The power of extragalactic jets

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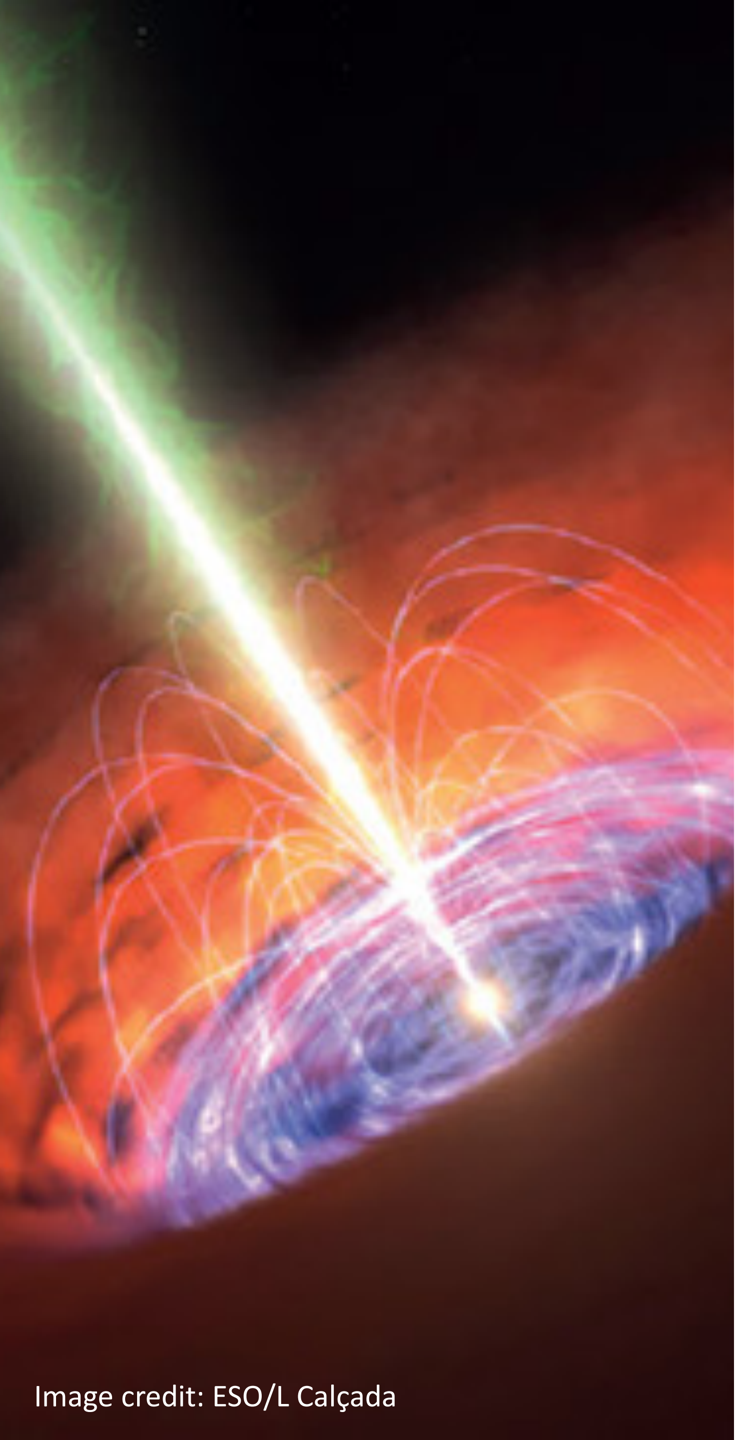
Shining from the heart of darkness: black hole accretion and jets – Kathmandu, October 19th, 2016



