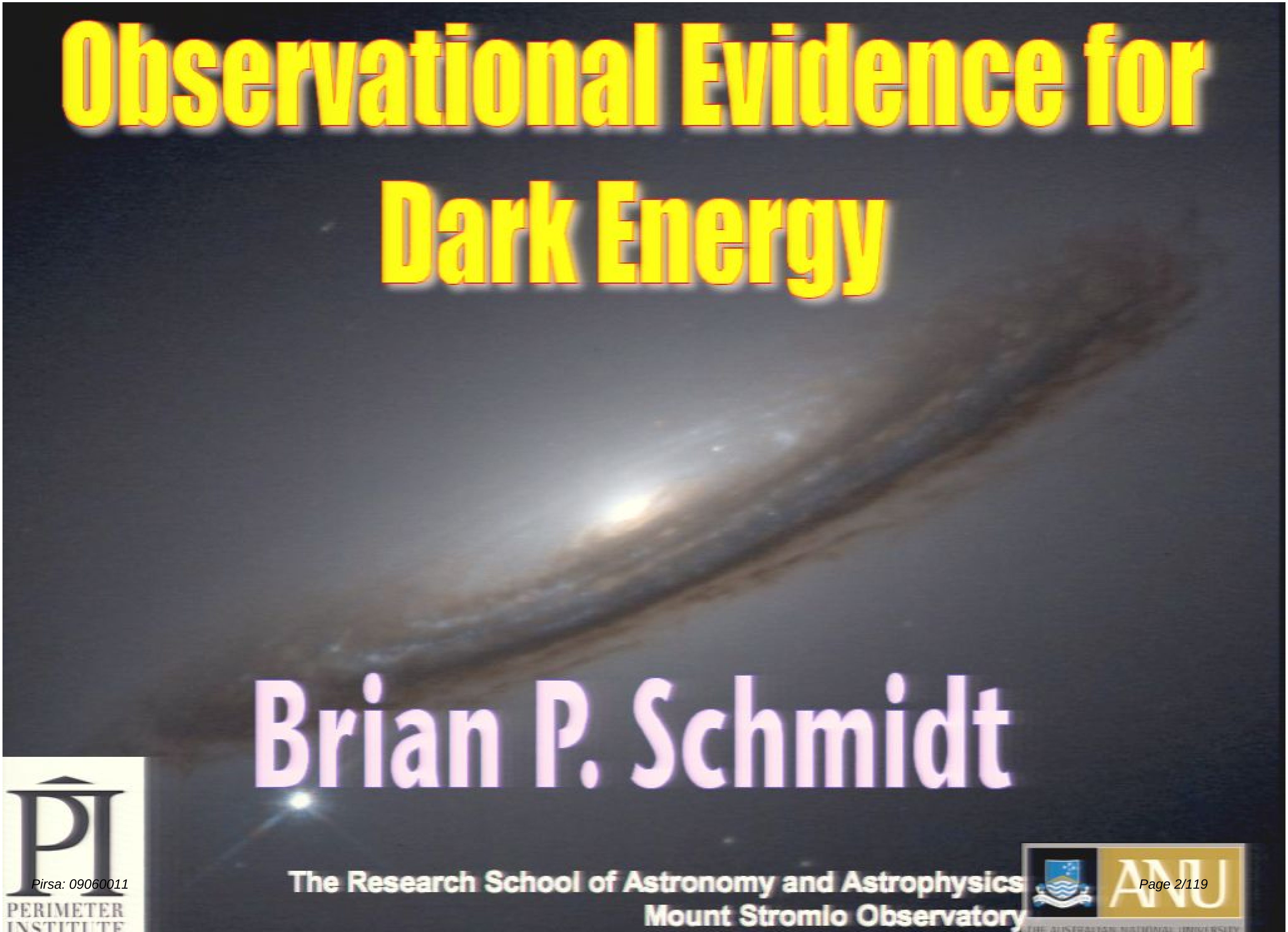
Title: Observational Evidence for Dark Energy

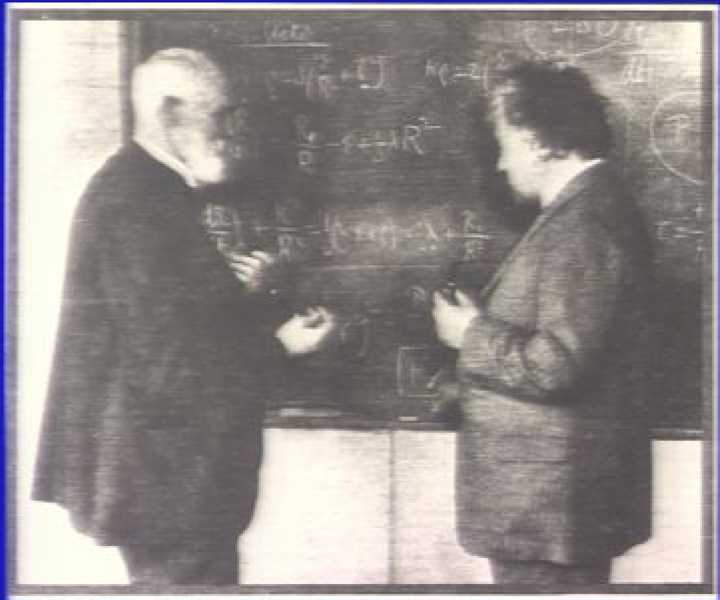
Date: Jun 02, 2009 04:00 PM

URL: http://pirsa.org/09060011

Abstract: Since Einstein first applied his equations of General Relativity to Cosmology, Dark Energy has had a major role in physicists’ efforts to explain the observations of our Universe. Many red herrings have been followed over the past 90 years, where Dark Energy has gone in and out of fashion. However, starting in the 1990s, a broadly supported and sustained view has emerged that the Universe is dominated by Dark Energy – a form of matter with negative pressure. I will give a brief overview of the history of Dark Energy, describe the range of observations that have lead to the adoption of Dark Energy in the standard model of Cosmology, and look to future observations that will refine our understanding of Dark Energy.


Observational Evidence for
Dark Energy
Brian P. Schmidt
The Research School of Astronomy and Astrophysics
Mount Stromlo Observatory
PERIMETER
ANU

The Birth of Modern Cosmological Theory



- 1915 General Relativity Published by Einstein and Hilbert
- 1916 first Cosmological Model published by de Sitter (empty Universe)
- 1917 Einstein's "static" Cosmological Constant Universe, de Sitter's Λ Universe.
- 1922 Friedmann's solutions for homogenous and

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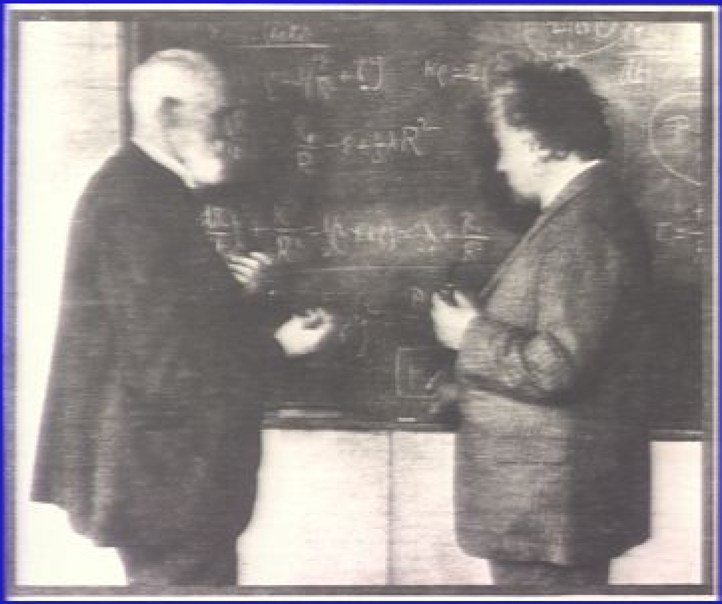

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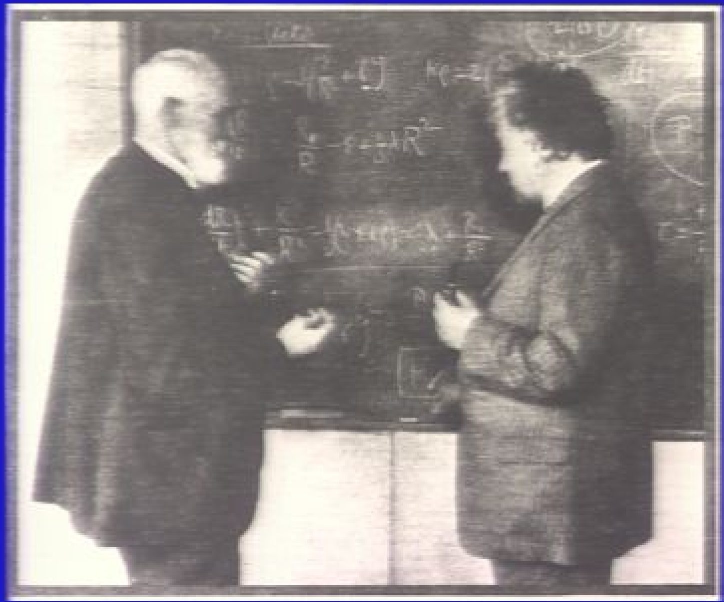

Birth of Observational Cosmology

- 1916 Slipher finds redshift of galaxies
- 1923 Hubble definitively shows galaxies are beyond the Milky Way
- 1927 Lemaitre's "homogeneous Universe of constant mass and growing radius accounting for the radial velocity of extragalactic nebulae"
  - Independently derived Friedmann Equations
  - Suggested Universe was expanding
  - Showed it was confirmed by Hubble's data.

  Mathematics accepted by Einstein, but basic idea rejected by Einstein as fanciful
- 1929 Hubble's Expanding Universe
  - Lemaitre invoking Λ to make Universe older than the Solar System

By the 1930s the basic Paradigm for Understanding The Universe was in place

- Theory of Gravity
  - General Relativity
- Assumption
  - Universe is homogenous and isotropic

The Standard Model

The Standard Model

Homogenous & Isotropic Universe

The Standard Model

Robertson-Walker line element

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

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a(t) is known as the scale factor-it tracks the size of a piece of the Universe $\frac{a}{a_0} = \frac{1}{(1+z)}$

General Relativity

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Friedmann Equation

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho_{tot}}{3} - \frac{k}{a^2}$$

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

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

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

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

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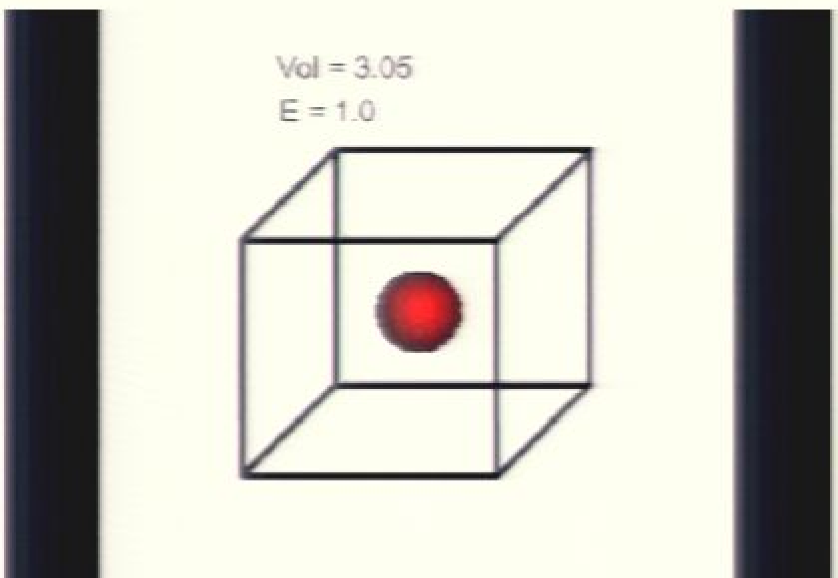

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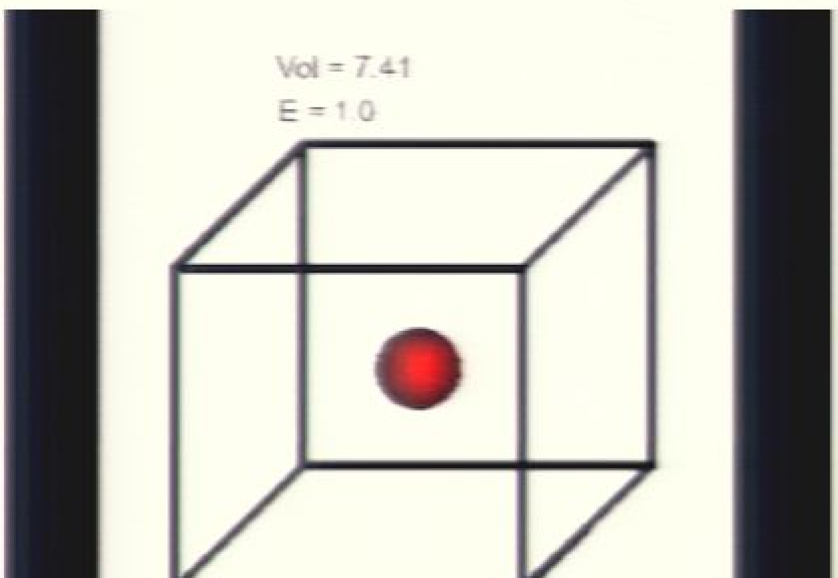

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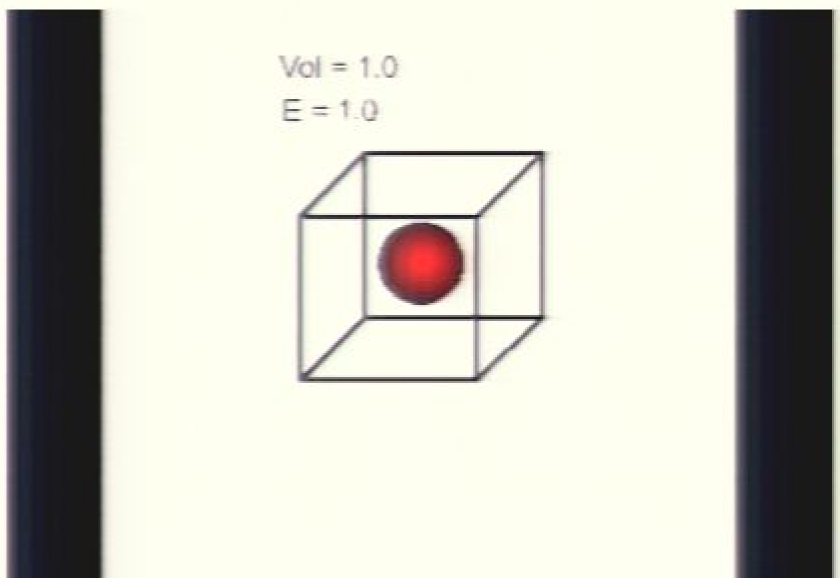

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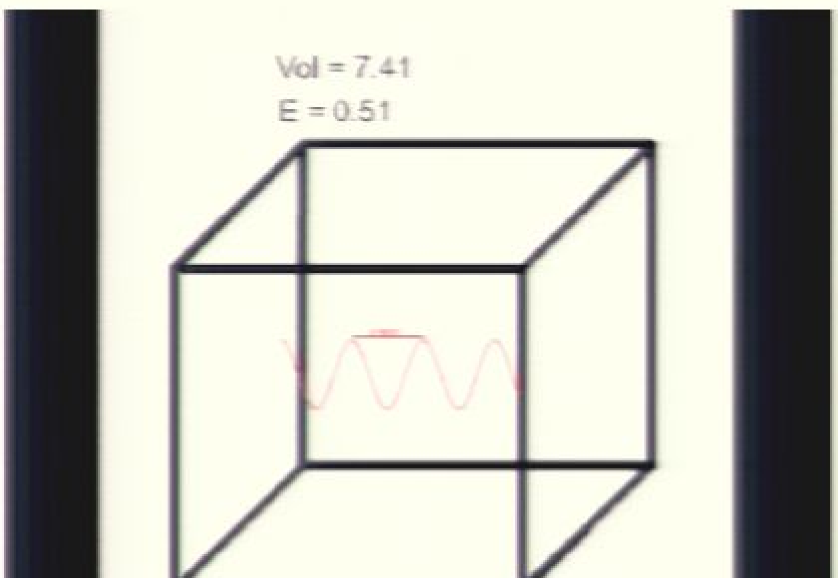

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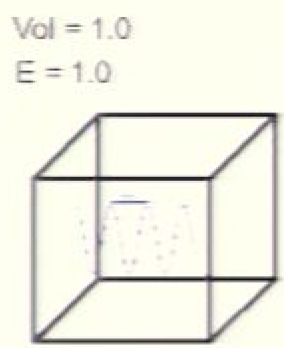

Flat Universe -Matter Dominated

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

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

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

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

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

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

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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

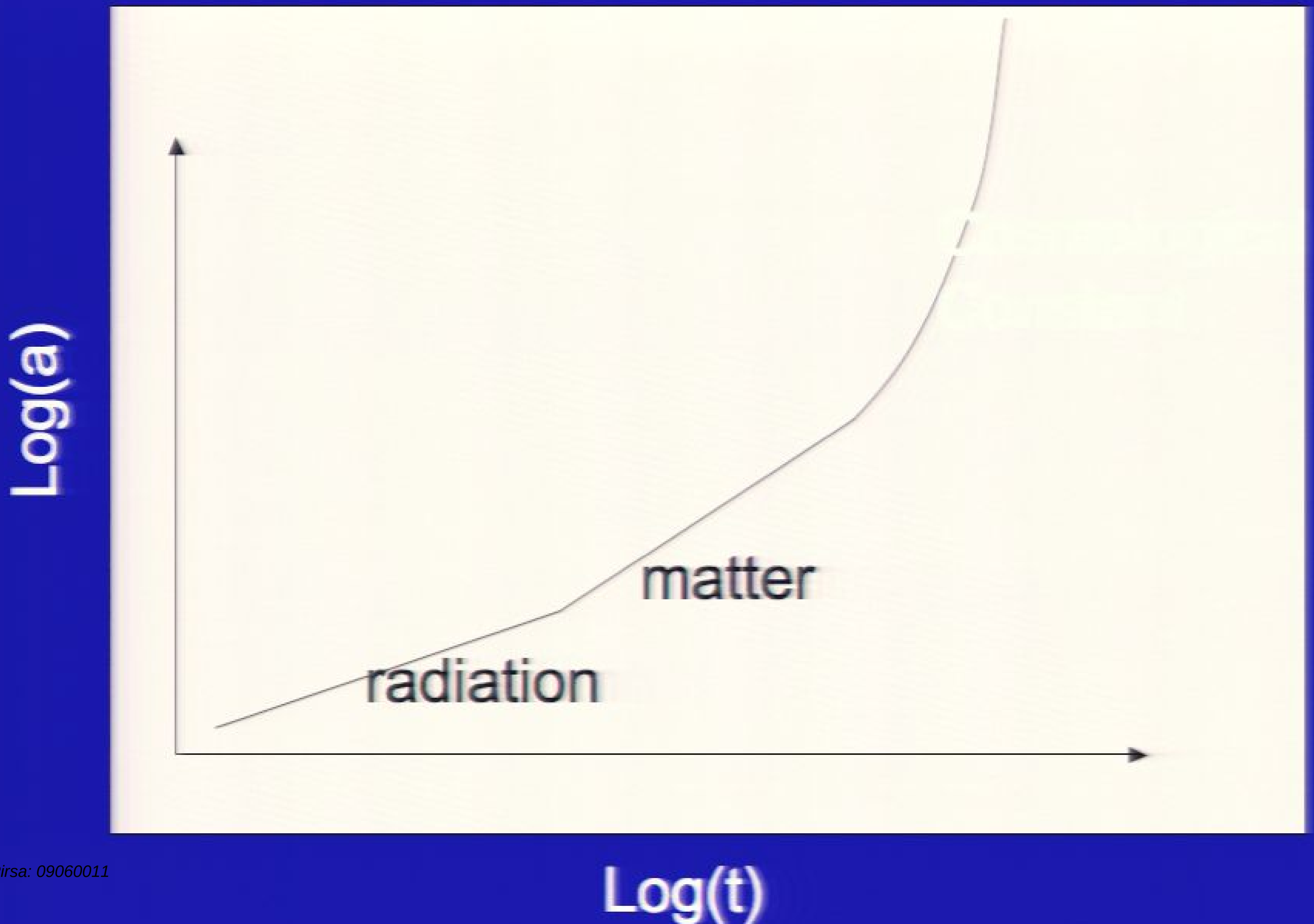
- As Universe Expands
  - Photon density increases as $(1+z)^4$
  - Matter density increases as $(1+z)^3$
  - Cosmological Constant invariant $(1+z)^0$

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

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

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

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


Log(a)
matter
radiation
Log(t)

Classical Observational Tests 1950s-1995

- Distances
  - Luminosity distance (How bright an object appears as a function of redshift)
  - Angular Size Distance (How big an object appears as a function of redshift)
- Age -
  - how old an object is as a function of redshift
- Volume
  - how many objects per unit redshift

Sandage "[Observational Cosmology is the quest for two numbers, H_0 and q_0]"

$$D_L = \sqrt{\frac{L}{4\pi F}}, \quad D_A \equiv \frac{l}{\theta}$$

the flux an observer sees of an object at redshift z

$$D_L = D_A(1+z)^2 = \frac{c}{H_0}(1+z)|\kappa_0|^{-1/2} S\left\{ |\kappa_0|^{1/2} \int_0^z dz' \left[\sum_i \Omega_i (1+z')^{3+3w_i} - \kappa_0 (1+z')^2 \right]^{-1/2} \right\}$$

$$\kappa_0 = \left(\Omega_{tot} = \sum_i \Omega_i \right) - 1$$

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

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

$$D_L = D_A(1+z)^2 = \frac{c}{H_0}\left[z + z^2 \left(\frac{1-q_0}{2} \right) + O(z^3) \right] = \frac{c}{H_0}\frac{1}{q_0^2}\left[q_0 z + (q_0 - 1)(\sqrt{1+2q_0 z} - 1) \right]$$

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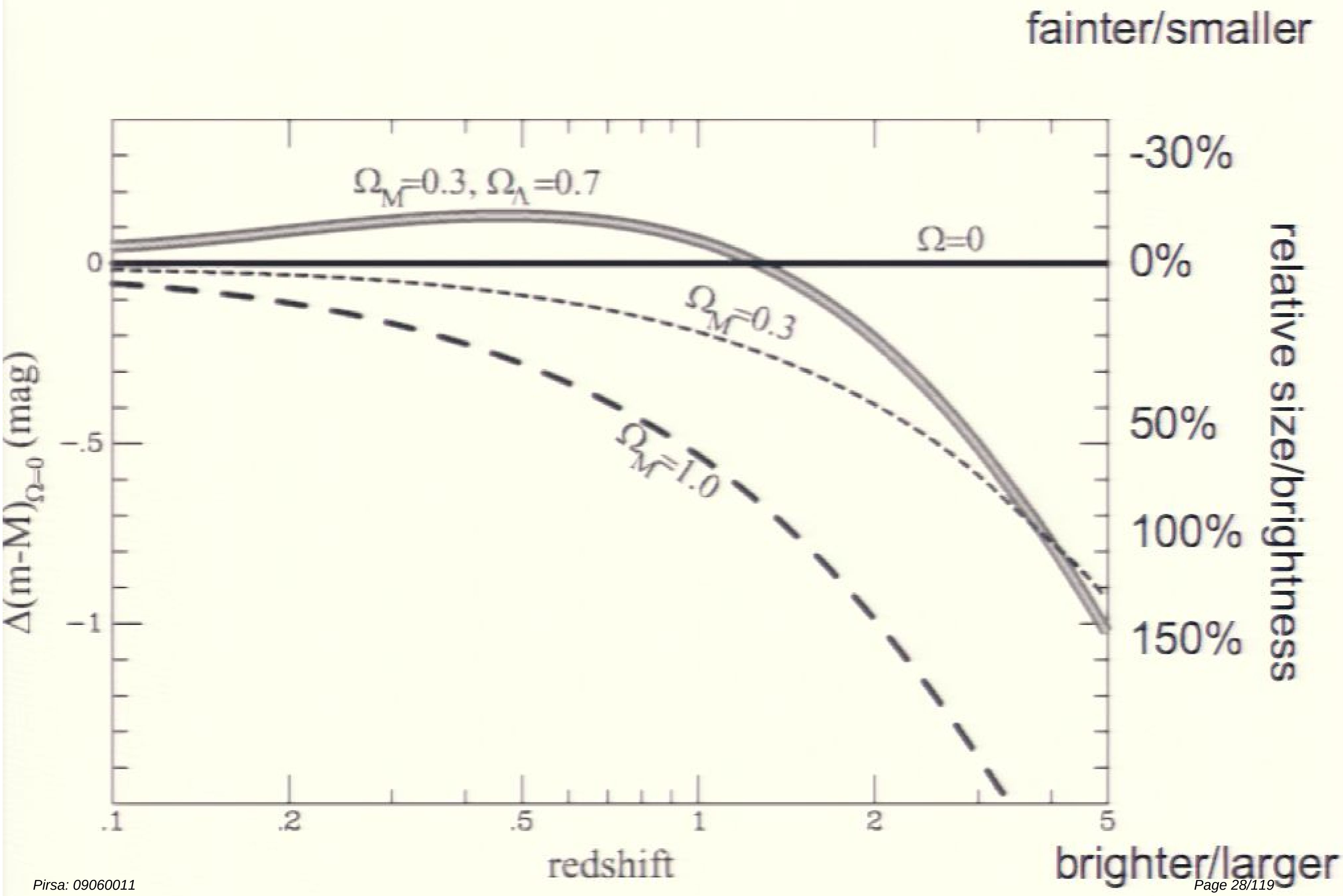
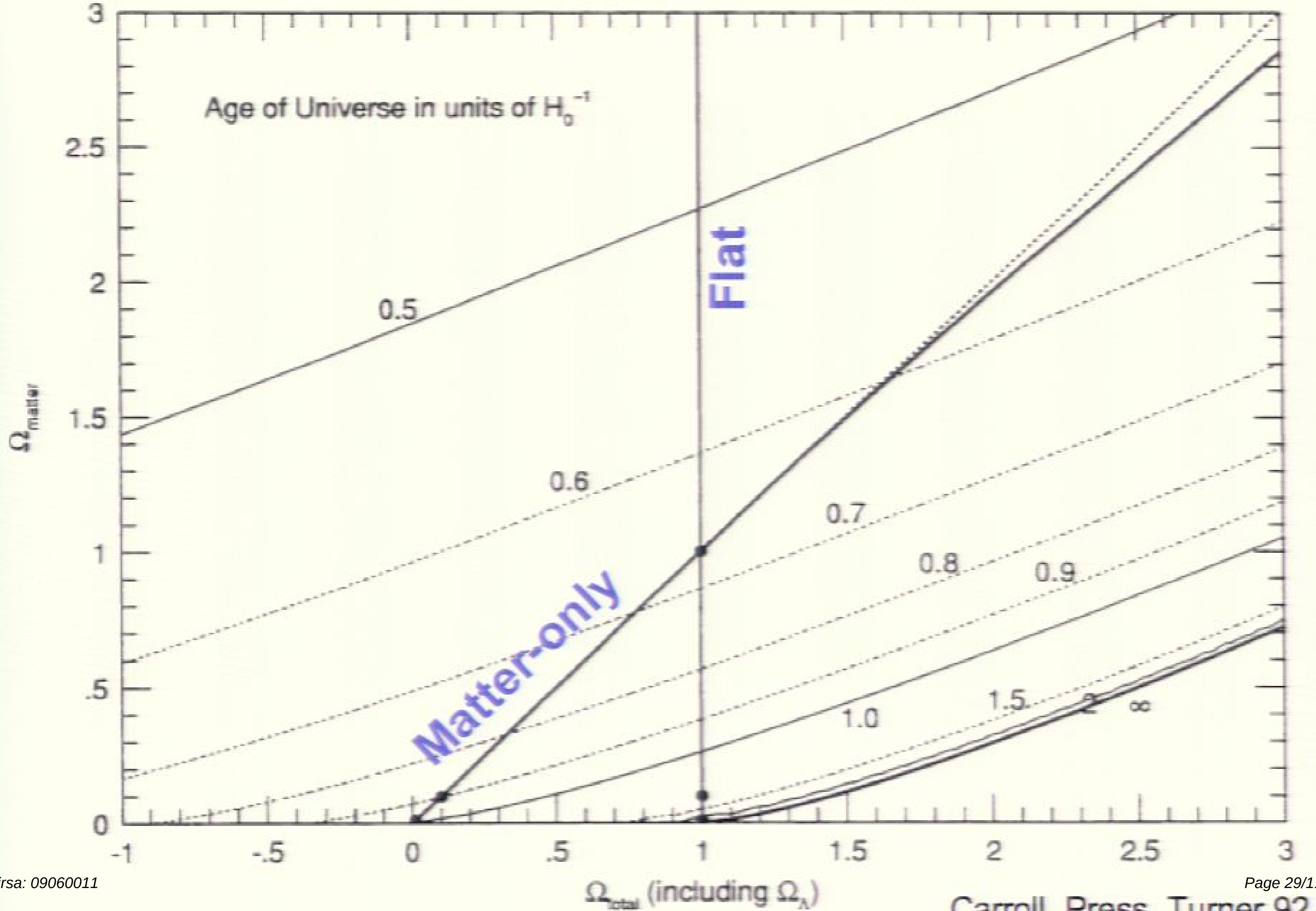
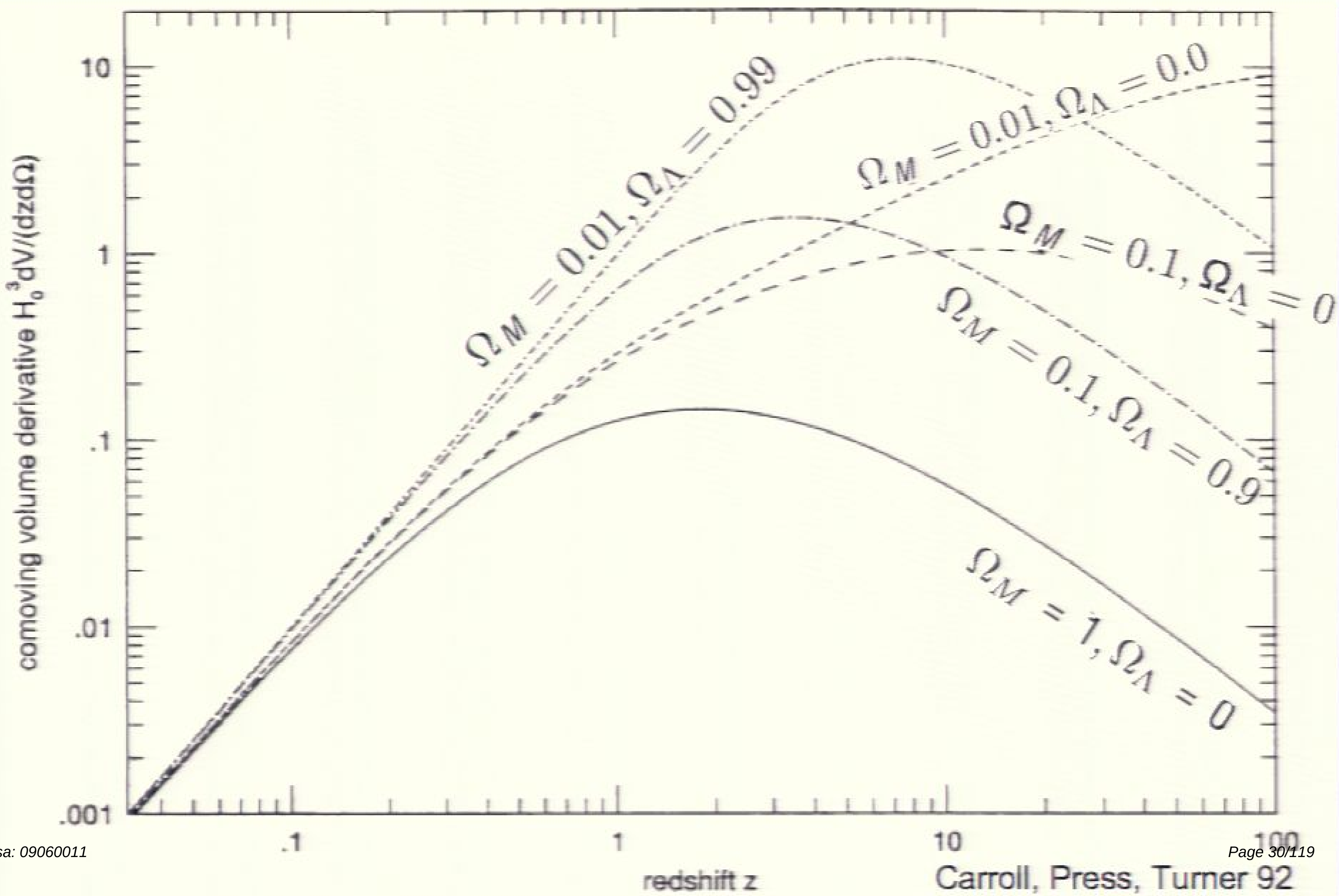

