Relativistic X-ray jets at high redshift and a connection to super-massive black holes

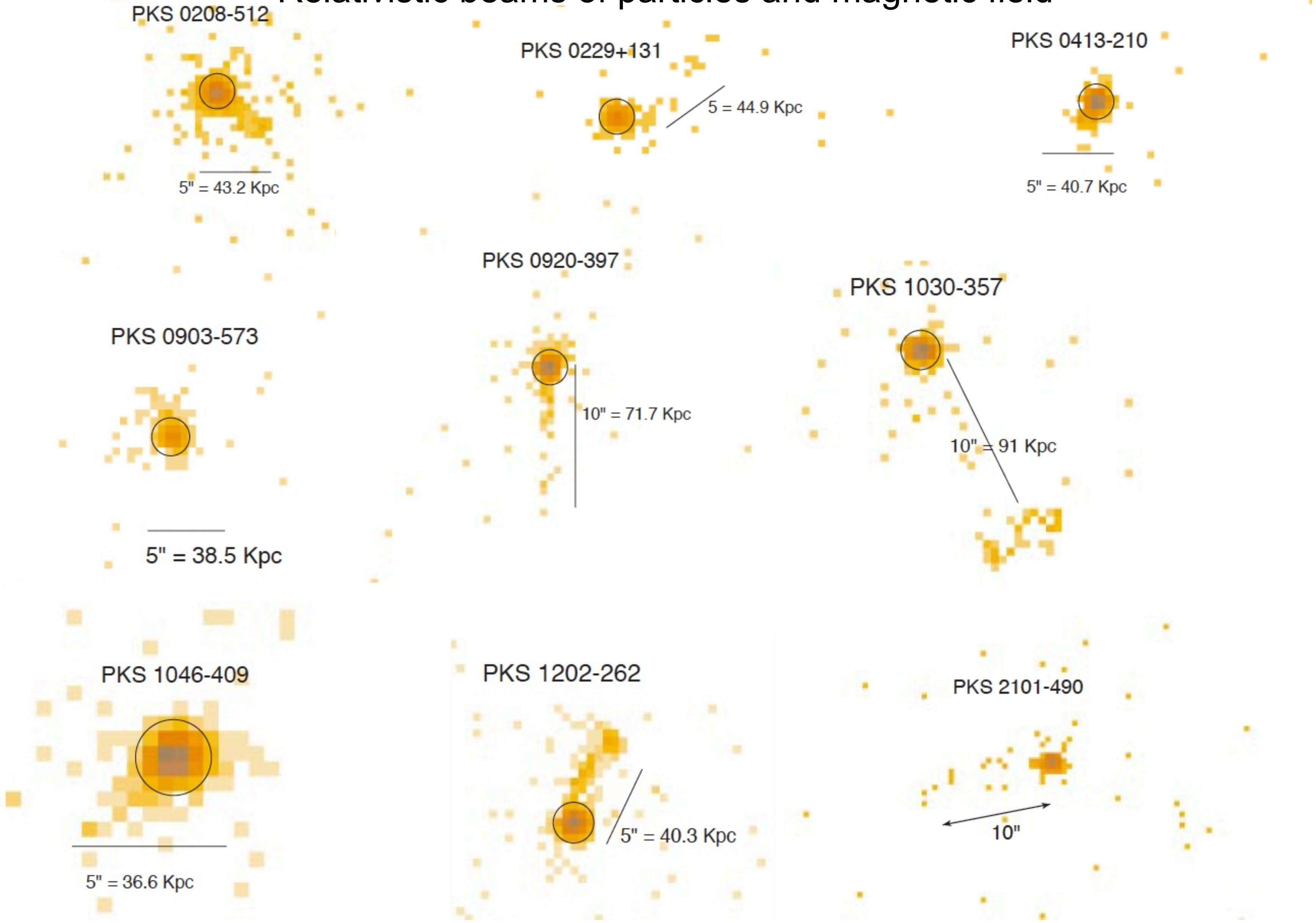
Dan Schwartz

Smithsonian Astrophysical Observatory
Chandra X-ray Center
September 10, 2018

A. Siemiginowska (SAO), D. M. Worrall (Bristol), M. Birkinshaw (Bristol) ,
C. C. Cheung (NRL), H. Marshall (MIT),
G. Migliori (Univ. Paris), J. Wardle (Brandeis), D. Gobeille (URI)

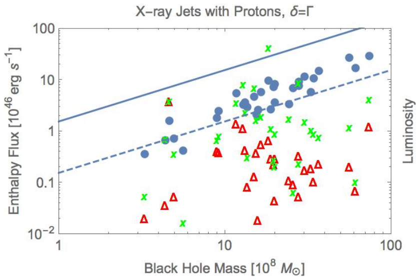
X-ray Jets

Relativistic beams of particles and magnetic field



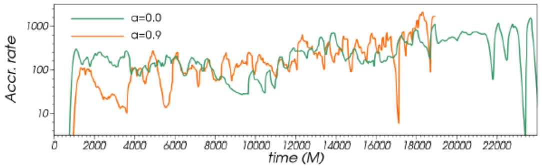
Jets are important

1. The energy carried by jets is an important part of the energy budget of the black hole.



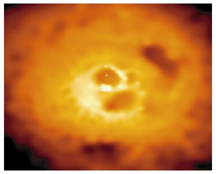
Schwartz+ 2015IAUS..313..219S

2. Jets can carry super Eddington energy flux. May be relevant to the rapid growth of SMBH in the early universe by allowing super Eddington accretion.



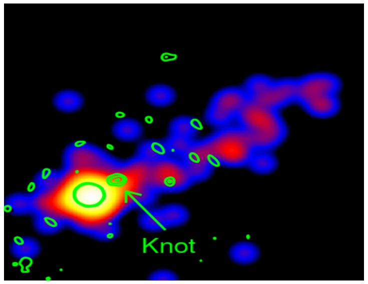
Sadowski et al. 2014

3. The enthalpy flux carried by jets prevents catastrophic collapse of clusters of galaxies, and is part of a feedback loop correlating SMBH with galaxy bulge masses.



Fabian et al. 2000

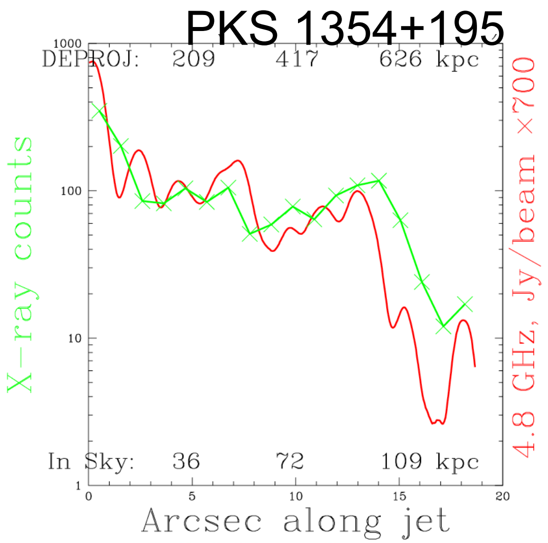
4. Inverse Compton jets will maintain near constant surface brightness at very large redshifts. May serve as “beacons” in the early universe.

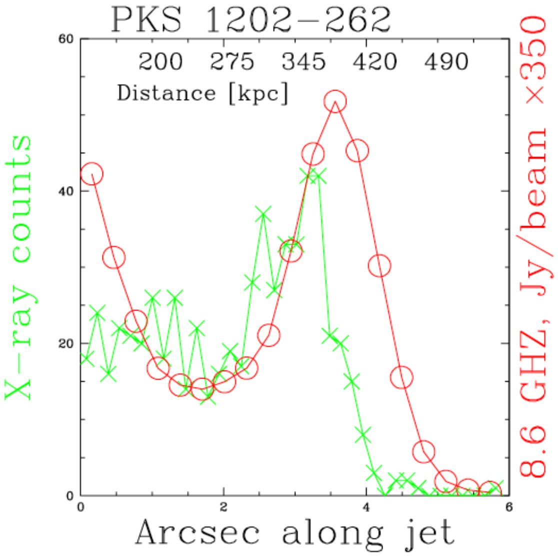


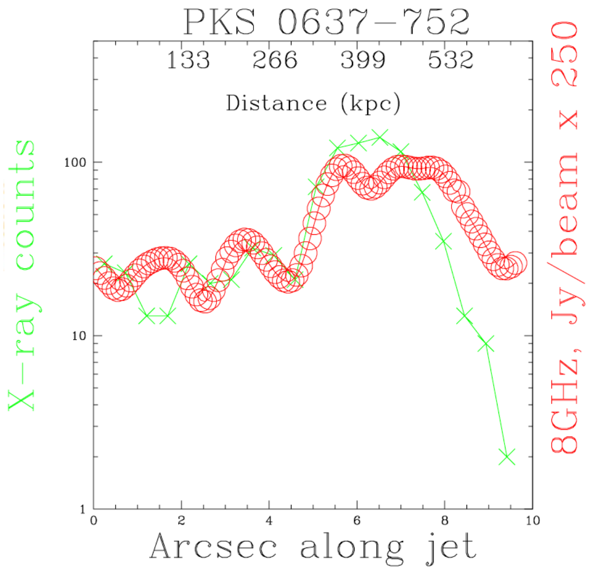
Simionescu et al. 2016

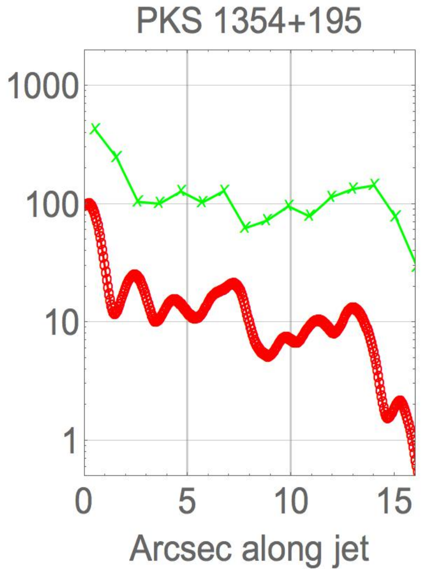
X-ray and radio jet morphology match

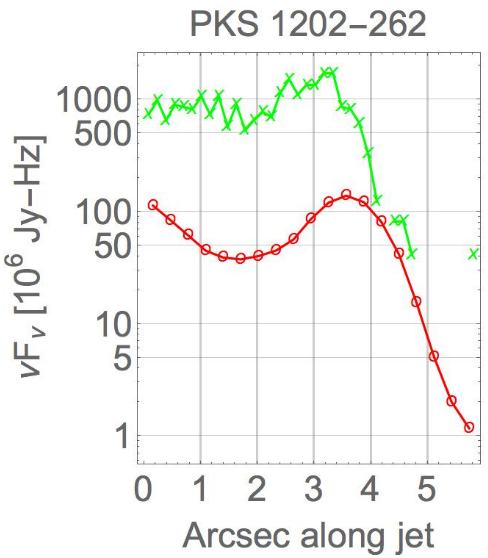
Hypothesize they are radiated by the same electron population

