Quasar Winds

Martin Elvis

Harvard-Smithsonian Center for Astrophysics

Lecture 2

AGN Winds: Outline

1. The quasar atmosphere
2. Broad Absorption line winds
3. Narrow Absorption line/ X-ray Warm absorber winds
4. High ionization broad emission line winds
5. Wind location from WA variability
6. Summary - geometry
7. Acceleration methods
8. What’s next

The emission/absorption features of quasars constitute the

Just as there are textbooks on ‘*Stellar Atmospheres*’

we need the subject of ‘*Quasar Atmospheres*’

Takes more than 1 step.

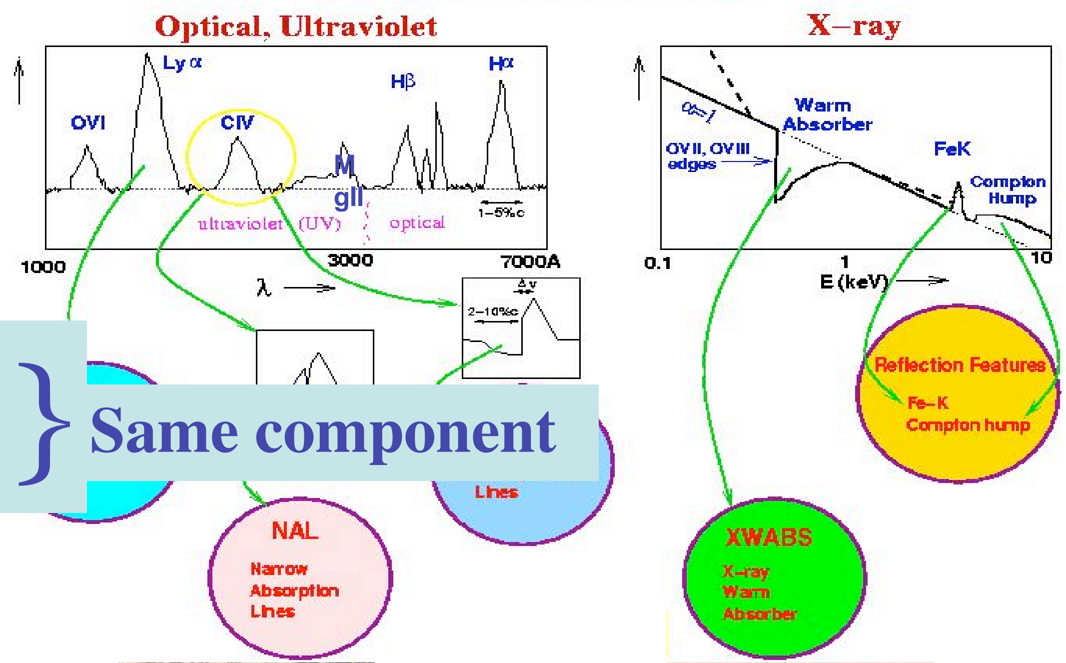
1st build an ***observational paradigm***

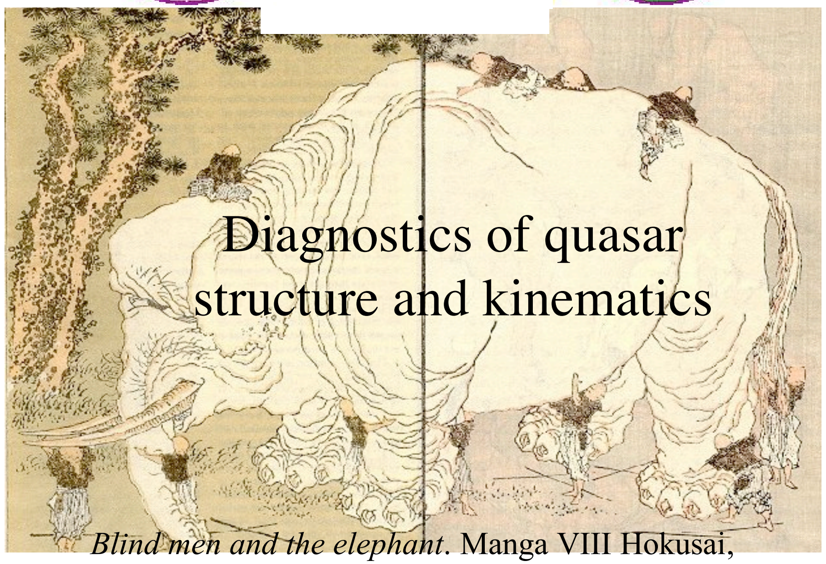
using Geometry & Kinematics

A Primer on Quasar emission/absorption features

1. Broad absorption lines (BALs)
2. Narrow Absorption Lines (NALs)
3. X-ray Warm Absorbers (WAs)
4. Broad emission lines (BELs)

} **Same component**





Blind men and the elephant. Manga VIII Hokusai, Katsushika (1760-1849)

Lest you despair…

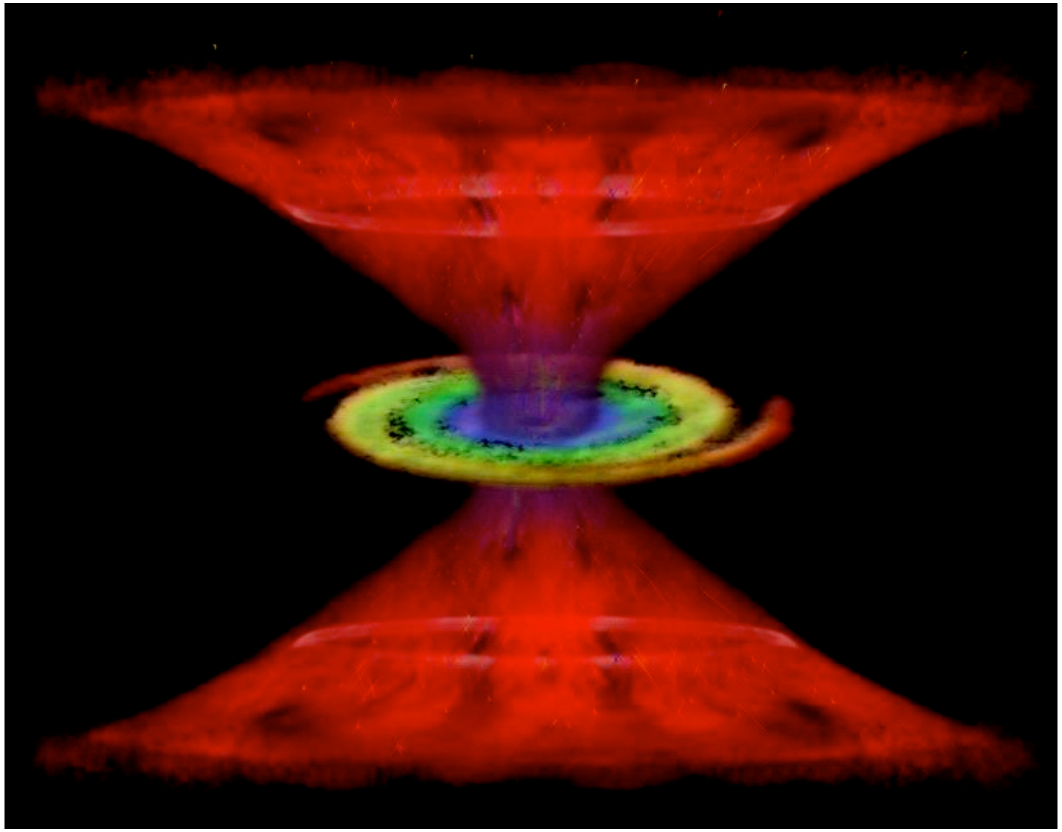
“A simple but grand arrangement is discoverable amid the confusion of objects and the prodigious variety of scenes.”

Alexis de Toqueville, ‘*Democracy in America*’,

Chapter I, Geography of North America.

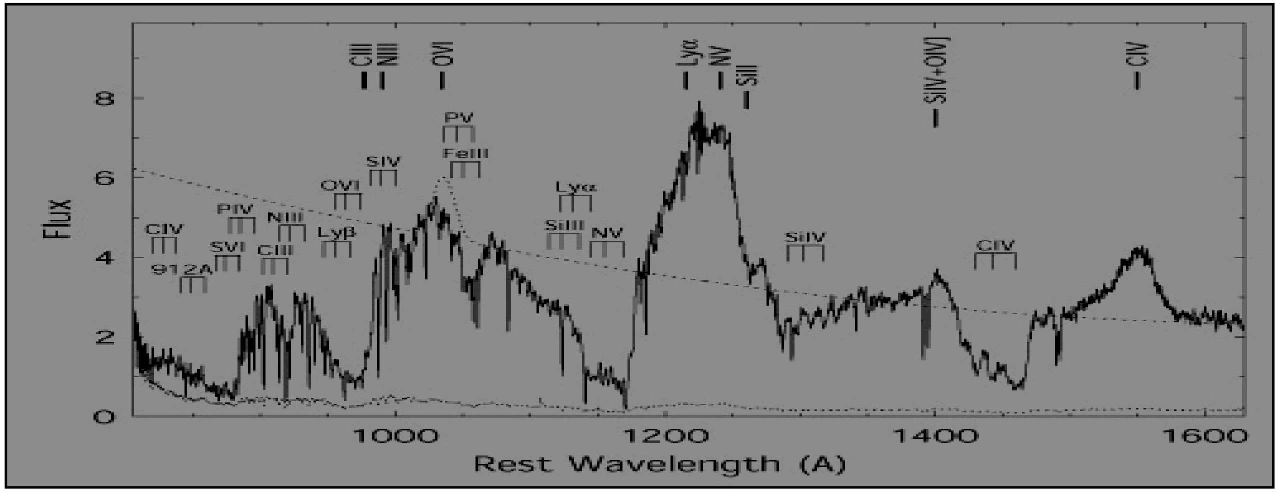
Translaton from http://xroads.virginia.edu/~HYPER/DETOC/1_ch01.htm

Winds provide a linking paradigm



Broad Absorption Lines

Broad Absorption Lines: BALs



Ferland & Hamann 1999
Annual Reviews of Astronomy & Astrophysics , 37, 487

- Velocities: always *blueshifts* ➔ ***Winds***
- Doppler widths ~2%*c* - 10%*c* ~10x NALs
  - Acceleration (or deceleration; Often complex sub-structure
- Which lines? Usually high ionization: CIV, NV, OVI…NVIII, PV
  - High ionization BALs 90%; Low BALs 10%; FeII BALs 1%
- BALs in 10-15% of all quasars
  - Special minority of AGNs? Eg high L, X-ray faint?
  - *Or* normal AGNs seen from a special angle?
- Column densities: *appear* small, but…

False Bottoms to BAL troughs

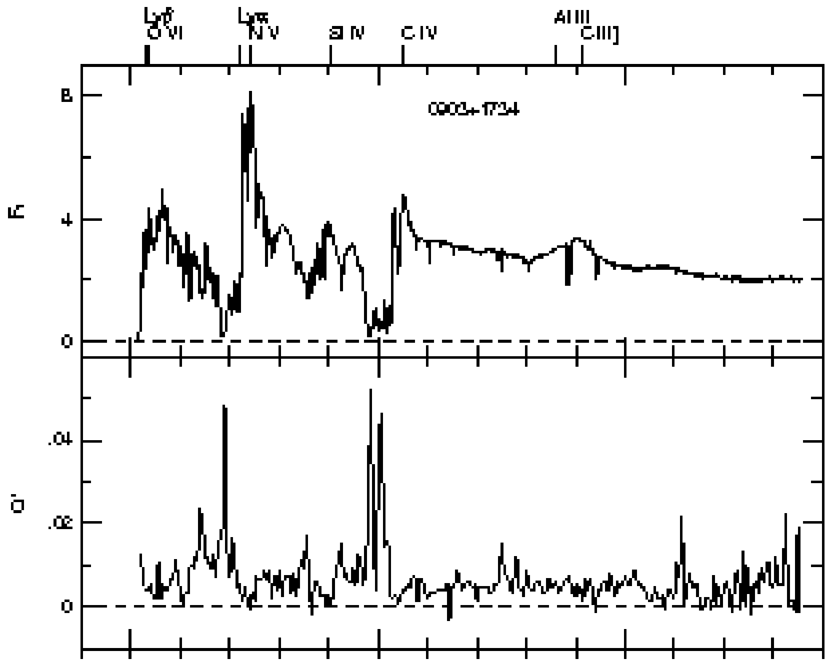
- BAL troughs are highly polarized
  scattered light off flattened structure

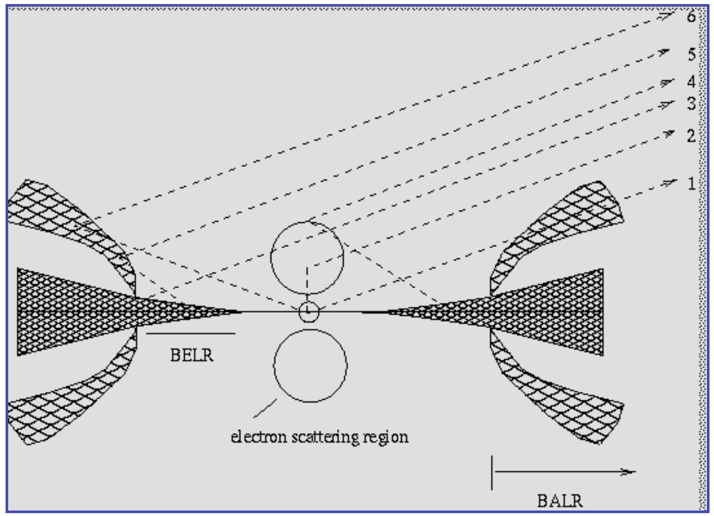
⇒ BALs are common

  ⇒ seen from a special angle

  ⇒ *Universal?*

- Thomson thick: $N_H >\sim 10^{24}$ cm^{-2}
  - X-ray Fe-K, Compton hump?
- Scattering solves other BAL problems:
  - ionization, abundances, N_H Hamann 1998 ApJ 500, 798; Telfer et al. 1998 ApJ 509, 132

