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Cosmographic tests of the Hubble law:

How far can one really go without a specific model for the cosmological equation of state?

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Viernes 18 Abril 2008

Abstract:

The Hubble law describes the recession of the galaxies and the expansion of the universe --- it is one of the foundation stones of 20th century cosmology.

In particular, subtle deviations from the naive linear Hubble law underlie recent claims that the expansion of the universe is accelerating.

I will present a broad overview of the current situation, and possible lessons for the future.

The original Hubble law:

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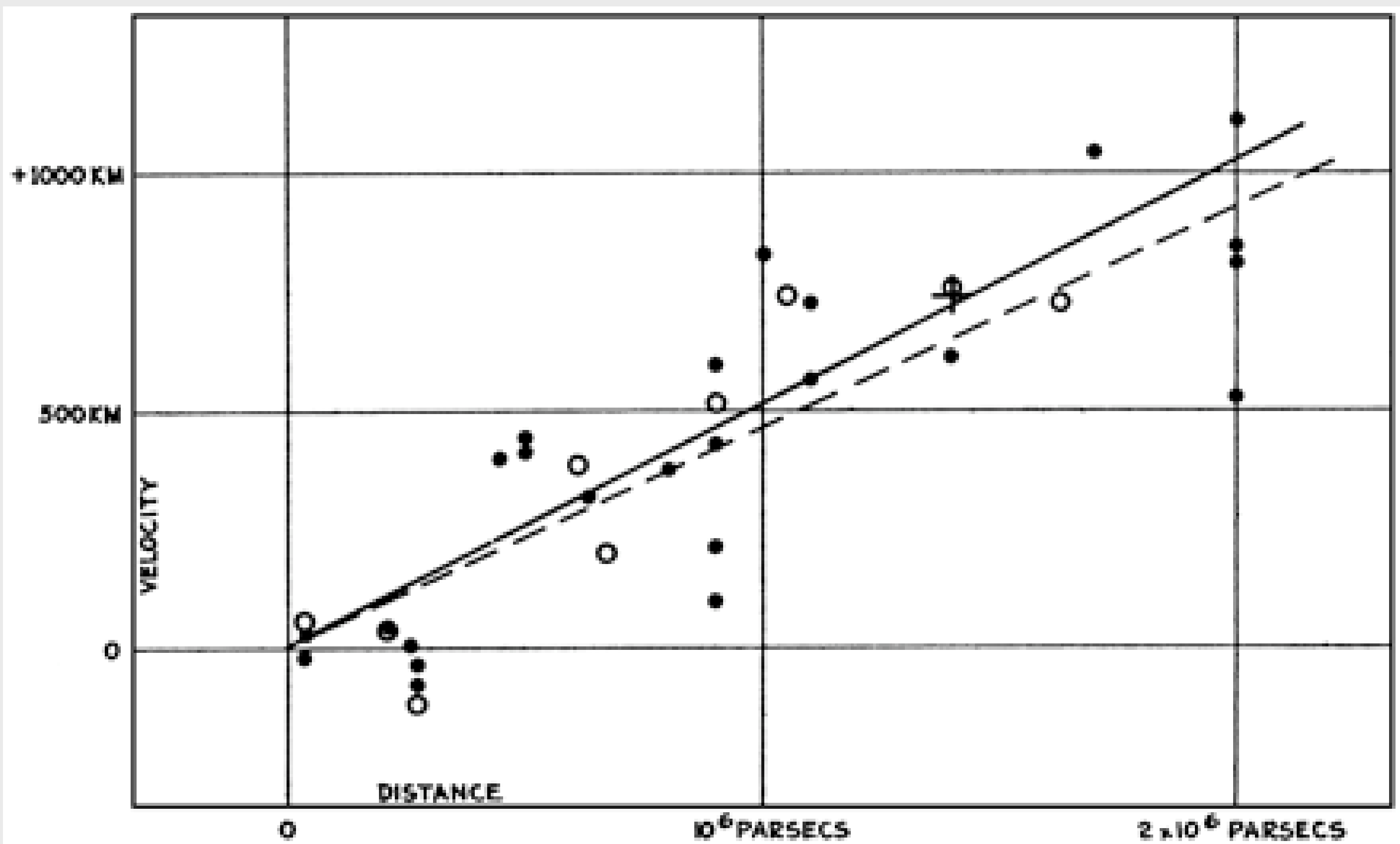
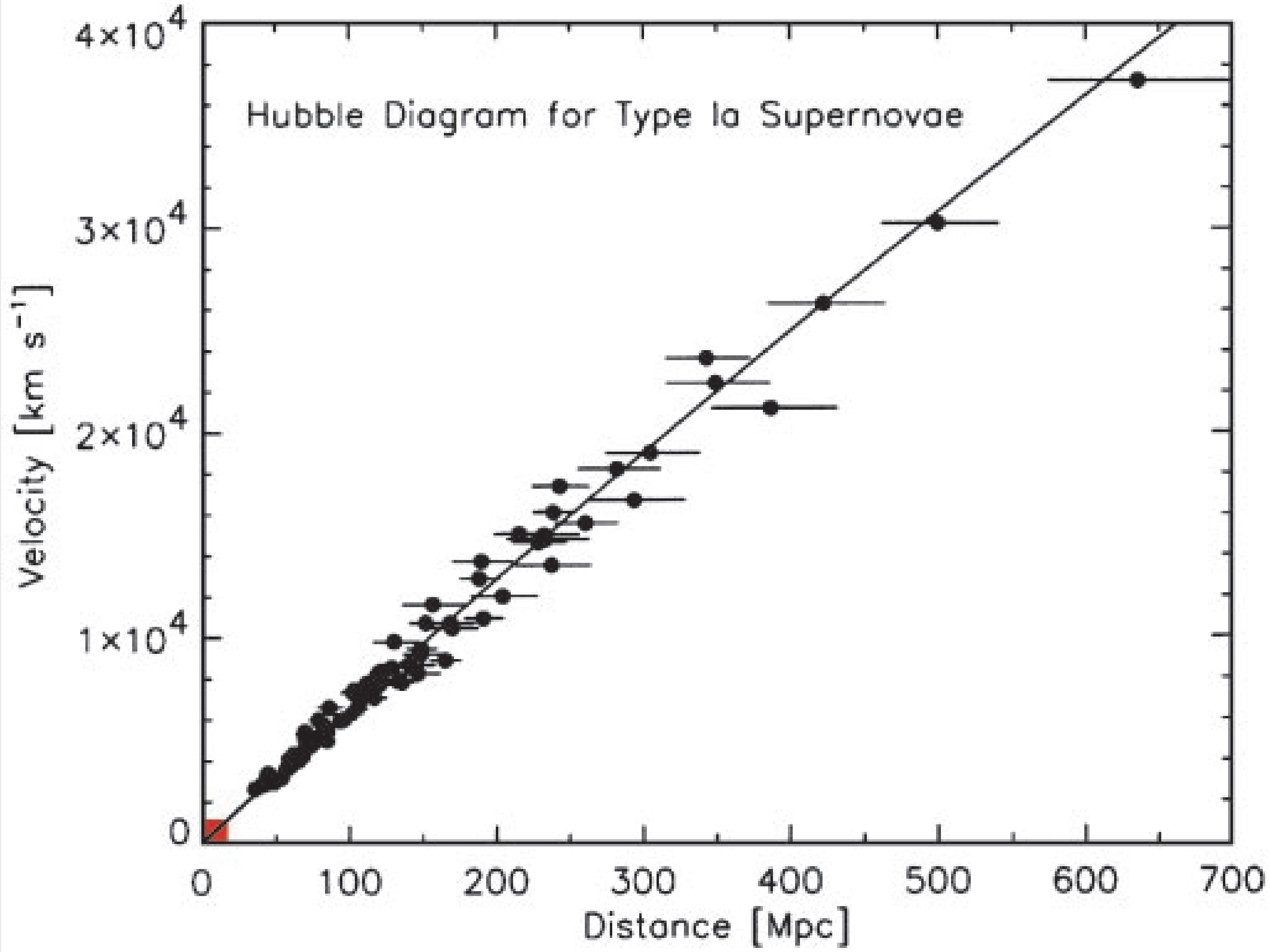
$$v = H_0\, d; \qquad H_0 \approx 500\ (\text{km/sec})/\text{Mpc}.$$



