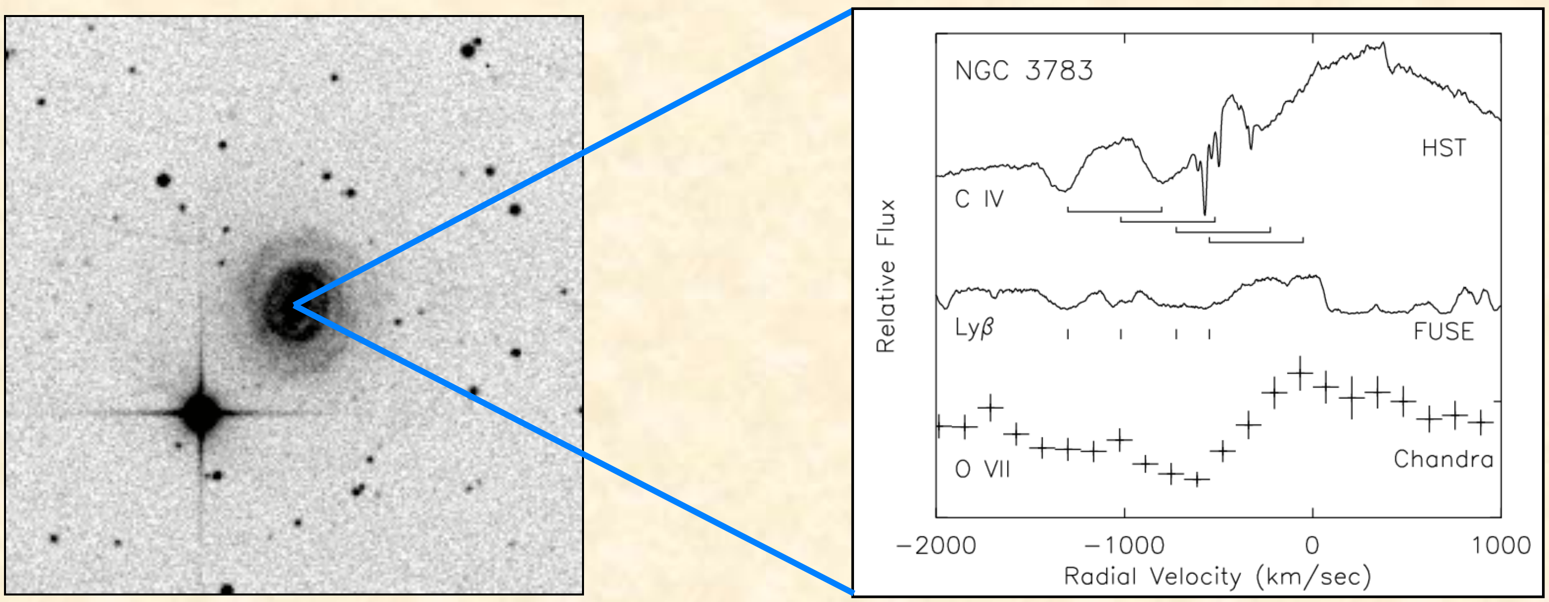
AGN Kinematics

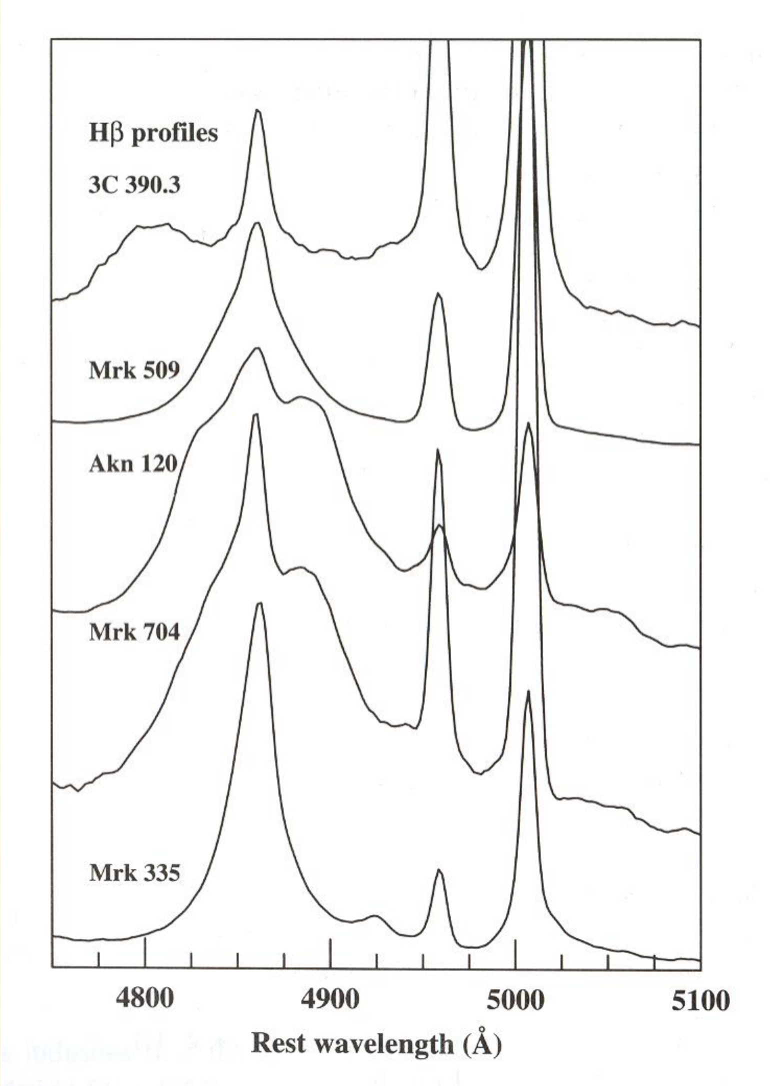
- BLR profiles and kinematics
- Outflows seen in Absorption (AGN Winds)
- Emission-Line Outflows in the NLR
- Combined Absorber and NLR Outflows Studies



BLR Profiles and Kinematics

BLRG

Sey 1



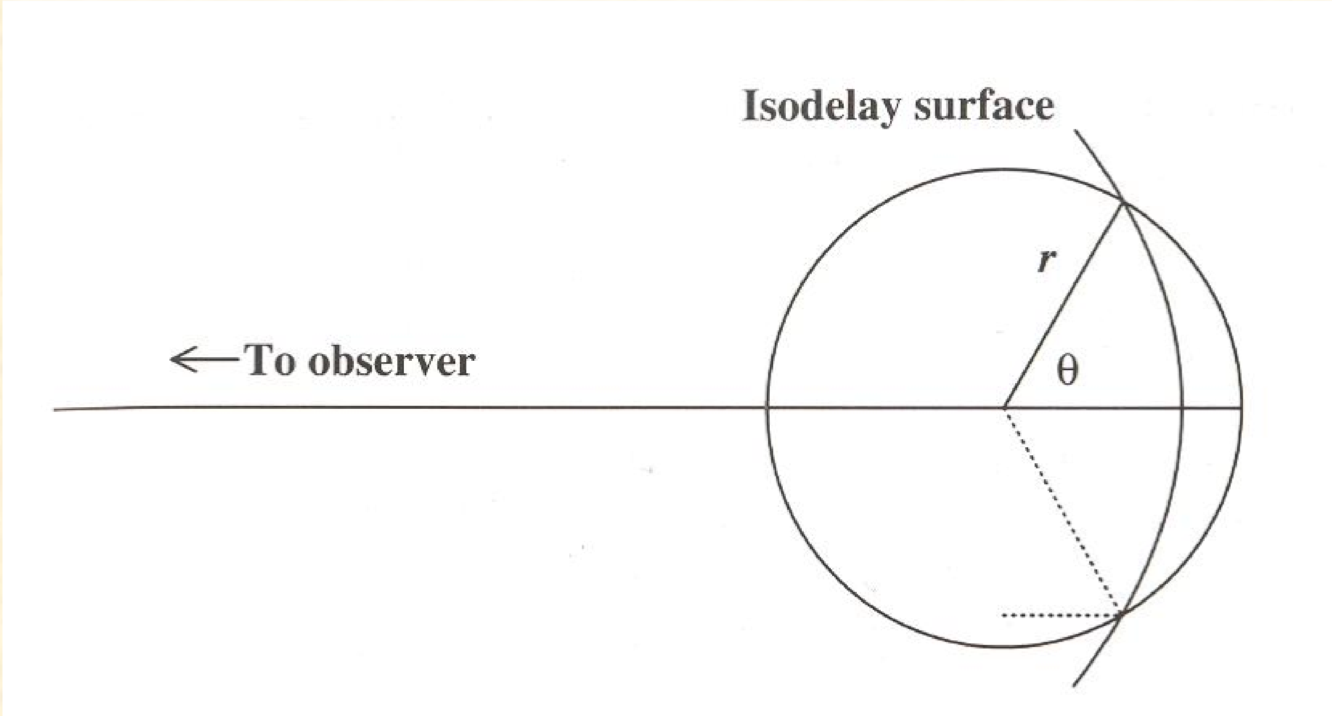
(Peterson, p. 69)

- Wide variety, many with bumps
- Many BLRGs have double-peaked profiles (after subtraction of NLR)
- Wings are logarithmic, but many kinematic models can reproduce them (Capriotti, et al. 1990, ApJ, 241, 903)

What is the BLR?
- bloated (irradiated) stars?
- surface of accretion disk?
- clouds in an outflowing wind?

Need more information on, size, geometry, and kinematics
→ Use variability and reverberation mapping

Reverberation Mapping



(Peterson, p. 83)

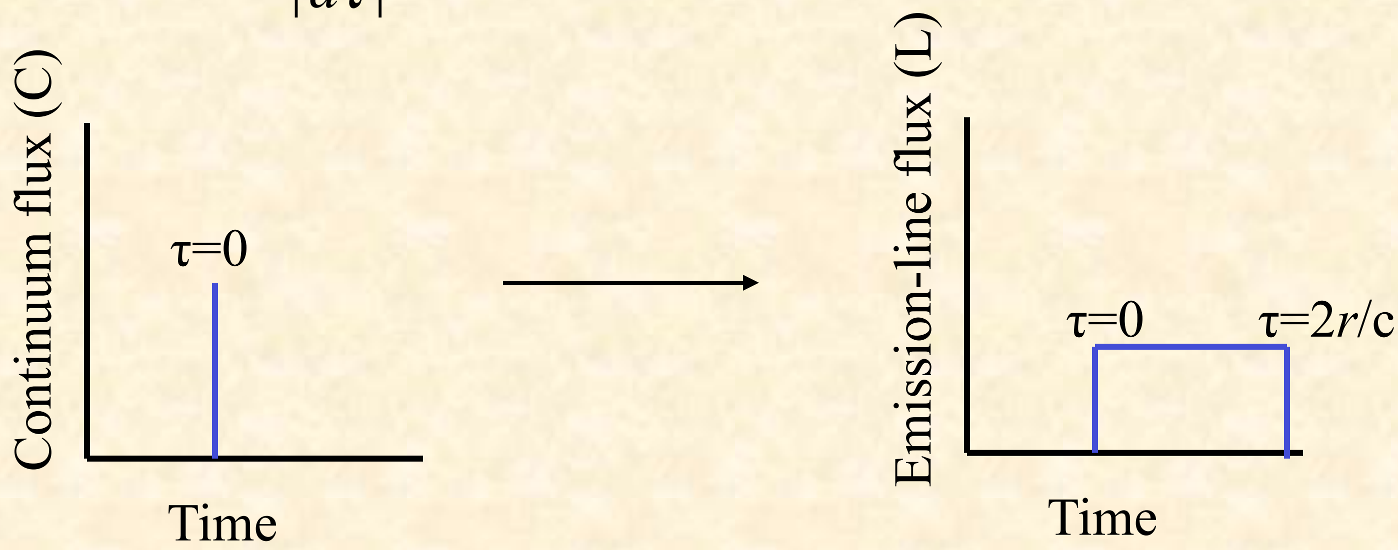
- Consider a δ-function continuum at $\tau = 0$, and a thin spherical shell BLR
- When the ionizing continuum reaches the shell, it responds instantaneously
- The observer sees isodelay surfaces at $\tau = (1 + \cos\theta) r/c$ →paraboloid
- Intersection with the shell gives an annulus with surface area $2\pi r^2 \sin\theta d\theta$
- If emissivity (ε) is same at all locations, the emission-line response is:

$$\psi(\theta)d\theta = 2\pi\varepsilon r^2 \sin\theta \; d\theta \quad (\psi:\ \text{transfer function},\ \varepsilon:\ \text{emissivity})$$

Since $\tau = \frac{(1+\cos\theta)r}{c}$, $d\tau = -\frac{r\sin\theta}{c} d\theta$

So the emission-line light curve looks like:

$$\psi(\tau)\, d\tau = \psi(\theta)\left|\frac{d\theta}{d\tau}\right| d\tau = 2\pi\varepsilon rc\; d\tau \; = \text{const. between } \tau = 0 \text{ and } 2r/c$$



- CCF from above will give a box with centroid (lag) of $\tau = r/c$
- In general, $\Psi(\tau)$ gives the emission-line light curve for a δ-function continuum (Blandford & McKee 1982, ApJ, 255, 419)
- Observationally, the continuum is not a δ-function, so the emission-line light curve is a convolution of the continuum and transfer function:

$$L(t) = \int_{-\infty}^{\infty} \psi(\tau)\, C(t-\tau)\, d\tau \qquad \text{(L = line flux, C = continuum flux)}$$

