Supernovae the Accelerating Cosmos and Dark Energy

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CAASTRO
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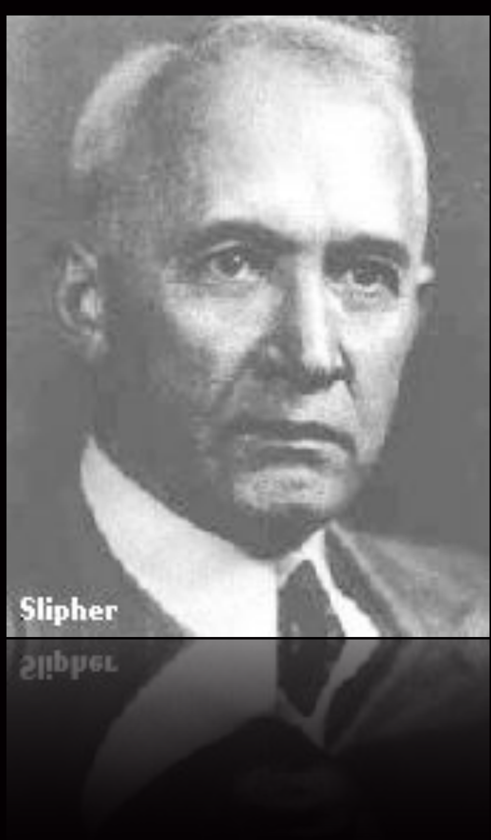
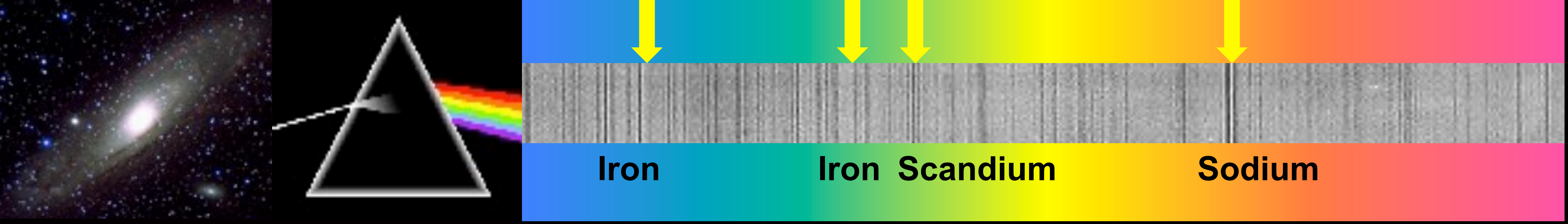
THE AUSTRALIAN NATIONAL UNIVERSITY

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

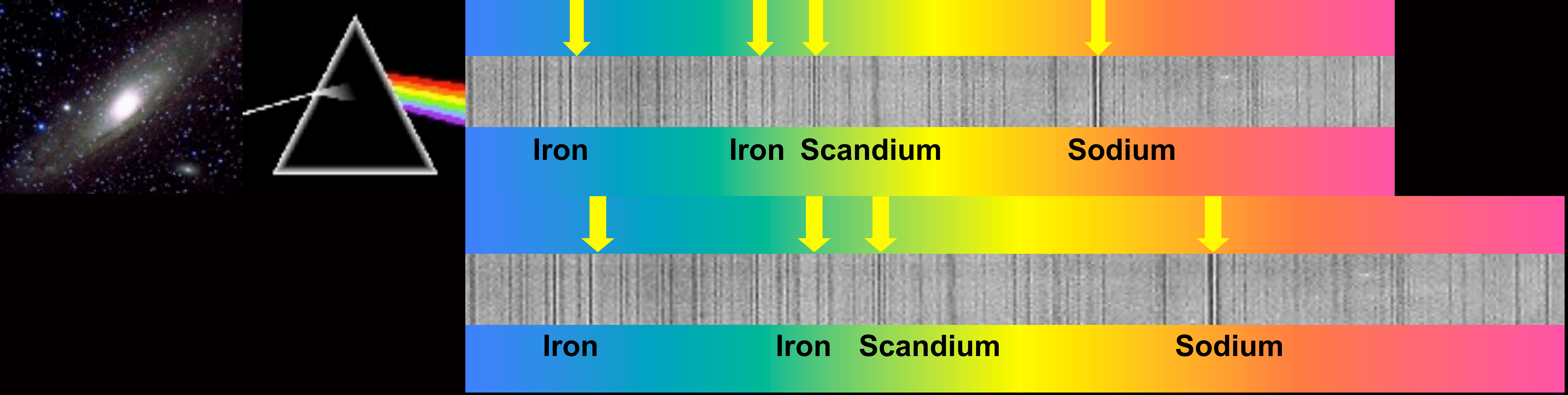
1916


Slipher

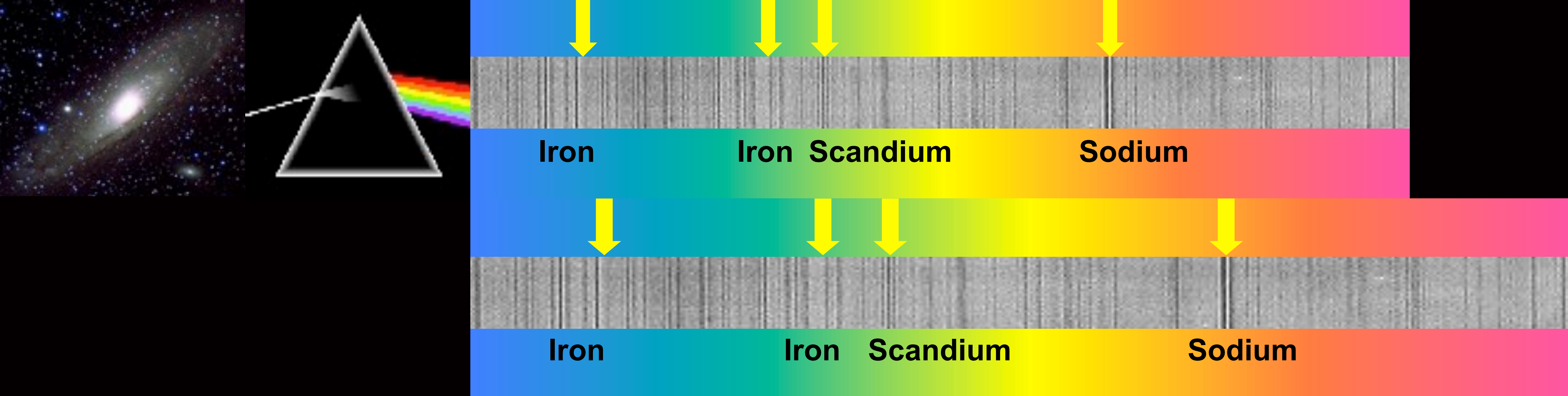

Slipher


Iron
Iron
Scandium
Sodium


Slipher

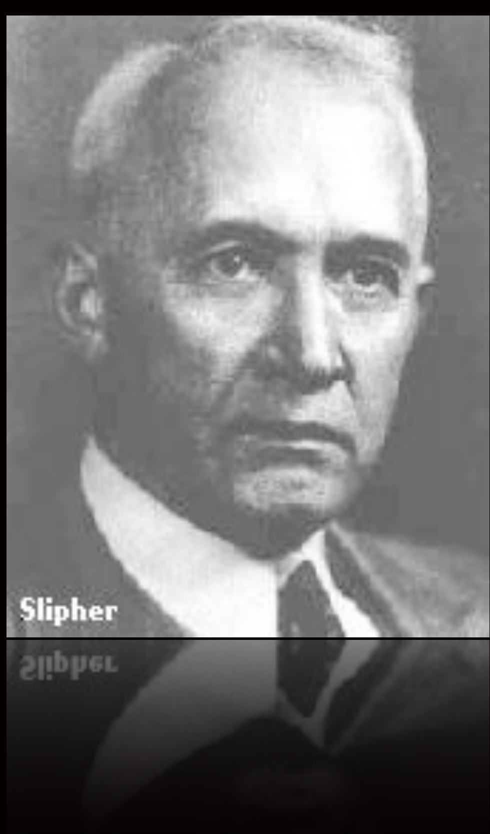


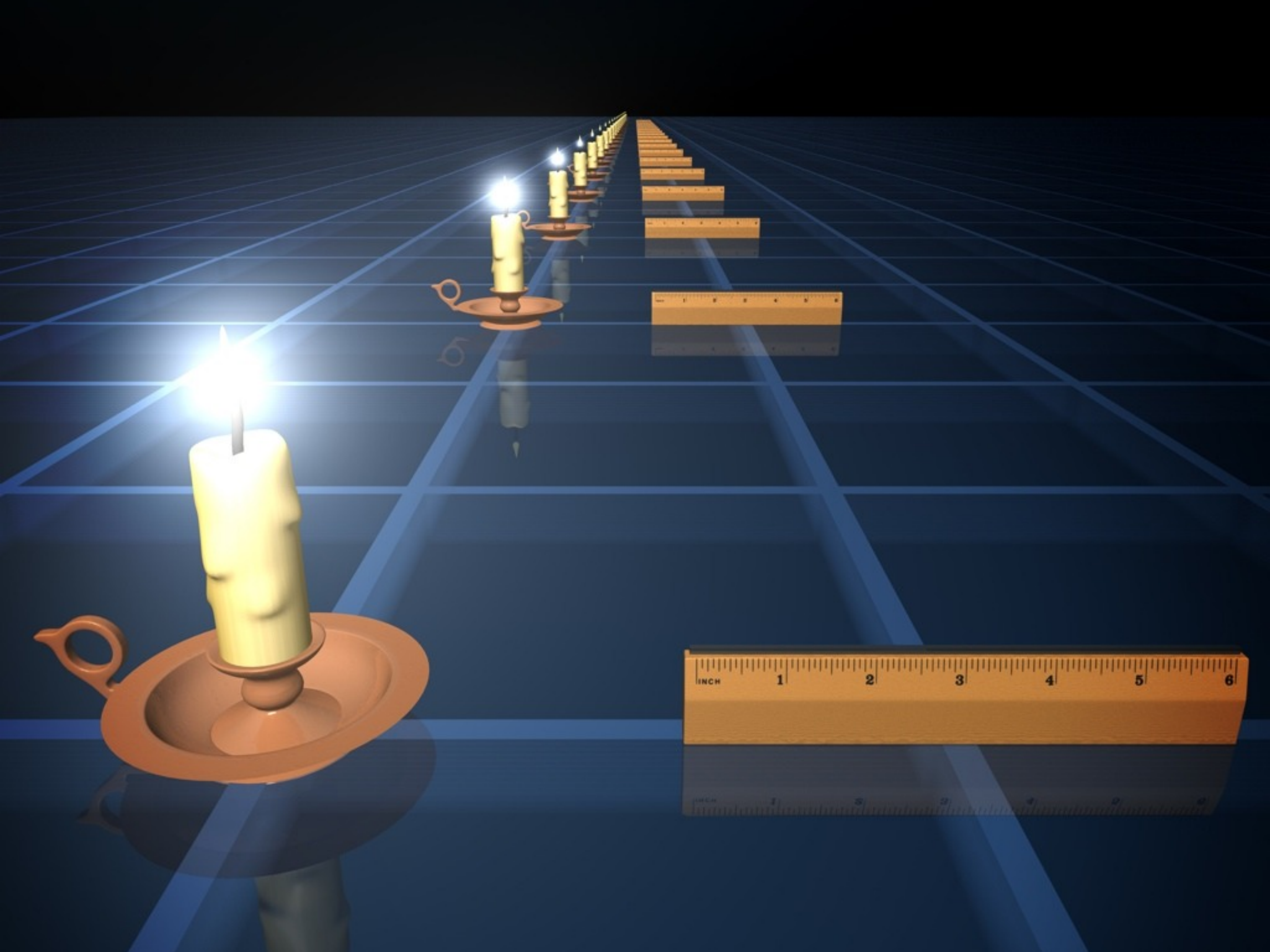
Doppler Shift Gives Velocity of Galaxy



Doppler Shift Gives Velocity of Galaxy

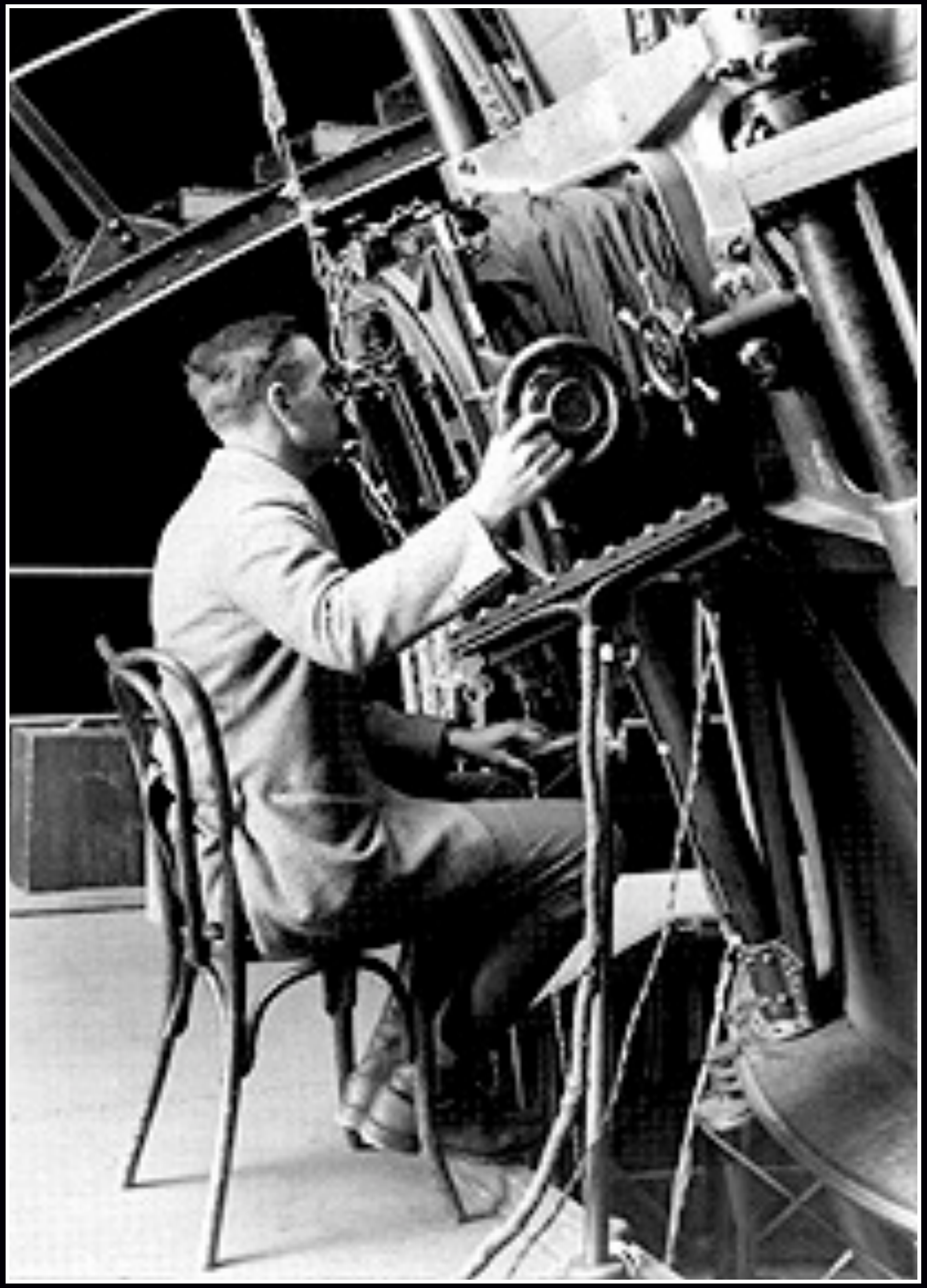
In 1916 Vesto Slipher measured velocities to nearby galaxies, and discovered they almost all had spectral shifts to the Red




INCH 1 2 3 4 5 6

1929

Hubble uses brightest stars to measure the distances to the nearest galaxies.



He assumes the brightest stars are all the same brightness.

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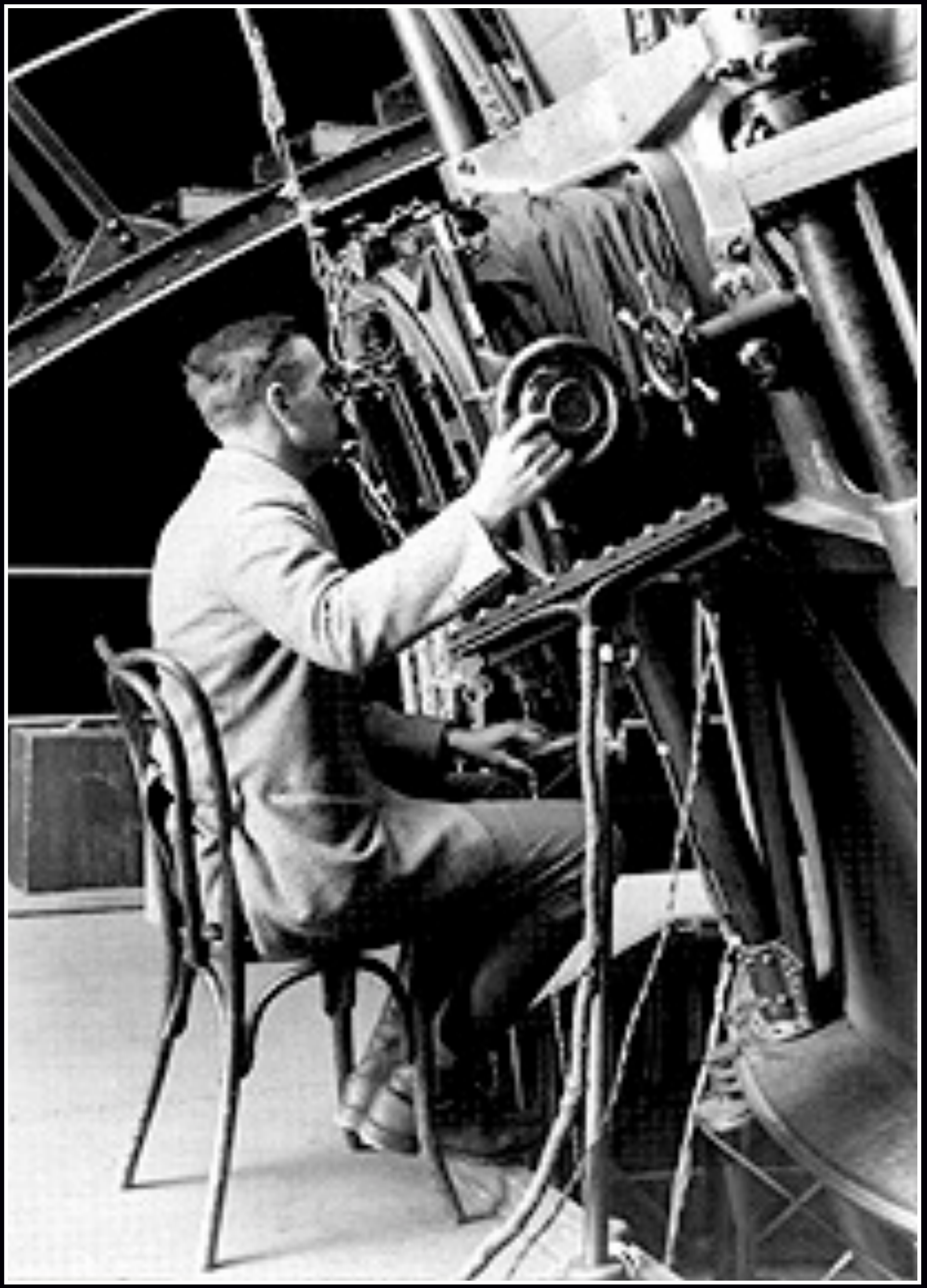


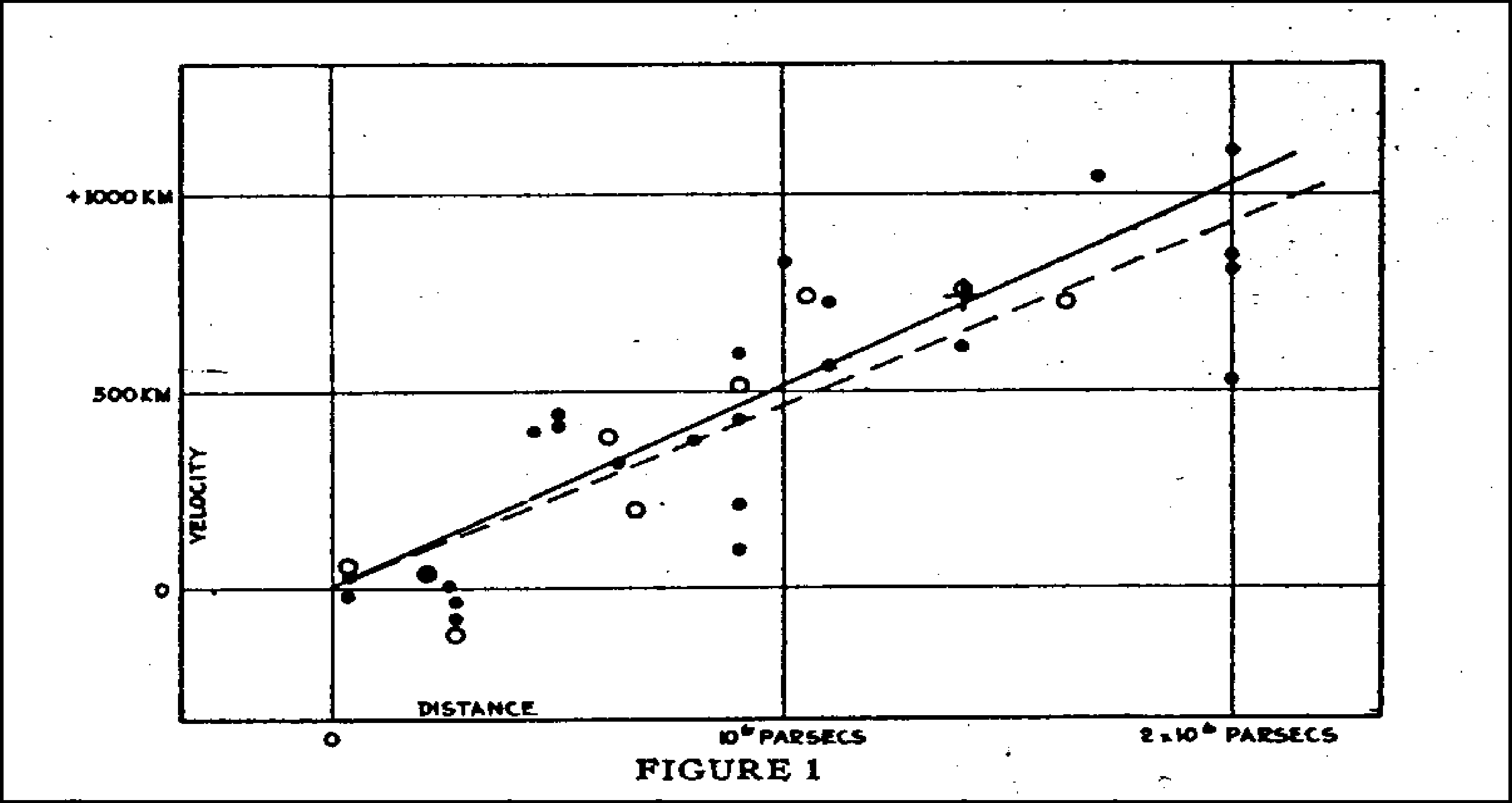
He assumes the brightest stars are all the same brightness.

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

Hubble's Data

High Redshift

Low Redshift

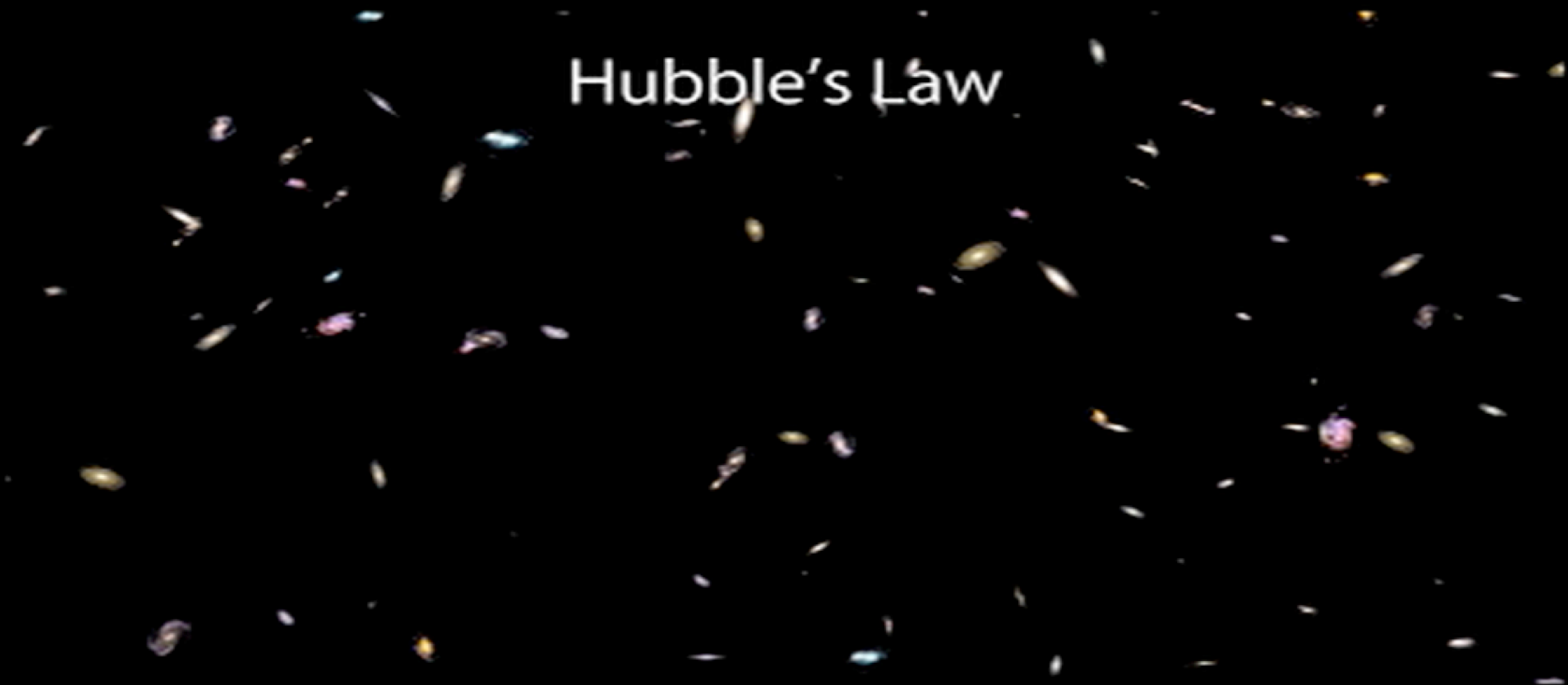


Brighter Stars

Fainter Stars

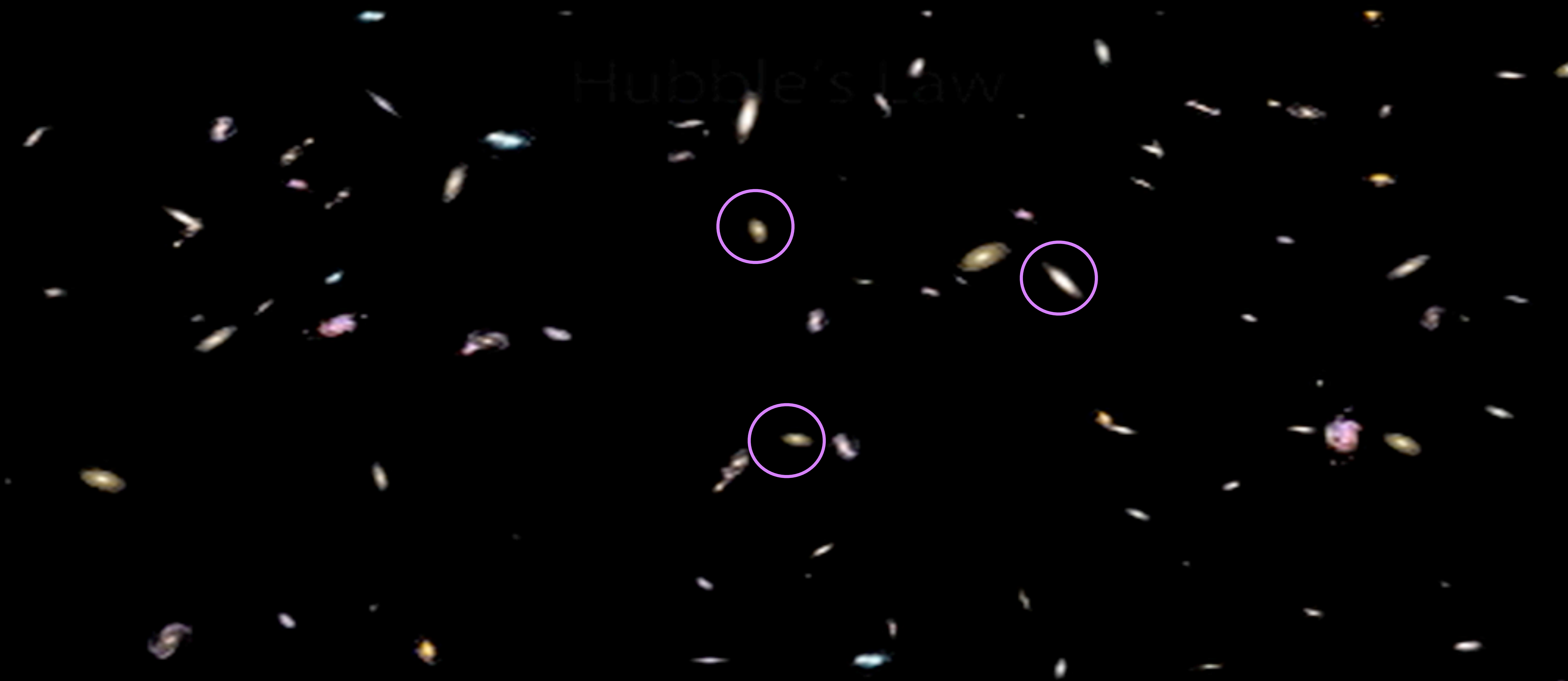
The Universe is Expanding

Hubble's Law



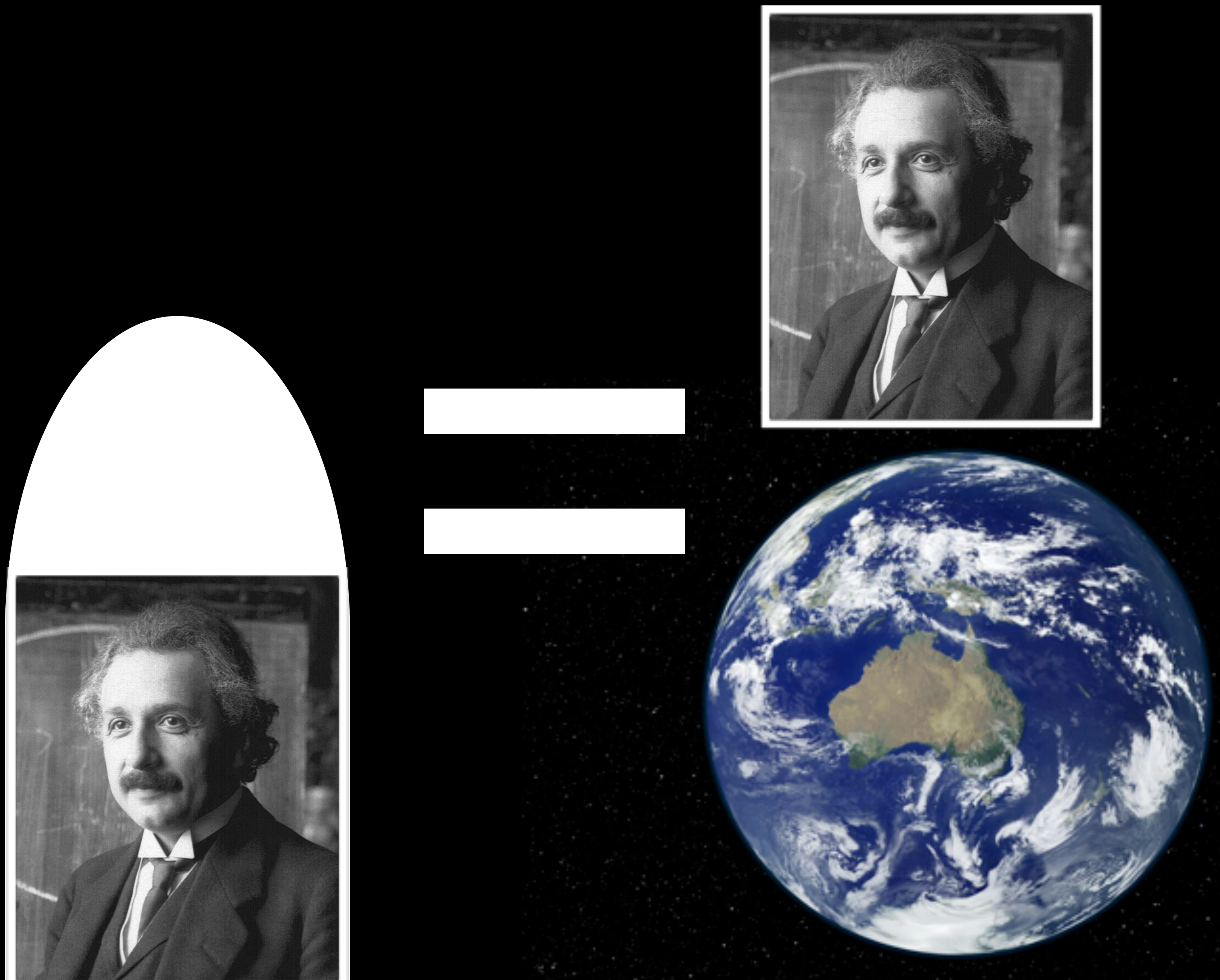
Hubble's Law

Hubble's Law



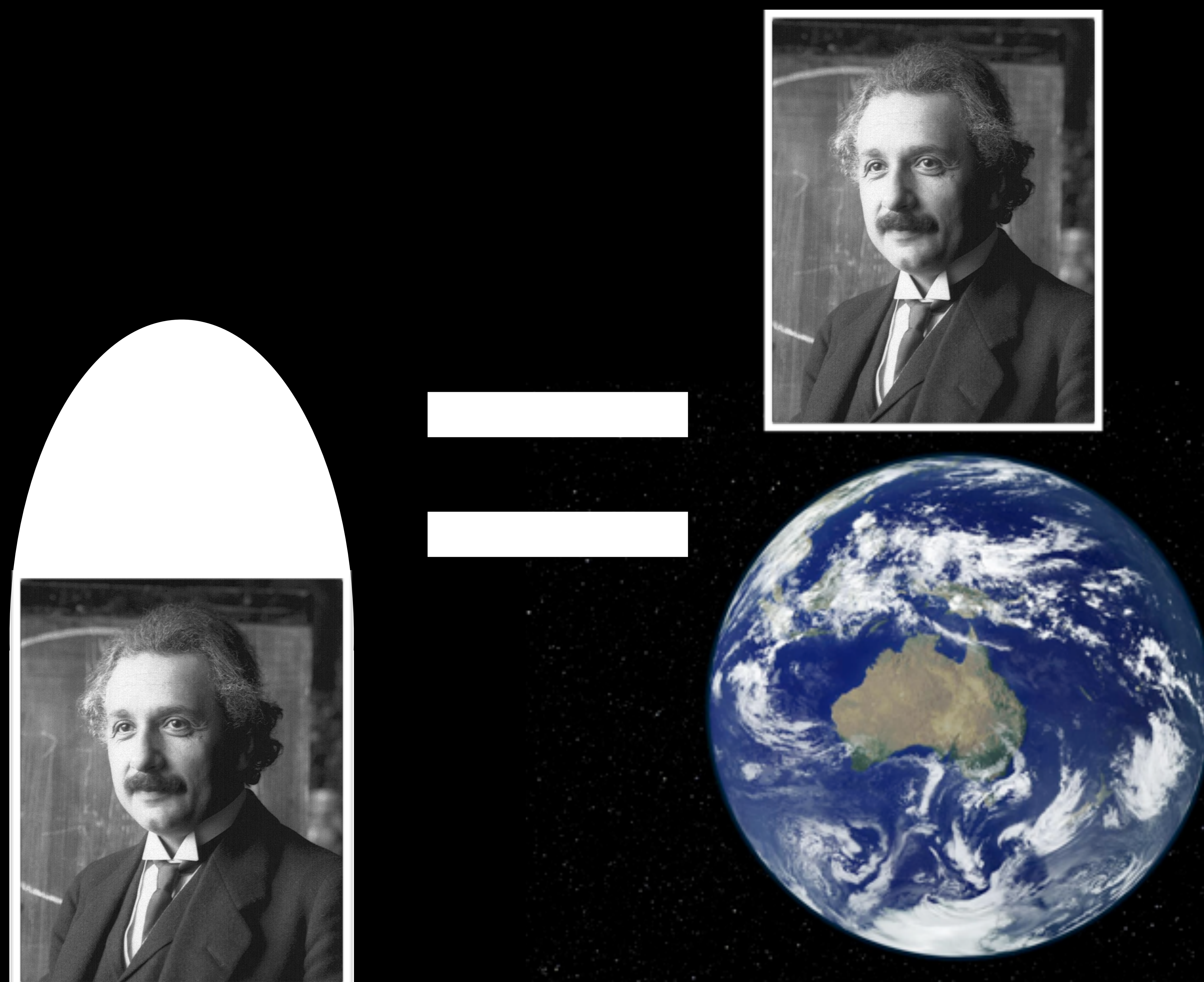

Hubble's Law

Einstein's Theory of Gravity



Einstein's Theory of Gravity

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



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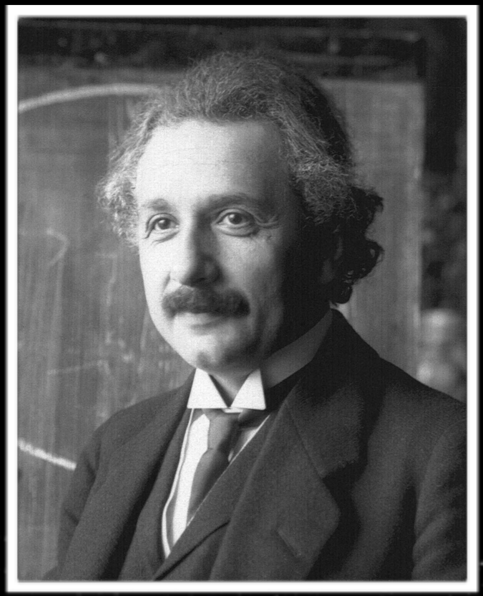
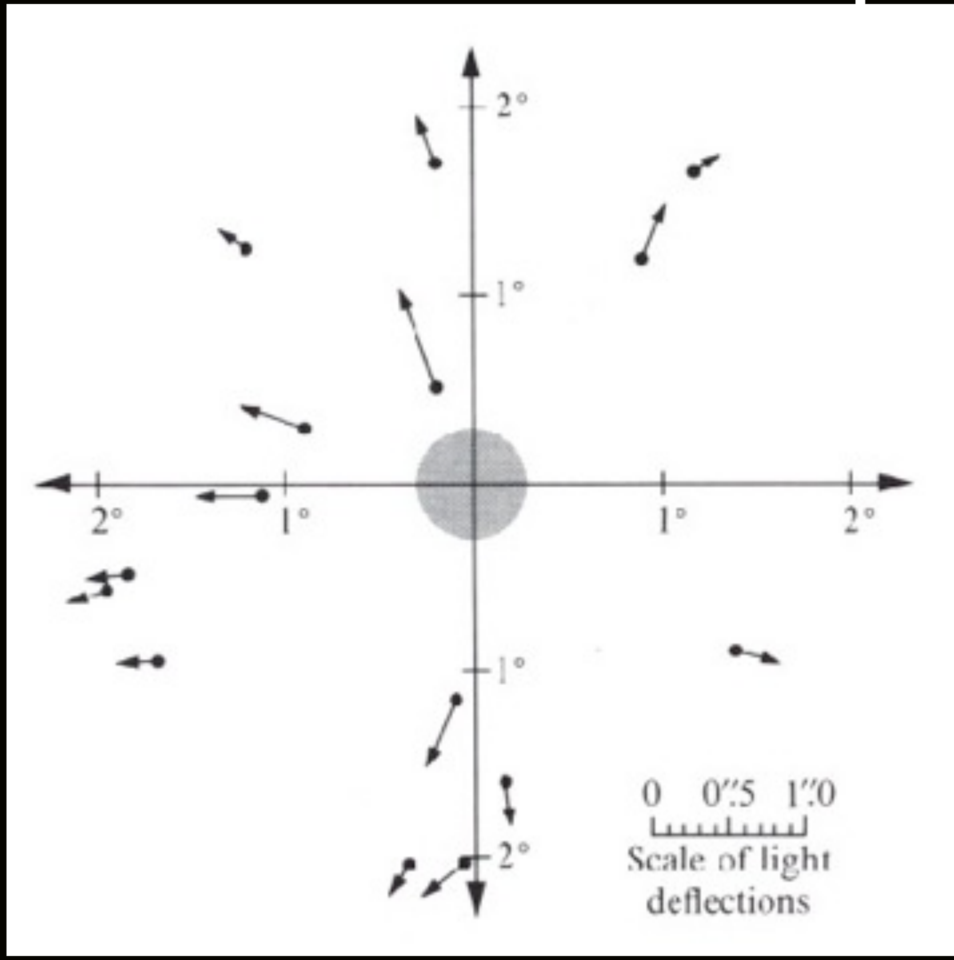
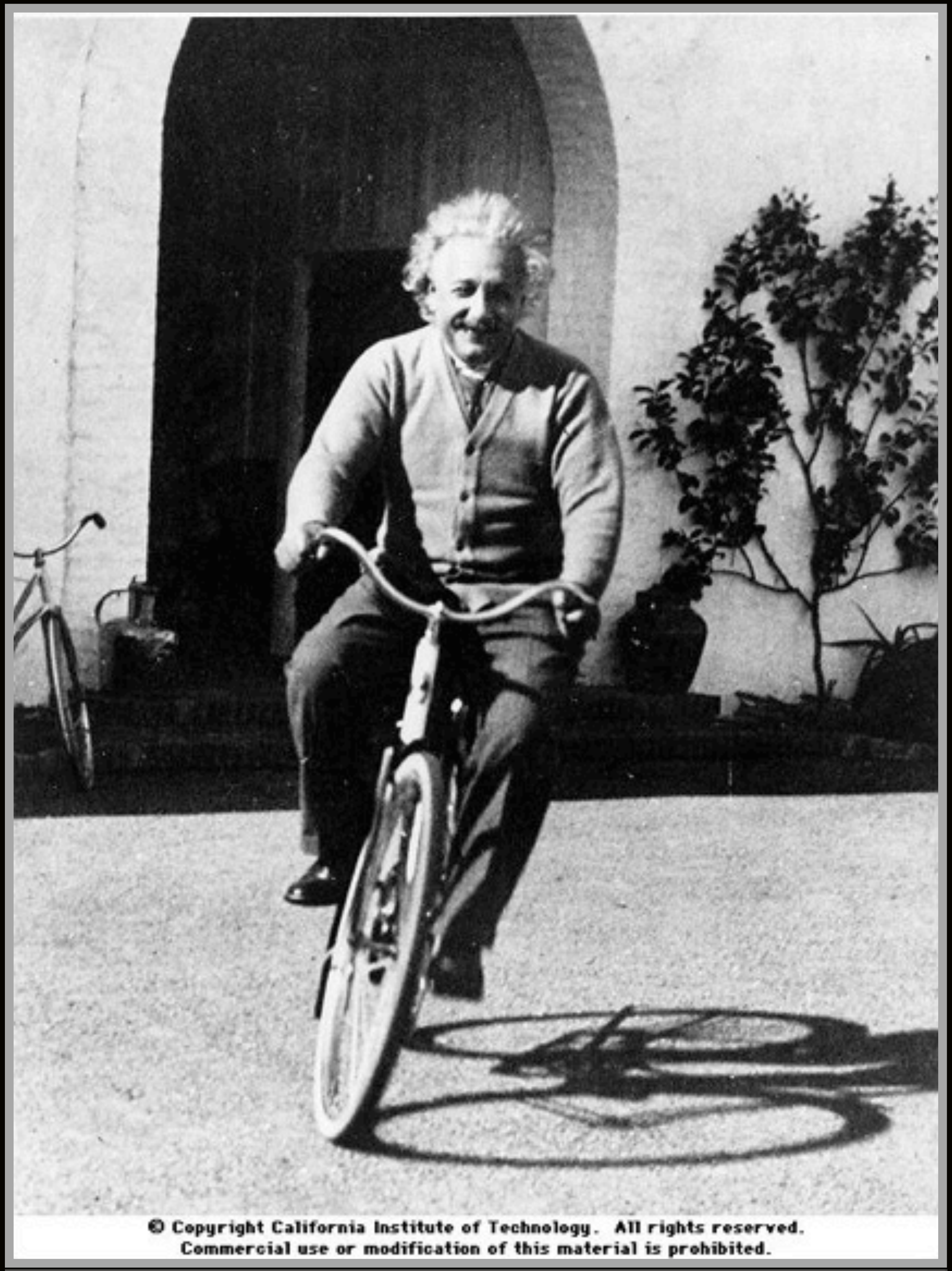


Predicted Curved Space



Allowed one to Solve Cosmology... But

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.

