The Accelerating Universe and the Properties of the Dark Energy

☆ ☆ ☆ ☆ ☆

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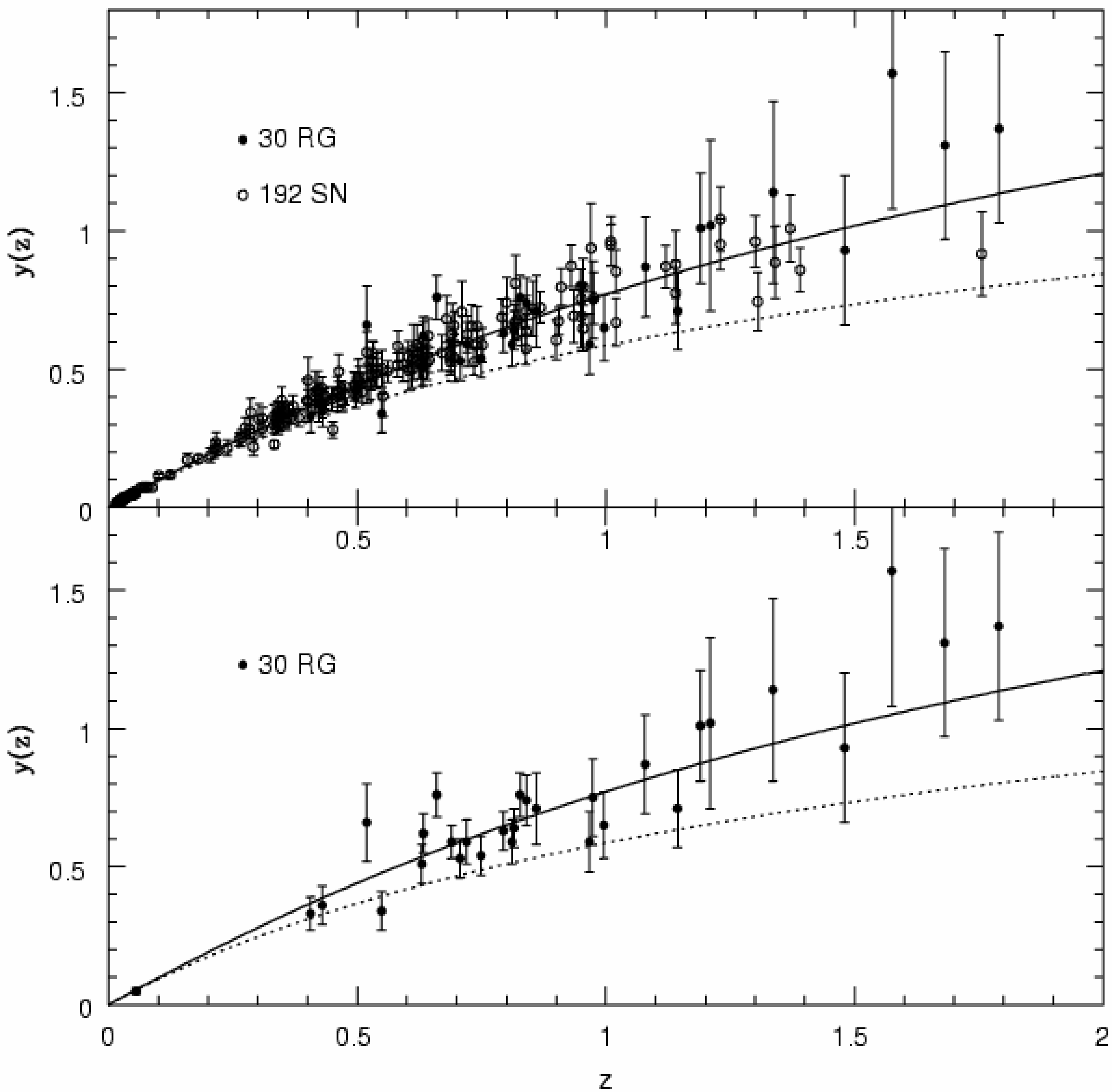
The acceleration history of the universe can be studied through measurements of coordinate distances (luminosity distances, or angular size distances) such as those that can be obtained using Type Ia Supernovae & FRIIb Radio Galaxies

RG and SN methods are completely independent & complementary methods.

Coordinate Distances to RG & SN



Daly et al. (2008) studied 192 SN of Davis et al. (2007), 182 SN of Riess et al. (2006), 115 SN of Astier et al. (2006), and 30 RG of Daly et al. (2007). The solid curve is the LCDM prediction, and the dotted curve is the flat matter-dominated prediction. High z RG have been on plot since 1998.

The coordinate distance, $(a_o r)$; luminosity distance $d_L = (a_o r)(1+z)$; angular size distance $d_A = (a_o r)\ (1+z)^{-1}$ all carry the same cosmological information.

It is convenient to work with $y(z)=H_0\,(a_o r)$, the dimensionless coordinate distance

SN: $5 \log [y(z)(1+z)] - m_{Beff}\,[\alpha] = -\mathcal{M}'_B = \text{const.}$

RG: $R^* = k_o y^{(6\beta-1)/7}\ (k_1 y^{-4/7} + k_2)^{\beta/3-1} = \kappa = \text{const.}$ (Daly 94)

where k_o, k_1, and k_2 are observed quantities.

Based on one empirically determined relationship (now understand the physical basis for relationship)

Study 30 RG from LMS89, LPR92, GDW00, & Kharb et al. '08 → Obtain y(z) to each source (Daly et al. 2007)

[just received VLA time for another 13 sources]

For k=0: $y = H_0(a_o r) = H_0 \int dt/a(t) = H_0 \int (\dot{a}/a)^{-1}\, dz$

Traditional Method: Assume FRW, theory of gravity (GR), select a specific DE model, assume 2 components, and solve for best fit model parameters.

Einstein Equation (<u>for k=0</u>):

$(\dot{a}/a)^2 = (8\pi G/3)\sum \rho_i = H_o^{\,2}[\Omega_{om}(1+z)^3 + f_E(z,w)]$

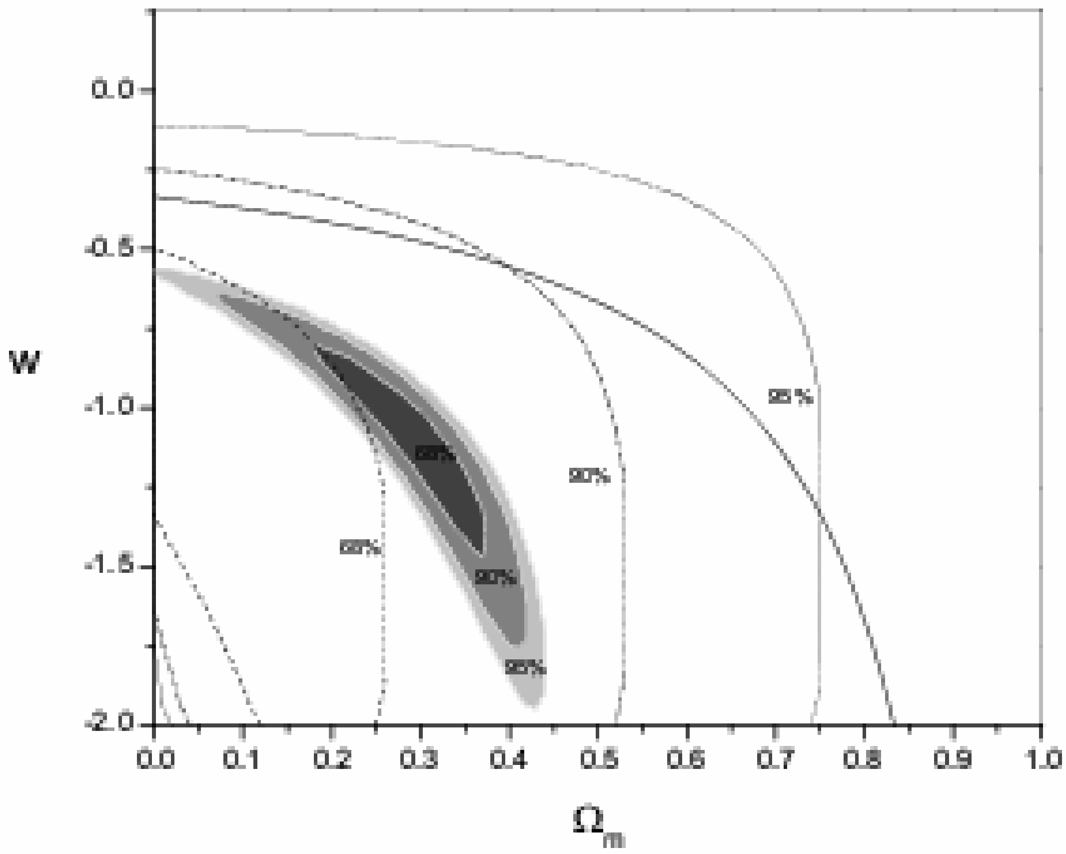
$\rho_E(z) = \rho_{oc} f_E(z,w)$; $w = P_E/\rho_E$; $f_E(0,w) = (1-\Omega_{om})$

For a quintessence model, <u>w=constant</u>, and

$f_E(z,w) = (1-\Omega_{om})(1+z)^{3(1+w)}$ or

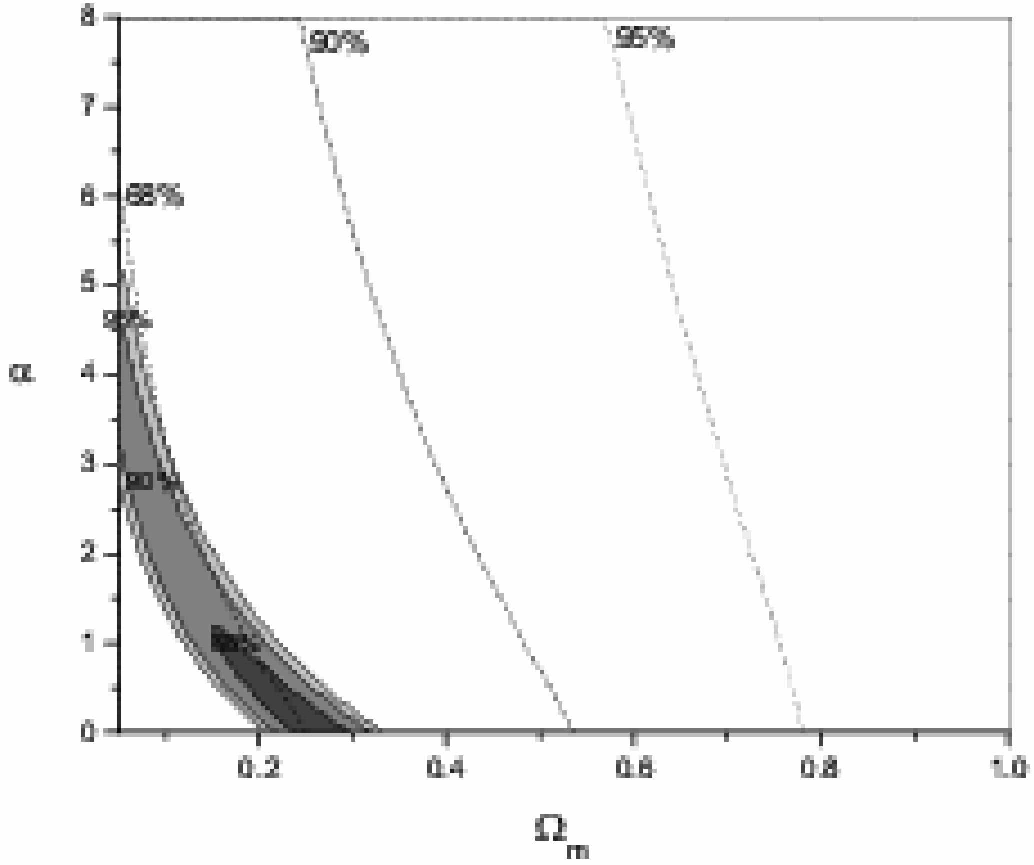
$(\dot{a}/a)^2 = H_o^{\,2}[\Omega_{om}(1+z)^3 + (1-\Omega_{om})(1+z)^{3(1+w)}]$

Constraints obtained in a Quintessence Model



From Daly et al. (2007) for a combined sample of 192 SN + 30 RG

Constraints obtained in a Rolling Scalar Field Model, with $V \sim \varphi^{-\alpha}$



Best fit value of α is zero.

(from Daly et al. 2007)

$$\int a_o\, dr/\sqrt{(1-kr^2)} = \int dt/a(t) = \int (\acute{a}/a)^{-1}\, dz$$

Traditional Method: Assume FRW, theory of gravity (GR), select a model for the DE, consider a universe with space curvature, & obtain the best fit model parameter values.

e.g. Einstein Equations for a Λ model:

$$(\acute{a}/a)^2=(8\pi G/3)\sum\rho_i - k/a^2$$

$$(\acute{a}/a)^2=H_o^2[\Omega_{om}(1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2]$$

where $\Omega_{om}+\Omega_\Lambda+\Omega_k=1$ and $\Omega_k=-k/(H_o a_o)^2$

Type Ia Supernovae (in particular models)

→ An Accelerating Universe

Radio Galaxies (in particular models)

→ An Accelerating Universe

The models assume a theory of gravity (GR), specify the properties and redshift evolution of the Dark Energy, assume something about space curvature, and consider a universe with two components, non-relativistic matter and dark energy.

Is there a model-independent way to determine if the universe is accelerating? Yes! DD03 proposed one.

Our Approach: Use $y(z)$ obtained directly from the data; differentiate $y(z)$ to obtain
$E(z) = (\dot{a}/a)/H_0$ and $q(z) = -\ddot{a}a/(\dot{a})^2$

$q(z)$ & $H(z)$ [or $E(z)$] only depend upon the FRW metric!

$$d\tau^2 = dt^2 - a^2(t)[dr^2/(1-kr^2) + r^2 d\theta^2 + r^2 \sin^2\theta \, d\varphi^2]$$

for a light ray from source, $dt = -a(t)(-dr)$ when $k=0$ so $dz/dt = -a_o^{-1}(1+z)(dr/dz)^{-1}$. Differentiating $(1+z) = a_o/a(t)$, $\dot{a} = -a_o(1+z)^{-2}(dz/dt) = (1+z)^{-1}(dr/dz)^{-1} \rightarrow$

$H(z) \equiv (\dot{a}/a) = (d(a_o r)/dz)^{-1} = H_o\,(dy/dz)^{-1}$.

$$E(z) \equiv H(z)/H_o = (dy/dz)^{-1}$$

More generally, $E(z) = (y')^{-1}(1+\Omega_k y^2)^{0.5}$ [Weinberg 1972]

Differentiating $\dot{a}$, $\rightarrow$

$\ddot{a} = -(1+z)^{-2}(dz/dt)(dr/dz)^{-1}[1+(1+z)(dr/dz)^{-1}(d^2r/dz^2)]$

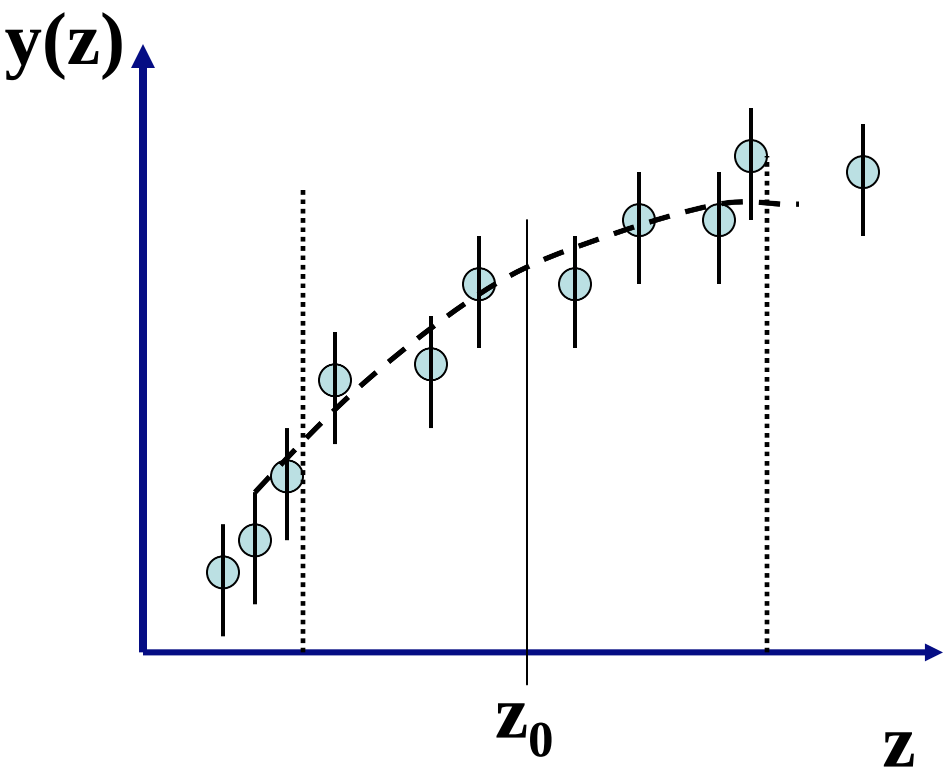
$q(z) \equiv -(\ddot{a}a)/\dot{a}^2 = -[1+(1+z)(dy/dz)^{-1} d^2y/dz^2]$ [D. 02]

More generally, [Daly 02; Daly & Djorgovski 2003] showed that:

$$q(z) = -1 - (1+z)y''/y' + \Omega_k y y'(1+z)/(1+y^2\Omega_k)$$

So, H(z) and q(z) can be obtained independent of GR & specific models for the "dark energy;" only assumes FRW metric.

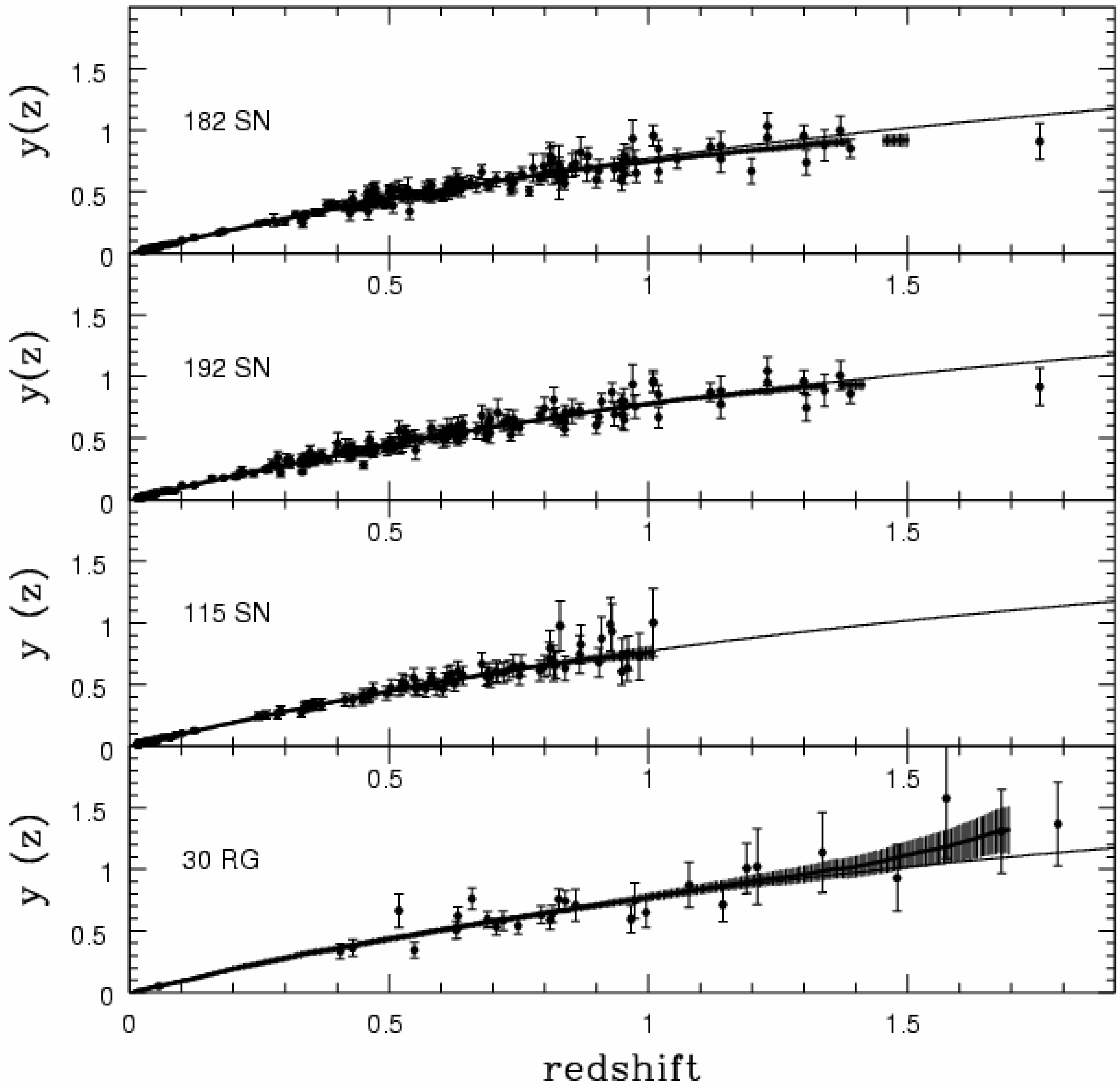
The Methodology



Fit a parabola in a sliding window of Δz around some z_0

From the local fit coefficients, get $y(z_0)$, dy/dz and d^2y/dz^2 *and their errors*

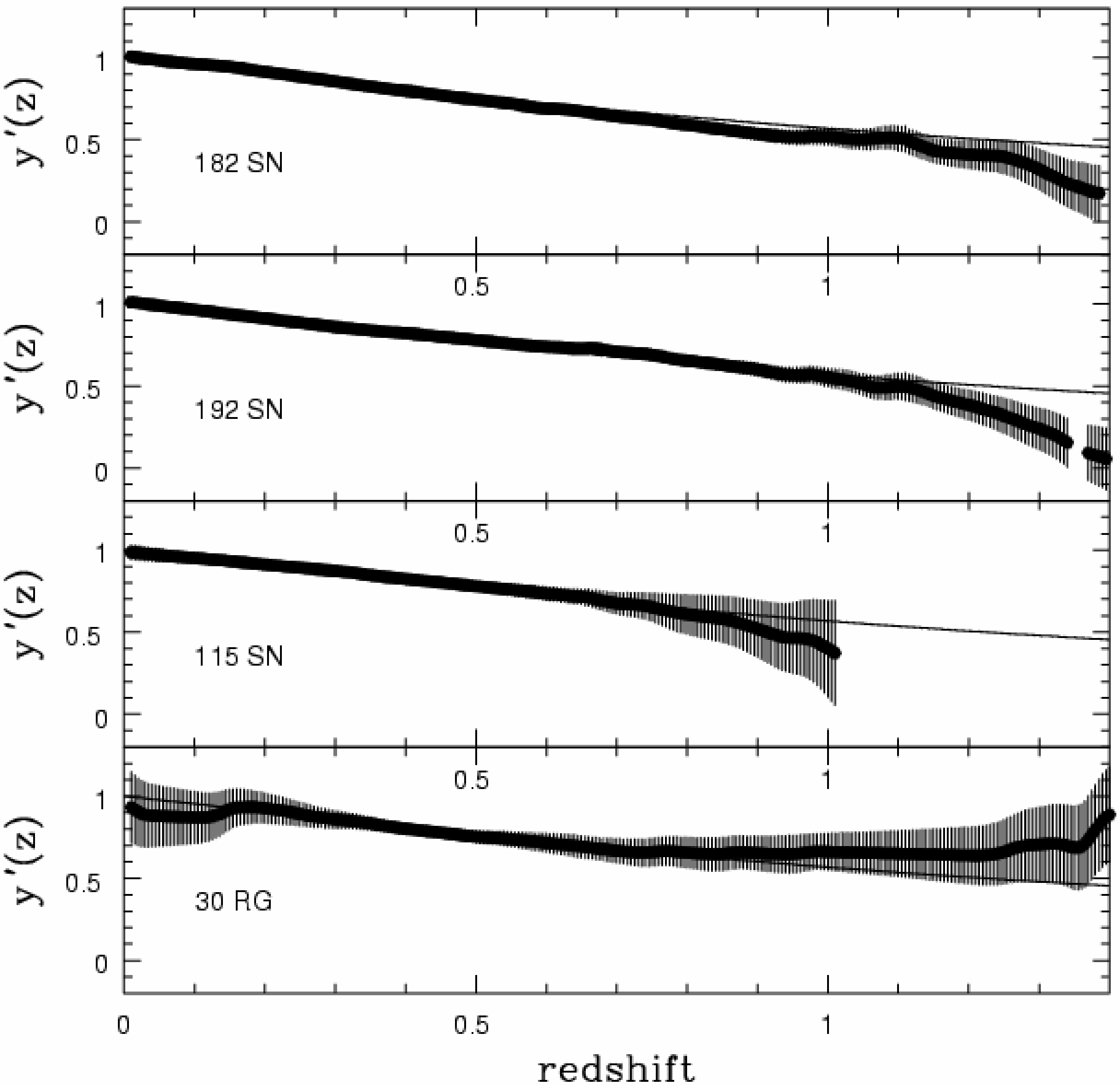
This is equivalent to a local Taylor expansion for y(z); a parabola is a minimum assumption local model for y(z). For noisy/sparse data, need a large Δz: poor redshift resolution, but can determine trends …



From Daly et al. (2008)

The solid curve is for a standard LCDM model with $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$.

High z RG have been on plot since '98

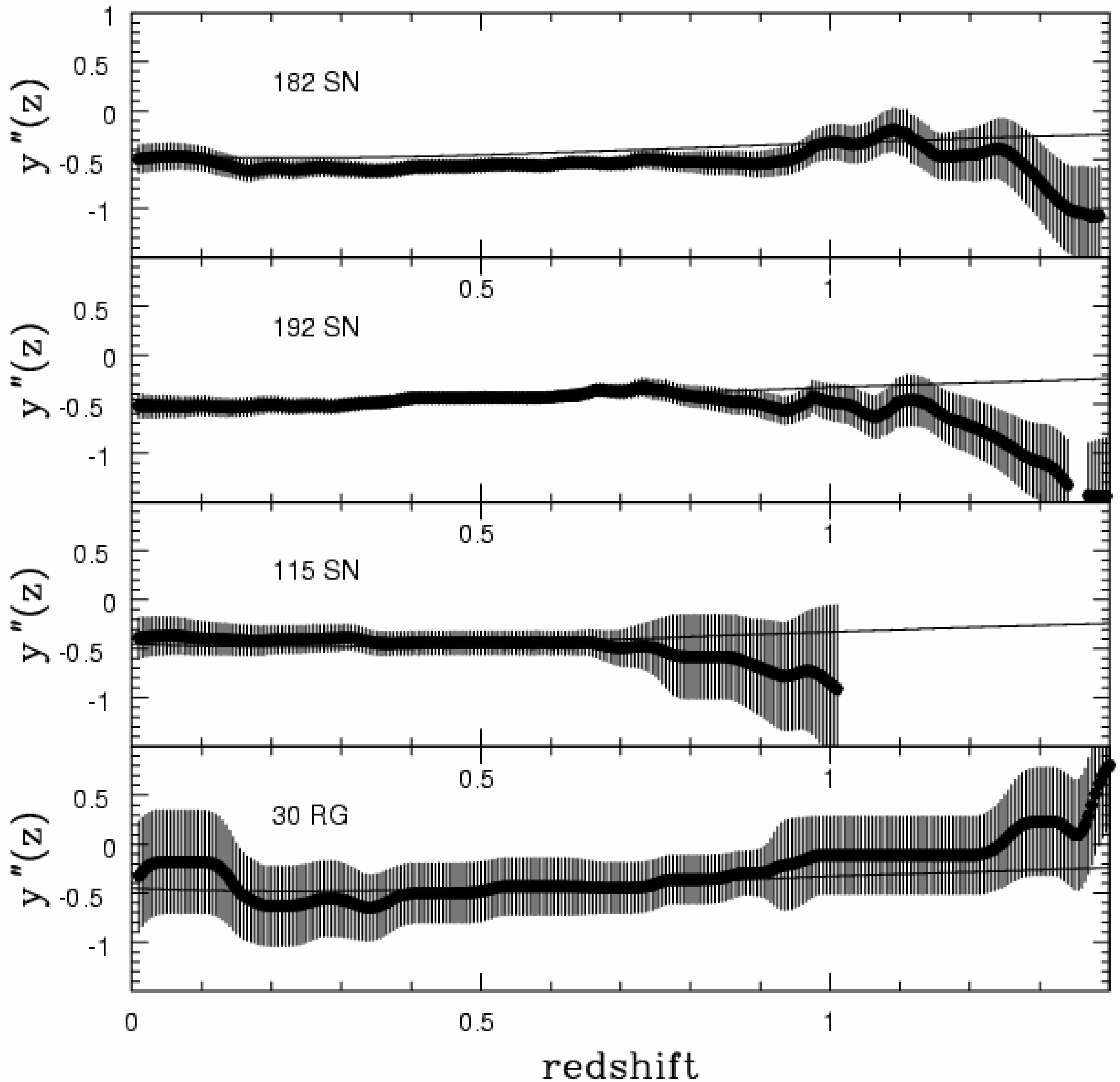


Y' = dy/dz

Model-independent: Provides a large scale test of GR.

Compare with prediction in LCDM model based on GR and Λ=0.7, Ω=0.3

Good agreement between RG & SN



$Y'' = d^2y/dz^2$

Model-independent

Provides a large scale test of GR.

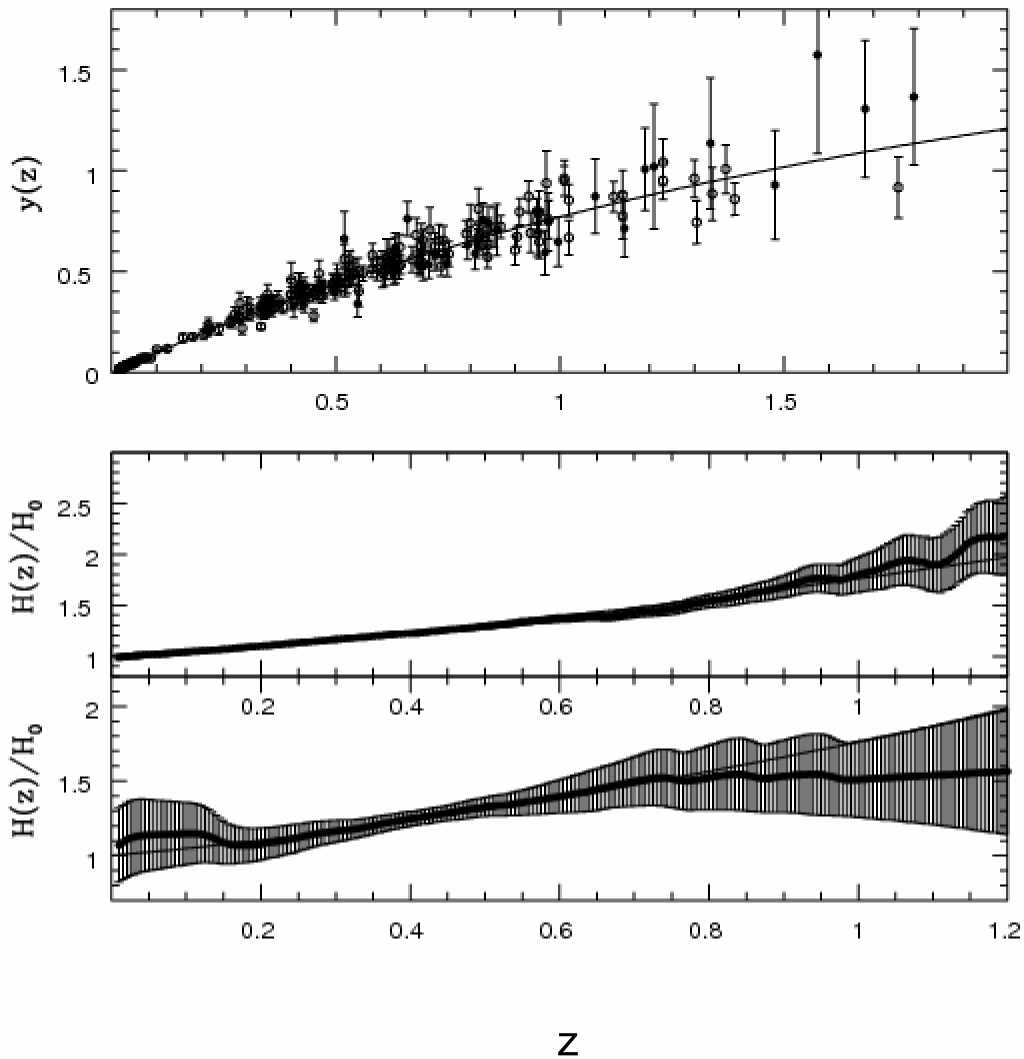
Compare with prediction in LCDM model based on GR

Good agreement between RG & SN

The values of y, y', and y'' indicated by the data are in very good agreement with those expected in a universe described by GR with $\Lambda \sim 0.7$. This provides a large scale test of GR over look back times of about ten billion years.

Good agreement between y, y', and y'' obtained with SN and RG.

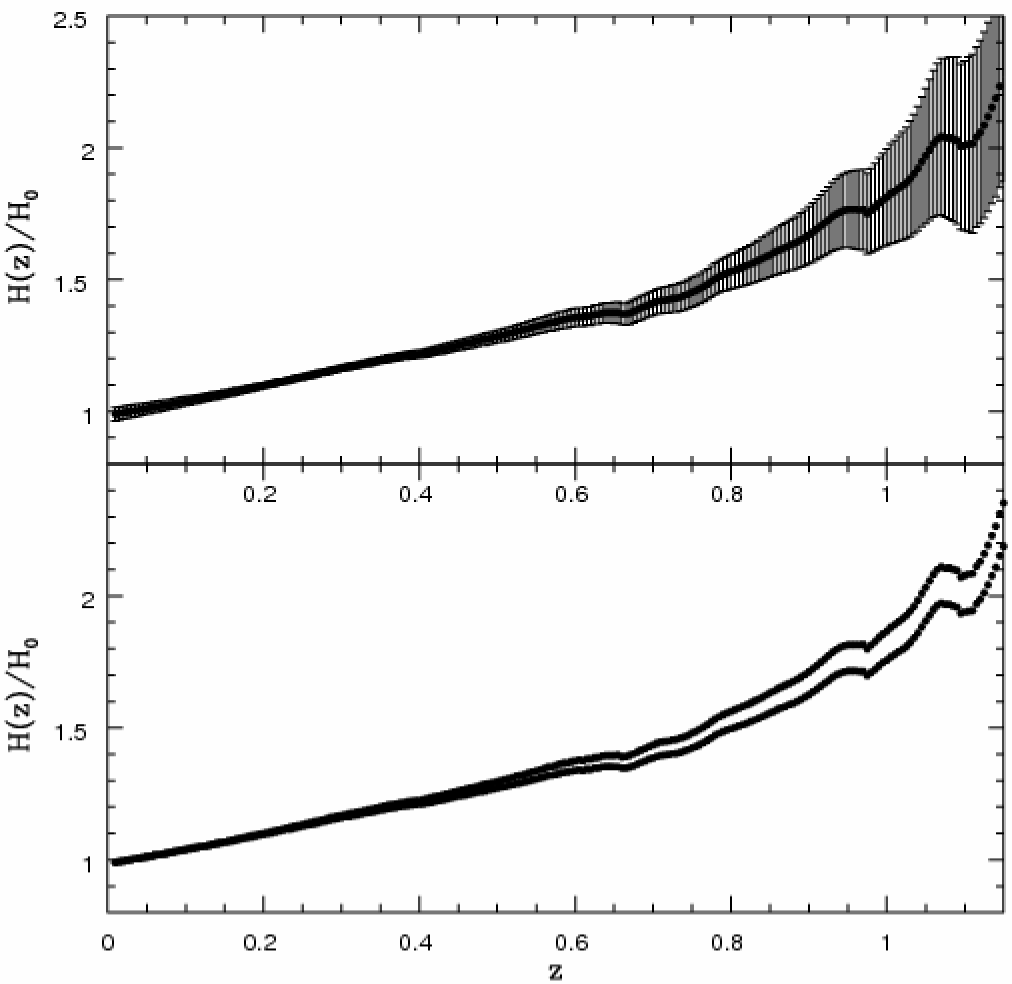
Model-Independent Determinations of $H = (y')^{-1}$ for k=0



H(z) shown here for 192SN of Davis et al. (2007) + 30 RG of Daly et al. (2007,2008)

LCDM shown as solid line

$$H(z)/H_0 = (y')^{-1} (1+\Omega_k y^2)^{1/2}$$



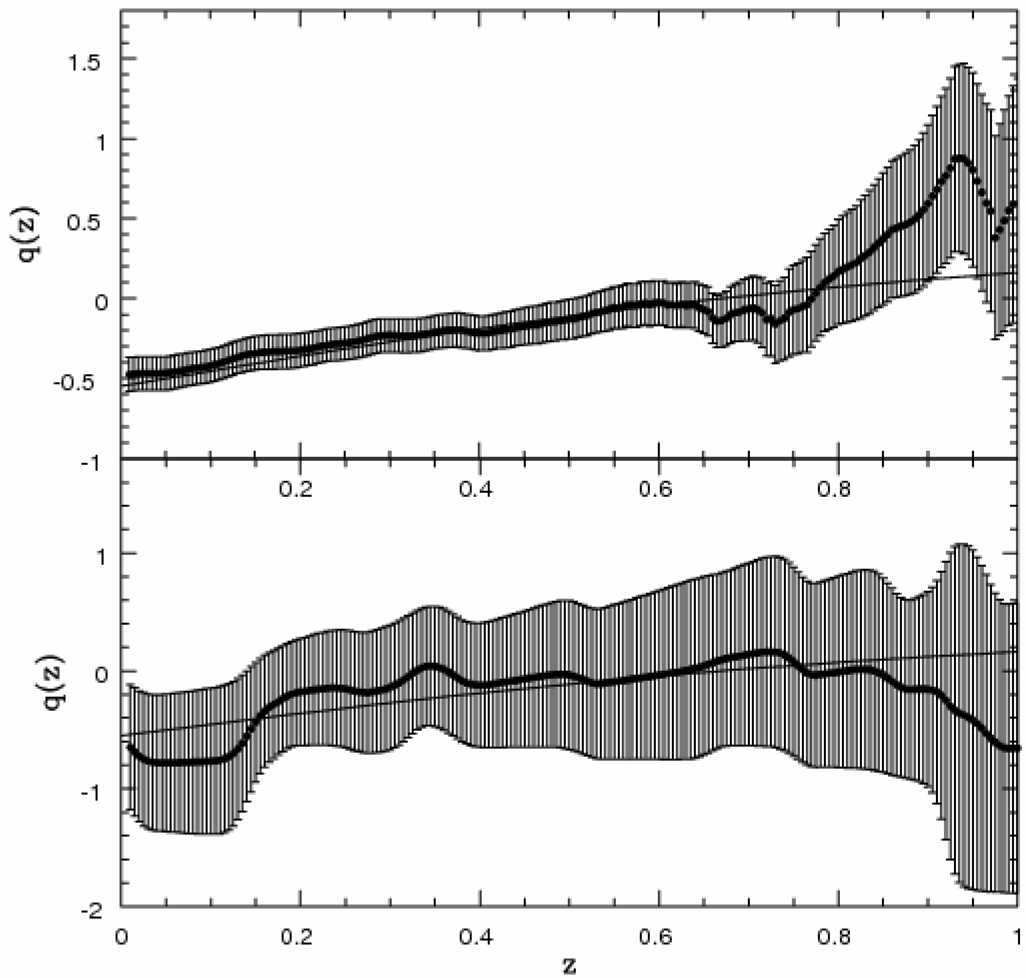
For 192 SN + 30 RG

Effect of k: small for reasonable values of k; Ω_k = 0.1(top) and -0.1(bot)

From Daly et al. (2008)

Model-Independent Determination of $q(z)$;
q_o depends only upon FRW metric, independent of k.

$q(z) = -1 - (1+z)y''/y'$ for $k = 0$



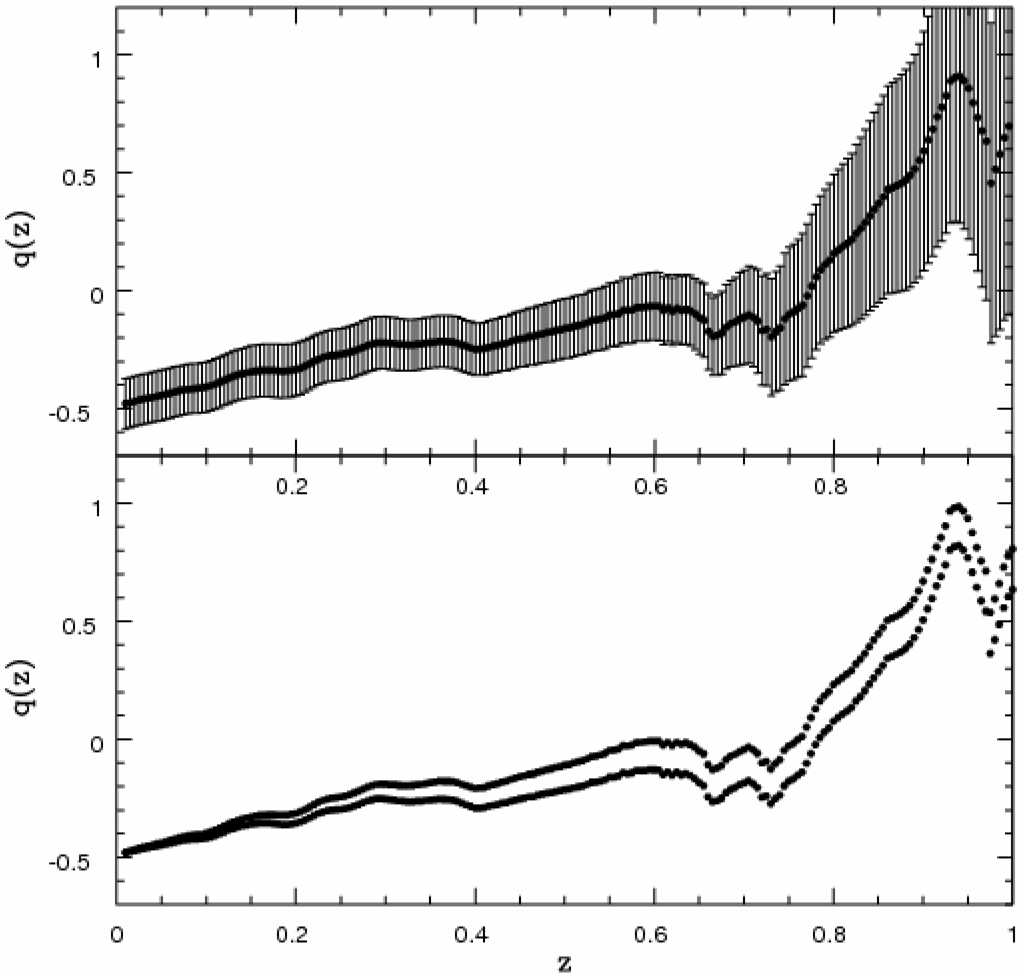
$q_o = -0.48 \pm 0.11$ &
$z_T = 0.8 \pm 0.2$ for
192 SN + 30 RG
(Daly et al. 2008)

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

Solid line is LCDM
with $\Omega_m = 0.3$

Model-independent determination of q(z):

$q(z) = -1 - (1+z)y''/y' + \Omega_k y y'(1+z)/(1+y^2\Omega_k)$



For 192 SN + 30 RG

Effect of k: none on q_0

small effect on z_T for reasonable values of k; $\Omega_k = 0.1$(top) & -0.1(bot)

D. et al. (2008)

So, we have shown that assuming only a FRW metric, q_o can be determined; q_0 does not depend on k, GR, or the contents of the universe. SN and RG show that the universe is accelerating today. SN at about 4 sigma, obtained using a sliding window function analysis.

We study the effect of k on q(z) and z_T, and find that it is small for reasonable values of k.

The data suggest that the universe was decelerating in the recent past (1 sigma), with values of q(z) and z_T consistent with predictions in a model based on GR with a cosmological constant and non-relativistic matter (a standard LCDM model).

Another model-independent quantity that can be studied is the Dark Energy Indicator:

A New Model-Independent Function (Daly et al. 2008) the Dark Energy Indicator, s,

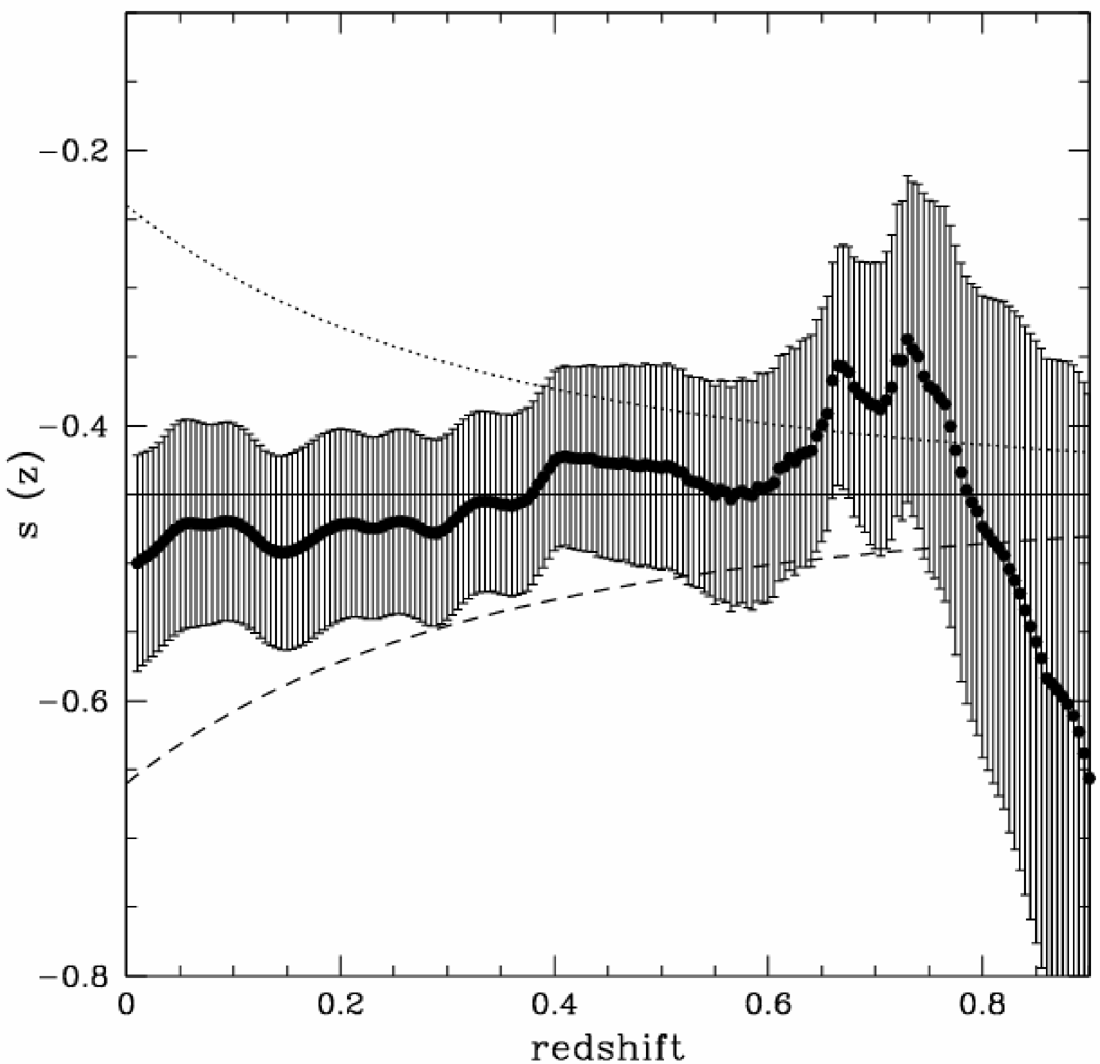
$$s = y'' (y')^{-3} (1+z)^{-2}$$

In a standard XCDM model based on GR, allowing for variable w, ρ_{DE}, & ρ_m, the predicted value of s is

$$s_p = -1.5\Omega_m [1+(w+1)(\rho_{DE}/\rho_m)]$$

If s is constant, it implies that $w = -1$ & $s = -1.5\ \Omega_m$, and s becomes a new and independent measure of Ω_m

In an XCDM model, $w = -1 -(\rho_{DE}/\rho_m)[2s/(3\Omega_m)+1]$



Dark Energy Indicator

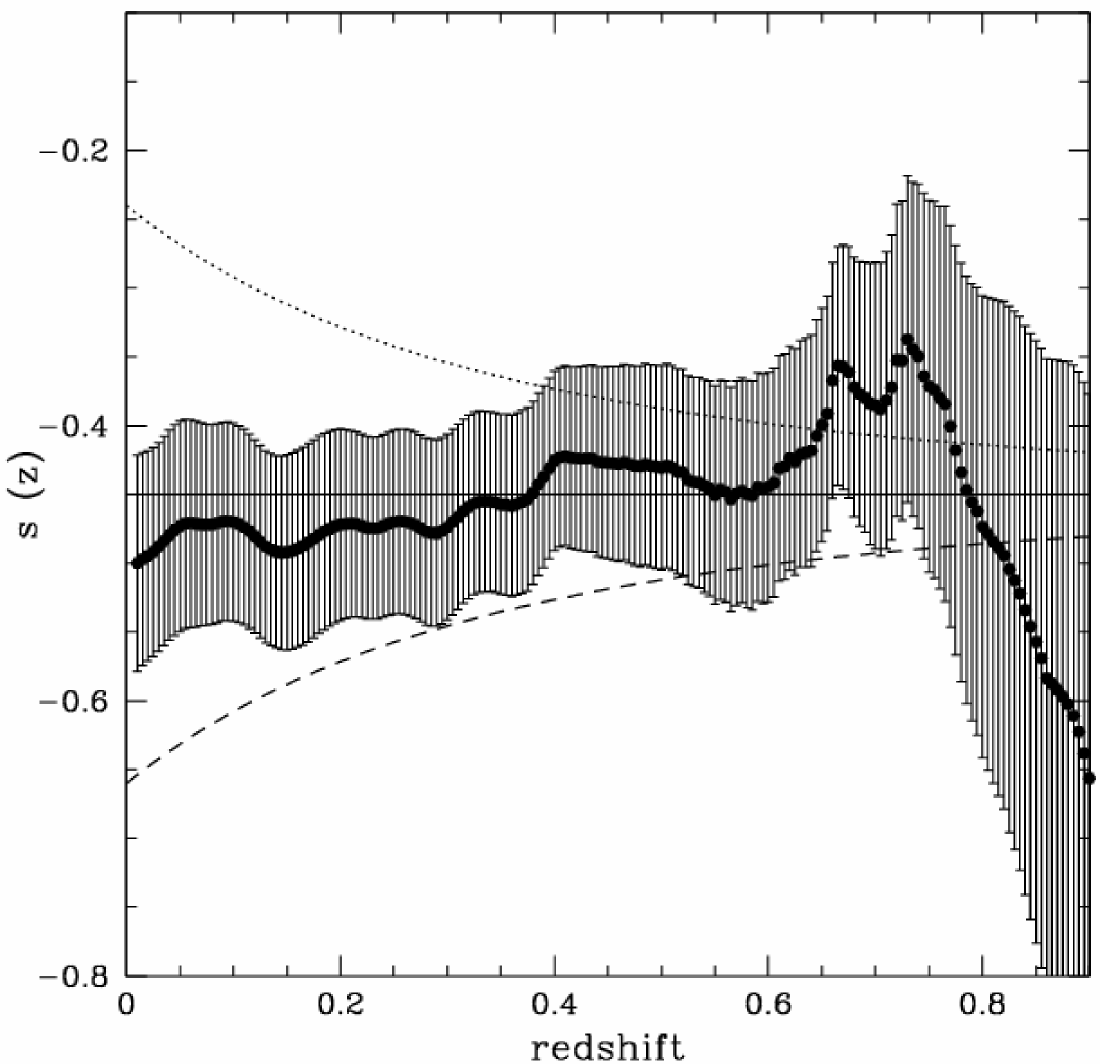
$s = y''(y')^{-3}(1+z)^{-2}$

In a standard XCDM model based on GR, the predicted value of s is

$-1.5\Omega_m[1+(w+1)(\rho_{DE}/\rho_m)]$

Shown: w = -1.2,-1,-0.8

with Ω_m=0.3 &
$(\rho_{DE}/\rho_m)[z=0]$ = .7/.3



S_0 = -0.50 ± 0.08

This implies
w_0 = -0.95 ± 0.08

for Ω_m = 0.3, and

$[\rho_m/\rho_{DE}](z=0)=0.3/0.7$

For w_0=-1, this implies

Ω_m = 0.33 ± 0.05

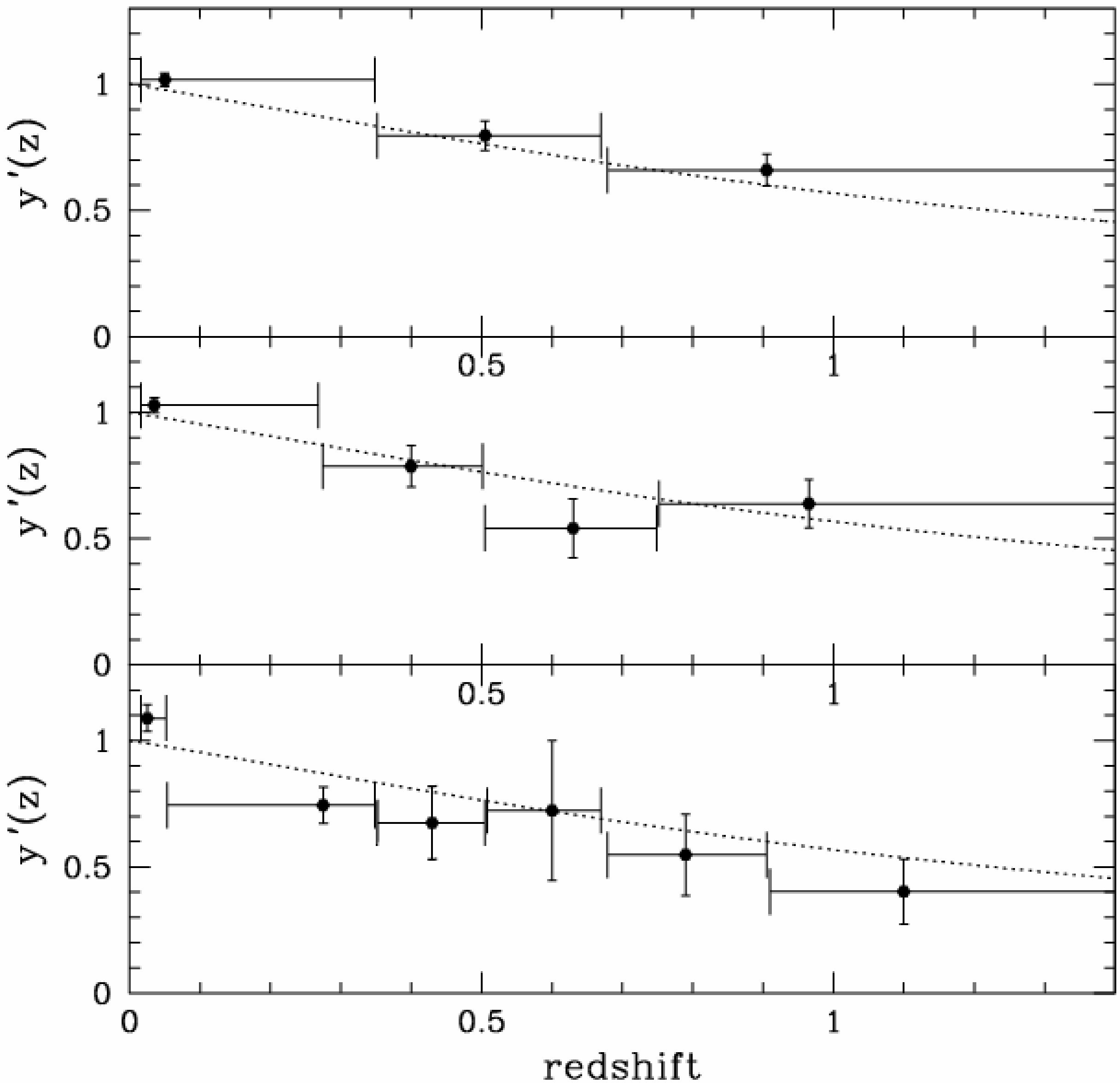
Also interesting to consider results obtained in independent redshift bins (Daly et al. 08); done here for sample of 222 sources (192SN + 30RG) split into

2 bins with 111 sources per bin;

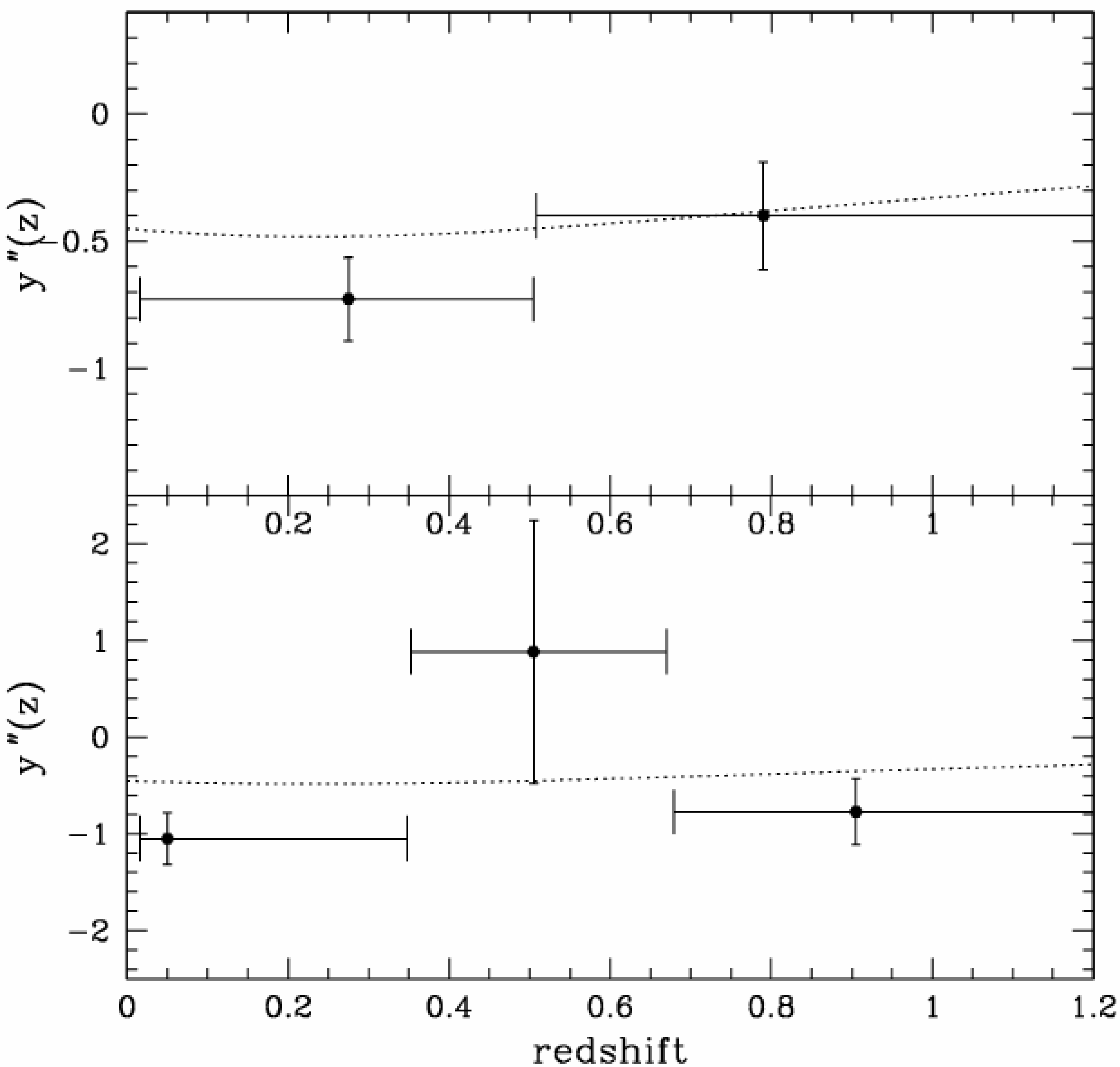
3 bins with 74 sources per bin;

4 bins with 55 sources per bin;

6 bins with 37 sources per bin.

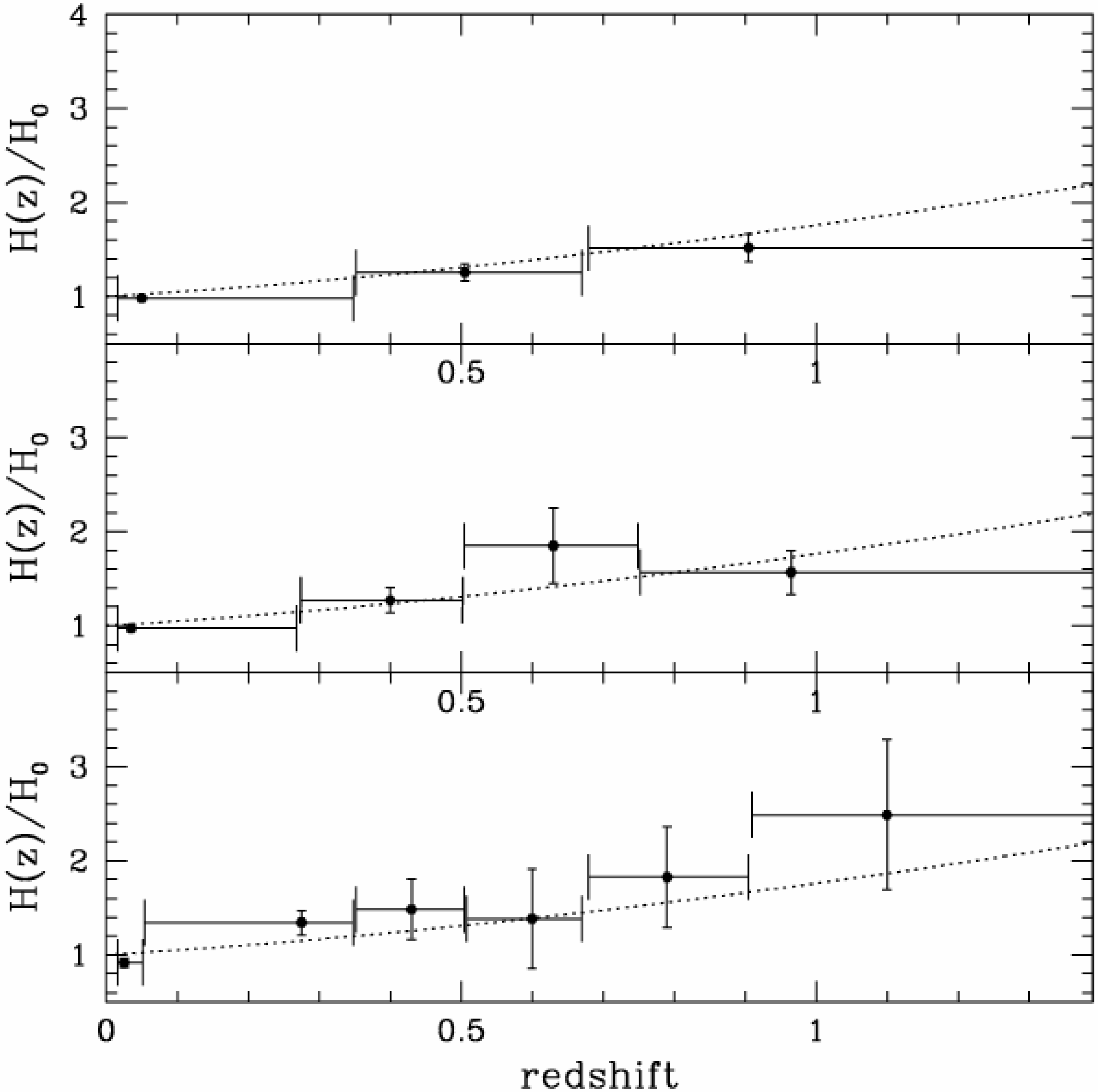


Model-independent results with data analyzed in independent redshift bins with 74 (top), 55 (middle), & 37 (bottom) sources in each bin. Dotted line is LCDM model prediction.

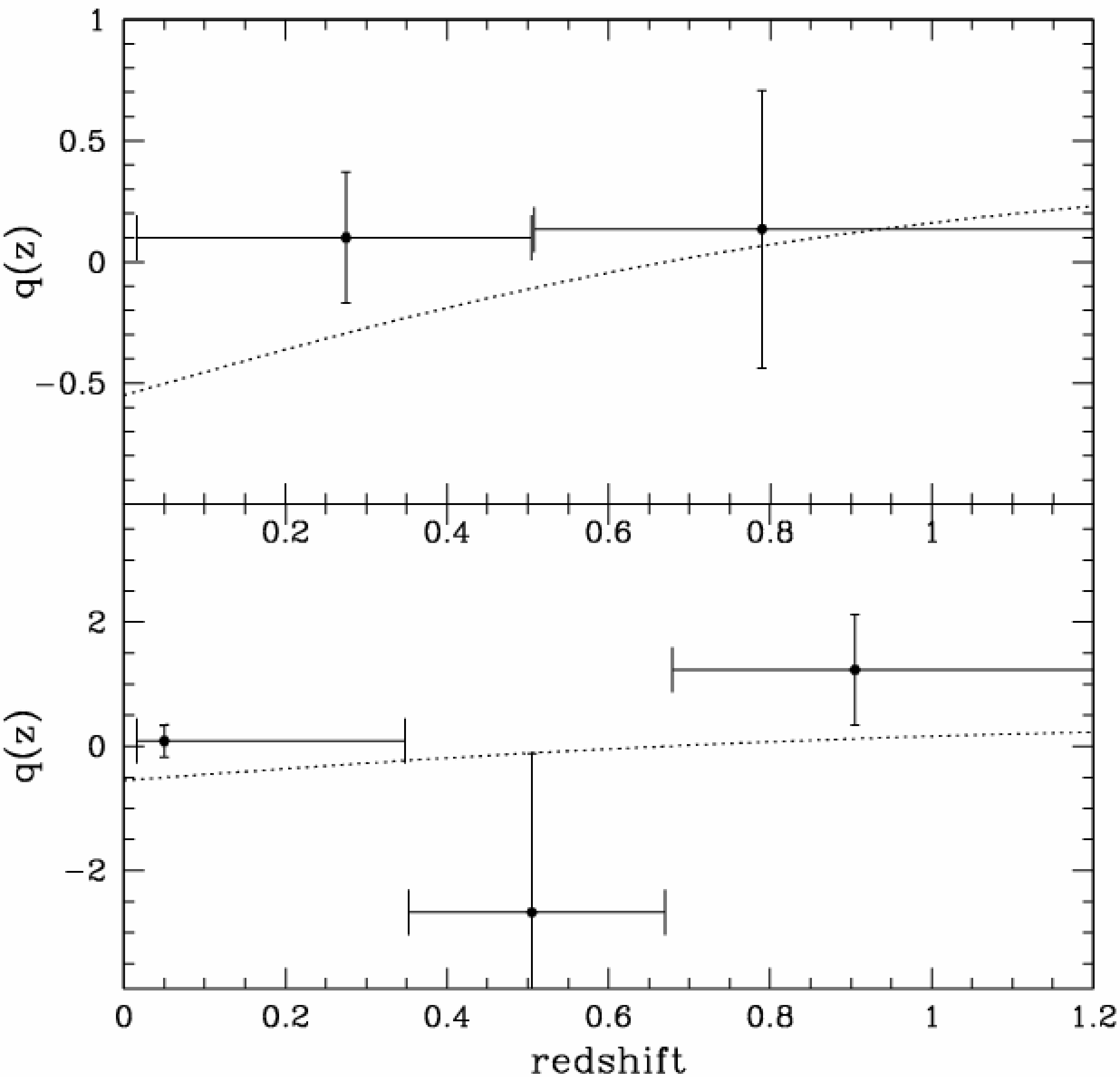


Model-independent results with data analyzed in independent redshift bins with 111 (top) & 74 (bottom) sources per bin.

The LCDM prediction is indicated by the dotted line.



Model-independent determination of H(z) for data analyzed in bins with 74 sources, 55 sources, & 37 sources each; using method of DD03. Dotted line shows the LCDM prediction.



Model-independent determination of q(z) for data analyzed in independent redshift bins of 111 sources (top) & 74 sources (bottom) per bin. Not enough data (yet) to confirm acceleration using binned data.

Now, specify a theory of gravity, GR, &

solve for the pressure $P_E(z)$ of the D.E.

Einstein Equations (for k=0):

$$\ddot{a}/a = -(4\pi G/3)\,[\rho_m + \rho_E + 3P_E]$$

$$(\dot{a}/a)^2 = (8\pi G/3)\,[\rho_m + \rho_E]$$

$\rightarrow p_E = [E^2(z)/3]\,[2\,q(z) - 1]$ or

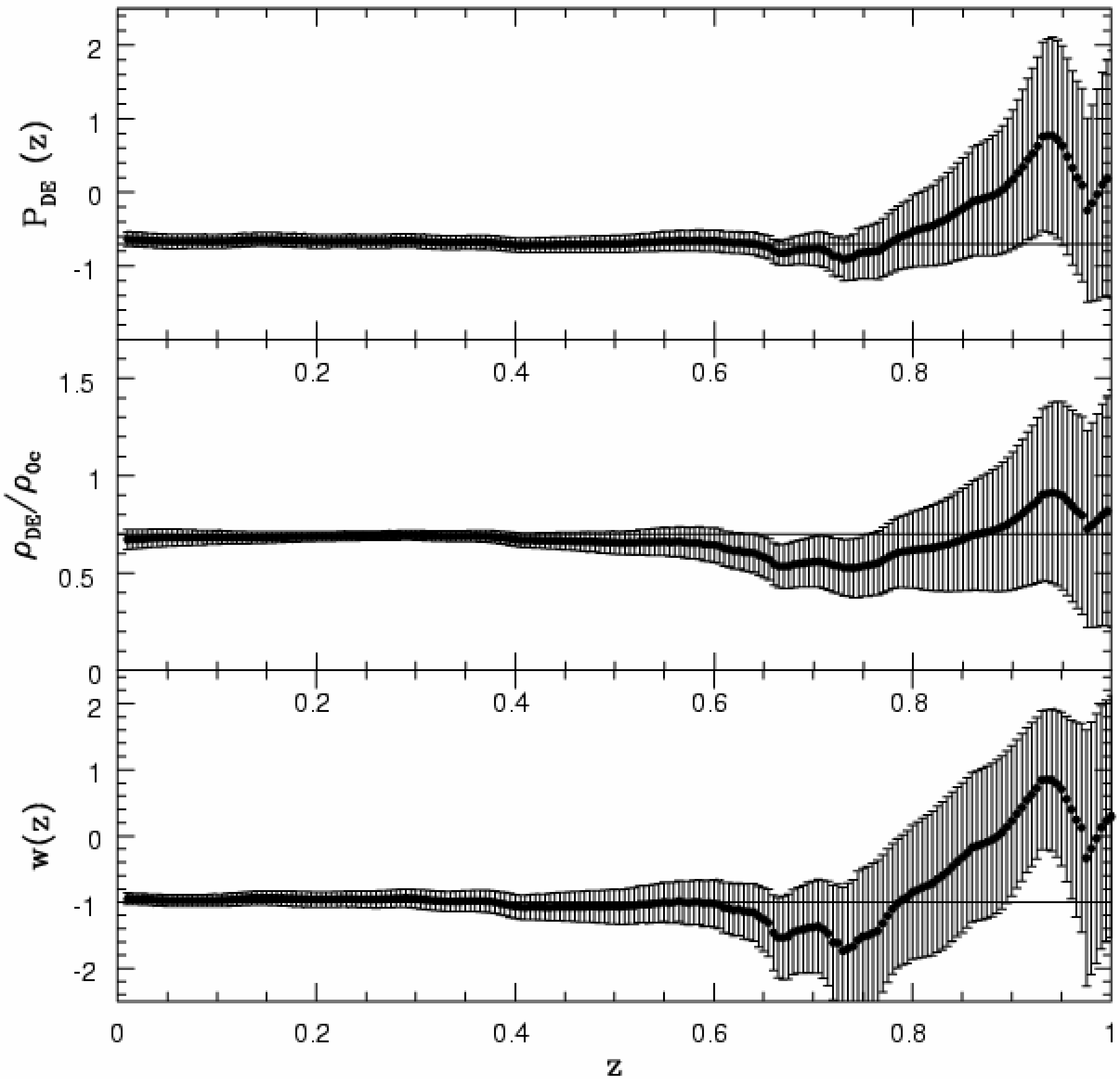
$p_E(z) = -(y')^{-2}[1+(2/3)(1+z)(y')^{-1}\,y'']$, where $p_E(z) \equiv P_E/\rho_{oc}$

With k=0, FRW, + GR, but no specific model for the DE, we have $P_E(z)$. Can also solve for the DE energy density and w:

$f_E(z) \equiv \rho_E(z)/\rho_{oc} = (y')^{-2} - \Omega_m(1+z)^3$

$w(z) = p_E(z)/\rho_E(z)$ so

$w = -[1+(2/3)(1+z)(y')^{-1}\,y'']/[1-(y')^2\,\Omega_m(1+z)^3]$



For Λ models, p=-$\Lambda \rightarrow$ direct measure of Λ

We measure P_0=-0.64 ± 0.1

Since $\rho_{0E}=p_0/w_0$, Ω_{0E}=0.64 ± 0.1 for w_0 = -1

We measure w_0 = -0.95±0.08 Consistent with Λ models, but possible evolution

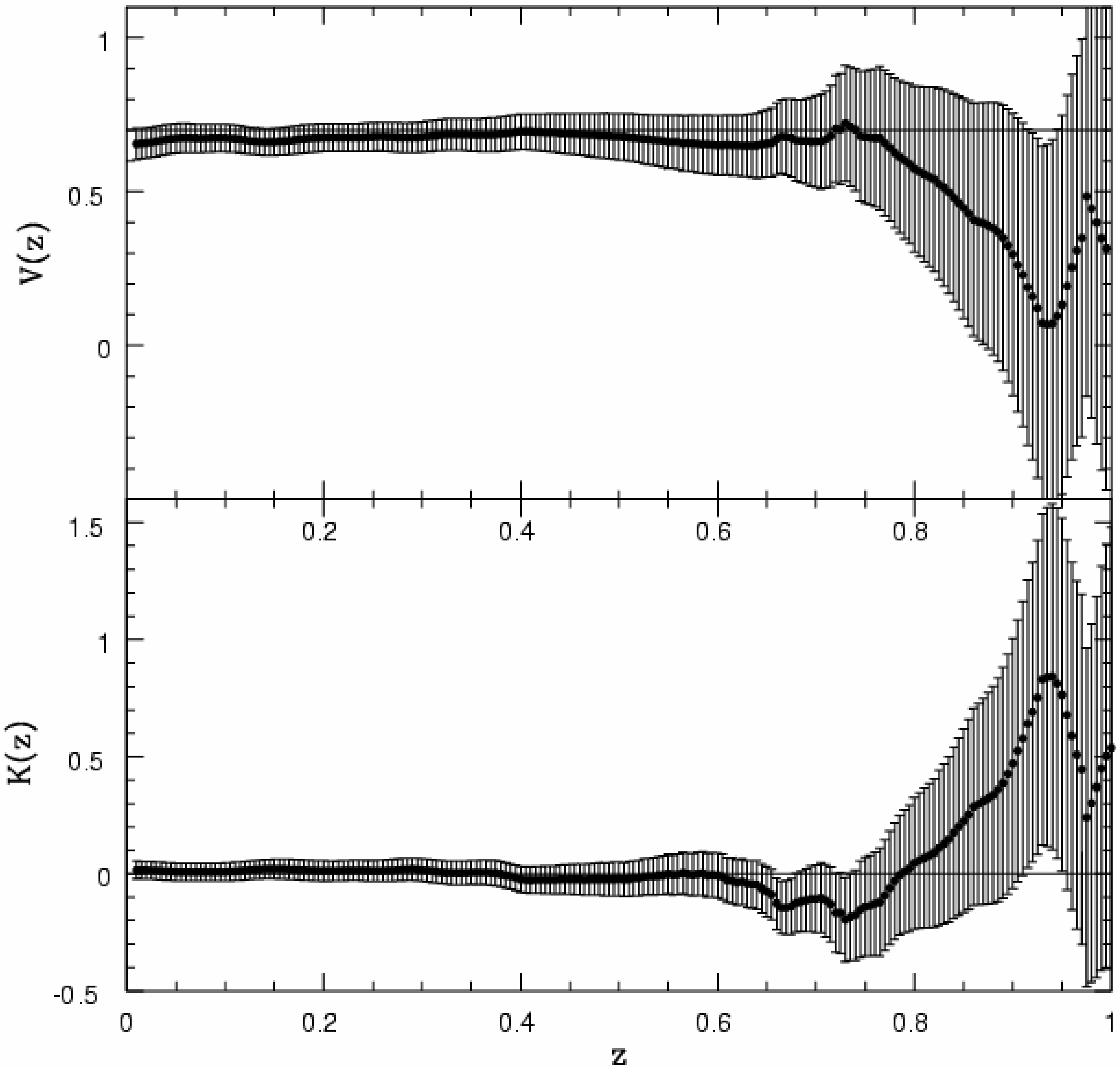
The potential energy density V of a dark energy scalar field and the kinetic energy density K are related to the energy density ρ and pressure P of the dark energy:

$$\rho = K + V; \quad P = K - V \text{ where } K = 0.5\, \acute{o}^2$$

$V = 0.5\,(\rho - P)$ and $K = 0.5\,(\rho + P)$

$$V(z)/\rho_{0c} = (y')^{-2}\,[1+(1+z)(y')^{-1}\,y''/3] - 0.5\Omega_{om}(1+z)^3$$

$$K/\rho_{oc} = -\,(1+z)\,[y']^{-3}y''/3 \;-\; 0.5(1+z)^3\Omega_{om}$$



We measure

V_0=0.65±0.05

and

K_0=0.01±0.03

It has now been about ten years since the acceleration of the universe was first announced. Results obtained with radio galaxies provided one of the first indications that the universe is accelerating (see my 2008 UCLA retrospective presentation, parts of which are included here).

1997 and 1998 were very exciting years for cosmology!!!

In late 1997, Steve Maran from the AAS press office contacted me and asked me if I would do a press release on cosmological studies with powerful radio galaxies for the January 1998 AAS meeting. At the time, I was on the faculty in the physics department at Princeton University, and I worked with the PU press office to prepare the press release.

The release explains how the angular diameter test works, and the relationship between the expansion rate of the universe and the intrinsic sizes of radio galaxies; for a given observed angular size, a large intrinsic size means that the universe was accelerating in its expansion.

Let's take a look at the press release and the parts that describe the acceleration of the universe.

News from
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Princeton, New Jersey 08544
Tel 609/258-3601; Fax 609/258-1301

Contact: Dr. Ruth Daly 609/258-4413 daly@pupgg.princeton.edu
Date: January 8, 1998

The Ultimate Fate of the Universe

Washington, DC -- Astrophysicists announced today new predictions of the ultimate fate of the universe obtained by calculating the characteristic or maximum size of very distant radio galaxies. Reports being presented by Dr. Ruth A. Daly, and Dr. Erick Guerra, both of Princeton University, in Princeton, New Jersey, to the American Astronomical Society meeting in Washington, DC, suggest that the expanding universe will continue to expand forever, and will expand more and more rapidly as time goes by.

Fourteen radio galaxies with redshifts between zero and two were used for this study. All of the radio galaxies included in the study are classical double radio sources similar to the nearby radio galaxy Cygnus A. Such classical double radio sources are cigar -shaped, with a black hole at the center and a radio "hot spot" at either end of the gaseous cigar. Astrophysicists consider the size of a classical double radio galaxy to be the distance between the two radio hot spots.

Previous work by the Princeton group had established that all classical double radio galaxies at a given redshift, or distance from earth, are of similar maximum or characteristic size; this size depends on the inverse of the distance from earth. The apparent characteristic or maximum size of the full population of radio galaxies at the same redshift depends on the distance to the sources. Thus, equating the two measures of the characteristic or maximum size of the sources allows an estimate of the distance to the sources. Knowing this distance is equivalent to knowing the global geometry of the universe, or the ultimate fate of the universe. This new work measures more radio galaxies, and radio galaxies at higher redshift, or greater distance from earth; it also involves more sophisticated statistical manipulations of the measurements.

The apparent size, or distance from hotspot to hotspot, of a high redshift radio galaxy is a clue to which of the competing models of the nature of the universe is most likely. A relatively small size at great distance from earth would suggest a universe that will halt its current expansion and recollapse; a larger size suggests a universe that will continue to expand forever, but at an ever decreasing rate; an even larger size suggests the universe will continue to expand, and will expand at a faster and faster rate. The current work finds that at high redshift the galaxies are very large, with widely separated radio hotspots. Thus, the universe will continue to expand forever and will expand at a faster and faster rate as time goes by.

The only other tool currently being used to investigate the global geometry of the universe is the maximum brightness of supernovae. These new measurements obtained using radio galaxies are derived by methods entirely different than the supernovae method, yet yield essentially the same result. "We can say, with 95% confidence, that the universe is open and will continue to expand forever," says Daly.

Daly and collaborators have identified 62 additional classical double radio galaxies with redshifts between zero and two that can be used to more tightly constrain the global geometry of the universe. They are moving forward with an observing program at the Very Large Array (VLA) in New Mexico to obtain the radio surface brightness maps that are needed to determine the characteristic size of each source. This will allow even more detailed measurements of the global geometry of the universe.

The same sources may be used to study evolution of gas in clusters of galaxies, and the Princeton group (including doctoral students Lin Wan and Greg Wellman) has used the sources to study evolution of clusters of galaxies to redshifts of two.

This work was supported by the National Science Foundation through a Graduate Student Fellowship to Guerra, and a National Young Investigator Award to Daly. The work was also funded by the Independent College Fund of New Jersey.

For more information:

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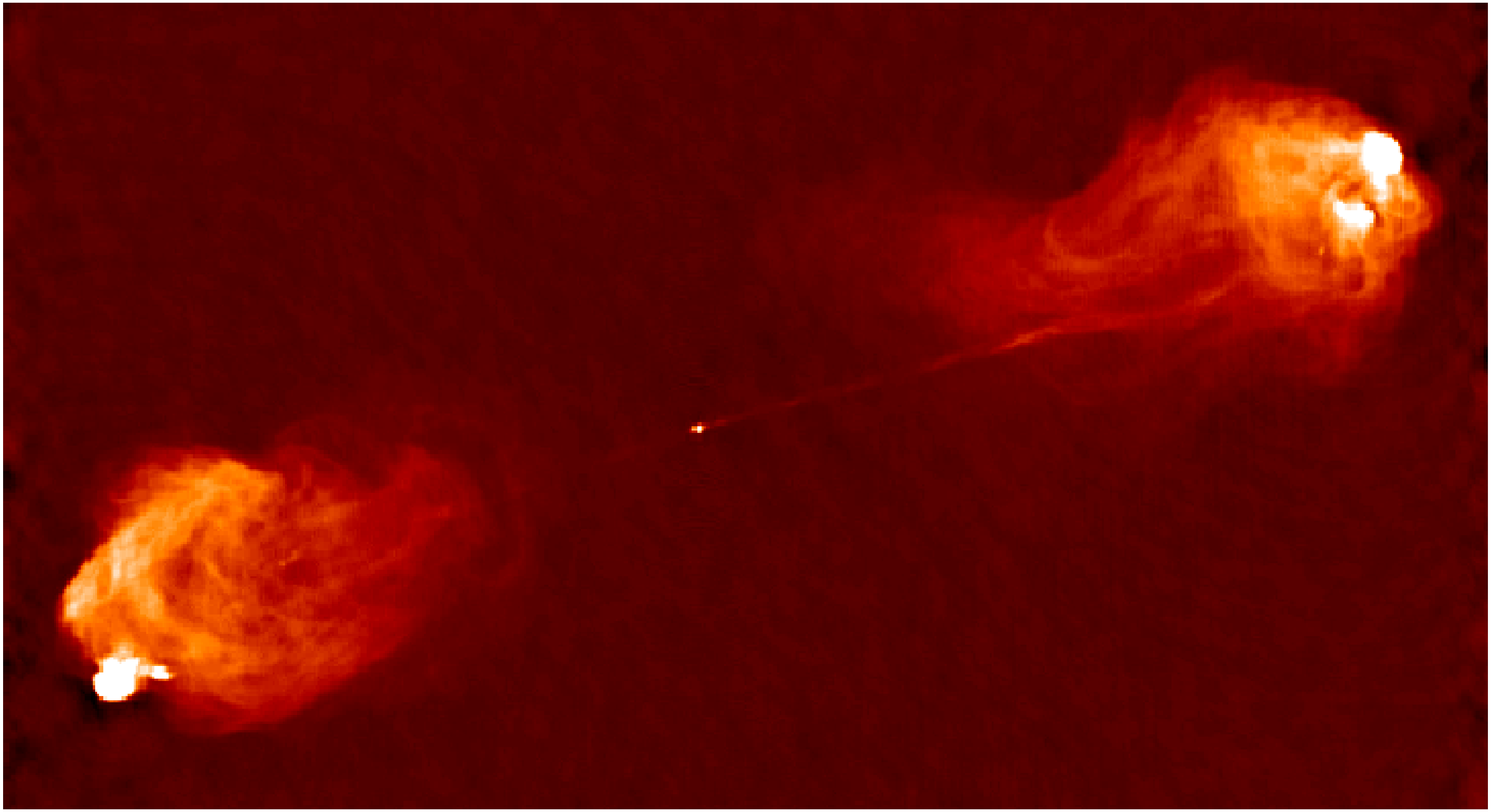
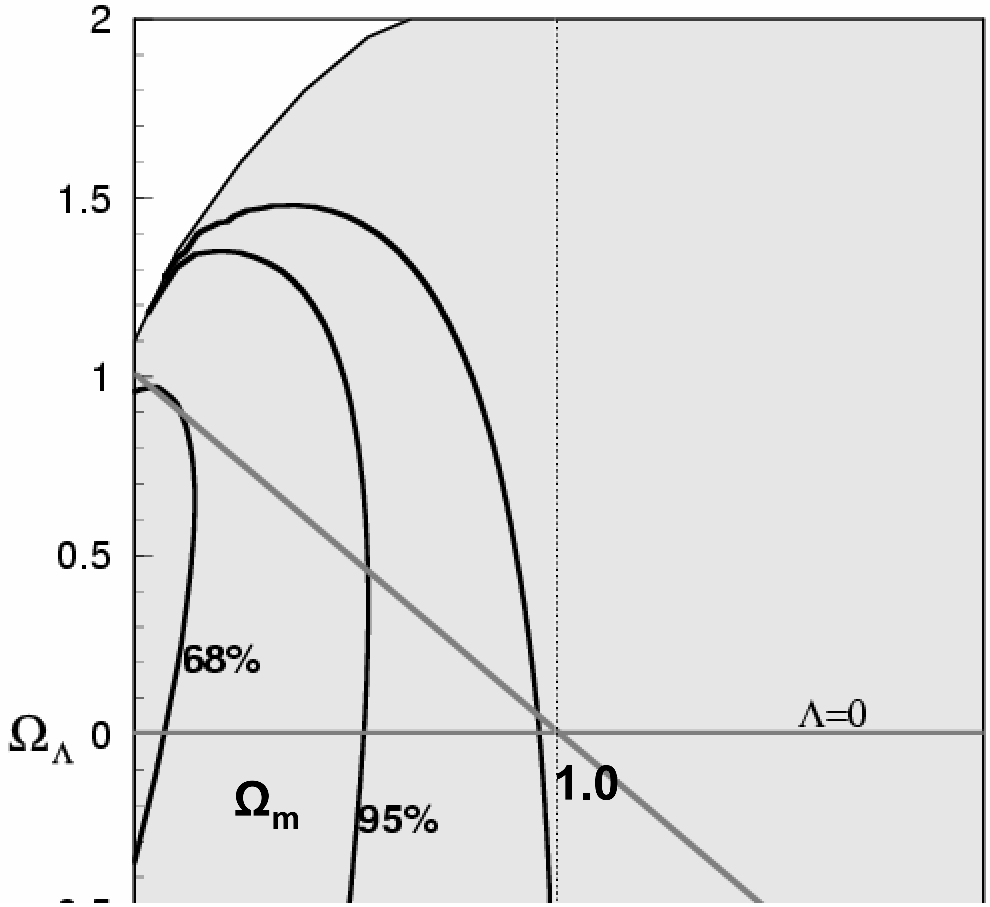


FRIIb Radio Galaxies

Method proposed by Daly in 1994

From Guerra, Daly, & Wan (1998)
(astro-ph/9807249)

And presented at Jan. 1998 AAS meeting.



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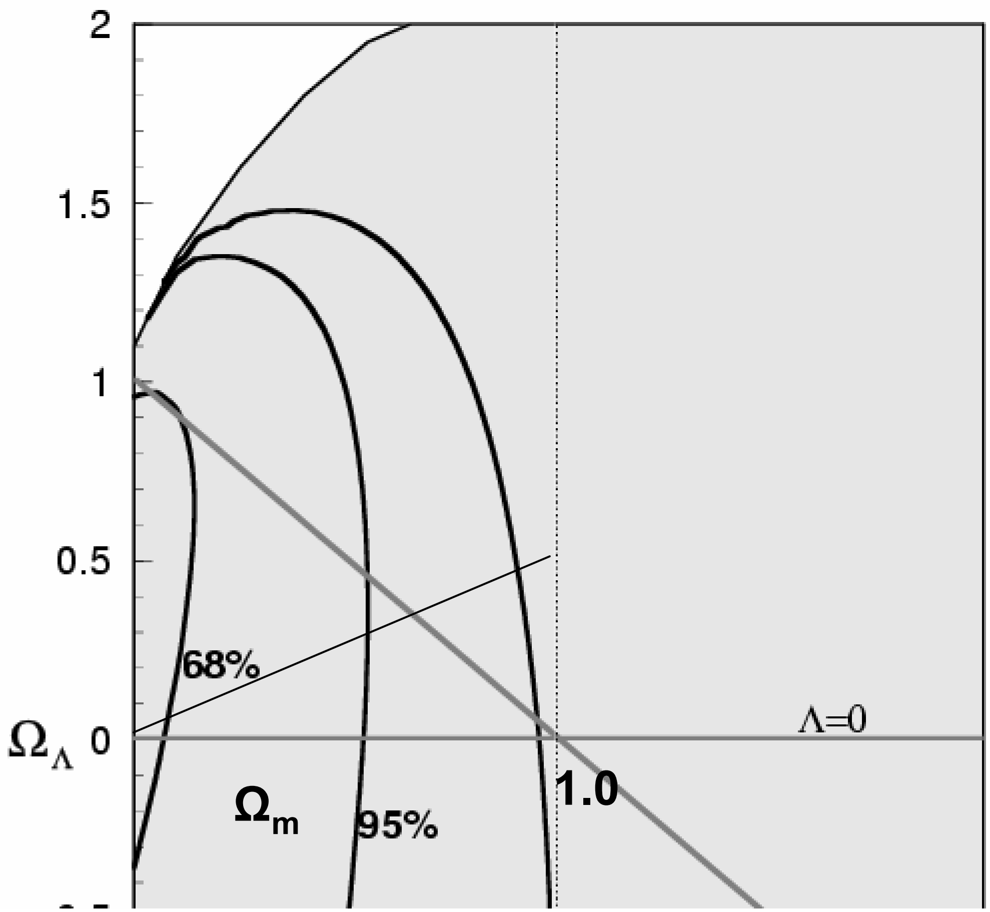
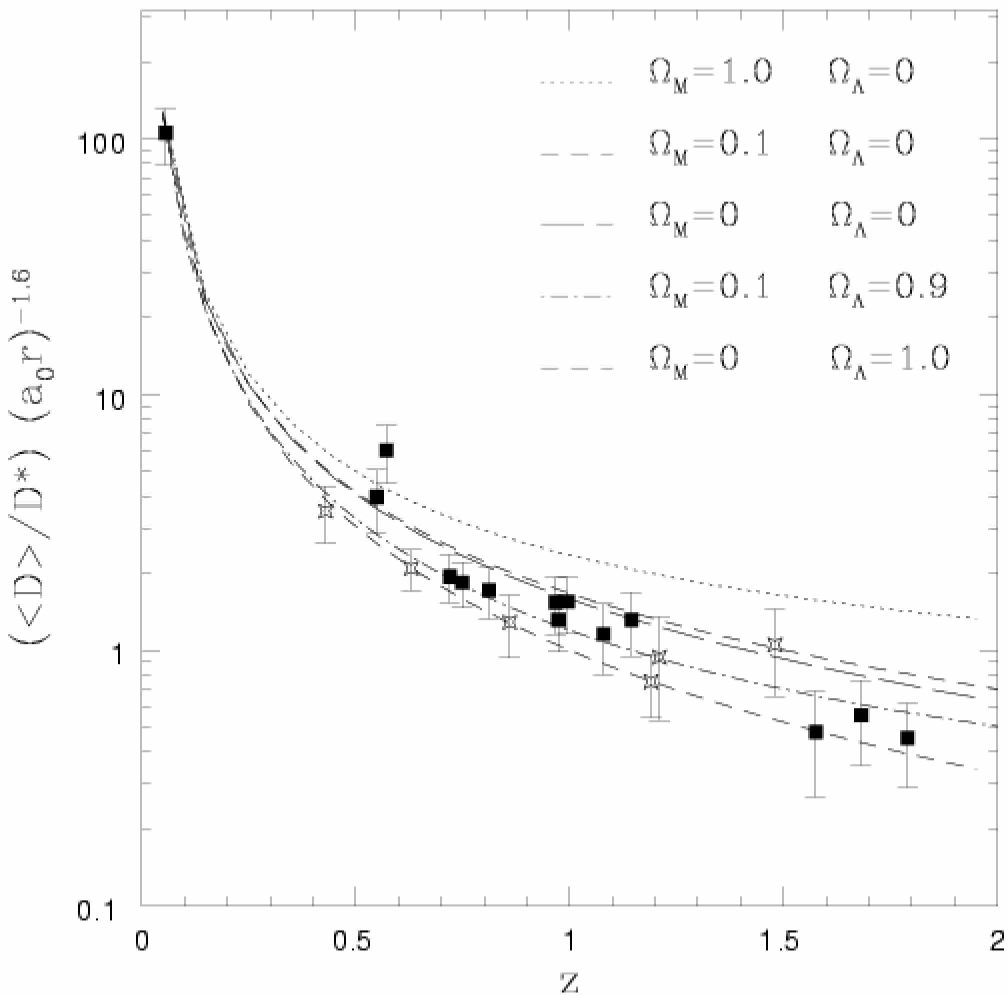




From Guerra, Daly, & Wan (1998) (astro-ph/9807249)

And presented at Jan. 1998 AAS meeting.

Note high z RG

This work was presented during the Jan. ‘98 press release session and during a regular AAS session. The press release session was very exciting. Adam Riess and Saul Perlmutter each presented results obtained using type Ia supernovae, and I presented results obtained using powerful radio galaxies.

At the time, I had the highest z source being used for cosmological studies, 3C 239 at a z of 1.79; a decade later, this is still the highest z RG or SN being used for cosmological studies.

A month later the SN groups announced the acceleration of the universe at the 1998 UCLA Dark Matter in the Universe conference.

The results indicated that in a standard model in which General Relativity is adopted as the correct theory of gravity, and the universe had two components, non-relativistic matter & a cosmological constant, and space curvature is included, the universe is accelerating today.

Later it became clear that these two completely independent methods, powerful radio galaxies and type Ia supernovae, based on totally different types of sources and source physics, give very similar results. This suggested that neither method was plagued by unknown systematic errors.

There was a concern about the model dependence of the result that the universe is accelerating today; the result was obtained in the context of a model with non-relativistic matter, a cosmological constant, and space curvature. Thus, the completely model-independent method of analyzing the data (published in 2002, 2003, and 2004) shows that the universe is accelerating today, and the result does not depend upon a particular model for the dark energy, the theory of gravity, or the contents of the universe.

The Radio Galaxy Method

The Sample:

We consider a subset of FRII radio sources

Leahy & Williams (1984) FRII-Type I (called FRIIb sources)

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

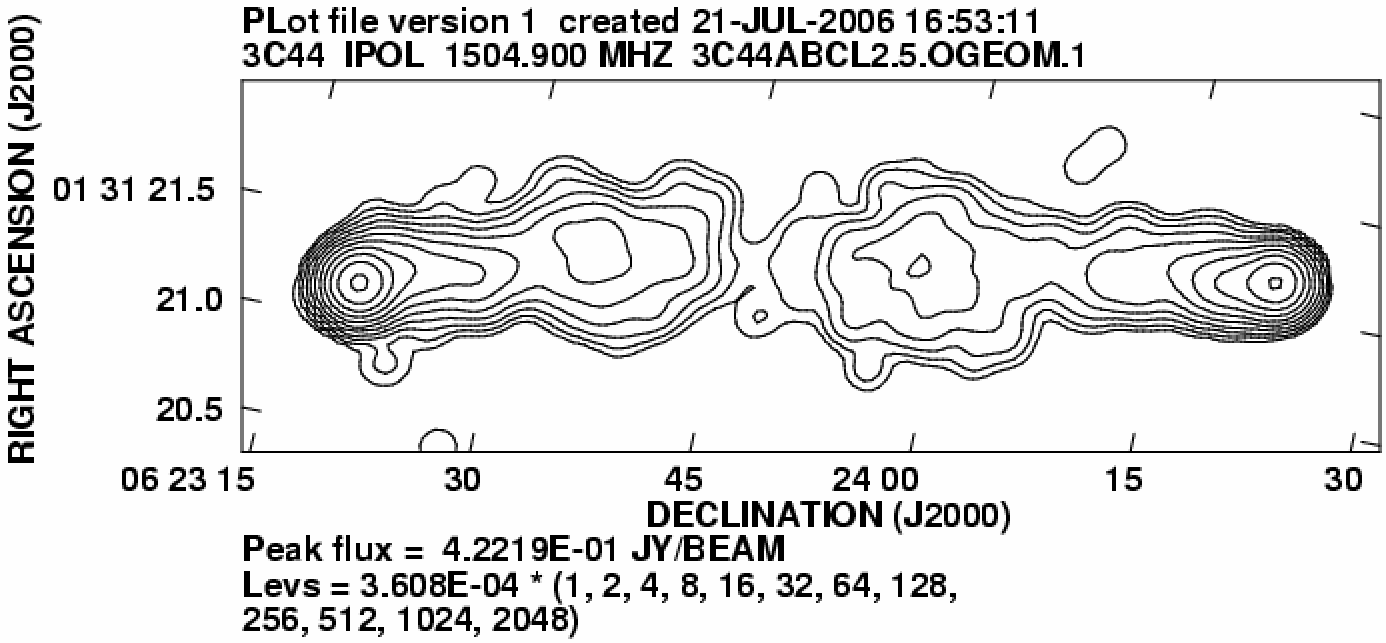
→ rate of growth well into supersonic regime

→ 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



Consider complete sample: 3CRR RG with P(178MHz) ≥ 3 x 10^{26} h^{-2} W/Hz/sr: → 70 RG, which form the parent population for the current study.

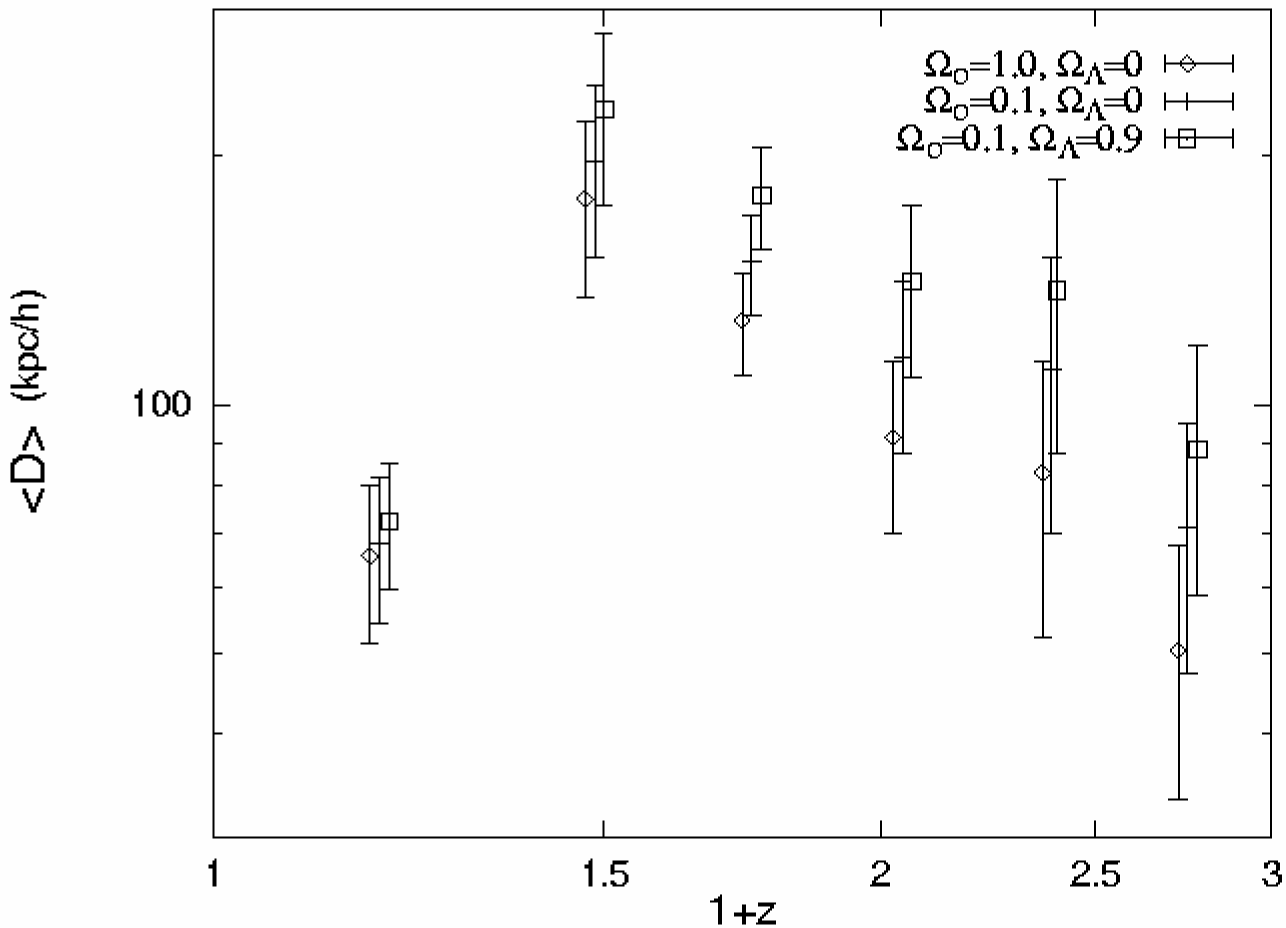
Have 30 RG with sufficient data to study source structure
z from 0 to 1.8, and D from 30 to 400 kpc

→ use data to obtain: 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)

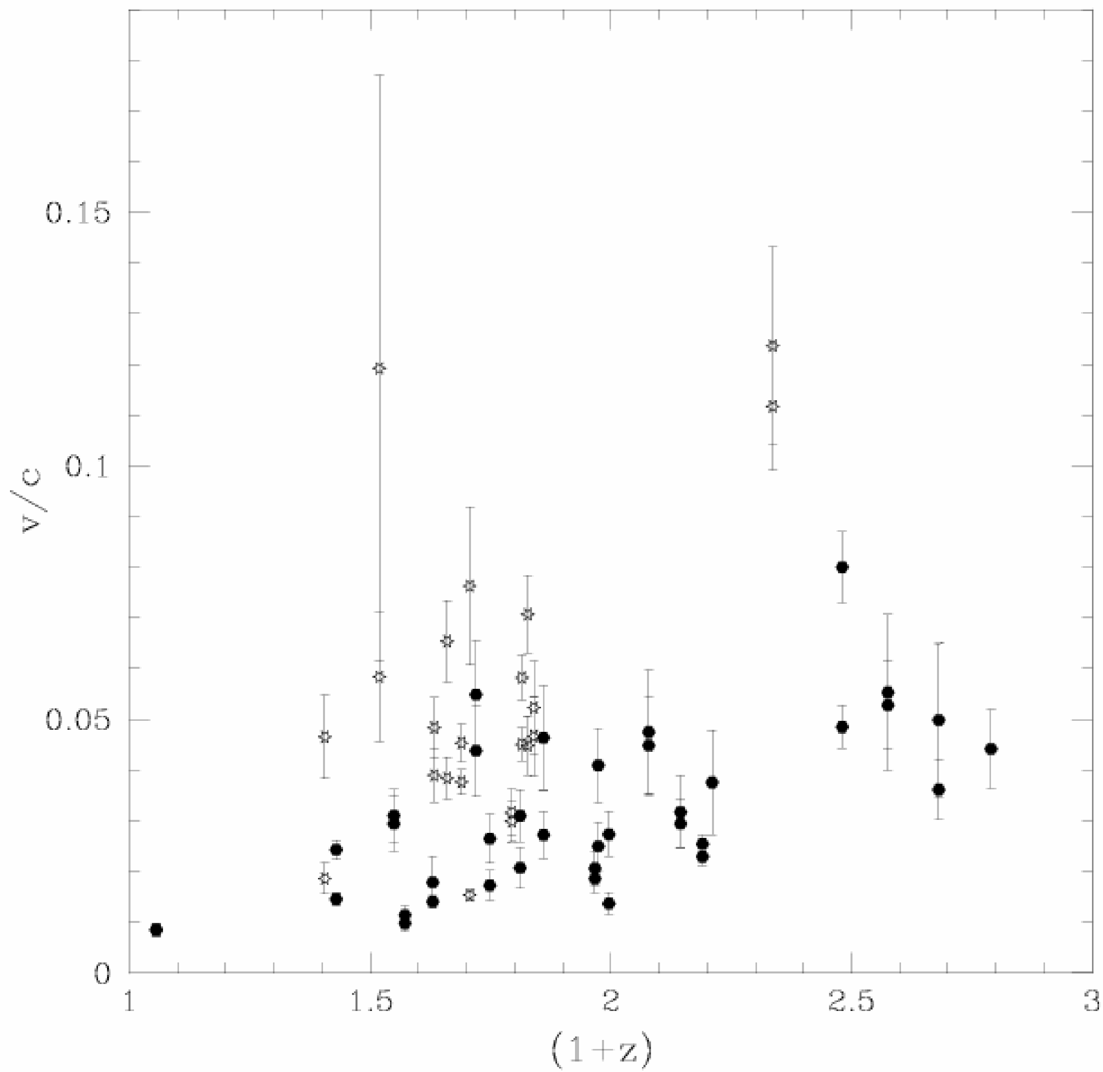
We allow for offsets of the radio emitting plasma from minimum energy conditions using $B = b\, B_{min}$; $P = [(4/3)\, b^{-1.5} + b^2]\, (B^2_{min})/24\pi$

<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 overall rate of growth of each side of each source



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.

The original 20 sources are shown as solid circles, and the 11 new sources are shown as open stars.

From O'Dea et al. ('08)

Interesting and unexpected that <D> has a small dispersion at a given z and is decreasing with z for $z \geq 0.5$; source v do not decrease with z.

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

Comparing the properties of individual sources, D_*, with those of parent population, <D>, minimizes the role of selection effects.

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

t_* = total outflow lifetime

Generalize the relationship between t_* & L_j to be $t_* \sim L_j^{-\beta/3}$
(Daly '94)

For an Eddington limited system, $\beta = 0$, which is a special case of this more general relationship. Other paths 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; applied across the leading edge)

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 $(a_o r)^{-0.6}$ for our best fit β of 1.5 (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; roughly **κ** $\sim \text{obs} \cdot (a_o r)^{1.6}$

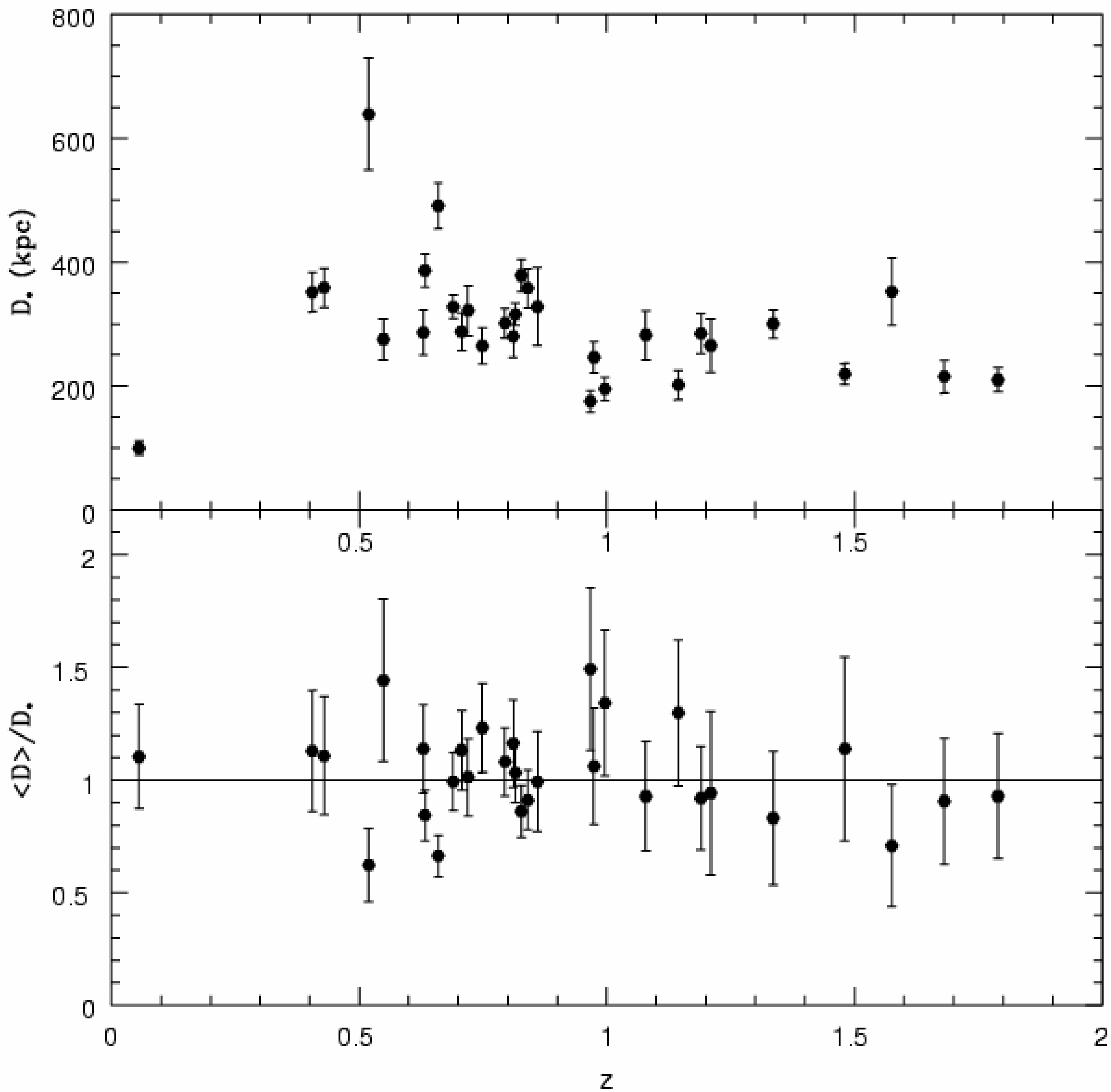
We obtain D_* for each of the 30 sources studied here and compare it with <D> for the parent population of 70 sources to solve for best fit values of β & cosm.

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)

We do not assume that any properties of the sources are constant, or pre-determined.

Only assumptions: $t_* \sim L_j^{-\beta/3}$, eqn. of strong shock physics apply, + v & L_j const for a given source over the source lifetime, which are consistent with the observations.

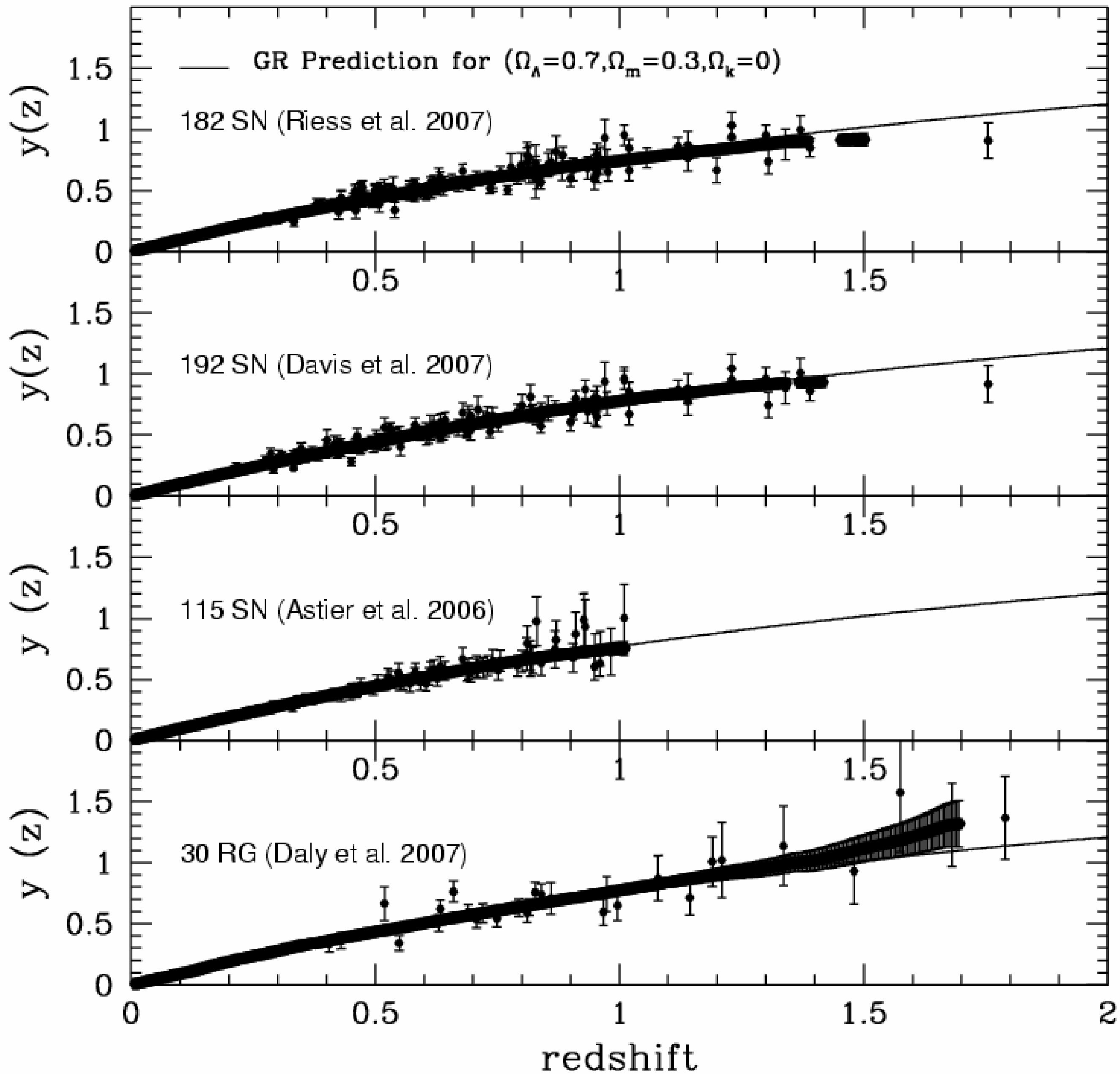
$D_* \sim v^{1-\beta/3} (a^2 P)^{-\beta/3} \sim v^{1/2} (a^2 P)^{-1/2}$ for $\beta = 1.5$



D_* shown for best fit parameters $\beta = 1.5 \pm 0.15$, $\Omega_m = 0.3 \pm 0.1$ and $w = -1.1 \pm 0.3$, obtained in a quintessence model.

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

From Daly et al. (2007)

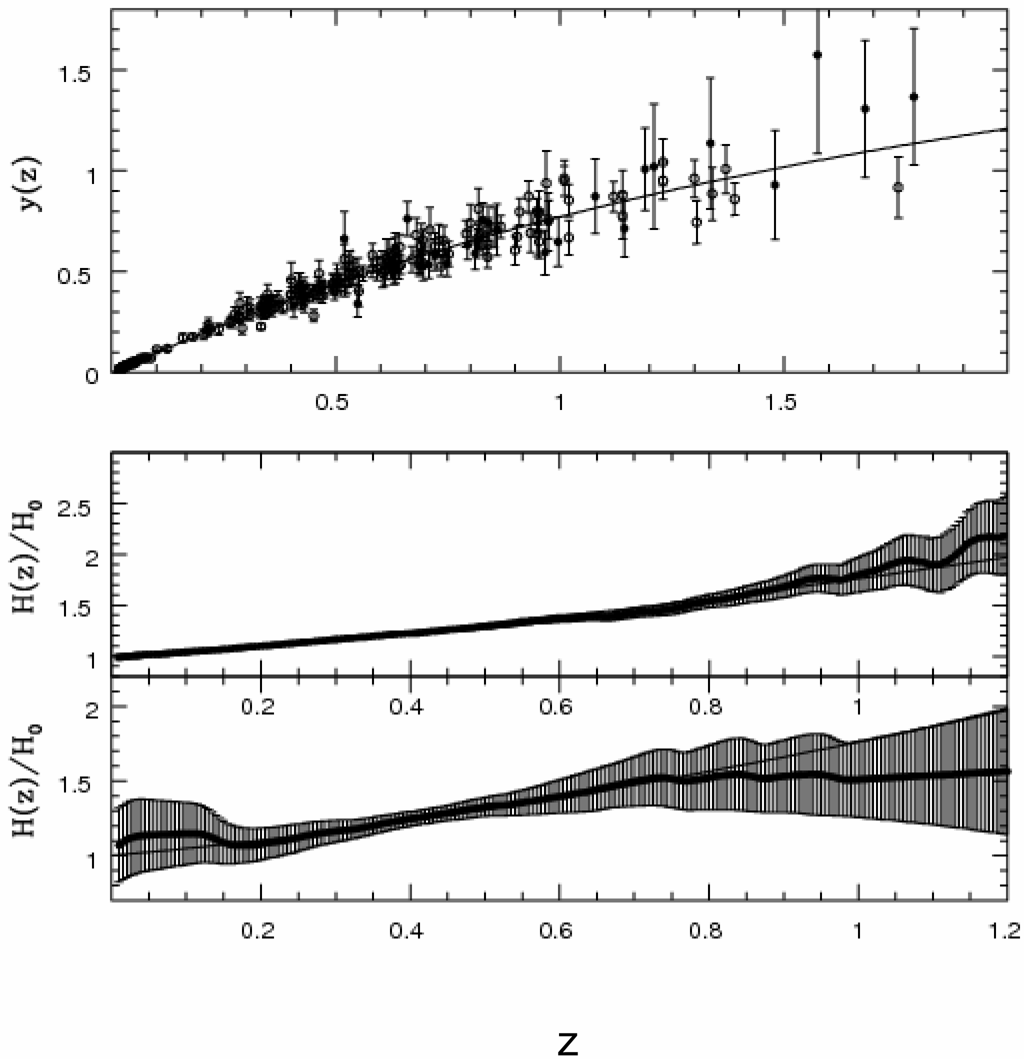


The values of ‹D›/D* are used to solve for the coordinate distance y without specifying a cosmological model (y is equivalent to a luminosity dist.)

There is very good agreement between SN and RG

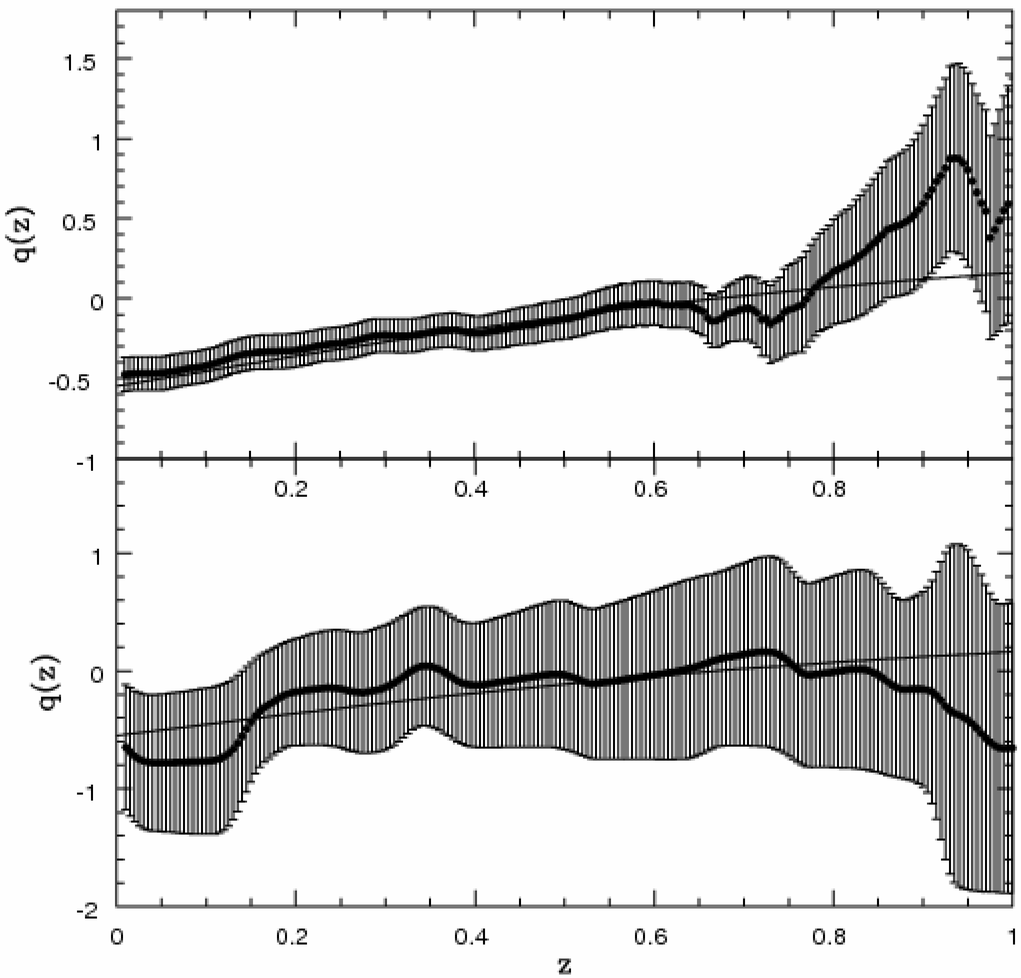
(from Daly et al. 2008)

Model-Independent Determinations of y, H, & q
(from Daly et al. 2008)



The coordinate distances, y, for RG and SN can be used to obtain H(z) and q(z) without having to specify a particular model (e.g. quintessence model); using a strictly kinematic approach. Shown here for 192SN of Davis et al. (2007) & 30 RG of Daly et al. (2007). For comparison the LCDM line for Ω_m = 0.3 is shown. Data are well described by LCDM model.

Model-Independent Determination of q(z); q_o depends only upon FRW metric; independent of k (from Daly et al. 2008)



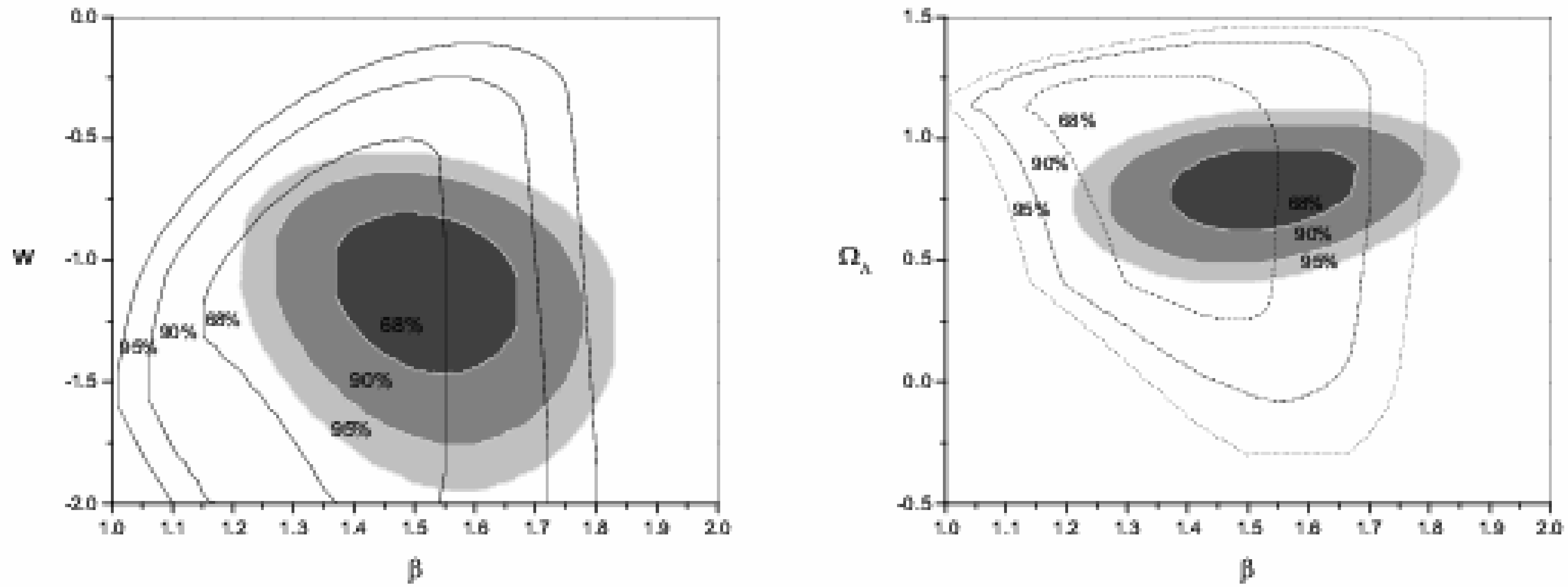
The data can be used to obtain q(z) in a completely model-independent way, using a strictly kinematic approach. Shown here for 192 SN & 30 RG; for SN find $q_o = -0.48 \pm 0.11$ & $z_T = 0.8 \pm 0.2$;

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

Solid line is LCDM with $\Omega_m = 0.3$

Good agreement between RG & SN

The RG model parameter β in a quintessence model for RG alone and combined 30 RG + 192 SN sample. The best fit value is β = 1.5 ± 0.15 and there is no covariance of β with w or Ω_Λ; very similar values obtained in other models (from Daly et al. 2007).



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):

$$L_j = 10^{45} (a/m)^2 B_4^2 M_8^2 \text{ erg/s} \sim (a/m)^2 B^2 M^2$$

$$E_* = 5 \times 10^{61} (a/m)^2 M_8 \text{ erg} \sim (a/m)^2 M$$

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

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

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

This 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 clearly not Eddington limited, since $\beta = 0$ is ruled out at 10σ.

The picture that emerges is: the relativistic outflow from the massive black hole is triggered when the magnetic field strength reaches a limiting or maximum value of B ~ (a/m). The value of B will be different for each BH and, since $L_j \sim E_*^2 B^2 (a/m)^{-2}$ for each BH, each BH will have $L_j \sim E_*^2$ when B ~ (a/m). The relationship indicated by our analysis is $L_j \sim E_*^2$.

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 lifetime of a given source is consistent with the data.

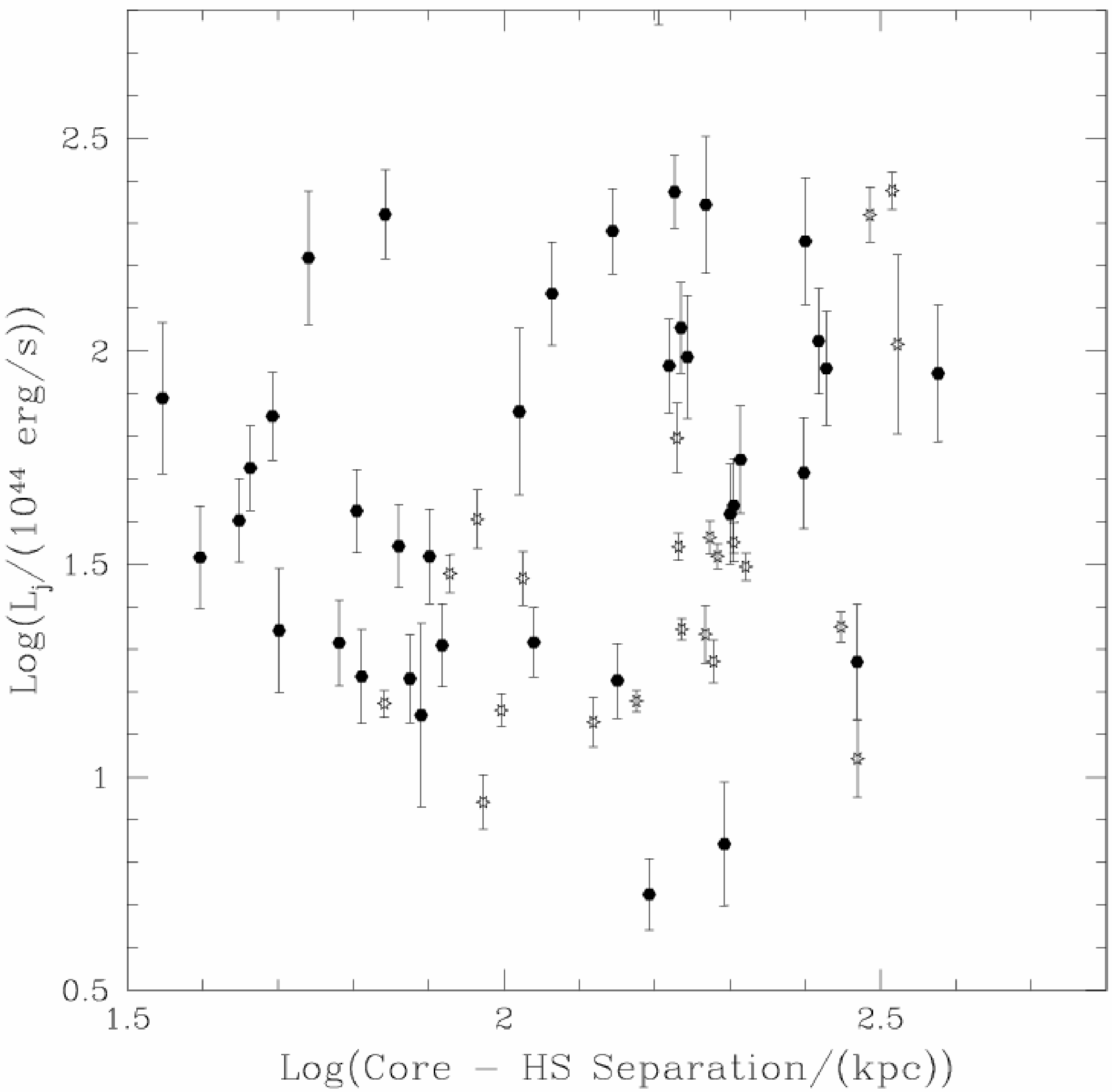
The relationship between the total time the AGN is on and the beam power is $t_* \sim L_j^{-1/2}$

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

(see Daly et al. 2007 for details)

The Beam Power $L_j = dE/dt \rightarrow$ the source



L_j is obtained by applying the strong shock equation:

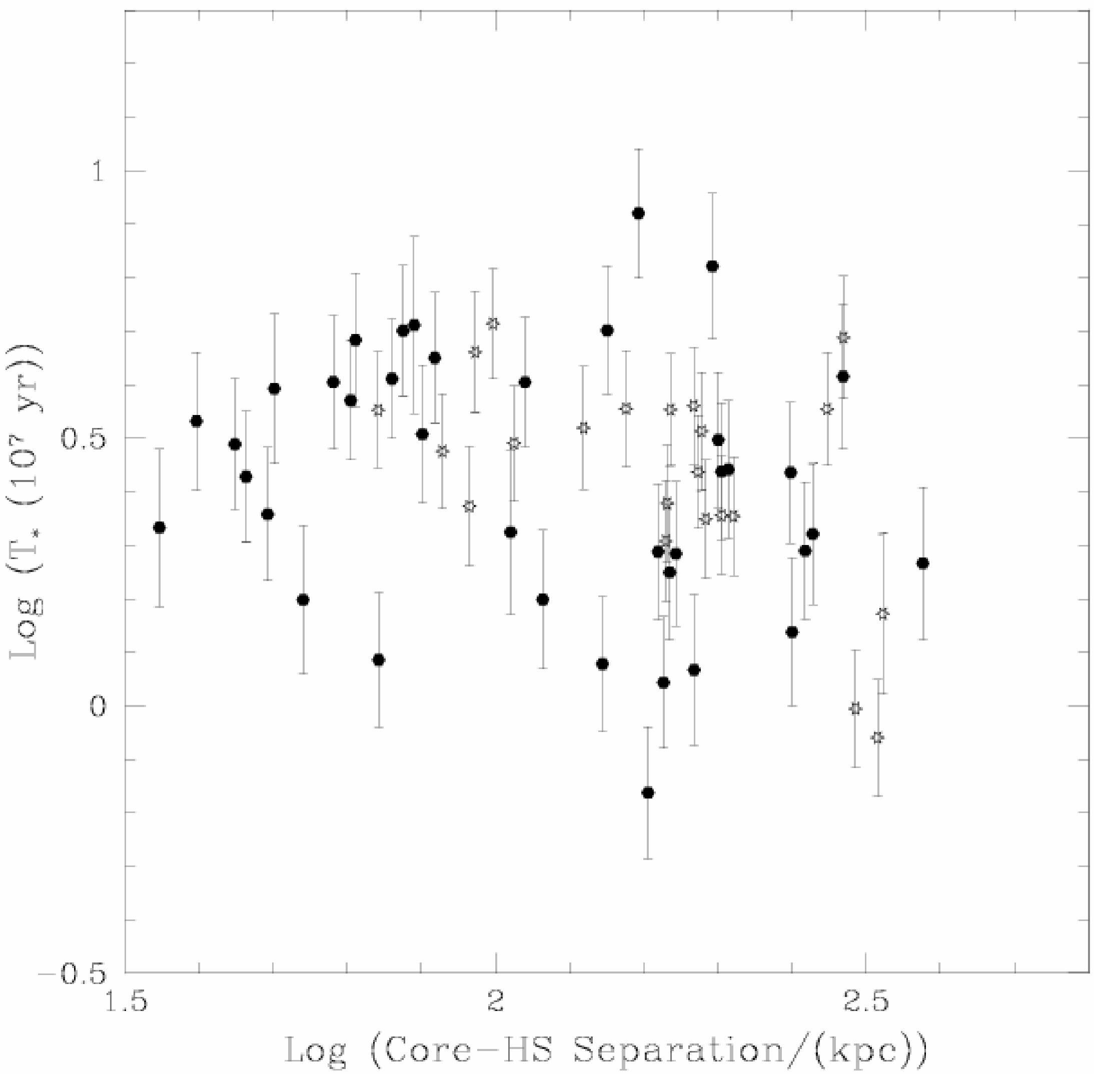
$L_j = a^2 P v$

Find no correlation between L_j & D

L_j obtained here is independent of offsets from minimum energy conditions due to the cancellation of B in v and P (O'Dea et al. 08)

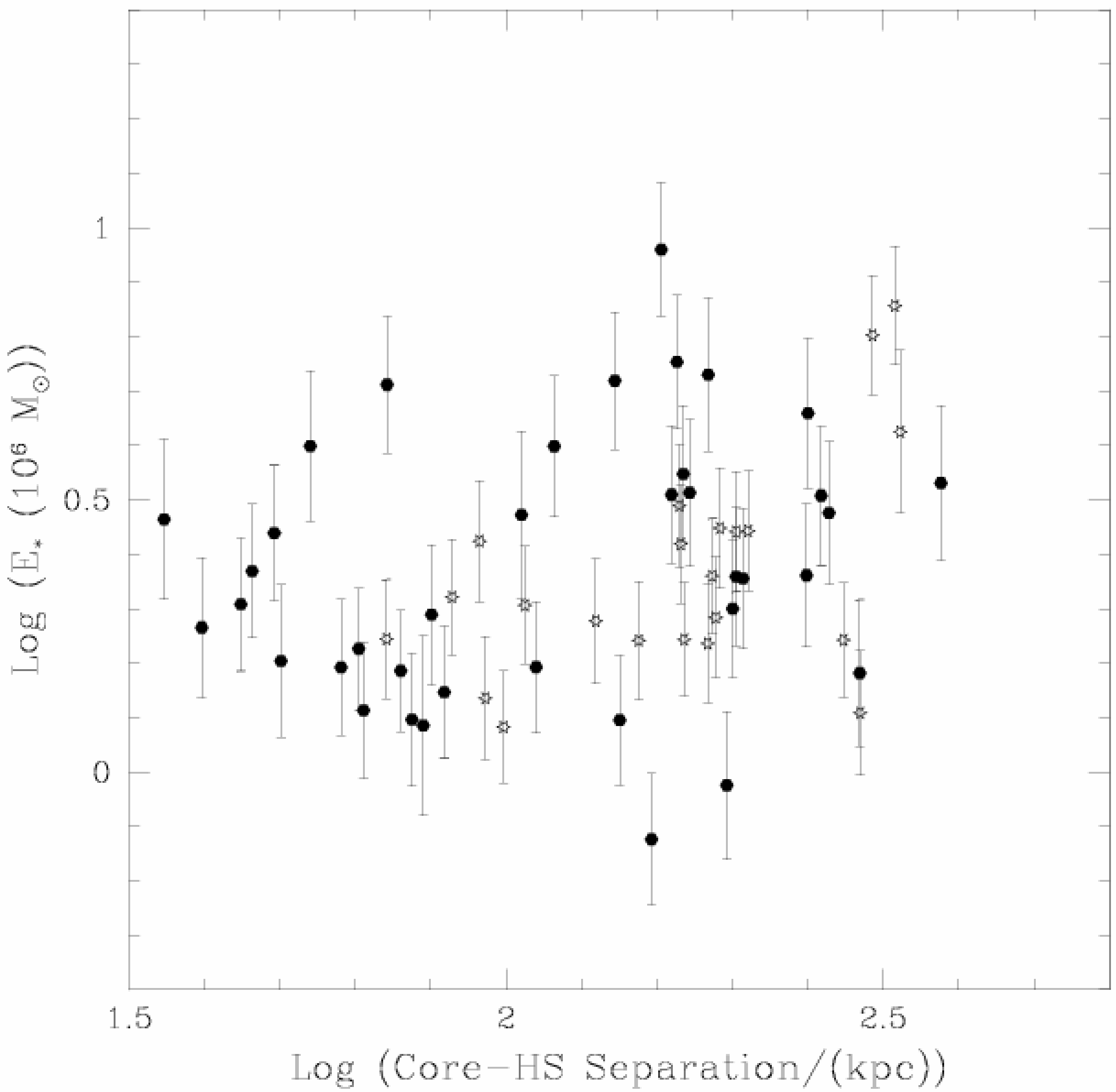
$L_{EDD} = 10^{47} M_9$ erg/s so all of these L_j can have $L_j \ll L_{EDD}$

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



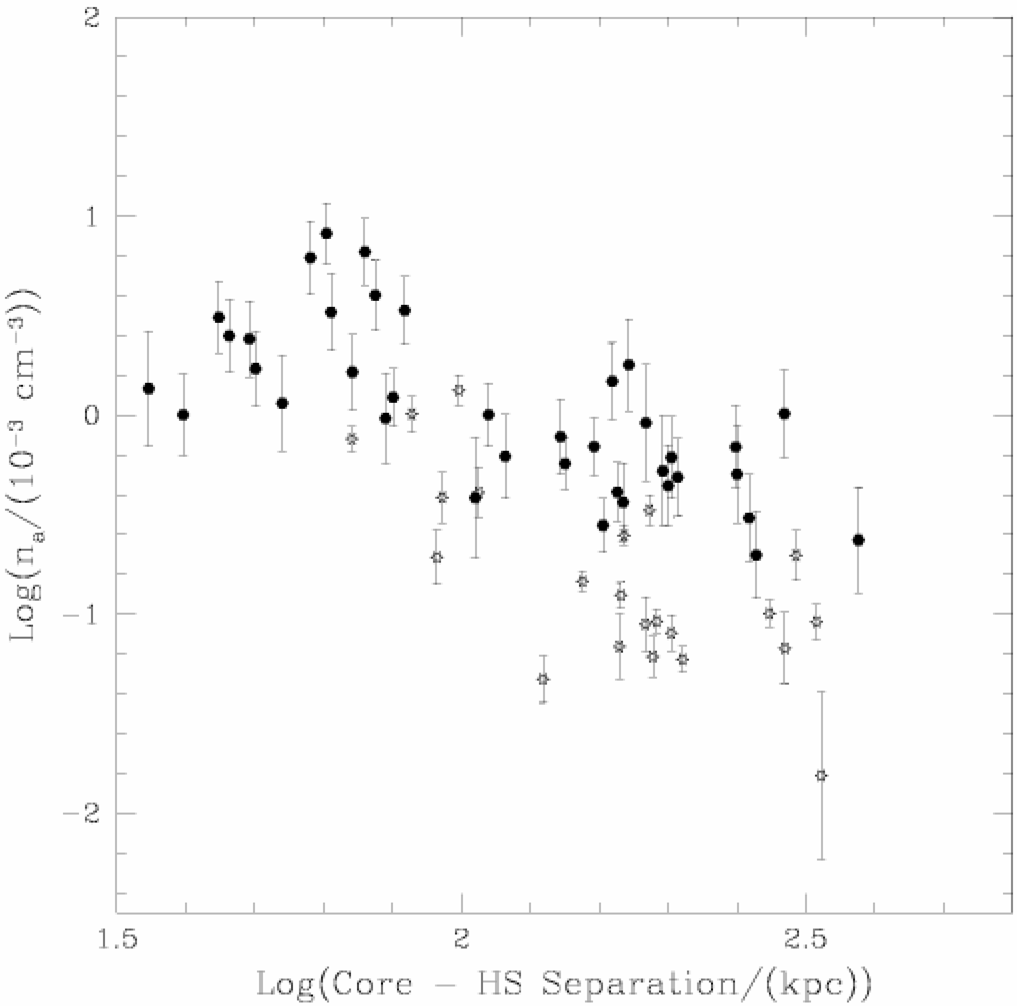
The fact that t_* is independent of D indicates that our determinations T_* are not biased by the epoch at which we observe a particular source, and that we are randomly sampling sources during their lifetimes.

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



The fact that E_* is independent of D indicates that our determinations of E_* are not biased by the epoch at which we observe the source.

The ambient gas density n_a



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

$n_a \sim P/v^2$

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

As expected for these values of D

(from O'Dea et al. 2008)

No assumptions about the source environments are made to obtain β and cosmological parameters.

Consistent with Croston et al. (2005) & Belsole et al. (2007).

Mini-Summary: the Radio Galaxy Method

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; no assumptions are made about the source environments or beam powers.

The cosmological parameters we determine are in very good agreement with those obtained by independent methods, such as the type Ia SN method.

The model parameter β can be analyzed in a standard magnetic braking model, and the value we obtain is a very special value, $\beta = 1.5 \pm 0.15$, which implies that $B \sim (a/m)$ for each source.

This leads to a picture in which the collimated 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 $L_j \sim E^2$.

The outflows are unrelated to the Eddington luminosity, and have beam powers well below L_{EDD}; there is no need to require that each source produces an outflow for the same total time.

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

Summary

Determinations of y, y’, & y”, which are completely model-independent, are in very good agreement with predictions in a standard LCDM model based on GR, $k = 0$, and a cosmological constant; this provides a large-scale test of GR over cosmological distances.

Good agreement between y, y’, and y” obtained with RG & SN; provides support for both methods.

Model-independent determinations of $H(z)$ and $q(z)$ have a very weak dependence on k for reasonable values of this parameter, and q_0 is independent of k.

We find $q_0 = -0.48 \pm 0.11$, and a transition redshift of about 0.8 ± 0.15.

A new model-independent function, the dark energy indicator, s, is introduced. A constant value of s indicates that $w = -1$.

We find that s is constant and that $w_0 = -0.95 \pm 0.08$.

The data may be used to solve for the properties of the DE as functions of redshift (e.g. P, ρ, w, V, & K) assuming GR is the correct theory of gravity and $k = 0$.

The empirical relationship that forms the basis of the RG method can be understood in context of a standard magnetic braking model for AGN.