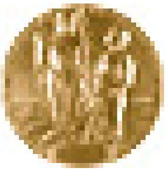
Scientific Background on the Nobel Prize in Physics 2011

THE ACCELERATING UNIVERSE

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.



The Nobel Prize in Physics 2011

Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

Let me start with a brief reminder about cosmology:

1- The Universe is isotropic and homogeneous.

2- We assume General Relativity

3- The metric is the Friedmann-Lemaitre-Robertson-Walker for an expanding Universe.

The FLRW metric

$$ds^2 = dt^2 - \left[dr^2 + r^2 d\Omega^2\right]$$

Minkowski metric you use in Special Relativity…

$$ds^2 = dt^2 - a^2(t)\left[dr^2 + r^2 d\Omega^2\right]$$

«Scale factor»

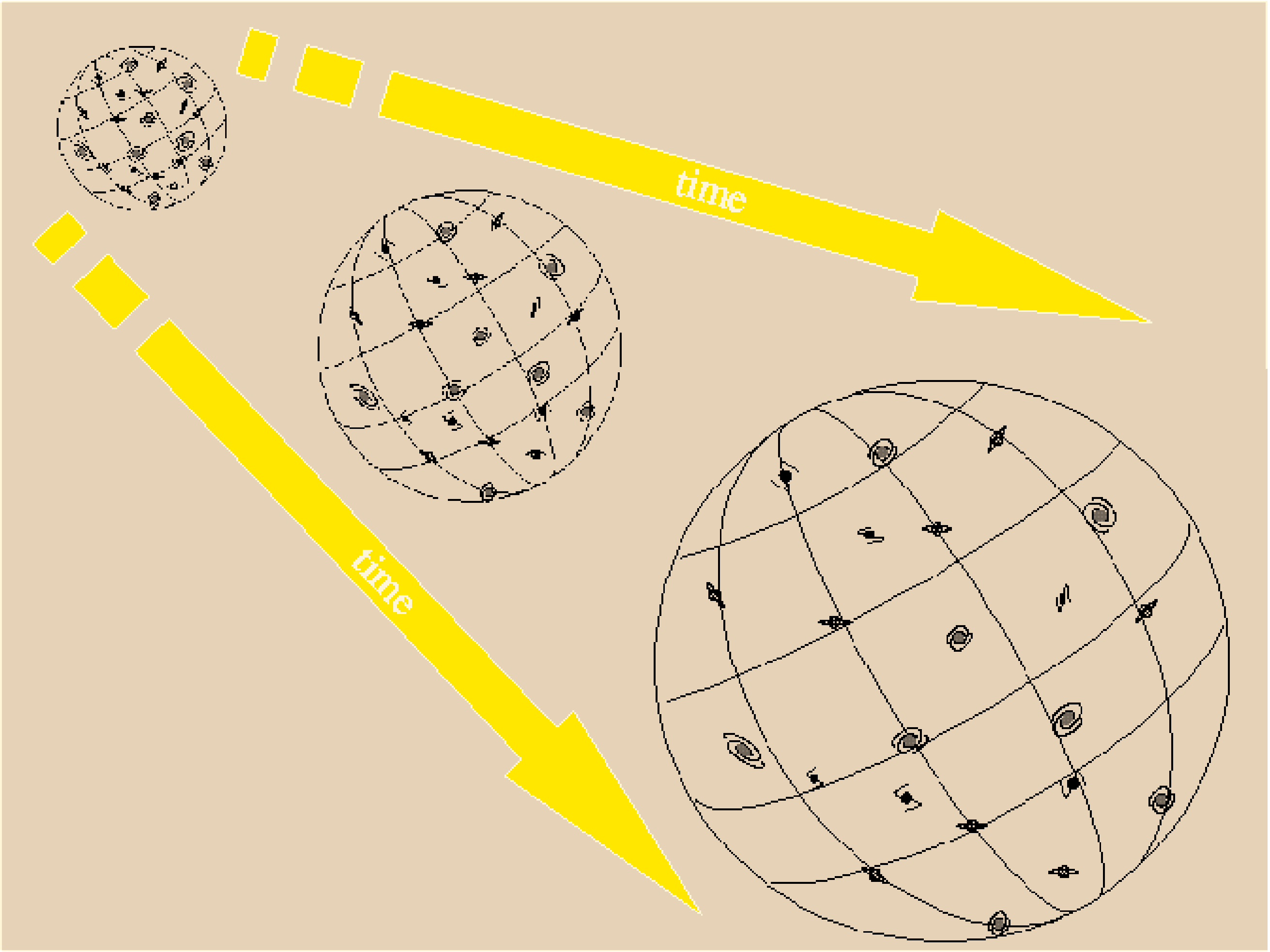
… but here the Universe is expanding. Spatial part multiplied by a scale factor solely function of time. Spatial coordinates are comoving. We can syncronize all the clocks in the universe at the same time t.a=1 today.

