Observing Accretion Disks III:

Emission and Absorption Lines from AGN Disks

by Mike Eracleous

XIV IAG USP School On Astrophysics,

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Organization of Lecture III

Emission lines from AGN disks

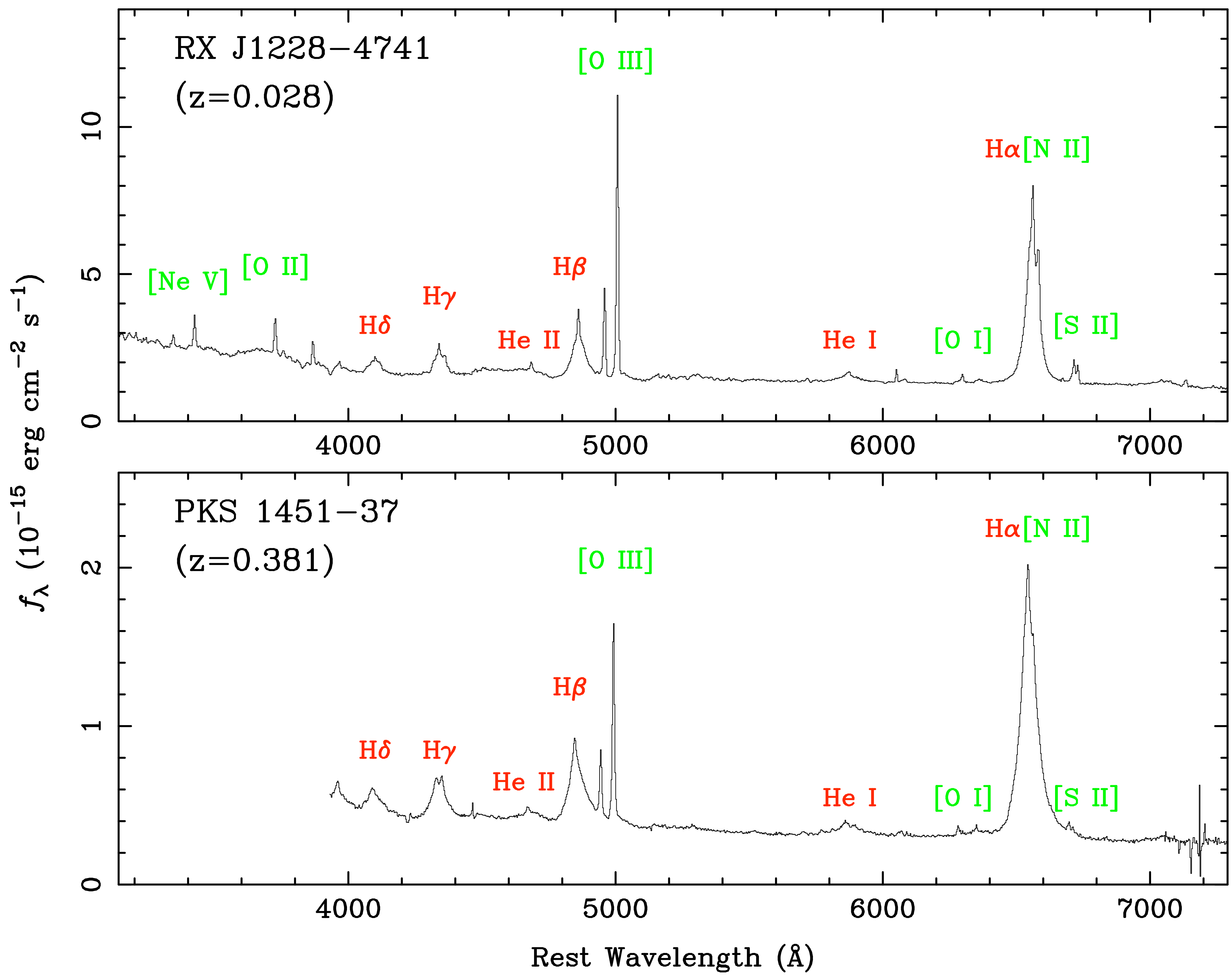
- Intro to AGN spectra and physical picture
- Optical emission lines from "outer" disk and their use as a tool to study disk structure
- X-ray emission lines from inner disk

Absorption lines from disk outflows

- Broad and narrow UV resonance lines
- high-velocity lines in X-ray band

4

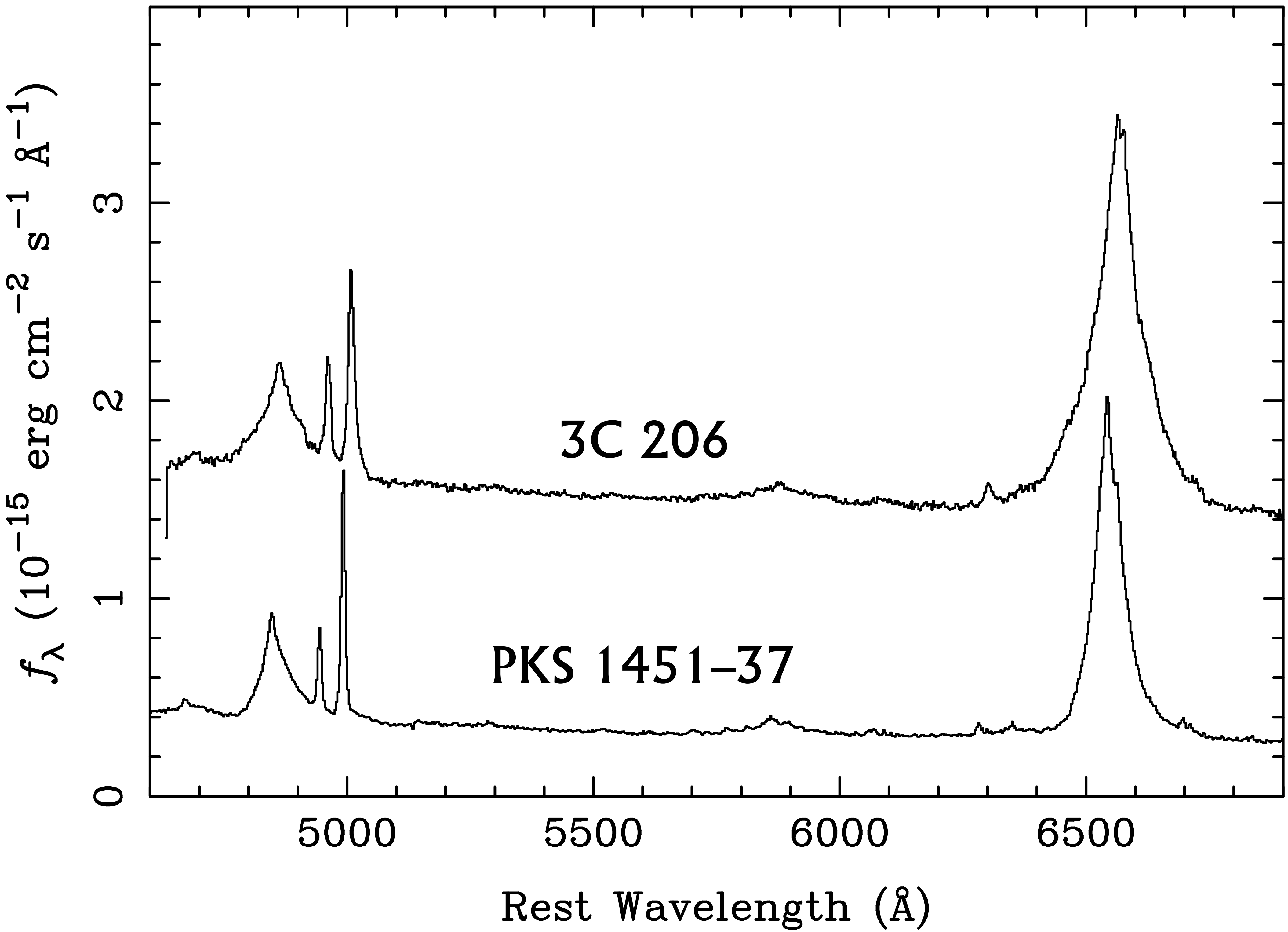
Crash course on AGN spectra



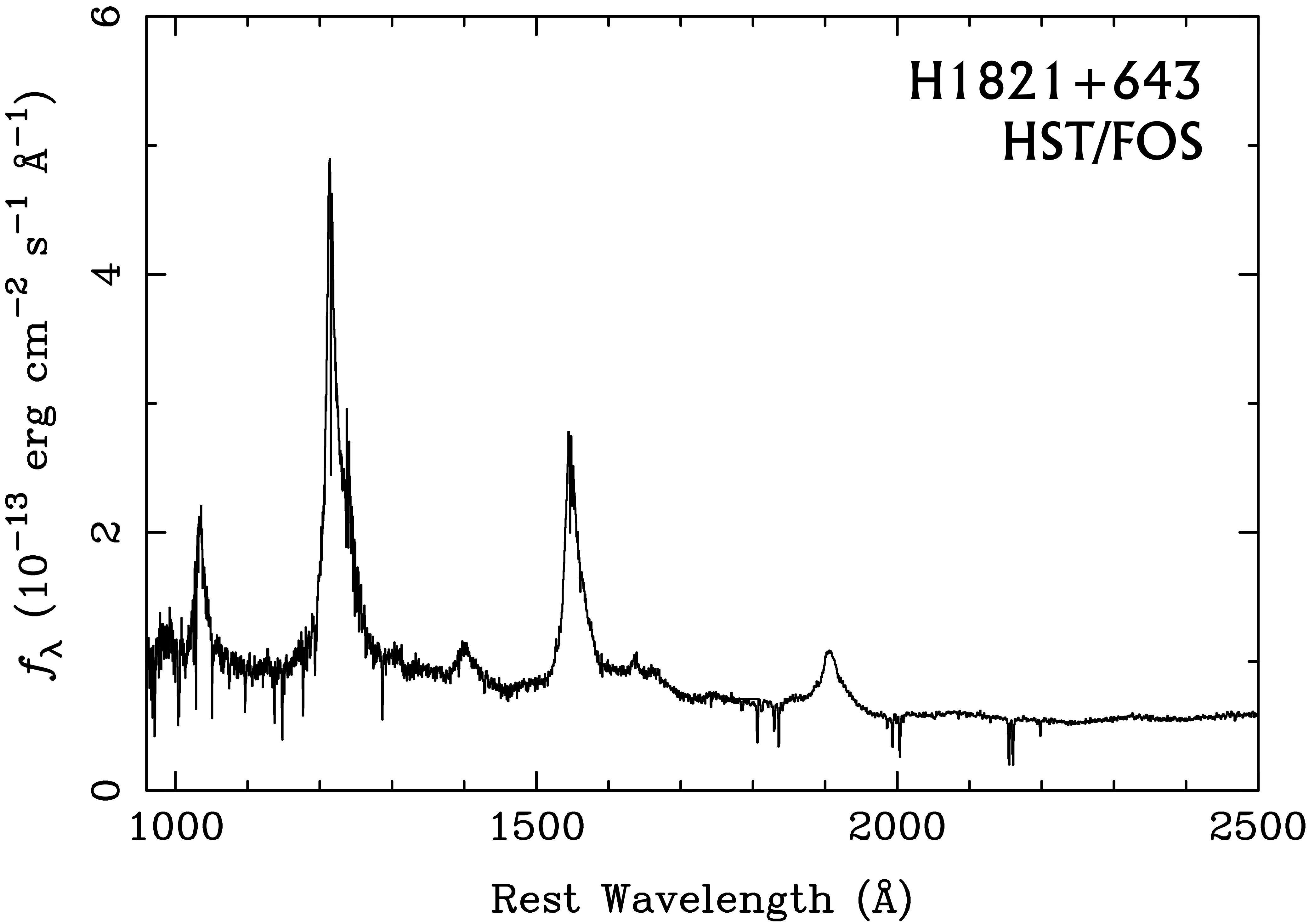
Animals in the zoo

- Quasars (QSRs, QSOs)
- Seyfert galaxies
  - type I, II
- LL-AGNs, LINERs
- NELGs, XBONGs
- Radio galaxies
  - BLRGs, NLRGs
  - FR I, FR II
  - GPS, CSS sources
- BL Lacs
  - HBL, LBL XBL, RBL
- Blazars
  - HPQ
  - FSRQs
  - OVVs

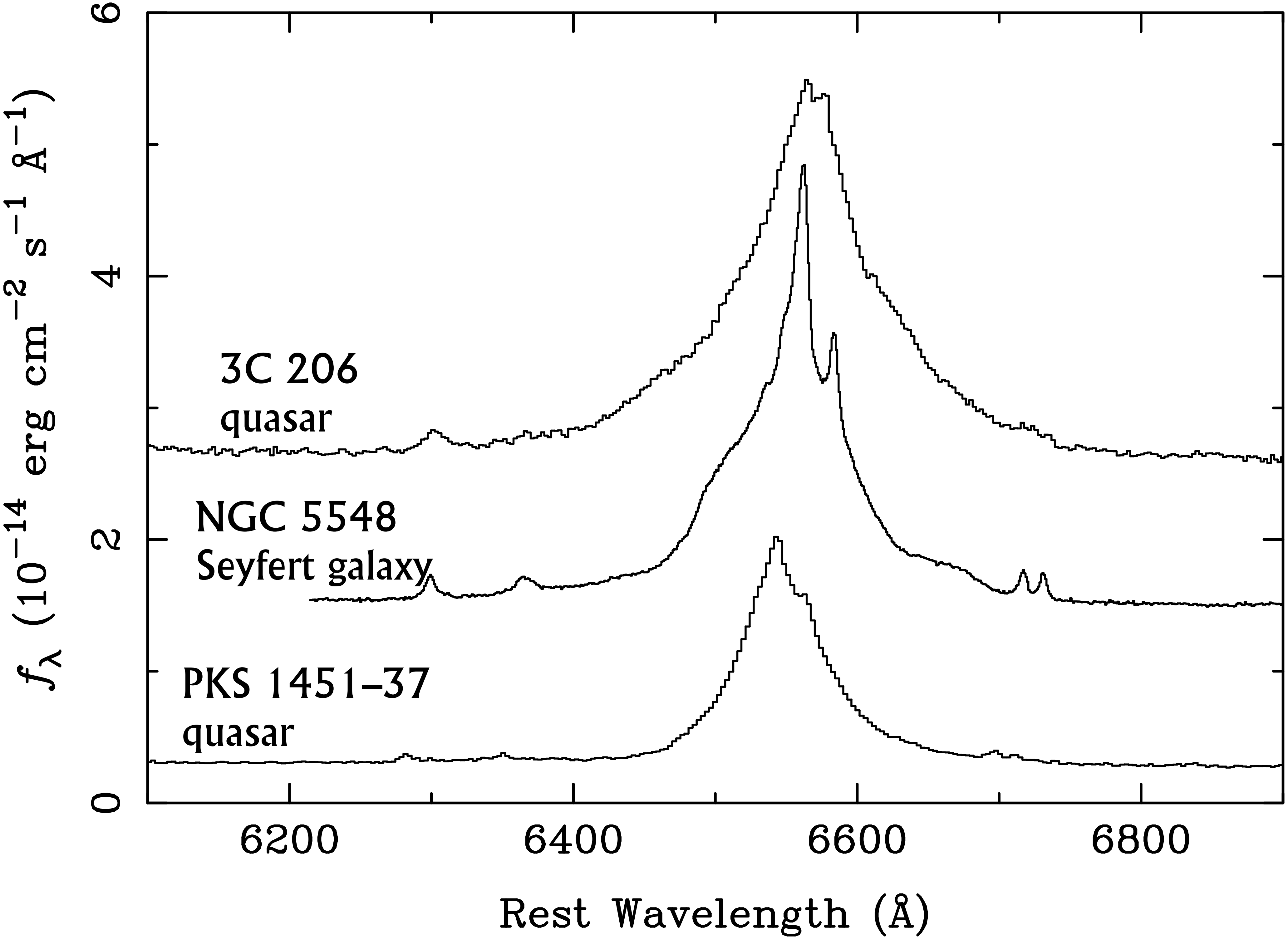
Optical spectra of quasars



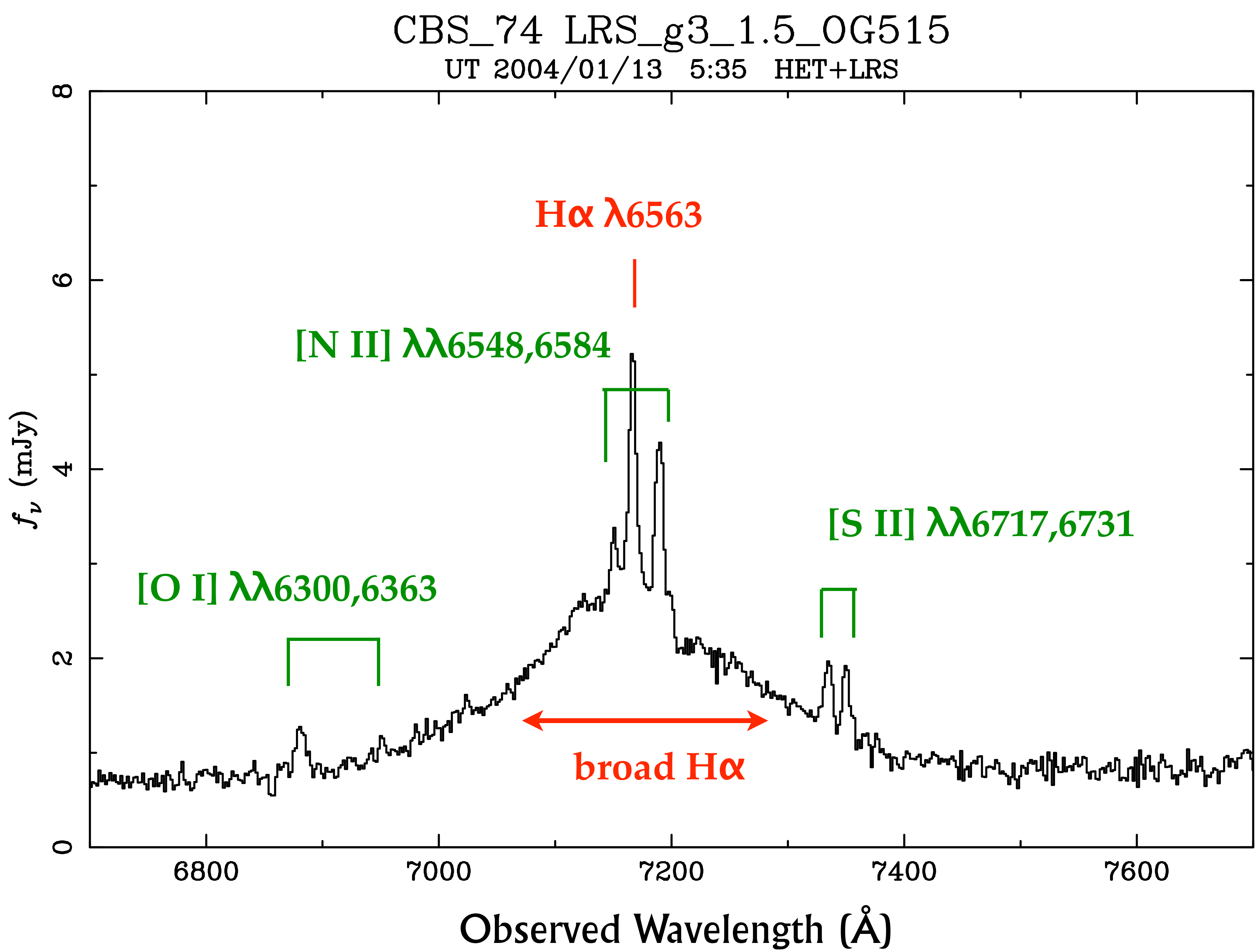
UV spectrum of a quasar



Examples of emission-line profiles



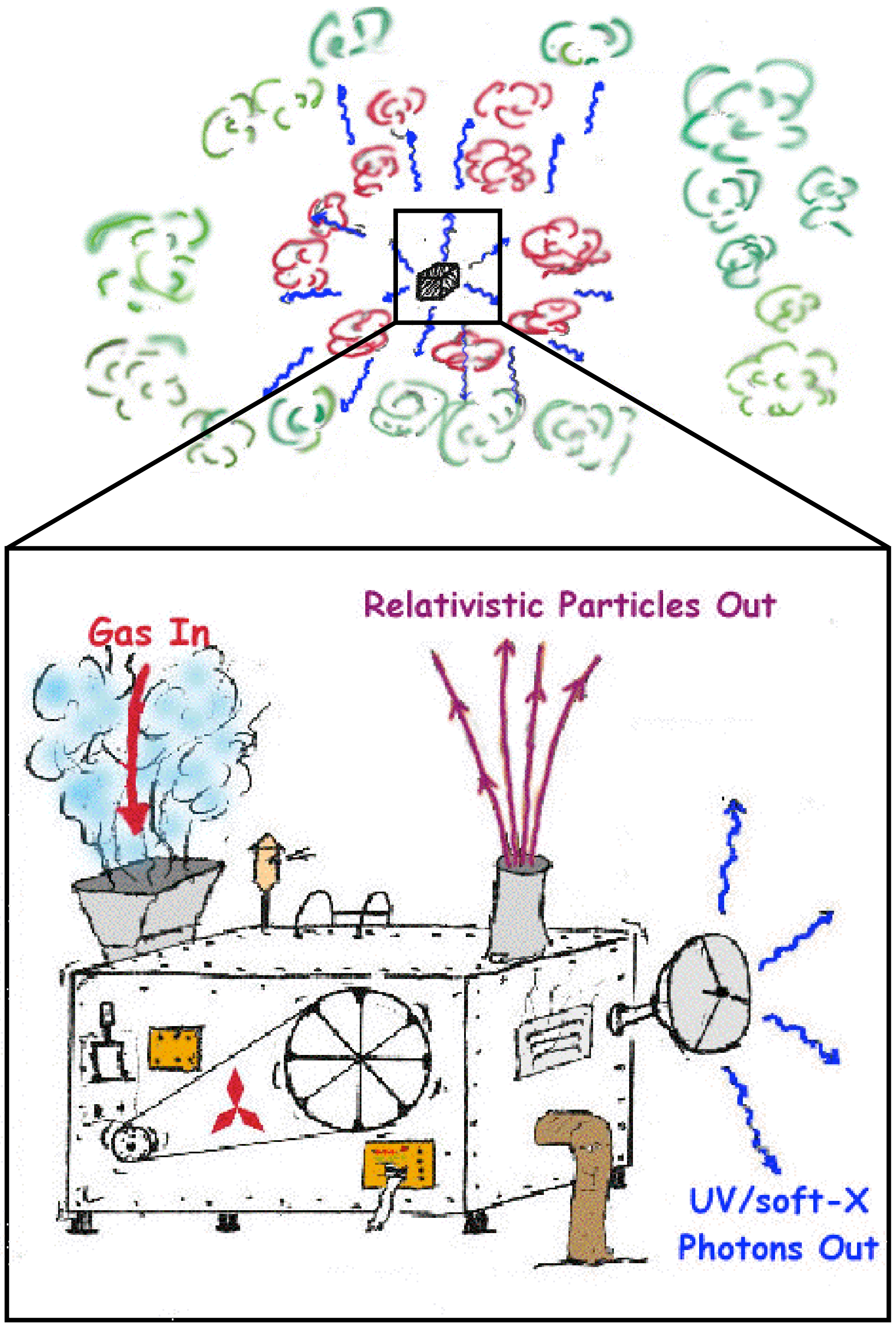
The Hα line close up



What is the AGN Broad-Line Region?

The old-fashioned view:

- "Clouds" orbiting the "central engine."
- Dynamics and survival were a puzzle.
- Idea of clouds entrenched. Not much attention to other plausible models.



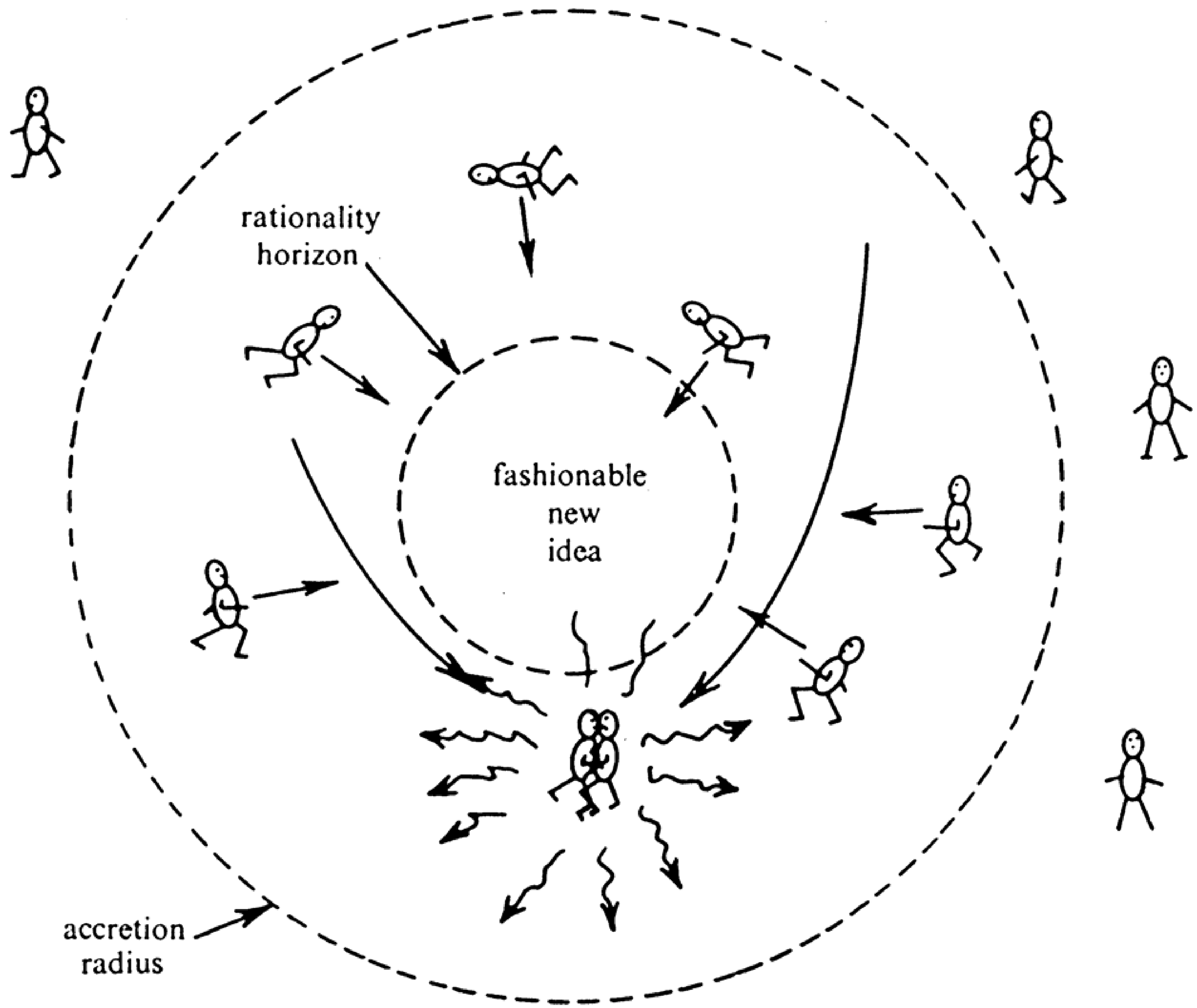


Fig. 1. Response of astronomers to a fashionable new idea.

