The Accelerating Universe

Brian P. Schmidt

CAASTRO
ALL-SKY ASTROPHYSICS

ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

The Research School of Astronomy & Astrophysics
Mount Stromlo and Siding Spring Observatories

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

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

Theory

- General Relativity

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

Theory

- General Relativity

and an assumption...

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

Theory

- General Relativity

and an assumption...

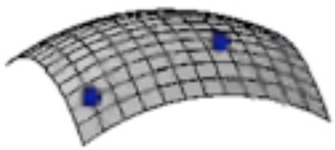
- The Universe is homogenous and isotropic on large scales

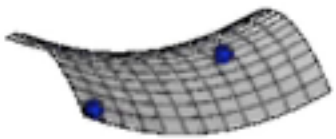
The Standard Model

The Standard Model

Robertson-Walker line element

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



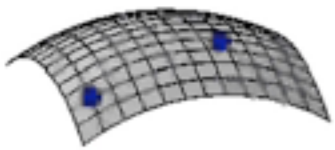


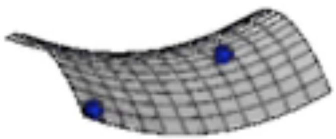
The Standard Model

Robertson-Walker line element

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

Distance



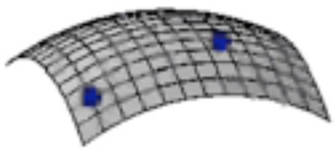


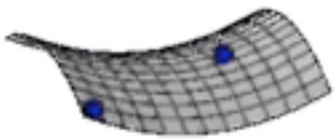
The Standard Model

Robertson-Walker line element

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

Distance Time



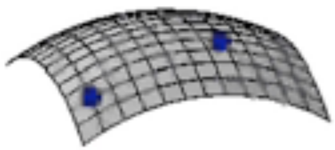


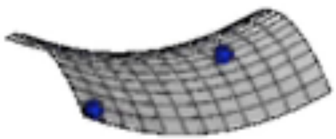
The Standard Model

Robertson-Walker line element

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

Distance Time Coordinates



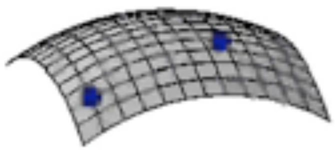


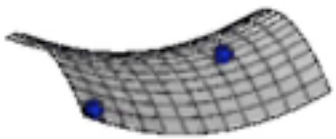
The Standard Model

Robertson-Walker line element

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

Distance Time Curvature Coordinates





The Standard Model

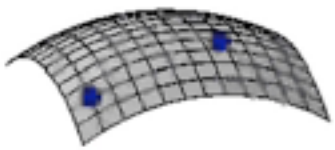
Robertson-Walker line element

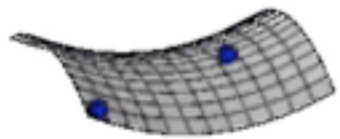
$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2\right]$$

Distance | Time | Dynamics | Curvature | Coordinates

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

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





The Standard Model

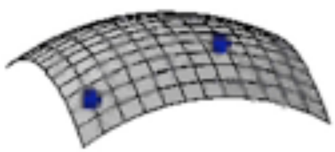
Robertson-Walker line element

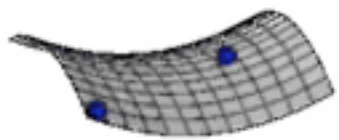
$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2\right]$$

Distance | Time | Dynamics | Curvature | Coordinates

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

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





THE STANDARD MODEL

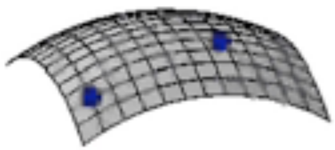
Robertson-Walker line element

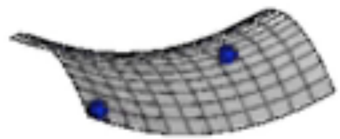
$$ds^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2\right]$$

Distance | Time | Dynamics | Curvature | Coordinates

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

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





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.,

Model Content of Universe by the Equation of State of the different forms of Matter/Energy

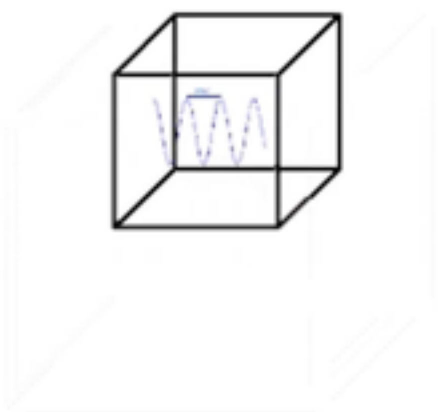
$$w_i \equiv \frac{P_i}{\rho_i} \qquad \rho_i \propto (\text{Volume})^{-(1+w_i)} \propto a^{-3(1+w_i)} \propto (1+z)^{3(1+w_i)}$$

$$\left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^3 = 1$$

e.g.,

w=0 ***for normal matter***

$$\rho \propto V^{-1}$$



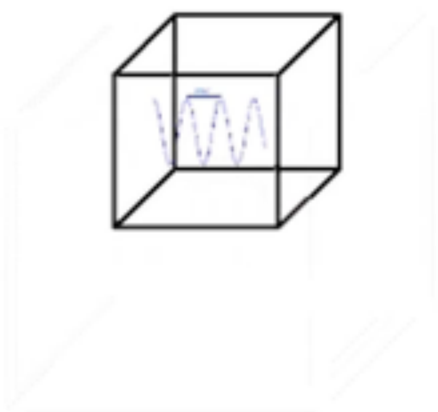
Model Content of Universe by the Equation of State of the different forms of Matter/Energy

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

e.g.,

w=0 ***for normal matter***

$$\rho \propto V^{-1} \qquad \left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^3 = 1$$



Model Content of Universe by the Equation of State of the different forms of Matter/Energy

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

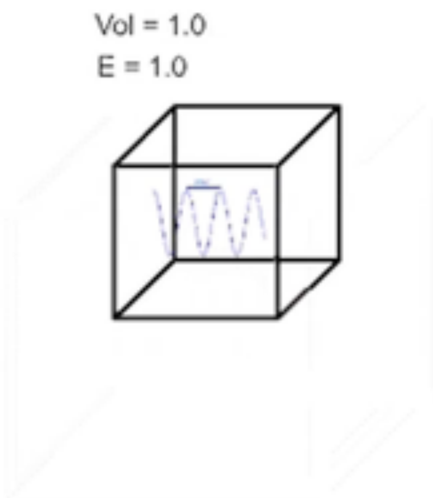
e.g.,

w=0 ***for normal matter***

$$\rho \propto V^{-1} \qquad \left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^3 = 1$$

w=1/3 ***for photons***

$$\rho \propto V^{-4/3} \qquad \left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^4 = 1$$



Model Content of Universe by the Equation of State of the different forms of Matter/Energy

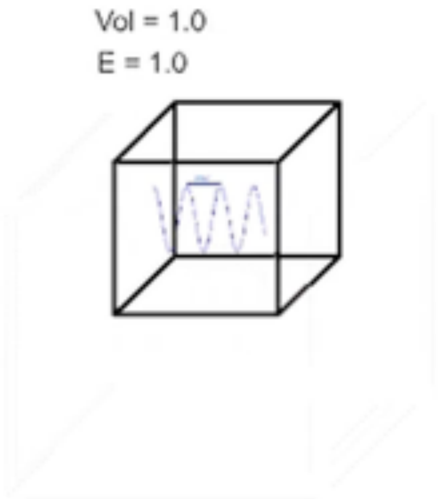
$$w_i \equiv \frac{P_i}{\rho_i} \qquad \rho_i \propto (\text{Volume})^{-(1+w_i)} \propto a^{-3(1+w_i)} \propto (1+z)^{3(1+w_i)}$$

e.g.,

w=0 ***for normal matter*** $\rho \propto V^{-1}$ $\left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^3 = 1$

w=1/3 ***for photons*** $\rho \propto V^{-4/3}$ $\left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^4 = 1$

w=−1 ***for Cosmological Constant*** $\rho \propto V^{0}$ $\left(\frac{\rho}{\rho_0}\right)\left(\frac{a}{a_0}\right)^0 = 1$



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 $(1+z)^0$

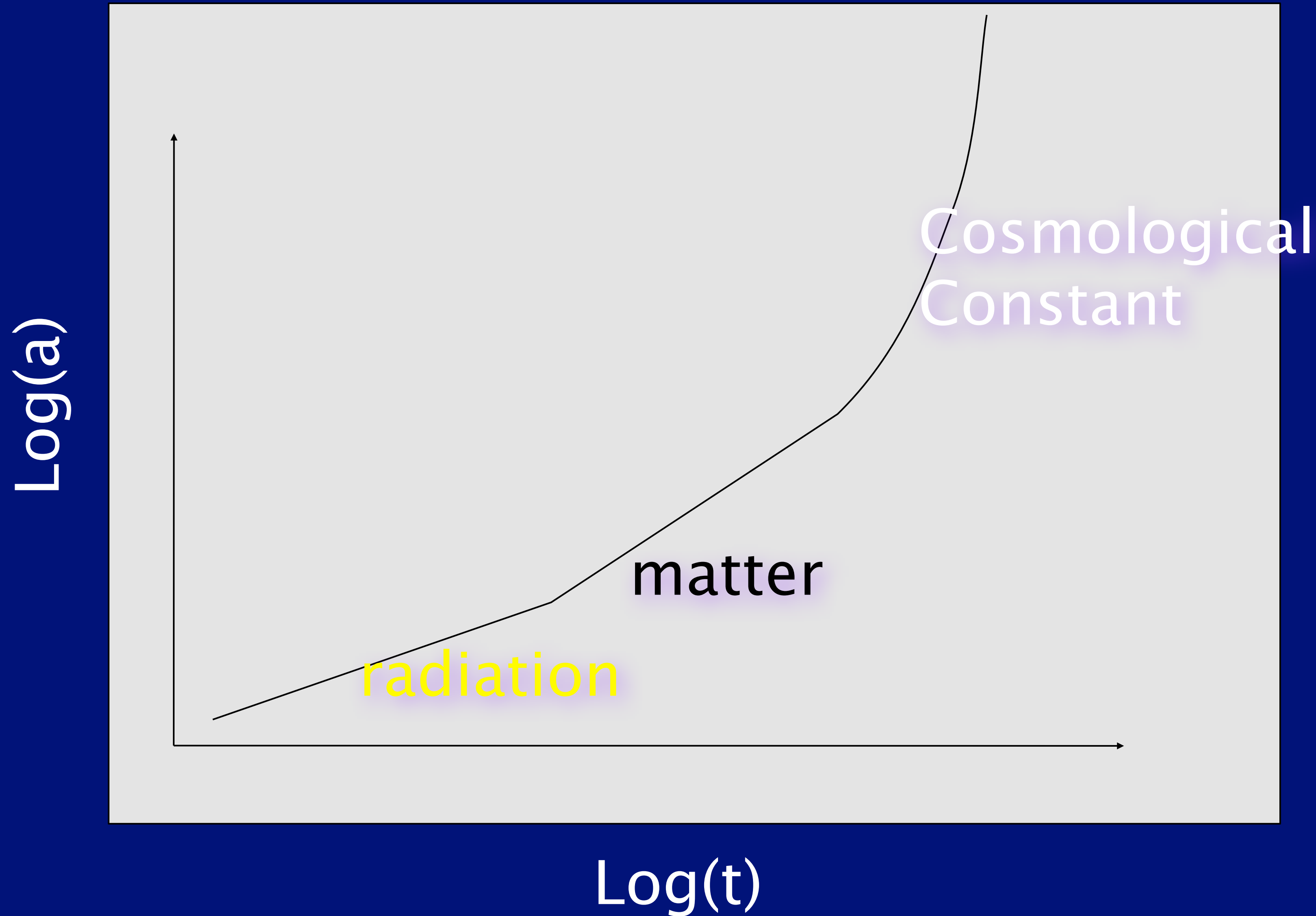
$$\Omega_i = \left(\frac{\rho_i}{\rho_{crit}}\right) = \left(\frac{\rho_i}{\frac{3H_0^2}{8\pi G}}\right)$$

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

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

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

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


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

Different Ways of Looking at the Universe - 1994

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

Different Ways of Looking at the Universe - 1994

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

(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)

Inflation+CDM paradigm correct
$\Omega \sim 1$
H_0 <=50km/s/Mpc
Observers are wrong on H_0 and Ω_M

(Observers)

$\Omega_M \sim 0.2$
H_0 =50-80km/s/Mpc
Inflation/CDM is wrong

1970s & 80s
Inflation + Cold Dark Matter

Inflation

- Explains Uniformity of CMB
- Provides seeds of structure formation

CDM

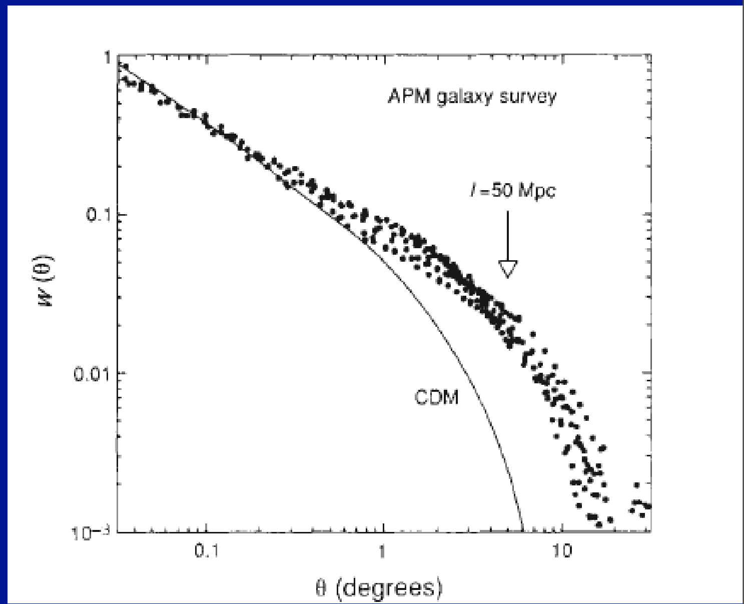
- Consistent with rotation curves of Galaxies
- Gives Structure formation

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 afore-mentioned 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.

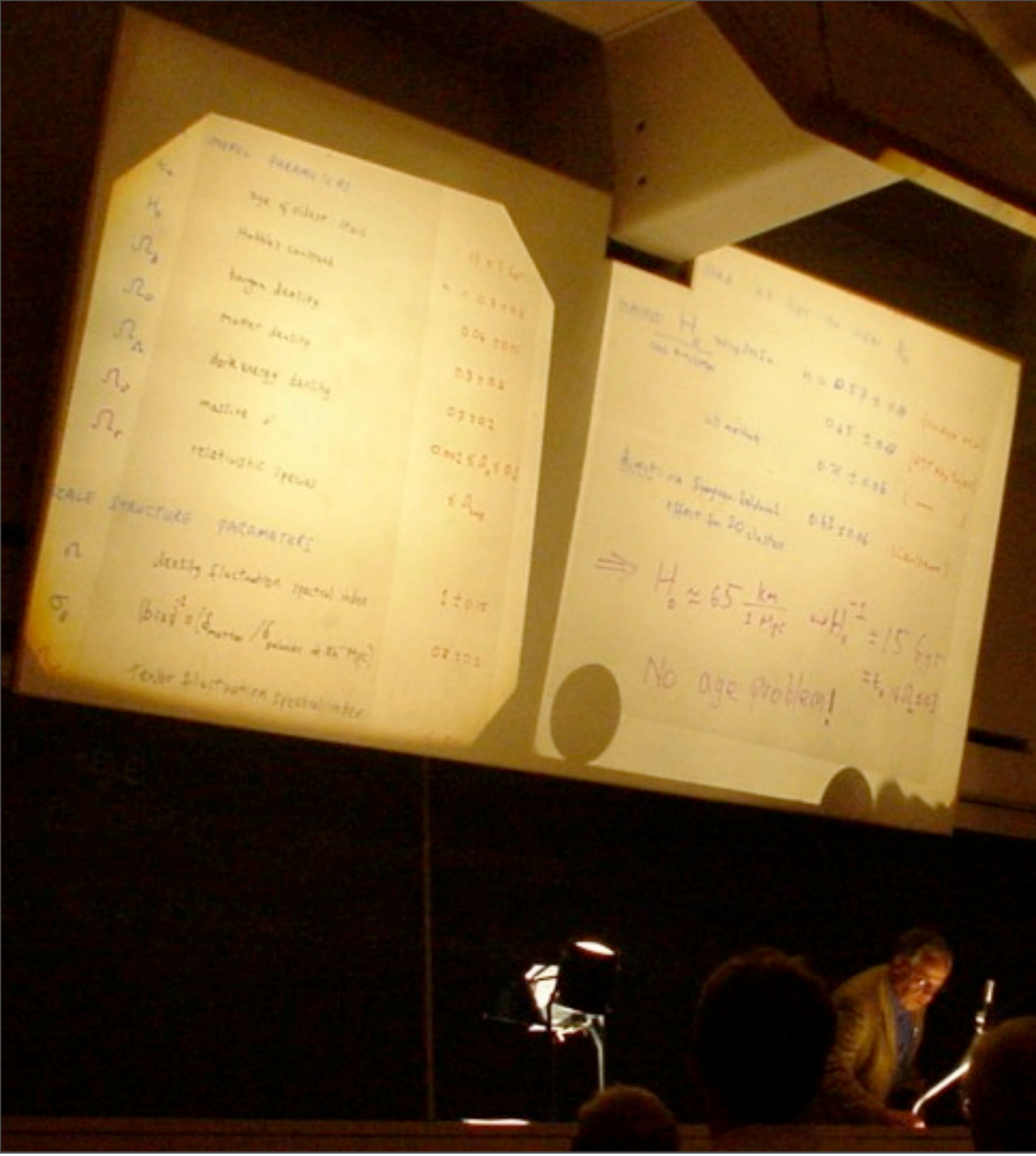
The loser of the wager shall present to the winner(s) one case of the Macallan, or equivalent quality, single malt Scotch whisky.

John Tonry | Brian Schmidt | Joe Silk

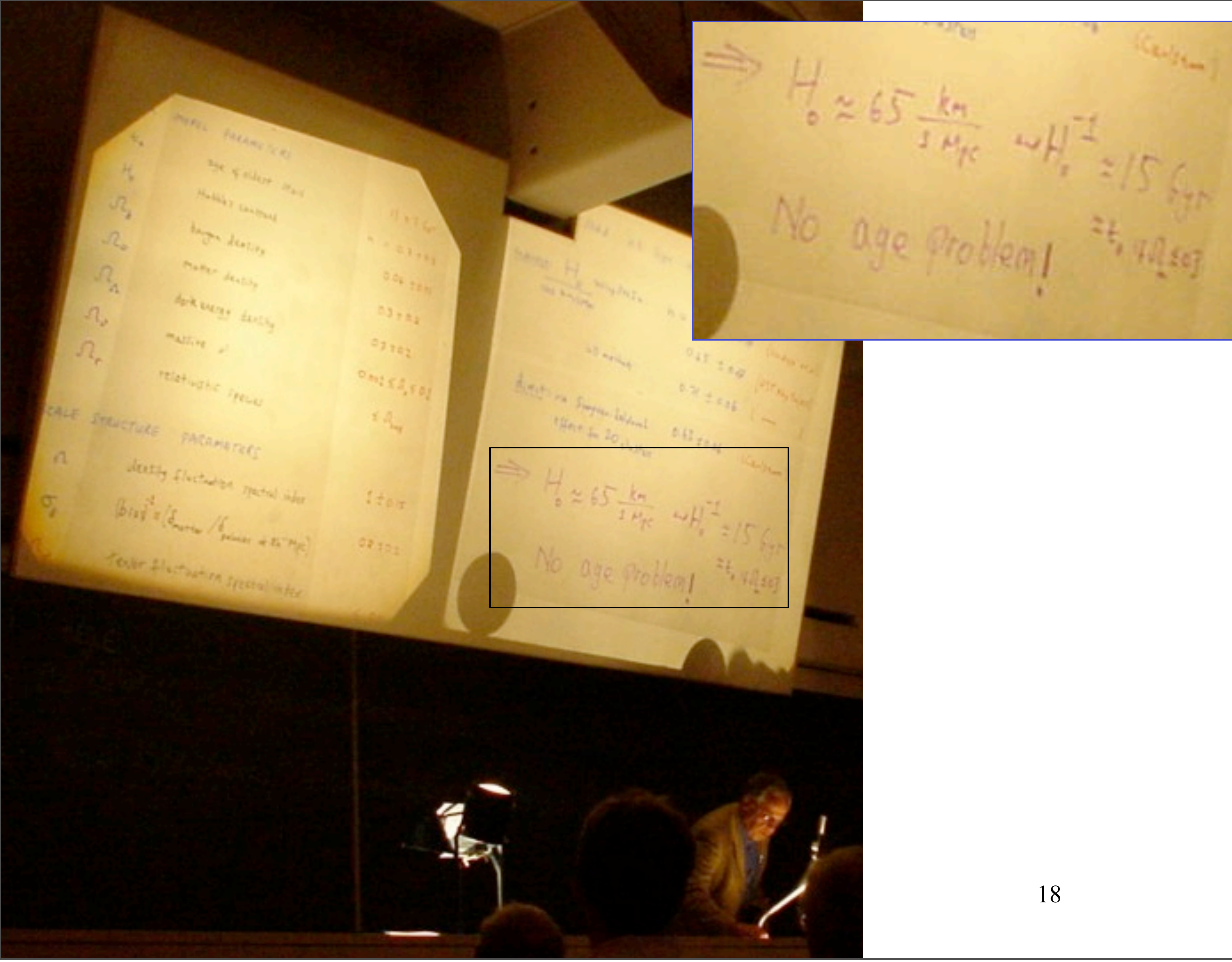
Witnessed this day 2 August 1995

Kenneth Freeman


H, <60



age of oldest stars
Hubble's constant
baryon density
matter density
dark energy density
massive ν
relativistic species
STRUCTURE PARAMETERS
density fluctuation spectral index
tensor fluctuation spectral index
No age problem!


$\Rightarrow H_0 \simeq 65 \frac{km}{s\ Mpc}$
No age problem!

