Active Galactic Nuclei (AGNs), Black Holes and their Impact on Galaxy Formation

Overview:

- **Manifestations of "nuclear activity"**
  - Nearby universe/low-luminosity AGN
  - QSO's and AGN in the high-z universe
- **Ubiquitous super-massive black holes at galaxy centers**
  - Our Milky Way
  - Nearby Galaxies
  - High-z galaxies
- **Cosmic Census of Accretion and Black Hole Growth**

- **The Impact of BH Accretion on Galaxies**

Literature:
"An Introduction to Active Galactic Nuclei", Bradley M. Peterson, Cambridge University Press, Cambridge
"Active Galactic Nuclei", Ian Robson, John Wiley & Sons, Chichester

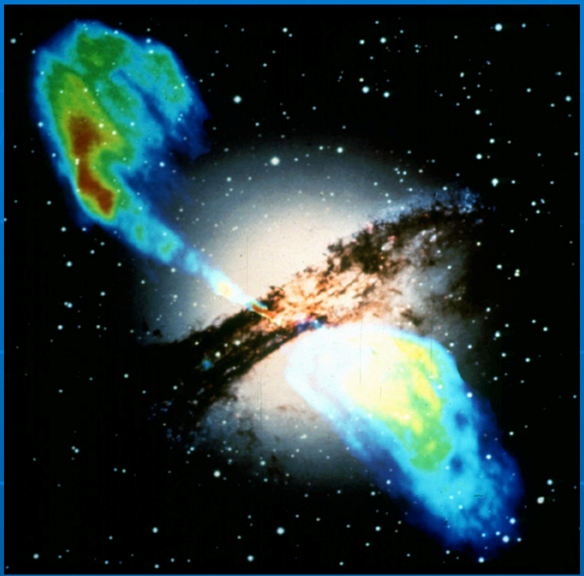
What is “Nuclear Activity”?

- The (geometric) centers of galaxies (few pc) exhibit local properties which cannot be found anywhere in the rest of the galaxy.
- It turns out that much of these phenomena are related to the “bottom of the potential well and black holes.

- compact, very bright centers, $R_{nucl} \simeq 3pc$
- spectra with strong emission lines
- ultraviolet-excess
- X-ray emission
- jets and double radio sources with $R_{jet} \sim kpc - Mpc$
- variability over the whole spectrum on short timescales: $t_{var} \sim minutes ... \sim days$
- AGN luminosities:

$$L_{nuc} = 10^{45} - 10^{48} \frac{erg}{s} \simeq 10^{12} - 10^{15} L_{\odot}$$

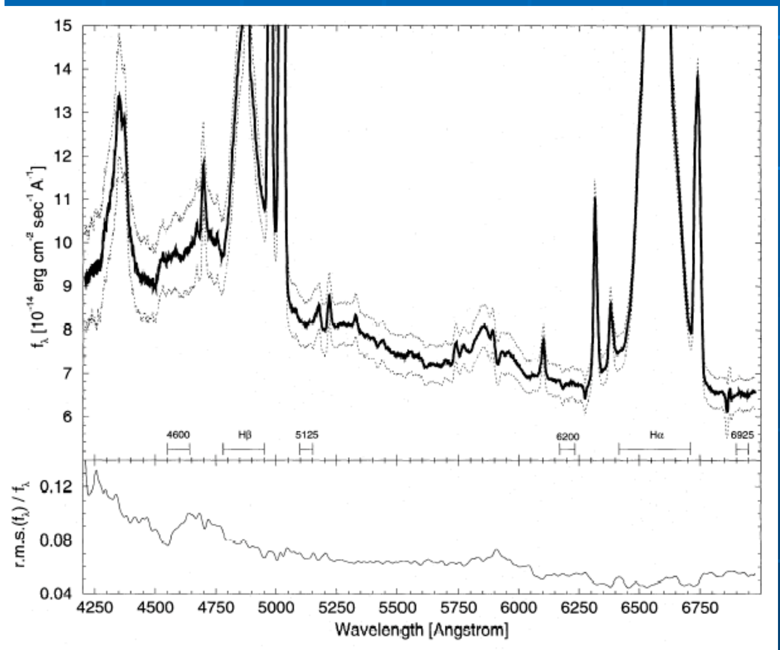
AGN Types
1) Radio Galaxies



- Radio emission comes from lobes 0.1-0.5Mpc
- Radiation is synchrotron emission
- $L_{radio} \sim 10^{8-10}\ L_o$
- Reside almost exclusively in massive galaxies
- Particle acceleration to >10^{12} MeV

- **Note:** all 'radio AGN' show other signs of nuclear activity, but not all AGN have radio jets/lobes

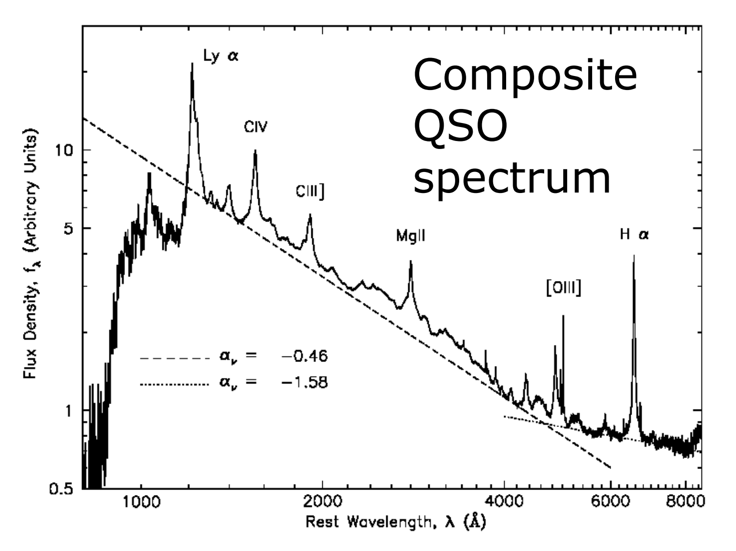
AGN Types
2) Seyfert galaxies



- Bright, unresolved nuclei 10^{45} erg/s
- Forbidden emission lines narrow (300km/s)
- Permitted emission lines (in Seyfert 1) broad: ~3000km/s
- Line ratios exclude photo-ionization by hot stars
- From Variability studies (light travel time continuum → broad lines:$R_{broa\text{-}lines}$ ~0.01-1pc

AGN Types: 3) luminous Quasars (QSO)

1963 M. Schmidt discovers that the radio source 3C273 can be identified with an optical point source (stellar) with a jet. The spectrum shows broad emission lines $H_{\beta,\gamma,\delta...}$, MgII, OIII ... which are redshifted by $z = 0.158 \Rightarrow v_rad = 47400\frac{km}{s}$. So, the object was called a **QUAsi StellAr Radio source** → QUASAR.



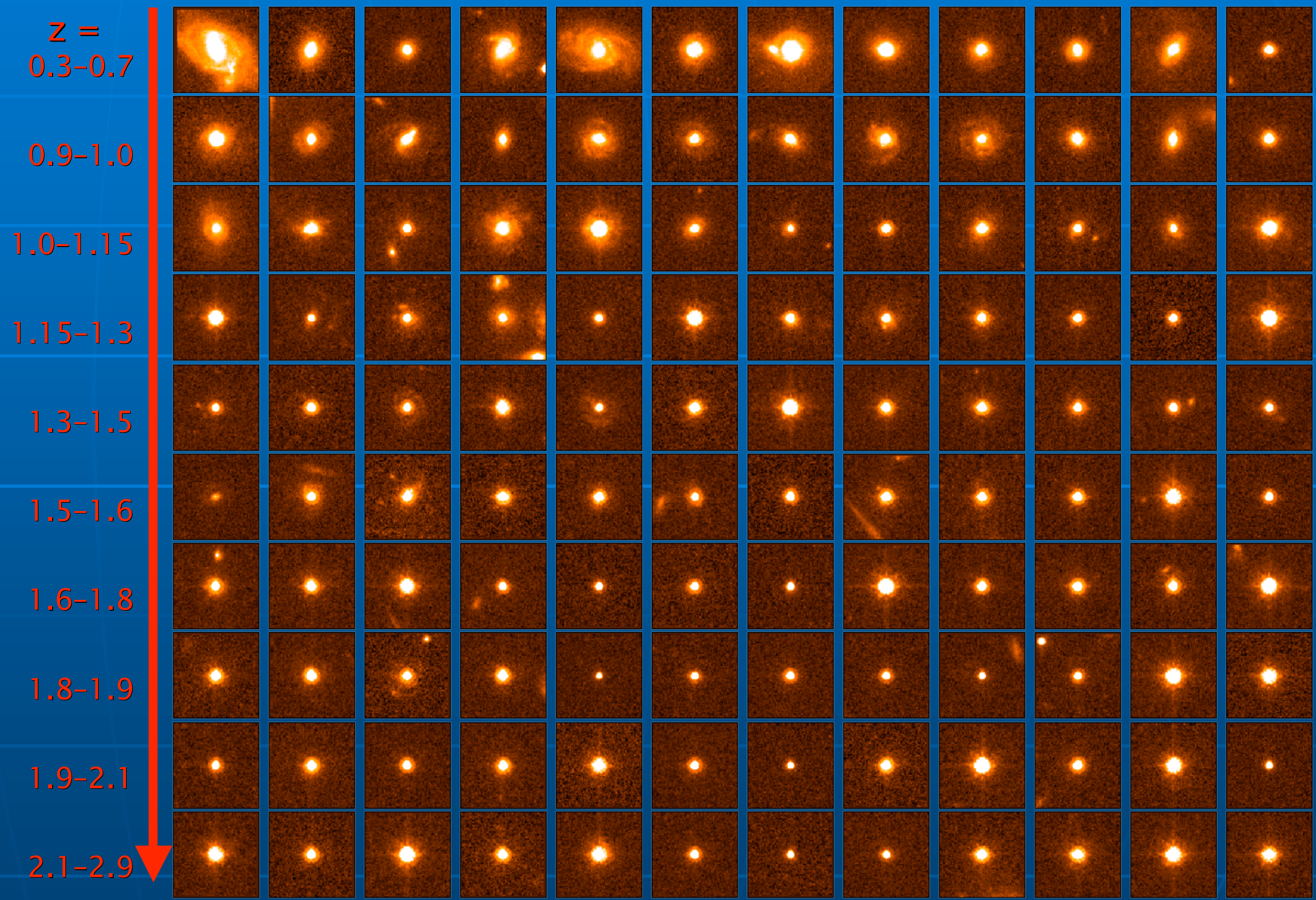
- Bright, unresolved nuclei of galaxies, at 10^{48} erg/s they can outshine their host galaxy by x100
- Continuum: not black-body
- Broad lines: ~3000km/s
- Found at redshifts z~0…6.5, with a peak at z~2 → phenomenon more common in the past
- Phenomenon rare or common but short-lived phase:

$n_{galaxy} \sim 100 - 10.000\ n_{QSO}$

Are QSOs actually active galactic nuclei?
(i.e. live in galaxy center)

Answer:

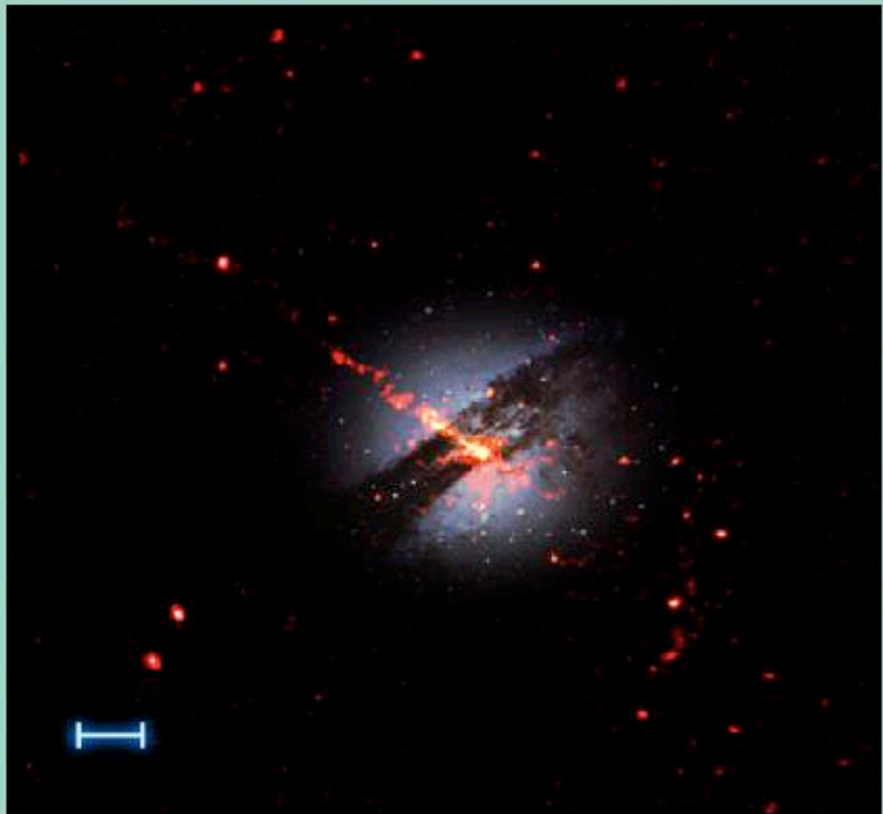
whenever on ‘has a chance’ to see a ‘host galaxy’ one does see one



HST imaging COSMOS: Jahnke et al 2007/8

Nuclear Activity across the Electromagnetic Spectrum

Active Galaxy Centaurus A



Chandra x-ray image overlaid on an optical image

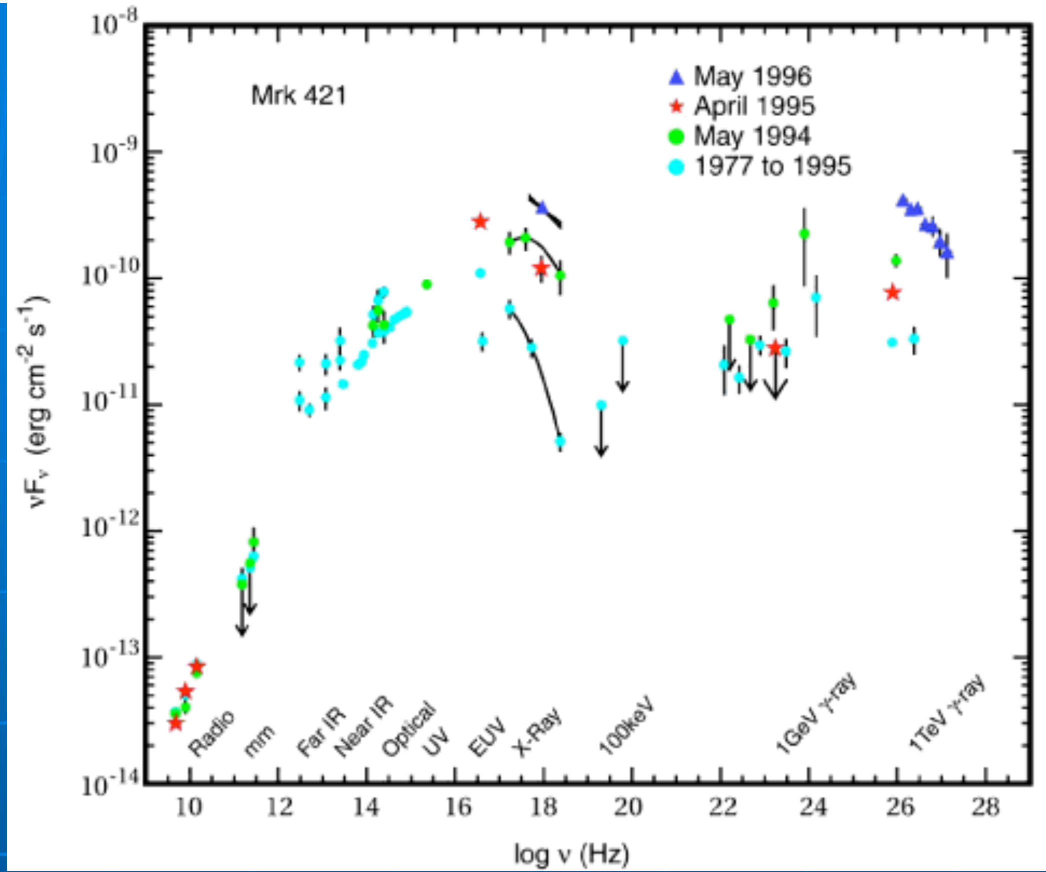
The image shows X-ray jets erupting from the center of the galaxy over a distance of 25,000 light years. The optical image shows that Centaurus A is an elliptical galaxy with huge dust lanes across the middle of the galaxy. The energetic central region, or nucleus, is obscured by the dust lanes in optical images, but shines clearly in X-rays, as do the dramatic jet structures extending in either direction from the nucleus well beyond the edges of the galaxy. The nucleus is believed to harbor a supermassive black hole. Numerous point-like sources of X rays, probably neutron stars and black holes in binaries, are also apparent. The scale bar represents 3,300 light years.

Radio overlaid on optical

Infrared

Optical

AGN Emission Across the Energy Spectrum



It turns out that to explain emission across such a vast range of energy, one needs a combination of:

- accretion disk (multiple black-bodies)
- Relativistic particle acceleration (including jets)
- Dust (at 50K), heated by the radiation from the accretion disk

Orientation effects (jets, relativistic beaming) must play role

What powers most AGN?

- From what region does the activity emerge?
- AGN vary at many wavelengths
- More rapid variability for more energetic variation
- Size < c x $t_{variability}$

radio/optical	$\Delta t_{obs} \simeq 10d$	$\Rightarrow$	$l_{emis} \simeq 0.01pc$
radio/optical	$\Delta t_{obs} \simeq 1d$	$\Rightarrow$	$l_{emis} \simeq 10^{-3}pc$
TeV	$\Delta t_{obs} \simeq 1h$	$\Rightarrow$	$l_{emis} \simeq 10^{-5}pc$

Possible Power Sources

- Stars?

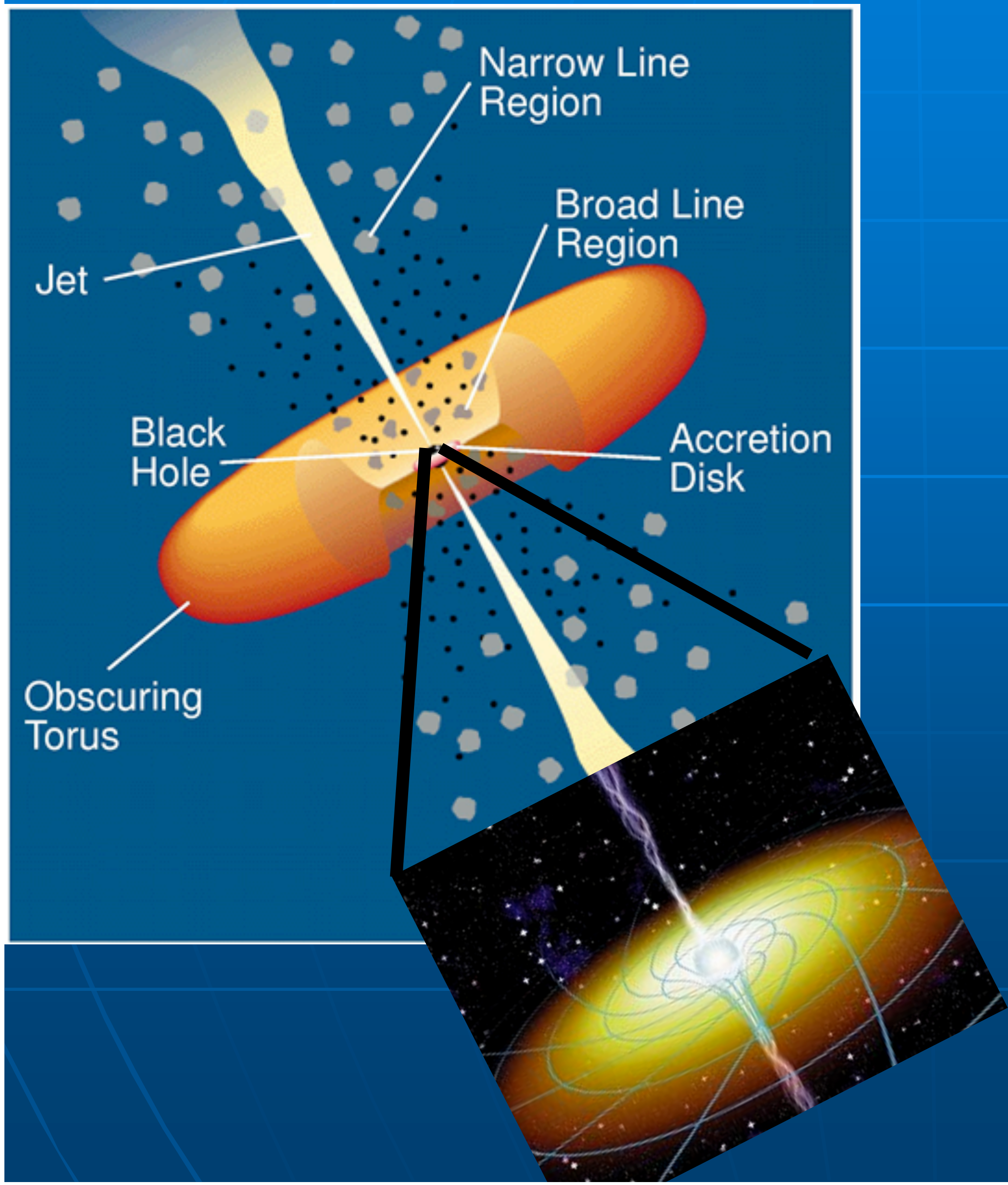
$$N_\star = 3 \cdot 10^8 \text{ O stars}$$

$$n_\star = \frac{N_\star}{\frac{4\pi}{3}[\frac{l}{2}]^3} \geq 2 \cdot 10^{14} pc^{-3}$$

