

IMAGING QUASARS WITH INTERFEROMETRY

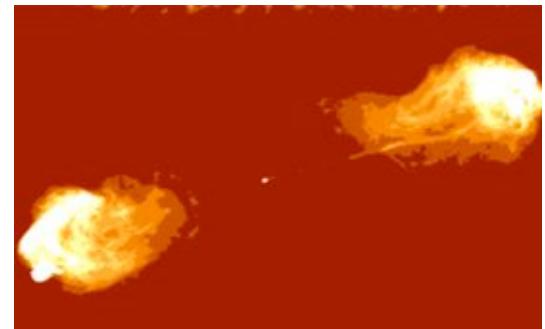
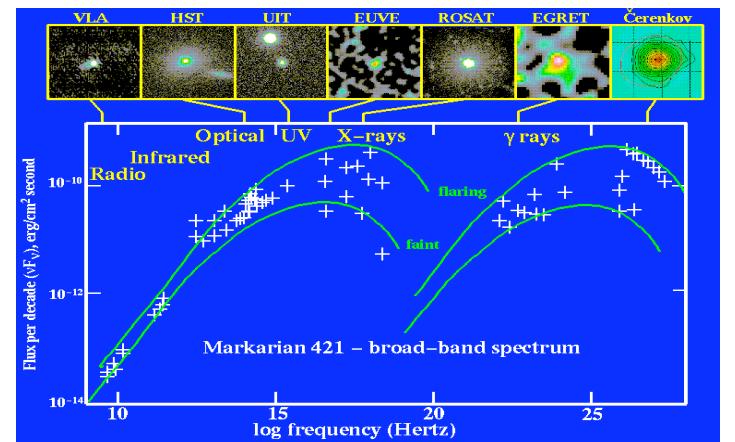
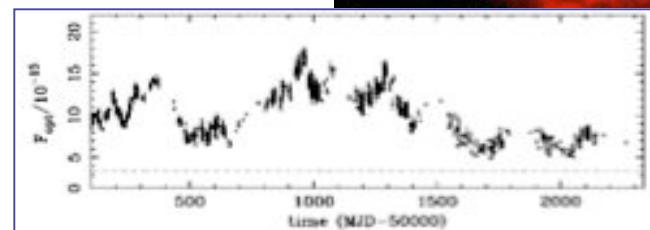
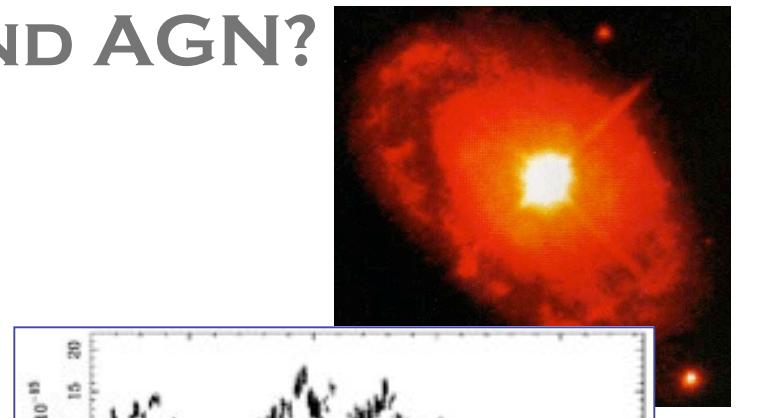
Martin Elvis

Harvard-Smithsonian Center for Astrophysics

WHY STUDY QUASARS AND AGN?

- UP TO 1000 GALAXY LUMINOSITIES
 - Visible to $z > 6$ (Age < 1 Gyr)
 - Evolve strongly in luminosity and space density
 - Variability: ‘*galaxy power from solar system scales*’
- GROWTH OF MASSIVE BLACK HOLES
 - Quasars & Active Galactic Nuclei are where SMBH grow from their $z \sim 10$ seeds.
 - Much of growth is hidden by dust & gas
- BLACK HOLE & GALAXY “CO-EVOLUTION”
 - M- σ . Why?
 - Feedback: limit cycle induced by AGN?
- EFFICIENT ENERGY EXTRACTION $\sim 0.1 M c^2$
 - vs $0.01 M c^2$ for nuclear fusion
 - Spectra nothing like starlight
 - similar power/decade from Far-IR to X-ray
 - Black Hole masses: $10^6 - 10^9 M_\odot$
 - Accretion disk $L_{\text{accretion}} = 5-20\% L_{\text{fusion}}$
- RELATIVISTIC JETS
 - accelerates matter in bulk to 99.5% c [$\Gamma=10$].
 - ‘superluminal motion’ c.f. 99.88% at Fermilab Tevatron;
 - electrons accelerated to $\Gamma=1000$ (TeV photons)
 - Linear: ‘*spherical cow*’ not a good approximation

Note: AGN (Active Galactic Nuclei) are just lower luminosity quasars)

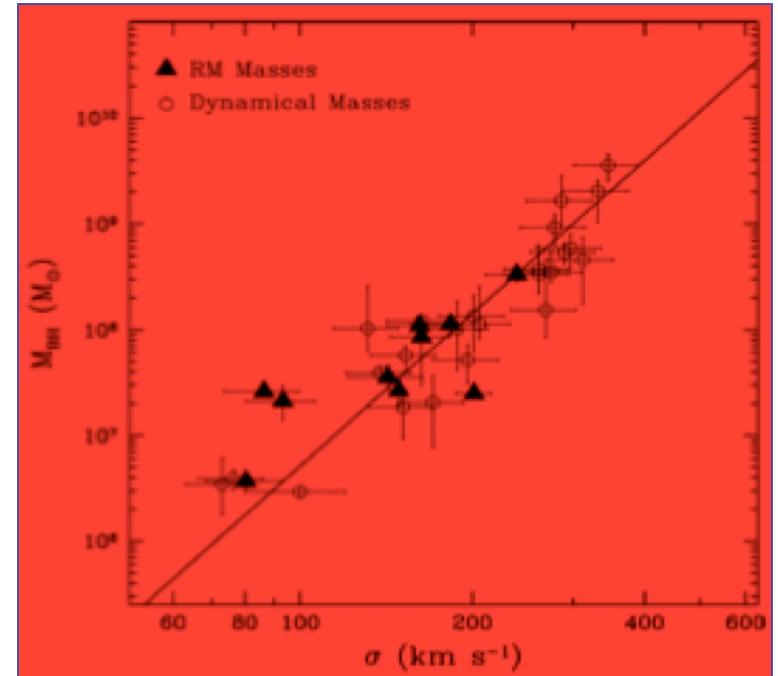


GALAXY & BLACK HOLE CO-EVOLUTION

FEEDBACK

Ferrarese & Ford 2005

- Galaxy bulges and central black hole masses correlate: $M_{\text{BH}} = 0.05[?] M_{\text{bulge}}$
 - Magorrian et al. 1998
 - Ferrarese & Merritt; Gebhardt et al. 2002[?]
 - Maiolino & Hunt 2004[?]
- Extraordinary link between accretion rates at kpc and μ pc scales
 - High angular momentum barrier
- Feedback from AGN
 - Radiation
 - Relativistic jets
 - Wind kinetic energy, momentum
 - *Matter (metals)*
- Invoked as a panacea in galaxy formation
 - How does it work?

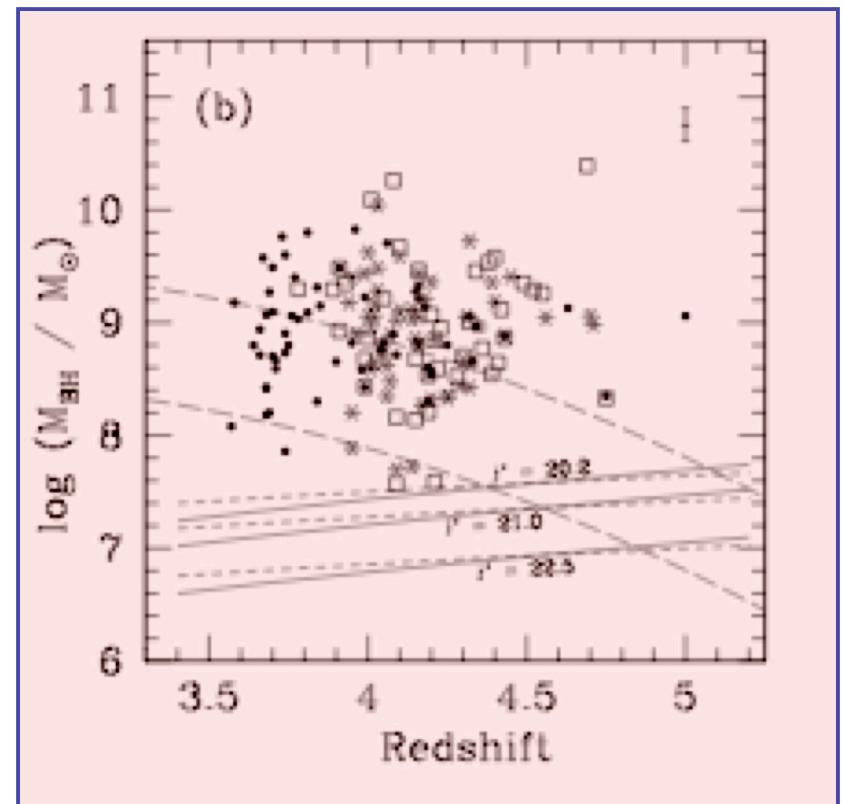


BLACK HOLE MASSES AT EARLY TIMES

BLACK HOLE GROWTH

Vestergaard 2004 ApJ 601, 676

- Reverberation mapping shows L-radius relation
- 2ndary BH masses from FWHM => $R_g + L_{\text{opt}} \Rightarrow cm$
- $z = 3 - 5$ quasar BH masses can exceed $10^9 M_{\odot}$
- Age 1.2-1.8Gyr,
- 0.8-1.4 Gyr from reionization
- Grow faster than Eddington rate?
 - Salpeter time = 4×10^7 yr (= mass e-folding time)
- Are masses overestimated?
- ***Check by measuring R(cm) directly***



QUASAR & AGN COMPONENTS

1. massive black hole ✓

Proposed: Lynden-Bell 1969

Demonstrated in AGN: Wandel & Peterson

Questions: Origin, co-evolution,
spin, Penrose process; GR tests

2. accretion disk ?

Proposed: Lynden-Bell 1969, Pringle & Rees 1972,
Shakura & Sunyaev 1972

Demonstrated?: Shields 78, Malkan 82, Eracleous?

Questions: proof. Viscosity=(MRI?), ang.mom, RIAF

3. relativistic jet ✓

Proposed: Rees 1967 [PhD], Blandford & Rees 1974

Demonstrated: Cohen et al. (VLBI)

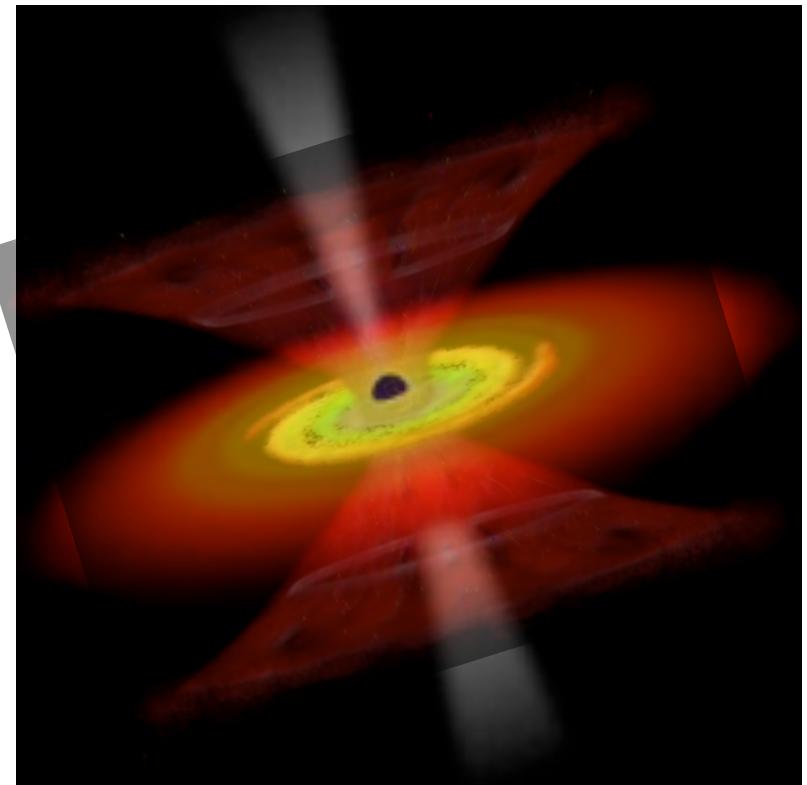
Questions: acceleration mechanism (Penrose/Blandford-Znajek?)

