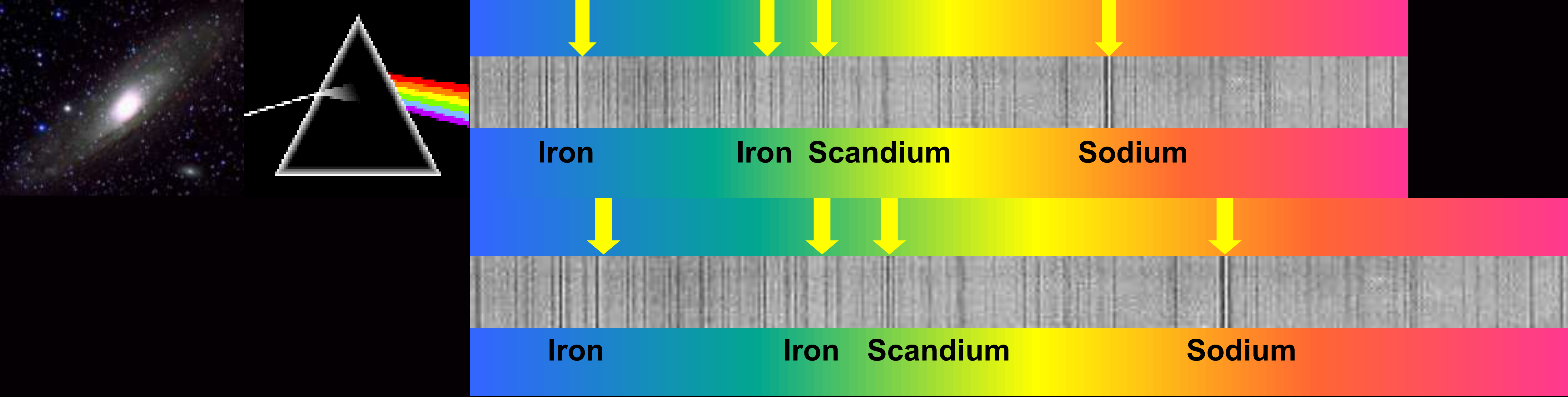
The Accelerating Universe

Brian P. Schmidt

CAASTRO
ALL-SKY ASTROPHYSICS

ANU
THE AUSTRALIAN NATIONAL UNIVERSITY

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

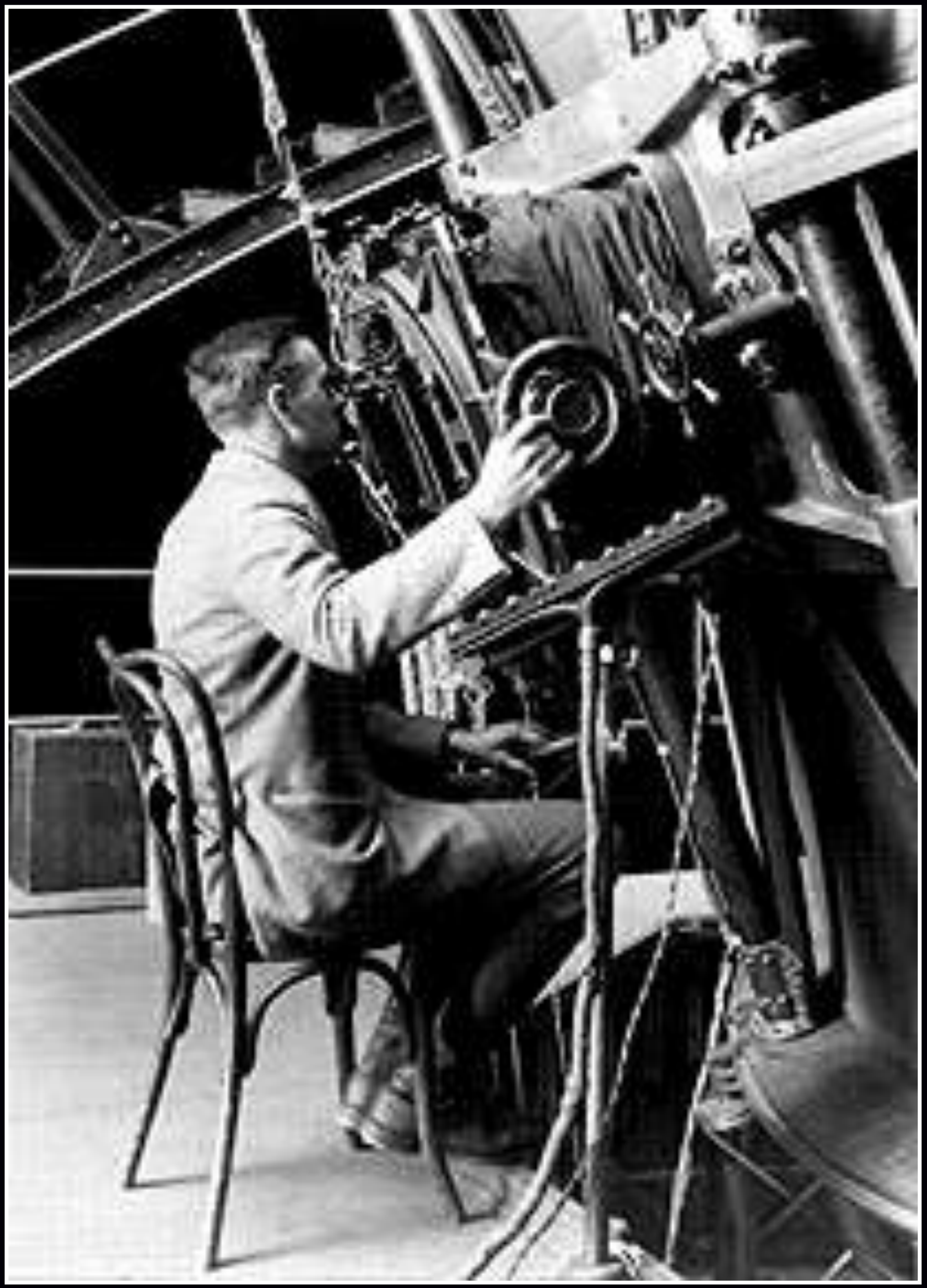


Doppler Shift Gives Velocity of Galaxy

In 1916 Vesto Slipher measured velocities to nearby galaxies, and discovered they were all moving away from us.

1929, Hubble uses brightest stars

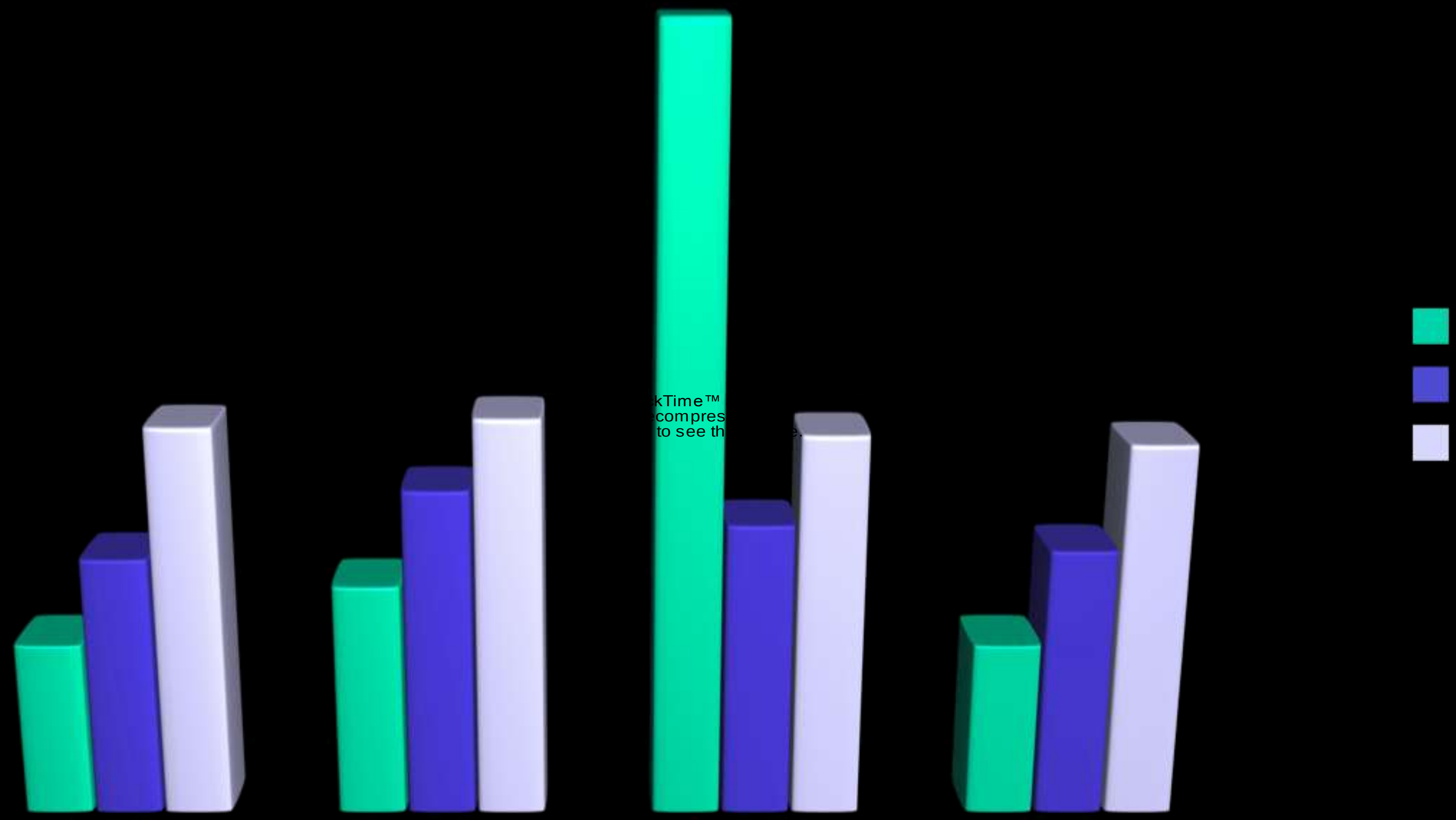
to measure the distances to the nearest galaxies.



He assumes the *brightest stars are all the same brightness.*

The faster the galaxy was moving, the fainter the stars!

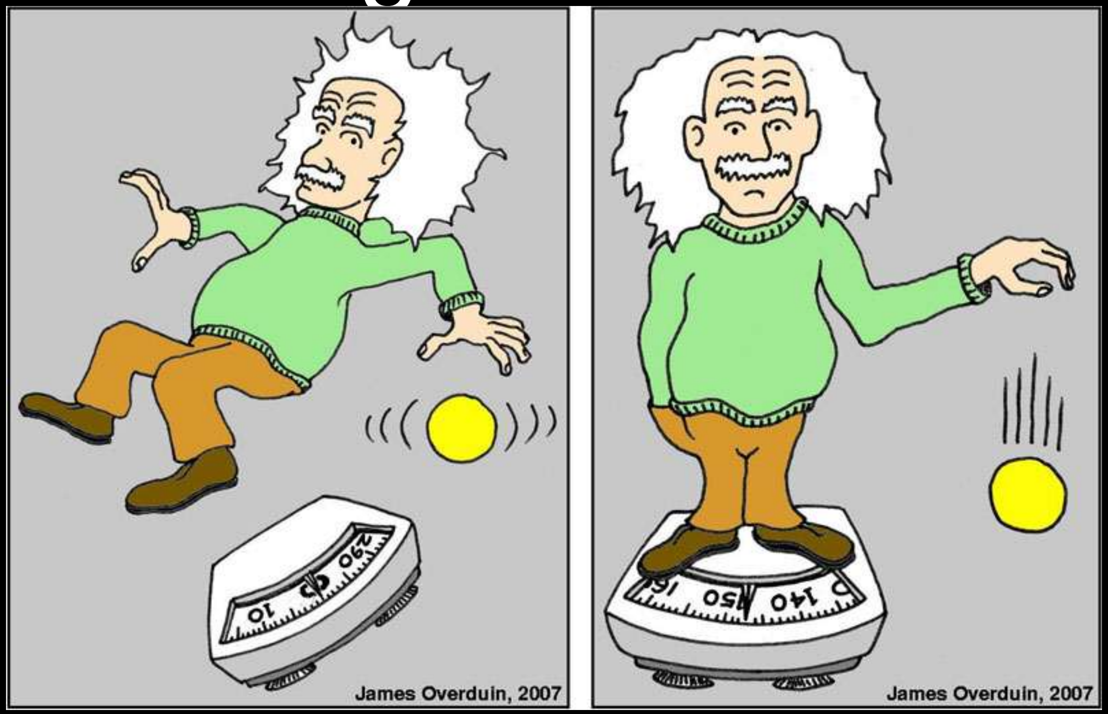
Hubble's Data

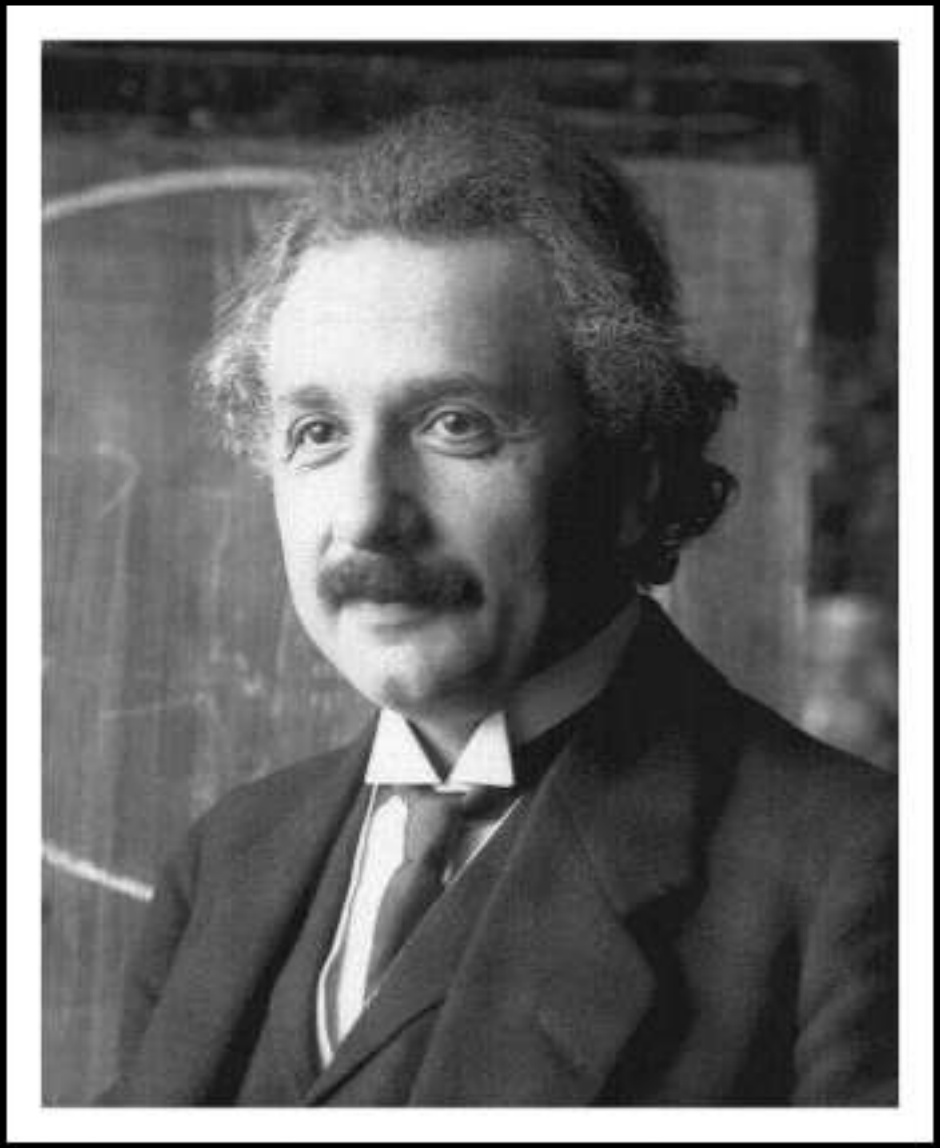


The Universe is Expanding

Einstein's Theory of Gravity

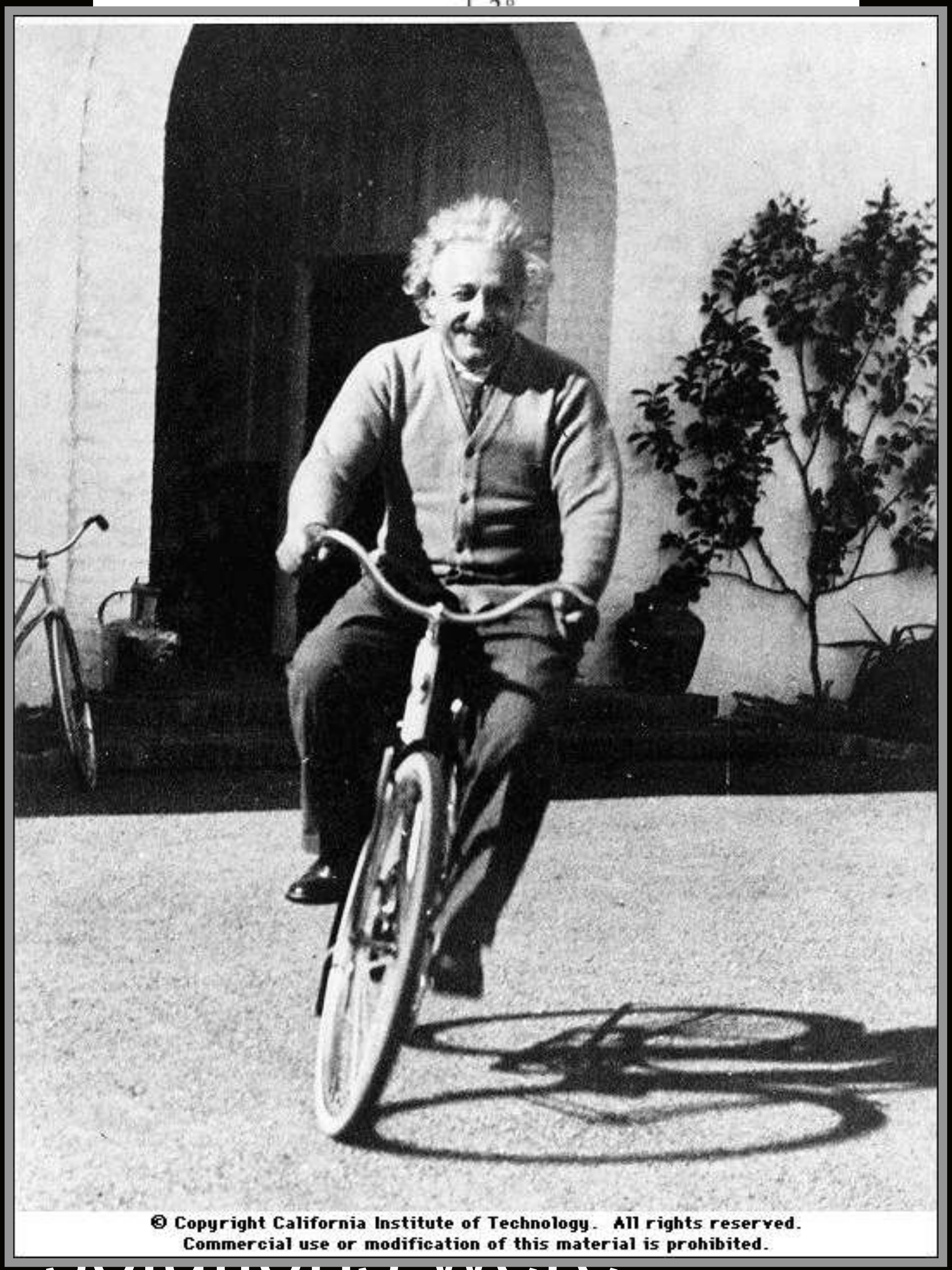
- In 1907 Einstein had a revelation that acceleration and gravity were indistinguishable.





1915...Equations of General Relativity

Predicted Curved Space



solutions were
dynamic - Universe
should be in Motion

The Cosmological Constant

Originally proposed by Einstein to counteract the Universe's gravitational attraction - it makes Gravity Push rather than Pull.

Later "retracted" once the expansion was discovered

It represents the energy of the vacuum (What is there when there is nothing there!)

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

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

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

QuickTime™ and a
H.264 decompressor
are needed to see this picture.

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H.264 decompressor
are needed to see this picture.

The Standard Model

Friedmann Equation

(assumes homogenous and isotropic Universe)

G.R.