Deconvolution requires high S/N spectra at high temporal resolution

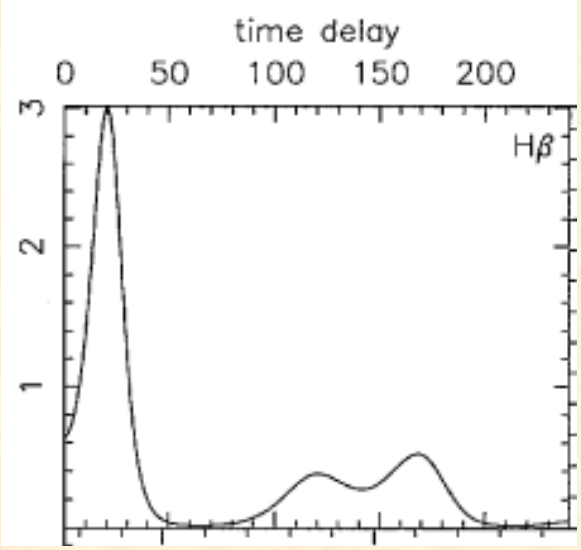
Observationally, we usually settle for the CCF:

$$\text{CCF} = \int_{-\infty}^{\infty} L(\tau)\, C(t-\tau)\, d\tau \quad \rightarrow \text{ peak gives an average "lag"} \rightarrow \text{ "radius" of BLR}$$

"It can be shown that" (Peterson, p. 84):

$$\text{CCF} = \int_{-\infty}^{\infty} \psi(\tau)\, \text{ACF}(t-\tau)\, d\tau \qquad \text{(ACF is for the continuum)}$$

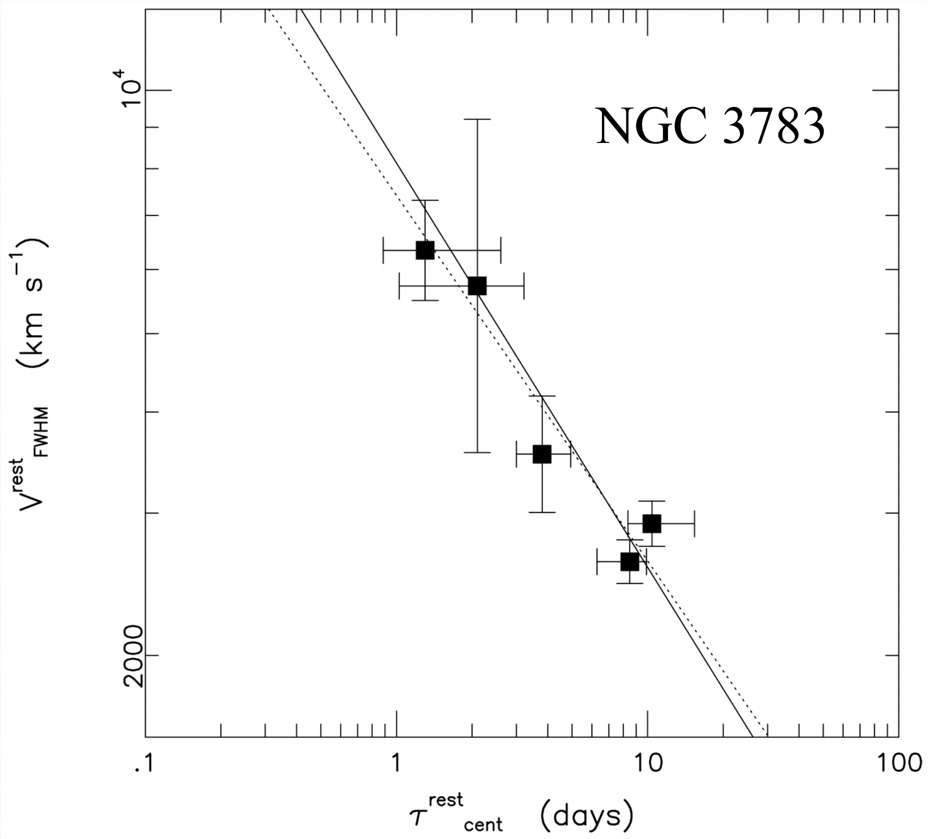
→ CCF gives a characteristic size, Ψ gives the geometry.



-Attempt to recover the transfer function for Hβ in NGC 5548 data set (Horne et al. 1991, ApJ, 367, L5)

- Lack of response at 0 time delay indicates
 1) Lack of gas in line of sight (disk?)
 or
 2) Optically thick gas in line of sight

Lags for Different Emission Lines



(Onken & Peterson, 2002, ApJ, 572, 746)

FWHM ~ $r^{-0.5}$

→ Suggests gravitational motion (or at least $1/r^2$ force)

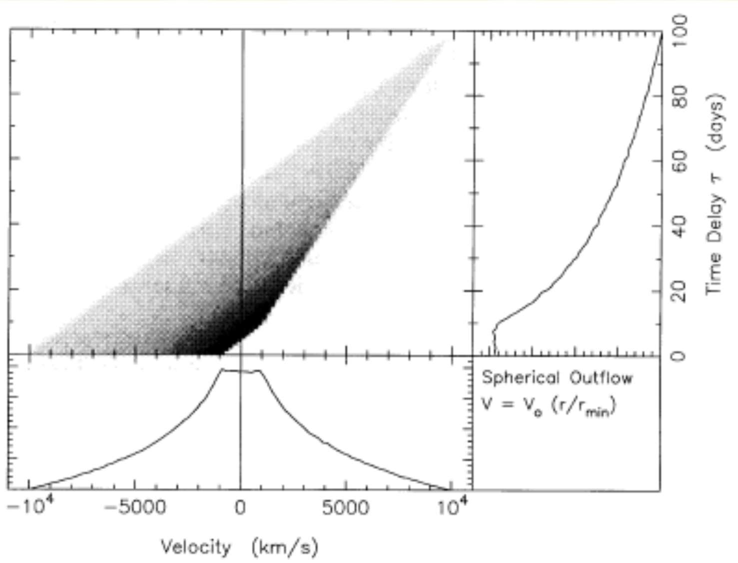
→ But radiation pressure could be important (Marconi et al. 2008)

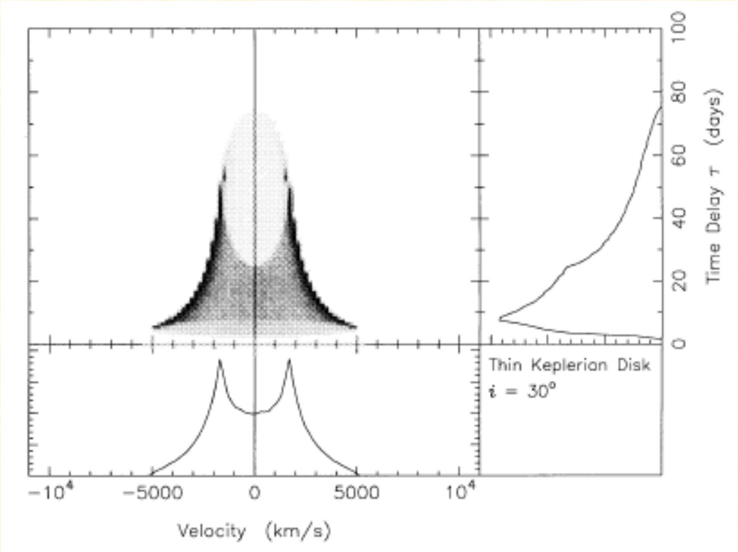
Determining the kinematics directly $\rightarrow$ (Radial) velocity-dependent Ψ

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

where $L(v,t)$ is the velocity-dependent profile

Examples of model $\Psi(v,\tau)$ (Welsh & Horne, 1991, ApJ, 379, 586):

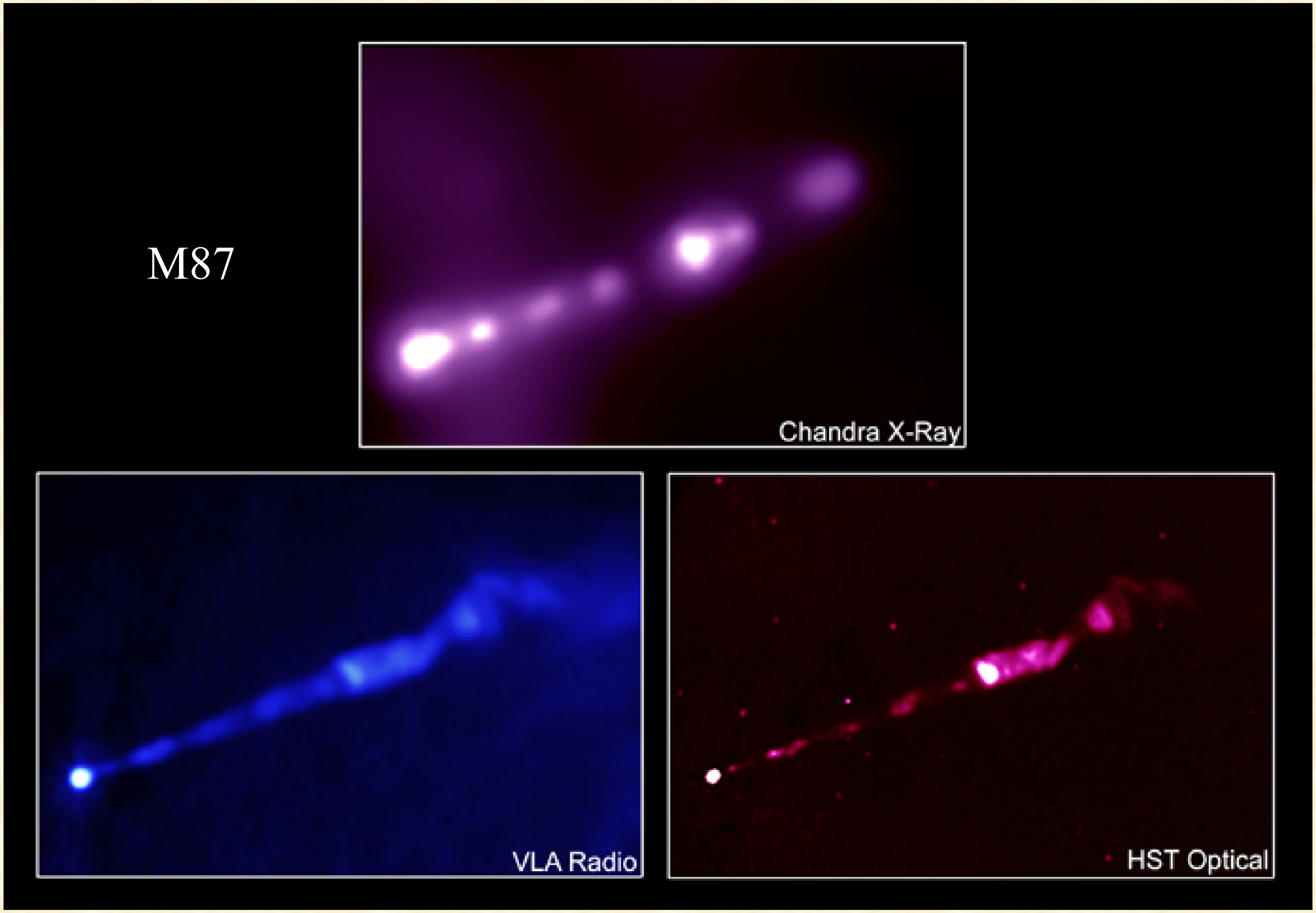




- Determine $\Psi(v,\tau)$ observationally and compare with models
- A few projects claim success, but no clear consensus yet (severe data requirements!)