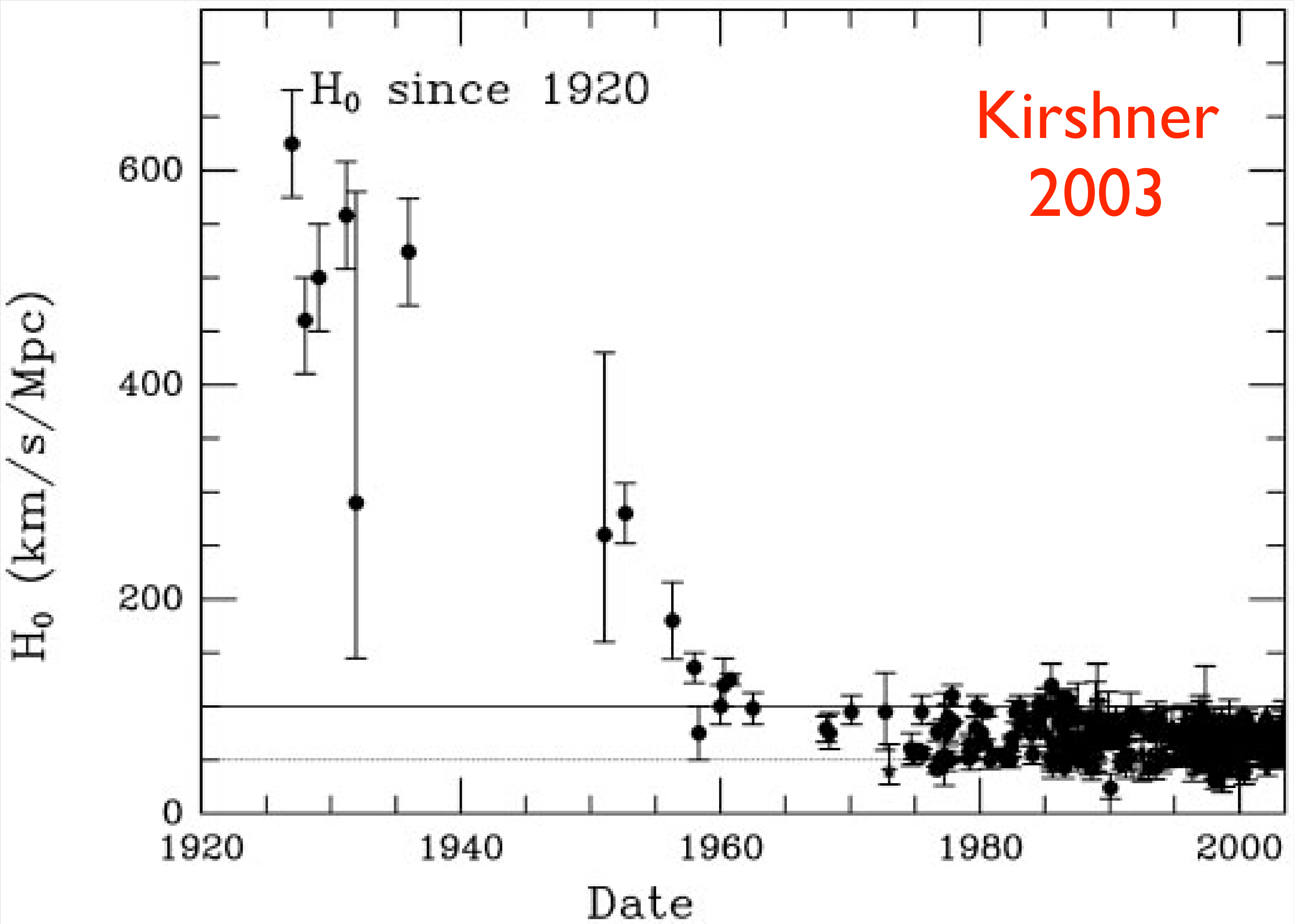
1929

[Hubble, E. P. (1929) *Proc. Natl. Acad. Sci. USA* 15, 168–173]

2003

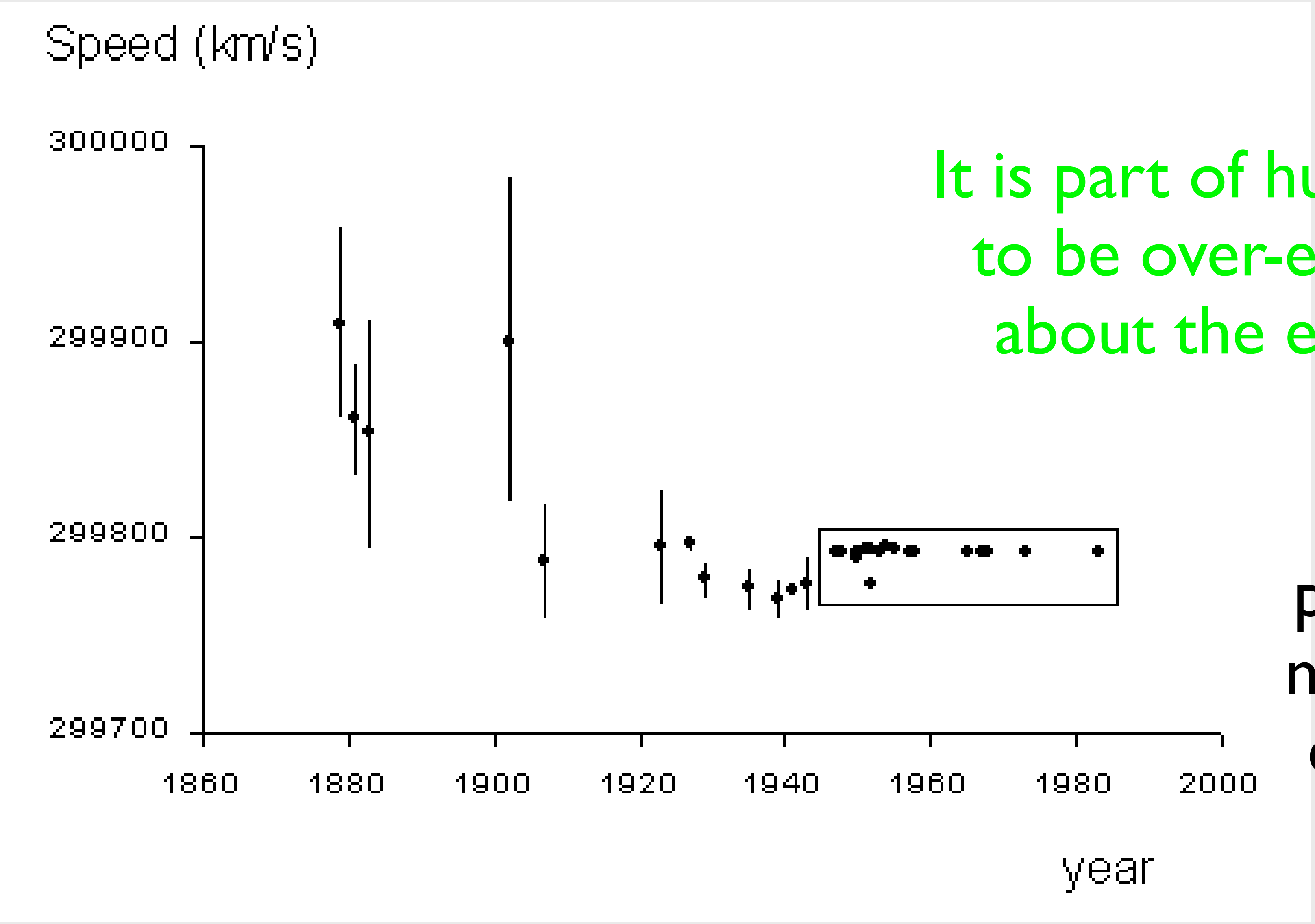


The Hubble diagram for type Ia supernovae. The scatter about the line corresponds to statistical distance errors of < 10% per object. The small red region in the lower left marks the span of Hubble's original Hubble diagram from 1929. [Kirshner 2003]



"Published values of the Hubble parameter versus time. At each epoch, the estimated error in the Hubble parameter is small compared with the subsequent changes in its value. This is a symptom of underestimated systematic errors."

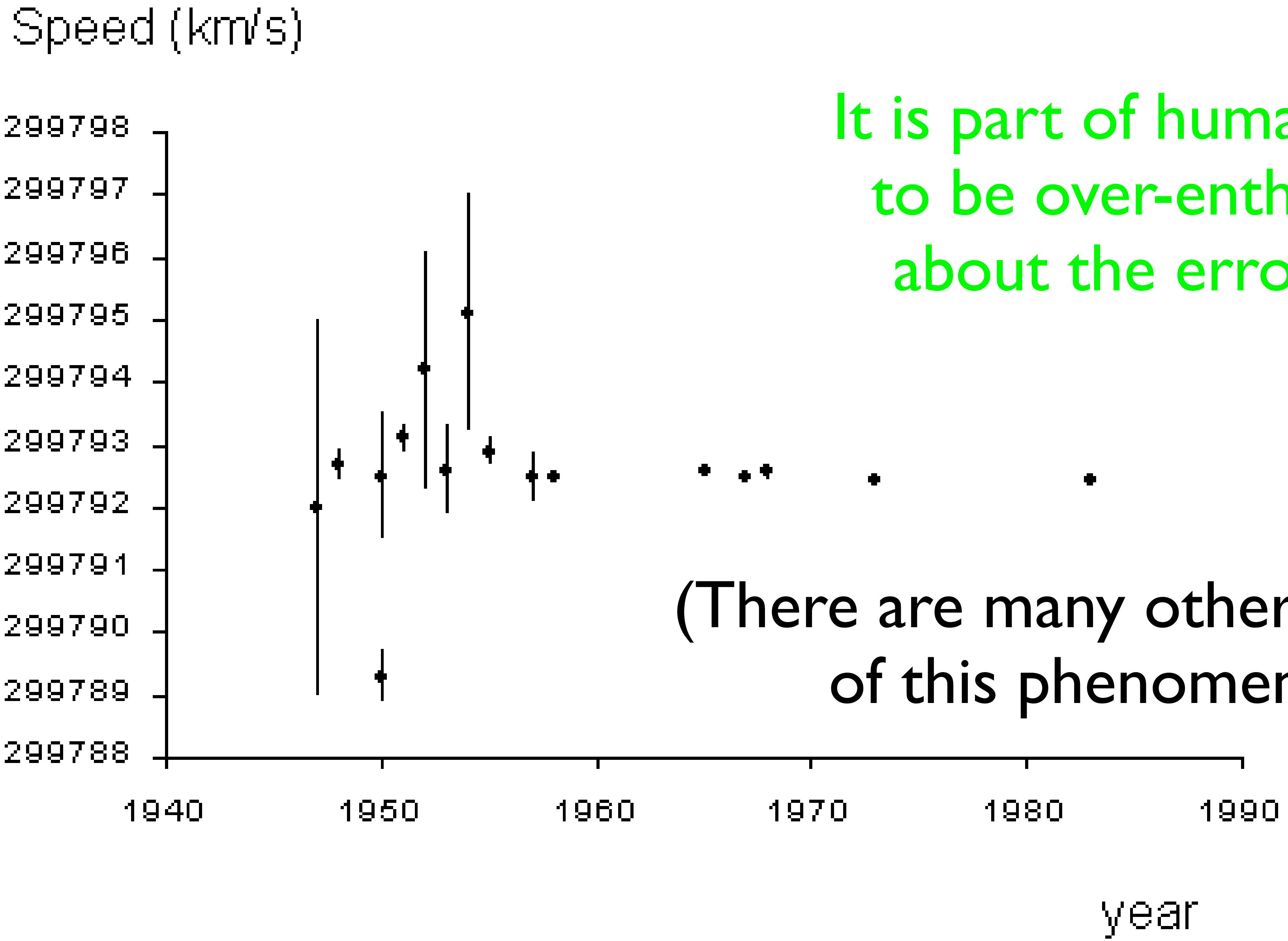
Speed of light since 1880:



It is part of human nature to be over-enthusiastic about the error bars.

