

The Accelerating Universe

BRIAN P. SCHMIDT



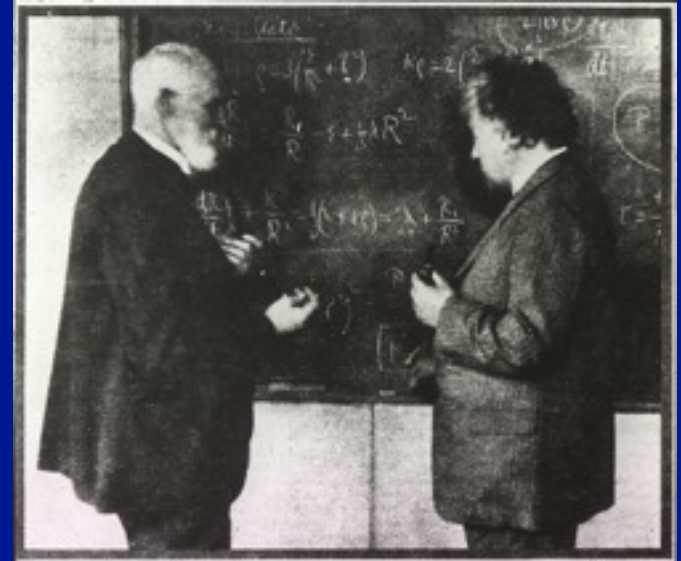
ANU

THE AUSTRALIAN NATIONAL UNIVERSITY

**THE RESEARCH SCHOOL OF ASTRONOMY &
ASTROPHYSICS
MOUNT STROMLO AND SIDING SPRING OBSERVATORIES**

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 isotropic Universe

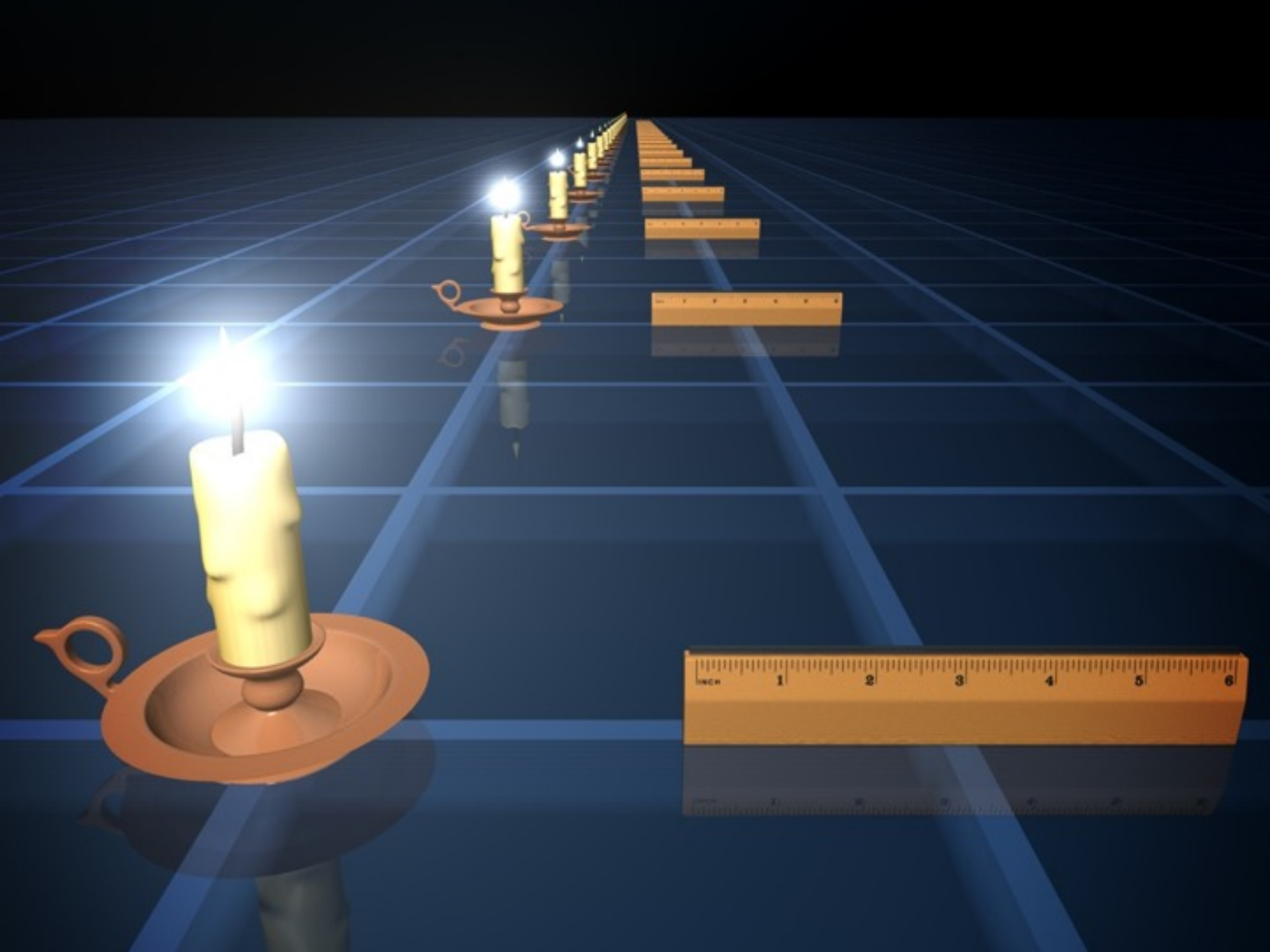


Birth of Observational Cosmology

- 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



*1929, Hubble uses brightest stars
to measure the
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*He assumes the
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**The faster the galaxy was moving,
the fainter the stars!**

Hubble's Data

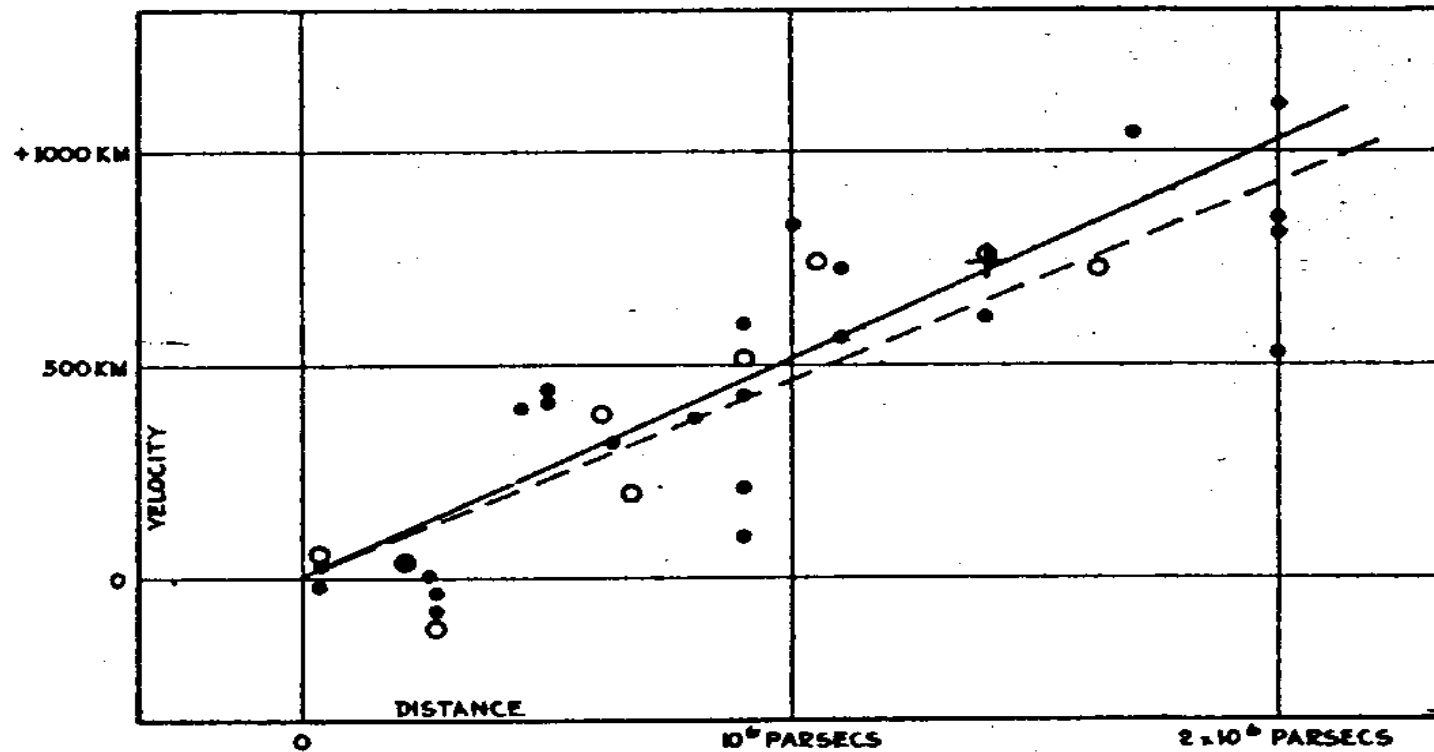


FIGURE 1

Brighter Stars

Fainter Stars

Low Redshift

High Redshift

**The
Universe is
Expanding**



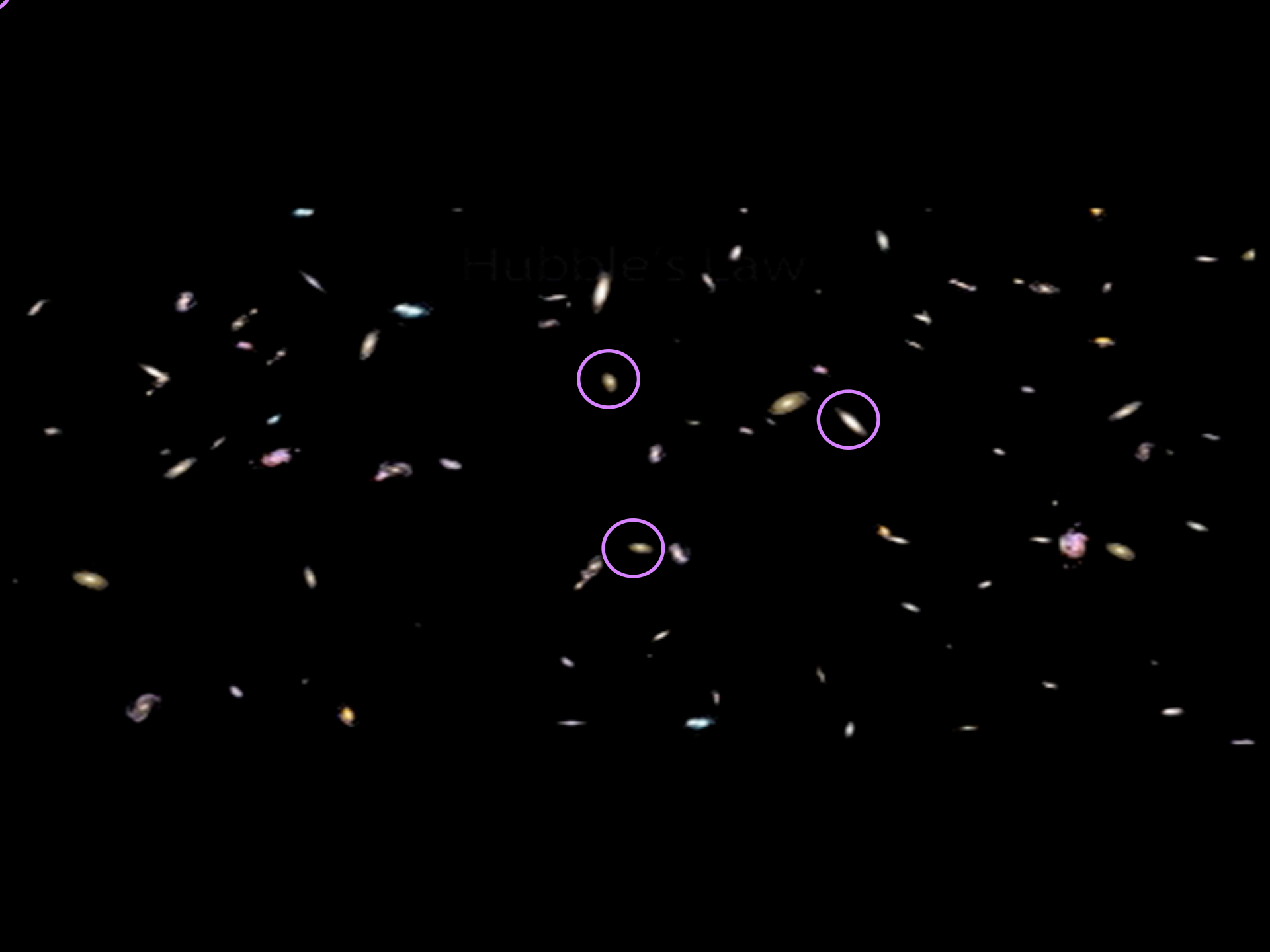
Hubble's Law



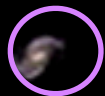
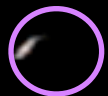
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Hubble's Law



Hubble's Law



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

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

Classical Observational Tests

1950s...

- **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]”

The Distance Between Two Galaxies

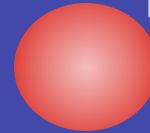
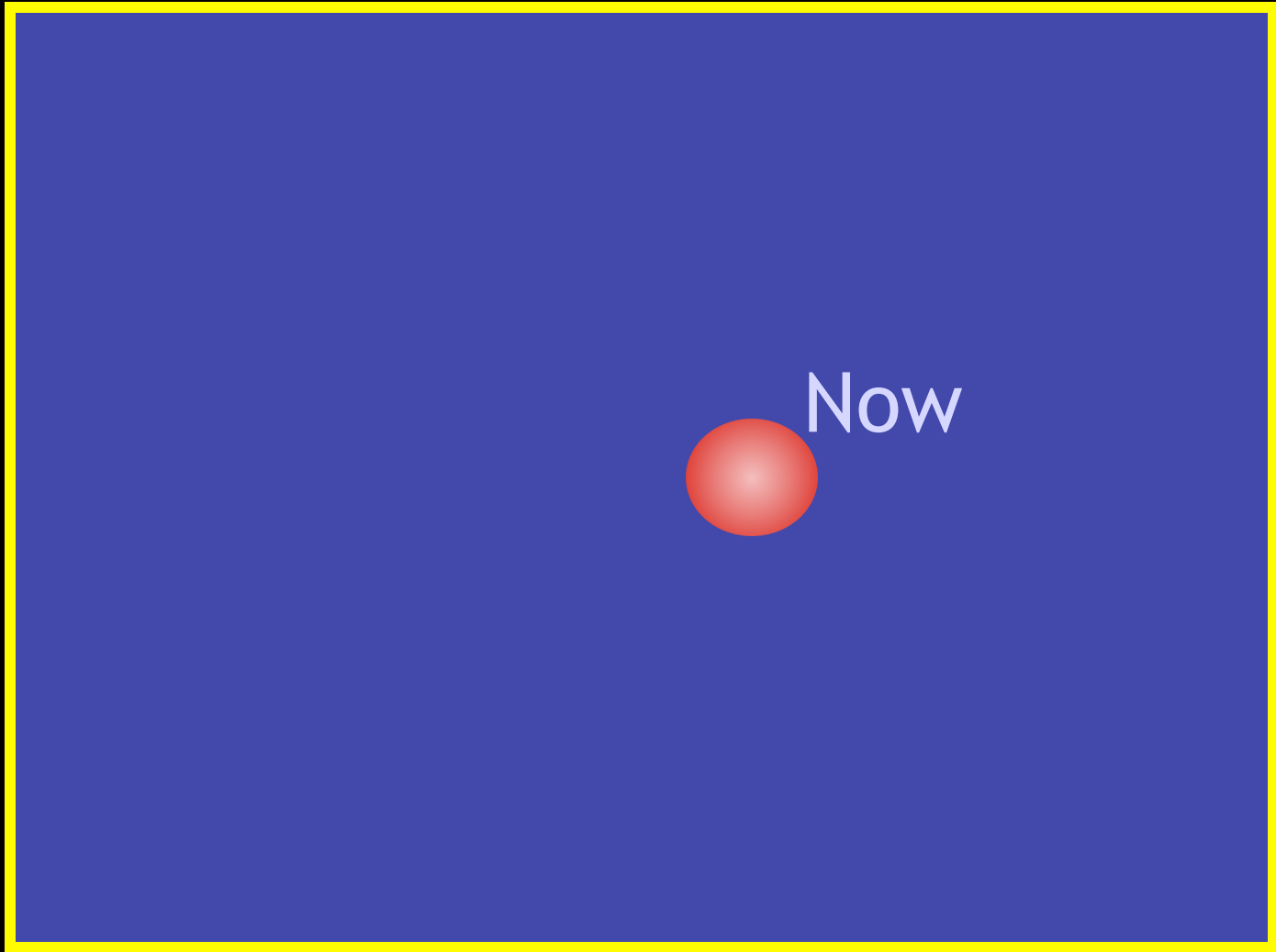
Separation



