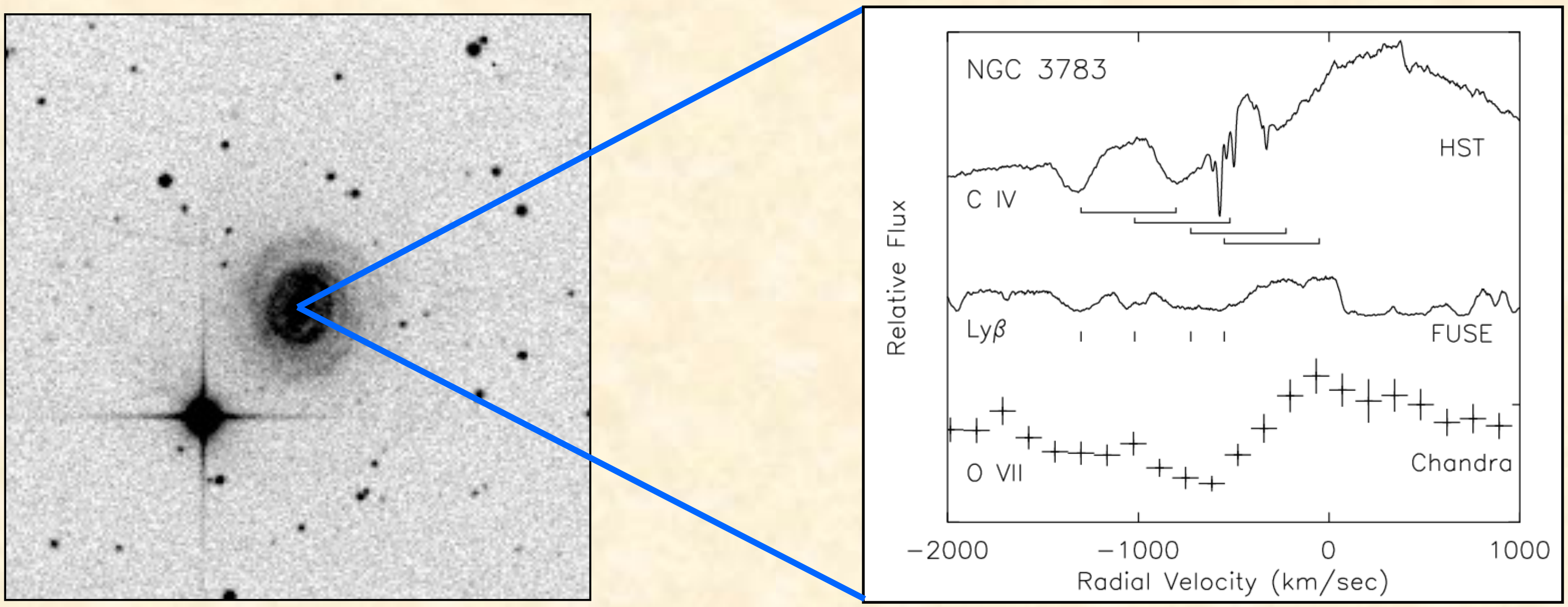
AGN Kinematics

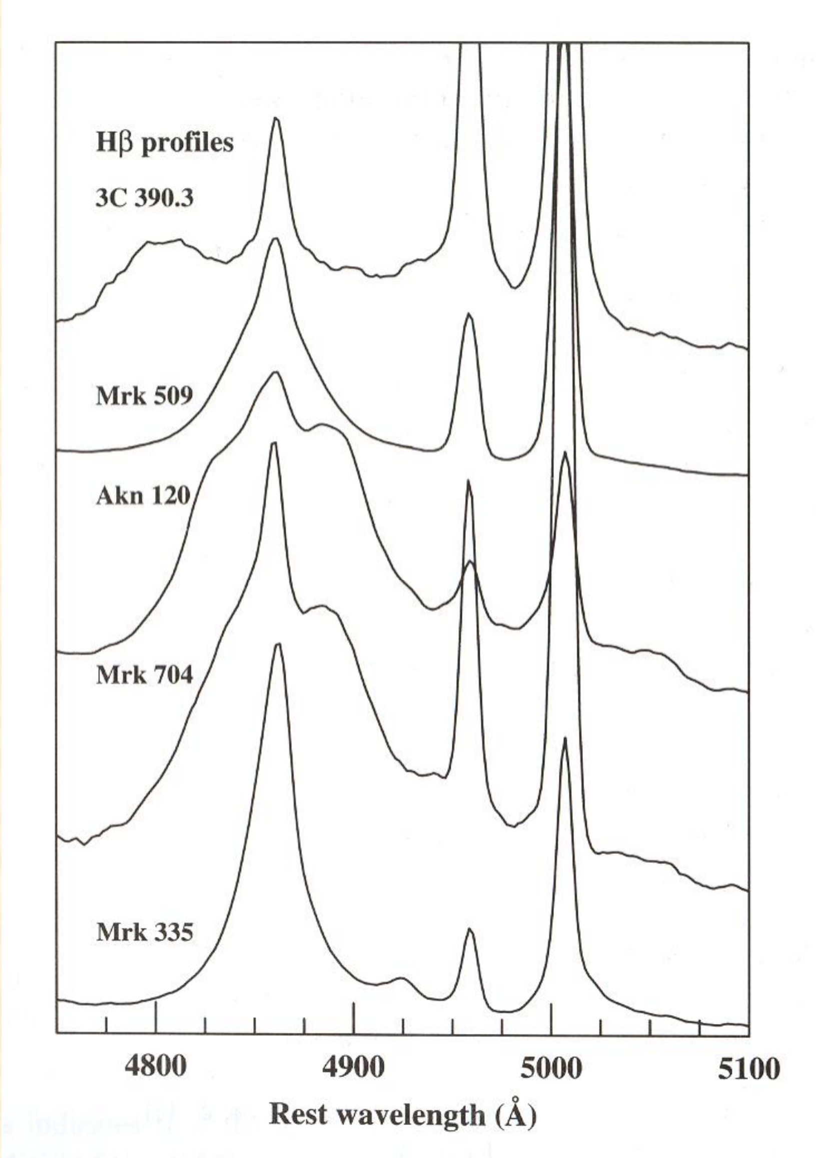
- BLR profiles and kinematics
- Outflows seen in Absorption (AGN Winds)
- Emission-Line Outflows in the NLR



BLR Profiles and Kinematics

BLRG

Sey 1



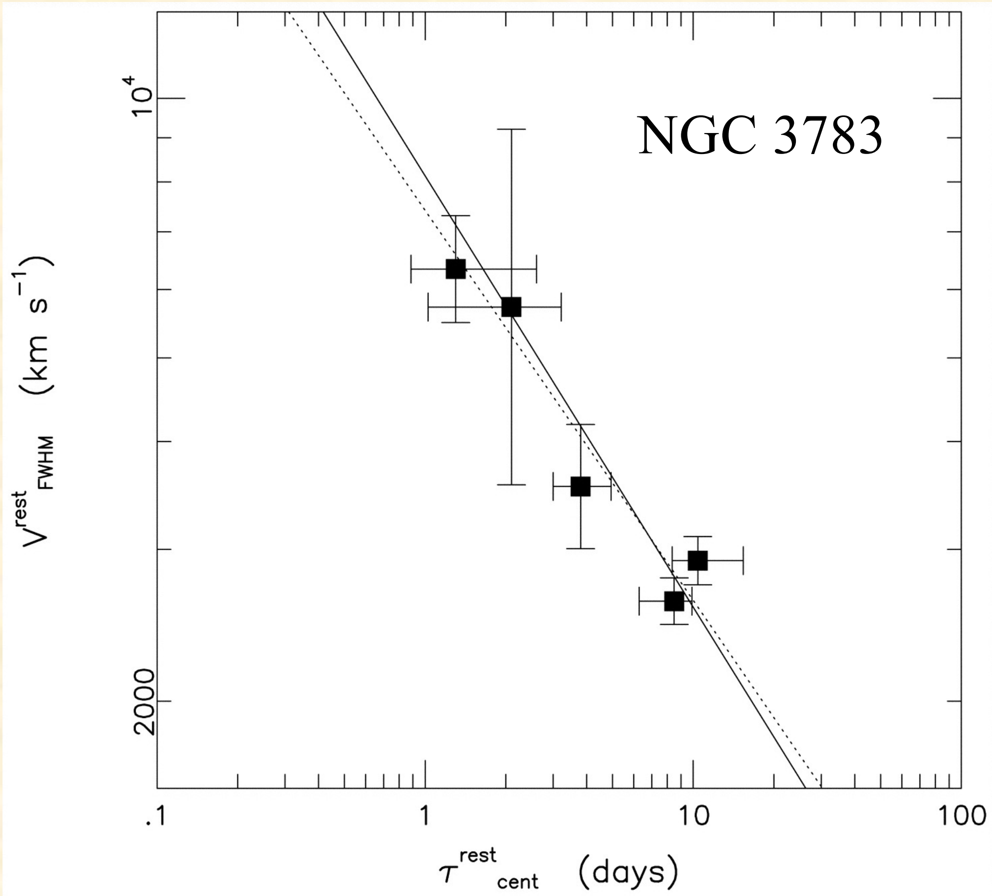
(Peterson, p. 69)

- 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

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)

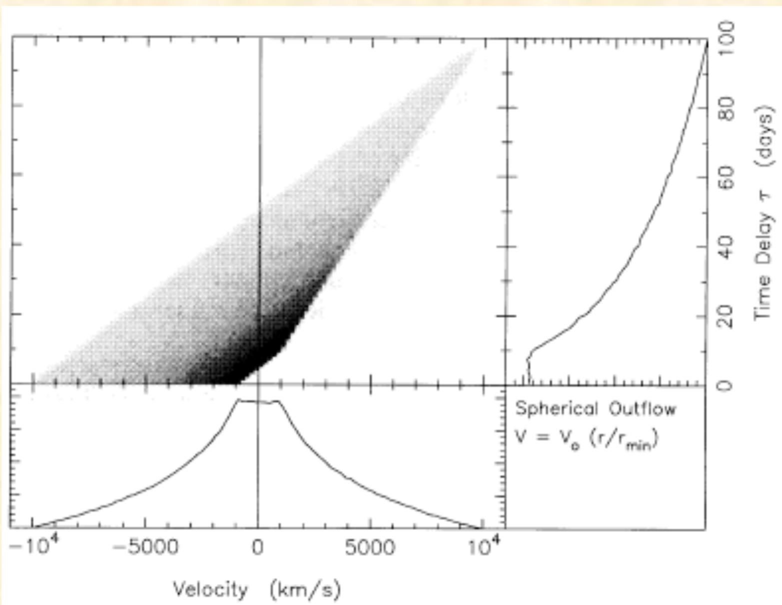
→ But radiation pressure could be important (Marconi et al. 2008)

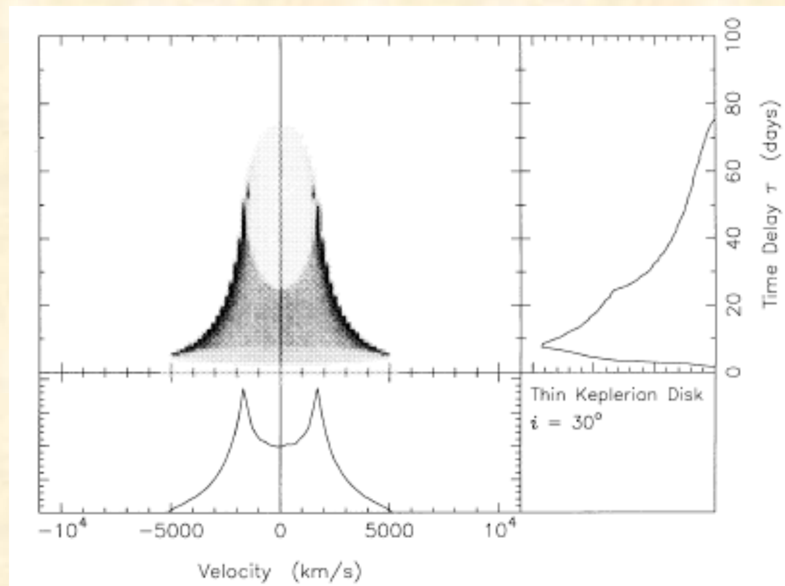
Determining the kinematics directly $\rightarrow$ (Radial) velocity-dependent Ψ