We think of it as the energy of the vacuum.

Quoted Later on in life as
“My Greatest Blunder”

The Standard Model

The Standard Model

Friedmann Equation (1923)

General Relativity

Isotropy & Homogeneity

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

The Standard Model

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General Relativity

Isotropy & Homogeneity

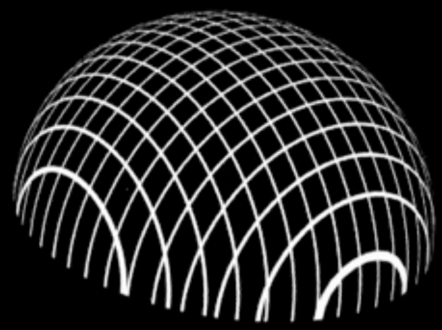
$$\frac{1}{c^2}\left(\frac{da}{dt}\right)^2 = \frac{8\pi G}{3c^2}\rho a^2 - k$$

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

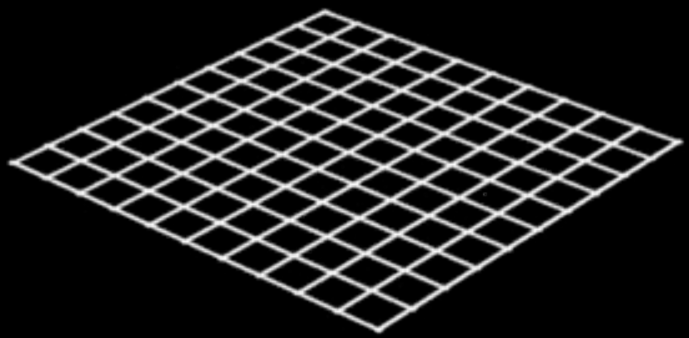
$$\frac{a}{a_0} = \frac{1}{(1+z)}$$

Observationally - it is tracked by redshift - and scale factor and redshift can be used interchangeably

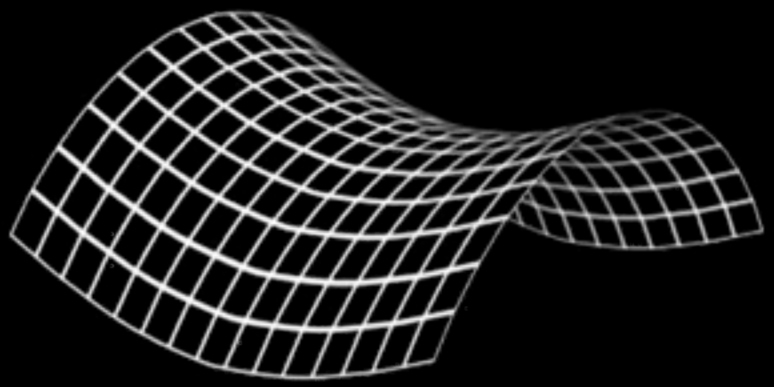
Cosmic Geometry-Curvature and Density



CLOSED



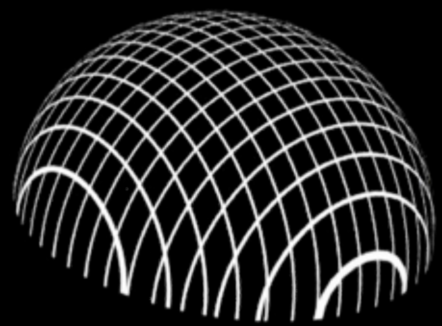
FLAT



OPEN

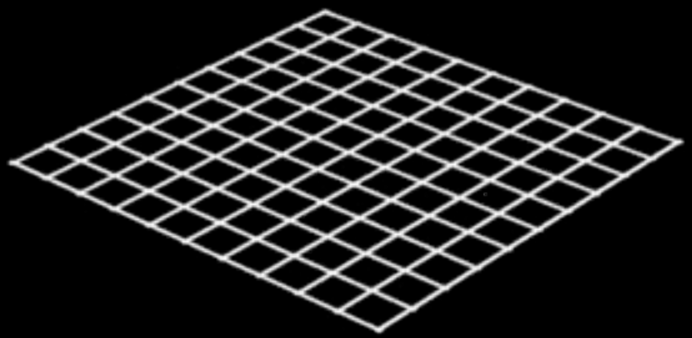
Cosmic Geometry-Curvature and Density

Heavy



CLOSED

k=+1



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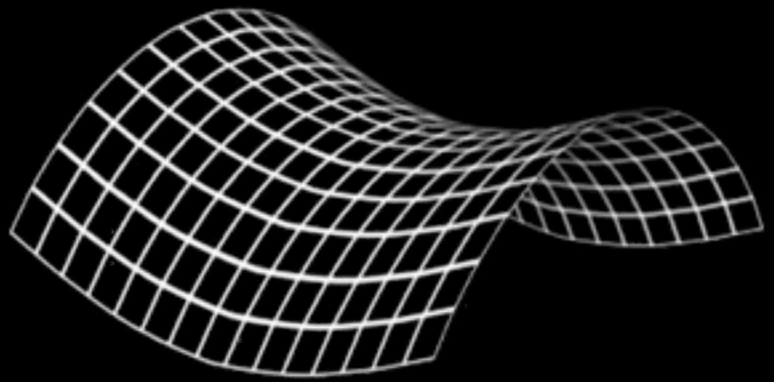

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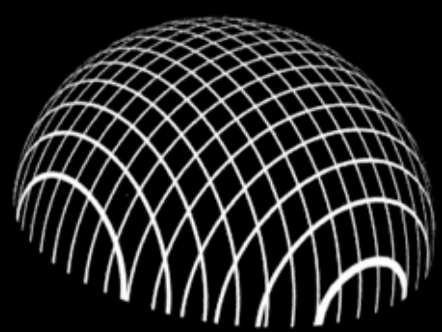

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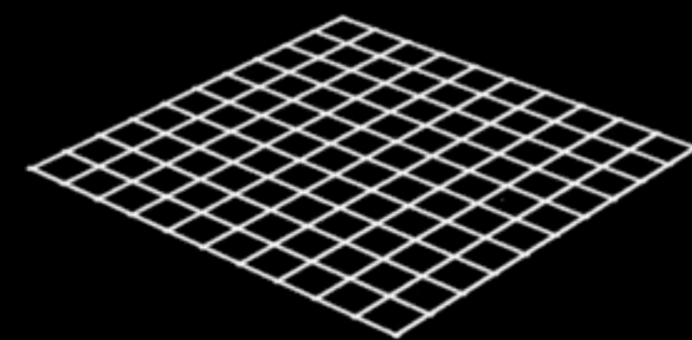
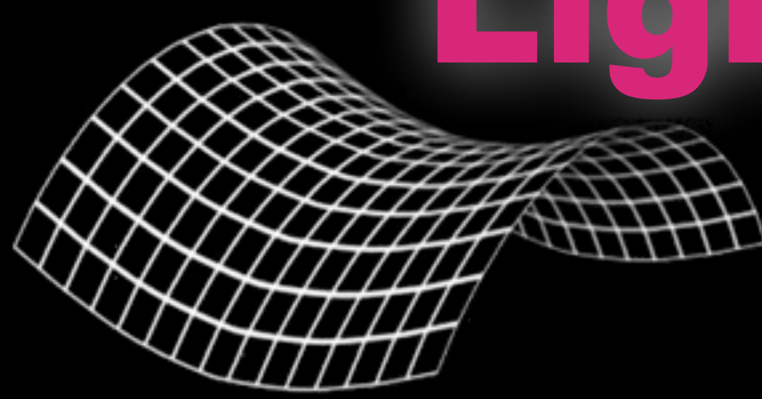


FLAT

Light k=-1



OPEN

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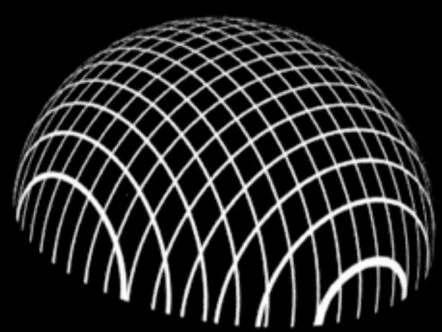
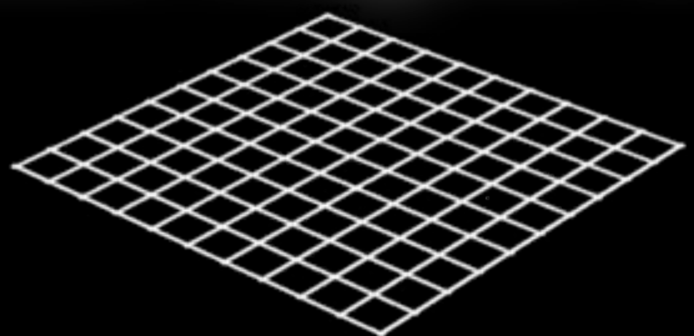


CLOSED

k=+1

Just Right k=0



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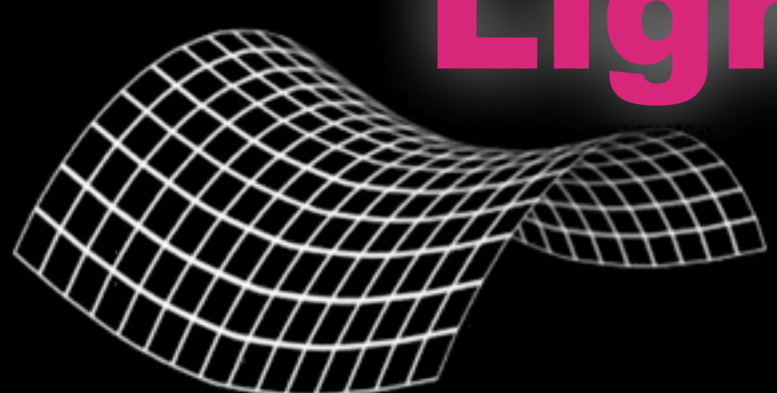

OPEN

Expansion Rate of the Universe

$$H(t) = \frac{\dot{a}}{a}$$

Hubble Parameter

$$H_0 = \frac{cz}{D} = 71 \pm 4\ km\ s^{-1} Mpc^{-1}$$

$$1/H_0 \sim 14\mathrm{Gyr}$$

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$$\rho_c = \frac{3H^2}{8\pi G}$$

Critical Density

k=0 Dividing line between k=+1 and k=-1

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

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

$$\Omega = \frac{\rho}{\rho_c}$$

Density Parameter

Density of the Universe relative to critical density

Solutions: Normal Matter Only Universe

$$\frac{a}{a_0} = \frac{\Omega_M}{2(1-\Omega_M)}(\cosh\eta - 1)$$

$$t = \frac{1}{H_0}\frac{\Omega_M}{2(1-\Omega_M)^{3/2}}(\sinh\eta - \eta)$$

k=-1

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

k=0

$$\frac{a}{a_0} = \frac{\Omega_M}{2(\Omega_M - 1)}(1-\cos\eta)$$

$$t = \frac{1}{H_0}\frac{\Omega_M}{2(\Omega_M - 1)^{3/2}}(\eta - \sin\eta)$$

k=+1

Friedmann's Past & Future

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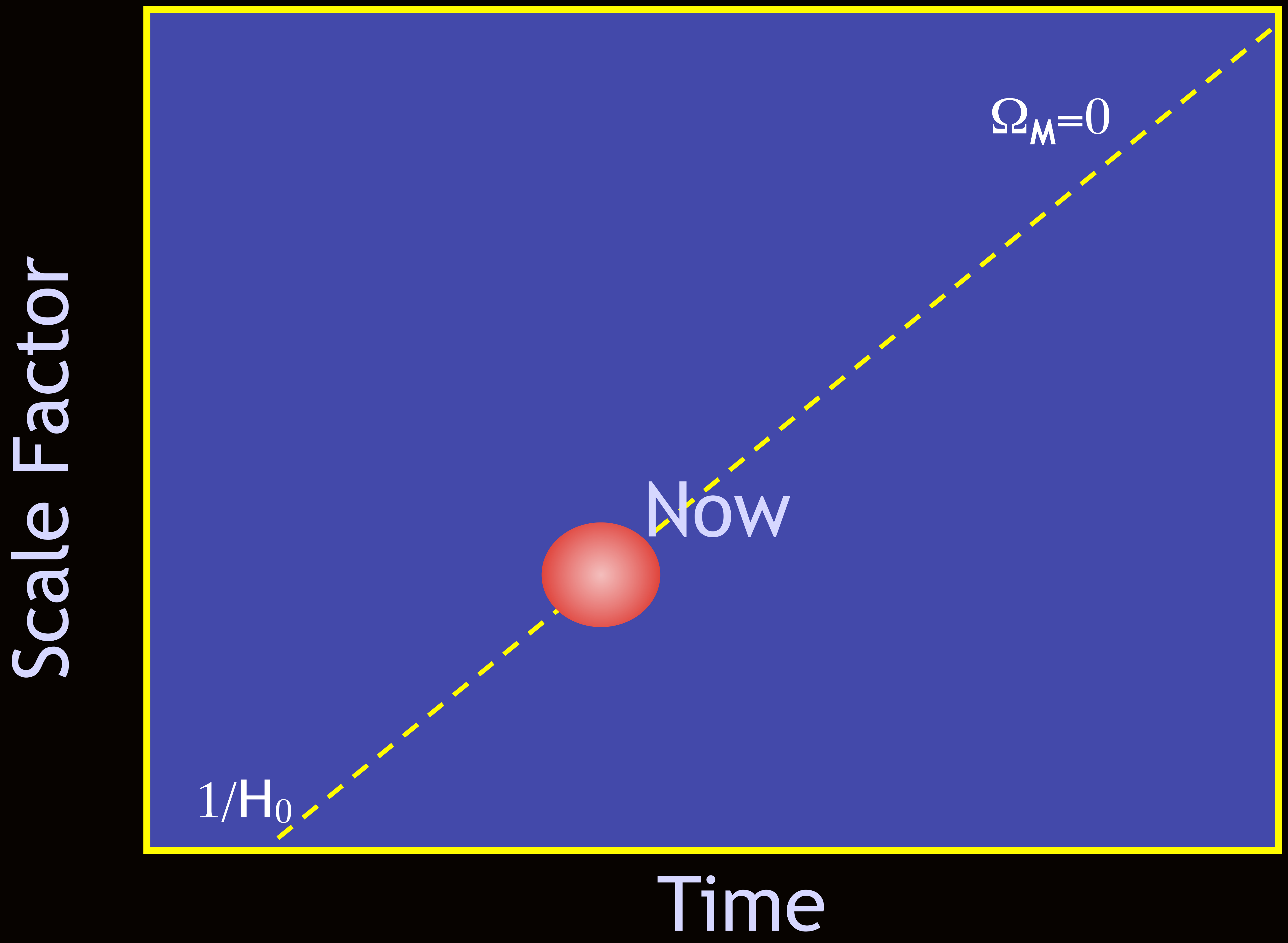

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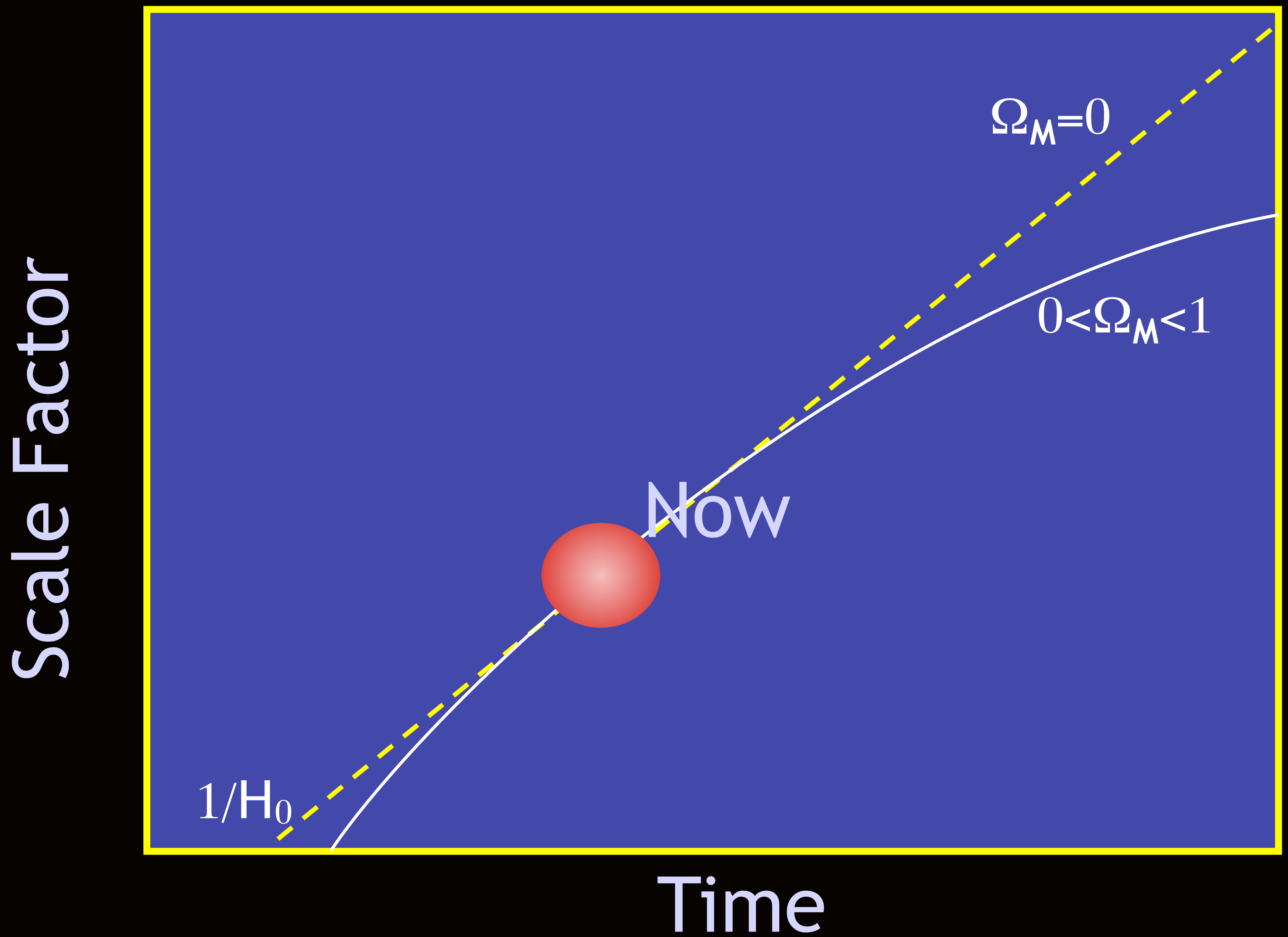

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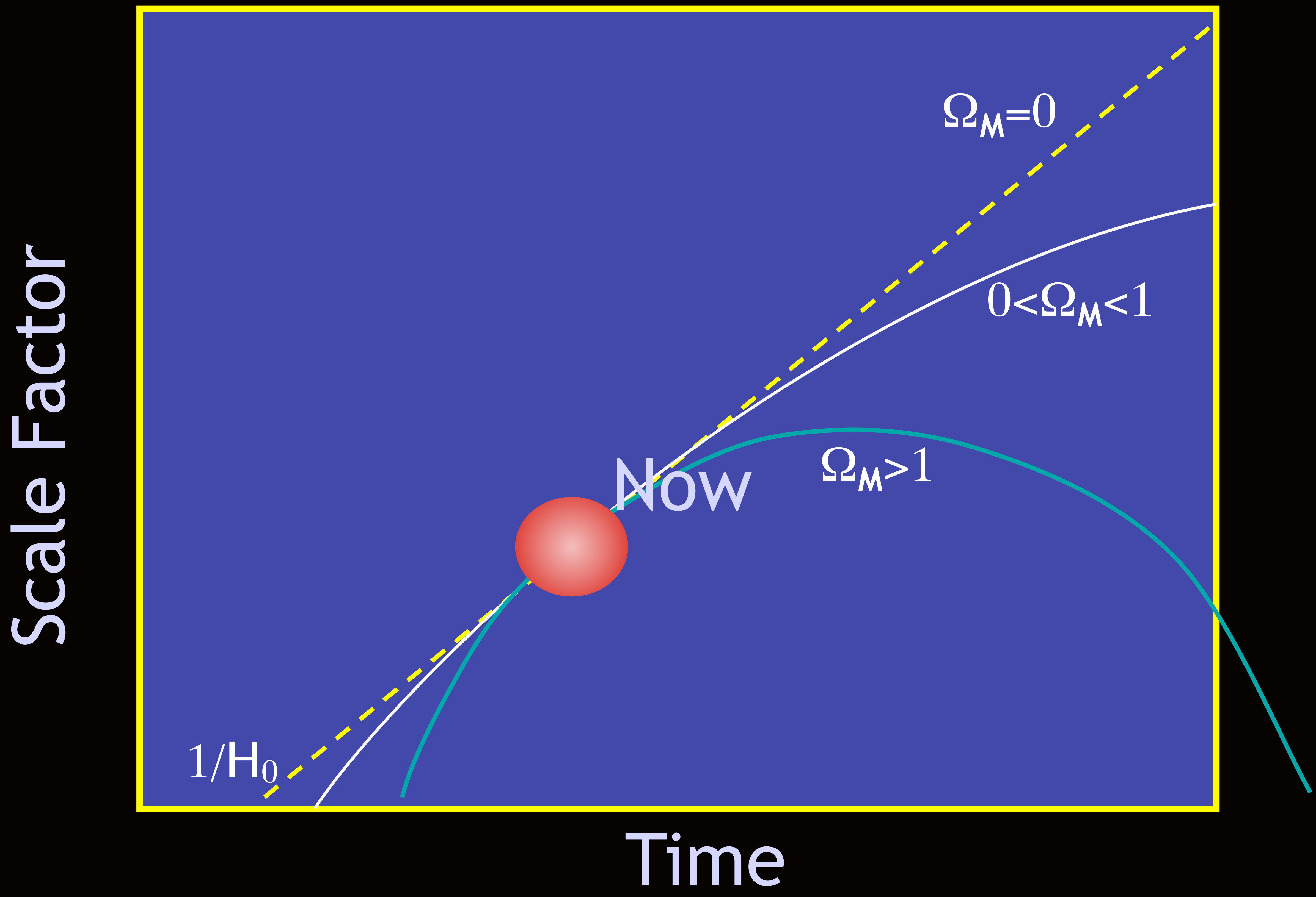

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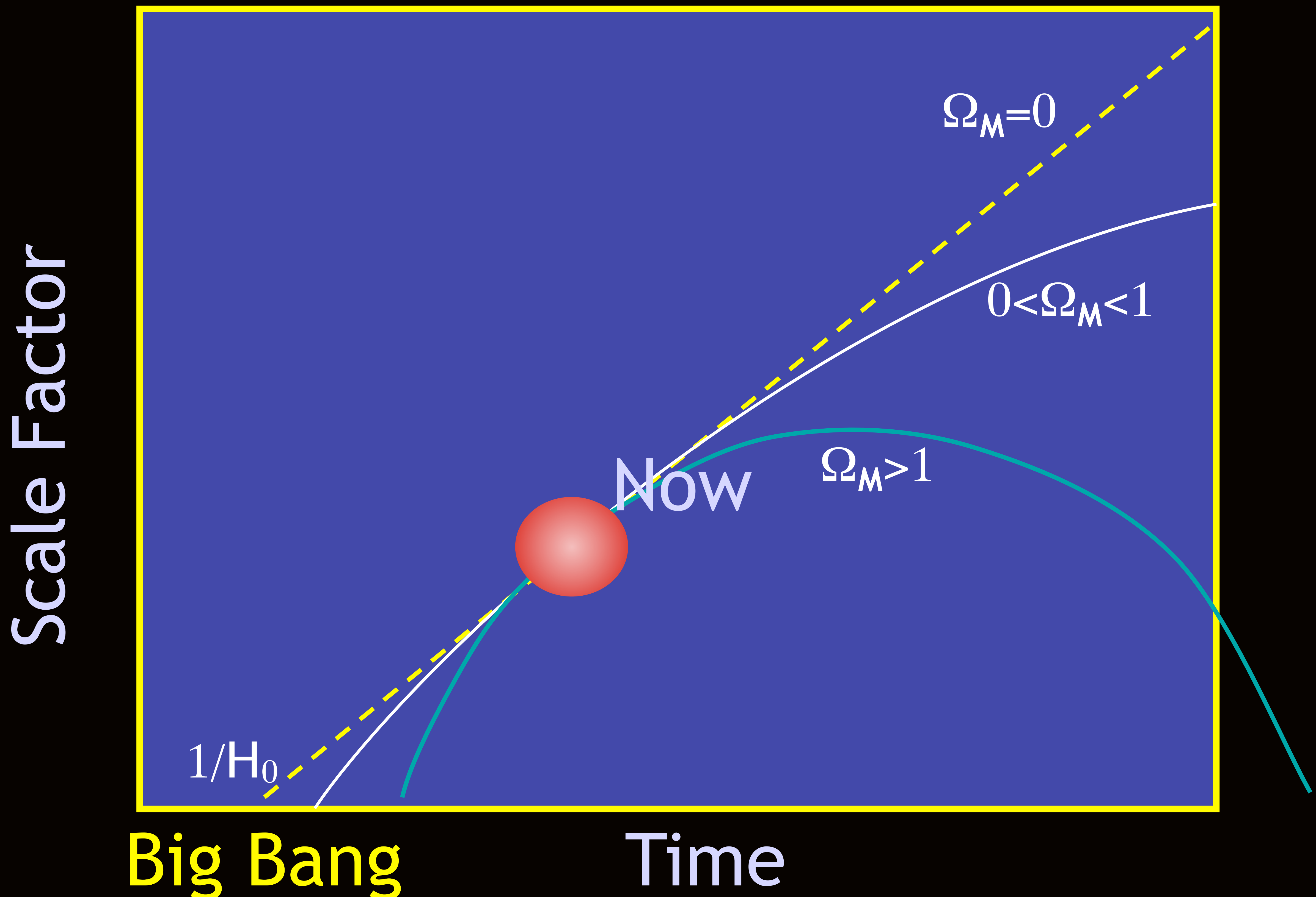

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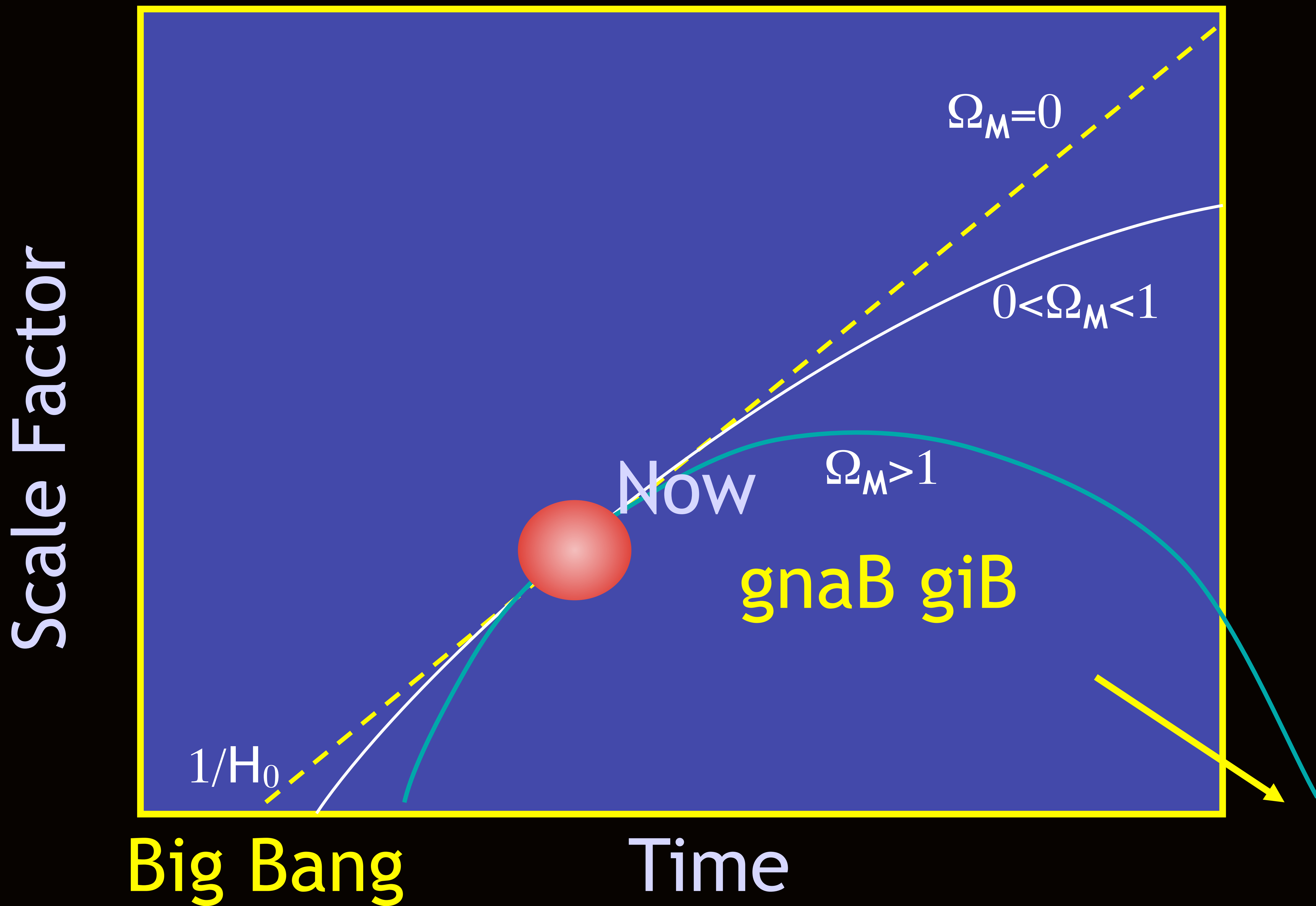

The Density parameter and Geometry

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

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

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

The Standard Model

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Friedmann Equation (1923)

G.R.

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Friedmann equation for Flat Universe

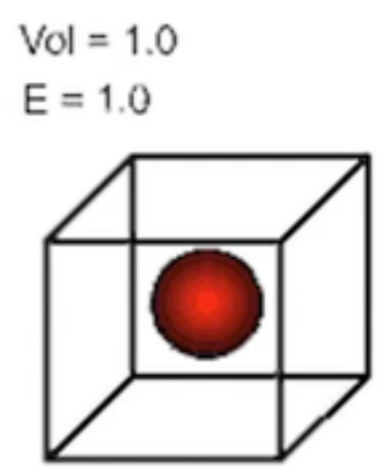
$$a(t=t_0)=a_0, \quad \rho(t=t_0)=\rho_0, \quad H(t=t_0)=H_0, \quad k=0$$

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

But Universe may be Made of More than just ordinary Matter.