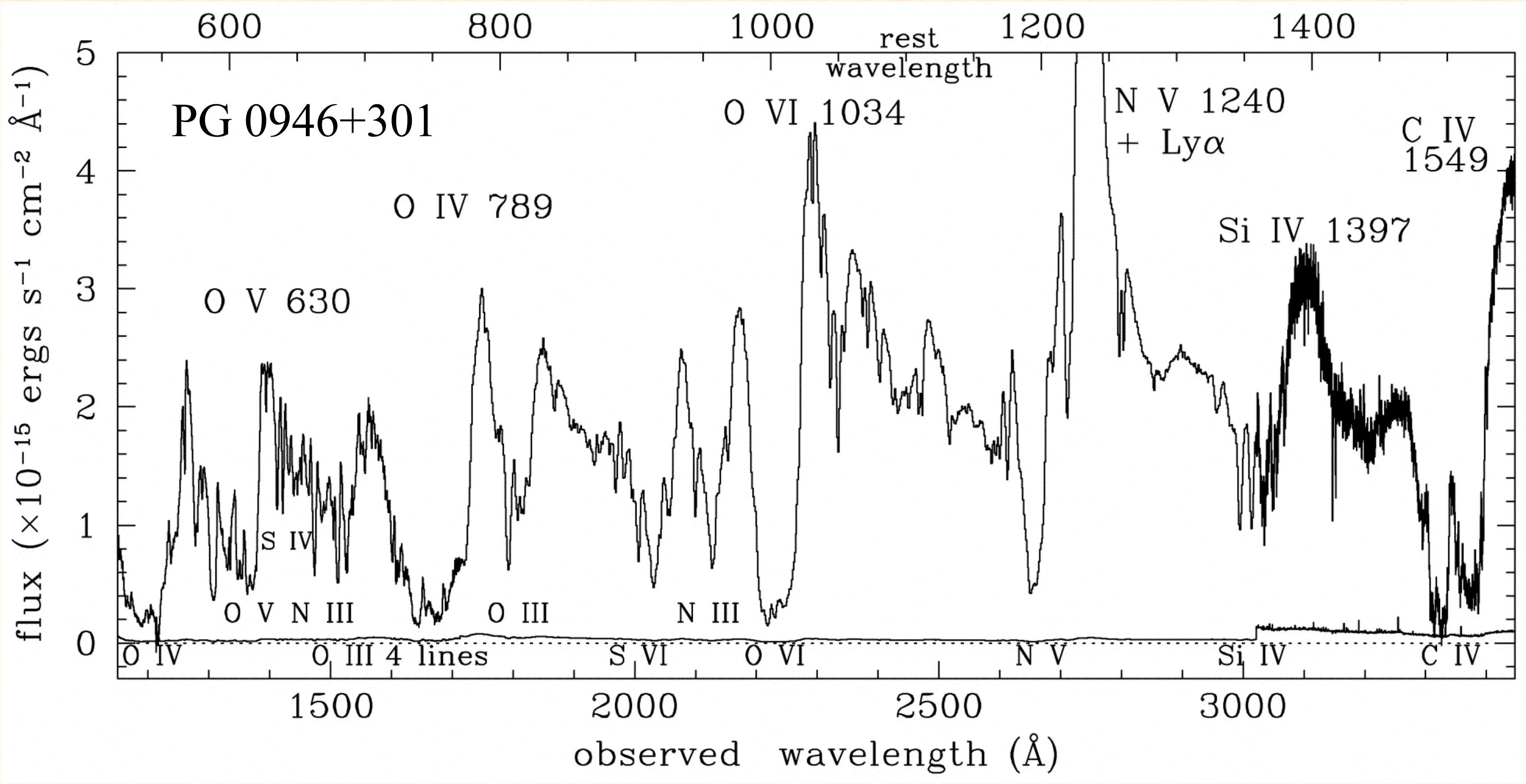
Outflows in AGN: Types

1) Jets in Radio-Loud Galaxies and Quasars



- Highly collimated, low density plasma traveling at relativistic speeds

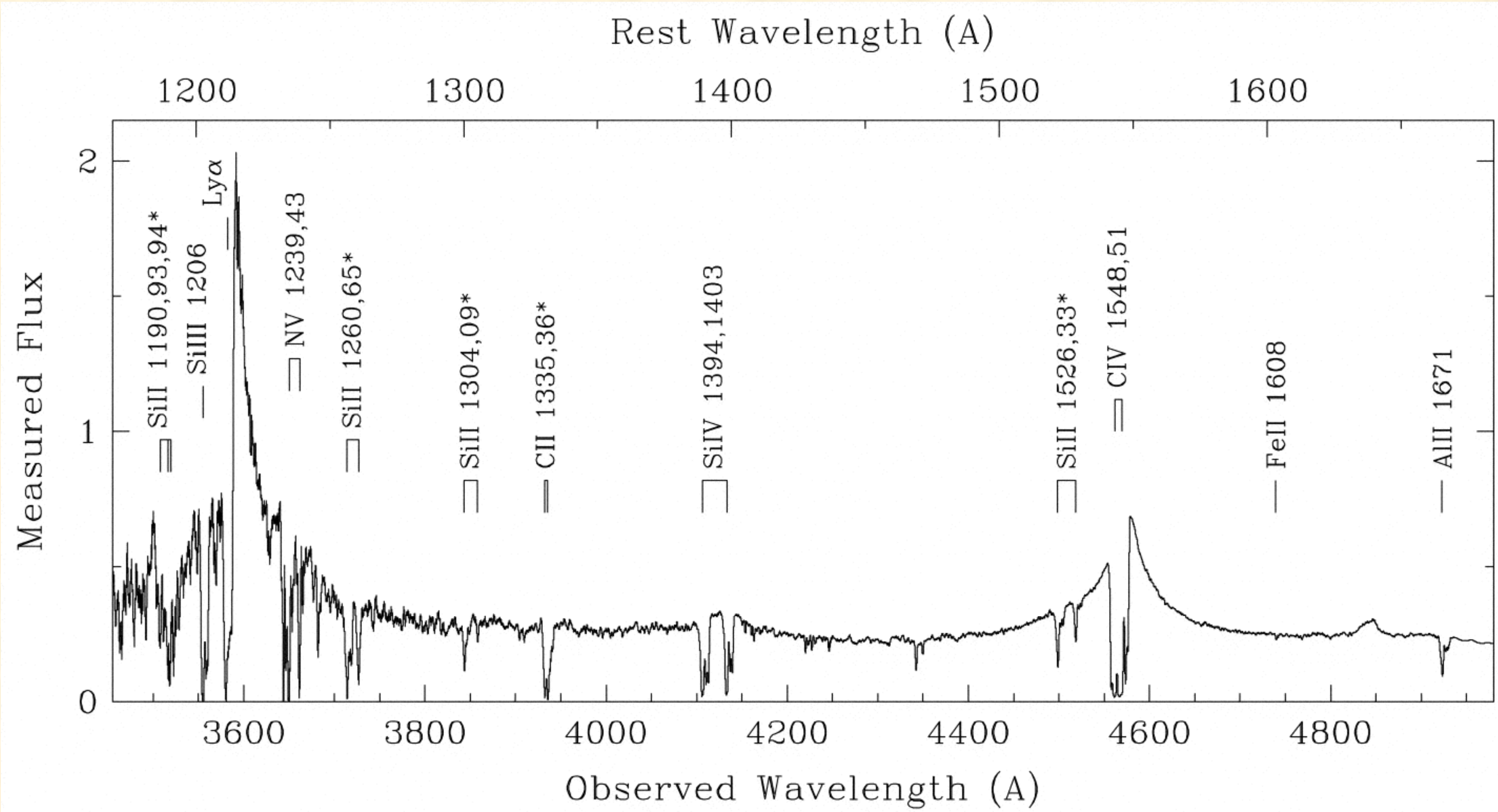
2) Broad Absorption-Line (BAL) Quasars



(Arav et al. 2001, ApJ, 561, 118)

- Blueshifted absorption troughs extending up to ~0.2c
- Observed in ~10% of radio-quiet quasars
- Possibly occur in most quasars, covering ~10% of the AGN sky

3) Quasar "Associated Absorption"

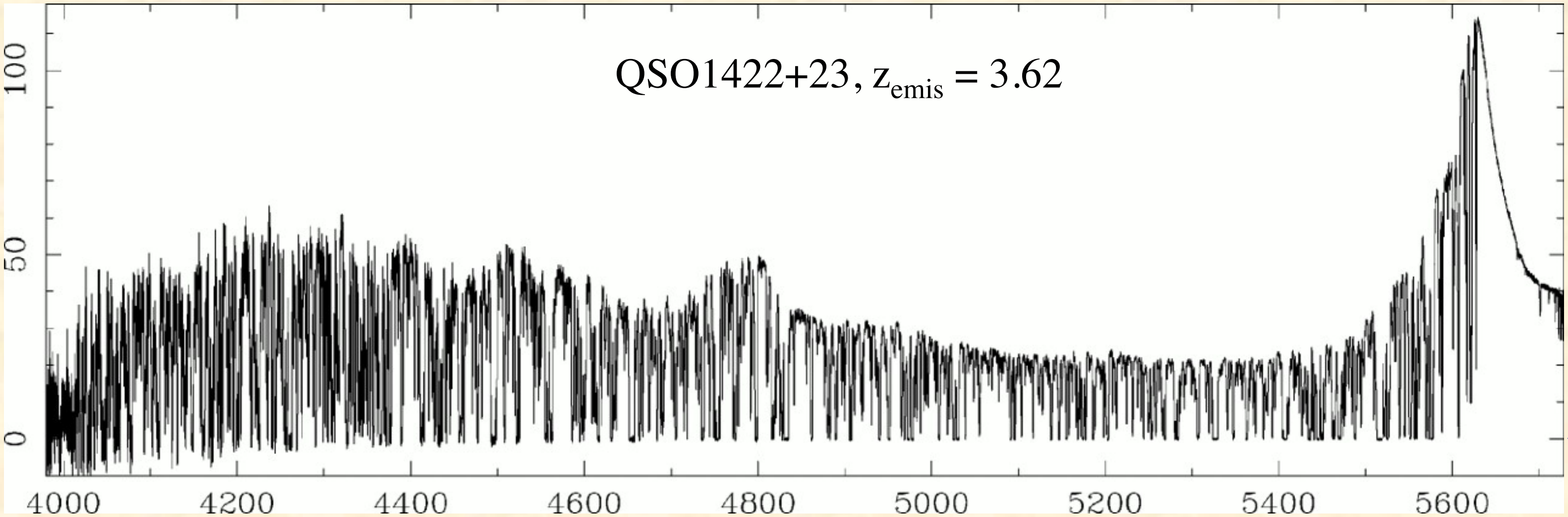


(Hamann et al. 2001, ApJ, 550, 152)

- Discovered as excess absorption lines near z of quasar ($z_{abs} \approx z_{emis}$)
- Narrow absorption (FWHM < 300 km s^{-1}) within 5000 km s^{-1} of z_{emis}
- Mostly blueshifted, which indicates outflow from nucleus

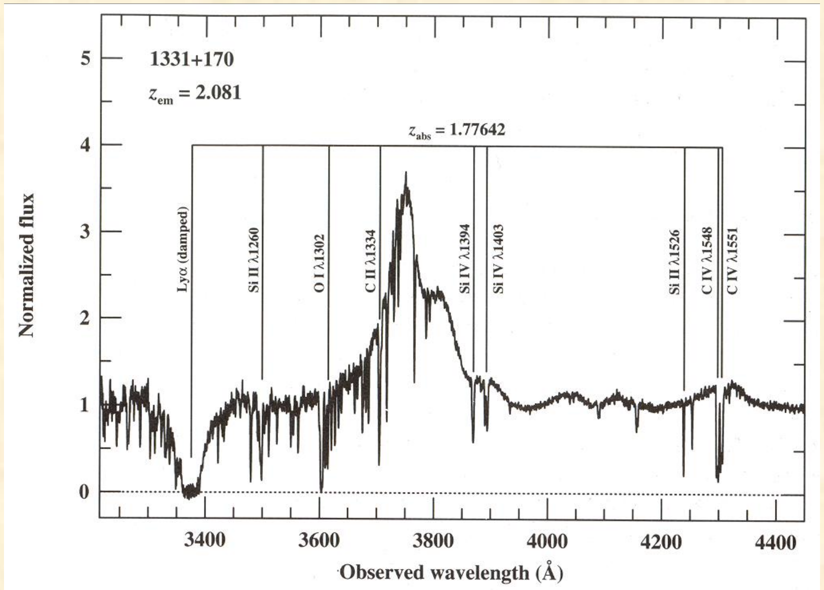
Not to be confused with absorption at $z_{abs} << z_{emis}$:

a) Lyα Forest - intervening clouds in the intergalactic medium



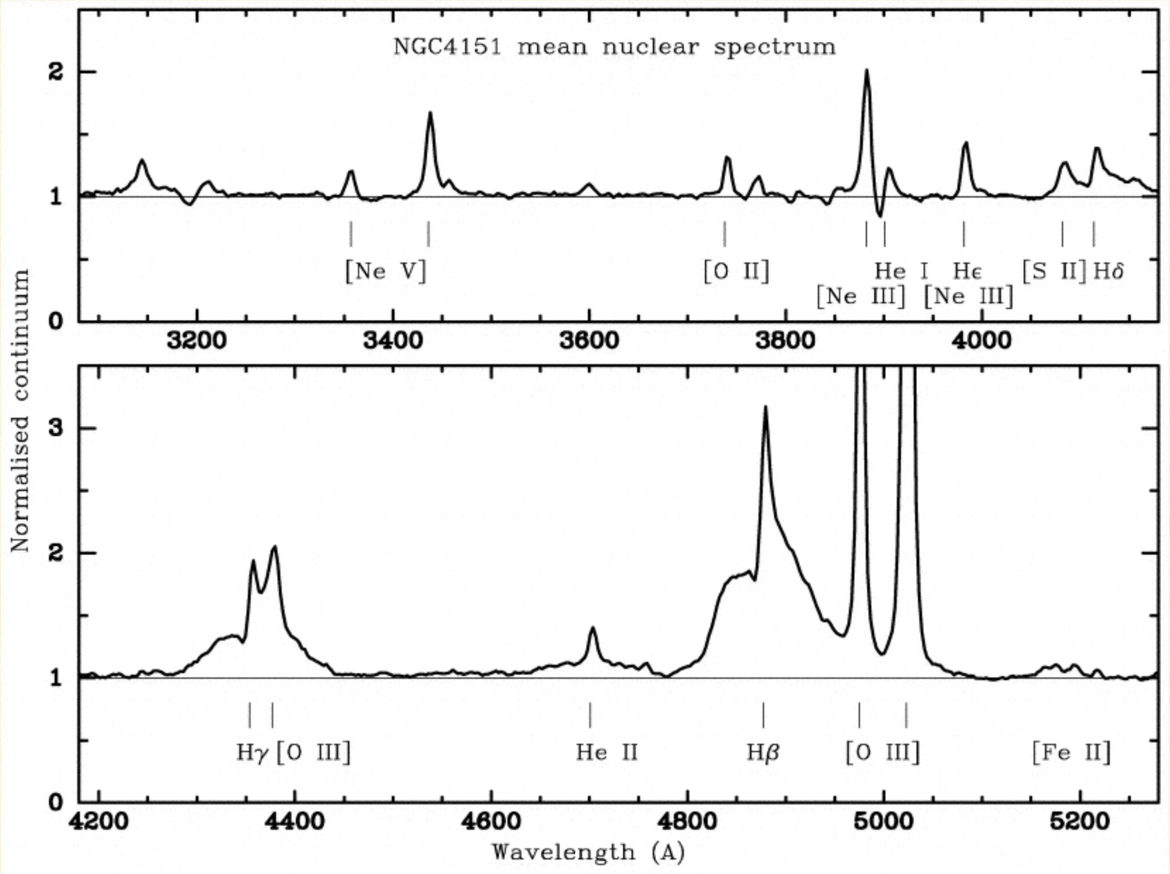
(Rauch, 1998, ARAA, 36, 267)

b) "Metal-line" systems - intervening galaxies and their halos



(Peterson, 1997, An Introduction to AGN, p. 201)