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

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

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

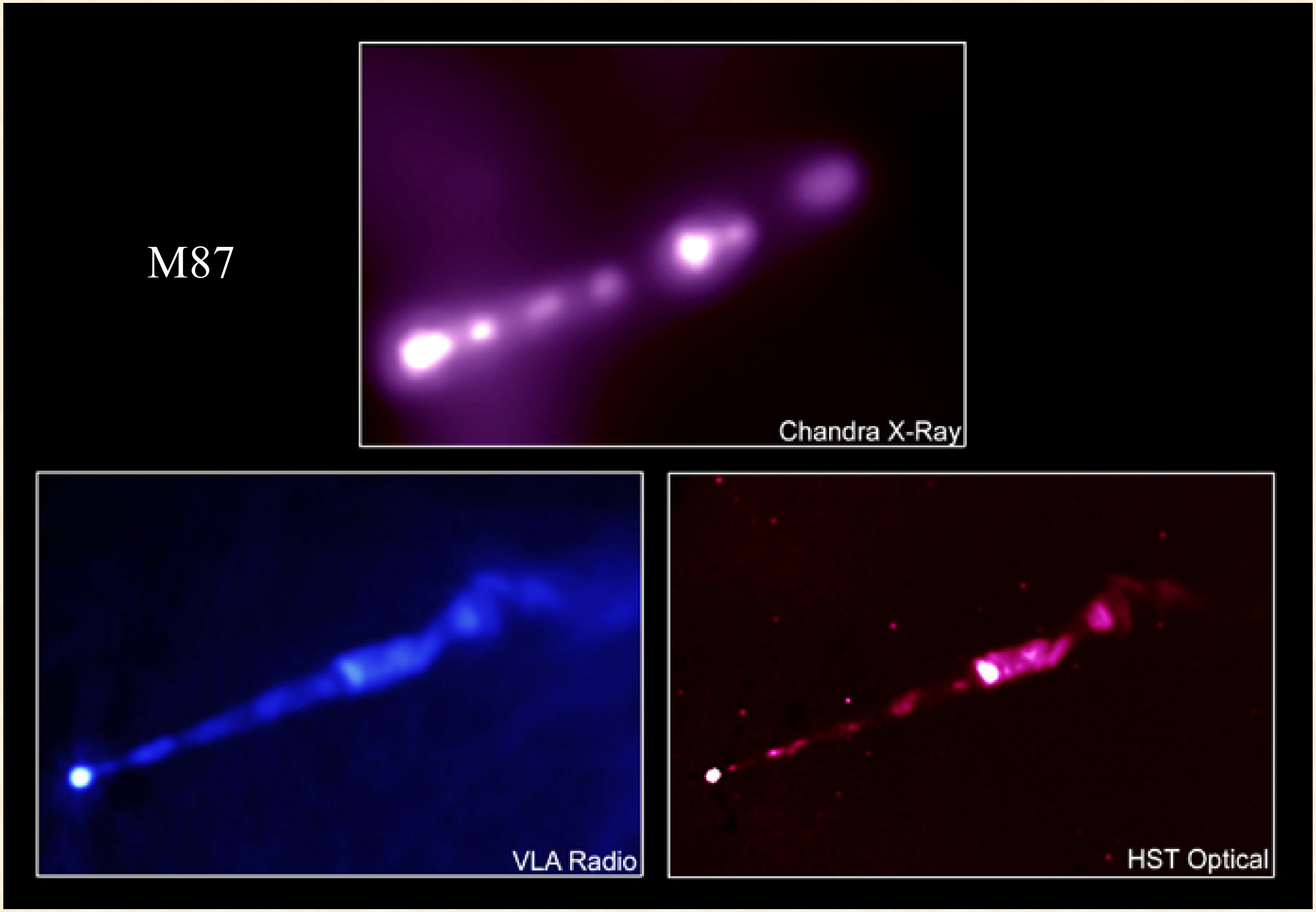




- Determine $\Psi(v,\tau)$ observationally and compare with models
- Recent results (also from forward-modeling simulations) indicate BLR is likely an accretion-disk wind.

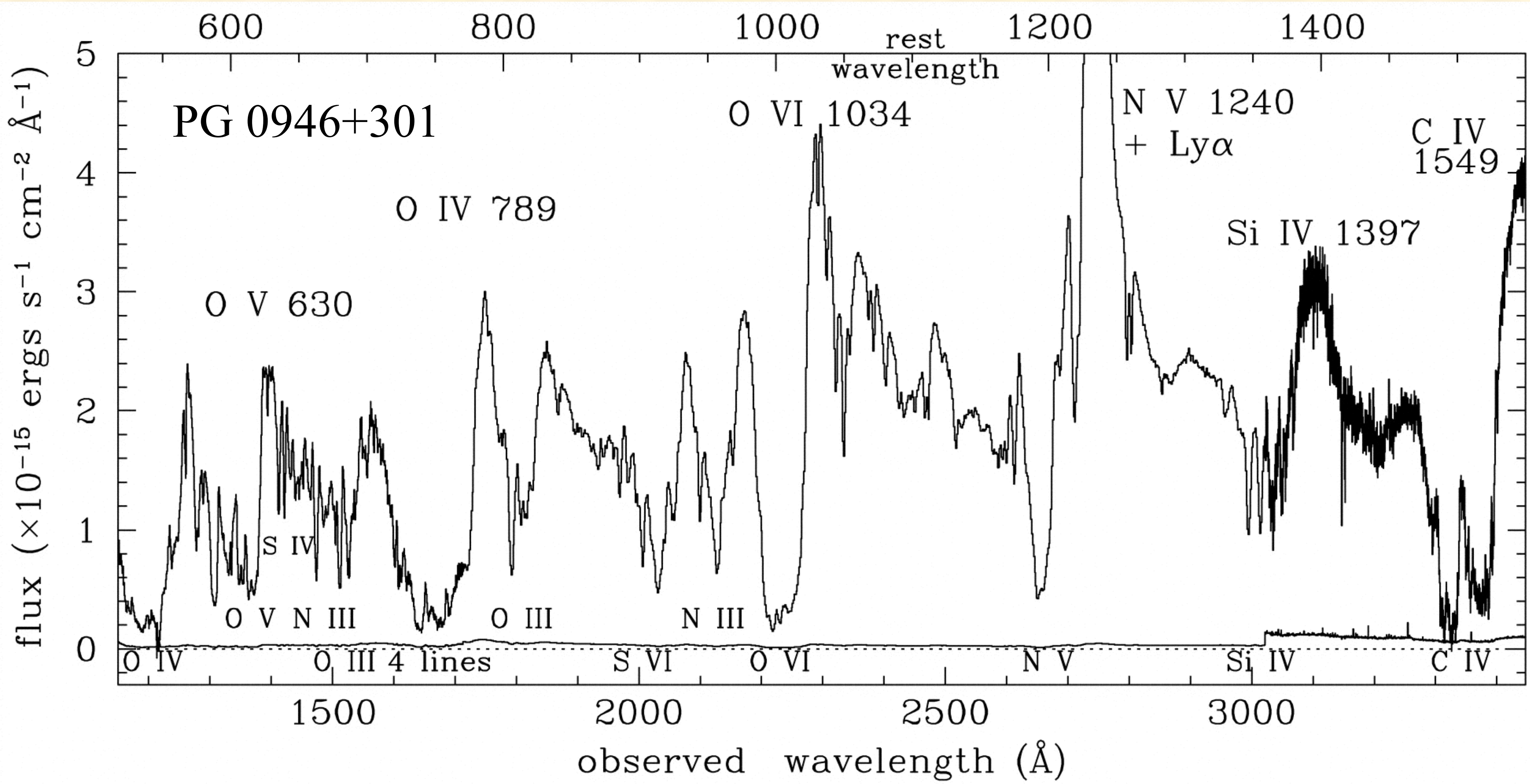
Outflows in AGN: Types

1) Jets in Radio-Loud Galaxies and Quasars



- Highly collimated, low density plasma traveling at relativistic speeds

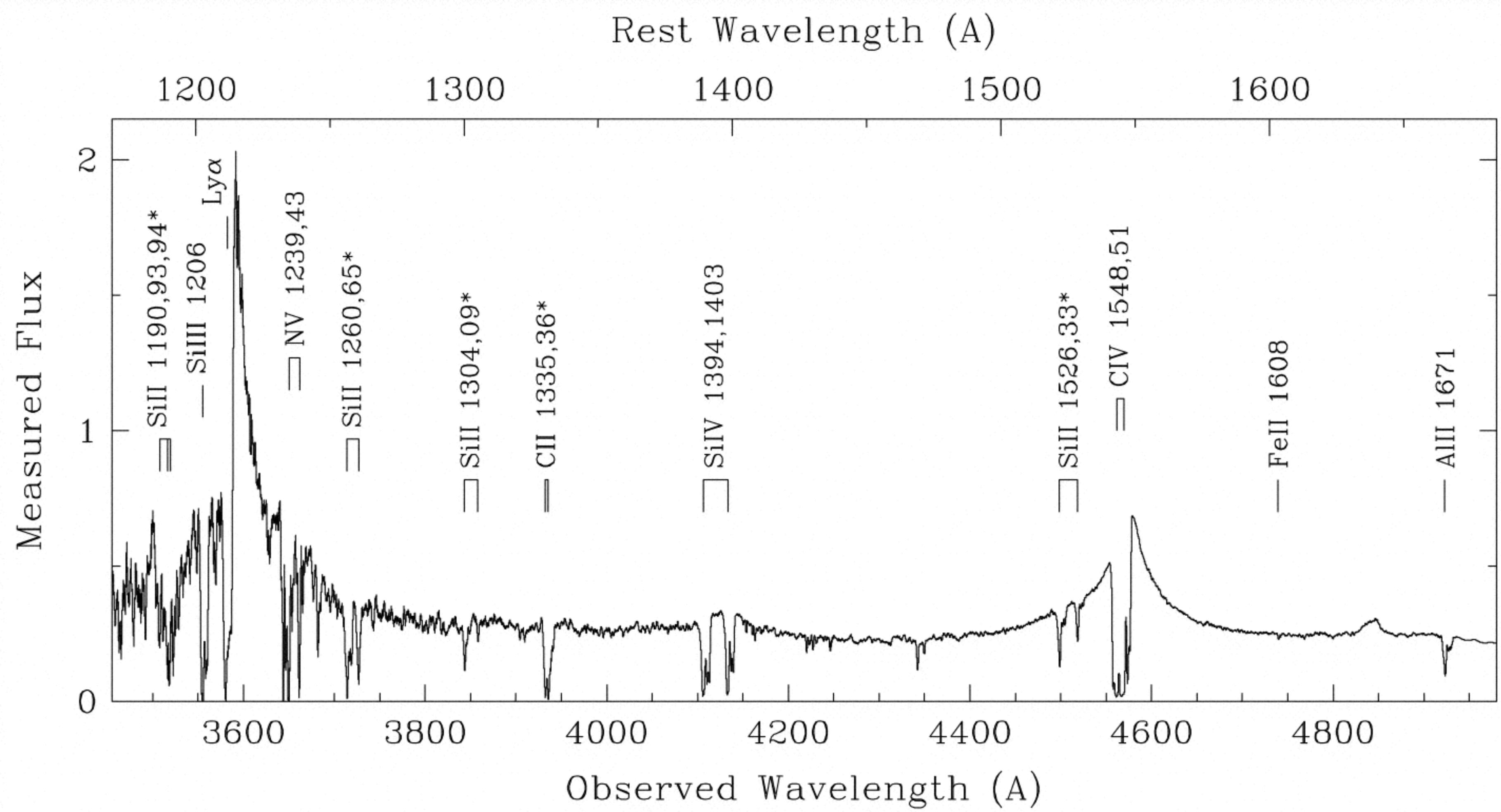
2) Broad Absorption-Line (BAL) Quasars



(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"

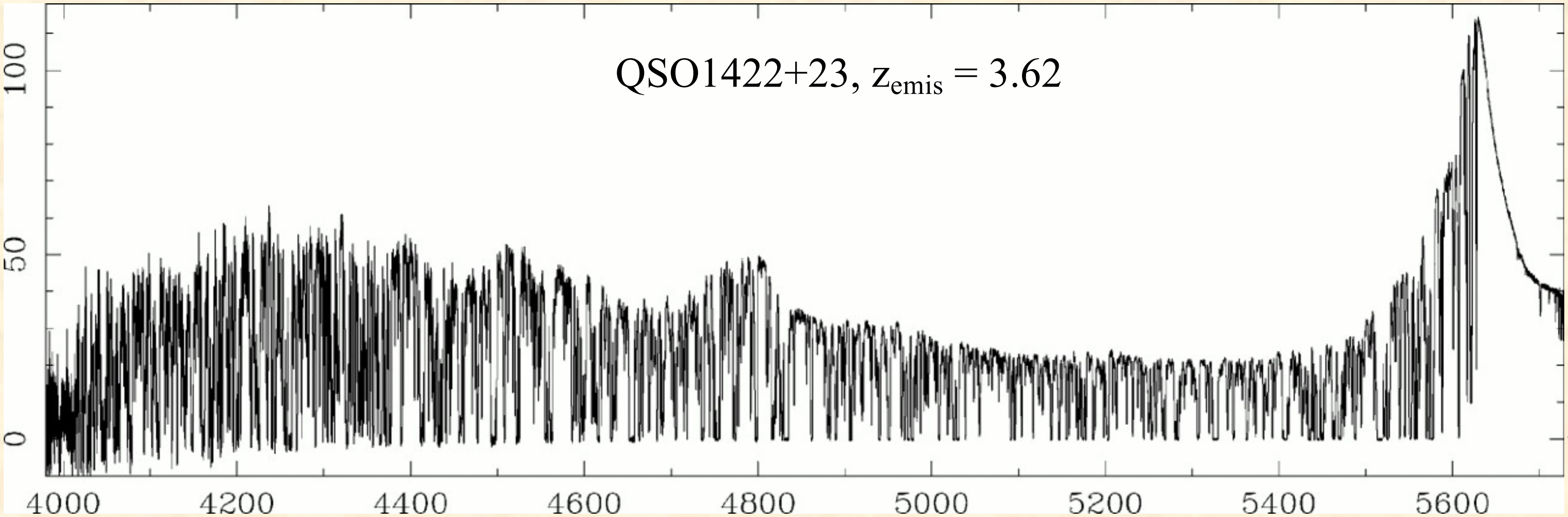


(Hamann et al. 2001, ApJ, 550, 152)