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

e.g.,



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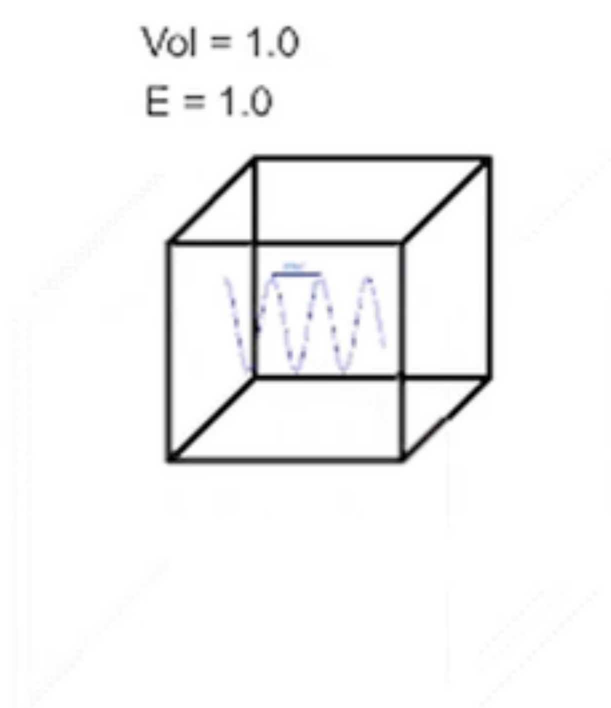
e.g.,

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

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



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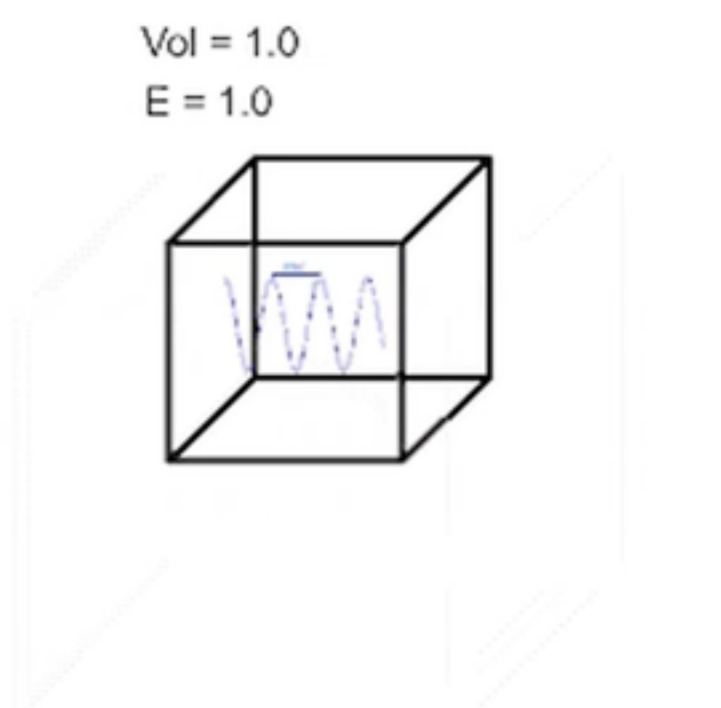
e.g.,

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

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

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

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



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e.g.,

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

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

w=−1 ***for Cosmological Constant***

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

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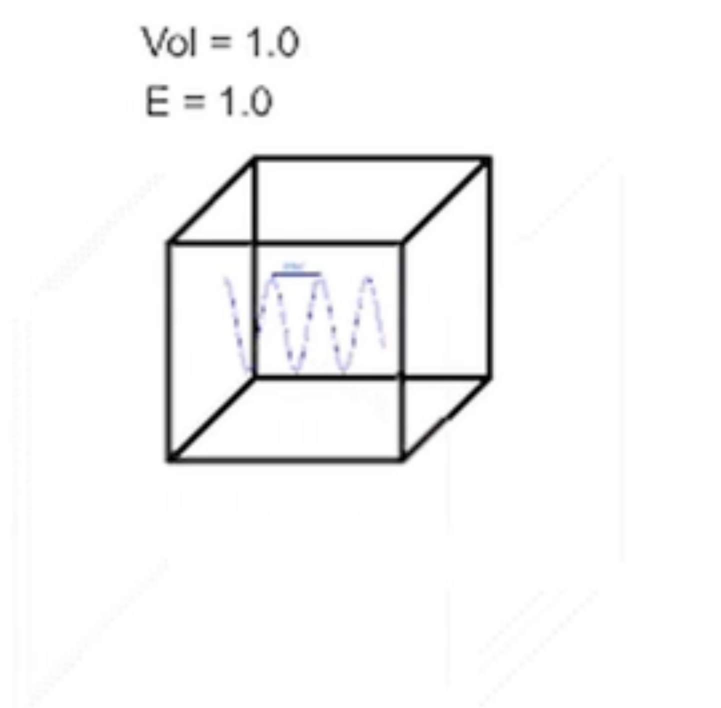
$$\rho \propto V^{0} \rightarrow \left(\frac{a}{a_0}\right)^0 \left(\frac{\rho_\Lambda}{\rho_0}\right) = 1$$



Flat Universe –Matter Dominated

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

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

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

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

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

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

Flat Universe – Radiation Dominated

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

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

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

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

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

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

Flat Universe –Cosmological Constant Dominated

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

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

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

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

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

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

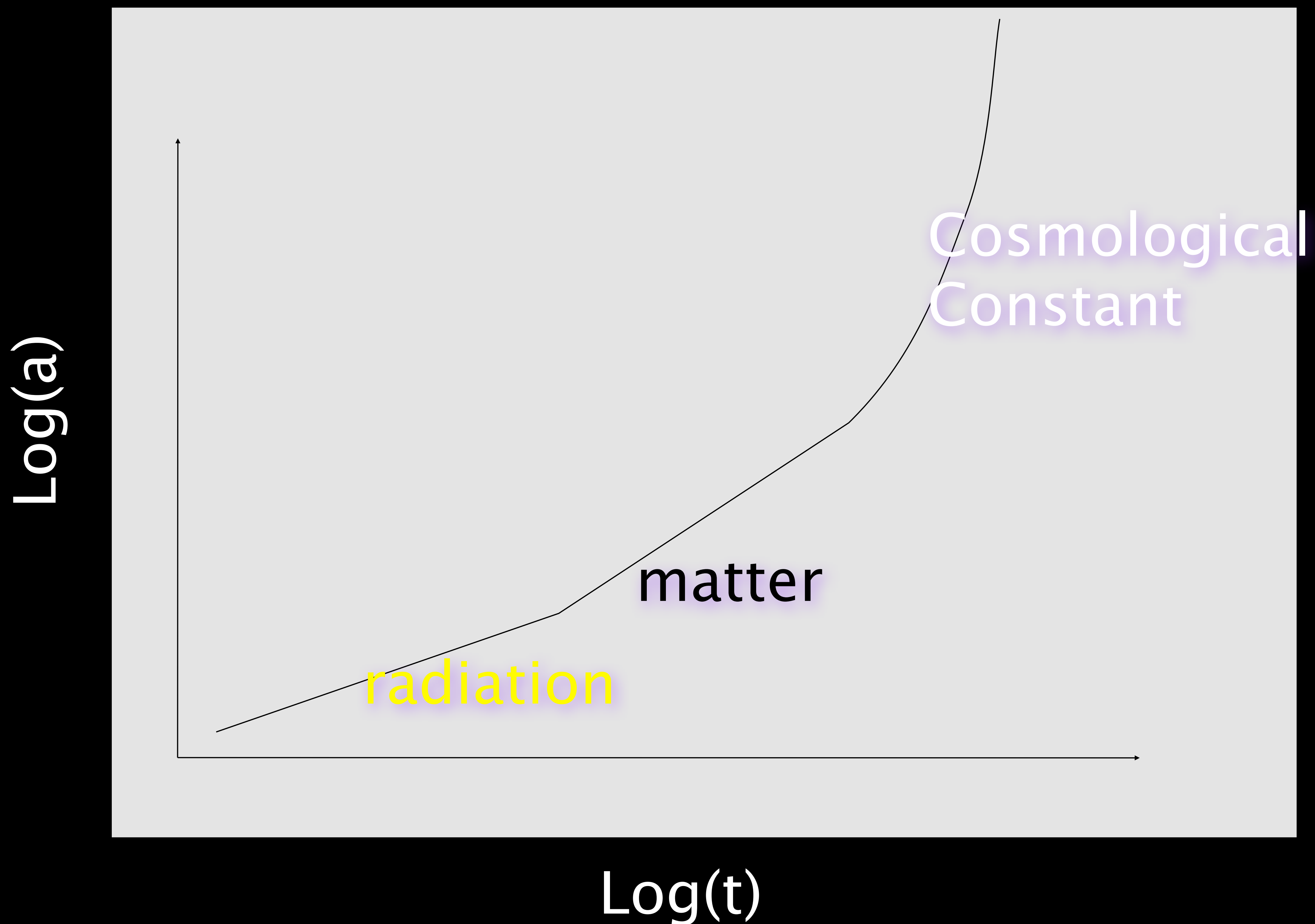
Domination of the Universe

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

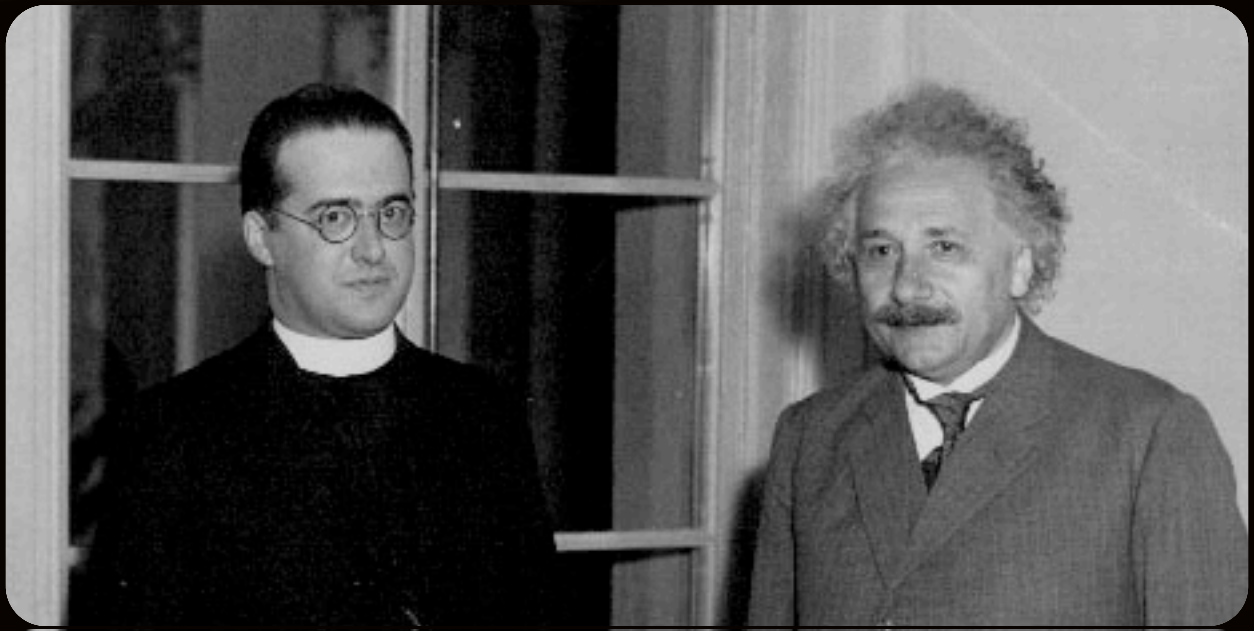
$$\frac{\Omega_{rad}}{\Omega_M} = \left(\frac{a}{a_0}\right)^{-1} = (1+z)$$

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

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

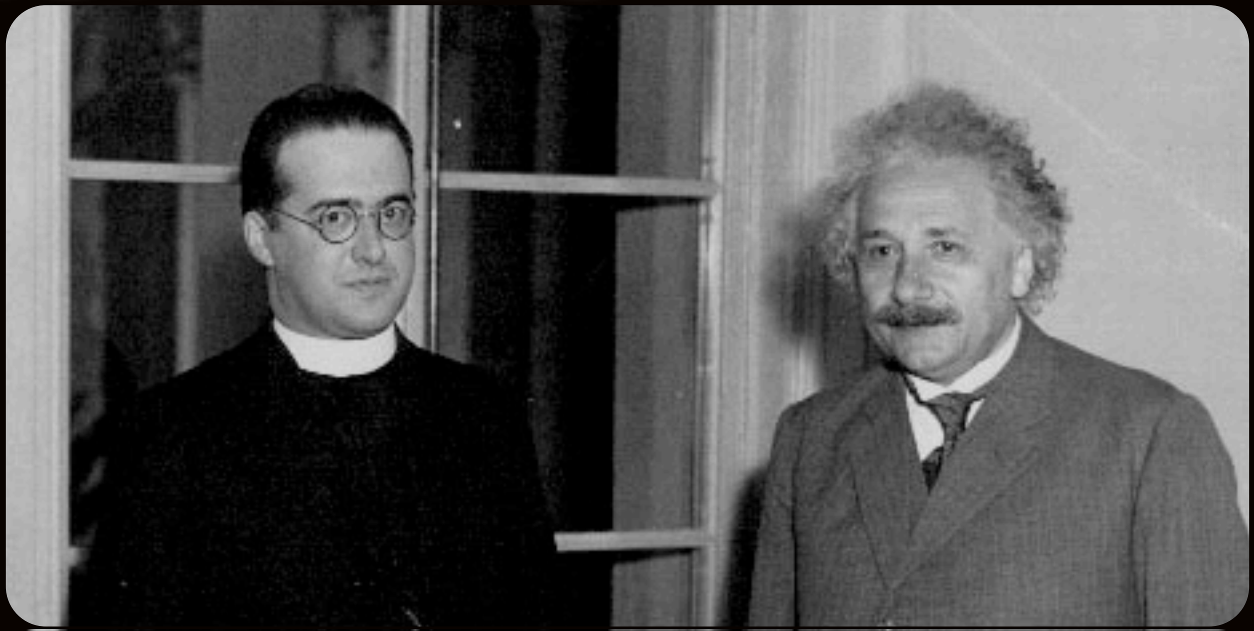

Log(a)
Cosmological
Constant
matter
radiation
Log(t)

Georges Lemaître



Georges Lemaître

- Seminary in 1923, ordained as a priest



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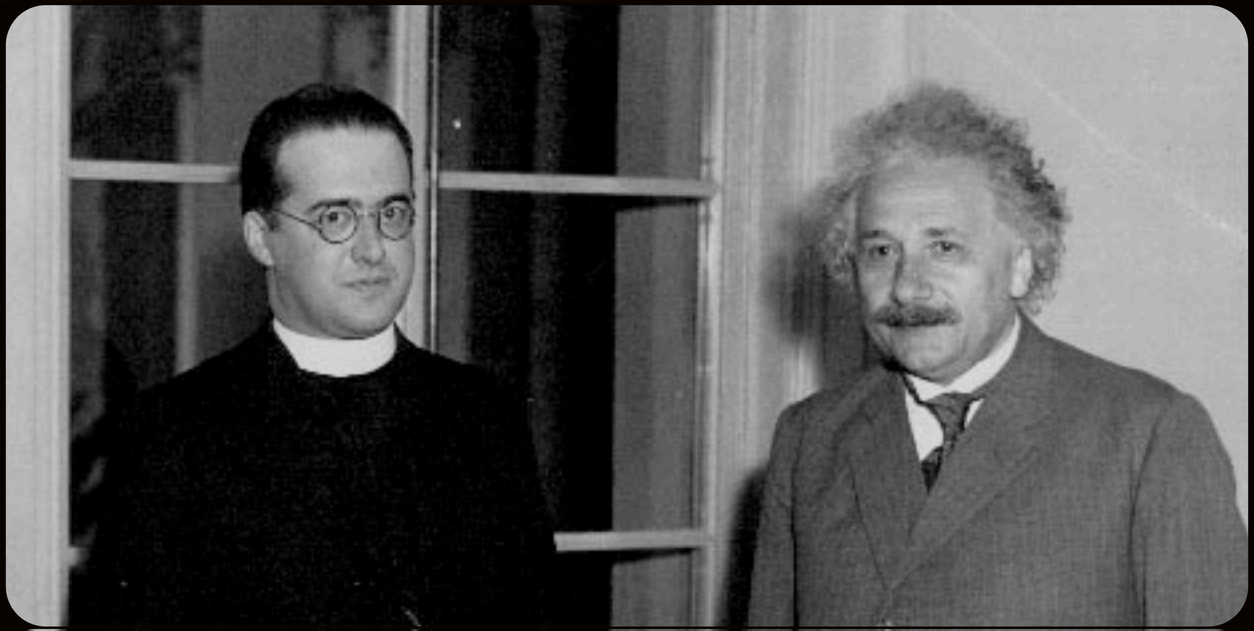

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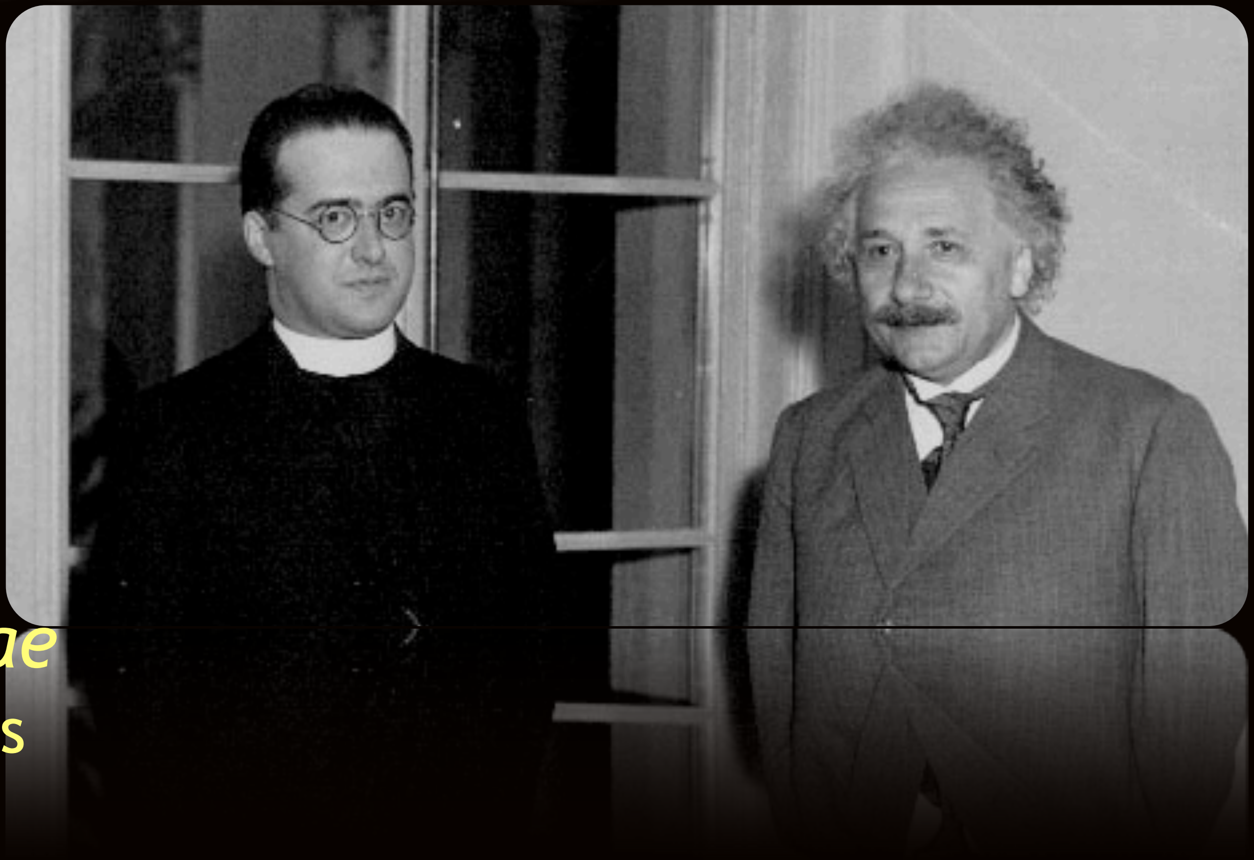

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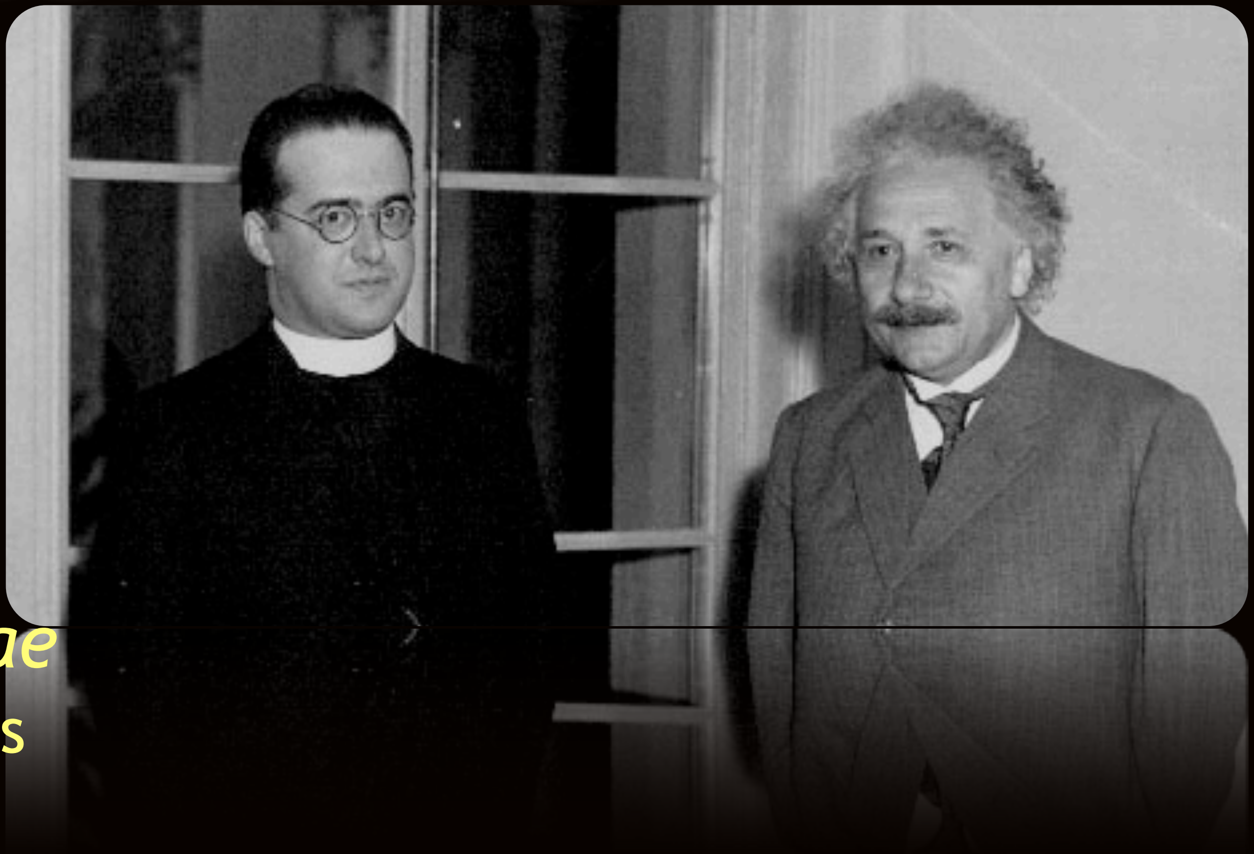
Georges Lemaître



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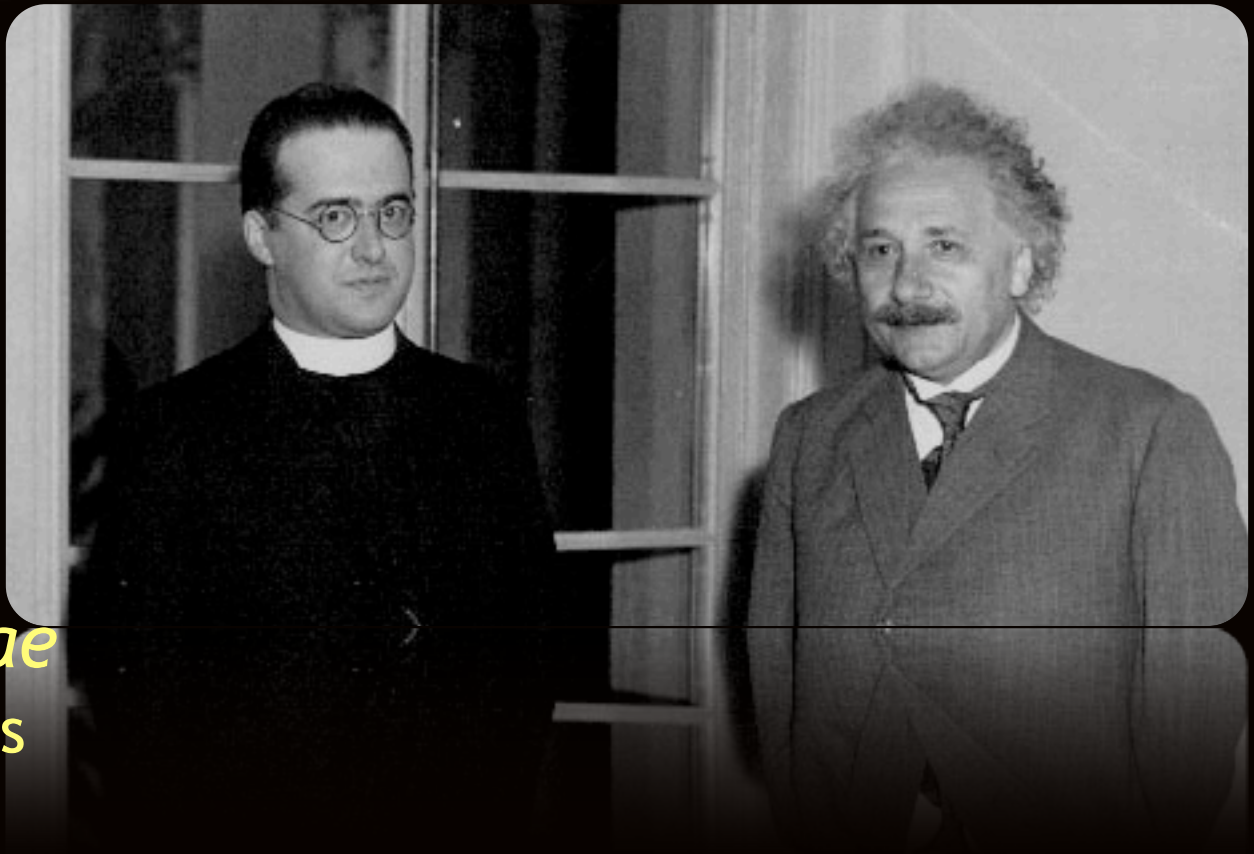

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1931 Discussed primeaval atom which everything grew out of – the Big Bang

Connecting To Observation

Connecting To Observation

Robertson-Walker line element

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

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Distance

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Distance Time

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Distance Time Coordinates

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Distance | Time | Curvature | Coordinates

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Distance | Time | Dynamics | Curvature | Coordinates

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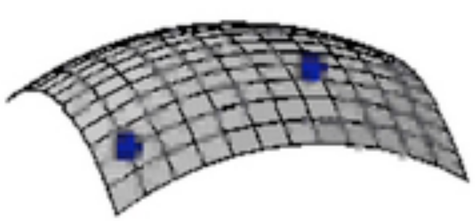
Distance | Time | Dynamics | Curvature | Coordinates



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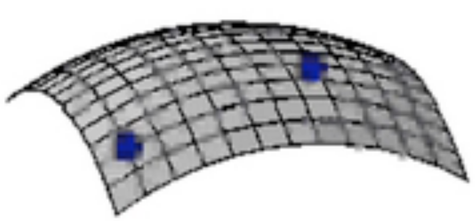
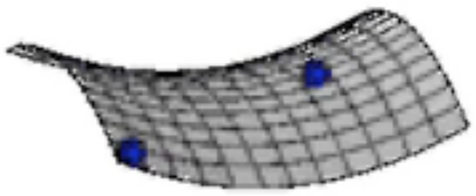




1970s & 80s
Inflation + Cold Dark Matter addition to Standard Model

Inflation

- Explains Uniformity of CMB
- Provides seeds of structure formation

Cold Dark Matter

- 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 - 1990

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

Different Ways of Looking at the Universe - 1990

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

(Theorists)

Inflation+CDM paradigm correct

$\Omega \sim 1$

H_0 <=50km/s/Mpc

Observers are wrong on H_0 and Ω_M

Different Ways of Looking at the Universe - 1990

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

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

Different Ways of Looking at the Universe - 1990

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

(Theorists)

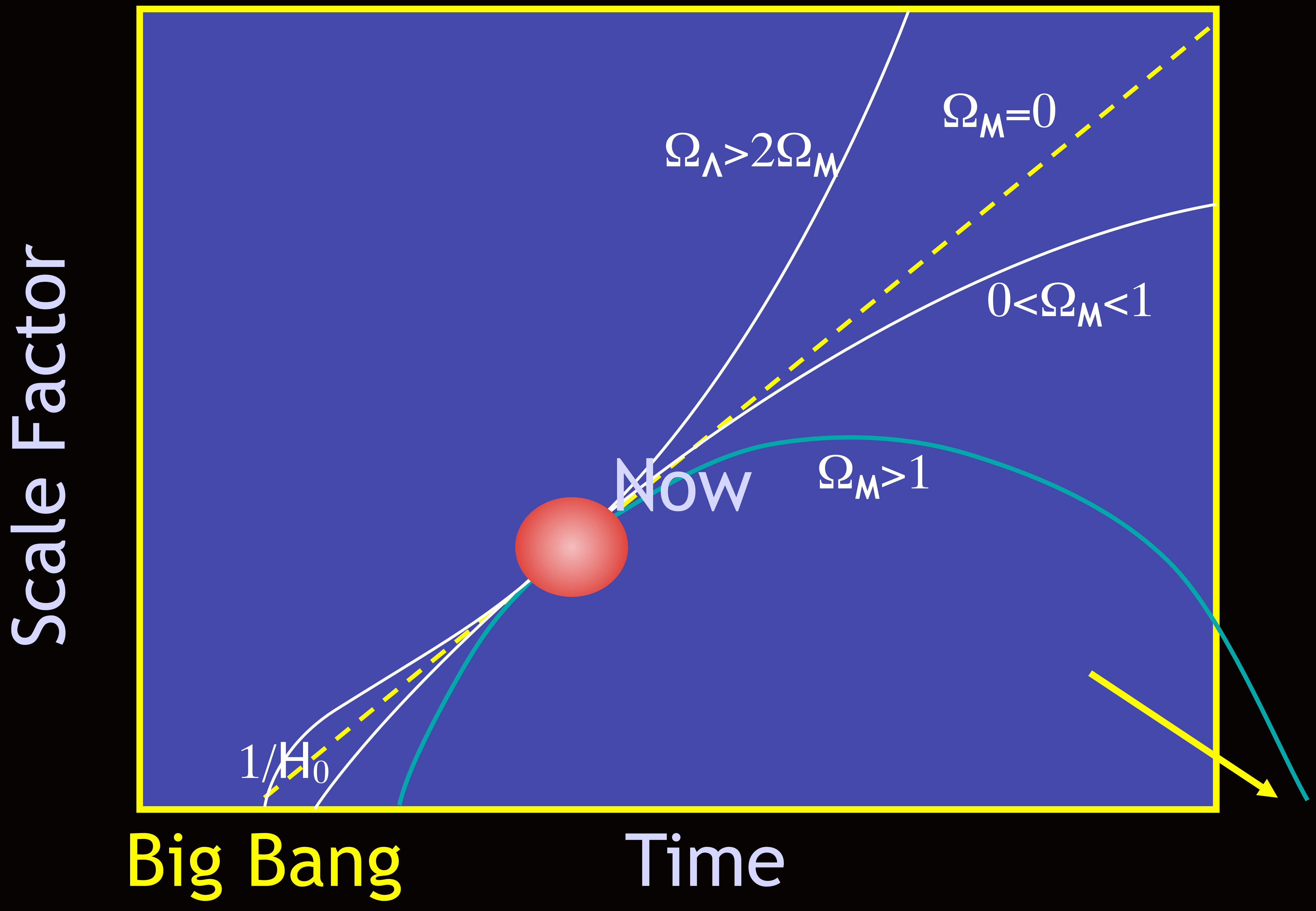
Inflation+CDM paradigm correct
$\Omega \sim 1$
H_0 <=50km/s/Mpc
Observers are wrong on H_0 and Ω_M

(Observers)

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

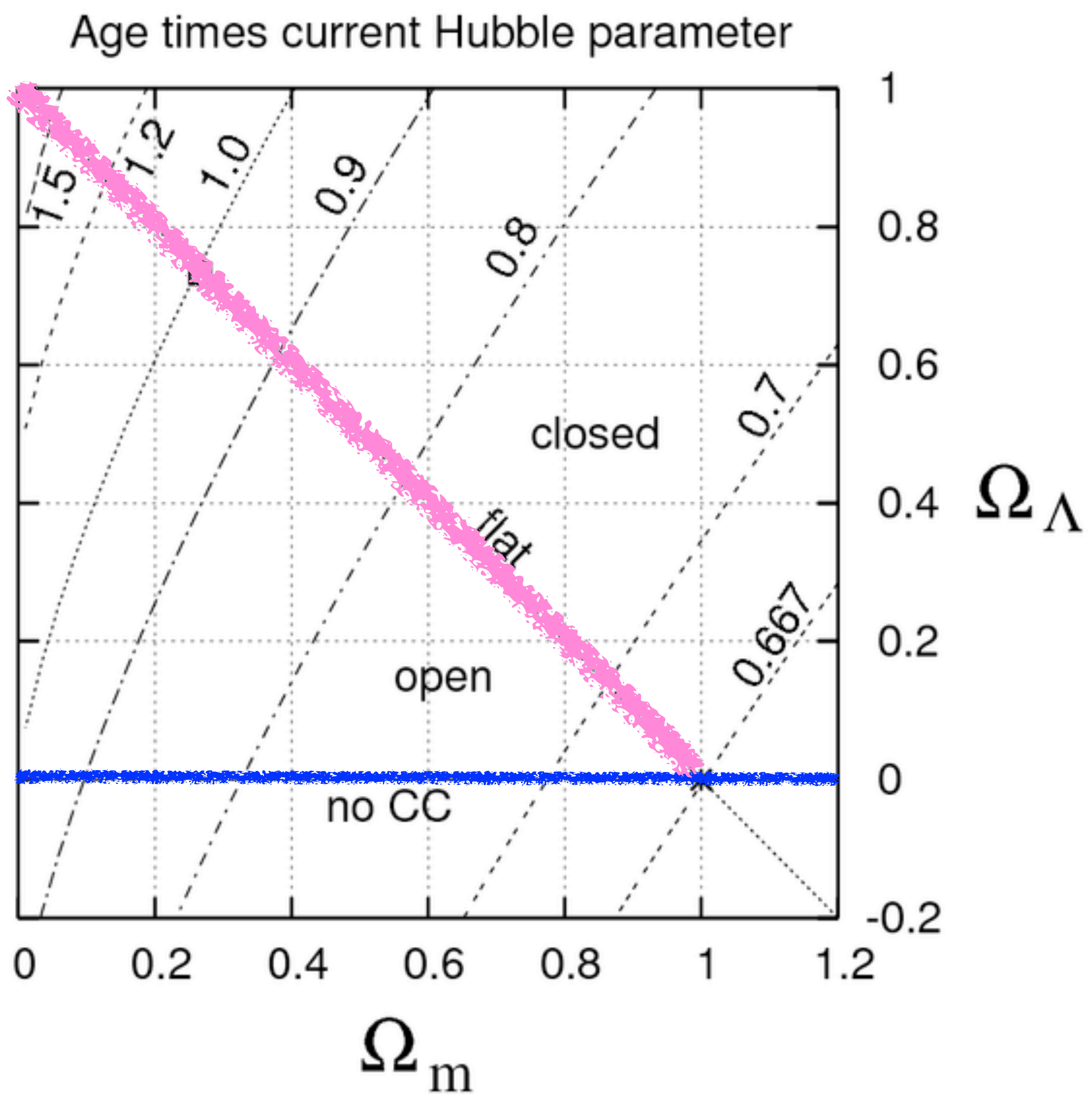
(People with Few Friends)

$\Omega_M \sim 0.2$ $\Omega_\Lambda \sim 0.8$
$H_0 \sim 70$ km/s/Mpc



Scale Factor
$\Omega_\Lambda > 2\Omega_M$
$\Omega_M = 0$
$0 < \Omega_M < 1$
$\Omega_M > 1$
Now
$1/H_0$
Big Bang
Time

Physics of interiors of oldest stars in Globular Clusters indicates ages of >12Gyr



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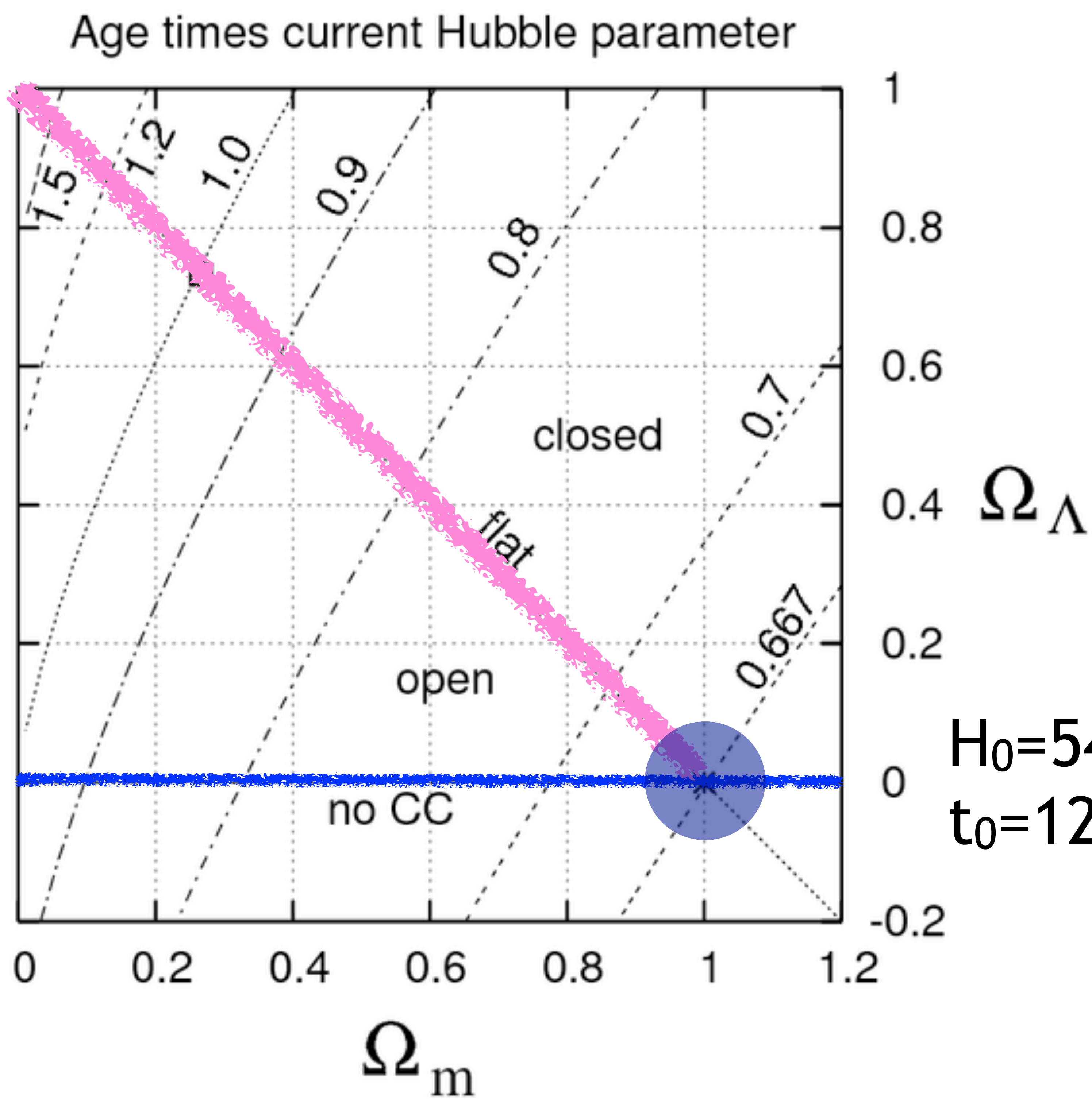
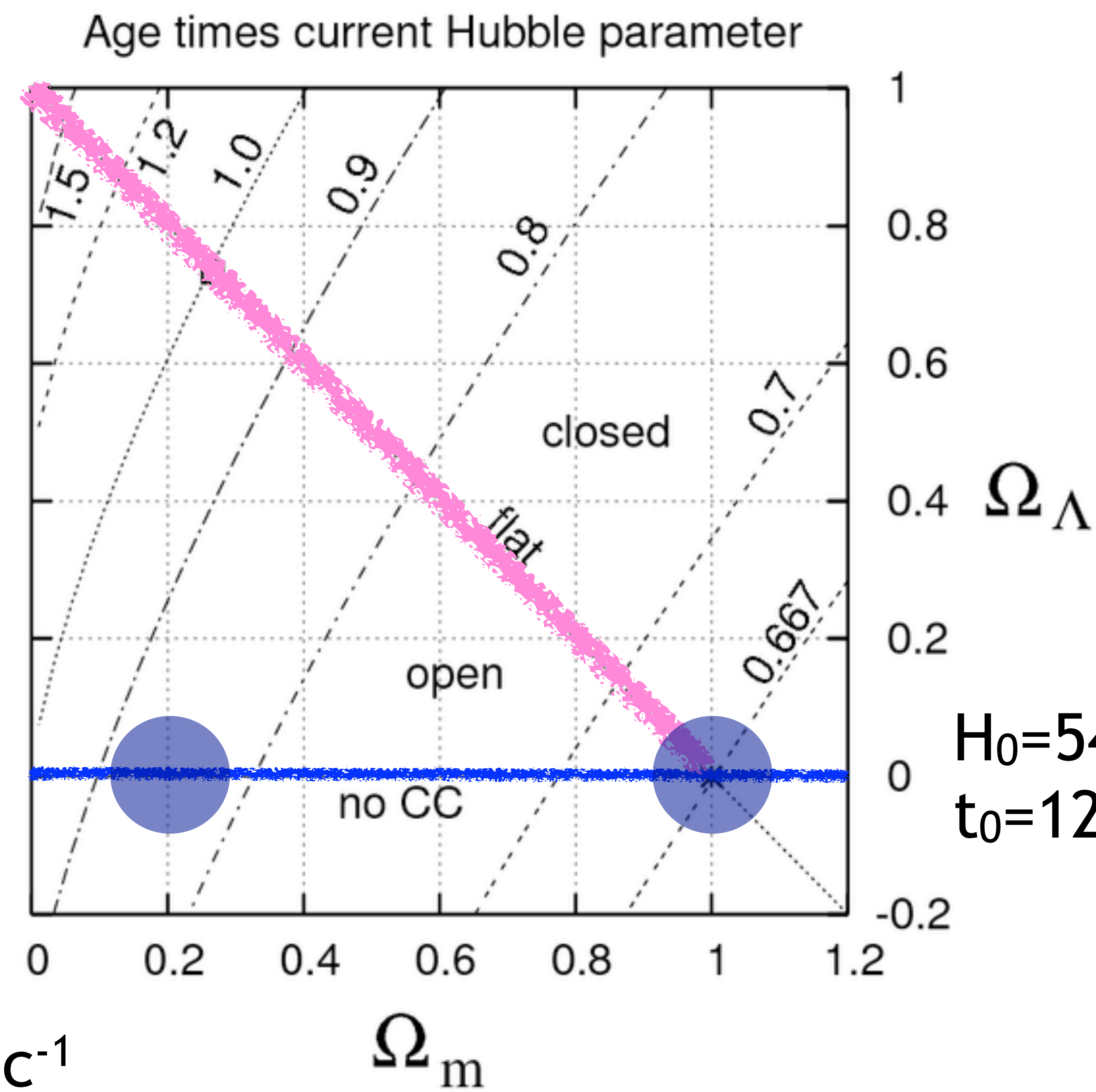


H_0=54 km s^{-1} Mpc^{-1}

t_0=12Gyr

Physics of interiors of oldest stars in Globular Clusters indicates ages of >12Gyr



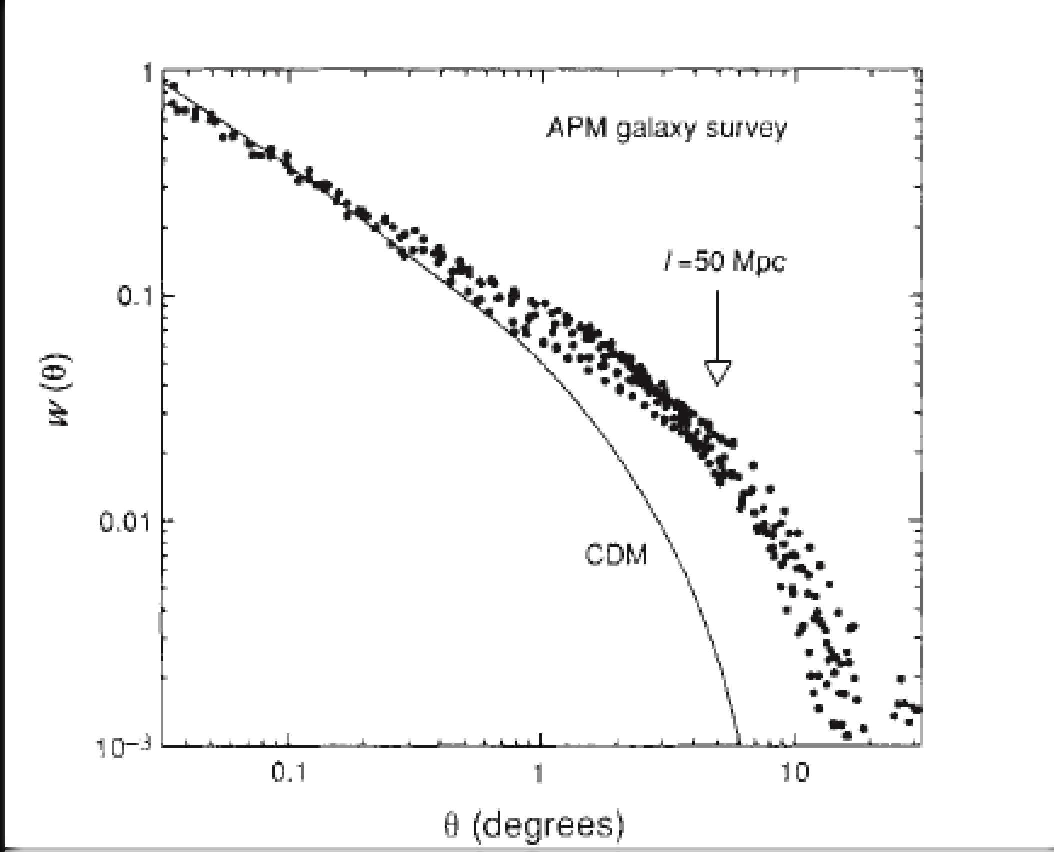
H_0=54 km s^{-1} Mpc^{-1}
t_0=12Gyr

H_0=70 km s^{-1} Mpc^{-1}
t_0=12Gyr

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



Some 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.