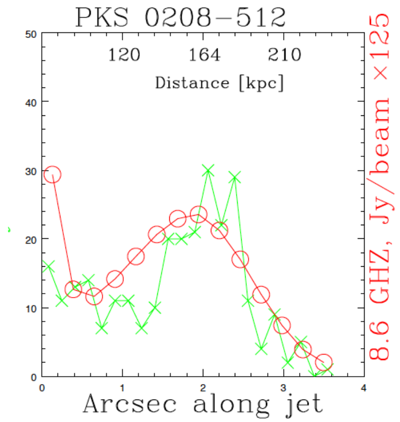


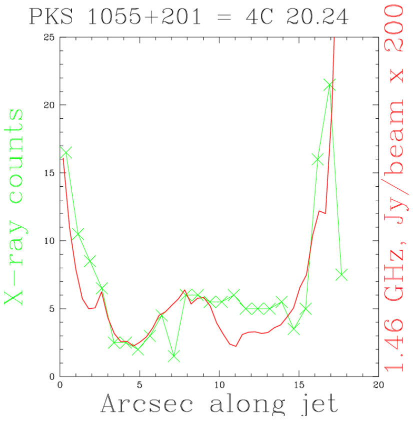












X-rays are more luminous than radio for much of jet

Inverse Compton scattering of the cosmic microwave background

Extension of the spectrum of radio sychrotron electrons to lower energy produces IC X-rays by scattering off the CMB.
For Relativistic jets, we must transform using the Doppler factor:

$\delta=1/(\Gamma(1-\beta\cos\theta))$

Assume minimum energy: $d\{B^2/(8\pi)+U_{rel}\}/dB = 0$
Projection and Light travel time: Volume = $V_{obs}/(\delta \sin\theta)$
CMB energy density is enhanced by Γ^2 in jet rest frame

Felten-Morrison ('66) IC formulas give

$$\langle u_{CMB}\rangle = 4aT^4(\Gamma^2-1/4)/3 \propto u_0(1+z)^4\ \Gamma^2$$

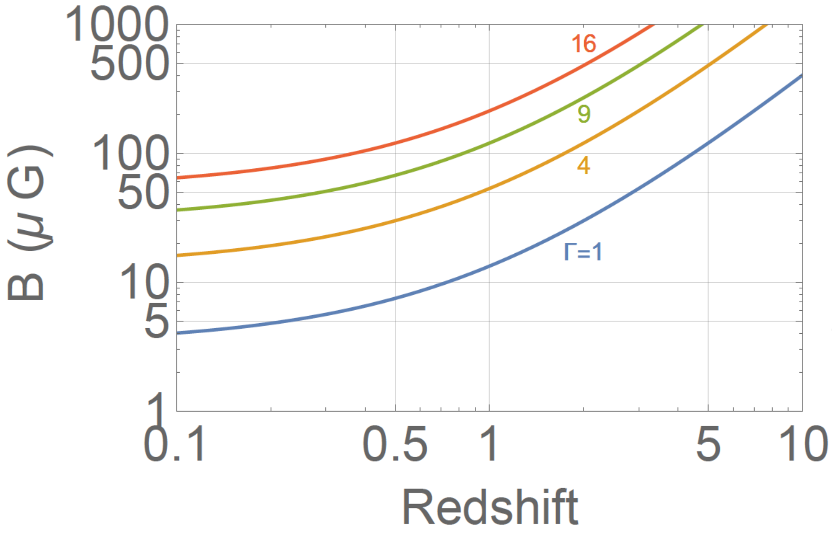
Cannot solve for all three quantities Γ, δ, and θ

1. Assume $\Gamma = \delta$ (maximum Γ is 2δ)

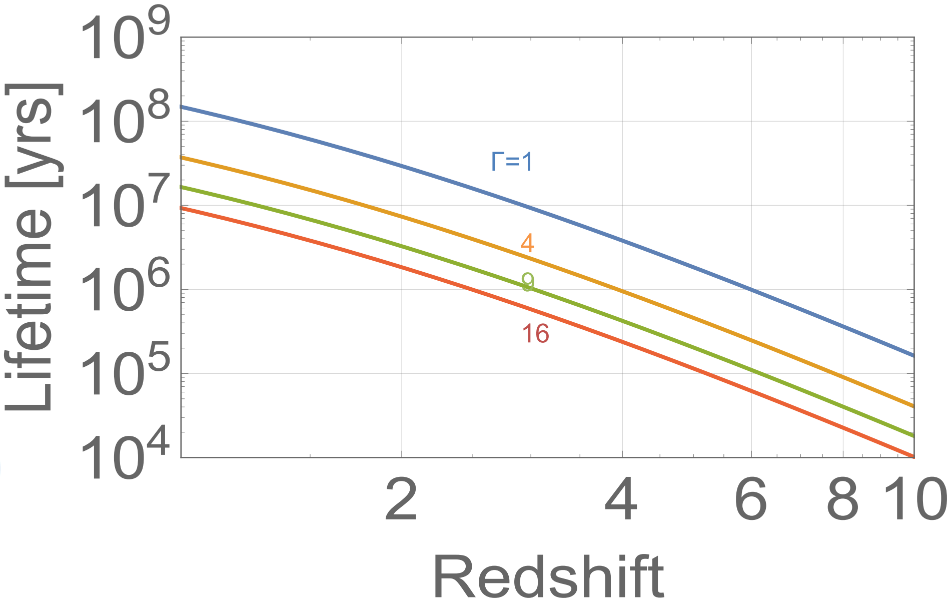
OR 2. Parameterize as a function of θ

$\Gamma = \delta$ often falls in a mid-range of reasonable θ

IC/CMB at high redshift



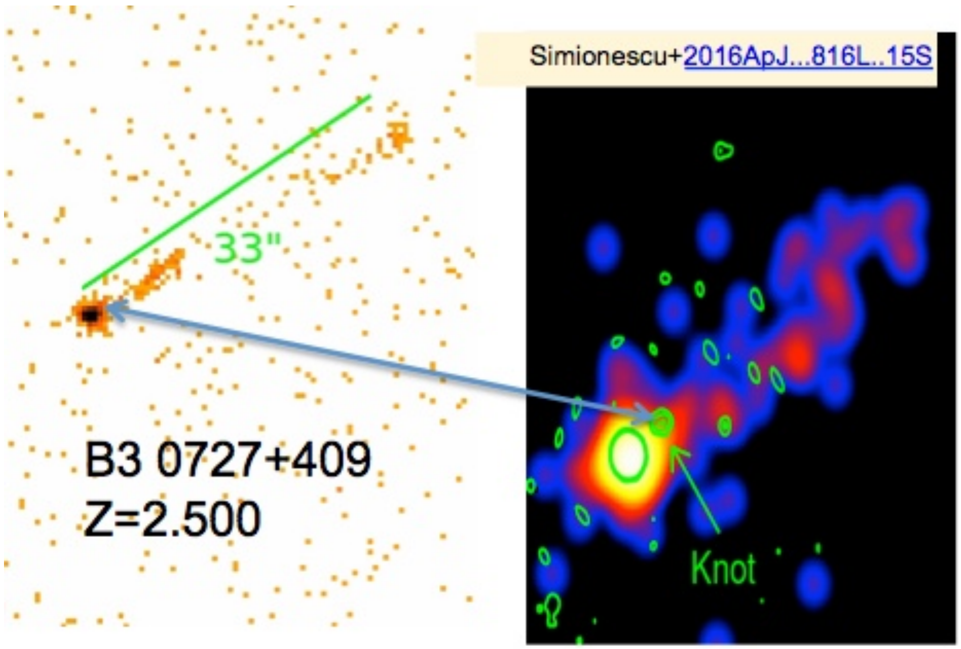
Energy Balance; B vs. CMB



Lifetime of X-ray emitting electrons

CMB energy density increases as $(1+z)^4$.
This compensates the cosmological diminution of surface brightness by $(1+z)^{-4}$.
Thus X-ray jets will become more prominent at large redshifts

X-ray Survey of High Redshift Radio Jets

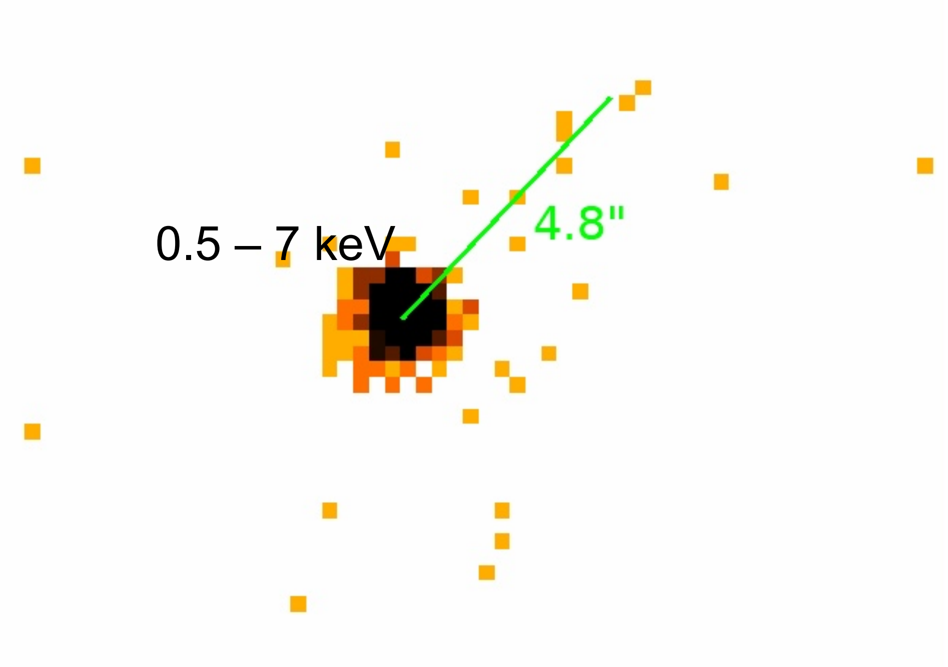

Simionescu+2016ApJ...816L..15S

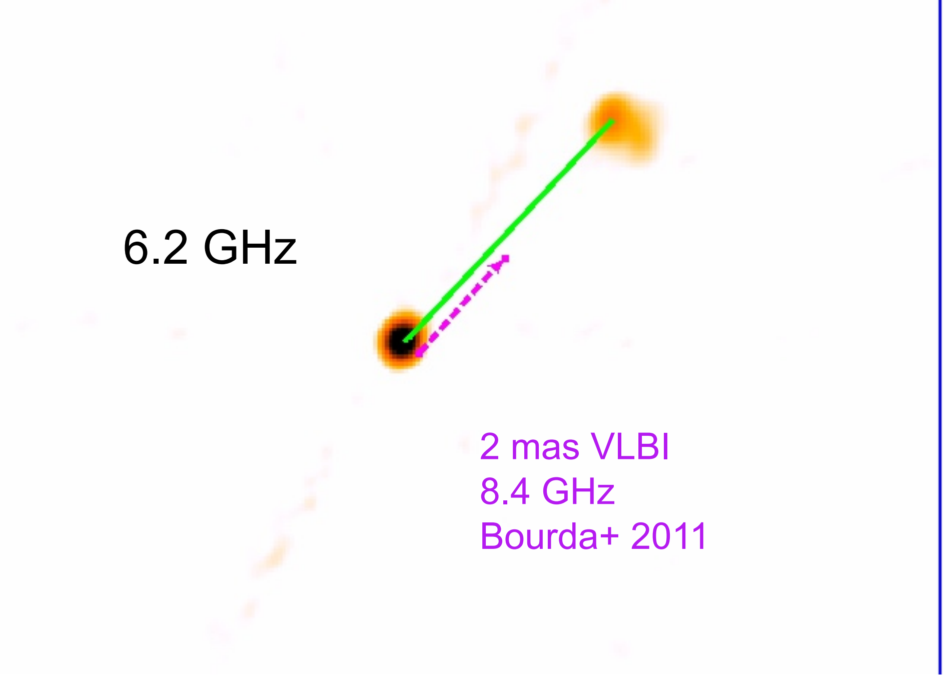
Parent Population: Complete survey, $S_{1.4 \text{ or } 5 \text{ GHz}}$ > 70mJy
    123 Quasars with spectroscopic redshift in joint FIRST/SDSS region
    (Gobeille 2011; Gobeille, Wardle & Cheung 2014)

Cycle 19 Survey: 14 sources at z>3., with one-sided radio structure
    (jet or knot or lobe).