- 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

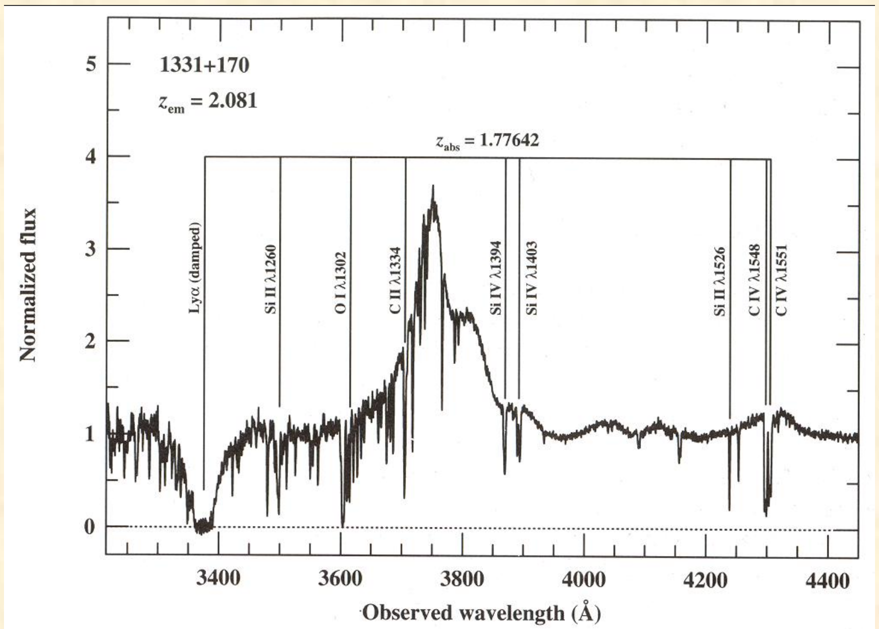
Not to be confused with absorption at $z_{abs} \ll z_{emis}$:

a) Lyα Forest - intervening clouds in the intergalactic medium



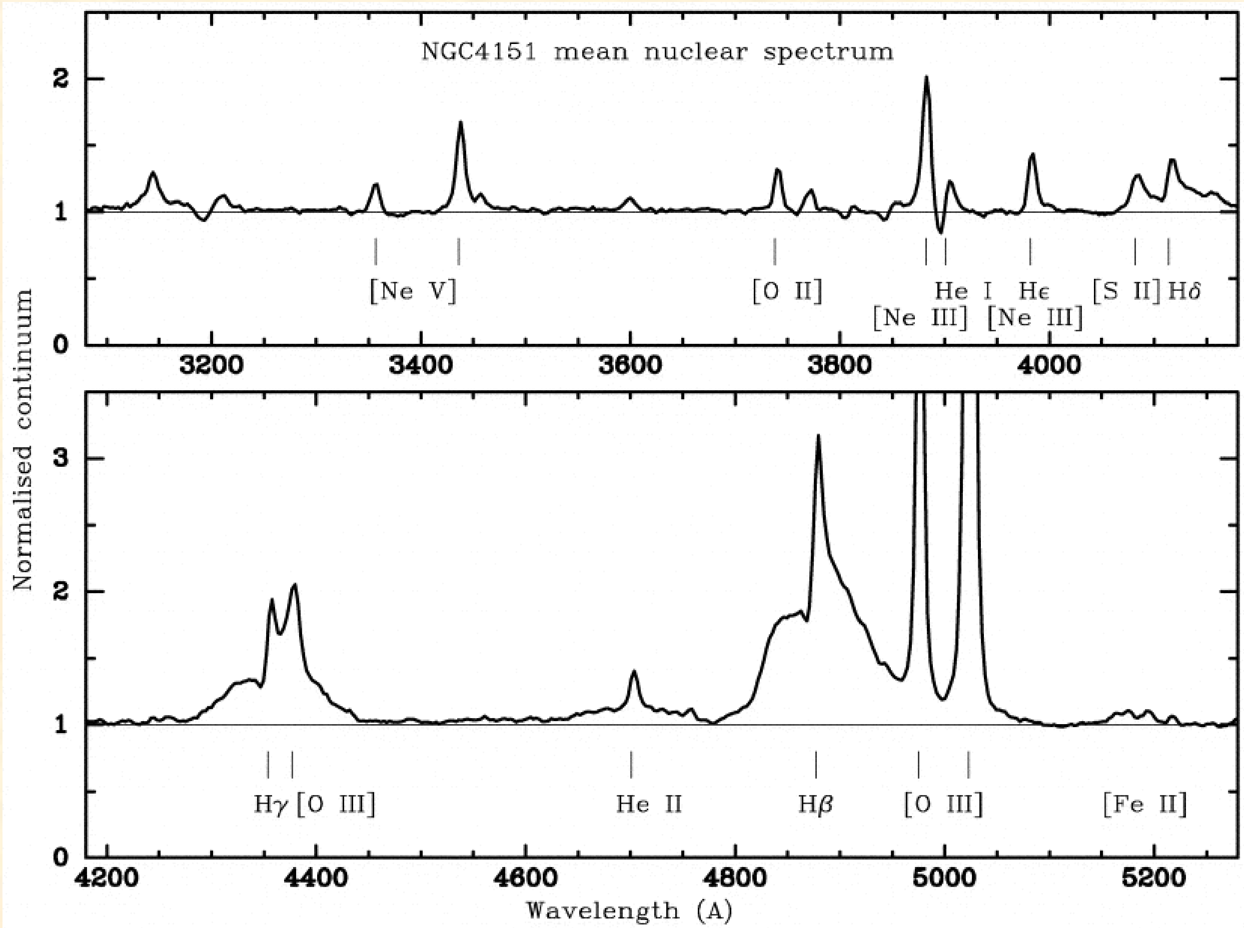
(Rauch, 1998, ARAA, 36, 267)

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



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

4) "Intrinsic Absorption" in Seyfert Galaxies



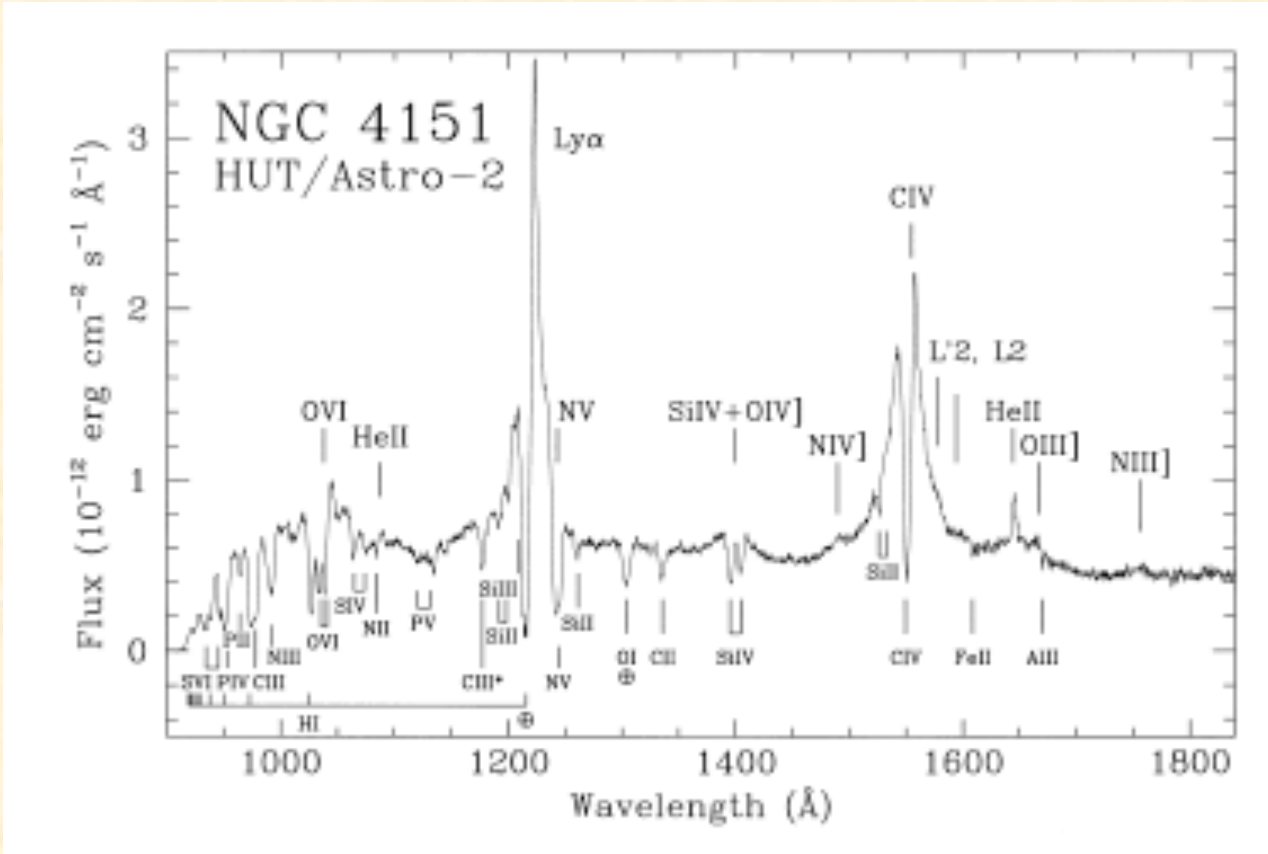
(Hutchings, et al., 2002, AJ, 224, 2543

- 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 (~60% of Seyferts) (Crenshaw, Kraemer, & George, 2003, ARAA, 41, 117).

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}

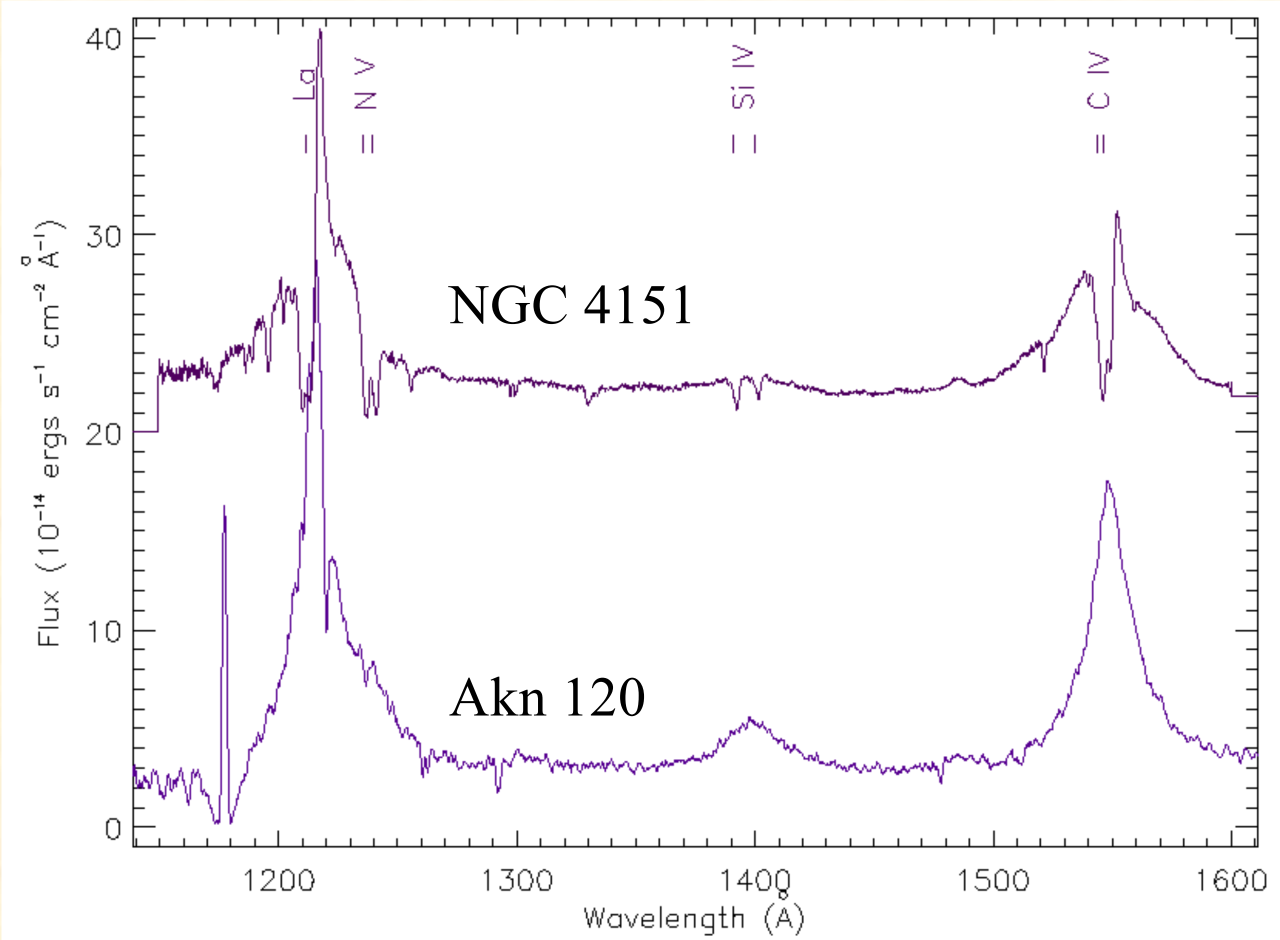
IUE/HUT Observations of Intrinsic UV Absorption



