Using Photoionization to Understand Outflows in AGN and Quasars

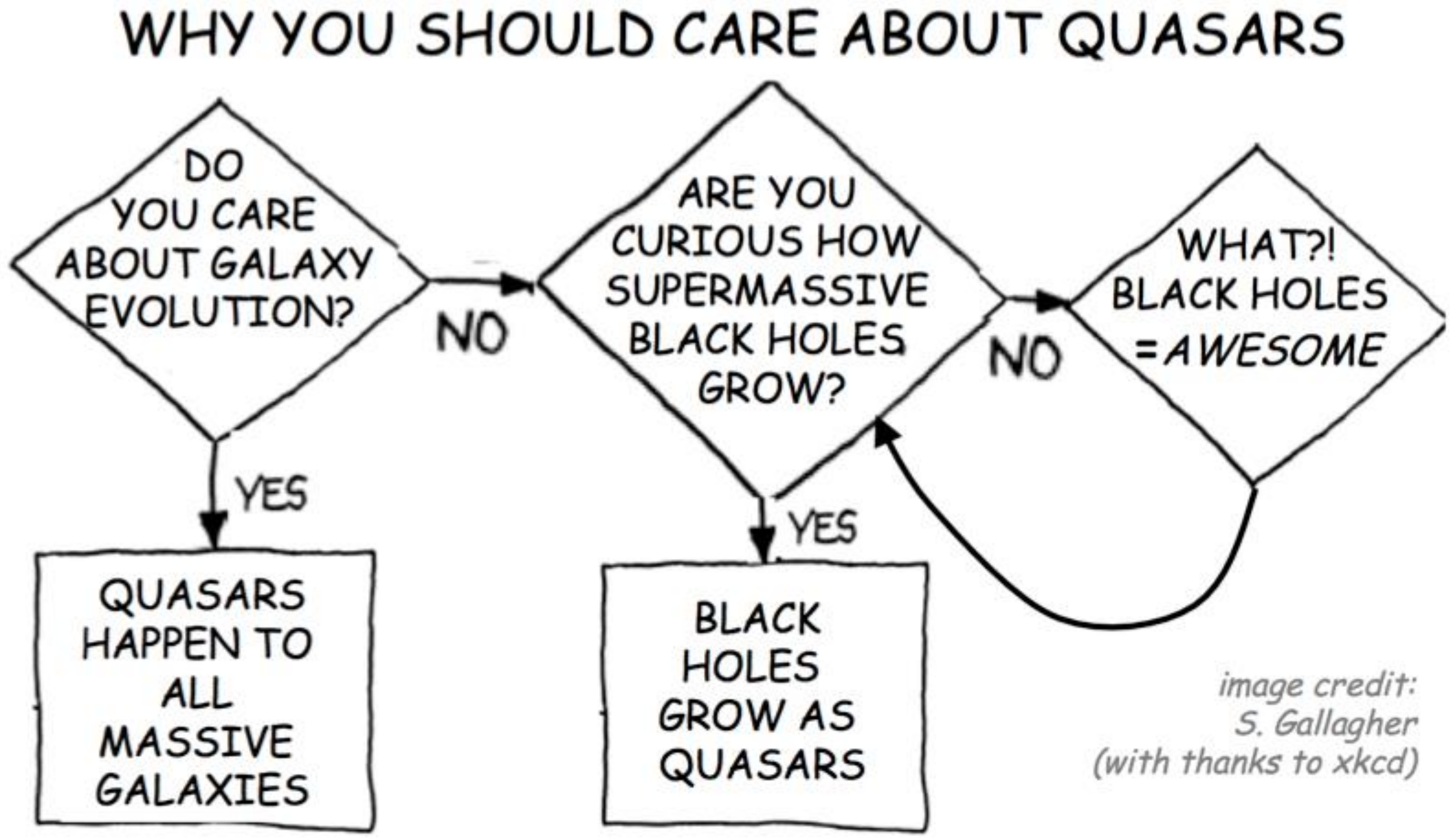
Karen M. Leighly (OU)

Collaborators

- Donald Terndrup (Ohio State University)
- Sarah Gallagher (Western University)
- Gordon Richards (Drexel University)
- Adrian Lucy (Columbia University)
- Darrin Casebeer (Boeing)
- Erin Cooper (OU)

Funding: NSF, STScI, FUSE

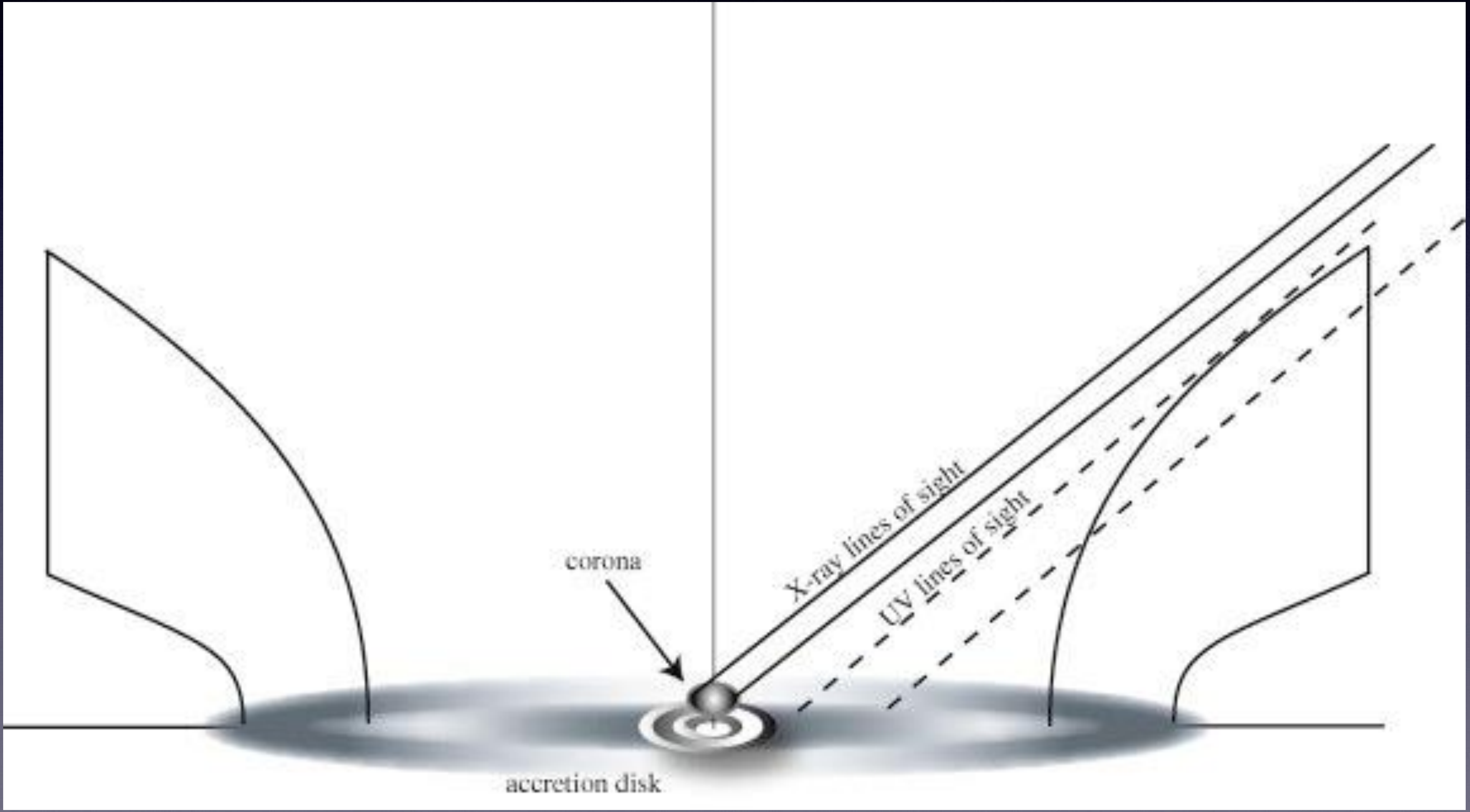
Why Study Quasars?



Emission and Absorption Lines in AGN and Quasars

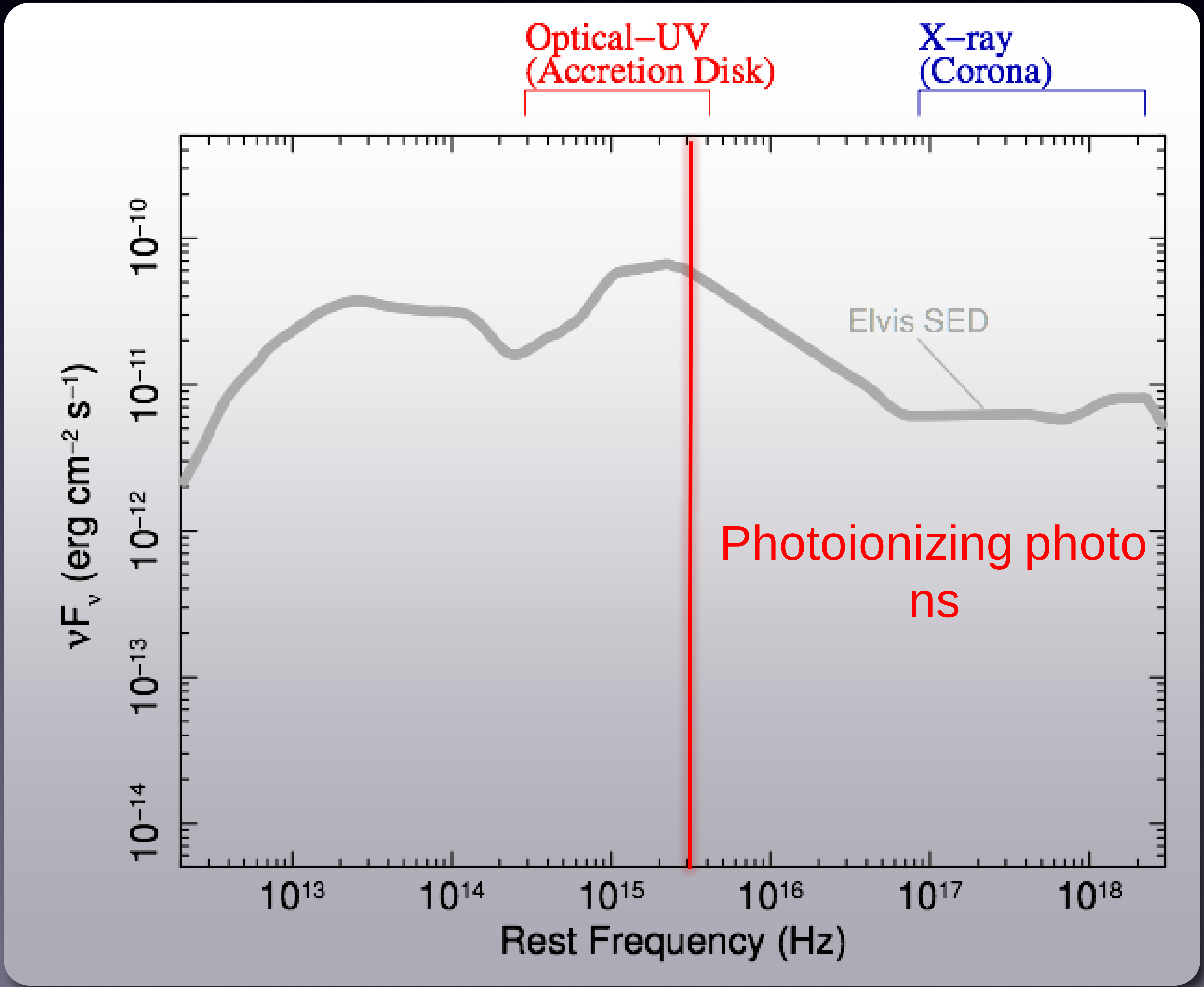
- My research uses rest-frame infrared – UV emission and absorption lines to understand the physics of AGN.
- These lines are powered by *photoionization by the continuum from the central engine*.
- In this talk, I will describe how we can use photoionization to determine the physical conditions of line emitting / absorbing gas.

The Central Engine
Optical & UV: hot accretion disk (somewhat like stars)
Xray: corona (like the solar corona)

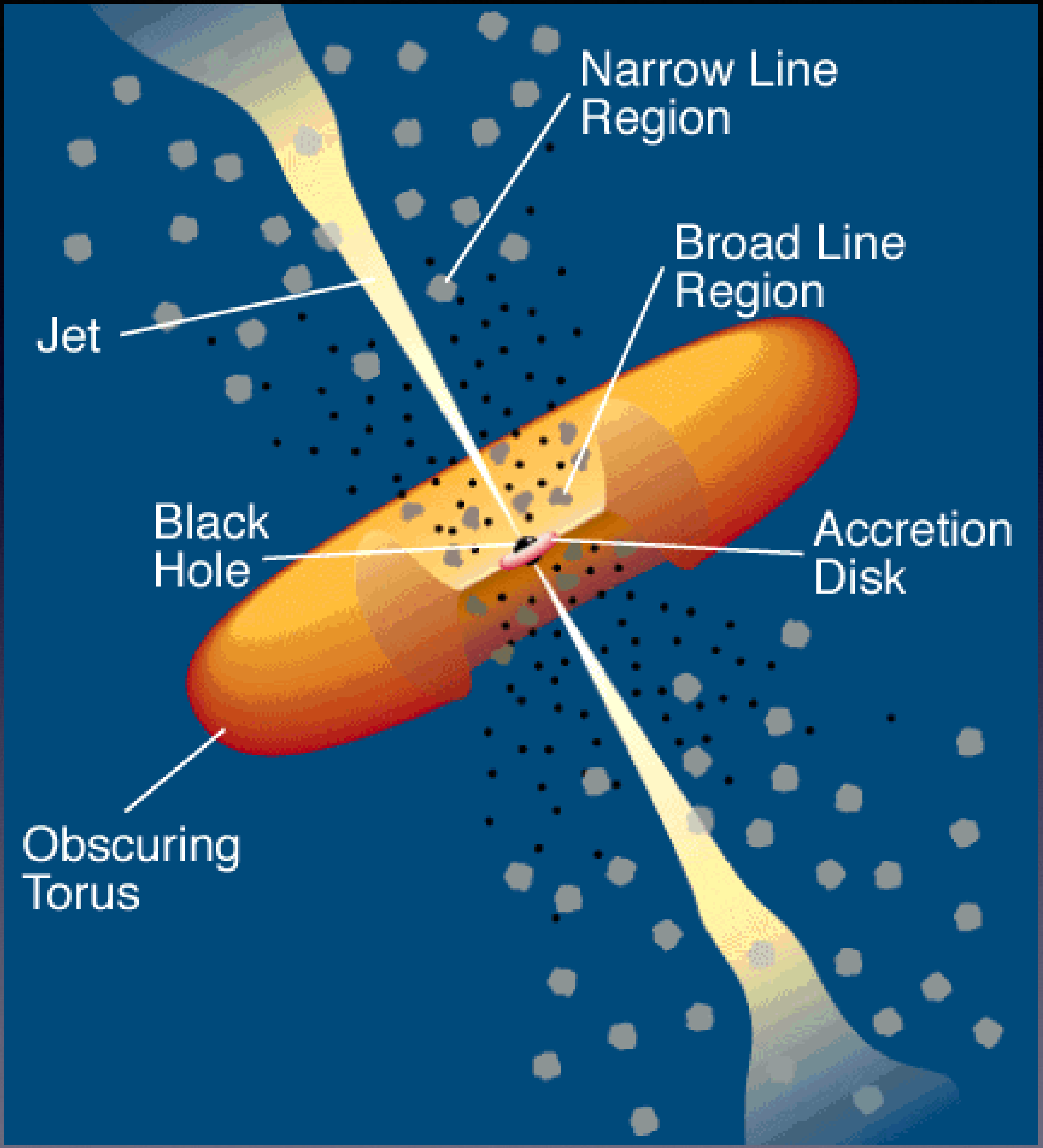


Typical SED

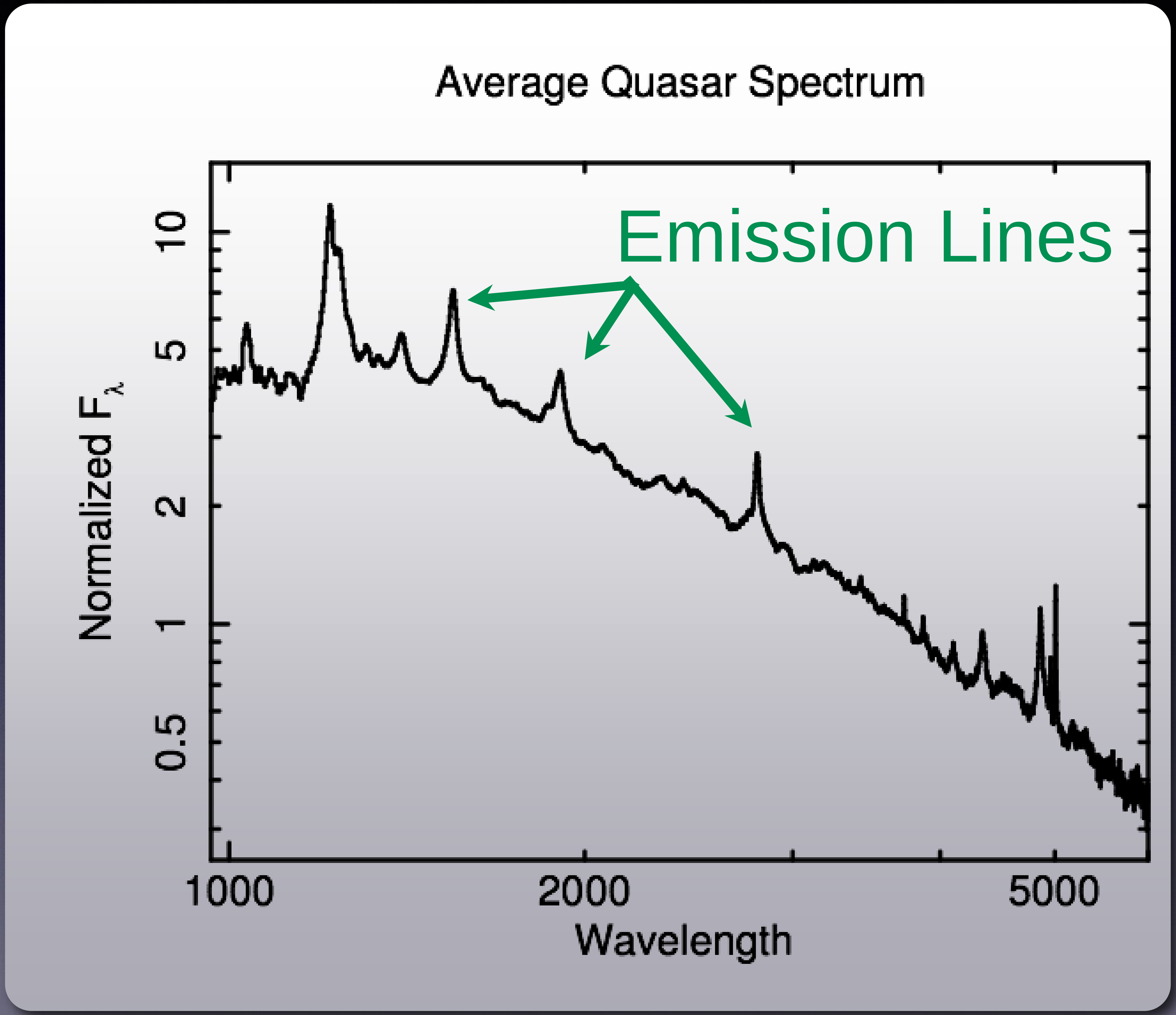
(spectral energy distribution)



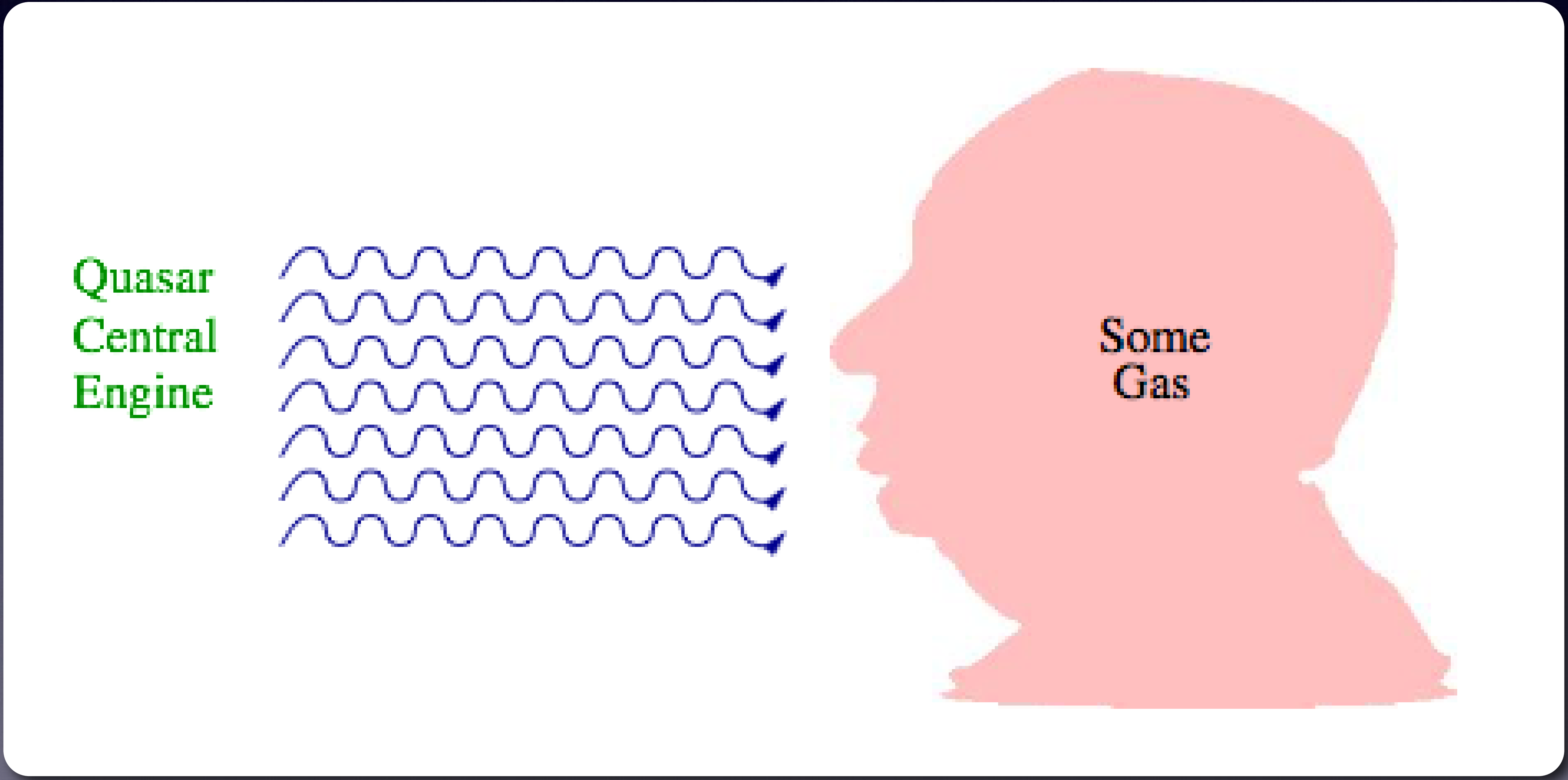
- Photoionizing photons emerge from the central engine.
- They illuminate and photoionize gas throughout the environment of the central engine.
- The photoionized gas produces emission lines.



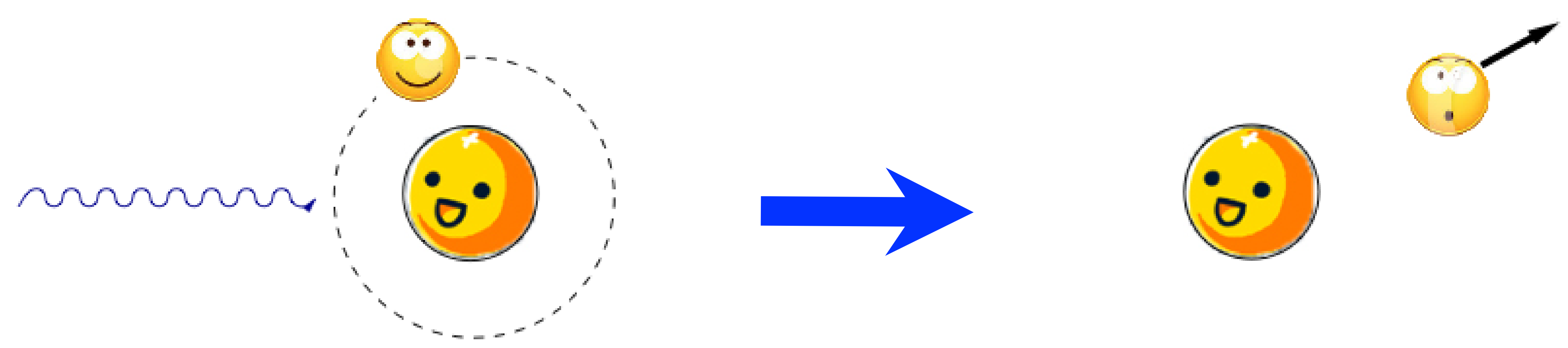
- Continuum: emission from the accretion disk.
- Emission lines are broad due to high, principally Keplerian velocities.



