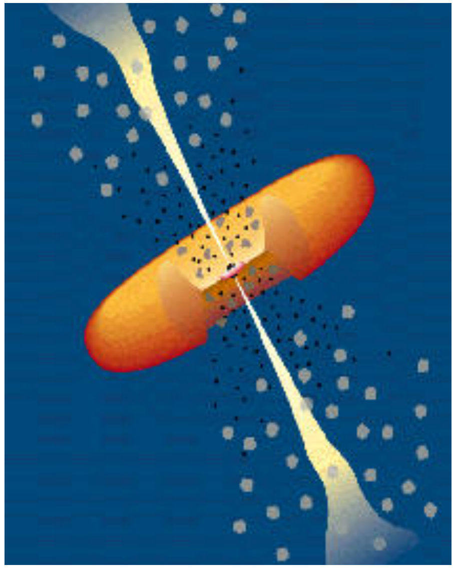
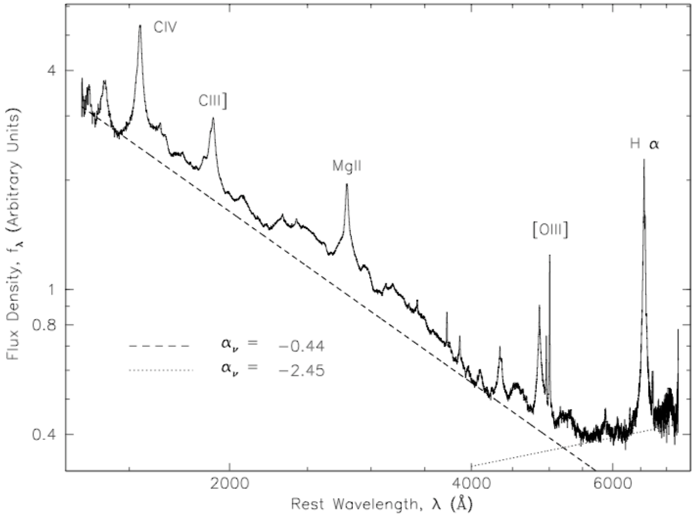
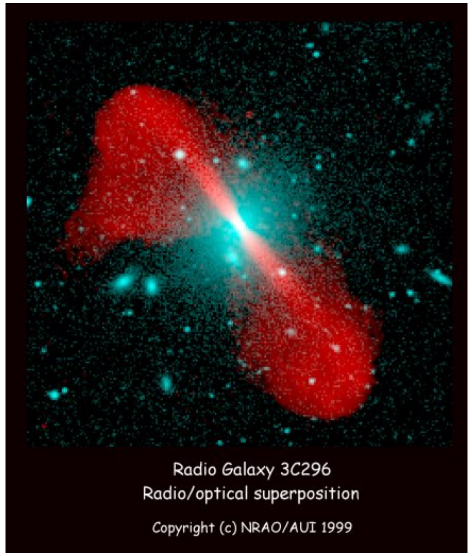


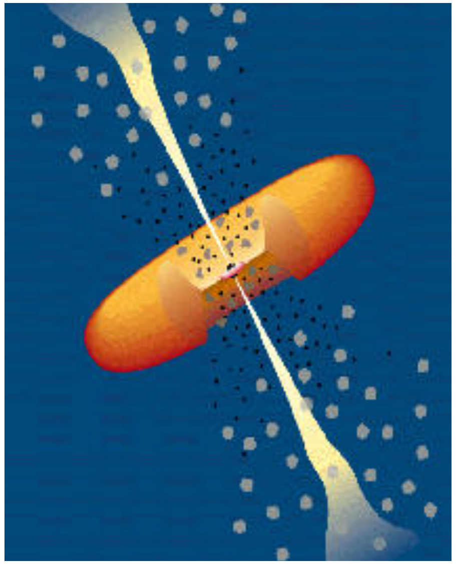


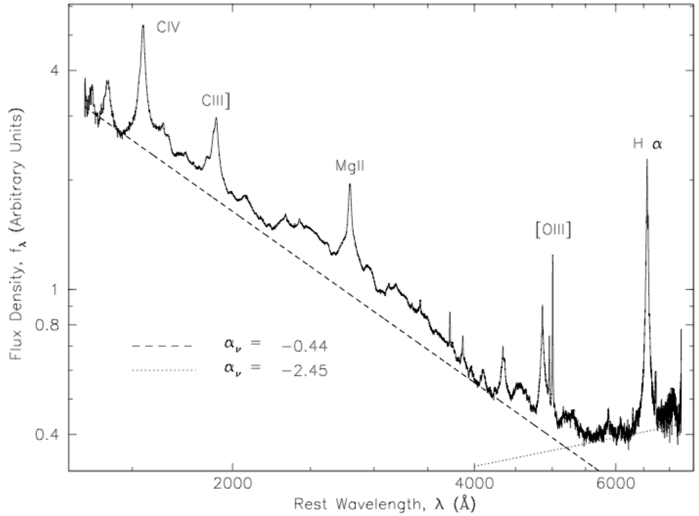



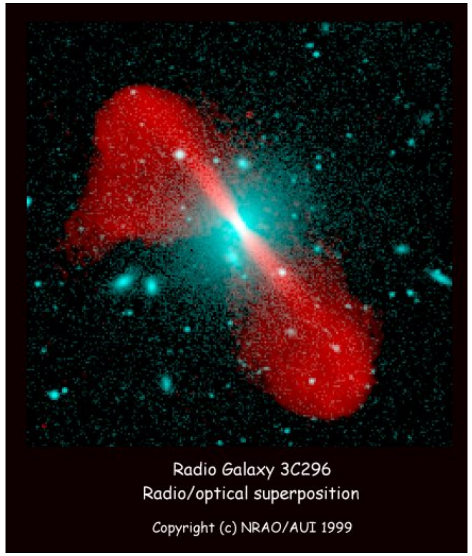

# Active Galactic Nuclei evolution

**Paolo Padovani, ESO, Germany**

- AGN main properties
- AGN evolution
- AGN masses and physical evolution
- The Big Picture and ~~our~~ my current understanding



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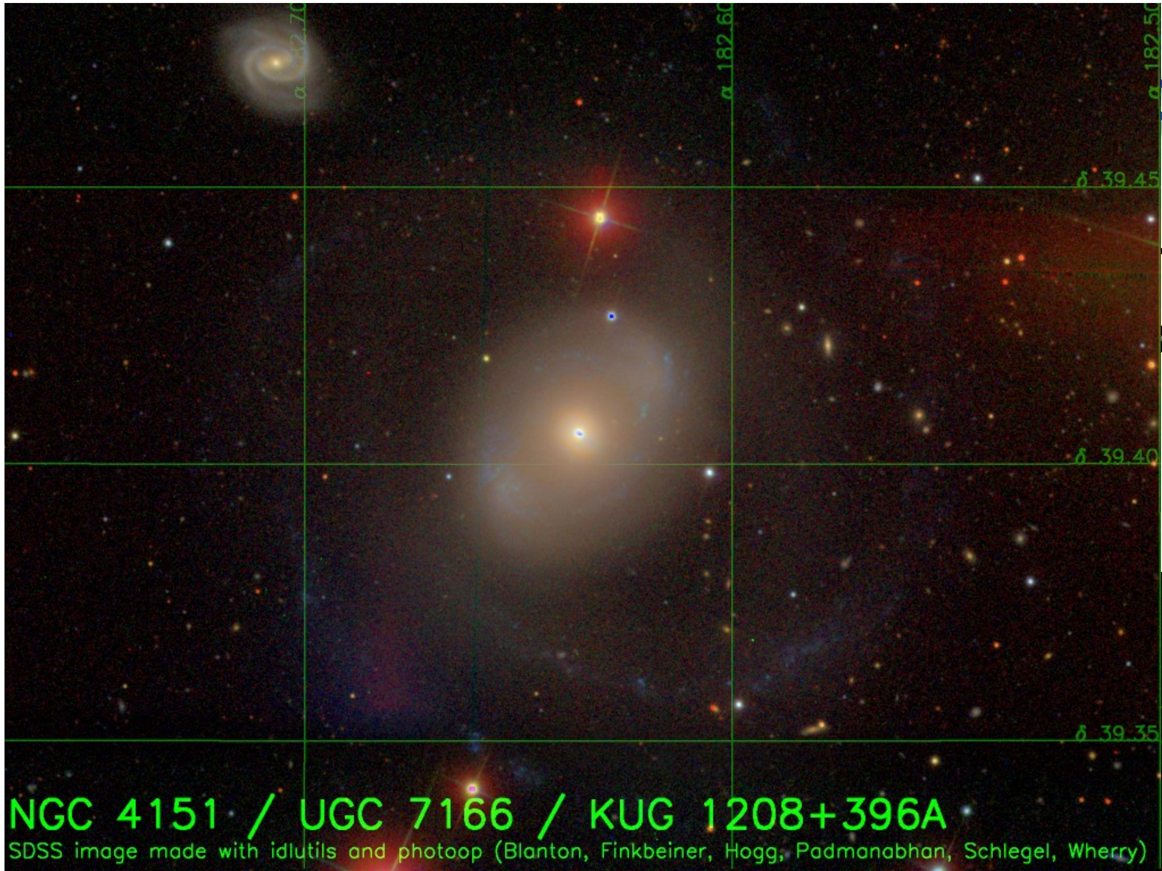
## Powerful AGN and Their Host Galaxies Across Cosmic Time