4) "Intrinsic Absorption" in Seyfert Galaxies



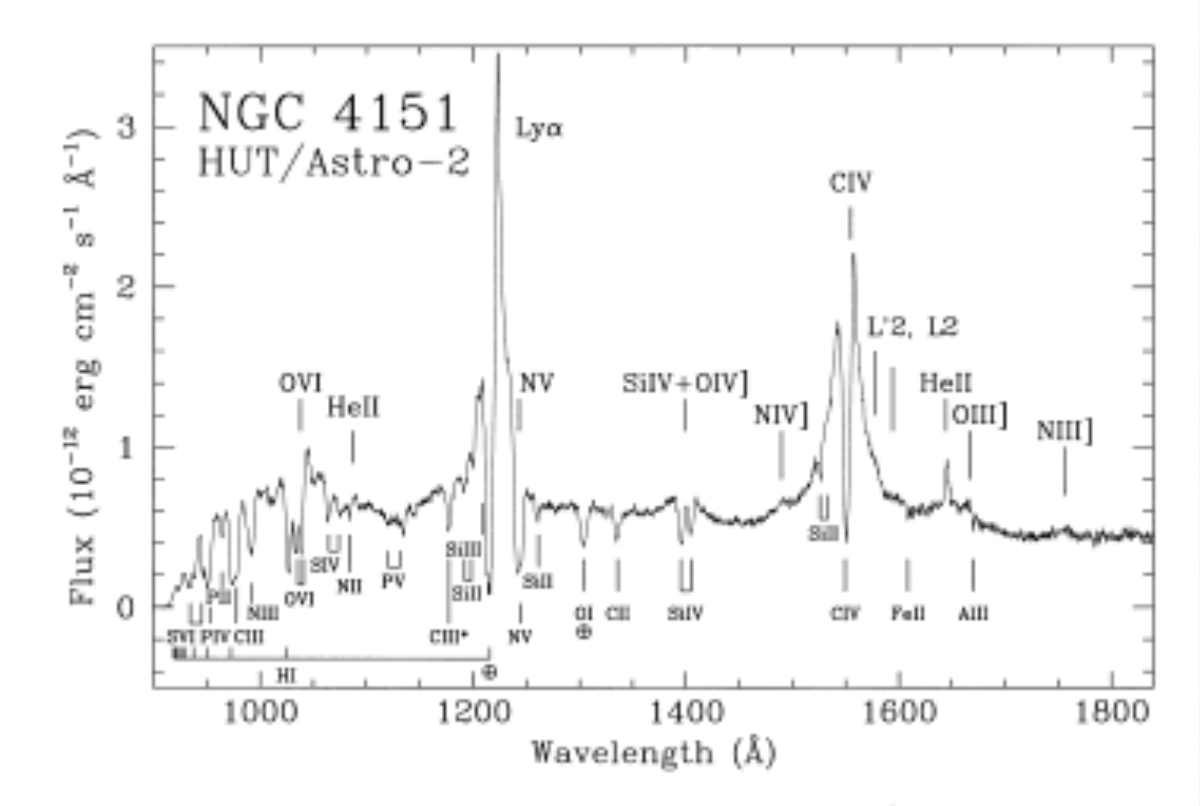
(Hutchings, et al., 2002, AJ, 224, 2543)

- Originally detected in optical spectra of NGC 4151 (Oke & Sargent 1968)
- Blueshifted He I and H I Balmer lines ($n_e > 10^8$ cm^{-3} → rare in Seyferts)
- UV absorption in resonance lines much more common (~50% of Seyferts)

Types of UV Absorption Lines - Summary

1. Galactic: Milky Way disk and halo ("high velocity clouds")
2. Intervening ($z_{abs} << z_{emis}$)
   - Metal-line systems ("damped Lyα"): galactic halos and disks
   - "Lyα forest": IGM clouds (also some O VI, other high-ionization lines)
3. Seyfert "intrinsic" absorption lines
   - Mass outflow: up to -4000 km s^{-1} (probably related to QSO associated)
   - Intrinsic to host galaxy (very narrow, within 300 km s^{-1} of galaxy z)
4. Quasar narrow absorption lines ("NALs"): FWHM ≤ 300 km s^{-1}
   - "Associated": mass outflow up to 5000 km s^{-1}
   - "High-velocity NALS": mass outflow up to 50,000 km s^{-1}
5. Quasar Broad Absorption Lines
   - Hi-BALs: velocity widths > 2000 km s^{-1}, outflow up to ~0.2;, high-ionization lines (C IV, N V, etc.)
   - Low-BALs: same as above, plus Mg II and other low-ionization lines
   - Mini-BALs: velocity widths between ~500 and 2000 km s^{-1}

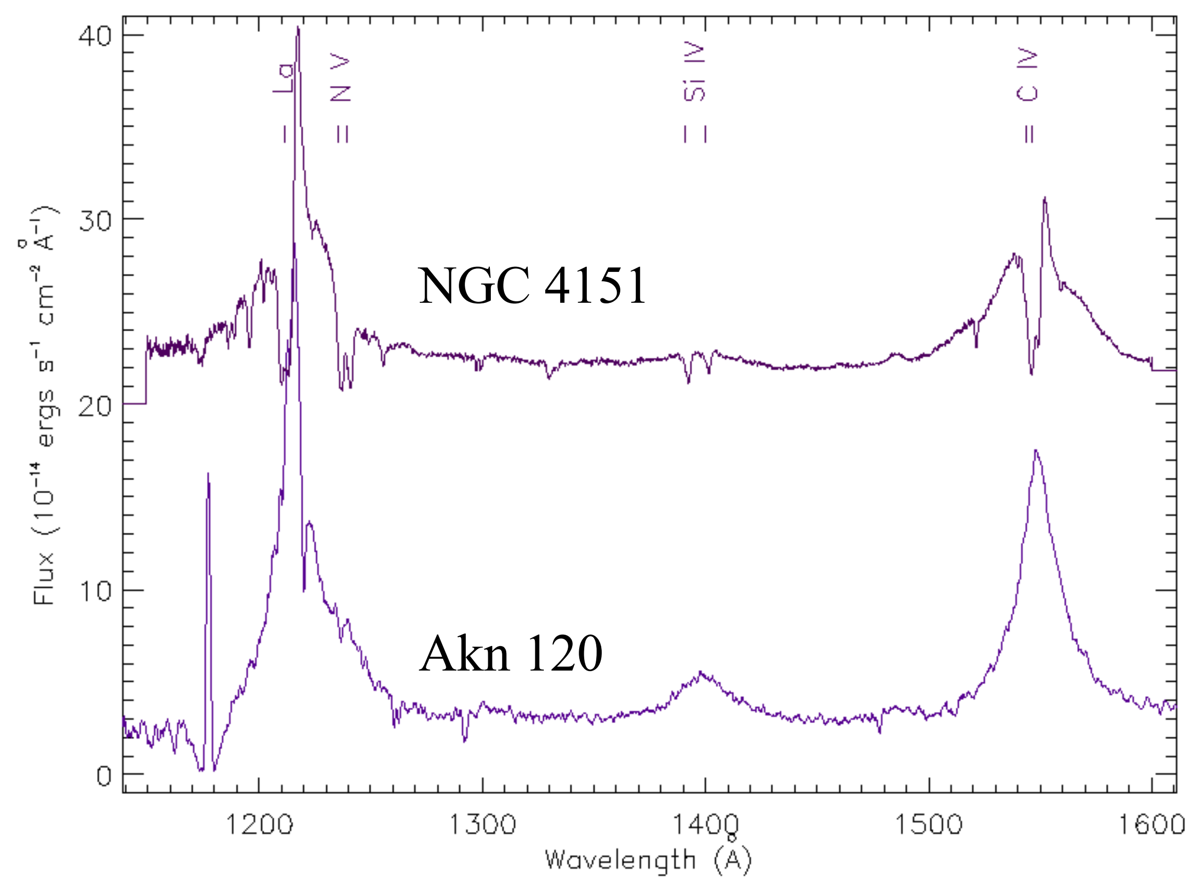
IUE/HUT Observations of Intrinsic UV Absorption



(Kriss et al., 1995, ApJ, 454, L7)

- *IUE* discovered absorption spanning a wide range in ionization (O I to N V)
- *HUT* extended the ionization range to O VI, in the far-UV
- Ulrich (1988) found that 3 - 10% of *IUE* Seyferts have intrinsic absorption

HST Survey of Seyfert Galaxies



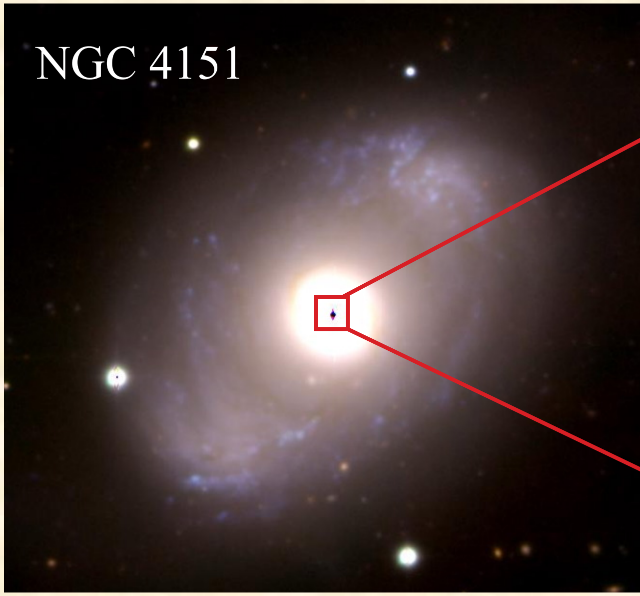
Intrinsic absorption

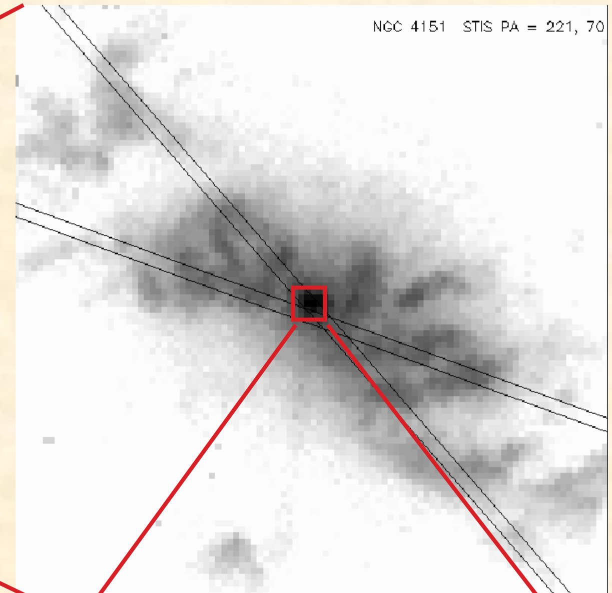
No intrinsic absorption

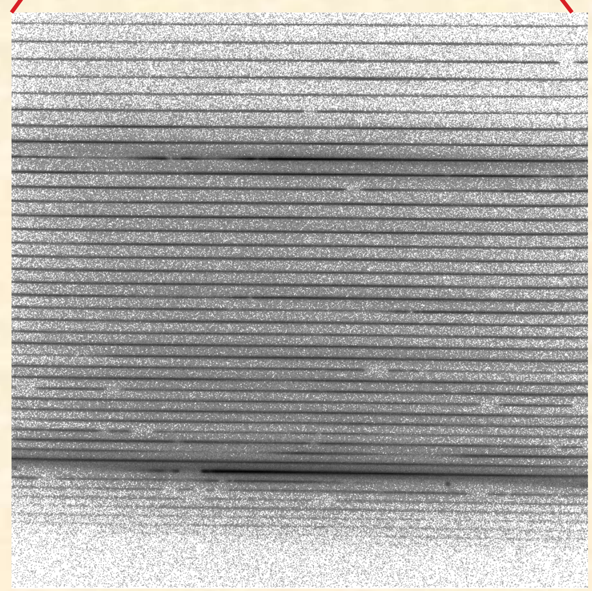
(Crenshaw et al. 1999, ApJ, 516, 750)