fainter/smaller
Ω_M=0.3, Ω_Λ=0.7
Ω=0
Ω_M=0.3
Ω_M=1.0
-30%
0%
50%
100%
150%
relative size/brightness
$\Delta(m\text{-}M)_{\Omega=0}$ (mag)
0
-.5
-1
.1
.2
.5
1
2
5
redshift
brighter/larger

Age



Carroll, Press, Turner 92

Volume

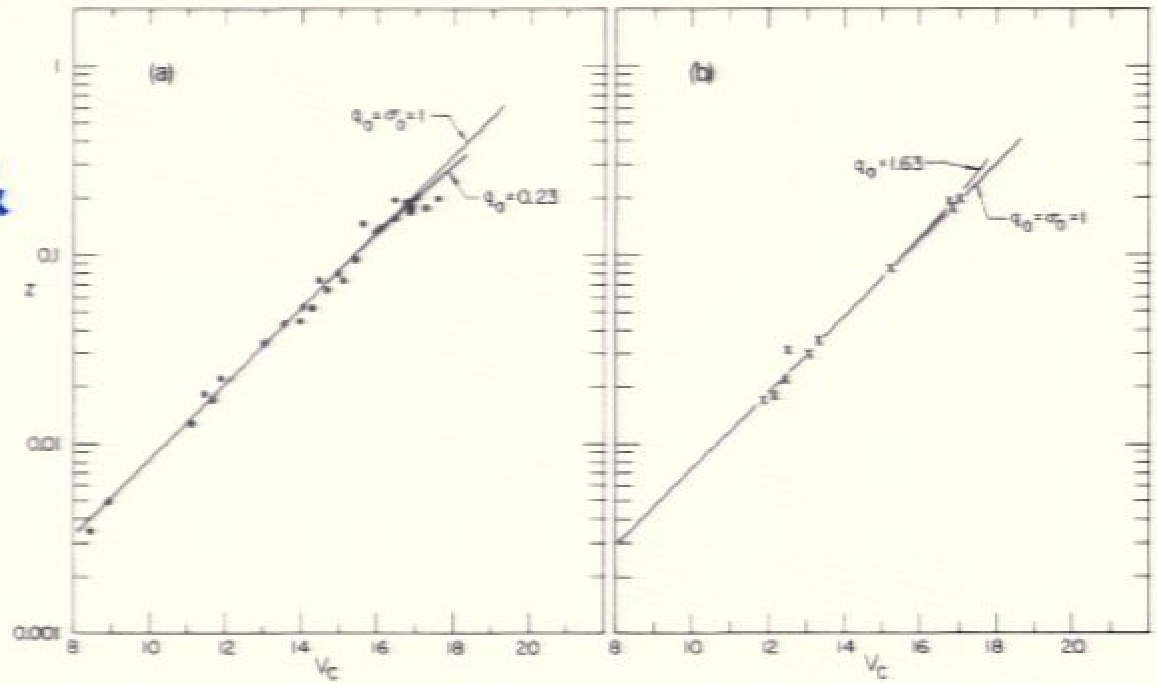


Carroll, Press, Turner 92

Brightest Cluster Galaxies

Sandage, Humason & Mayhall 1956
Baum 1957
Peach 1970

Deceleration $q_0 > 1$



Gunn and Oke 1975
Gunn and Tinsley 1975

An accelerating Universe

James E. Gunn*

Hale Observatories, California Institute of Technology, Carnegie Institution of Washington, Pasadena, California 91125

Beatrice M. Tinsley*†

Lick Observatory, University of California at Santa Cruz, California 95060

But Tinsley 1976 showed Evolution dominates Cosmology

Age Measurements 1950-1990

Hubble Constant Measurements Difficult!

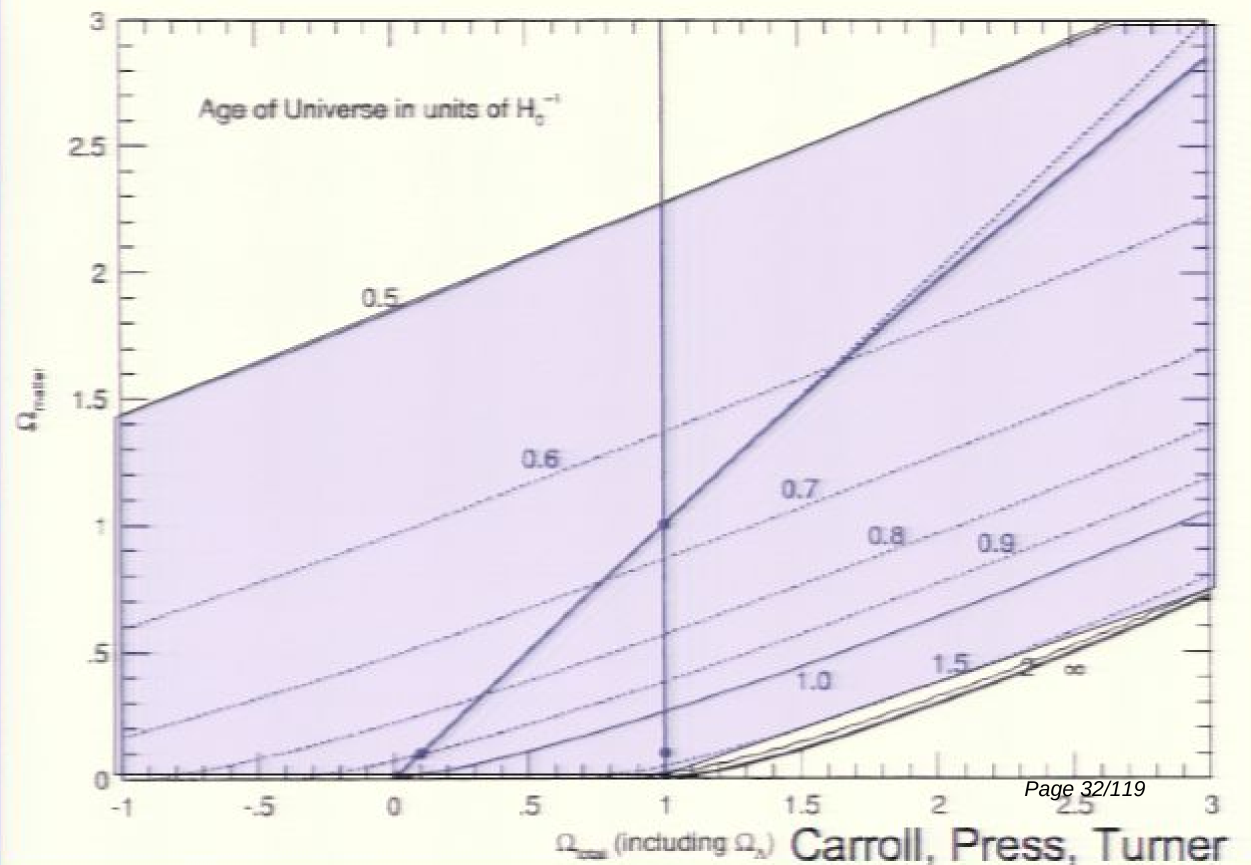
$40 < H_0 < 100$ km/s/Mpc

$24.5 > 1/H_0 > 9.8$ Gyr

Oldest star ages

13-20 Gyr

$0.53 < H_0 t < 2.05$



Carroll, Press, Turner

Excess z~2 QSOs: Loitering Universe

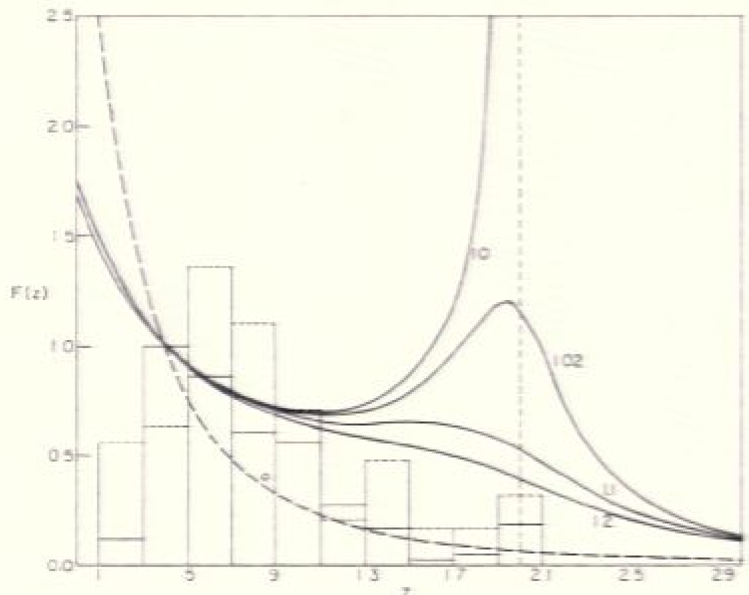
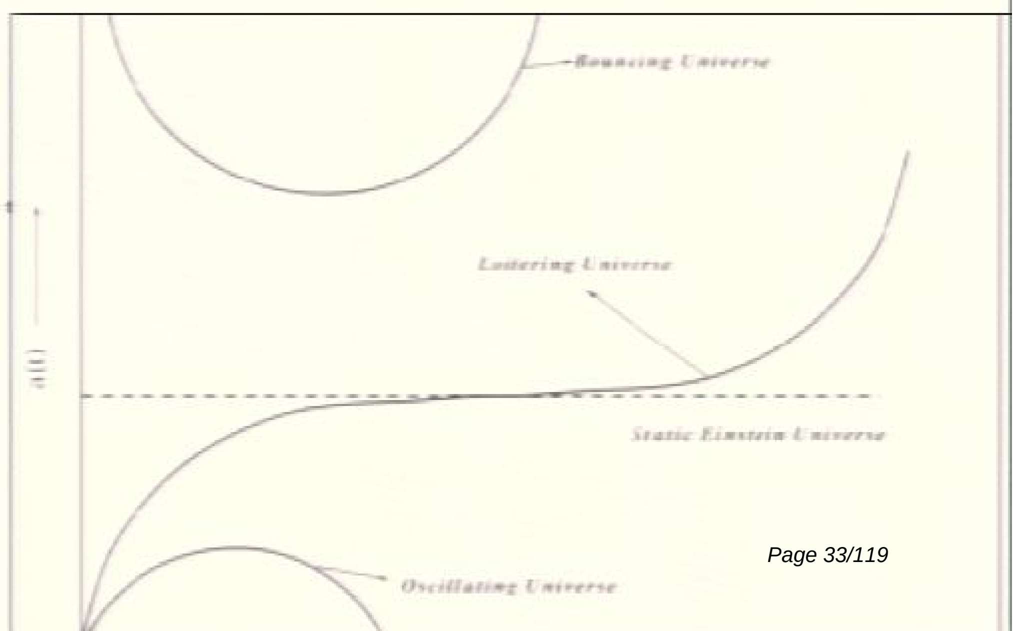


FIG. 2.—The integrated intensity function F plotted against redshift z. Curves are labeled by t value of the cosmological constant x. Solid histogram for optical data, dashed for radio.



Petrosian, V., Saltpeter, E.E. & Szekeres, P. 1967

1970s & 80s
Inflation + Cold Dark Matter addition to Standard Model

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.

Different Ways of Looking at the Universe

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

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

(Theorists)

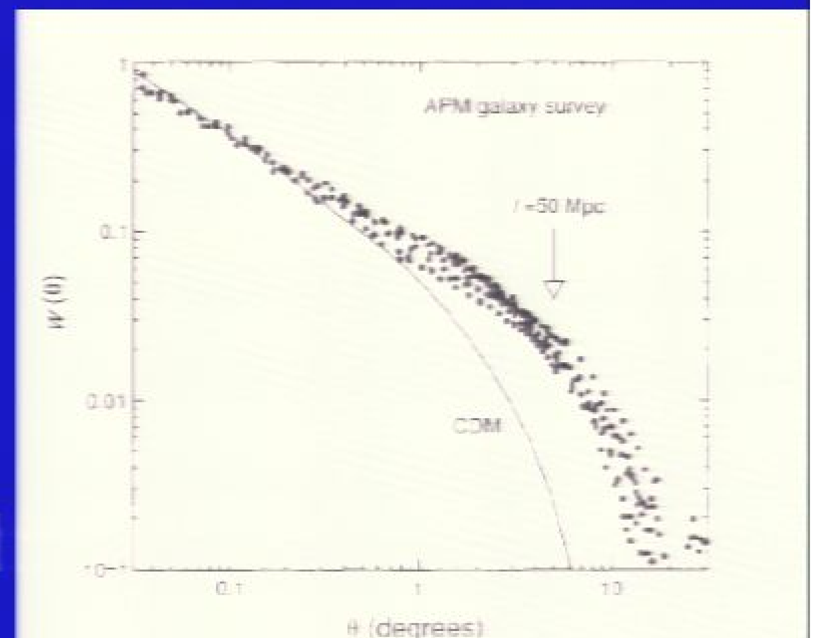
- Inflation+CDM paradigm correct
- $\Omega \sim 1$
- $H_0 <= 50$km/s/Mpc
- Observers are wrong on H_0 and Ω_M

(Observers)

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

1990 - CDM Picture conflicts with what is seen

- Requires flatness, but Ω_M~0.2 from clusters
- Too much power on large scales in observations
- Efstathiou, Sutherland, and Maddox showed that compared to Ω_M=1,
  a Ω_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.

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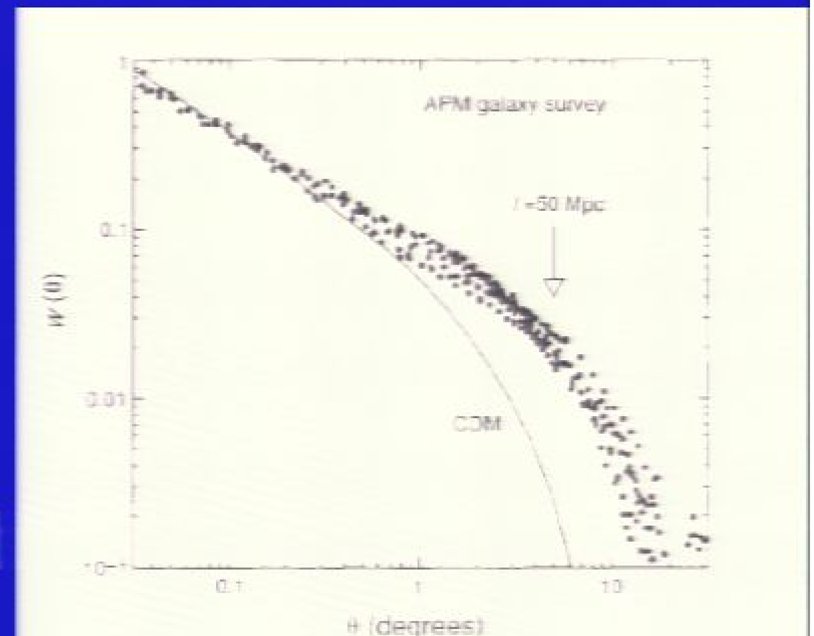

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Title: The Case for a Hubble Constant of 30 km/s/Mpc

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.

Title: The Cosmological Constant is Back

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

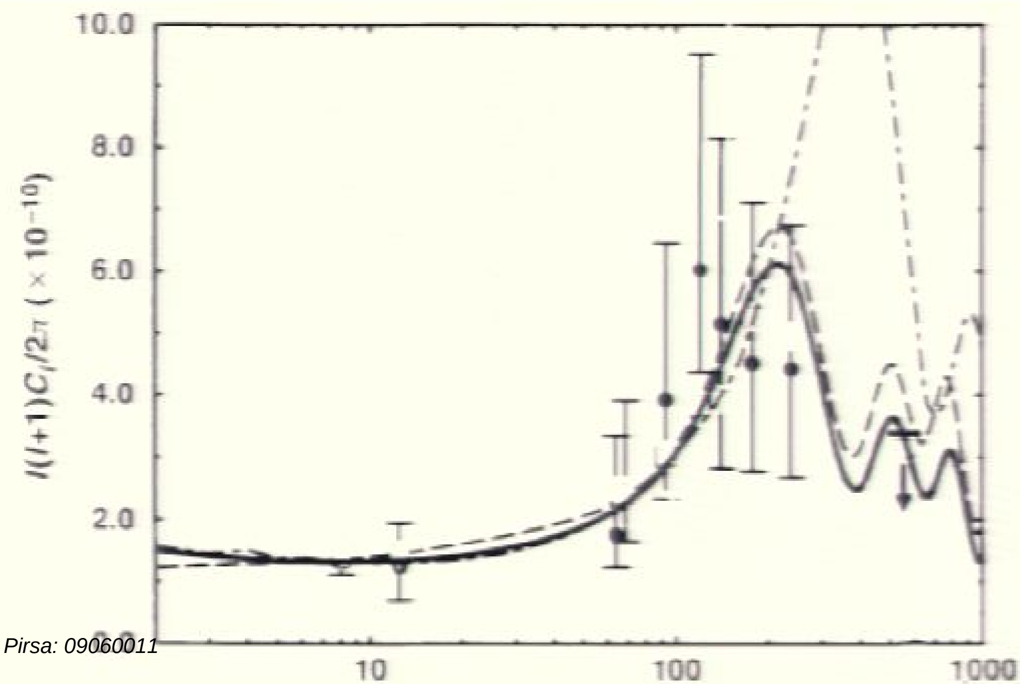
Abstract: A diverse set of observations now compellingly suggest that Universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological constant corresponds to the energy density of the vacuum, and the wanted value for the cosmological constant corresponds to a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

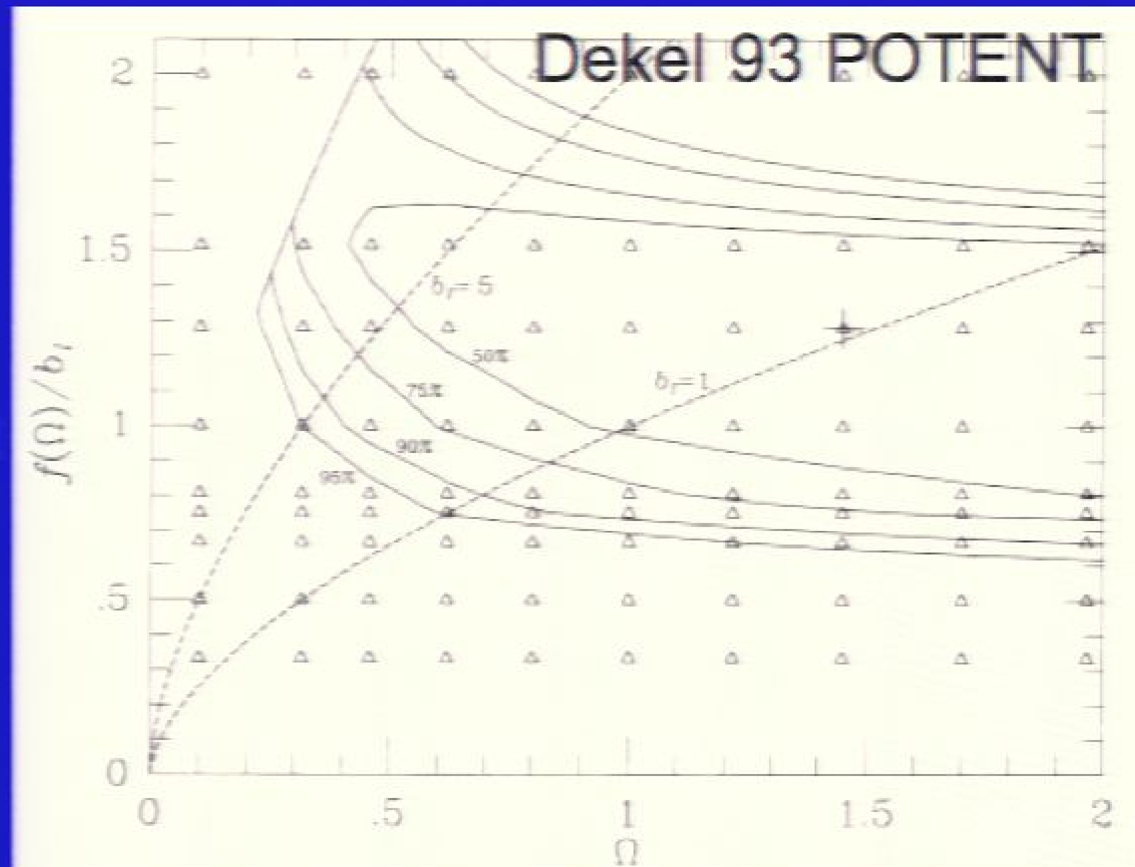
NATURE · VOL 377 · 19 OCTOBER 1995



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_x, η, AND α DISTRIBUTIONS

Parameter	*Einstein*	Ω=1	Ω_o=0.2 & λ_o=0.8	Ω_o=0.2
w_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)	[illegible]5 (0.02)
α	1.75 (0.32)	1.82 (0.36)	2.68 (0.27)	2.88 (0.36)

Angular Size Distance with Compact Radio Sources

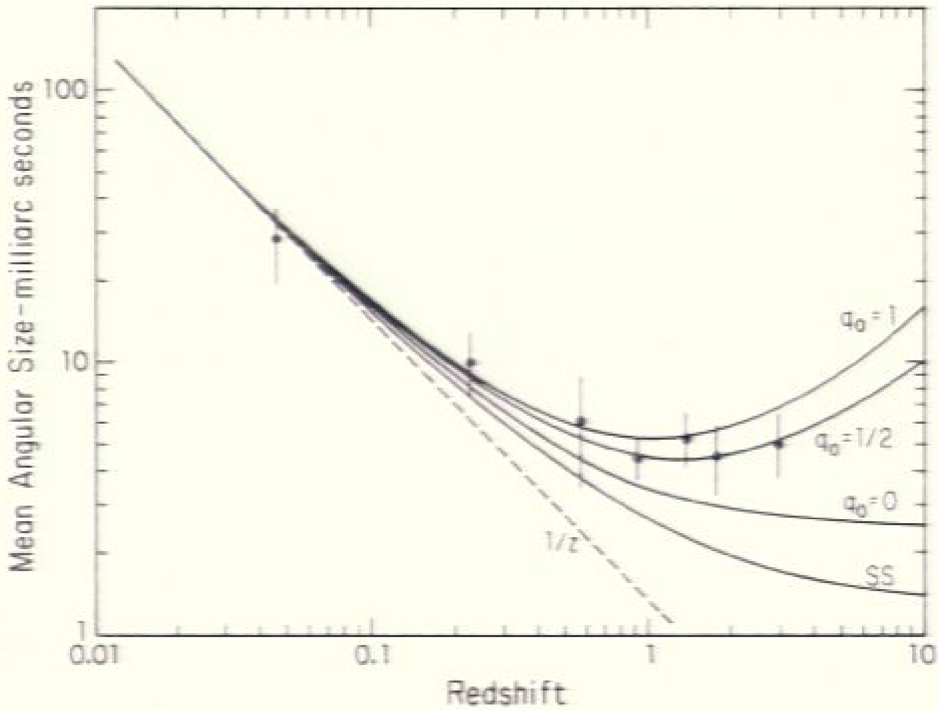


Fig. 1. Mean angular size vs. redshift for 82 compact sources. From left to right each point is based on 8, 4, 11, 13, 20, 13, and 10 sources respectively. The solid curves represent the expected dependence for Friedmann world models with various values of the deceleration parameter q_0 and the Steady State model. The dashed line represents the linear 1/z law found for the separation of double lobed extended sources.

