Implications of the enthalpy flux carried by powerful quasar jets*

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XXIX IAU GA: Accretion on all Scales

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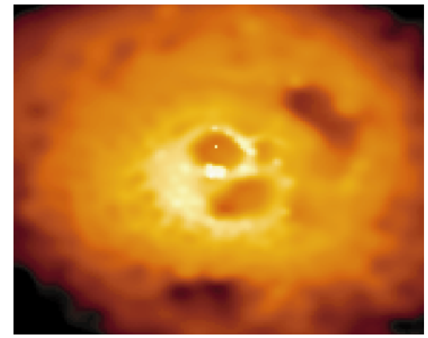
*From a Chandra Survey, Marshall et al., ApJS **156**, 13, 2005; and **193**, 15, 2011

Chandra

X-Ray Observatory

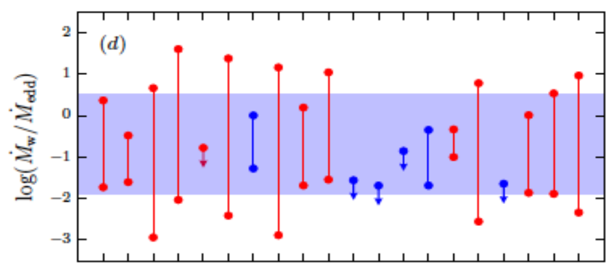
Relativistic Jet Power: Why we care

1. Enthalpy flux of jets can reverse the cooling flow catastrophe in clusters of galaxies



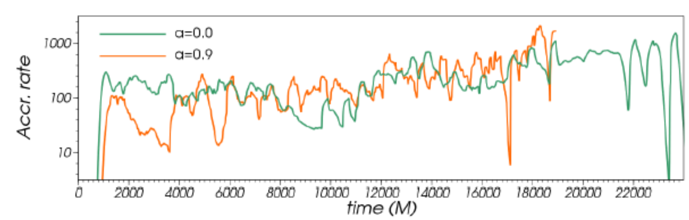
Fabian et al. (2000MNRAS.318L..65F)

2. Jet power significant in black hole energy budget – indicates available energy which may be manifested in other channels (e.g., winds)



Gofford et al.2015MNRAS.451.4169G

3. Comparable or greater than the black hole luminosity: supports calculations of super Eddington accretion & rapid growth at large redshift.



Sadowski et al. 2014MNRAS.439..503S

Power: aka kinetic flux, Enthalpy Flux

Definition*: Γ^2 * velocity * Area * Density of {Relativistic enthalpy + Poynting flux – rest mass}

$$= \Gamma^2 \beta c \text{ Area } [\, 2 B^2/8\pi + (1-1/\Gamma)(1+k_2)\, \rho c^2]$$

X-ray observations of kpc scale jets allow us to estimate B and Γ

- For relativistic jets
- Inverse Compton scattering the CMB

*Bicknell, G. V. 1994, ApJ, 422, 542

IC/CMB interpretation

Extension of the radio-emitting sychrotron electrons to lower energy produces IC x-rays by scattering off the Γ^2 enhanced CMB