(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



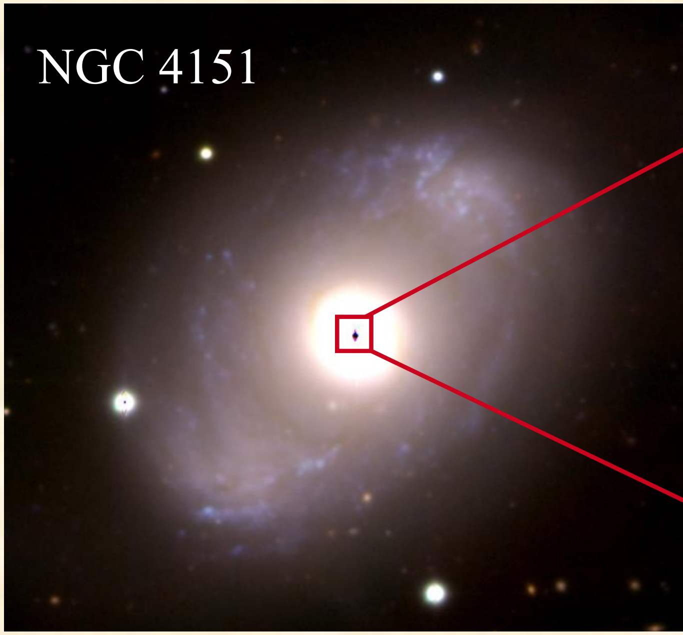
Intrinsic absorption

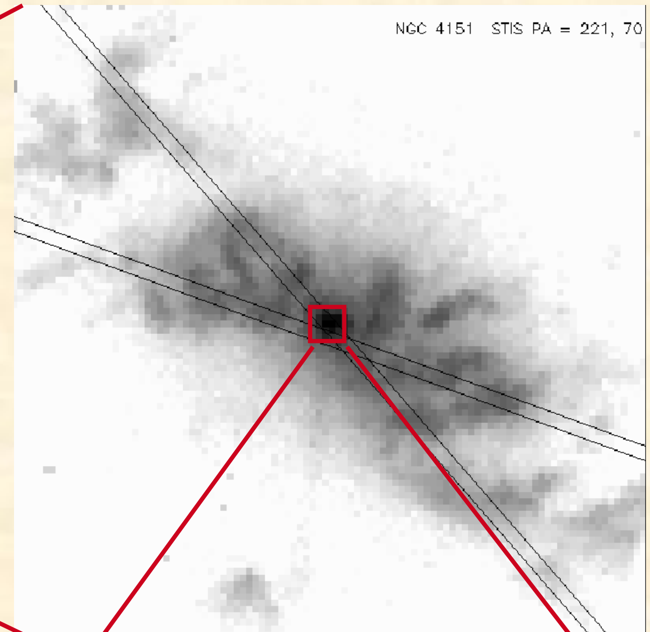
No intrinsic absorption

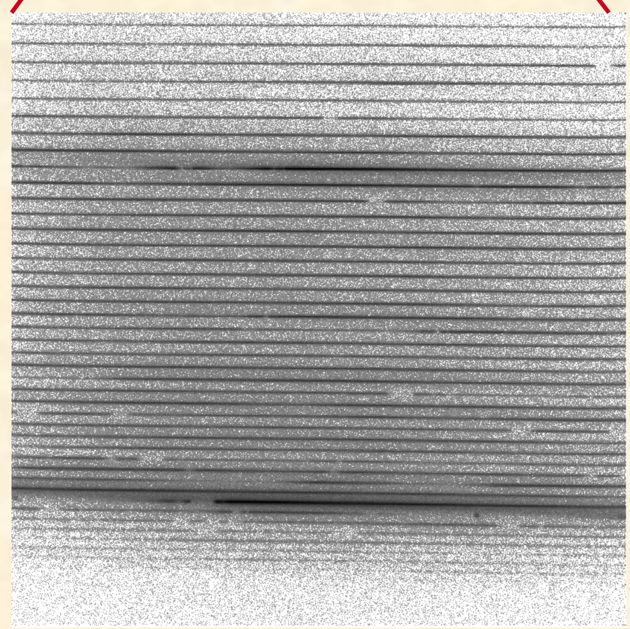
(Crenshaw et al. 1999, ApJ, 516, 750)

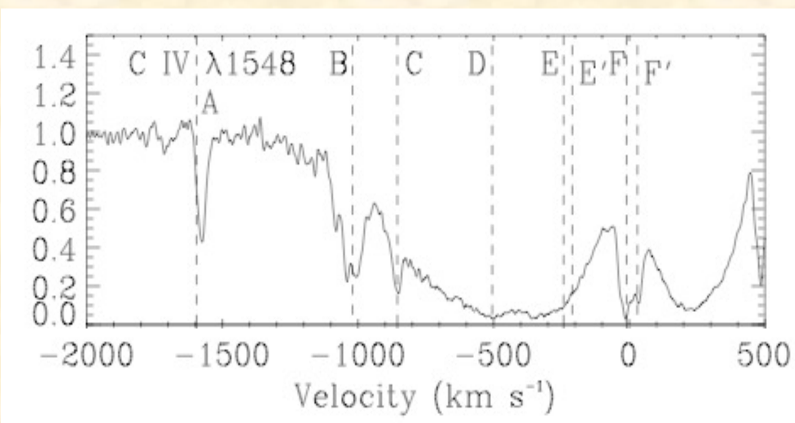
- 60% of Seyfert 1 galaxies show intrinsic absorption; those that show UV absorption also show X-ray absorption.
- Global covering of the continuum source and BLR: C_g = 0.5 - 1.0
- Most absorbers are highly ionized (C IV, N V); only 10% show Mg II

HST/STIS High-Resolution Spectra

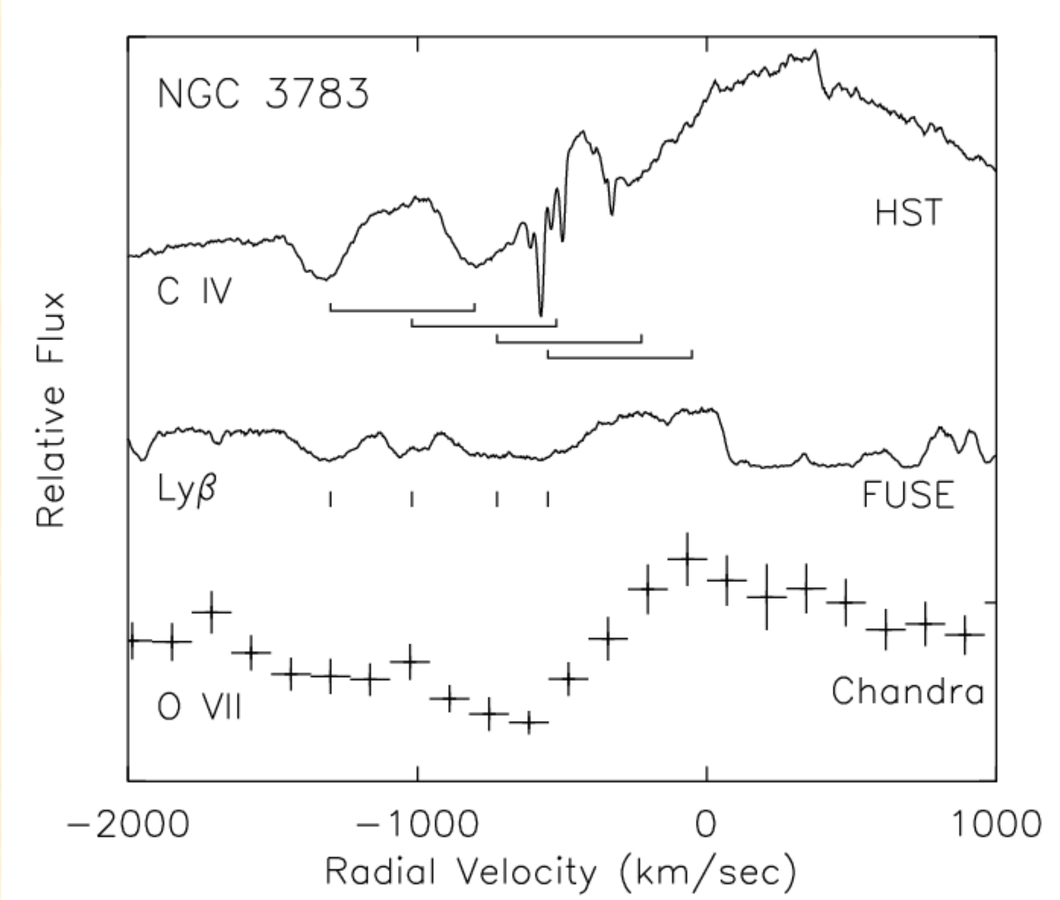








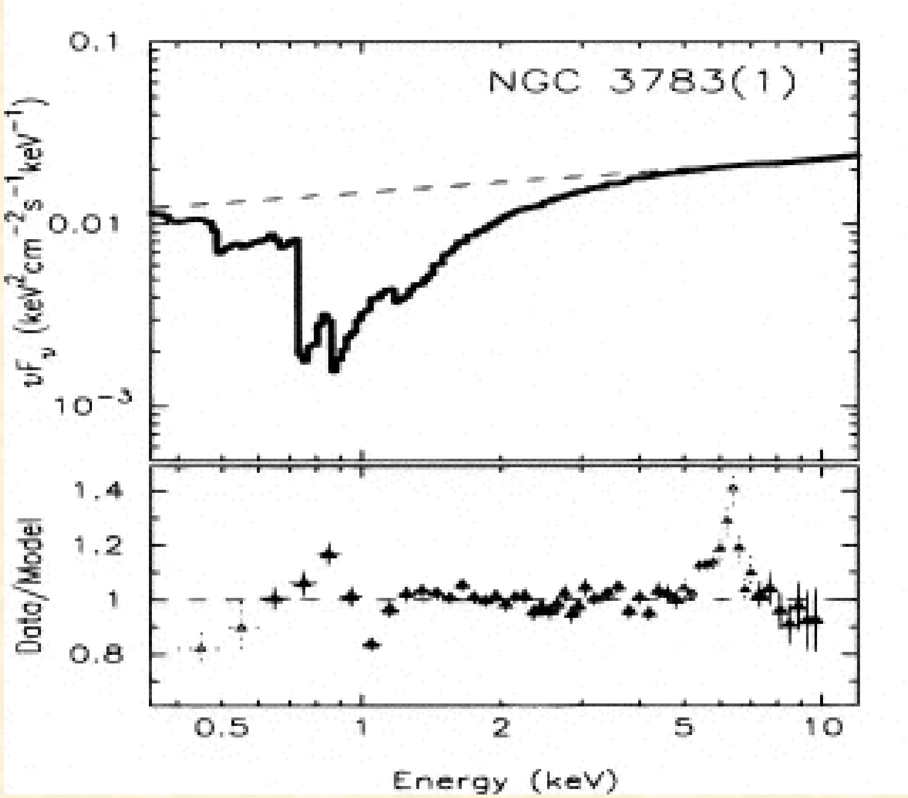
High Resolution Spectra



(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 can be 10 to 1000x the accretion rates (Crenshaw et al. 2012)