This phenomenon not limited to cosmology...

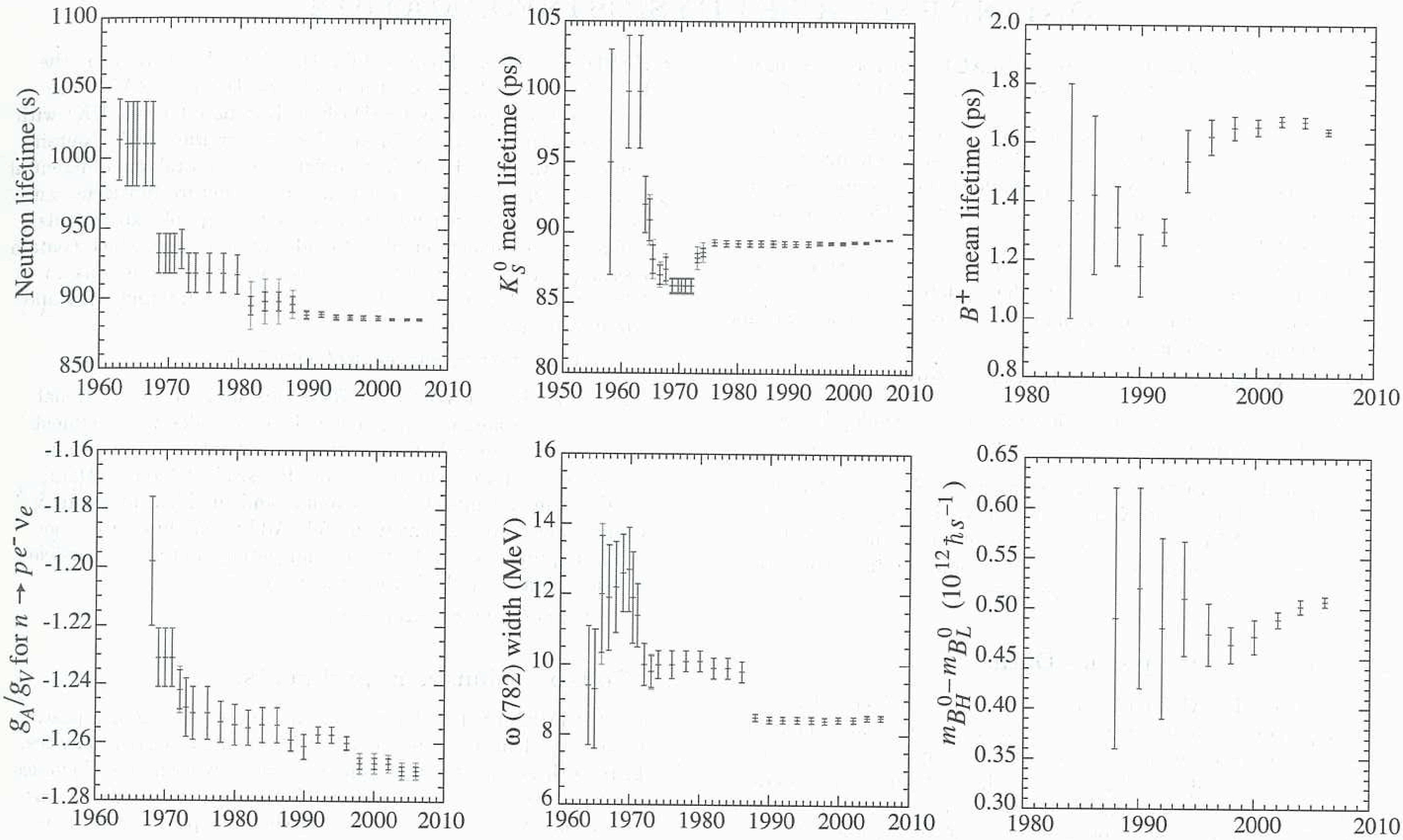
Speed of light since 1940:



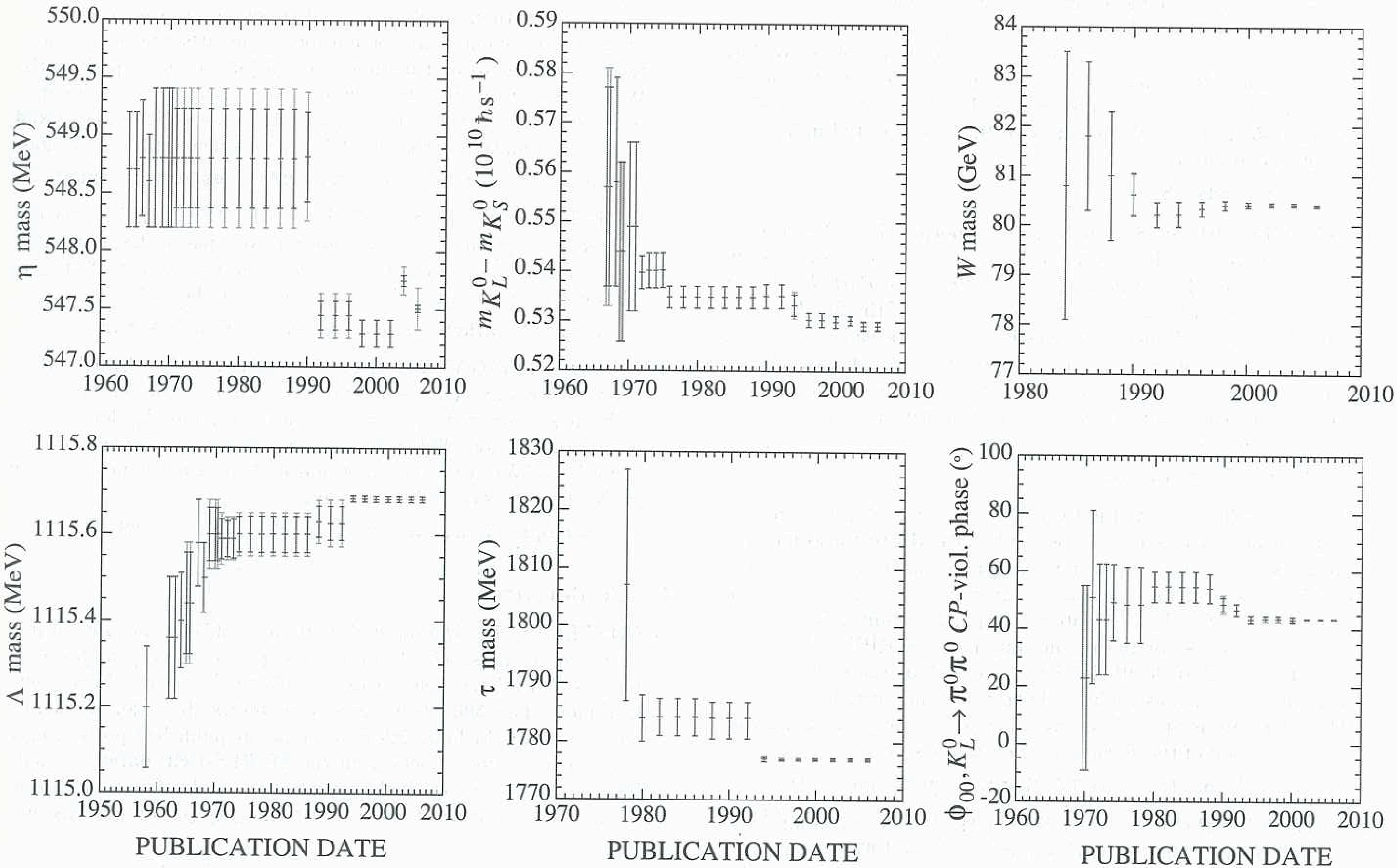
It is part of human nature to be over-enthusiastic about the error bars.

(There are many other examples of this phenomenon.)

Selected measurements from particle physics:



Selected measurements from particle physics:



Modern version of Hubble law:

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People prefer to work with redshift:

$$d = \frac{c\ z}{H_0} + \mathcal{O}(z^2).$$

$$1 + z = \frac{\lambda_{\text{received}}}{\lambda_{\text{emitted}}} = \frac{\omega_{\text{emitted}}}{\omega_{\text{received}}}.$$

Redshift is “easy” to measure...
distance is extremely difficult to measure...

What's with the $\mathcal{O}(z^2)$?

As the universe expands, one might reasonably expect the expansion to slow down...

The expansion is after all fighting against gravity...

So as you look further out into the night sky, since you are also looking further back in time, you might quite reasonably expect to be looking back to a time when the expansion might be faster than it is today.

Textbook cosmology:

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[for example: Weinberg, Peebles]

FLRW universe:

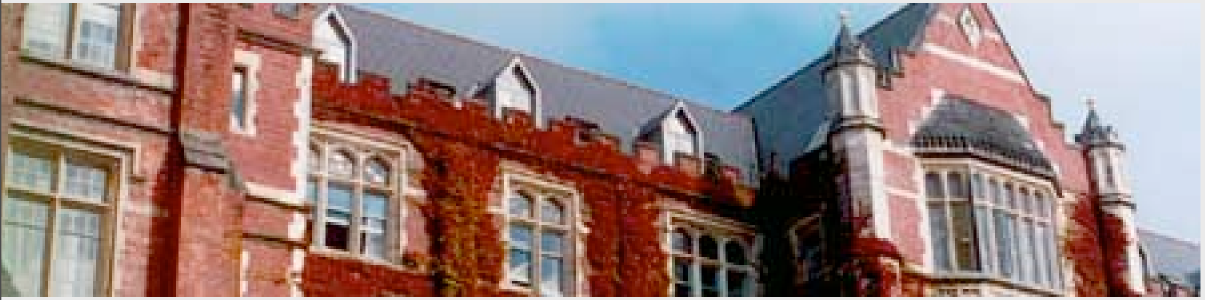
$$\mathrm{d}s^2 = -c^2\,\mathrm{d}t^2 + a(t)^2 \left\{ \frac{\mathrm{d}r^2}{1-kr^2} + r^2\left[\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2\right] \right\}$$

$a(t)$ is the "scale factor" of the universe; units of distance.

r is just a label, dimensionless.

$$k \in \{-1, 0, +1\}.$$

To do this you just need symmetries,
no dynamical assumptions...