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

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

1. Use $\Gamma = \delta$
2. Set Γ = some number
3. Parameterize as a function of θ

Relate B to the relativistic particle density via minimum energy

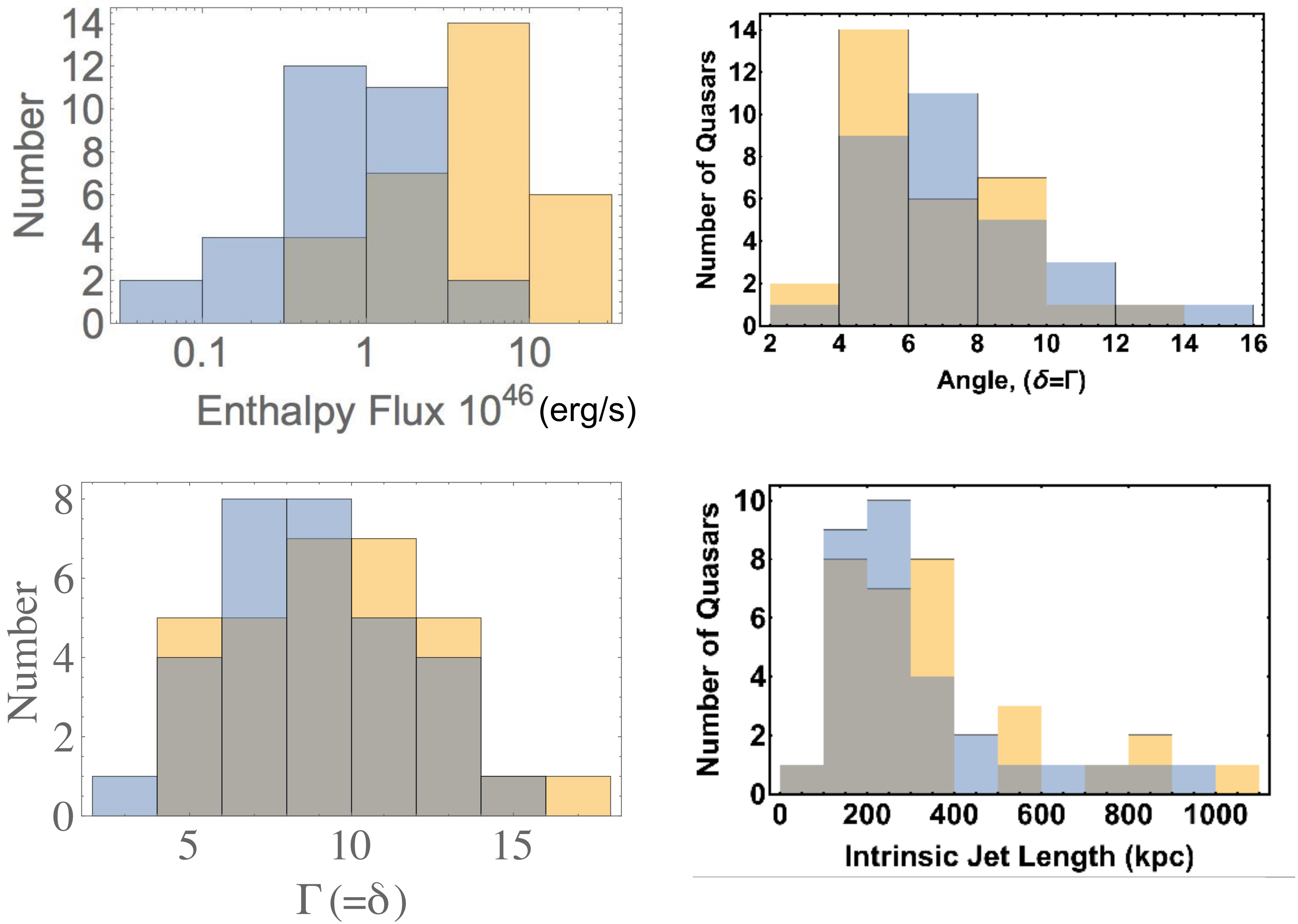
Usual assumptions of uniformity, isotropy in rest frame, electron cutoff below $\gamma_{min} = 30$, $r_{jet} = 2$kpc, are there p or e^+ ?

