TYPE IA SUPERNOVAE THE ACCELERATING COSMOS AND DARK ENERGY

Brian P. Schmidt

Mount Stromlo Observatory

Australian National University

Our Paradigm for Understanding the Global Evolution of the Universe is based on:

OUR PARADIGM FOR UNDERSTANDING THE GLOBAL EVOLUTION OF THE UNIVERSE IS BASED ON:

- Theory

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and an assumption...

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and an assumption...

- The Universe is homogenous and isotropic on large scales

THE STANDARD MODEL

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Robertson-Walker line element

$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2\right]$$

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Distance

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Distance Time

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Distance

Time

Coordinates

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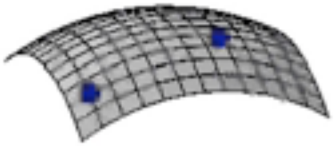
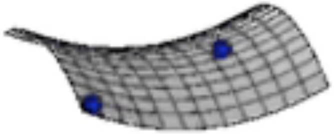
Distance Time

Curvature Coordinates





The Standard Model

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Distance Time Dynamics Curvature Coordinates

a(t) is known as the scale factor-it tracks the size of a piece of the Universe

$$\frac{a}{a_0} = \frac{1}{(1+z)}$$

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THE STANDARD MODEL

Friedmann Equation

(assumes homogenous and isotropic Universe)

$$a(t = t_0) = a_0, \quad \rho(t = t_0) = \rho_0, \quad H(t = t_0) = H_0, \quad k = 0$$

$$\left(\frac{1}{a_0}\frac{da}{dt}\right)^2 = H_0^2 \left(\frac{\rho}{\rho_0}\right)^2 \left(\frac{a}{a_0}\right)^2$$

Friedmann equation for Flat Universe

MODEL CONTENT OF UNIVERSE BY THE EQUATION OF STATE OF THE DIFFERENT FORMS OF MATTER/ENERGY

$$w_i \equiv \frac{P_i}{\rho_i} \qquad \rho_i \propto (\text{Volume})^{-(1+w_i)} \propto a^{-3(1+w_i)} \propto (1+z)^{3(1+w_i)}$$

e.g.,

w=0 ***for normal matter*** $\rho \propto V^{-1}$

w=1/3 ***for photons*** $\rho \propto V^{-4/3}$

w=−1 ***for Cosmological Constant*** $\rho \propto V^{0}$

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Flat Universe –Matter Dominated

$$\left(\frac{1}{a_0}\frac{da}{dt}\right)^2 = H_0^2\left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^2 \text{ Friedman Equation for a flat Universe}$$

$$y \equiv \frac{a}{a_0}, \left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^3 = 1 \text{ for matter dominated universe}$$

$$\left(\frac{dy}{dt}\right)^2 = H_0^2\left(\frac{a}{a_0}\right)^{-1} = H_0^2 y^{-1}$$

$$\sqrt{y}dy = H_0 dt$$

$$\frac{2}{3}y^{3/2}dy = H_0 t$$

$$y = \frac{a}{a_0} = \left(\frac{3H_0 t}{2}\right)^{2/3}$$

Flat Universe – Radiation Dominated

$$\left(\frac{dy}{dt}\right)^2 = H_0^2\left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^2$$

$$\left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^4 = 1 \text{ for radiation dominated universe}$$

$$\left(\frac{dy}{dt}\right)^2 = H_0^2\left(\frac{a}{a_0}\right)^{-2} = \frac{H_0^2}{y^2}$$

$$ydy = H_0 dt$$

$$\frac{y^2}{2} = H_0 t$$

$$y = \frac{a}{a_0} = \left(2H_0 t\right)^{1/2}$$

Flat Universe –Cosmological Constant Dominated

$$\left(\frac{dy}{dt}\right)^2 = H_0^2\left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^2$$

$$\left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^0 = 1 \text{ for cosmological constant dominated universe}$$

$$\left(\frac{dy}{dt}\right)^2 = H_0^2\left(\frac{a}{a_0}\right)^2 = H_0^2 y^2$$

$$\frac{1}{y}dy = H_0 dt$$

$$\ln(y) = H_0 t$$

$$y = \frac{a}{a_0}e^{H_0 t}$$

DOMINATION OF THE UNIVERSE

- As Universe Expands
  - Photon density increases as $(1+z)^4$
  - Matter density increases as $(1+z)^3$
  - Cosmological Constant invariant $(1+z)^0$

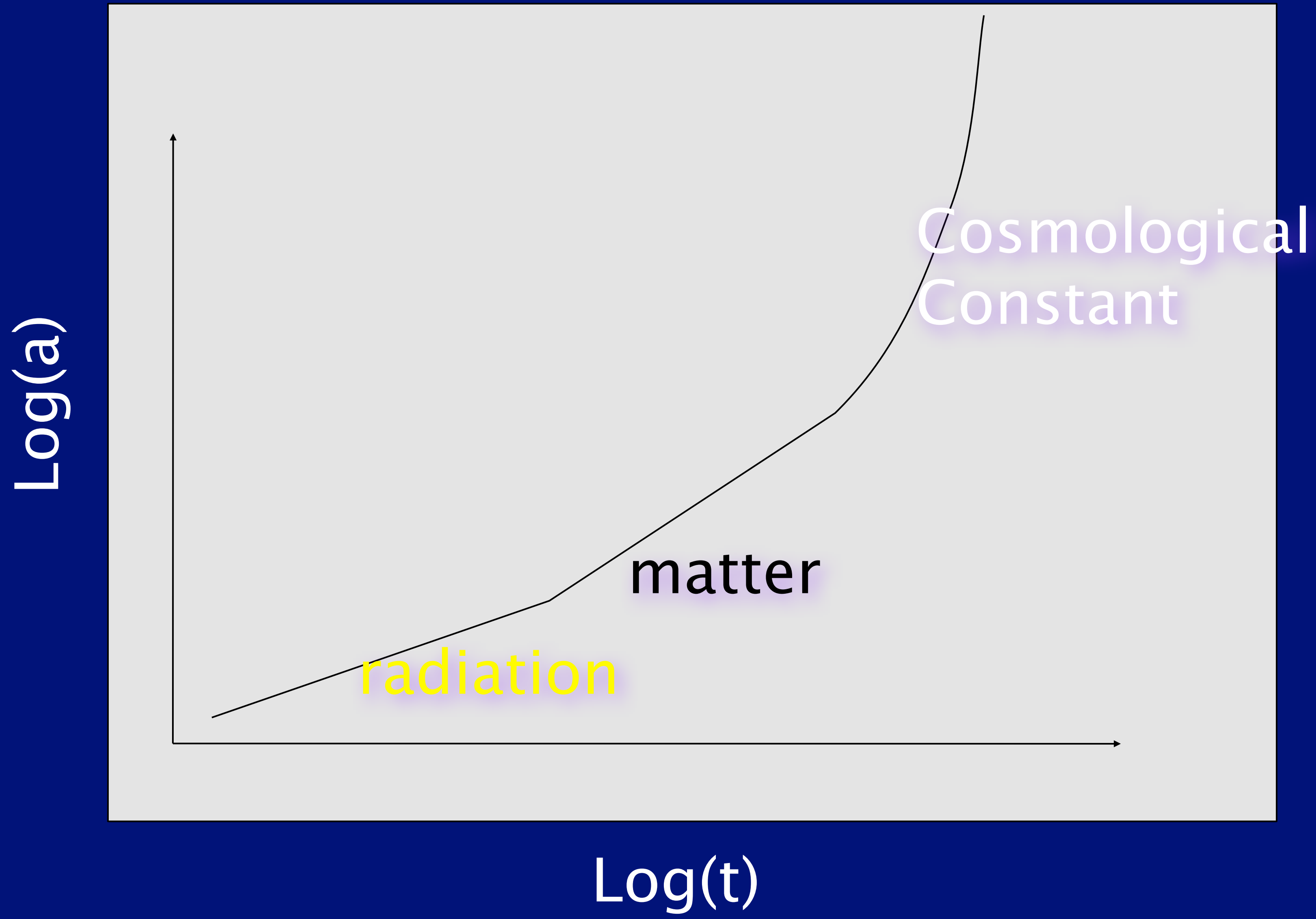
$$\Omega_i = \left(\frac{\rho_i}{\rho_{crit}}\right) = \left(\frac{\rho_i}{\frac{3H_0^2}{8\pi G}}\right)$$

$$\frac{\Omega_{rad}}{\Omega_M} = \left(\frac{a}{a_0}\right)^{-1} = (1+z)$$

$$\frac{\Omega_\Lambda}{\Omega_M} = \left(\frac{a}{a_0}\right)^{3} = (1+z)^{-3}$$

$$\frac{\Omega_w}{\Omega_M} = \left(\frac{a}{a_0}\right)^{-3w} = (1+z)^{3w}$$

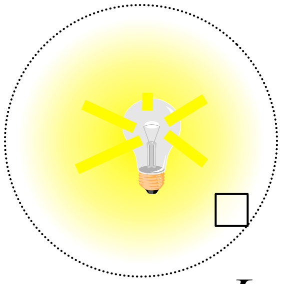
- Note that exactly flat Universe remains flat – i.e. $\Sigma\Omega_i=1$
- Accelerating Models tend towards flatness overtime (w<−1/3)
- Non accelerating(w>−1/3)


Log(a)
Cosmological
Constant
matter
radiation
Log(t)

LUMINOSITY DISTANCE

for a monochromatic source
(defined as inverse-square law)

$$D_L = \sqrt{\frac{L}{4\pi F}},$$



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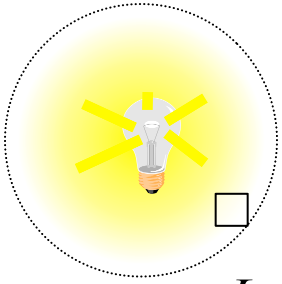

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the flux an observer sees of an object at redshift z

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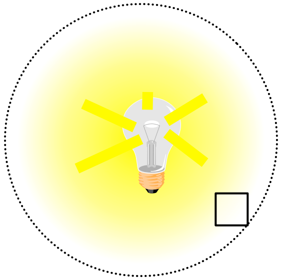

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$$D_L = \frac{c}{H_0}(1+z)\Omega_k^{-1/2} S\left\{\Omega_k^{1/2}\int_0^z dz' \left[\sum_i \Omega_i (1+z')^{3+3w_i} - \Omega_k (1+z')^2\right]^{-1/2}\right\}$$

$$\Omega_k = \left(\sum_i \Omega_i\right) - 1$$

$$S(x) = \begin{cases} \sin(x) & \text{k} = 1 \\ x & \text{k} = 0 \\ \sinh(x) & \text{k} = \text{-1} \end{cases}$$

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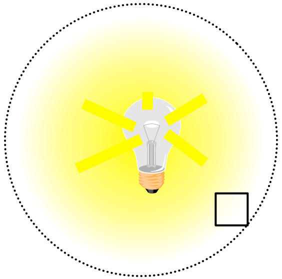

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Brightness of object depends exclusively on what is in the Universe - How much and its equation of state.

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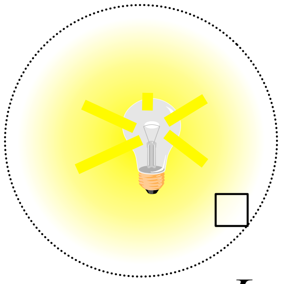

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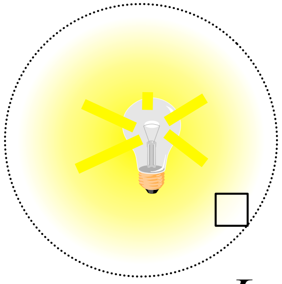

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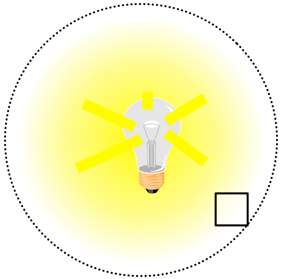

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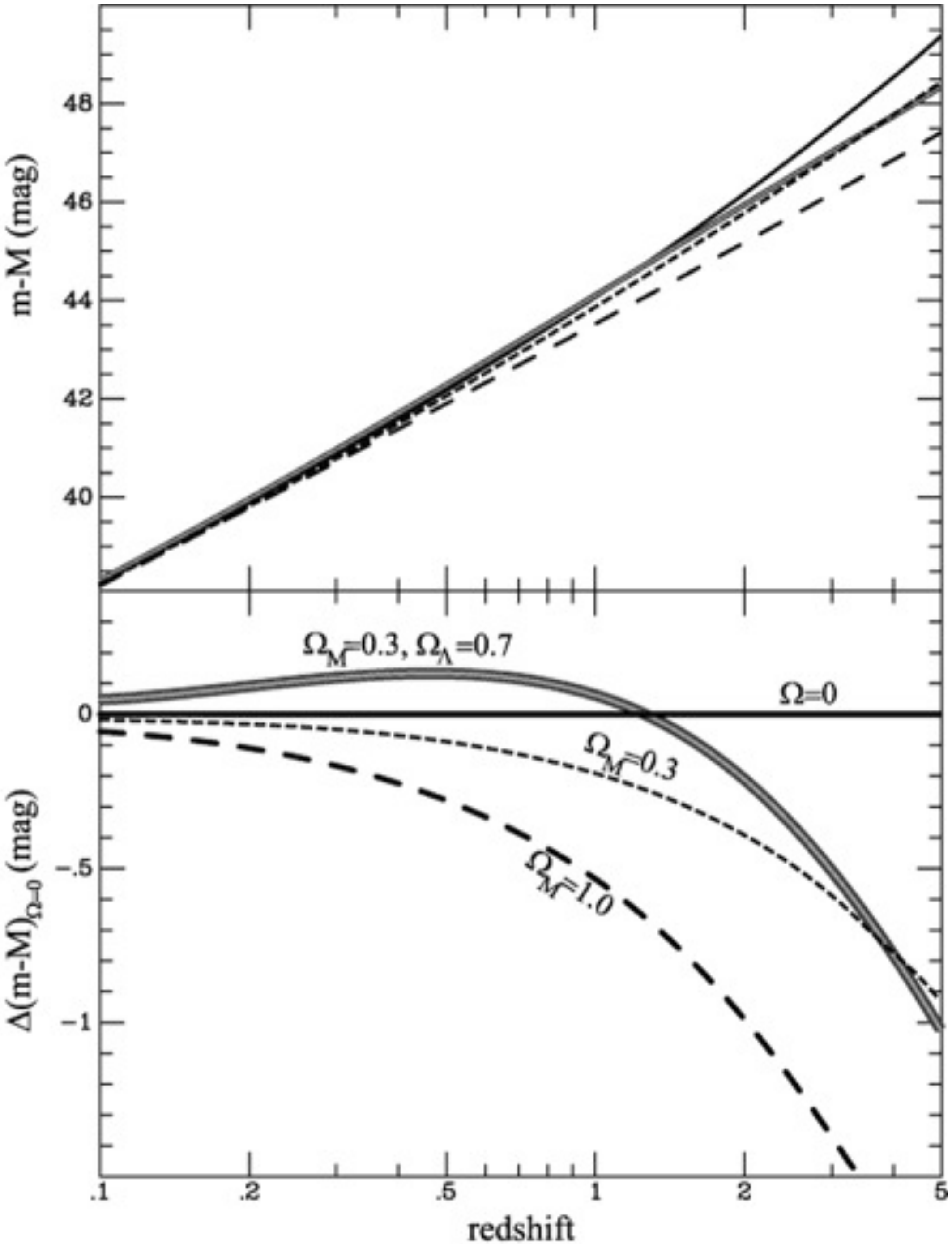
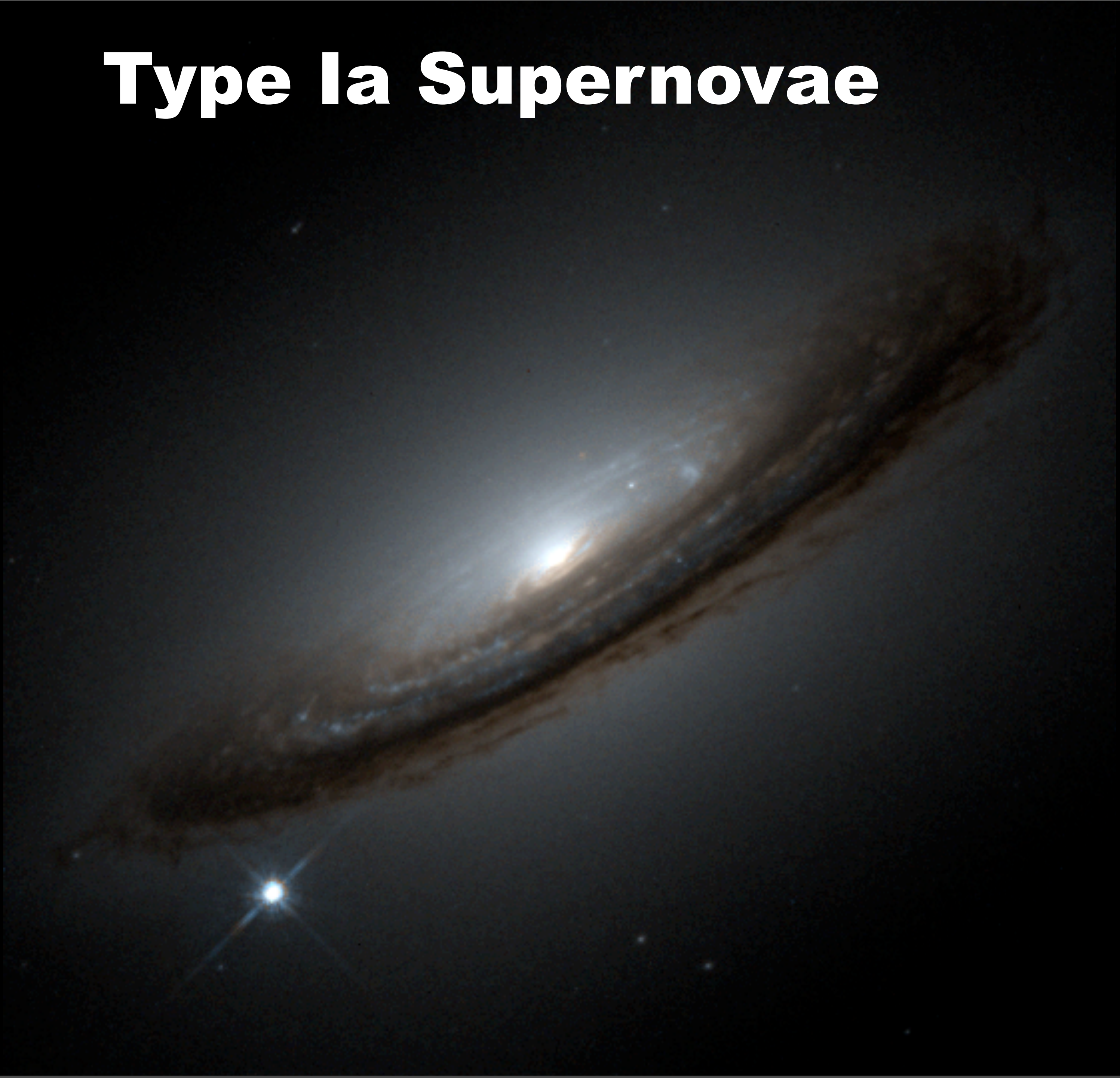


m-M (mag)
48
46
44
42
40
Δ(m-M)$_{\Omega=0}$ (mag)
0
-.5
−1
Ω_M=0.3, Ω_Λ=0.7
Ω=0
Ω_M=0.3
Ω_M=1.0
.1
.2
.5
1
2
5
redshift

Type Ia Supernovae



0 days

HIGH-Z SN IA HISTORY

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Zwicky's SN Search from 1930s-1960s giving Kowal's Hubble Diagram in 1968

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1st distant SN discovered in 1988 by a Danish team (z=0.3)

- 7 SNe discovered in 1994 by Perlmutter et al. at z = 0.4
- Calan/Tololo Survey of 29 Nearby SNe Ia completed in 1994


HAMUY


SUNTZEFF SCHOMMER


PHILLIPS


SMITH

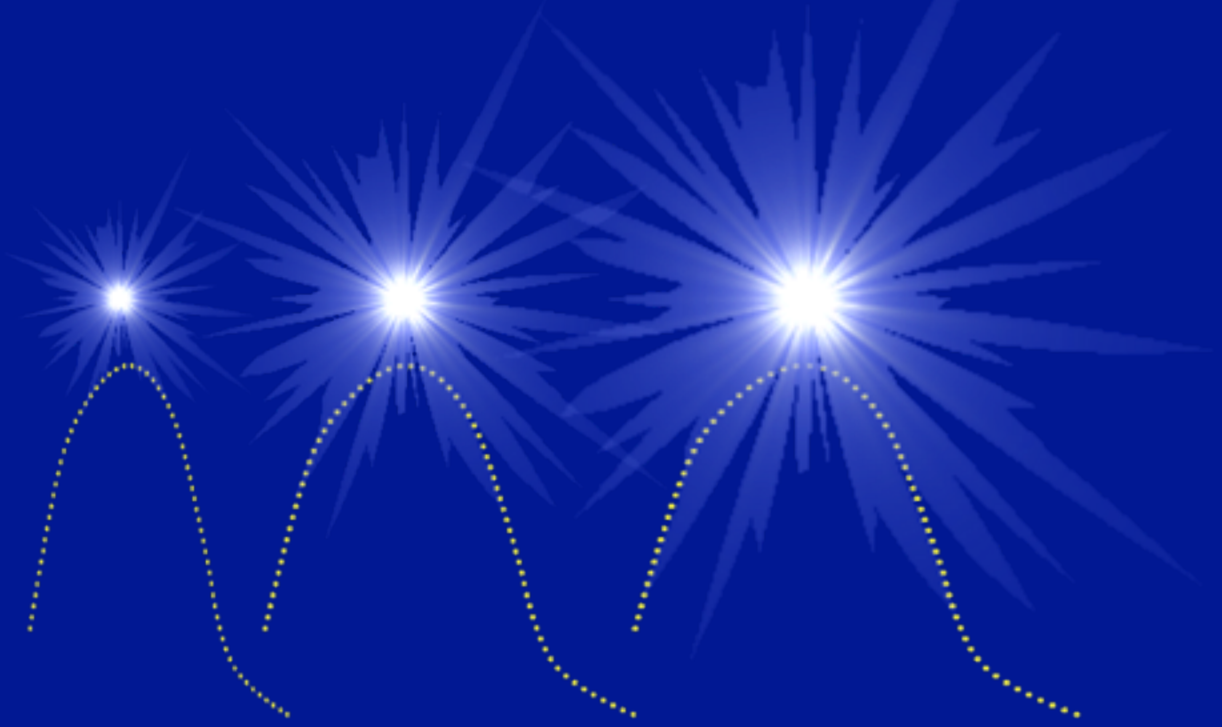

MAZA

Calan-Tololo SN Search

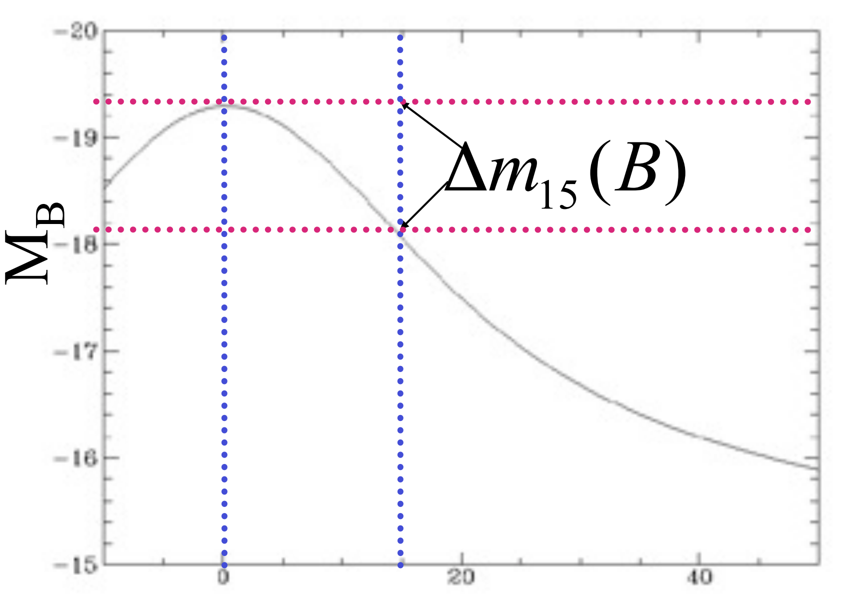
Refining Type Ia Distances

Mark Phillips (1993)

How fast a Supernova Fades is related to its intrinsic brightness.



A Most Useful Way of Parameterizing SNe Ia is by the Shape of their Light Curve



Phillips (1993) & Hamuy et al. (1996)

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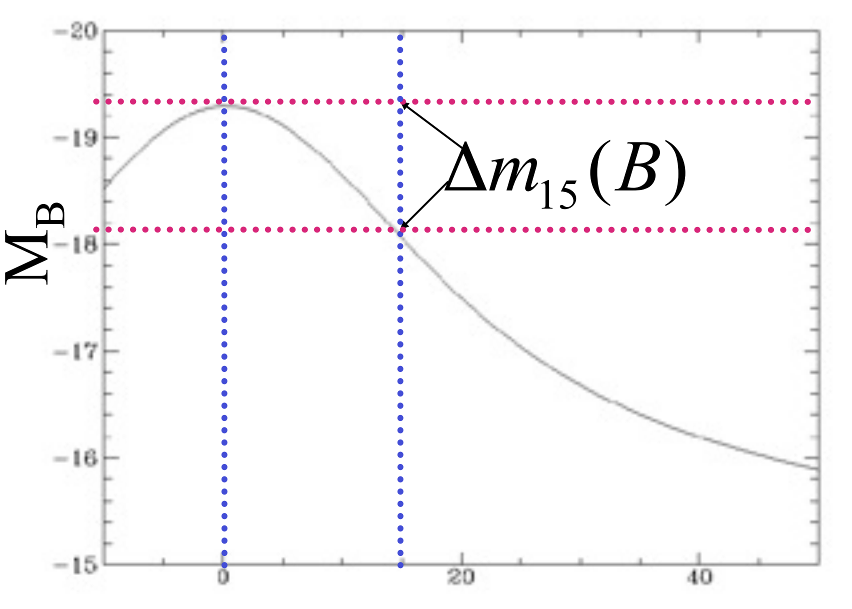
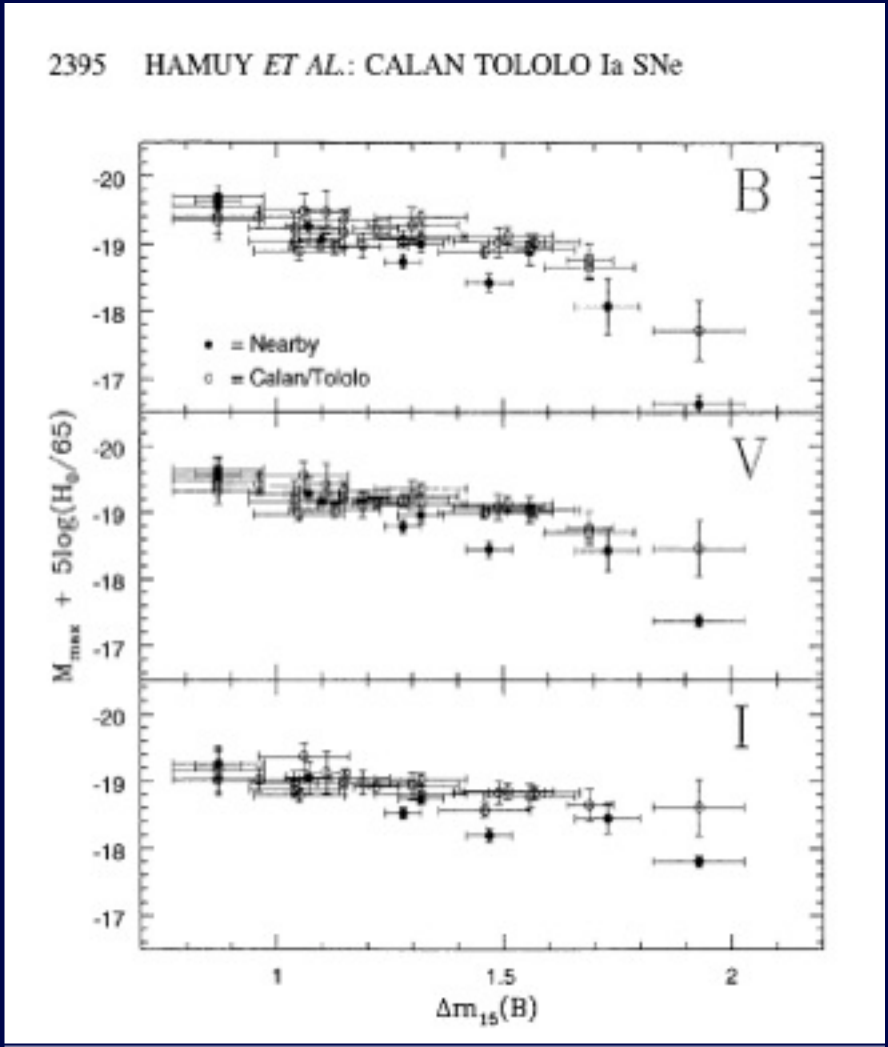
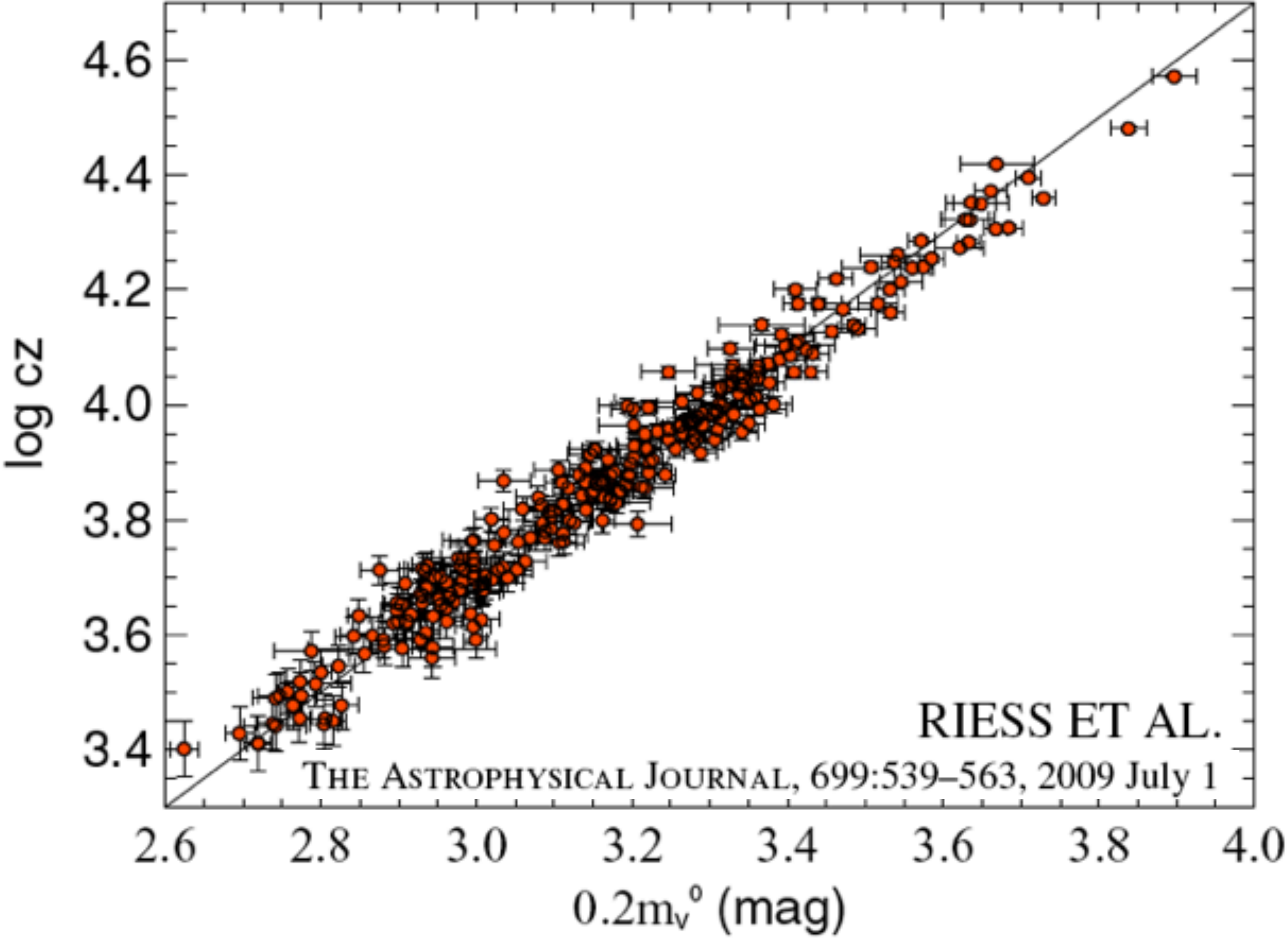




Phillips (1993) & Hamuy et al. (1996)

Proof is really that it works…
Empirically SN are good to 6%–7%



Different Ways of Looking at the Universe - 1994

It was widely presumed that Universe was made up of normal matter

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(Theorists)

Inflation+CDM paradigm correct

$\Omega \sim 1$

H_0 <=50km/s/Mpc

Observers are wrong on

H_0 and Ω_M

Different Ways of Looking at the Universe - 1994

It was widely presumed that Universe was made up of normal matter

(Theorists)	(Observers)
Inflation+CDM paradigm correct	Ω_M~0.2
Ω ~ 1	H_0 =50-80km/s/Mpc
H_0 <=50km/s/Mpc	Inflation/CDM is wrong
Observers are wrong on H_0 and Ω_M	

1970s & 80s
Inflation + Cold Dark Matter

Inflation

- Explains Uniformity of CMB
- Provides seeds of structure formation

CDM

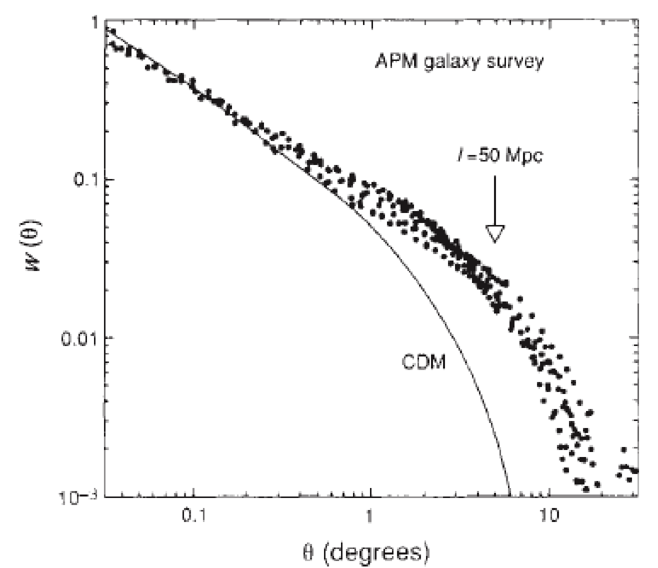
- Consistent with rotation curves of Galaxies
- Gives Structure formation

Predicts Flatness and how Structure Grows on different scales.