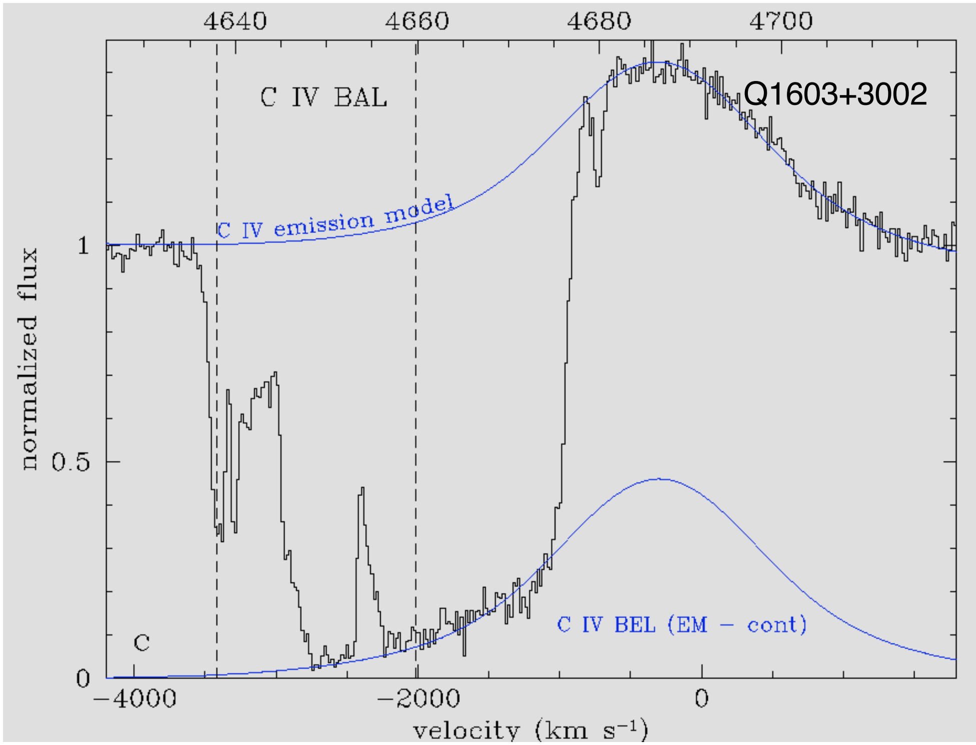




Ogle et al. ,1999 ApJS, 125, 1; Ogle 1998 PhD thesis, CalTech

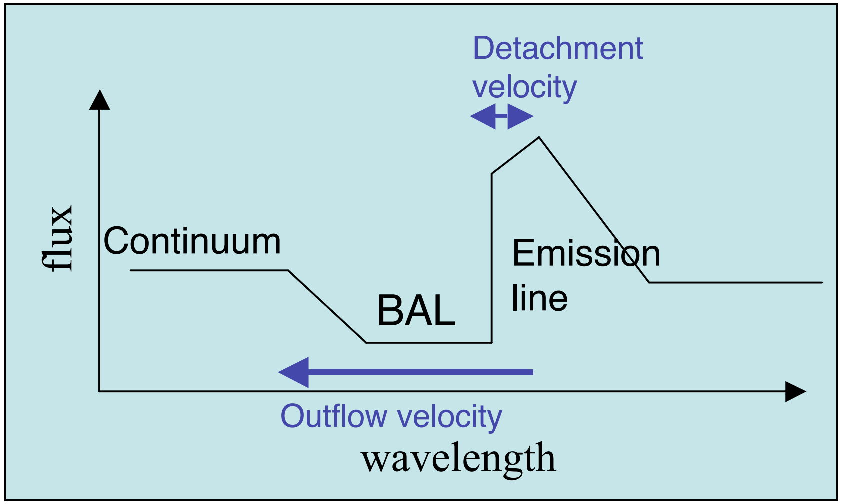
BAL wind does not cover Broad Em. lines

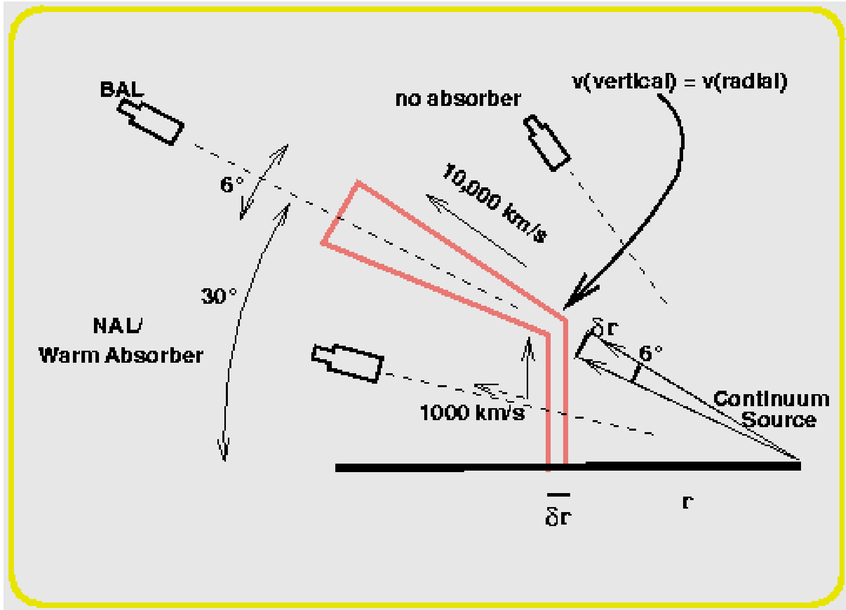
- BAL flow < few light-day dia.
- BAL gas probably close to nucleus



Arav et al., 1999 ApJ, 524, 566

Onset velocity of BALs: not a pure radial flow

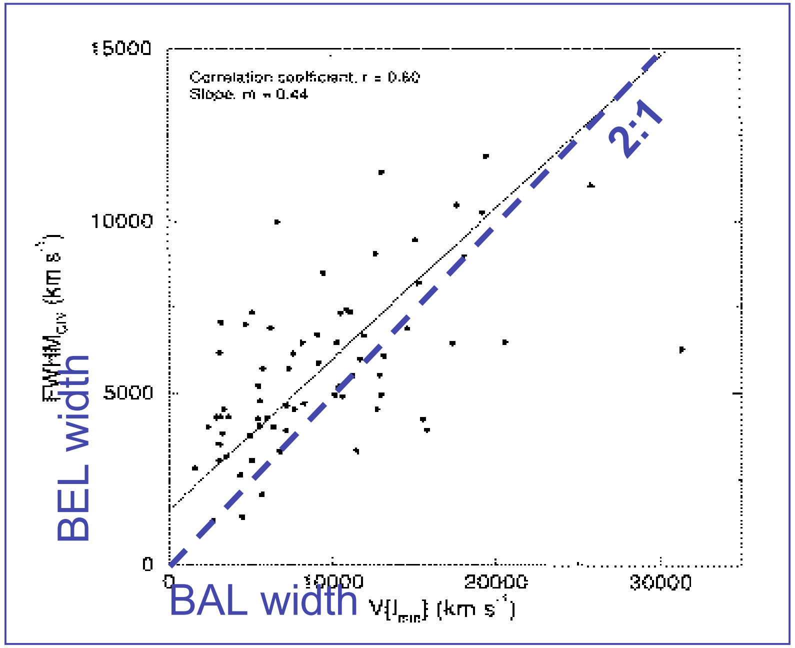




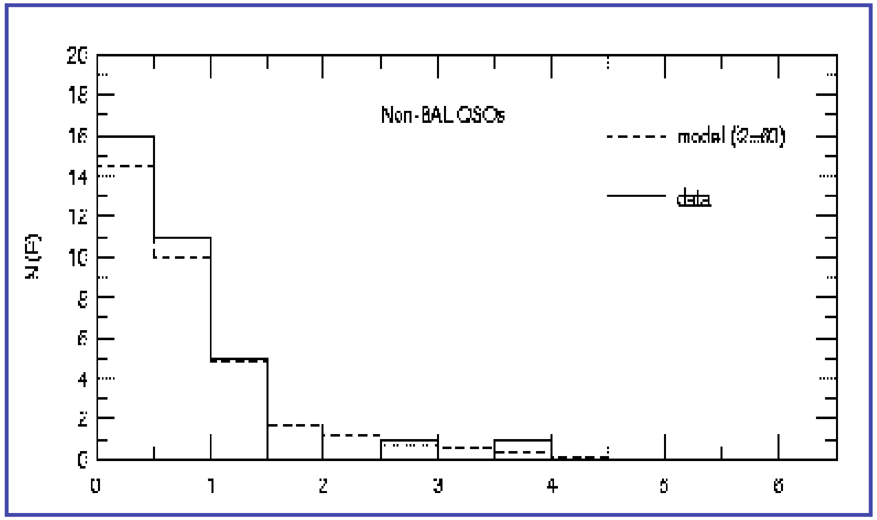
- ‘detached BALs’
- Accelerating wind bends into our line of sight?
- bends when $v_{radial} = v_{vertical}$
- BAL covering factor from divergence angle

BAL gas in all AGNs?

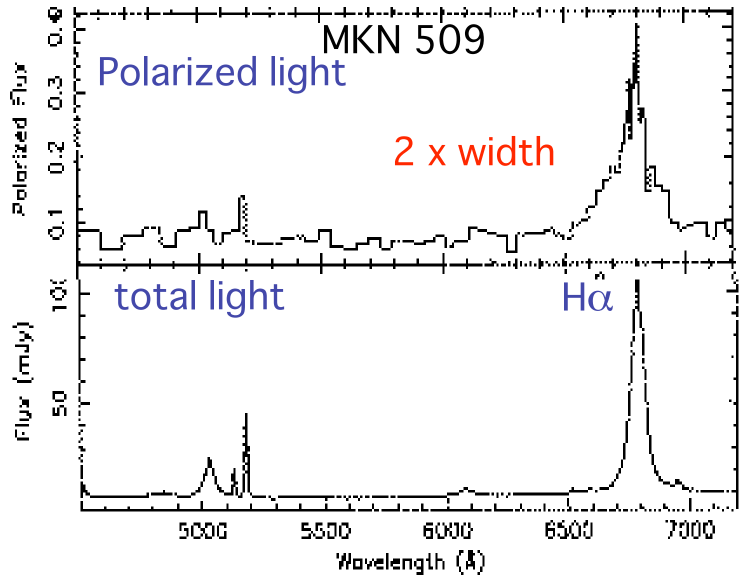
- BEL FWHM correlates with BAL velocity: V(BAL) ~ 2 FWHM(BEL)
  - I.e. BAL gas knows about BEL gas
- BAL width polarized emission lines in non-BAL AGNS
- Bi-cone model *predicts* distribution of non-BAL quasar polarization
  - Theory from Be star winds



Lee & Turnshek 1995 ApJ 453 L61



Ogle 1998 PhD thesis, CalTech

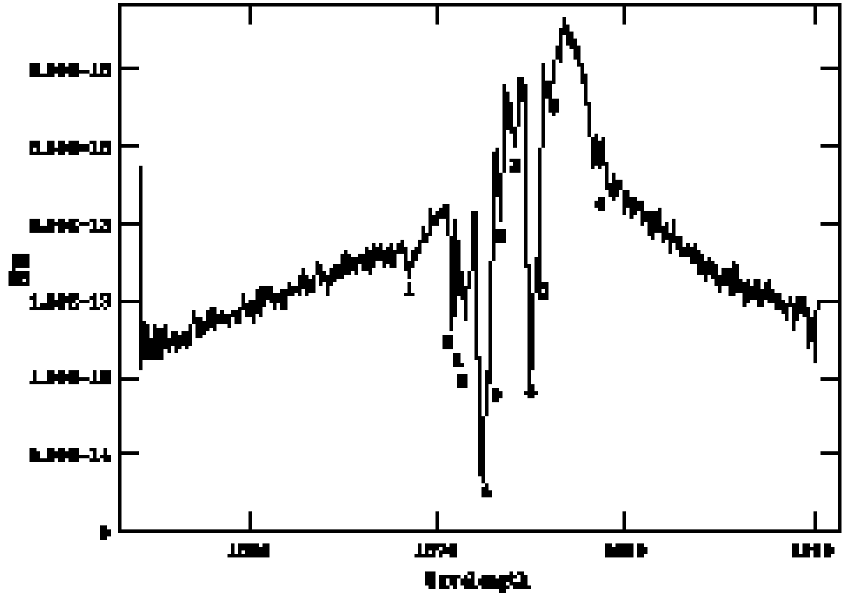


Young et al. 1999 MNRAS 303, 227

Narrow Absorption Lines & X-ray Warm Absorbers

Narrow Absorption Lines: NALs

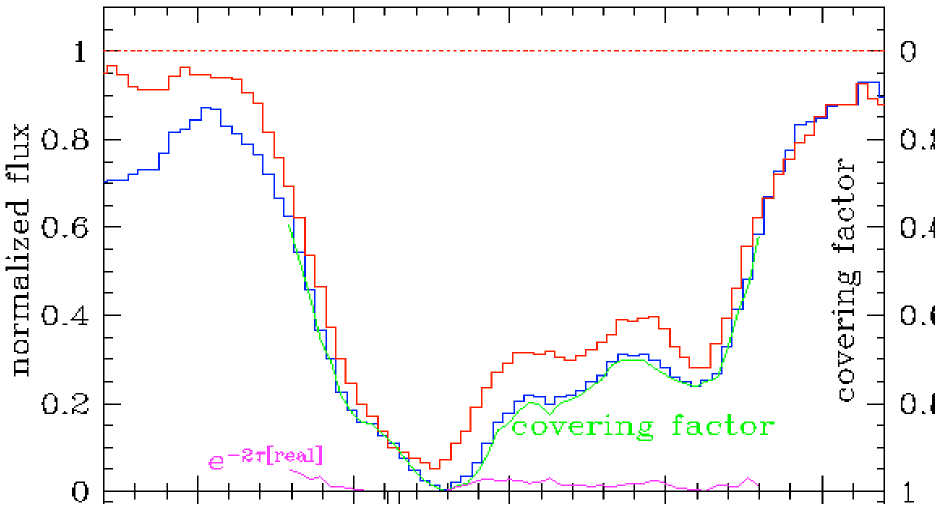
- Velocities: ~few100-1000km/s
  - always *blueshifts* ➔ ***Winds***
  - Absorption is unambiguous, unlike emission lines
- Widths: 100-300 km/s
  - Substructure 10’s km/s
- Covering factors
  - Global >~50%
  - Line of sight: complex: *see next slide*
- Which lines? High ionization:
  - CIV, OVI
- Column densities: uncertain due to incomplete covering factor

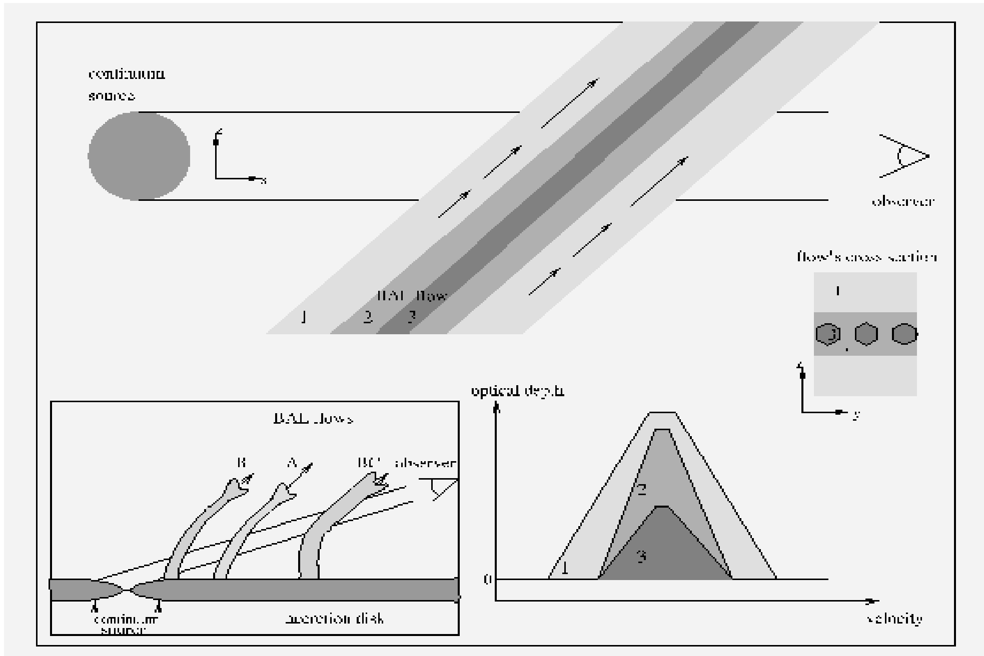


Fɪɢ. 1.—GHRS G160M spectrum of C ɪᴠ line in NGC 5548. It is smoothed to display the multiple absorption components clearly (marked 1–6).