Consider a quasar illuminating some gas

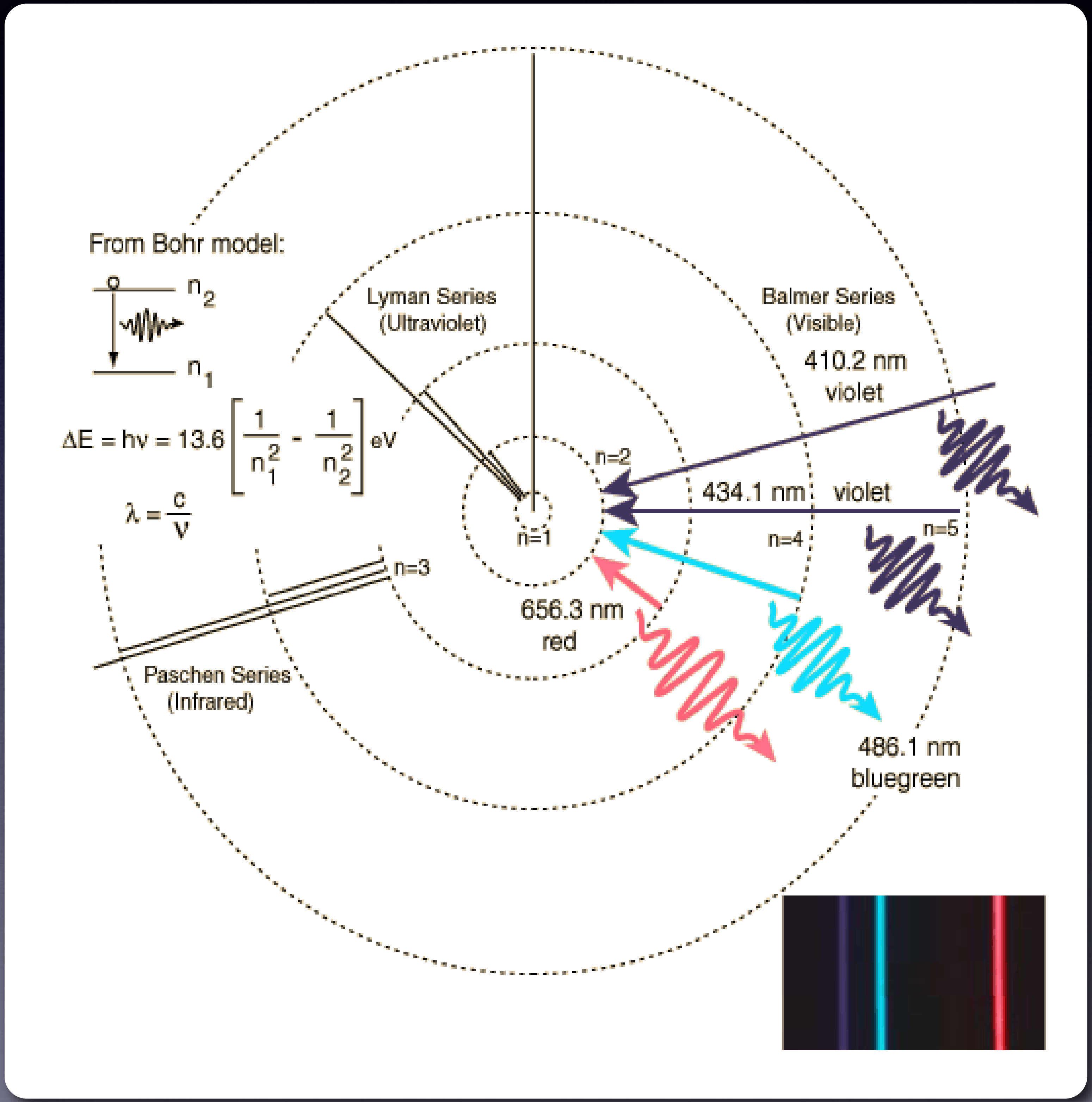


Zooming in on a hydrogen atom



Photoionization ⇒ frees an electron

Followed by Recombination

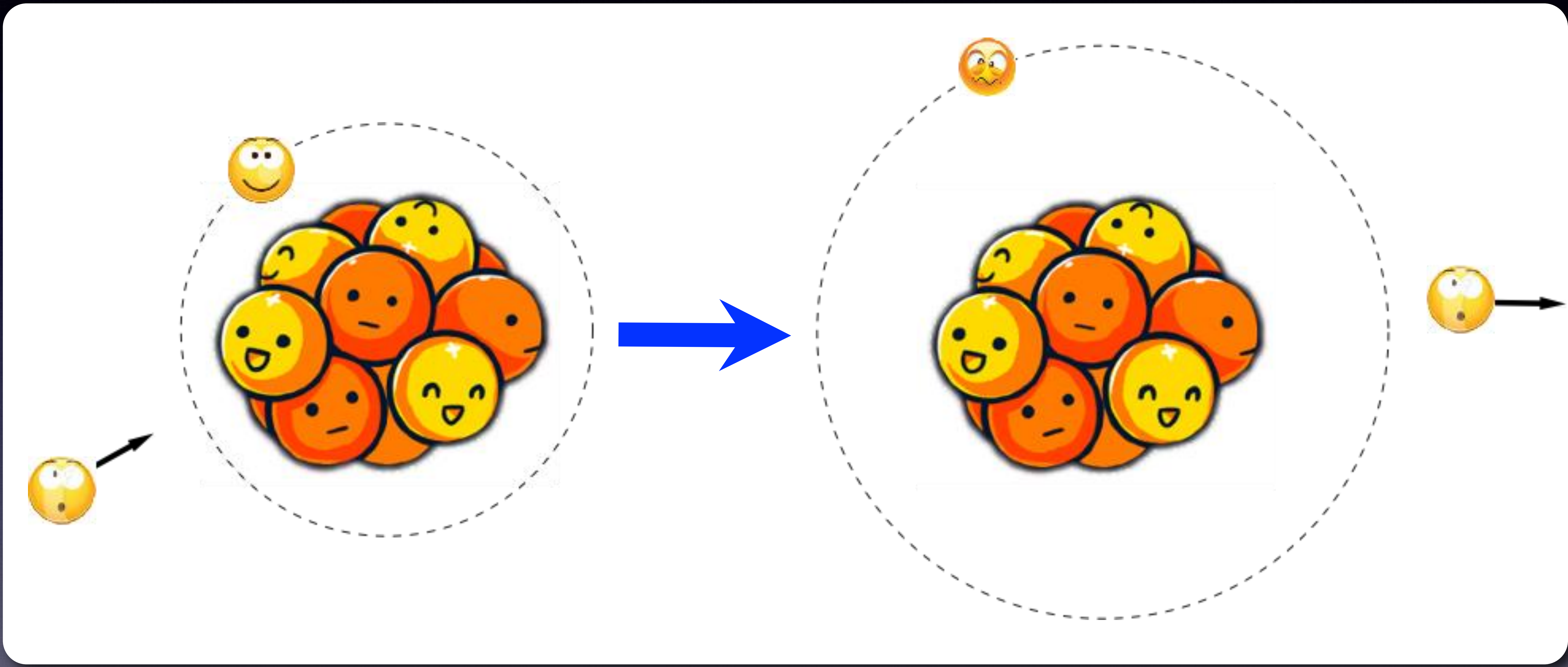


- *Hydrogen and helium emission lines* are produced by recombination.

Photoionization Equlibrium

- But there is a lot more to photoionization than simple photoionization / recombination.
- Solve:
  - ★ Photonization equilbrium equations
  - ★ Thermal equilibrium equations
- And:
  - ★ Do it for all elements/ions
  - ★ Transfer the radiation

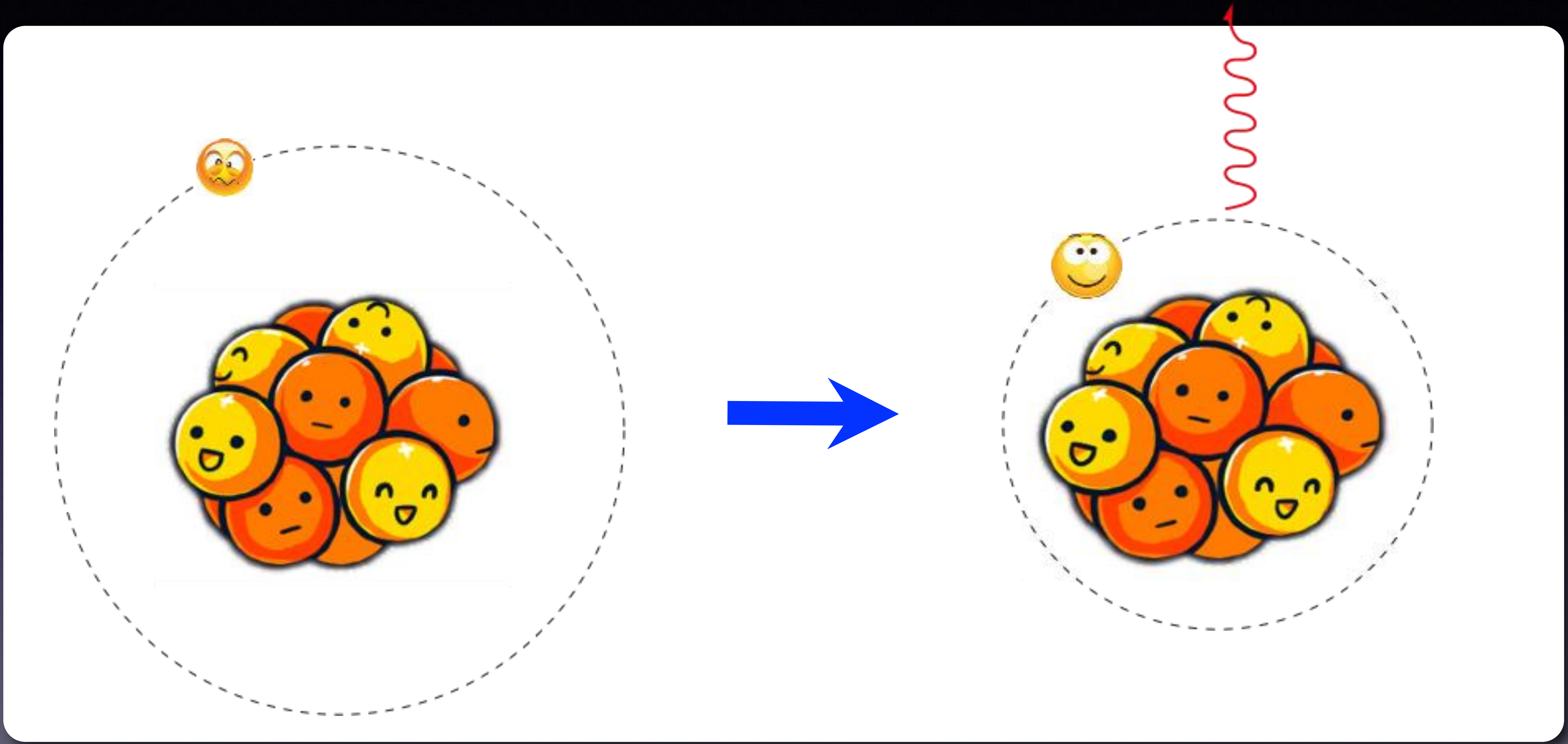
Collisional Excitation



Free electron collides with an ion

⇨ "Collisional Excitation"

Then....



Practically every other common line (CIV, SiIV, OVI) is produced by collisional excitation.

Other Processes

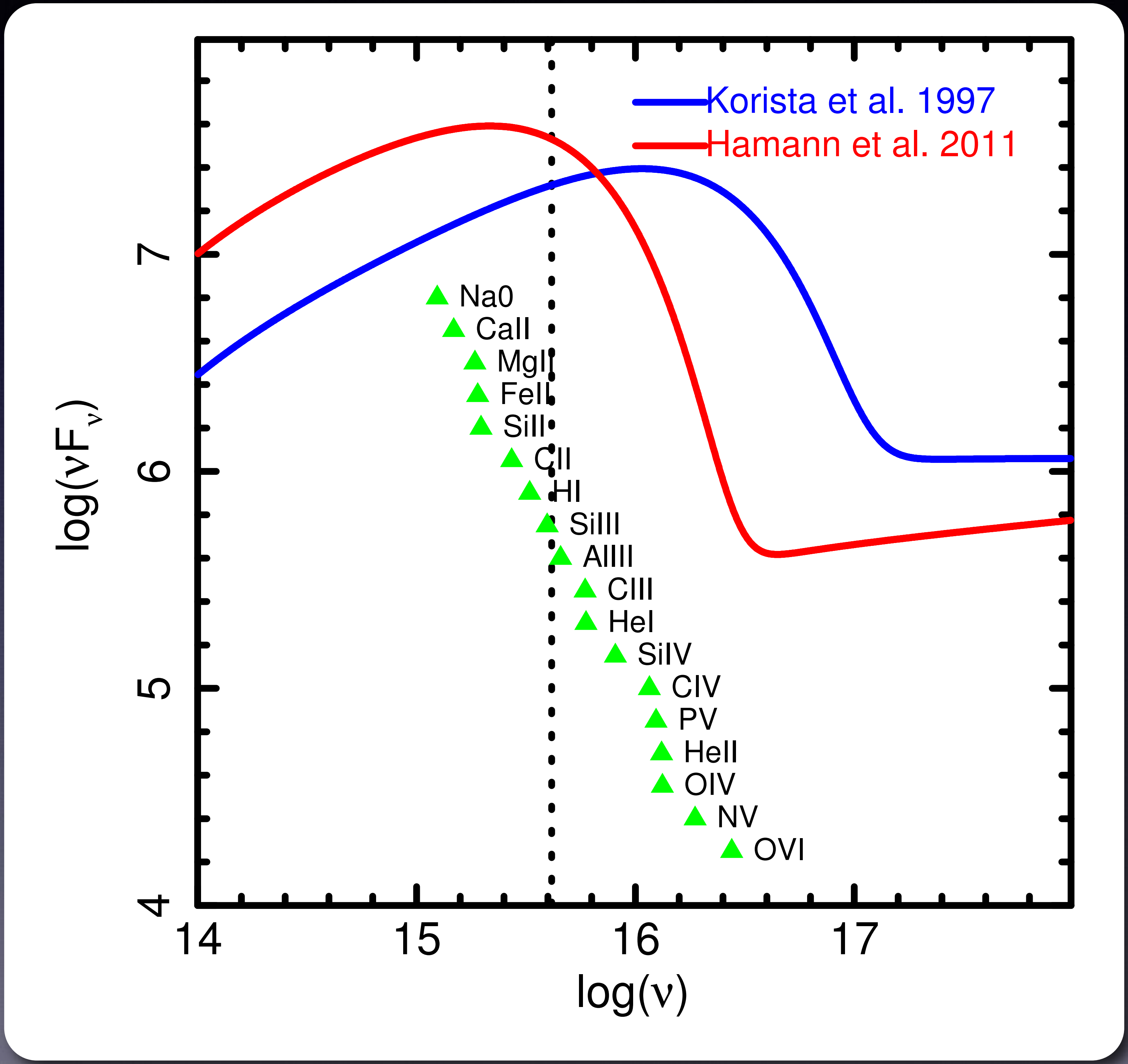
- Photoexcitation
- Charge exchange
- Collisional deexcitation
- Photoionization / collisional excitation from excited states
- Effects of turbulence on line transfer
- ….

Cloudy

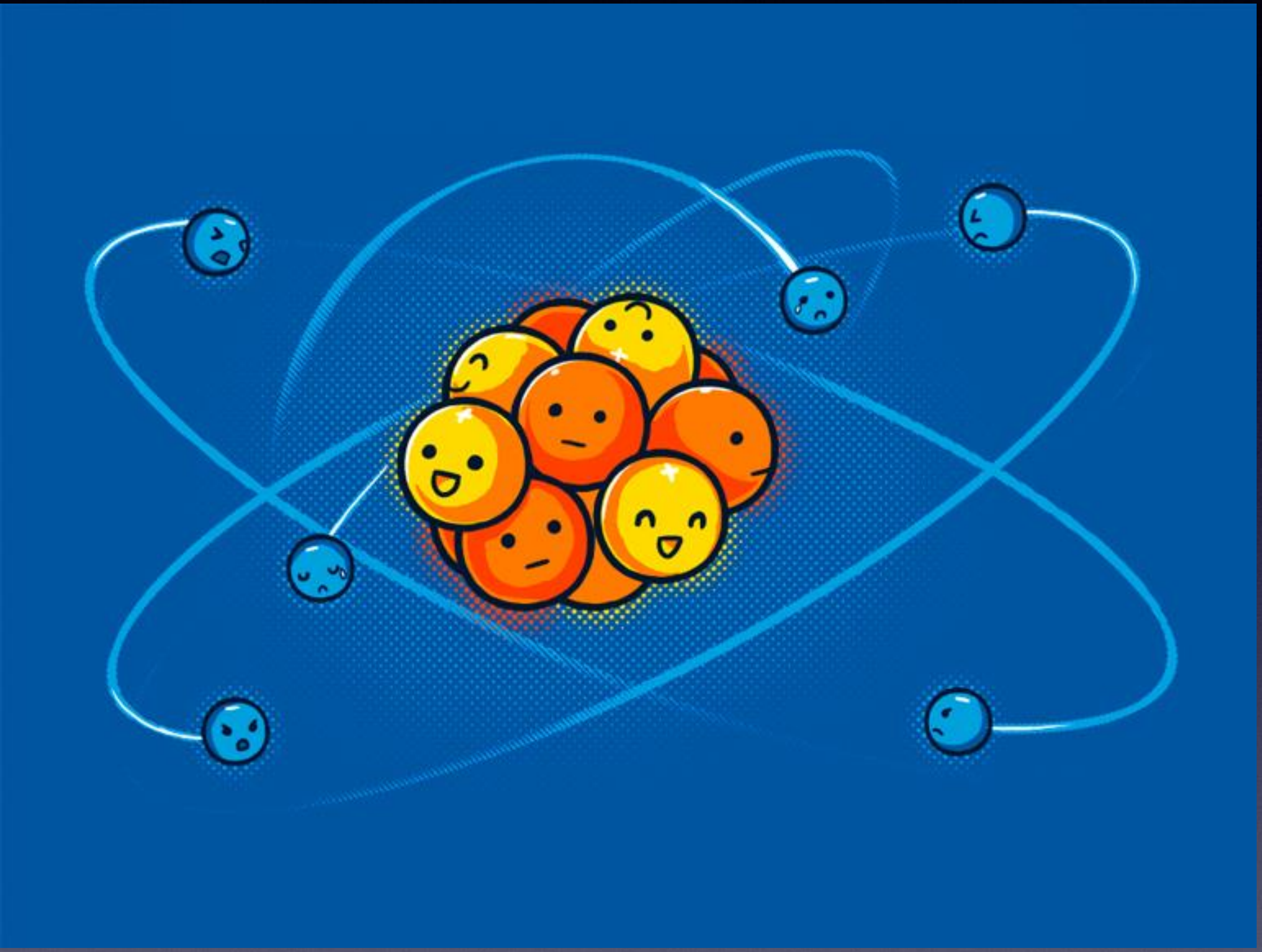
- Fortunately there is a freely-available code that can do this for us.
- *Cloudy* – developed by Gary Ferland and collaborators over the period of last 38 years (!).

The Spectral Energy Distribution

- The spectral energy distribution varies from one quasar to the next.
- This may be a consequence of varying accretion rates / black hole masses.



Creating Ions

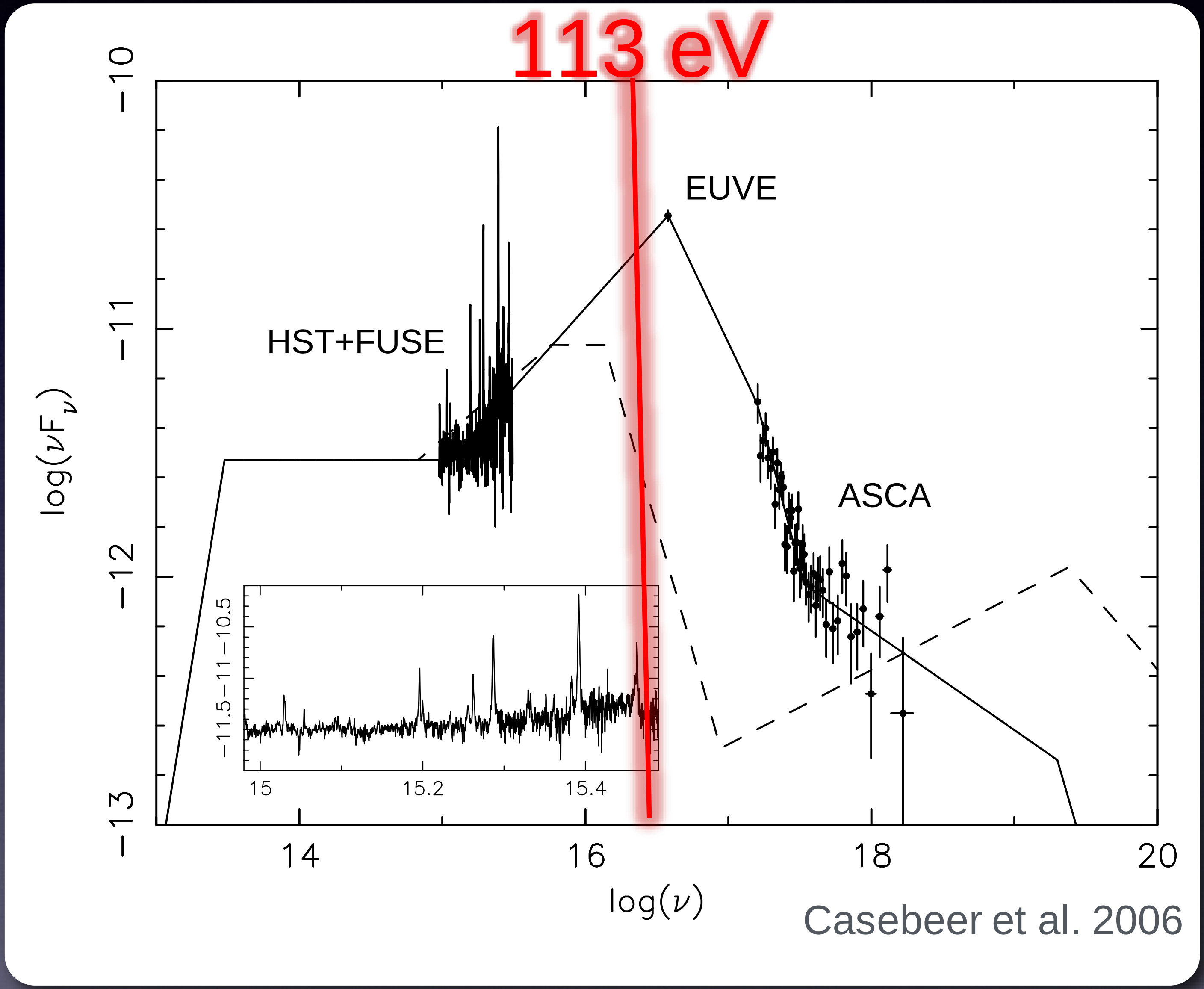


- C^{+}: E_{thresh}=11.3 eV
- C^{+2}: E_{thresh}=24.4 eV
- C^{+3}: E_{thresh}=47.9 eV

Higher energy photons are required to create highly ionized ions because remaining electrons are held more tightly.

