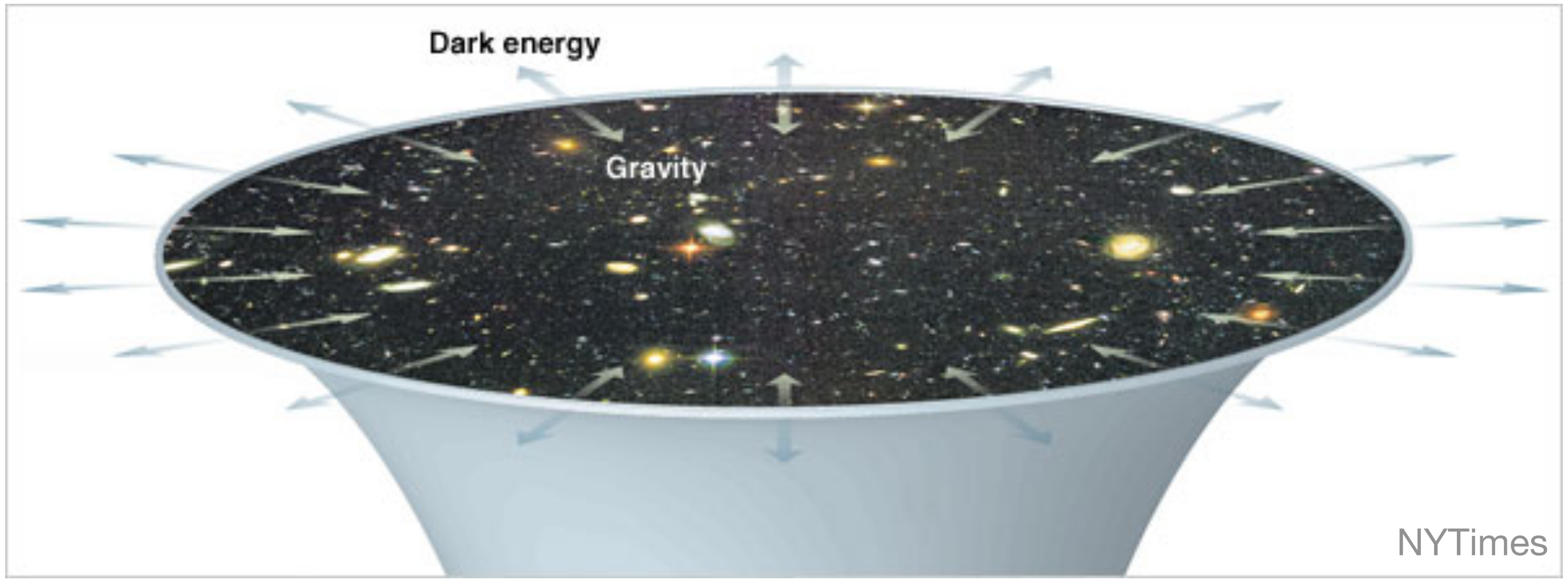
Dark Energy and the Accelerating Universe

Prof. Neelima Sehgal

Stony Brook University

DMSS 2018
July 20th, 2018



Einstein field equations

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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Ω_Λ = % of dark energy density

Ω_M = % of matter density (including dark matter)

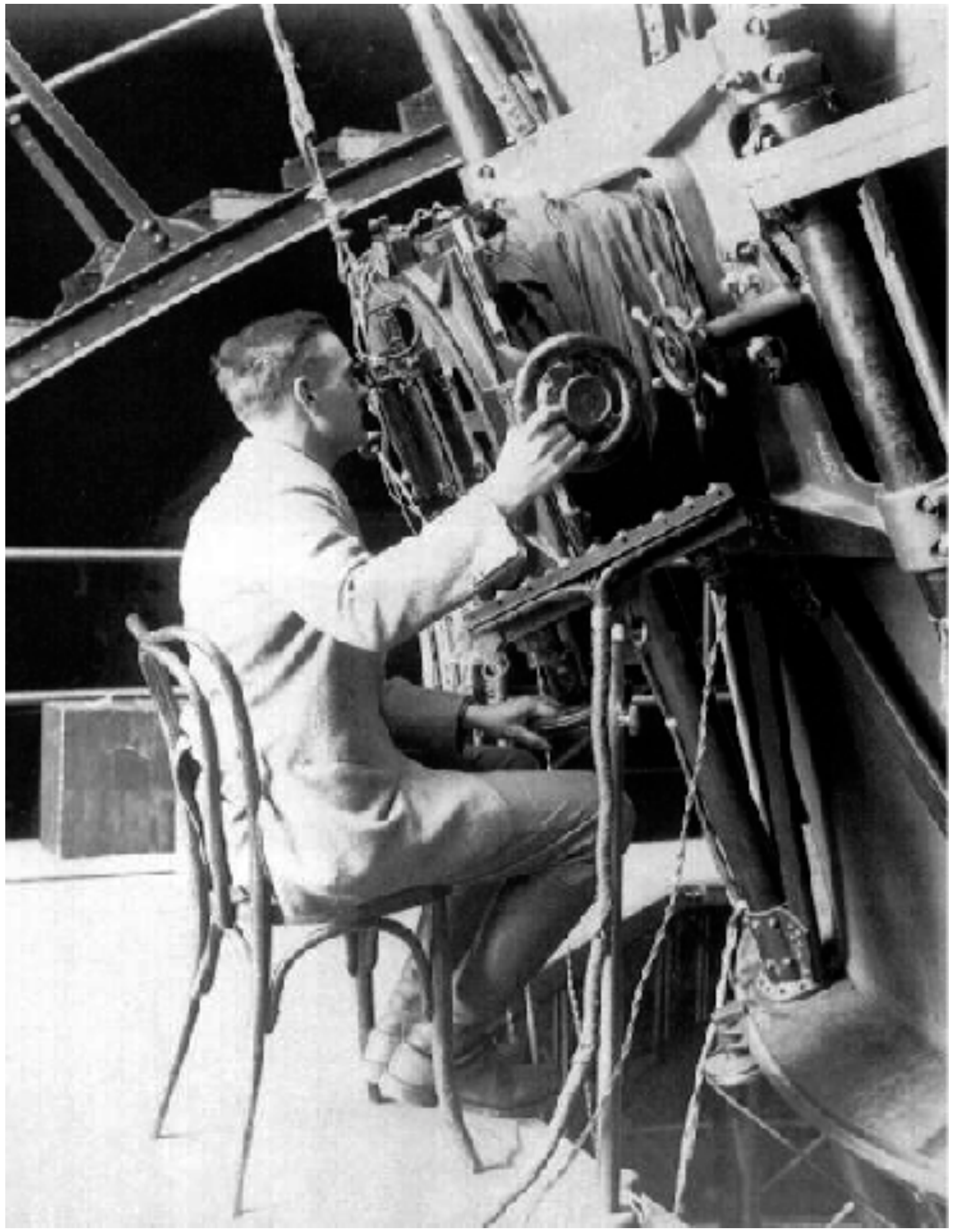
In 1917, Einstein introduced Lambda into his field equations to keep the Universe static

Edwin Hubble

2012 Hubble eXtreme Deep Field

Credit: NASA; ESA; G. Illingworth, D. Magee, and P. Oesch, University of California, Santa Cruz; R. Bouwens, Leiden University; and the HUDF09 Team

Edwin Hubble



Edwin Hubble at the 100-inch telescope at Mt. Wilson

Hubble 1929

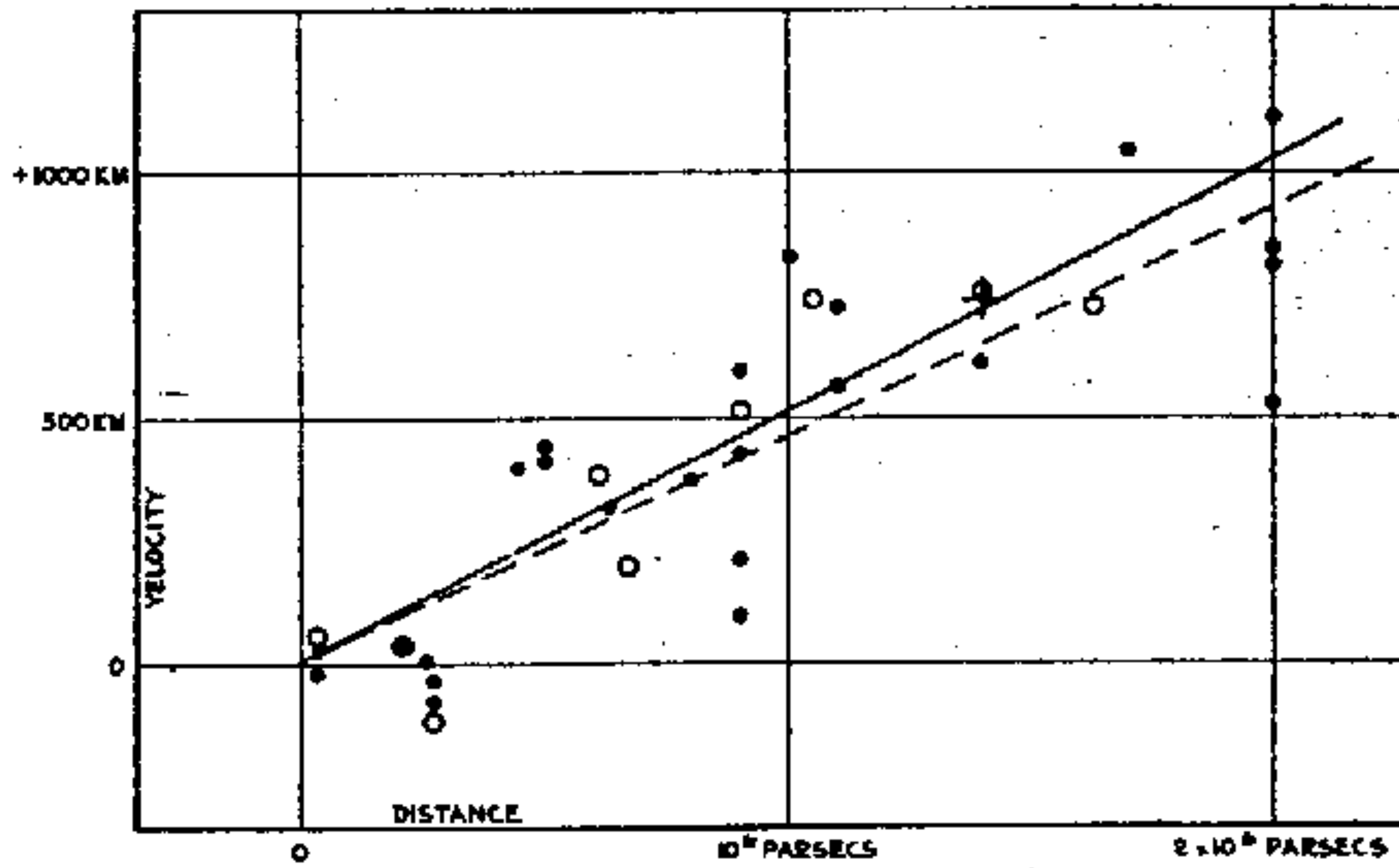


FIGURE 1

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Hubble 1929

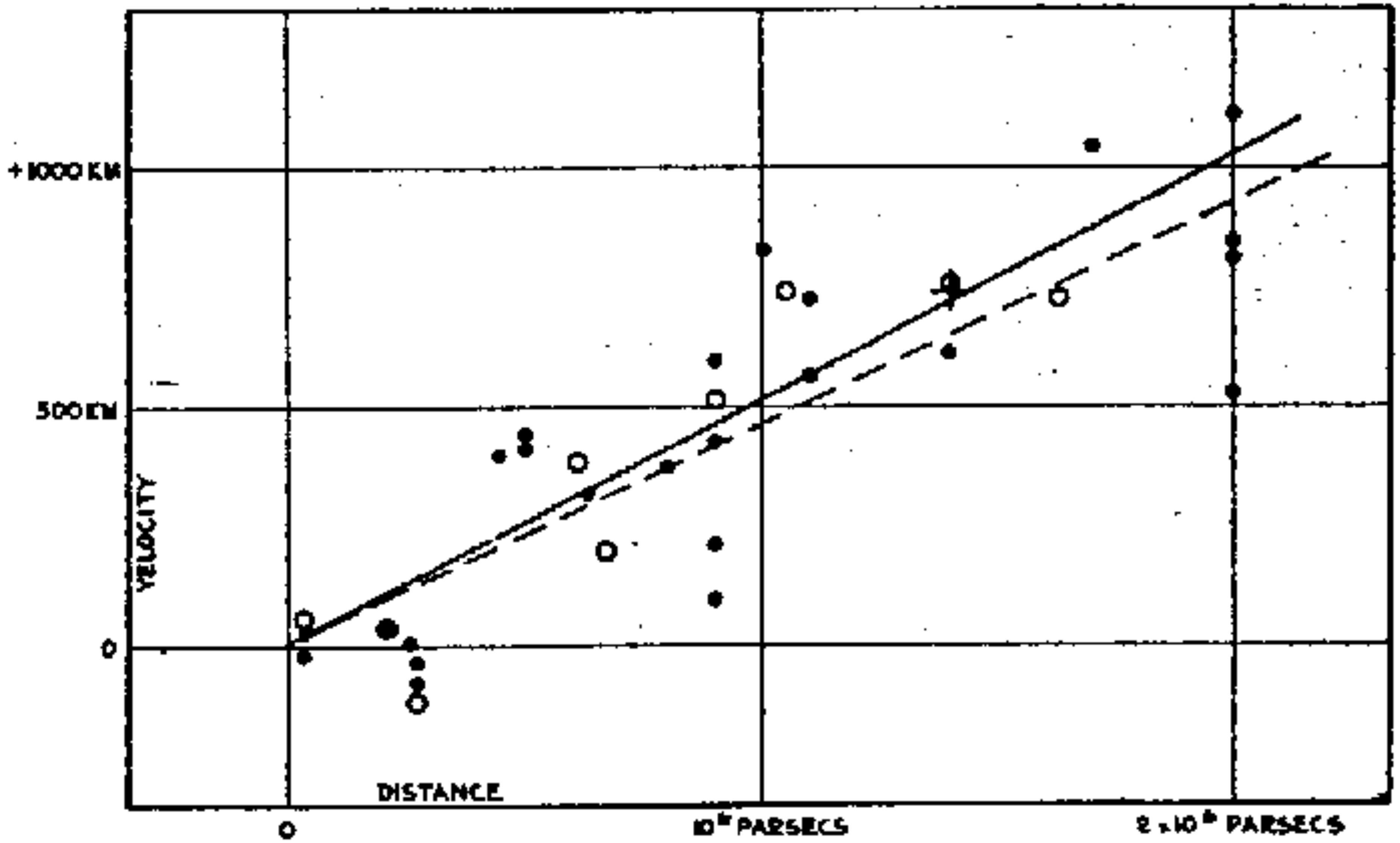

FIGURE 1

$$v = H_0 D$$

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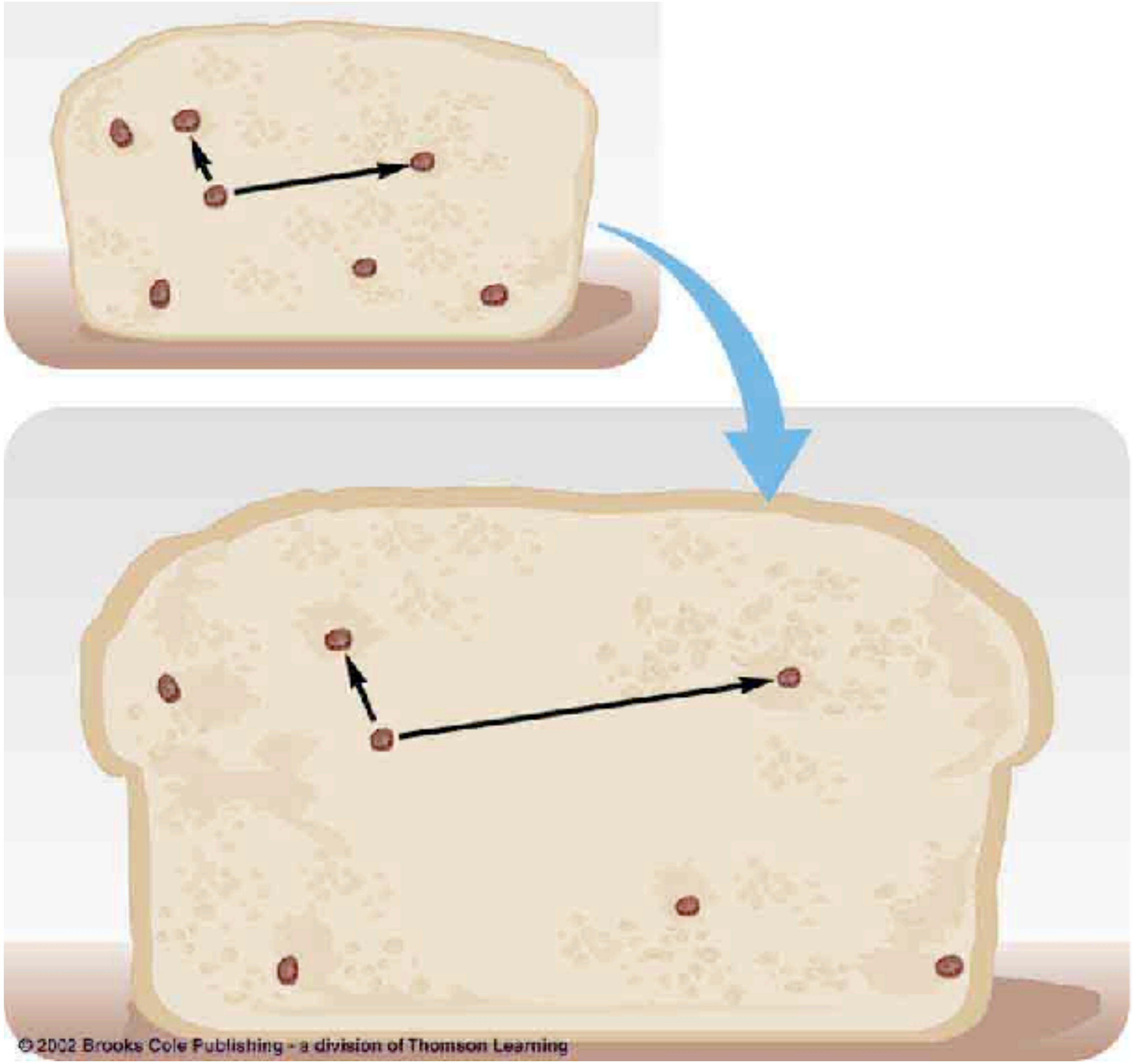

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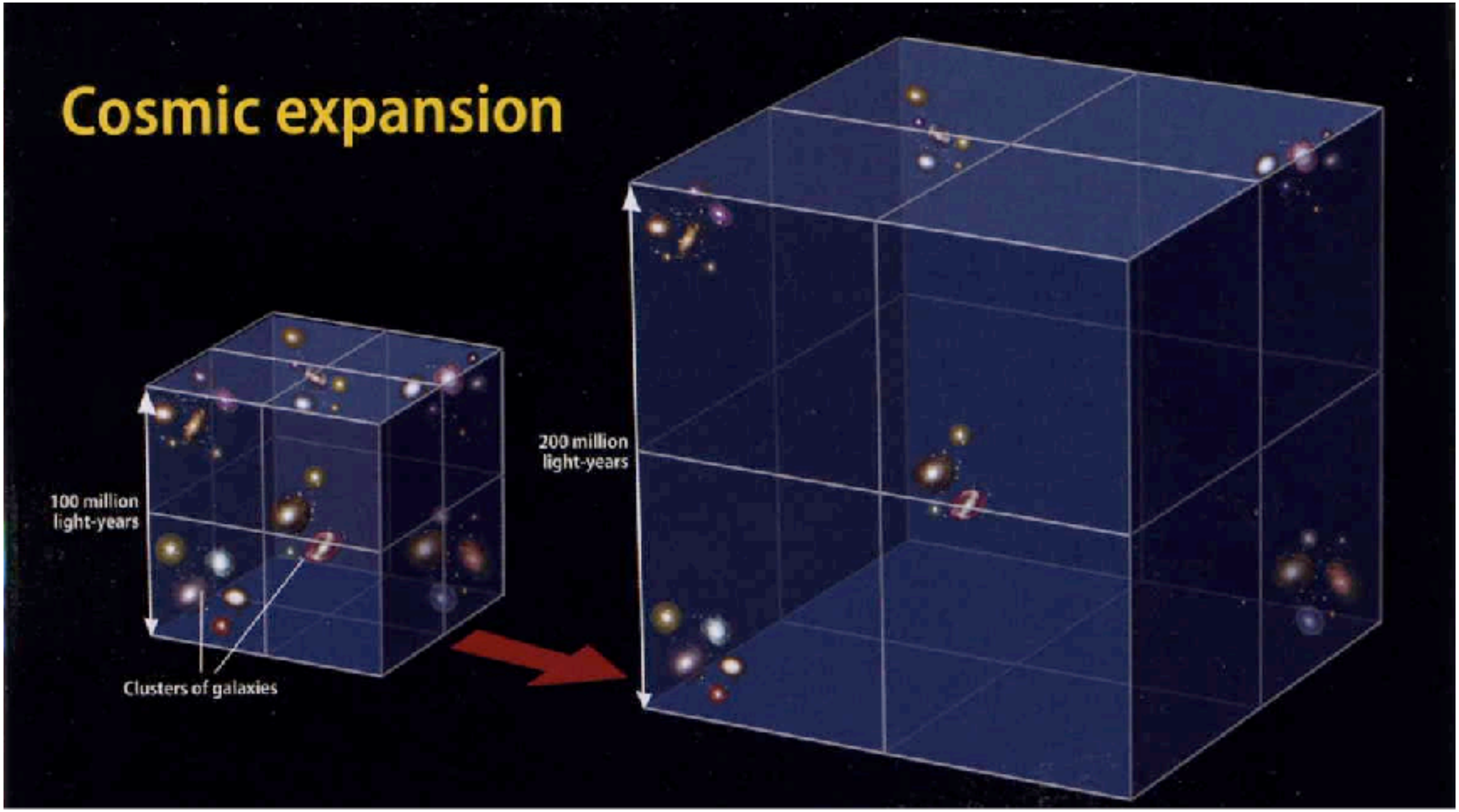
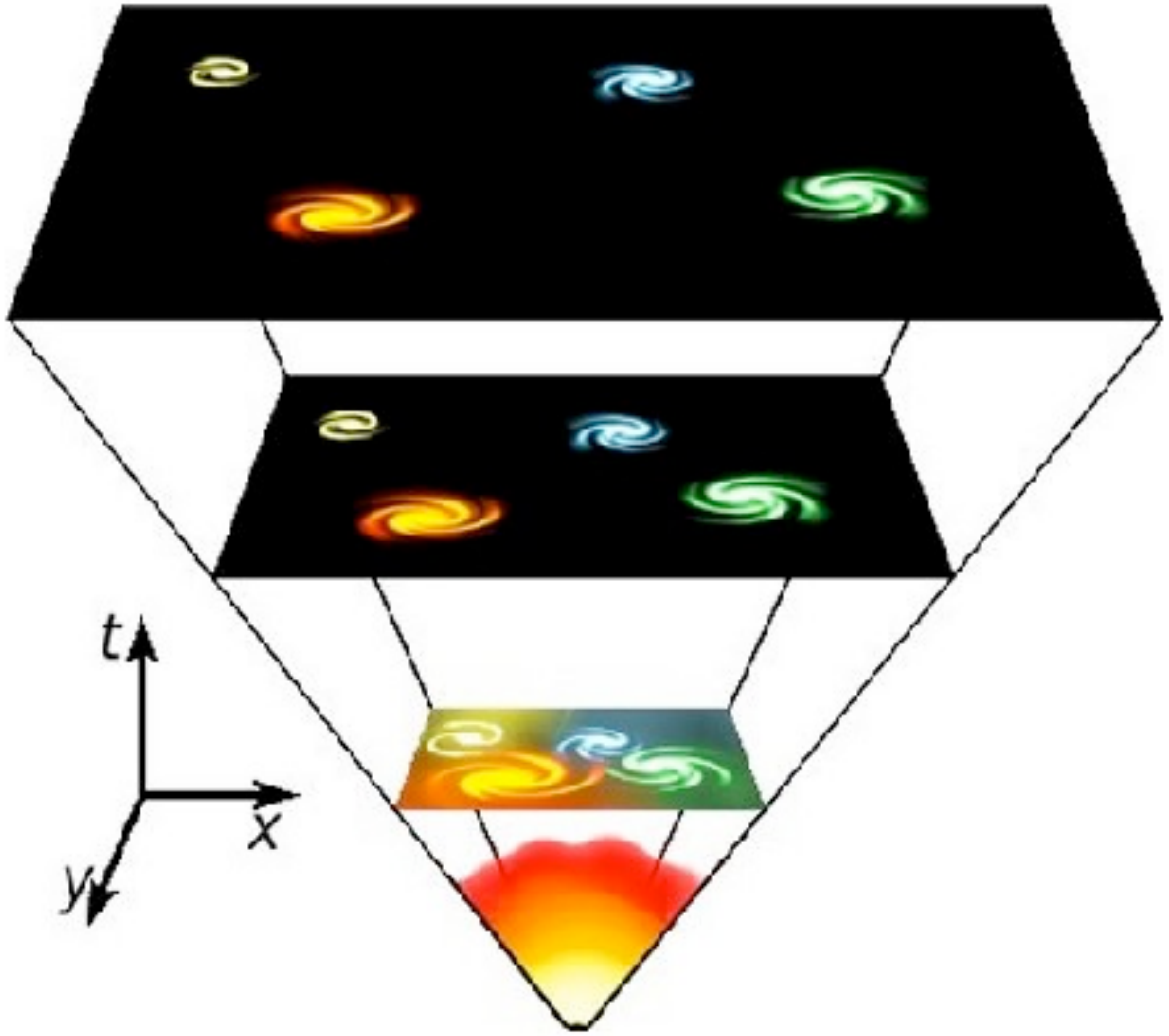


Image credit: http://home.earthlink.net

Big Bang Theory



Source: Wikipedia: http://en.wikipedia.org/wiki/Big_Bang

Hubble and Einstein 1931

Albert Einstein, Edwin Hubble, and Walter Adams (l-r) in 1931 at the Mount Wilson Observatory 100" telescope, in the San Gabriel Mountains of southern California. It was here in 1929 that Hubble discovered the cosmic expansion of the universe. *Courtesy of the Archives, California Institute of Technology*

