Imaging Quasars with Interferometry

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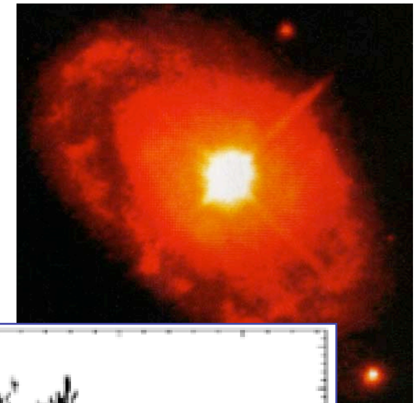
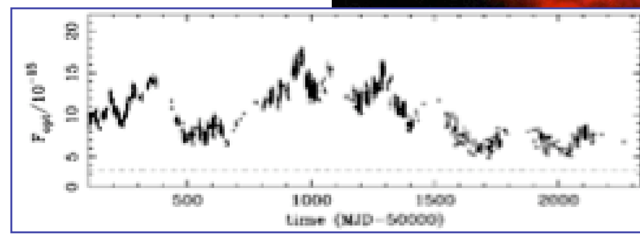
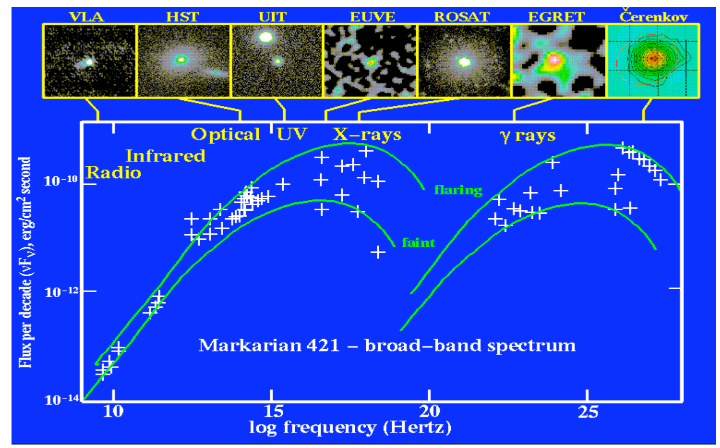
Why Study Quasars and AGN?

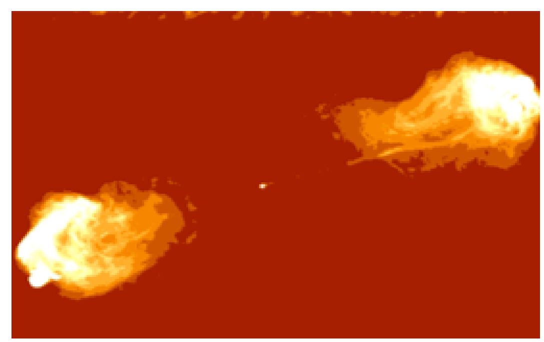
- **Up to 1000 Galaxy Luminosities**
  - Visible to $z > 6$ (Age < 1 Gyr)
  - Evolve strongly in luminosity and space density
  - Variability: *'galaxy power from solar system scales'*
- **Growth of Massive Black holes**
  - Quasars & Active Galactic Nuclei are where SMBH grow from their z~10 seeds.
  - 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 ~0.1Mc^2**
  - vs 0.01 Mc^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 $L_{accretion}$ = 5-20% L_{fusion}
- **Relativistic Jets**
  - accelerates matter in bulk to 99.5% *c* [Γ=10].
  - *'superluminal motion'* c.f. 99.88% at Fermilab Tevatron;
  - electrons accelerated to Γ=1000 (TeV photons)
  - Linear: ***'spherical cow' not a good approximation***

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





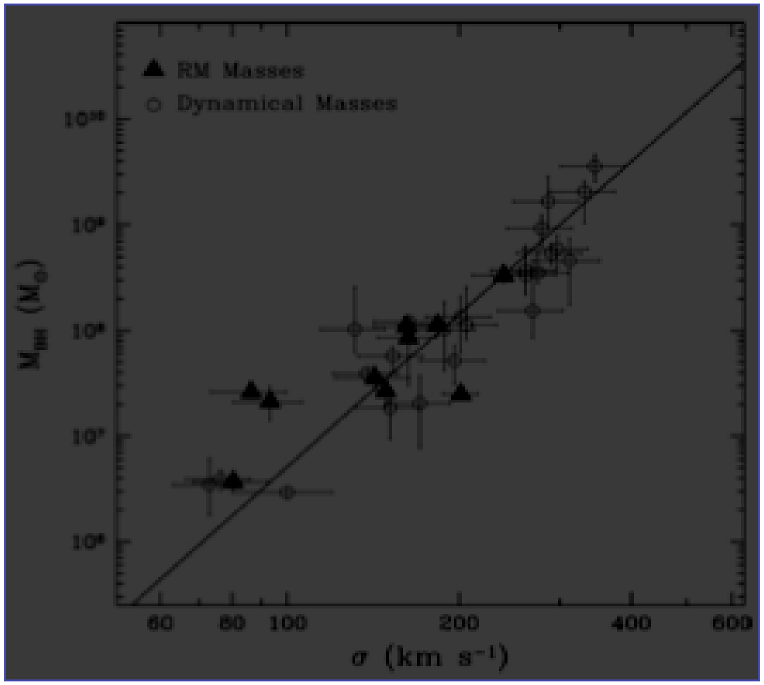




Galaxy & Black Hole Co-evolution
Feedback

- Galaxy bulges and central black hole masses correlate: $M_{BH} = 0.05[?]\ M_{bulge}$
  - Magorrian et al. 1998
  - Ferrarese & Merritt; Gebhardt et al. 2002[?]
  - Maiolino & Hunt 2004[?]
- Extraordinary link between accretion rates at kpc and μpc 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?

Ferrarese & Ford 2005

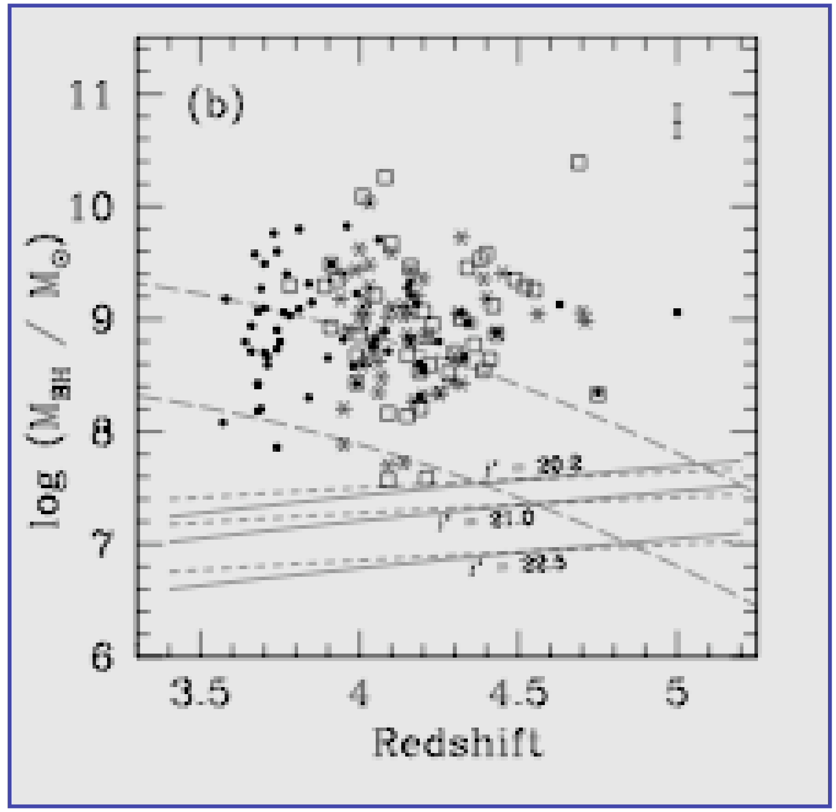


Black Hole Masses at Early Times

Black Hole Growth

Vestergaard 2004 ApJ 601, 676

- Reverberation mapping shows L-radius relation
- 2ndary BH masses from FWHM => R_g + L_{opt} => *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 x 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?: Shields78, Malkan82, Eracleous?

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

3. relativistic jet ✓

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

Demonstrated: Cohen et al. (VLBI)

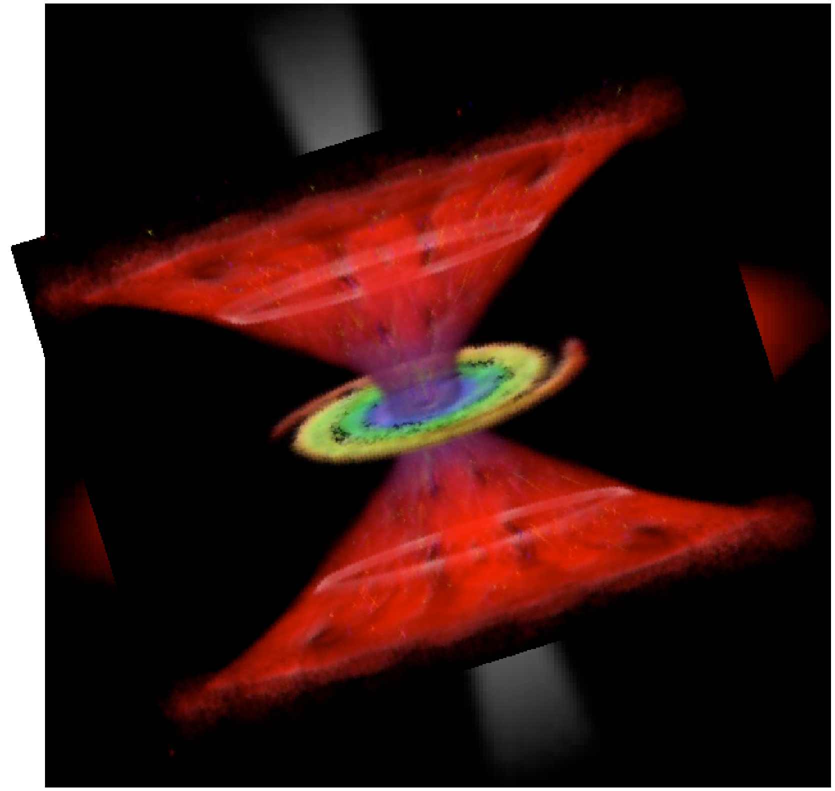
Questions: acceleration mechanism (Penrose/Blandford-Znajek?)