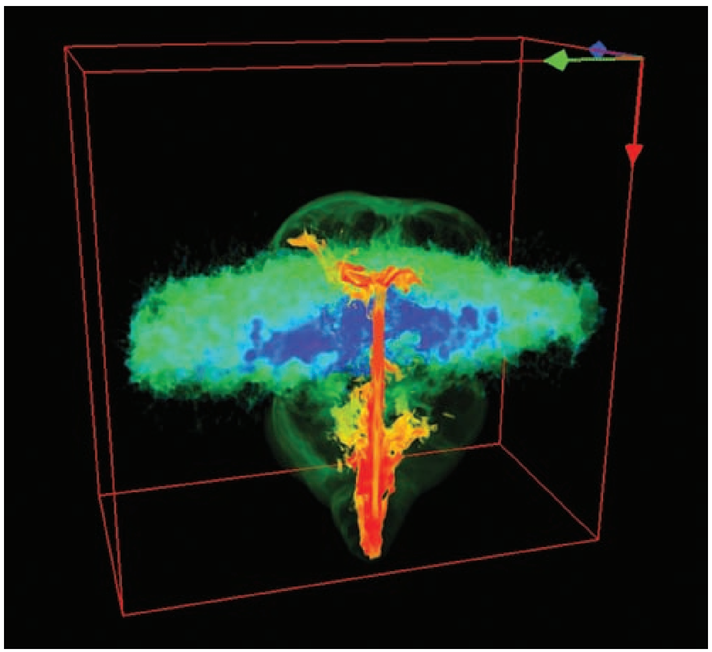
Outline

- Importance of jet power measurements

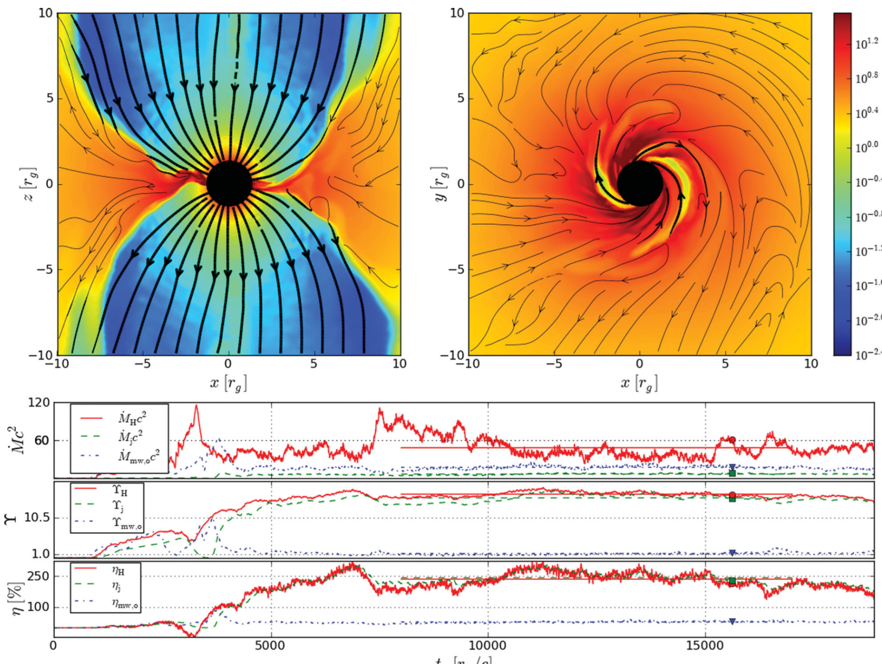
  (why do we care?)
- Main methods
- Comparison of results
- Discussion

Why do we care?

- AGN feedback
- Verification of jet ejection and jet structure models



Gaibler et al. (2011)



McKinney, Tchekhovskoy & Blandford (2012),
Narayan, Igumenshchev & Abramowicz (2003)

Main methods of measurement

Time-averaged jet powers:

- Radio lobe energy content
- X-ray cavities

+ scaling relations

Instantaneous jet powers:

- Spectral fitting of blazar models
- Radio core shift method

http://fiveminutemarketing.com/2016/09/marketing-measurement-matters/

1. Radio lobe energy content

Steve Rawlings & Richard Saunders (1991)

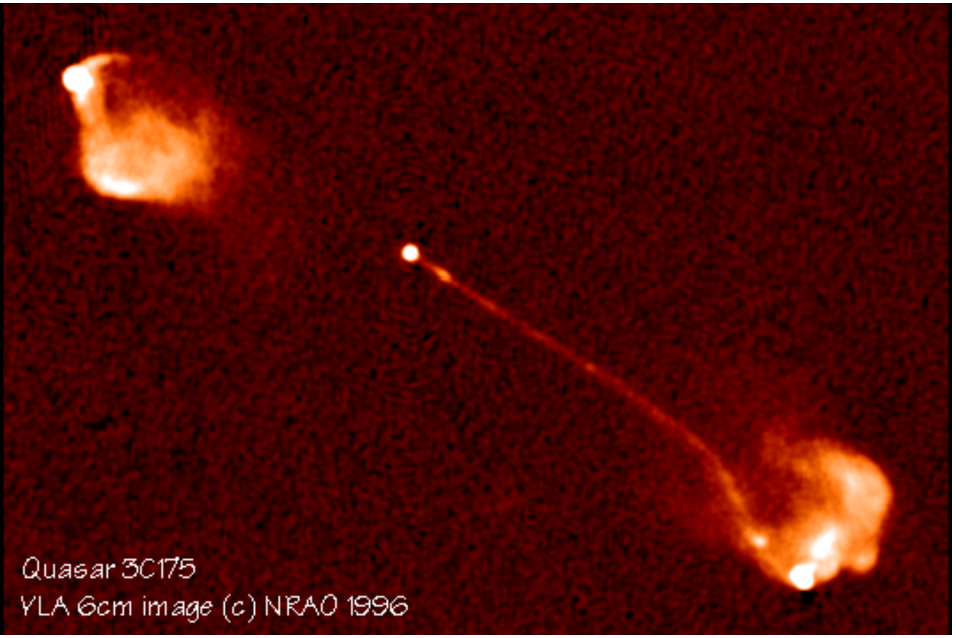


Image credit: NRAO/VLA; Alan Bridle, David Hough, Colin Lonsdale, Jack Burns and Robert Laing

$$P_j = \frac{4}{3}\frac{E_{lobe}}{T}$$

Lobe energy content:

- equipartition between electrons and B
- shape assumptions
- lower limit

Age estimate:

- spectrally from cooling timescales
- ram pressure balance from X-ray data

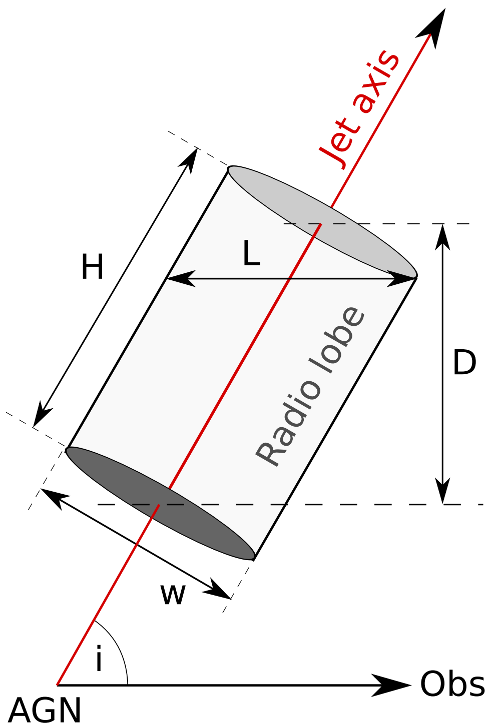
-> velocity

- 0.1c

Note (Scheuer 1974): $P_j \gg P_{rad}$

1. Radio lobe energy content

The formalism of Chris Willott et al. (1999)



$$P_j = f \frac{U_{base}}{t}$$

Correction factors:

- Geometry: $\left\langle \frac{D}{w} \right\rangle = 5, \langle i \rangle = 60° \rightarrow f_{geom}$
- Spectrum: $\nu_{min} = 10\text{MHz} \rightarrow f_{lowE}$
- Minimum energy condition: f_{min}
- Expansion work: g_{exp}
- Bulk and turbulent energy: g_{ke}

$$1 \leq f \leq 20$$

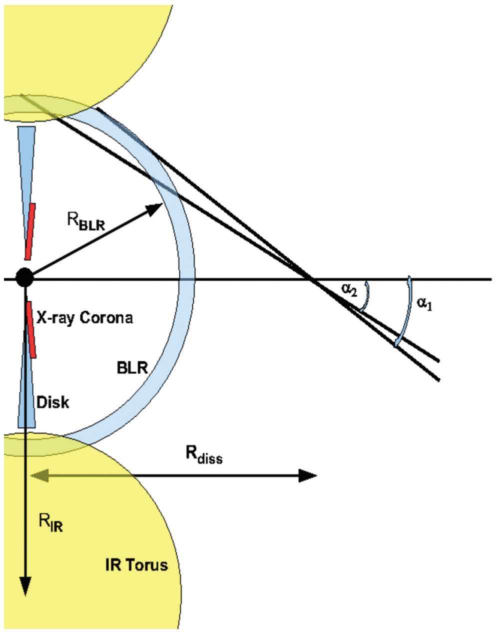
Age calculation:

- Self-similar evolution of the lobe
- $n(r_{100}) = n_{100} r_{100}^{-\beta}, \beta \sim 1.5$ (RWB)

$$P_j^W \simeq 4 \times 10^{45} f^{3/2} \text{ erg/s} \times \left(\frac{D}{110 \text{ kpc}} \right)^{-4/7+\beta/2} \left(\frac{c_1(f)}{5.4} \right)^{(5-\beta)/2} \times \left(\frac{\rho_{100}}{3 \times 10^{-3} \frac{m_P}{\text{cm}^3}} \right)^{-1/2} \left(\frac{L_{151}}{10^{35} \frac{\text{erg}}{\text{s sr Hz}}} \right)^{6/7}.$$

2. Blazar models

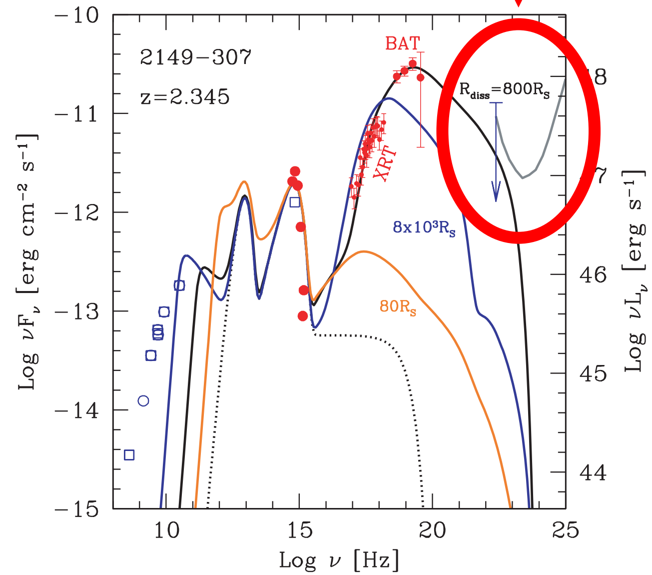
$P_{bol} \sim P_\gamma$



Ghisellini & Tavecchio (2009)

A one-zone blazar model:

- Accretion disk
- X-ray corona
- BLR, IR torus → SSC, EC
- CMB
- Internal B (synchrotron)



Ghisellini & Tavecchio (2009)

Fit parameters: $M_{BH}, L_d, R_{diss}, P_{inj}, B, \Gamma_{max}, \Theta_j, \gamma_b, \gamma_{max}, p_2$

$P_i, P_e, P_B, P_{rad}, P_j$

Ghisellini et al. (2014)

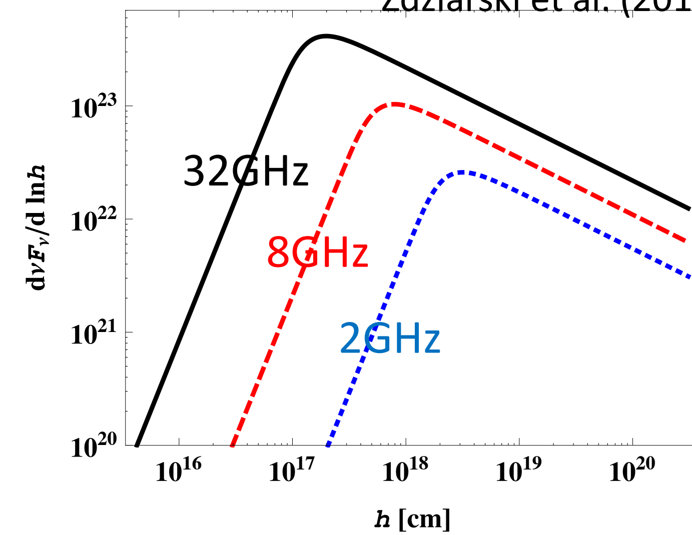
3. Radio core shift method

RELATIVISTIC JETS AS COMPACT RADIO SOURCES[1]
R. D. BLANDFORD AND ARIEH KÖNIGL
W. K. Kellogg Radiation Laboratory, California Institute of Technology
Received 1978 December 26; accepted 1979 March 1

ABSTRACT

Variable extragalactic radio sources, associated with the nuclei of galaxies and quasars, are interpreted in terms of a supersonic relativistic jet. It is proposed that radio emission originates

Zdziarski et al. (2015)



Extended jet model:

- $\Gamma, \Theta = const.$
- $N_e \propto z^{-2}\gamma^{-p}$
- $B \propto z^{-1}$