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Others took this approach

Others took this approach

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)

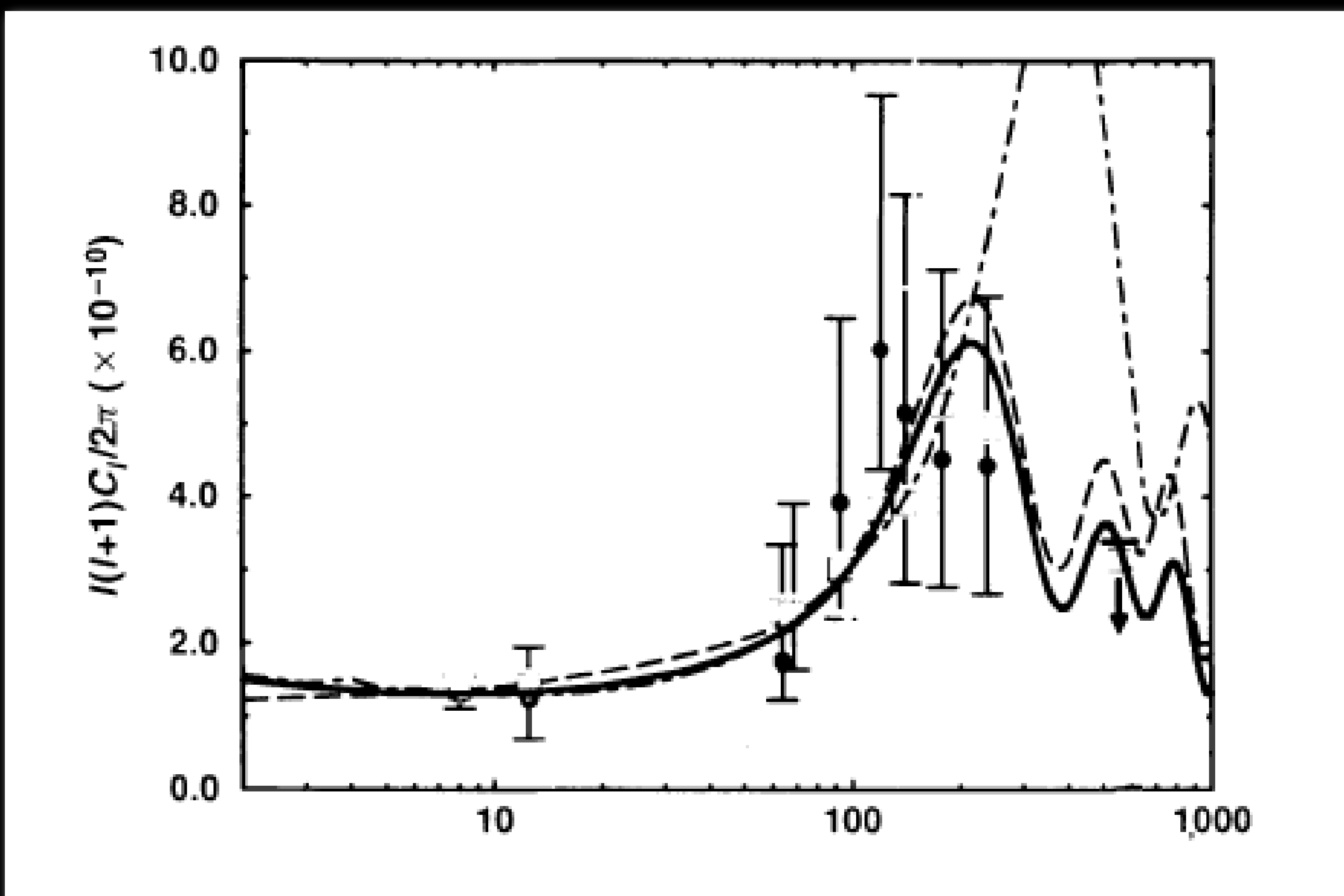
Abstract: A diverse set of observations now compellingly suggest that Universe possesses a nonzero cosmological constant. In the context of quantum-field theory a cosmological constant corresponds to the energy density of the vacuum, and the wanted value for the cosmological constant corresponds to a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

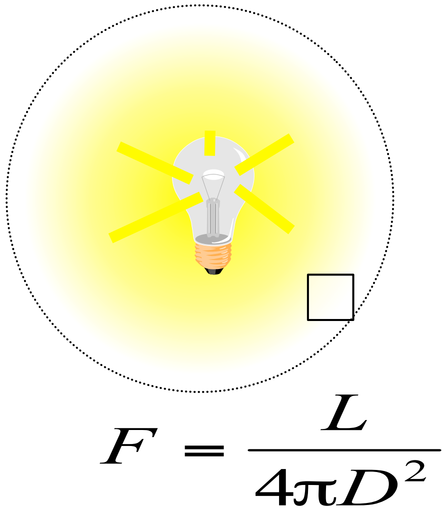


Used same CDM +inflation orthodoxy, but "measured" flatness from CMB.

Luminosity Distance

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

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



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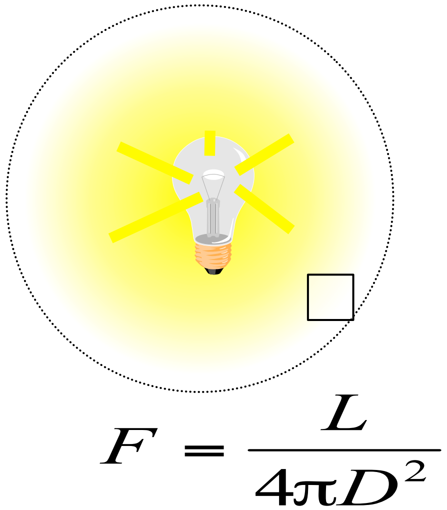

the flux an observer sees of an object at redshift z

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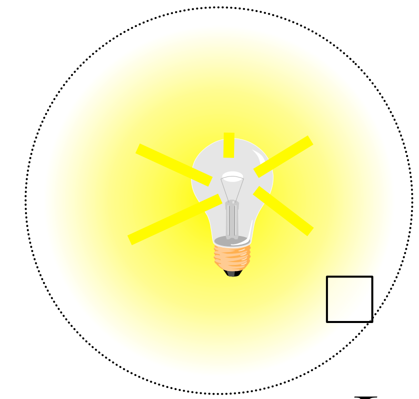

$$F = \frac{L}{4\pi D^2}$$

the flux an observer sees of an object at redshift z

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

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

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

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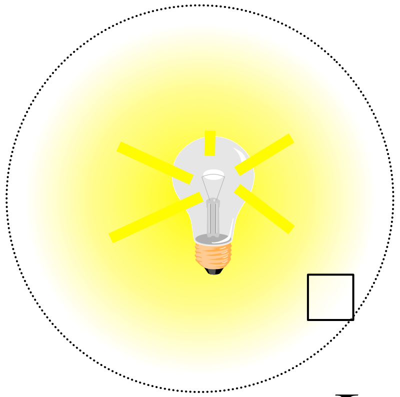

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Brightness of object depends exclusively on what is in the Universe - How much and its equation of state.

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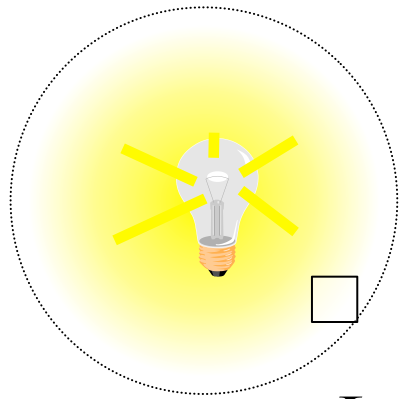

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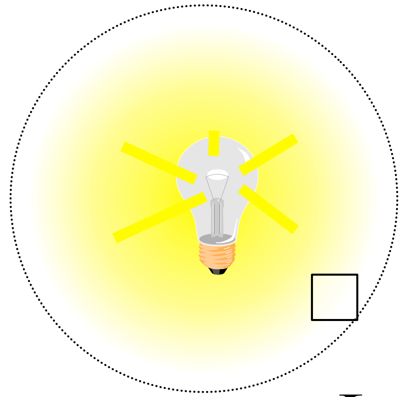

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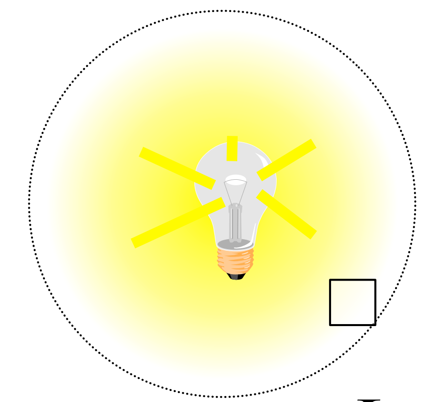

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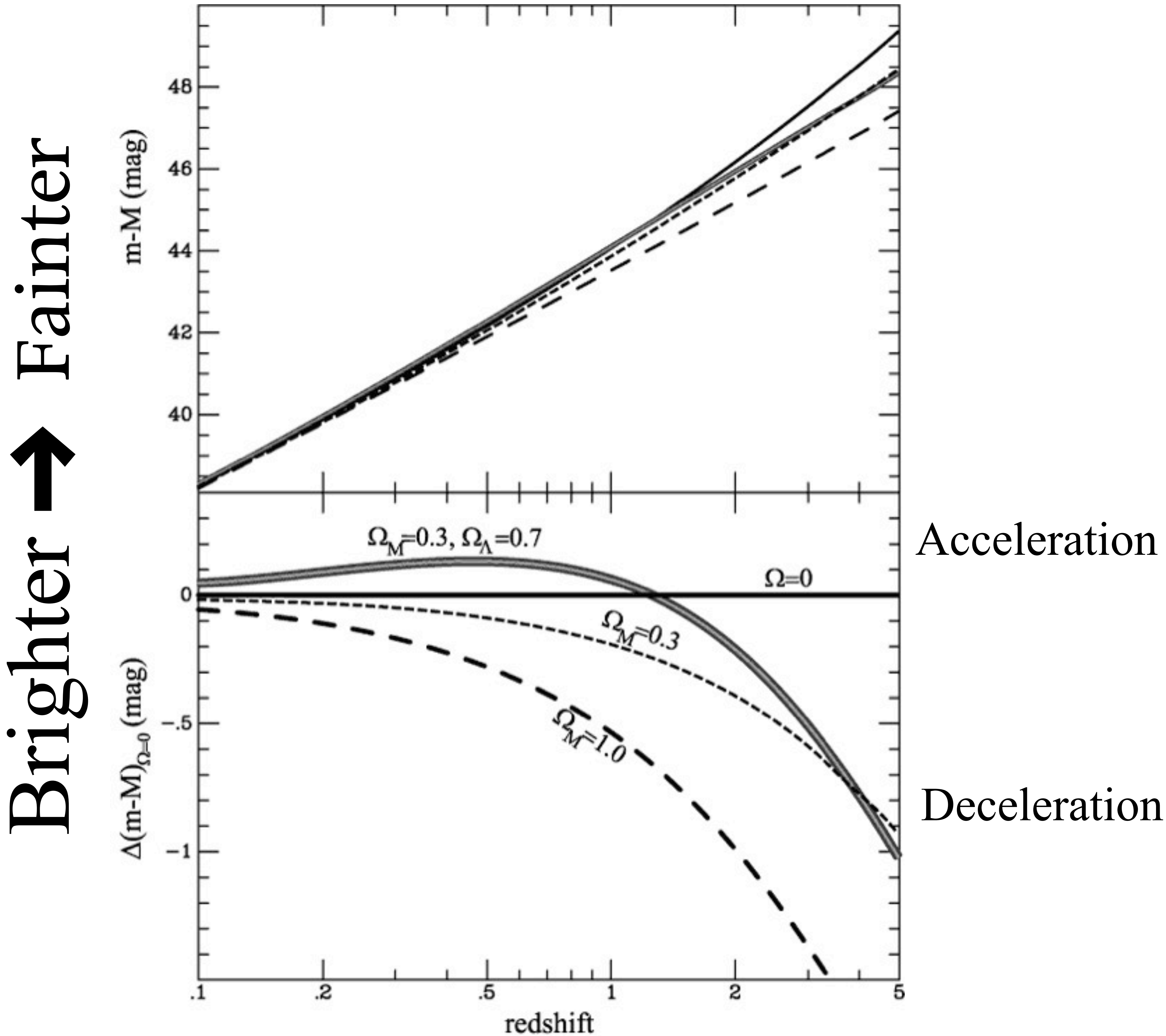

Brighter → Fainter
m-M (mag)
48
46
44
42
40
Ω_M=0.3, Ω_Λ=0.7
Ω=0
Ω_M=0.3
Ω_M=1.0
0
-.5
−1
Δ(m-M)$_{\Omega=0}$ (mag)
.1
.2
.5
1
2
5
redshift
Acceleration
Deceleration

Type Ia Supernovae

First use of Supernovae to Measure Distances

Fritz Zwicky

18in Schmidt Telescope

Charlie Kowal 1968

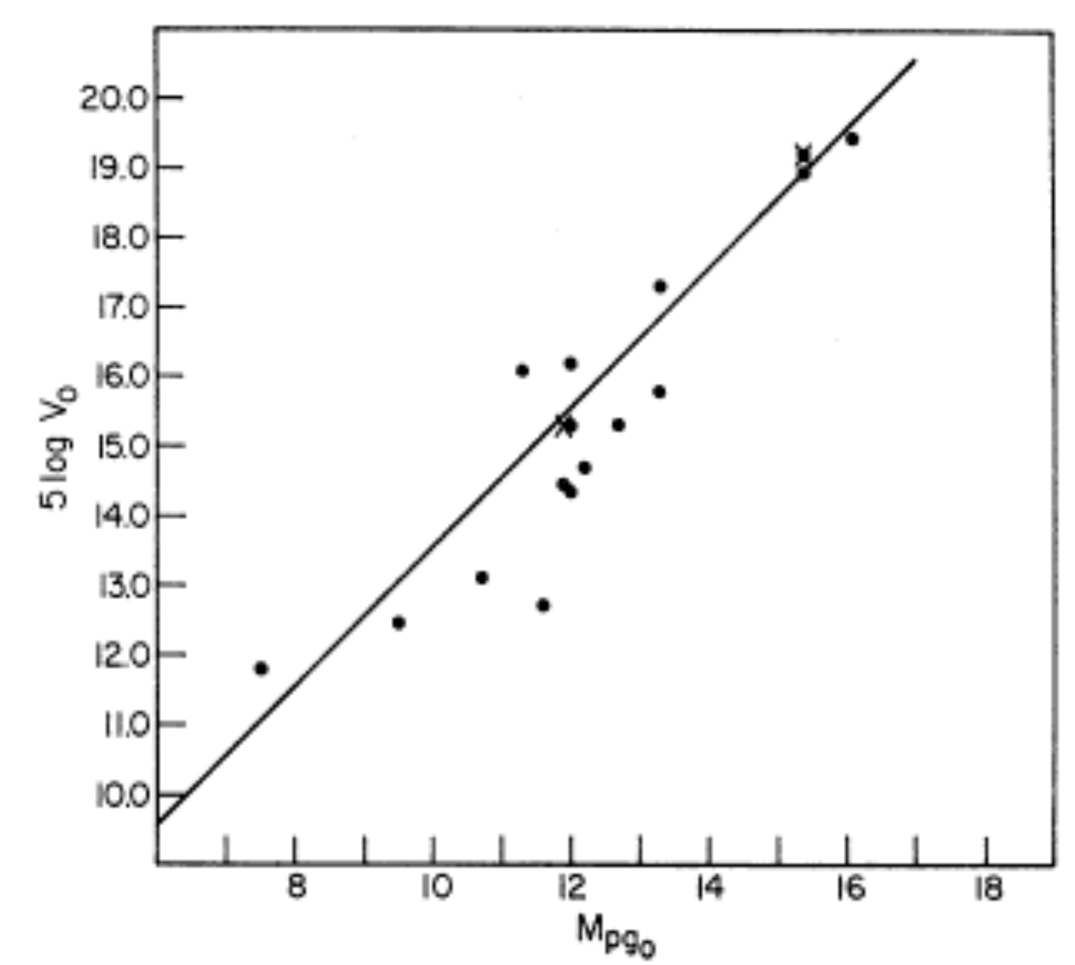

FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

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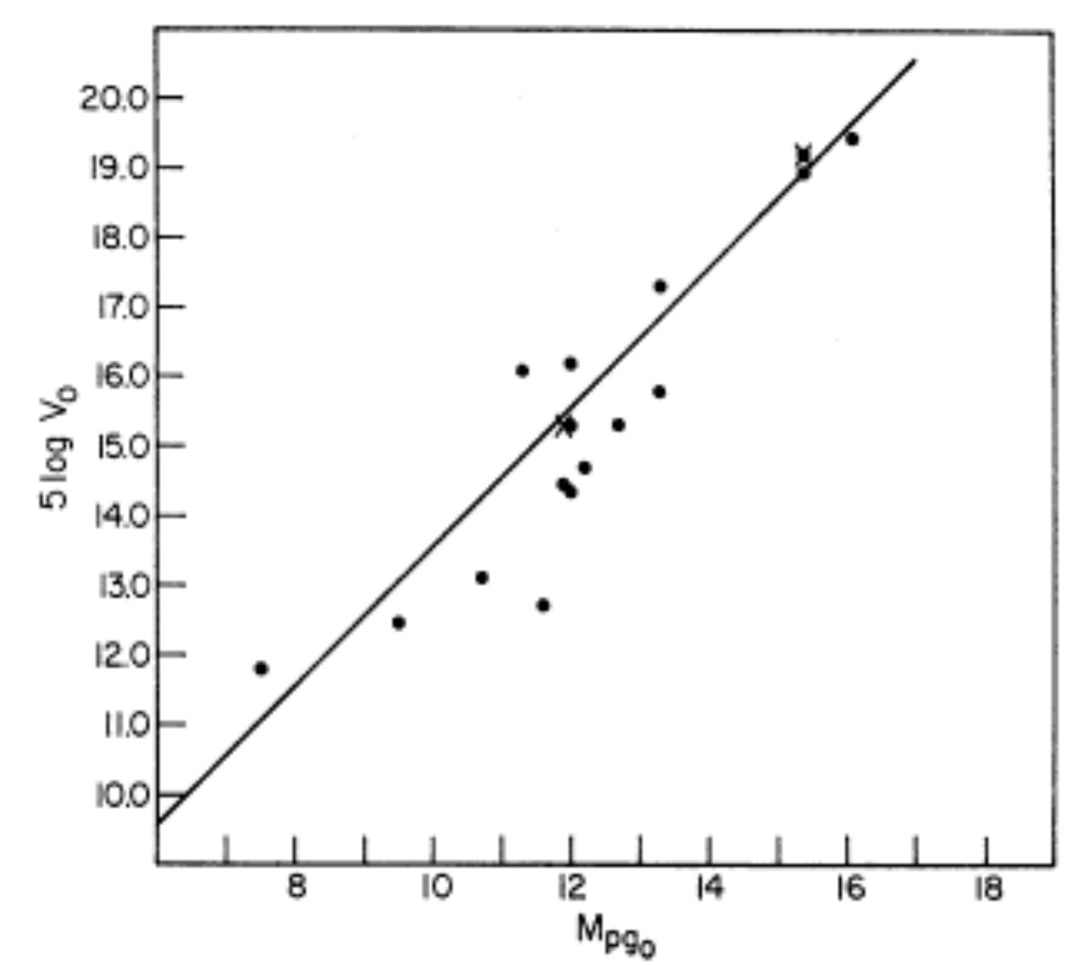

FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

First Distant SN detected in 1988 by Danish Team

0 days

Calan-Tololo SN Search

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!

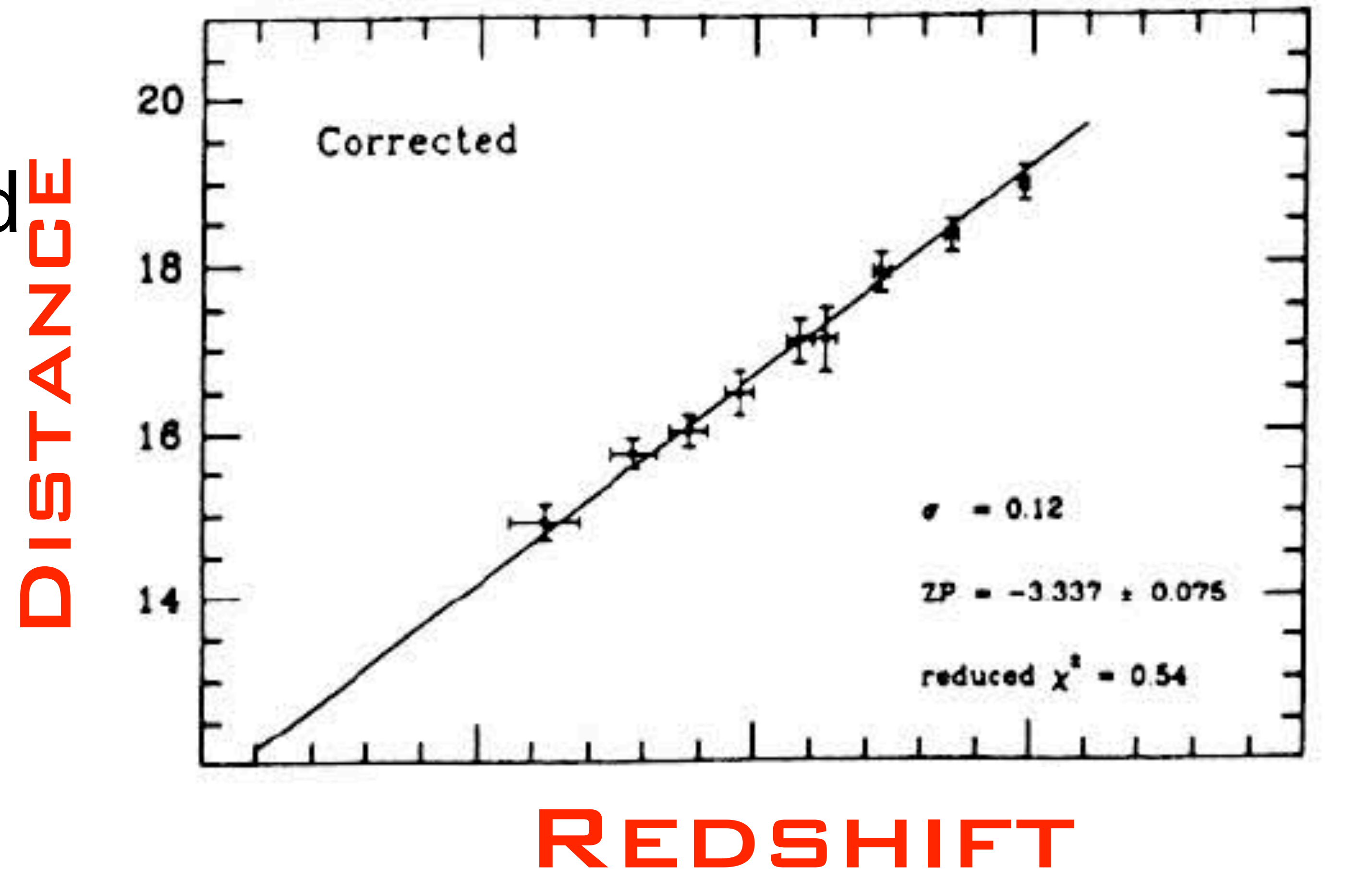

Figure 1: Hubble diagram of SNe Ia in the Calán/Tololo SN survey.

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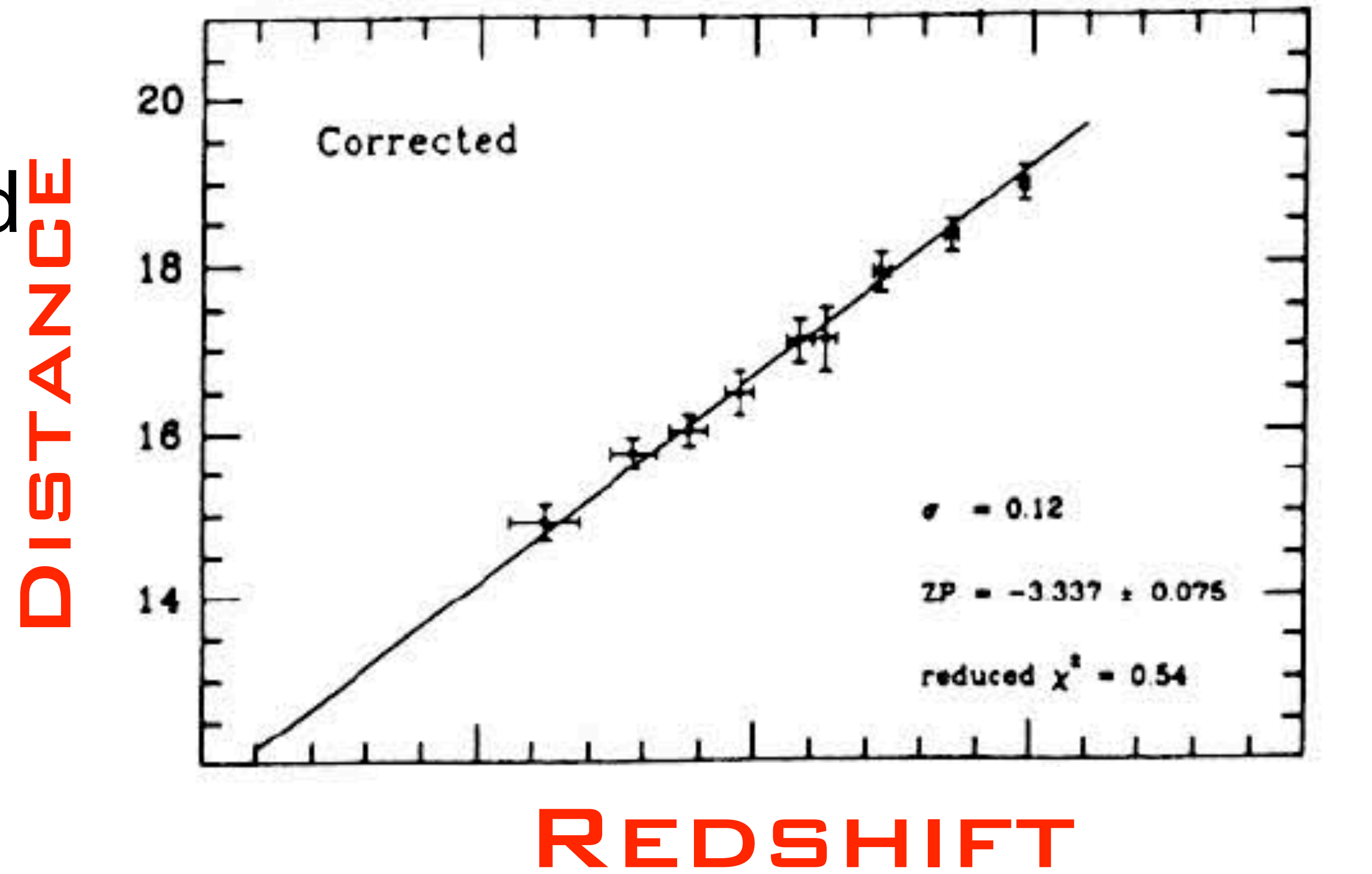


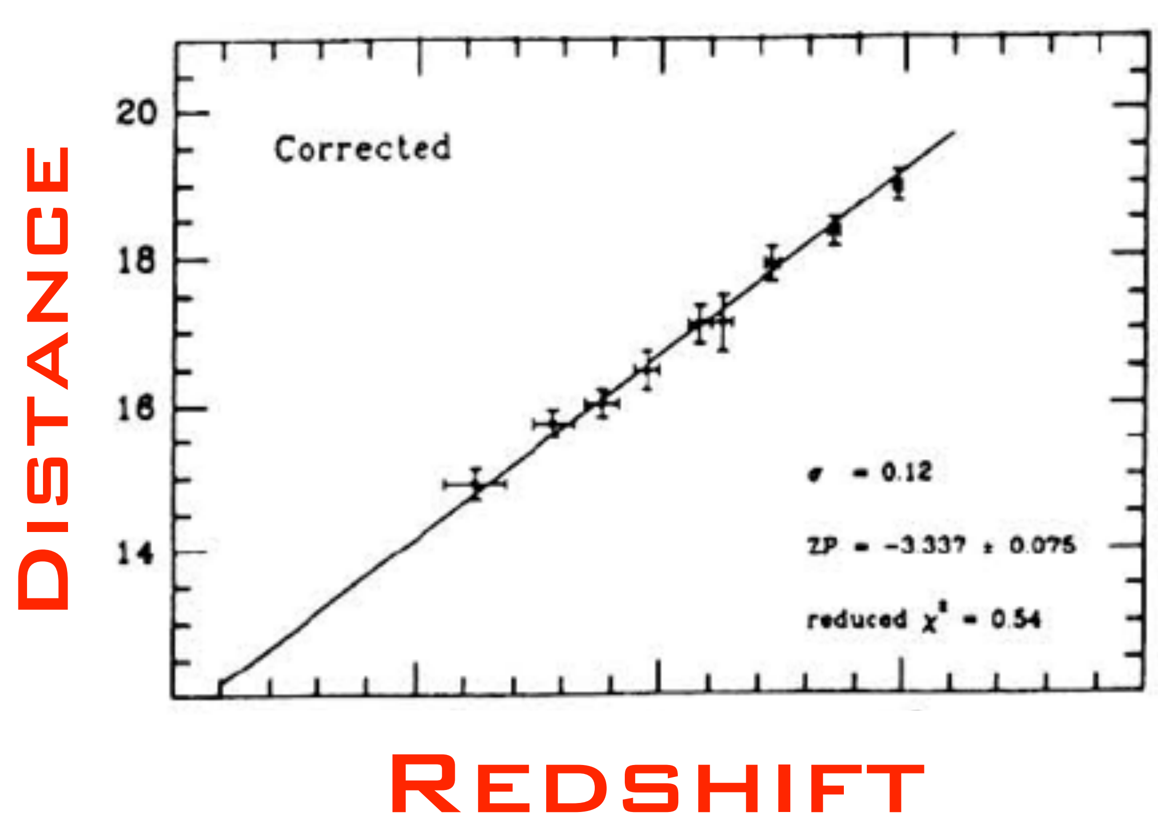
Figure 1: Hubble diagram of SNe Ia in the Calán/Tololo SN survey.

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 breakthoughs



Figur... survey.

