How far away from their black holes are quasar outflows located?

Dunn et al. 2010 (ApJ 709, 611)

Arav et al. 2008 (ApJ 681, 954)

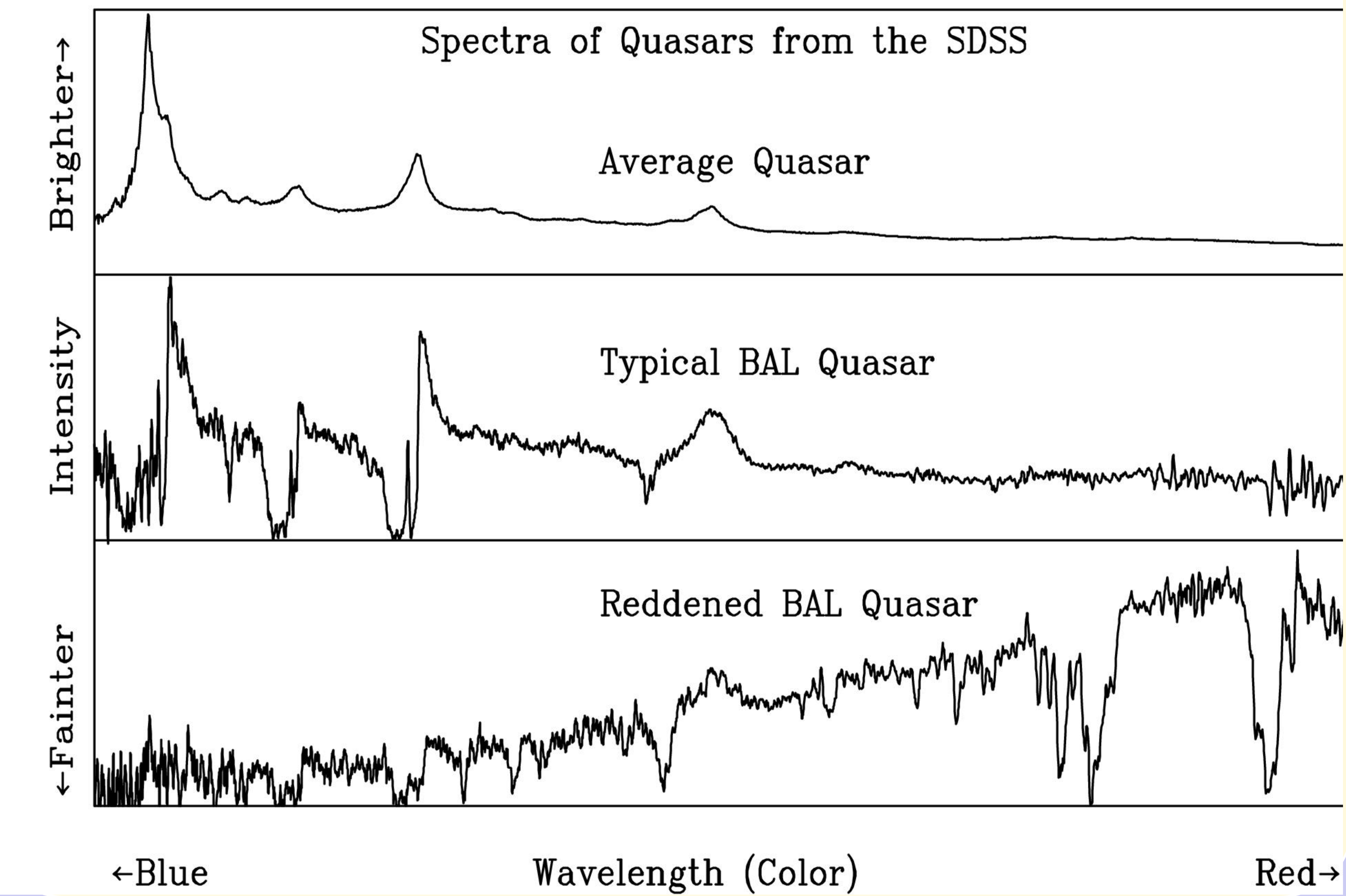
[Korista+ 2008, Moe+ 2009, Bautista+ 2010]

[Chajet et al. 2011]

Feedback from Quasar Outflows

- Some 20% of quasars show broad absorption line (BAL) troughs; $f_{BAL} \simeq 0.2$
- Outflow velocities from 0 to 60,000 km/s
- Velocity widths $>$ 1000 km/s (mini-BALs) or $>$2000 km/s
- Most common BAL trough is C IV 1548,1550 doublet (Δv=500 km/s); always blended, almost always saturated
- Less common are Mg II 2798,2803 (770 km/s) and Fe II (many!)
- How important are BAL outflows as feedback mechanisms? Want to know mass-loss rate, kinetic luminosity, momentum flux.

SDSS targets included normal quasars, ‘typical’ BAL quasars...



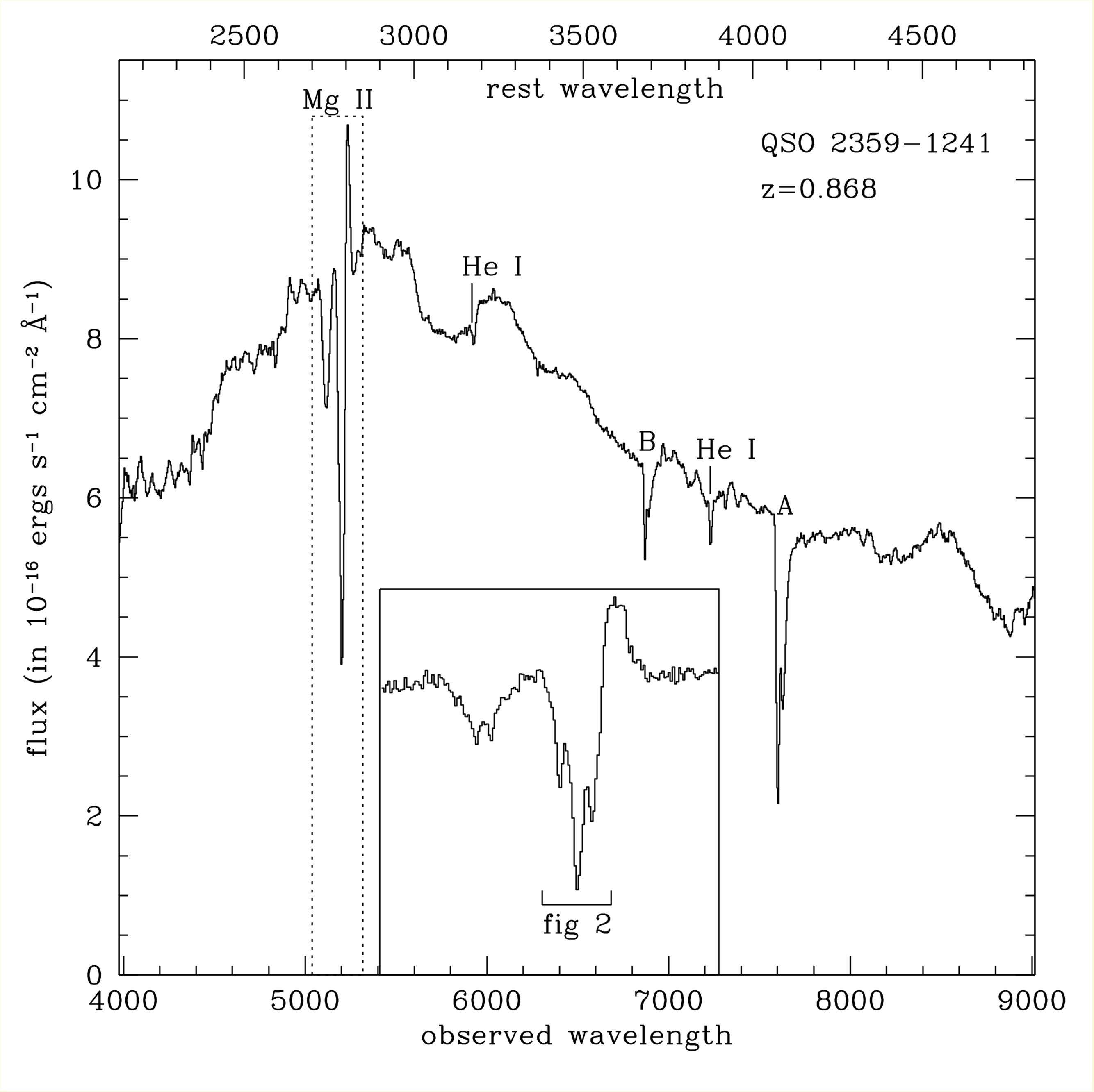
Determining the Mass-Loss Rate

- Assume outflow has mass m in thin shell at radius R which covers fractional solid angle Ω as seen from the quasar. Then
  $m = 4\pi R^2 \Omega \mu m_p N_H$
  where μm_p is the mean mass per particle and $N_H = \int n_H \, dR$ is the total hydrogen column density along our sightline.
- Spectra give us the outflow's velocity v along our sightline.
- Minimum avg. mass loss rate: assume mass m ejected time $t = R/v$ ago into fixed Ω. Then (assuming one trough only)
  $\dot{M}_{min} = m/t = 4\pi \mu m_p R \Omega N_H v$
- Measure N_{ion}; need N_H and R to get $\dot{M}_{min}$.
- Can constrain $\Omega \leq f_{BAL}$ (due to obscuration).

