
Nathan's
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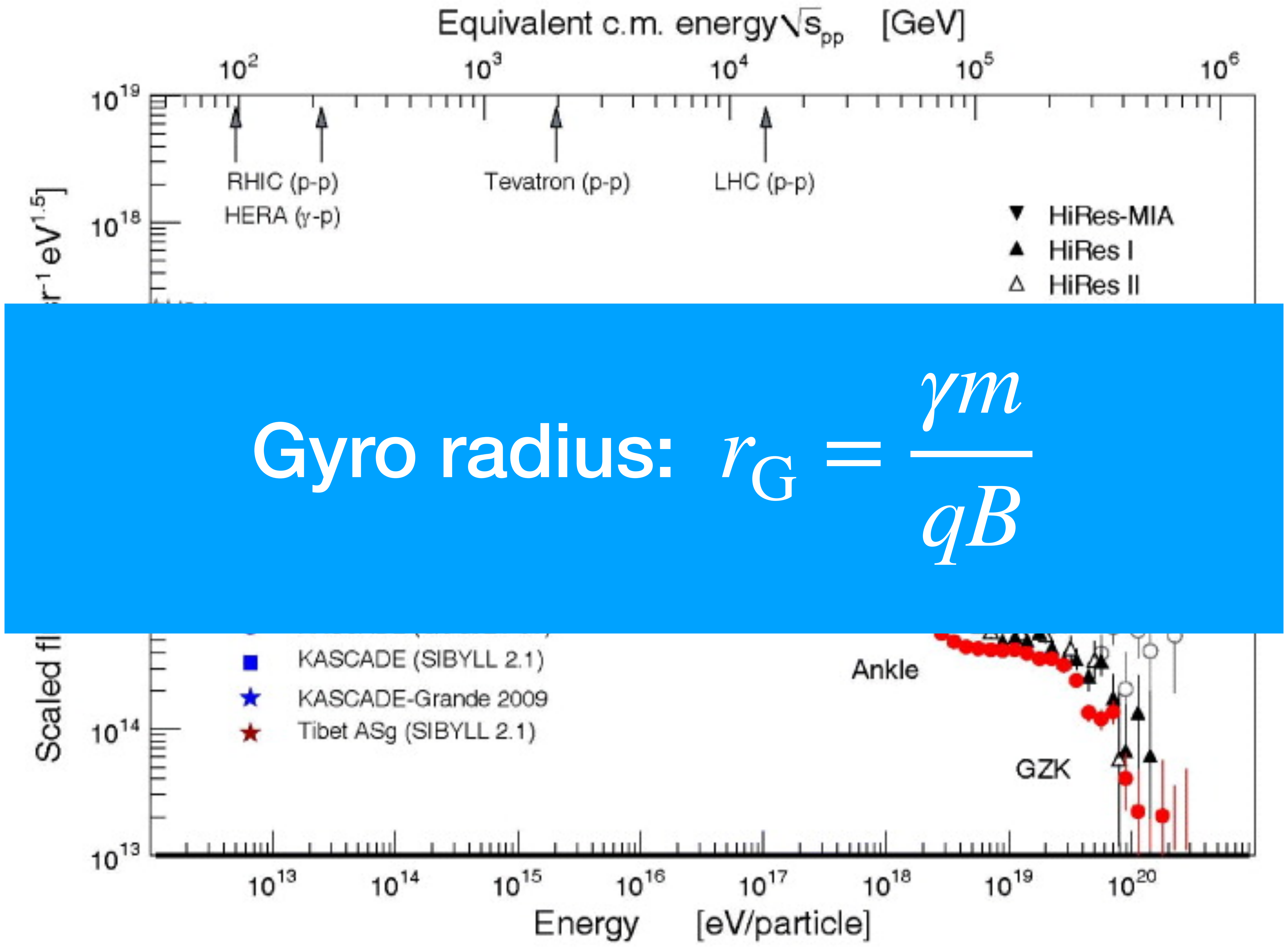
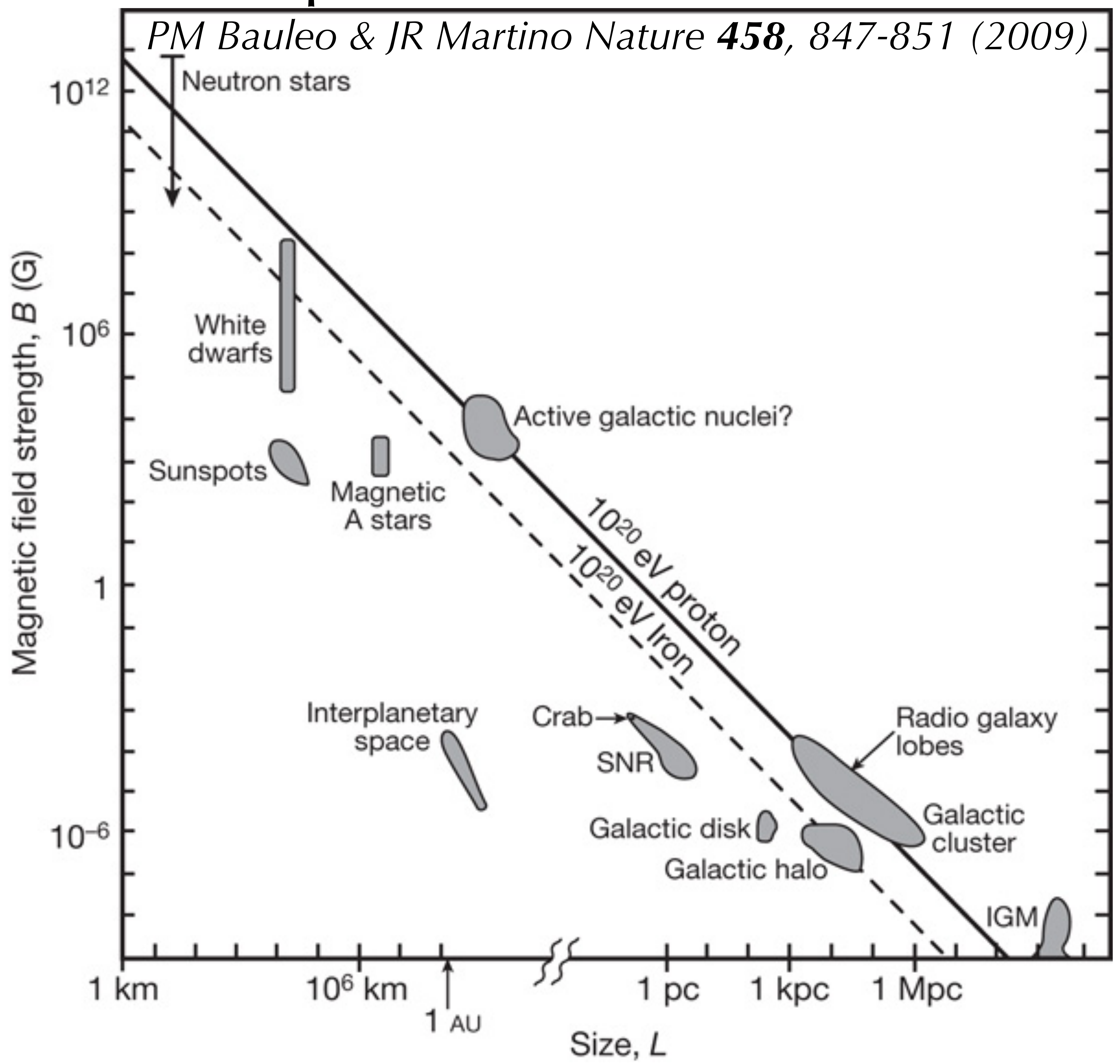
Ultra-High Energy Cosmic Rays



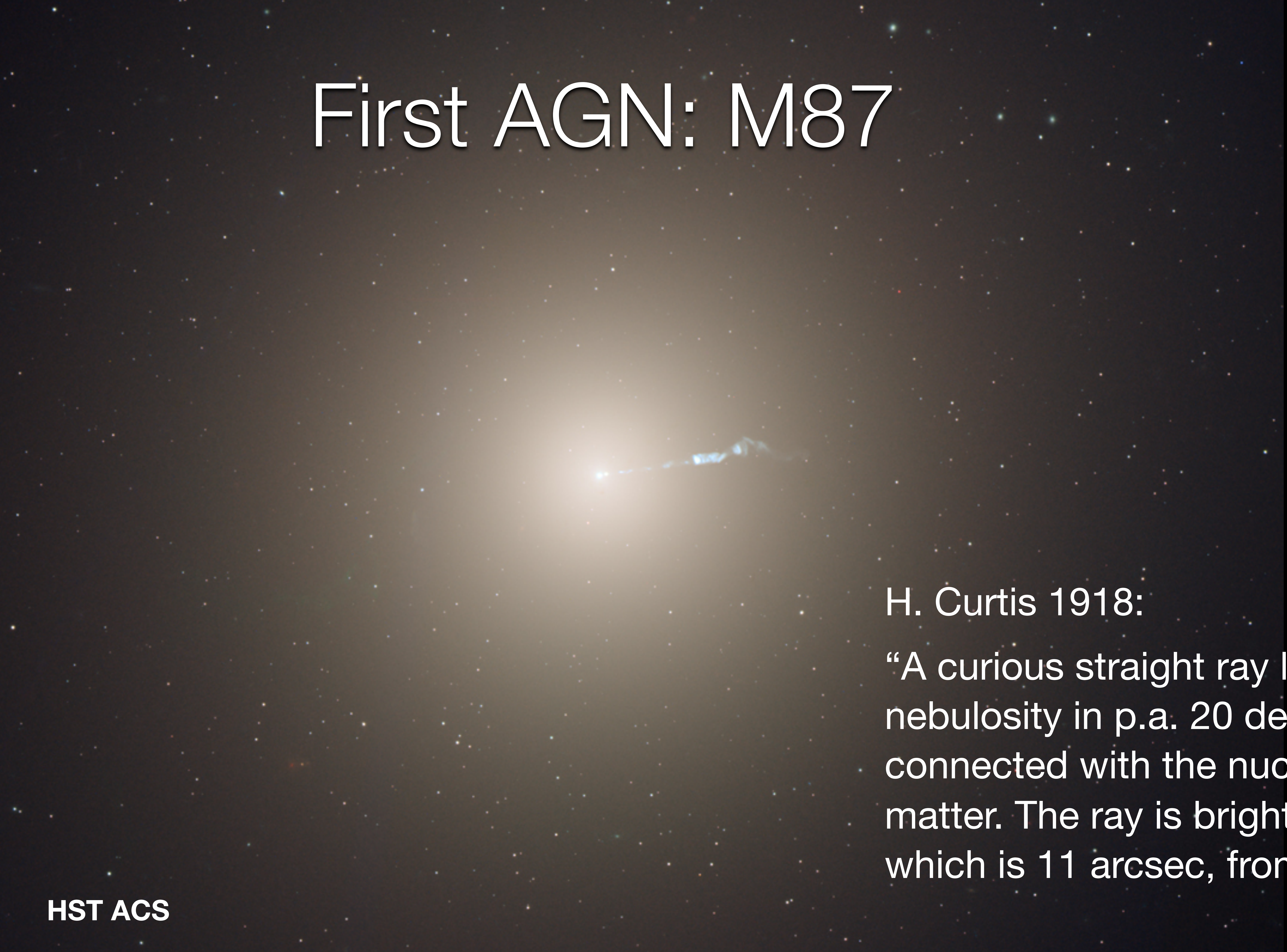
Gyro radius: $r_G = \frac{\gamma m}{qB}$

Hillas plot:

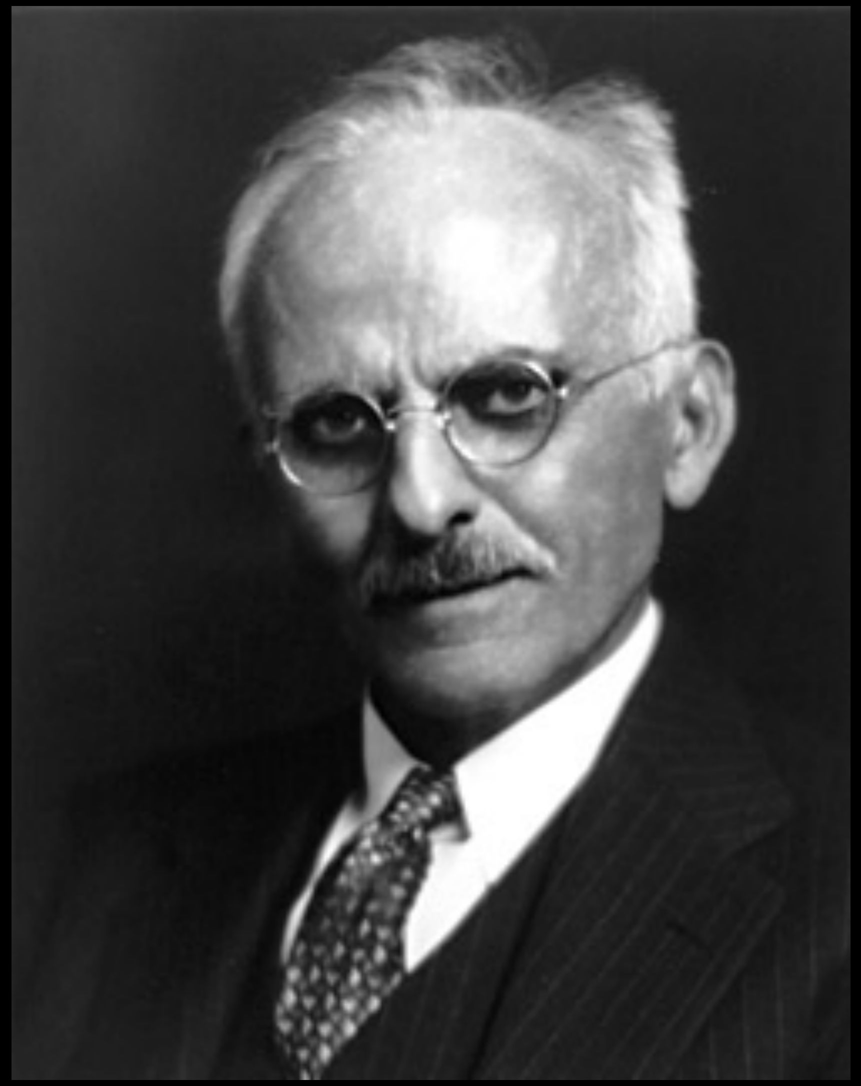


R. Engel, Auger Collaboration 2011

First AGN: M87



HST ACS



H. Curtis 1918:

“A curious straight ray lies in a gap in the nebulosity in p.a. 20 deg, apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end, which is 11 arcsec, from the nucleus.''

First AGN: M87

W. Baade & R. Minkowski 1954:

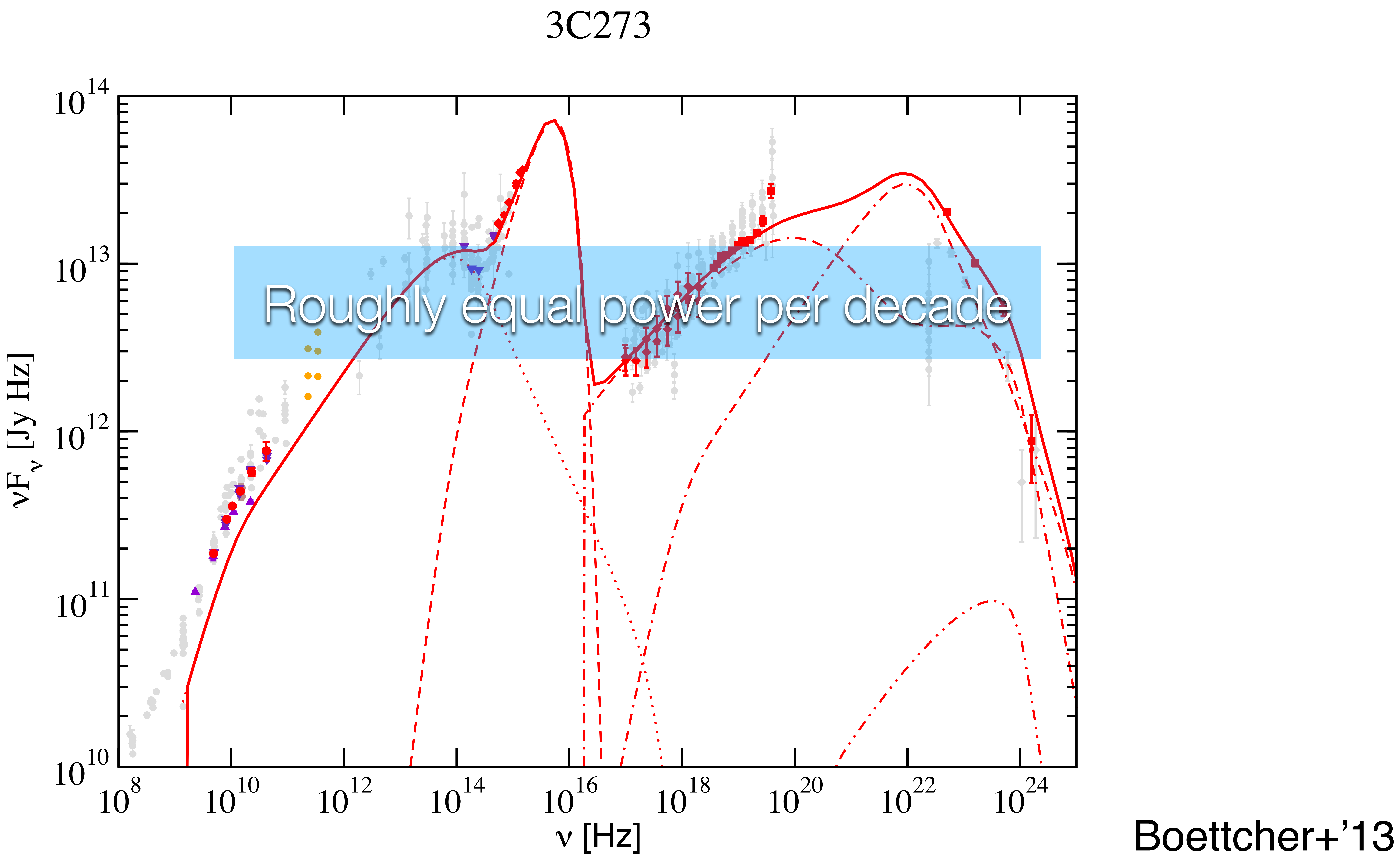
- M87 is radio source—suggests connection

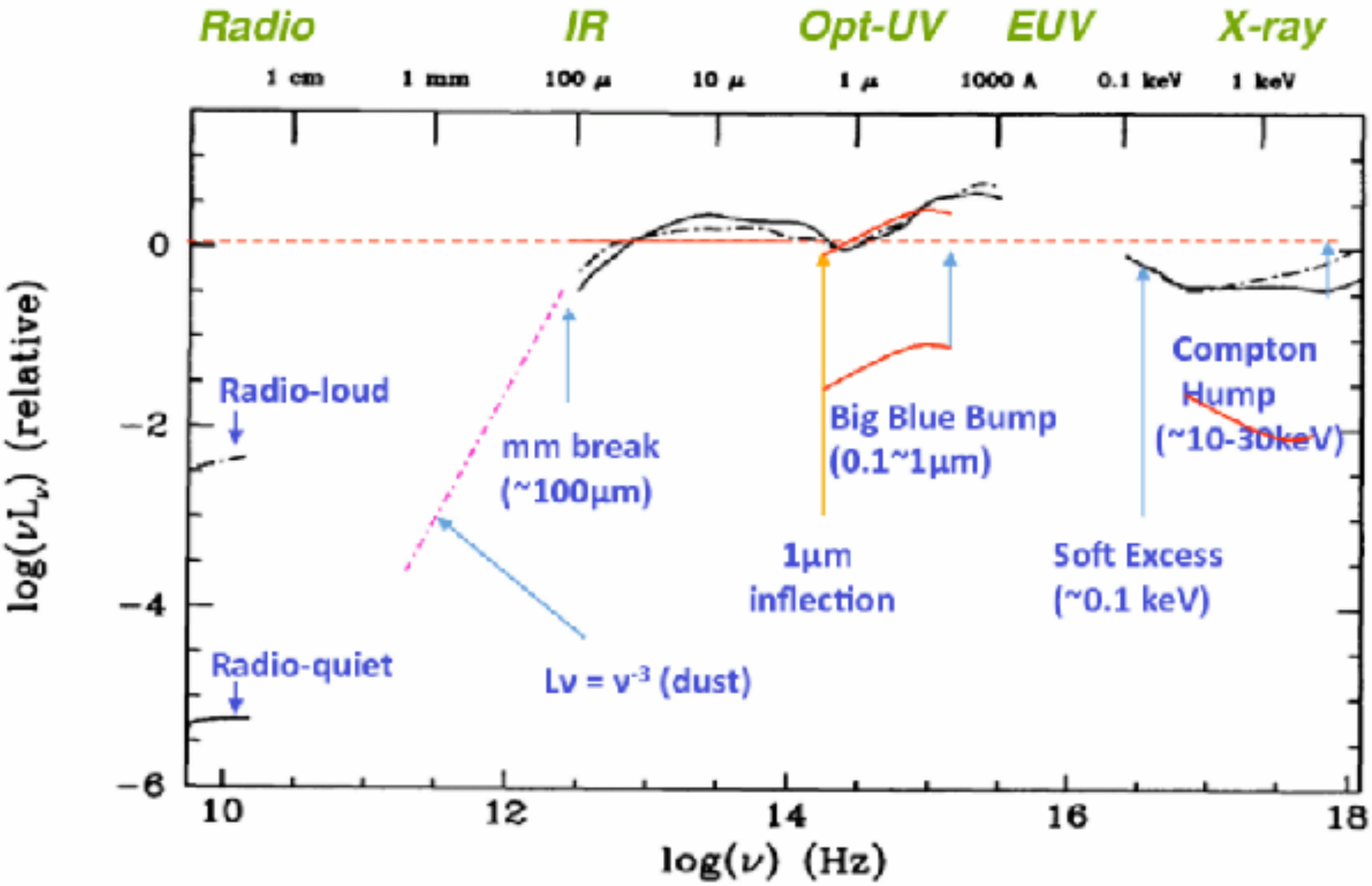
"The interpretation which suggests itself is that the jet was formed by ejection from the nucleus and that the [OII] line is emitted by a part of the material which forms the jet and is still very close to, if not still inside the nucleus."