Ten quasars observed to date. Two have extended X-ray structure without
    underlying radio emission.

J1610+1811 Z=3.118





Quasar: $5.2\mathrm{x}10^{-13}$ erg cm^{-2} s^{-1}
$L_x = 3.2\mathrm{x}10^{46}$ erg s^{-1}

Jet: $9.2\mathrm{x}10^{-15}$ erg cm^{-2} s^{-1}
$L_x = 8.3\mathrm{x}10^{44}$ erg s^{-1}
iC/CMB model of jet:

$\Gamma = \delta = 9.4$

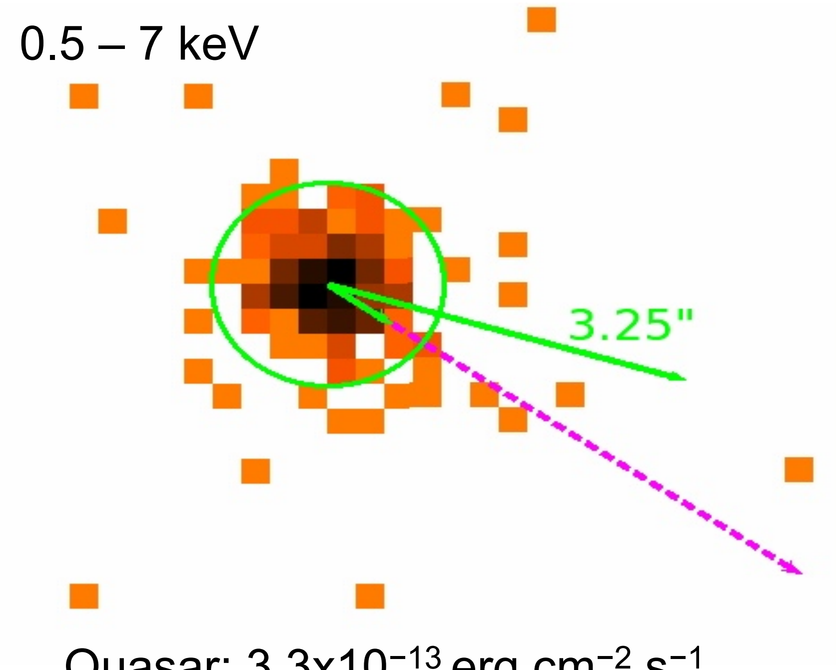
B=12.3 μGauss

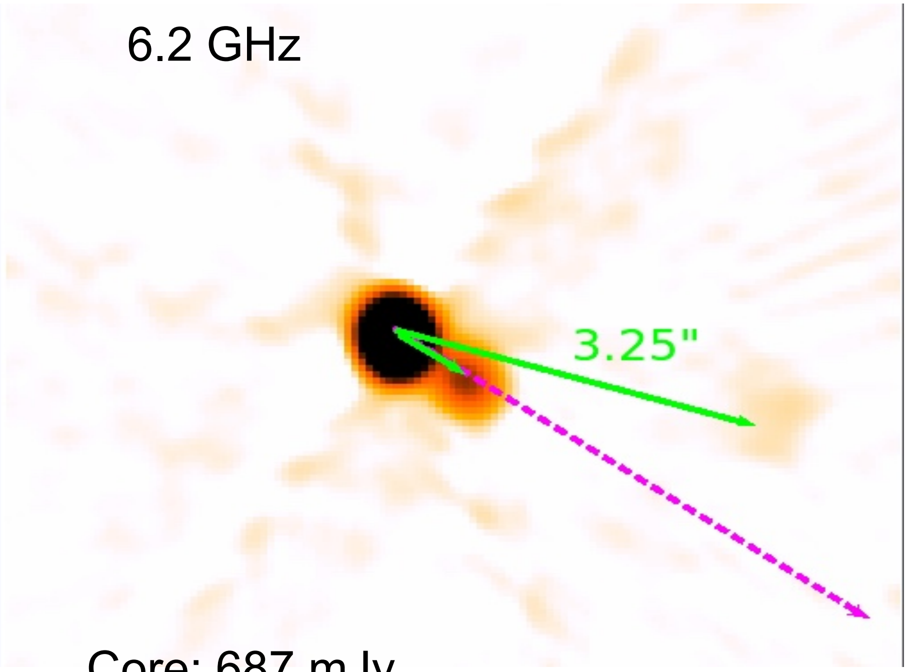
Power=1.4 x 10^{46} erg s^{-1}
T_{ic} = 8500 yrs (radio electrons)

Core: 64.8 mJy

Jet: < 1 mJy
Lobe: 8..2 mJy
Lobe Model: 145 μGauss
$4.2\ 10^{58}$ ergs
t_{fill} = 96,000 yrs
t_s = 250,000 yrs.

J1405+0415   Z=3.209





Quasar: 3.3×10^{-13} erg cm^{-2} s^{-1}
$L_x = 3.1 \times 10^{46}$ erg s^{-1}

Jet: 8.6×10^{-15} erg cm^{-2} s^{-1}
$L_x = 8.2 \times 10^{44}$ erg s^{-1}

iC/CMB model:

$\Gamma = \delta = 4$

B=156 μGauss

Power=35 x 10^{46} erg s^{-1}

Core: 687 mJy
Yang+ 2008   758 mJy

Jet: 27.7 mJy
$\alpha = 0.91 \pm 0.09$

Lobe: 2.9 mJy
$\alpha = 1.66 \pm 0.40$
model:

X-ray Survey of Lower Redshift Radio Jets (z= ~0.3 –- 2.)

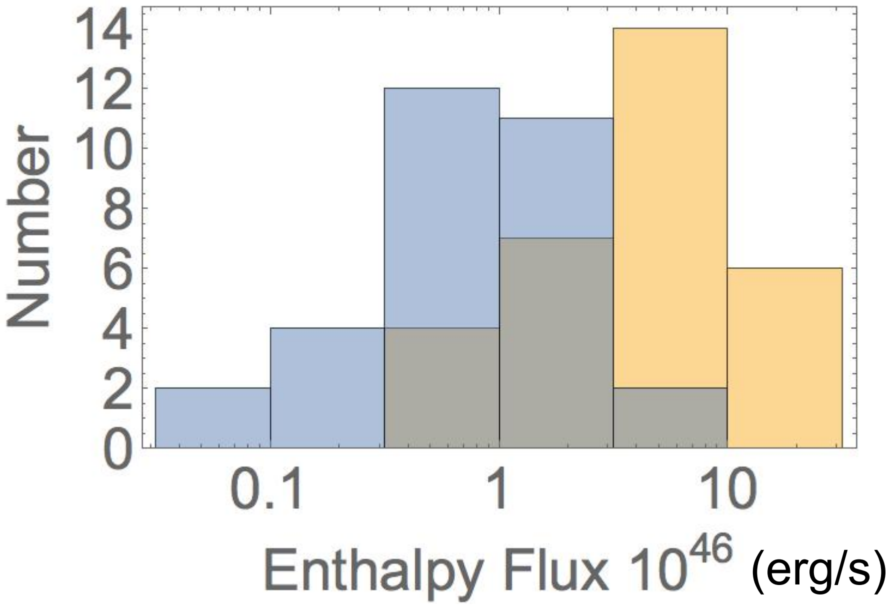
1. Selection of flat spectrum radio sources from
    1. VLA , $S_5 > 1$ jy
    2. ATCA, $S_{2.7} > 0.34$ Jy

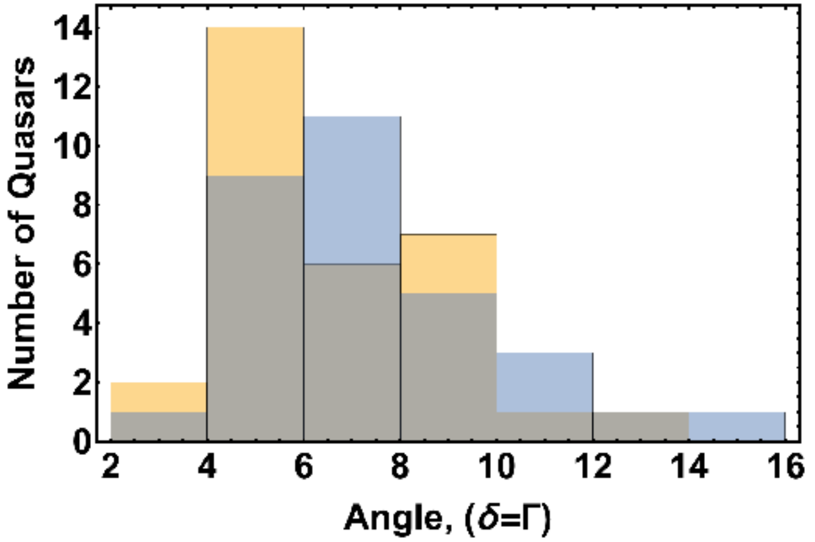
2. Radio jet longer than 2”

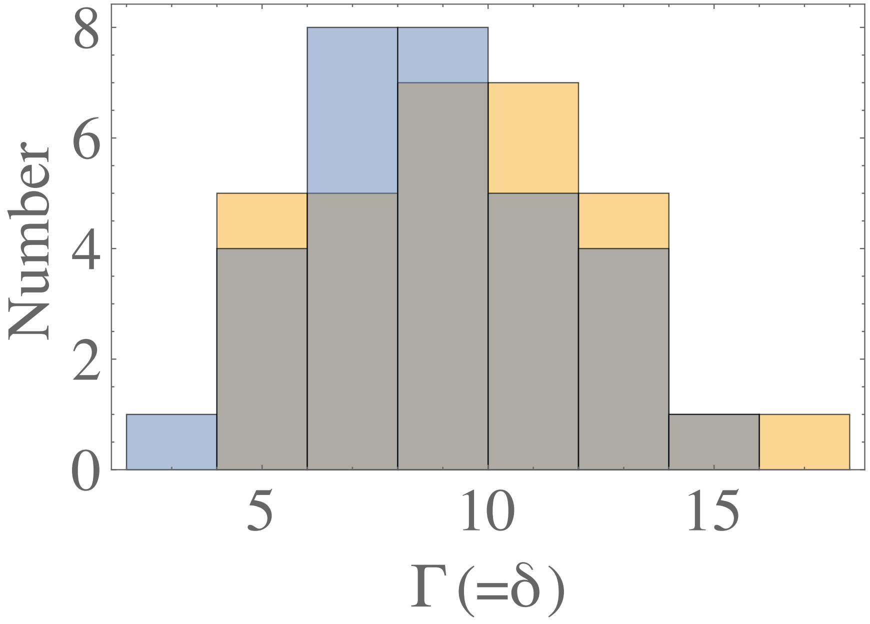
3. Detect 31 of 52.