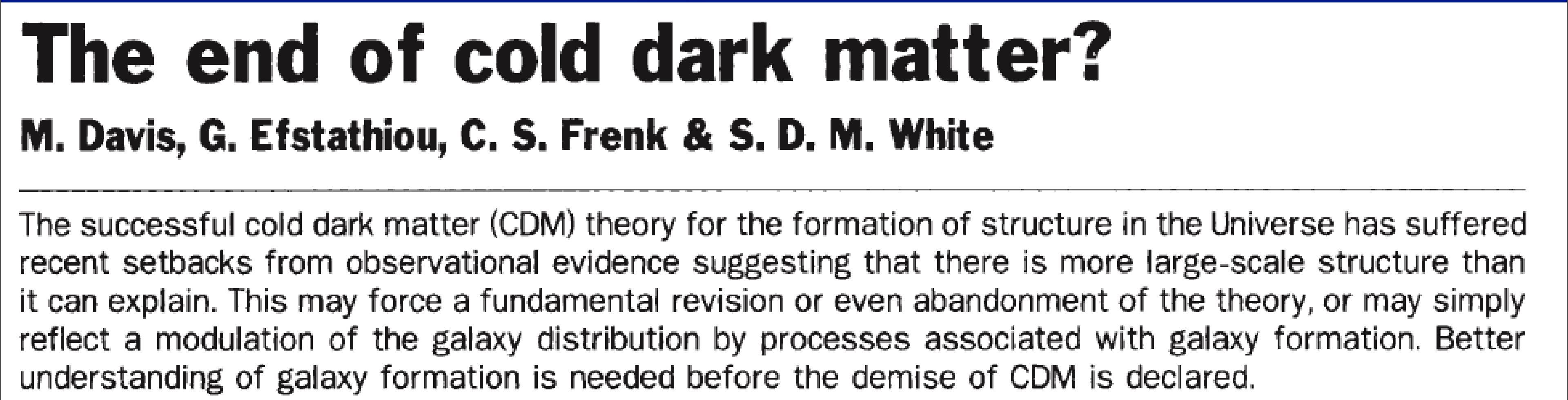
1990 - CDM Picture conflicts with what is seen

- Requires flatness, but $\Omega_{\mathbb{M}}$~0.2 from clusters
- Too much power on large scales in observations
- Efstathiou, Sutherland, and Maddox showed that compared to $\Omega_{\mathbb{M}}$=1,

  a $\Omega_{\mathbb{M}}$~0.2, Ω_{Λ}~0.8 fixed both problems



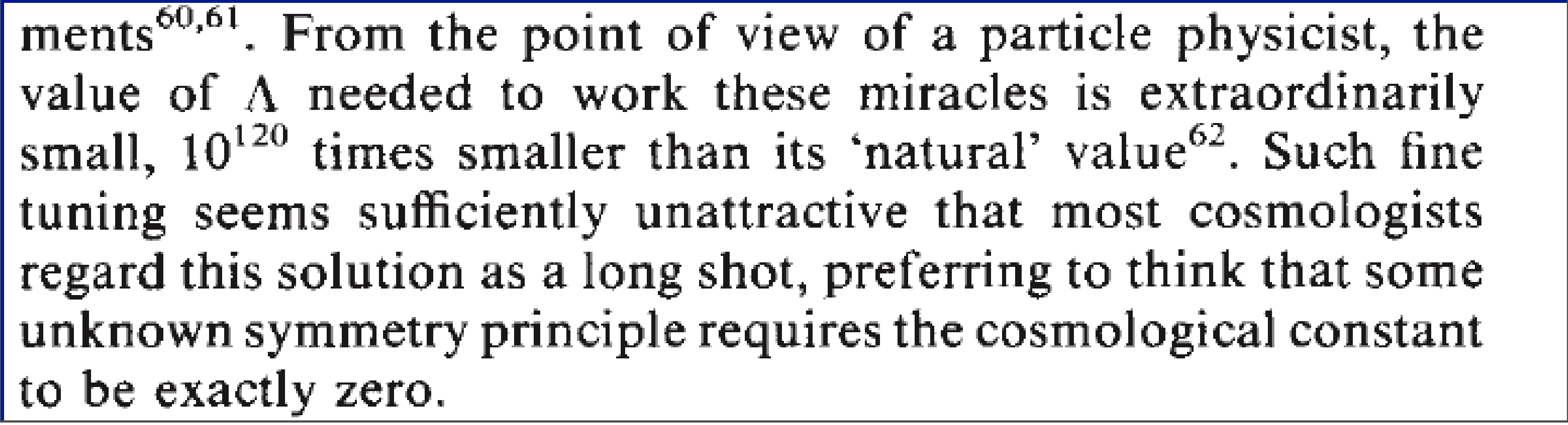
CDM theorists took this approach



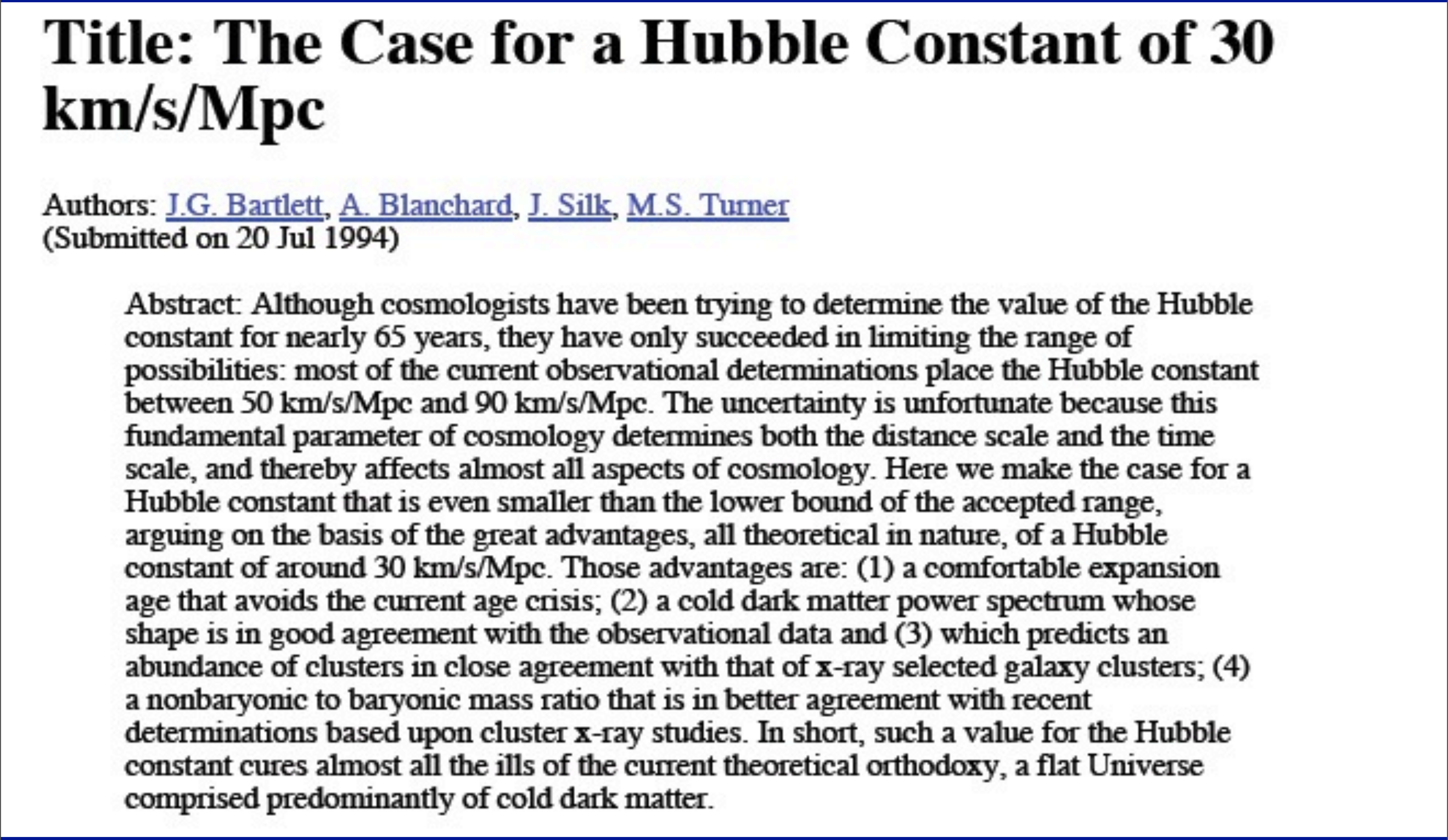
The end of cold dark matter?

M. Davis, G. Efstathiou, C. S. Frenk & S. D. M. White

The successful cold dark matter (CDM) theory for the formation of structure in the Universe has suffered recent setbacks from observational evidence suggesting that there is more large-scale structure than it can explain. This may force a fundamental revision or even abandonment of the theory, or may simply reflect a modulation of the galaxy distribution by processes associated with galaxy formation. Better understanding of galaxy formation is needed before the demise of CDM is declared.



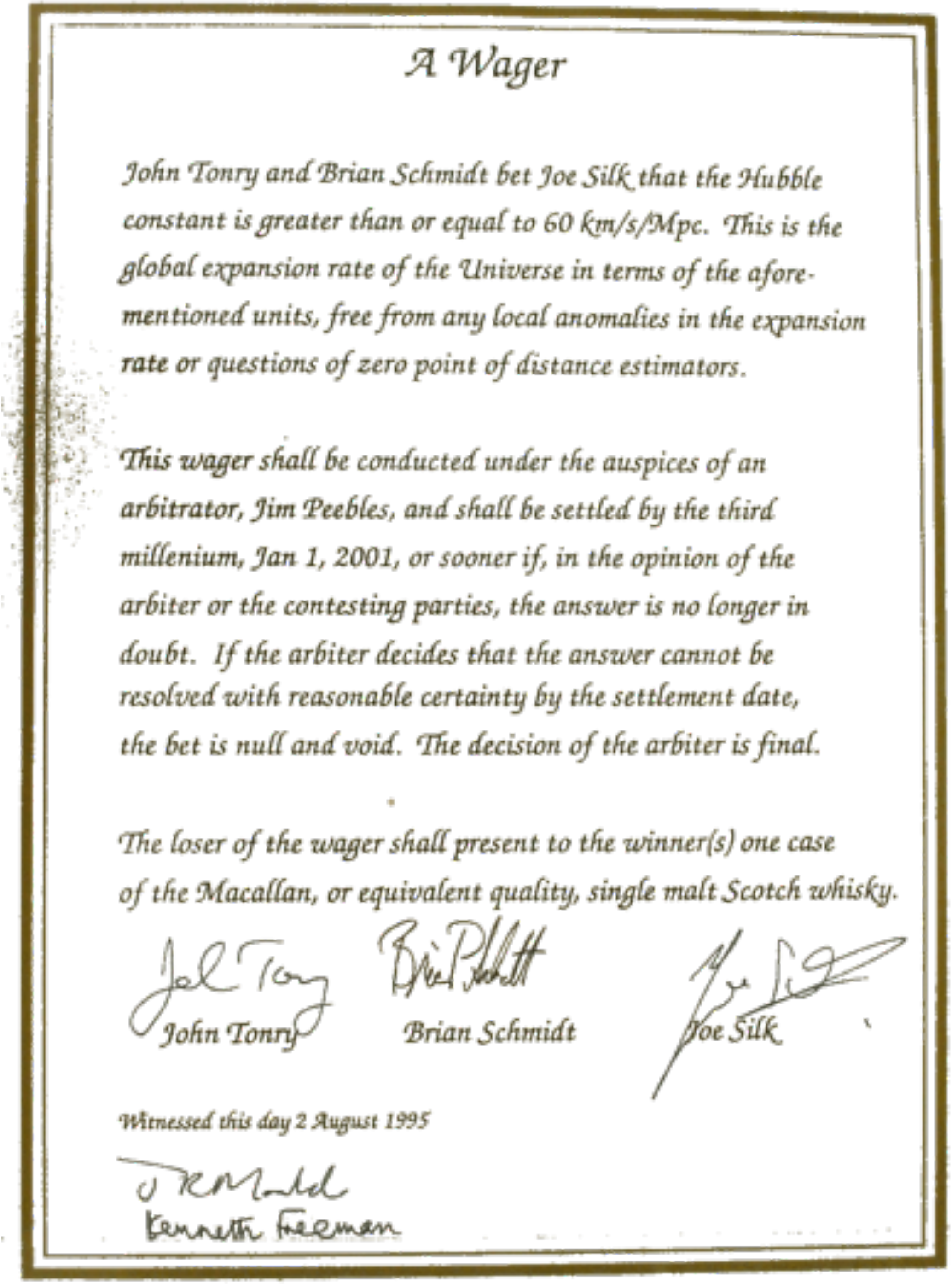
ments[60,61]. From the point of view of a particle physicist, the value of Λ needed to work these miracles is extraordinarily small, 10^{120} times smaller than its 'natural' value[62]. Such fine tuning seems sufficiently unattractive that most cosmologists regard this solution as a long shot, preferring to think that some unknown symmetry principle requires the cosmological constant to be exactly zero.



Title: The Case for a Hubble Constant of 30 km/s/Mpc

Authors: J.G. Bartlett, A. Blanchard, J. Silk, M.S. Turner
(Submitted on 20 Jul 1994)

Abstract: Although cosmologists have been trying to determine the value of the Hubble constant for nearly 65 years, they have only succeeded in limiting the range of possibilities: most of the current observational determinations place the Hubble constant between 50 km/s/Mpc and 90 km/s/Mpc. The uncertainty is unfortunate because this fundamental parameter of cosmology determines both the distance scale and the time scale, and thereby affects almost all aspects of cosmology. Here we make the case for a Hubble constant that is even smaller than the lower bound of the accepted range, arguing on the basis of the great advantages, all theoretical in nature, of a Hubble constant of around 30 km/s/Mpc. Those advantages are: (1) a comfortable expansion age that avoids the current age crisis; (2) a cold dark matter power spectrum whose shape is in good agreement with the observational data and (3) which predicts an abundance of clusters in close agreement with that of x-ray selected galaxy clusters; (4) a nonbaryonic to baryonic mass ratio that is in better agreement with recent determinations based upon cluster x-ray studies. In short, such a value for the Hubble constant cures almost all the ills of the current theoretical orthodoxy, a flat Universe comprised predominantly of cold dark matter.



A Wager

John Tonry and Brian Schmidt bet Joe Silk that the Hubble constant is greater than or equal to 60 km/s/Mpc. This is the global expansion rate of the Universe in terms of the aforementioned units, free from any local anomalies in the expansion rate or questions of zero point of distance estimators.

This wager shall be conducted under the auspices of an arbitrator, Jim Peebles, and shall be settled by the third millenium, Jan 1, 2001, or sooner if, in the opinion of the arbiter or the contesting parties, the answer is no longer in doubt. If the arbiter decides that the answer cannot be resolved with reasonable certainty by the settlement date, the bet is null and void. The decision of the arbiter is final.

The loser of the wager shall present to the winner(s) one case of the Macallan, or equivalent quality, single malt Scotch whisky.

John Tonry *Brian Schmidt* *Joe Silk*

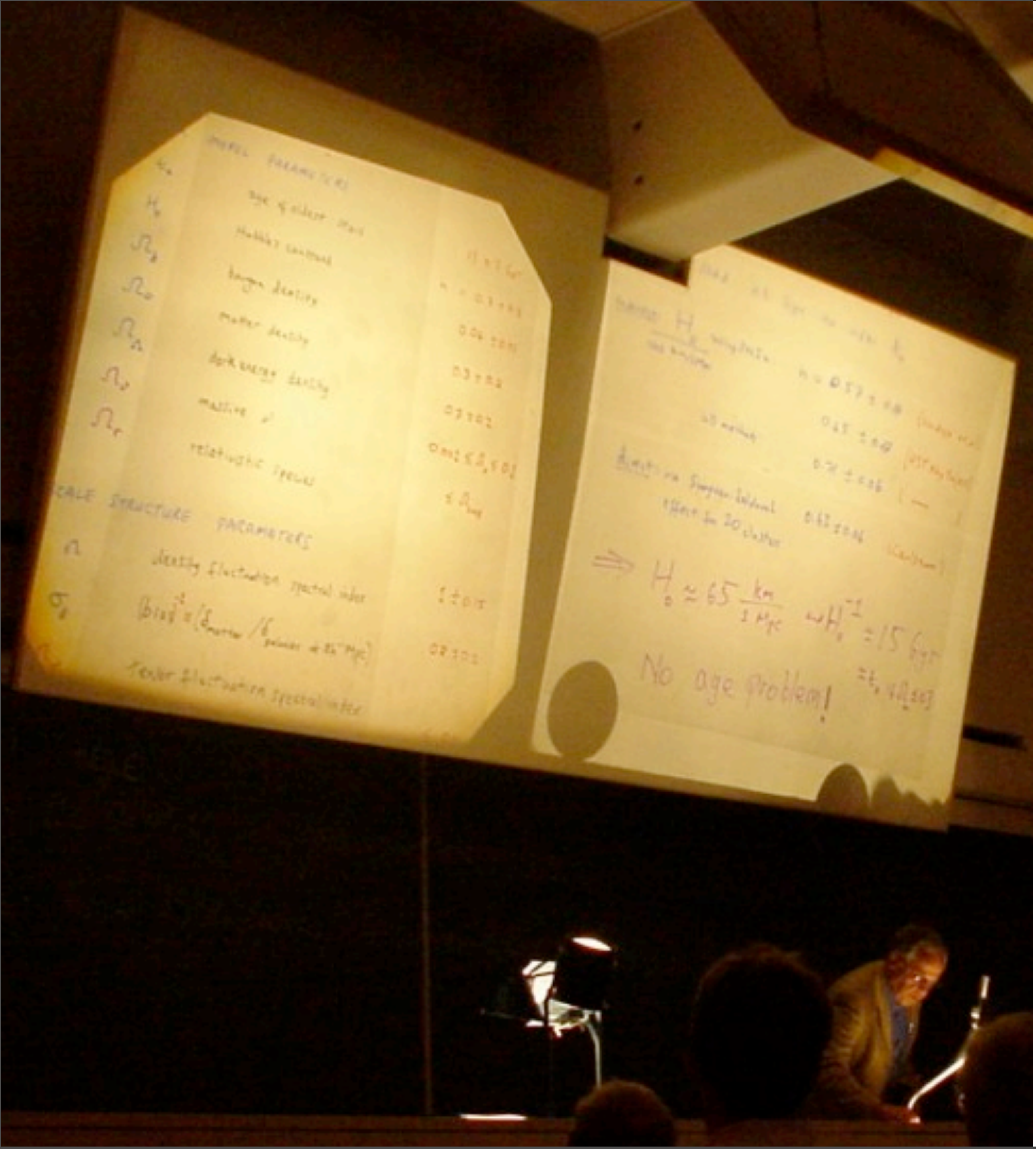
Witnessed this day 2 August 1995

J R Mould

Kenneth Freeman

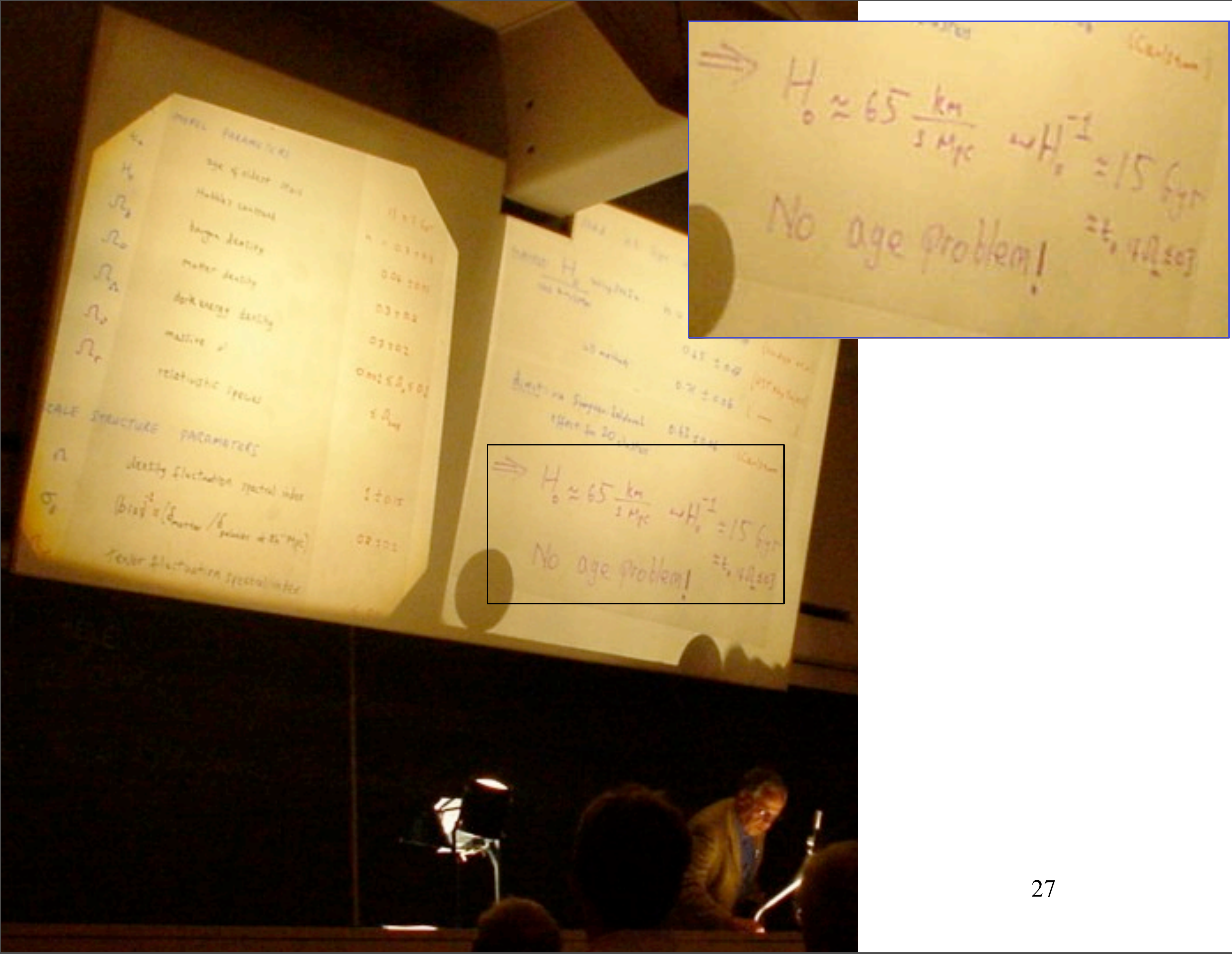

$H_0 < 60$

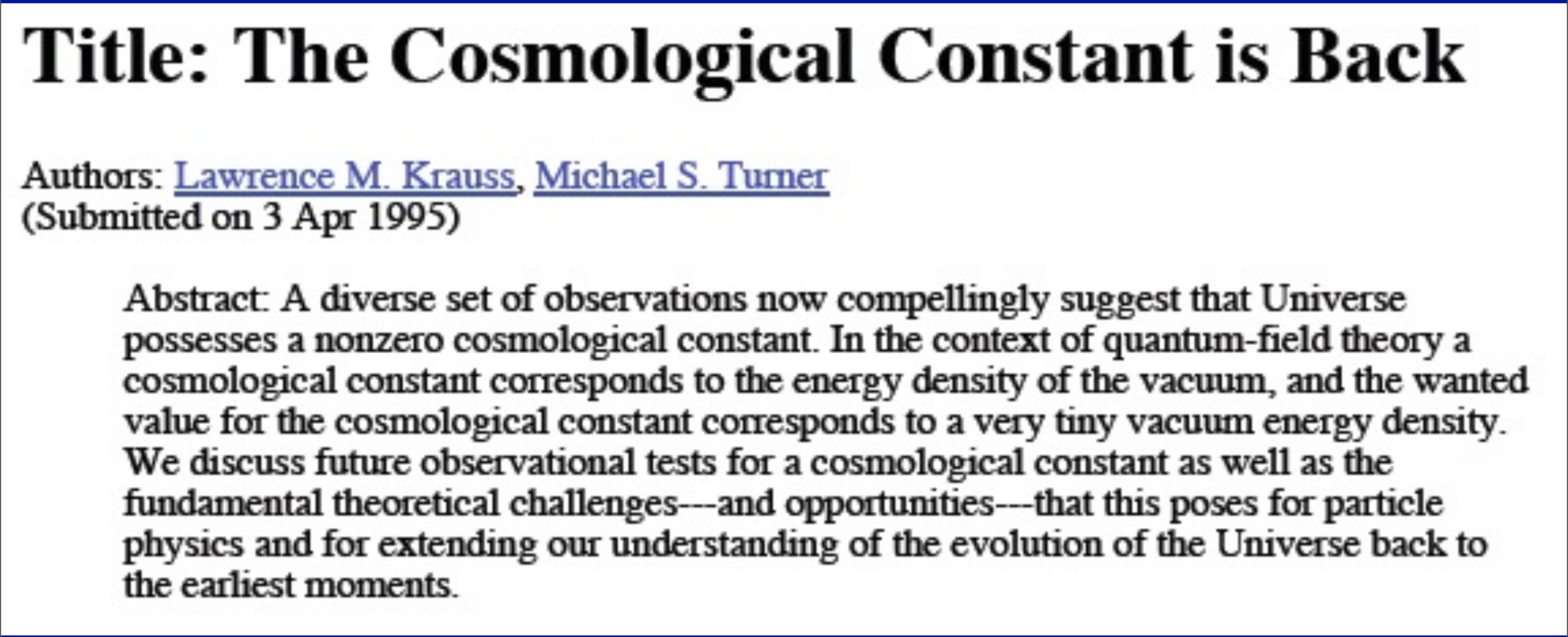

≥60



$\Rightarrow H_0 \simeq 65 \frac{km}{1\,Mpc}$ and $H_0^{-1} \simeq 15$ Gyr

No age problem!