- AGN do not show stellar spectra
- → **No!**

- Supernovae?
- $L_{supernova} \sim 10^9 L_*$ → every QSO has 10^4 SN at any point in time
- → **No!**

The (Now) Standard Picture:
AGN are Powered by Accretion onto Black Holes



- **What are black holes?**
  - **GR analog to point masses**
  - **Two numbers to characterize them**
    - **Mass M_{BH}**
    - **Spin (or not)**
  - **"Size of the black hole" Schwarzschild Radius**

$$R_S = \frac{2GM_{BH}}{c^2}$$

$\frac{M}{M_\odot}$	R_S
10^6	$10^{-7}pc$
10^8	$10^{-5}pc$
10^9	$30^{-4}pc$

Energetics of accretion onto a black hole

- As material moves to the black hole, its potential energy is converted into kinetic energy.
- If that kinetic energy is converted into thermal energy (dissipation) then it will be radiated away

$$\boxed{L_{Acc} \simeq \frac{1}{16} \dot{m} c^2} \quad 1g \rightarrow 10^6 \; kWh$$

efficiency of hydrogen burning is:

$$\boxed{L_{H-burn} \simeq 0.007 \dot{m} c^2}$$

- Such luminous accretion of an ionized plasma has a natural upper limit, the Eddington limit:
  - Gravitational pull on proton > radiation pressure on electron (Thompson cross section)

$$L_{Edd} = \frac{4\pi c G M_{BH} m_p}{\sigma_{Te^-}}$$

Energetics of accretion onto a black hole

$$L_{Edd} = 1.3 \cdot 10^{38} \frac{M_{BH}}{M_\odot} \left[\frac{erg}{s}\right]$$

This implies

$$M_{BH} \geq 10^7 M_\odot$$

for Seyfert galaxies, and

$$M_{BH} \simeq 10^9 M_\odot$$

for quasars. Using

$$L_{Acc} \simeq \frac{1}{16} \dot{m} c^2 = L_{Edd}$$

yields the corresponding maximum accretion rate:

$$\dot{m}_{Edd} \simeq 5 \cdot 10^{-10} \frac{M_{BH}}{M_\odot} \left[\frac{M_\odot}{yrs}\right]$$

NB:

In an accretion disk it is assumed that the conversion of energies E_{pot} → $E_{thermal}$ (→ $E_{radiation}$ black body) happens locally and much faster than the inflow

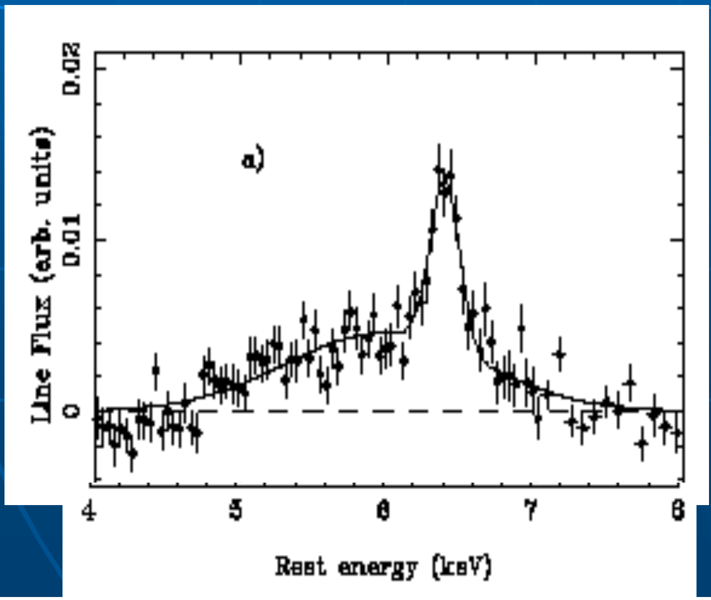
→ gravitational energy is instantly exploited.

This need not be the case. There is an old-puzzle why some galaxy centers are so 'dark', despite the presence of BHs and gas at galaxy centers (e.g. Galactic center)

→ 'advection dominated' accretion (ADAF) ← no radiation

Proving the Existence of Black Holes and Measuring their Masses

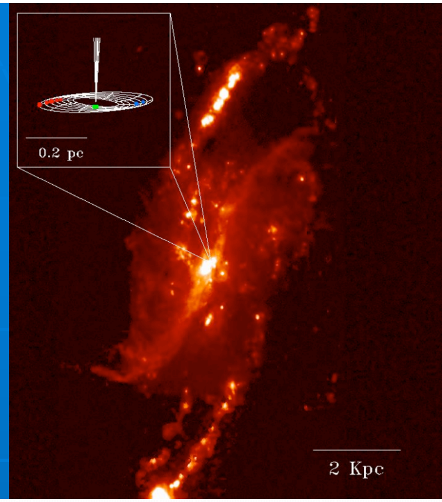
- **X-ray spectroscopy of AGN reveals an Fe K-line (transition in tighly bound electrons of Iron). Its rest-energy is 6.7KeV**
- **Very broad (50.000km/s) line-profiles, offset to the red → gravitational redshift!**

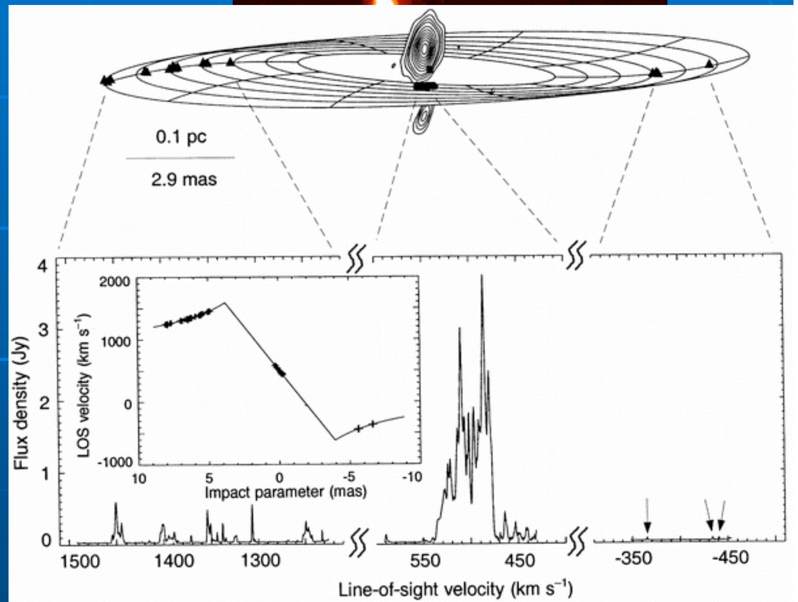


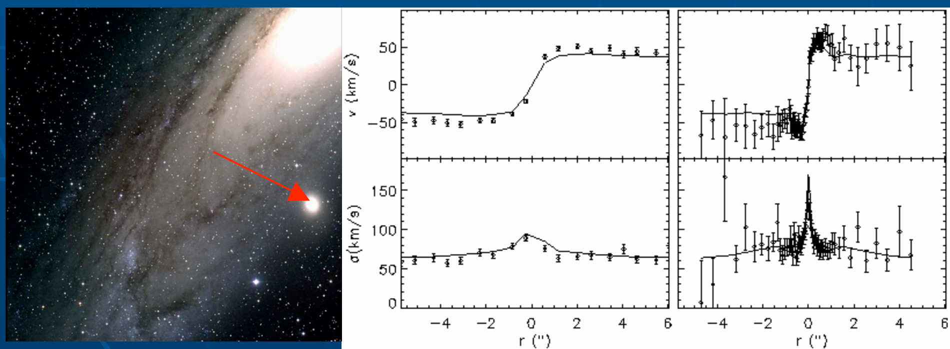
In nearby galaxies: masses from resolved kinematics

- NGC4258 appears to have a central disk of molecular gas → water maser lines → high-resolution measurements are possible.
- → $M_{dark\ object}$?=? $M_{BH} = 4x10^7\ M_o$
- Density > $10^{10}\ M_o/pc^3$

- **Note: also "inactive" nearby nuclei (e.g. M32) show kinematics that require a supermassive dark object/black hole to be explained**
- **→ are black holes ubiquitous?**



