The Properties of Very Powerful Classical Double Radio Galaxies

Ruth A. Daly

Collaborators: Chris O'Dea, Preeti Kharb, Stefi Baum, George Djorgovski, Megan Donahue, Kenny Freeman, Eddie Guerra, & Matt Mory.

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The Sample

We consider a subset of radio sources

Leahy & Williams (1984) FRII-Type I

Leahy, Muxlow, & Stephens (1989): most powerful FRII RG, $P_r(178MHz) \geq 3 \times 10^{26}\ h^{-2}$ W/Hz/sr (about 10 x classical FRI/FRII).

→ sources have very regular bridge structure

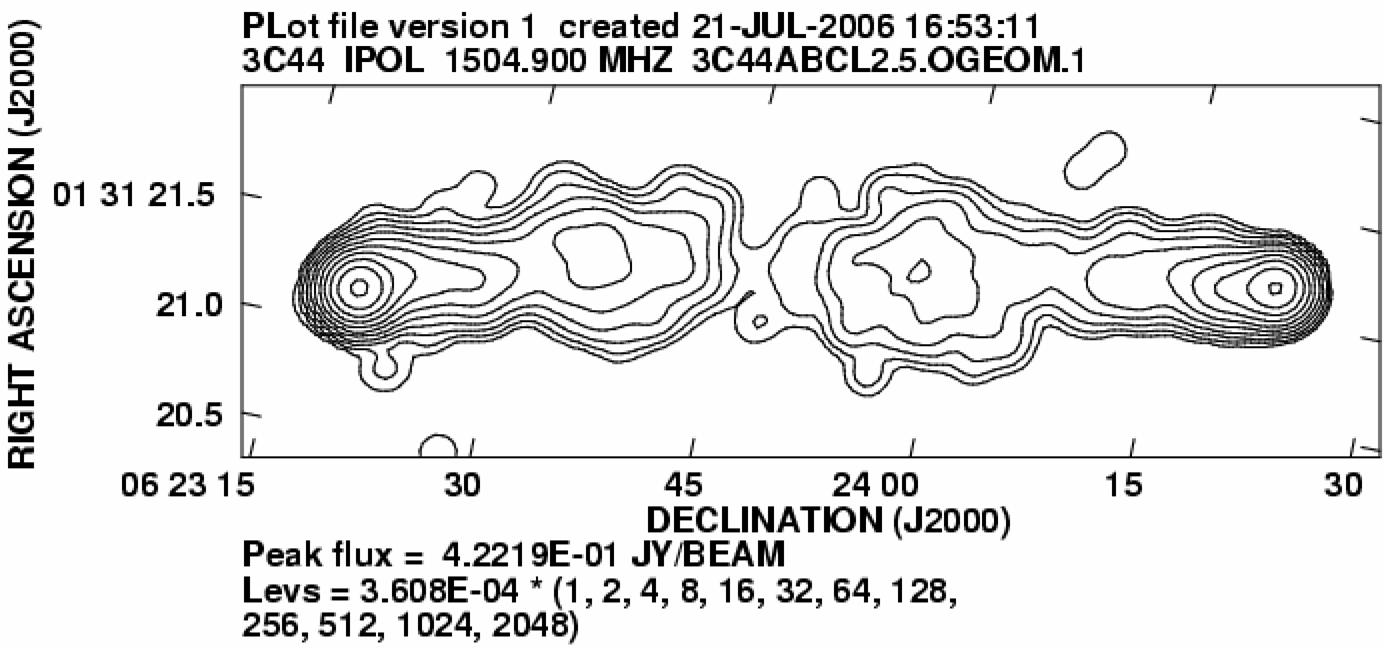
→ rate of growth well into supersonic regime

→ equations of strong shock physics apply & negligible backflow in bridge (LMS89).

→ Form a very homogenous population

& RG (not RLQ) to minimize projection effects.

For example, here is the 1.5 GHz image of 3C 44



70 RG form the parent pop: 3CRR RG with P(178MHz) ≥ 3 x 10^{26} h^{-2} W/Hz/sr

Recently obtained multi-frequency observations of 11 RG; combine with 9 RG from LMS89, 4 from LPR92, 6 from GDW00

→ have 30 RG with sufficient data to study source structure
z from 0 to 1.8, and D from 30 to 400 kpc (for h=0.7, Ω_m = 0.3, and Ω_Λ = 0.7)

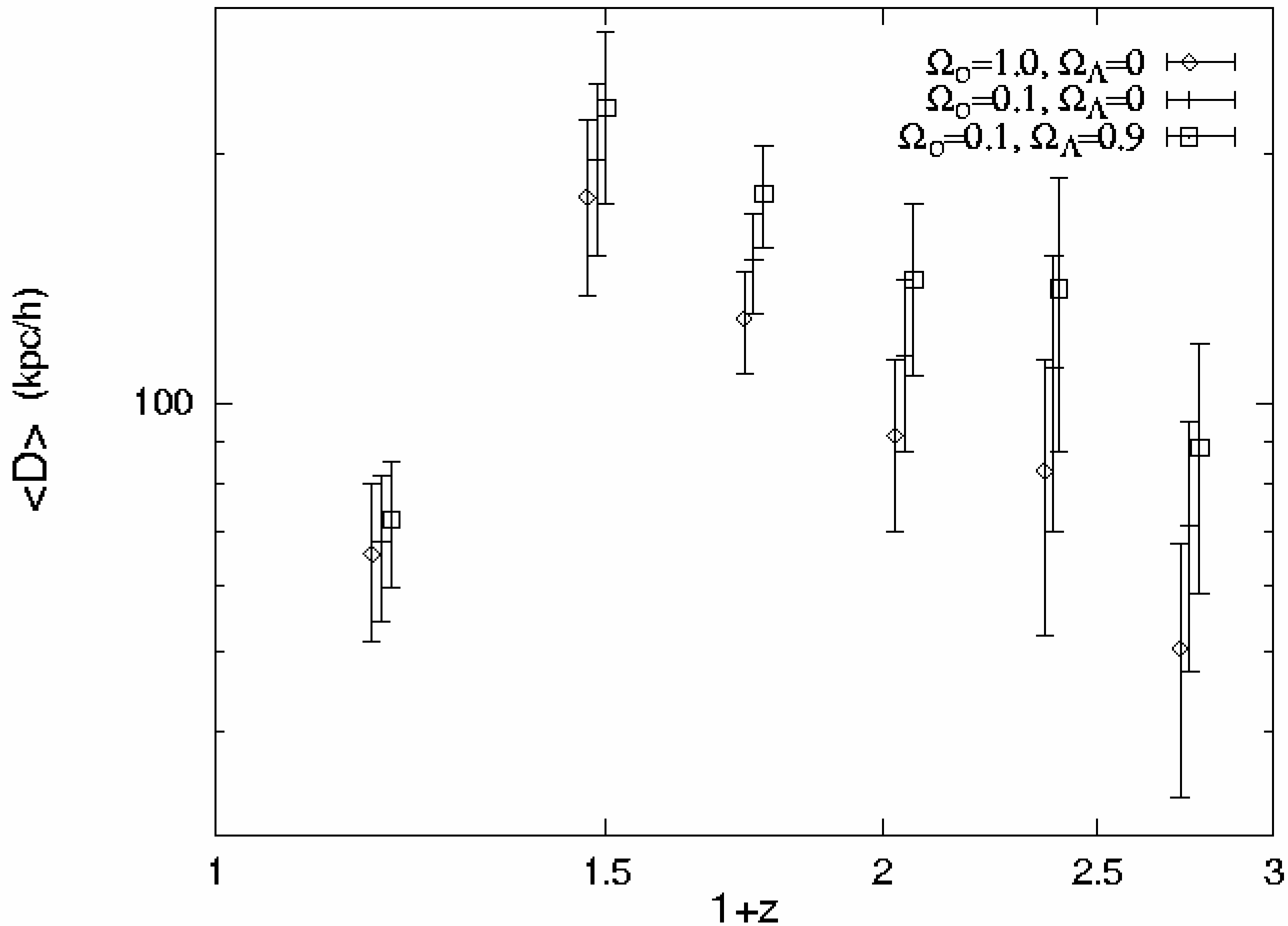
→ overall rate of growth, v, along the symmetry axis of the source, the source width, and the source pressure for 30 sources [VLA time for additional 13]

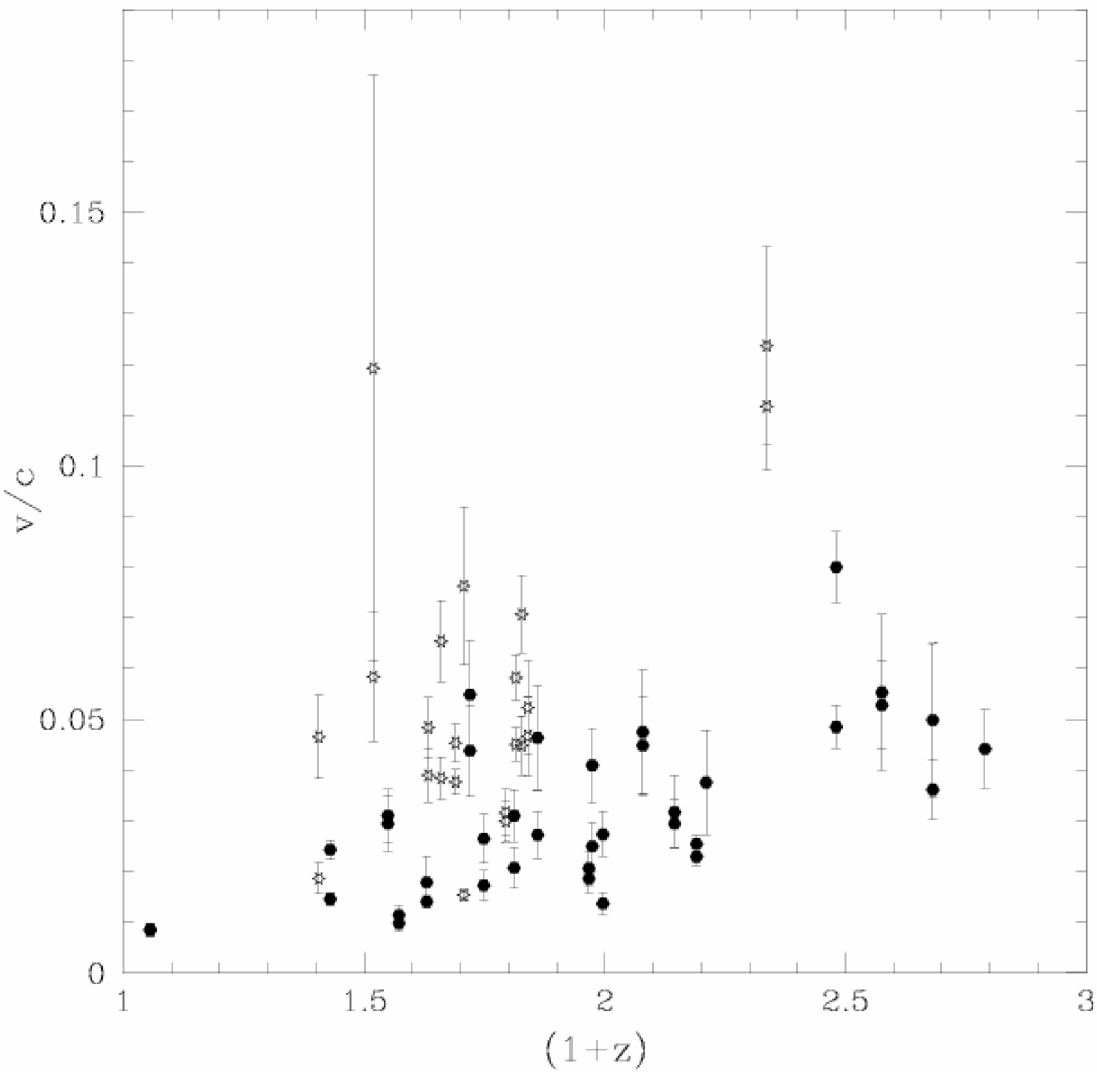
Velocities determined using spectral aging analysis; recent work by Machalski et al. (2007) shows spectral aging analysis gives ages in good agreement with predictions in the context of a detailed model for the sources. And, a comparison of spectral ages with other age determinations also indicates that the spectral age provides a good global parametric fit to the source age.

We allow for offsets of the radio emitting plasma from minimum energy conditions using $B = b\, B_{min}$; $P = [(4/3)\, b^{-1.5} + b^2]\, (B^2_{min})/24\pi$

<D> for the parent population of 70 3C Radio Galaxies with 178 MHz powers > 3 h^{-2} x 10^{26} W/Hz/sr

<D> is defined using the largest linear size





The source sizes decrease systematically with z, but rate of growth of sources do not decrease with z.

We find no statistically significant correlation of v with z.

Interesting and unexpected that <D> has a small dispersion at a given z and is decreasing with z for $z \geq 0.5$. Radio powers increase with z, and source velocities increase with radio power (A87; AL87; LMS89; LPR92); source v do not decrease with z.

The studies of Neeser et al. (1995) of D, P, and z, of classical doubles indicate that D and P are not correlated, but D and z are correlated; also indicated by detailed physical models for the sources.

The average size of a given source should mirror that of the parent population at that z, so $D_* \sim \langle D \rangle$.

The average size of a given source is $D_* \sim v\, t_*$

Note: for an Eddington limited system, t_* does not depend upon the luminosity L_j or the total energy E_* , and is expected to be roughly constant; doesn't look good for these sources.

Generalize t_* to be $t_* \sim L_j^{-\beta/3}$

For an Eddington limited system, expect $\beta = 0$; an Eddington limited system is a special case; several other detailed arguments lead to this relation.

Thus, $D_* = v\, t_* \sim v\, L_j^{-\beta/3}$

$L_j \sim v\, a^2 P$ (from strong shock physics)

So $D_* \sim v^{1-\beta/3} (a^2 P)^{-\beta/3}$

(could also view as purely empirical relation)

This determination of the average size of a given source depends upon the model parameter β and the coordinate distance $(a_o r)$ to the source, going roughly as $(a_o r)^{-0.6}$ (after accounting for v, a, and P)

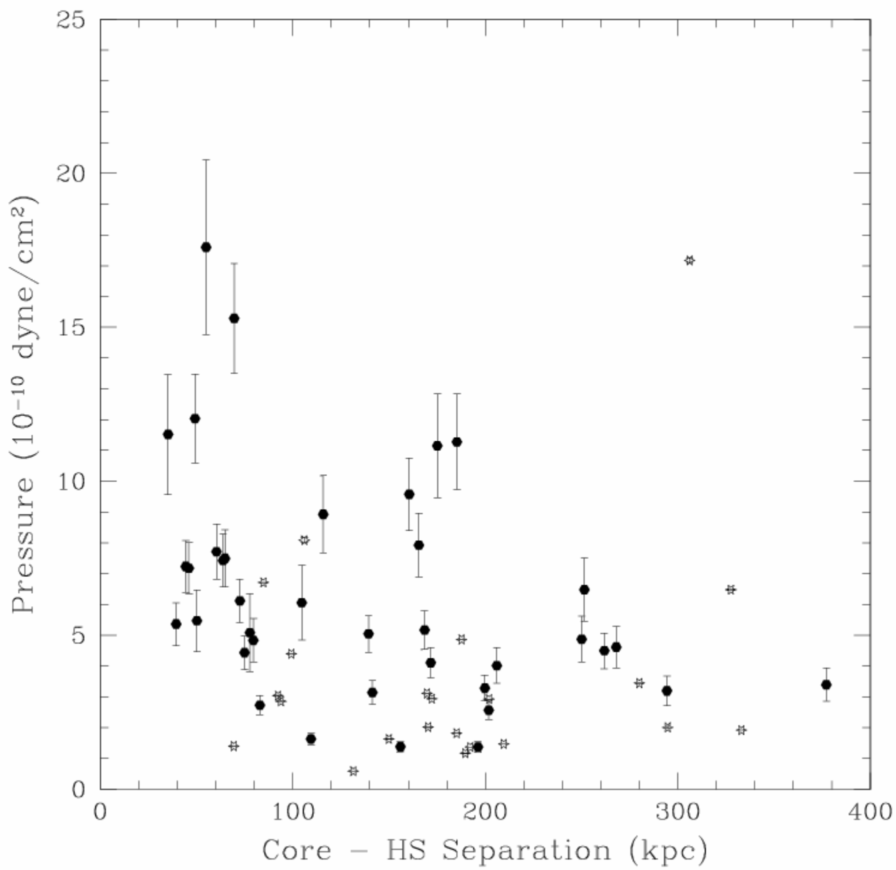
Comparing <D>, which goes as $(a_o r)$, with D_* allows a determination of β and cosmological parameters

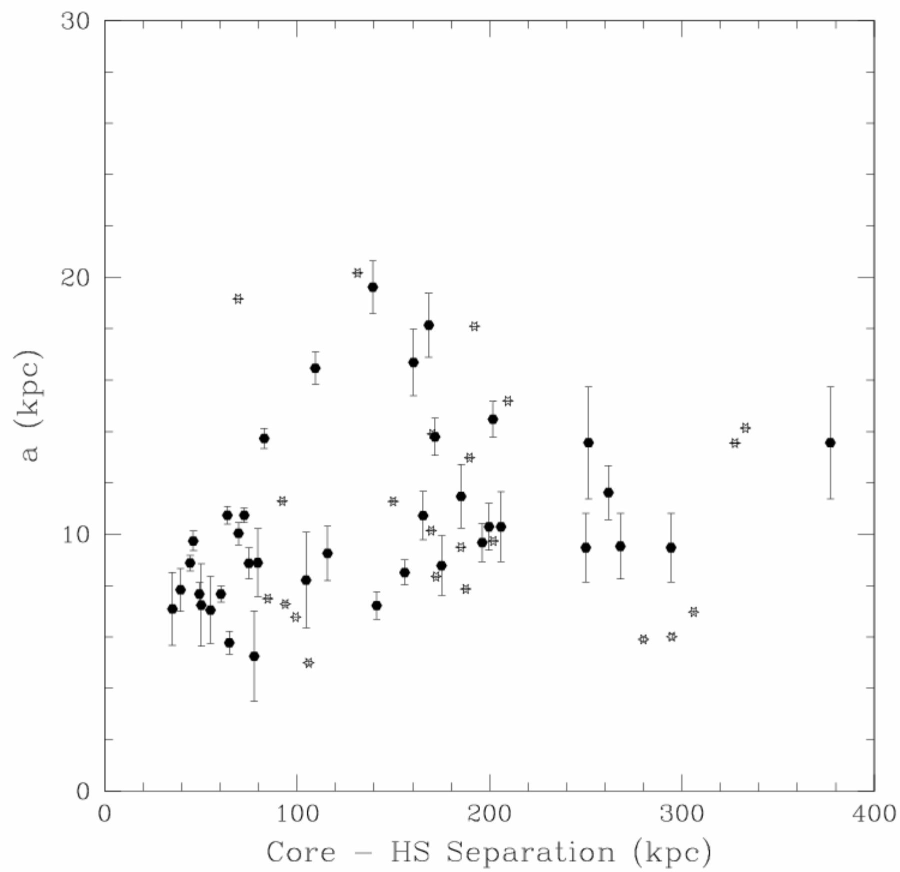
→ require $\langle D\rangle/D_* = \kappa$ and solve for $(a_o r)$ and β; goes **κ** $\sim (a_o r)^{1.6}$

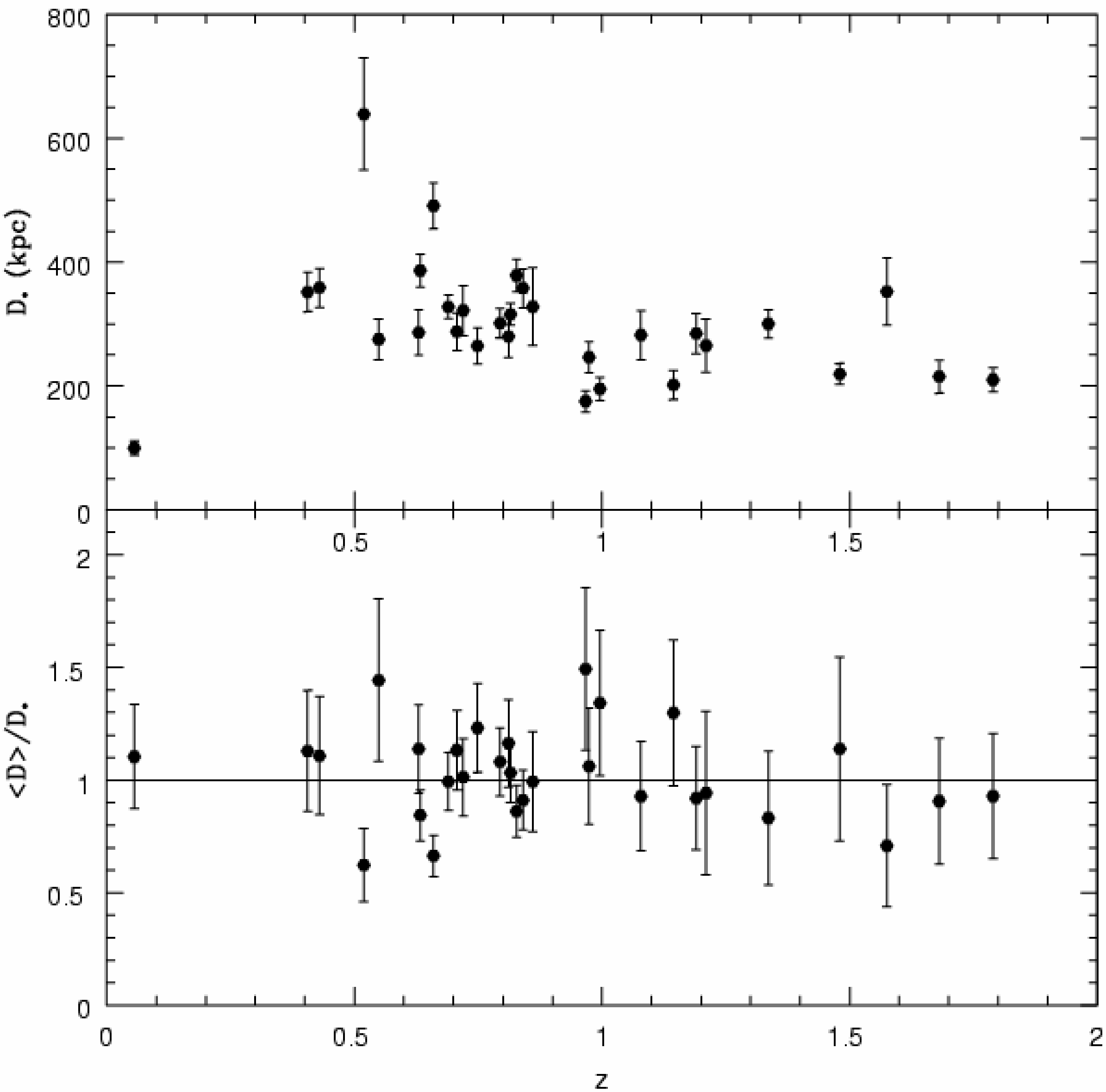
We obtain D_* for each of the 30 sources studied here and compare it with <D> for the parent population of 70 sources.

The method accounts for variations in L_j from source to source and variations in source environments (i.e. we do not make any assumptions about n_a)

Source Pressures and Widths measured 10 kpc behind the hot spot (toward the core) to obtain the time-averaged post shock conditions (from O'Dea et al. 2007)

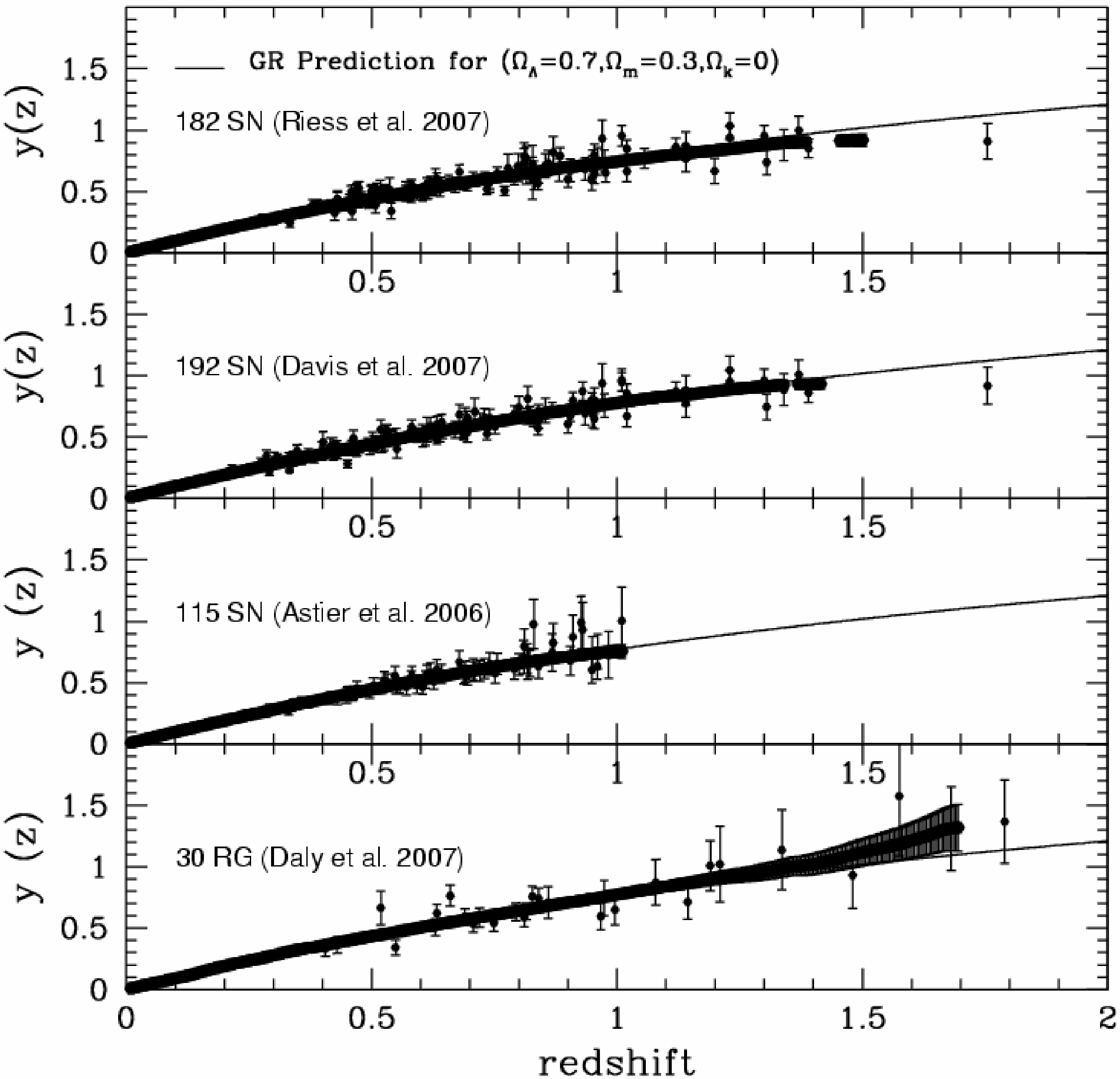






D_* shown for best fit parameters β = 1.5 ± 0.15, Ω_m =0.3 ± 0.1 and w = -1.1 ± 0.3, obtained in a quintessence model

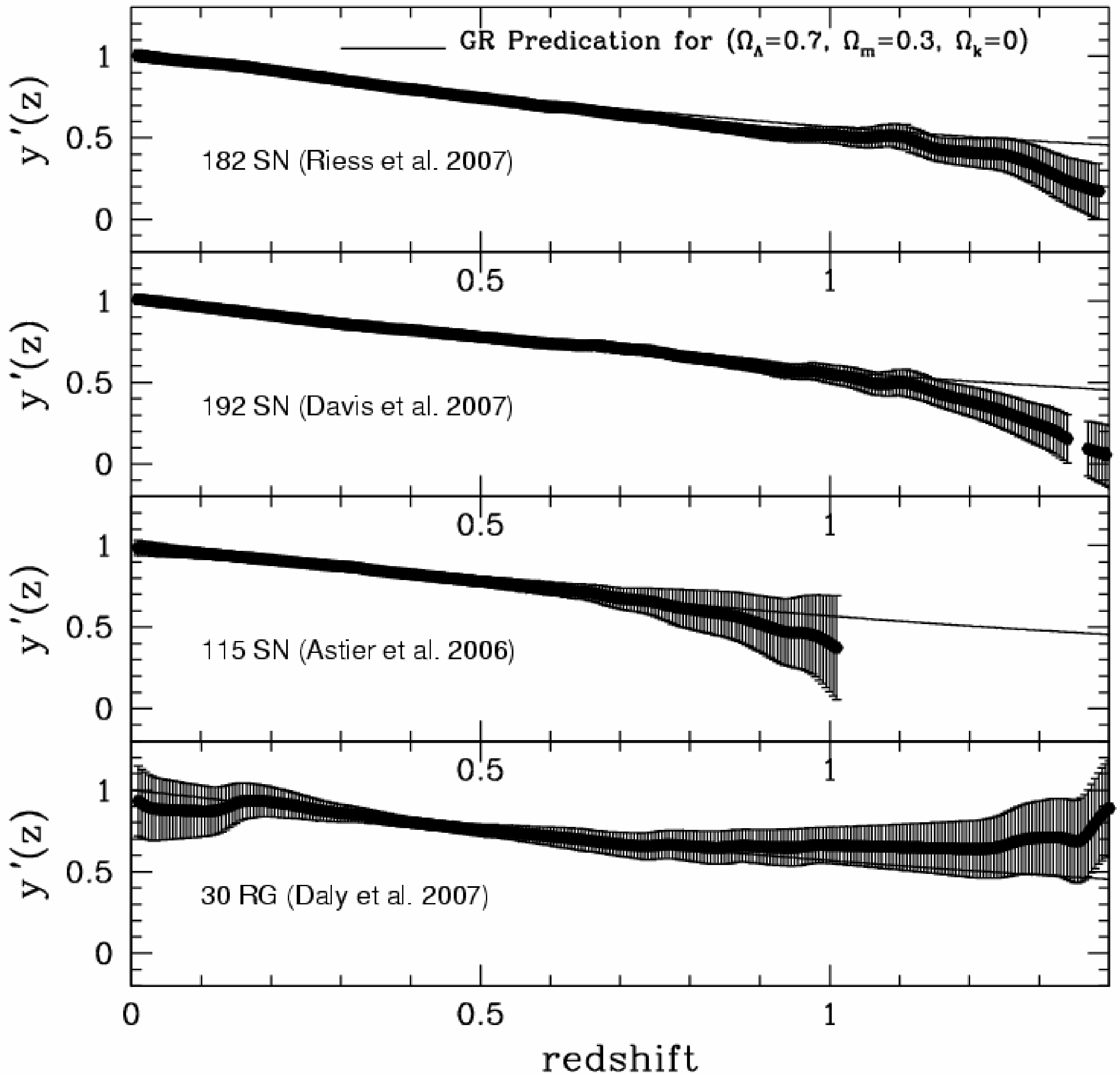
The χ^2_r of the fit is about 1 (1.03)



This special category of RG can be used for cosmology.

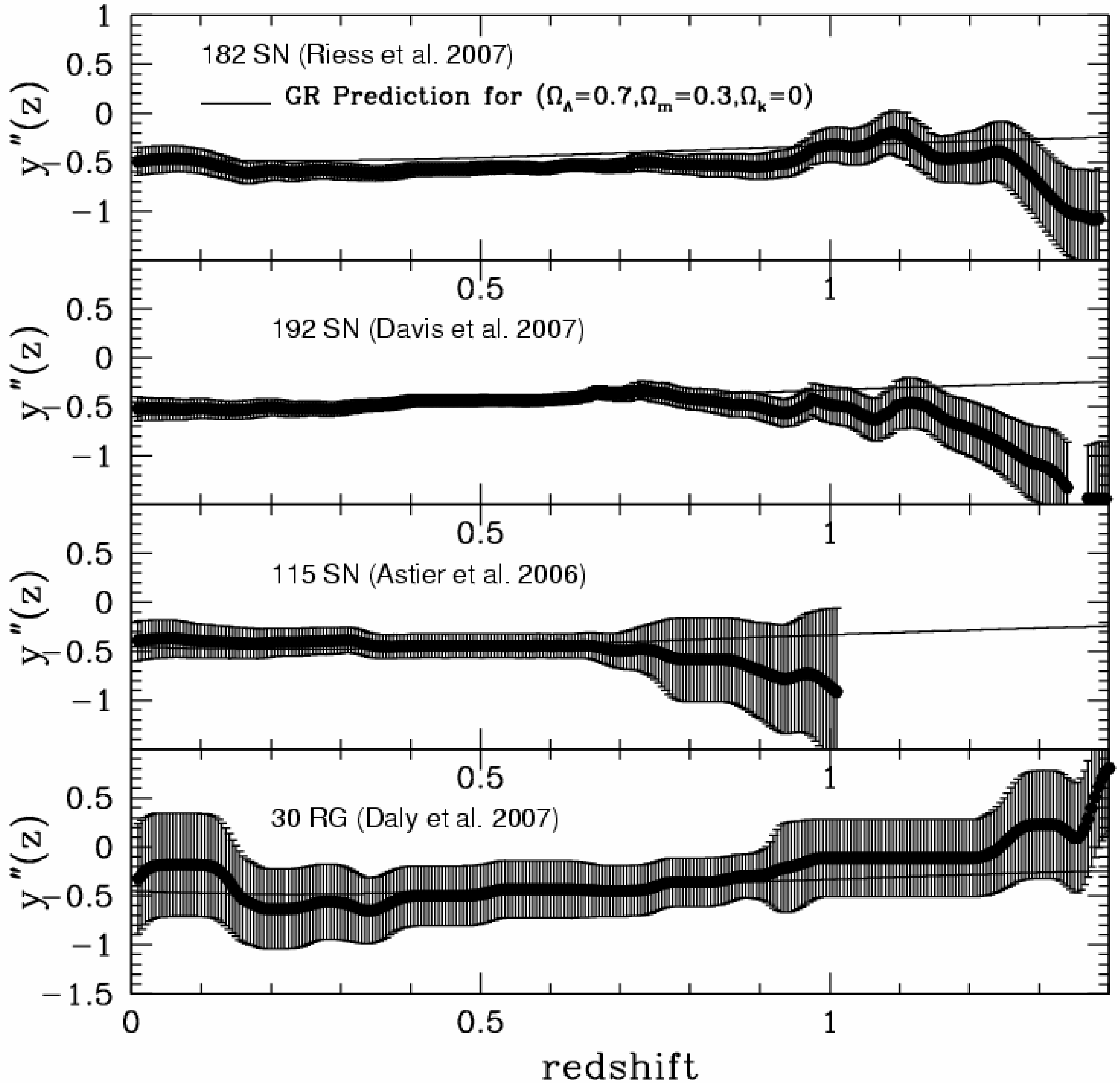
Good Agreement between SN and RG

(from Daly et al. 2007)



Y' = dy/dz is obtained directly from y(z) & provides a direct measure of $H(z)/H_0$

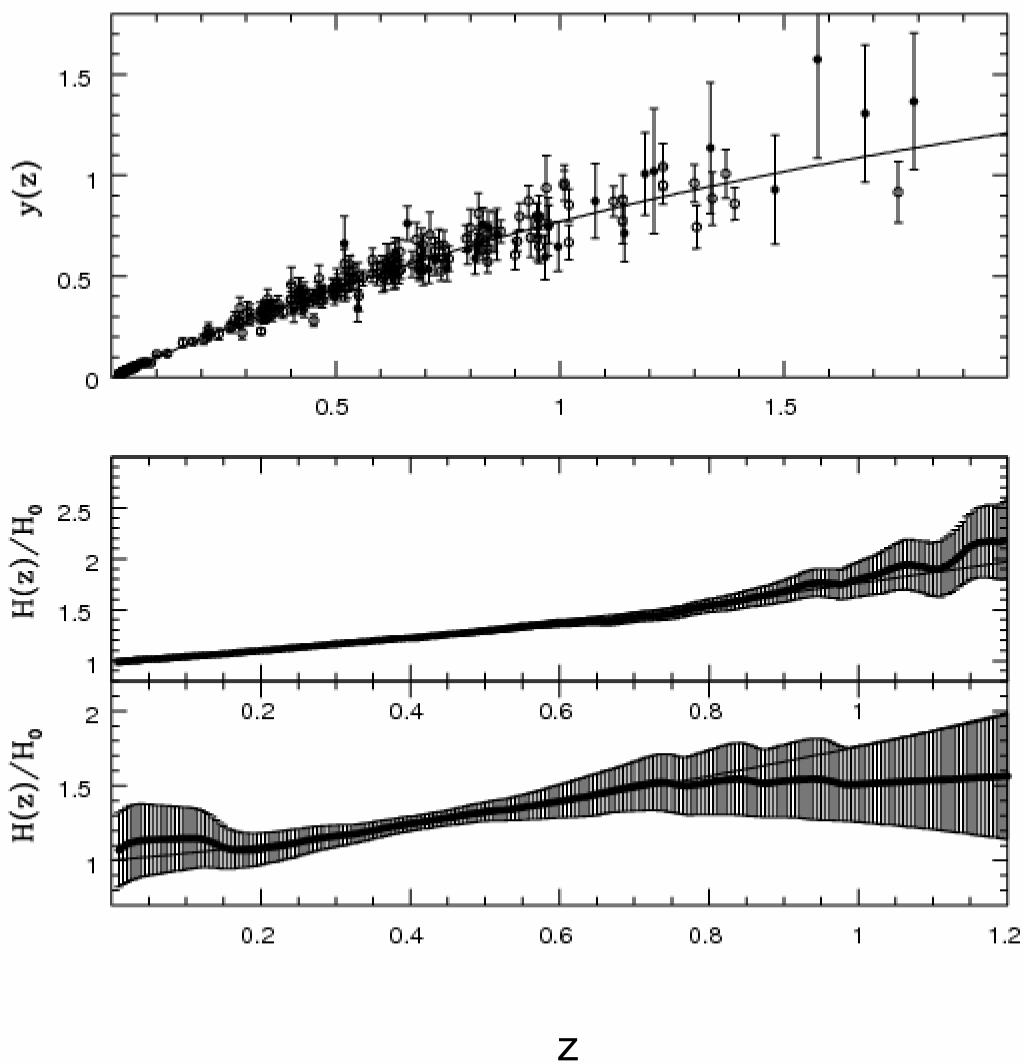
(DD03,04)



$Y'' = d^2y/dz^2$ can also be obtained directly from the data and allows a model-independent measure of q(z).

(DD03, 04).

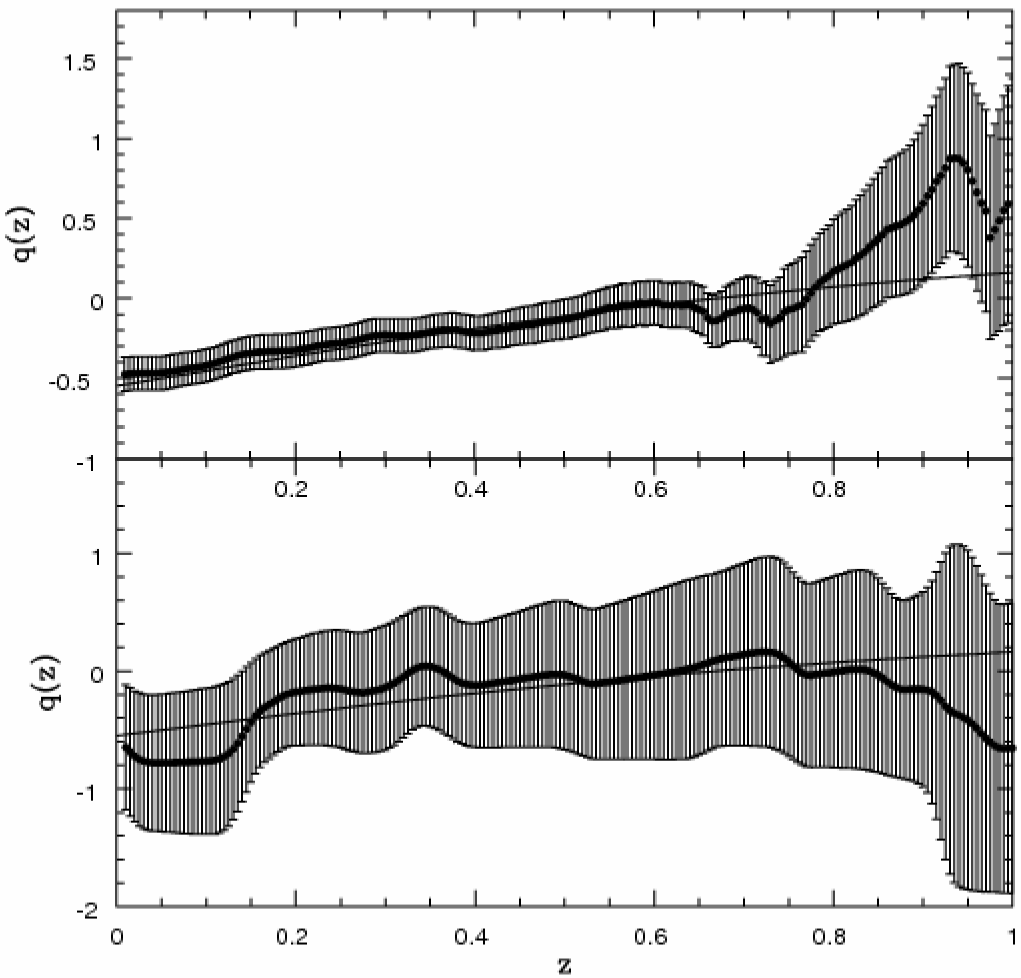
Model-Independent Determinations of y, H, & q



Dimensionless coordinate distance can be determined to each RG and SN

Using the methods of DD03, y(z) → can be used to obtain H(z) and q(z); shown here for 192SN of Davis et al. (2007) + 30 RG of Daly et al. (2007)

Model-Independent Determination of q(z); q_o depends only upon FRW metric; independent of k [Daly et al. 2007]

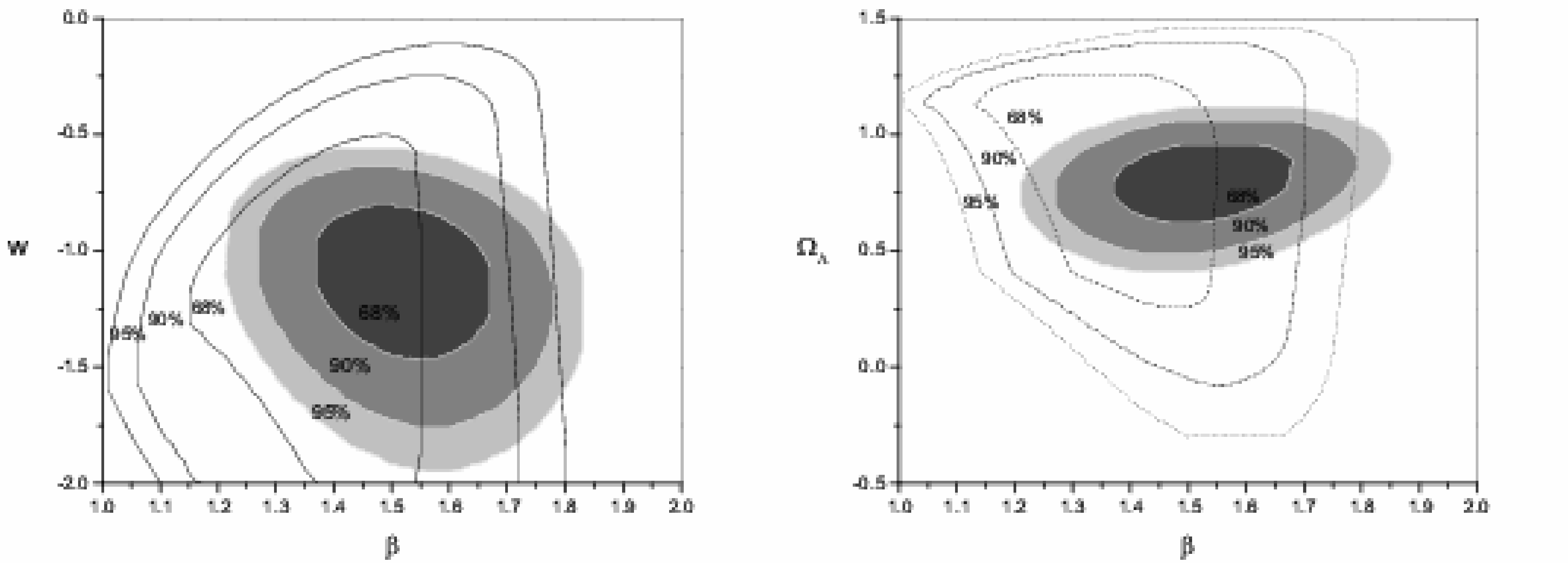


From Daly et al. (2007); for 192 SN + 30 RG find $q_o = -0.48 \pm 0.11$ & $z_T = 0.8 \pm 0.2$;

for 30 RG alone $q_o = -0.65 \pm 0.5$;

Solid line is LCDM with $\Omega_m = 0.3$

The RG model parameter β in a quintessence model for RG alone and combined 30 RG + 192 SN sample; best fit value is β = 1.5 ± 0.15 and no covariance β with w or Ω_Λ; very similar values obtained in other models.



What does our best fit value of $\beta = 1.5 \pm 0.15$ suggest about the production of relativistic jets from the AGN?

In a standard magnetic braking model in which jets are produced by extracting the spin energy of a rotating massive black hole with spin angular momentum per unit mass a, gravitational radius m, black hole mass M, and magnetic field strength B, we have (Blandford 1990),

$L_j \sim (a/m)^2 B^2 M^2$

$E_* \sim (a/m)^2 M$

In our parameterization, $E_* = L_j t_* \sim L_j^{1-\beta/3}$, which implies that

$B \sim M^{(2\beta-3)/2(3-\beta)} (a/m)^{\beta/(3-\beta)} \sim (a/m)$ for $\beta = 1.5$

Our empirical determination of β implies that $\beta = 1.5 \pm 0.15$

This is a very special value of β indicates that B depends only upon (a/m) and does not depend explicitly on the black hole mass M.

It suggests that the relativistic outflow is triggered when the magnetic field strength reaches this limiting or maximum value, and is ultimately the cause of the decrease in <D> for this type of radio source.

The outflows are not Eddington limited, since $\beta = 0$ is clearly ruled out.

When the relativistic outflow is triggered, the jet carries a roughly constant beam power L_j for a total time t_*, releasing a total energy E_*

A roughly constant beam power L_j over the course of the source lifetime is suggested by the data.

The relationship between the total time the AGN is on and the beam power is

$t_* \sim L_j^{-1/2}$

The relationship between the beam power and the total energy is

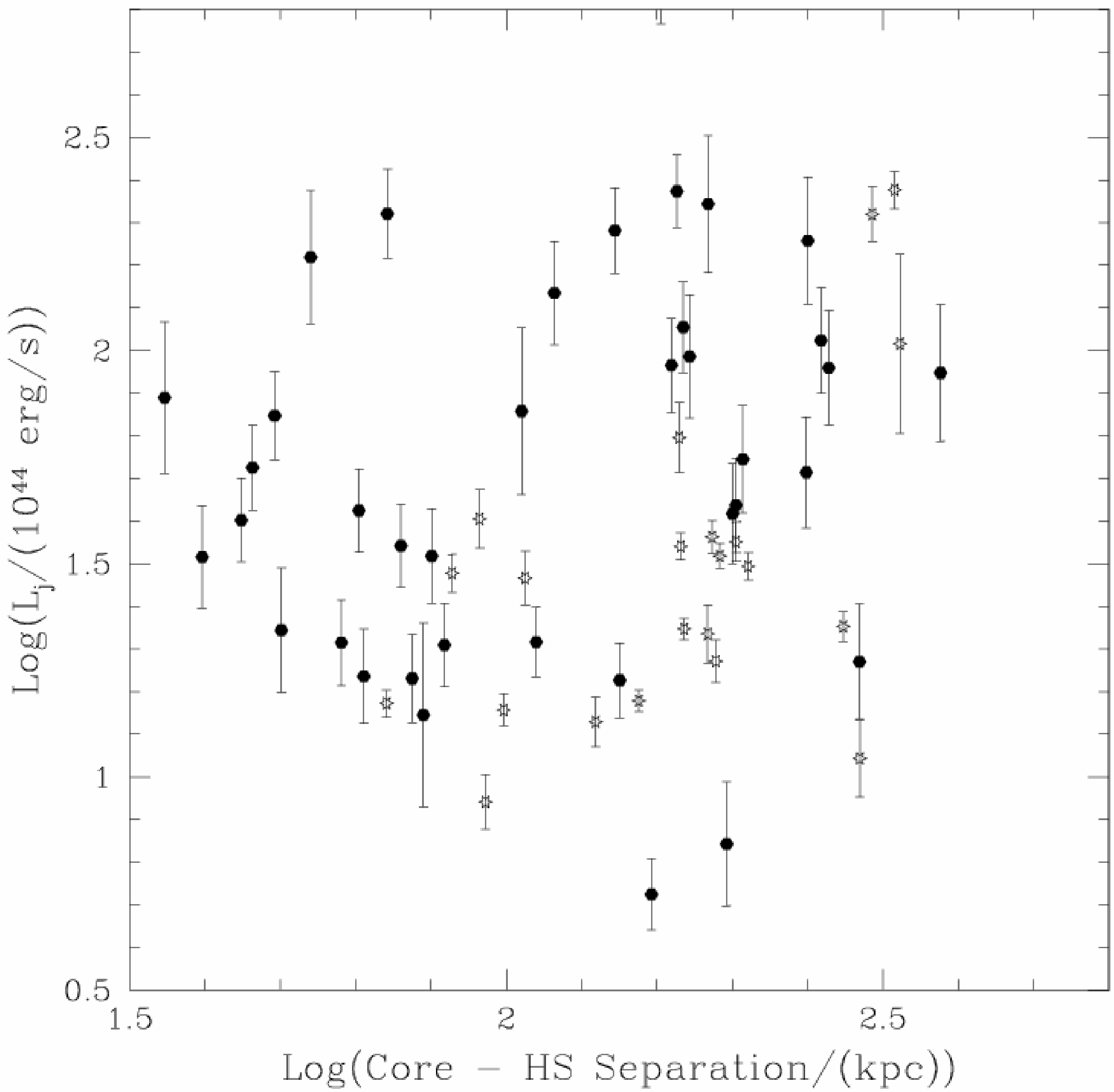
$L_j \sim E_*^2$

And, the relationship between the total energy and total lifetime is

$t_* \sim E_*^{-1}$

All of these relationships follow from the facts that

$L_j \sim E^2$ when $B \sim (a/m)$, and $E_* \sim L_j\, t_*$ [Daly et.al. 2007]



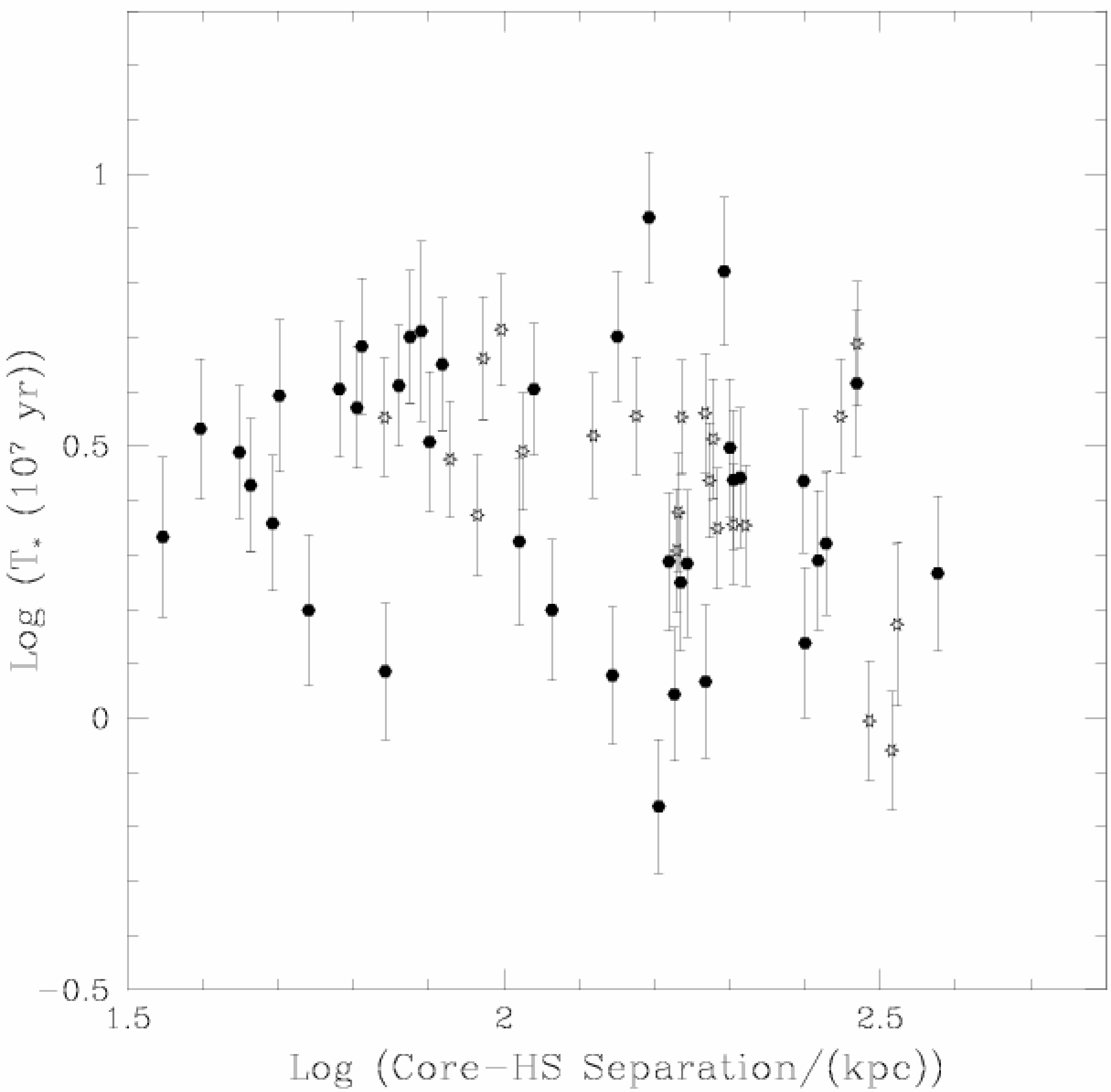
L_j is obtained by applying the strong shock equation:

$L_j = a^2 P v$

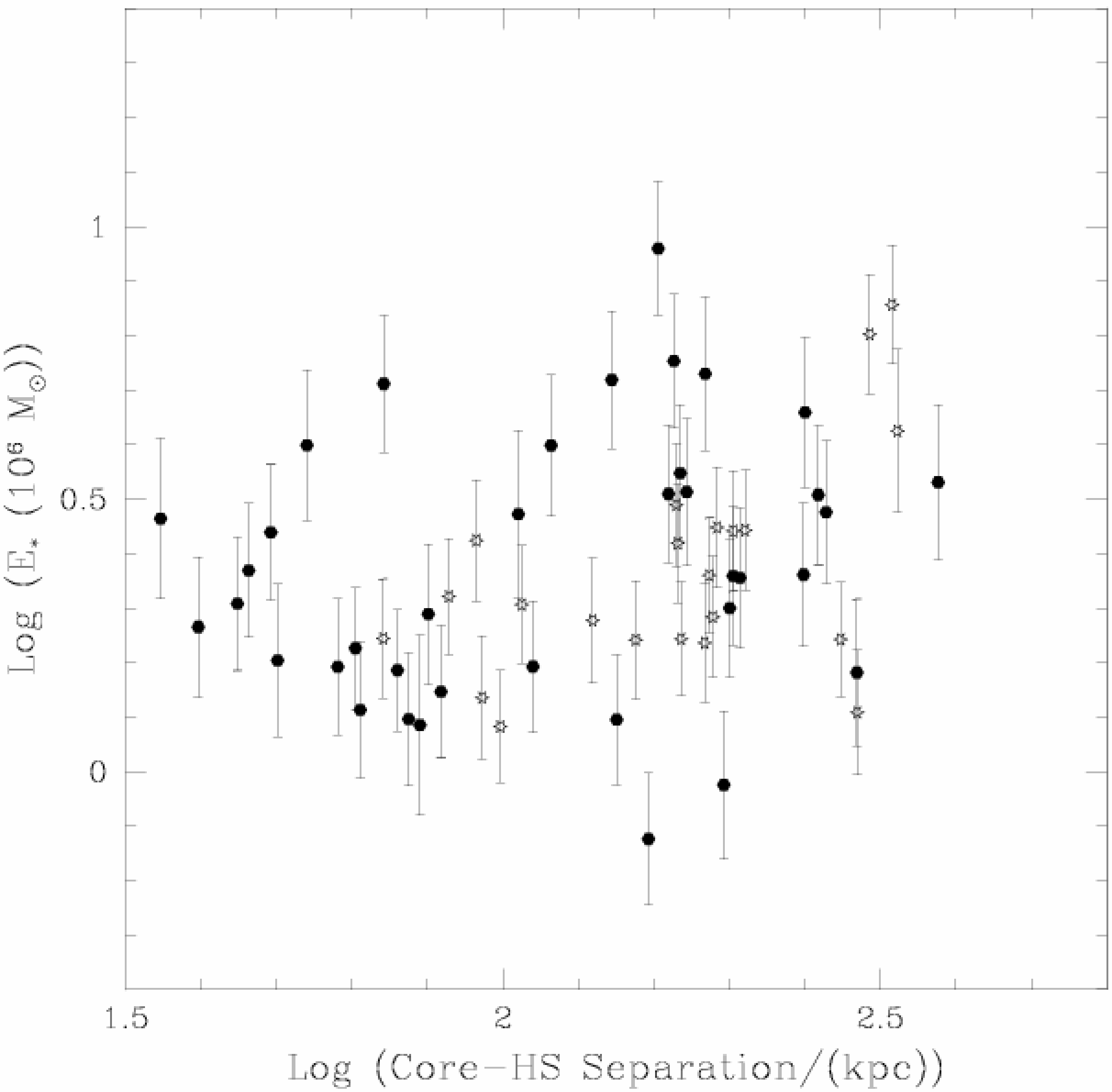
Find no correlation between L_j & D

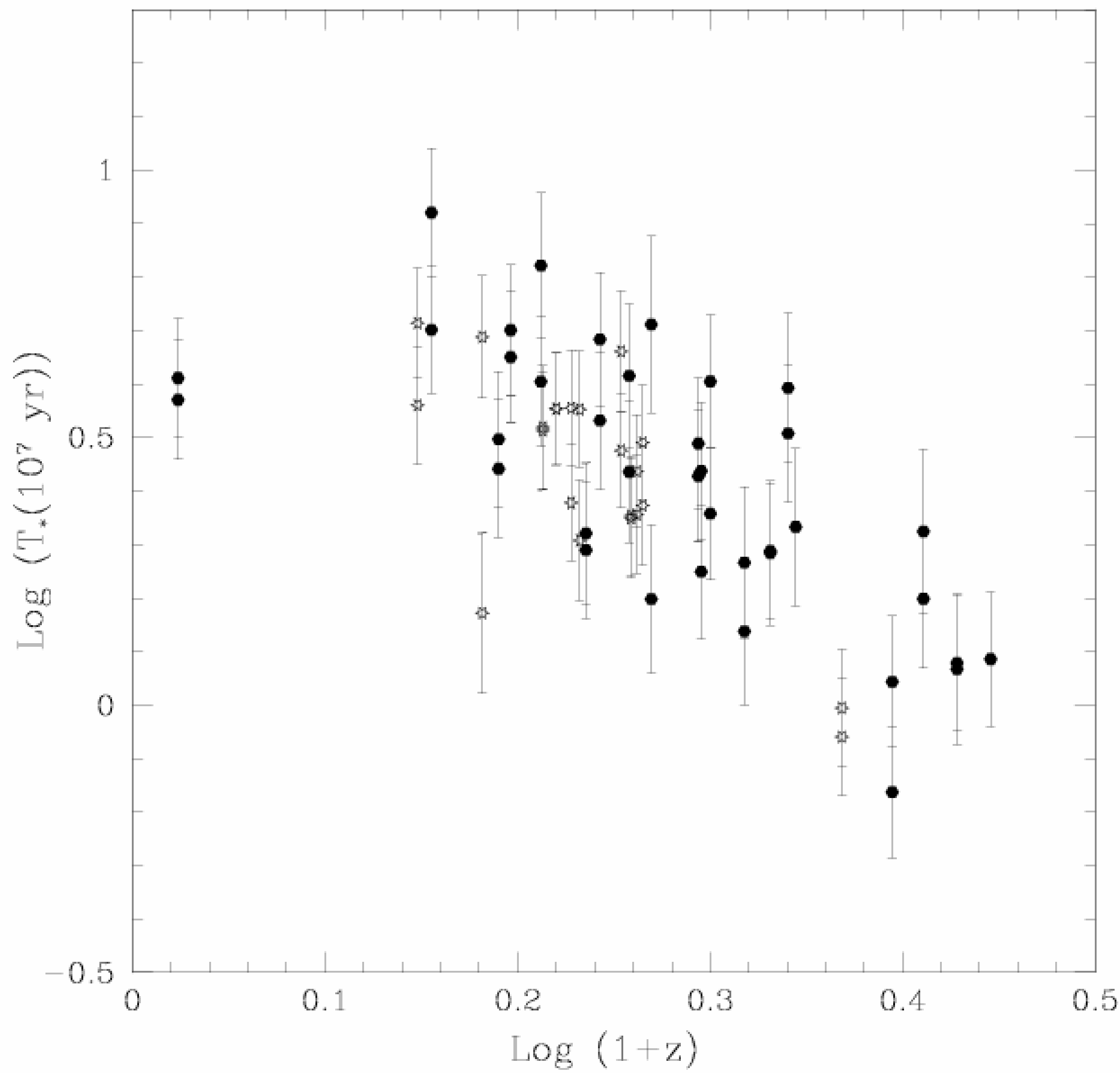
L_j obtained here is independent of offsets from minimum energy conditions (O'Dea et al.07)