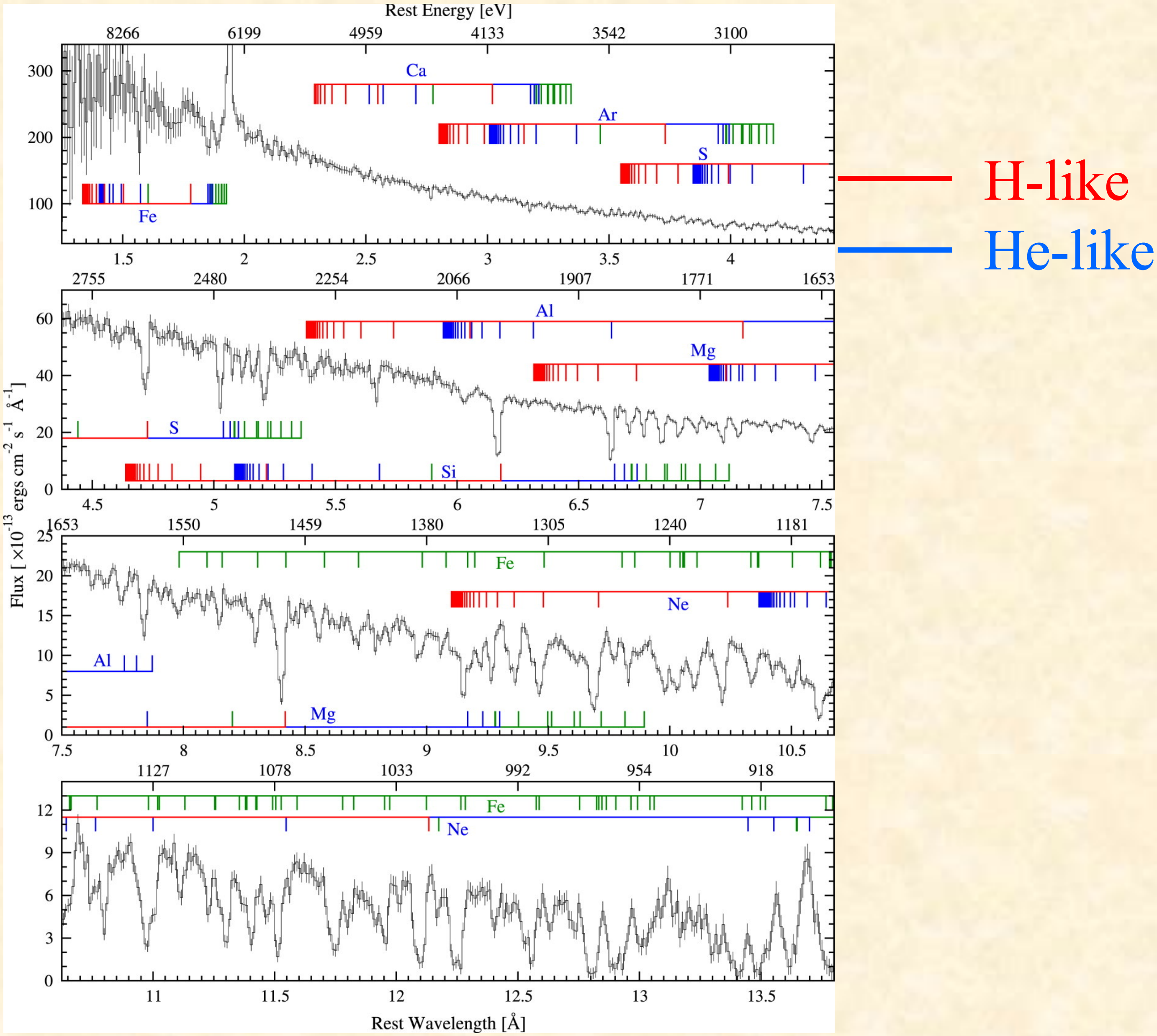
5) X-ray "Warm Absorbers" in Seyferts



(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 VIII 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)

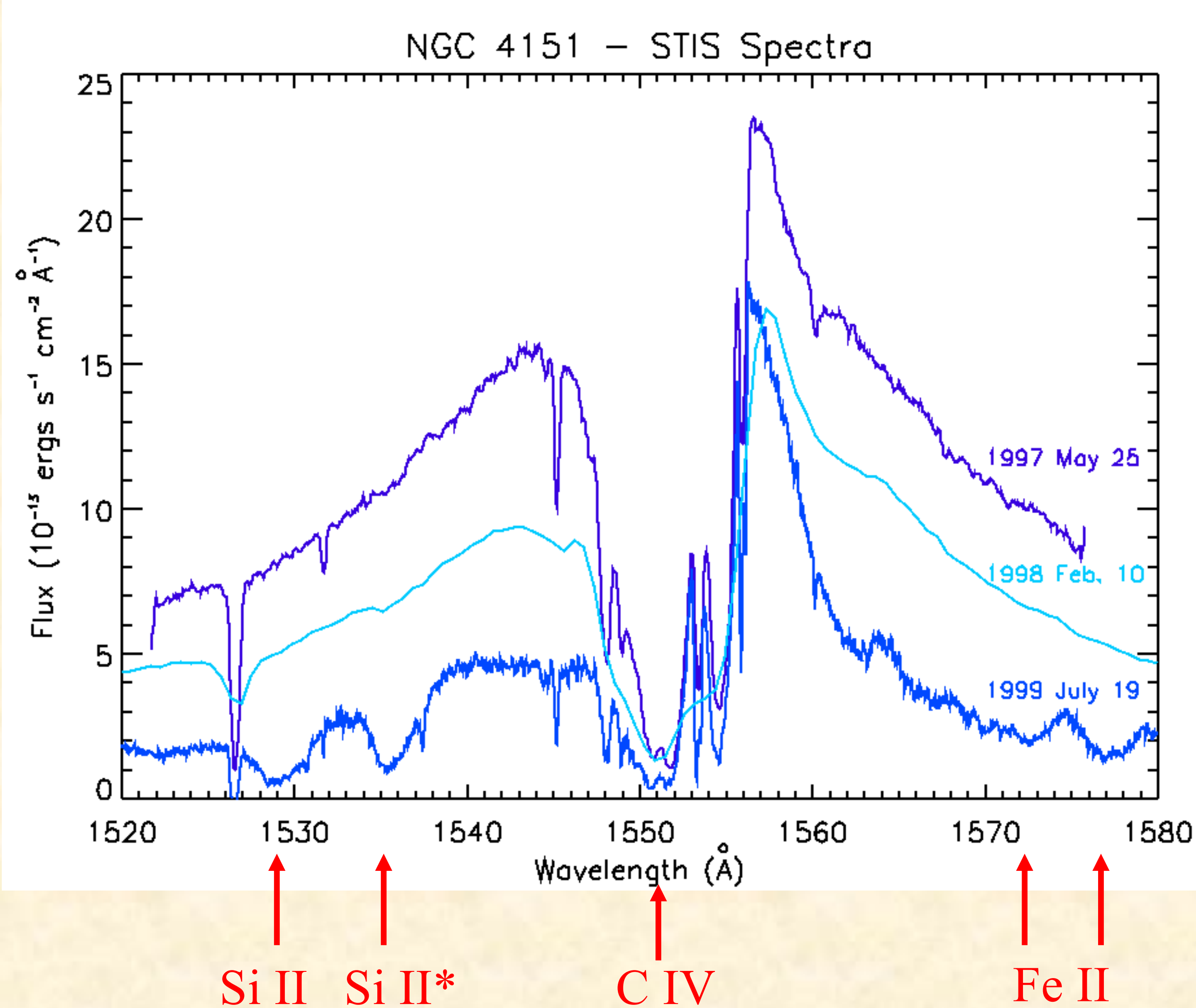
  2) Transverse motion of cloud across the BLR + continuum (variable N_H or covering factor in the line of sight)
- Variable ionizing continuum: can determine density (n_e) and distance from source (r) from time scale of variability (t)

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

- Transverse motion: can determine the transverse velocity

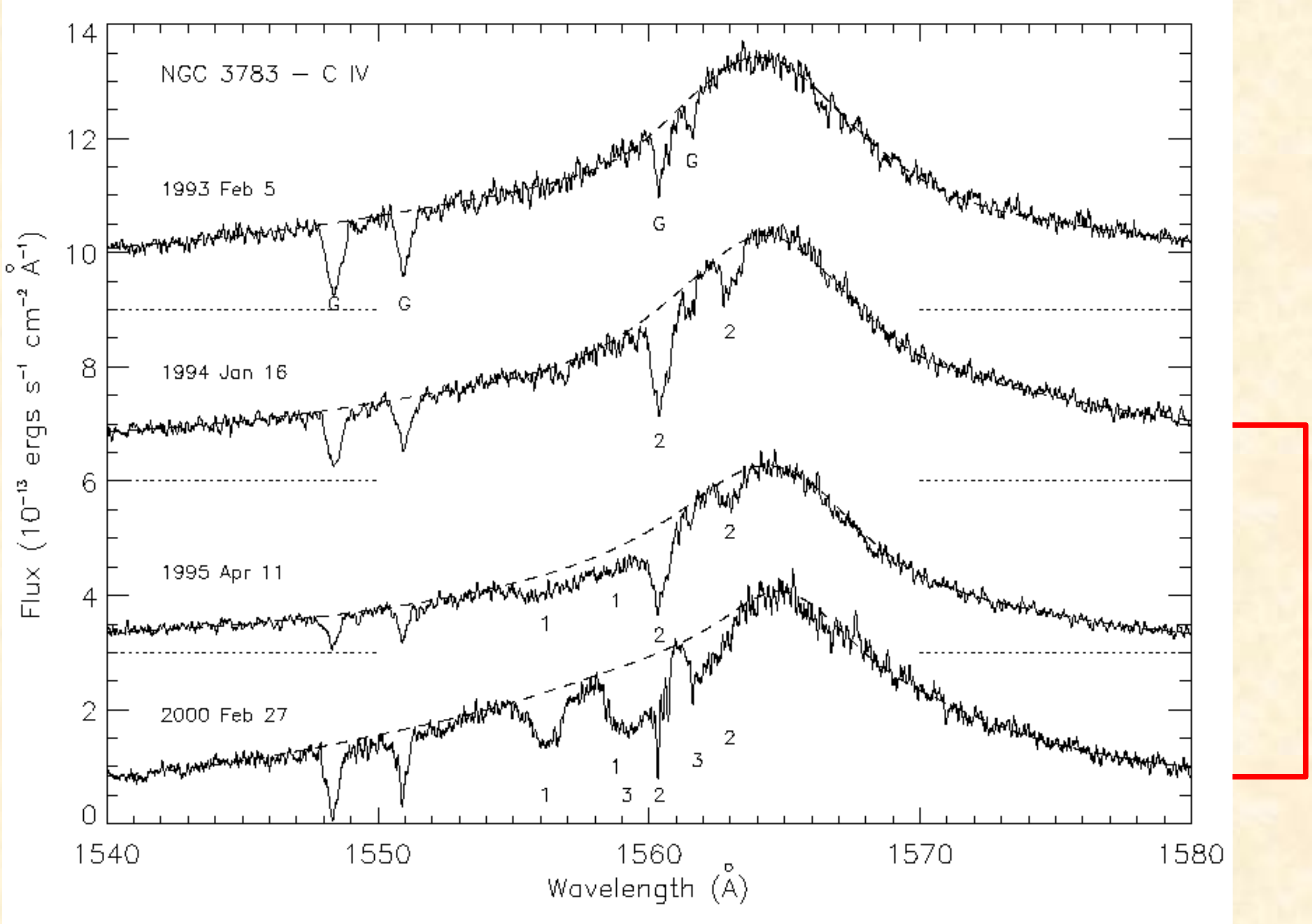
$$v_T = \sqrt{C_{BLR}}\, d_{BLR} / t, \quad \text{where } C_{BLR} \text{ is the los covering factor}$$

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: $v_T = \sqrt{C_{BLR}\, d_{BLR}} / \Delta t \;\geq\; 550$ km s^{-1}

Why are AGN outflows important?

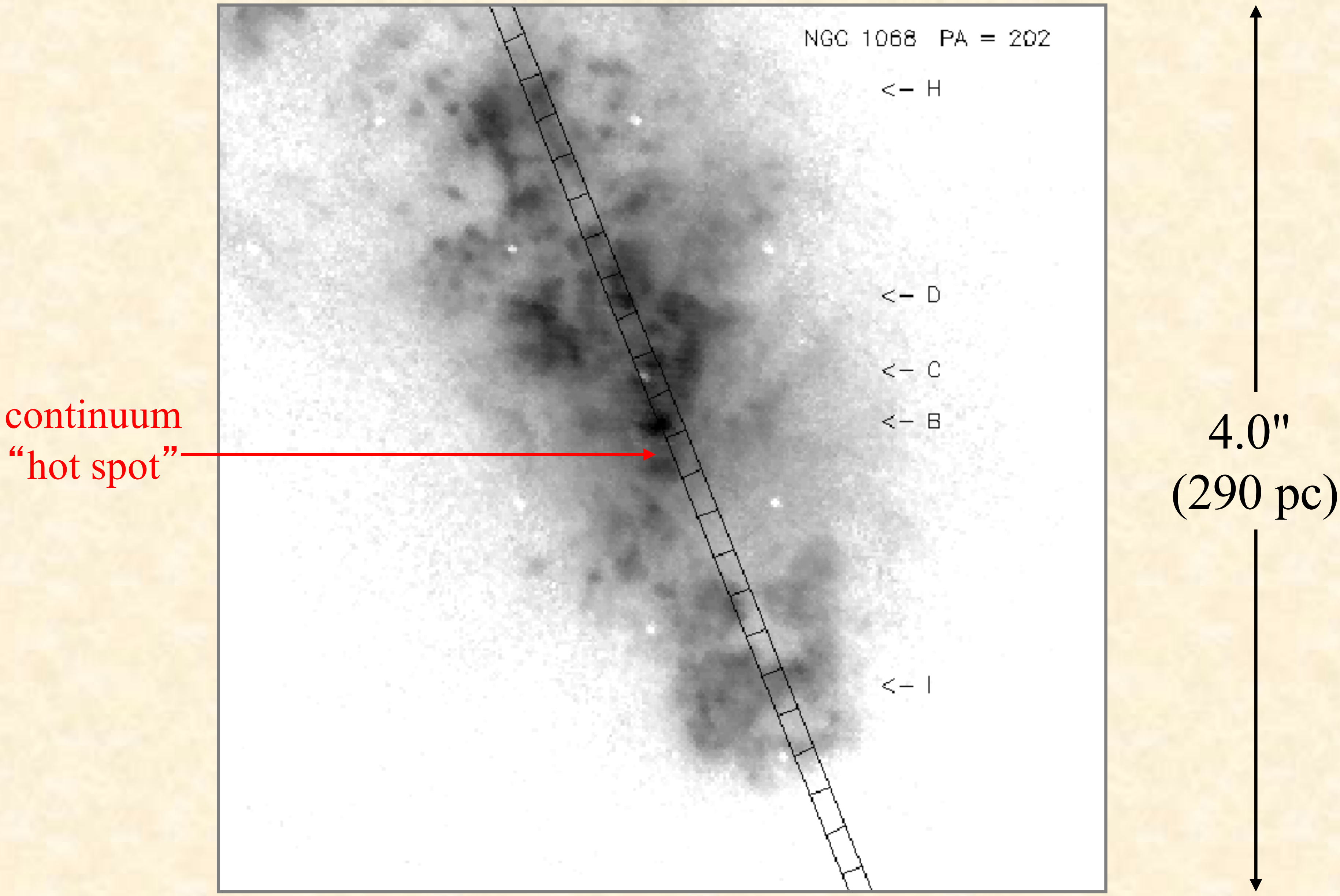
- Quasar outflows have likely:
  1) contributed to the heavy-element abundance of the IGM (Hamann & Ferland, 1999, ARA&A, 37, 487)
  2) influenced formation of structure in the early Universe (Scannapieco & Peng 2004, ApJ, 608, 62)
  3) regulated the growth of supermassive black holes and galactic bulges (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.