- 1956: Optical polarization suggests synchrotron

HST ACS

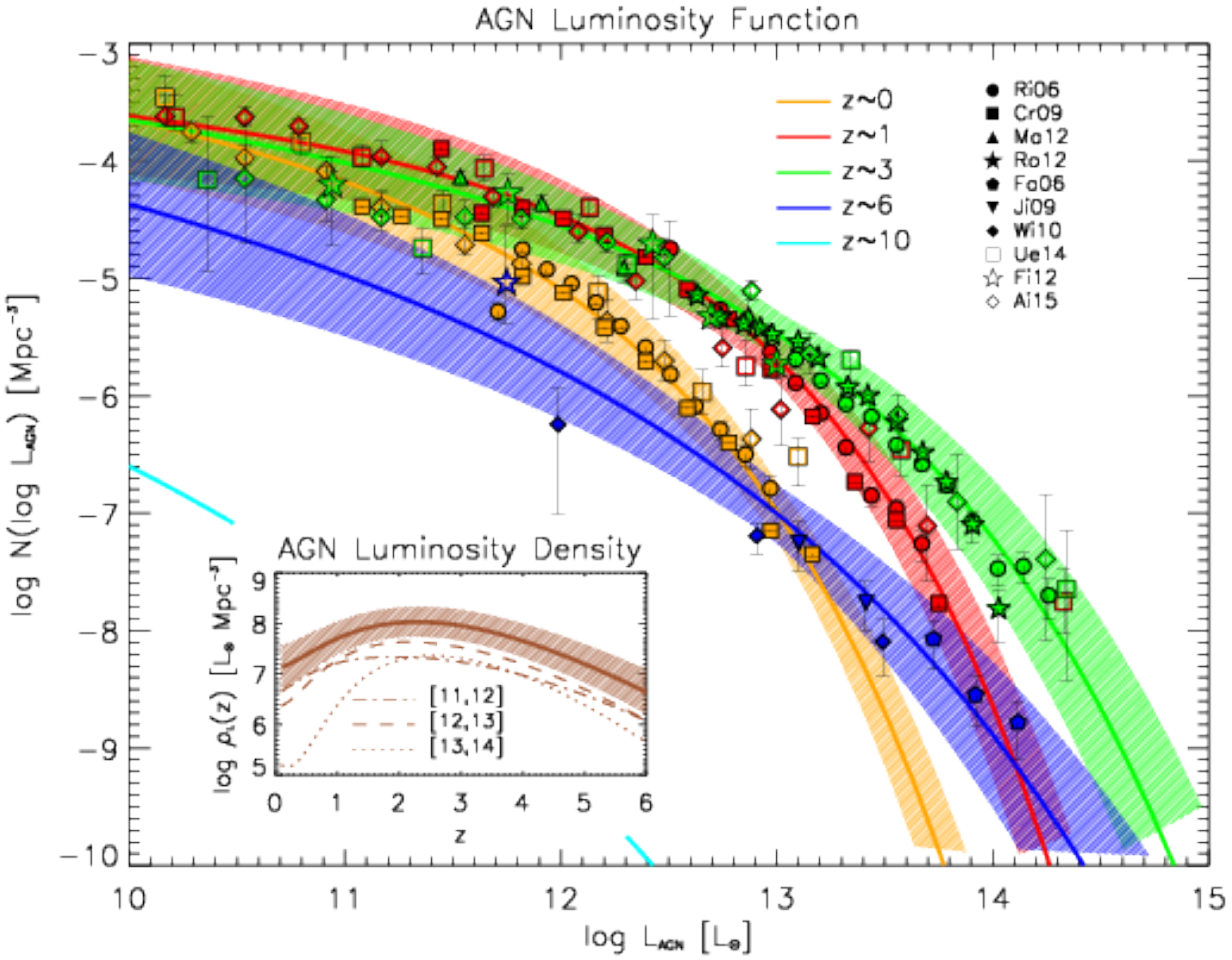

Kovalev' +16
3C273: VLBA, 1.7 GHz
NOAO
Schmidt '63

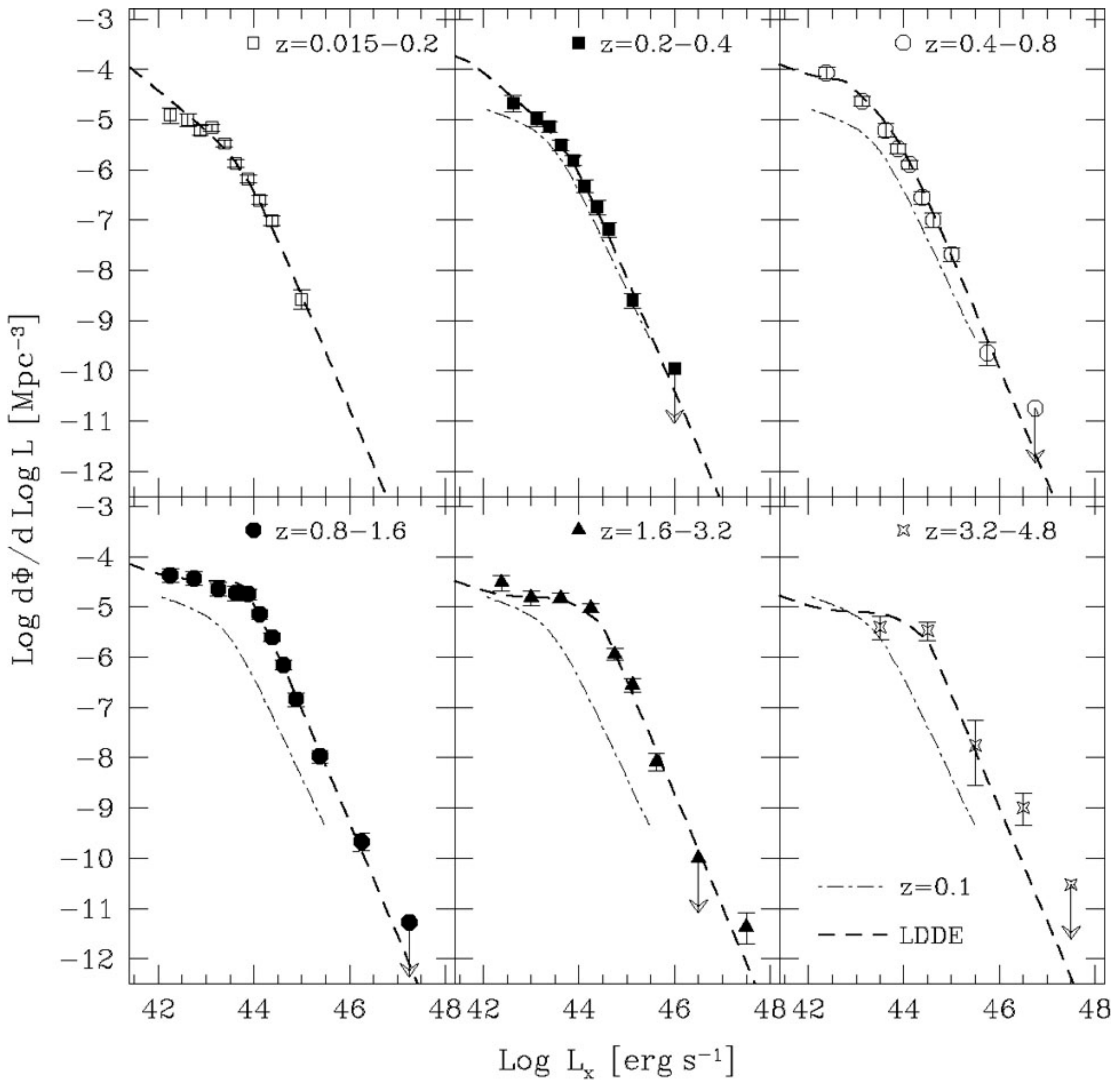

3C273
Roughly equal power per decade
νF_ν [Jy Hz]
ν [Hz]
Boettcher+'13



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

AGN Luminosity Function

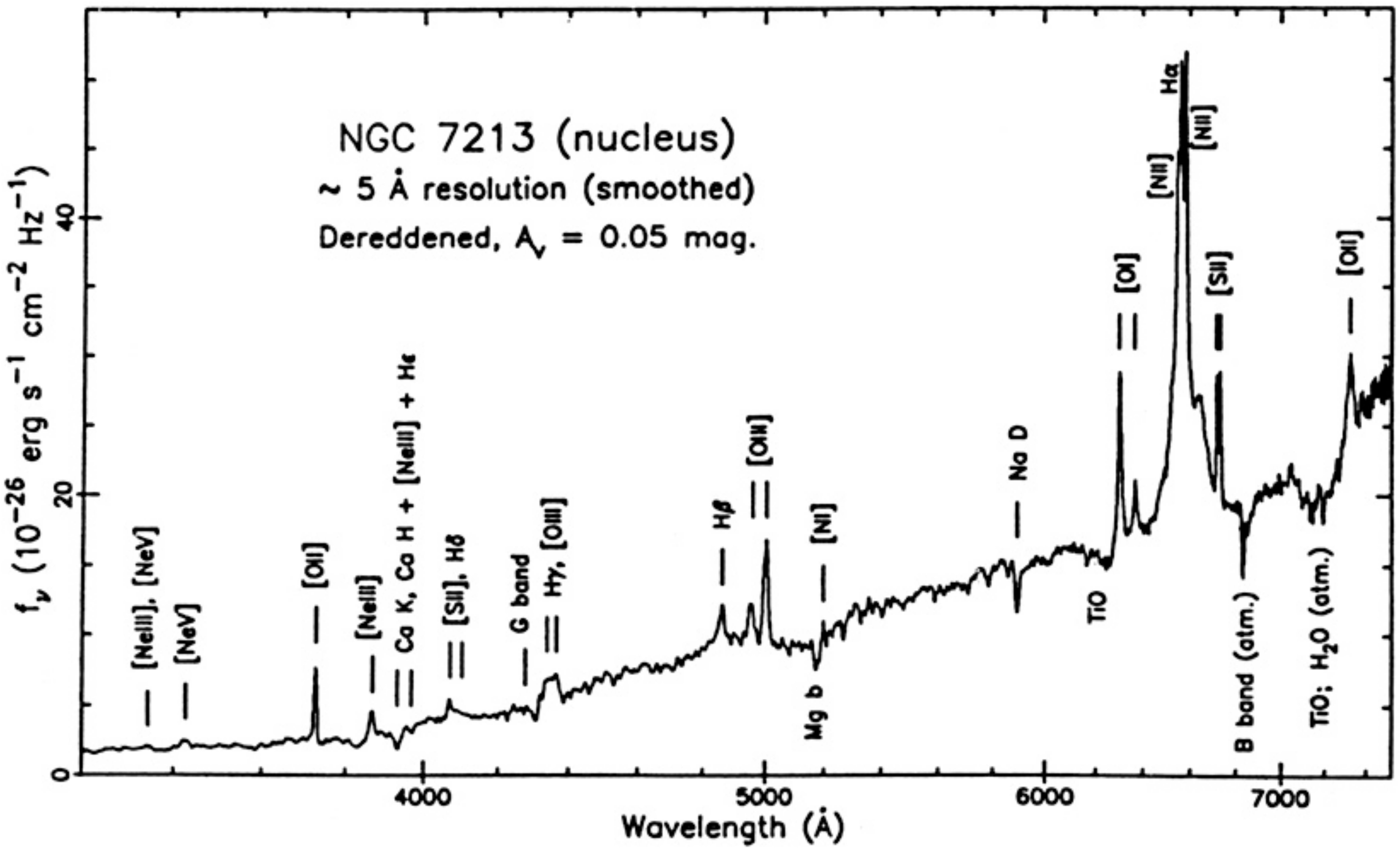




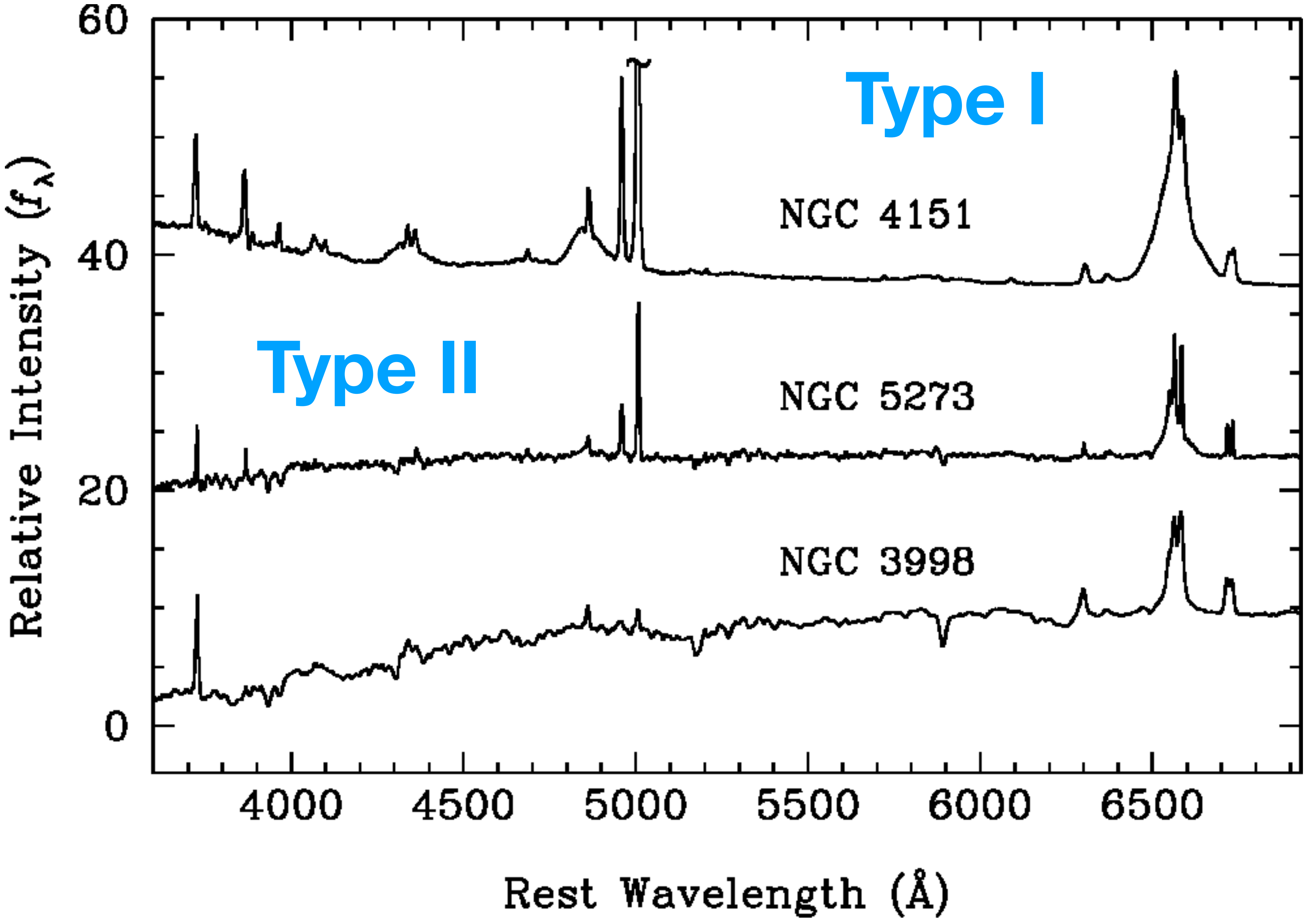
Aversa+ ’15

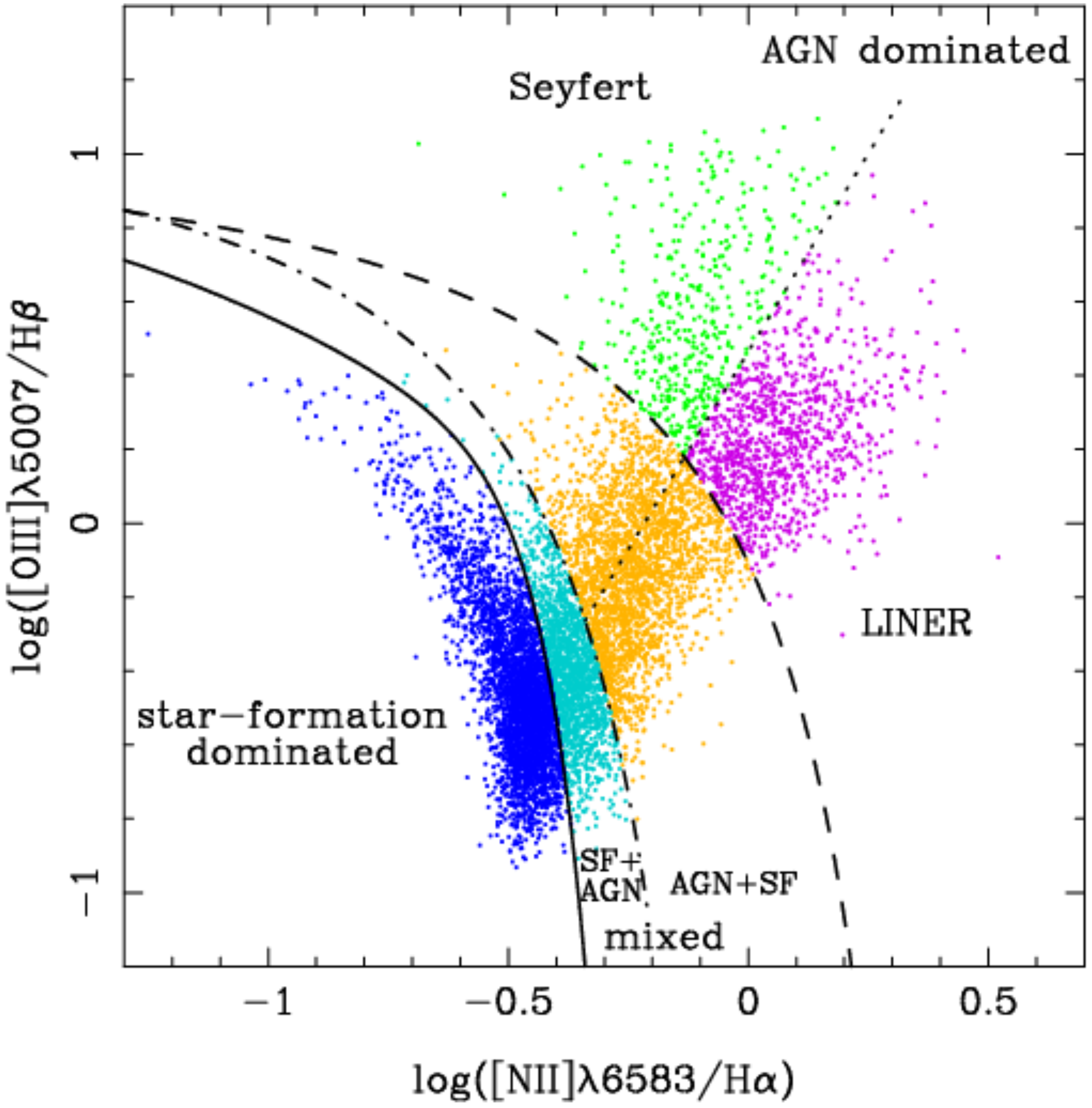
Hasinger+ ’05

Emission Lines



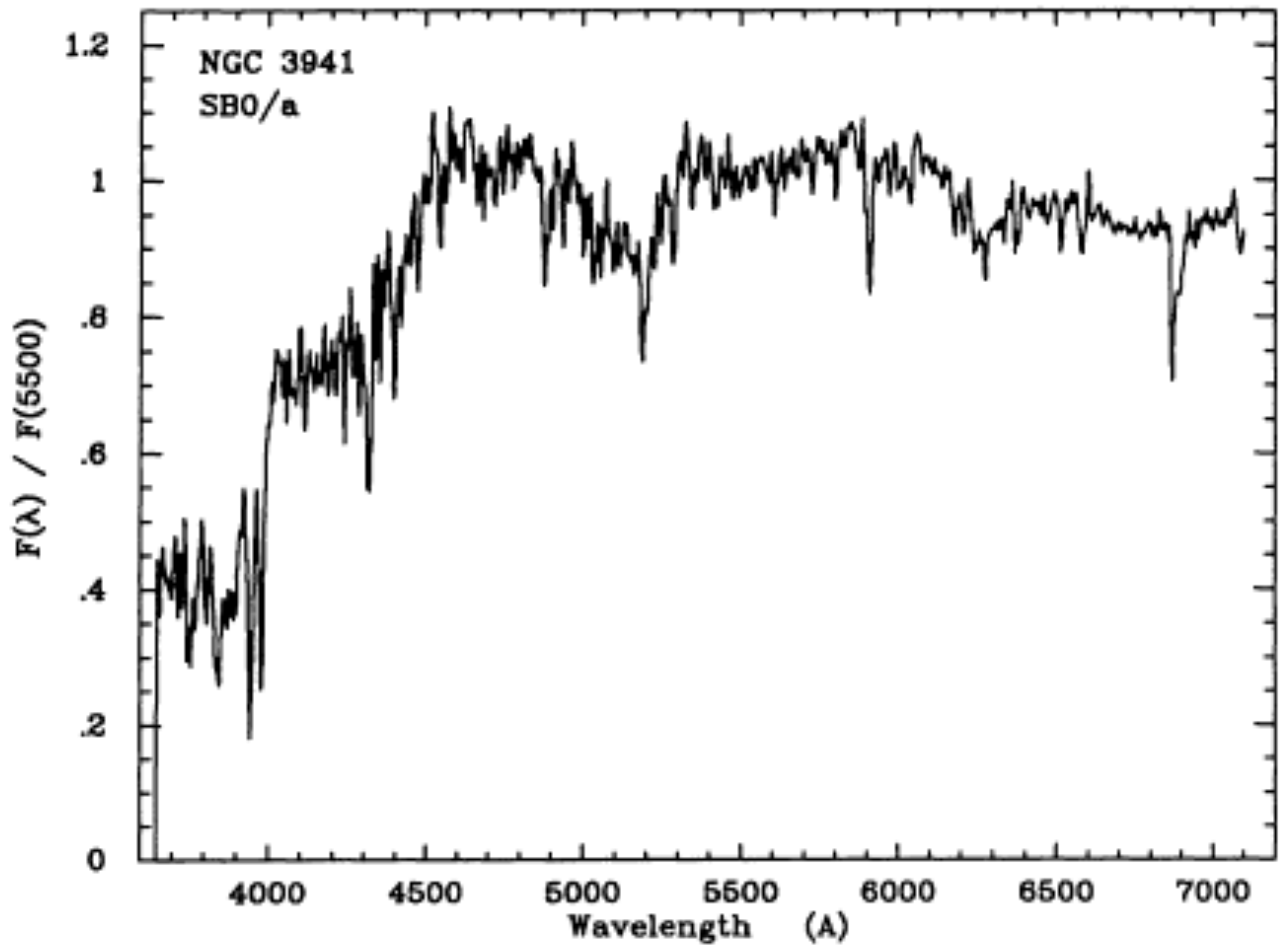
AGN Diagnostics

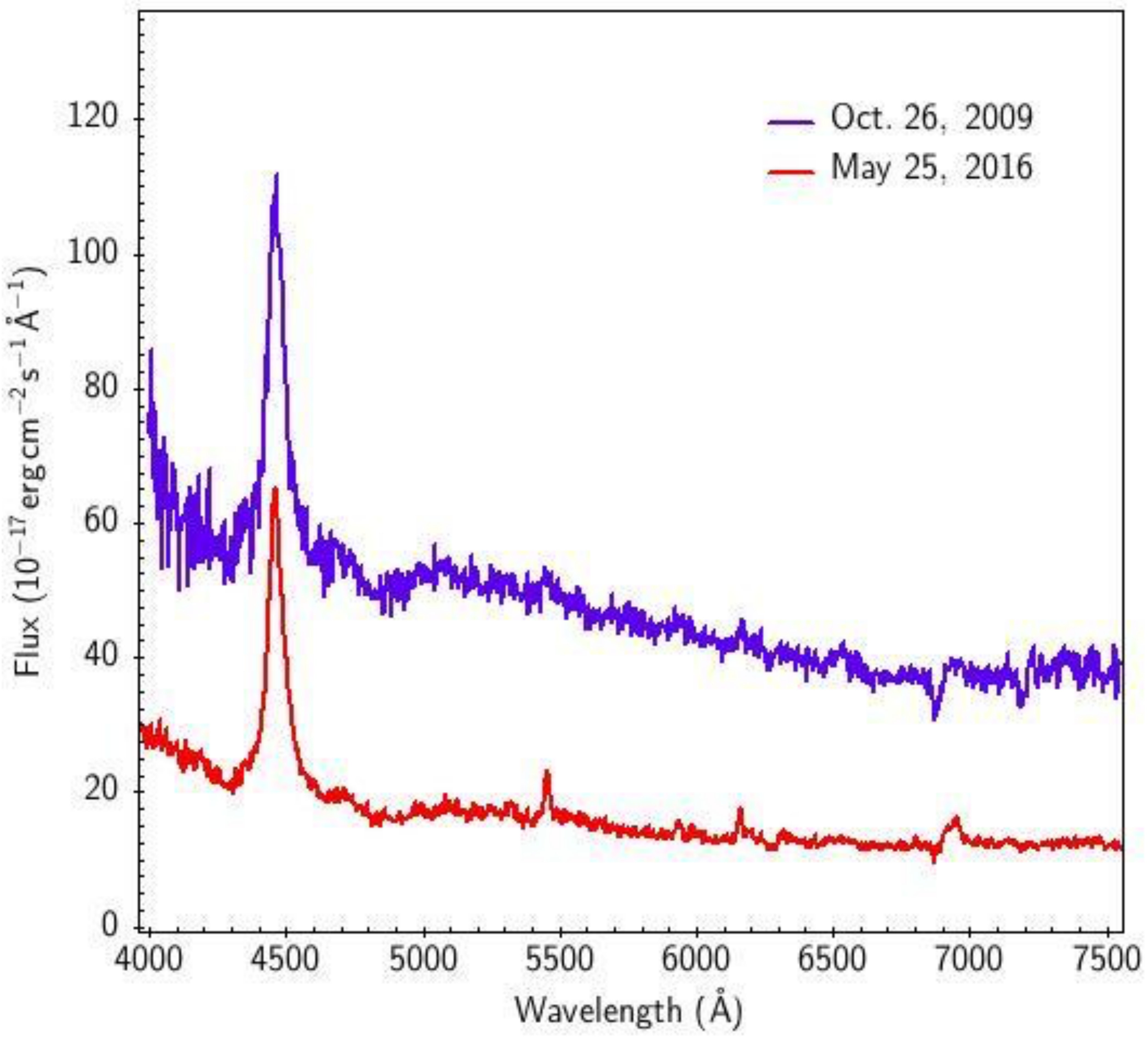




Bamford+ '08

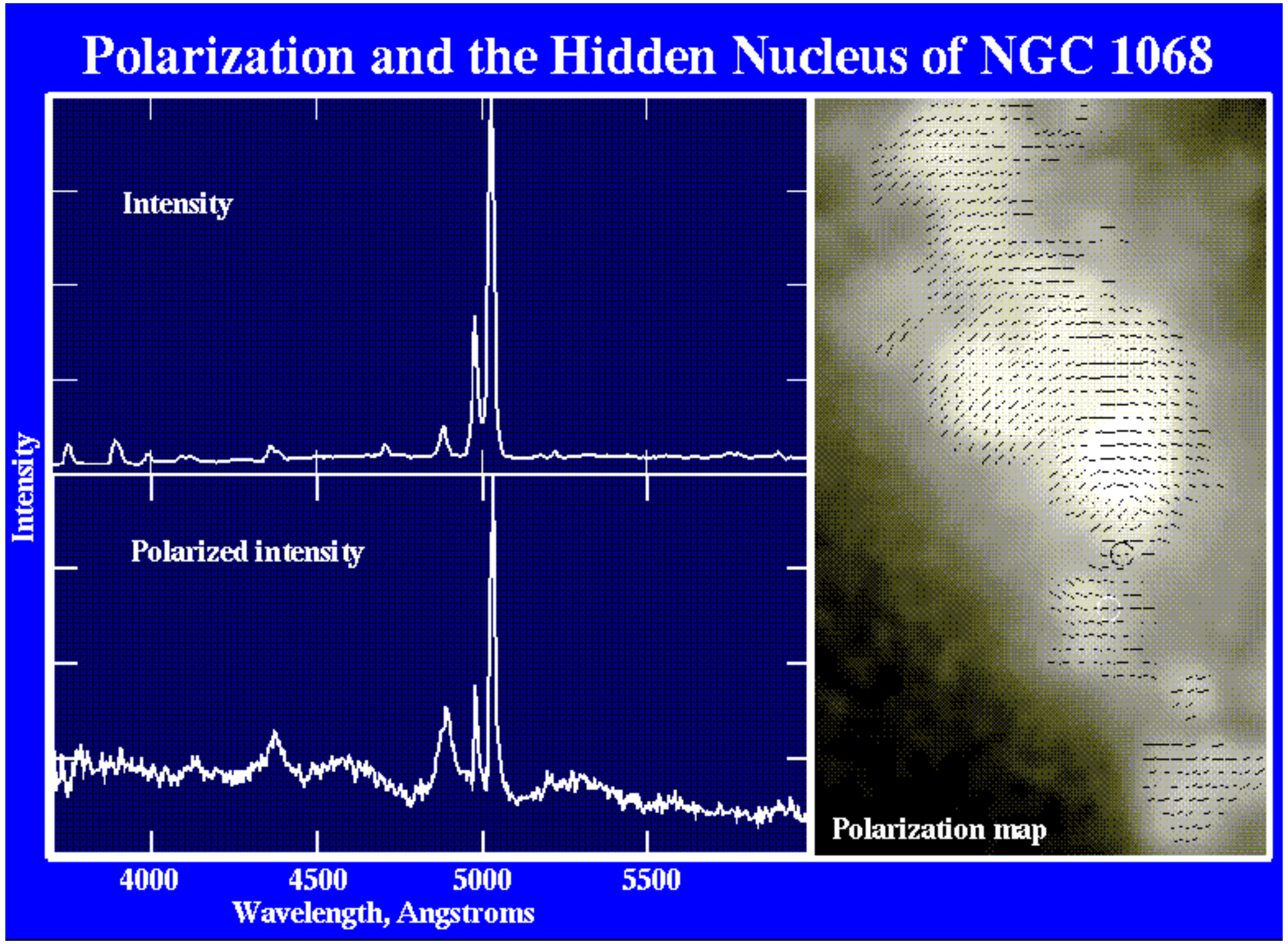
BL Lacs and Blazars

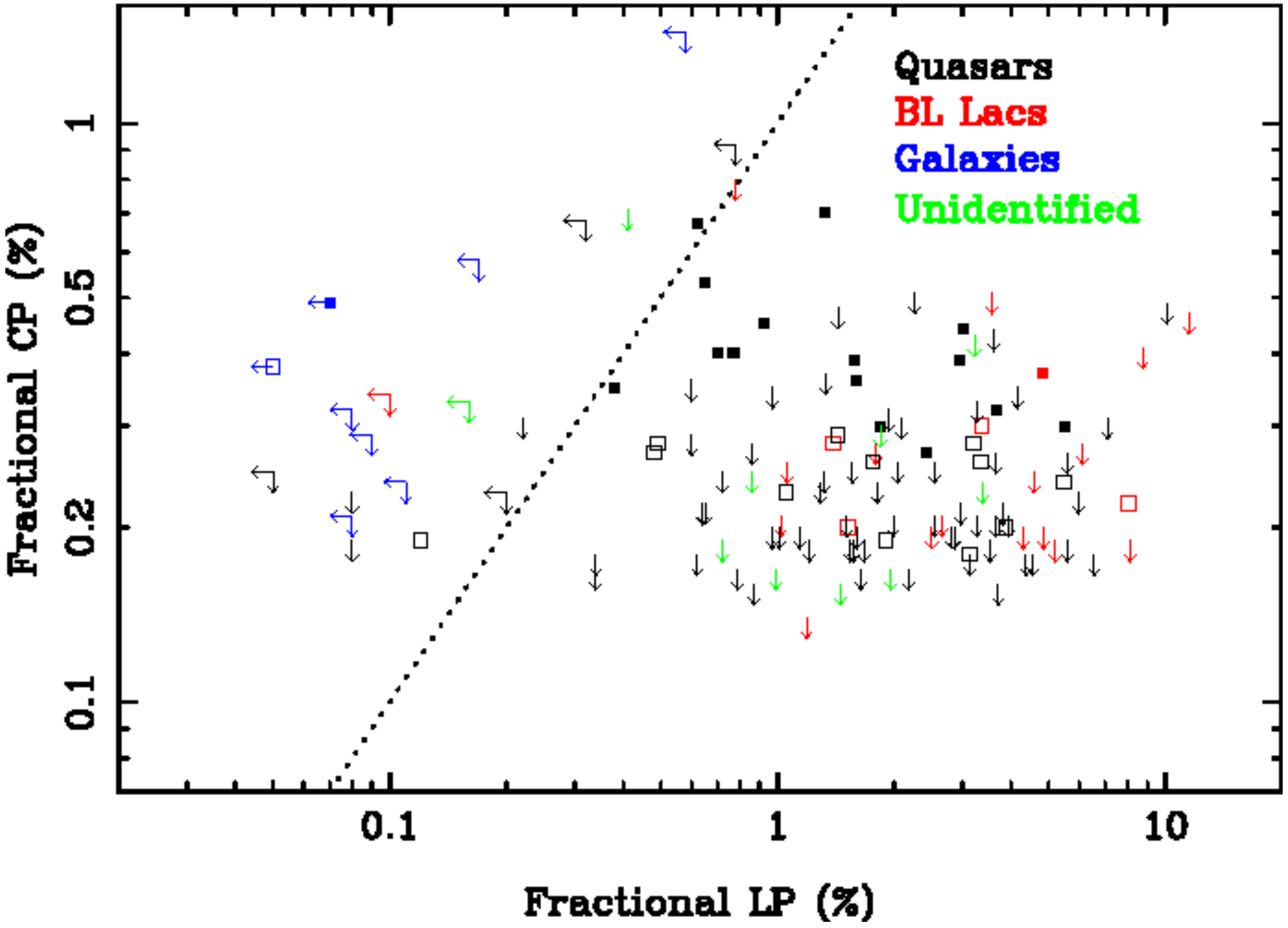




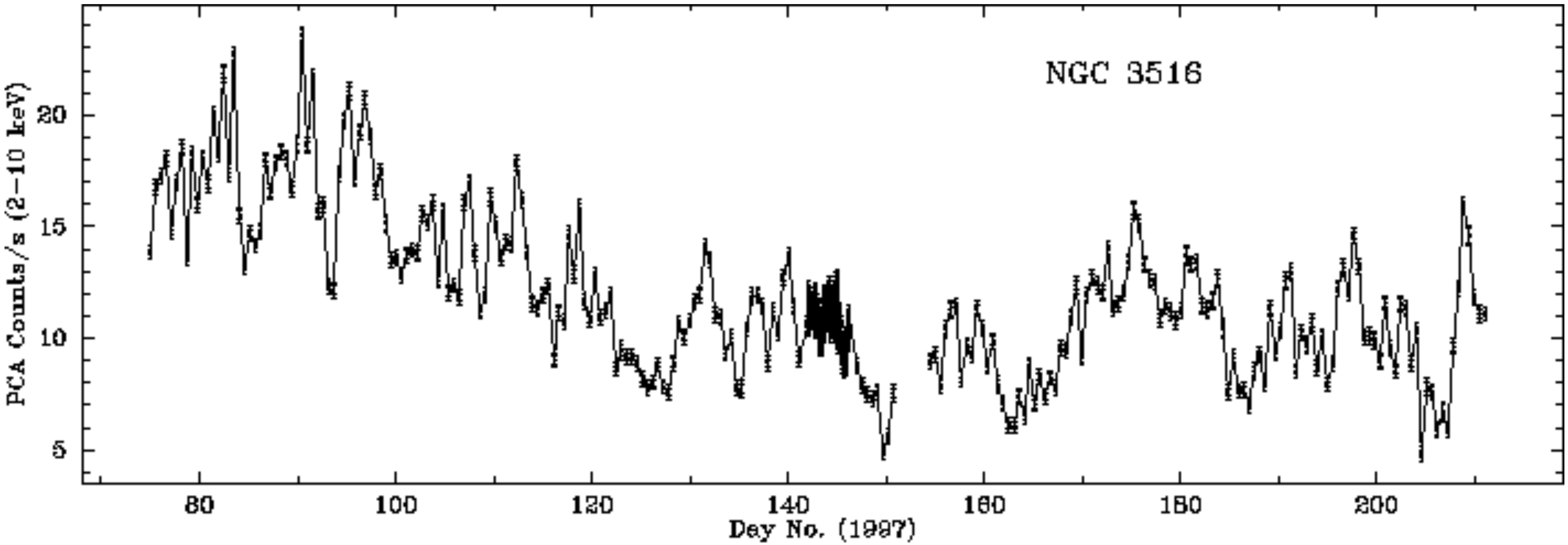
La Mura+ ‘17

Polarization





Variability



Causality

- $\Delta R \leq c\Delta t$
- $\Delta t < 1\,\mathrm{hr}$
- $\Delta R \leq 10^{14}\,\mathrm{cm} \sim 1\,\mathrm{AU}$
- **Fuel-consumption time:**

$$t_{\dot{M}} = \frac{M}{\dot{M}} \sim 4 \times 10^{7}\,\mathrm{yrs}\frac{\eta}{10\,\%}$$

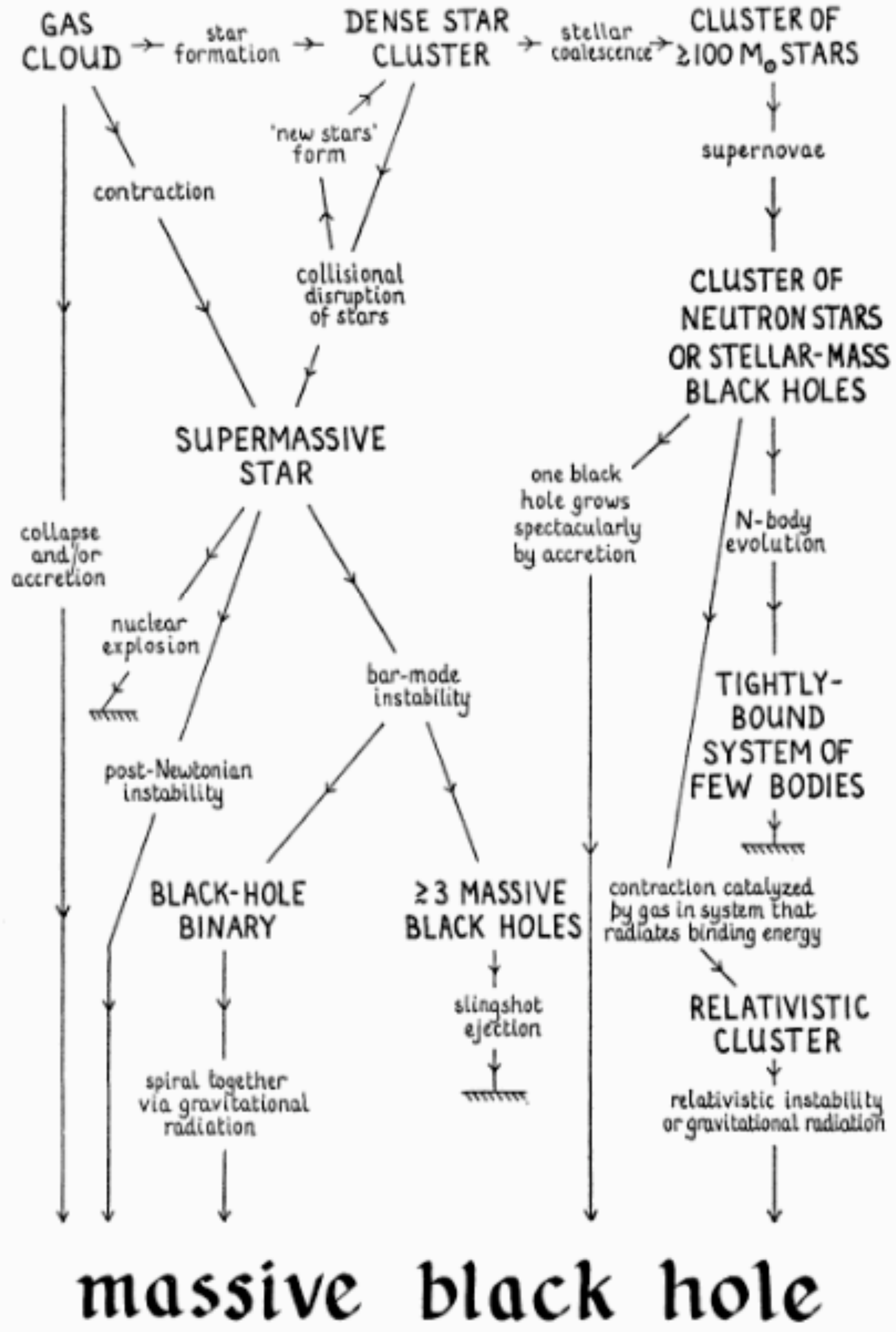


Fig. 2

Possible modes of formation of a massive black hole in a galactic nucleus.

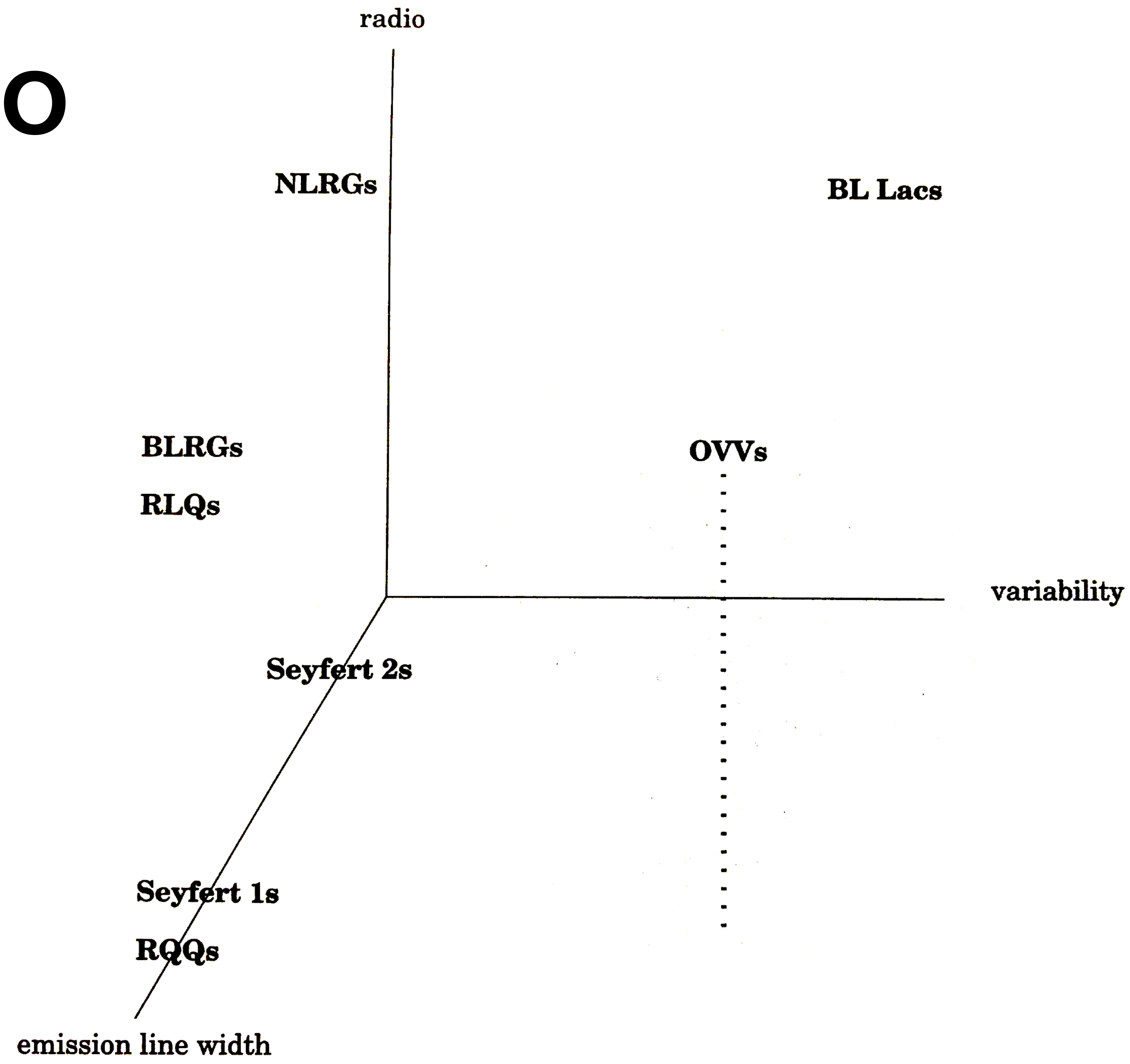
AGN Taxonomy