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:*

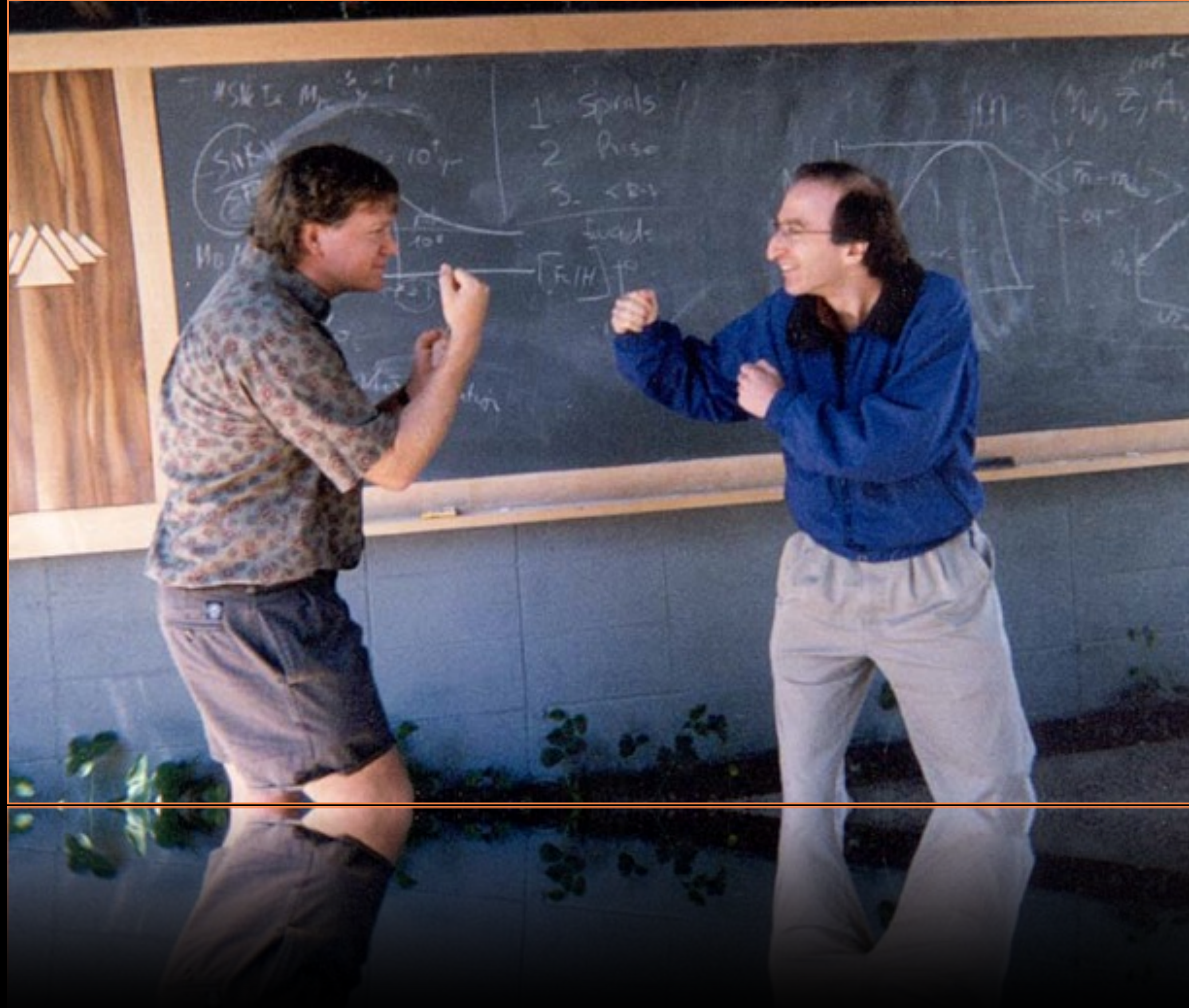
TITLE: A Pilot Project to Search for Distant Type Ia Supernovae

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)

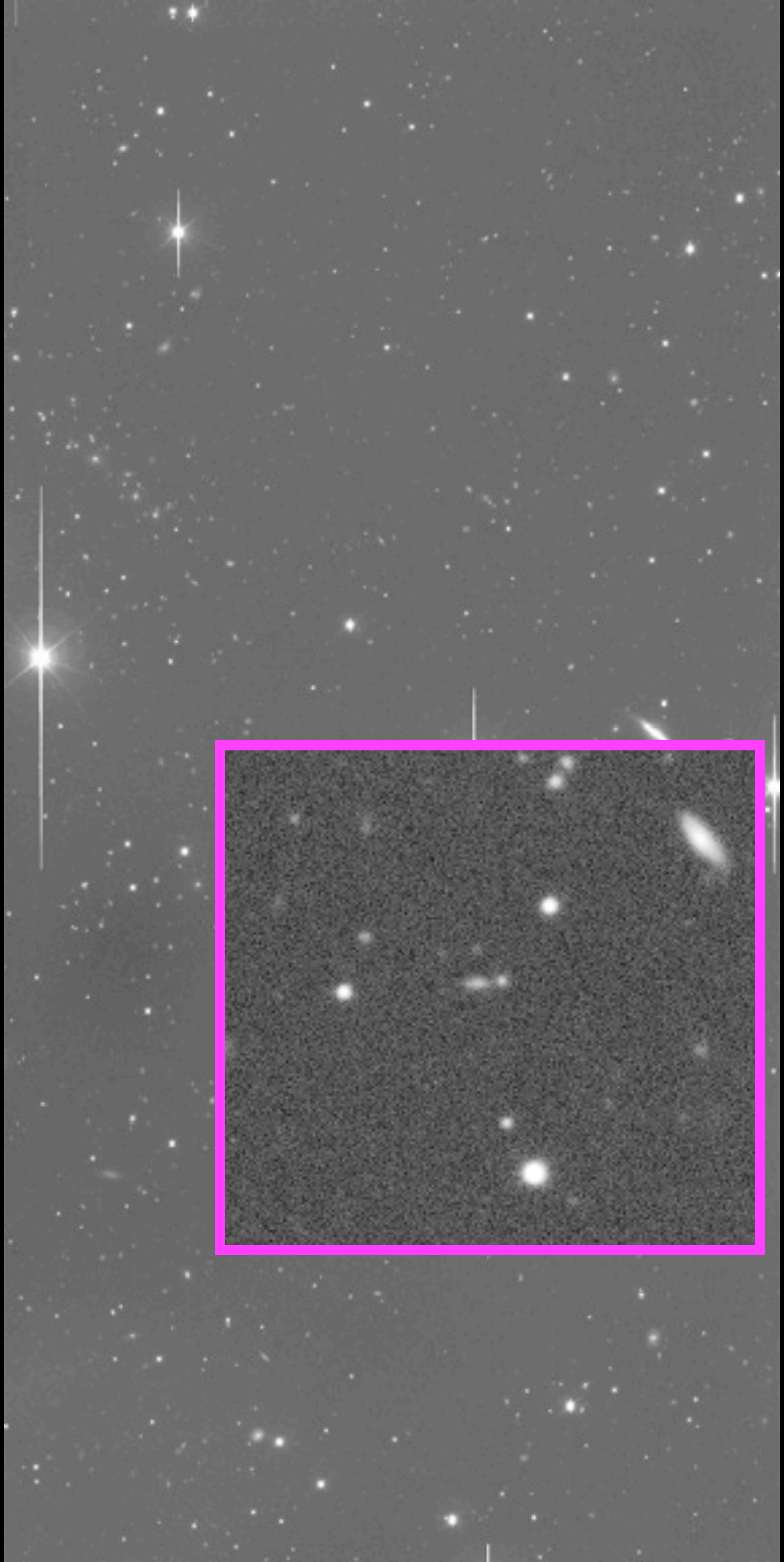
Abstract of Scientific Justification:

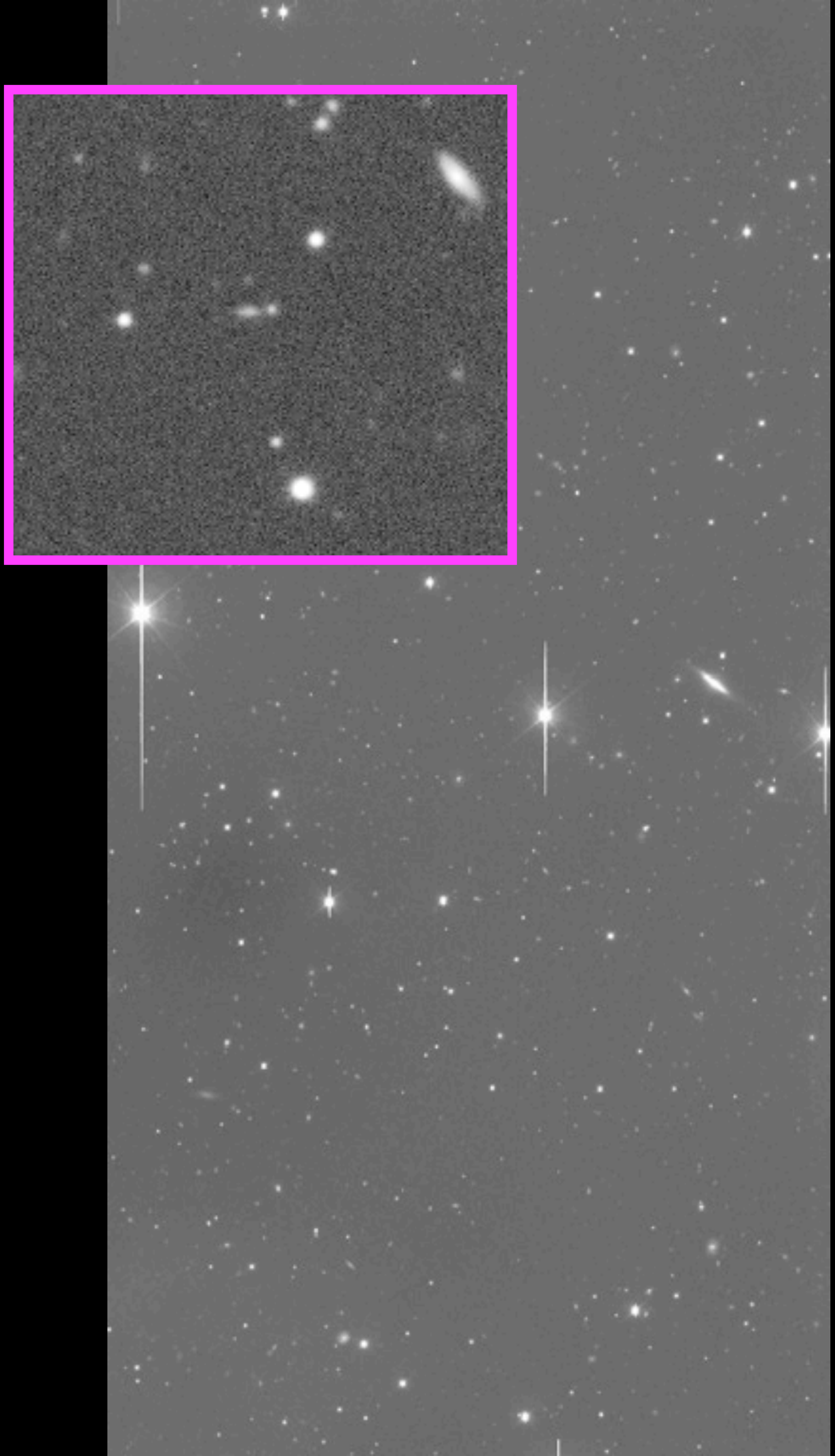
We propose to initiate a search for Type Ia supernovae at redshifts to $z \sim 0.3 - 0.5$ in equatorial fields using the CTIO 4m telescope. This program is the next step in the Calán/Tololo SN survey, where we have found ~ 30 Type Ia supernovae out to $z \sim 0.1$. The proposed program is a pilot project 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.

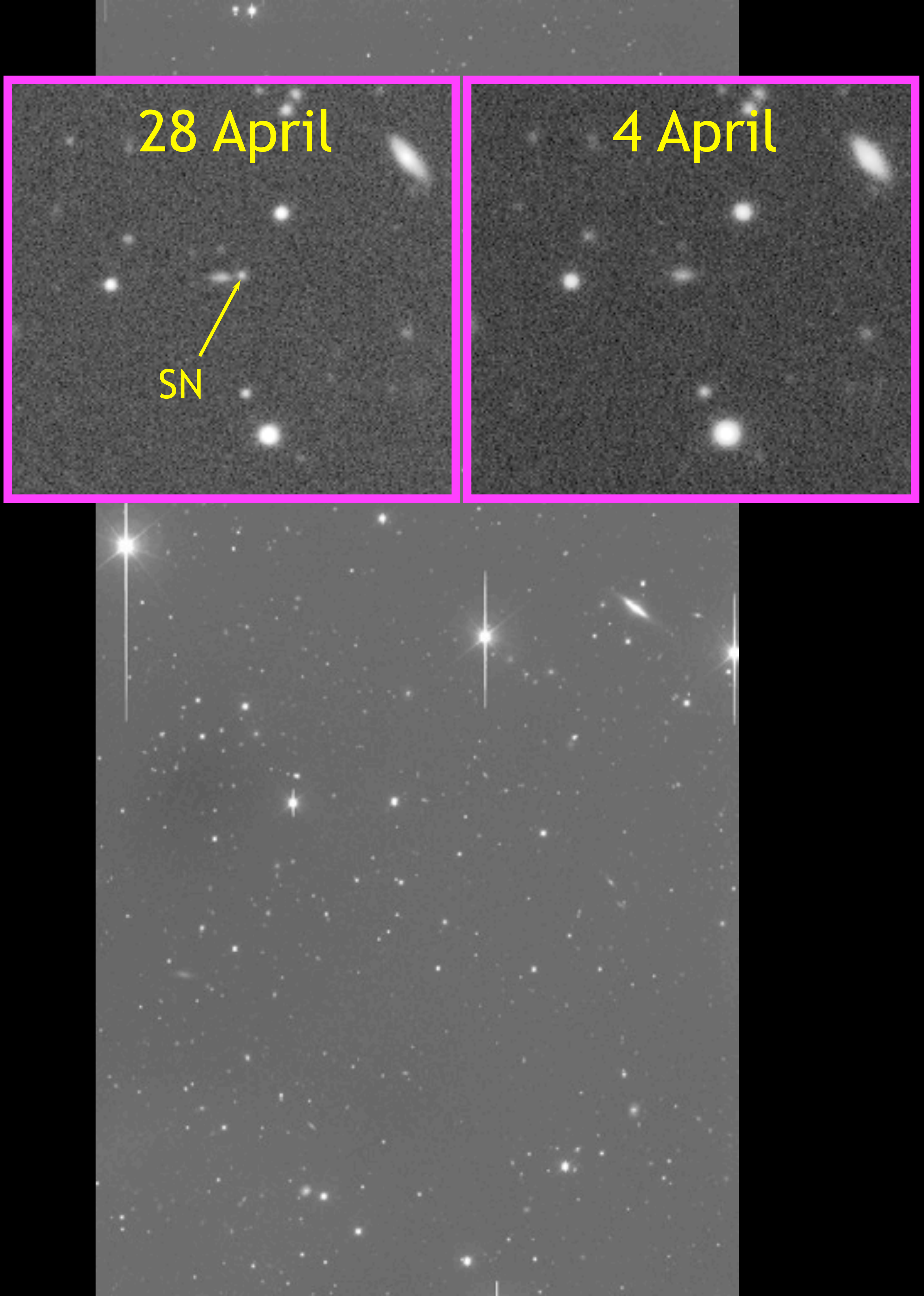

1 Spirals
2 Rise

The High-Z Team

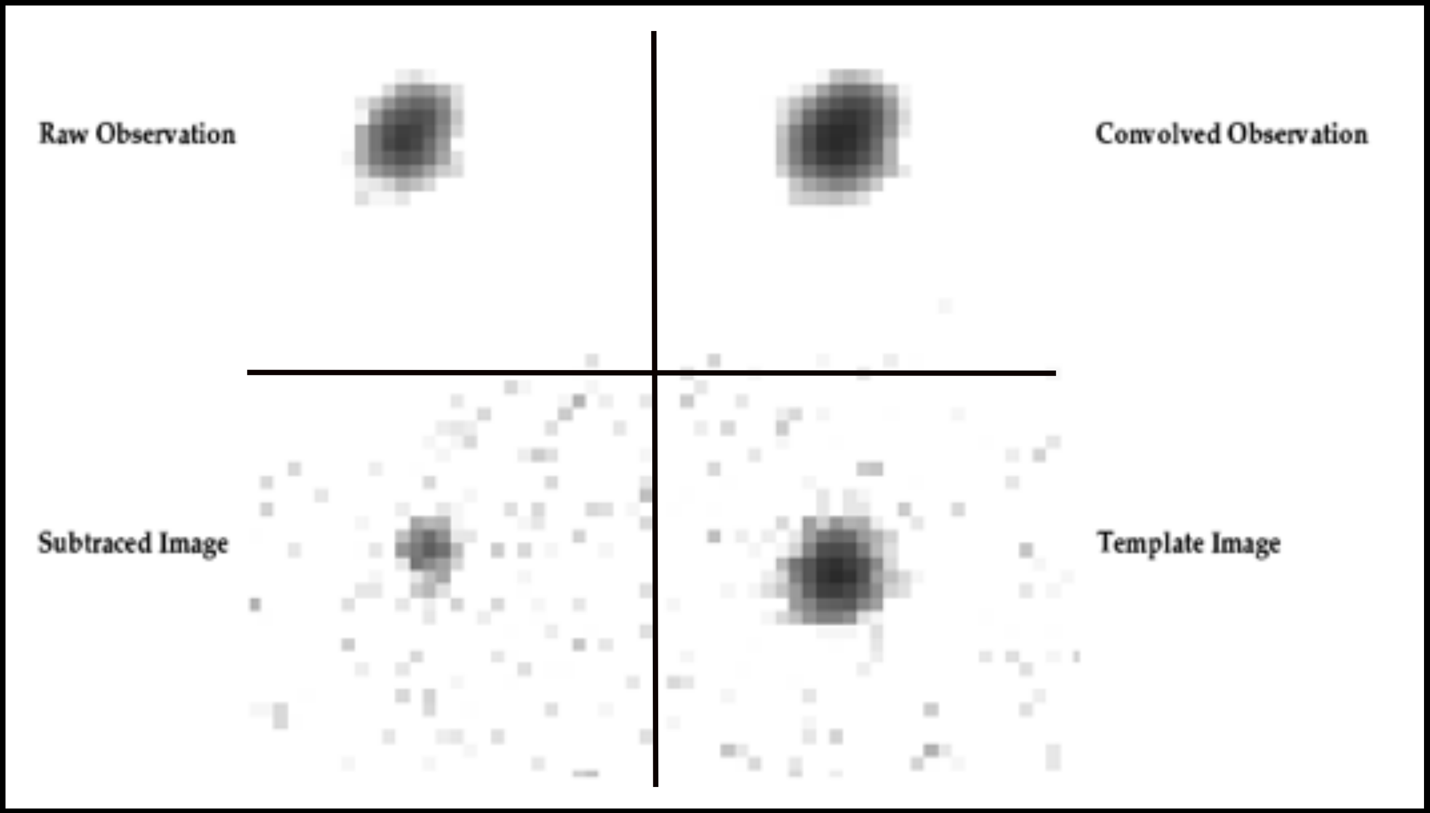
The Supernova Cosmology Project





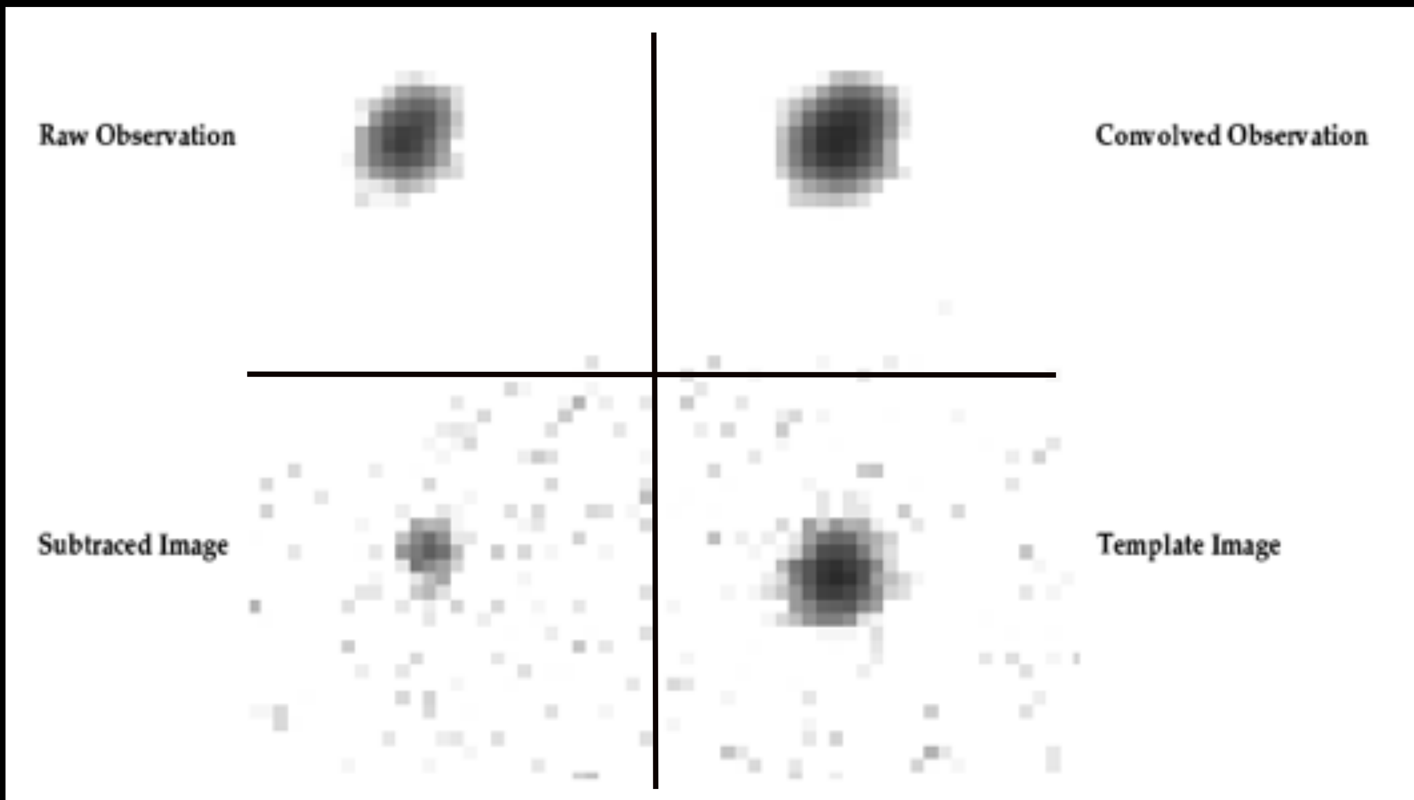


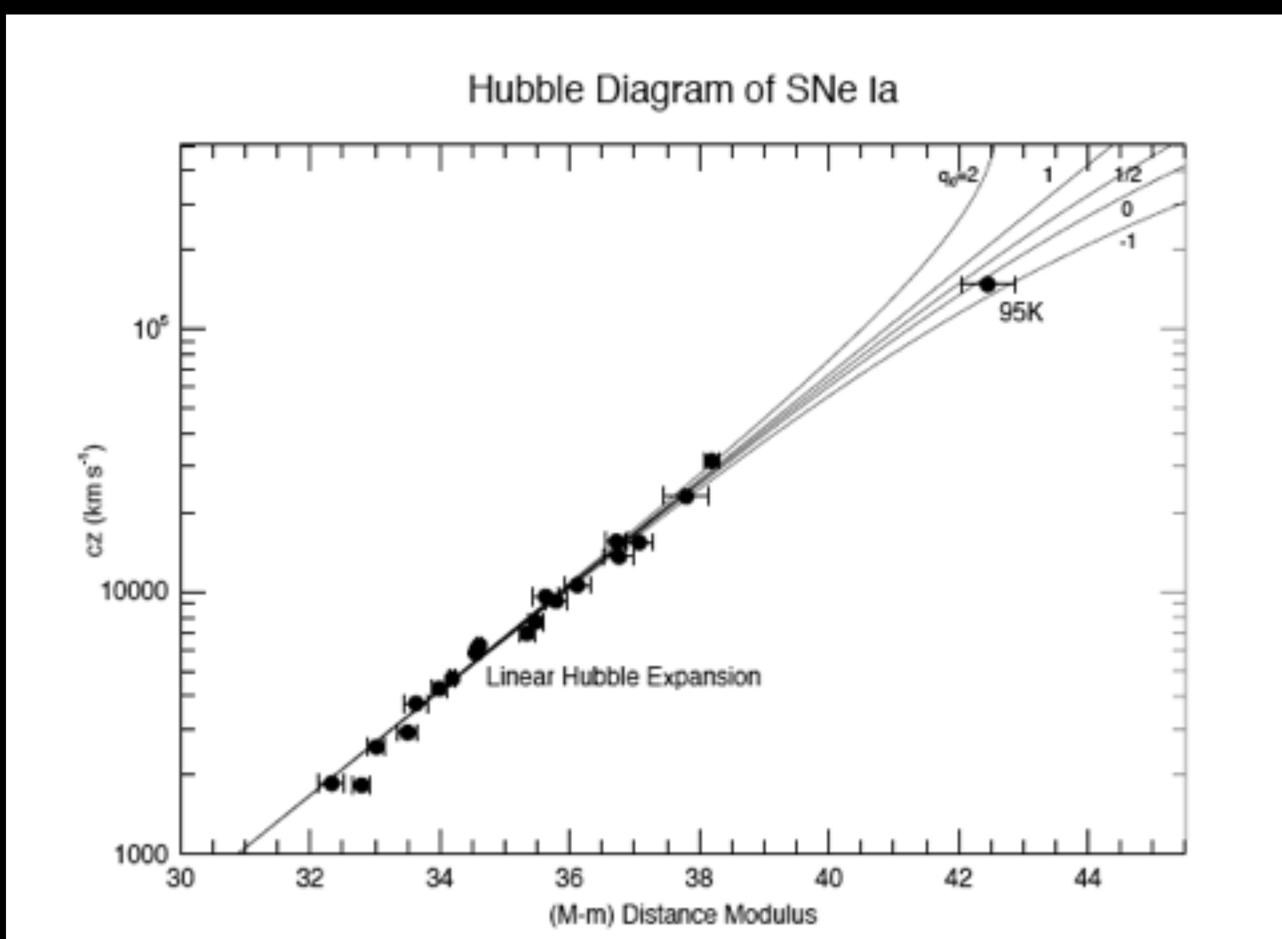
28 April
SN
4 April

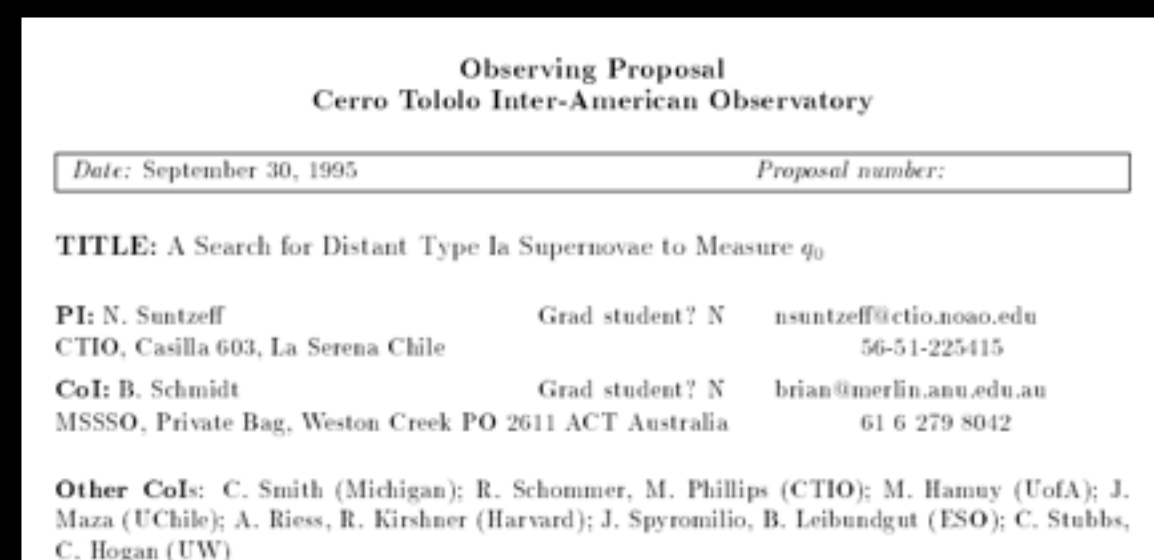


Our First Supernova SN 1995K

Our First Supernova
SN 1995K







Observing Proposal
Cerro Tololo Inter-American Observatory

Date: September 30, 1995	*Proposal number:*

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

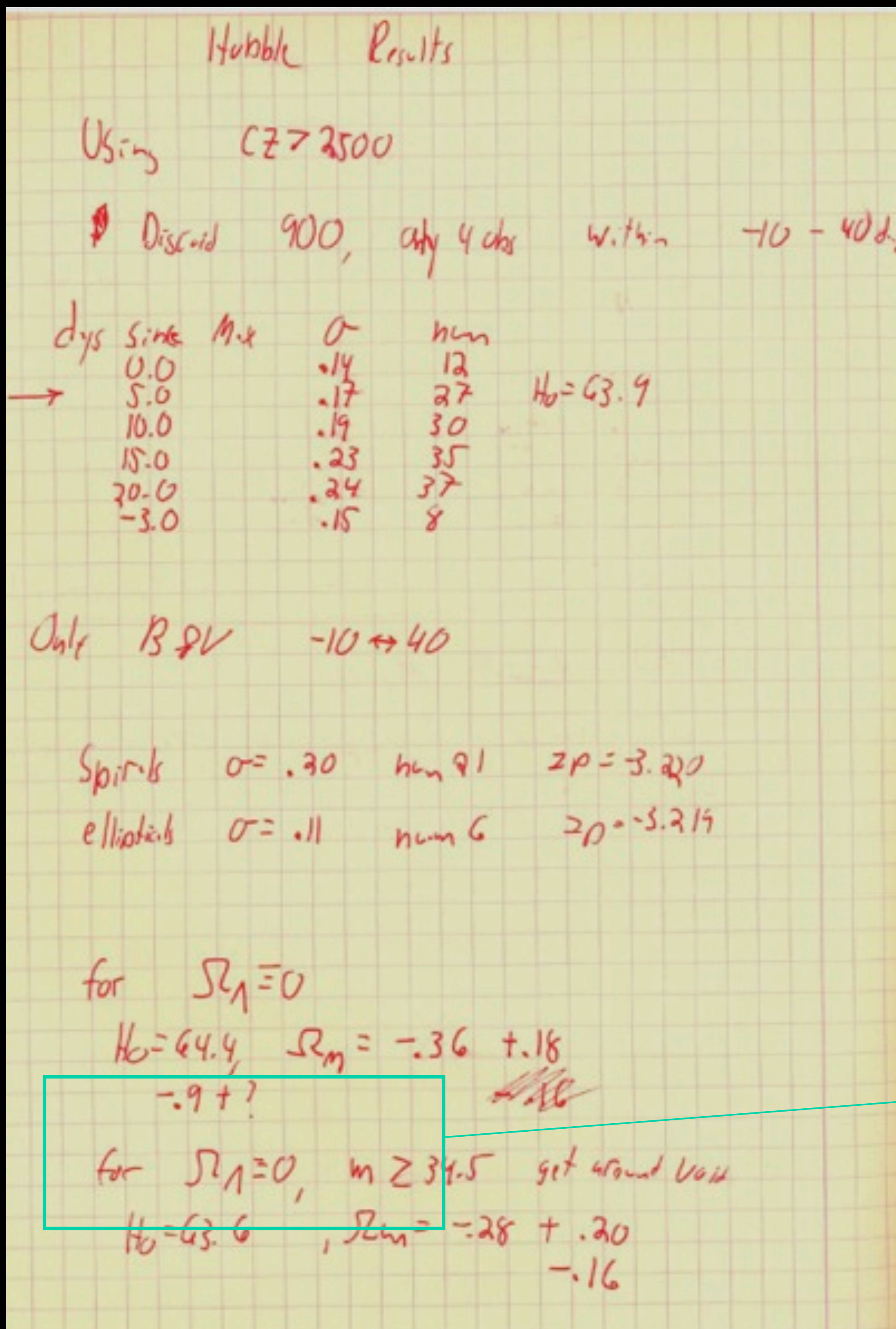
PI: N. Suntzeff — Grad student? N — nsuntzeff@ctio.noao.edu
CTIO, Casilla 603, La Serena Chile — 56-51-225415

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

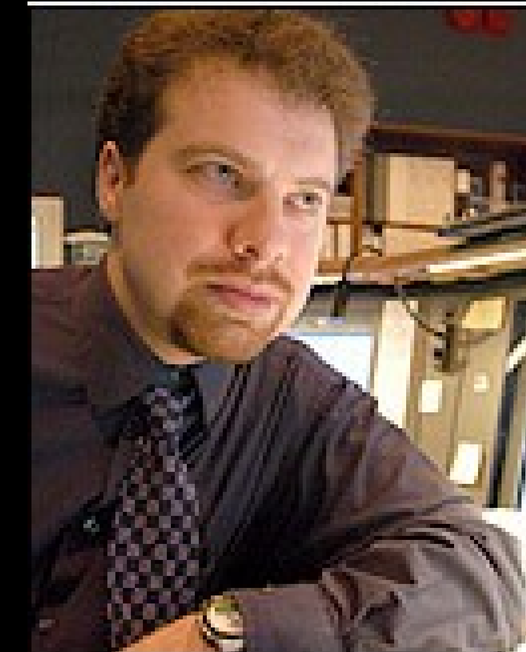
Other CoIs: C. Smith (Michigan); R. Schommer, M. Phillips (CTIO); M. Hamuy (UofA); J. Maza (UChile); A. Riess, R. Kirshner (Harvard); J. Spyromilio, B. Leibundgut (ESO); C. Stubbs, C. Hogan (UW)

EUREKA?

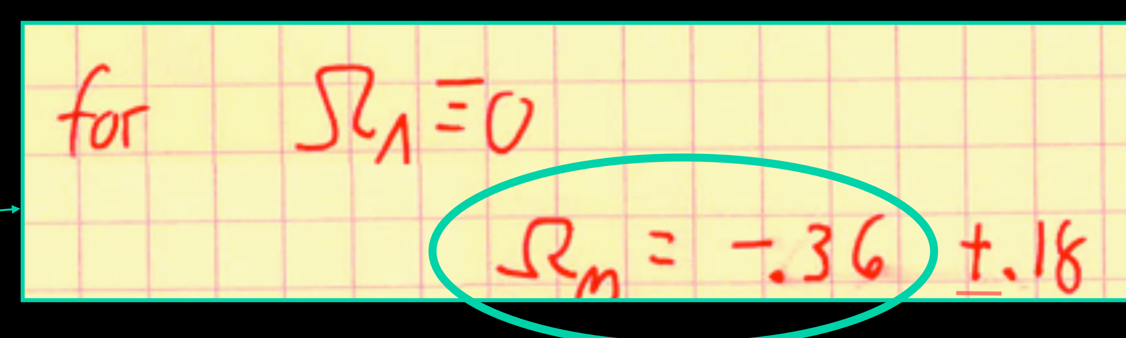
Adam's Lab book, Key Page, Fall 1997:

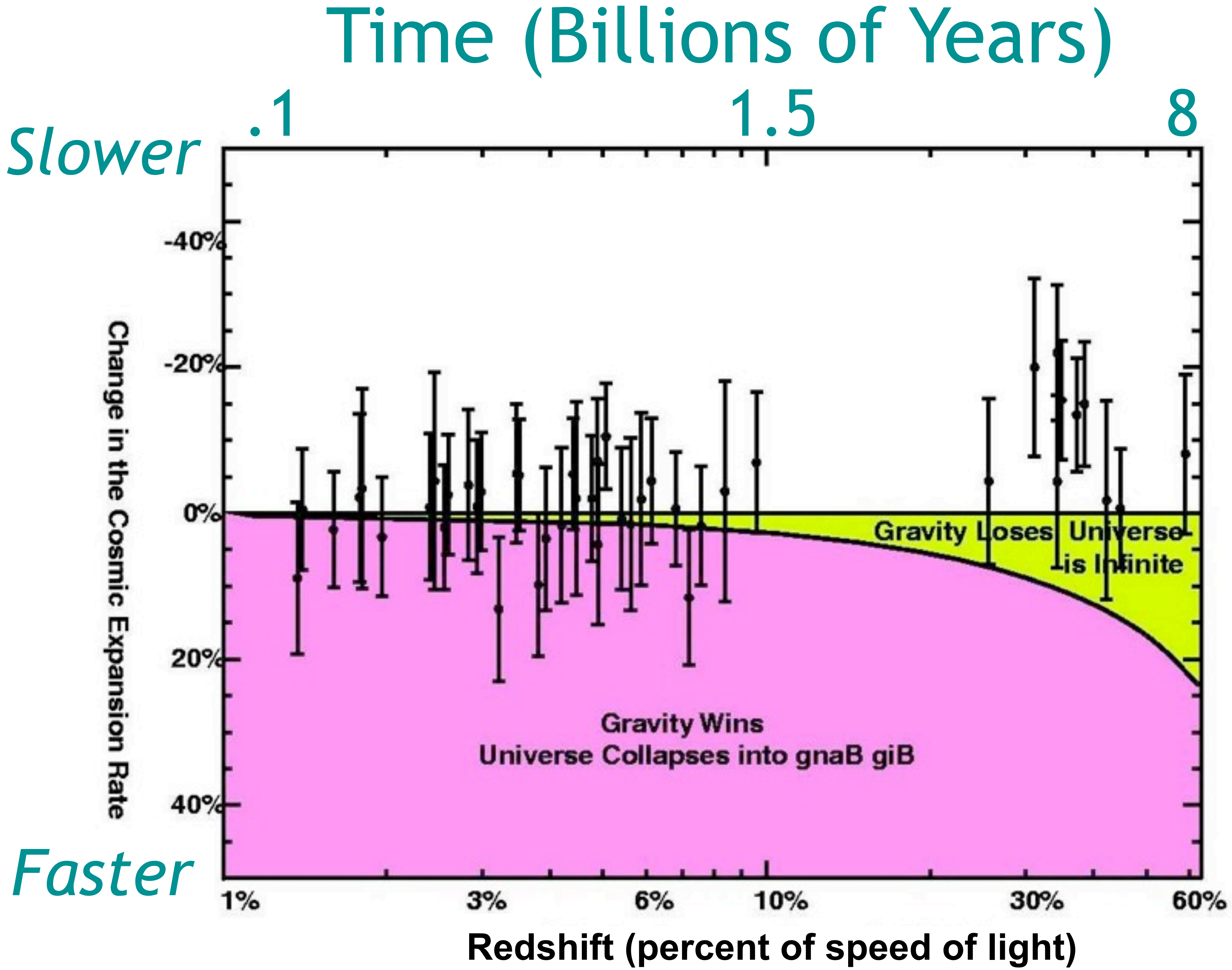


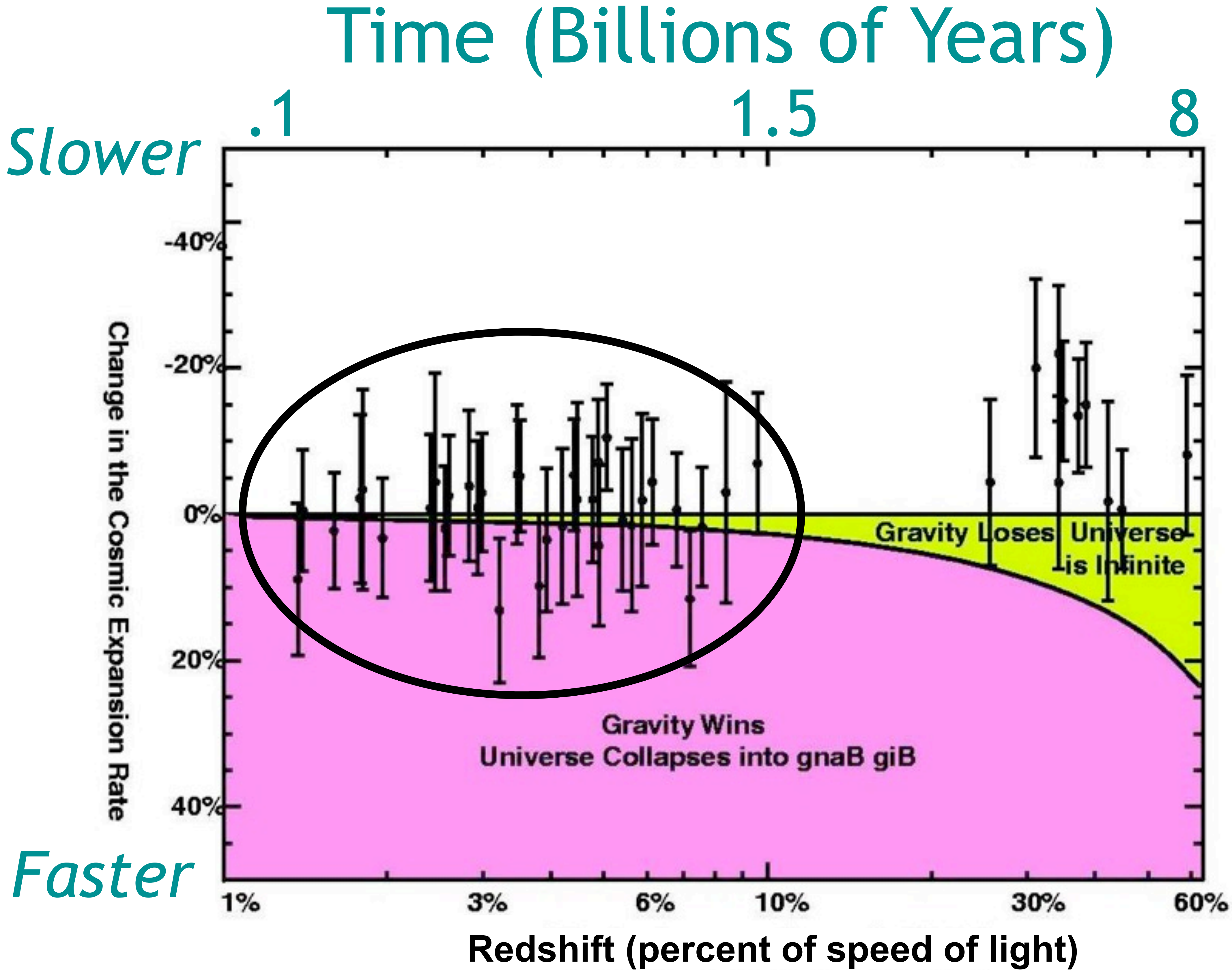
Adam Riess was leading our efforts in the fall of 1997 to increase our sample of 4 objects to 15.