Emission-Line Outflows in the NLR

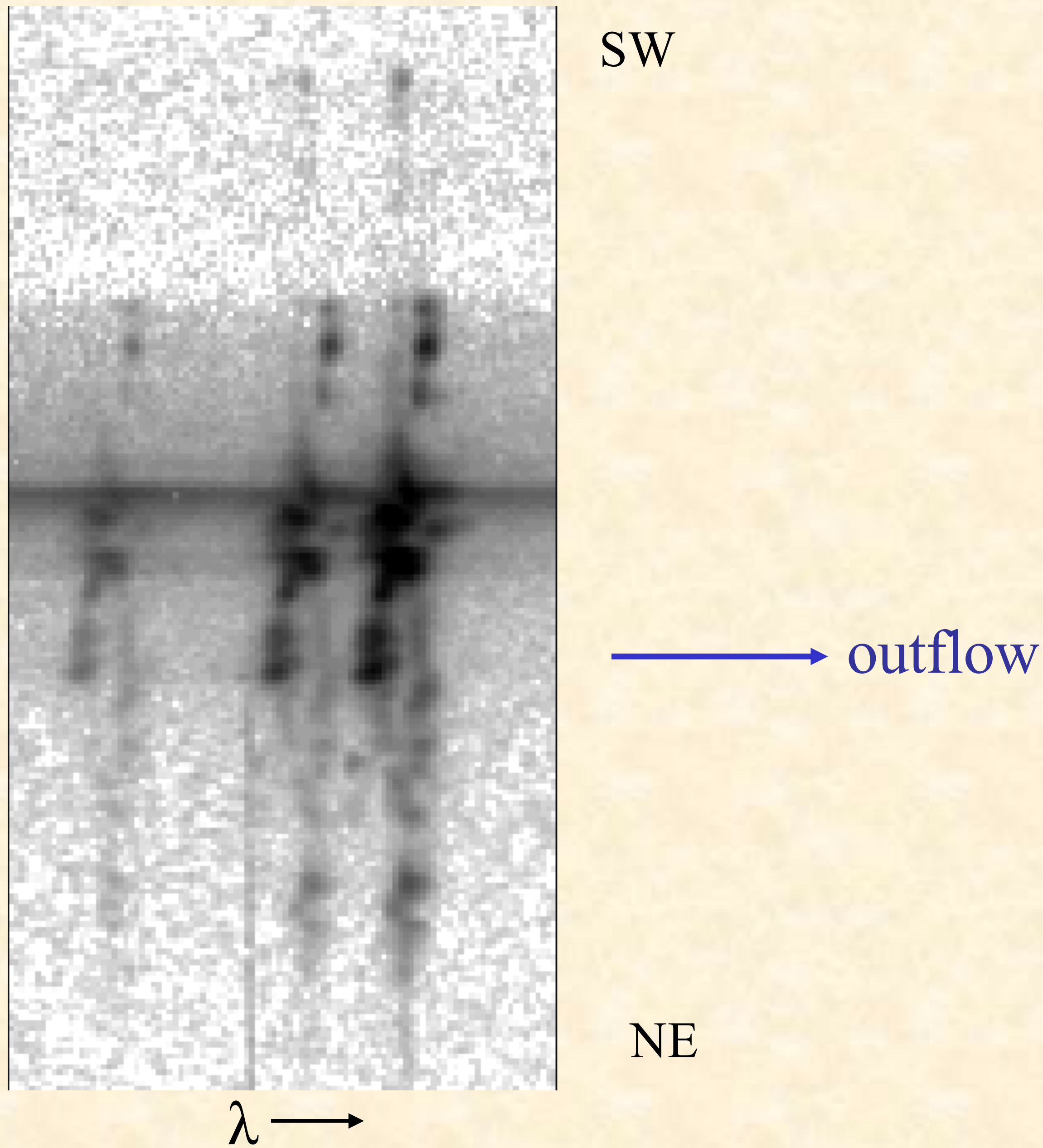
- Previous ground-based studies have claimed infall, rotation, parabolic orbits, outflow, etc.
- The problem: they relied on spatially integrated line profiles, since the NLR is only a few arcsecs across.
- HST/Space Telescope Imaging Spectrograph has angular resolution ~ 0.1".
- Large ground-based telescopes + 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)

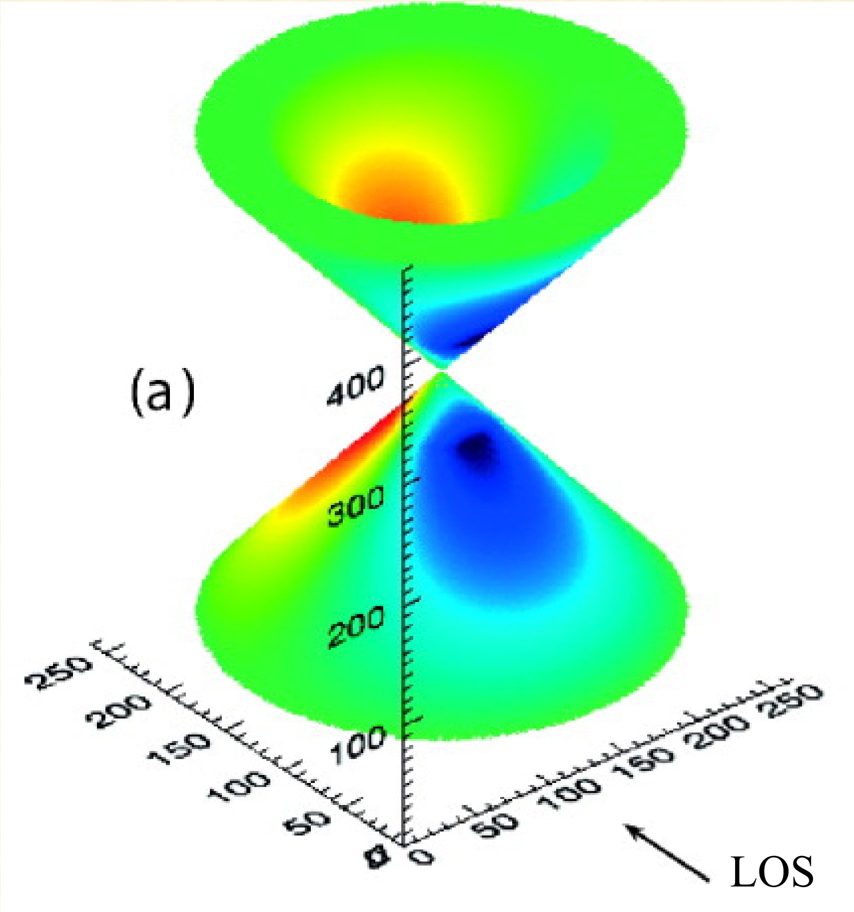
NGC 1068: NLR – [O III] Image

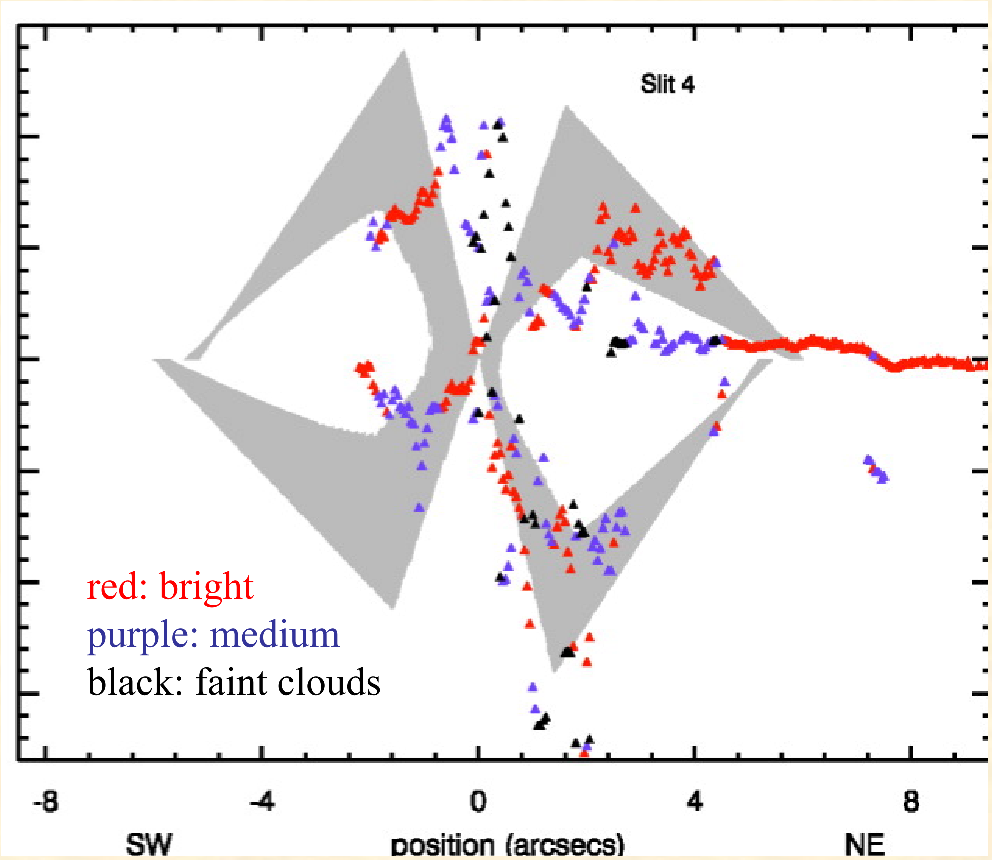


NGC 1068: STIS Long-Slit Spectrum (Hβ, [O III])



Biconical Outflow Model for the NLR in NGC 1068



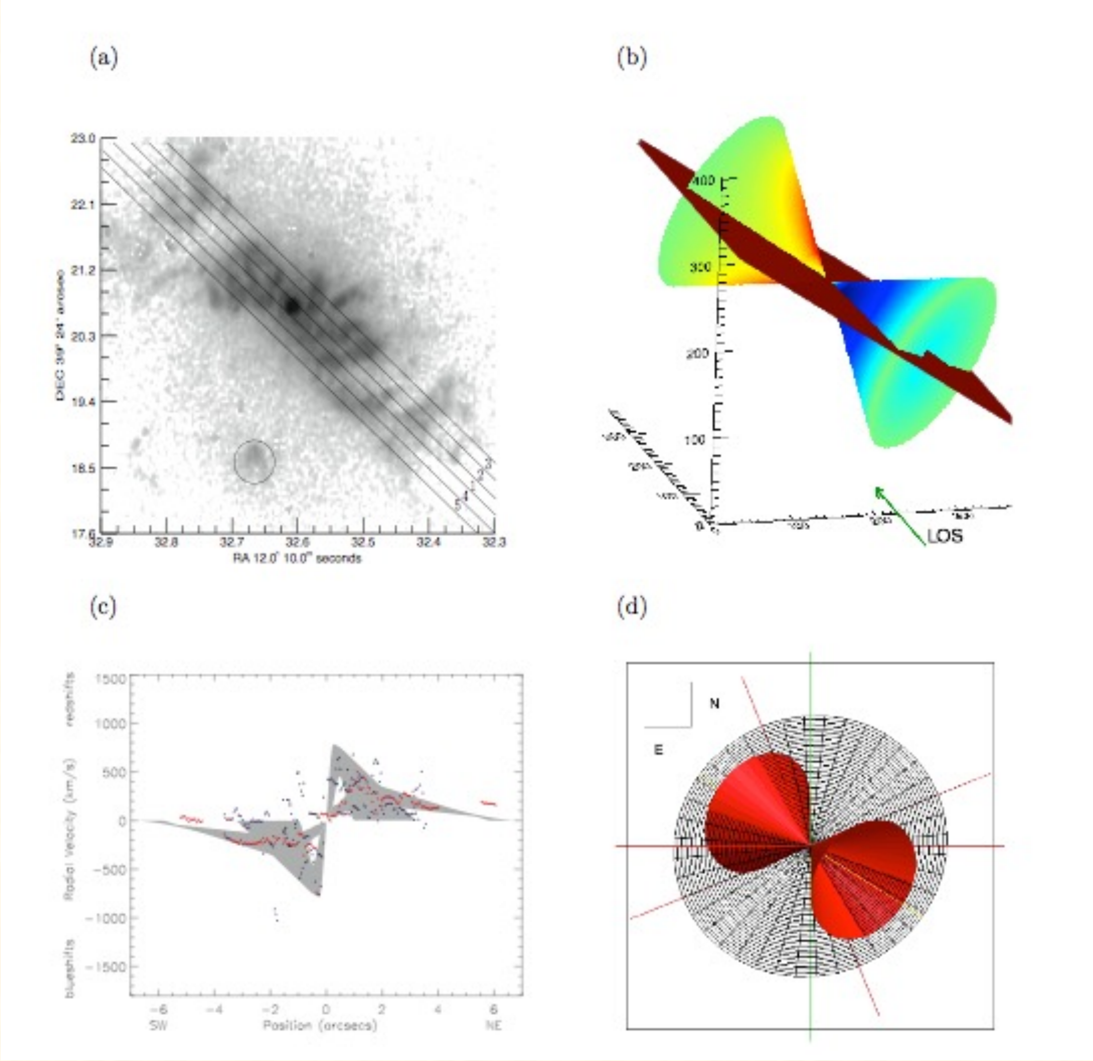


(Das et al. 2006, AJ, 132, 620)

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.