Isotropy & Homogeneity

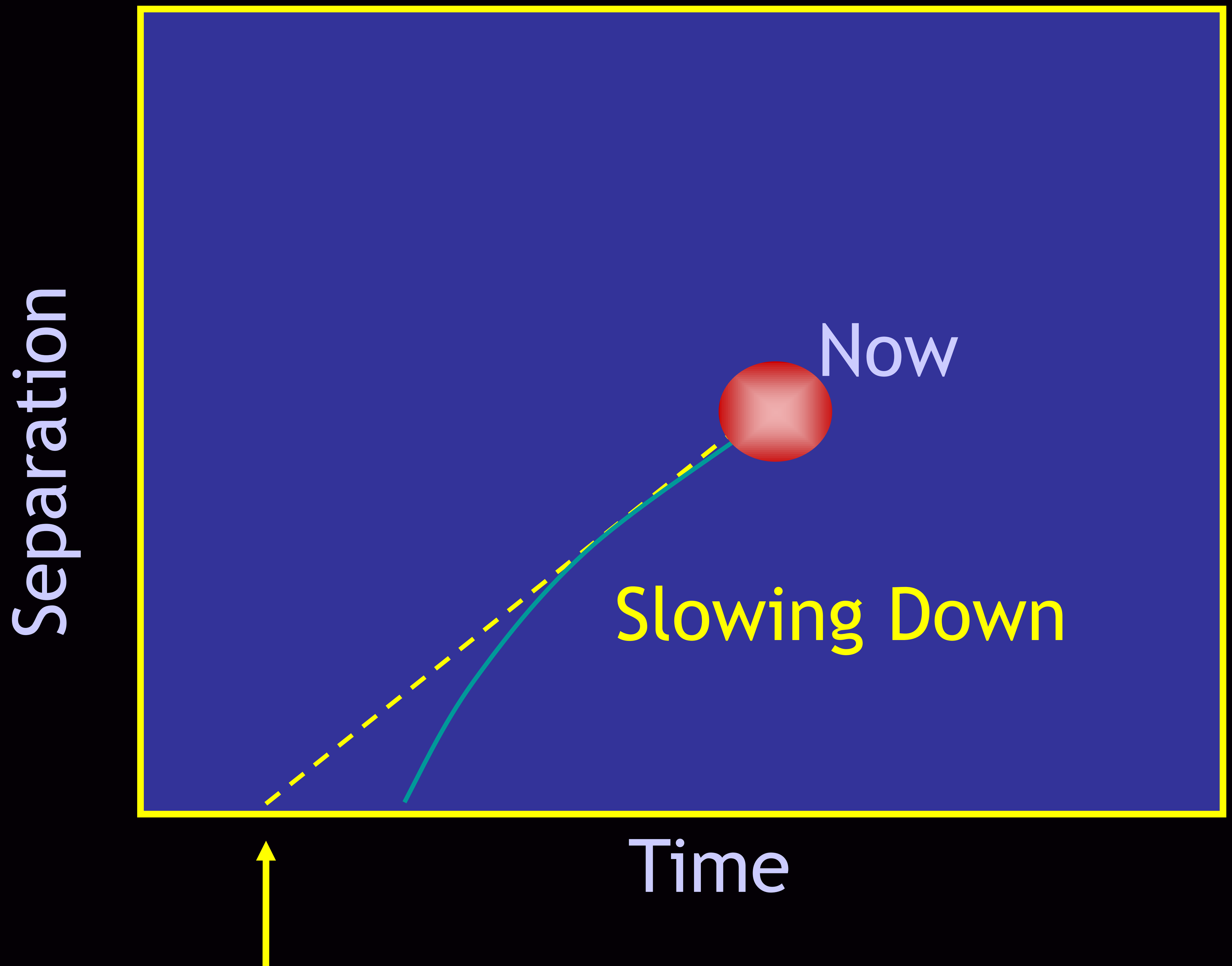
$$\frac{1}{c^2}\left(\frac{da}{dt}\right)^2 = \frac{8\pi G}{3c^2}\rho a^2 - k$$

Friedmann equation for Flat Universe

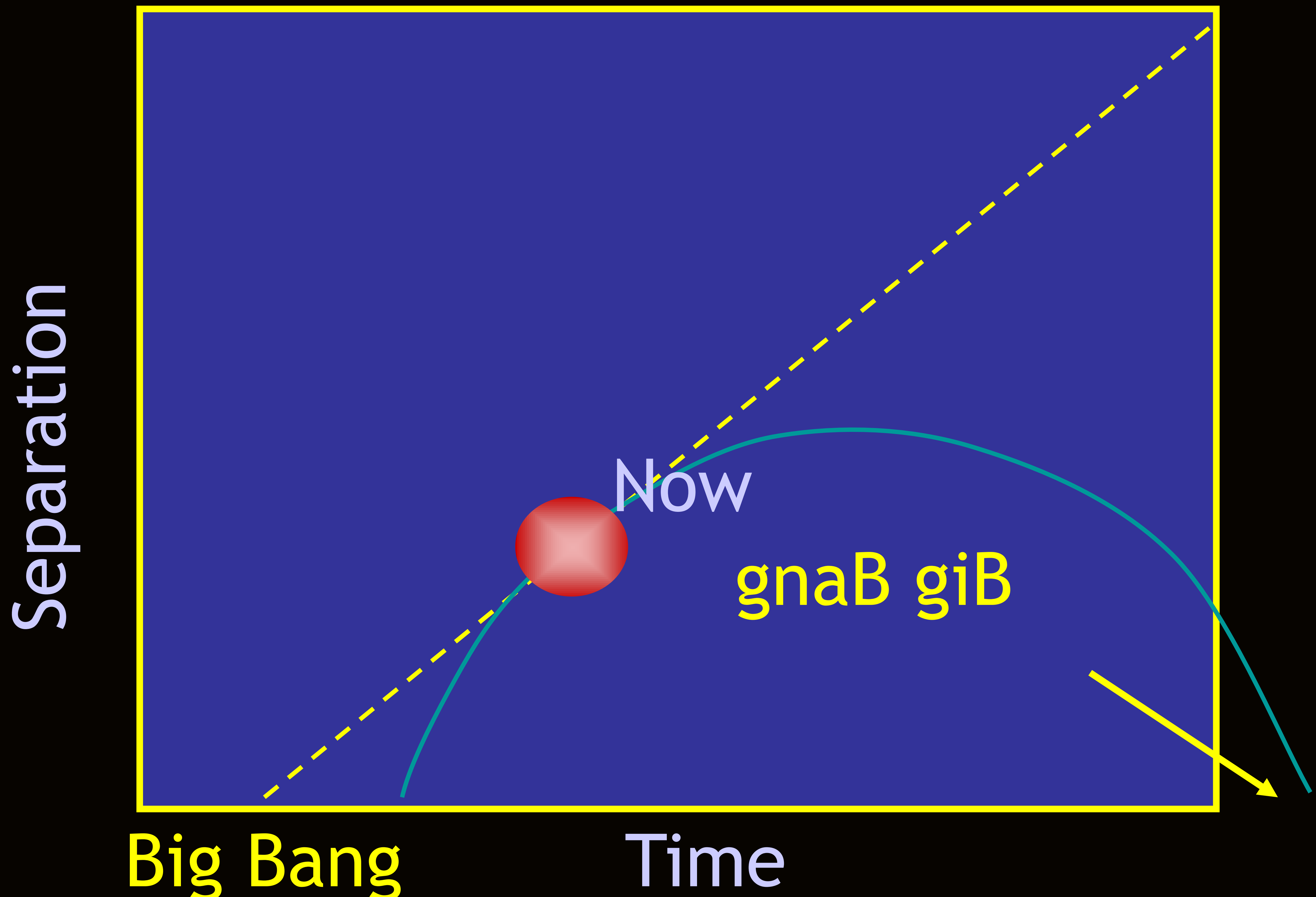
$$a(t=t_0)=a_0, \quad \rho(t=t_0)=\rho_0, \quad H(t=t_0)=H_0, \quad k=0$$

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

The Distance Between Two Galaxies



Looking towards the Future



The Density parameter and Geometry

$$\rho_{c,0} = \frac{3H_0^2}{8\pi G}$$

$$\rho_{c,0} = 9.2x10^{-27} kg/m^3 \left(\frac{H_0}{70km/s/Mpc} \right)^2$$

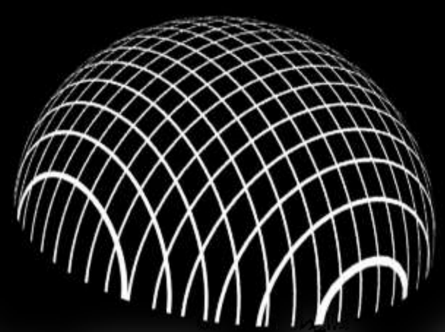
$$\Omega_0 = \sum \frac{\rho_{i,0}}{\rho_{crit,0}} = \sum \Omega_{i,0}$$

$$\Omega_0 = \Omega_{M,0} + \Omega_{\gamma,0} + \Omega_{\upsilon,0} + \Omega_{\Lambda,0} + \Omega_{?,0}$$

$$\begin{array}{r} \text{FLAT} \\ \text{OPEN} \\ \text{CLOSED} \end{array} \left\{ \begin{array}{lll} \Omega_0 = 1 & k = 0 & \Omega(t) = 1 \\ \Omega_0 < 1 & k = -1 & \Omega(t) < 1 \\ \Omega_0 > 1 & k = +1 & \Omega(t) > 1 \end{array} \right\} \text{for all time}$$

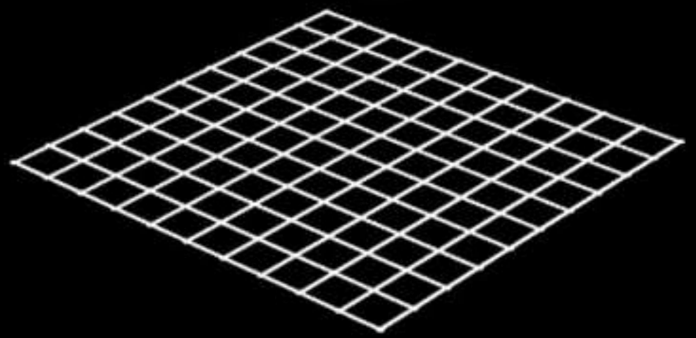
Cosmic Geometry-Curvature and Density

Heavy

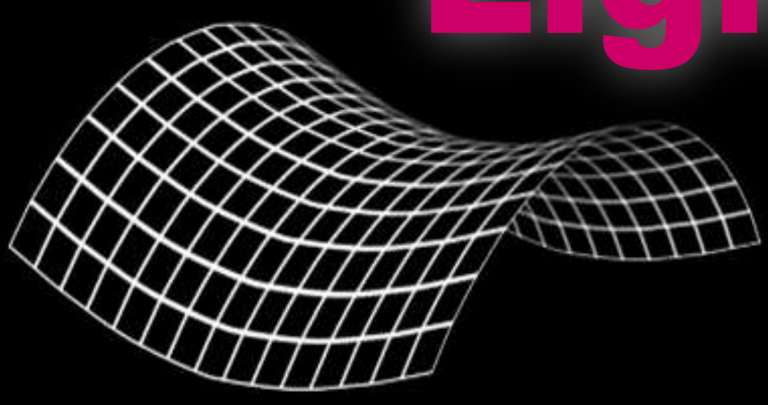


k=+1

Just Right k=0



Light k=-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***

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

w=−1 ***for Cosmological Constant***

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

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

$$\rho \propto V^{0} \rightarrow \left(\frac{a}{a_0}\right)^0 \left(\frac{\rho_\Lambda}{\rho_0}\right) = 1$$

QuickTime™ and a H.264 decompressor are needed to see this picture.

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

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

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

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

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

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

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

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

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

$$y\,dy = H_0\,dt$$

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

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

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

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

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

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

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

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

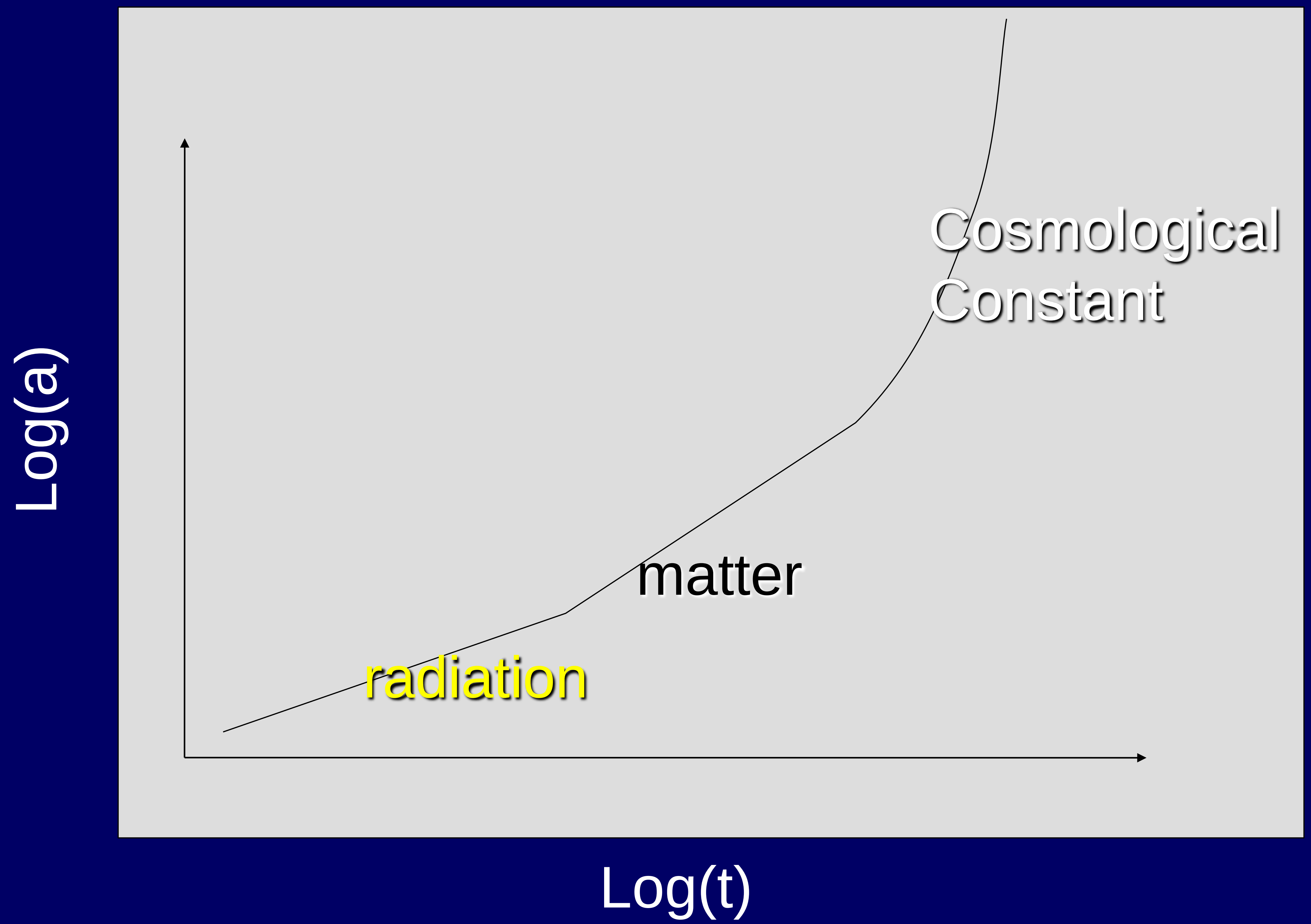
Domination of the Universe

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

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

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

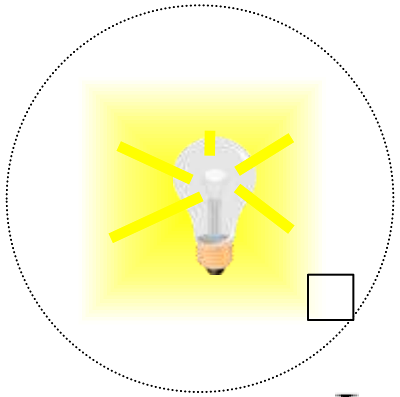
$$\frac{\Omega_w}{\Omega_M} = \left(\frac{a}{a_0}\right)^{-3w} = (1+z)^{3w}$$


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

Luminosity Distance

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

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



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

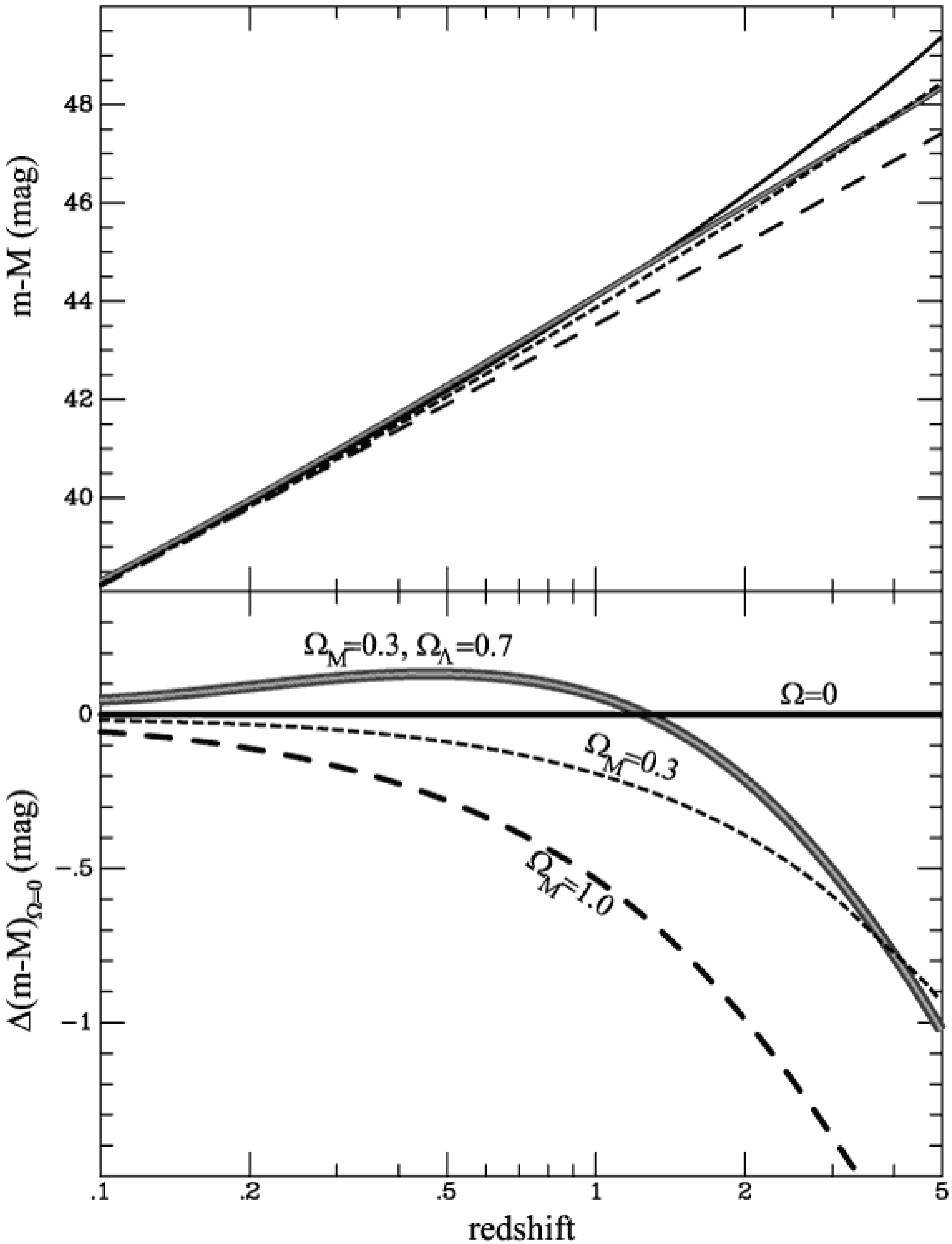
the flux an observer sees of an object at redshift z

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

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

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

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


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

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

$\wedge \sim 1$

H_0 <=50km/s/Mpc

Observers are wrong on H_0 and $\wedge_M$

(Observers)

$\wedge_M \sim 0.2$

H_0 =50-80km/s/Mpc

Inflation/CDM is wrong

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.

1990 - CDM Picture conflicts with what is seen

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

  a $\wedge_M$~0.2, $\wedge_{\not\subset}$~0.8 fixed both problems

QuickTime™ and a
decompressor
are needed to see this picture.

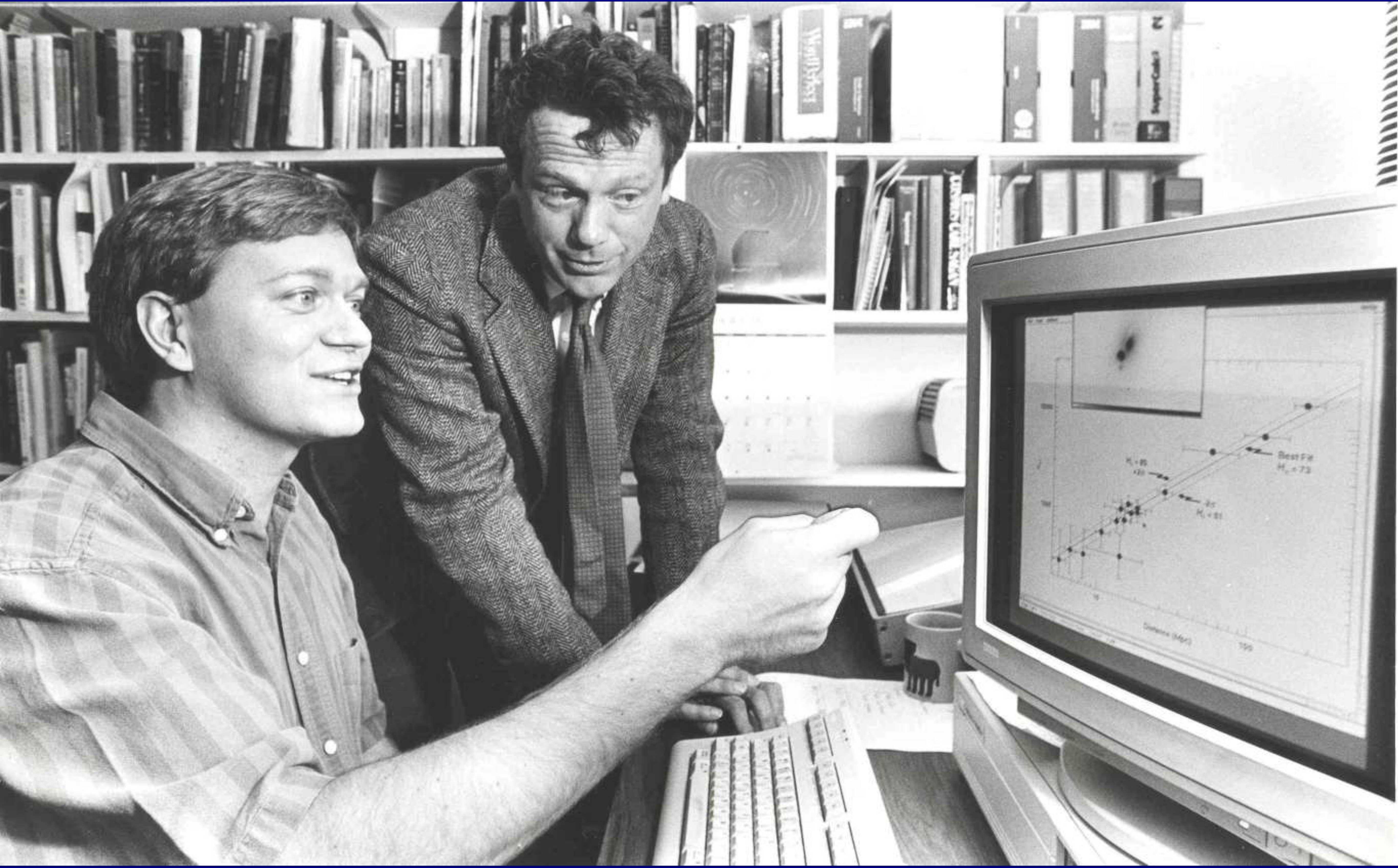
CDM theorists took this approach

QuickTime™ and a
decompressor
are needed to see this picture.

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.


Best Fit
$H_0 = 73$
Distance (Mpc)
100

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.