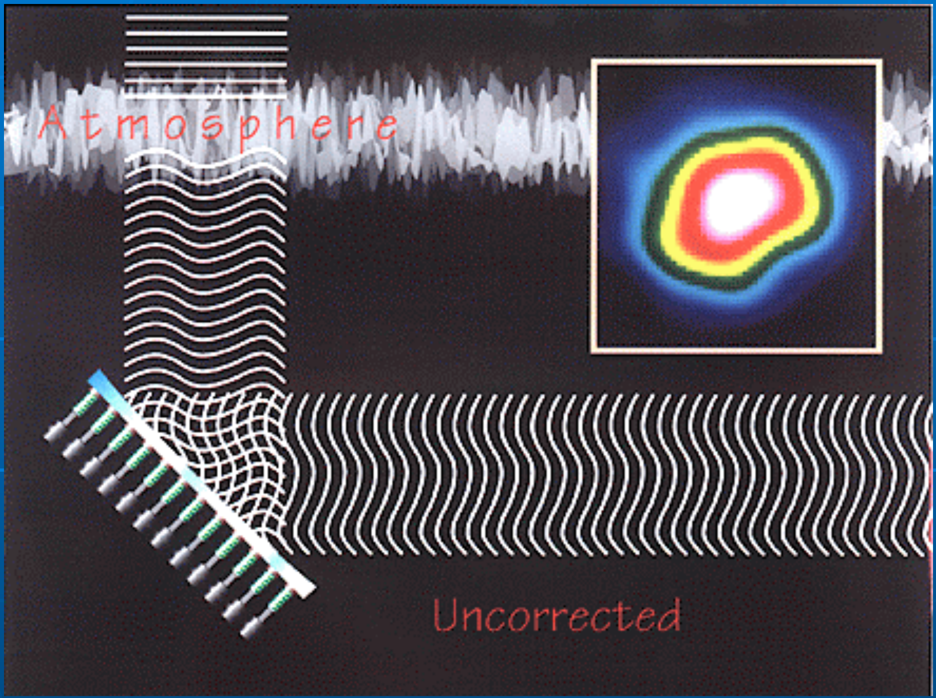


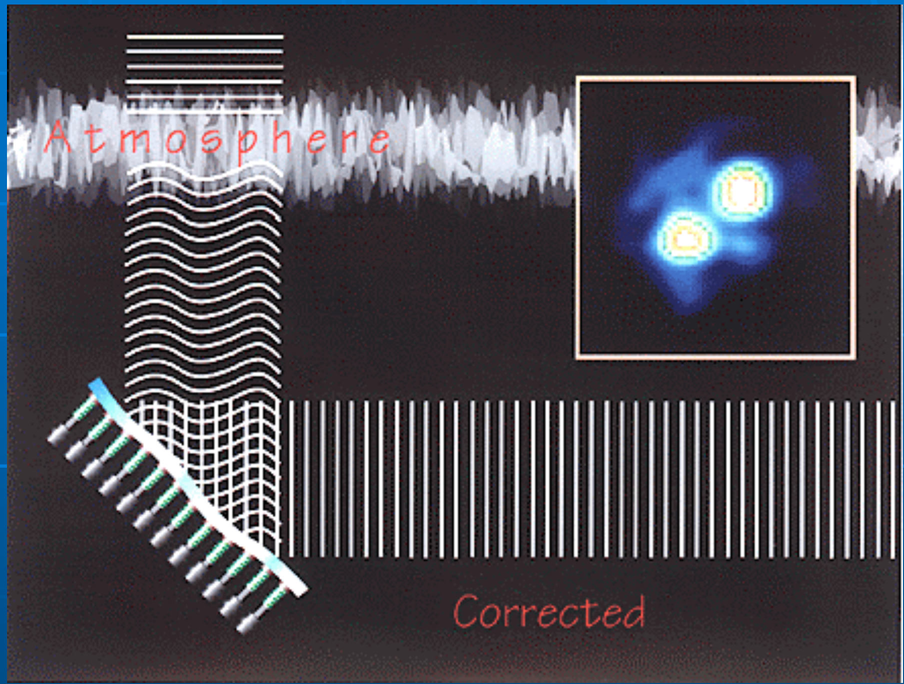


Exploring the Center of Our Milky Way

Genzel at al; Ghez et al 2003

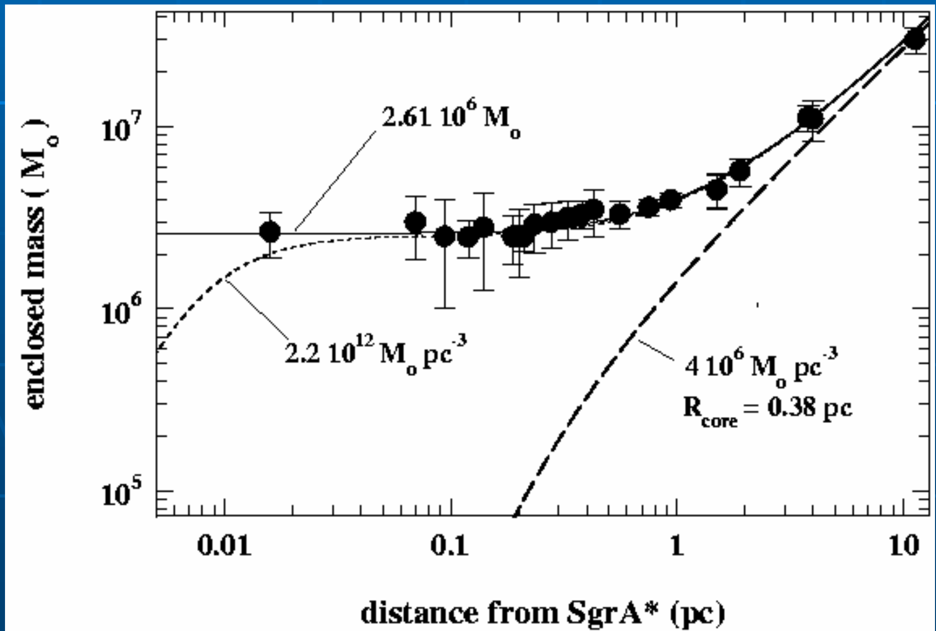
Use adaptive optics to compensate for image degradation due to atmospheric turbulence

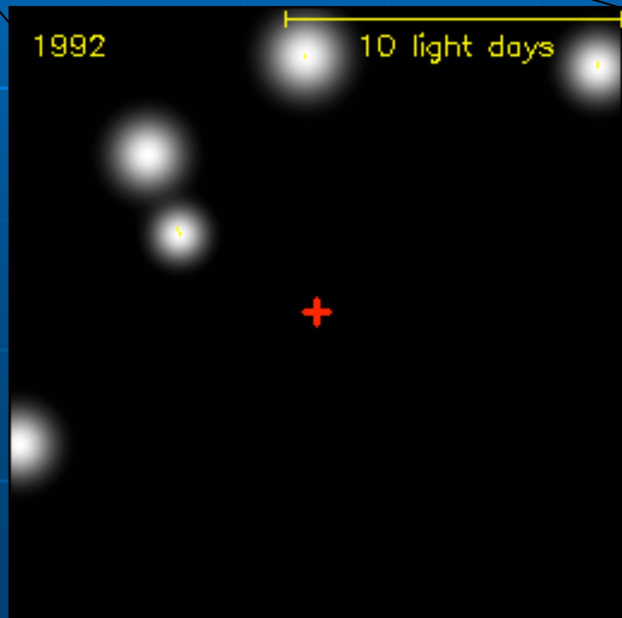




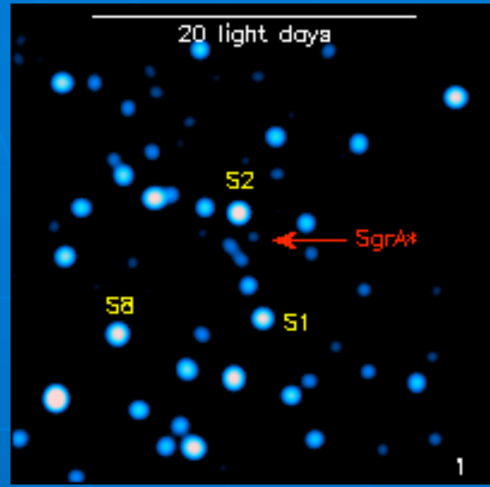
The Center of the Milky Way

- Only observable in the IR: A_V~20 magnitudes
- Resolved stellar motions with adaptive optics
- (e.g. Genzel et al 1998 ..2005)

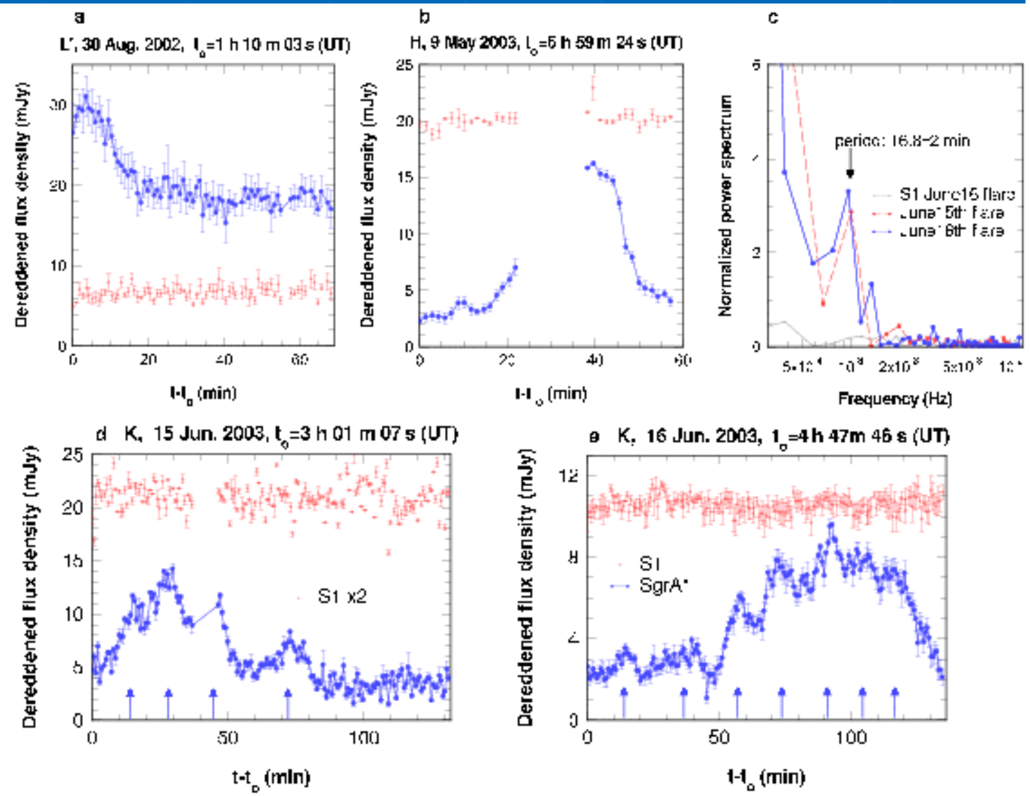




The Galactic Center: Information Close from the Black Hole?



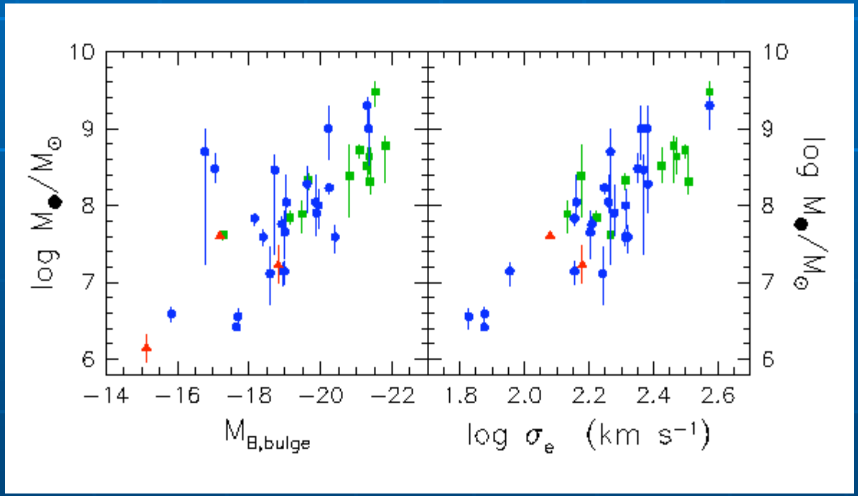
- The Galactic Center Source shows light variations with a period of 16 minutes.
- The last stale orbit around a BH with 3×10^6 Mo is ~25 minutes
- ..but it is shorter if the black hole is spinning..!