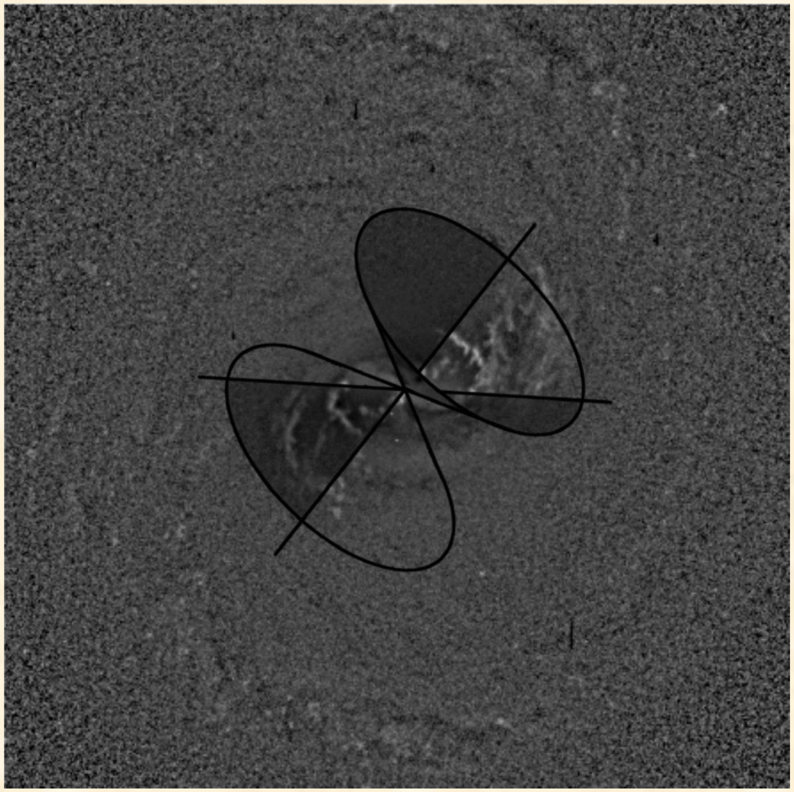
Kinematics of the Narrow-Line Region in NGC 4151

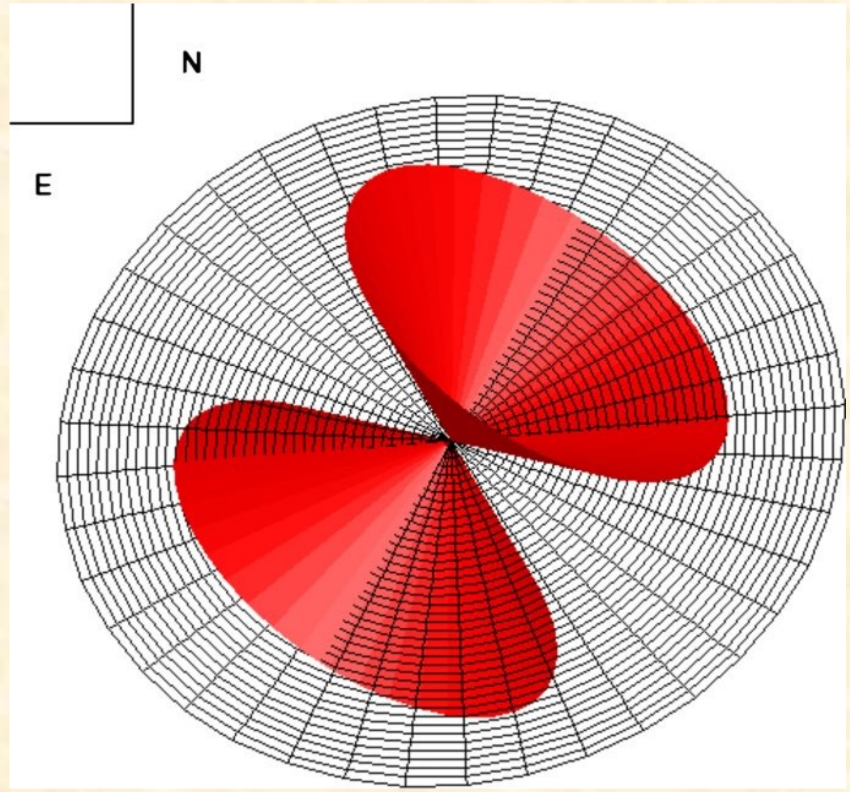


(Das et al. 2005, AJ, 130, 945)

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?

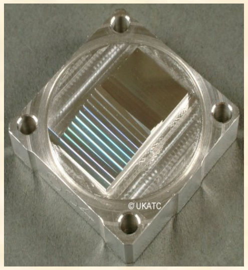
- Provide AGN feedback on scales of hundreds of parsecs

  → may regulate black hole growth, terminate star formation, and explain black-hole mass/bulge correlations
- Provide alternate explanation for double-peaked NLR emission lines (Fischer et al. 2011)

  → 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)

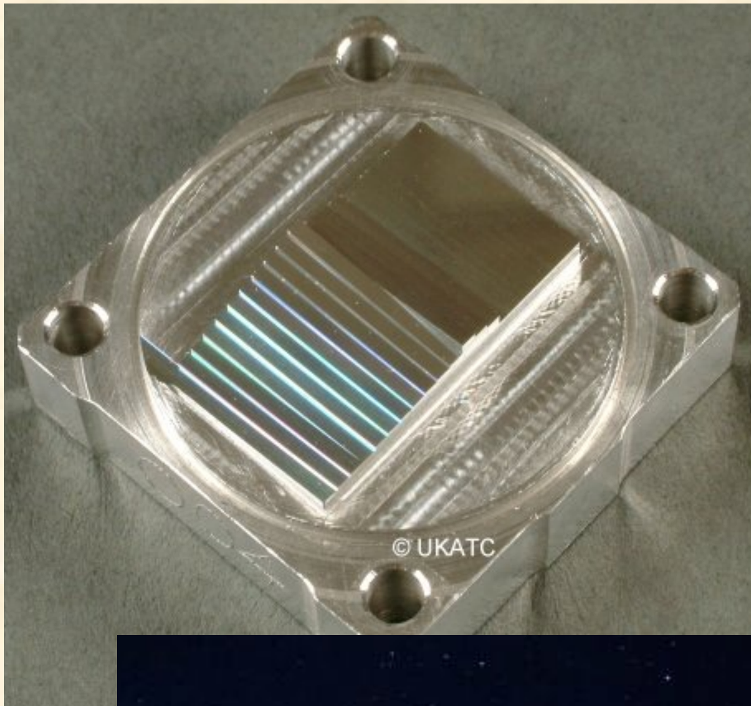
  → Investigate how intrinsic properties (SED, BLR velocities, absorber column densities) change with polar angle

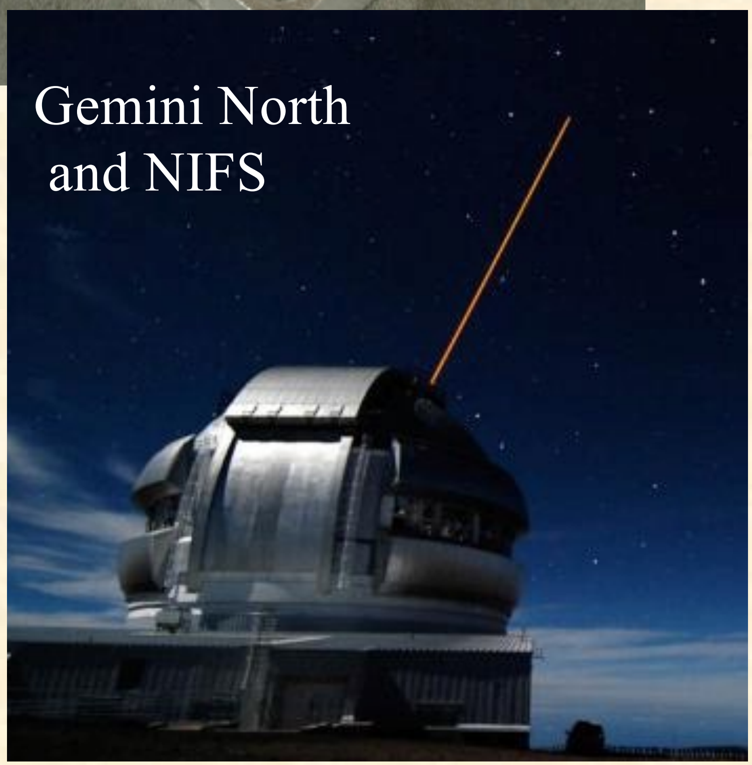
NLR Studies: Integral Field Units

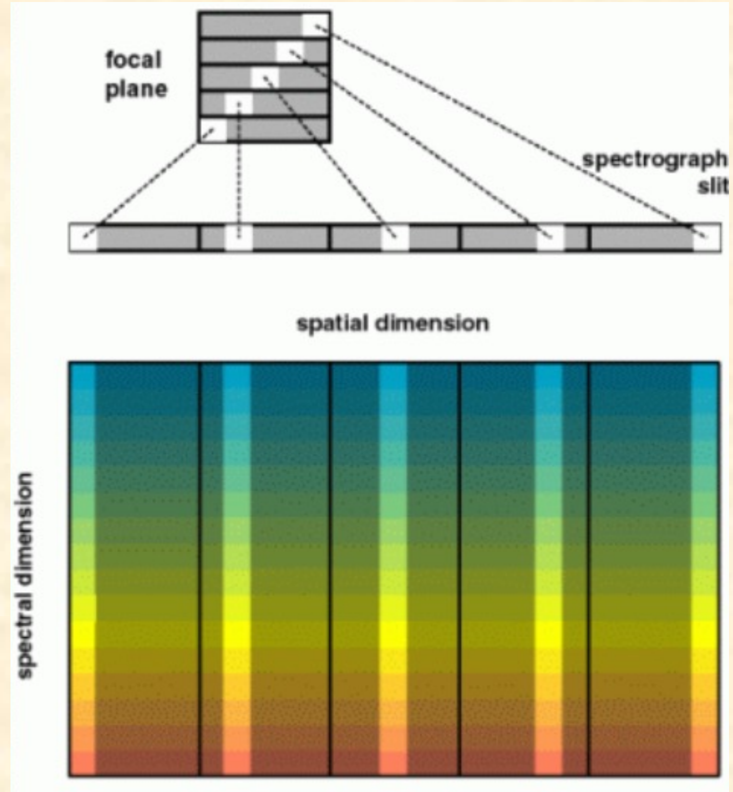


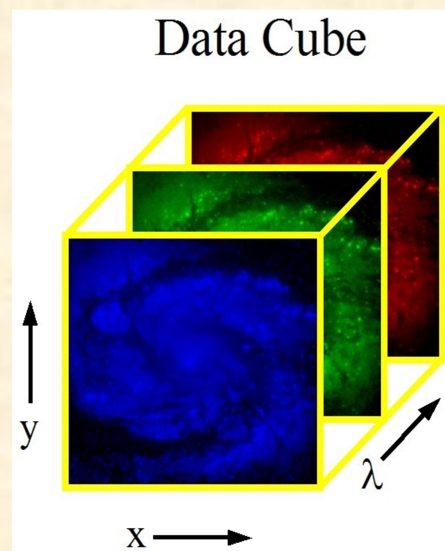
- Spectrum for every position in a field of view
- Three Basic Types
  - Lenslets: microlens array can be tilted around the optical axis so that spectra do not run into each other (allowed length of spectra is small) Ex) WHT Sauron
  - Fiber Optics: fibers transfer light to the spectrograph slit (there are gaps between the fibers) Ex) Gemini GMOS
  - Image Slicers: instrument mirror segmented into thin vertical slices that are slightly tilted with respect to each other (difficult to fabricate) Ex) Gemini NIFS
- Best used with adaptive optics (AO) on large telescopes to give angular resolution of ~0.1"