Total source lifetime determined from $t_* \sim L^{-1/2}$

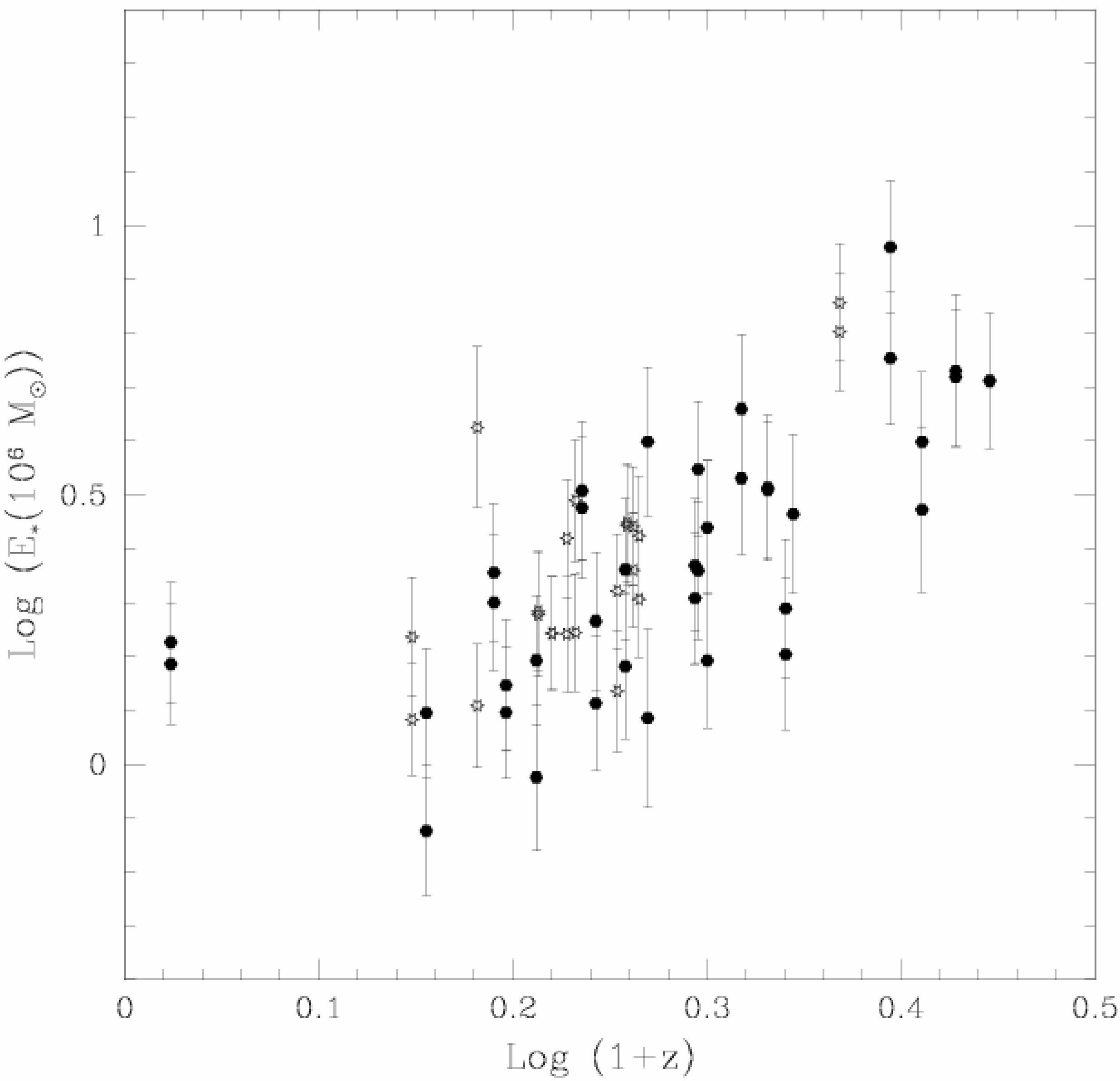


Total Energy $E_* = L_j t_* \sim L_j^{1/2}$

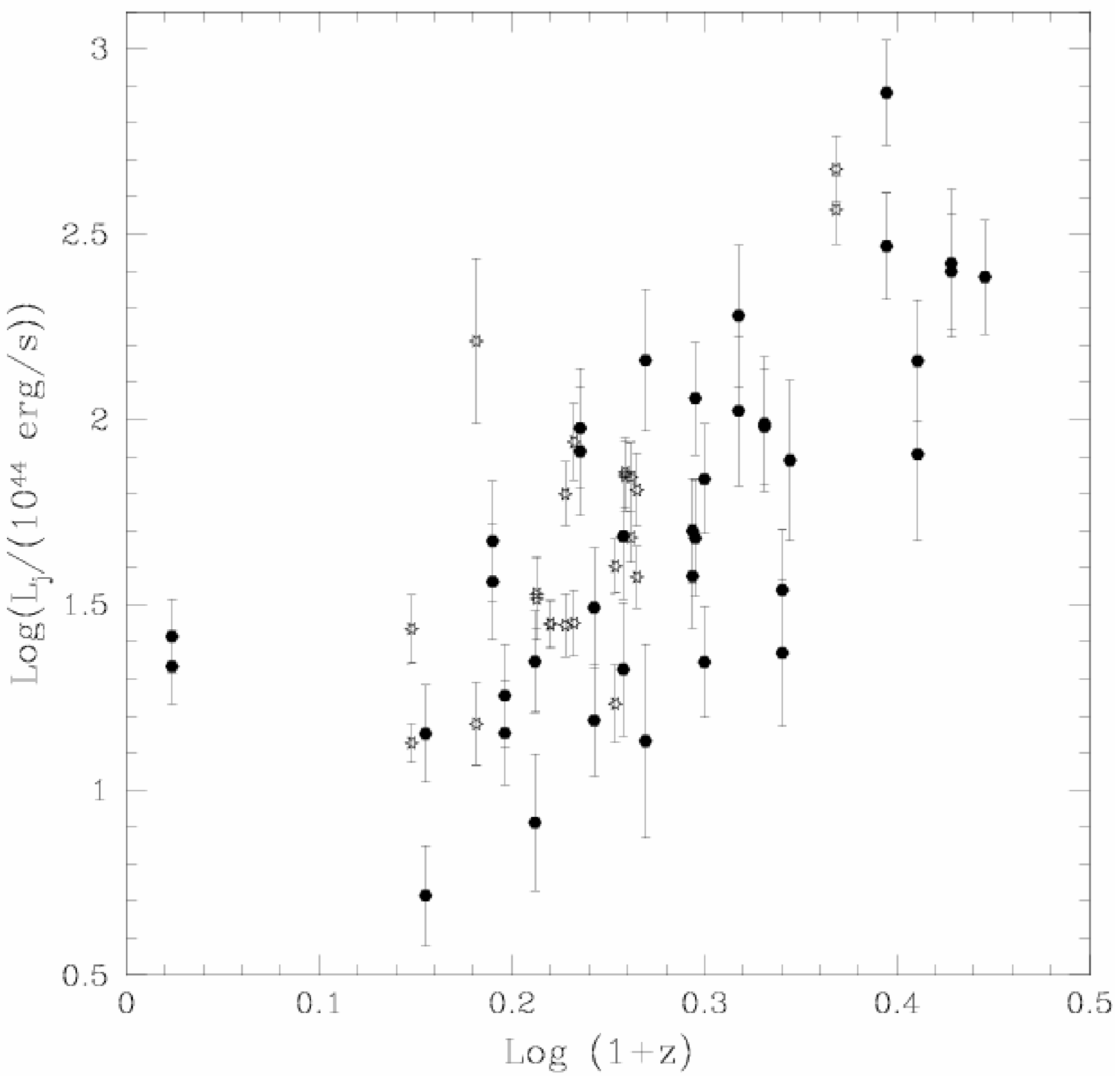




Log (T*(10^7 yr))
1
0.5
0
−0.5
0
0.1
0.2
0.3
0.4
0.5
Log (1+z)



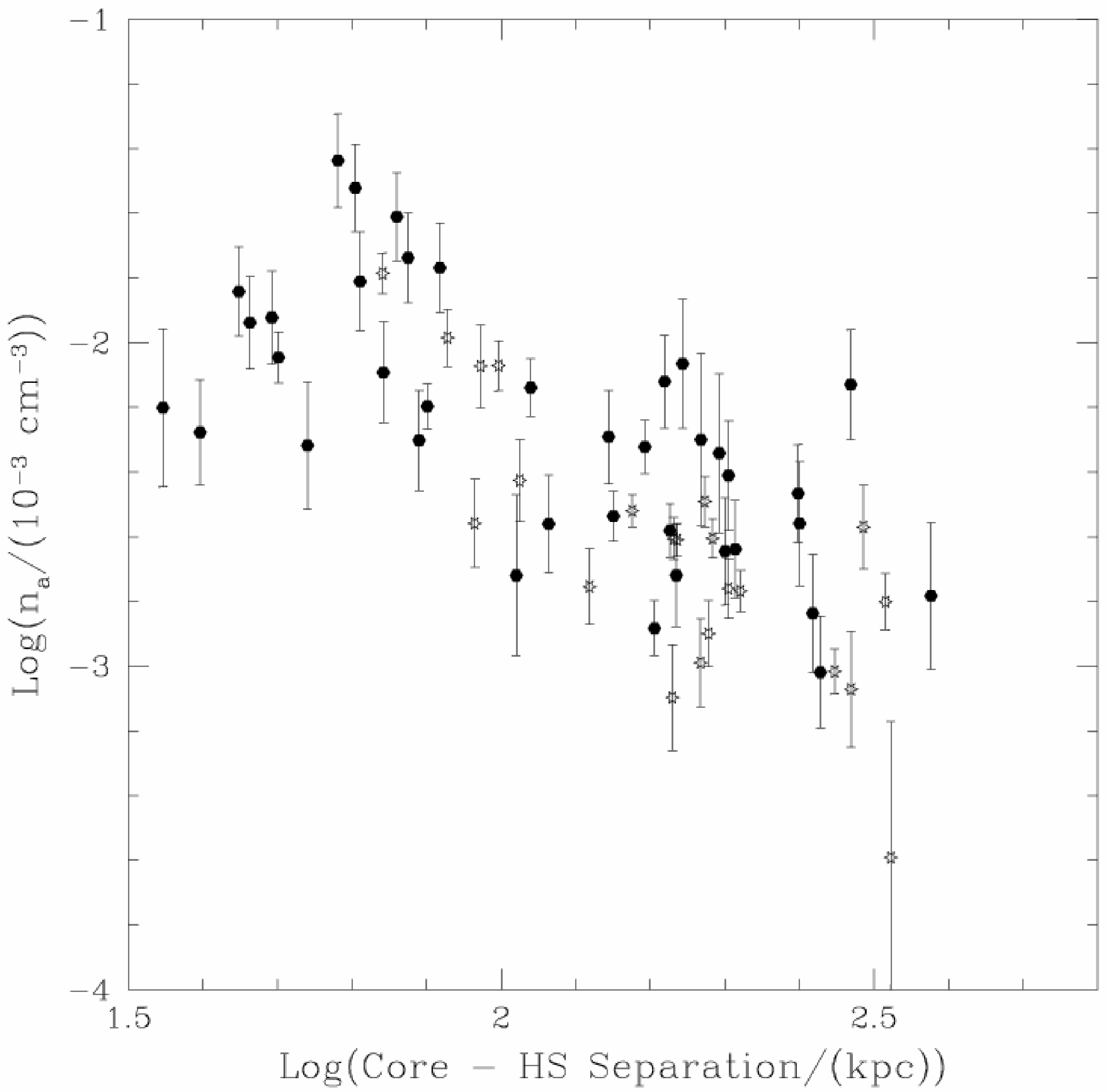
Log (E*(10^6 M⊙))
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
Log (1+z)



L_j ↑ by 2 orders of magnitude!

At a given z, L_j has a range of an order of magnitude.

Our determinations of L_j are independent of offsets of the B field from minimum energy conditions [O'Dea eta. 07]



The ambient gas density is obtained using the equation of ram pressure confinement

$n_a = P/v^2$

$n_a \sim D^{-1.9 +/- 0.6}$

As expected for these values of D

(from O'Dea et al. 2007)

Summary

With the very simple relations, $D_* = v\, t_*$, $t_* \sim L^{-\beta/3}$, and applying the strong shock relation $L \sim v\, a^2 P$ near the forward region of the shock, we can solve for the model parameter β and cosmological parameters.

The cosmological parameters we determine are in very good agreement with those obtained by independent methods; note that our high z data points have been on the plots since 1998.

The model parameter β can be analyzed in a standard magnetic braking model, and the value we obtain is a very special value, for which $B \sim (a/m)$. This then implies that $L_j \sim E_*^2$ for these sources.

The idea is that the outflow is triggered when B reaches this limiting or maximum value, producing jets with roughly constant L_j over their lifetime t_*, and $t_* \sim L_j^{-1/2}$, $t_* \sim E_*^{-1}$, and $E_* \sim L_j^{1/2}$.

More coming soon….we have VLA time to study another 13 sources