Kellerman (1993)

Stepanas & Saha (1995) showed not that constraining

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 $K(2.2\ \mu m)$-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.

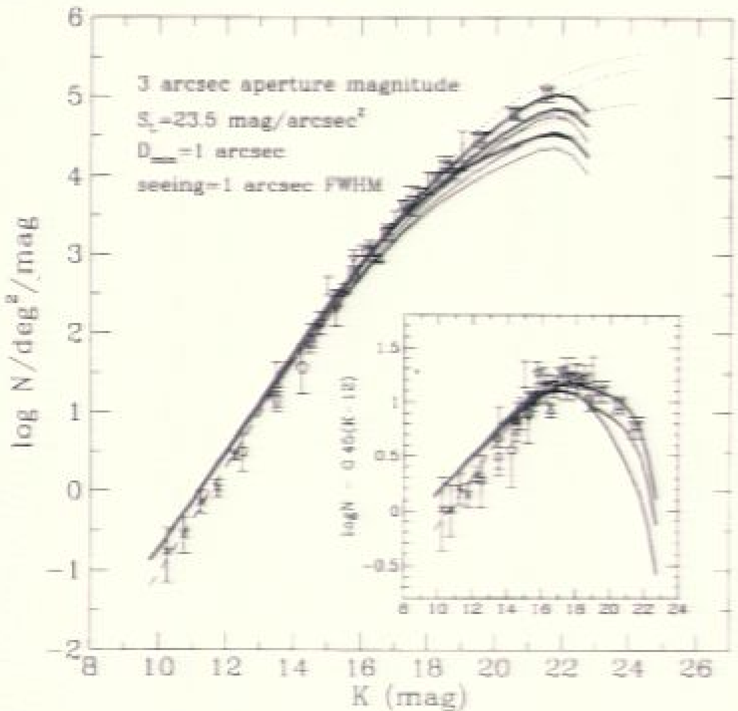


FIG. 2a

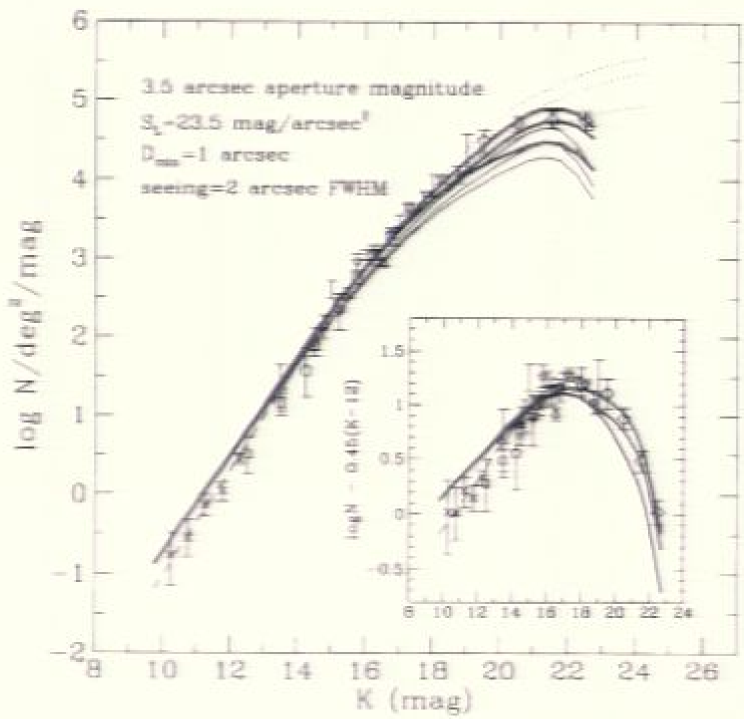
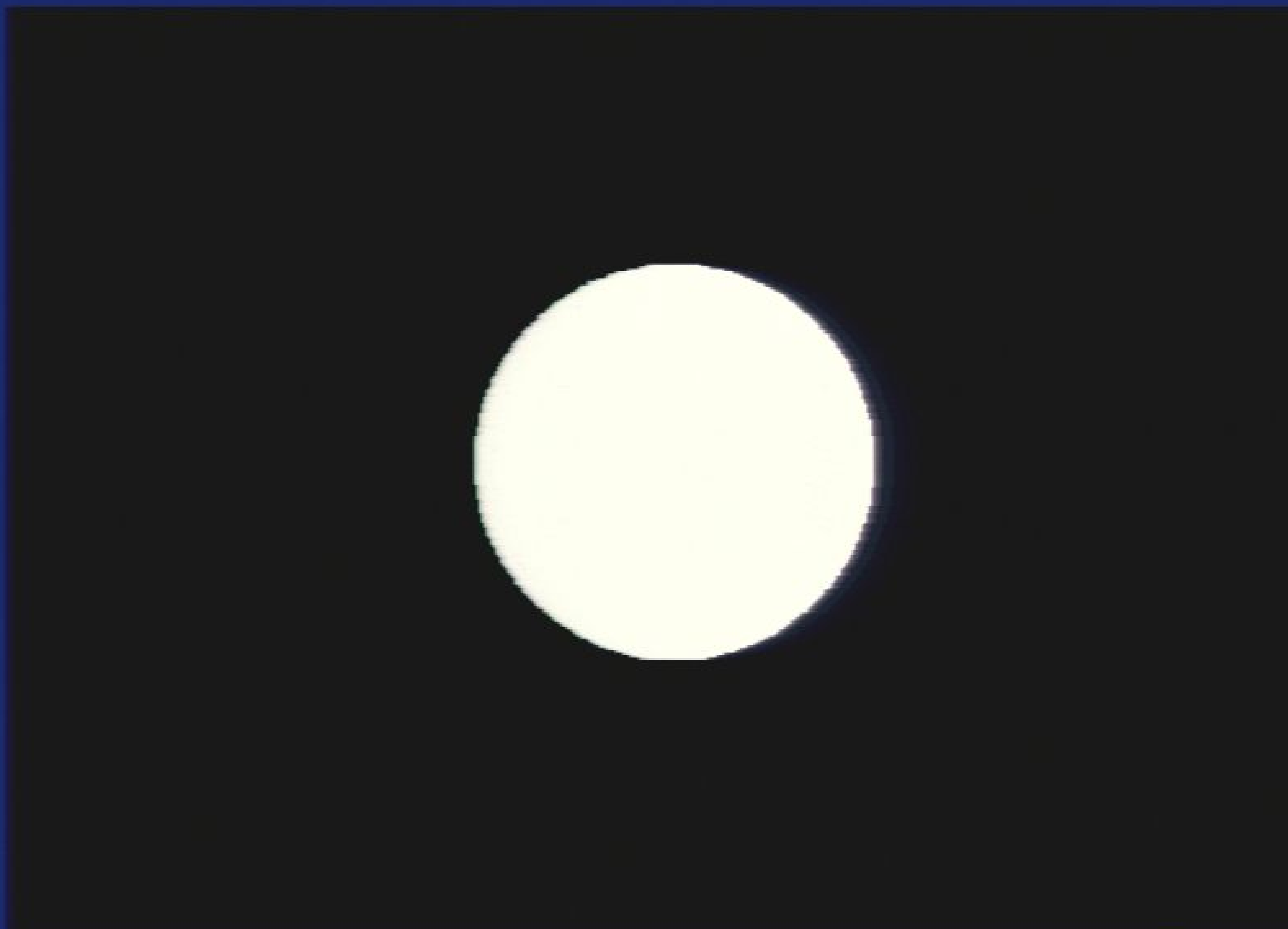
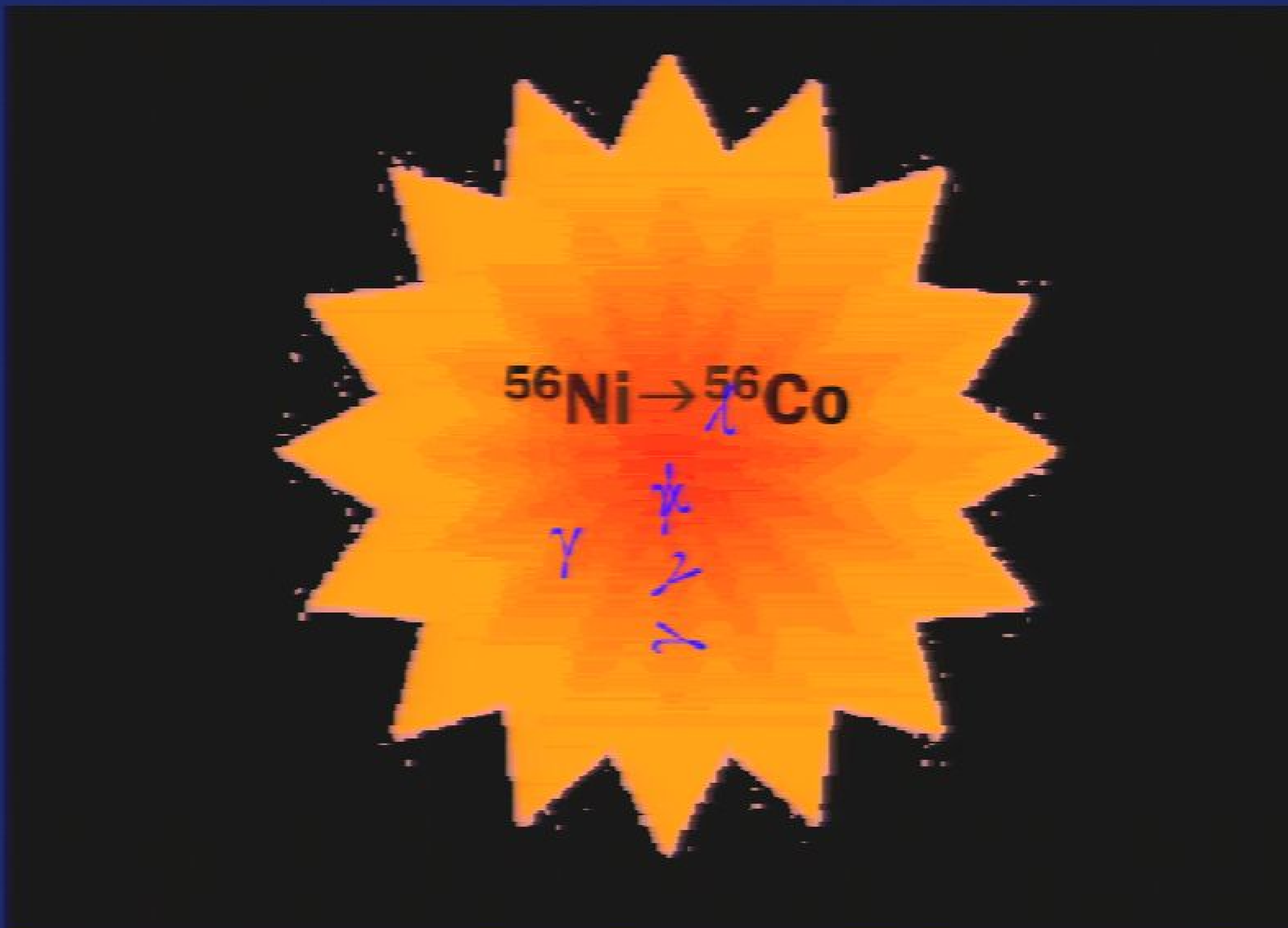


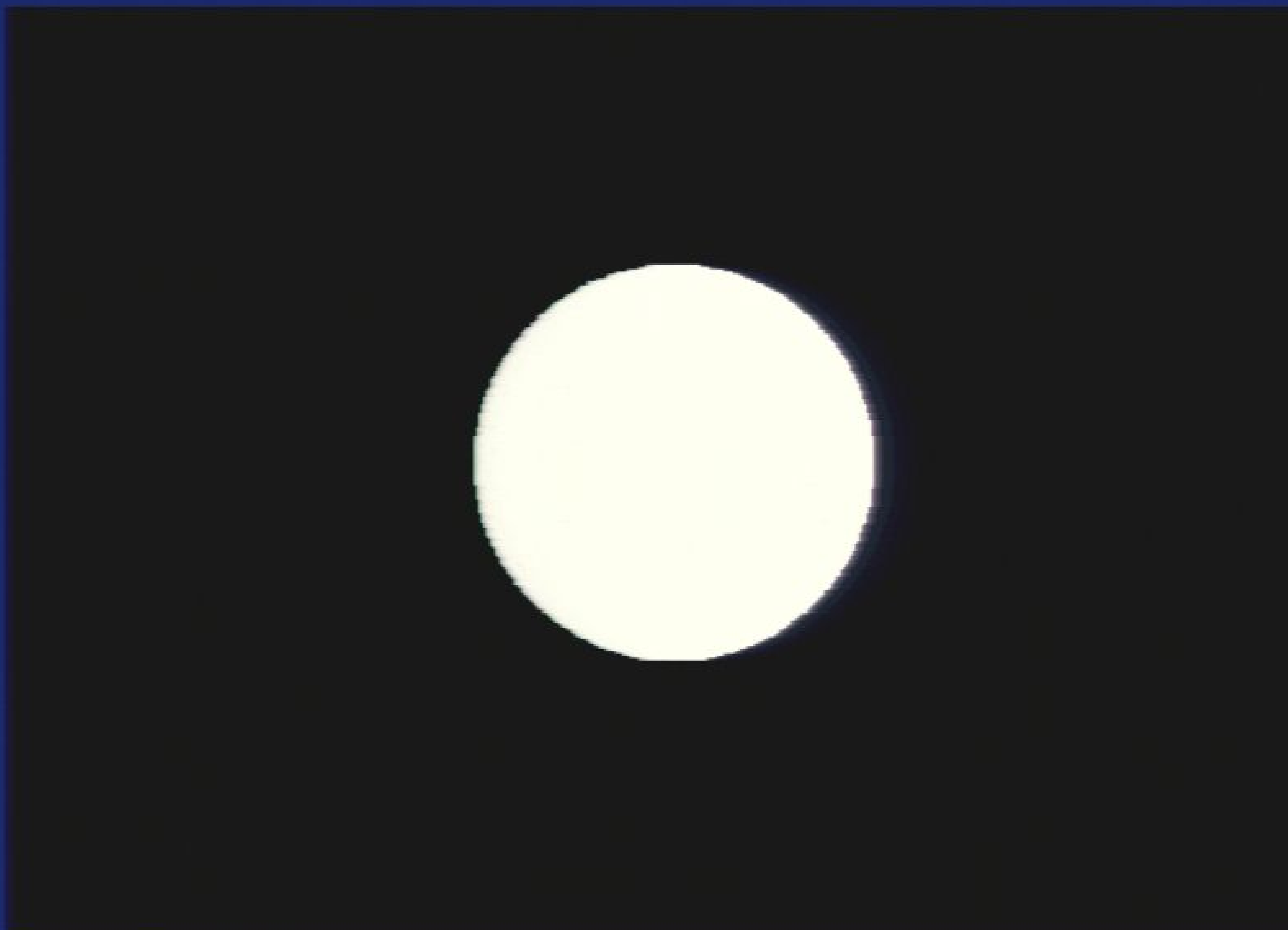
FIG. 2b

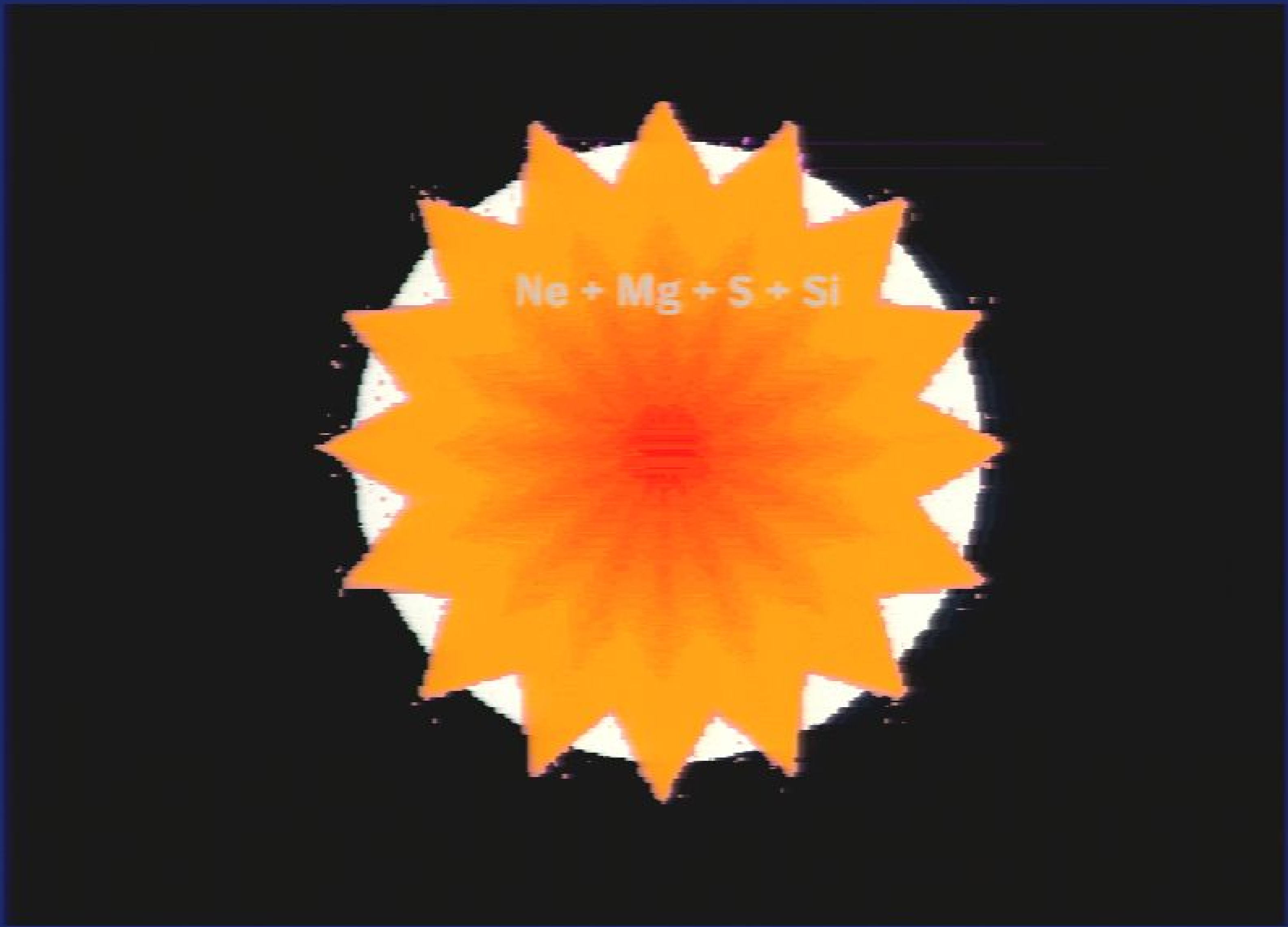

Type Ia Supernovae

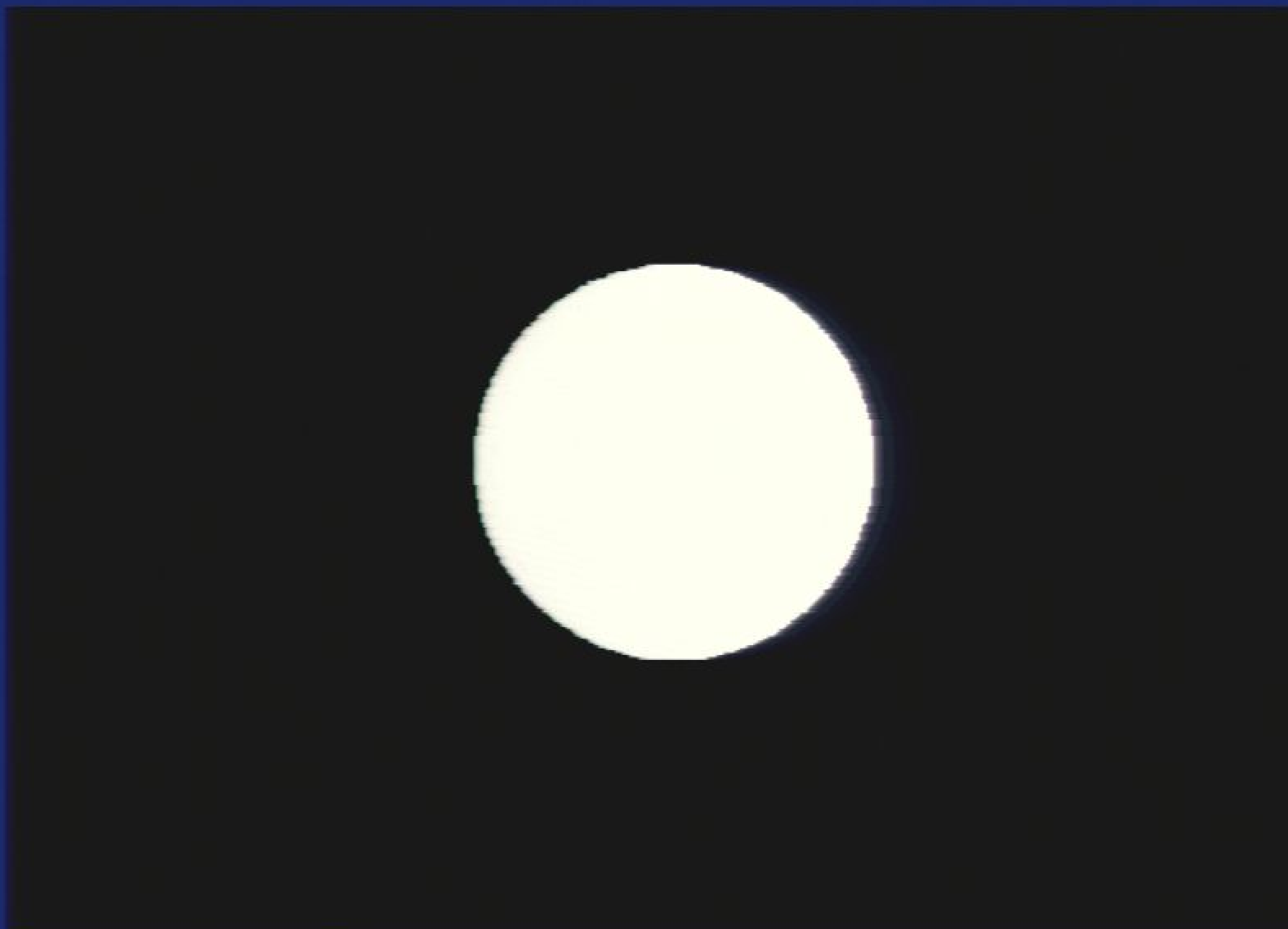



Detonation
Ne + Mg + S + Si


$^{56}Ni \rightarrow ^{56}Co$




Ne + Mg + S + Si



High-Z SN Ia History

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

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Ib/Ic SN Contamination realised in 1984/5

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

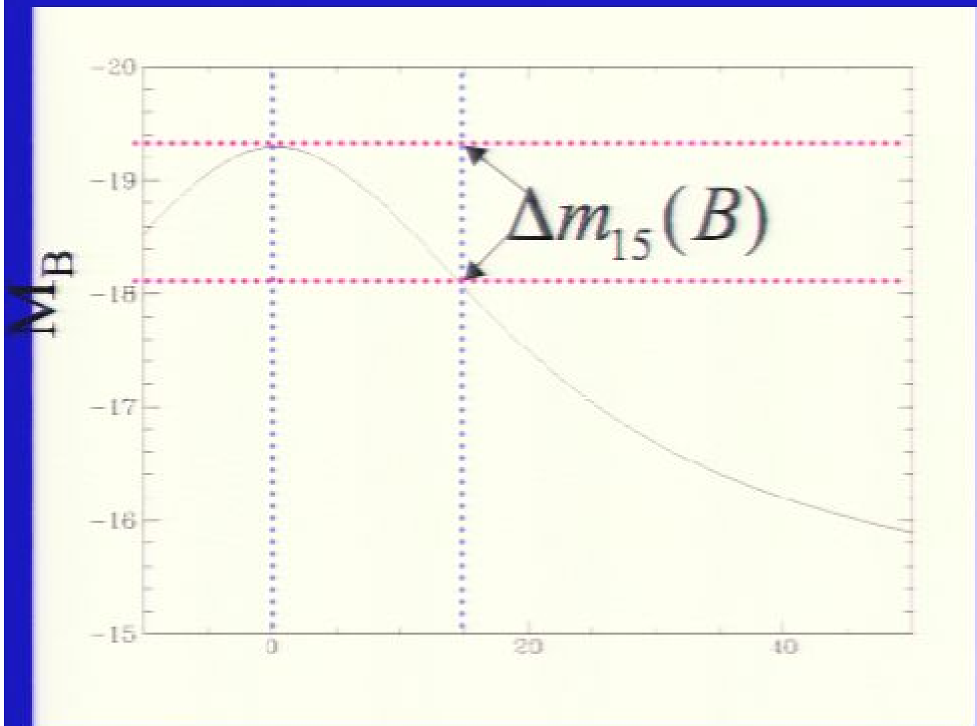

Hamuy
Suntzeff Schommer
Phillips
Smith
Maza
Calan-Tololo SN Search

Refining Type Ia Distances

Mark Phillips (1993)

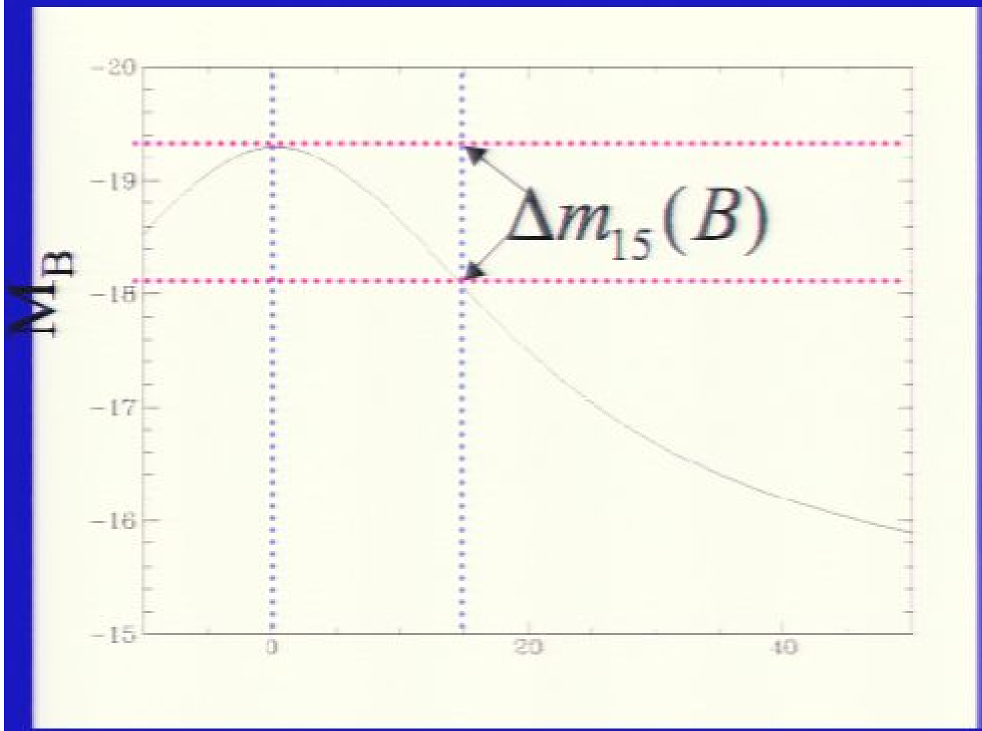
How fast a Supernova Fades is related to its intrinsic brightness.