Supernovae Teams Aimed to Measure Deceleration of Universe

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Type Ia Supernova

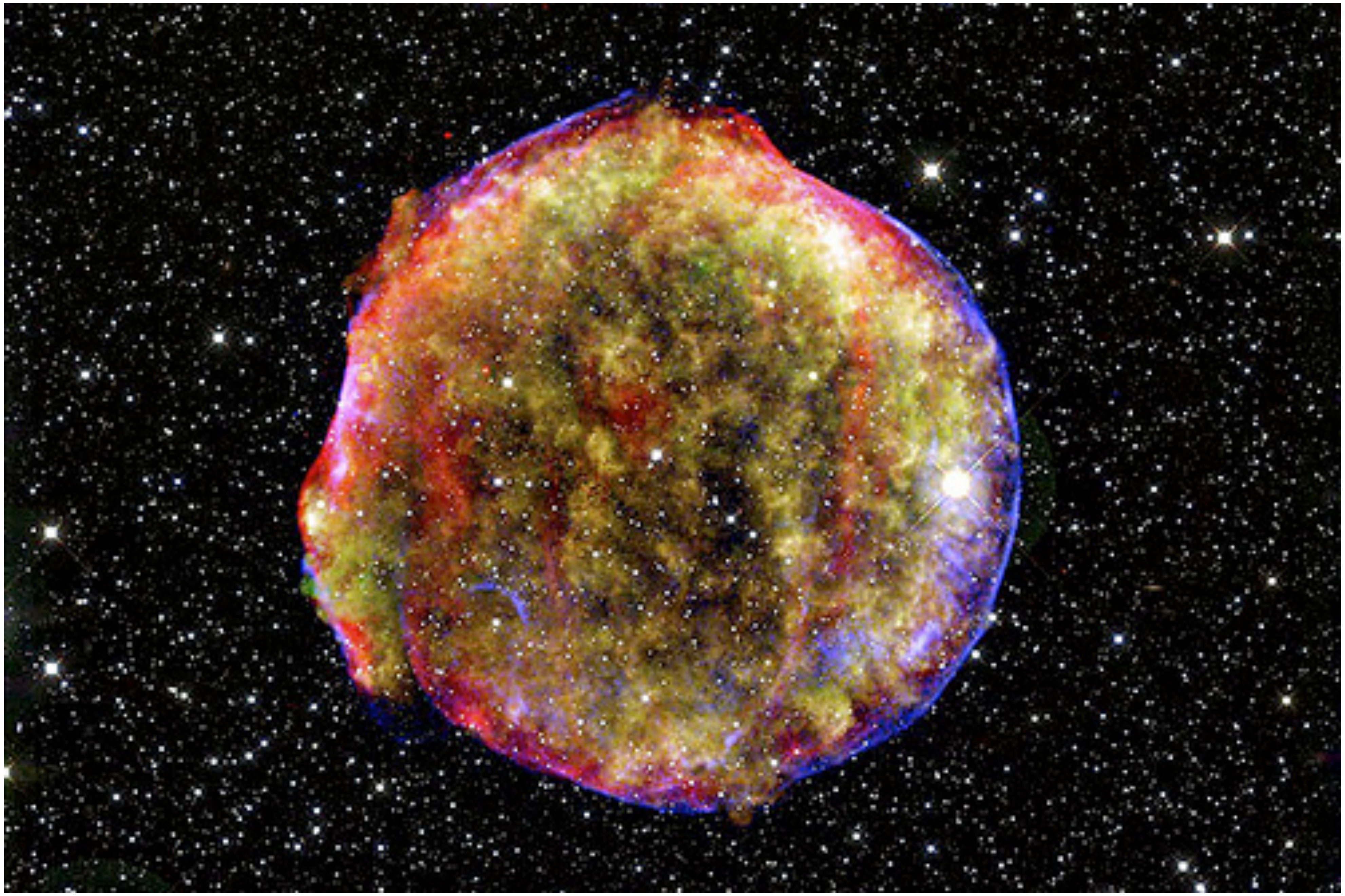
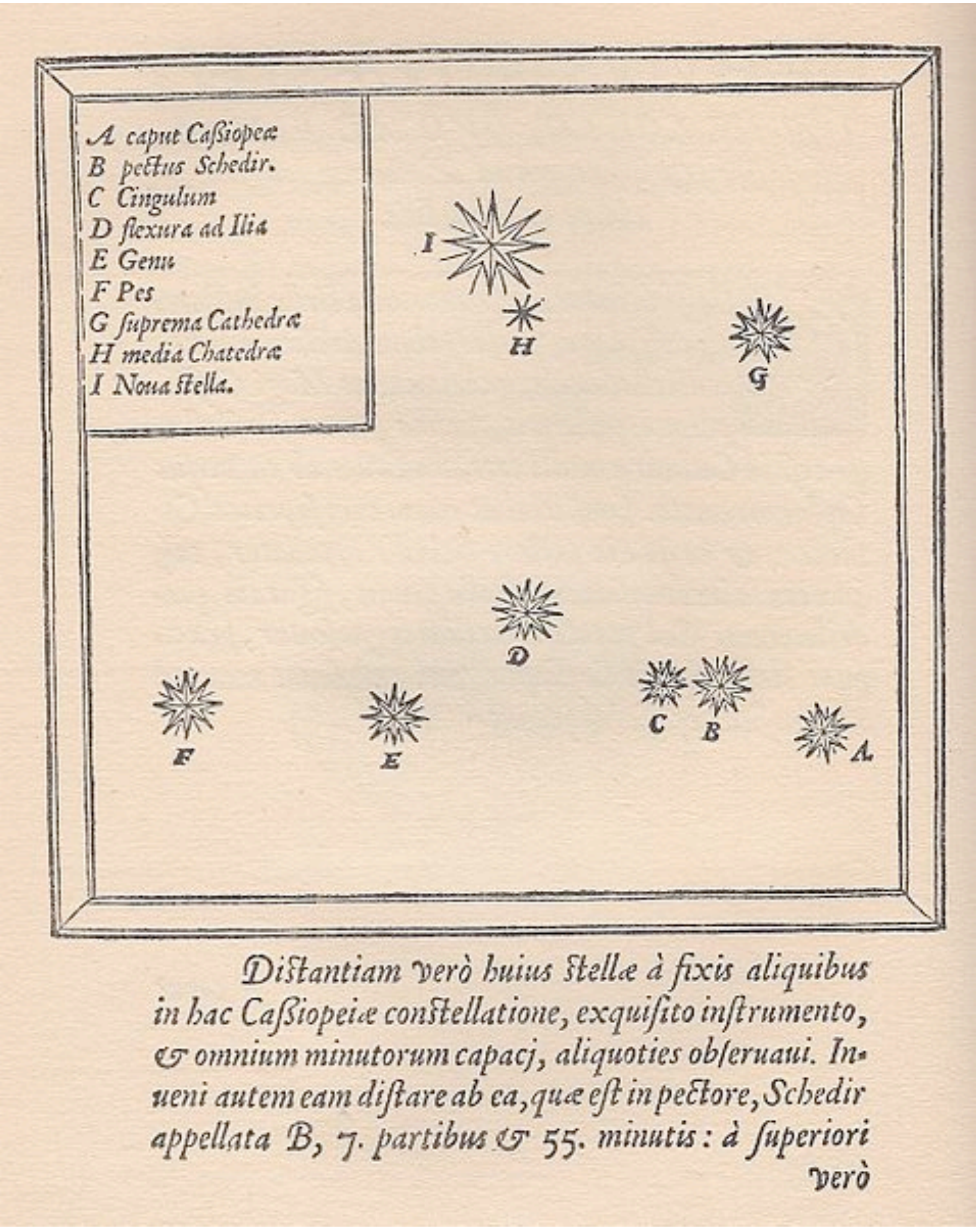


Image of remnant from the type Ia Tycho supernova: X-ray: NASA/CXC/SAO, Infrared: NASA/JPL-Caltech; Optical: MPIA, Calar Alto, O.Krause et al.

Tycho’s Supernovae 1572



A caput Caßiopeæ
B pectus Schedir.
C Cingulum
D flexura ad Ilia
E Genu
F Pes
G ſuprema Cathedræ
H media Chatedræ
I Noua ſtella.

Diſtantiam verò huius ſtellæ à fixis aliquibus in hac Caßiopeiæ conſtellatione, exquiſito inſtrumento, & omnium minutorum capacj, aliquoties obſeruaui. Inueni autem eam diſtare ab ea, quæ eſt in pectore, Schedir appellata B, 7. partibus & 55. minutis: à ſuperiori verò

November 11, 1572

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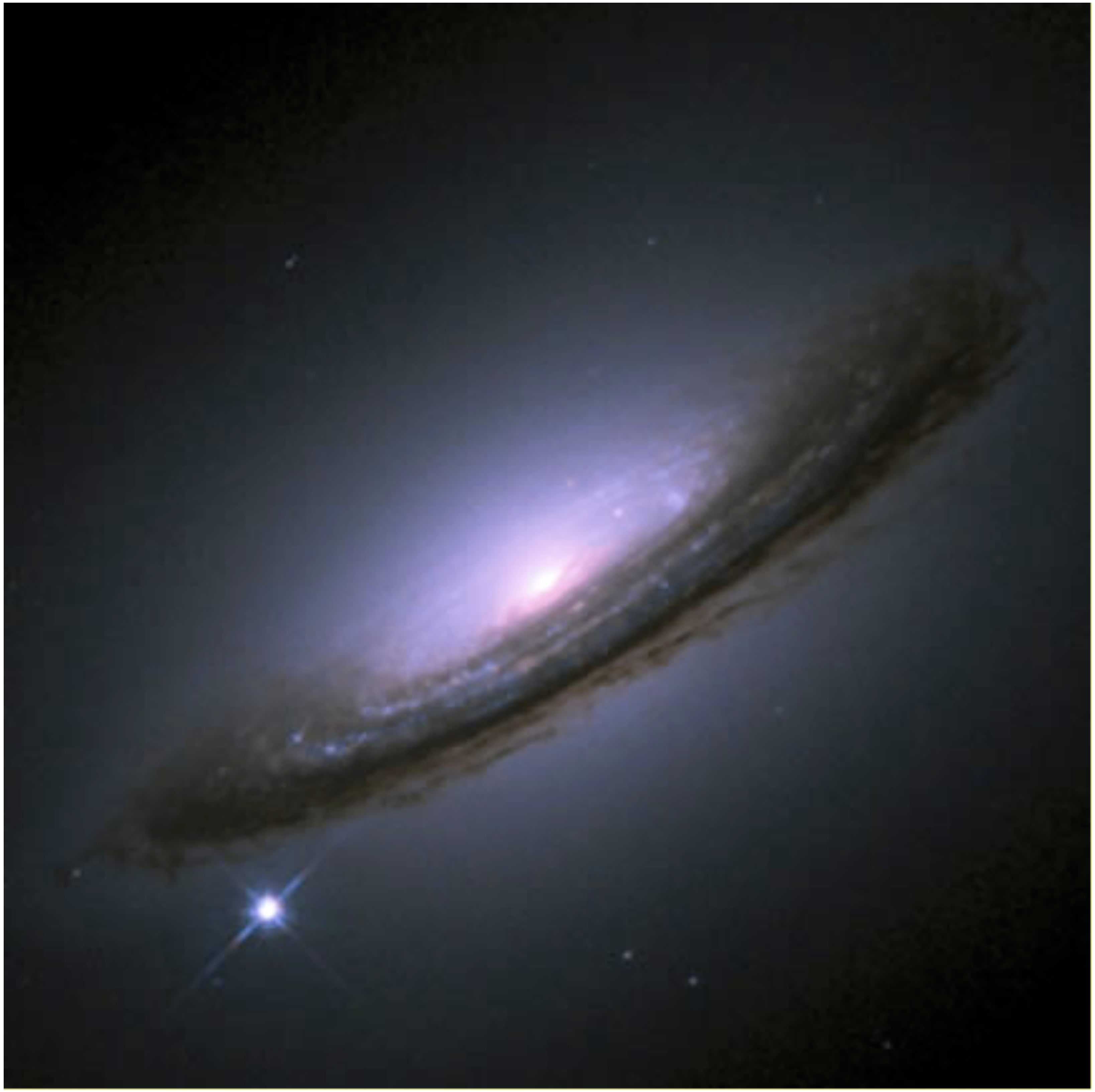
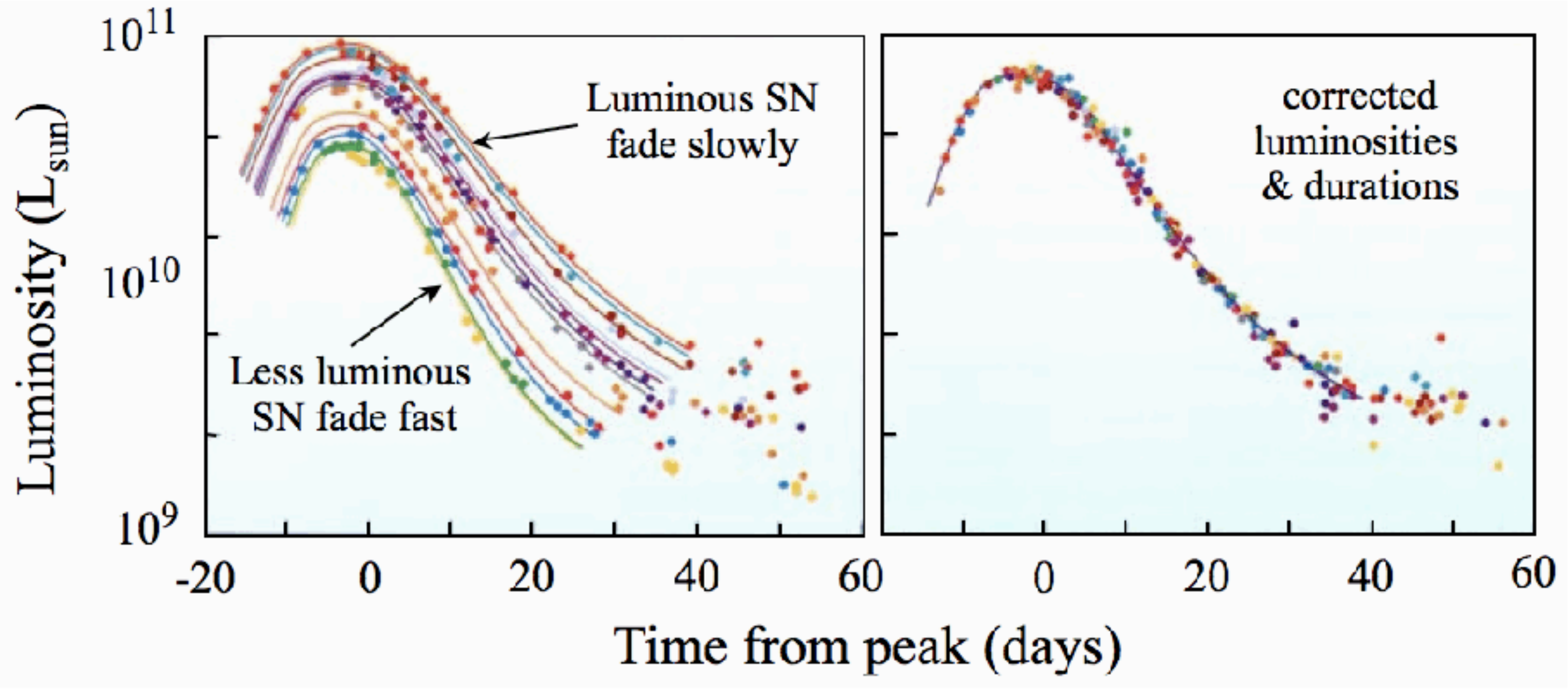


Credit: NASA and the High-Z Supernovae Search Team

Standard Candles

Credit: Lawrence Livermore National Laboratory/Universe Adventure

Need Supernovae Images to Measure Decline of Light Curves



http://community.dur.ac.uk/john.lucey/bridge/SN2015M_bridge.html

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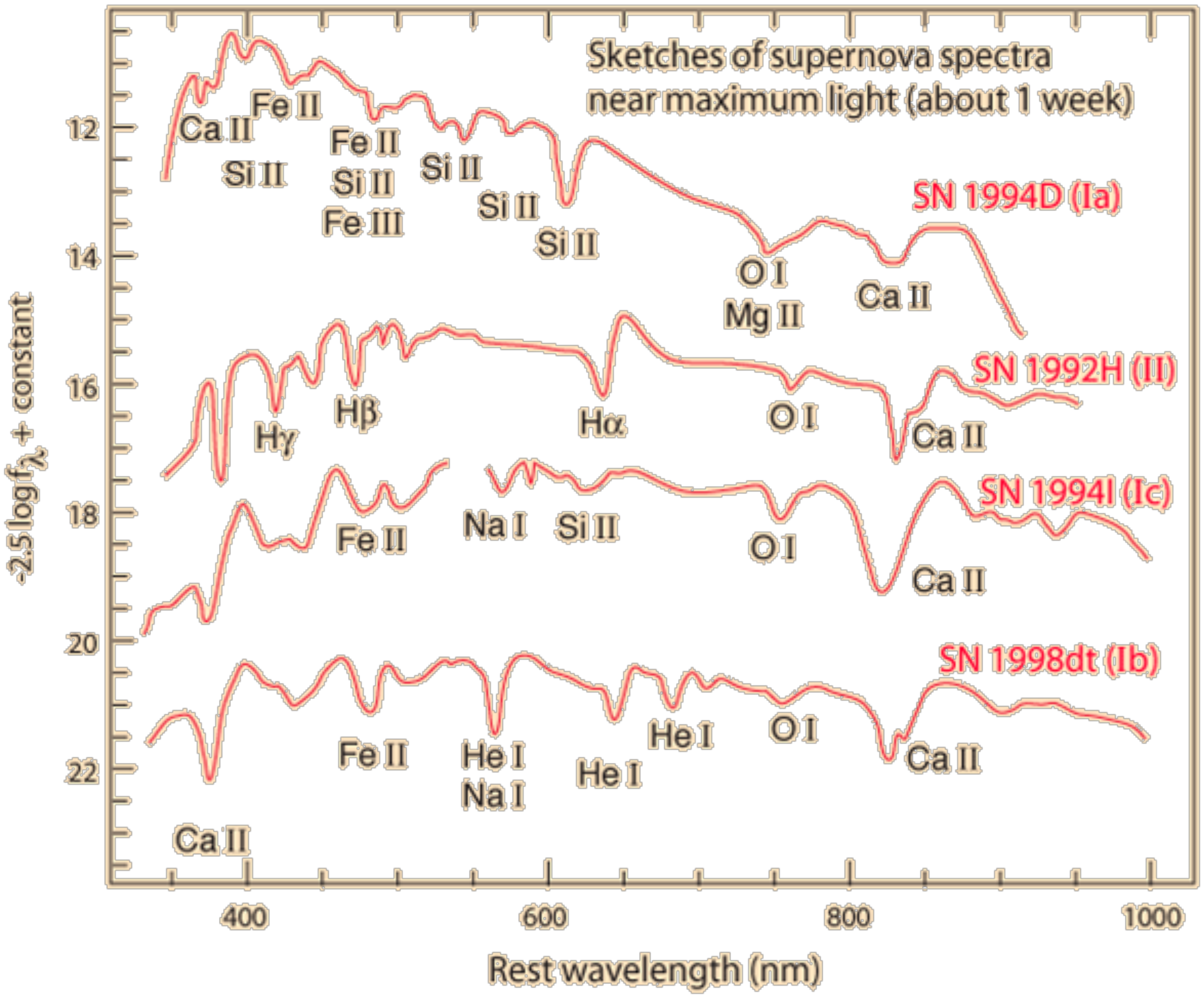
Need Spectra to Determine Supernova Spectral Type and Redshift



Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

Type Ia SN have no hydrogen or helium lines, and strong Si II lines, unlike other SN

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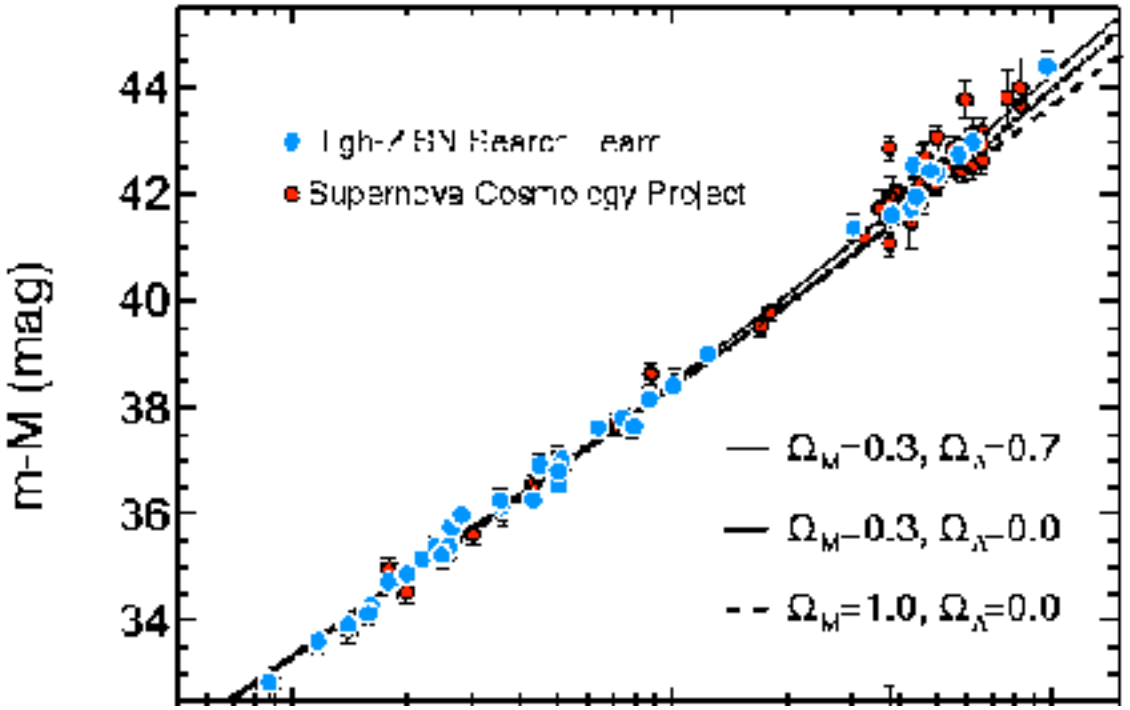
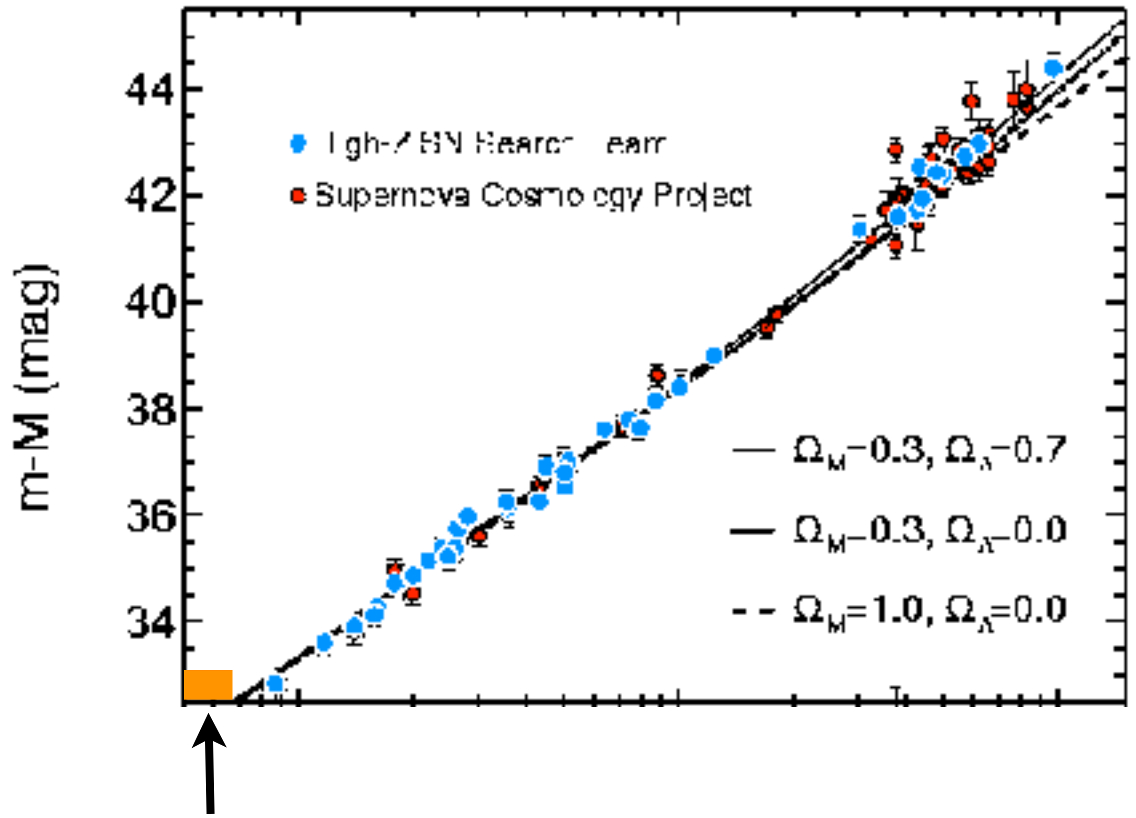
Supernovae Data in 1998-1999