NAL line-of-sight covering factor

- Covering factor of continuum is velocity dependent
  - → Absorber moves transversely, across our line-of-sight
  - →True space velocity is larger than observed blueshift
- Accelerates ~300 km/s in ~50 r_g (UV continuum size)
  - → Absorber probably close to continuum source



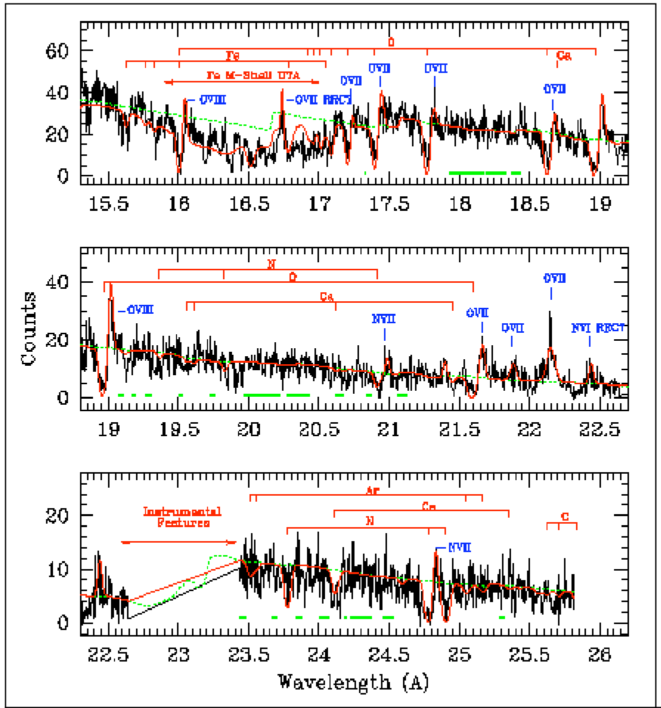


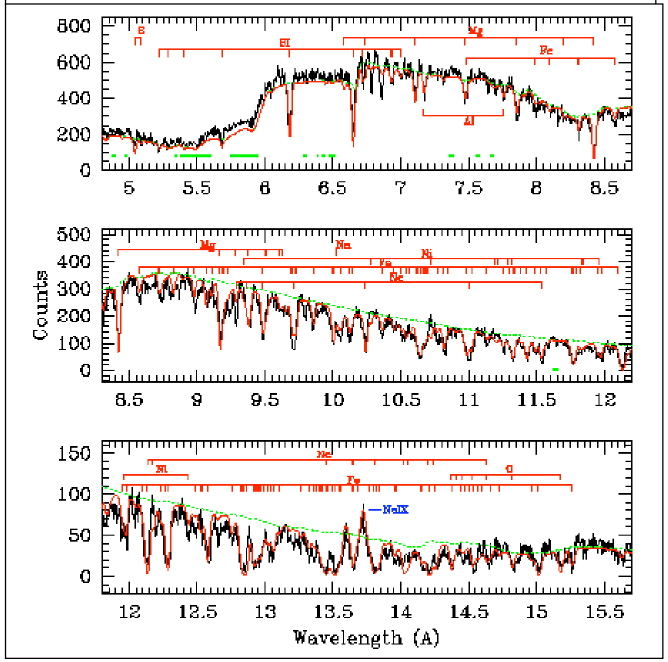
Arav, Korista & de Kool 2002, ApJ 566, 699

Arav, et al., 1999, ApJ 516, 27

X-ray Warm Absorbers: WAs

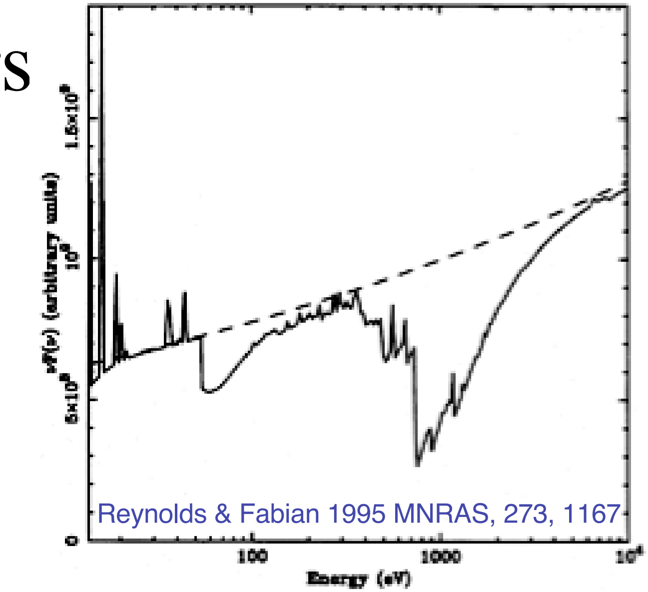
- Common in Low and high L AGNs
  - Reynolds 1998, Piconcelli et al. 2005
- Velocities: ~1000-2000 km/s
  - always *blueshifts* ➔ ***Winds***
- Widths: <500 km/s. [$R=\lambda/\Delta\lambda\sim400$]
  - Can't look for substructure
- Covering factors
  - Global >~ 50%
  - Line of sight: ? Insufficient resolution
- Which lines?
  - OVII, Fe-M 'UTA'; OVIII, Fe-L
  - Range of ionization:
    - multiple phases, or continuous range?

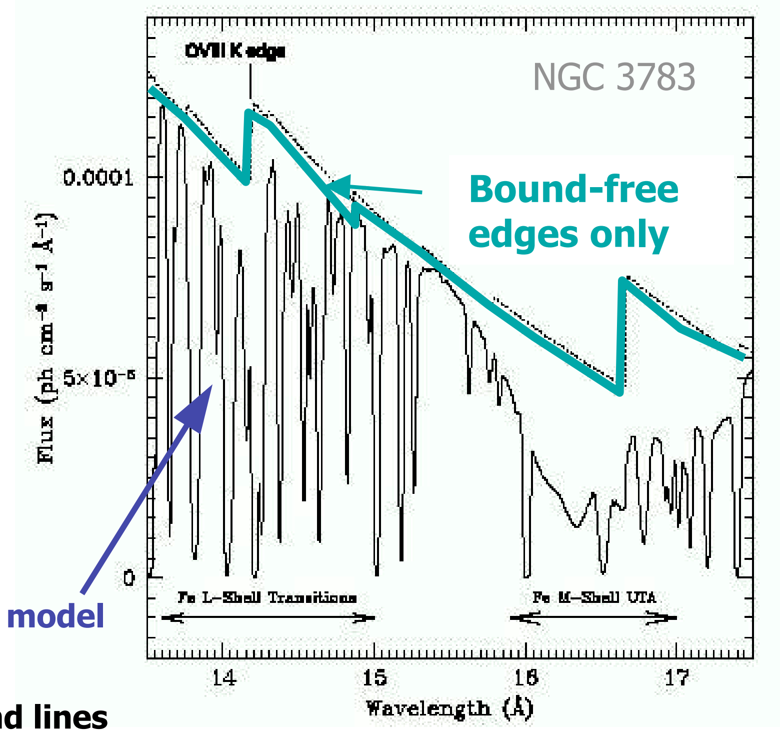




Warm Absorbers

- ‘Warm’ = ionized
  - Photoionized, not thermal
- Elements with Z<8 (up to oxygen) are fully* ionized
  - Cannot absorb photoelectrically
- Oxygen retains 1-2 electrons
  - O K-edge (and lines) puts ‘notch’ in soft X-ray spectrum at ~0.8keV
- Column densities
  - N_H~few x $10^{22}cm^{-2}$ in early fits
  - Now ~few x $10^{21}cm^{-2}$
    - Better models with many more transitions: higher opacity at given N_H





Black line: **full PHASE model**
(Krongold et al., 2003)
including bound-bound lines

UV NALs = X-ray Warm Absorbers = Wind

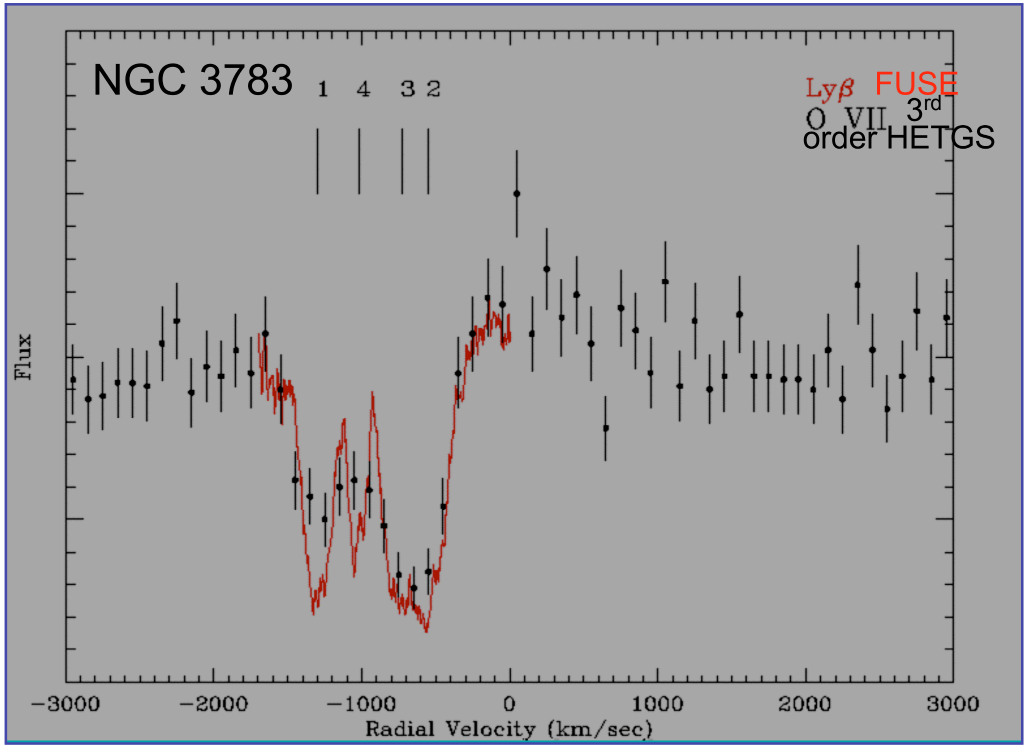
Narrow UV lines	Narrow X-ray lines
Outflow ~1000 km s^{-1}	***Same* Outflow ~1000 km s^{-1}**
Seen in 50% of quasars	**Seen in *same* 50% of quasars**
High ionization CIV, OVI	**High Ionization** OVII, OVIII

Same outflow

Caveats:

•Not all X-ray gas -> UV absorption (too ionized)

•Not all UV gas -> X-ray absorption (too small a column density)



Gabel et al. 2004

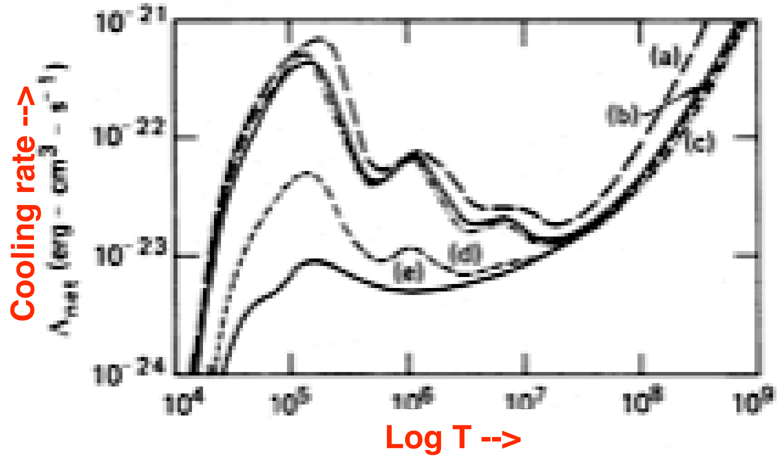
Photoionized gas

- Cooling curve for photoionized gas has several peaks

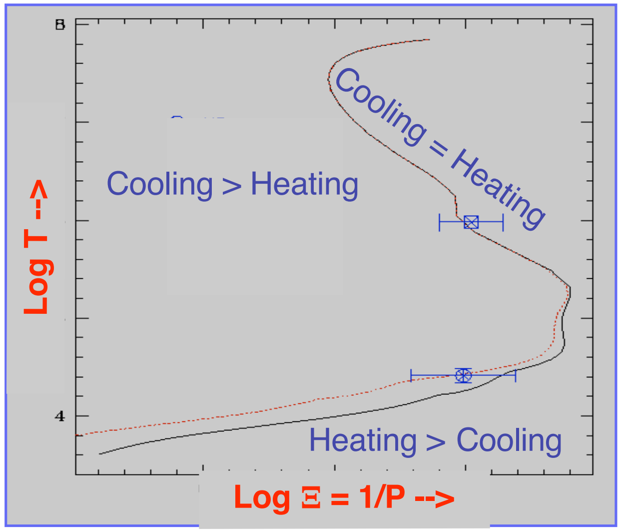
 →Gas tends to lie in valleys

 → Multi-phase gas

- Phases depend on:
  - ionizing continuum shape
  - gas abundances
- Observed WA ionization finds 2-3 phases at same pressure
- Phases lie on or near stable parts of cooling curve.