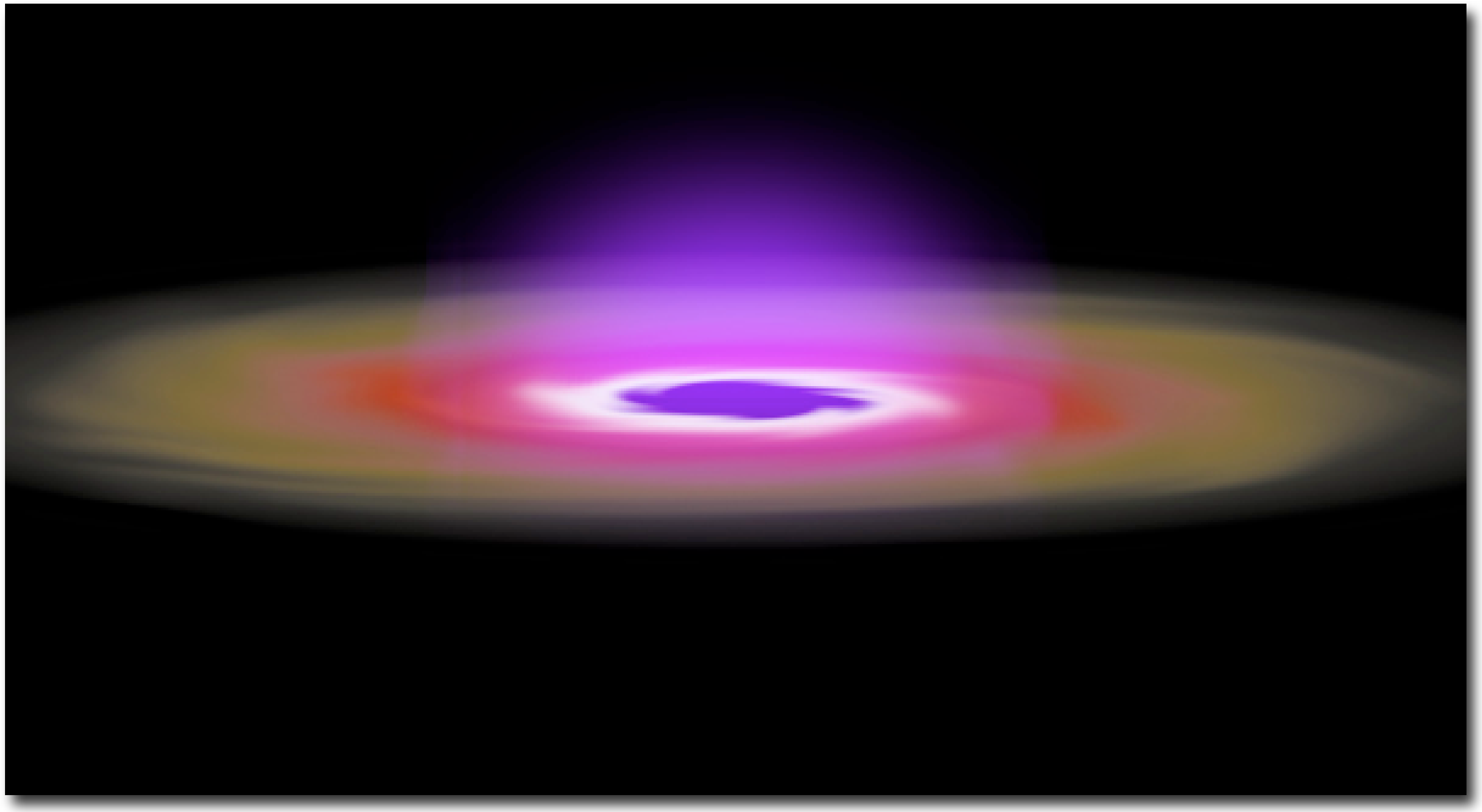
from McCray, 1979, in “Active Galactic Nuclei,” eds. Hazard, C. & Mitton, S. (Cambridge: Cambridge University Press), p.227

Physical Models for the BLR

The accretion disk?

(Collin-Souffrin 1987, Collin-Souffrin & Dumont 1989, 1990a–d, Rokaki et al. 1992)

Density too high to emit all lines; two regions required for low- and high-ionization lines.

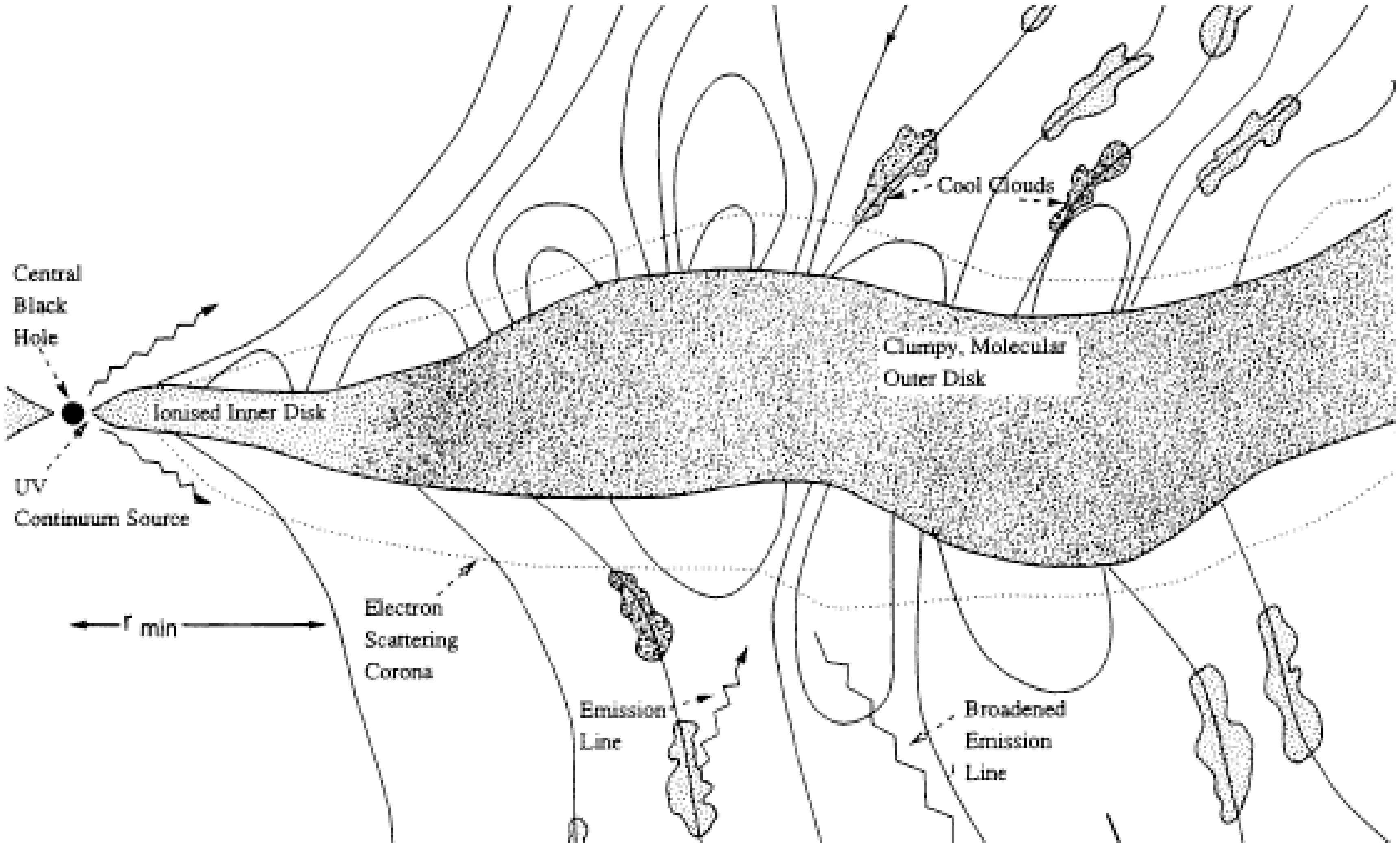


Physical Models for the BLR

A hydromagnetic wind?

(Emerring, Blandford & Shlosman 1992, ApJ, 385, 460; Köenigl & Kartje 1994).

Serves to remove angular momentum from the disk too.

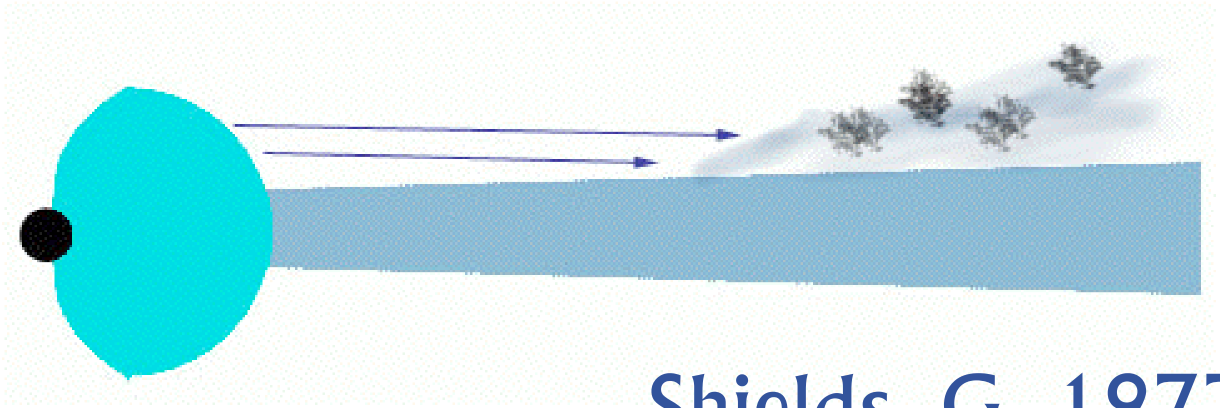


Physical Models for the BLR

Radiatively accelerated wind?

(Shields 1977; Mestel, 1979; Arav et al. 1994; Murray et al. 1995; Proga et al. 1998–...)

Explains BAL quasars and has implications for galaxy evolution.



Shields, G. 1977, ApL, 18, 119

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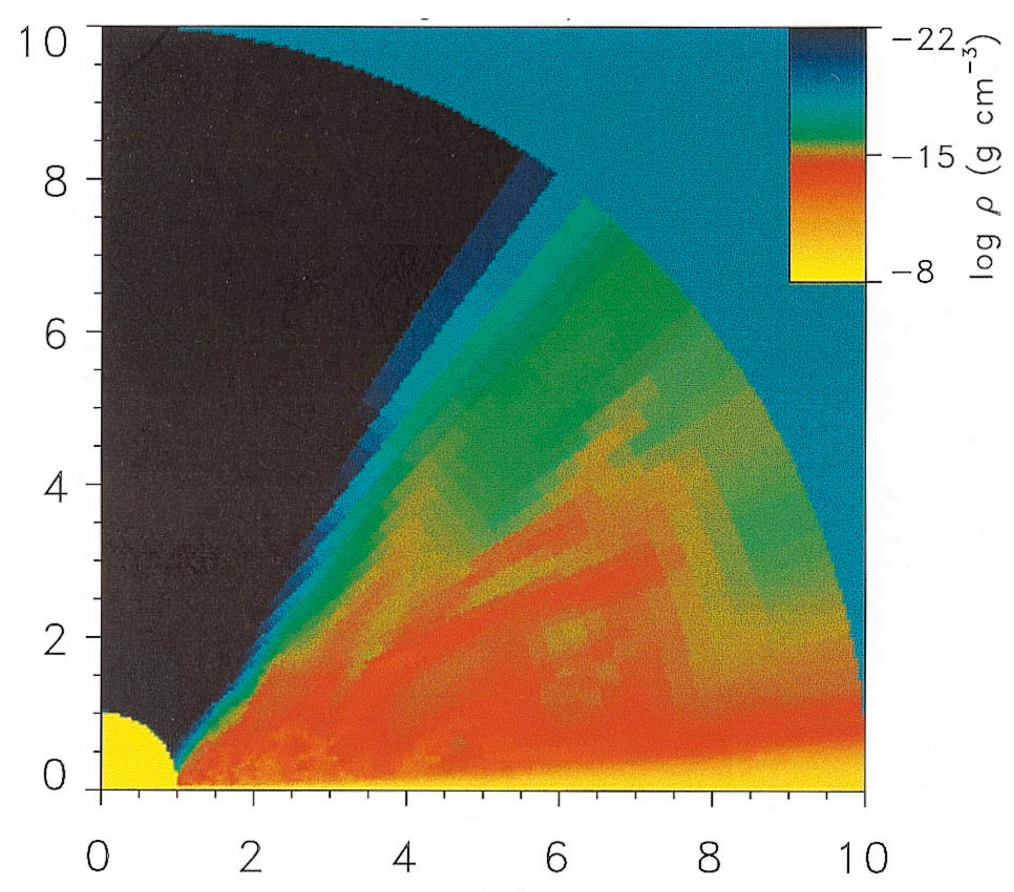
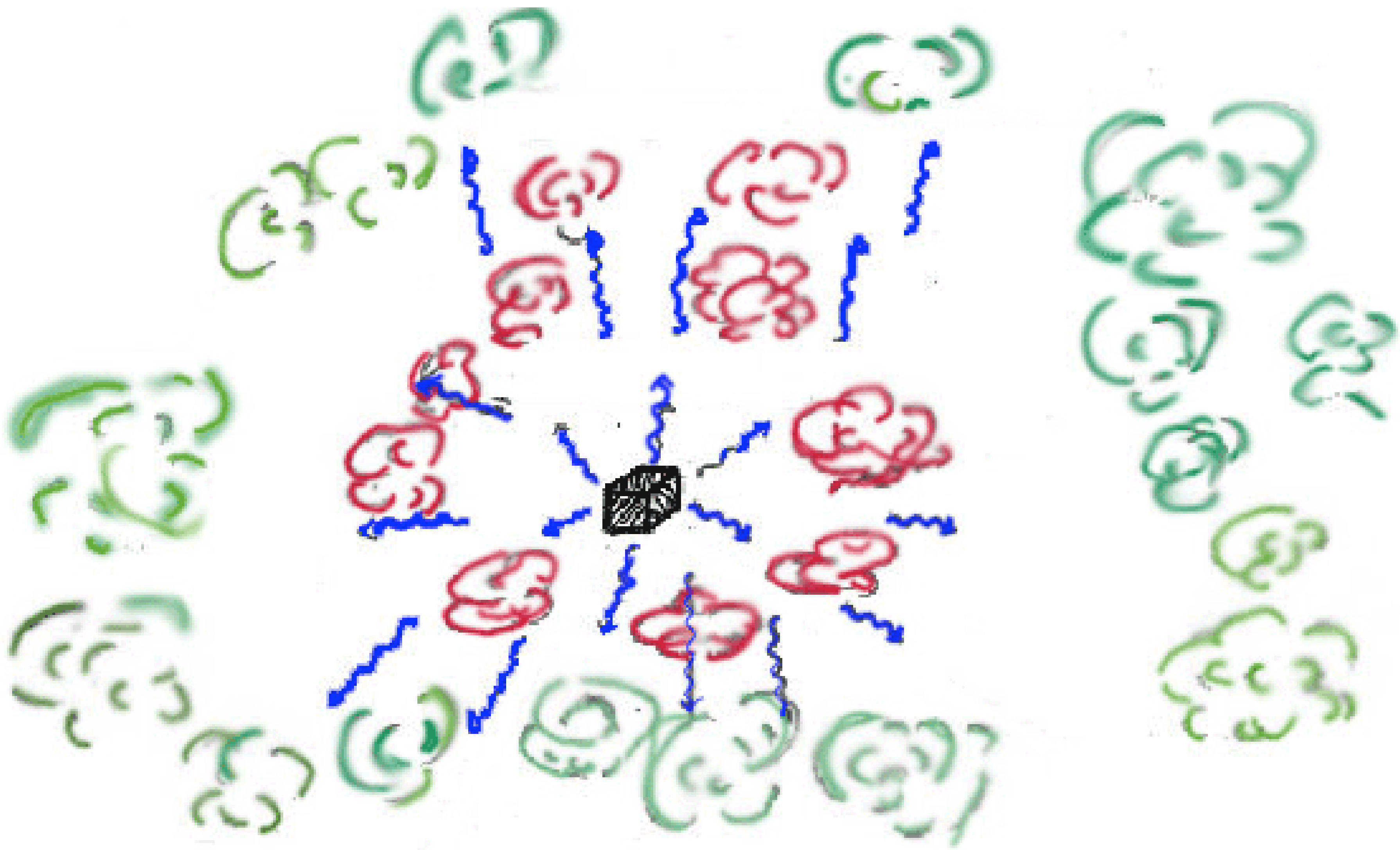
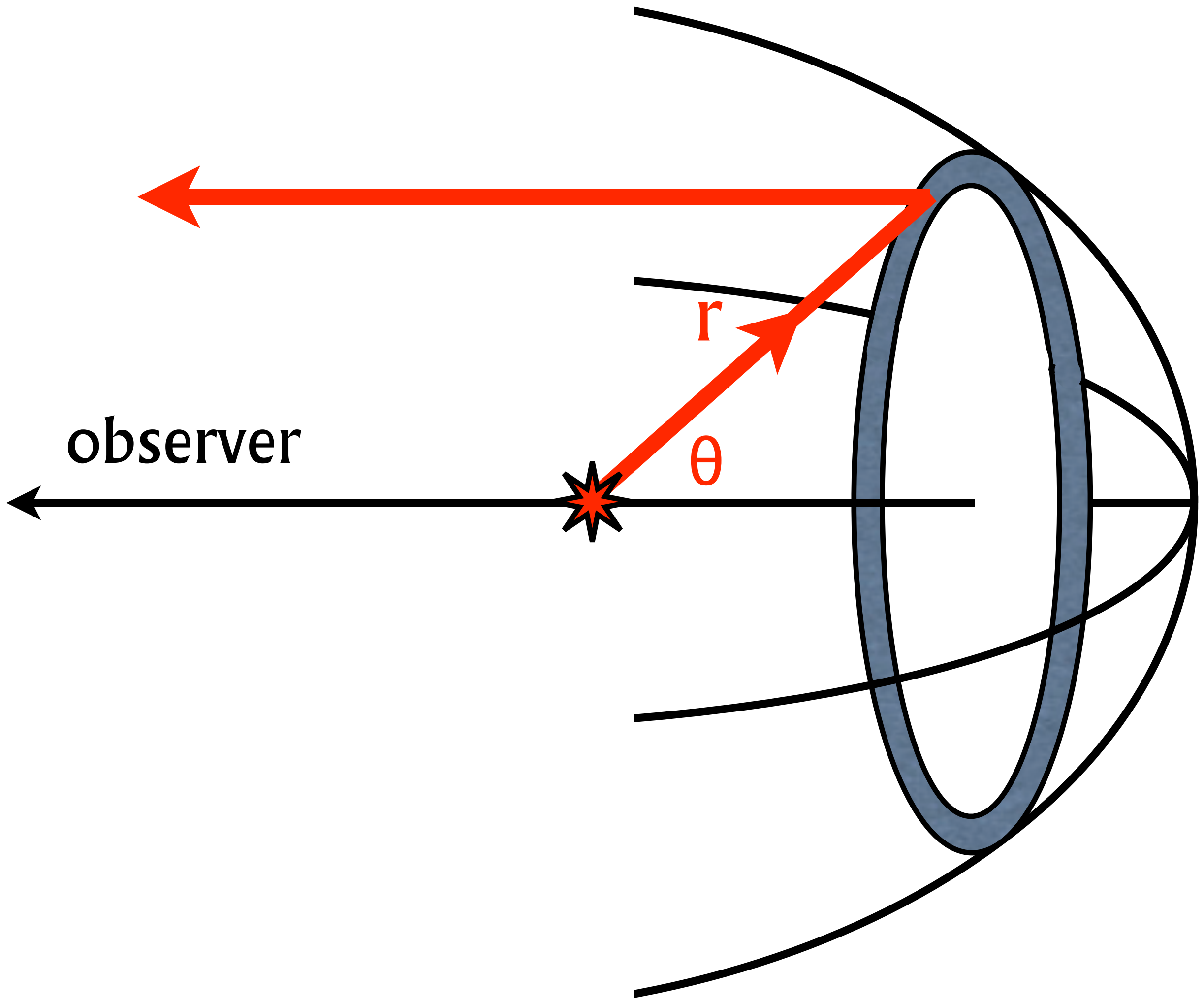


from Proga et al. 2000, ApJ, 543, 686

BLR structure from Reverberation

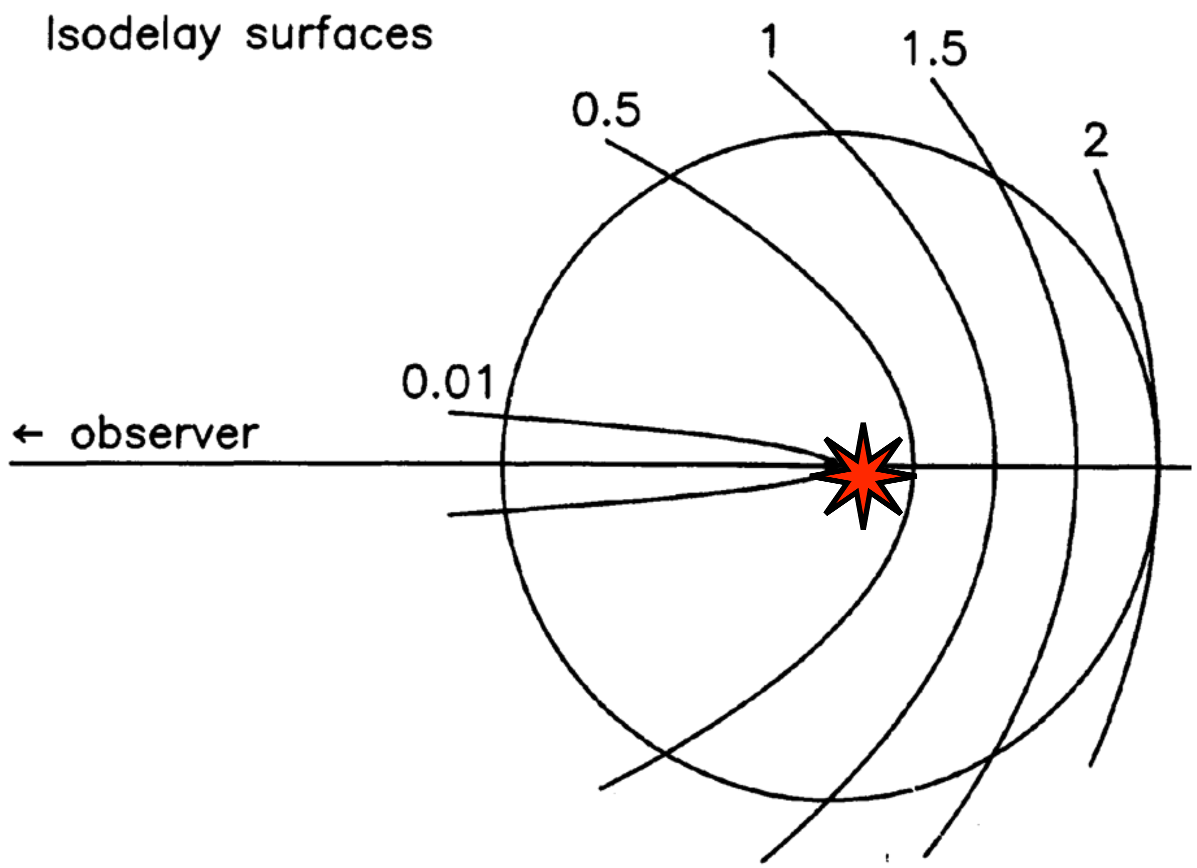


Rverberation Mapping



- A continuum flare is followed by an echo in the emission-line region
- Isodelay surfaces defined by $c\,r\,(1+\cos\theta)=\tau$