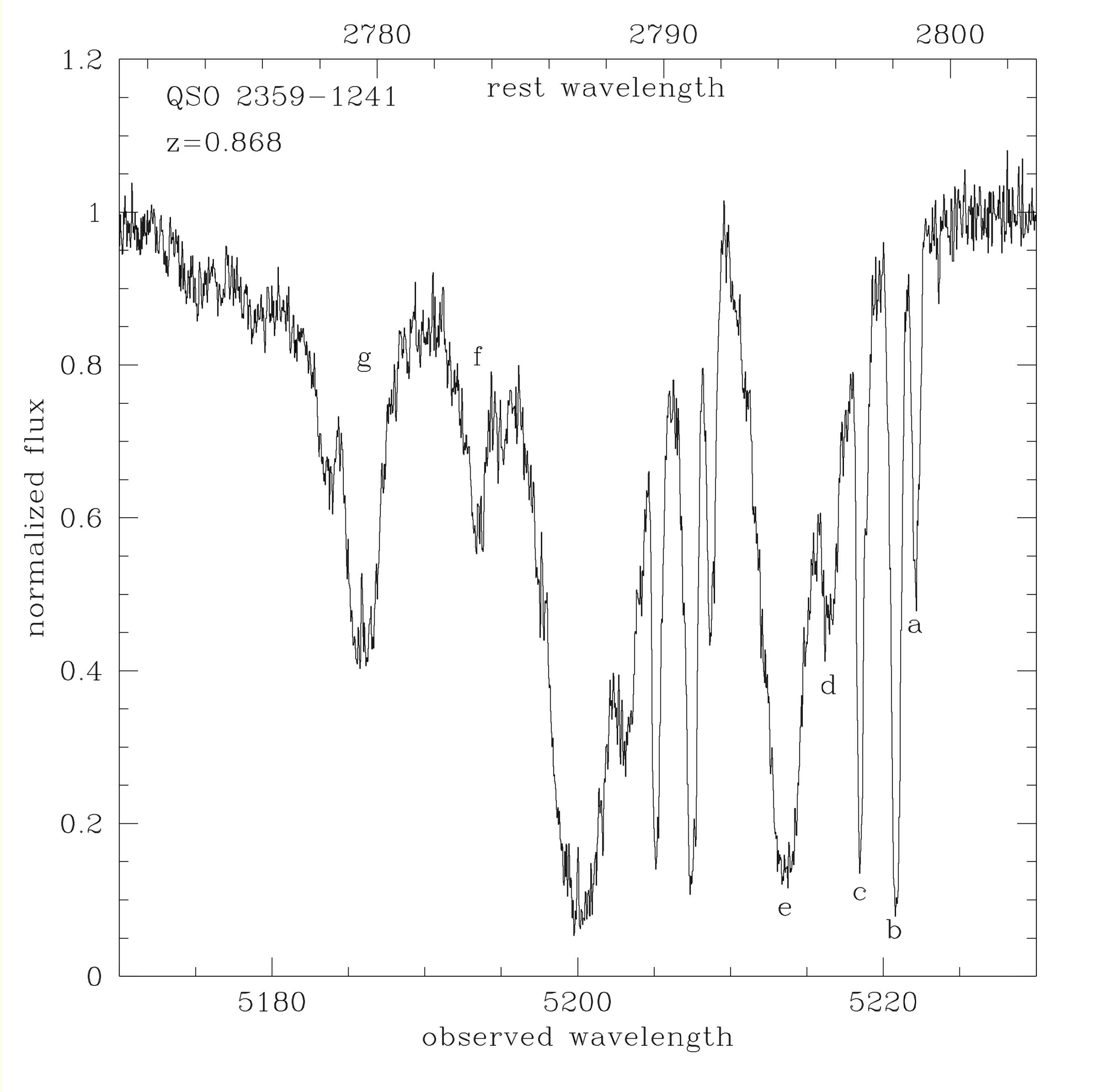
Determining the Kinetic Luminosity

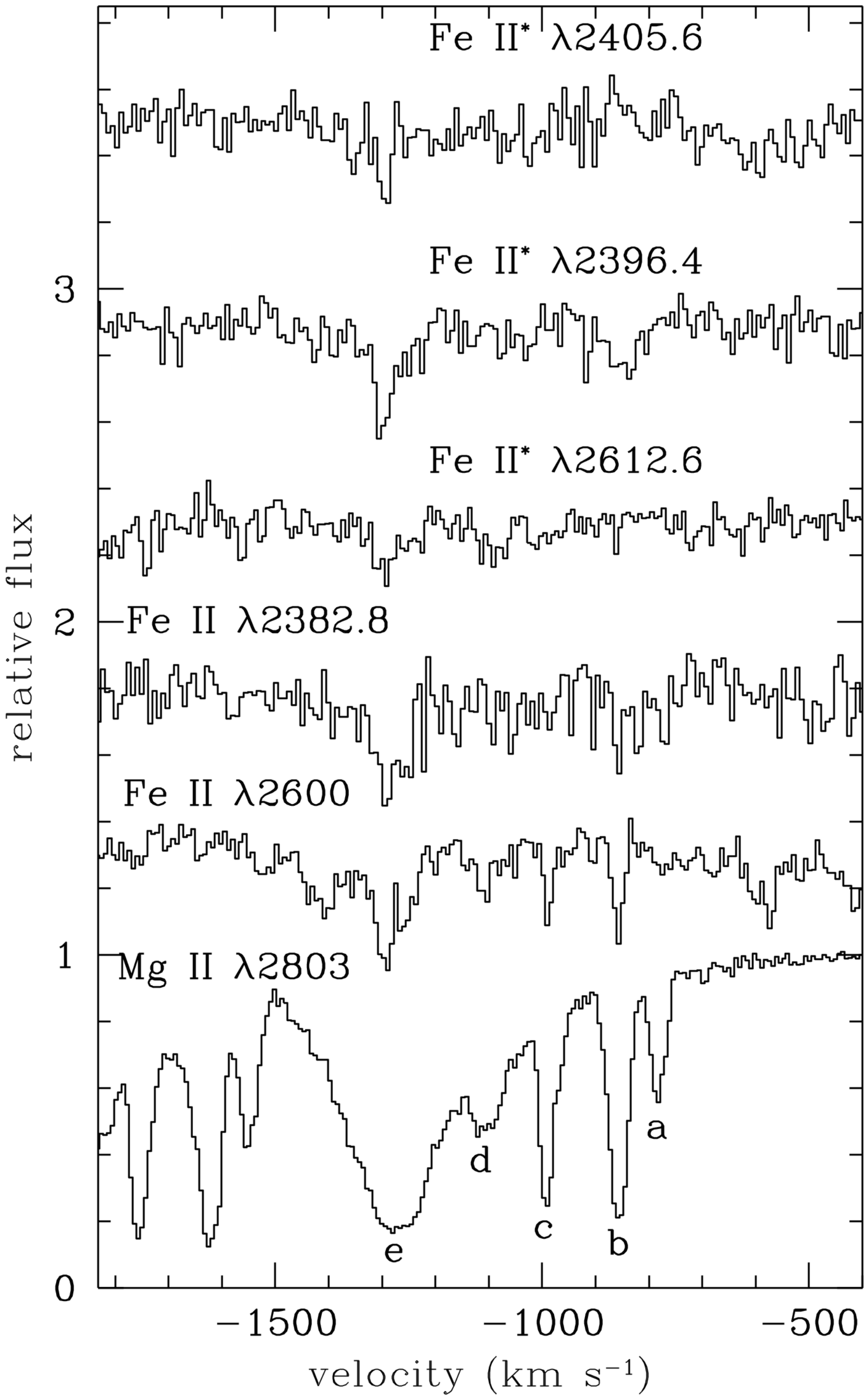
- To find N_H and R, first find $n_e \simeq n_H$ using collisionally excited to ground state population ratios of C II, Si II, Fe II, Ni II...
- Next, model the ionization structure of a constant-density slab with ionization parameter U_H at its face:
  $U_H = Q_H / 4\pi R^2 c n_H$
  where Q_H is the # of H-ionizing photons s^{-1} from the quasar:
  $Q_H = \int_{1\,Ry}^{\infty} \frac{L_\nu}{h\nu}\, d\nu$
- Find value of U_H and column density N_H at which predicted column densities of observed ions best match observations. Need to explore ranges of plausible L_ν and metallicity to find best fit and uncertainties for N_H and R.
- Kinetic Luminosity is $\dot{E}_k = \frac{1}{2}\dot{m}v^2 = 2\pi\mu m_p \Omega R N_H v^3$

Low-resolution spectrum of Arav et al. 2008 quasar

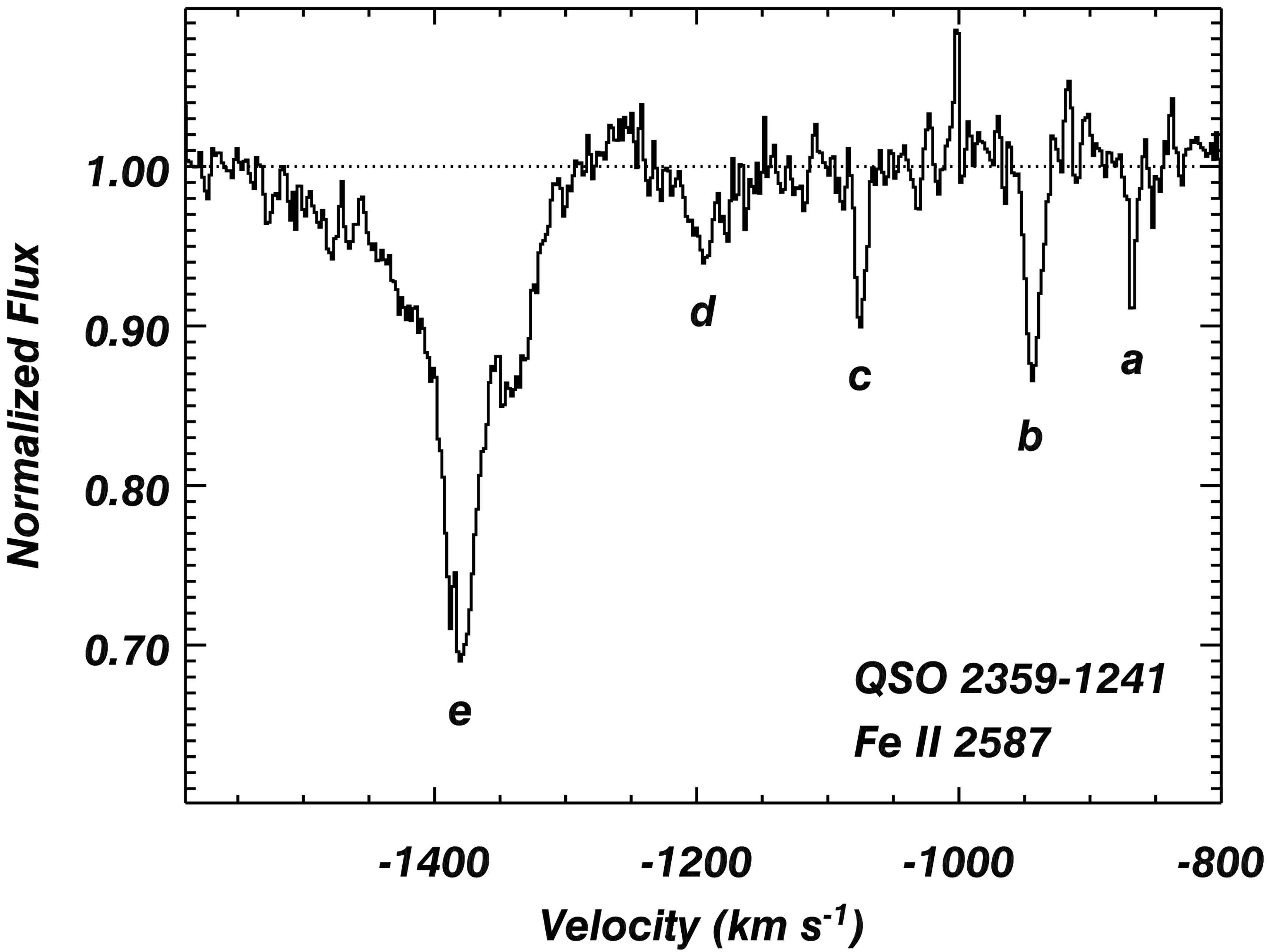


High-resolution spectrum of Mg II region




Fe II* λ2405.6
Fe II* λ2396.4
Fe II* λ2612.6
Fe II λ2382.8
Fe II λ2600
Mg II λ2803
a
b
c
d
e
relative flux
0
1
2
3
−1500
−1000
−500
velocity (km s⁻¹)

One Fe II transition (2010 data)



From observed residual intensities to physical parameters:

- **Imagine an absorber of optical depth τ in some transition in front of a background source with intensity I_λ^{src}.**
- **Complete covering: $I_\lambda^{out} = I_\lambda^{src} e^{-\tau}$ or $I_\lambda \equiv I_\lambda^{out} / I_\lambda^{src} = e^{-\tau}$.**

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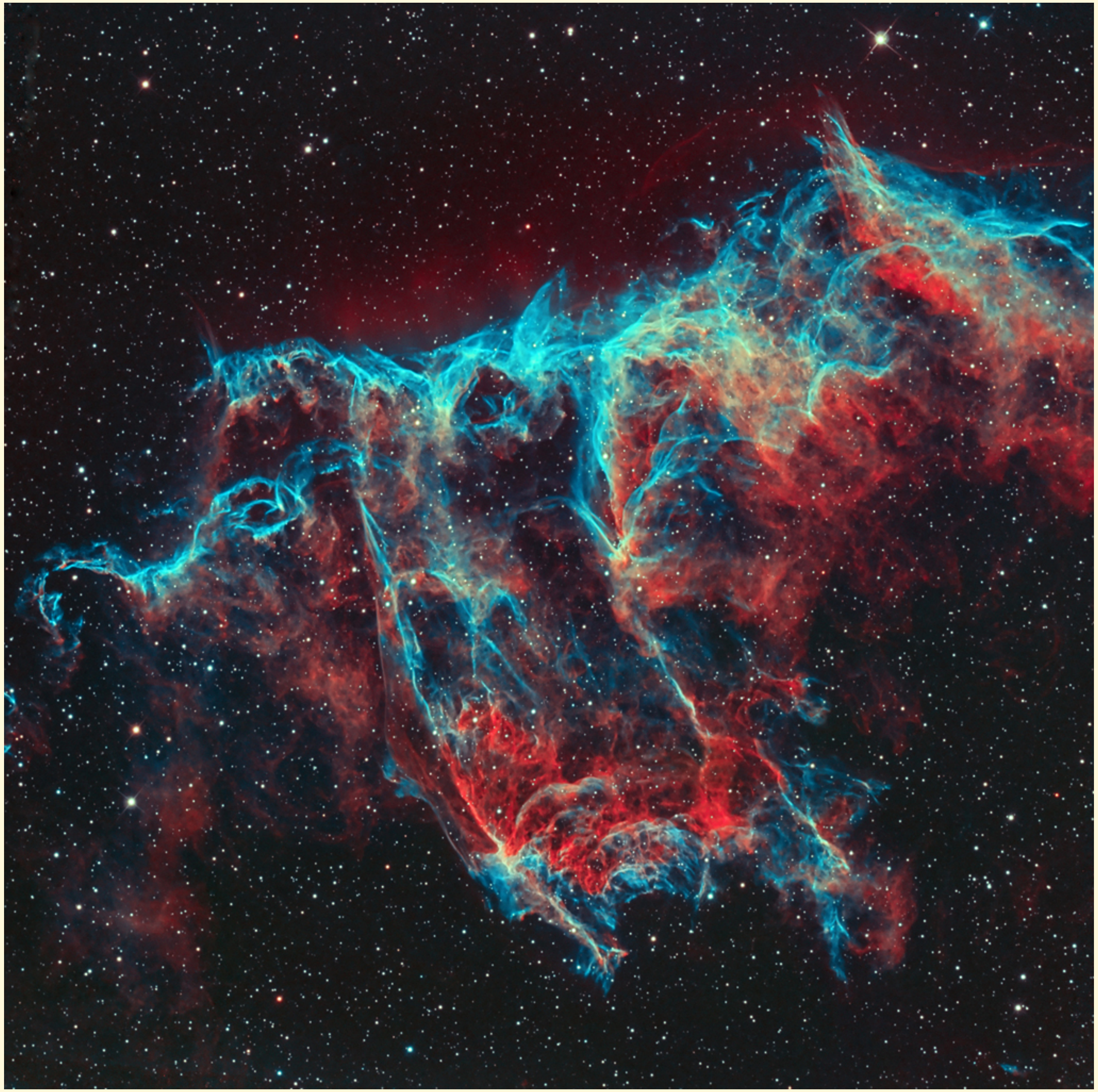
- For doublets, 2 equations & 2 unknowns $[C(v), \tau(v)]$ at each v: can always get a solution.
- **When $\geq$3 transitions from same ion are available, can check how good an approximation partial covering is.**
- **In many cases, a better approximation is needed.**

How best to approximate complex absorbing structures?



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- **Complete covering:** $I_\lambda^{out} = I_\lambda^{src} e^{-\tau}$ **or** $I_\lambda \equiv I_\lambda^{out} / I_\lambda^{src} = e^{-\tau}$
- **Partial covering:** $I_\lambda(v) = 1 - C(v)[1 - e^{-\tau(v)}]$
- **General inhomogeneous absorber:**

  $e^{-\tau(v)} = \int_x \int_y e^{-\tau(x,y)}\, dx\, dy$

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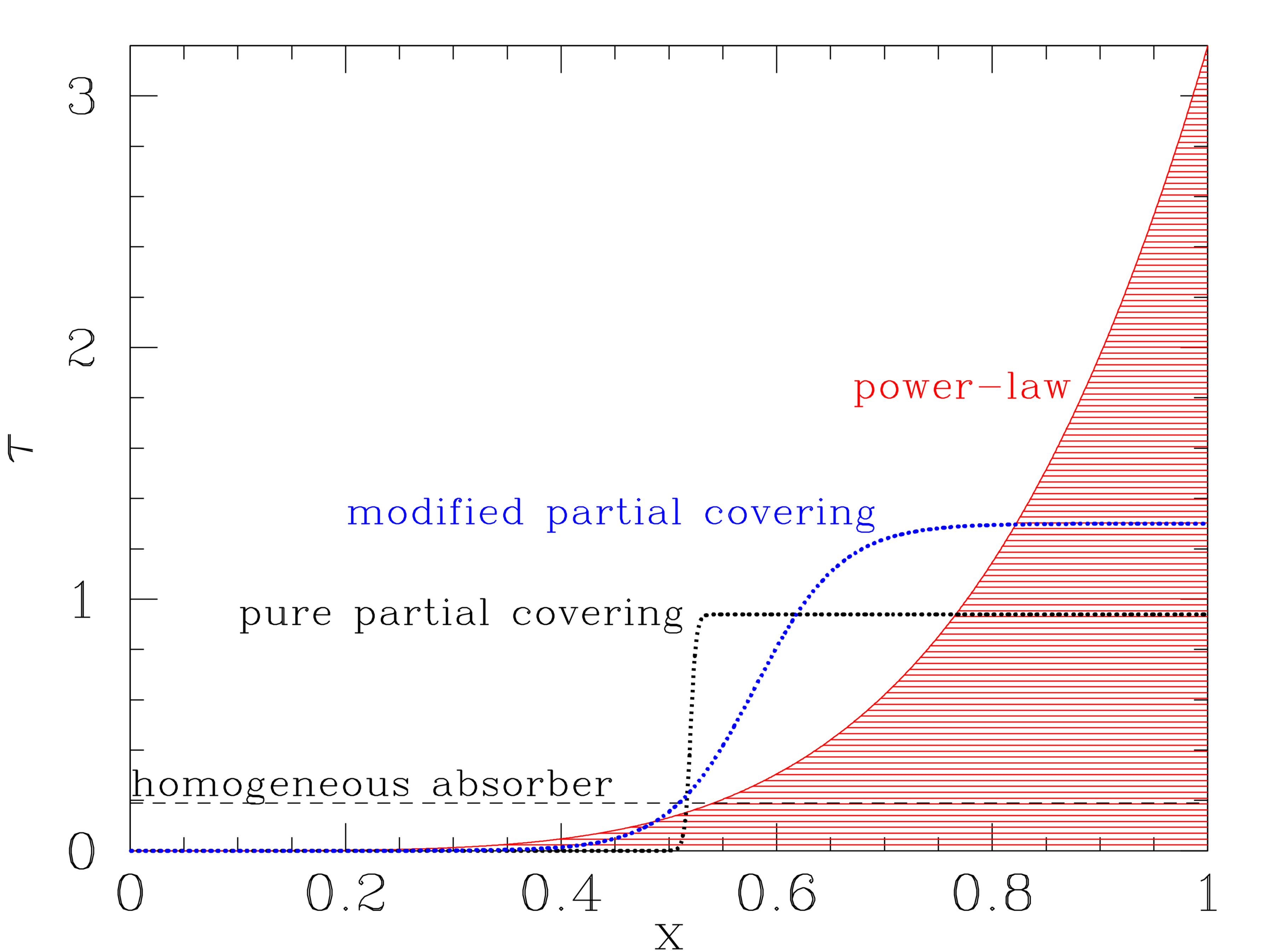
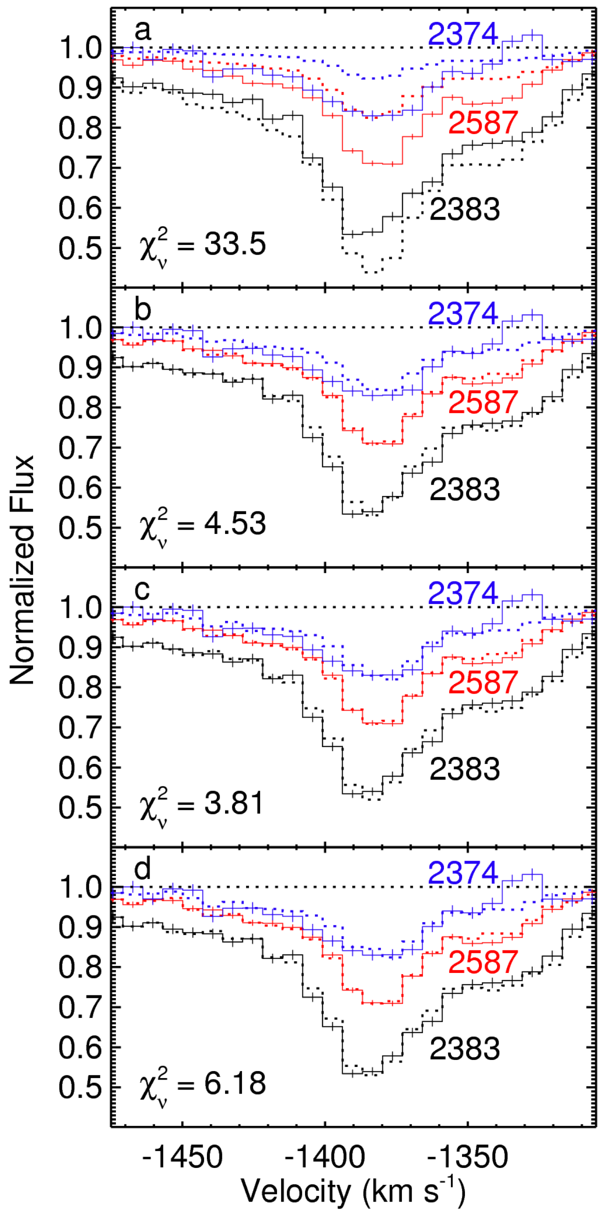
- **Partial covering:** $I_\lambda(v) = 1 - C(v)[1 - e^{-\tau(v)}]$
- **General inhomogeneous absorber: collapse to one dimension, and adopt power-law distribution of optical depths** $\tau(v) = \int_x \tau_{max}\, x^a\, dx$ **:**
  $I_\lambda(v) = \int_x \exp(-\tau_{max}(v)\, x^a)\, dx$
- **Alternatively, modify partial covering by adding 3rd parameter (width of transition from** $\tau = 0$ **to** $\tau = \tau_{max}$**)**

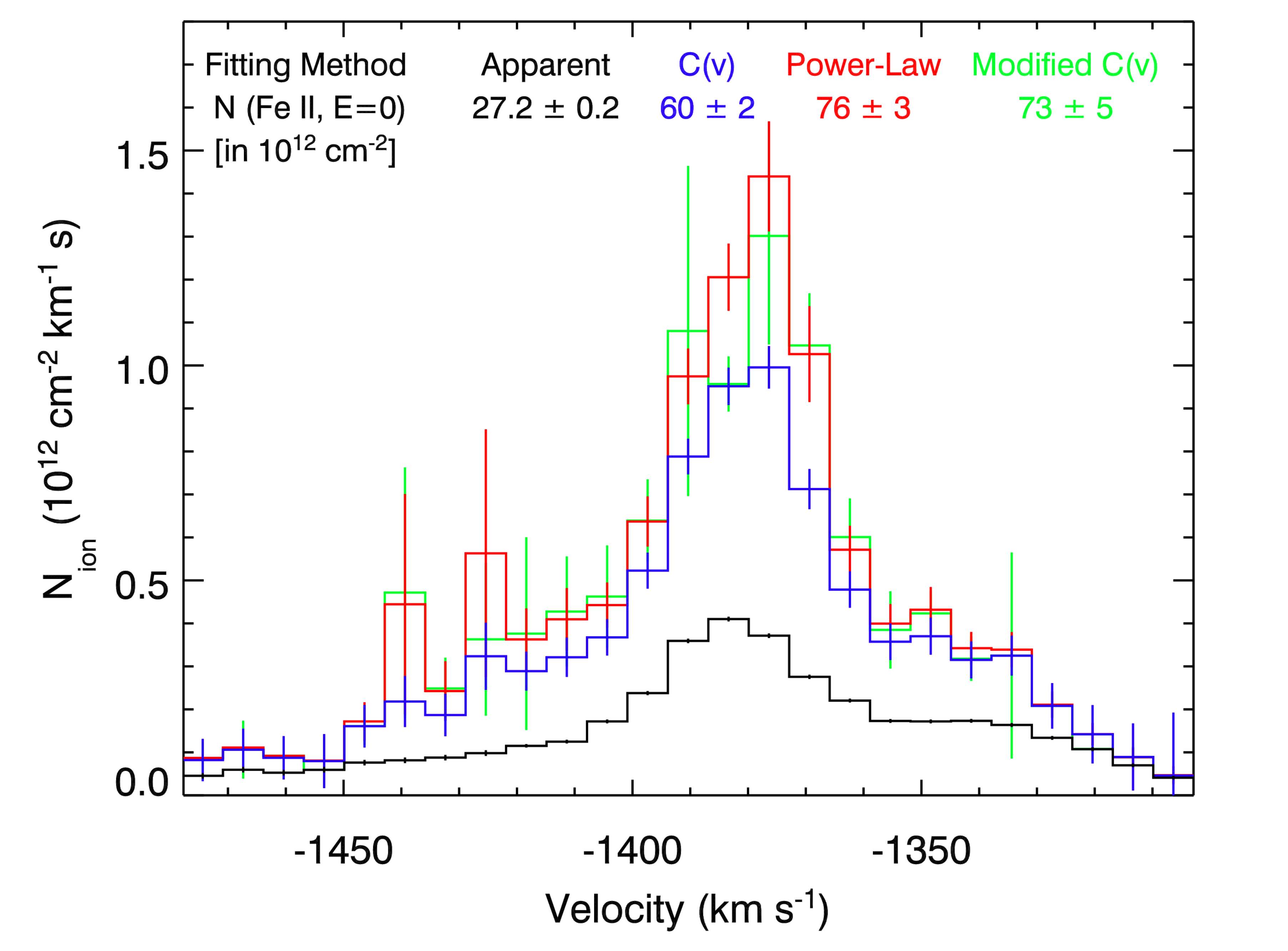
Four ways to column densities



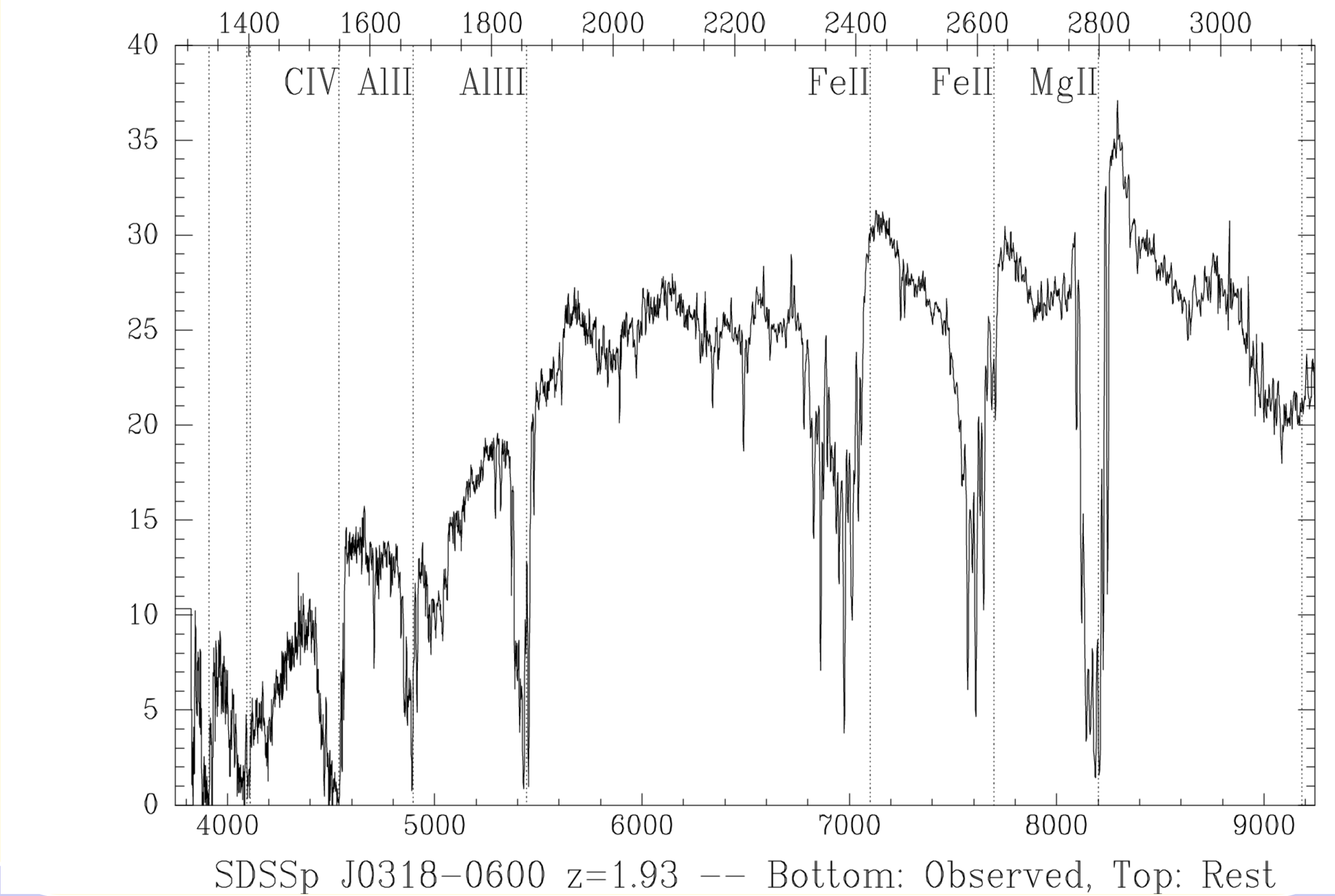
Fitting 3 Fe II lines 4 ways. From top: homogeneous, partial covering, power-law [best fit], modified partial covering.



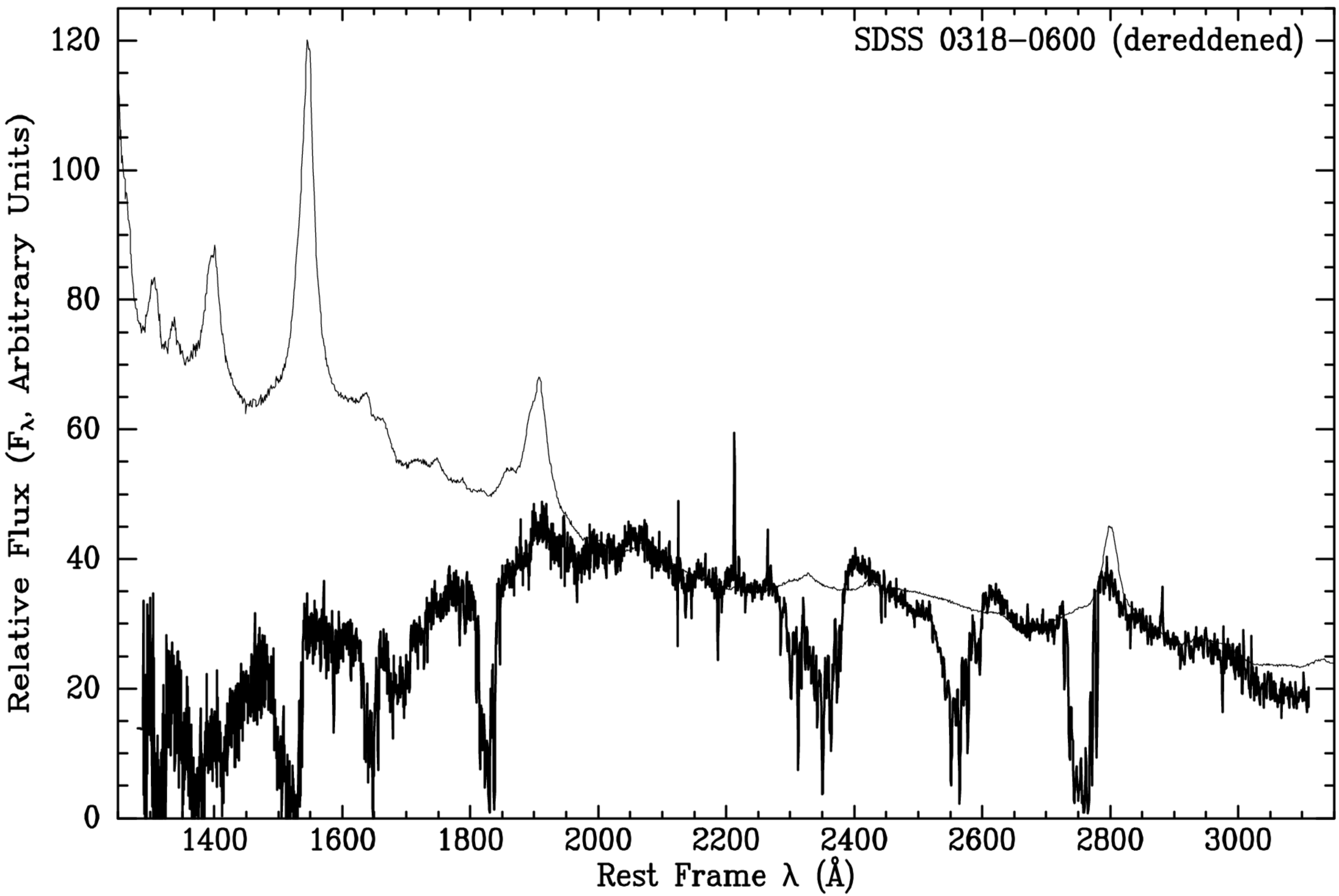
Resulting Fe II column as f(velocity)



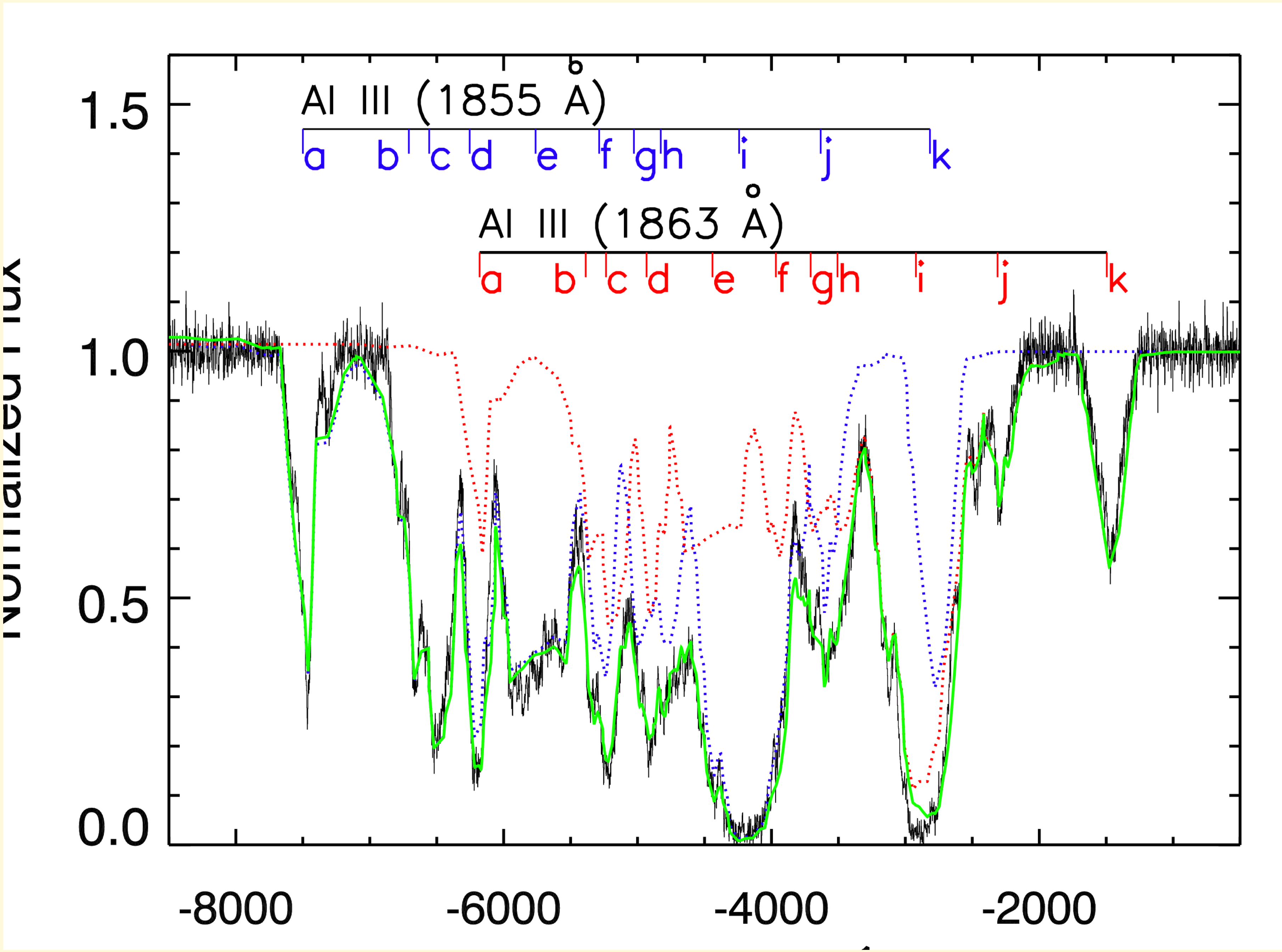
SDSS spectrum of more complex BAL quasar (Dunn et al.)



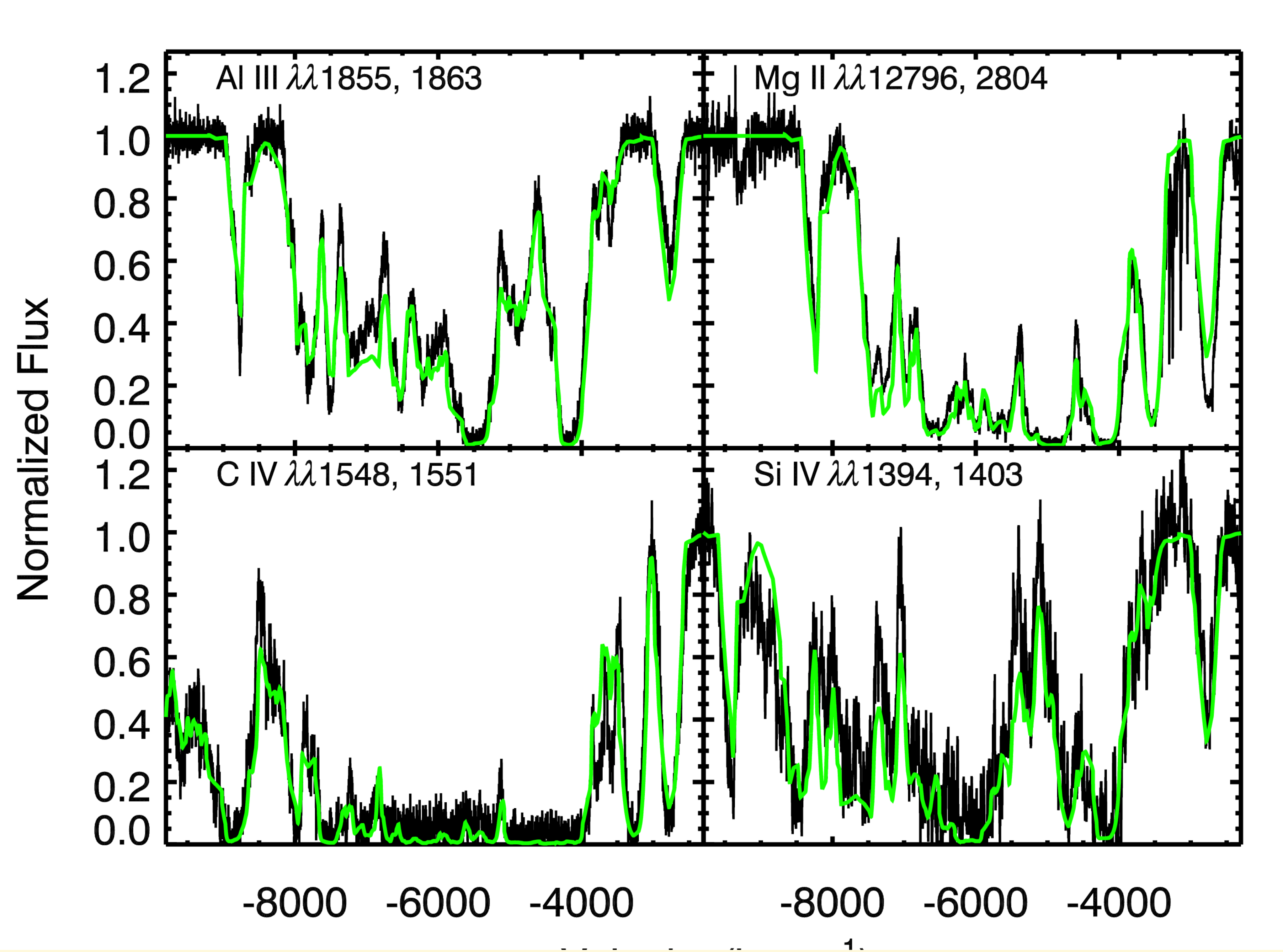
Dereddened by SMC extinction curve



Use Al II singlet as templates for Al III doublet...



...and other lines (green fits to black data)



From N$_{ion}$ to N$_H$

- **Column density measurements N_{ion} are reasonably secure.**
- **Uncertainties: oscillator strengths, continuum placement, coverage of accretion disk vs. broad emission line region.**
- **Relate N_{ion} to N_H through photoionization modeling, for which a range of SEDs must be considered, and the hydrogen particle density n_H is needed as input.**

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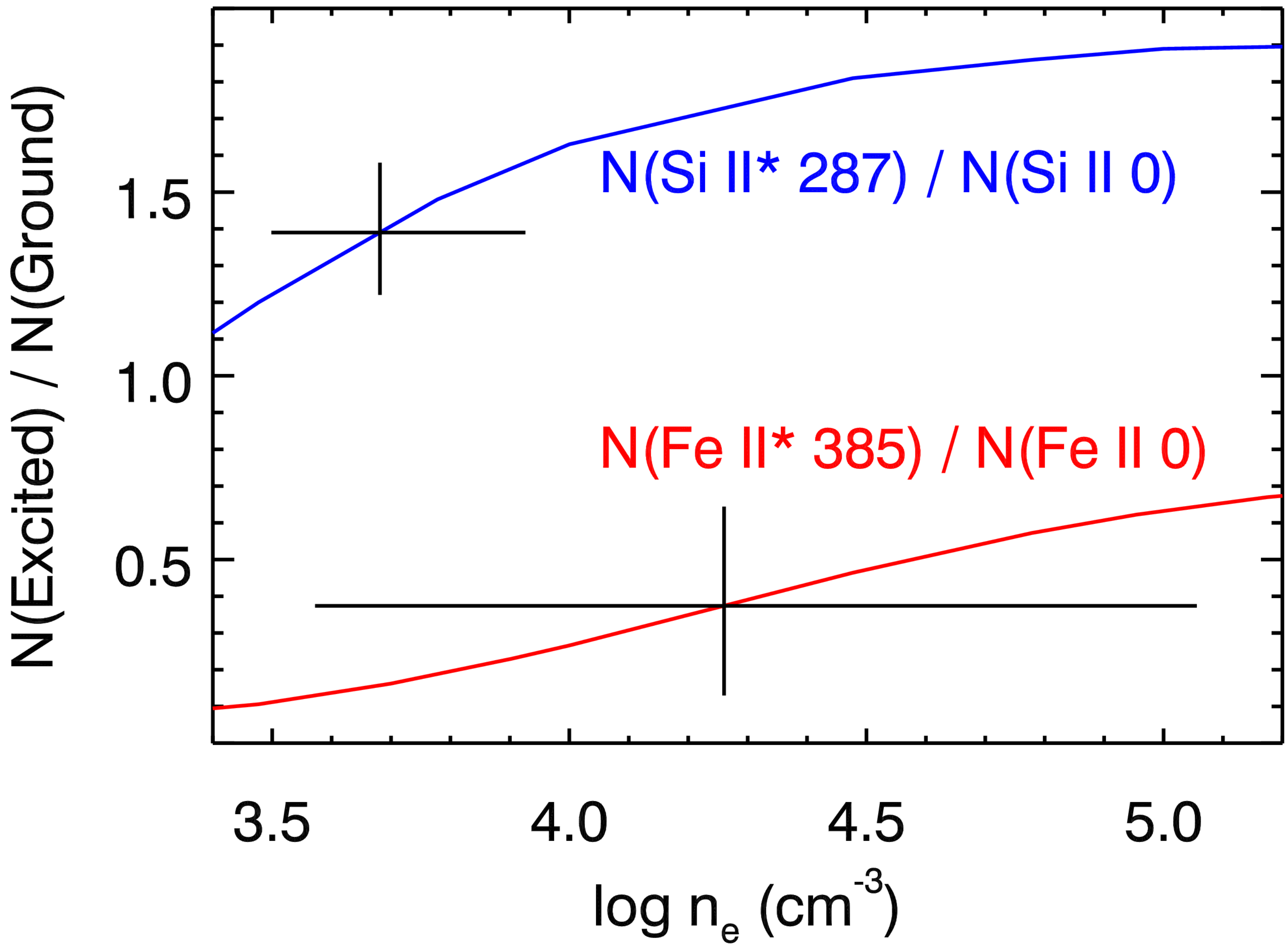
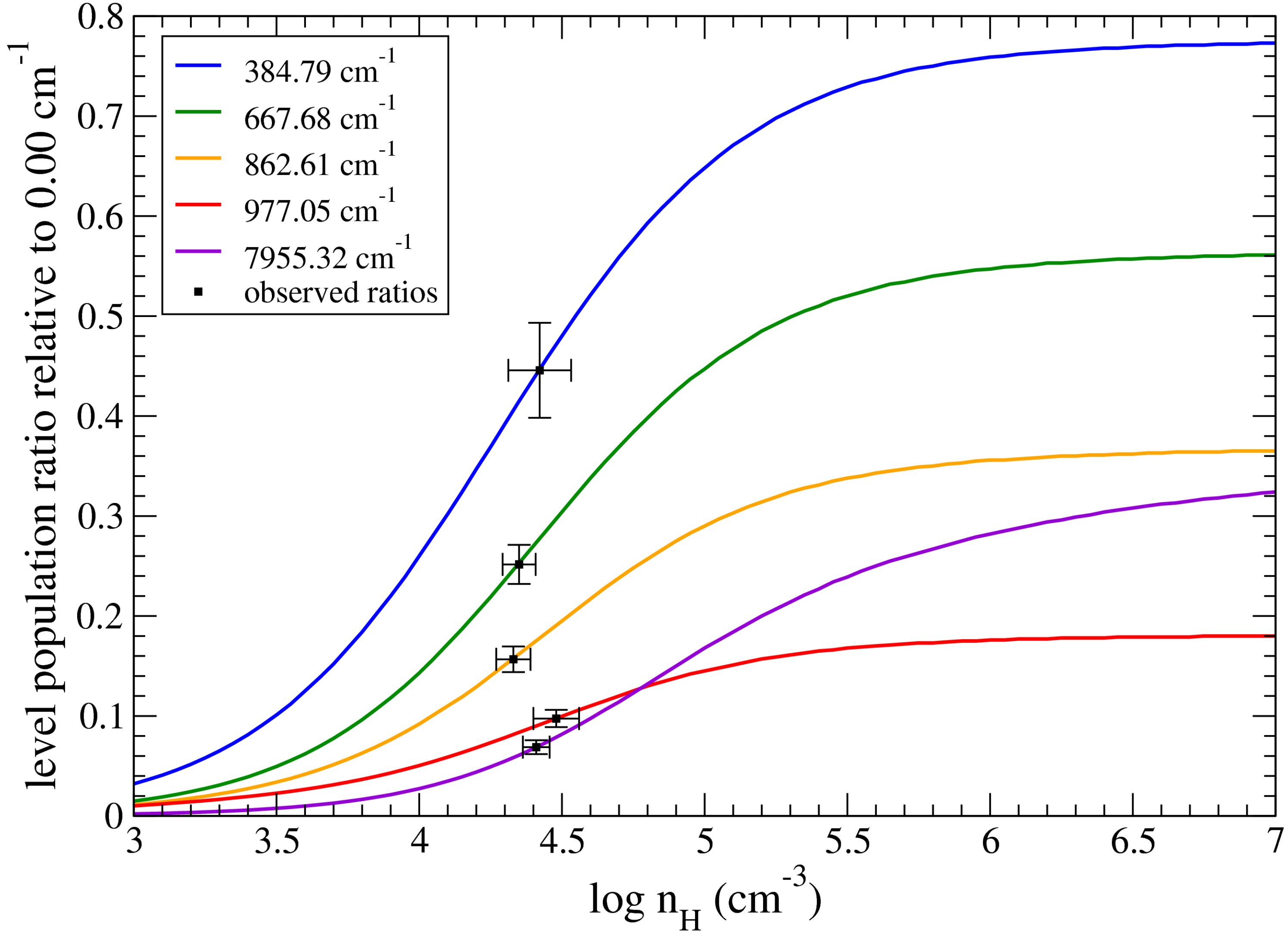
- **Density constrained by looking for absorption from low-lying, metastable excited states (e.g., Fe II*)**
- **The column density ratio of Fe II* to Fe II increases rapidly near the critical n_e for that Fe II* transition.**
- **Secondary dependences on temperature, radiative effects.**

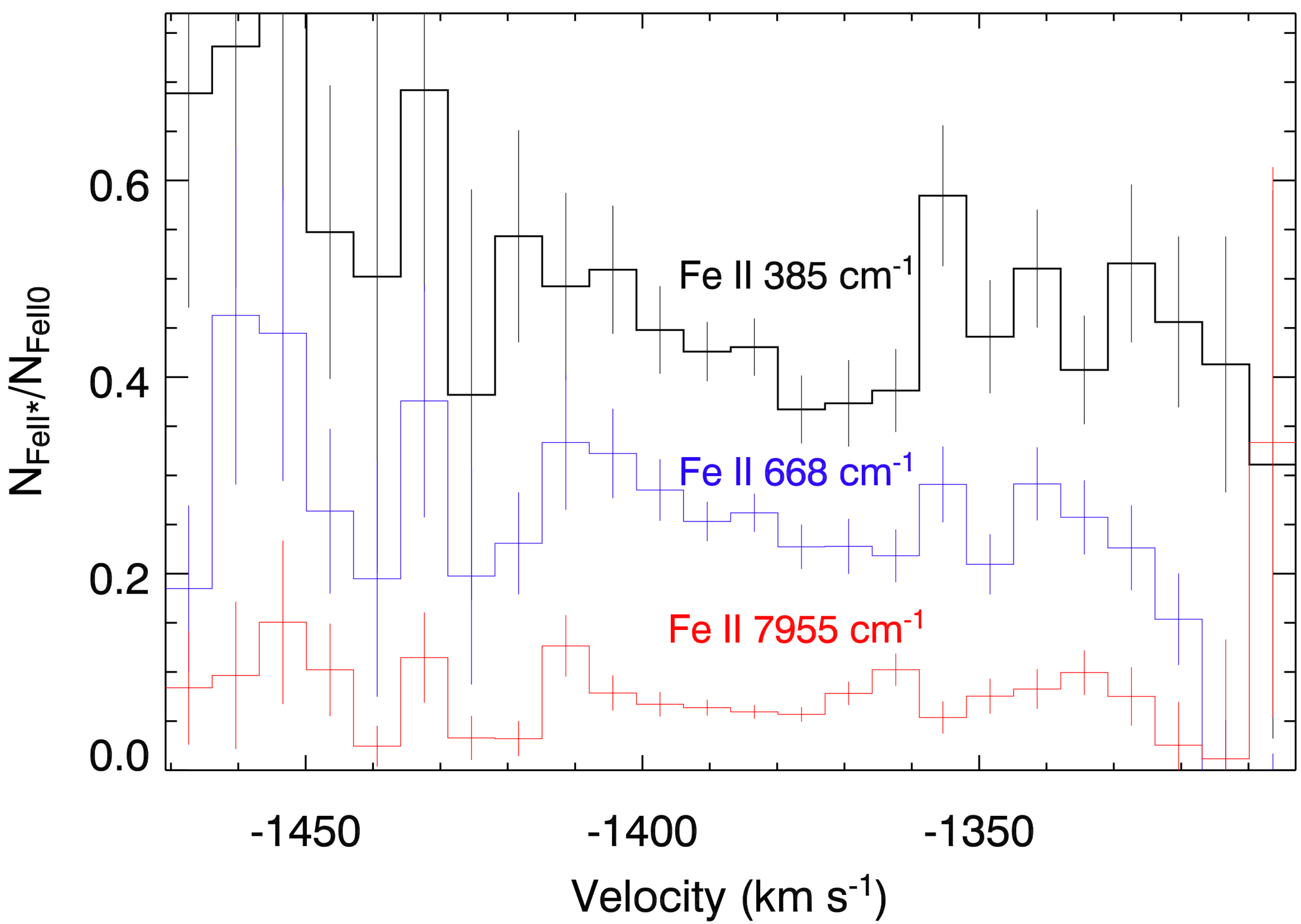
Density example: log n_e=3.75±0.22 (Moe et al.)



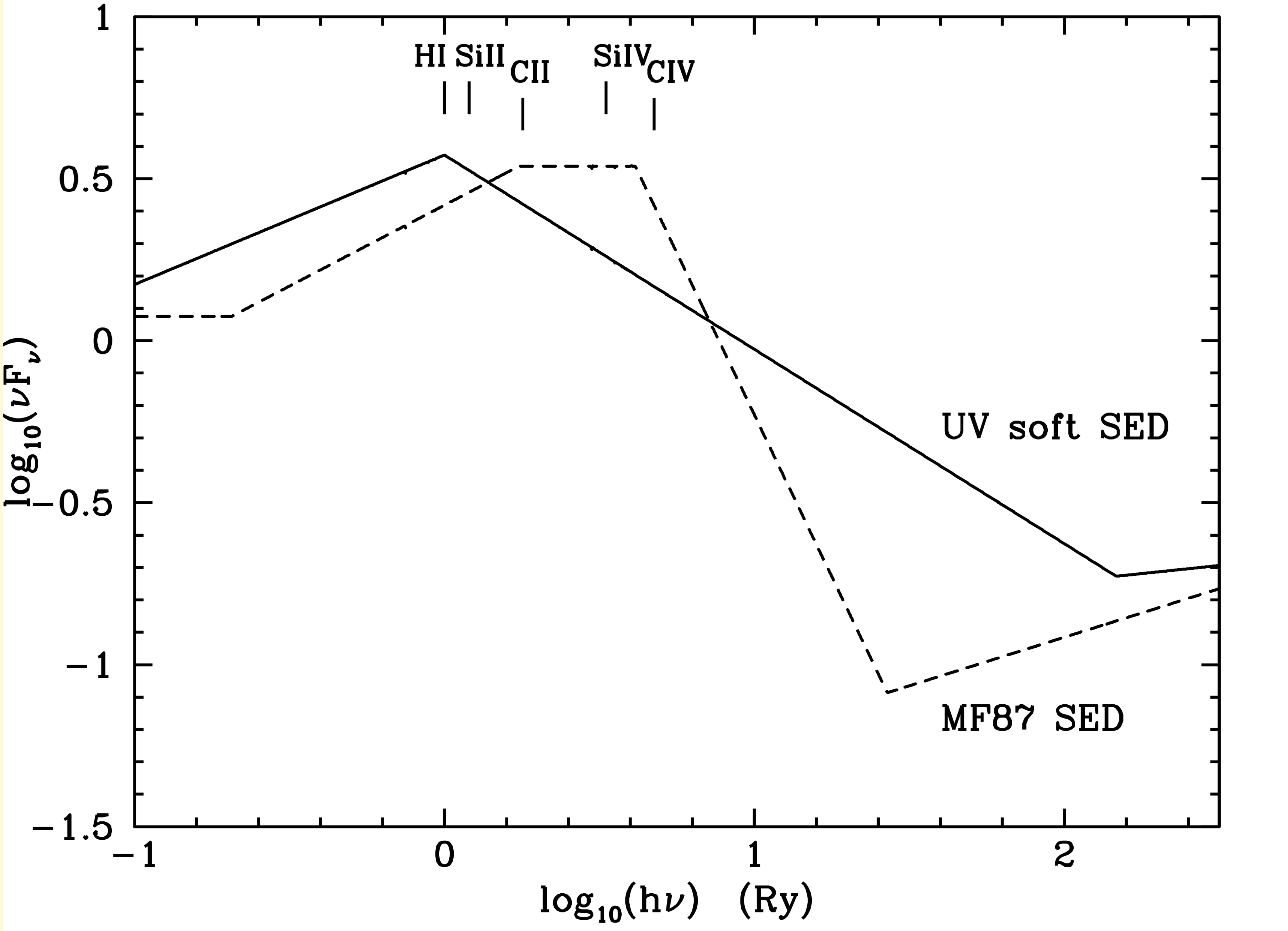
Density example: log n_e=4.4±0.1 (Korista et al.)



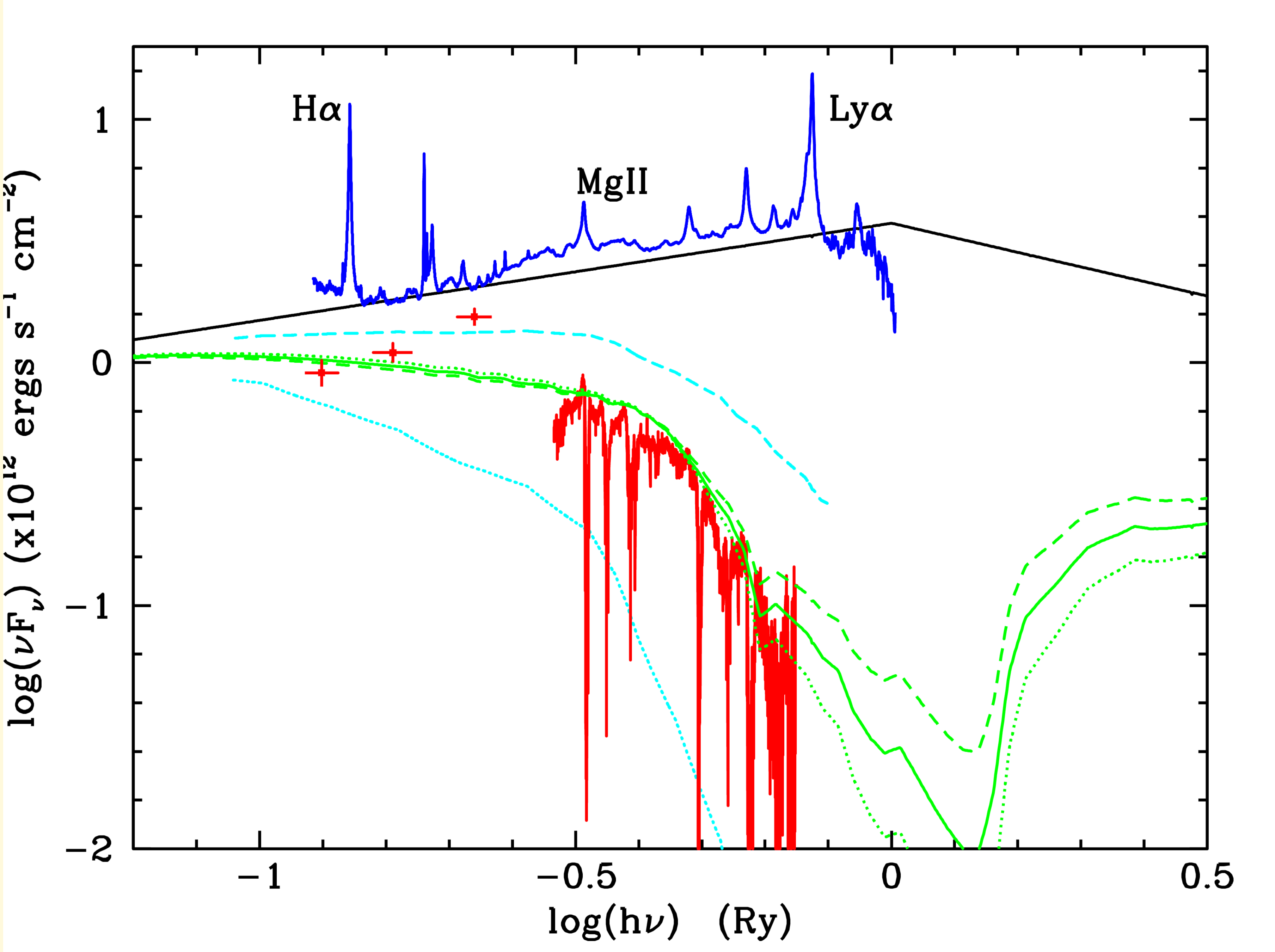
Density roughly constant with v, so sum N_{ion} over v



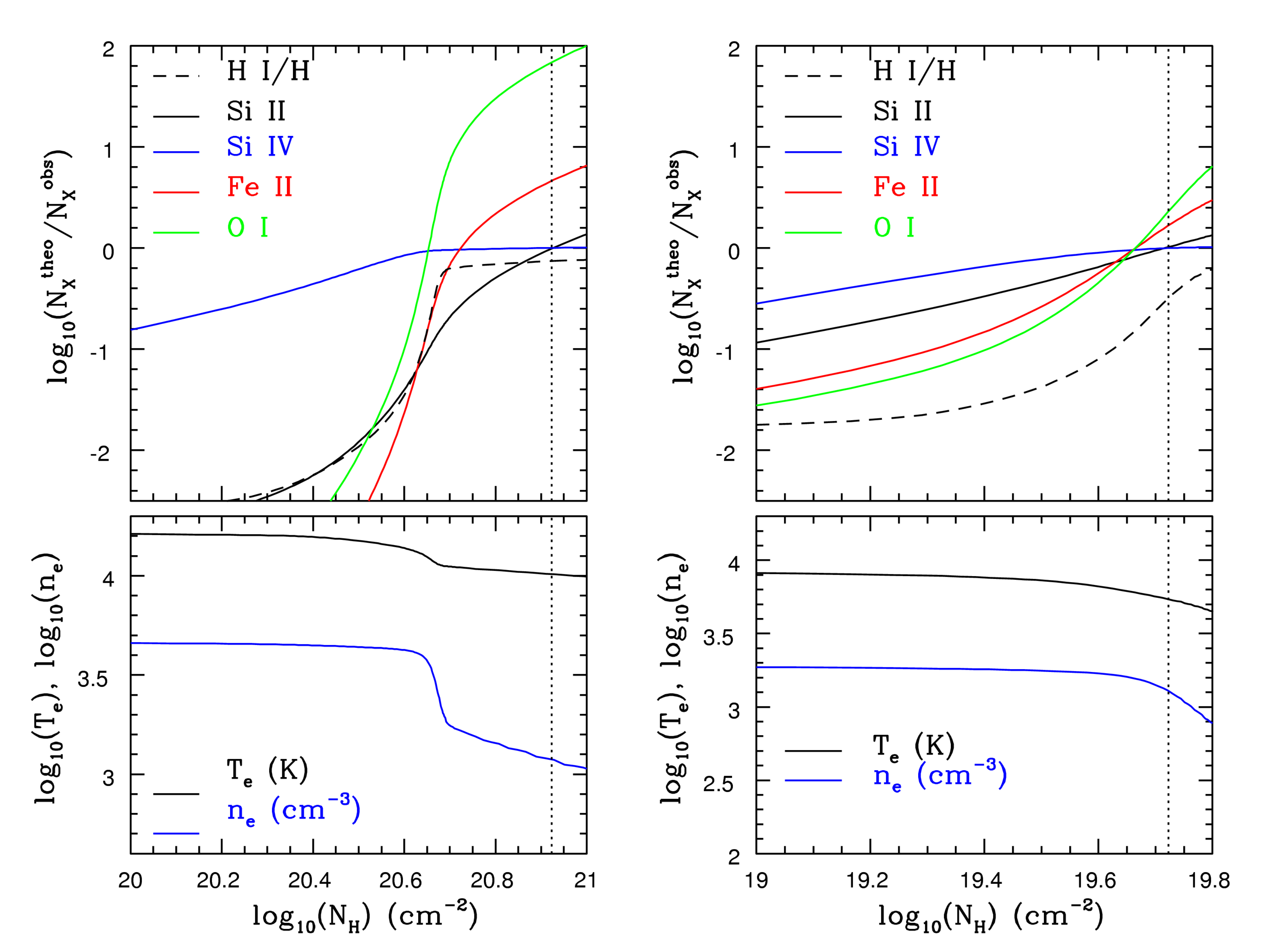
SEDs studied in Dunn et al.



Attenuated & unattenuated SEDs also considered.



Top panels: N_{model}/N_{data} for $Z_\odot$ (left) & $7.2Z_\odot$ (right) models



Results for Q0318-0600 (Dunn et al.)

- Best fit is attenuated SED,
  4.2 $Z_\odot$, log U=-3.02, log N_H=20.1 cm^{-2}, $R = 5.5$ kpc
- Also acceptable fit from unattenuated SED,
  7.2 $Z_\odot$, log U=-2.85, log N_H=19.9 cm^{-2}, $R = 18.7$ kpc
- $\dot{M}$ = 160–330 $M_\odot$ yr^{-1} ($\Omega = 0.2$)
- L_k/L_{bol} = 0.2–0.4% ($\Omega = 0.2$)

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- $\dot{M}$ = 160–330 $M_\odot$ yr^{-1} ($\Omega = 0.2$)
- <u>L_k/L_{bol} = 0.2–0.4% ($\Omega = 0.2$)</u>
- Other outflows have up to 10x higher L_k/L_{bol}, but still that's at most a few % of L_{bol} in kinetic luminosity.
- However, most studies to date done at low $v < 5000$ km/s
- Plus, any hotter phase of the outflow isn't sampled, and in Seyferts that can be a multiplier of 4–100 (Gabel et al 2005, Arav et al 2007)

Table 9. Properties of Measured Outflows to Date

Object	R^a (kpc)	log N_H (cm^{-2})	log U$_H$	log $\dot{E}_k$ (ergs s^{-1})	$\dot{M}$ ($M_\odot$ yr^{-1})	Reference^b
QSO 0059-2735	0.001 - 0.05	$\gtrsim$21.5^c	−0.7	$\gtrsim$41.1 - 42.8	$\gtrsim$0.2	1
3C 191	28	20.3	−2.8	44.0	310	2
QSO 1044+3656	0.1 - 2.1	20.0 - 22.0	−1.0 - −6.0	44.5 - 45.4	74 - 530	3
FIRST 1214+2803	0.001 - 0.03	21.4 - 22.2	−2.0 - −0.7	41.6 - 43.8	0.3 - 55	4
FIRST 0840+3633	0.001	∼21.3	<−1.8	>41.9	>0.3	5
FIRST 0840+3633^d	0.23	–	–	–	–	5
QSO 2359-1241	3	20.6	−2.4	43.7	93	6
SDSS J0838+2955	3.3	20.8	−1.9	45.7	590	7
SDSS J0318-0600	6 or 17	19.9 or 20.0	−3.1 or −2.7	44.8 or 45.4	120 or 450	8

[a]For relative accuracies, see Section 1.

[b]1-Wampler et al. (1995), 2-Hamann et al. (2001), 3-de Kool et al. (2001), 4-de Kool et al. (2002a), 5-de Kool et al. (2002b), 6-Korista et al. (2008), 7-Moe et al. (2009), 8-This Work

[c]Based on Table 5 in Wampler et al. (1995)

[d]Distance derived from Fe II fluorescence and no photoionization modeling was performed for this object

Uncertainties in R

- $L_k = \frac{1}{2}\dot{M}v^2$ where $\dot{M} \geq 4\pi\mu m_p v N_H R\Omega$
- C II* & Si II* have low critical densities
- Recall $U_H = Q_H/4\pi R^2 c n_H$: take an outflow of the observed low n_H and move it closer to quasar. As R decreases, U_H increases; eventually, low-ionization gas will disappear
- But at smaller R, higher-density gas can still have U_H low enough for Fe II to exist, and some Fe II* lines have high critical densities
- Such higher-density tracers (incl. C III*, Fe III*) should probe to smaller distances; outflows at many scales?
- Separate issue: X-ray absorption can modify spectrum, reduce distance (Everett et al 2002)

Uncertainties in Ω

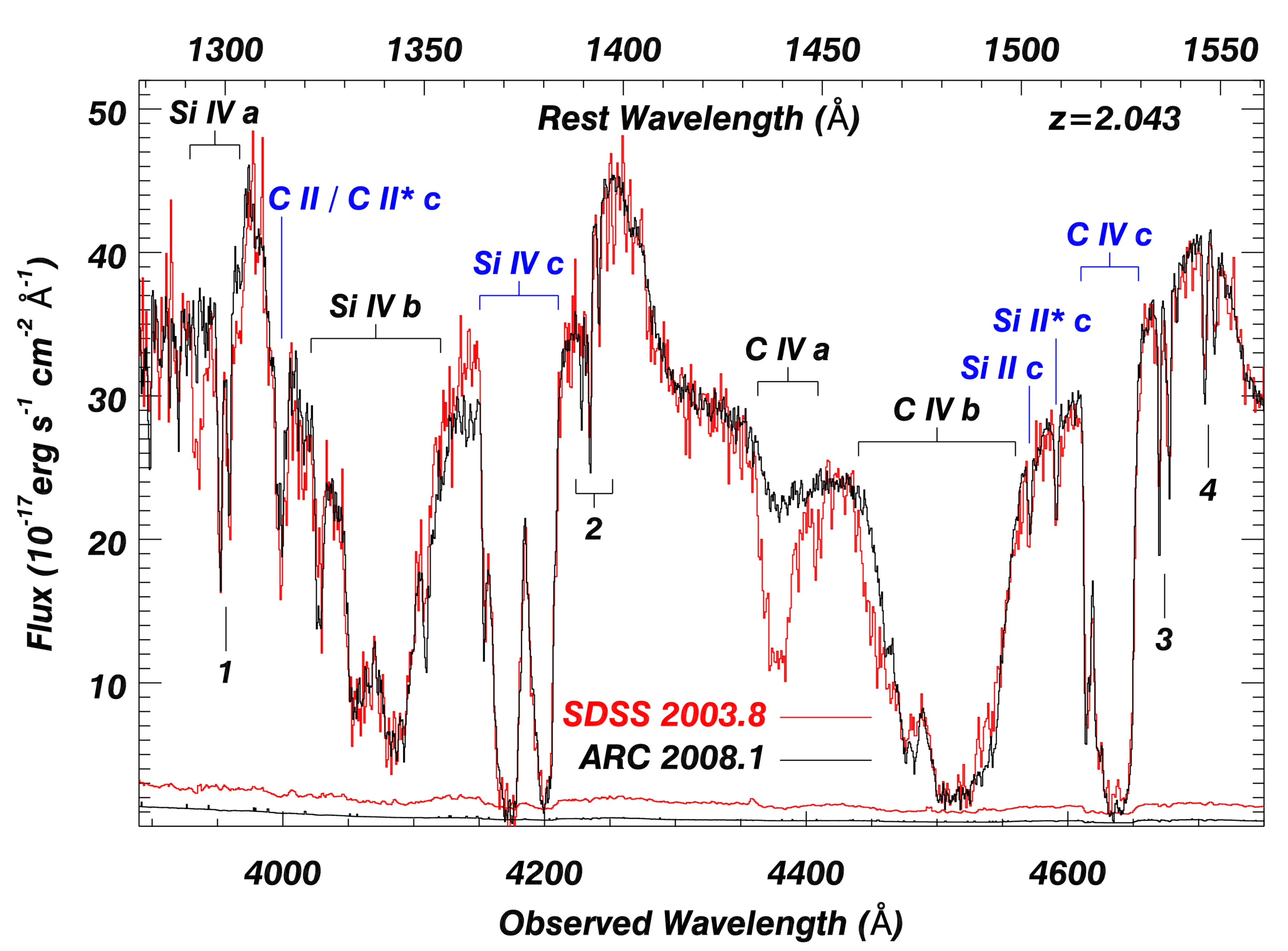
- $L_k = \frac{1}{2}\dot{M}v^2$ where $\dot{M} \geq 4\pi\mu m_p v N_H R\Omega$
- What Ω to use? $\Omega_{obs} = 0.2$: 20% of our sightlines to quasars have BALs in them, but if 50% of quasars are obscured, BALs cover only 10% of the sky as seen from the quasar ($\Omega \leq f_{BAL}$)
- To date, distance measurements made only for the 1 in 100 BAL quasars with Fe II*, C II*, Si II*. So, $\Omega = 0.002$?
- No. But fair to ask how similar are excited-state sightlines to more typical sightlines (answer: a few times higher column).
- Test by looking at S IV* / S IV (Dunn in prep.); same ionization as C IV, detected at rate consistent with same $\Omega = 0.2$
- Regardless, need many objects to get average outflow picture

Conclusions

- Ionic column densities can be measured if care is taken (partial covering or more sophisticated models)
- To date, C II & Si II used to probe low n_e and thus preferentially larger distances, but that is changing
- Photoionization modeling yields N_H, but I would like to see a wider range of models explored (e.g.: continuous wind; physical model for location of X-ray obscuration)
- Nevertheless, some outflows are tens of kpc away from the BH that launched them (3C 191)
- Some are only few pc away (Hall et al. arXiv next week)
- Atomic data often a limiting factor


QUASARS

Moe et al. (2009) quasar SDSS J0838+2955



Moe et al. (2009) joint U_H, N_H constraints