4. Disk wind atmosphere ✓ BELR, WA, BALs, NELR

Proposed: Mushotzky+1972 – Murray+1995 – Elvis 2000, Proga 2000

Demonstrated: Krongold et al. 2006 – NGC4051

Questions: acceleration mechanism; M/Medd, eigenvector 1,
impact on environment



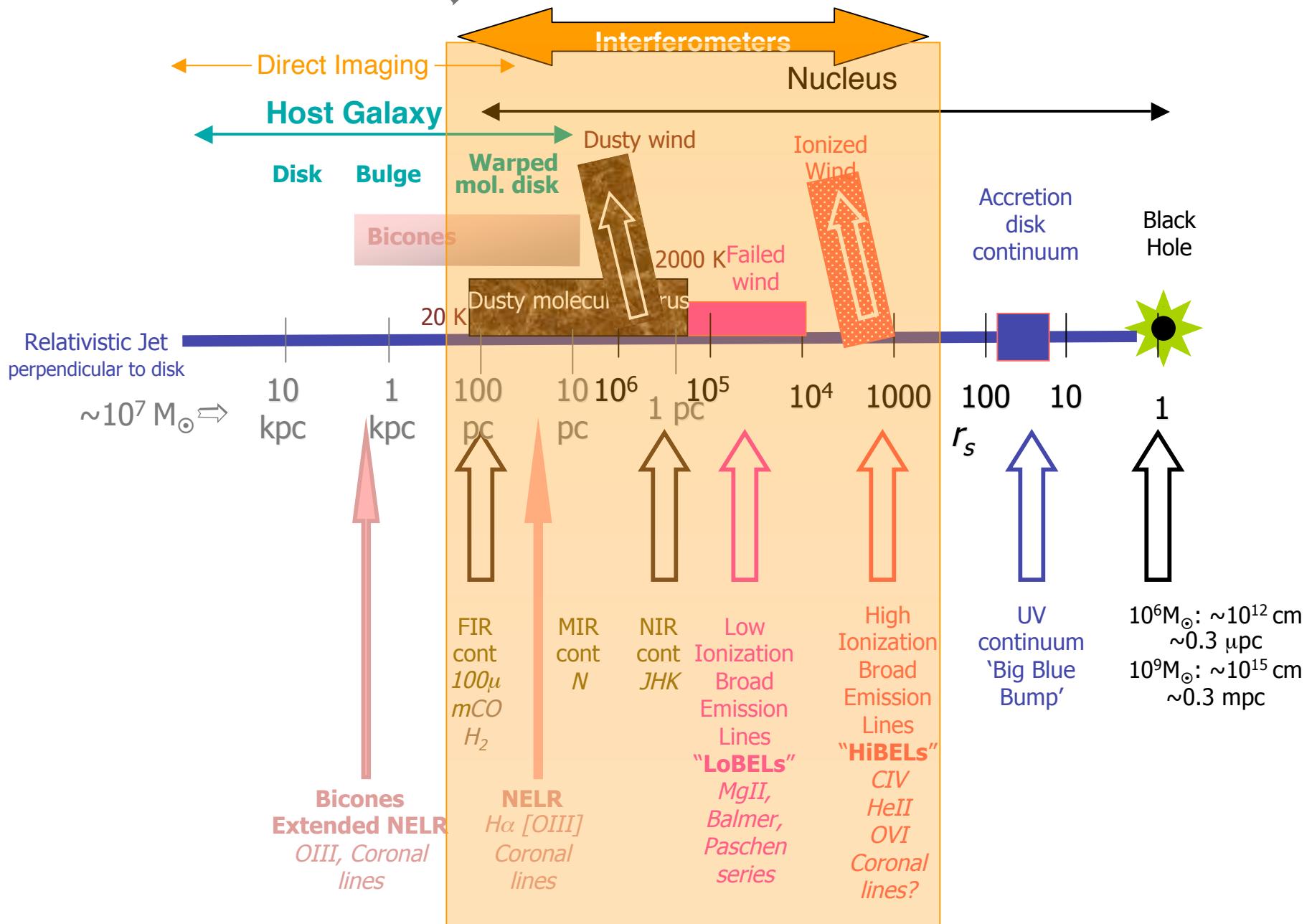
5. Obscuring torus ✓

Proposed: Lawrence & Elvis 1982

Demonstrated: Antonucci & Miller 1985,
Urry et al.

Questions: Beyond the Bagel: host
and/or disk

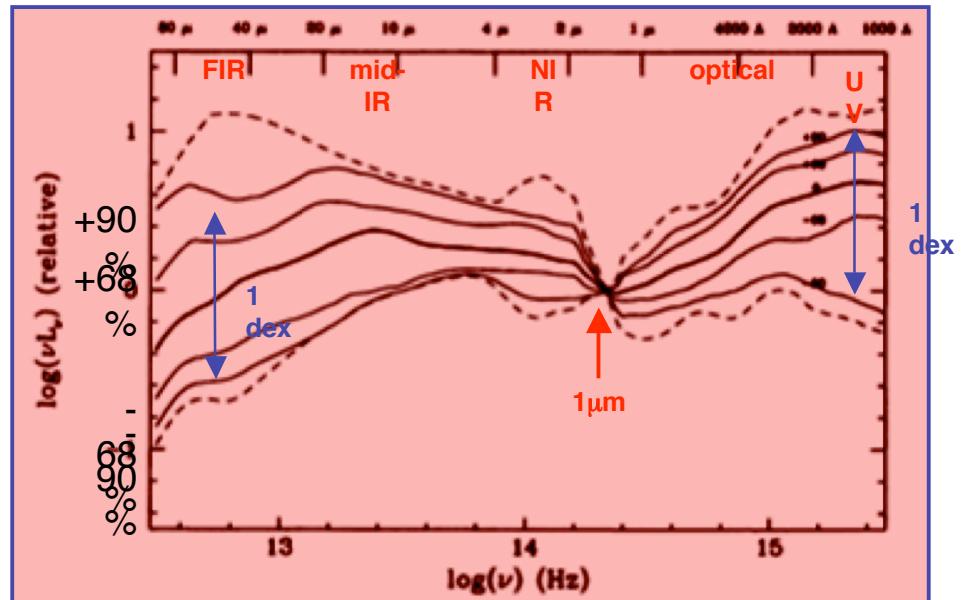
SCALE OF QUASAR/AGN COMPONENTS



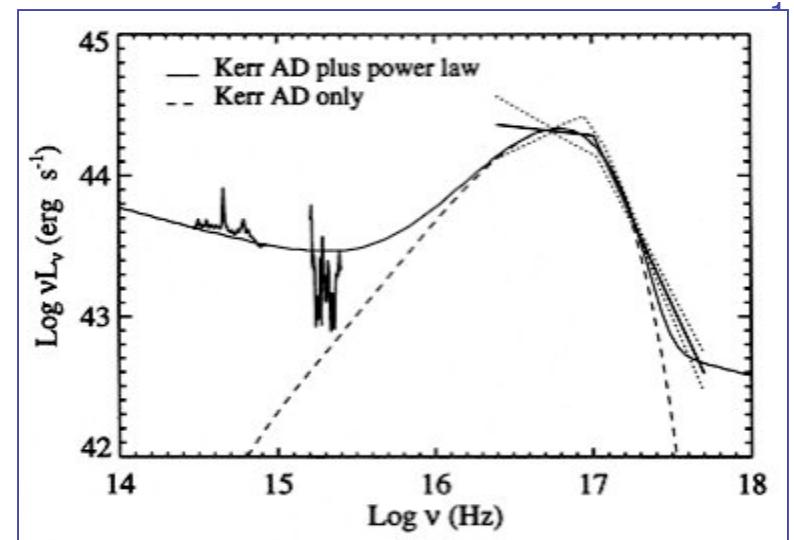
IMAGING THE AGN UV/OPTICAL CONTINUUM

ACCRETION DISK PHYSICS

- Wide SED spread: No theory, no correlations
- Presumed to be accretion disk
 - 50 - 100 Schwarzschild radii
 - **~ 100 nano-arcsec**
- Underlying power-law component
 - Occasionally dominates
 - Jet? Bremsstrahlung?
 - Jet dia. Few $\times 100 R_s$
- Challenging
 - Not the next generation interferometers?