RE 1034+39

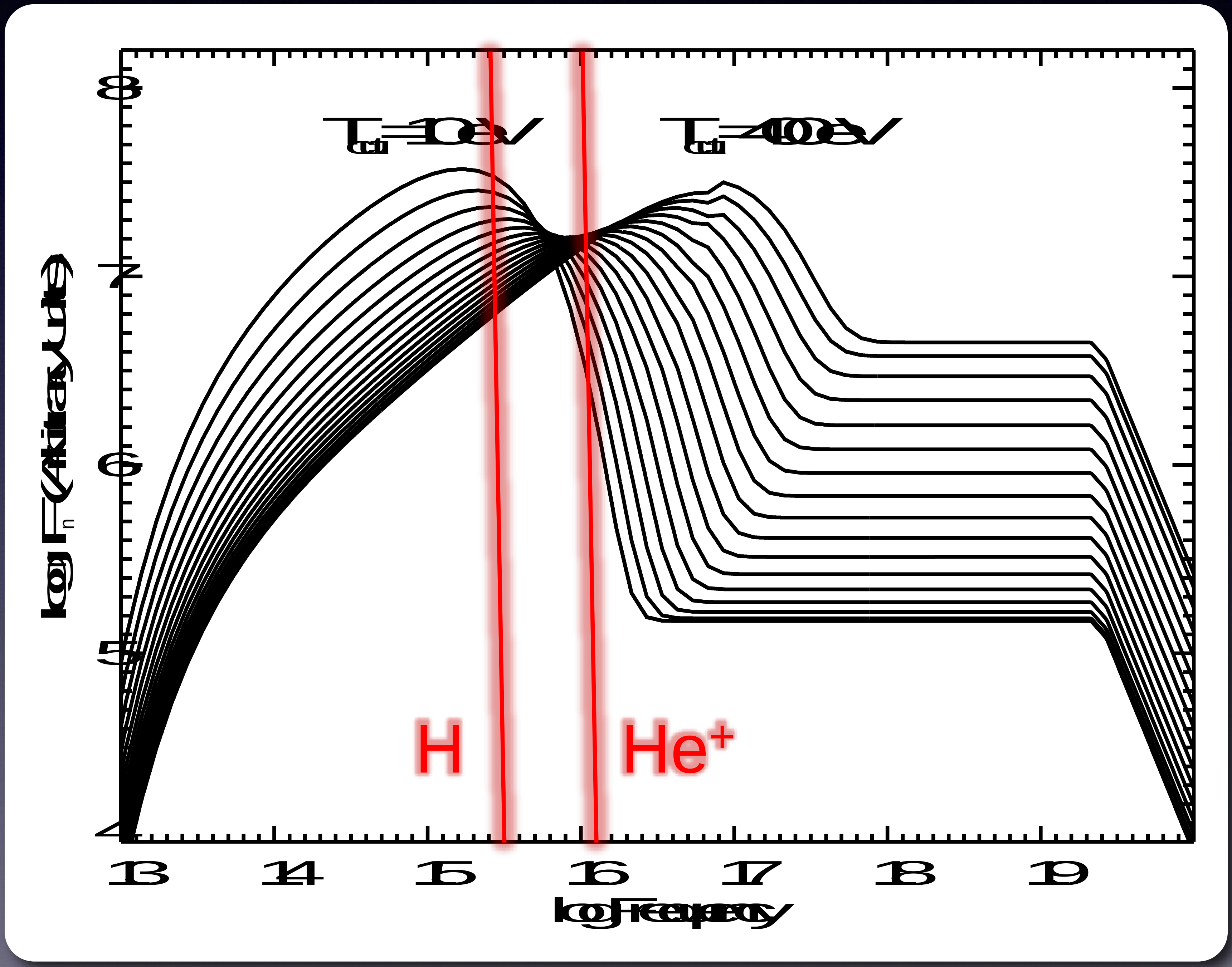
- RE 1034+39 has a very hard (X-ray bright) spectral energy distribution.
- We expected it to have very strong high-ionization lines.
- E.g., OVI has an ionization potential of 113 eV.

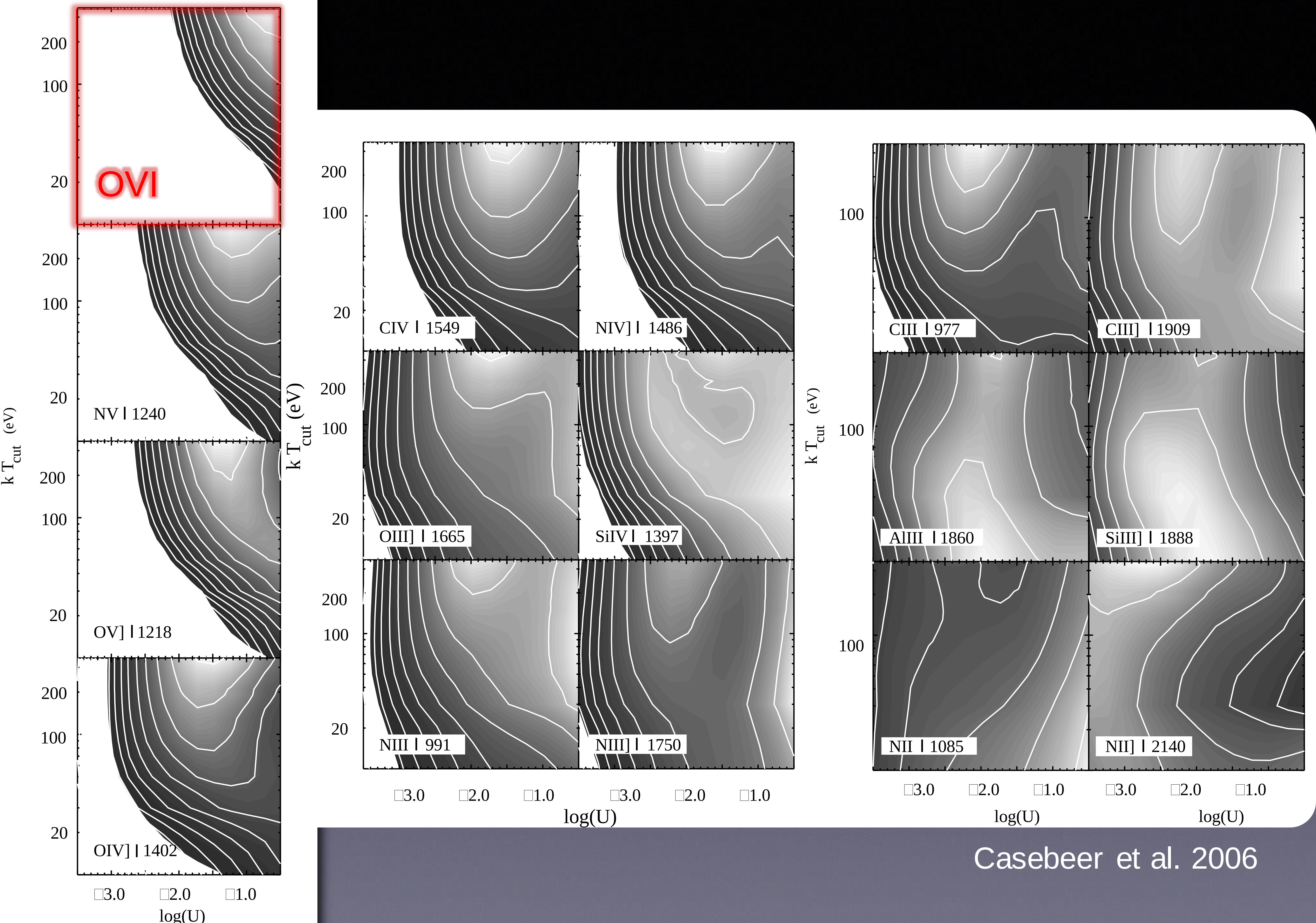


(Spectroscopic notation: OVI is the photon emitted by O^{+5}.)

Check with Simulations

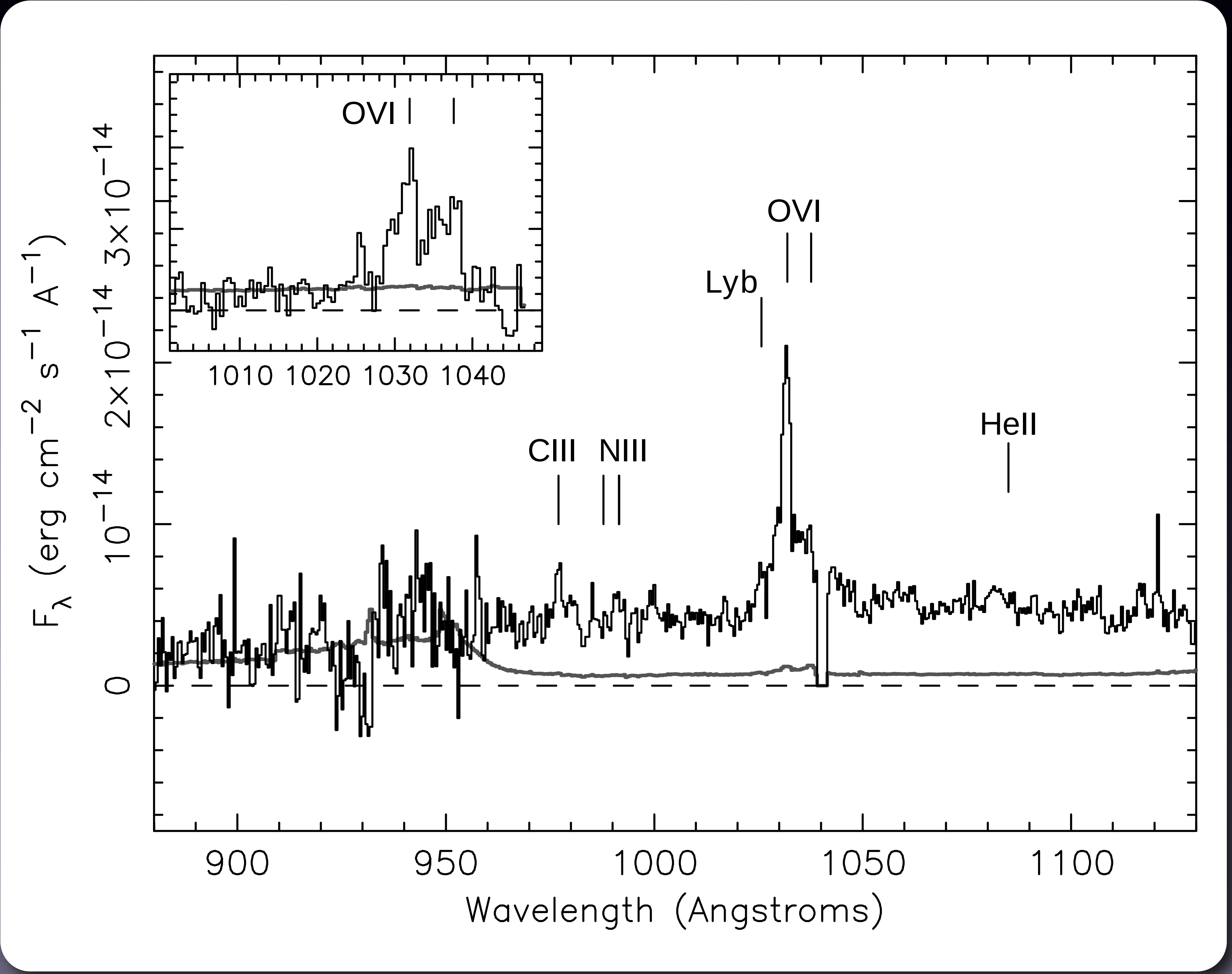
- We developed semi-empirical spectral energy distributions to systematically test SED dependence.
- Parameterized by the energy of the exponential rolloff.

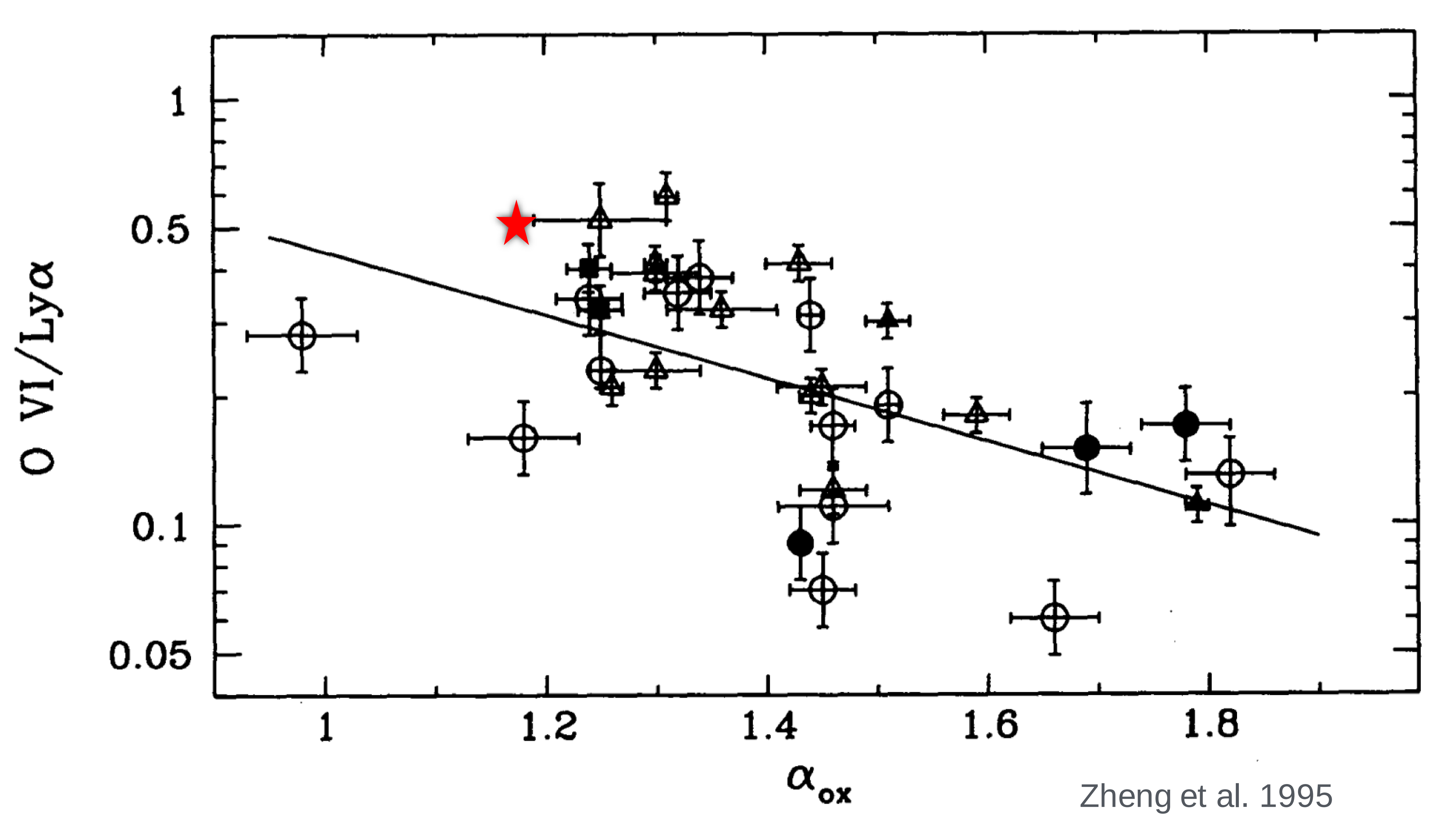



OVI
NV λ 1240
OV] λ 1218
OIV] λ 1402
CIV λ 1549
NIV] λ 1486
OIII] λ 1665
SiIV λ 1397
NIII λ 991
NIII] λ 1750
CIII λ 977
CIII] λ 1909
AlIII λ 1860
SiIII] λ 1888
NII λ 1085
NII] λ 2140
k T_cut (eV)
log(U)
Casebeer et al. 2006

Strong OVI Confirmed

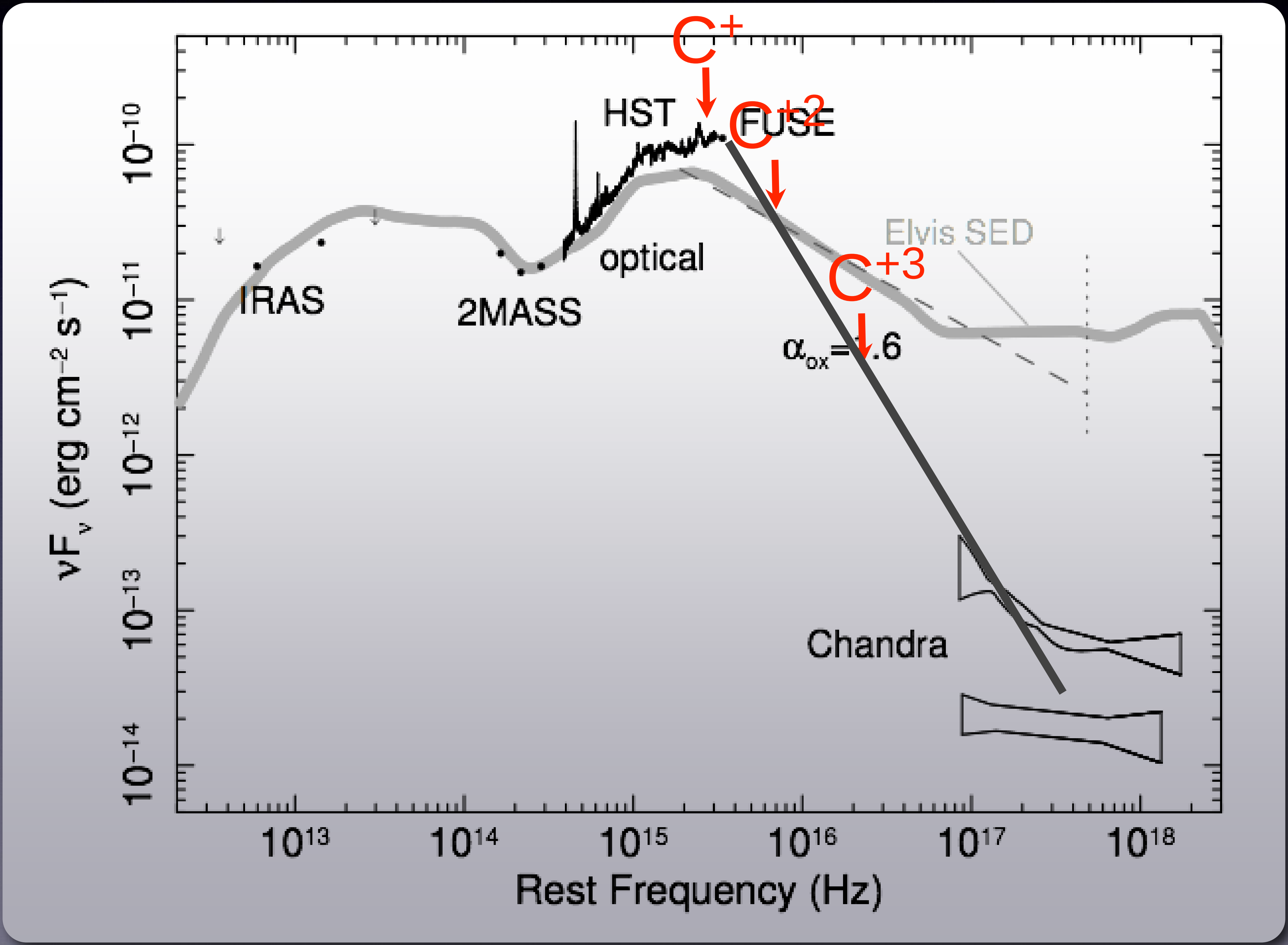
RE 1034+39 was a faint object for *FUSE*, but we were able to successfully observe the strong OVI line.





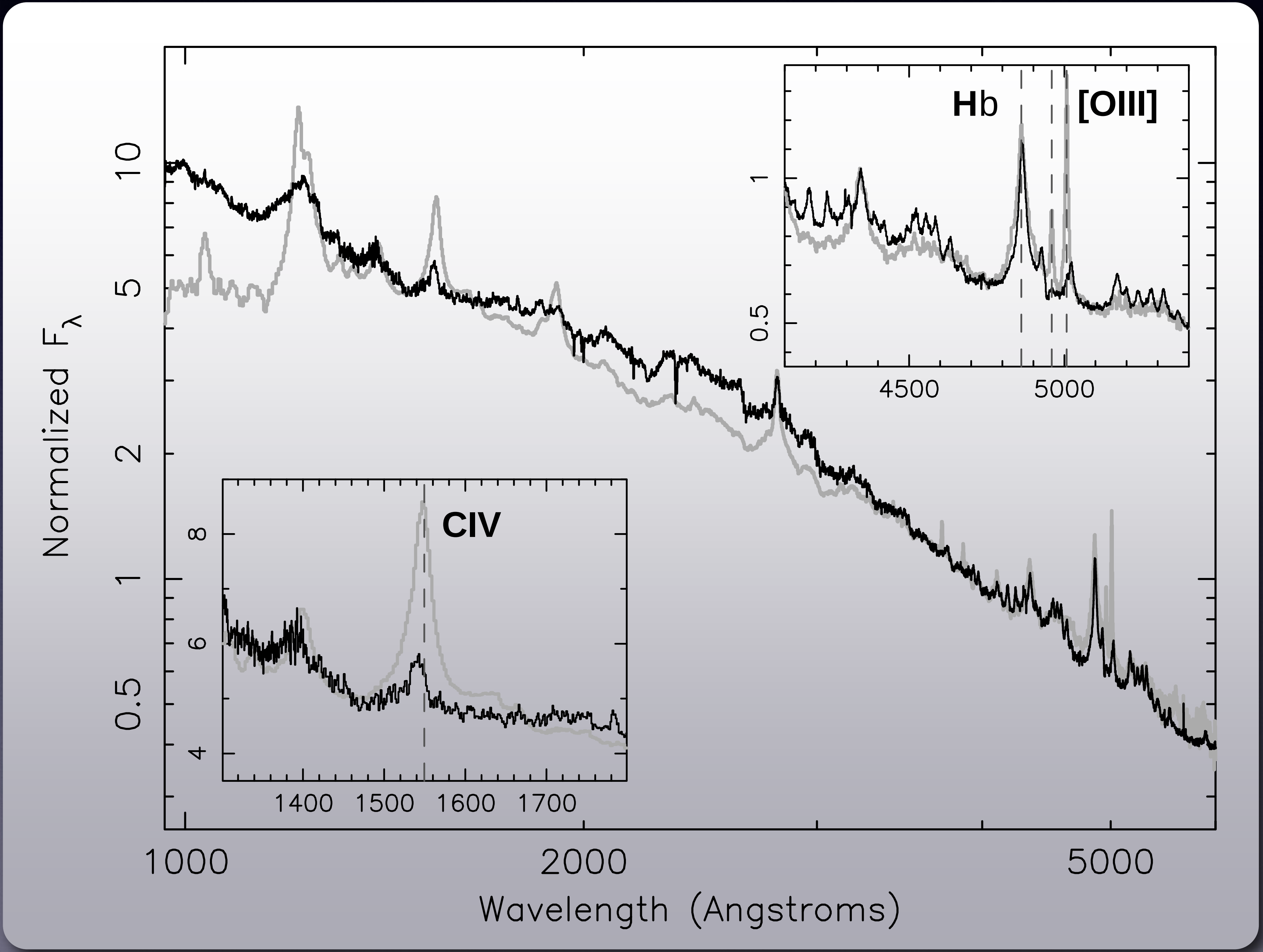
The OVI line is comparable with other quasars that have similar values of alpha$_{ox}$, the point-to-point slope between 2500 A (UV) and 2 keV (X-ray).