Textbook definitions:

$$H(t) = \frac{\dot{a}(t)}{a(t)};$$ Hubble parameter.

$$q(t) = -\frac{\ddot{a}(t)\, a(t)}{\dot{a}(t)^2};$$ dimensionless deceleration parameter.

Until about 10 years ago everyone was expecting:

$$q(t) > 0; \qquad \Leftrightarrow \qquad \ddot{a} < 0.$$

Current data seems to suggest the opposite:

$$q(t) < 0; \qquad \Leftrightarrow \qquad \ddot{a} > 0. \qquad ???$$

Textbook exercise:

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[for example: Weinberg, Peebles]

For a suitable definition of distance: [luminosity distance]

$$d_L(z) = \frac{c\ z}{H_0}\left\{1 + \frac{1}{2}\left[1 - q_0\right] z + O(z^2)\right\}.$$

$$H_0 = \frac{\dot{a}(t_0)}{a(t)}; \qquad q(t_0) = -\frac{\ddot{a}(t_0)\ a(t_0)}{\dot{a}(t_0)^2}.$$

That is, evaluate the Hubble and deceleration parameters now (current epoch).

Modern version of Hubble law:

[for example: Chiba, Sahni, Visser]

$$d_L(z) = \frac{c\, z}{H_0}\left\{1 + \frac{1}{2}\left[1 - q_0\right] z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 + \frac{kc^2}{H_0^2\, a_0^2}\right] z^2 + O(z^3)\right\}.$$

"Jerk" parameter:

$$j(t) = \frac{\dddot{a}(t)\; a(t)^2}{\dot{a}(t)^3}; \qquad j_0 = \frac{\dddot{a}(t_0)\; a(t_0)^2}{\dot{a}(t_0)^3}.$$

Higher-order expansions are possible... [Visser]

Mechanics	Cosmology
position	scale factor
velocity	Hubble parameter
acceleration	deceleration
jerk	jerk parameter
snap	snap parameter
crackle	...
pop	...

Modern tests:

Latest tests of the Hubble law are based largely on supernova data, approximately 200 supernovae.

Now have data out to redshift: $z \sim 1.75$

Major datasets:
- Gold+Silver+Nearby (gold06)
- Supernova Legacy Survey (legacy05)

Lots of little "quirks" hiding in the processed data.

Photon flux version of the Hubble law:

$$d_F(z) = d_H\ z\left\{1 - \frac{1}{2}q_0 z + \frac{1}{24}\left[3 + 10q_0 + 12q_0^2 - 4(j_0 + \Omega_0)\right] z^2 + O(z^3)\right\}.$$

[count photons, not energy]

Transform it:

[Visser, Cattoen]

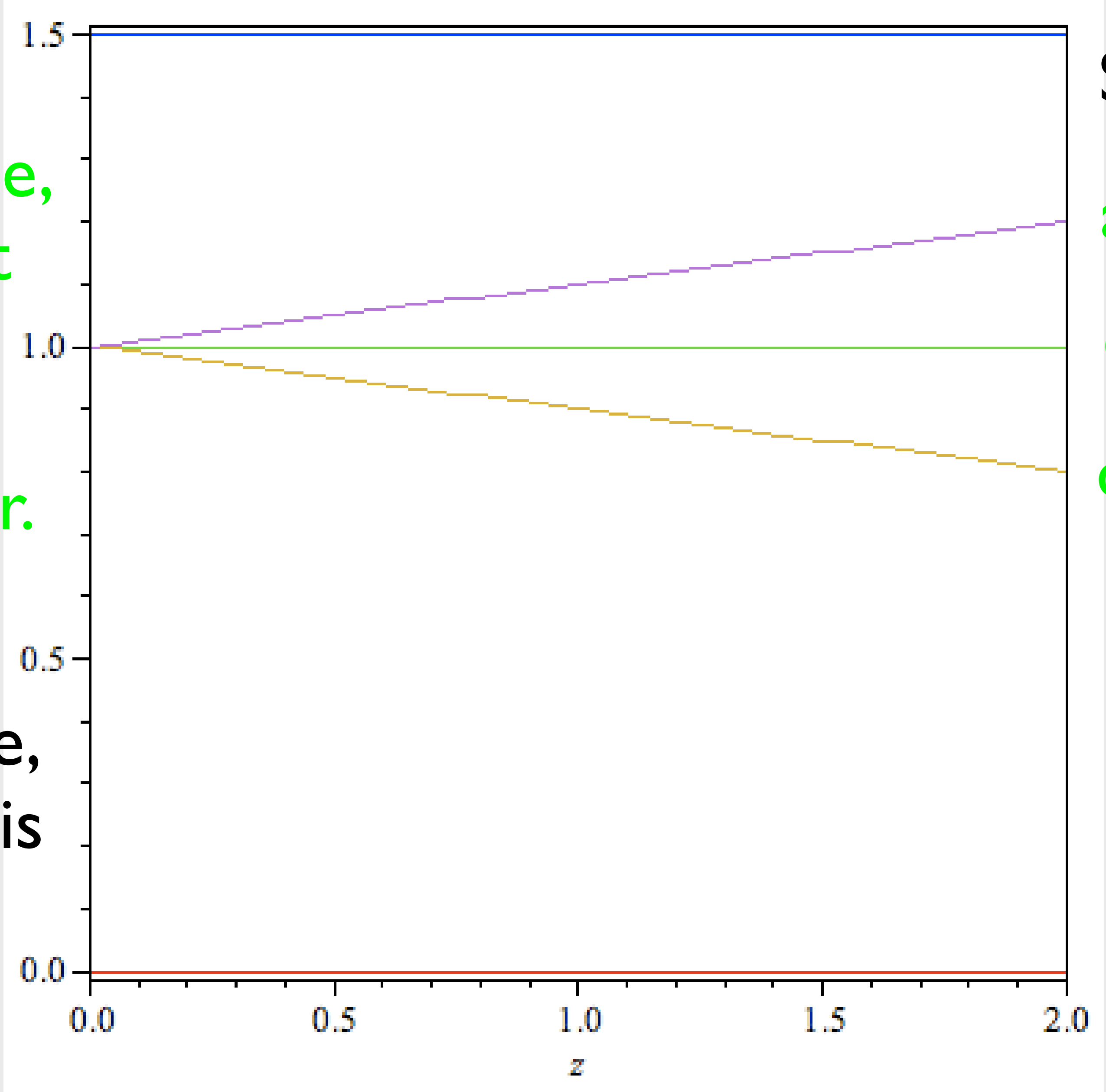
$$\begin{aligned}\ln[d_F/(z\ \mathrm{Mpc})] &= \frac{\ln 10}{5}[\mu_D - 25] - \ln z - \frac{1}{2}\ln(1+z) \\ &= \ln(d_H/\mathrm{Mpc}) \\ &\quad - \frac{1}{2}q_0 z + \frac{1}{24}\left[3 + 10q_0 + 9q_0^2 - 4(j_0 + \Omega_0)\right] z^2 + O(z^3).\end{aligned}$$

--- simple probe for deceleration parameter

--- stellar magnitude and redshift provided in the data

--- plot the data...

We expect something like this:



In principle, intercept yields Hubble parameter.

In practice, intercept is noise...

Slope yields:

acceleration

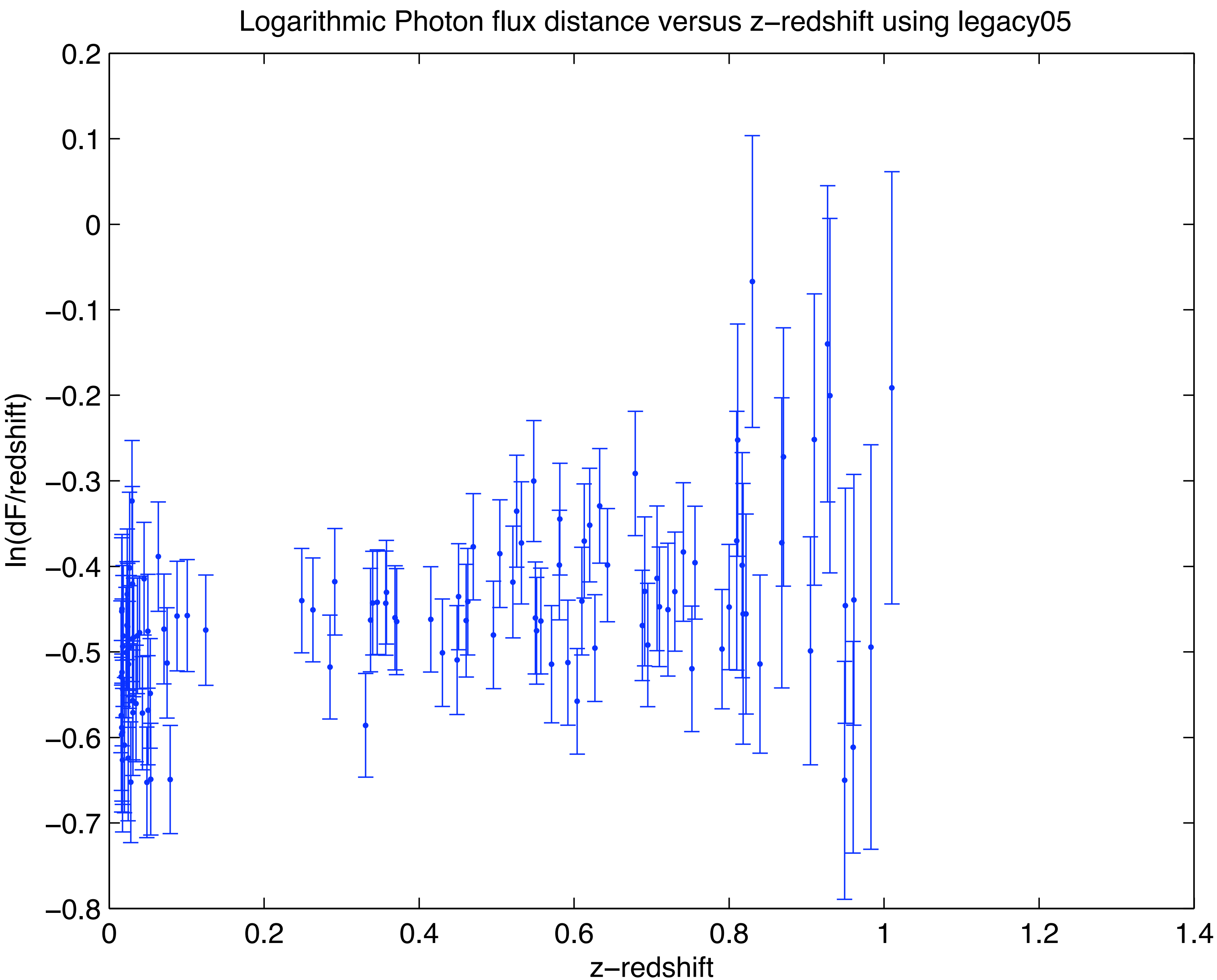
coasting

deceleration

(overall calibration difficult...)