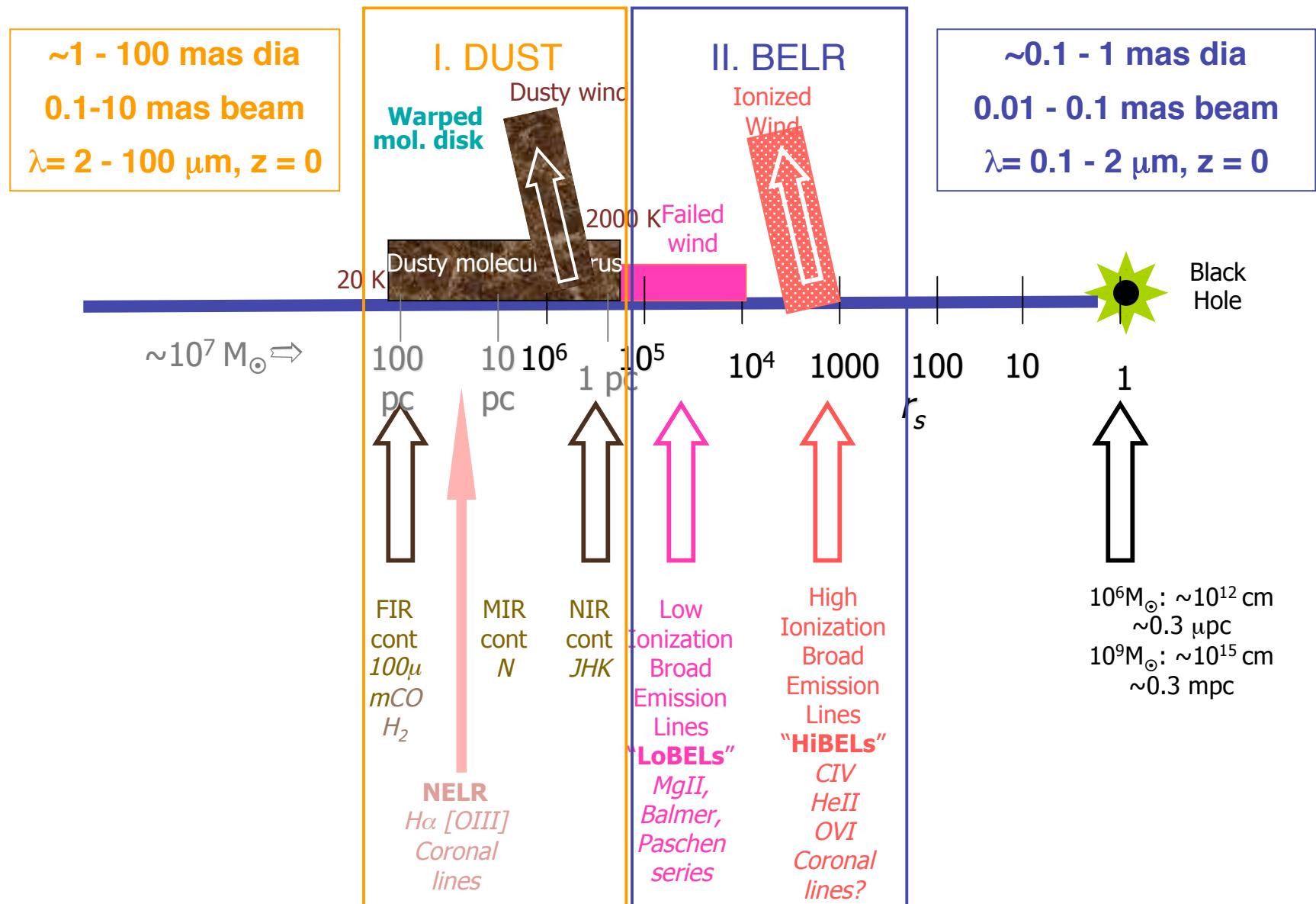


Elvis et al., 1994, ApJ, 95,



Puchnarewicz et al., 1995, MNRAS, 276, 20P

INTERFEROMETER ACCESSIBLE RANGES: DUST AND BROAD EMISSION LINES



IMAGING QUASARS I: DUST

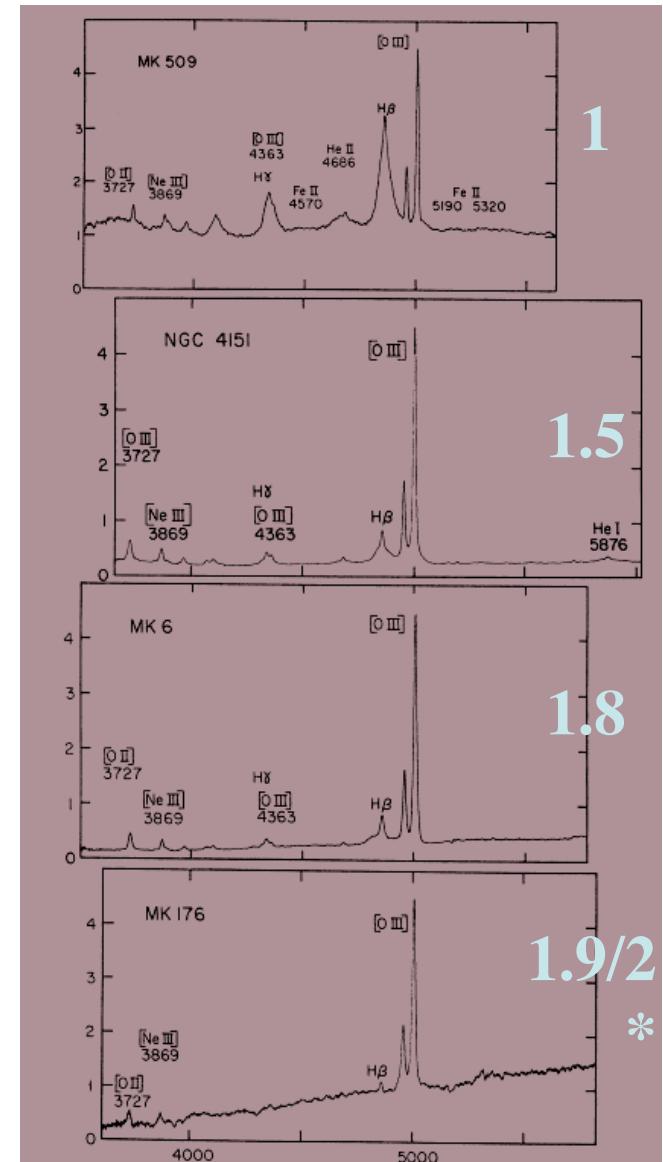
BLACK HOLE GROWTH, ACCRETION PHYSICS

- Strong dust reddening between NELR and BELR - AGN types. Very common.
- ⇒ ‘Unified Model’
- Minimum radius set by maximum dust evaporation temperature

$$R_{\min} = 1.3 L_{\text{UV},46}^{1/2} T_{1500}^{-2.8} \text{ pc}$$

Barvainis 1987 ApJ 320, 544

- $R_{\min} \sim 10 \text{ pc}$ for the most luminous quasars
- $R_{\min} \sim 1 \text{ pc}$ for 3C273 (Quasar)
- $R_{\min} \sim 0.1 \text{ pc}$ for NGC5548 (AGN)
- Absorbed radiation re-emitted: 1-100μm IR
- First dust forms in AGN winds?
- Brightest AGNs in Near-IR:
 - “NGC Seyferts” $K = 10 - 12$

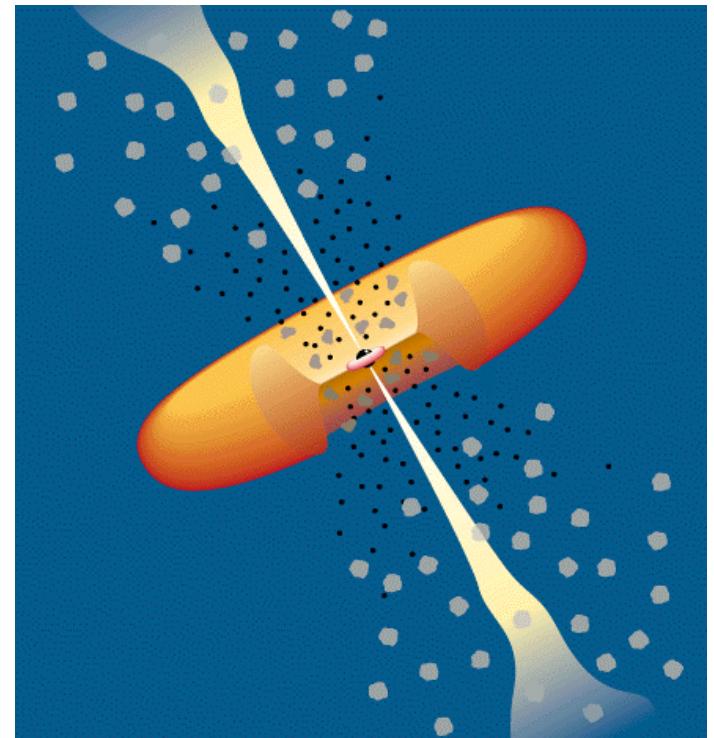


Osterbrock & Koski 1976

STANDARD TORUS: STANDARD ISSUES

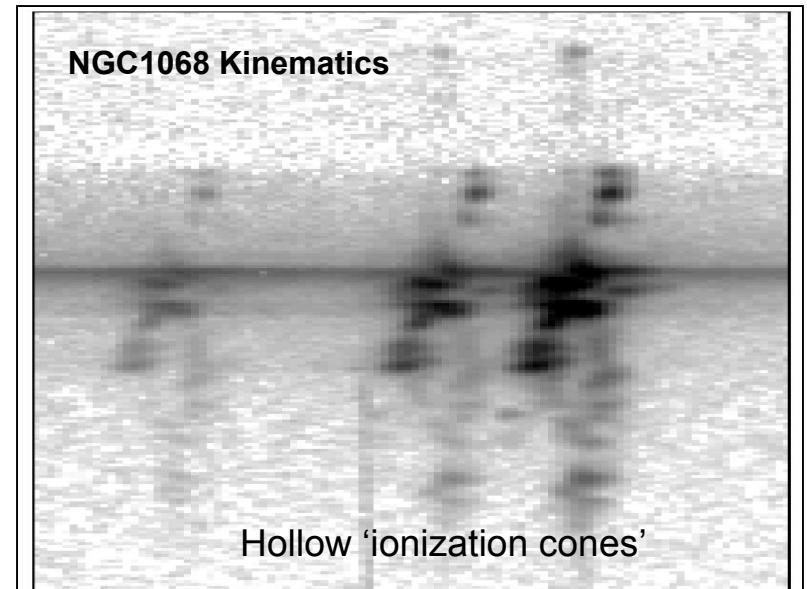
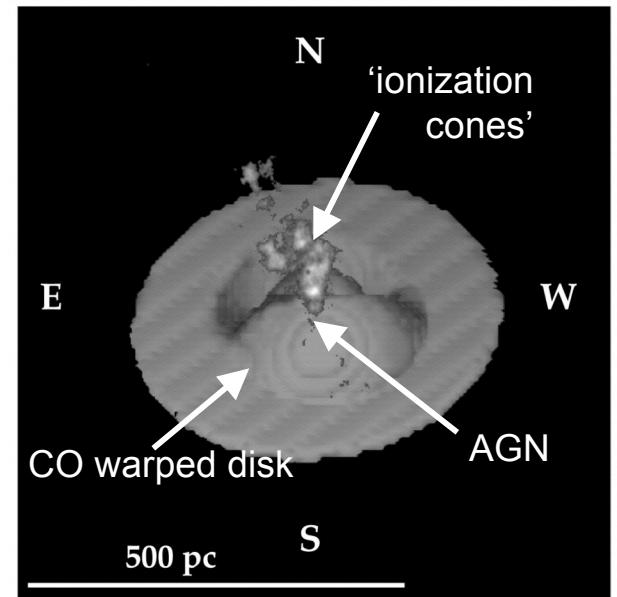
- ‘Torus’ obscures 4/5 AGN
- How is donut supported?
 - Covering fraction >50%
 - yet cold (dusty)
 - Cloud-cloud collisions should flatten structure
 - Thick clumpy accretion needs $M_{\text{torus}} > M_{\text{Edd}}$ see *SgrA**

Vollmer, Beckert & Duschl 2004 A&A 413, 949



TORUS ALTERNATIVES: 1. WARPED DISK

- Warped CO disk on ~100 pc scale in NGC1068 [Schinnerer et al. 2000 ApJ 533, 850](#)
- NGC 1068 has hollow ‘ionization’ cones
 - I.e. Matter bounded
 - a true outflow cone
 - *Not* ISM illuminated by collimated continuum

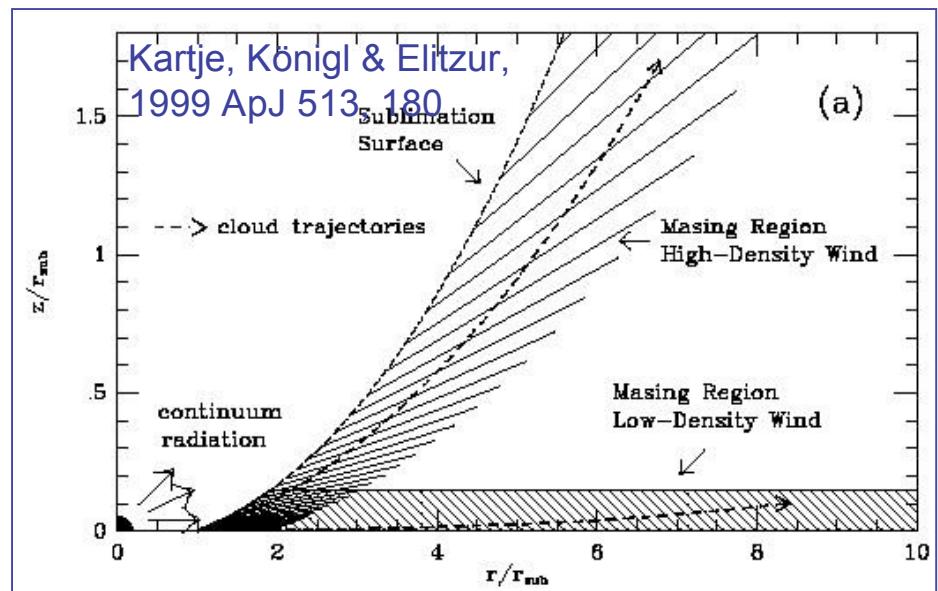
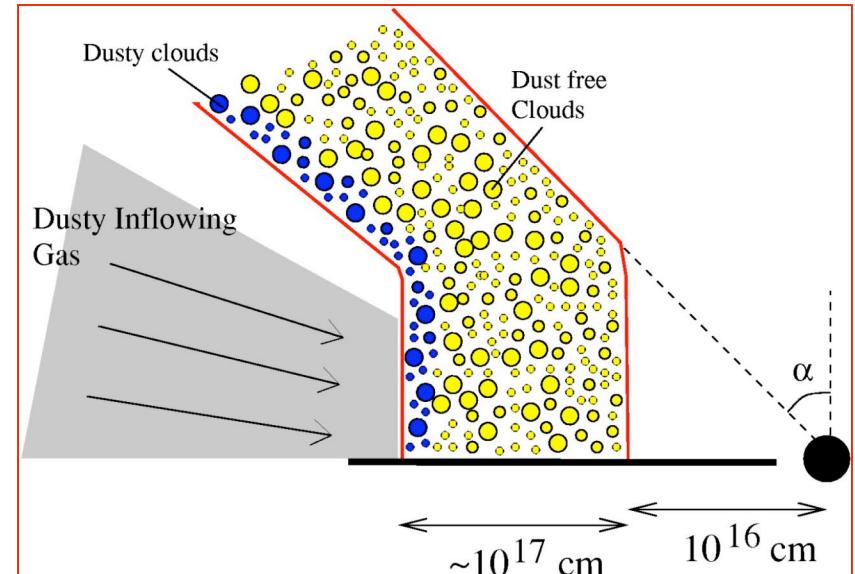


TORUS ALTERNATIVE: 2. DISK WIND

- Rapid absorption variability
 - days, hours
 - ⇒ accretion disk scale obscurer
- Eases torus physics:
 - No problem supporting large covering factor
- Aids Feedback:
 - Radiation still blocked
 - Matter escapes