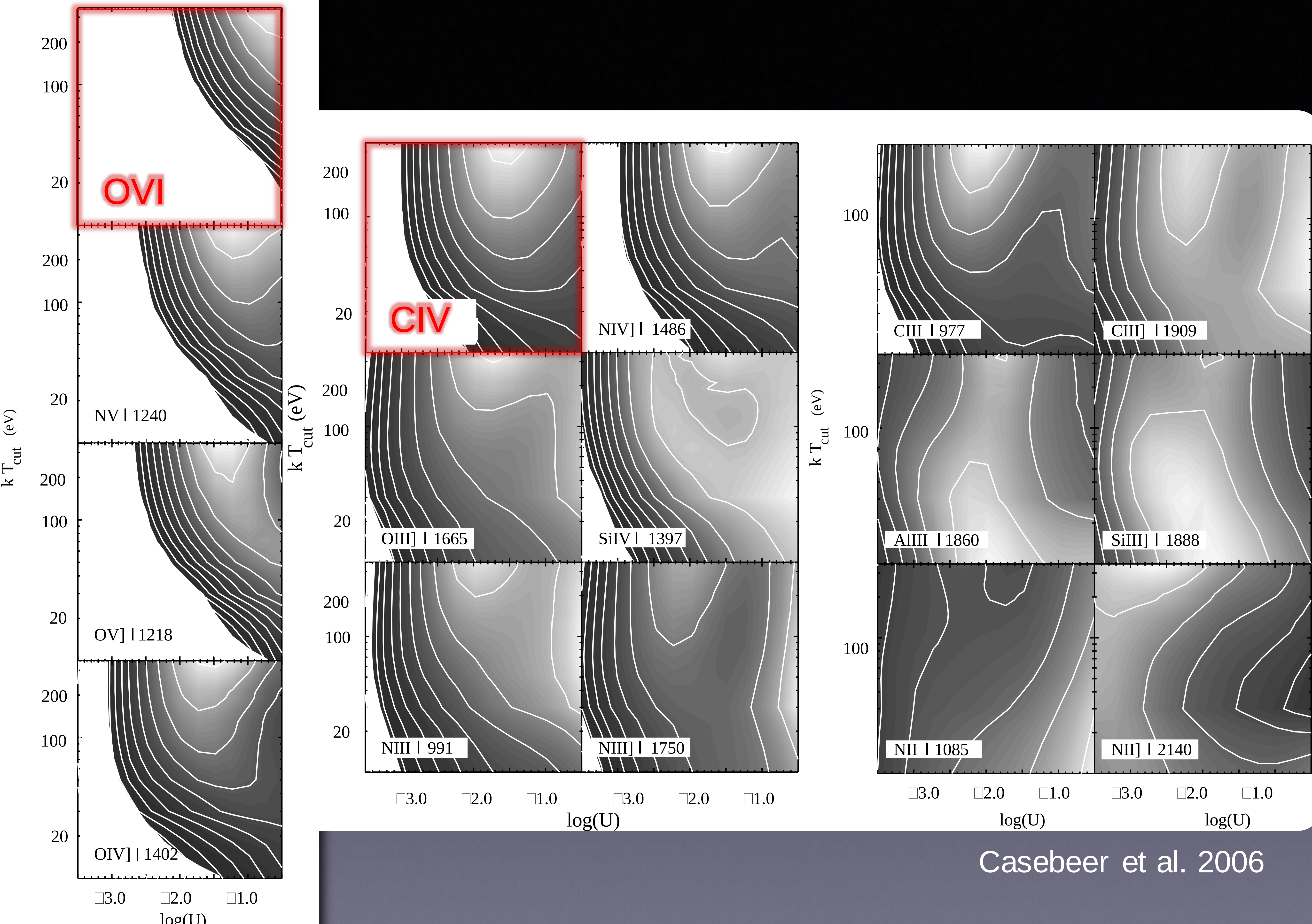
PHL 1811 – X-ray Weak SED



High-ionization Lines are Weak

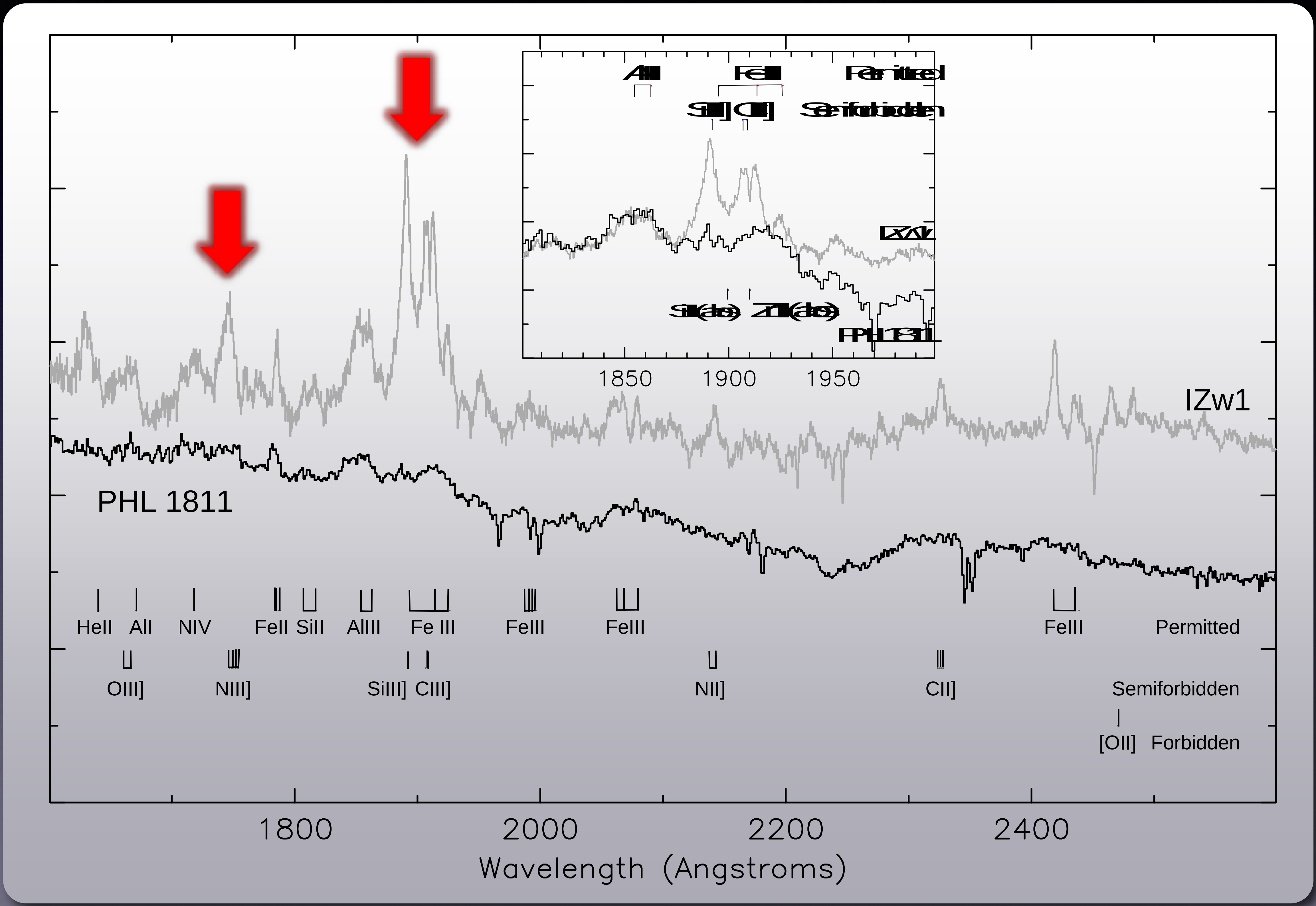
- Typical high-ionization lines such as CIV are weak.



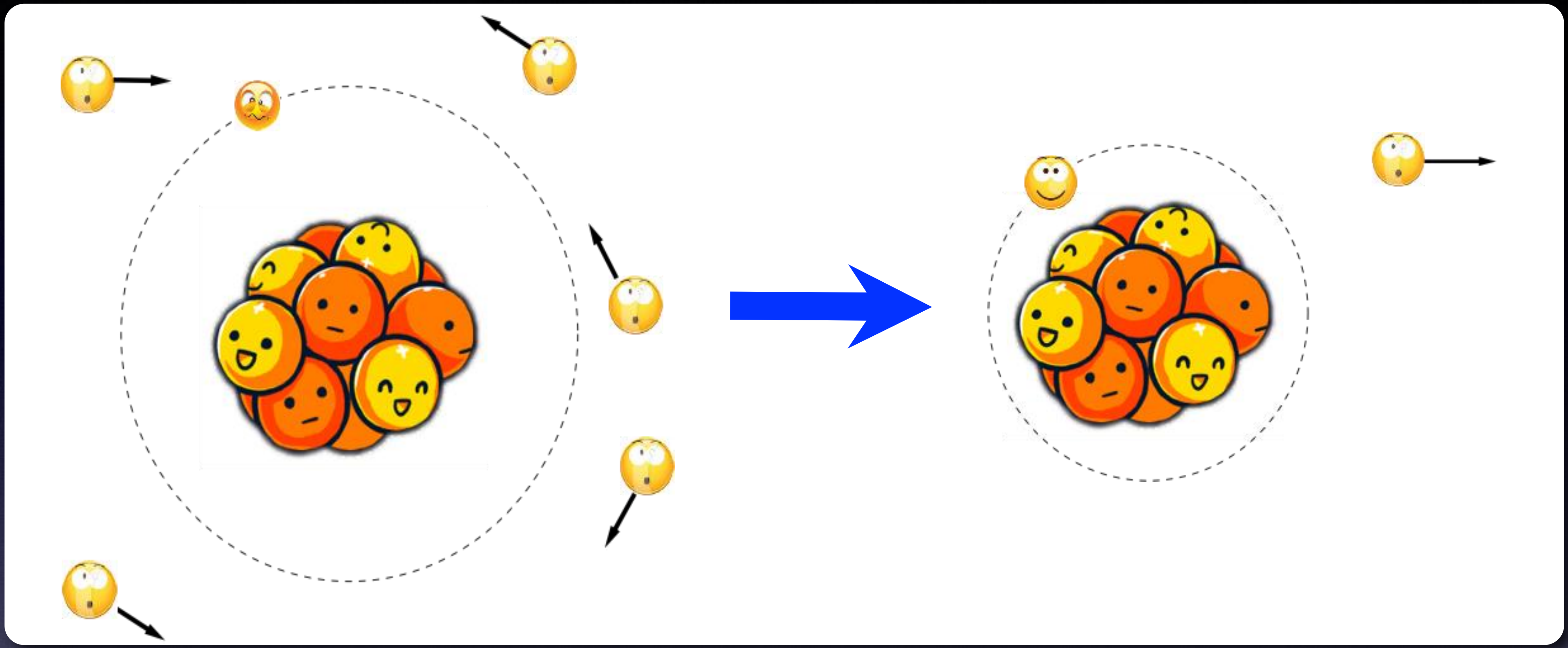


Casebeer et al. 2006

Semiforbidden Lines are also weak



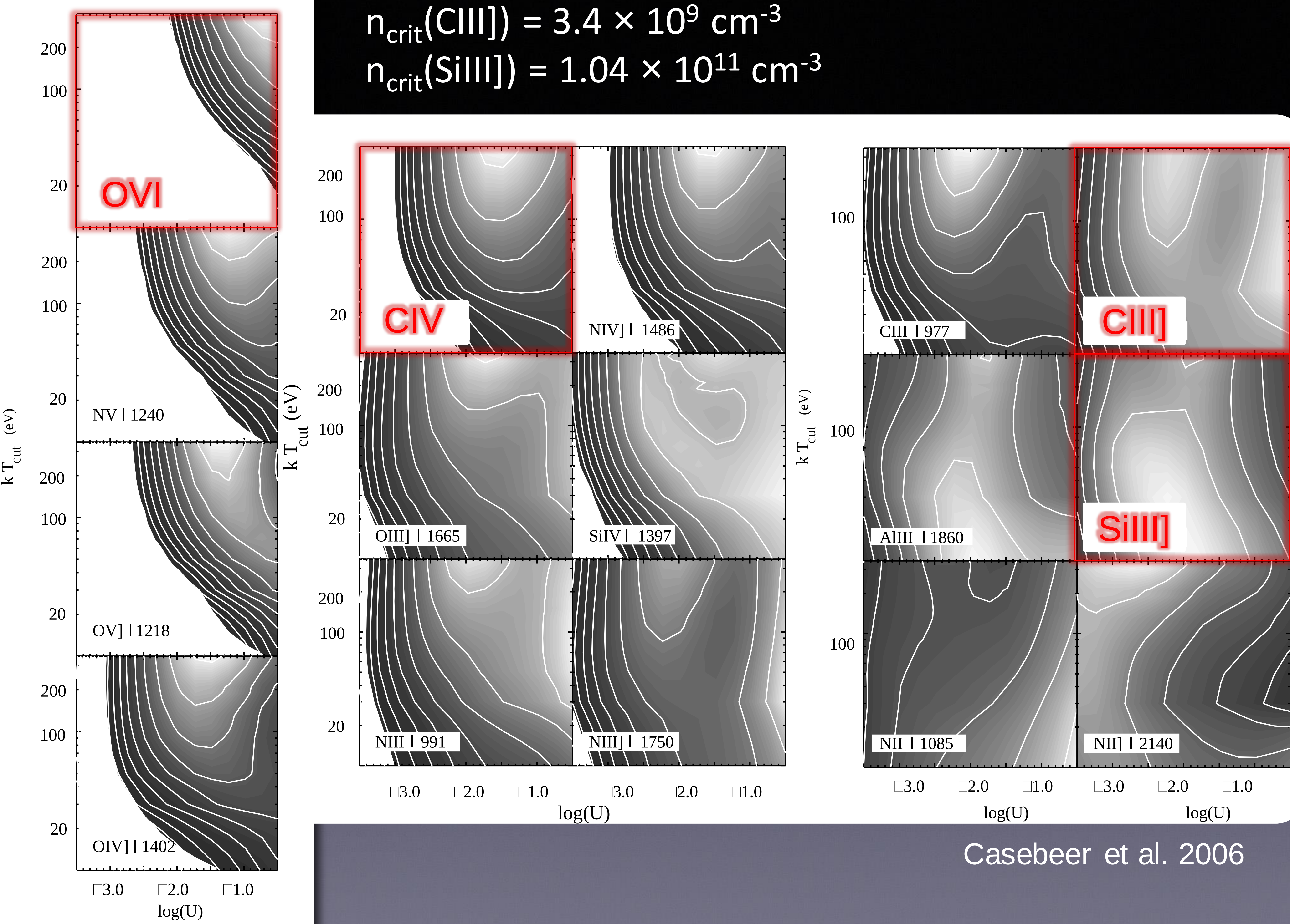
Collisional Deexcitation



- If the excited-state lifetime is long compared with the time scale for collisions → no photon is produced.
- *Critical density*: collisional deexcitation rate equal to spontaneous emission rate.
- Semiforbidden lines (e.g., CIII], SiIII]) have somewhat low critical densities.

$n_{crit}(CIII]) = 3.4 \times 10^{9}\ cm^{-3}$

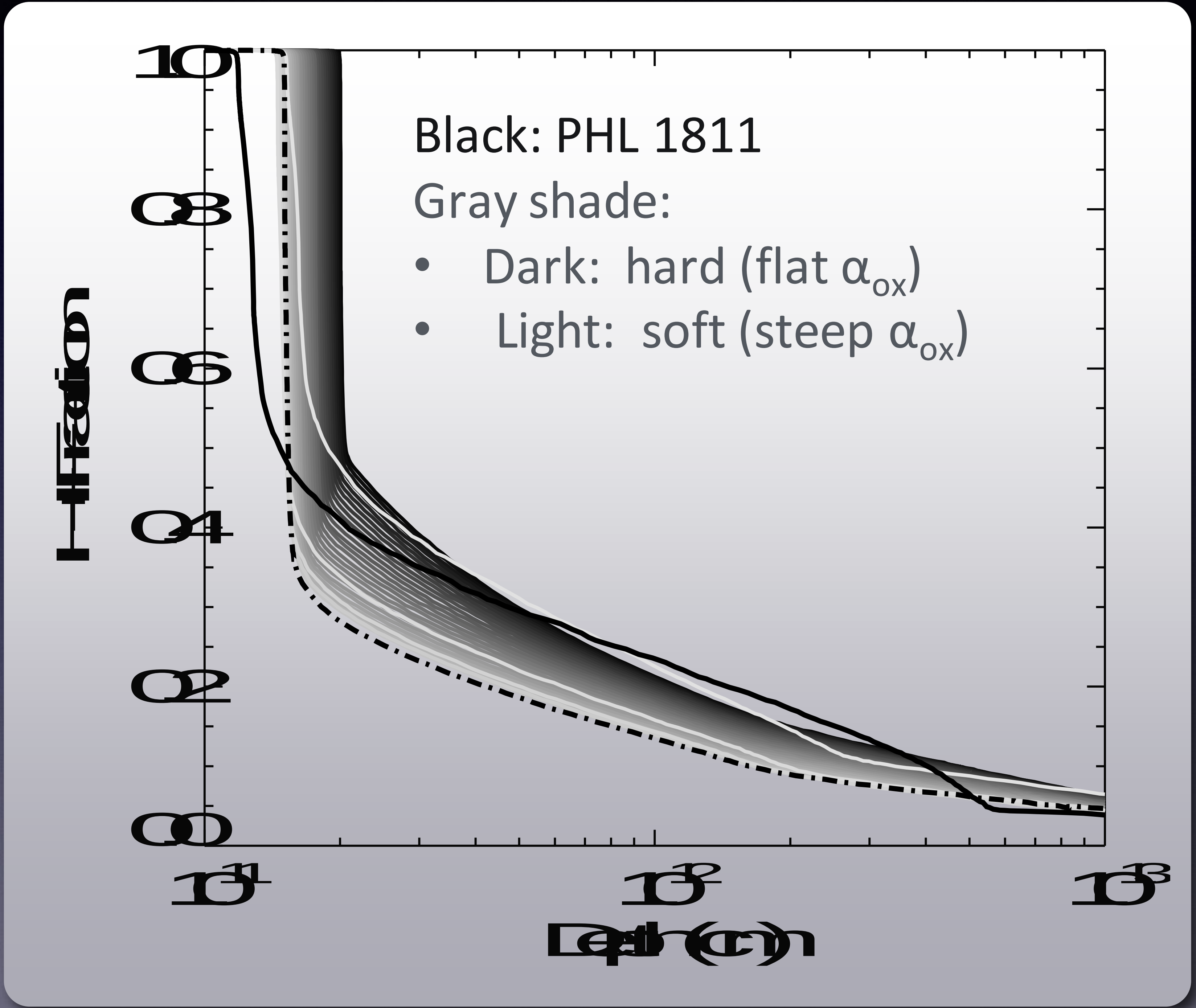
$n_{crit}(SiIII]) = 1.04 \times 10^{11}\ cm^{-3}$



Casebeer et al. 2006

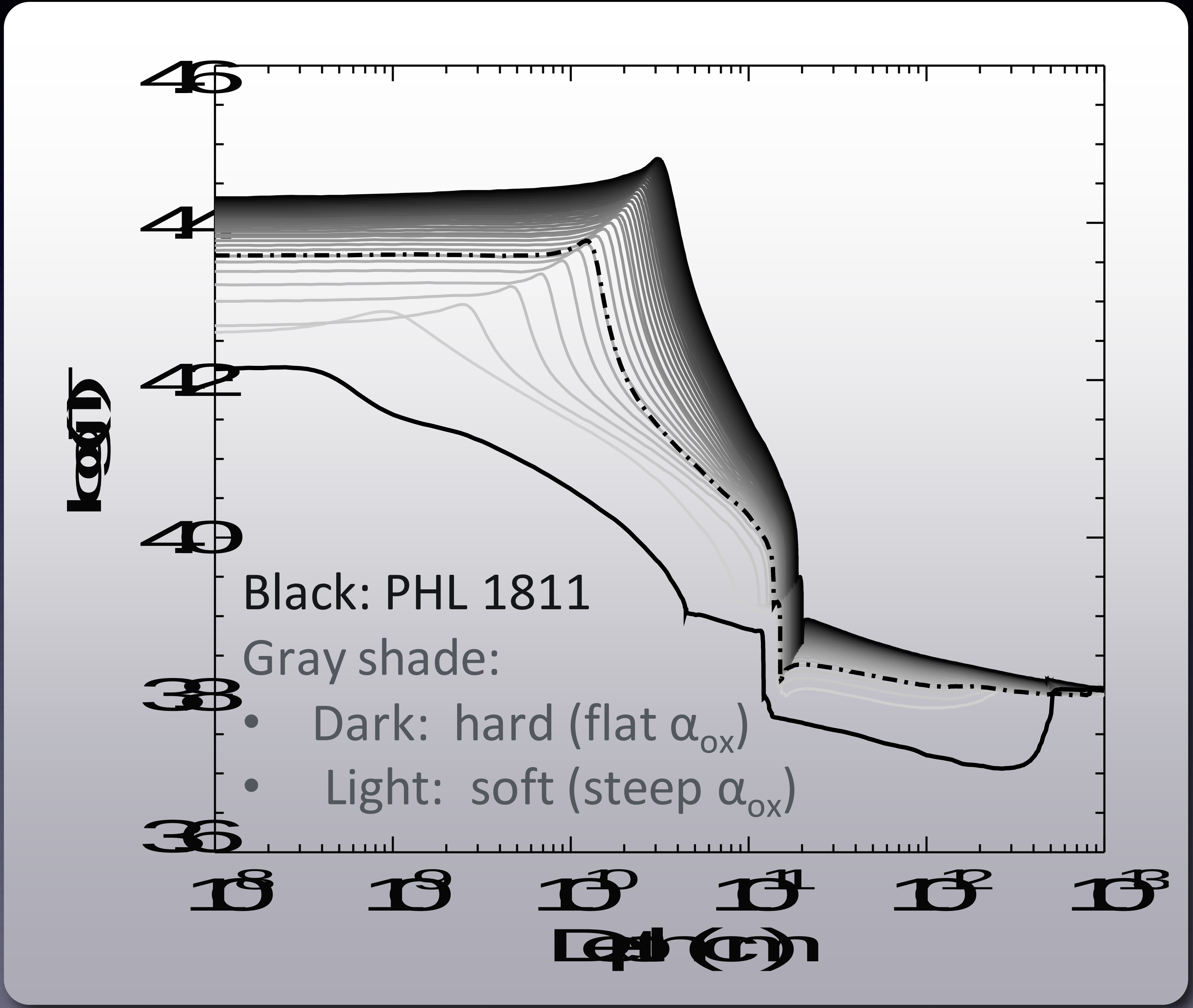
WTF?

- Generally, the fraction of ionized hydrogen beyond the hydrogen ionization front is anticorrelated with α_{ox}, since X-rays can photoionize in that region.
- We see that the trend is *reversed* for the X-ray weakest objects

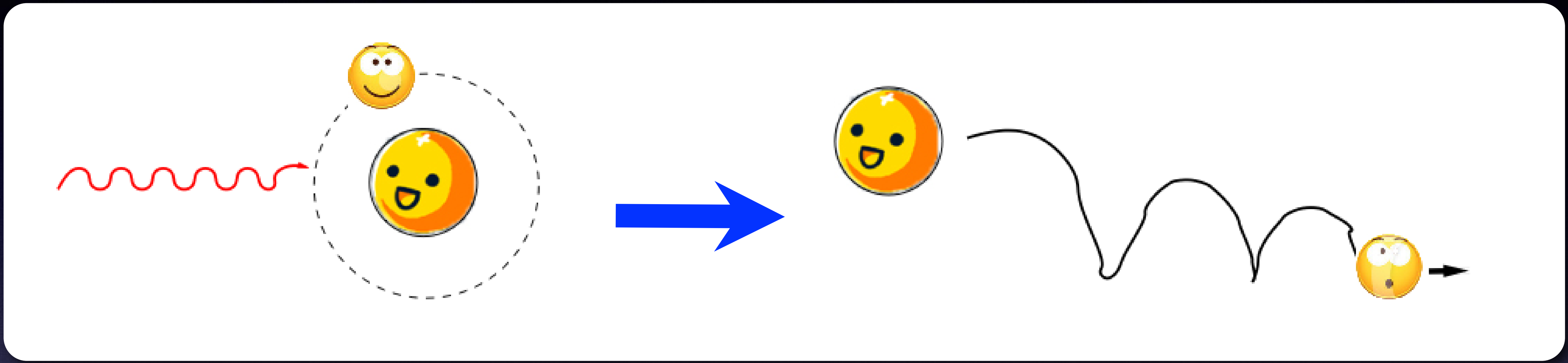


Cold Gas

The key is the ultra-low temperature of the ionized gas in PHL 1811.



Why so cold?



- Temperature of the gas is related to the energy of the photolelectrons.

- X-ray weak SED → most photoionizing photons have low energy → leaving photoelectrons have low energy → low temperature.

“Cooling Challenged” BLR

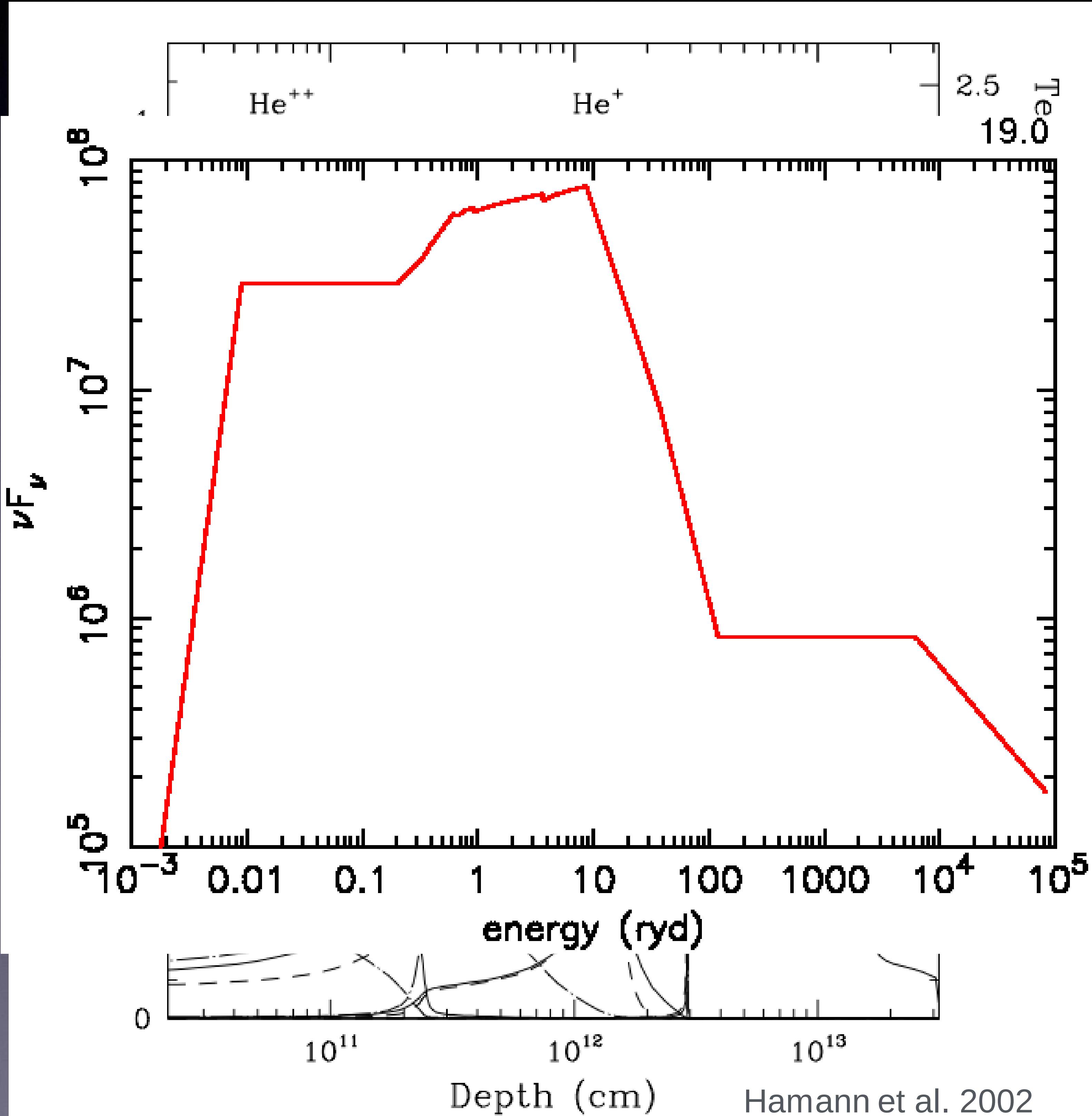
- ➔The gas is *too cool* for effective collisional excitation.
- Yet the flux from the central engine is intense.
- The photoionization energy goes to excited states of hydrogen and continuum emission.
- The result is *overall* weak line emission, not just the high-ionization lines.