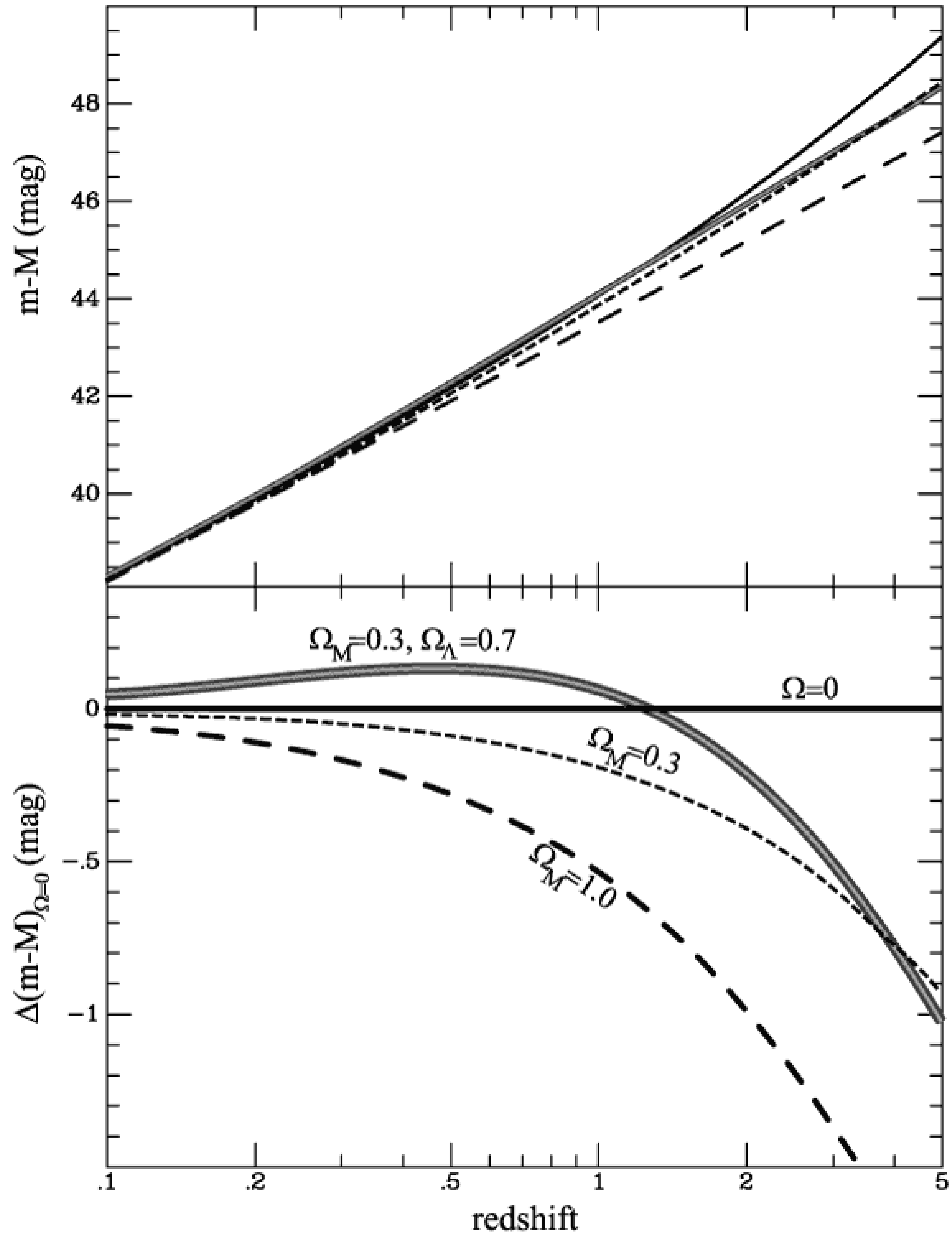
This wager shall be conducted under the auspices of an arbitrator, Jim Peebles, and shall be settled by the third millenium, Jan 1, 2001, or sooner if, in the opinion of the arbiter or the contesting parties, the answer is no longer in doubt. If the arbiter decides that the answer cannot be resolved 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

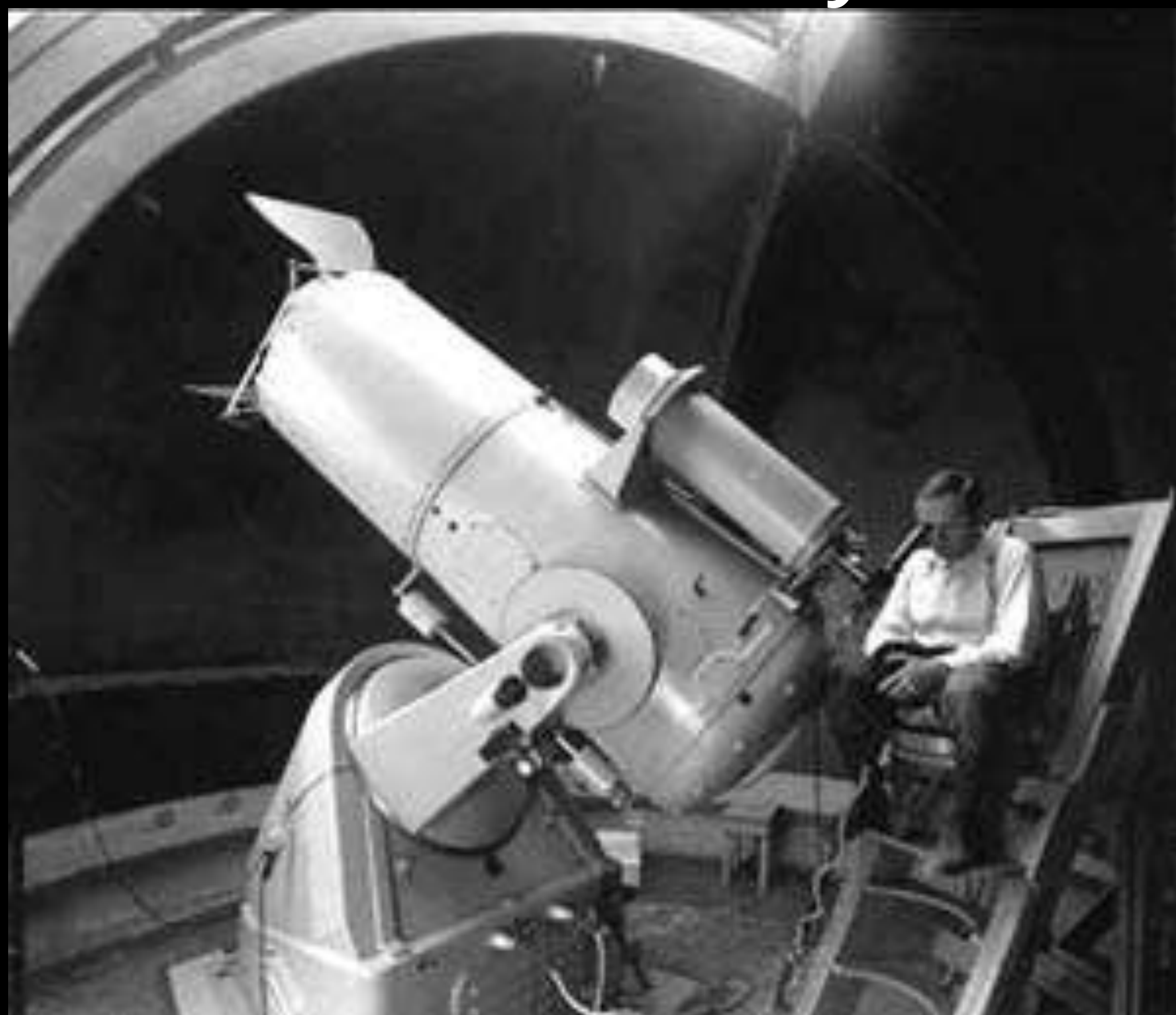
J R Mould
Kenneth Freeman



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

First use of Supernovae to Measure Distances

Fritz Zwicky



18in Schmidt Telescope

Charlie Kowal 1968

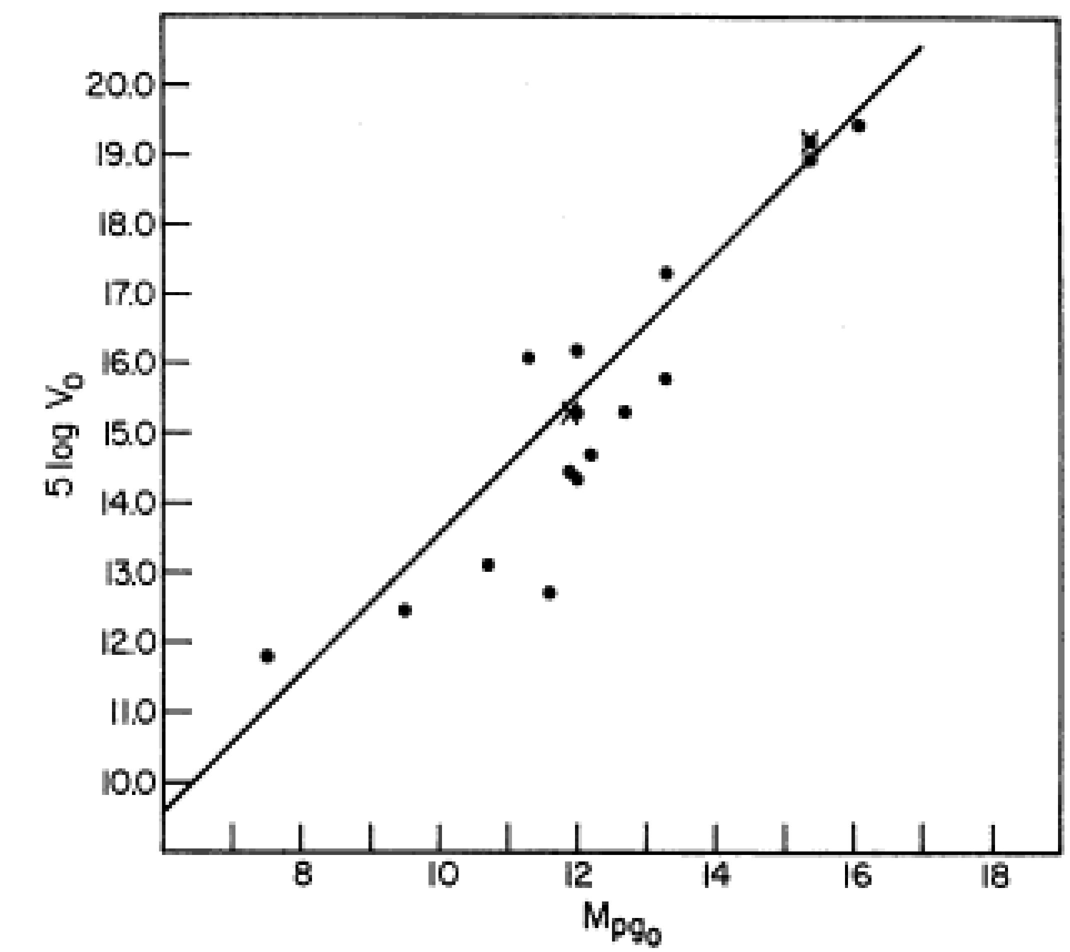


FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

First Distant SN detected in 1988 by Danish Team

Type Ia Supernovae

QuickTime™ and a
Animation decompressor
are needed to see this picture.

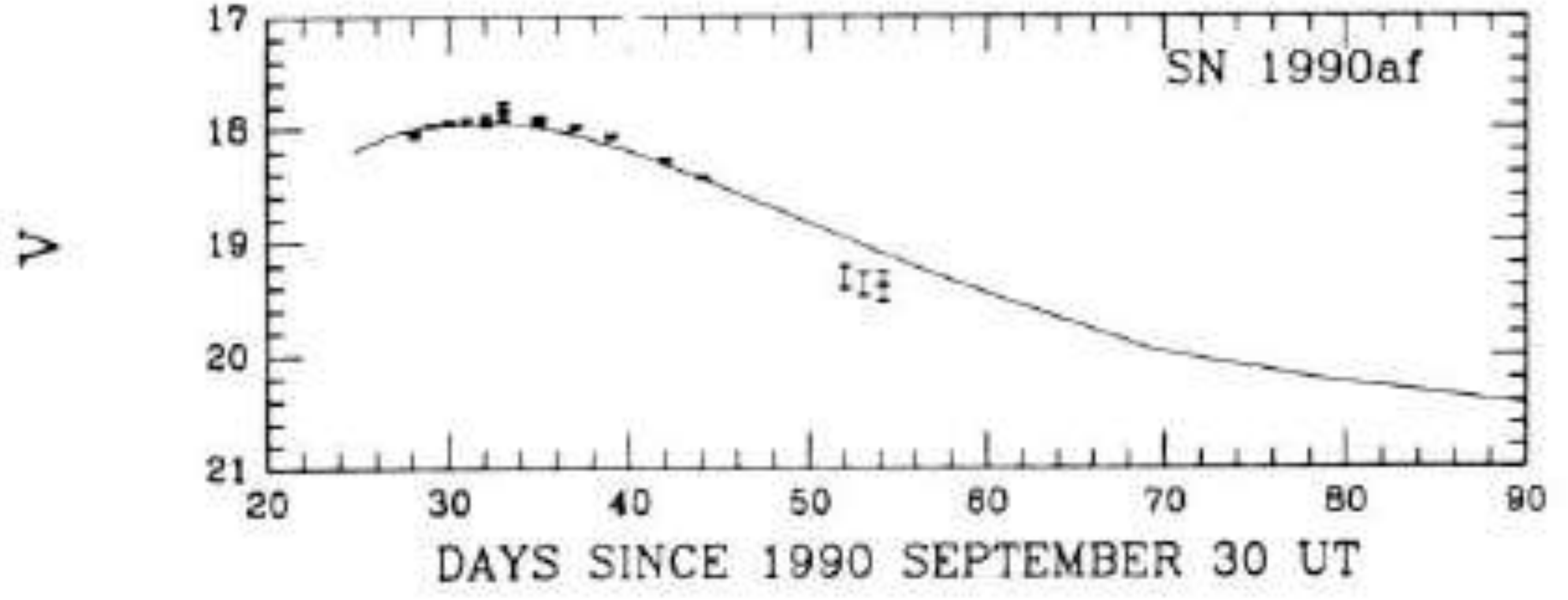
Calan-Tololo SN Search

Antezana

Aviles

Wischnjewsky

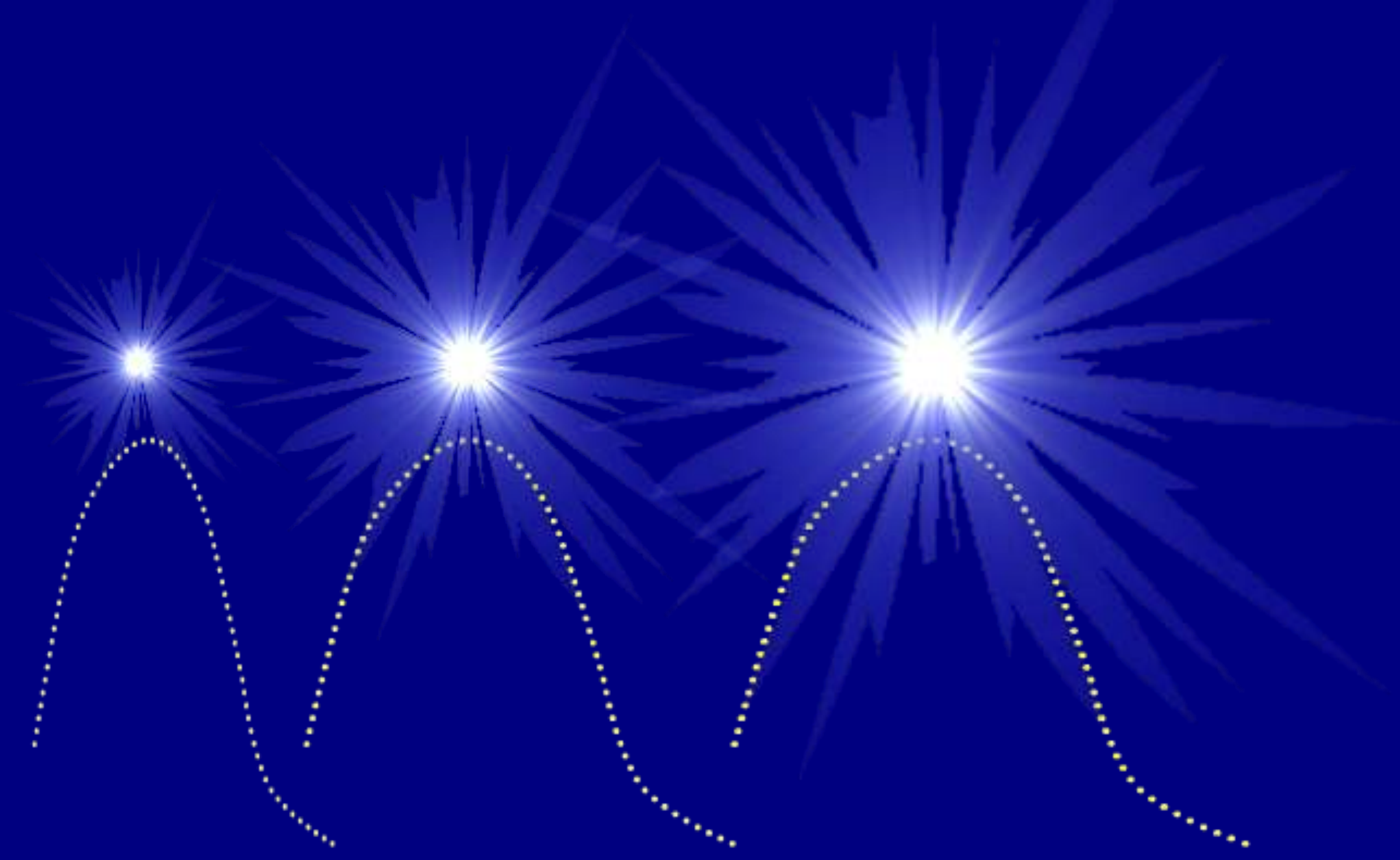
SN1990af: faded quickly and was fainter than normal



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!

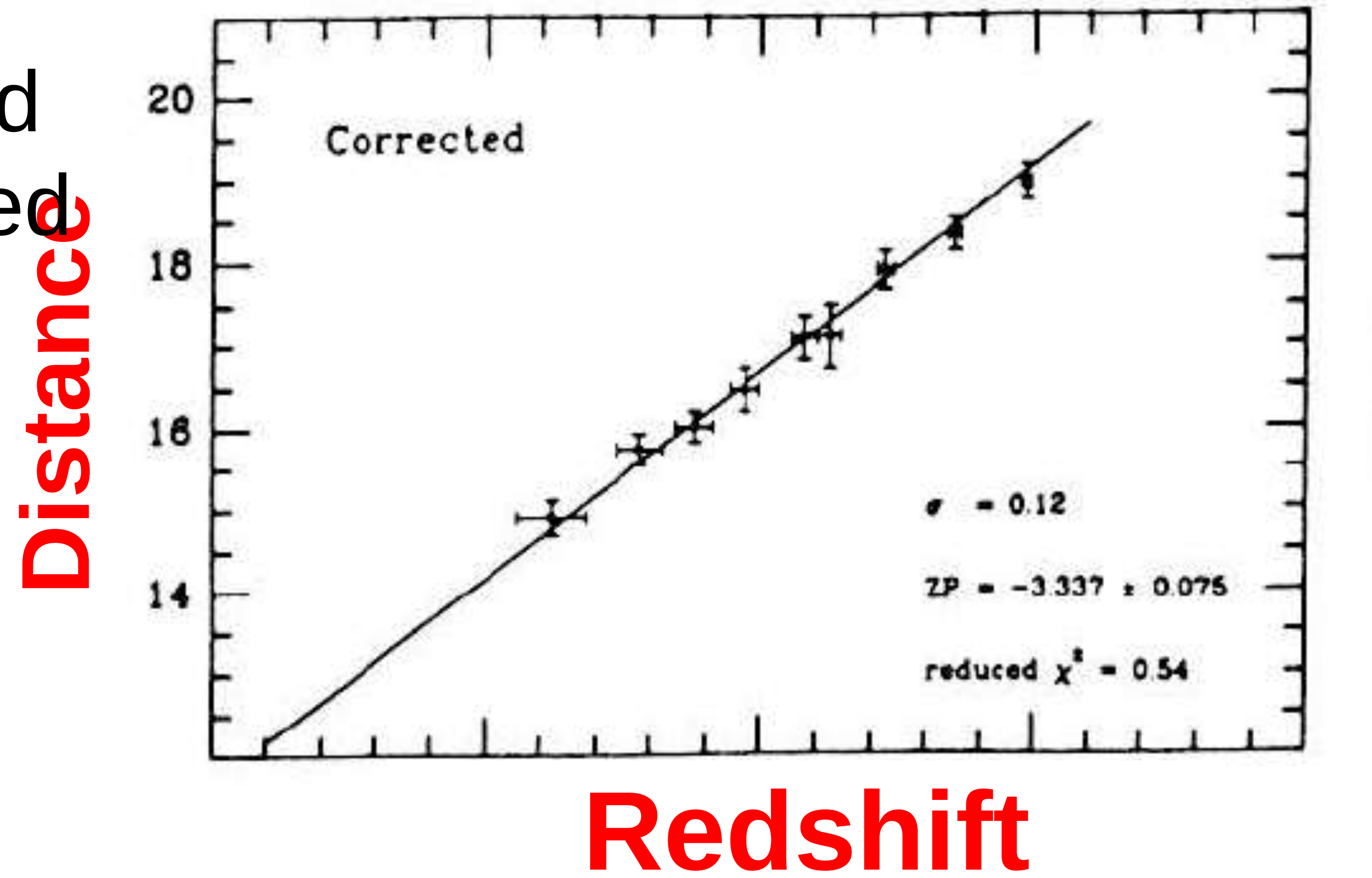


Figure 1: Hubble diagram of SNe Ia in the Calán/Tololo SN survey.

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

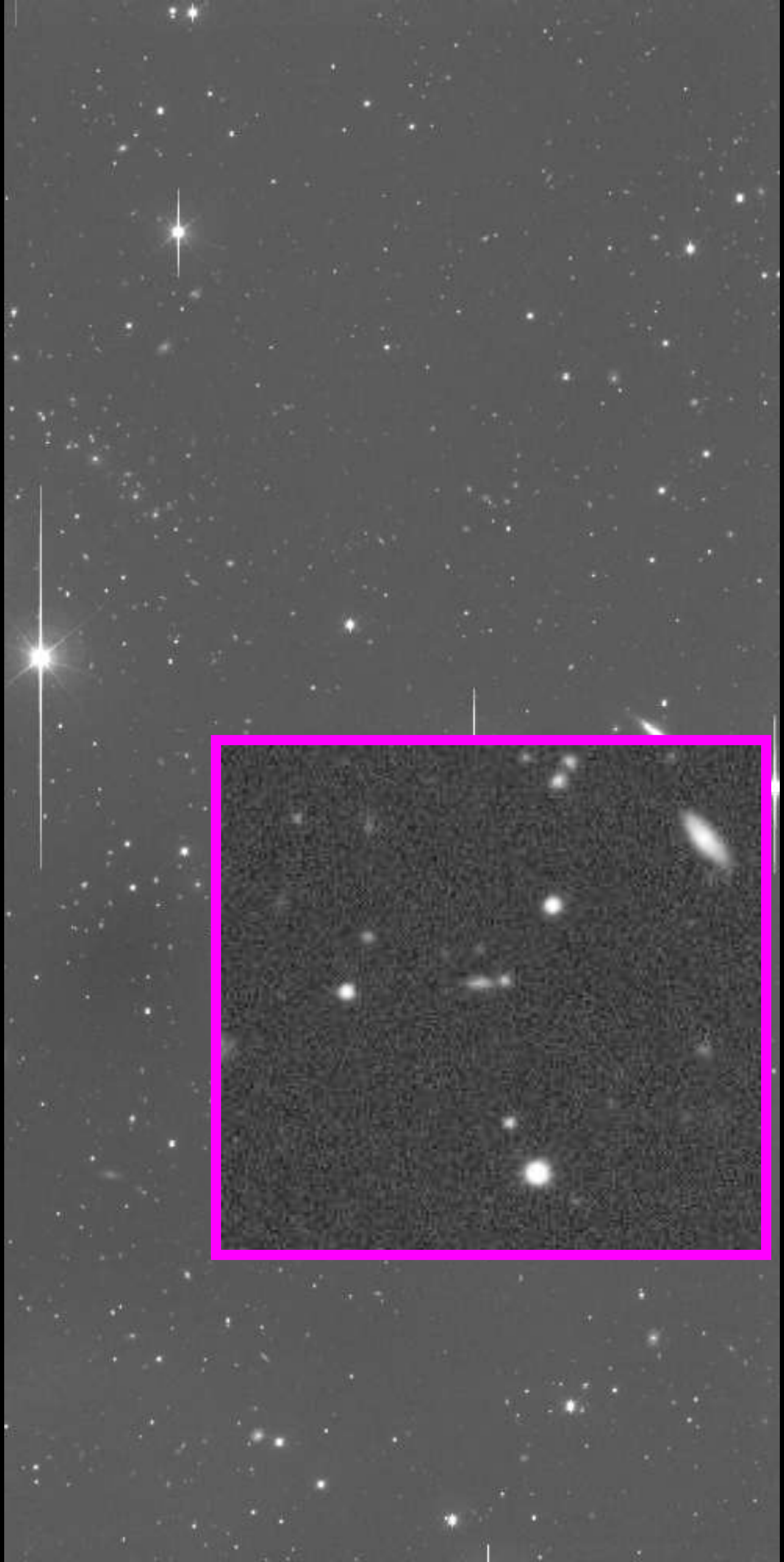
- A month later, Saul Perlmutter asked us at Harvard to confirm a possible supernovae- we found it to be a distant SN Ia -

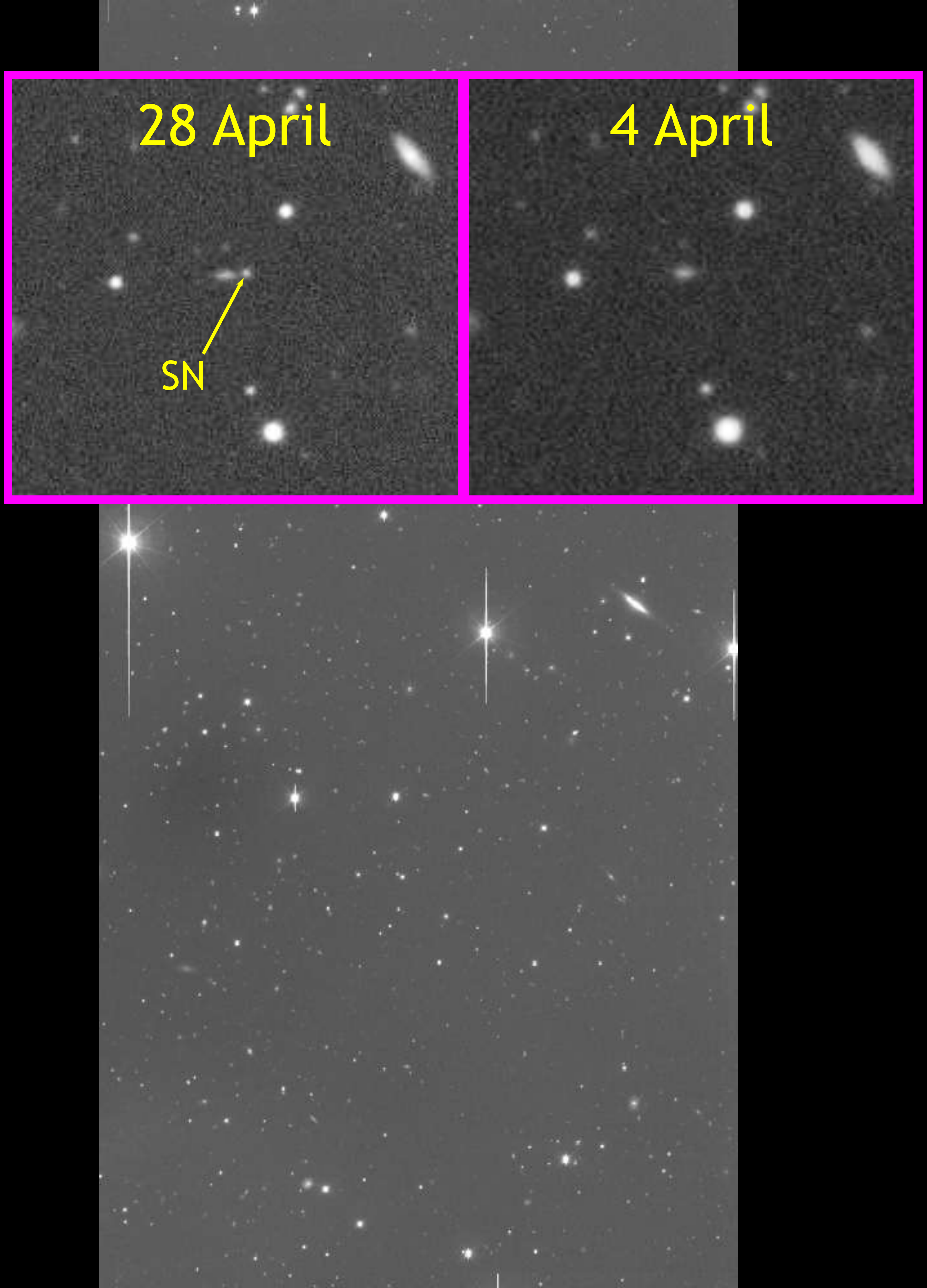
SUPERNOVAE 1994F, 1994G, 1994H

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.