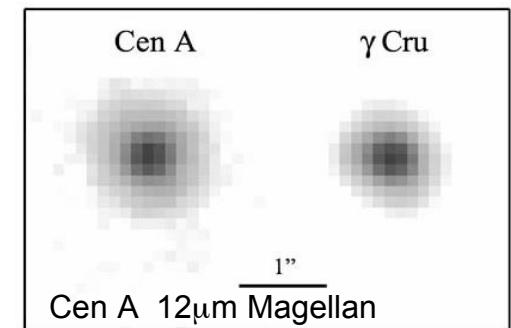
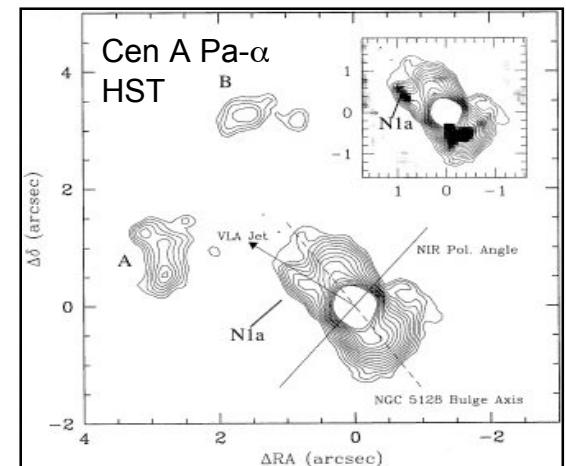
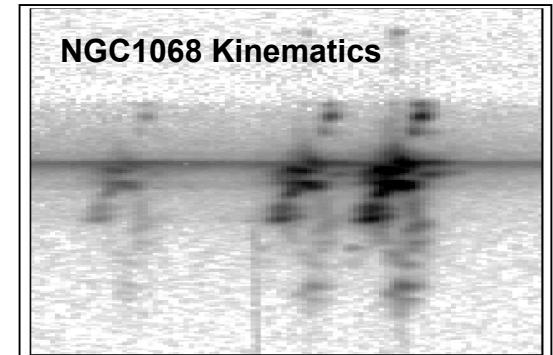
Host ISM can be affected

➤ *Imaging the torus will decide*



BEGINNINGS OF IMAGING AGN TORUS FEEDBACK

- NGC 1068 has hollow cones in ENLR
Crenshaw & Kraemer 2000 ApJ 532, L101
- Cen A [3 Mpc]
 - $0.1'' = 1.5 \text{ pc}$, same as 15mas @ 20 Mpc
 - HST Pa α image: disk or bicone?
Schreier et al. 1998 ApJ 499, L143
 - Magellan resolved $10\mu\text{m}$ emission $r \sim 1 \text{ pc}$
Karovska et al. 2003
- NGC4151 [20 Mpc]
 - hot dust:
 - $r = 0.1 \text{ pc}$ Keck K interferometry, Swain et al. 2003 ApJ 596, L163
 - $r = 0.04 \text{ pc}$ reverberation Minezaki et al. 2003 ApJ 600, L35
 - 48 ± 2 light-days
 - ***Range of sizes: multiple origins?***



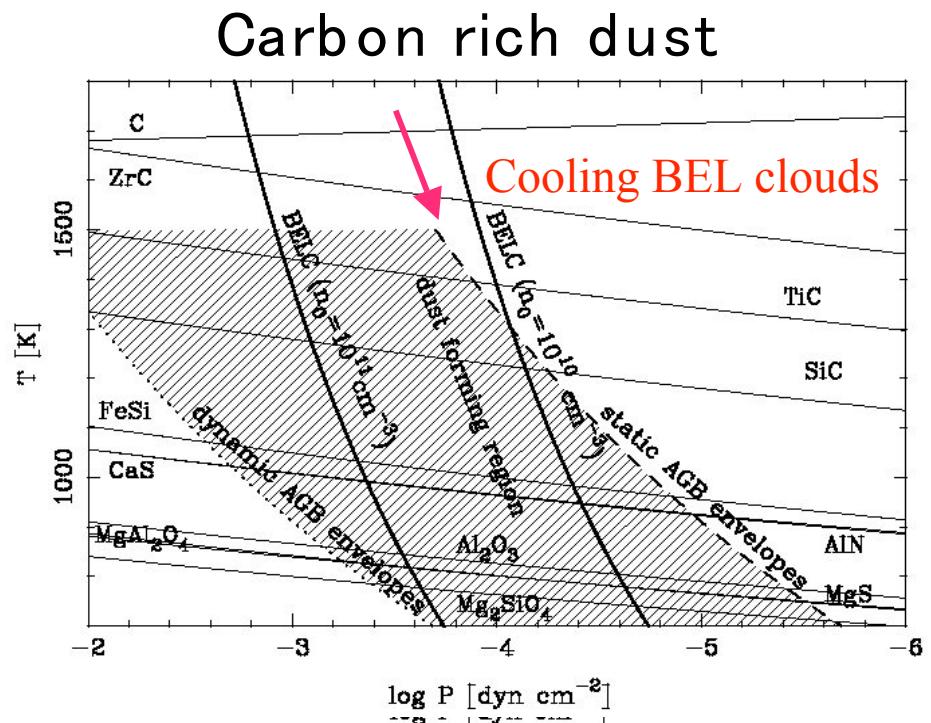
QUASARS AS DUST FACTORIES

EARLY STAR FORMATION

Elvis, Marengo & Karovska, 2002 ApJ, 567, L107

Dust:

- Hard to make: high density, low T
- Important catalyst of star formation
- Could quasars be the source of the first dust in the universe?
- Outflowing BEL gas expands and cools adiabatically
- BEL adiabats track through dust formation zone of *AGB stars*
- AGN Winds must create dust copiously
- Applies to Carbon-rich and Oxygen-rich grains



Applies to Carbon-rich and Oxygen-rich grains

HIGH z QUASAR DUST: AN EXAMPLE

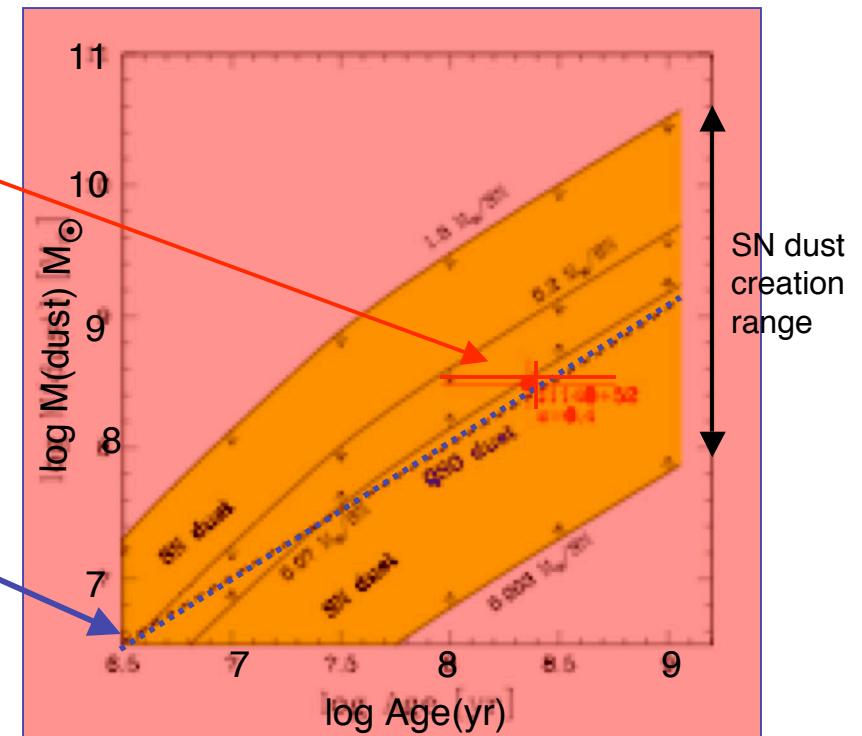
Maiolino et al. 2006, astro-ph/0603261

- Highest z quasar: SDSSJ1148+52 $z=6.4$
- $M_{\text{dust}} = 10^{8.5} M_{\odot}$ Bertoldi et al. 2003
- Assumptions:
 - $M_{\dot{\text{dust}}} = m_{\dot{\text{dust}}}(\text{Edd})$, always
 - $M_{\dot{\text{dust}}}(\text{wind}) = 0.5 \times 10^{-8} M_{\text{BH}}/M_{\odot}$
 - $Z = 10 Z_{\odot}$
 - Milky Way dust depletion
- Dust formation rate is sufficient
 \rightarrow *quasar winds may be important for dust creation at high z*

$$R_{\min} = 1.3 L_{\text{UV},46}^{1/2} T_{1500}^{-2.8} \text{ pc}$$

Barvainis 1987 ApJ 320, 544

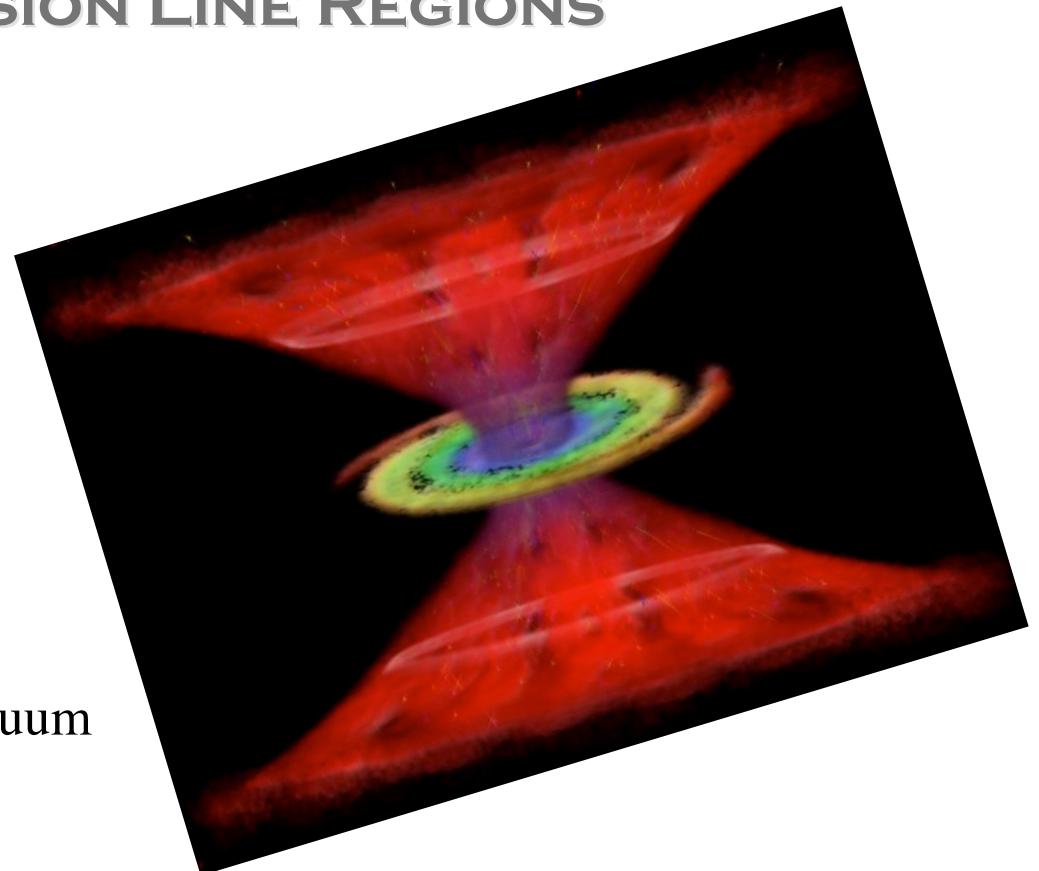
- The most luminous $z=5-6$ quasars
 - $R \sim 10 \text{ pc} \sim 6 \text{ mas}$
 - $J = 15 - 16, K = 14-15$ Agueros et al.
2005, AJ 130, 1022