Column Density

How thick the gas is.

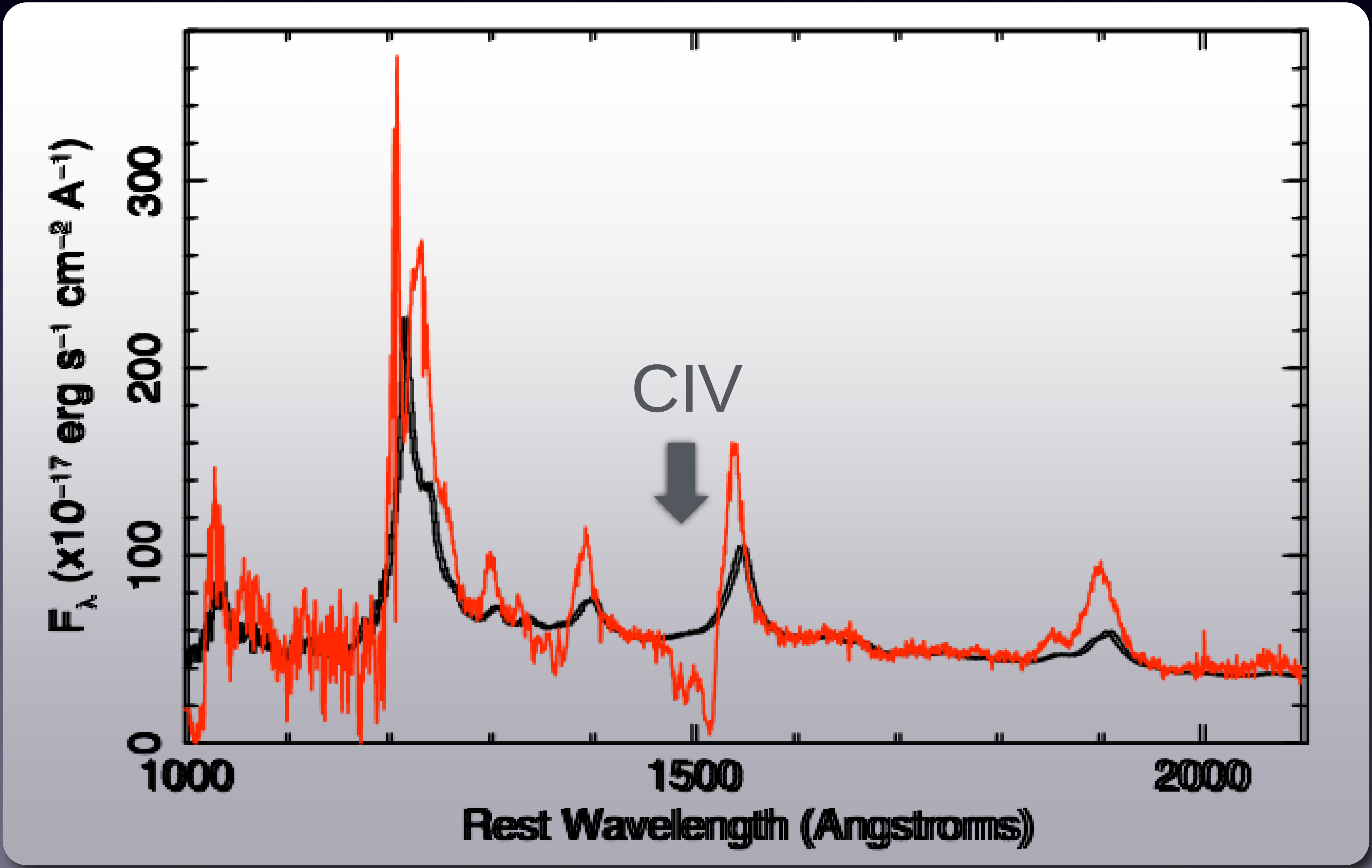
Ionized Slab

- The photoionizing spectrum is a steep function of energy.
- The photoionizing continuum is depleted of photons that can ionize particular ions as it traverses the slab.
- The ions present depend on where we truncate the slab.

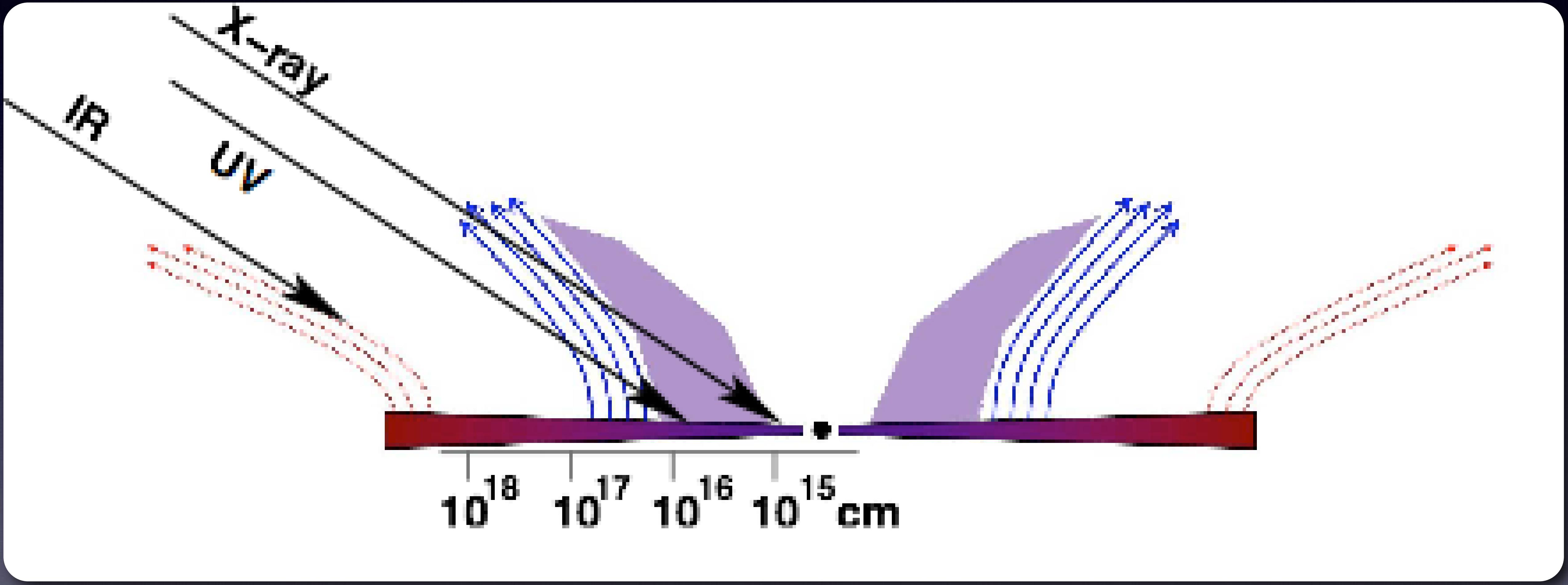


Hamann et al. 2002

Broad Absorption Line Quasars (BALQSOs)



Winds in Quasars

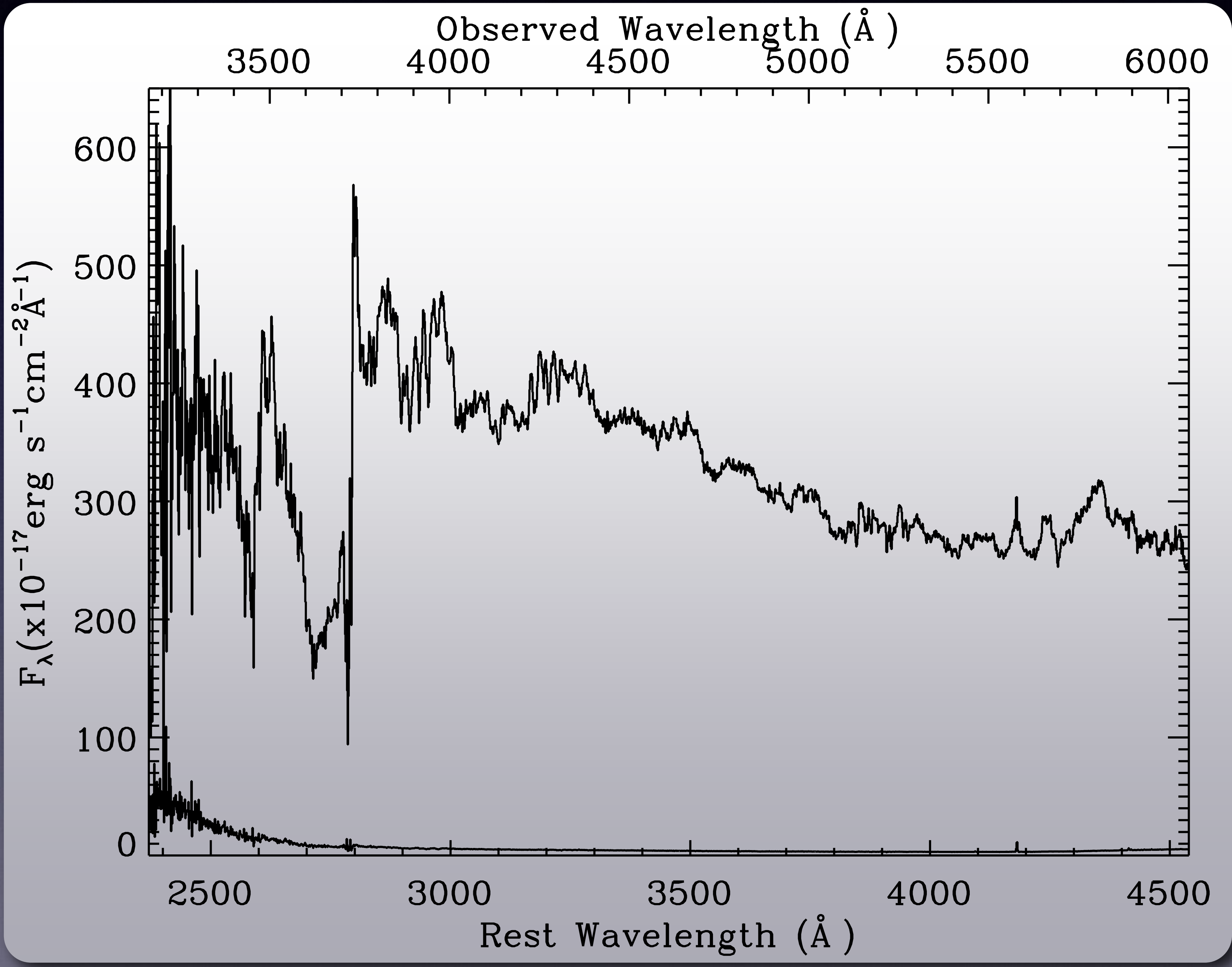


Gallagher & Everett 2007

We see the central engine continuum transmitted through the outflowing ionized gas.

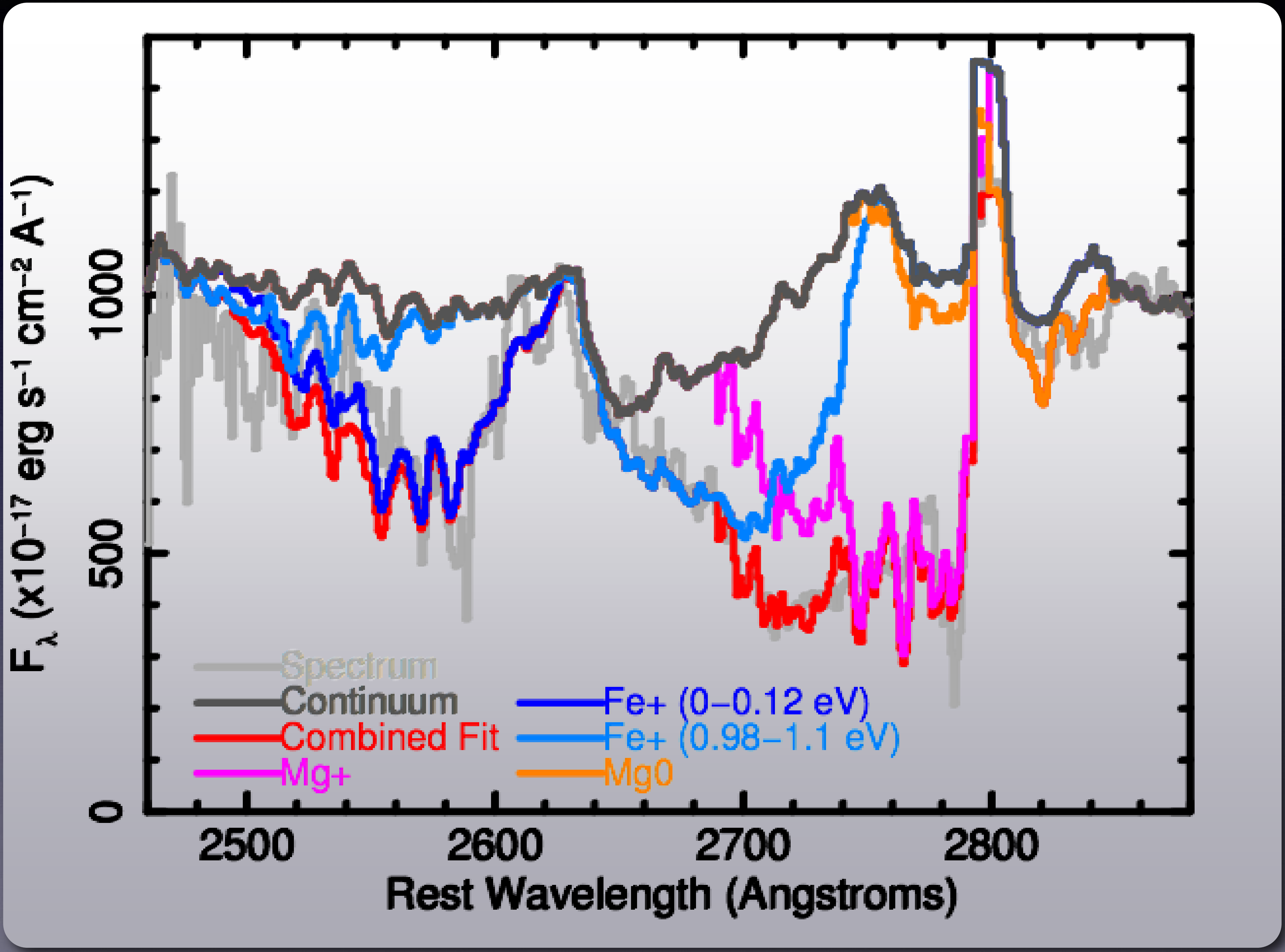
FBQS J1151+3822

- FBQS J1151+3822 is a low redshift (z=0.3344) quasar.
- Observed at Kitt Peak National Observatory 4m telescope



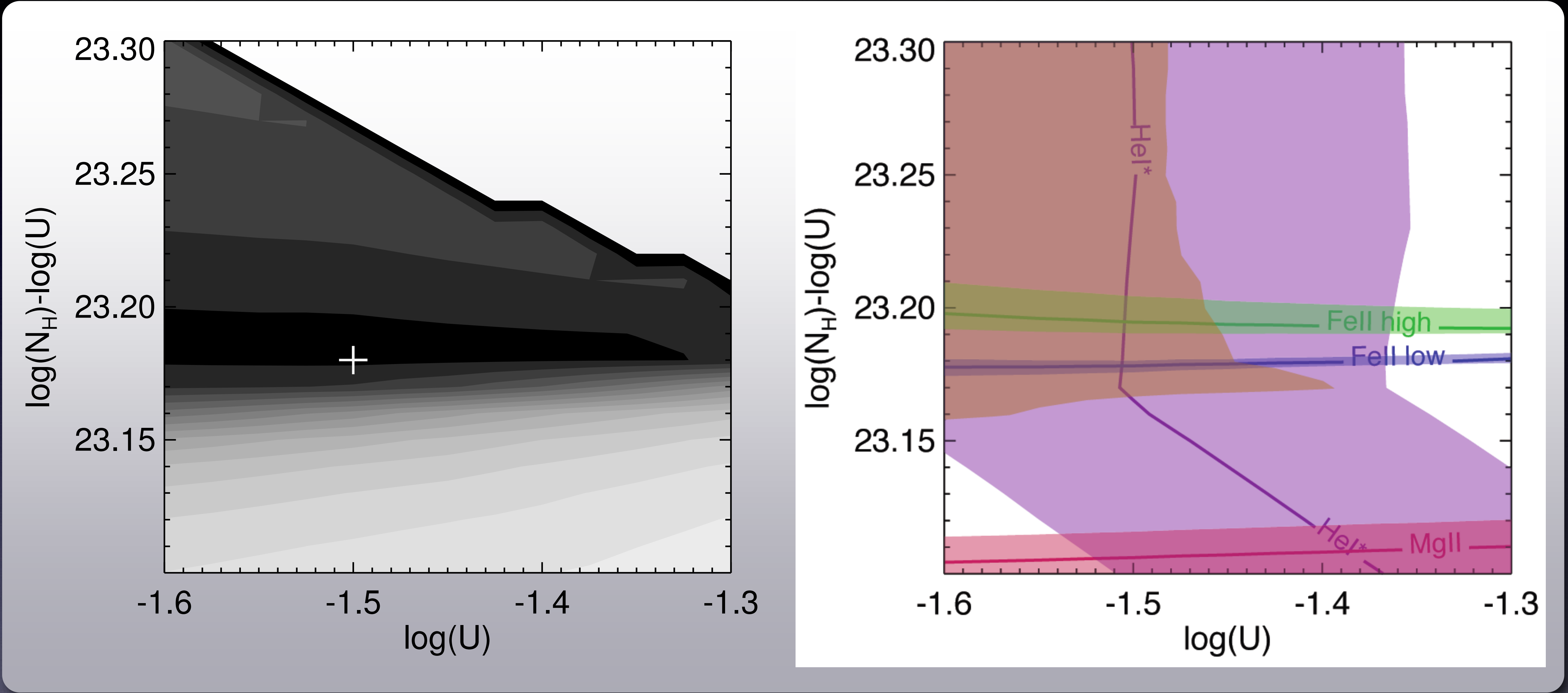
Lucy et al. 2014

FBQS J1151+3822



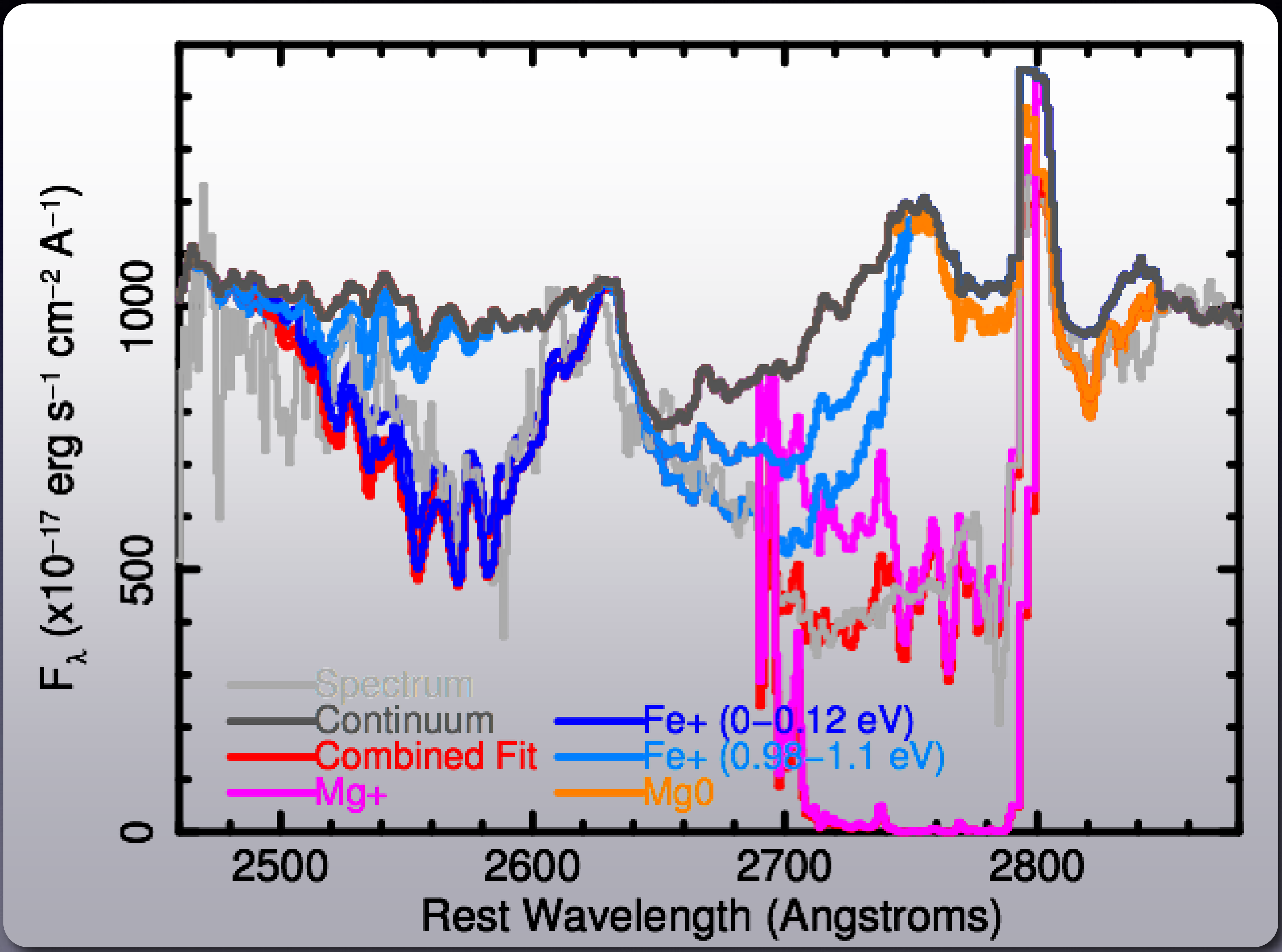
Lucy et al. 2014

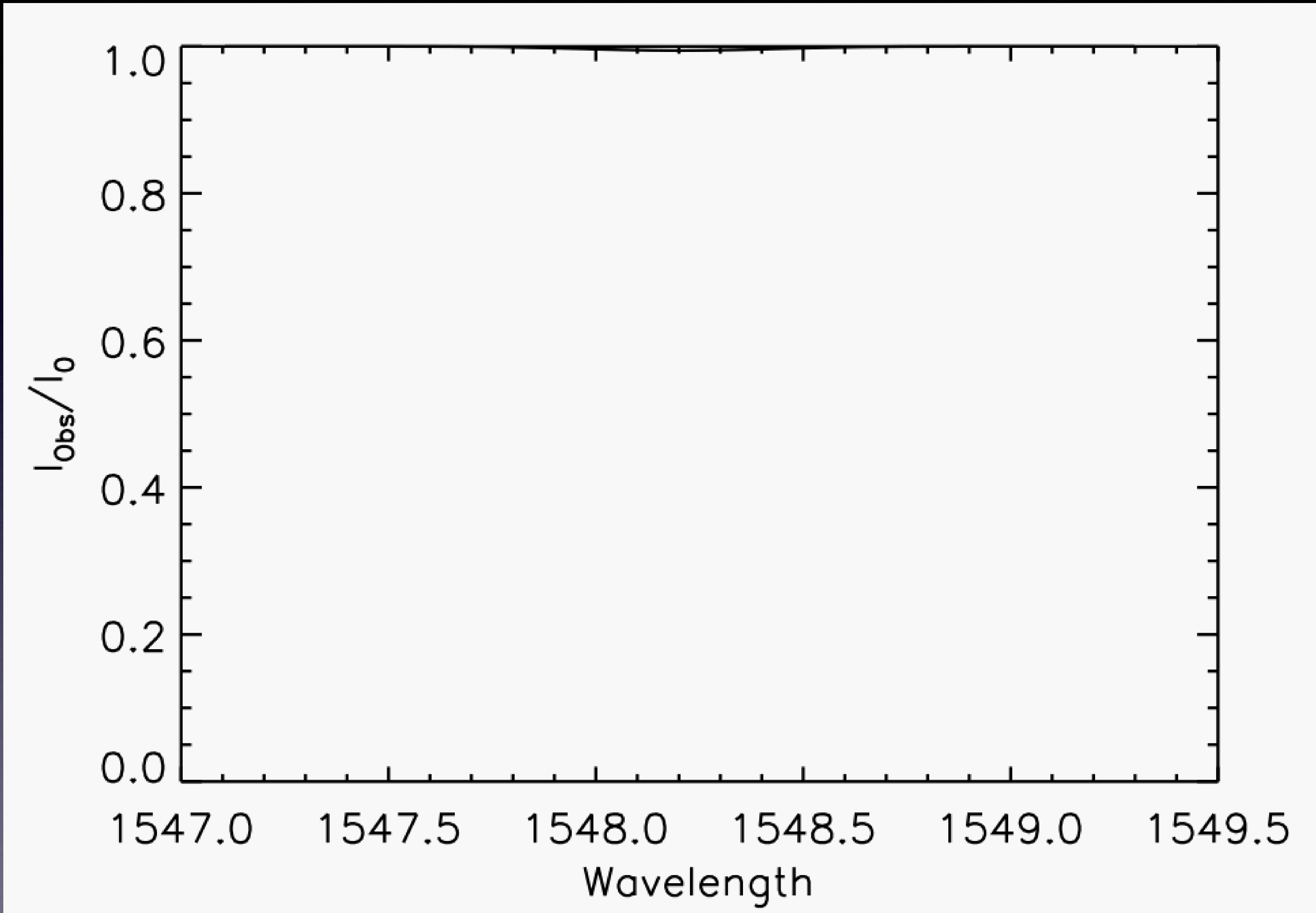
Standard Analysis



1. Measure all the lines.
2. Use the line depths / opacity to estimate the amount of each ion.
3. Use *Cloudy* to determine the location in parameter space that is closest to matching the measurements.