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




Time (Billions of Years)
.1
1.5
8
Slower
Faster
-40%
-20%
0%
20%
40%
Change in the Cosmic Expansion Rate
Gravity Loses Universe
is Infinite
Gravity Wins
Universe Collapses into gnaB giB
1%
3%
6%
10%
30%
60%
Redshift (percent of speed of light)



Time (Billions of Years)
.1
1.5
8
Slower
Faster
-40%
-20%
0%
20%
40%
Change in the Cosmic Expansion Rate
Gravity Loses Universe is Infinite
Gravity Wins
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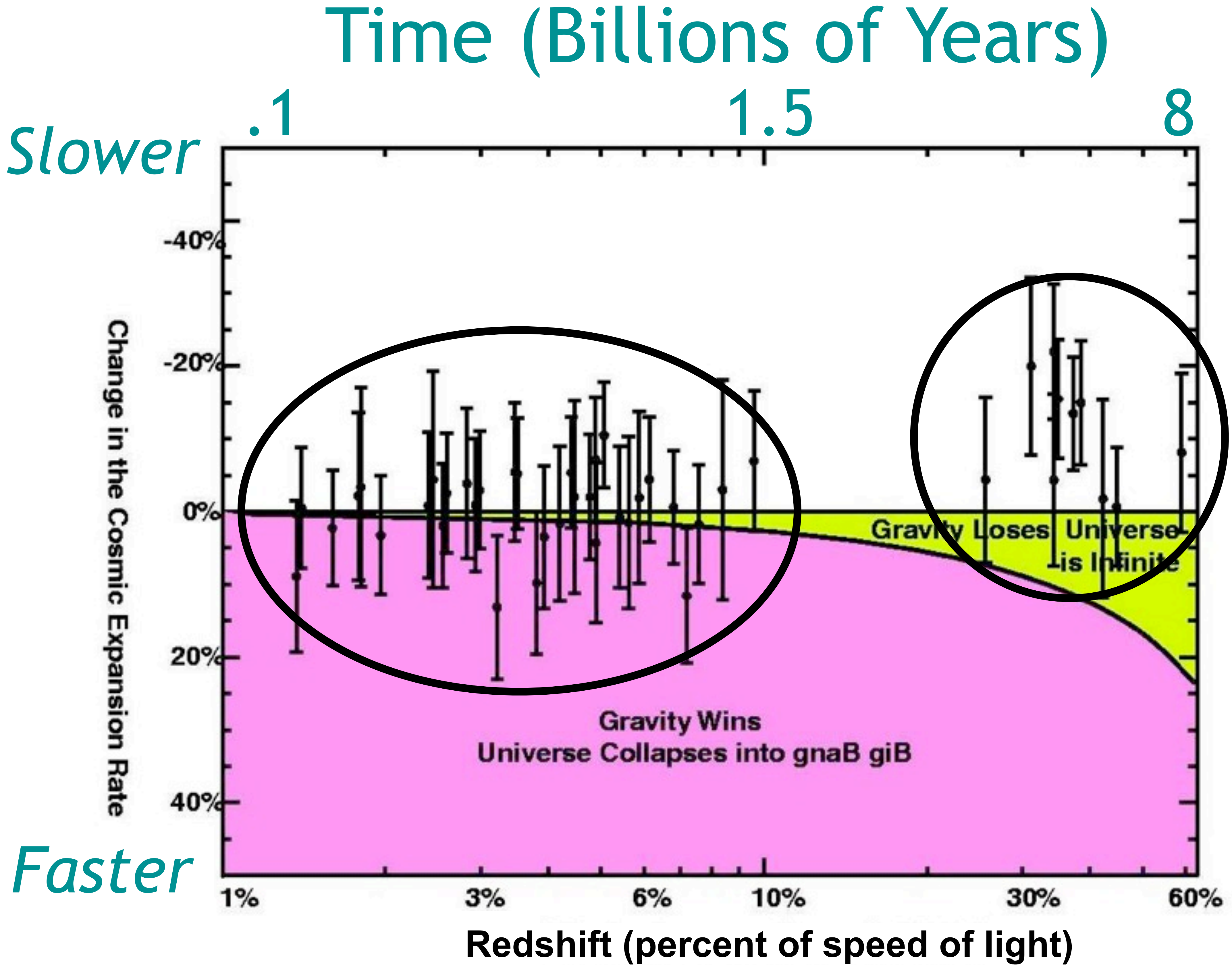
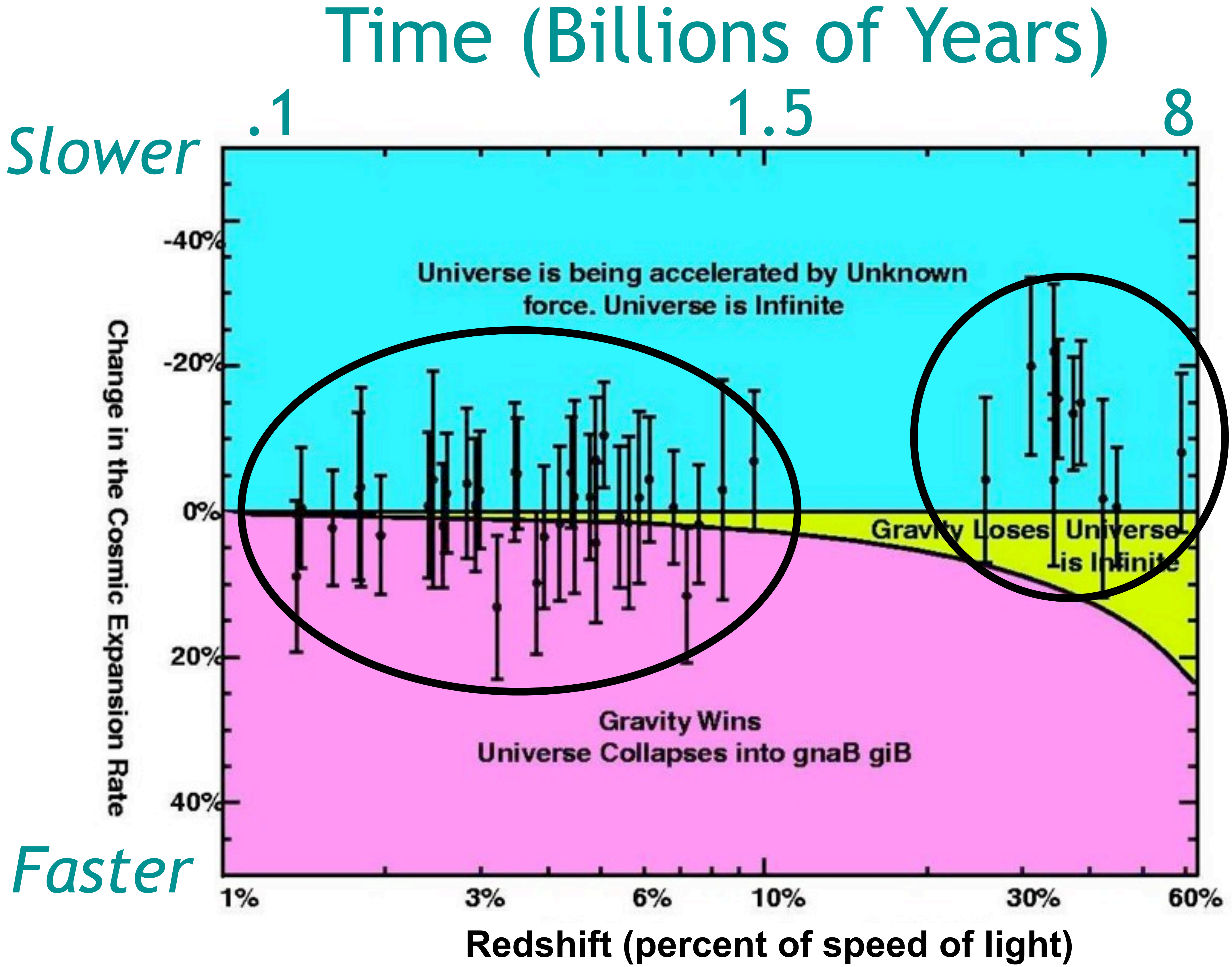


Time (Billions of Years)
.1
1.5
8
Slower
Faster
-40%
-20%
0%
20%
40%
Change in the Cosmic Expansion Rate
Gravity Loses Universe is Infinite
Gravity Wins
Universe Collapses into gnaB giB
1%
3%
6%
10%
30%
60%
Redshift (percent of speed of light)



Time (Billions of Years)
.1
1.5
8
Slower
Faster
-40%
-20%
0%
20%
40%
Change in the Cosmic Expansion Rate
Universe is being accelerated by Unknown force. Universe is Infinite
Gravity Loses Universe is Infinite
Gravity Wins
Universe Collapses into gnaB giB
1%
3%
6%
10%
30%
60%
Redshift (percent of speed of light)

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

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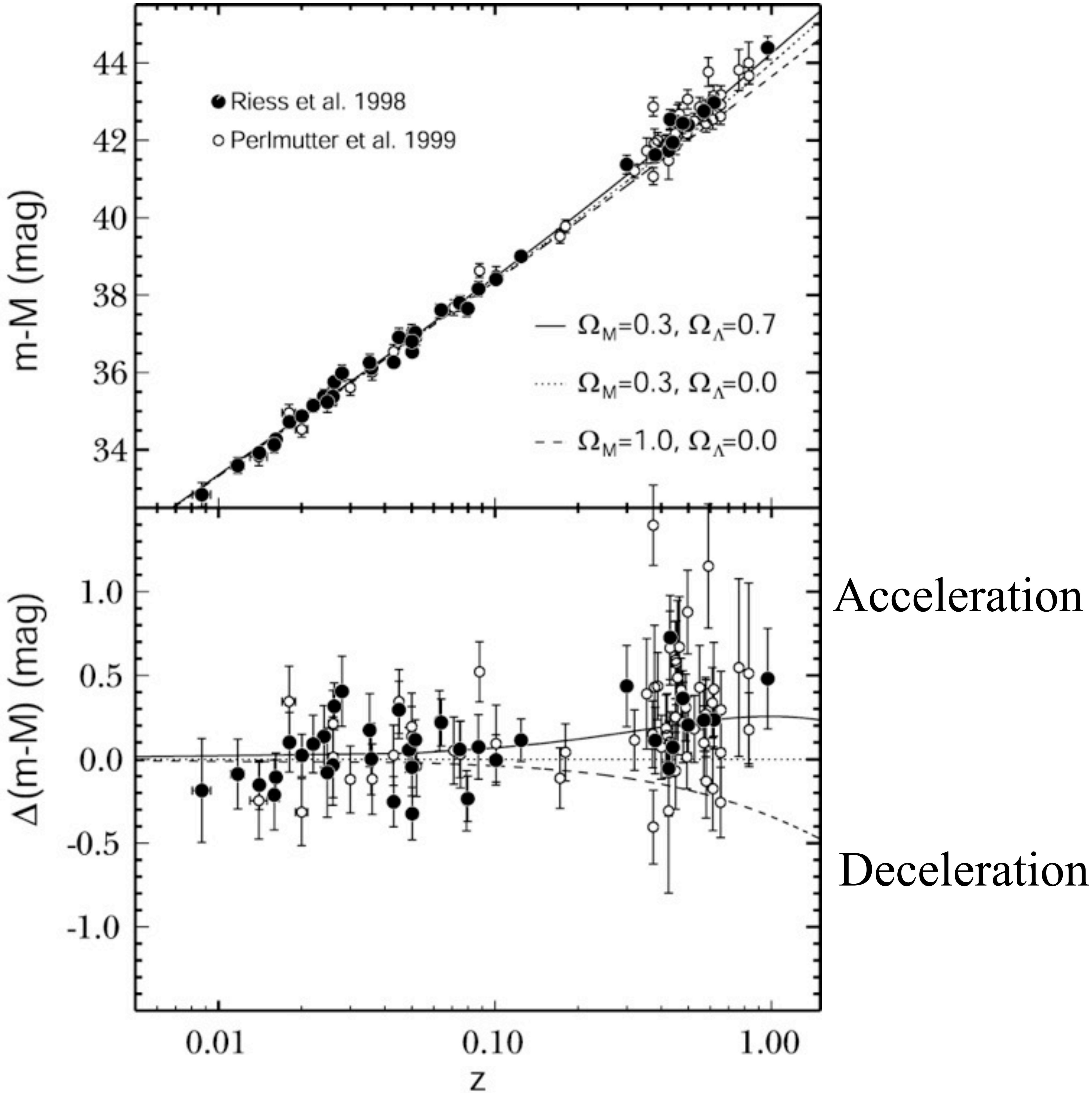
N. Suntzeff Chile 1/13/1998 1:47pm: "I really encourage you [Adam] to work your butt off on this. We need to be careful…If you are really sure that the [cosmological constant] is not zero—my god, get it out! I mean this seriously—you probably never will have another scientific result that is more exciting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



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

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

Adam G. Riess,[1] Alexei V. Filippenko,[1] Peter Challis,[2] Alejandro Clocchiatti,[3] Alan Diercks,[4]
Peter M. Garnavich,[2] Ron L. Gilliland,[5] Craig J. Hogan,[4] Saurabh Jha,[2] Robert P. Kirshner,[2]
B. Leibundgut,[6] M. M. Phillips,[7] David Reiss,[4] Brian P. Schmidt,[8,9] Robert A. Schommer,[7]
R. Chris Smith,[7,10] J. Spyromilio,[6] Christopher Stubbs,[4]
Nicholas B. Suntzeff,[7] and John Tonry[11]

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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Institute for Nuclear and Particle Astrophysics, E. O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720

C. Lidman
European Southern Observatory, La Silla, Chile

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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)

MEASU ... UPERNOVAE

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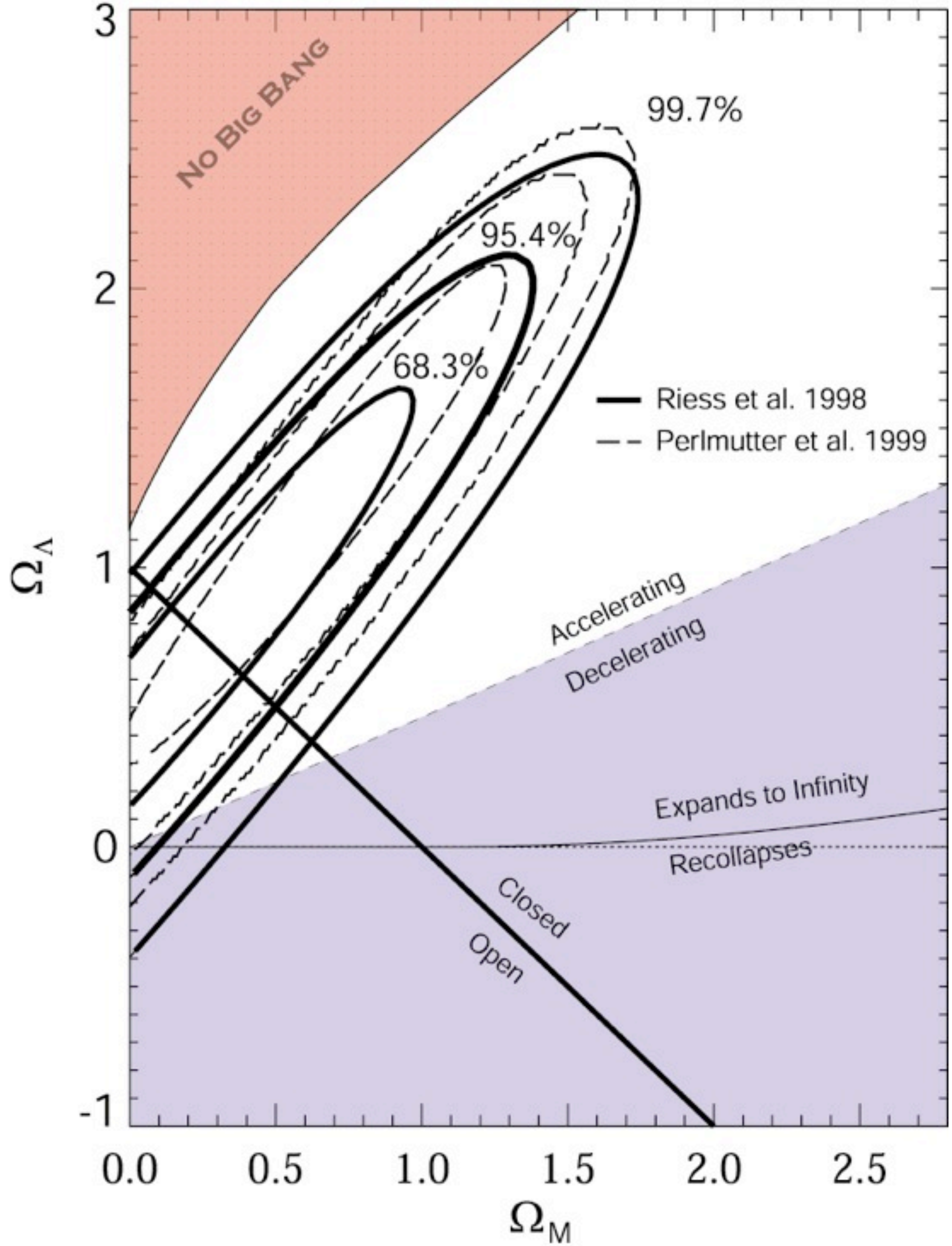
Institute fo ... Berkeley, CA 94720


Text
NOBELPRISET
The Nobel Prize

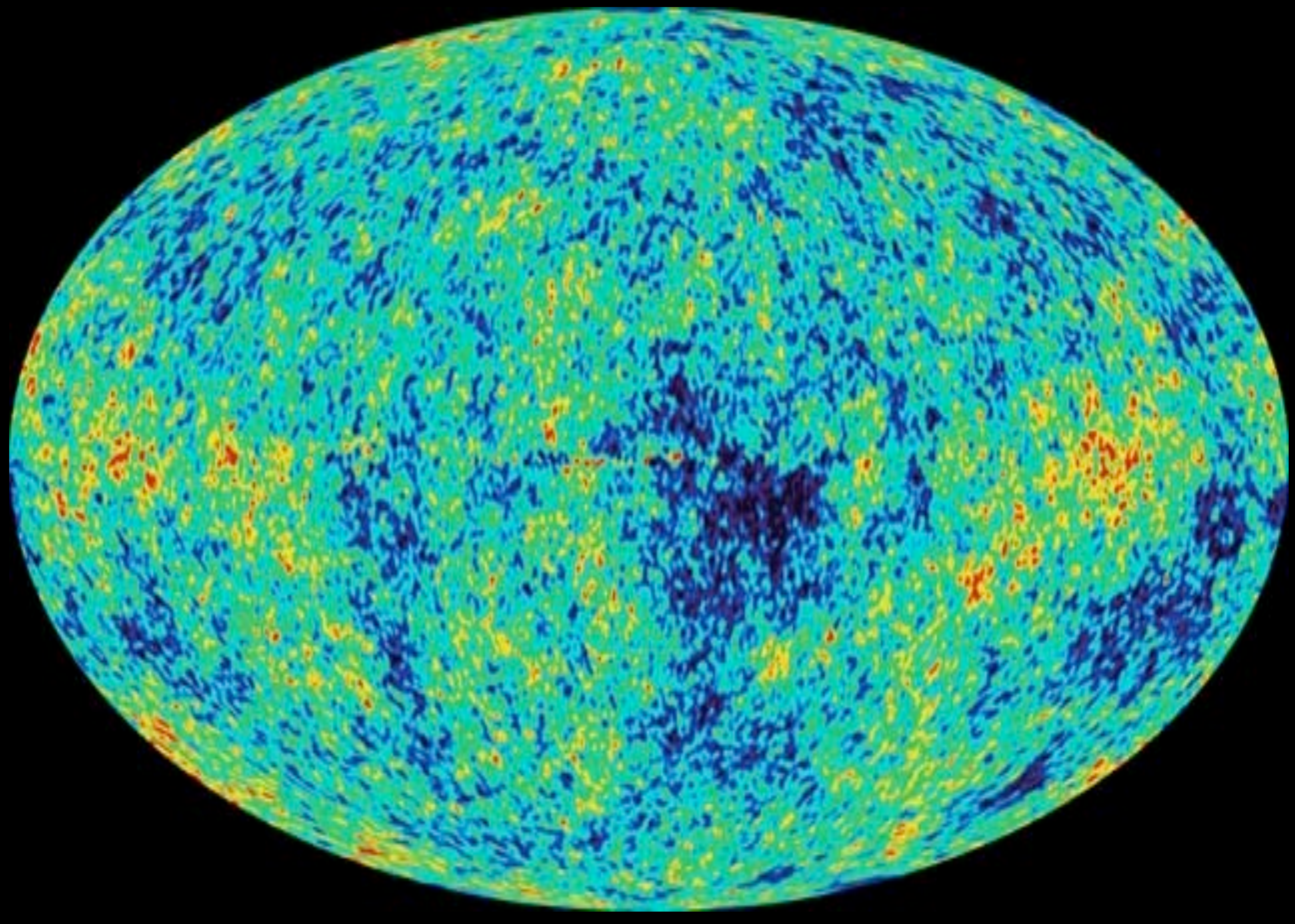


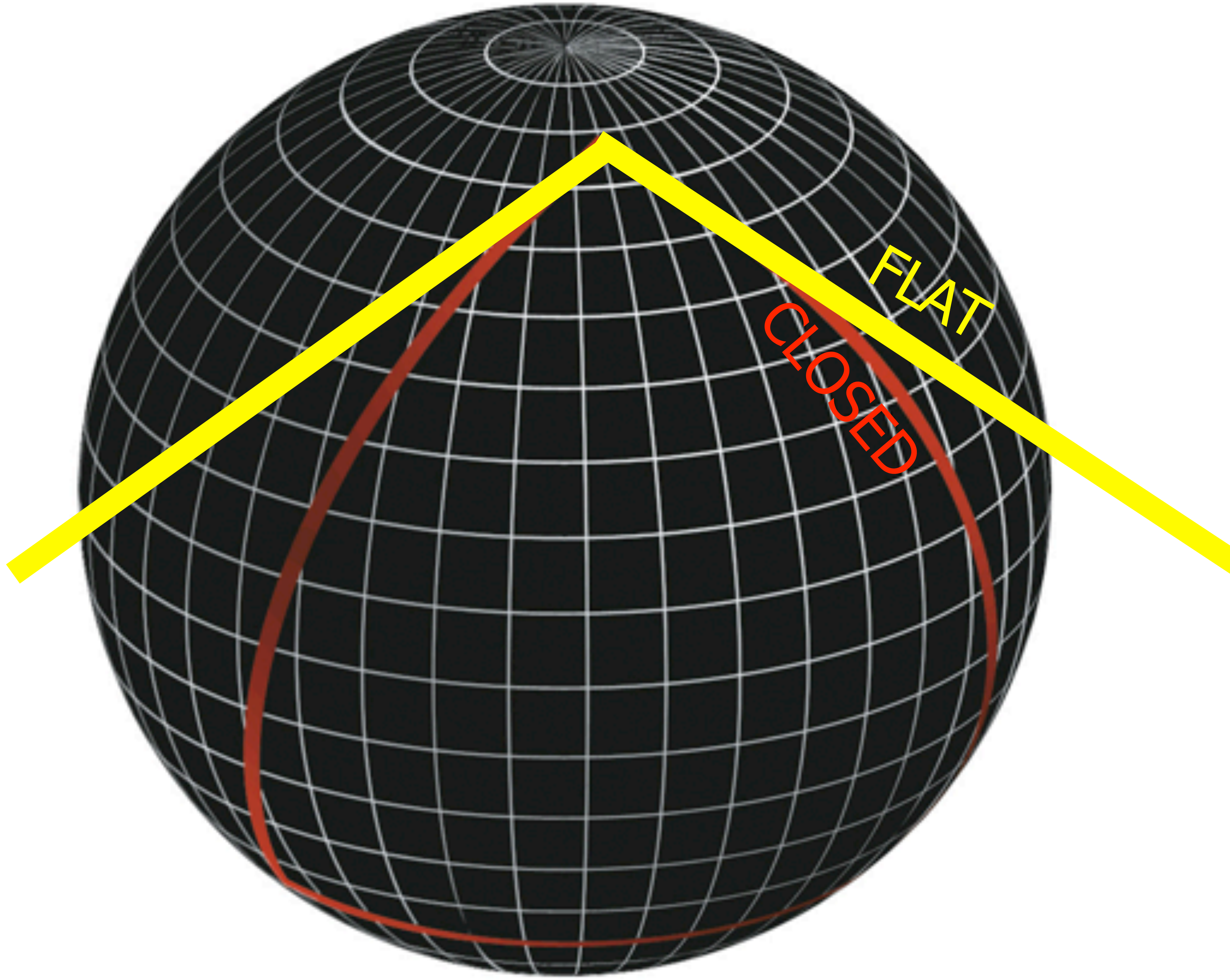
No Big Bang
99.7%
95.4%
68.3%
Riess et al. 1998
Perlmutter et al. 1999
Accelerating
Decelerating
Expands to Infinity
Recollapses
Closed
Open
Ω_Λ
Ω_M
3
2
1
0
-1
0.0
0.5
1.0
1.5
2.0
2.5

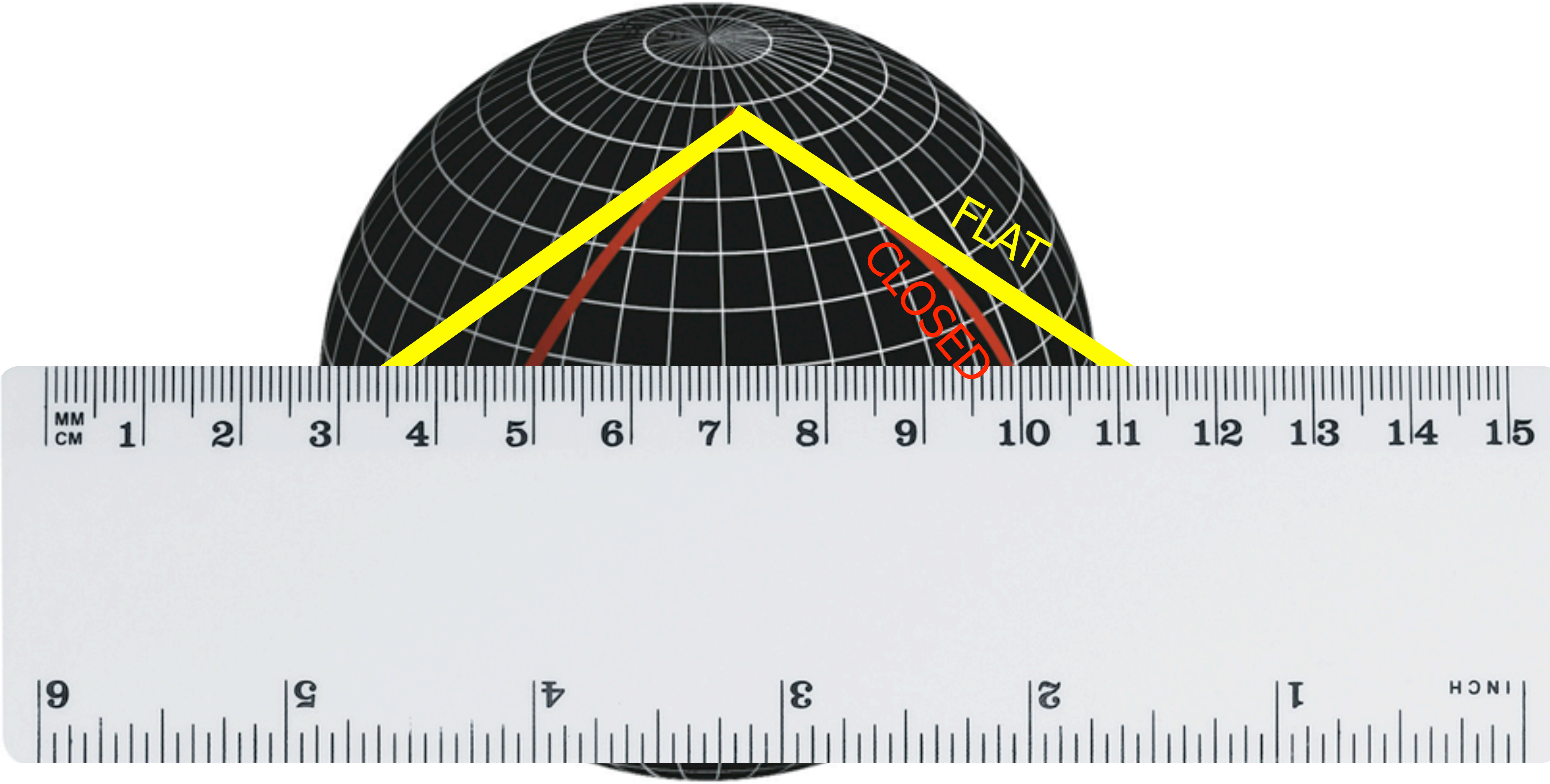
Sound Waves of Matter Splashing Around the Universe

C_S=.577c

Largest sound waves have been propagating for 380,000 years




FLAT
CLOSED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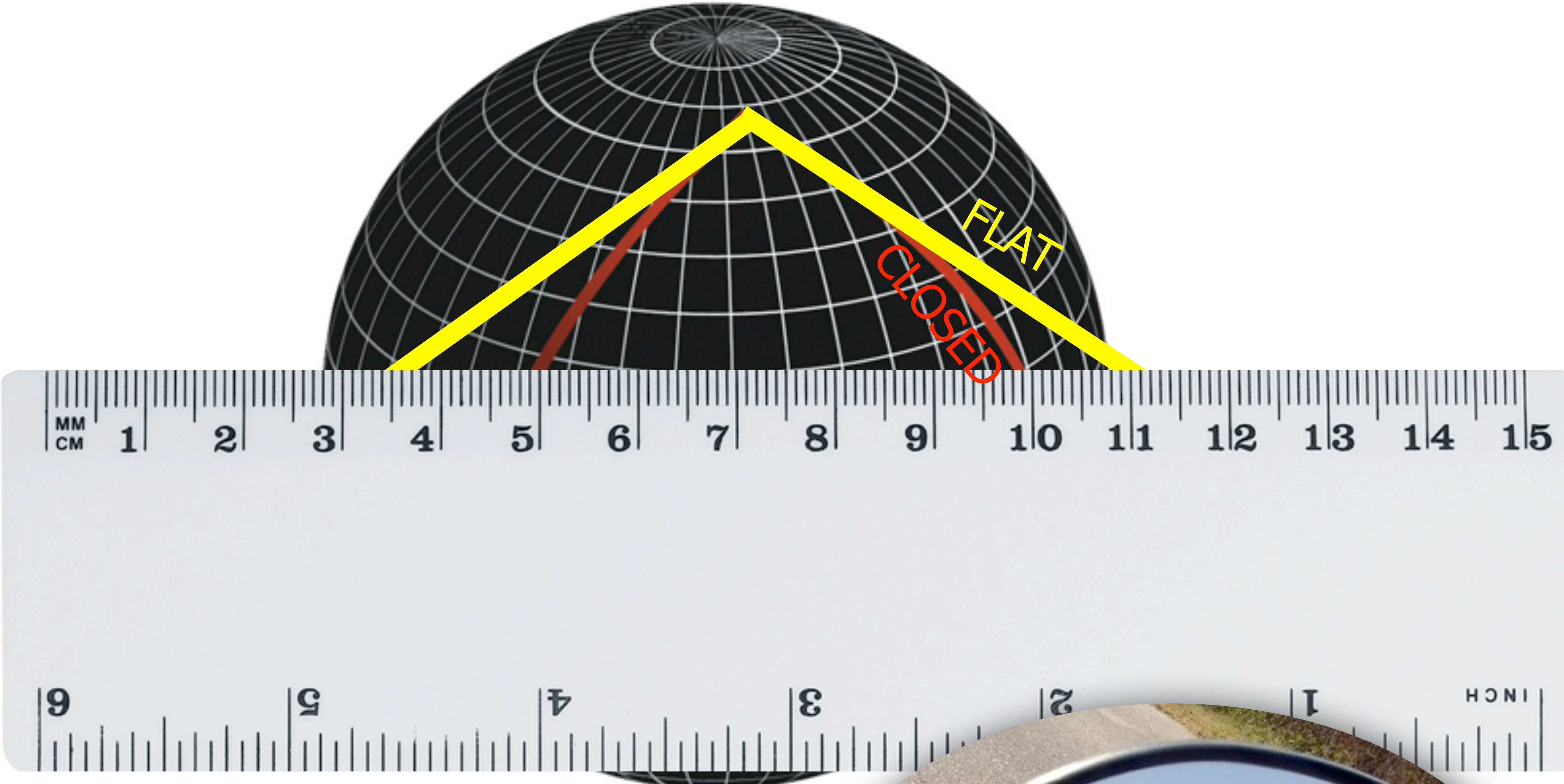
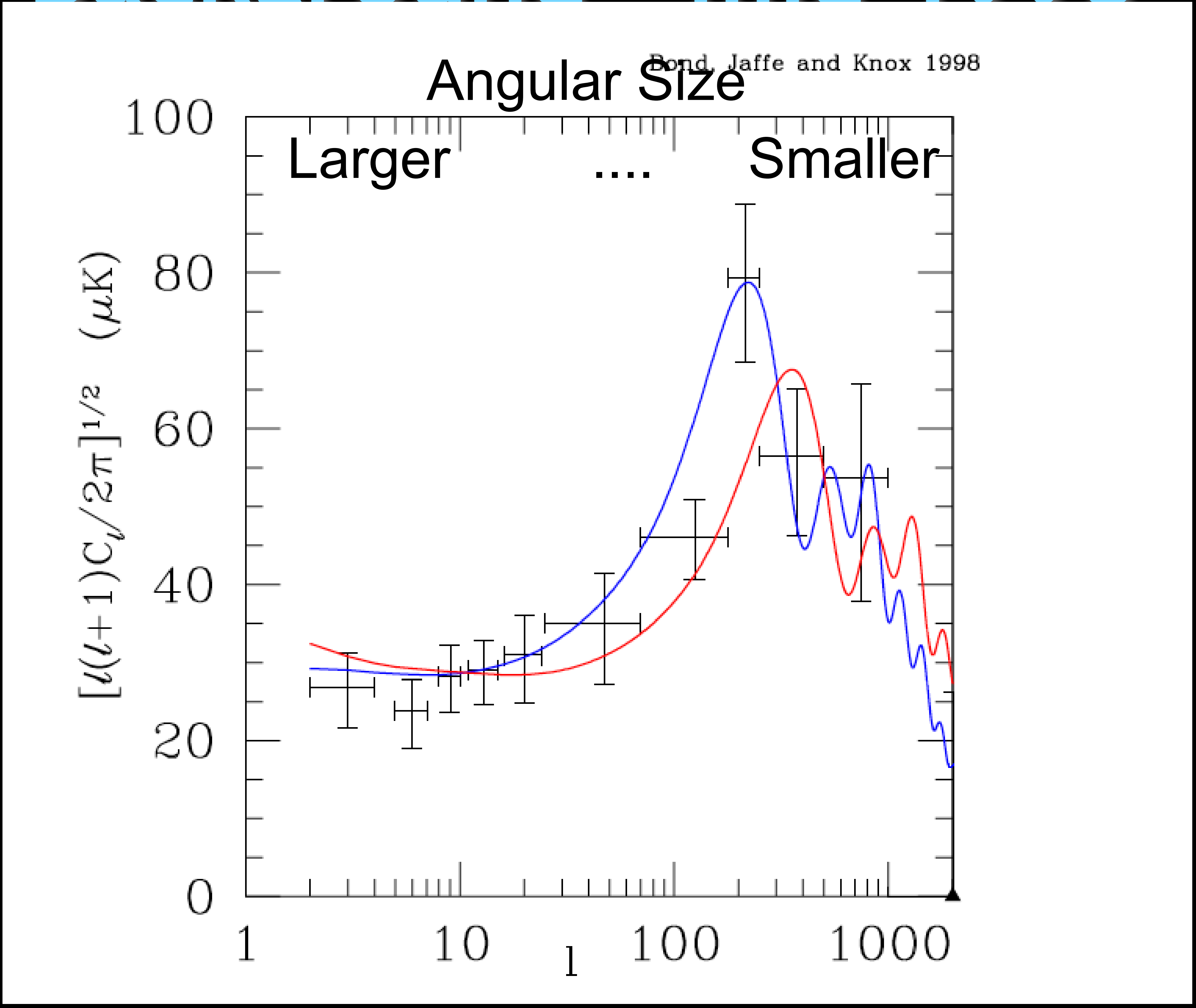
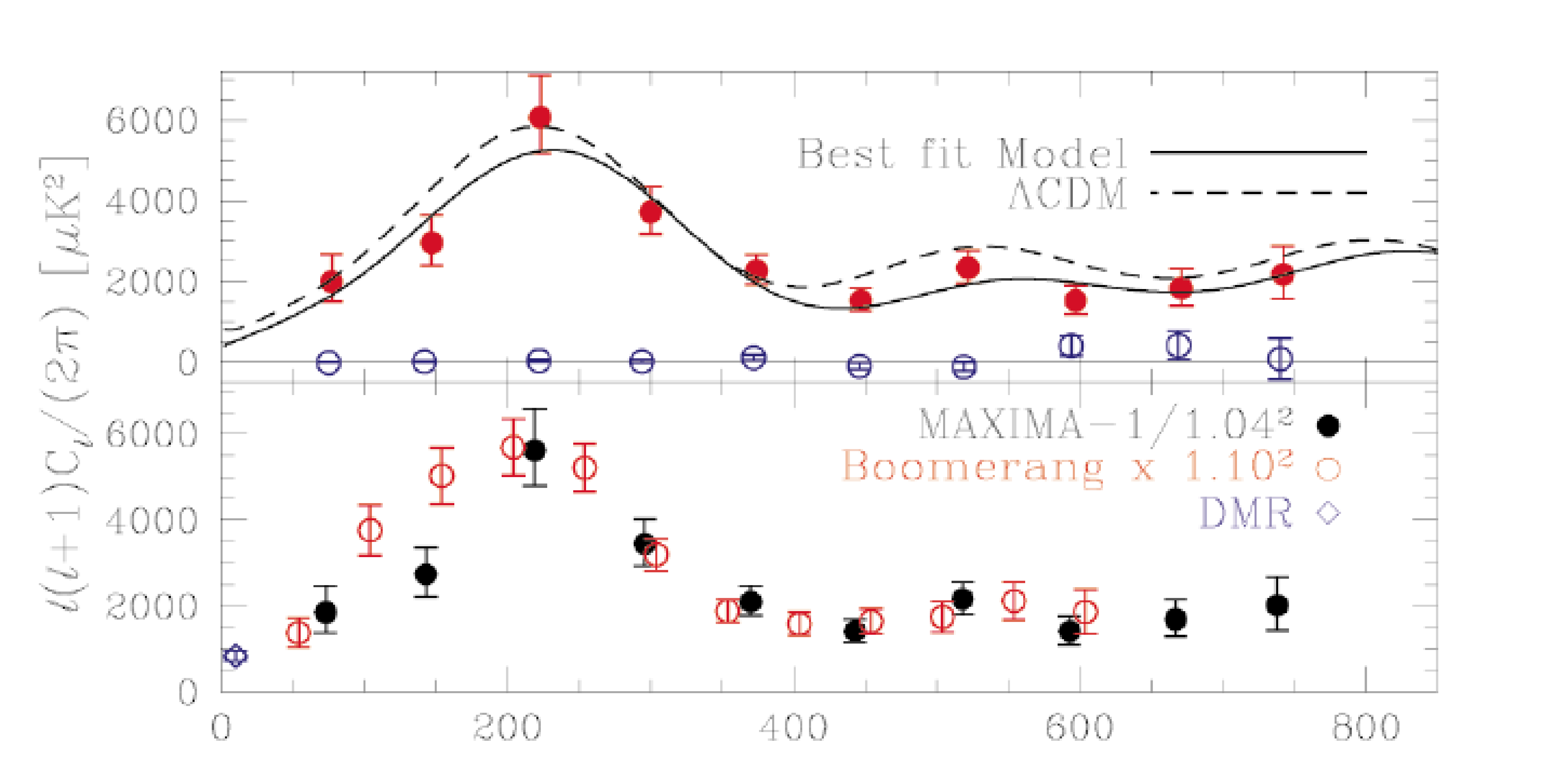