Isodelay surfaces superposed on a disk



from Peterson 1993, PASP, 105, 247

Potential and Results

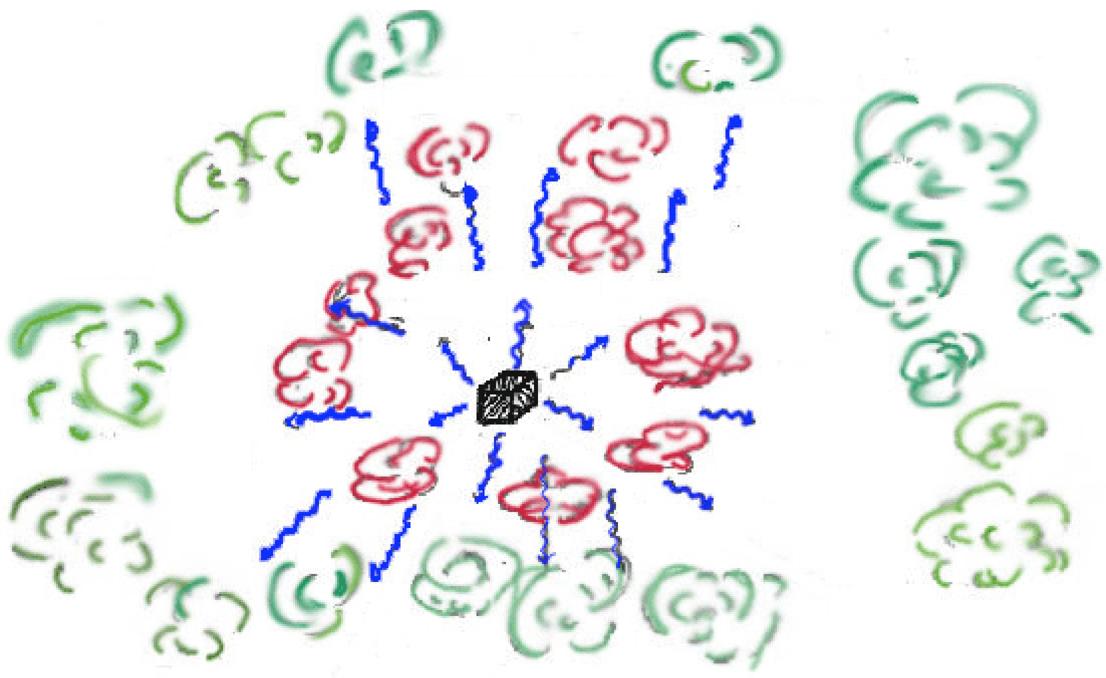
- **Basic principle (Blandford & McKee 1982): transfer equation**

$$L(v,t) = \int_{-\infty}^{\infty} \Psi(v,\tau)\, C(t-\tau)\, d\tau$$

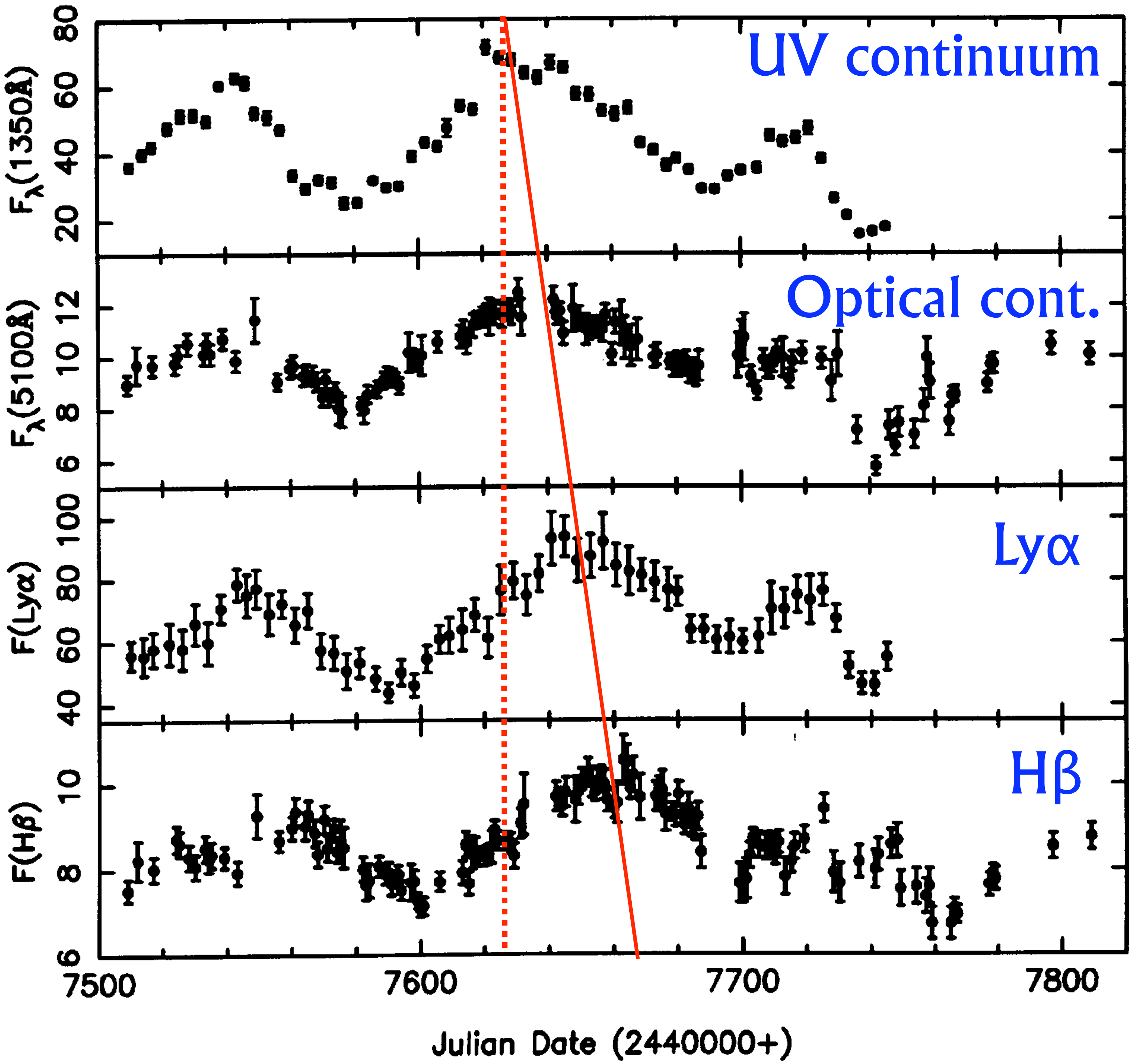
emission-line light curve

transfer function

continuum light curve at retarded time



Examples of Observed Time Lags



from Peterson 1993, PASP, 105, 247

Immediate Results

Systematic reverberation mapping of about two dozen AGNs in the optical.

A few objects targeted in multi-wavelength campaigns (optical +UV+X-Ray)

The emission-line fluxes respond to changes in the continuum with some delay but the line profiles do not change appreciably

The hope of mapping the velocity-dependent structure of the broad-line region has not been realized.

What did we learn?

- **Hardly any radial motion of the gas**

  Both sides of line profile respond at the same time

- **Light-crossing time of broad-line region**

  Typically a few light weeks but stratified in ionization (higher-ionization lines respond first)

- **Correlation between size and luminosity**

  $R_{BLR} \propto L_c^p$ with $p \approx 0.5$

- **Line ratios change as the continuum fluctuates**

  Continuum shape changes with luminosity

One More Clue

Smothness of line profiles

(e.g., Arav et al. 1997, 1998; Laor et al. 2006).

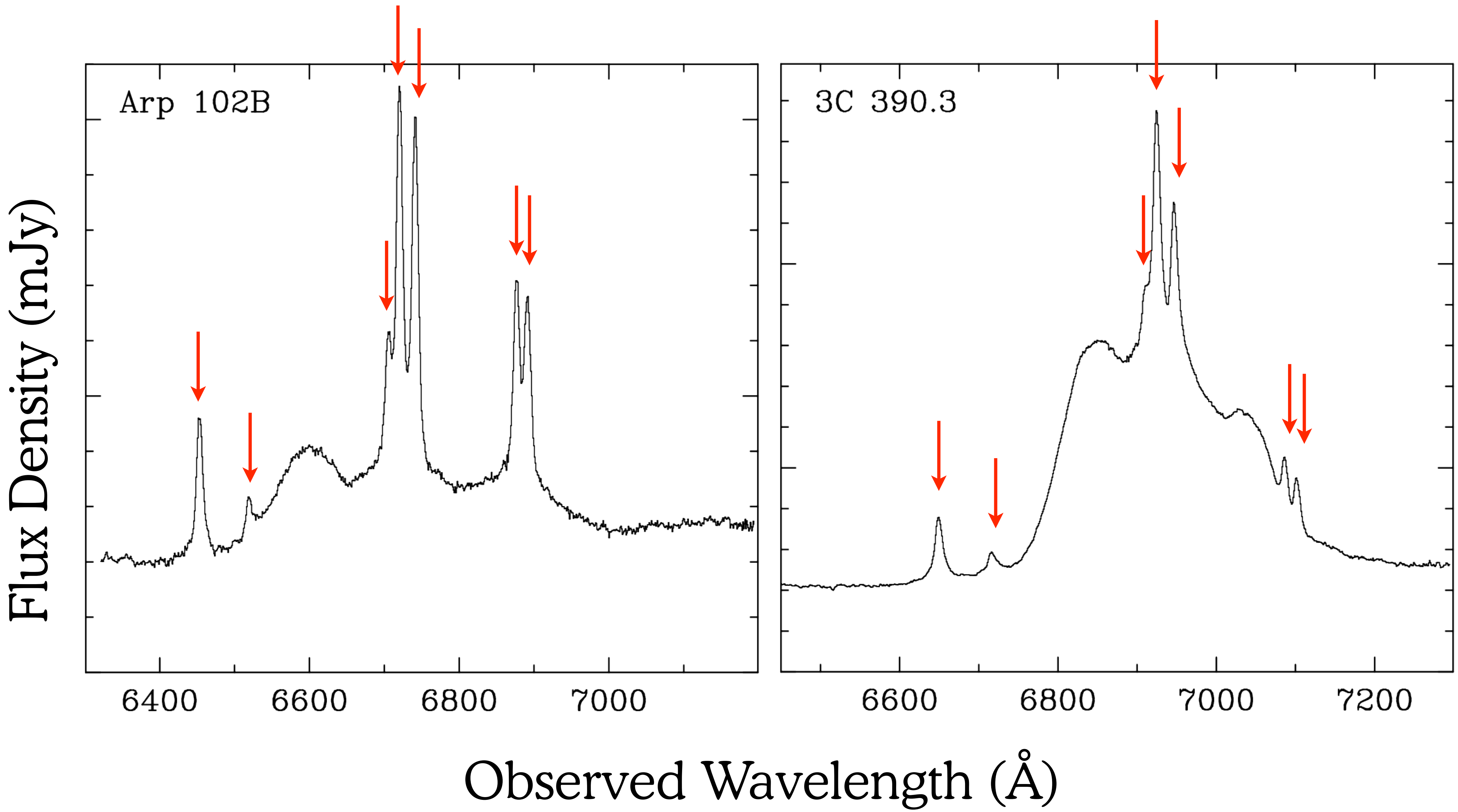
Requires a large namber of "clouds"

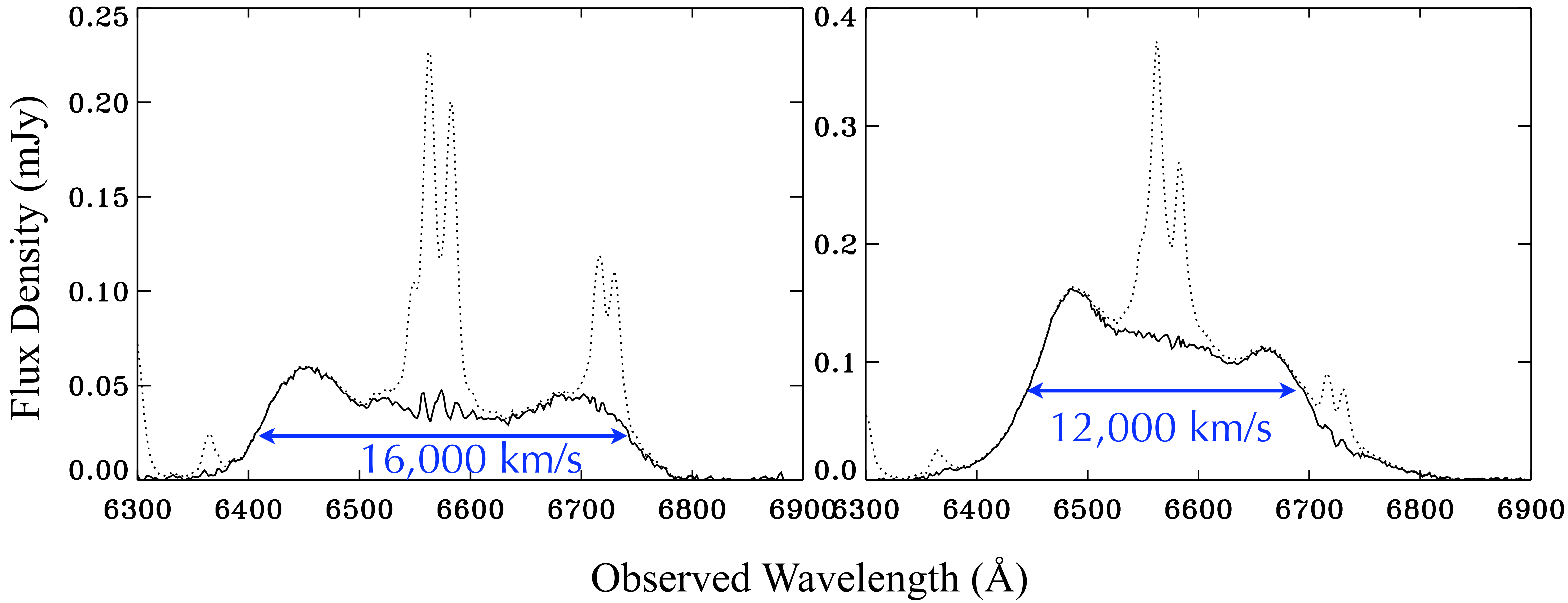
BUT...

Photoionization models and luminosity

yield a small region that cannot fit all of these clouds
(discrepancy by 1-2 orders of magnitude)

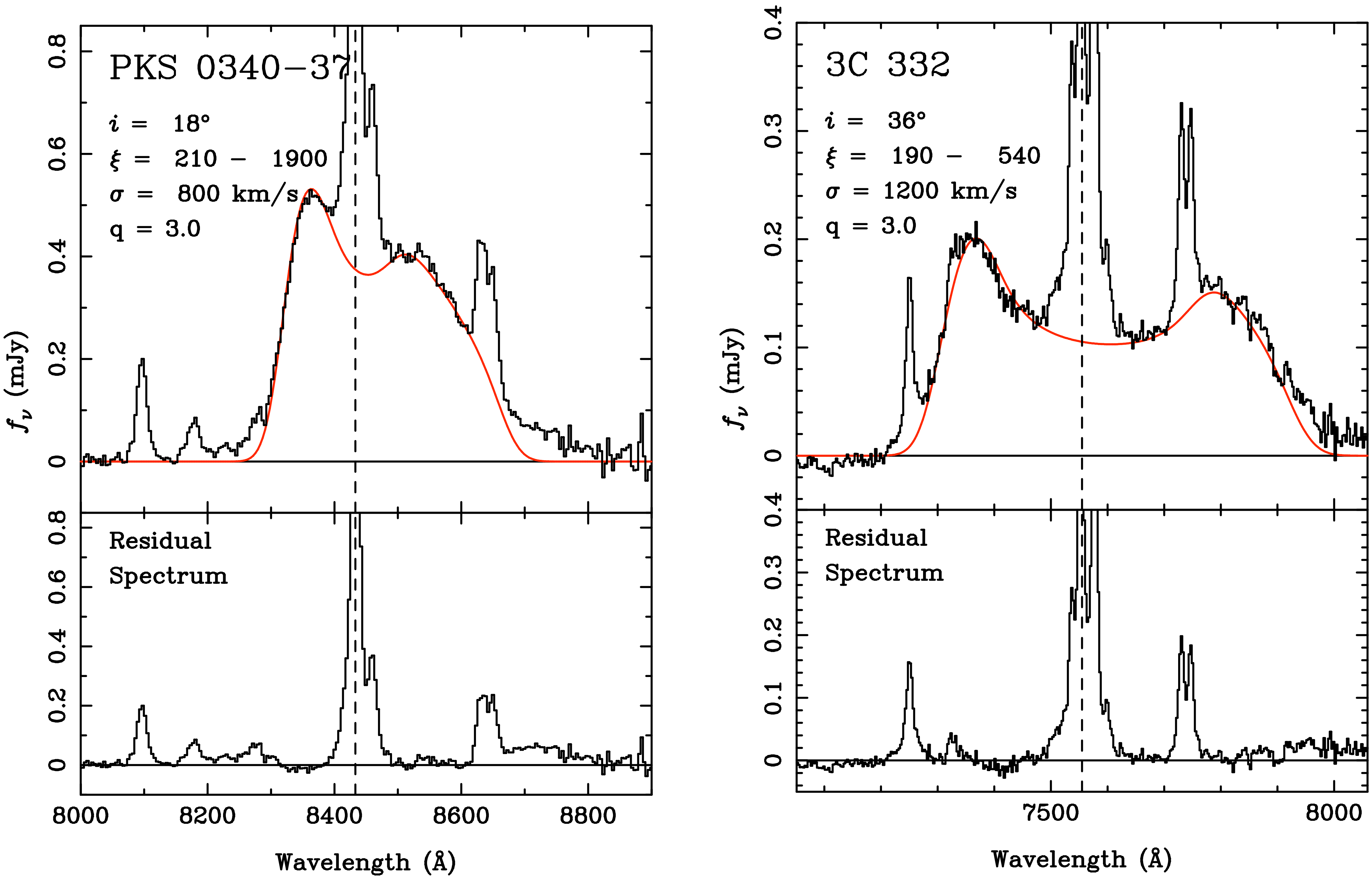
Double-Peaked Balmer Lines





- FWHM ~ 15,000 km/s (up to 40,000 km/s!)
- Corresponds to ξ ~ 500
  (in an edge-on accretion disk)
- Relativistic effects (special+general) are important but can be treated approximately

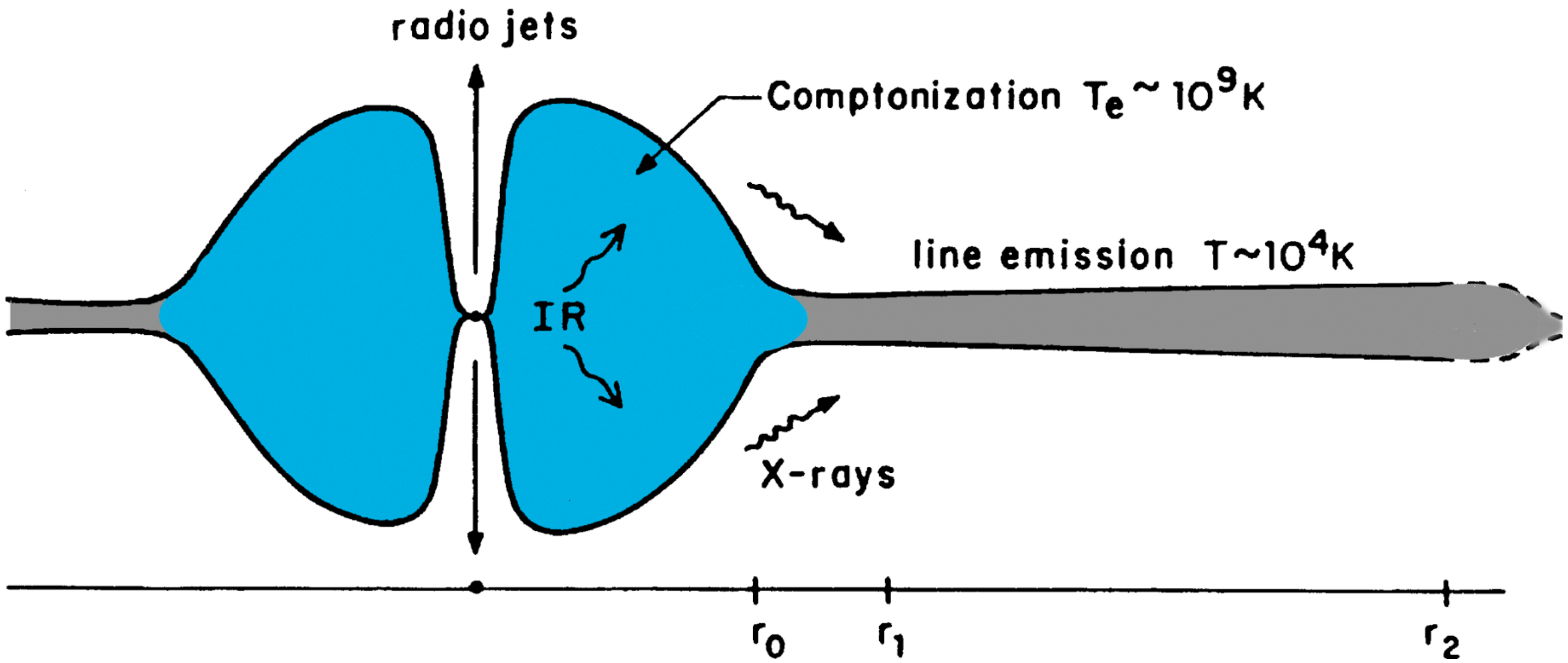
Fits to the line profiles



from Eracleous & Halpern 1994, ApJS, 90, 1

What powers the emission lines?

- **Energy budget test → photoionization**
  (e.g., Strateva et al. 2006, 2008)
  - → leads to ion torus hypothesis

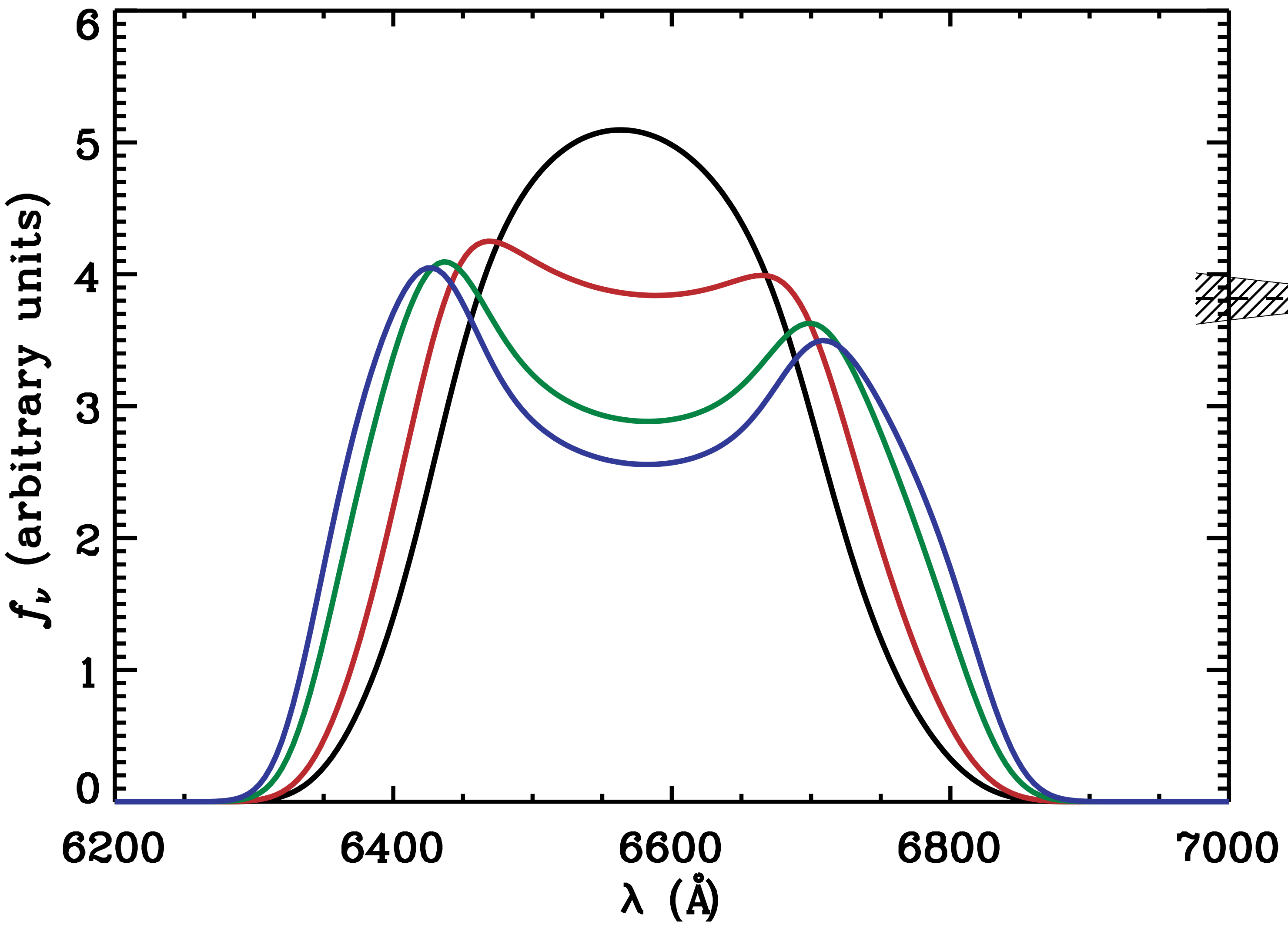


Chen & Halpern 1989, ApJ, 344, 115

inspired by Rees et al. 1982, Nature, 295, 17

- **Black hole masses → Eddington ratios**
  (Lewis & Eracleous 2006)
  - → ion torus not a universal scenario

In the grand scheme of things...