Title: The Cosmological Constant is Back

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

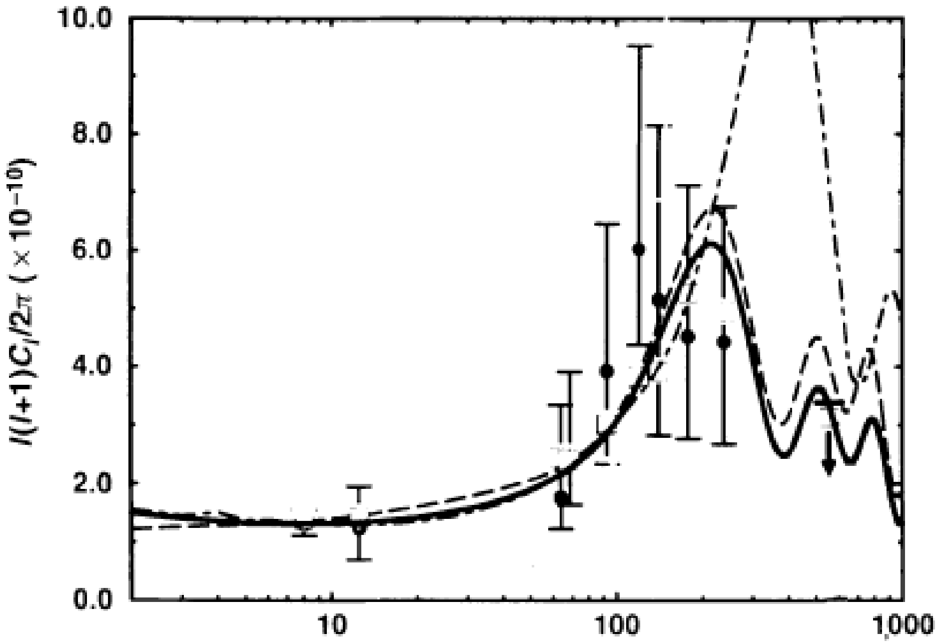
Abstract: A diverse set of observations now compellingly suggest that Universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological constant corresponds to the energy density of the vacuum, and the wanted value for the cosmological constant corresponds to a 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†

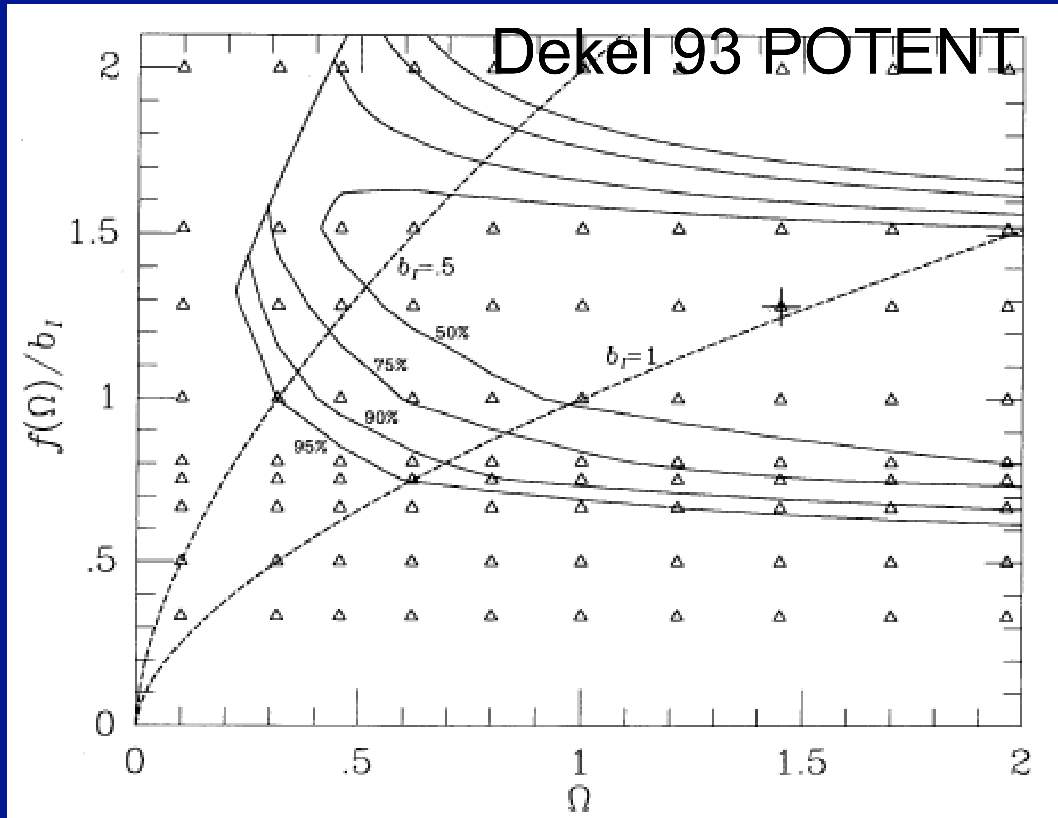
NATURE · VOL 377 · 19 OCTOBER 1995



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



CLUSTER X-RAY MORPHOLOGIES

TABLE 3 Mohr et al 1995

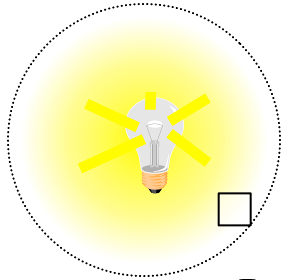
MEAN (and rms) OF $w_{\bar{x}}$, η, AND α DISTRIBUTIONS

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)

Luminosity Distance

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

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

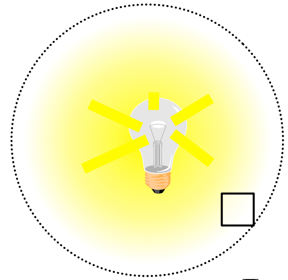


$$F = \frac{L}{4\pi D^2}$$

Luminosity Distance

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

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



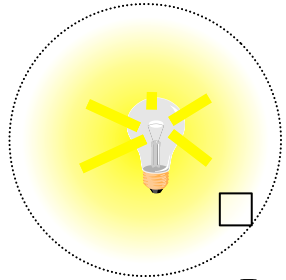
$$F = \frac{L}{4\pi D^2}$$

the flux an observer sees of an object at redshift z

Luminosity Distance

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

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



$$F = \frac{L}{4\pi D^2}$$

the flux an observer sees of an object at redshift z

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

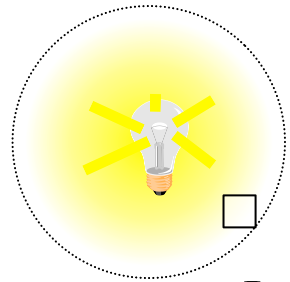
$$\Omega_k = \left(\sum_i \Omega_i \right) - 1$$

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

Luminosity Distance

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

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



$$F = \frac{L}{4\pi D^2}$$

the flux an observer sees of an object at redshift z

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

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

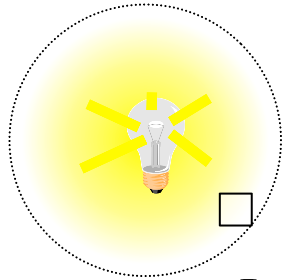
$$S(x) = \begin{cases} \sin(x) & \mathrm{k} = 1 \\ x & \mathrm{k} = 0 \\ \sinh(x) & \mathrm{k} = \text{-}1 \end{cases}$$

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

LUMINOSITY DISTANCE

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

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



$$F = \frac{L}{4\pi D^2}$$

the flux an observer sees of an object at redshift z

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

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

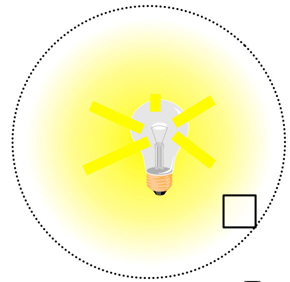
$$S(x) = \begin{cases} \sin(x) & k = 1 \\ x & k = 0 \\ \sinh(x) & k = -1 \end{cases}$$

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

Luminosity Distance

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

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



$$F = \frac{L}{4\pi D^2}$$

the flux an observer sees of an object at redshift z

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

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

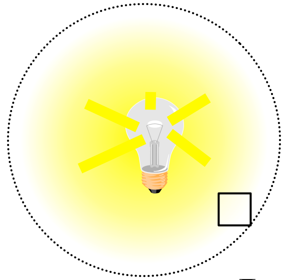
$$S(x) = \begin{cases} \sin(x) & k = 1 \\ x & k = 0 \\ \sinh(x) & k = -1 \end{cases}$$

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

Luminosity Distance

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

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



$$F = \frac{L}{4\pi D^2}$$

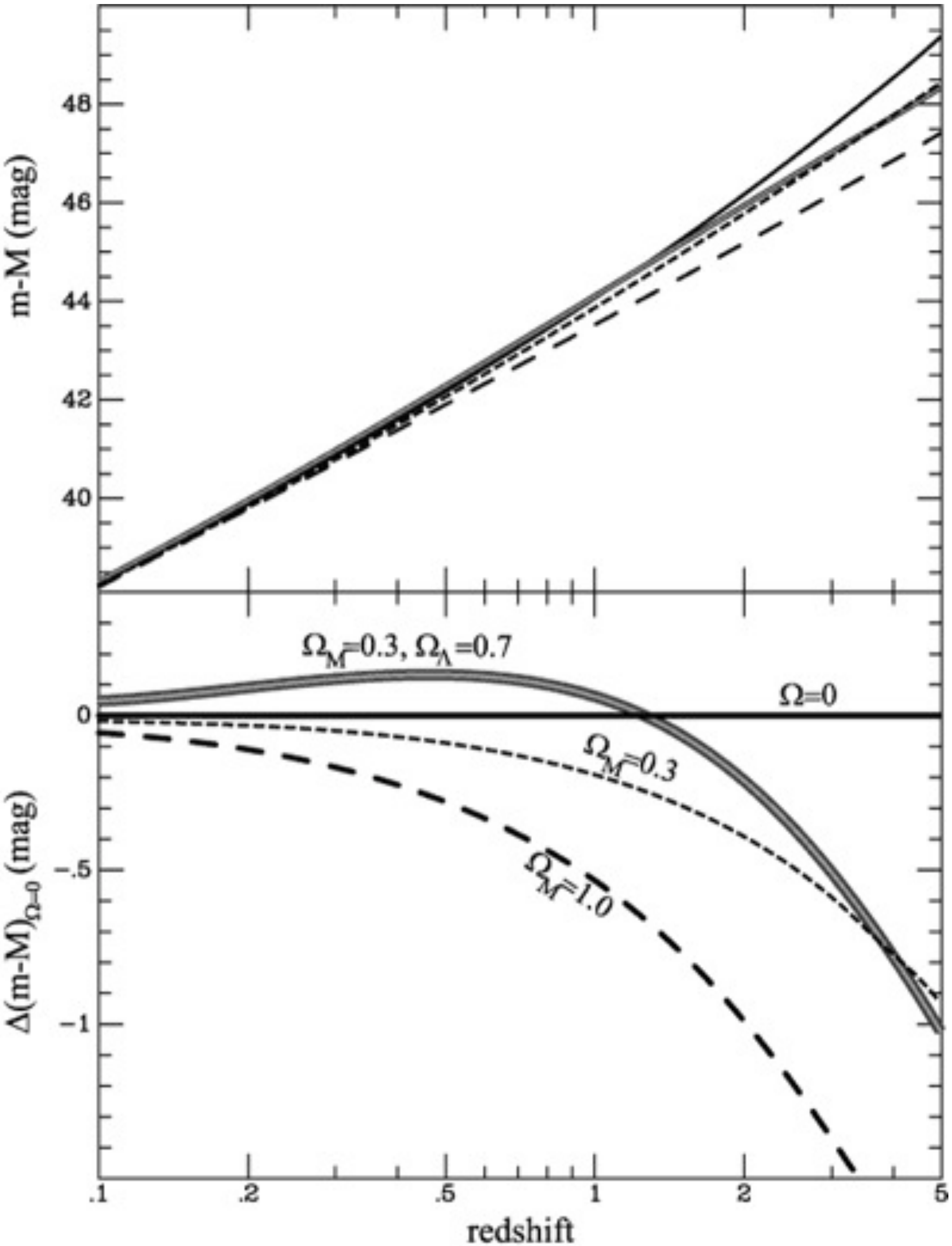
the flux an observer sees of an object at redshift z

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

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

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

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



m-M (mag)
48
46
44
42
40
Ω_M=0.3, Ω_Λ=0.7
Ω=0
Ω_M=0.3
Ω_M=1.0
Δ(m-M)_Ω=0 (mag)
0
-.5
−1
.1
.2
.5
1
2
5
redshift

Type Ia Supernovae

First use of Supernovae to Measure Distances

Fritz Zwicky

18in Schmidt Telescope

Charlie Kowal 1968

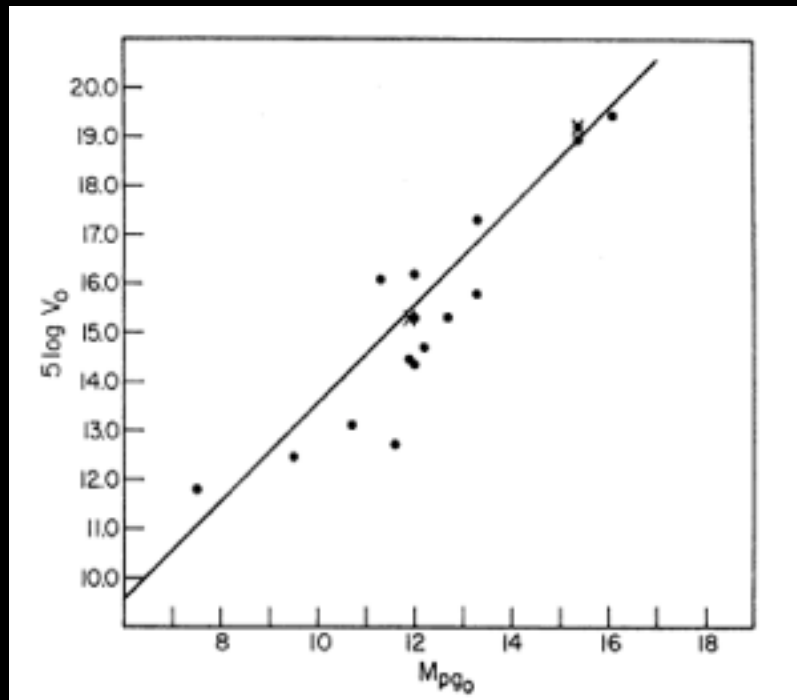
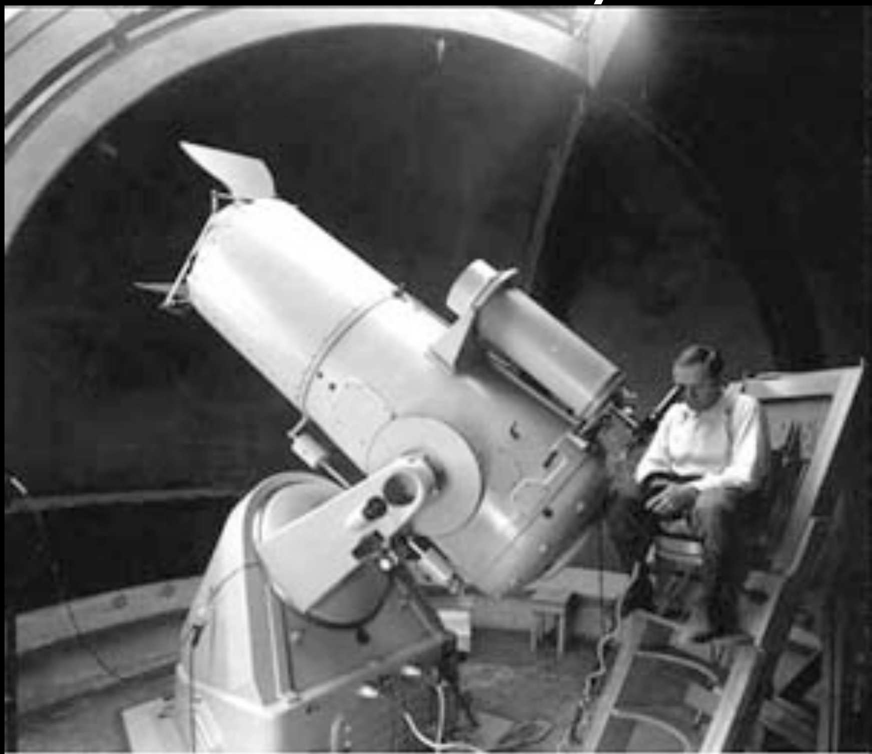


Fig. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

First use of Supernovae to Measure Distances

Fritz Zwicky



18in Schmidt Telescope

Charlie Kowal 1968

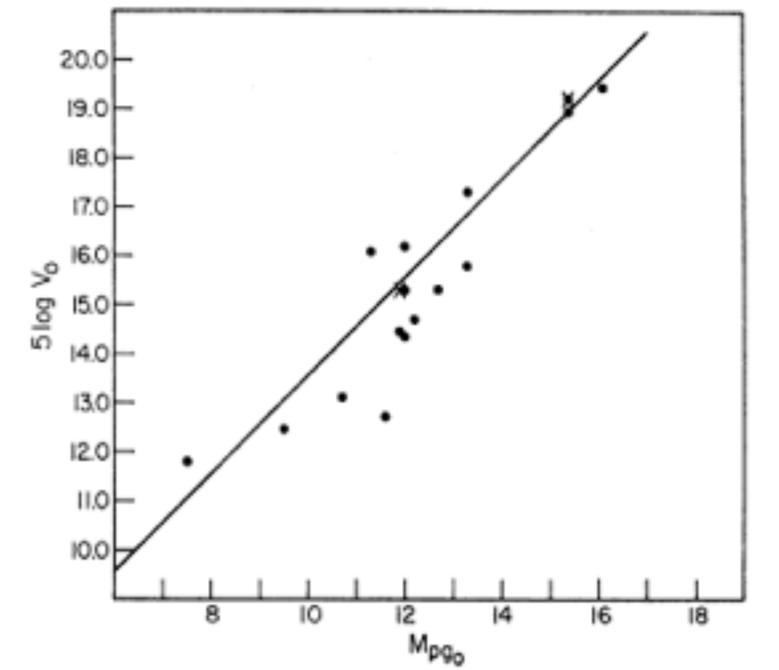


FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

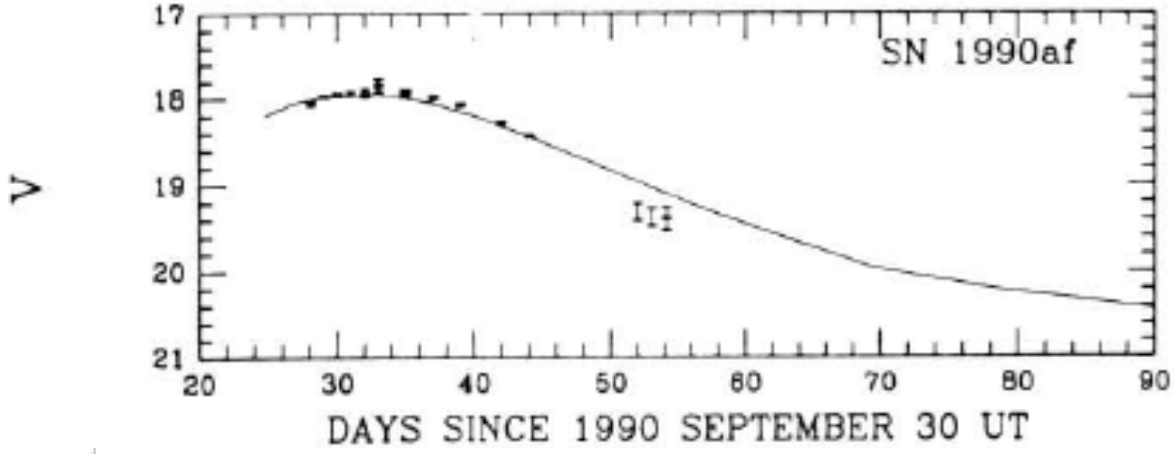
First Distant SN detected in 1988 by Danish Team

ANTEZANA

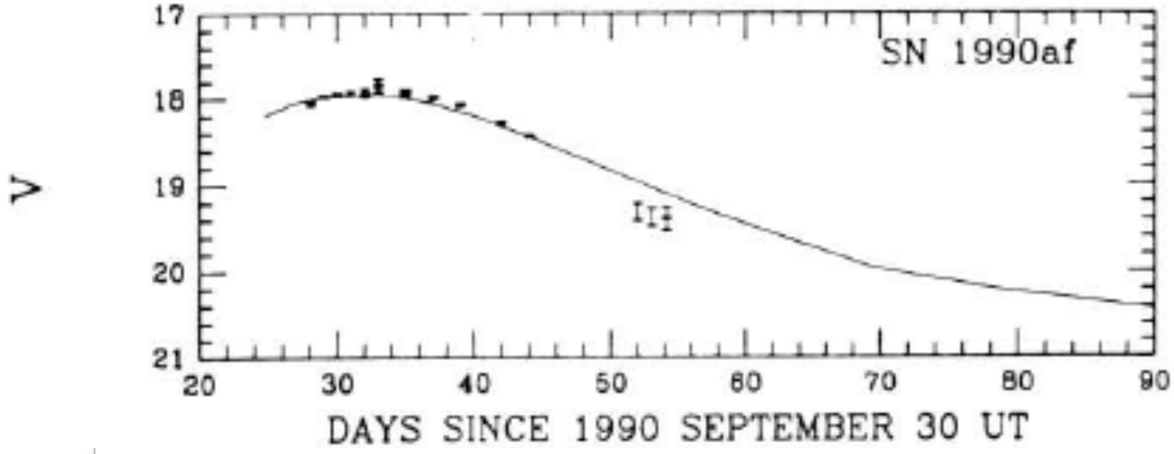
AVILES

WISCHNJEWSKY

Calan-Tololo SN Search


SN 1990af
V
17
18
19
20
21
20
30
40
50
60
70
80
90
DAYS SINCE 1990 SEPTEMBER 30 UT

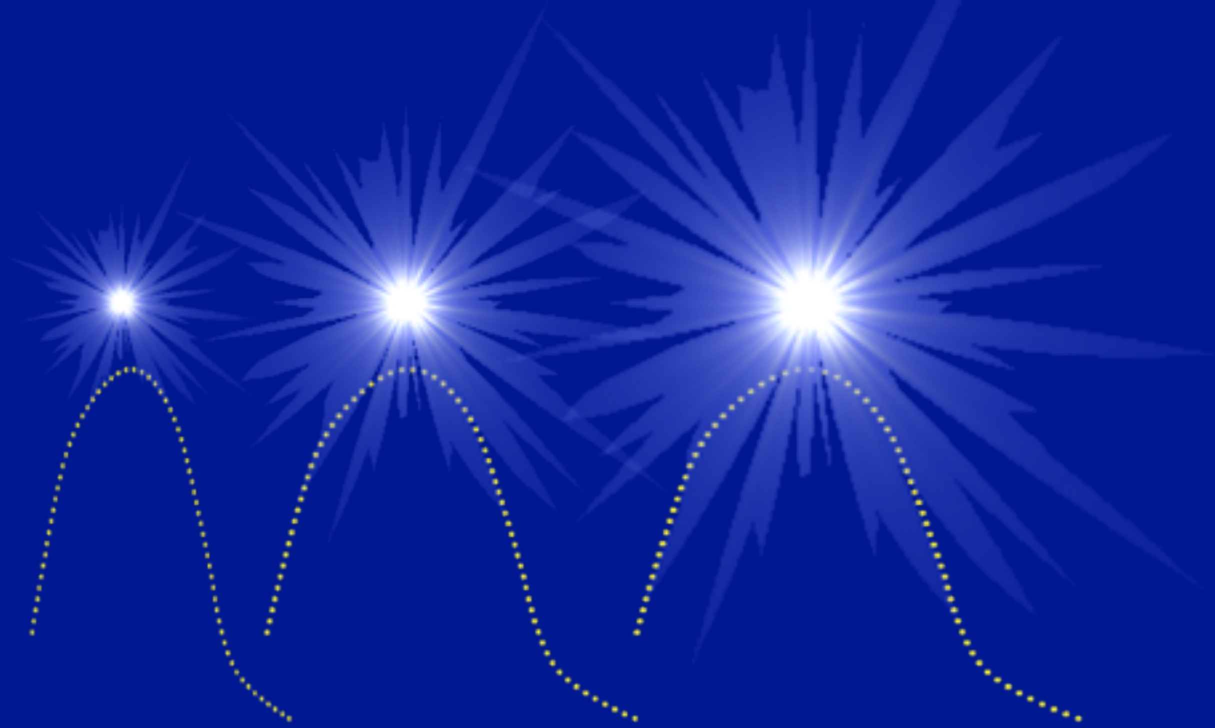
SN1990af: faded quickly and was fainter than normal



Refining Type Ia Distances

Mark Phillips (1993)

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



1994 Visit to Harvard
Mario Hamuy showed us this Diagram.

SN Ia are Precision Distance Indicators!