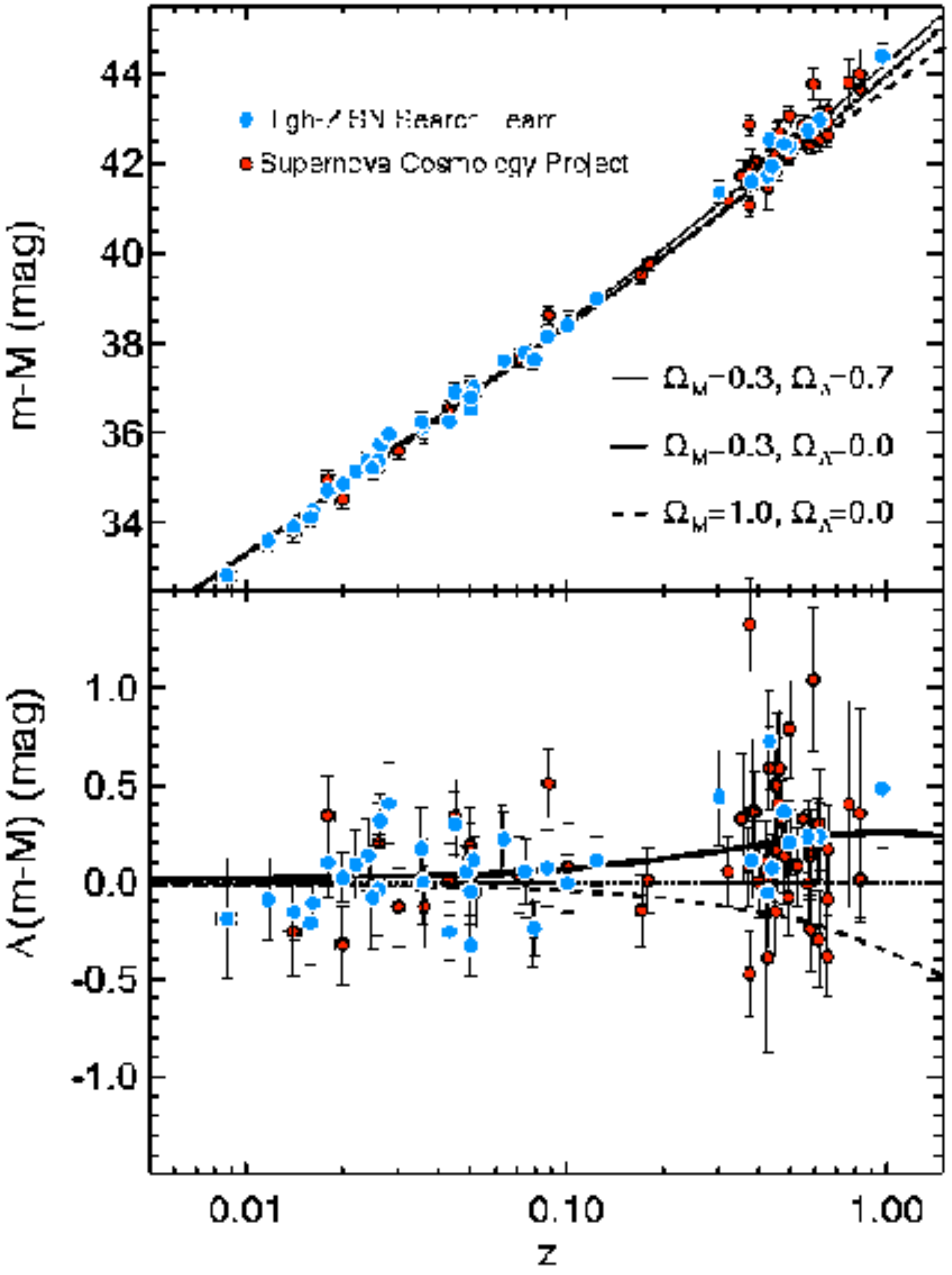


Supernovae Data in 1998-1999



Hubble Data

Supernovae Data in 1998-1999



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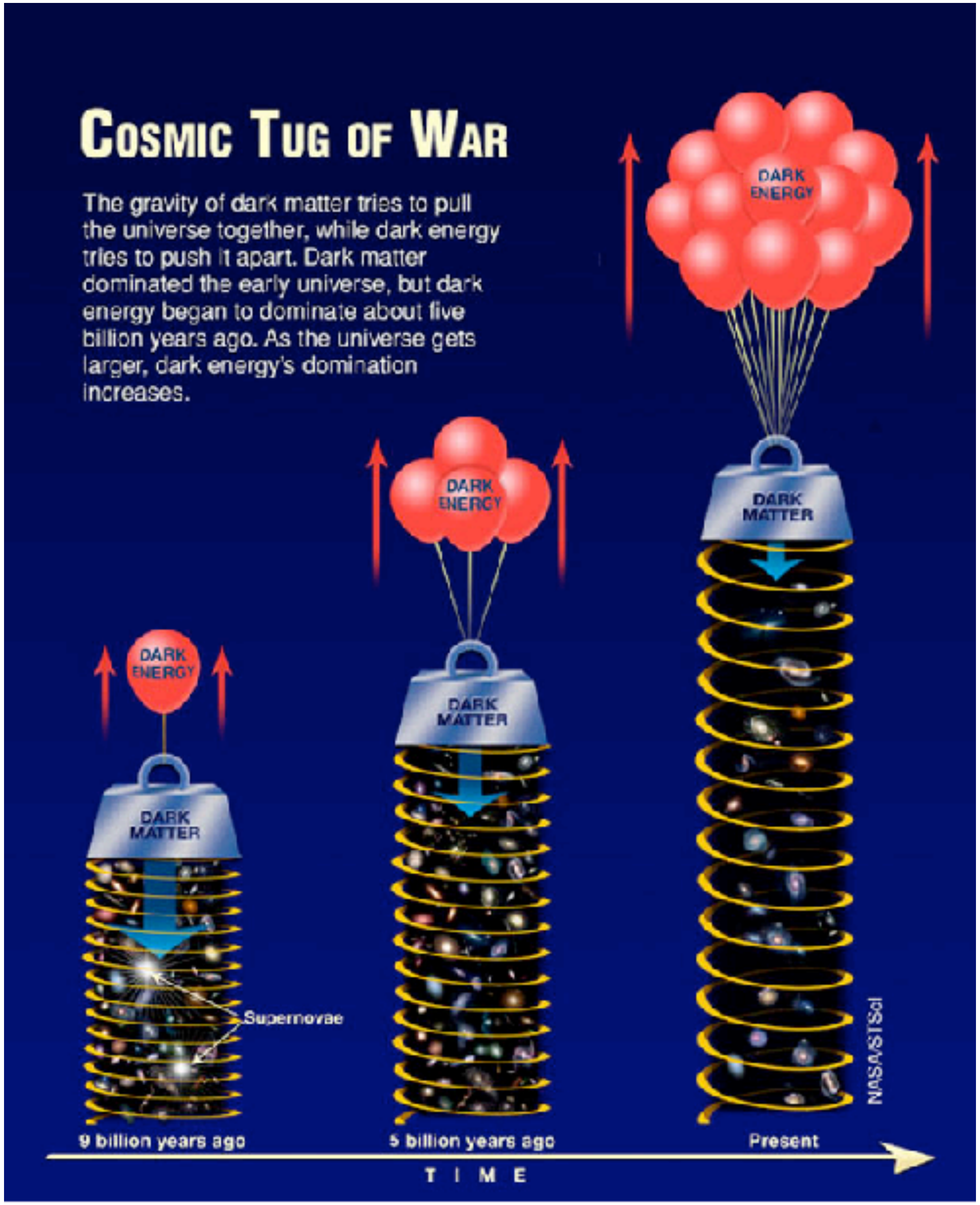

COSMIC TUG OF WAR

The gravity of dark matter tries to pull the universe together, while dark energy tries to push it apart. Dark matter dominated the early universe, but dark energy began to dominate about five billion years ago. As the universe gets larger, dark energy's domination increases.

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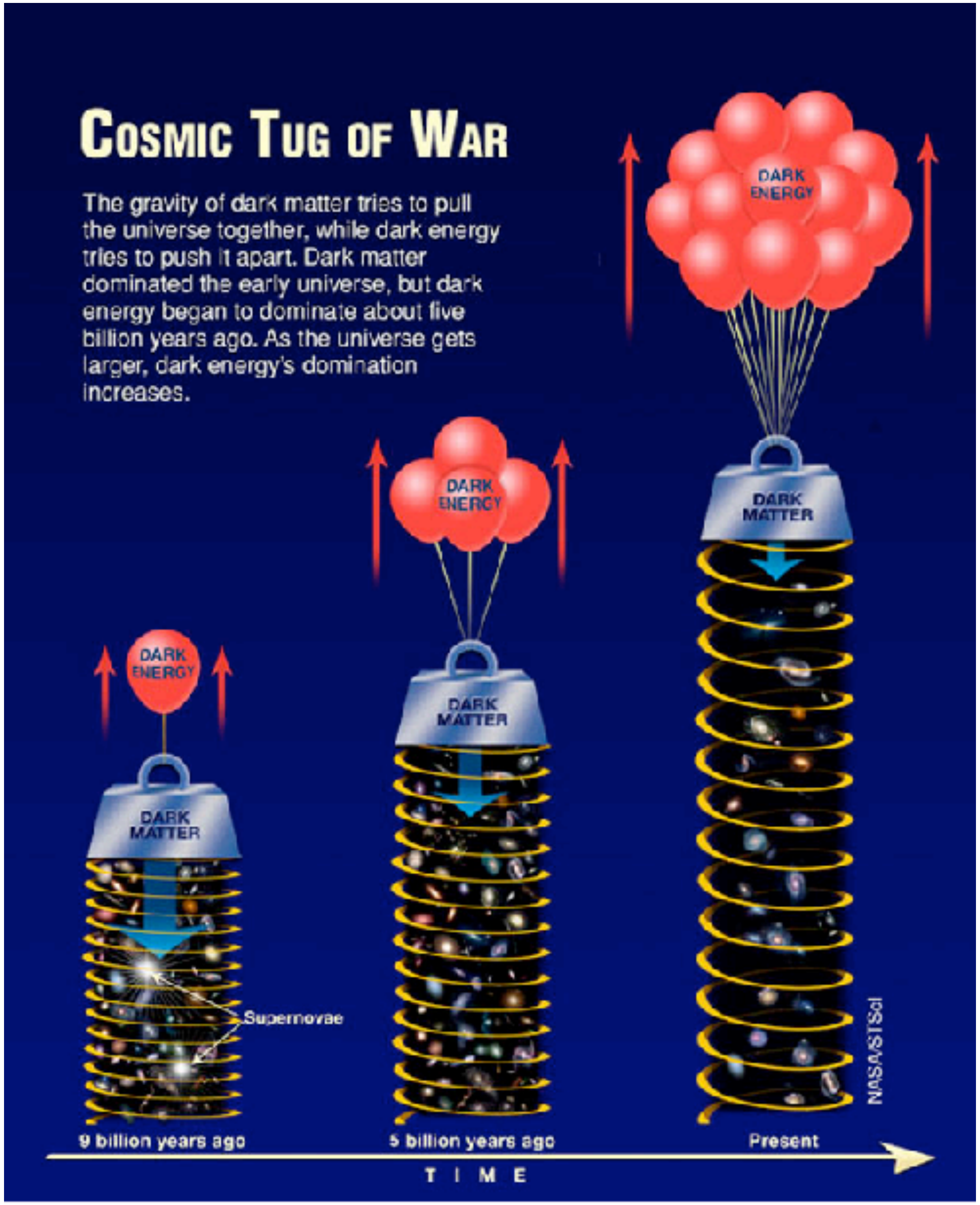

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Dark Energy is something that is causing an apparent accelerated expansion

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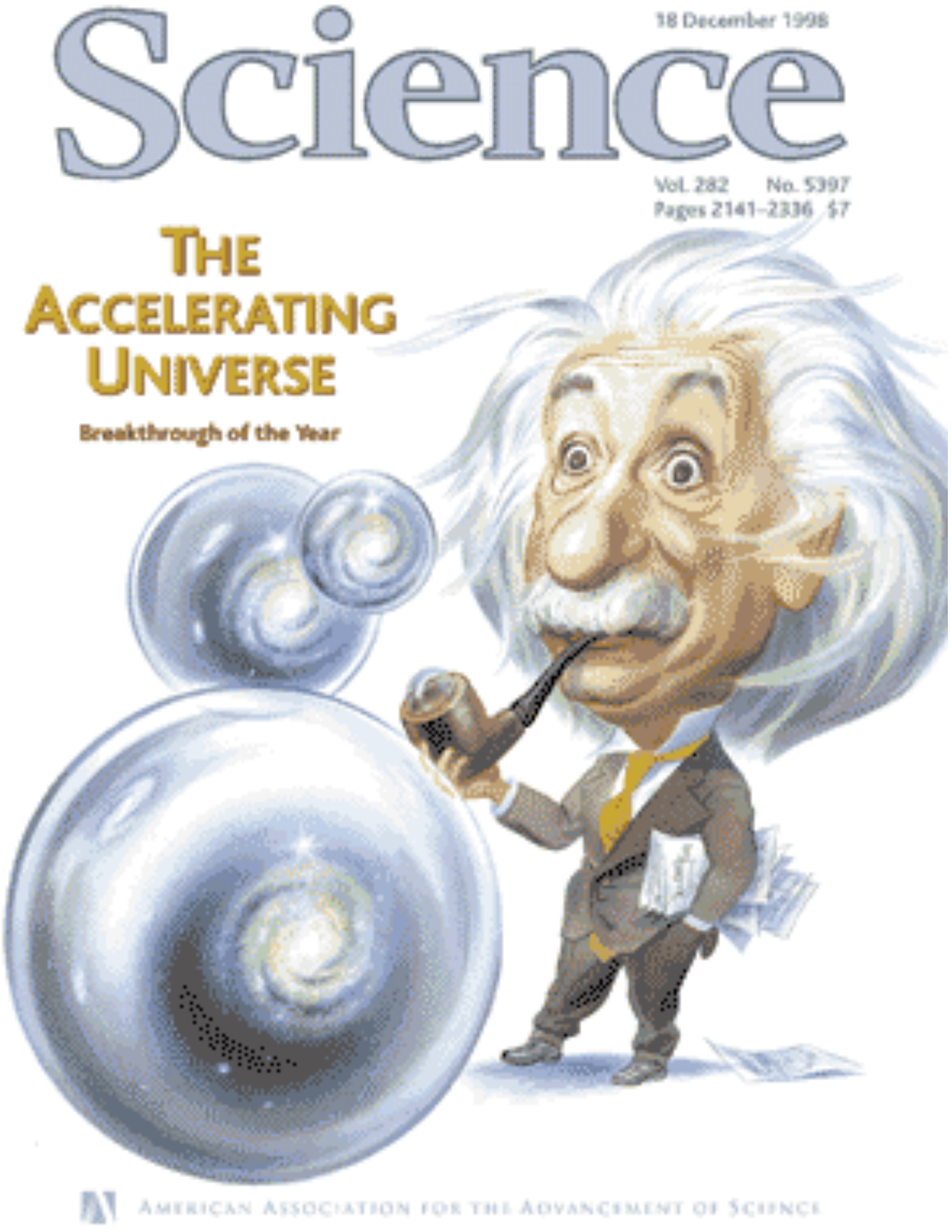
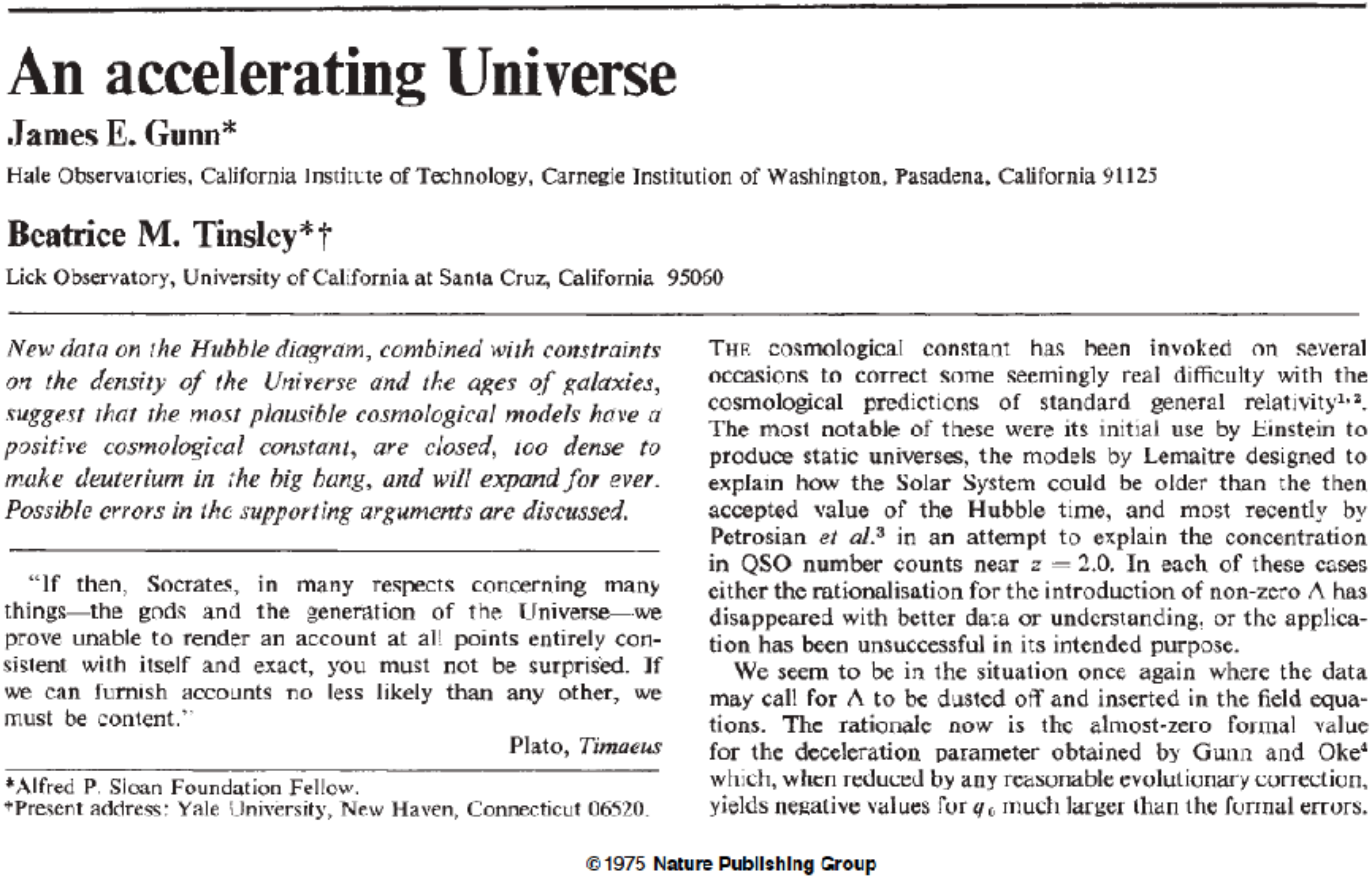
Science announces Accelerating Universe is Breakthrough of the Year



Nobel Prize

Physics 2011



An accelerating Universe

James E. Gunn*
Hale Observatories, California Institute of Technology, Carnegie Institution of Washington, Pasadena, California 91125

Beatrice M. Tinsley*†
Lick Observatory, University of California at Santa Cruz, California 95060

New data on the Hubble diagram, combined with constraints on the density of the Universe and the ages of galaxies, suggest that the most plausible cosmological models have a positive cosmological constant, are closed, too dense to make deuterium in the big bang, and will expand for ever. Possible errors in the supporting arguments are discussed.

> "If then, Socrates, in many respects concerning many things—the gods and the generation of the Universe—we prove unable to render an account at all points entirely consistent with itself and exact, you must not be surprised. If we can furnish accounts no less likely than any other, we must be content."
>
> Plato, *Timaeus*

THE cosmological constant has been invoked on several occasions to correct some seemingly real difficulty with the cosmological predictions of standard general relativity[1,2]. The most notable of these were its initial use by Einstein to produce static universes, the models by Lemaitre designed to explain how the Solar System could be older than the then accepted value of the Hubble time, and most recently by Petrosian *et al.*[3] in an attempt to explain the concentration in QSO number counts near $z = 2.0$. In each of these cases either the rationalisation for the introduction of non-zero Λ has disappeared with better data or understanding, or the application has been unsuccessful in its intended purpose.

We seem to be in the situation once again where the data may call for Λ to be dusted off and inserted in the field equations. The rationale now is the almost-zero formal value for the deceleration parameter obtained by Gunn and Oke[4] which, when reduced by any reasonable evolutionary correction, yields negative values for q_0 much larger than the formal errors.

---

*Alfred P. Sloan Foundation Fellow.
†Present address: Yale University, New Haven, Connecticut 06520.

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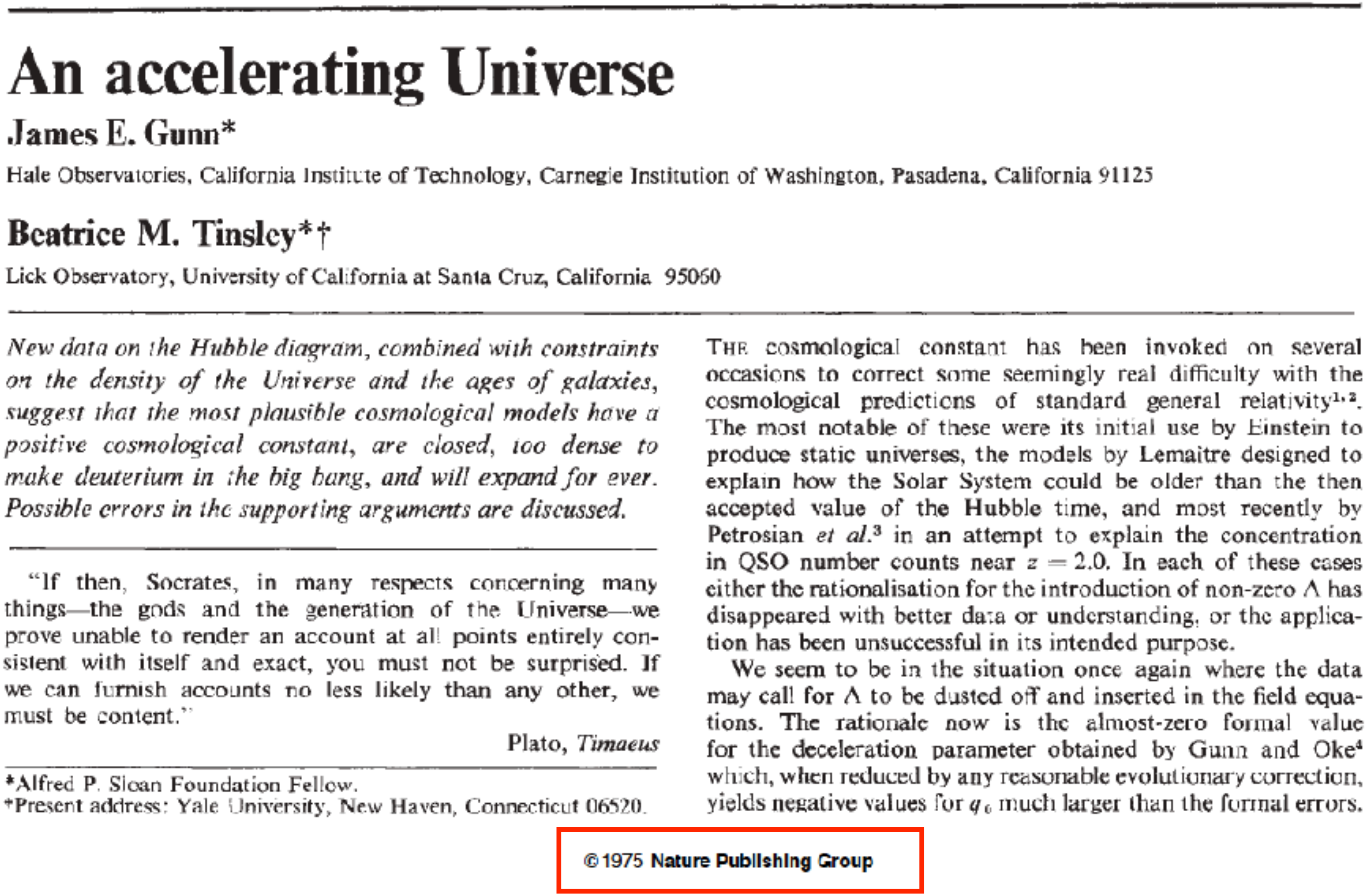

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The observational case for a low-density Universe with a non-zero cosmological constant

J. P. Ostriker* & Paul J. Steinhardt†

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† Department of Physics and Astronomy, University of Pennsylvania,
Philadelphia, Pennsylvania 19104, USA

OBSERVATIONS are providing progressively tighter constraints on cosmological models advanced to explain the formation of large-scale structure in the Universe. These include recent determinations of the Hubble constant[1–3] (which quantifies the present expansion rate of the Universe) and measurements of the anisotropy of the cosmic microwave background[4,5]. Although the limits imposed by these diverse observations have occasionally led to suggestions[6] that cosmology is facing a crisis, we show here that there remains a wide range of cosmological models in good concordance with these constraints. The combined observations point to models in which the matter density of the Universe falls well below the critical energy density required to halt its expansion. But they also permit a substantial contribution to the energy density from the vacuum itself (a positive 'cosmological constant'), sufficient to recover the critical density favoured by the simplest inflationary models. The observations do not yet rule out the possibility that we live in an ever-expanding 'open' Universe, but a Universe having the critical energy density and a large cosmological constant appears to be favoured.

Cosmological models can be categorized according to their mechanism for generating seeds for the formation of large-scale structure. The standard Big Bang model successfully explains the Hubble expansion, the primordial formation of the elements, and the origin of cosmic background radiation. However, it offers no explanation for how structure formed. Recognizing that the Big Bang picture is incomplete, cosmologists have put forth various theoretical proposals to address that issue.

Our focus will be on a leading candidate, the inflationary model of the Universe[7–9] although our analysis also extends to current alternatives. The inflationary model proposes that the seeds for large-scale structure formation were produced by microscopic quantum fluctuations in the energy density during the first instants after the Big Bang[10–13]. There was subsequently a burst of spectacular, superluminal expansion (inflation) that stretched the Universe and the fluctuations to cosmic dimensions. The resulting spectrum of primordial fluctuations is nearly scale-invariant: if the fluctuation in density over space is expressed as a Fourier sum of waves with amplitude $\delta(\lambda)$, the waves have nearly equal amplitude independent of wavelength, λ. Cosmologists parametrize the spectrum in terms of a spectral index n, defined by the relation $\delta \propto \lambda^{(1-n)/2}$. In the early 1970s, before the inflationary model was proposed, Harrison[14], Zel'dovich[15] and Peebles and Yu[16] had argued that a scale-invariant spectrum ($n=1$) is the most plausible because the amplitude did not diverge at small wavelengths, which would produce too many black holes, or at large wavelengths, which would produce too much distortion in the cosmic background radiation. Hence, it was regarded as a major triumph when it was discovered that inflation naturally generates a nearly scale-invariant spectrum.