⇒ $H_0 \simeq 65 \frac{km}{s\ Mpc}$ ~$H_0^{-1} \simeq 15$ Gyr
No age problem!
$\simeq t_0$ if $\Omega_\Lambda \simeq 0.7$



Title: The Cosmological Constant is Back

Authors: Lawrence M. Krauss, Michael S. Turner
(Submitted on 3 Apr 1995)

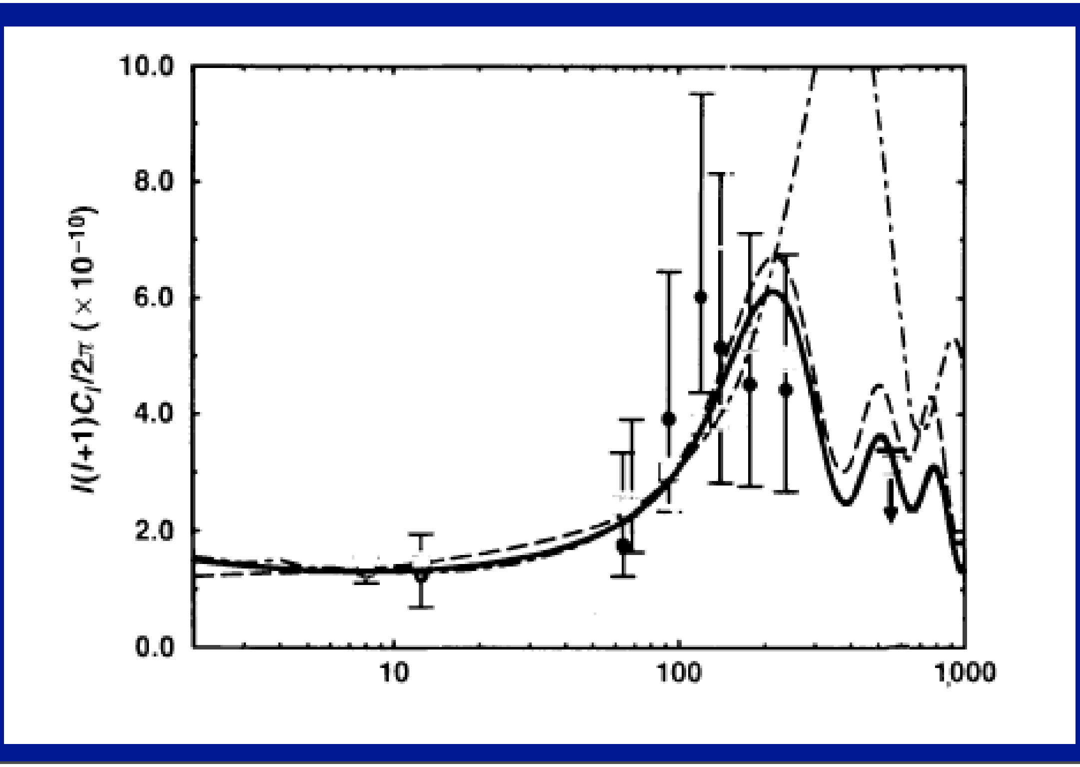
Abstract: A diverse set of observations now compellingly suggest that Universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological constant corresponds to the energy density of the vacuum, and the wanted value for the cosmological constant corresponds to a very tiny vacuum energy density. We discuss future observational tests for a cosmological constant as well as the fundamental theoretical challenges---and opportunities---that this poses for particle physics and for extending our understanding of the evolution of the Universe back to the earliest moments.

Common theme - Written by Theorists with the assertion- inflation+CDM are right

The observational case for a low-density Universe with a non-zero cosmological constant

J. P. Ostriker* & Paul J. Steinhardt†

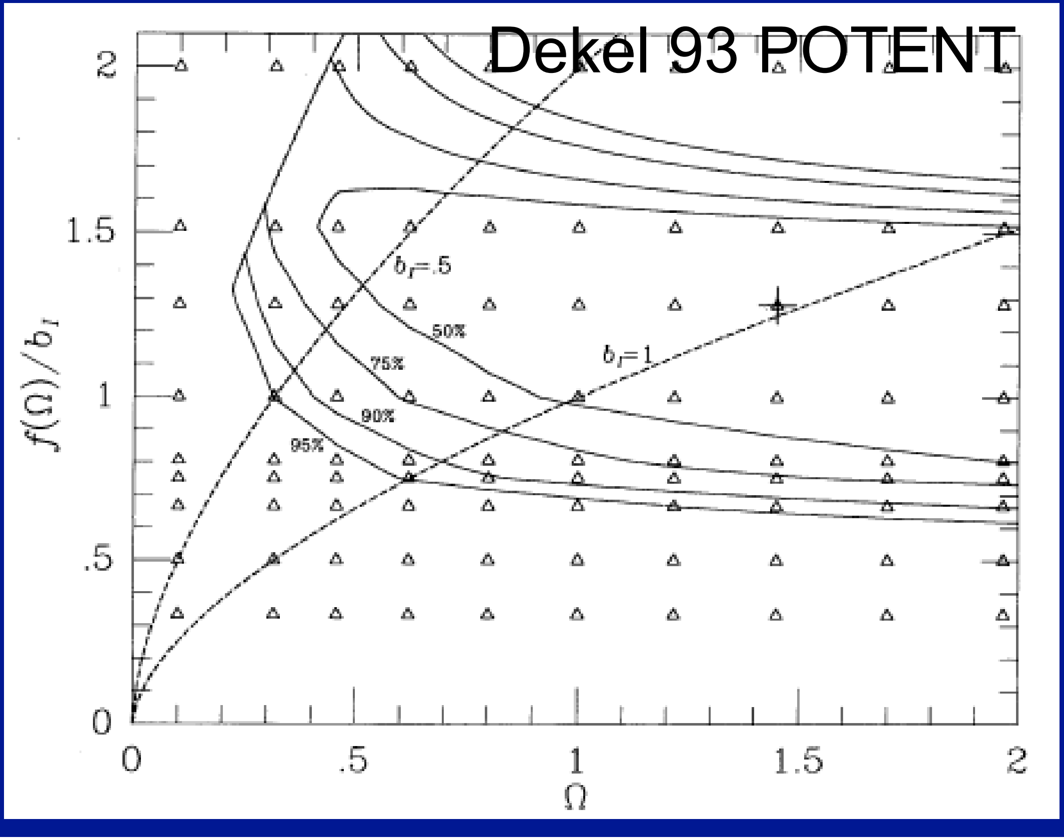
NATURE · VOL 377 · 19 OCTOBER 1995



Used same CDM +inflation orthodoxy, but “measured” flatness from CMB.

Value of Ω_M was not Crystal Clear

- While much of the evidence favoured that Ω_M~0.2,
- There was also evidence suggesting Ω_M ~1


Dekel 93 POTENT

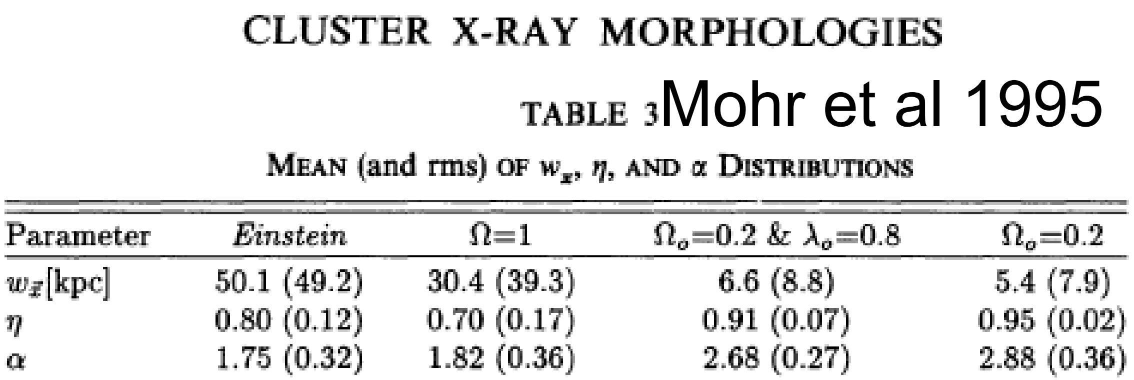

CLUSTER X-RAY MORPHOLOGIES

TABLE 3 Mohr et al 1995

MEAN (and rms) OF w_x, η, AND α DISTRIBUTIONS

Parameter	*Einstein*	Ω=1	Ω_o=0.2 & λ_o=0.8	Ω_o=0.2
$w_{\bar{x}}$[kpc]	50.1 (49.2)	30.4 (39.3)	6.6 (8.8)	5.4 (7.9)
η	0.80 (0.12)	0.70 (0.17)	0.91 (0.07)	0.95 (0.02)
α	1.75 (0.32)	1.82 (0.36)	2.68 (0.27)	2.88 (0.36)

THE ASTROPHYSICAL JOURNAL, 444:15–20, 1995 May 1

Number counts of Galaxies suggest Λ

INTERPRETATION OF THE FAINT GALAXY NUMBER COUNTS IN THE *K* BAND

YUZURU YOSHII[1,2,3] AND BRUCE A. PETERSON[2,3]

Received 1994 February 28; accepted 1994 November 7

But Galaxy evolution
not trusted

ABSTRACT

Number counts of K(2.2 μm)-selected galaxies reaching to $K = 23$ mag are compared to model predictions which take into account the selection bias against high-redshift galaxies inherent in the methods used to detect faint galaxy images. Using a standard model for galaxy luminosity evolution with a constant comoving density of galaxies, we find that these number count data favor a flat, low-density $\Omega_0 \sim 0.2$ universe with a nonzero cosmological constant. We argue that the agreement with the model predictions for a low-density universe considerably diminishes any need to introduce a hypothetical population to explain the excess galaxies found in deep blue surveys.

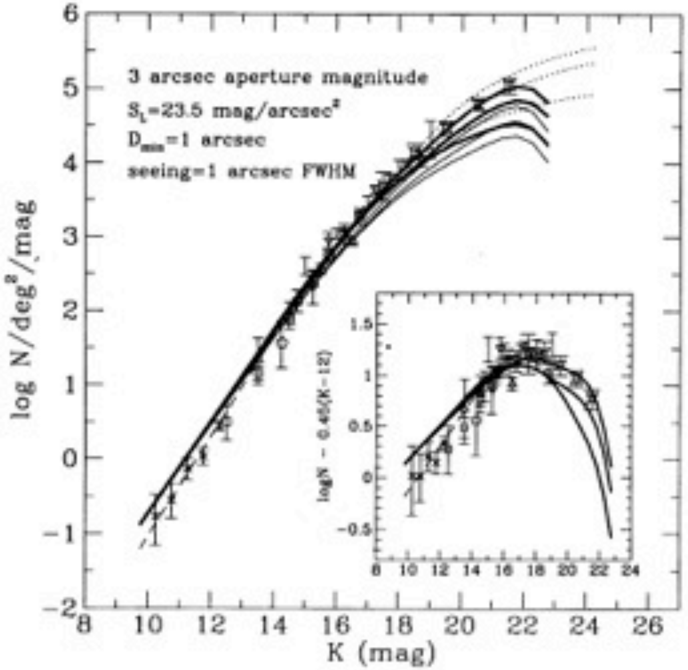


FIG. 2*a*

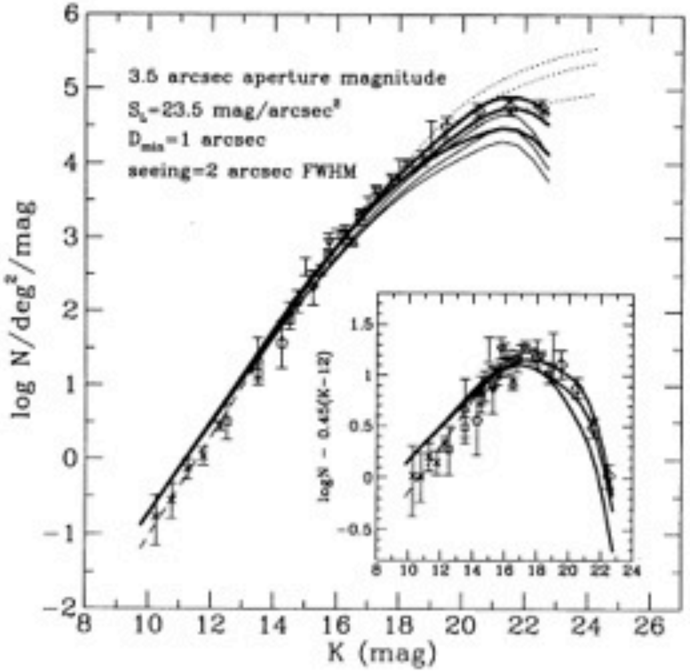
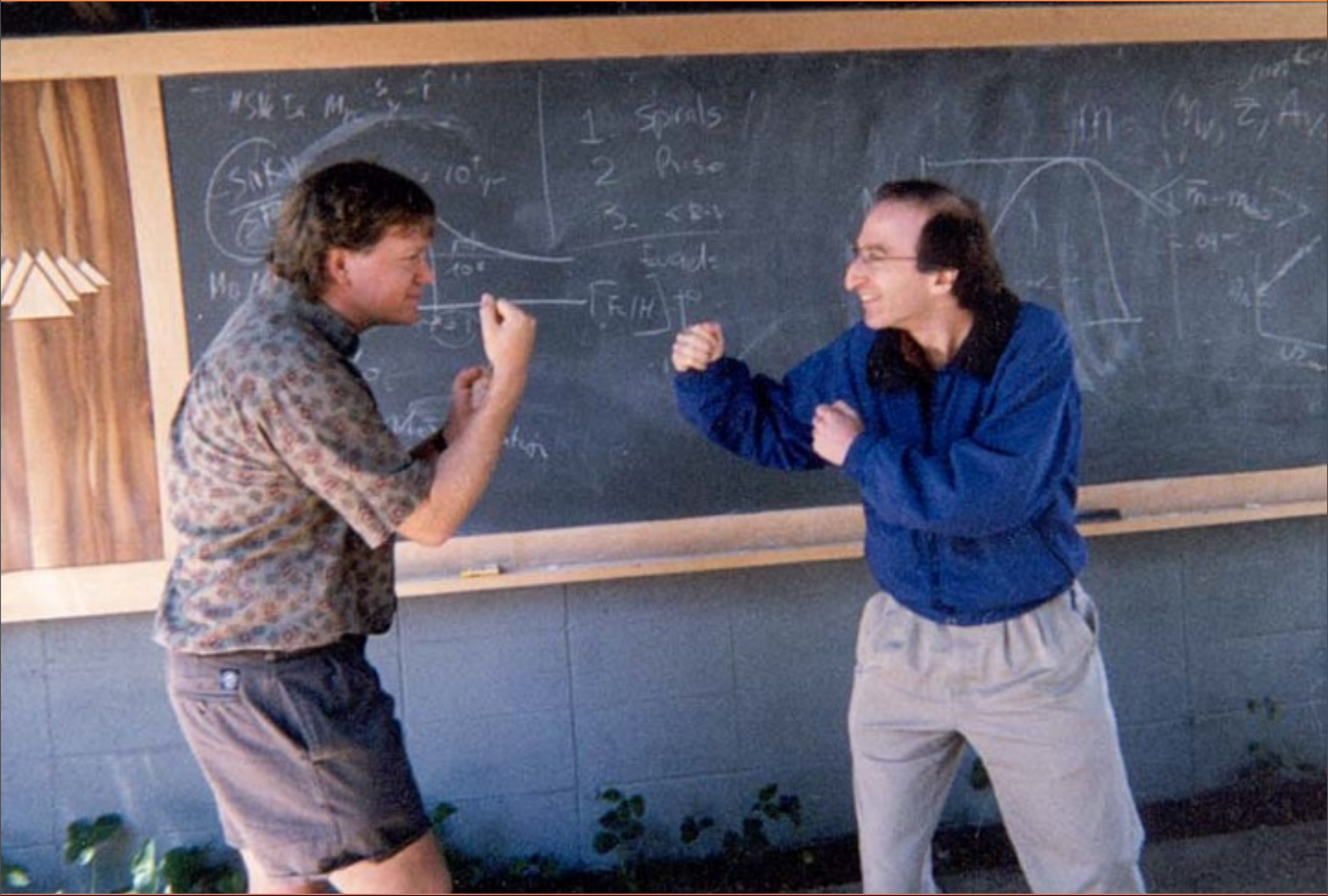
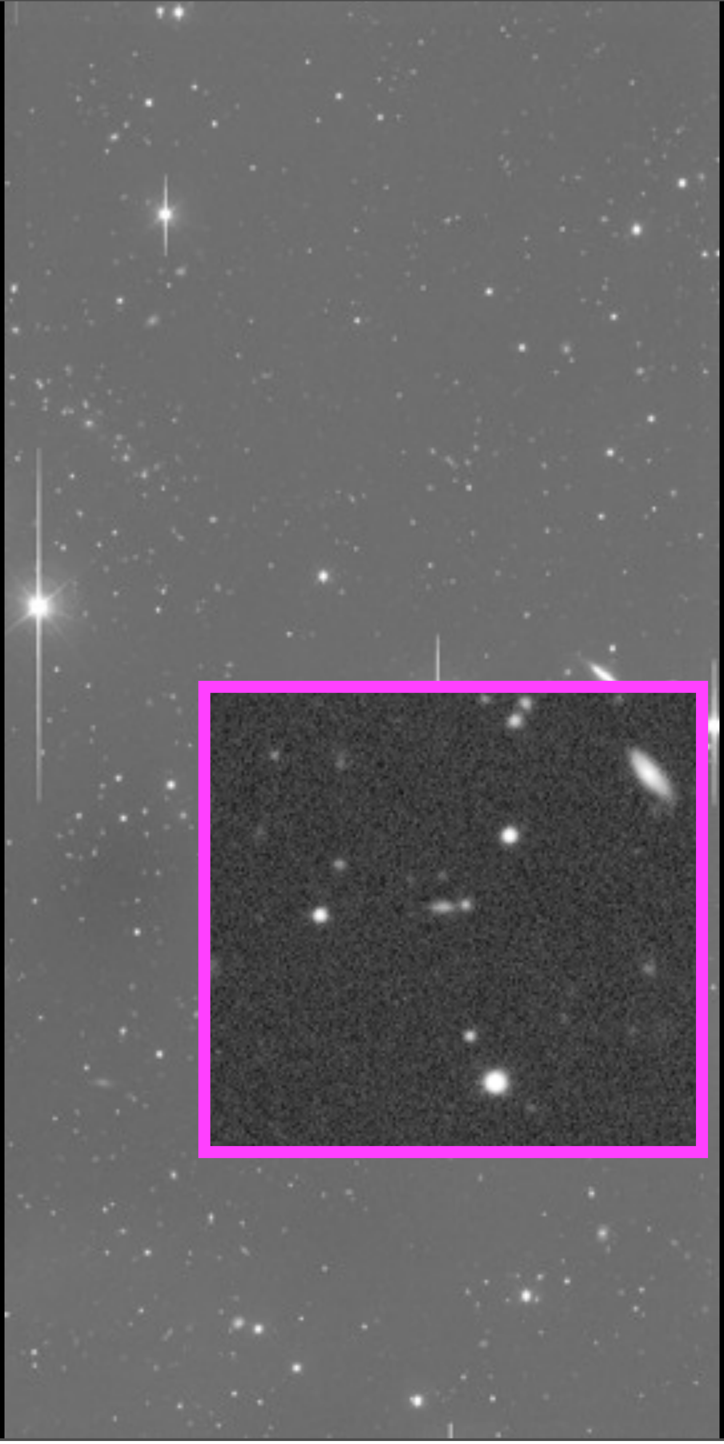
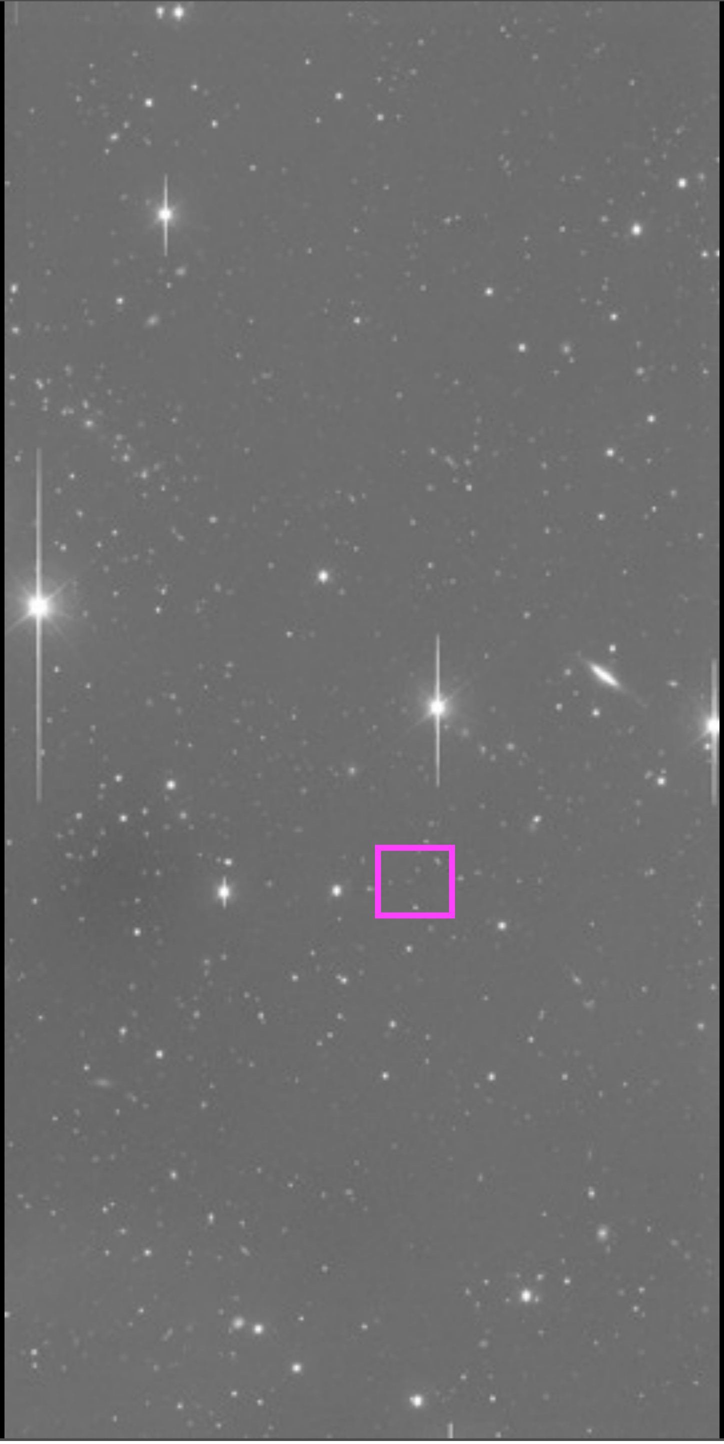
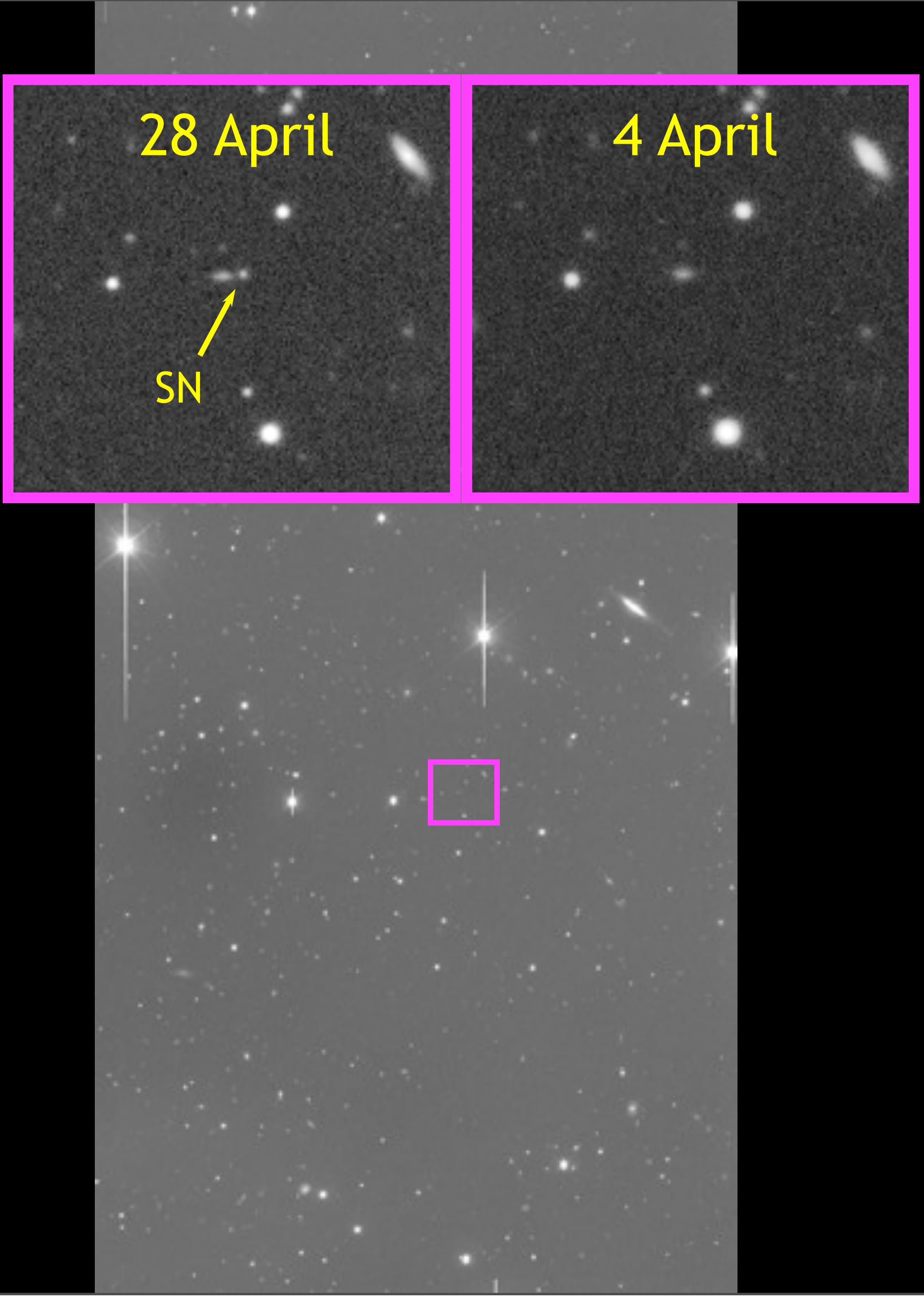


FIG. 2*b*


1. Spirals

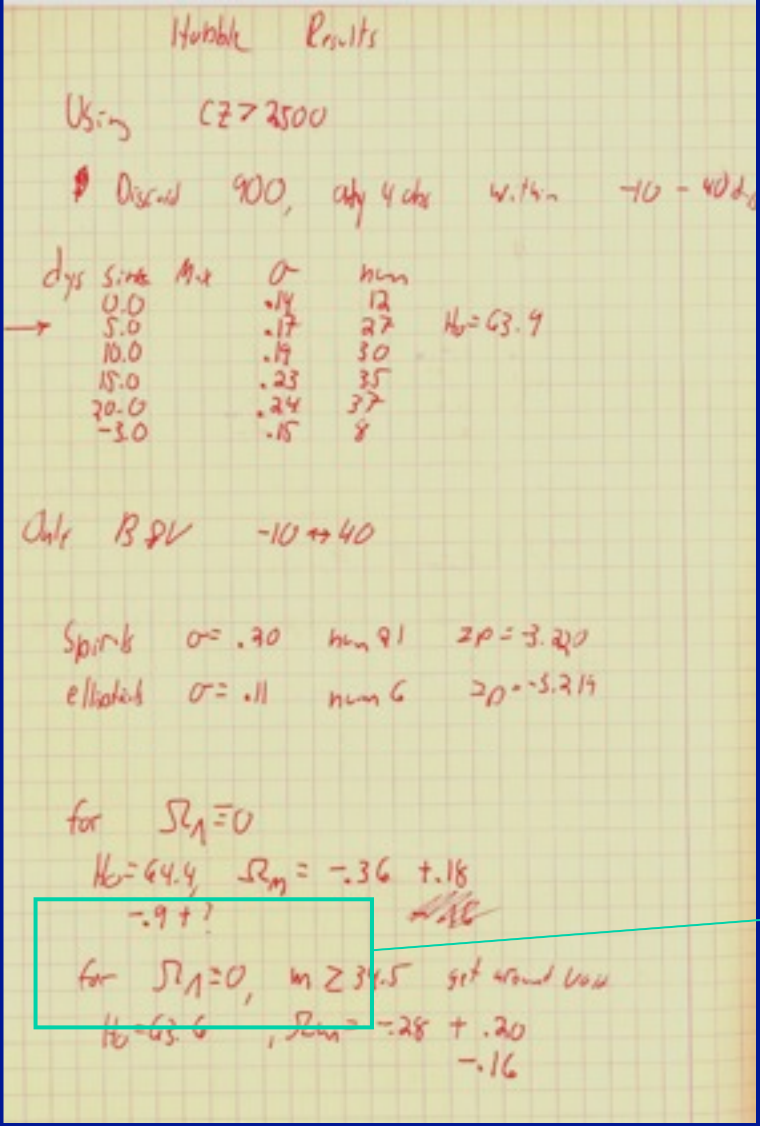





28 April
SN
4 April

EUREKA?

Adam's Lab book, Key Page, Fall 1997:



Hubble Results

Using $cz > 2500$

Discard 900, only 4 obs within -10 - 40 d

days since Max	σ	num	
0.0	.14	12	
5.0	.17	27	$H_0 = 63.9$
10.0	.19	30	
15.0	.23	35	
20.0	.24	37	
-3.0	.15	8	

Only B & V $-10 \leftrightarrow 40$

Spirals $\sigma = .20$ num 91 $zp = -3.220$

elliptical $\sigma = .11$ num 6 $zp = -3.214$

for $\Omega_\Lambda = 0$

$H_0 = 64.4$ $\Omega_m = -.36 \;{}^{+.18}_{-.16}$

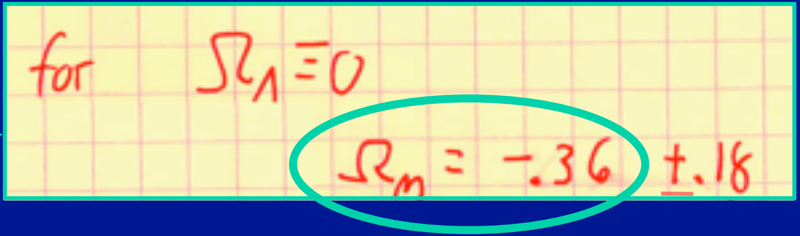
$-.9 + ?$

for $\Omega_\Lambda = 0$, $m \geq 34.5$ get around [illegible]

$H_0 = 63.6$, $\Omega_m = -.28 \;{}^{+.20}_{-.16}$

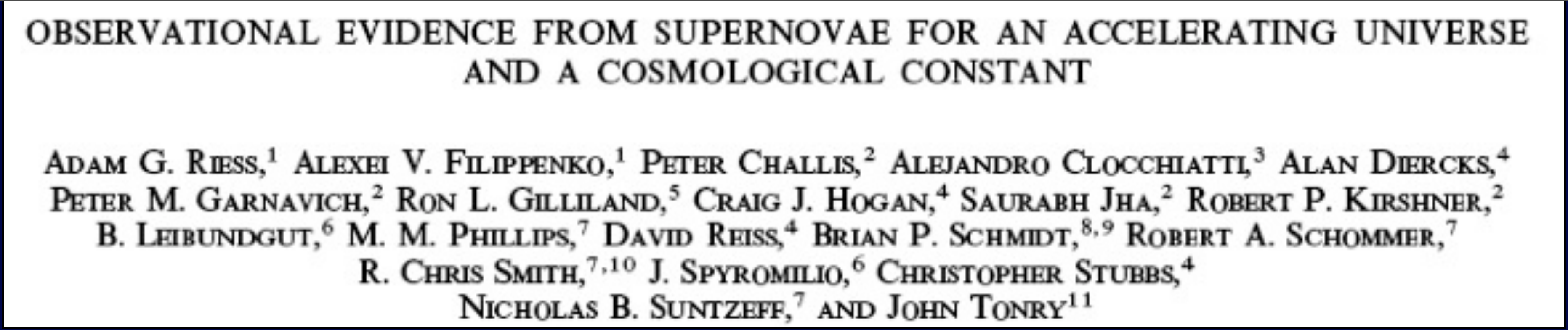
Adam Riess was leading our efforts in the fall of 1997 to increase our sample of 4 objects to 15.

He found the total sum of Mass to be negative - which meant acceleration.



for $\Omega_\Lambda = 0$

$\Omega_m = -.36 \;\underline{+}.18$



OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

Adam G. Riess,[1] Alexei V. Filippenko,[1] Peter Challis,[2] Alejandro Clocchiatti,[3] Alan Diercks,[4]
Peter M. Garnavich,[2] Ron L. Gilliland,[5] Craig J. Hogan,[4] Saurabh Jha,[2] Robert P. Kirshner,[2]
B. Leibundgut,[6] M. M. Phillips,[7] David Reiss,[4] Brian P. Schmidt,[8,9] Robert A. Schommer,[7]
R. Chris Smith,[7,10] J. Spyromilio,[6] Christopher Stubbs,[4]
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MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. Perlmutter,[1] G. Aldering, G. Goldhaber,[1] R. A. Knop, P. Nugent, P. G. Castro,[2] S. Deustua, S. Fabbro,[3]
A. Goobar,[4] D. E. Groom, I. M. Hook,[5] A. G. Kim,[1,6] M. Y. Kim, J. C. Lee,[7] N. J. Nunes,[2] R. Pain,[3]
C. R. Pennypacker,[8] and R. Quimby
Institute for Nuclear and Particle Astrophysics, E. O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720

C. Lidman
European Southern Observatory, La Silla, Chile

R. S. Ellis, M. Irwin, and R. G. McMahon
Institute of Astronomy, Cambridge, England, UK

P. Ruiz-Lapuente
Department of Astronomy, University of Barcelona, Barcelona, Spain

N. Walton
Isaac Newton Group, La Palma, Spain

B. Schaefer
Department of Astronomy, Yale University, New Haven, CT

B. J. Boyle
Anglo-Australian Observatory, Sydney, Australia

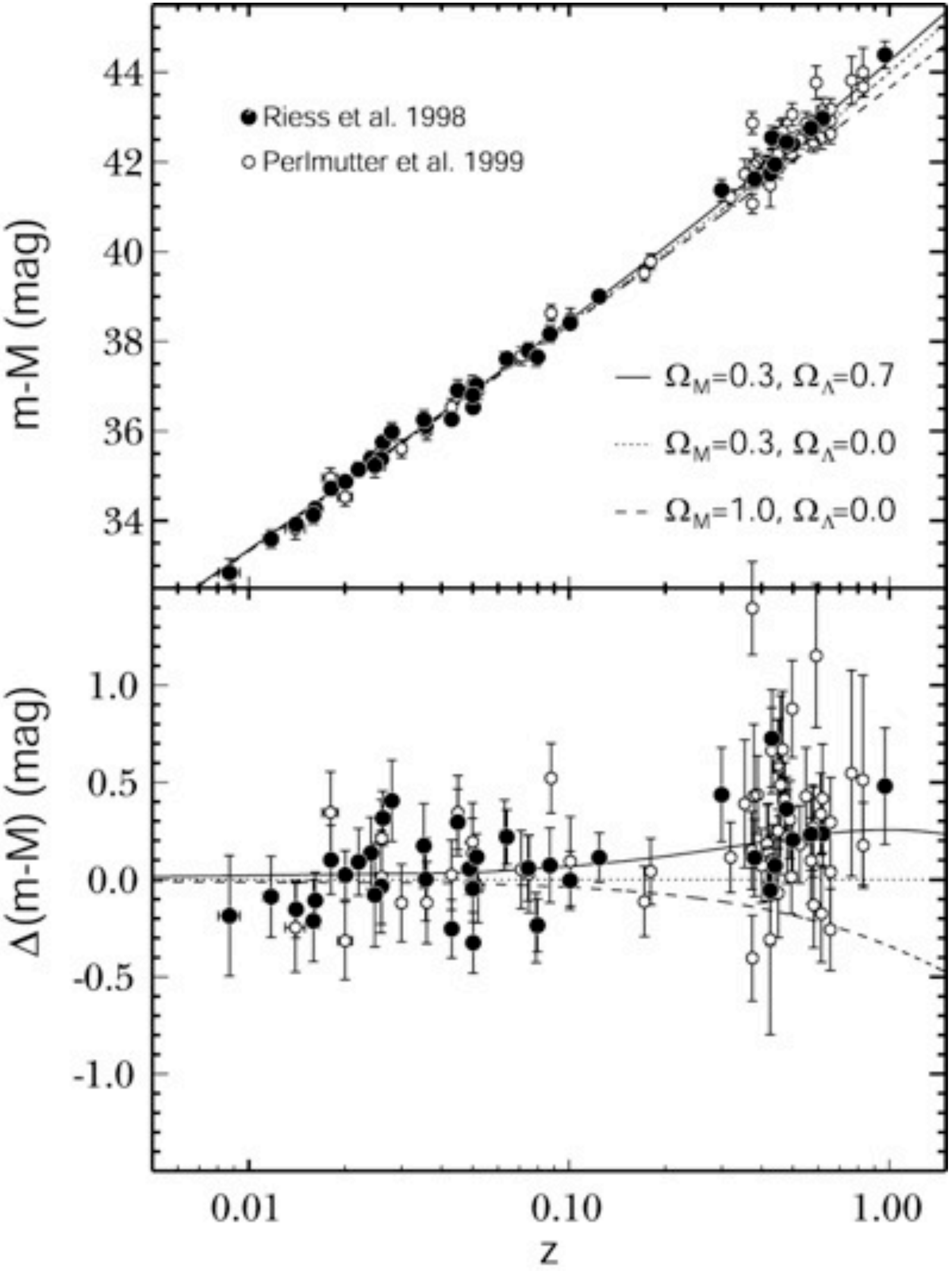
A. V Filippenko and T. Matheson
Department of Astronomy, University of California, Berkeley, CA

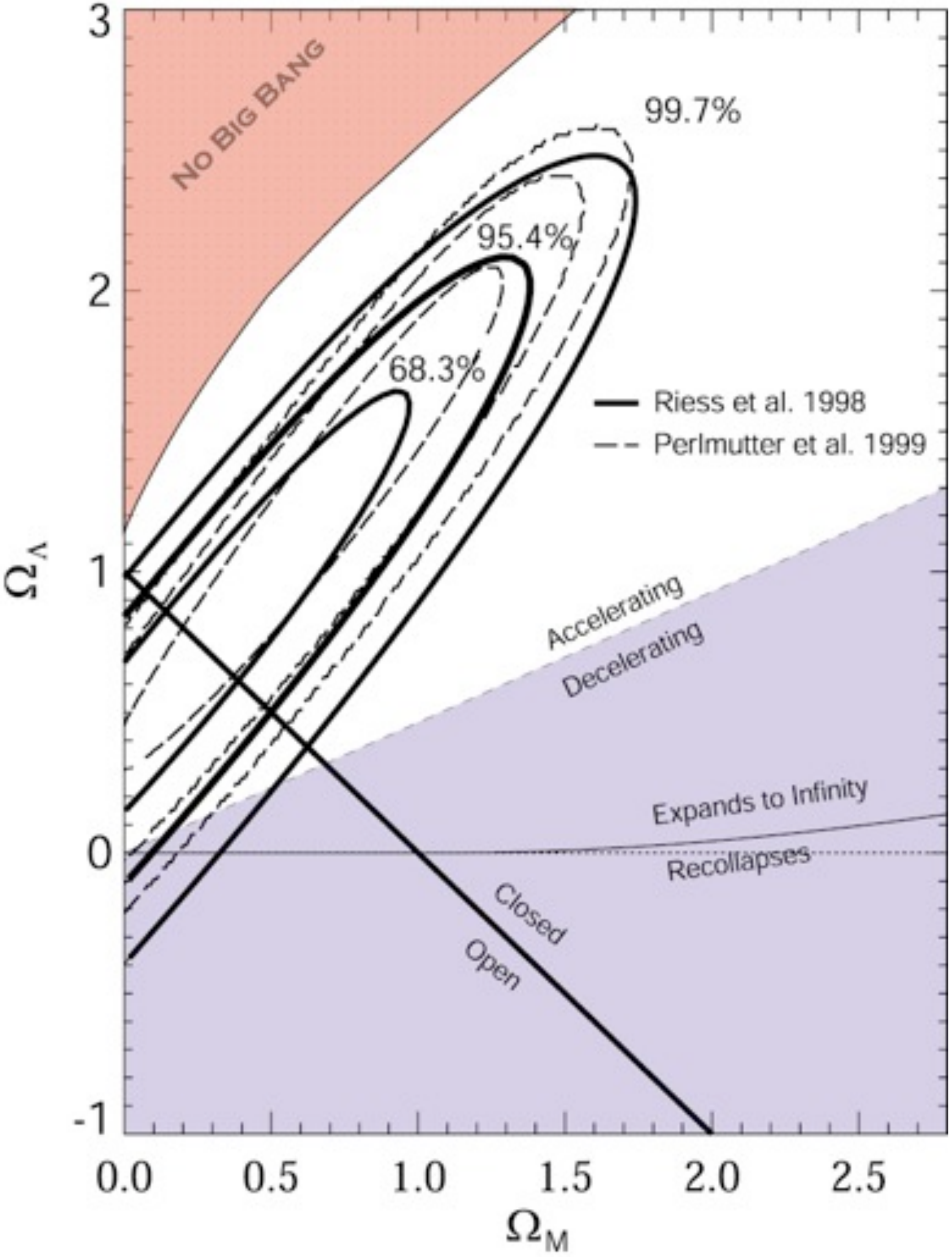
A. S. Fruchter and N. Panagia[9]
Space Telescope Science Institute, Baltimore, MD

H. J. M. Newberg
Fermi National Laboratory, Batavia, IL

and

W. J. Couch
niversity of New South Wales, Sydney, Australia
The Supernova Cosmology Project)


● Riess et al. 1998
○ Perlmutter et al. 1999
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
m-M (mag)
44
42
40
38
36
34
Δ(m-M) (mag)
1.0
0.5
0.0
-0.5
-1.0
0.01
0.10
1.00
z



No Big Bang
99.7%
95.4%
68.3%
Riess et al. 1998
Perlmutter et al. 1999
Accelerating
Decelerating
Expands to Infinity
Recollapses
Closed
Open
3
2
1
0
-1
Ω_Λ
0.0
0.5
1.0
1.5
2.0
2.5
Ω_M

- High-Z SN Observations directly measured distances which were incompatible with any matter-only Universes.
- But SN Ia themselves might be affected by Dust, evolution or measurement difficulties, and Community felt they were not to be completely trusted on their own.

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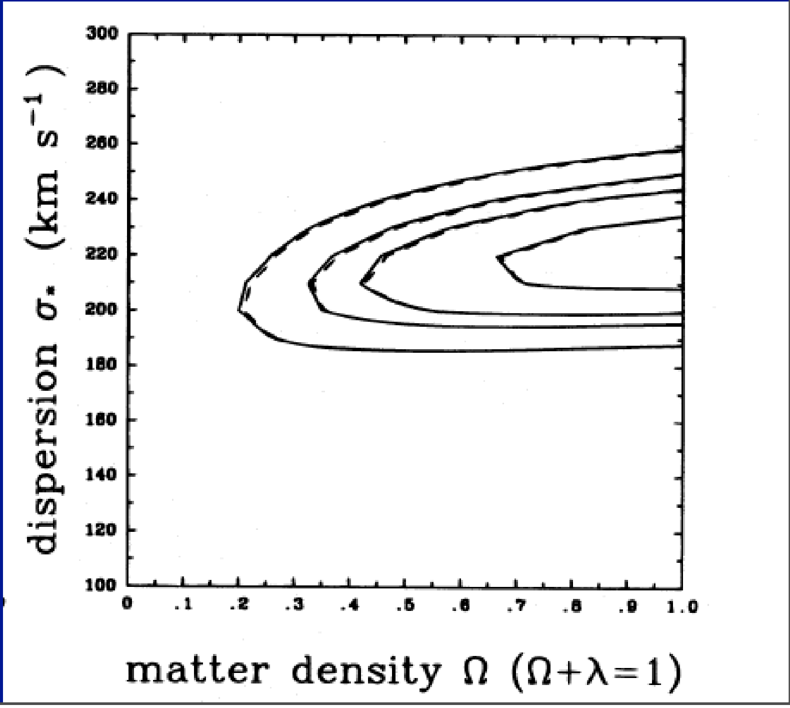
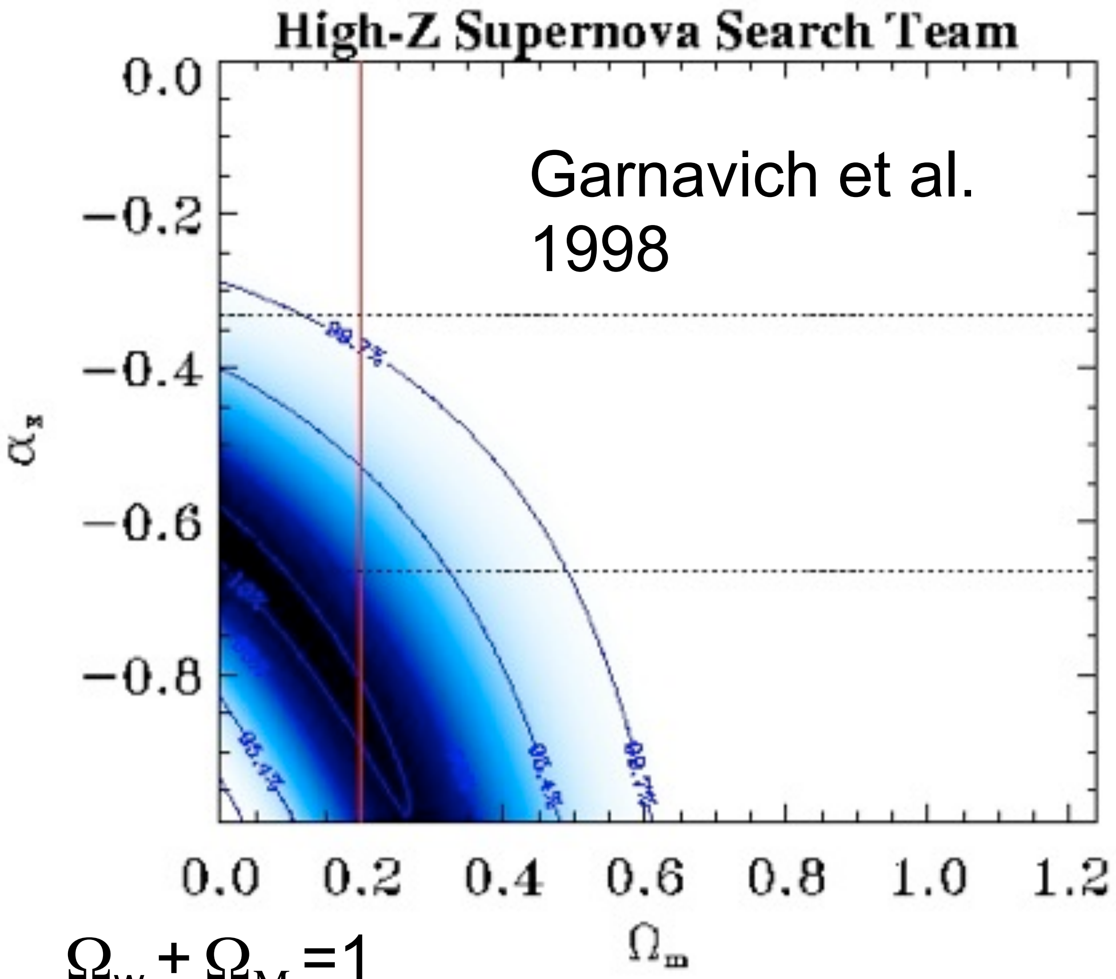
- But SN Ia themselves might be affected by Dust, evolution or measurement difficulties, and Community felt they were not to be completely trusted on their own.

•Ω_M=0.25, Ω_Λ=0.75 Universe compatible with most Cosmological measurements except for lensing limits (Kochanek 1996) and high Ω_M measurements.



The Equation of State



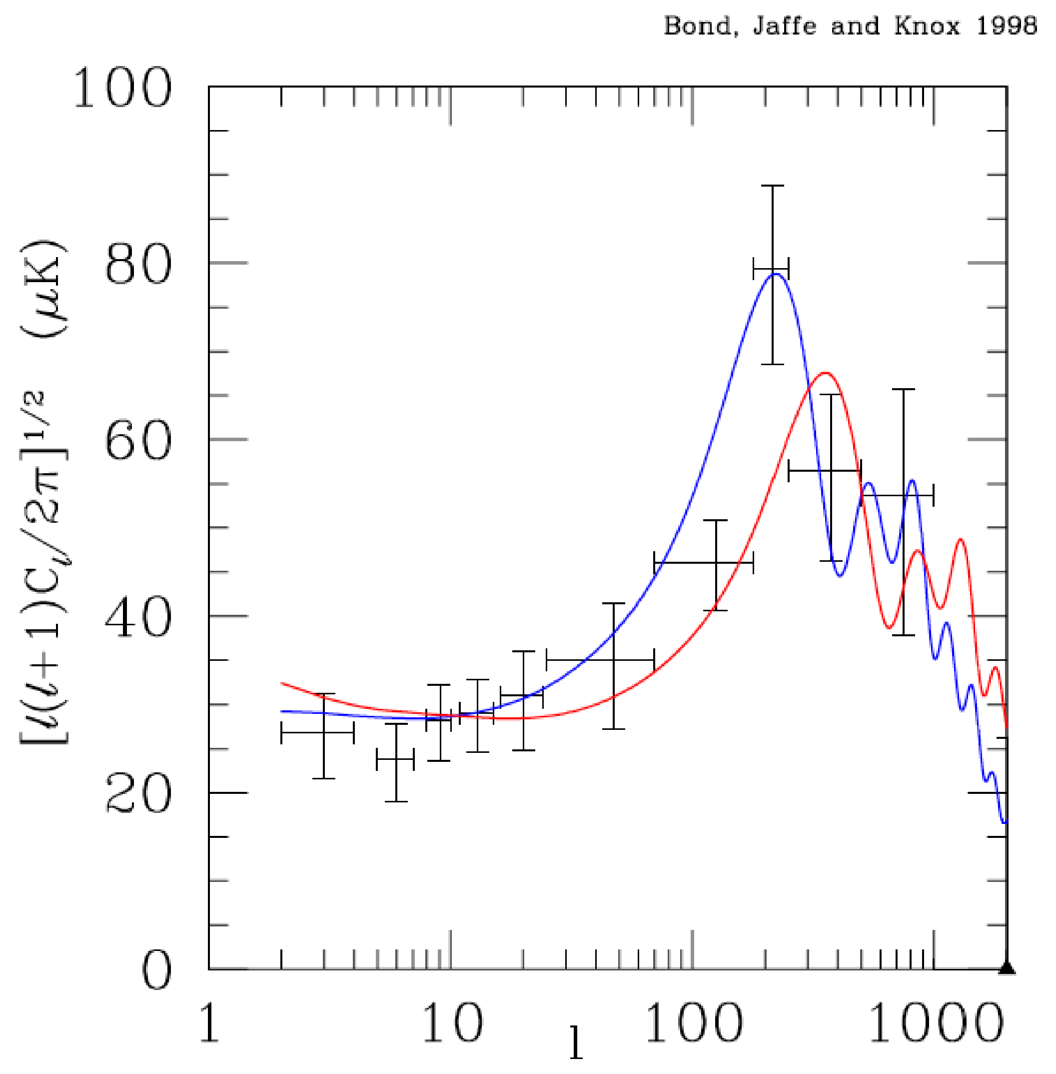
Garnavich et al. 1998

$\Omega_w + \Omega_M = 1$

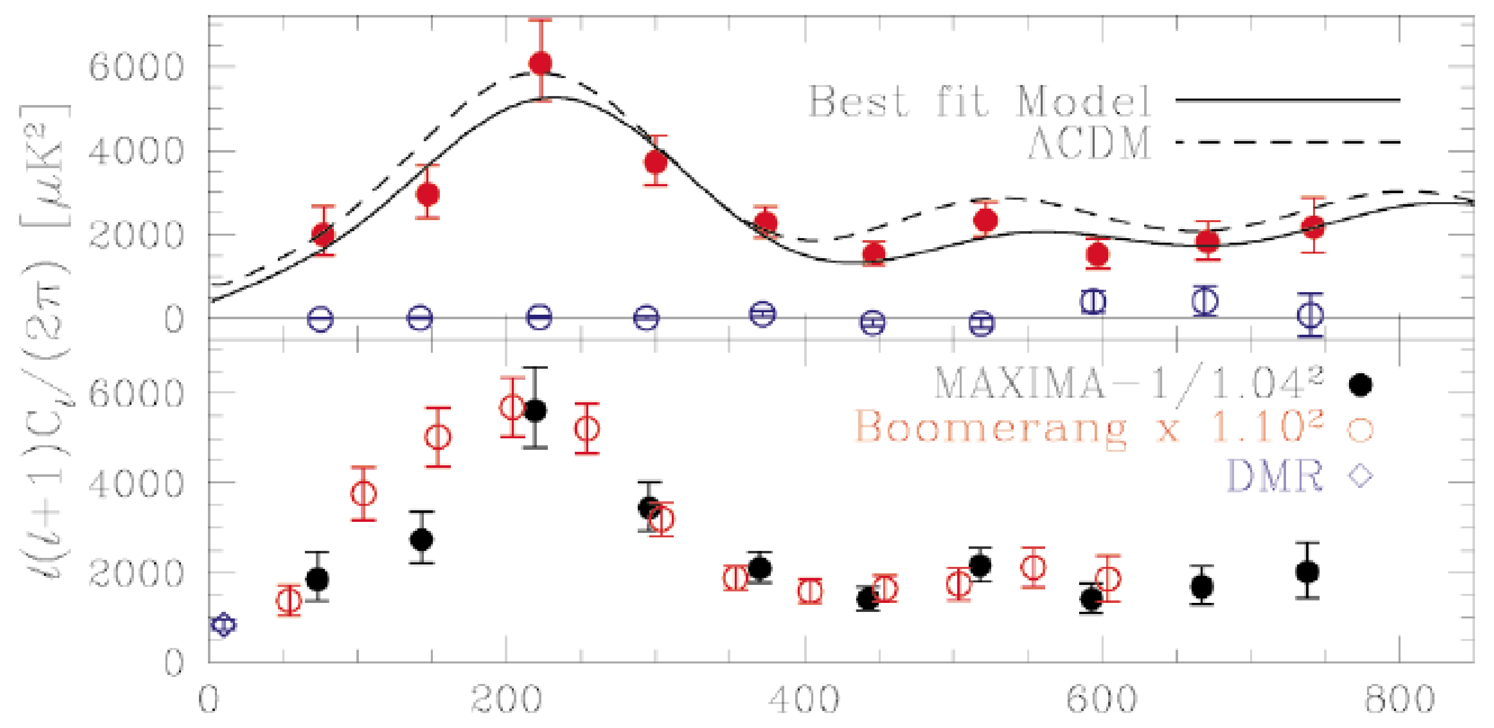
The beginnings of the quest to measure the equation of state of Dark Energy

EOS was new stuff to us, so we had no problem giving the constant the name α

CMB - mid 1998

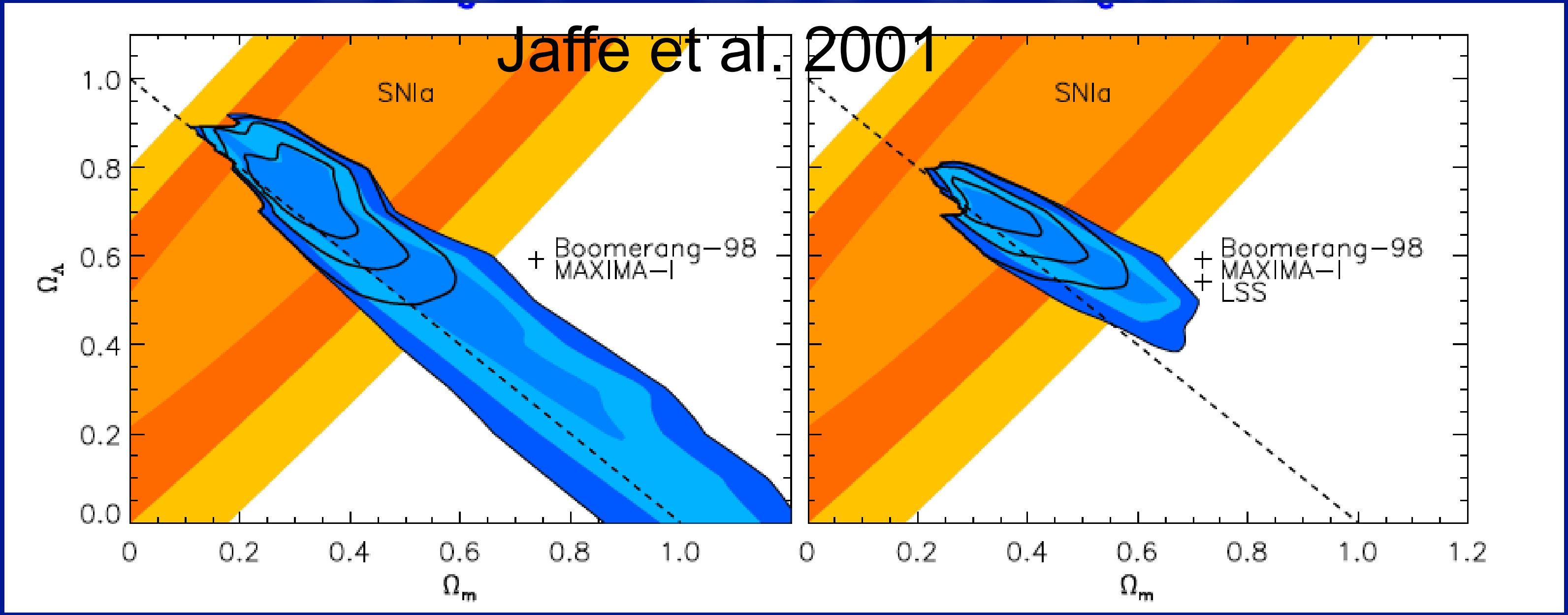

Bond, Jaffe and Knox 1998
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ (μK)
100
80
60
40
20
0
1
10
l
100
1000

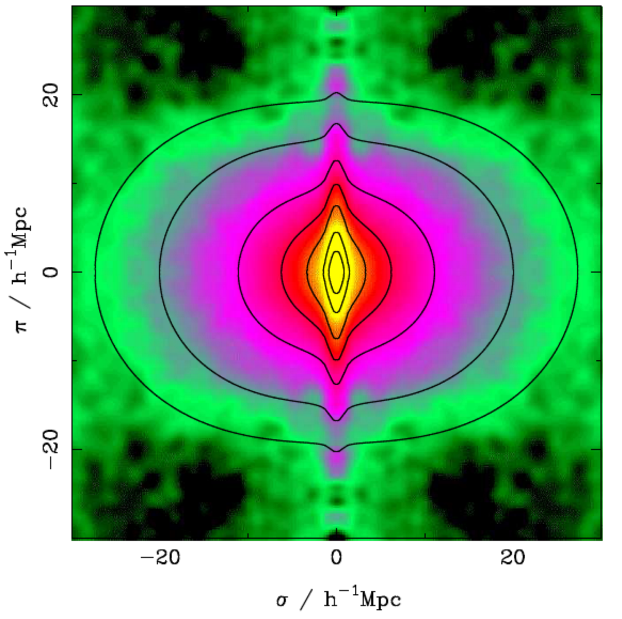
2000 - Boomerang & MAXIMA Clearly see 1st Doppler Peak



Once a Flat Universe was measured, the SN Ia measurements went from being 3-4σ to >7σ