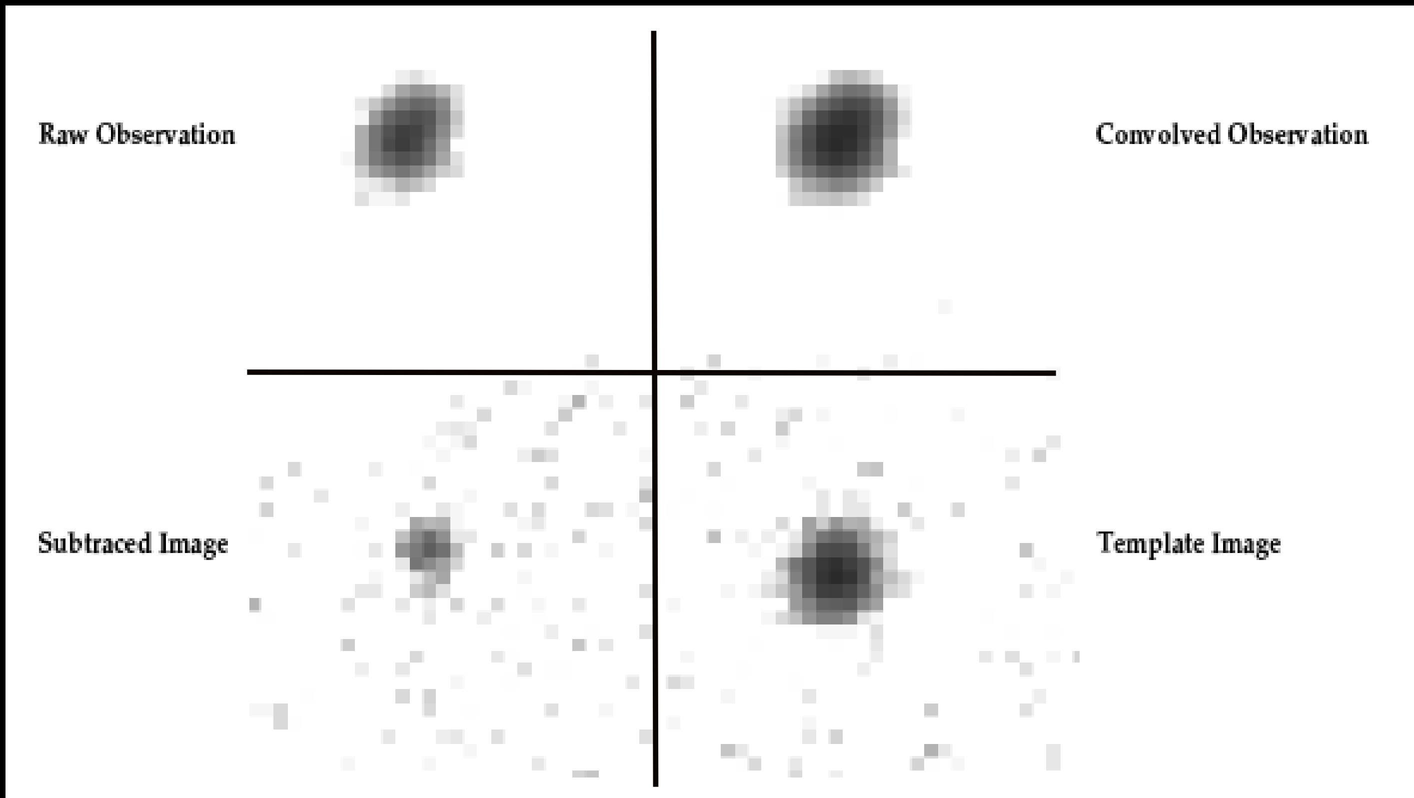
The Birth of the High-Z Team

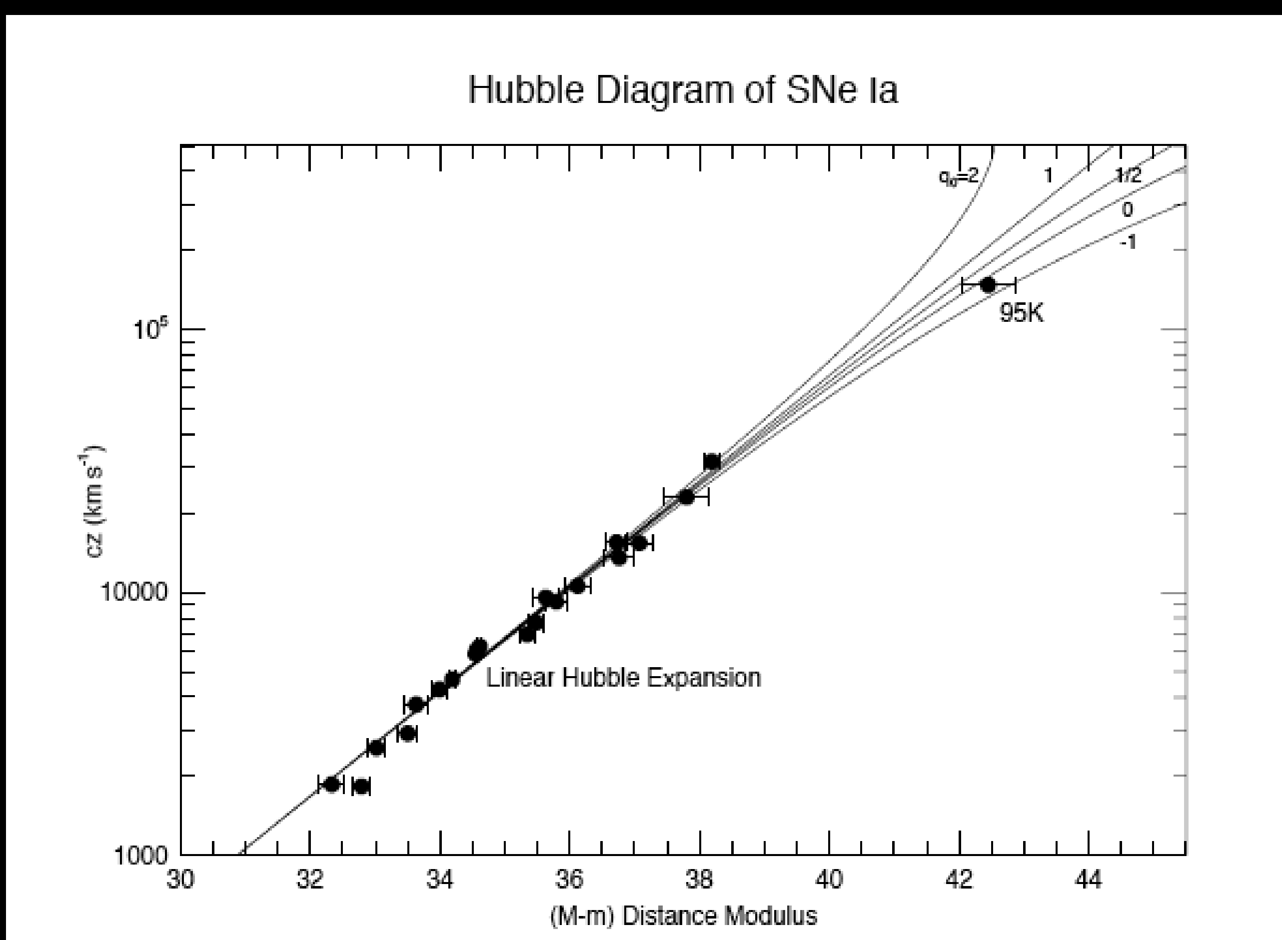
- I was down visiting Nick Suntzeff in July 1994, and we discussed the idea of doing our own High-Z SN Ia experiment




28 April
4 April
SN

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

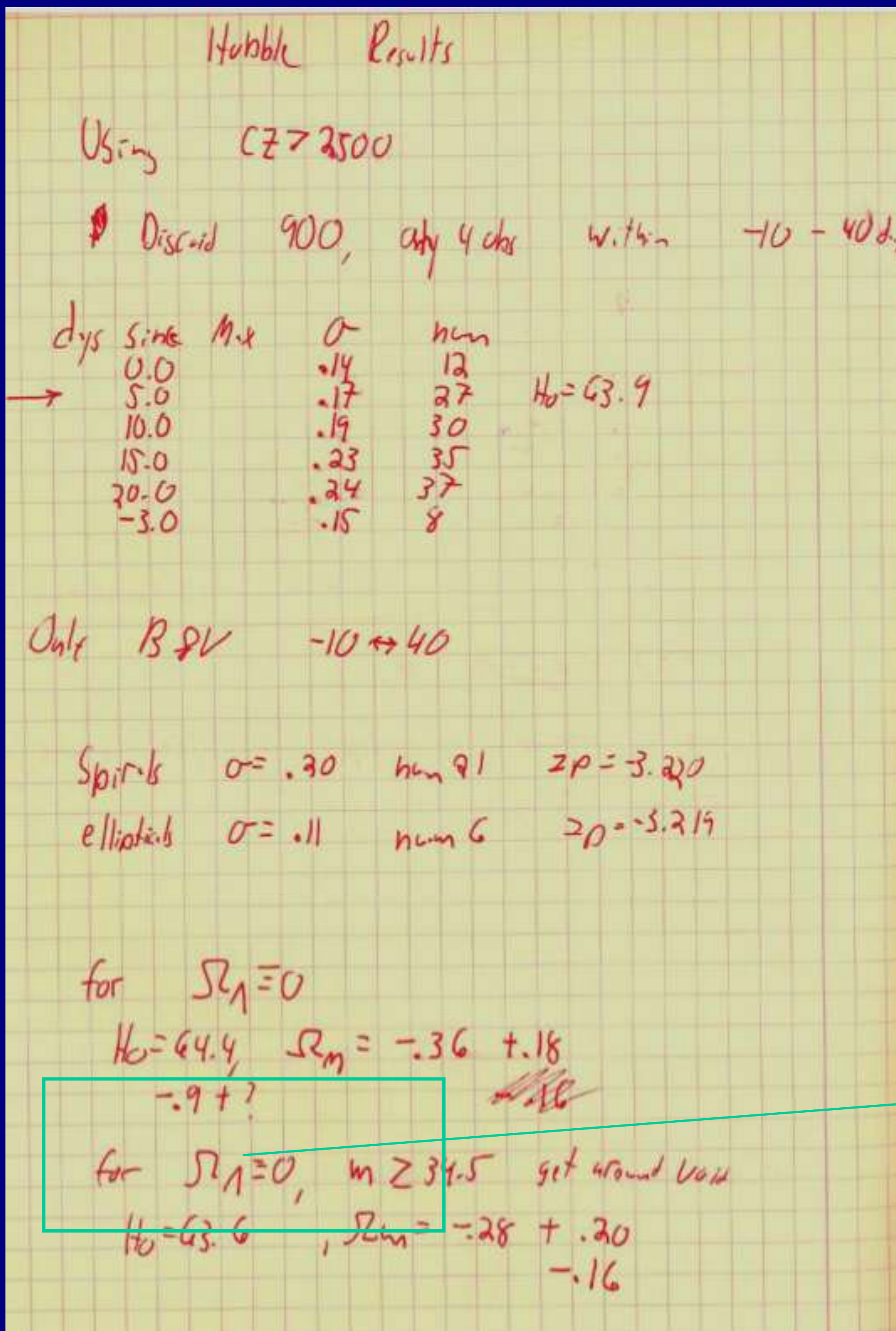
Other CoIs: C. Smith (Michigan); R. Schommer, M. Phillips (CTIO); M. Hamuy (UofA); J. Maza (UChile); A. Riess, R. Kirshner (Harvard); J. Spyromilio, B. Leibundgut (ESO); C. Stubbs, C. Hogan (UW)

Potential Pitfalls to High-Z SNe Ia Distances

- **Extinction**
  - Are the Dust Properties of High-Z and low-Z SNe the same?
- **Evolution**
  - Are the SNe Seen today the same as the SNe of yesterday?
- **Selection Effects?**
  - Are the corrections larger than the measurement?
- **K-corrections**
  - How accurately can we transform to the restframe?
- **Gravitational Lensing**
  - Does Weak Lensing significantly bias the measurement?

EUREKA?

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


Hubble Results

Using $cz > 3500$

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

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

Only B & V $-10 \leftrightarrow 40$

Spirals $\sigma = .30$ num 91 $zp = -3.220$

ellipticals $\sigma = .11$ num 6 $zp = -3.219$

for $\Omega_\Lambda \equiv 0$

$H_0 = 64.4$ $\Omega_m = -.36 \pm .18$

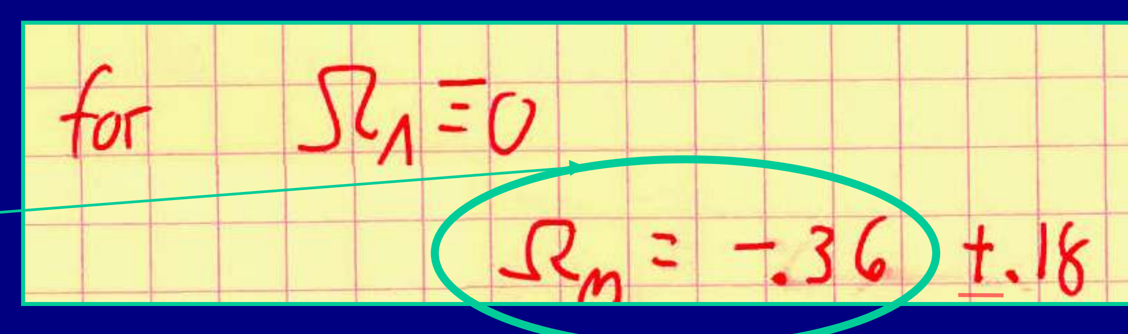
$-.9 + ?$

for $\Omega_\Lambda = 0$, $m \geq 34.5$ get around void

$H_0 = 63.6$, $\Omega_m = -.28 {+.30 \atop -.16}$

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

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



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"

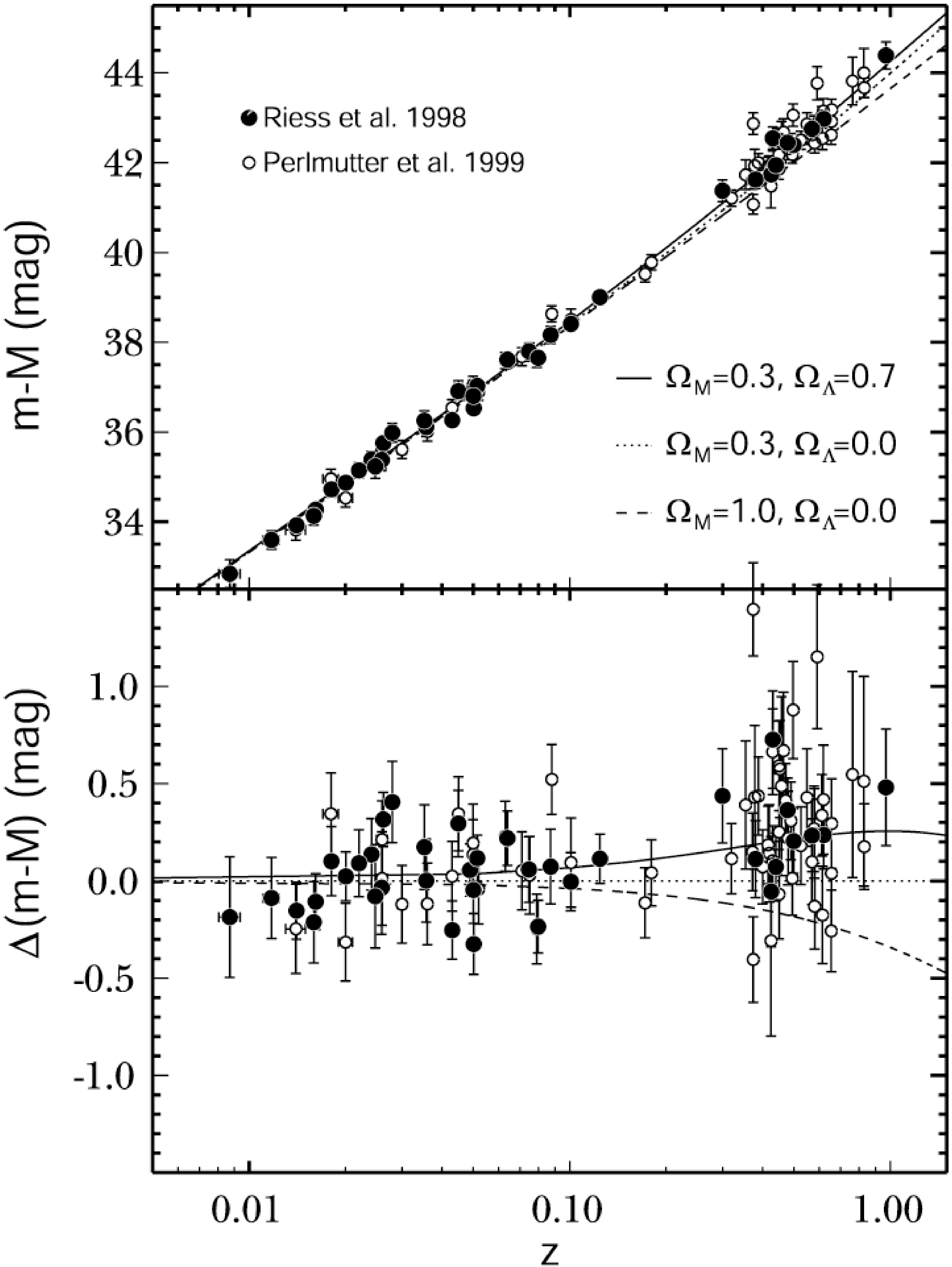
J. Tonry, Hawaii, 1/12/1998, 11:40 am:"…who remembers the detection of the magnetic monopole and other gaffs?…on the other hand, we should not be shy about getting our results out …"

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."

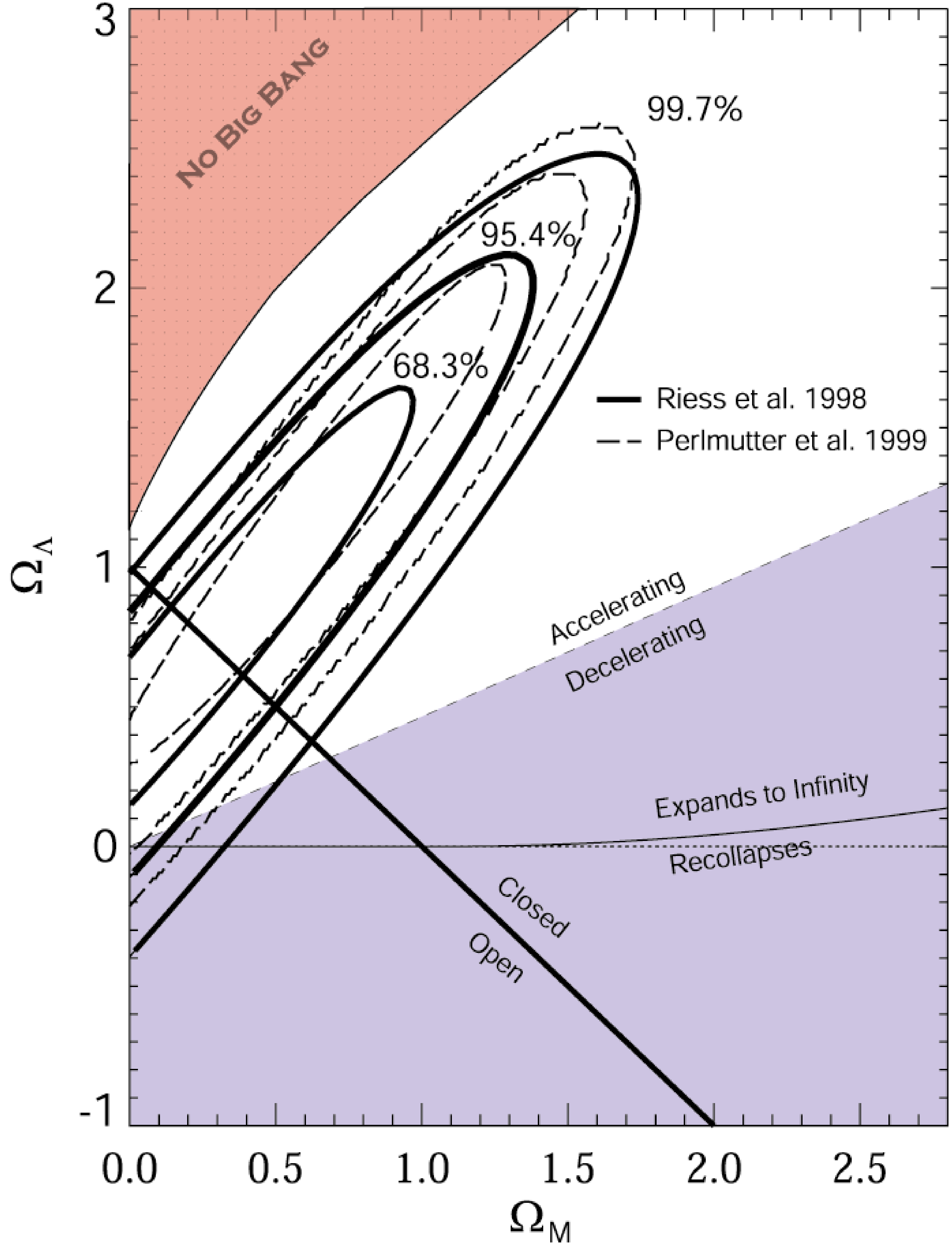
A. Riess Berkeley, CA 1/12/1998 6:36pm: "The results are very surprising, shocking even. I have avoided telling anyone about them because I wanted to do some cross checks (I have) and I wanted to get further into writing the results up…The data require a nonzero cosmological constant! Approach these 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."