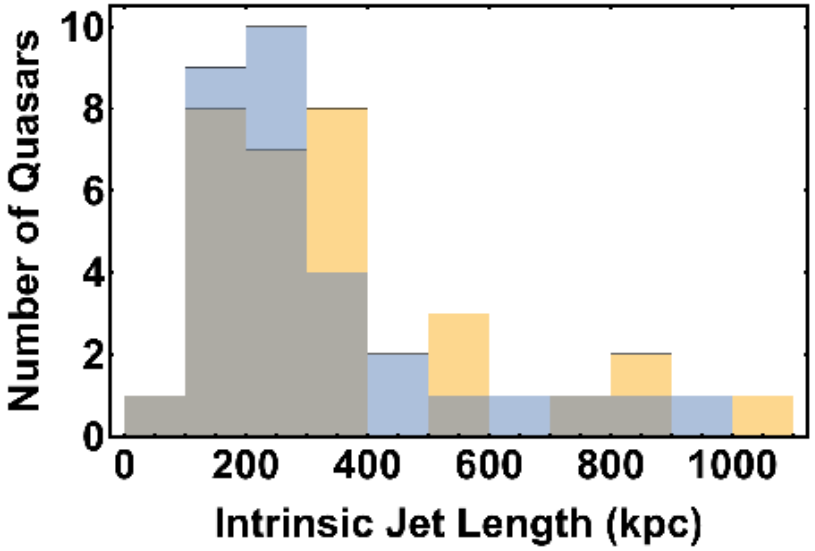
Lower Z Survey

Charge neutrality via Protons (orange) or Positrons (blue), Γ = δ



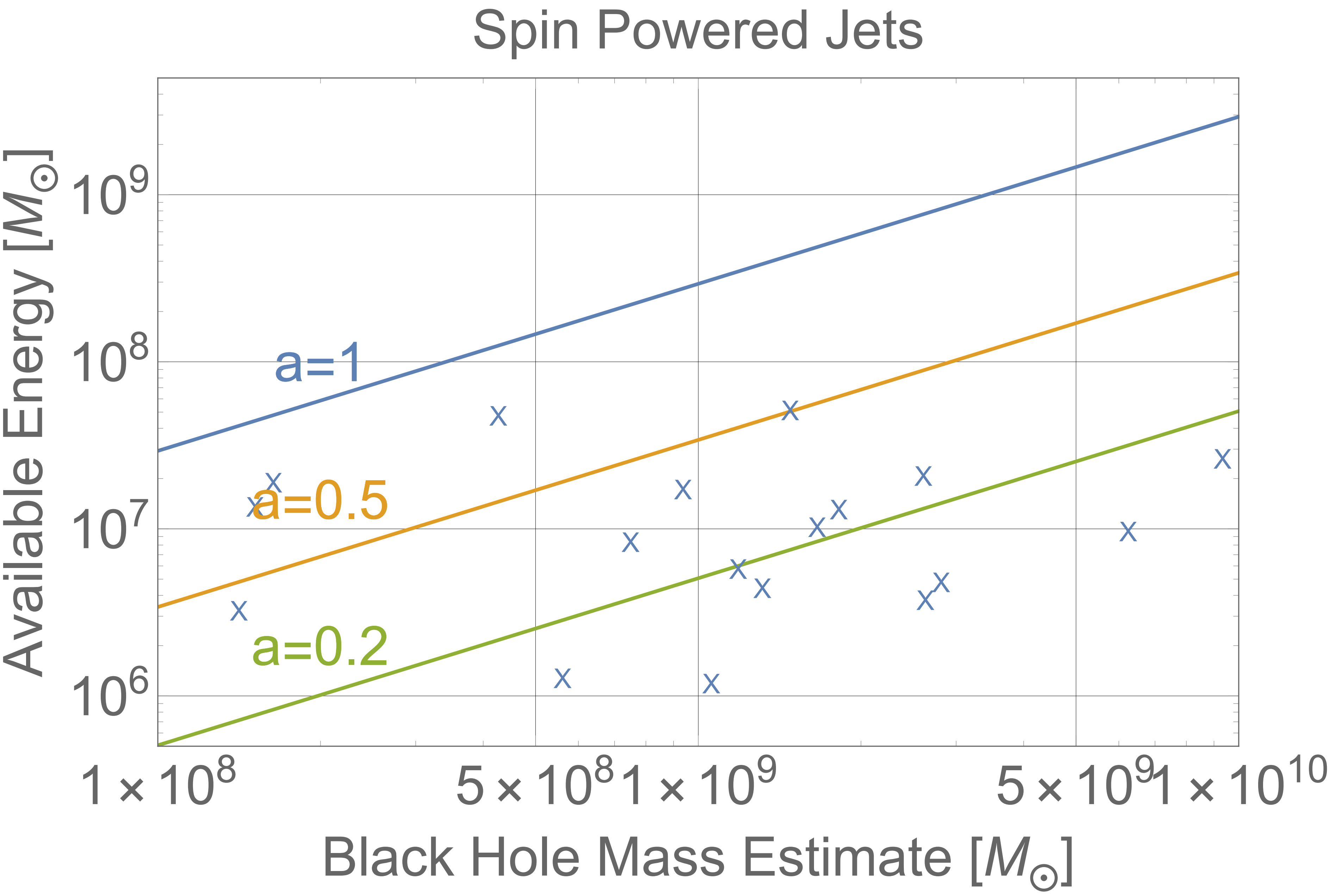




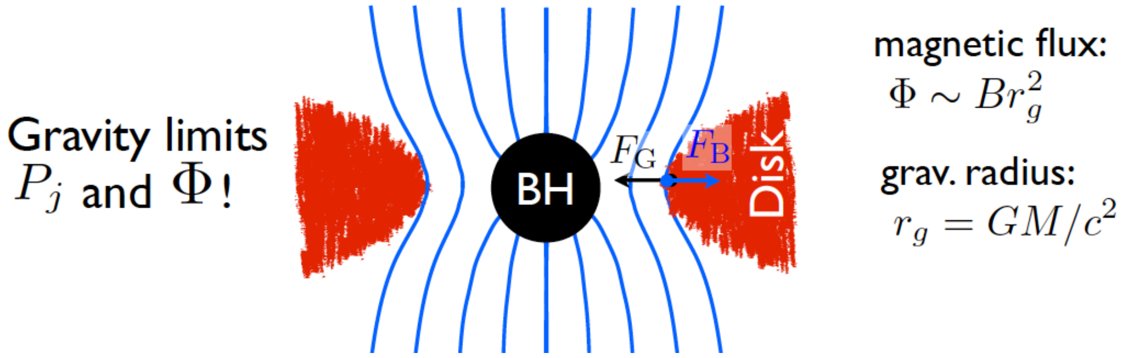


Black holes with spin a>0.2 can power quasar jets for up to 10^7 yr

(alternate mass estimates, from Xiong+2014 and refs., Shen+2011)



Tchekhovskoy, 2015, Krakow conf. relativistic jets

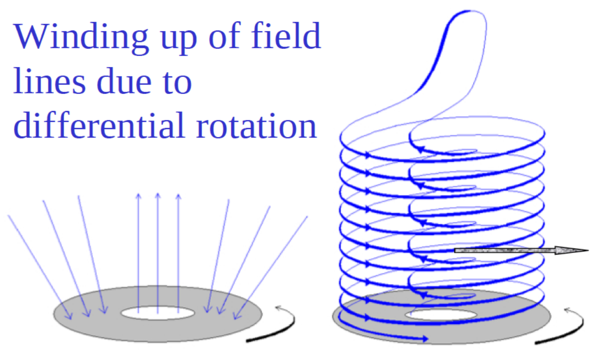


Gravity limits P_j and Φ!

magnetic flux:
$\Phi \sim B r_g^2$

grav. radius:
$r_g = GM/c^2$

Gabuzda, 2015, Krakow conf. relativistic jets



Winding up of field lines due to differential rotation

Assume a helical magnetic field extracts the rotational energy, winds tightly around the jet spin axis

Angle ξ between plane of (E,H) and plane orthogonal to spin axis

Poynting flux $dE/(dt dA) = S = c\,(E \times H)/4\pi$

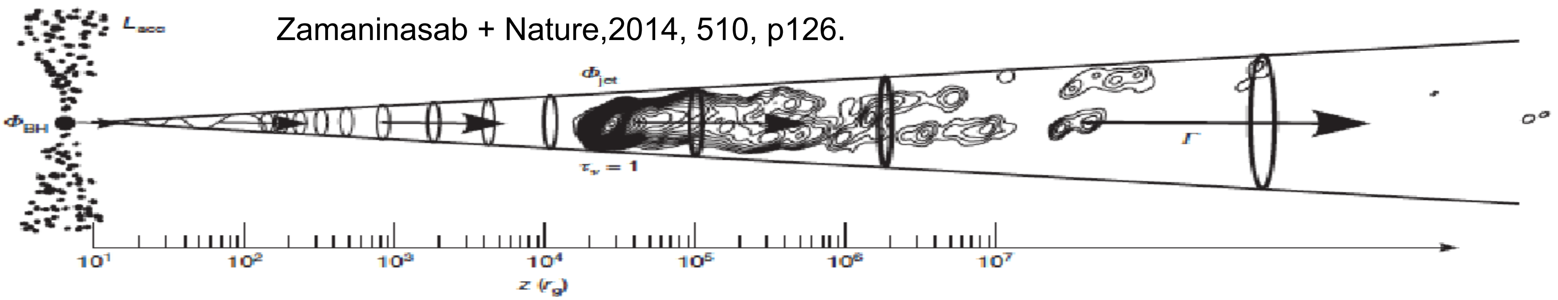
$$\langle \text{power} \rangle_z = S_z\, \pi r^2 = c\, H^2\, (r^2/4)\, \sin(\xi)$$