# Nuclei

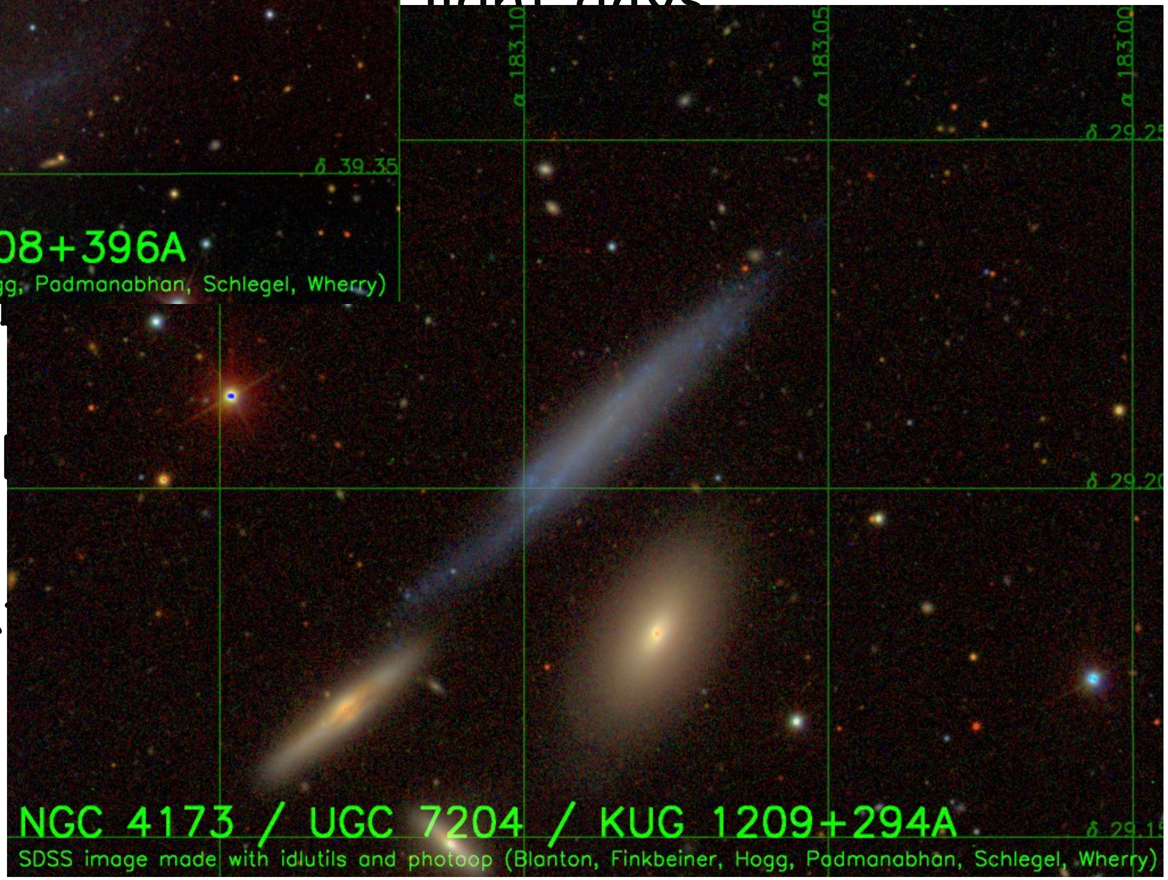



naracteristics include:
on-explosive" sources in

current record z = 7.1
light days

3. Broad-band, varia
the $\gamma$-ray band
4. Strong evolution:
at z ≈ 2

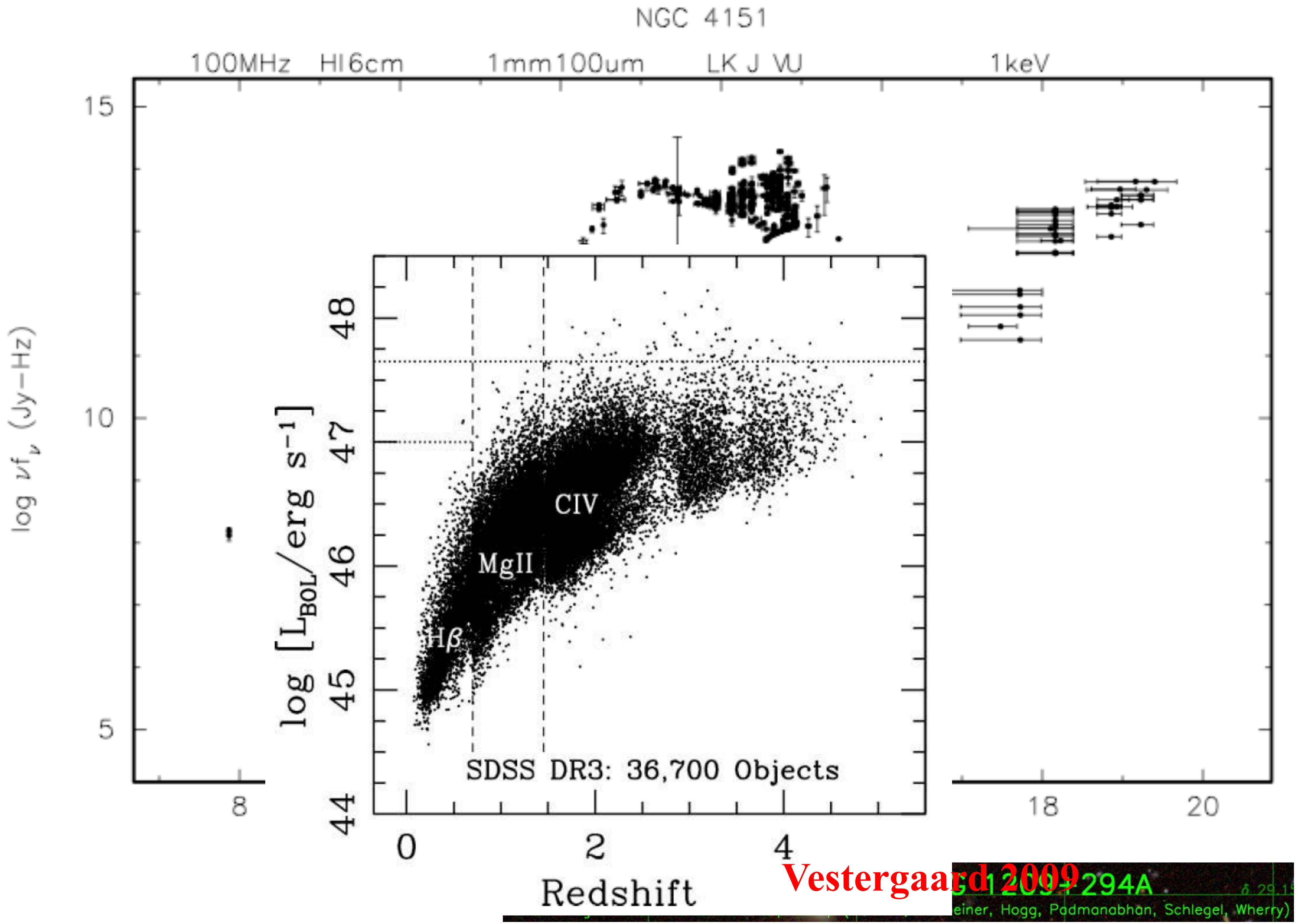
- AGN phenomenon rela



# Active Galactic Nuclei

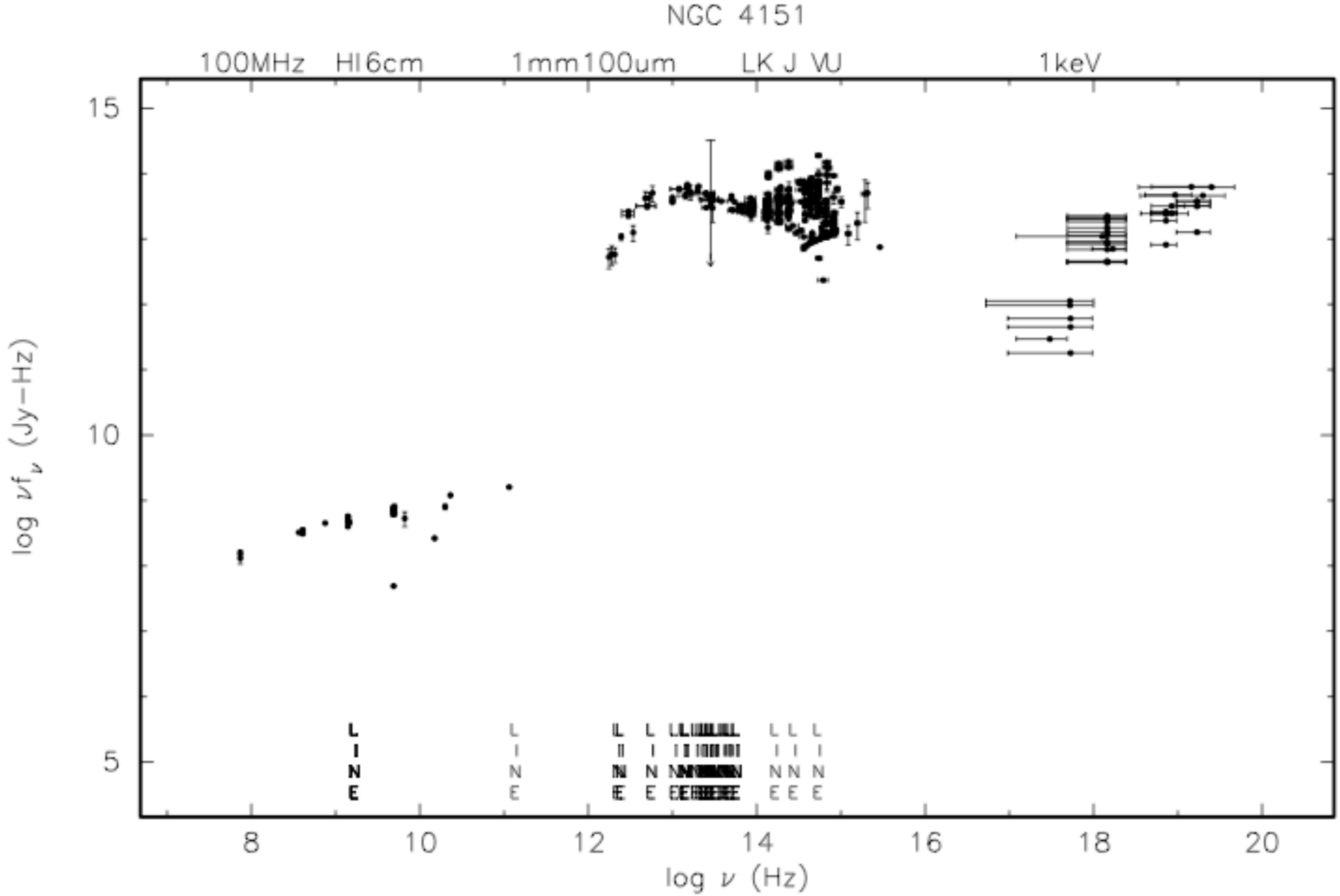
- Active Galactic Nuclei (AGN) main characteristics include:
  1. High powers: most powerful "non-explosive" sources in the Universe
     - ✓ visible up to large distances: current record z = 7.1
  2. Small emitting regions: ≈ a few light days (1 lt-day = 2.6 $10^{15}$ cm ≈ 1 millipc); $R \leq c\ t_{var}/(1+z)$
     - ✓ extremely large energy densities (≈ 1,000 galaxies packed in the Solar System!)
  3. Broad-band, variable emission: from the radio- to the $\gamma$-ray band
  4. Strong evolution: higher powers in the past, with peak at z ≈ 2
- AGN phenomenon relatively rare: it affects ≈ 1% of galaxies

# Nuclei




Vestergaard 2009

# Nuclei


NGC 4151
100MHz
HI6cm
1mm100um
LK J VU
1keV
log $\nu f_\nu$ (Jy−Hz)
log $\nu$ (Hz)
LINE


NGC 4173 / UGC 7204 / KUG 1209+294A
SDSS image made with idlutils and photoop (Blanton, Finkbeiner, Hogg, Padmanabhan, Schlegel, Wherry)

# Gravitational power

$$E_{acc} = \frac{GMm}{R} \qquad L_{acc} = \frac{GM\dot{m}}{R} = \frac{GM\dot{m}}{kR_S} = \frac{GM\dot{m}}{k\frac{2GM}{c^2}} = \frac{c^2}{2k}\dot{m}$$