Krolik, McKee & Tarter, 1981, ApJ, 249, 422
See also: Reynolds & Fabian 1995 MNRAS 273 116
Komossa & Fink, 1995

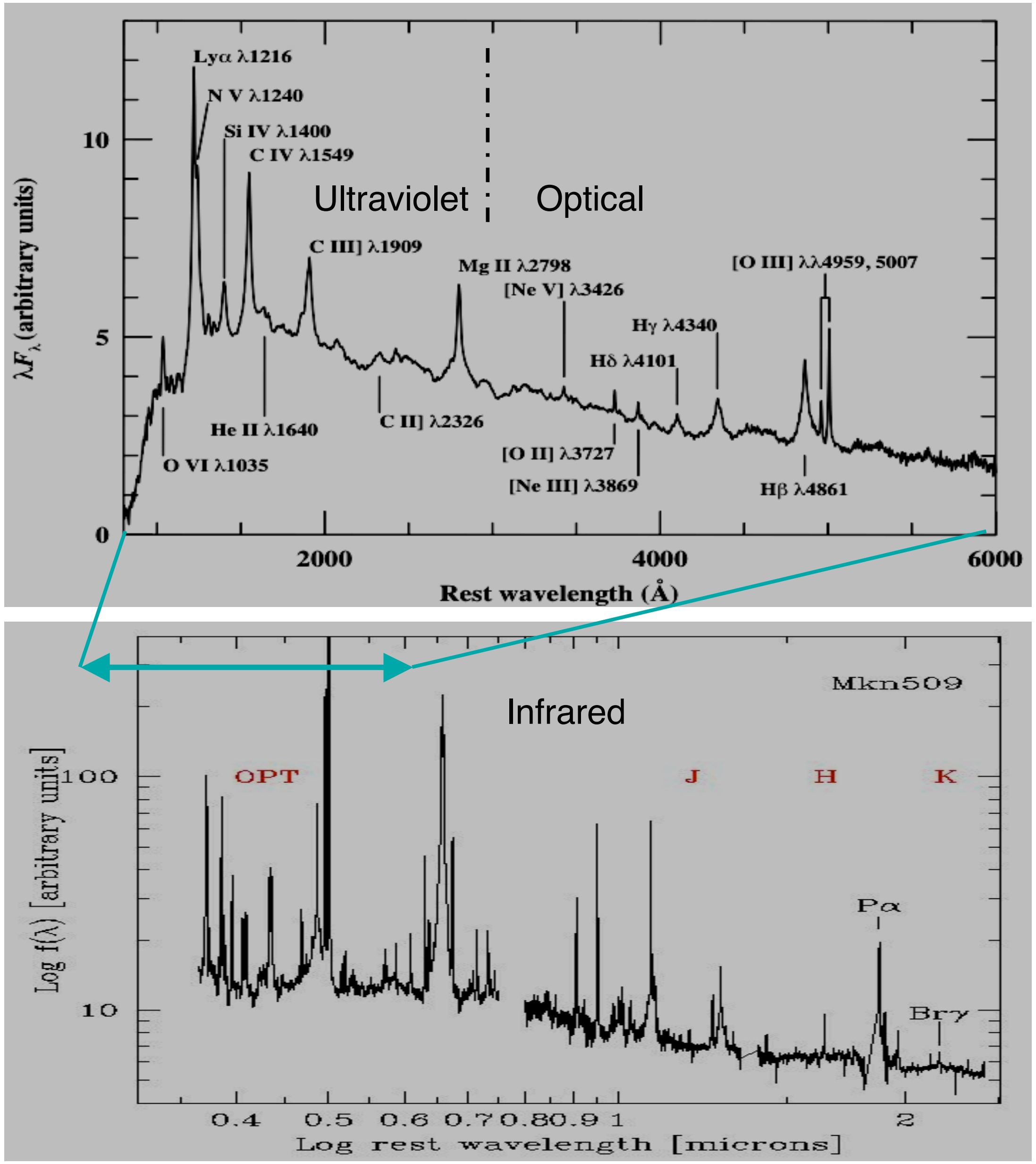


Krongold,et al., 2003 ApJ 597, 832
See also: Netzer et al., 200x, ApJ,
Krongold et al. 2004, ApJ, NGC985
Krongold et al., 2006, ApJ, NGC4051

Broad Emission Lines

Broad Emission Lines: BELs

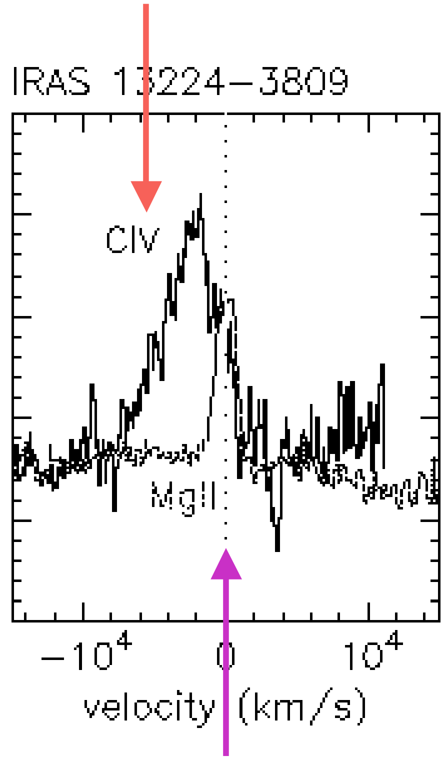
- Universal
  - All are permitted transitions
    - High densities $\sim 10^{10-12}$ cm^{-3}
  - Can be hidden (type 2 AGN)
  - Can be overwhelmed (blazars)
- Widths
  - FWHM ~ 5000 km/s (1000km/s - 15000 km/s)
- Profiles
  - logarithmic (triangular)
  - rare 2-horned profiles (disks)
- Which lines?
  - High Ionization: CIV, NV, OVI, HeII
    - *blueshifts* - ***winds***
  - Low Ionization: MgII, FeII
    - disk? *Collin et al.*
  - FWHM(HiBELs)>FWHM(LoBELs)



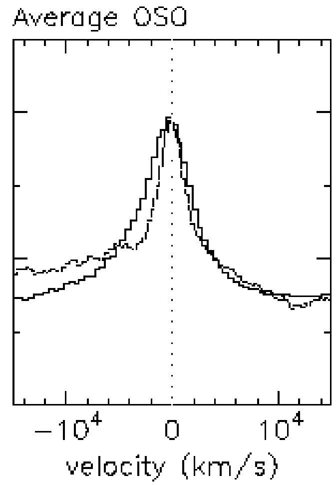
Broad Emission Line Region is a Wind

- Some AGNs (NLSy1s) show strongly **blueshifted high ionization (CIV) lines**
- disk wind
- redshifted lines hidden by disk
- Low ionization lines (MgII) have no blueshift
- outer disk Collin-Souffrin, Hameury & Joly,1988 A&A 205, 19

High ionization
CIV



Low ionization
MgII



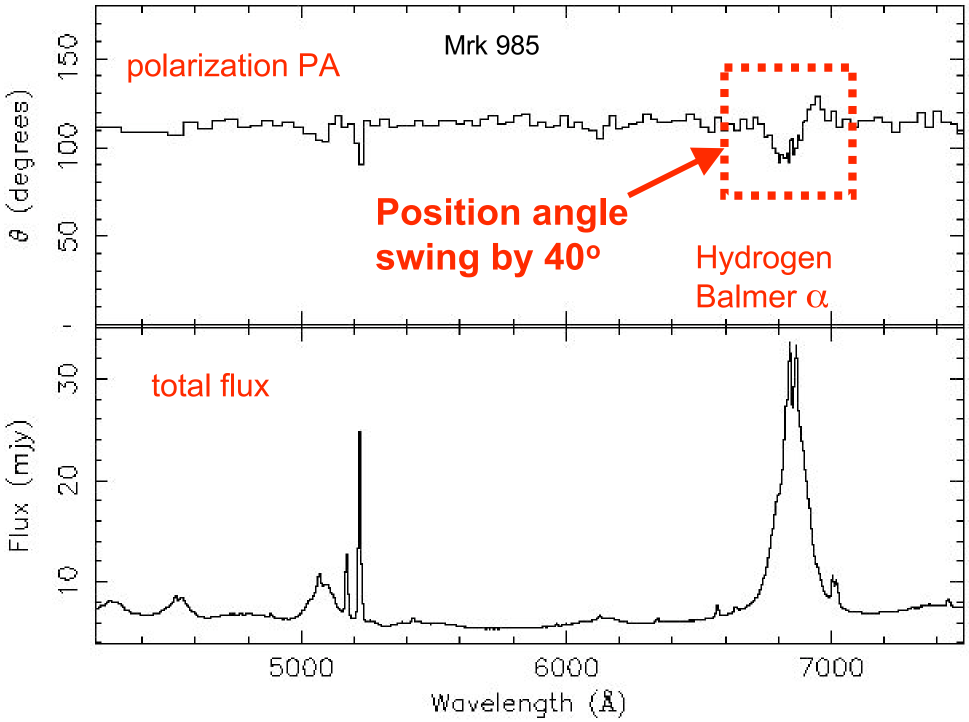
See: **Gaskell** 1982

Wilkes 1984

Leighly & Moore 2004, ApJ, 611, 107L

Broad Emission Line Region is Rotating

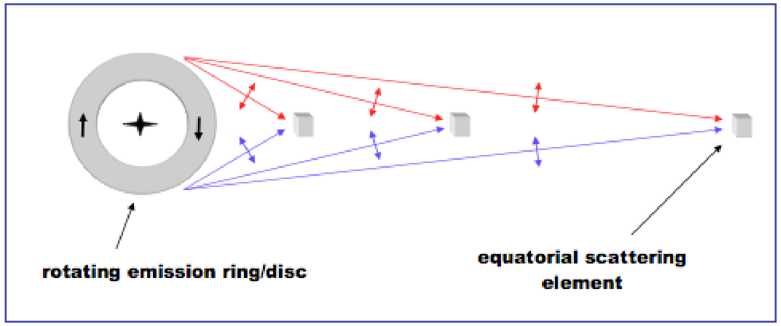
Polarization Position Angle swings through ~40deg.
Scattering region views an extended BELR



Smith J.E., 2002, MNRAS astro-ph/0205204

Smooth rotation requires rotation

PA rotation angle measures distance of scatterer as ratio to BELR size



Smith J.E., 2005, MNRAS astro-ph/0501640

Where does the AGN Wind start?

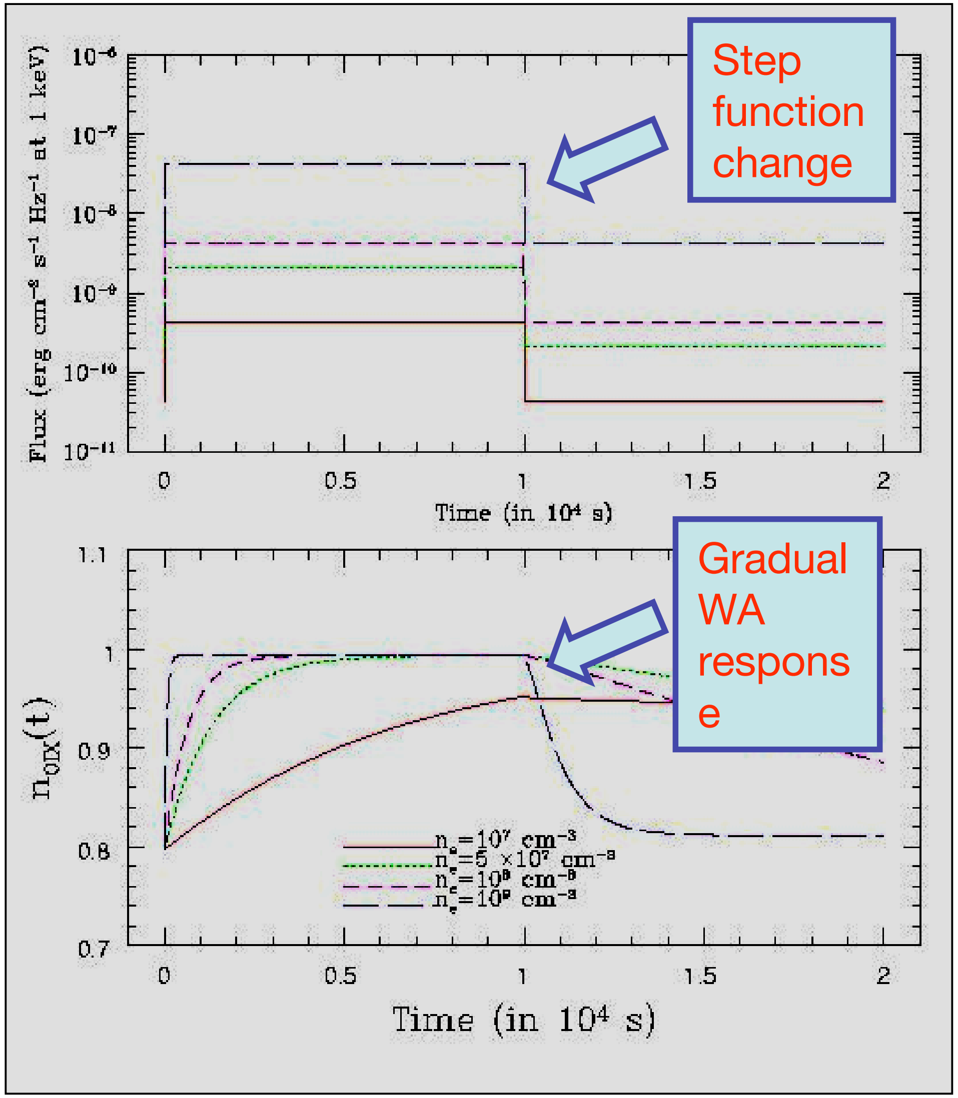
Where does the wind come from?