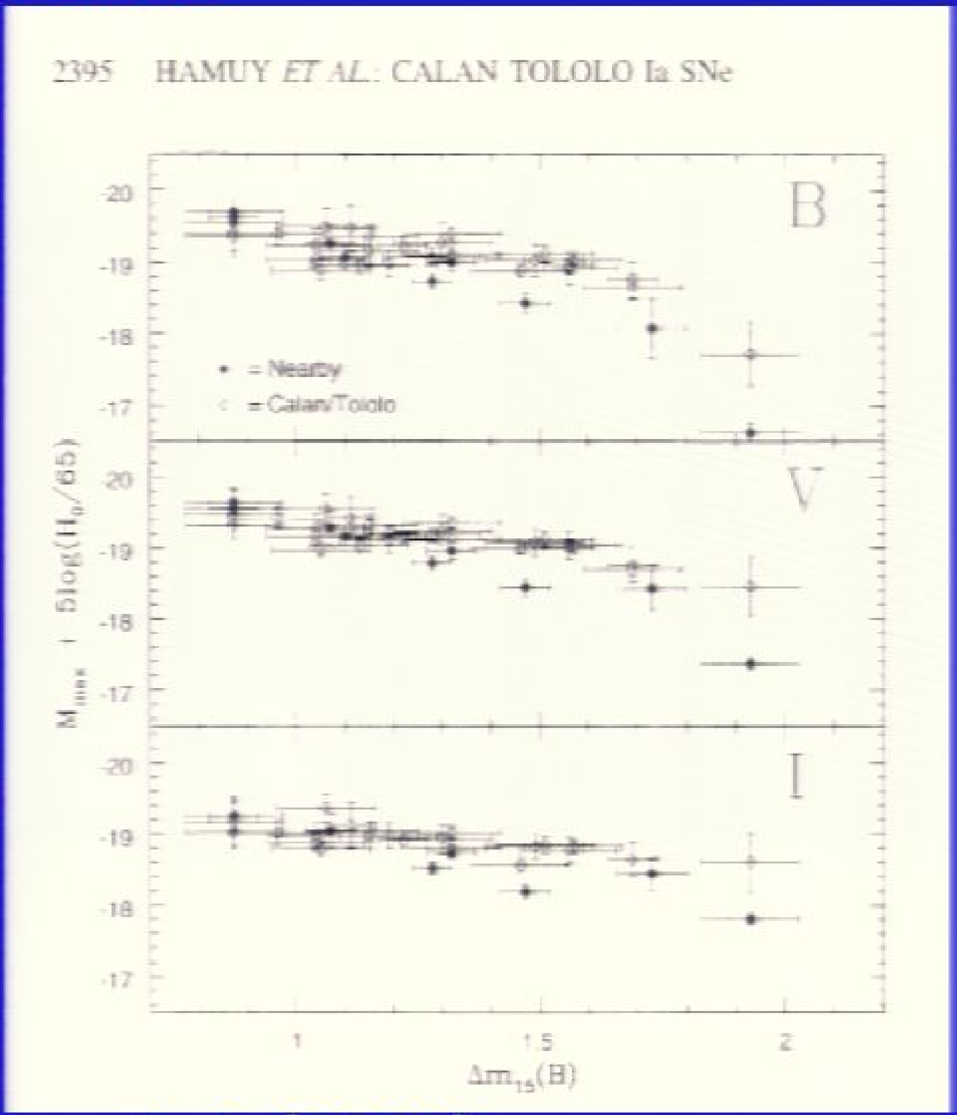
A Most Useful Way of Parameterizing SNe Ia is by the Shape of their Light Curve



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

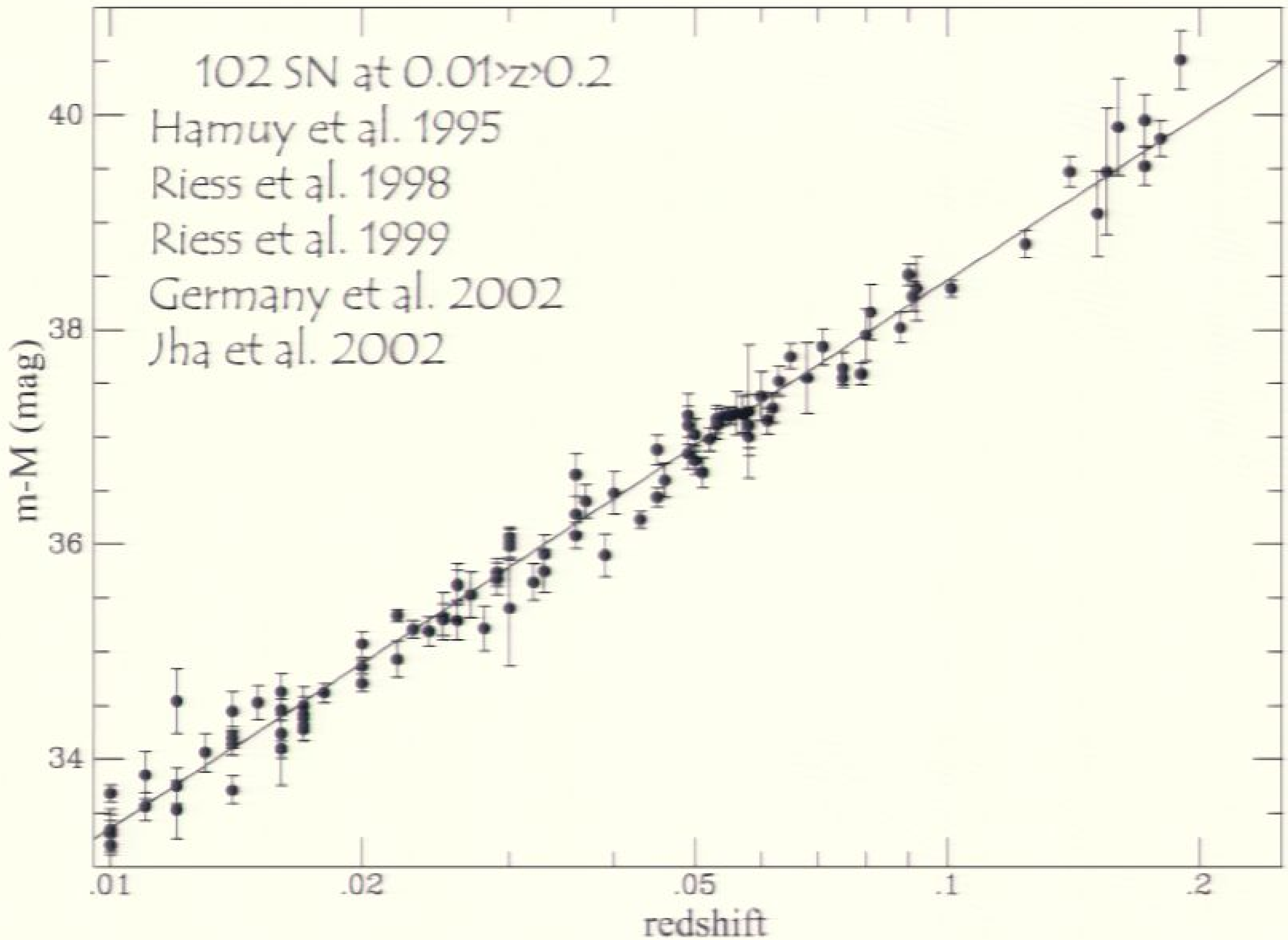
A Most Useful Way of Parameterizing SNe Ia is by the Shape of their Light Curve



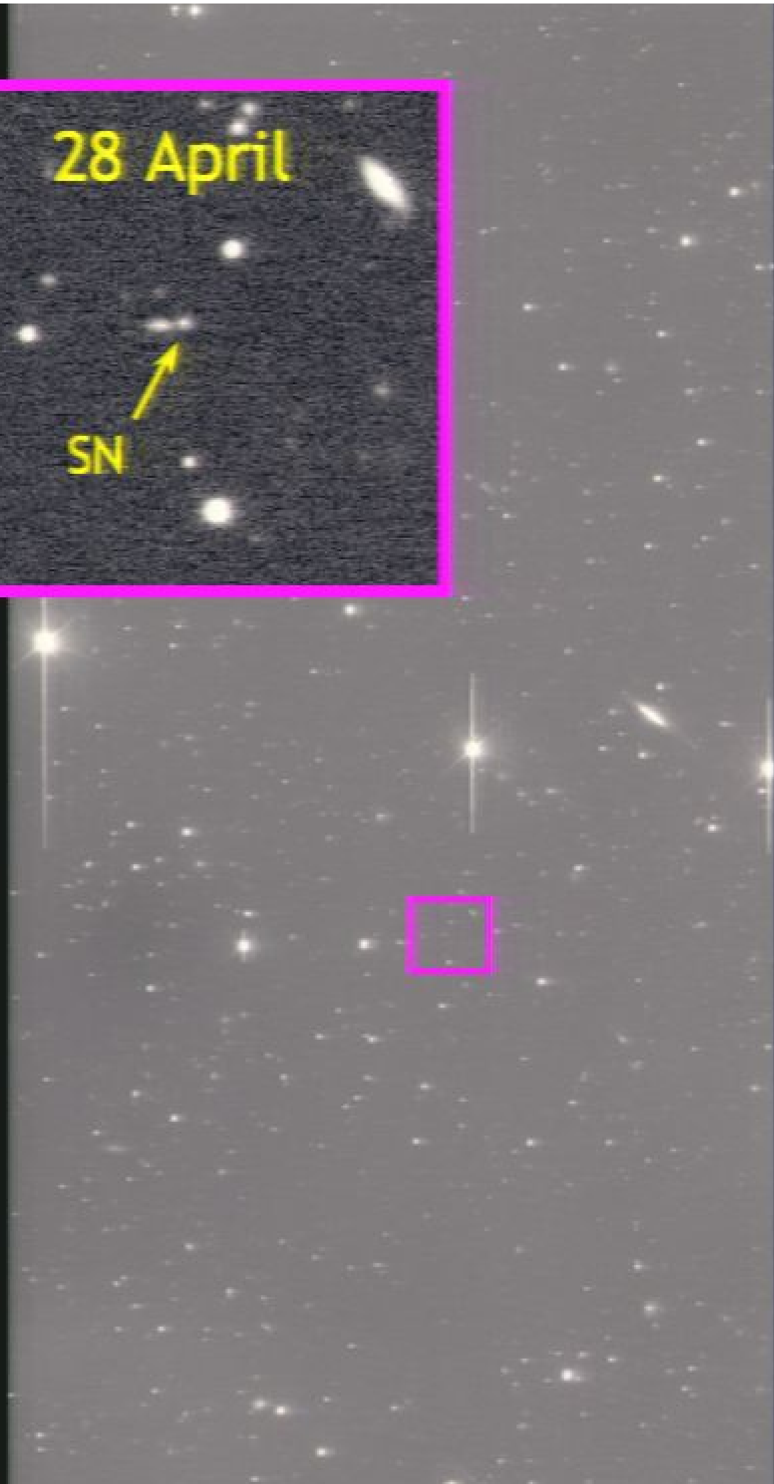


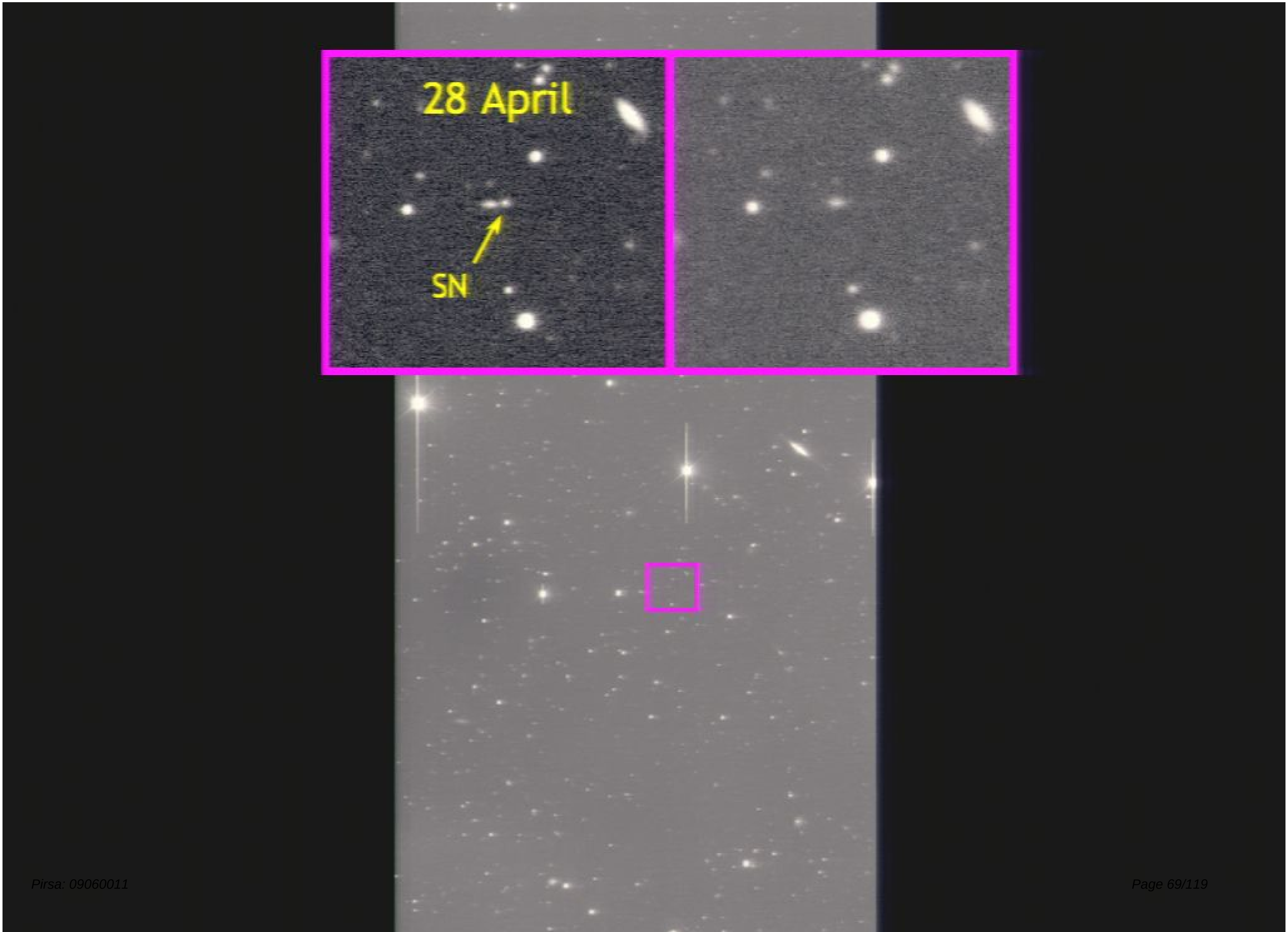
Phillips (1993) & Hamuy et al. (1996)

Proof is really that it works…



dm15, MLCS, stretch, BATM, SALT Sifto Cmagic

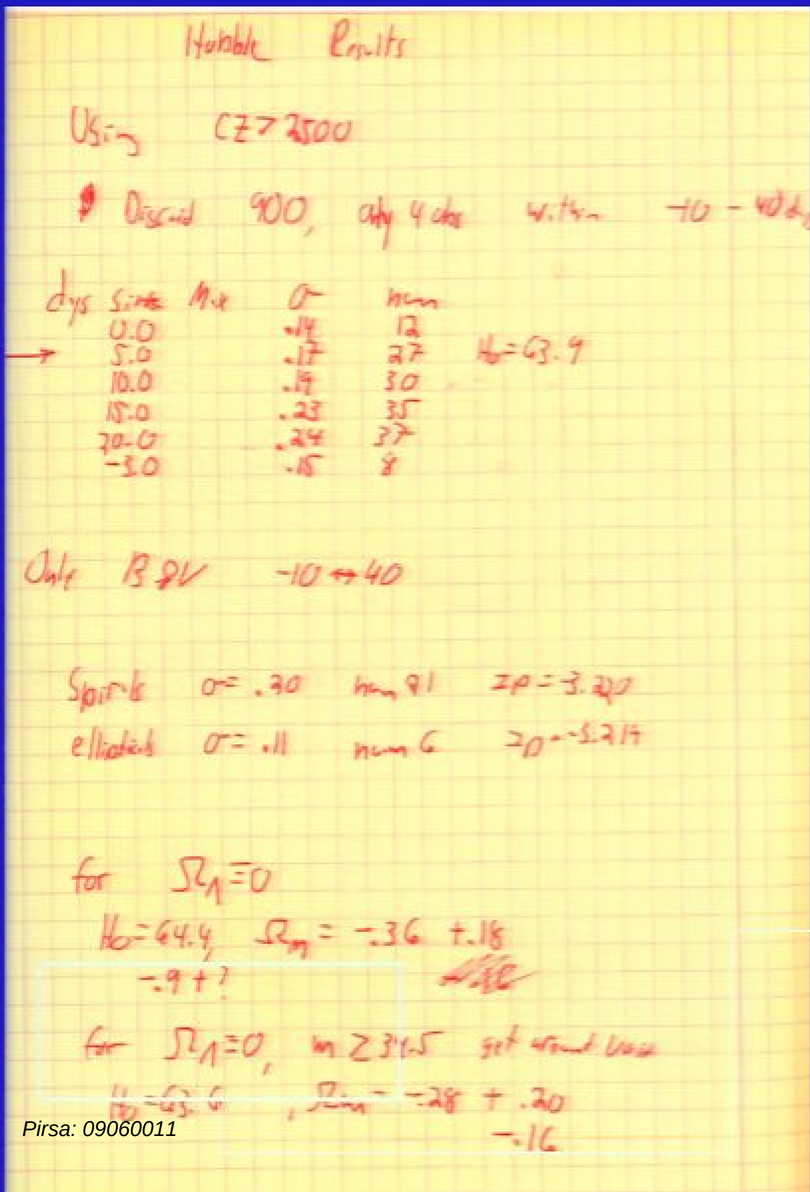

28 April
SN


28 April
SN

EUREKA?

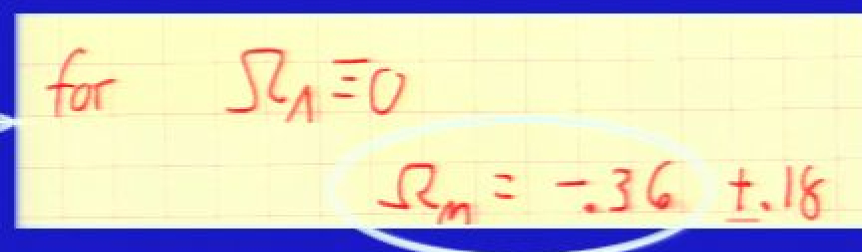
EUREKA?

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.



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]

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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

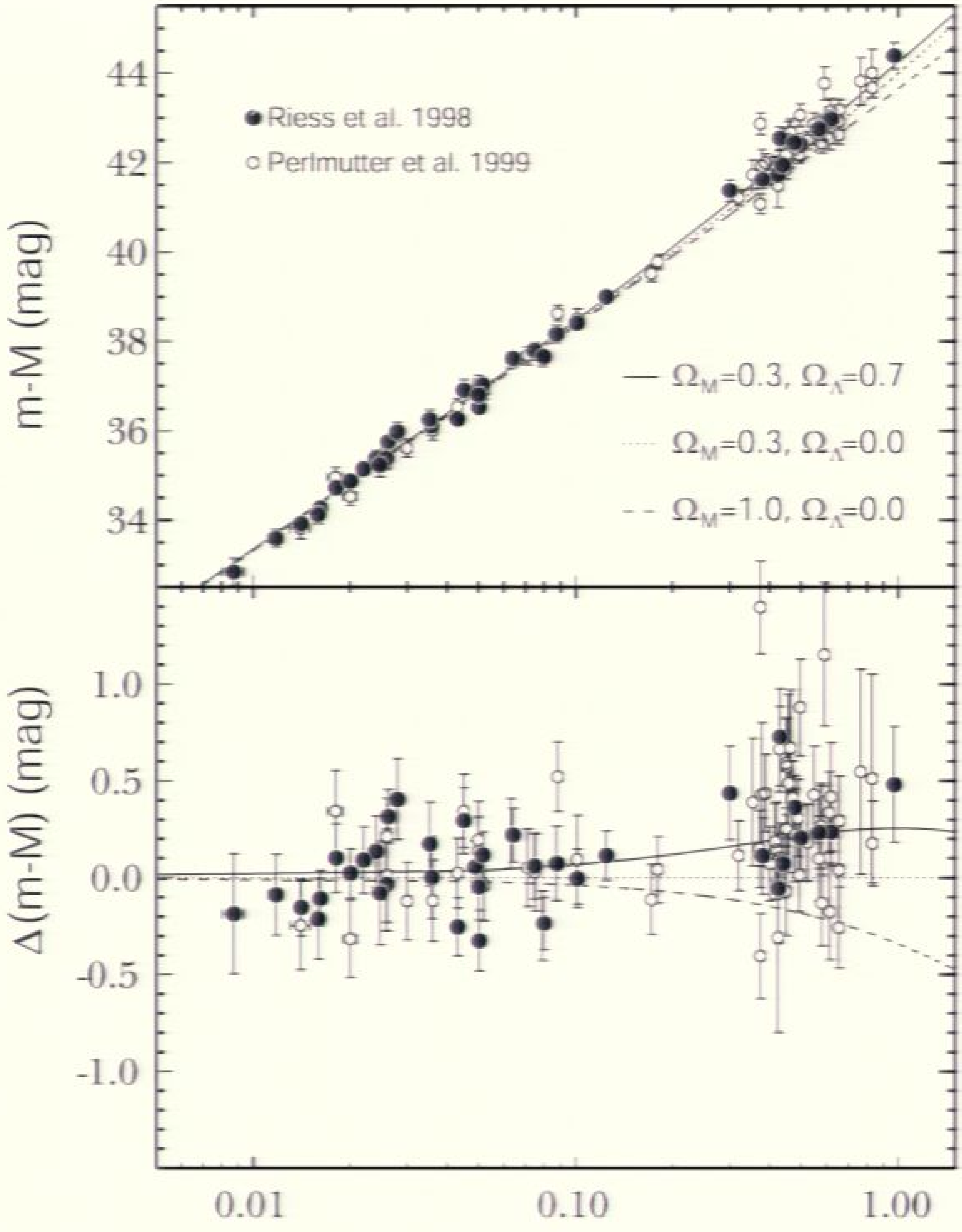
A. S. Fruchter and N. Panagia[9]
Space Telescope Science Institute, Baltimore, MD

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

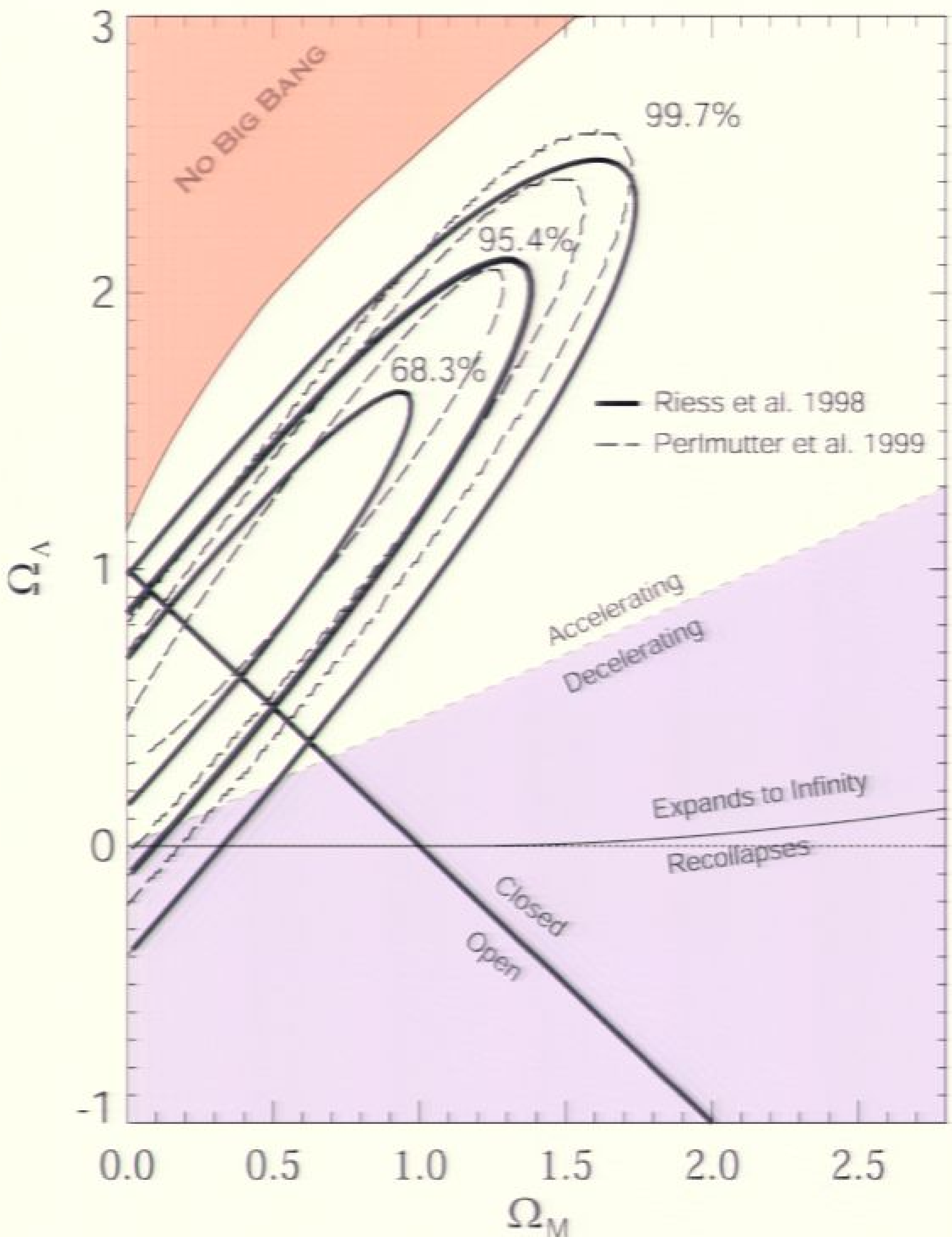
and

W. J. Couch
University of New South Wales, Sydney, Australia

(The Supernova Cosmology Project)



Riess et al. 1998
Perlmutter et al. 1999
m-M (mag)
44
42
40
38
36
34
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)
1.0
0.5
0.0
-0.5
-1.0
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
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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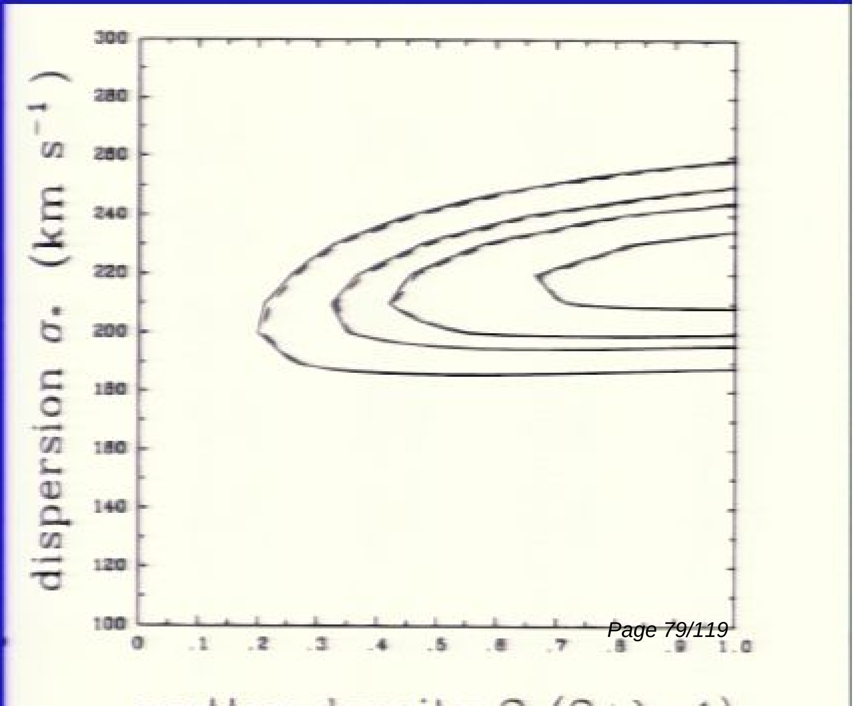
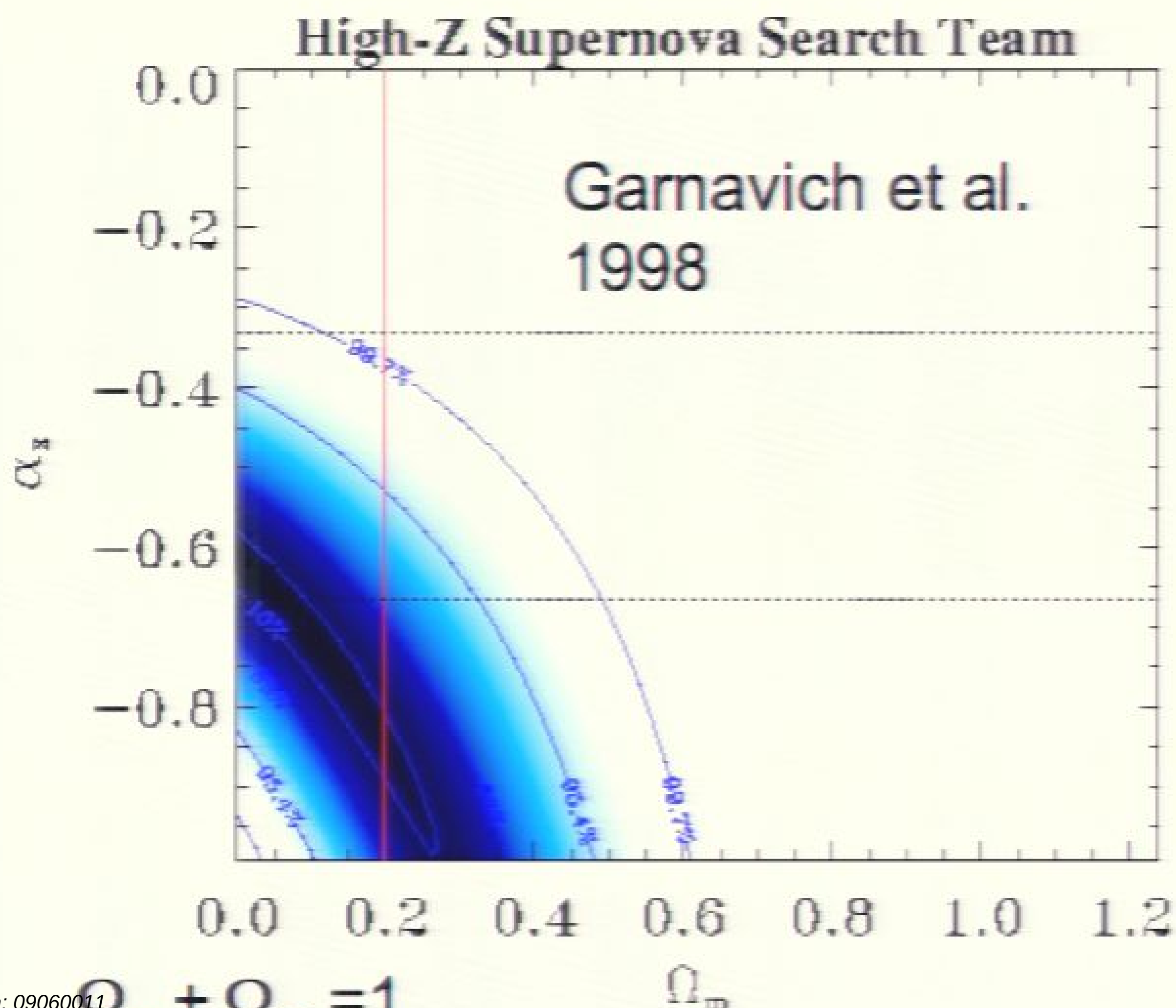
- But SN Ia themselves might be affected by Dust, evolution or measurement difficulties, and Community felt they were not to be completely trusted on their own.