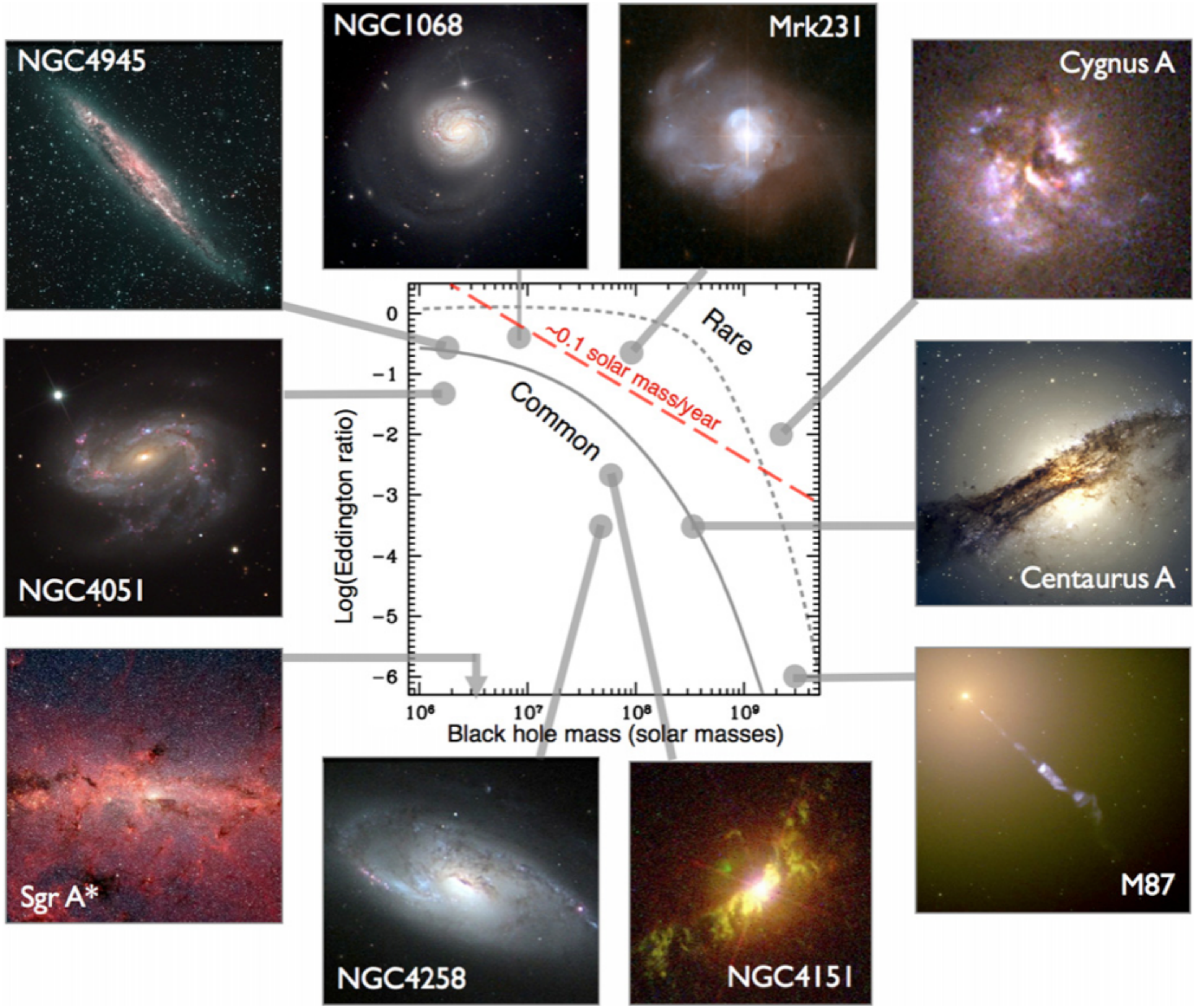
$$\boxed{L_{acc} = \eta \dot{m} c^2}$$

$\eta \simeq$ 0.06 non-rotating BH
$\eta \simeq$ 0.42 maximally rotating BH
c.f. $\eta \simeq$ 0.007 for Hydrogen burning

$$\dot{m} \cong 2\frac{(L_{acc}/10^{46})}{(\eta/0.1)} M_{\odot}/yr$$

$$L_{Edd} = 1.3\ 10^{46}(M/10^{8} M_{\odot}) erg/s$$

$L/L_{Edd}$ measures how close to maximum accretion a BH is


NGC4945
NGC1068
Mrk231
Cygnus A
NGC4051
Centaurus A
Sgr A*
NGC4258
NGC4151
M87
Rare
Common
~0.1 solar mass/year
Log(Eddington ratio)
Black hole mass (solar masses)
0
−1
−2
−3
−4
−5
−6
10⁶
10⁷
10⁸
10⁹

# The AGN Zoo

AGN come in a large (and scary!) number of sub-classes:

**Radio-quiet AGN**

Type 1 & 2, QSO, QSO2, Seyfert 1, Seyfert 2, Seyfert 1.5, Seyfert 1.8, Seyfert 1.9, Narrow-line Seyfert 1, Liners

**Radio-loud AGN**

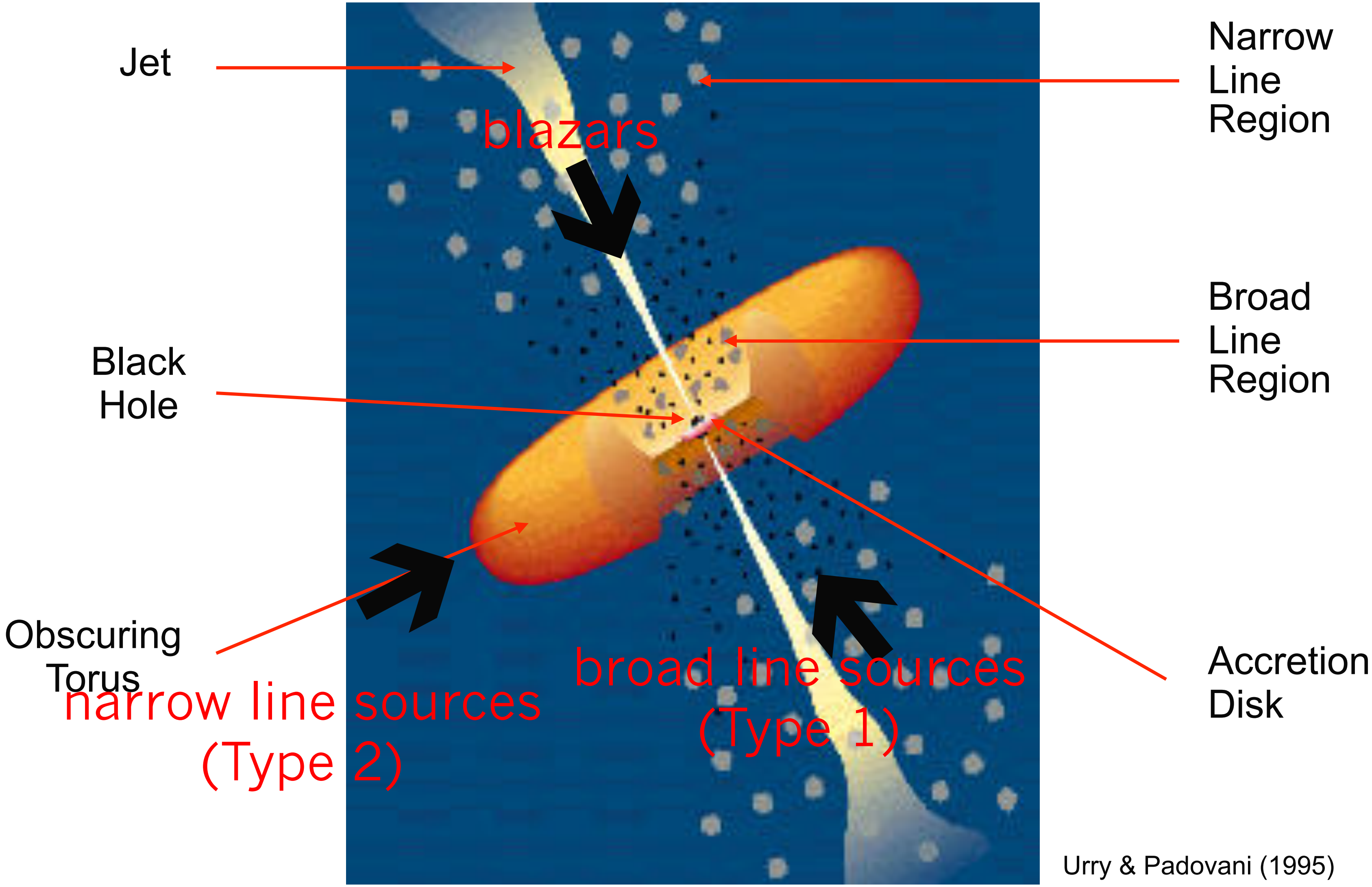
Type 1 & 2, blazars, flat- and steep-spectrum radio quasars, core-dominated, lobe-dominated, optically violent variable quasars, BL Lacertae objects (*high-peaked, low-peaked, radio-selected, X-ray selected*), high- and low-polarization quasars

Radio-galaxies: Fanaroff-Riley I & II, narrow-lined, broad-lined, high-excitation, low-excitation, GHz-peaked

# AGN "Really" Fundamental Parameters

- The full AGN variety can be explained by only three parameters:
  - ✓ angle; *Seyfert 1 – 2, radio quasars – radio galaxies, etc.* [apparent]

# AGN Unified Schemes




Urry & Padovani (1995)

# AGN "Really" Fundamental Parameters

- The full AGN variety can be explained by only three parameters:
  - ✓ angle; *Seyfert 1 – 2, radio quasars – radio galaxies, etc.* [apparent]
  - ✓ presence (or lack of) jets; *radio-loud – radio-quiet* [intrinsic]
  - ✓ accretion rate: [intrinsic]
    - ➢ $L/L_{edd} > 0.01 \rightarrow$ efficient accretors (radiative-mode AGN)
    - ➢ $L/L_{edd} < 0.01 \rightarrow$ inefficient accretors (jet-mode AGN)