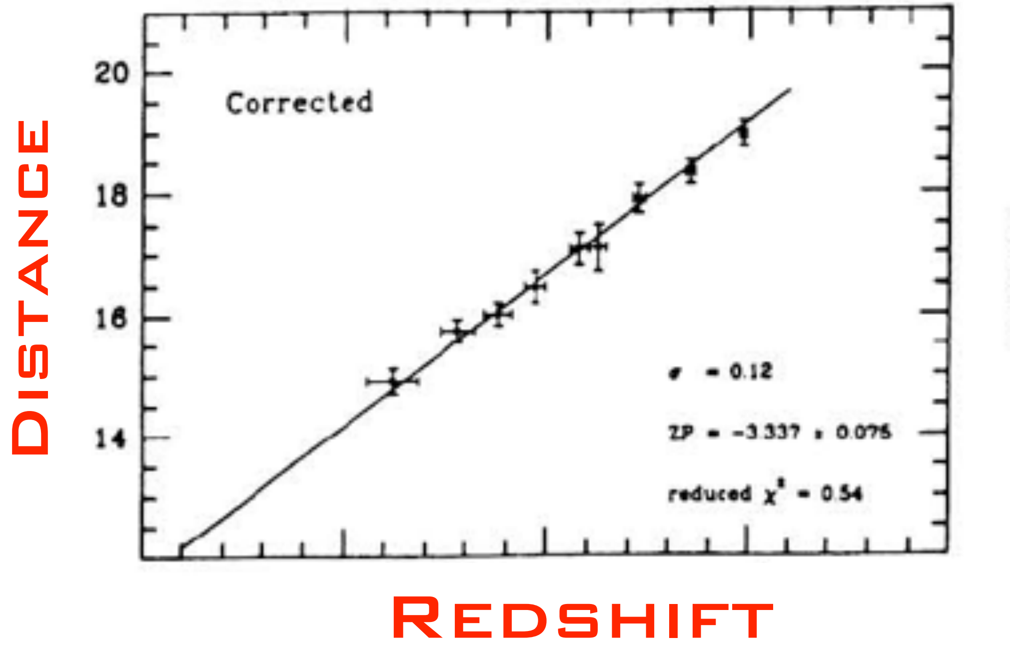


Figure 1: Hubble diagram of SNe Ia in the Calán/Tololo SN survey.

1994 Visit to Harvard
Mario Hamuy showed us this Diagram.

SN Ia are Precision Distance Indicators!

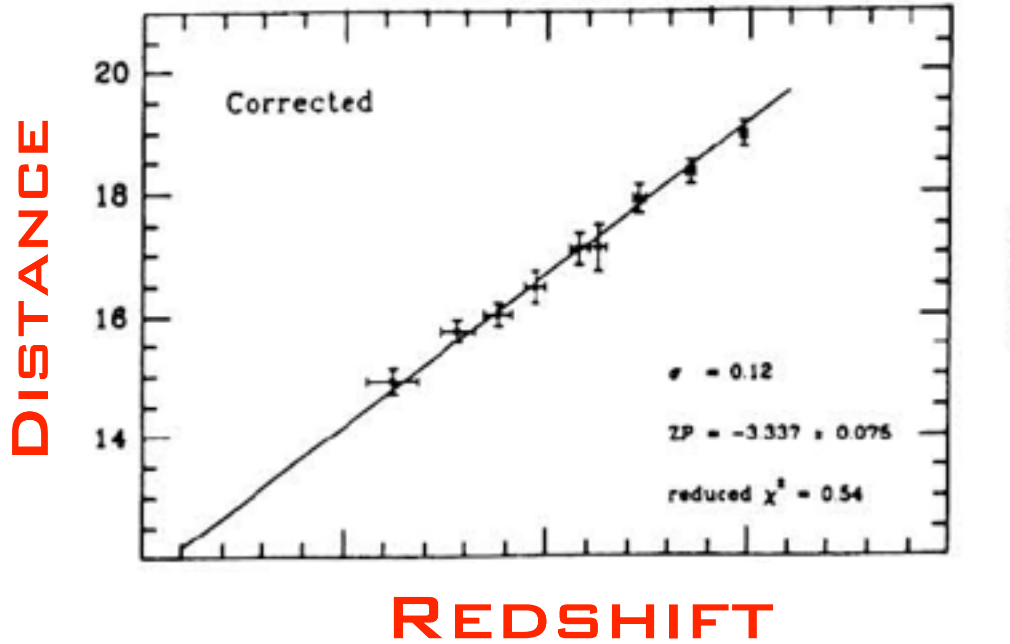


Figure 1: Hubble diagram of SNe Ia in the Calán/Tololo SN survey.

Eventually 29 Type Ia supernovae

Provided the fundamental basis of using SN Ia as accurate distance indicators

Used by Both Teams to measure Acceleration

The Birth of the High-Z Team

- A month later, Saul Perlmutter asked us at Harvard to confirm a possible supernovae - we found it to be a distant SN Ia -

SUPERNOVAE 1994F, 1994G, 1994H

S. Perlmutter, C. Pennypacker, G. Goldhaber, A. Goobar, R. Pain, B. Grossan, A. Kim, M. Kim, and I. Small, Lawrence Berkeley Laboratory and the Center for Particle Astrophysics, Berkeley, report three discoveries from a search for pre-maximum-light, high-redshift supernovae by themselves and R. McMahon, Institute of Astronomy, Cambridge; P. Bunclark, D. Carter, and M. Irwin, Royal Greenwich Observatory; M. Postman and W. Oegerle, Space Telescope Science Institute; T. Lauer, National Optical Astronomy Observatory; and J. Hoessel, University of Wisconsin. Following are given the designation, date of first detection, discovery magnitude and telescope (INT = 2.5-m Isaac Newton Telescope; KPNO = 4-m Kitt Peak telescope), supernova position for equinox 1950.0, offsets from the host galaxy's center, and date of the previous image of the galaxy not showing the supernova (to limiting mag about 24): SN 1994F, Jan. 9, R = 22.0, INT, R.A. = 11h47m25s.15, Decl. = +10o59'38".8, 1".1 west, 0".2 north, 1993 Dec. 22; SN 1994G, Feb. 13, I = 21.8, KPNO, R.A. = 10h16m17s.38, Decl. = +51o07'23".5, 1".4 east, 0".1 north, 1994 Jan. 16; SN 1994H, Jan. 8, R = 21.9, INT, R.A. = 2h37m32s.22, Decl. = -1o46'57".5, 1".2 west, 0".1 south, 1993 Dec. 20. On Jan. 18, spectra of SN 1994F were obtained by J. B. Oke with the Keck Telescope Low Resolution Imaging Spectrograph; the host galaxy redshift is 0.354, and the spectrum of SN 1994F matched that of a type-Ia supernova a week past maximum light. On Mar. 9 and 10, spectra of SN 1994G were obtained by A. Riess, P. Challis, and R. Kirshner at the Multiple Mirror Telescope, in which emission lines of [O II] and [O III] from the host galaxy give a redshift of z = 0.425; the spectrum of the SN 1994G, though noisy, is consistent with a type-I supernova about a week past maximum light. SN 1994H was observed on numerous nights from Jan. 10 to Feb. 16 at the INT, at Kitt Peak by G. Jacoby and others, at the European Southern Observatory by M. Turrato, and at Siding Spring Observatory by M. Dopita; the resulting photometry is consistent with a type-Ia supernova at an implied redshift of about 0.32 (the host galaxy is on the periphery of a cluster with that redshift), with maximum light around Jan. 12.

The Birth of the High-Z Team

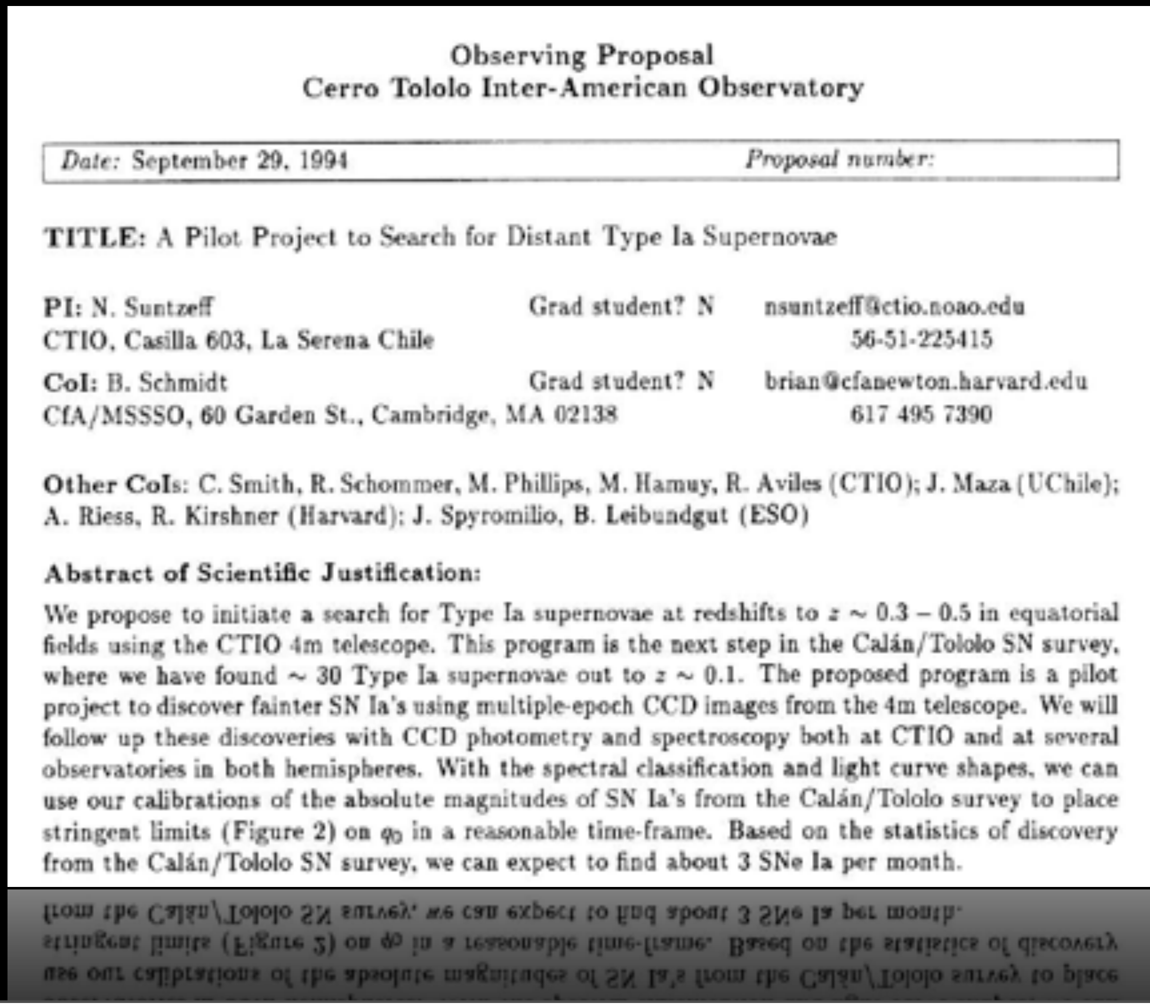
- I was down visiting Nick Suntzeff in July 1994, and we discussed the idea of doing our own High-Z SN Ia experiment

The Birth of the High-Z Team

- I was down visiting Nick Suntzeff in July 1994, and we discussed the idea of doing our own High-Z SN Ia experiment

The Birth of the High-Z Team

- I was down visiting Nick Suntzeff in July 1994, and we discussed the idea of doing our own High-Z SN Ia experiment



Observing Proposal
Cerro Tololo Inter-American Observatory

Date: September 29, 1994 *Proposal number:*

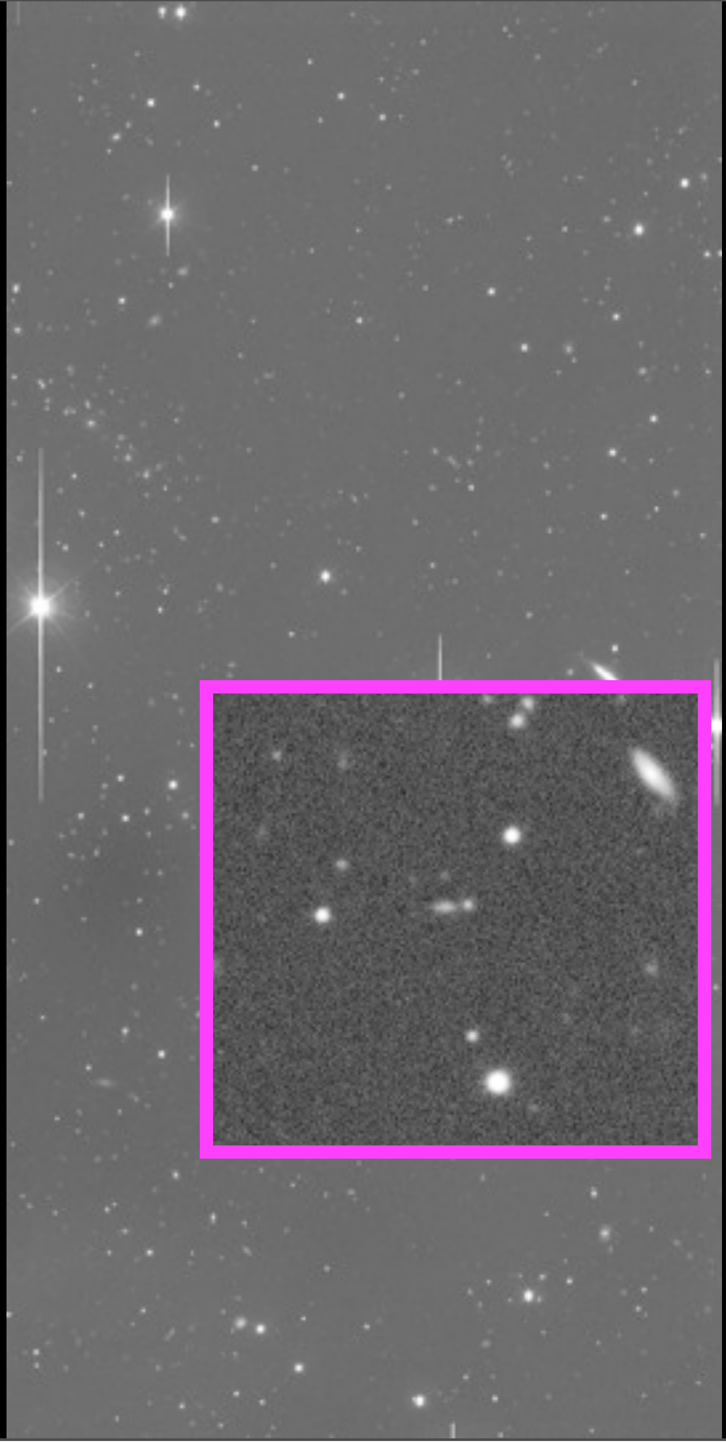
TITLE: A Pilot Project to Search for Distant Type Ia Supernovae

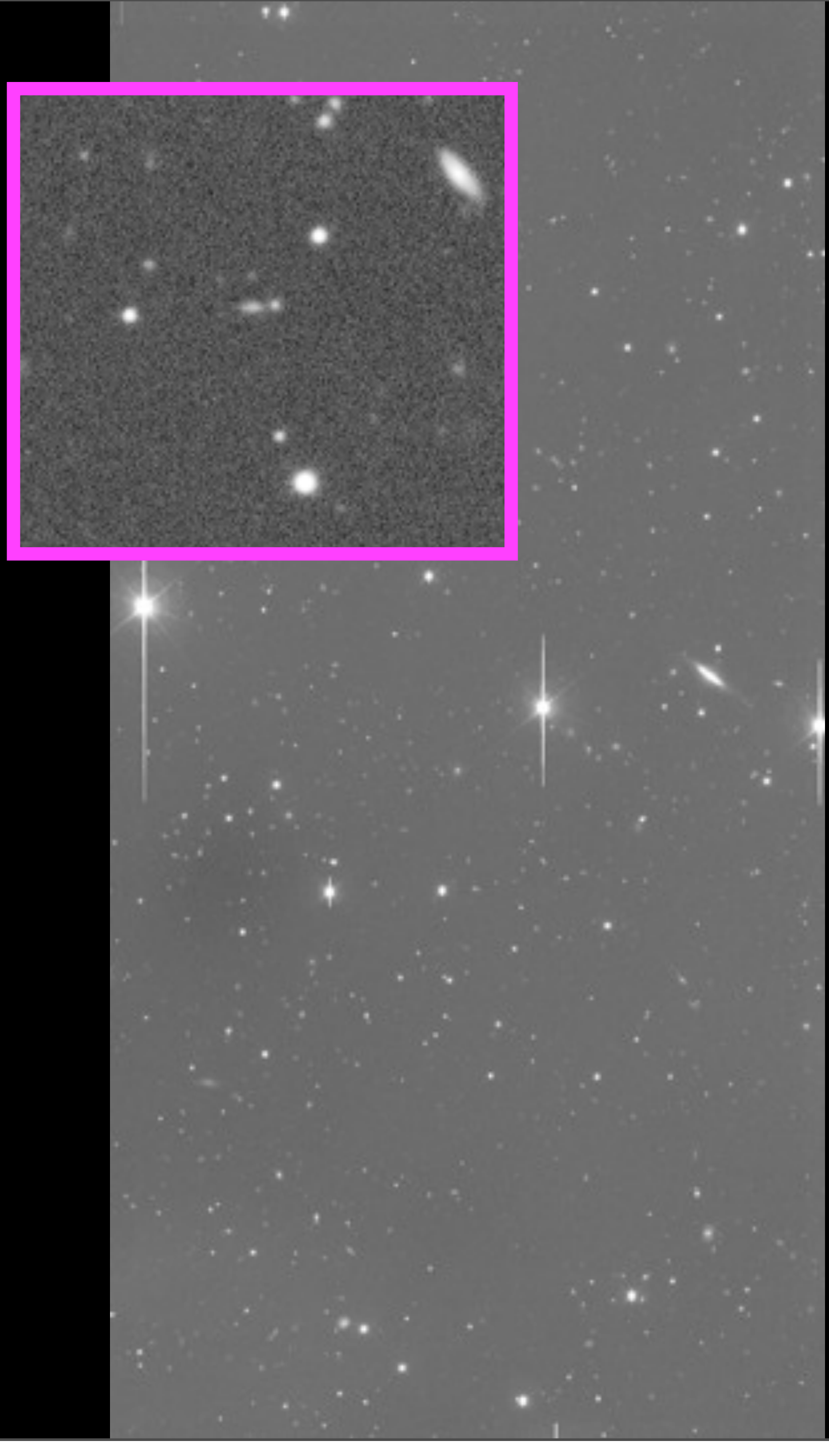
PI: N. Suntzeff Grad student? N nsuntzeff@ctio.noao.edu
CTIO, Casilla 603, La Serena Chile 56-51-225415
CoI: B. Schmidt Grad student? N brian@cfanewton.harvard.edu
CfA/MSSSO, 60 Garden St., Cambridge, MA 02138 617 495 7390

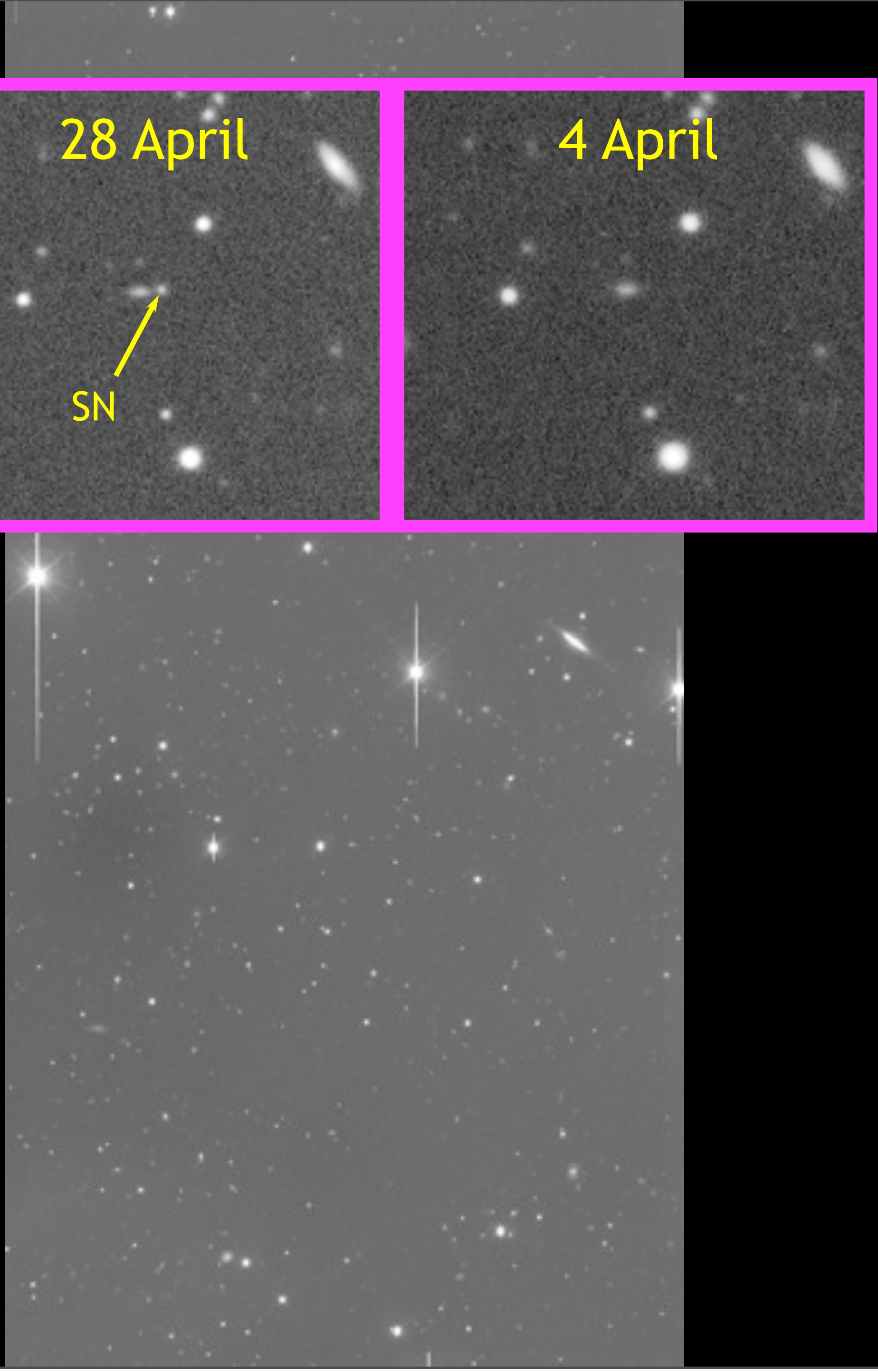
Other CoIs: C. Smith, R. Schommer, M. Phillips, M. Hamuy, R. Aviles (CTIO); J. Maza (UChile); A. Riess, R. Kirshner (Harvard); J. Spyromilio, B. Leibundgut (ESO)