Objects Appear Larger in Curved Finite Space

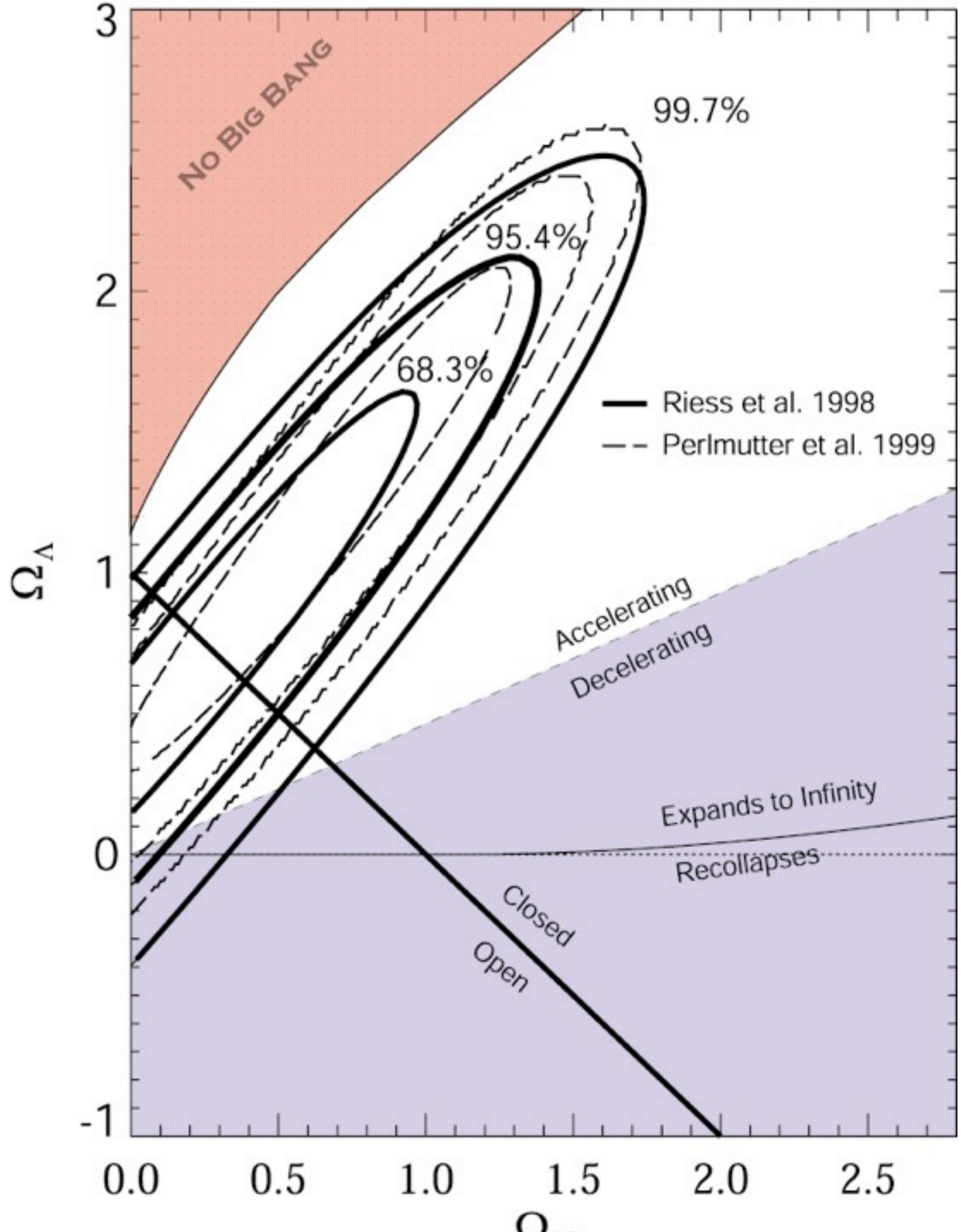
Cosmic Microwave Background - mid 1998



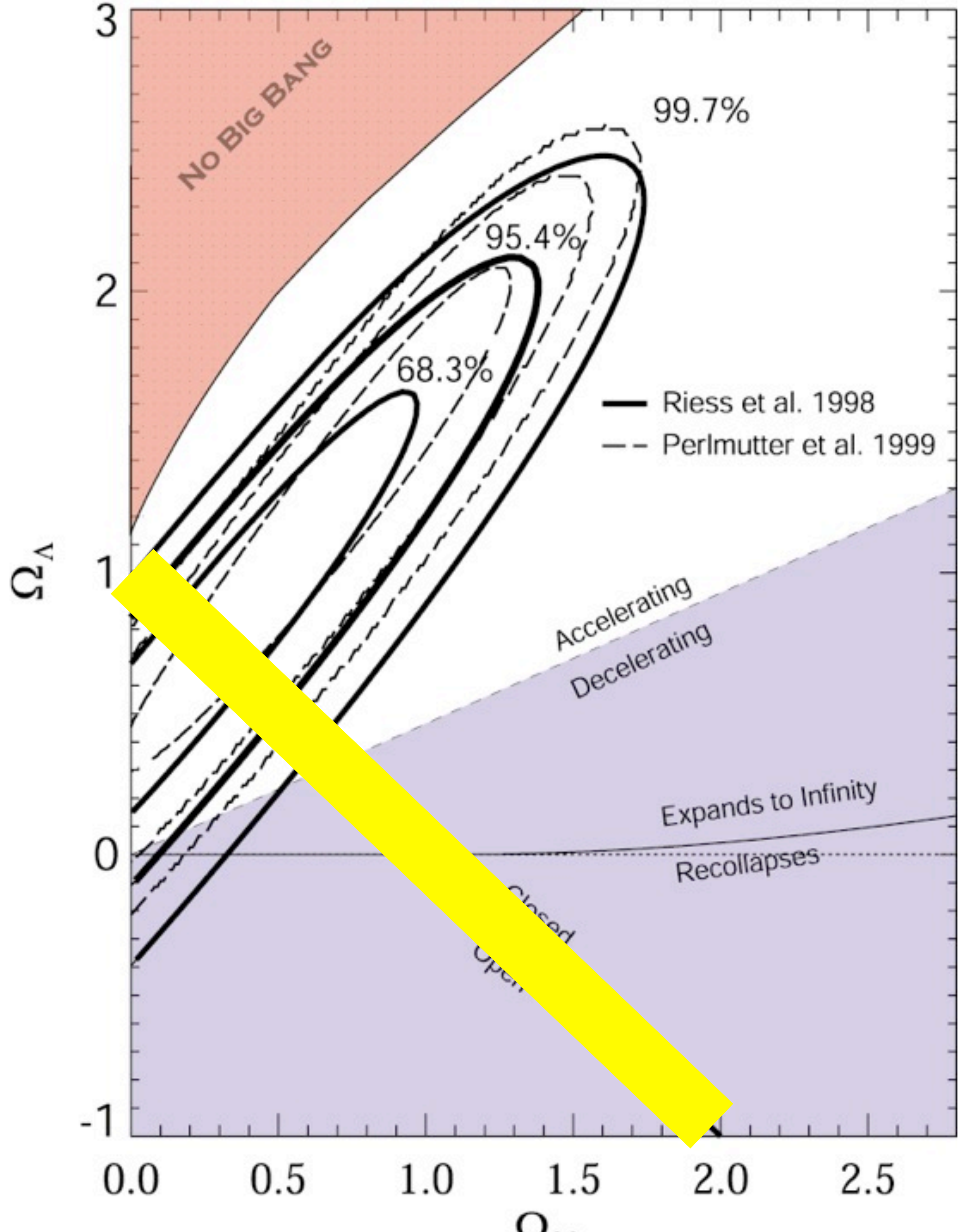
2000 - Boomerang & MAXIMA Clearly see 1st Doppler Peak



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



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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2
1
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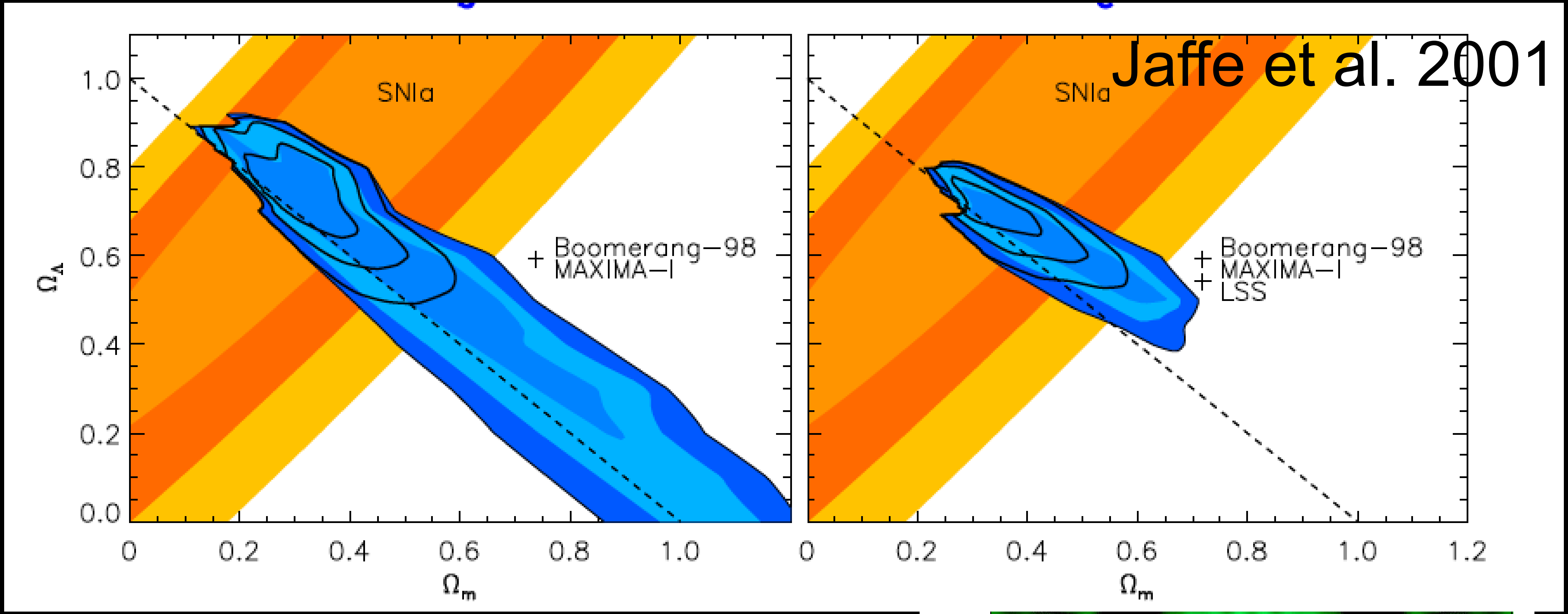
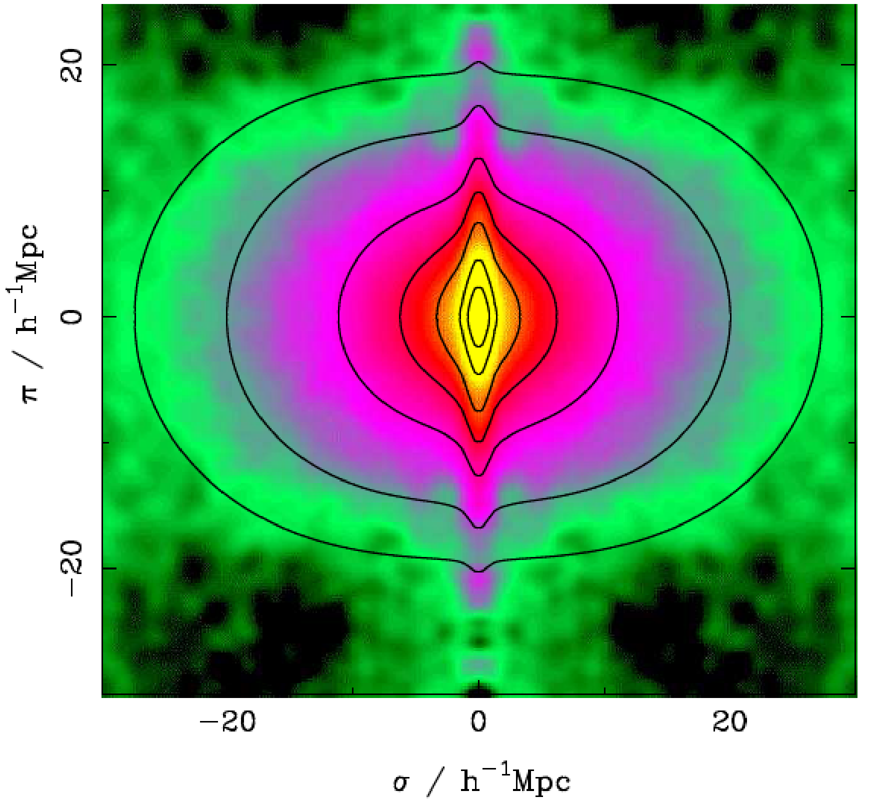
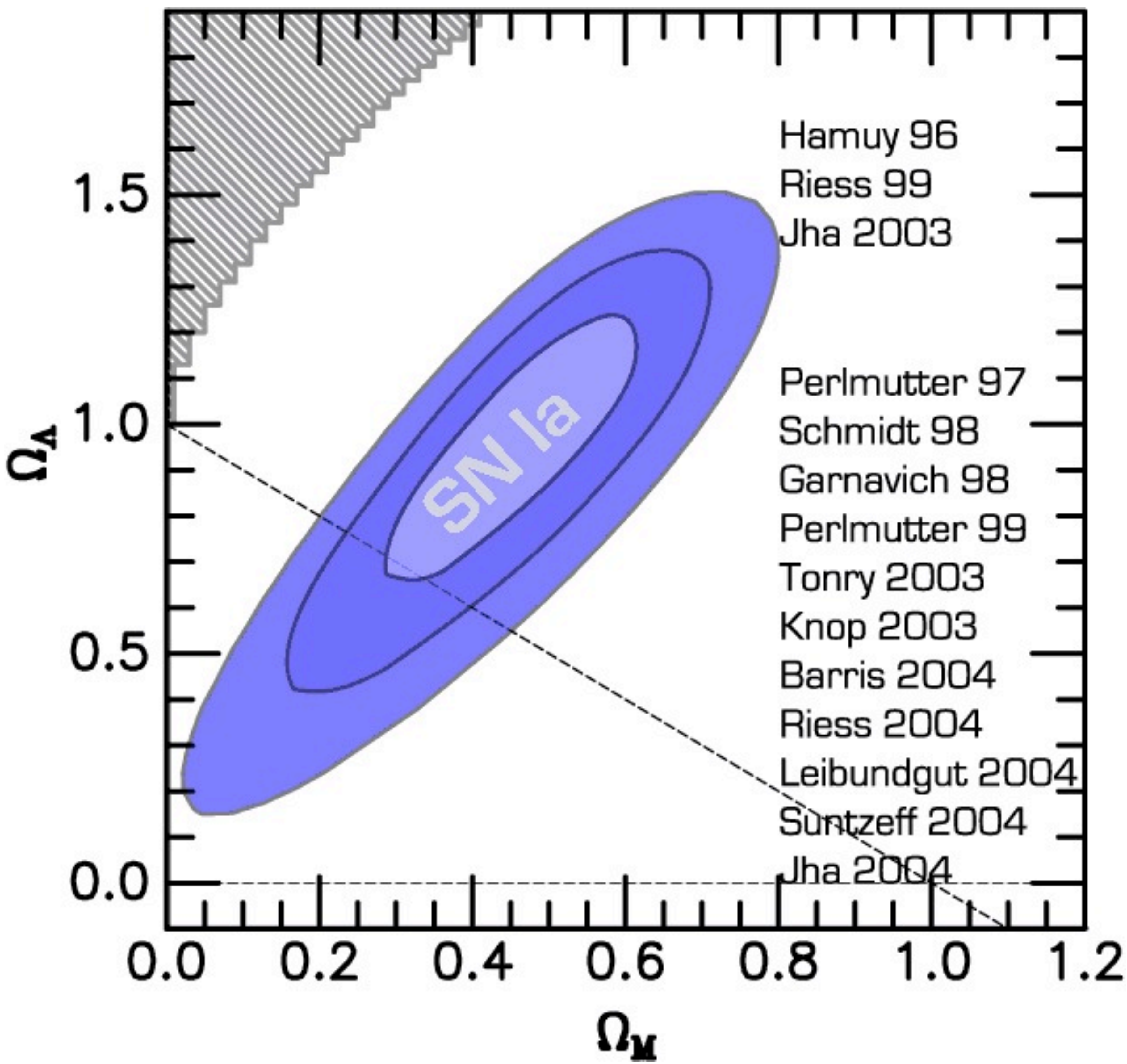
1.0
1.5
2.0
2.5

2001 - Large Scale Structure & CMB

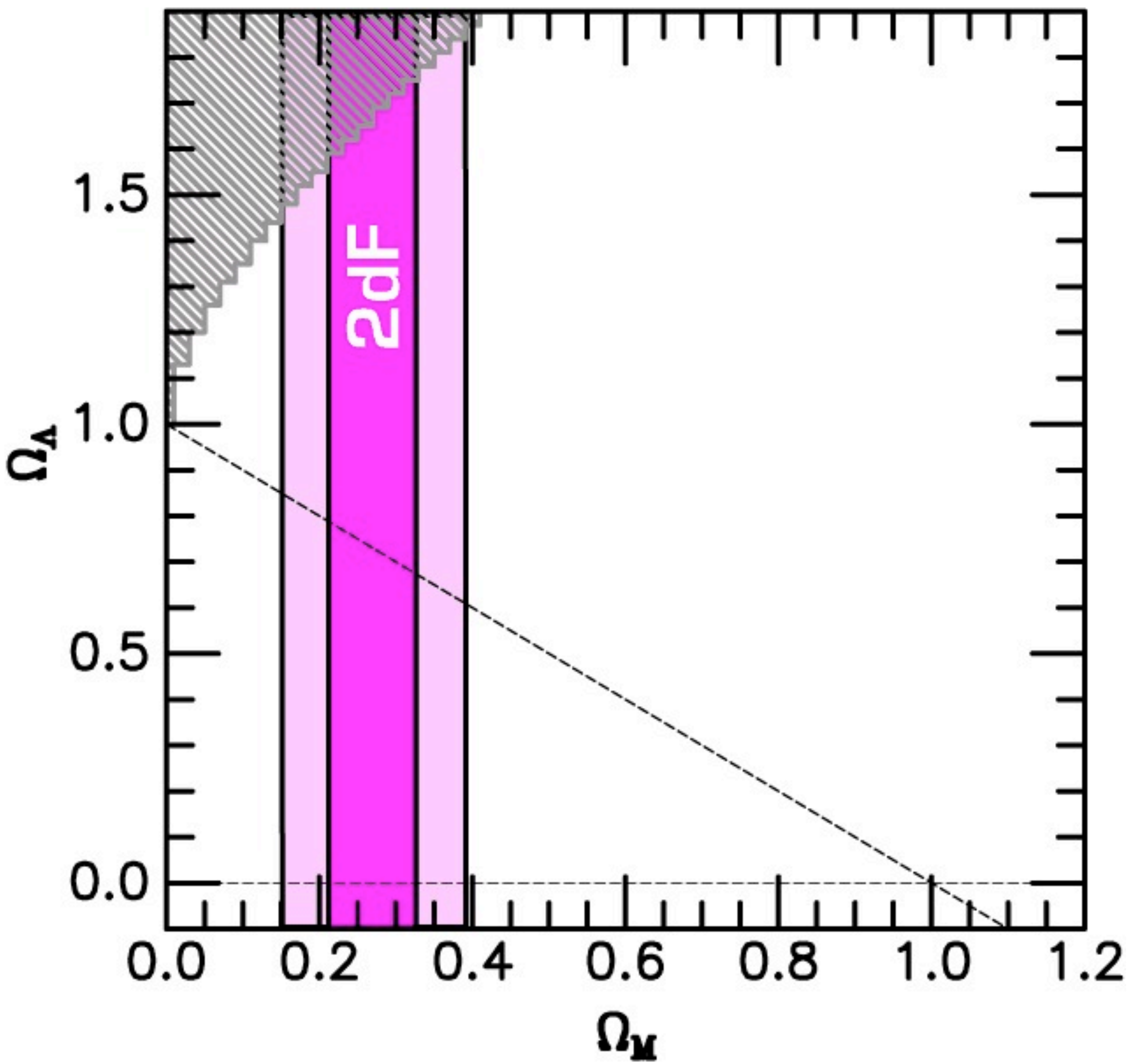


2dF redshift survey finds Ω_M~0.3 from power spectrum and infall

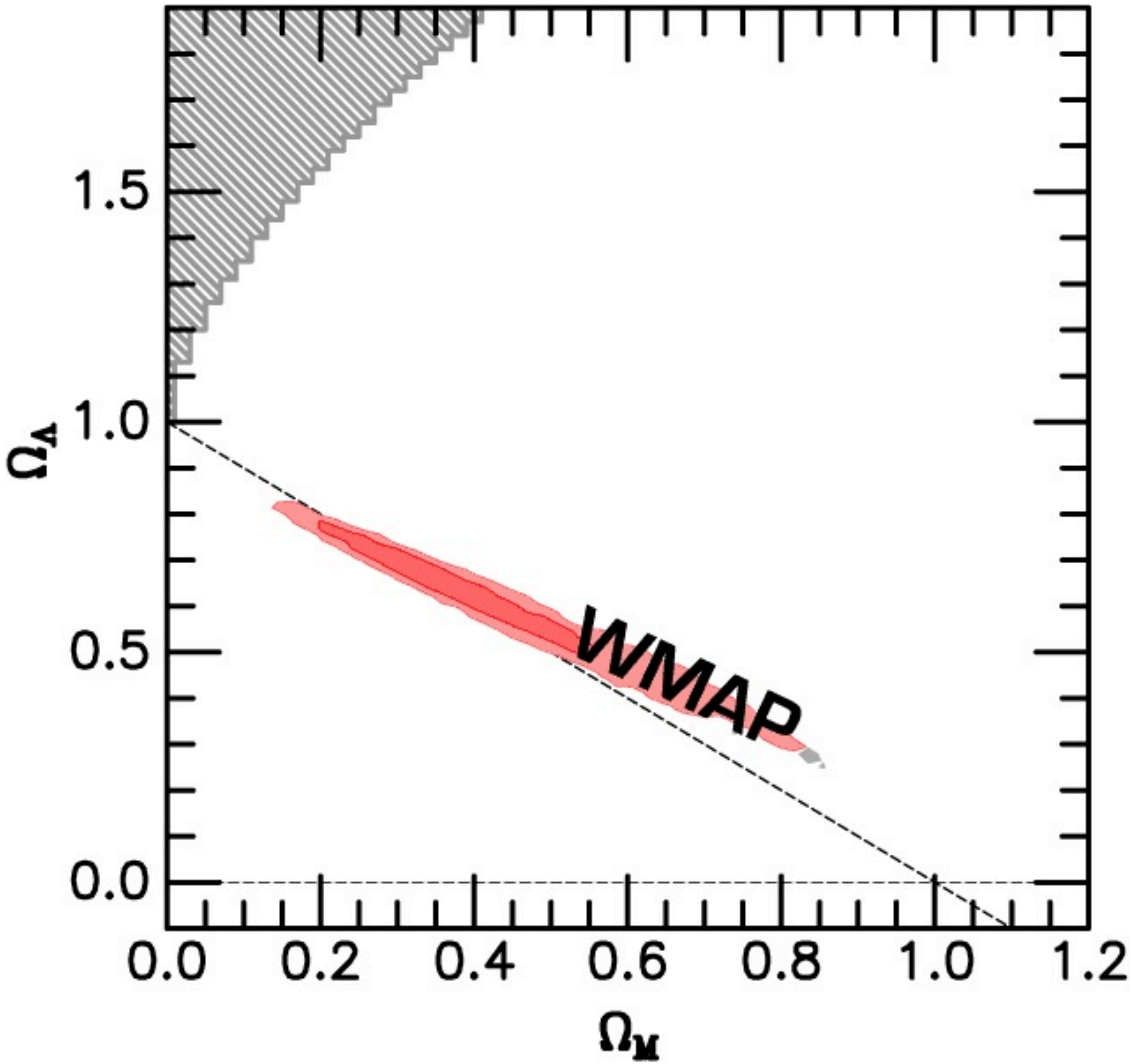




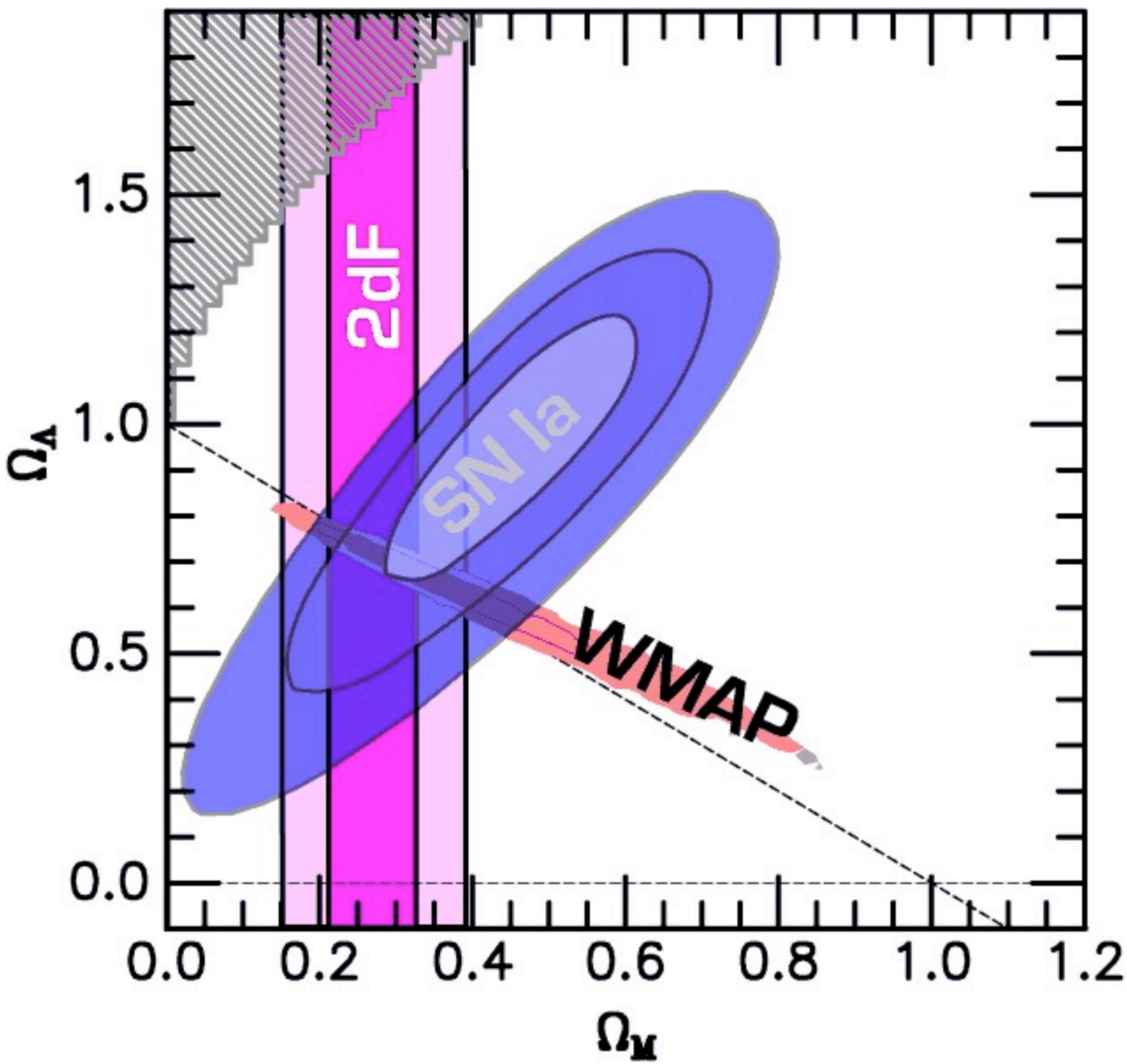
SN Ia
Hamuy 96
Riess 99
Jha 2003
Perlmutter 97
Schmidt 98
Garnavich 98
Perlmutter 99
Tonry 2003
Knop 2003
Barris 2004
Riess 2004
Leibundgut 2004
Suntzeff 2004
Jha 2004
Ω_Λ
Ω_M
0.0
0.5
1.0
1.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2



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



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



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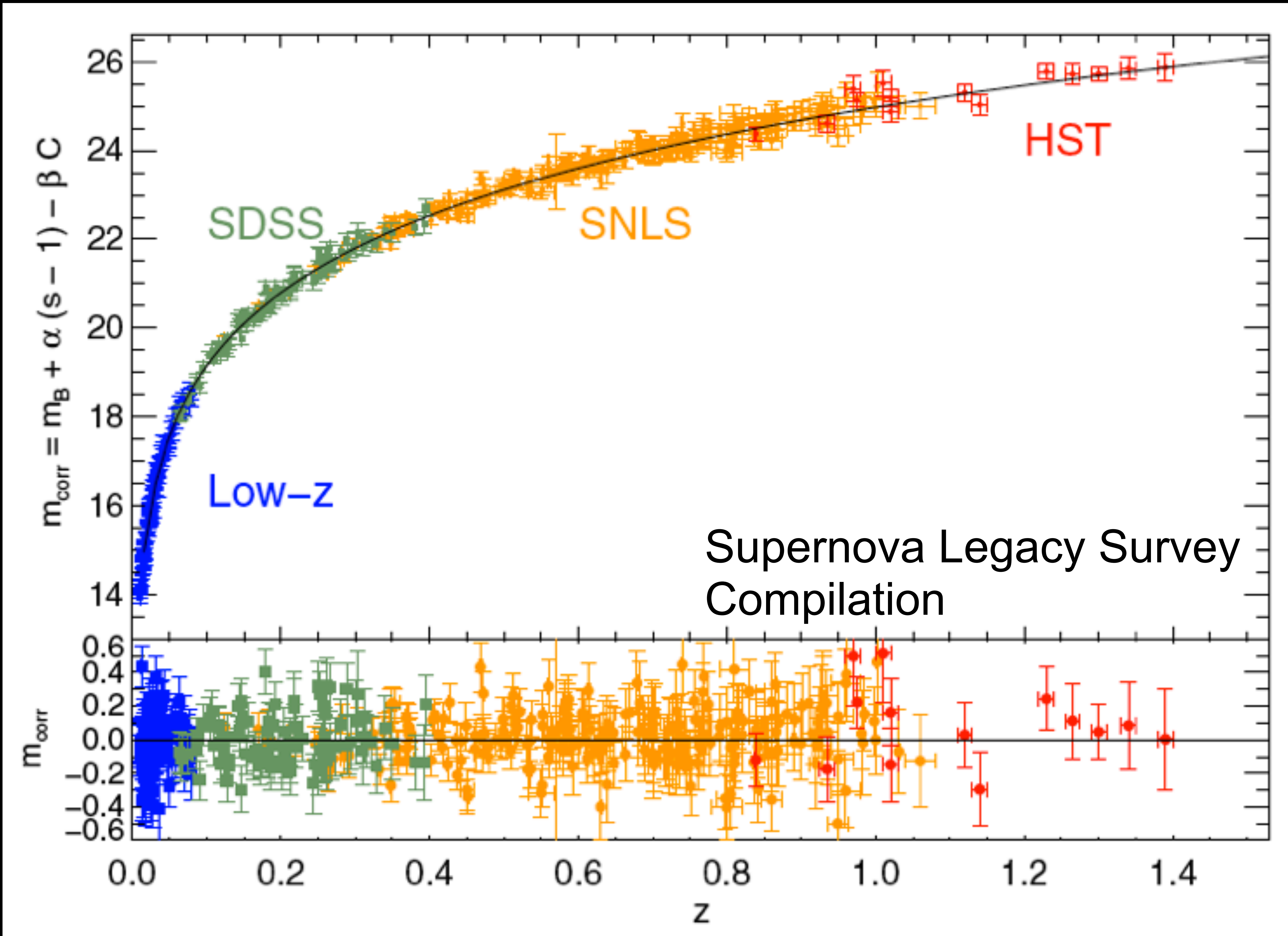
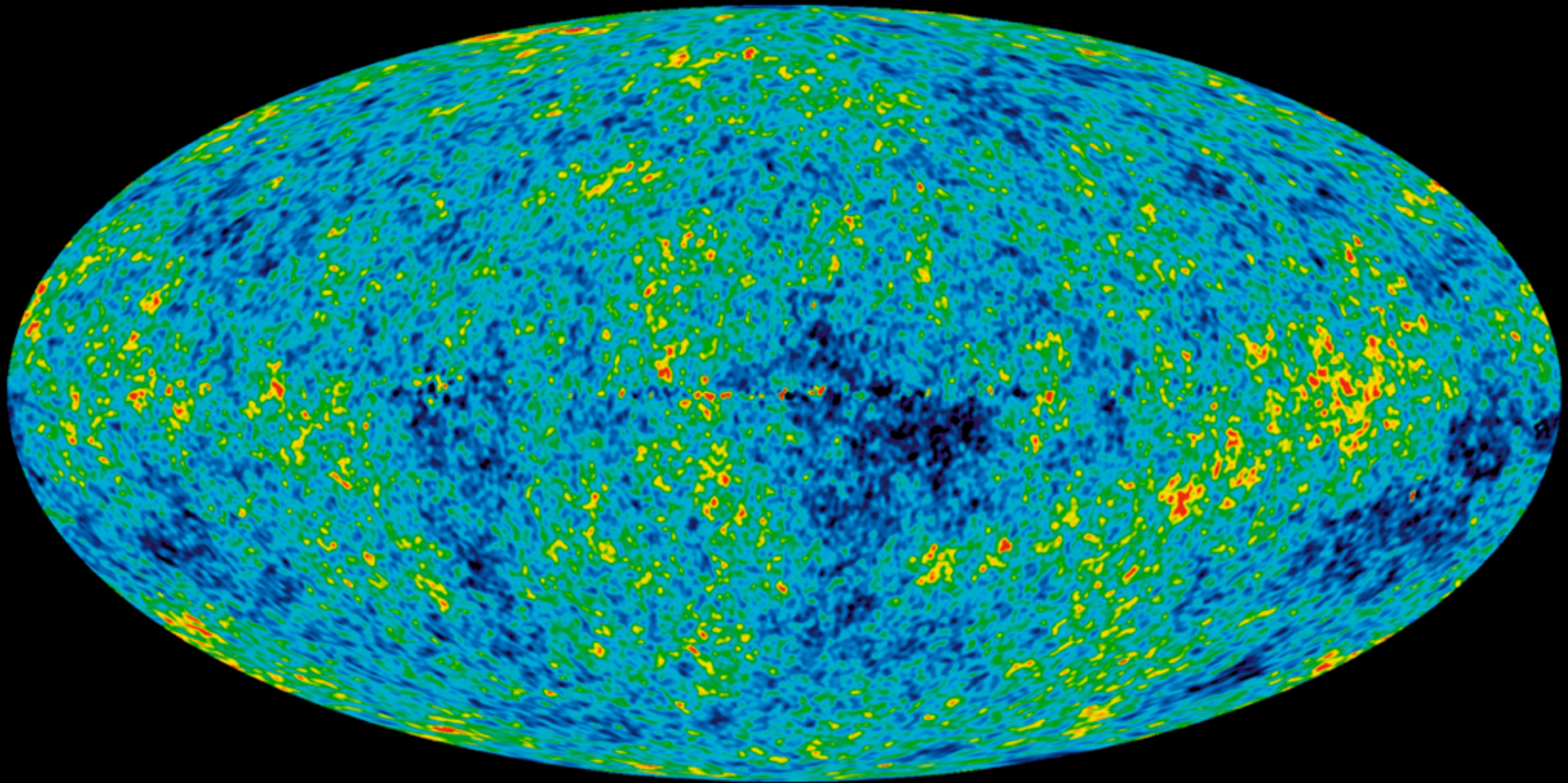
1.0
1.2
Ω_Λ
Ω_M
2dF
SN Ia
WMAP

Where we Stand now - SN Ia



Baryon Acoustic Oscillations



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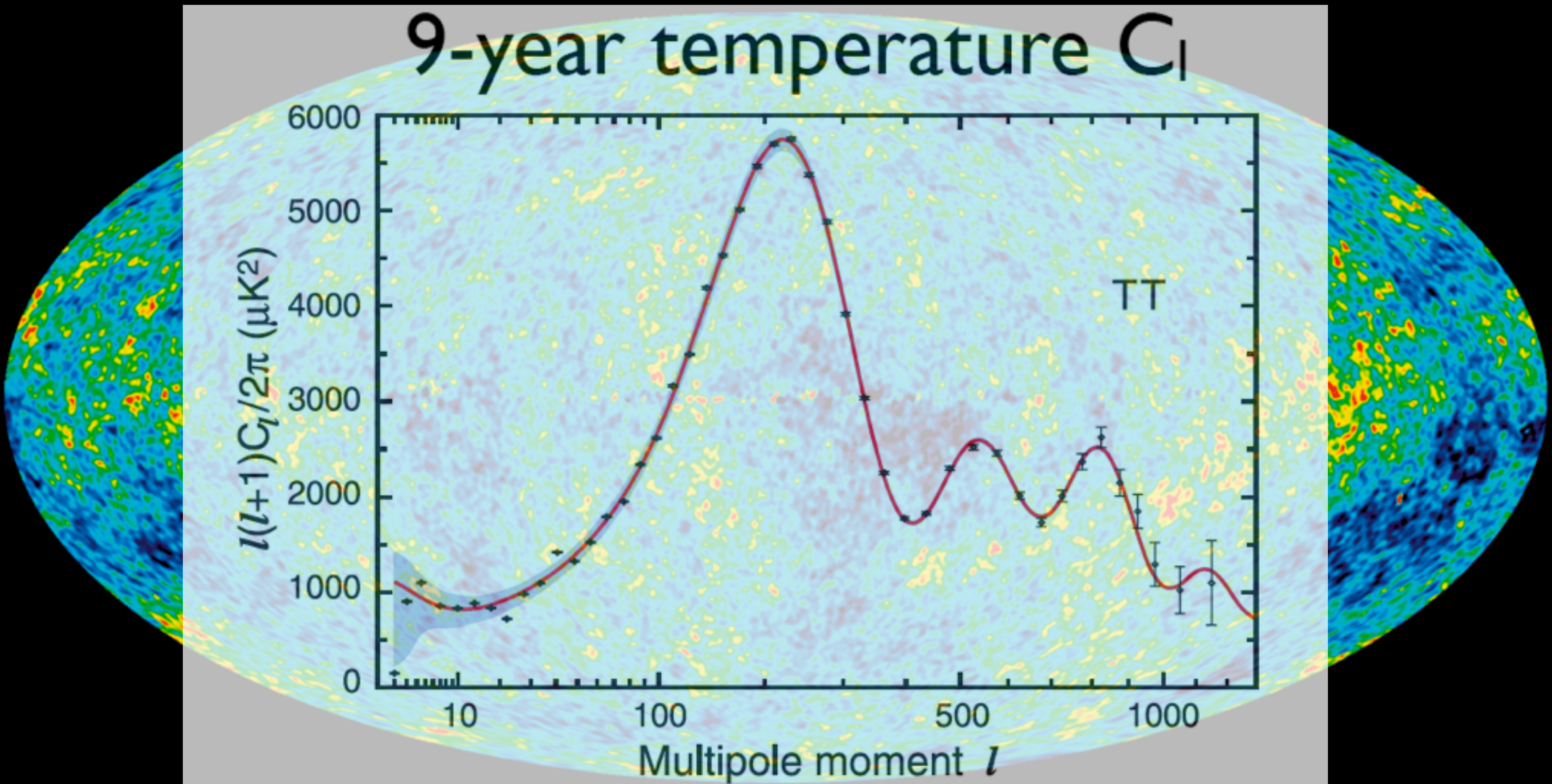
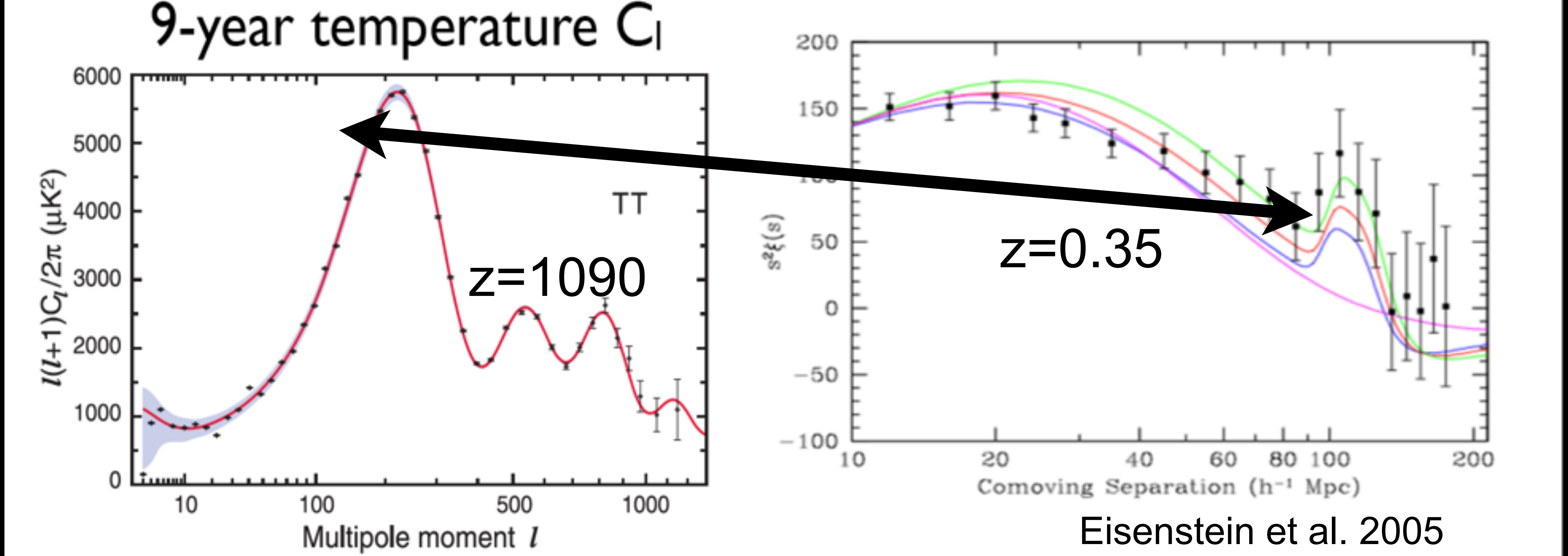
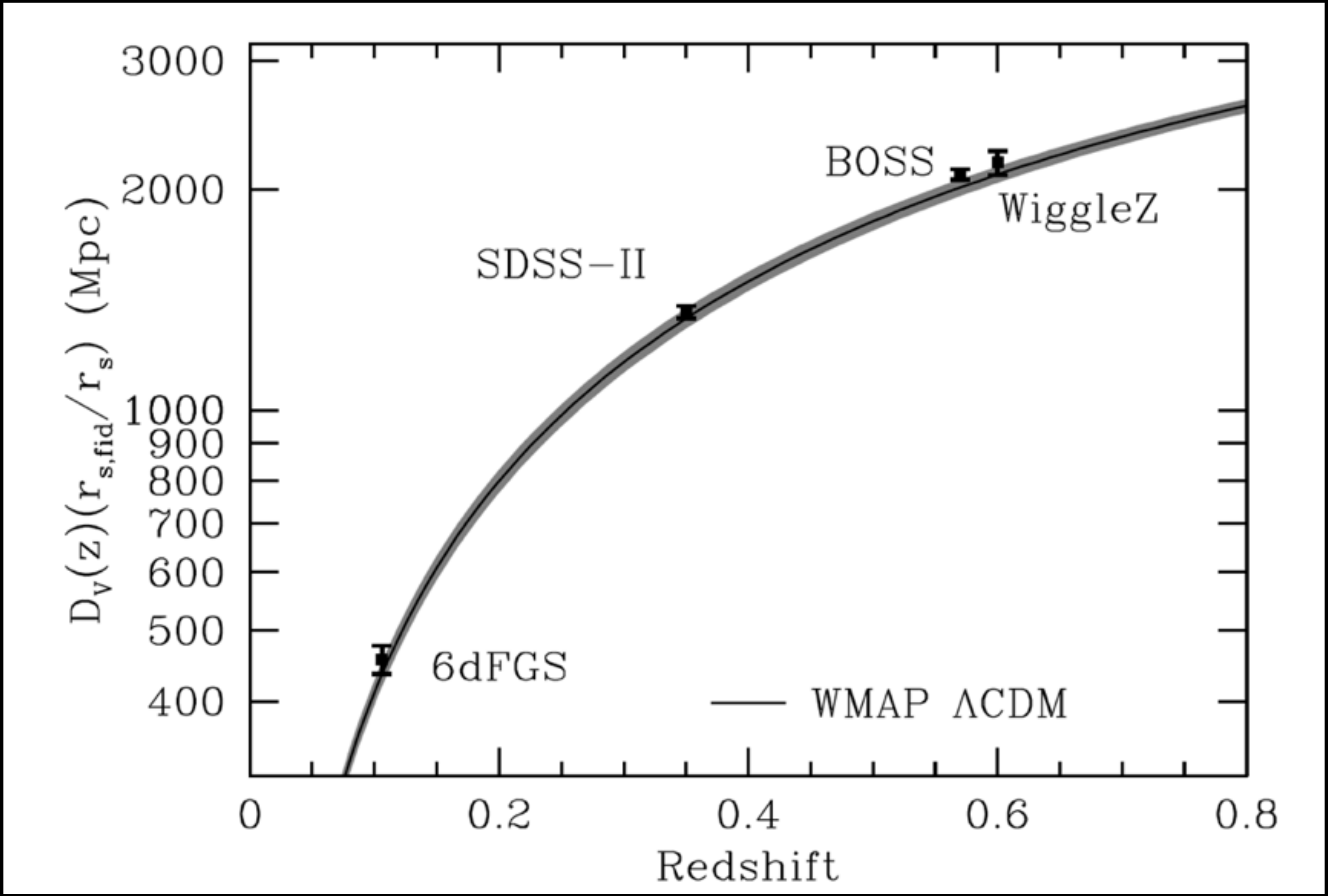