# Number counts and evolution

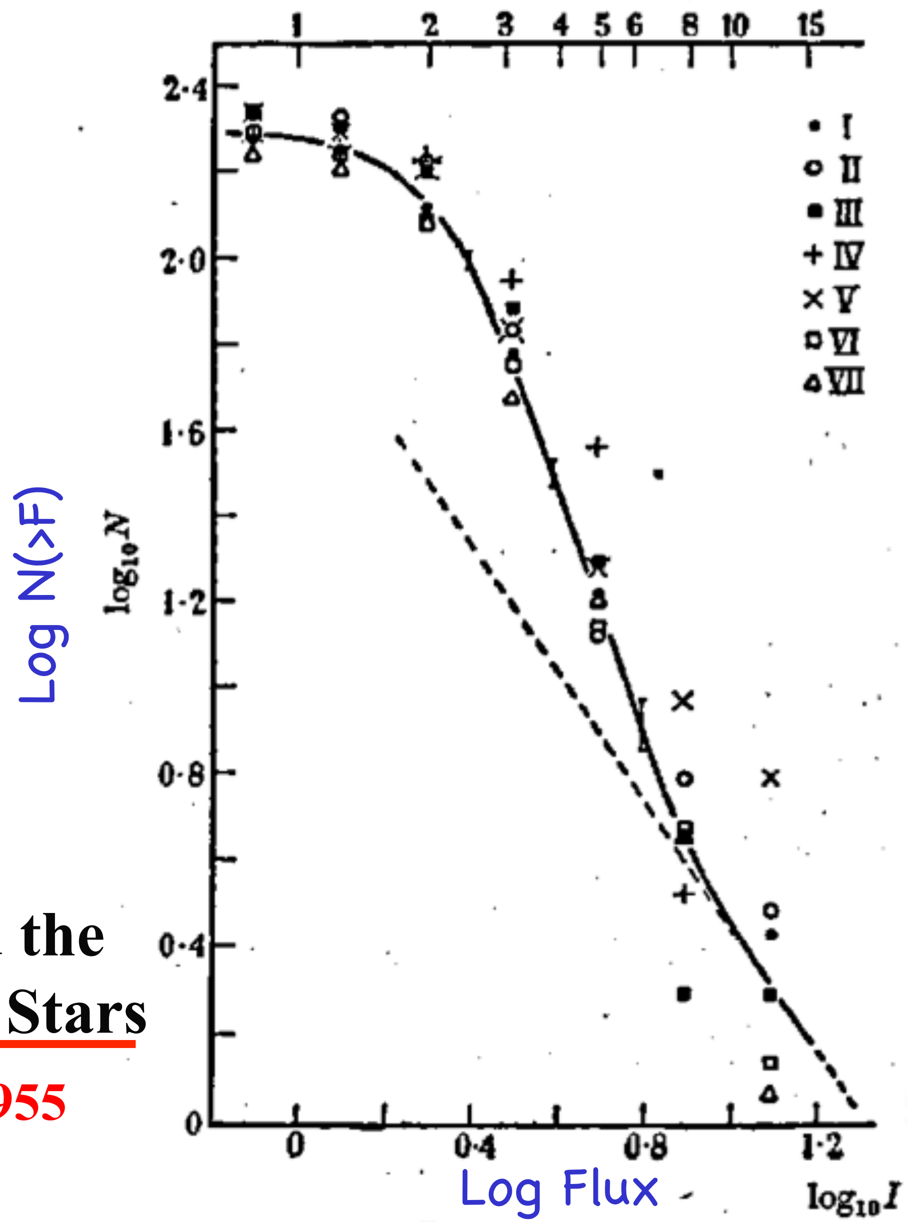



FIGURE 1

**The Spatial Distribution and the Nature of Radio Stars**

**Ryle & Scheuer 1955**

# Number counts and evolution

- Uniform distribution and Euclidean space:

Number $\propto D^3 = (L/4\pi S)^{3/2} \rightarrow N(\geq S) \propto S^{-3/2} \rightarrow N(S) \propto S^{-5/2}$

$$\frac{N(S)}{4\pi} = 4\pi \frac{c}{H_0} \int_{z_{\min}(S)}^{z_{\max}(S)} \frac{\phi[L(S,z),z] D_L^4(z) dz}{(1+z)^{(3-\alpha)} \sqrt{(1+z)^2(1+\Omega_m z) - z(z+2)\Omega_\Lambda}}$$