Best Fit is Not Good

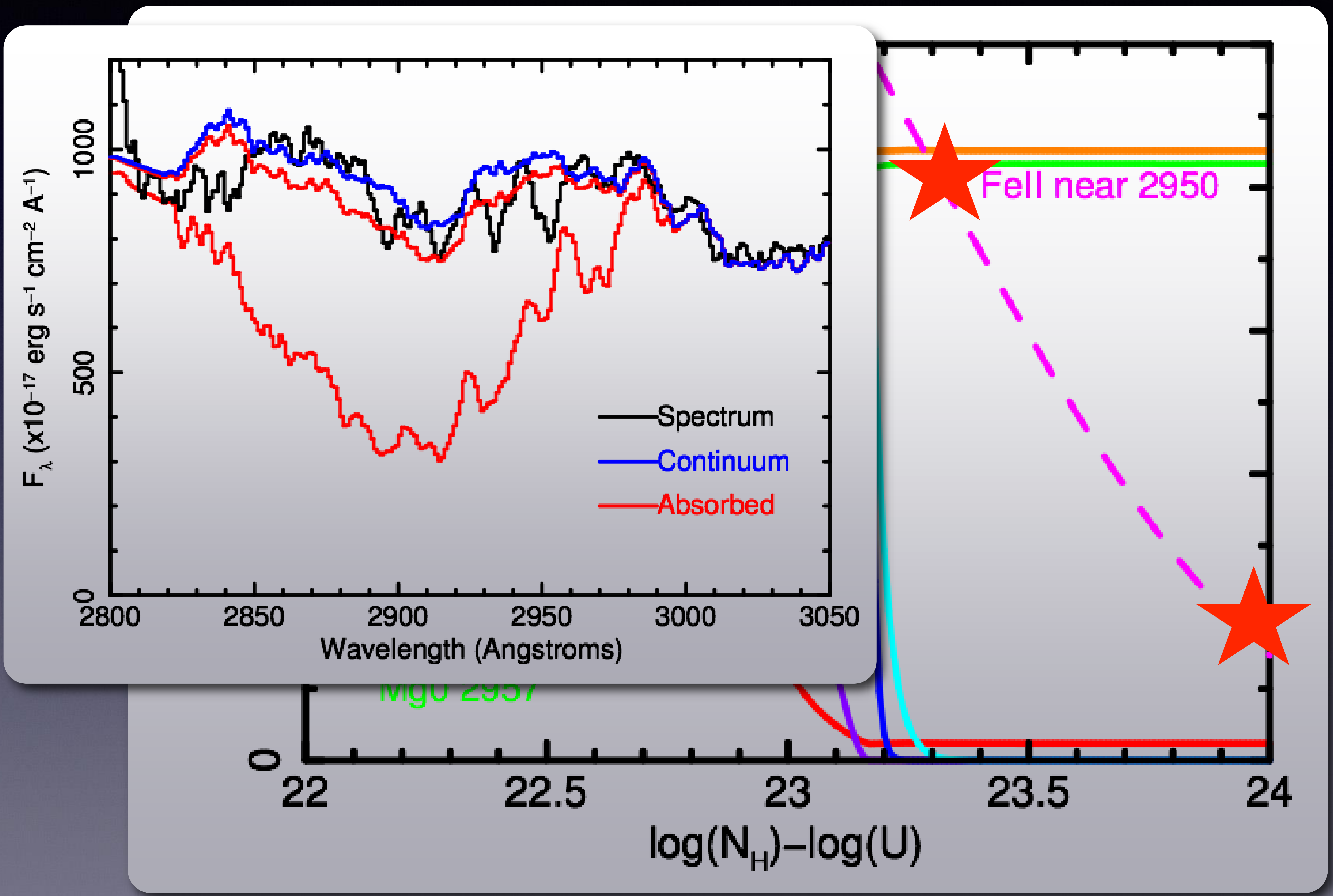



1.0
0.8
0.6
0.4
0.2
0.0
I_{Obs}/I_0
1547.0
1547.5
1548.0
1548.5
1549.0
1549.5
Wavelength

Identifying Unsaturated Lines

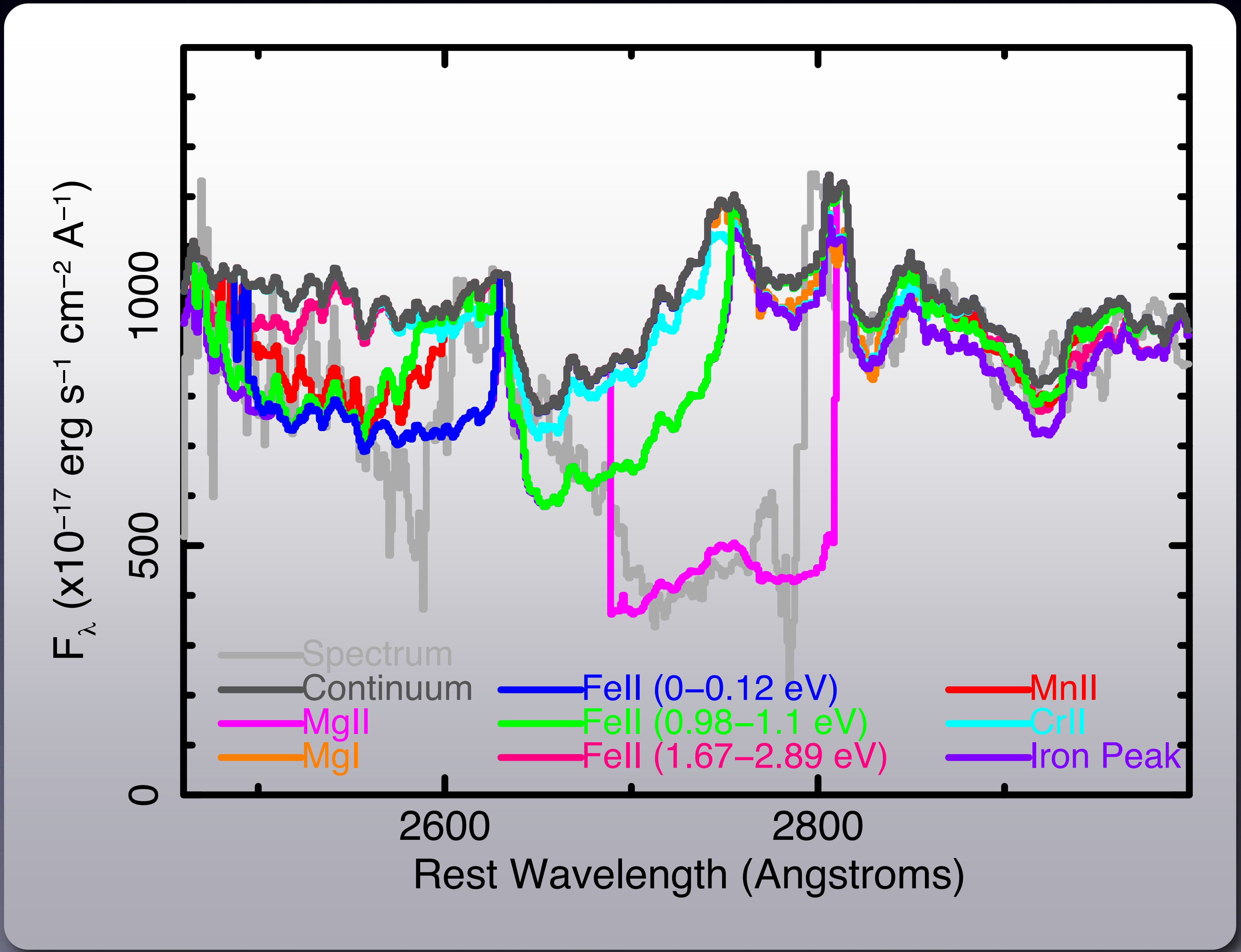
- Look for lines that ar  saturated.
- Adrian was able to f ell, MnII lines near 2950 A that were n .
    - MnII – Mn is tw agnitude lower abundance thar
    - FeII – these lines were m excited states (E> 1eV).

Spectrum/Continuum



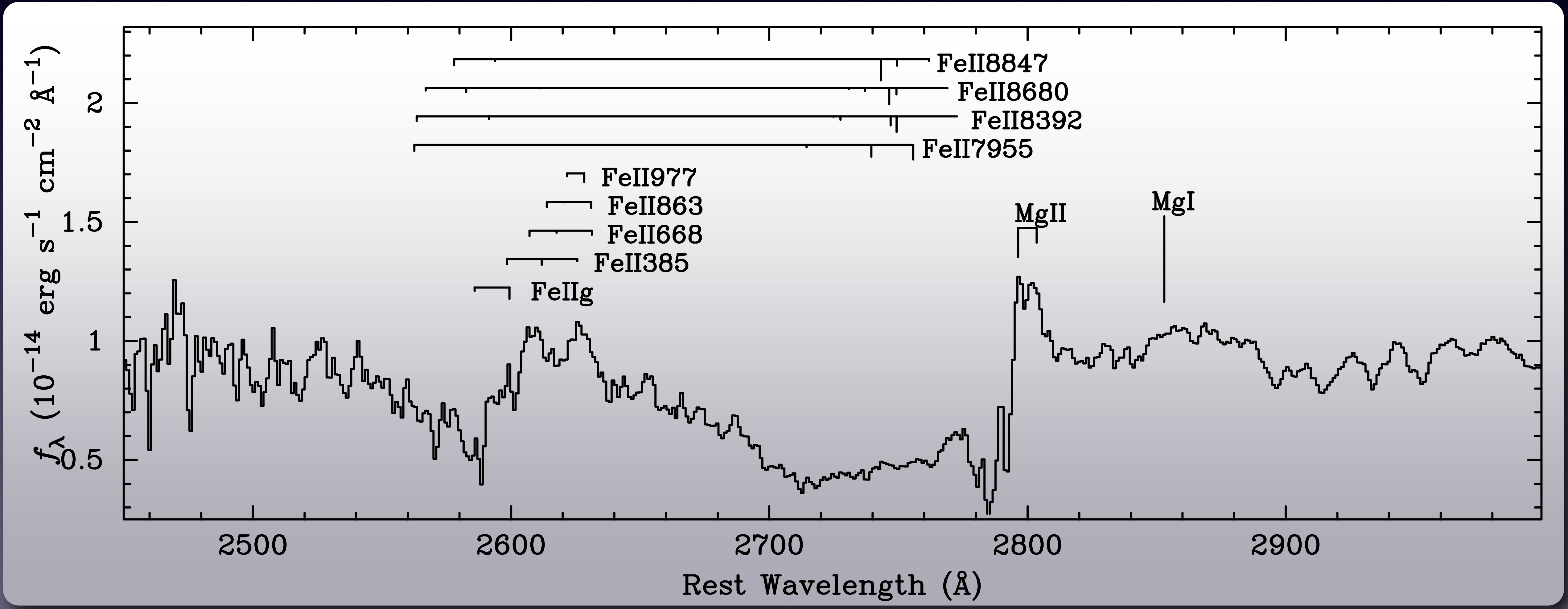
A Better Fit

Unsaturated lines from MnII, CrII, very high excitation FeII



Density Sensitivity

- The FBQS J1151+3822 analysis also revealed density sensitivity.



- Lines near 2950A arise from higher levels than lines near 2600 or 2400A.

Collisional Excitation

- The difference between photoionized gas and thermally-excited (hot) gas is that the energy source for ionization is *external*.
- So, the excitation of the gas is high compared with its electron temperature.
- What this means is that most atoms are in the ground state most of the time.
- The exception are a few ions with low-lying levels that can be populated *if the density is high enough*.

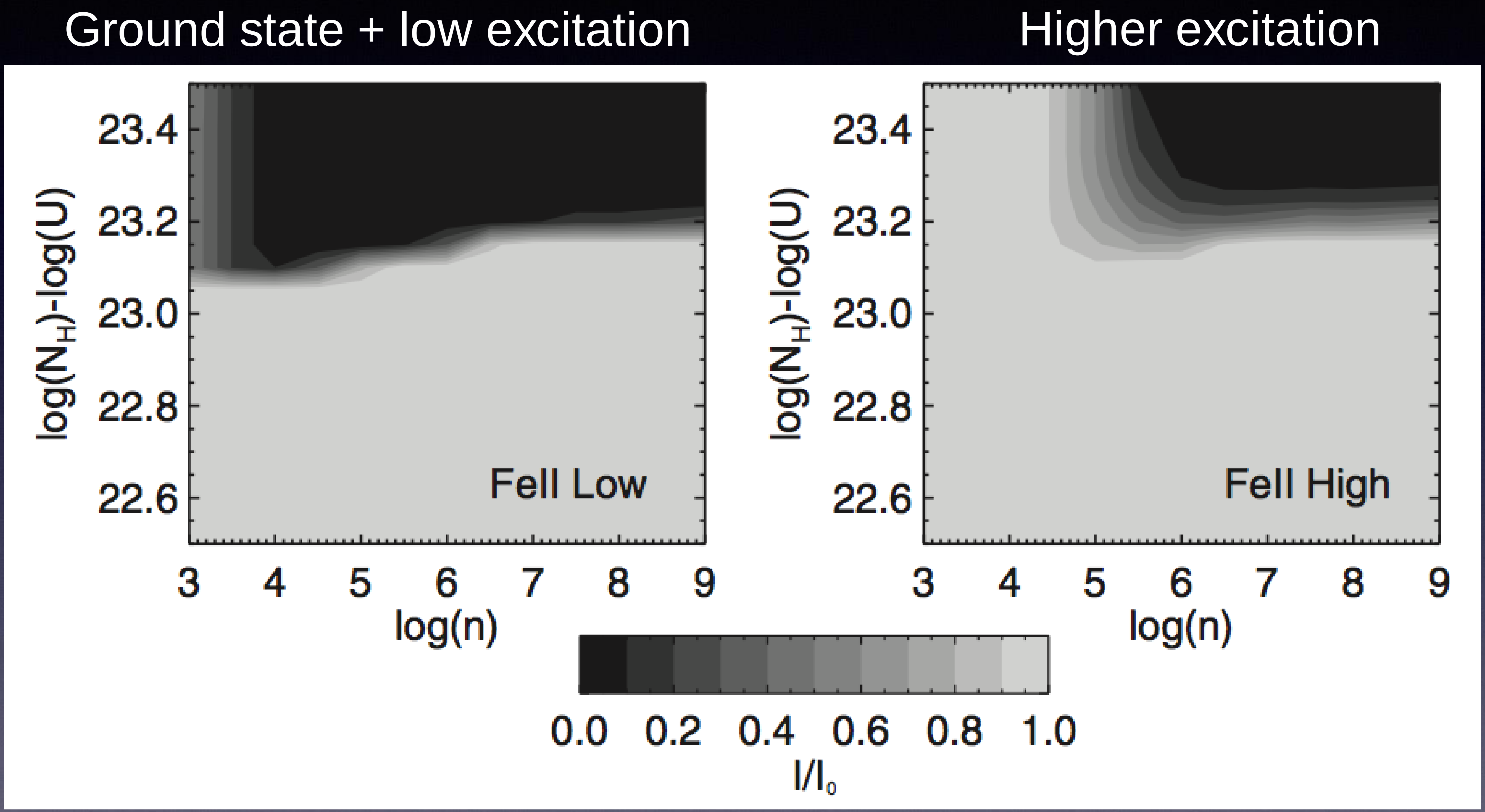
Low Densities

⇨ Few collisions between gas particles

High Densities

➪ Many collisions between gas particles, maintaining excited state populations

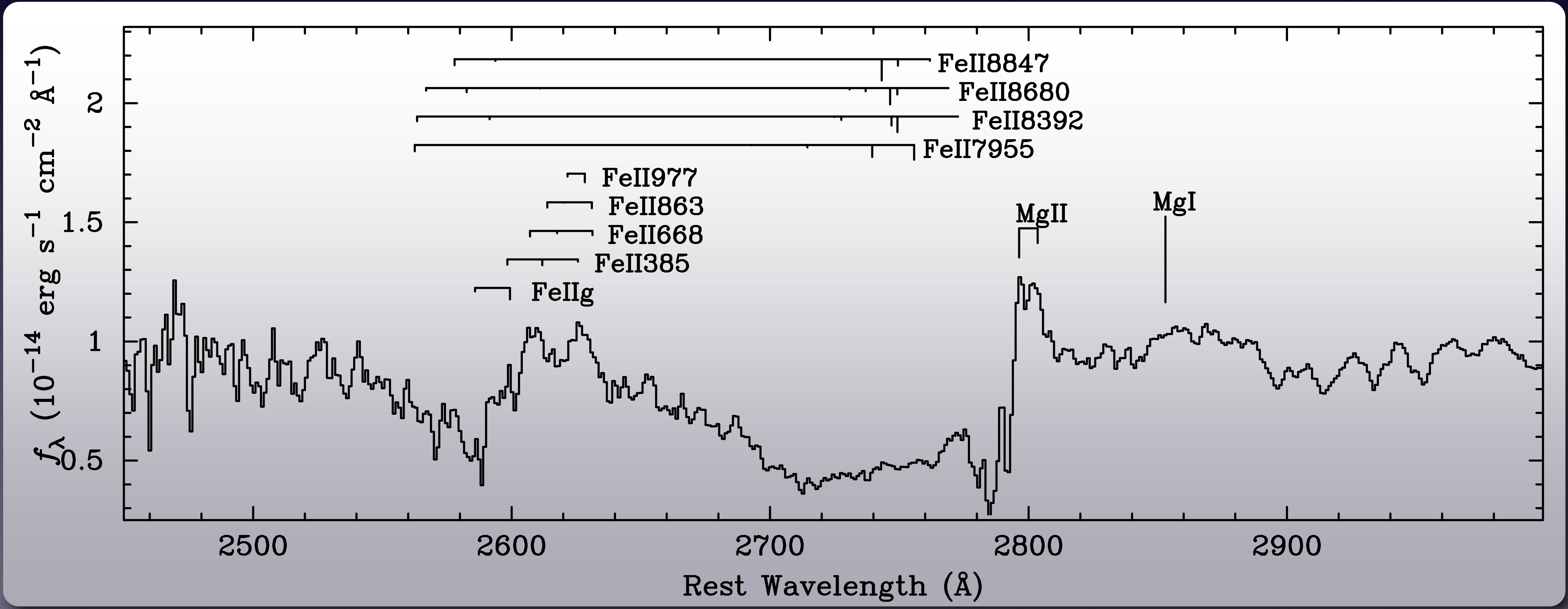
Density Sensitivity



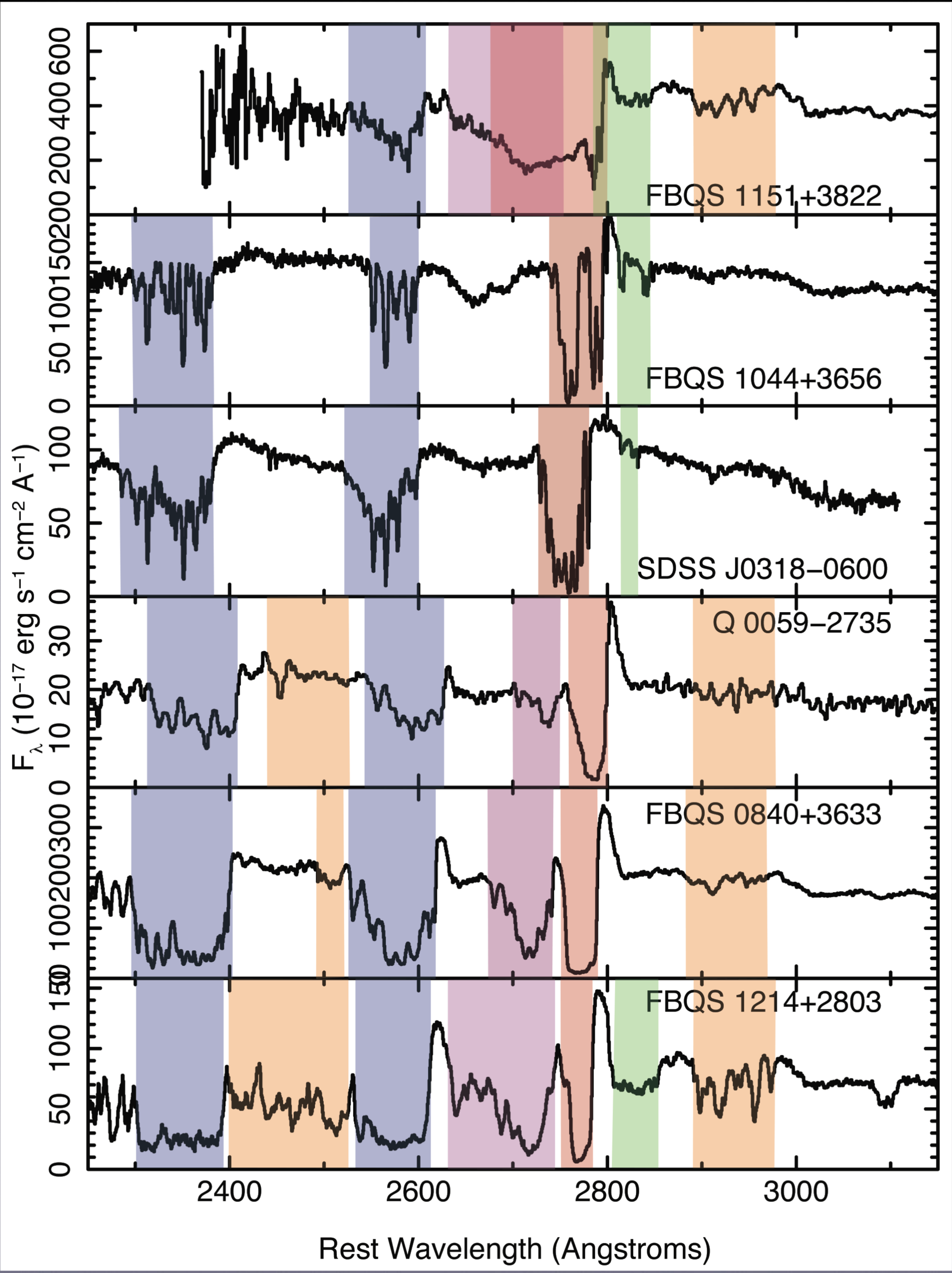
- Collisional excitation is a function of density.

Density Sensitivity

- The presence of the lines near 2950 indicate higher densities.



- We compared FBQS 1151 with other FeII BALQSOs
- We found that some included absorption near 2750 A, and some did not.
- Indicator of gas density.

