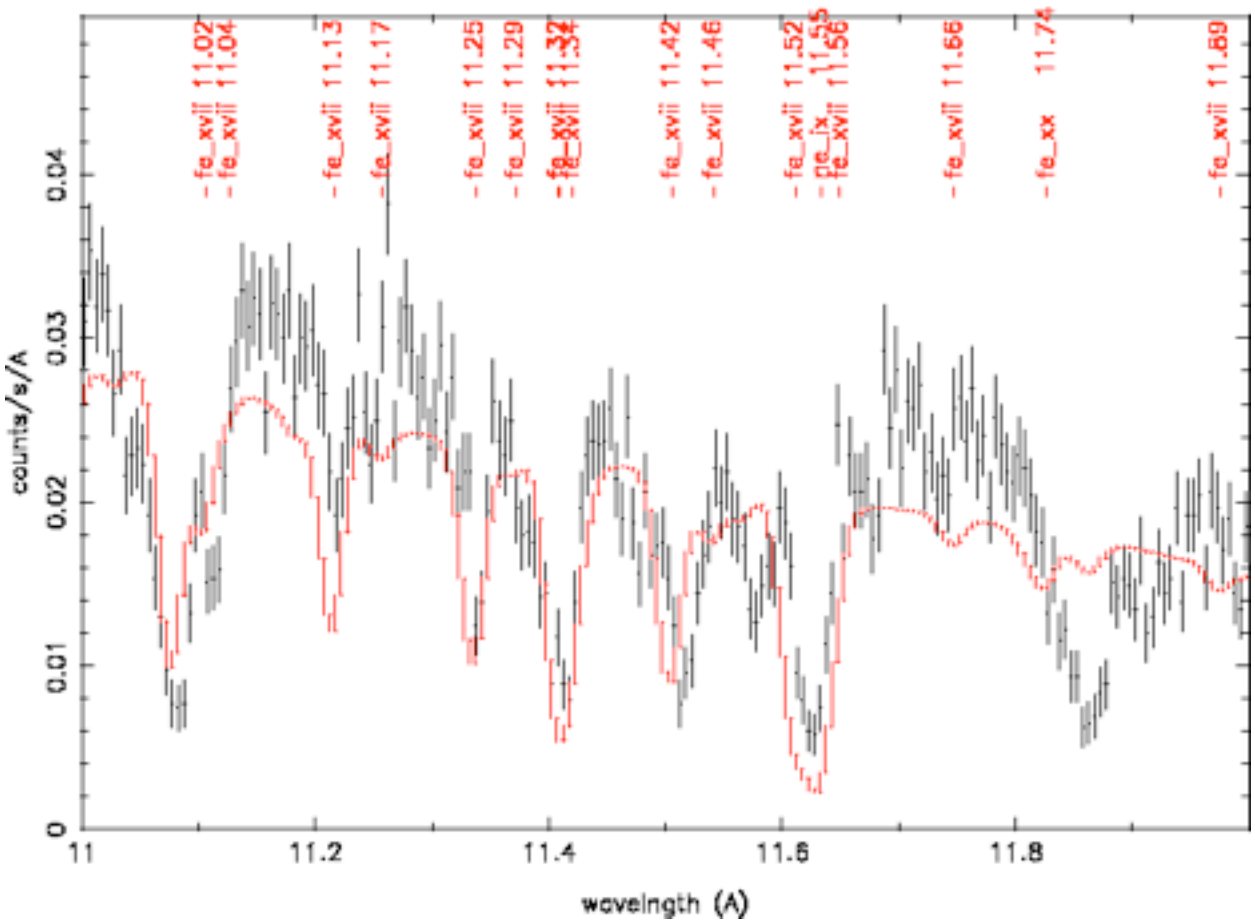
Fit of photoionization model to Chandra HETG observtion of NGC 3783



2 Component Fit, logξ=2.2, 0.1

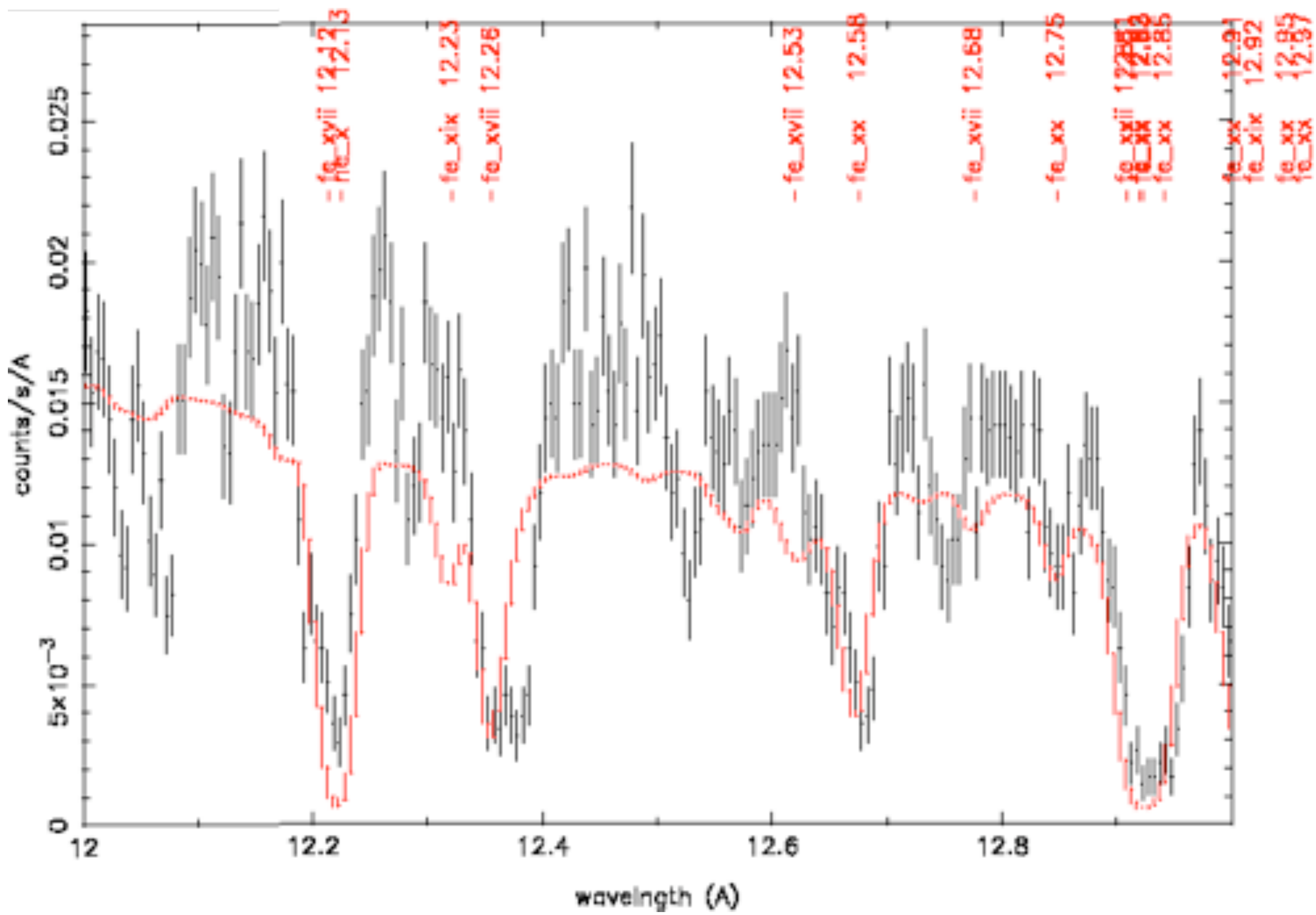
χ^2~111105/8192, voff=700 km/s vturb=300 km/s