Table 1.1: The Menu

Property	Popularity	Comments and Exceptions
Very small angular size	Many	Wavelength-dependent
Galactic (or greater) luminosity	Many	Lower luminosity is hard to find; obscuration and beaming may mislead
Broad-band continuum	Most	Often $dL/d\log\nu \simeq const.$ from IR to X-rays; sometimes to γ-rays
Strong emission lines	Most	Sometimes very broad, sometimes not
Variable	Most	Modest amplitude; short wavelengths stronger, faster than long
Weakly polarized	Most	$\sim 1\%$ linear; a minority much stronger
Radio emission	Minority	Sometimes, but not always, extended on enormous scales
Strongly variable and polarized	Small minority	Correlated with bright radio and high-energy γ-rays; in some cases emission lines absent

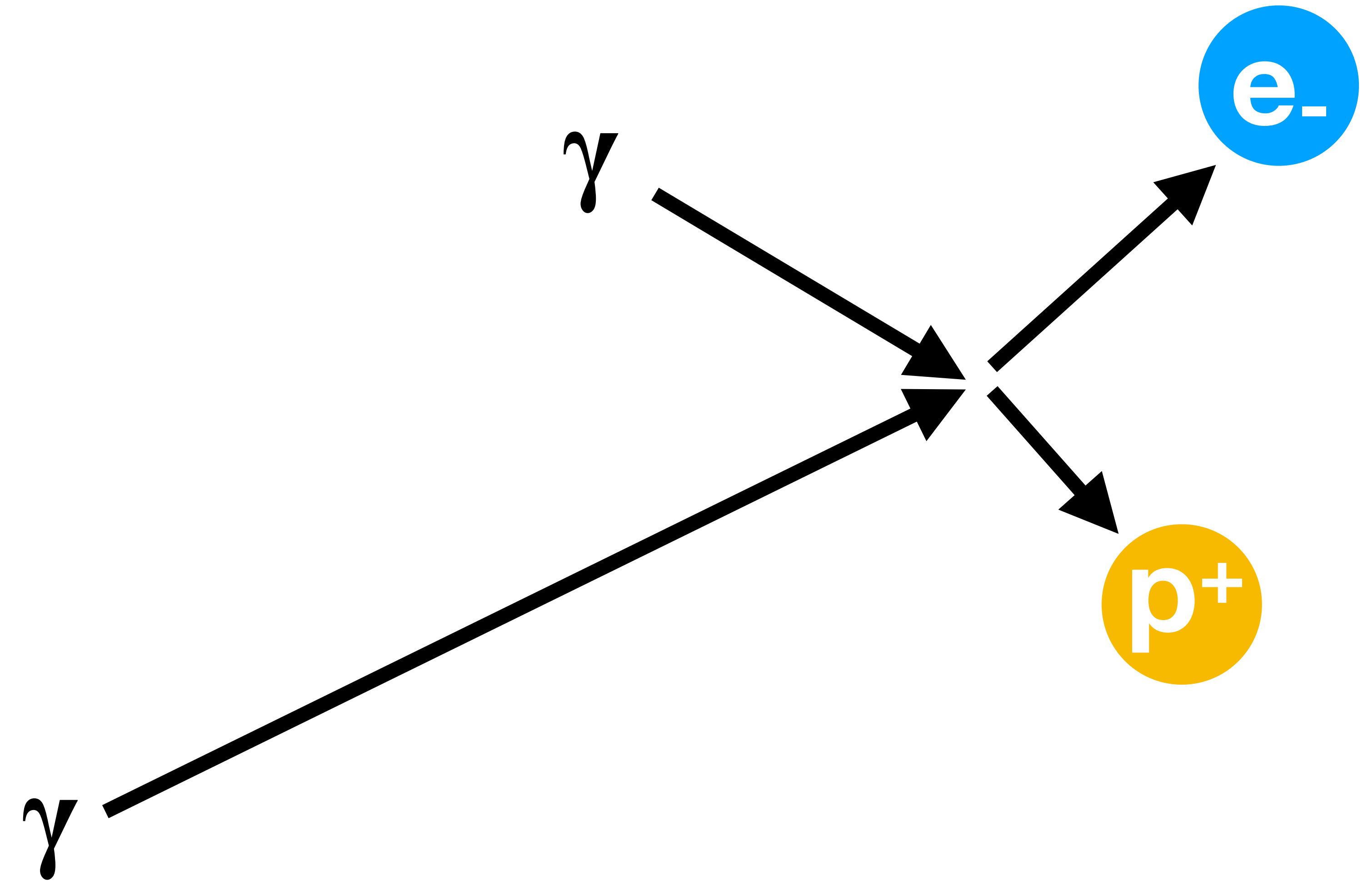
Krolik 03

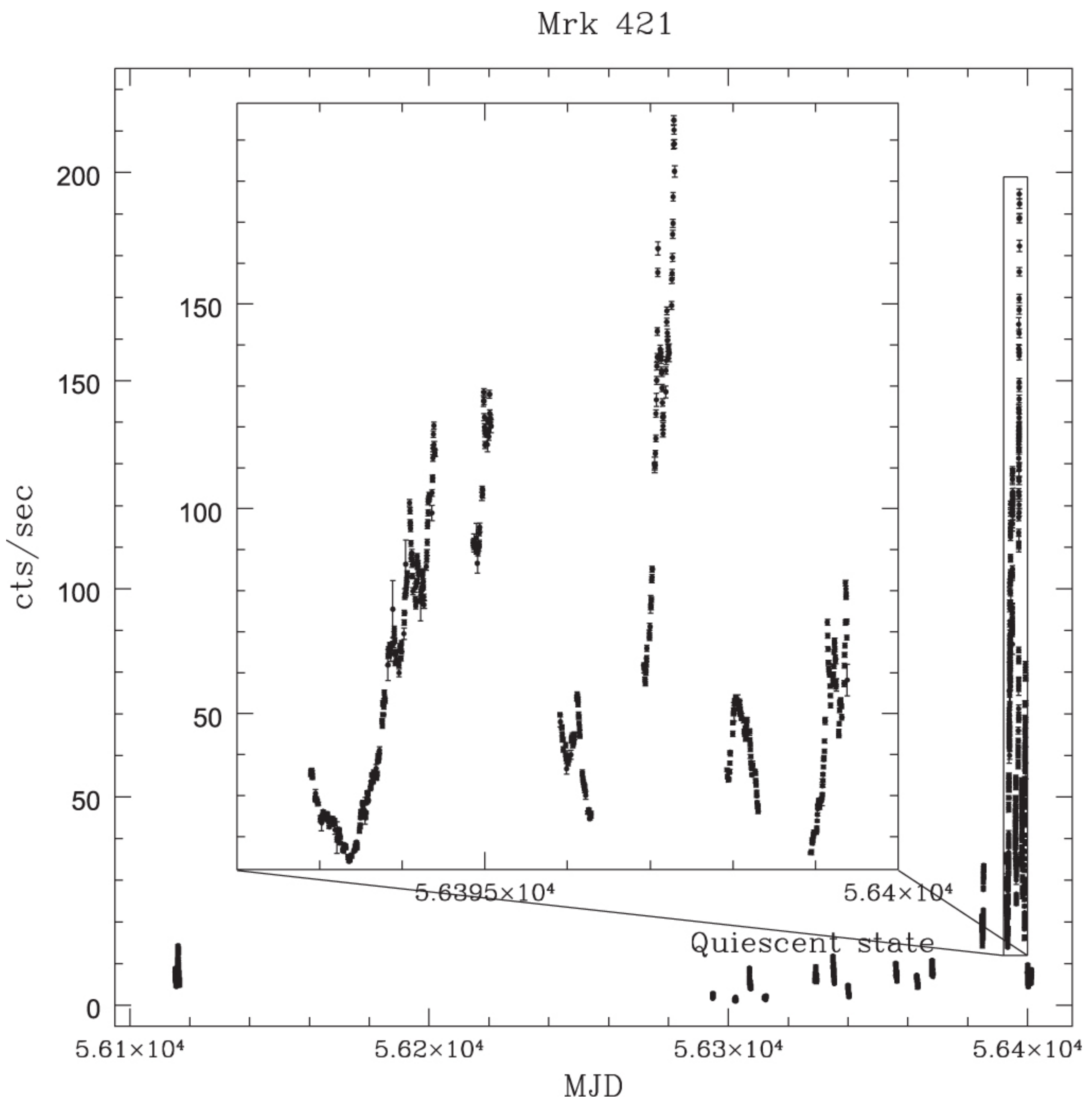
AGN Zoo



Krolik 03

Pair Creation and Compactness





$$l \equiv \frac{L\sigma_{\rm T}}{R m_{\rm e} c^2} \sim \tau_{\gamma\gamma} = 1000 \frac{L}{10^{46}\,{\rm ergs\,s^{-1}}} \frac{10^5}{s}$$

Blazar Brightness Temps

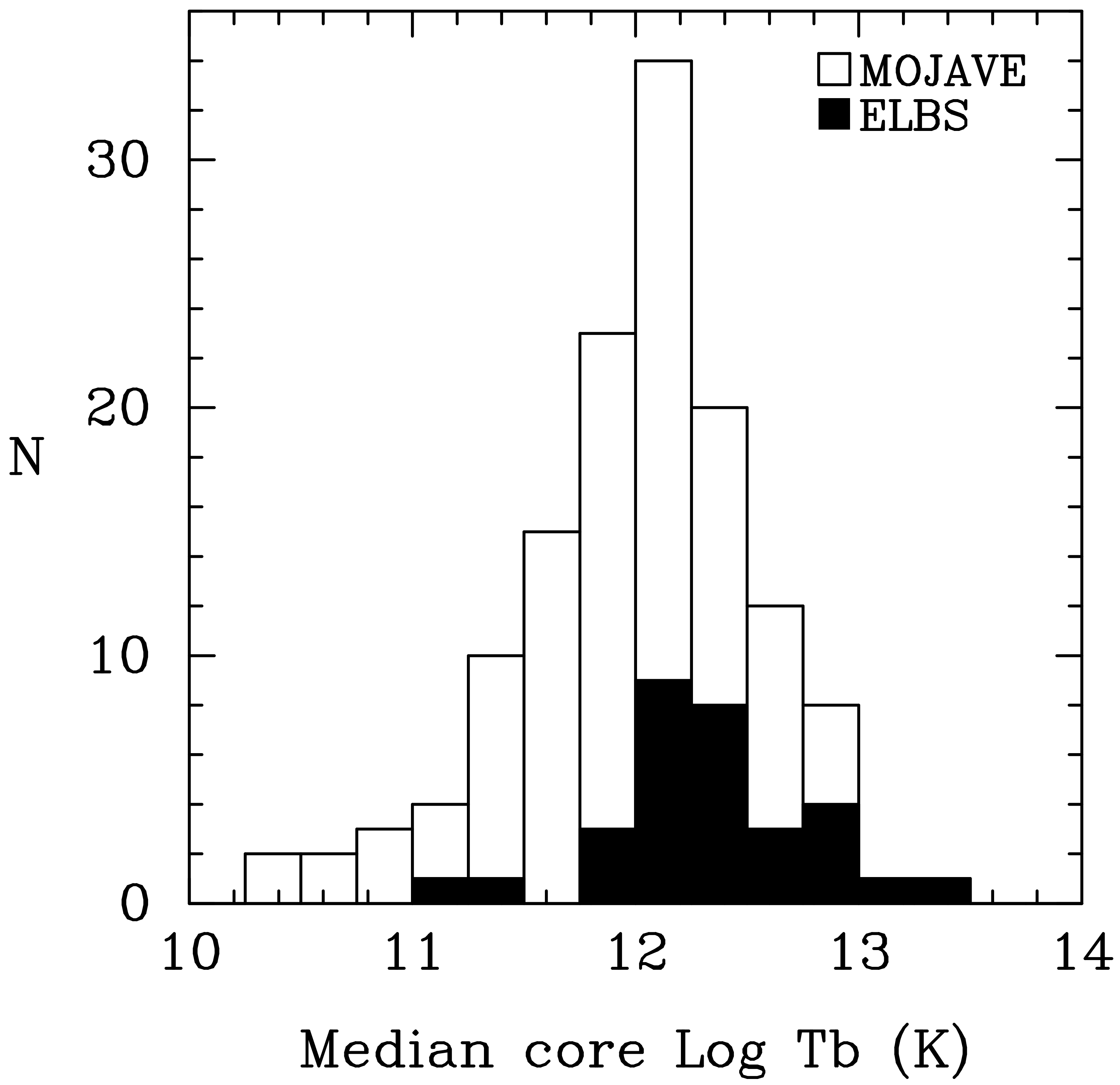


FIG. 5.— Distribution of median brightness temperature values, T_b of VLBI cores in the complete MOJAVE sample. The shaded areas represent the LAT-detected objects in the sample.