•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

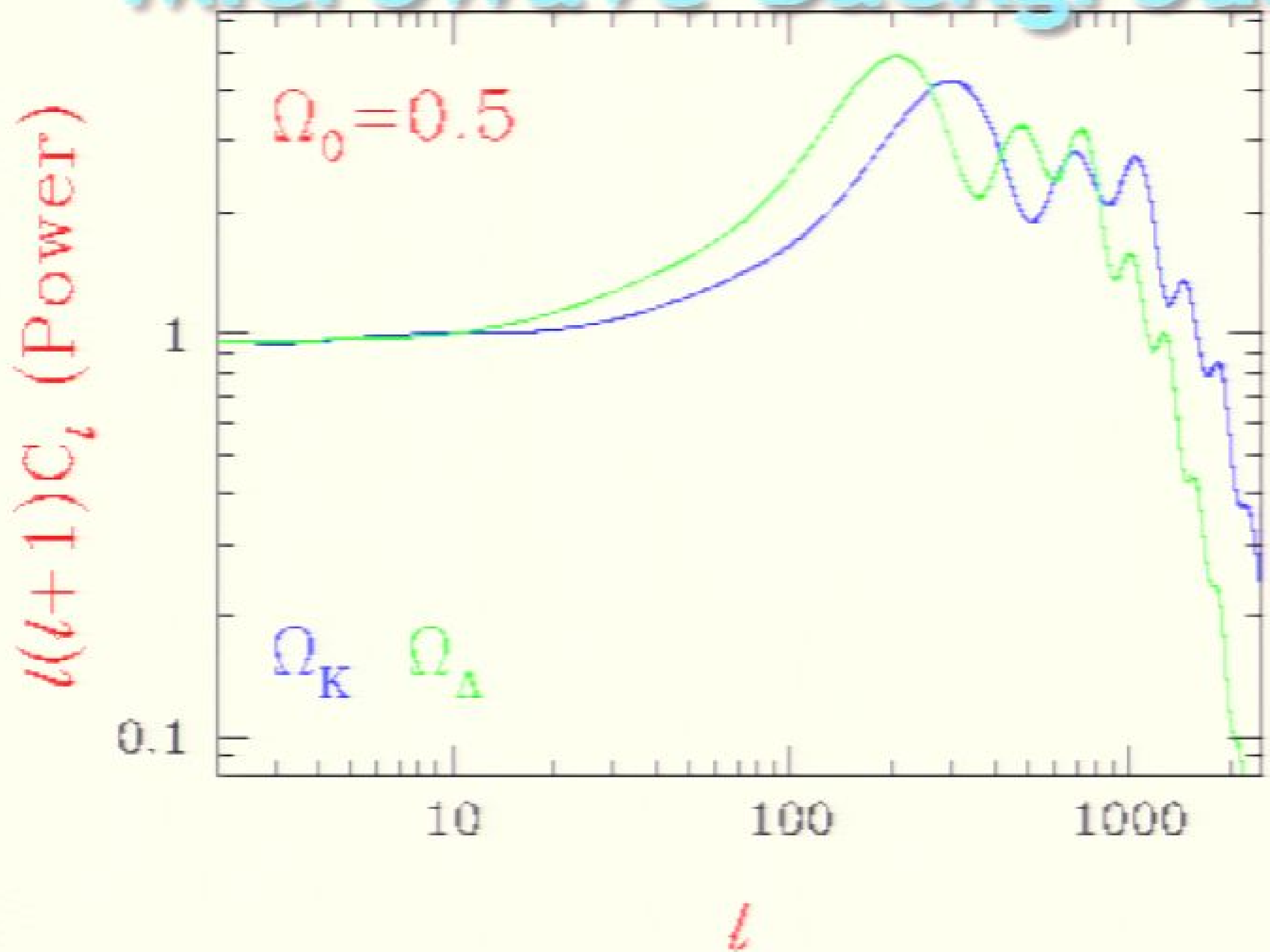


$\Omega_w + \Omega_M = 1$

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

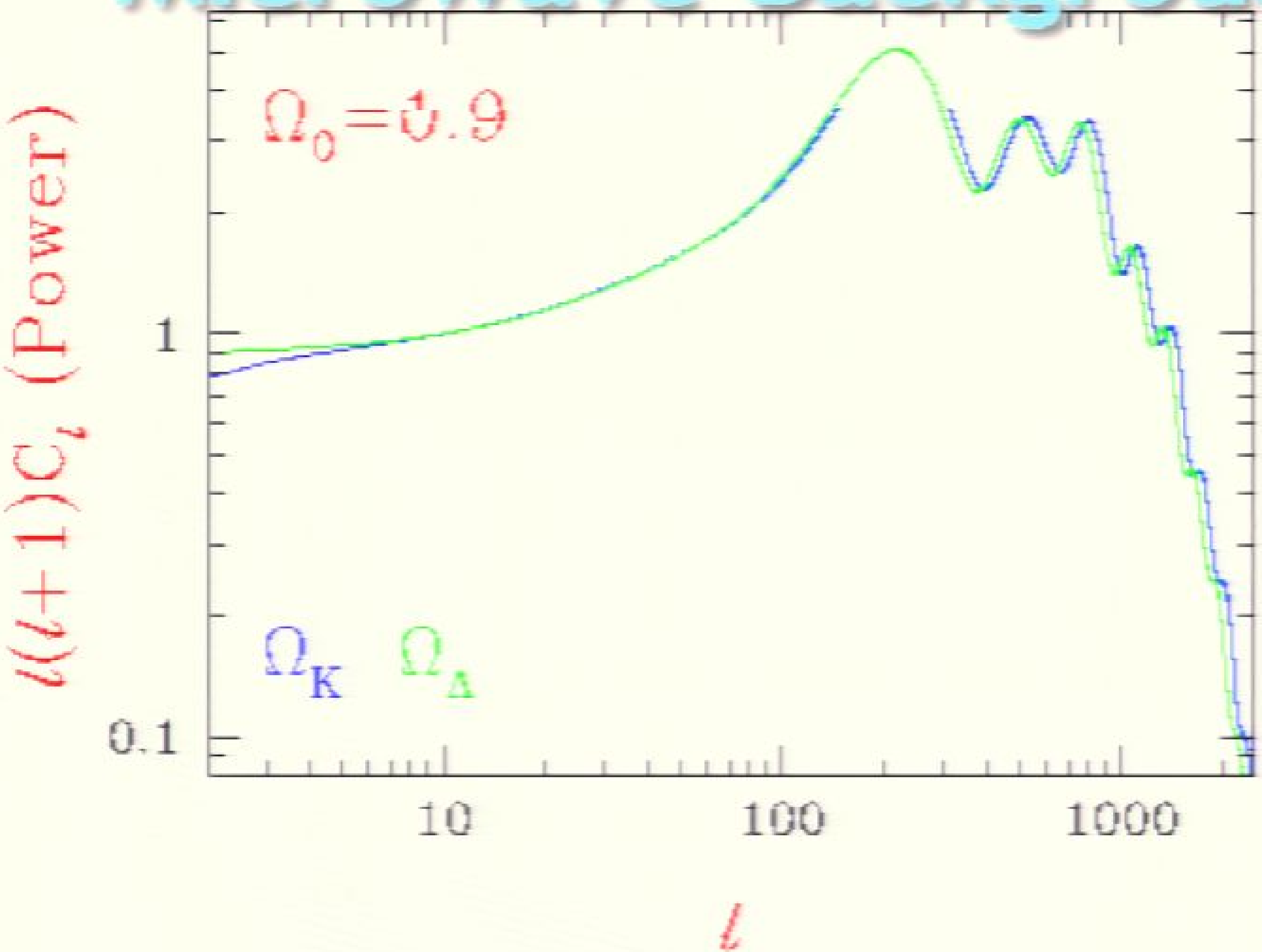
EOS was new stuff to us, so we had no problem giving the constant the name α

1994-7
CDM+Inflation applied to Microwave Background



W. Hu

1994-7
CDM+Inflation applied to Microwave Background



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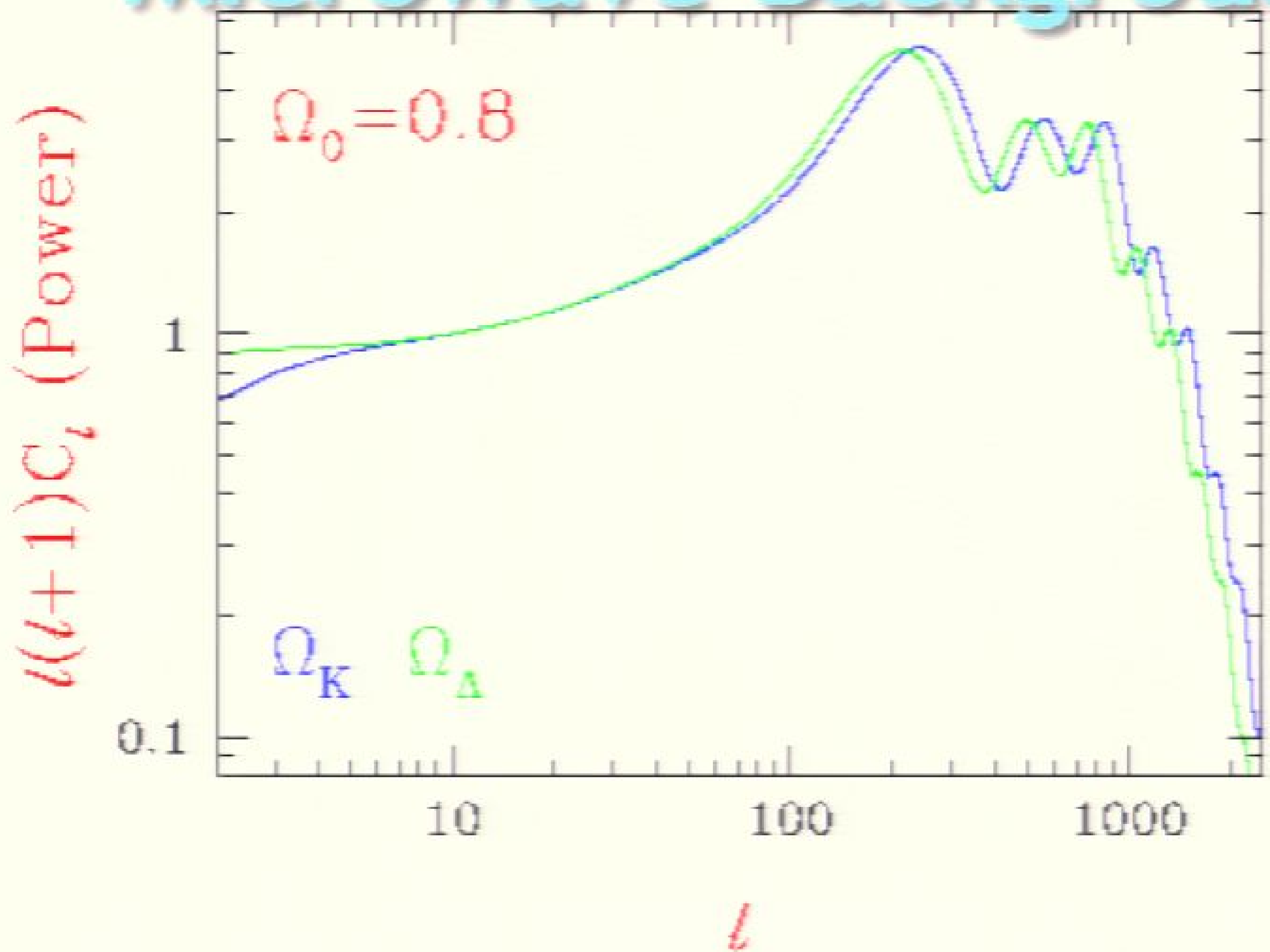

W. Hu

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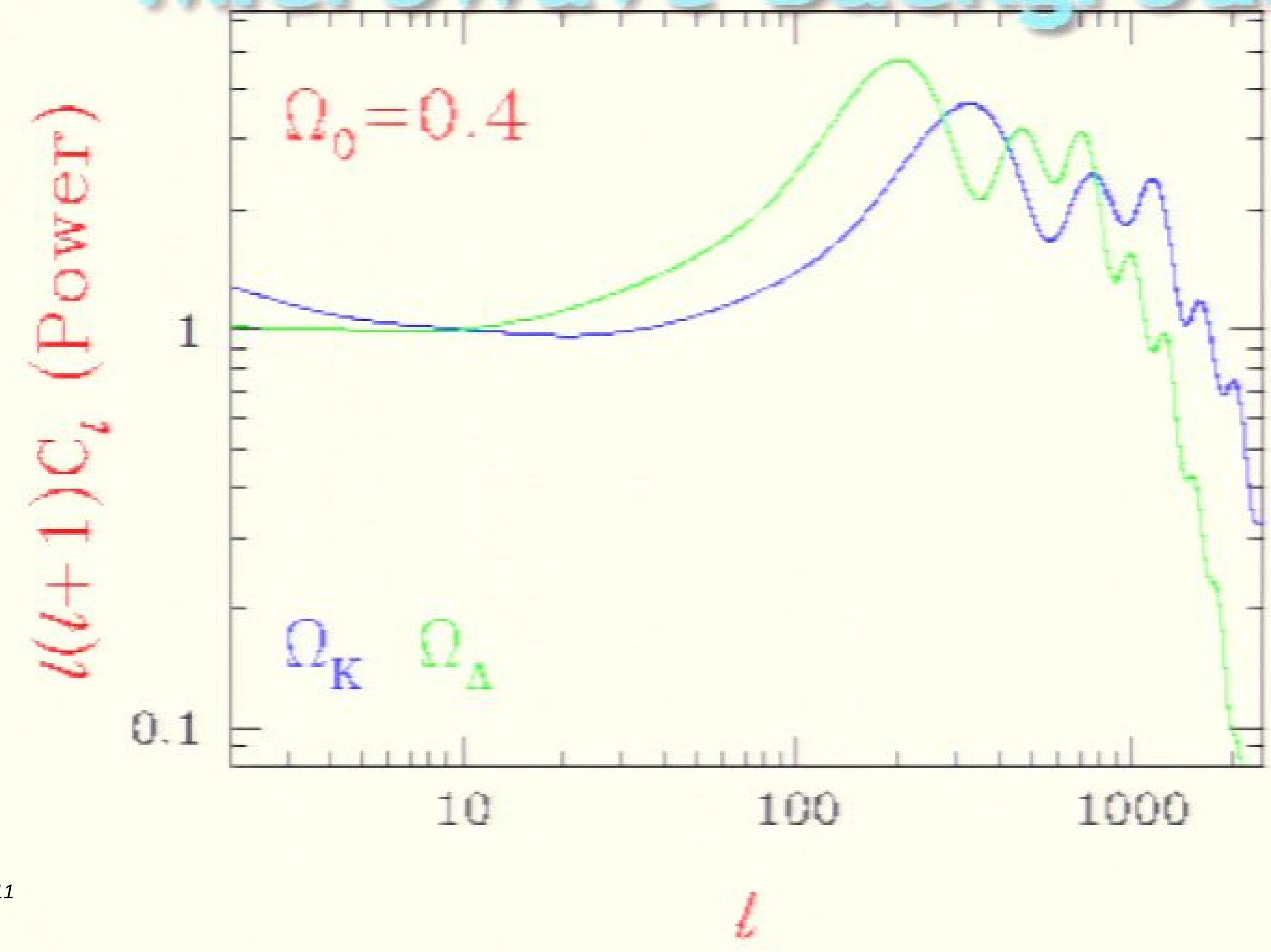
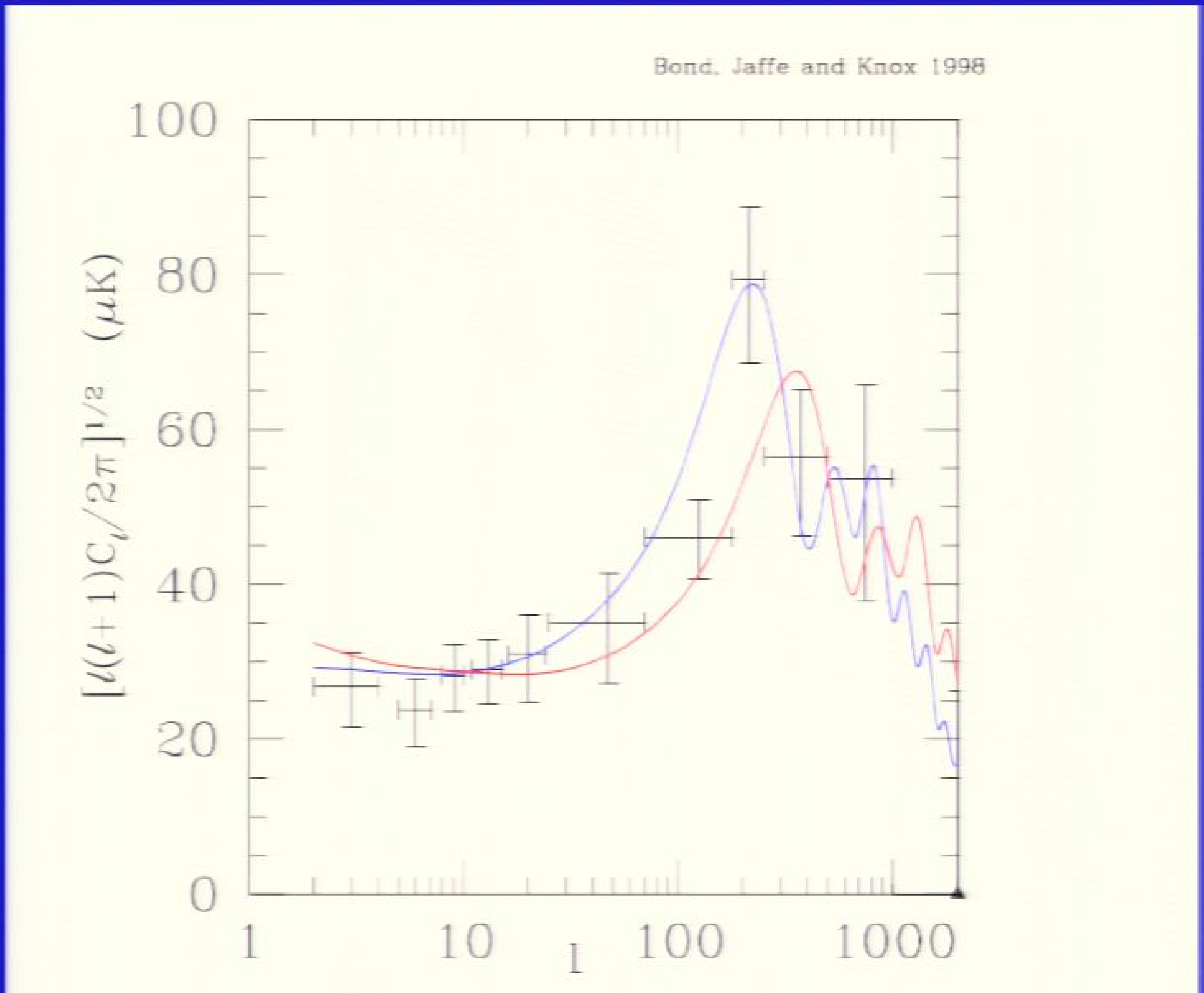