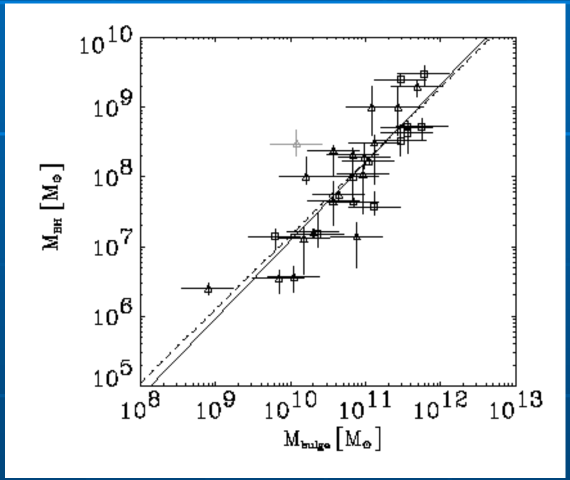


Black Hole Masses and Host Galaxy Properties

- Spatially resolved spectroscopy with the Hubble Space Telescope (HST) has been key to measuring black hole masses in nearby galaxies

- Gebhardt et al 1999; Ferrarese and Merritt 1999:
  - Black hole mass correlates with the stellar velocity dispersion σ_e of the host galaxy's bulge (~40% scatter)





Haering and Rix, 2004

Note: $R_{schw}(10^7 M_0) = 10^{12}$ cm ←→ $R_{bulge} = 10^{22}$cm

Nature and origin of this relation are not (yet) known

BH Mass estimates in high-z objects

(only in accreting object)

Three approaches:

1)Eddington-limit arguments:

$$L \leq L_{Eddington} \Rightarrow M > M_{min}(L_{Eddington})$$

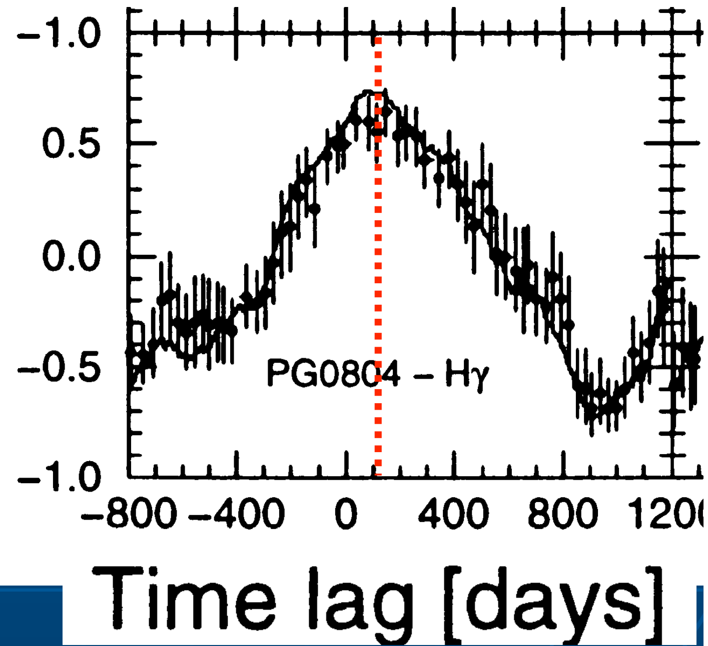
2) Reverberation mapping (Kaspi et al 2000)

$$M_{BH} \sim \sigma^2_{BLR} \times (t_{lag} \times c) \rightarrow$$

Time lag of variations in

Continuum (accr. Disk) and Hγ (BLR)

→ BLR size



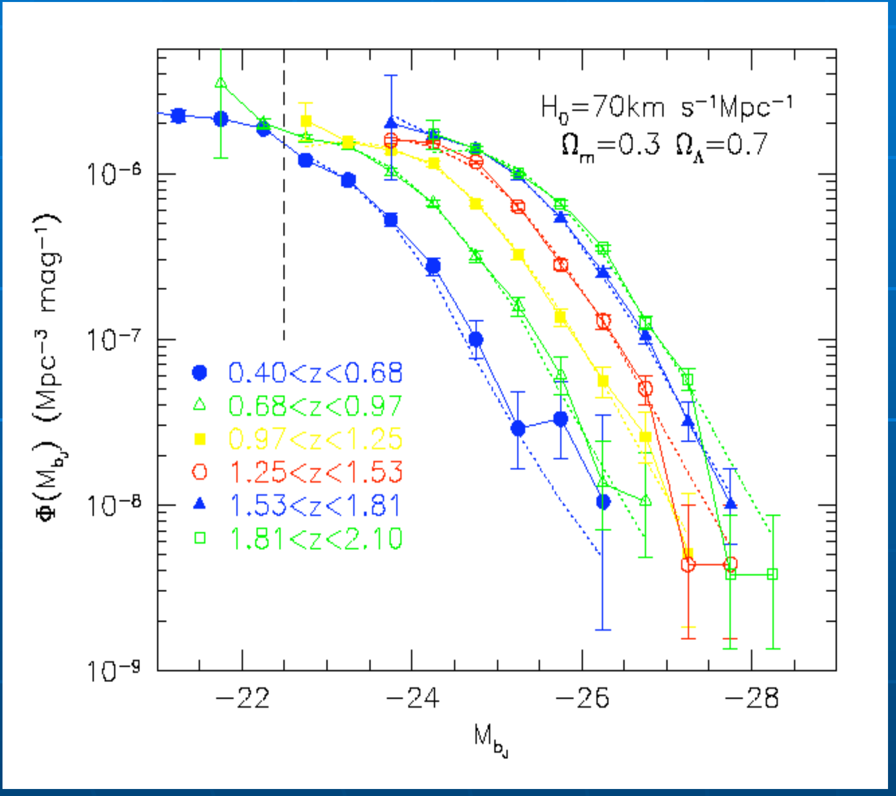
3) Photo-ionization models

- given $L_{continuum}$, at which R do emission lines form?
- Calibrate from method 2)

$$\log M_{BH}(H_\beta,\ \text{rms or S-E}) = \log\left\{\left[\frac{\text{FWHM(C IV)}}{1000\ \text{km s}^{-1}}\right]^2\left[\frac{\lambda L_\lambda(1350\ \text{Å})}{10^{44}\ \text{ergs s}^{-1}}\right]^{0.7}\right\} + 6.2 \pm 0.03(\pm 0.45)\ .$$

Cosmic Evolution of the AGN Activity

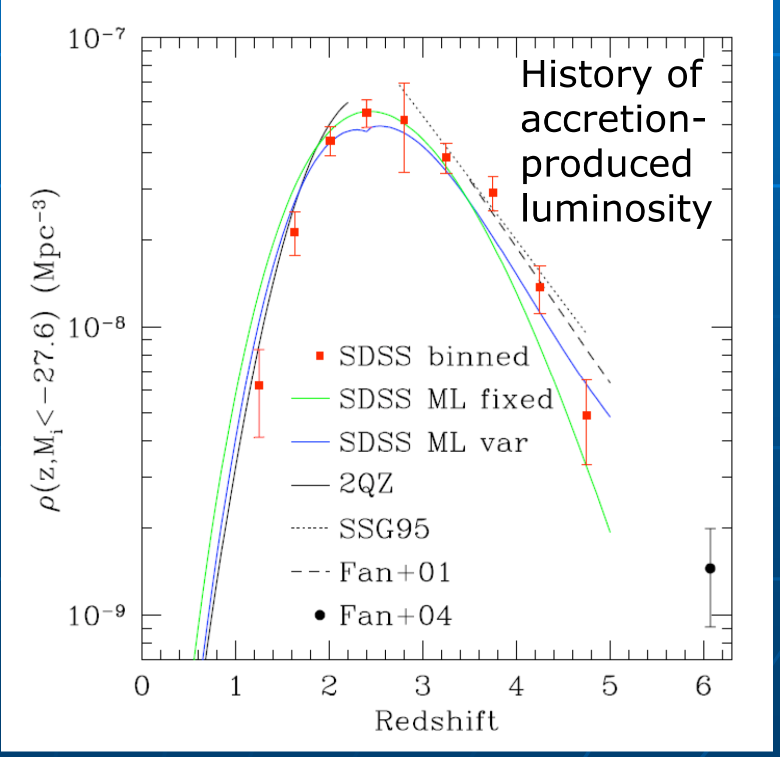
- Describe the distribution of accretion luminosities at different cosmic epochs by the "quasar-luminosity-function" at different redshifts



2DF Survey: Croom et al 2004

Abundance of luminous QSOs has decreased by 2 orders of magnitude since early epochs!

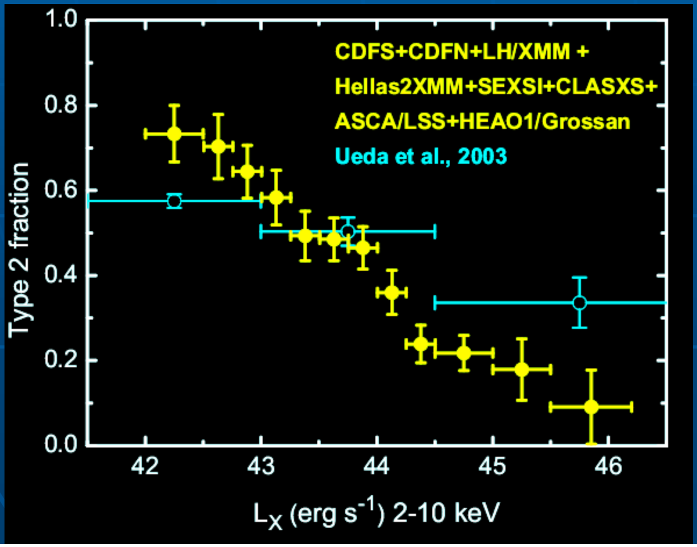
(e.g. SDSS Richards et al 2006)