It should be emphasized, however, that inflation does not predict a precisely $n=1$ spectrum. Rather, depending on the rate of inflation and the details of how inflation ends, the spectral index can take values between roughly $n=0.7$ and 1.2 (refs 5, 17). It is an important aspect of our tests that we do not fix the spectral index *ab initio*, but rather treat it as a free parameter to be constrained by observational data. In particular, we have found cases in which models have been judged inconsistent with large-scale observations under the strict assumption that $n=1$ (ref. 18). Yet a relatively modest deviation of n from unity, well within the bounds permitted by inflation, brings the model back into concordance.

Models can be further distinguished by the values of other cosmological parameters such as the Hubble expansion rate, H_0, the density of baryons (ordinary matter), the total matter density including any dark matter, and the vacuum energy density or, equivalently, the cosmological constant (Λ). The symbols Ω_B,

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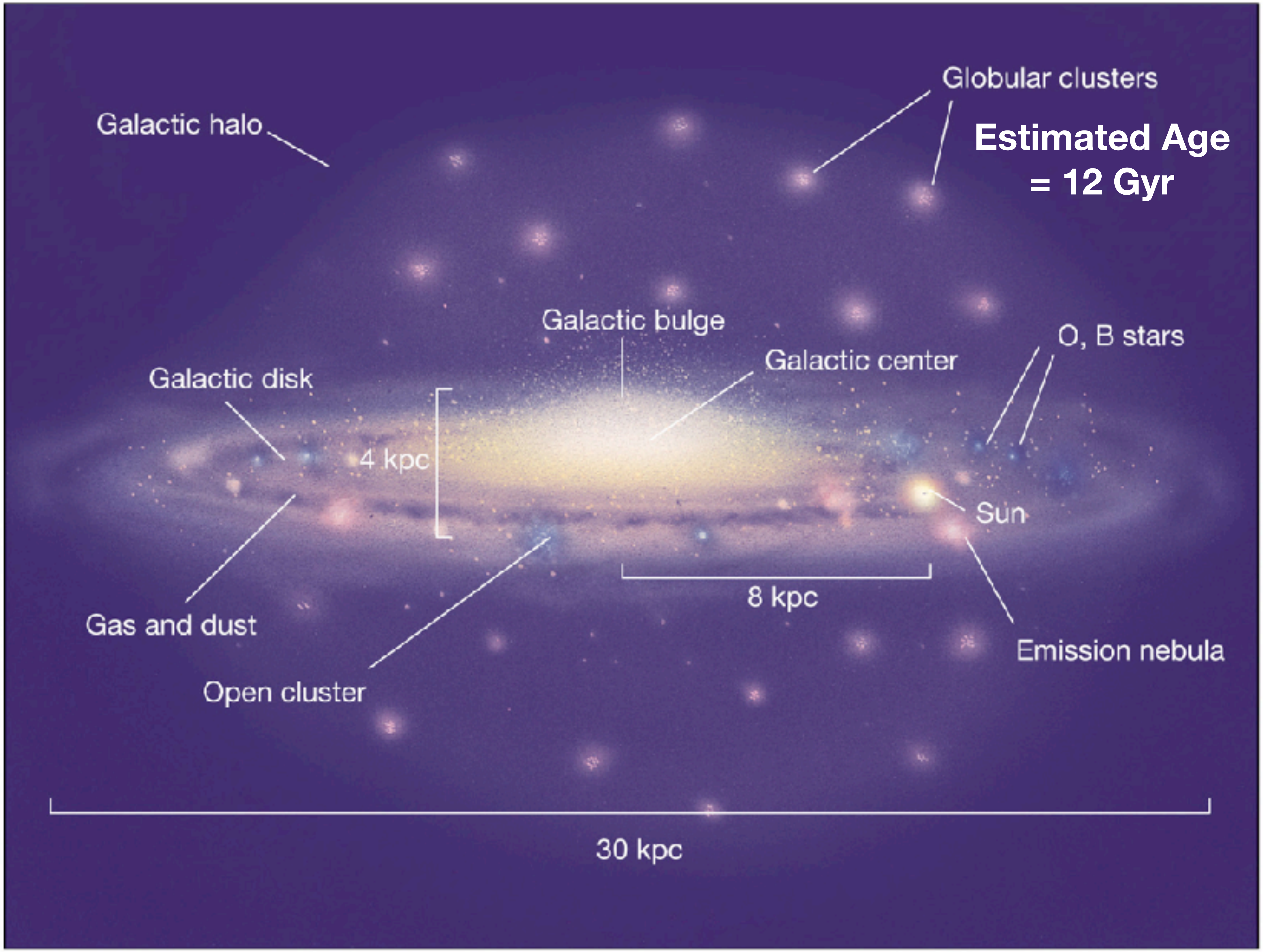
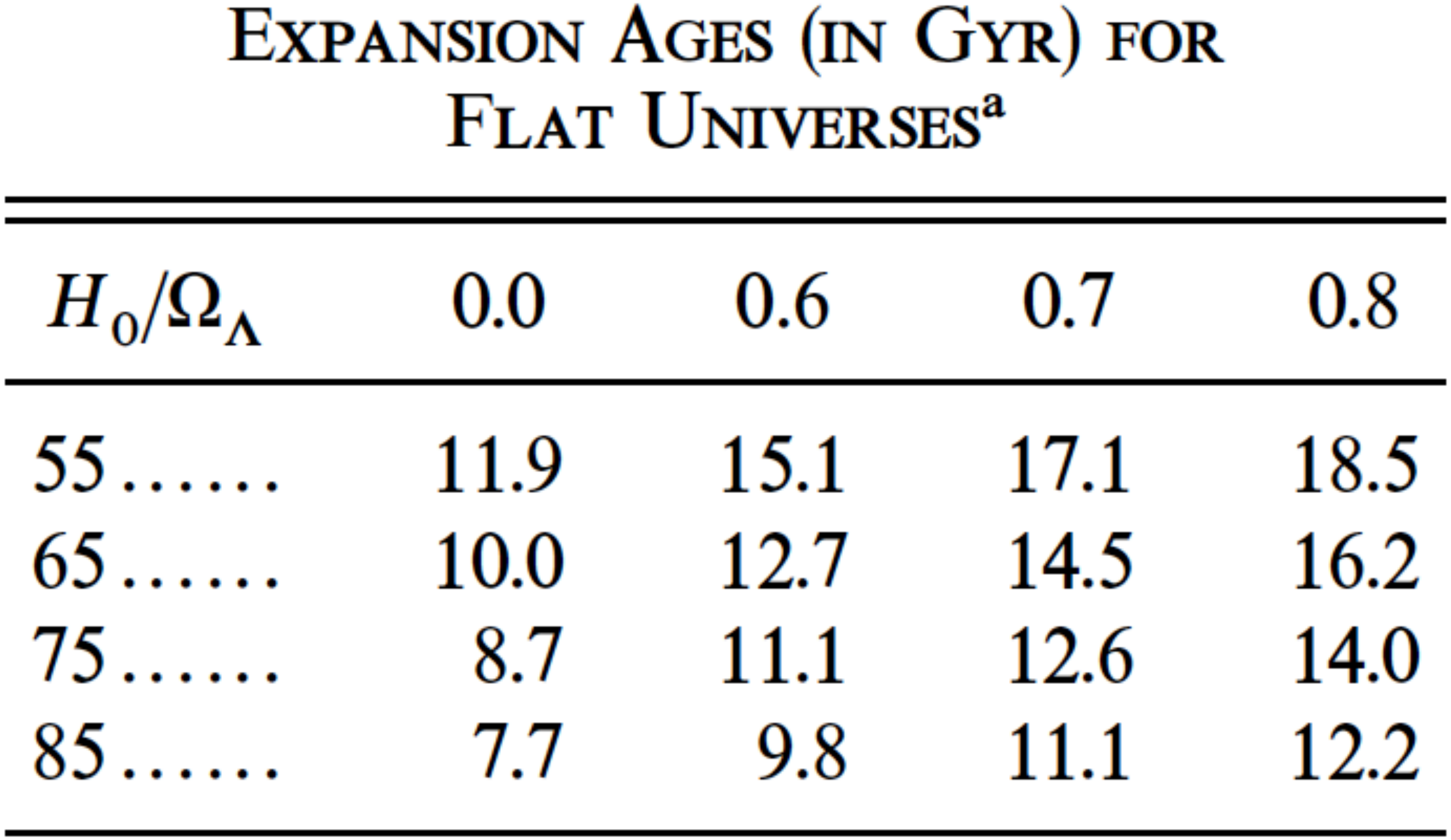
Age Problem Globular Clusters



Hubble Space Telescope Key Project (2001)



EXPANSION AGES (IN GYR) FOR FLAT UNIVERSES[a]

H_0/Ω_Λ	0.0	0.6	0.7	0.8
55……	11.9	15.1	17.1	18.5
65……	10.0	12.7	14.5	16.2
75……	8.7	11.1	12.6	14.0
85……	7.7	9.8	11.1	12.2

Freedman et al. 2001

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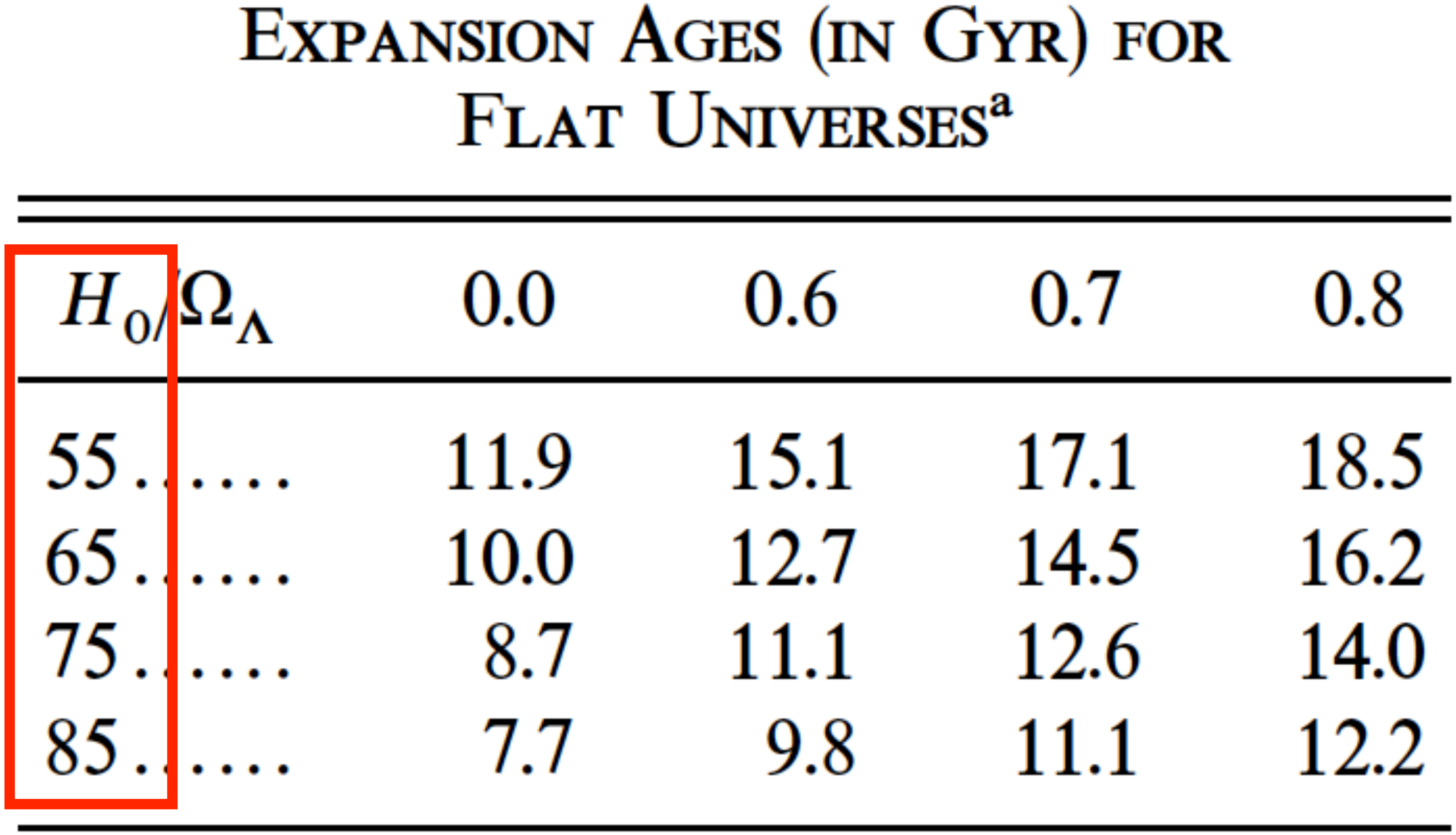

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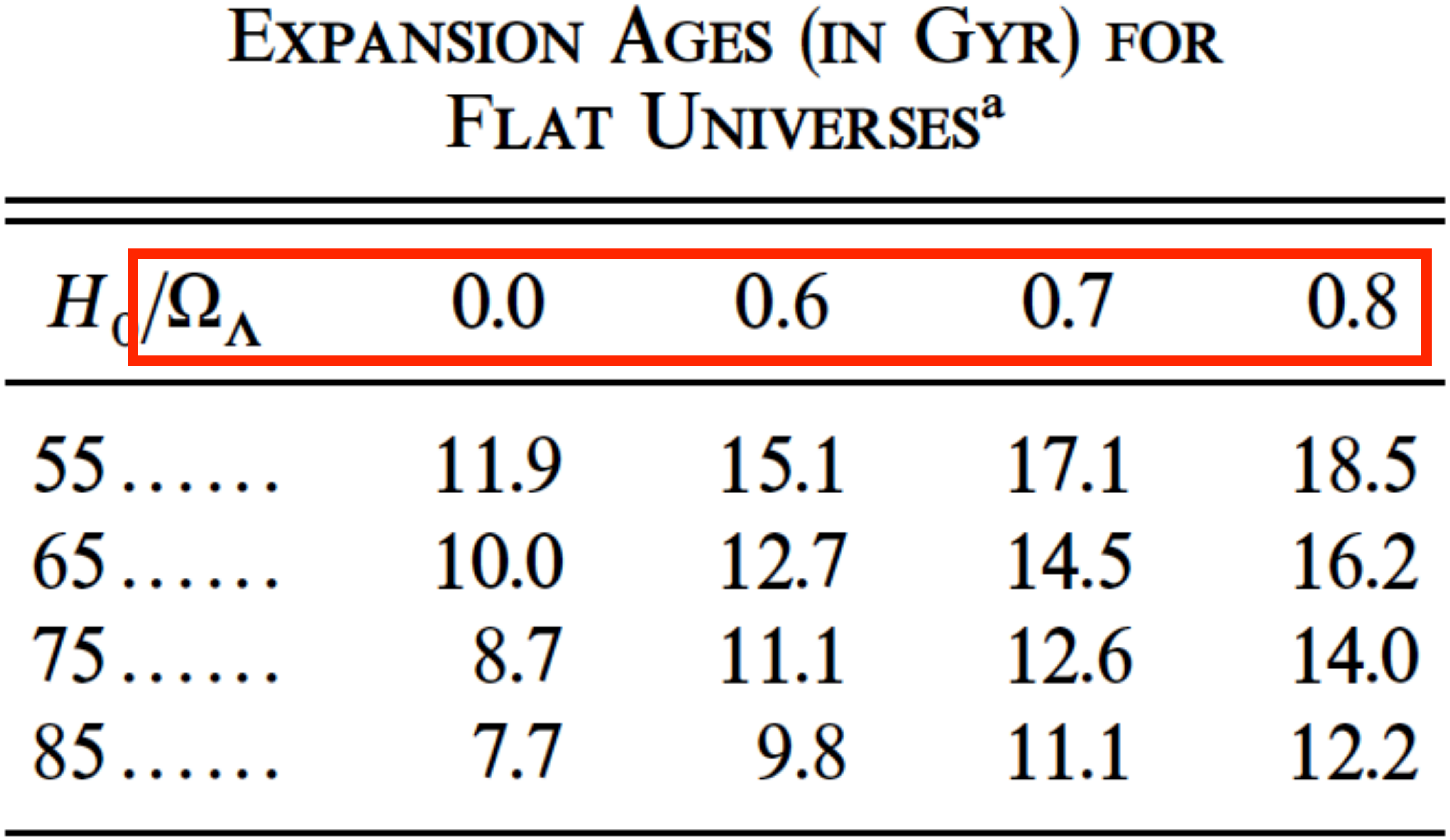

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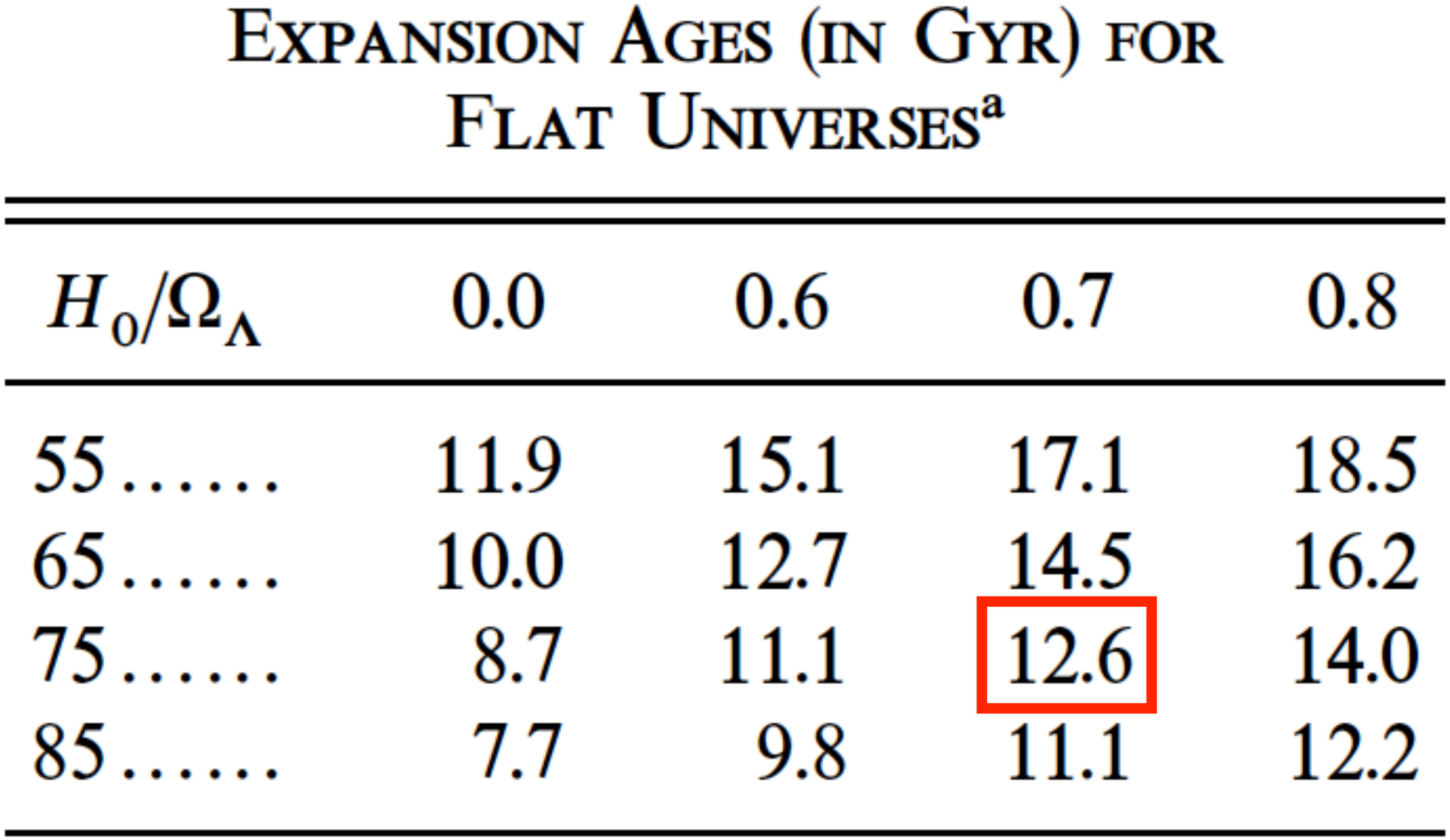

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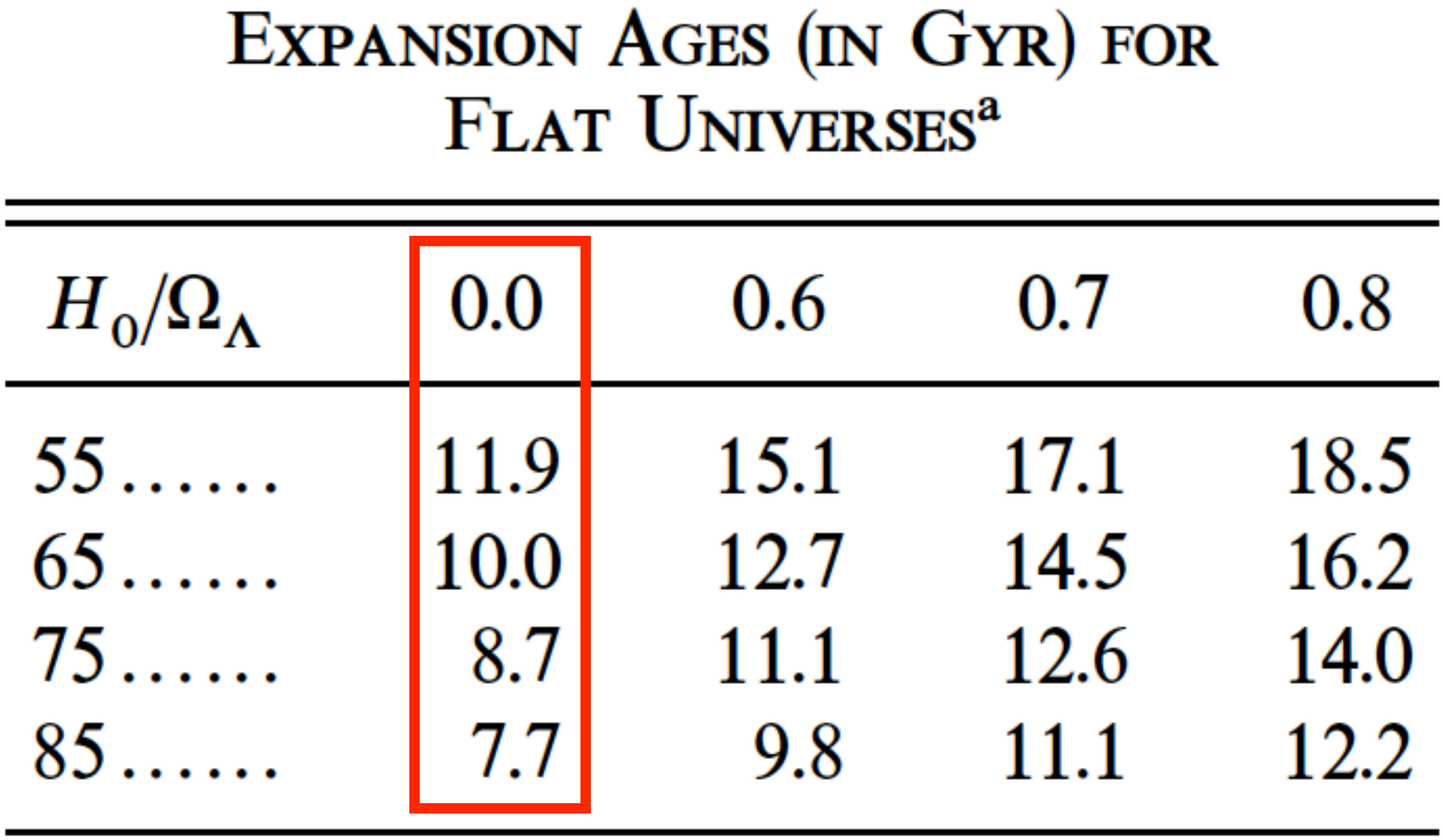

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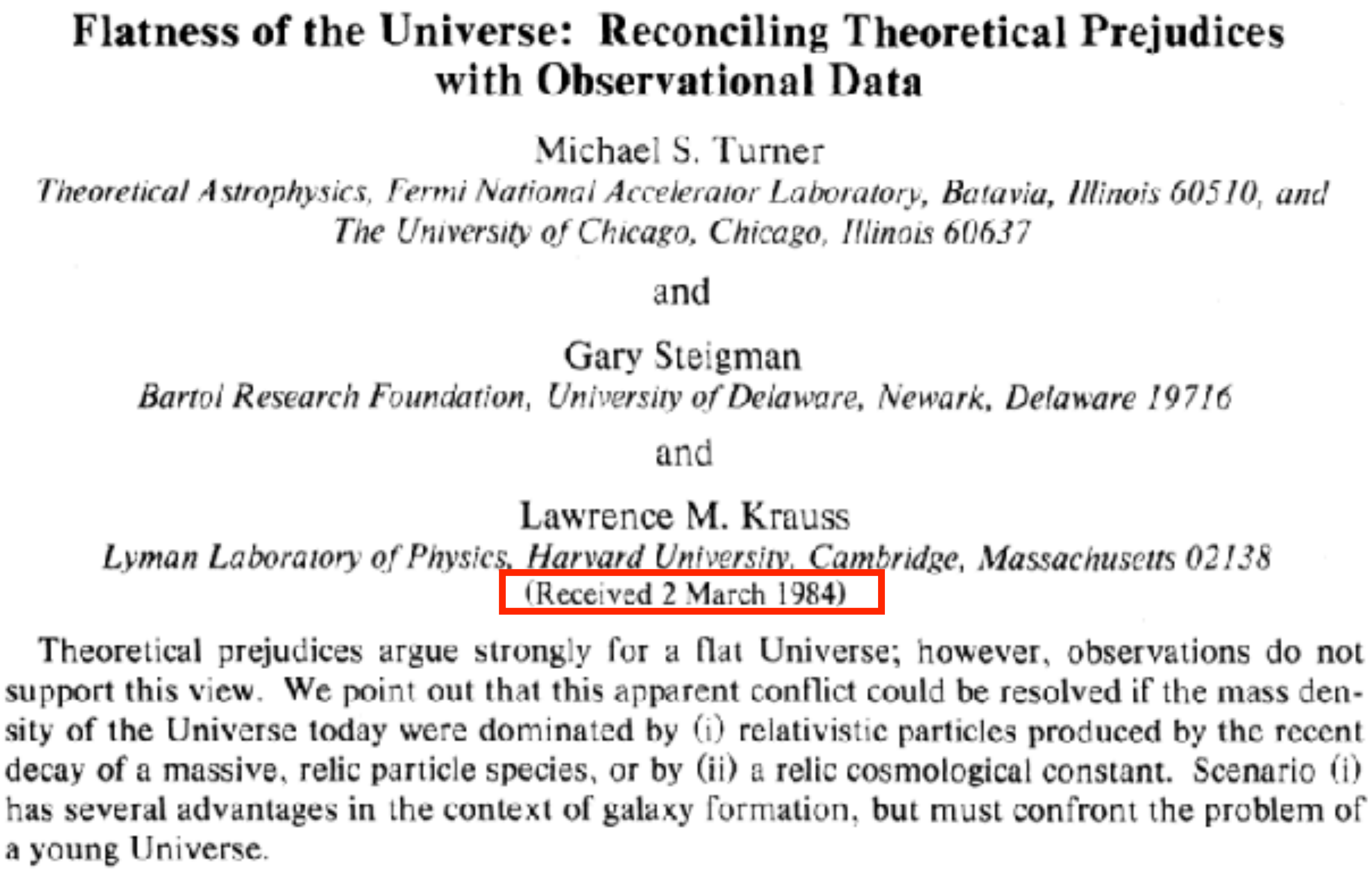
Freedman et al. 2001

Theoretical Prejudice for Dark Energy



Flatness of the Universe: Reconciling Theoretical Prejudices with Observational Data

Michael S. Turner
Theoretical Astrophysics, Fermi National Accelerator Laboratory, Batavia, Illinois 60510, and
The University of Chicago, Chicago, Illinois 60637

and

Gary Steigman
Bartol Research Foundation, University of Delaware, Newark, Delaware 19716

and

Lawrence M. Krauss
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 2 March 1984)

Theoretical prejudices argue strongly for a flat Universe; however, observations do not support this view. We point out that this apparent conflict could be resolved if the mass density of the Universe today were dominated by (i) relativistic particles produced by the recent decay of a massive, relic particle species, or by (ii) a relic cosmological constant. Scenario (i) has several advantages in the context of galaxy formation, but must confront the problem of a young Universe.