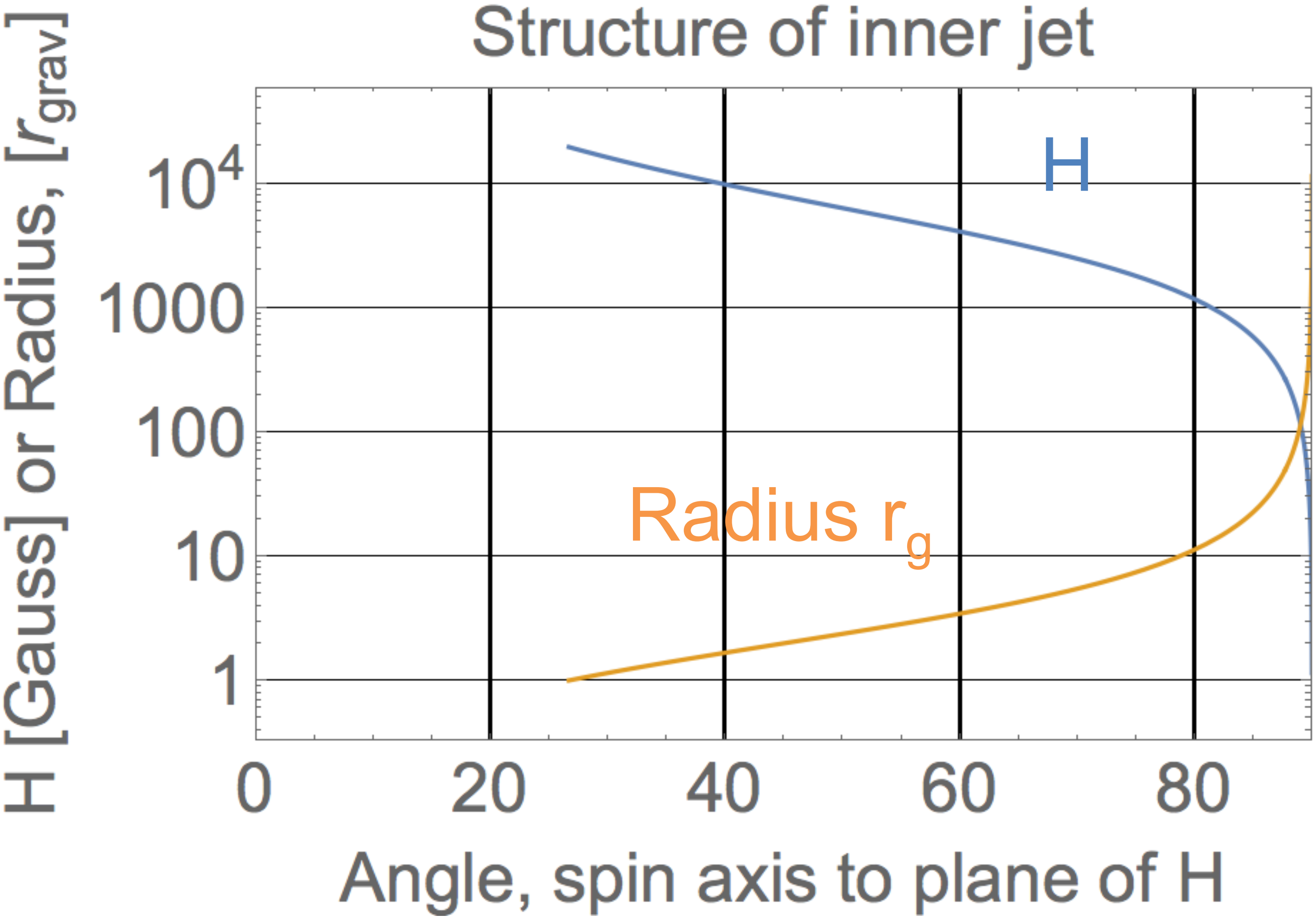
Momentum flux $p = S/c$

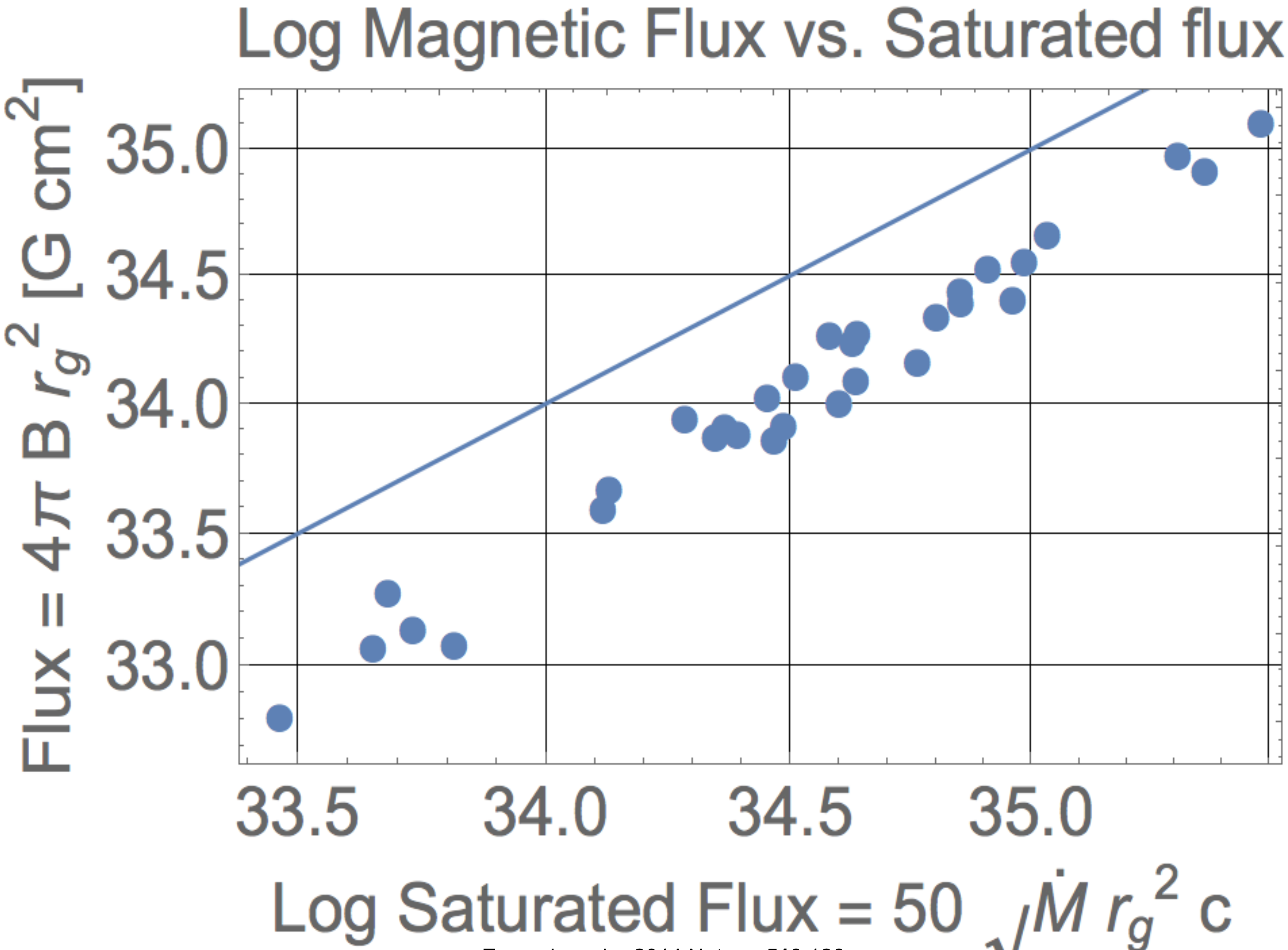
Angular momentum flux $dL/(dt dA) = r \times p$

$$\langle dL/dt \rangle_z = H^2\, (r^3/4)\, \cos(\xi)$$

And $\langle L_z \rangle = U/\omega$ (Jackson, 1962 problem 6.12)


Zamaninasab + Nature,2014, 510, p126.




Log Magnetic Flux vs. Saturated flux

Zamaninasab+ 2014,Nature, **510**,126

Summary

1. We use Chandra X-ray observations to estimate the power of jets, by observing the jet itself. We tie this to the central black hole mass on an individual object basis.

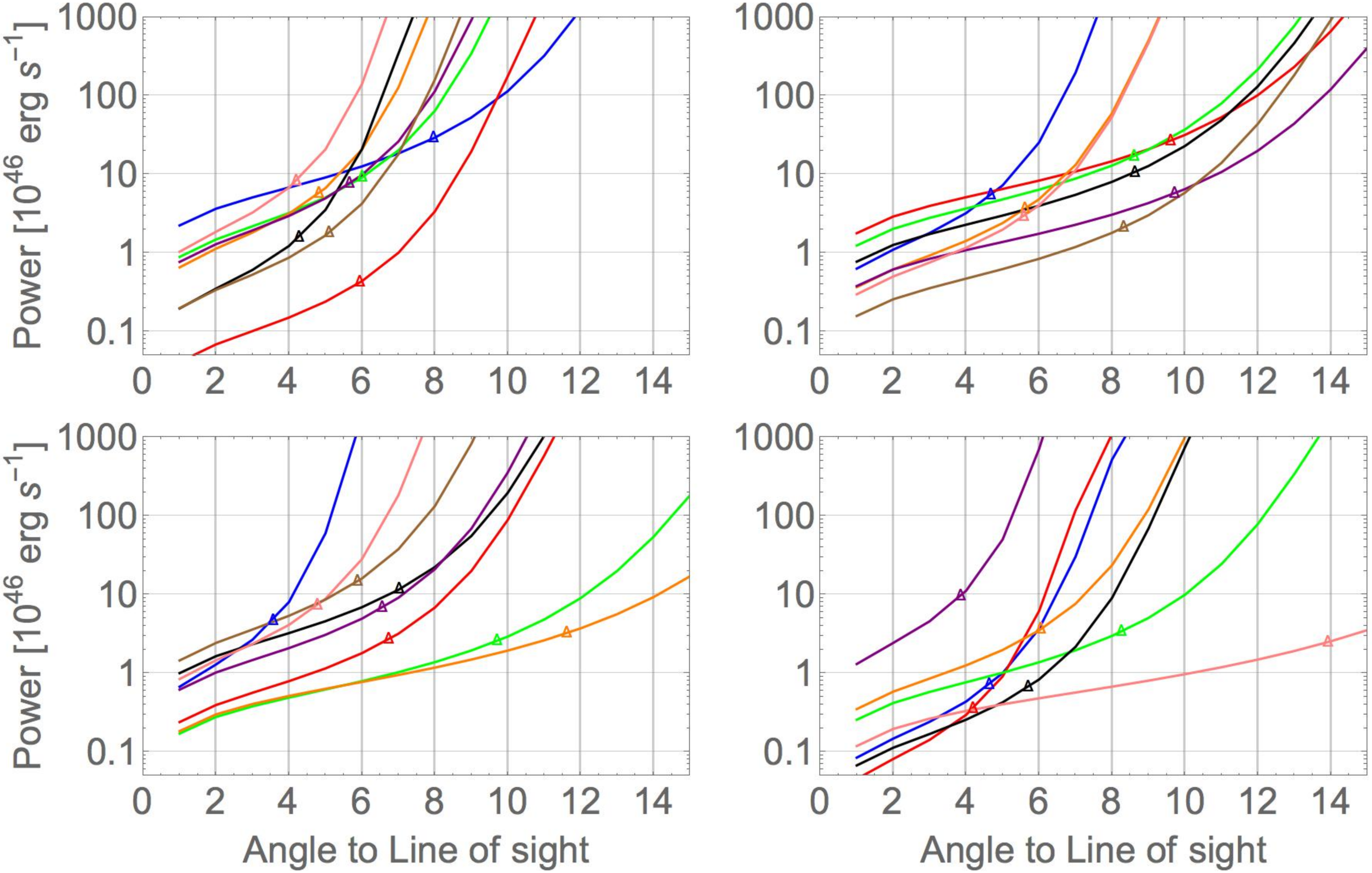
2. The rotational energy of supermassive black holes can power these quasar jets, even with spin parameters as low as $a=0.2$ for lifetimes longer than millions of years.