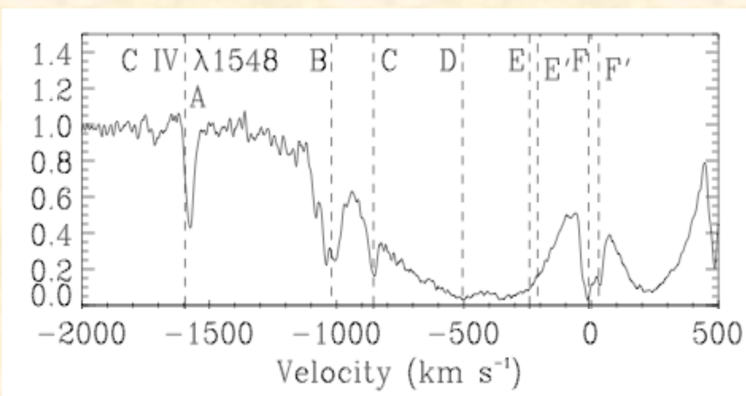
- 60% of Seyfert 1 galaxies show intrinsic absorption; those that show UV absorption also show X-ray absorption.
- Global covering of the continuum source and BLR: $C_g = 0.5 - 1.0$
- Most absorbers are highly ionized (C IV, N V); only 10% show Mg II

HST/STIS High-Resolution Spectra

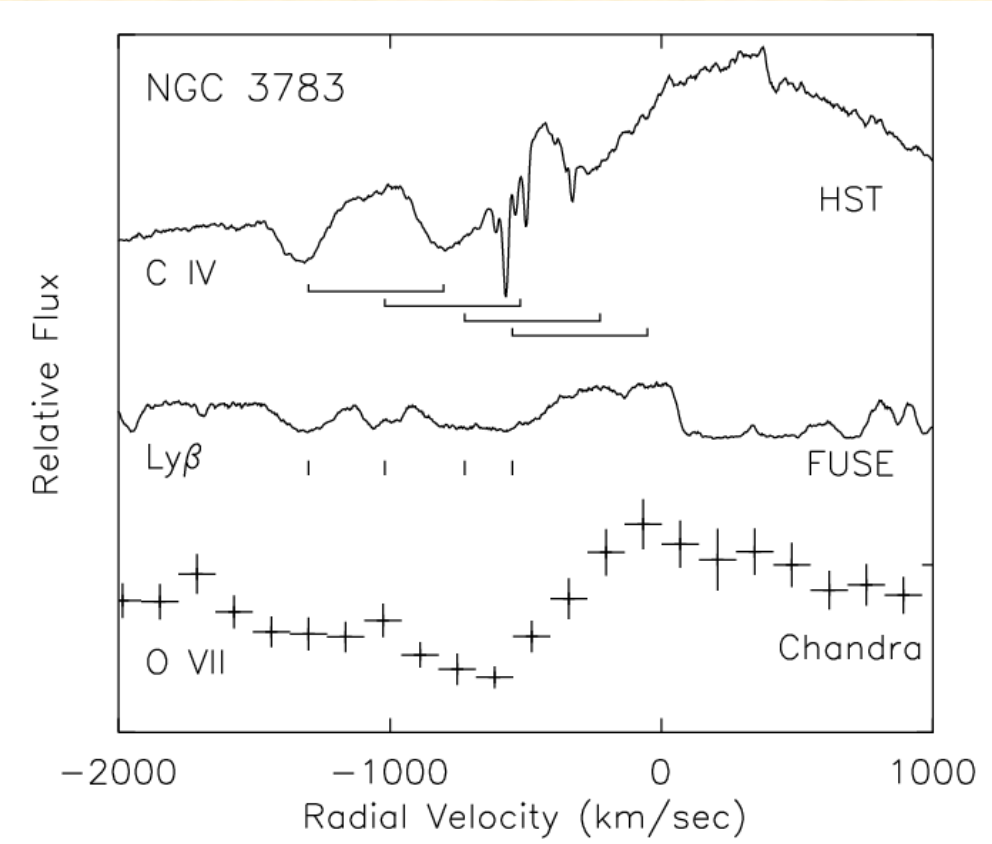








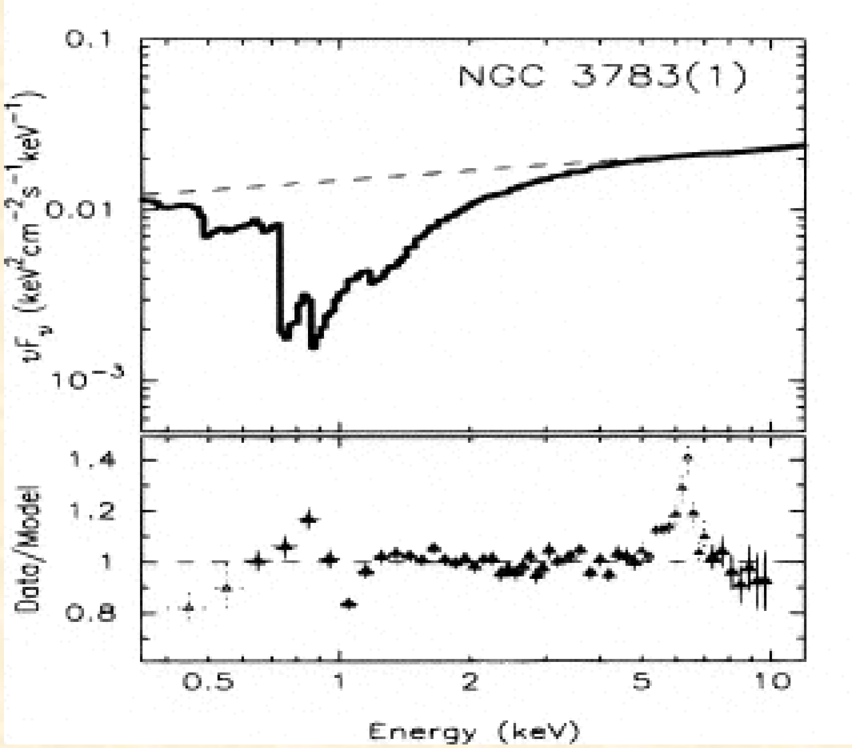
High Resolution Spectra



(Gabel, et al. 2003, ApJ, 583, 178)

- Multiple outflowing components detected in UV and far-UV.
- Similar velocity coverage for X-ray absorbers; however X-ray absorbers have higher ionization parameters (U) and column densities (N_H)
- Comparison of UV doublets indicates partial covering of BLR in some cases
- Mass outflow rates are comparable to accretion rates (~ 0.01 to 0.1 $M_{\odot}$/yr)

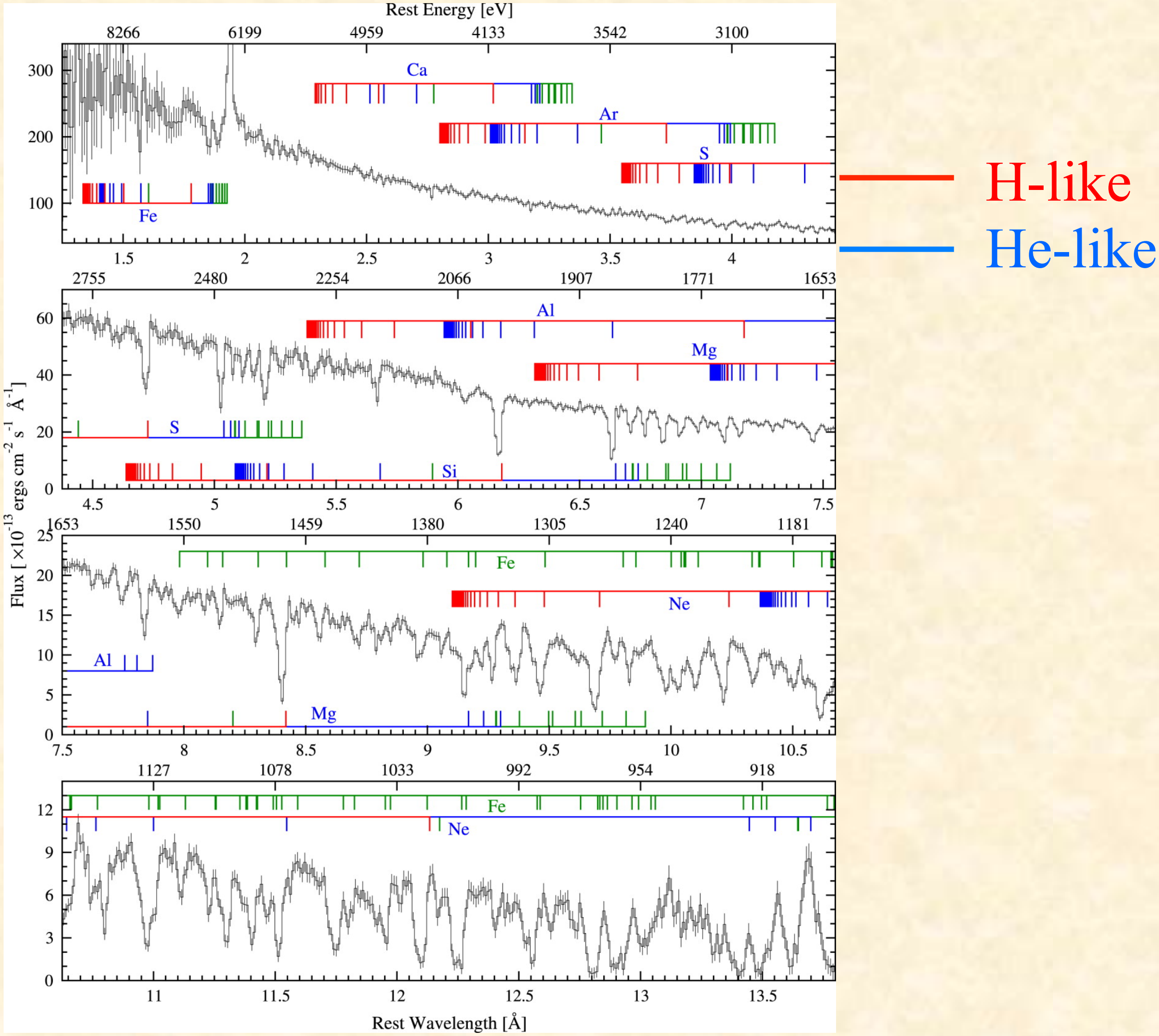
5) X-ray “Warm Absorbers” in Seyferts



(George, et al. 1998, ApJS, 114, 73

- Absorption by highly-ionized gas first claimed by Halpern (1984)
- Confirmed by *ASCA* detections of O VII and O VII edges (see above)
- Mathur (1994) claimed a connection between X-ray and UV absorbers
- Blueshifted absorption lines seen by *Chandra* confirmed outflow

Chandra 900 ks Spectrum of NGC 3783



(Kaspi et al. 2002, ApJ, 574, 643)

How do we get more Info? →Variability Monitoring

- Nearly all Seyfert 1 galaxies with intrinsic UV absorption show components with variable equivalent widths (EWs)
- Sources of EW (or ionic column density) variations:

  1) Variations in the ionizing continuum flux (variable U)

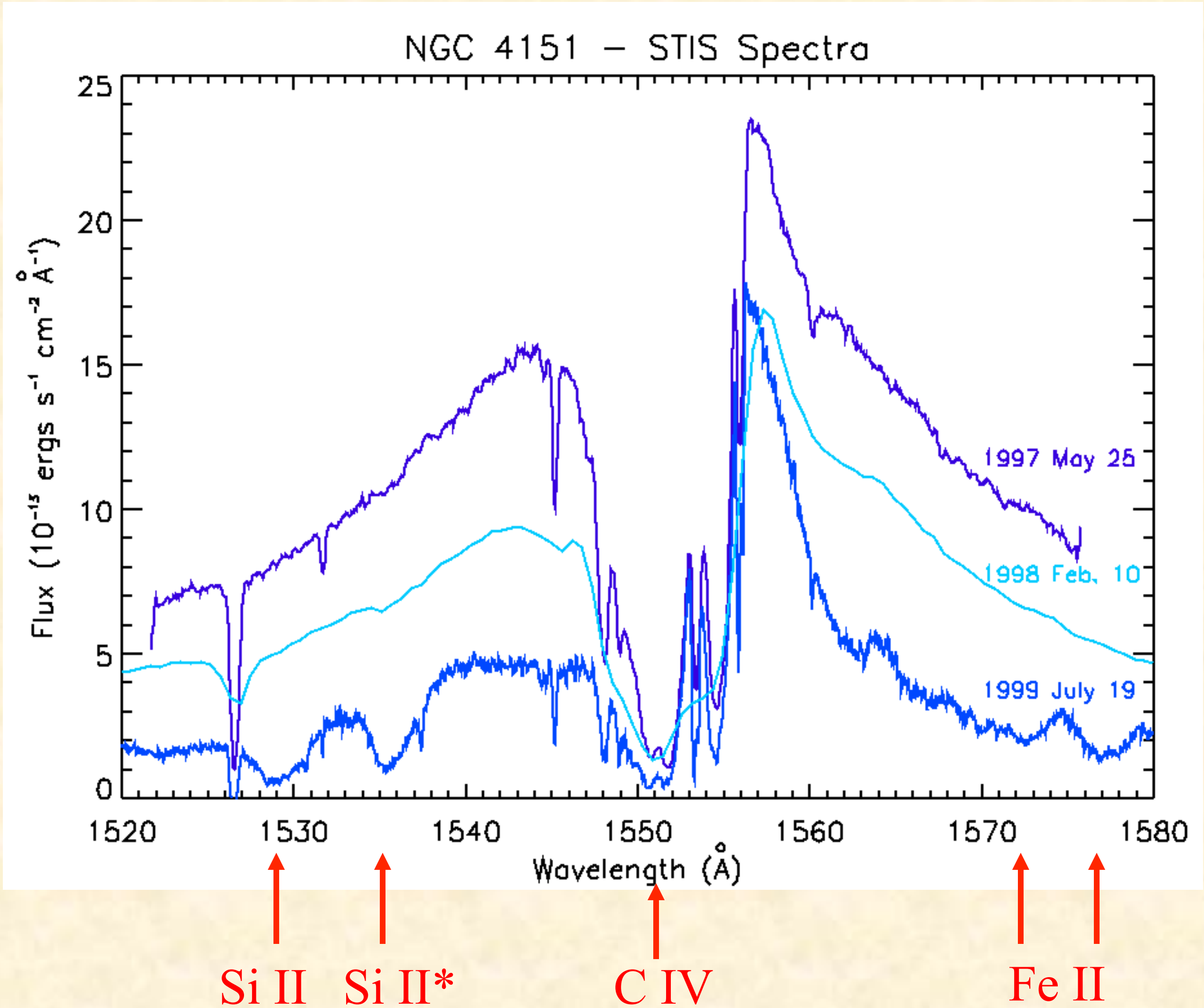
  2) Transverse motion of cloud across the BLR + continuum (variable N_H or covering factor in the line of sight)
- Variable ionizing continuum: can determine density (n_e) and distance from source (r) from time scale of variability (t)

$$n_e \approx \frac{1}{\alpha\, t_{rec}} \qquad U = \frac{\int_{\nu_0}^{\infty} L_\nu / h\nu \, d\nu}{4\pi r^2 c\, n_e} \quad \text{(U from photoion. models)}$$