Proton energy = electron energy

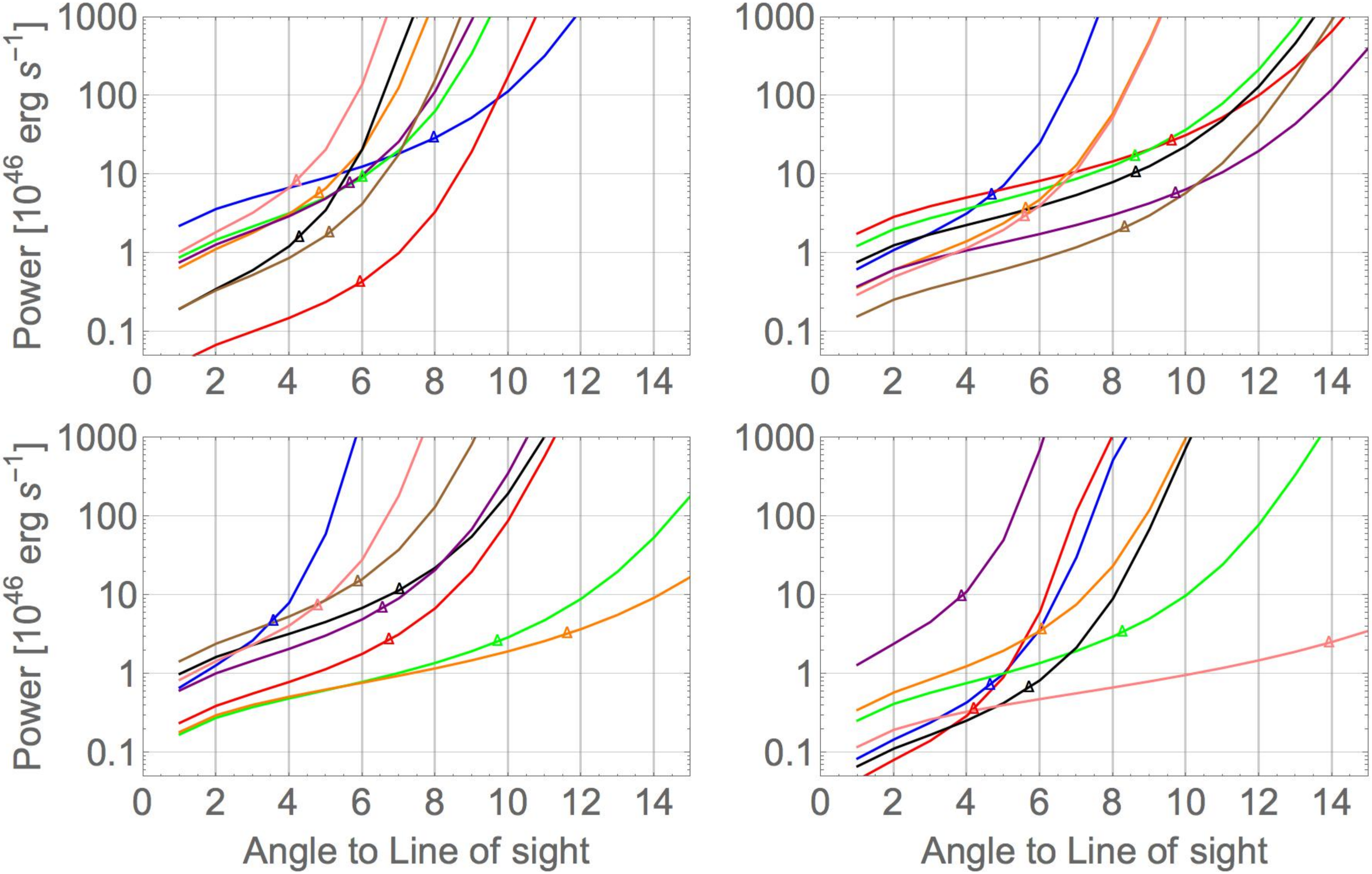
Supersnapshot transformation: Volume = $V_{obs}/(\delta \sin\theta)$

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

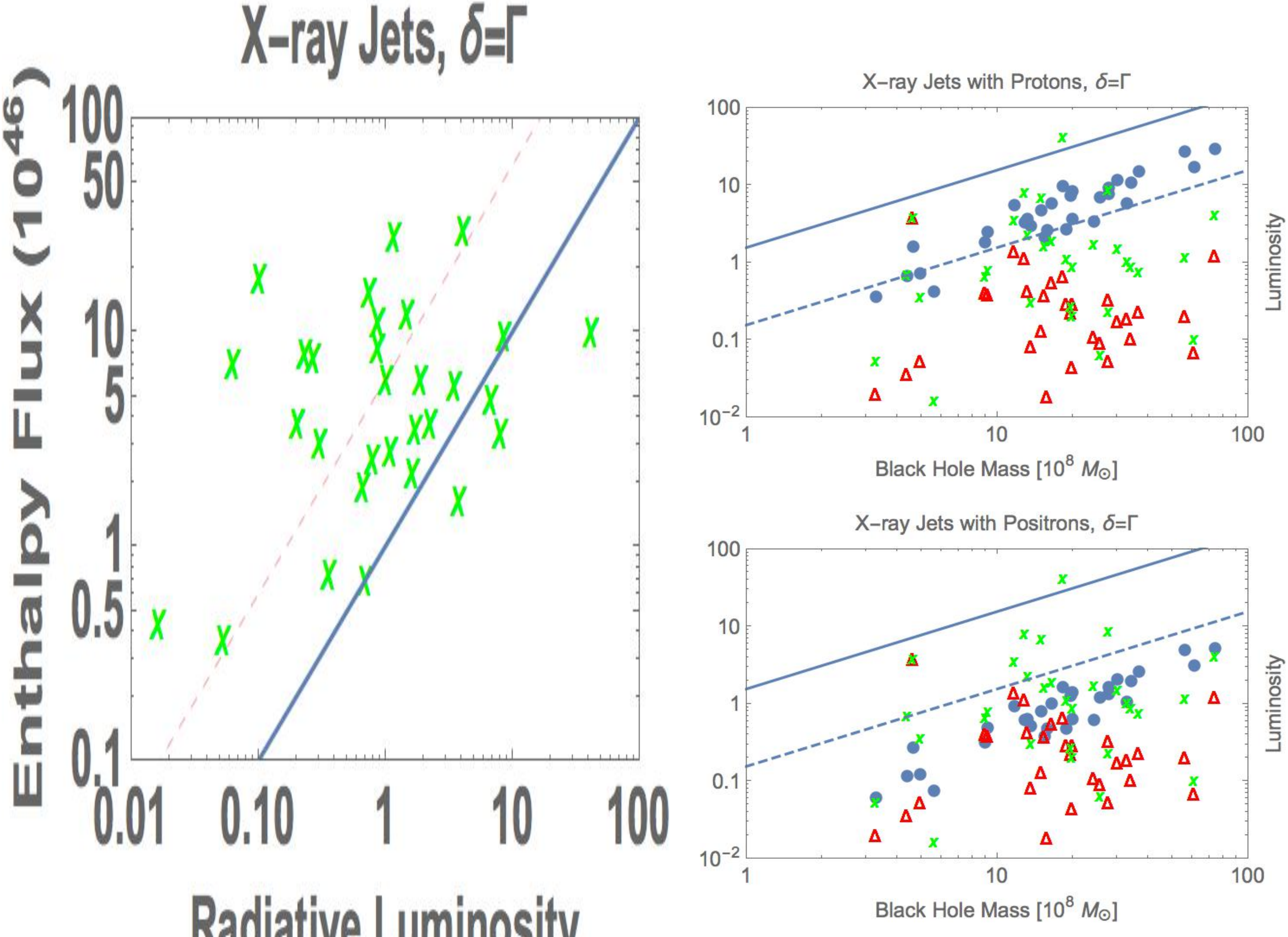
Comparison of Proton (orange) and Positron (blue) jets, for Γ = δ



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



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


X-ray Jets, δ=Γ
Enthalpy Flux (10^46)
Radiative Luminosity
100
50
10
5
1
0.5
0.1
0.01
0.10
1
10
100
X-ray Jets with Protons, δ=Γ
Luminosity
Black Hole Mass [10^8 M⊙]
10^-2
0.1
1
10
100
X-ray Jets with Positrons, δ=Γ
Luminosity
Black Hole Mass [10^8 M⊙]

Summary
X-ray jet results from a Chandra Quasar Survey

Jet Enthalpy flux ~ bolometric radiation of quasar

Assuming $\Gamma = \delta$ gives reasonable results for B, electron density, enthalpy flux, lengths and Lorentz factors for the survey properties

Jets are at small angles to line of sight, ≤ 10 degrees

Kinetic flux 5-10 E46 erg/s for proton jets, 1-2 E46 for $e^{+/-}$ jets, for minimum energy conditions