3. If the power we observe originates as a pure Poynting flux, we derive initial magnetic field strengths of order 10's of kiloGauss.
   Conserving the energy loss and angular momentum loss of the black hole gives a relation between magnetic field strength and jet radius. For models of Magnetically Arrested Disks (e,g., Narayan+ 2003, Sadowski+2014, Tchekhovskoy+ 2011, Zamaninasab+ 2014) the inferred magnetic flux is of order of magnitude of predictions, for Eddington limited accretion.

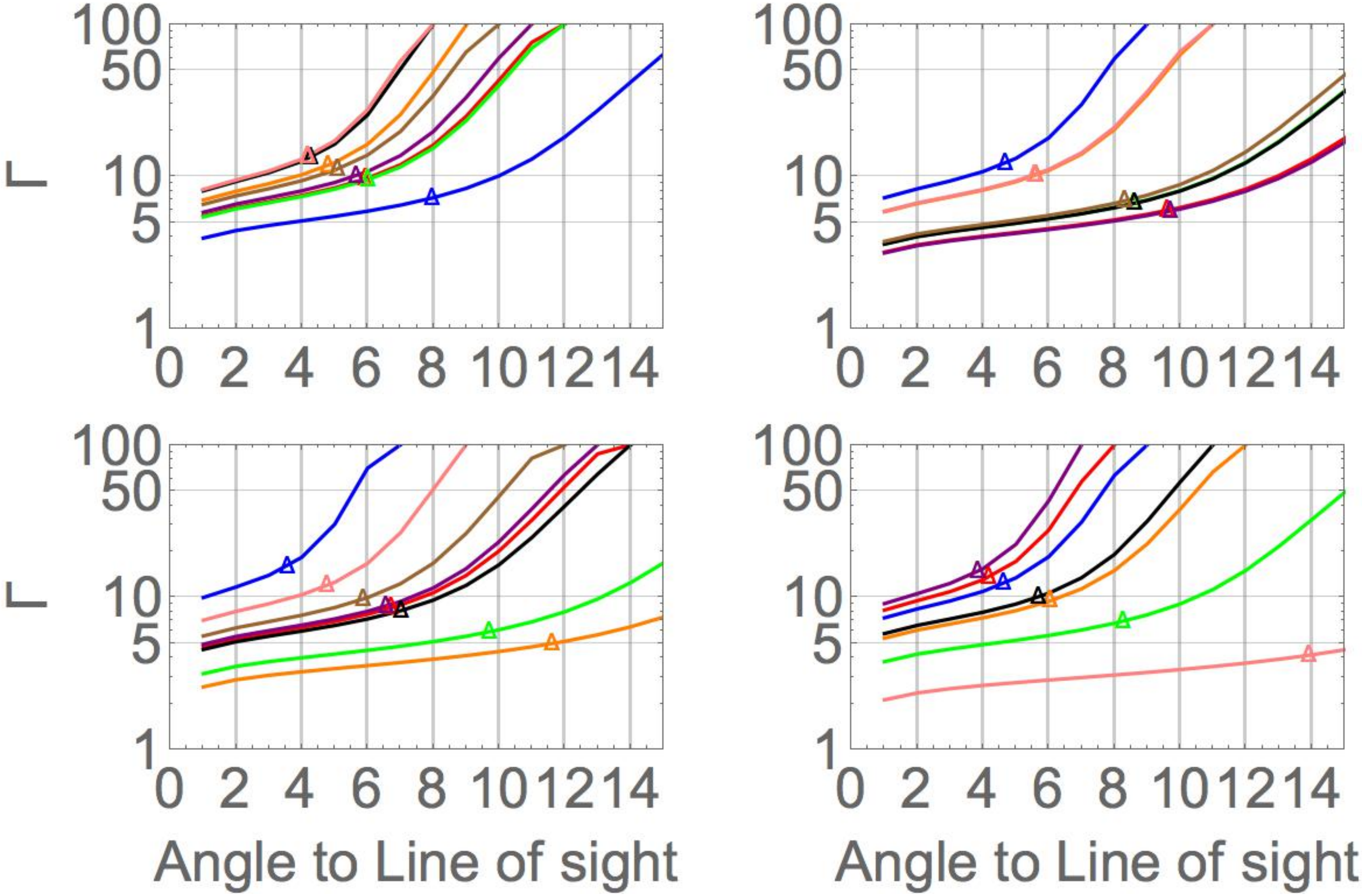
4. Isolated X-ray jets at Z > 2 are a population. Presently, X-ray jet information biased by selecting them based on radio emission. The future Lynx observatory has the sensitivity and field of view to select via X-ray surveys!

Supplemental Slides

Γ = δ (triangles) gives reasonable results for enthalpy flux

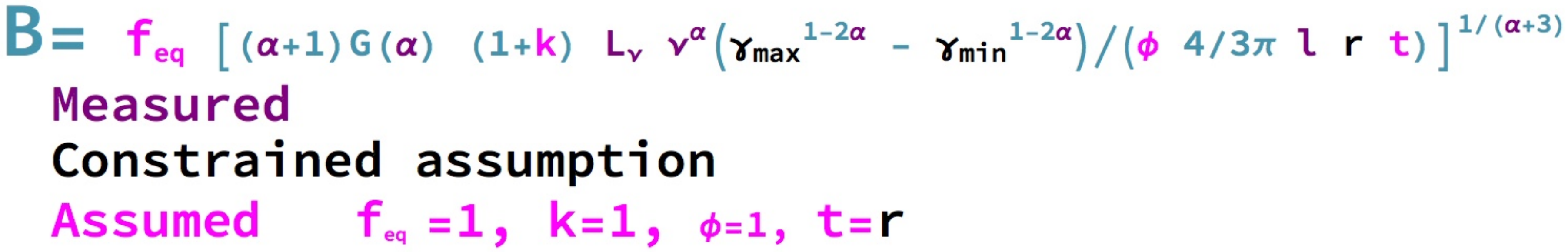


Power vs. angle to line of sight, for δ NE Γ


Γ
100
50
10
5
1
0
2
4
6
8
10
12
14
Angle to Line of sight
Angle to Line of sight

Minimum energy formulation:

$$d\{B^2/(8\pi)+U_{rel}\}/dB = 0$$



$$B = f_{eq}\left[(\alpha+1)G(\alpha)\ (1+k)\ L_\nu\ \nu^\alpha\left(\gamma_{max}{}^{1-2\alpha} - \gamma_{min}{}^{1-2\alpha}\right)/(\phi\ 4/3\pi\ l\ r\ t)\right]^{1/(\alpha+3)}$$

Measured

Constrained assumption

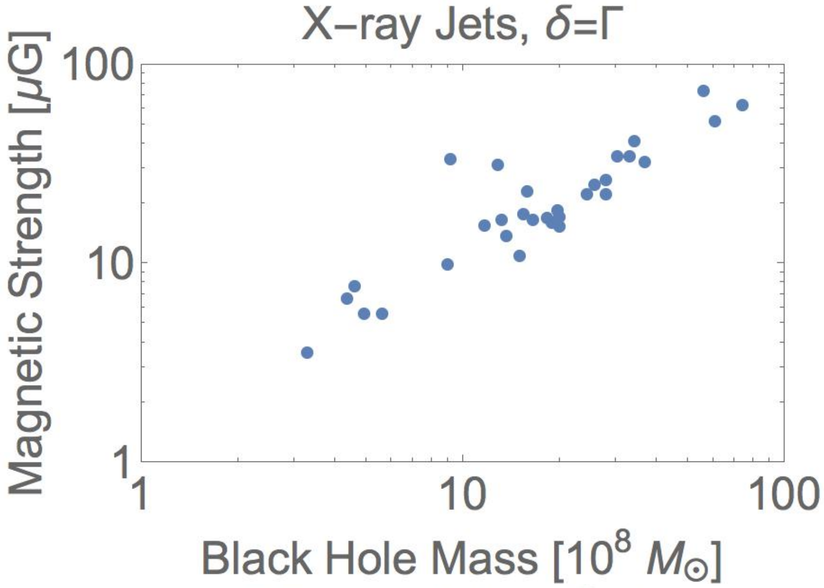
Assumed $f_{eq} = 1$, $k=1$, $\phi=1$, $t=r$

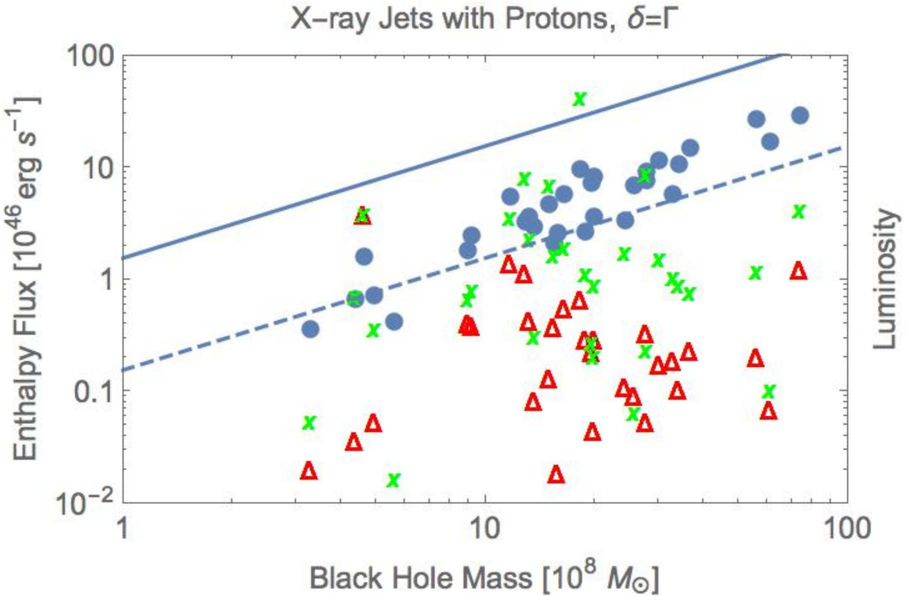
Lynx*, the next generation X-ray Observatory ($2m^2$, 0.5 arcsec) offers measurements of:

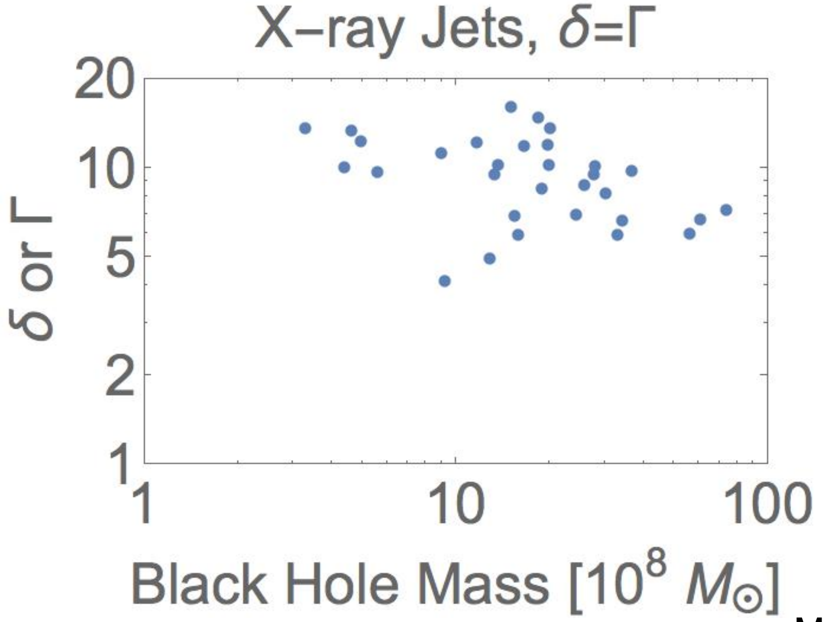
- r via improved statistics on cross-jet profile
- γ_{min} via measurement of soft X-ray turn-over
- γ_{max} via Fermi or ALMA data