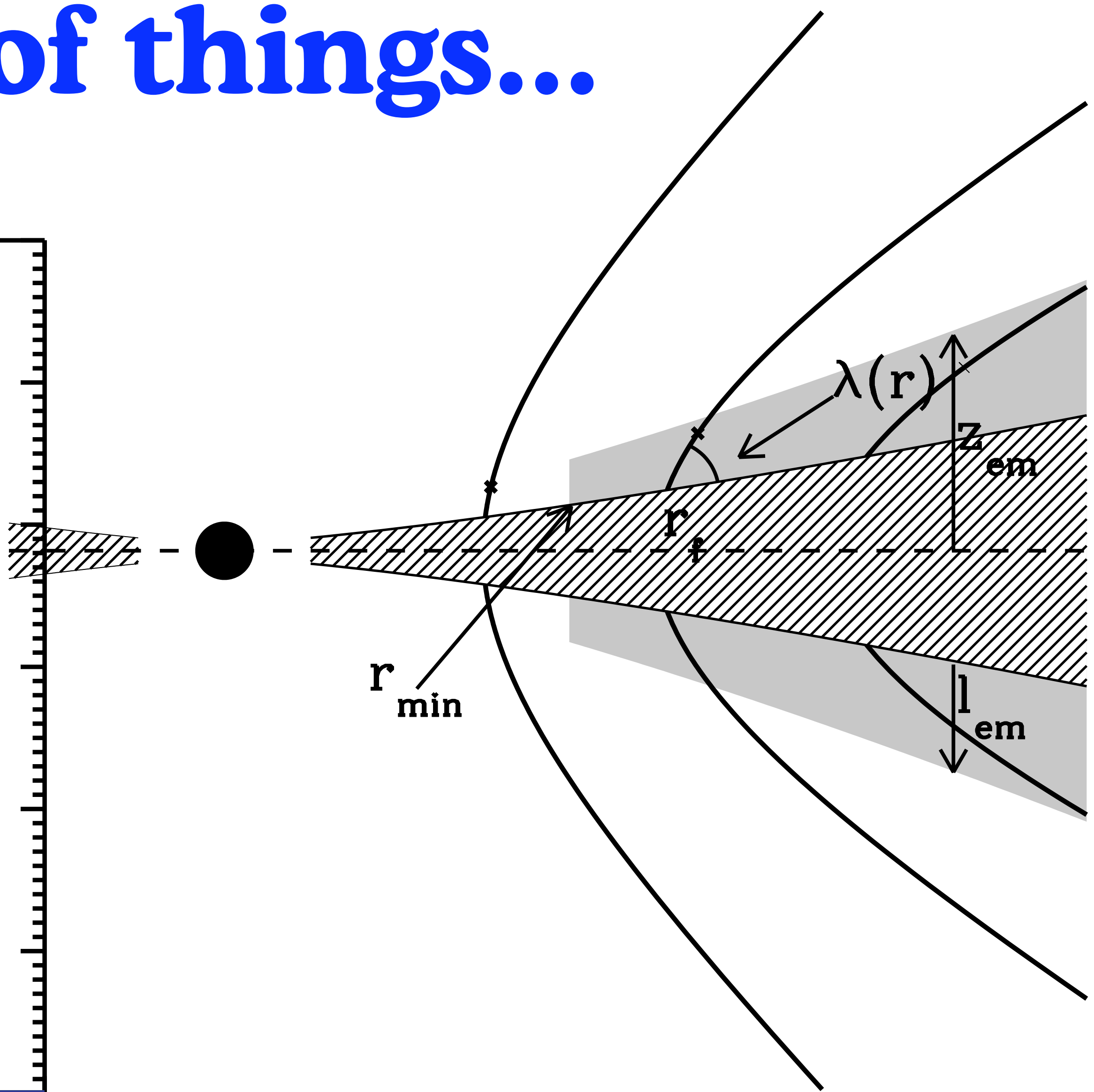


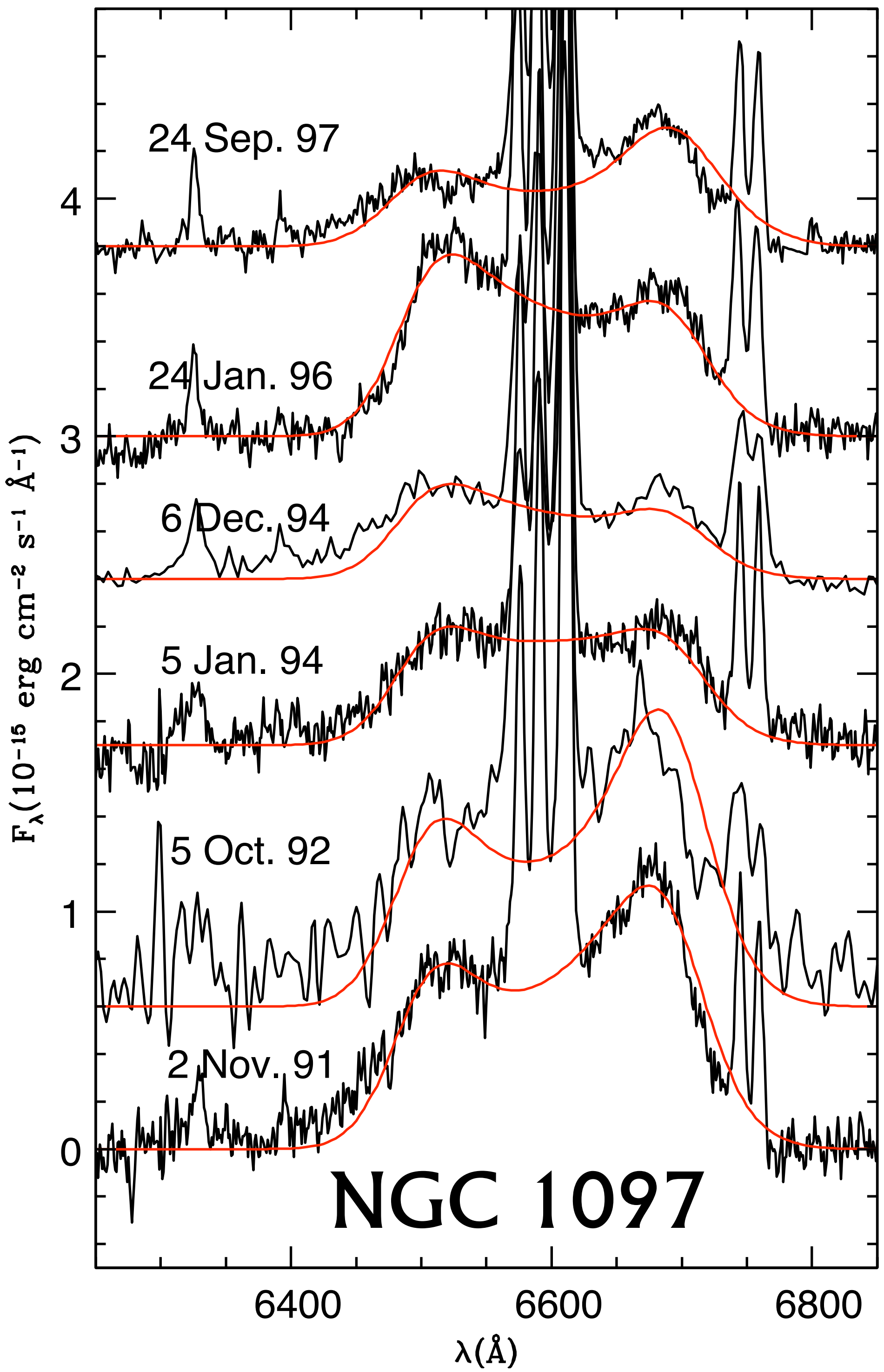
figure from Flohic, 2008, PhD Thesis, Penn State

from Murray et al. 1995, ApJ, 451, 498

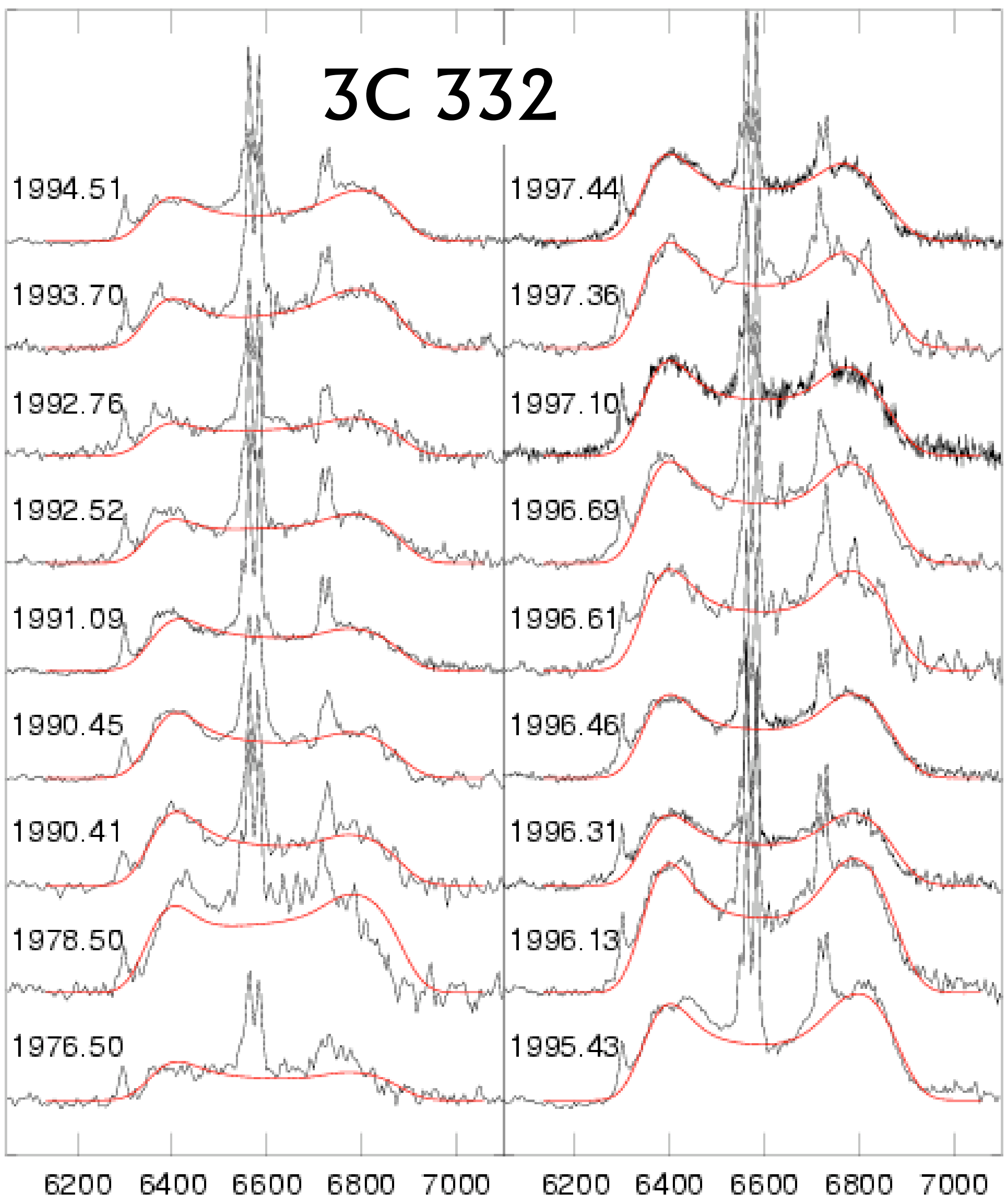
Most Relevant Time Scales

Light-Crossing:	$6\ M_8\ \xi_3$ days
Dynamical:	**$6\ M_8\ \xi_3^{3/2}$ months**
Thermal:	**$5\ \alpha_{-1}^{-1}\ M_8\ \xi_3^{3/2}$ years**
Sound-Crossing:	**$70\ M_8\ \xi_3\ T_5^{-1/2}$ years**
Viscous:	$10^6\ \alpha_{-1}^{-4/5}\ M_8^{3/2}\ \xi_3^{5/4}\ m_{-1}^{-3/10}$ years

Large profile variations over time

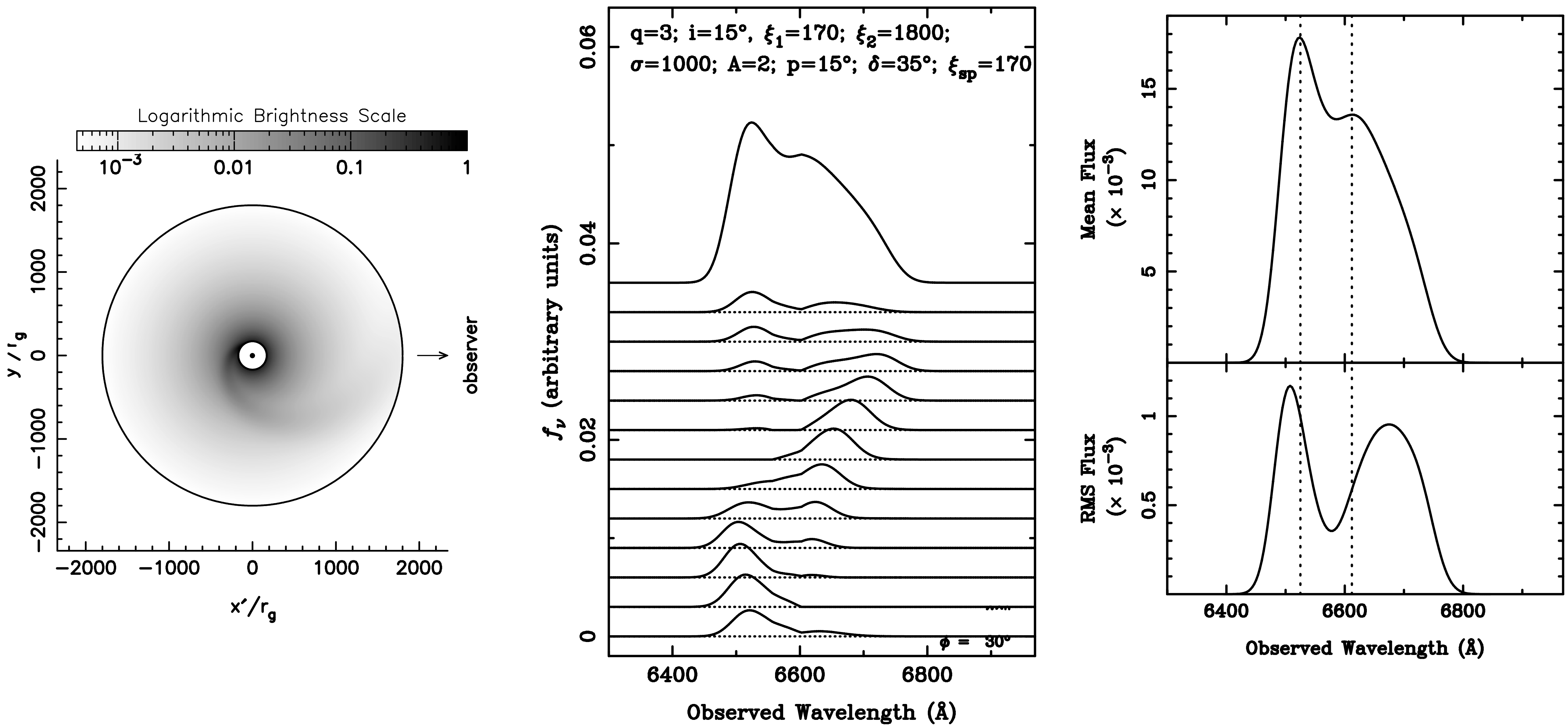


Storchi-Bergmann et al. 2003, ApJ, 598, 956



Gilbert et al. 1998

Models for the variations



From Lewis et al 2008, in preparation

Diagnostic tests so far...

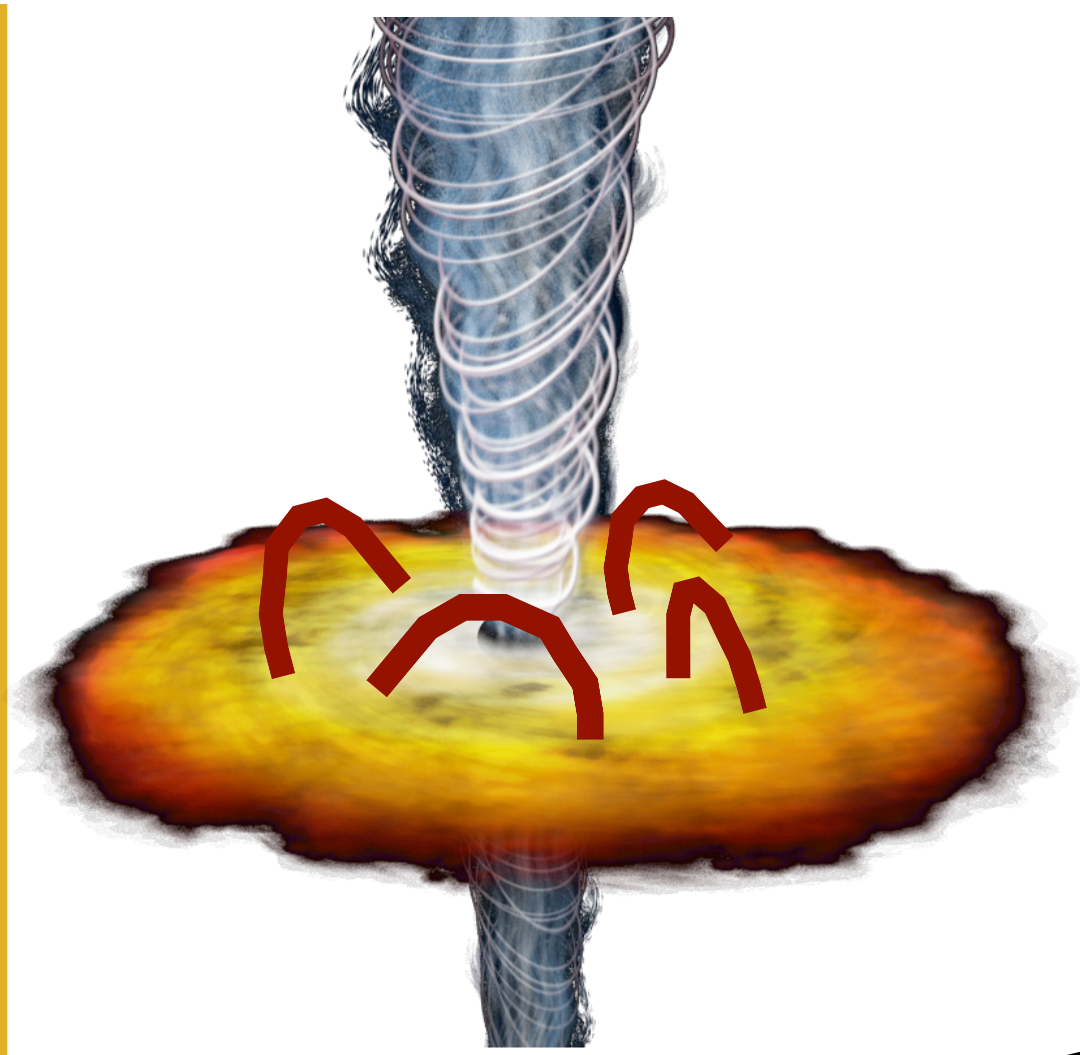
- **Long-term monitoring** → global perturbations of the disk (e.g., Gilbert et al. 1998, Storchi-Bergmann et al. 2003, Gezari et al. 2007, Lewis et al. 2008)
- **Velocity-resolved power spectra** → disk fragmentation (Flohic & Eracleous 2008)
- **UV spectroscopy** → ionization structure of disk, feeble outflows (Halpern et al. 1996, Eracleous et al. 2003)
- **Connection to the greater AGN population** (Flohic & Eracleous 2008, in preparation)

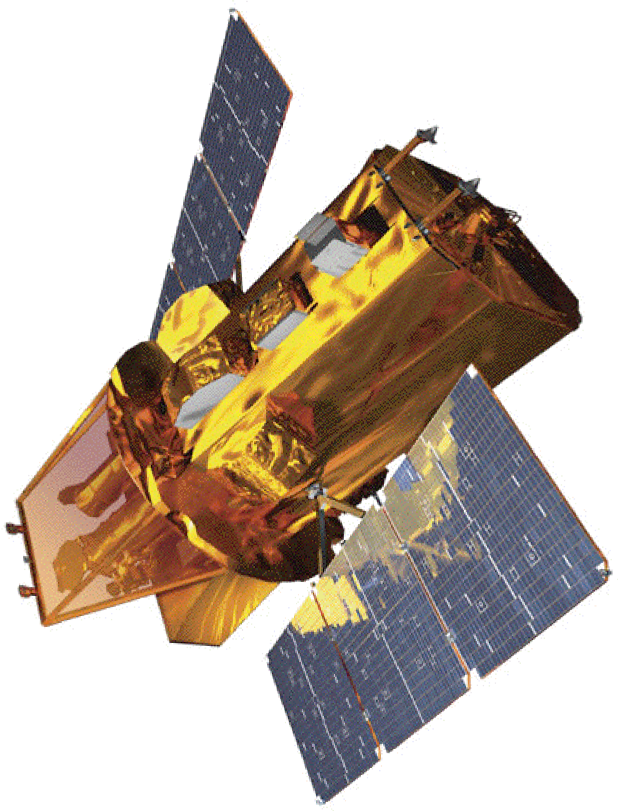
X-Ray Emission From AGNs

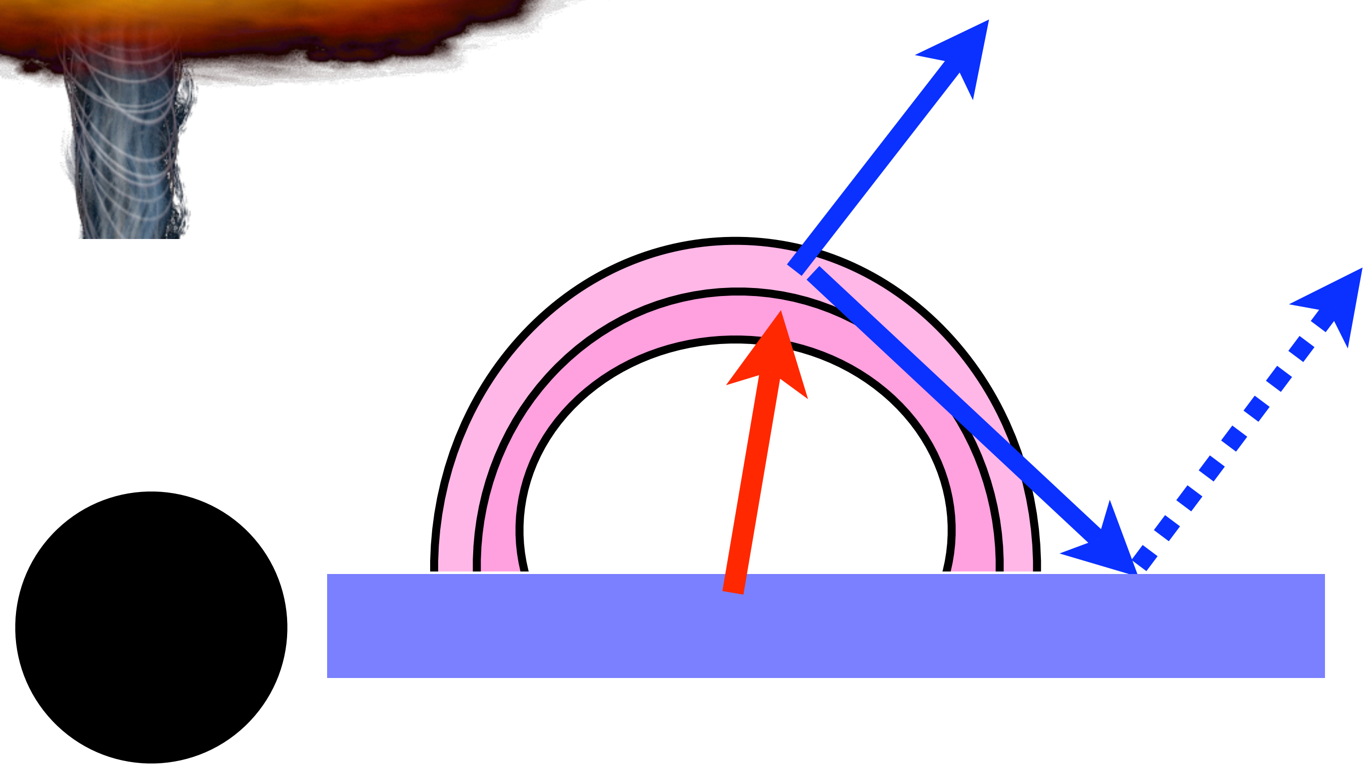
The basic picture

- **The accretion disks of AGNs are not hot enough to emit thermal X-rays. Recall Lecture 1: $T \sim 10^5$ K**
- **But AGNs emit hard X-rays, up to ~100 keV**
  - Observed X-ray spectrum is roughly a power law
  - $F(E) \propto E^{-\alpha}$ with $\alpha \approx 0.8$–1.0
- **In a small fraction of objects, the X-rays are produced in a jet pointed at us.**