- Narrow emission line region ~ kpc
- Obscuring Molecular Torus: ~ pc evaporation
  - Krolik & Kriss 2001, ApJ, 561, 684; Krolik & Kriss 1995, ApJ, 447, 512
- Outer, dusty, accretion disk ~0.1 pc
  - Kartje, Konigl, Elitzur, 1999, ApJ, 513, 180
- Hi-BEL region (mid-disk) ~.001 pc
  - Murray & Chiang 1995 ApJ 454, L105 and subsequent papers
  - Elvis 2000 ApJ 545, 63; 2003 astro-ph/0311436
  - Nicastro 2000 ApJ, 530, L651

10^6 !

Diagnostic: Time Evolving Photoionization

- Response of gas ionization state to a continuum change is not instantaneous:
- 'Ionization time' and 'Recombination time' measure n_e
- $U_X \sim n_e \, .4\pi \, L_x/R^2$
- WA independently measures U_x
- hence measures R



Nicastro et al., 1999, ApJ, 512, 184

Response of WA to Variability gives physics

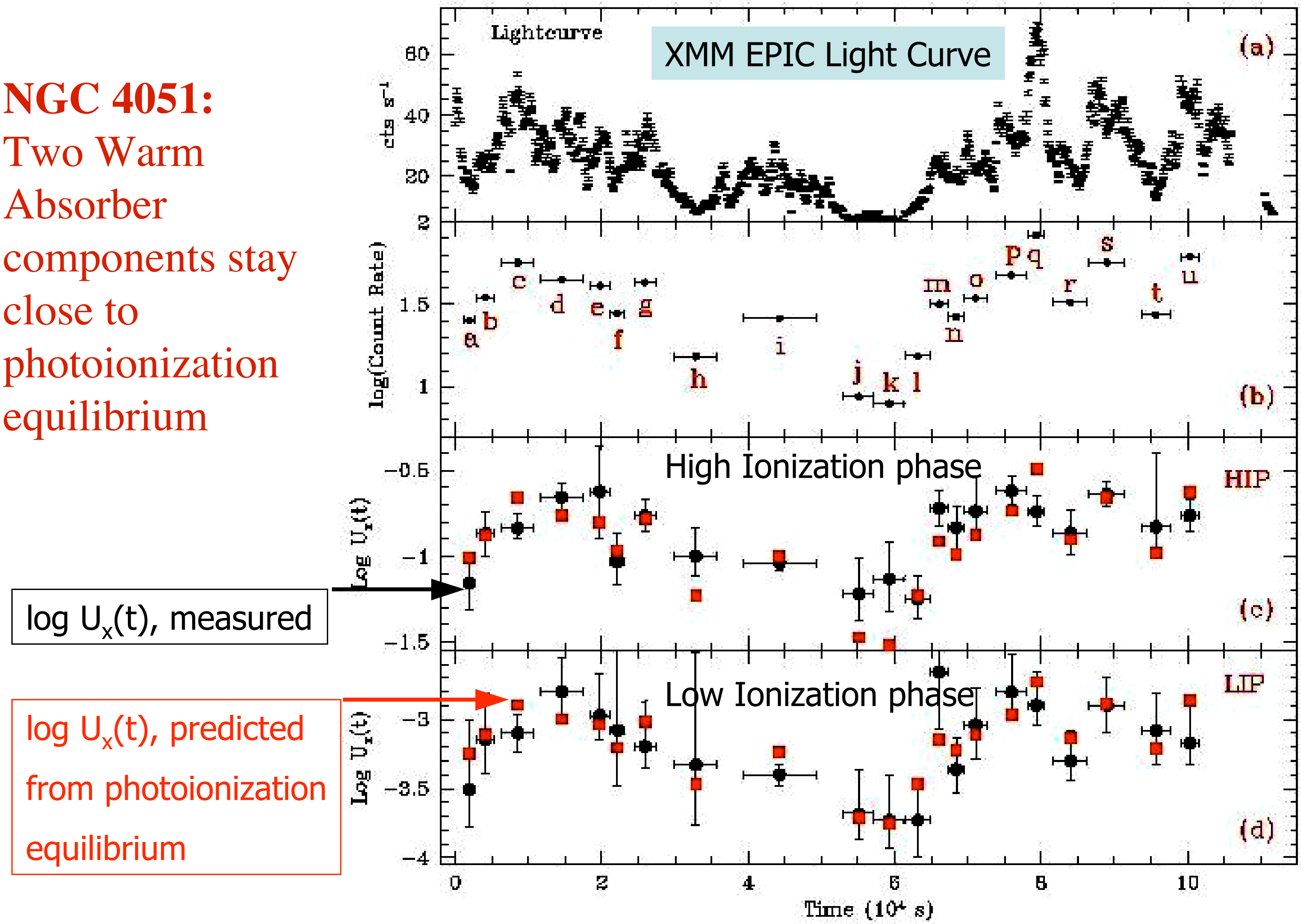
Fully characterized plasma:

- Density n_e*:* recombination/ionization time lag to cont. changes
- Radial Distance, r*:* $n_{e,}$ ionization parameter (n_{ph} /n_e), L_{cont}
- WA thickness, δr*:* N_H, n_e
- WA temperature, *T:* WA ionization equilibrium fit
- Pressure, P: n_e, T
- **Mass outflow rate**, m_{dot}: $n_{e,}$ velocity v

See: Mathur, Elvis & Wilkes 1995 ApJ 452, 230.

Nicastro, Fiore, Perola & Elvis 1999, ApJ 512, 184

NGC 4051: Two Warm Absorber components stay close to photoionization equilibrium



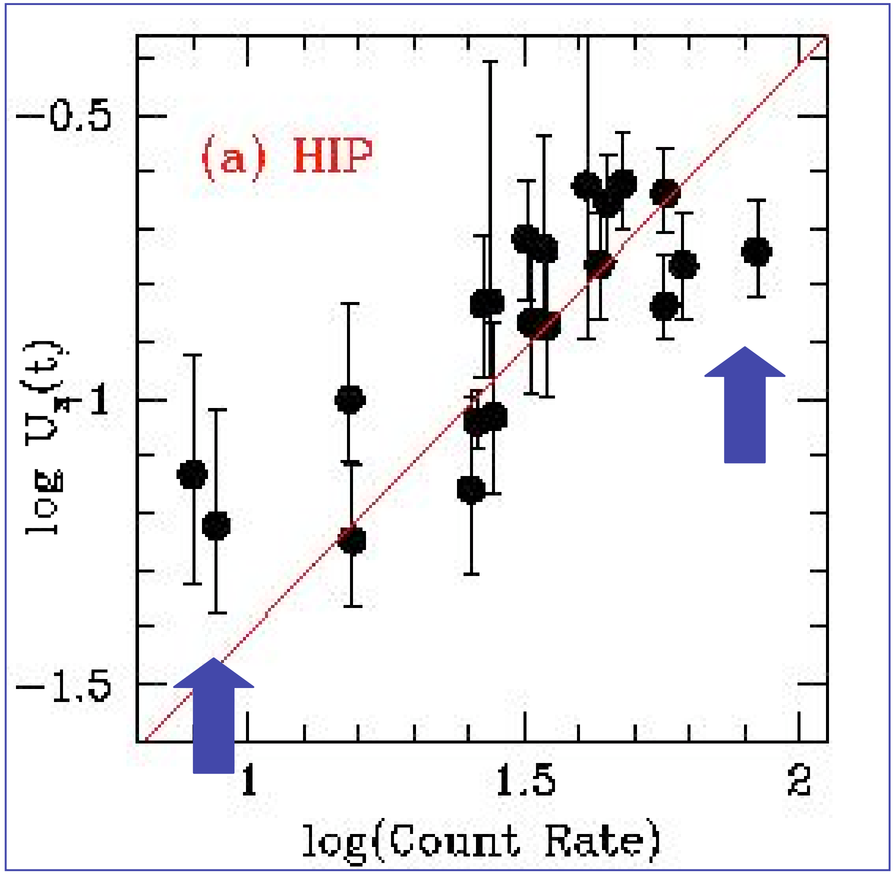
Krongold et al., 2006, ApJ, submitted

Measurement of n_e and hence R

- At extremes (high and low) high ionization component of WA (HIP) is *out of photoionization equilibrium*
  $t_{eq}^{i,j+k}(HIP) > \Delta t^{j+k} = 10$ ks
- Responds slower than Low Ionization gas - lower density
- HIP is in eq. at moderate fluxes

  $t_{eq}^{l,m}(HIP) < \Delta t^{l,m} = 3$ ks

  $n_e(HIP)=(0.6\text{-}2.1) \times 10^7\ cm^{-3}$



➔ R(HIP) = (1.3- 2.6)x 10^{15} cm = (0.5-1.0) light days

NGC4051 Warm Absorber is Radially Thin

- From the independent measure of N_H(HIP) $3.2\times10^{21}\,cm^{-2}$

$$\Delta R = 1.23\ N_H/n_e$$

$\Delta R(LIP) < 9\times10^{12}$ cm

$\Delta R(HIP) = (1.9\text{-}7.2)\times10^{14}$ cm

- **$(\Delta R/R)_{HIP} = 0.1\text{-}0.2$; $(\Delta R/R)_{LIP} < 10^{-3}$**
  - From the estimates of n_e and (n_eR^2):

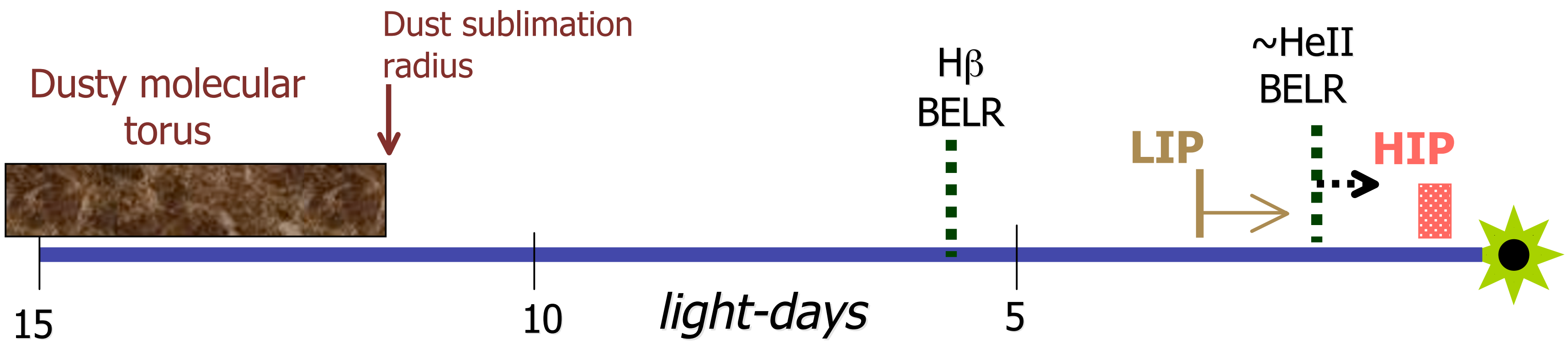
$$(\Delta R/R) = 1.23\ N_H\ n_e^{-1/2}\ (n_eR^2)^{-1/2}$$

$$(\Delta R/R)_{LIP} = 1\ \%\ (\Delta R/R)_{HIP}$$

either the LIP is embedded in the HIP **- pressure balance**

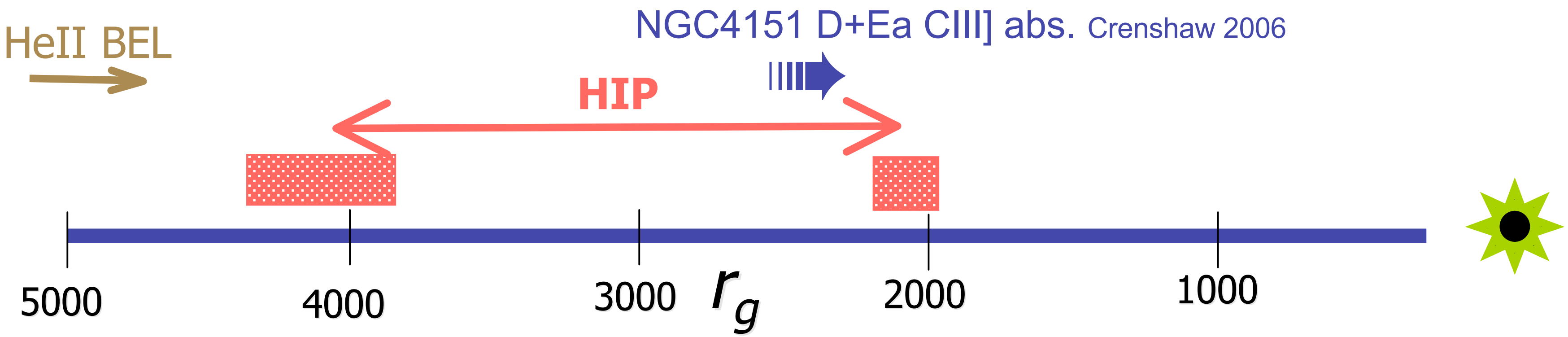
- *or* the LIP is a boundary layer of the HIP

Scale Map of an AGN: outer



- R_{HIP} ~ 0.5-1.0 light-day = (1.3-2.6) x 10^{15} cm
- R_{LIP} < 3.5 light-day: *consistent*
- ***Rules out*** *Narrow Emission Line Region* (kpc scale)
- ***Rules out*** Obscuring molecular torus (Krolik & Kriss, 2001)
  - Minimum dust radius, r_{subl}(NGC4051) ~ 12-170 light-days
- ***Rules out*** Hβ broad emission line region (BELR)
  – R(Hβ) = 5.9 light-days (Peterson et al. 2000)