Inverse Compton Catastrophe

$$P_{\mathrm{IC}} \propto U_\gamma$$

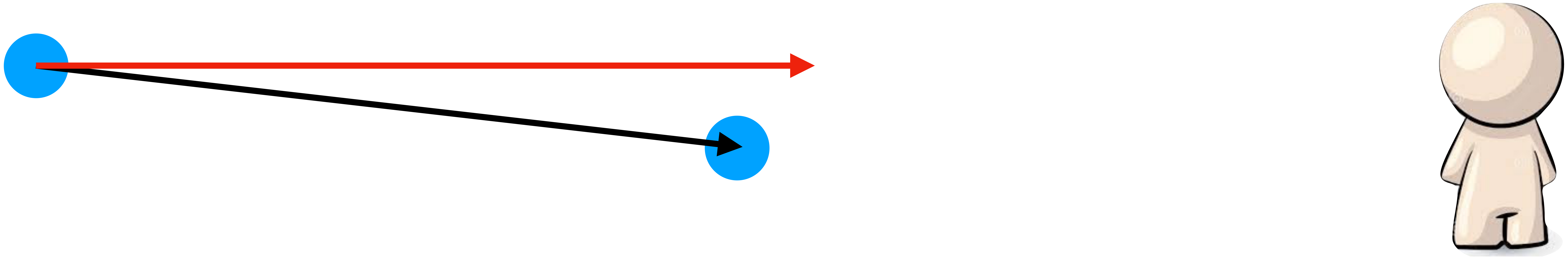
$$U_\gamma = U_{\mathrm{CMB}} + U_{\mathrm{IC}} + U_{\mathrm{sync}}$$

$$U_{\mathrm{synch}} = \frac{P_{\mathrm{synch}}}{c\Delta R^2} \qquad U_{\mathrm{IC}} = \frac{P_{\mathrm{IC}}}{c\Delta R^2}$$

$$\frac{P_{\mathrm{sync}}}{c\Delta R^2} \propto I_{\mathrm{sync}} < I_{\mathrm{max}}$$

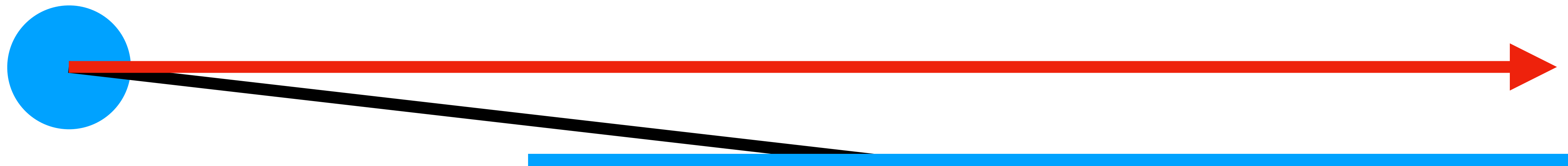
$$T_{\mathrm{B}} \leq 10^{12}\ \mathrm{K}$$

Variability in Ultra-Relativistic Flows



$$\delta x = \delta t \left(1 - \beta \cos(\theta)\right) \sim \delta t \left(1 - \beta\right) \sim \delta t \left(1 - \sqrt{1 - \frac{1}{\Gamma^2}}\right) \sim \delta t \frac{1}{2\Gamma^2}$$

Jet Speeds?



Relativistivity Solves all timing and brightness issues

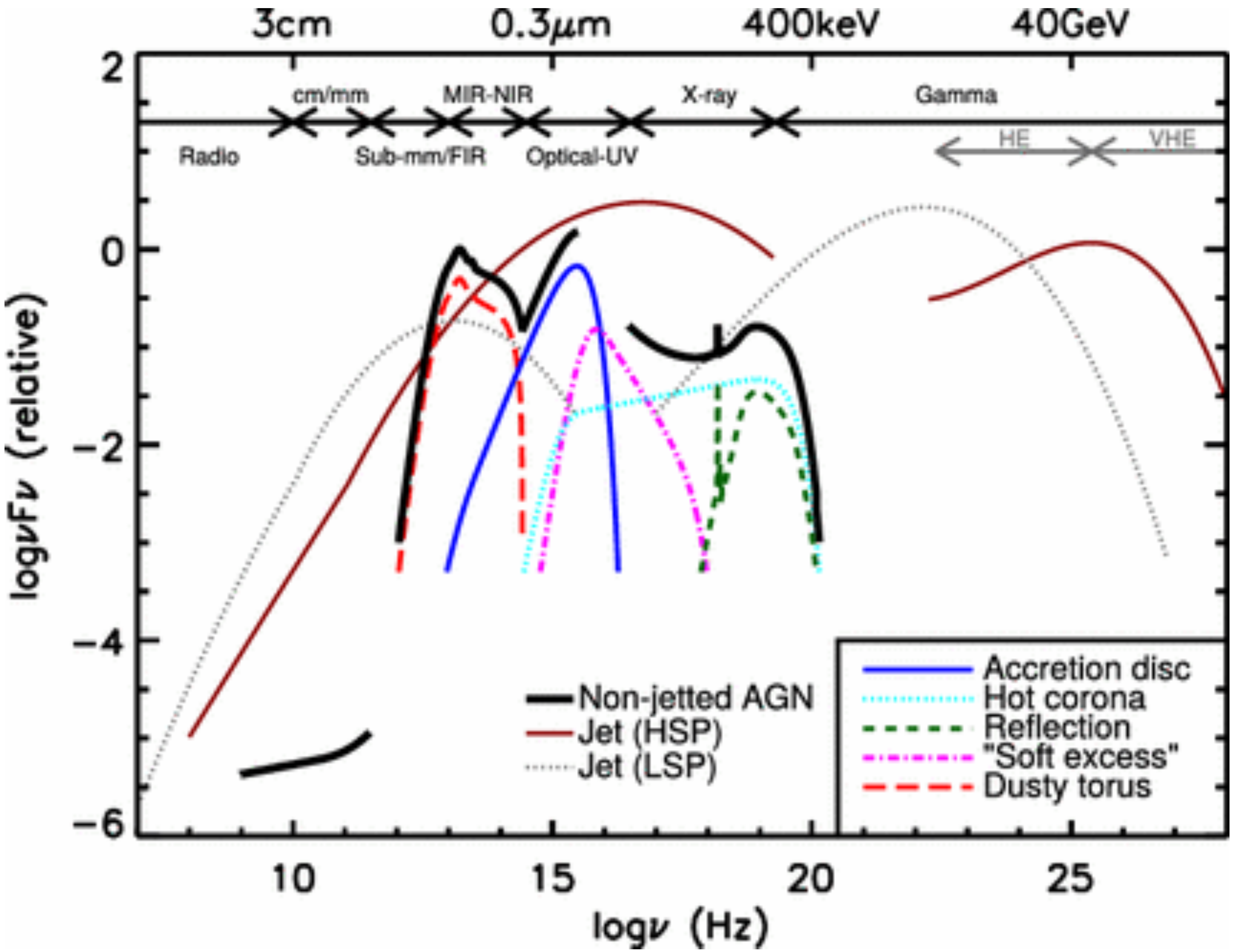
$\delta \equiv \Gamma \left(1 - \right.$

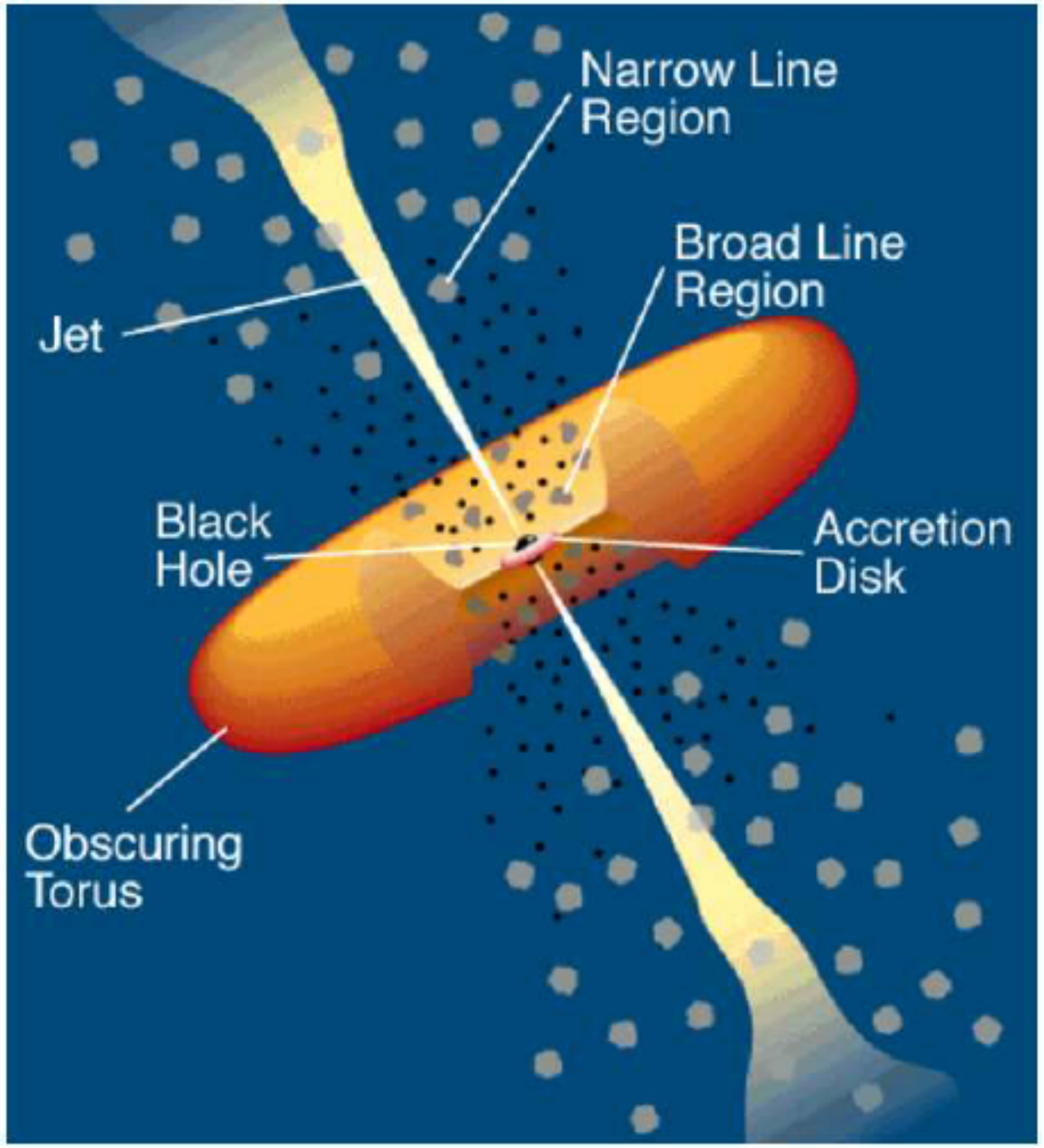
$I_\nu = I'_{\nu'} \delta^3 = I_{\nu} \ldots$

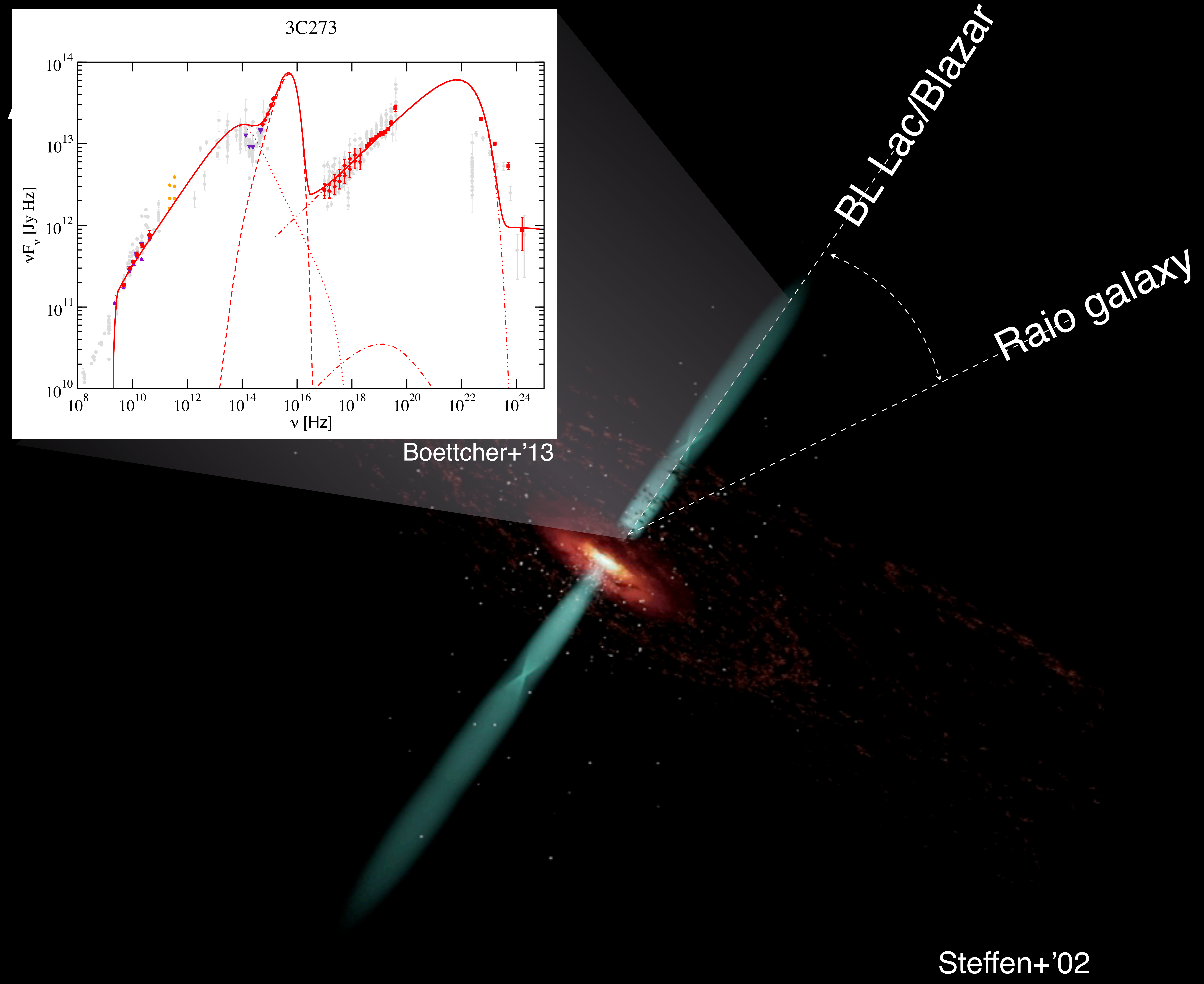
$\ldots \beta \cos(\theta) \Big]^{3+\alpha}$

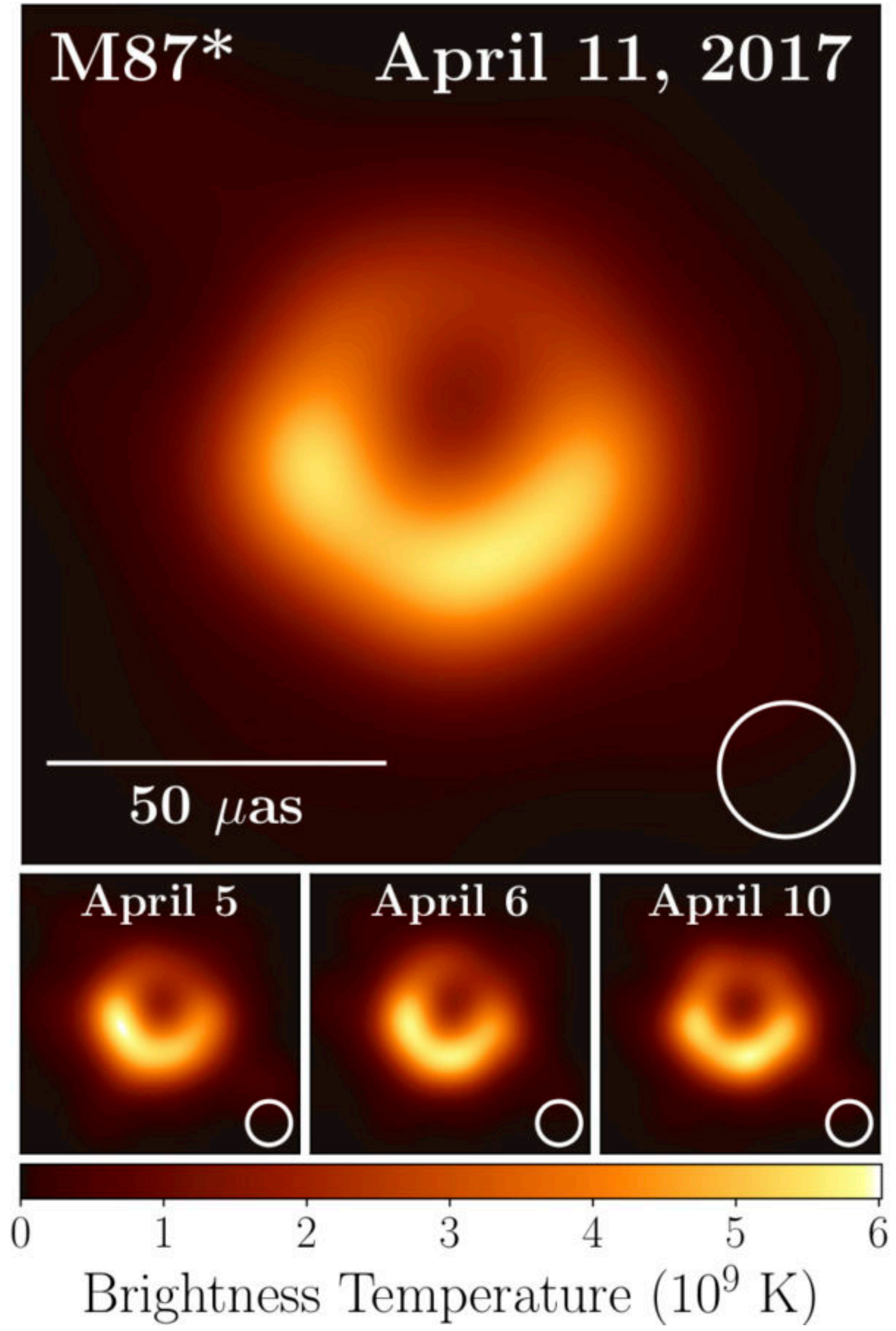
$I_\nu^- \ldots \delta^{-3+\alpha} \ldots \left[1 + \beta \cos(\theta) \right]$

AGN Unification



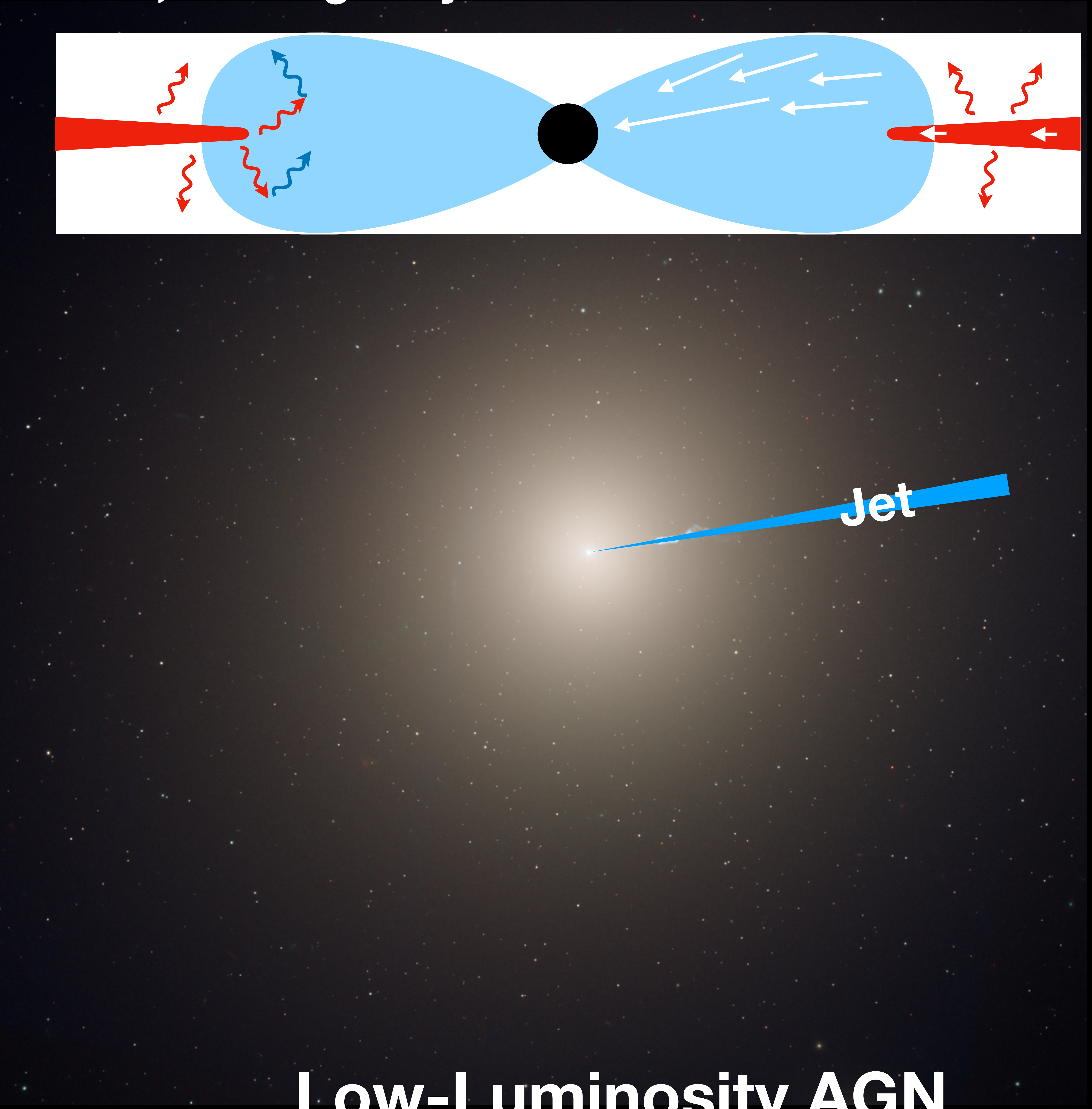



3C273
νF_ν [Jy Hz]
ν [Hz]
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
10^{24}
Boettcher+'13
BL Lac/Blazar
Raio galaxy
Steffen+'02


M87*
April 11, 2017
50 μas
April 5
April 6
April 10
0
1
2
3
4
5
6
Brightness Temperature (10^9 K)