44
42
40
38
36
34
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
1.0
0.5
0.0
-0.5
-1.0
Δ(m-M) (mag)
0.01
0.10
1.00
z



No Big Bang
99.7%
95.4%
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Accelerating
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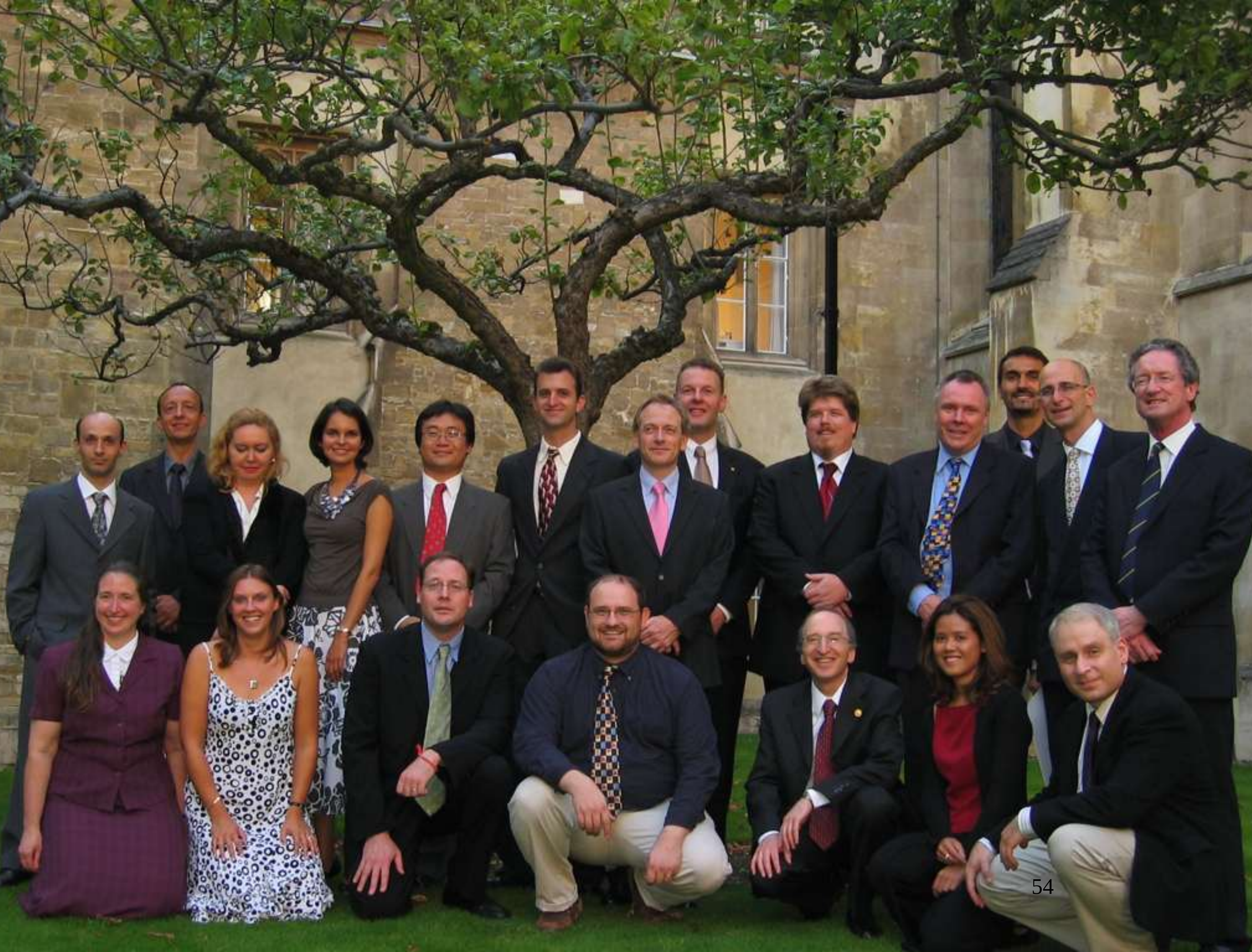
Expands to Infinity
Recollapses
Closed
Open
3
2
1
0
-1
Ω_Λ
0.0
0.5
1.0
1.5
2.0
2.5
Ω_M

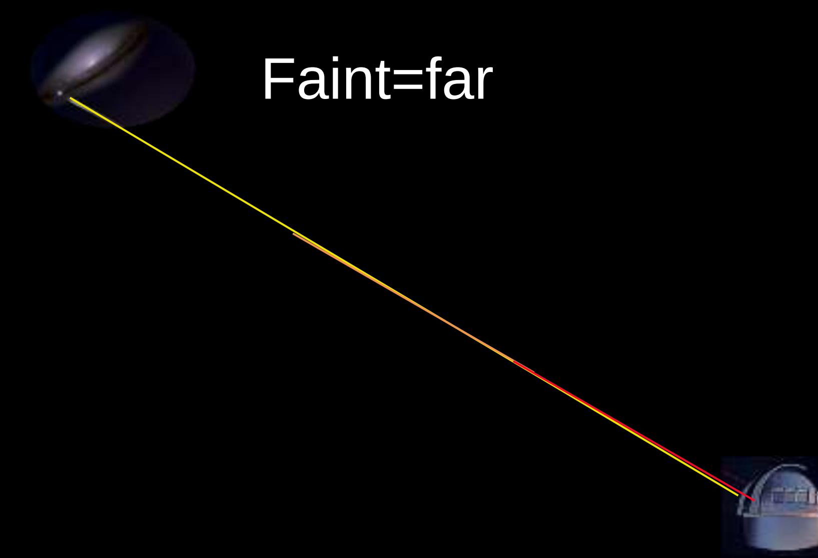
OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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]

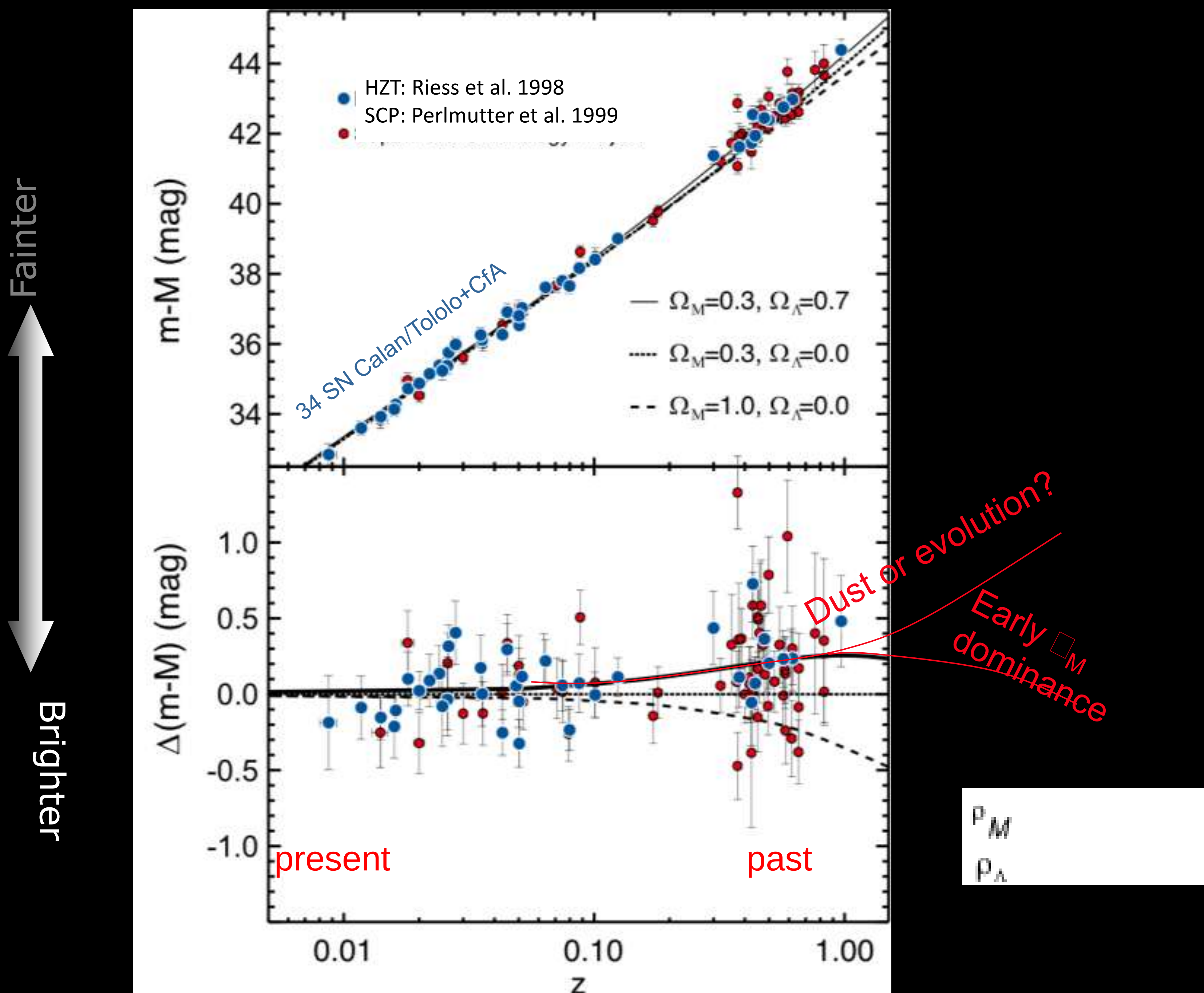


Alternative Explanations for faint=far supernovae

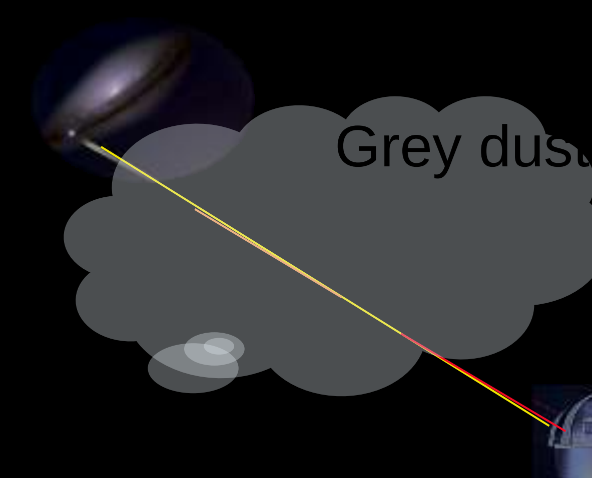
Steady dimming from grey dust or evolution instead?
Test: brighter at z>1 (i.e., prior deceleration)?



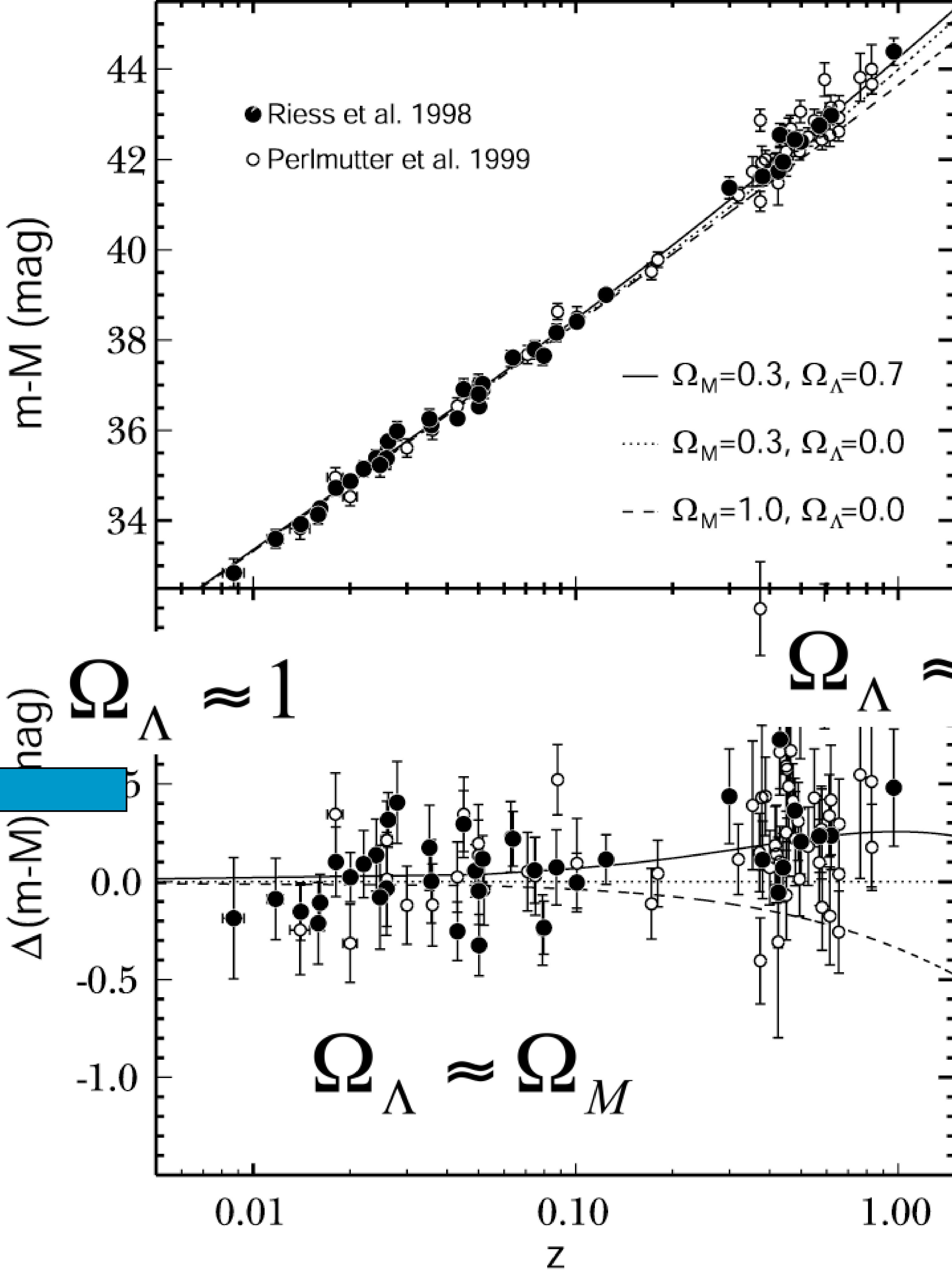
Universe accelerating



Faint=grey dust, not far



Not accelerating



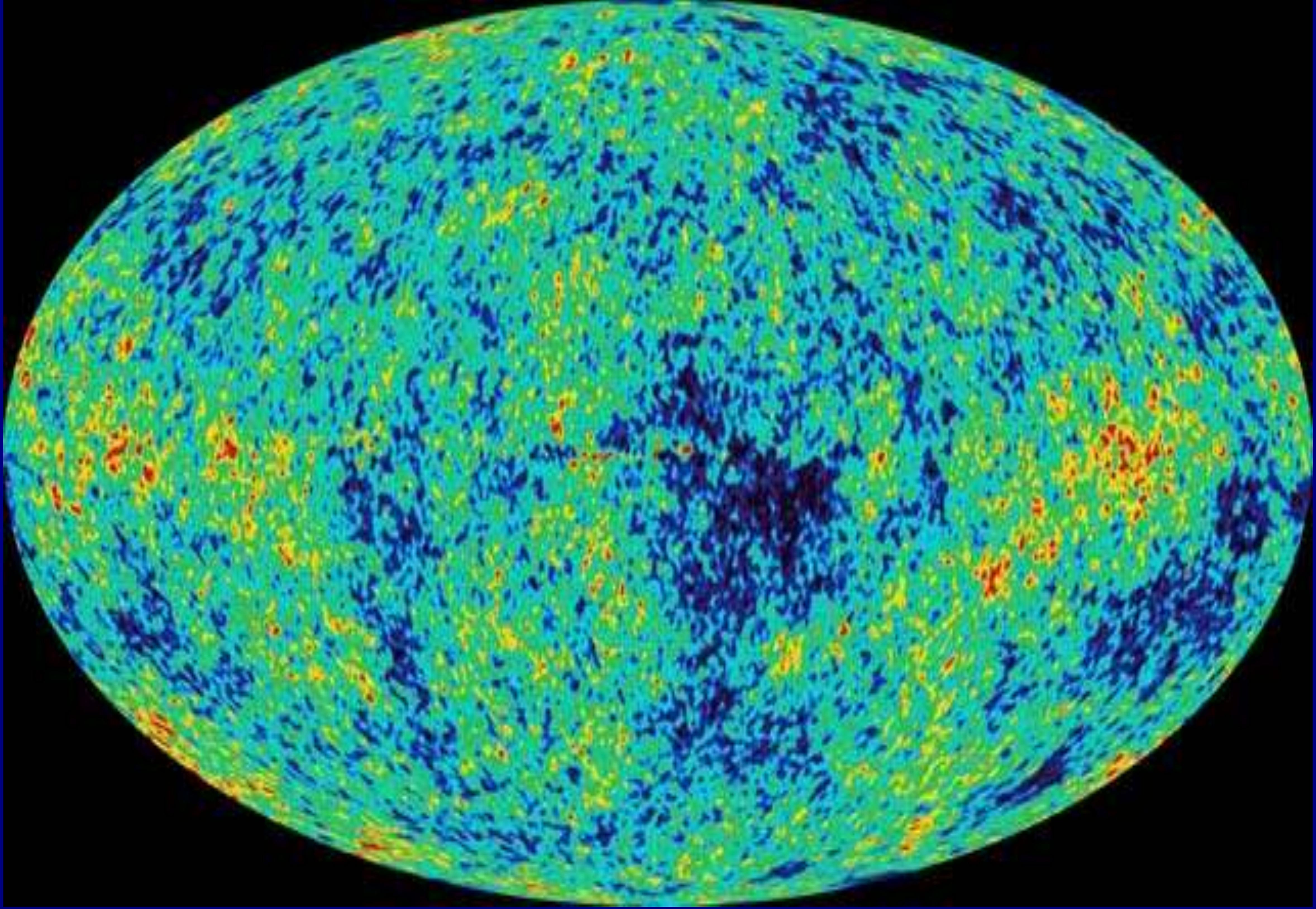
$\Omega_\Lambda \approx 1$

$\Omega_\Lambda \approx 0$

$\Omega_\Lambda \approx \Omega_M$

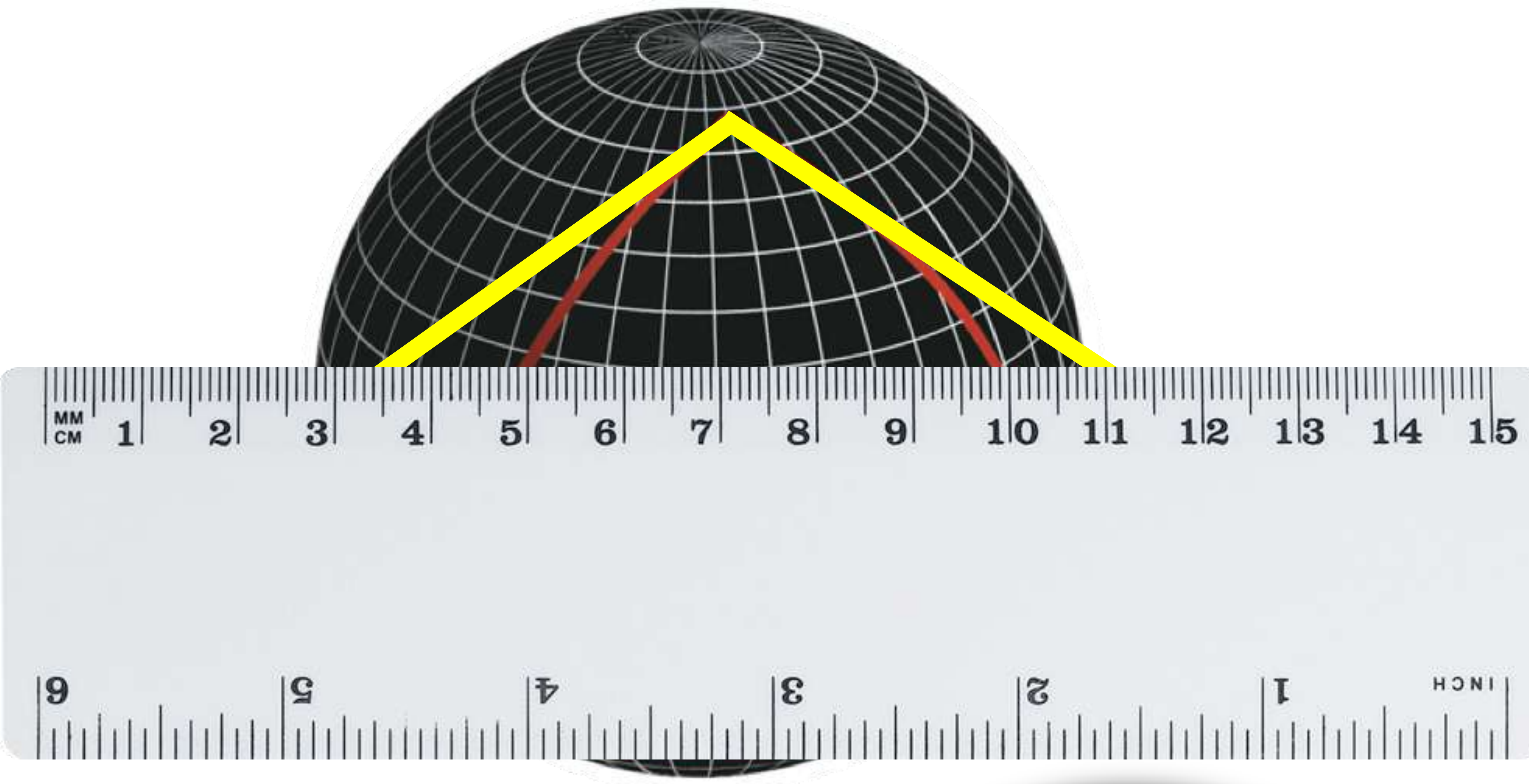
$$\frac{\Omega_M}{\Omega_\Lambda} \propto (1+z)^3$$

Why Now?



Sound Waves Propogating Since Big Bang

C_S=.577c



Objects Appear Larger in Curved Finite Space

CMB - mid 1998

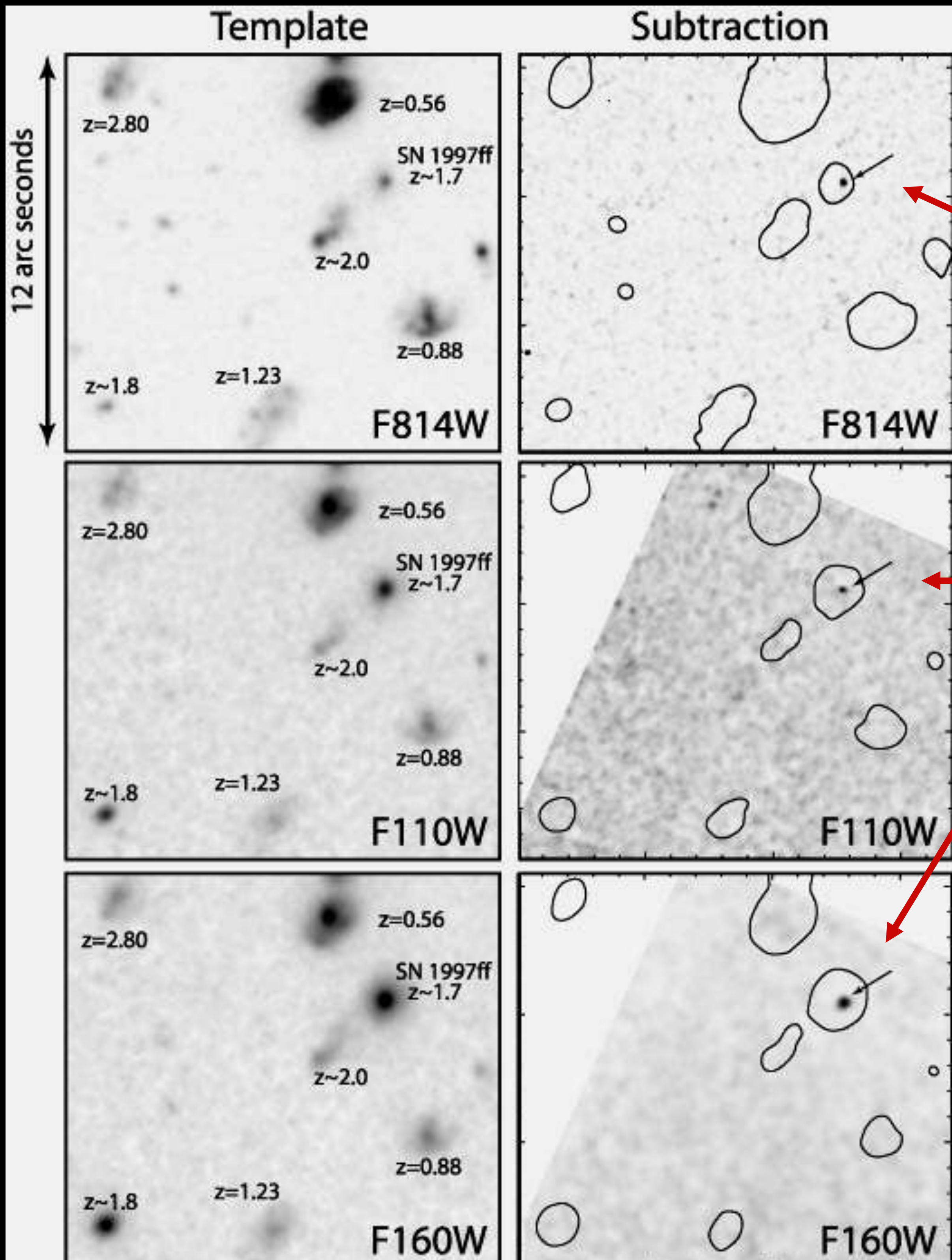
QuickTime™ and a
decompressor
are needed to see this picture.

2000 - Boomerang & MAXIMA Clearly see 1st Doppler Peak Showing Universe is Flat

QuickTime™ and a
decompressor
are needed to see this picture.

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

A First Glimpse at Decelerating Universe…2001



SN Ia 1997ff, z=1.7

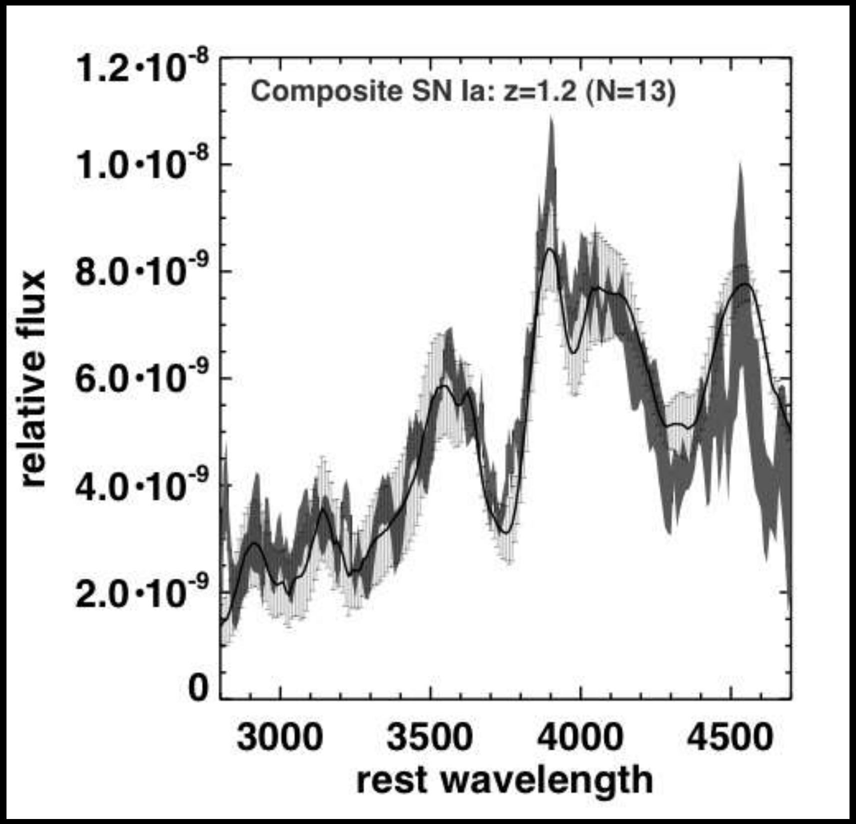
Discovery:
The Hubble Deep Field, WFPC2, 1997 (Gilliland & Phillips).

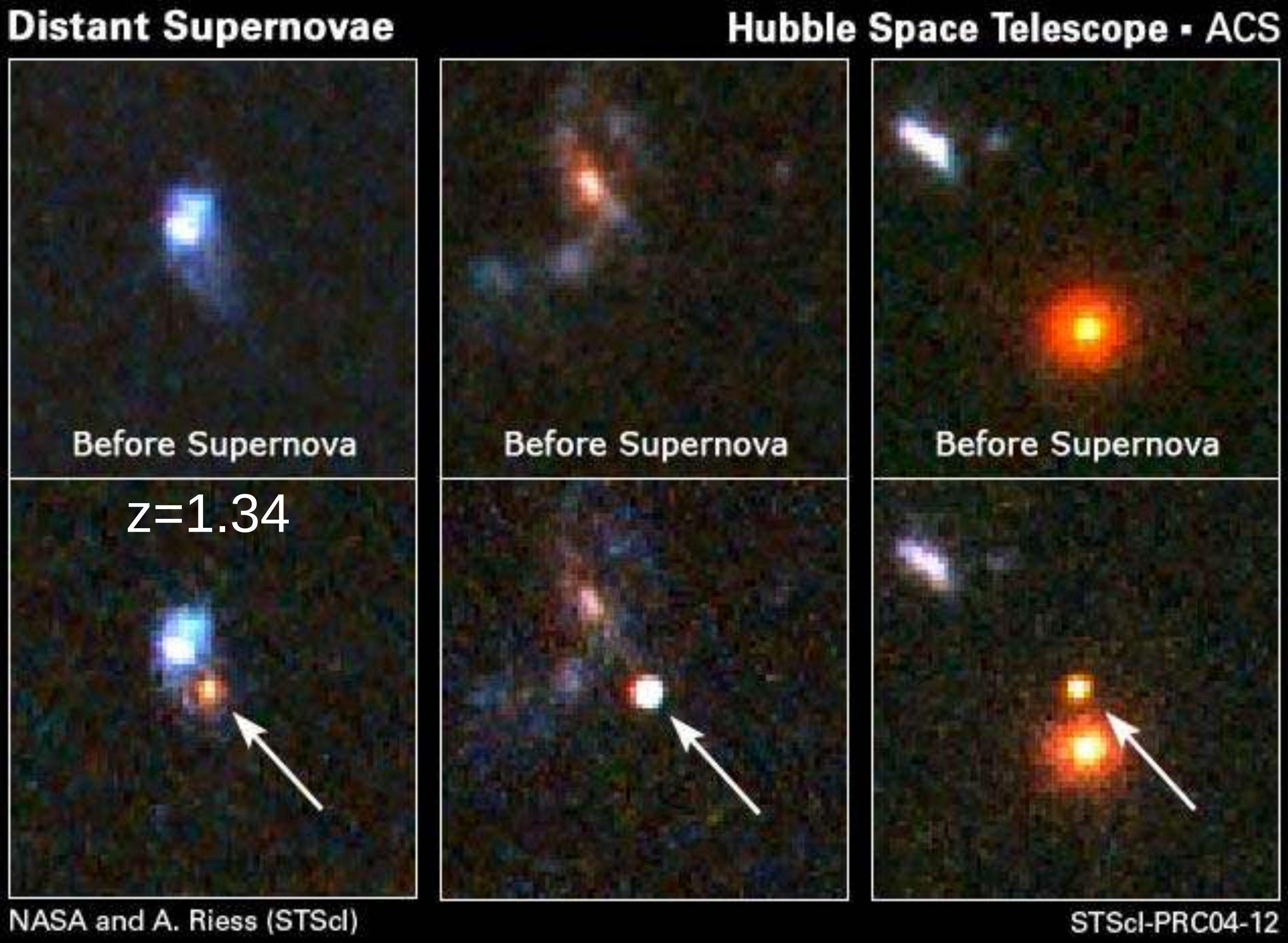
Rediscovery:
Light Curve Measured from ***Serendipitous*** Observations and timing of the NICMOS Near-Infrared Deep Field; (Riess et al 2001)

Results supported accelerating-interpretation of high-z SNe Ia, but with only one object conclusion not very robust

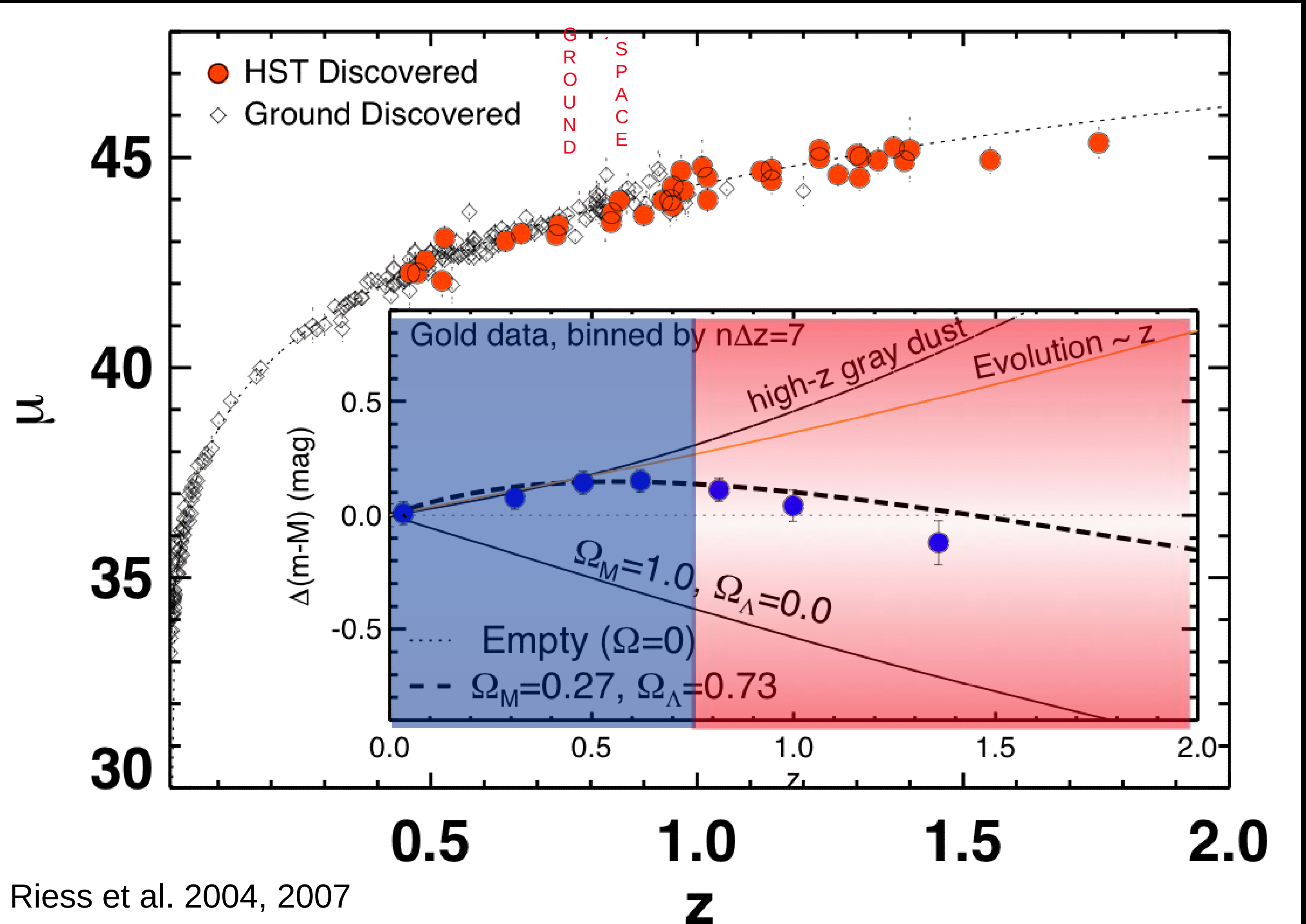
Hubble gets new camera, can measure SNe Ia at z>1, 2002

- In 2002 Astronauts install ACS
- From 2002-2007 the *Higher*-z Team measured 23 new SNe Ia at z>1





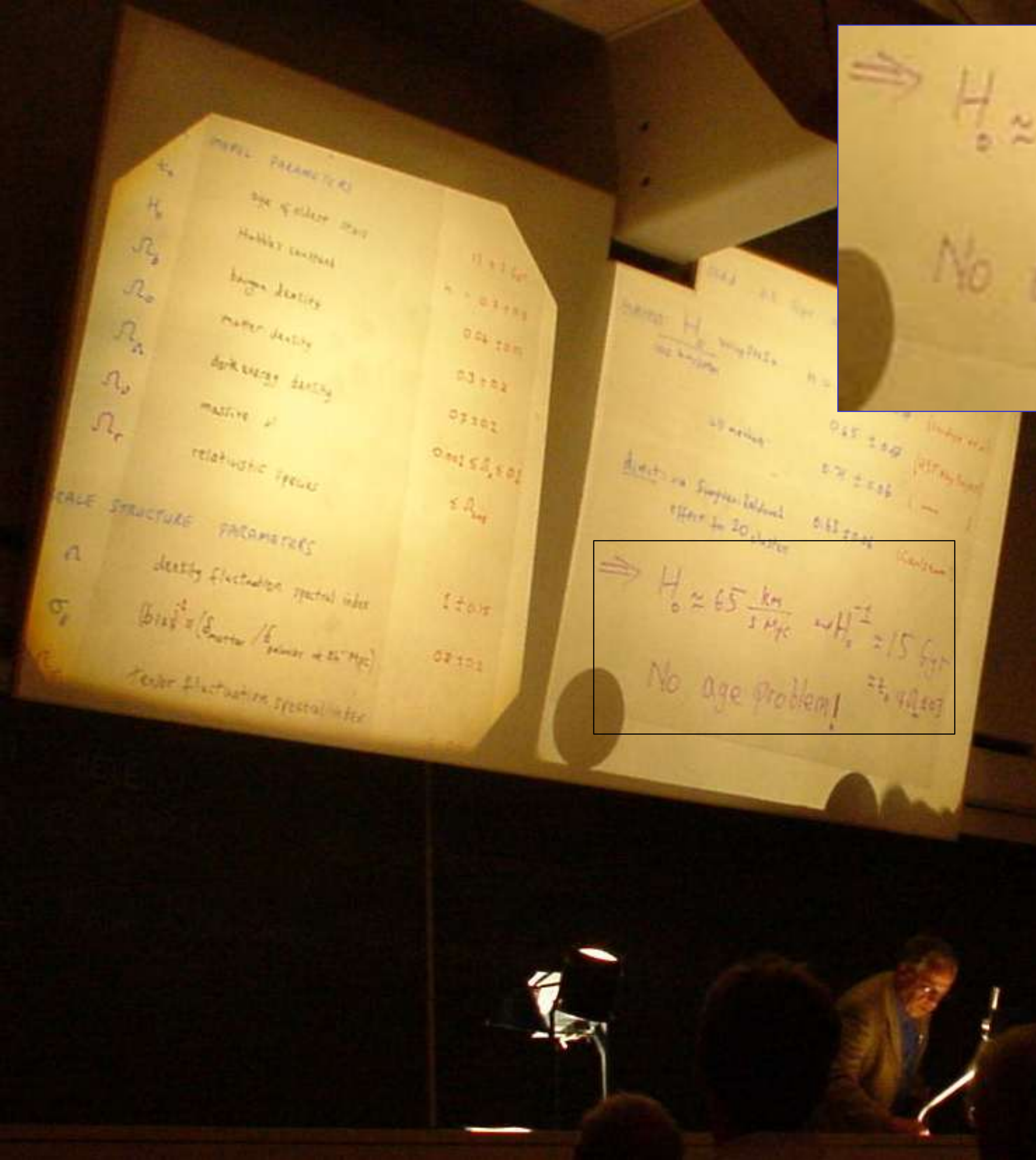
23 HST SN, see brightening/deceleration z>1, acceleration passes test!

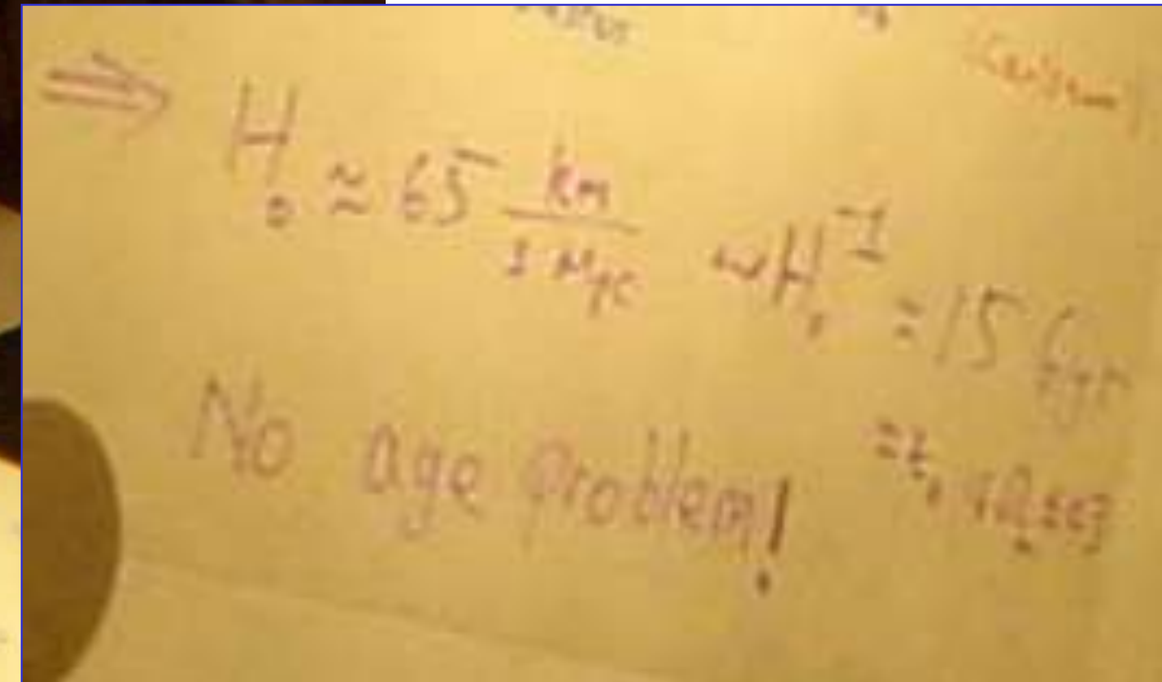


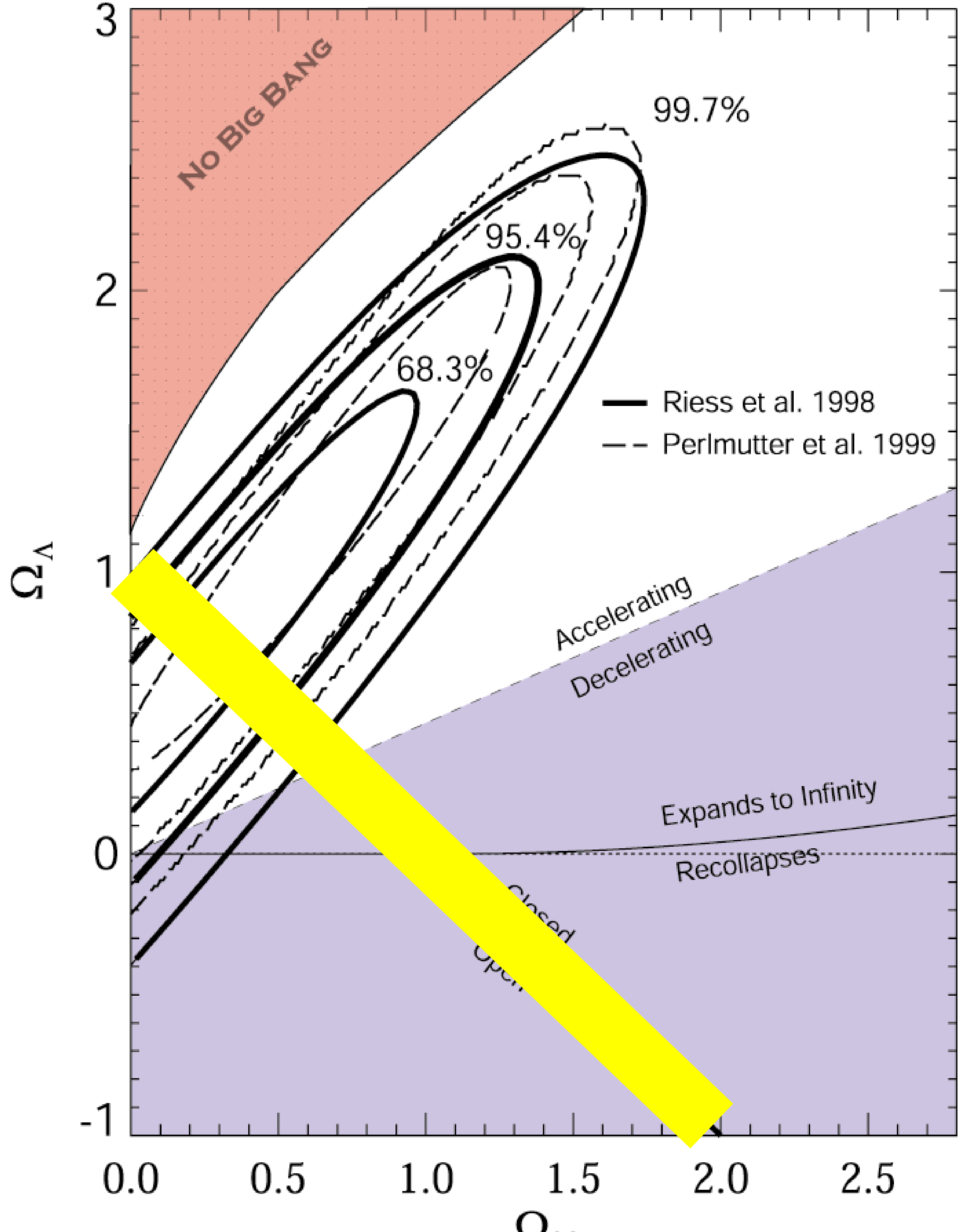
Riess et al. 2004, 2007

Not just supernovae require “dark energy”…

H₀ ≥60




⇒ $H_0 \simeq 65 \frac{km}{s\ Mpc}$ $\sim H_0^{-1} \simeq 15$ Gyr
No age problem!



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Ω_Λ
Ω_M
3
2
1
0
-1
0.0
0.5
1.0
1.5
2.0
2.5

2001 - Large Scale Structure & CMB

Jaffe et al. 2001

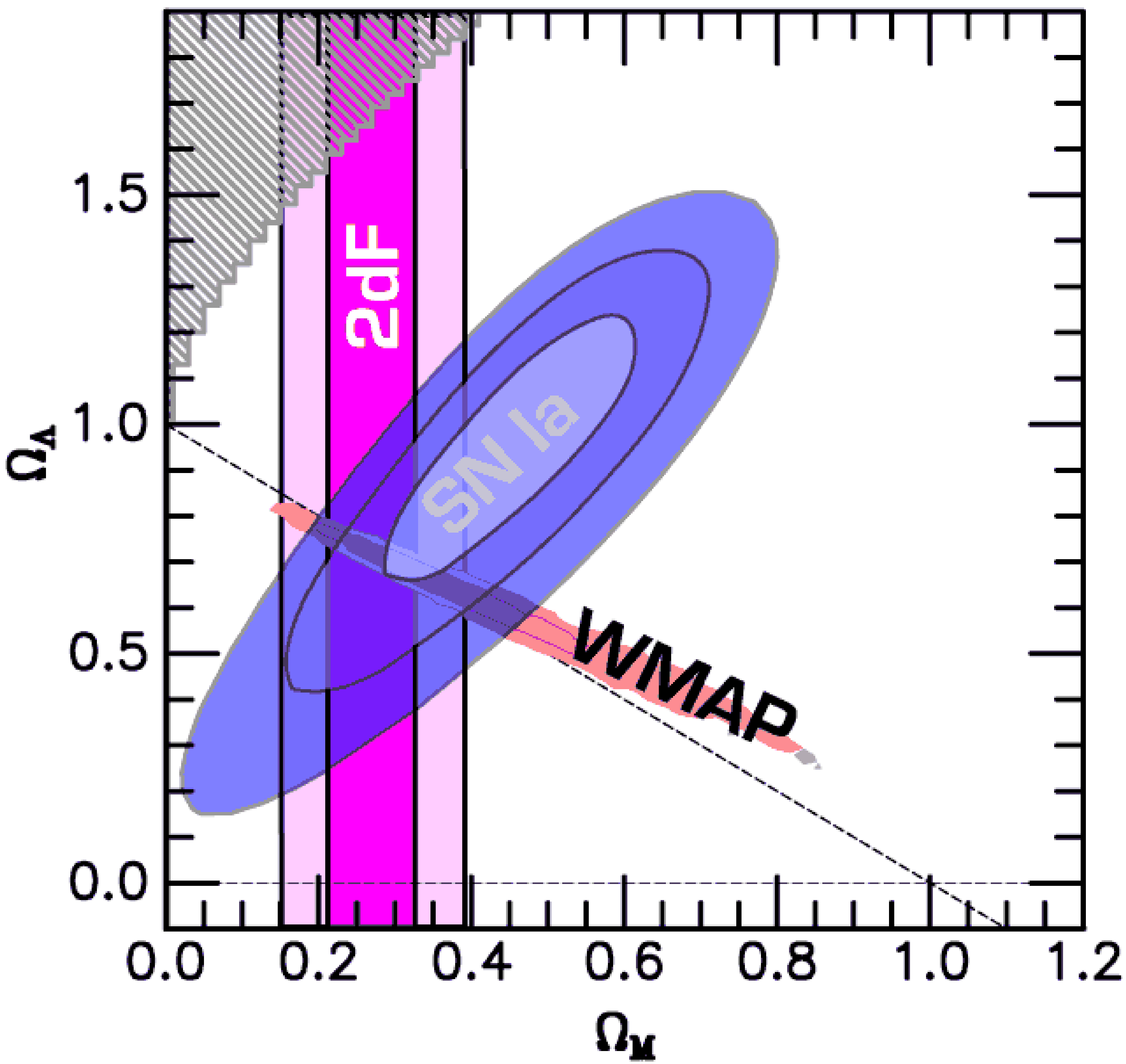
Peacock et al 2001

QuickTime™ and a
decompressor
are needed to see this picture.

2dF redshift survey finds

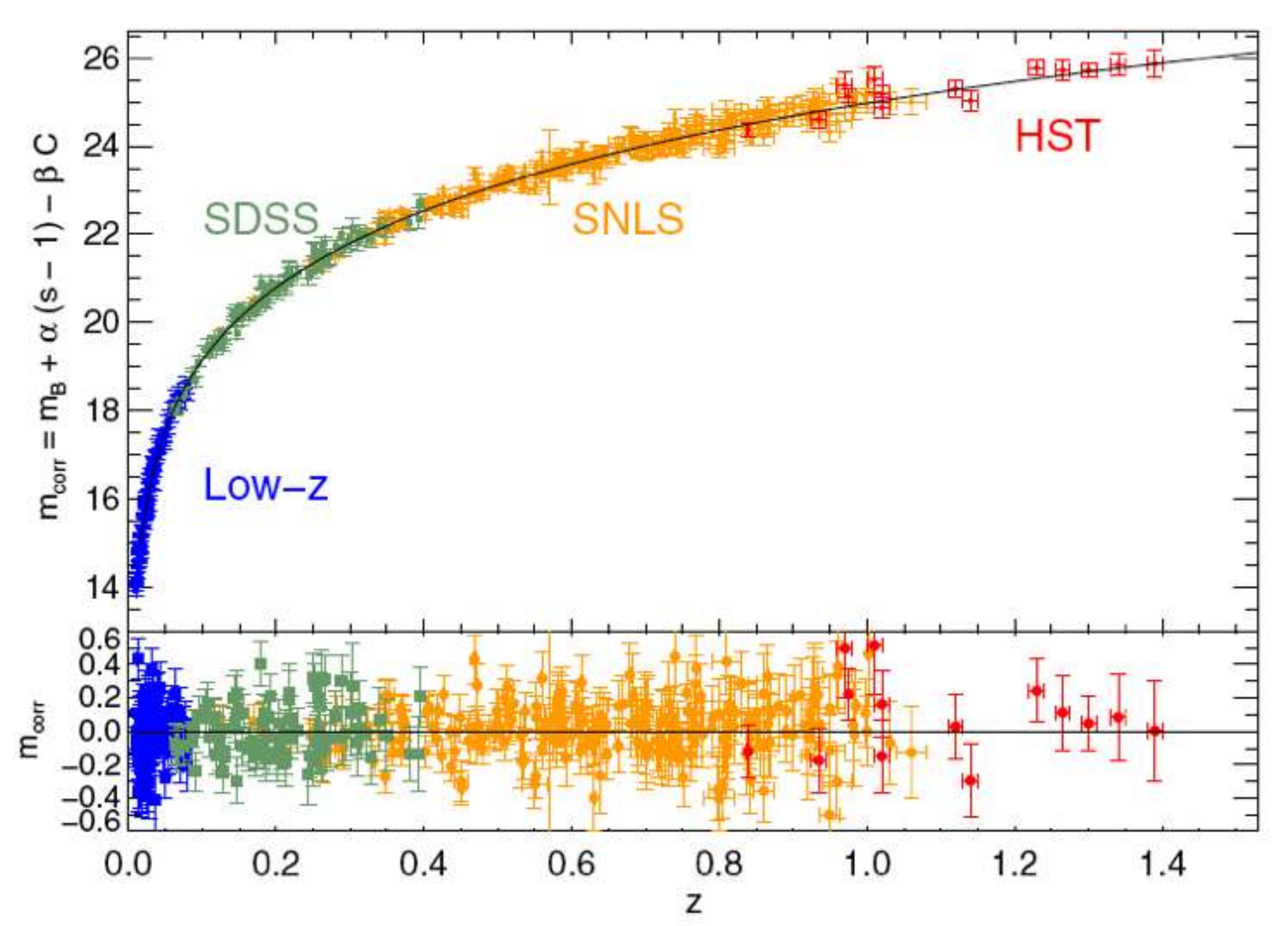
$\wedge_M \sim 0.3$ from power spectrum and infall

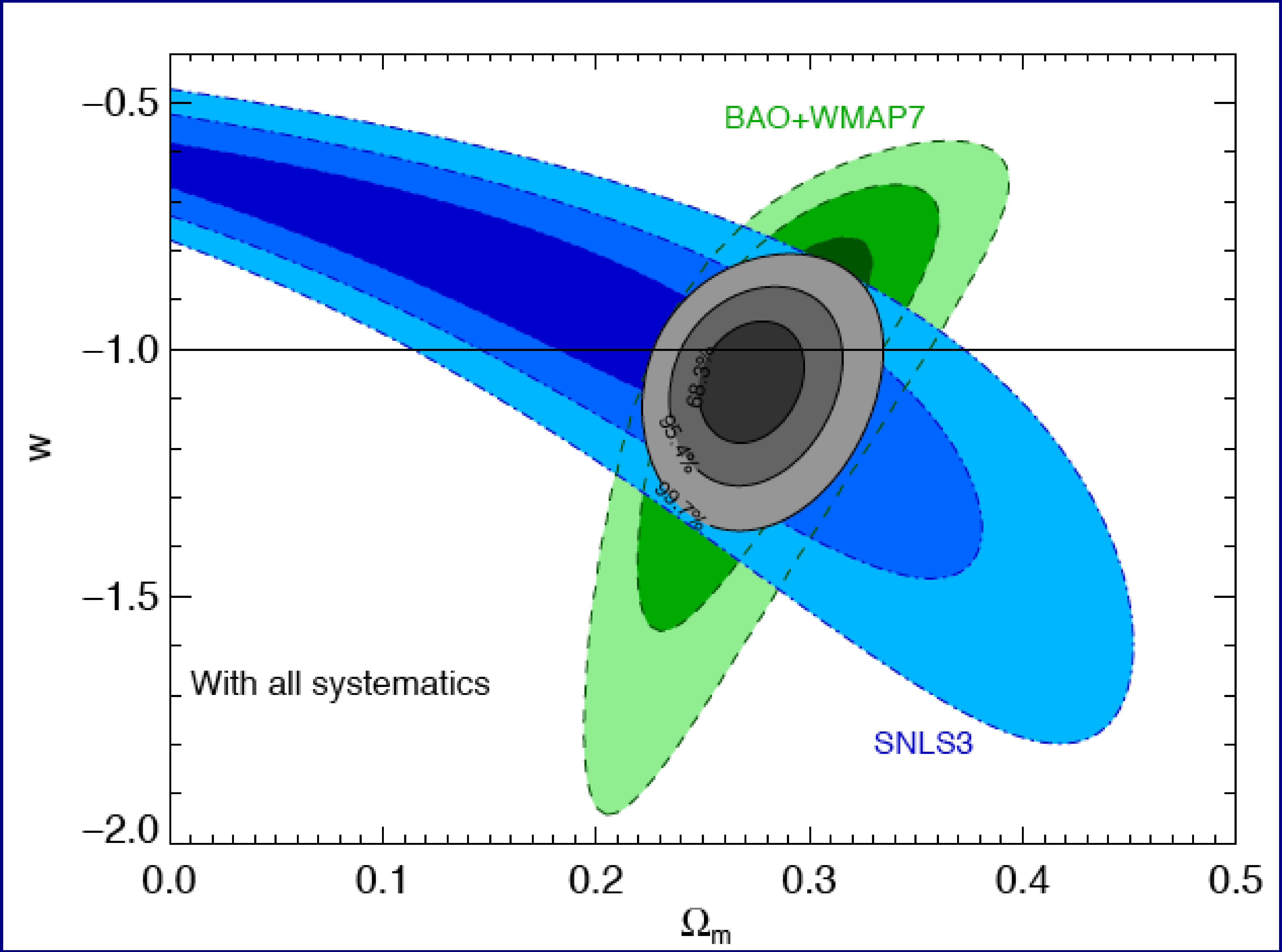
QuickTime™ and a
decompressor
are needed to see this picture.



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

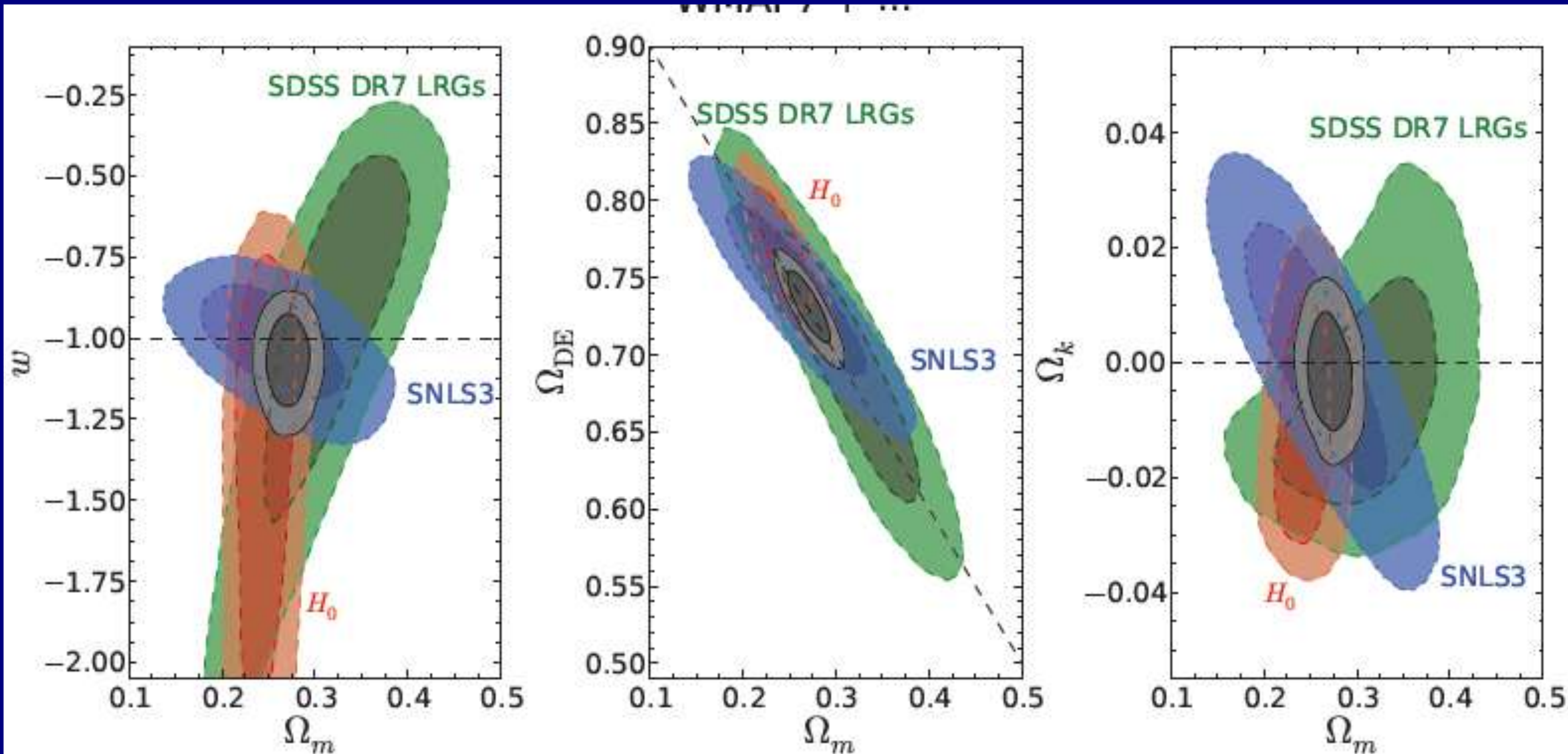
Where we Stand now - SN Ia





Sullivan et al 11

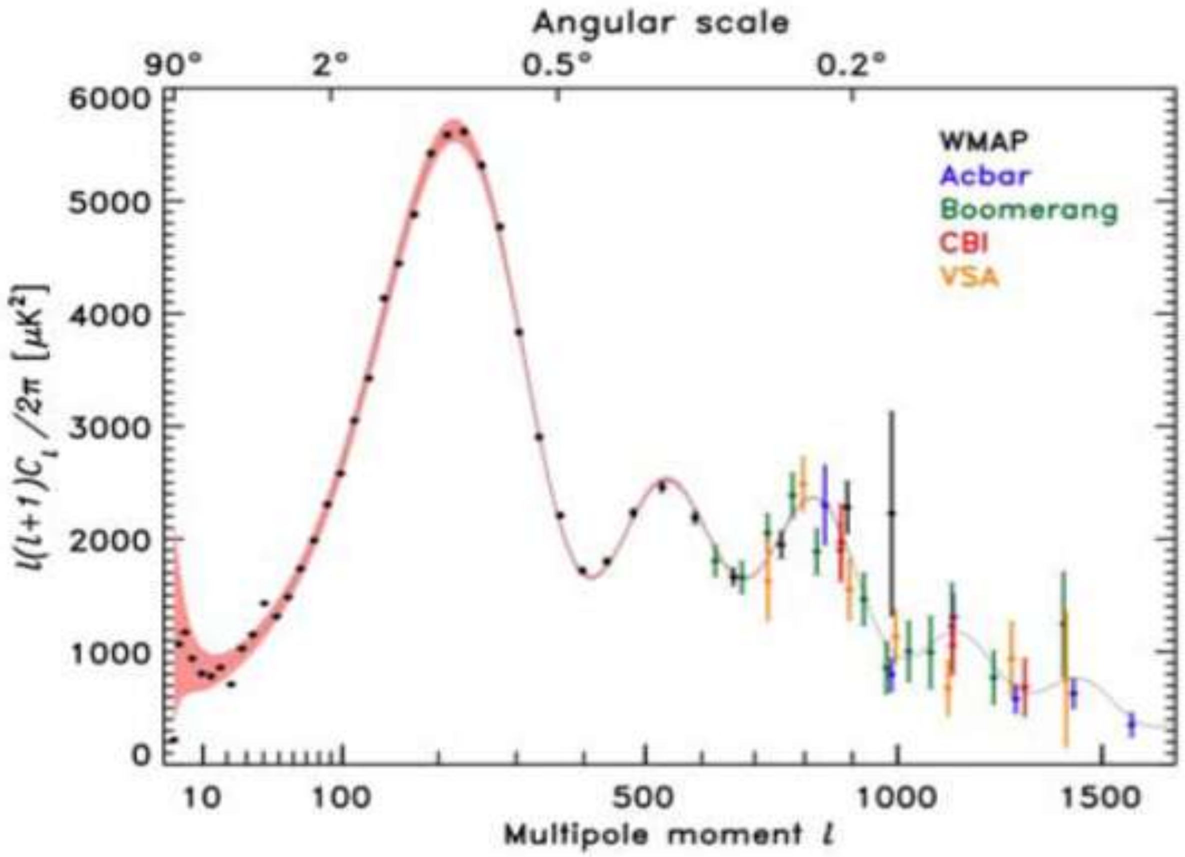
WMAP7 + ...

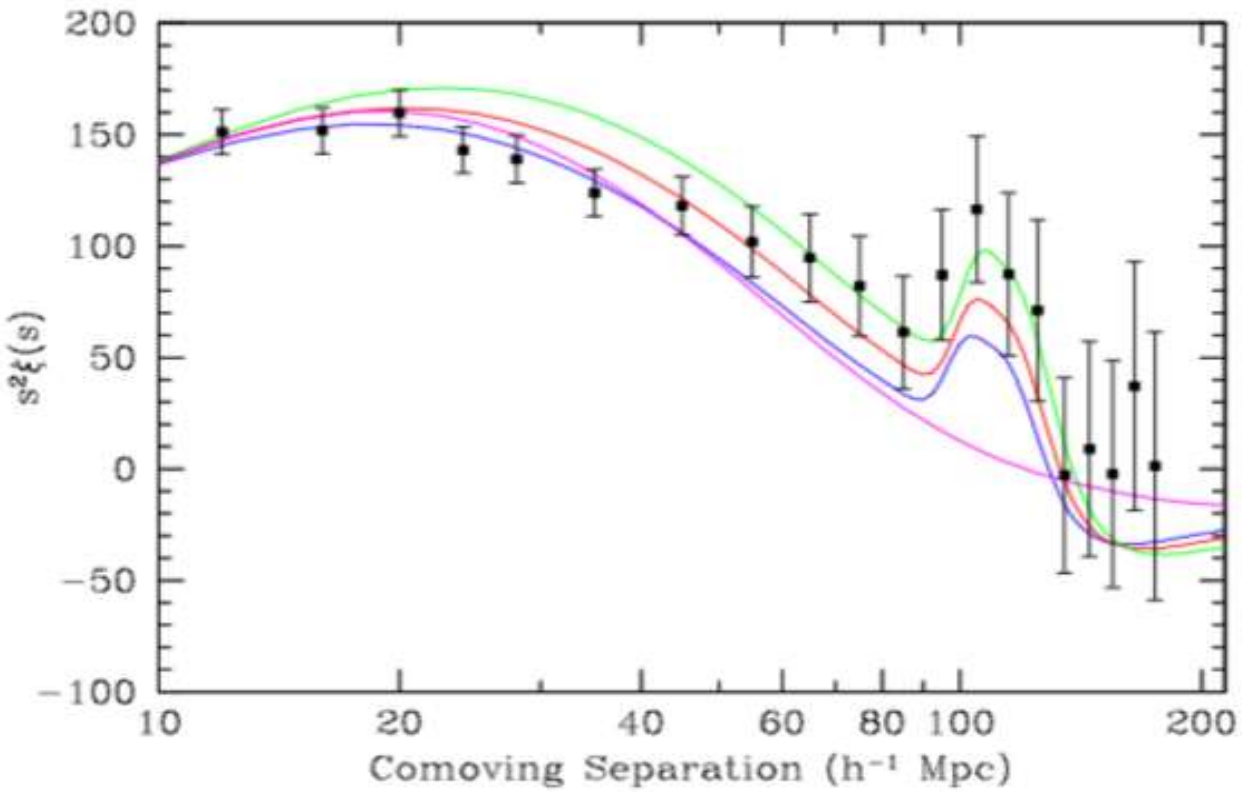


W ,∧W, ∧⊂, ∧⊇

all constrained simultaneously

Sullivan et al 11

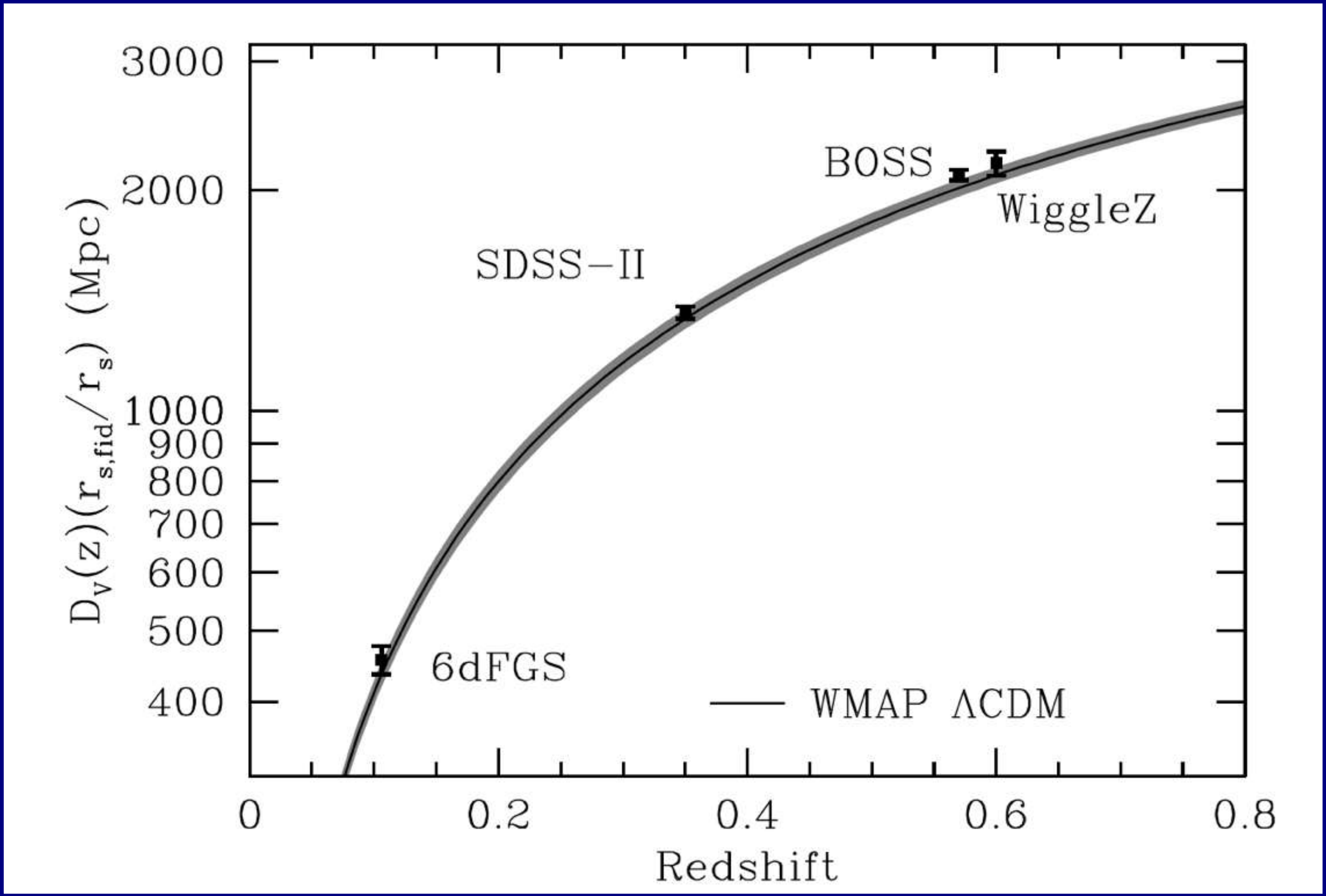




Eisenstein et al. 2005

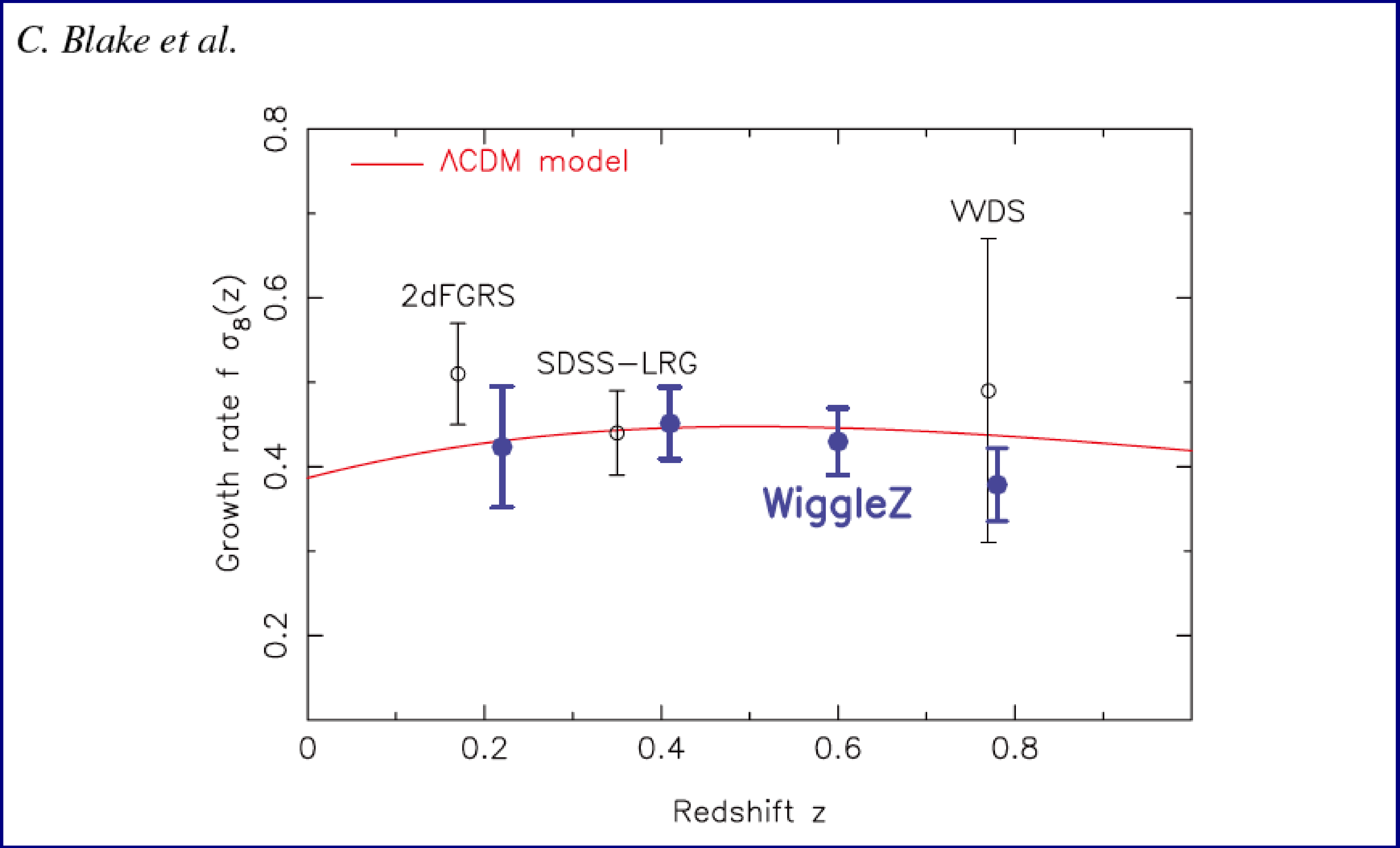
- The physics of these *baryon acoustic oscillations* (BAO) is well understood, and their manifestation as wiggles in the CMB fluctuation spectrum is modeled to very high accuracy – the 1st peak has a size of ~150 Mpc (co-moving)
- They are then a standard Ruler we can look at through time.

Where we Stand now - BAOs



Blake et al 2011 Anderson et al 2012

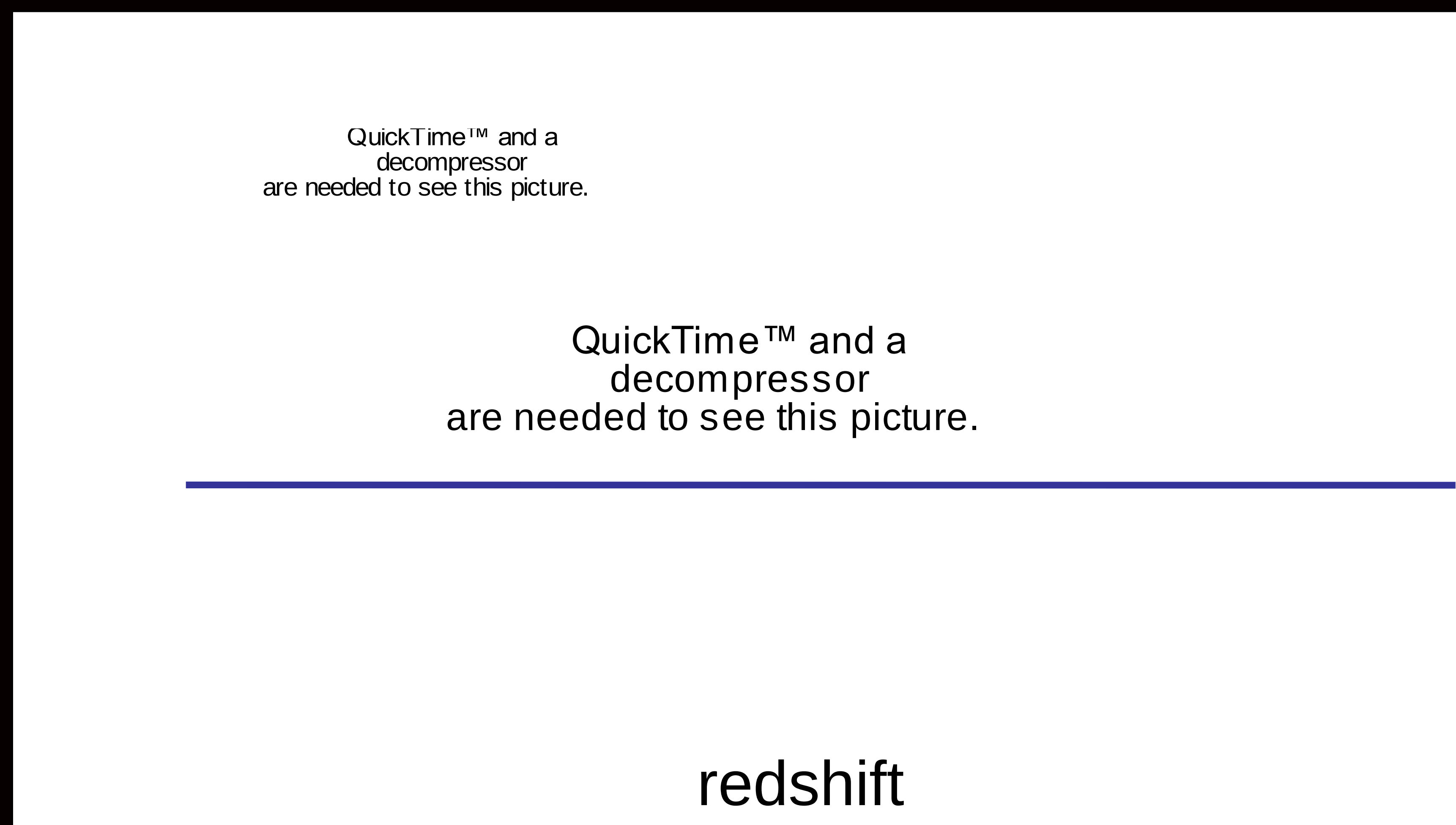
Growth of Structure is also Consistent!



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

Acceleration 

?

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 perfectly matched to the acceleration.

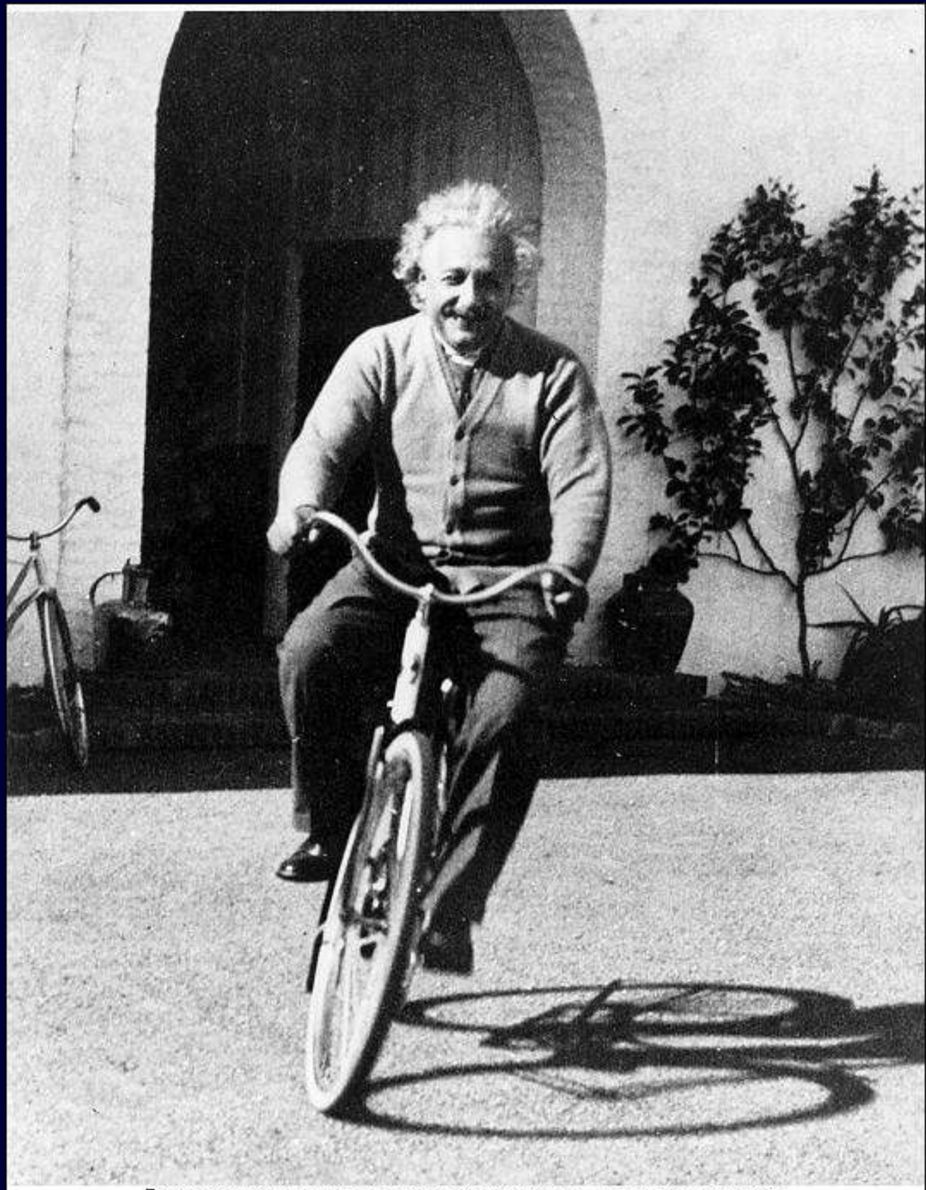
Theoretical Discussion on whether or not the growth of structure can perturb the metric in such a way to mimic the effects of Dark Energy. This is the only way out I can see - But controversial!

So What is the Dark Energy?

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.



If dark energy is due to a cosmological constant, its ratio of pressure to energy density (its equation of state) is $w = P/\rho = -1$ at all times. This is testable!

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 looking like a Cosmological Constant to well beyond any foreseeable measurement precision.

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.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

from Karl Glazebrook

The Future of the Universe seems to be Dark Energy

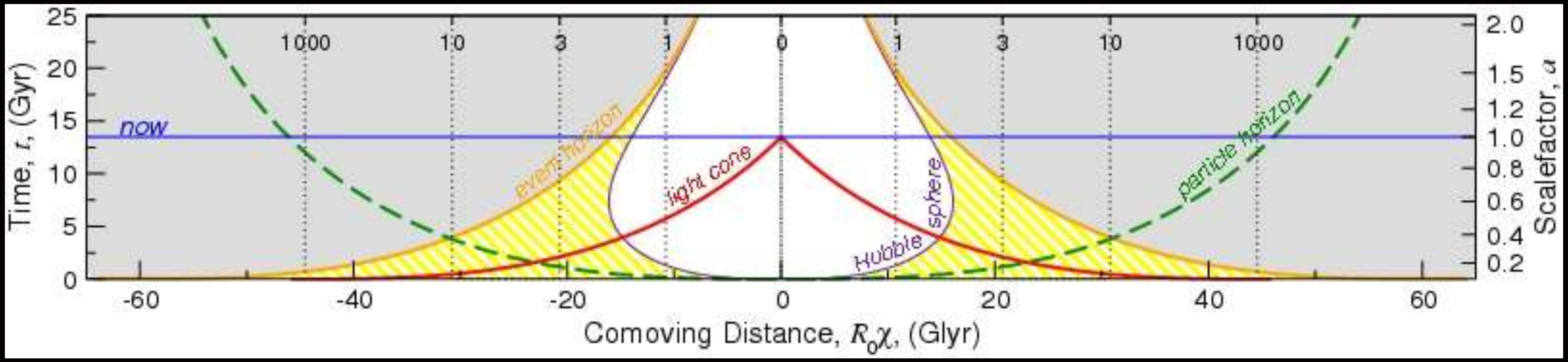
- Does it created exactly with space (w=-1) or a bit faster or a bit slower…
- This is considered one of Physics Biggest Questions, with both Astronomy and Physics communities putting significant effort into understanding the answer.
- EUCLID, WFIRST, LSST,BIGBOSS, BOSS, DECCAM, WIGGLEZ...
- .

The Big Chill?

Λ

Dark Energy has won the battle of the Universe, and will continue to accelerate the Cosmos.

- The creation of space happens more quickly than light can travel through it.



- Eventually we will live in an empty universe except for our own “super galaxy”

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...

Dark Energy Futures
The Unexpected

- Physics 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

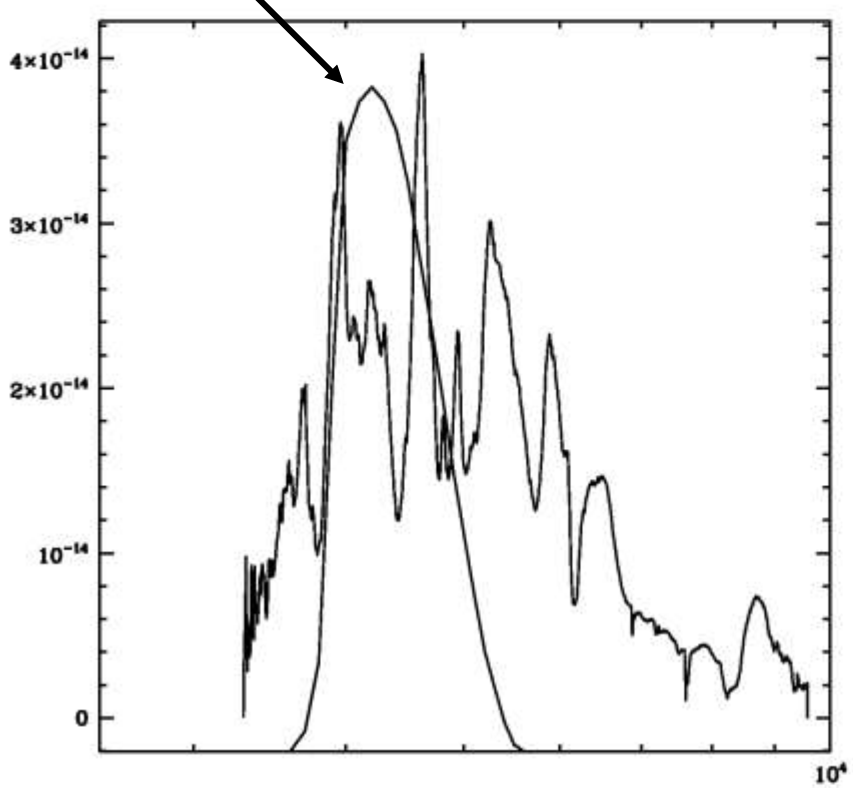
This is my Best Bet for Understanding Dark Energy

For now, if the acceleration continues, the Universe will, at an ever increasing rate, expand and fade away...

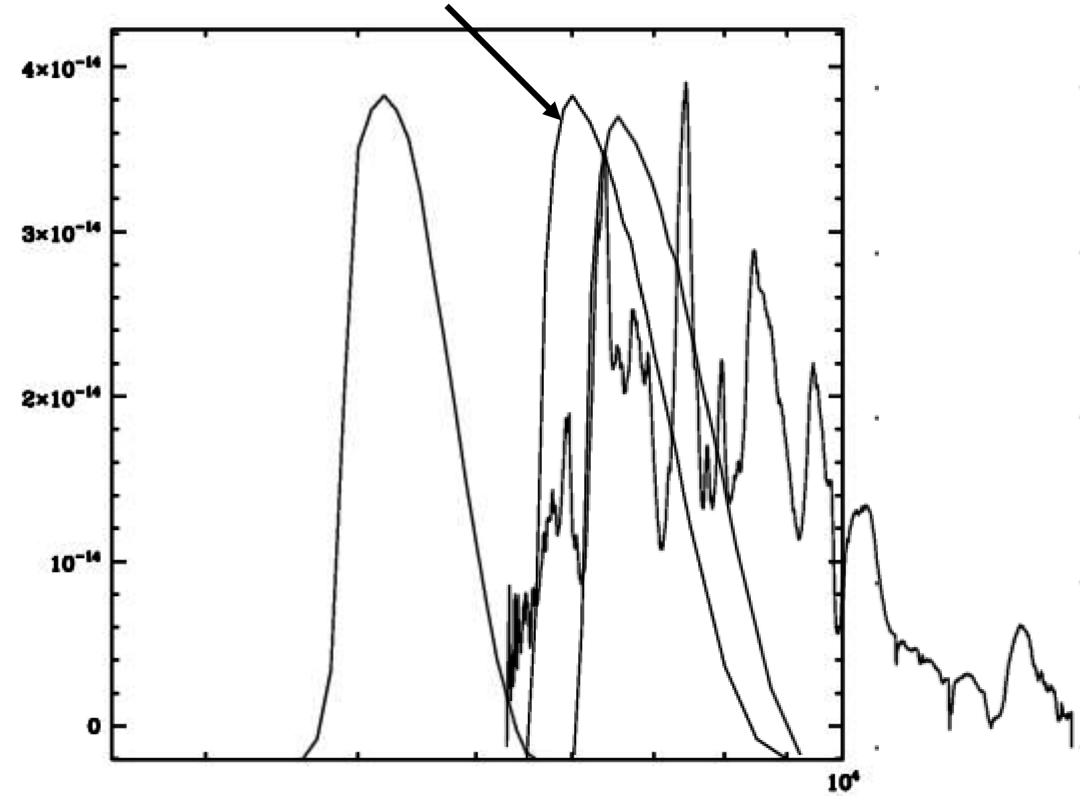
K-Corrections

As the light of an object become redshifted, we see it at different wavelengths

B band (440nm) **R band (650nm)**



Z=0



Z=0.5

Photometry and K-corrections

1 $m_i = M_i + 5\log(D_L/10pc)$ definition of absolute mag

2 $(m-M) \equiv 5\log\left(\frac{D_L}{10pc}\right)$ definition of distance modulus

3 $F(\lambda,z)d\lambda = \frac{L\left(\frac{\lambda}{(1+z)}\right)\frac{d\lambda}{(1+z)}}{4\pi D_L^2}$ Flux of redshifted source

4 $m_i = Z_i - 2.5\log\frac{\int S_i(\lambda)F(\lambda)d\lambda}{\int S_i(\lambda)d\lambda}$ definition of mag

5 $M_i = Z_i - 2.5\log\frac{\int S_i(\lambda)L(\lambda)d\lambda}{\int S_i(\lambda)d\lambda}\left(\frac{1}{4\pi(10pc)^2}\right)$

6 $m_i(z) = Z_i - 2.5\log\frac{\int S_i(\lambda)\frac{L\left(\frac{\lambda}{(1+z)}\right)\frac{d\lambda}{(1+z)}}{4\pi D_L^2}}{\int S_i(\lambda)d\lambda}$

7 $(m_i(z) - M_i) = \left(Z_i - 2.5\log\frac{\int S_i(\lambda)\frac{L\left(\frac{\lambda}{(1+z)}\right)\frac{d\lambda}{(1+z)}}{4\pi D_L^2}}{\int S_i(\lambda)d\lambda}\right) - \left(Z_i - 2.5\log\frac{\int S_i(\lambda)L(\lambda)d\lambda}{\int S_i(\lambda)d\lambda}\left(\frac{1}{4\pi(10pc)^2}\right)\right)$

8 $(m_i(z) - M_i) = 2.5\log\left(\frac{\int S_i(\lambda)L(\lambda)d\lambda}{\int S_i(\lambda)L\left(\frac{\lambda}{(1+z)}\right)\frac{d\lambda}{(1+z)}}\right) + 5\log\left(\frac{D_L}{10pc}\right)$

9 $(m-M) = (m_i(z) - M_i) - K_i$

where,

10 $K_i(z) = 2.5\log\left[(1+z)\frac{\int S_i(\lambda)L(\lambda)d\lambda}{\int S_i(\lambda)L\left(\frac{\lambda}{(1+z)}\right)d\lambda}\right]$

analagous for two different filters is

11 $(m-M) = (m_i(z) - M_j) - K_{ij}(z)$,

where

12 $K_{ij}(z) = 2.5\log\left[(1+z)\frac{\int S_i(\lambda)L(\lambda)d\lambda}{\int S_j(\lambda)L(\lambda/(1+z))d\lambda}\right] + Z_j - Z_i$

e.g SN Ia at z=0.5 has R=22.2 and K-Corr (R->B) =–0.75 and M_B =-19.5
its (m-M) = 22.2 + 0.75 + 19.5 = 42.45

K-Corrections

$$m_i = Z_i - 2.5\log\frac{\int S_i(\lambda)F(\lambda)d\lambda}{\int S_i(\lambda)d\lambda}$$

$$K_i = 2.5\log\left[(1+z)\frac{\int S_i(\lambda)F(\lambda)d\lambda}{\int S_i(\lambda)F(\lambda/(1+z))d\lambda}\right]$$

$$K_{ij} = 2.5\log\left[(1+z)\frac{\int S_i(\lambda)F(\lambda)d\lambda}{\int S_j(\lambda)F(\lambda/(1+z))d\lambda}\right] + Z_j - Z_i$$

$$(m-M) = m_j - K_{ij} - M_i$$