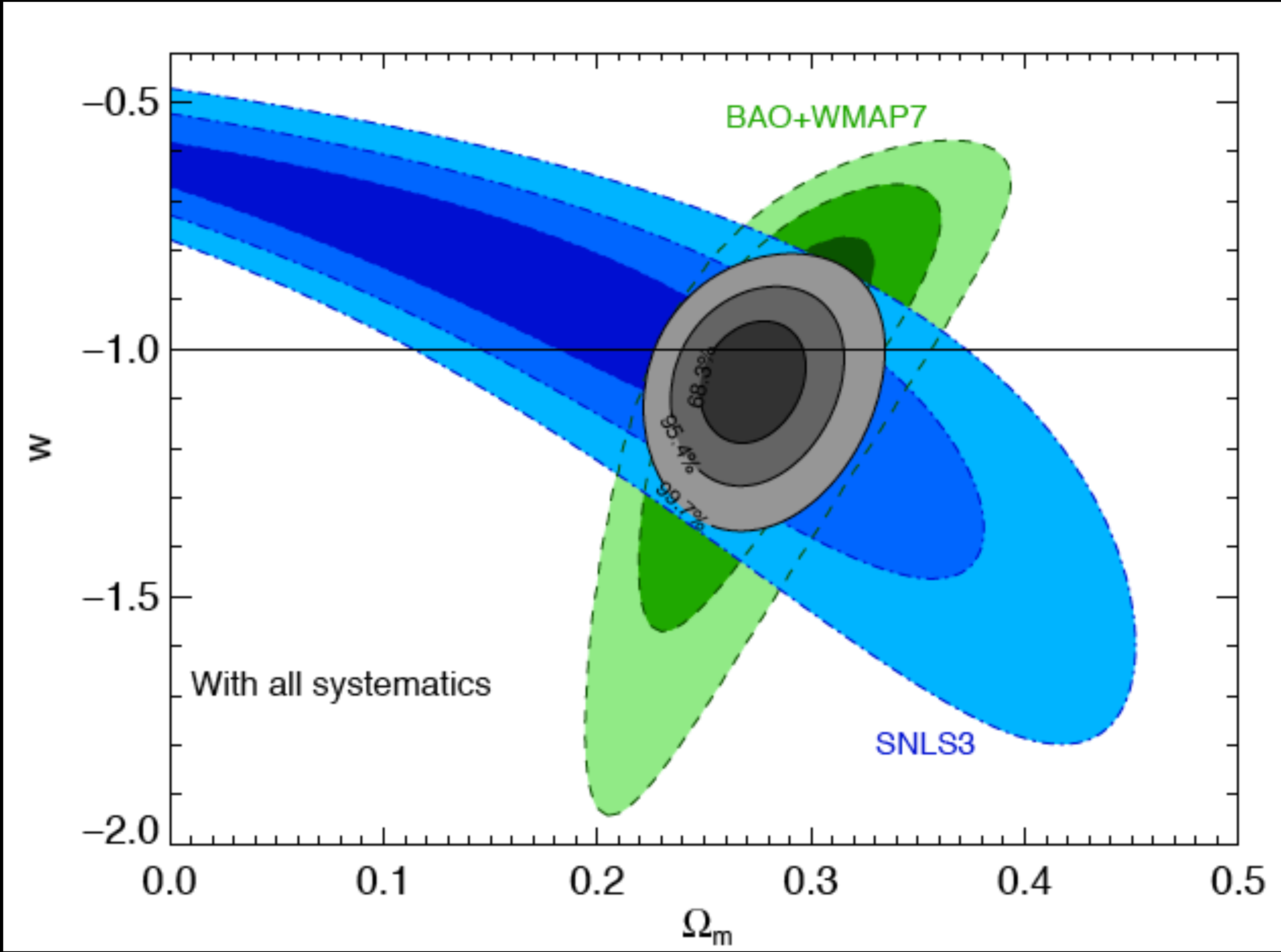


- The physics of *baryon acoustic oscillations* (BAO) is well understood, and their manifestation as wiggles in the CMB fluctuation spectrum is modeled to very high accuracy – the 1st peak has a size of ~150 Mpc (co-moving)
- They are then a standard Ruler we can look at through time.

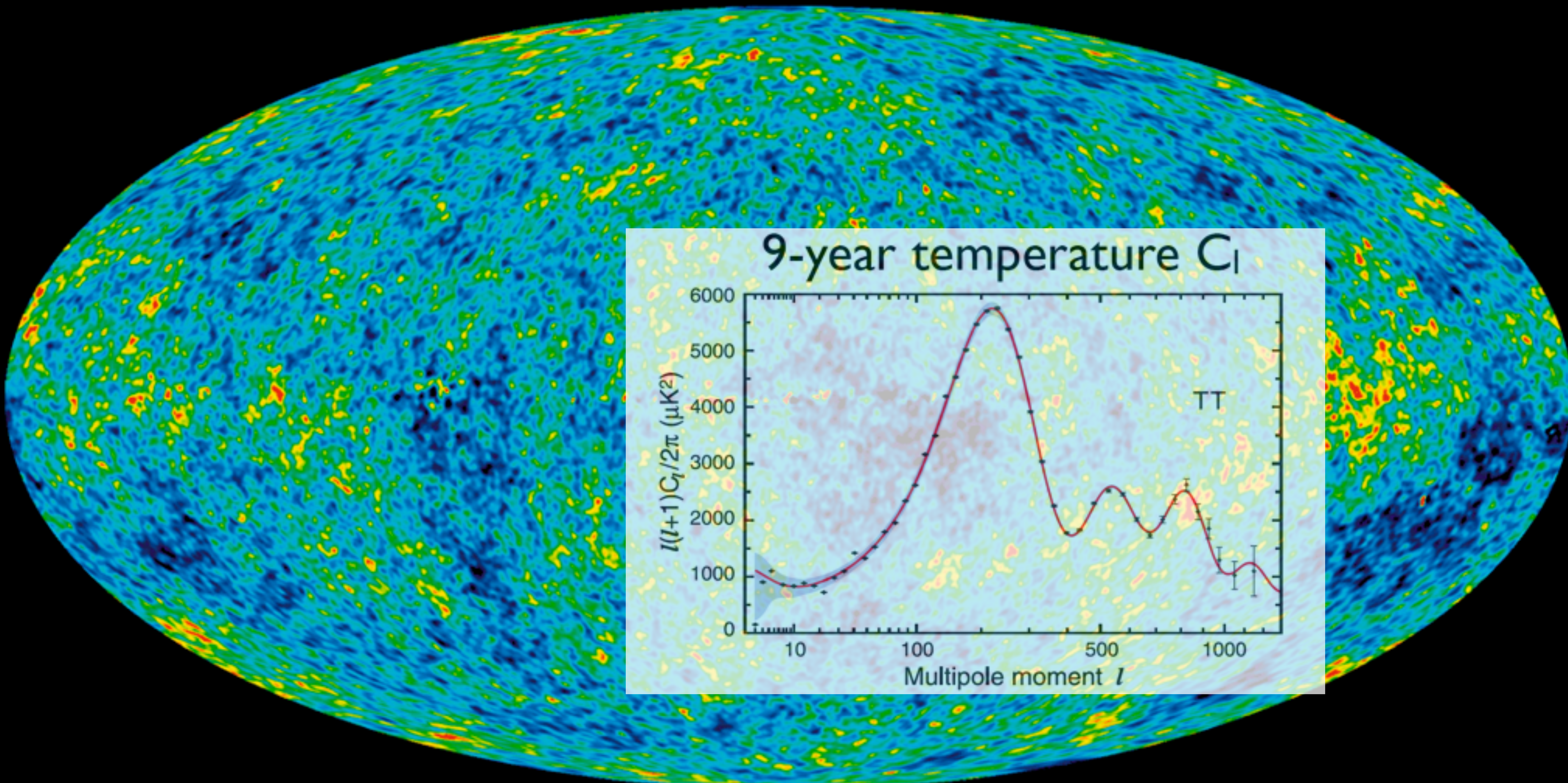
Where we Stand now - BAOs



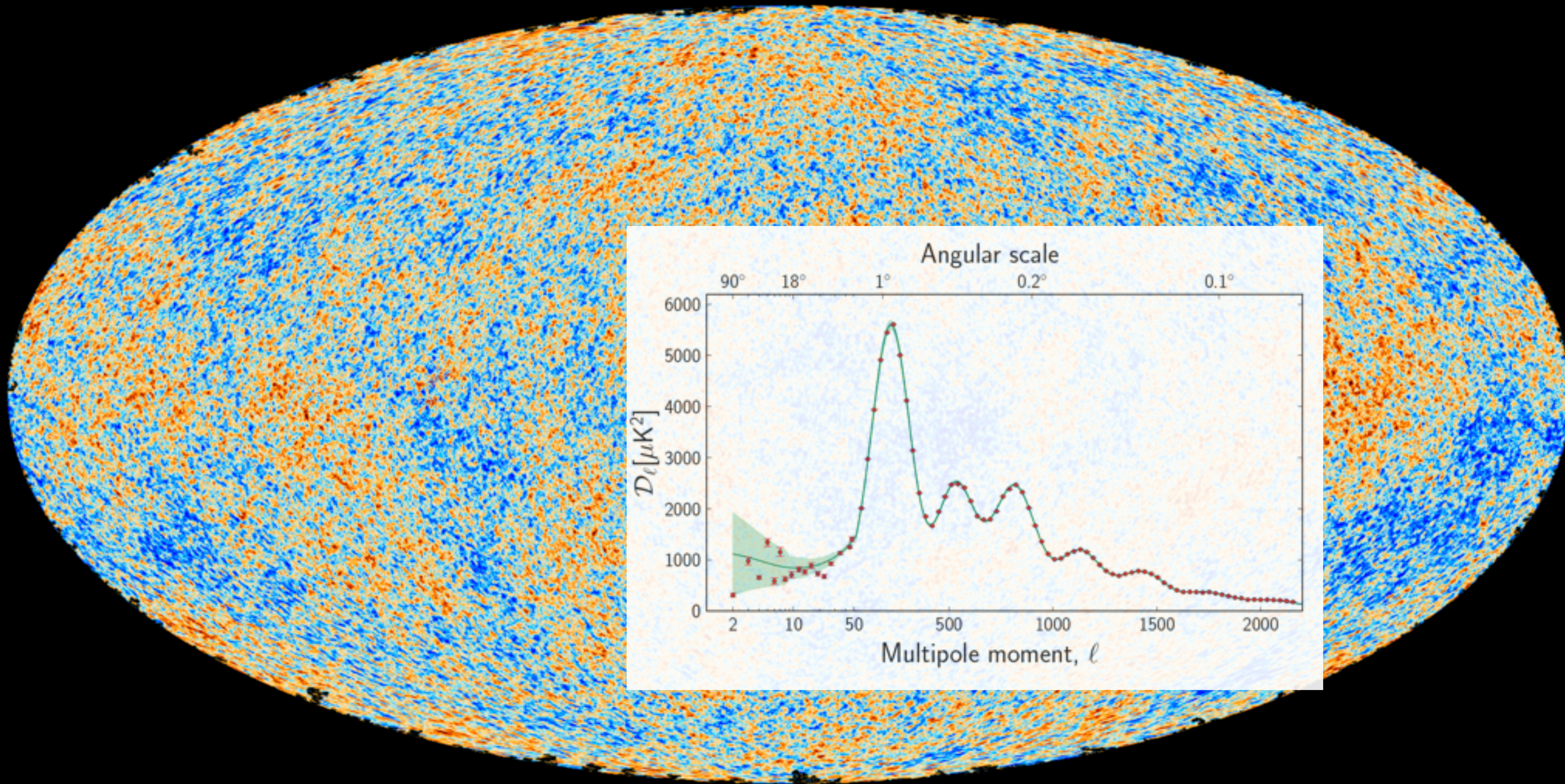
Eisenstein 2005 Blake et al 2011 Beutler 2011 Anderson et al 2012



Sullivan et al 11

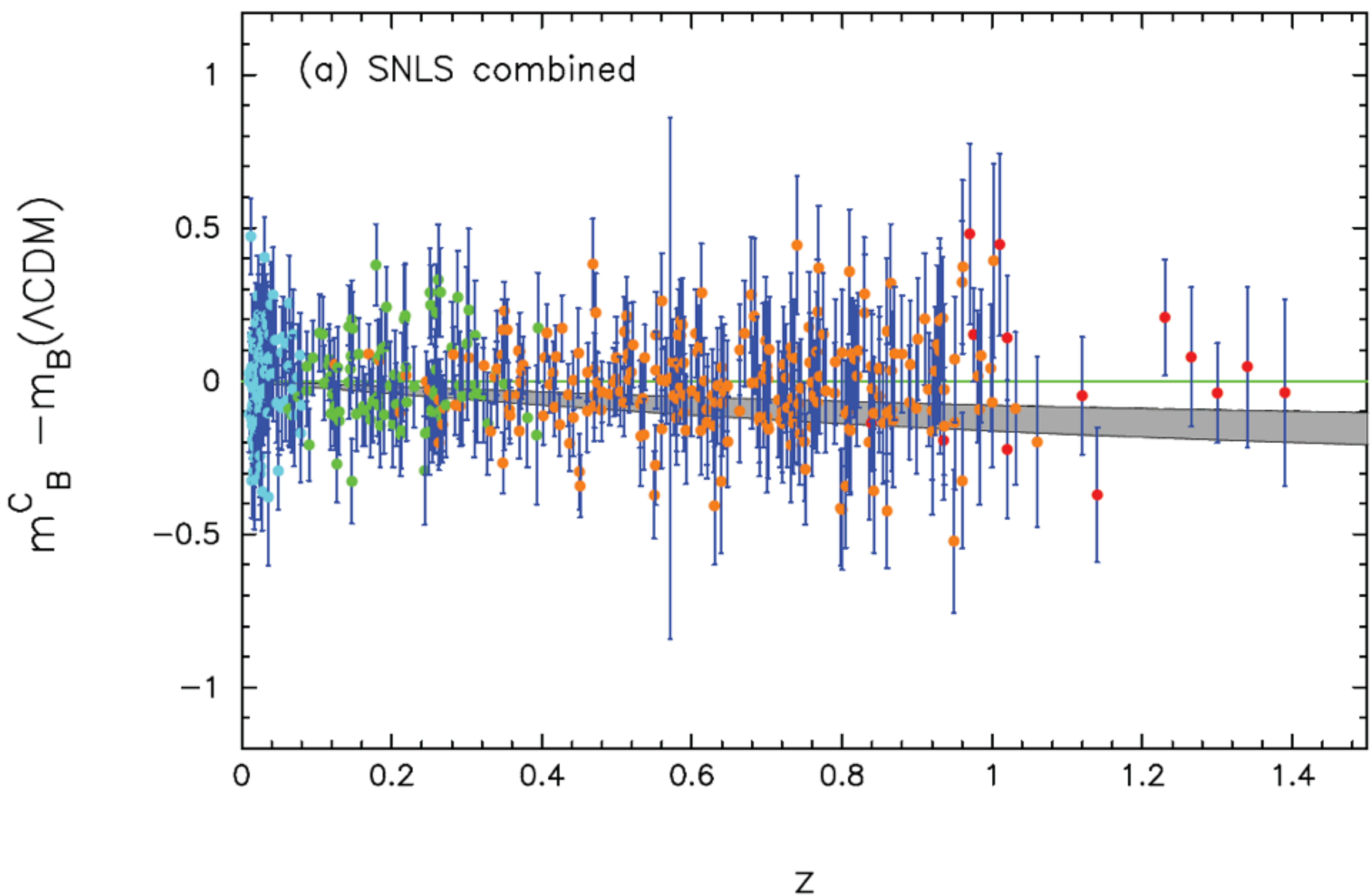


9-year temperature C_l
$l(l+1)C_l/2\pi$ (μK^2)
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment l
TT



Angular scale
90°
18°
1°
0.2°
0.1°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell[\mu K^2]$
2
10
50
500
1000
1500
2000
Multipole moment, ℓ

Distance scale comparison: SNe



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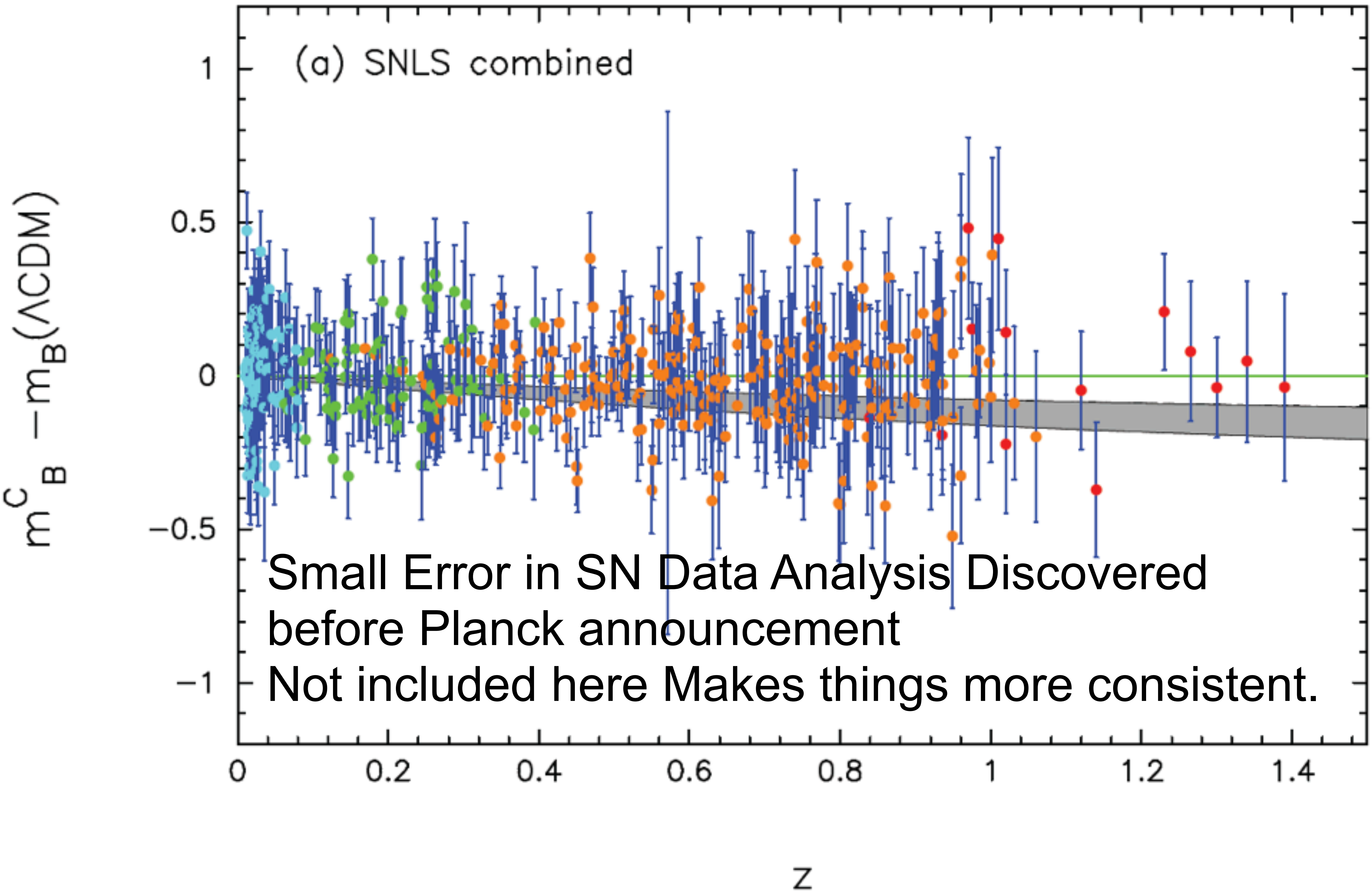

Hubble Constant

- Planck
  - 67.8 ± 0.8 km/s/Mpc
- Local Measures $H_0 = v/D$ (Riess et al 2011)
  - 73.8 ± 2.4 km/s/Mpc
- Very different measures of the Hubble Constant - one is one of 6 parameters in a flat Λ-CDM model - other is direct measure
- But Local measurement is hard...

Calibration is almost Everything!

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Riess et al. 2011 use

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  (71.3 ± 3.8)

  Parallax Distances to Milky Way Cepheids (75.7 ± 2.6)

- 72.8 ± 2.4 km s^{-1} Mpc^{-1}

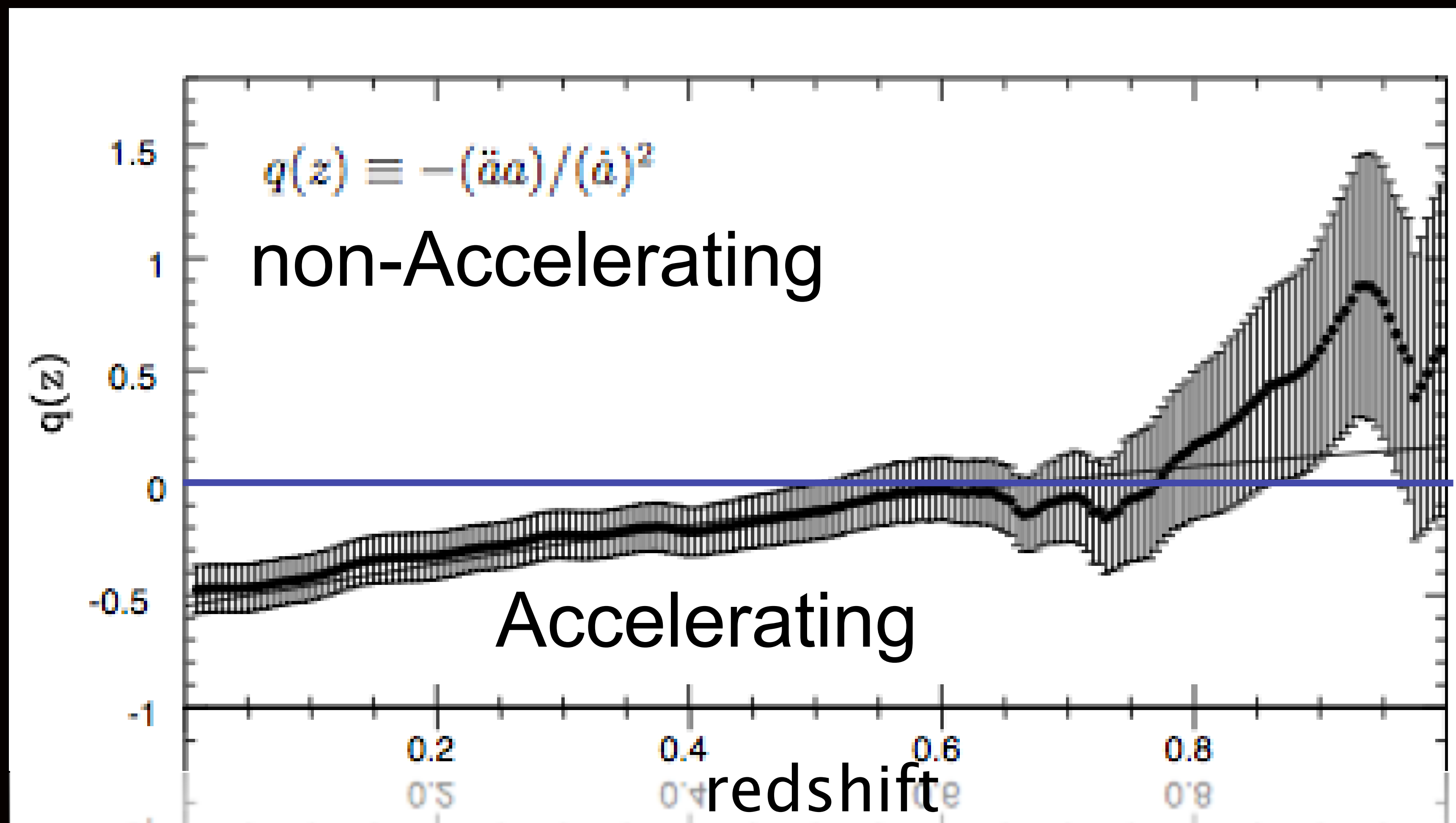
So My Take

- Flat Λ-CDM still fits any given set of data - but there are small inconsistencies between datasets
- But we can improve our optical data sets
  - SN Ia at $z>0.6$
  - Local H_0
- All Analysis from here on out needs to be done as a blind analysis.

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  ?

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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.

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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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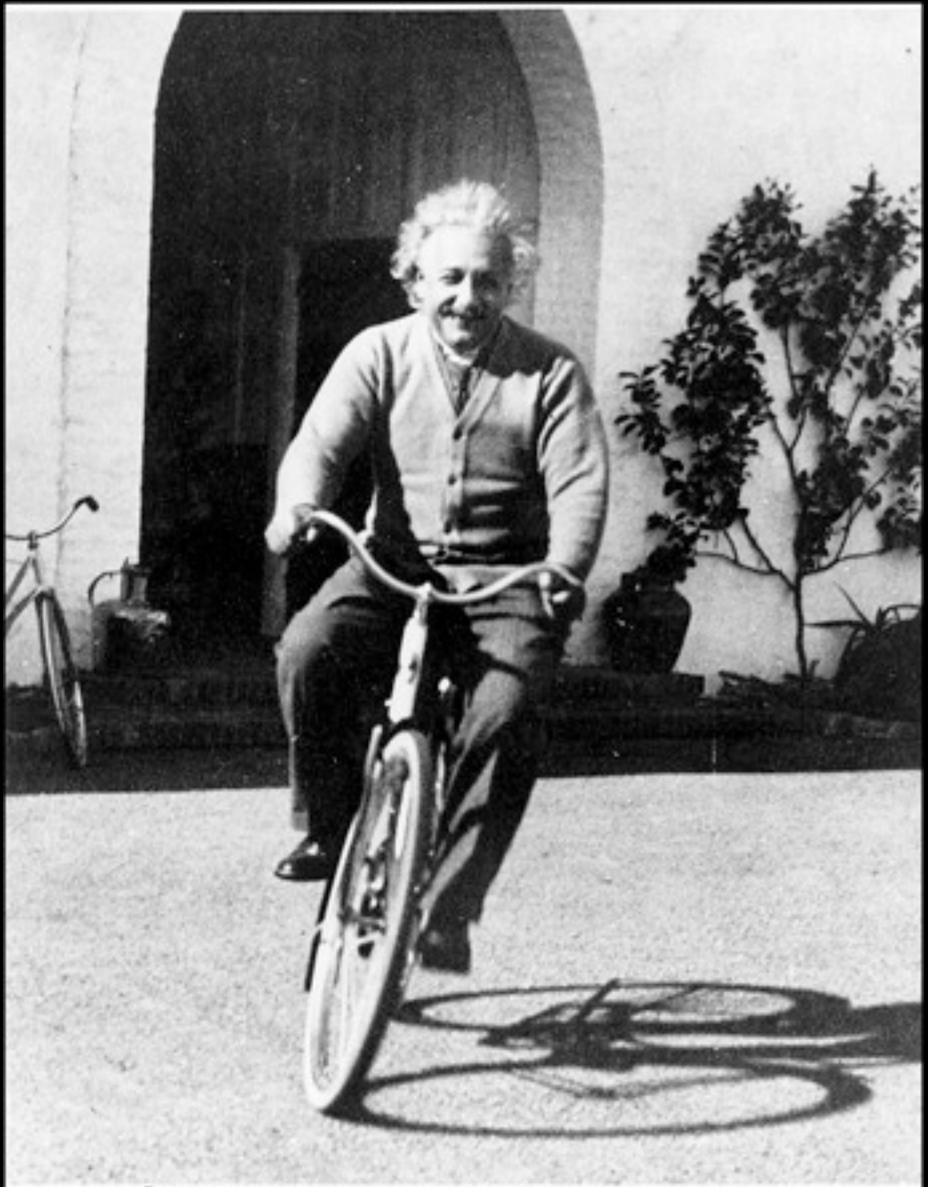
- Quantum Field Theory suggests quantum fluctuations should give a value for Λ, 10^{120} larger than observed
- If dark energy is due to a cosmological constant, its equation of state is $w = P/\rho = -1$ at all times. This is testable!



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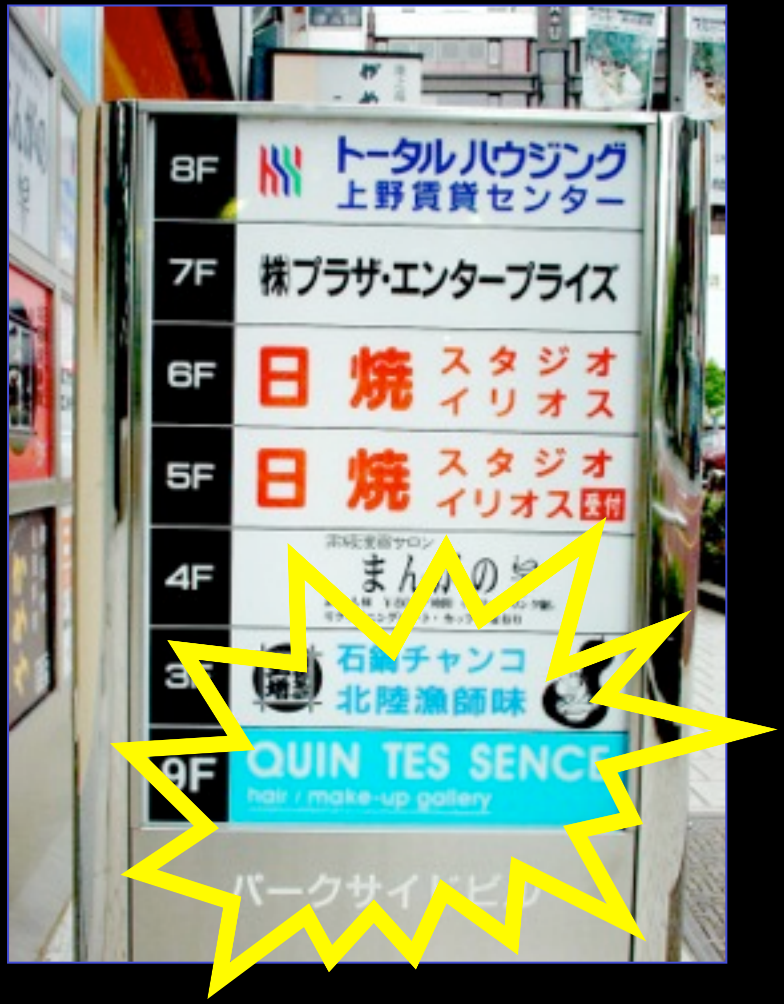

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Dark Energy Ideas

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

The Standard Model

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- Isotropy
- Inflation (Initial Conditions)
  - Flatness, structure seeds, Uniform CMB
- (5%)Atoms
- (25%)Cold Dark Matter
- (70%) Cosmological Constant
- H_0=70 km/s/Mpc

Predicts

- Expansion History of the Universe
- Growth of Structure of the Universe
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Principal Issue is 95% of Universe is not understood

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- Theoretical Insight
  - Why do quantum fluctuations not lead to an enormous Cosmological Constant?
  - Why Does Dark Energy Exist?

Dark Energy Futures
Expect the Unexpected

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- Physics is still full of Mysteries
- By continuing to explore the Universe around us from the solar system to 13.8 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

The Future of the Universe seems to be Dark Energy

The Big Chill?

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Dark Energy is Λ - it gets created exactly as space gets Created.

$w=-1$

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The Big Chill?

Dark Energy is Λ - it gets created exactly as space gets Created.

w=-1

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

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

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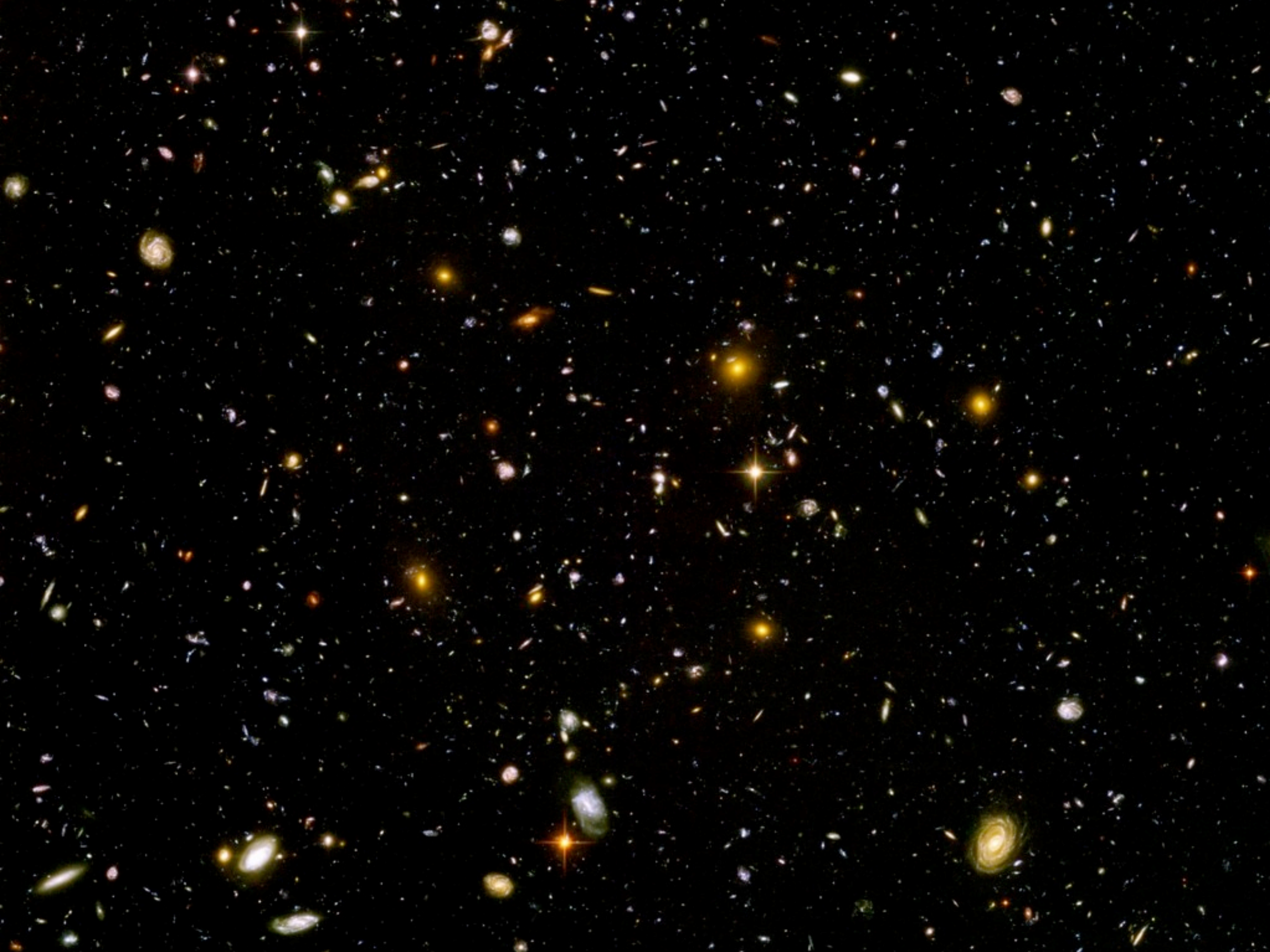
anything is possible.

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...