Fe XXII

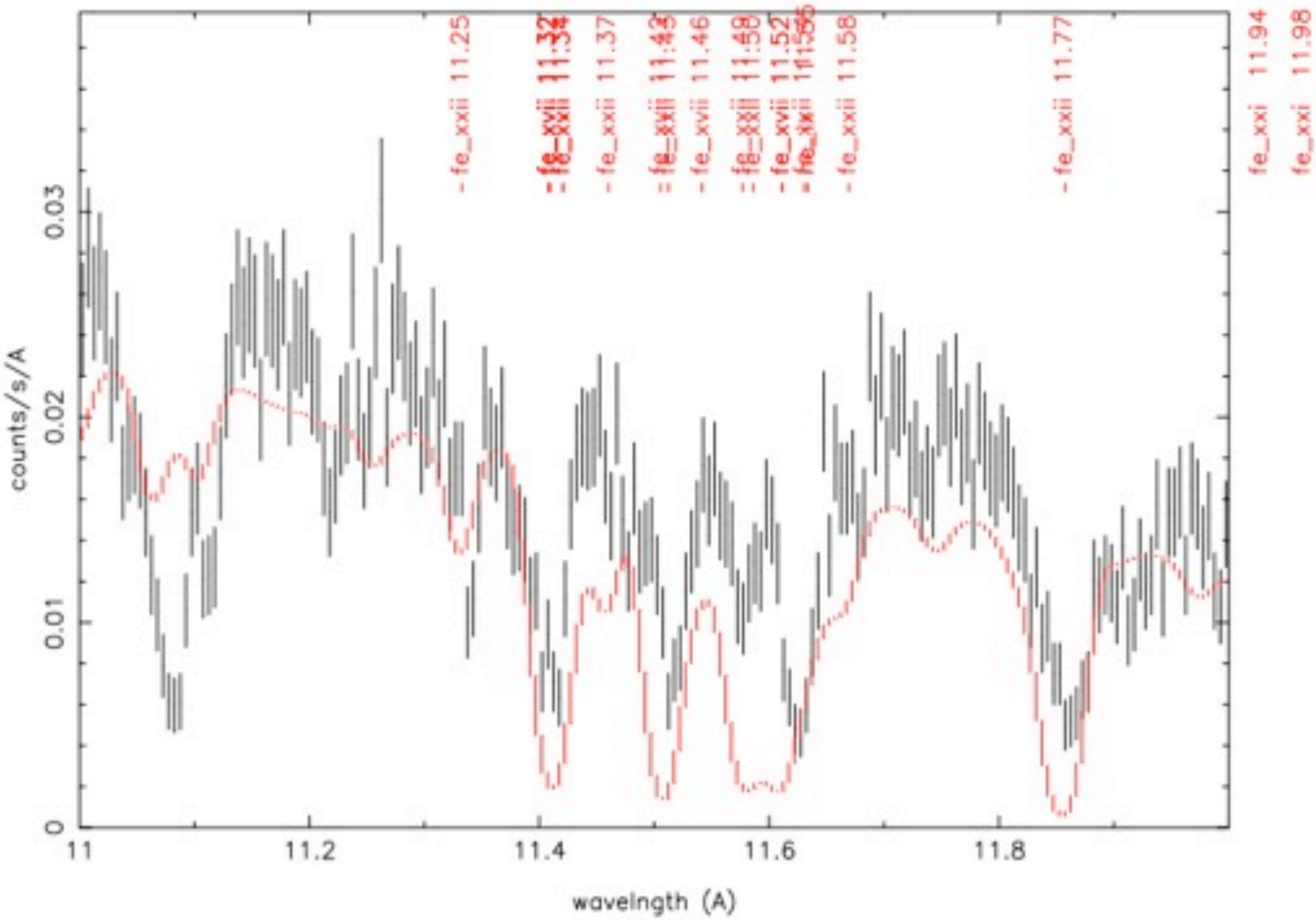


baseline

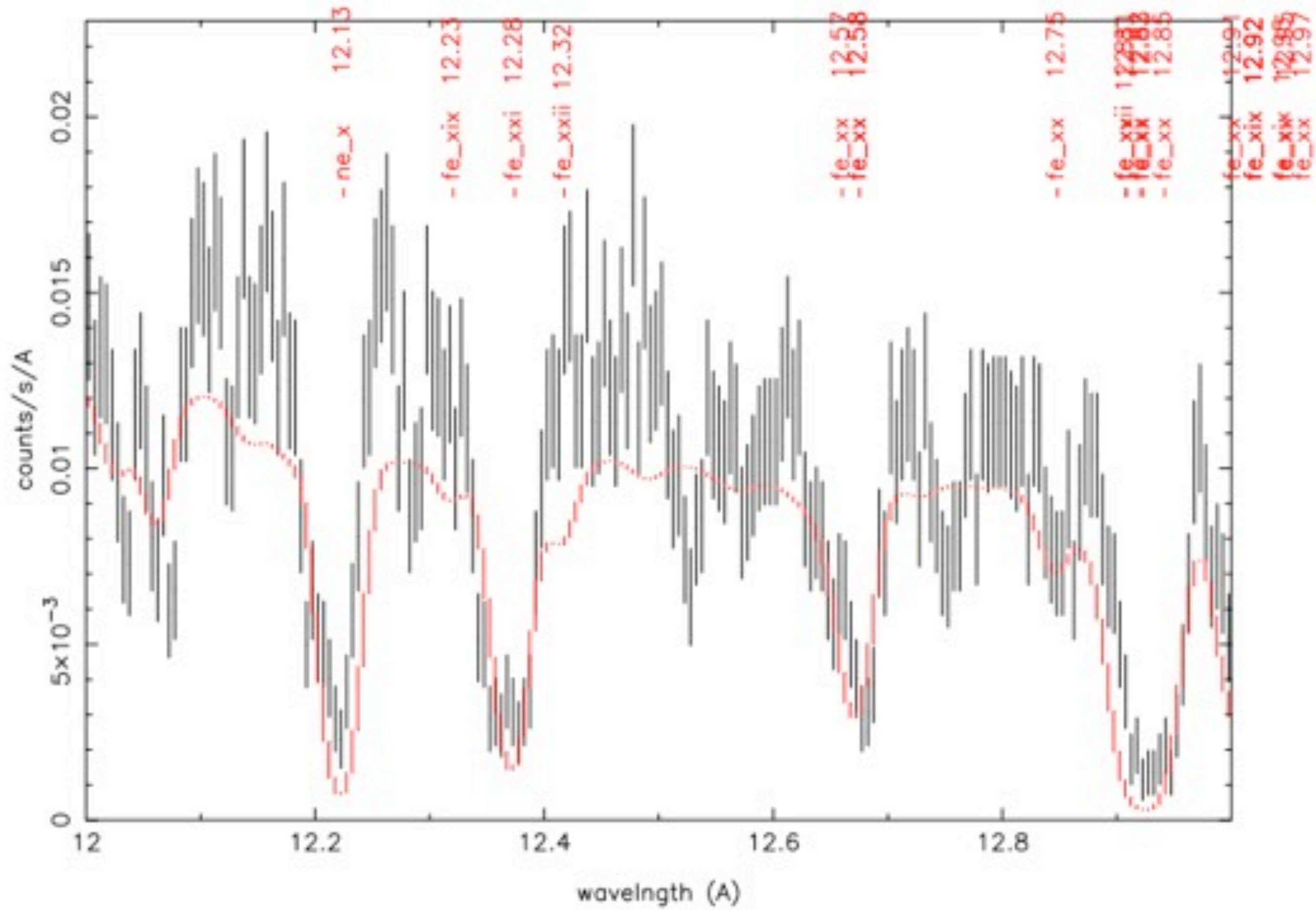
Fe XXI



baseline



Perturbed DR



Perturbed DR

Photoionized Fitting results: ngc3783

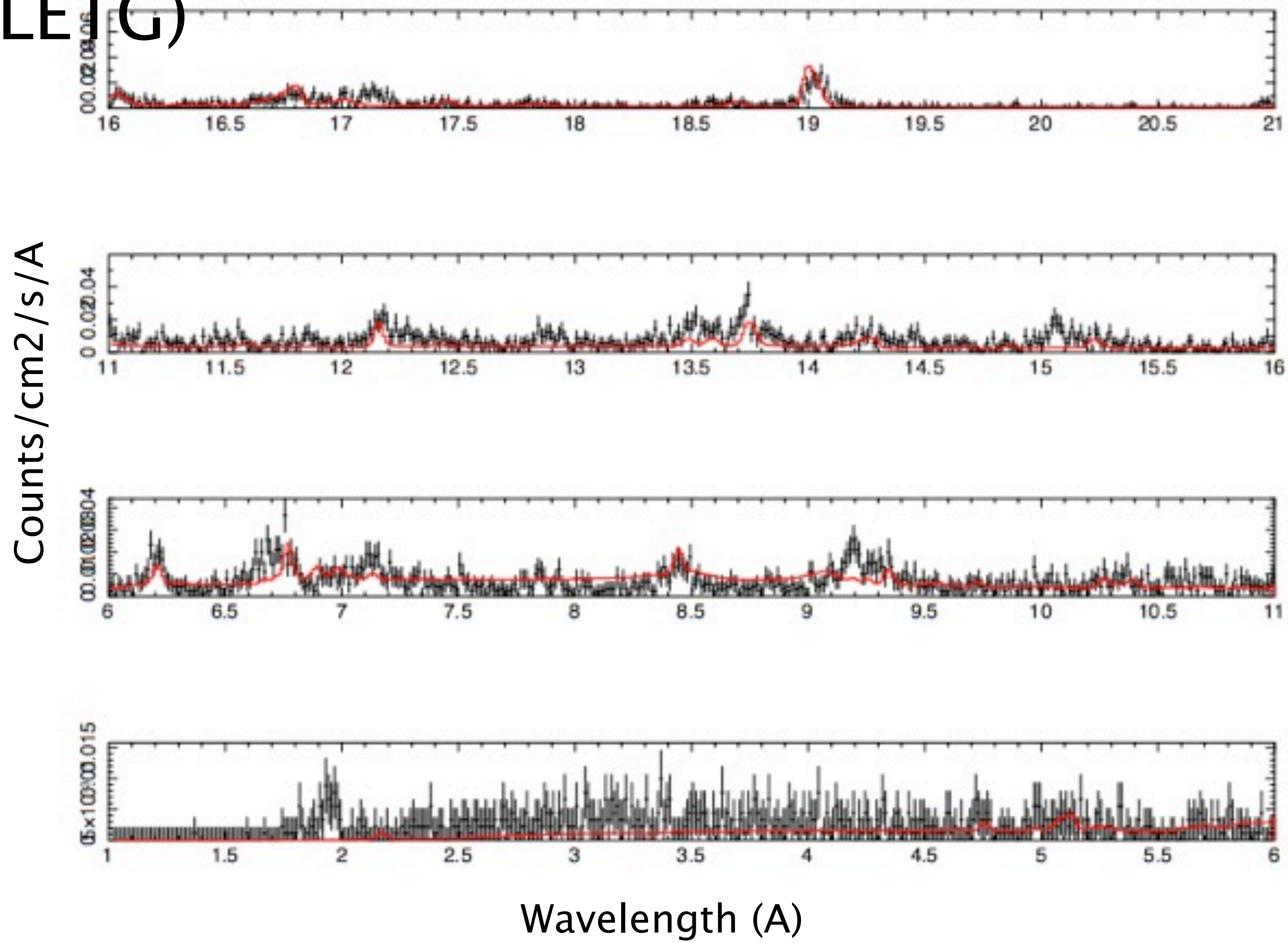
- For baseline model:
  - χ^2=11105/8192 (NOT acceptable, ~OK for discussion)
  - Log(ξ)=2.2,0.1 (similar to Krongold et al.)
  - Abundances:[Ne/O]=1, [Si/O]=1, [S/O]=2, [Fe/O]=0.4
- With perturbed DR, no iterations
  - χ^2=17660/8192
- With perturbed DR, iteratively fit
  - χ^2=13072/8192 (worse!)
  - Log(ξ)=2.9,0.1 (Significantly different!)