X-Ray Emission from AGNs



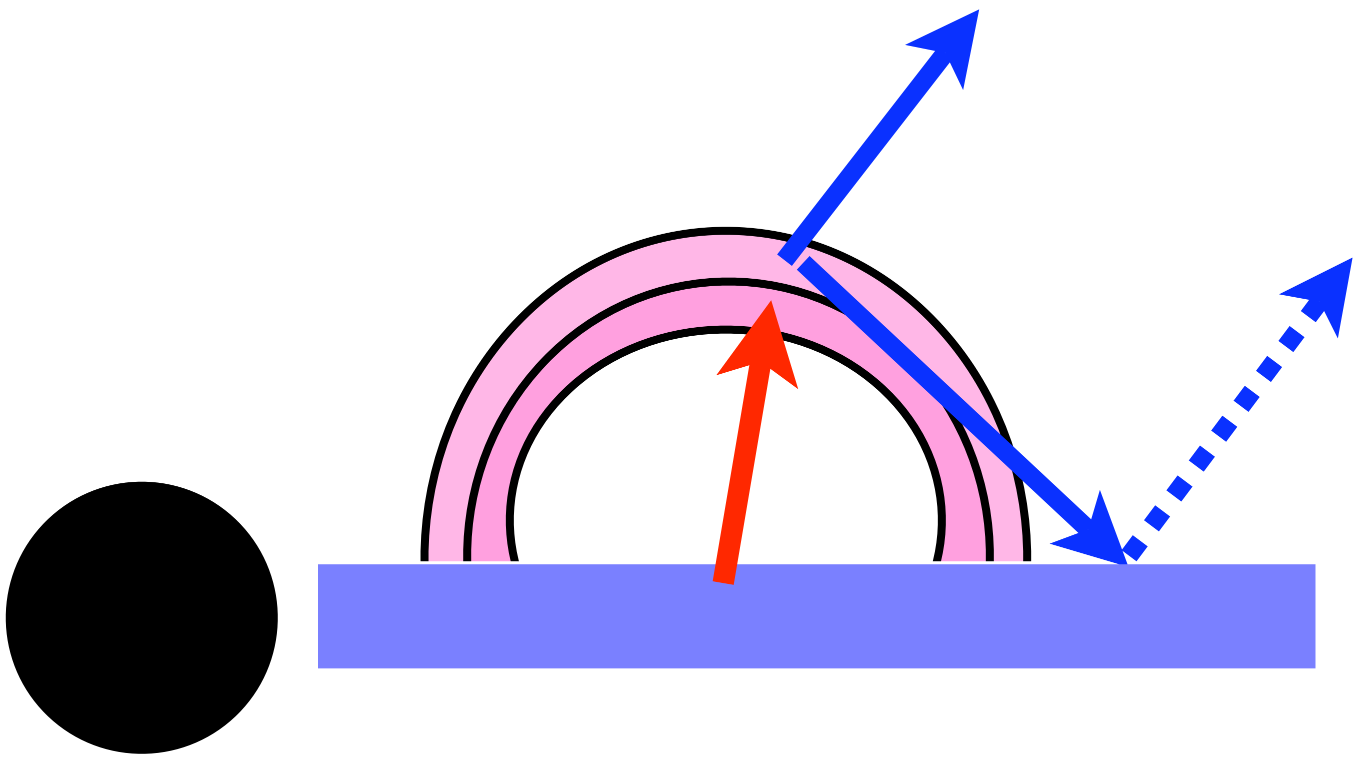




X-Ray Emission Flowchart

Hot corona

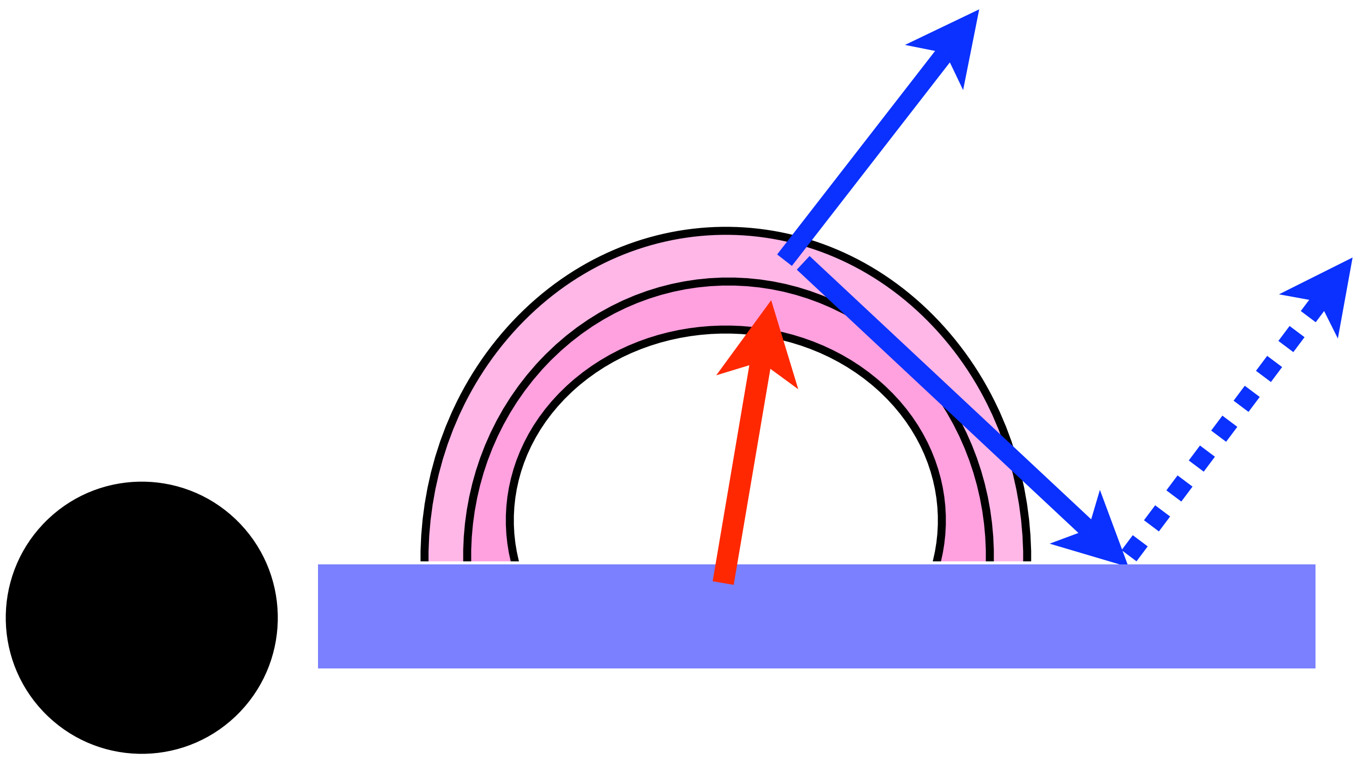
- May resemble coronal loops of stars.
- Powered by magic.
- Electrons may have power-law (or thermal?) energy distribution.



X-Ray Emission Flowchart

Soft photons from the disk (kT~20 eV) illuminate the coronal plasma.

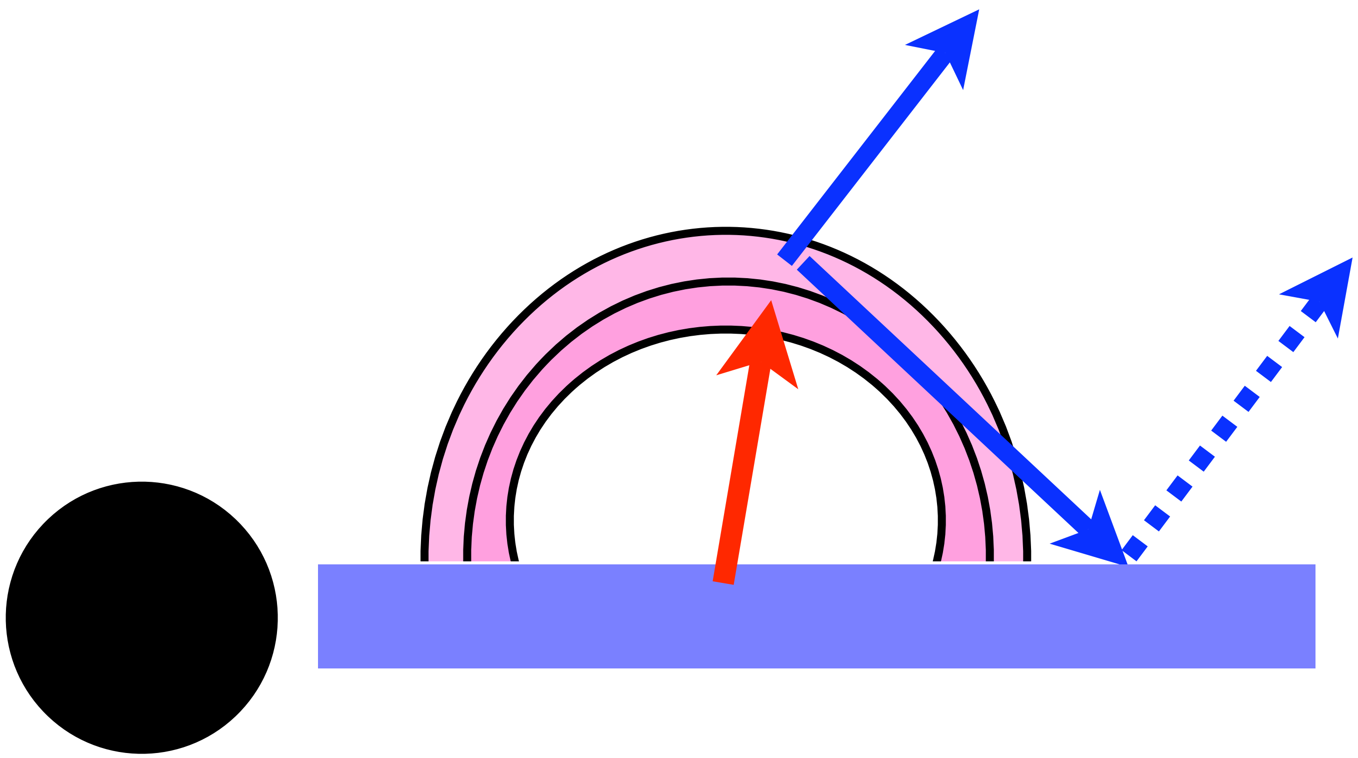
- Compton up-scattering 20 eV → 1–100 keV
- Some up-scattered photons go to the observer and some go back to the disk



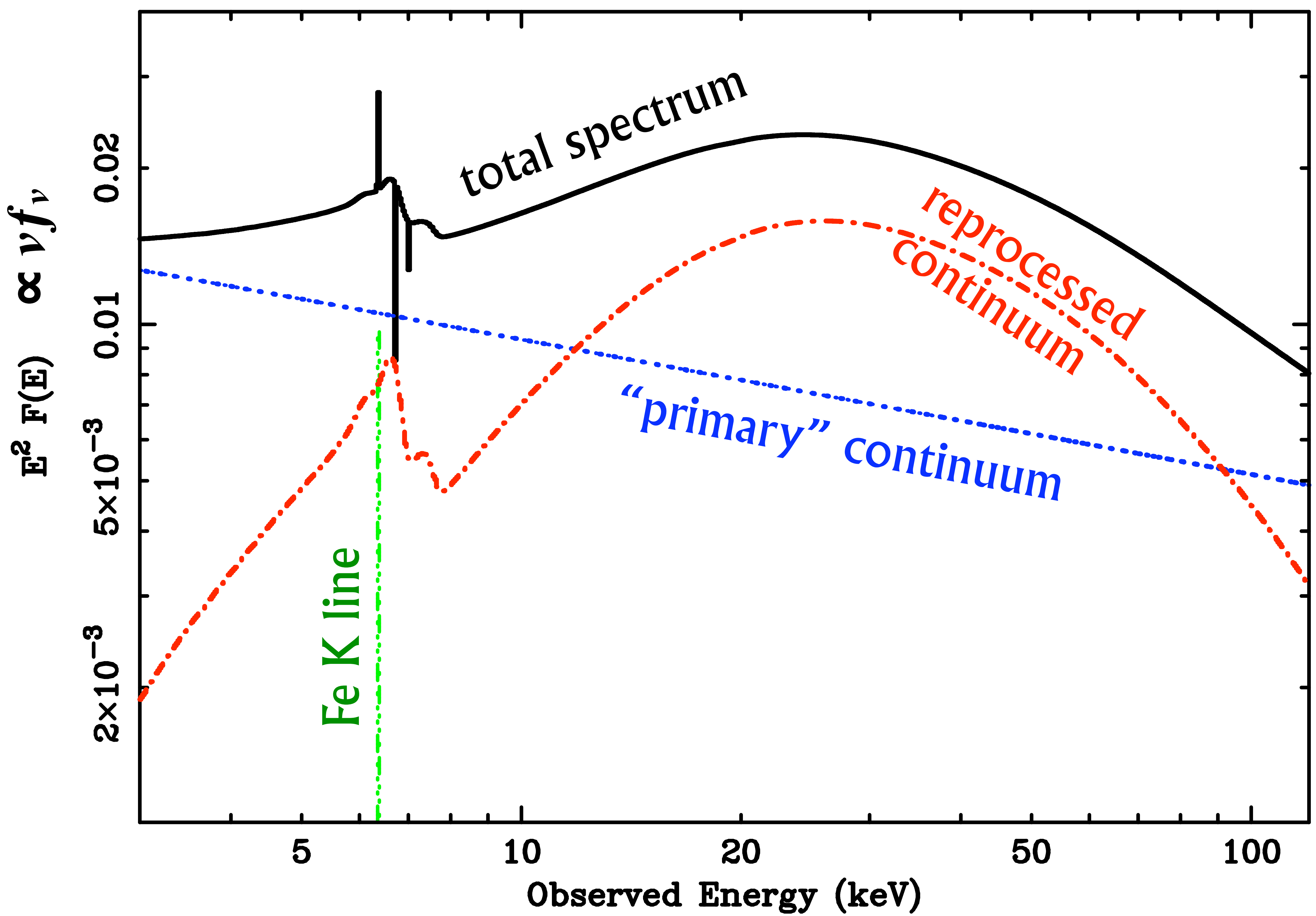
X-Ray Emission Flowchart

Photons returning to the "cool" disk...

- ionize it and heat it up,
- some are scattered back out by bound atomic electrons, suffering photoelectric absorption along the way



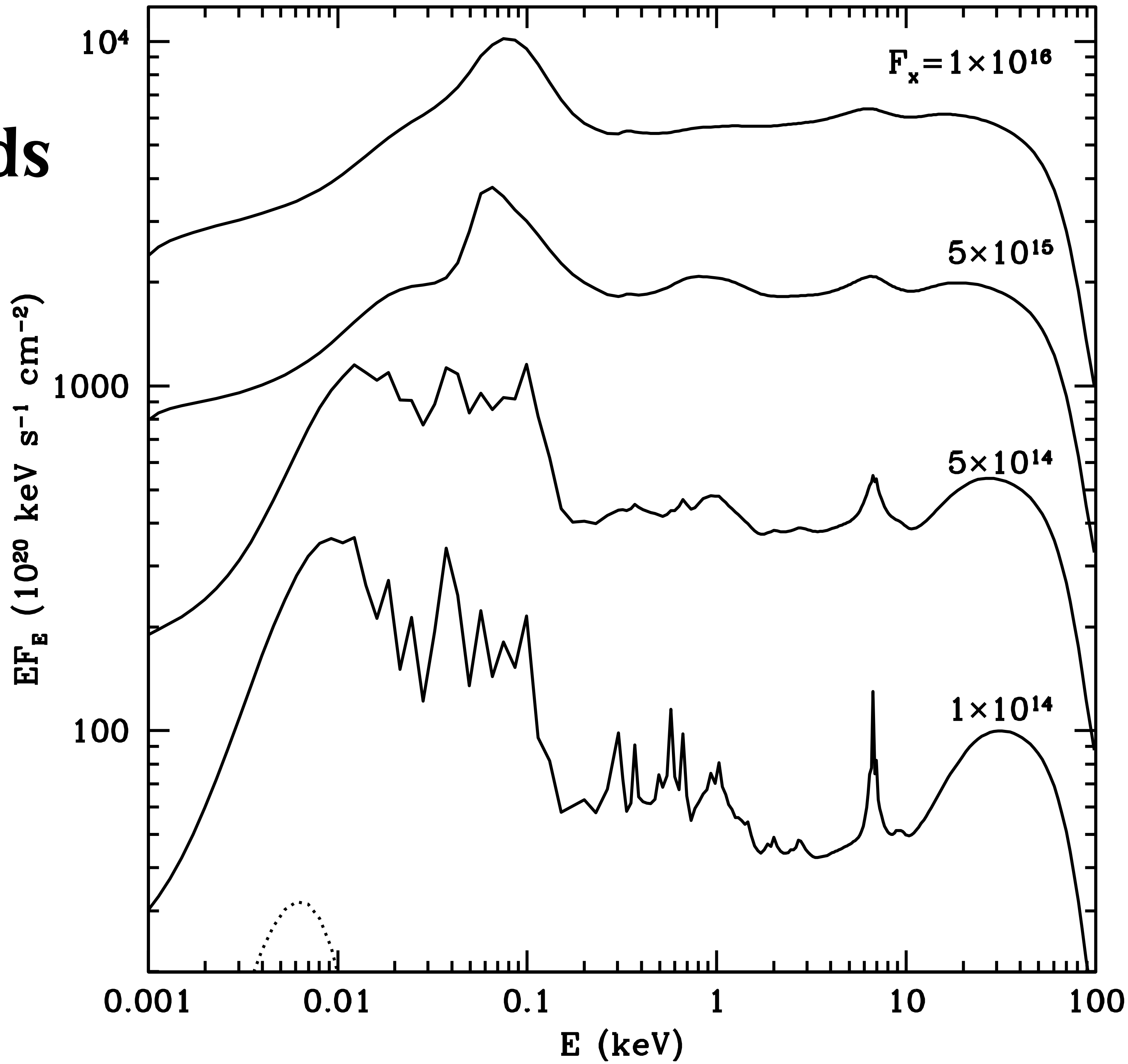
Observer sees sum of all spectra



from Minuitti et al. 2007, PASJ, 59S, 315

Emergent disk spectrum

- Emergent disk spectrum depends on ionization state



from Ballantyne et al 2001, MNRAS, 327,10

Emergent disk spectrum

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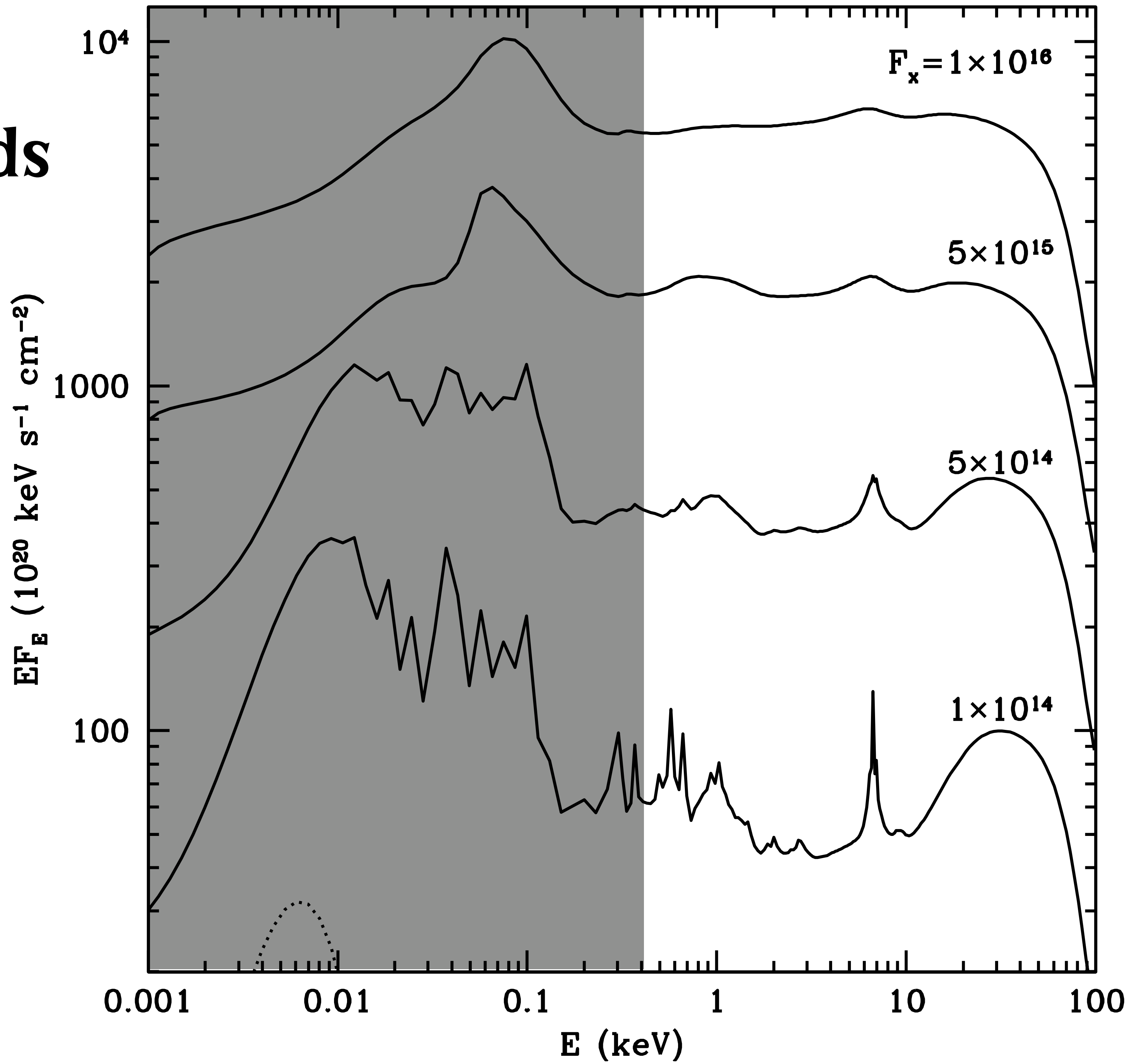
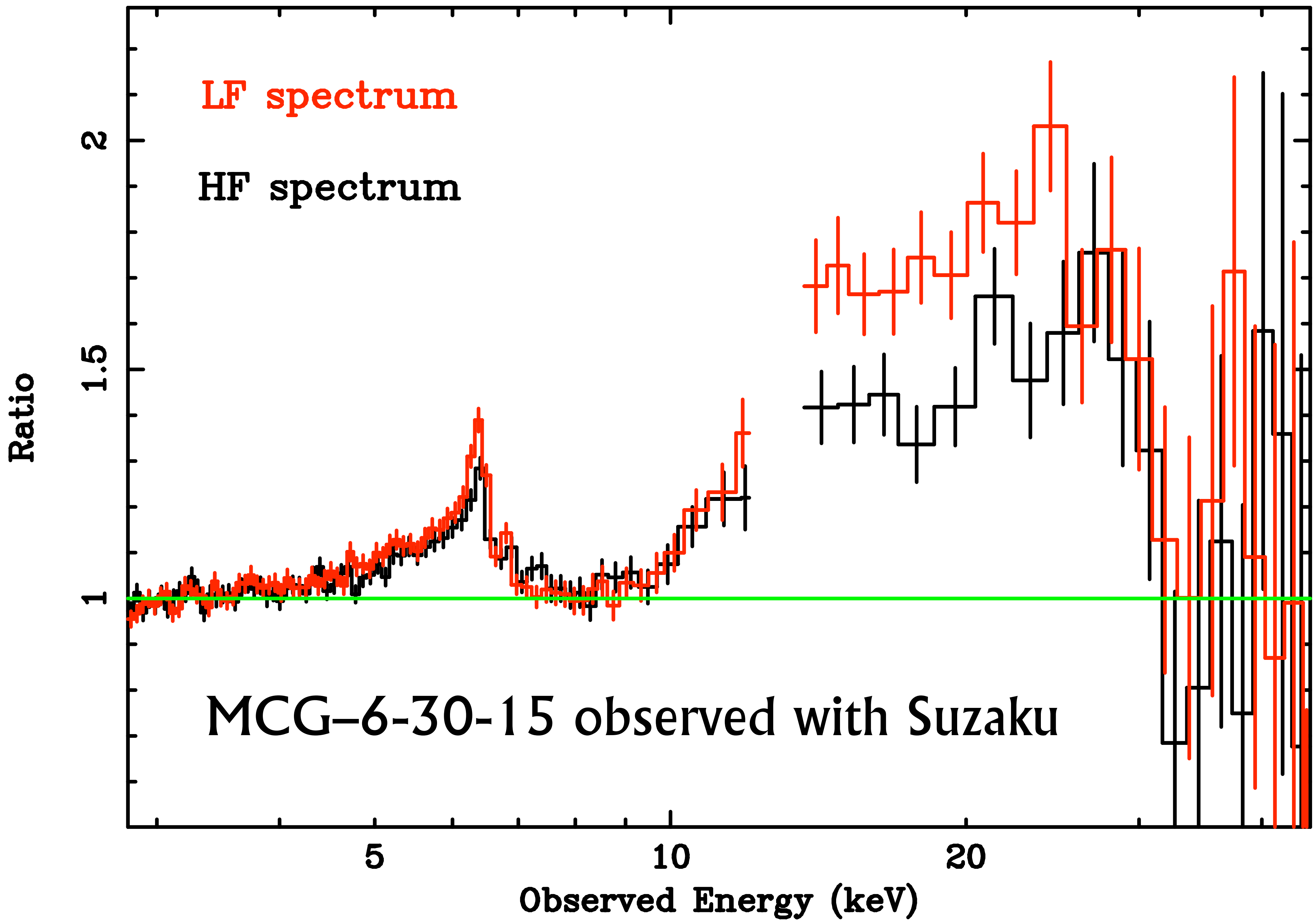