(diagnostic?)

We get this:



legacy05

Smaller dataset, but homogeneous.

We get this:

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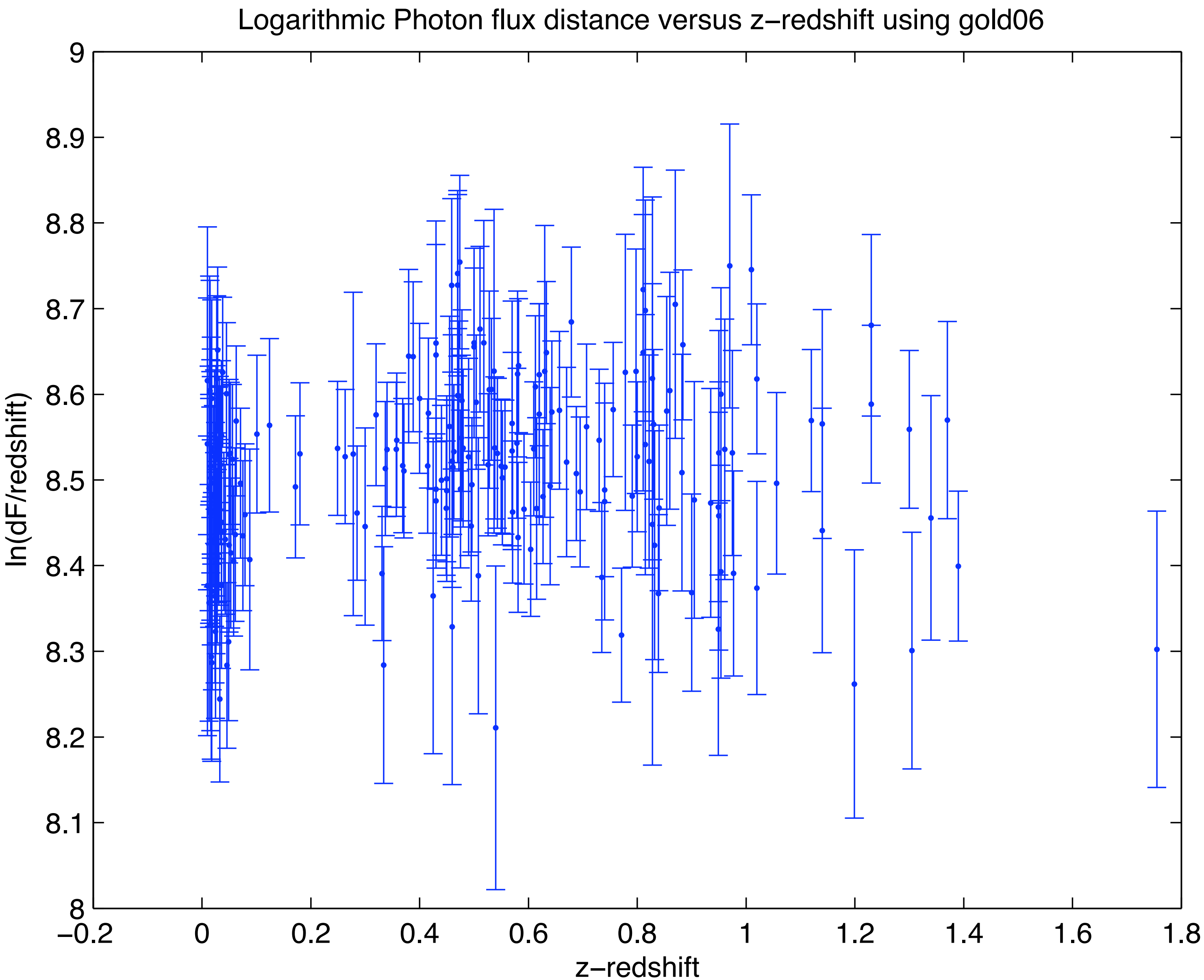

gold06

Larger dataset, but not homogeneous.

Combined dataset from six different observing platforms.

Lies,
damned lies,
and statistics...

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The situation is actually worse than it looks because the plotted error bars report only part of the uncertainty...

The plots include photometric uncertainties plus "intrinsic variability" in the supernovae...

The supernovae are not quite "standard candles", they are only "standard on average"...

You have to estimate intrinsic variability by looking at nearby supernovae, where we have independent distance measurements...

Lies, damned lies, and statistics...

The plots do not include systematic uncertainties, neither "known unknowns" nor a budget for "unknown unknowns".

(This is traditional in cosmology...)

"Known unknowns" are estimated to permit an uncertainty amounting to a drift of about 5% in distance measurements over a redshift range of: $\Delta z = 1.$

"Unknown unknowns" can be estimated historically...

Historical uncertainties:

Most recent:

- As of 2006 the high redshift supernovae have all moved 5% closer than estimated in 2004.

  (Improved understanding and characterization of nonlinearities in the photodetectors.)

- Over the last decade there have still been 15% disagreements over the size of our own galaxy... (Hipparcos satellite data.)

- Hubble's mis-calibrated Cephid variables led to some 666% error...

NIST guidelines:

Type B evaluations of uncertainty:

"any method of evaluation of uncertainty by means other than the statistical analysis of a series of observations"

"A type B evaluation of standard uncertainty is usually based on scientific judgment using all of the relevant information available, which may include: previous measurement data, etc..."

NIST Technical Note 1297.

Lies, damned lies, and statistics...

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In the total error budget you should really include:

statistical	photometric
	intrinsic
	* modelling *
systematic	known unknowns
	unknown unknowns

* more on this later...

NIST recommended practice:

* Treat all uncertainties, whatever their source, "as though" they were statistical, and report an "equivalent one-sigma uncertainty"...

* Always combine uncertainties in quadrature, unless you have good reason to believe there is a correlation...

* In particular, combine statistical and systematic uncertainties in quadrature...

Modelling uncertainty:

Essentially, ask the same statistical question several slightly different ways, and see if the estimates are close to each other...

There are at least five different "natural" ways of estimating the deceleration and jerk parameters...

Perform least squares fits to the five models, all slightly different...

Then extract five (slightly?) different estimates of the deceleration and jerk parameters...

Other "distances"

- The "photon flux distance":

$$d_F = \frac{d_L}{(1+z)^{1/2}}.$$

- The "photon count distance":

$$d_P = \frac{d_L}{(1+z)}.$$

- The "deceleration distance":

$$d_Q = \frac{d_L}{(1+z)^{3/2}}.$$

- The "angular diameter distance":

$$d_A = \frac{d_L}{(1+z)^{2}}.$$

It should not matter which notion of distance you use...

Other Hubble laws:

$$d_L(z) = d_H\ z\left\{1 - \frac{1}{2}\left[-1 + q_0\right] z + \frac{1}{6}\left[q_0 + 3q_0^2 - (j_0 + \Omega_0)\right] z^2 + O(z^3)\right\}.$$

$$d_F(z) = d_H\ z\left\{1 - \frac{1}{2} q_0 z + \frac{1}{24}\left[3 + 10q_0 + 12q_0^2 - 4(j_0 + \Omega_0)\right] z^2 + O(z^3)\right\}.$$

$$d_P(z) = d_H\ z\left\{1 - \frac{1}{2}\left[1 + q_0\right] z + \frac{1}{6}\left[3 + 4q_0 + 3q_0^2 - (j_0 + \Omega_0)\right] z^2 + O(z^3)\right\}.$$

$$d_Q(z) = d_H\ z\left\{1 - \frac{1}{2}\left[2 + q_0\right] z + \frac{1}{24}\left[27 + 22q_0 + 12q_0^2 - 4(j_0 + \Omega_0)\right] z^2 + O(z^3)\right\}.$$

$$d_A(z) = d_H\ z\left\{1 - \frac{1}{2}\left[3 + q_0\right] z + \frac{1}{6}\left[12 + 7q_0 + 3q_0^2 - (j_0 + \Omega_0)\right] z^2 + O(z^3)\right\}.$$

What you actually use:

data

$$\ln[d_L/(z\ \text{Mpc})] = \frac{\ln 10}{5}[\mu_D - 25] - \ln z$$

$$= \ln(d_H/\text{Mpc})$$

$$- \frac{1}{2}\left[-1 + q_0\right] z + \frac{1}{24}\left[-3 + 10q_0 + 9q_0^2 - 4(j_0 + \Omega_0)\right] z^2 + O(z^3).$$

noise?