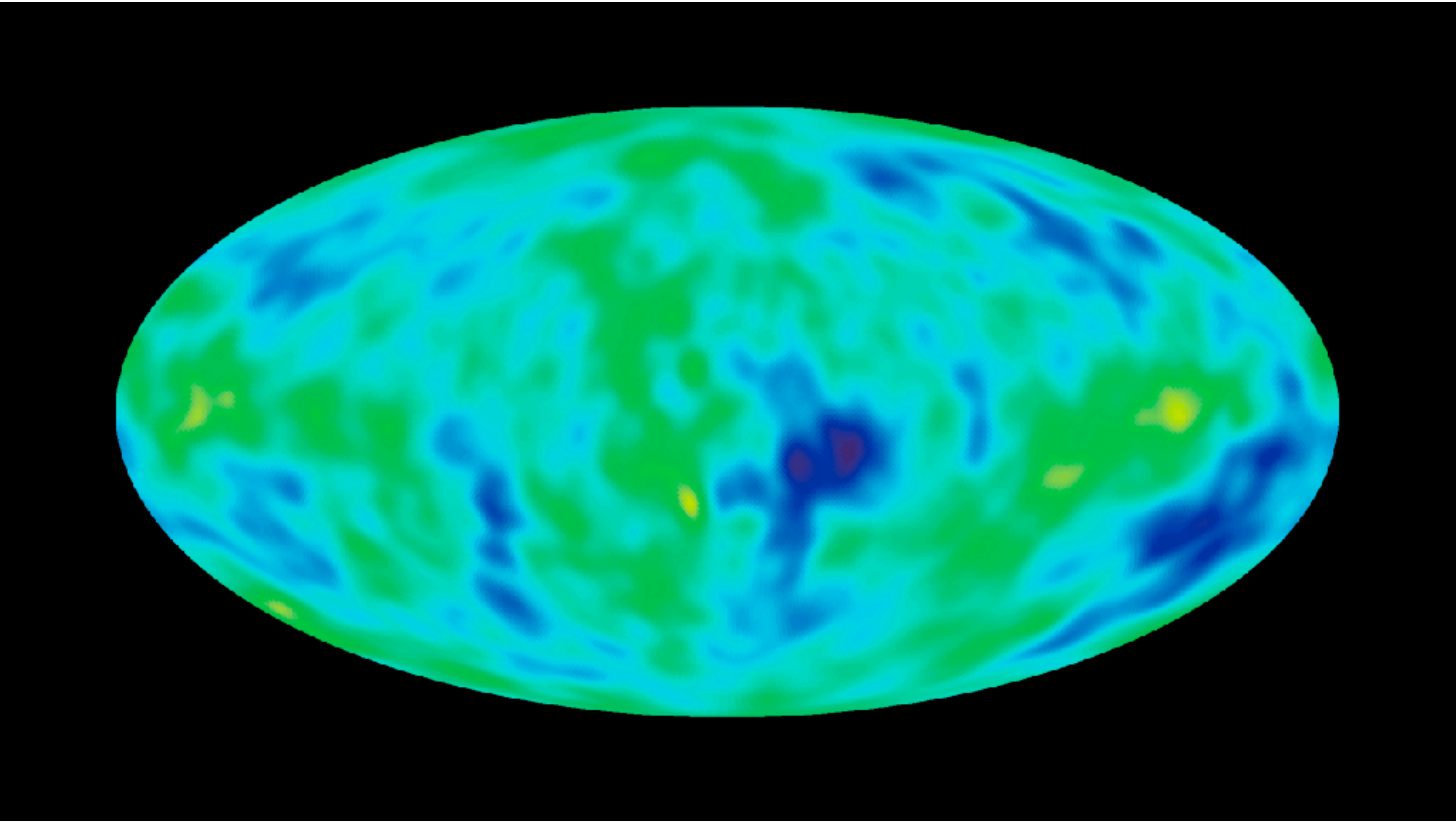
Theorists like the idea of inflation that was developed in the 1980s because it solves the horizon, flatness, and monopole problems

However, inflation implies the Universe is very flat today.

That is in conflict with low Ω_m unless there is Ω_Λ as well so that

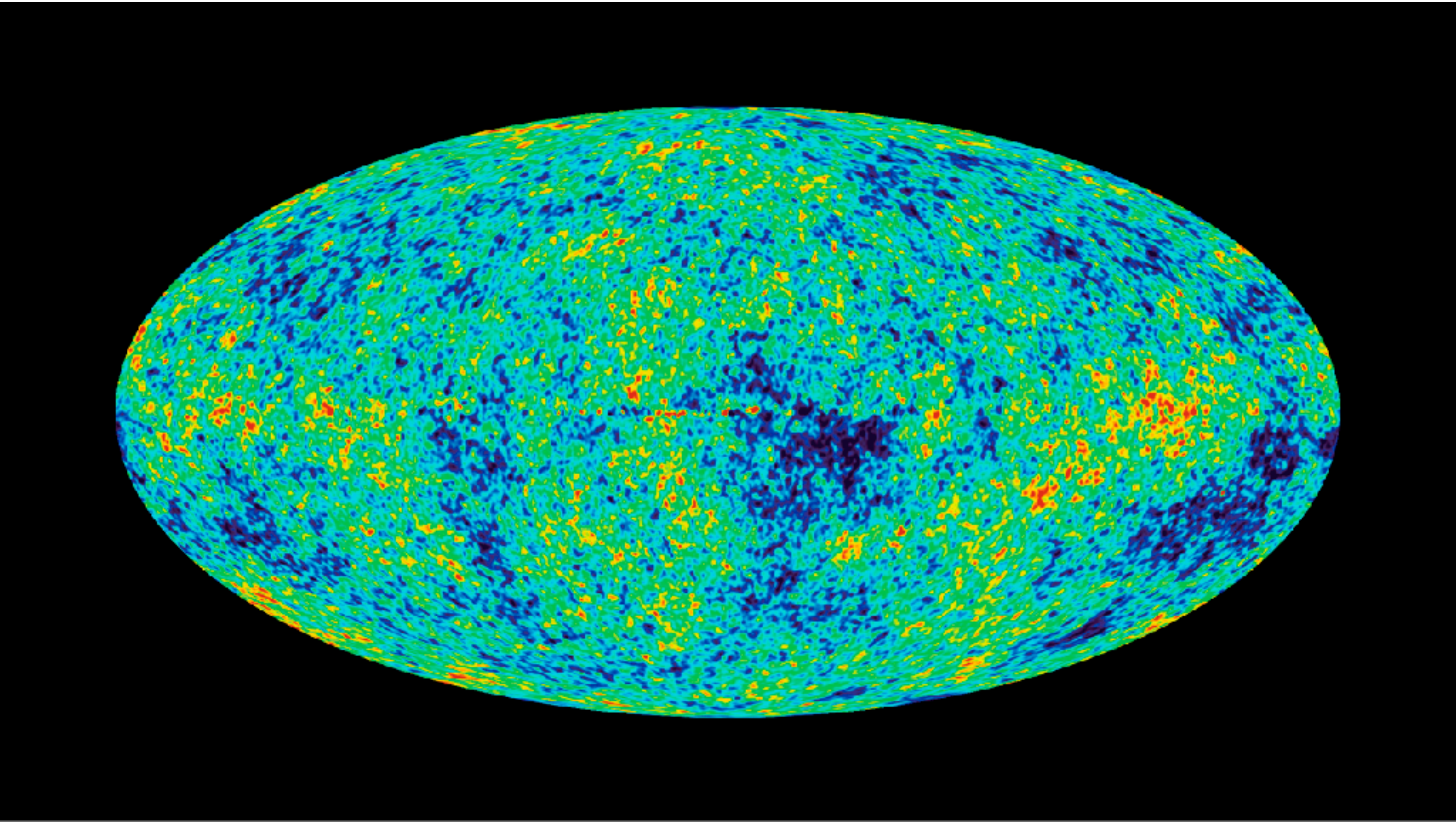
$$\Omega_m + \Omega_\Lambda = 1$$

Cosmic Microwave Background (CMB)



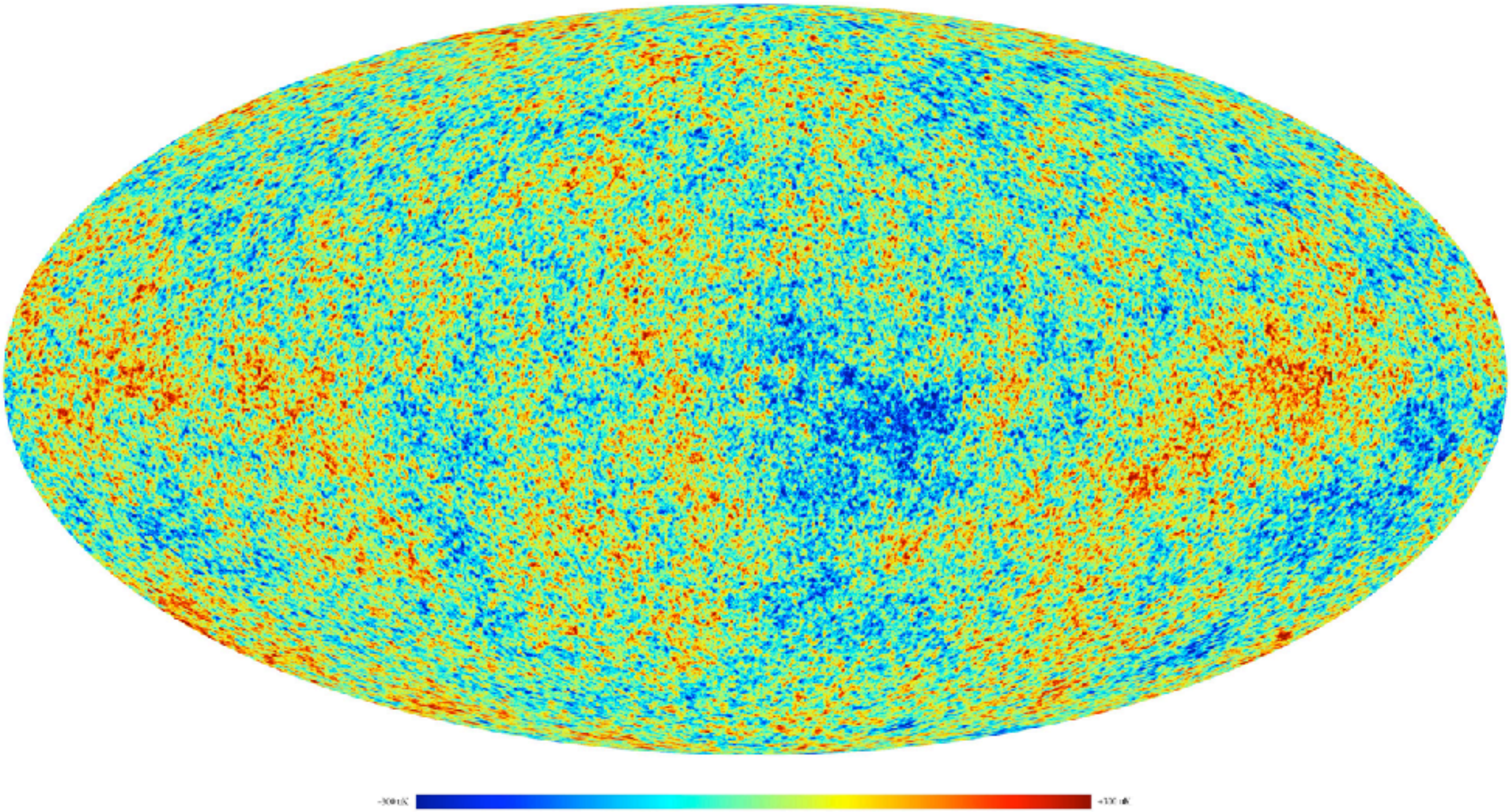
COBE Satellite 1991

Cosmic Microwave Background (CMB)

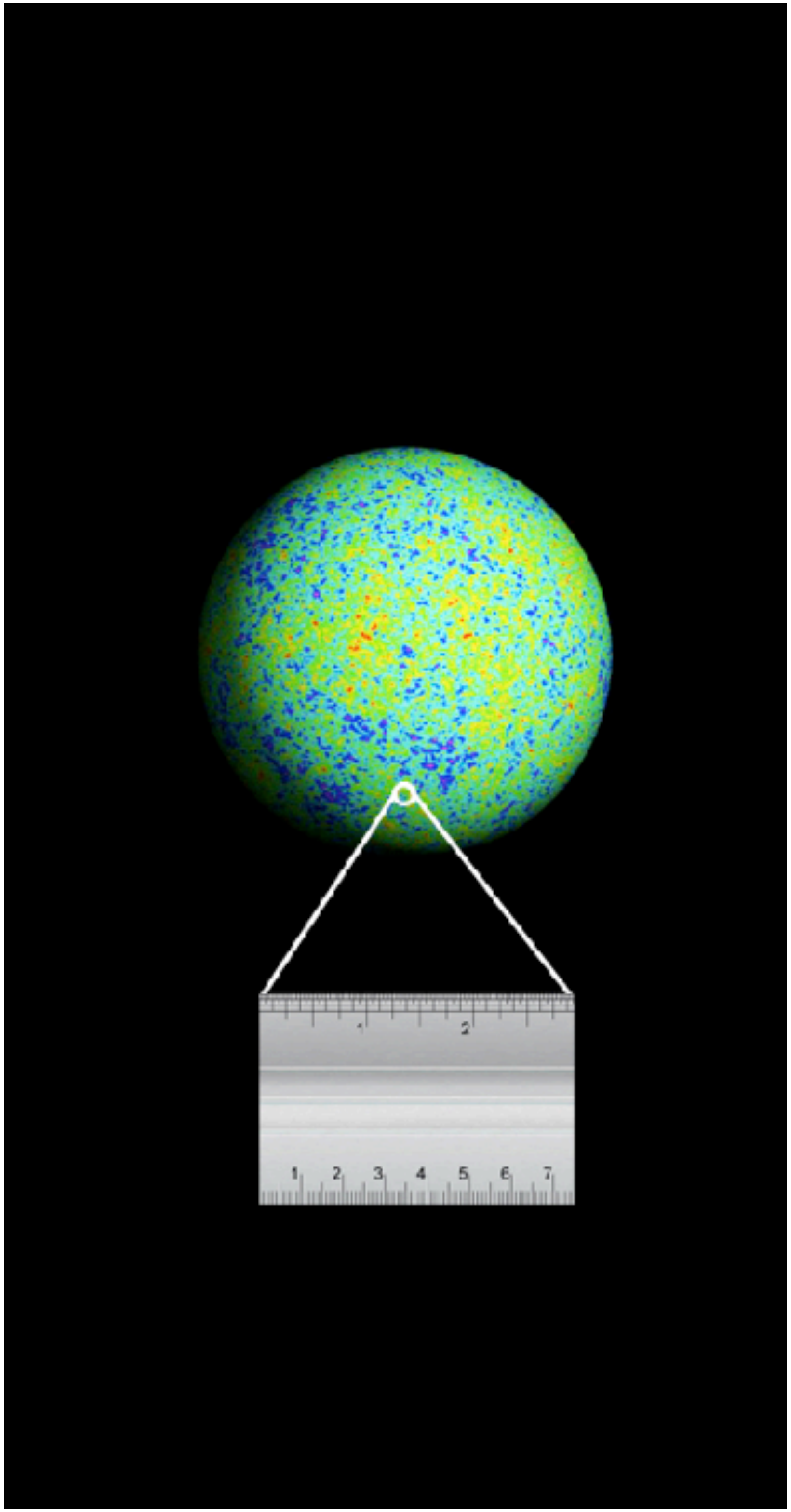


WMAP Satellite 2003

Cosmic Microwave Background (CMB)



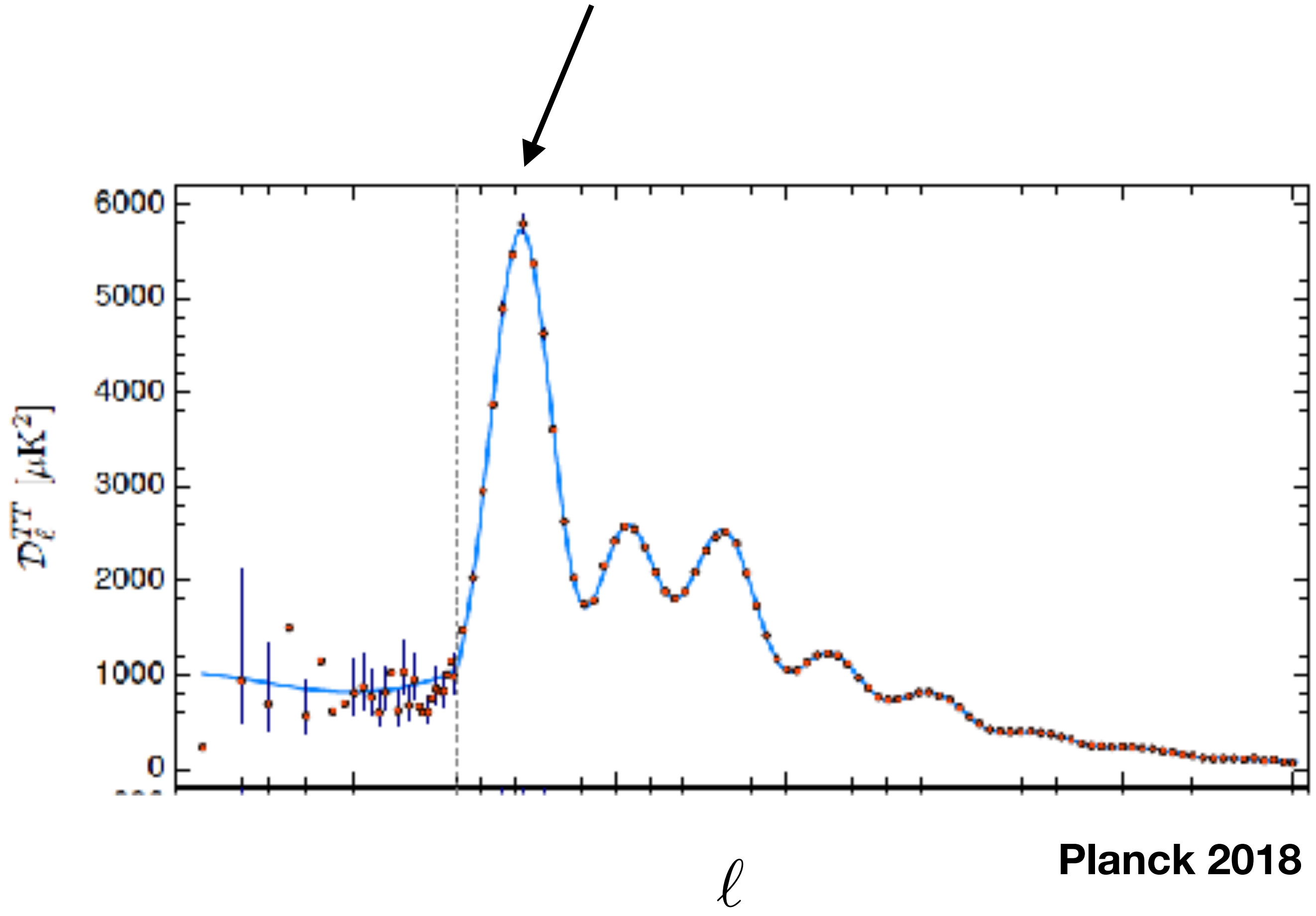
Planck Satellite 2013



The CMB acts as a Standard Ruler.

We know how far a sound wave can physically travel by the time the CMB is formed 400,000 years after the Big Bang.

Then we look at the angle that distance subtends on the sky to tell how space has expanded between then and now.



About 1 degree

Planck 2018

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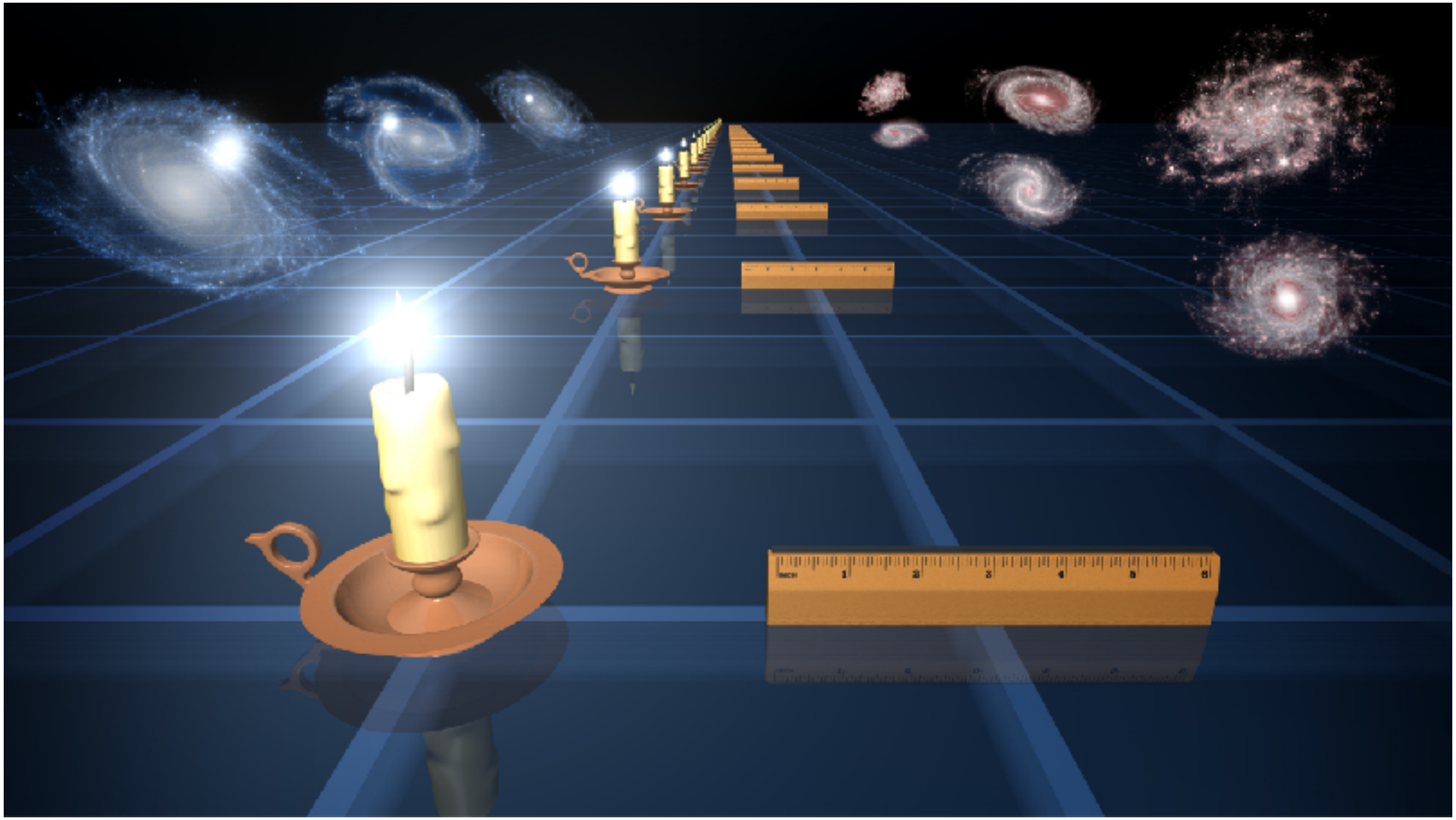
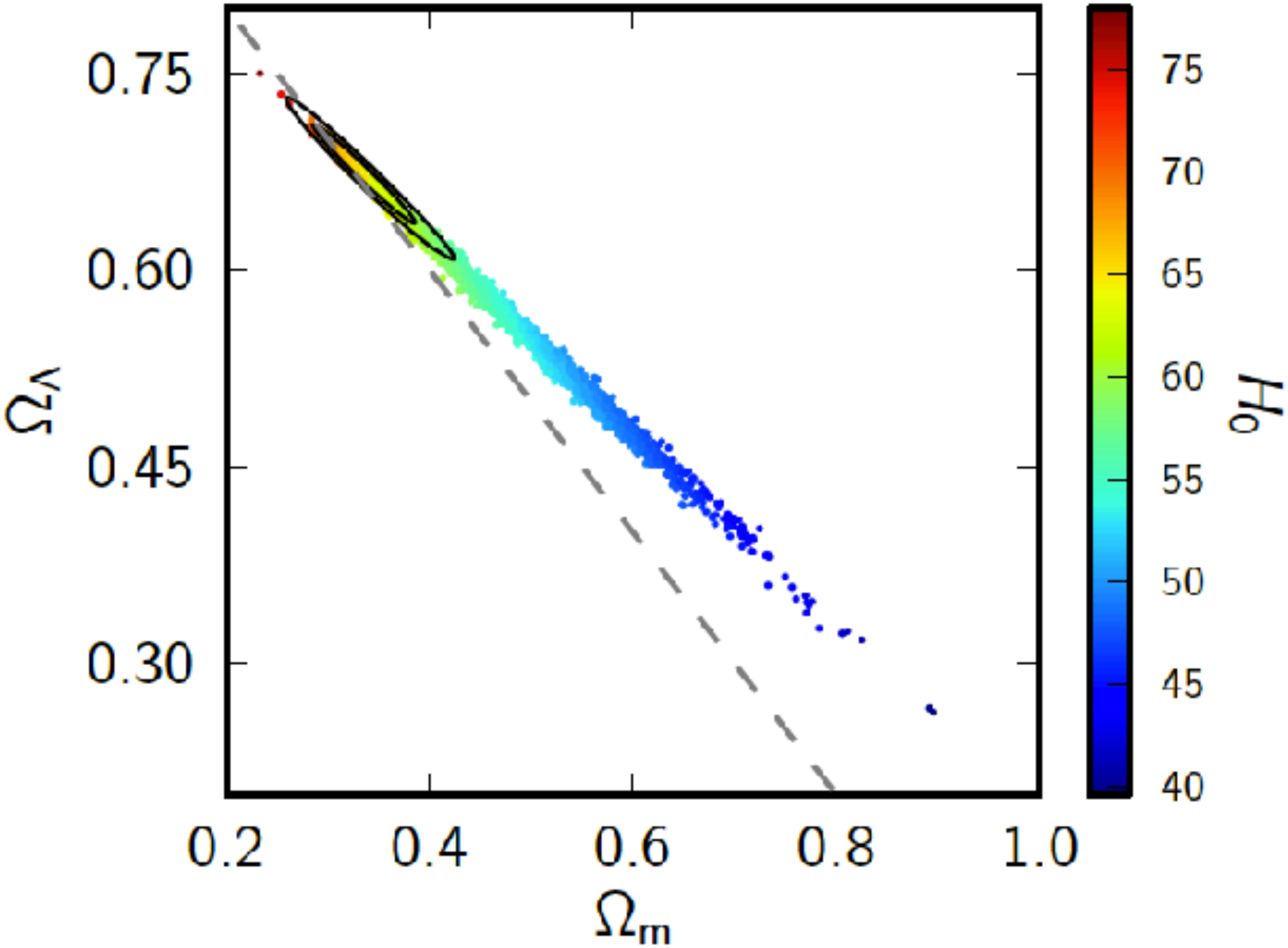
Standard Rulers