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

Proposed: Mushotzky+1972 - Murray+1995- Elvis 2000,Proga2000

Demonstrated: Krongold et al. 2006 - NGC4051

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



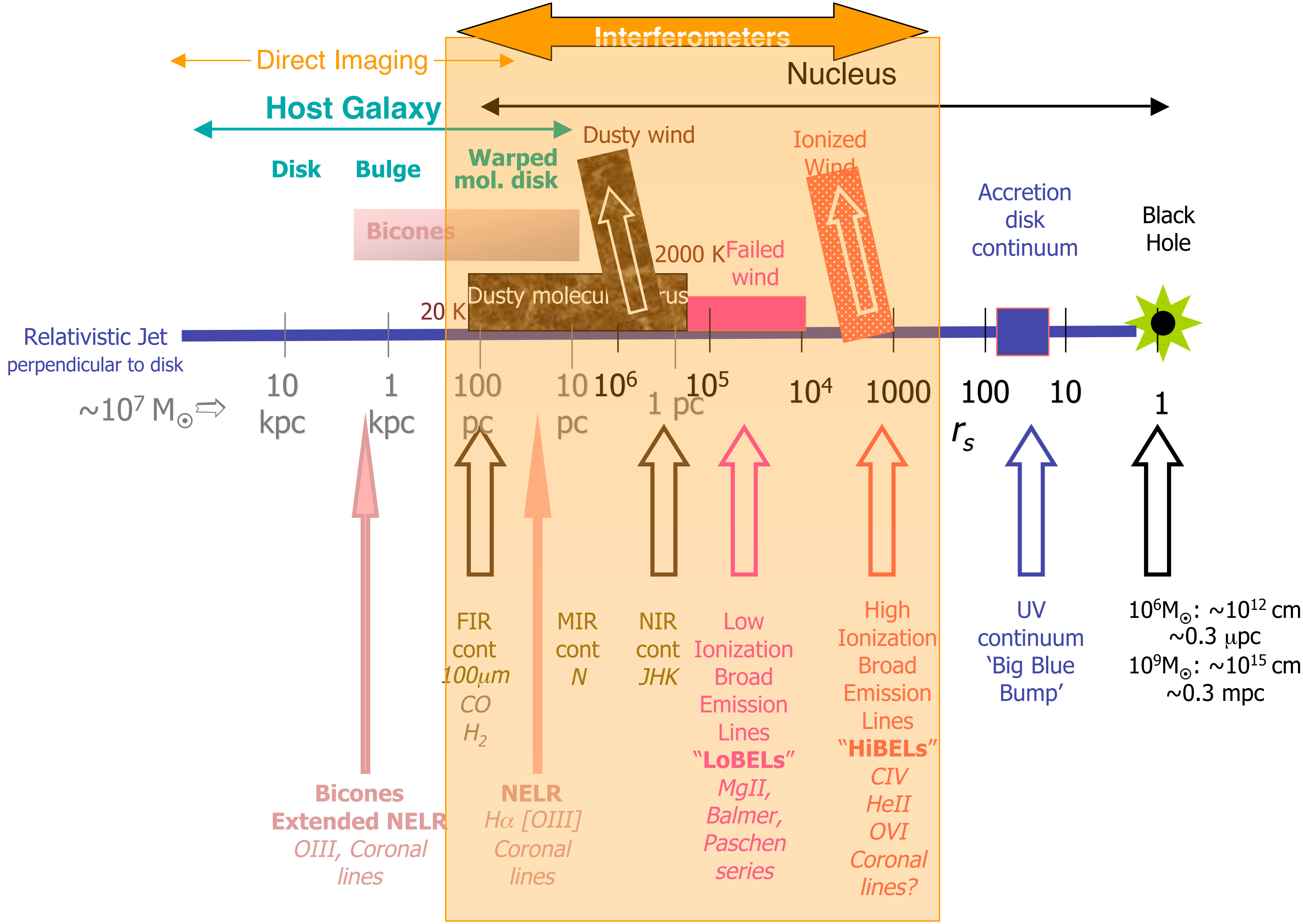
5. Obscuring torus ✓

Proposed: Lawrence & Elvis 1982

Demonstrated: Antonucci & Miller 1985, Urry et al.