IMAGING QUASARS II: BROAD EMISSION LINE REGIONS

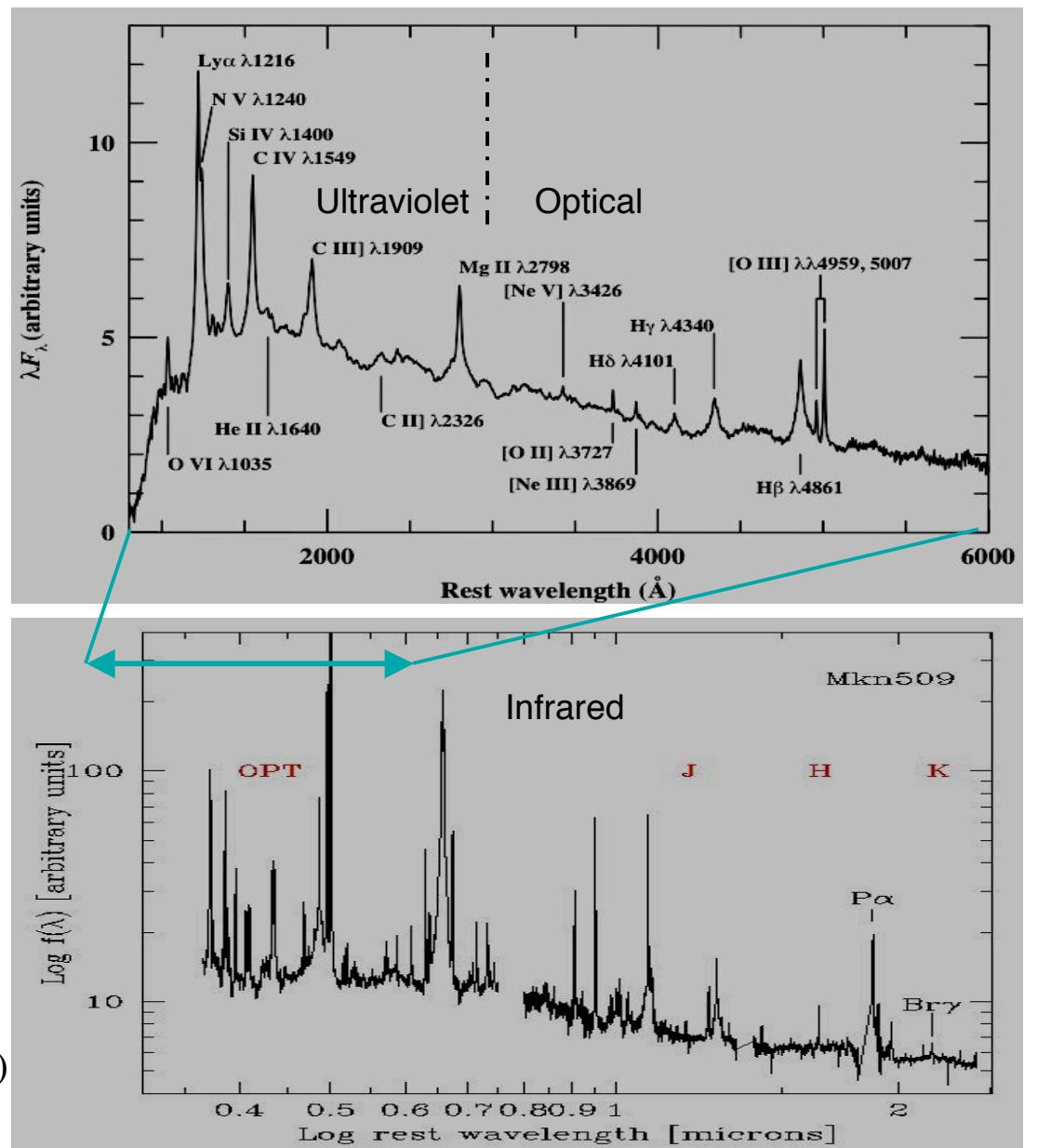
Broad Emission Lines (BELs)

- FWHM = 2000 - 10000 km/s
- few 1000 r_g location
- EW up to 200 Å (H α , L α)
- Brightness T \sim 10,000K
- Logarithmic profiles:
- Line flux proportional to continuum
 - no beaming
 - Photoionized
- High velocity gas closer to Black Hole
 - Velocity resolved imaging



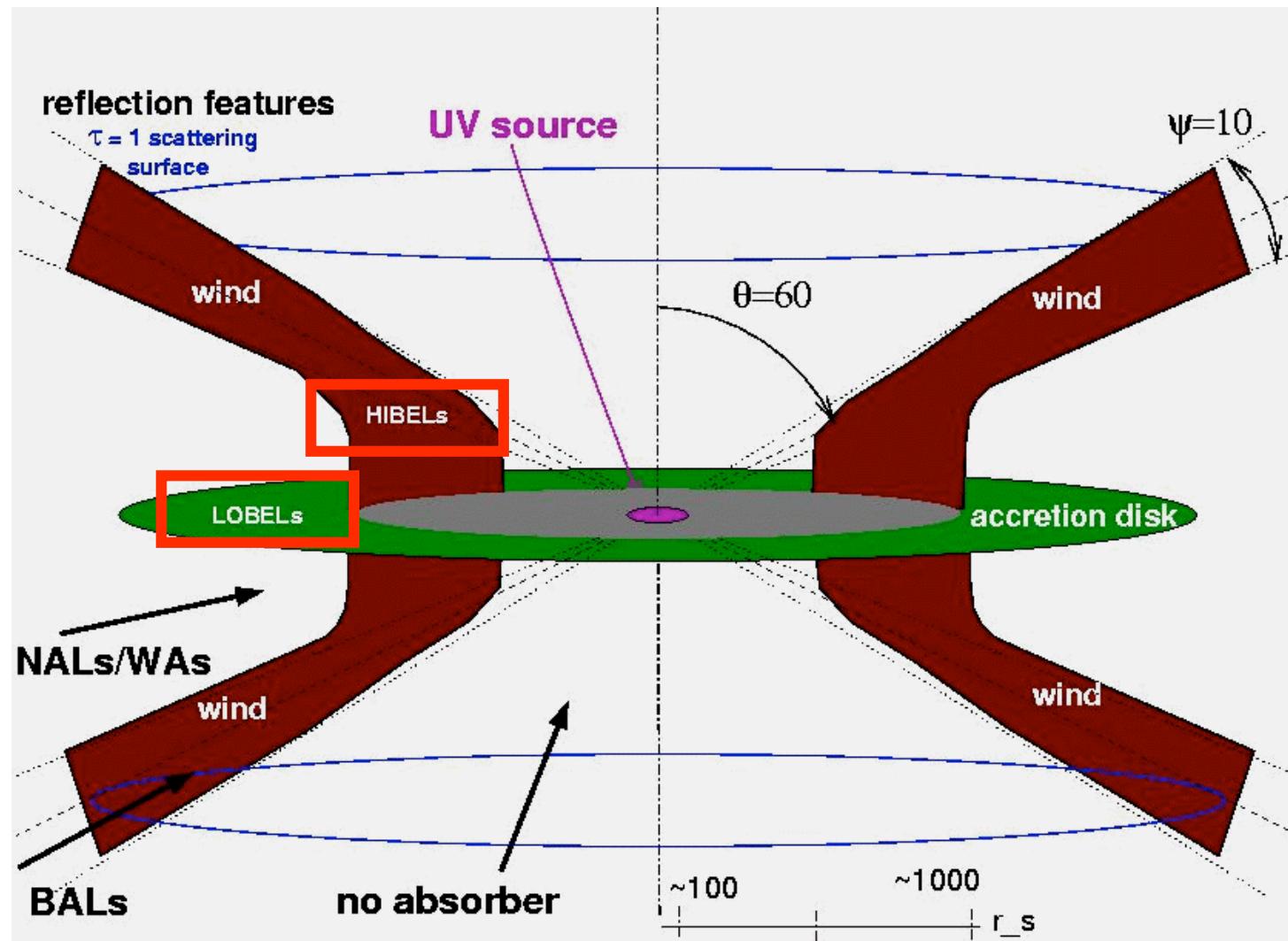
BROAD EMISSION LINES: BELS

- Universal
 - All are permitted transitions
 - High densities $\sim 10^{10-12} \text{ cm}^{-3}$
 - Can be hidden (type 2 AGN)
 - Can be overwhelmed (blazars)
- Properties:
 - Bright: 2 meter telescopes need 1/2 hr
 - logarithmic profiles(triangular)
 - rare 2-horned profiles (disks)
- Which lines?
 - **High Ionization:** CIV, NV, OVI, HeII
 - blueshifts - *winds* esp. Leighly 2004
 - **Low Ionization:** MgII, FeII, Pa, Br
 - *disk?* Collin et al. 1988
 - FWHM(HiBELs) > FWHM(LoBELs)



A PLAUSIBLE MODEL FOR THE BROAD EMISSION LINE REGIONS

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



Becoming a secure basis for physical wind models: allow tests

IMAGING BROAD EMISSION LINE REGIONS FEEDBACK, ACCRETION PHYSICS

LoBELs: MgII, Balmer, Paschen

- Observe outer accretion disk

⇒ **Precision BH masses**

HiBELs: OVI, Ly α , CIV} all UV, HeII} weak

- Measure acceleration law

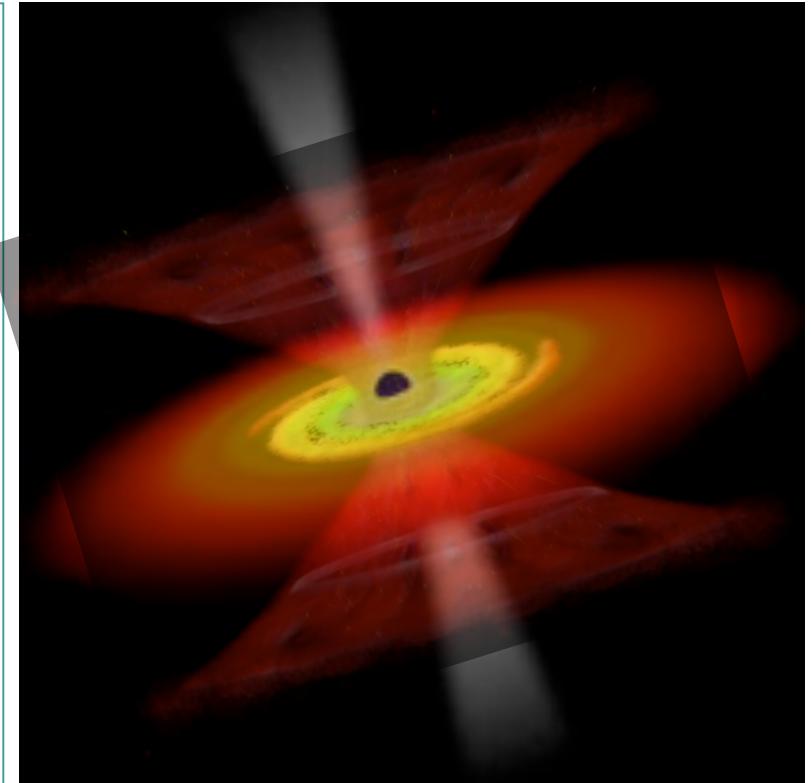
⇒ **Choose between wind models**

[Line driven, hydromagnetic, thermal]

- Measure m_{dot} in wind

⇒ **Determine cosmic feedback**

- Observe secular changes in structure (years)