Scale Map of an AGN: inner



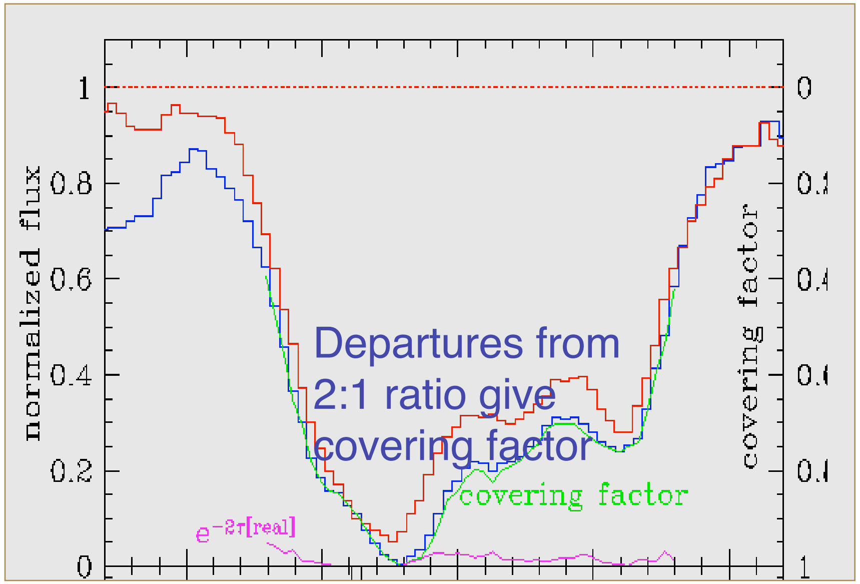
- R_{HIP} ~ 0.5-1 light-day ~2200 - 4400 R_g
  - M_{bh}=1.9+/-0.78 x 10^6 M_{sol} (Peterson et al. 2004) **face-on?*

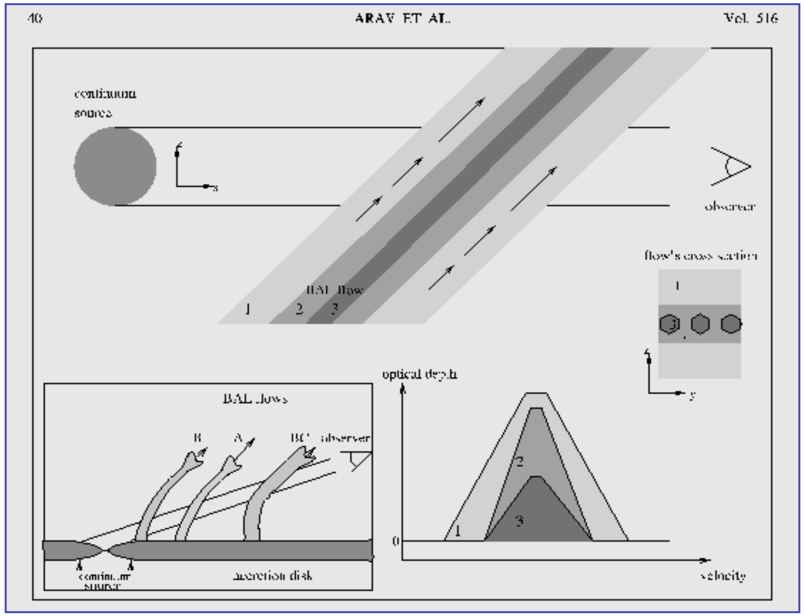
Disk winds arise on accretion disk scale

- Consistent with high-ionization BEL size
  - R(HeII) ~< 2 light days. **HeII** blueshift ~400km/s = wind signature?
  - Is the high ionization BELR a wind?
- Thin: ΔR = 10% - 20% R. Why?

WA radial velocity < escape velocity!

Recall:
NALs already shows flow is transverse
Most of wind velocity is perpendicular to our line of sight



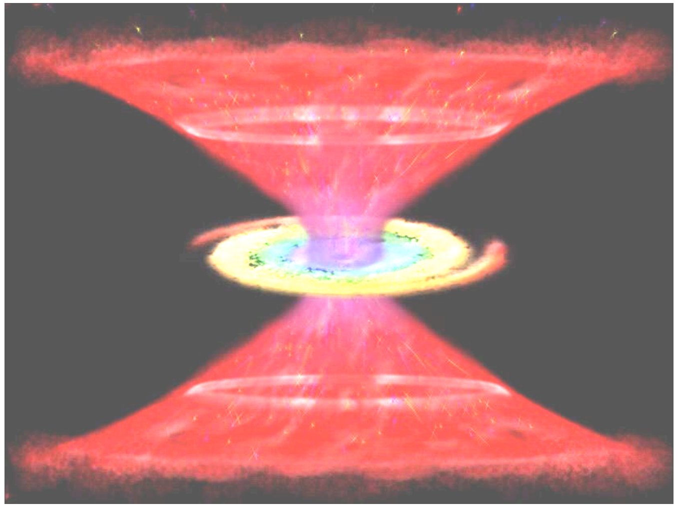


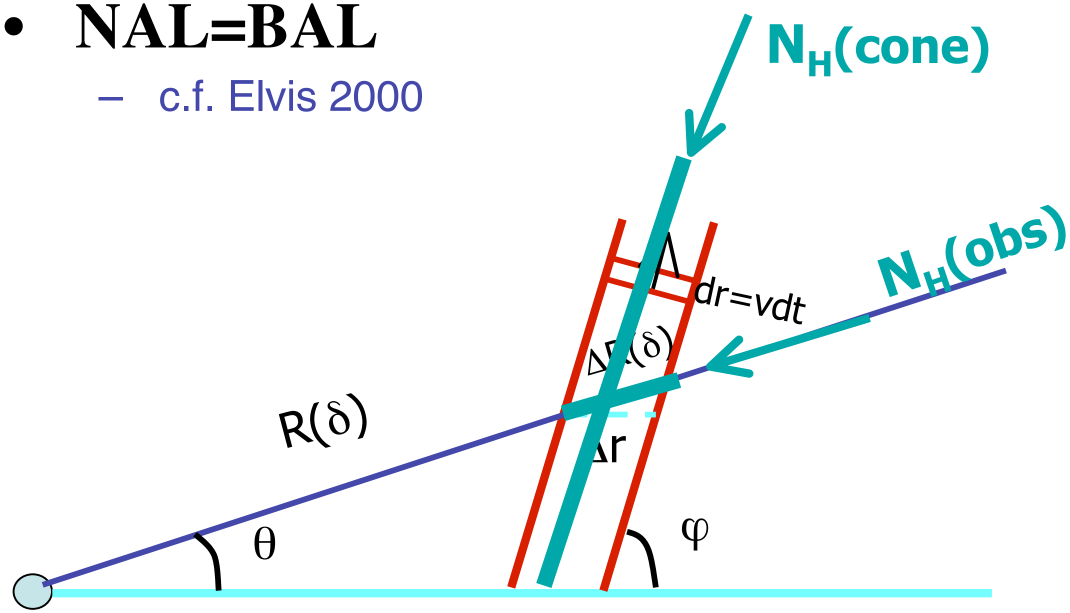
Arav, Korista & de Kool 2002, ApJ 566, 699

Arav, Korista, de Kool, Junkkarinen & Begelman 1999 ApJ 516, 27

Large N_H , velocity along flow: BALs

- N_H along flow direction N_H(cone) ~ $R.n_e$
- $R.n_e$(HIP) ~ 5 x 10^{22} cm^{-2}
  - **N_H(cone) >10 x N_H(obs)**
- Approaches BAL column densities
- Larger velocity & velocity spread
  - *V(cone) ~ 4 v_r ~4000 - 8000 km/s*
- **NAL=BAL**
  - c.f. Elvis 2000





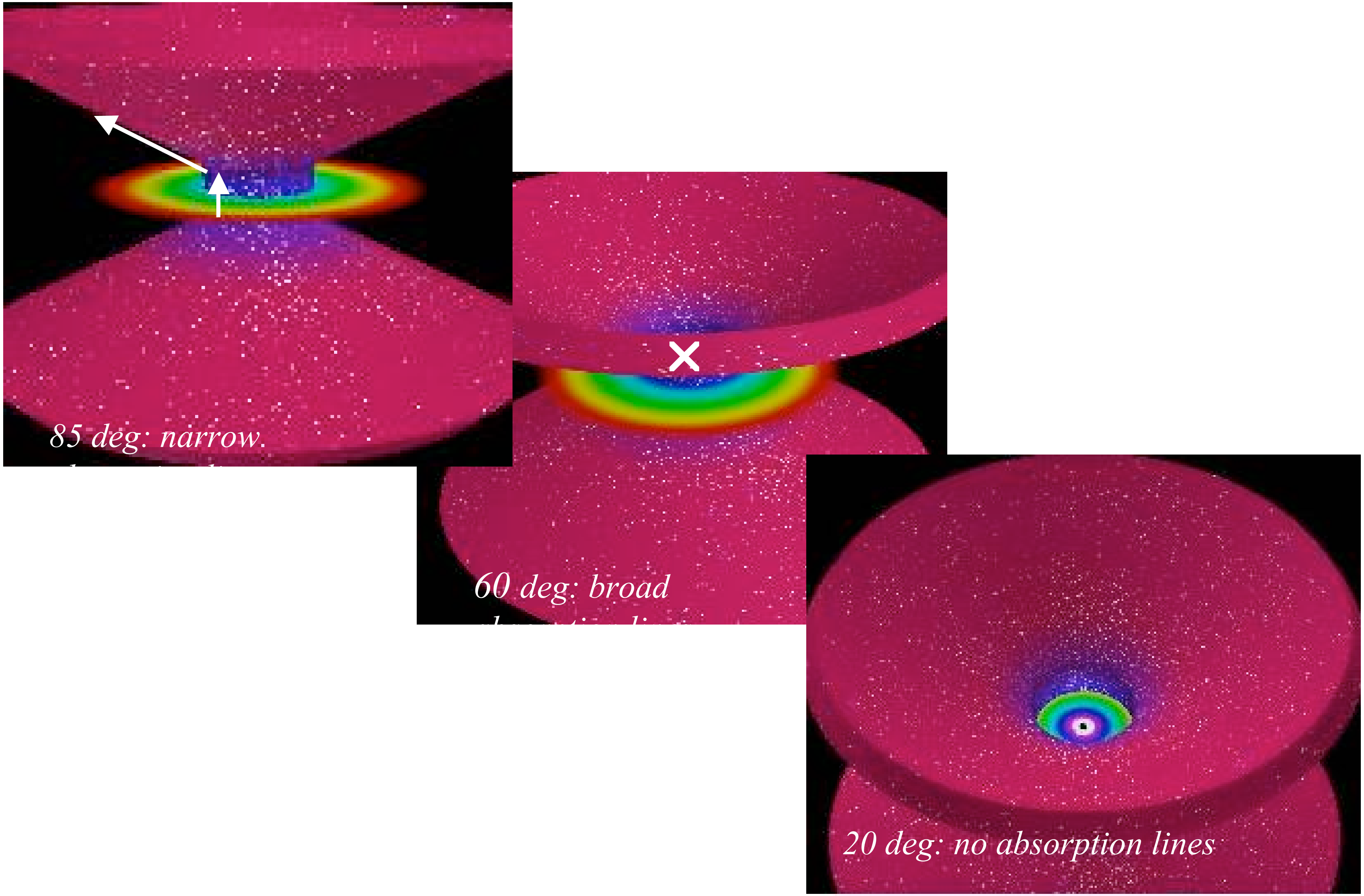
Feedback:
Power in wind underestimated by $(v_{rad}/v_{los})^2$ ~ 100

Summary of Observations

- BALs, NALs: Winds are normal in AGNs
- BAL first seen at few 1000 km/s: bends into our line of sight
- NALs mostly crossing our line of sight
- NAL/WA start from accretion disk
- High Ionization BELs also have wind component, dominated by rotation

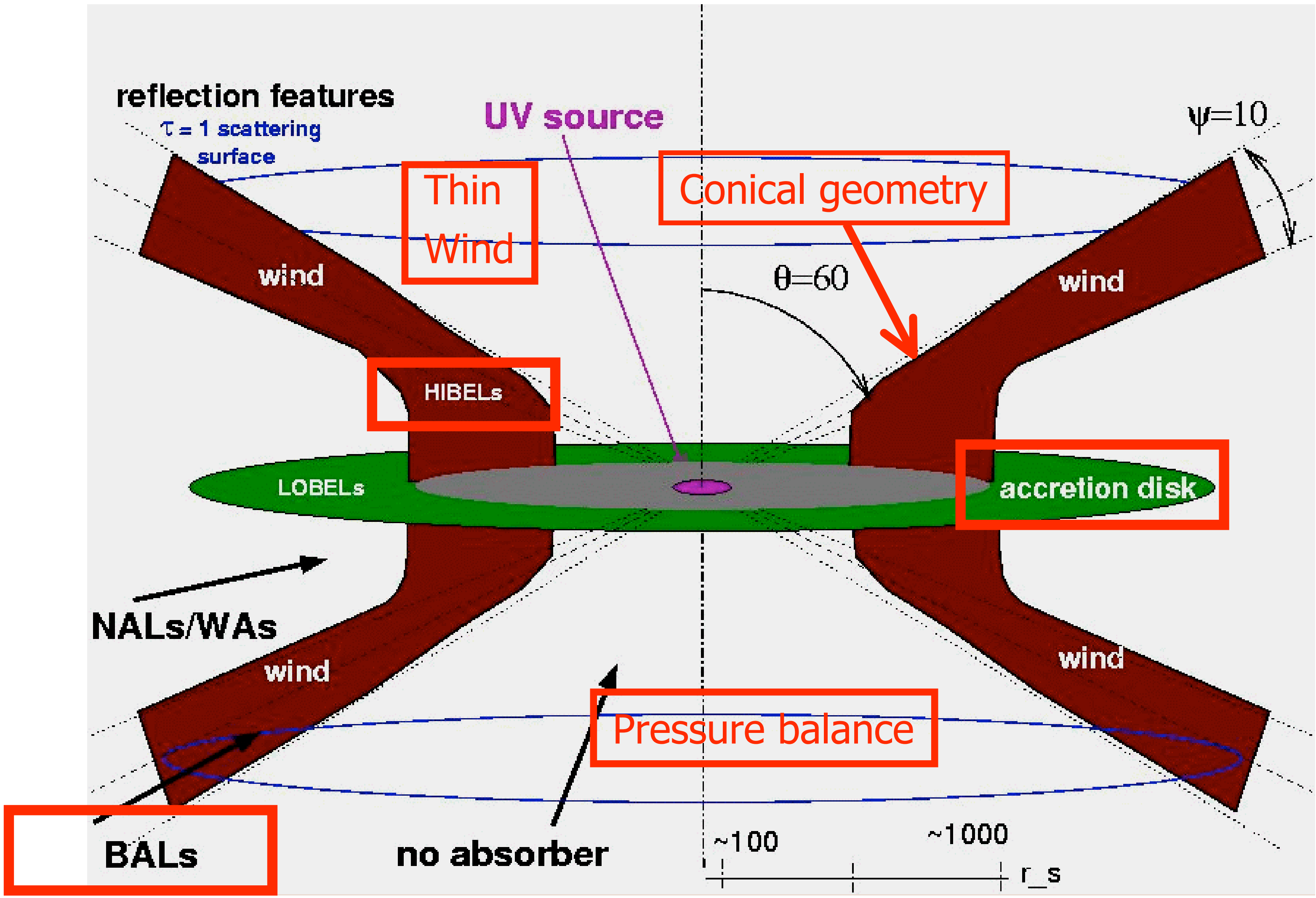
Combine to form a simple picture…

Geometry unites all the quasar atmosphere features



Confirms Major Features of 'funnel wind'