fit

Other Hubble laws:

$$\ln[d_F/(z\ \mathrm{Mpc})] = \frac{\ln 10}{5}[\mu_D - 25] - \ln z - \frac{1}{2}\ln(1+z)$$
$$= \ln(d_H/\mathrm{Mpc})$$
$$-\frac{1}{2}q_0 z + \frac{1}{24}\left[3 + 10q_0 + 9q_0^2 - 4(j_0+\Omega_0)\right] z^2 + O(z^3).$$

$$\ln[d_P/(z\ \mathrm{Mpc})] = \frac{\ln 10}{5}[\mu_D - 25] - \ln z - \ln(1+z)$$
$$= \ln(d_H/\mathrm{Mpc})$$
$$-\frac{1}{2}\left[1+q_0\right] z + \frac{1}{24}\left[9 + 10q_0 + 9q_0^2 - 4(j_0+\Omega_0)\right] z^2 + O(z^3).$$

$$\ln[d_Q/(z\ \mathrm{Mpc})] = \frac{\ln 10}{5}[\mu_D - 25] - \ln z - \frac{3}{2}\ln(1+z)$$
$$= \ln(d_H/\mathrm{Mpc})$$
$$-\frac{1}{2}\left[2+q_0\right] z + \frac{1}{24}\left[15 + 10q_0 + 9q_0^2 - 4(j_0+\Omega_0)\right] z^2 + O(z^3).$$

$$\ln[d_A/(z\ \mathrm{Mpc})] = \frac{\ln 10}{5}[\mu_D - 25] - \ln z - 2\ln(1+z)$$
$$= \ln(d_H/\mathrm{Mpc})$$
$$-\frac{1}{2}\left[3+q_0\right] z + \frac{1}{24}\left[21 + 10q_0 + 9q_0^2 - 4(j_0+\Omega_0)\right] z^2 + O(z^3).$$

Huh, why are the estimates different?

Because the process of performing a least squares fit
does not commute
with the process of truncating a Taylor series...

(And the amount by which these processes fail to commute gives you an estimate of the extent to which you should trust the output of the statistical analysis...)

((Trust me, you really do not want to see the relevant formulae))

[Cattoen, Visser, gr-qc/0703122]

legacy05 dataset

distance	q_0	$j_0 + \Omega_0$
d_L	-0.48 ± 0.17	$+0.43 \pm 0.60$
d_F	-0.56 ± 0.17	$+1.16 \pm 0.65$
d_P	-0.62 ± 0.17	$+1.92 \pm 0.69$
d_Q	-0.69 ± 0.17	$+2.69 \pm 0.74$
d_A	-0.75 ± 0.17	$+3.49 \pm 0.79$

With 1-σ statistical uncertainties.

gold06
dataset

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distance	q_0	$j_0 + \Omega_0$
d_L	-0.37 ± 0.11	$+0.26 \pm 0.20$
d_F	-0.48 ± 0.11	$+1.10 \pm 0.24$
d_P	-0.58 ± 0.11	$+1.98 \pm 0.29$
d_Q	-0.68 ± 0.11	$+2.92 \pm 0.37$
d_A	-0.79 ± 0.11	$+3.90 \pm 0.39$

With 1-σ statistical uncertainties.

Combine the analyses:

dataset	redshift	$q_0 \pm \sigma_{\text{statistical}} \pm \sigma_{\text{modelling}}$
~~legacy05~~	~~y~~	~~$-0.66 \pm 0.38 \pm 0.13$~~
legacy05	z	$-0.62 \pm 0.17 \pm 0.10$
~~gold06~~	~~y~~	~~$-0.94 \pm 0.29 \pm 0.22$~~
gold06	z	$-0.58 \pm 0.11 \pm 0.15$

With 1-σ statistical uncertainties and 1-σ model building uncertainties, no budget for "systematic" uncertainties.

(We shall draw a veil of discrete silence over the unfortunate status of the jerk parameter.)

Include systematics:

dataset	redshift	$q_0 \pm \sigma_{\text{statistical}} \pm \sigma_{\text{modelling}} \pm \sigma_{\text{systematic}} \pm \sigma_{\text{historical}}$
~~legacy05~~	~~y~~	~~$-0.66 \pm 0.38 \pm 0.13 \pm 0.09 \pm 0.09$~~
legacy05	z	$-0.62 \pm 0.17 \pm 0.10 \pm 0.09 \pm 0.09$
~~gold06~~	~~y~~	~~$-0.94 \pm 0.29 \pm 0.22 \pm 0.09 \pm 0.09$~~
gold06	z	$-0.58 \pm 0.11 \pm 0.15 \pm 0.09 \pm 0.09$

With 1-σ effective statistical uncertainties for all components.

I think you can see where this is headed...

(Some astrophysicists think we should provide even larger historical uncertainties.)

New redshift variable:

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No one can stop me from defining:

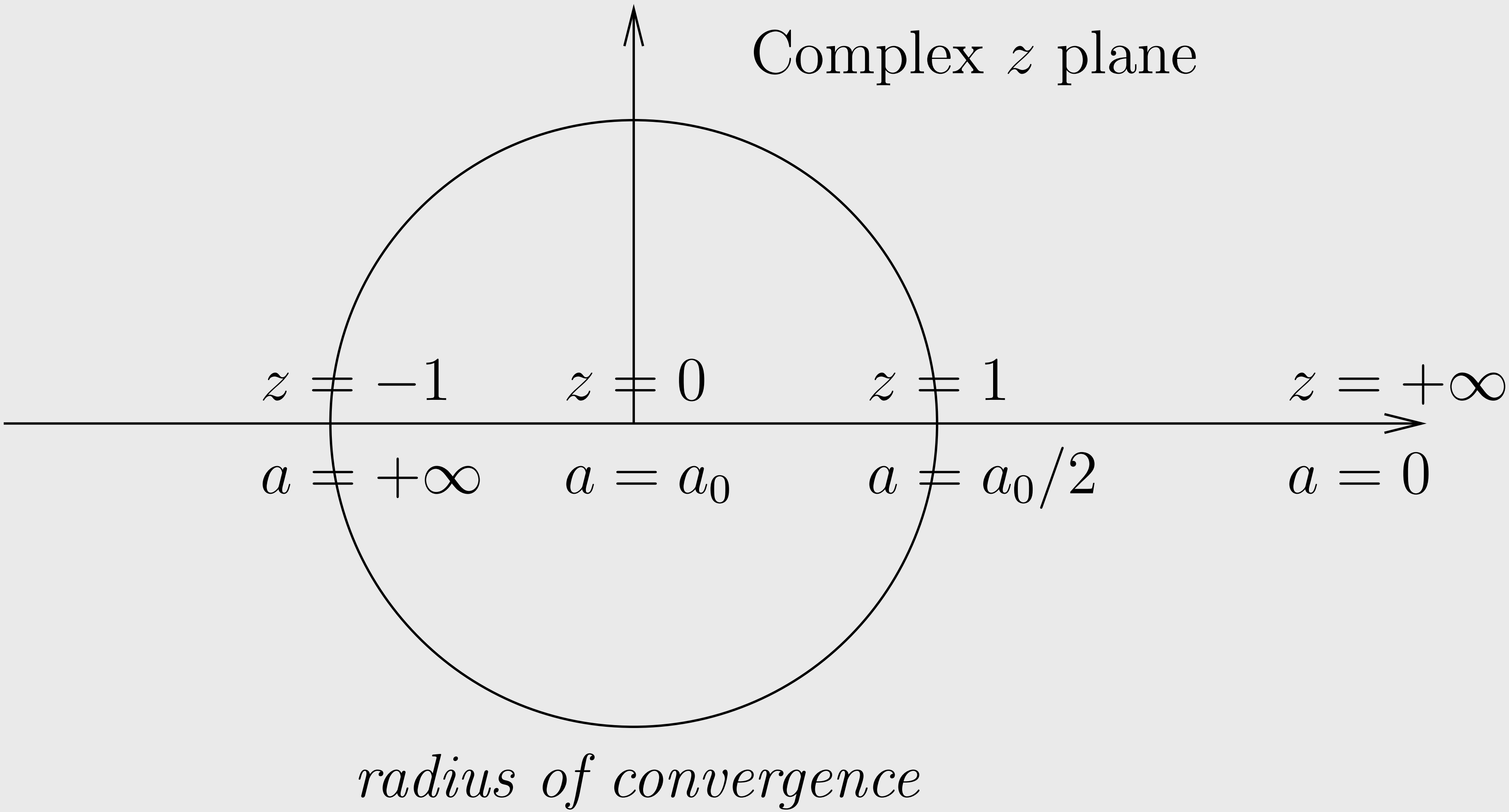
$$y = \frac{\lambda_0 - \lambda_e}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0}$$