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

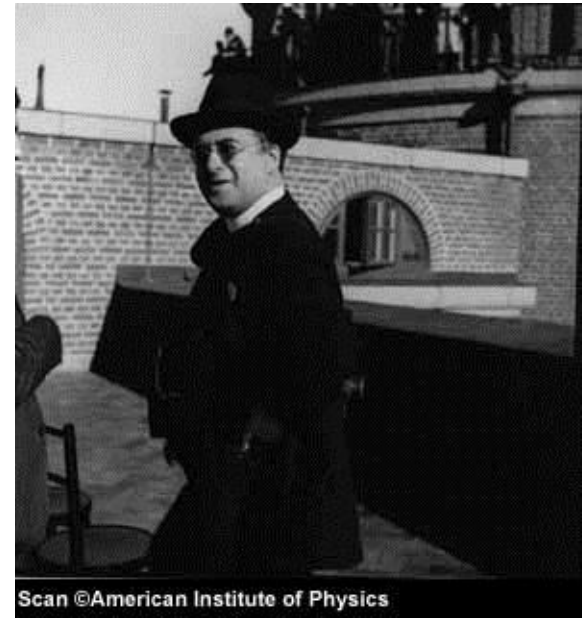
«Curvature»

… the spatial part could also be non-Euclidean. k>0 means closed universe, k<0 means open universe. k is a constant.

Friedmann's Universe



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

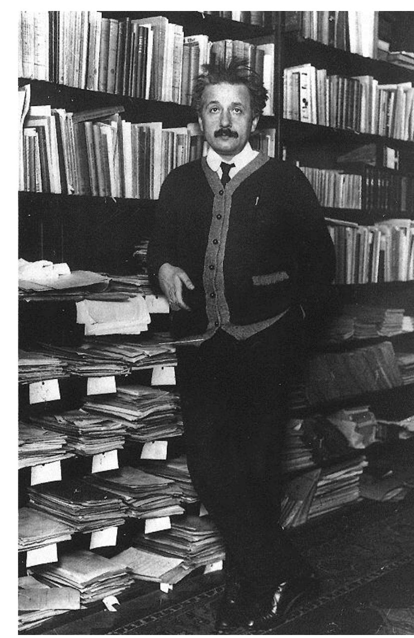


Around 1922 Friedmann and, independently, Lemaitre (1927) independently proposed an expanding universe and therefore no need for a cosmological constant term. Einstein, at the beginning,
rejected the idea of an expanding universe.
In particular Einstein commented the idea as:

"…. while mathematically correct it's of
no physical significance"

While, according to Lemaitre, he was telling him:

"Vos calculs sont corrects, mais votre physique est abominable"



But an expanding universe his is exactly what was measured by Wirtz, Hubble and Humason …