- Transverse motion: can determine the transverse velocity

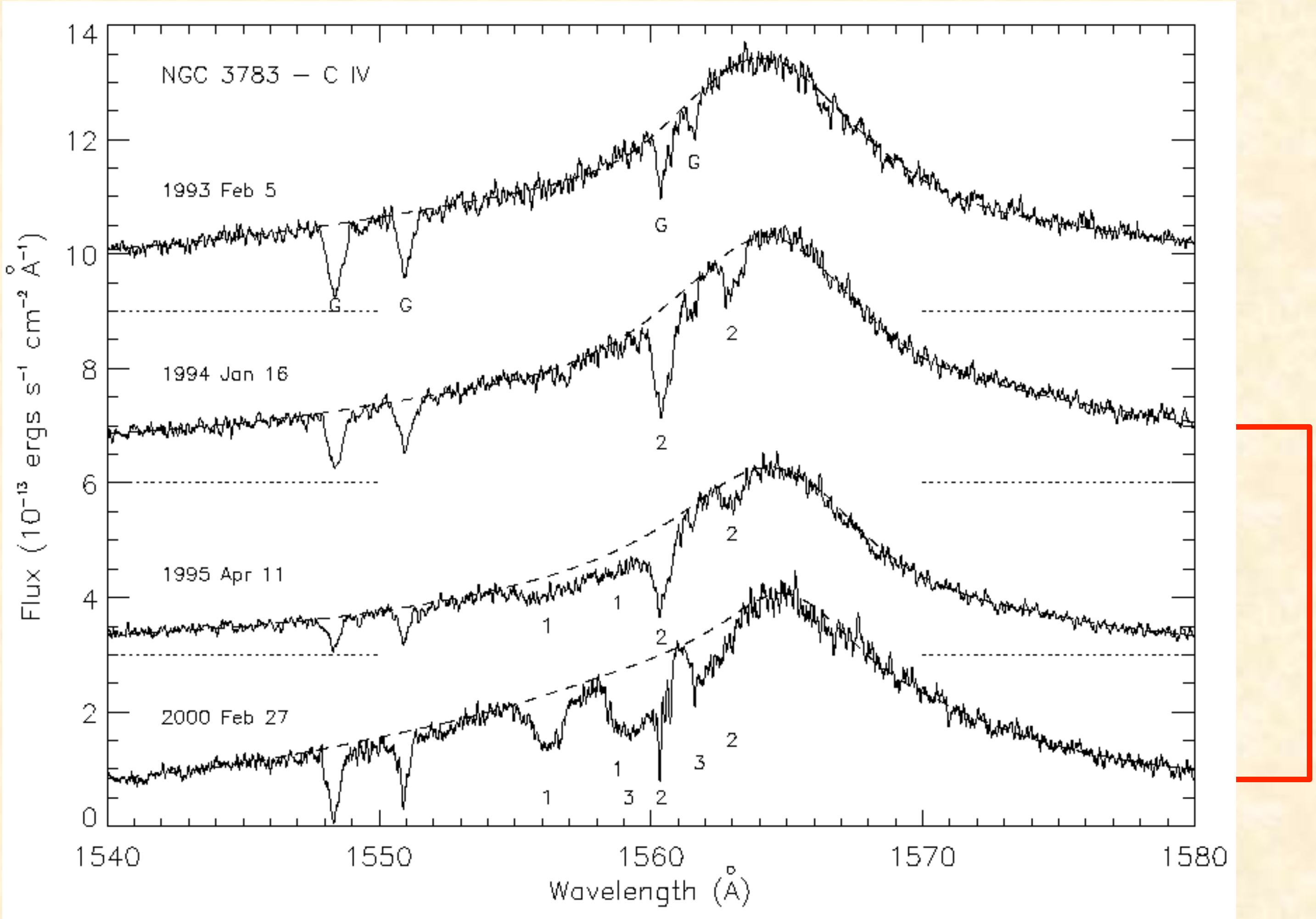
$$v_T = \sqrt{C_{BLR}}\, d_{BLR} / t, \quad \text{where } C_{BLR} \text{ is the los covering factor}$$

NGC 4151 - Variability in Ionizing Flux



- Low-ionization lines "appear at low continuum → variable U

NGC 3783 – Variability due to Transverse Motion



Comp. 1 transverse velocity: $v_T = \sqrt{C_{BLR} d_{BLR}} / \Delta t \geq 550 \text{ km s}^{-1}$

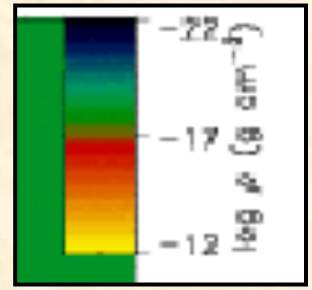
Why are AGN outflows important?

- Quasar outflows have likely:
  1) contributed to the heavy-element abundance of the IGM (Hamann & Ferland, 1999, ARA&A, 37, 487)
  2) influenced formation of structure in the early Universe (Scannapieco & Peng 2004, ApJ, 608, 62)
  3) regulated the growth of supermassive black holes and galactic bulges (Ciotti & Ostriker, 2001, ApJ, 551, 131)
- Seyfert galaxies are the best AGN for probing the machinery of mass outflow in the form of AGN winds.
  1) Of all AGN, they have the largest apparent brightness.
  2) They are nearby ($z < 0.1$), and offer the best hope of directly resolving the outflowing gas.

So what are the absorbers?

- What is their origin?
  - Accretion disk, BLR, torus, NLR?
  - Some absorption lines come from the host galaxy's disk or halo (within ~300 km s^{-1} of systemic velocity)
- What are their dynamics?
  - Radiatively-driven, thermal wind, hydromagnetic flows? (see Crenshaw, Kraemer, & George, 2003, ARA&A, 41, 117)
- Specific models?
  - Accretion-disk winds, evaporation from torus
- WE NEED TO KNOW THEIR LOCATIONS
  - Current indications: most are at distances of tenths to tens of parsecs from their SMBHs
  - Not near the accretion disk! [but high ionization, high velocity (~0.1c) outflows might be acc. disk winds]

Accretion-Disk Wind Movie



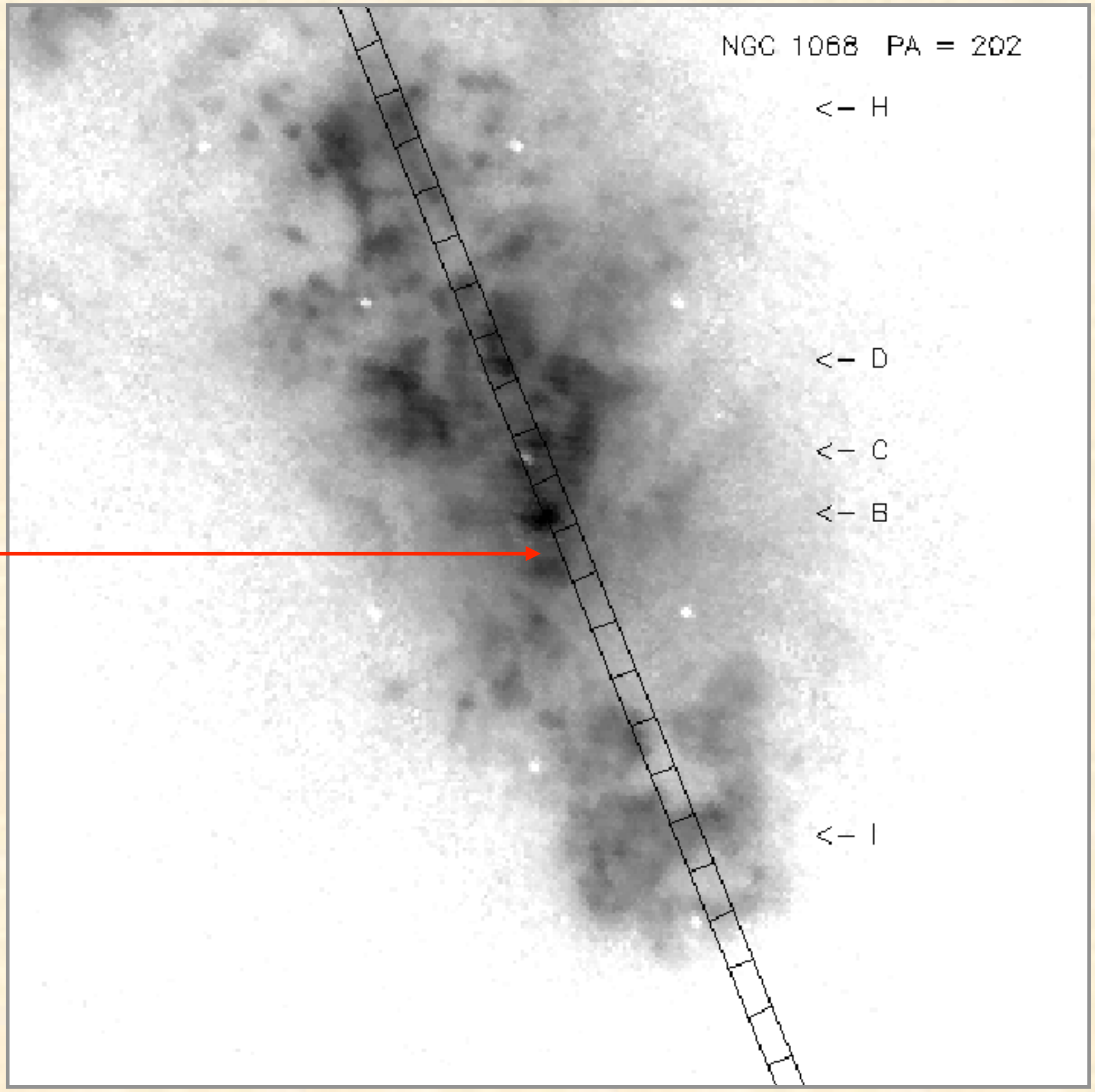
Proga et al.