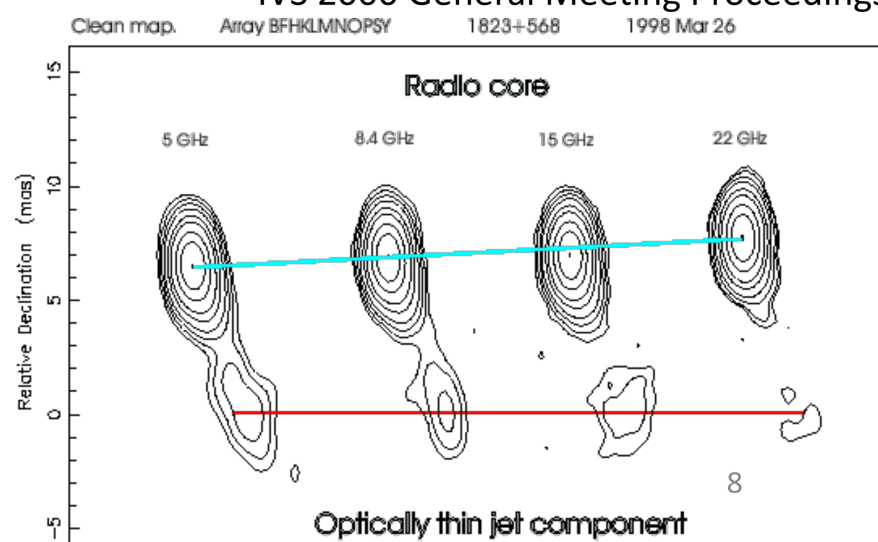
Peak of synchrotron emission at frequency ν

$$r_{core} \propto \nu^{-1/k_r} \sim \nu^{-1}$$

The core shift measure (Lobanov 1998)

$$\Omega_{r\nu} = 1mas \frac{D_L[pc]\Delta\Theta[mas]}{(\nu_1[GHz]^{-1} - \nu_2[GHz]^{-1})(1+z)^2}$$

Image: VLBI; Z. Paragi, I. Fejes, S. Frey;
IVS 2000 General Meeting Proceedings

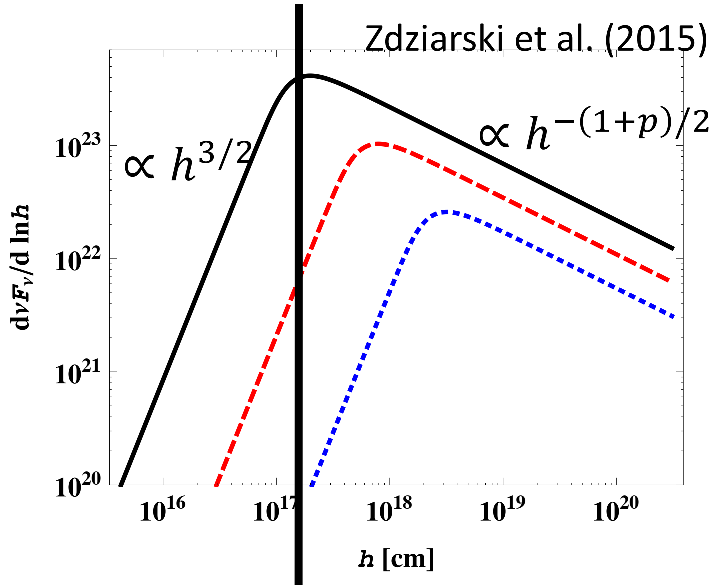


3. Radio core shift method

$$h_{peak} = \frac{\left(\frac{\pi}{4}\right)^{\frac{2}{p+4}} h_g \nu_g}{\nu} \sim h(\tau_\nu = 1)$$

ν_0 is the turnover frequency at h_0:

$$\left[\frac{(1+z)h_P \nu_g}{m_e c^2}\right]^{\frac{p+4}{2}} = \frac{\pi C_2(p) \sigma_T K_g h_g tan\Theta_j}{\alpha_f sini} \left(\frac{\delta B_g}{B_{cr}}\right)^{\frac{p+2}{2}}$$



More measurements / assumptions needed:

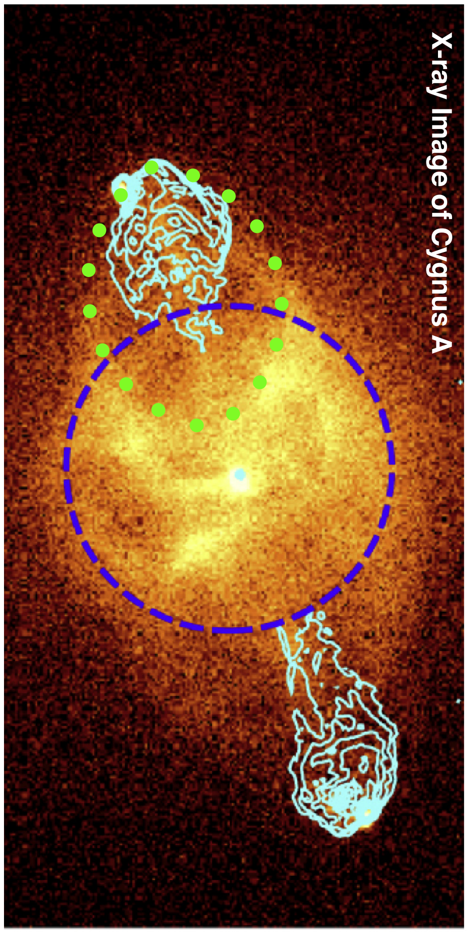
- $\Theta_j \Gamma_j \sim 0.1 - 0.2$, Γ_j (observations)
- equipartition (Lobanov 1998, Hirotani 2000)
- opening angle (Slish 1963, Williams 1963, Hirotani 2005)
- flux at $\alpha = 0$ (Zdziarski et al. 2015)

$P_B, \mathrm{P_j}$

- $\sigma_B \simeq \left(\frac{\Theta_j \Gamma_j}{s}\right)^2$ for $B_\phi \leftrightarrow B_z$ relation (Tchekhovskoy et al. 2009)

4. X-ray cavities

(Diana's talk on Monday)



Cyg A: 0.5-8keV Chandra, 6cm
Guo (2016), Reynolds et al. (2015)
Perley et al. (1984)