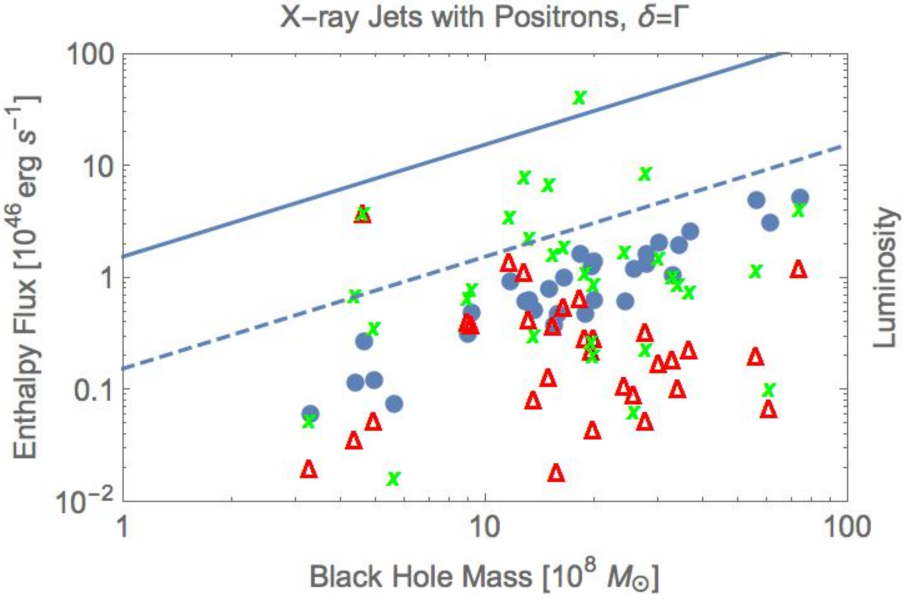
*www.lynxobservatory.com

Correlation of derived properties with the Black Hole Mass









Mass from fundamental plane in Gultekin+ 2009, ApJ 706, 404

IC/CMB interpretation

Extension of the radio sychrotron electrons to lower energy produces IC X-rays by scattering off the CMB.
Projection and Light travel time: Volume = $V_{obs}/(\delta \sin\theta)$
CMB energy density is enhanced by Γ^2 in jet rest frame

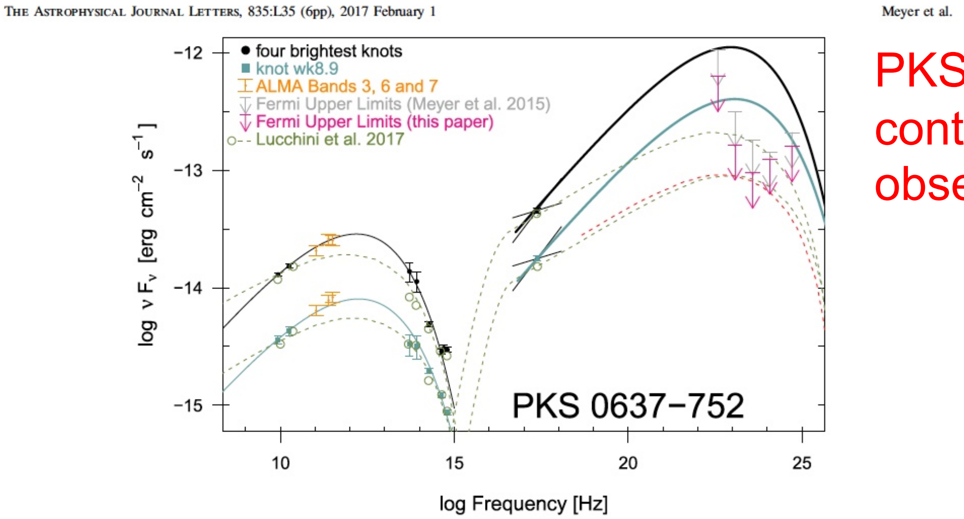
Felten-Morrison (‘66) IC formulas give combination of δ & Γ

$$<u_{CMB}> = 4aT^4(\Gamma^2-1/4)/3 \propto u_0(1+z)^4\ \Gamma^2$$

Cannot solve for all three quantities Γ, δ, and θ

1. Use Γ = δ

OR 2. Parameterize as a function of θ



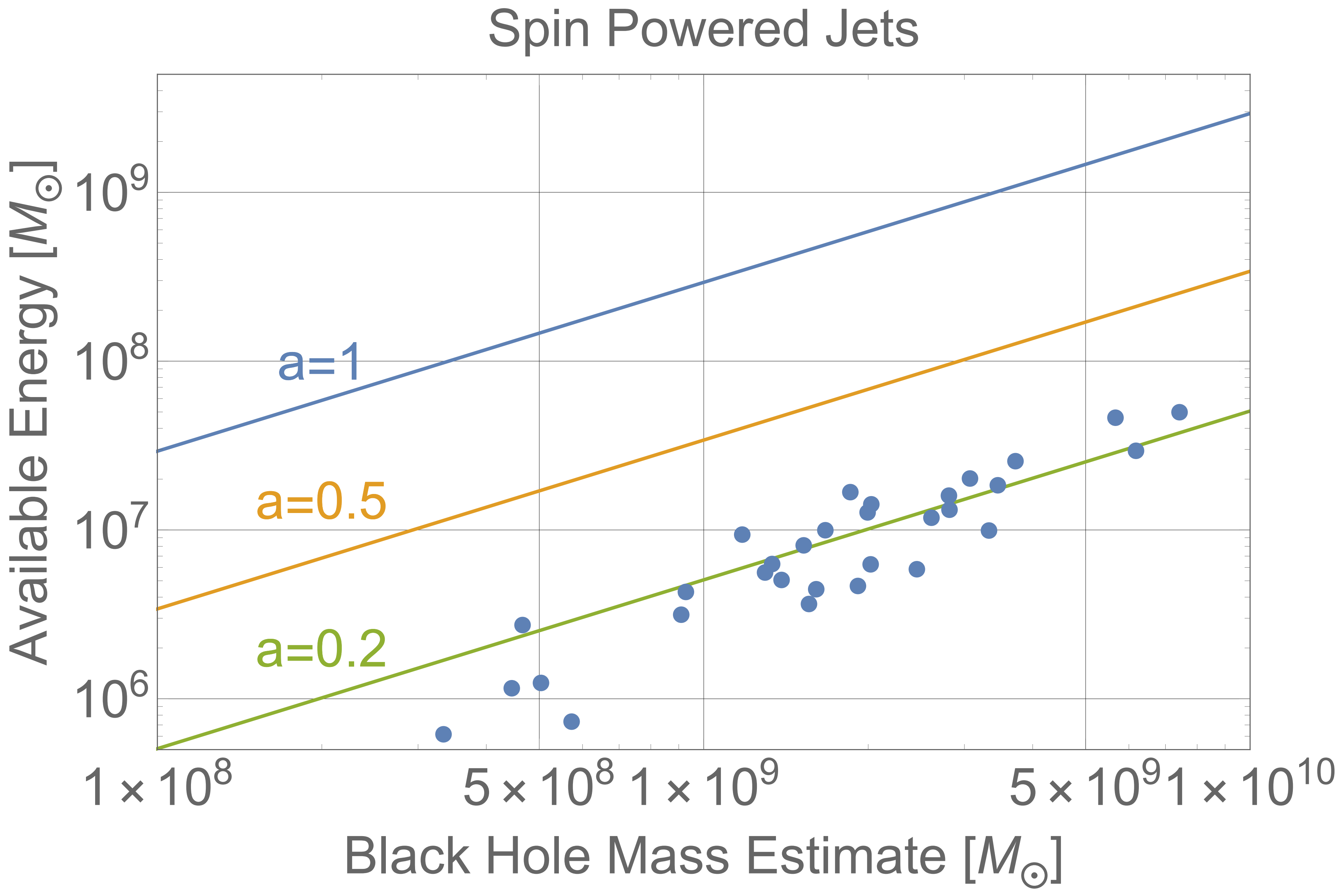
The Astrophysical Journal Letters, 835:L35 (6pp), 2017 February 1

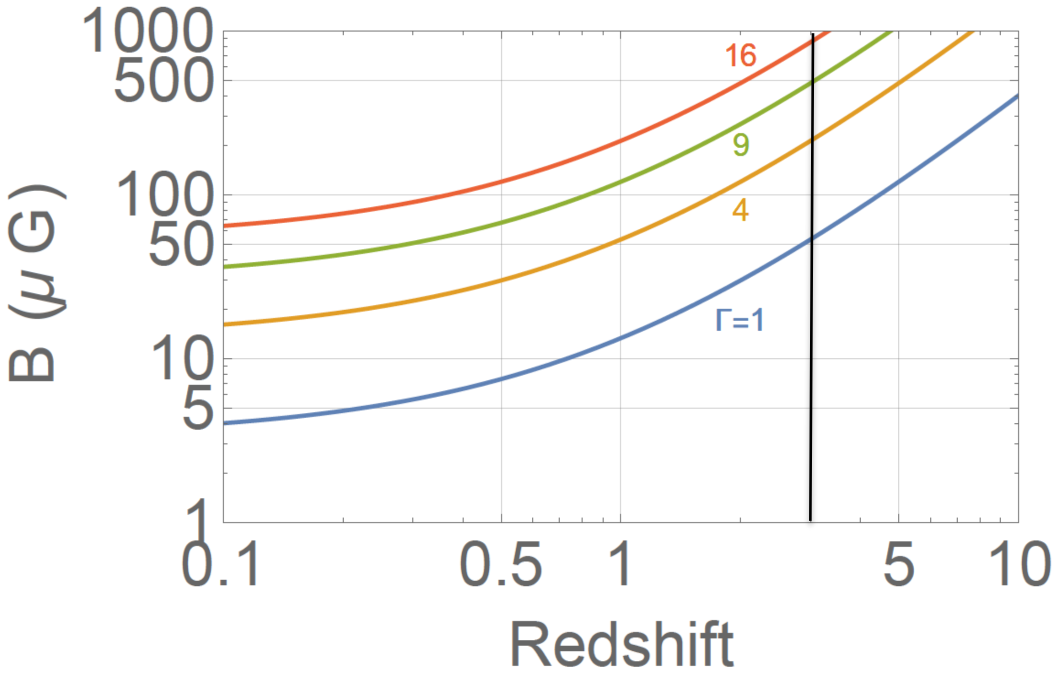
Meyer et al.