Emission-Line Outflows in the NLR

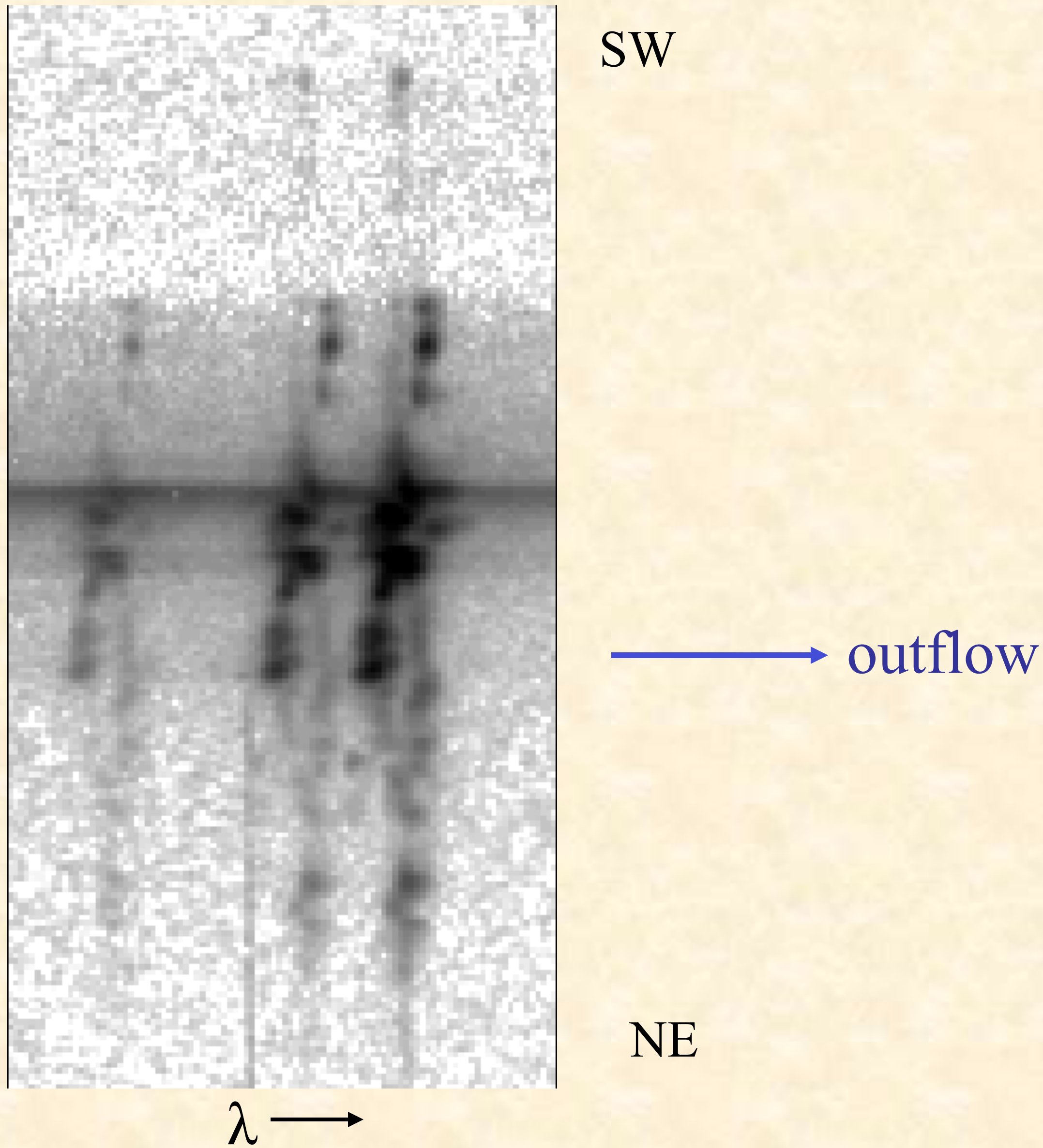
- Previous ground-based studies have claimed infall, rotation, parabolic orbits, outflow, etc.
- The problem: they relied on spatially integrated line profiles, since the NLR is only a few arcsecs across.
- HST/Space Telescope Imaging Spectrograph has angular resolution ~ 0.1”.
- Large ground-based telescopes + adaptive optics (AO) + integral-field units (IFUs) also approach this resolution

  → strong evidence for outflows in the NLR (Crenshaw et al. 2010, ApJ, 708, 419)

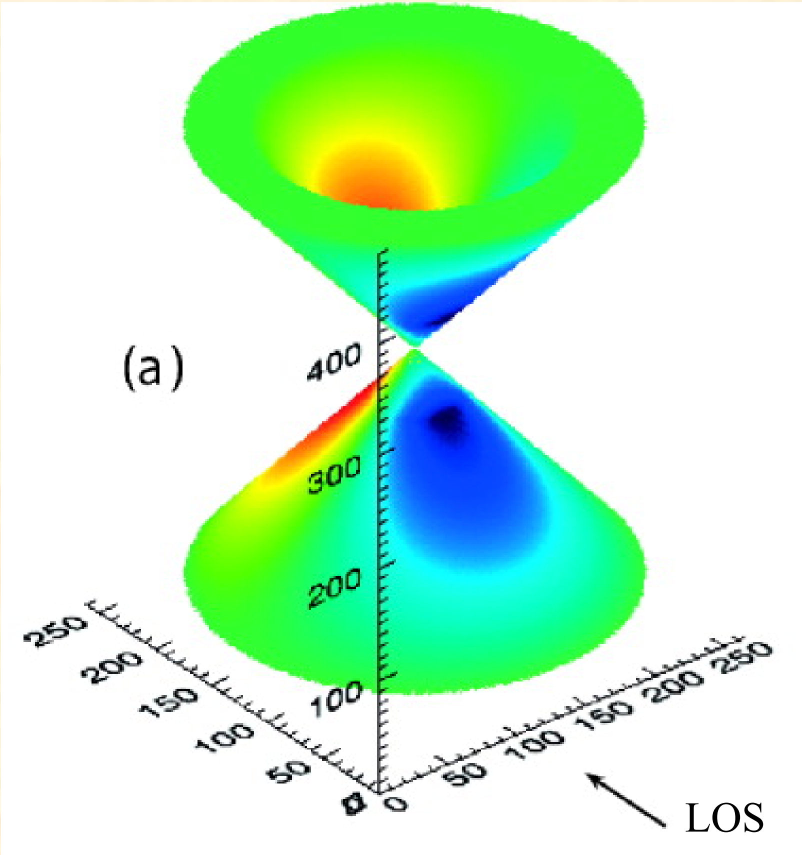
NGC 1068: NLR – [O III] Image

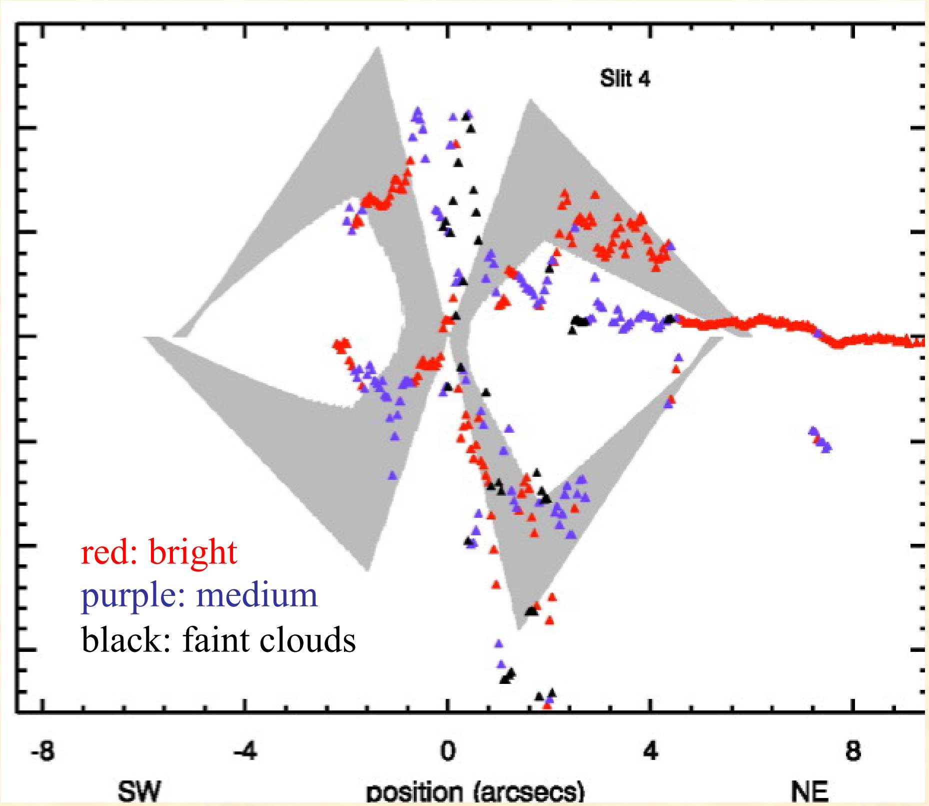


NGC 1068: STIS Long-Slit Spectrum (Hβ, [O III])



Biconical Outflow Model for the NLR in NGC 1068



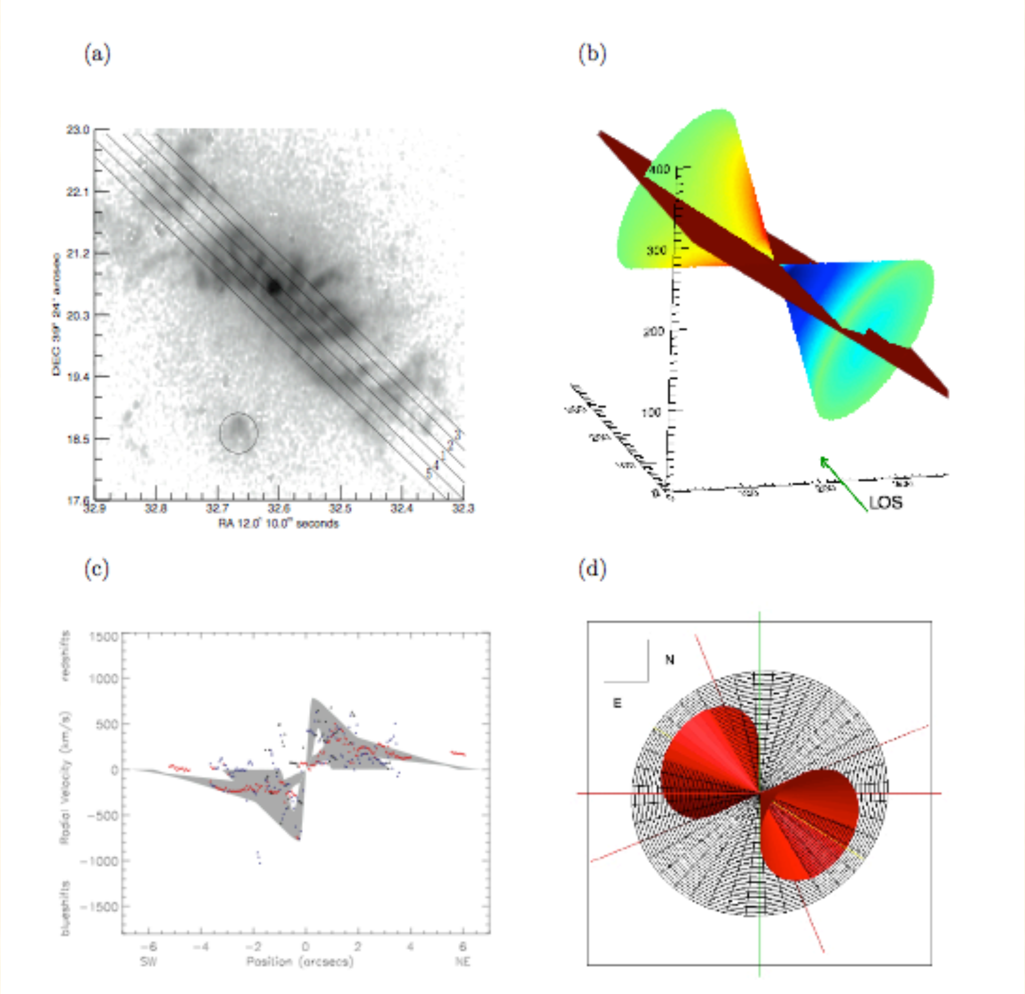


(Das et al. 2006, AJ, 132, 620)

incl = 5°, θ_{max} = 40°, θ_{min} = 26°, v_{max} = 1300 km/sec, r_t = 137 pc

- Outflow matches the general trend.
- Radial acceleration followed by deceleration.

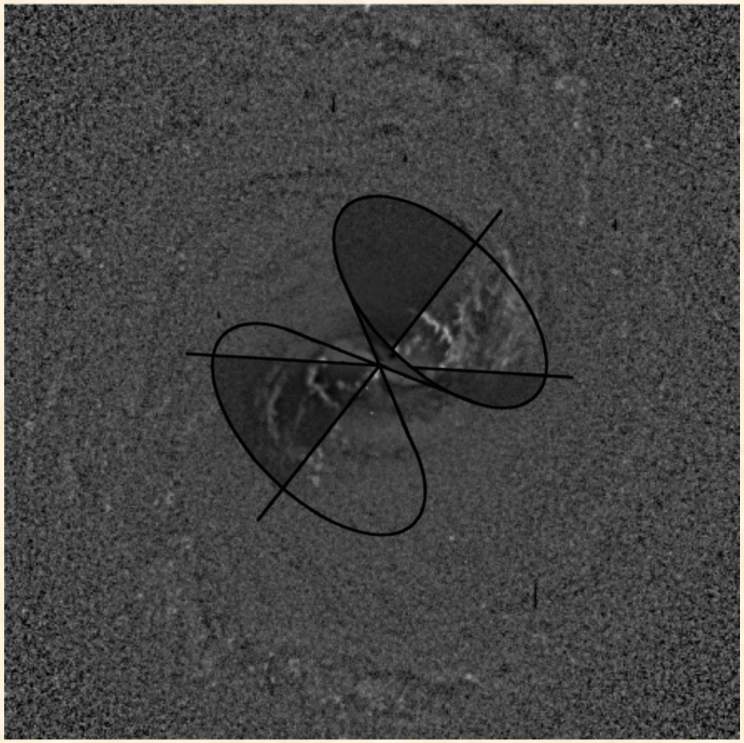
Kinematics of the Narrow-Line Region in NGC 4151

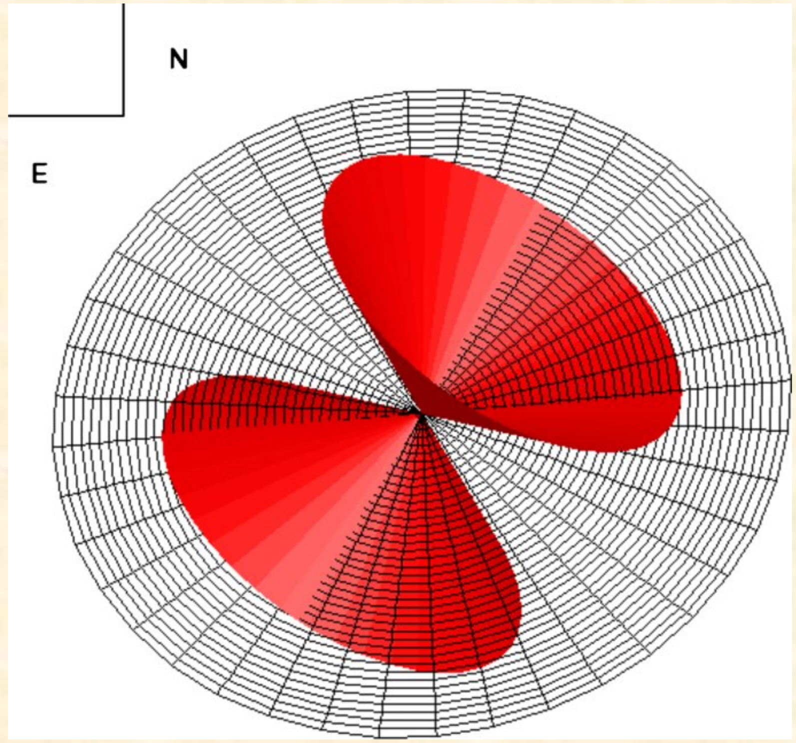


(Das et al. 2005, AJ, 130, 945)

incl = 45°, θ_{max} = 33°, θ_{min} = 15°, v_{max} = 800 km/sec, r_t = 96 pc

Mrk 573 – Ionized Spirals in the NLR





(Fischer et al. 2010, AJ, 140, 577)

- NLR geometry due to intersection between host disk and ionizing bicone.
- Kinematic indicate “in situ” acceleration of gas from the dust spirals.