Cavities observed in ICM around AGN:
(Perseus - Boehringer et al. 1993, Cyg A – Carilli, Perley & Harris 1994; Hydra A – McNamara et al. 2000)

- Almost devoid of X-ray gas
- Aligned with radio emission
- Shock features

Heinz, Reynolds & Begelman (1998)

Gas displaced by expanding radio source

McNamara et al. (2000)

Jet power measure

P, V

$$\boxed{P_j \simeq \frac{n \cdot PV}{t}, n \sim 4}$$

$t_{sound}, \mathrm{t_{buoy}}$

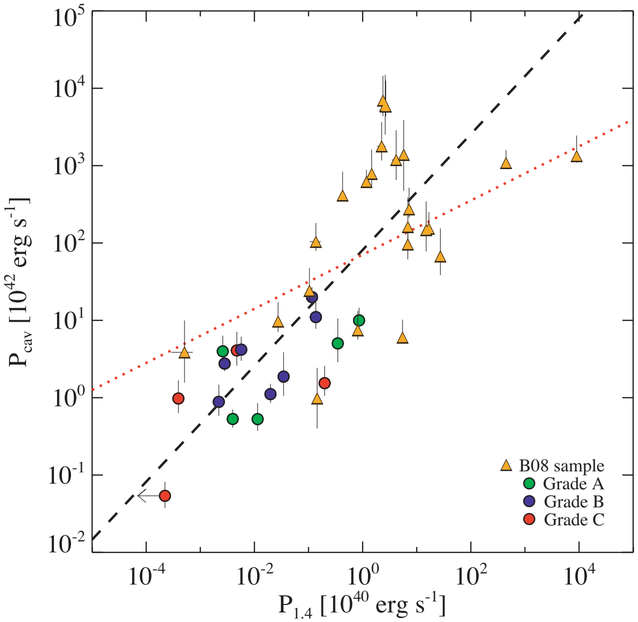
5. Scaling relations

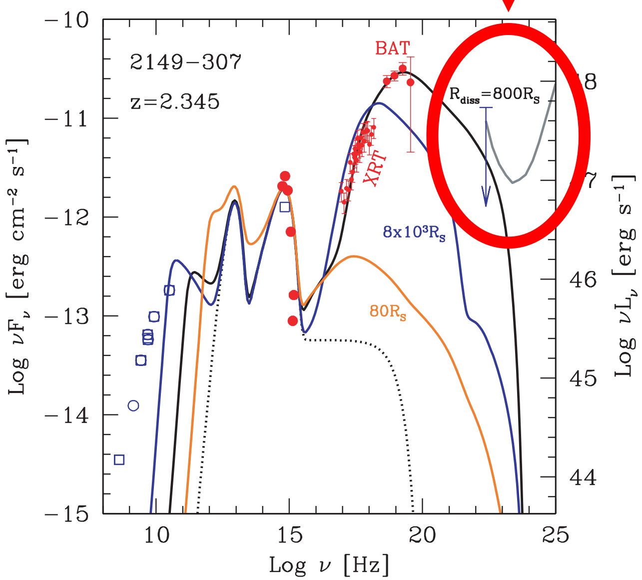
- γ-ray luminosity (Ghisellini et al. 2014)
- various scaling relations

with radio luminosities

(e.g. Cavagnolo et al 2010)

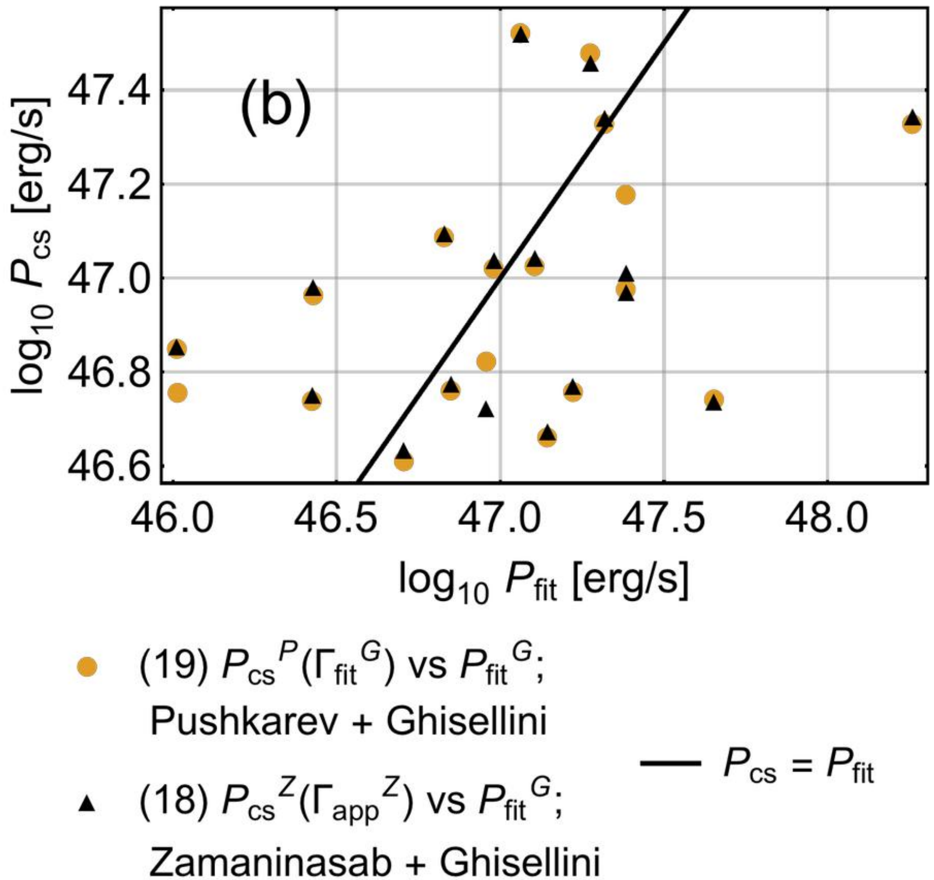
$P_{bol} \sim P_{\gamma}$





Ghisellini & Tavecchio (2009)