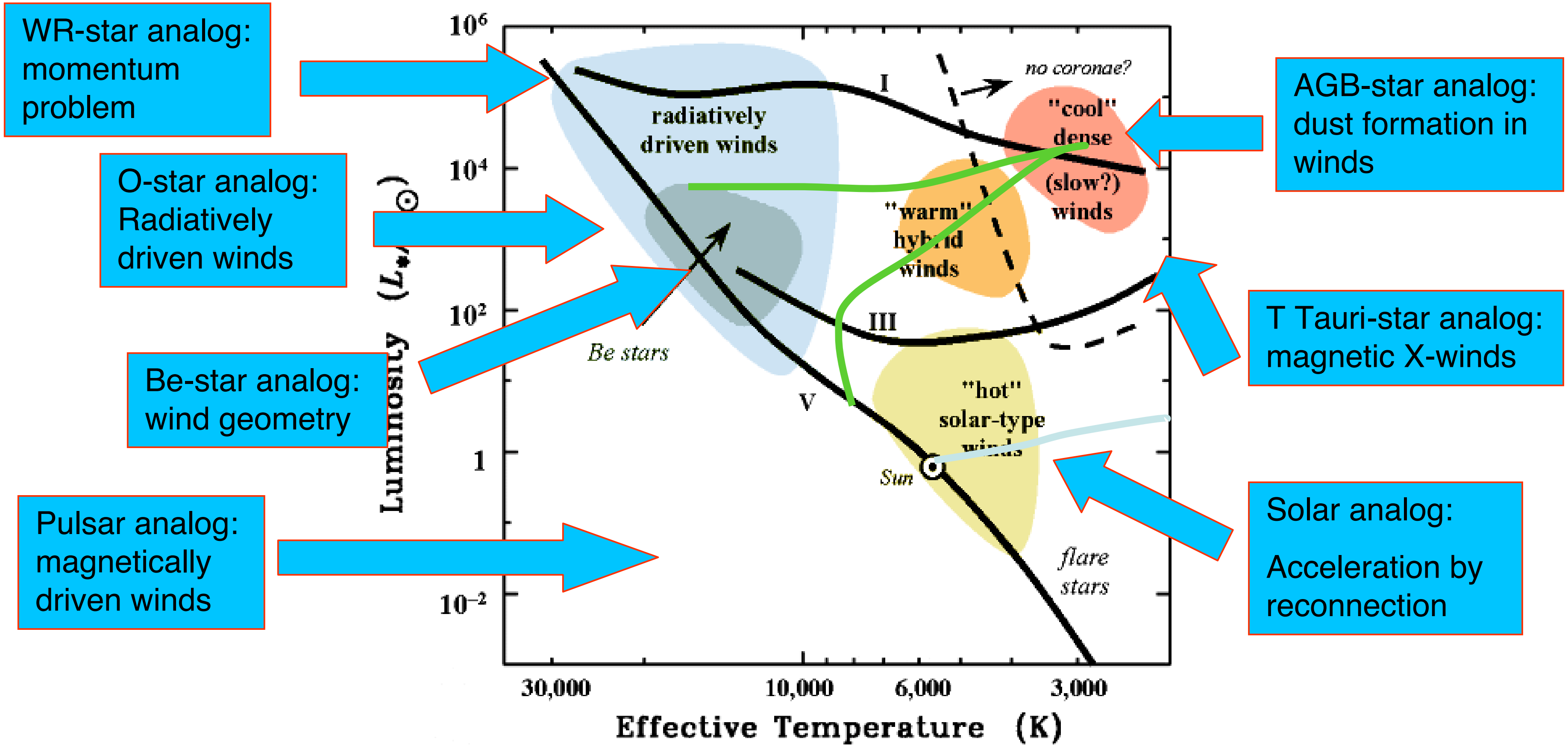
Elvis 2000 ApJ 545, 63; 2003 astro-ph/0311436



Becoming a secure basis for physical wind models: will allow extrapolation

How are Winds Accelerated?

Wind Paradigm connects Quasars to established Astrophysics



Steve Cranmer: http://cfa-www.harvard.edu/~scranmer/cranmer_st_cool.html

3 Ways to Accelerate Quasar Winds

Stellar Analogs start to help

1. Thermal Pressure Driven
   As in Supernovae (but continuous)
2. Radiation Line Driven
   As in O-stars
3. Magnetic ‘slingshot’
   As in T Tauri stars

Caveat: Stellar Analogs may not be enough

Are there processes unique to 2-D disk geometry?

Thermally Driven Winds

As in Supernovae… but continuous

- Quasar continuum heats gas
- Hot gas pressure pushes wind
- Ablate inner edge of obscuring torus? Krolik & Kriss 1995
  - Large radius for WA (~0.1-1 pc)
- Low maximum velocity:
  - $V_{max} \sim V_{sound}$ @ 10^6K ~ 100km/s
- Isotropic pressure

  ~100% filling factor Balsara & Krolik 1993, ApJ, 402, 109
- Cosmic Ray heating
  - Proton decay delays heating to larger radii Begelman, deKool & Sikora 1991

Line Driven Winds

As in O-stars

- Winds from O-stars discovered 1979
- Castor, Abbott & Klein 1975, ApJ,195,157
  - Resonant line absorption, mainly in UV, increases cross-section far above Compton scattering (~100s)
    - Winds possible at 1/100s of L_{Edd}
  - Initial acceleration Doppler shifts lines to new part of continuum
    - Continued acceleration
- Highly ionization dependent: overionized gas has only electron scattering cross-section and does not accelerate
  - Need to shield wind gas from X-rays
- Radial force
- $V_{max} \sim 2x\ V_{Kepler} \sim 10{,}000$ km/s
- Textbook: Lamers & Cassinelli '*Introduction to Stellar Winds*' (chapter 3 for simple treatment)

Mushotzky, Solomon & Strittmatter 1972 BALs; Wolfe 1974 BELR; deKool & Begelman 1995; Murray, Chiang, Grossman & Voit, 1995 BALs; **Murray & Chiang** 1995 Warm Absorbers; Chiang & Murray 1996 BELR; Proga , Stone & Drew 1999 CVs; Proga 2000; **Proga** 2003 BELR; Chelouche & Netzer

Magnetic 'slingshot' Driven Winds

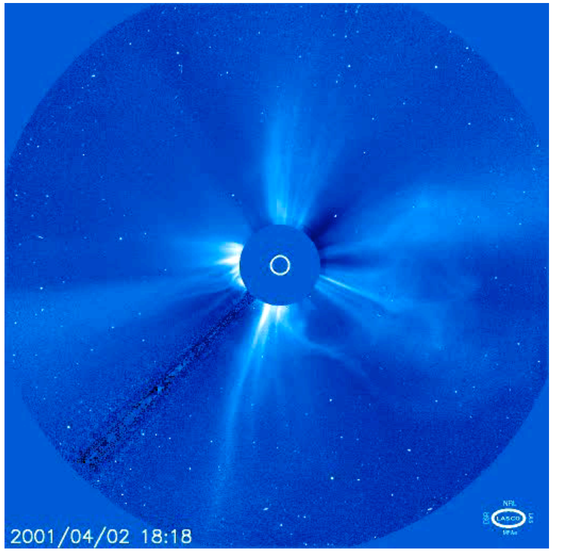
As in T Tauri stars

- Accretion disk viscosity thought to be magnetic in origin (MRI)
- Gas will flow along open field lines
  - 'beads on a wire'
  - Blandford & Payne 1982 MNRAS, 199, 883; Kartje, Konigl, Elitzur 1999 ApJ, 513, 180; Everett 2005, ApJ, 631, 689
- Pre-main sequence stars have biconical winds from their protoplanetary disks
  - Shu 'X-winds' Shu et al. 1995 ApJ 455, L155; Shu et al., 2002 ApJ, 564, 853
- Bi-conical
  - Re-collimate? → jets?
- Maximum velocity $v_{max} \sim c$

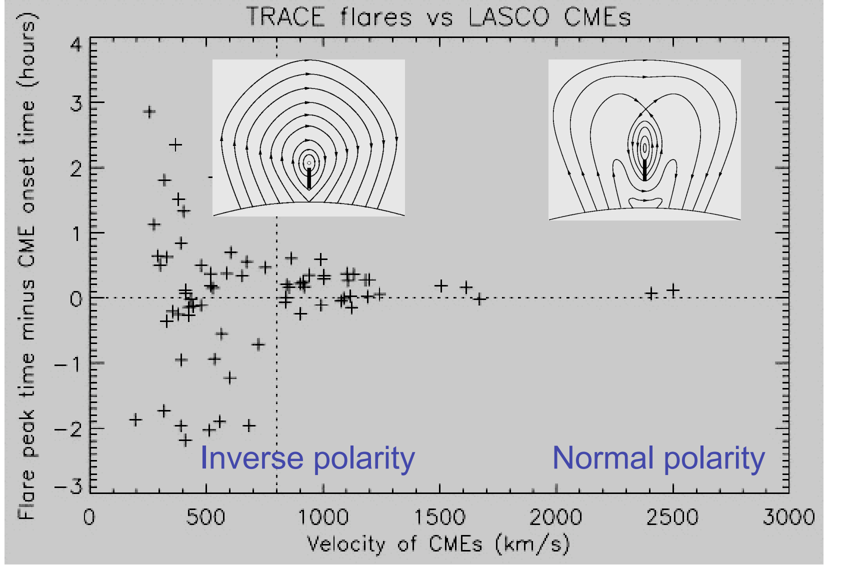
Blandford & Payne 1982; Emmering, Blandford & Shlosman 1992; Königl & Kartje 1994; Bottorf et al. 1997; **Everett,** Königl, Kartje 2001; Proga 2000; **Proga** 2003

Magnetic Reconnection

As on the Sun



- Wind launching may be separate from wind acceleration
- Solar analog
  - Coronal Mass Ejections (CME)
  - launch cool gas (10^4K) at ~1000 km/s
- Magnetic reconnection could eject material from disk
  1. Overlying **B** field opens
  2. Cool, dense filament moves up and out
  3. Reconnection of **B** below heats surface, producing soft X-ray postflare loops
- *Stellar Analogs may not be enough*
  e.g. MRI driven outflows Liu, Goodman & Ji 2006



thanks to Leon Golub

5. What next?

Future of Quasar Accretion Disk Winds

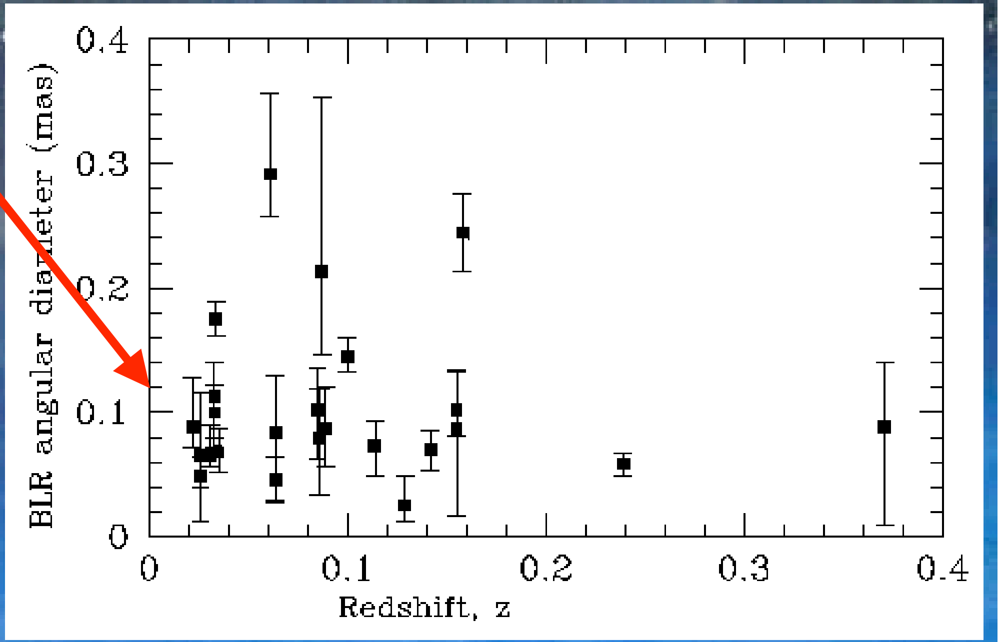
- **Determine location, structure, mass loss rates:**
  - n_e, radius from WA variability *XMM, Suzaku*
  - BAL opening angles from non-BAL polarization *VLT*
  - Polarization PA swings of high and low ionization BELs *VLT*
  - Are ‘ionization cones’ the outer part of the disk wind? *revived STIS?*
- **Test acceleration mechanisms**:
  - Is wind weaker in X-ray loud quasars, as predicted for line driving? *SDSS/XMM*
  - Does wind model produce observed properties? N_H, thickness, ionization
  - Model must explain ‘eigenvector 1’: X-ray spectrum, variability, strong FeII
  - Must explain Baldwin effect: weaker CIV EW at high L
  - Must predict a few phase WA
  - Accretion disks must create winds naturally: constraint on disk physics
- *Image the BELR in 3D…*

Imaging Quasars

What we really want is to *look* at quasar atmospheres

Low z BELR sizes are ~0.1 mas

Elvis & Karovska, 2002 ApJ



Resolvable with planned ground interferometers

VLT-I, Ohana

Ideal telescopes:

- Image the wind in space and velocity
- 5 km-10 km IR 2μm interferometer
    - Dome C' in Antartica?
- 0.5-1km UV space interferometer

  = NASA 'Stellar Imager'

Sizes are implicit in:

Peterson et al. 1999 ApJL 520, 659.