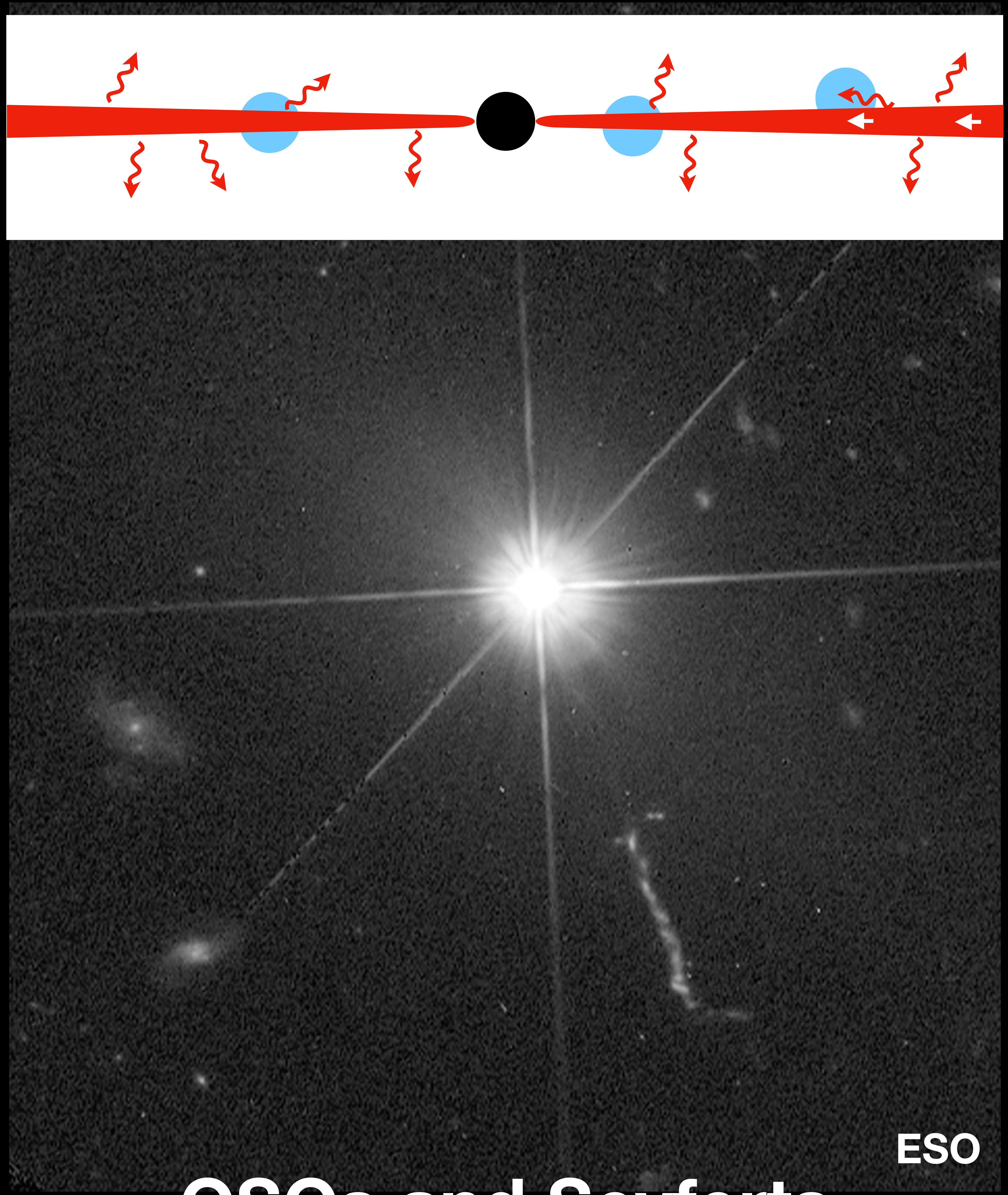

Credit: Nicolle R. Fuller/NSF

M87, Radio galaxy = advection dominated flow



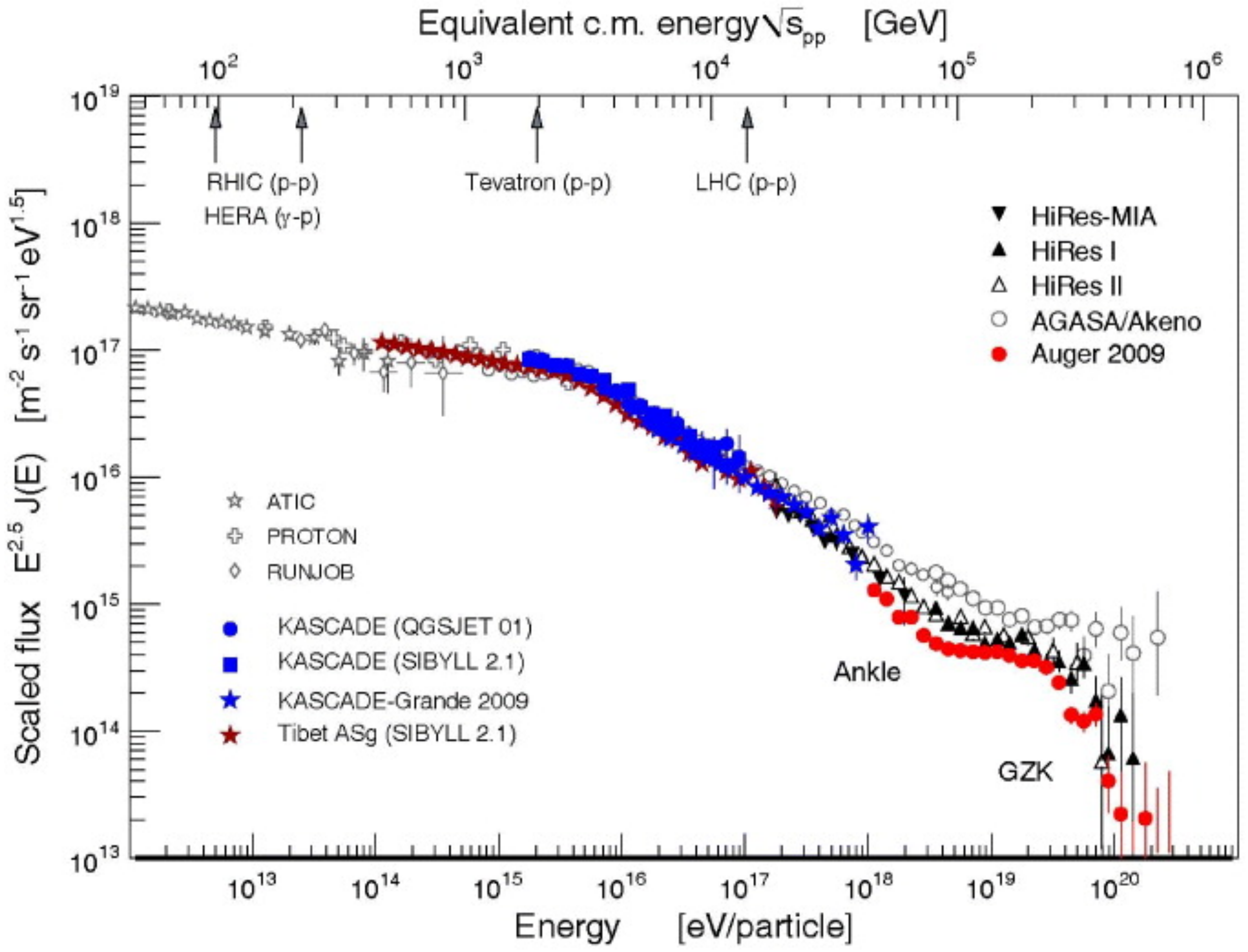
Low-Luminosity AGN

3C273, Quasar = radiative accretion flow



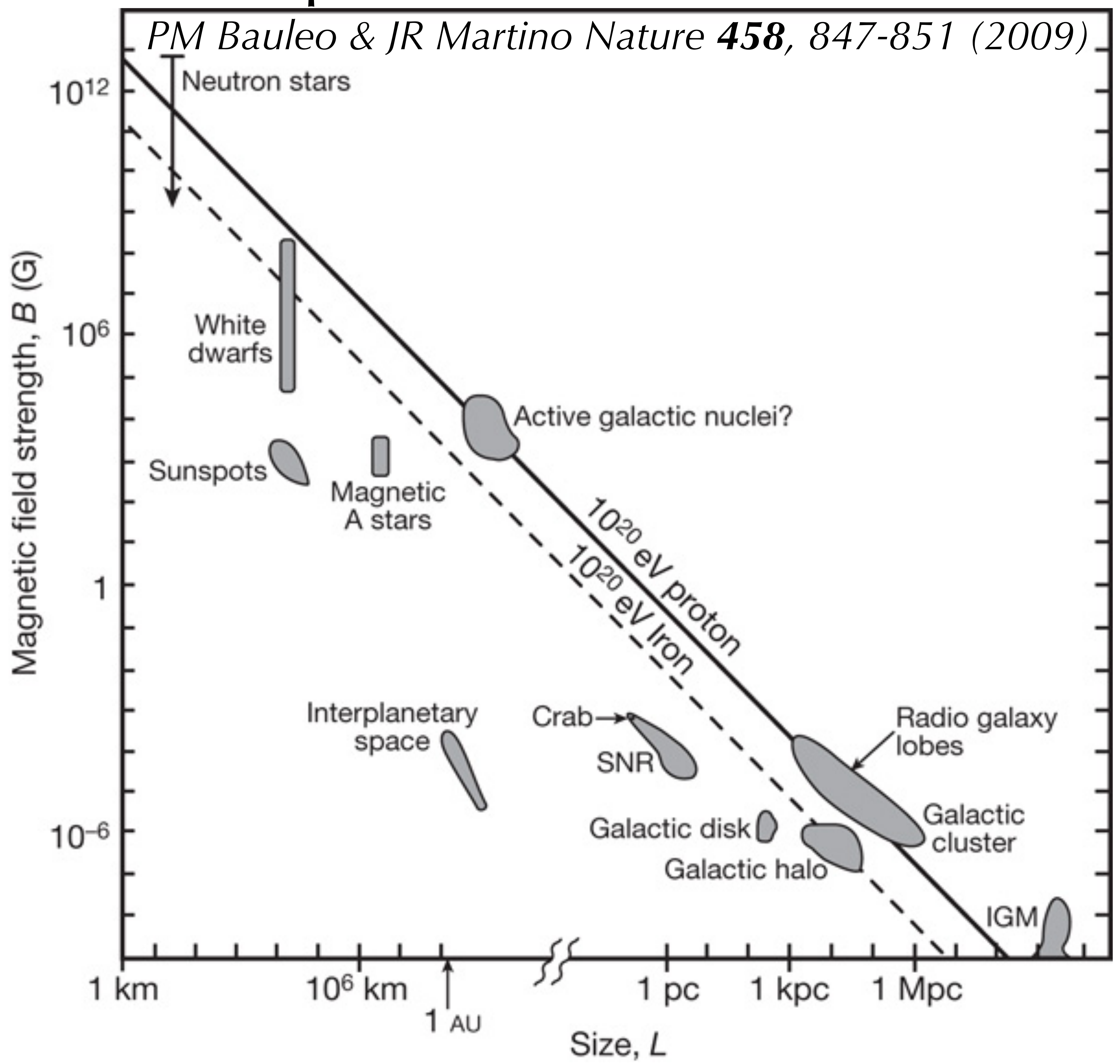
QSOs and Seyferts

Accretion disks as accelerators?

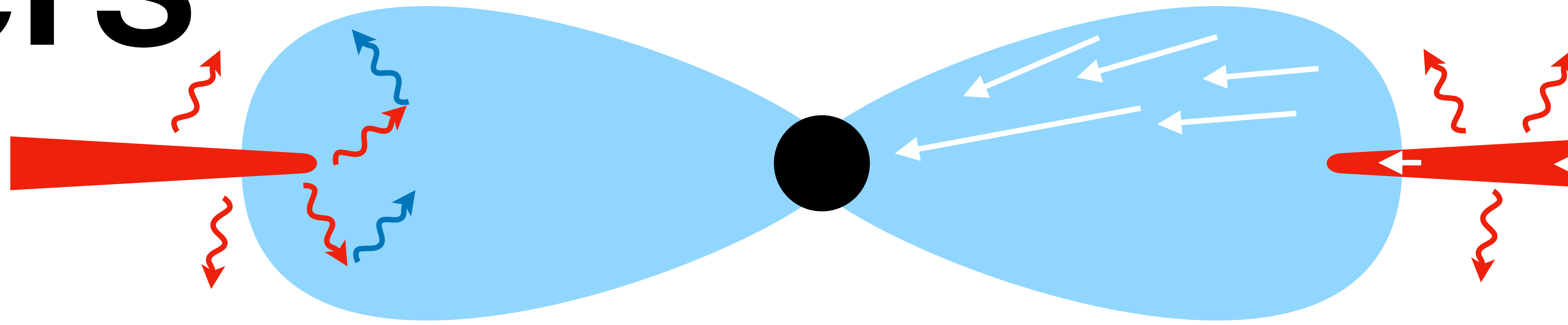


R. Engel, Auger Collaboration 2011

Hillas plot:



Accretion Parameters



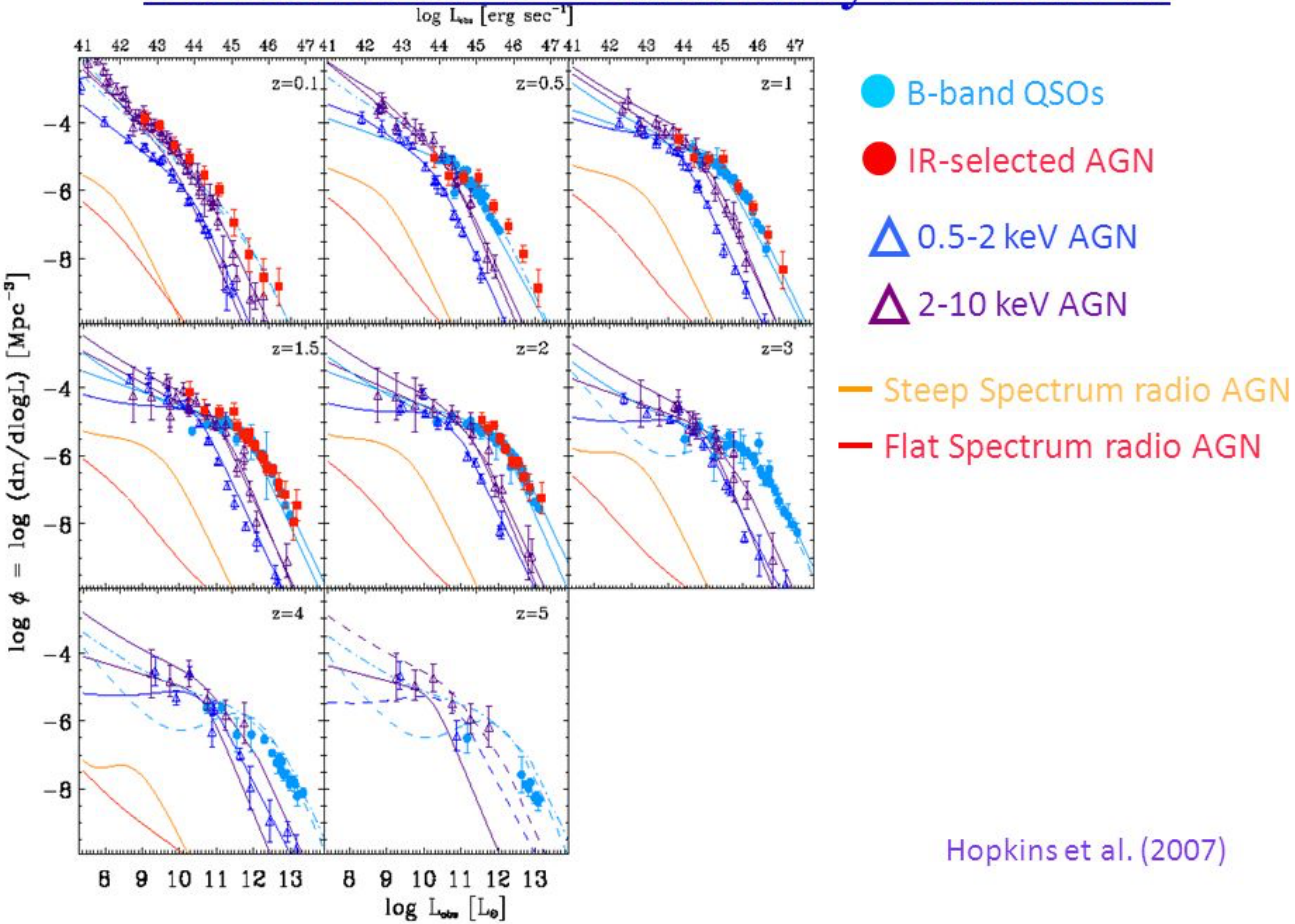
- Luminosity: $L = \lambda L_{\rm Edd} \sim 1.2 \times 10^{38}\,{\rm ergs\,s^{-1}}\; M/M_\odot$
- Accretion rates: $\dot{M} = \lambda \dot{M}_{\rm Edd} \sim \lambda \times 2 \times 10^{-8} M_\odot\,{\rm yr^{-1}}\, M/M_\odot$
- Radial velocity: $v_{\rm R} \sim \alpha v_{\rm K}$

Pressure: $$p \sim \frac{c^4}{\eta G M \sigma T}\frac{\dot{M}}{\dot{M}_{\rm Edd}} \sim 10^7\,{\rm ergs\,cm^{-3}}\frac{\dot{M}}{\dot{M}_{\rm Edd}}\frac{10^9 M_\odot}{M}$$

B-field: $$B \sim 10^4\,{\rm G}\left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\frac{10^9 M_\odot}{M}\right)^{1/2}$$

Evolution

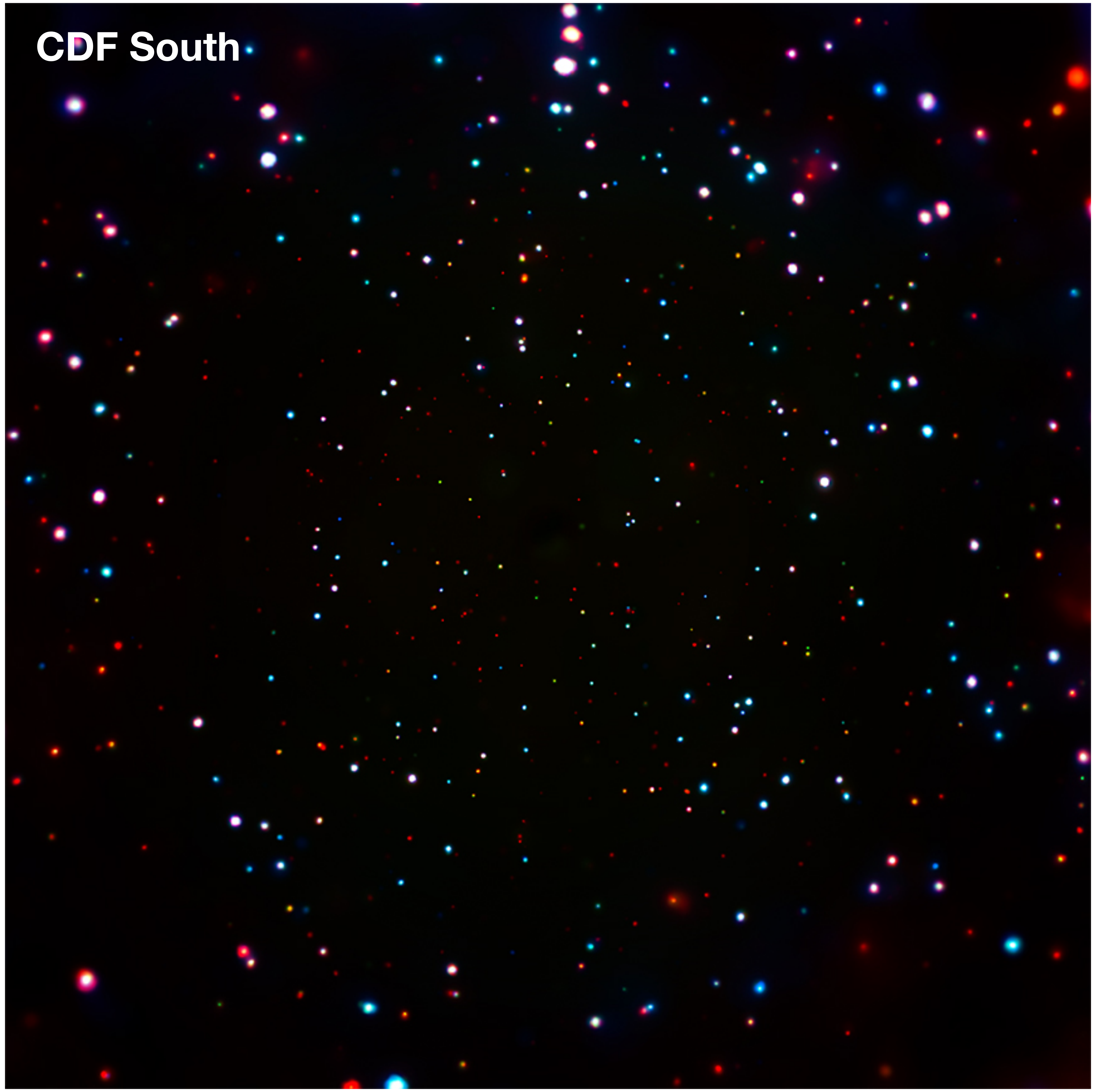
Panchromatic Luminosity Functions



Hopkins et al. (2007)