Questions: Beyond the Bagel: host and/or disk

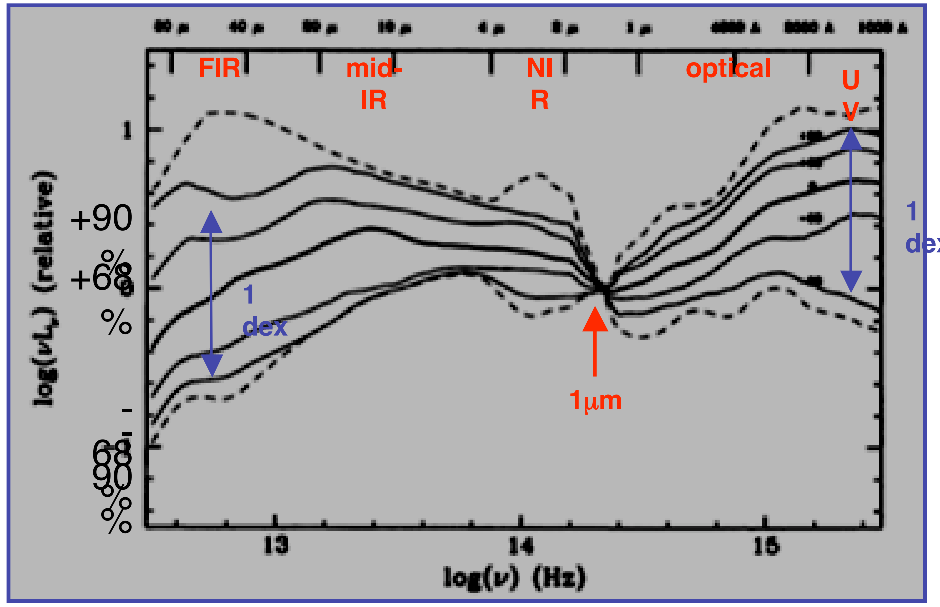
Scale of Quasar/AGN Components



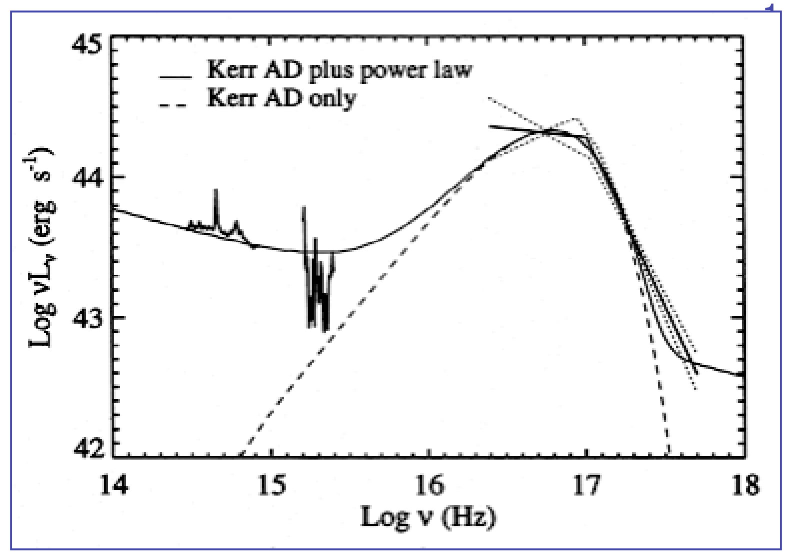
Imaging the AGN UV/Optical Continuum

Accretion Disk Physics

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

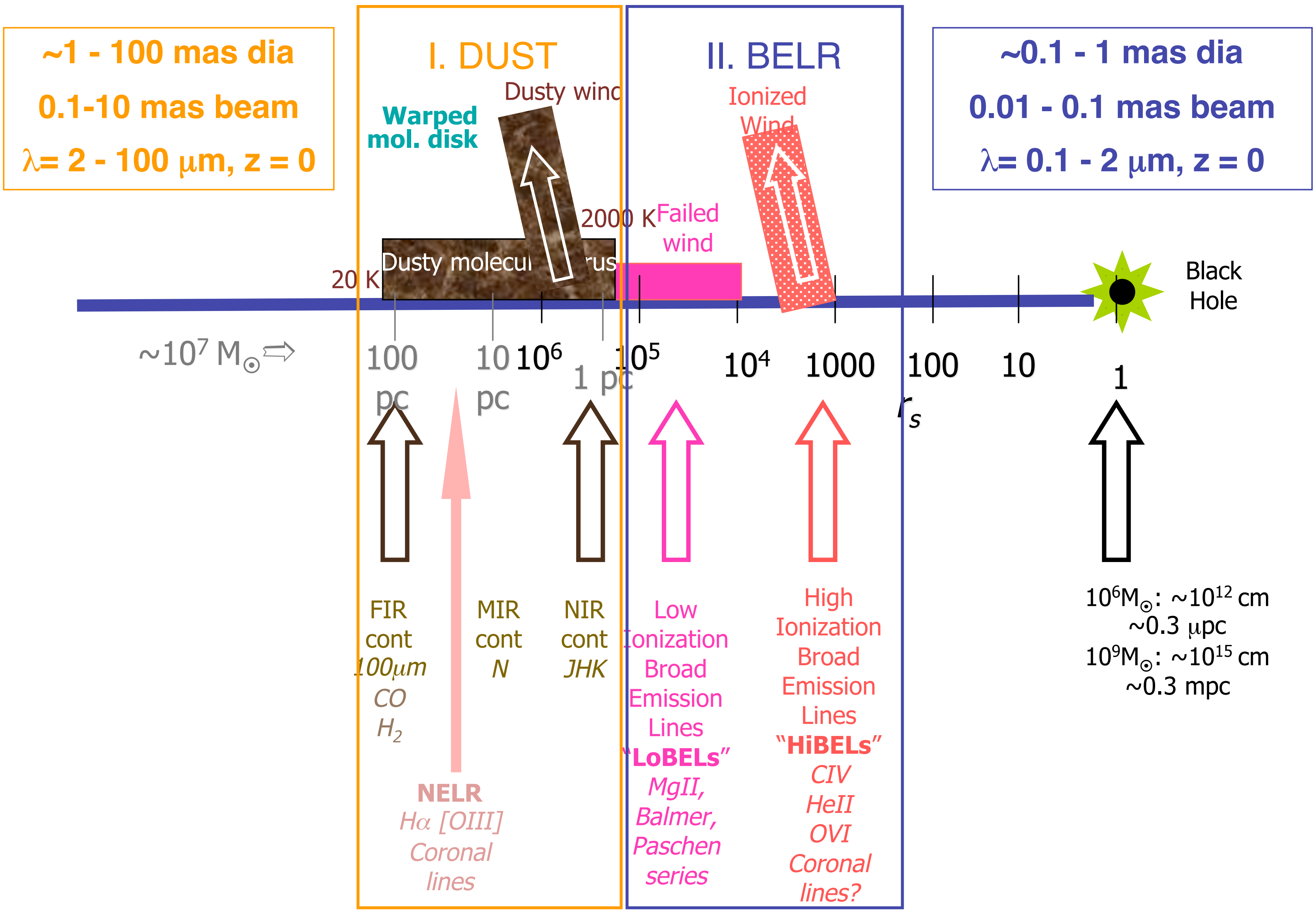


Elvis et al., 1994, ApJ, 95, 1



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

Interferometer Accessible Ranges: Dust and Broad Emission Lines



Imaging Quasars I: Dust

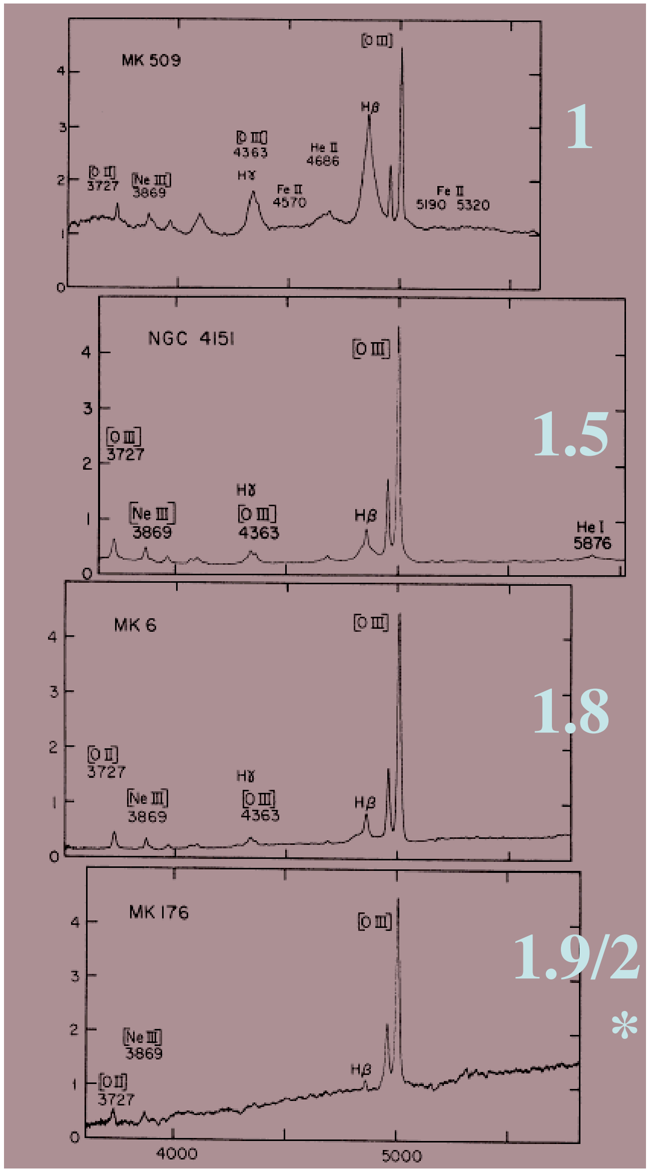
Black Hole Growth, Accretion Physics

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

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

Barvainis 1987 ApJ 320, 544

  – **R_{min} ~ 10 pc** for the most luminous quasars
  – **R_{min} ~ 1 pc** for 3C273 (Quasar)
  – **R_{min} ~ 0.1 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**

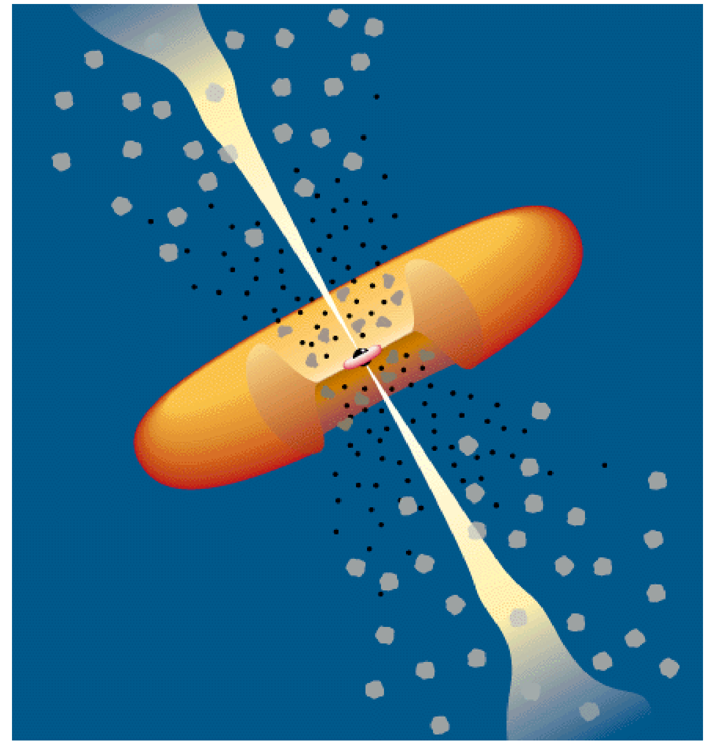


Osterbrock & Koski 1976

Standard Torus: Standard Issues

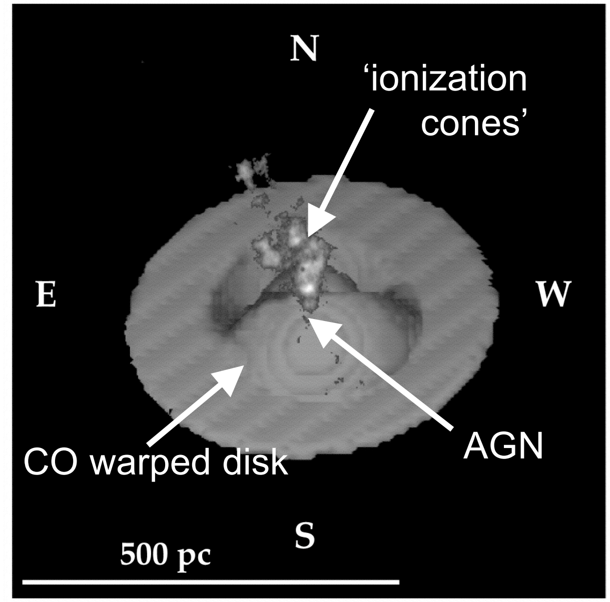
- ‘Torus’ obscures 4/5 AGN
- How is donut supported?
  - Covering fraction >50%
  - yet cold (dusty)
  - Cloud-cloud collisions should flatten structure
  - Thick clumpy accretion needs $M_{torus} > M_{Edd}$ *see SgrA**

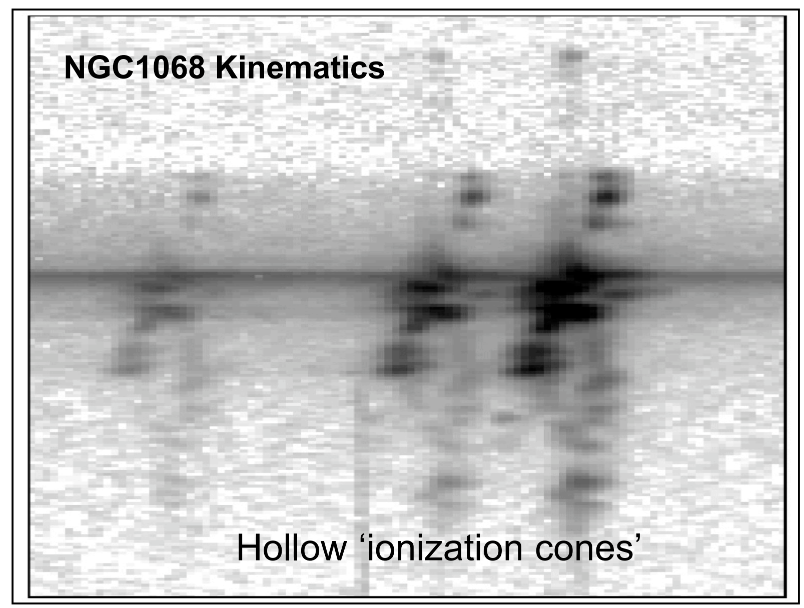
Vollmer, Beckert & Duschl 2004 A&A 413, 949



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 Crenshaw & Kraemer 2000 ApJ 532, L101
  - I.e. Matter bounded
  - a true outflow cone
  - *Not* ISM illuminated by collimated continuum