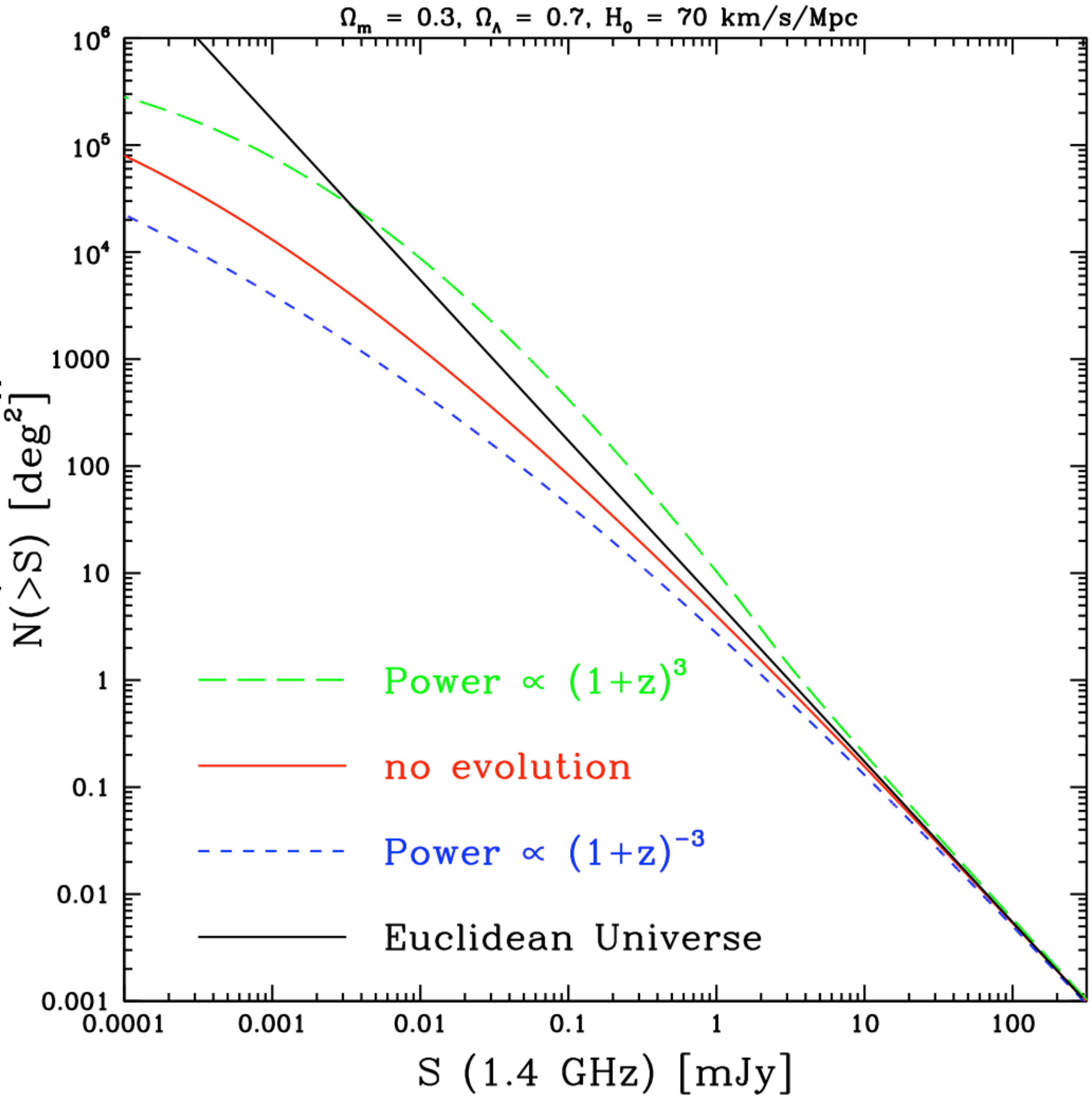
LF and its evolution

geometry

- Uniform

Number ∝

$$\frac{N(S)}{4\pi} = 4\pi$$

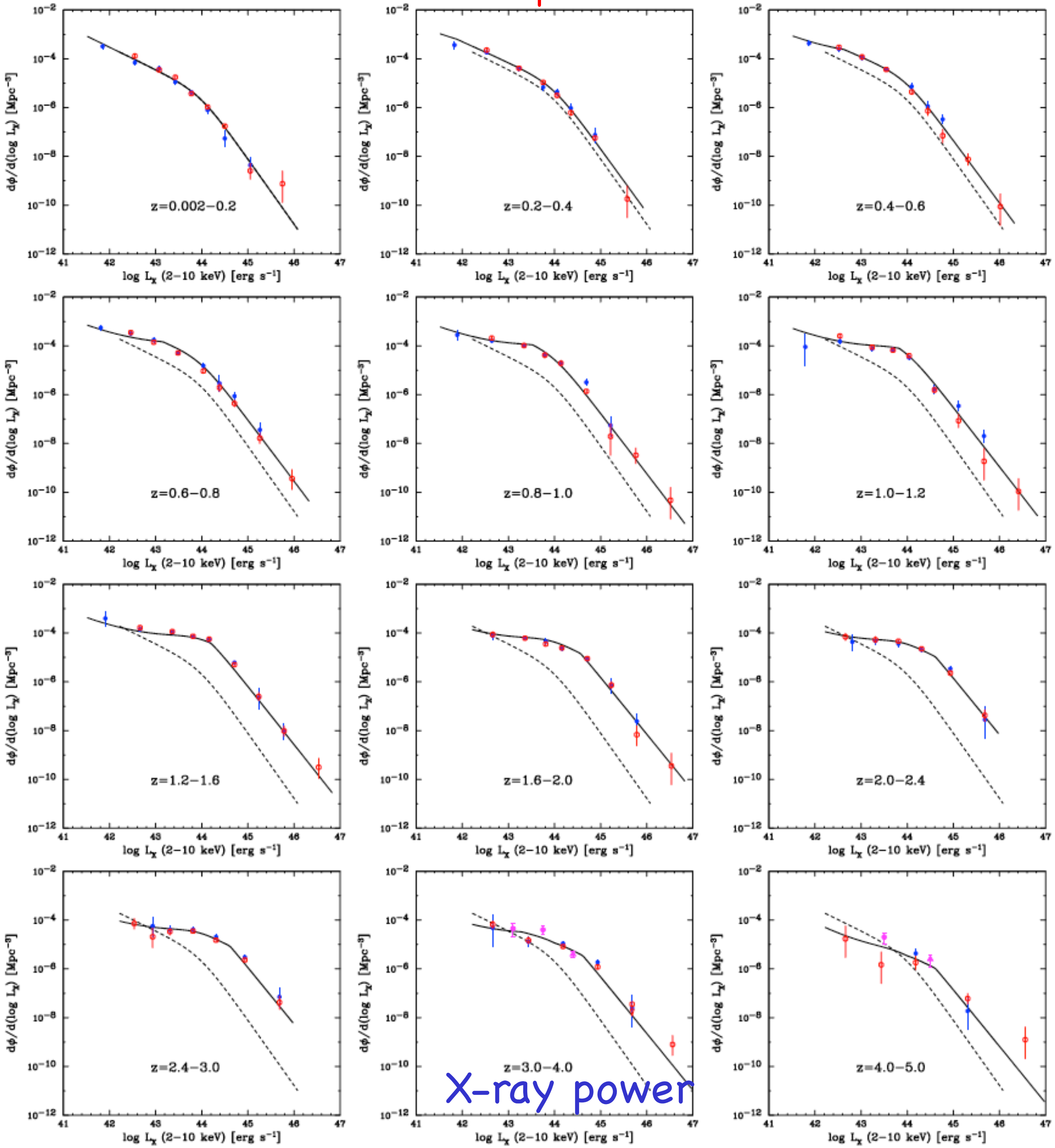



$= \Lambda$

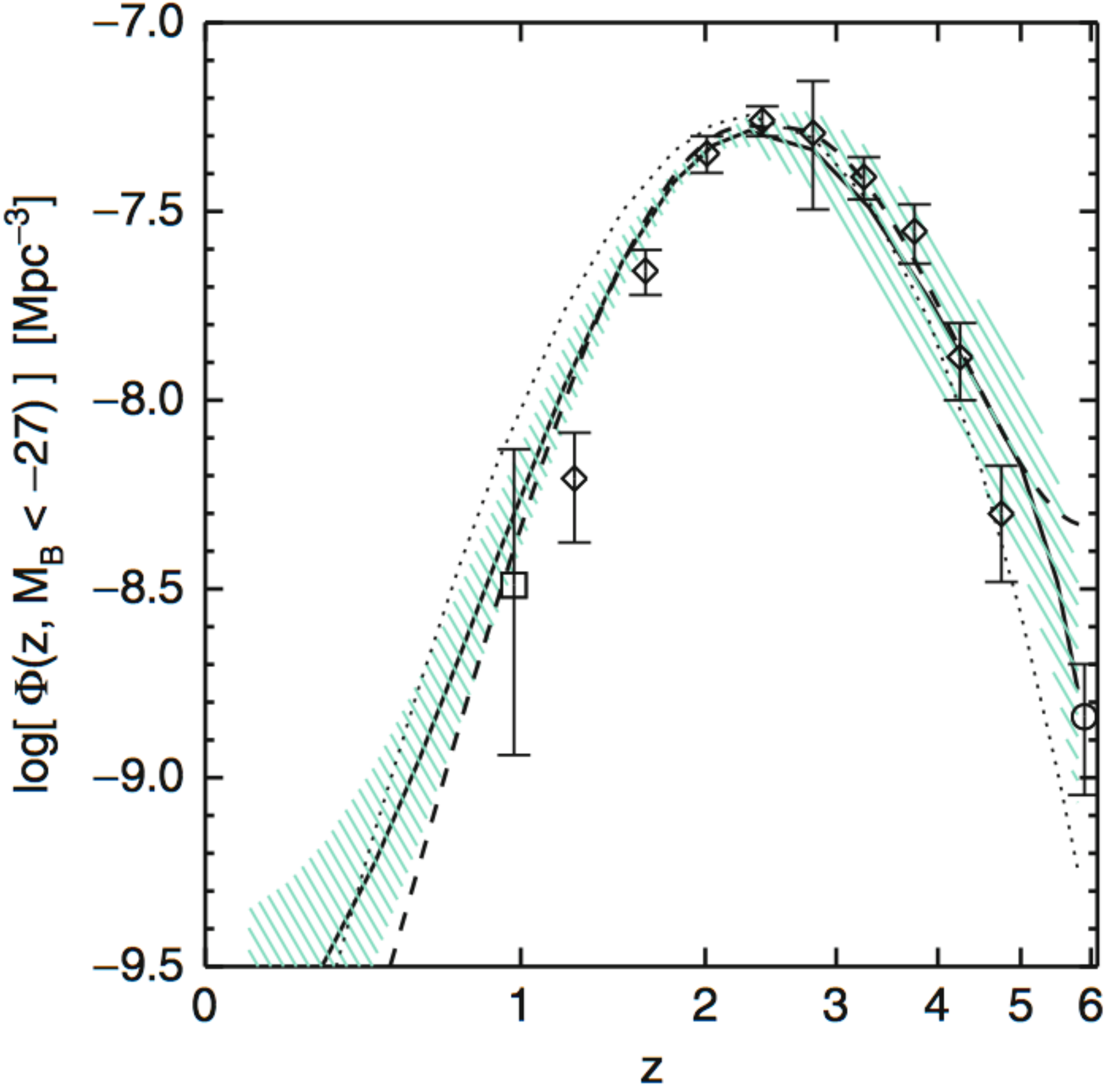
THE ASTROPHYSICAL JOURNAL, 786:104 (28pp), 2014 May 10 radio-quiet — efficient accretors UEDA ET AL.

X-ray

Number density




X-ray power




**Hopkins et al. 2007**

# Population vs. individual (physical) evolution

- Luminosity functions give us information on the ``population" history:
  - ✓ was the typical power larger at higher z? YES
  - ✓ were the typical number densities larger at higher z? YES
- Nothing can be inferred on ``individual" sources:
  - ✓ are the same sources being continuously active? ?
  - ✓ are most galaxies active only a small fraction of their lifetime? ?

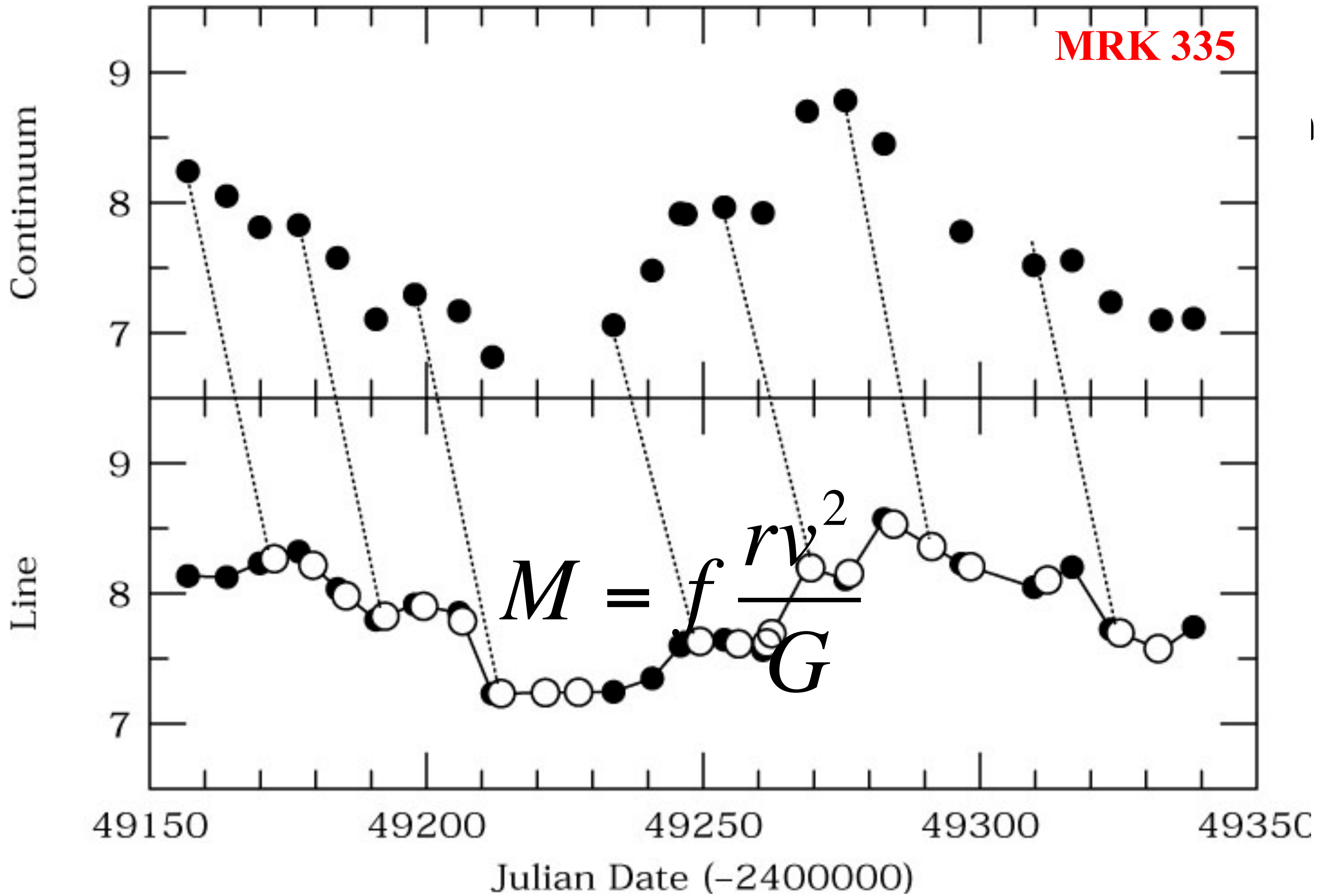
# AGN masses

- Estimated through the virial theorem applied to the broad line clouds
- $\langle T \rangle = -\langle U \rangle/2$: $mv^2/2 = GmM/2r \rightarrow M = rv^2/G$
- Two parameters needed:
  - ✓ velocity → from Doppler line broadening
  - ✓ distance → through "reverberation mapping"

$$M = f\,\frac{rv^2}{G}$$

- Mass range: $10^6 - 10^9$ Mo
- Almost always $L \lesssim L_{Edd}$

# AGN masses




$$M = f\frac{rv^2}{G}$$

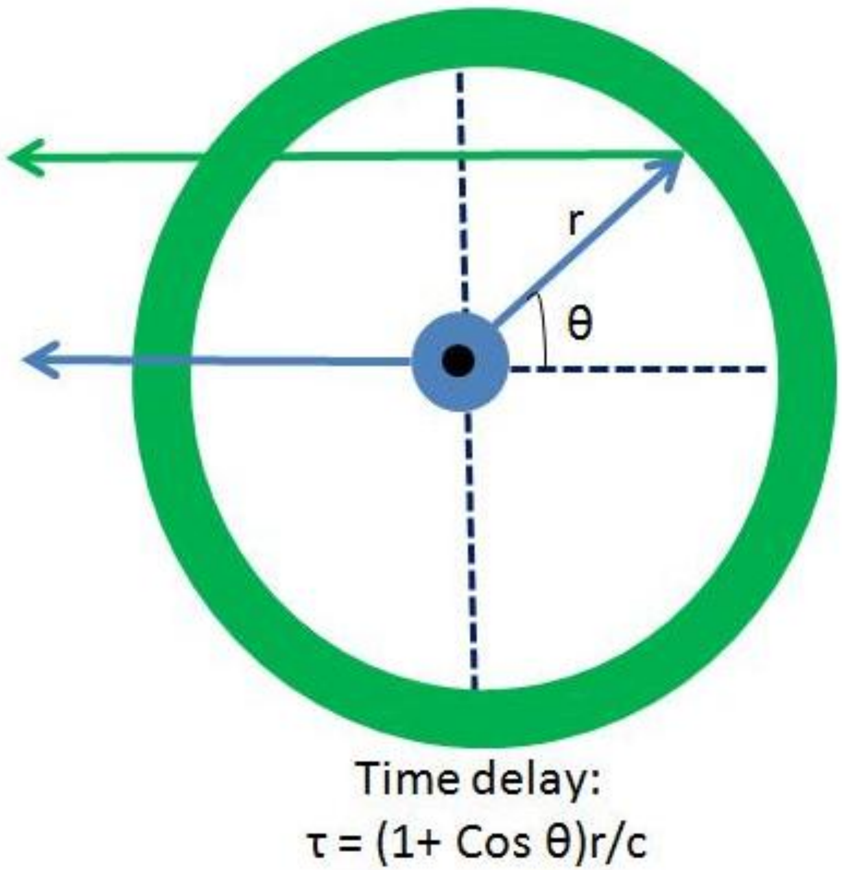
ıe

Peterson 2001

# AGN masses

**MRK 335**

- Estimated … plied to the broad line cl…
- $\langle T \rangle = -\langle U \rangle$, … $v^2/G$
- Two param…
  - ✓ velocit… ning
  - ✓ distanc… apping"