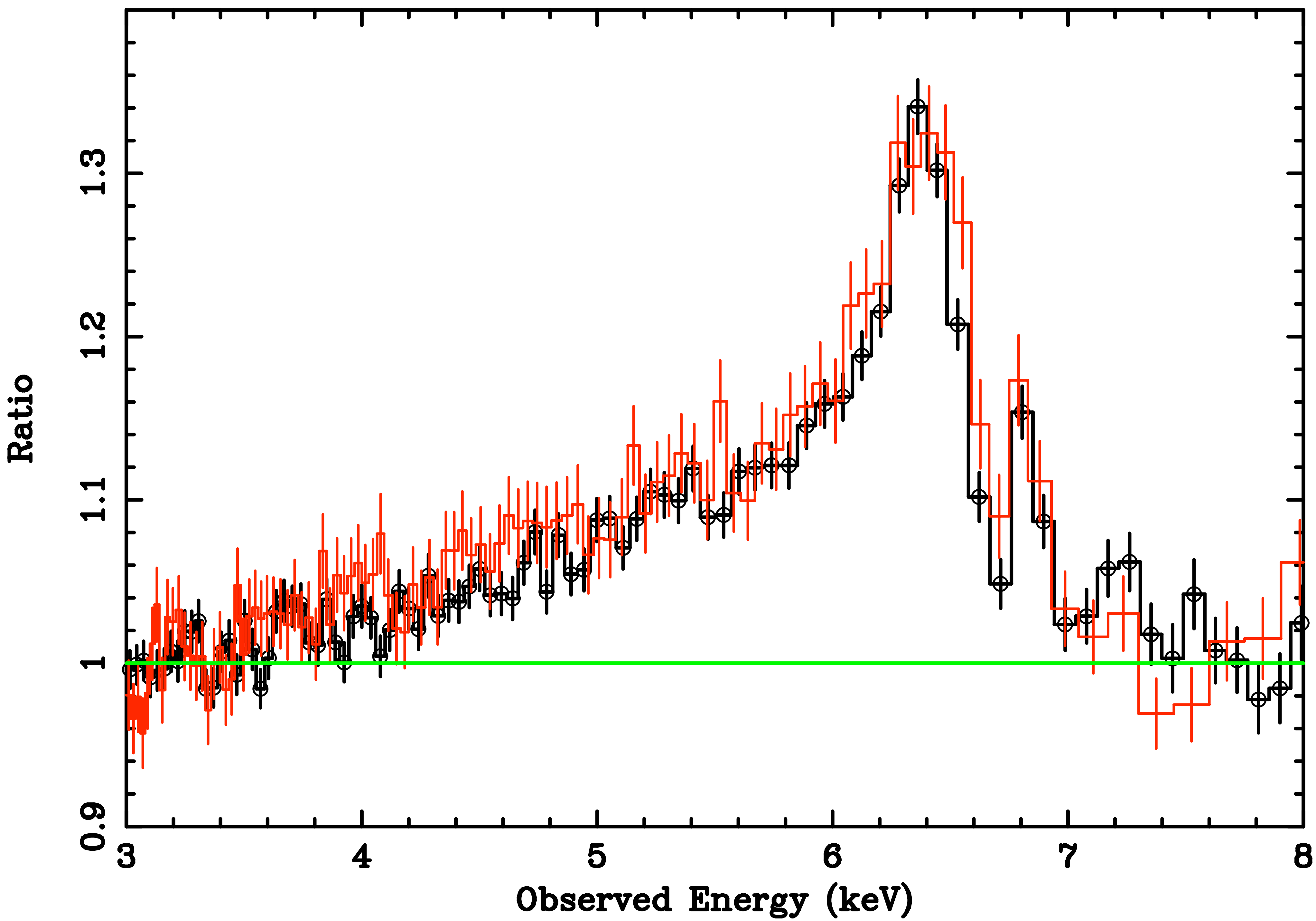
from Ballantyne et al 2001, MNRAS, 327,10

Comparison of Model to Data



from Minuitti et al. 2007, PASJ, 59S, 315

Zooming in on the Fe Kα Line



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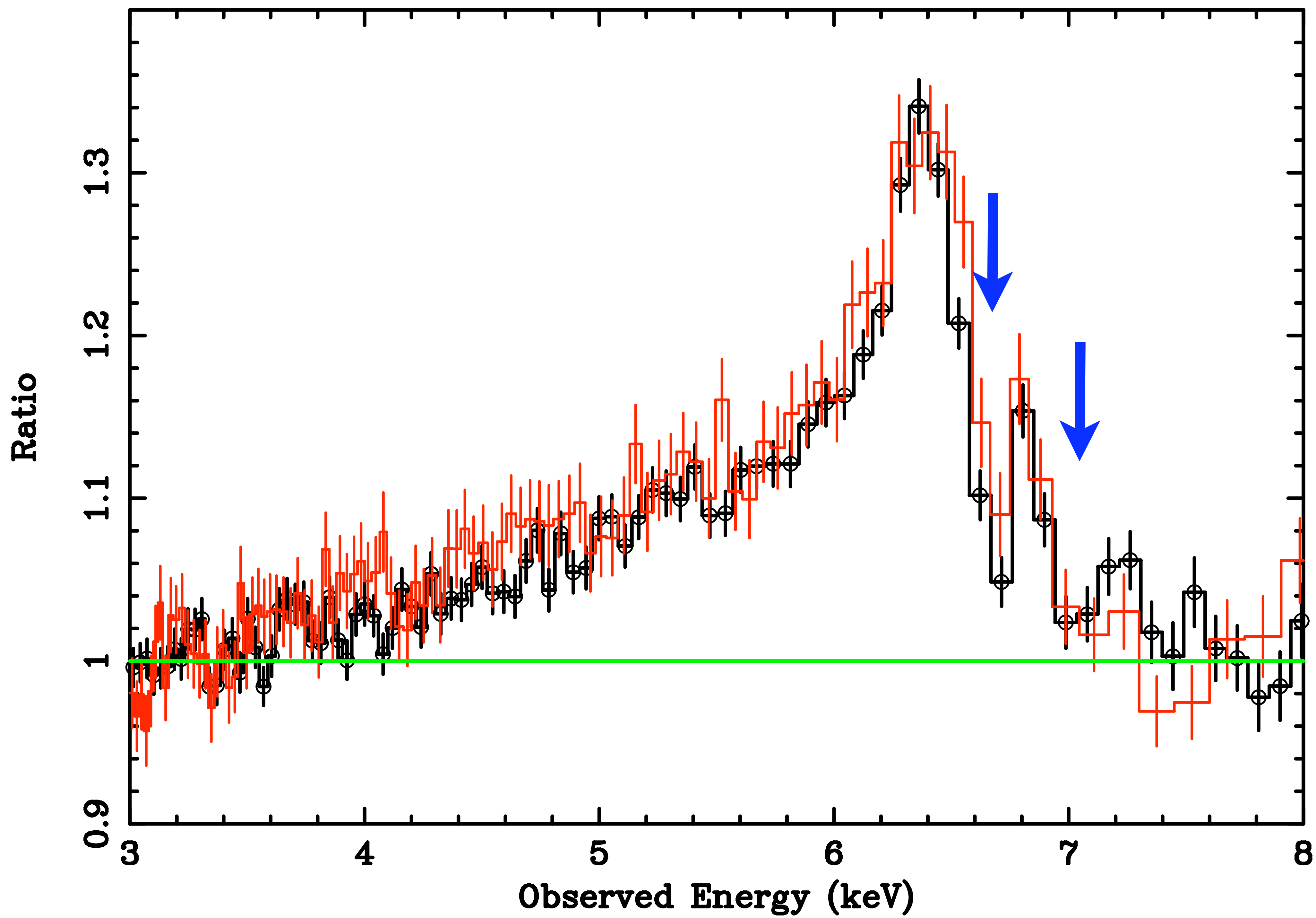
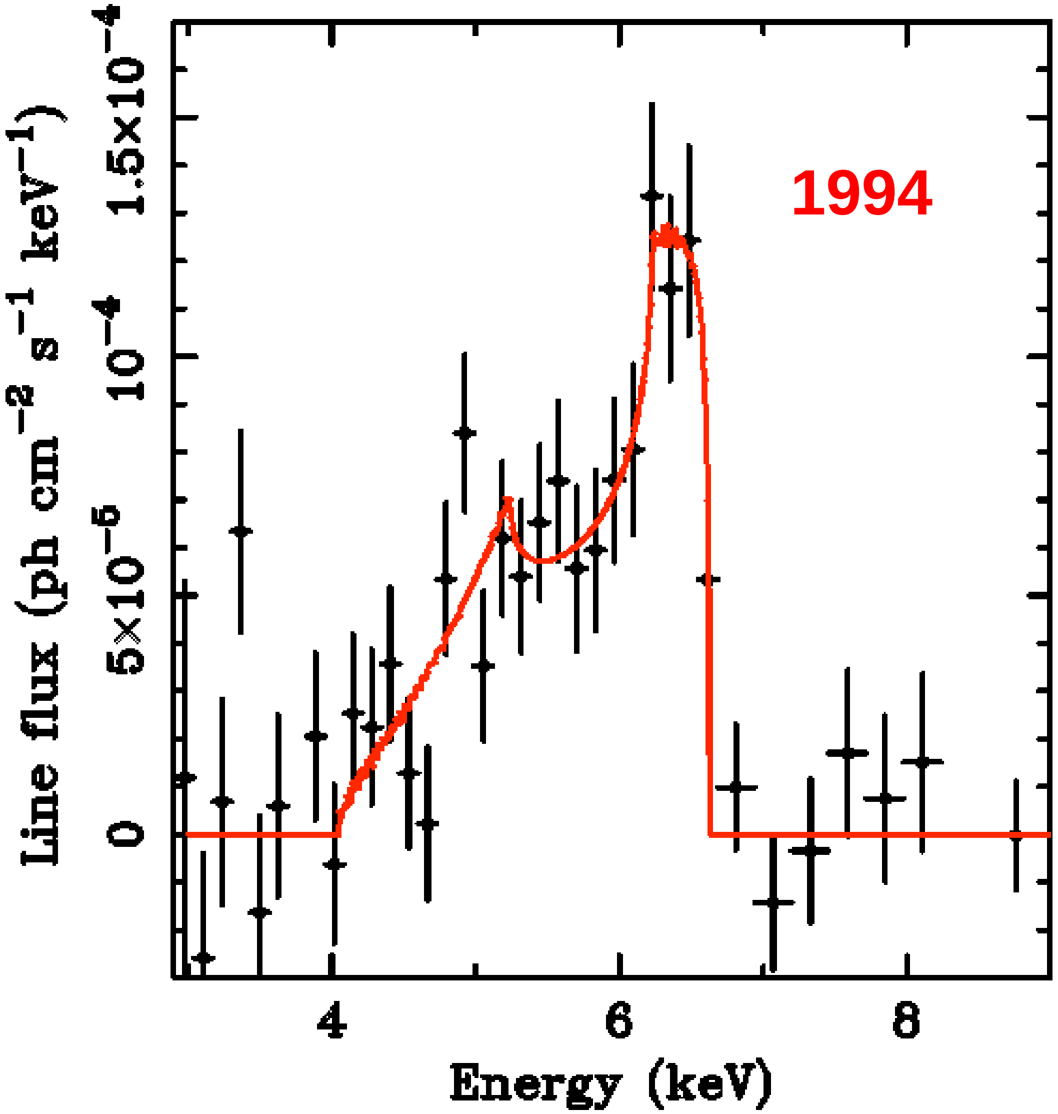
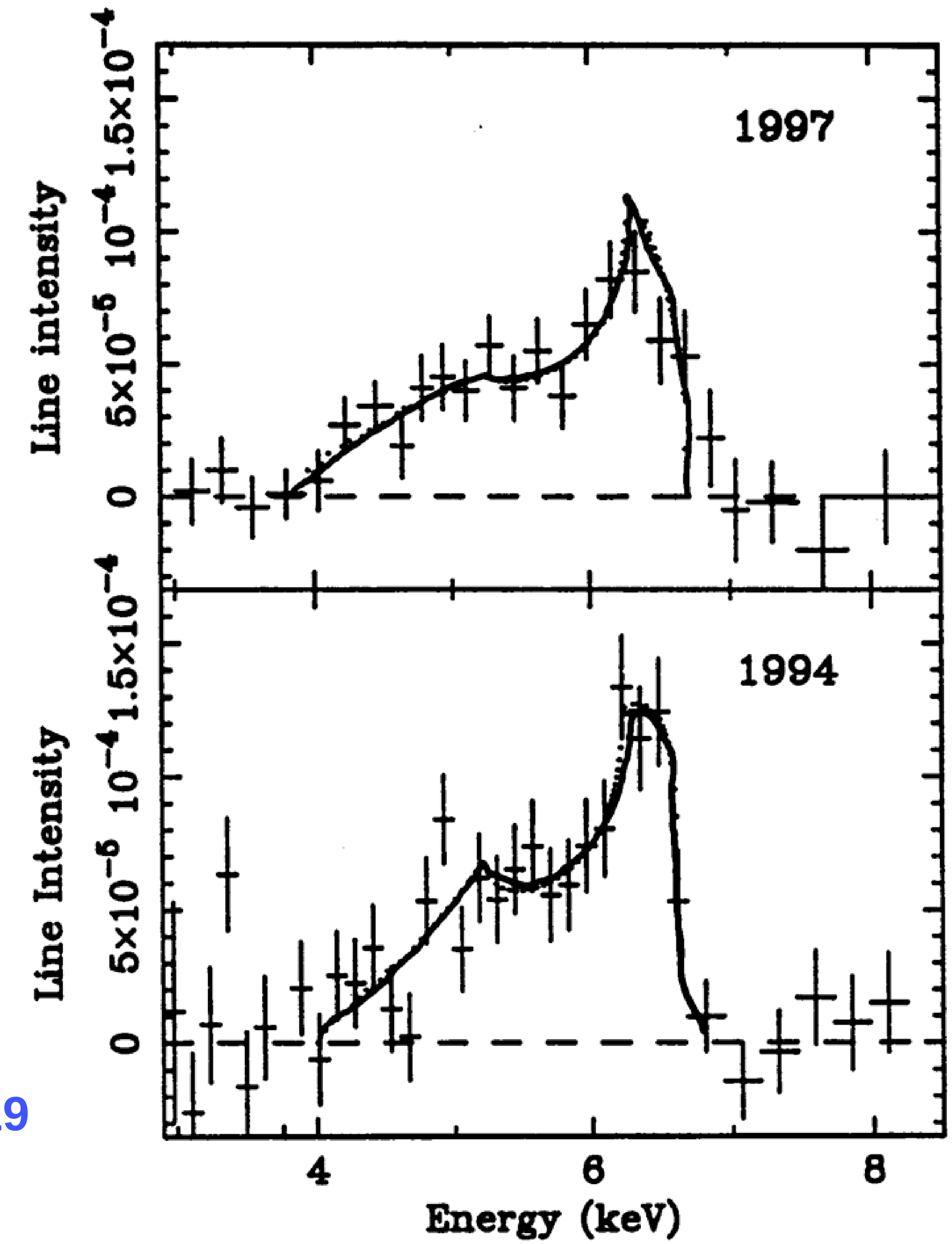


from Minuitti et al. 2007, PASJ, 59S, 315

First Fe Kα profiles from ASCA





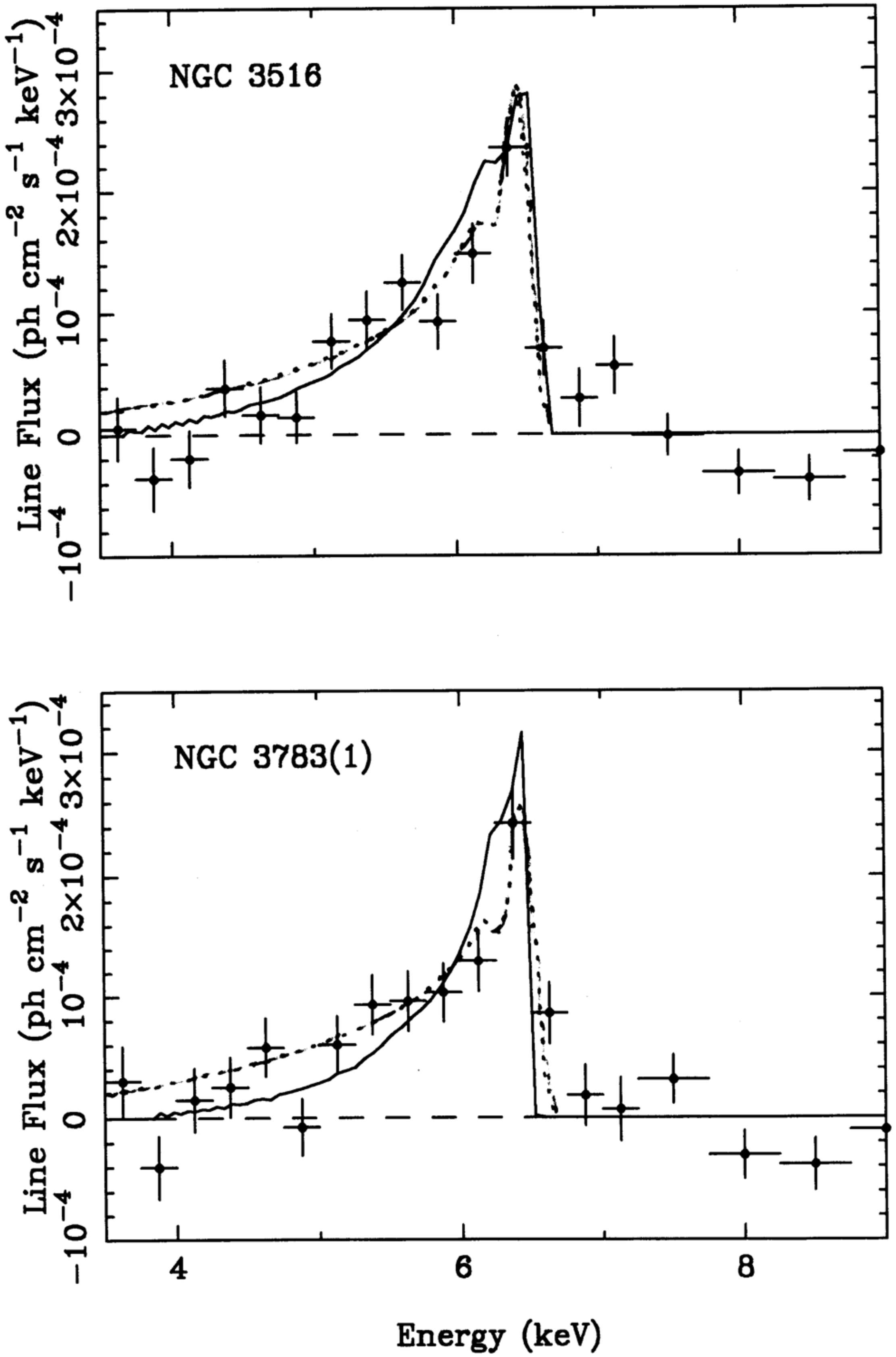
MCG –6-30-15:

figures from
Tanaka et al. 1995, Nature, 375, 659
Iwasawa et al. 1999, MNRAS, 306, L19

Spinning or Not?