Blazar models agree with radio core shifts



Combined samples:

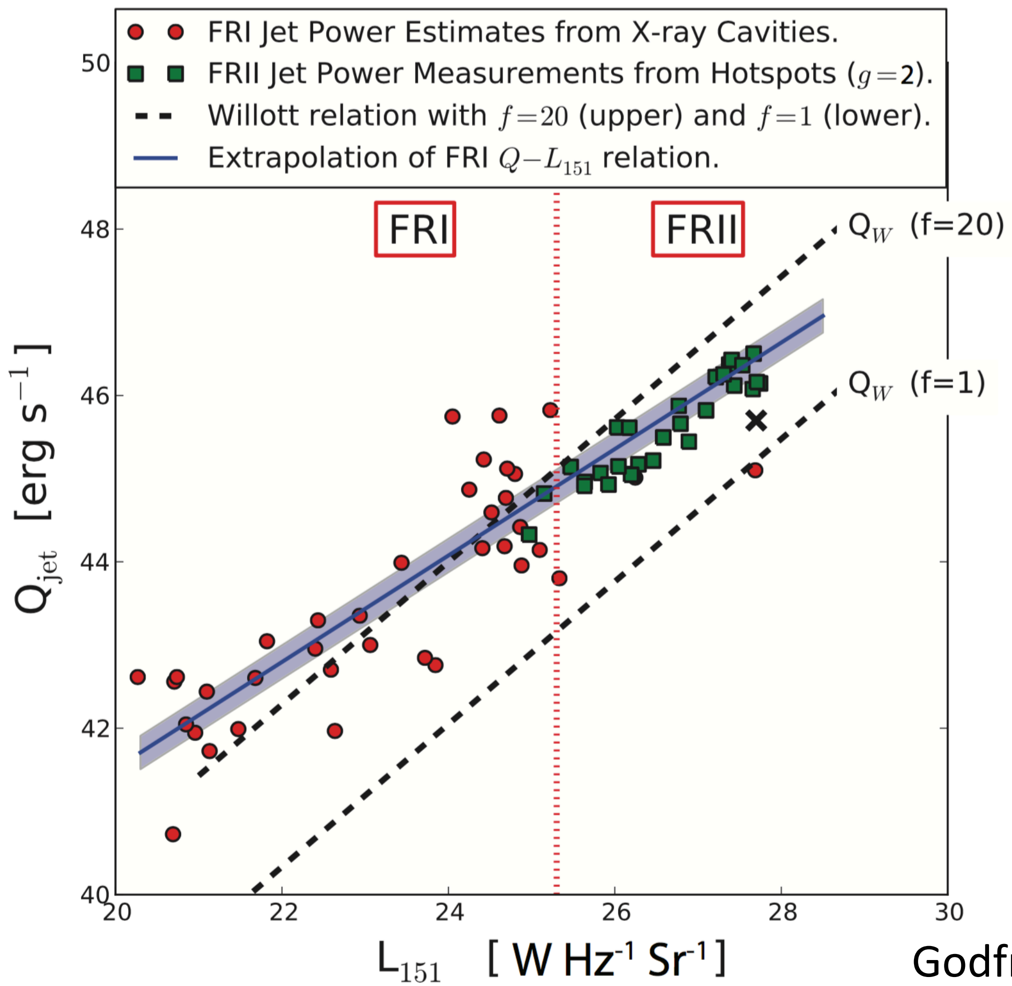
- $\Delta\Theta < 1°$
- $\frac{\Delta z}{z} < 0.1$

Pjanka, Zdziarski & Sikora (2016) in prep.

$$\left\langle \log_{10} \frac{P_{cs}}{P_{fit}} \right\rangle = 0.0 \pm 0.4$$

Pushkarev et al. (2012)
Ghisellini et al. (2014)
Zamaninasab et al. (2014)