- Mass range: …
- Almost always $L \lesssim L_{Edd}$



**Peterson 2001**

# AGN physical evolution. 1.

$$M = \int \dot{m}\, dt + M_i = \frac{(1-\eta)}{\eta c^2} \int L(t)\, dt + M_i$$

$$M \cong 1.6\, 10^9 \frac{(L_{acc}/10^{46})(\Delta T/Gyr)}{(\eta/0.1)} M_\odot + M_i \quad (L = const!)$$

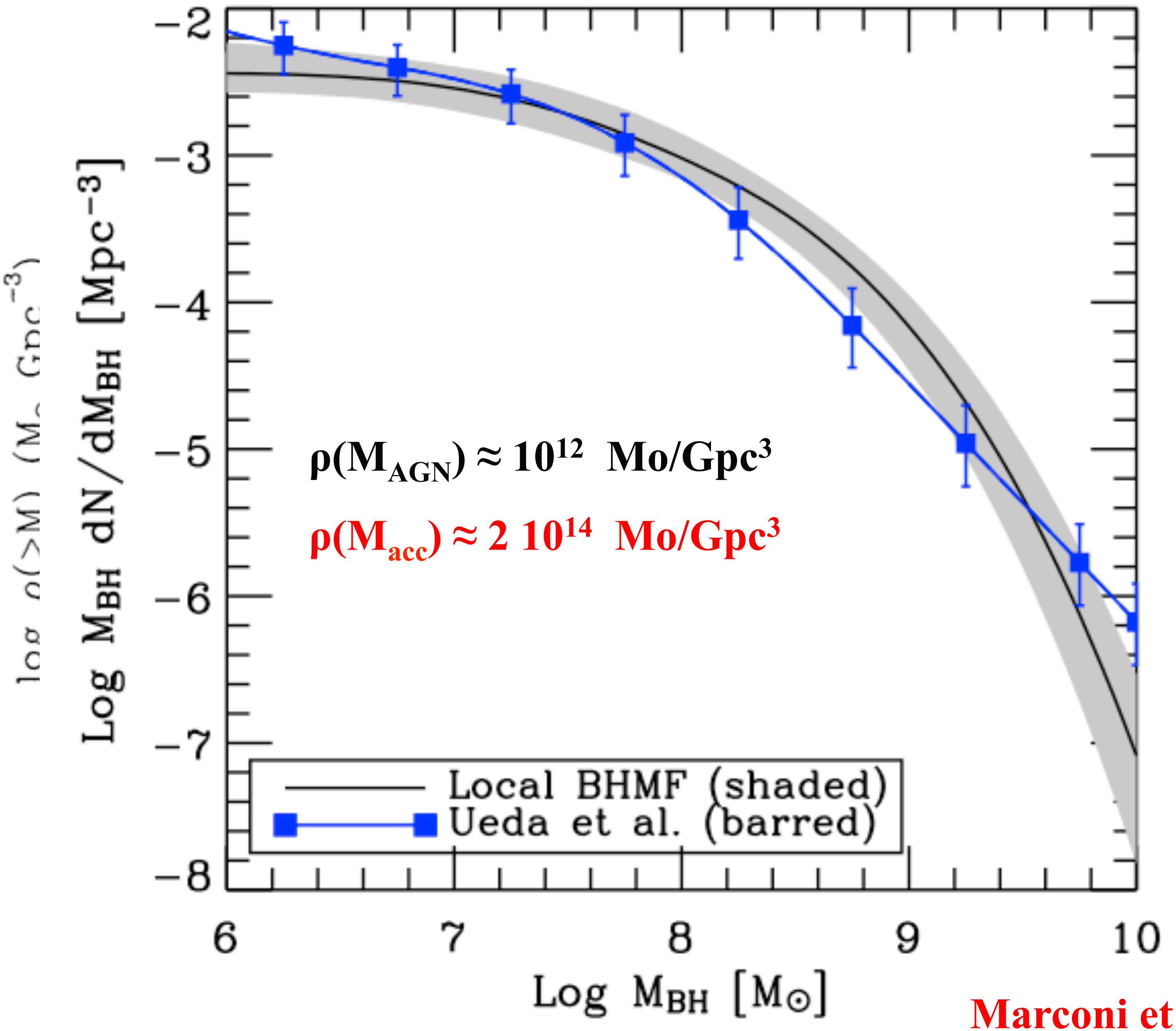
$$3C273 \qquad M \approx 10^9 M_\odot \,\&\, L_{acc} \approx 2x10^{46} erg/s \rightarrow \Delta T < 3\, 10^8\, yr$$

$$NGC4151 \qquad M \approx 5x10^7 M_\odot \,\&\, L_{acc} \approx 7x10^{43} erg/s \rightarrow \Delta T < 4\, Gyr$$

$$M87 \qquad M \approx 6x10^9 M_\odot \,\&\, L_{acc} \approx 10^{41} erg/s \rightarrow \Delta T < 370{,}000\, Gyr$$

# AGN physical evolution. 2.

- Efficient accretors (strong disk emission) must have been active (i.e. accreting at current rate) for $t \ll t_{Hubble}$
- Inefficient accretors (strong jet emission) must have been much more active (i.e. accreting at rate >> than current rate) in the past



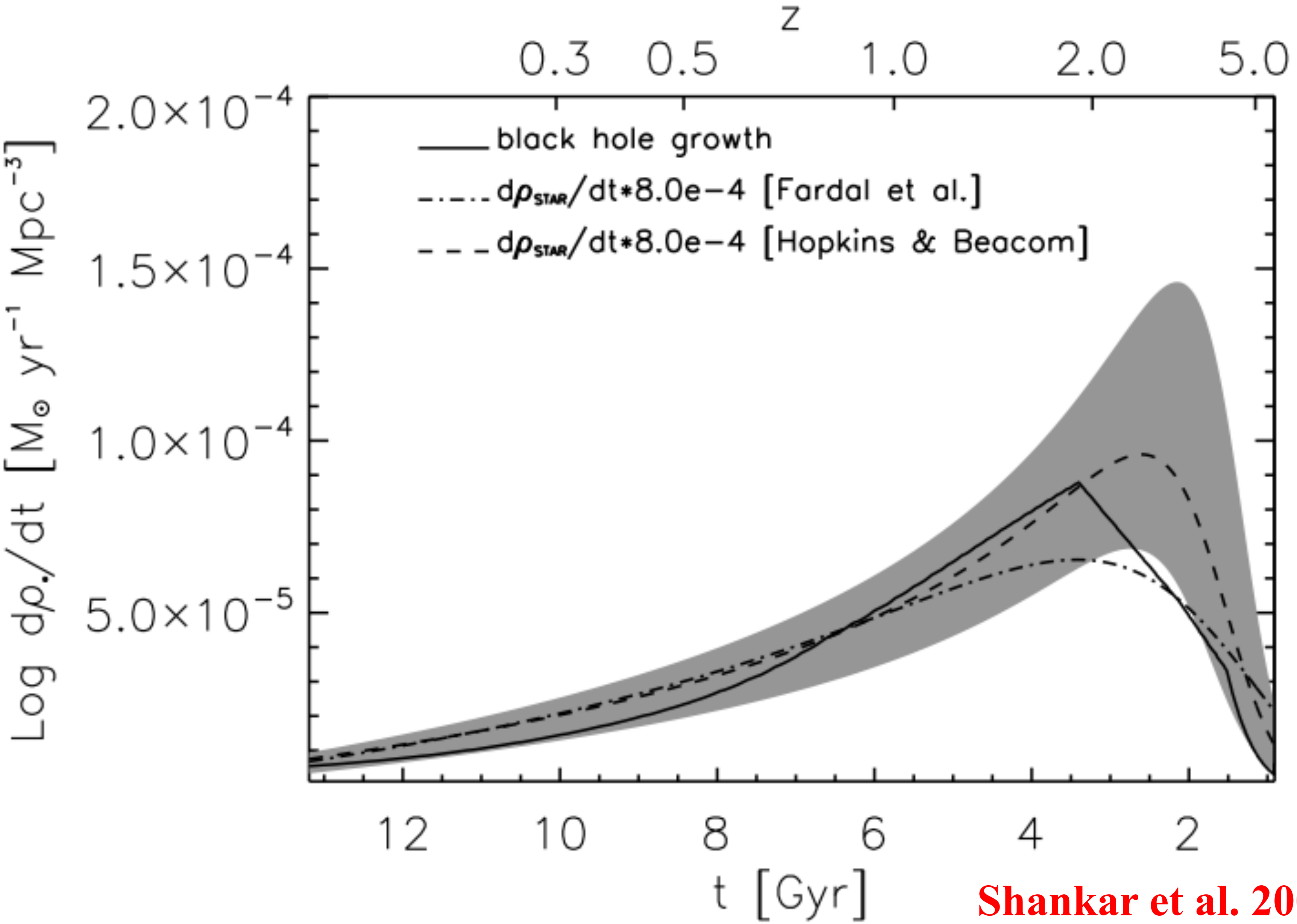

2)

y

.990

**Marconi et al. 2004**

# Why?
# The Big Picture: the AGN – galaxy connection




**Shankar et al. 2009**

# AGN Feedback: a simple estimate (adapted from Fabian 2012)

$$E_{\rm gal} \approx M_{\rm gal}\sigma^2 (\text{from U} \sim GM^2/R \text{ and taking } GM/R \approx \sigma^2)$$

$$E_{\rm BH} = \int L(t)dt = \eta c^2 \int \dot{m} dt = \eta M_{\rm BH} c^2$$

$$M_{\rm BH} \approx 5 \times 10^{-3} M_{\rm gal} \text{ (Kormendy \& Ho 2013)}$$