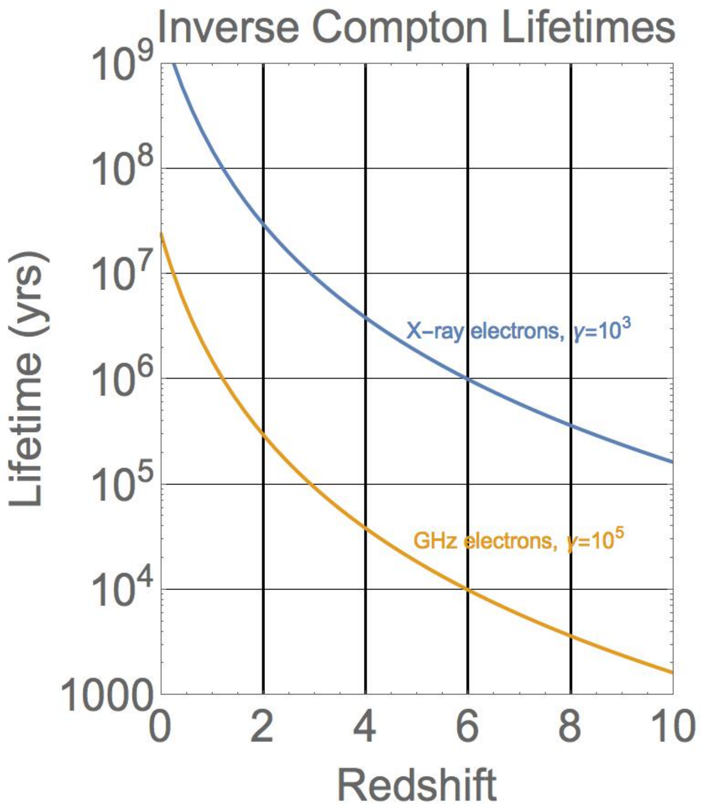
PKS 0637-752 iC/CMB model predictions contradicted by FERMI upper limit observations.

Black holes with spin a>0.2 can power quasar jets for up to 10^7 yr

(fundamental plane mass estimates, using Gultekin+2009,**706**,404)

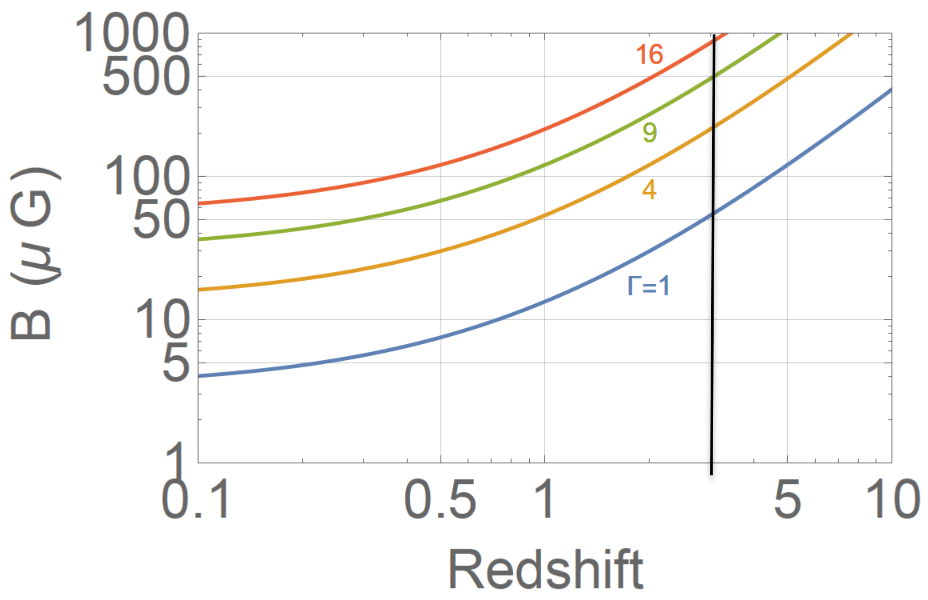




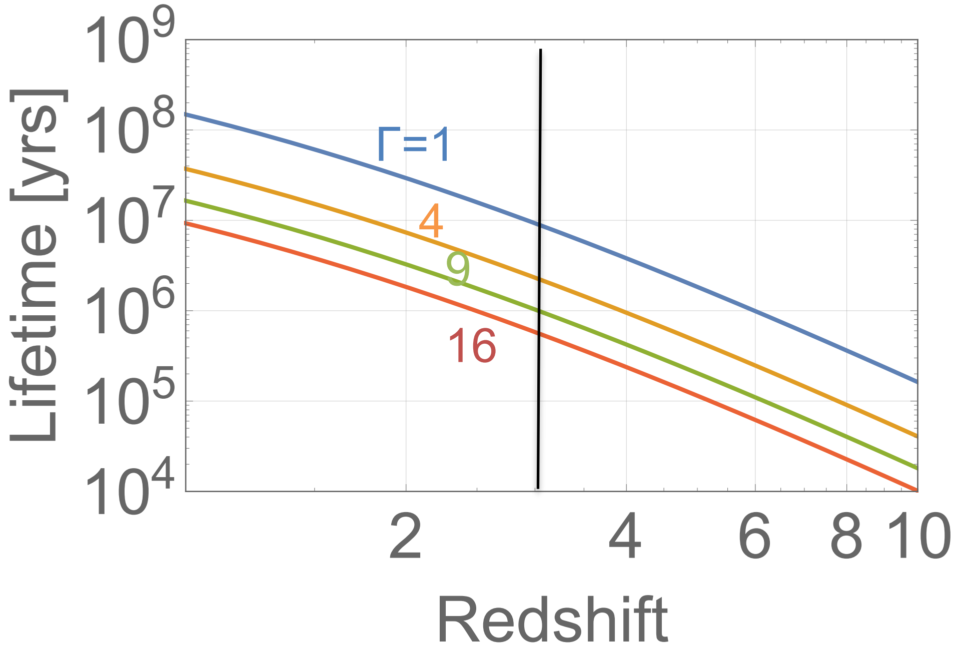


Magnetic field strength in the rest frame of the jet vs. redshift. For a given bulk Lorentz factor Γ, inverse Compton scattering of the microwave background will dominate the radiation unless the field is above the corresponding curve for Γ. For redshifts above 3, (vertical black line) this implies 100's of μG for even mildly relativistic jets.

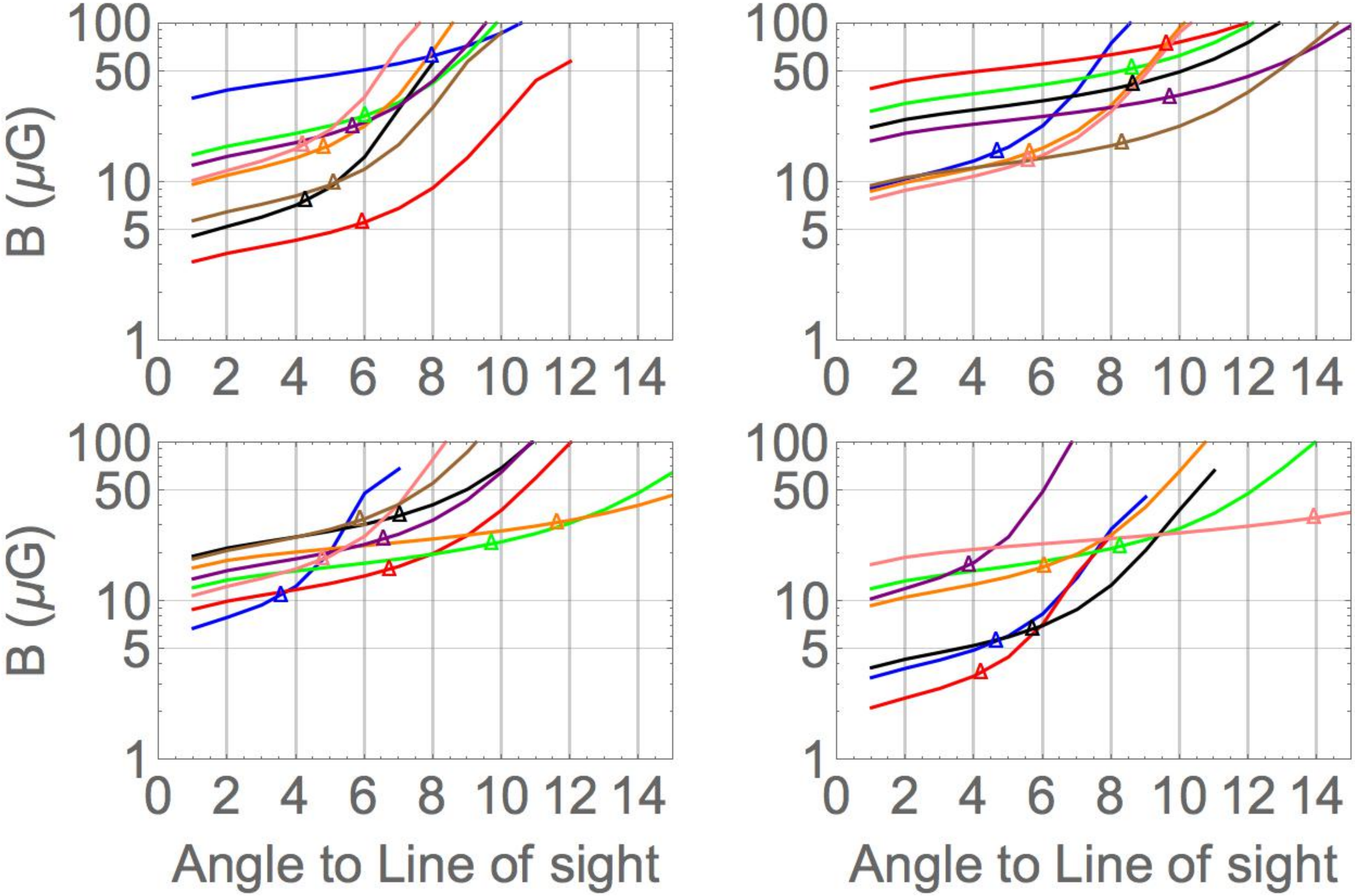
Lifetime of electrons with γ=1000 against losing half their energy by scattering of the CMB. Electrons producing 1 keV X-rays by inverse Compton have energies roughly γ/Γ, while GHz producing electrons are ~100 times more energetic, with 0.01 shorter lifetimes.



Magnetic field strength in the rest frame of the jet vs. redshift. For a given bulk Lorentz factor Γ, inverse Compton scattering of the microwave background will dominate the radiation unless the field is above the corresponding curve for Γ. For redshifts above 3, (vertical black line) this implies 100’s of μG for even mildly relativistic jets.



Lifetime of electrons with γ=1000 against losing half their energy by scattering of the CMB. Electrons producing 1 keV X-rays by inverse Compton have energies roughly γ/Γ, while GHz producing electrons are ~100 times more energetic, with 0.01 shorter lifetimes.



B (μG)
B (μG)
100
50
10
5
1
0
2
4
6
8
10
12
14
Angle to Line of sight
Angle to Line of sight