Abstract of Scientific Justification:

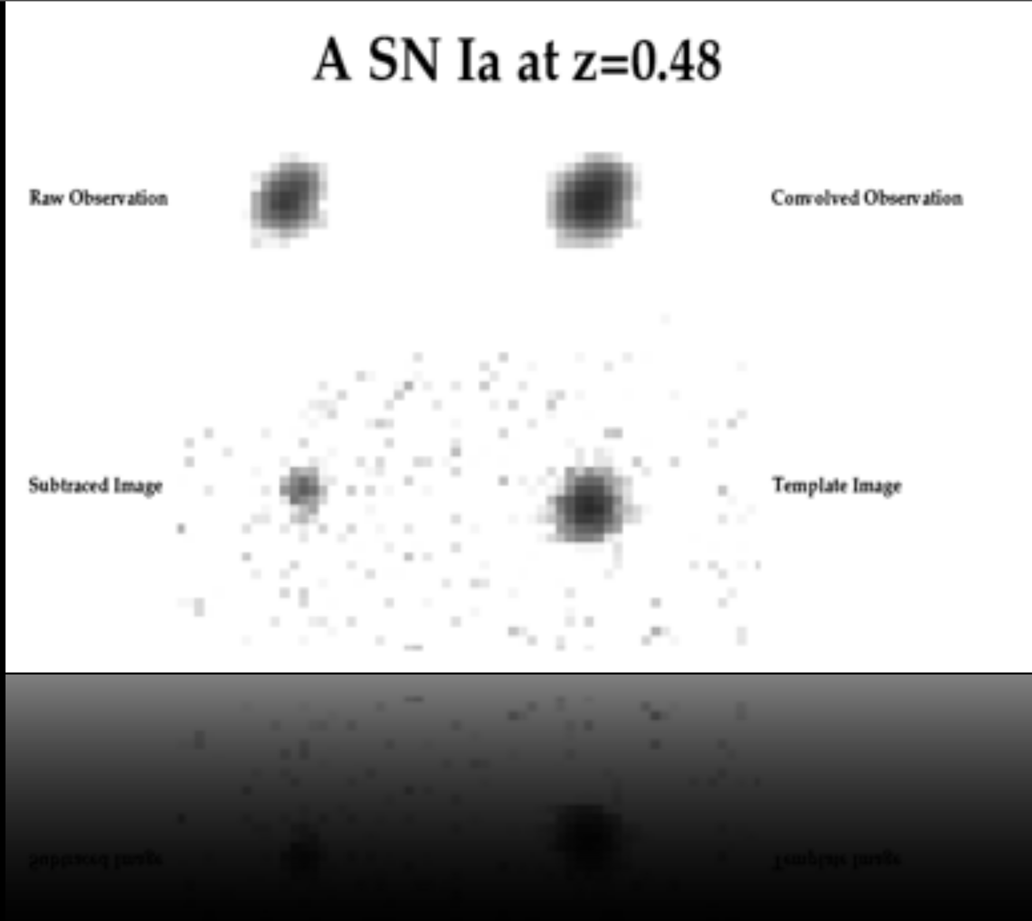
We propose to initiate a search for Type Ia supernovae at redshifts to $z \sim 0.3 - 0.5$ in equatorial fields using the CTIO 4m telescope. This program is the next step in the Calán/Tololo SN survey, where we have found $\sim$ 30 Type Ia supernovae out to $z \sim 0.1$. The proposed program is a pilot project to discover fainter SN Ia's using multiple-epoch CCD images from the 4m telescope. We will follow up these discoveries with CCD photometry and spectroscopy both at CTIO and at several observatories in both hemispheres. With the spectral classification and light curve shapes, we can use our calibrations of the absolute magnitudes of SN Ia's from the Calán/Tololo survey to place stringent limits (Figure 2) on q_0 in a reasonable time-frame. Based on the statistics of discovery from the Calán/Tololo SN survey, we can expect to find about 3 SNe Ia per month.



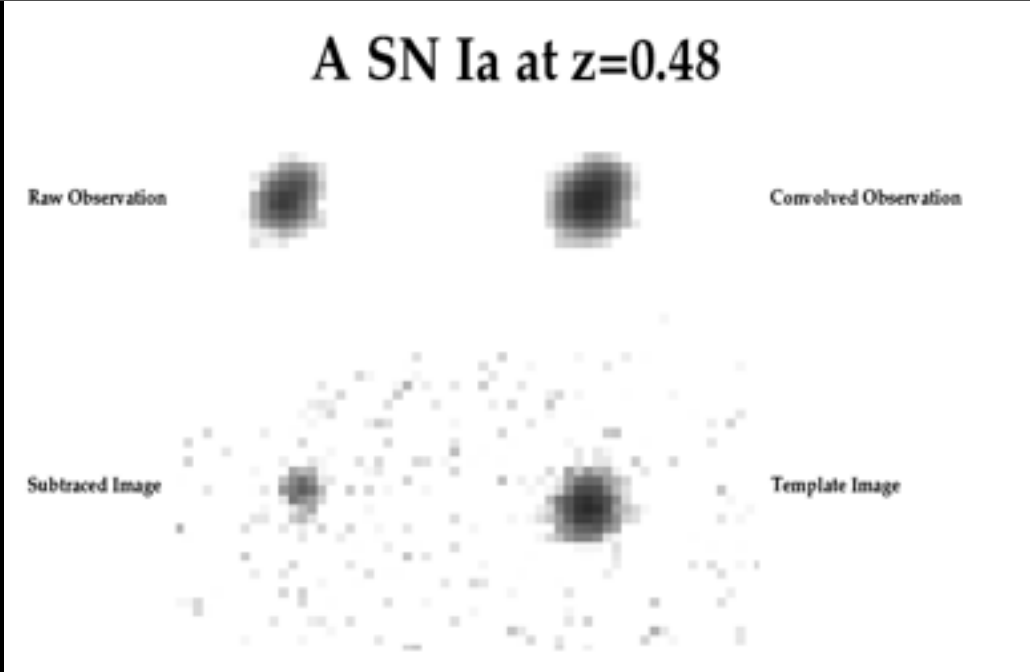



28 April
SN
4 April

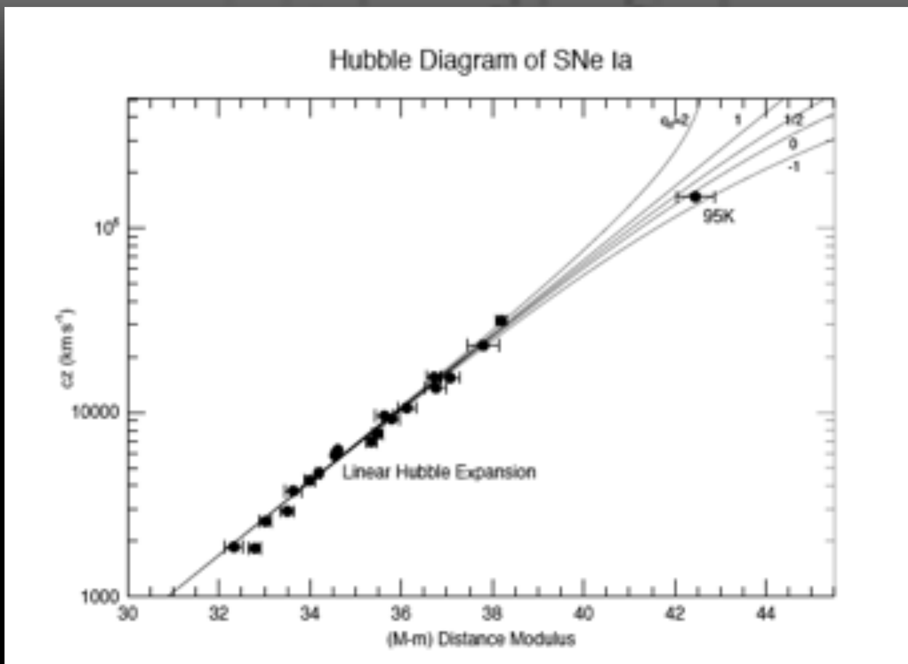

Sun

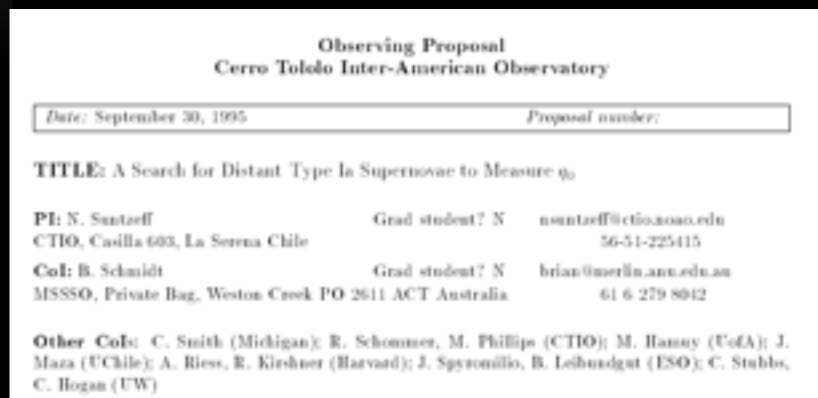


Our First Supernova
SN 1995K



Our First Supernova
SN 1995K




Observing Proposal
Cerro Tololo Inter-American Observatory

Date: September 30, 1995	*Proposal number:*

TITLE: A Search for Distant Type Ia Supernovae to Measure q_0

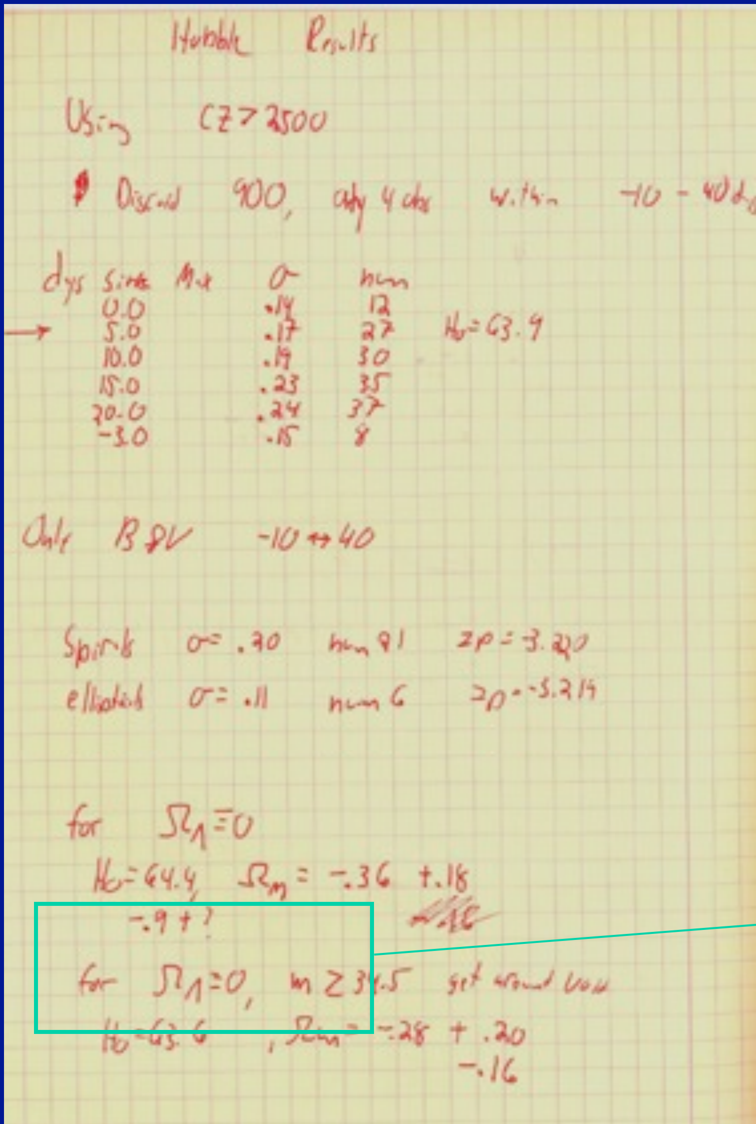
PI: N. Suntzeff Grad student? N nsuntzeff@ctio.noao.edu
CTIO, Casilla 603, La Serena Chile 56-51-225415

CoI: B. Schmidt Grad student? N brian@merlin.anu.edu.au
MSSSO, Private Bag, Weston Creek PO 2611 ACT Australia 61 6 279 8042

Other CoIs: C. Smith (Michigan); R. Schommer, M. Phillips (CTIO); M. Hamuy (UofA); J. Maza (UChile); A. Riess, R. Kirshner (Harvard); J. Spyromilio, B. Leibundgut (ESO); C. Stubbs, C. Hogan (UW)

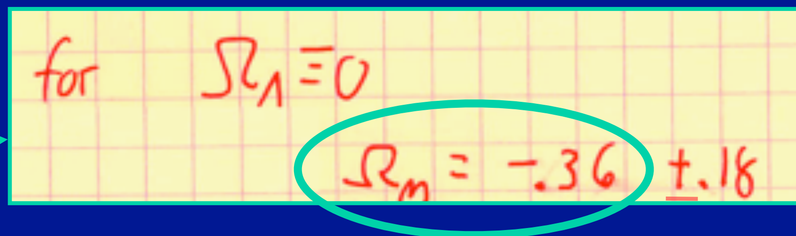
EUREKA?

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



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.



The Team is Excited, Worried (over 4 continents, email)...

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: “Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer.”

The Team is Excited, Worried (over 4 continents, email)...

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: "Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer."

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am "Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article, if we are not very sure we are getting the right answer."

The Team is Excited, Worried (over 4 continents, email)...

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: "Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer."

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am "Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article, if we are not very sure we are getting the right answer."

B. Schmidt, Australia, 1/11/1998: 7:13pm "I agree our data imply a cosmological constant, but how confident are we in this result? I find it very perplexing…."

The Team is Excited, Worried (over 4 continents, email)…

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: "Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer."

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am "Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article, if we are not very sure we are getting the right answer."

B. Schmidt, Australia, 1/11/1998: 7:13pm "I agree our data imply a cosmological constant, but how confident are we in this result? I find it very perplexing…."

R. Kirshner Santa Barbara, CA 1/12/1998 10:18am: "I am worried. In your heart you know [the cosmological constant] is wrong, though your head tells you that you don't care and you're just reporting the observations…It would be silly to say 'we MUST have a nonzero [cosmological constant]' only to retract it next year."

The Team is Excited, Worried (over 4 continents, email)…

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: “Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer.”

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am “Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article, if we are not very sure we are getting the right answer.”

B. Schmidt, Australia, 1/11/1998: 7:13pm “I agree our data imply a cosmological constant, but how confident are we in this result? I find it very perplexing….”

R. Kirshner Santa Barbara, CA 1/12/1998 10:18am: “I am worried. In your heart you know [the cosmological constant] is wrong, though your head tells you that you don’t care and you’re just reporting the observations…It would be silly to say ‘we MUST have a nonzero [cosmological constant]’ only to retract it next year.”

M. Phillips Chile, 1/12/1998, 04:56 am: “…As serious and responsible scientists (ha!), we all know that it is FAR TOO EARLY to be reaching firm conclusions about the value of the cosmological constant”

The Team is Excited, Worried (over 4 continents, email)…

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: "Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer."

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am "Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article, if we are not very sure we are getting the right answer."

B. Schmidt, Australia, 1/11/1998: 7:13pm "I agree our data imply a cosmological constant, but how confident are we in this result? I find it very perplexing…."

R. Kirshner Santa Barbara, CA 1/12/1998 10:18am: "I am worried. In your heart you know [the cosmological constant] is wrong, though your head tells you that you don't care and you're just reporting the observations…It would be silly to say 'we MUST have a nonzero [cosmological constant]' only to retract it next year."

M. Phillips Chile, 1/12/1998, 04:56 am: "…As serious and responsible scientists (ha!), we all know that it is FAR TOO EARLY to be reaching firm conclusions about the value of the cosmological constant"

J. Tonry, Hawaii, 1/12/1998, 11:40 am: "…who remembers the detection of the magnetic monopole and other gaffs?…on the other hand, we should not be shy about getting our results out …"

The Team is Excited, Worried (over 4 continents, email)…

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: "Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer."

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am "Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article, if we are not very sure we are getting the right answer."

B. Schmidt, Australia, 1/11/1998: 7:13pm "I agree our data imply a cosmological constant, but how confident are we in this result? I find it very perplexing…."

R. Kirshner Santa Barbara, CA 1/12/1998 10:18am: "I am worried. In your heart you know [the cosmological constant] is wrong, though your head tells you that you don't care and you're just reporting the observations…It would be silly to say 'we MUST have a nonzero [cosmological constant]' only to retract it next year."

M. Phillips Chile, 1/12/1998, 04:56 am: "…As serious and responsible scientists (ha!), we all know that it is FAR TOO EARLY to be reaching firm conclusions about the value of the cosmological constant"

J. Tonry, Hawaii, 1/12/1998, 11:40 am: "…who remembers the detection of the magnetic monopole and other gaffs?…on the other hand, we should not be shy about getting our results out …"

A. Filippenko 1/12/1998, 12:02 pm: "If we are wrong in the end, then so be it. At least we ran in the race."

The Team is Excited, Worried (over 4 continents, email)...

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: "Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer."

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am "Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article, if we are not very sure we are getting the right answer."

B. Schmidt, Australia, 1/11/1998: 7:13pm "I agree our data imply a cosmological constant, but how confident are we in this result? I find it very perplexing...."

R. Kirshner Santa Barbara, CA 1/12/1998 10:18am: "I am worried. In your heart you know [the cosmological constant] is wrong, though your head tells you that you don't care and you're just reporting the observations...It would be silly to say 'we MUST have a nonzero [cosmological constant]' only to retract it next year."

M. Phillips Chile, 1/12/1998, 04:56 am: "...As serious and responsible scientists (ha!), we all know that it is FAR TOO EARLY to be reaching firm conclusions about the value of the cosmological constant"

J. Tonry, Hawaii, 1/12/1998, 11:40 am: "...who remembers the detection of the magnetic monopole and other gaffs?...on the other hand, we should not be shy about getting our results out ..."

A. Filippenko 1/12/1998, 12:02 pm: "If we are wrong in the end, then so be it. At least we ran in the race."

A. Riess Berkeley, CA 1/12/1998 6:36pm: "The results are very surprising, shocking even. I have avoided telling anyone about them because I wanted to do some cross checks (I have) and I wanted to get further into writing the results up...The data require a nonzero cosmological constant! Approach these results not with your heart or head but with your eyes. We are observers after all!"

The Team is Excited, Worried (over 4 continents, email)…

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: "Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer."

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am "Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article, if we are not very sure we are getting the right answer."

B. Schmidt, Australia, 1/11/1998: 7:13pm "I agree our data imply a cosmological constant, but how confident are we in this result? I find it very perplexing…."

R. Kirshner Santa Barbara, CA 1/12/1998 10:18am: "I am worried. In your heart you know [the cosmological constant] is wrong, though your head tells you that you don't care and you're just reporting the observations…It would be silly to say 'we MUST have a nonzero [cosmological constant]' only to retract it next year."

M. Phillips Chile, 1/12/1998, 04:56 am: "…As serious and responsible scientists (ha!), we all know that it is FAR TOO EARLY to be reaching firm conclusions about the value of the cosmological constant"

J. Tonry, Hawaii, 1/12/1998, 11:40 am: "…who remembers the detection of the magnetic monopole and other gaffs?…on the other hand, we should not be shy about getting our results out …"

A. Filippenko 1/12/1998, 12:02 pm: "If we are wrong in the end, then so be it. At least we ran in the race."

A. Riess Berkeley, CA 1/12/1998 6:36pm: "The results are very surprising, shocking even. I have avoided telling anyone about them because I wanted to do some cross checks (I have) and I wanted to get further into writing the results up…The data require a nonzero cosmological constant! Approach these results not with your heart or head but with your eyes. We are observers after all!"

A. Clocchiatti, Chile 1/13/1998 07:30pm: "If Einstein made a mistake with the cosmological constant…Why couldn't we?"

The Team is Excited, Worried (over 4 continents, email)…

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: "Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer."

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am "Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article, if we are not very sure we are getting the right answer."

B. Schmidt, Australia, 1/11/1998: 7:13pm "I agree our data imply a cosmological constant, but how confident are we in this result? I find it very perplexing…."

R. Kirshner Santa Barbara, CA 1/12/1998 10:18am: "I am worried. In your heart you know [the cosmological constant] is wrong, though your head tells you that you don't care and you're just reporting the observations…It would be silly to say 'we MUST have a nonzero [cosmological constant]' only to retract it next year."