Courtesy NASA / JPL-Caltech

Evidence for Dark Energy from the CMB Alone

Primordial CMB spectrum plus **CMB lensing**



Planck Results 2013, Paper 17

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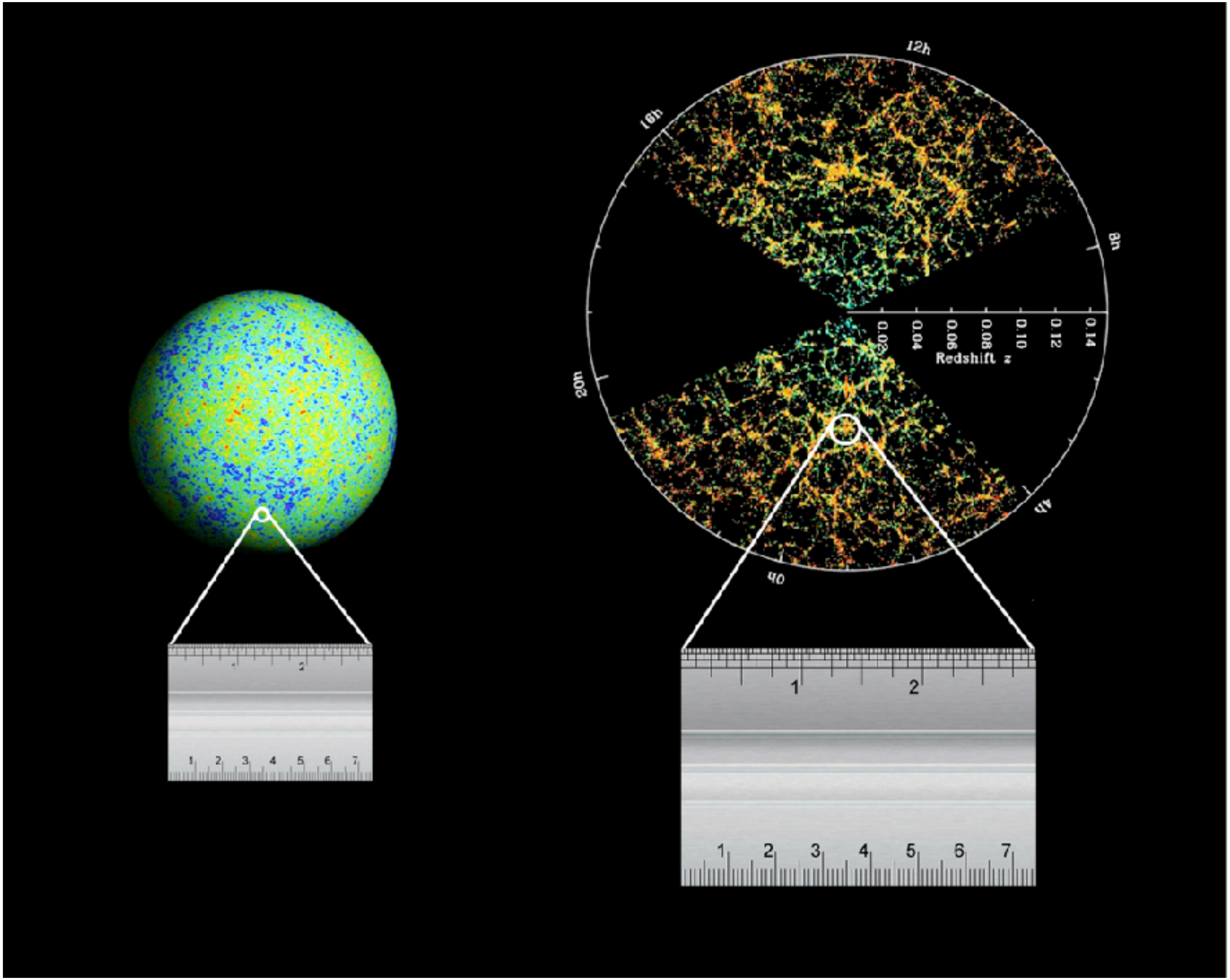

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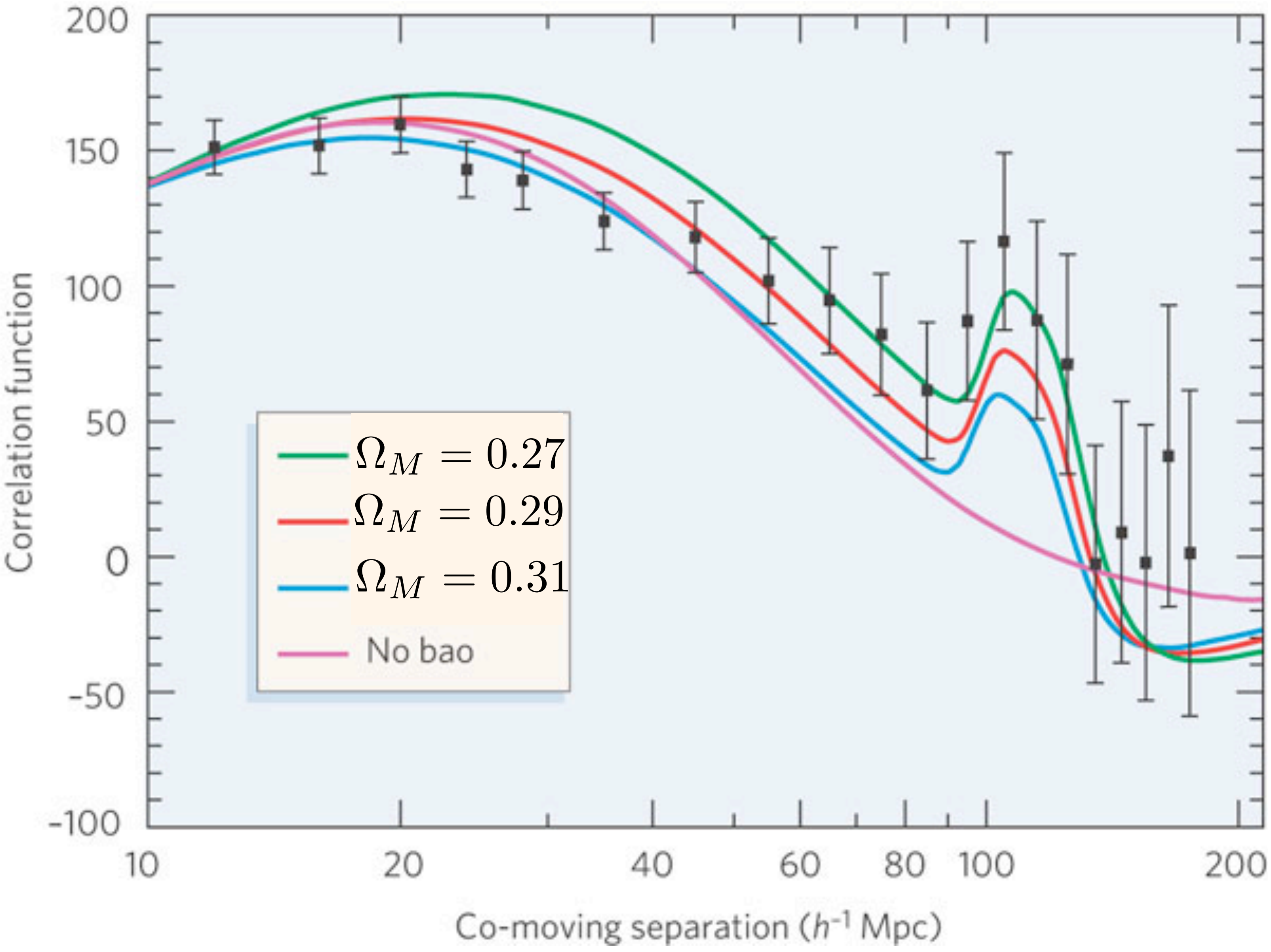
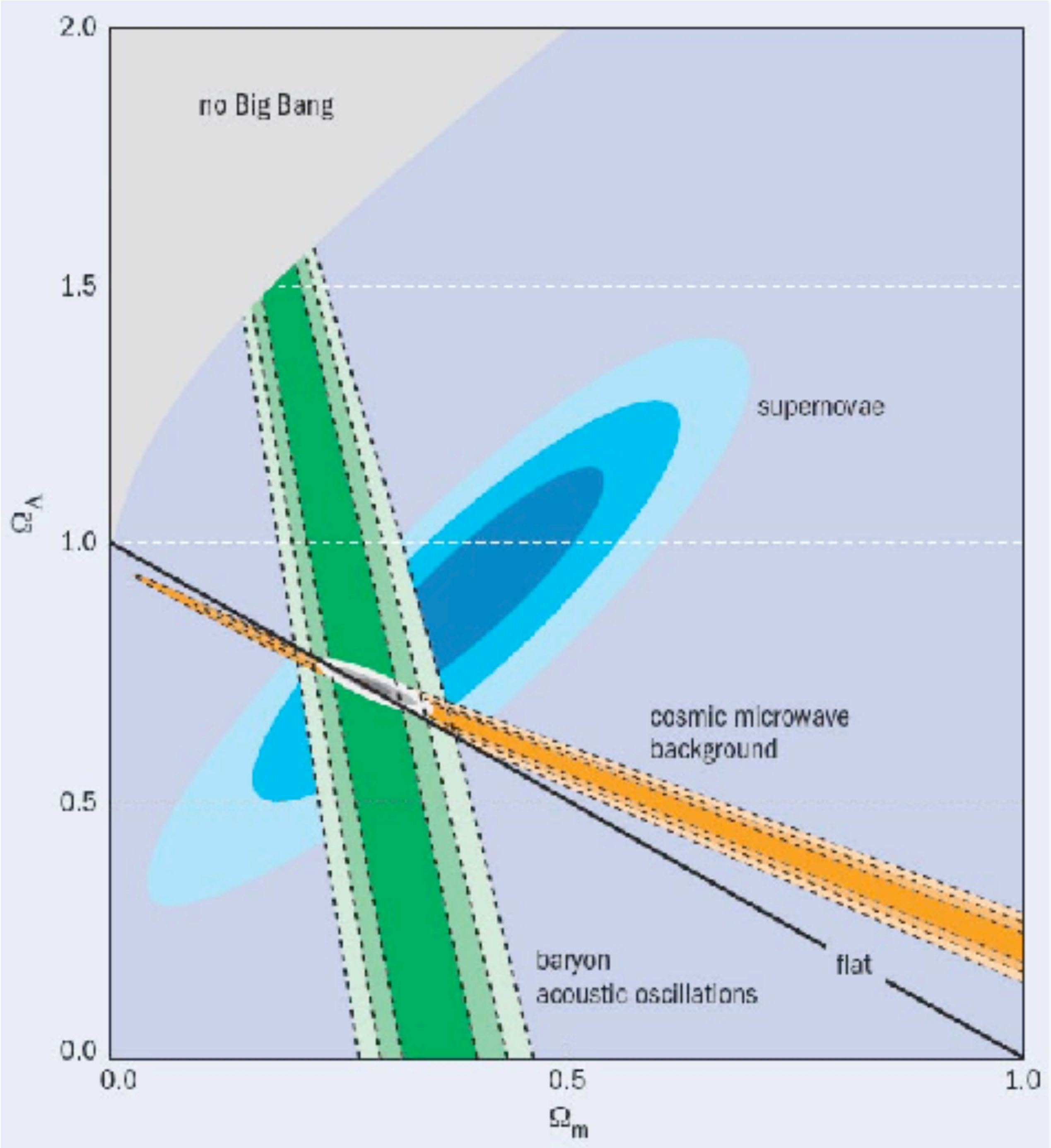
Baryon Acoustic Oscillations are also a Standard Ruler



Eisenstein et al., ApJ 2005

Evidence for Dark Energy is now from Multiple Data Sets



Adapted from M Kowalski *et al.* 2008 *Astrophys. J.* **686** 749

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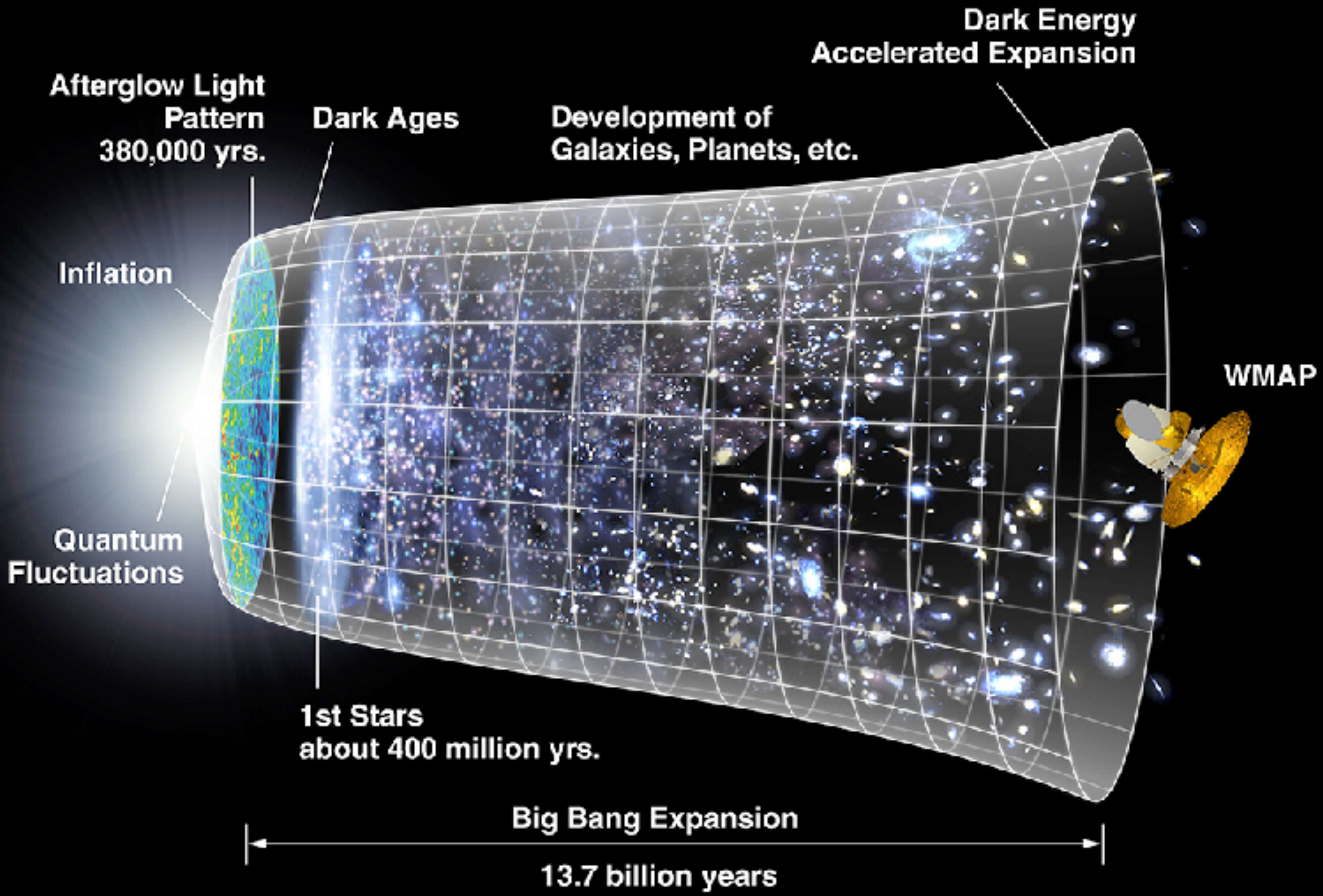
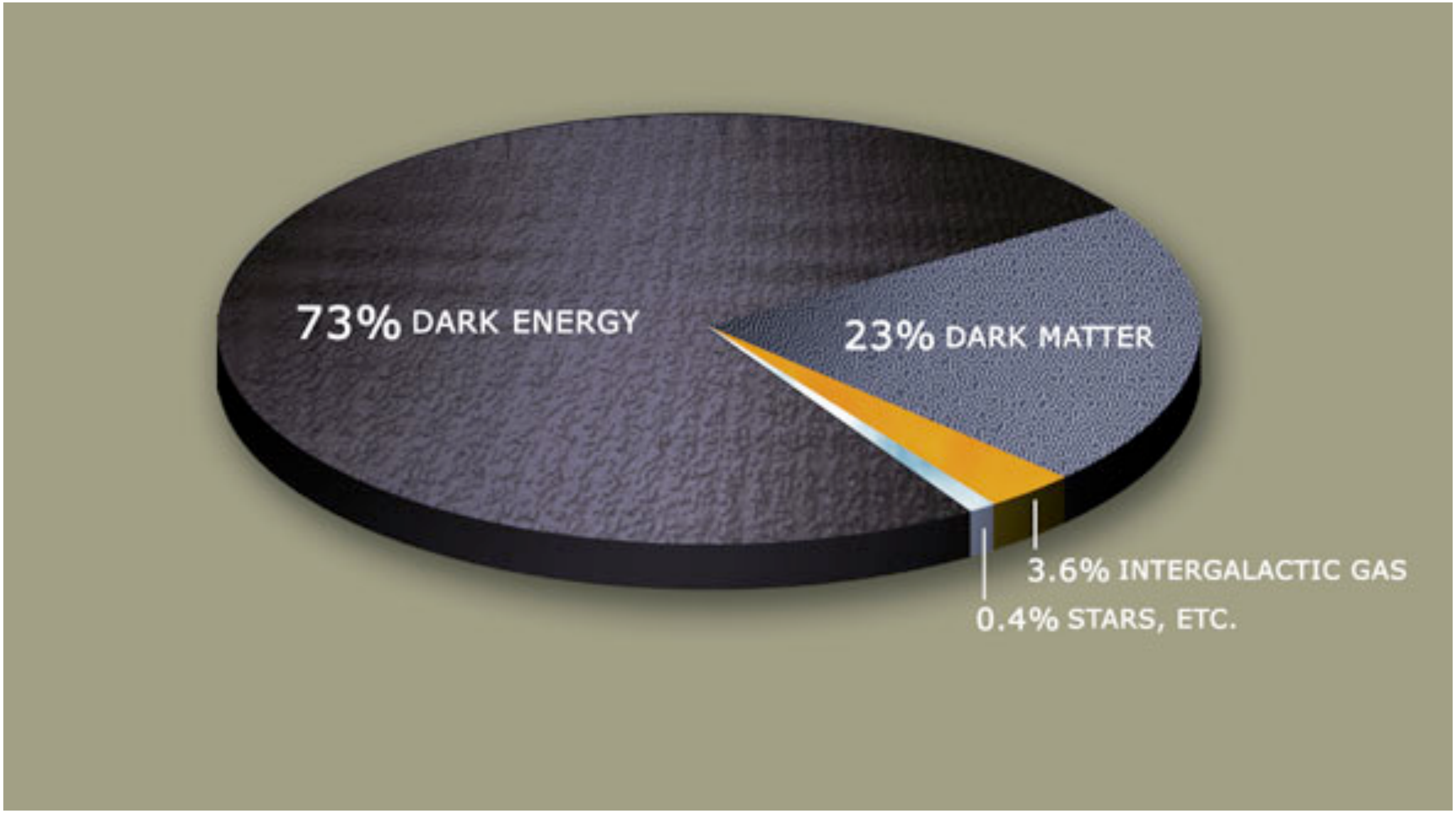
A STANDARD MODEL FOR COSMOLOGY



NASA/WMAP Science Team



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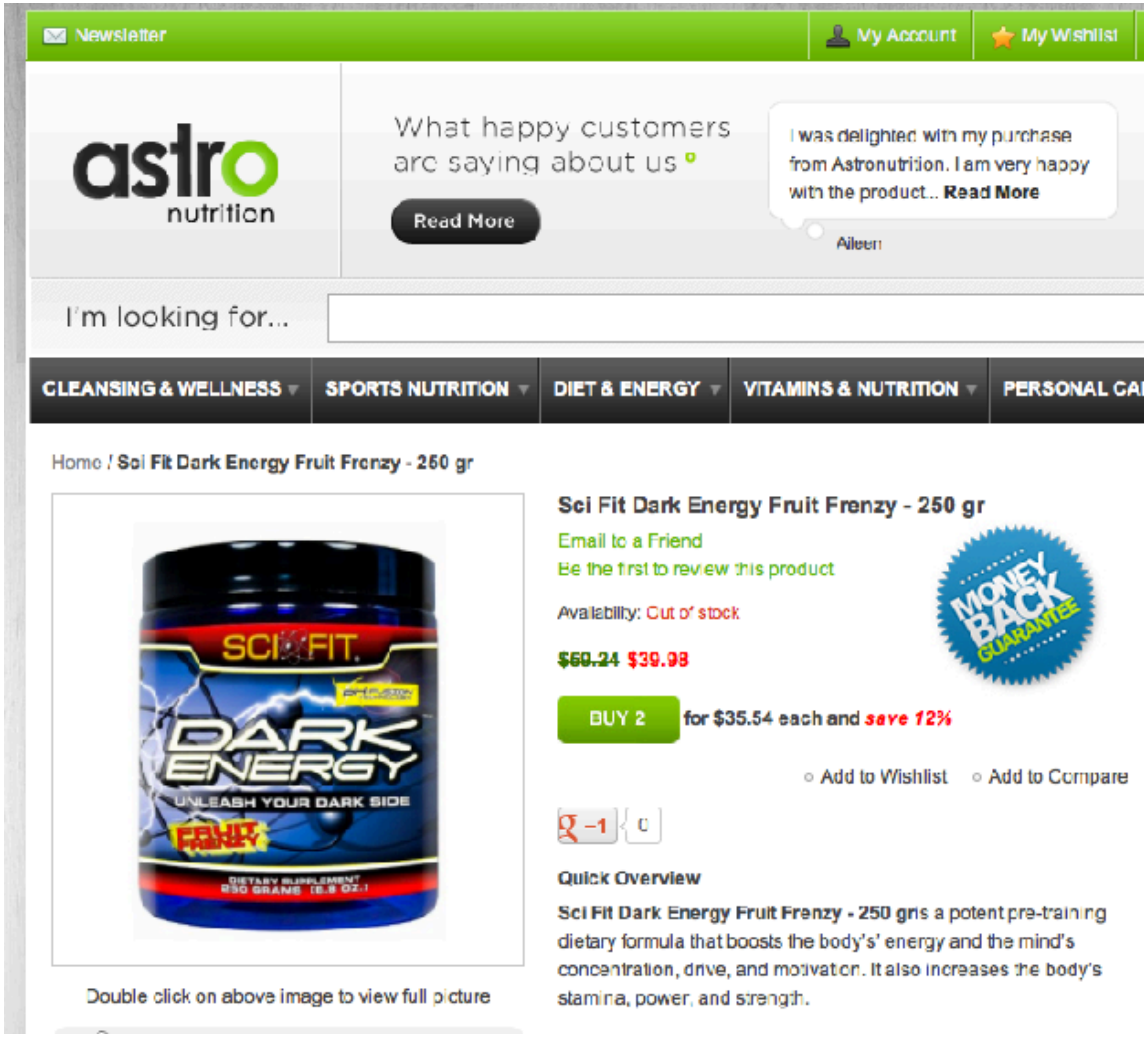
What is Dark Energy?

What is Dark Energy?



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Sci Fit Dark Energy Fruit Frenzy - 250 gr

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Quick Overview

Sci Fit Dark Energy Fruit Frenzy - 250 gr is a potent pre-training dietary formula that boosts the body's' energy and the mind's concentration, drive, and motivation. It also increases the body's stamina, power, and strength.

Double click on above image to view full picture

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Vacuum Energy?