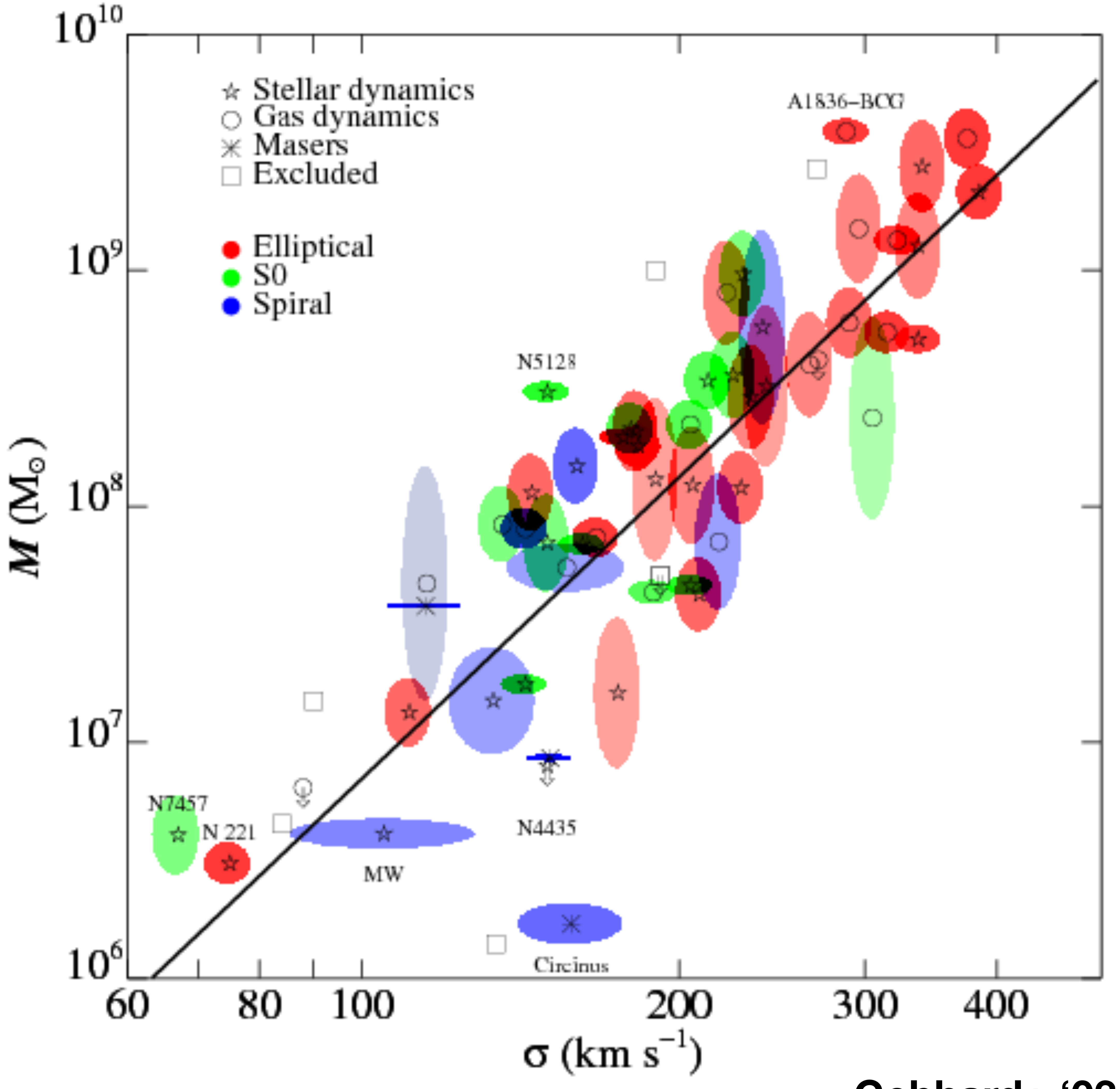
X-Ray Background

ESO

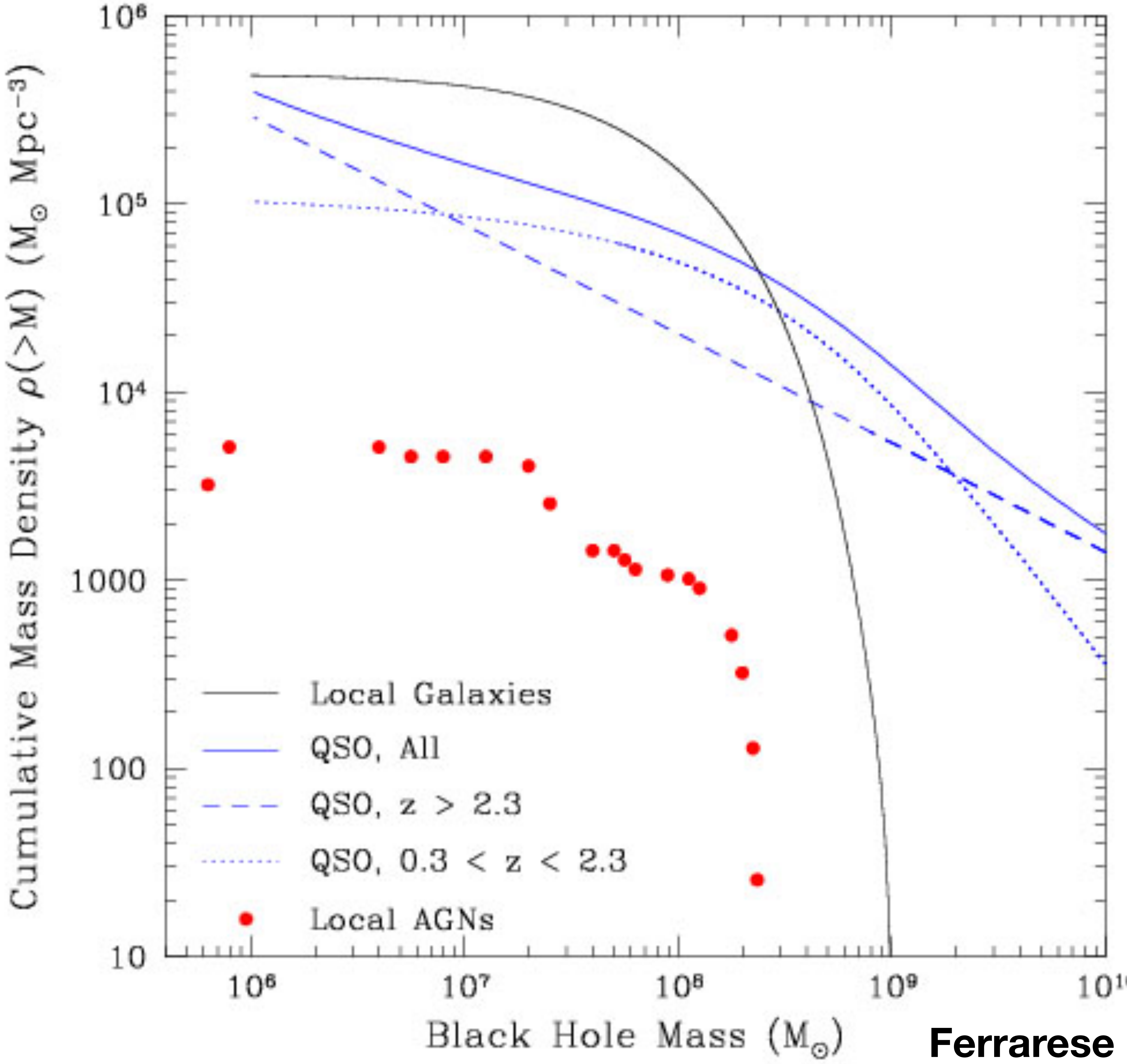


Luo+ ‘16

Black Hole Mass Density

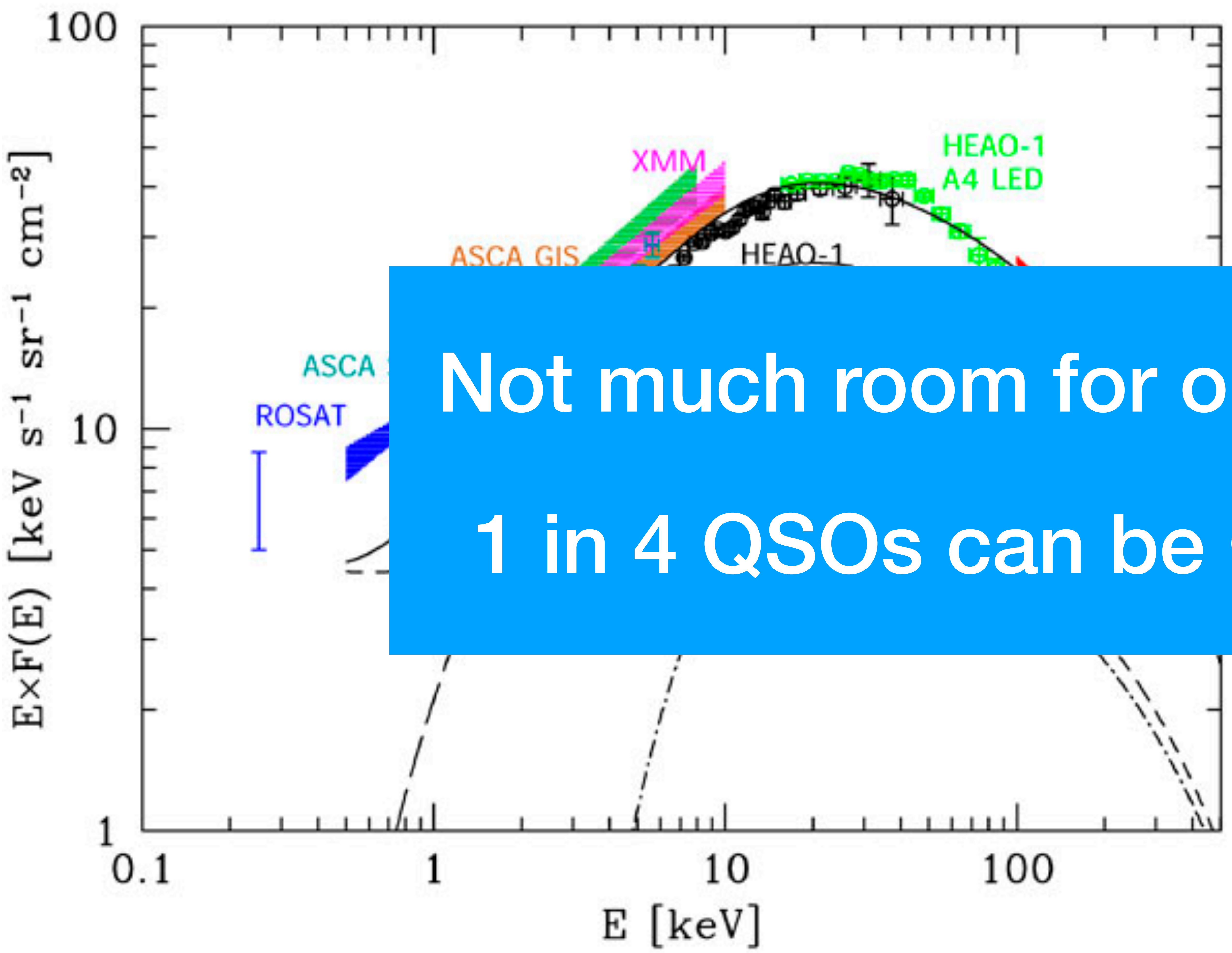


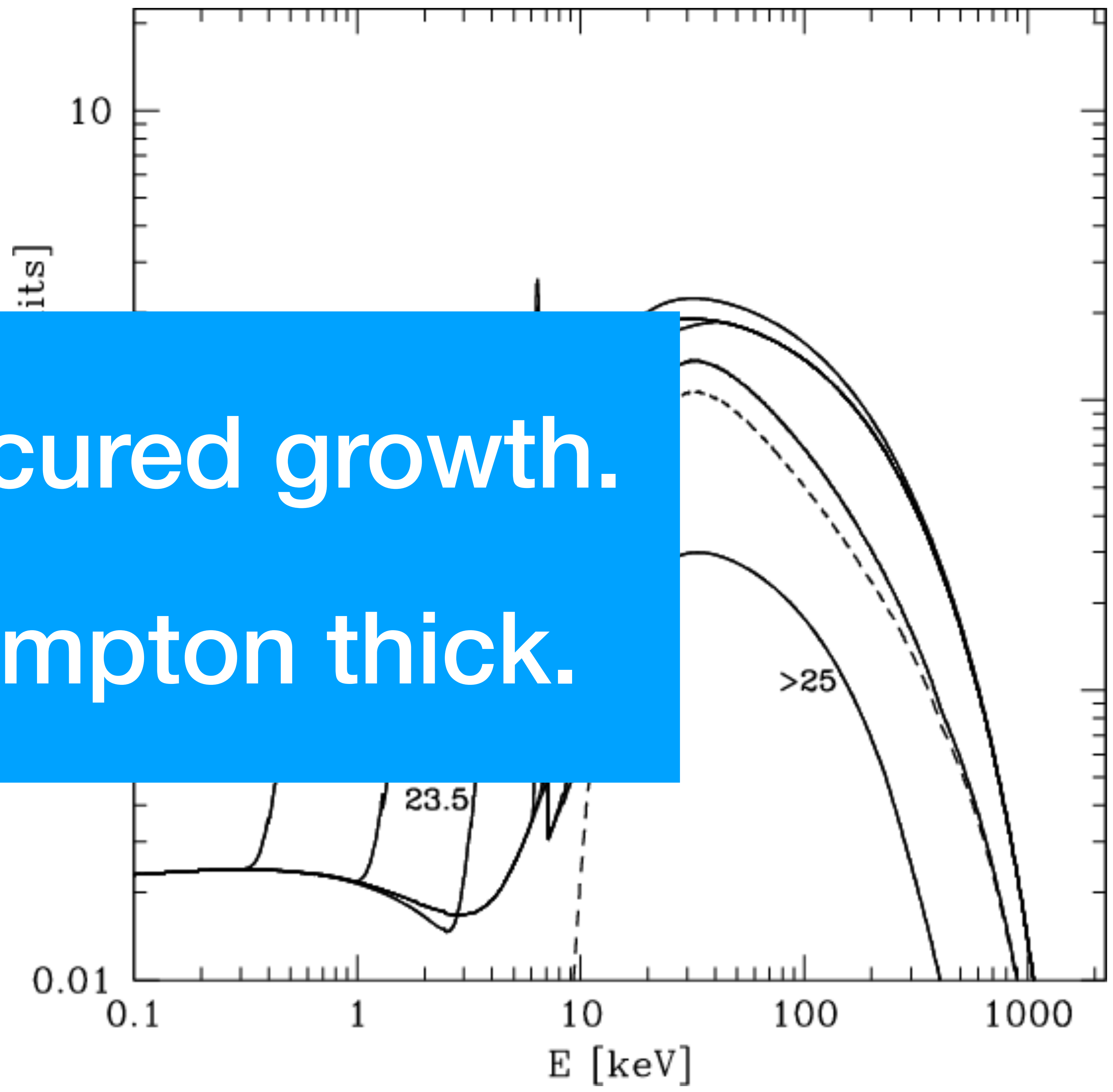
Gebhard+ ‘03



Ferrarese

X-Ray Background

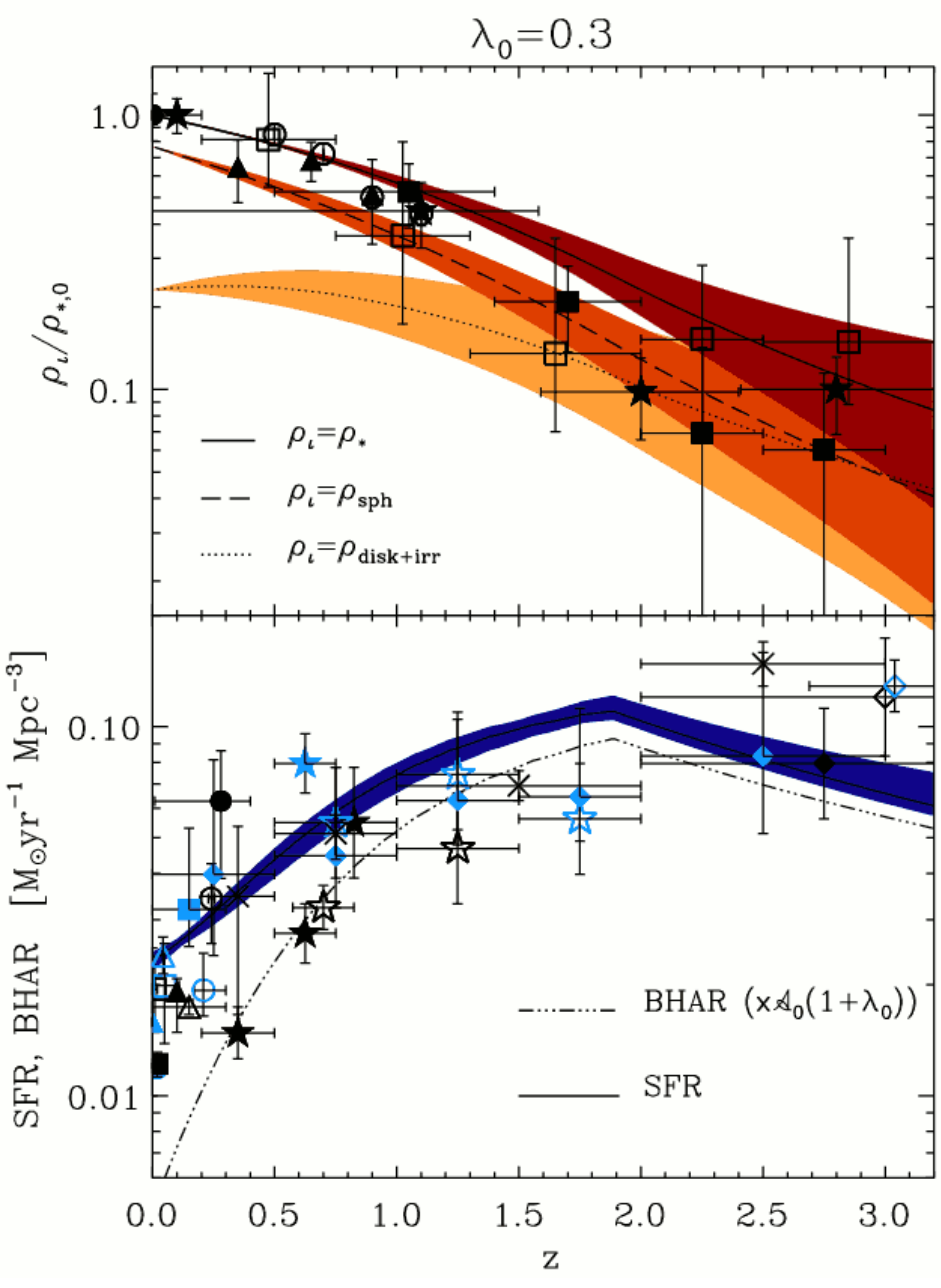


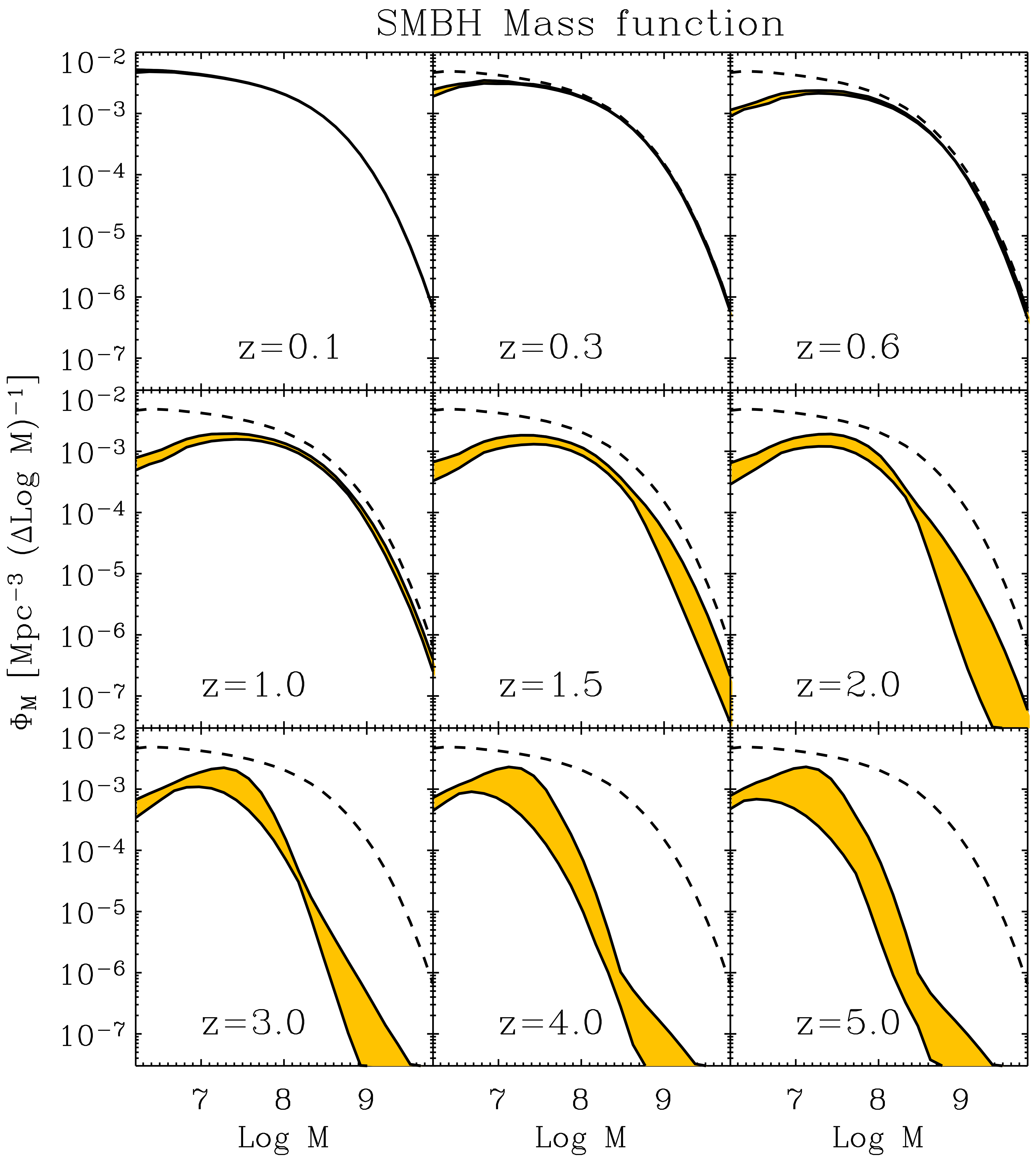


Not much room for obscured growth.

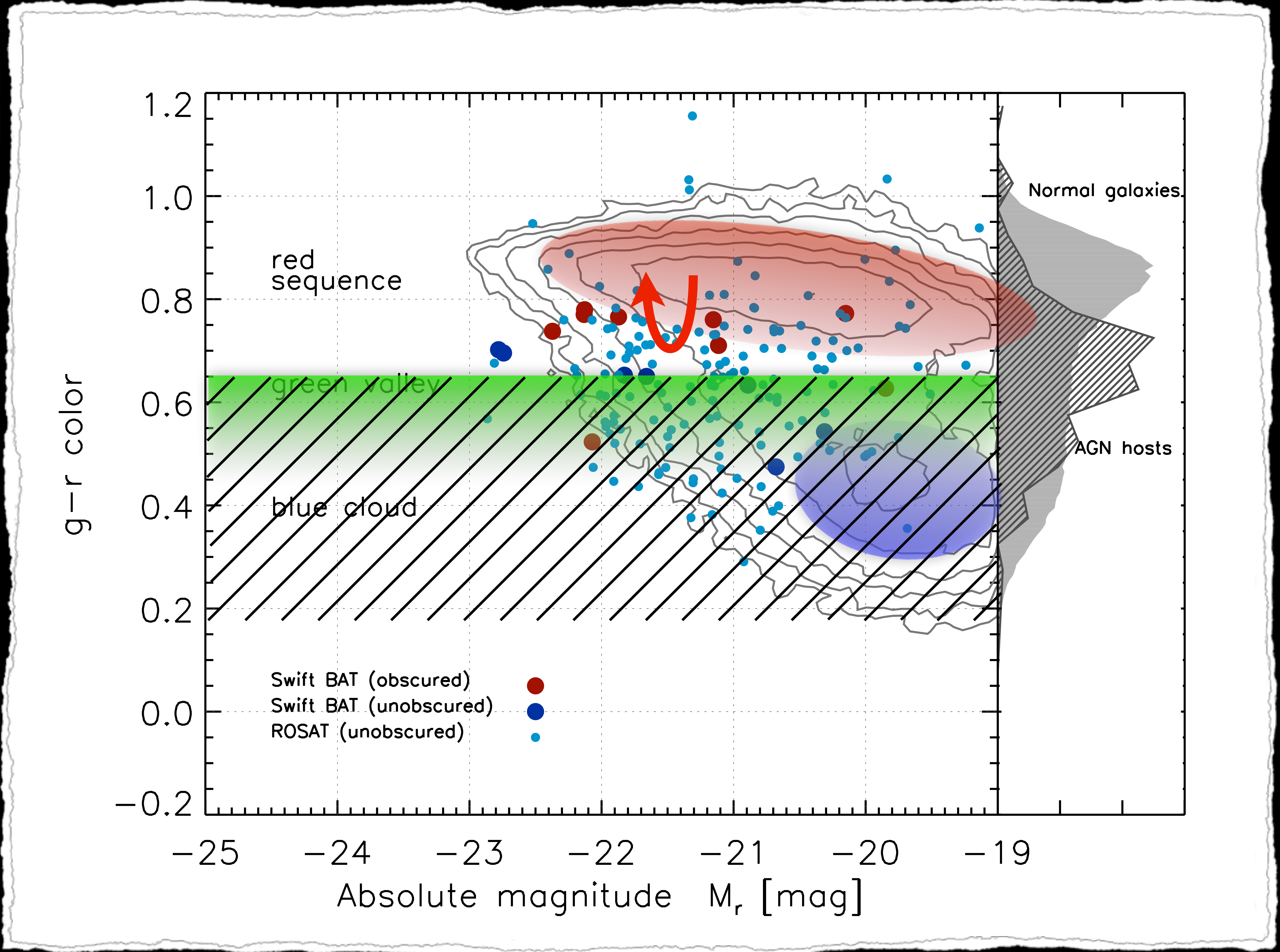
1 in 4 QSOs can be Compton thick.

Merloni & Heinz 2008

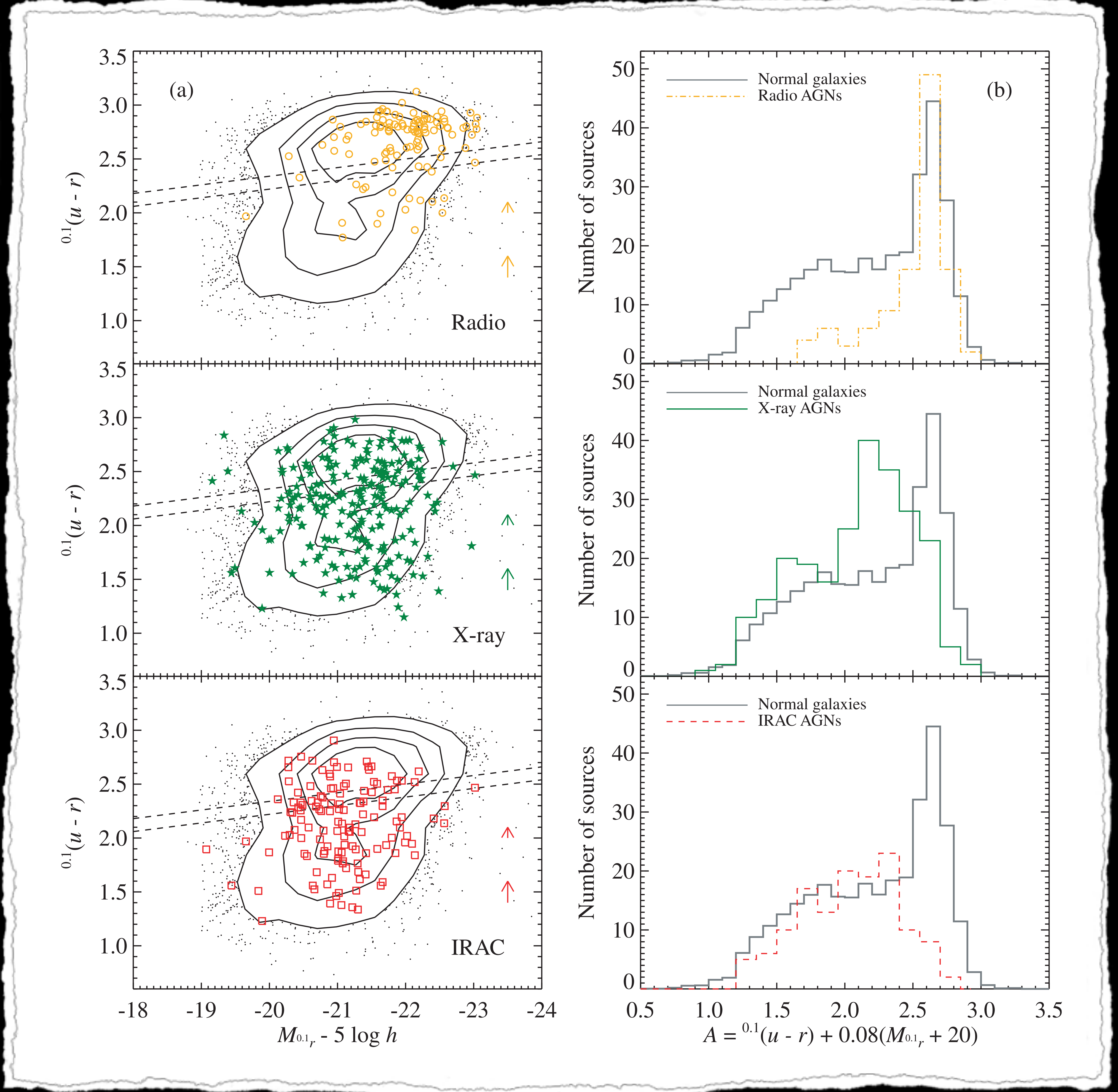




AGN Hosts

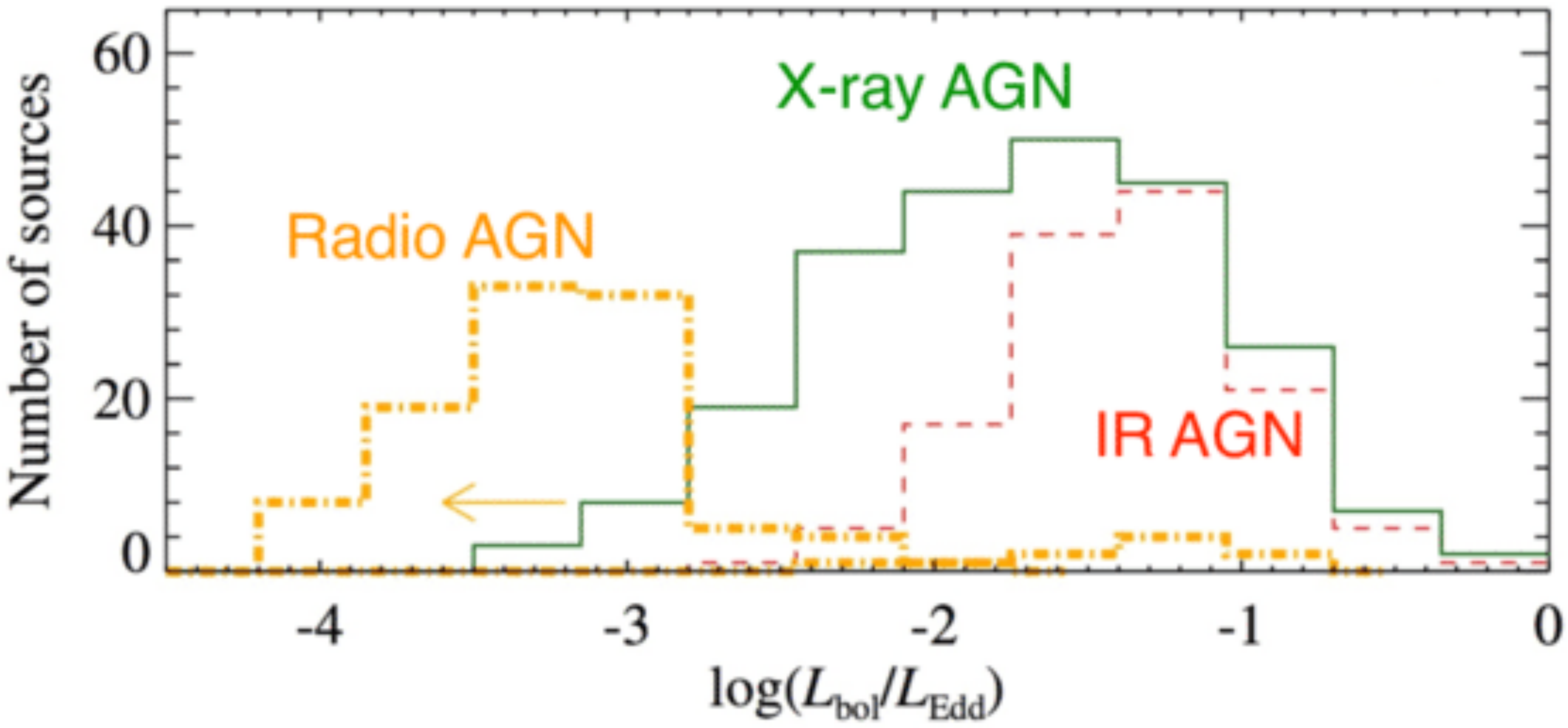


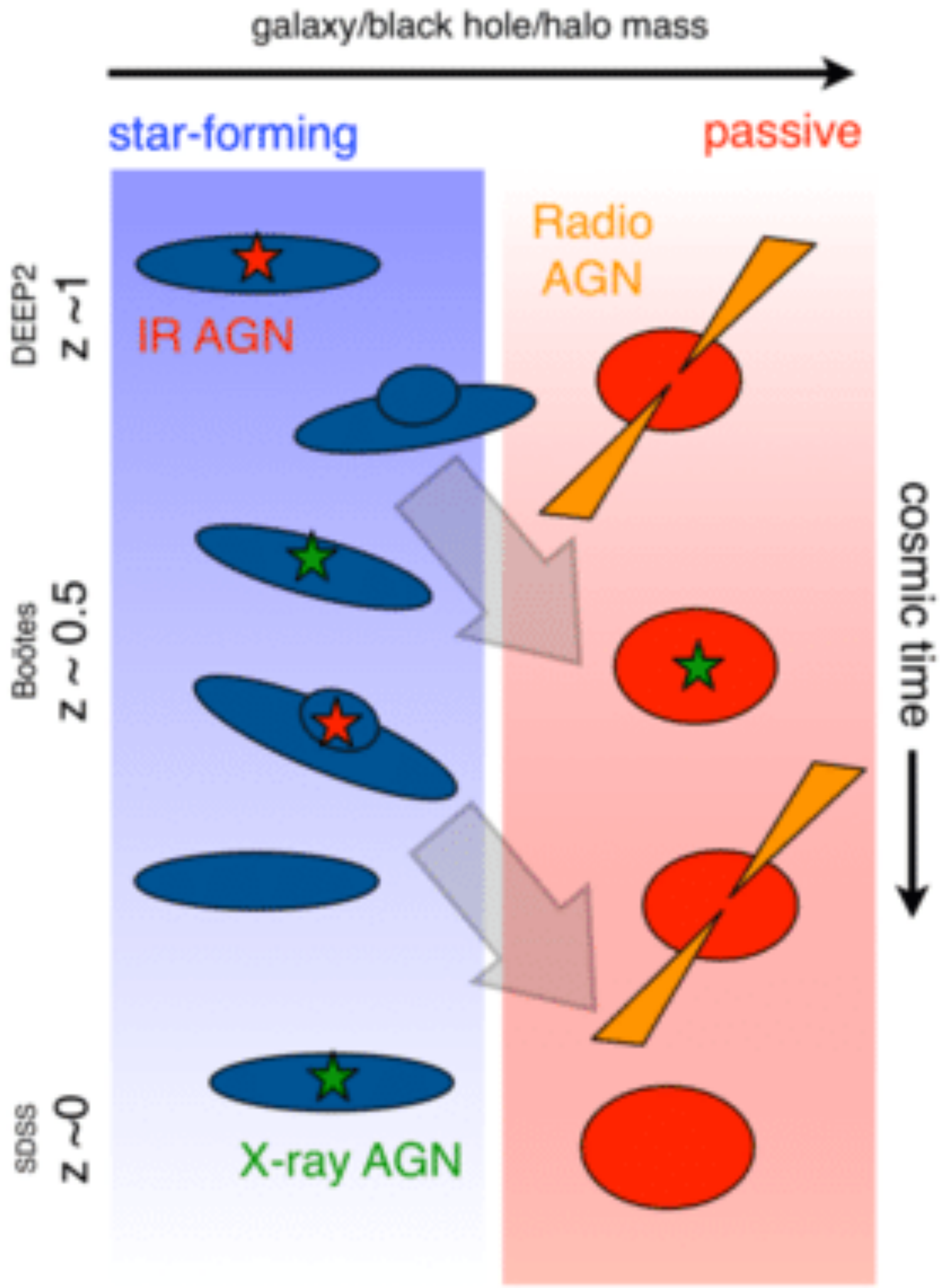
Croton et al. 2006, Schawinski et al. 2009