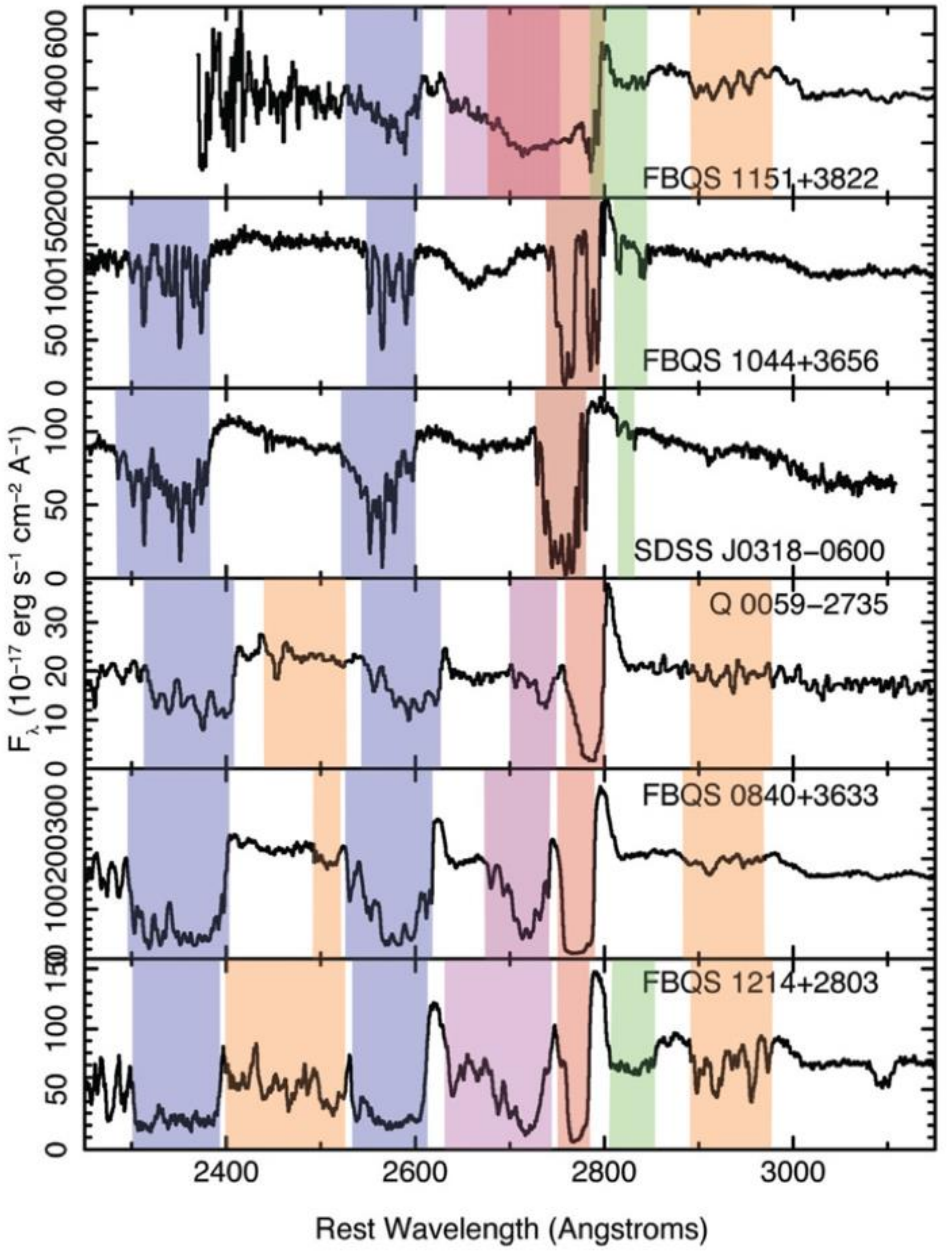


Absorber Distance

- We can infer the absorber distance, because the recombination rate is a function of density.
  - ★ The lines / ions observed determine the ionization rate vs recombination rate equilibrium point.
  - ★ The recombination rate is known (from the density)
  - ★ Then the photoionization flux can be estimated.
  - ★ And therefore the distance from the central engine.

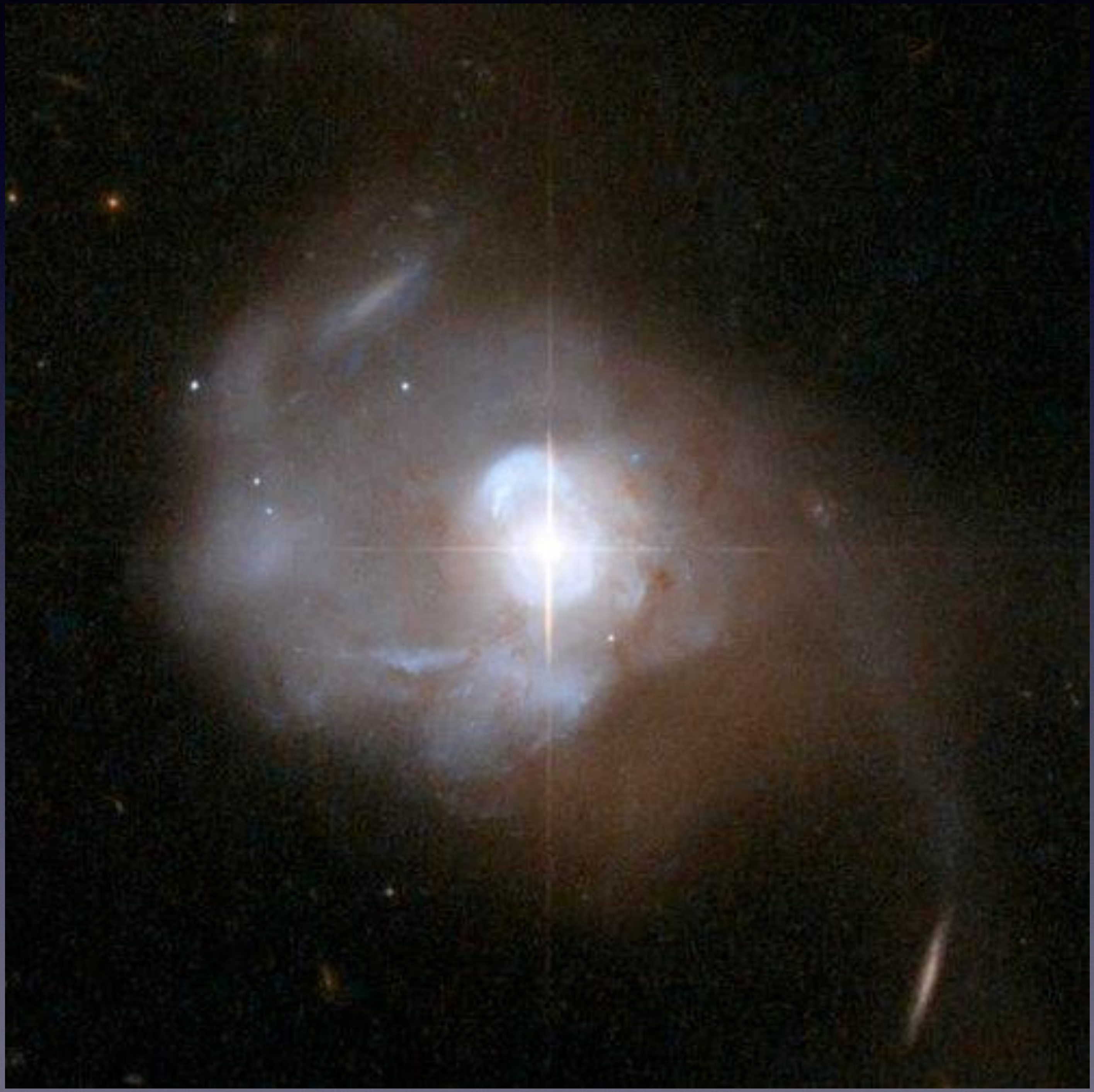
These two outflows lie far from the central engine.

These three outflows lie close to the central engine.



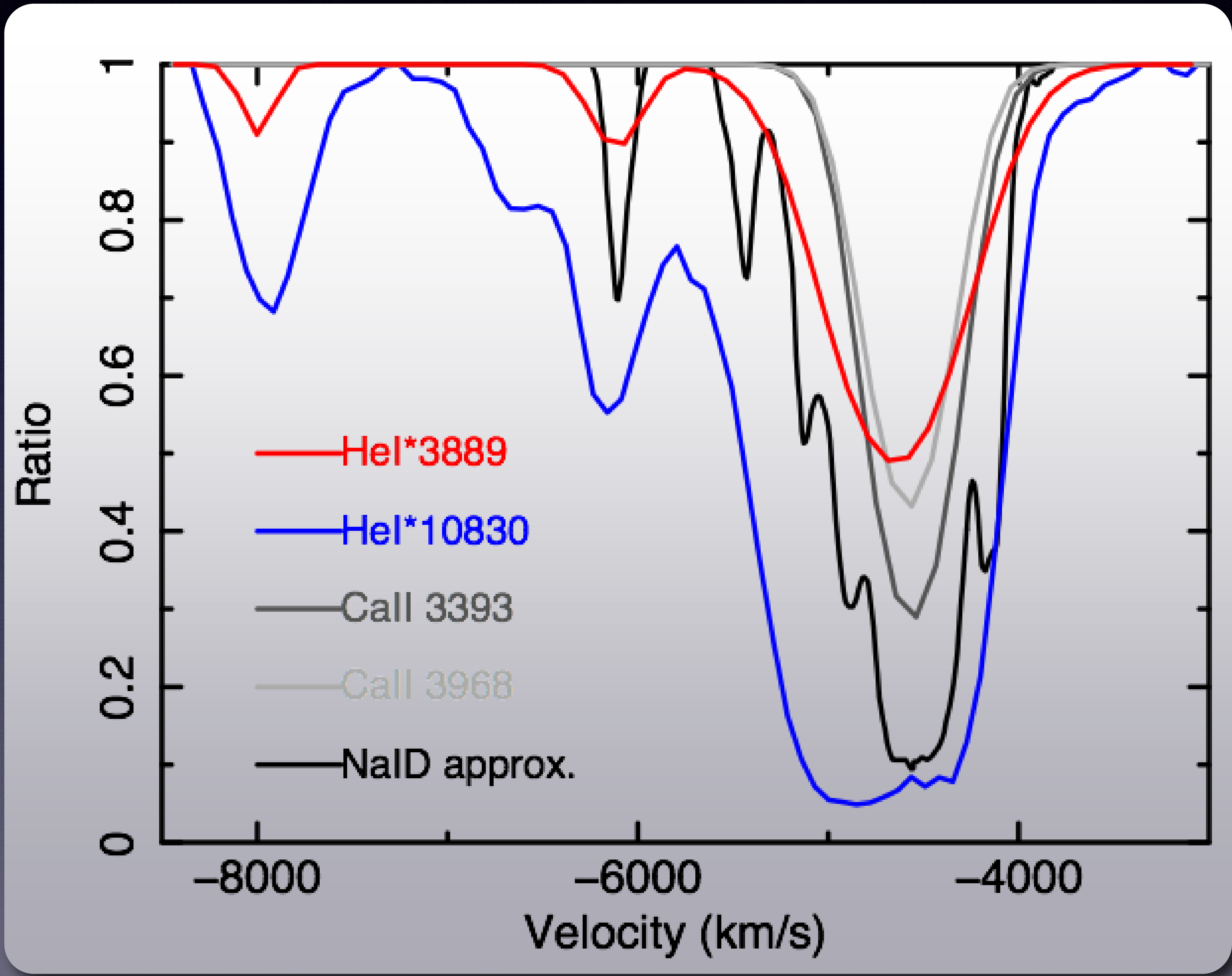
Mrk 231

- A famous, nearby ($z=0.0421$) ultraluminous infrared galaxy
- Nuclear starburst
- Galactic outflow
- Seyfert 1 spectrum
- NaID ***broad*** absorption line



Absorption Lines

- Absorption Lines have similar profiles ➠ same absorbing gas
- But high-ionization lines (HeI*) have *higher velocity* than low-ionization lines (CaII and NaID)

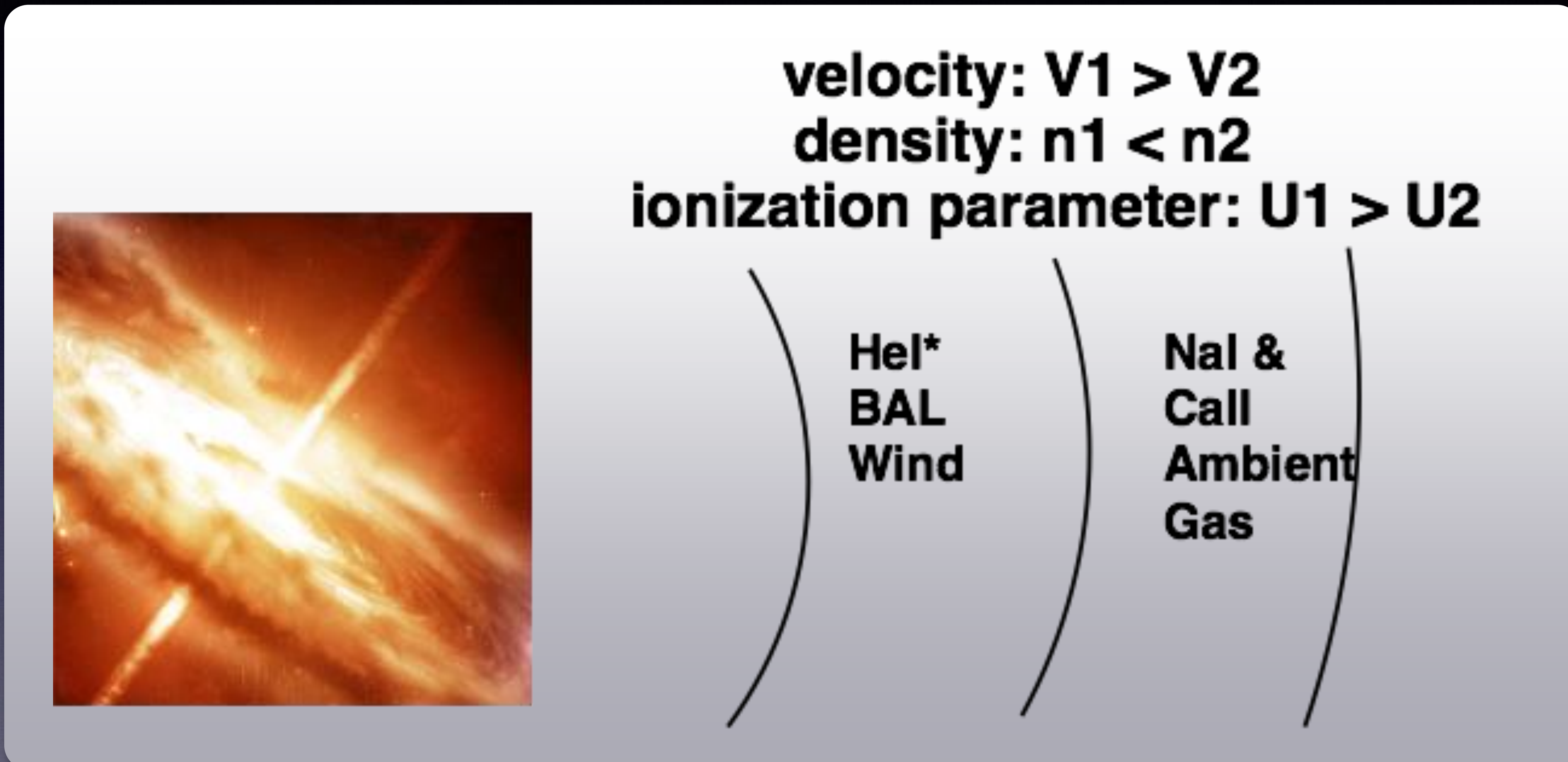


HeI* NaID

- Neutral Helium in the 2s state, created by recombination onto He+.
- Found in the HII zone, along with, e.g., CIV.
- Requires relatively high ionization

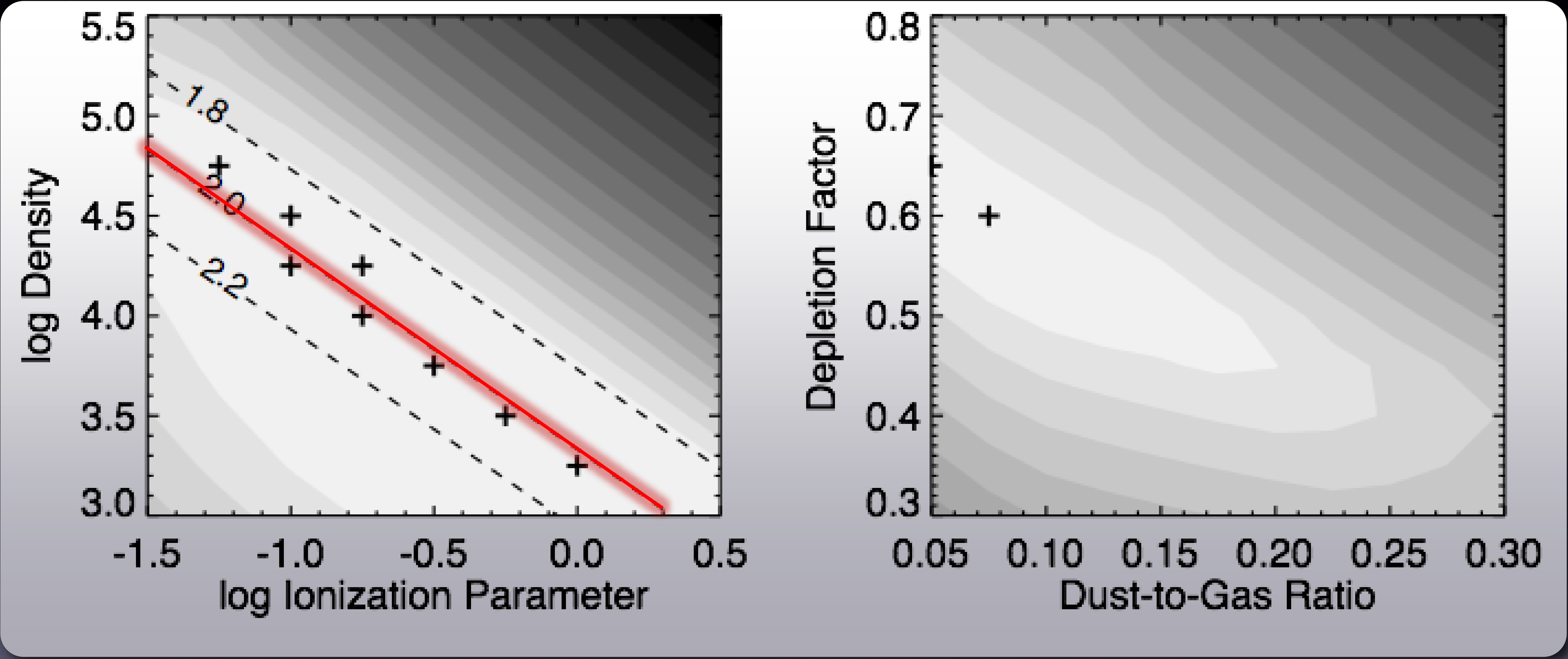
- Neutral Sodium, destroyed by photons with E> 5.14 eV.
- Found deep in the partially ionized zone.
- Requires relatively low ionization.

Our Solution



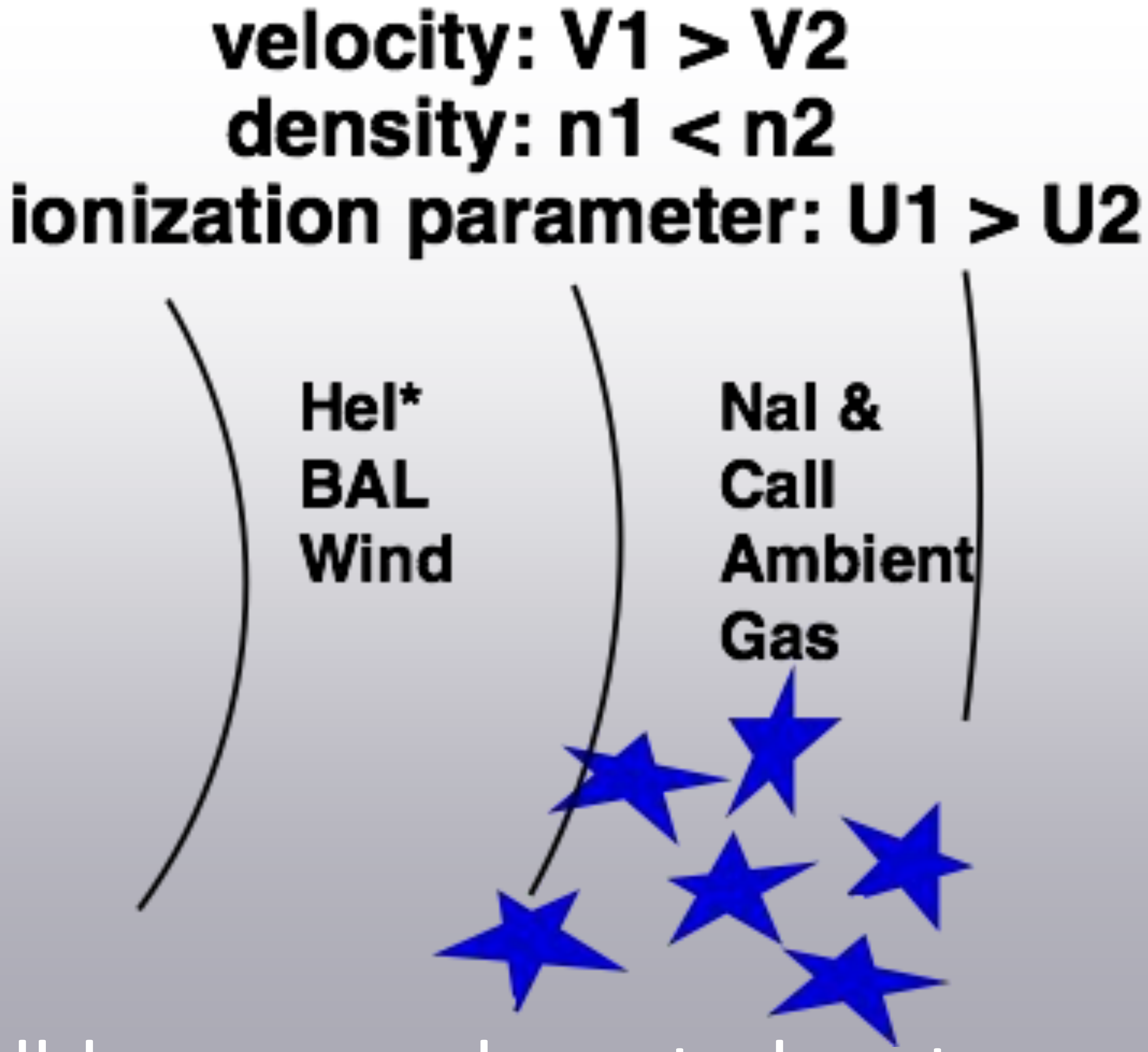
- HeI* absorbing BAL wind impacts upon and accelerates dusty ambient gas.

Cloudy Models



- + mark locations where predicted column densities are consistent with measurements and limits.
- ~100 parsecs from central engine - nuclear starburst

Source of Ambient Gas?



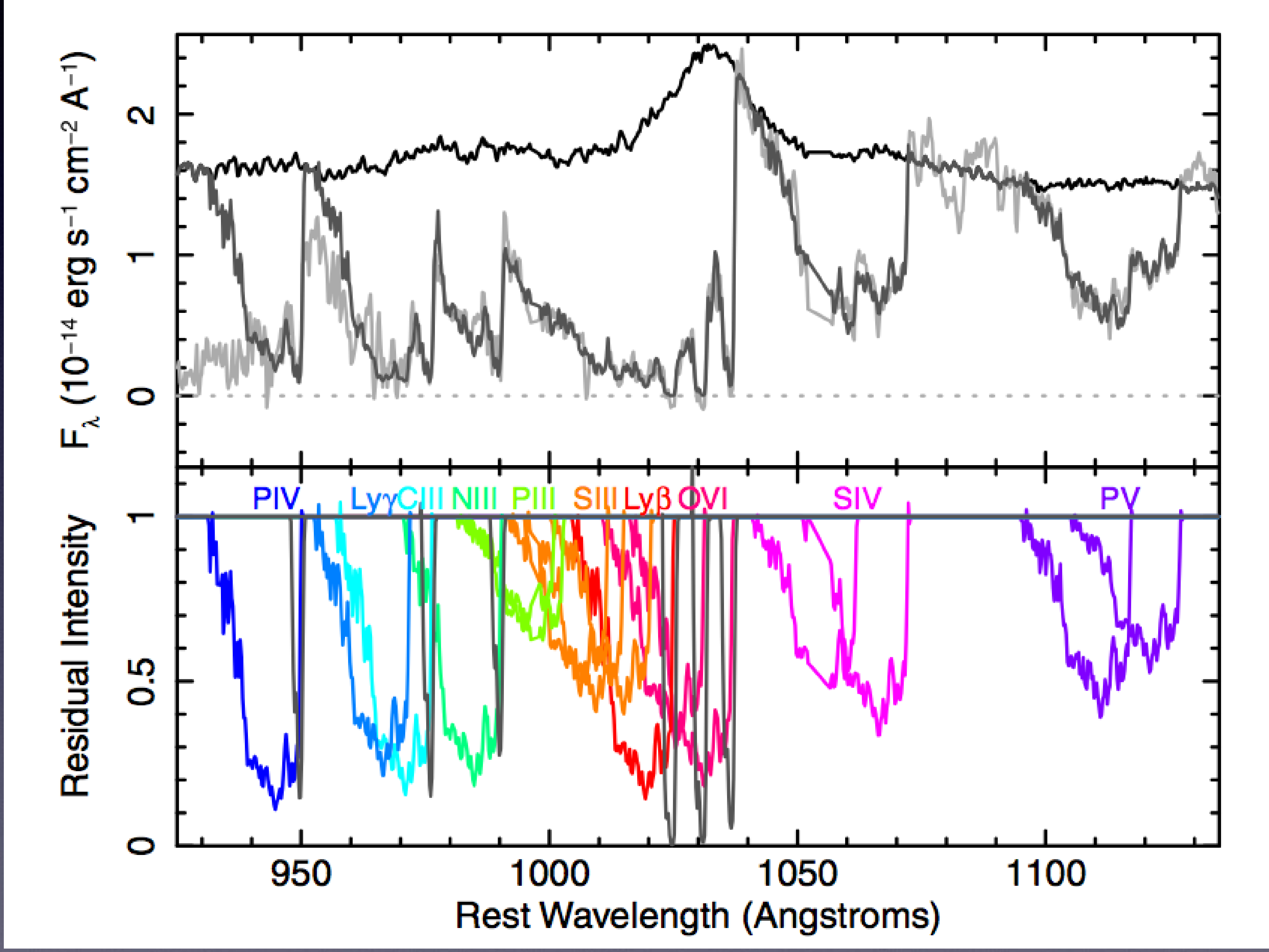
- Mrk 231 has a well-known nuclear starburst ~150-200pc and 10-100 Myr (Davies et al. 2004)

Feedback in Action?

- The interaction of the BAL wind with the stellar effluvia in Mrk 231 may be an example of feedback in action.
- The problem is that at the densities inferred, assuming an $\Omega=0.2$ global covering fraction, an enormous [OIII] emission line is predicted.
- Such an emission line is not seen.
- This is a generic problem for outflows with low densities ($\sim 10^4$ cm^{-3}).

WPVS 007

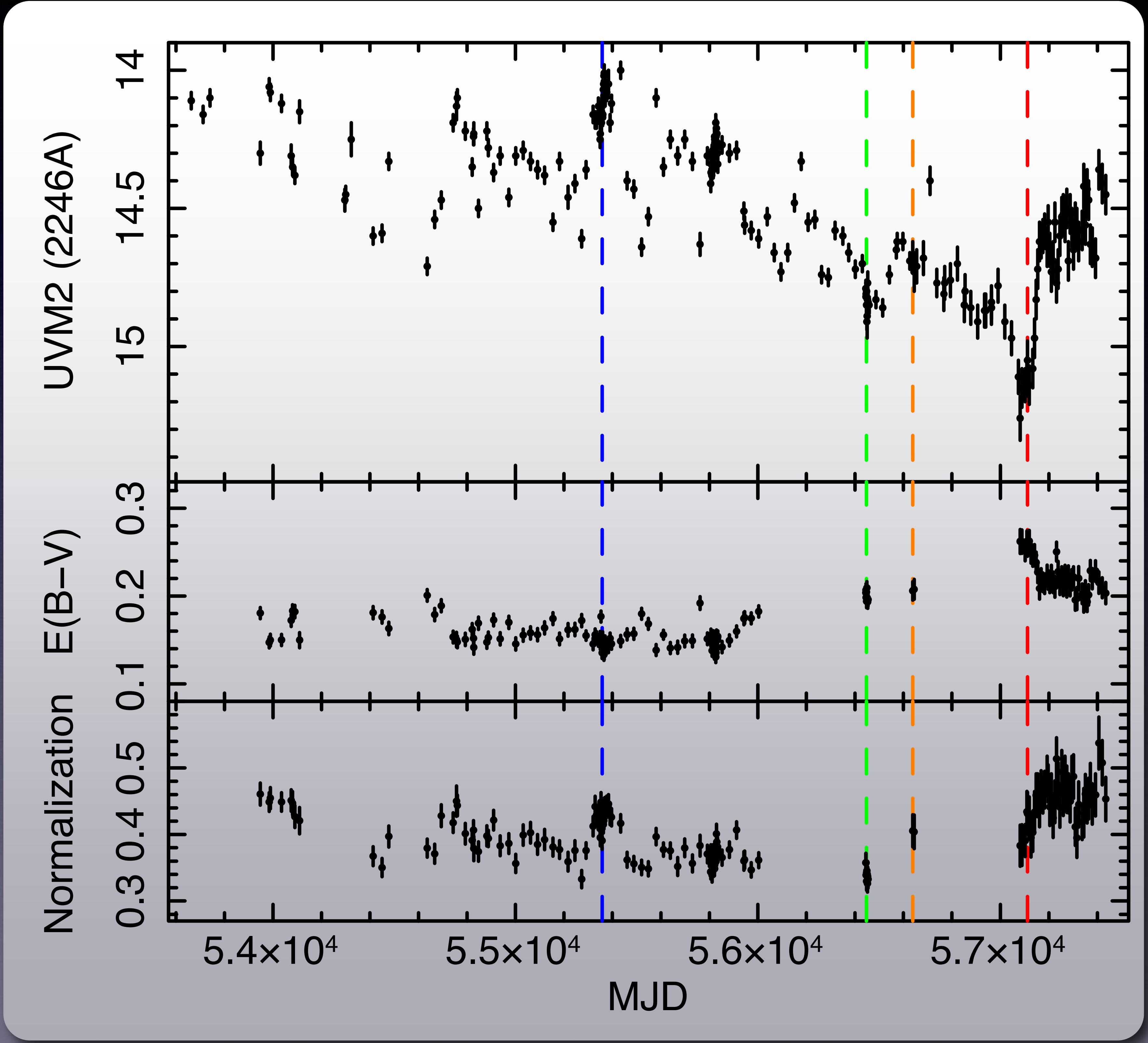
- The FUSE spectrum of WPVS 007 includes SIV 1063 and SIV*1073.
- We use the ratio to estimate the density and the distance to the central engine.



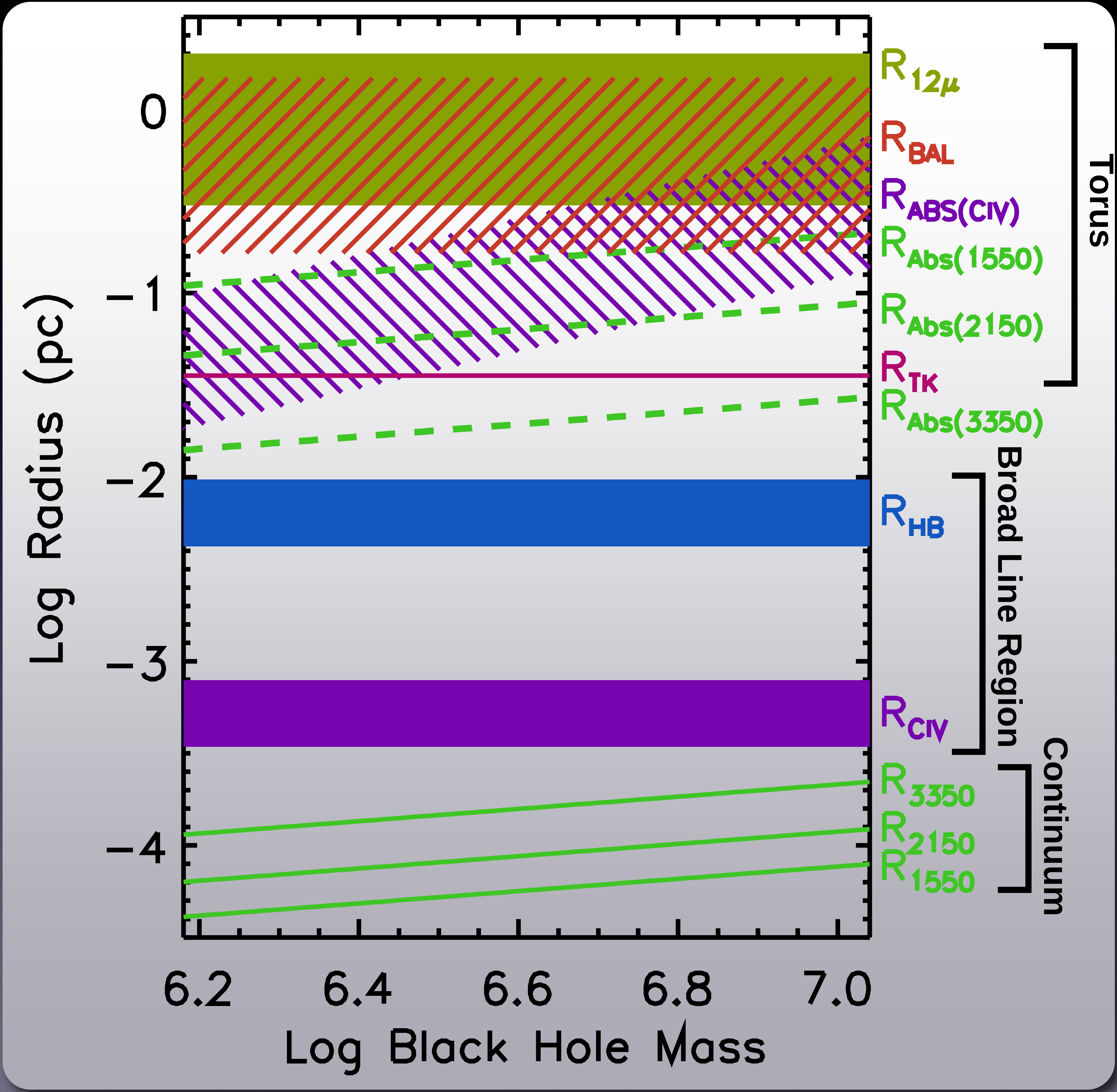
Leighly et al. 2009

Occultation

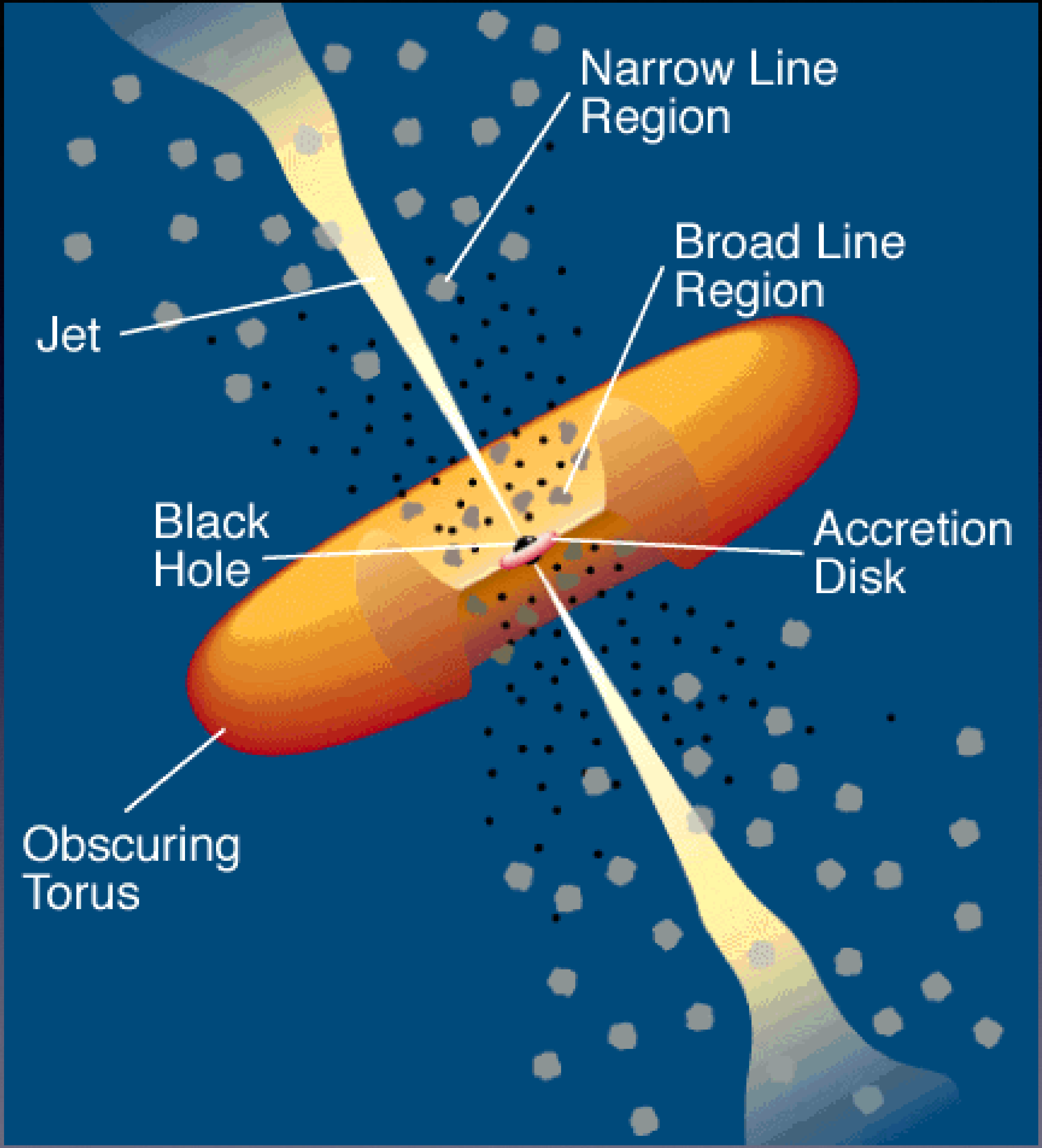
- We have been monitoring WPVS 007 for > 10 years using Swift.
- In late 2014 / early 2015, we observed an occultation.
- Assuming Keplerian velocity, we obtained the distance of the occultor.



We found that the broad absorption line gas, *and* the occultor were located the same distance.

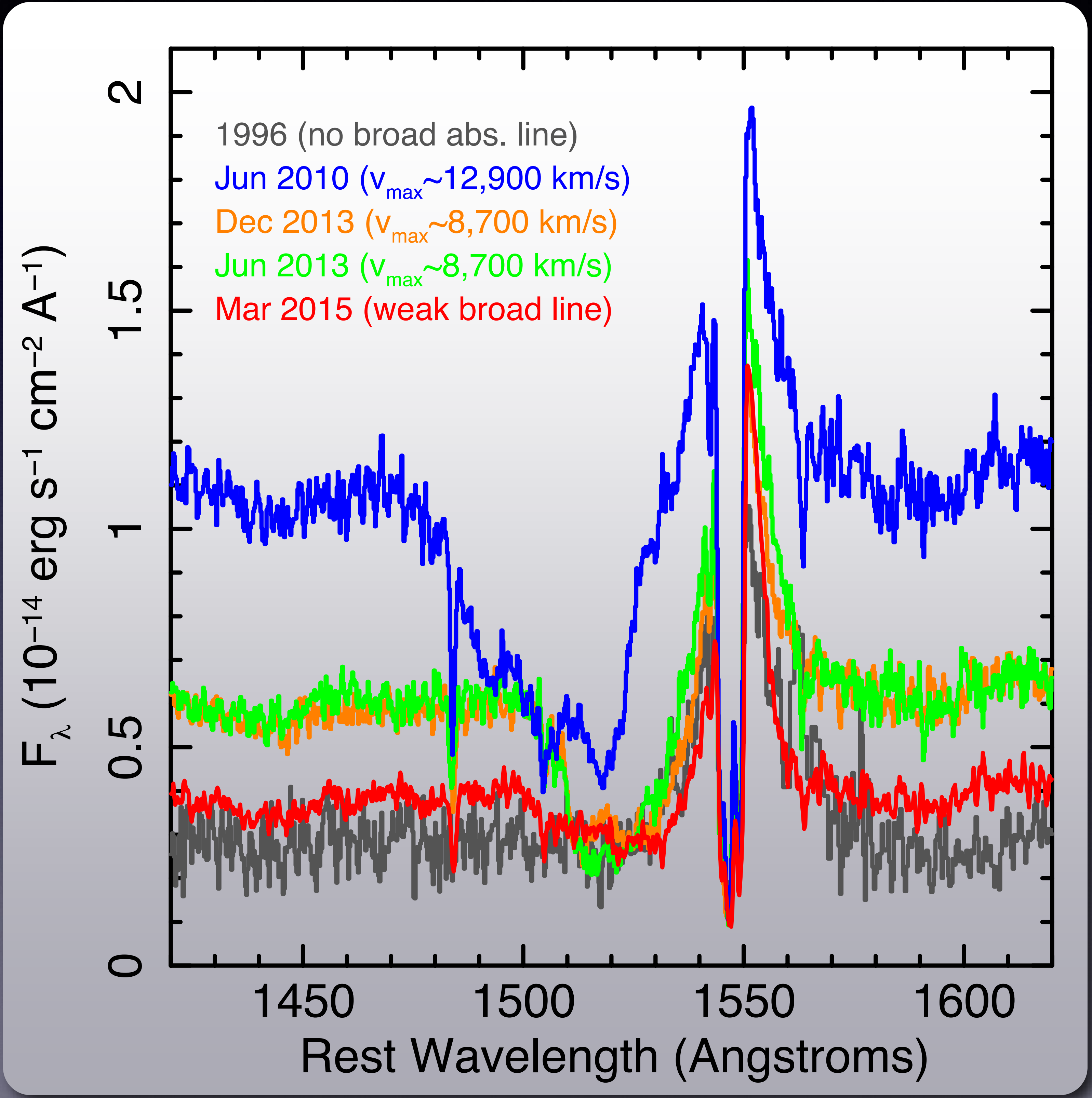


We find that both are consistent with the torus.

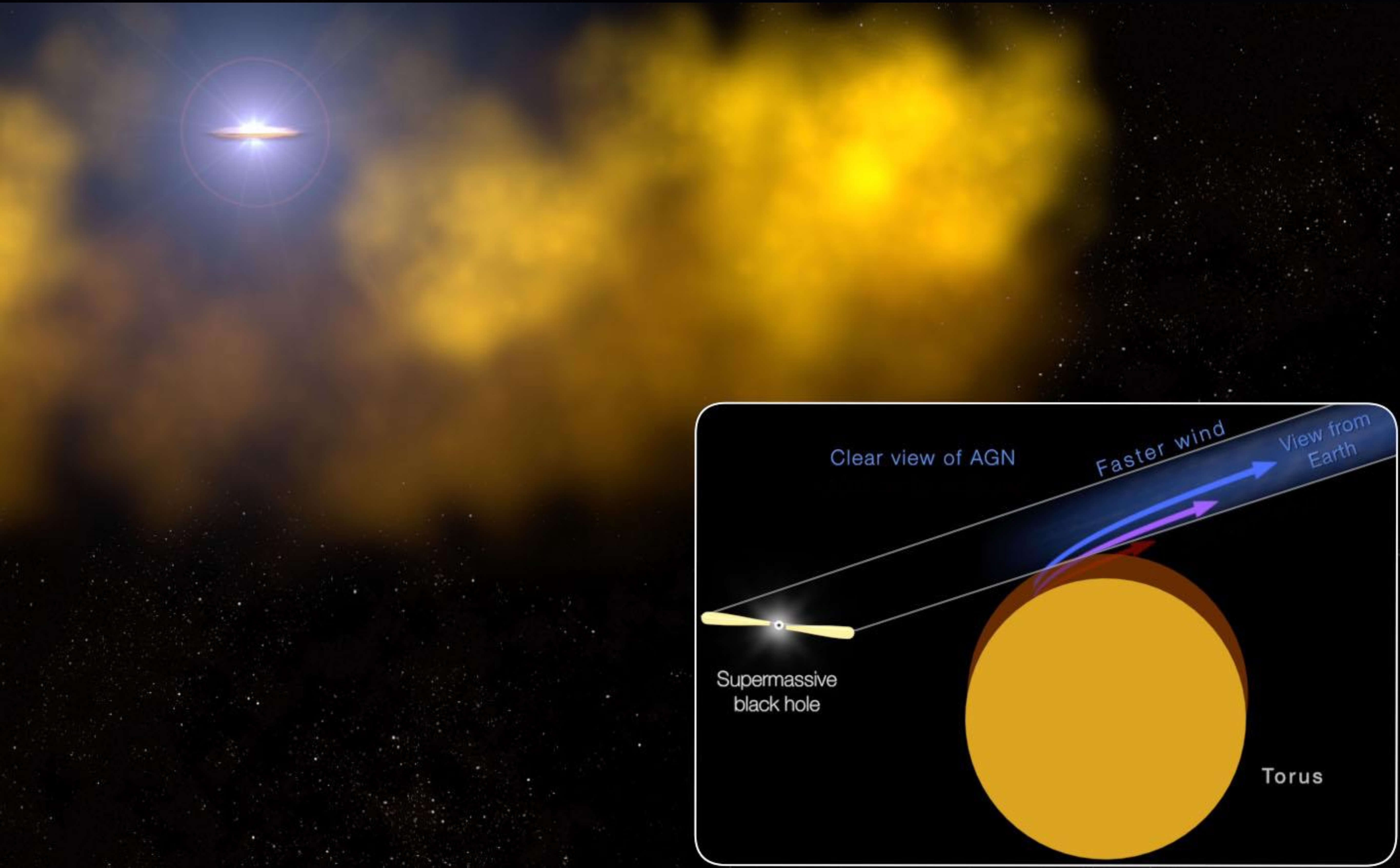


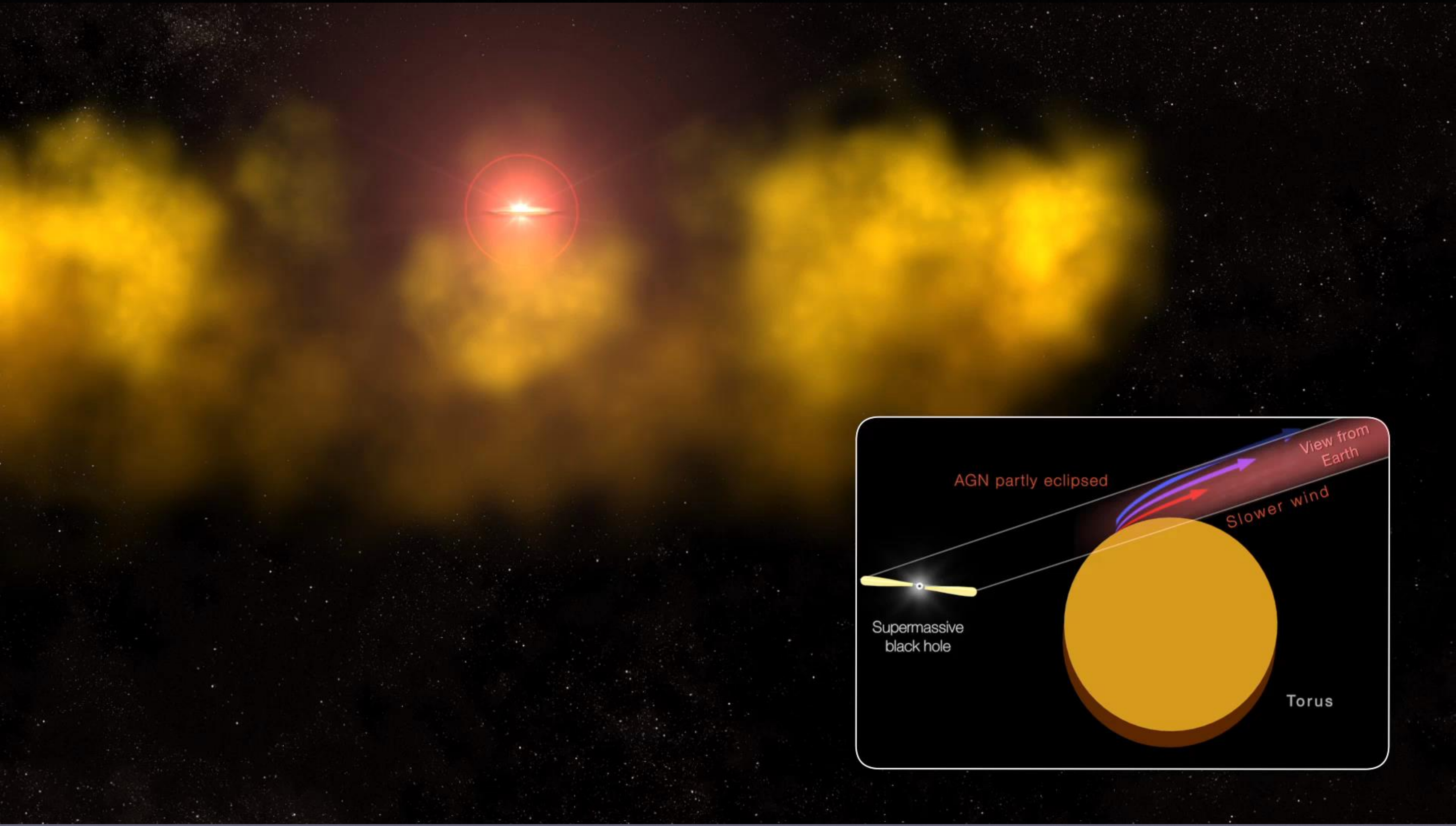
Velocity Variability

The *highest* velocity is observed when the object is the *least* reddened.



Clumpy Torus Model





AGN partly eclipsed
View from Earth
Slower wind
Supermassive black hole
Torus

Summary

Understanding AGN emission and absorption lines using photoionization diagnostics.

- ★ Spectral Energy Distribution
- ★ Column Density
- ★ Density