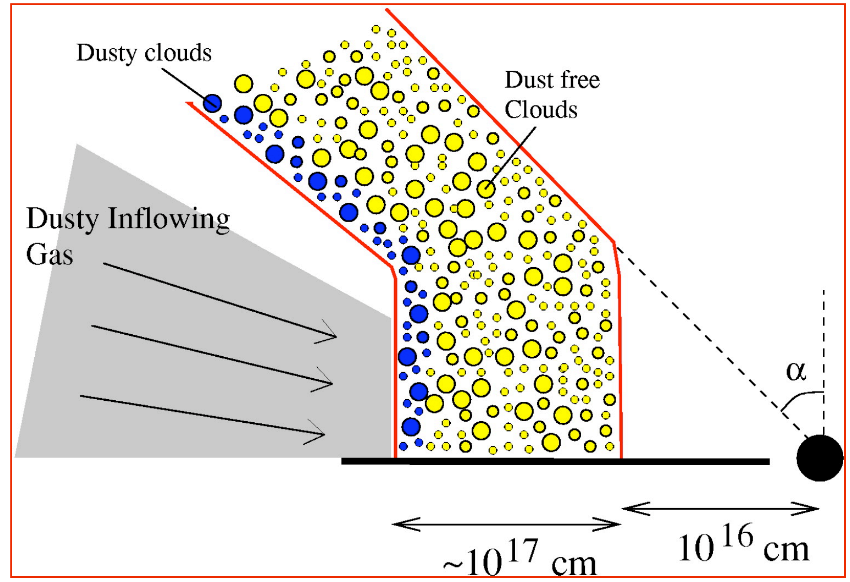


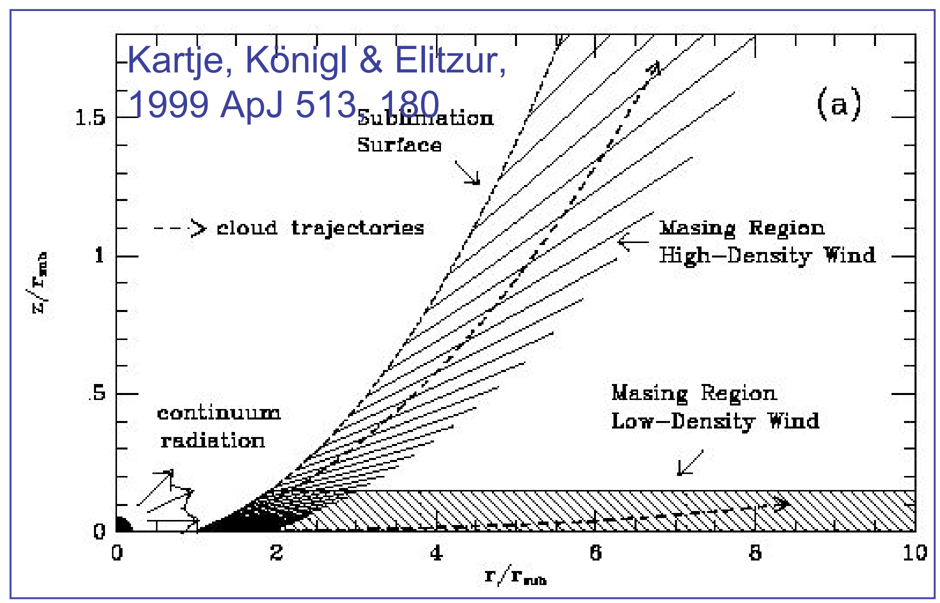
Torus Alternative: 2. Disk Wind

- 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***

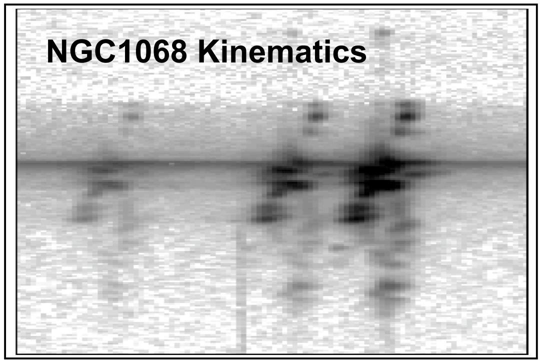


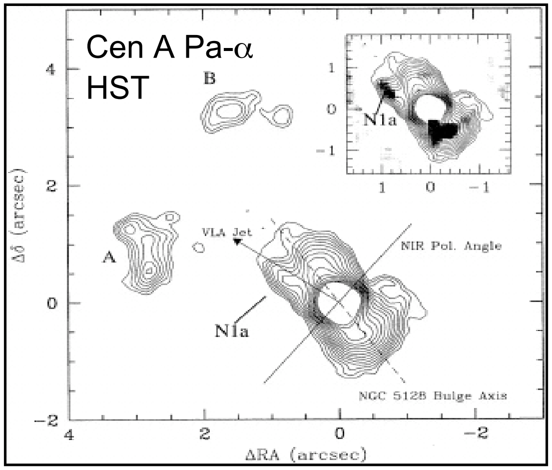


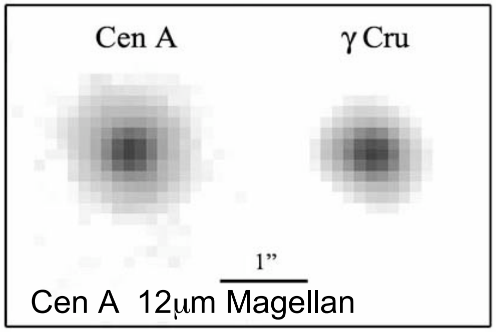
Kartje, Königl & Elitzur, 1999 ApJ 513, 180

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 pc, same as 15mas @ 20 Mpc
  - HST Pα image: disk or bicone?
    Schreier et al. 1998 ApJ 499, L143
  - Magellan resolved 10μm emission *r ~1 pc*
    Karovska et al. 2003
- NGC4151 [20 Mpc]
  - hot dust:.
  - *r = 0.1 pc* Keck K interferometry, Swain et al. 2003 ApJ 596, L163
  - *r = 0.04 pc* reverberation Minezaki et al. 2003 ApJ 600, L35
    - 48+/-2 light-days
  - ***Range of sizes: multiple origins?***







Princeton AGN Physics with the SDSS, 29 July 2003

Quasars as Dust Factories

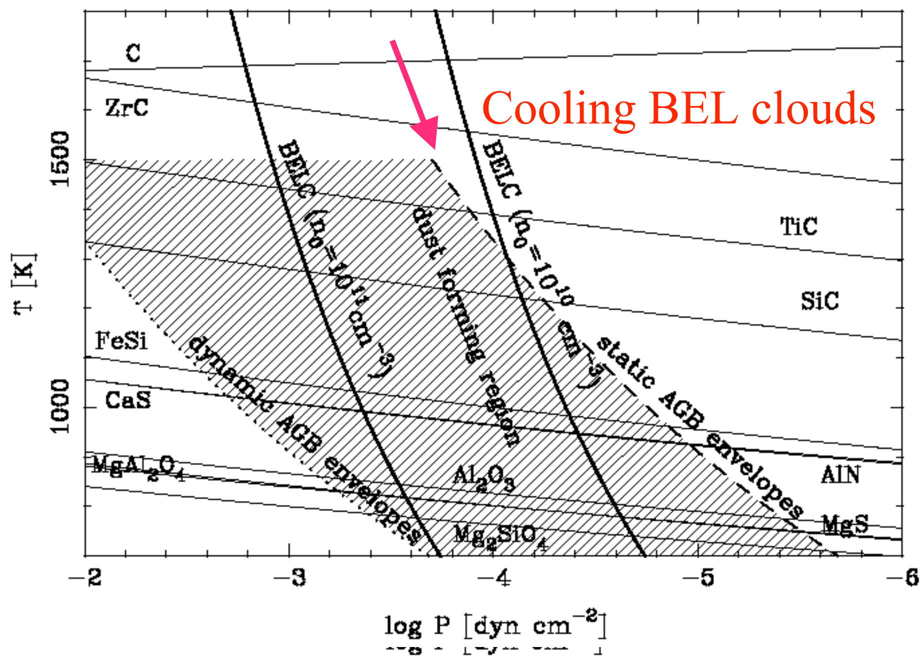
Early Star Formation

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

Carbon rich dust



Applies to Carbon-rich and Oxygen-rich grains

High z Quasar Dust: an example

Maiolino et al. 2006, astro-ph/0603261

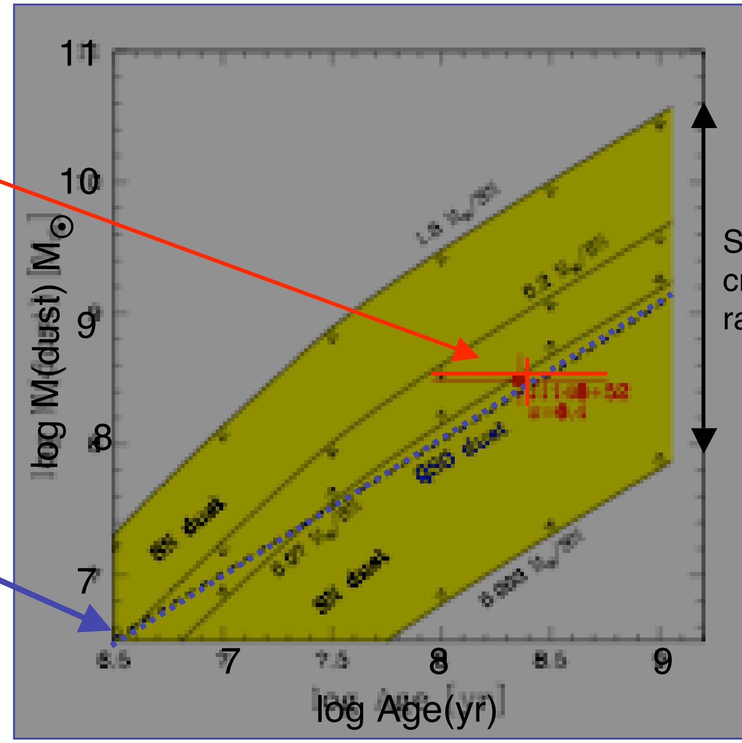
- Highest z quasar: SDSSJ1148+52 z=6.4
- $M_{dust} = 10^{8.5} M_{\odot}$ Bertoldi et al. 2003
- Assumptions:
  - $M_{dot} = m_{dot}(Edd)$, always
  - $M_{dot}(wind) = 0.5 \times 10^{-8} M_{BH}/M_{\odot}$
  - $Z = 10 Z_{\odot}$
  - Milky Way dust depletion
- Dust formation rate is sufficient

→ *quasar winds may be important for dust creation at high z*

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

Barvainis 1987 ApJ 320, 544

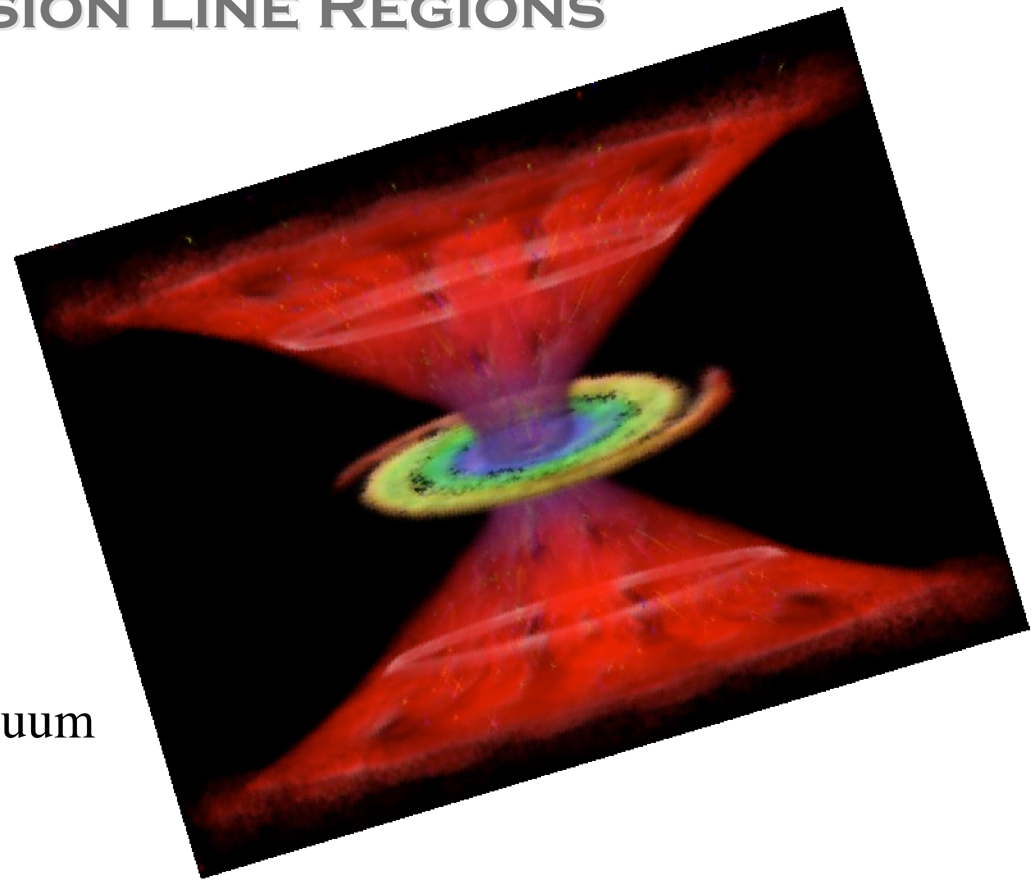
- The most luminous z=5-6 quasars
  - **R ~ 10 pc ~ 6 mas**
  - **J = 15 - 16, K = 14-15** Agueros et al. 2005, AJ 130, 1022