2001 - LSS & CMB

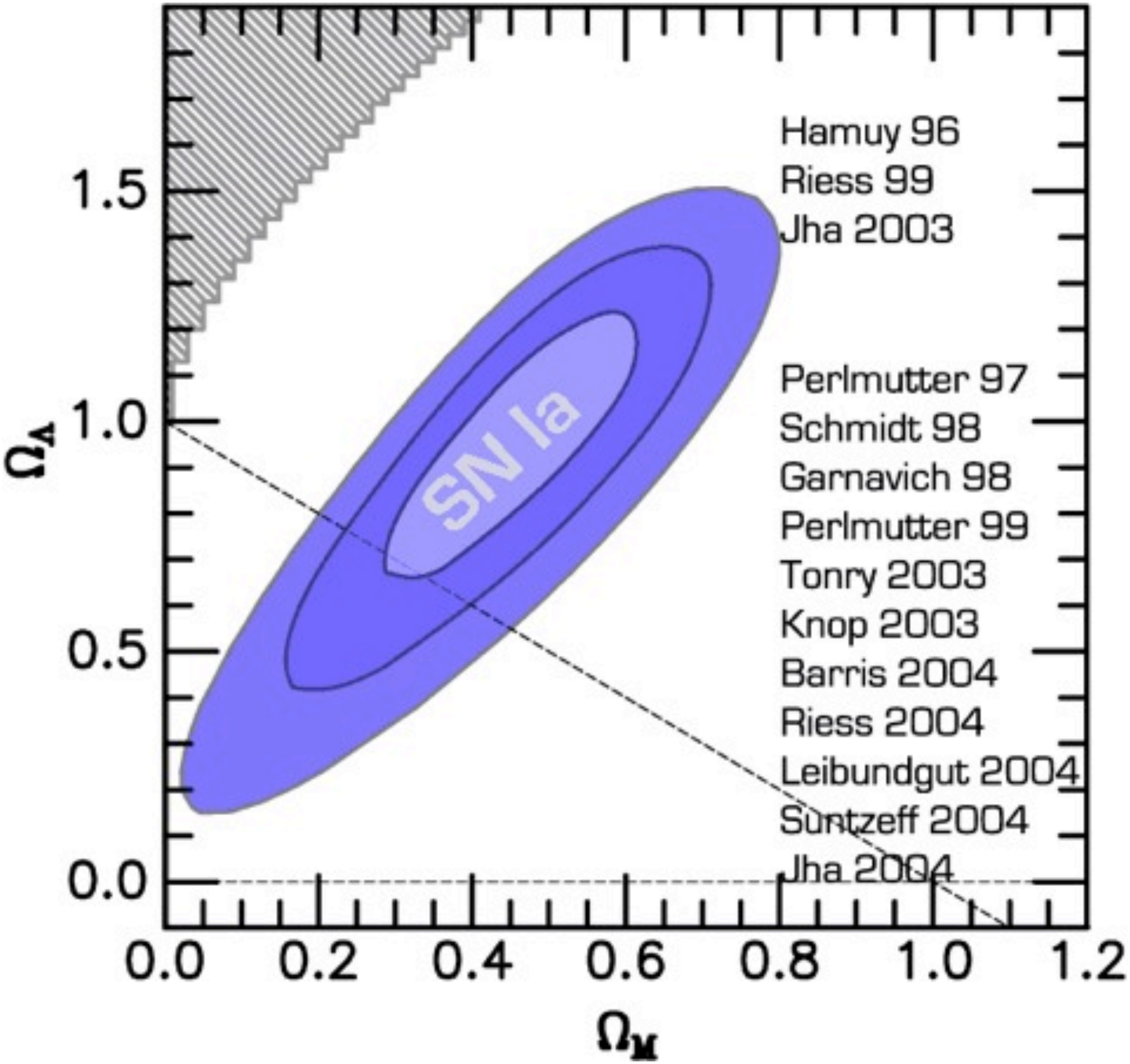


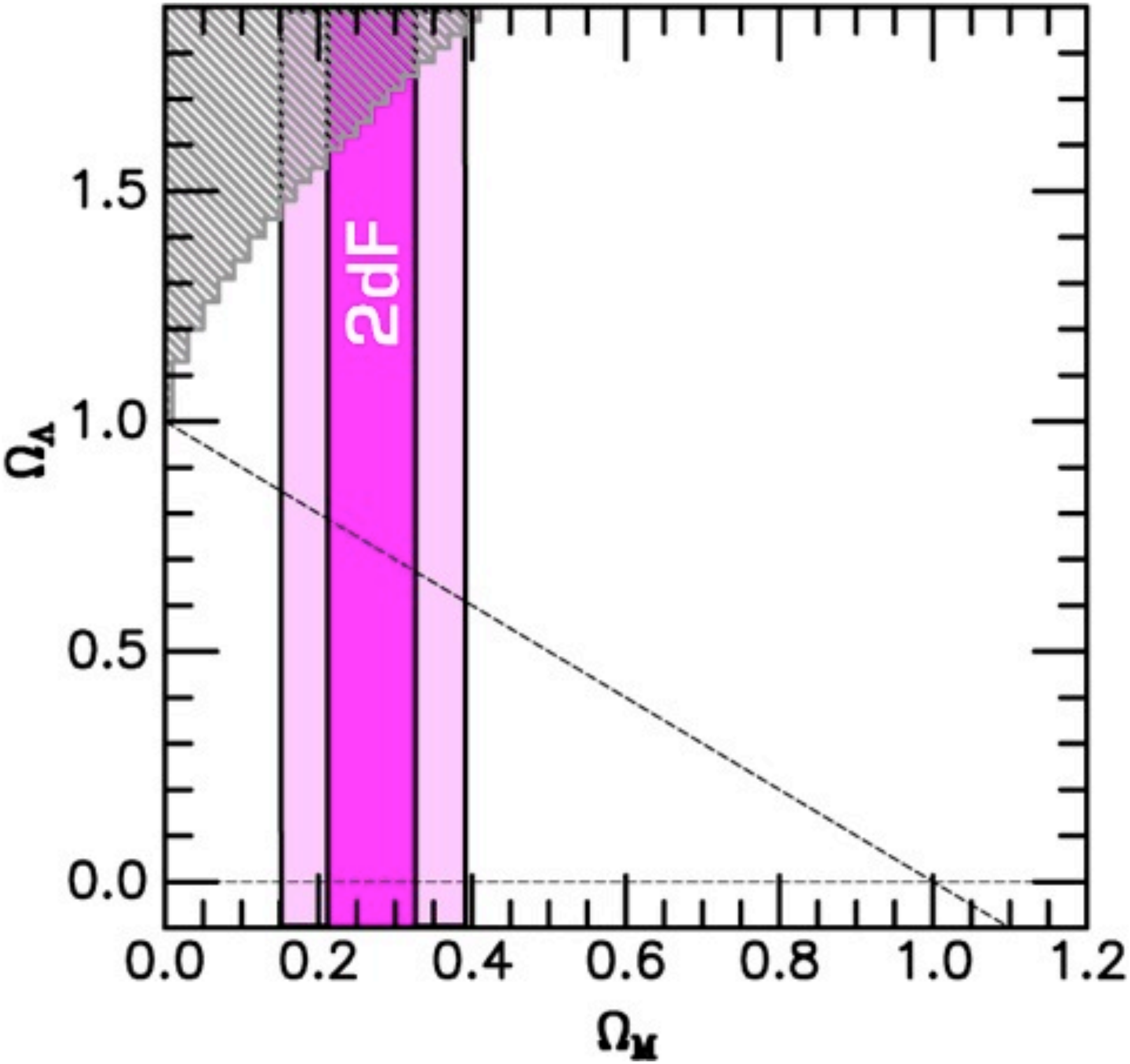


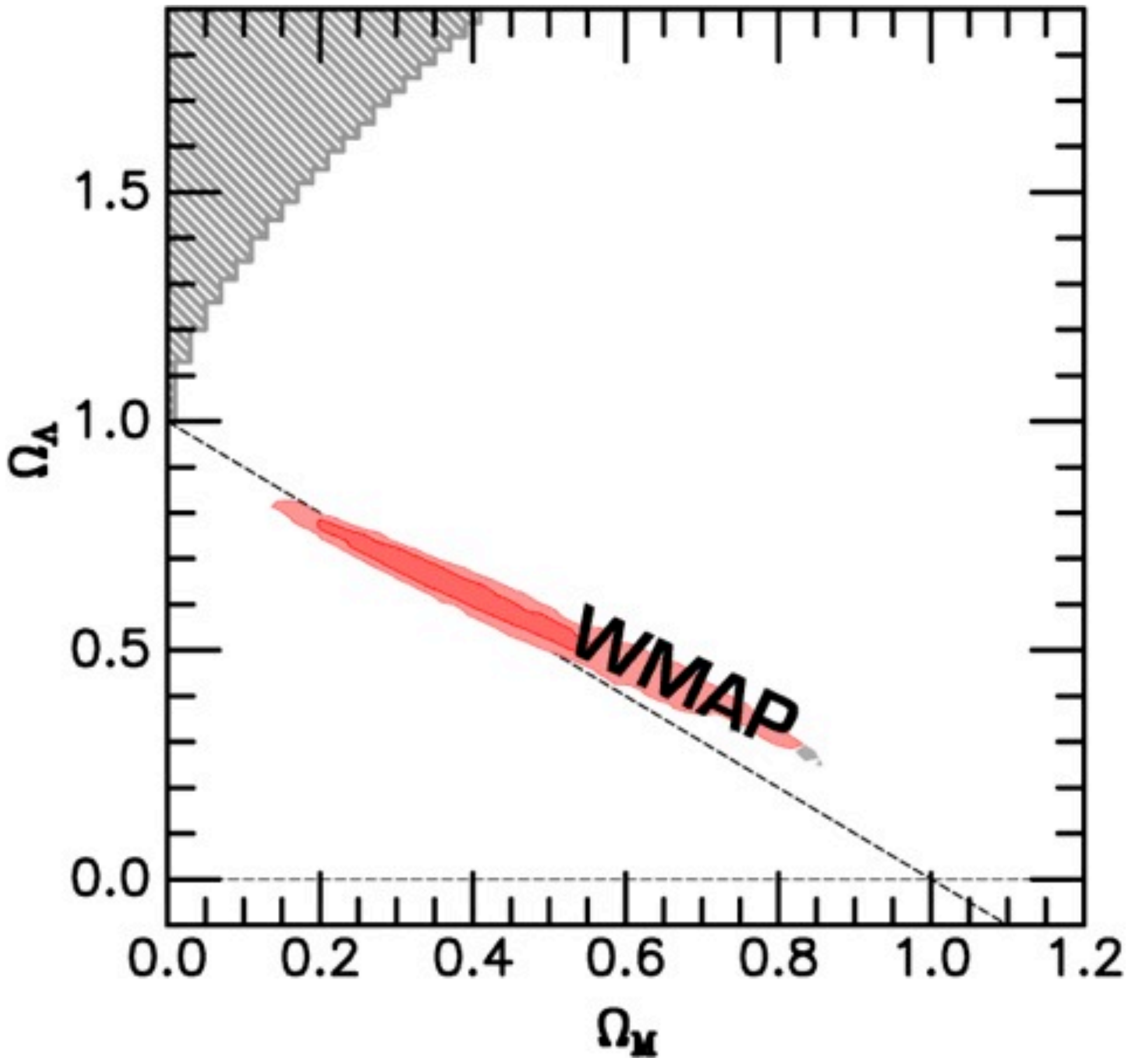
2dF redshift survey finds

$\Omega_{\mathbb{M}}$~0.3 from power

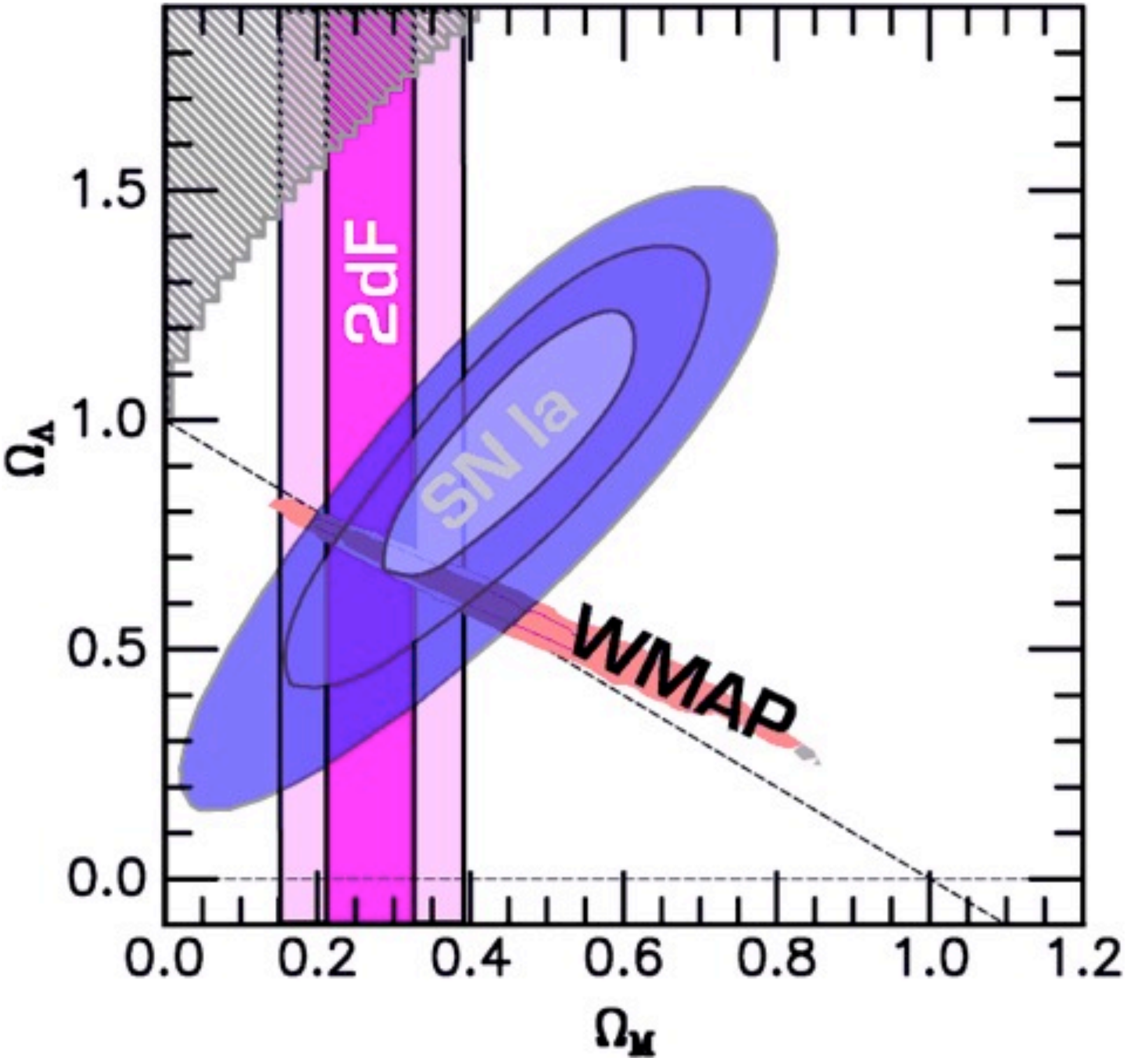
spectrum and infall


SN Ia
1.5
1.0
0.5
0.0
Ω_Λ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ω_M
Hamuy 96
Riess 99
Jha 2003
Perlmutter 97
Schmidt 98
Garnavich 98
Perlmutter 99
Tonry 2003
Knop 2003
Barris 2004
Riess 2004
Leibundgut 2004
Suntzeff 2004
Jha 2004


2dF
1.5
1.0
0.5
0.0
Ω_Λ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ω_M



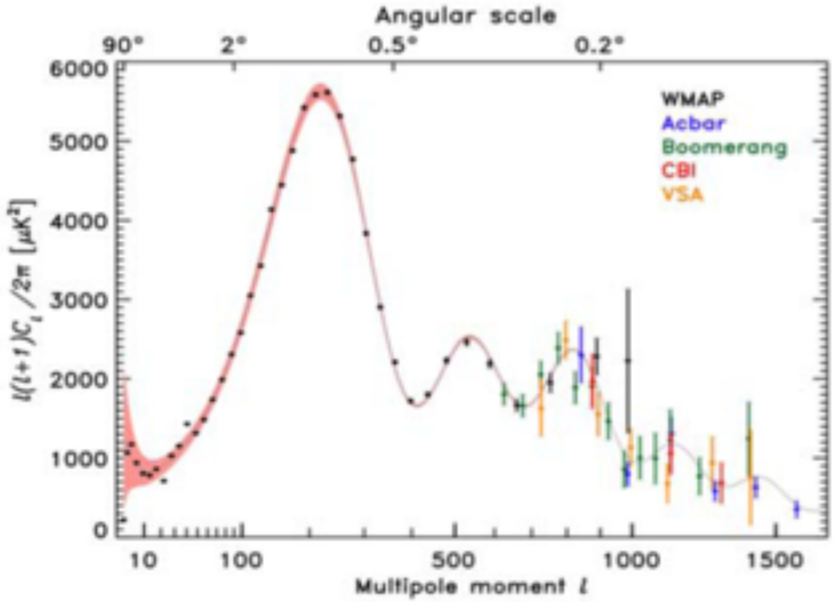
1.5
1.0
0.5
0.0
Ω_Λ
WMAP
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ω_M

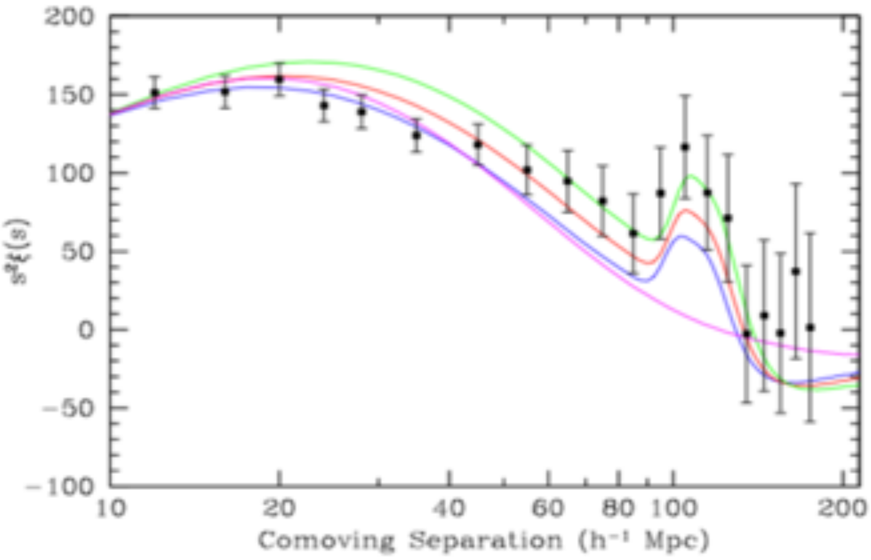

1.5
1.0
0.5
0.0
Ω_Λ
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ω_M
2dF
SN Ia
WMAP

1998-2005
The Rise of Baryon Acoustic Oscillations

From any initial density fluctuation, a expanding spherical perturbation propagates at the speed of sound until recombination.

The physics of these *baryon acoustic oscillations* (BAO) is well understood, and their manifestation as wiggles in the CMB fluctuation spectrum is modeled to very high accuracy - the 1st peak has a size of 147±2 Mpc (co-moving), from WMAP-5

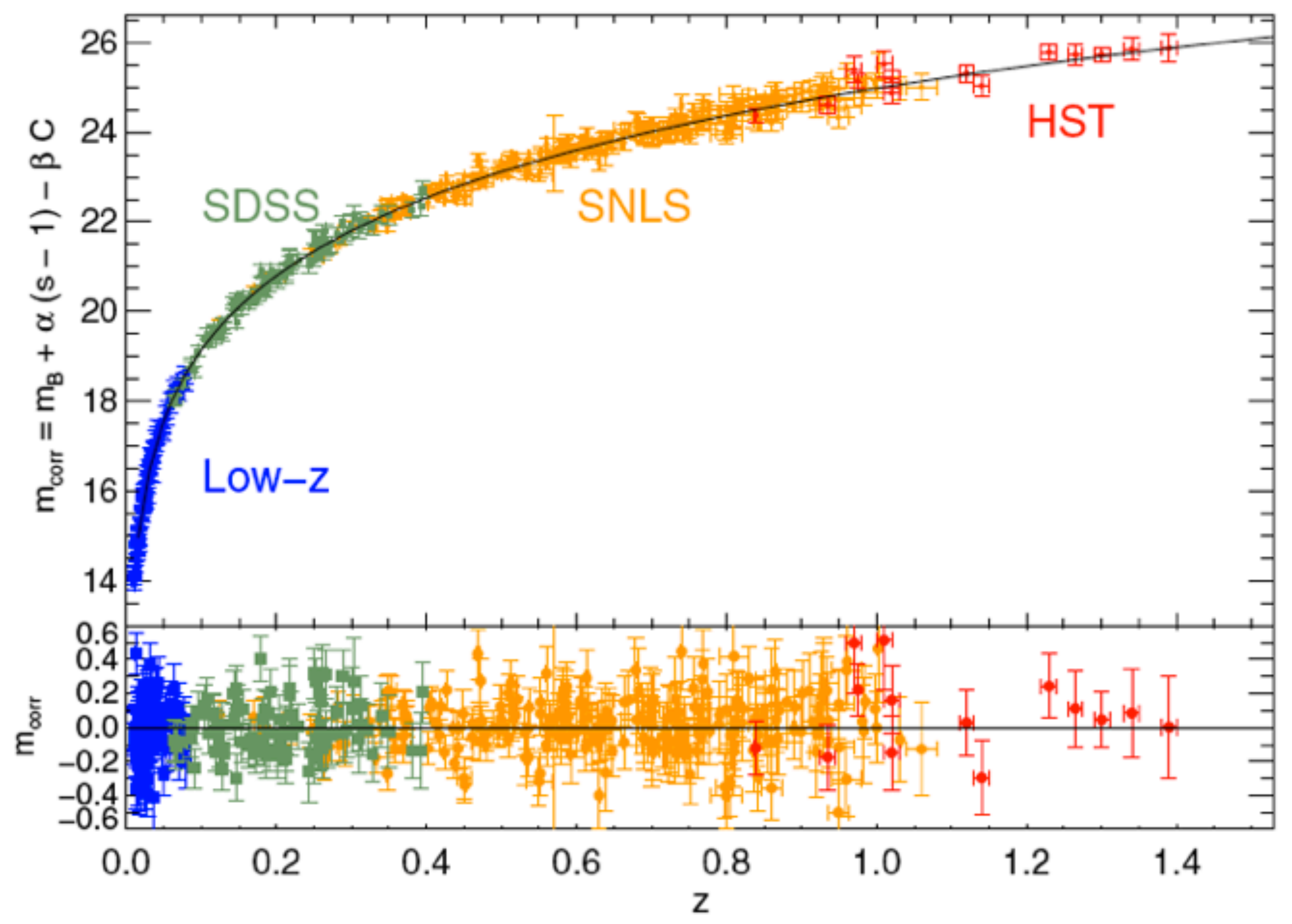




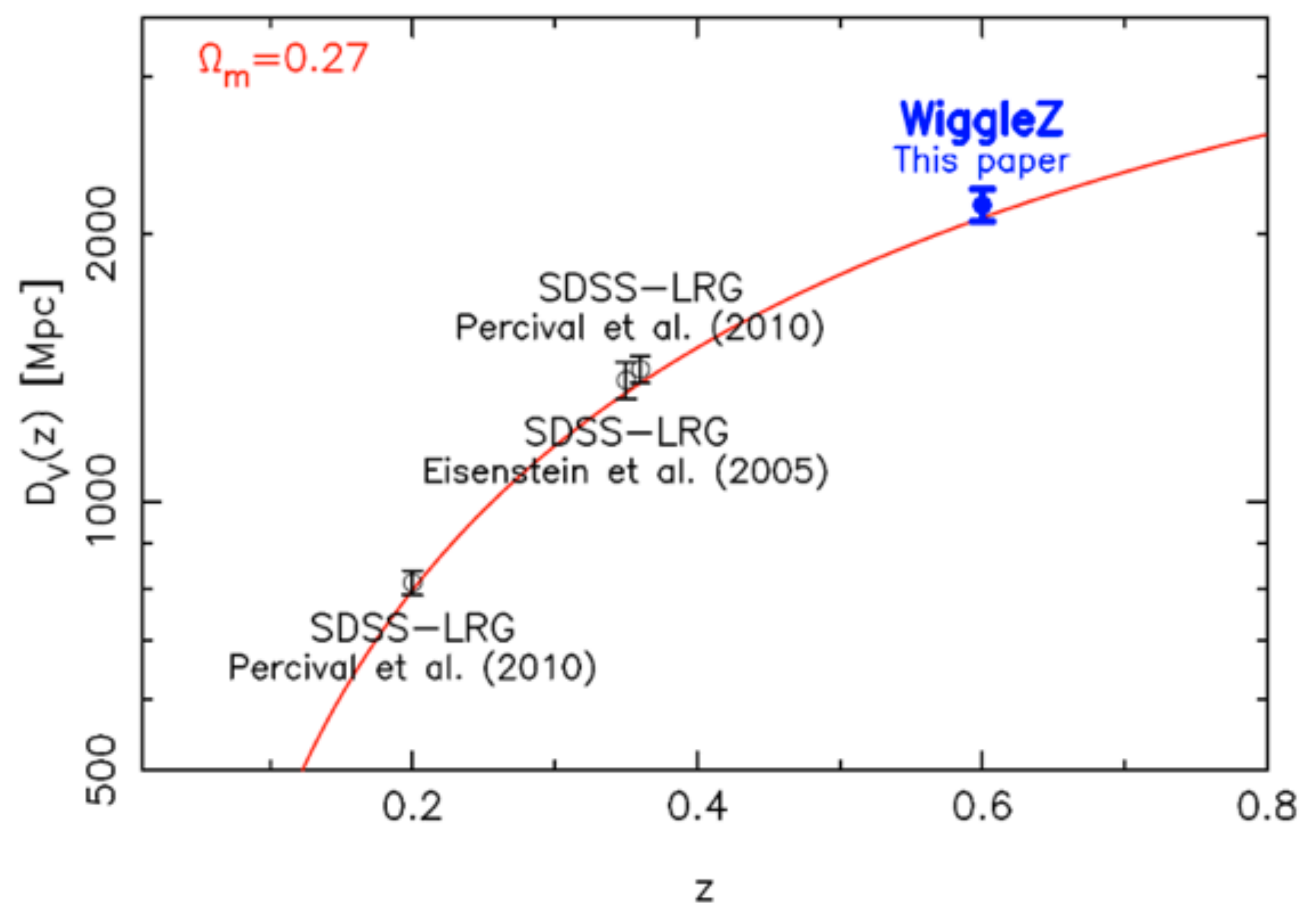
Eisenstein et al. 2005

- Modelling shows that this scale is preserved in the Dark Matter and Baryons. A survey of the galaxy density field should reveal this characteristic scale.
- Need Gpc^3 and 100,000 test particles to reasonably measure the acoustic scale. Angular measurement gives you an Angular-size distance to compare to the CMB scale - and potentially a redshift-based scale that measures H(z).
- The largest galaxy surveys to date, the 2dF, and Sloan Digital Sky Survey, and Wigglez have yielded a detection of the BAO at <z>=0.2, <z>=0.35, and <z>=0.6