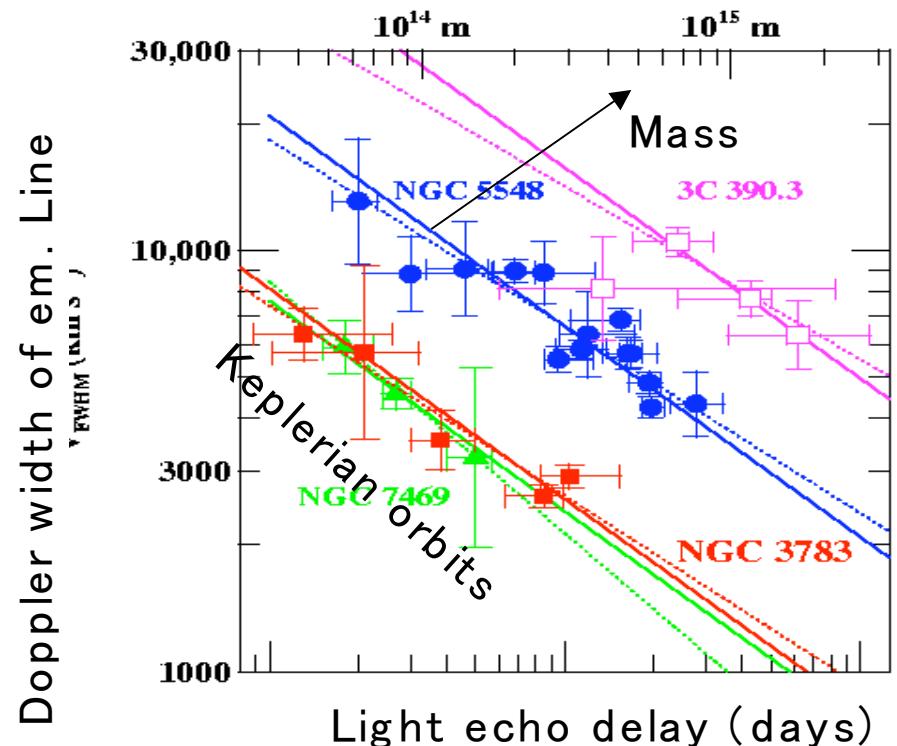


BELR SIZE: REVERBERATION MAPPING

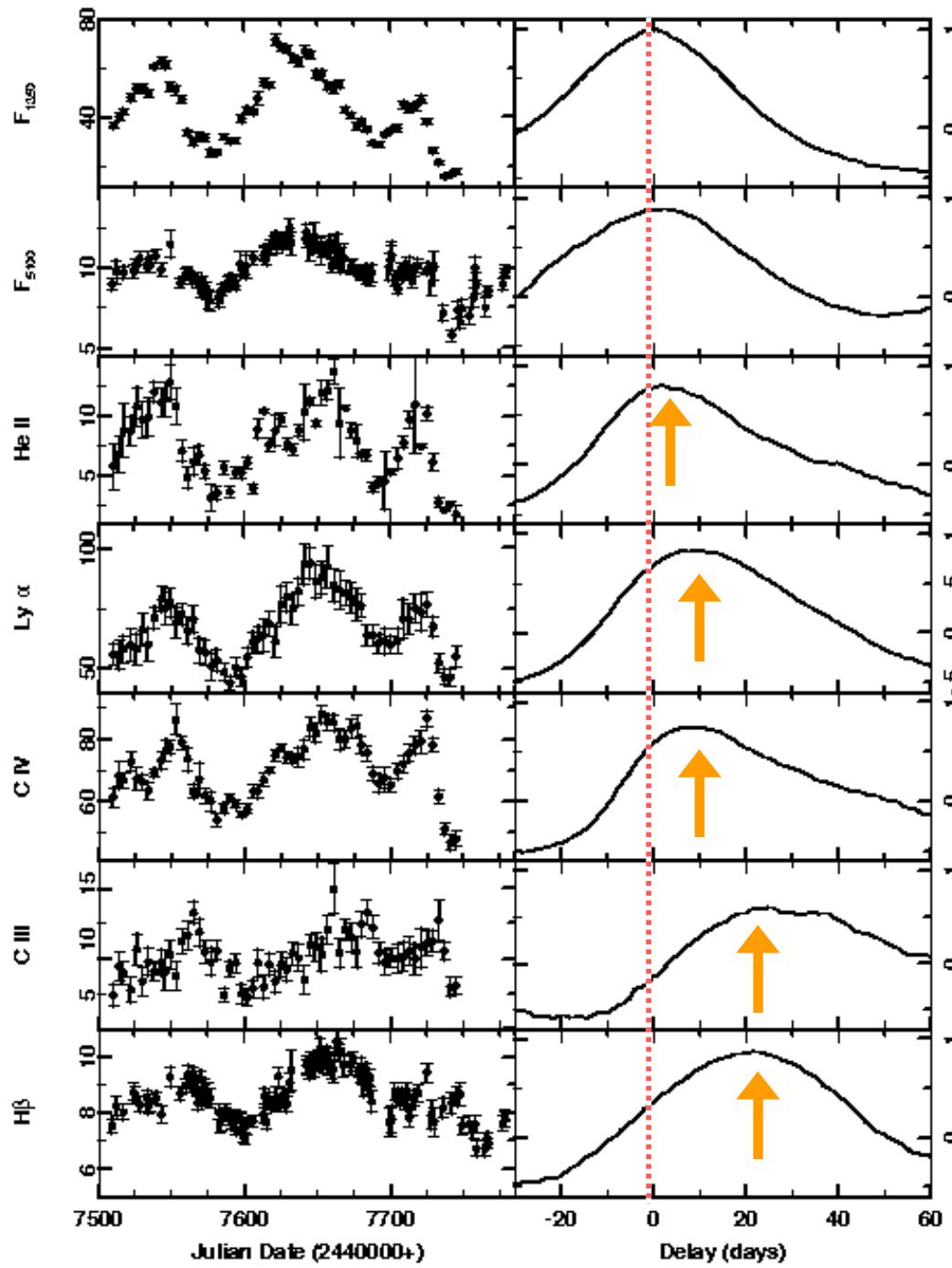
Peterson & Wandel 2000 ApJ 540, L13

Onken & Peterson 2002

- Reverberation mapping shows Keplerian velocity relation in BELs
- FWHM gives size in r_s
- Light echo delay gives size in cm
- Ratio gives r_s in cm, hence M_{BH}
- $M_{BH} = fc\tau\Delta v^2/G$



Thanks to Brad Peterson



REVERBERATION MAPPING RESULTS

- Scale is light-days in moderate luminosity AGN
- Highest ionization emission lines respond most rapidly
⇒ ionization stratification

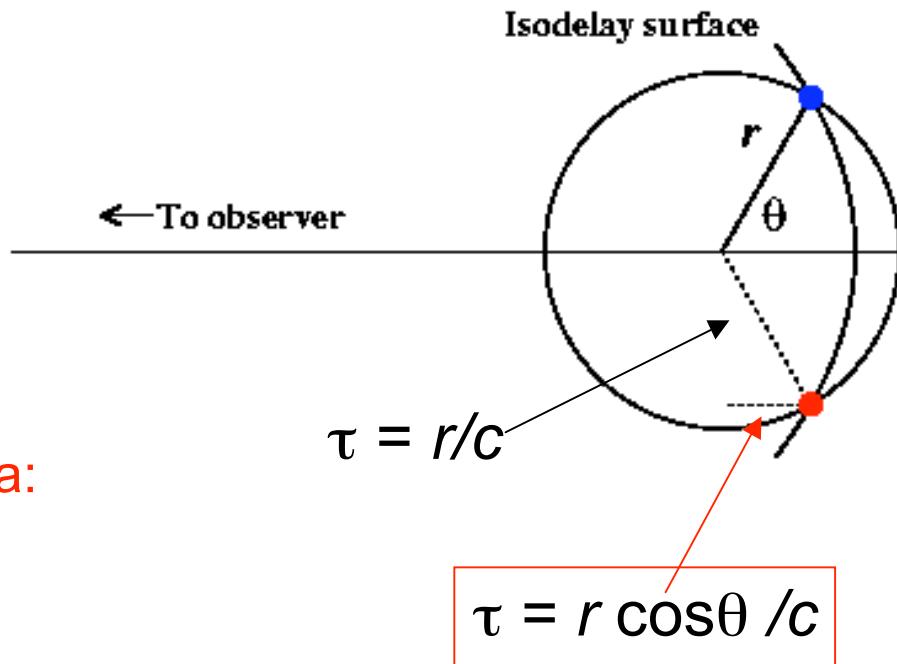
Thanks to Brad Peterson

BELR SIZES FROM REVERBERATION MAPPING: RESPONSE OF AN EDGE-ON RING

- Suppose line-emitting clouds are on a circular orbit around the central source.
- Compared to the signal from the central source, the signal from anywhere on the ring is delayed by light-travel time.

The isodelay surface is a parabola:

$$r = \frac{c\tau}{1 + \cos\theta}$$

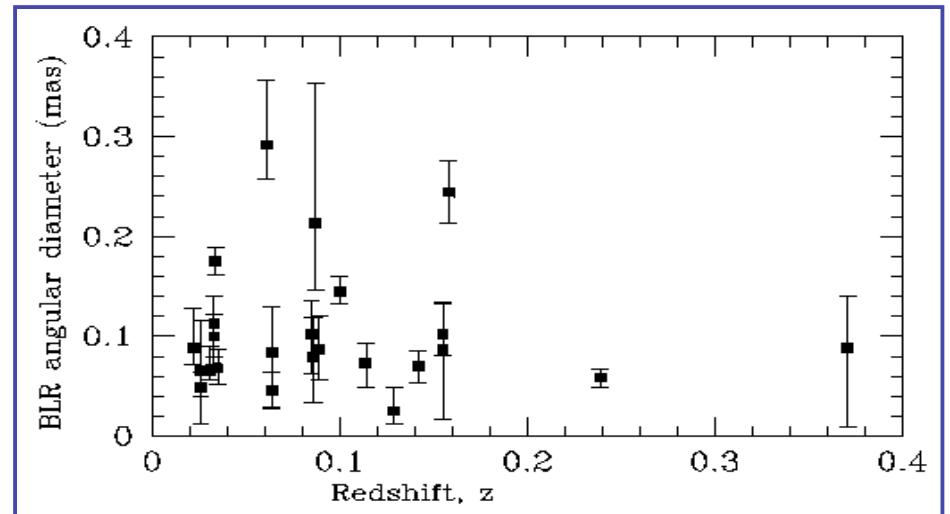


Thanks to Brad Peterson

IMAGING THE BROAD EMISSION LINE REGION FEEDBACK

Elvis & Karovska, 2002 ApJ, 581, L67

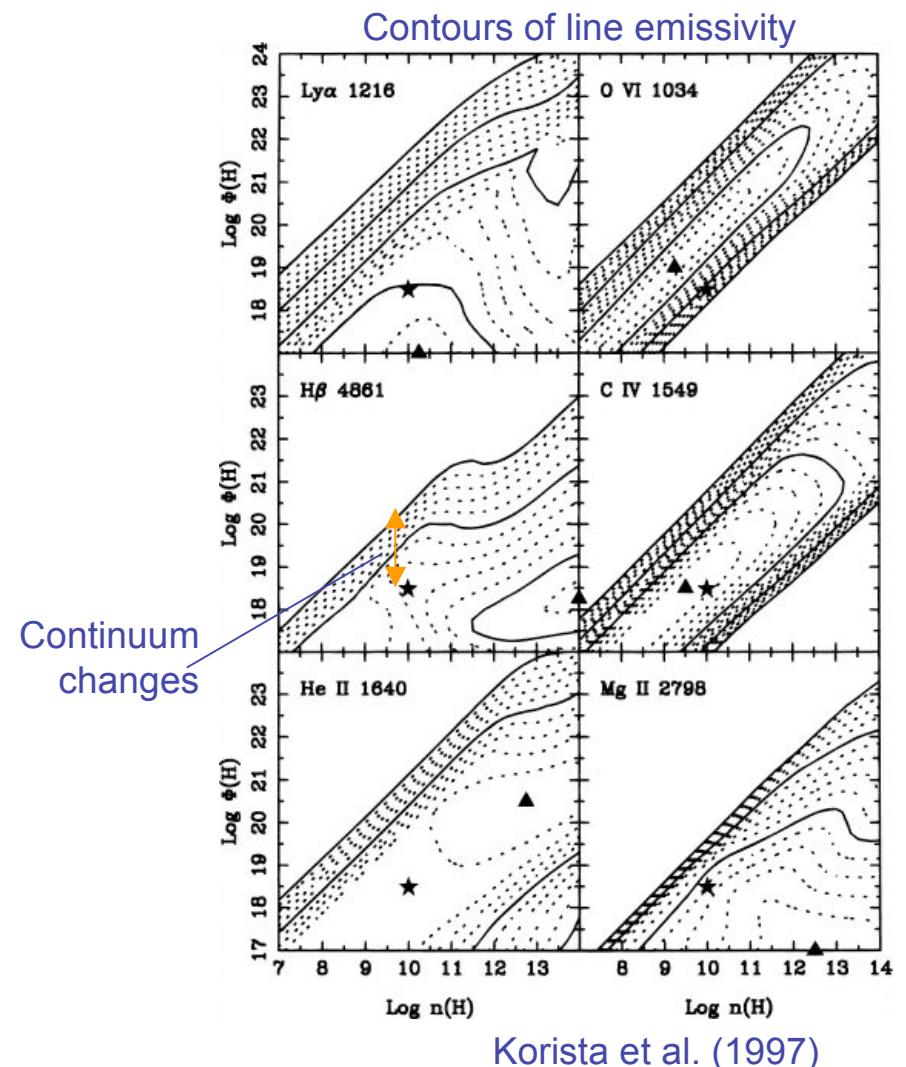
- H β High Ionization BELR have ~0.1mas diameters in nearby AGN
- Begins to be resolved with VLT-I, *Ohana*, though in near-IR
- 10 times better resolution (few km baselines) would be enough to see shape
- Interferometer at Antarctica Dome C?



CAUTION!