Imaging Quasars II:
Broad Emission Line Regions

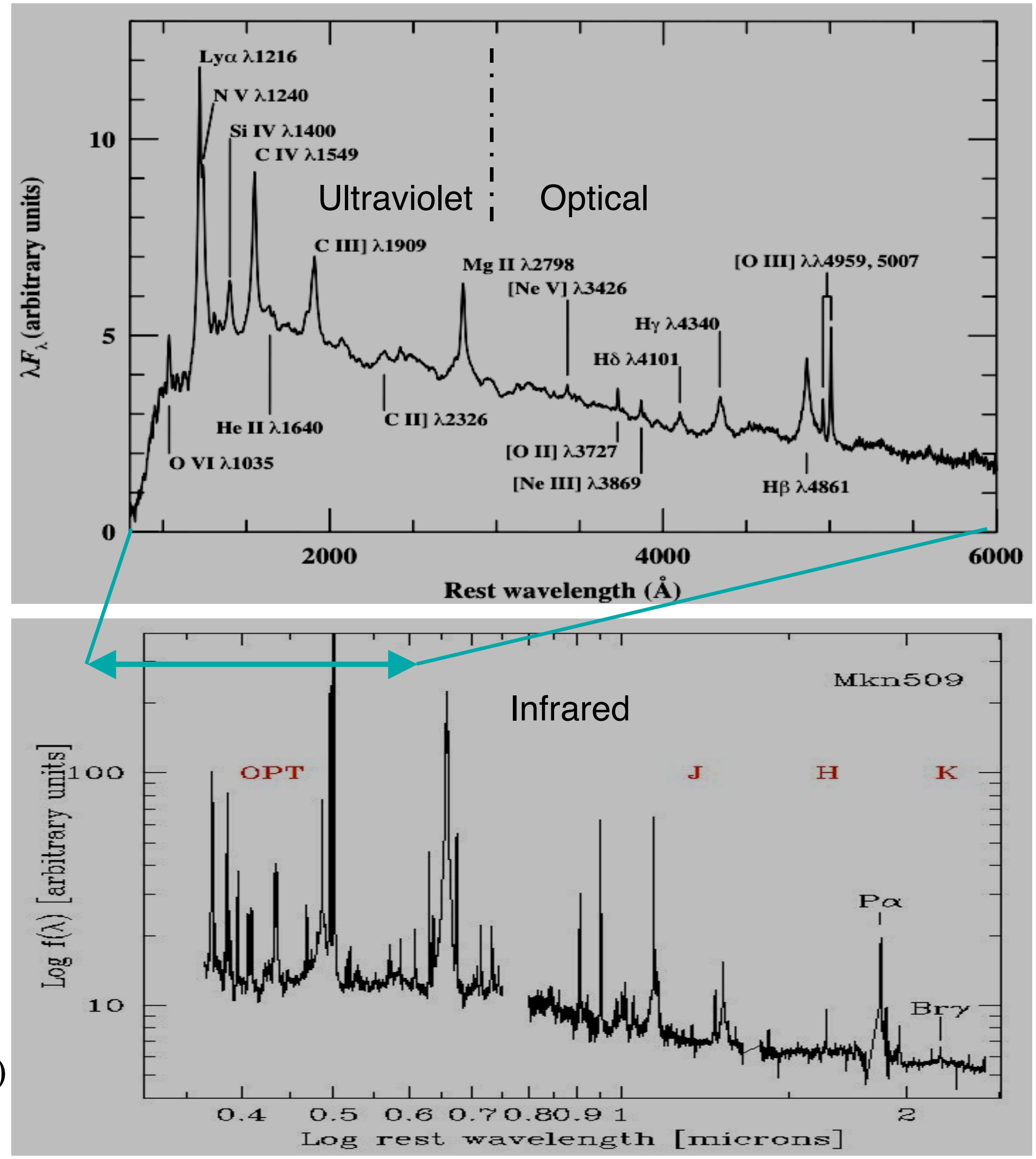
Broad Emission Lines (BELs)

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



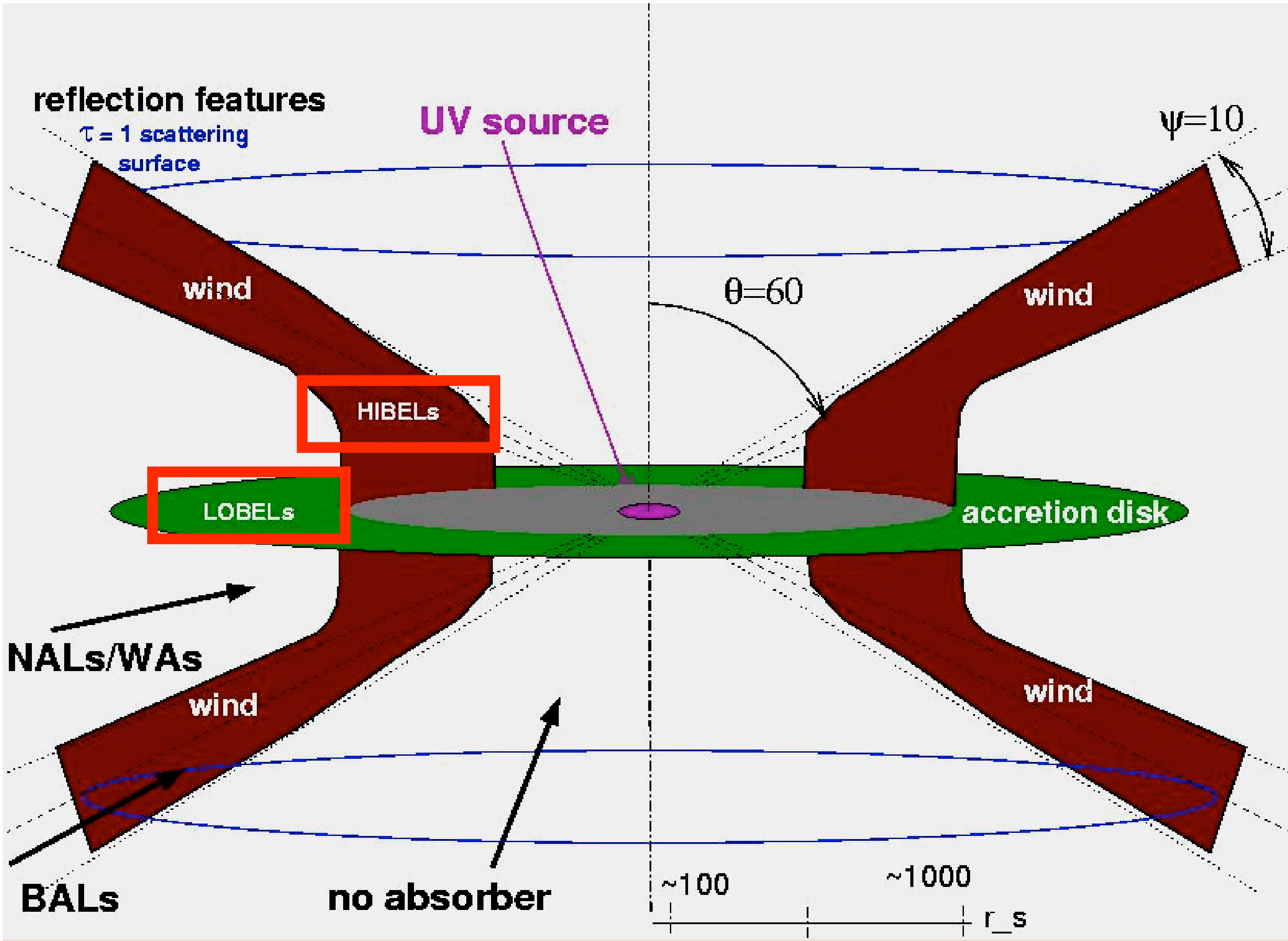
Broad Emission Lines: BELs

- Universal
  - All are permitted transitions
    - High densities ~10^{10-12} 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, Lyα, CIV} all UV, HeII} weak

- Measure acceleration law

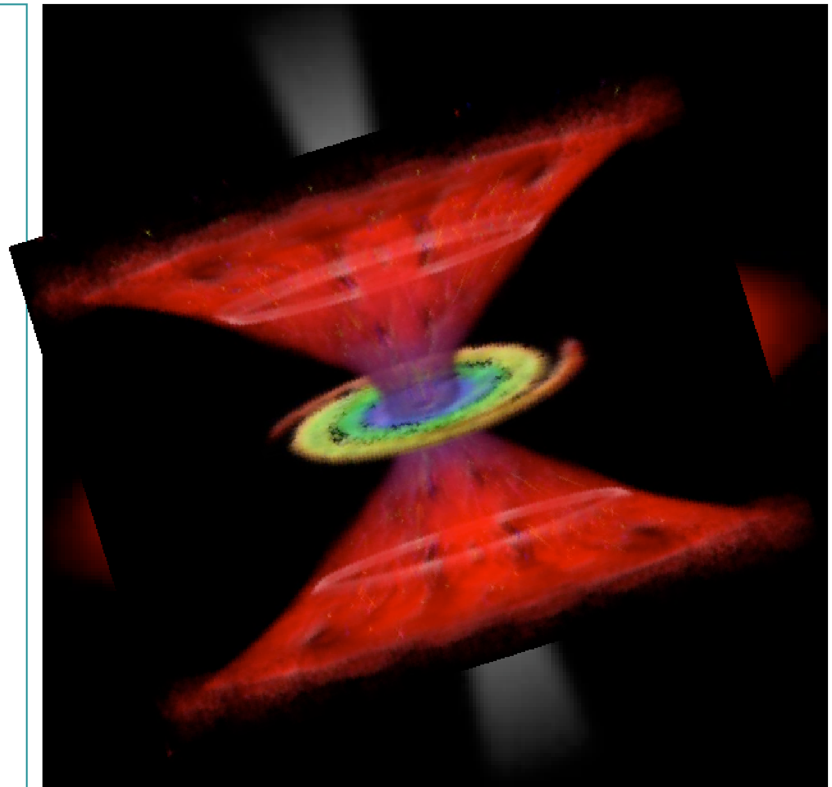
⇨ **Choose between wind models**

[Line driven, hydromagnetic, thermal]