Integral Field Unit – Image Slicer





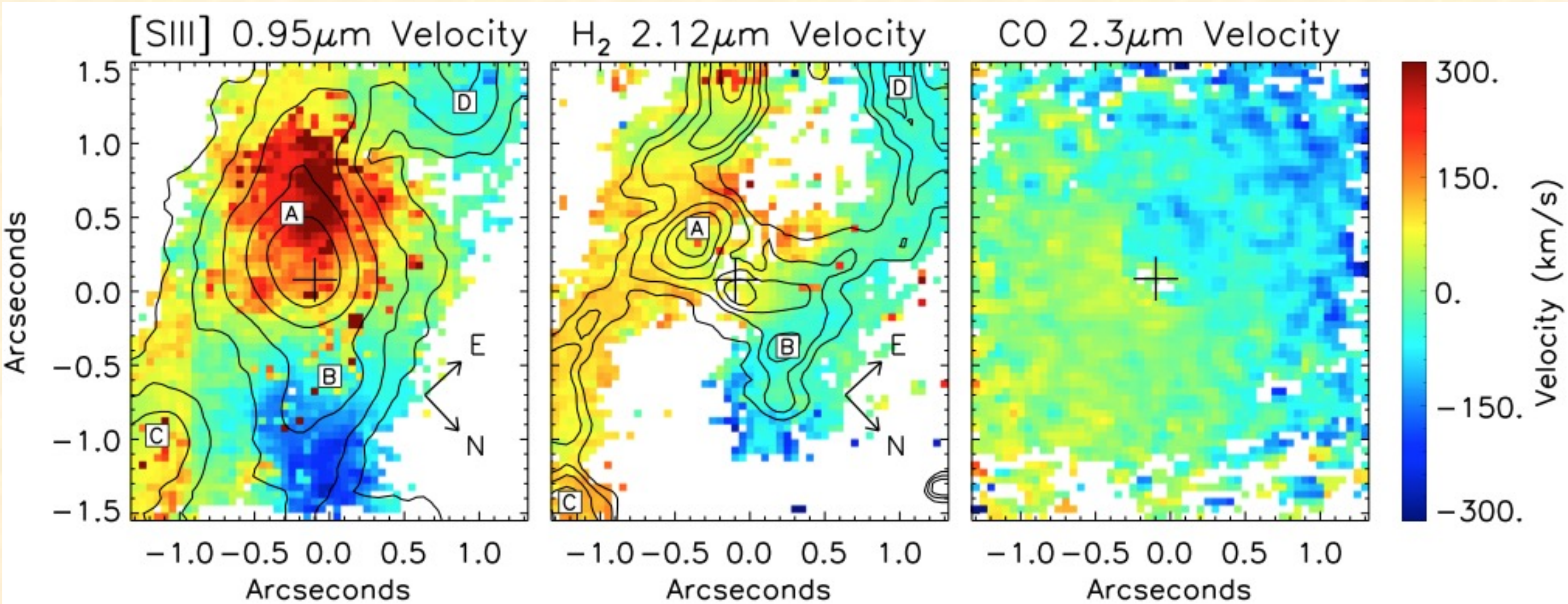




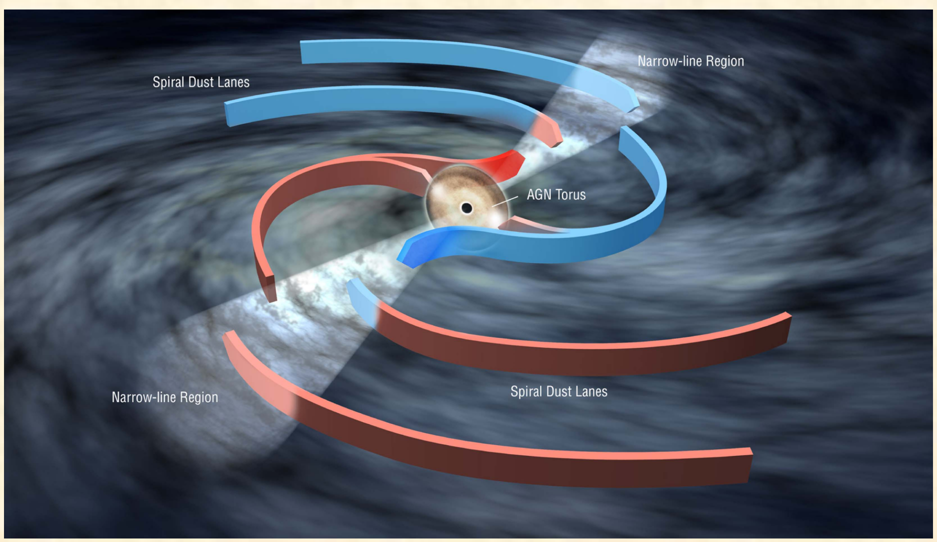
Near-infrared Integral Field Spectrometer (NIFS)

- Only available on Gemini North
- Spectral Resolving Power ~ 5000 over 3" x 3" at ~ 0.1" angular resolution
- Spectra in Z (0.9 – 1.1μm), J (1.1 – 1.3μm), H (1.5 – 1.8μm), and K (2.0 – 2.4 μm) bands
- Works with adaptive optics system ALTAIR using natural or laser guide stars
- For AGN, access to:
  - [S III] emission in Z band to map ionized gas in the NLR
  - H_2 emission lines in K band to map warm molecular gas
  - CO bandheads and other stellar features in H and K bands to map stellar velocities and dispersions for determining black hole masses.

Gemini NIFS Observations of Mrk 573



(Mrk 573: Fischer+ 2017, ApJ, 834, 30)



- Gas in dusty molecular spirals is ionized and radiatively driven outward
- Mass outflow rate peaks at ~3 M_{Sun}/yr (Revalski et al. 2018, 2021).

Dynamical Forces in the Narrow-Line Region (NLR)

Radiative acceleration: $a_r(r) = \dfrac{L\sigma_T\mathcal{M}}{4\pi r^2 c\mu m_p}$ (μ = mean atomic mass = 1.4, addition to Das+2006)

Gravitational deceleration: $a_g(r) = -\dfrac{GM(r)}{r^2}$ ($\mathcal{M}$ = force multiplier compared to Thomson scattering

($M(r)$ = enclosed mass)

Total acceleration: $a(r) = a_r(r) + a_g(r)$

$$a(r) = \frac{dv}{dt} = \frac{dv}{dr}\frac{dr}{dt} = \frac{dv}{dr}\,v$$

$$\int_0^v v\,dv = \int_{r1}^{r} [a_r(r) + a_g(r)]\,dr$$

$$v = \sqrt{2\int_{r1}^{r} [a_r(r) + a_g(r)]\,dr} \qquad v = \sqrt{2\int_{r1}^{r} \left[\frac{L\sigma_T\mathcal{M}}{4\pi r^2 c\mu m_p} - \frac{GM(r)}{r^2}\right] dr}$$

Velocity Profile:

$$v(r) = \sqrt{\int_{r1}^{r} \left[4885\,\frac{L_{44}\mathcal{M}}{r^2} - 8.6\times10^{-3}\,\frac{M(r)}{r^2}\right] dr}$$

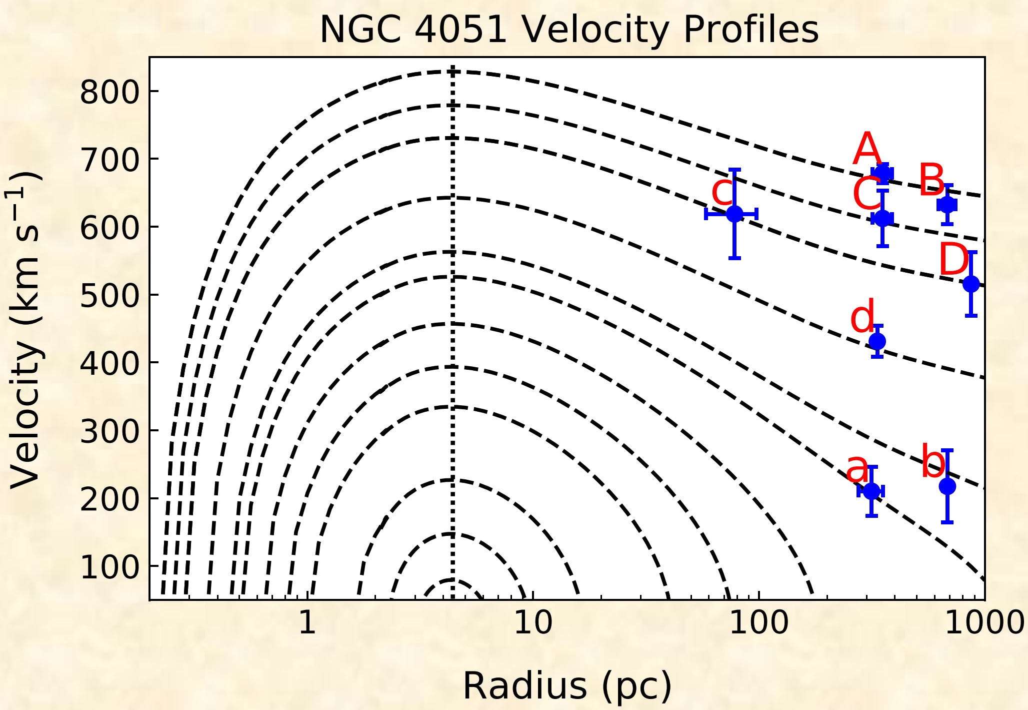
$v\left(\mathrm{km\ s^{-1}}\right)$; $r(\mathrm{pc})$; L_{44} (10^{44} erg $\mathrm{s^{-1}}$); $M(M_\odot)$

Launch radius (r_1) − match calculated and observed v(r) for a NLR knot to get r_1(the only unknown):

$$v(r) = \sqrt{\int_{r_1}^{r} \left[4885 \frac{L_{44}\mathcal{M}}{r^2} - 8.6 \times 10^{-3} \frac{M(r)}{r^2}\right] dr} \qquad (r - r_1 = \text{distance traveled}, \ t = \sum \frac{\Delta r}{v} = \text{time traveled})$$

Model velocity turnover (max launch radius): $a_r(r_m) = a_g(r_m)$ $\quad r_m = r_1$ (max), independent of other r_1

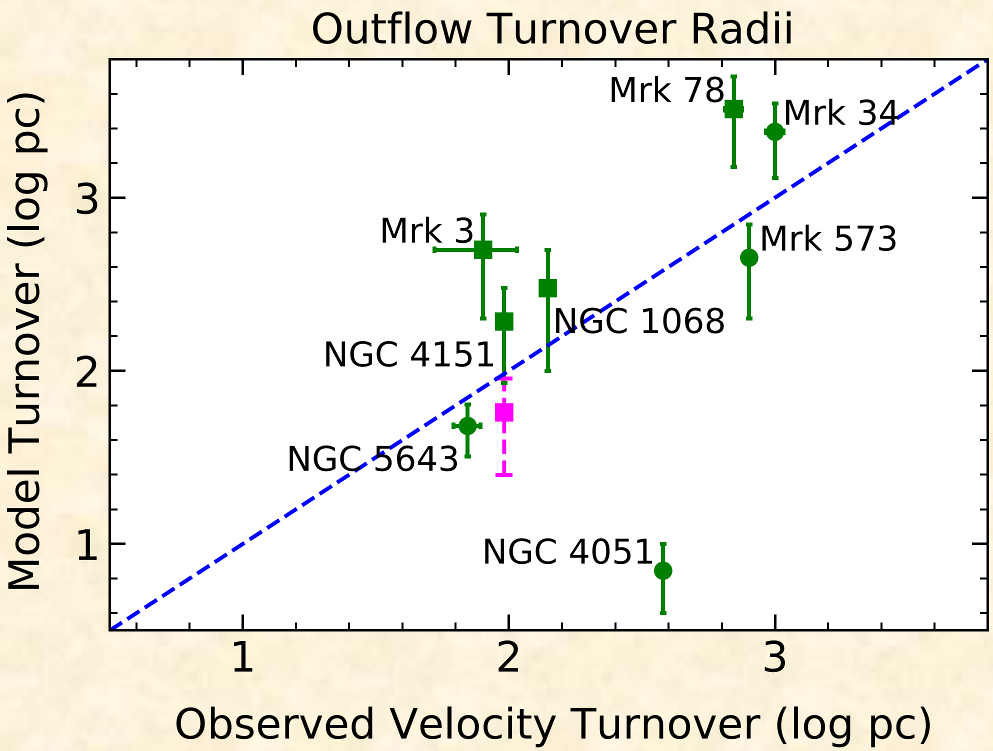
Note: The above assumes:
1) purely radial motion - gas at launch point is not rotating, so no azimuthal velocity
2) spherical symmetry (e.g., bulge dominates near core) or axisymmetry (e.g. radial motion in disk)



(Meena+ 2021, 916, 31)

NGC 4051:
- Clouds launched between 0.2 – 4 pc.
- Max launch radius ≈ 4 pc, all velocities turn over at this point
- Clouds can travel up to ~1 kpc.

Comparison with Observations



(Meena+2023, ApJ, 943, 98)

- Increasing luminosity to the right.
- Correlation indicates radiative driving + grav. decel. control NLR dynamics.
- Any acceleration of gas or increasing $\dot{M}_{out}$ beyond r_{mod} would indicate additional forces.
- What value of $\mathcal{M}$ would get the best match (excluding NGC 4151)? – about 500
- Does this relation hold for low luminosity? (may not be able to resolve turnover point)
- LINERs (with $L/L_E < 10^{-3}$) should not be able to radiatively launch outflows.