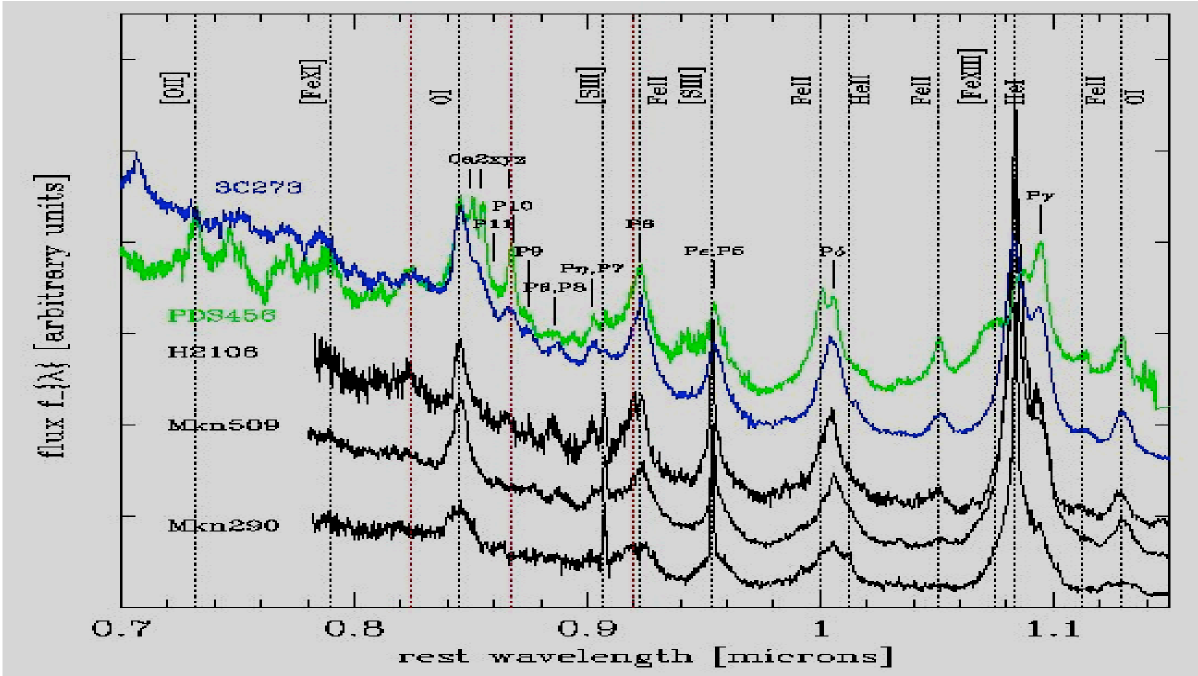
Kaspi et al. 2001 ApJ 533, 631

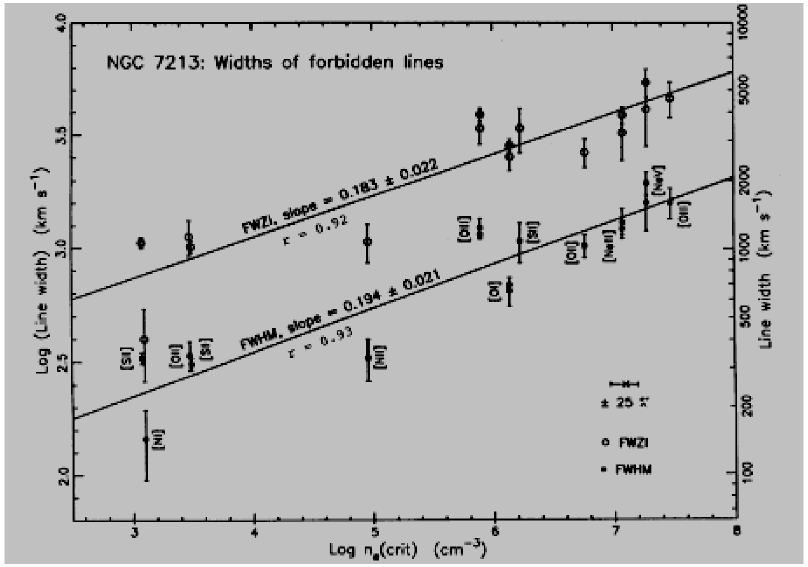
=> SOLVE QUASAR ATMOSPHERES

No more fancy indirect deductions!

Narrow Emission Lines: NELs

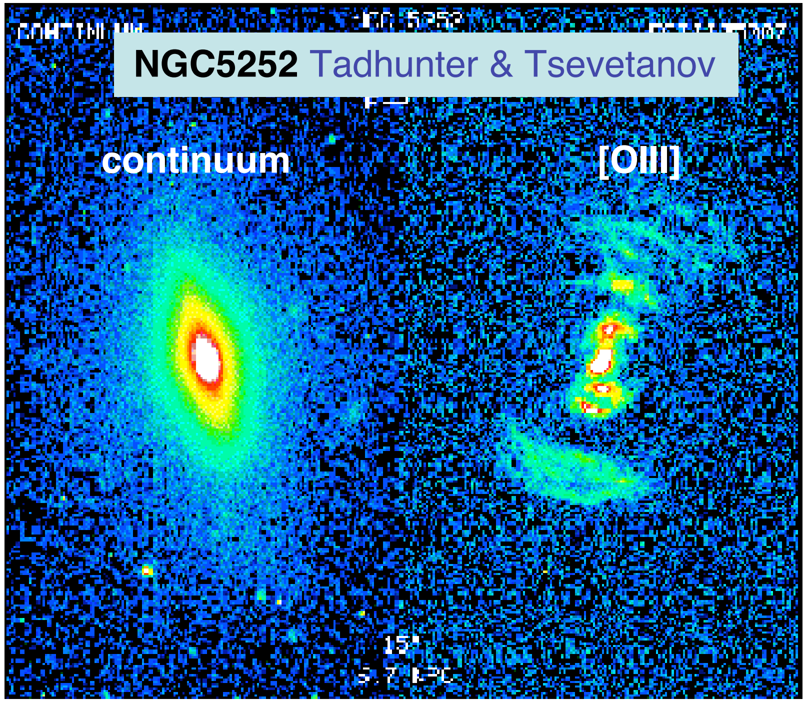
- All forbidden transitions
  - Low densities
    - Close to critical density
  - Layered?
- Universal
  - BEL/NEL stronger at high L
- Widths:
  - < 1000 km/s,
  - > 200 km/s: not galaxy ISM
- Covering factors
  - Global
  - Line of sight
- Which lines? Ionization
  - [OI] to [FeXIV]
  - >= [FeX] are 'coronal lines'
  - Erkens et al.
- Column densities
- Resolved size, morphology
  - Bi-cones

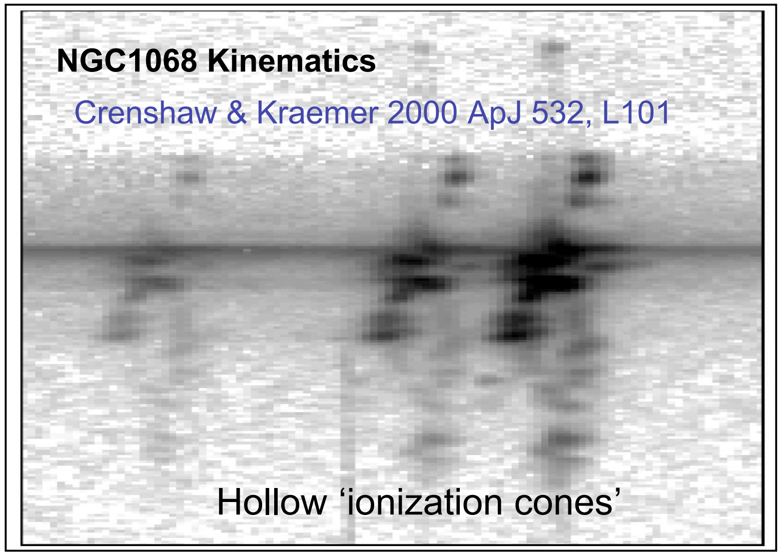




Narrow Emission Lines: structure

- Resolved size
  - Larger than ‘obscuring torus’, ~ kpc
- morphology
  - Fraction are bi-cones
    - ENLR “extended NLR”
- Kinematics
  - Like ISM Whittle: illumination
  - Outflows Crenshaw/Kraemer

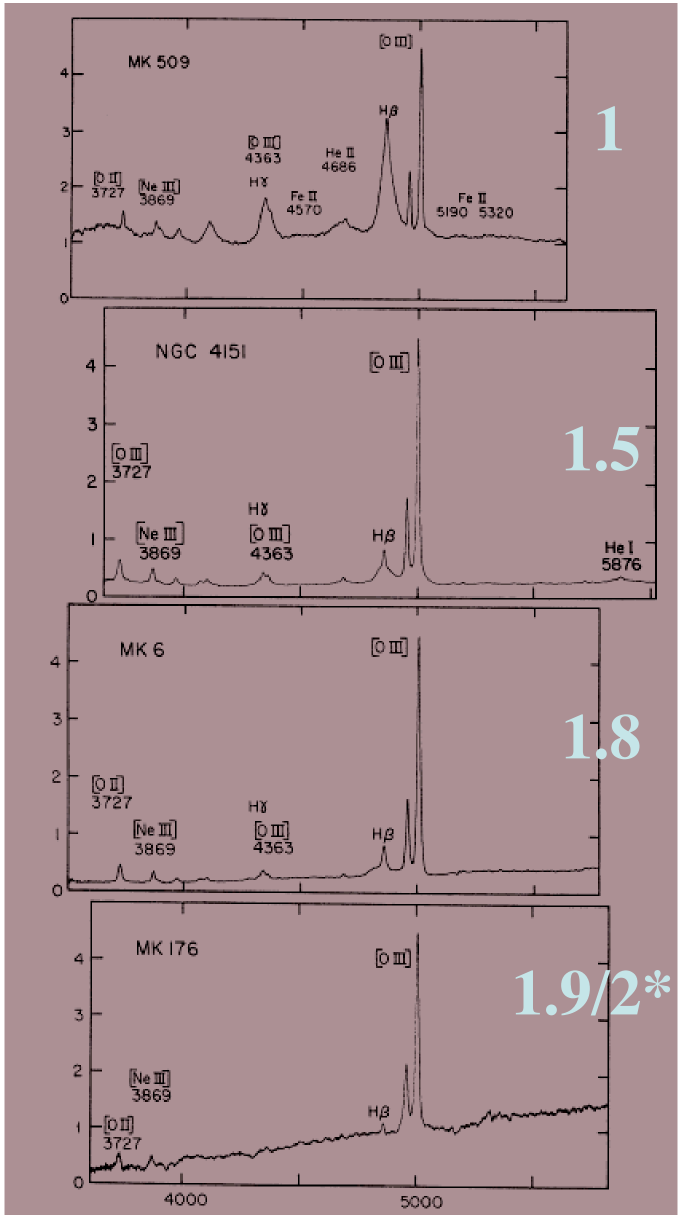




BEL/NEL ratio: AGN Types

- Type 1/Type 2
  - Khachikian & Weedman 1974 ApJ 192, 581
- Type 1.5
  - NGC4151 MNRAS, 176, 61P
- Type 1.8, 1.9
  - Osterbrock 1981 ApJ 249, 462

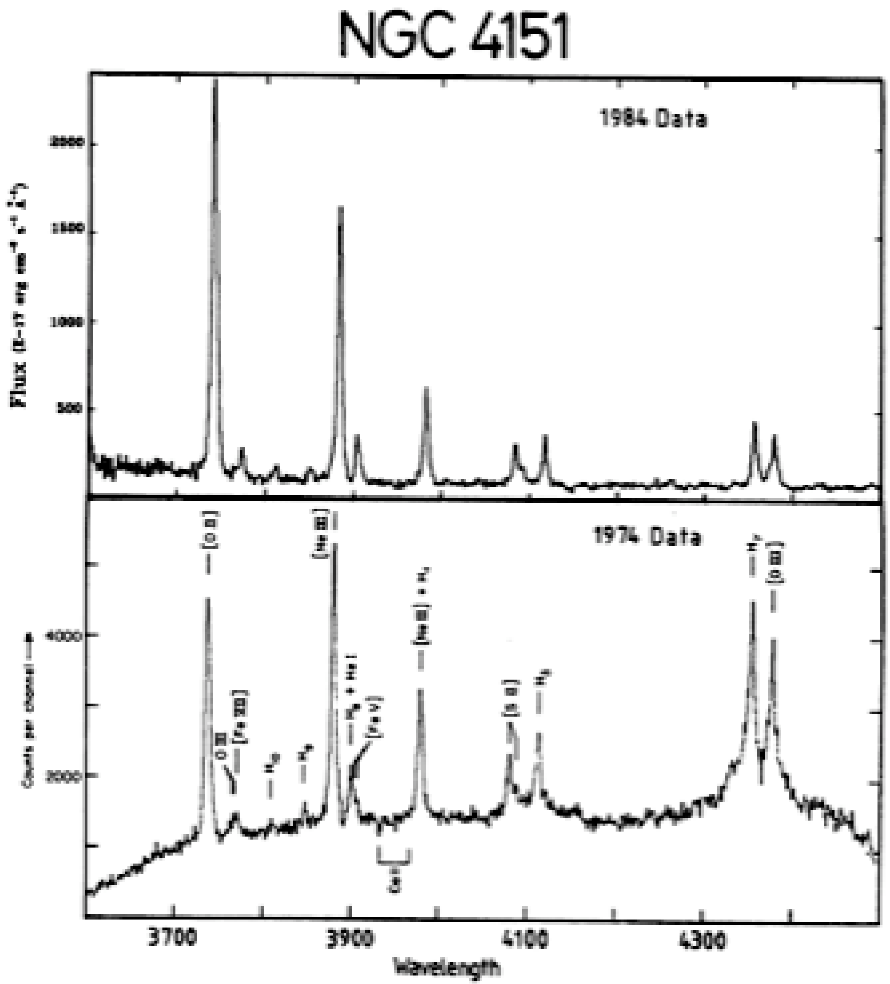
  = X-ray ‘narrow emission line galaxies’ w. broad Hα (Ward et al. 1979)
- Progression of narrow/broad component flux ratio
  - Due to reddening $A_V \sim 1 - 5$
    - Ha/Hb (balmer decrement)
    - Continuum slope
  - Correlates with X-ray NH
    - At factor 10 low dust/gas ratio
      - Maccacaro et al. 1981, Maiolino et al. 2001
- Leads to ‘Obscuring Torus’ Unified Model



Osterbrock & Koski 1976

Type-changing AGNs

- Several AGNs have changed between type1 and type 2 in months-years
  - Tohline & Osterbrock 1976
  - Penston & Perez 1984
- 'Off-state' quite common
  - Not all type 2s are obscured
- X-ray 'Compton-thick/-thin' transitions also fairly common
  - Can be rapid (days, even hours)
  - Elvis et al. 2004, ApJ, 615, L25
  - Matt et al., 2005
  - Risaliti et al. 2005



Penston & Perez 1984 MNRAS, 211, 33P