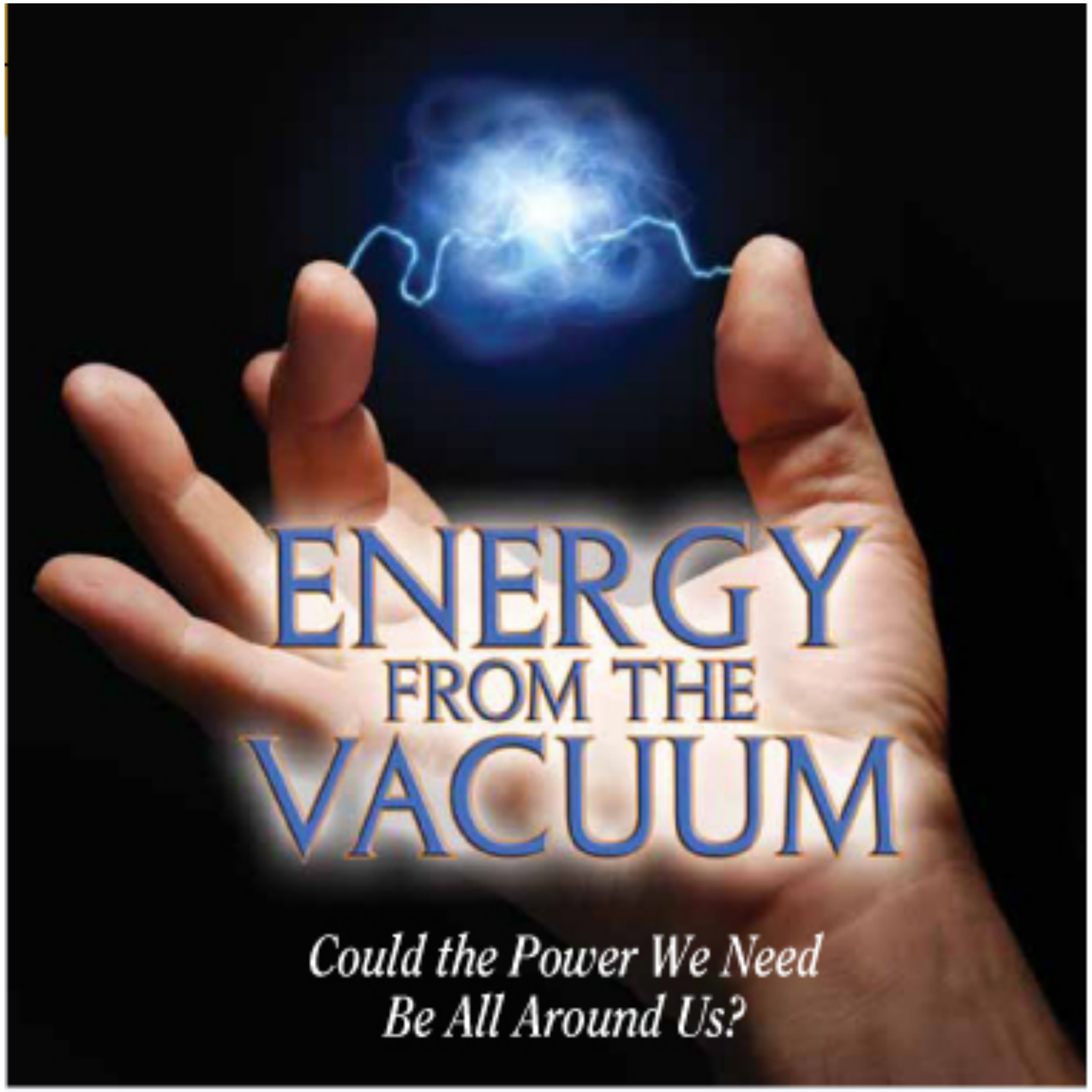
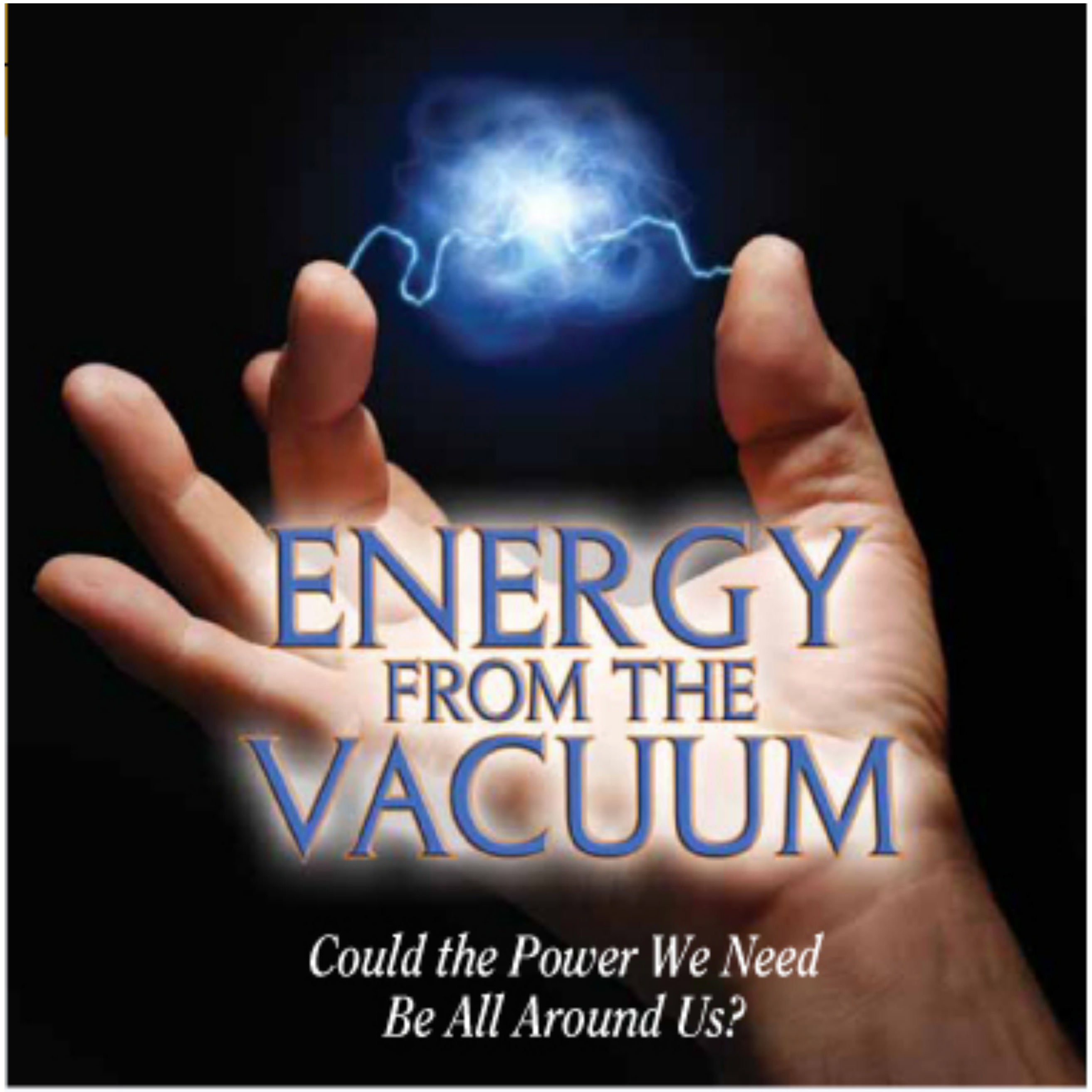


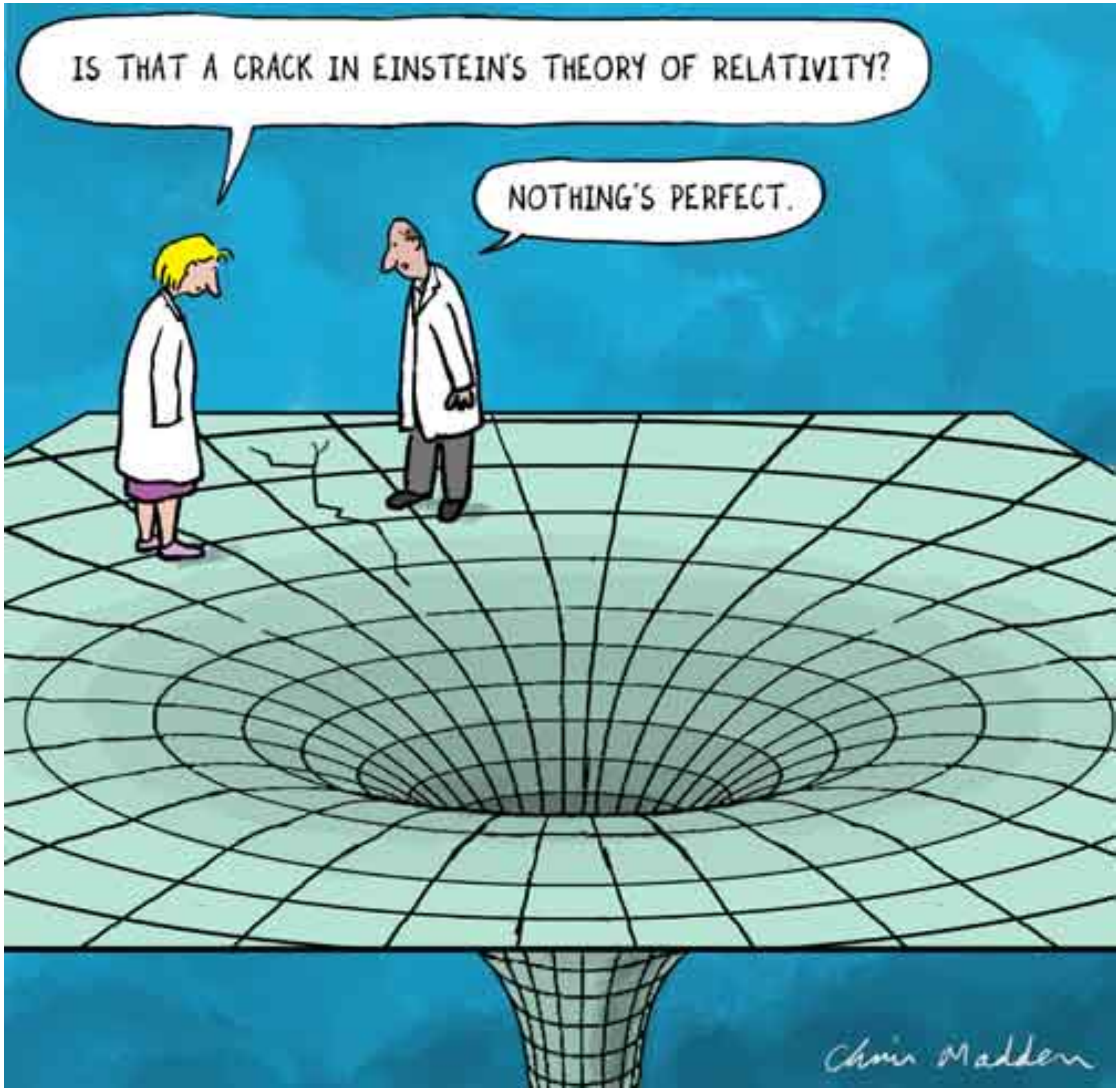
Image credit: Atlantis Rising Magazine

Vacuum Energy?



Problem: We have too much vacuum energy - 10^{120} times too much

Breakdown of General Relativity?



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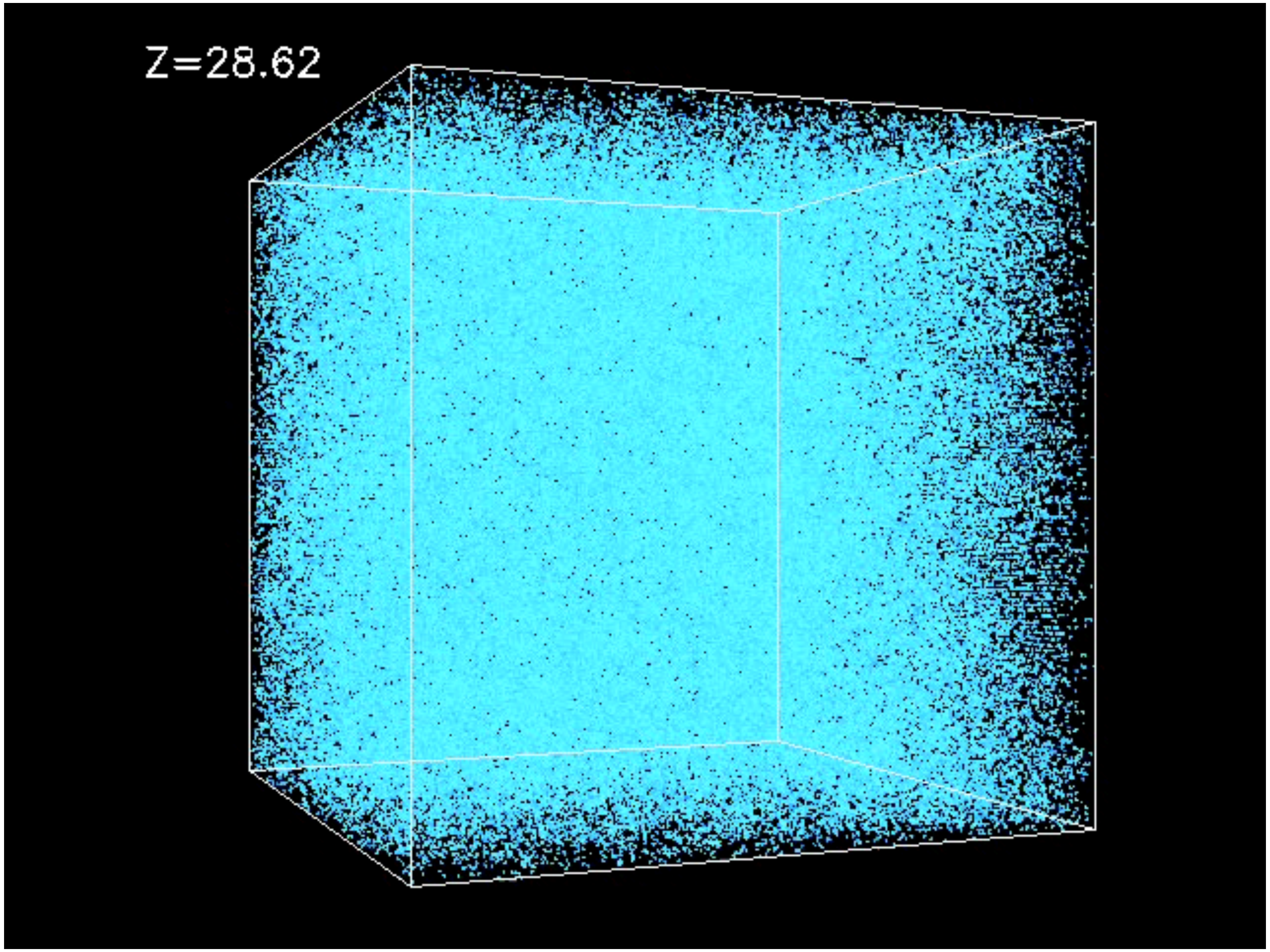
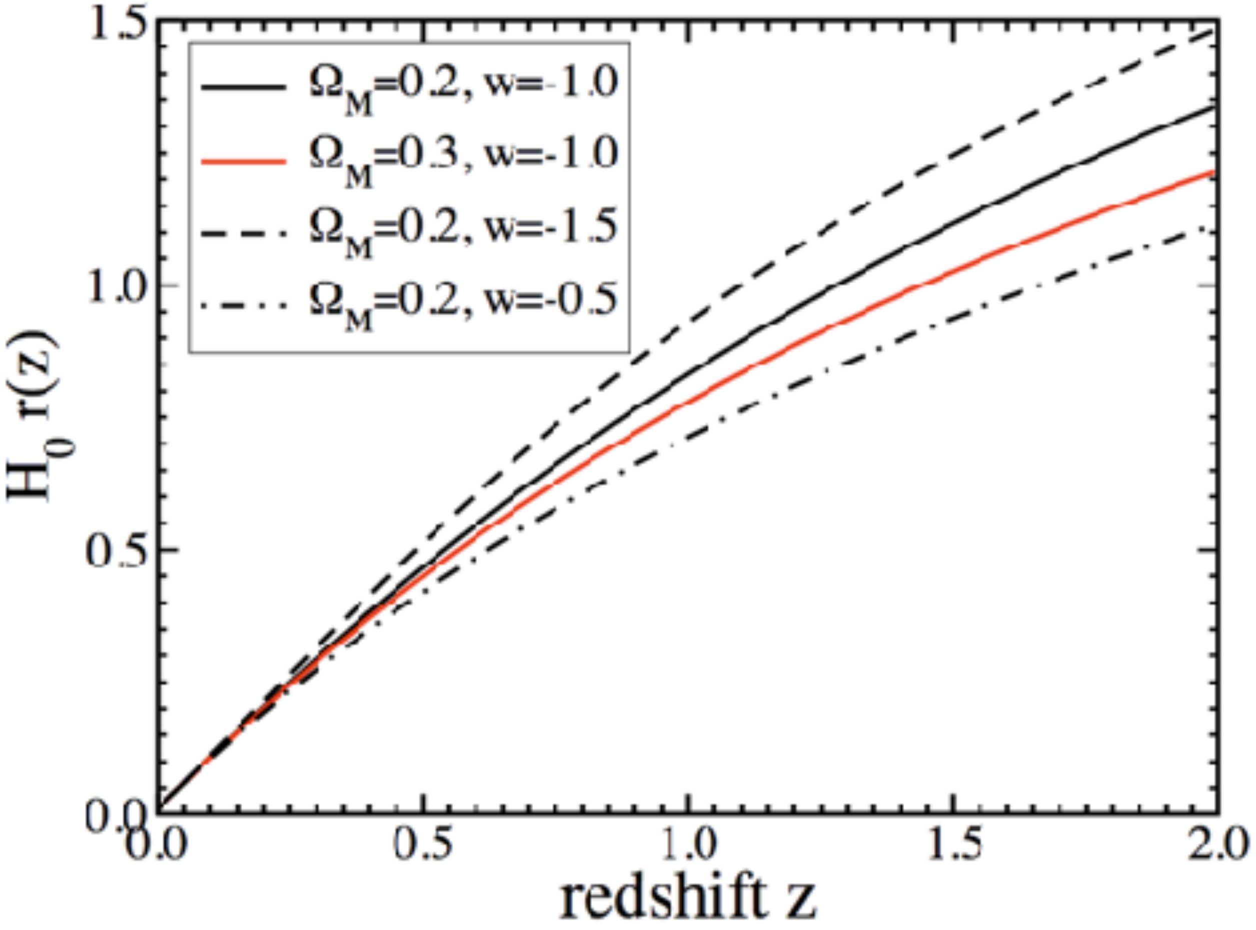
Next Steps

Growth of Structure

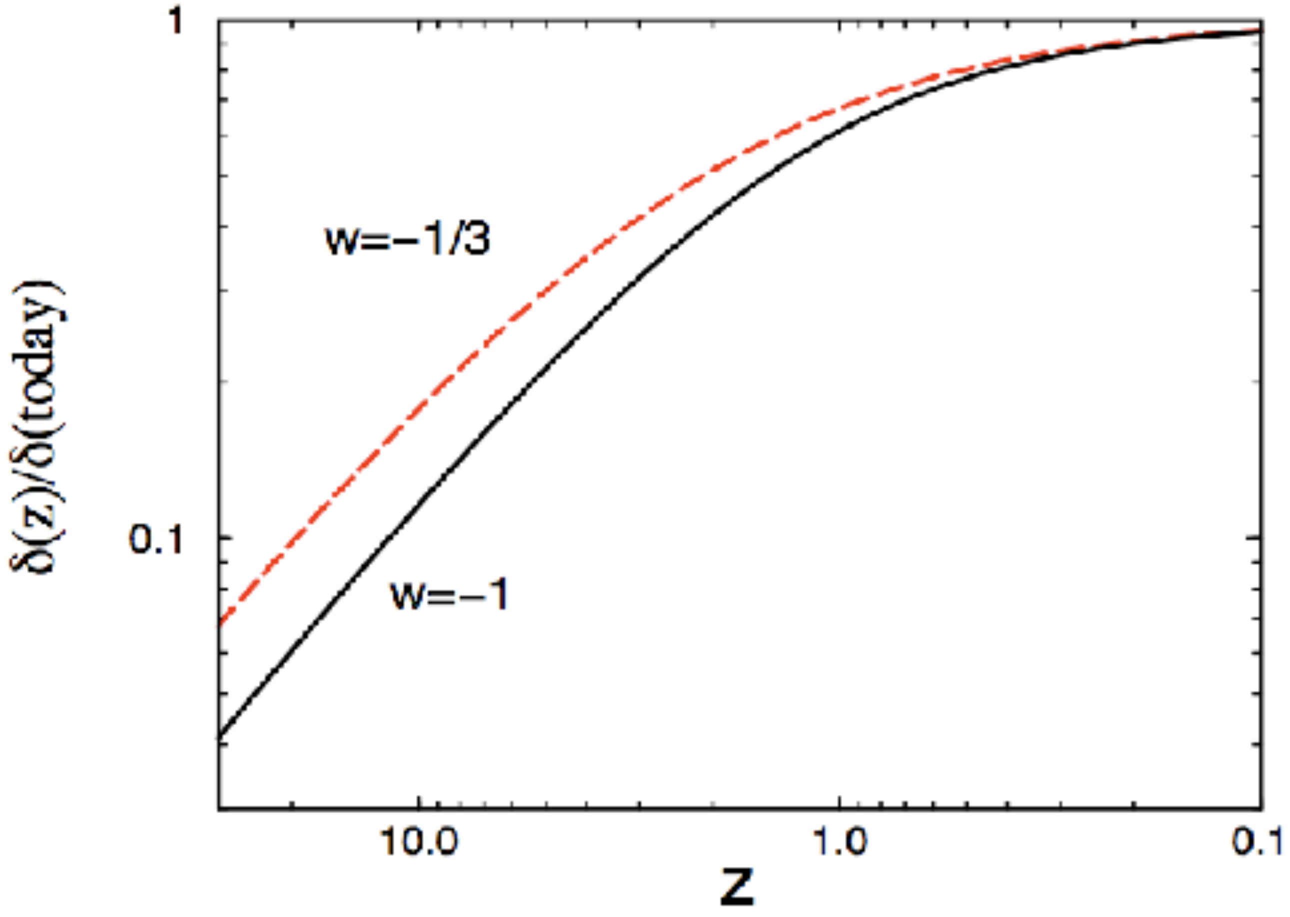


Two Different Types of Probes of Cosmology

Expansion rate



Growth of Structure

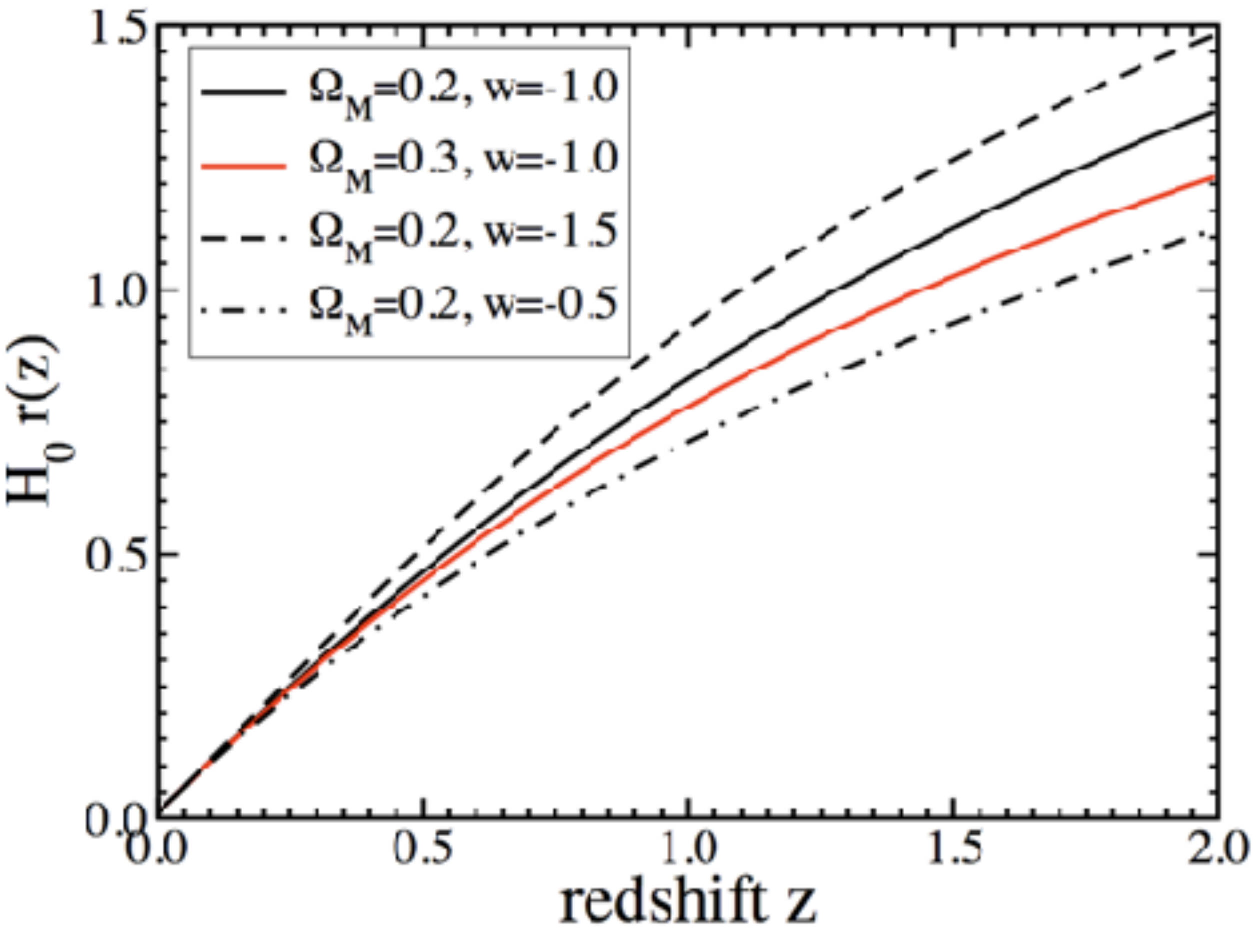


Frieman, Turner, Huterer, ARA&A 2008

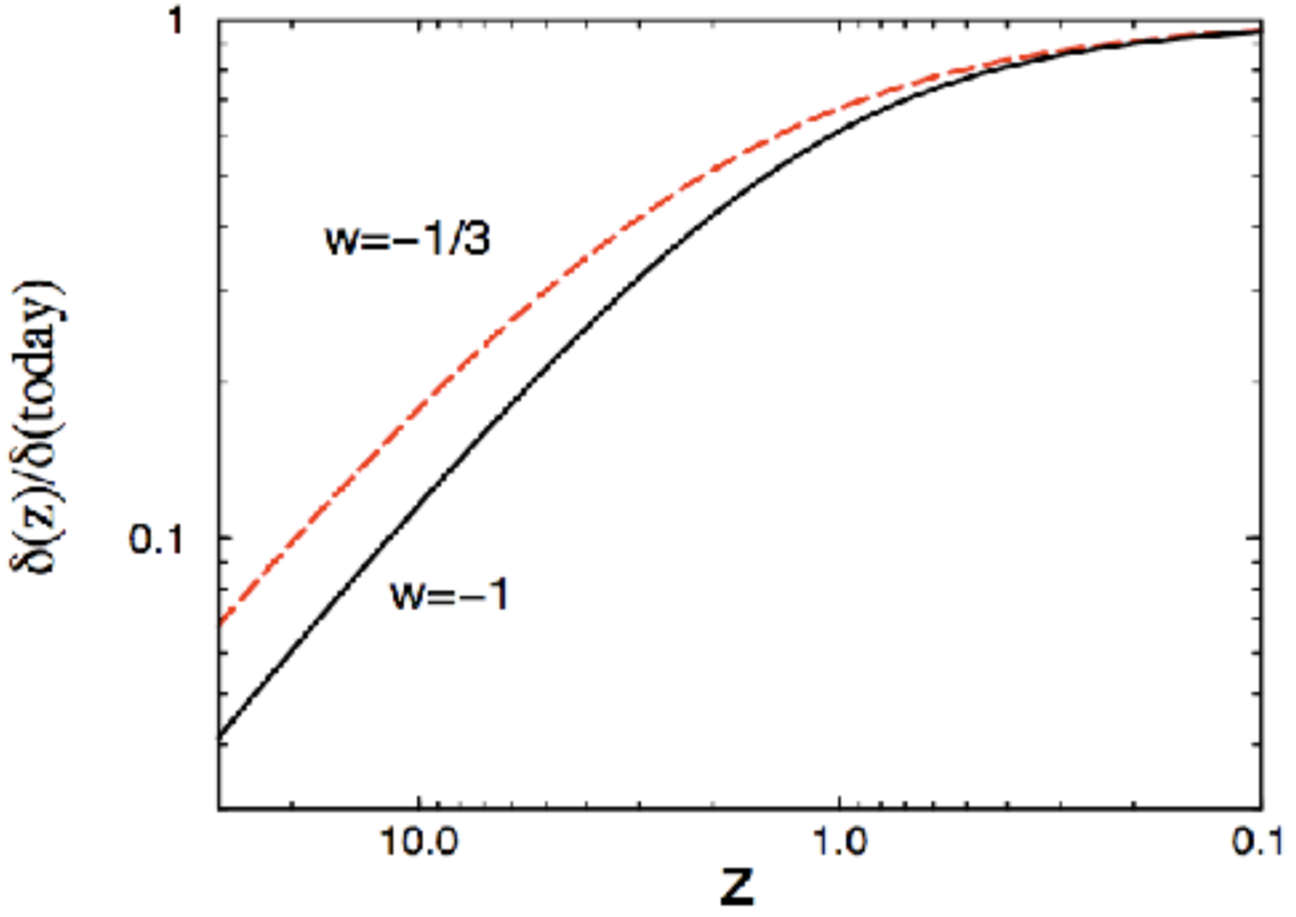
Expansion rate probes (e.g. SN Ia, CMB, BAO) suggest ΛCDM Universe