Hickox et al. 2009

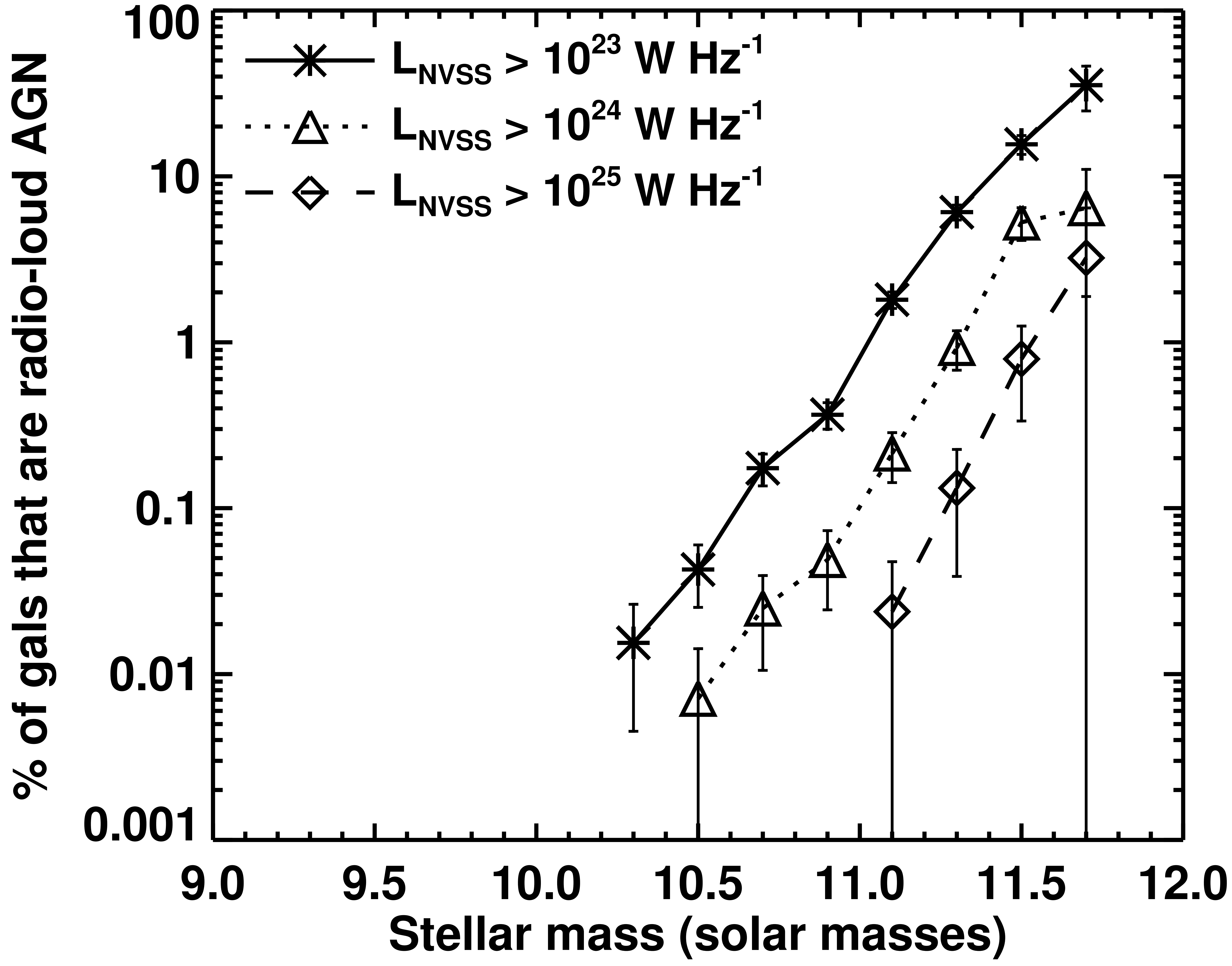
AGN Hosts





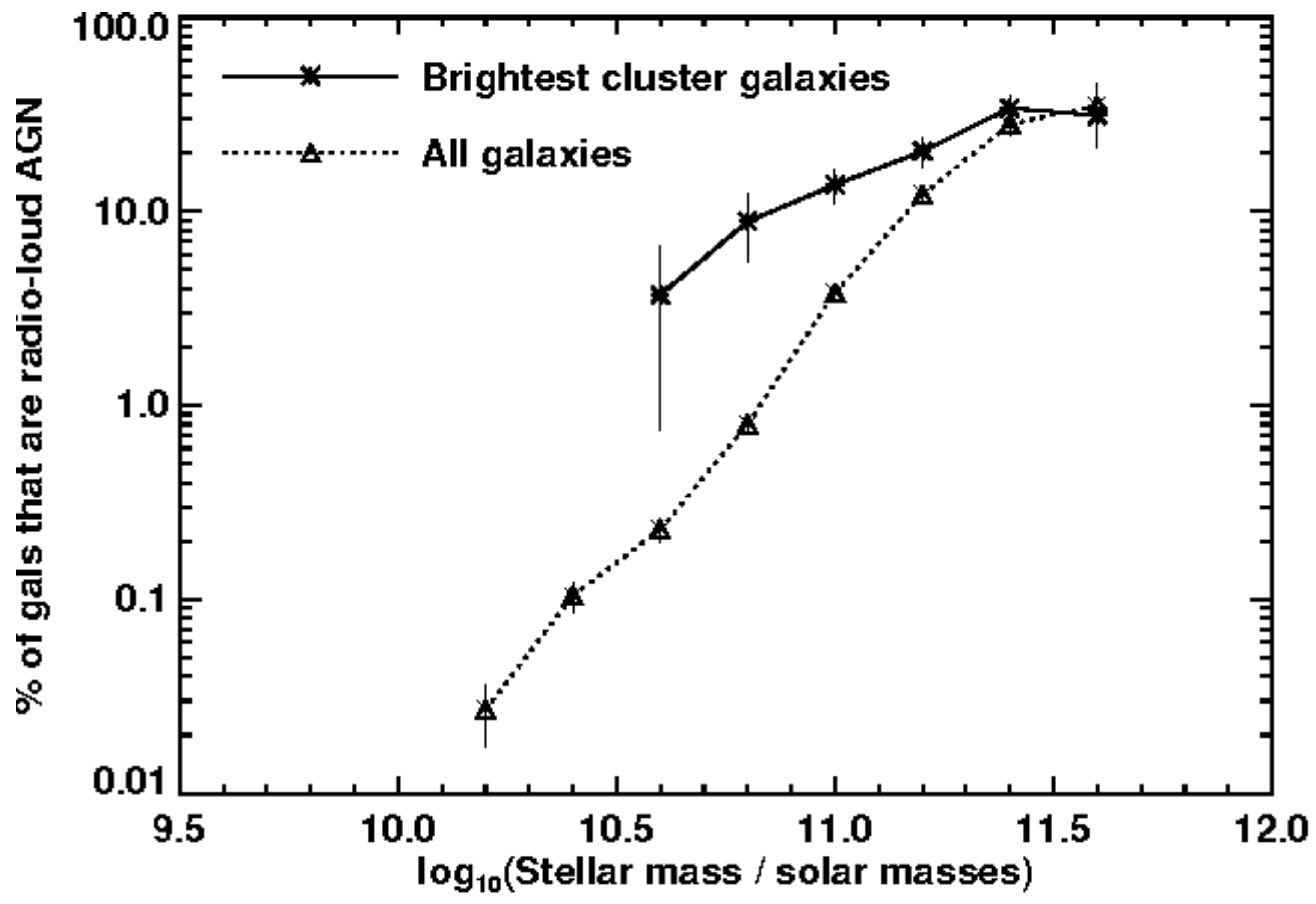
Hickox+ '09

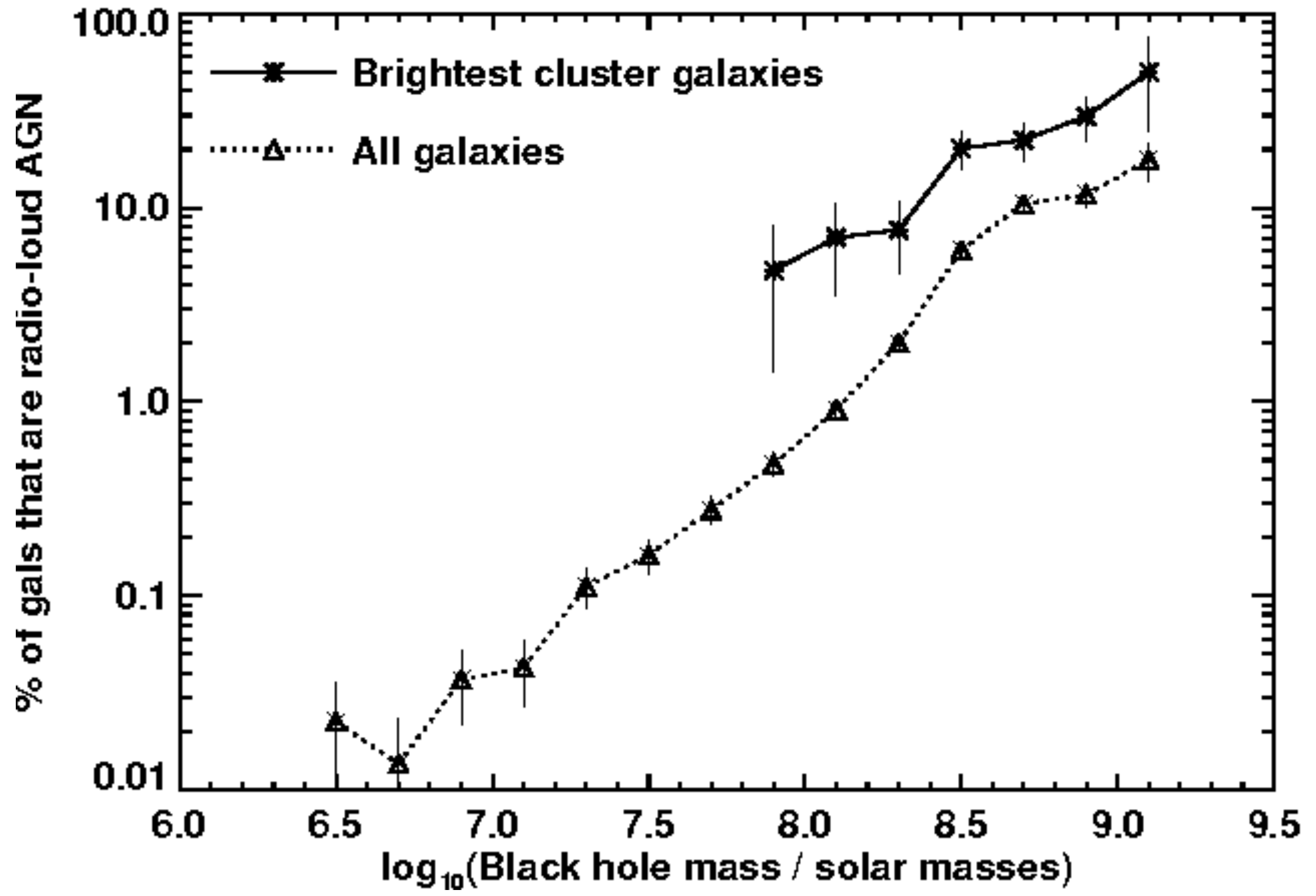
Radio Loudness

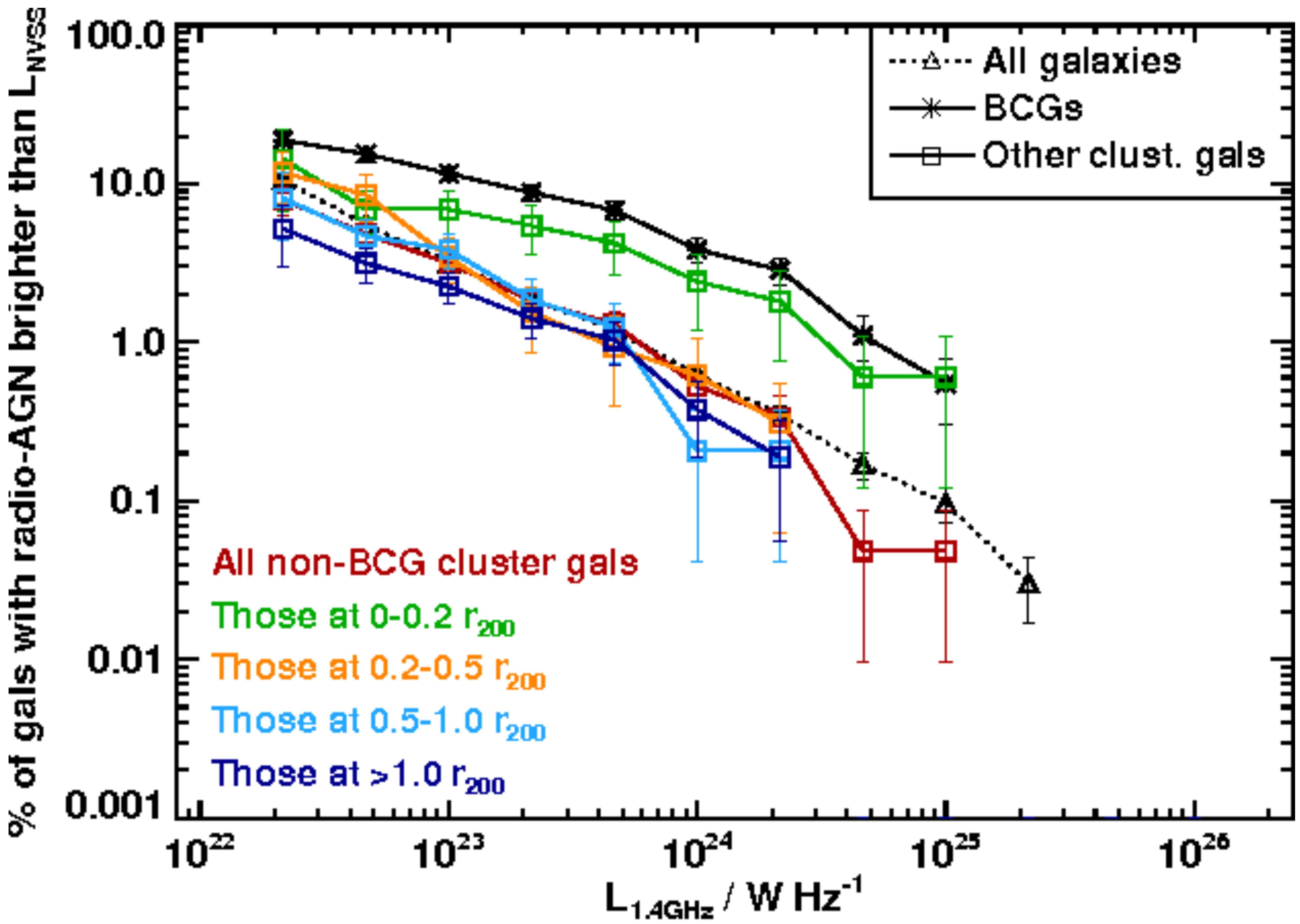


Best+ ’07

Radio AGN Environments



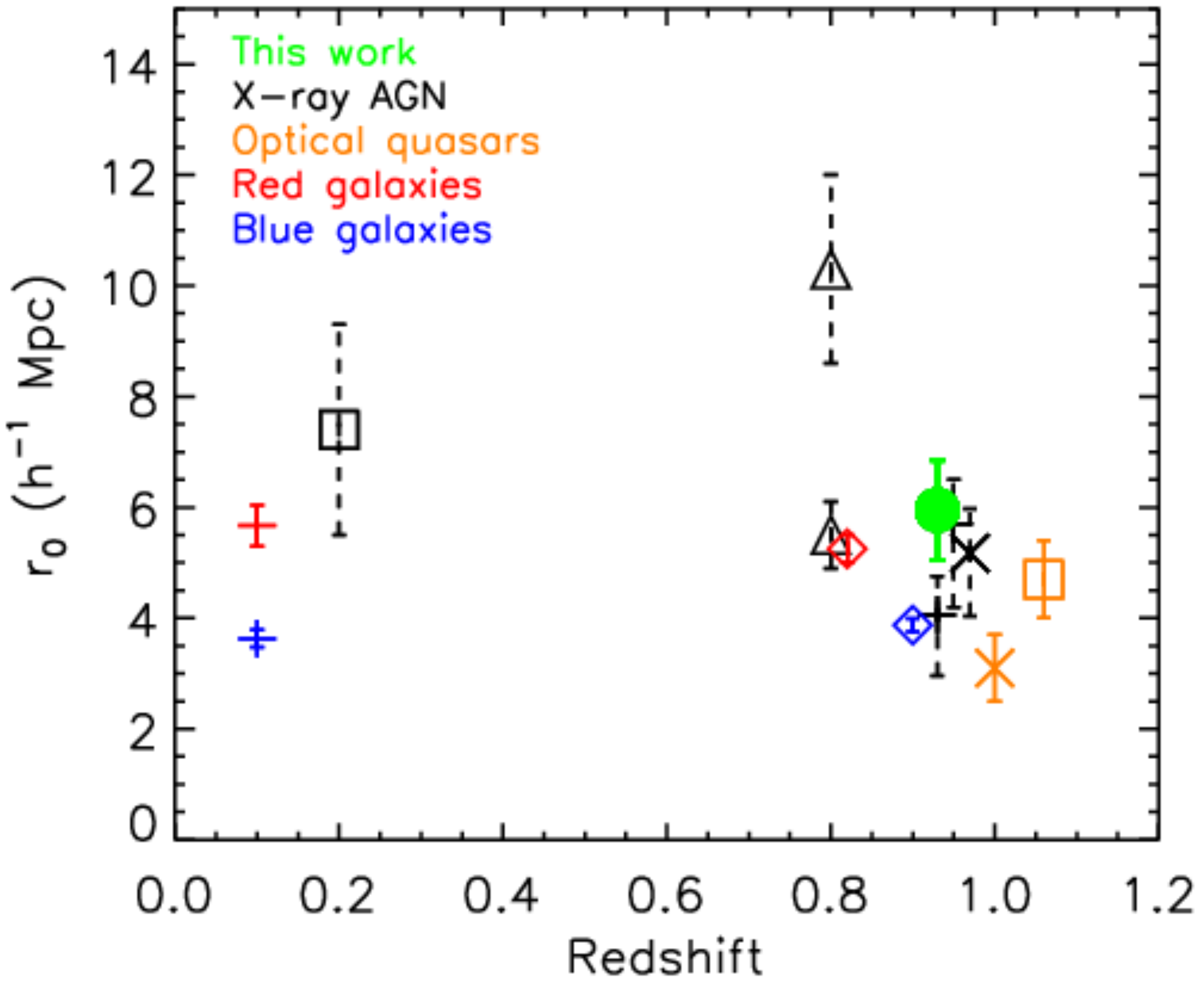




Best+ '07

$$\xi_2\left(|\vec{x}_1 - \vec{x}_2|\right) = \xi_2(\vec{\Delta}) \equiv \frac{1}{V}\int d^3x\,\delta(\vec{x})\,\delta(\vec{x} + \vec{\Delta})$$

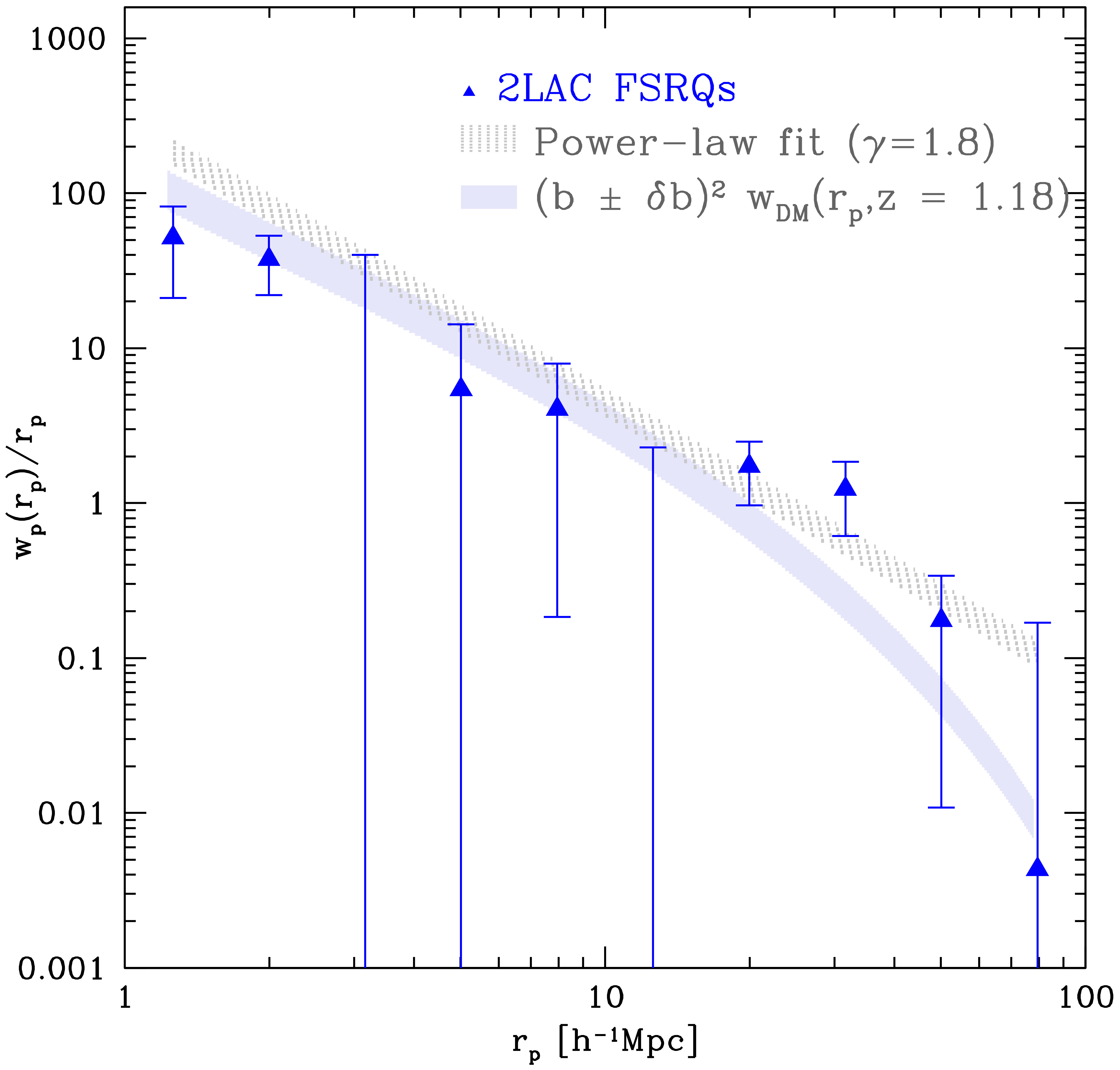
- X-ray AGN more strongly clustered
- Located in more massive halos?