Sensitivity of astrophysical fits to atomic data

- if: Δ log(DR rate coefficients) ~0.1
- --> Δ log(ξ_{peak}) ~0.2 or greater
  - Detailed abundances of minority ions change by factors ~several
  - Results of fitting to Chandra spectrum detectable, Δ (DEM)~0.5 in log(ξ)
  - Smaller effects are associated with 100% changes in Auger

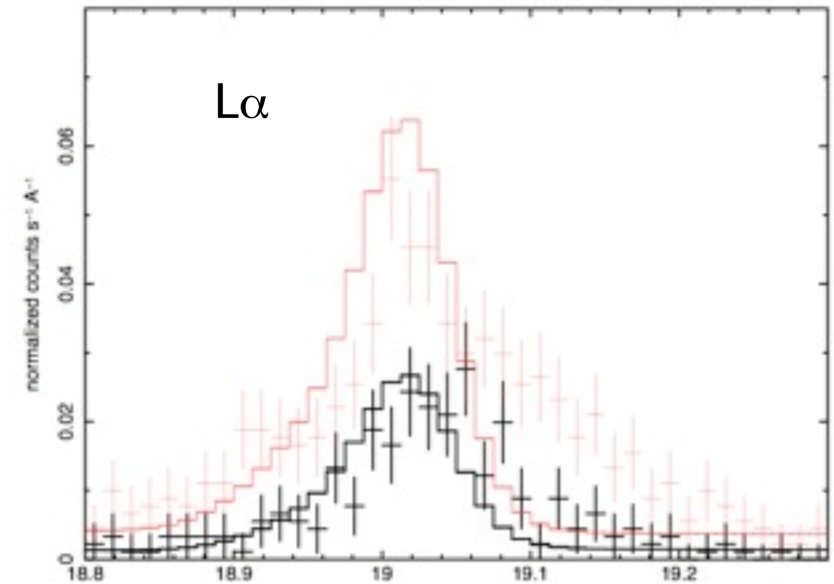
This represents statistically significant effects on the spectrum, which affect quantititative results.

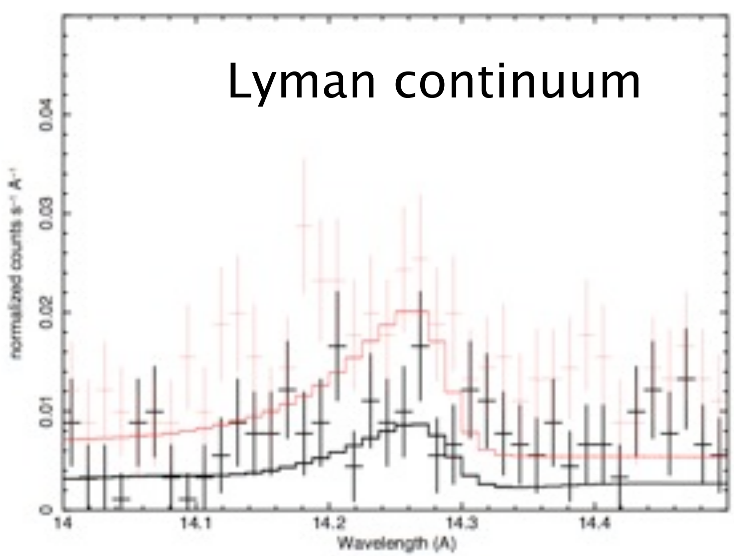
Another Example: Spectrum of NGC1068 (LETG)

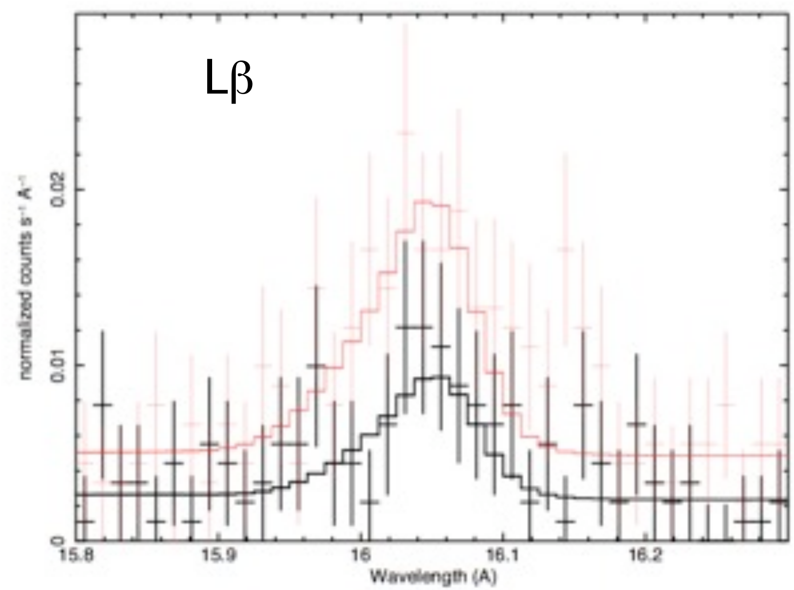


Zoom 1: O VIII Lyman lines

- Ratios indicate scattering
  - Case A recombination makes Lα:Lβ:Lc=5:1:10
  - We see 3:1:2
- Profile structure is asymmetric--

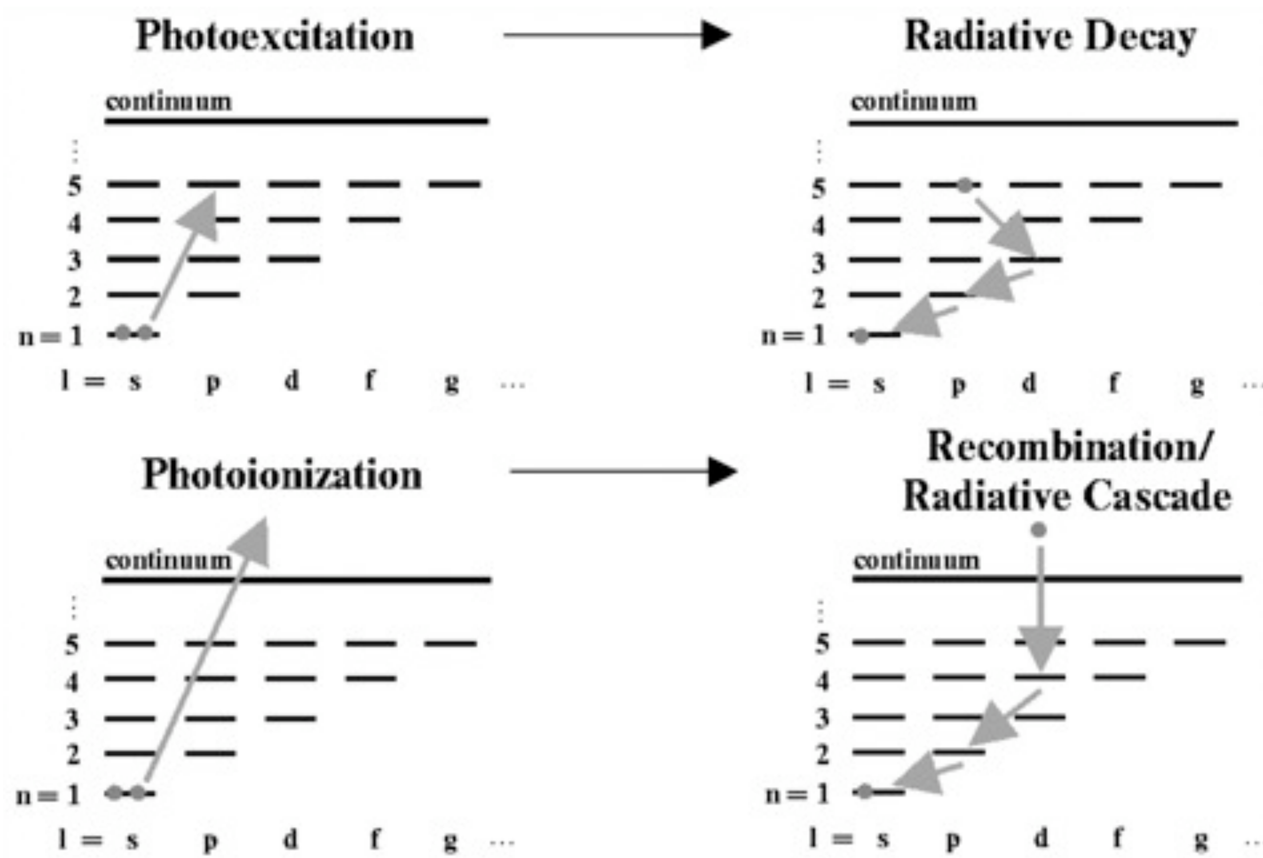






Scattering vs. recombination

- Scattering refers to bound-bound resonant excitation
- Recombination occurs after bound-free photoionizatio n



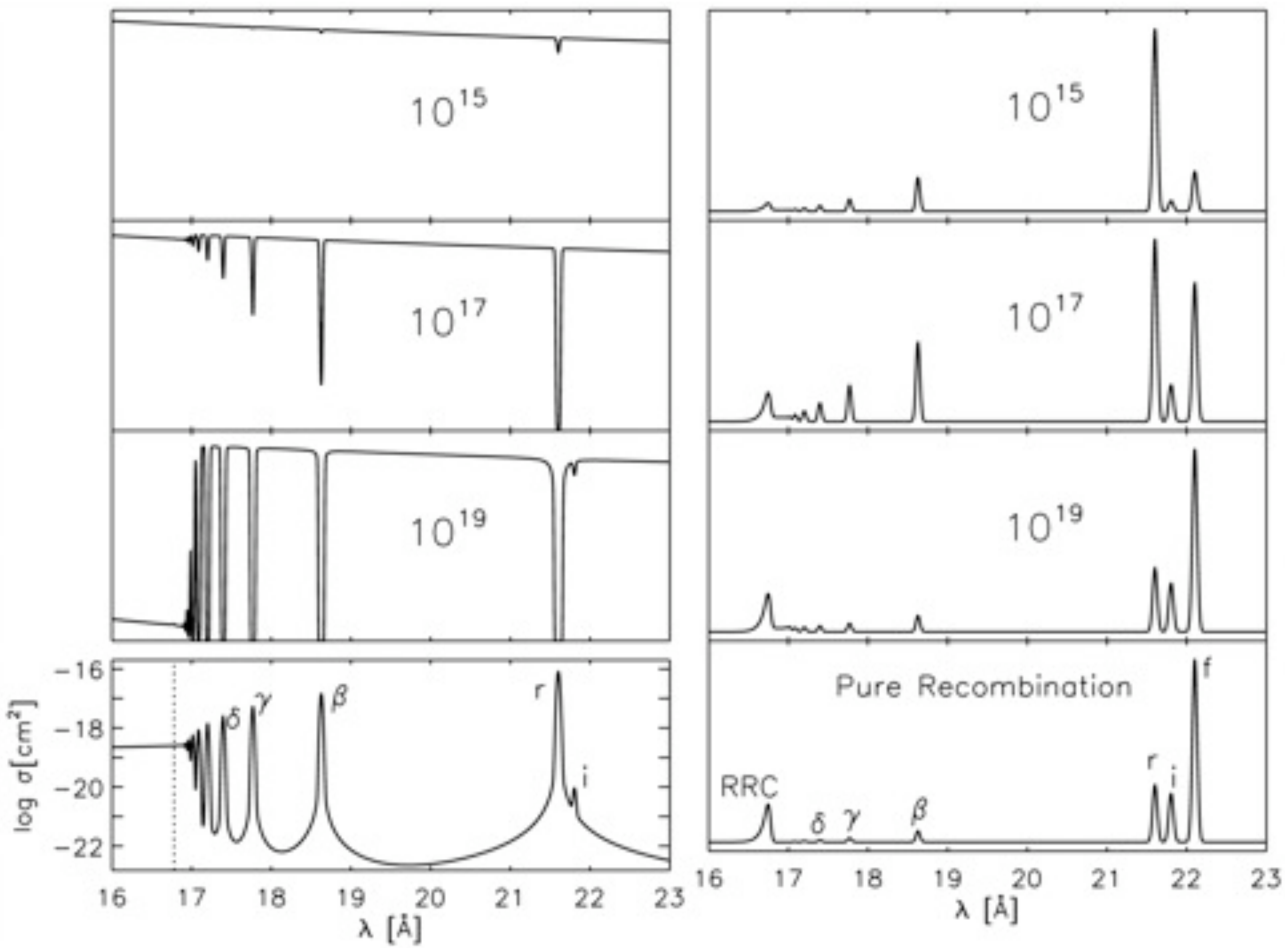
Scattering vs. recombination

- Scattering wins at low columns
- Makes strong allowed lines
- Recombination wins at high columns
- Makes recombination continua, forbidden lines emitted following cascade
- Column density diagnostic

O VII spectrum

absorption

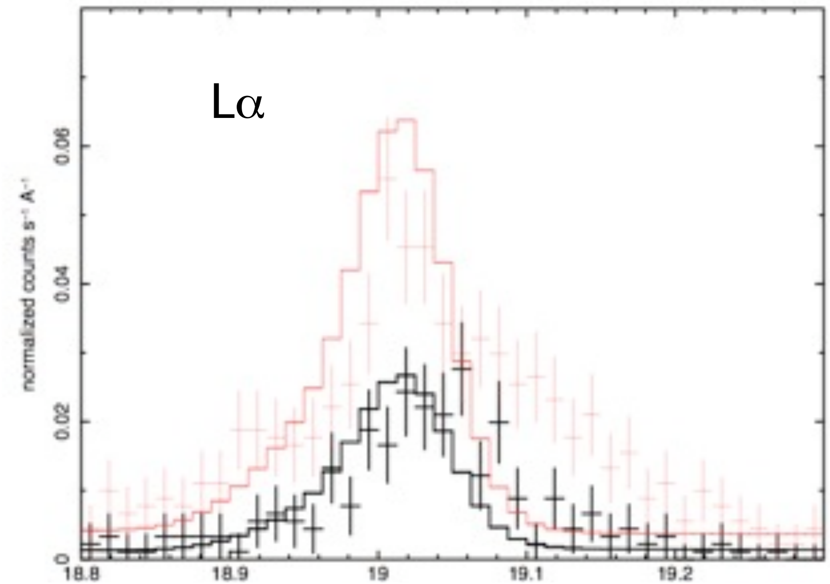
emission

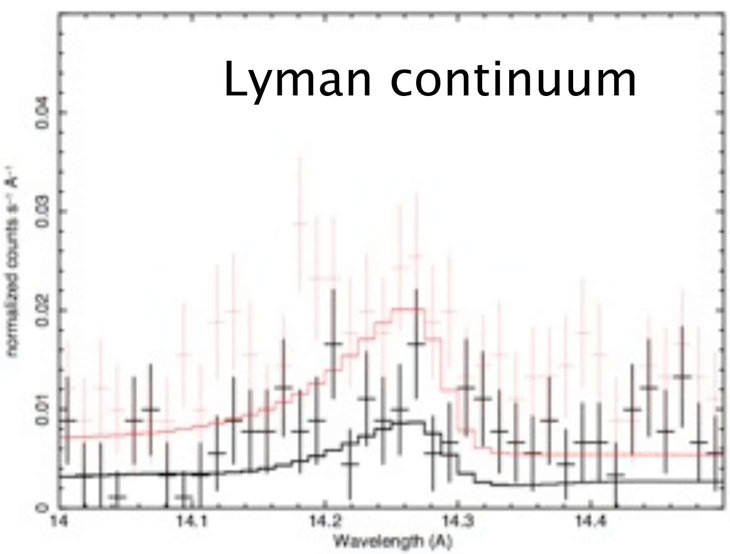


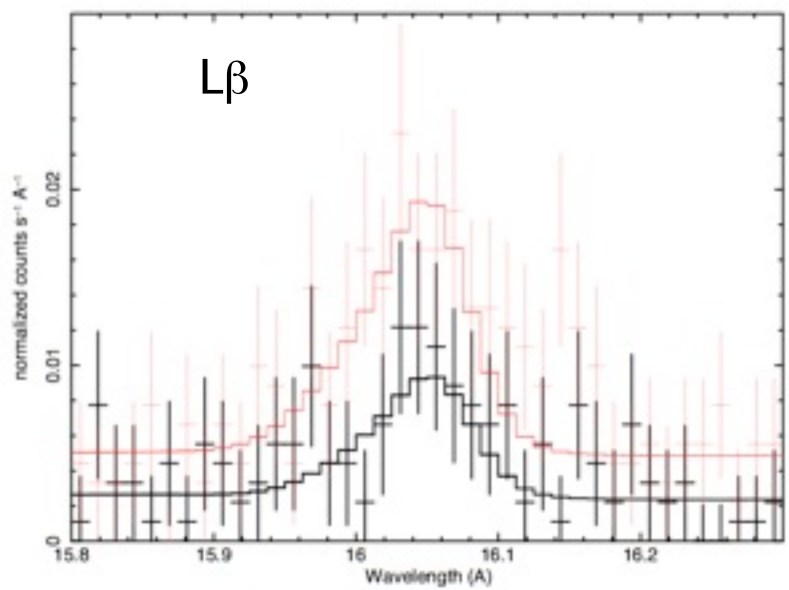
(Kinkhabwala et al. 2003)

Zoom 1: O VIII Lyman lines

- Ratios indicate scattering:
  - Case A recombination makes Lα:Lβ:Lc=5:1:10
  - We see 3:1:2
- Profile structure is asymmetric-->absorption?

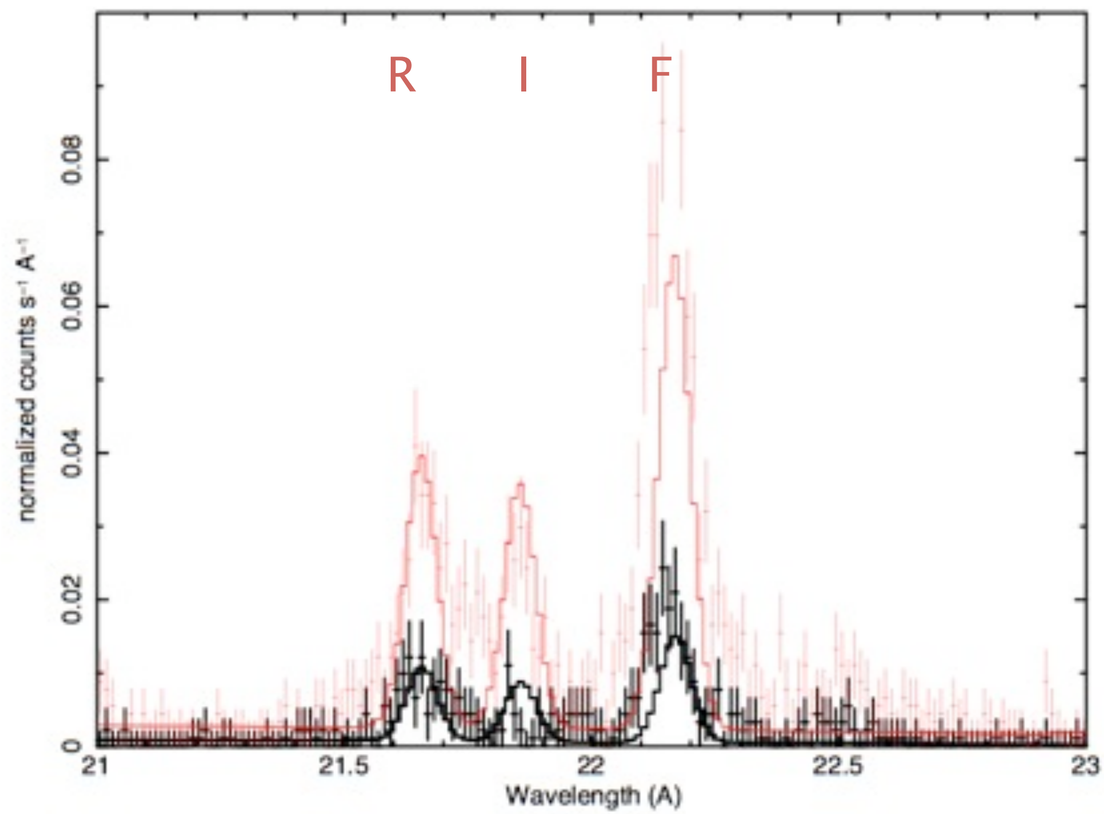






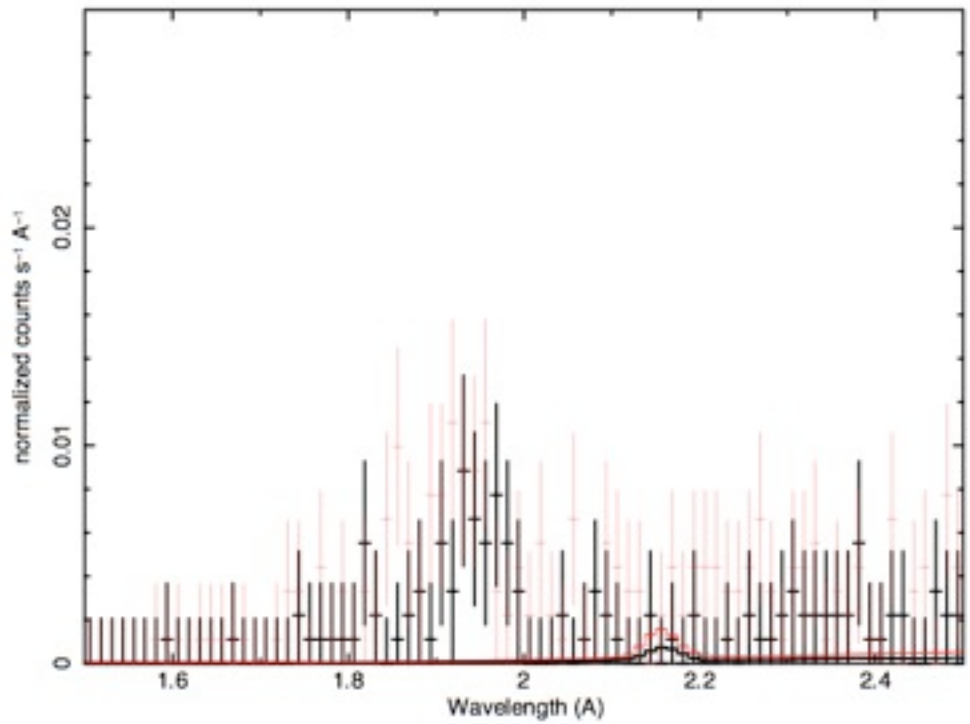
Zoom 2: He-like O VII

- Emission ratios indicate recombination in low density gas
  - $N < 10^8\ cm^{-3}$



Zoom 3: Iron K line

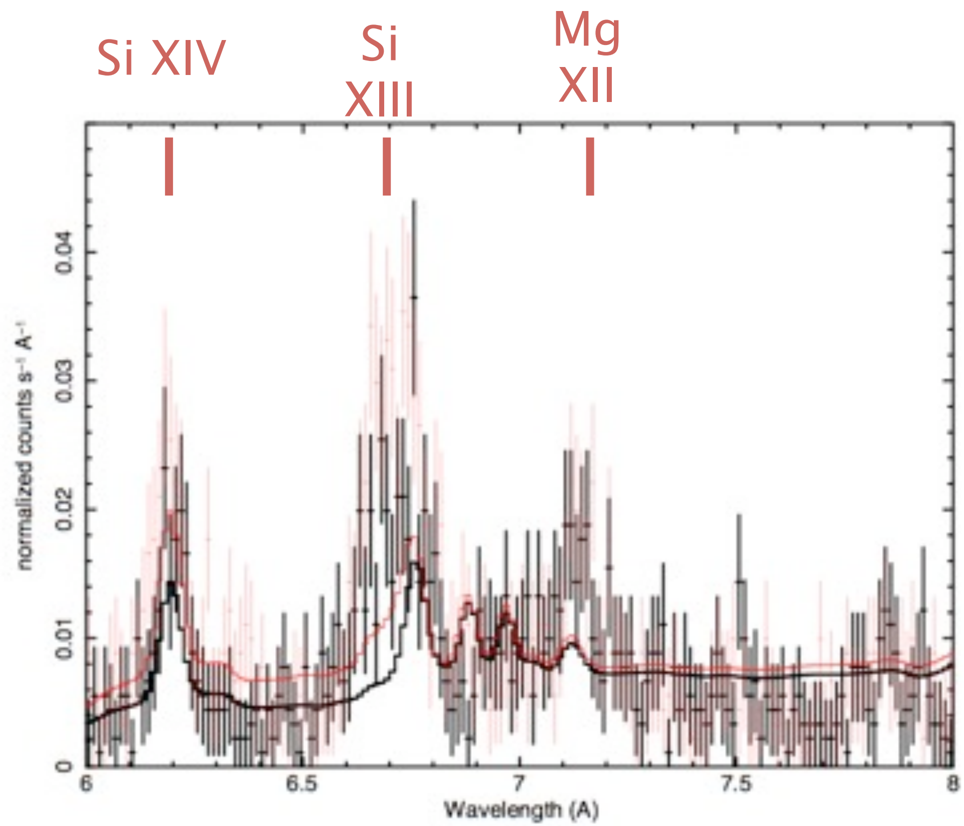
- Photons emitted by decay following creation of K shell vacancy from photoionization
- Indicates low ionization material, large column density
- Cannot be seen in absorption
- Line luminosity=1.1 x 10^{40} erg/s
    - Compare with continuum: L=2.7 x 10^{40} erg/s