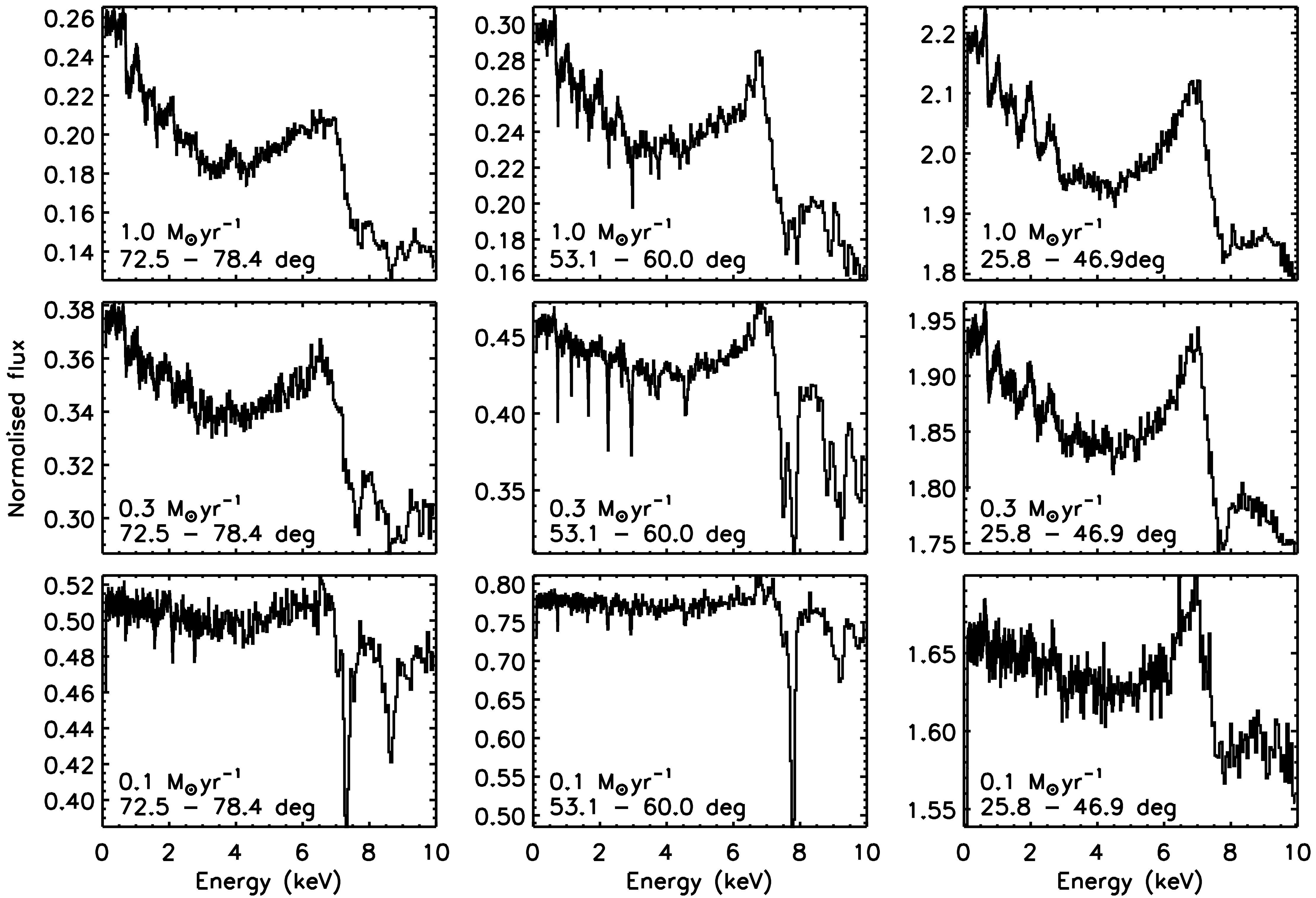
From Nandra et al. 1997

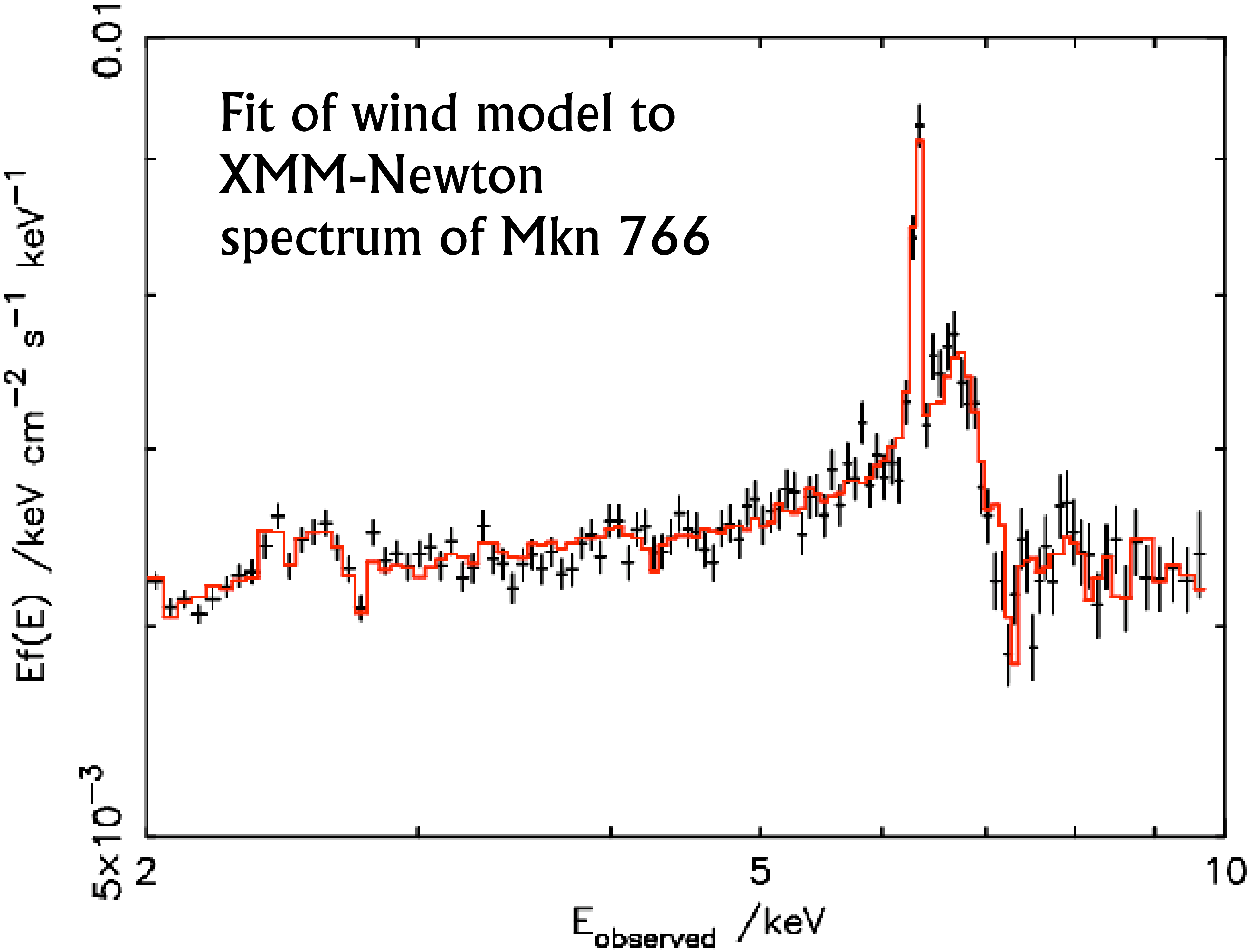
ApJ, 477, 602



Absorption+Scattering Though Wind

From Sim et al. 2008, MNRAS, in press

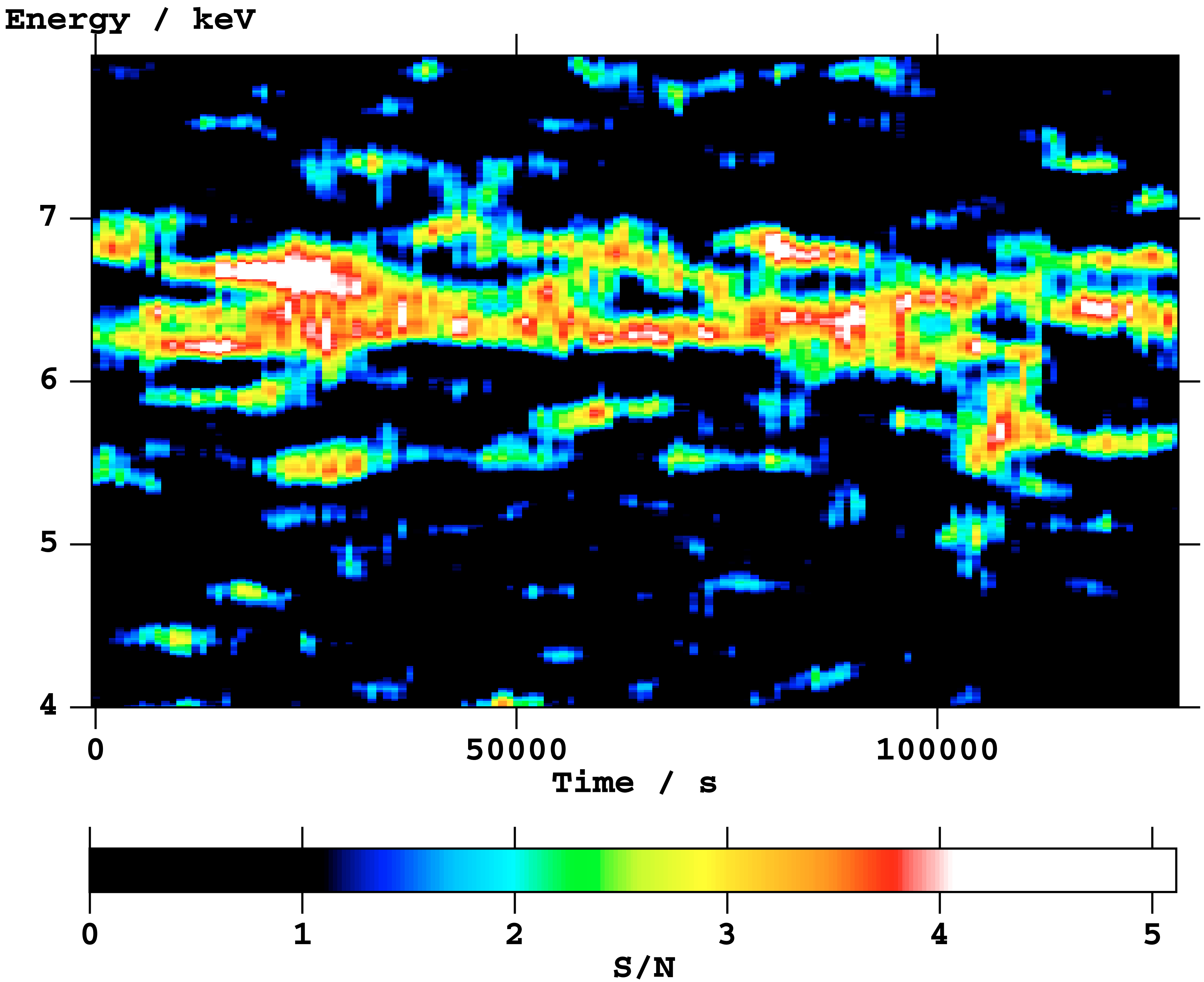




From Sim et al. 2008, MNRAS, in press

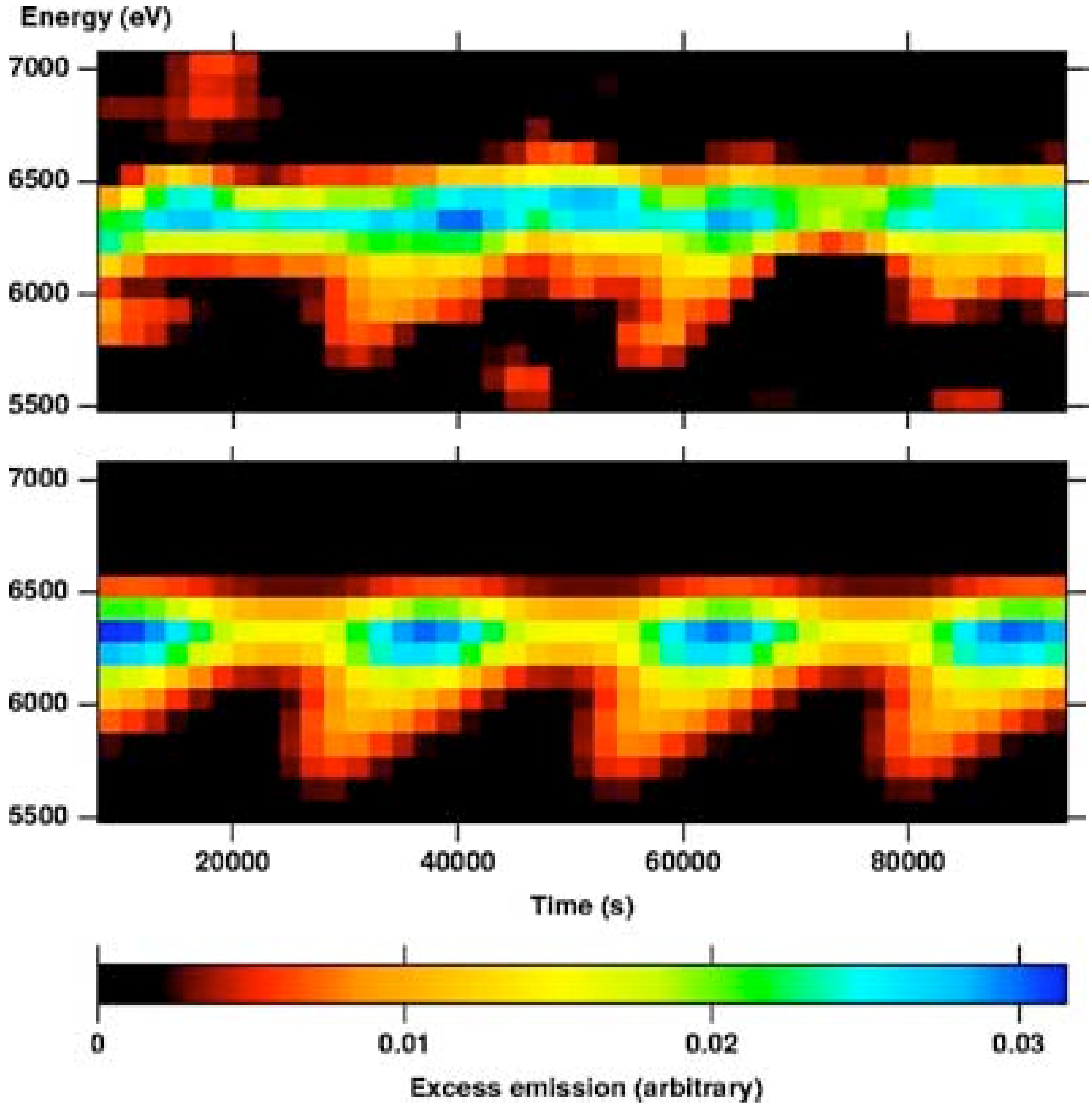
If the line is coming from the disk...

Mrk 766



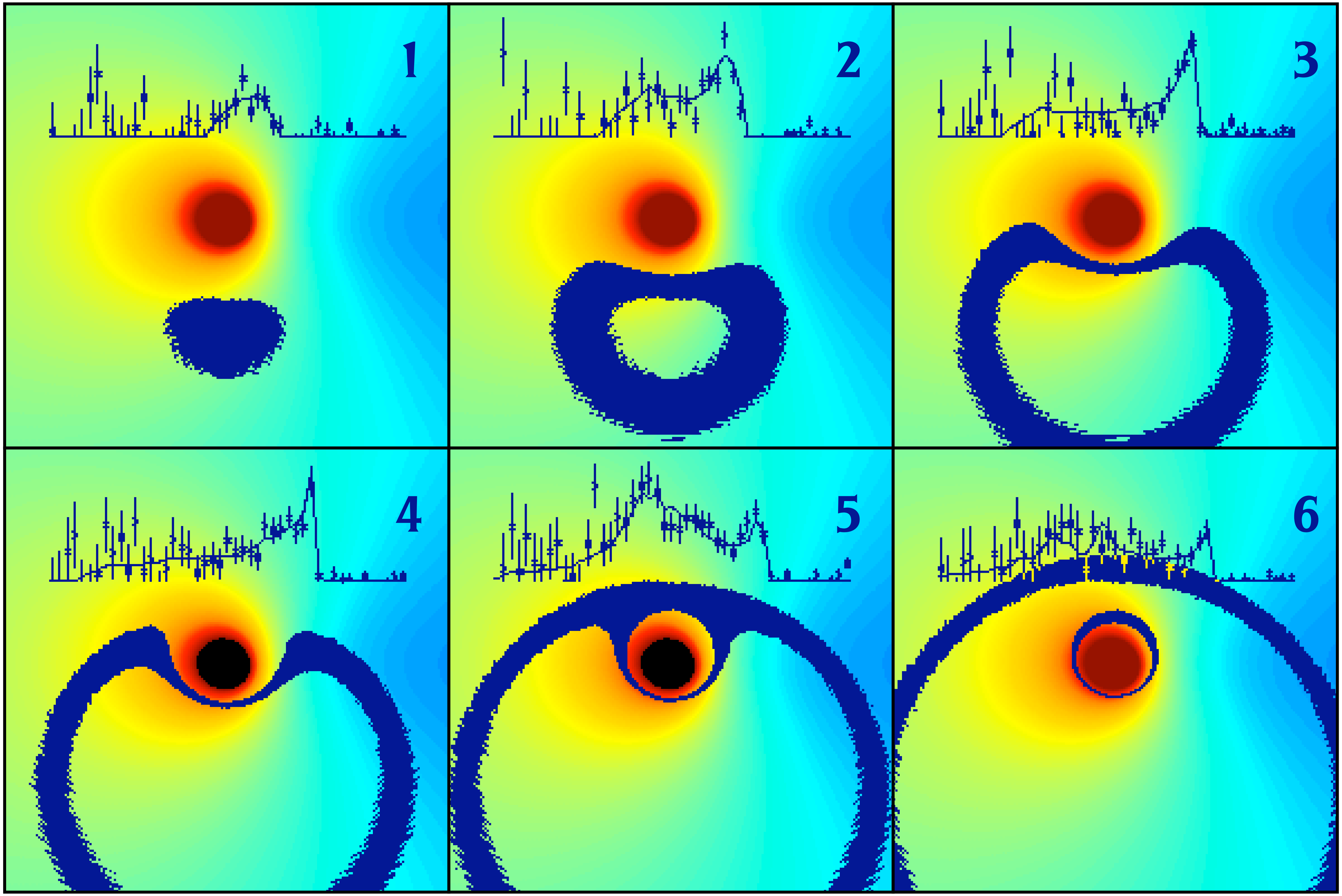
from Turner et al. 2006, A&A, 445, 59

NGC 3516



from Iwasawa et al. 2004, MNRAS, 355, 1073

In the Future: Echos of Flares



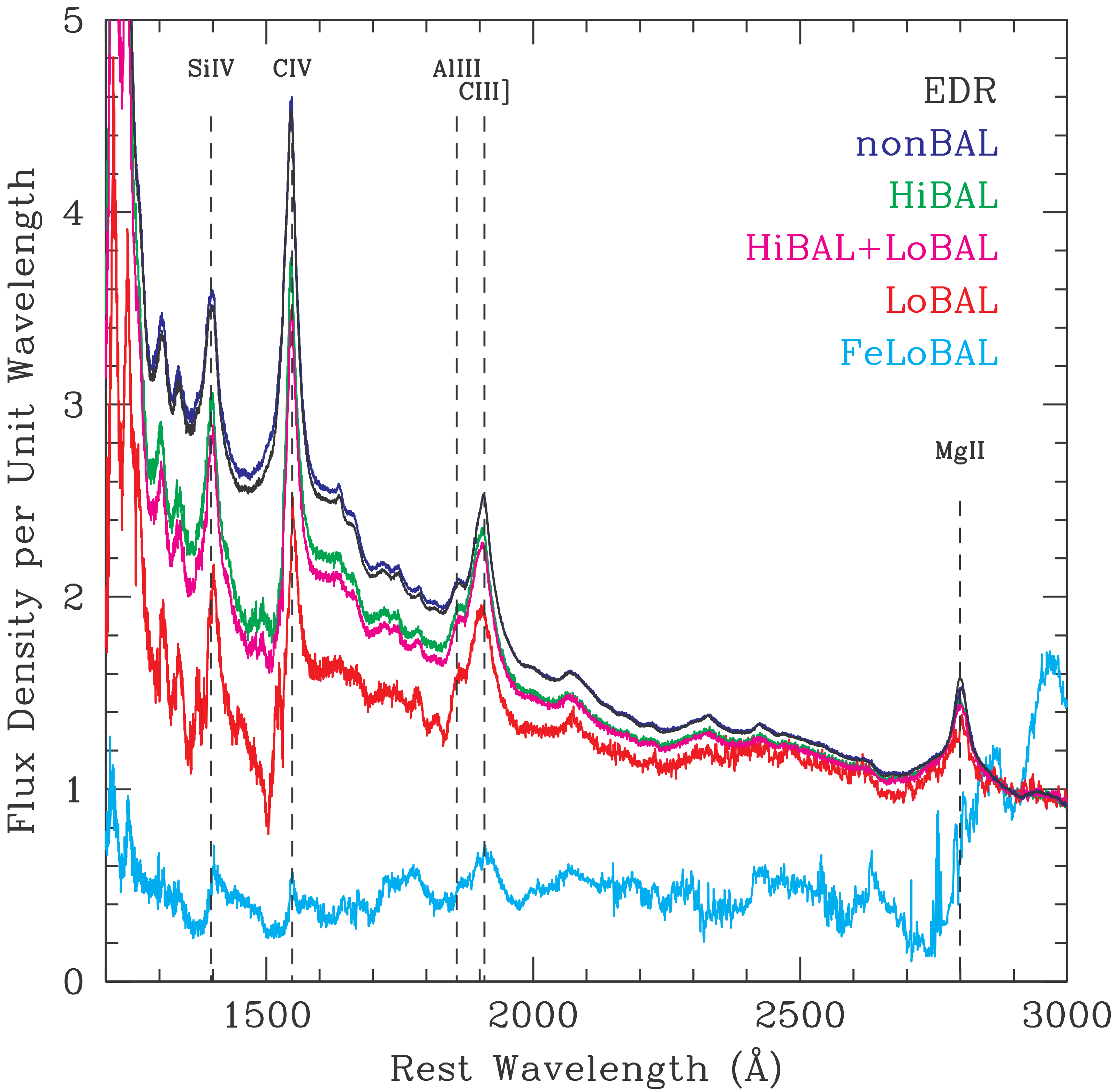
Young & Reynolds 2000, ApJ, 529, 101

Absorption from Outflows

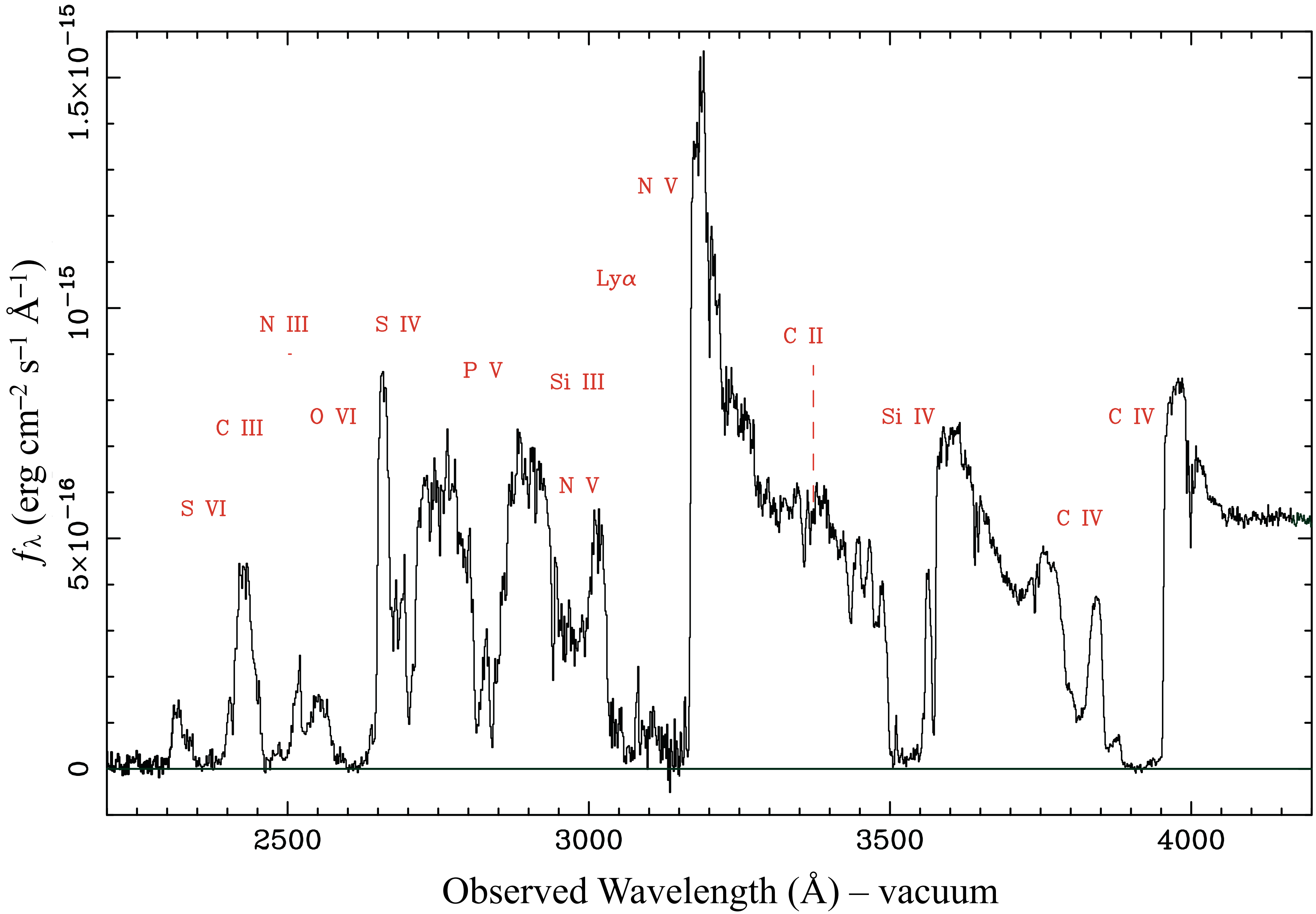
The zoo of UV absorption lines

- **BALs: Broad Absorption Lines**
  - smooth, deep, blue-shifted absn. troughs in UV resonance lines
  - FWHM > 2,000 km/s (traditional definition) and easily up to 30,000 km/s
  - found in ~20% of all quasars
  - do these absorbers/outflows represent a phase in the evolution of every quasar, or do they cover a small solid angle in all quasars ?

Progression of BALs



CSO 673: Example of a BAL Quasar

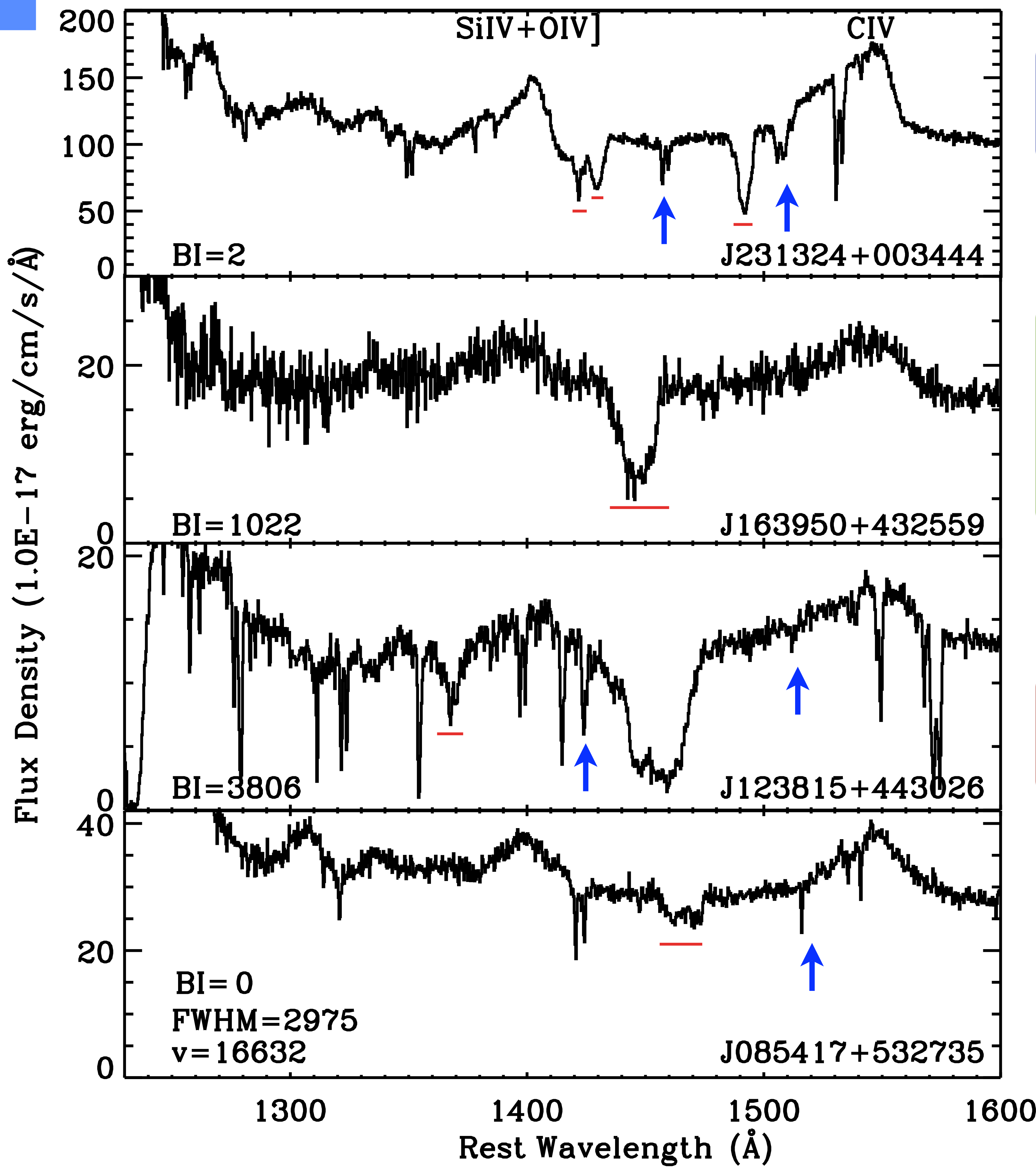


from Junkkarinen et al. in prep (plot courtesy of Fred Hamann)

Zoo of UV absorption lines continued

- **NALs: Narrow Absorption Lines**
  - UV resonance doublets must not be blended
  - FWHM < 500 km s^{-1}, based on C IV λλ1448,1451
- **"mini-BALs": narrower than BALsCatch-all for everything in between**
  - wide variety of profiles
- are they "mini-BALs" or "super-NALs"?