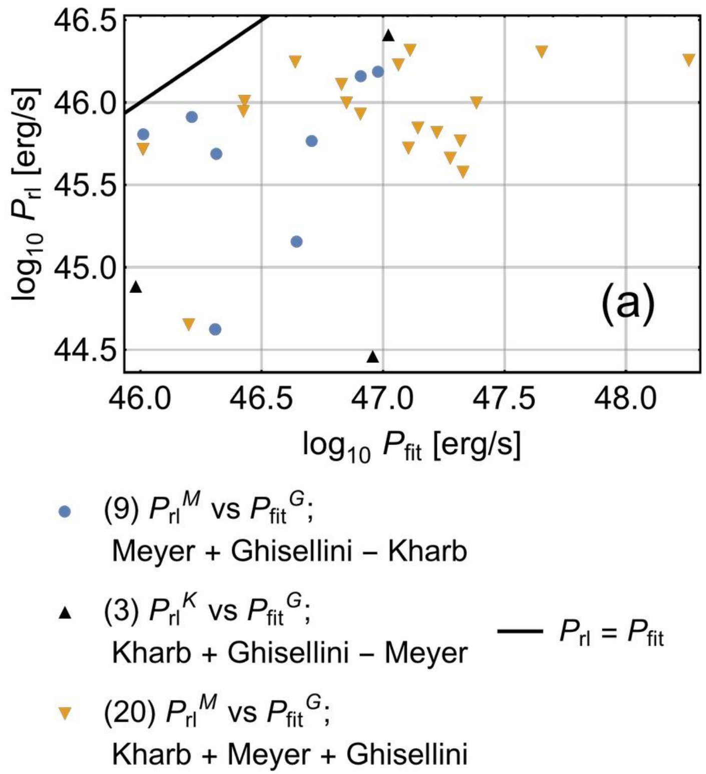
Radio lobe method < X-ray cavities



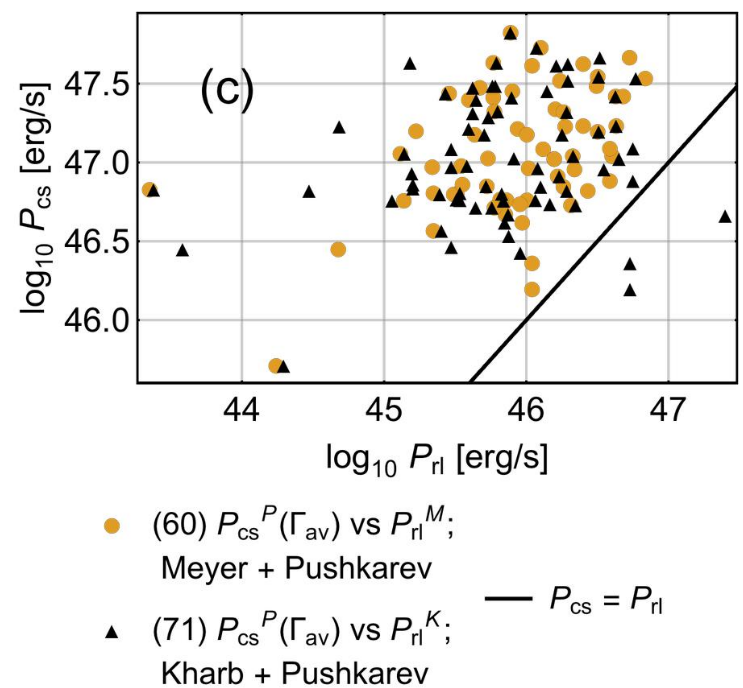
Godfrey & Shabala (2013)

Pjanka, Zdziarski & Sikora (2016) in press

Radio lobe method < Blazar model fits



$$\left\langle \log_{10} \frac{P_{rl}^{M}}{P_{fit}} \right\rangle = -1.0 \pm 0.5$$

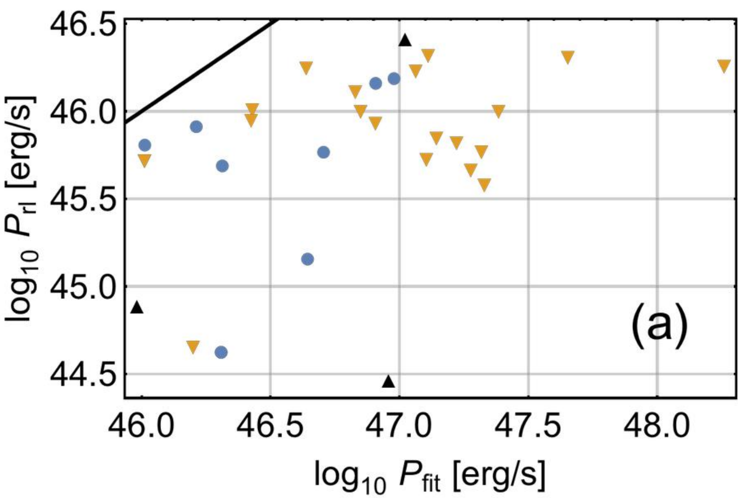


$$\left\langle \log_{10} \frac{P_{rl}^{M}}{P_{cs}} \right\rangle = -1.0 \pm 0.3$$

Kharb et al. (2010), Meyer et al. (2011), Pushkarev et al. (2012), Ghisellini et al. (2014)