M. Phillips Chile, 1/12/1998, 04:56 am: "…As serious and responsible scientists (ha!), we all know that it is FAR TOO EARLY to be reaching firm conclusions about the value of the cosmological constant"

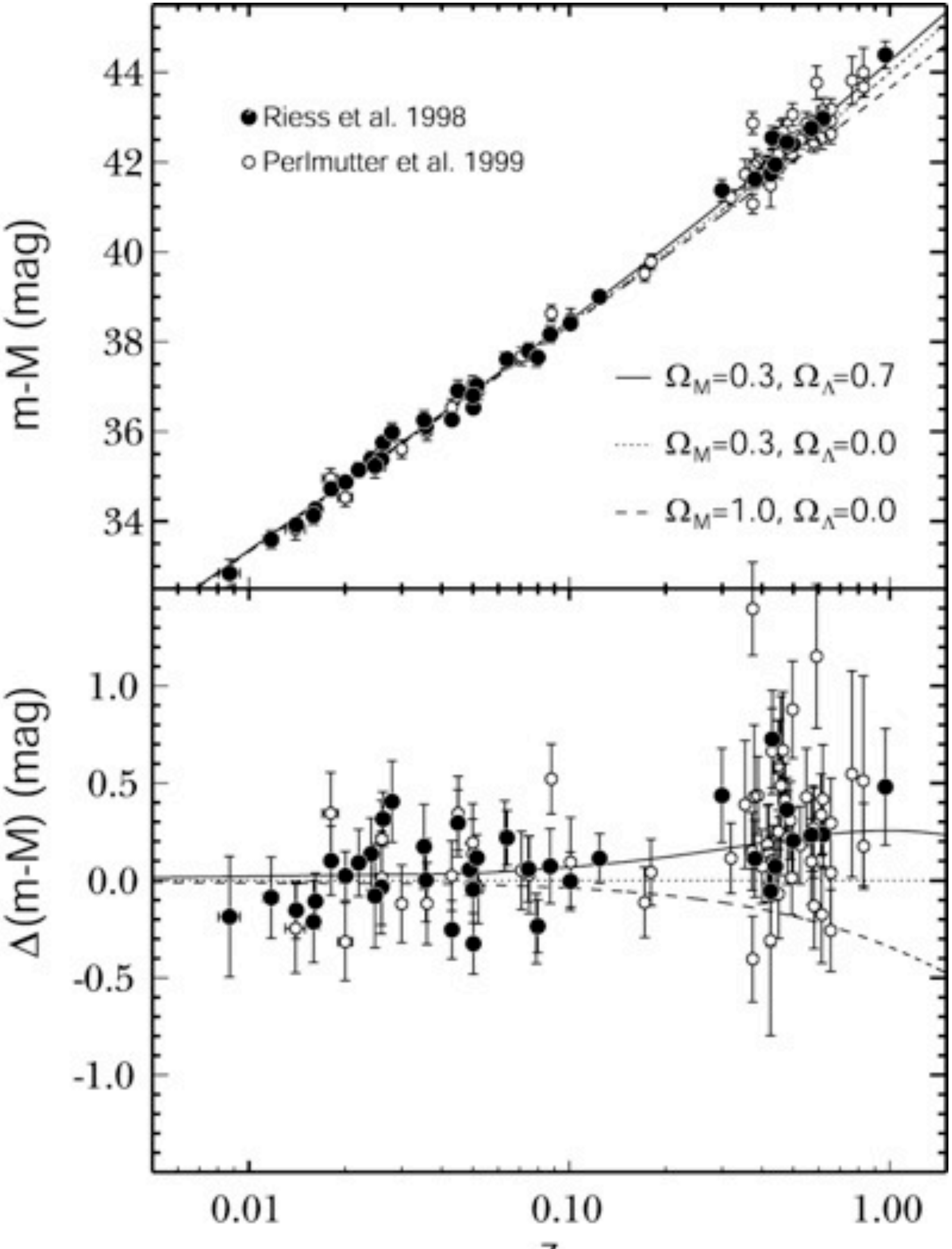
J. Tonry, Hawaii, 1/12/1998, 11:40 am: "…who remembers the detection of the magnetic monopole and other gaffs?…on the other hand, we should not be shy about getting our results out …"

A. Filippenko 1/12/1998, 12:02 pm: "If we are wrong in the end, then so be it. At least we ran in the race."

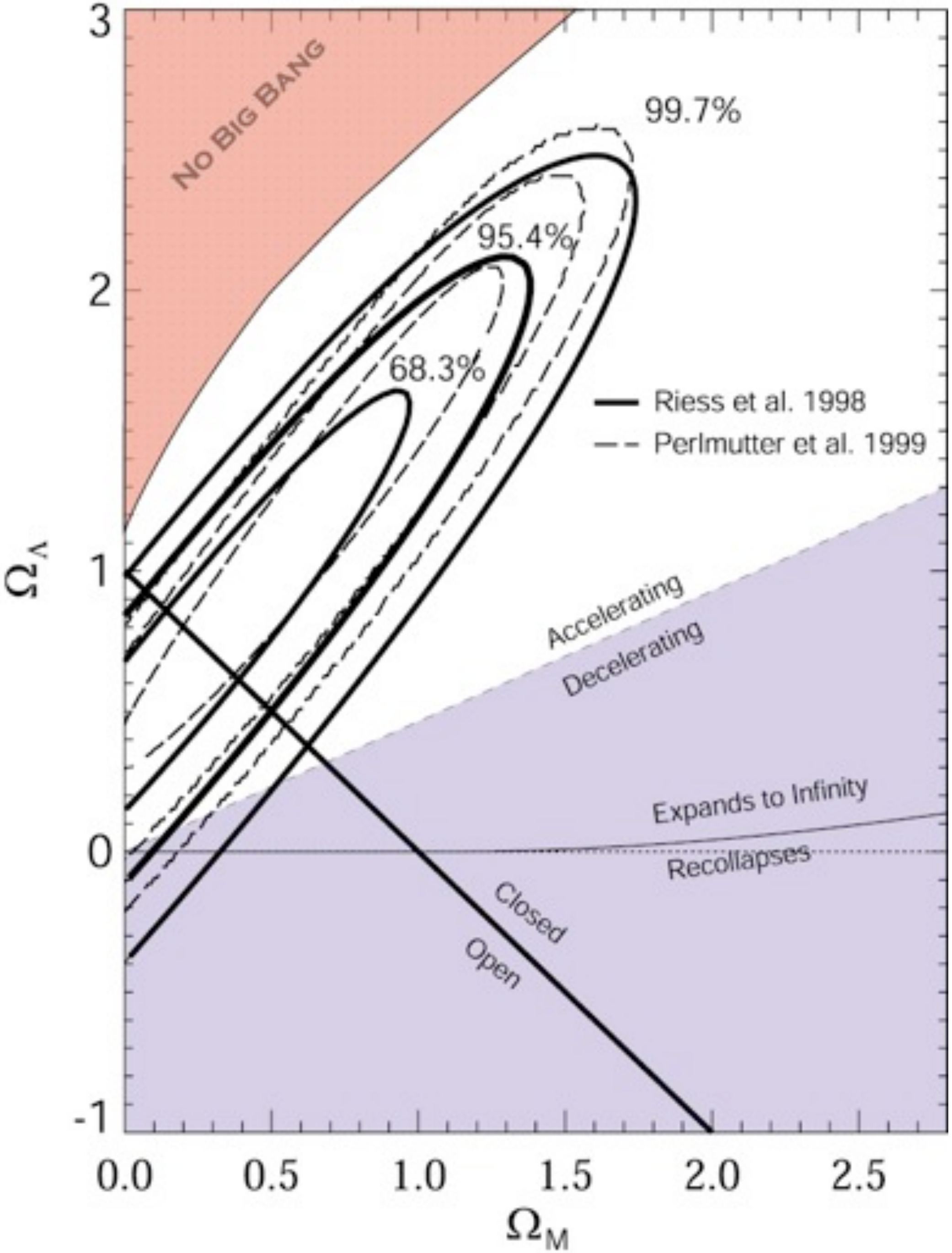
A. Riess Berkeley, CA 1/12/1998 6:36pm: "The results are very surprising, shocking even. I have avoided telling anyone about them because I wanted to do some cross checks (I have) and I wanted to get further into writing the results up…The data require a nonzero cosmological constant! Approach these results not with your heart or head but with your eyes. We are observers after all!"

A. Clocchiatti, Chile 1/13/1998 07:30pm: "If Einstein made a mistake with the cosmological constant…Why couldn't we?"

N. Suntzeff Chile 1/13/1998 1:47pm: "I really encourage you [Adam] to work your butt off on this. We need to be careful…If you are really sure that the [cosmological constant] is not zero—my god, get it out! I mean this seriously—you probably never will have another scientific result that is more exciting come your way in your lifetime."



Riess et al. 1998
Perlmutter et al. 1999
m-M (mag)
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Δ(m-M) (mag)
z
0.01
0.10
1.00



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
0.0
0.5
1.0
1.5
2.0
2.5
Ω_Λ
Ω_M

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]
Nicholas B. Suntzeff,[7] and John Tonry[11]

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

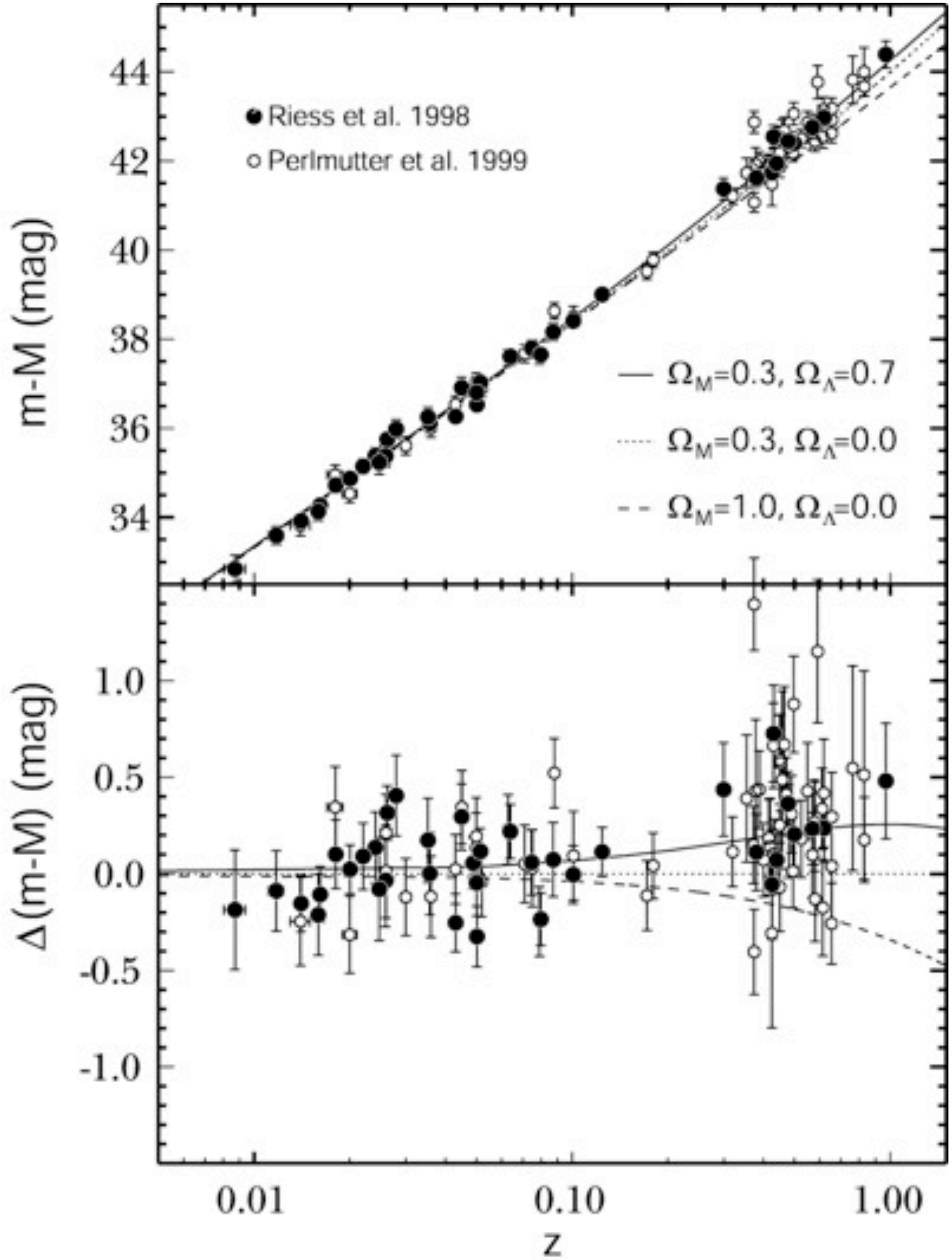
A. V Filippenko and T. Matheson
of California, Berkeley, CA

N. Panagia[9]
te, Baltimore, MD

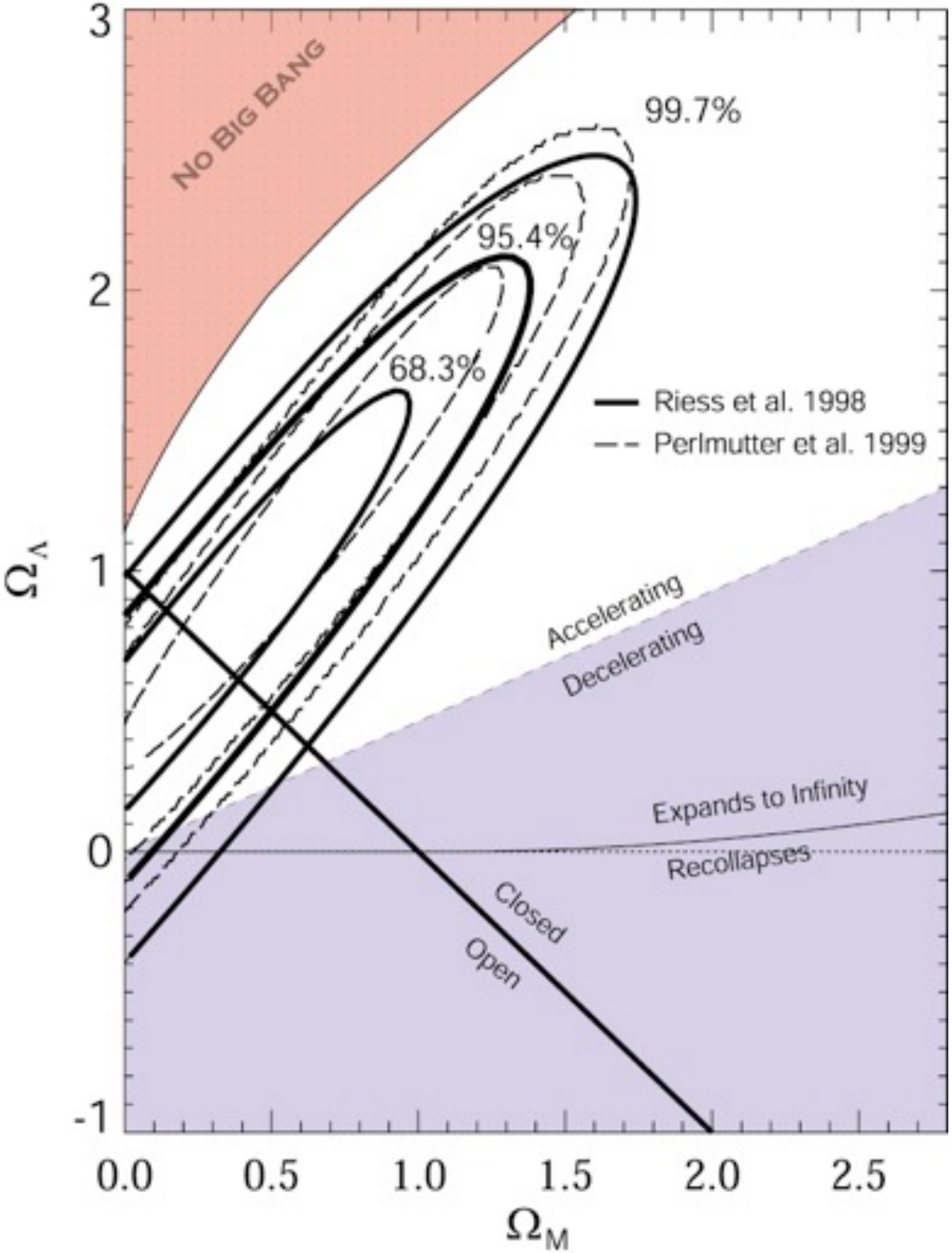
BERG
y, Batavia, IL

H
, Sydney, Australia

LOGY PROJECT)



Riess et al. 1998
Perlmutter et al. 1999
m-M (mag)
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Δ(m-M) (mag)
z
0.01
0.10
1.00

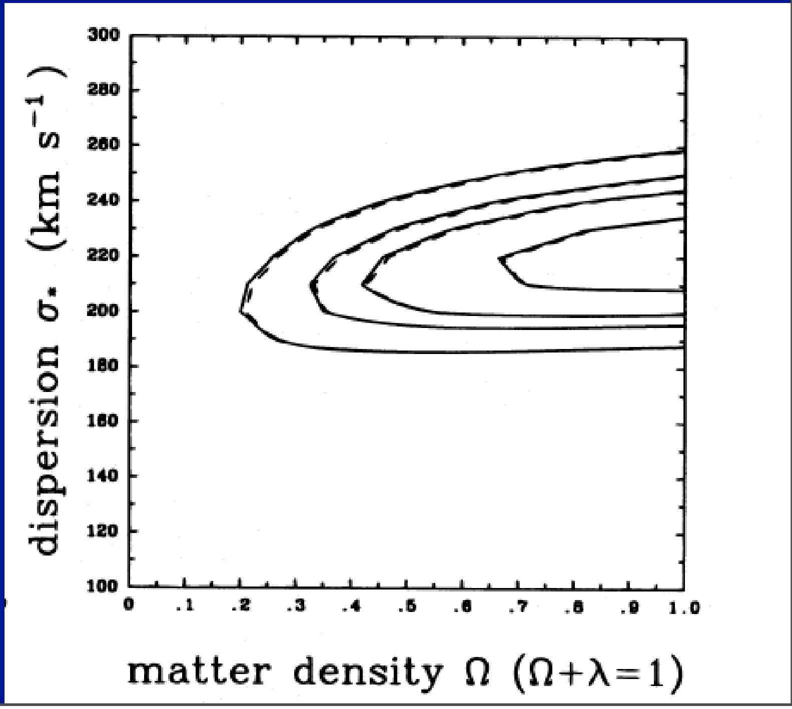


No Big Bang
99.7%
95.4%
68.3%
Riess et al. 1998
Perlmutter et al. 1999
Accelerating
Decelerating
Expands to Infinity
Recollapses
Closed
Open
Ω_Λ
Ω_M
3
2
1
0
-1
0.0
0.5
1.0
1.5
2.0
2.5

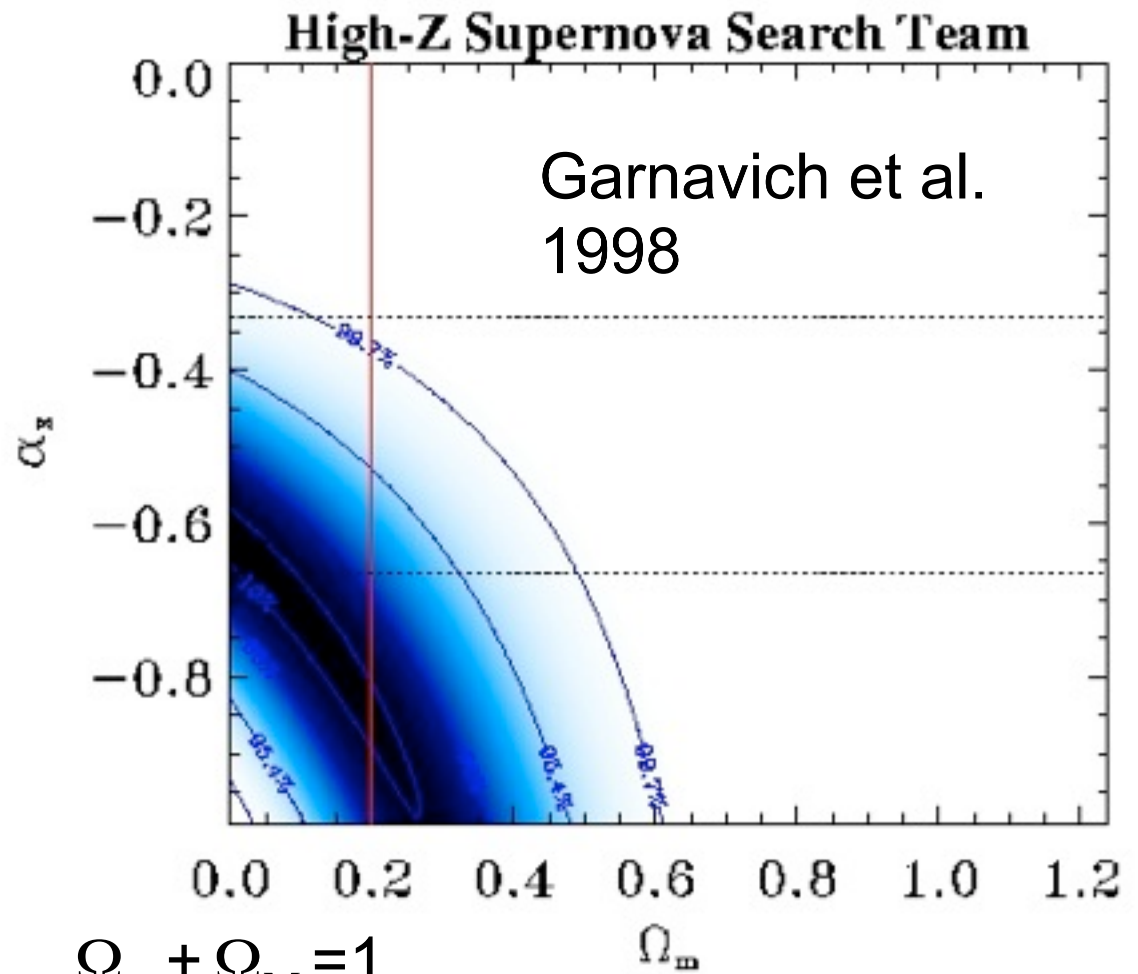
- High-Z SN Observations directly measured distances which were incompatible with any matter-only Universes.
- But SN Ia themselves might be affected by Dust, evolution or measurement difficulties, and Community felt they were not to be completely trusted on their own.

- 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.