in which case

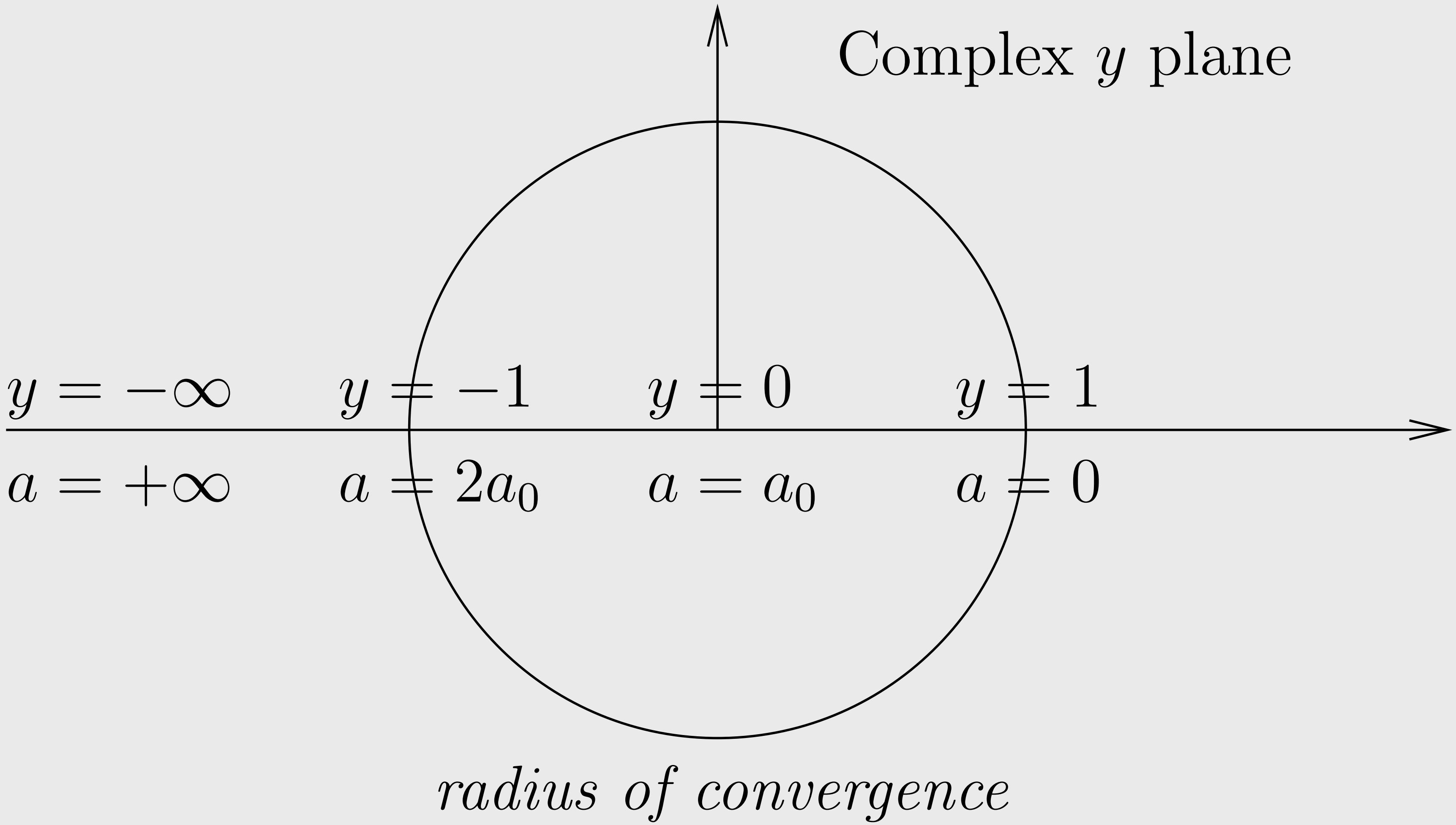
$$1 - y = \frac{\lambda_e}{\lambda_0} = \frac{a(t_e)}{a(t_0)} = \frac{1}{1+z}.$$

There is no physics reason to prefer "z" over "y", and for some purposes "y" is better...

(better convergence properties for "z" > 1.)



Complex z plane
$z = -1$
$z = 0$
$z = 1$
$z = +\infty$
$a = +\infty$
$a = a_0$
$a = a_0/2$
$a = 0$
radius of convergence



Complex y plane
$y = -\infty$
$y = -1$
$y = 0$
$y = 1$
$a = +\infty$
$a = 2a_0$
$a = a_0$
$a = 0$
radius of convergence

Other Hubble laws:

$$d_L(y) = d_H\ y\left\{1 - \frac{1}{2}\left[-3 + q_0\right] y + \frac{1}{6}\left[12 - 5q_0 + 3q_0^2 - (j_0 + \Omega_0)\right] y^2 + O(y^3)\right\}.$$

$$d_F(y) = d_H\ y\left\{1 - \frac{1}{2}\left[-2 + q_0\right] y + \frac{1}{24}\left[27 - 14q_0 + 12q_0^2 - 4(j_0 + \Omega_0)\right] y^2 + O(y^3)\right\}.$$

$$d_P(y) = d_H\ y\left\{1 - \frac{1}{2}\left[-1 + q_0\right] y + \frac{1}{6}\left[3 - 2q_0 + 3q_0^2 - (j_0 + \Omega_0)\right] y^2 + O(y^3)\right\}.$$

$$d_Q(y) = d_H\ y\left\{1 - \frac{q_0}{2} y + \frac{1}{12}\left[3 - 2q_0 + 12q_0^2 - 4(j_0 + \Omega_0)\right] y^2 + O(y^3)\right\}.$$

$$d_A(y) = d_H\ y\left\{1 - \frac{1}{2}\left[1 + q_0\right] y + \frac{1}{6}\left[q_0 + 3q_0^2 - (j_0 + \Omega_0)\right] y^2 + O(y^3)\right\}.$$

Other Hubble laws:

$$\ln[d_L/(y\ \mathrm{Mpc})] = \frac{\ln 10}{5}[\mu_D - 25] - \ln y$$
$$= \ln(d_H/\mathrm{Mpc})$$
$$-\frac{1}{2}\left[-3 + q_0\right] y + \frac{1}{24}\left[21 - 2q_0 + 9q_0^2 - 4(j_0 + \Omega_0)\right] y^2 + O(y^3).$$

$$\ln[d_F/(y\ \mathrm{Mpc})] = \frac{\ln 10}{5}[\mu_D - 25] - \ln y + \frac{1}{2}\ln(1-y)$$
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$$\ln[d_Q/(y\ \mathrm{Mpc})] = \frac{\ln 10}{5}[\mu_D - 25] - \ln y + \frac{3}{2}\ln(1-y)$$
$$= \ln(d_H/\mathrm{Mpc})$$
$$-\frac{1}{2}q_0\, y + \frac{1}{24}\left[3 - 2q_0 + 9q_0^2 - 4(j_0 + \Omega_0)\right] y^2 + O(y^3).$$

$$\ln[d_A/(y\ \mathrm{Mpc})] = \frac{\ln 10}{5}[\mu_D - 25] - \ln y + 2\ln(1-y)$$
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(never mind the details, you just need to know that such expansions exist...)

Combine the analyses:

dataset	redshift	$q_0 \pm \sigma_{\text{statistical}} \pm \sigma_{\text{modelling}}$
legacy05	y	$-0.66 \pm 0.38 \pm 0.13$
legacy05	z	$-0.62 \pm 0.17 \pm 0.10$
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With 1-σ statistical uncertainties and 1-σ model building uncertainties, no budget for "systematic" uncertainties.

(We shall draw a veil of discrete silence over the unfortunate status of the jerk parameter.)

Include systematics:

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gold06	z	$-0.58 \pm 0.11 \pm 0.15 \pm 0.09 \pm 0.09$

With 1-σ effective statistical uncertainties for all components.

I think you can see where this is headed...

(Some astrophysicists think we should provide even larger historical uncertainties.)

Combine uncertainties:

$$\sigma_{\text{combined}} = \sqrt{\sigma^2_{\text{statistical}} + \sigma^2_{\text{modelling}} + \sigma^2_{\text{systematic}} + \sigma^2_{\text{historical}}}.$$

Expanded uncertainty: $$U_k = k\,\sigma_{\text{combined}}.$$ [NIST]

Used when you need to be "certain" for either scientific or legal/ regulatory reasons...

Bitter experience in particle physics:

"If it's not 3-sigma, it's not physics..."

$$U_3 = 3\,\sigma_{\text{combined}}.$$ [now 5-sigma?]

The 3-sigma standard:

Three-sigma corresponds to being 99.5% statistically sure you have a real effect...

Three-sigma is the minimum standard considered acceptable in particle physics before claiming "new physics"...

(This is of course a scientific judgment based on the historical record of what has worked in the past...)

The 3-sigma standard:

dataset	redshift	$q_0 \pm \sigma_{\text{combined}}$	$q_0 \pm U_3$
legacy05	y	-0.66 ± 0.42	-0.66 ± 1.26
legacy05	z	-0.62 ± 0.23	-0.62 ± 0.70
gold06	y	-0.94 ± 0.39	-0.94 ± 1.16
gold06	z	-0.58 ± 0.23	-0.58 ± 0.68

That is: not statistically significant at three-sigma.

Preponderance of evidence:

The universe is accelerating.

But (based on supernova data alone), this acceleration is not established "beyond reasonable doubt".

There are an awful lot of subtleties hiding in the woodwork of the statistical analyses...

Antidote to excessive statistical sophistication:

Antidote:

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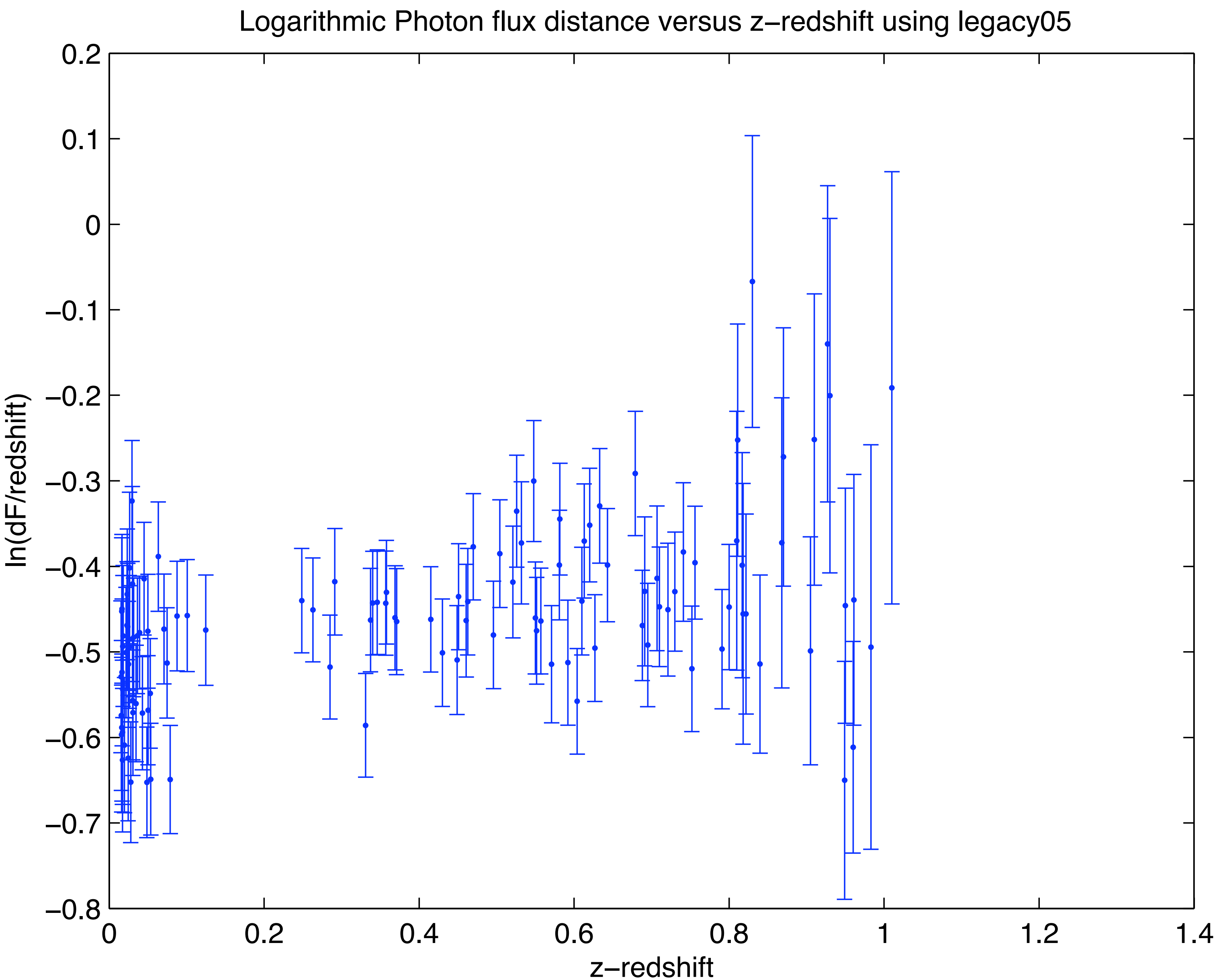