Where we Stand now - SN Ia



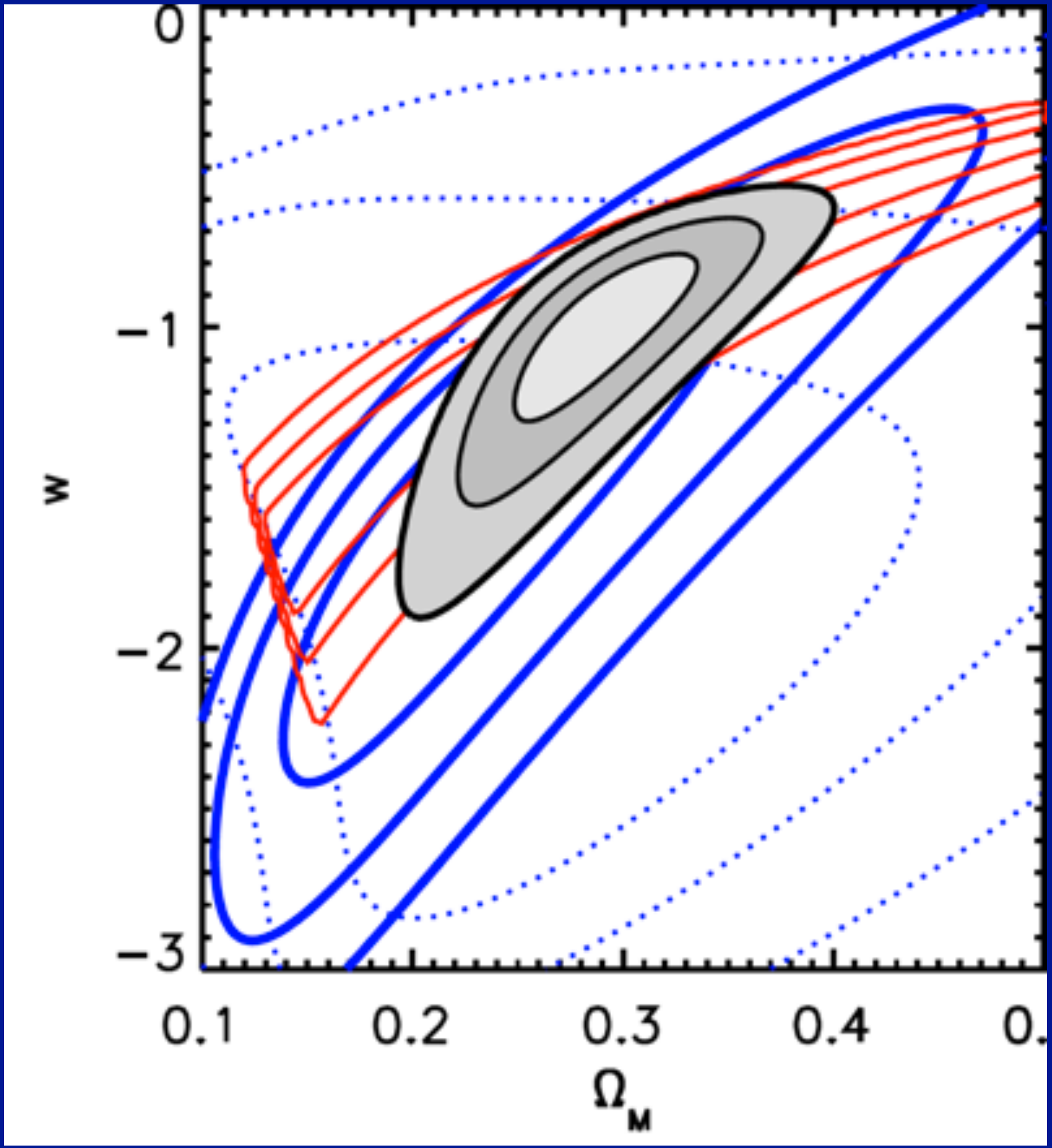
Where we Stand now - BAOs

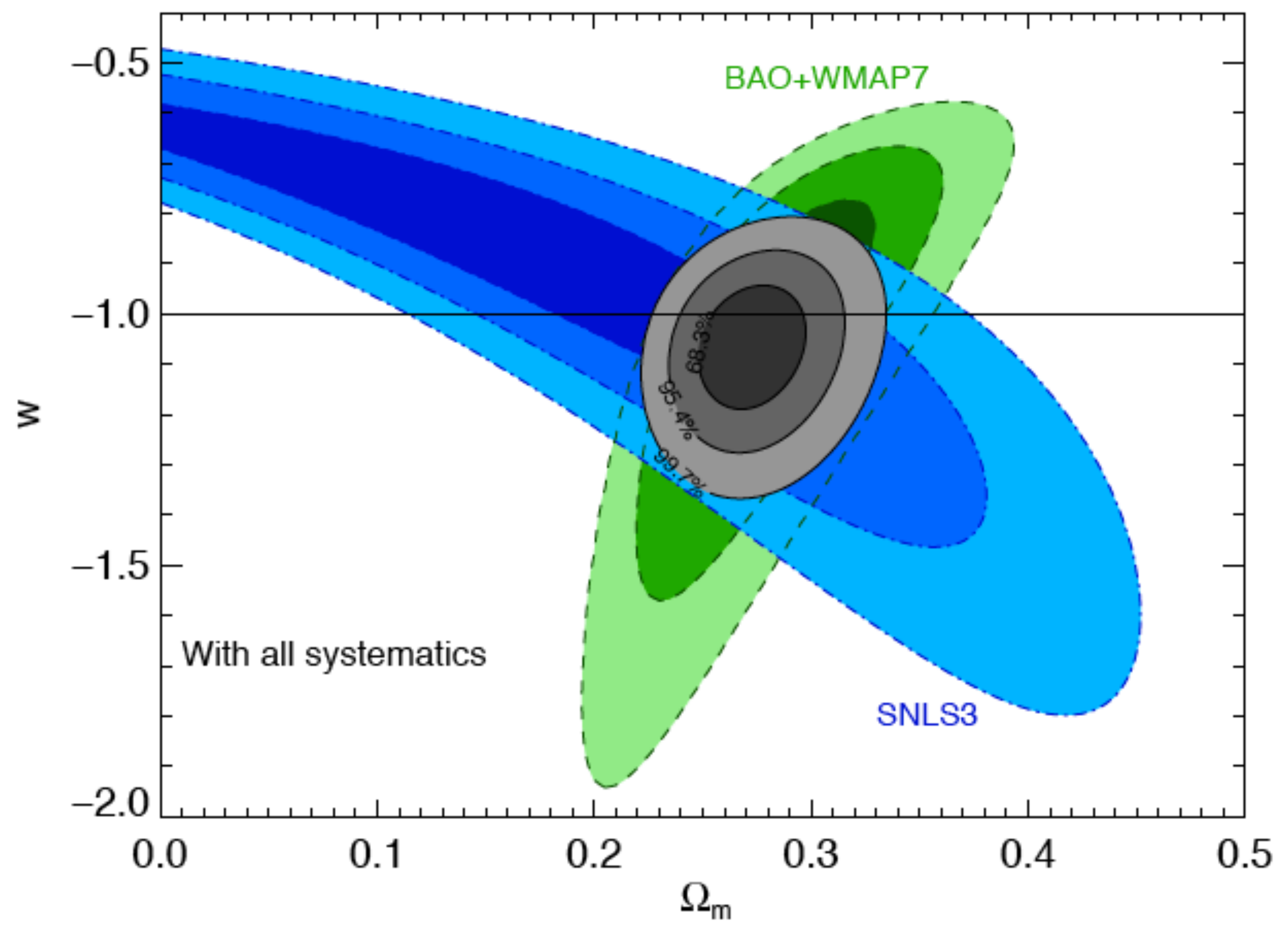


Blake et al 2011

Blake et al 2011

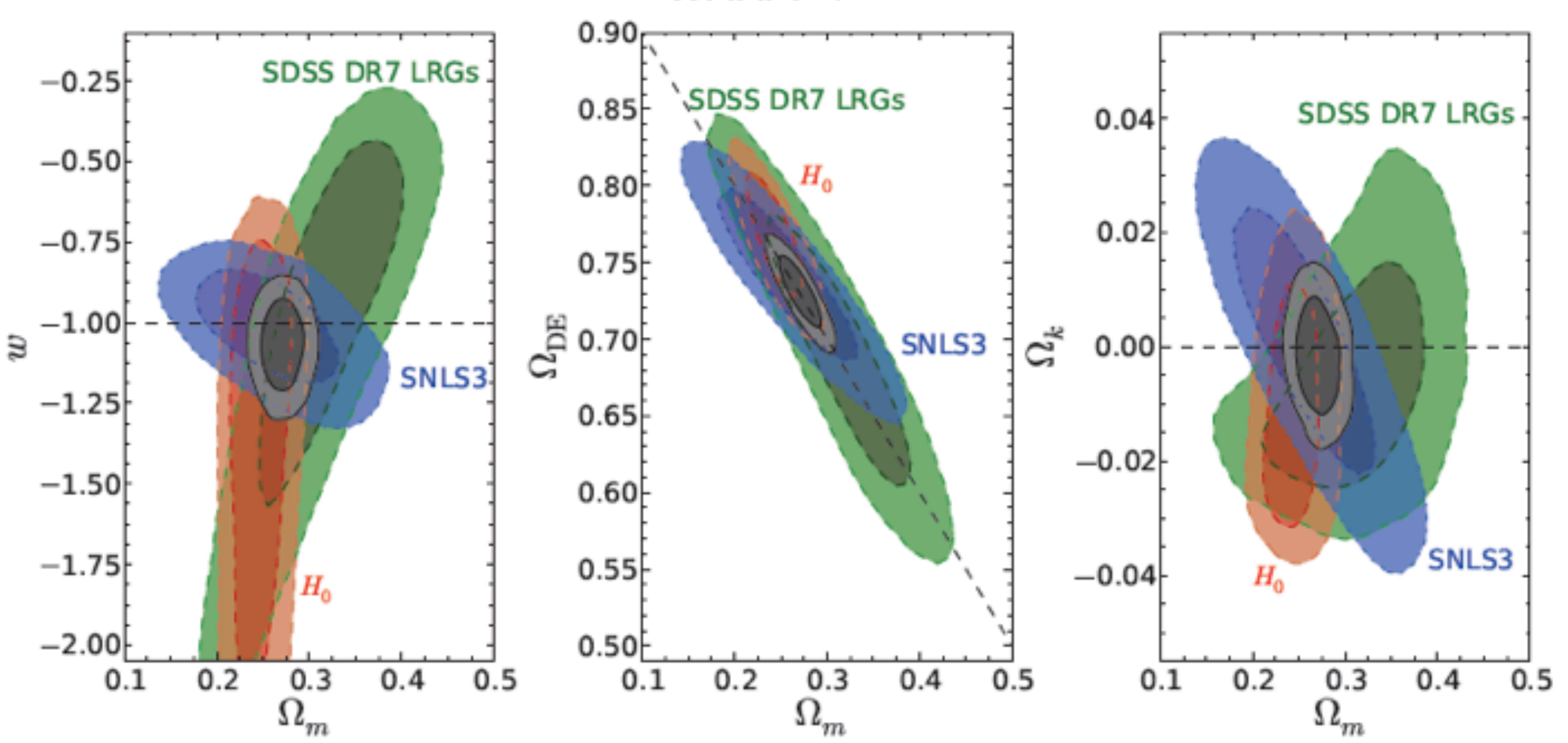
Where we Stand now - BAOs





Sullivan et al 11

WMAP7 + ...



w $,\Omega_w, \Omega_M, \Omega_K$

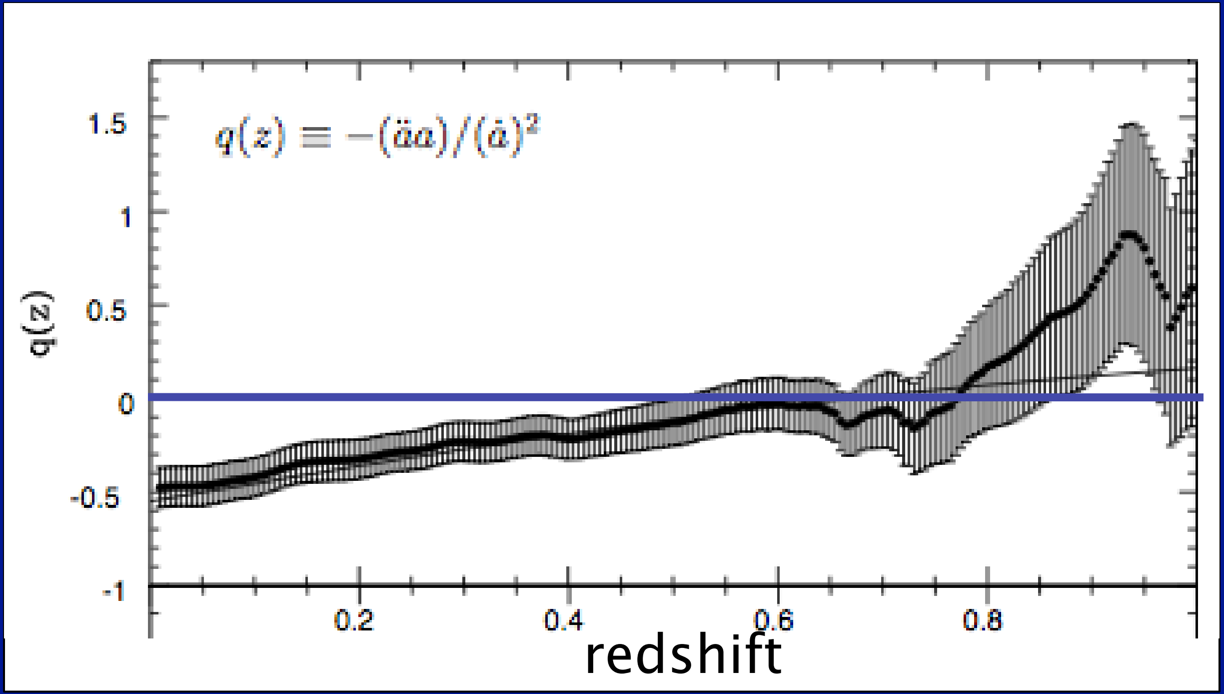
all constrained simultaneously

Sullivan et al 11

If the Universe is Homogenous and Isotropic the Universe is Accelerating!

- Expand the Robertson-Walker Metric and see how D(1+z,q_0)...

Supernova Data are good enough now to show the acceleration independent of assuming General Relativity.



Daly et al.

Dark Energy  ?

Dark Energy  ?

only if the **Universe is not homogenous or isotropic** – Robertson Walker Metric invalid.

Occam’s Razor does not favour us living in the center of a spherical under-density whose size and radial fall-off is matched to the acceleration.

Dark Energy  ?

only if the **Universe is not homogenous or isotropic** – Robertson Walker Metric invalid.

Occam's Razor does not favour us living in the center of a spherical under-density whose size and radial fall-off is matched to the acceleration.

Theoretical Discussion on whether or not the growth of structure can kink the metric in such a way to mimic the effects of Dark Energy. This is the only way out I can see - But controversial!

So What is the Dark Energy?

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One possibility is that the Universe is permeated by an energy density, constant in time and uniform in space.

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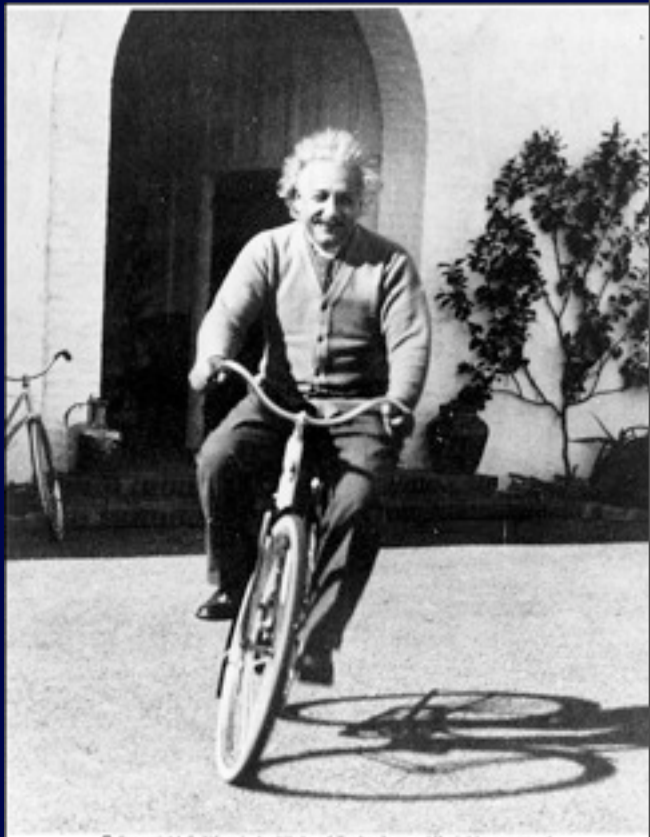
Such a “cosmological constant” (Lambda: Λ) was originally postulated by Einstein, but later rejected when the expansion of the Universe was first detected.



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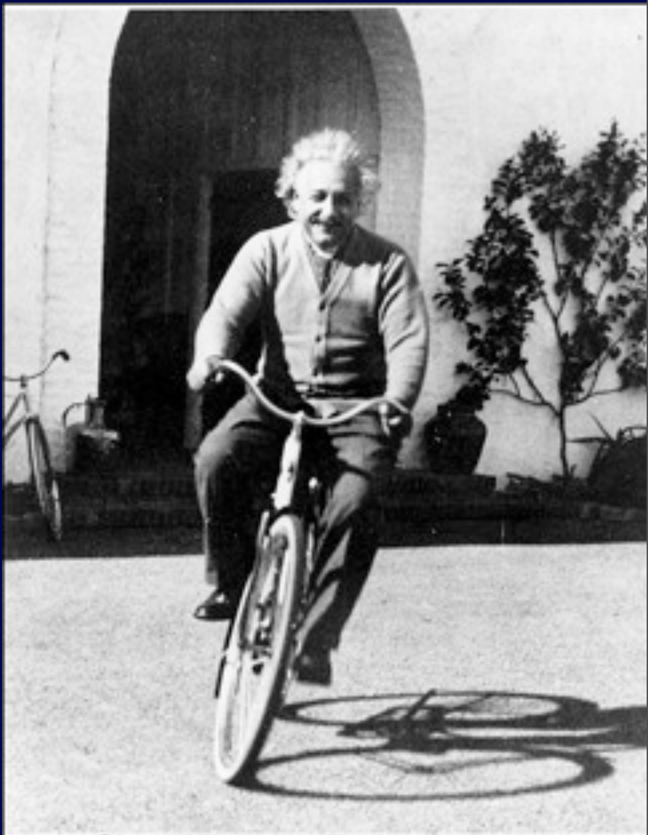
Such a “cosmological constant” (Lambda: Λ) was originally postulated by Einstein, but later rejected when the expansion of the Universe was first detected.

General arguments from the scale of particle interactions, however, suggest that if Λ is not zero, it should be very large, larger by a truly enormous factor than what is measured.



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Unfortunately these theories offer infinite flexibility, can reproduce any observation we make, and can spend much of their time

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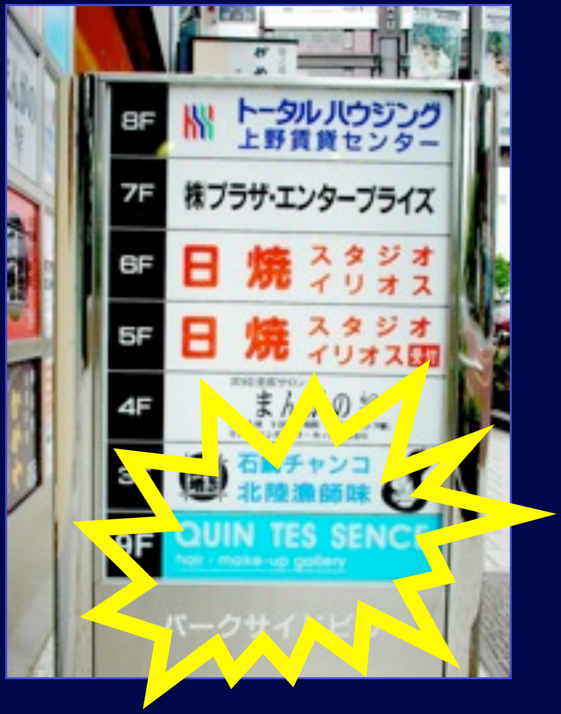

So What is the Dark Energy?

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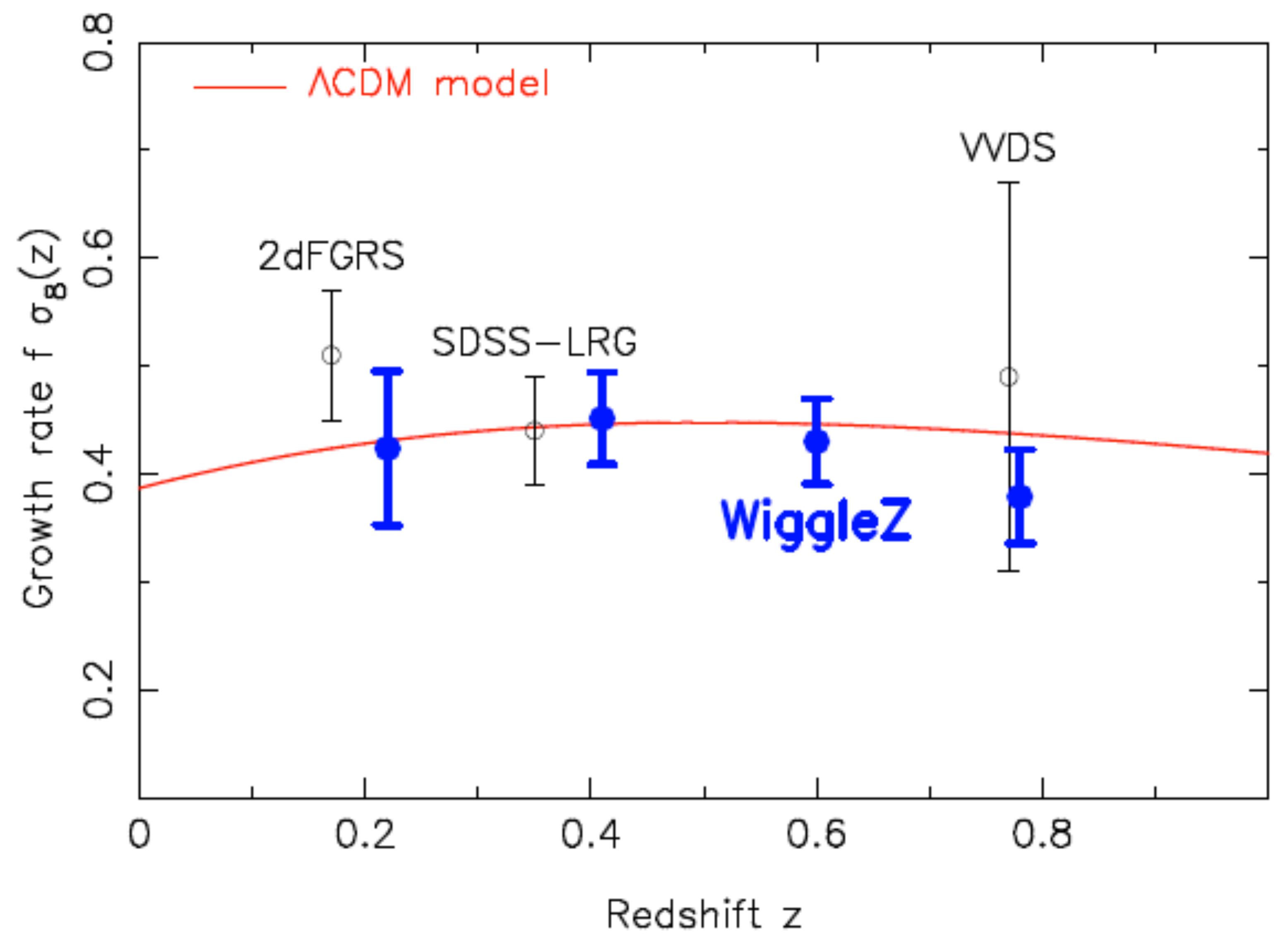
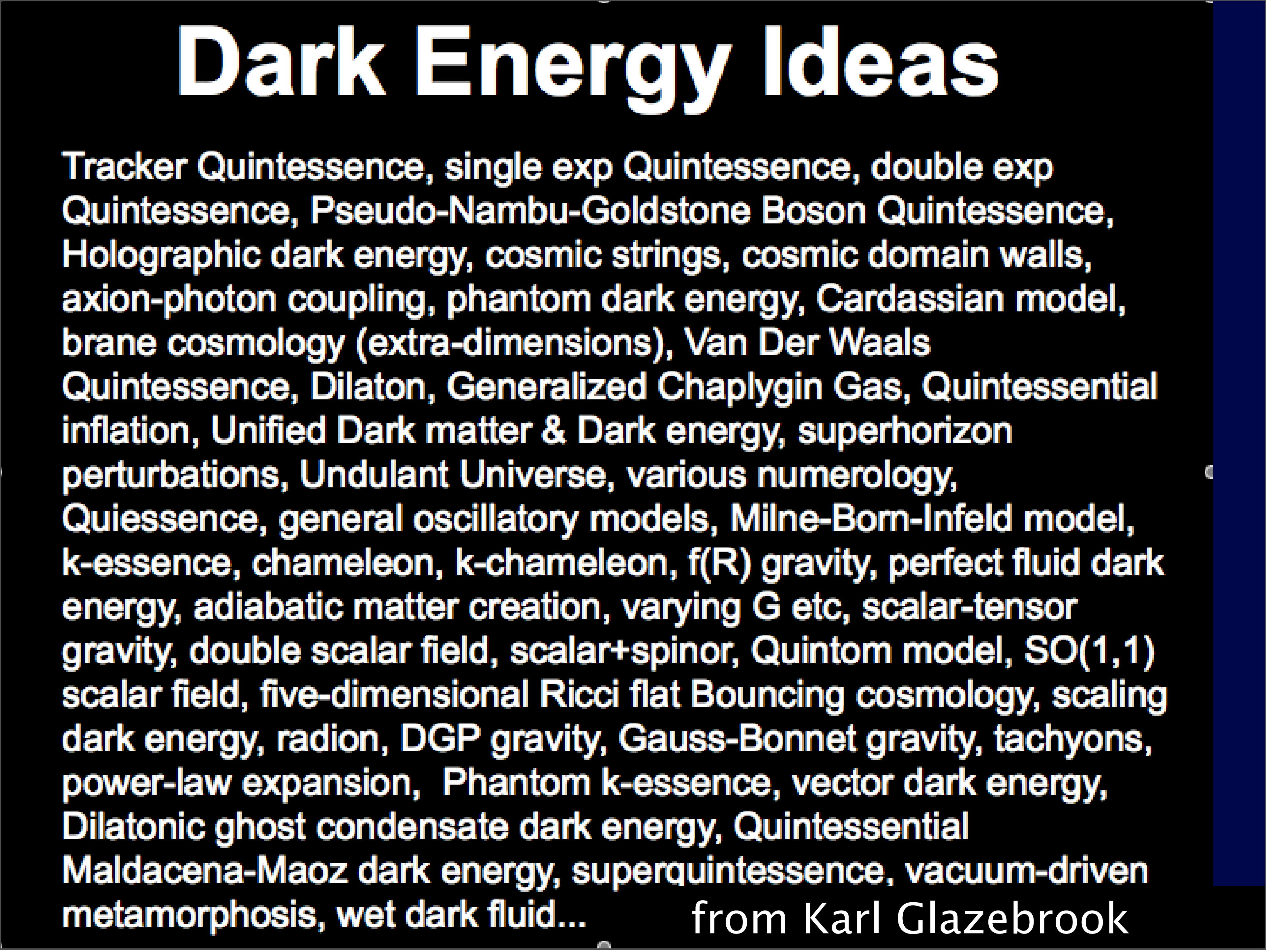
But we can start to test this.

Blake et al 2011





Dark Energy Ideas

Tracker Quintessence, single exp Quintessence, double exp Quintessence, Pseudo-Nambu-Goldstone Boson Quintessence, Holographic dark energy, cosmic strings, cosmic domain walls, axion-photon coupling, phantom dark energy, Cardassian model, brane cosmology (extra-dimensions), Van Der Waals Quintessence, Dilaton, Generalized Chaplygin Gas, Quintessential inflation, Unified Dark matter & Dark energy, superhorizon perturbations, Undulant Universe, various numerology, Quiessence, general oscillatory models, Milne-Born-Infeld model, k-essence, chameleon, k-chameleon, f(R) gravity, perfect fluid dark energy, adiabatic matter creation, varying G etc, scalar-tensor gravity, double scalar field, scalar+spinor, Quintom model, SO(1,1) scalar field, five-dimensional Ricci flat Bouncing cosmology, scaling dark energy, radion, DGP gravity, Gauss-Bonnet gravity, tachyons, power-law expansion, Phantom k-essence, vector dark energy, Dilatonic ghost condensate dark energy, Quintessential Maldacena-Maoz dark energy, superquintessence, vacuum-driven metamorphosis, wet dark fluid...

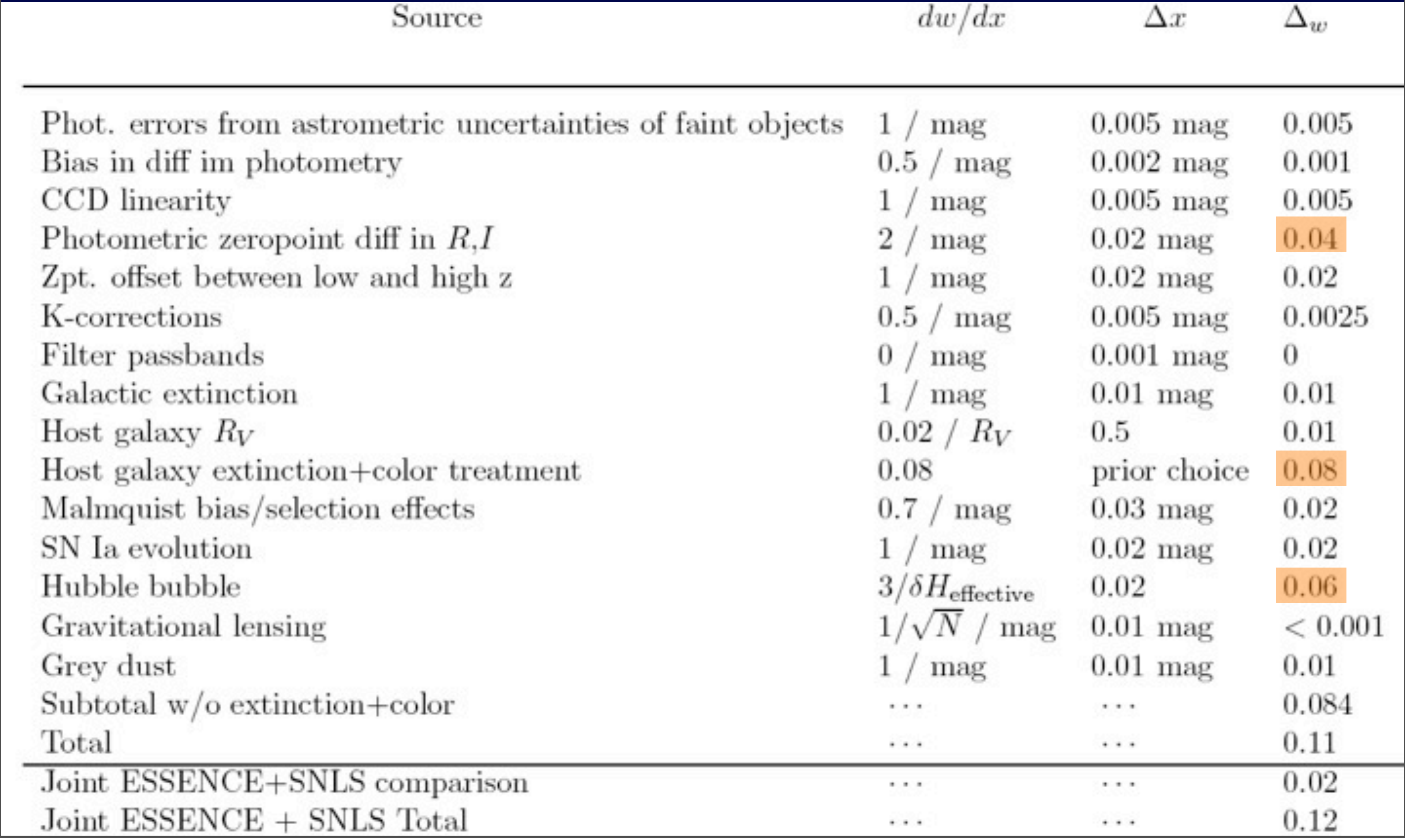
from Karl Glazebrook

Using SN to measure w(z)

- Right now, most precise technique
- Effort to use goes as ~$(1+z)^6$
  - Fainter
  - spectrum moves into IR where background is much brighter and detectors are much more expensive and less sensitive.
- Relatively Sensitive to $w(z) \neq -1$ @ $z<0.5$
- Susceptible to systematic errors

Everybody has Dirty Laundry...

Systematic Errors in SN Ia



Source	dw/dx	Δx	Δ_w
Phot. errors from astrometric uncertainties of faint objects	1 / mag	0.005 mag	0.005
Bias in diff im photometry	0.5 / mag	0.002 mag	0.001
CCD linearity	1 / mag	0.005 mag	0.005
Photometric zeropoint diff in R,I	2 / mag	0.02 mag	0.04
Zpt. offset between low and high z	1 / mag	0.02 mag	0.02
K-corrections	0.5 / mag	0.005 mag	0.0025
Filter passbands	0 / mag	0.001 mag	0
Galactic extinction	1 / mag	0.01 mag	0.01
Host galaxy R_V	0.02 / R_V	0.5	0.01
Host galaxy extinction+color treatment	0.08	prior choice	0.08
Malmquist bias/selection effects	0.7 / mag	0.03 mag	0.02
SN Ia evolution	1 / mag	0.02 mag	0.02
Hubble bubble	$3/\delta H_{\text{effective}}$	0.02	0.06
Gravitational lensing	$1/\sqrt{N}$ / mag	0.01 mag	< 0.001
Grey dust	1 / mag	0.01 mag	0.01
Subtotal w/o extinction+color	⋯	⋯	0.084
Total	⋯	⋯	0.11
Joint ESSENCE+SNLS comparison	⋯	⋯	0.02
Joint ESSENCE + SNLS Total	⋯	⋯	0.12

Evolution…Most of you think this is our Biggest Problem...I wished you were right!

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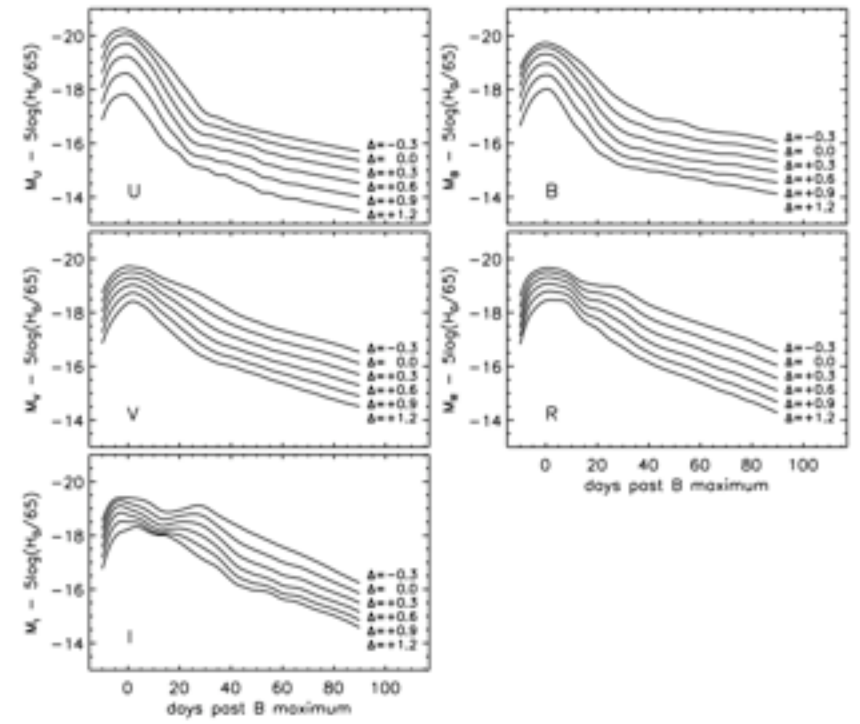
Measuring Distances with SN Ia

SN Ia brightness depends on their light curve shape, extinction, and possibly colour

MLCS/dm15 explicity attribute colour to extinction - but allows colour to correlate with light curve shape - does not allow colour to independentally correlate with luminosity

SALT/SiFTO empirically derives colour-luminosity dependence.



- M_B – absolute magnitude
- α – parameterises the stretch—luminosity relation
- β – parameterises the colour—luminosity relation

$$\mu_B = m_B - M_B + \alpha(s-1) - \beta c$$

On the face of it...MLCS2k2 treatment seems the way to go...