- 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

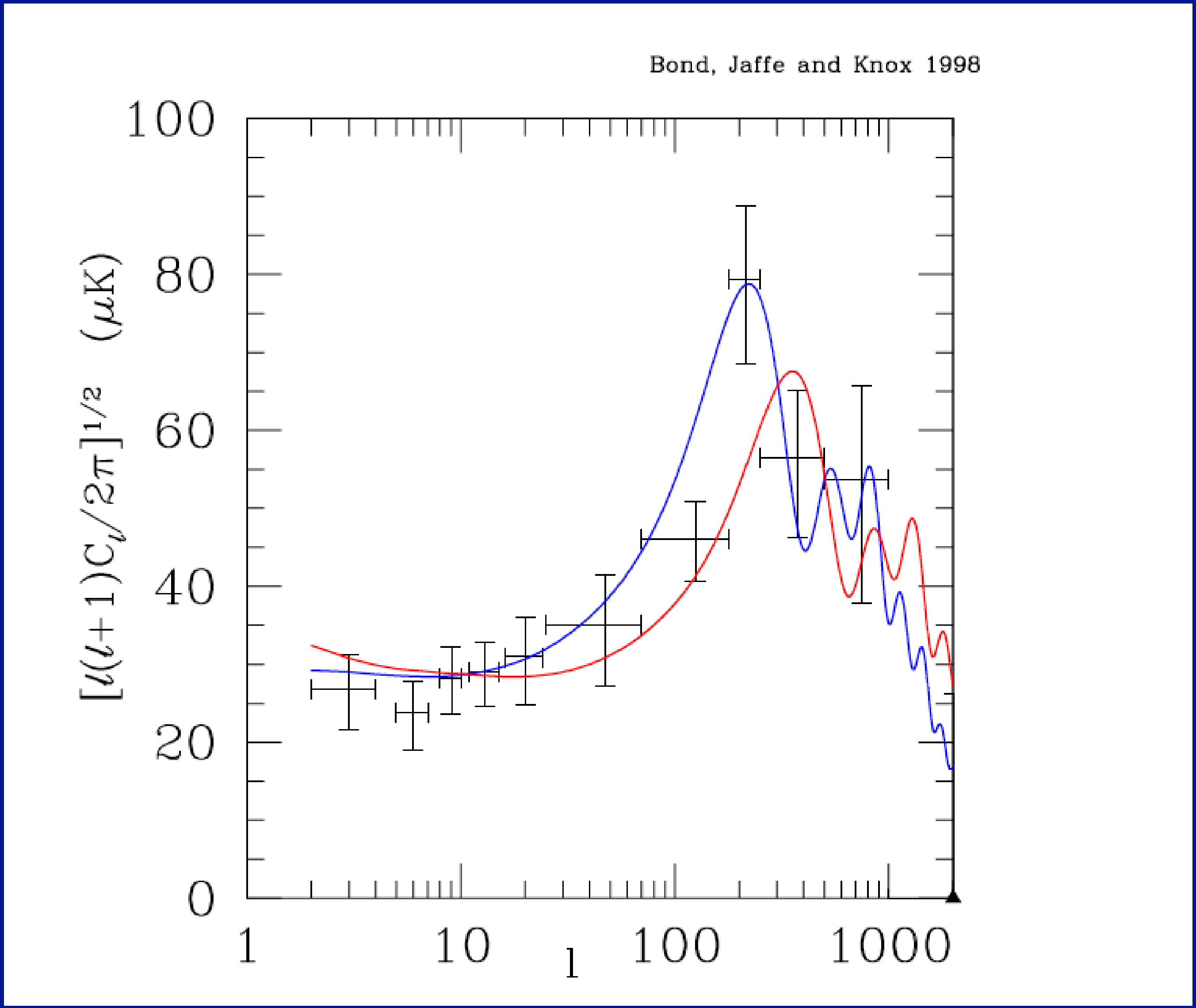


$\Omega_w + \Omega_M = 1$

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

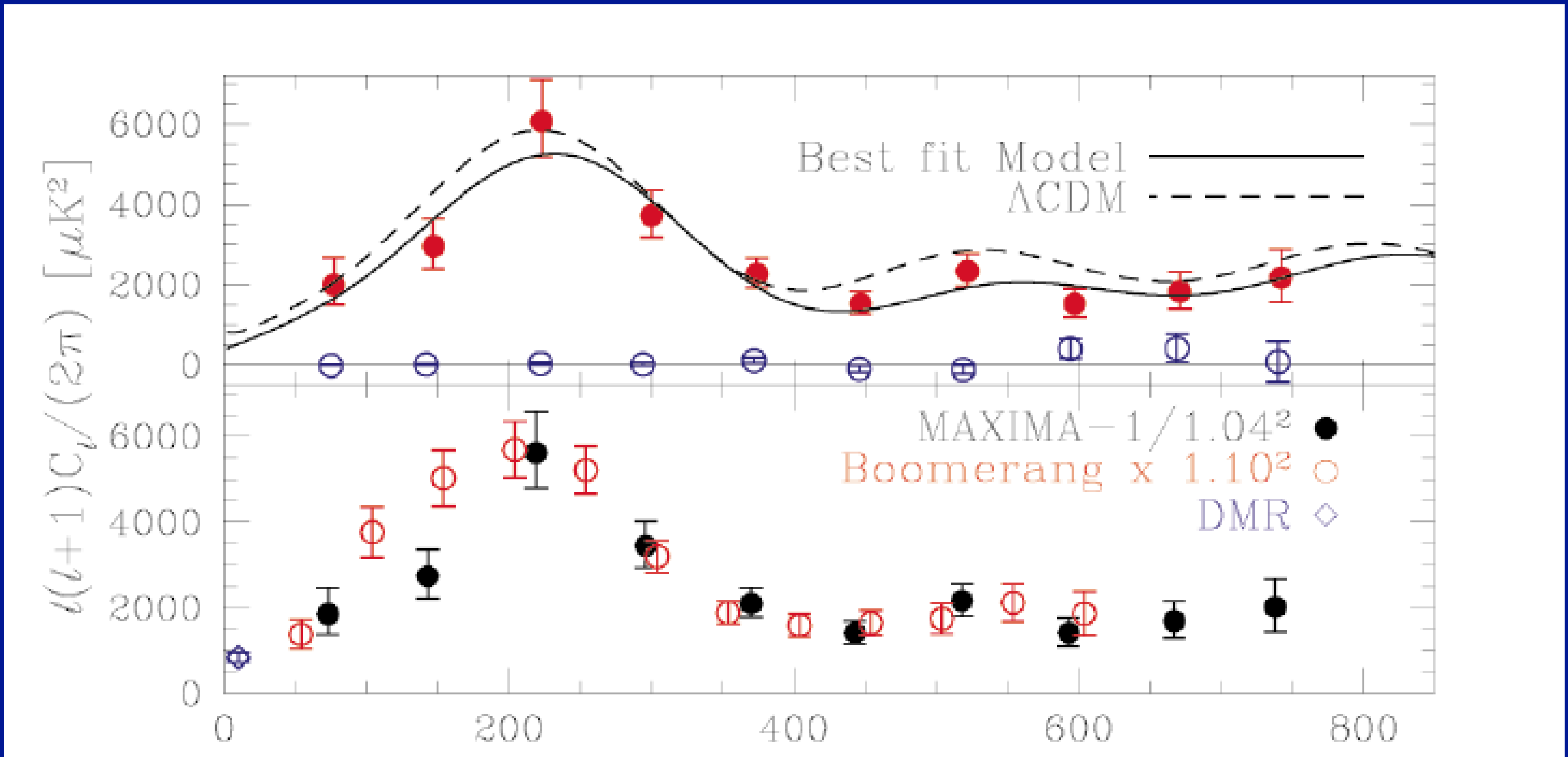
EOS was new stuff to us, so we had no problem giving the constant the name α

CMB - mid 1998



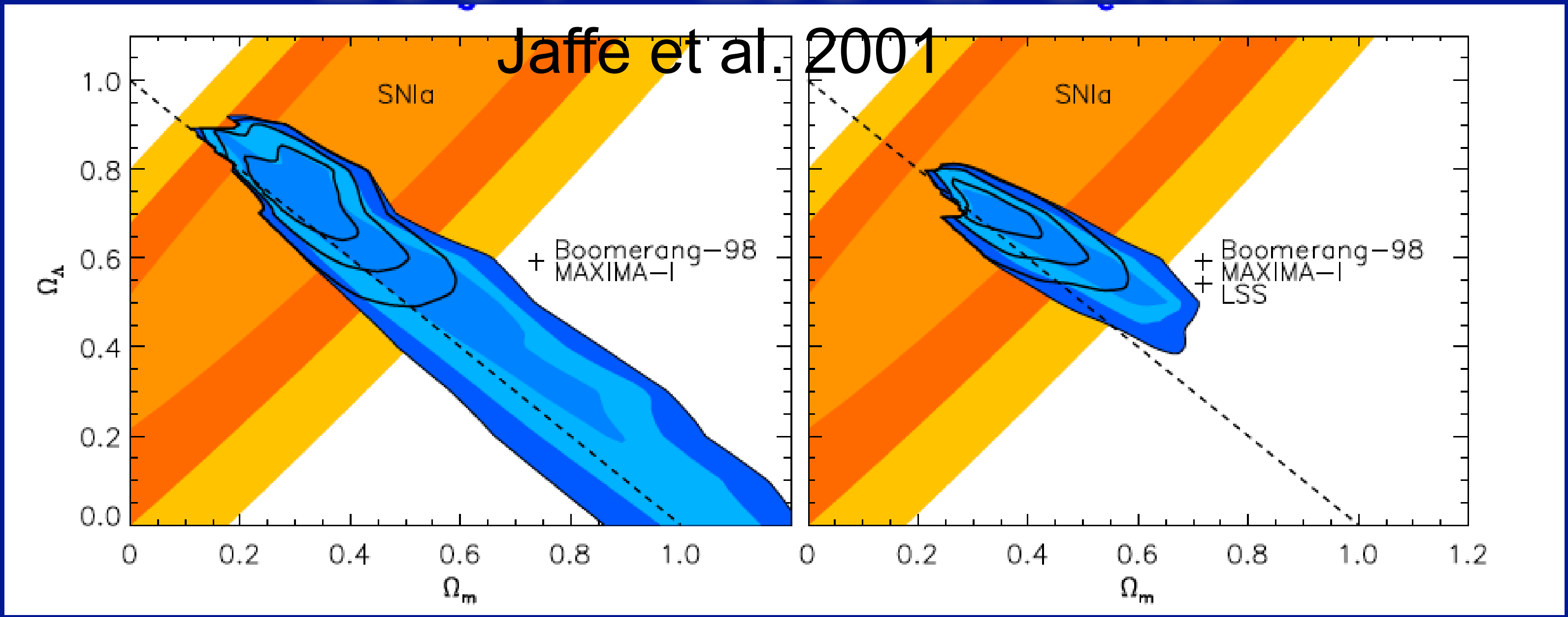
Bond, Jaffe and Knox 1998
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ (μK)
100
80
60
40
20
0
1
10
l
100
1000

2000 - Boomerang & MAXIMA Clearly see 1st Doppler Peak

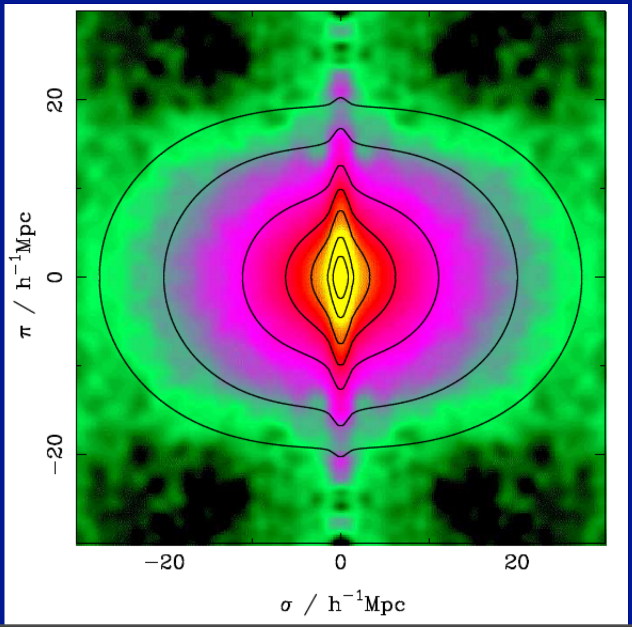


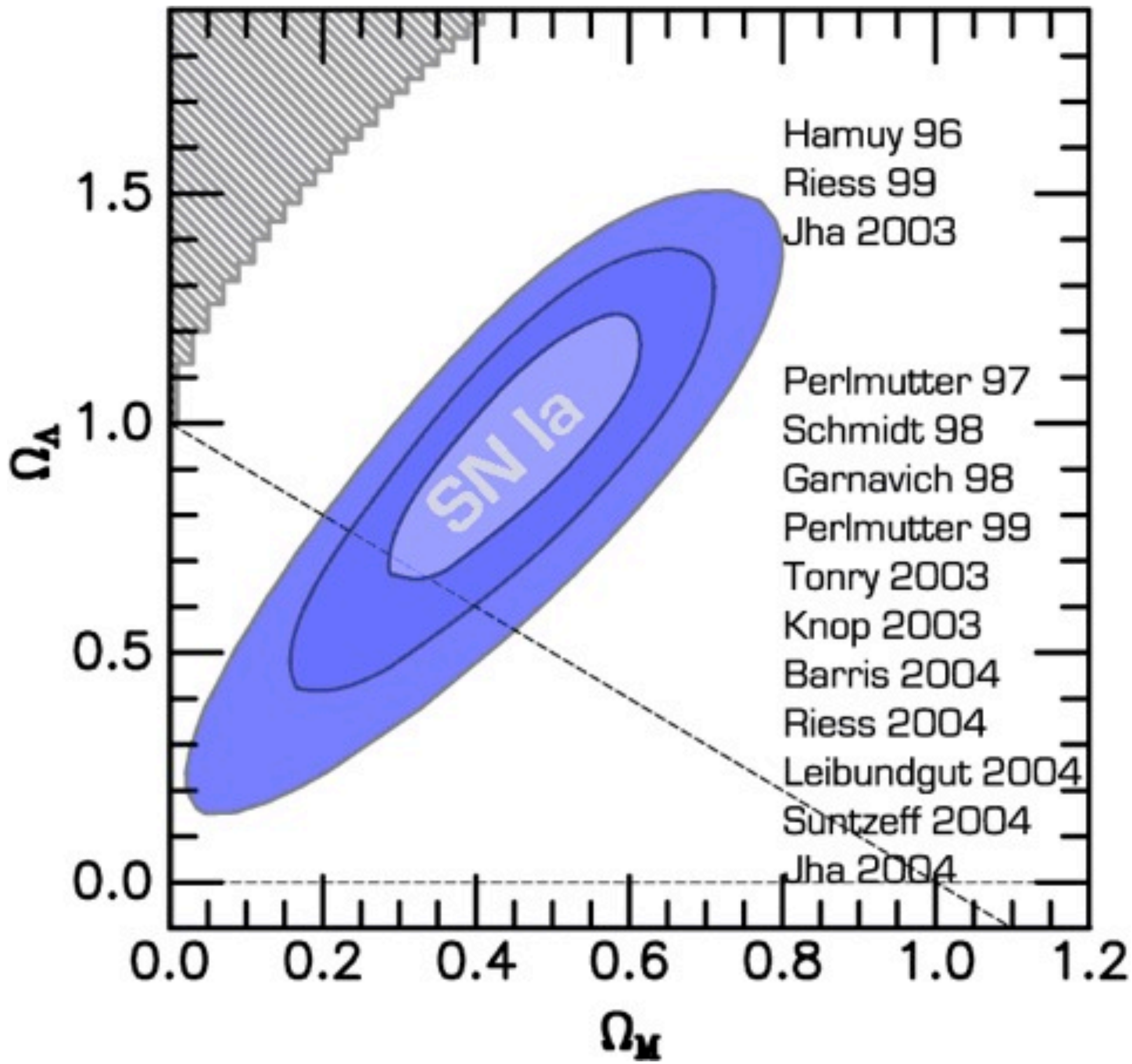
Once a Flat Universe was measured, the SN Ia measurements went from being 3-4σ to >7σ

2001 - LSS & CMB

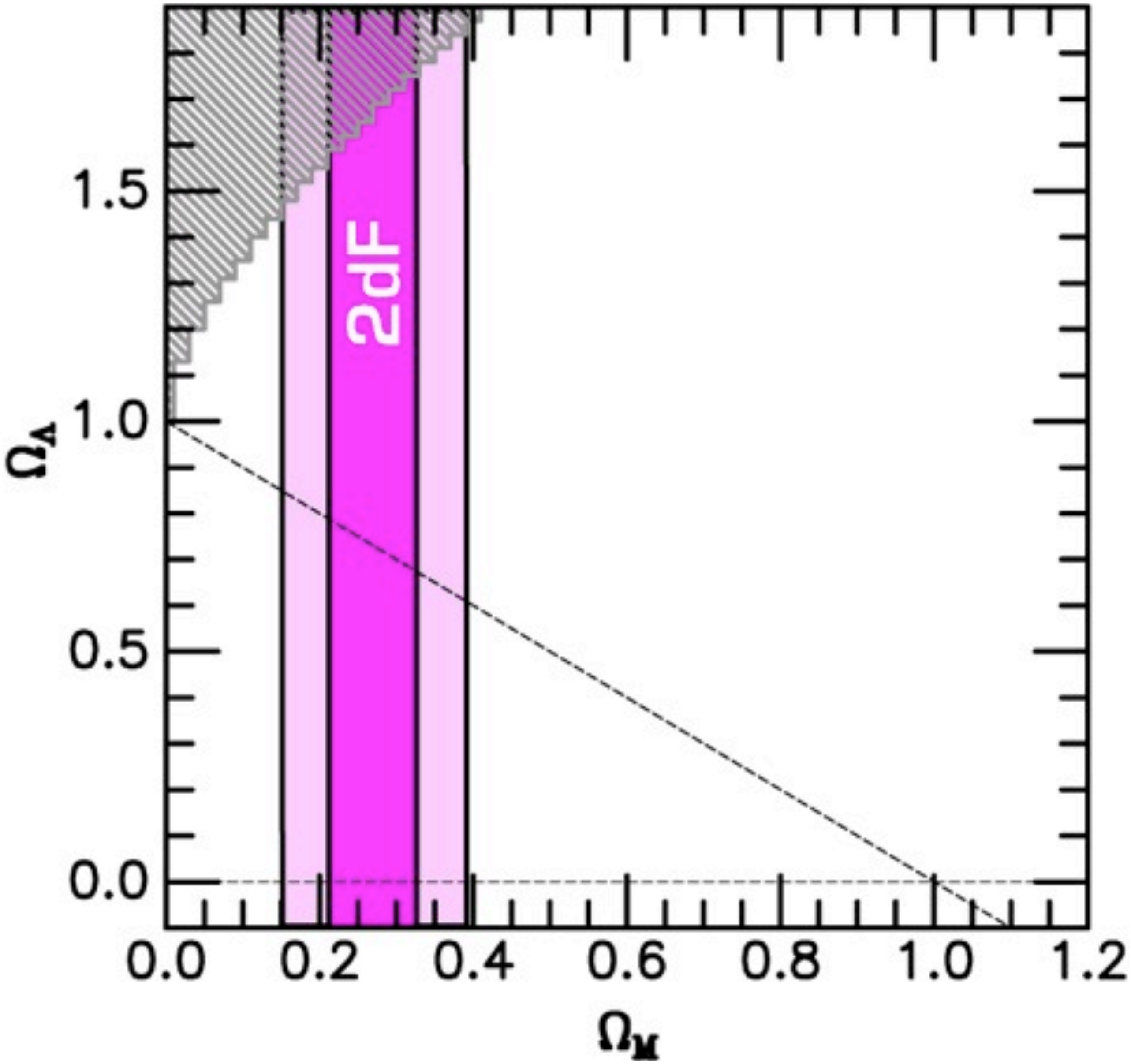


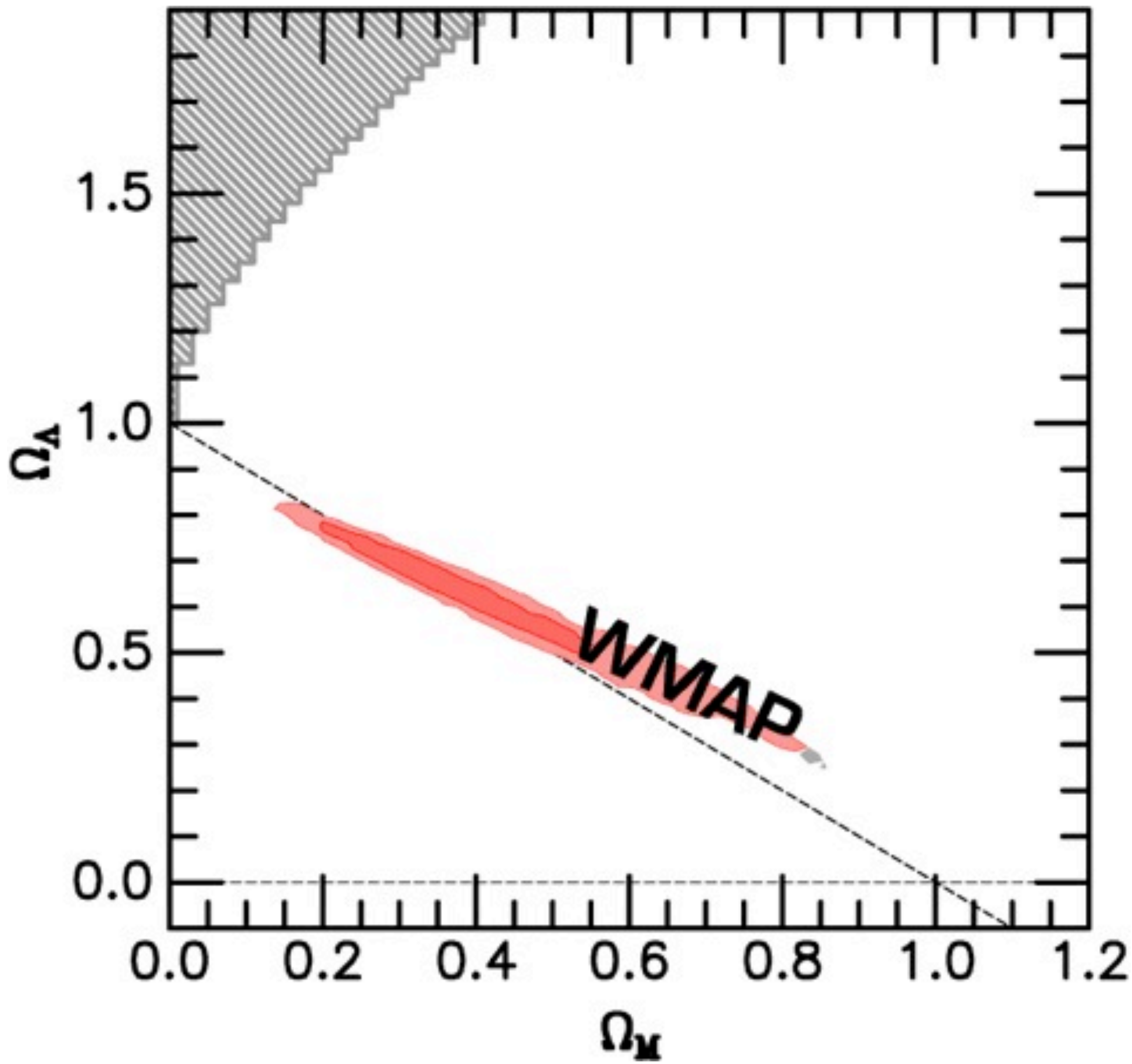
2dF redshift survey finds $\Omega_{\mathbb{M}}$~0.3 from power spectrum and infall