Coil+ ‘09

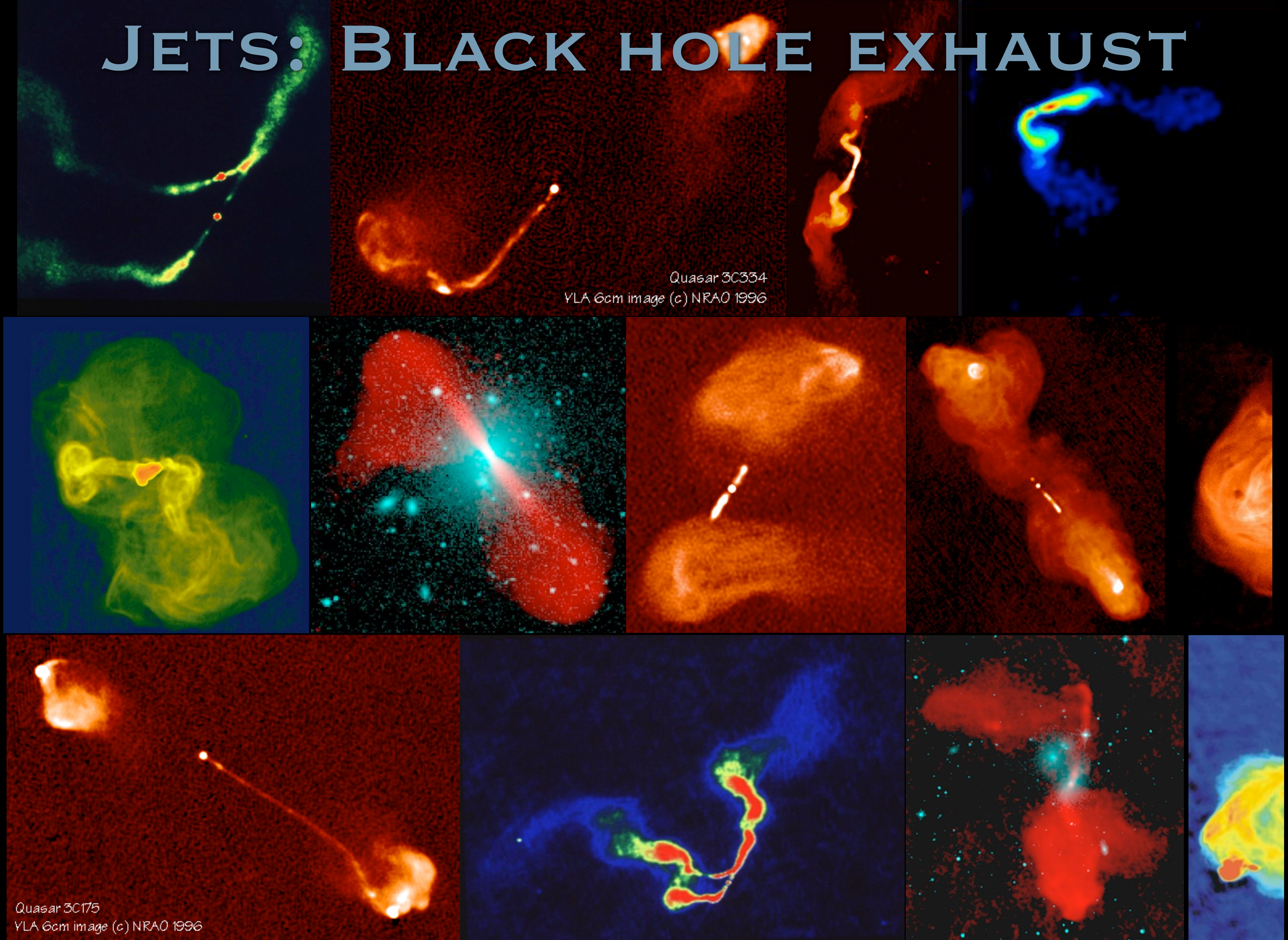
Blazar Clustering

- Radio AGN most strongly clustered
- Gamma-ray blazers similarly clustered
- Located in most massive halos



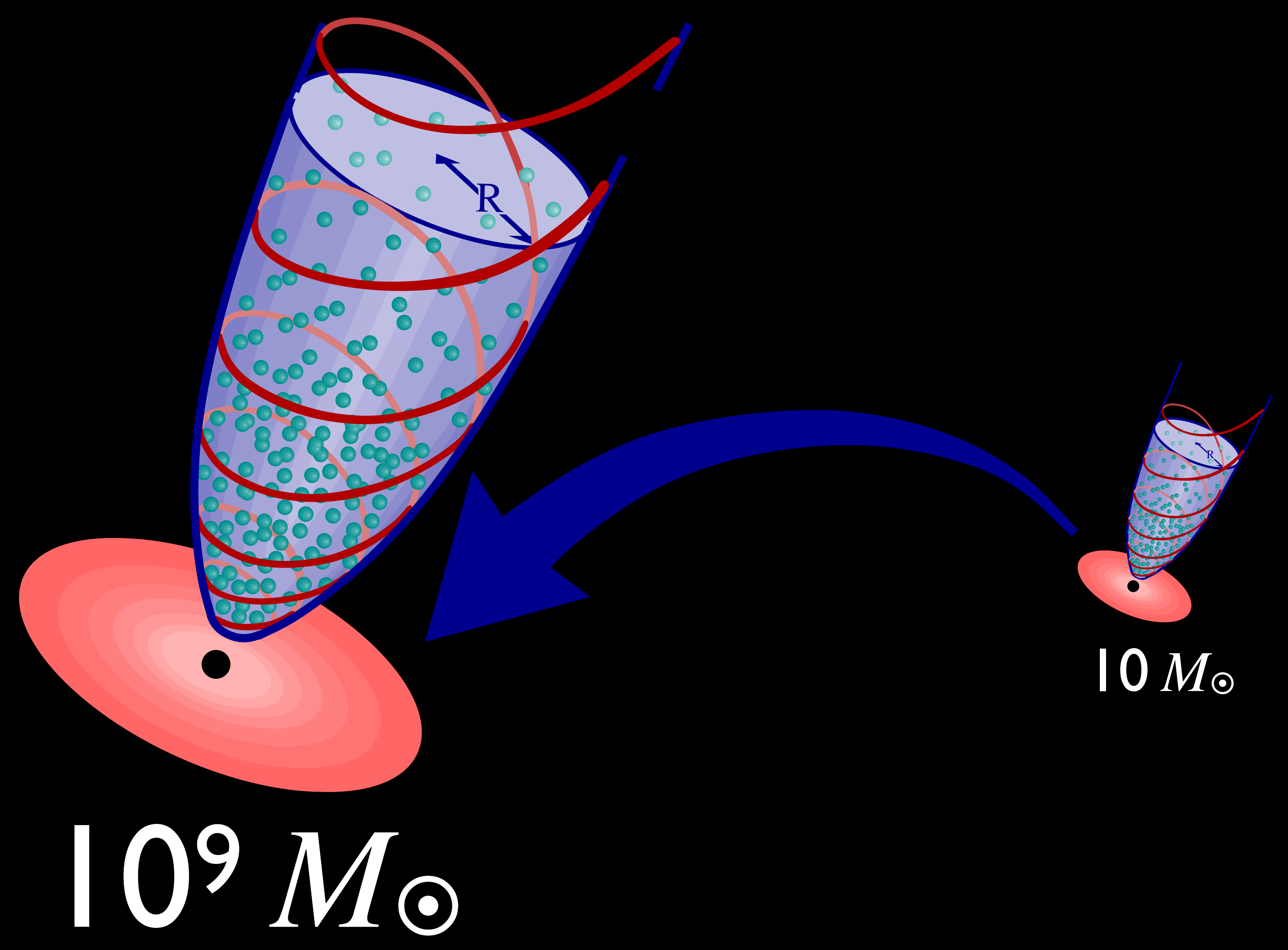
Allevato+ '18

Jets: Black hole exhaust

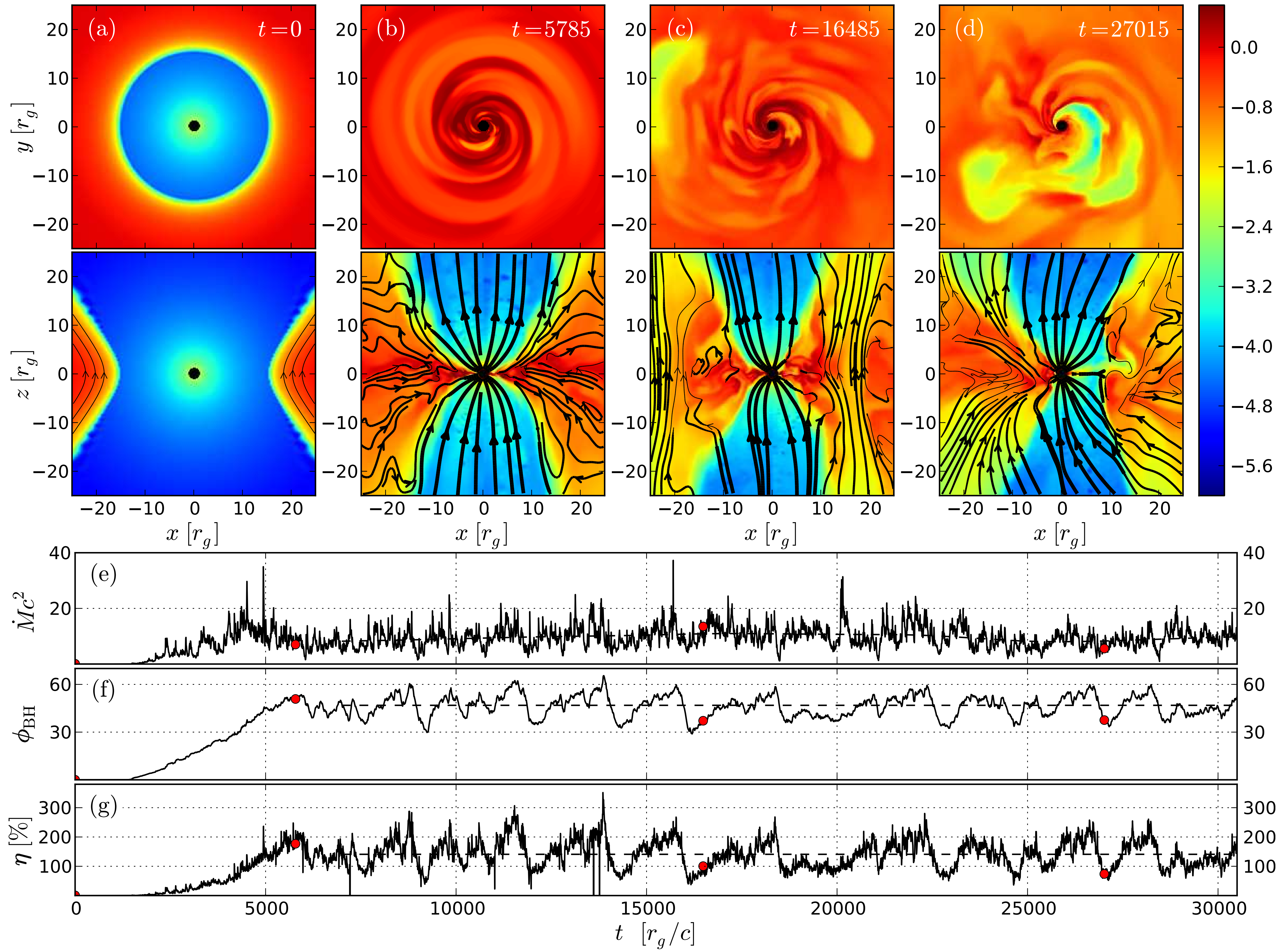


Central Hypothesis

- Black hole at the center
- *Mass* governs *scale*
- All other properties are functions of
  - ★ accretion rate $\dot{m}$
  - ★ spin a
  - ★ net external magnetic flux φ_B

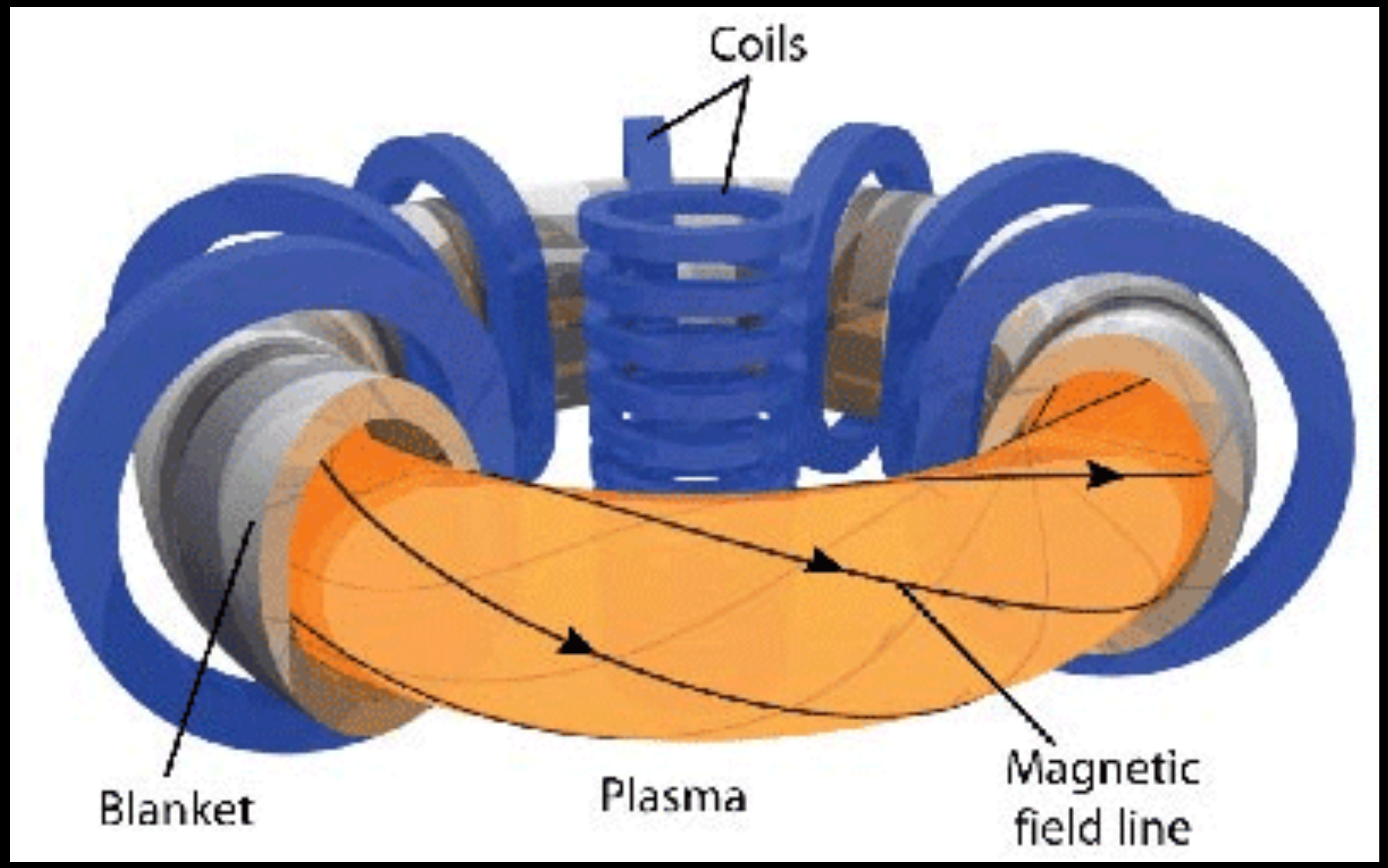


Jet Acceleration



Collimation

- Ballistic?
  - ★ Requires tight initial collimation
- External confinement?
  - ★ Requires large external pressure
- MHD?
  - ★ Requires stabilization

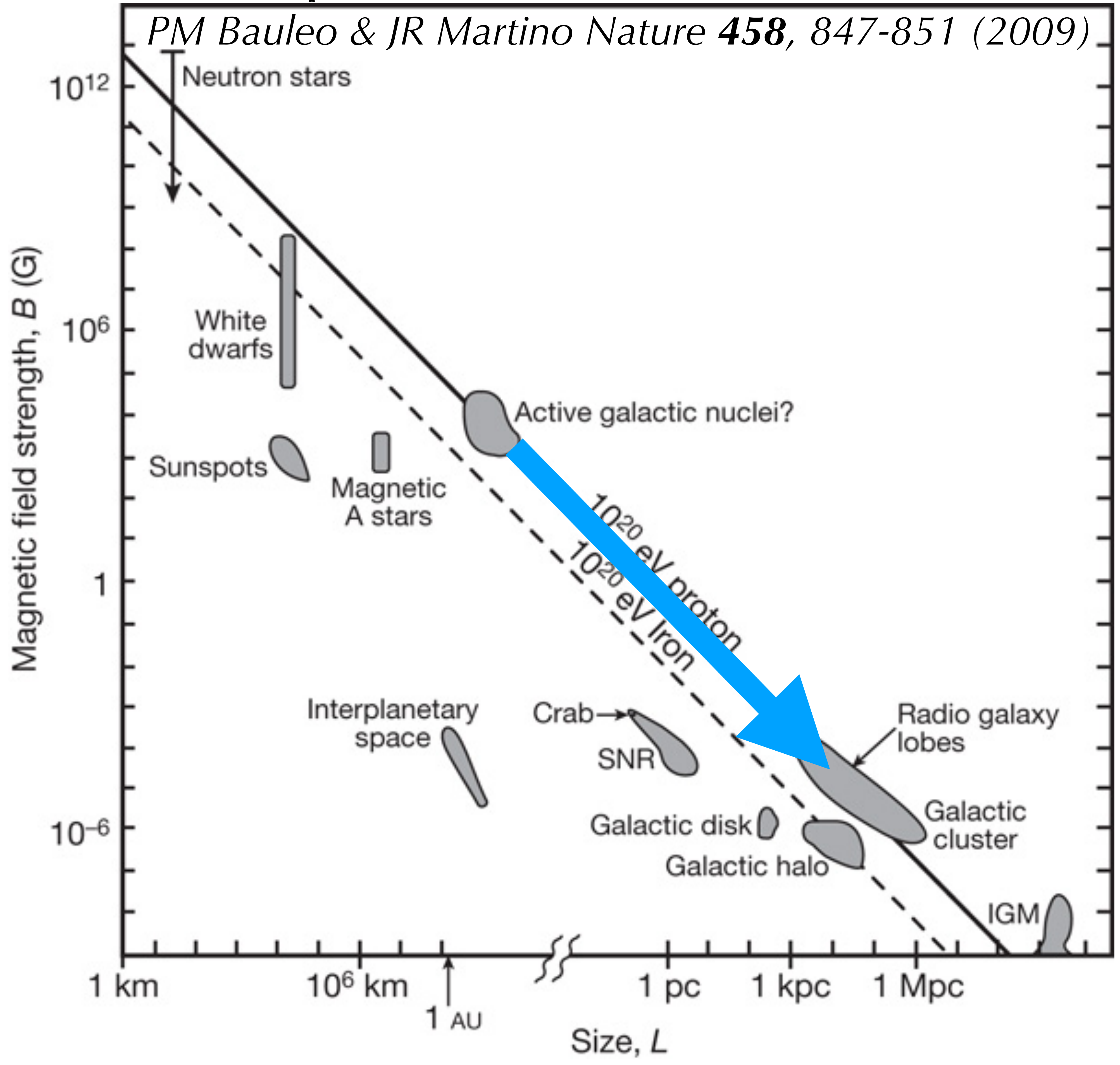


Jet Parameters

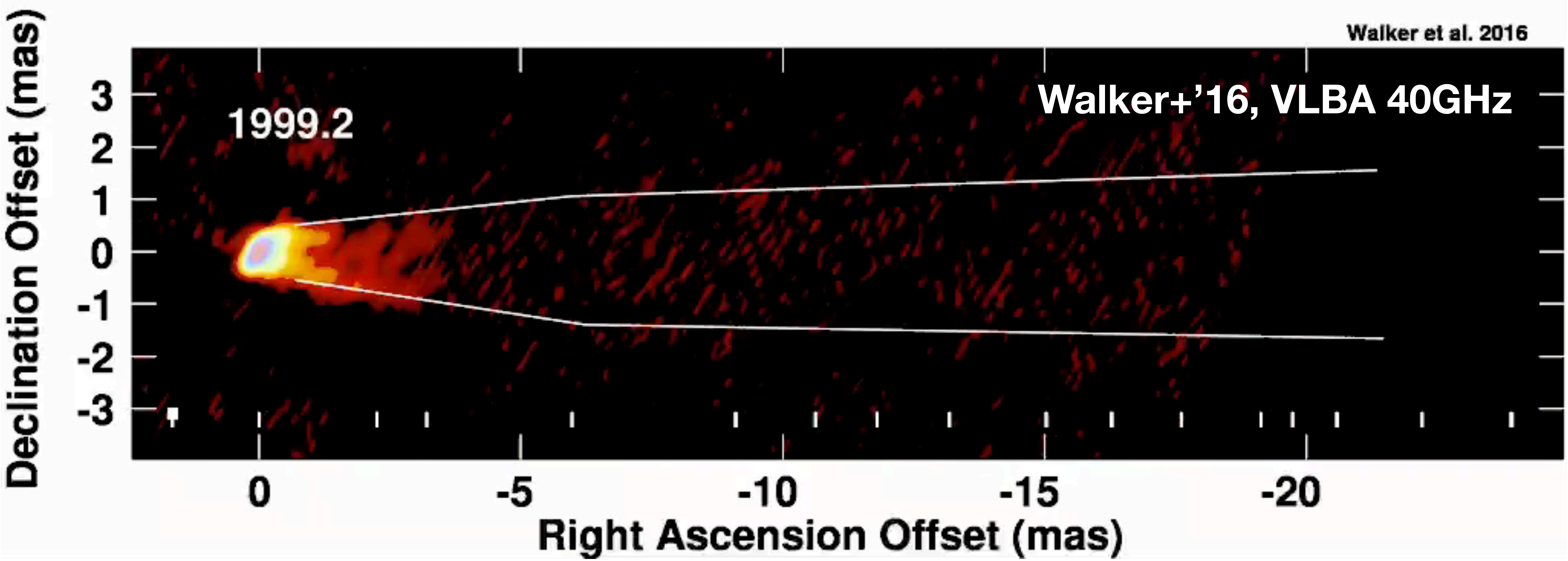
- B-fields: Gauss (pc scales) to mGauss (kpc scales)
- Lorentz Factor: 5 (M87) to 50 (Mojave)
- Power: 10^{42} ergs/s to 10^{47} ergs/s
- Composition: ???
- Hoop stress confinement:

$$B_\varphi \propto \frac{1}{R_{\rm jet}}$$

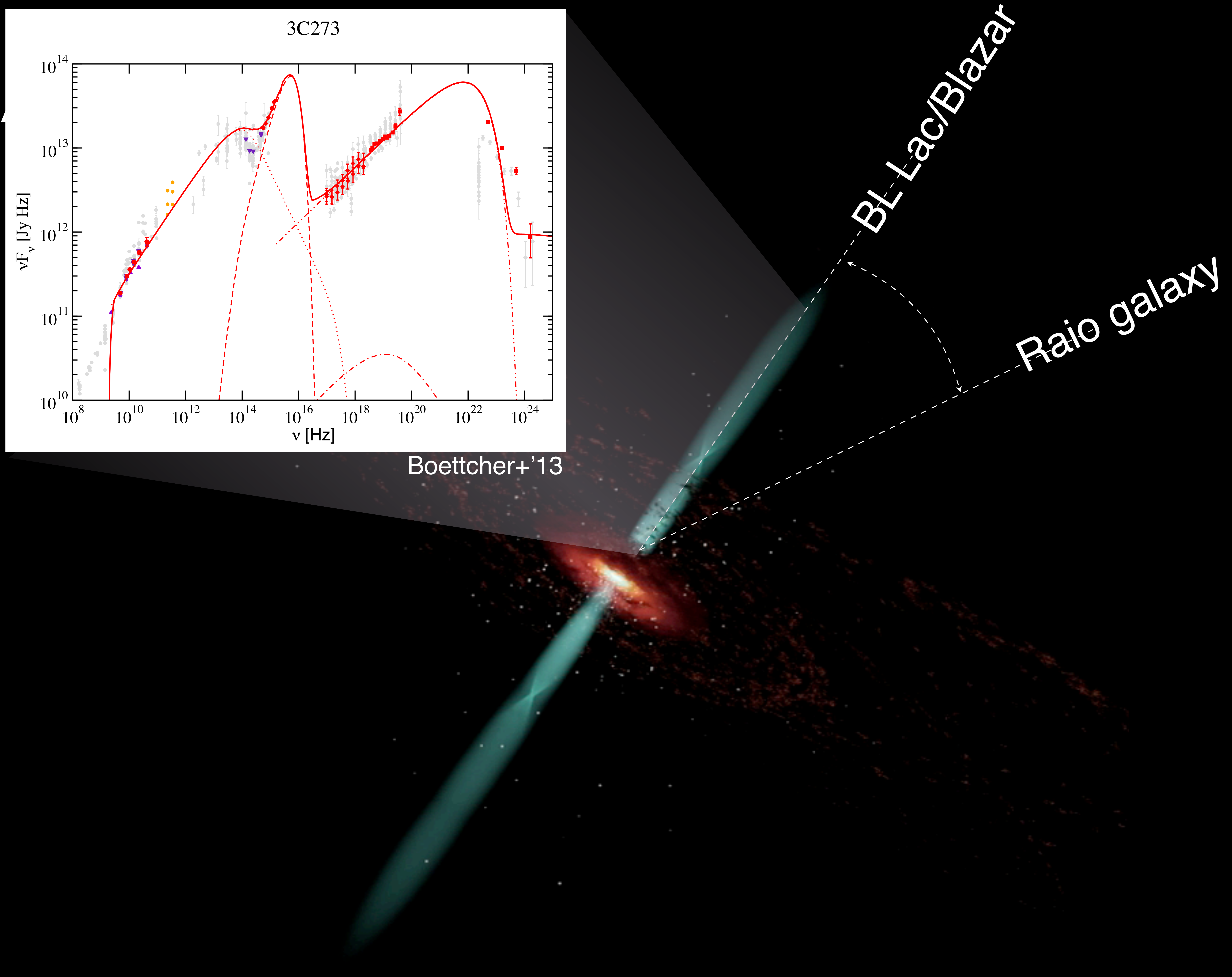
Hillas plot:



Jets


Walker et al. 2016
Walker+'16, VLBA 40GHz
1999.2
Declination Offset (mas)
3
2
1
0
-1
-2
-3
0
-5
-10
-15
-20
Right Ascension Offset (mas)

~150 R_S



Steffen+'02

Jet Parameters

Hillas plot: