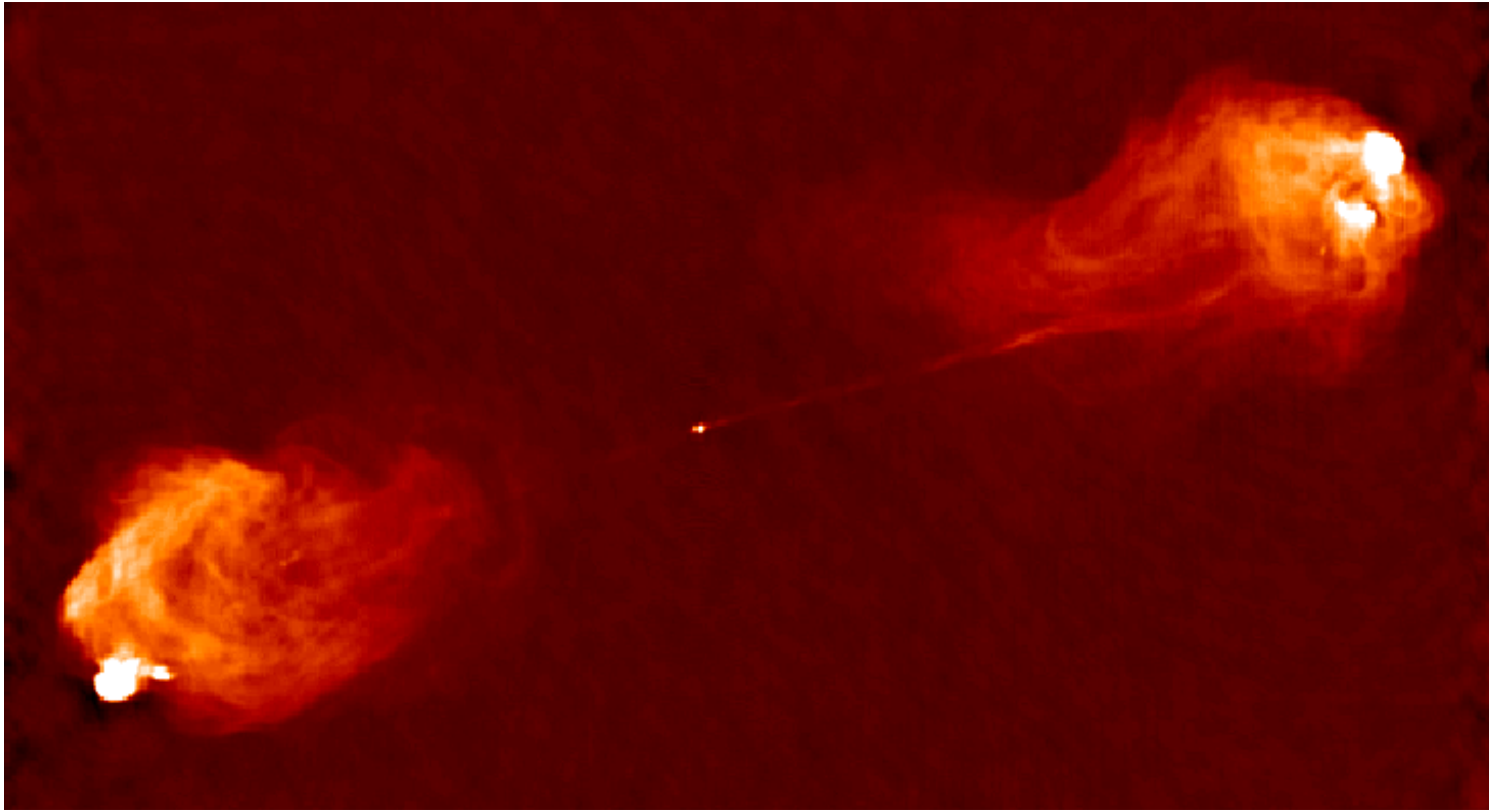
Spin Properties of Supermassive Black Holes with Powerful Outflows

Ruth A Daly



Radio Image of Cygnus A; Carilli et al. (1991)

Studied a sample of powerful FRII (classical double) radio sources for which have estimates of fundamental physical variables

L_j , M, L_{bol}

to learn about the spin properties of the sources

Beam Power of the jet powering the large-scale radio source is $L_j = dE/dt$;
The black hole mass is M, and
the **bolometric luminosity of the accretion disk is L_{bol}**

The **beam power ($L_j = dE/dt$)** is obtained by studying multi-frequency radio maps of the extended radio emitting regions of the source – these regions are isotropic emitters and **are not affected by Doppler beaming of radiation**. The equations of strong shock physics are applied to obtain the beam power; done in collaboration with Chris O'Dea, Preeti Kharb, and Stefi Baum.

Parent population - powerful FRII sources

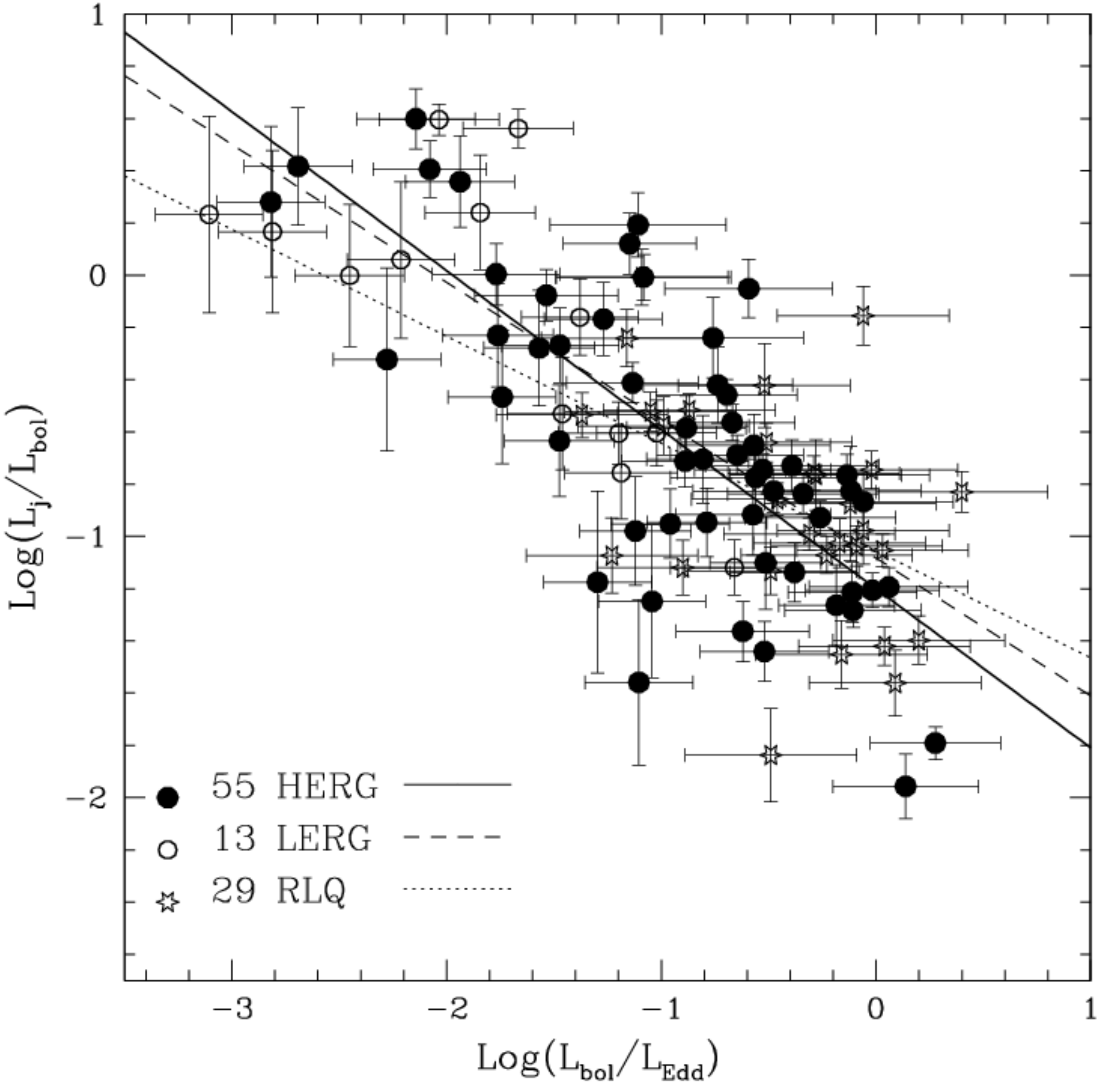
L_j from O'Dea et al. (2009) and Daly & Sprinkle (2014)

L_{bol} is obtained from the [OIII]λ5007 luminosities listed by Willott (L_{bol} = 3500 L_{OIII}) (Heckman et al. 2004; Dicken et al. 2014 using Spitzer Mid-IR show that [OIII] is one of the best indicators of L_{bol} ; Hardcastle et al. 2009 and Mingo et al. 2014 find similar results.)

M is obtained from McLure et al. (2006)

=> a sample of 29 RLQ; 55 HERG; and 13 LERG with z from about 0 to 2.

Results presented here are summarized by Daly, 2016, MNRAS, 458, L24



Clear sequence from LERG → HERG → RLQ as L_{bol}/L_{EDD} ↑ and L_j/L_{bol} ↓ (with overlap)

Slopes of best fit lines:
(all fits are unweighted)

55 HERG: - 0.61 ± 0.07

13 LERG: - 0.53 ± 0.15

29 RLQ: - 0.41 ± 0.15

All sources: - 0.56 ± 0.05

Slopes are consistent
=> a value of - 0.5

Key empirical results:

$$(L_j / L_{bol}) \propto (L_{bol} / L_{EDD})^{-1/2}$$

Now $L_{bol} \propto (\varepsilon\, dM/dt) \Rightarrow L_{bol} \propto (\varepsilon\, \dot{m}\, M)$

where $\dot{m} = (dM/dt)/(dM_{EDD}/dt)$ And $dM_{EDD}/dt = L_{EDD}\, c^{-2}$

Parameterize the beam power as $L_j \propto [\dot{m}^a M^b f(j)]$

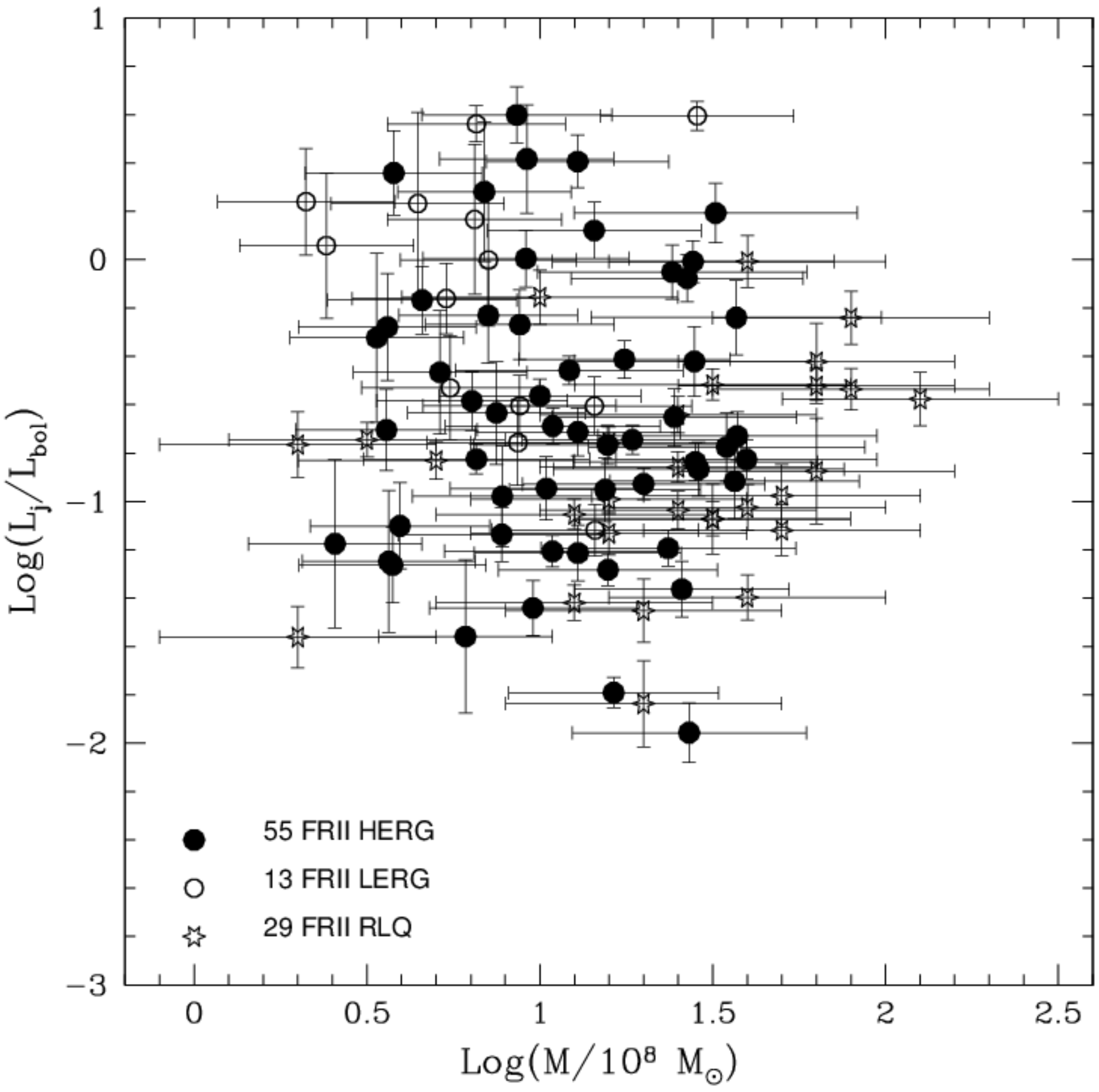
where j is the spin of the black hole

Combining these expressions indicates that

$$\dot{m}^a M^b f(j) \propto (\varepsilon\, \dot{m})^{1/2} M$$

This suggests that b = 1, in which case the ratio of

L_j/L_{bol} is expected to be independent of M, which it is



There is no correlation between L_j / L_{bol} and black hole mass M

Slopes of best fit lines:
(all fits are unweighted)

55HERG: - 0.07 ± 0.24

13 LERG: - 0.40 ± 0.51

29 RLQ: - 0.26 ± 0.17

All sources: - 0.17 ± 0.14

This implies that $L_j \propto \dot{m}^a M f(j) \propto (\varepsilon \dot{m})^{1/2} M$

The simplest solutions are [$\varepsilon \propto \dot{m}$ and $a = 1$]
or [ε = constant and $a = ½$]

Consider the solution $\varepsilon \propto \dot{m}$ and $a = 1$:

For the generalized BZ process, $L_j \propto B^2 M^2 f(j)$
(e.g. Blandford & Znajek 1977; Blandford 1990; Tchekhovskoy, Narayan, & McKinney 2010)
In most accretion disk models, including ADAF and MAD: $B^2 \propto (\dot{m} M^{-1})$
Which implies that $L_j \propto (\dot{m} M) f(j)$ => matches sol. with $a = 1$

So the generalized BZ process of powering outflows is consistent with the relationships between L_j, L_{bol}, and L_{EDD} obtained here.

In general, the data indicate that $(L_j/L_{bol}) \propto (L_{bol}/L_{EDD})^{-1/2}$

Combine this with the expressions for L_j and L_{bol} normalized so that the maximum value of L_j (max) = g_j L_{EDD} and that of L_{bol} (max) = g_b L_{EDD} implies that

$$\dot{m}^a = (\varepsilon\, \dot{m})^{1/2}$$

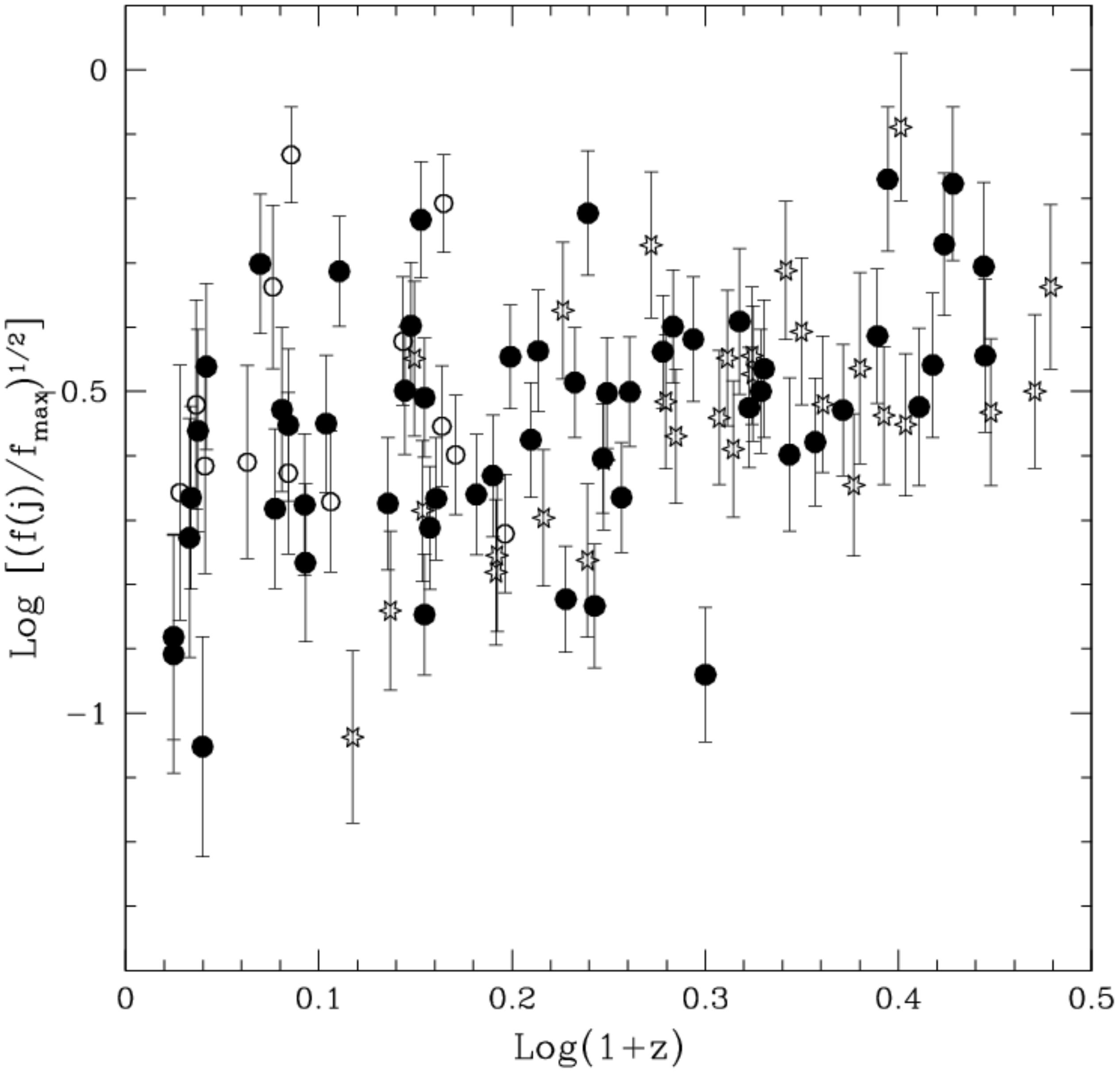
$$L_{bol,44} = 130\, g_b\, (\varepsilon\, \dot{m})\, M_8$$

$$L_{j,44} = 130\, g_j\, \dot{m}^a\, M_8\, f(j)/f_{max}$$

which imply that the spin function is

$$f(j)/f_{max} = (L_{j,44}/g_j)\, (g_b/[130\, L_{bol,44}\, M_8])^{1/2}$$

Independent of the value of a (and hence of the outflow model)



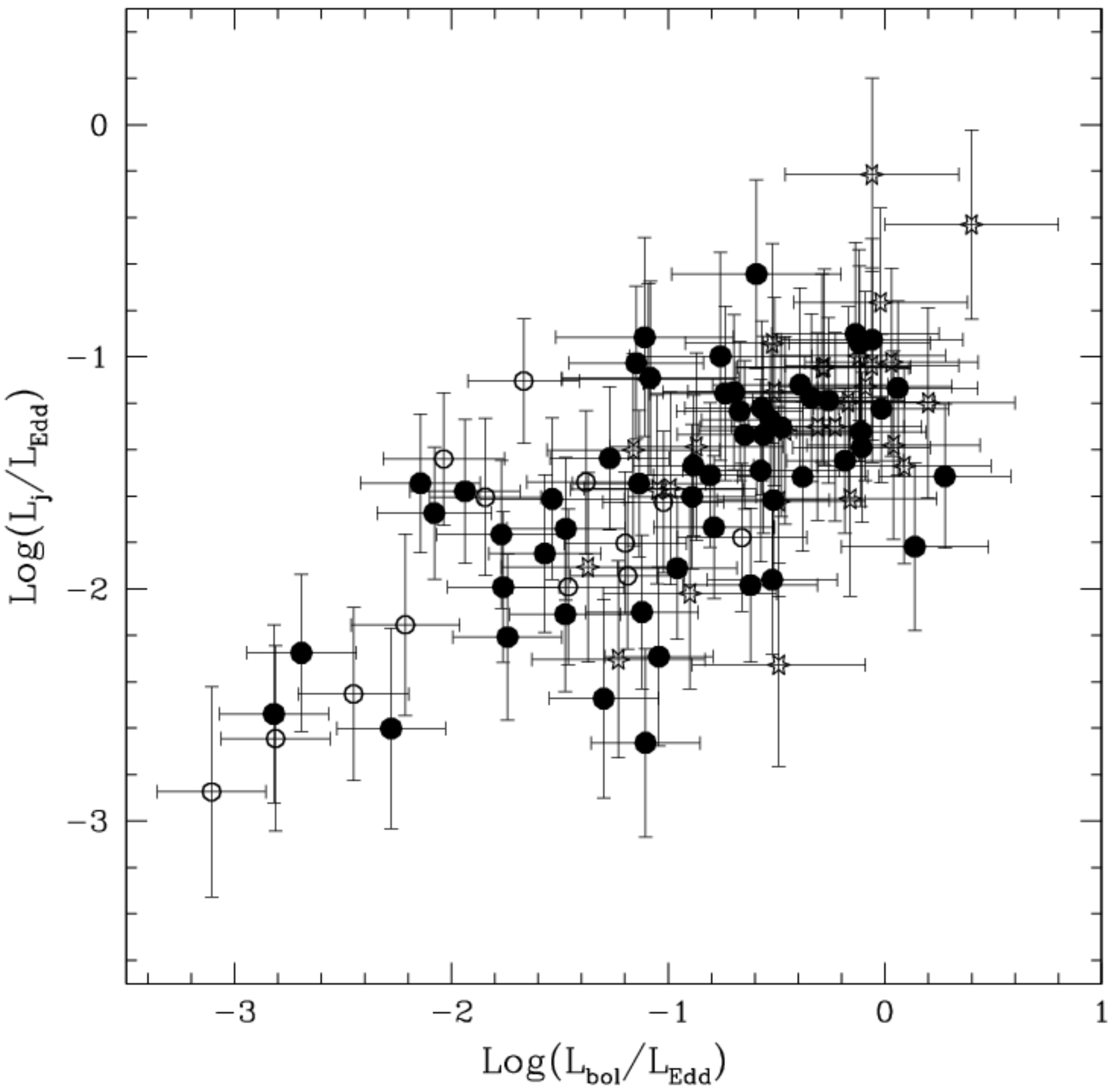
For many processes $[f(j)/f_{max}]^{1/2} \propto$ j to 1st order in j

Range of values similar for all AGN types, suggesting that spin and AGN type are not related

Obtained for $g_b = 1$ and $g_j = 1$. As shown on the next slide, the data indicate that $g_b \approx 1$ and $g_j <$ or $= 1$.

So $f(j)/f_{max}$ can only be greater than or equal to that shown here, and can only increase until the maximum values ≈ 1. Since