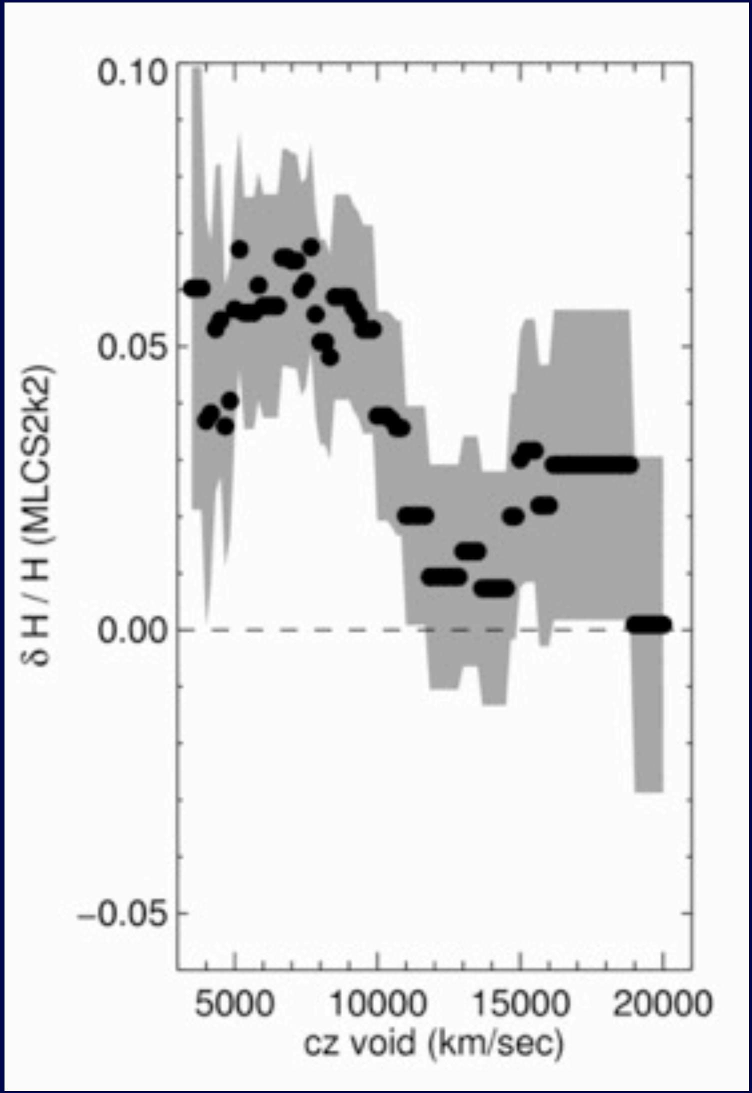
If the intrinsic colour-luminosity relationship does not exactly mimic the extinction law, If the average extinction amount of two samples is different, (or the extinction law changes), there will be a systematic bias.

However, finding the intrinsic colour-luminosity relationship for SN Ia is non-trivial. There are inter-dependencies between SN light curve shape, SN light curve colour, Host Galaxy Properties, Extinction, and K-corrections

Many would argue that the SALT approach seems to be working better presently for Cosmological samples

The Hubble Bubble

- 3σ decrease in Hubble constant at ≈7400 km/sec – local value of H_0 high; distant SNe too faint
- Local void in mass density?



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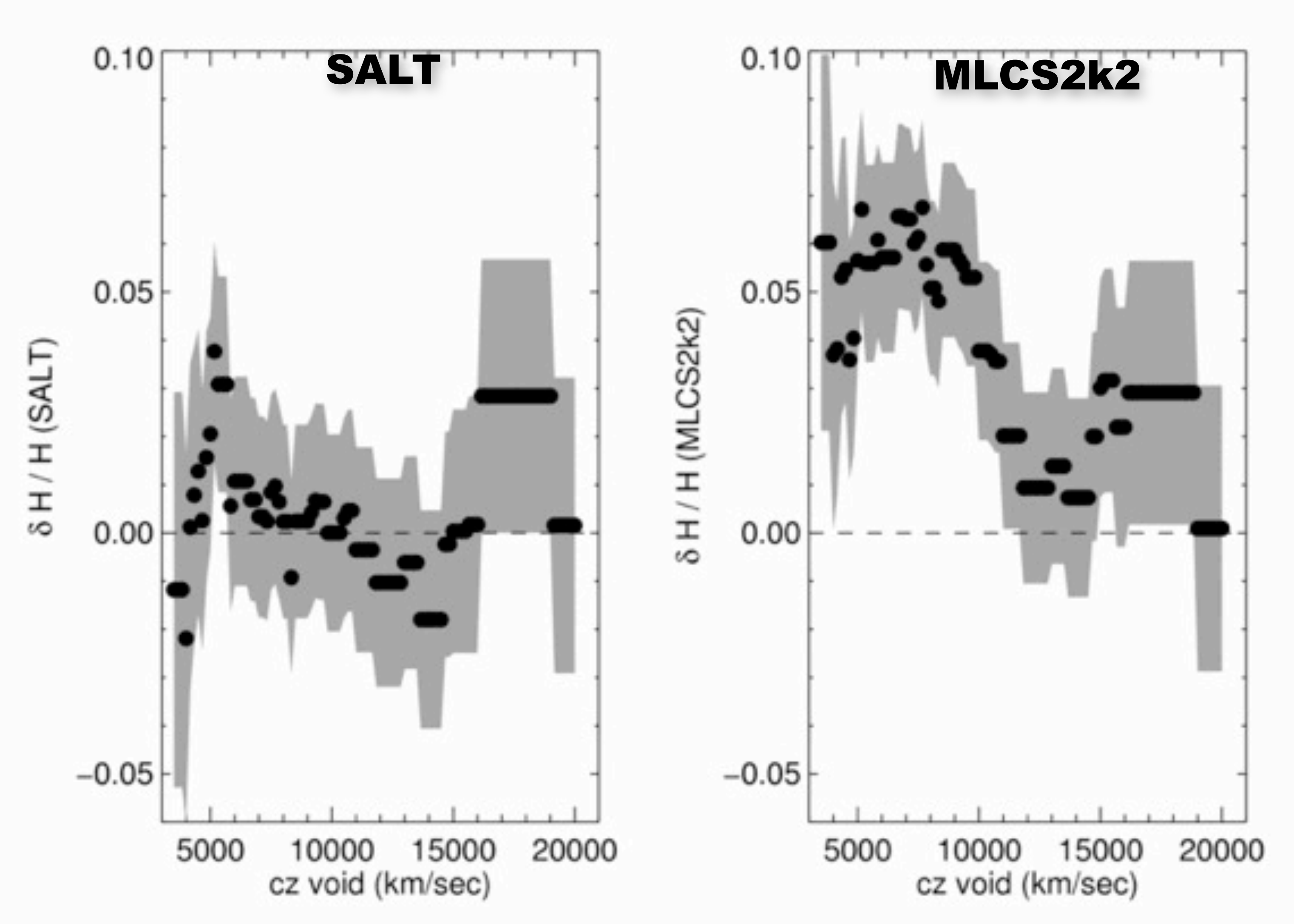
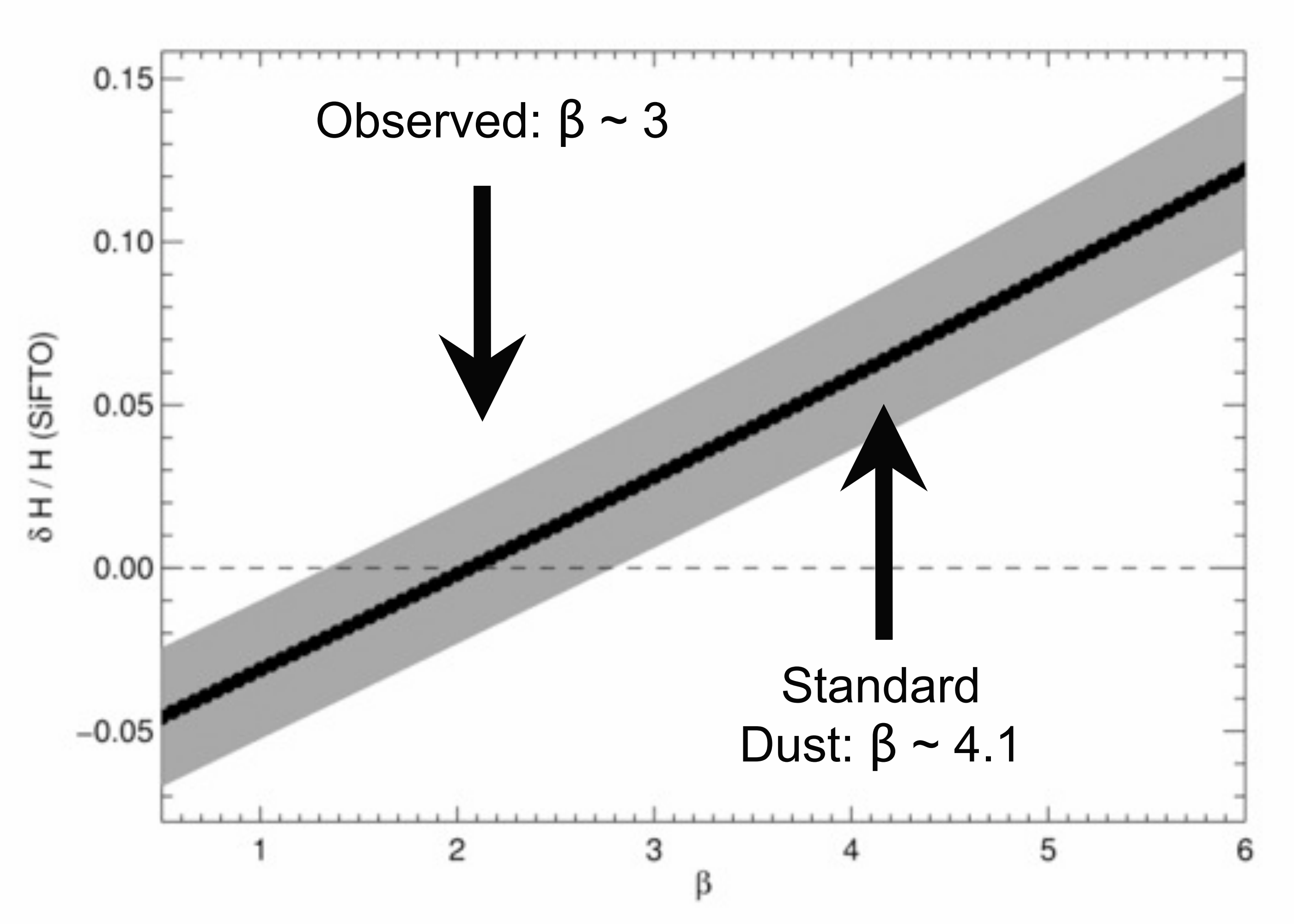


Conley et al. (2007)

“Bubble” significance



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Hubble Bubble Has Gone away

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- Bigger sample (Hicken et al) with IR, improvements in Dust treatment, the Hubble Bubble has gone away for both distance indicators.

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To first order... implies the dust law in host galaxies is very different than what we see in our Galaxy (Astronomical talk: R_V=2.2 which is 2 mags of extinction for each magnitude of reddening in B–V colour, instead of the canonical 3.1)

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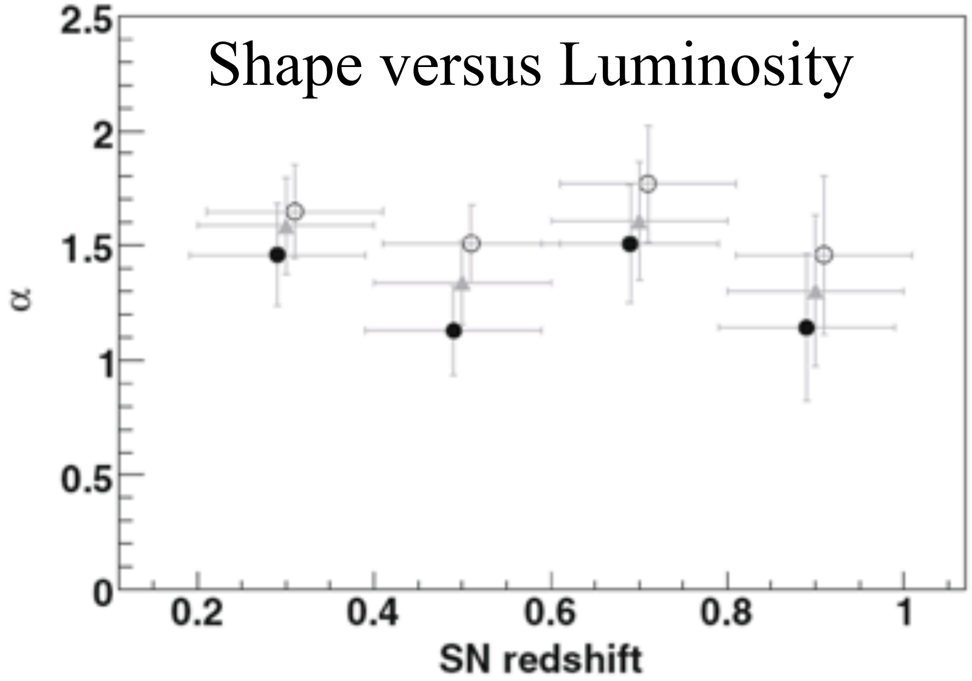
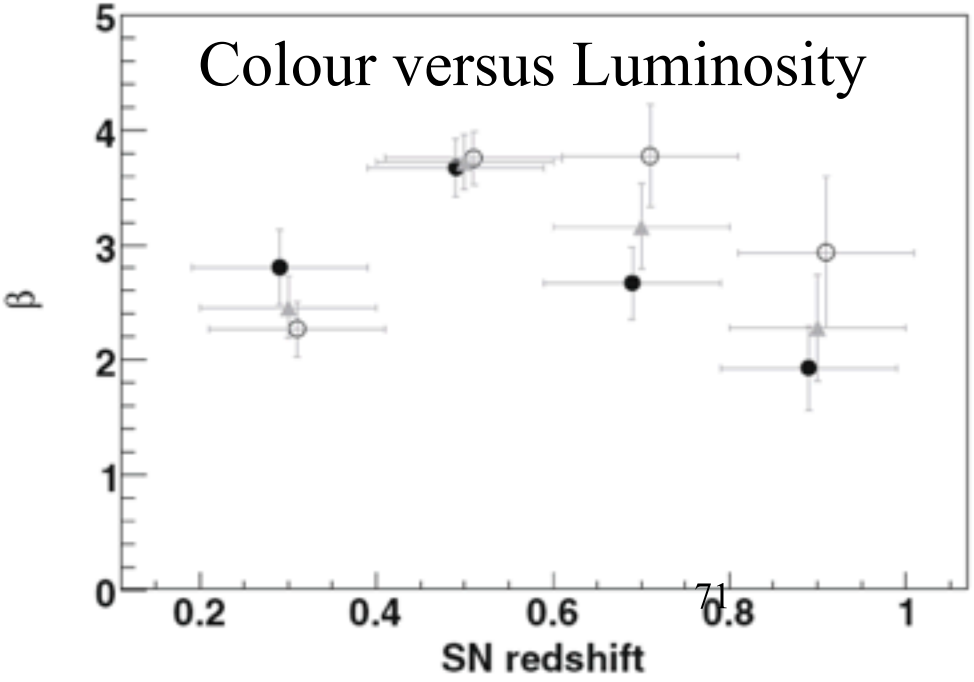
- Light echoes off Dust?

How we treat dust affects Cosmological

- Using the two approaches affects Cosmological measurement at the w=+/-0.1 level.
- How to correct...
  - IR data (Hard – Sky is Bright/Space is expensive!)
  - Understand extinction/colour better in the nearby Universe

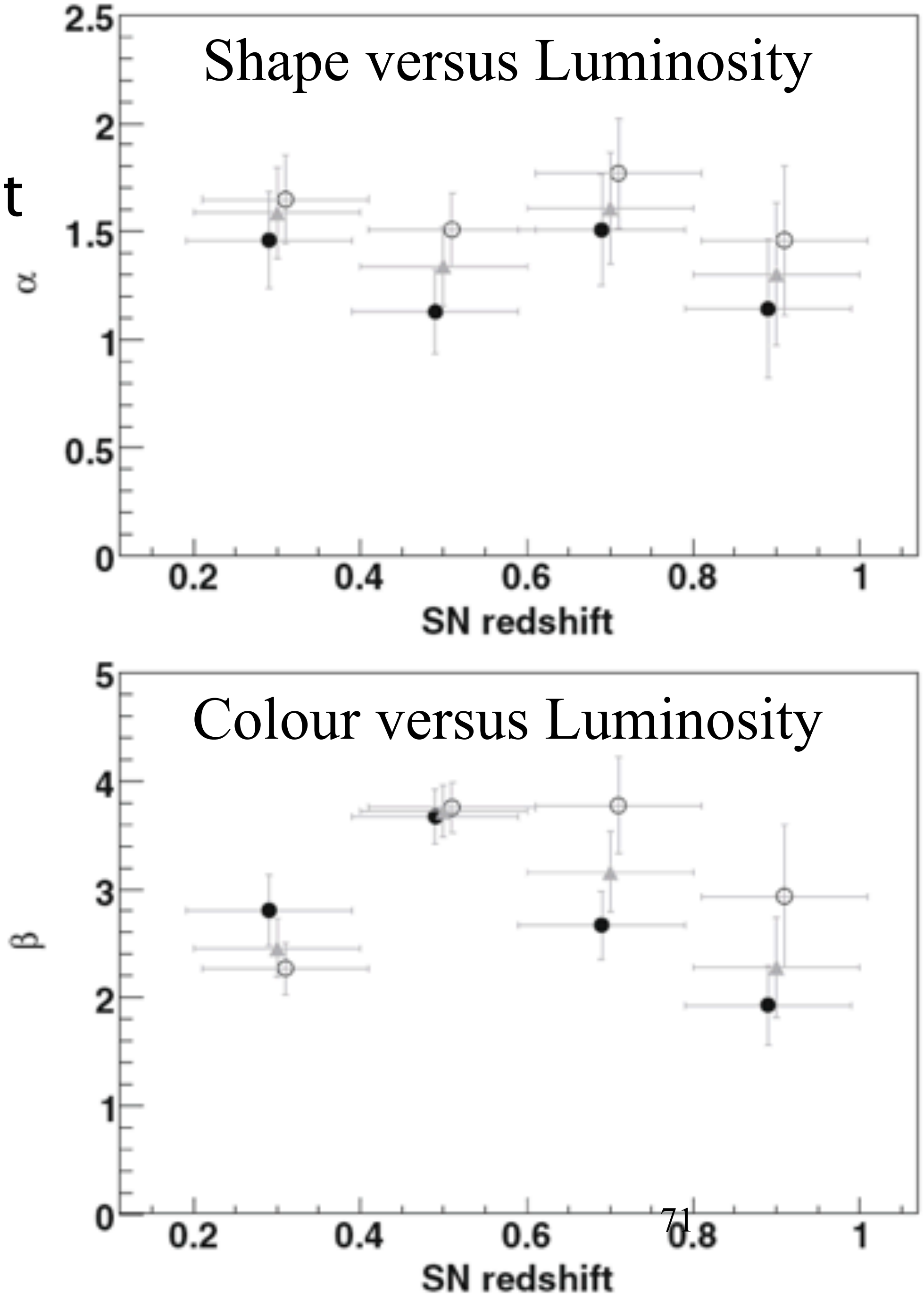


Shape versus Luminosity



Colour versus Luminosity

Guy et al 2010 SN Ia do not change much over redshift...



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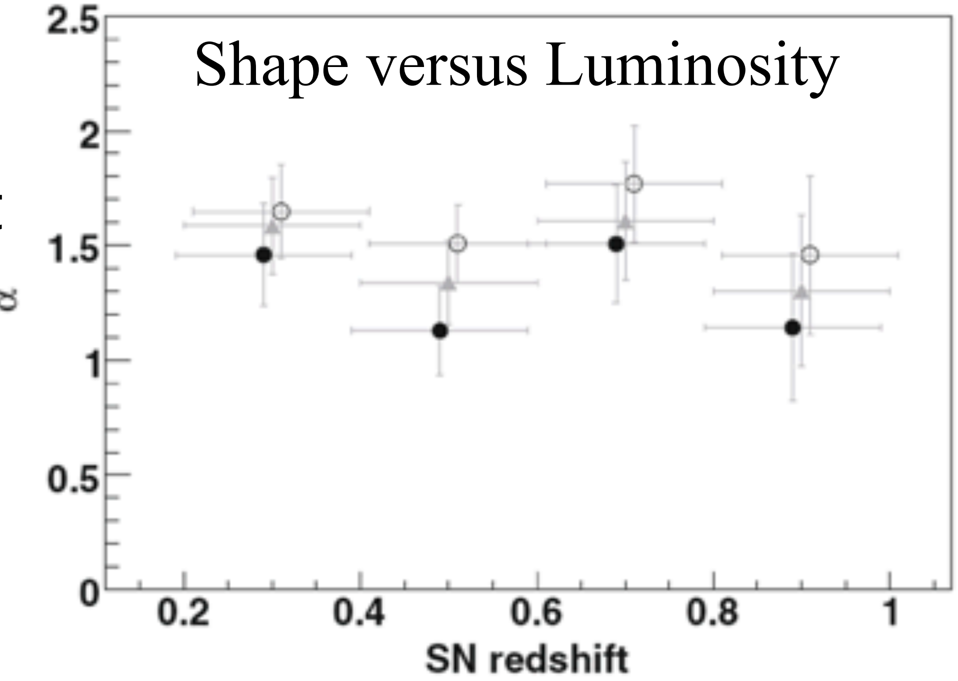

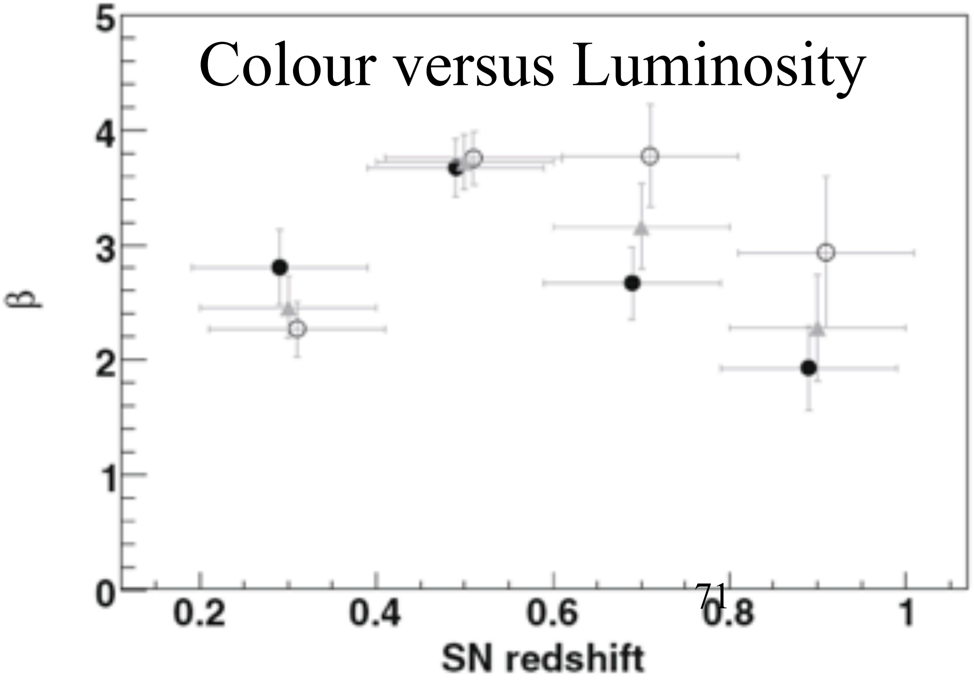

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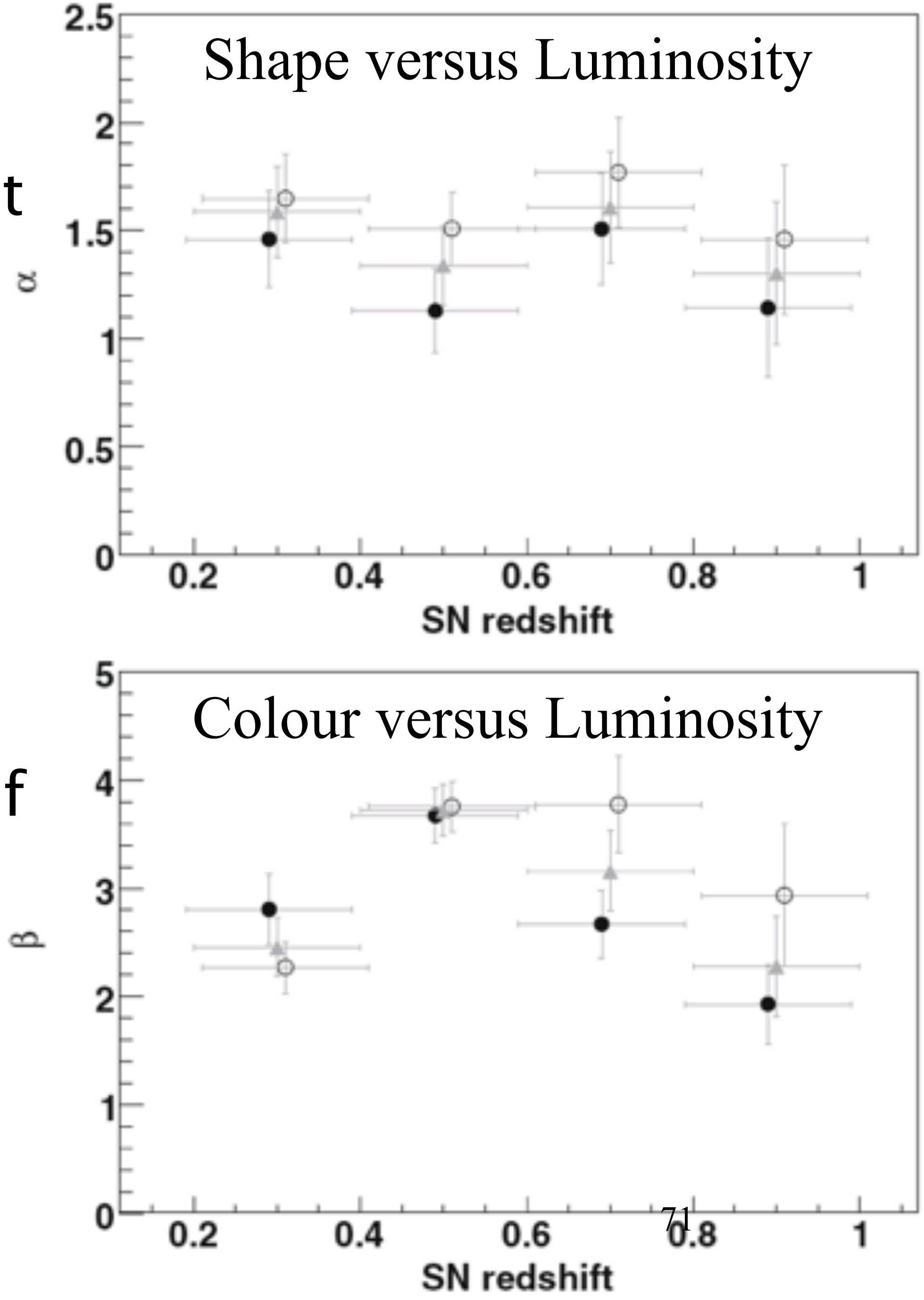

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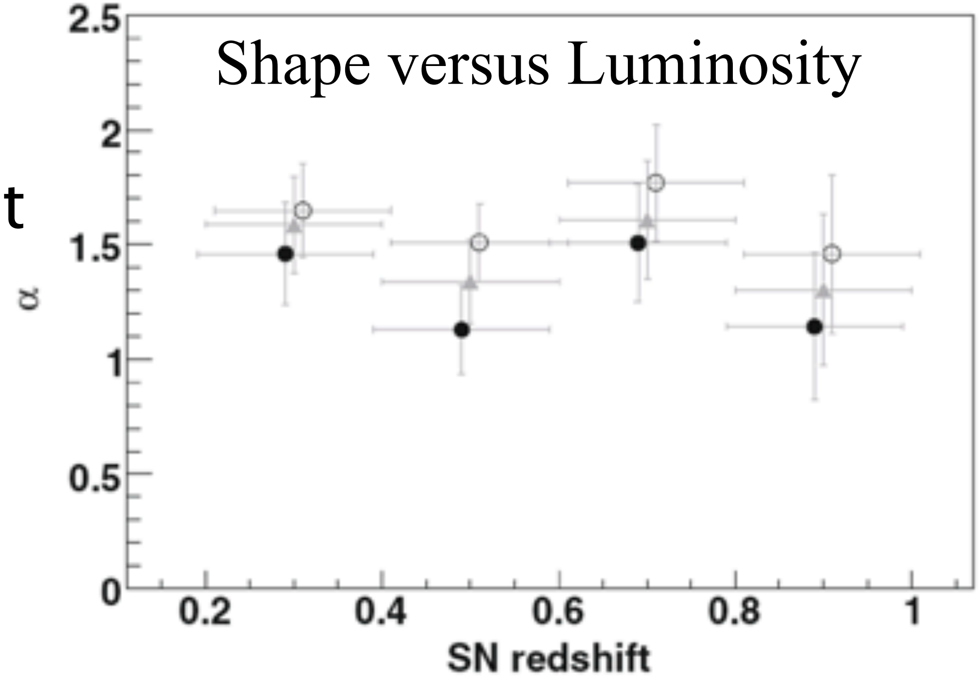