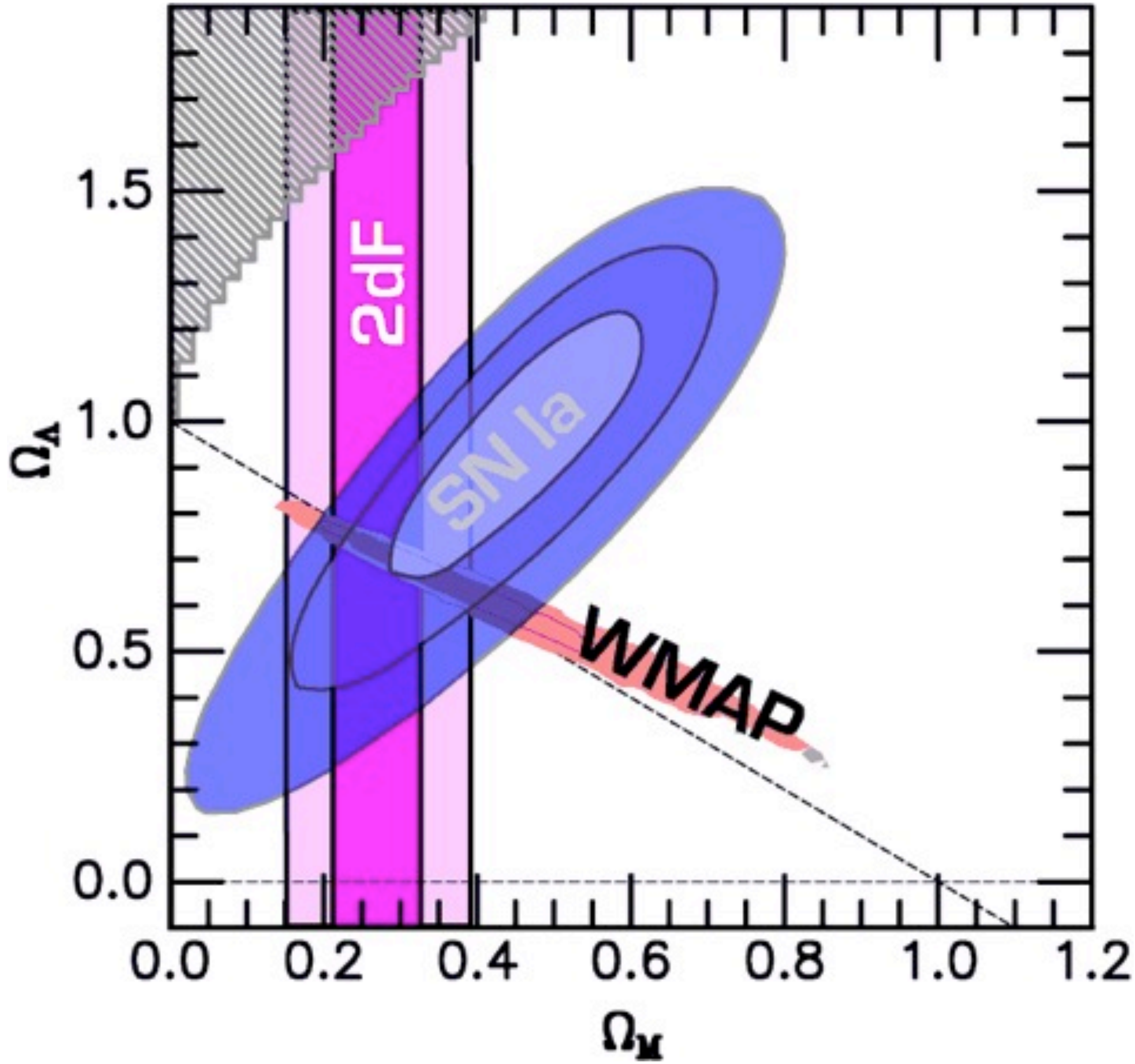


Hamuy 96
Riess 99
Jha 2003
Perlmutter 97
Schmidt 98
Garnavich 98
Perlmutter 99
Tonry 2003
Knop 2003
Barris 2004
Riess 2004
Leibundgut 2004
Suntzeff 2004
Jha 2004
SN Ia
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ω_Λ
Ω_M


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

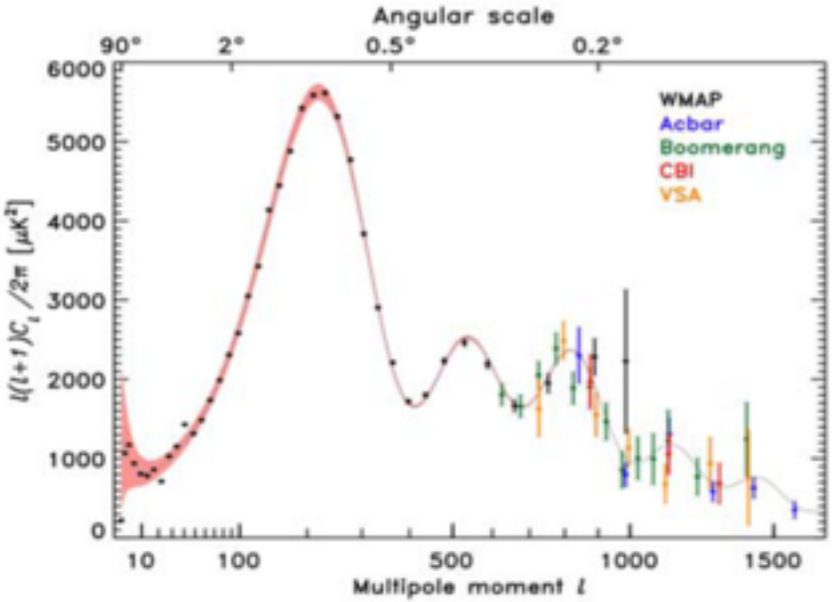


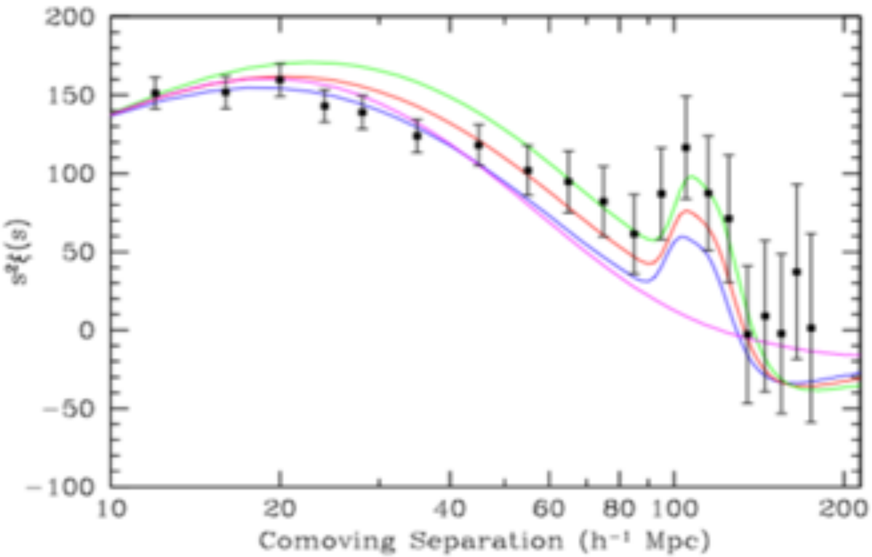
1.5
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ω_Λ
Ω_M
2dF
SN Ia
WMAP

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

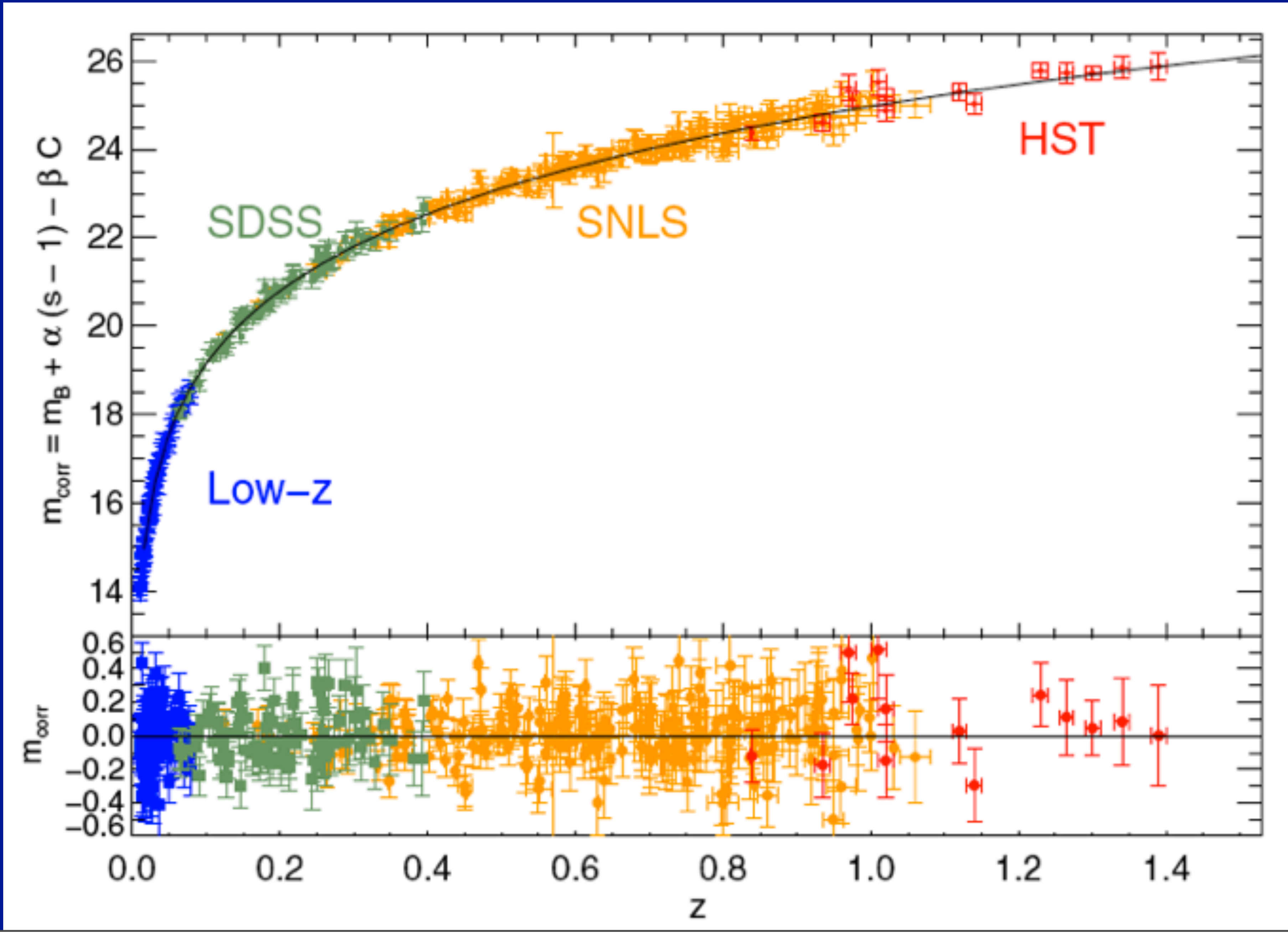




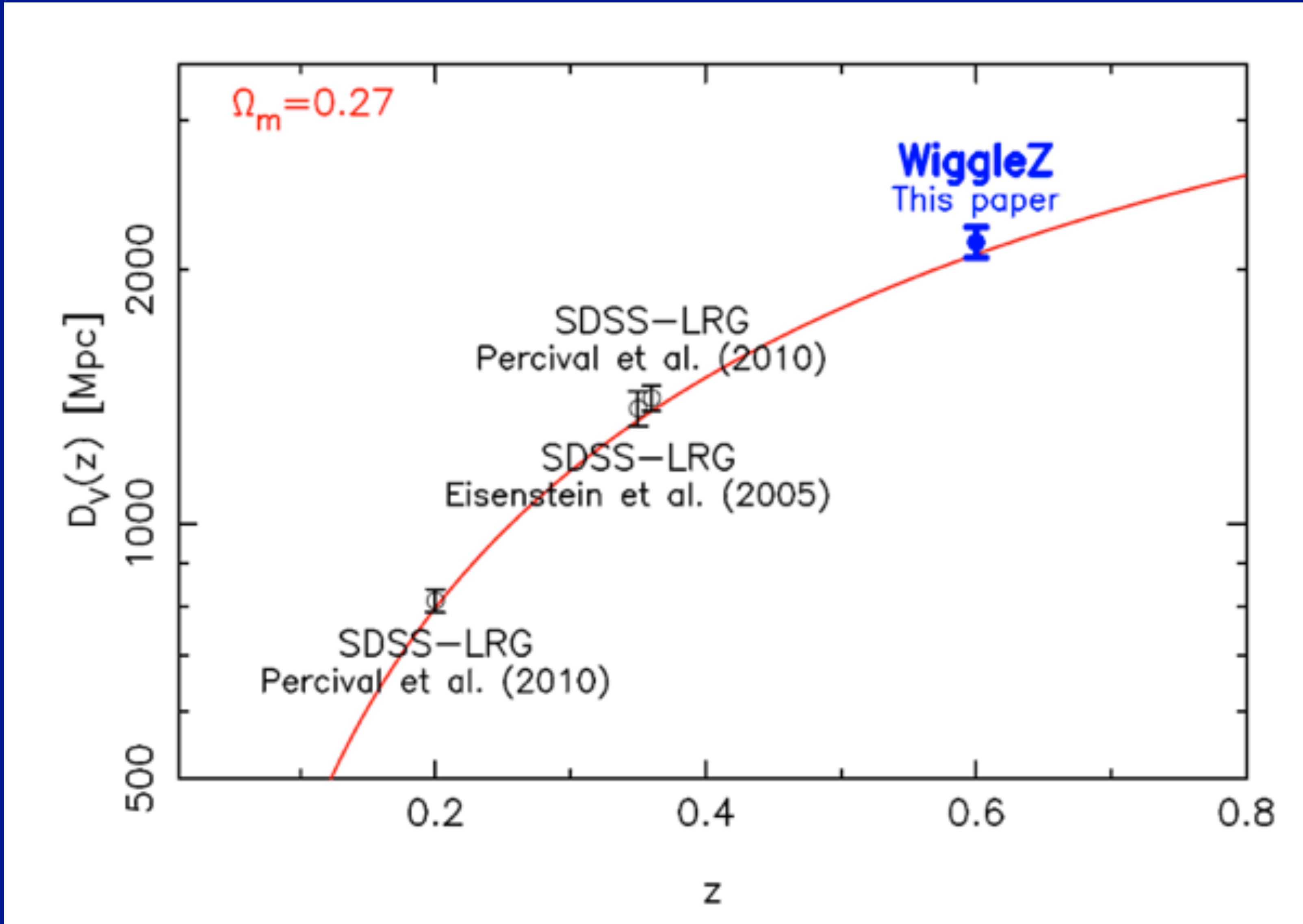
Eisenstein et al. 2005

- 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, WiggleZ, and now BOSS have yielded a detection of the BAO at <z>=0.2 to <z>=0.7

Where we Stand now - SN Ia



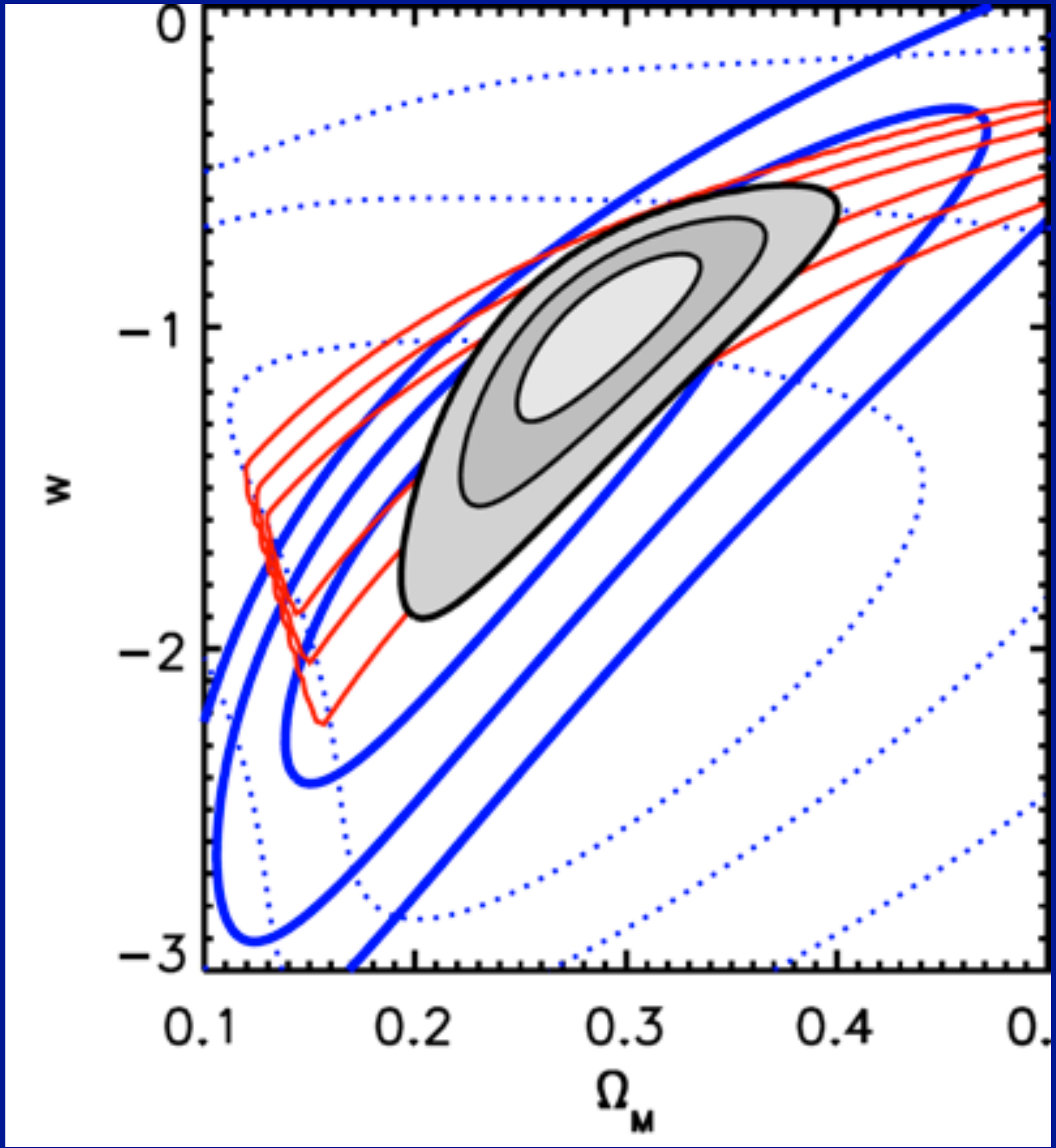
Where we Stand now - BAOs

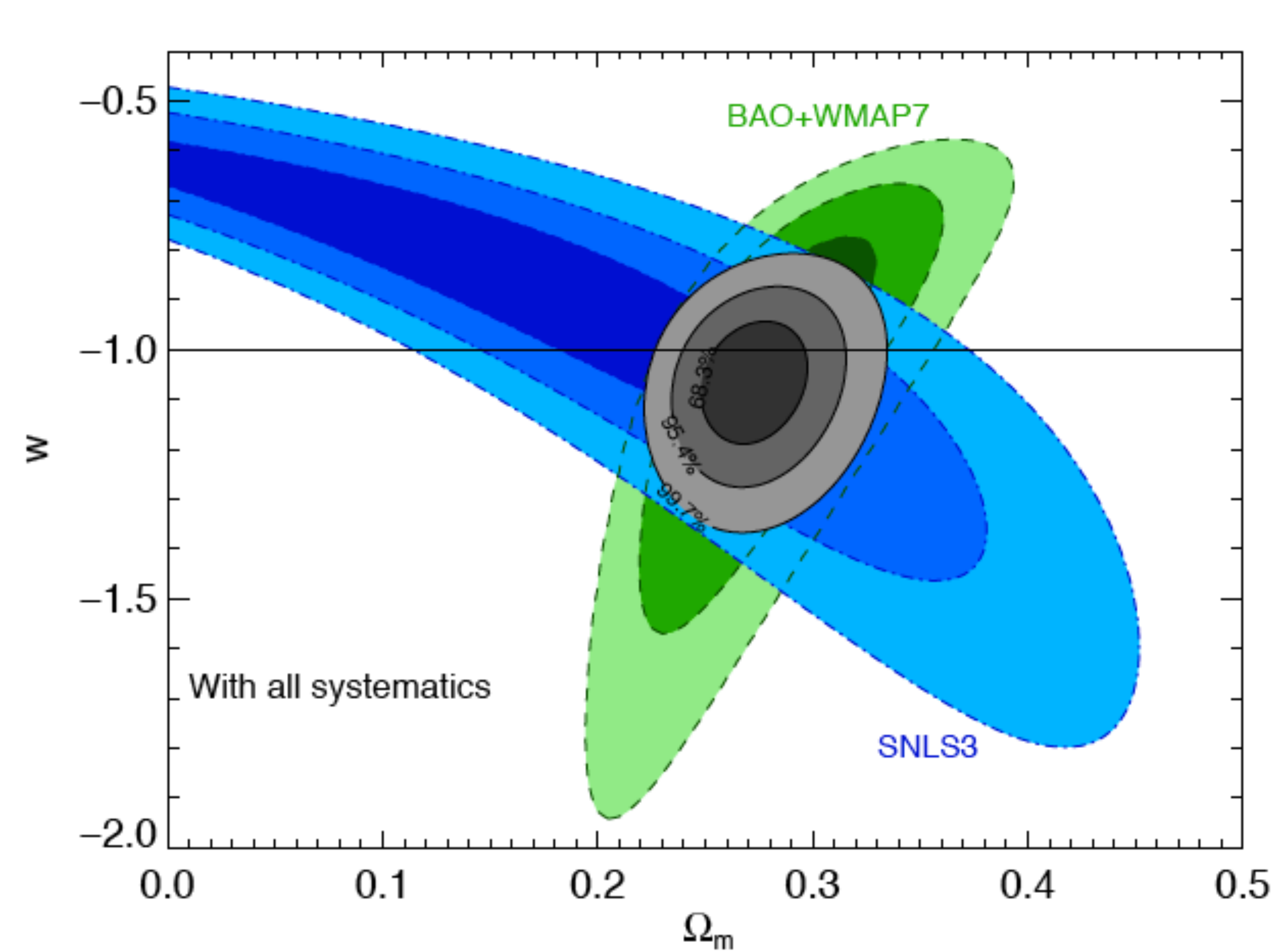


Blake et al 2011

Where we Stand now - BAOs

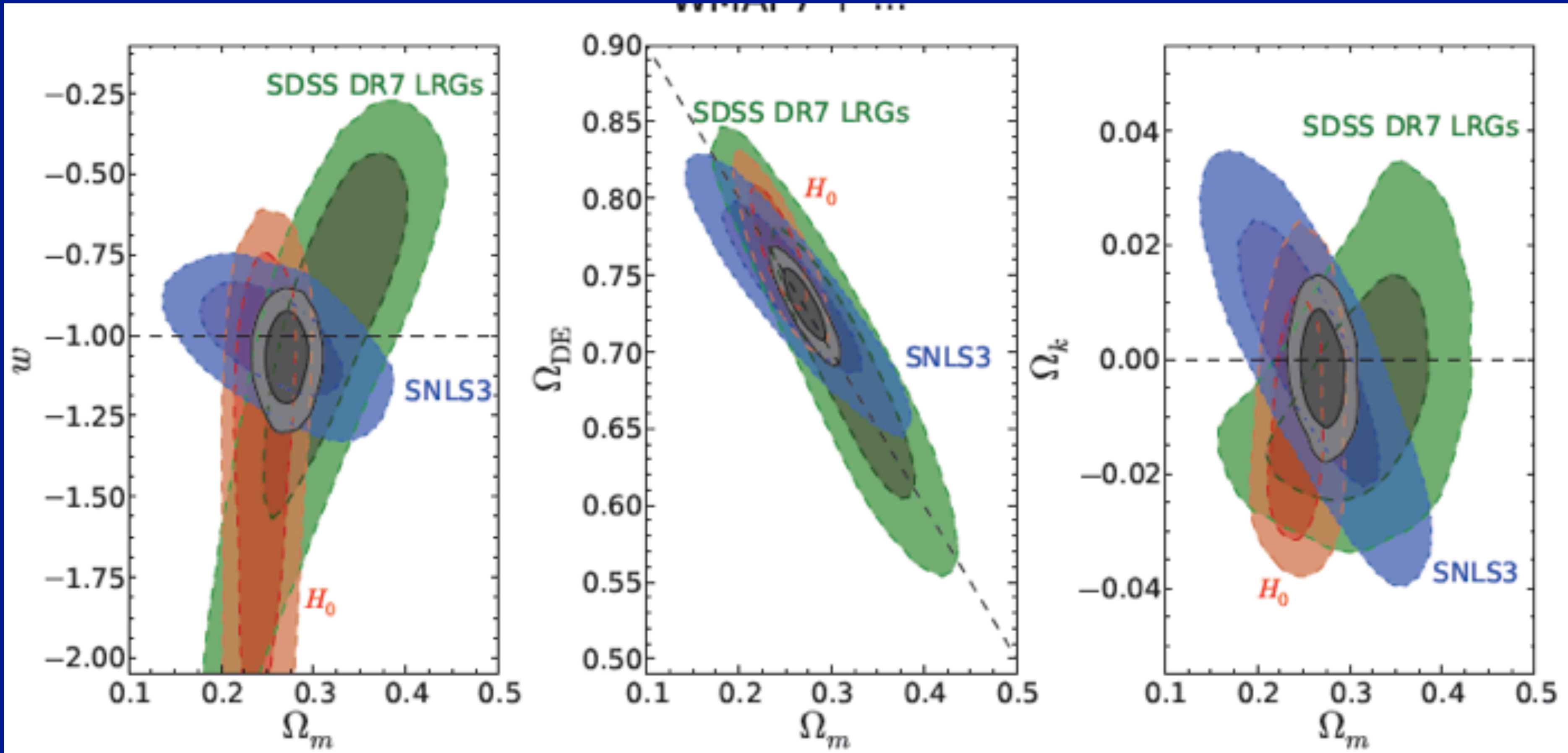
Blake et al 2011





Sullivan et al 11

WMAP7 + ...