What is the importance of NLR outflows?

- Provide AGN feedback on scales of hundreds of parsecs
  → may regulate black hole growth, terminate star formation, and explain black-hole mass/bulge correlations
- Provide alternate explanation for double-peaked NLR emission lines (Crenshaw et al. 2010)
  → Often used to claim double SMBHs in distant merging galaxies
- Kinematic models can determine the *inclination* of the AGN system (bicone, torus, and presumably accretion disk)
  → Investigate how intrinsic properties (SED, BLR velocities, absorber column densities) change with polar angle

Combined Studies of Absorbers and NLR Gas

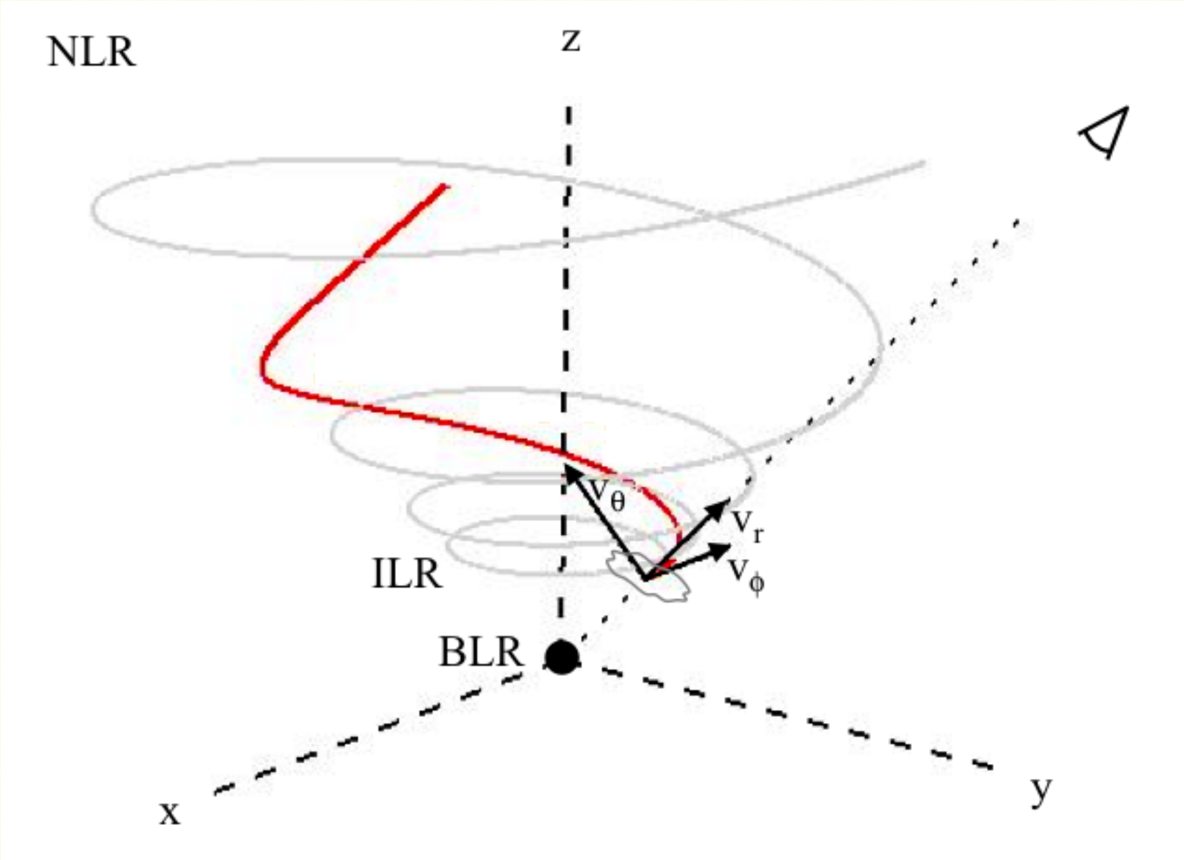
- The absorbers and inner NLR have similar kinematics and locations in Seyferts (tenths to tens of pc, Crenshaw & Kraemer 1985).
- However, the NLR tends to have lower ionization parameters (U) and higher column densities (N_H) than UV absorbers.
- NLR global covering factor is typically only $C_g = 0.02$, whereas $C_g = 0.5$ for Seyfert UV absorbers.

  → The UV absorbers may be a high-ionization, diffuse component of the inner NLR (or "intermediate-line region).

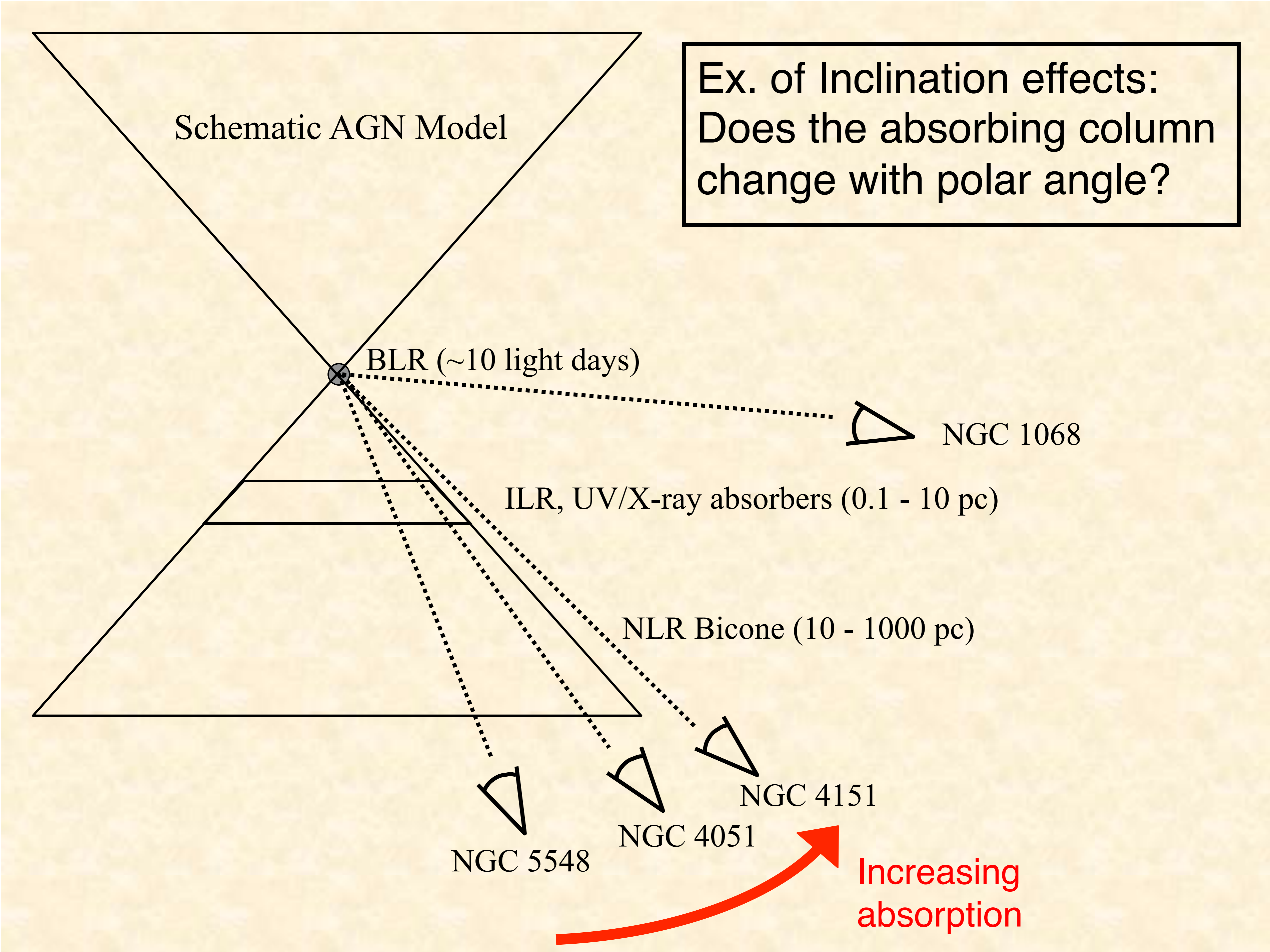
What are our goals?

- What is the structure and kinematics of AGN Winds?
- What is their impact in terms of AGN feedback?

Simple Geometric Model - UV absorber in NGC 4151



- r = 0.1 pc, $\theta = 45°$, $v_r = v_{los} = -490$ km s^{-1},
- Assume $v_\Phi = 0$, then $v_\theta = v_T = 2100$ km s^{-1}
  ($v_T = 10{,}000$ km s^{-1} also shown)


Schematic AGN Model
Ex. of Inclination effects:
Does the absorbing column
change with polar angle?
BLR (~10 light days)
NGC 1068
ILR, UV/X-ray absorbers (0.1 - 10 pc)
NLR Bicone (10 - 1000 pc)
NGC 4151
NGC 4051
NGC 5548
Increasing
absorption

Feedback Constraints: UV/X-ray Absorbers

What are their mass outflow rates and kinetic luminosities?

$$\dot{M}_{out} = 8\pi r N_H \mu m_p C_g v_r, \qquad L_{KE} = \tfrac{1}{2}\dot{M}_{out} v_r^2$$

C_g = global covering factor $\approx$ 0.5

Sample

Table 1. AGN Fundamental Parameters

Name	log (L_{bol} /ergs s^{-1})	log (M_{BH} /$M_\odot$)	L/L_{Edd}	($\dot{M}_{acc}$) ($M_\odot$ yr^{-1})	Reference
NGC 3516	44.16	7.50	0.036	0.026	1
NGC 3783	44.25	7.47	0.047	0.032	2
NGC 4051	42.81	6.24	0.030	0.001	1
NGC 4151	43.87	7.66	0.013	0.013	3
NGC 4395	40.77	5.56	0.001	1.06E-5	4
Mrk 279	44.87	7.54	0.169	0.134	4
NGC 5548	43.90	7.64	0.014	0.014	1
Mrk 509	45.27	8.16	0.104	0.336	2
Akn 564	44.61	6.42	1.242	0.074	5
NGC 7469	44.71	7.09	0.335	0.093	2

Table 2. AGN Feedback Parameters

Name	$\dot{M}_{out}$ ($M_\odot$ yr^{-1})	log (L_{KE} /ergs s^{-1})	$\dot{M}_{out}/\dot{M}_{acc}$	L_{KE}/L_{bol}
NGC 3516	9.8E-03 – 7.7E+00	39.13 – 42.76	0.4 – 300	9.2E-06 – 4.0E-02
NGC 3783	1.0E+01 – 5.9E+01	42.75 – 43.18	320 – 840	3.2E-02 – 8.5E-02
NGC 4051	2.1E-03 – 6.6E-02	38.11 – 39.84	1.8 – 56	2.0E-05 – 1.1E-03
NGC 4151	6.5E-01 – 1.3E+00	40.70 – 41.48	48 – 100	6.8E-04 – 4.1E-03
NGC 4395	1.7E-05 – 2.8E-04	36.58 – 37.04	1.63 – 26	6.4E-05 – 1.9E-04
NGC 5548	>1.6E+00	>41	>110	>4.6E-03
NGC 7469	<1.1E+01	<42	<120	<4.6E-03

Conclusions

- Outflow rates are much higher than accretion rates → most of the infalling gas gets blown out before it reaches the inner accretion disk
- Kinetic luminosities are likely high enough to provide the 0.5 – 5% required in feedback models (see Hopkins & Elvis 2010)
- Outflow rates in NLR can be higher than those from UV absorbers → in situ acceleration in NLR (see direct evidence in Fischer et al. 2010, AJ, 140, 577)