Two Different Types of Probes of Cosmology

Expansion rate



Growth of Structure



Frieman, Turner, Huterer, ARA&A 2008

Expansion rate probes (e.g. SN Ia, CMB, BAO) suggest ΛCDM Universe
ΛCDM makes definitive prediction of structure growth

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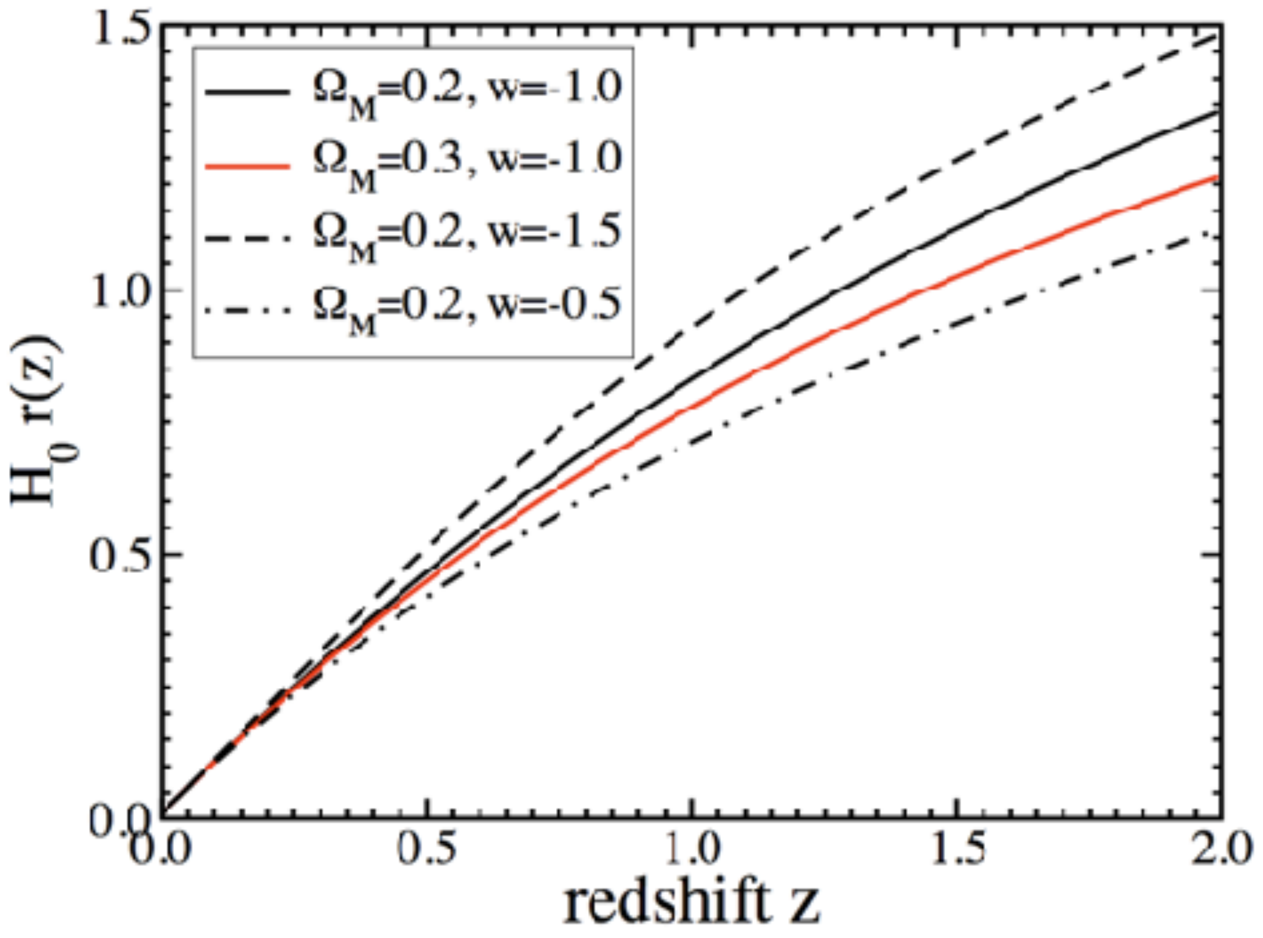
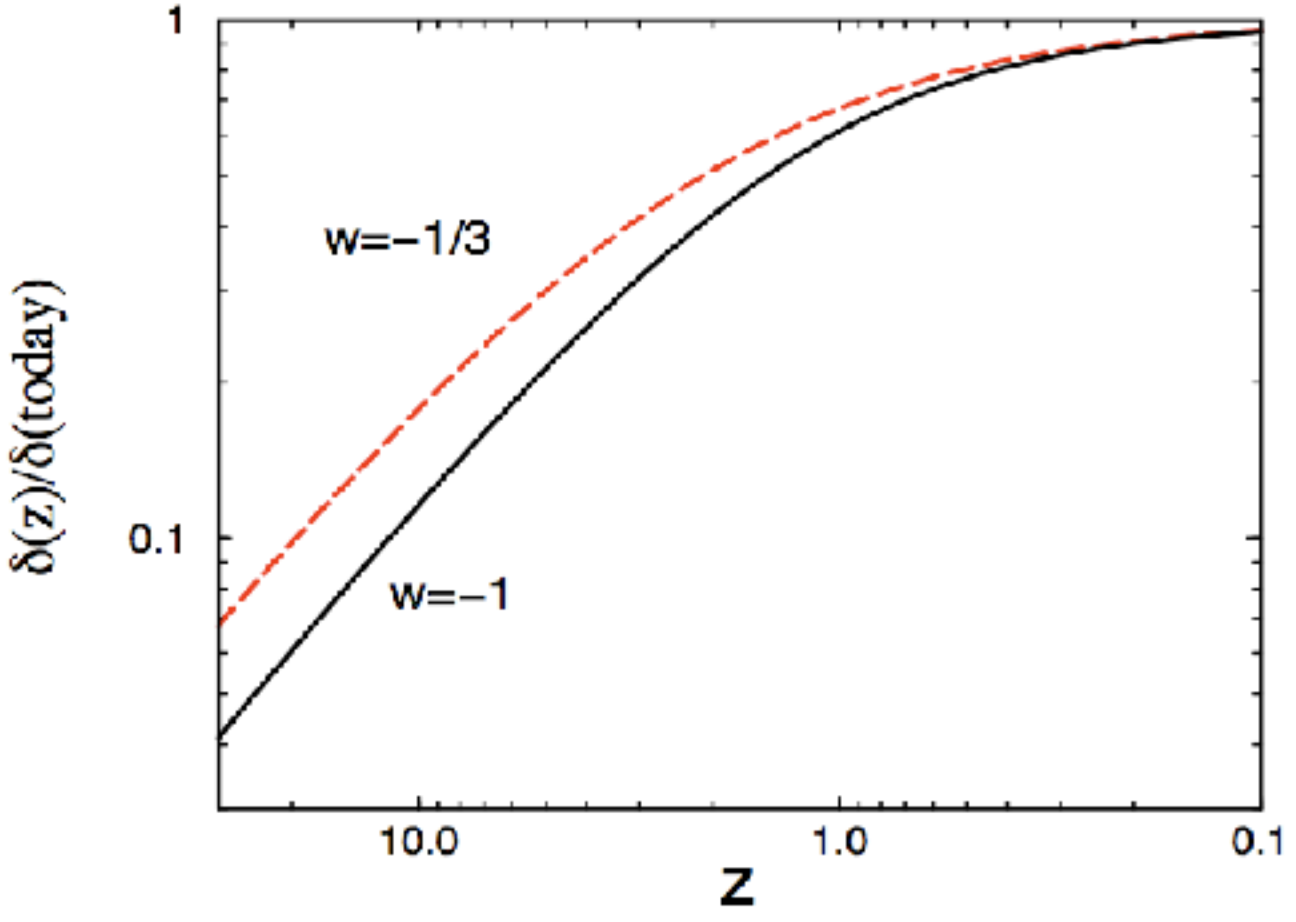


Growth of Structure

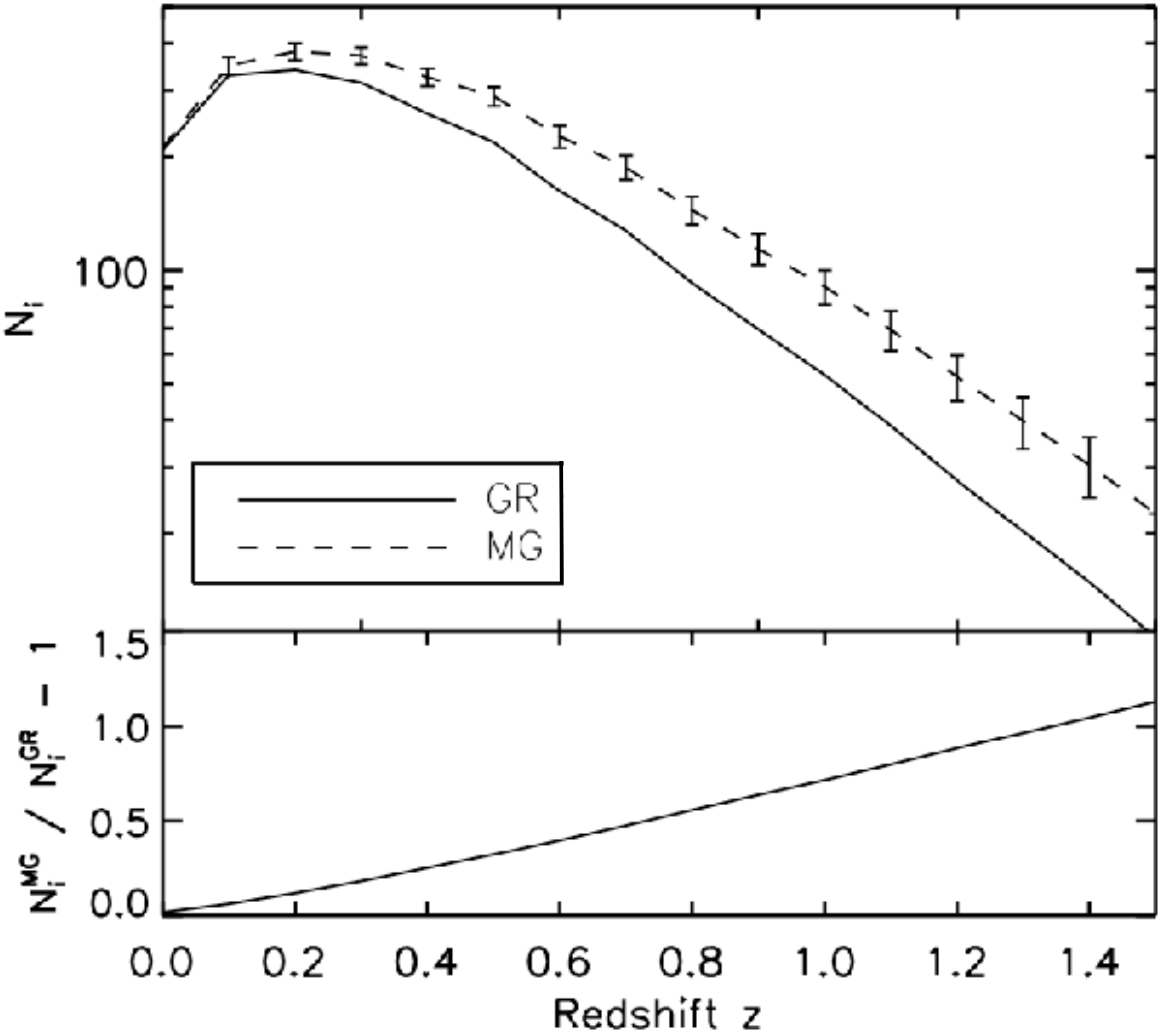


Frieman, Turner, Huterer, ARA&A 2008

Expansion rate probes (e.g. CMB, SN Ia, BAO) suggest ΛCDM Universe
ΛCDM makes definitive prediction of structure growth
Look for deviations from this prediction to test ΛCDM

Learning about Dark Energy

An alternative model to GR can give the same expansion rate but different growth of structure



Shapiro, Dodelson, Hoyle, Samushia, Flaugher (1004.4810)

Two Additional Cosmological Parameters of Interest

$w = p/\rho$ = equation of state of dark energy
(ΛCDM is model of Universe where $w = -1$)

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nature of dark energy

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nature of dark energy

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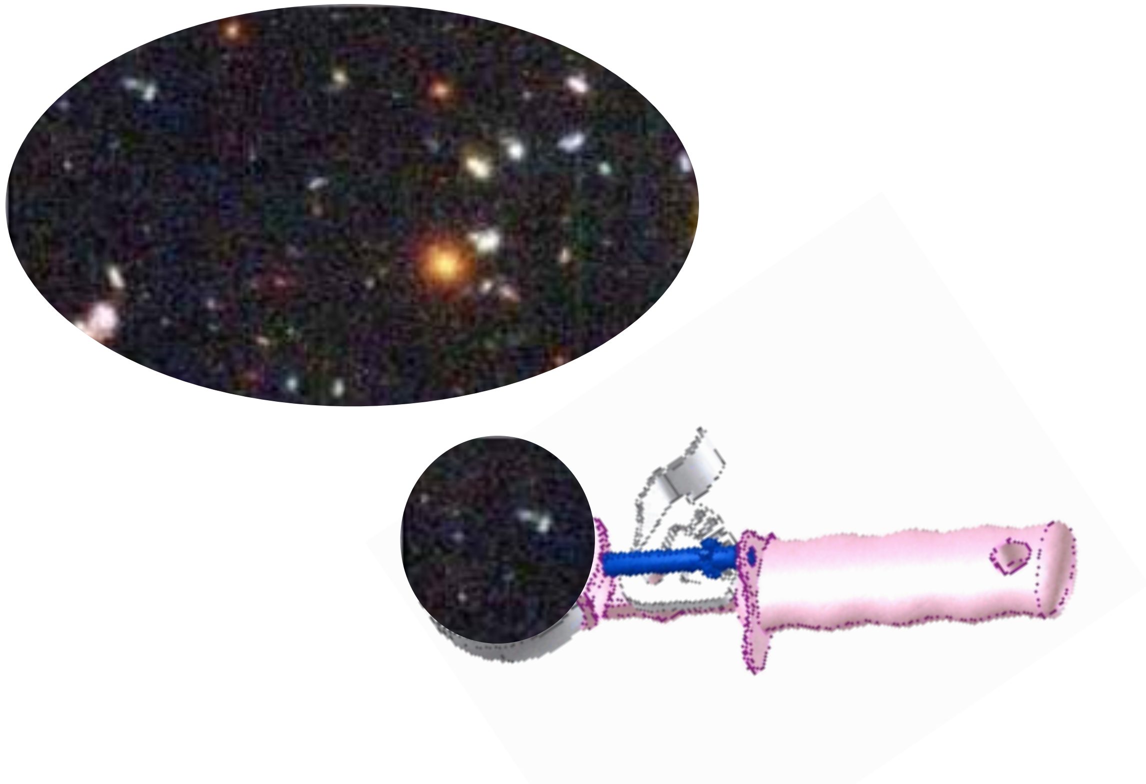
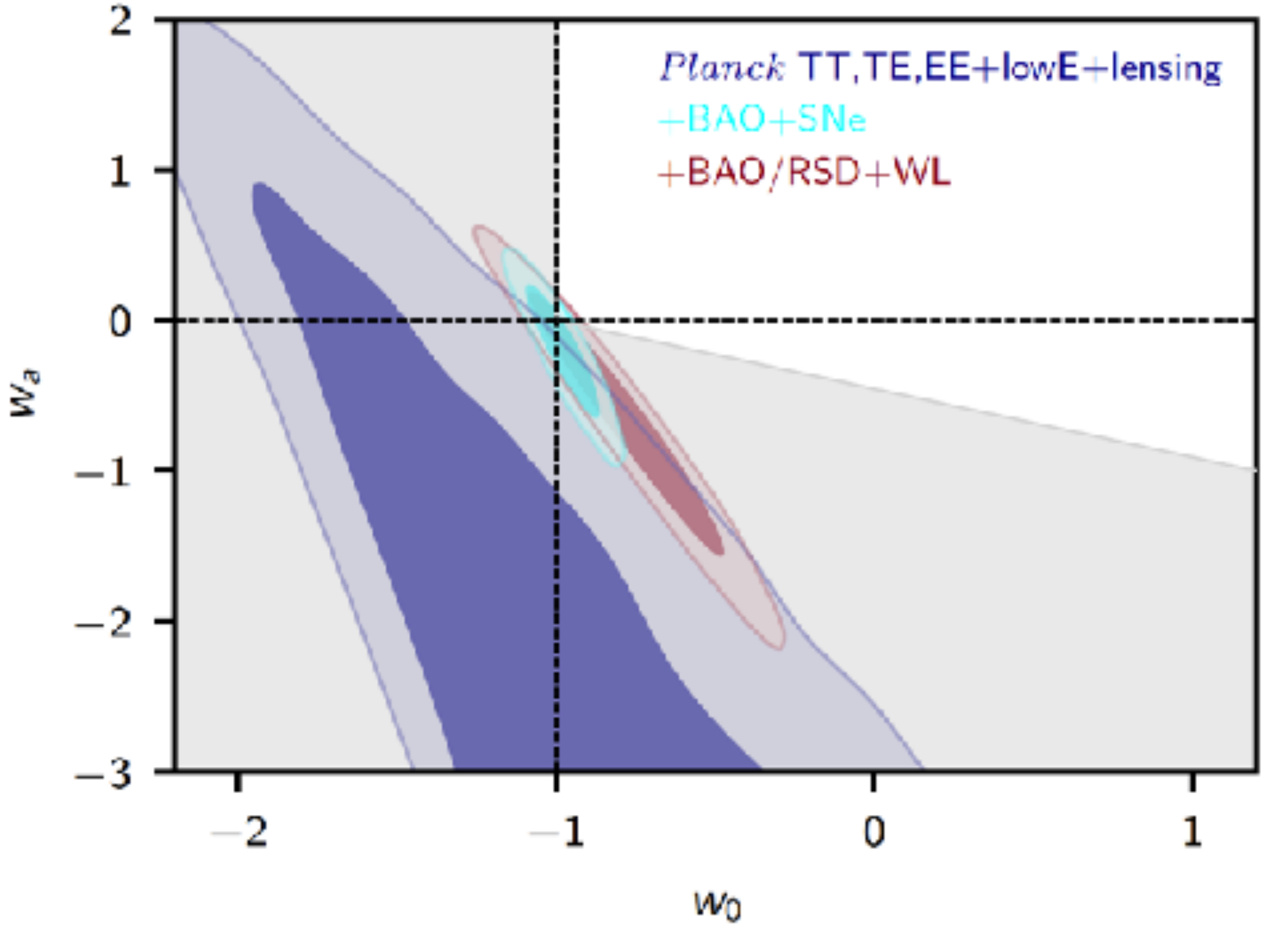


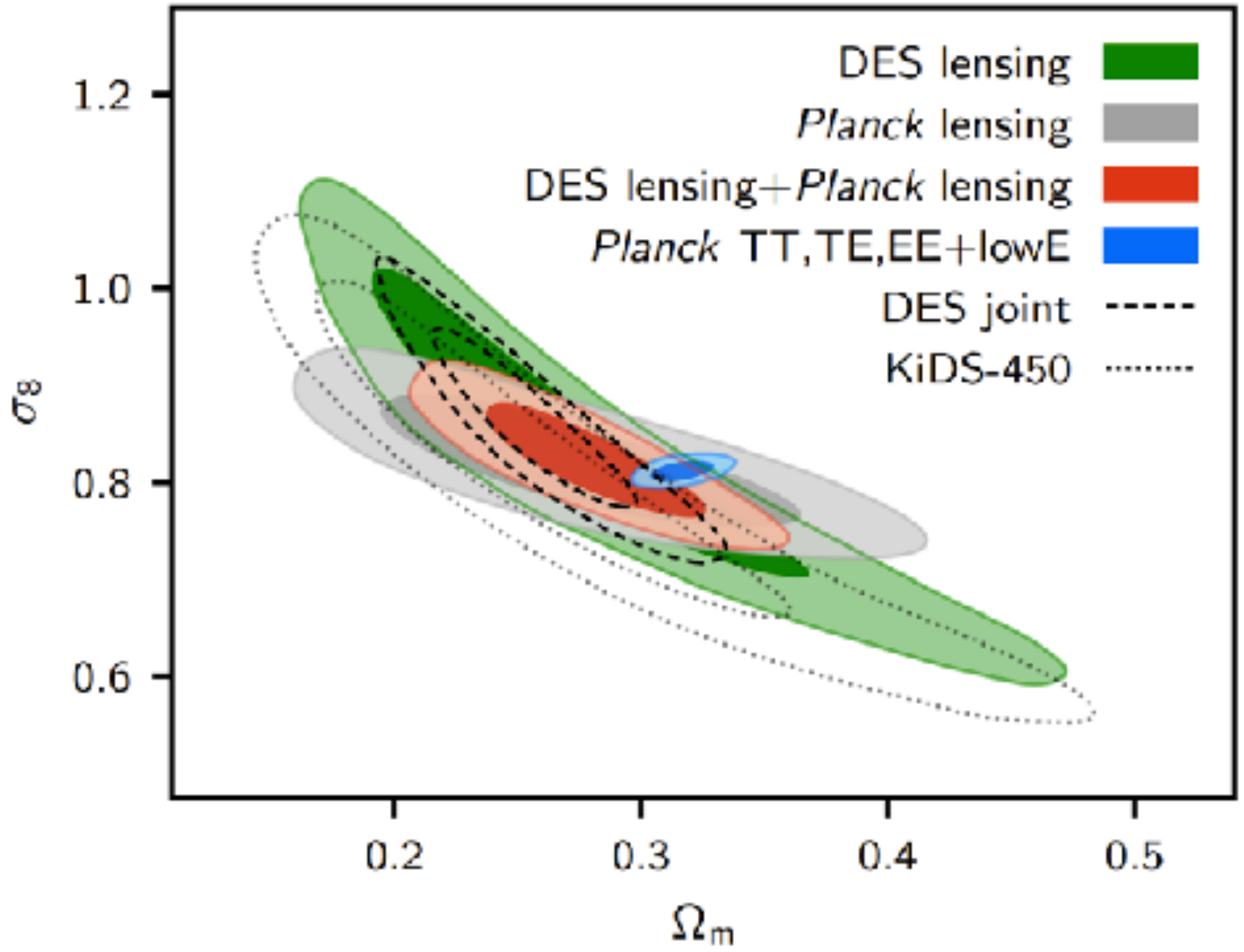
measure of structure growth

Latest Planck results out this past Tuesday

Planck 2018 Final Results



Planck 2018 Results Paper VI



Large Synoptic Survey Telescope (LSST)

- 8-m telescope in Chile
- maps Southern sky every 3 days
- 30 TB data/night, public immediately
- wide, fast, deep
- complete in ~2020

Summary

- Evidence for Dark Energy has been growing since mid 1970s
- Now we have many different independent data sets indicating Dark Energy must exist
- However, we do not know what is the nature of this energy component
- The next decade will have a focus on understanding this using instruments like the LSST, WFIRST, and Euclid