w $,\Omega_w$, Ω_M, Ω_K

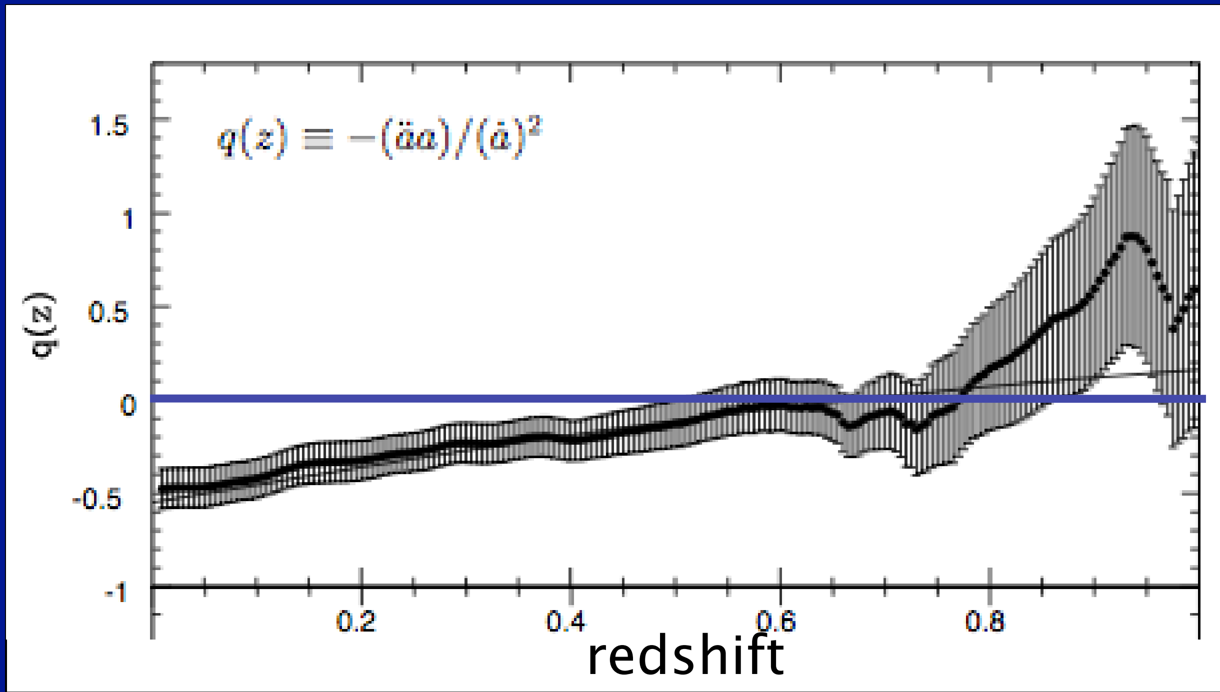
all constrained simultaneously

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.

I feel 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.

I feel 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 perturb 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?

So What is the Dark Energy?

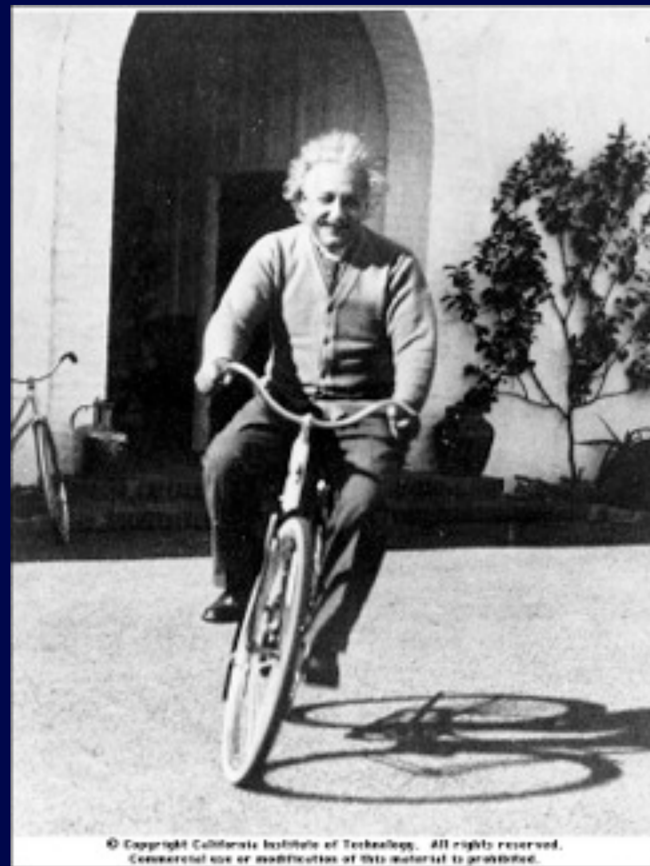
So What is the Dark Energy?

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

So What is the Dark Energy?

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

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

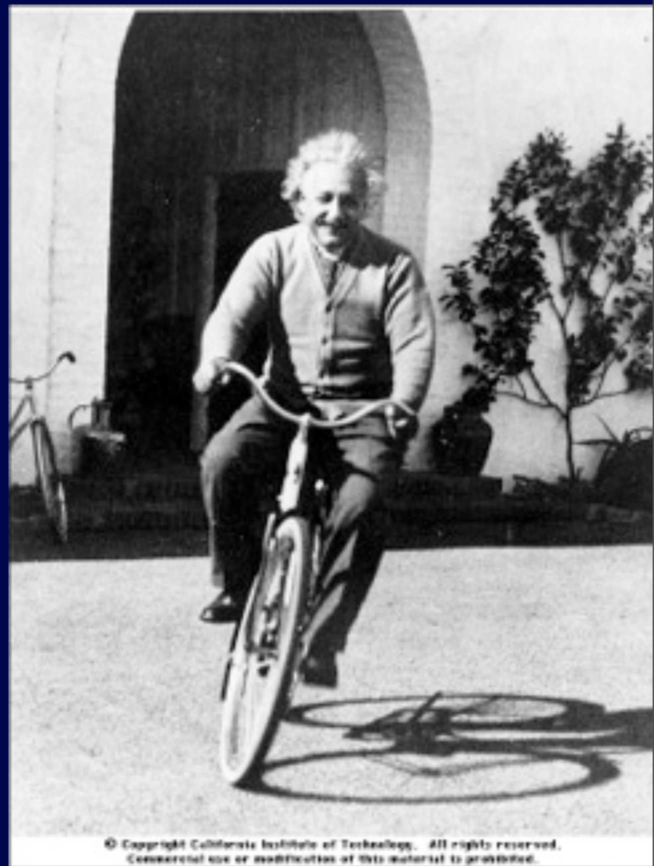


So What is the Dark Energy?

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

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.



So What is the Dark Energy?

So What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what is postulated to have caused inflation.

So What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what is postulated to have caused inflation.

In this case the equation of state of the fluid would likely not be constant, but would vary with time.

So What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what is postulated to have caused inflation.

In this case the equation of state of the fluid would likely not be constant, but would vary with time.

Different theories of dynamical dark energy are distinguished through their differing predictions for the evolution of the equation of state.

So What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what is postulated to have caused inflation.

In this case the equation of state of the fluid would likely not be constant, but would vary with time.

Different theories of dynamical dark energy are distinguished through their differing predictions for the evolution of the equation of state.

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

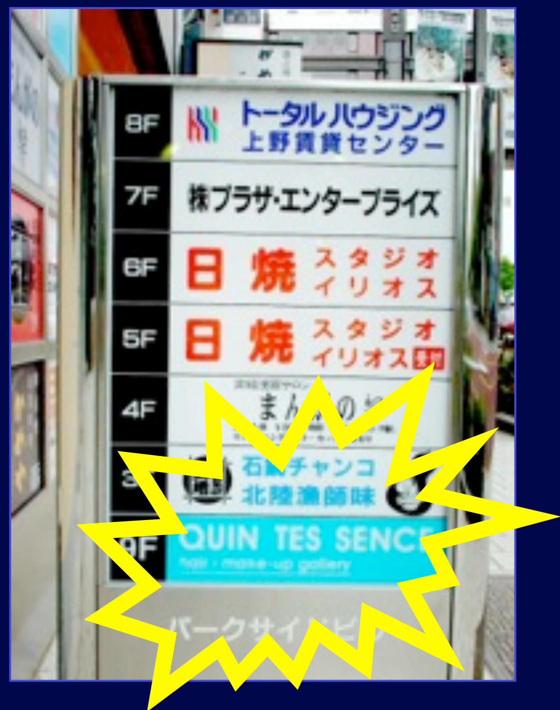
So What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what is postulated to have caused inflation.

In this case the equation of state of the fluid would likely not be constant, but would vary with time.

Different theories of dynamical dark energy are distinguished through their differing predictions for the evolution of the equation of state.

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



So What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what is postulated to have caused inflation.

In this case the equation of state of the fluid would likely not be constant, but would vary with time.

Different theories of dynamical dark energy are distinguished through their differing predictions for the evolution of the equation of state.

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

So What is the Dark Energy?

Another possibility is that the dark energy is some kind of dynamical fluid, not previously known to physics, but similar to what is postulated to have caused inflation.

In this case the equation of state of the fluid would likely not be constant, but would vary with time.

Different theories of dynamical dark energy are distinguished through their differing predictions for the evolution of the equation of state.

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

So What is the Dark Energy?

An alternative explanation of the accelerating expansion of the Universe is that general relativity or the standard cosmological model is incorrect.

General Relativity is well measured in the strong-field regime through pulsars, but also in various Solar system and Earth-based experiments. These leave a little wiggle-room for modifications of GR.

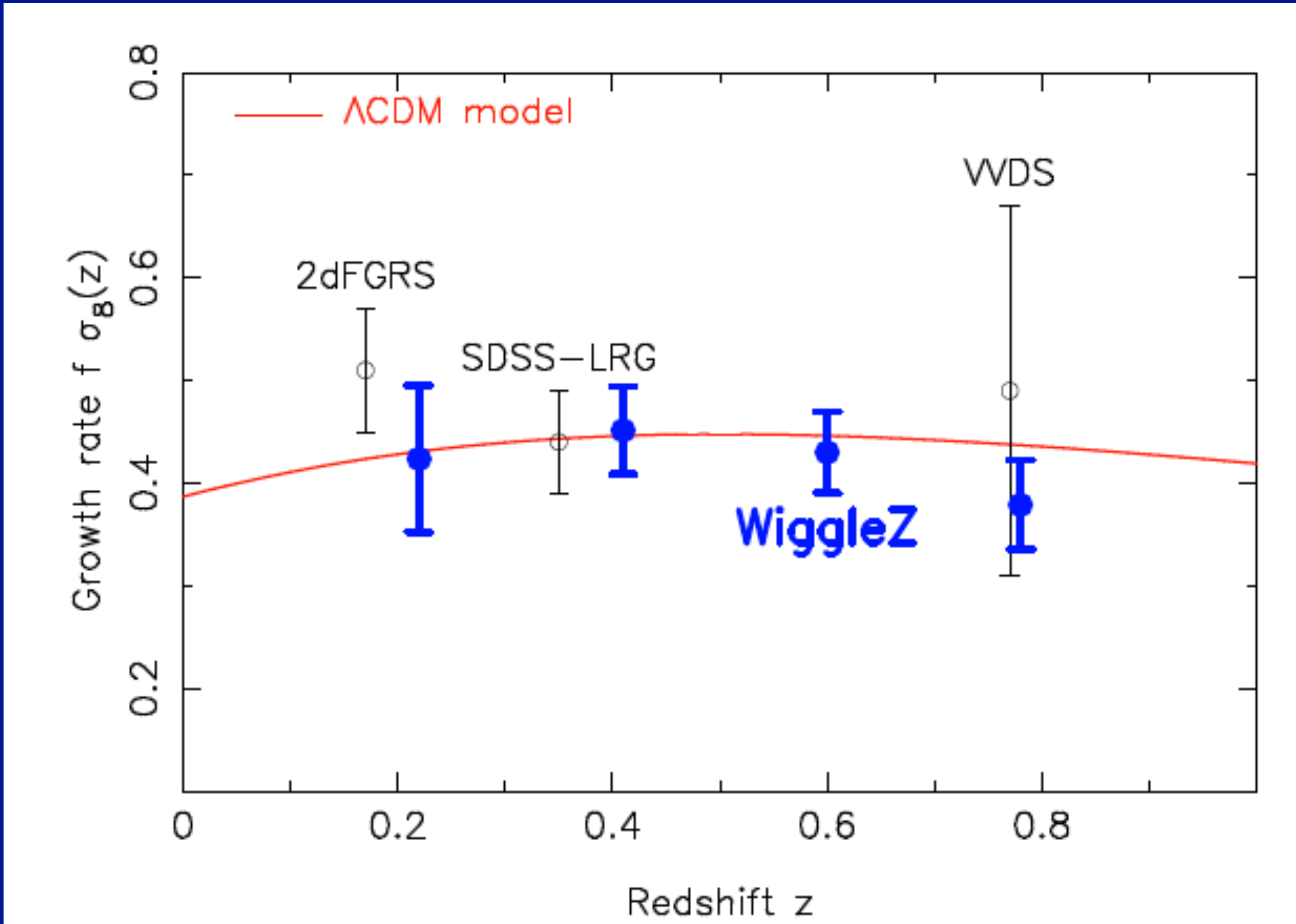
So What is the Dark Energy?

An alternative explanation of the accelerating expansion of the Universe is that general relativity or the standard cosmological model is incorrect.

General Relativity is well measured in the strong-field regime through pulsars, but also in various Solar system and Earth-based experiments. These leave a little wiggle-room for modifications of GR.

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

Dark Energy looks a lot like Λ

Dark Energy looks a lot like Λ

- In total, as near as we can tell the Universe is expanding just as a Cosmological Constant would predict.

Dark Energy looks a lot like Λ

- In total, as near as we can tell the Universe is expanding just as a Cosmological Constant would predict.
- Observers are searching blindly, hoping to find something that distinguishes it from Λ.

Dark Energy looks a lot like Λ

- In total, as near as we can tell the Universe is expanding just as a Cosmological Constant would predict.
- Observers are searching blindly, hoping to find something that distinguishes it from Λ.

Dark Energy looks a lot like Λ

- In total, as near as we can tell the Universe is expanding just as a Cosmological Constant would predict.
- Observers are searching blindly, hoping to find something that distinguishes it from Λ.

- Current currency that describes our progress is
  - ★ uncertainty in the measurement of w
  - ★ future progress is to be measured in the $w=w_0+w_1(a)$ plane

Dark Energy looks a lot like Λ

- In total, as near as we can tell the Universe is expanding just as a Cosmological Constant would predict.
- Observers are searching blindly, hoping to find something that distinguishes it from Λ.

- Current currency that describes our progress is
  - ★ uncertainty in the measurement of w
  - ★ future progress is to be measured in the $w=w_0+w_1(a)$ plane

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)

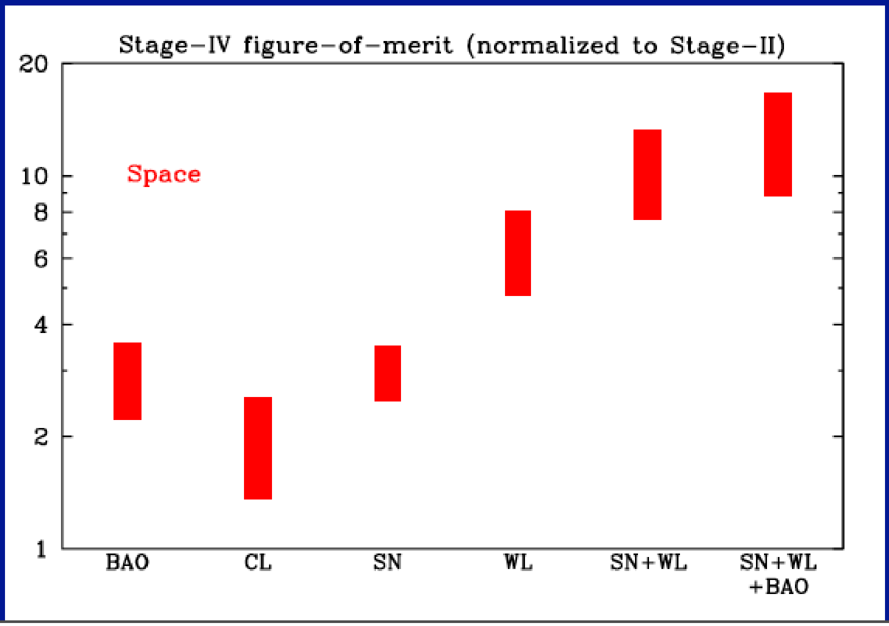
WMAP/Planck Detection of Polarization B-modes could confirm/revolutionise basic Inflation-CDM picture

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

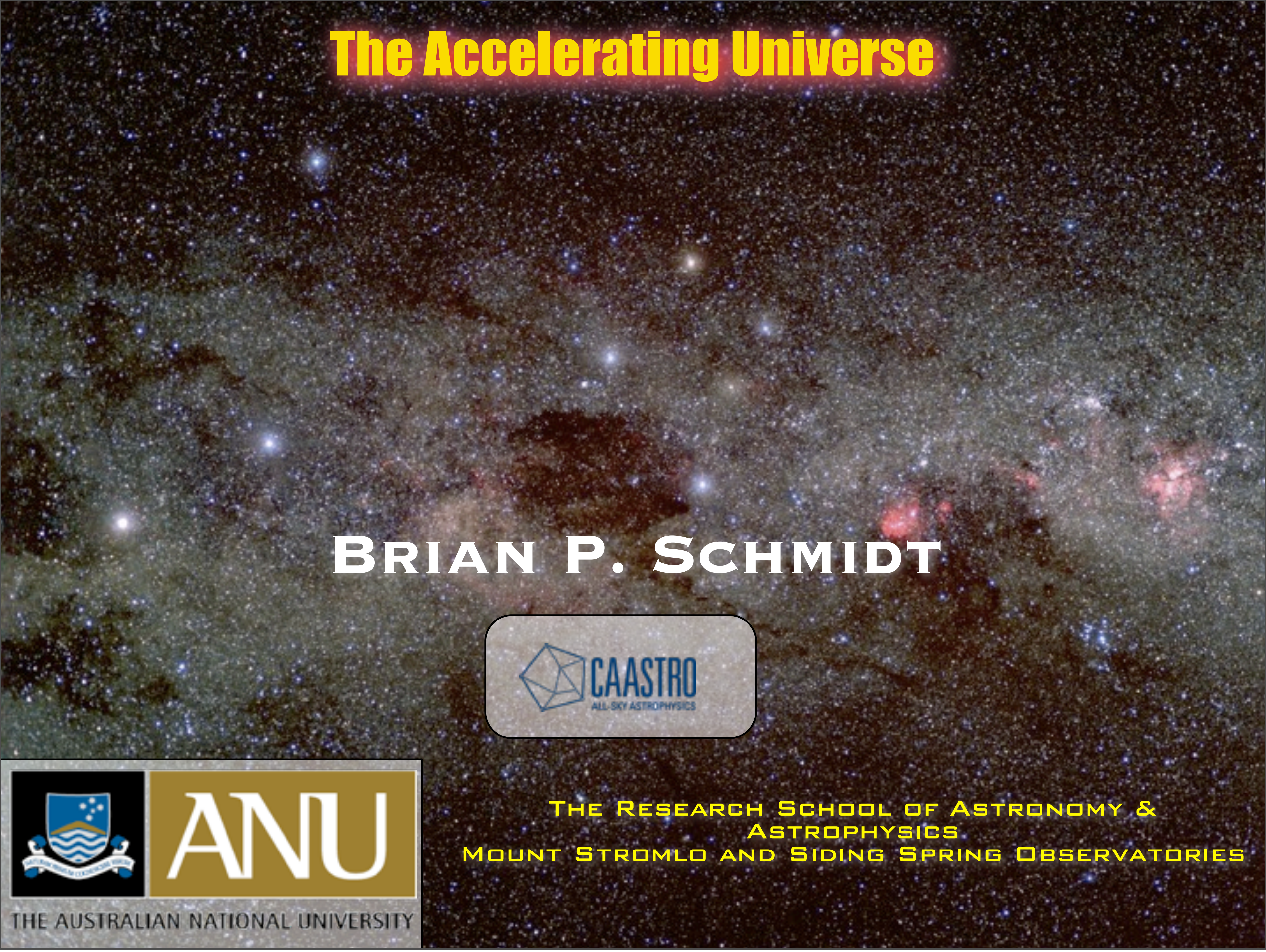
Dark Energy Futures
The Unexpected

- 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

Dark Energy Futures
The Unexpected

- 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

This is my Best Bet for Understanding Dark Energy



Friday, 27 January 12