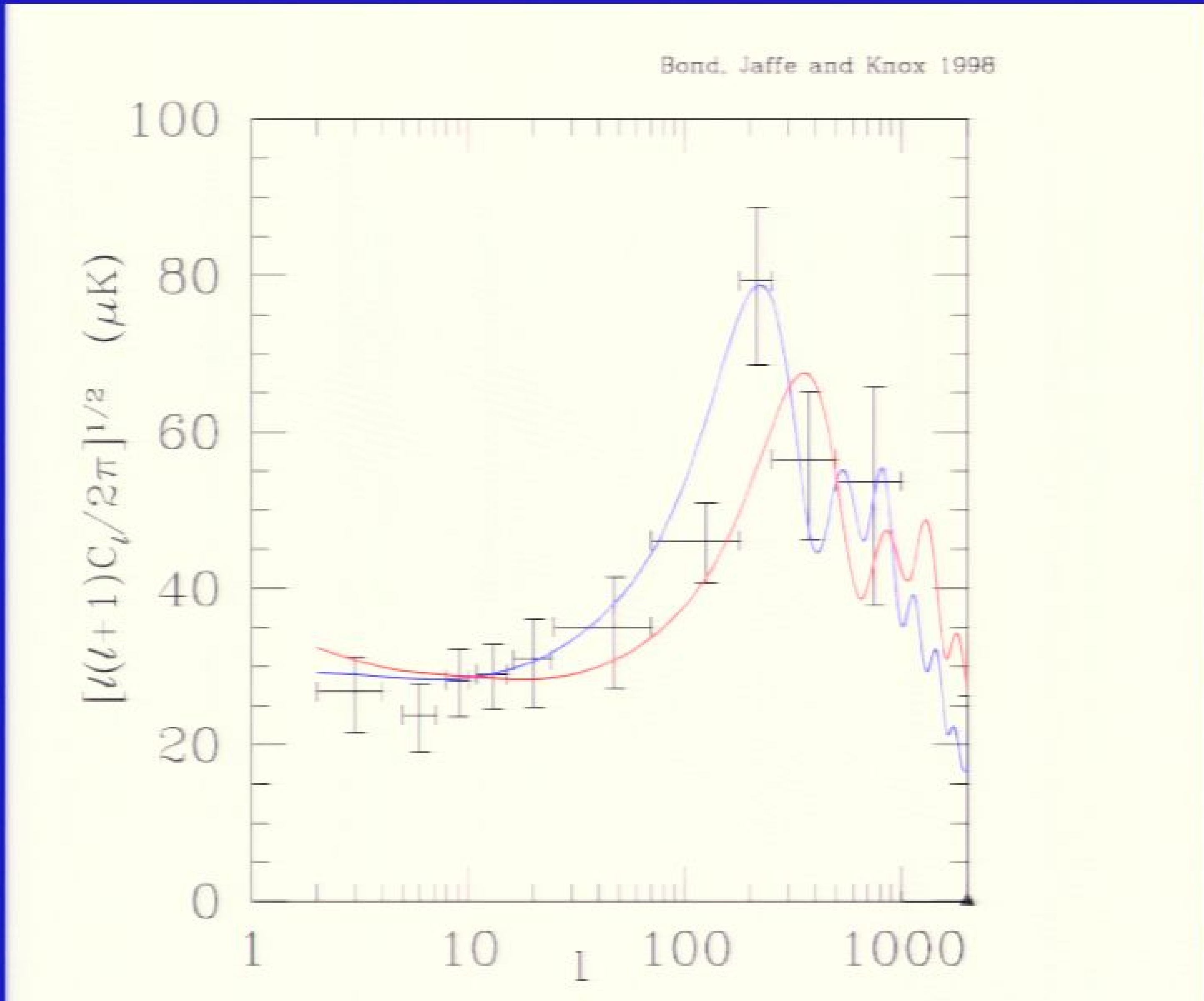
W. Hu

CMB - mid 1998



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

CMB - mid 1998



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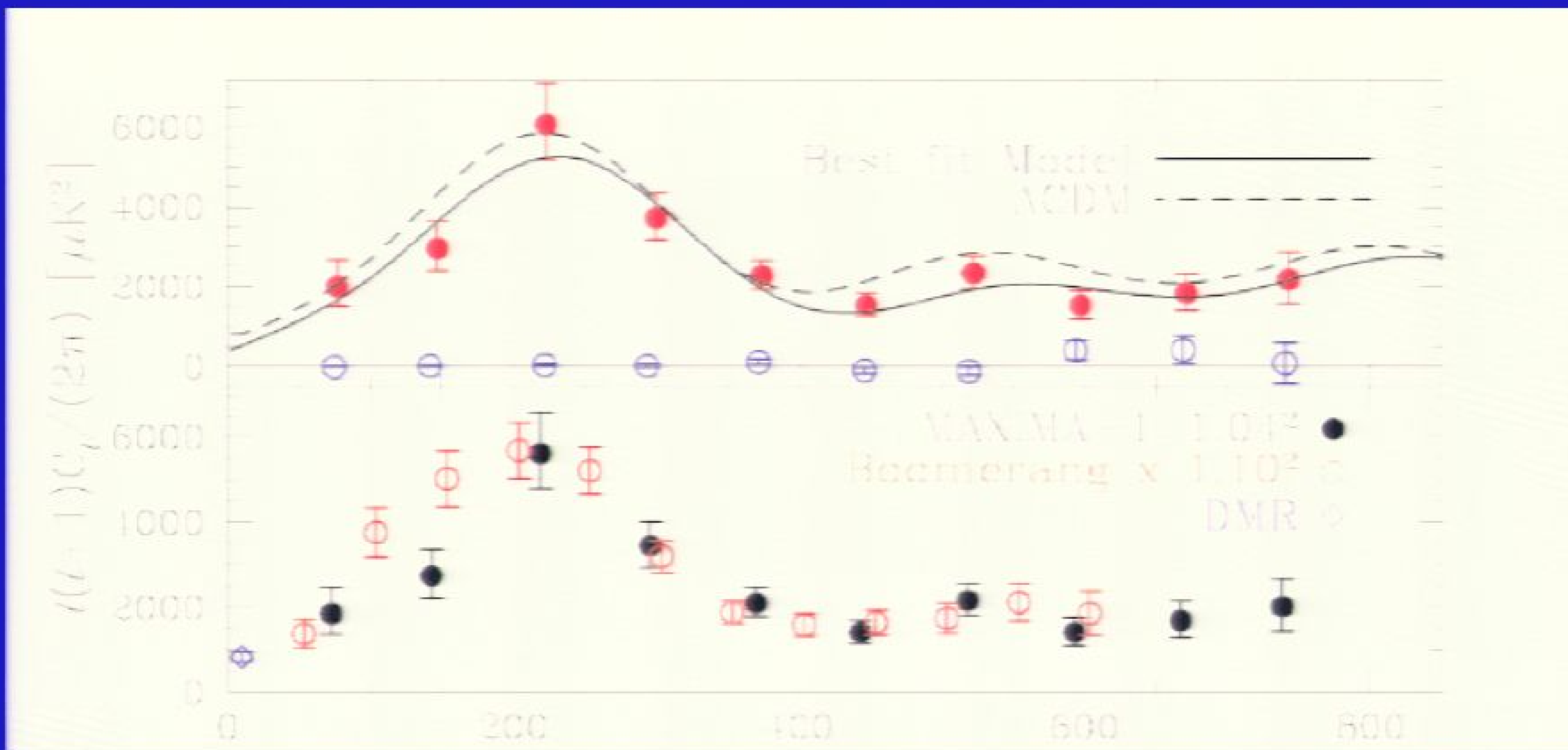
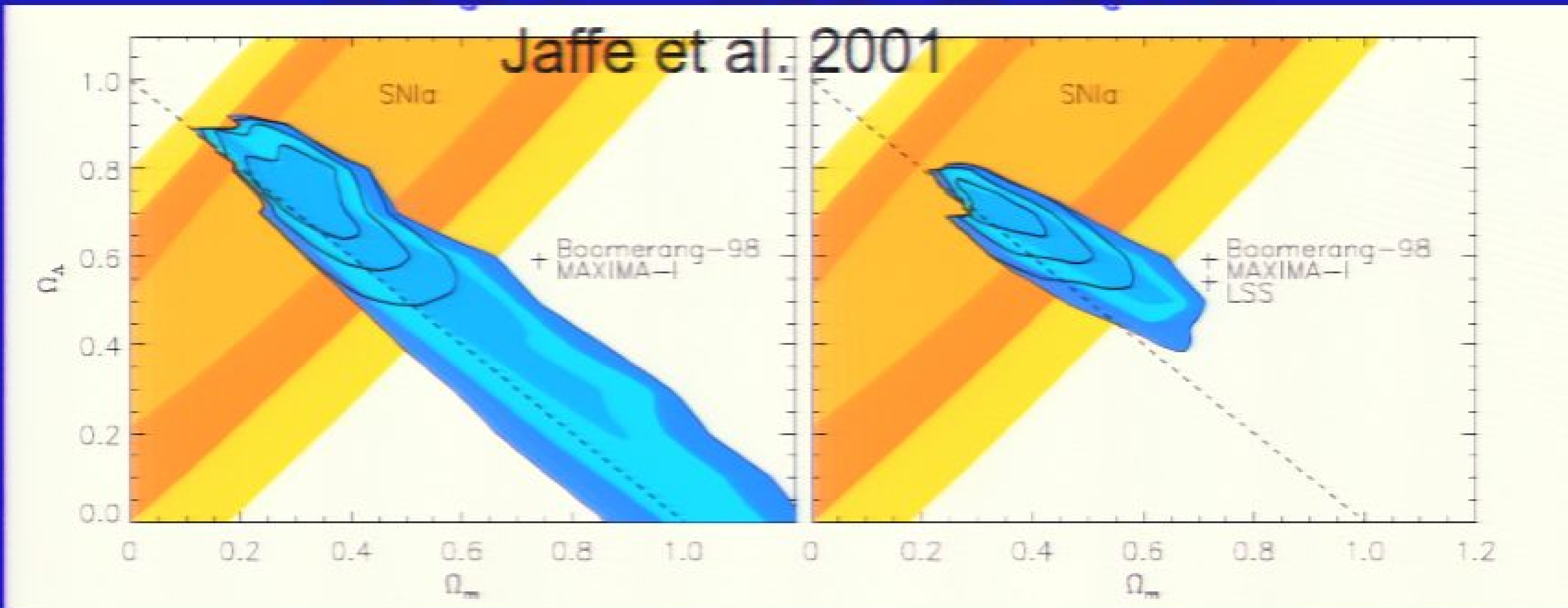
100
80
60
40
20
0
$[l(l+1)C_l/2\pi]^{1/2}$ (μK)
1
10
100
1000
l

2000 - Boomerang & MAXIMA Clearly see 1st Doppler Peak



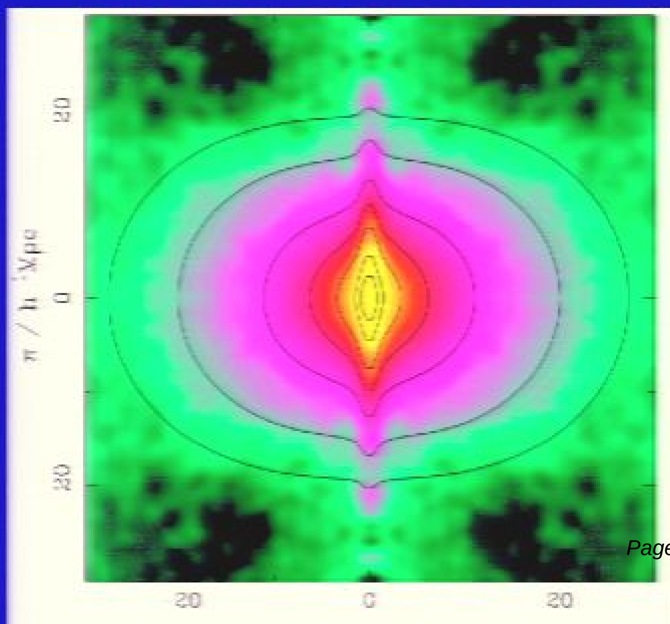
Once a Flat Universe was measured, the SN Ia measurements went from being 3-4σ to >7σ

2001 - LSS & CMB

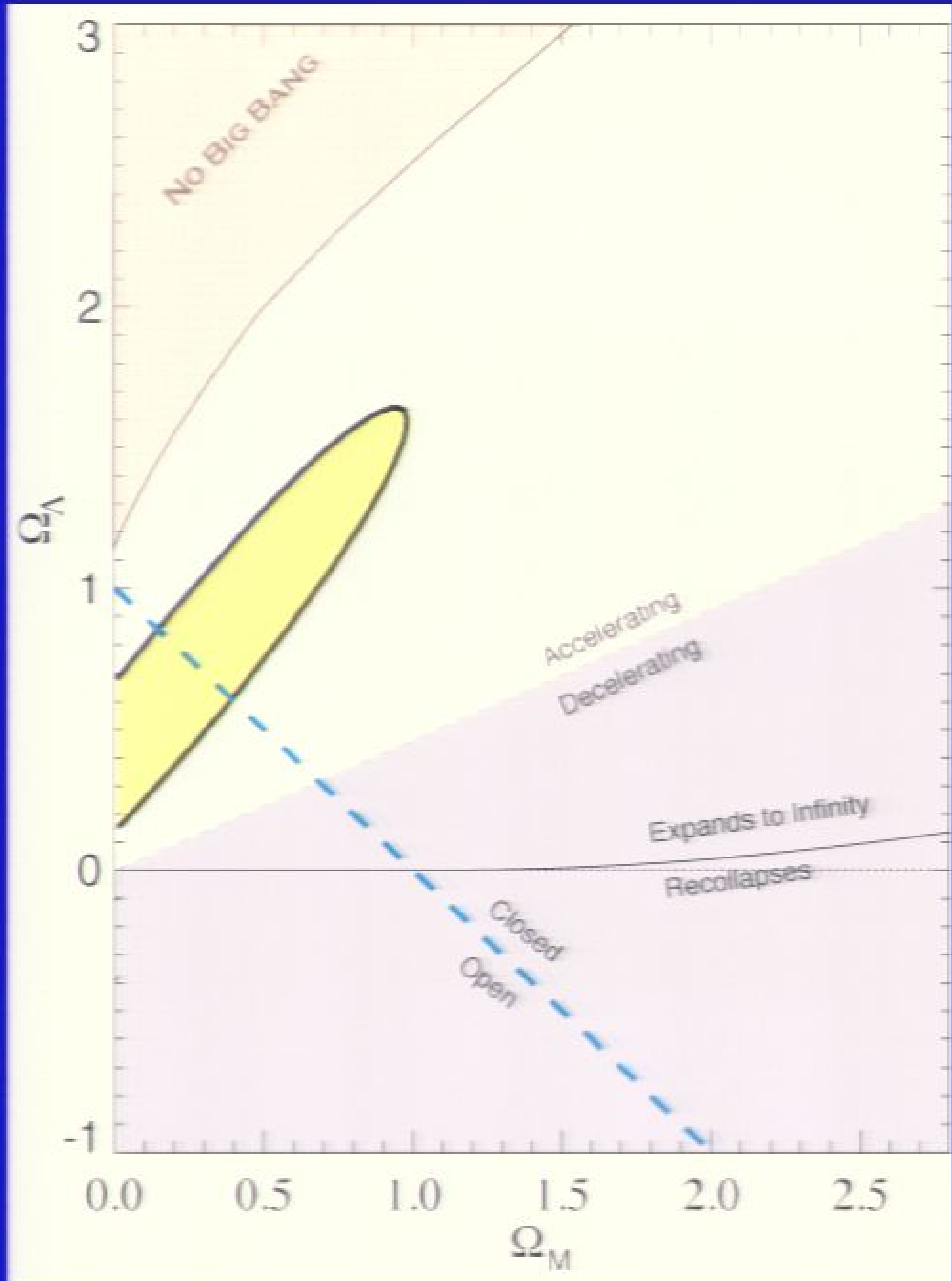


2dF redshift survey finds

Ω_M~0.3 from power spectrum and infall



Getting Rid of Dark Energy requires 2 out of 3 experiments to be wrong



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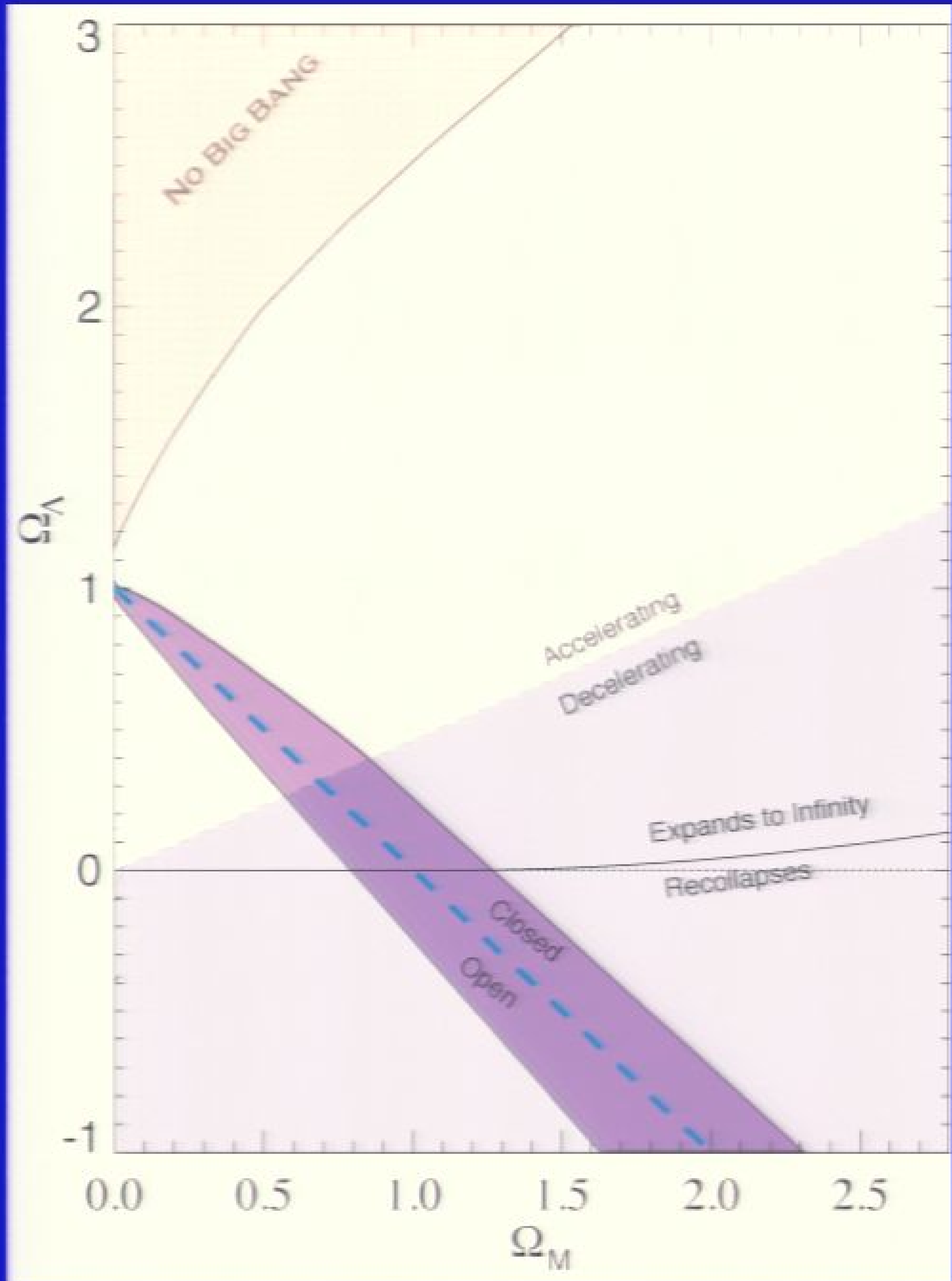
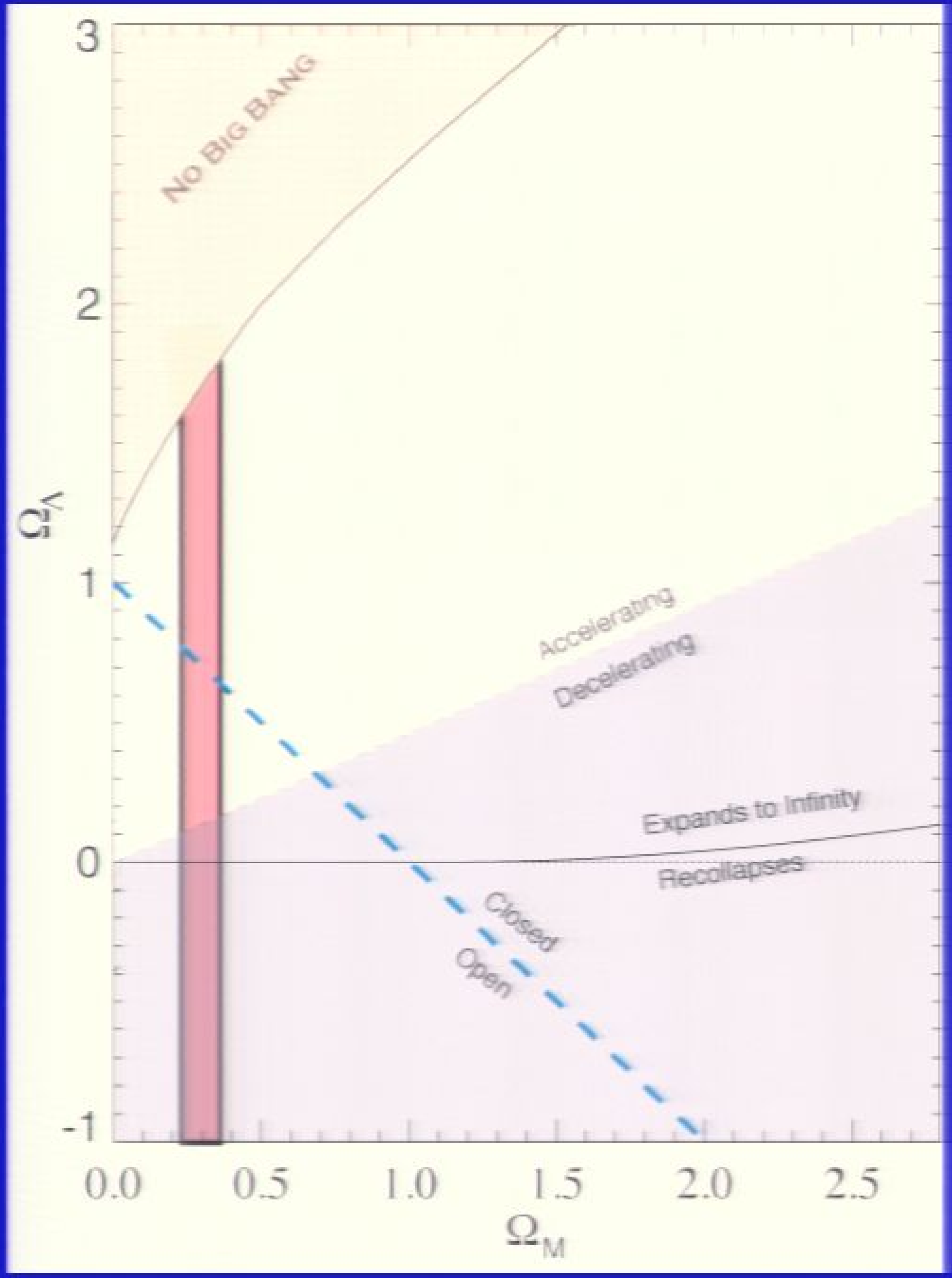
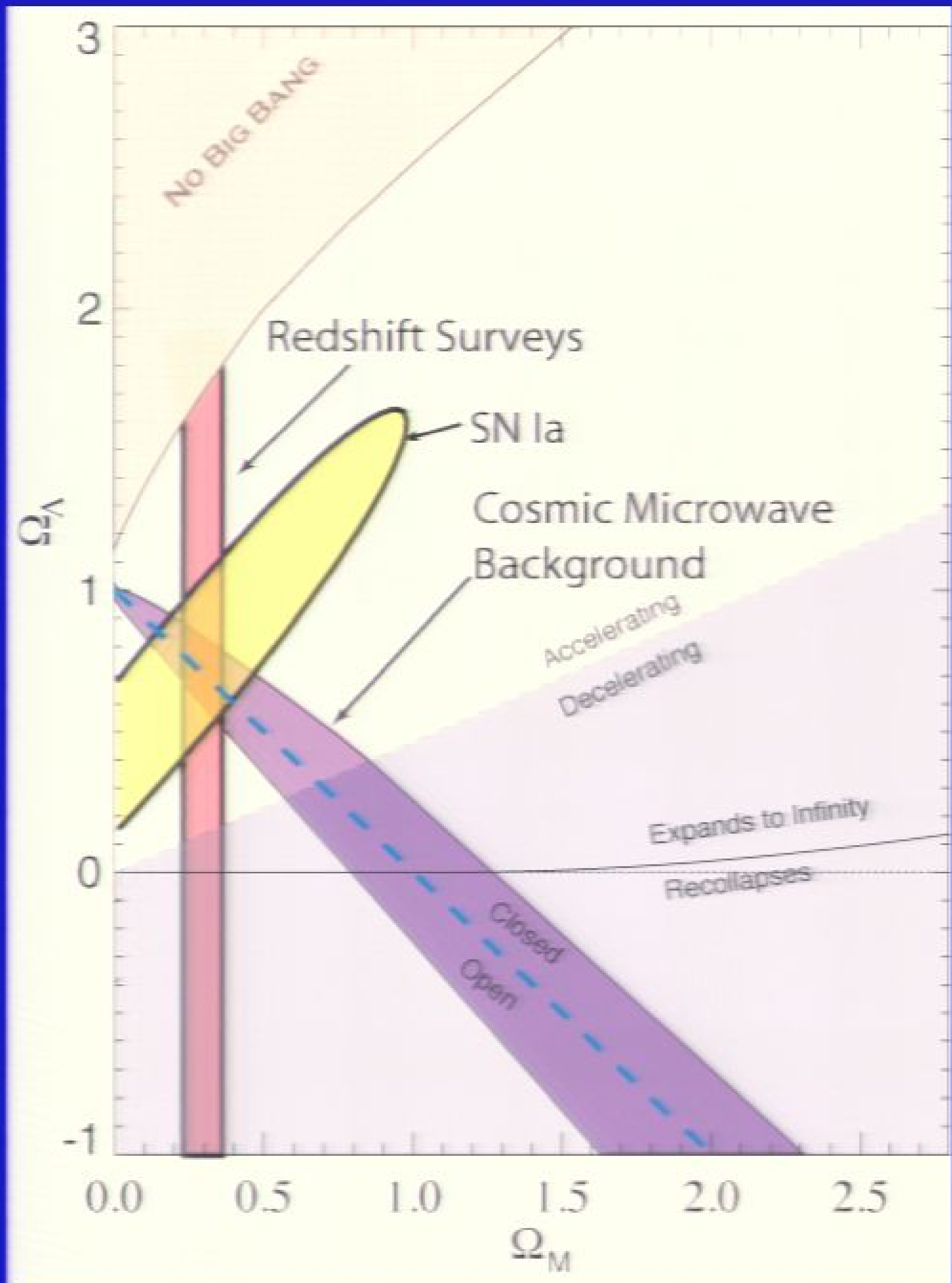


Getting Rid of Dark Energy requires 2 out of 3 experiments to be wrong

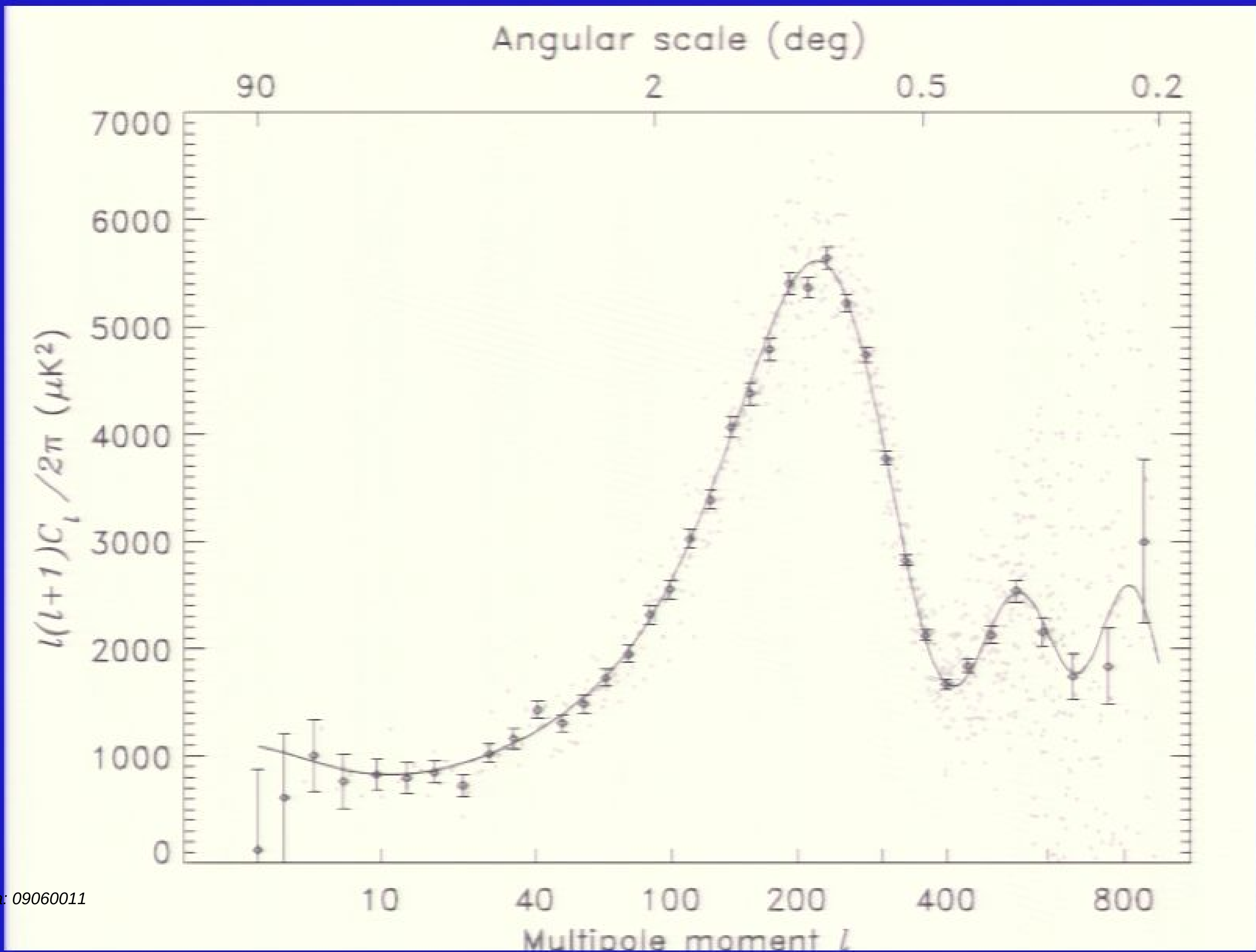


Getting Rid of Dark Energy requires 2 out of 3 experiments to be wrong

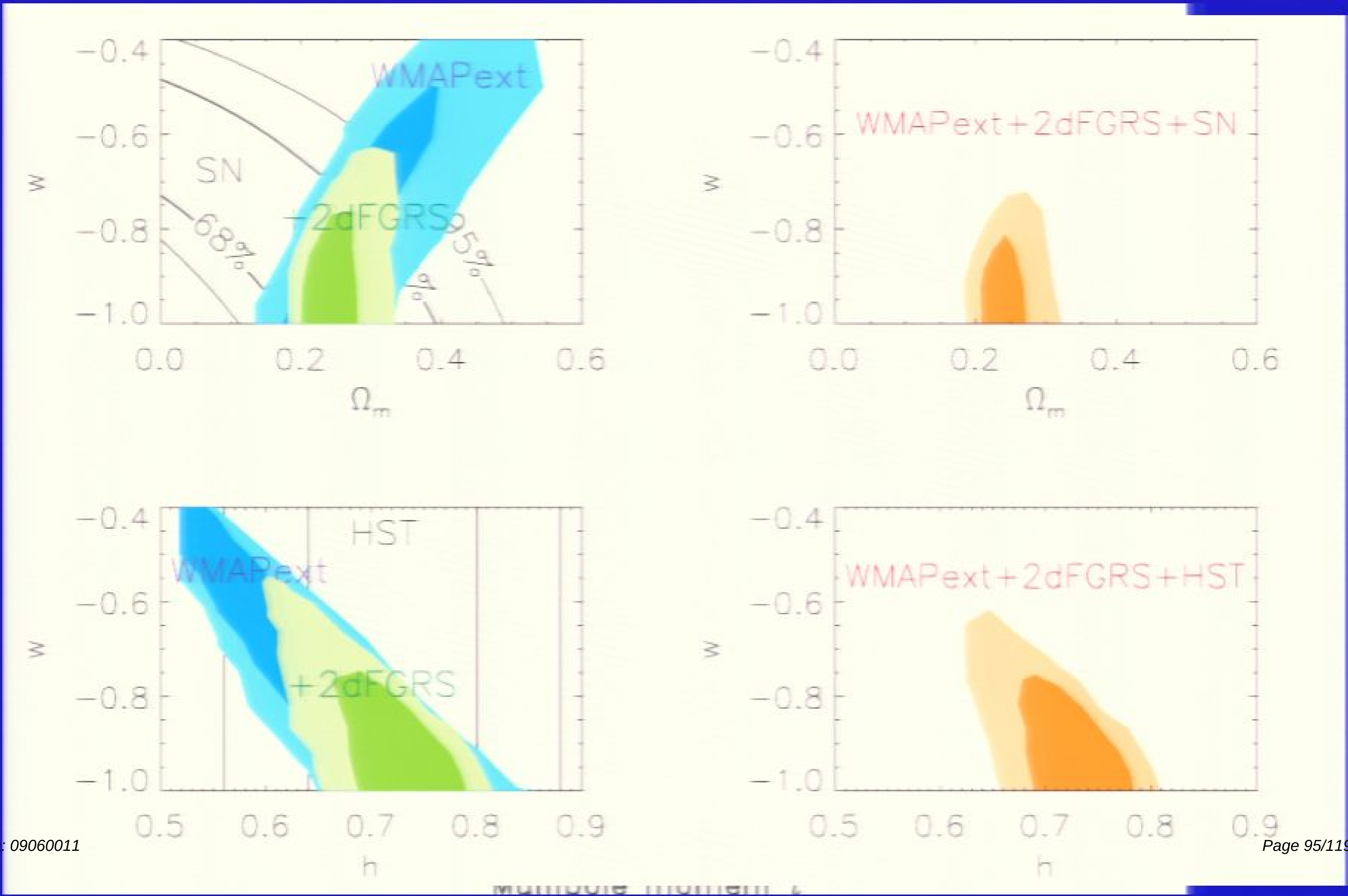


Getting Rid of Dark Energy requires 2 out of 3 experiments to be wrong

2003 - WMAP+2dF+SNIa+H_0



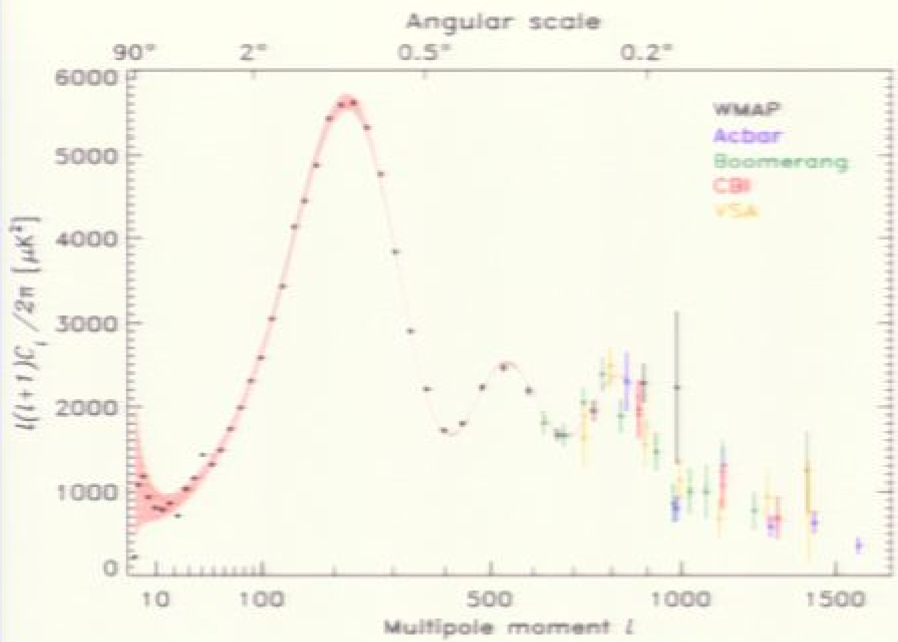
2003 - WMAP+2dF+SNIa+H_0

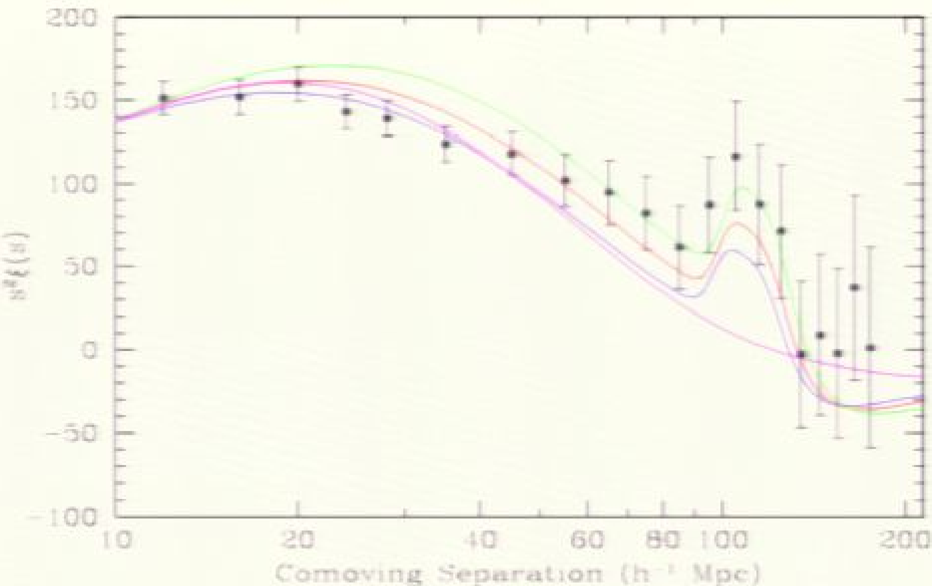


1998-2005
The Rise of Baryon Acoustic Oscillations

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



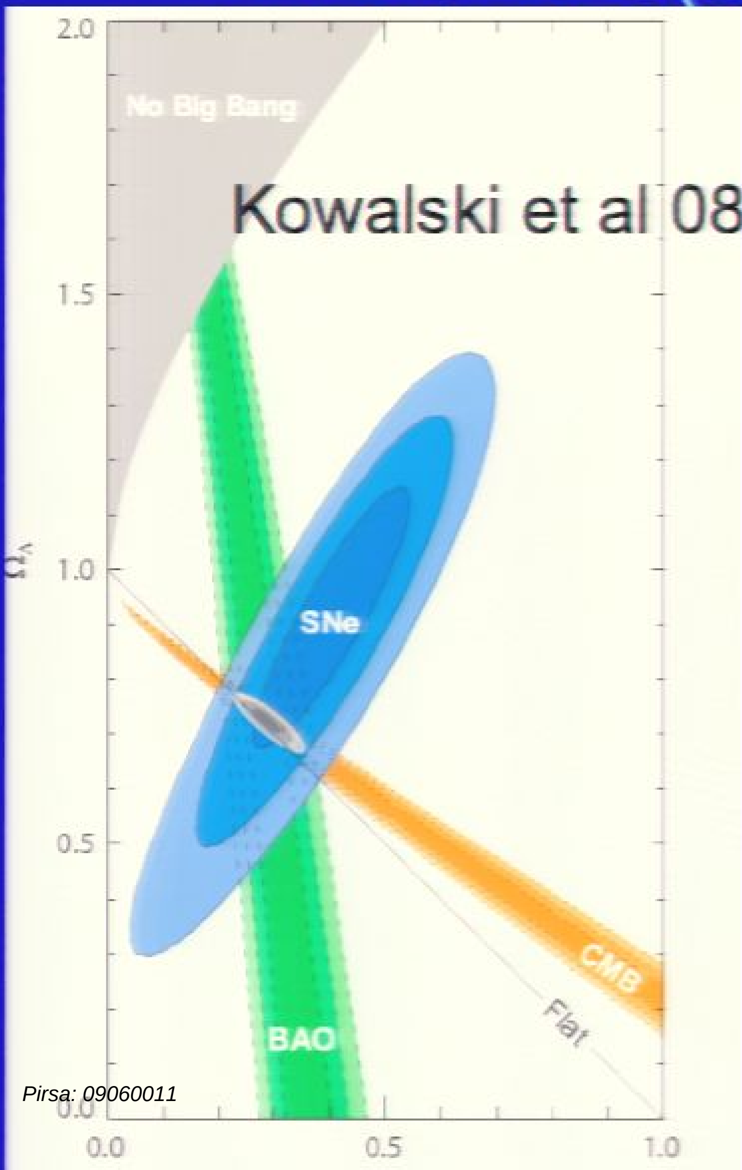


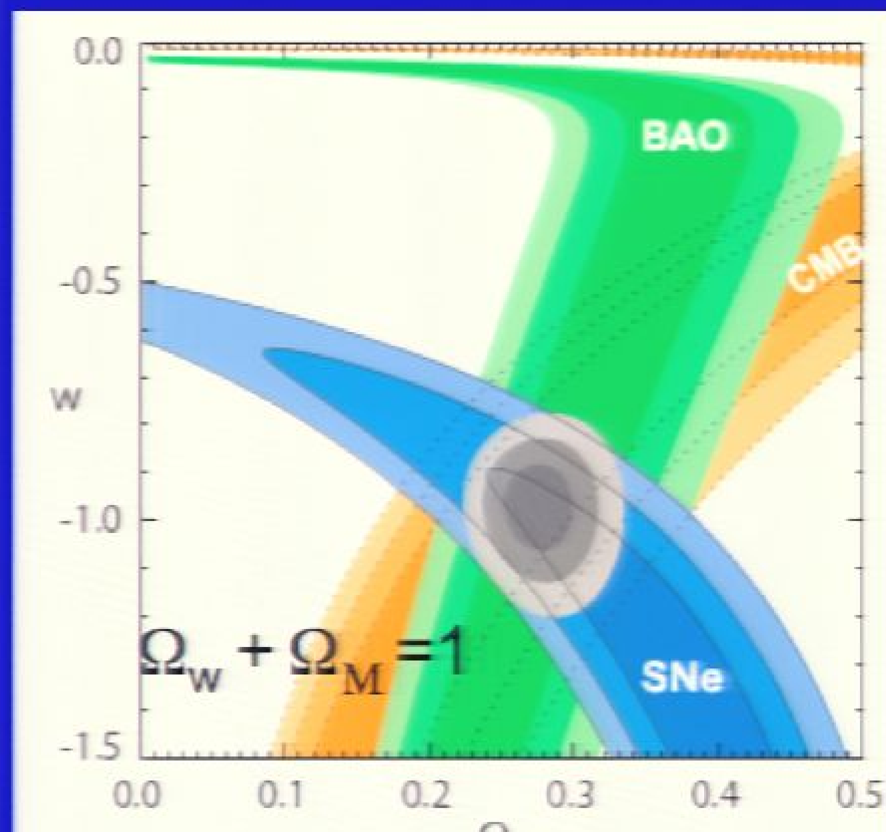
Eisenstein et al. 2005

- 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, have yielded a detection of the BAO at <z>=0.2 and <z>=0.35

Where we Stand now

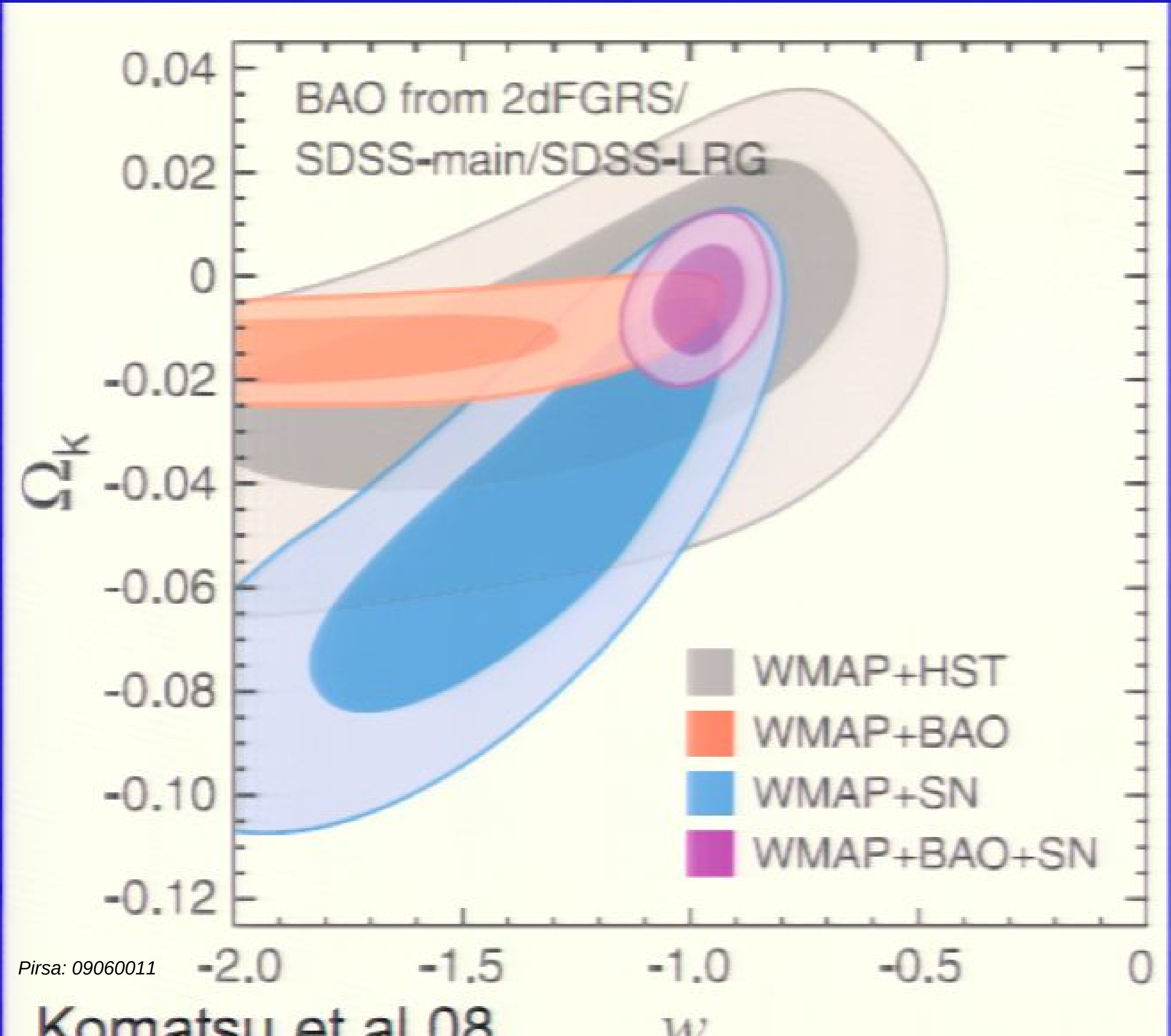
SN Ia (SNLS, Higher-Z, Essence, low-Z stuff) +
WMAP5 +BAO(SDSS)+ HST H_0





Where we Stand now

SN Ia (SNLS, Higher-Z, Essence, low-Z stuff) + WMAP5 +BAO(SDSS & 2dF) + HST H_0



Komatsu et al 08

w

Ω_w

Ω_M

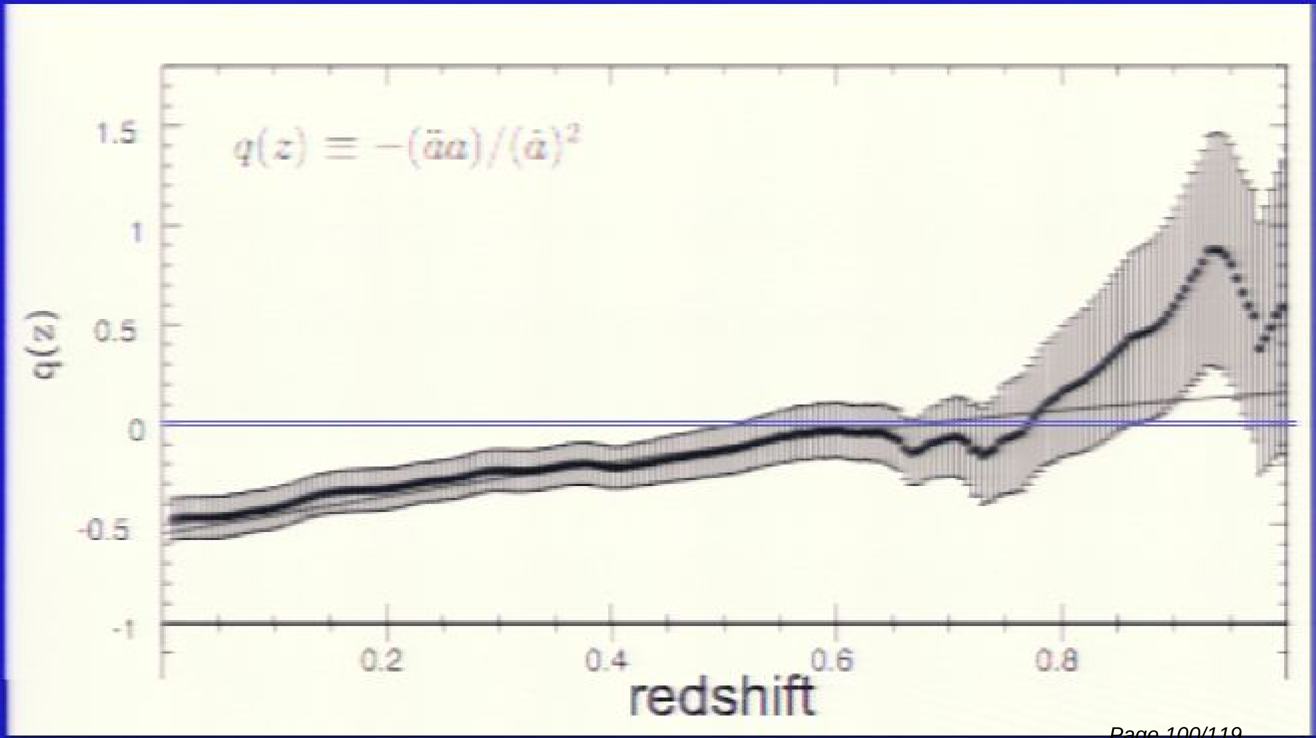
Ω_K

all constrained simultaneously

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. 2008

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!

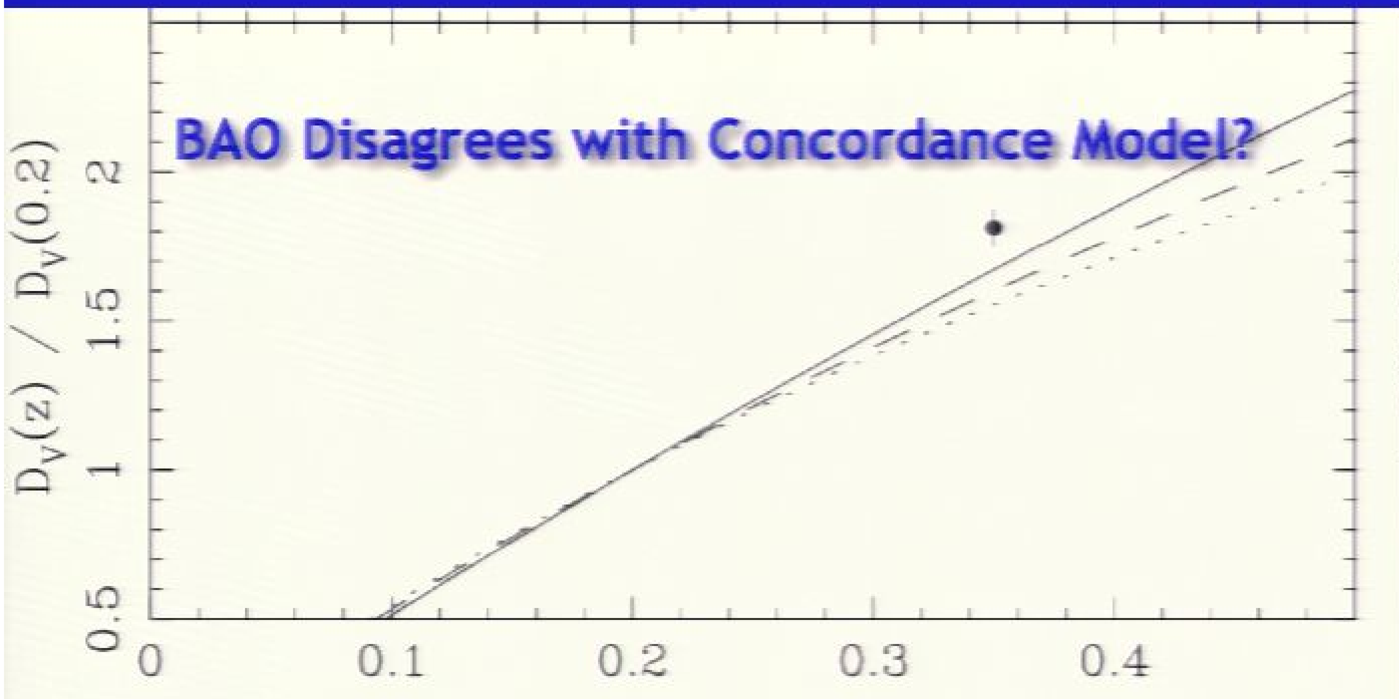
Dark Energy looks a lot like Λ

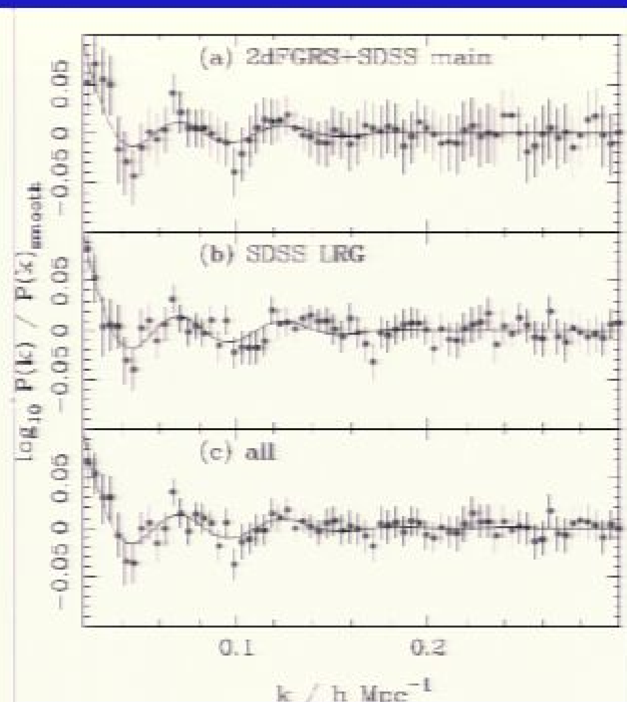
- In total, as near as we can tell the Universe is expanding just as a Cosmological Constant would predict.
- Observers are searching blindly, hoping to find something that distinguishes it from Λ.

- 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

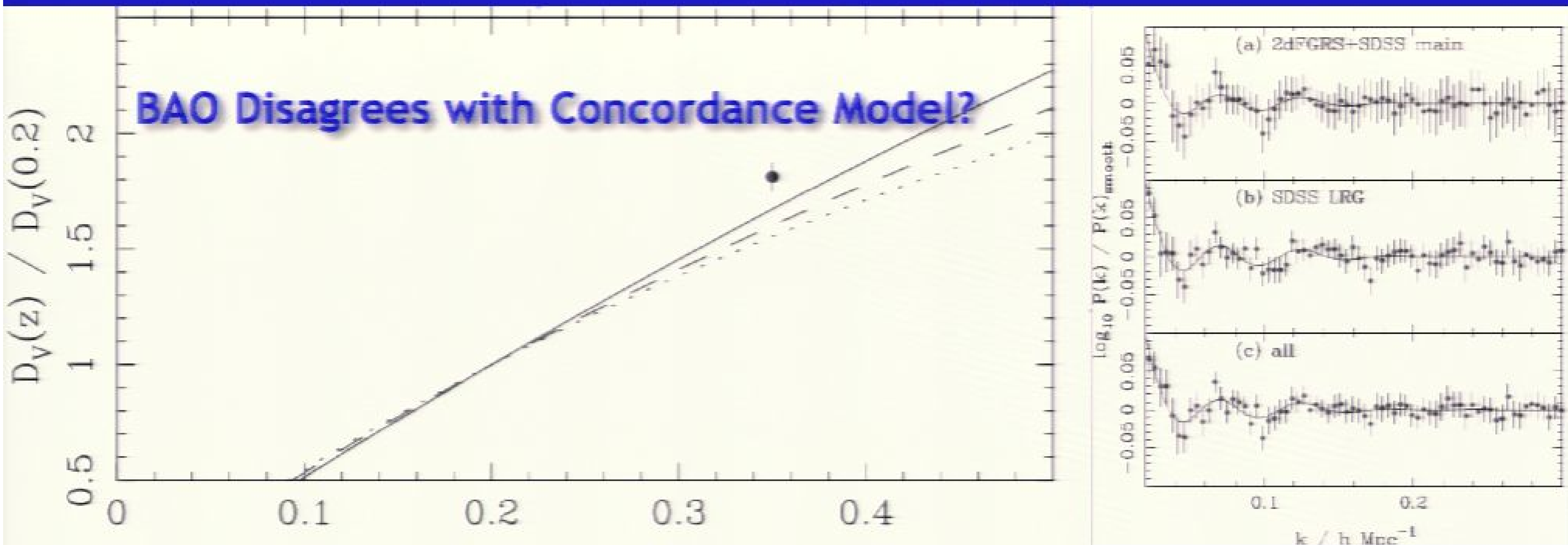
We need to remember this is parameterized ignorance. The Goal is to constrain physics based models, not essentially meaningless numbers.