Possible interpretations

- Intermittency



Blazar jets are active ~10% of the AGN lifetime

- Pair content

$$P_{rl} = P_p + \mathrm{P_B}$$

$$P_p = \frac{n_p}{n_e} P_{p=e}$$

$$\frac{n_e}{n_p} \simeq \frac{P_{p=e}}{P_{rl} - P_B}$$

$$\frac{n_e}{n_p} \simeq 30 \Rightarrow \frac{n_{pair}}{n_p} \simeq 15$$

Jet production efficiency

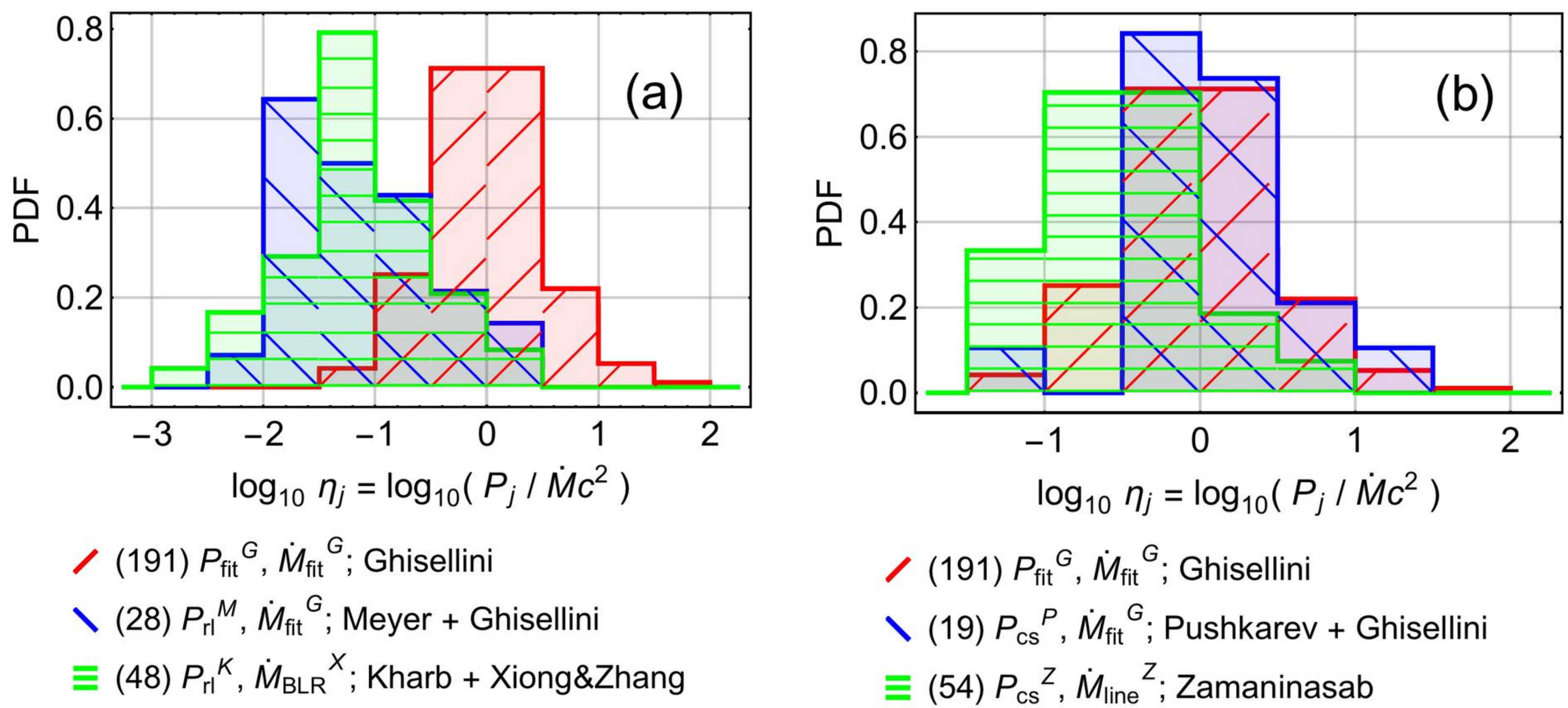


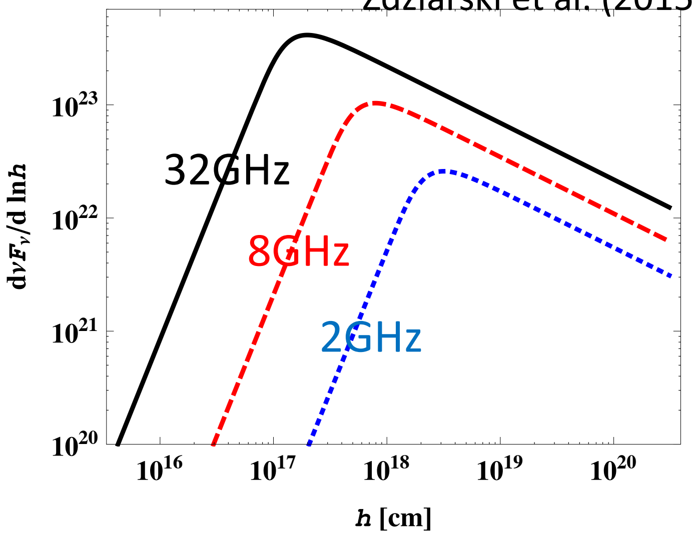
Image credit: ESO/L Calçada
Dial: http://www.machine-dro.co.uk /mitutoyo-30mm-long-stroke-dial-indicator.html

Summary

- Multiple ways to measure jet power:
  - Radio lobes
  - Radio core shift
  - Blazar models
  - X-ray cavities
- Inconsistencies remain
  → hints on jet physics!

Magnetic field power vs height

Zdziarski et al. (2015)

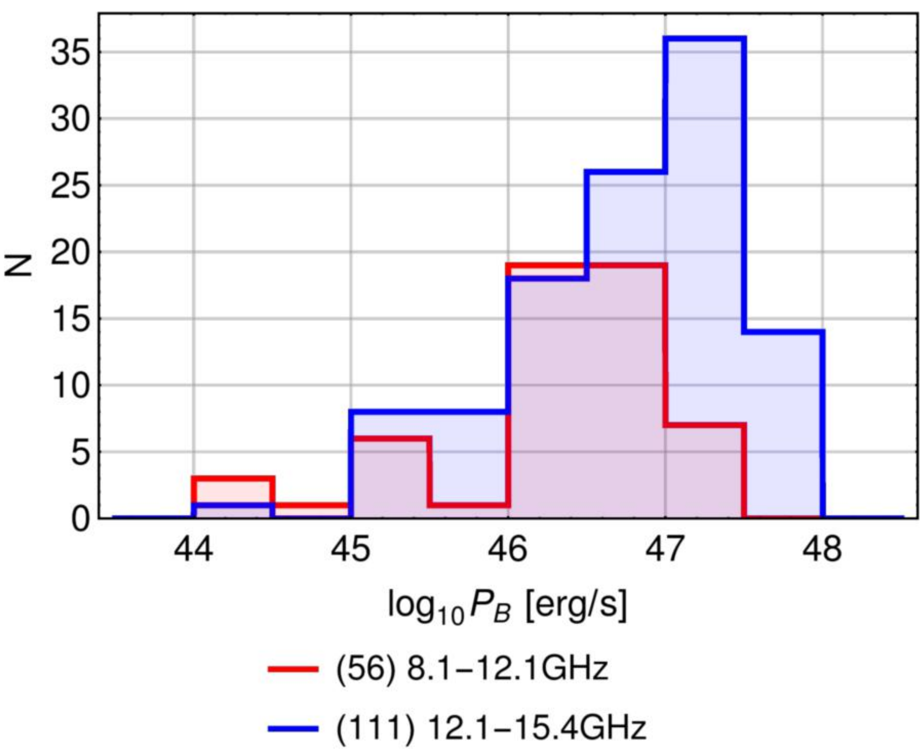


$$r_{core} \propto \nu^{-1/k_r} \sim \nu^{-1}$$

Distance ratio:

$$\frac{1}{10} / \frac{1}{13} = 1.3/1$$

Data: Pushkarev et al. (2009)



Comparison of methods

Radio lobe energy content:
- + relatively easy
- - the f-factor
- - require well-defined lobe structure

Blazar models:
- + accounts for the physics
- + less assumptions
- - simplified models
- - broad SED coverage required

Radio core shift:
- + accounts for the physics
- + less assumptions
- - simplified models
- - observational difficulty

X-ray cavities:
- + directly coupled to AGN feedback problem
- - assumptions, cavity counting
- - jet-cavity link relatively unsure

Thank you
for your attention