Examples of mini-BALs and NALs



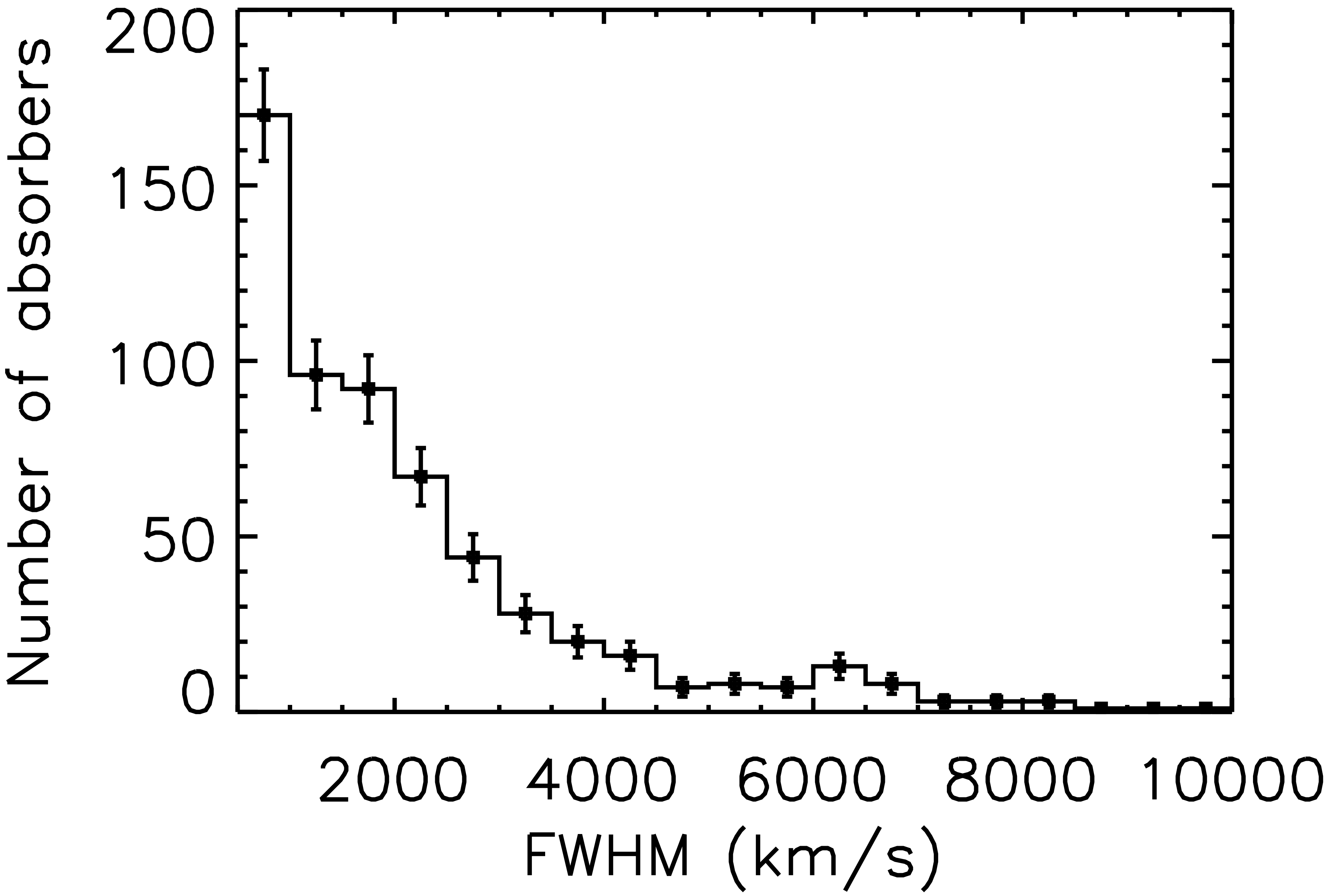
Multiple NAL or mini-BAL systems are possible

Mini-BALs can be fairly broad (~ 2000 km/s) with significant substructure (cf., HS 1603+3820)

NALs and mini-BALs can co-exist with BALs

from Rodriguez et al. in prep (plot courtesy of Paola Rodriguez)

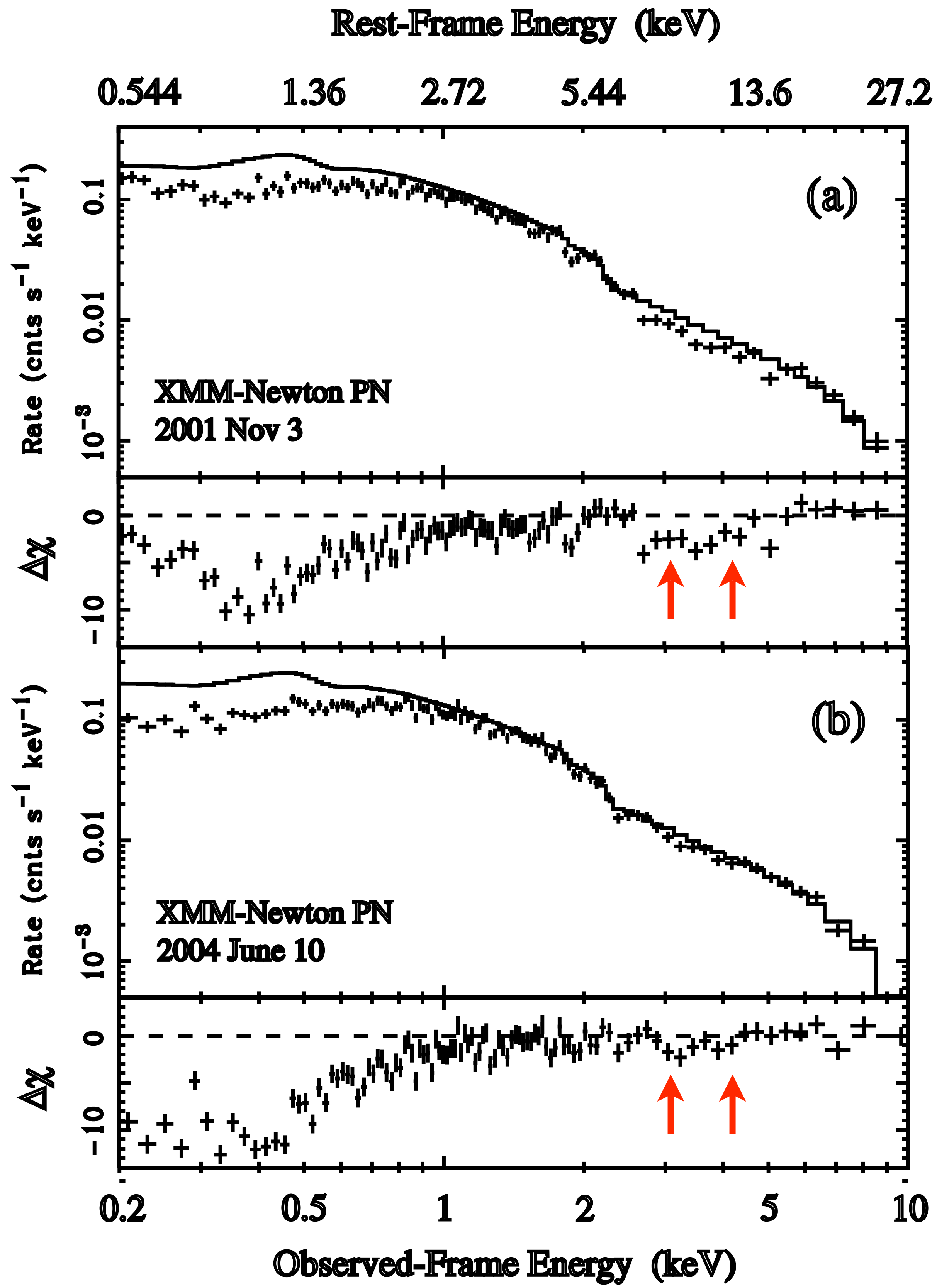
Distribution of Line Widths



from Rodriguez et al. in prep (plot courtesy of Paola Rodriguez)

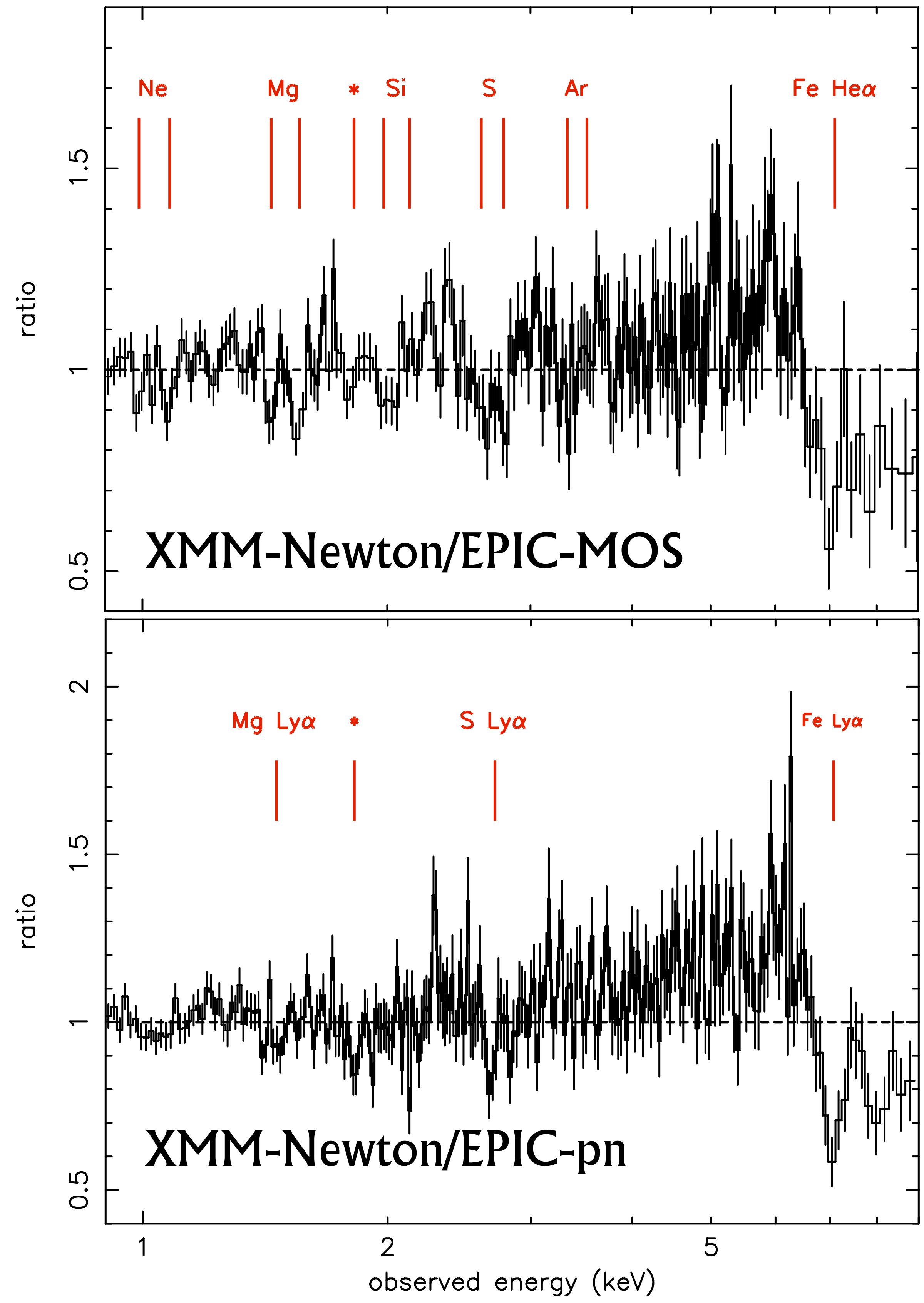
High-Velocity X-ray lines in quasars

- Example: PG 1115+080
  - z=1.72 (lensed)
  - Fe XXV and XXVI
  - $\Delta\upsilon \sim 0.36$ c
  - Variable lines
  - Chartas et al. 2007, AJ, 133 1849

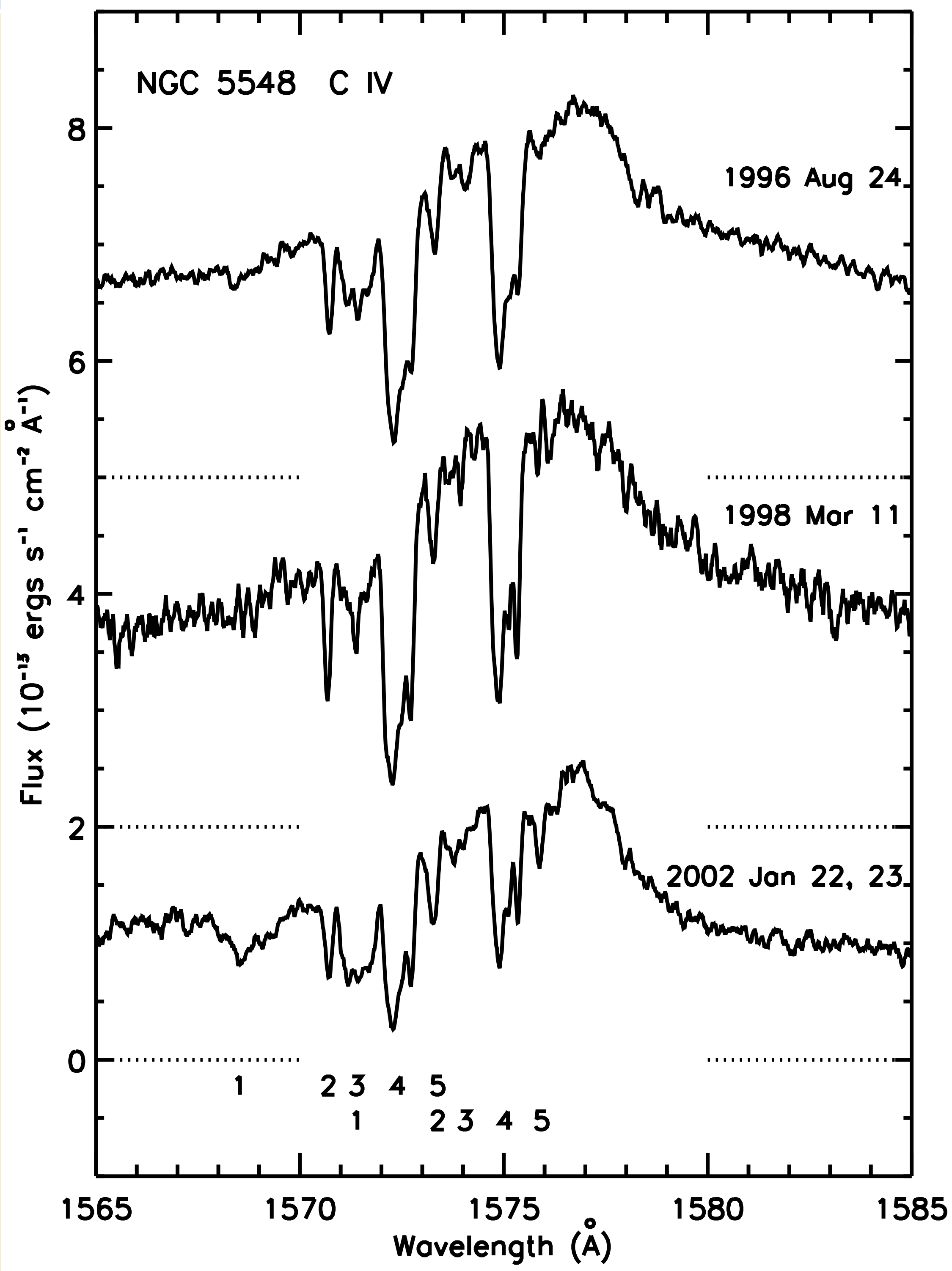


High-Velocity X-ray lines in quasars

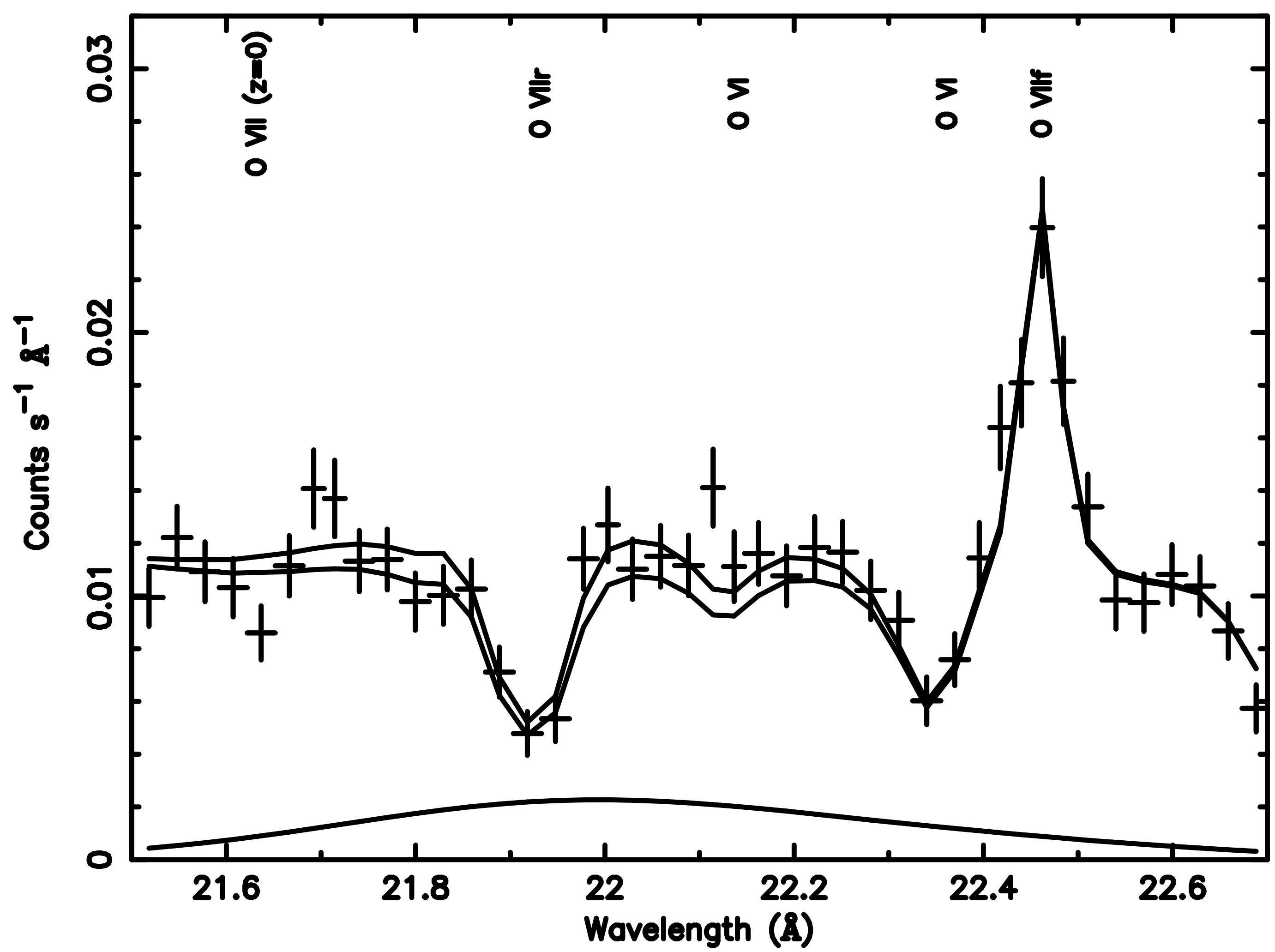
- **Example: PG 1211+143**
  - $z = 0.0809$
  - Multiple lines
  - $\Delta\upsilon \sim 0.14$ c
  - $\dot{M}_{out} \sim 3.4\ M_{\odot}/yr$
  - Pounds & Page 2006, MNRAS, 372, 1275



UV and X-ray absorption in Seyferts



Example:
UV and X-Ray absorption lines in NGC 5548; $\Delta \upsilon \sim 2000$ km/s

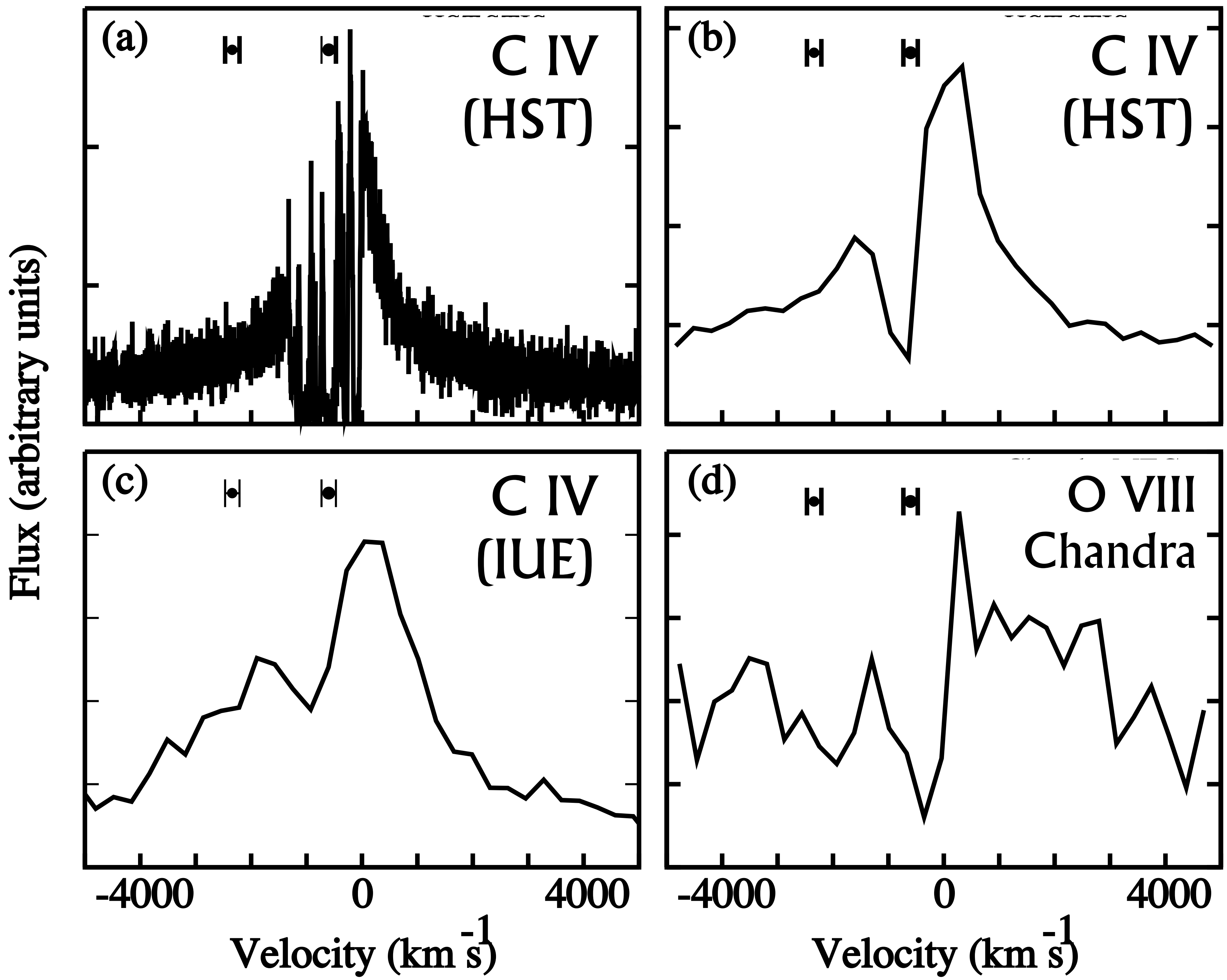


Crenshaw et al. 2003, ApJ, 594, 116

Steenbrugge et al. 2005, A&A, 434, 469

Comparison of X-ray and UV lines

NGC 4051

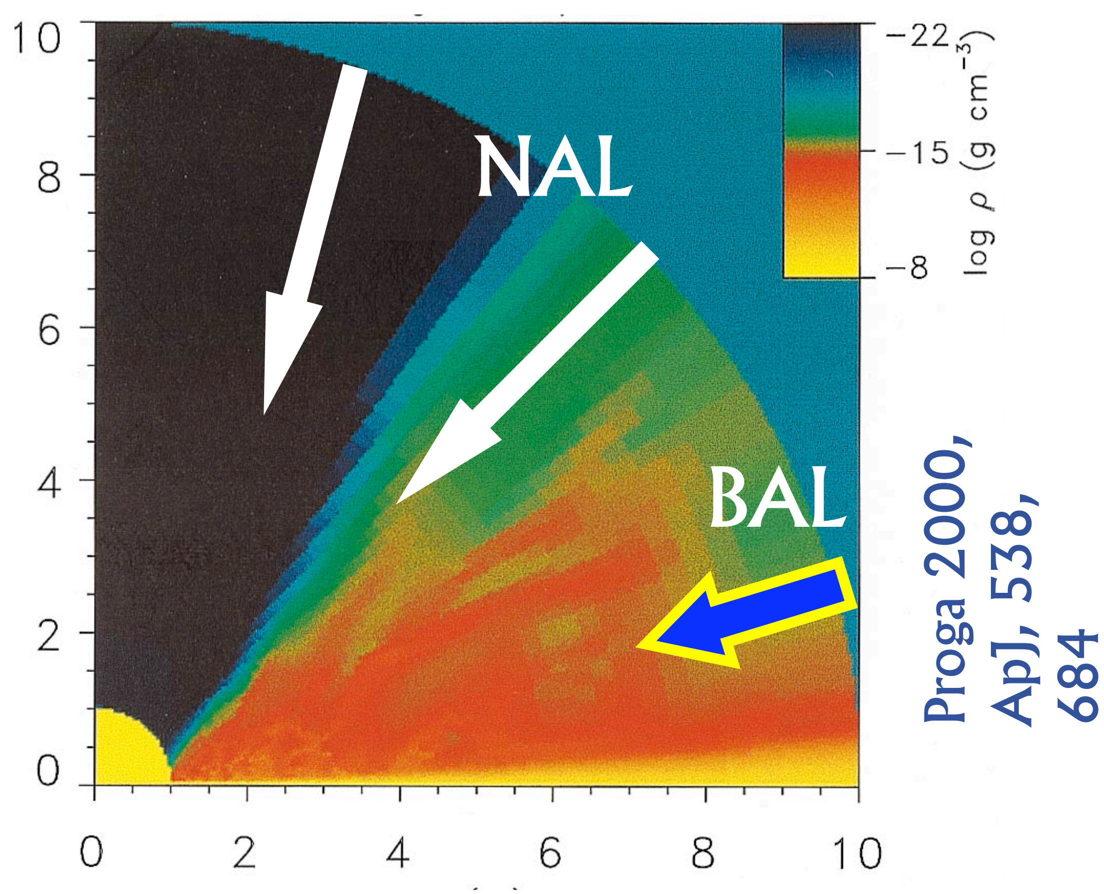


Collinge et al. 2001, ApJ, 552, 2

Properties of absorption lines

- **BALs found in ~ 20% of quasars**
  - same family as mini-BALs
  - FWHM up to 30,000 km s^{-1}
- **NALs found in ~50% of quasars**
  - up to $\Delta\upsilon$ ~ 60,000 km s^{-1}
  - ~ 30% of all NALs are intrinsic
- **UV and X-Ray abs lines in ~ 50% of Seyferts**
  - $\Delta\upsilon$ ~ 2,000 km s^{-1}
  - similar UV and X-ray line profiles

Families of disk wind models



- Line-Driven
  - Murray+05; Proga+…
- Magnetocentrifugal+Line
  - Köenigl & Kartje 94; Proga 00; Everett 05
- Thermally Driven (via X-Ray heating of dusty torus)
  - Krolik & Kriss 95,01; Chelouche & Netzer 05

The End