BAO can measures effects of Dark Energy itself





BAO can measures effects of Dark Energy itself



Percival et al. 07 - ratio of BAO (2dF+SDSS vs. SDSS LRG) distances

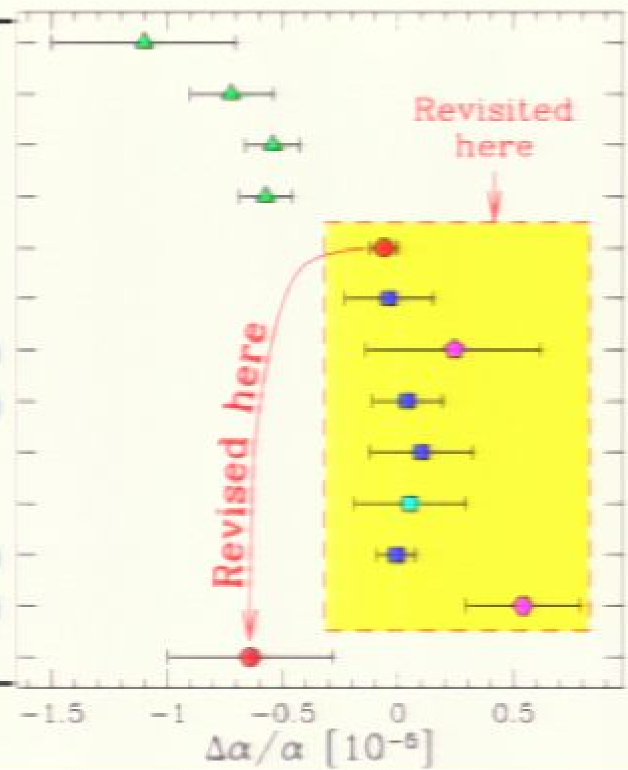
Problem with BAO distances - Concordance Universe

Problem with SN Ia - Non-Λ Dark Energy

Measuring α astronomically

Measure wavelengths of various transitions of lines seen in Quasars

Instrument	N_{abs}	z_{abs}	$\Delta\alpha/\alpha$ [10^{-5}]	Reference
HIRES	30	0.5–1.6	−1.100 ± 0.400	Webb et al. (1999)
HIRES	49	0.5–3.5	−0.720 ± 0.180	Murphy et al. (2001a)
HIRES	128	0.2–3.7	−0.543 ± 0.116	Murphy et al. (2003)
HIRES	143	0.2–4.2	−0.573 ± 0.113	Murphy et al. (2004)
UVES	23	0.4–2.3	−0.060 ± 0.060	Chand et al. (2004)
UVES	1	1.151	−0.040 ± 0.190 ± 0.270	Quast et al. (2004)
UVES	1	1.839	+0.240 ± 0.380	Levshakov et al. (2005)
UVES	1	1.151	+0.040 ± 0.150	Levshakov et al. (2005)
UVES	1	1.151	+0.100 ± 0.220	Chand et al. (2006)
HARPS	1	1.151	+0.050 ± 0.240	Chand et al. (2006)
UVES	1	1.151	−0.007 ± 0.084 (± 0.100)	Levshakov et al. (2006)
UVES	1	1.839	+0.540 ± 0.250	Levshakov et al. (2007)
UVES	23	0.4–2.3	−0.640 ± 0.360	This work



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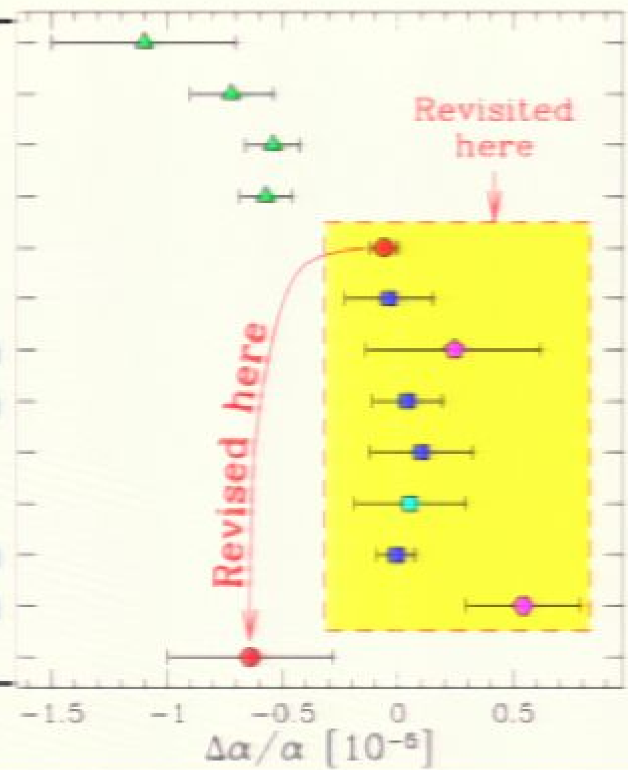


Do I believe α has been measured? Not yet.

Has this result been disproved? Not Yet.

Really requires specific instrumentation

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 5 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

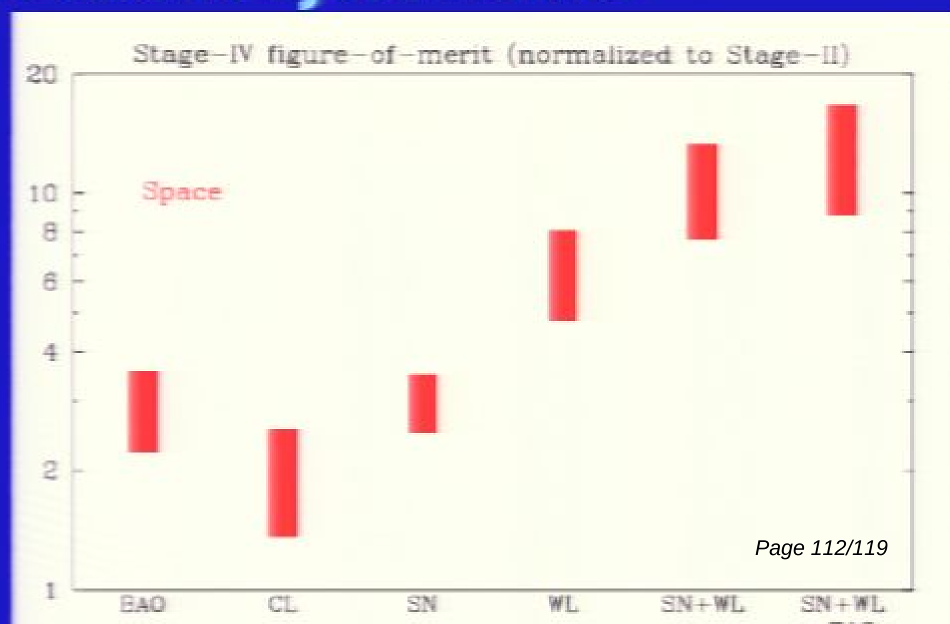
Future BAO surveys

Instrument	Telescope	Redshift range	Area (deg^2)	Volume (Gpc^3)	Start?	Cost
AAOmega	AAT	0.5–1.0	1000	3.0	2006	Already exists
FMOS	Subaru	1.0–1.5	300	1.4	2007?	Already exists
HETDEX	HET	1.8–3.8	200	4.7	2009	$20M?
SDSS-III	2.5m SDSS	0.3–0.6	8000	7.4	2008	$20M?
WFMOS	Subaru	0.5–1.5 2.5–3.5	2000 300	19	2012?	$60M
ADEPT	1.3m space NIR slitless spectroscopy	1.3–2	30,000	230	2012?	$600M
SKA	Large phased array?	<1.5?	30,000	250	2015?	$1B

from Glazebrook

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.



Dark Energy Futures
The Unexpected

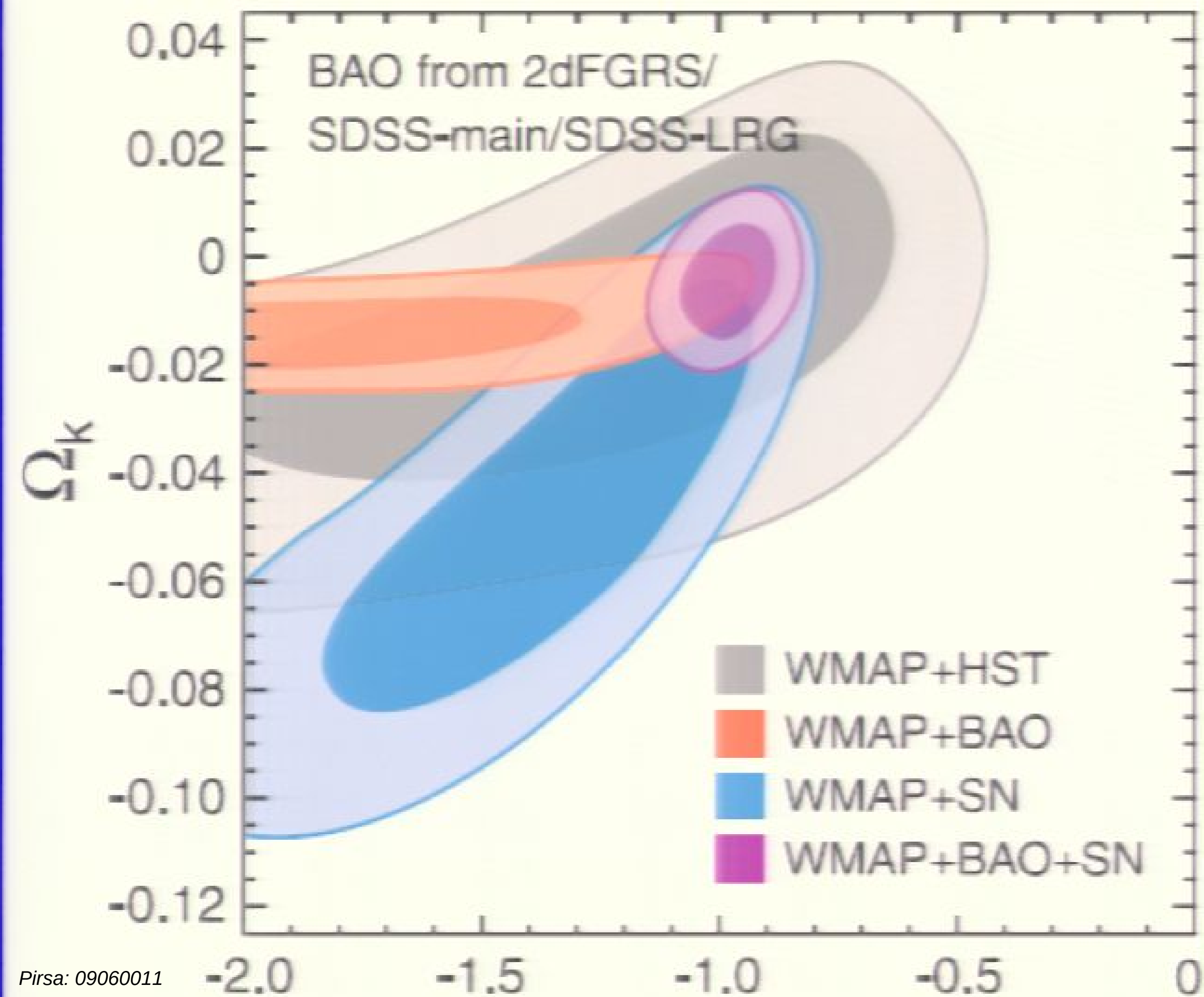
- Astronomy is full of Mysteries besides Dark Energy

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

Where we Stand now

SN Ia (SNLS, Higher-Z, Essence, low-Z stuff) + WMAP5 +BAO(SDSS & 2dF) + HST H_0



w

Ω_w

Ω_M

Ω_K

all constrained simultaneously

Komatsu et al 08

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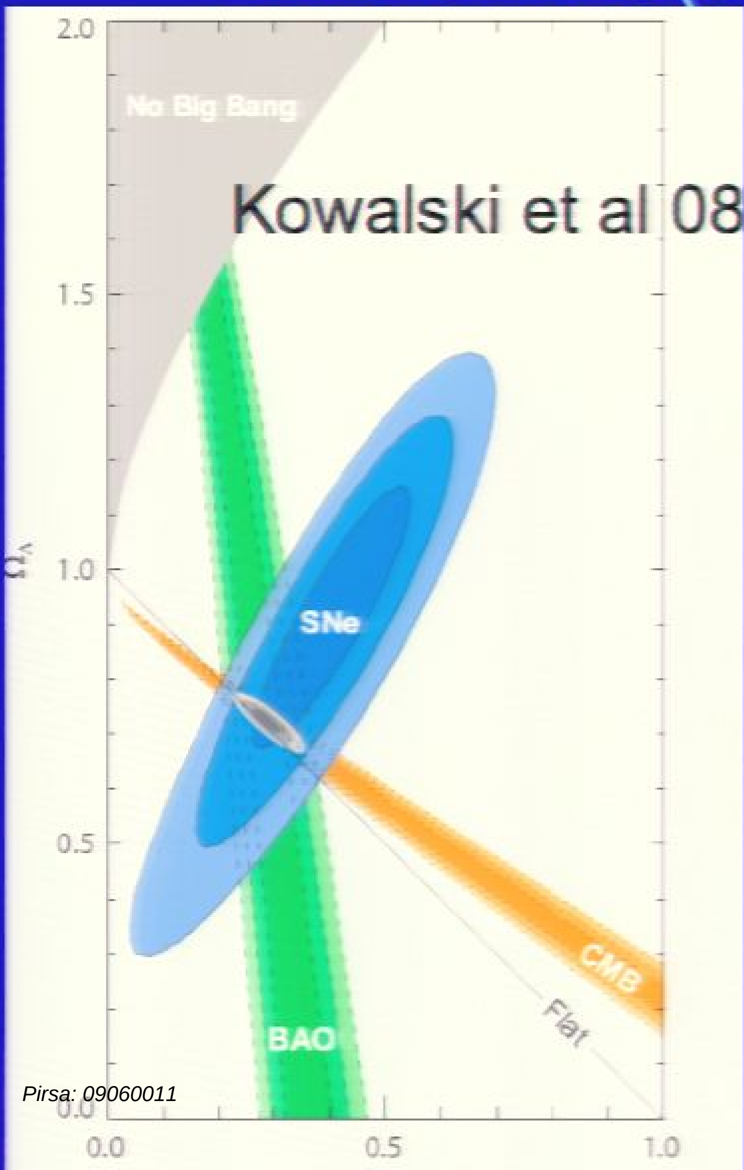

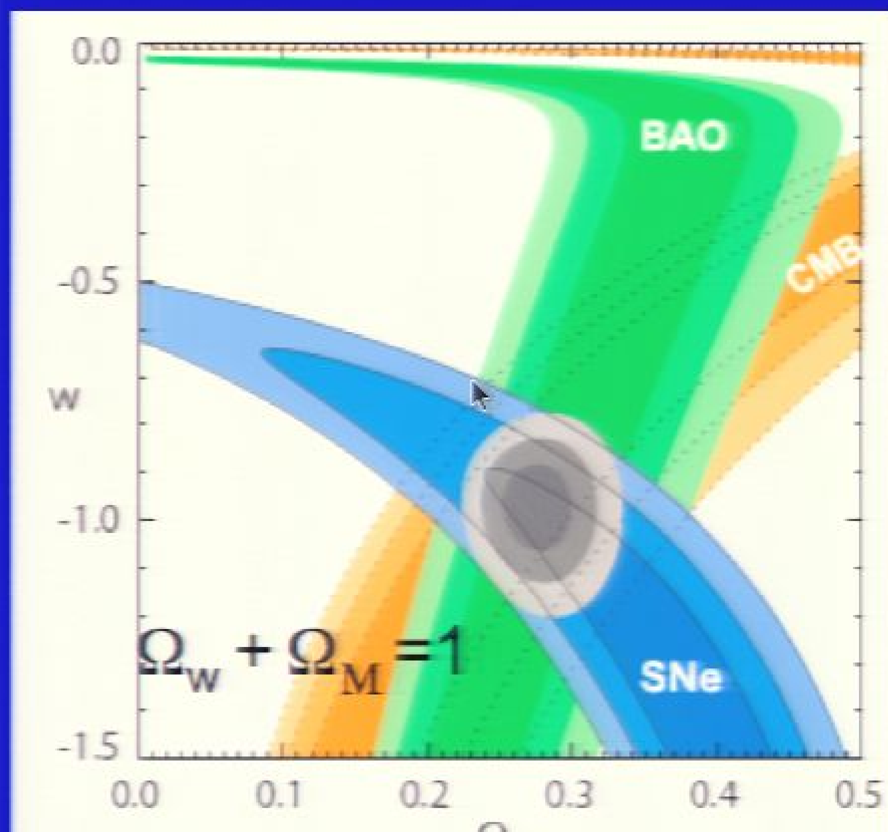

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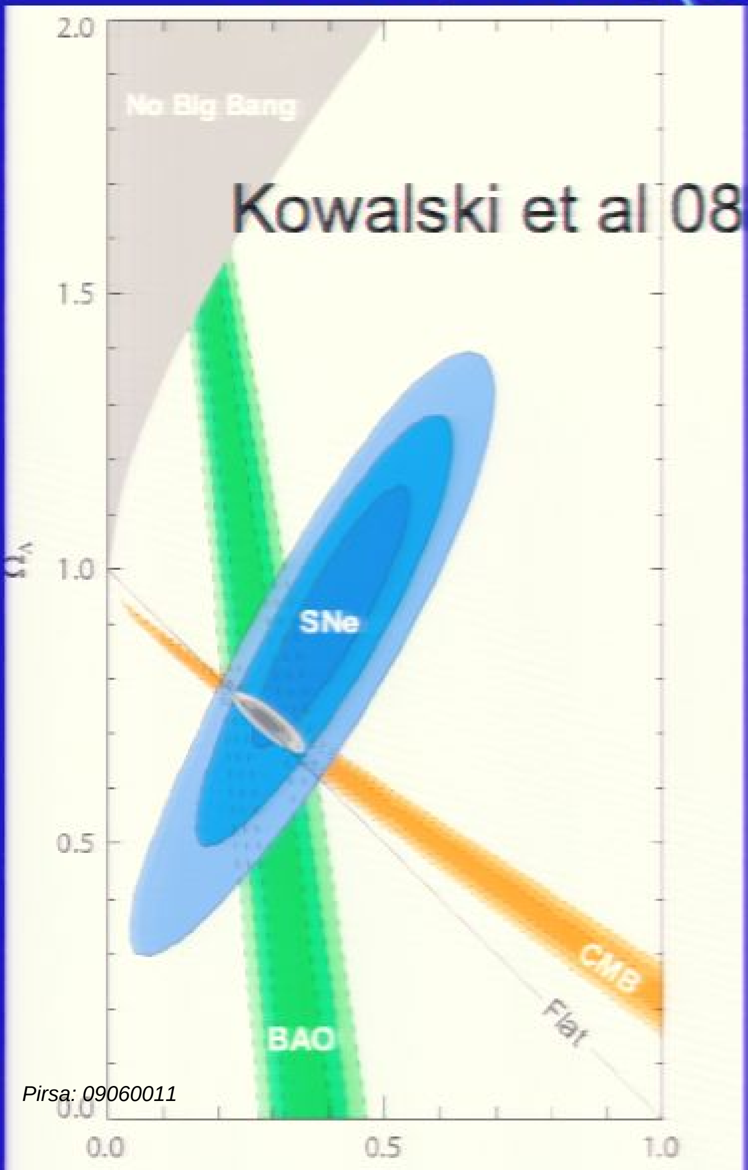

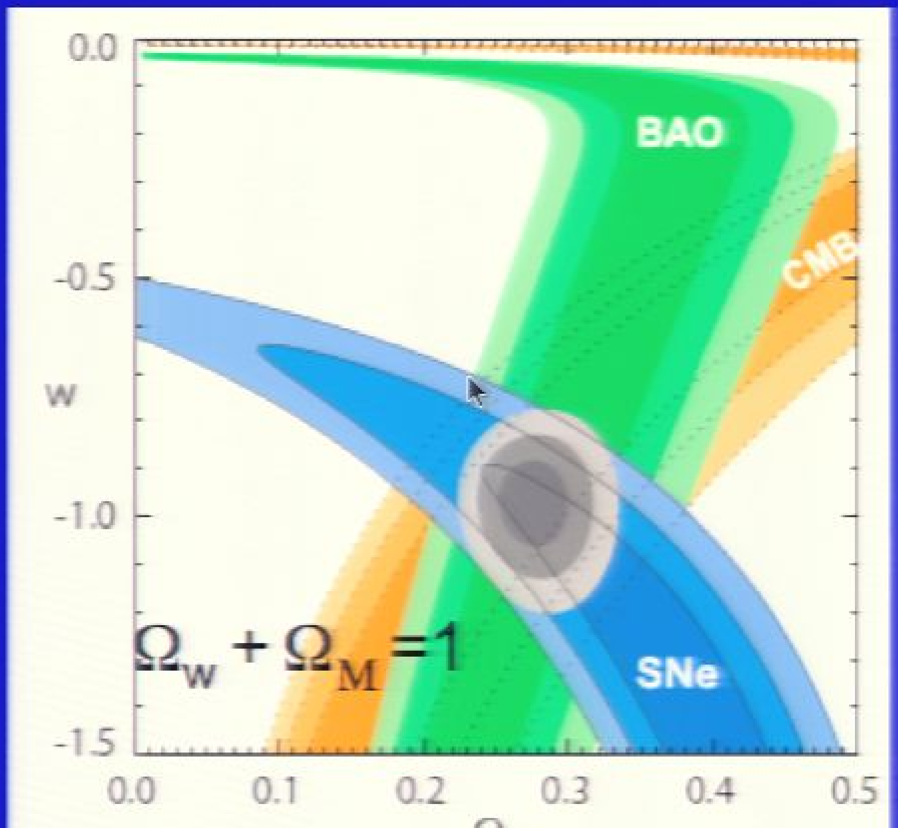

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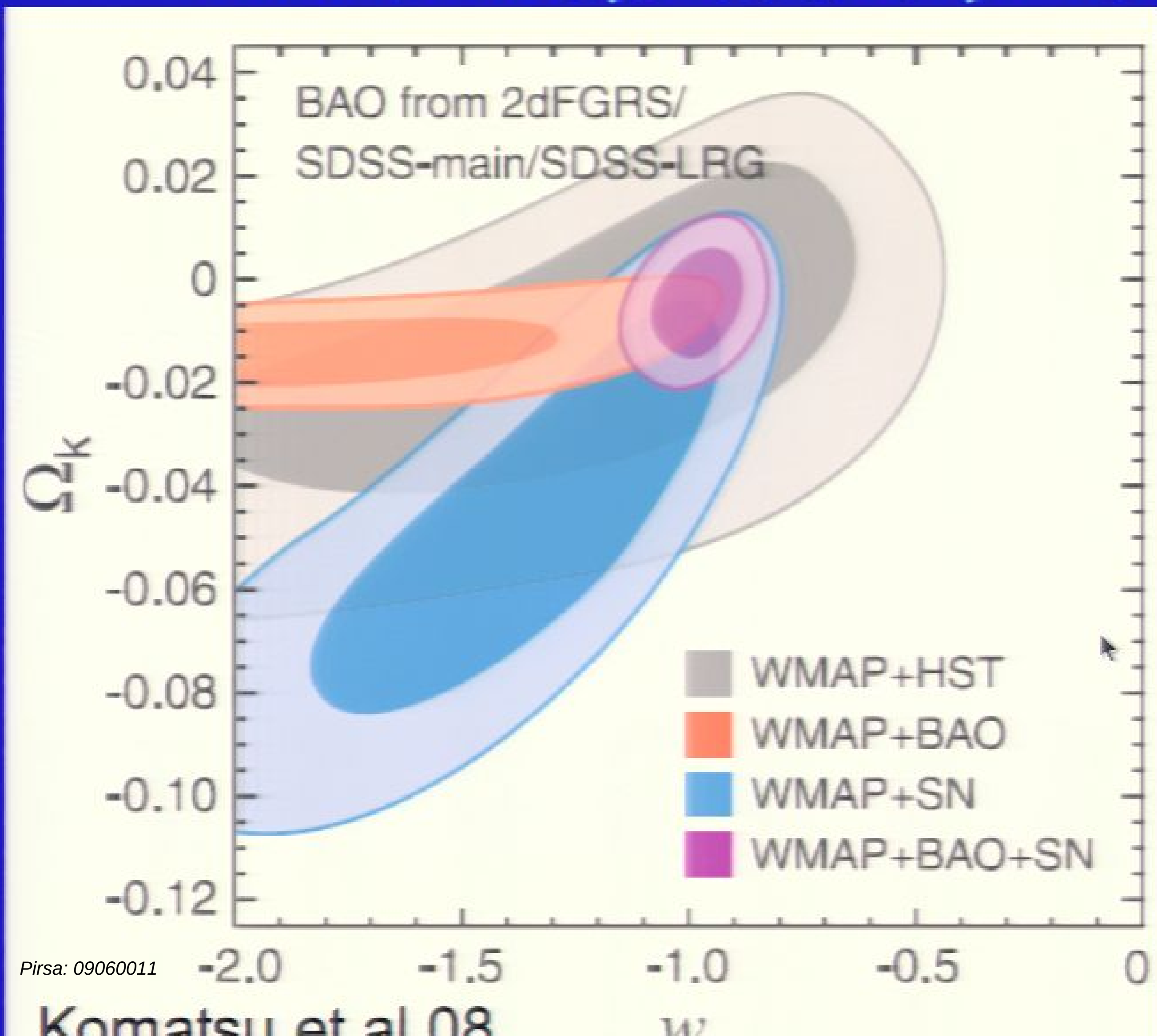

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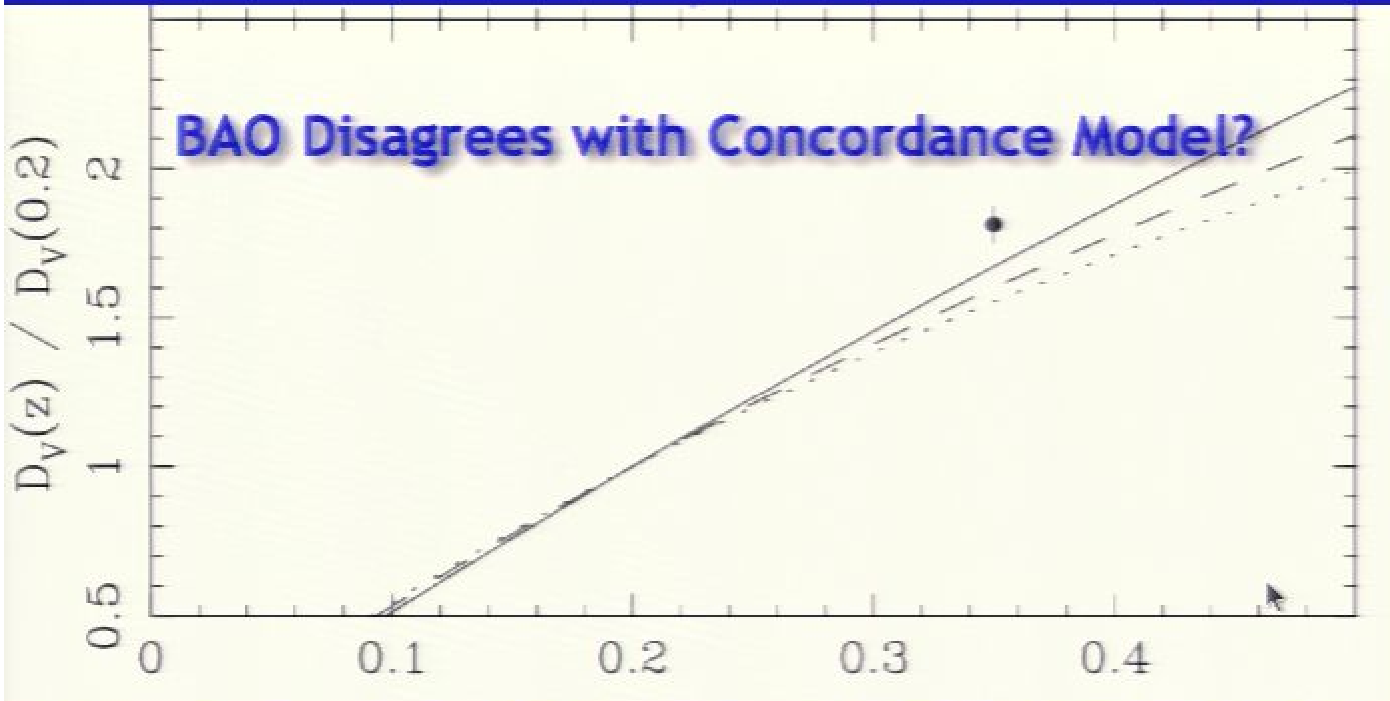

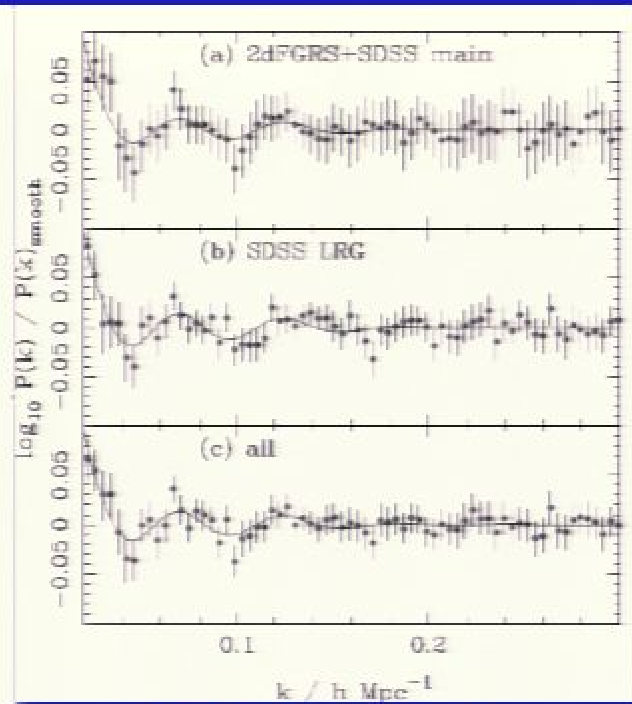

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