$$f(j)/f_{max} = (L_{j,44} / g_j)\, (g_b/[130\, L_{bol,44}\, M_8])^{1/2}$$

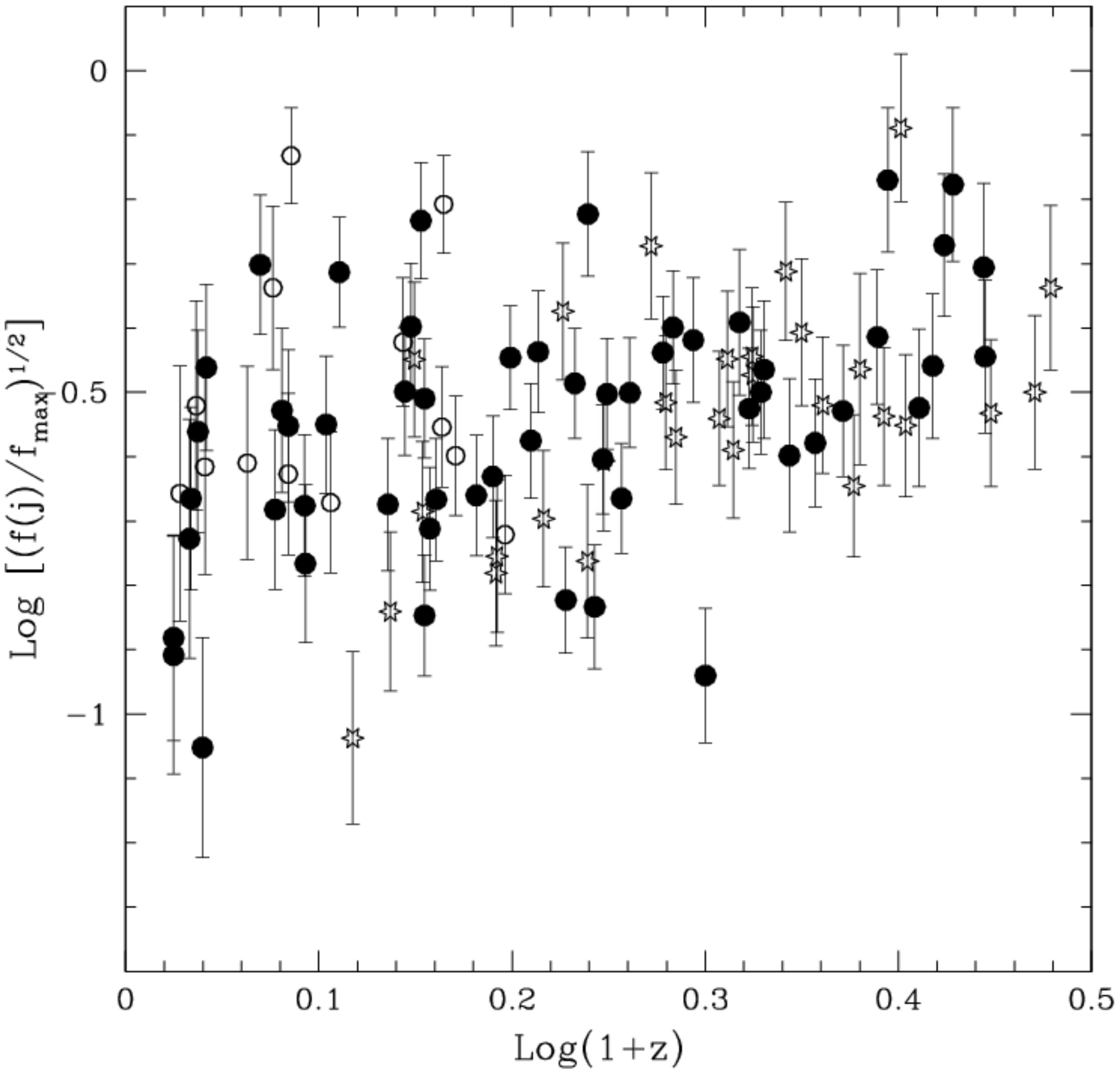


L_{bol} (max) = g_b L_{EDD}
L_j (max) = g_j L_{EDD}

This indicates that $g_b \approx 1$ and g_j is between about 0.4 and 1

$$f(j)/f_{max} = (L_{j,44}/g_j) \times (g_b/[130 L_{bol,44} M_8])^{1/2}$$

$f(j)/f_{max}$ can increase slightly but cannot decrease



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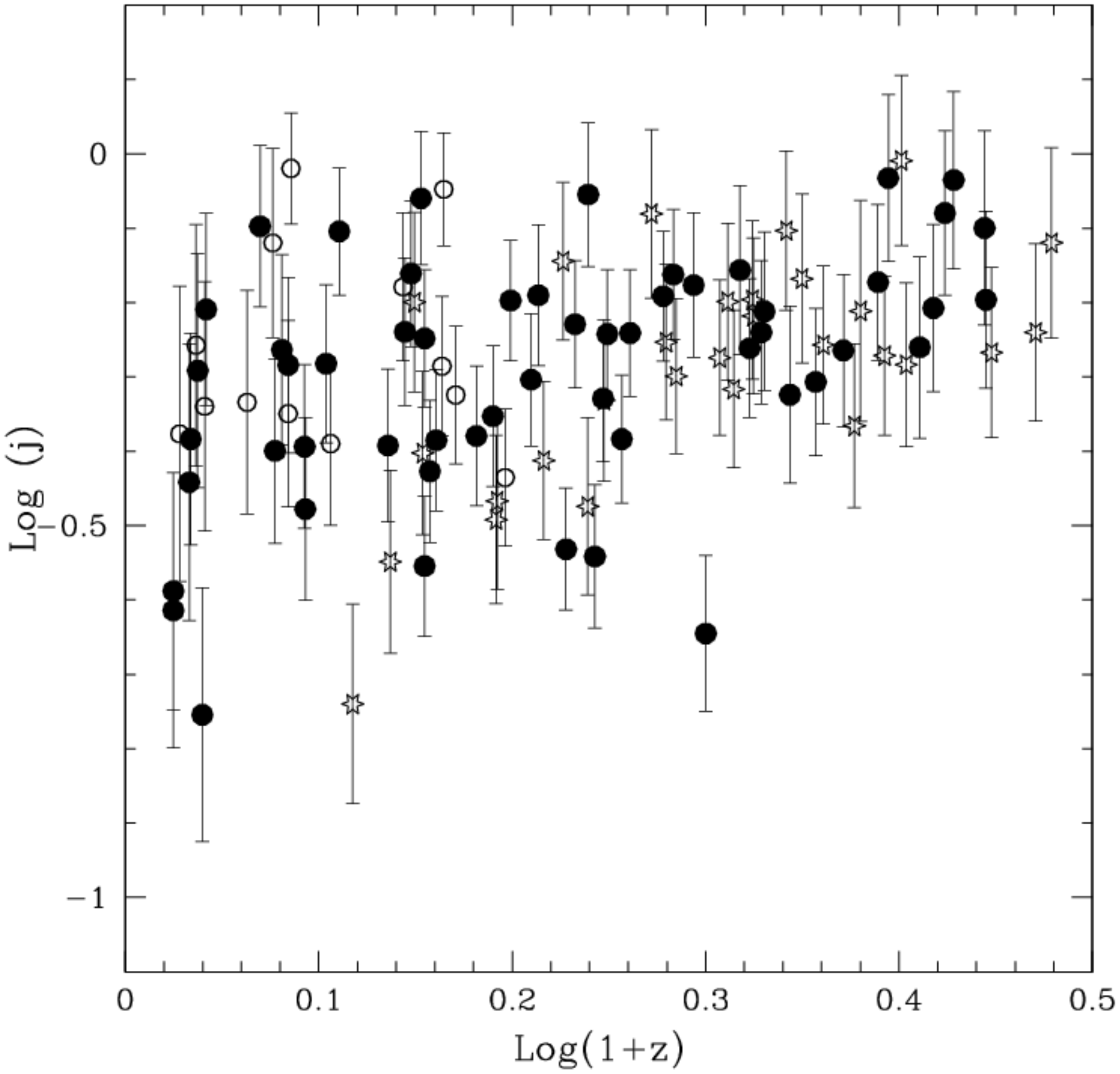

In the generalized BZ model

$(f(j)/f_{max})^{1/2} = j\ (1+ [1-j^2]^{1/2}\ )^{-1}$

(e.g. Blandford & Znajek 1977; Tchekhovskoy et al. 2010; Yuan & Narayan 2014).

Spin j obtained in the generalized BZ model with g_j = 1 and g_b = 1.

Most values of j lie between about 0.3 and 1.

Summary and Conclusion

A sample of 55 HERG, 13 LERG, and 29 RLQ with $0 < z < 2$ for which L_{bol} of the accretion disk, L_j of the outflow, and M of the BH are known was studied.

The empirical relations obtained were similar for all types of sources and indicate that L_j/L_{bol} is independent of M, and

$$L_j/L_{bol} \propto (L_{bol}/L_{EDD})^{-1/2}$$

Writing

$$L_{bol} \propto (\varepsilon \dot{m} M) \text{ and } L_j \propto [\dot{m}^a M^b f(j)]$$

and applying the empirically determined relations it was found that one solution has a functional form for L_j that is identical to that expected in the generalized BZ model.

The general solution (valid for all values of a) allows a determination of the spin function $f(j)/f_{max}$ independent of specific outflow models. A broad range of values is obtained, and similar values are obtained for all types of sources, suggesting that AGN type and spin are not related.

The spin function $f(j)/f_{max}$ was interpreted in the context of the generalized BZ model to obtain specific values of the black hole spin j; most values lie between about 0.3 and 1.