Time

The Distance Between Two Galaxies

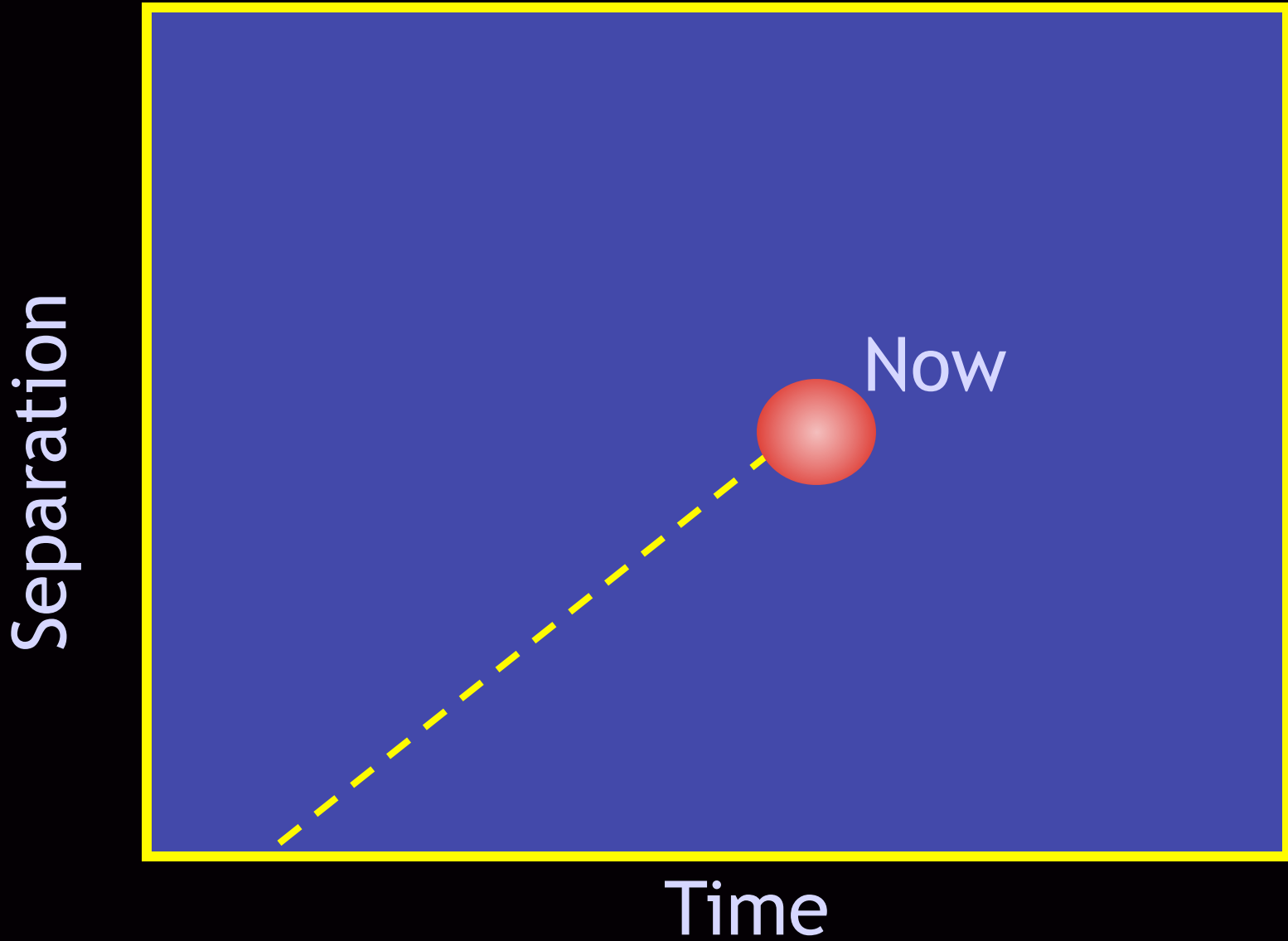
Separation



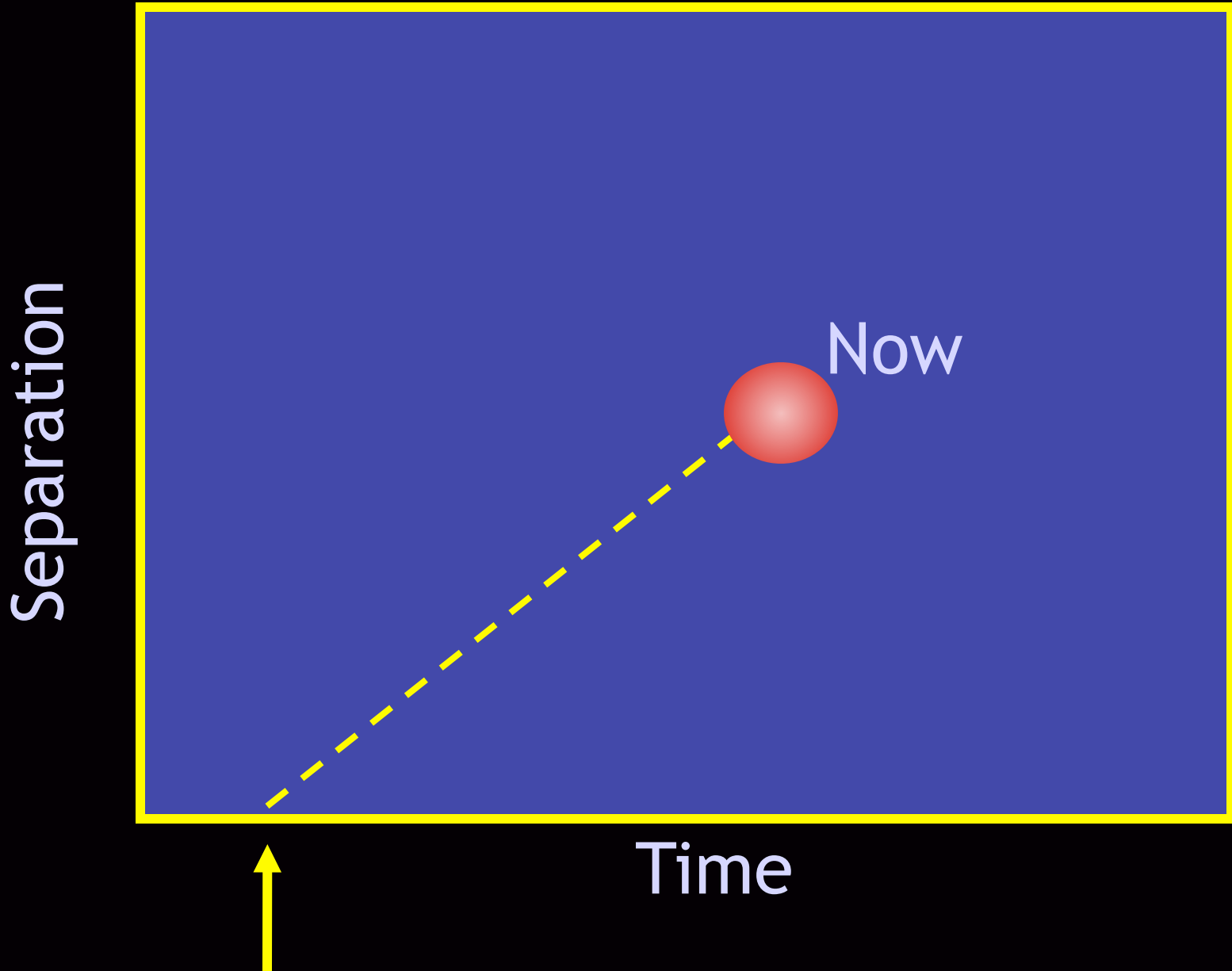
Now

Time

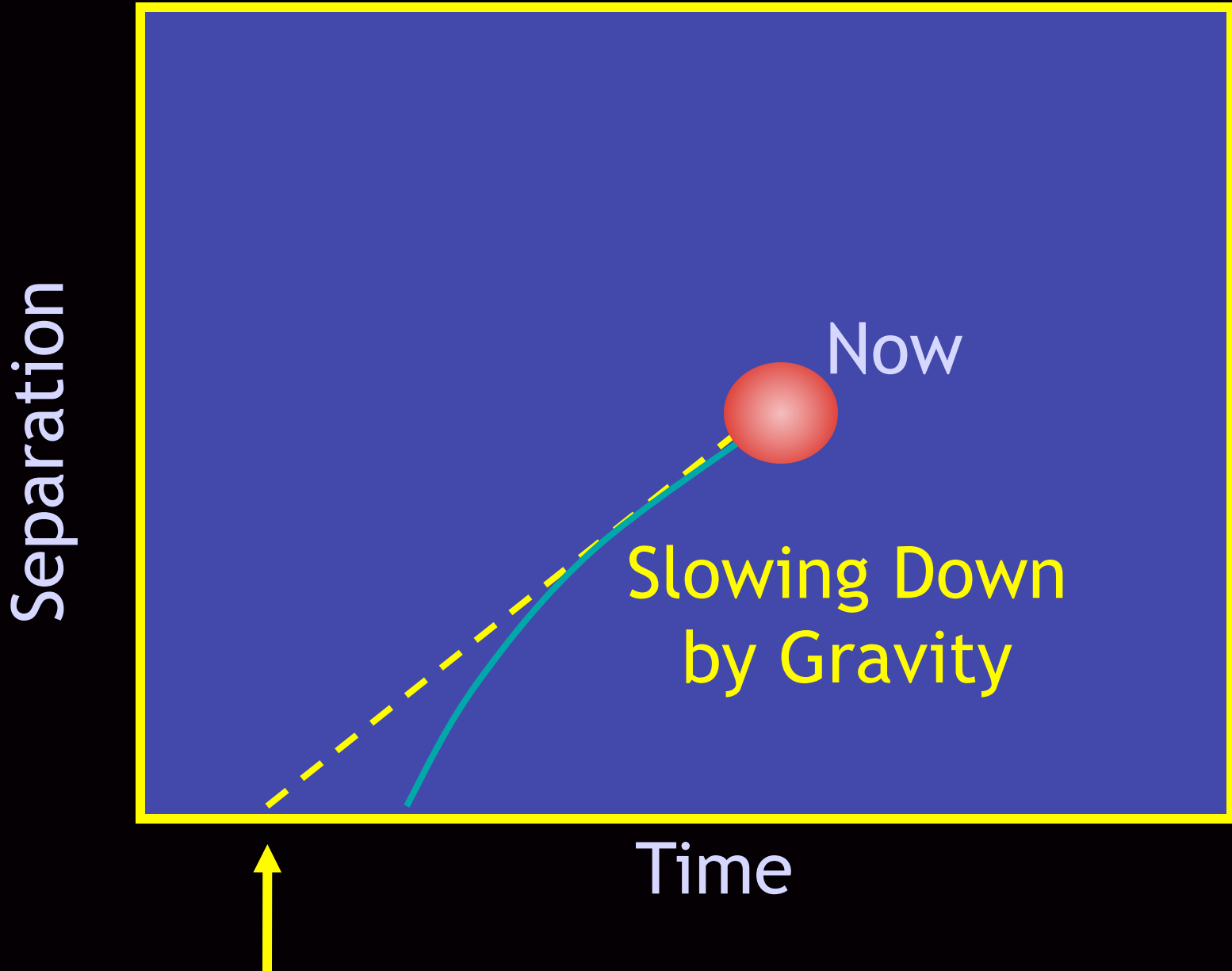
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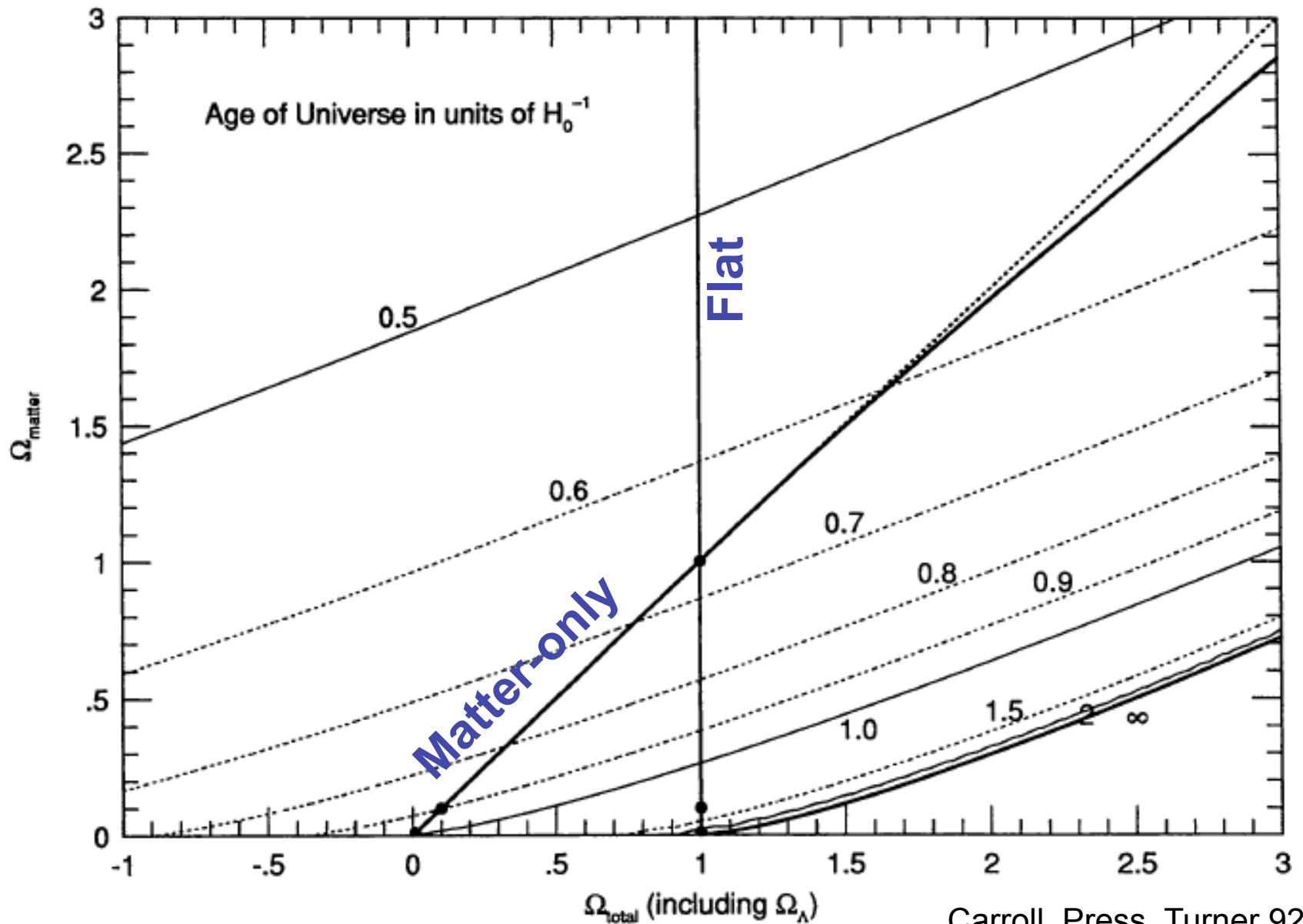
The Distance Between Two Galaxies



The Distance Between Two Galaxies



Age



Age Measurements 1950-1990

Hubble Constant Measurements Difficult!

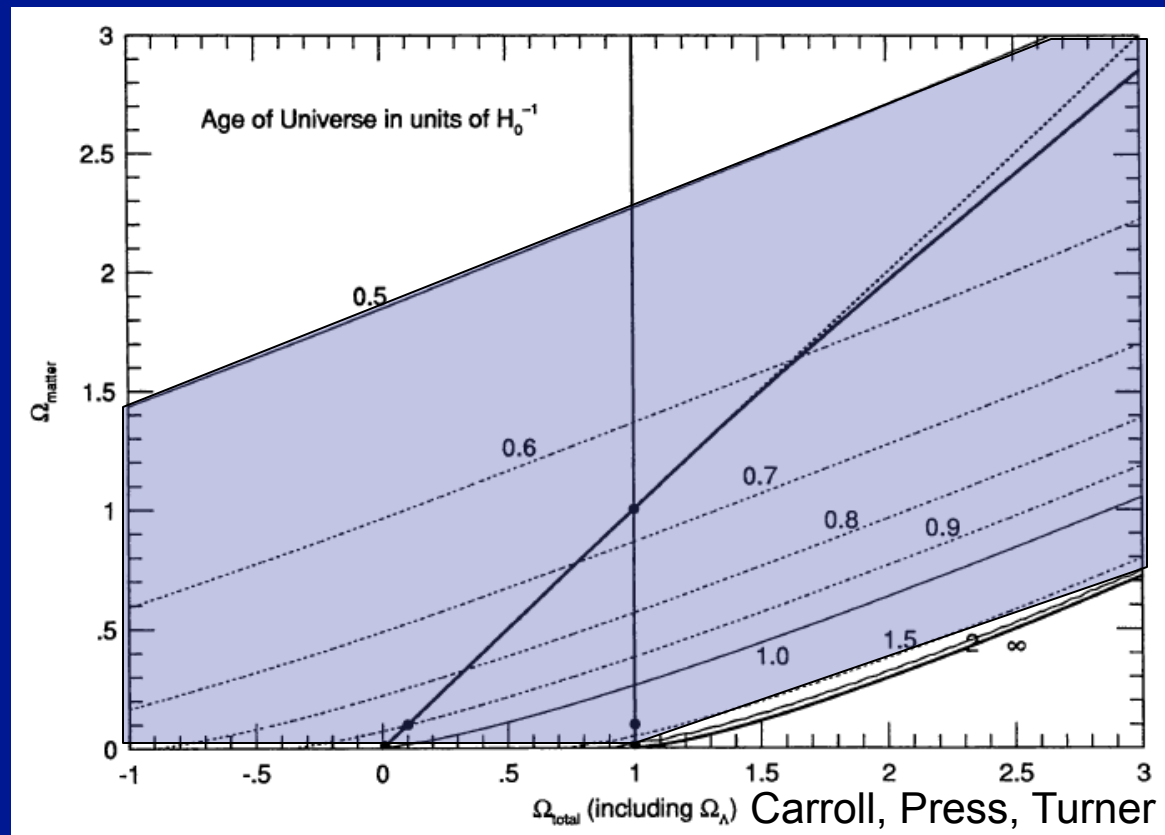
$$40 < H_0 < 100 \text{ km/s/Mpc}$$

$$24.5 > 1/H_0 > 9.8 \text{ Gyr}$$

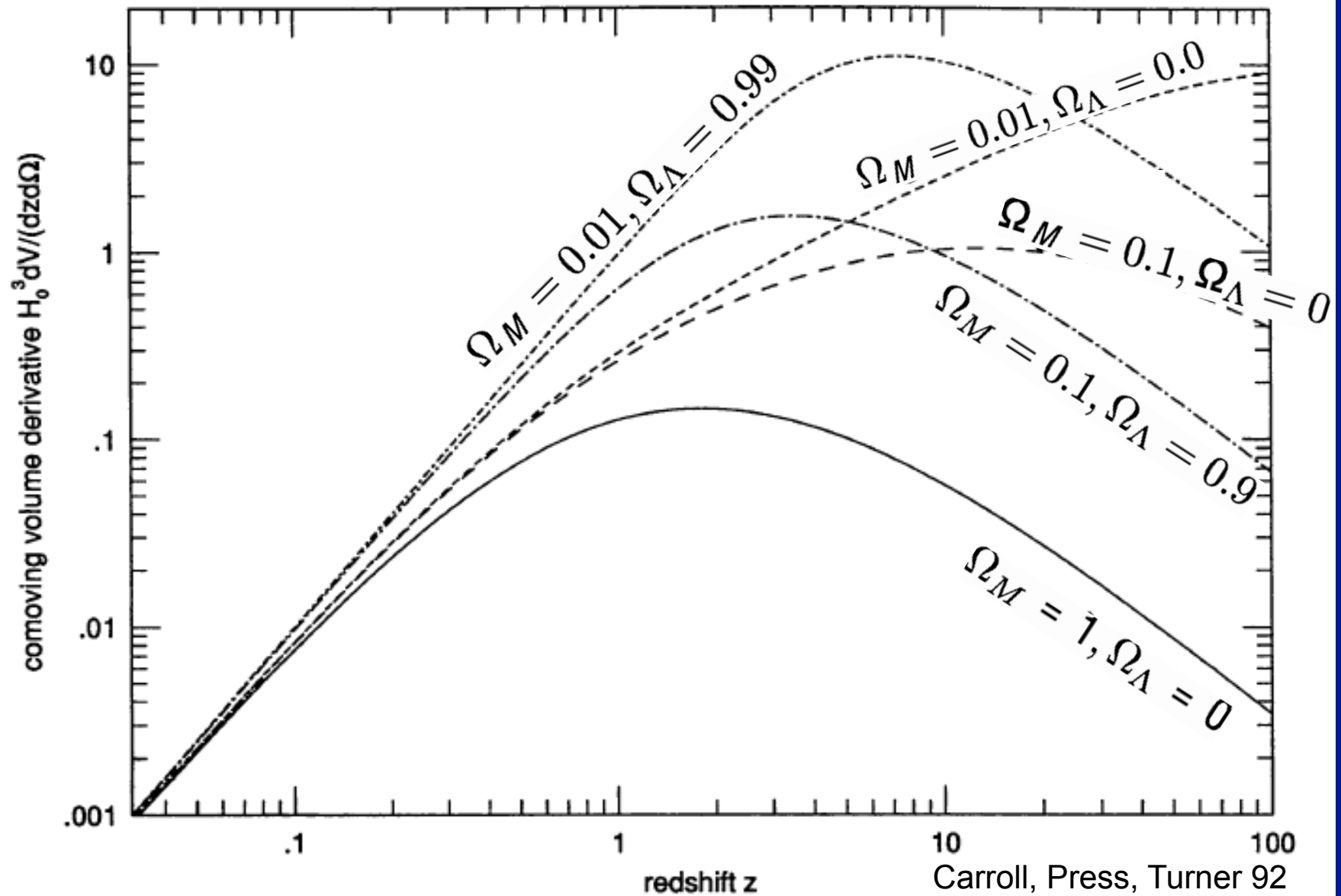
Oldest star ages

$$13\text{-}20 \text{ Gyr}$$

$$0.53 < H_0 t < 2.05$$



Volume



Excess $z \sim 2$ QSOs: Loitering Universe

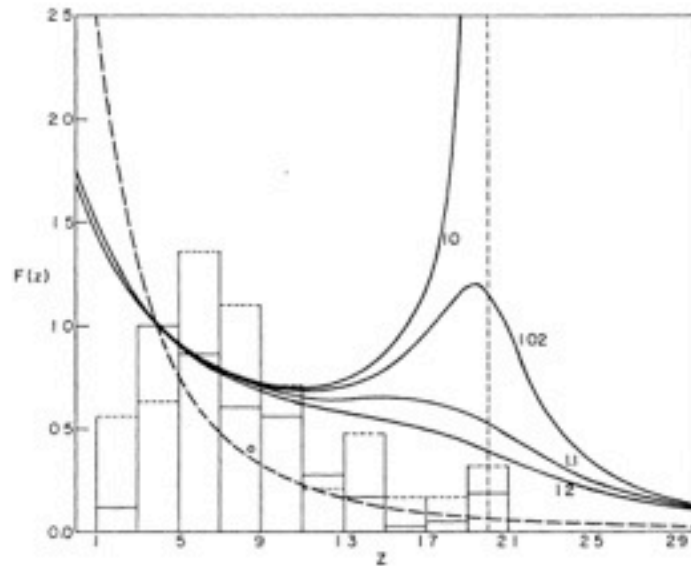
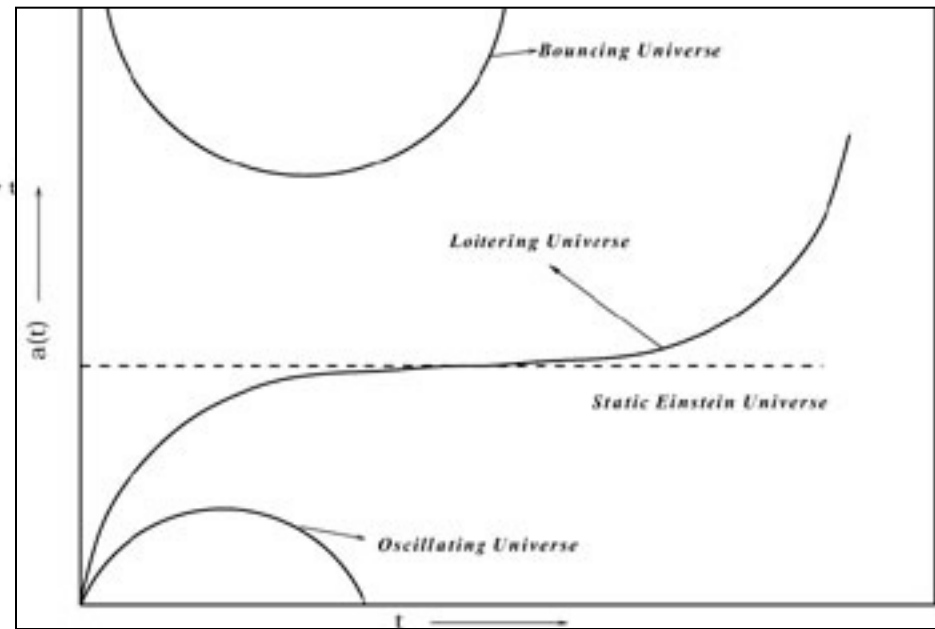


FIG. 2.—The integrated intensity function F plotted against redshift z . Curves are labeled by the value of the cosmological constant α . Solid histogram for optical data, dashed for radio.

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



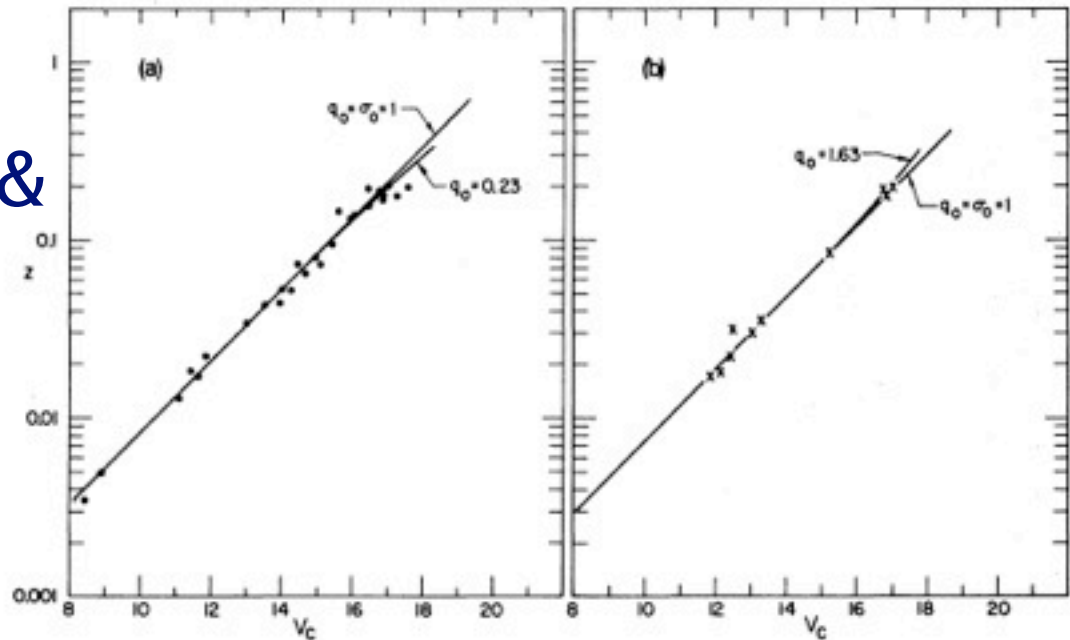
Brightest Cluster Galaxies

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

1970s & 80s

Inflation + Cold Dark Matter

Inflation

- Explains Uniformity of CMB

- Provides seeds of structure formation

CDM

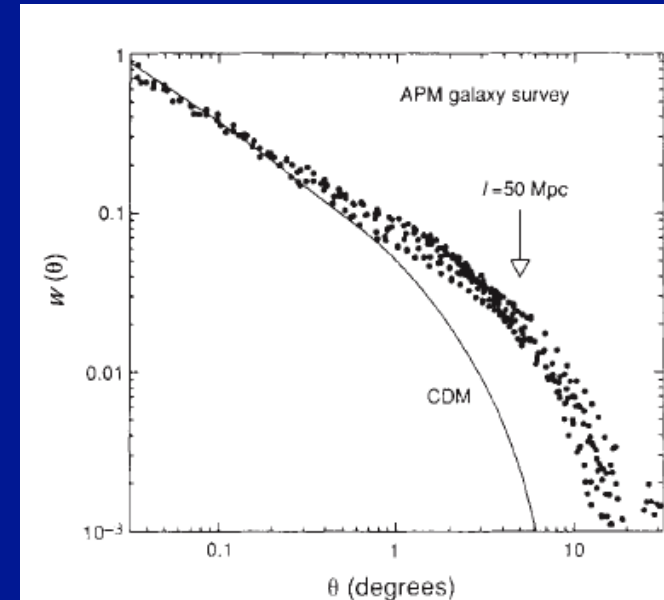
- Consistent with rotation curves of Galaxies

- Gives Structure formation

Predicts Flatness and how Structure Grows on different scales.

1990 - CDM Picture conflicts with what is seen

- Requires flatness, but $\Omega_M \sim 0.2$ from clusters
- Too much power on large scales in observations
- Efstathiou, Sutherland, and Maddox showed that compared to $\Omega_M = 1$,
a $\Omega_M \sim 0.2$, $\Omega_\Lambda \sim 0.8$ 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.

Different Ways of Looking at the Universe - 1993

It was widely presumed that
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(Theorists)

Inflation+CDM paradigm correct

$\Omega \sim 1$

$H_0 \leq 50 \text{ km/s/Mpc}$

Observers are wrong on

H_0 and Ω_M

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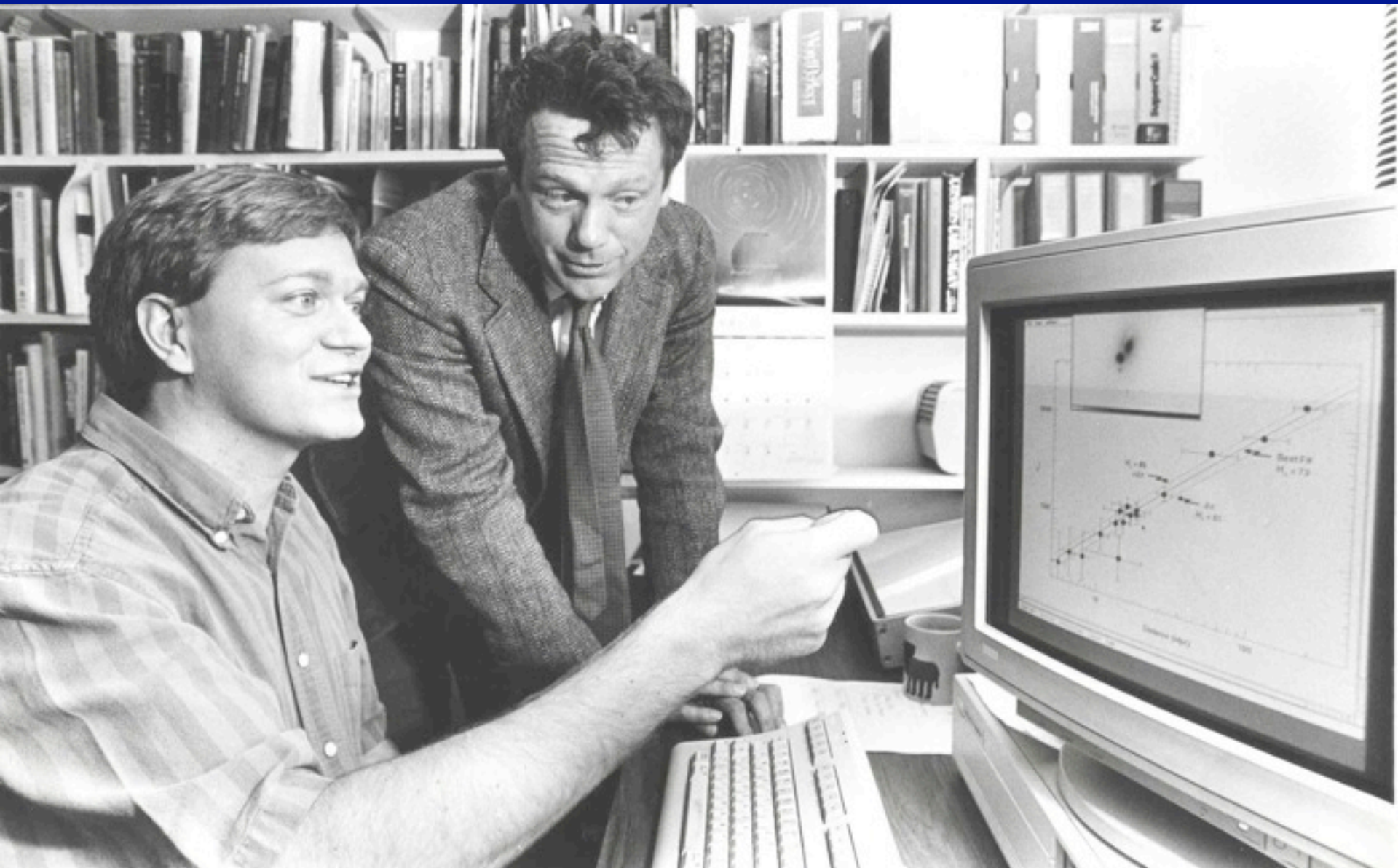
$H_0 = 50-80 \text{ km/s/Mpc}$

Inflation/CDM is wrong

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

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

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



A Wager

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

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


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


John Tonry


Brian Schmidt


Joe Silk

Witnessed this day 2 August 1995


Kenneth Freeman





MODEL PARAMETERS

H_0	age of oldest stars	$11 \pm 1 \text{ Gyr}$
Ω_b	Hubble constant	$h = 0.7 \pm 0.1$
Ω_m	baryon density	0.04 ± 0.01
Ω_Λ	matter density	0.3 ± 0.2
Ω_s	dark energy density	0.7 ± 0.2
Ω_r	radiation	0.0001 ± 0.0001
Ω_{rel}	relative species	0.001 ± 0.001

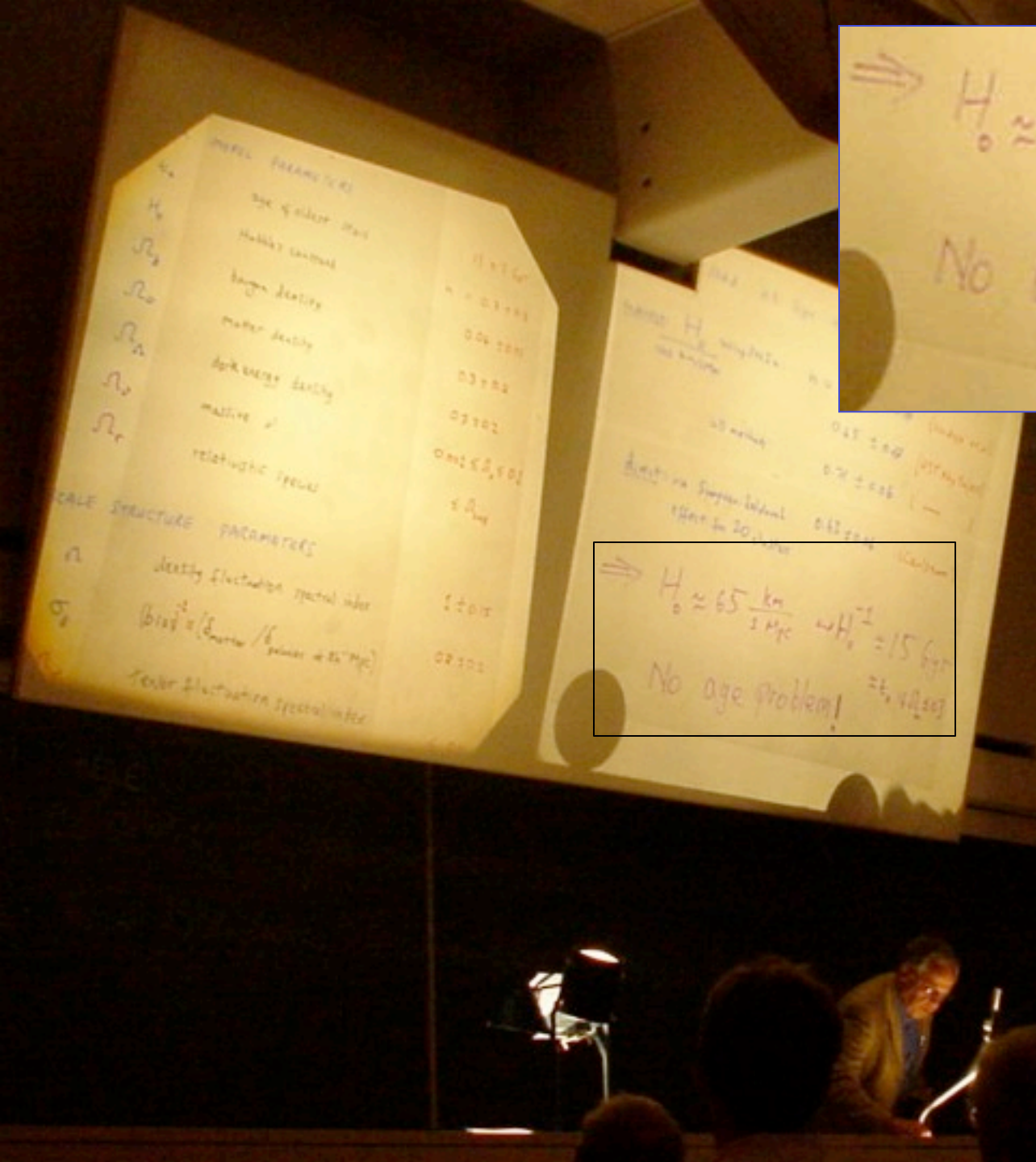
SCALE STRUCTURE PARAMETERS

σ_8	density fluctuation spectral index	1 ± 0.1
σ_8	$(\delta_{rms})^2 \propto (\delta_{rms} / \delta_{rms} \approx 10^{-4} \text{ Mpc}^{-3})$	0.7 ± 0.2
σ_8	Tensor fluctuation spectral index	

MODEL FITS

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$\Rightarrow H_0 \approx 65 \frac{\text{km}}{\text{Mpc}} \Rightarrow H_0^{-1} = 15 \text{ Gyr}$
 $\approx 15 \text{ Gyr}$
 No age problem!



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No age problem! $z \approx 0.4$

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Title: The Cosmological Constant is Back

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

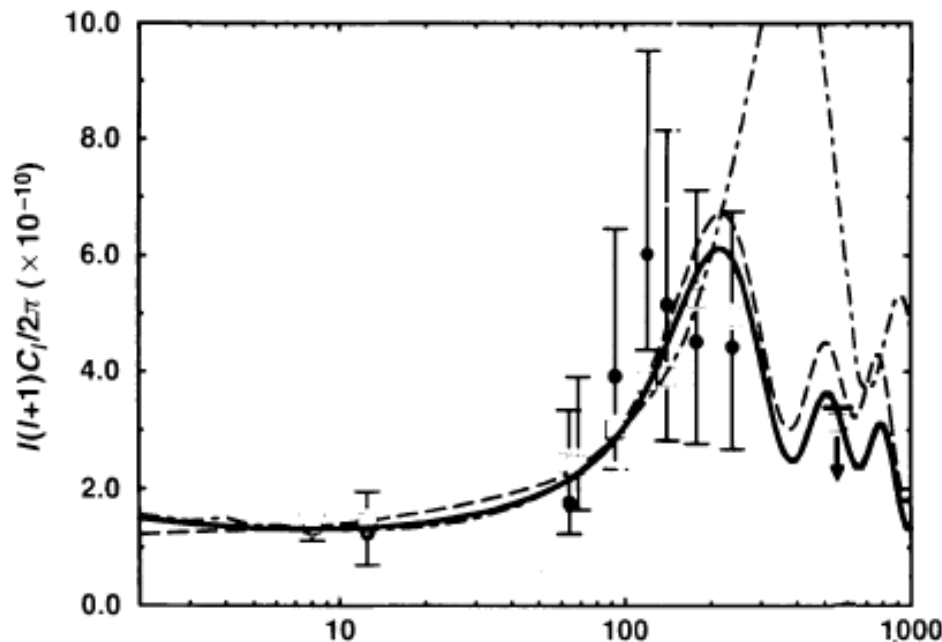
Abstract: A diverse set of observations now compellingly suggest that Universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological constant corresponds to the energy density of the vacuum, and the wanted value for the cosmological constant corresponds to a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

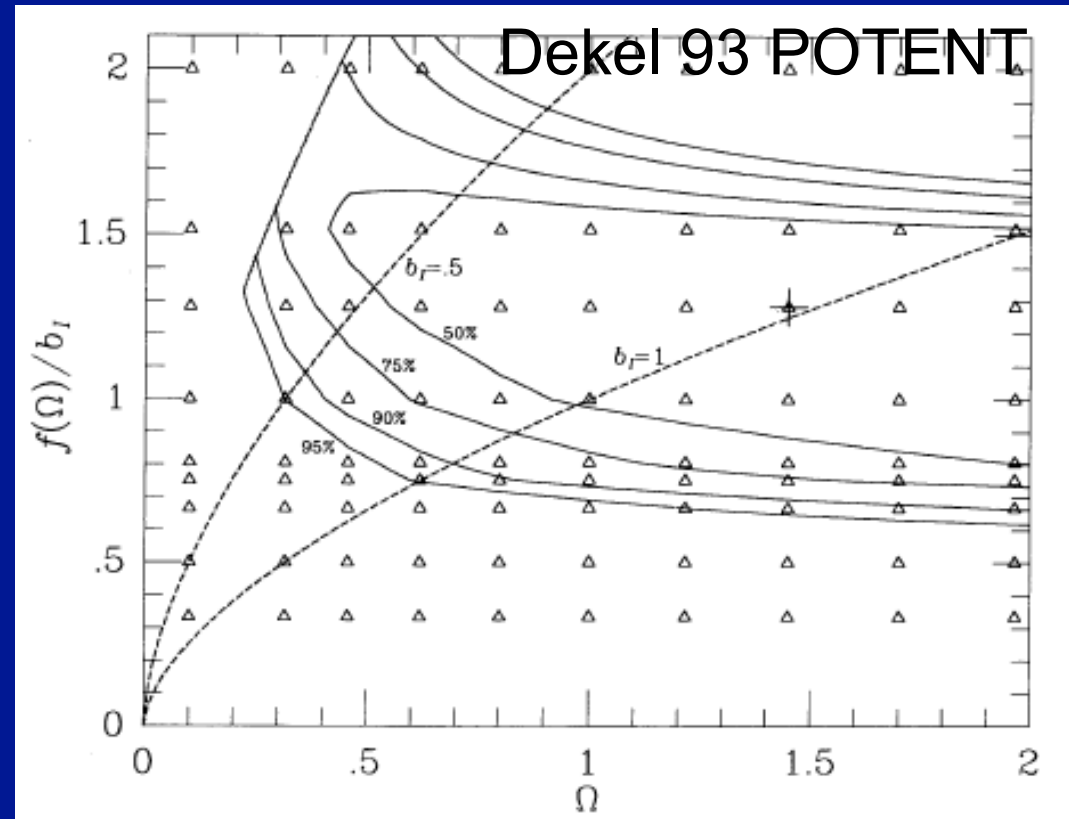
NATURE · VOL 377 · 19 OCTOBER 1995



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 $\Omega_M \sim 0.2$,
There was also evidence suggesting $\Omega_M \sim 1$



CLUSTER X-RAY MORPHOLOGIES

TABLE 3 Mohr et al 1995

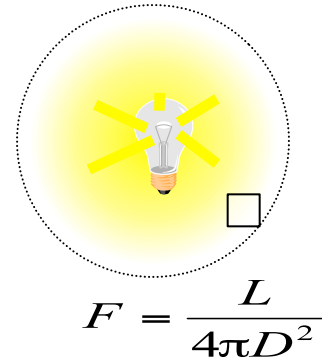
MEAN (and rms) OF w_x , η , AND α DISTRIBUTIONS

Parameter	<i>Einstein</i>	$\Omega=1$	$\Omega_o=0.2$ & $\lambda_o=0.8$	$\Omega_o=0.2$
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)	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)*

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

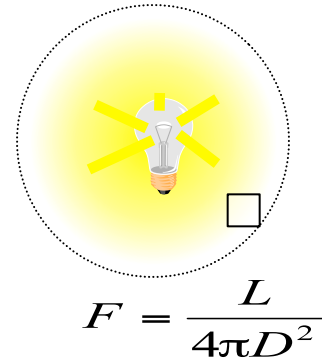


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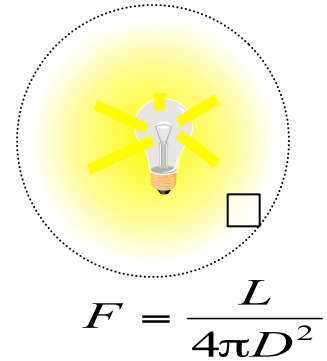
the flux an observer sees of an object at redshift z

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

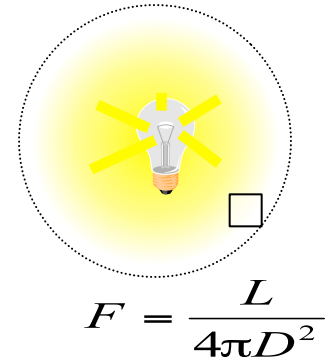
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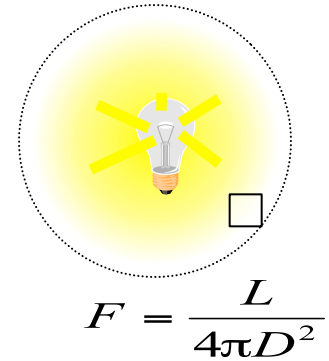
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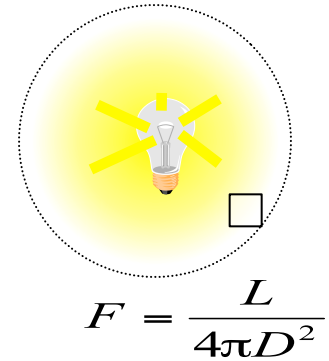
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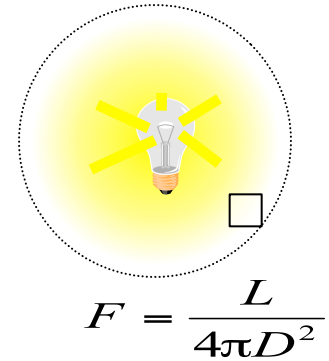
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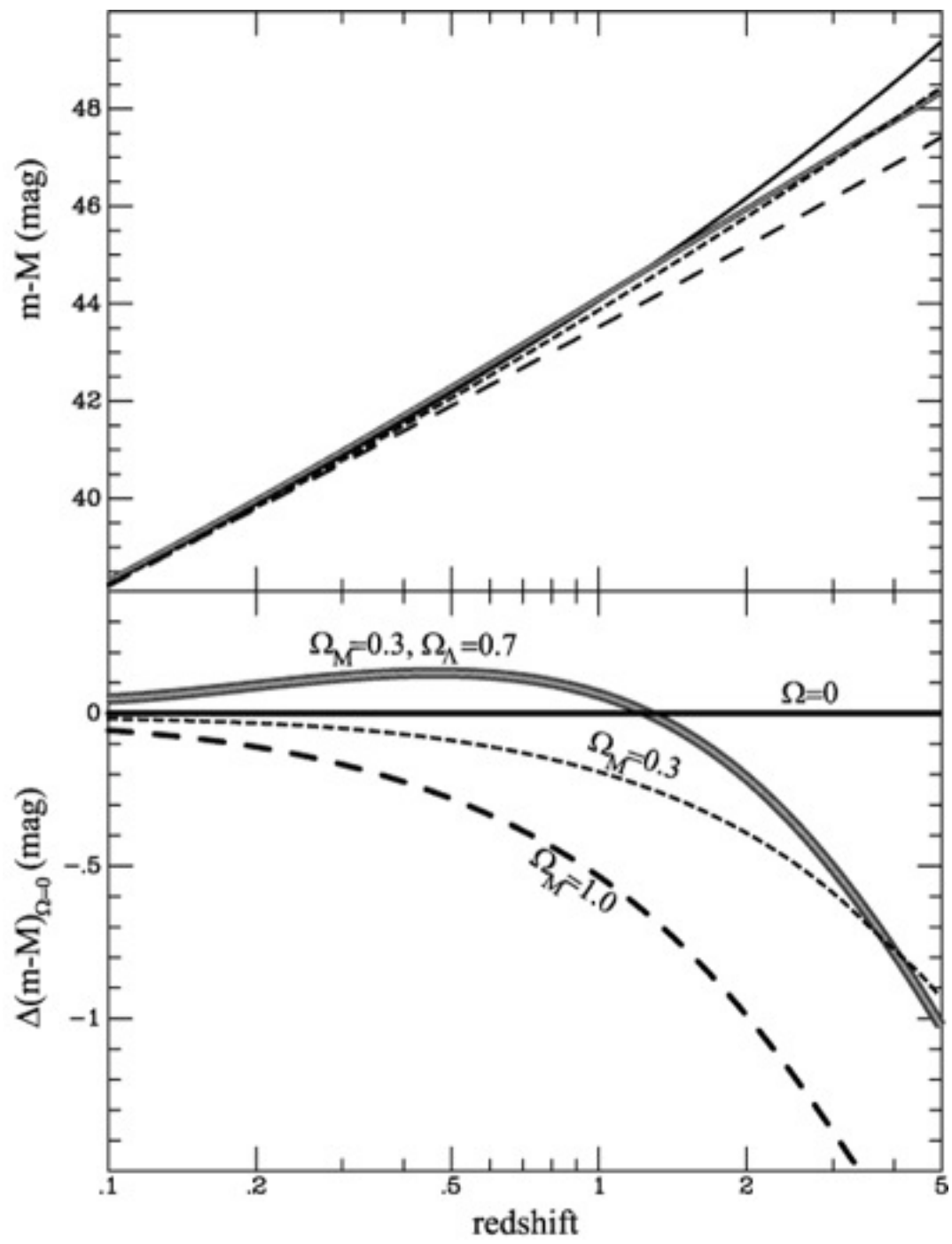
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Type Ia Supernovae



First use of Supernovae to Measure Distances

Fritz Zwicky

Charlie Kowal 1968



18in Schmidt Telescope

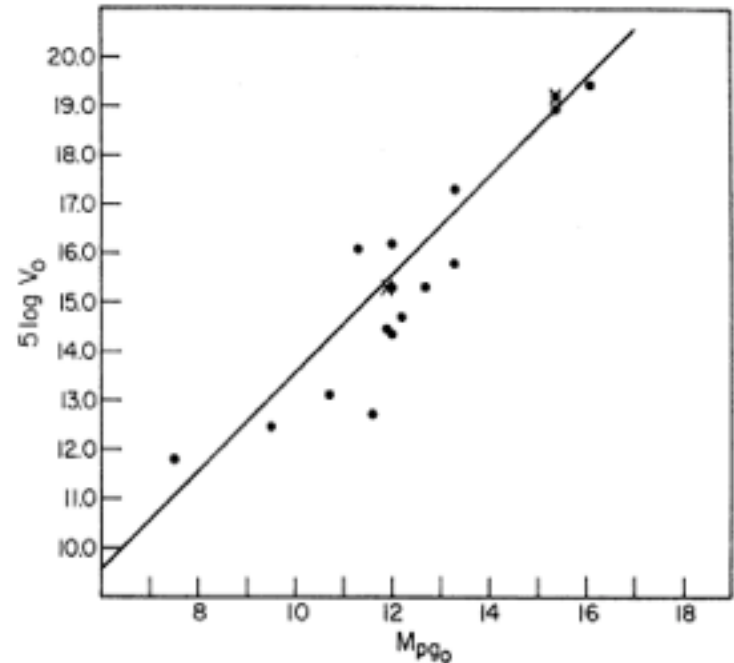
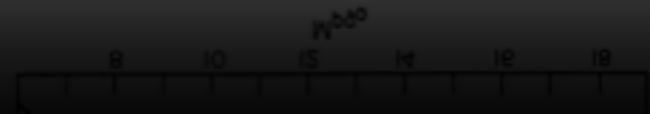


FIG. 1. The redshift-magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

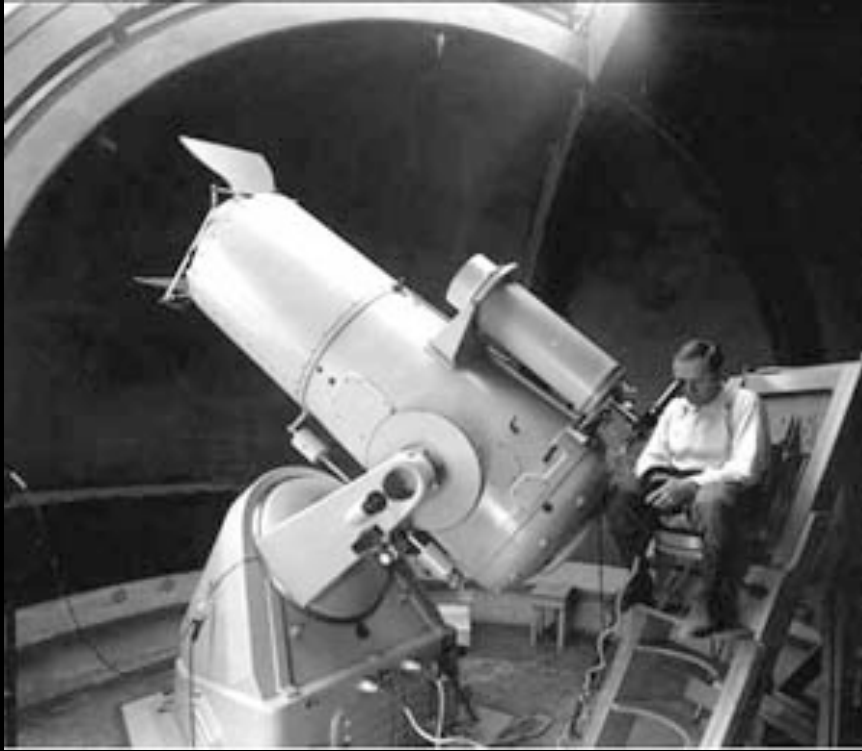
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18in Schmidt Telescope

First Distant SN detected in 1988 by Danish Team

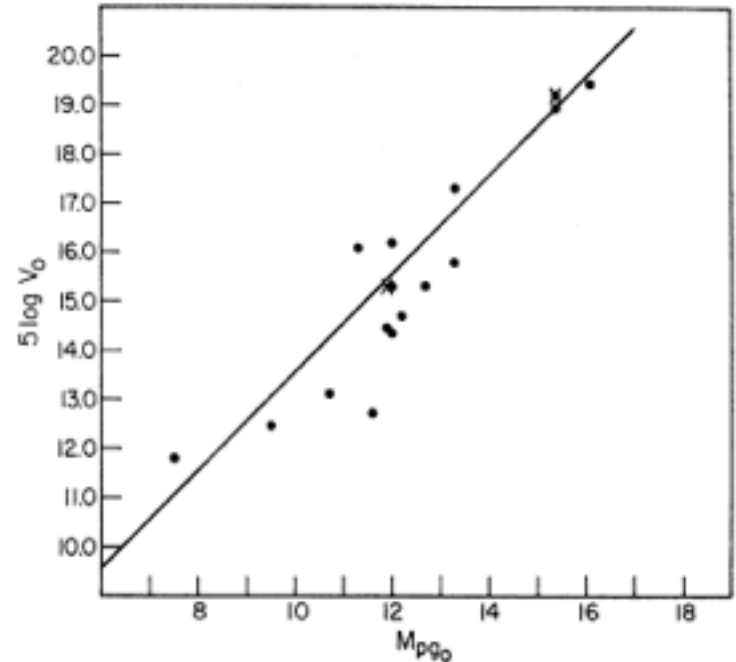


FIG. 1. The redshift-magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

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HAMUY



SUNTZEFF SCHOMMER



PHILLIPS



ANTEZANA



SMITH



AVILES

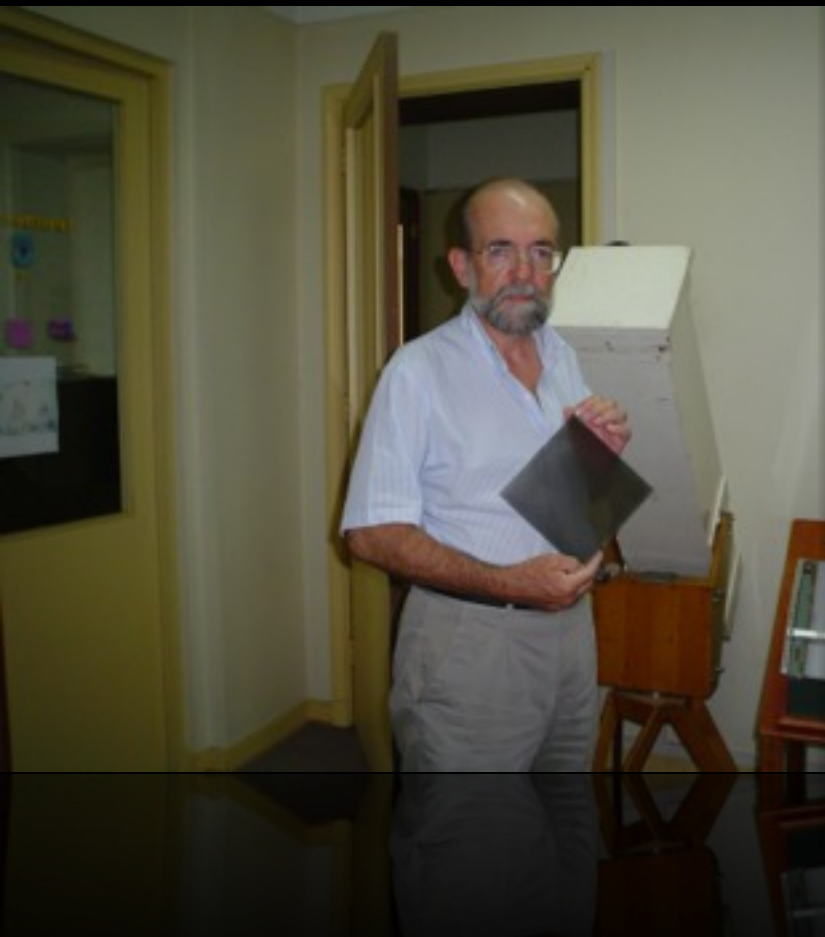


WISCHNJEWSKY

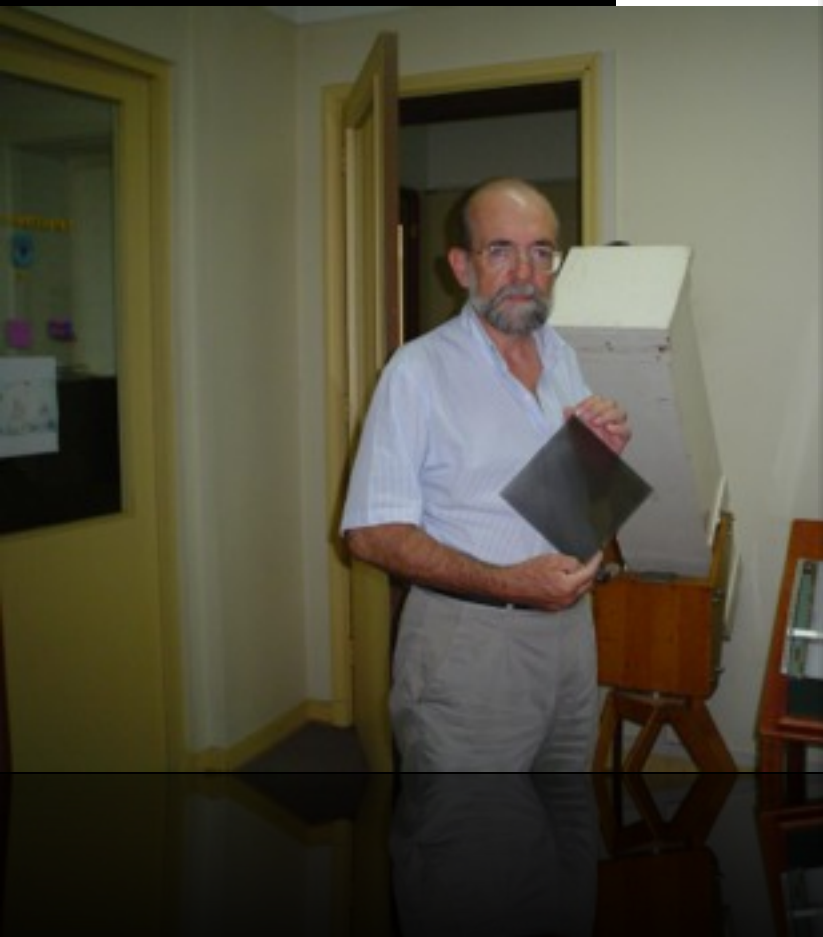
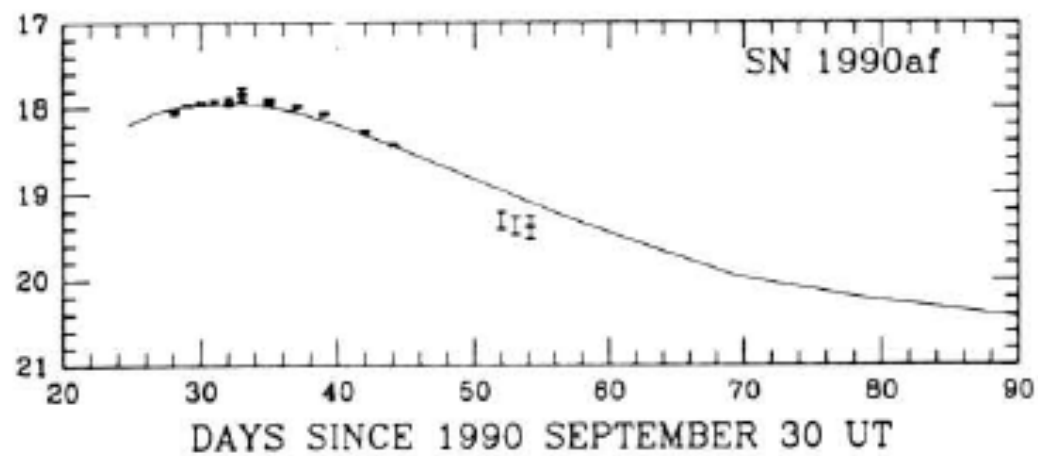


MAZA

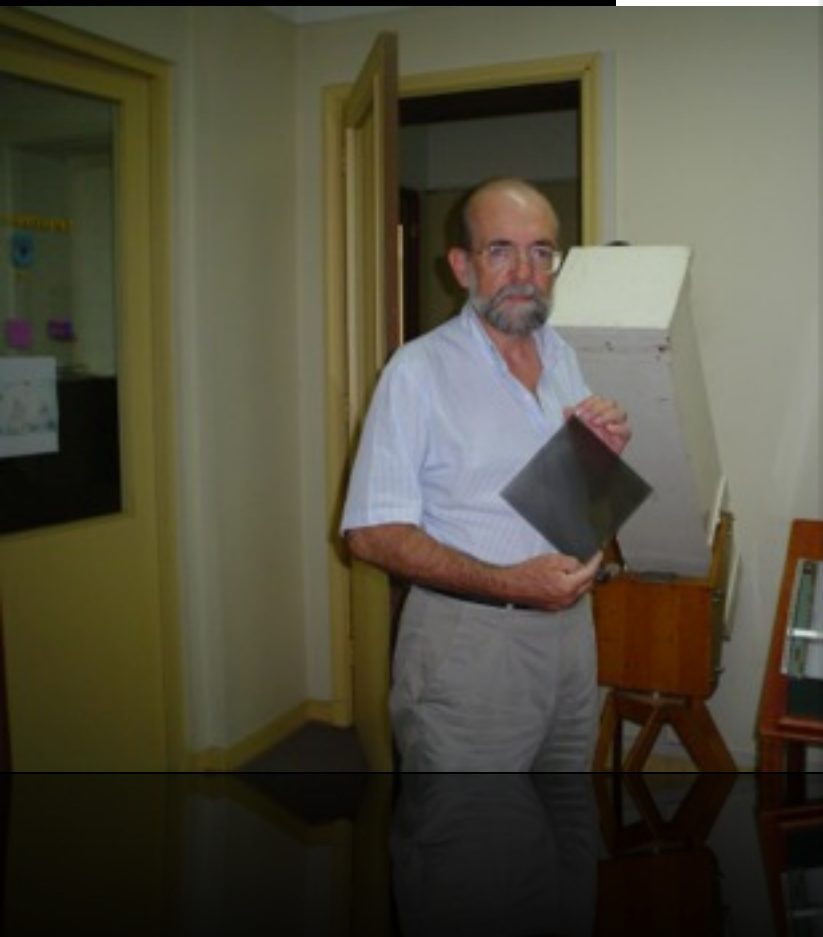
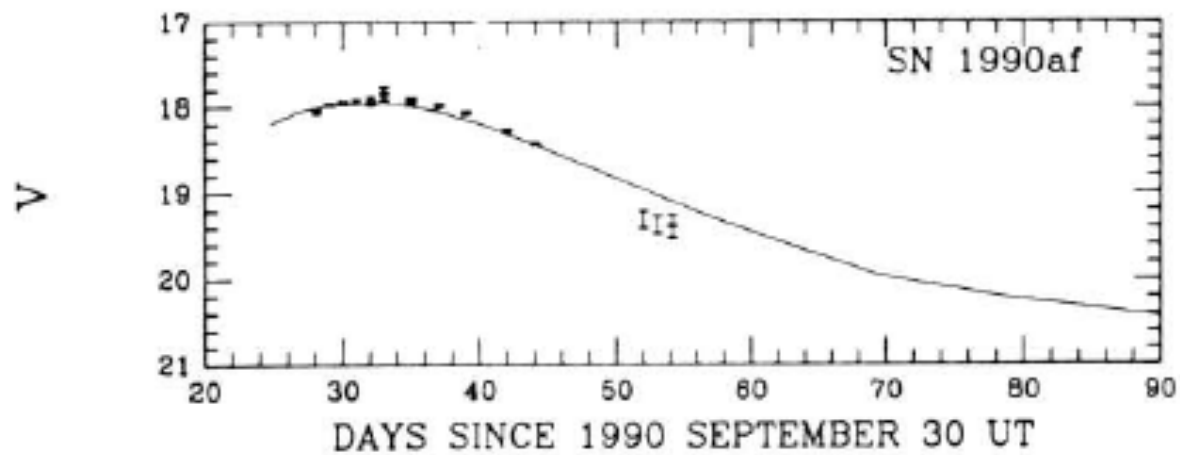
Calan-Tololo SN Search



V



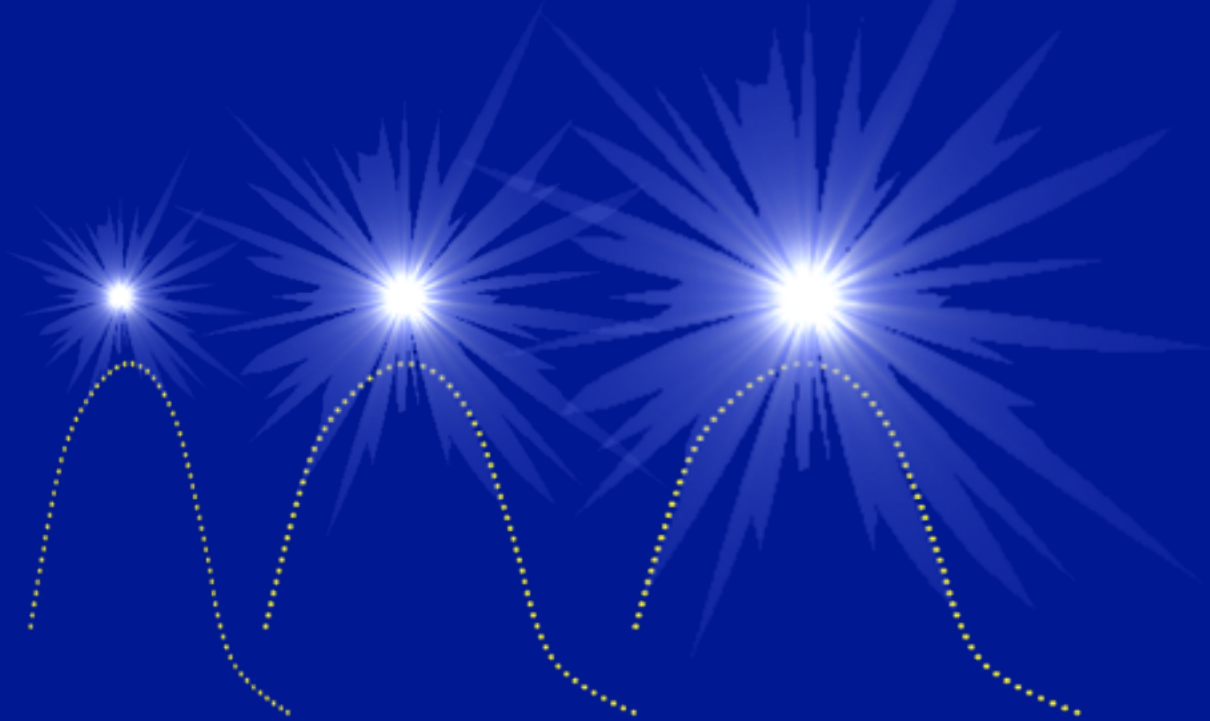
SN 1990af: faded
quickly
and was fainter
than
normal



Refining Type Ia Distances

MARK PHILLIPS (1993)

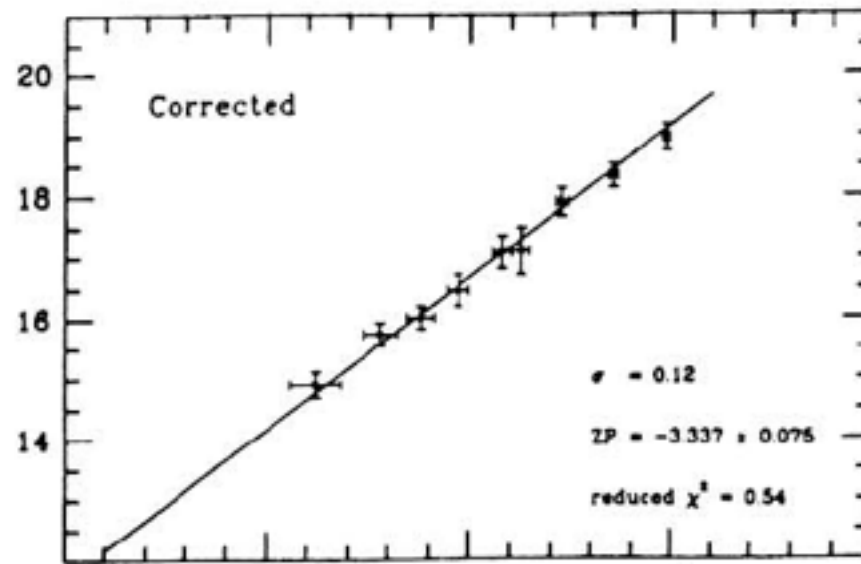
HOW FAST A SUPERNOVA
FADES IS RELATED TO ITS
INTRINSIC BRIGHTNESS.



1994 Visit to Harvard
Mario Hamuy showed
us this Diagram.

SN Ia are Precision
Distance Indicators!

DISTANCE



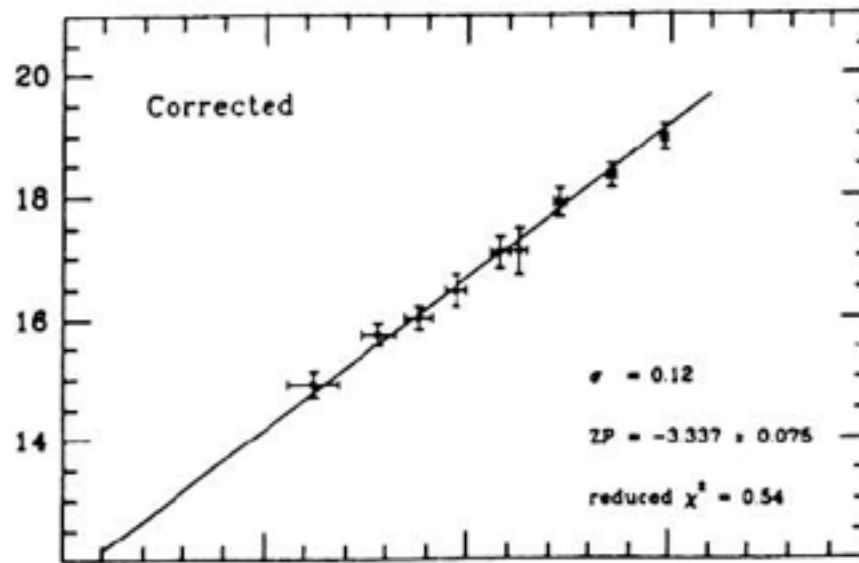
REDSHIFT

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

1994 Visit to Harvard
Mario Hamuy showed
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SN Ia are Precision
Distance Indicators!

DISTANCE



REDSHIFT

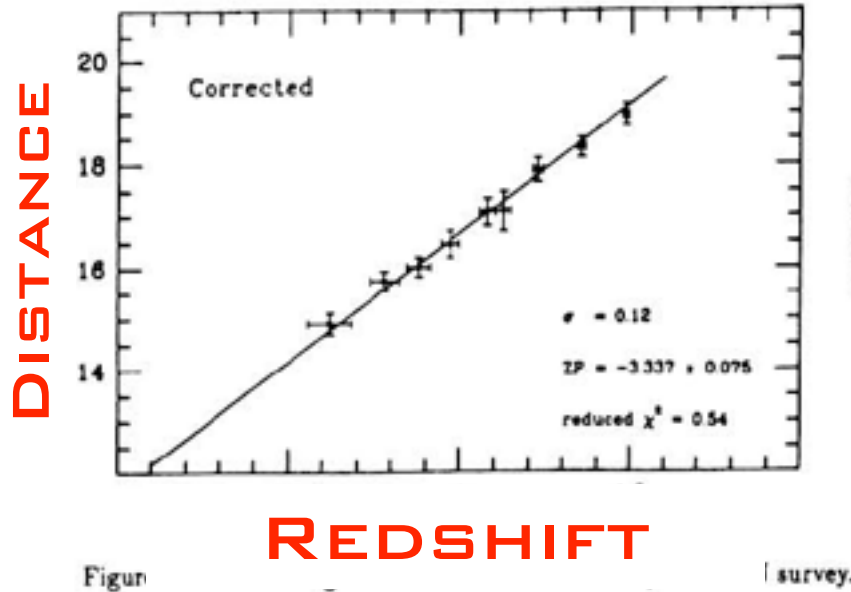
Figure 1: Hubble diagram of SNe Ia in the Calán/Tololo SN survey.

Eventually 29 Type Ia supernovae

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

Used by Both Teams to measure Acceleration

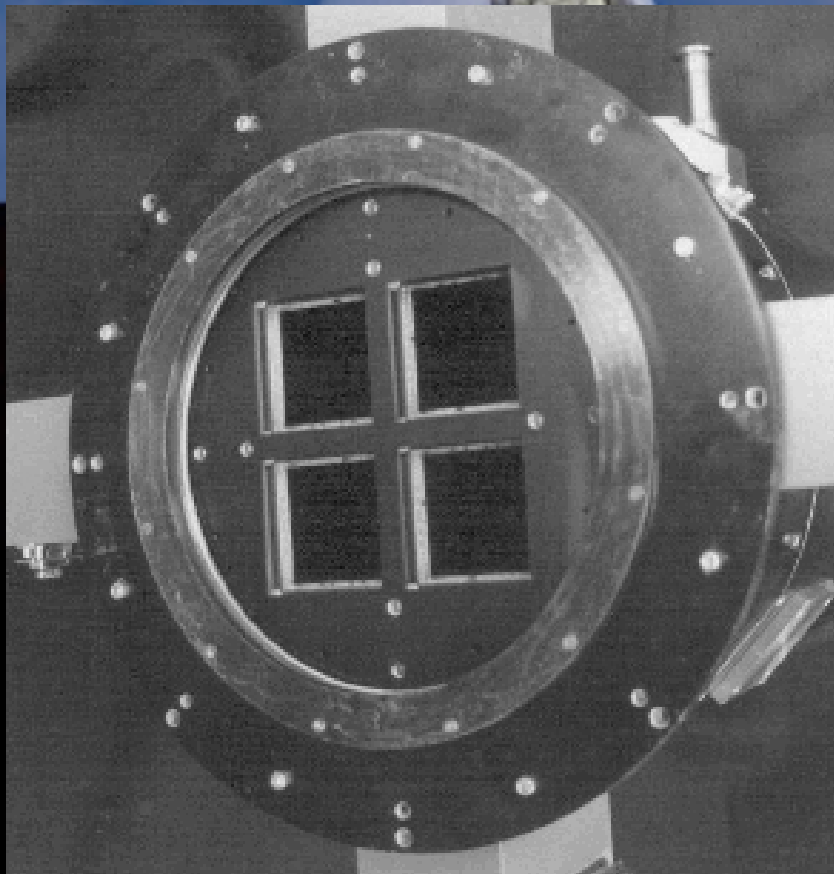
1994 - Two breakthroughs

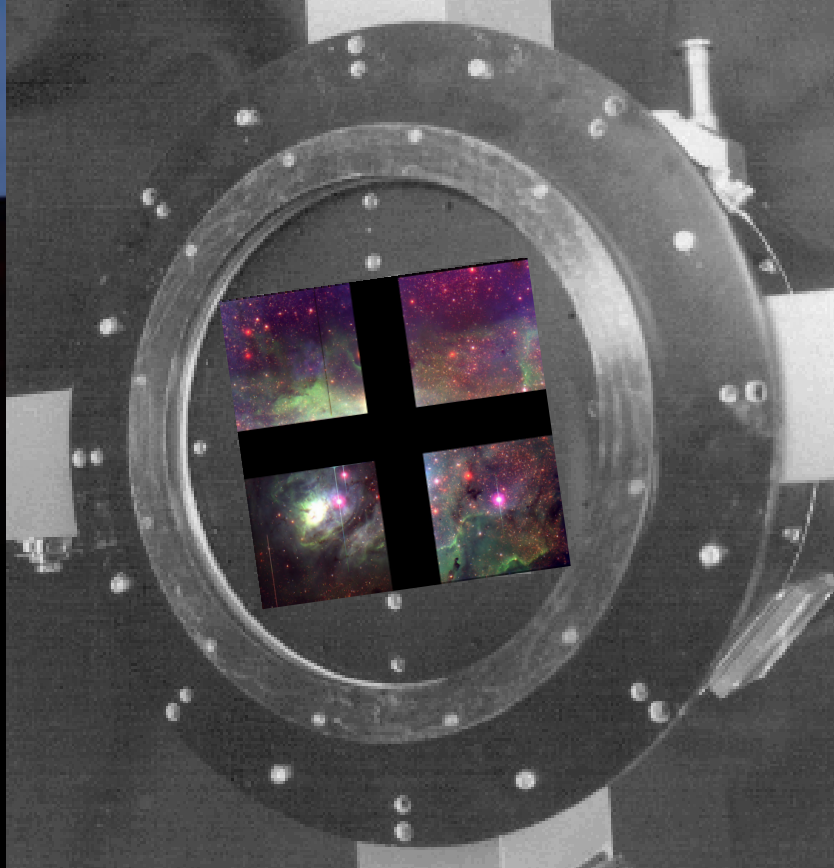


SUPERNOVAE 1994F, 1994G, 1994H

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

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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 ~ 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.

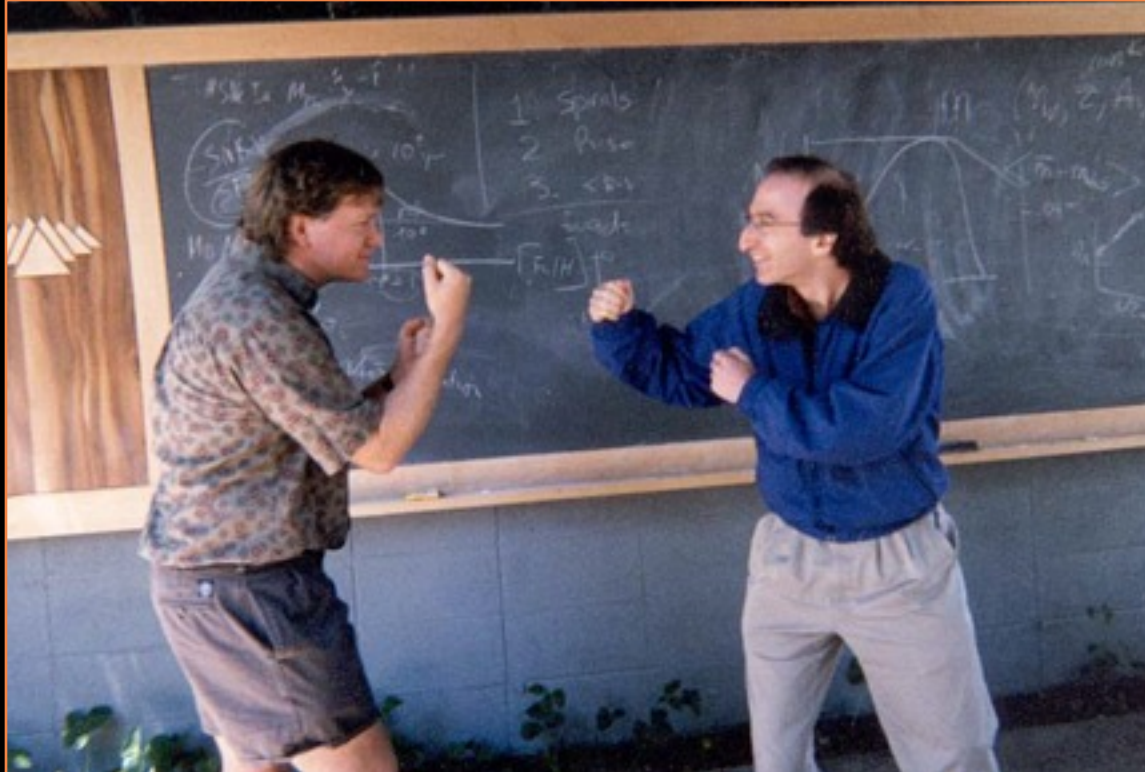
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A. Fruchter, N. Panagia (STScI)
A. Goobar (Univ of Stockholm)
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- Bruno Leibundgut and Jason Spyromilio (ESO)
- Bob Kirshner, Peter Challis, Tom Matheson (Harvard)
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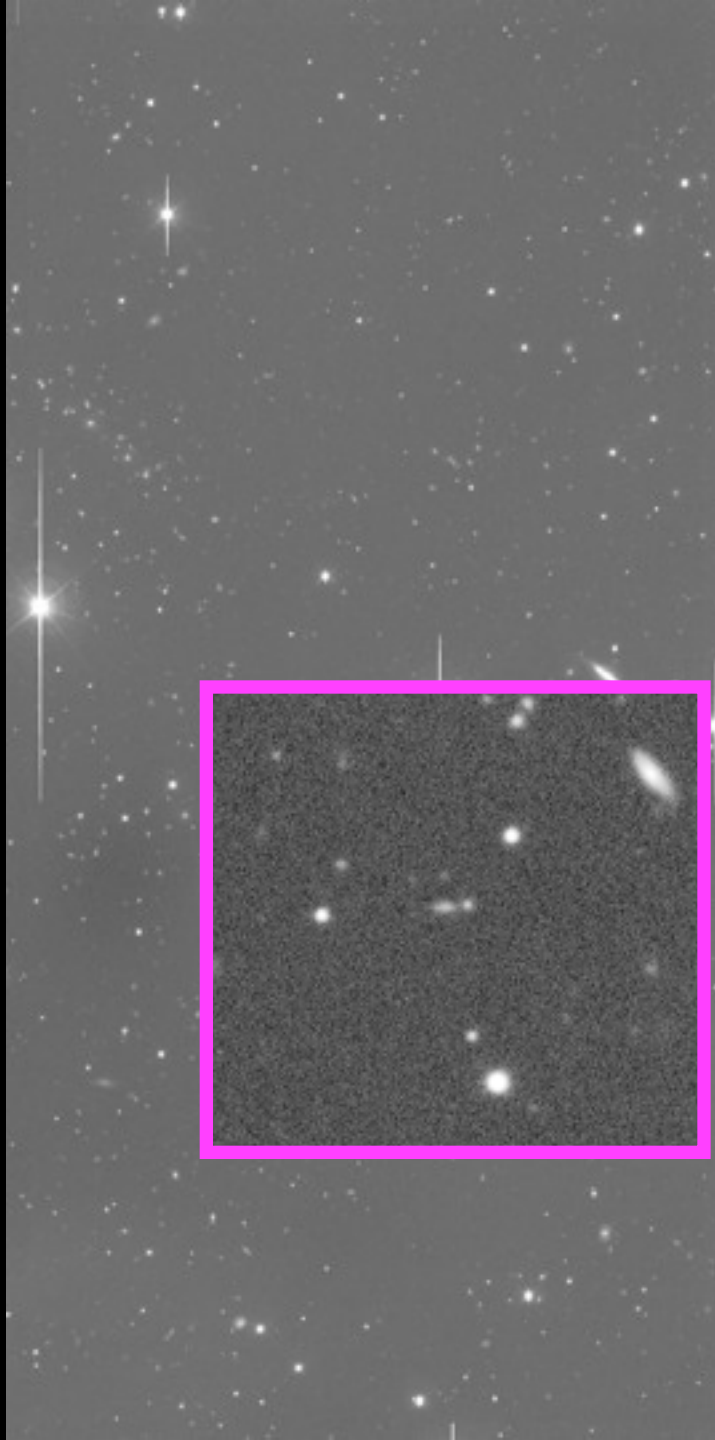
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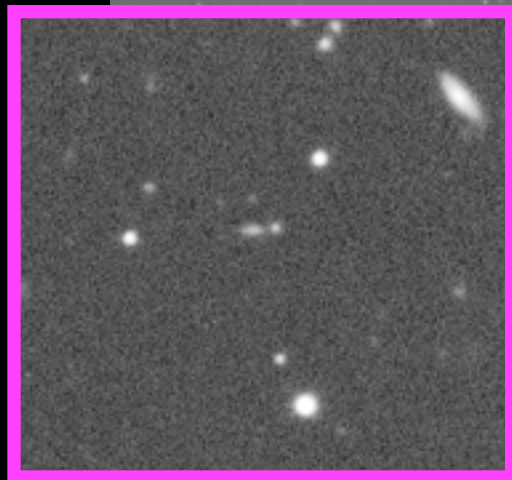
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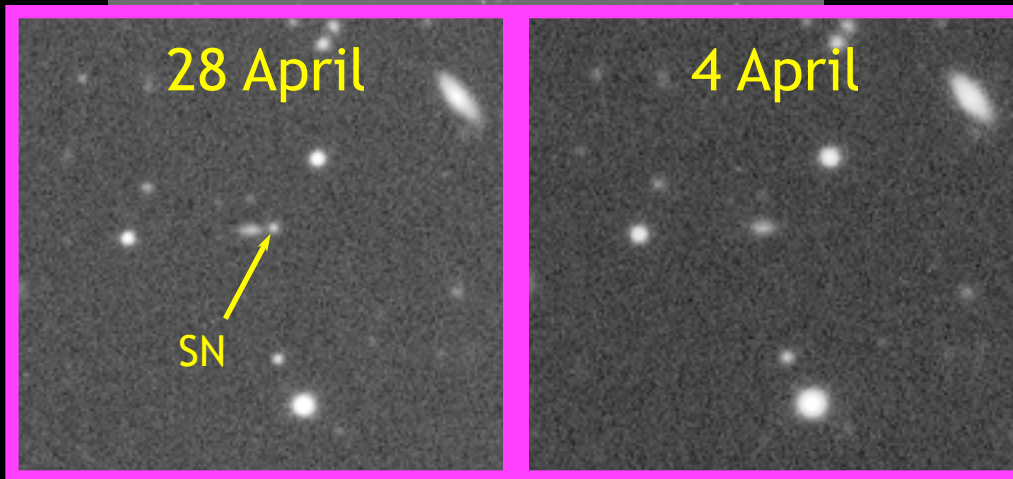


28 April

SN



4 April



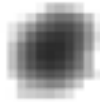


A SN Ia at $z=0.48$

Raw Observation



Convolved Observation



Subtracted Image



Template Image



Subtracted Image



Template Image



Our First Supernova SN 1995K

A SN Ia at $z=0.48$

Raw Observation



Convolved Observation



Subtracted Image

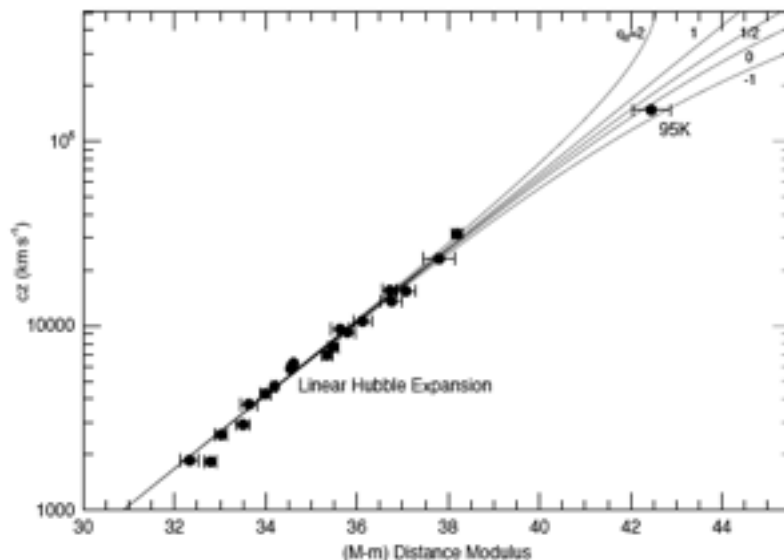


Template Image



Our First Supernova SN 1995K

Hubble Diagram of SNe Ia



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 nuntzeff@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

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C. BODDY (LMA)

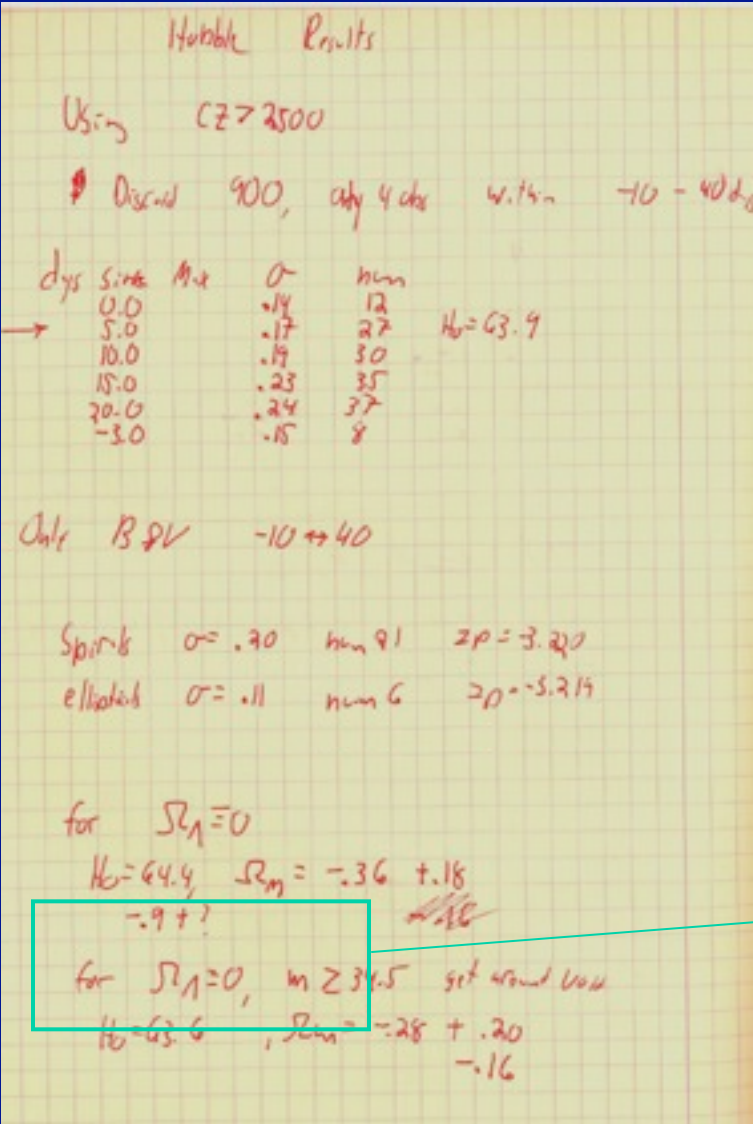
PROPOSAL: A Search for Distant Type Ia Supernovae to Measure q_0

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EUREKA?

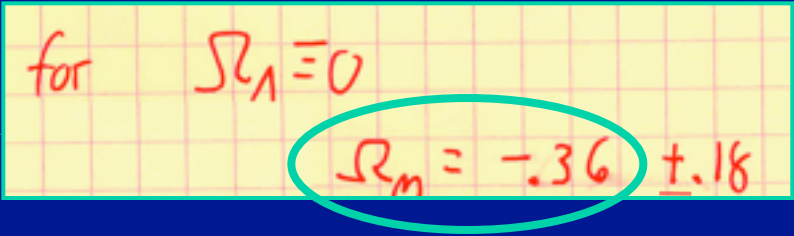
Adam's Lab book, Key Page, Fall 1997:



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)...

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

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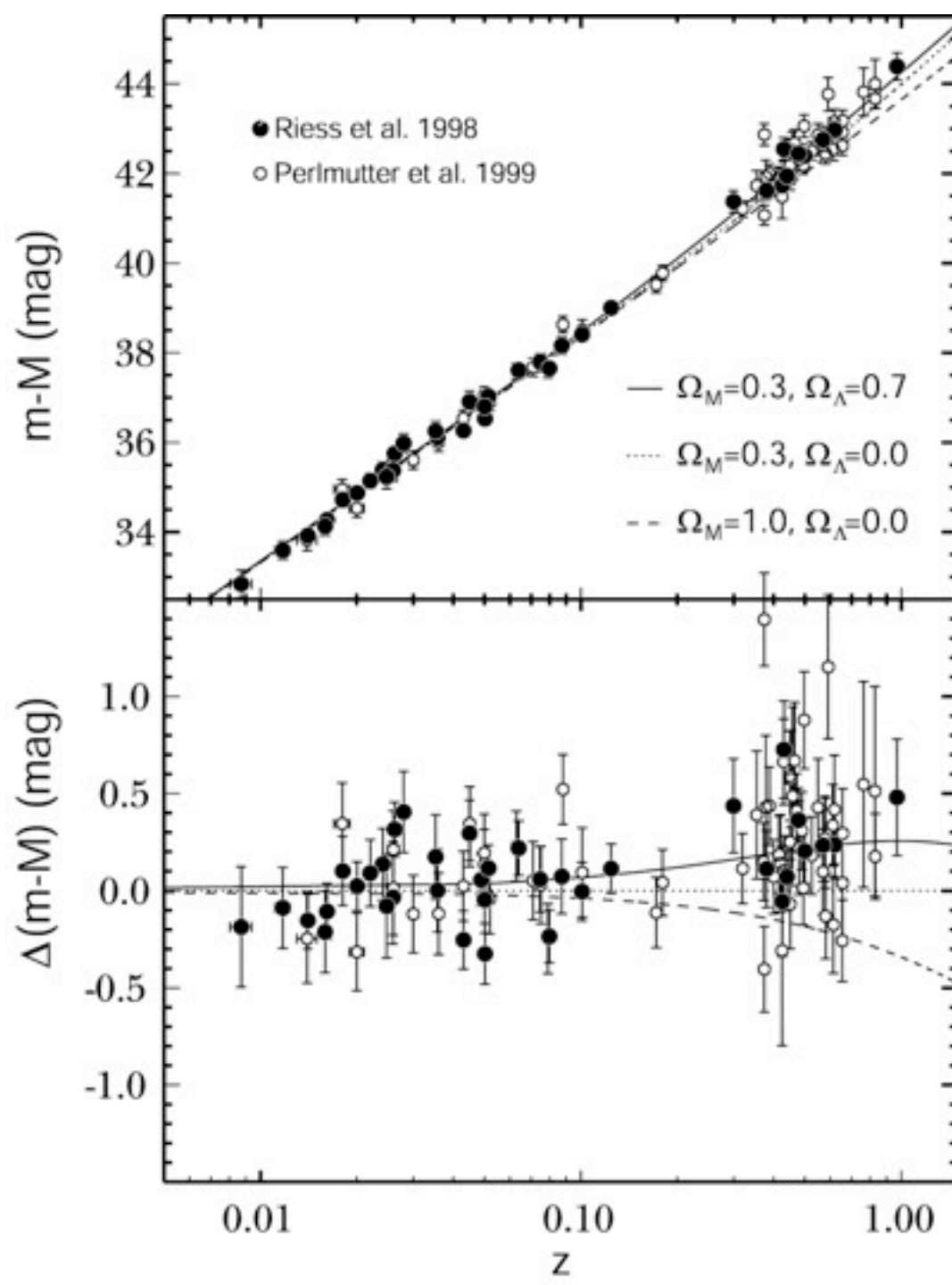
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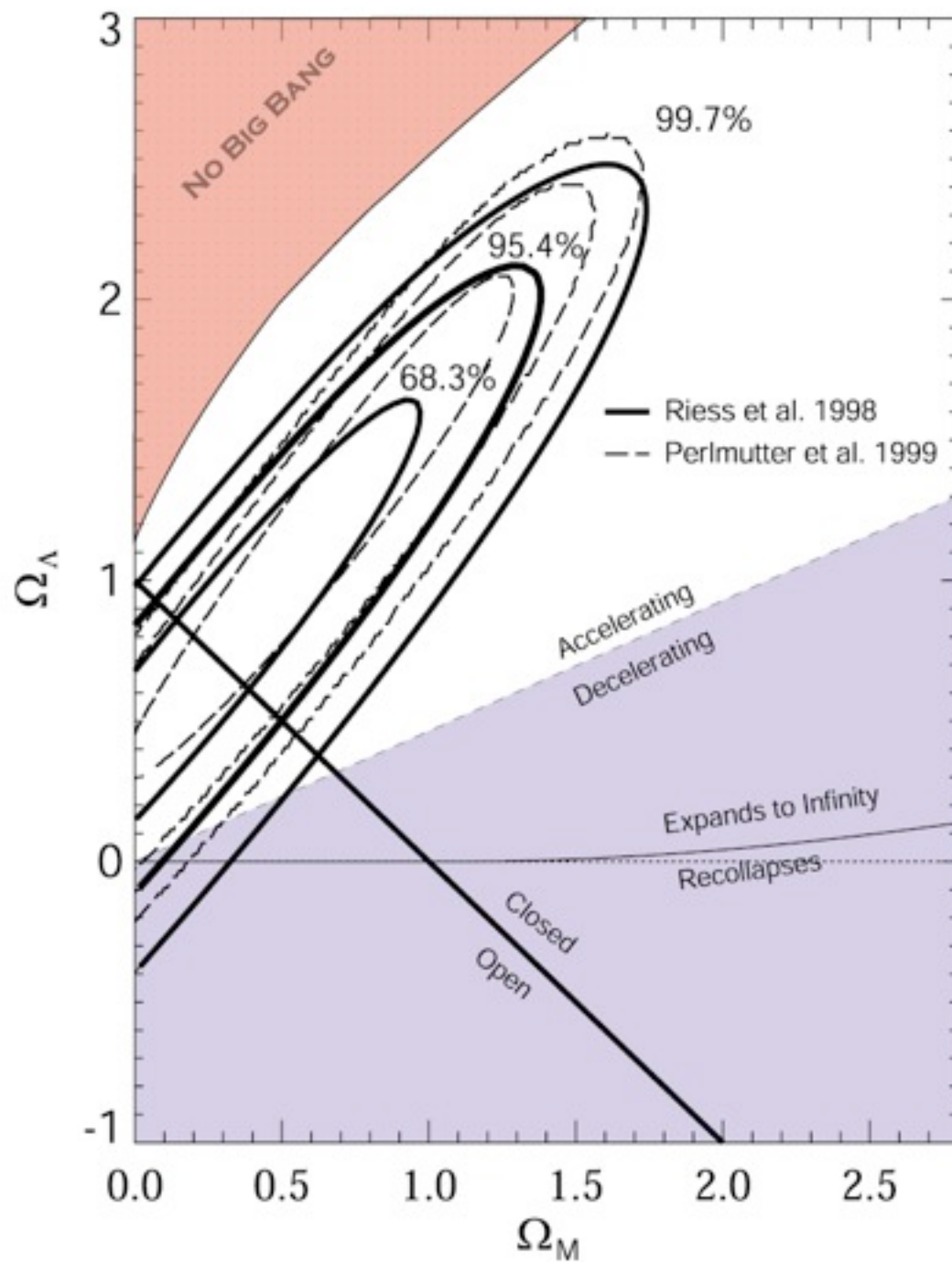
A. Filippenko 1/12/1998, 12:02 pm: "If we are wrong in the end, then so be it. At least we ran in the race."

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."





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 TONRY¹¹



MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. PERLMUTTER,¹ G. ALDERING, G. GOLDBABER,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
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Institute of Astronomy, Cambridge, England, UK

P. RUIZ-LAPUENTE

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N. WALTON

Isaac Newton Group, La Palma, Spain

B. SCHAEFER

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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)





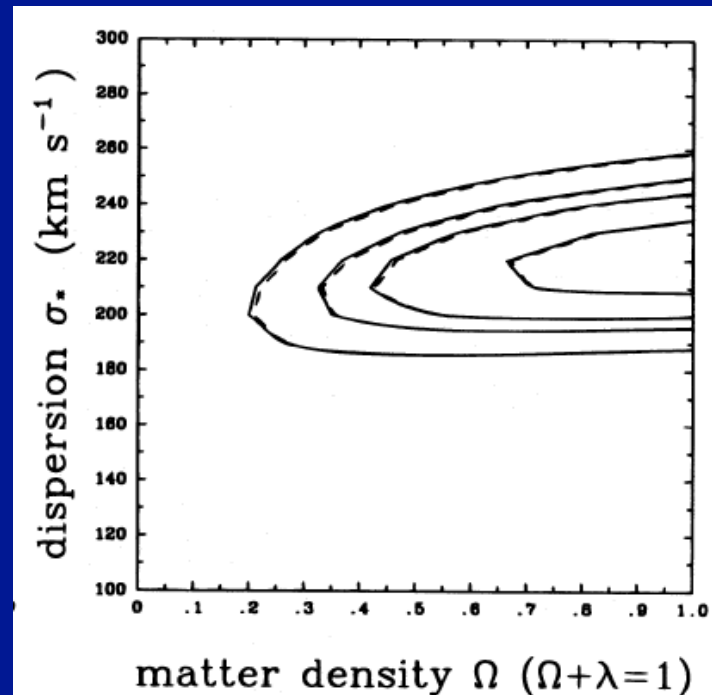




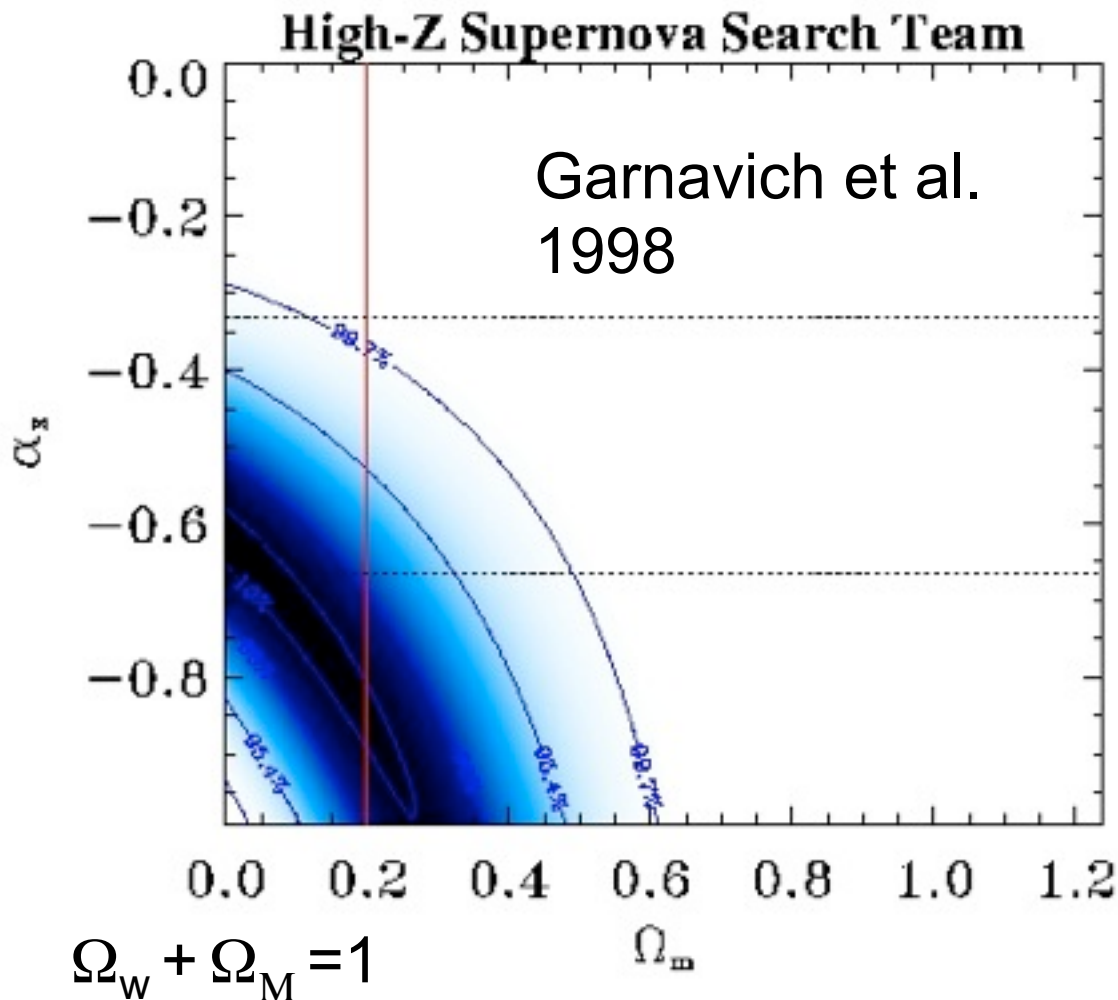
- High-Z SN Observations directly measured distances which were incompatible with any matter-only Universes.
- But SN Ia themselves might be affected by Dust, evolution or measurement difficulties, and Community felt they were not to be completely trusted on their own.

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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.

• $\Omega_M = 0.25$, $\Omega_\Lambda = 0.75$ Universe
compatible with most
Cosmological measurements
except for lensing limits
(Kochanek 1996)
and high Ω_M measurements.



The Equation of State

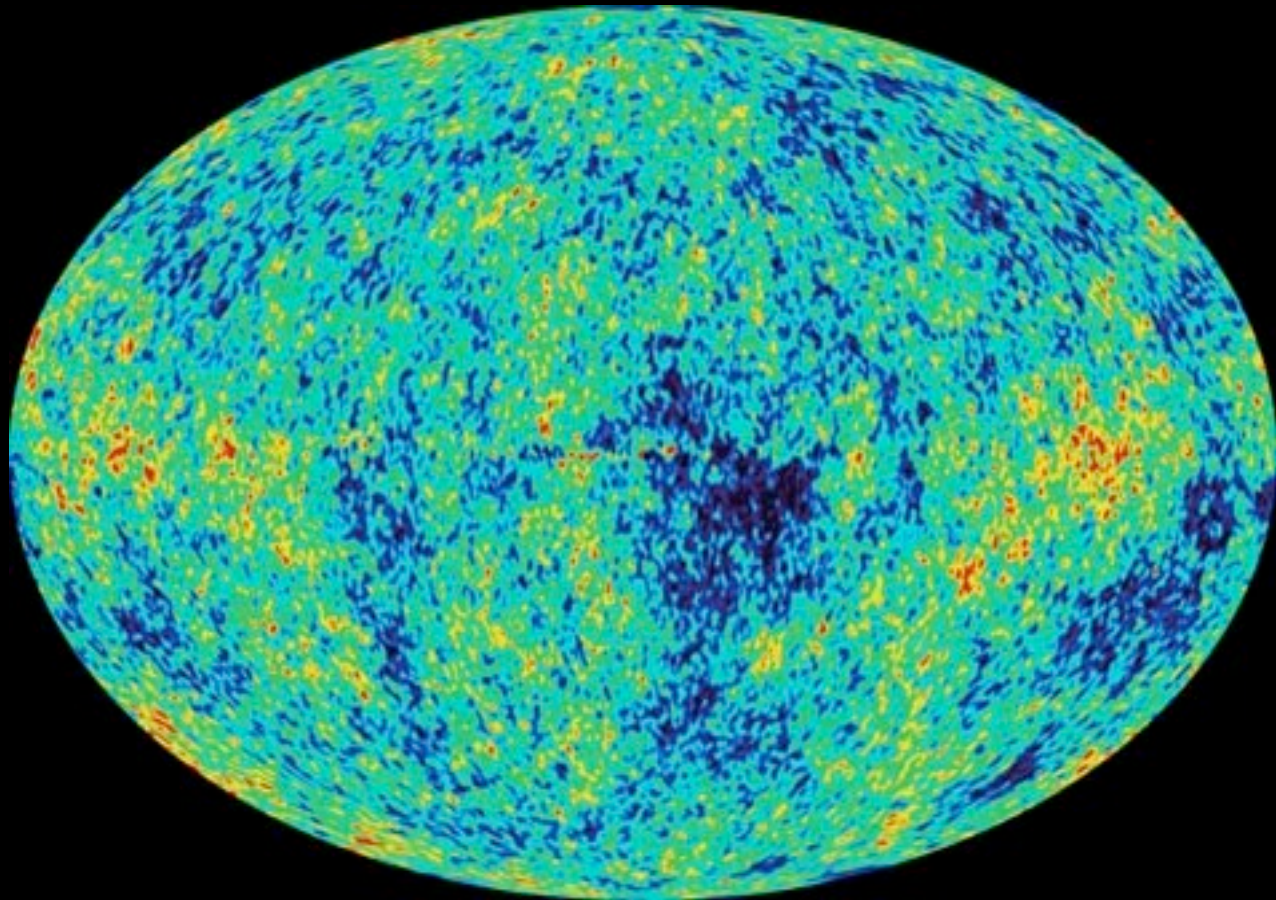


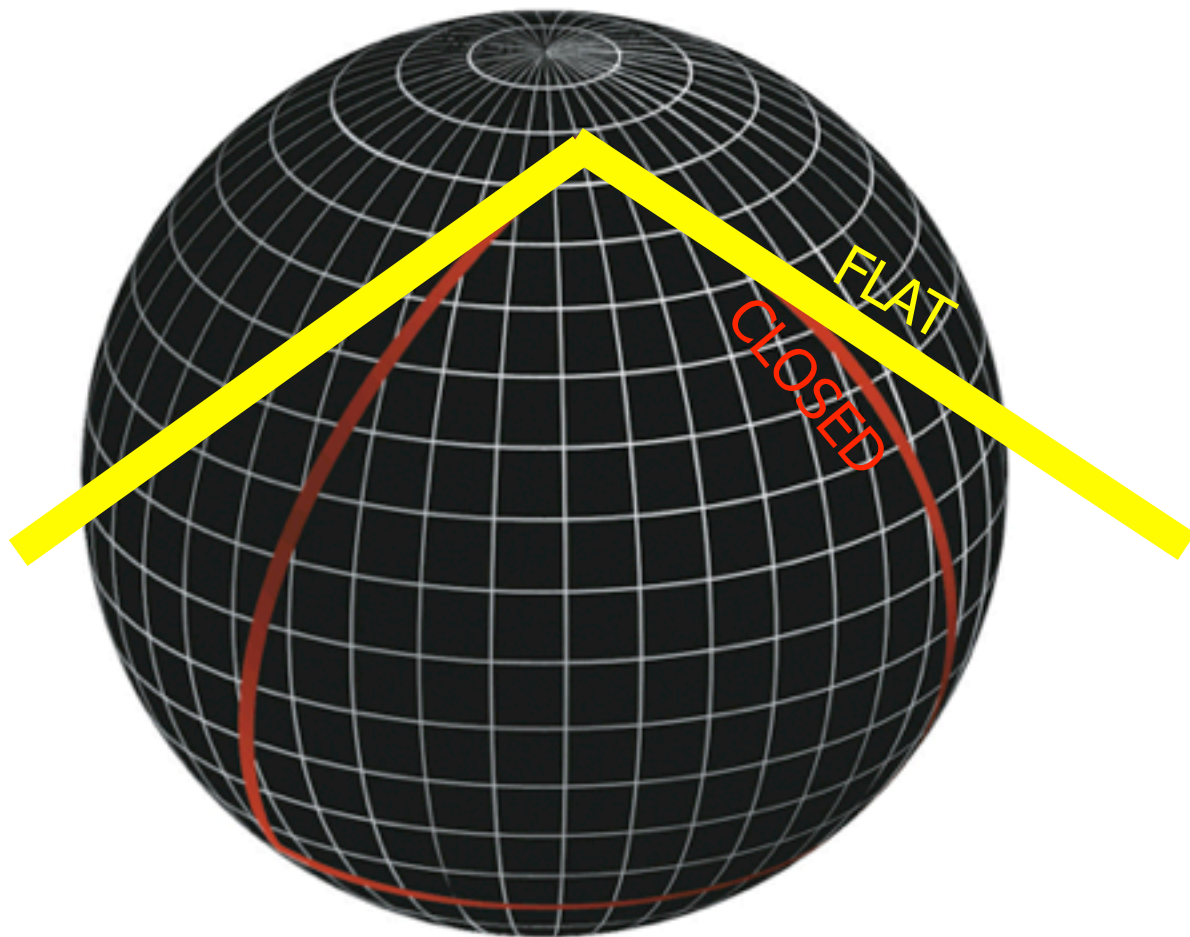
The beginnings of the quest to measure the equation of state of Dark Energy

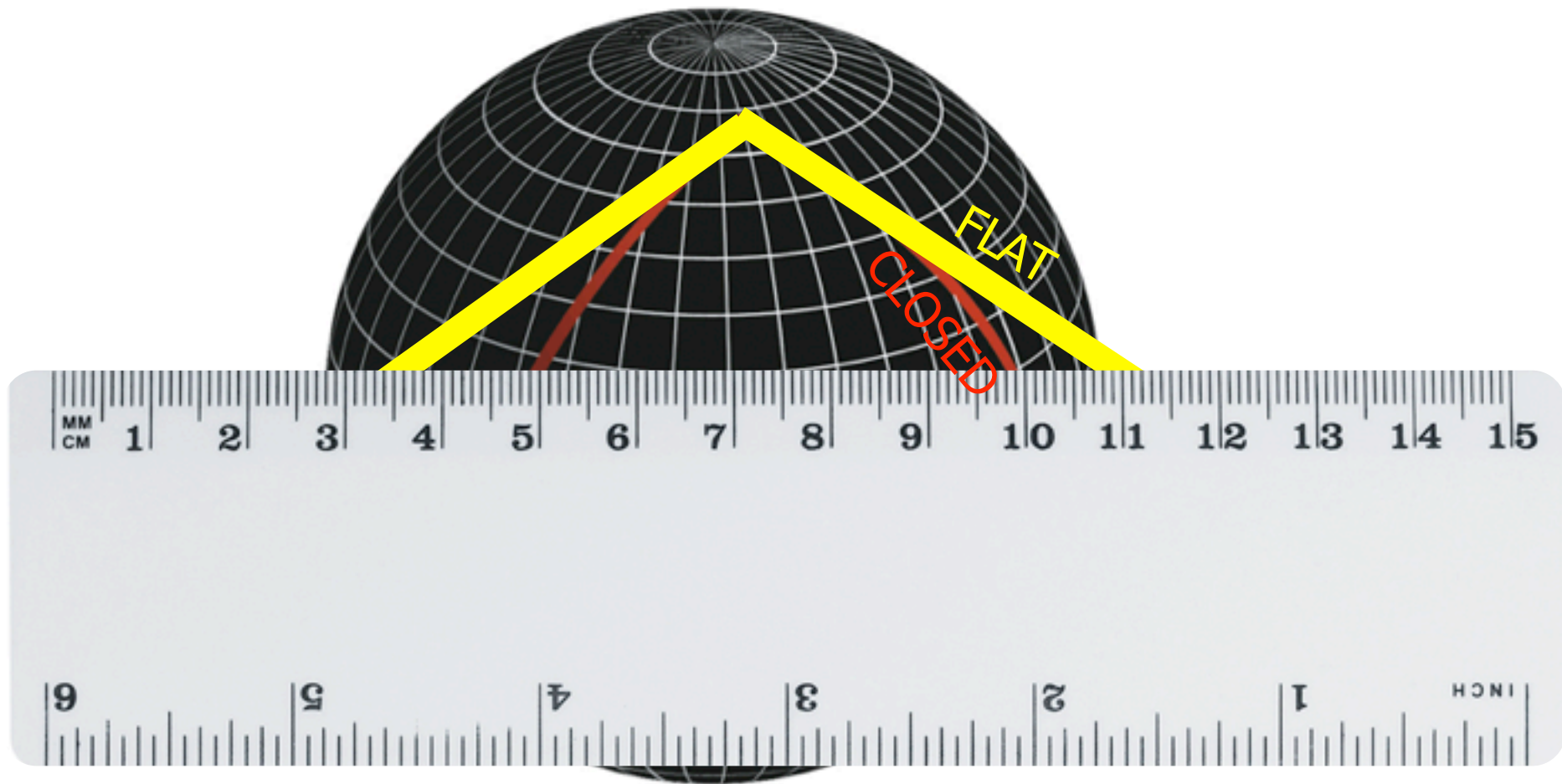
EOS was new stuff to us, so we had no problem giving the constant the name α

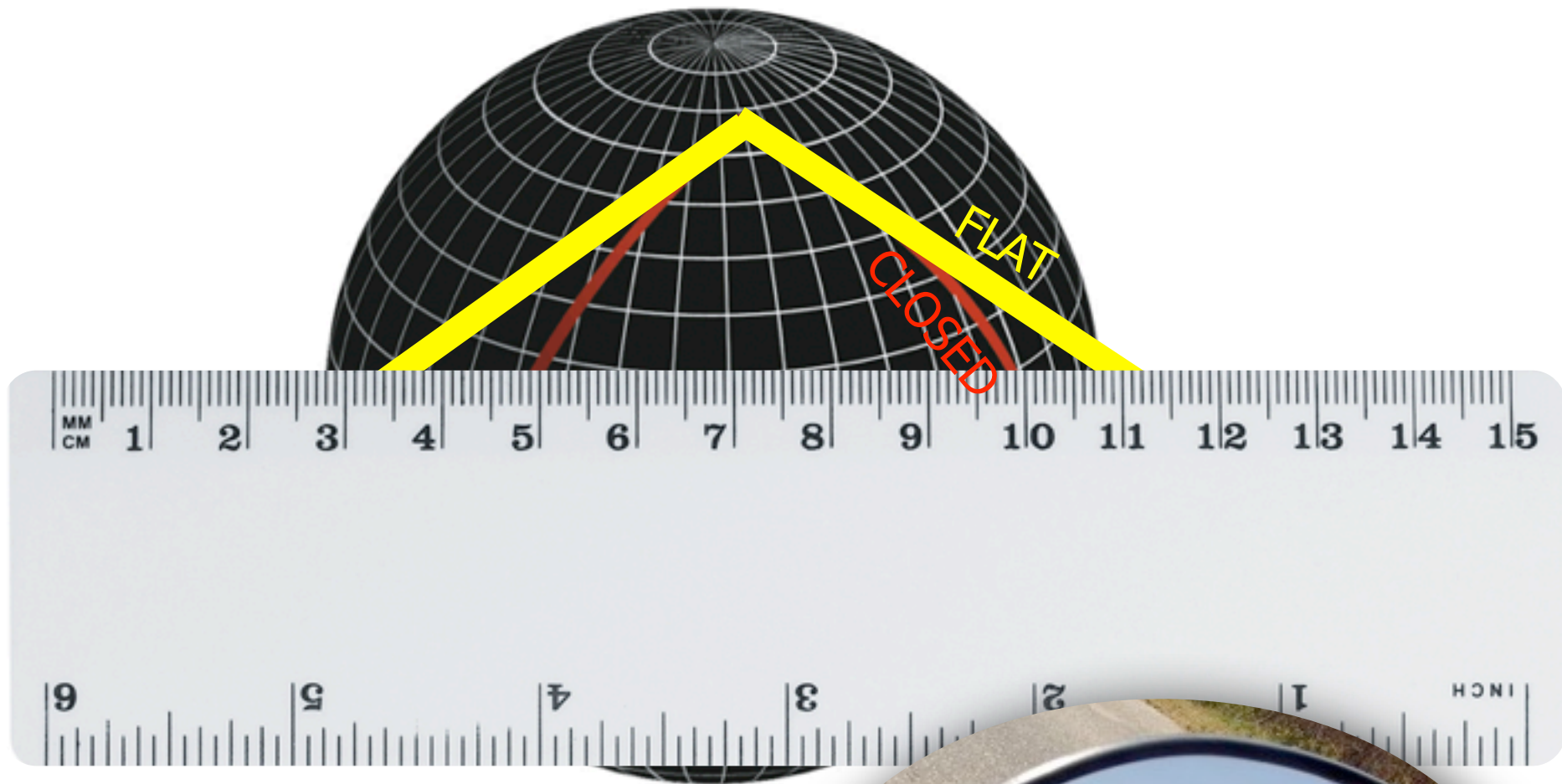
Sound Waves of Matter Splashing Around the Universe

Physics tells us that the largest sound waves are 450,000 light years long





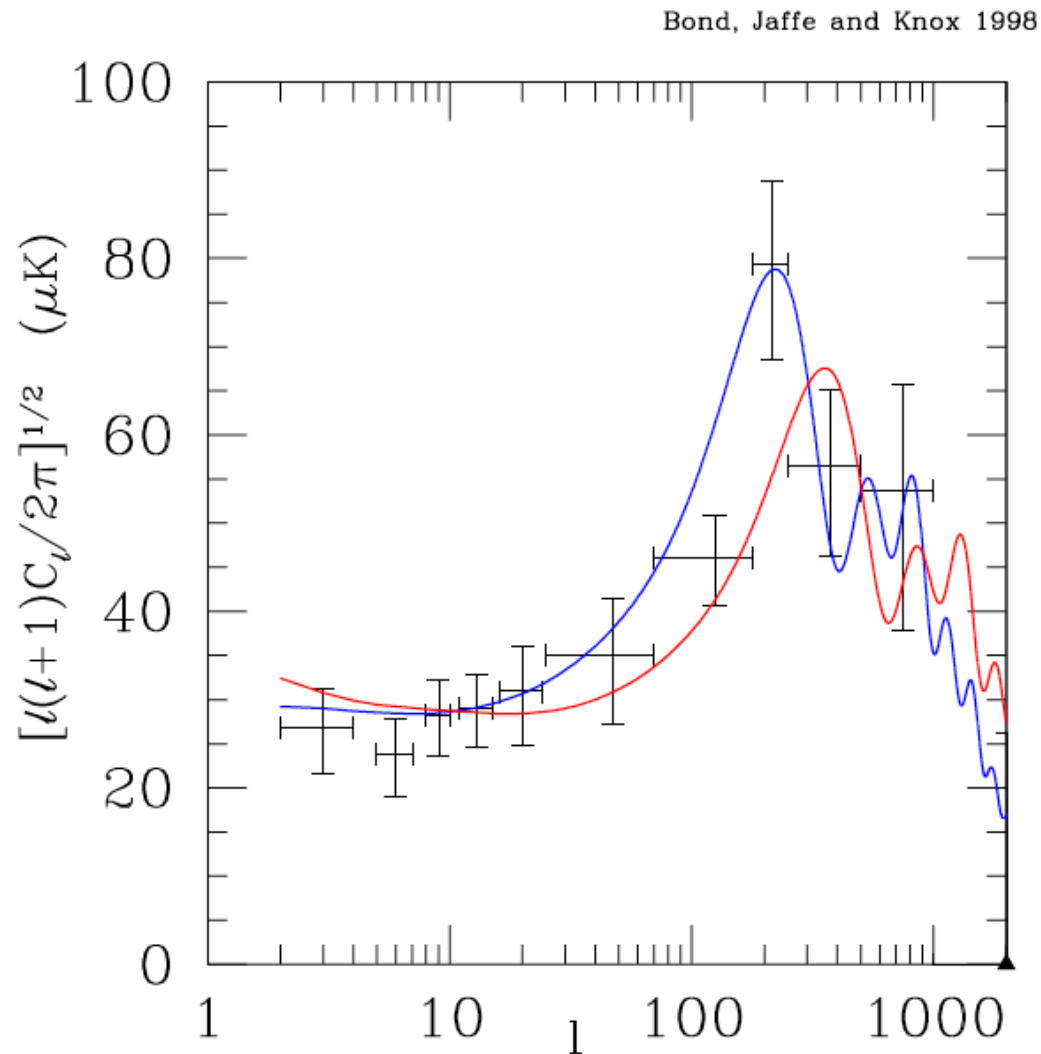




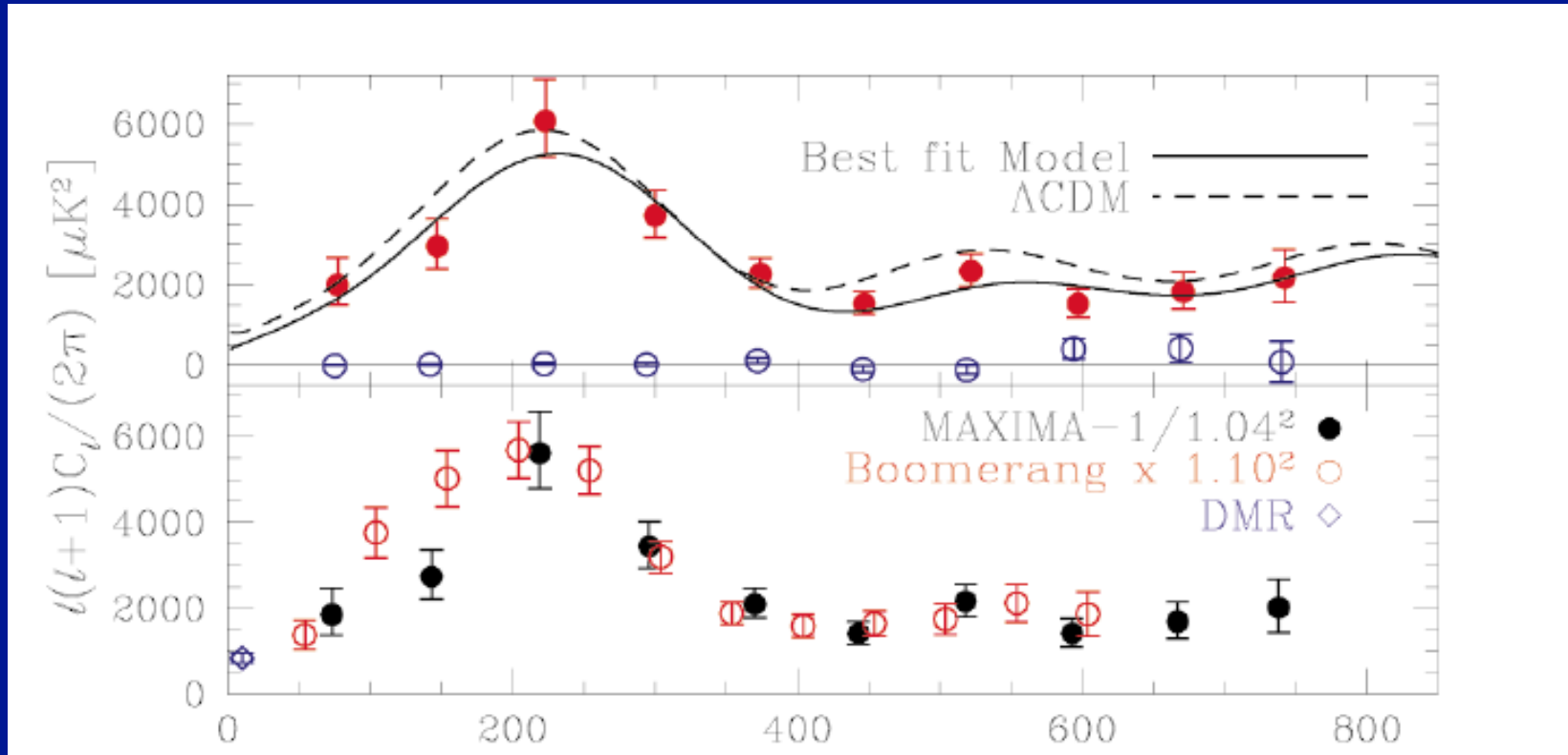
**Objects Appear Larger in
Curved Finite Space**



CMB - mid 1998

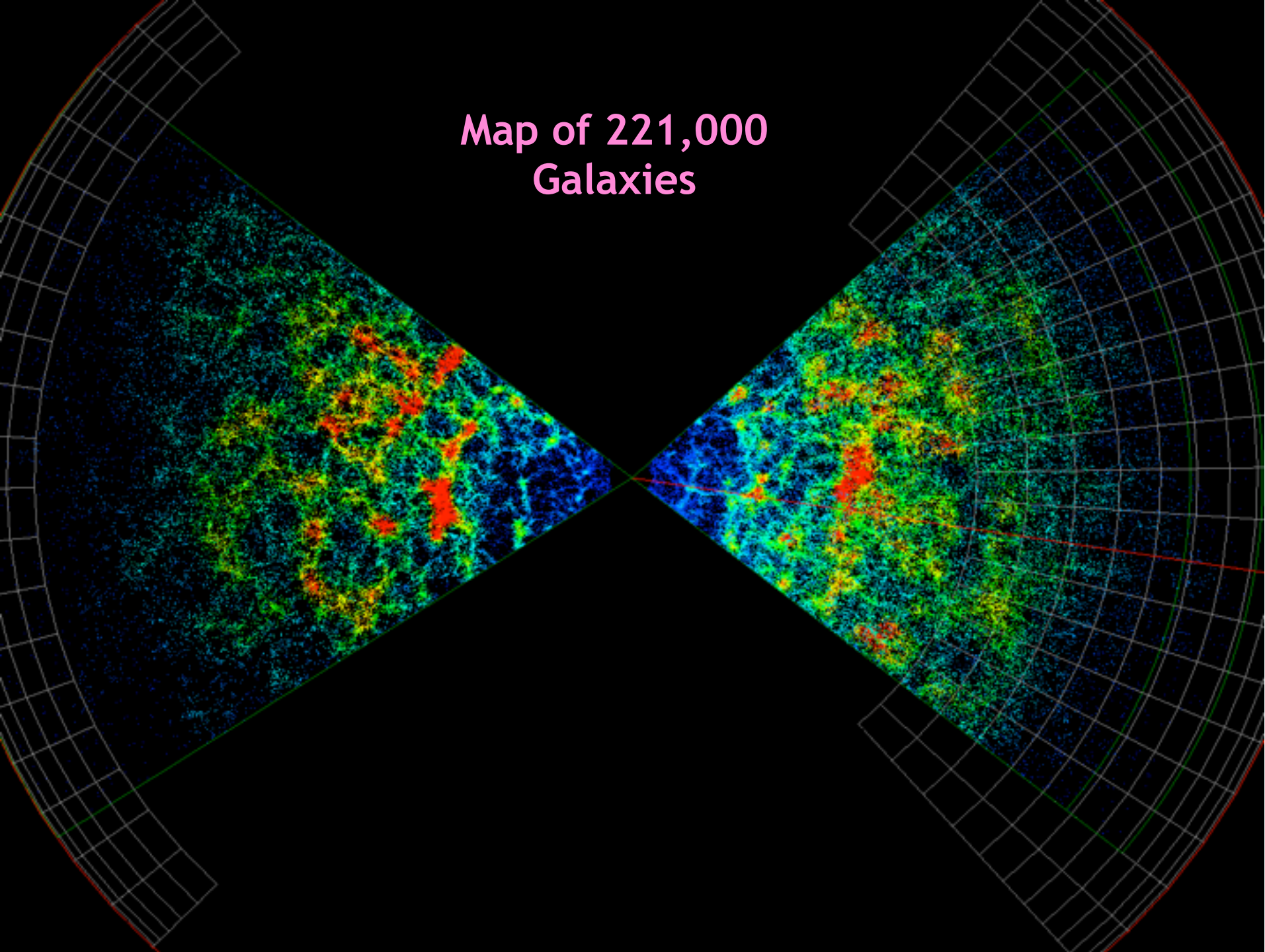


2000 - Boomerang & MAXIMA Clearly see 1st Doppler Peak

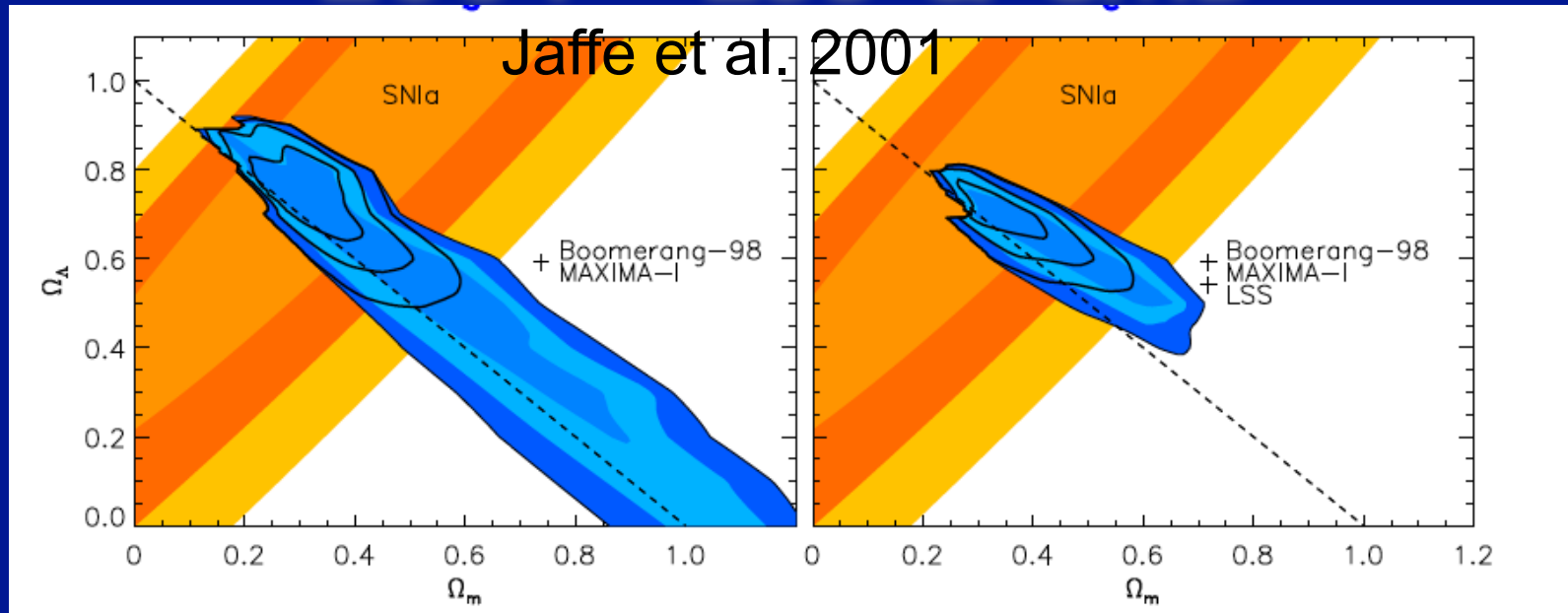


Once a Flat Universe was measured, the SN Ia measurements went from being 3-4 σ to >7 σ

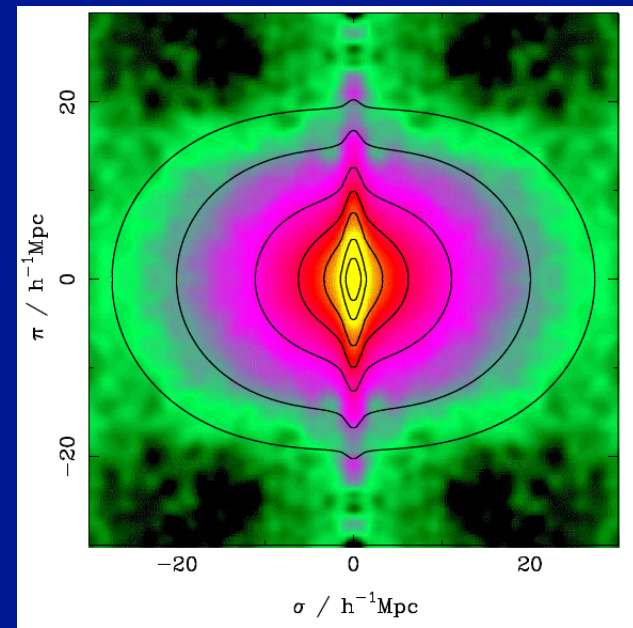
Map of 221,000 Galaxies



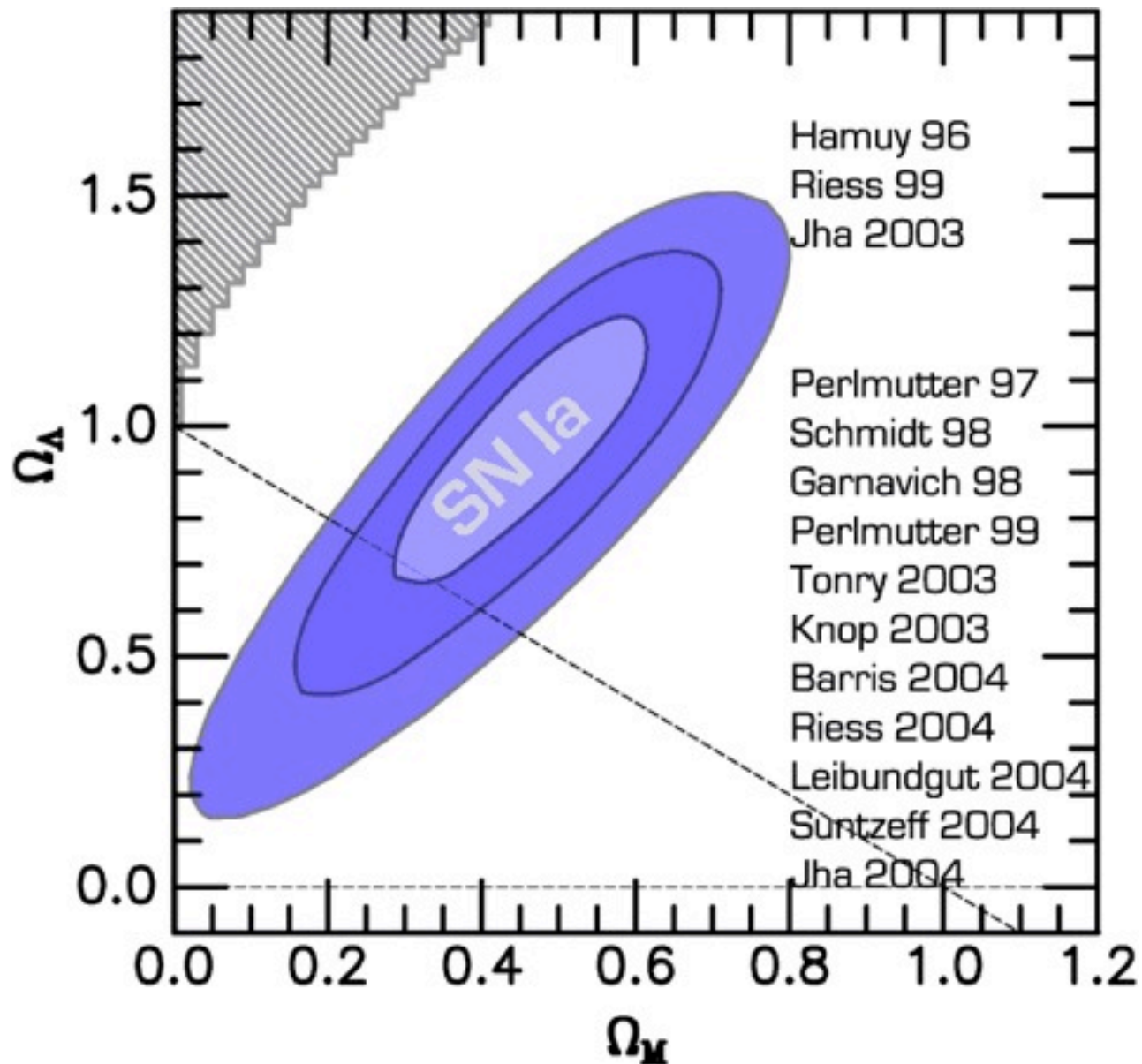
2001 - LSS & CMB



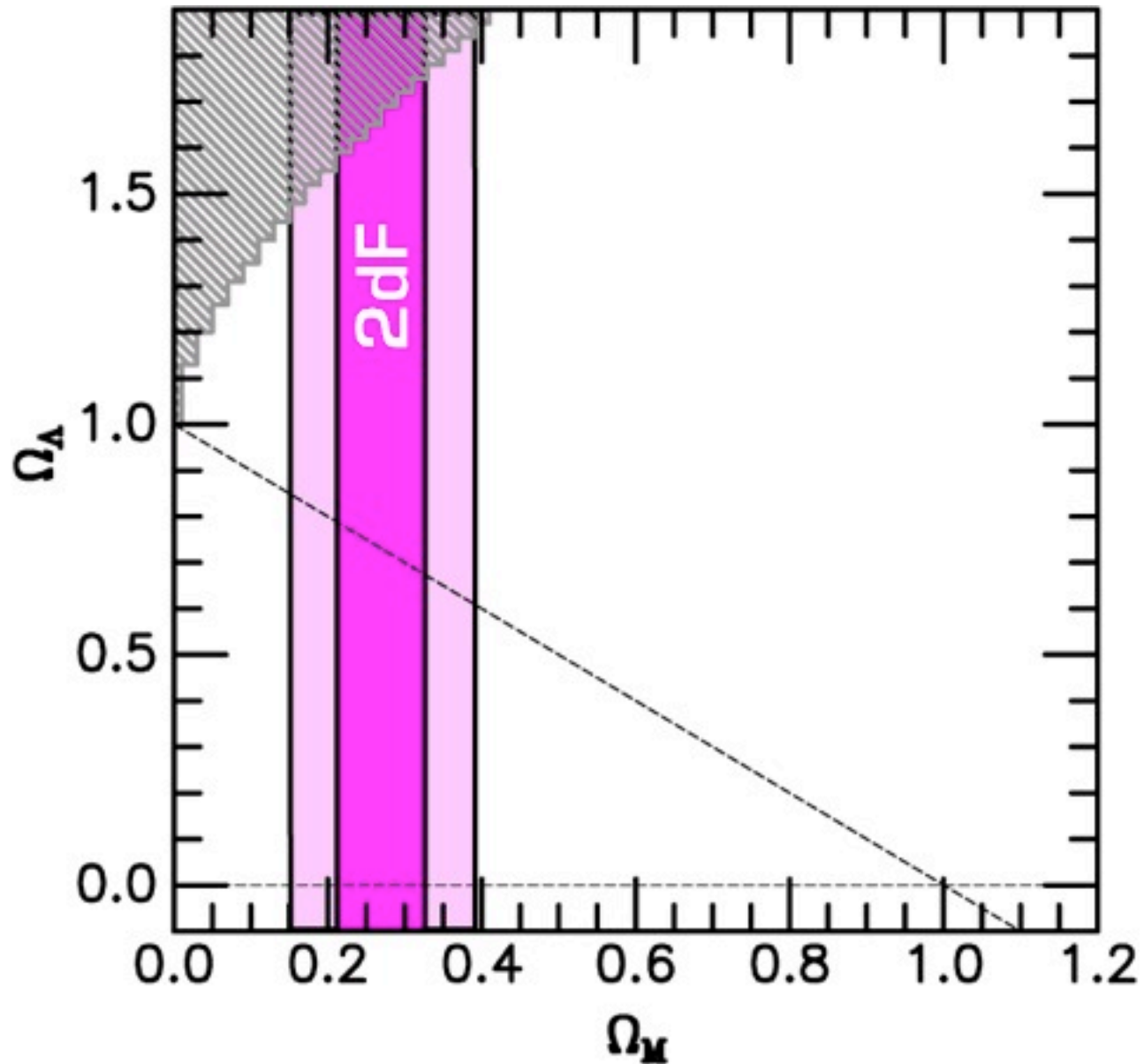
2dF redshift survey finds
 $\Omega_M \sim 0.3$ from power
spectrum and infall



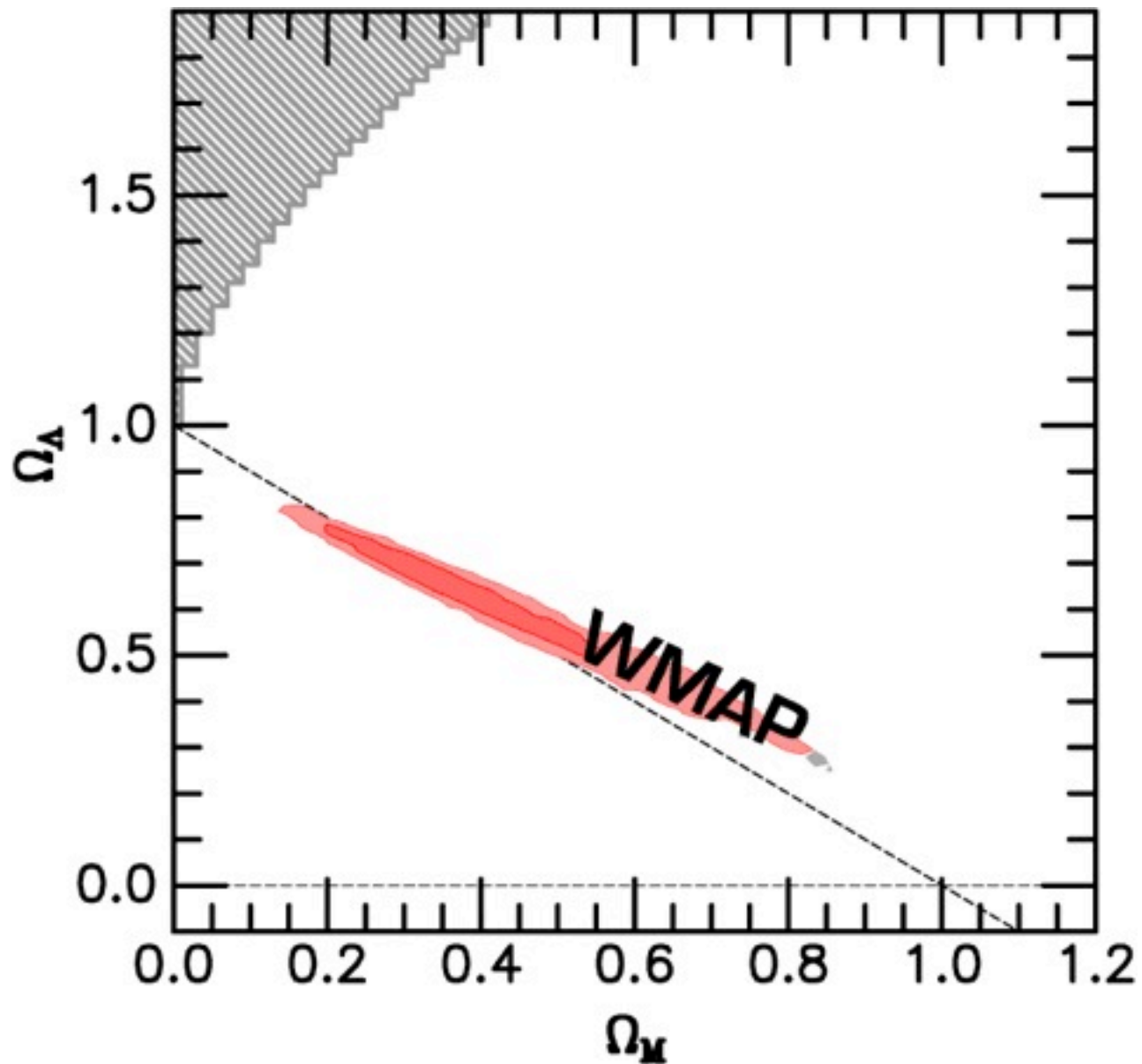
2003 - Cosmic Concordance



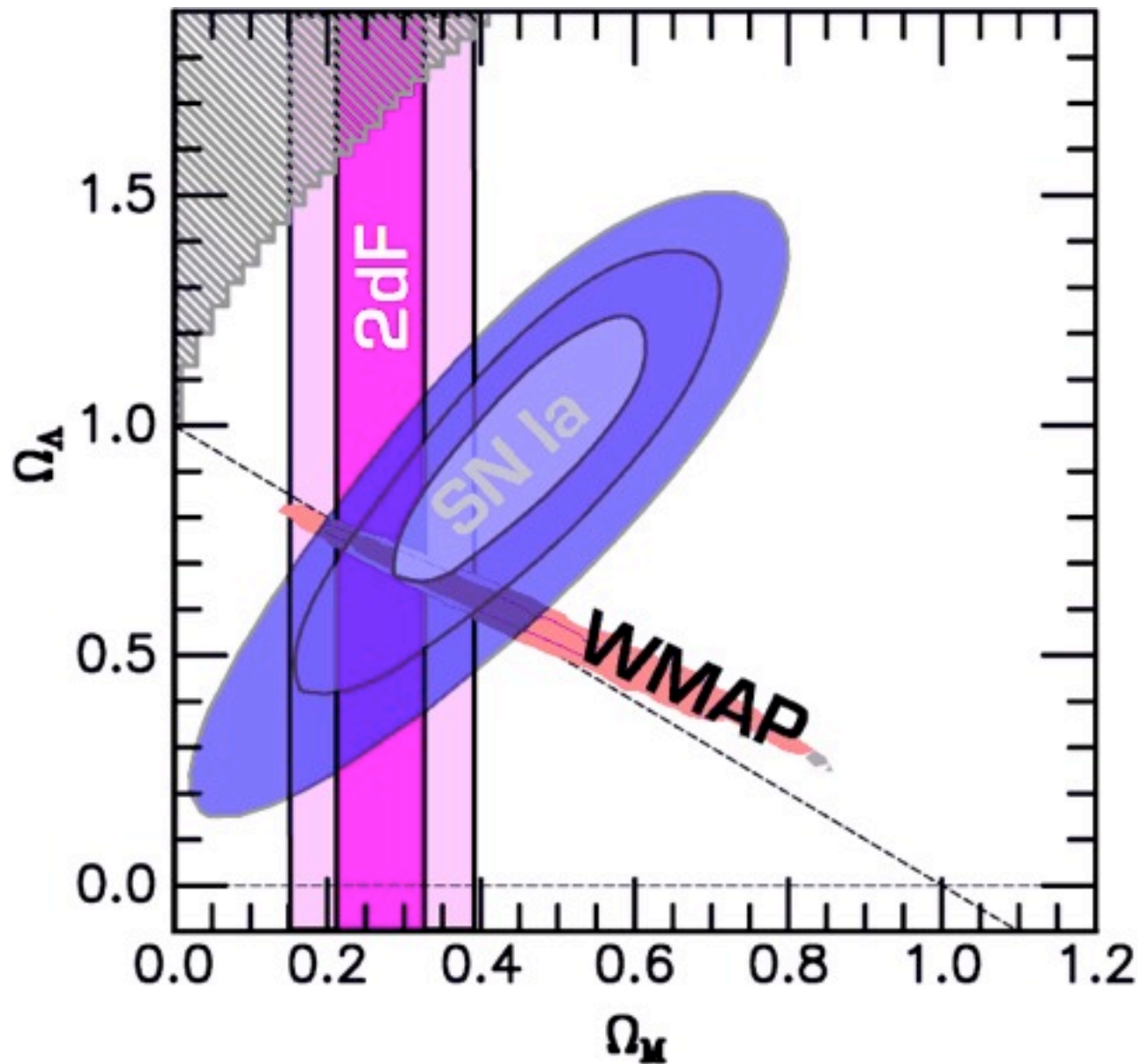
2003 - Cosmic Concordance



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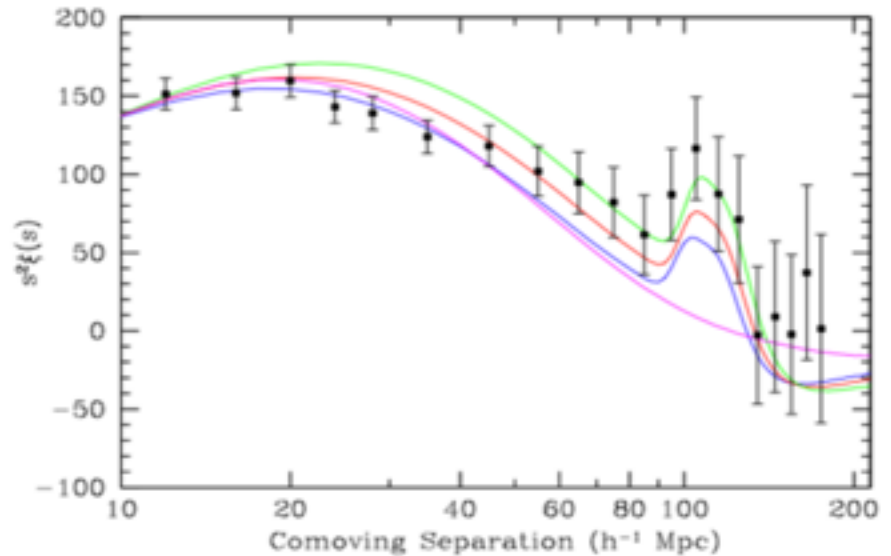
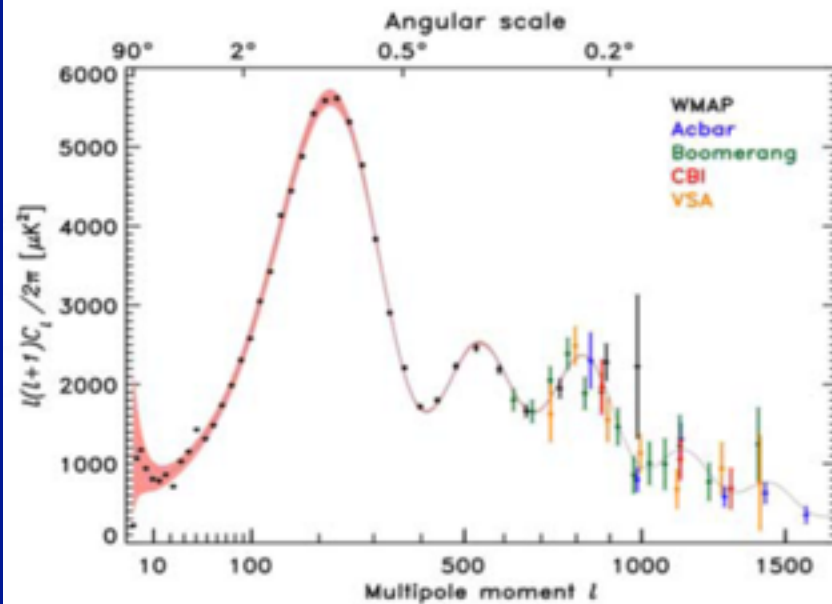
2003 - Cosmic Concordance

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.

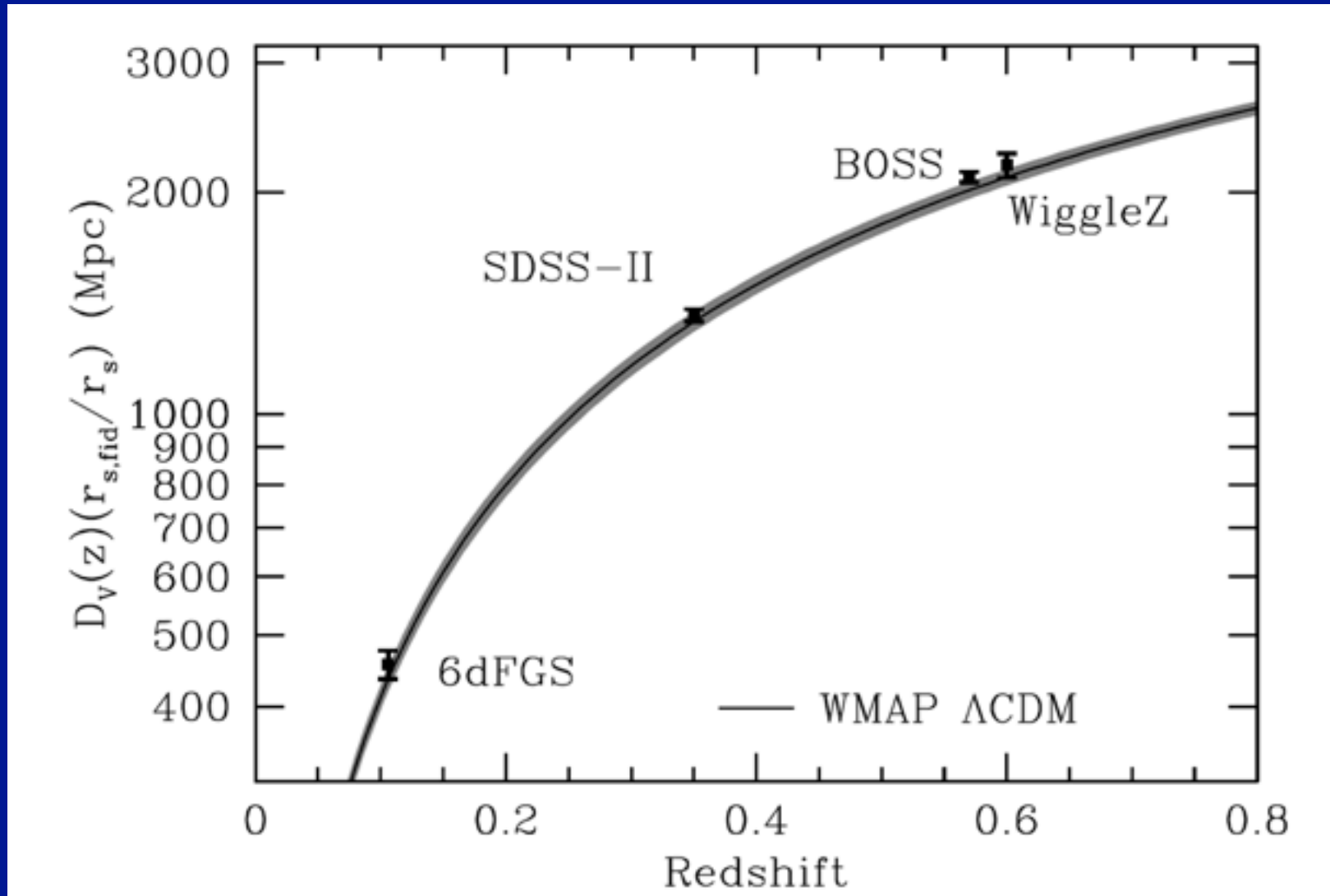
The physics of these *baryon acoustic oscillations* (BAO) is well understood, and their manifestation as wiggles in the CMB fluctuation spectrum is modeled to very high accuracy - the 1st peak has a size of 150 Mpc (co-moving), from WMAP



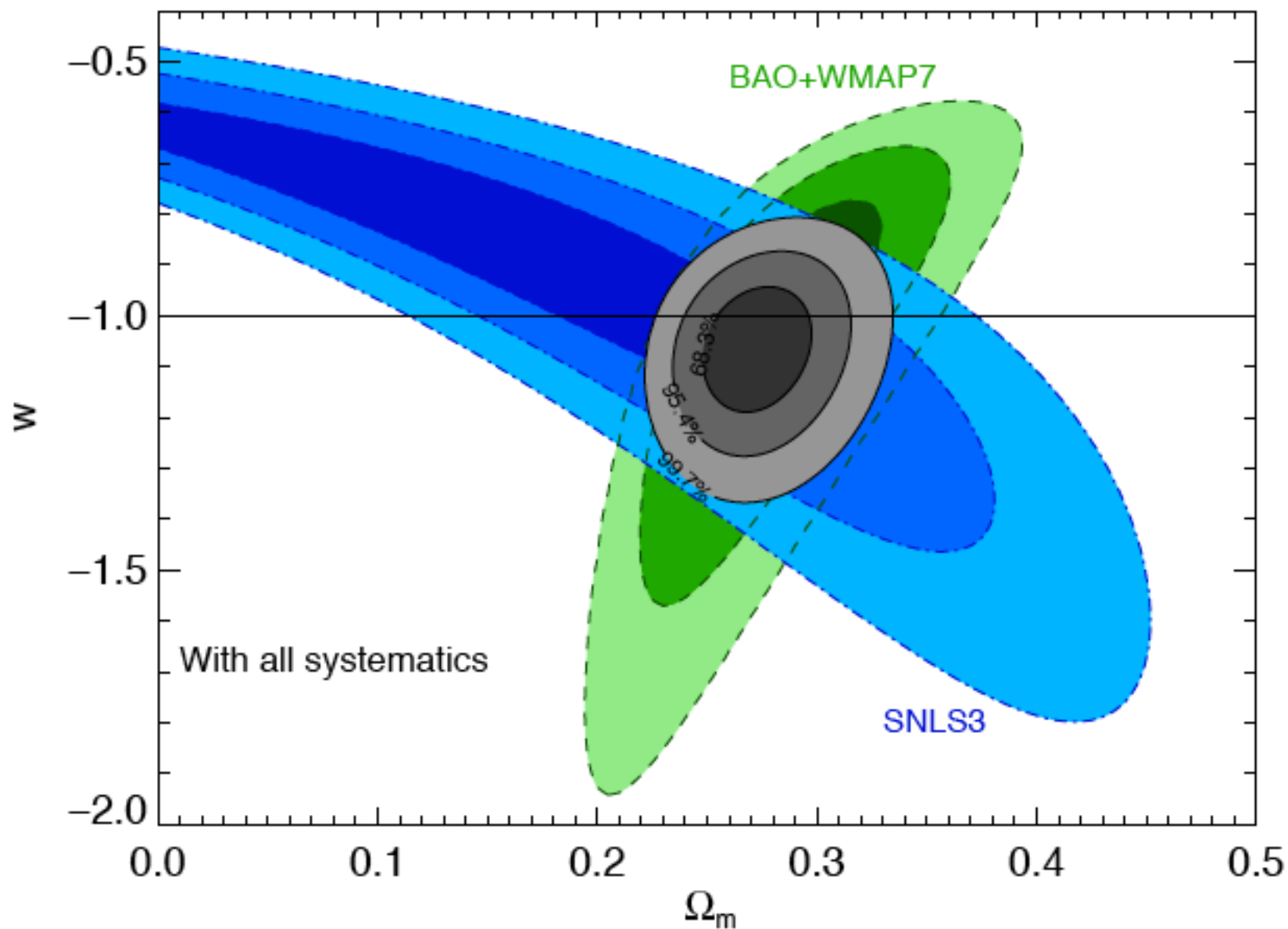
Eisenstein et al. 2005

- 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 $\langle z \rangle = 0.2$ to $\langle z \rangle = 0.7$

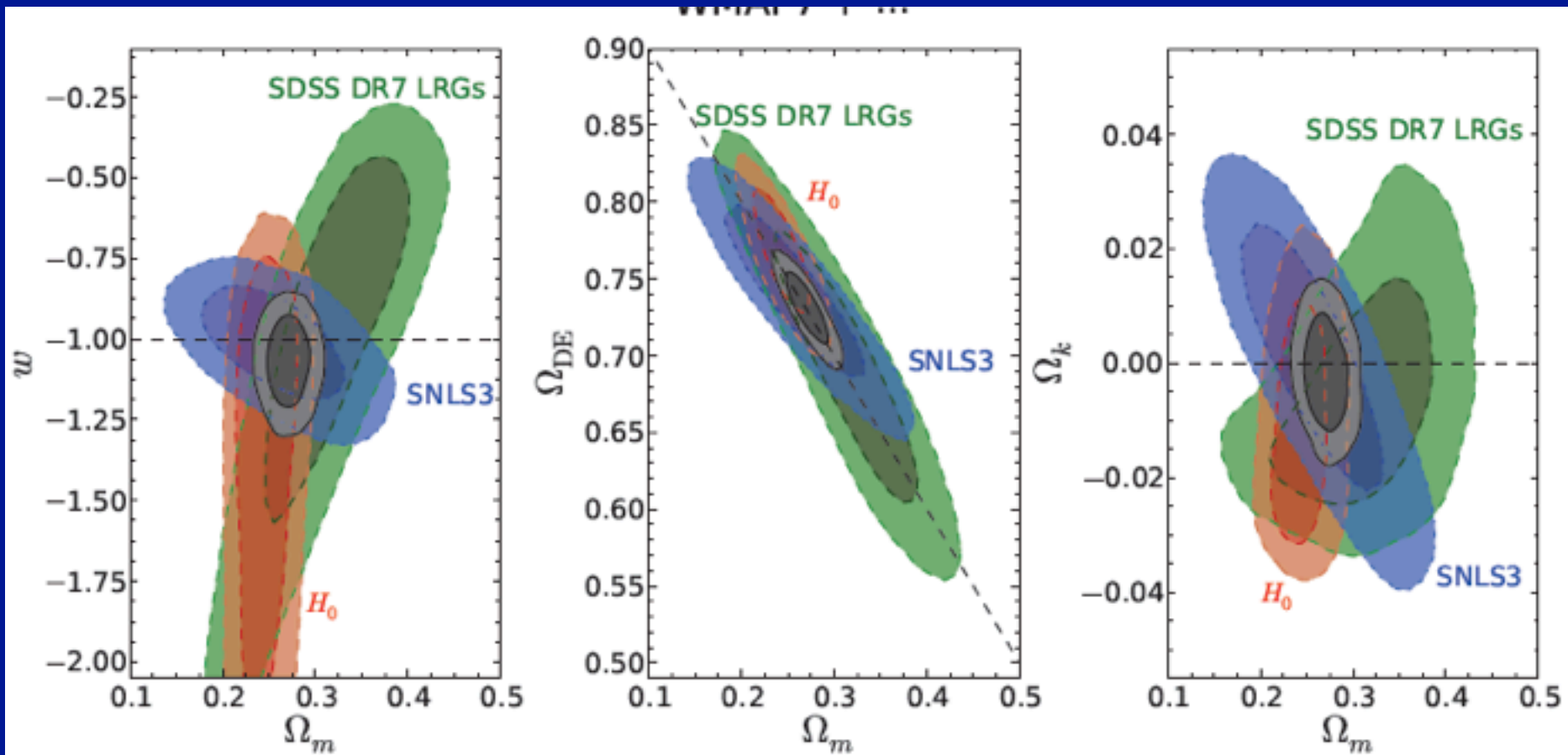
Where we Stand now - BAOs



Eisenstein et al. 2005 Percival et al 2010 Beutler et al 2011 Blake et al 2011 Anderson et al 2012



WMAP7 + ...

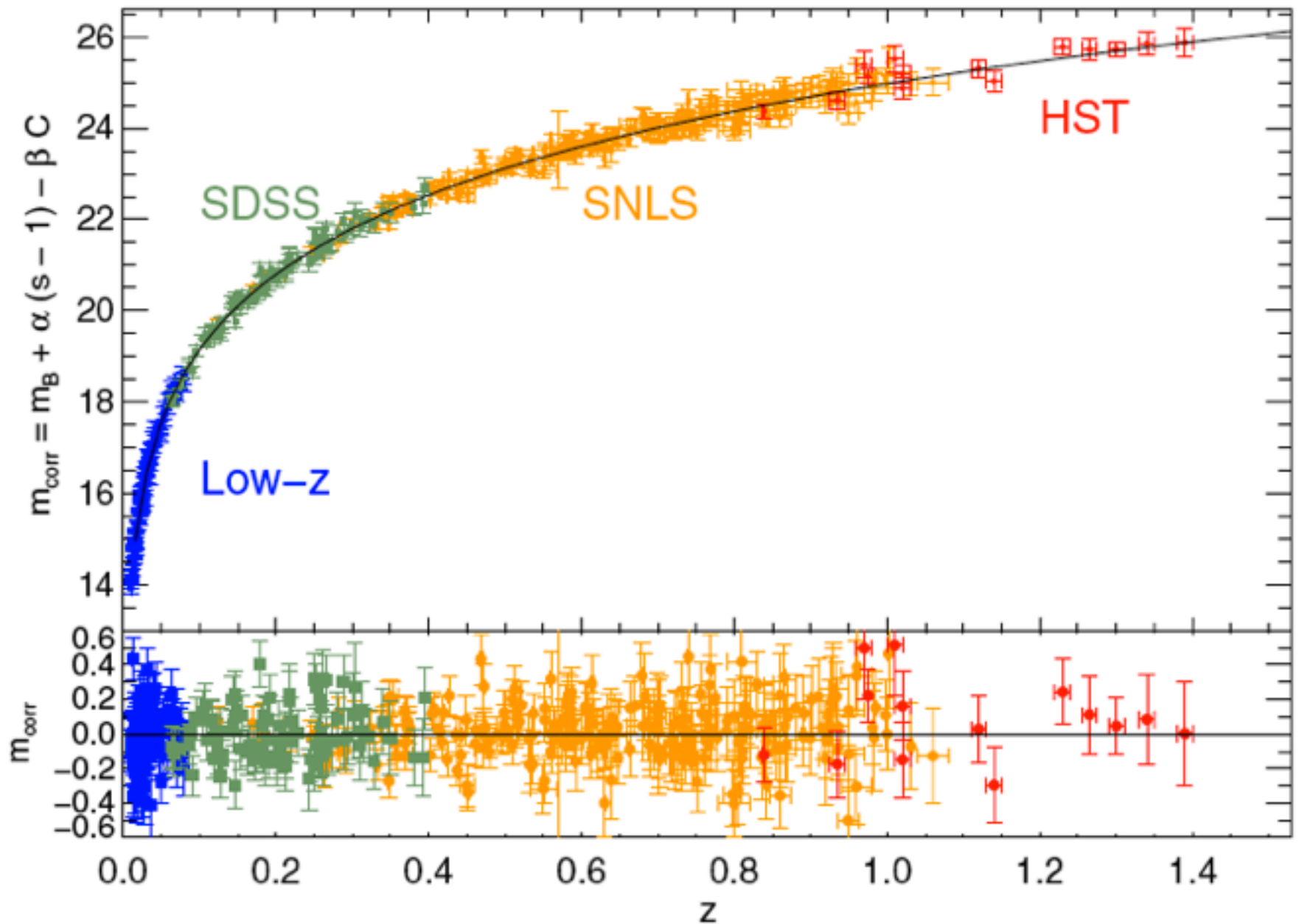


$w, \Omega_w, \Omega_M, \Omega_K$

all constrained simultaneously

Sullivan et al 11

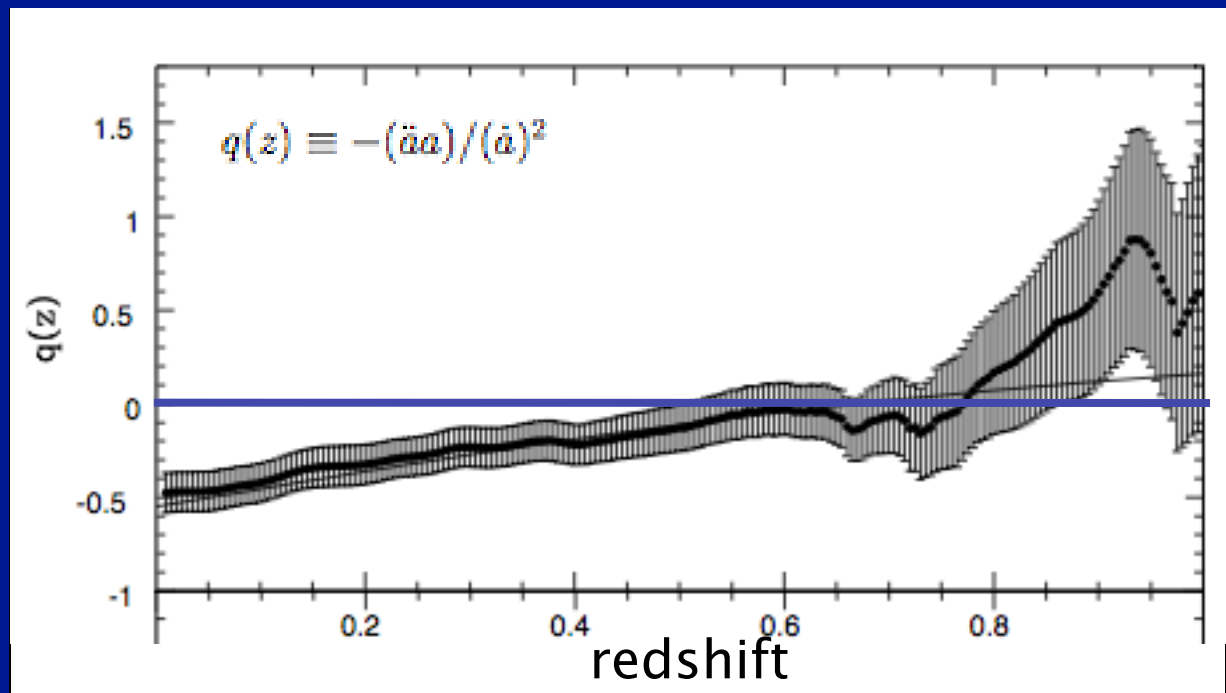
Where we Stand now - SN Ia



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

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

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



Daly et al.

Dark Energy ?



Dark Energy



?

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

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



Dark Energy



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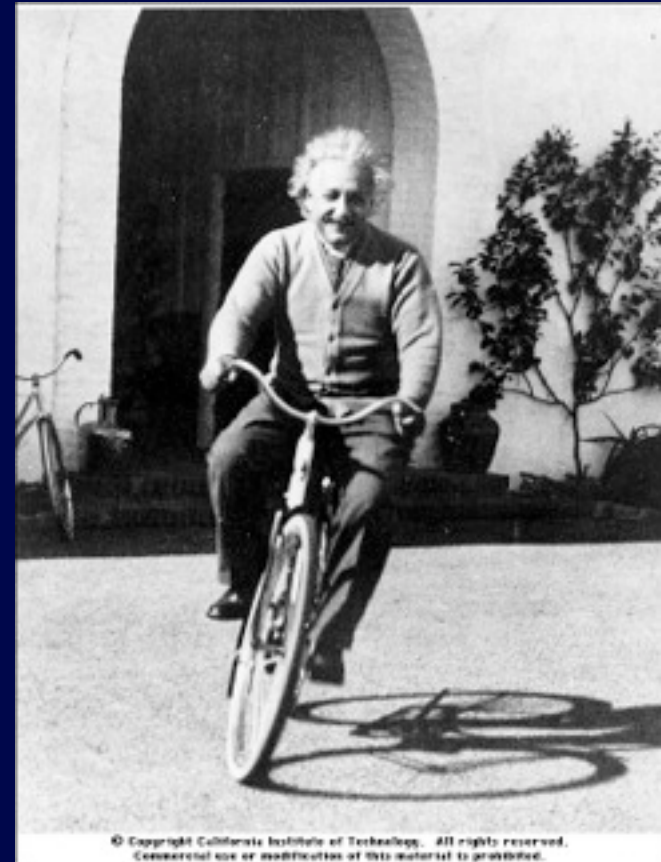
Theoretical Discussion on whether or not the growth of structure can perturb the metric in such a way to mimic the effects of Dark Energy. *This is the only way out I can see - But controversial!*

So What is the Dark Energy?

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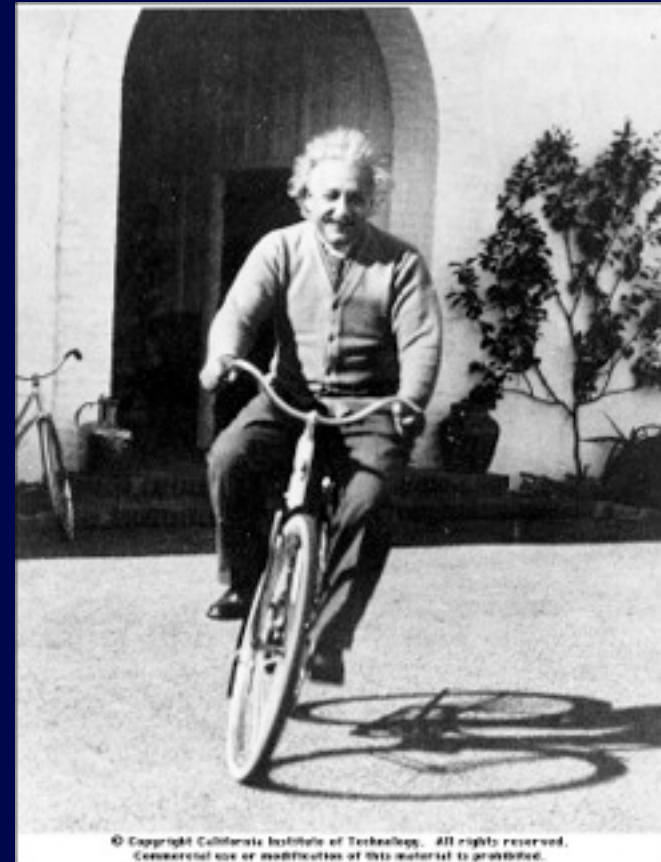
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Such a “cosmological constant” (Λ) was originally postulated by Einstein, but later rejected when the expansion of the Universe was first detected.



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

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

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



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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.

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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

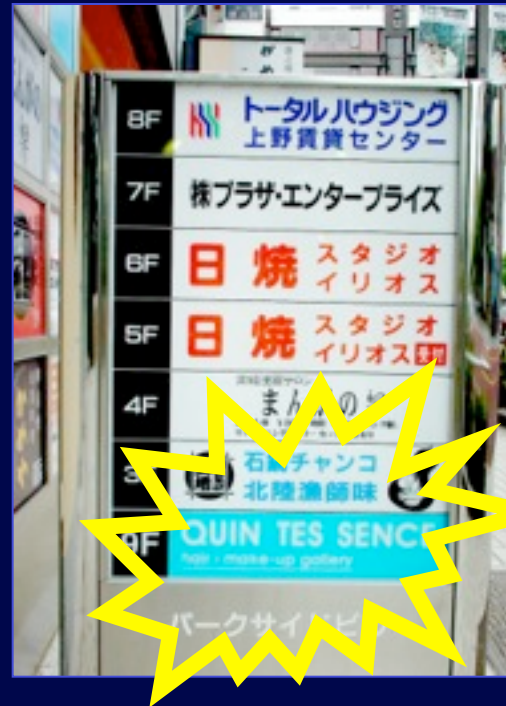
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An alternative explanation of the accelerating expansion of the Universe is that general relativity or the standard cosmological model is incorrect.

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.

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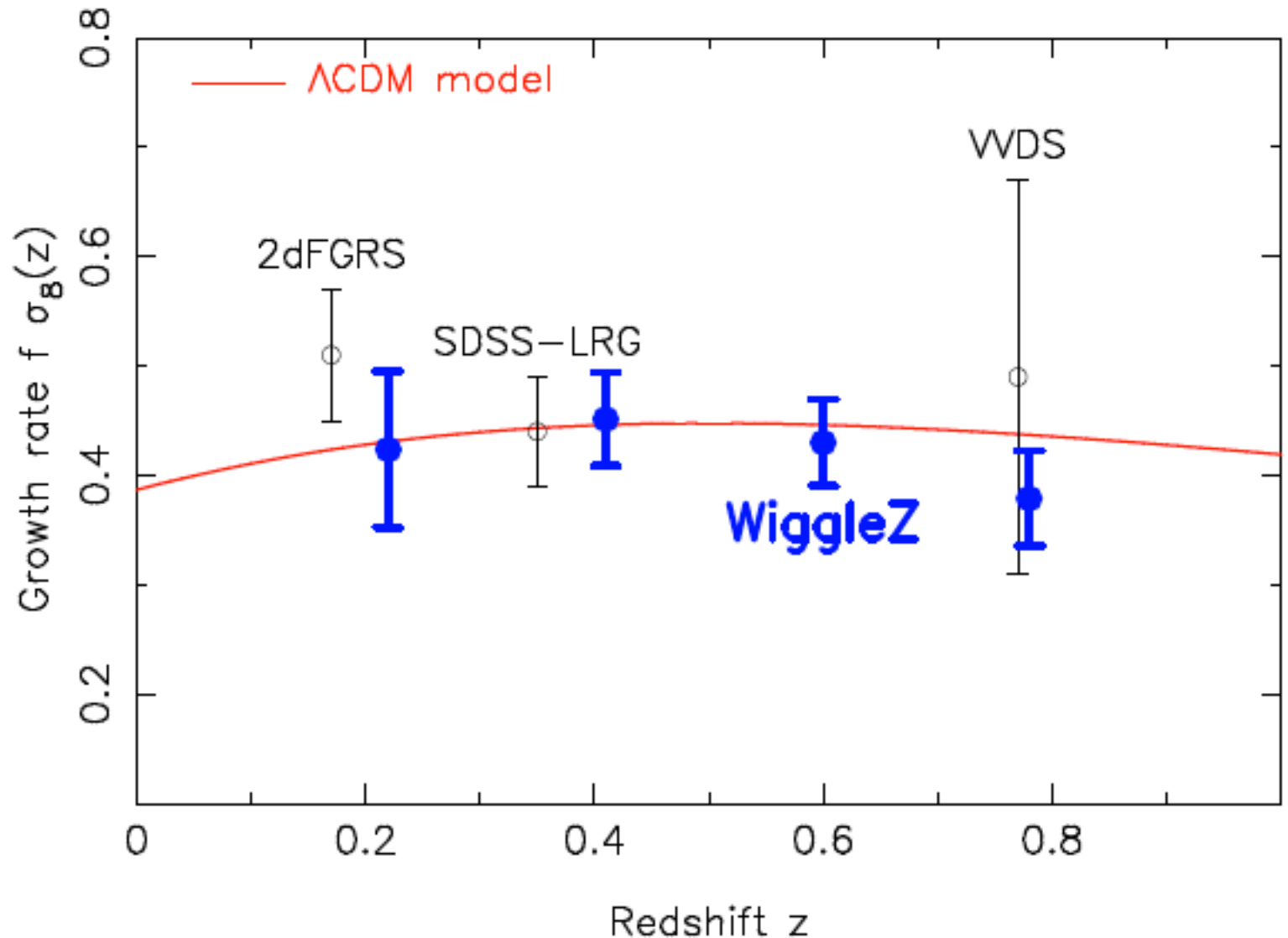
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But we can start to test this.

Blake et al 2011



Dark Energy Ideas

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

from Karl Glazebrook

Dark Energy looks a lot like
 Λ

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

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- Observers are searching blindly, hoping to find something that distinguishes it from Λ .

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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 experiment to date - but I believe we are reaching a systematic wall
 - Photometric Zero Points
 - Dust, 2nd order luminosity effects
- A precise measurement (1-2%) of D_L from $0 < z < 1.5$

Dark Energy Futures

CMB

- WMAP 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 improved Geometric distances (Riess et al. 2011)

- Maser Distances
- Cepheid Parallax Measurements

Potential for Future Geometric Distances (more distant NGC4258s, or Gravity Waves from merging black-holes)

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

Dark Energy Futures

BAOs

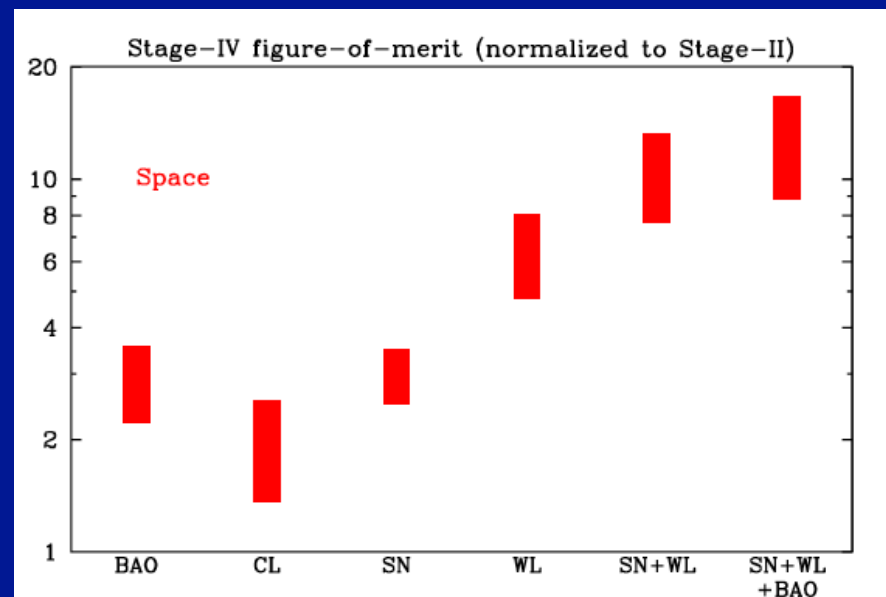
- BAO experiments are by very simple and promise precise measurements potentially immune from systematic error.
 - 2dF, SDSS, 6dF, WiggleZ now
 - BOSS is here and improving
 - EUCLID, HETDEX BigBoss, & DECSPEC for the future?
- So simple - how can it go wrong?

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!

LSST - EUCLID



Dark Energy Futures

The Unexpected

Dark Energy Futures

The Unexpected

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

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This is my Best Bet for Understanding Dark Energy

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**The More Space Expands - the More Dark Energy
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***The creation of space happens more quickly than
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Our Island Universe

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- **Attractive Gravity has defeated Dark Energy in our part of the Universe
WE ARE NOT EXPANDING!**

Our Island Universe

- **Attractive Gravity has defeated Dark Energy in our part of the Universe
WE ARE NOT EXPANDING!**
- **Eventually, the nearest galaxies and the Milky Way will merge into a super-galaxy**



Our Island Universe

- But the rest of the Universe will be accelerated out of sight

***We will see stars,
but look out onto an empty Universe***

**But Until we understand what
is accelerating the Cosmos...**

anything is possible.

**But Until we understand what
is accelerating the Cosmos...**

anything is possible.

**Dark Energy might change in the future and slow
the Universe up, or even accelerate the Cosmos at
an even faster rate...**



**- unless Dark Energy suddenly
Disappears -**

**The Universe will
at an ever increasing rate
expand and fade away...**