INTERFEROMETRY AND REVERBERATION MEASURE DIFFERENT QUANTITIES

- Interferometry measures total line flux on each baseline/physical scale
- Reverberation measures *change* in line flux - which comes from region where emissivity changes most
- “Locally Optimally Emitting Cloud” models [Korista et al. 1997](#)
 - Ionization parameter vs. gas column density
- Requires:
 - Simultaneous reverberation and interferometry
 - Could pick high/low states from simple photometric monitoring
 - Best solution: make reverberation measurements with interferometer
 - Highly intensive campaigns

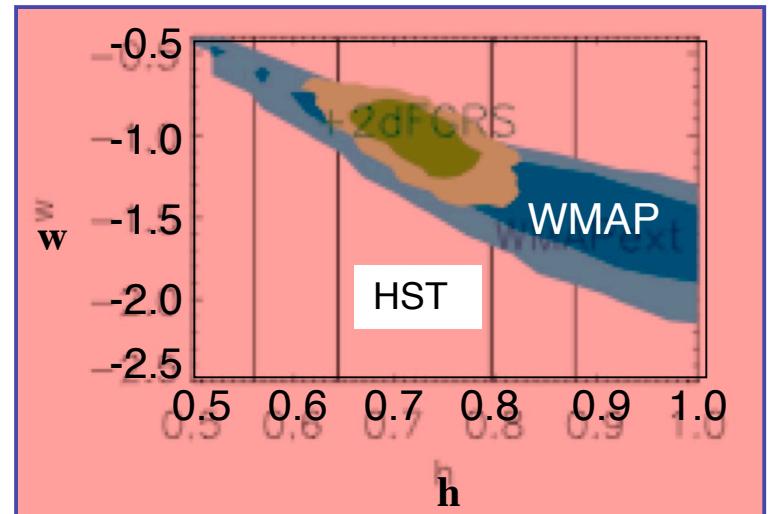


REVERBERATION + INTERFEROMETRY

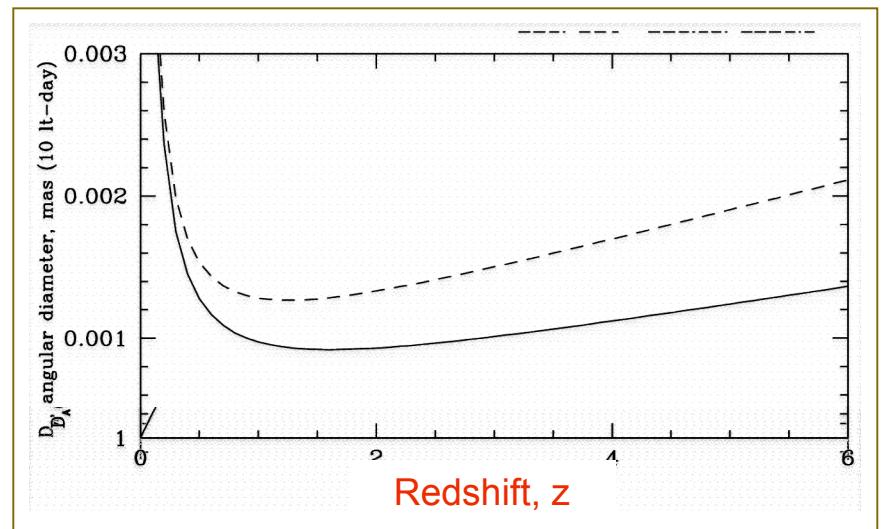
COSMOLOGY

Elvis & Karovska, 2002 ApJ 581, L67

- H_0 now measured to 10%
- H_0 errors dominate uncertainties on WMAP cosmology parameters
- Imaging reverberation mapping could give H_0 to <5%
- Reverberation gives BEL radius in *cm*
- Interferometry gives BEL radius in *mas*
- Ratio gives Angular dia. Distance vs. z i.e.
- Works up to $z \sim 6$ cf 1.5 for SN1a
- Metric plus luminosity evolution keeps sizes (relatively) large $> 1 \mu\text{as}$



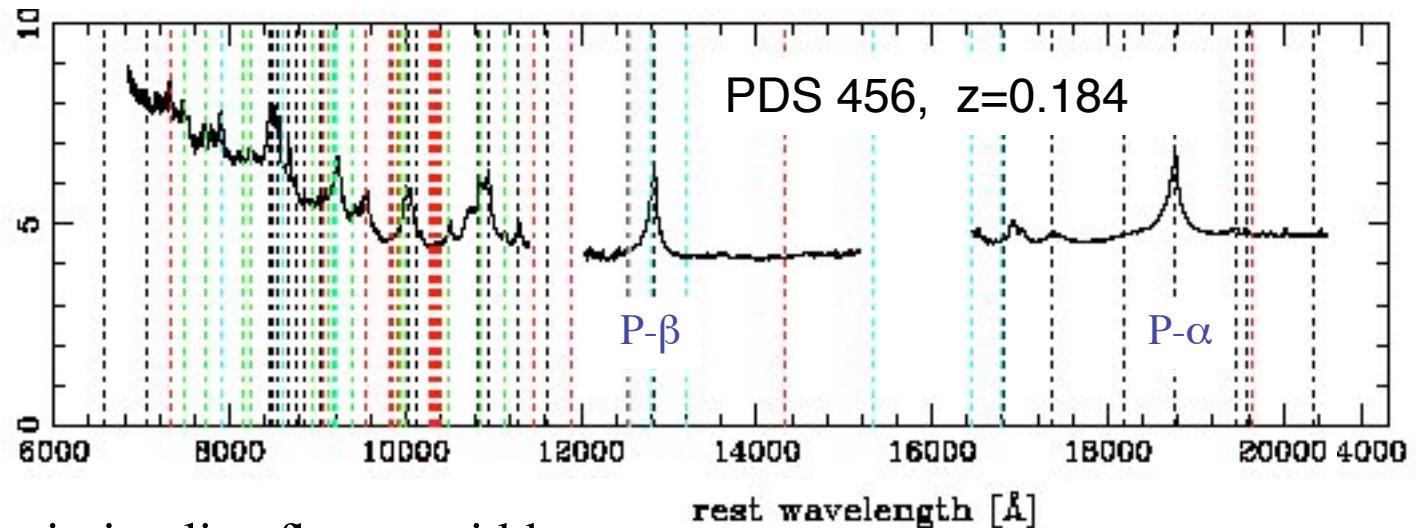
Spergel et al. 2003, 1 year WMAP results



NEAR-IR BELS: A PREPARATORY CAMPAIGN

Hermine Landt et al. 2007 in prep.

- Need AGN NIR emission line fluxes, widths for reverberation and ground-based interferometry



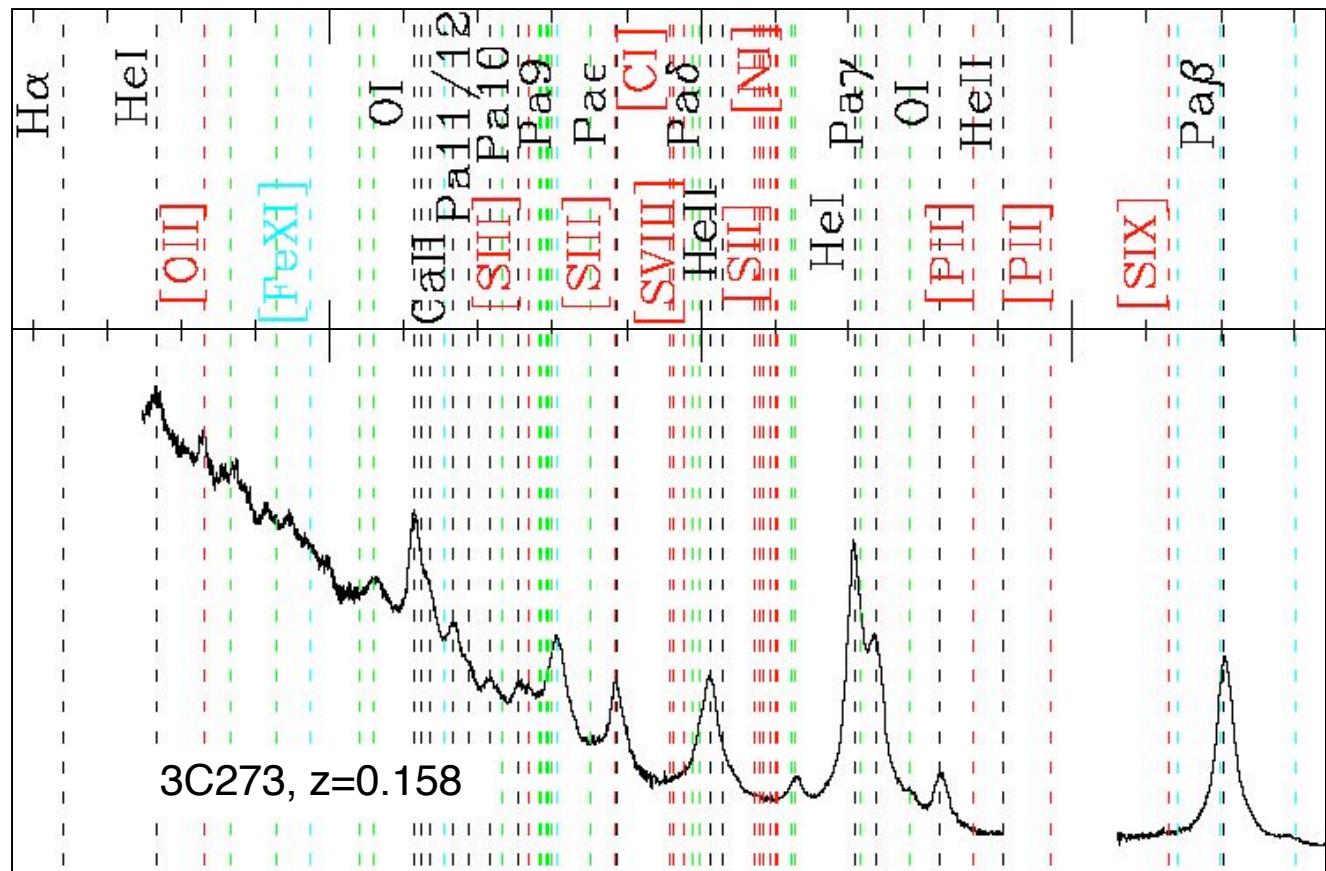
- Need AGN NIR emission line fluxes, widths for reverberation and ground-based interferometry
- No JHK spectra of unobscured AGNs in literature.
- 2 year IRTF/SPEX campaign to get Paschen α, β, and higher series fluxes
- Selected sample of bright ($J < 14$) nearby ($z < 0.3$) AGN

P- α	1.8751 μm
P- β	1.2818 μm
P- γ	1.0941 μm
P- δ	1.0052 μm
P- ϵ	0.9548 μm
Br- β	2.6269 μm
Br- γ	1.9451 μm
Br- δ	1.8181 μm
Br- ϵ	1.7367 μm
Br-limit	1.459 μm

NEAR-IR BELS

Hermine Landt et al. 2007 in prep.

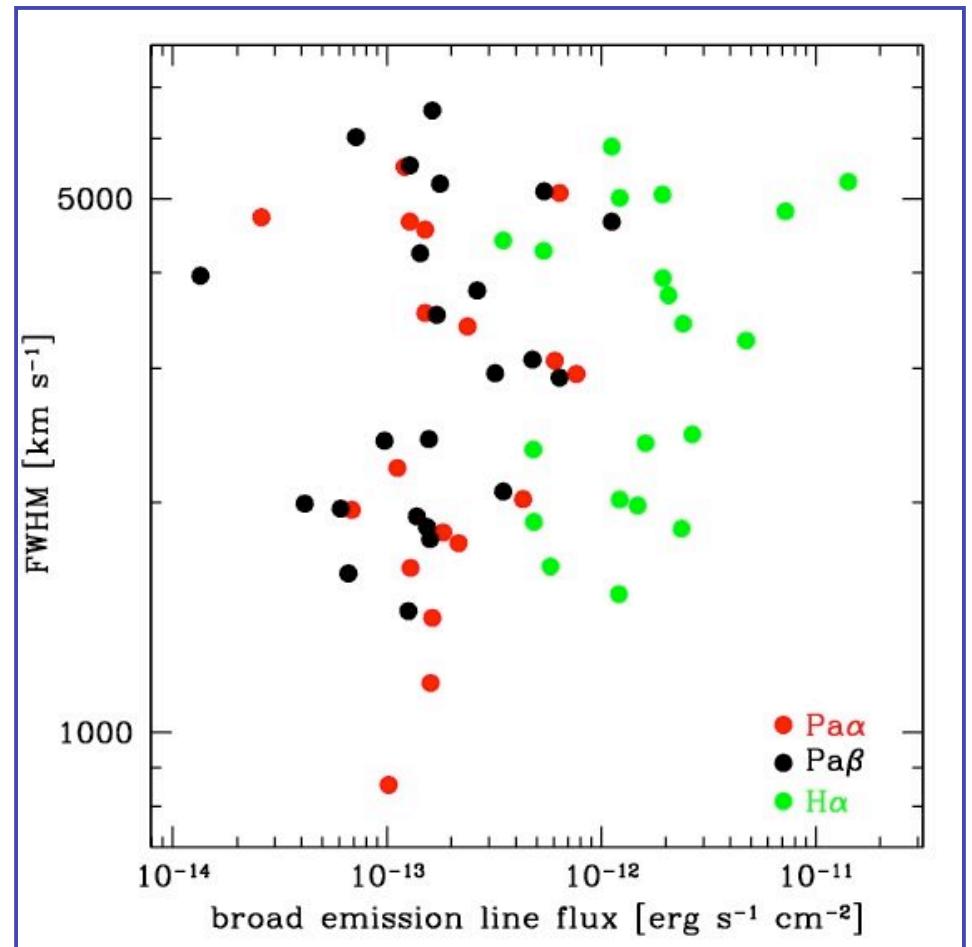
- Blending issue for many lines
- Pa- α , Pa- β , Pa- ϵ clean