$$E_{\rm BH}/E_{\rm gal} \approx (\eta/0.1)\; 5 \times 10^{-4} (c/\sigma)^2$$

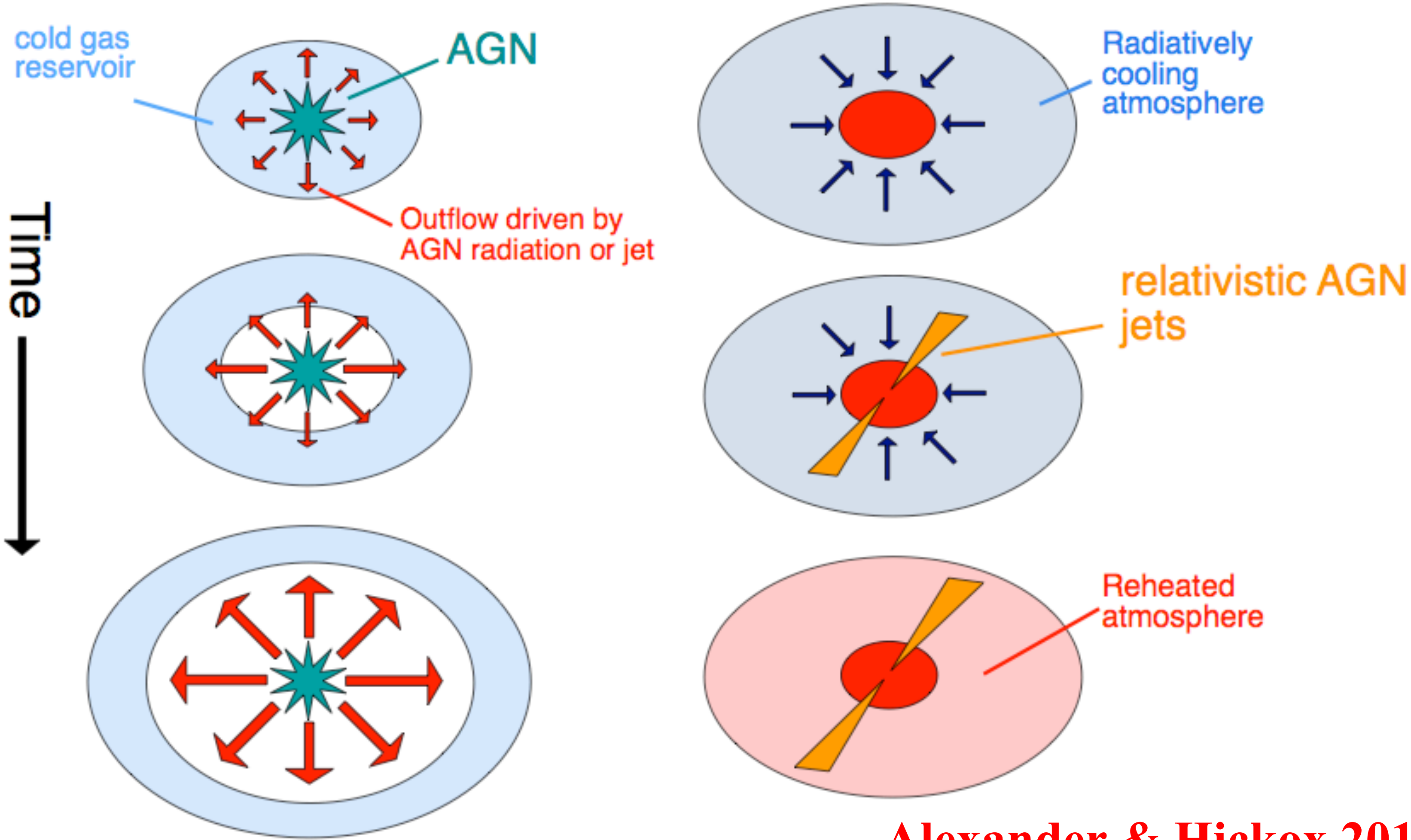
$$\sigma < 400 \text{ km/s} \rightarrow E_{\rm BH}/E_{\rm gal} > 280$$

## radiative-mode "Superwind"

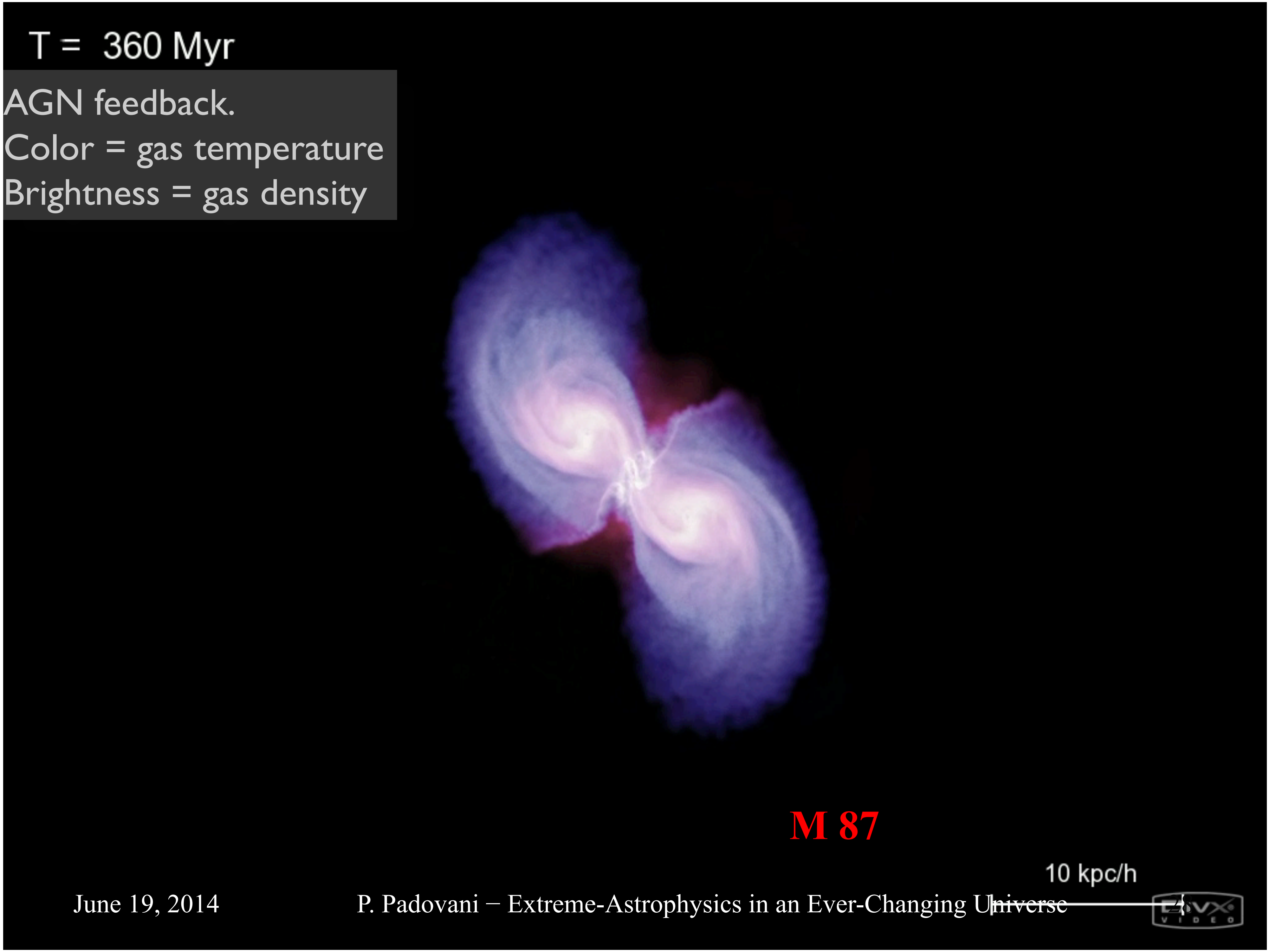
expels cold gas reservoir

## jet-mode "Radio"

reheats cooling atmosphere




**Alexander & Hickox 2012**


T = 360 Myr
AGN feedback.
Color = gas temperature
Brightness = gas density
10 kpc/h

**M 87**

The Astrophysical Journal, 782:9 (11pp), 2014 February 10 doi:10.1088/0004-637X/782/1/9
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# BLACK HOLE VARIABILITY AND THE STAR FORMATION–ACTIVE GALACTIC NUCLEUS CONNECTION: DO ALL STAR-FORMING GALAXIES HOST AN ACTIVE GALACTIC NUCLEUS?

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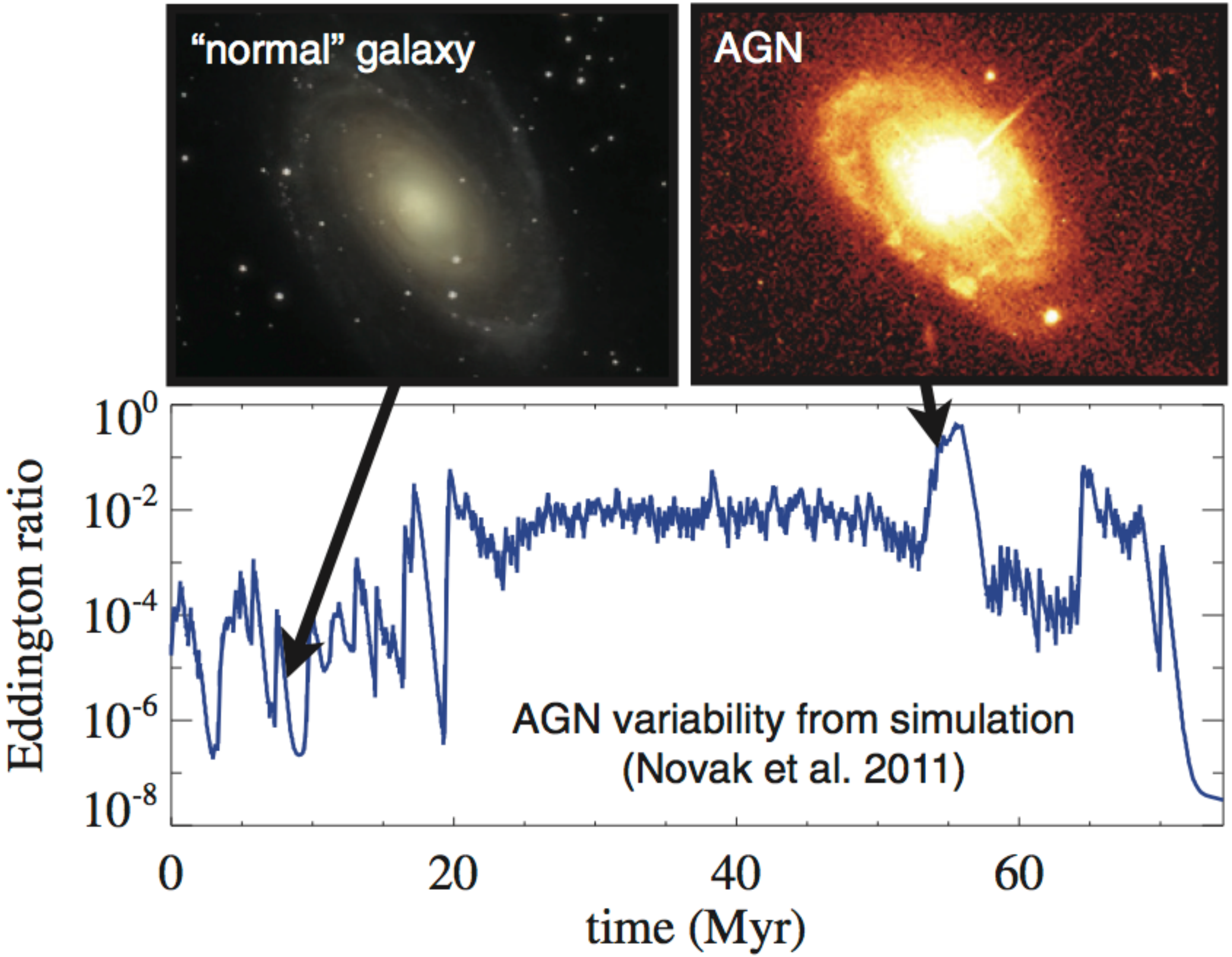
## ABSTRACT