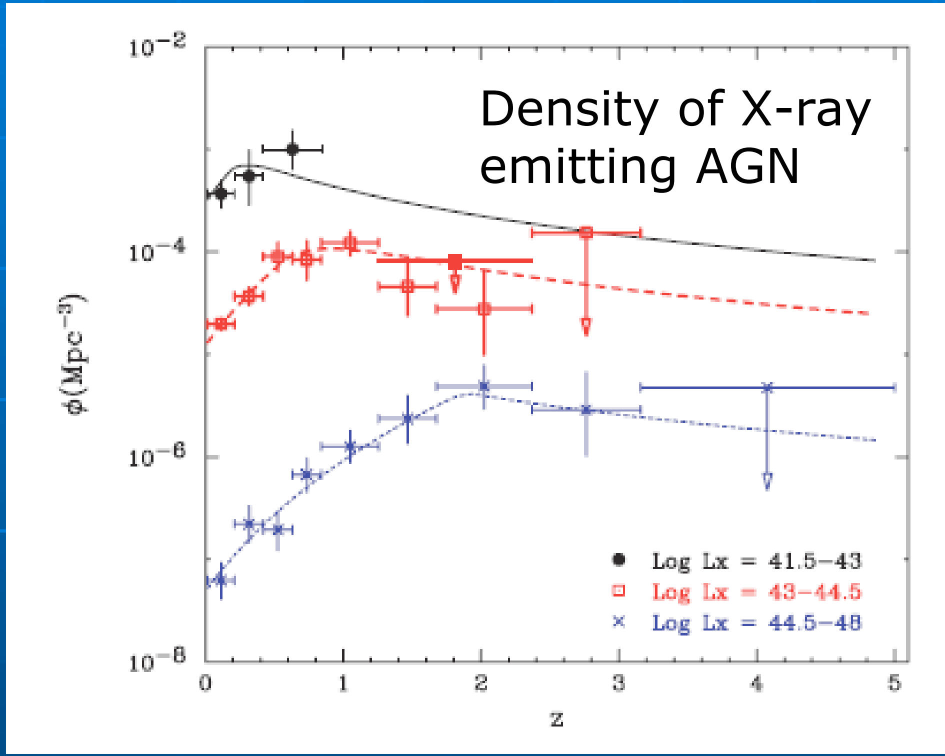


Note the 'Cosmic Evolution' for less luminous AGN looks different ('downsizing')

- If AGN luminosity is less drastic, not all material may get blown out → obscured AGN → still detectable in X-rays or mid-IR
- Density of X-ray AGN accretion

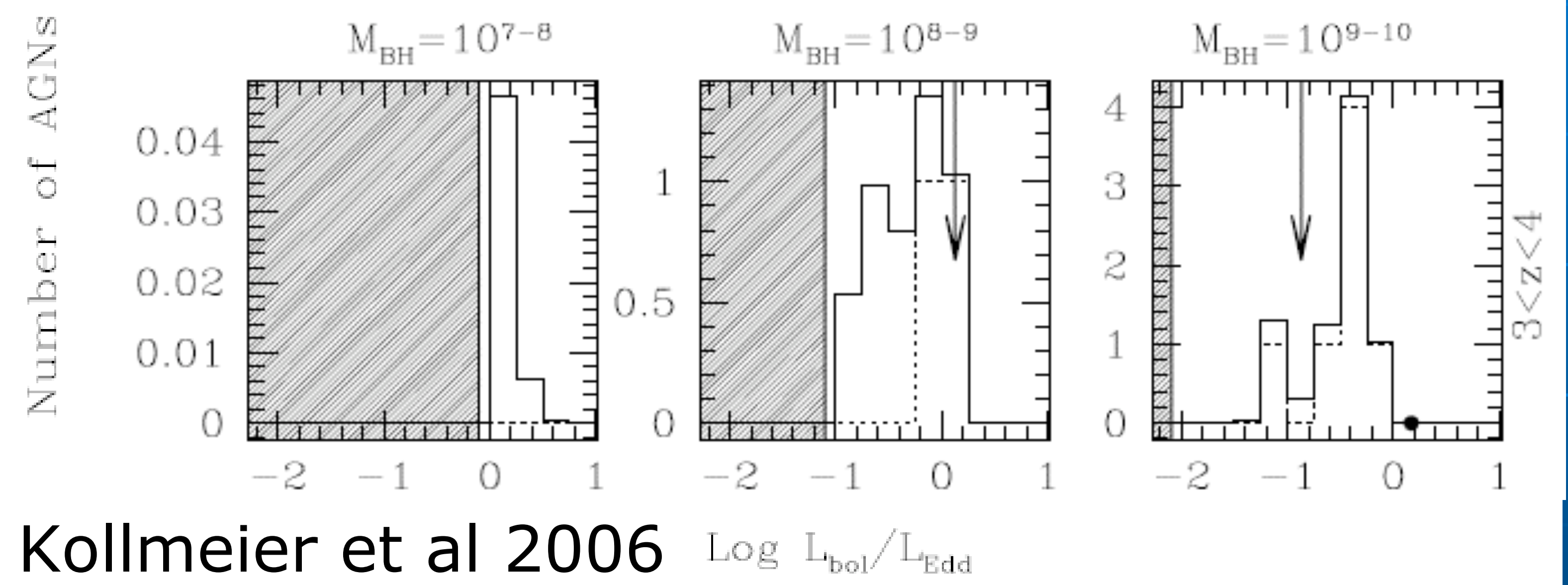
Ueda et al 2003





How do BH's increase the bulk of their in practice?

- Long-ish phases of $L<<L_{Eddington}$?
- Is most growth at $L \sim L_{Eddington}$ with off-state in between? (it seems that this is the case..)



Kollmeier et al 2006

- If galaxies merger, then their central black holes should merge, too….
  - Importance of this effect not known (yet)
  - Can BHs get ejected before merging?

Does the observed BH accretion match the present-day black hole density?

- Taking the MBH-s relation and using the stellar velocity dispersion measured by SDSS, one gets the present epoch debsity of (mostly dormant) black holes:

$$\rho_{\bullet,L}(z=0) \simeq 2.9 \times 10^5\, M_\odot\, \mathrm{Mpc}^{-3}.$$

- Integrating the (emitted) energy from AGNs, assuming

$$L_{rad}(\mathrm{optical}) \approx \varepsilon \frac{\dot{M}_{BH} c^2}{2} \quad \text{with } \varepsilon \sim 0.1$$

yields consistency!
(Yu and Tremaine 2002)

→ Do we ‘see’ most accretion?
→ Picture does ‘hang together’?

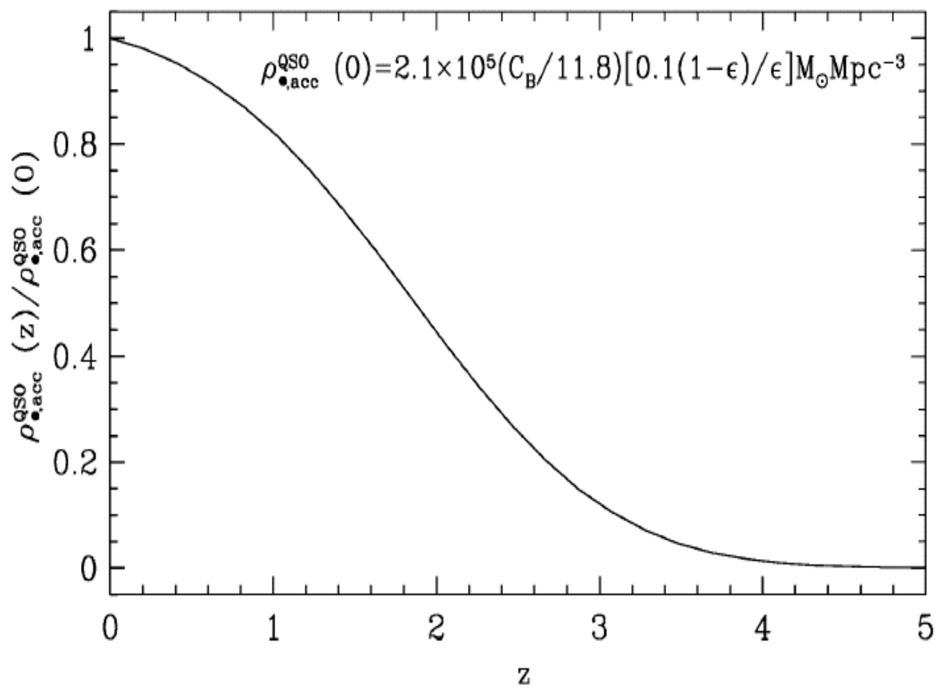


Figure 1. The history of the comoving massive BH mass density due to accretion during optically bright QSO phases. The QSO luminosity function

'Duty Cycle' and Lifetime of Luminous Accretion Phases

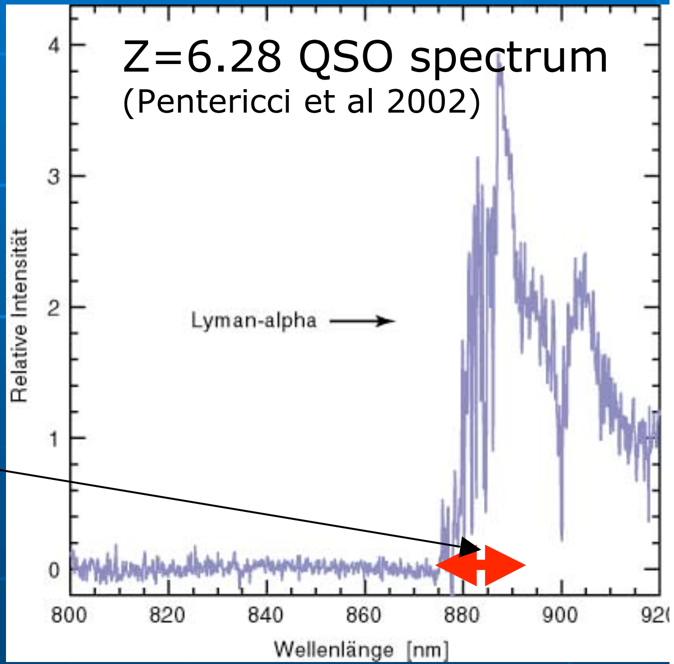
- Duty cycle, i.e. the fraction of time that a black hole is in a high accretion state

  If 1 galaxy ←→ 1 black hole

  $f \sim n_{AGN}(>L|z) / n_{Gal}(>M|z)) \sim 10^{-3}$

  Find corresponding galaxies and AGN via
    - Correlation function (equally clustered)
    - Host galaxies
    - Accretion history
- Lifetime (of individual luminous phase)
  - indirect arguments suggest few x 10^7 yrs
  - Direct: measure size of 'over-ionized' sphere around high-z QSO