- Measure m_{dot} in wind

⇨ **Determine cosmic feedback**

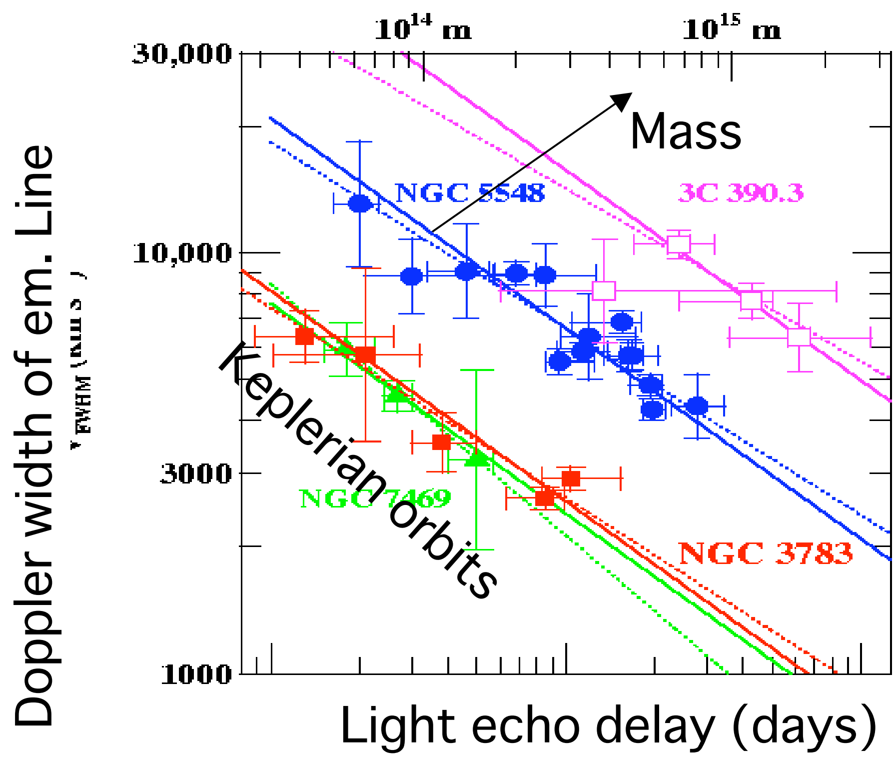
- Observe secular changes in structure (years)



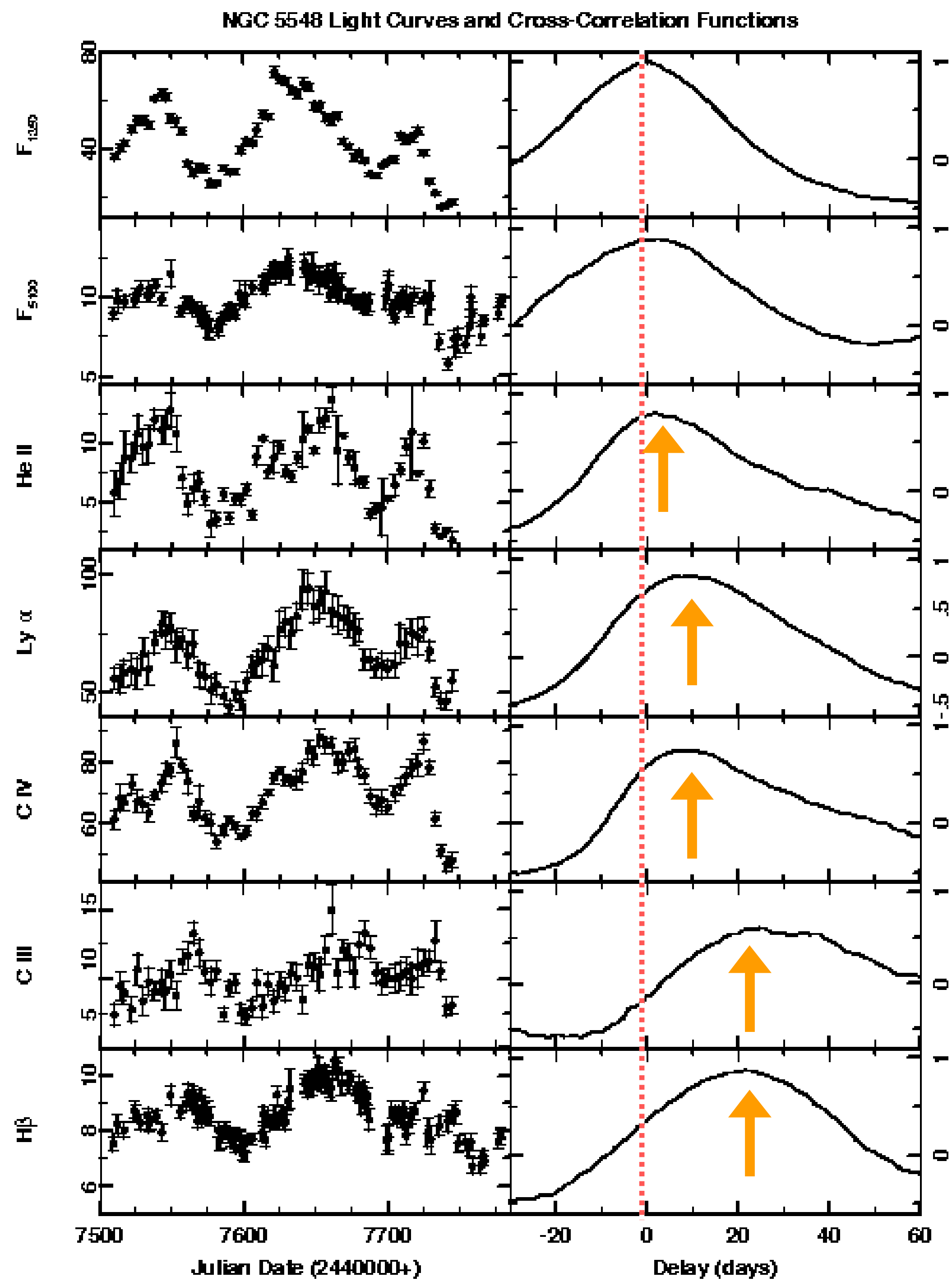
BELR Size: Reverberation Mapping

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



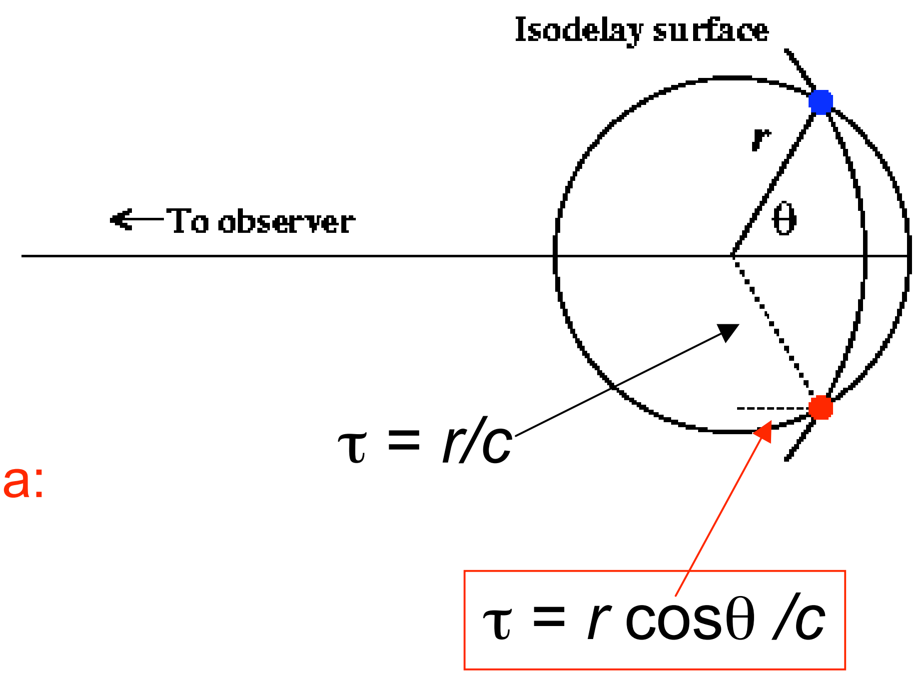
Reverberation Mapping Results

- Scale is light-days in moderate luminosity AGN
- Highest ionization emission lines respond most rapidly $\Rightarrow$ 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:

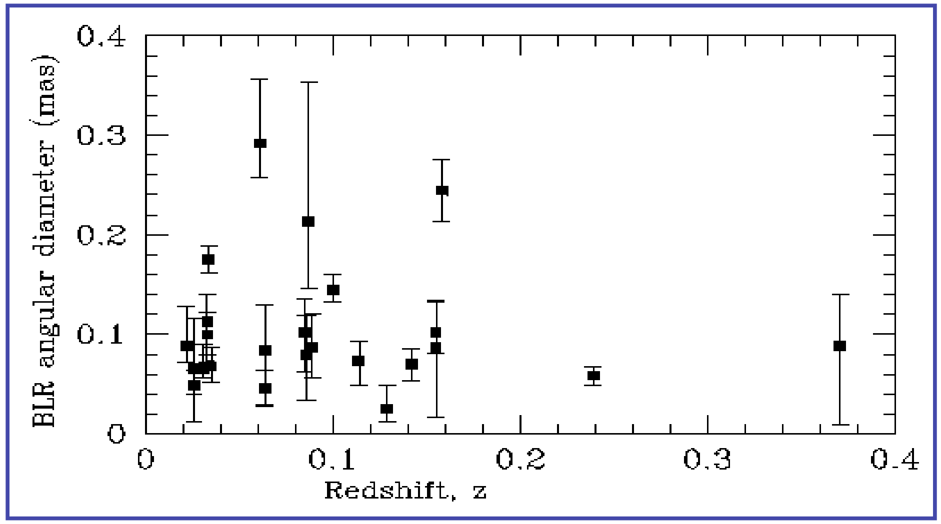
$$r = \frac{c\tau}{1+\cos\theta}$$

Thanks to Brad Peterson

Imaging the Broad Emission Line Region
Feedback

Elvis & Karovska, 2002 ApJ, 581, L67

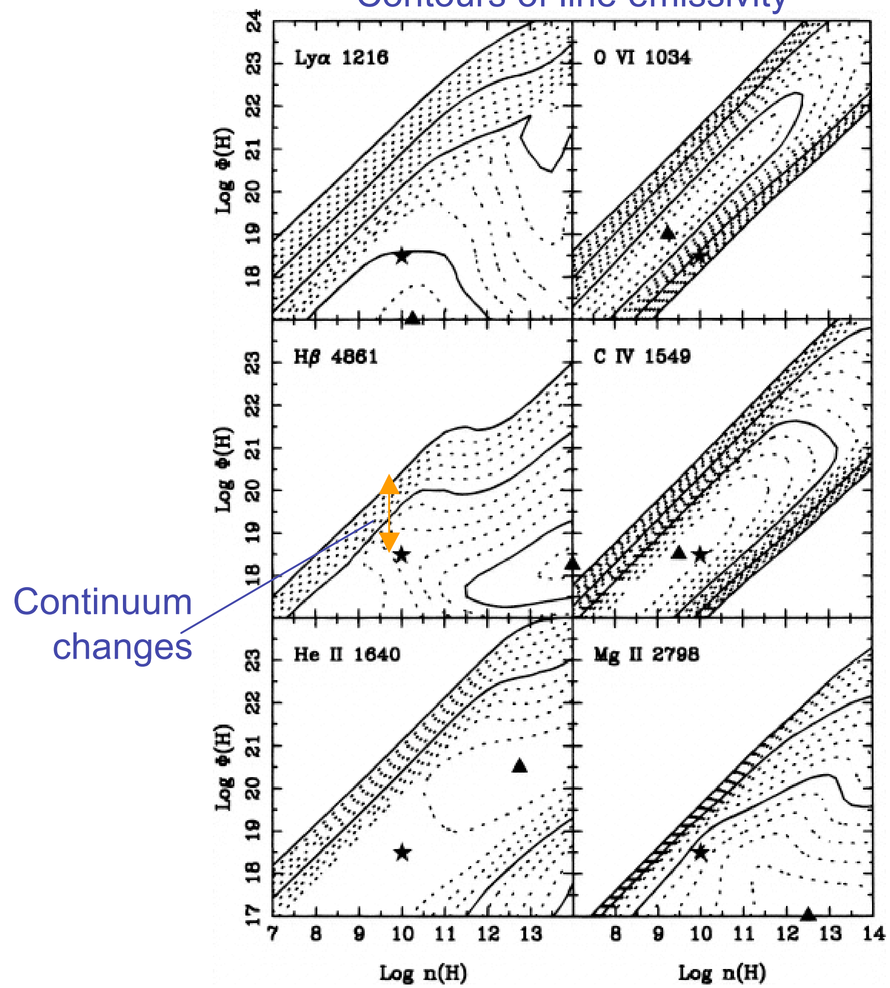
- Hβ High Ionization BELR have ~0.1mas diameters in nearby AGN
- Begins to be resolved with VLT-I, *Ohana*, though in near-IR
- 10 times better resolution (few km baselines) would be enough to see shape
- Interferometer at Antarctica Dome C?



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

Contours of line emissivity



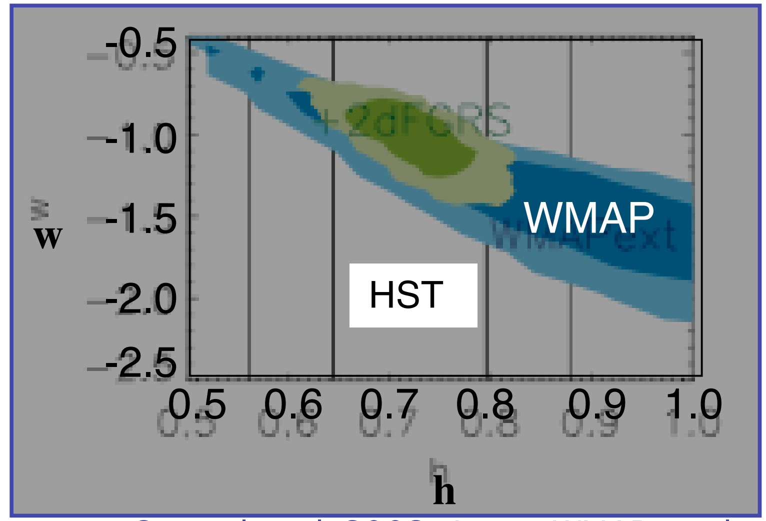
Korista et al. (1997)

Reverberation + Interferometry

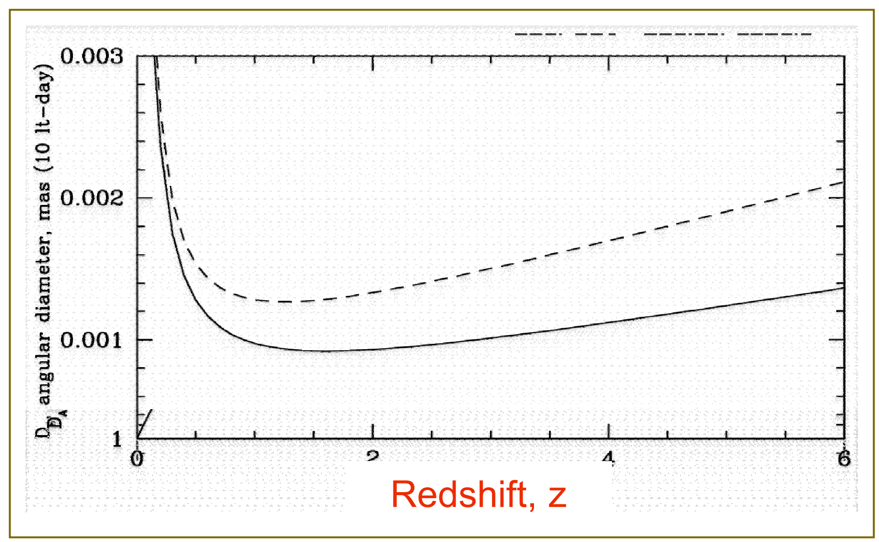
Cosmology

Elvis & Karovska, 2002 ApJ 581, L67

- *H0* now measured to 10%
- ***H0 errors dominate uncertainties*** on WMAP cosmology parameters
- Imaging reverberation mapping could give *H0* 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~6 cf 1.5 for SN1a
- Metric plus luminosity evolution keeps sizes (relatively) large >1μas



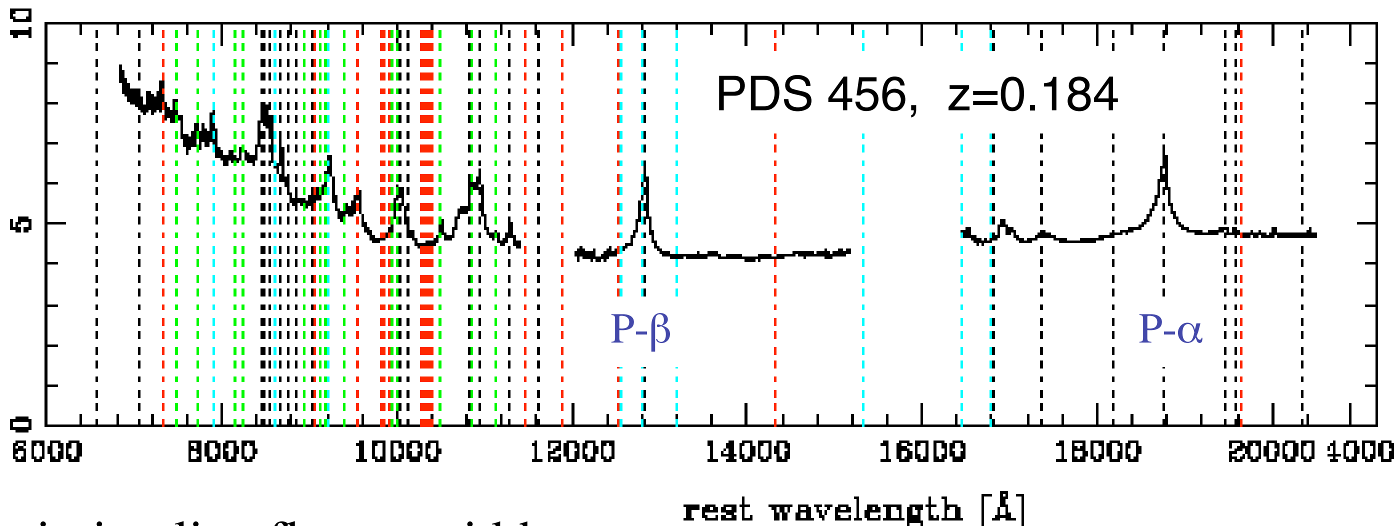
Spergel et al. 2003, 1 year WMAP results



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



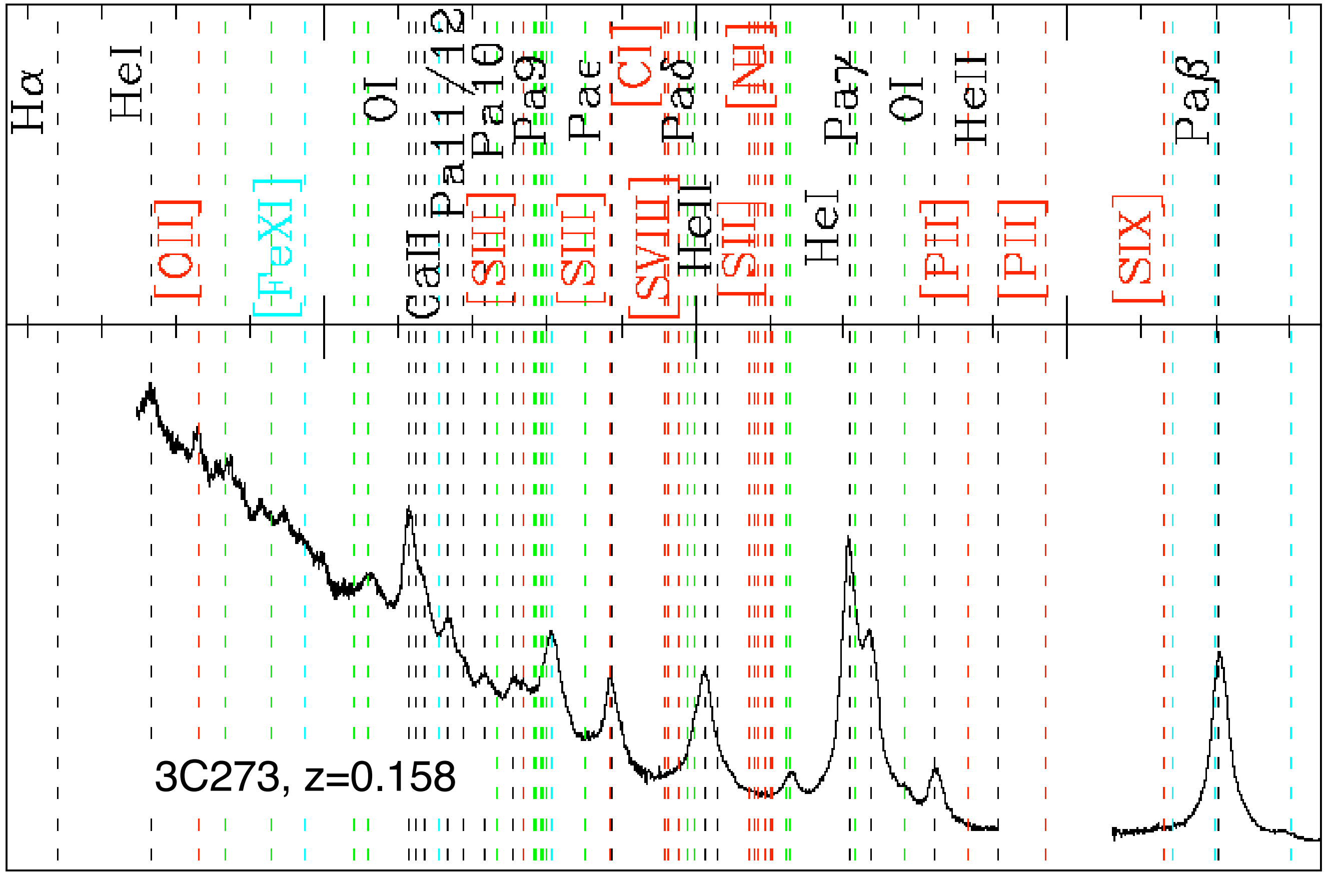
- Need AGN NIR emission line fluxes, widths for reverberation and ground-based interferometry
- No JHK spectra of unobscured AGNs in literature.
- 2 year IRTF/SPEX campaign to get Paschen α, β, and higher series fluxes
- Selected sample of bright (J<14) nearby (z<0.3) AGN

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.