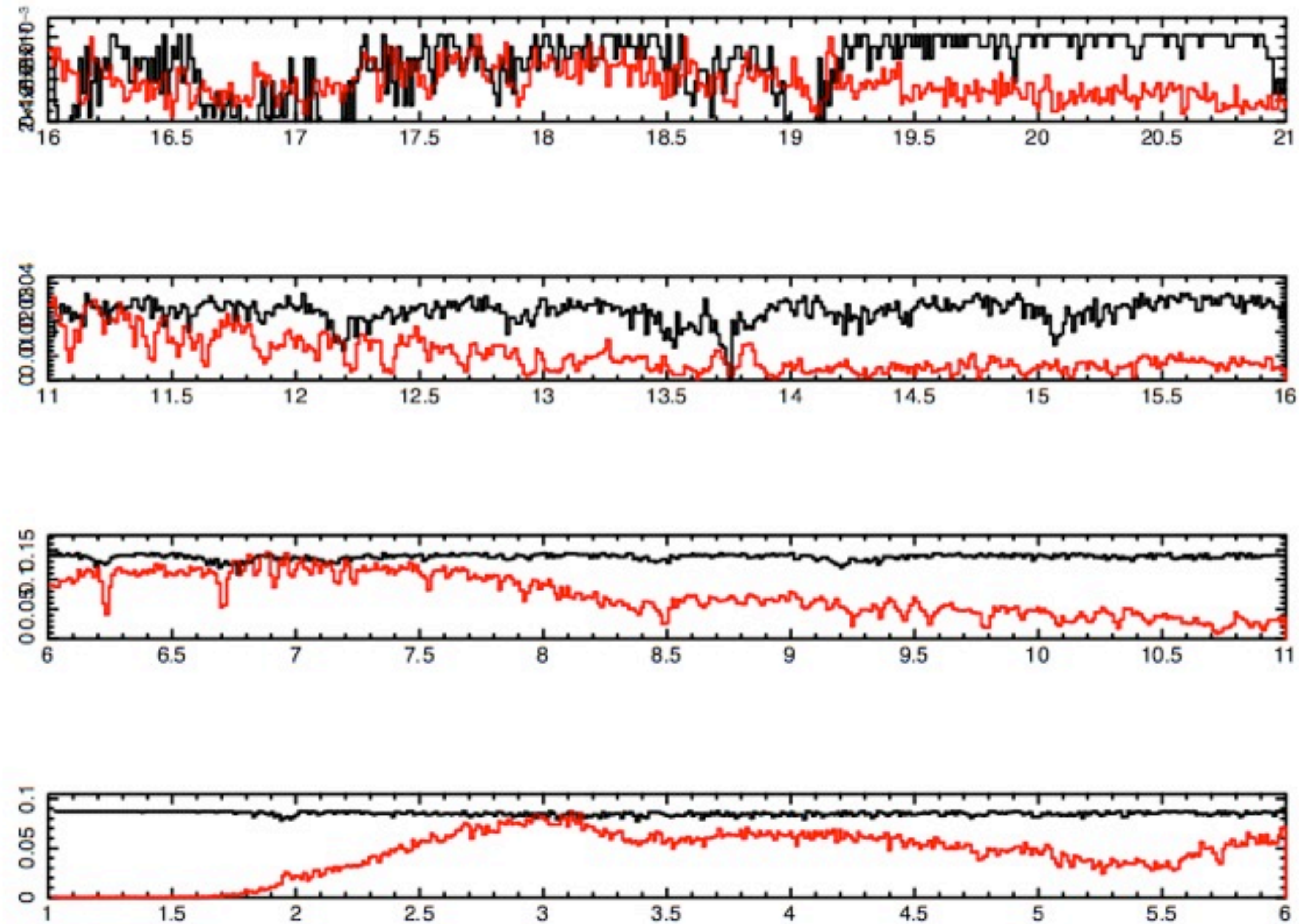
Stronger than ngc 3783!

Zoom 4: Si K lines

- Lines due to Si XIV and Si XIII indicate highly ionized gas
- Lines due lower states of Si, not detected, likely due to limited s/n, low fluorescence



Comparison: Ngc 3783 (red) vs. inverted ngc 1068 (black)



Additional diagnostic information from NGC 1068

- Column densities: from scattering vs. recombination $N_H \sim 10^{22}$ cm^{-2}
- Kinematics: from line profiles: outflow with v~500–1000 km/s
- Density from O VII lines: < 10^8 cm^{-3} (contradicts NGC 3783)
- Ionization state: ionization balance depends on:

photoionization vs. recombination

~flux ~density

==> define ionization parameter: $\xi = 4\pi$ flux/density

  - Low ionization material (<==> iron K lines), ξ <10 erg cm/s
  - High ionization material (<==> O VII, O VIII), $\xi \sim 100$ erg cm/s
- Almost entirely consistent with Example 1: NGC 3783

Status of modeling seyfert

- For NGC1068, we get acceptable χ^2 for fit to single component model
- letg data do not stress the model
  - This is not a bright source
  - But there are hints that the spectrum is not simple
- A more severe test is due to ngc 3783
  - $\chi^2/\nu \sim 2$, not good!
  - ~half the lines in the spectrum are missing from models
- Sensitivity analysis suggests much of this