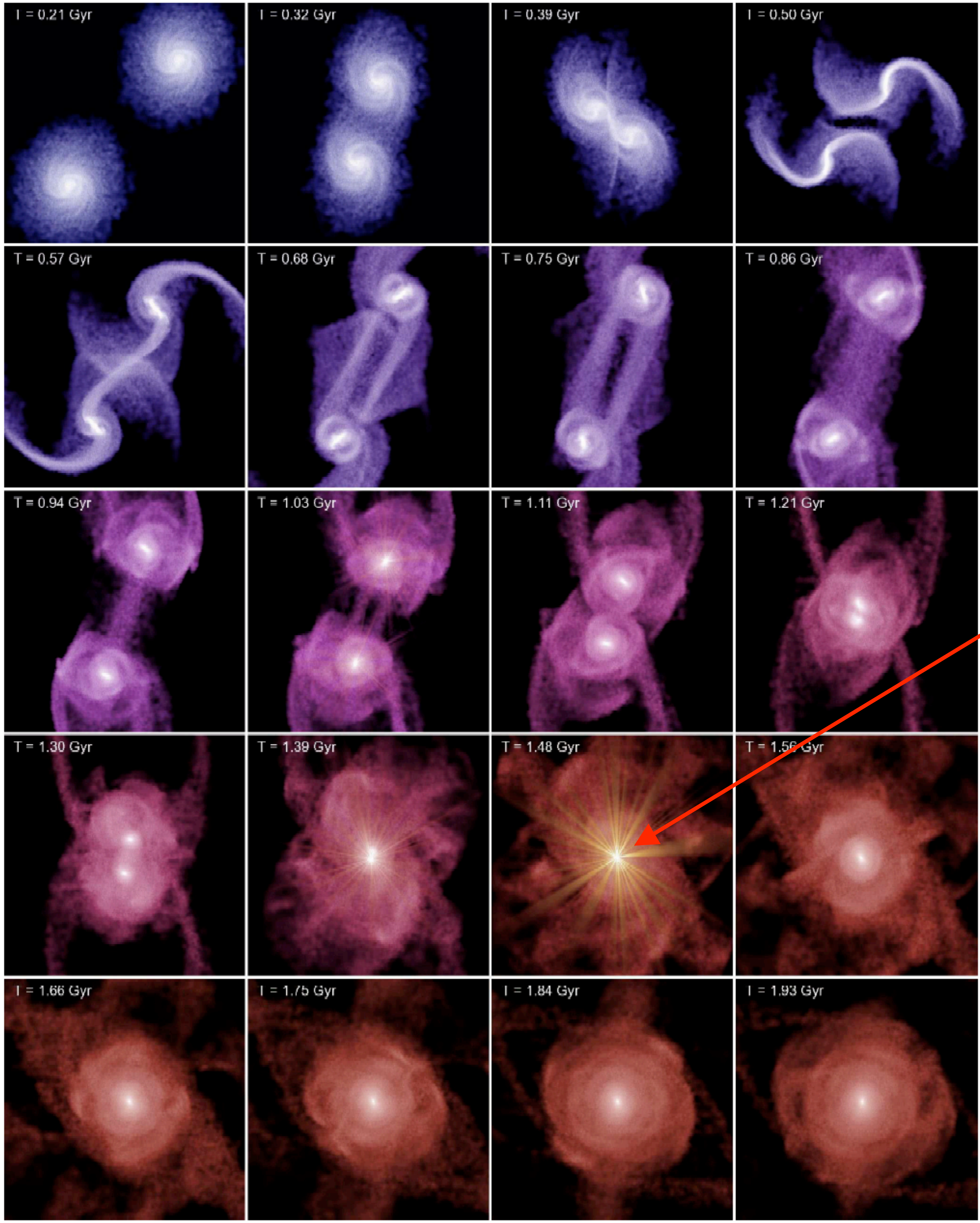
$$t_{\text{UV-bright lifetime}} > \frac{r_{\text{ionized}}}{c} = 2\times10^7\,\text{yrs}$$



  - Compare to e-folding time

$$t_{\text{Salpeter}} \approx \frac{M_{BH}}{\dot{M}_{BH}} = 4\times10^7 \left[\frac{\varepsilon}{0.1}\right] \text{yrs} \quad \text{at Eddington rate}$$

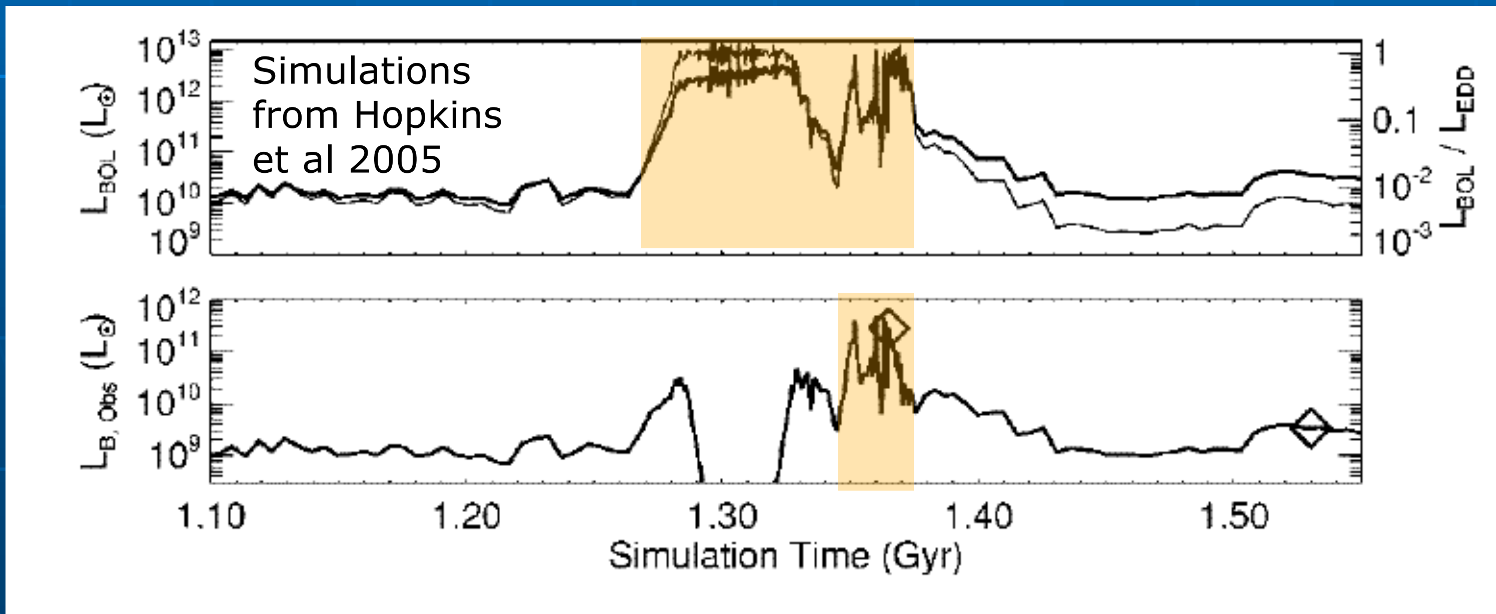
→ M_{BH} may e-fold in one QSO phase!



- QSO/AGN phases as shortlived stages of a galaxy merger where gas is being funneled to the center
- Hydrodynamical simulations by Hopkins and Springel

Scenarios emerging from these simulations:
Merger of gas rich galaxies
→ gas to the center → (dust-enshrouded) star-burst
→ black hole accretion → whose energy output blows out gas

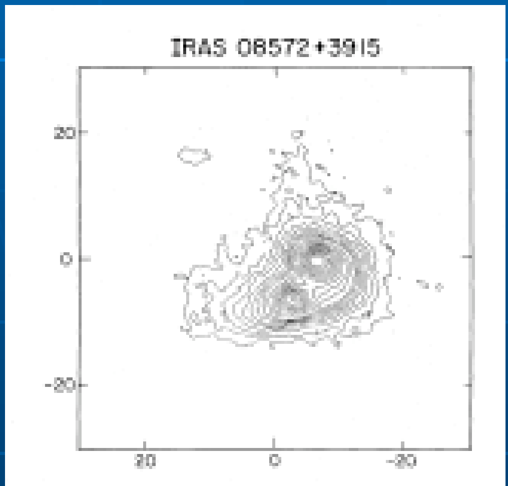
total accretion phase is longer than 'optically bright' QSO phase



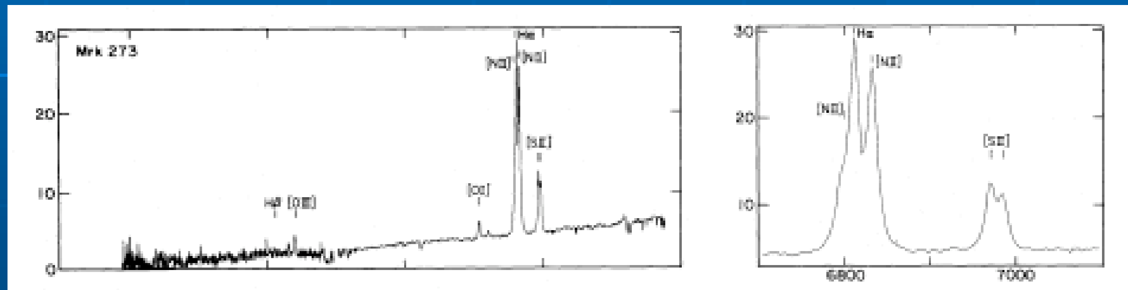
Observational Connection
ULIRGS and QSOs

- ULIRGS:
  ultra-luminous IR galaxies == dust-enshrouded star bursts
- QSOs: rapidly accreting supermassive black holes

- Sanders et al 1988 (>1000 citations!):
  - Mergers – ULIRGS - AGNs often occur together

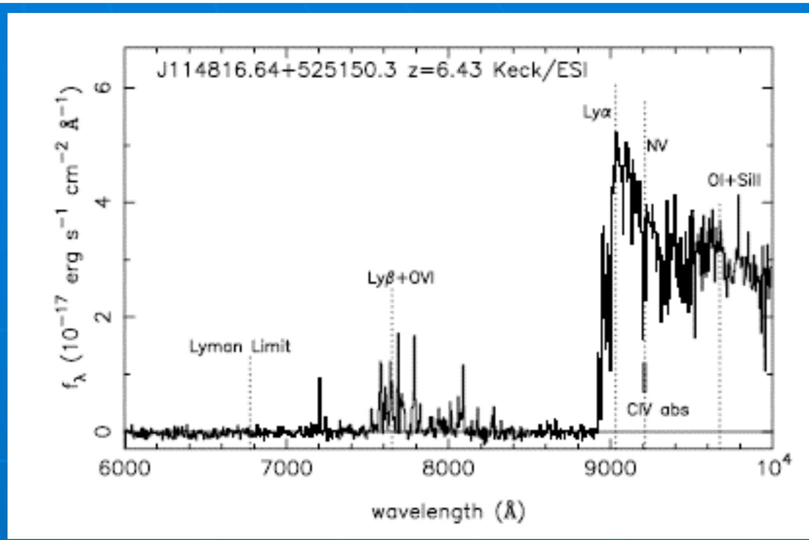


ULIRG morphology



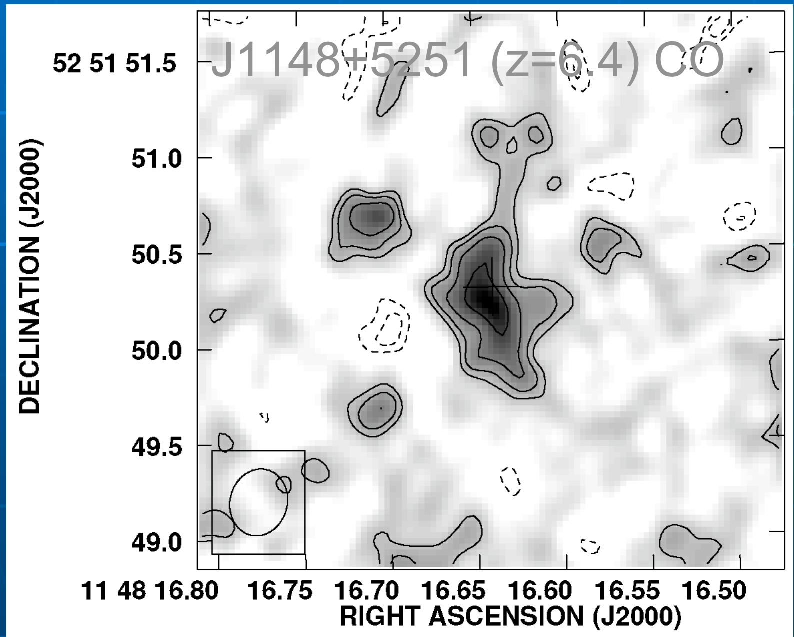
ULIRG spectra with AGN-like emission lines