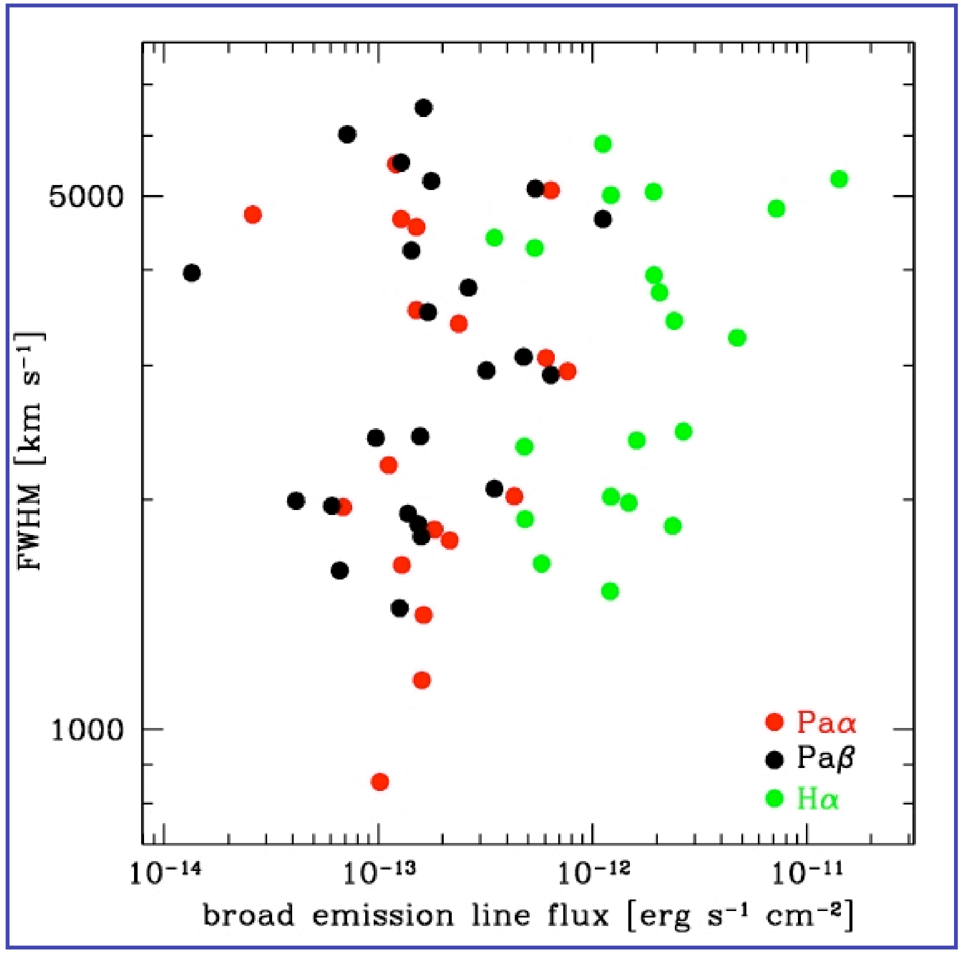
- Blending issue for many lines
- Pa-α, Pa-β, Pa-ε clean



Observability of Near-IR BELs

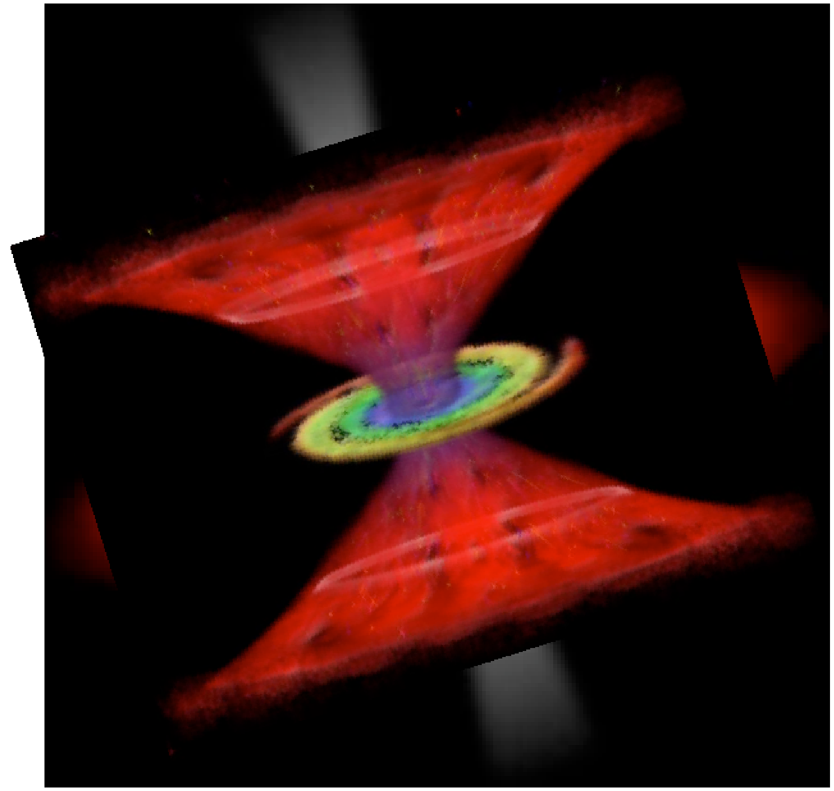
Hermine Landt et al. 2007 in prep.

- Low z AGN sample
  - $z = 0.009 - 0.300$
  - $V = 11.8 - 16.4$
  - $J = 10.3 - 13.9$
- NIR BEL properties
  - Pa-α/H-α, Pa-β/H-α ~ 0.1
  - FWHM similar
    - 1000 - 7000 km s^{-1}
    - . Δλ ~30 - 200 Å



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~ 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)

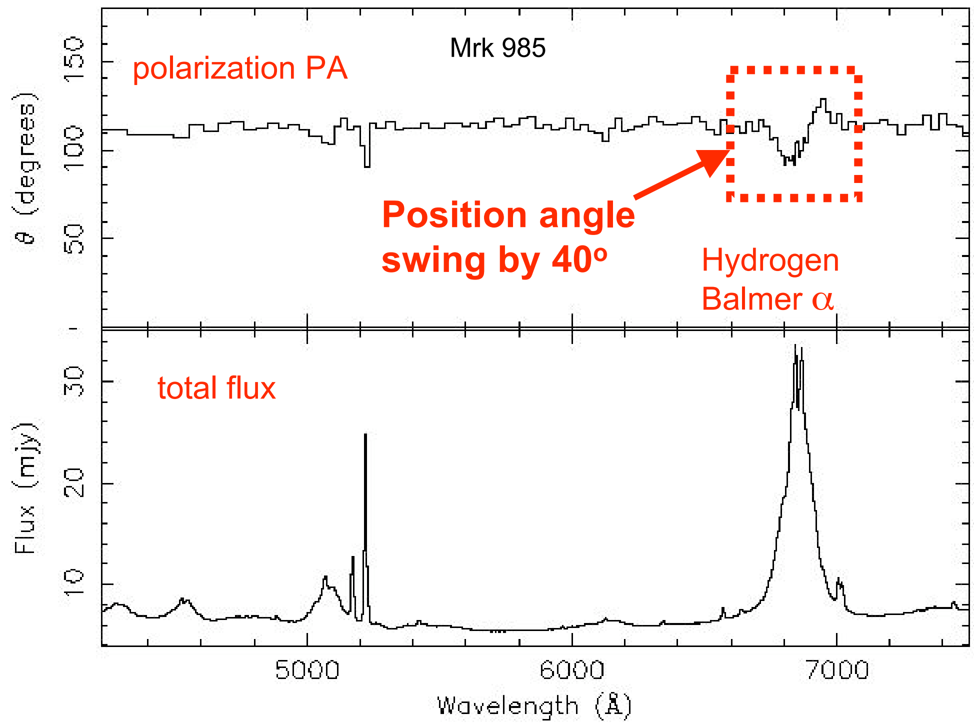
http://hea-ww.harvard.edu/~elvis/motion.html

A sociological note:

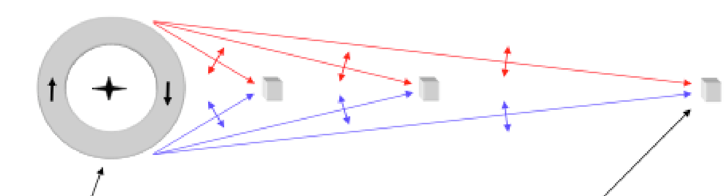
- Extragalactic astronomers generally do not ask for high angular resolution because what they do does not need it
- What they do does not need high angular resolution just because they *can* do it now.
- I.e. *They never thought about it*
- Why not image Sn1a to get Baade-Wesselink distances?
- Or axion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

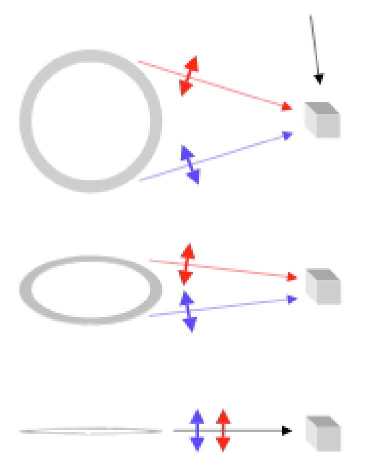
A long term challenge: BEL Imaging Polarimetry

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 τ=1 e^- scattering surface	~few x *r*(BELR) ~light months ~0.1pc	~few mas	VLTI, Magdalena Ridge at 1 - 2 μm JHK, Pα
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	

smaller

Quasars effects on Cosmology

Effect	Pathway	Happens?	Caveats
M_{BH}-σ^*	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