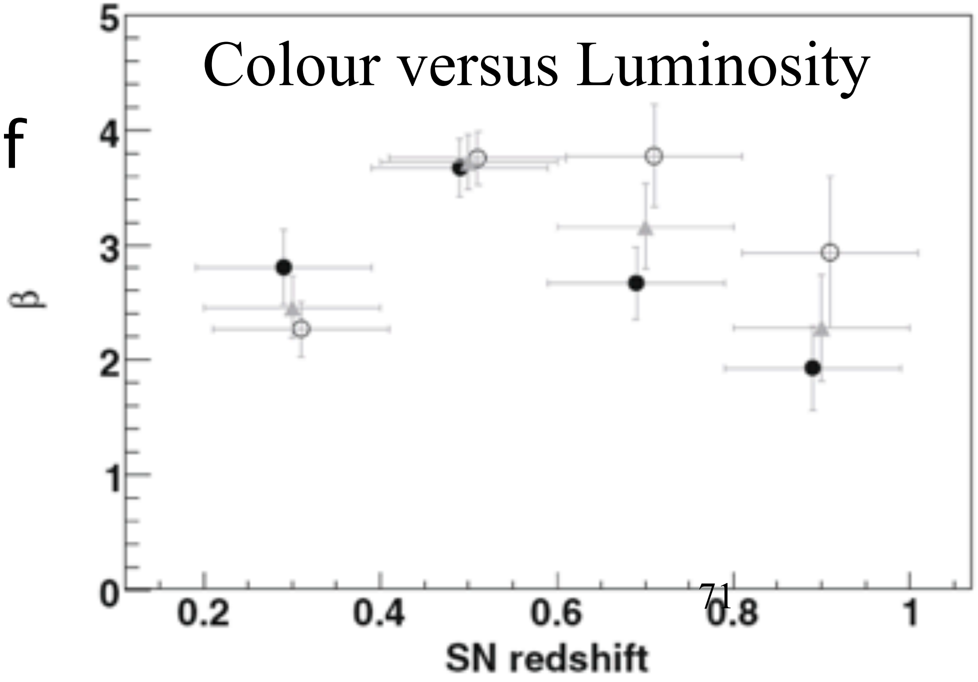

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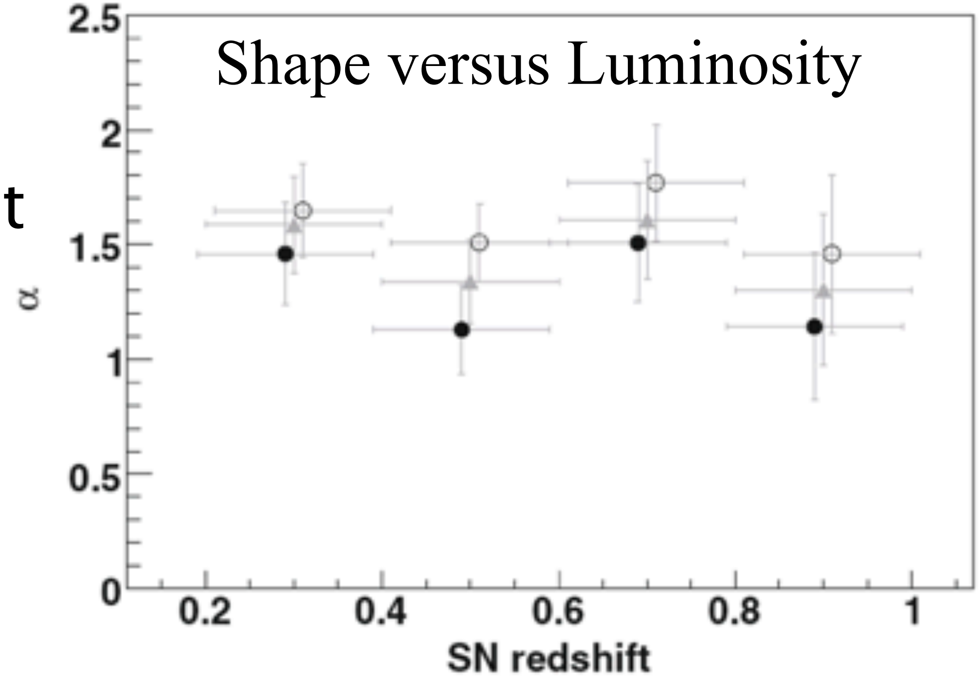

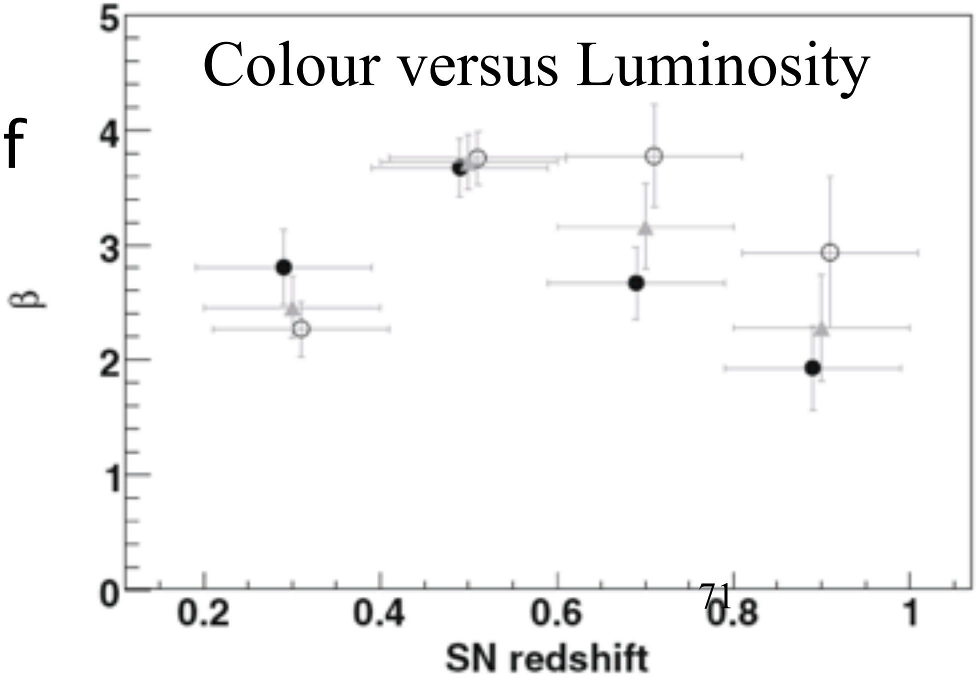

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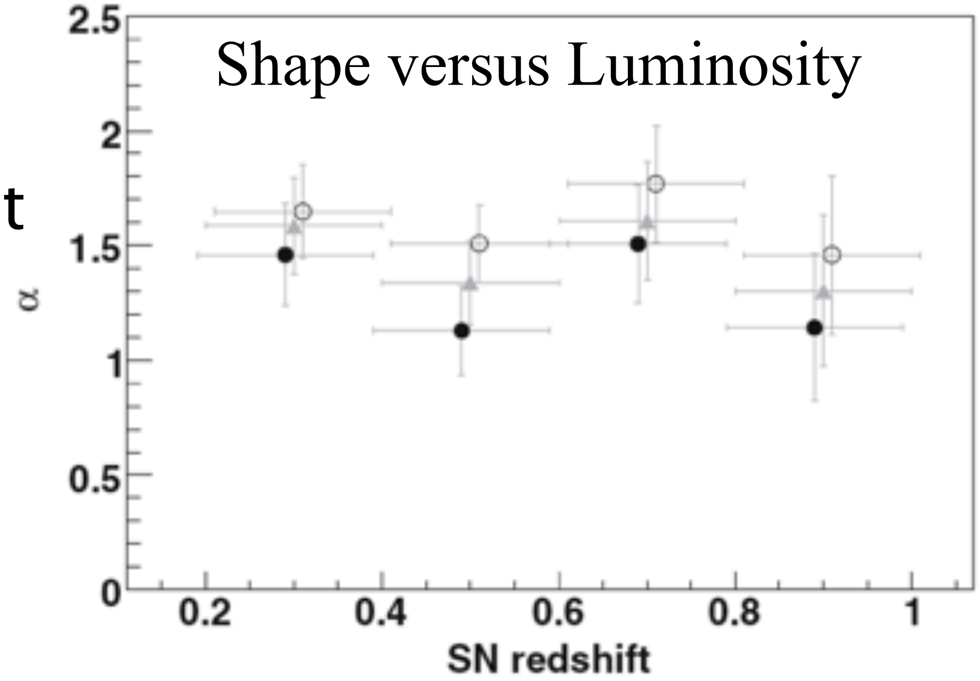

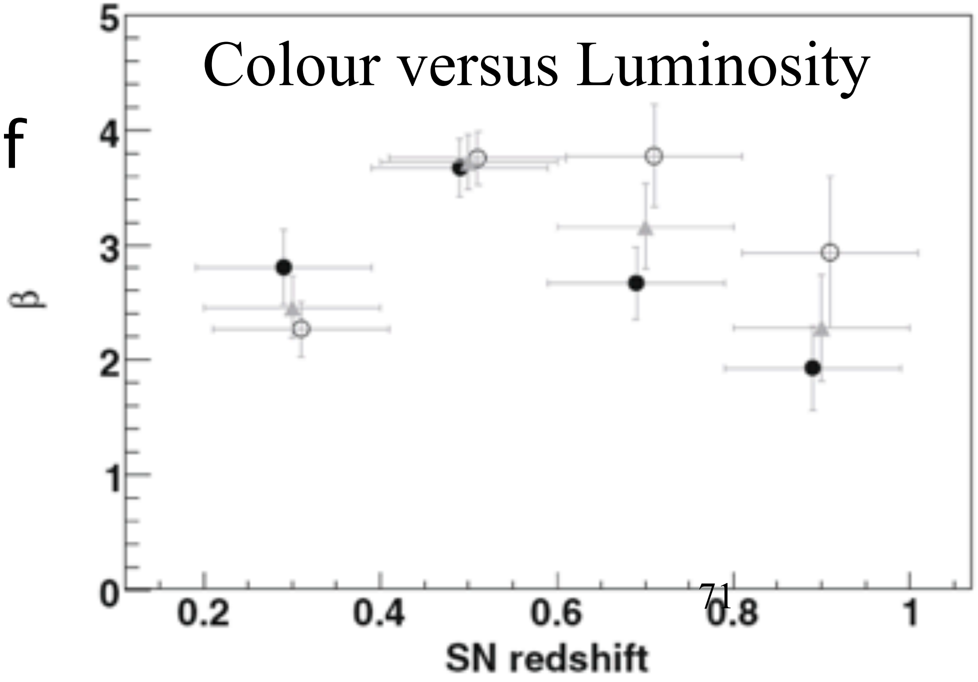

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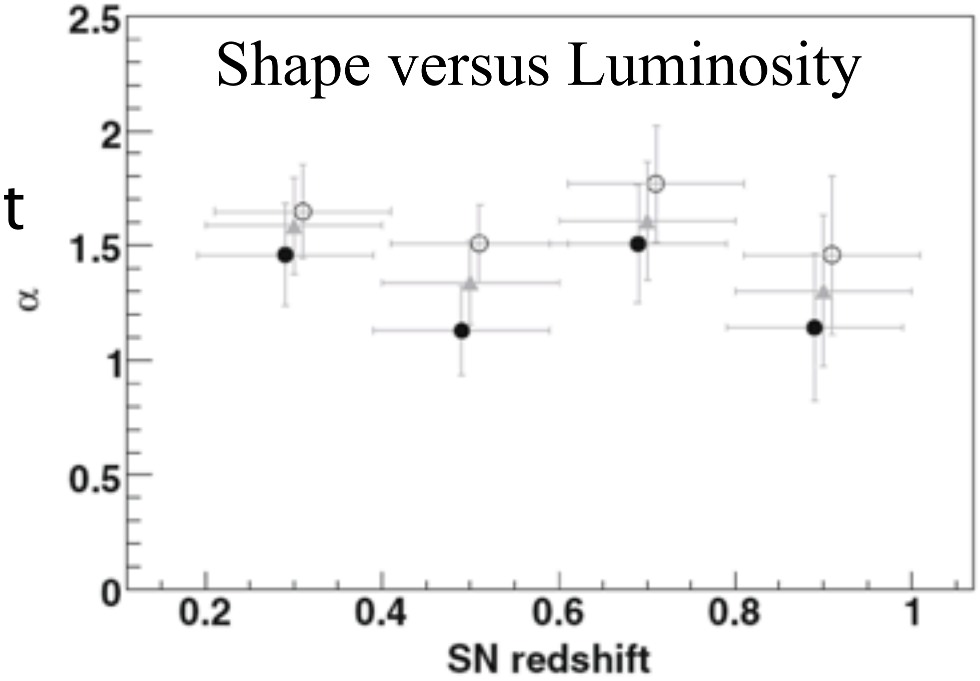
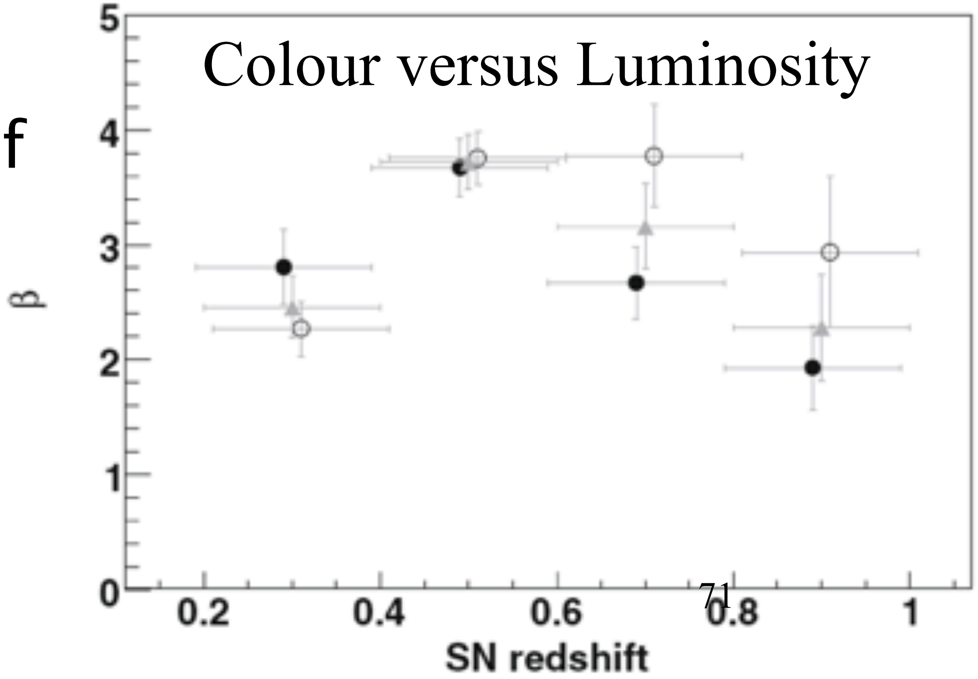
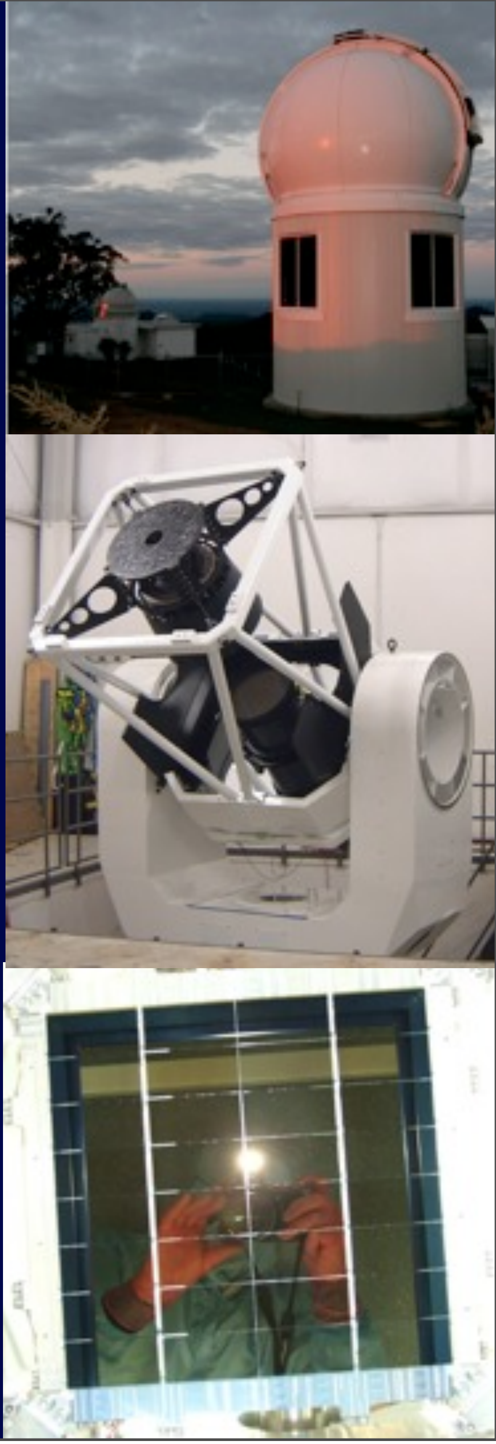




SkyMapper

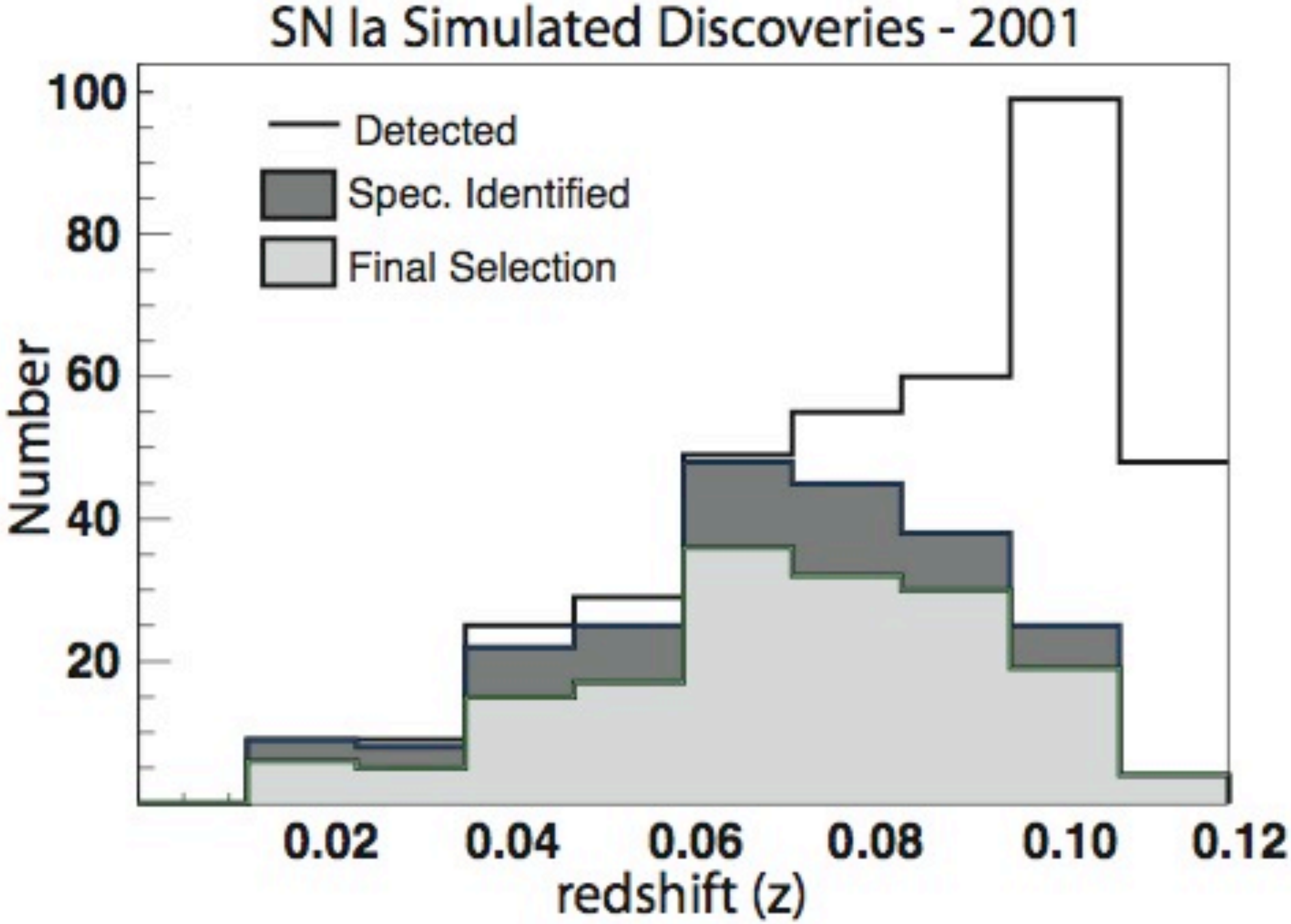
- 1.35m telescope with 5.7 sq degree imager (~10s readout time 0.5”/pixel)
- All Southern Sky Survey (2pi steradians) 6 colours 6 epochs
  - 0.5 mag deeper than SDSS
- 1000 sq-degrees continually covered in poor seeing will find 150 SN Ia at $z<0.1$ per year…



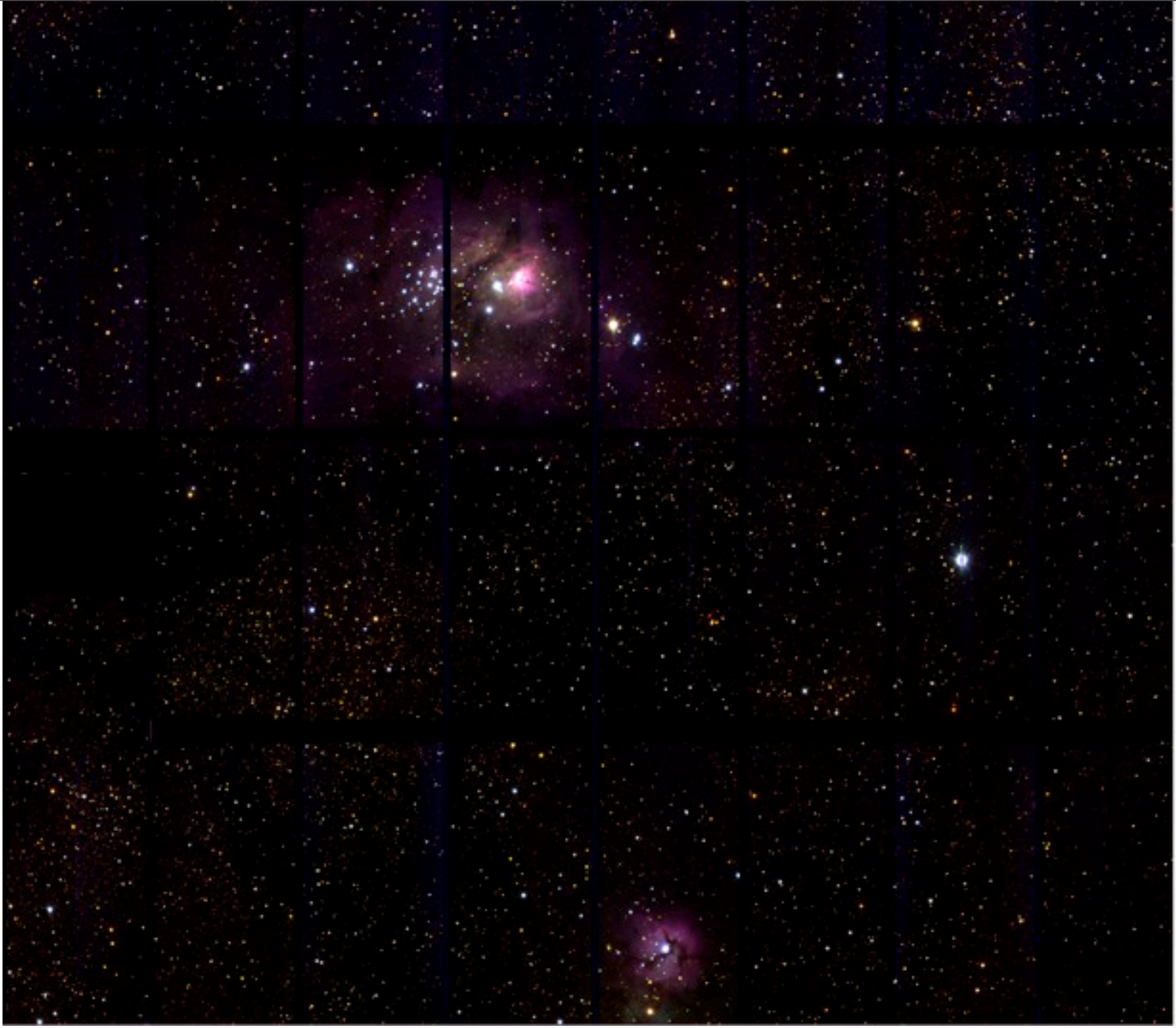
SOUTHERN SKY SURVEY
20000 SQ/DEGREES -6 COLOURS - 6 EPOCHS

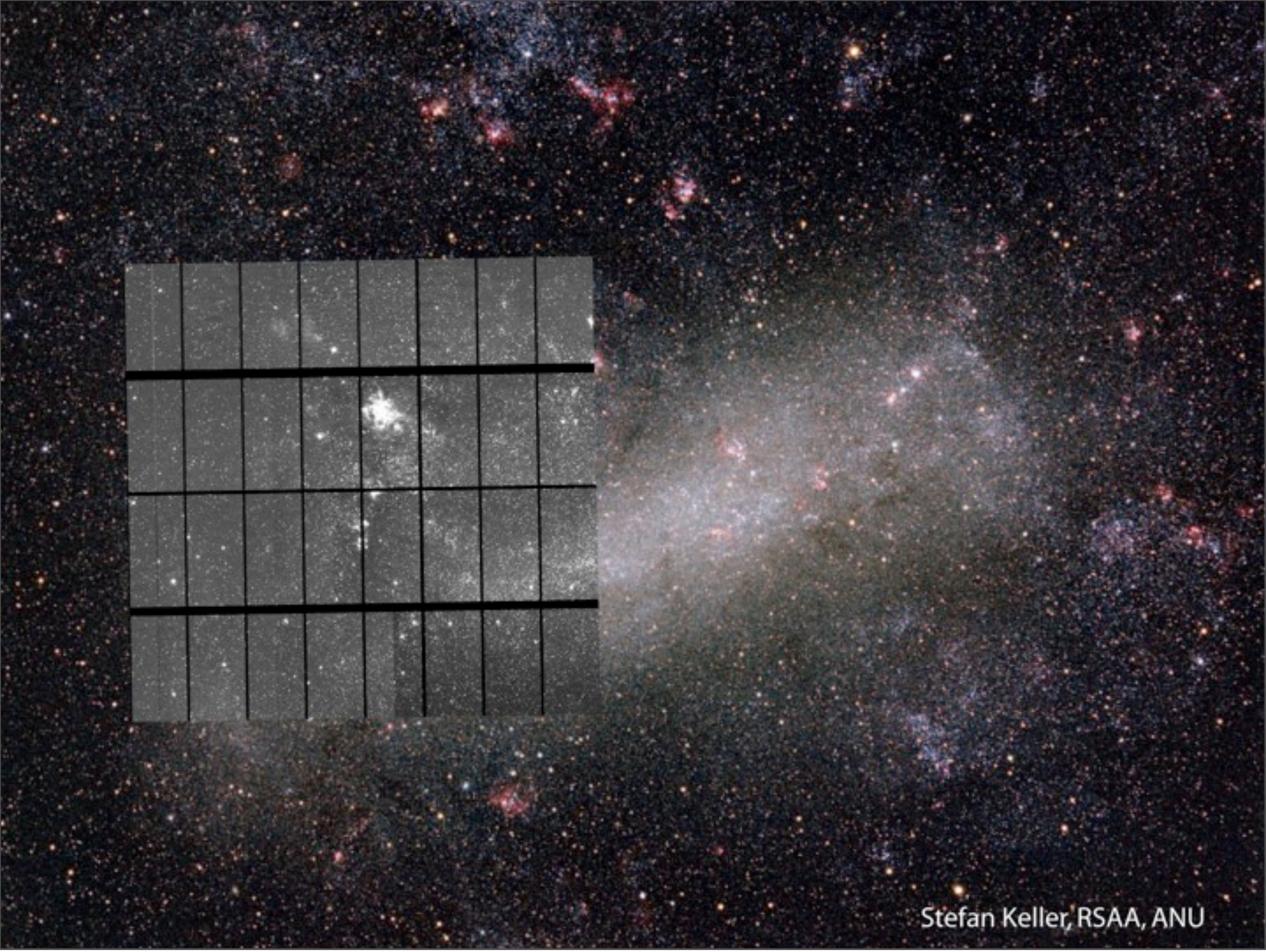
	u	*v*	*g*	*r*	*i*	*z*
1 epoch	21.5	21.3	21.9	21.6	21.0	20.6
6 epochs	22.9	22.7	22.9	22.6	22.0	21.5
Sloan Digital Sky Survey comparison	22.0	n/a	22.2	22.2	21.3	20.5

AB mag. for signal-to-noise = 5 from 110s exposures



Nicholas Regnault & Julien Guy from LPNHE Paris





Stefan Keller, RSAA, ANU

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We need to remember this is parameterized ignorance. The Goal is to constrain physics based models, not essentially meaningless numbers.

Dark Energy Futures
SN Ia

- 2nd Generation Surveys Provide distances to 1000s+ objects at $0.05<z<1.5$ (include SNLS, Higher-Z, Essence, SDSS-II Experiments, SkyMapper, Pan-Starrs, PTI ...)
- Most Precise Measurements of Dark Energy's Properties of any experiments to date - but are we reaching a systematic wall?

- Blue-Chip stock over the short-term, but long term future is hazy

Dark Energy Futures
CMB

- WMAP =7 may have milked the Sky for what it is worth when it comes to Dark Energy

Possible excitement through improved measurements of H_0

- Through tying distance scale to NGC4258 Maser Distance rather than LMC. (Riess et al)
- Potential for Future Geometric Distances (more distant NGC4258s, or Gravity Waves from merging black-holes)

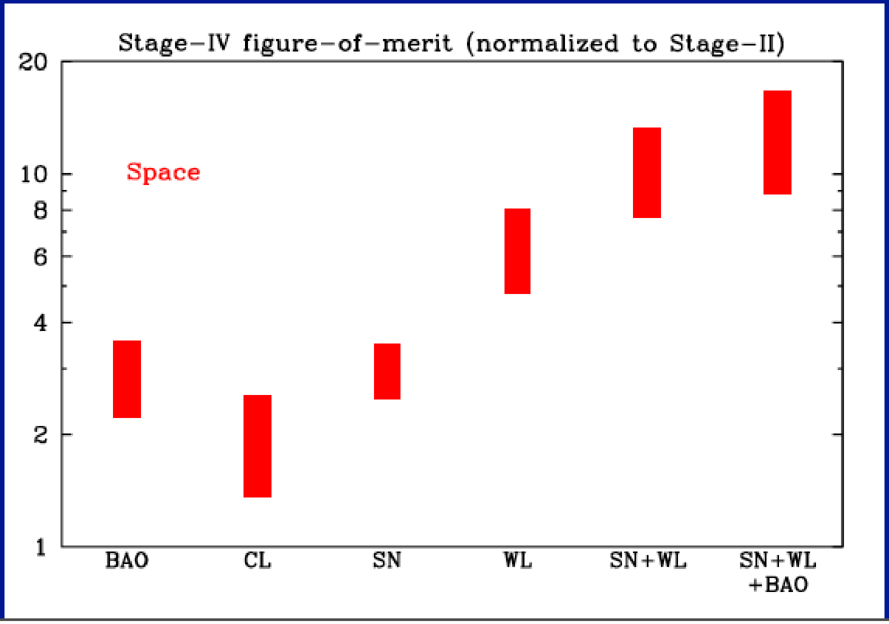
WMAP/Planck Detection of Polarization B-modes could confirm/revolutionise basic Inflation-CDM picture

Dark Energy Futures
BAOs

- Low Risk Growth Stock
  - BAO experiments are by very simple and promise precise measurements potentially immune from systematic error.
  - WiggleZ now
  - BOSS soon
  - BigBoss, EUCLID for the future?

Dark Energy Futures
Growth of Structure

- **High Risk - High Growth Stock**
  - Measuring the growth of Dark Matter structures as a function of redshift is potentially the most powerful probe of Dark Energy we have.
  - Weak Lensing and Clusters provide ways forward, but questions about systematics abound.There will be surely be lots of interesting astrophysics, but maybe too much!



Dark Energy Futures
The Unexpected

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- Astronomy is full of Mysteries besides Dark Energy
- By continuing to explore the Universe around us from the solar system to 13.7 Gyr ago, we might well gain insight in Dark Energy from an Unexpected Place

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This is my Best Bet for Understanding Dark Energy

TYPE IA SUPERNOVAE THE ACCELERATING COSMOS AND DARK ENERGY

Brian P. Schmidt

Mount Stromlo Observatory

Australian
National
University