We investigate the effect of active galactic nucleus (AGN) variability on the observed connection between star formation and black hole accretion in extragalactic surveys. Recent studies have reported relatively weak correlations between observed AGN luminosities and the properties of AGN hosts, which has been interpreted to imply that there is no direct connection between AGN activity and star formation. However, AGNs may be expected to vary significantly on a wide range of timescales (from hours to Myr) that are far shorter than the typical timescale for star formation ($\gtrsim$100 Myr). This variability can have important consequences for observed correlations. We present a simple model in which *all* star-forming galaxies host an AGN when averaged over ~100 Myr timescales, with long-term average AGN accretion rates that are perfectly correlated with the star formation rate (SFR). We show that reasonable prescriptions for AGN variability reproduce the observed weak correlations between SFR and $L_{AGN}$ in typical AGN host galaxies, as well as the general trends in the observed AGN luminosity functions, merger fractions, and measurements of the average AGN luminosity as a function of SFR. These results imply that there may be a tight connection between AGN activity and SFR over galaxy evolution timescales, and that the apparent similarities in rest-frame colors, merger rates, and clustering of AGNs compared to "inactive" galaxies may be due primarily to AGN variability. The results provide motivation for future deep, wide extragalactic surveys that can measure the *distribution* of AGN accretion rates as a function of SFR.

*Key words:* galaxies: active – galaxies: evolution – quasars: general

*Online-only material:* color figures


"normal" galaxy
AGN
Eddington ratio
$10^0$
$10^{-2}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
AGN variability from simulation
(Novak et al. 2011)
0
20
40
60
time (Myr)

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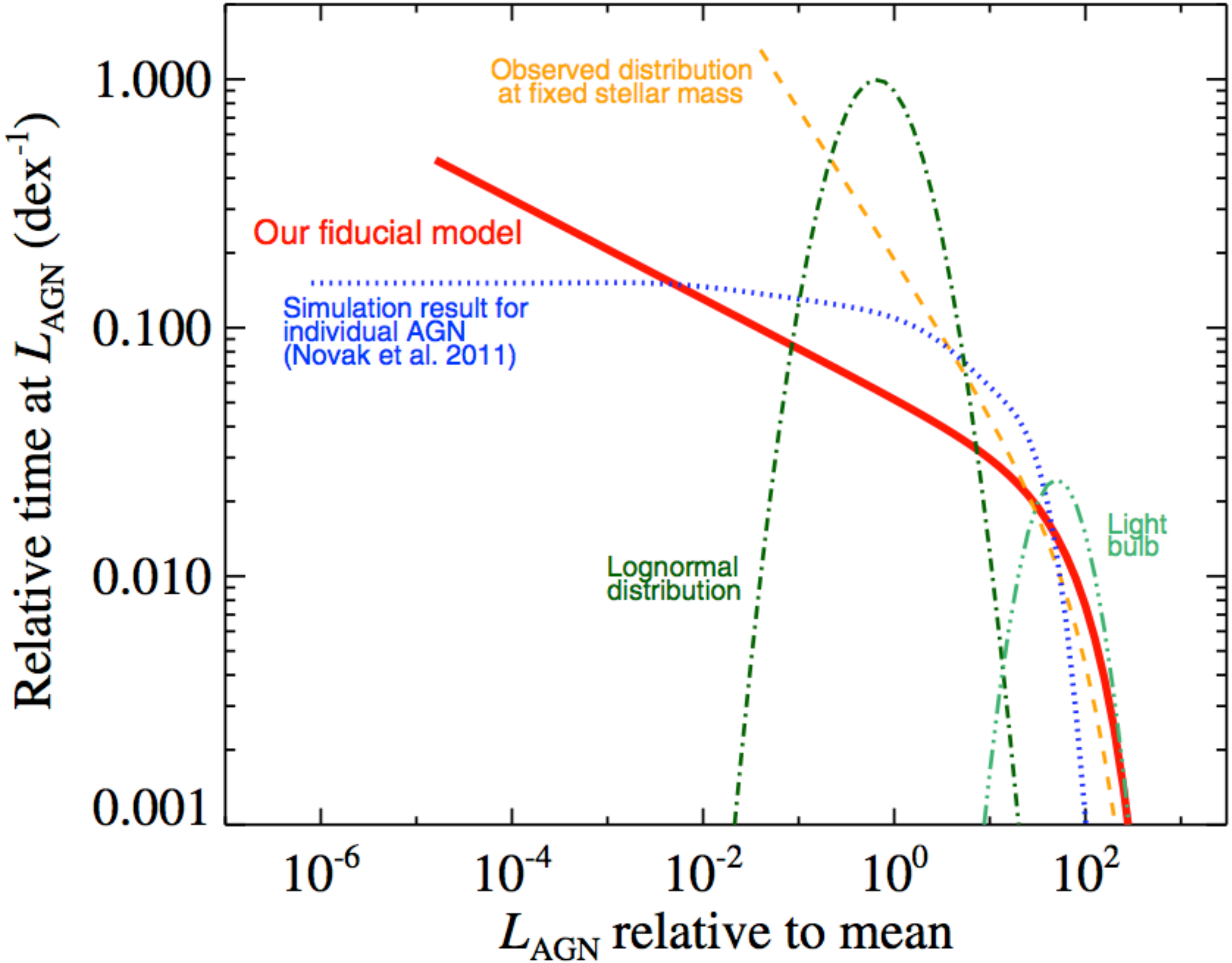

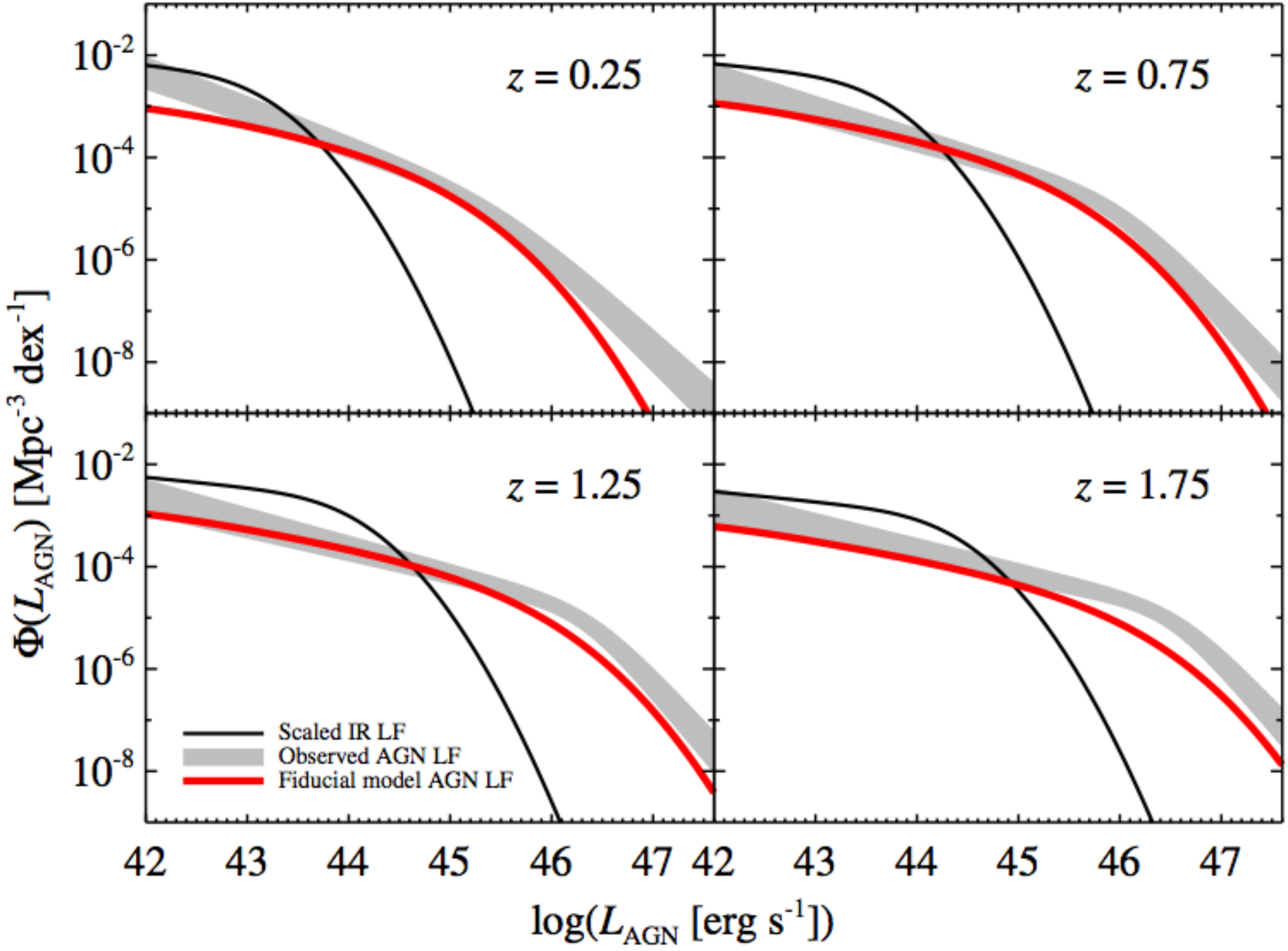

z = 0.25
z = 0.75
z = 1.25
z = 1.75
Scaled IR LF
Observed AGN LF
Fiducial model AGN LF
Φ(L_AGN) [Mpc^-3 dex^-1]
log(L_AGN [erg s^-1])

# Summary

- AGN evolve over most of the age of the Universe
- The evolution of the most common AGN type (efficient accretors: radio-quiet/radiative-mode) *might* be explained as related to the variation in star formation rate on cosmic time scales (once the different variability time scales are taken into account)
- The evolution of the inefficient accretors (jet-mode) *can* be understood as a result of a strong burst of star formation at high z followed by a "cleaning up" of the gas (death of activity and of star formation)
- Only by comparing the short (~ days to years) with the very long (~ Gyr) time scales one can understand AGN evolution!