The Nature of QSOs at very high redshift



startling intial example: J1148+5251 at z=6.42

Walter et al. 2004



- $M_{gas} = 2 \times 10^{10}\ M_{sun}$
- $M_{dyn} \sim 6 \times 10^{10}\ M_{sun}$
- $M_{BH} = 3 \times 10^{9}\ M_{sun}$

$M_{dyn} \sim 3\ M_{gas}$

$M_{dyn} = 20\ M_{BH}$

SFR ~ 1000 M/yr (?)

The highest z QSO is a merger -- star-burst -- massive accreting BH !

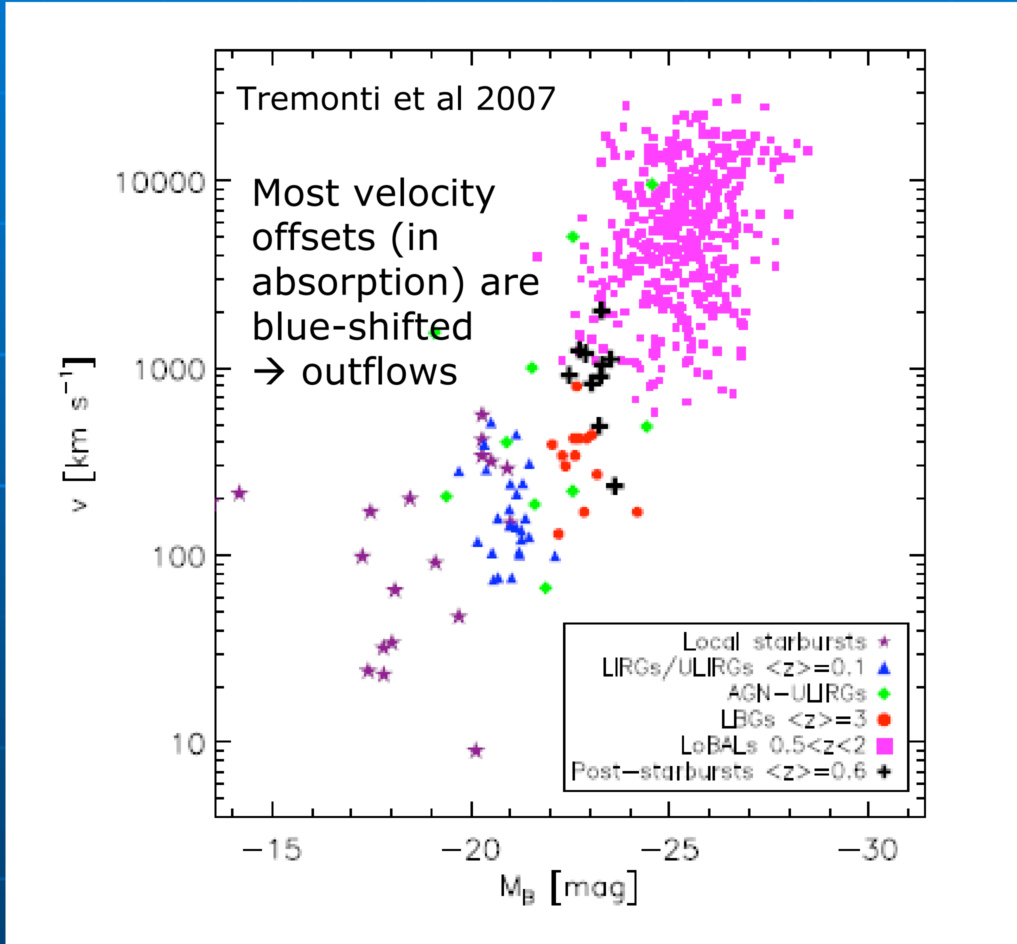
Are QSO's actually observed to drive gas out of galaxies, or does that just happen in the movies?

Is the sequence:

- Merger
- Gas inflow
- Star-burst
- Ramping-up of nuclear accretion
- "self-inflicted" shut-off of the phenomenon

  (=feedback)

right?



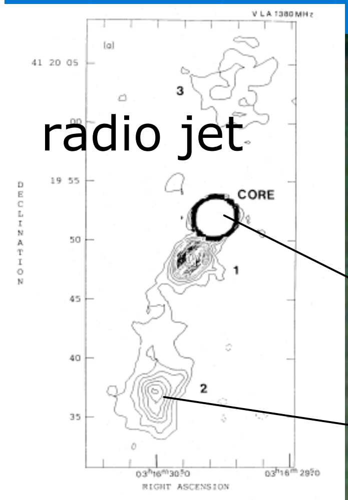
Also:

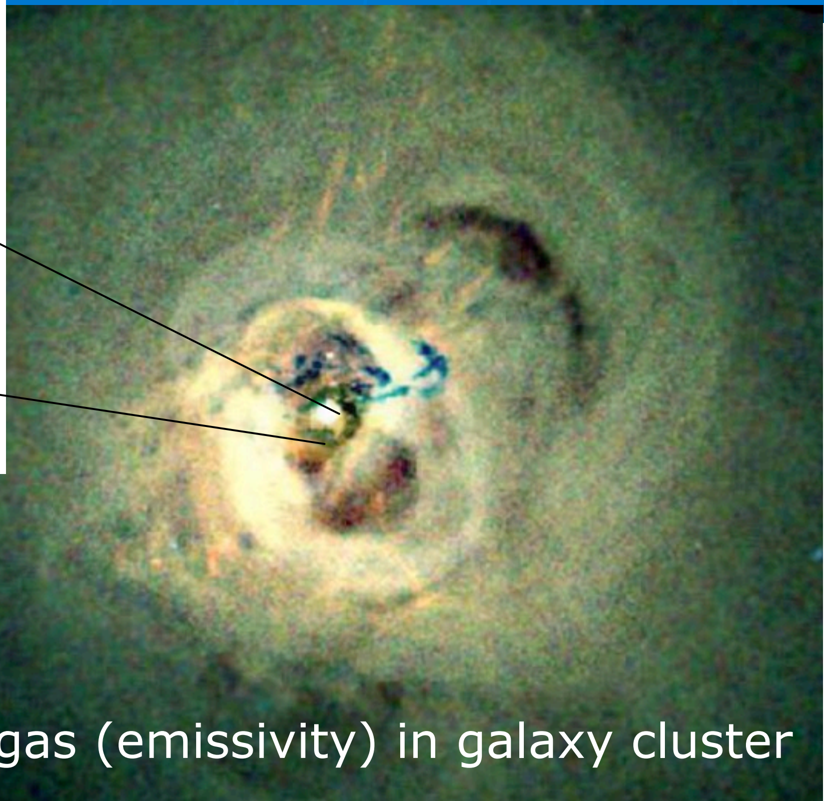
Read recent papers by Phil Hopkins

2006, ApJ, 163, 1

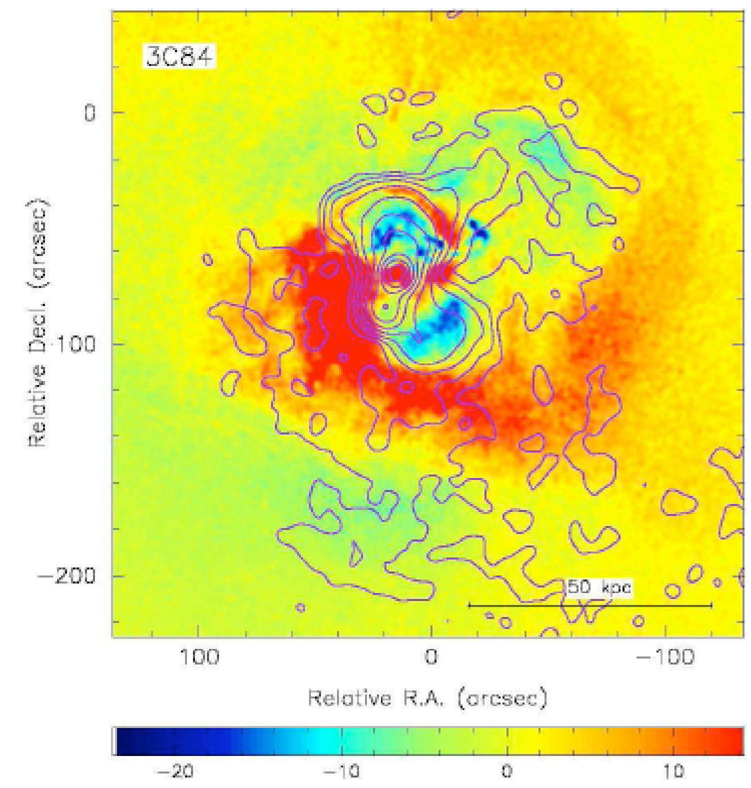
The Impact of AGN's on their Host Galaxies
Case study: radio AGN in the Perseus cluster

(e.g. Fabian et al 2003)





radio emission (relativistic particles) → X-ray (=gas) holes



Radio-mode feed-back (e.g. Croton et al 2006)

- only effective in (massive) halos that have 'hot' X-ray atmosphere
- energetic feed-back that requires no star-formation itself
- Efficiency increases with M_{BH} →? only effective after the BH has grown?

→ explanation of why massive galaxies no longer form stars?

Summary

- A wide range of energetic phenomena at galaxy centers can be explained best material accreting onto supermassive black holes.
- Dynamical/observational evidence for black holes is very solid in many objects
- Black holes are (nearly?) ubiquitous in the centers of nearby massive galaxies.
  - M_{Bh} correlates (surprisingly?) well with σ_* or M_*
- AGNs (quasars, etc,…) are *shortlived* phases in the lives of *normal* galaxies