OBSERVABILITY OF NEAR-IR BELS

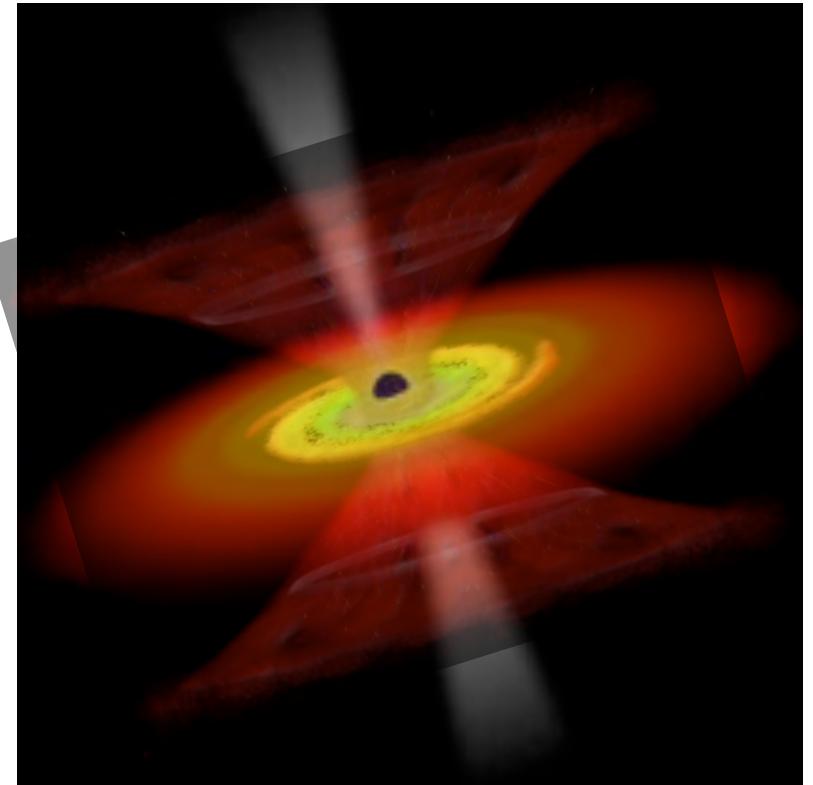
Hermine Landt et al. 2007 in prep.

- Low z AGN sample
 $z = 0.009 - 0.300$
 $V = 11.8 - 16.4$
 $J = 10.3 - 13.9$
- NIR BEL properties
 - $\text{Pa-}\alpha/\text{H-}\alpha, \text{Pa-}\beta/\text{H-}\alpha \sim 0.1$
 - FWHM similar
 - $1000 - 7000 \text{ km s}^{-1}$
 - $\Delta\lambda \sim 30 - 200 \text{ \AA}$



IMAGING QUASARS AND AGN: SUMMARY

- Pretty good astrophysics
 - Black hole growth
 - Cosmic Feedback
 - Accretion physics
 - Bulk acceleration of matter
- Needs: [~ 10 pixels/dia]
 - 0.1 mas for dust
 - 0.01 mas for LoBELs
 - 0.003 mas for [UV] HiBELs
 - 0.001 mas for high z LoBELs
- Near-IR BELs are promising
 - $R = 1000 - 6000$ [500 - 3000 km/s]
- Brightest
 - nearby objects $K = 10 - 12$
 - $z=6$ quasars $K \sim 14-15$
 - Use unresolved accretion disk continuum as reference?



CODA

INTERFEROMETRY THEME: MOVIES VS. SNAPSHOTS

Astronomy suffers from a ‘static illusion’

- what we can image changes on timescales longer than our lifetimes

At <1 arcsec resolution we start to see changing structures

Qualitatively new view of universe

A partial list: (*please send additions*)

Galactic Center stars (AO)

HH-30 expanding jets (HST)

Rotating pinwheel around WR104

XZ Tau expanding jet (HST)

Mizar A binary orbit

V1663Aql - Nova expansion

SN 1987A expansion/rings (speckle, HST)

Crab nebula wisps (Chandra)

Vela SN jet (Chandra)

Superluminal radio jets (VLBA)

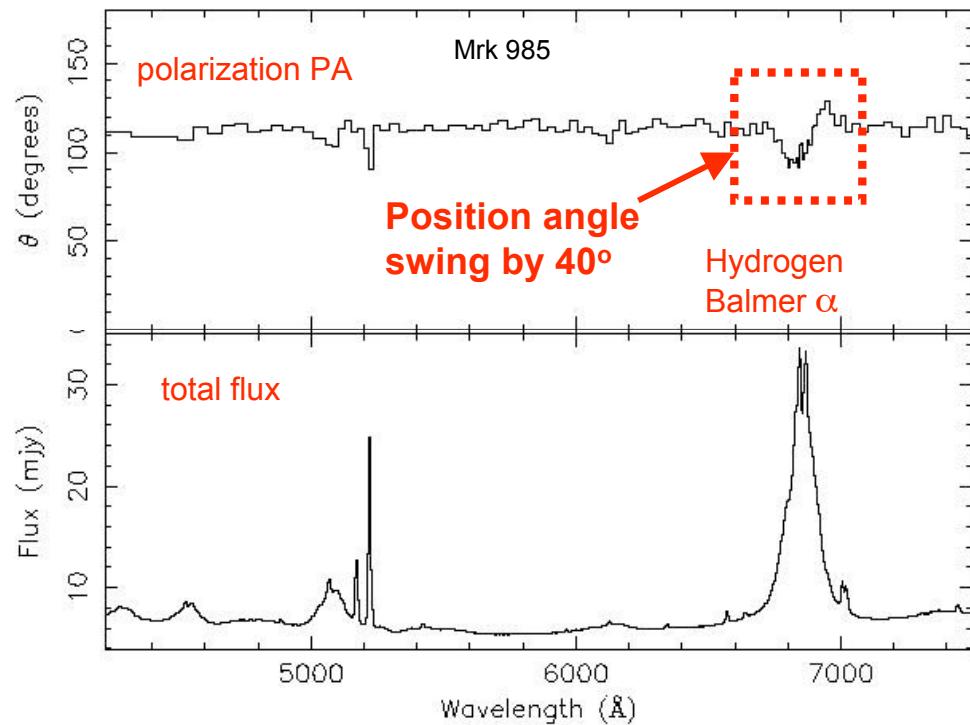
<http://hea-www.harvard.edu/~elvis/motion.html>

A sociological note:

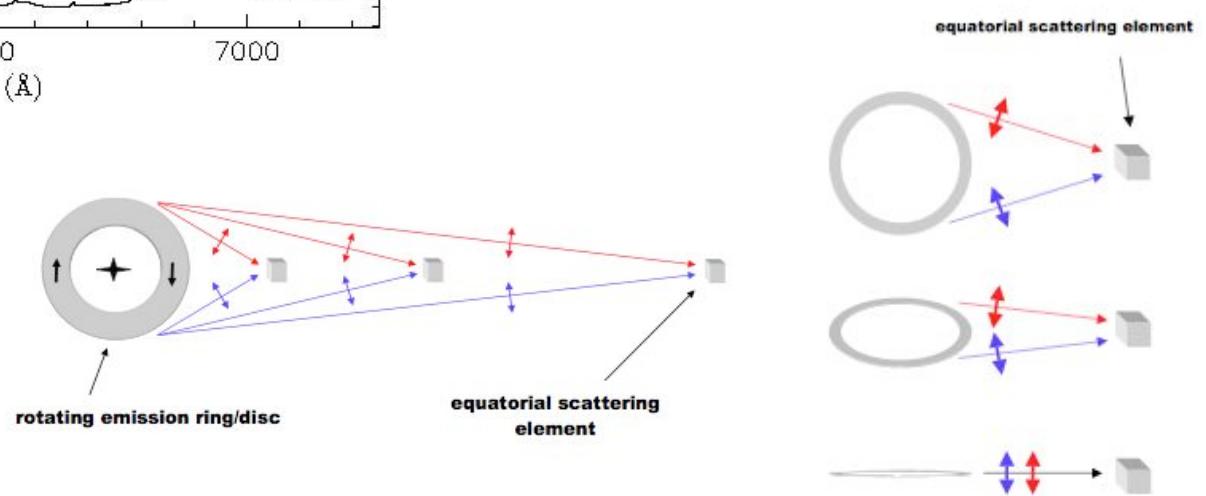
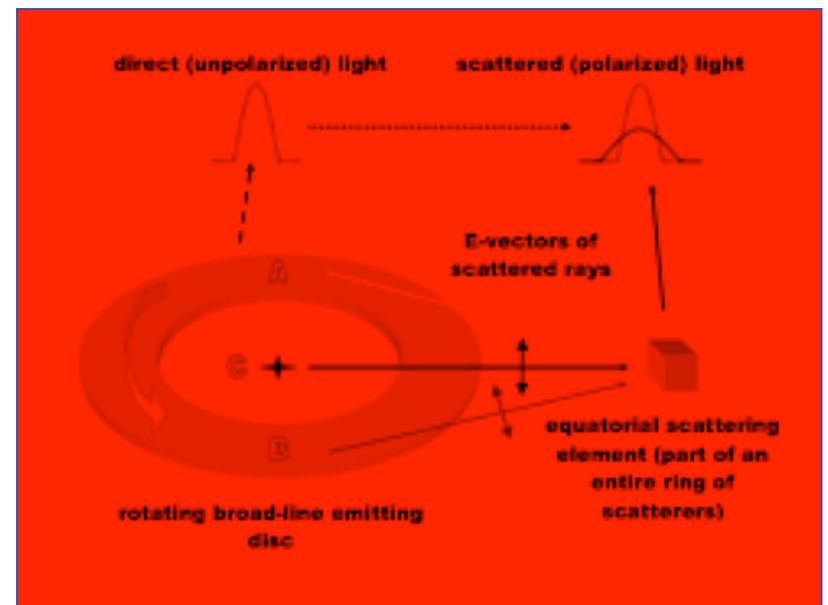
- Extragalactic astronomers generally do not ask for high angular resolution because what they do does not need it
- What they do does not need high angular resolution just because they *can* do it now.
- I.e. *They never thought about it*
- Why not image Sn1a to get Baade-Wesselink distances?
- Or axion constraints from stellar diameters/pulsations? [Physics Today]

A LONG TERM CHALLENGE: BEL IMAGING POLARIMETRY

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

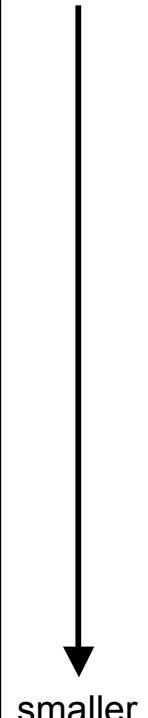


Smith J.E., 2005, MNRAS astro-ph/0501640



IMAGING QUASARS & AGN

AGN Wind feature	Physical size pc	Angular size at 20 Mpc	Resolvable with
BELR forms dust	~few pc	~few 10s mas	VLTI at 10μm, N
Torus/Dust sublimation radius $\tau=1$ e ⁻ scattering surface	~few x r (BELR) ~light months ~0.1pc	~few mas	VLTI, Magdalena Ridge at 1 - 2 μm JHK, P α
Winds/High ionization BELR	~light weeks ~0.01 pc	~0.1 mas	VLTI at U band? 1km UV space interferometer
High z BELRs	~light months ~0.1pc	10μas at any z	100km 2 μm interferometer at Dome C , Antarctica 10km UV space interferometer
Accretion Disk/ UV-optical continuum	~light days	~0.01mas	



Quasars effects on Cosmology

Effect	Pathway	Happens?	Caveats
$M_{BH}-\sigma^*$	Radiation	Yes	Too many mechanisms
Dry Mergers	Radiation Winds	possibly	True SED? Obscuration
Enrichment of IGM	Winds Jets	Yes, but is it dominant?	
High z dust	Winds	Yes, but is it dominant	
Inhibit cooling flows	Jets	YES	
Max. galaxy mass	Jets	Probably	Same as cooling flows