(statistical uncertainties only)

(legacy05)

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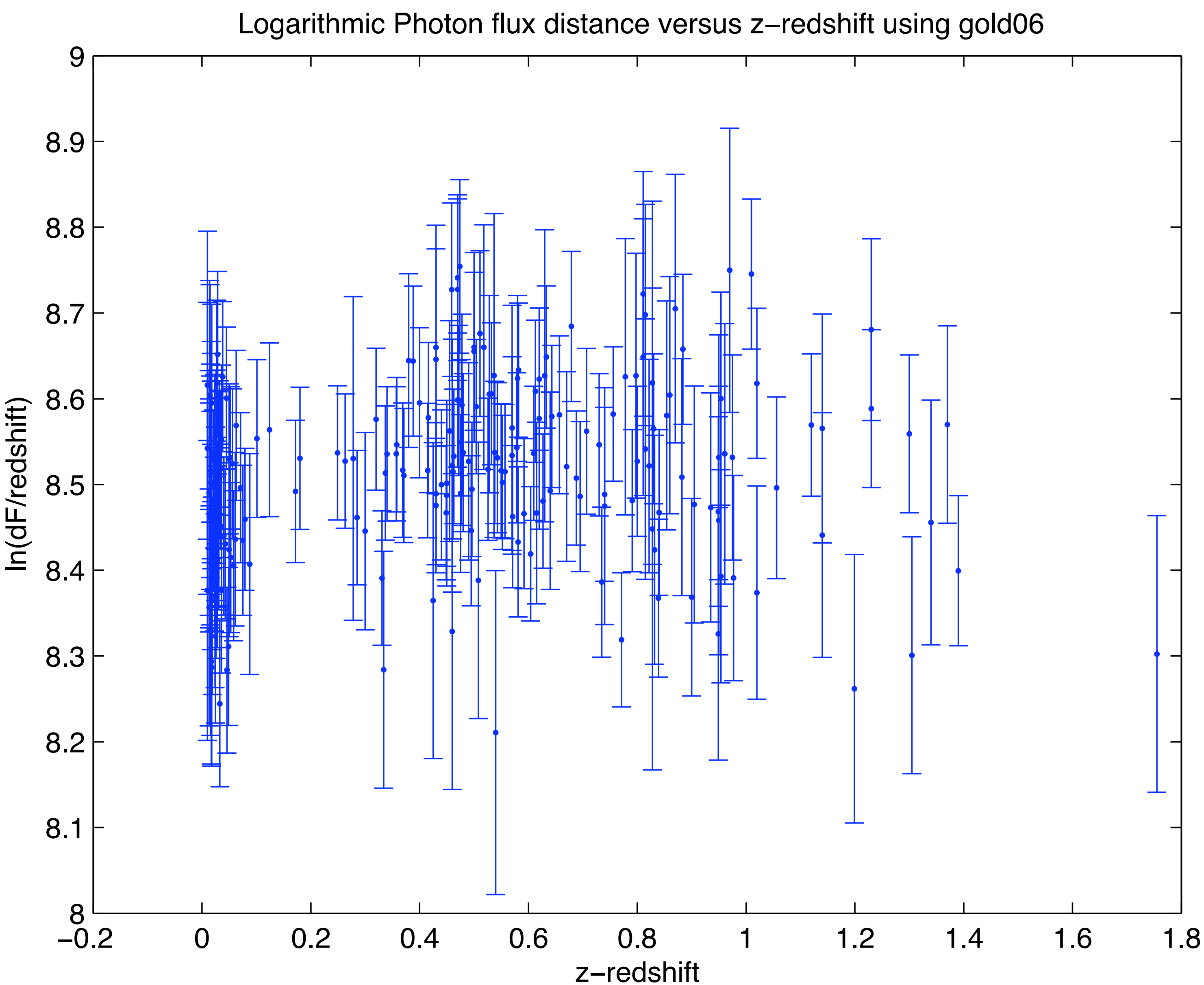


(statistical uncertainties only)

(gold06)

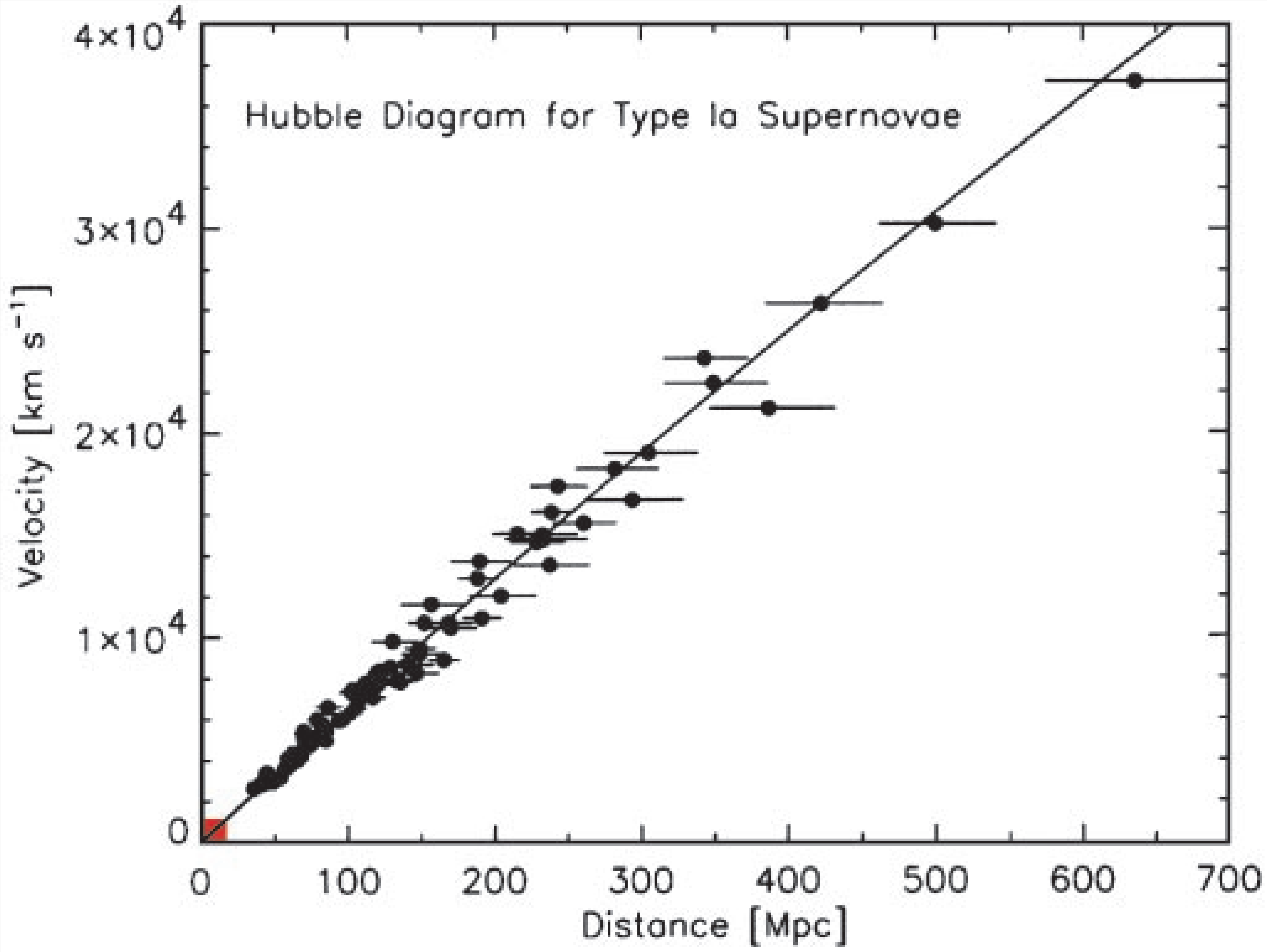
* The fact that there is no overwhelmingly obvious visual trend in these two graphs tells you that extracting the deceleration parameter will at best be a very tricky and uncertain process.

* However, the leading term in the Hubble law,

$$d = \frac{c\; z}{H_0} + \mathcal{O}(z^2),$$

is certainly well supported by the supernova data.

Kirshner 2003



* Some parts of cosmology are already precision science.

* Cosmological distance determinations, however, are not yet precision science.

"Precision cosmology? Not just yet."

[astro-ph/0303180]

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“It is important to keep an open mind; just not so open that your brains fall out”

--- Albert Einstein