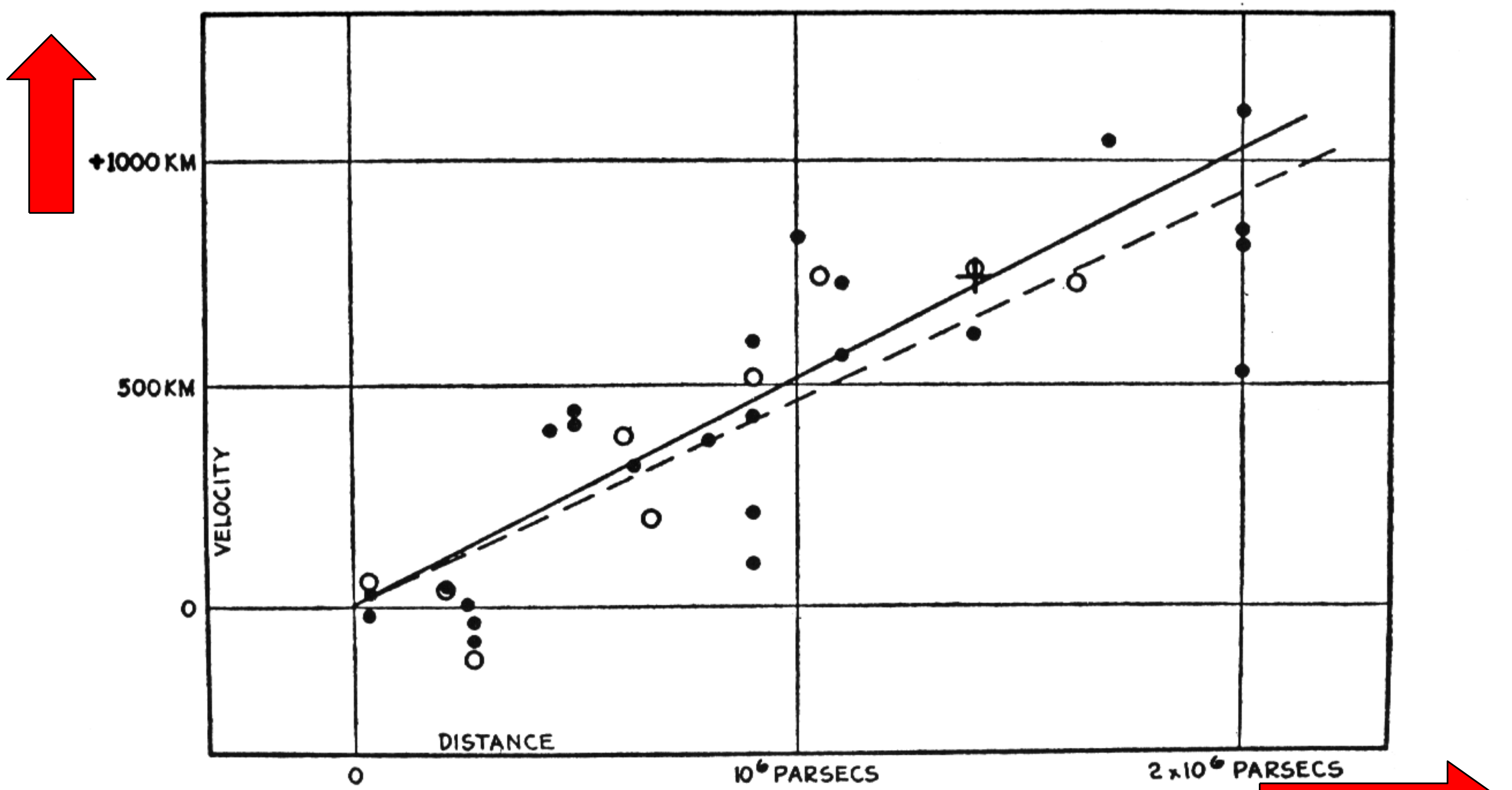


FIG. 9. *The Formulation of the Velocity-Distance Relation.*

Distance

The Friedmann Equations

Einstein's equation: $$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$g_{\mu\nu} \equiv \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & a^2 & 0 & 0 \\ 0 & 0 & a^2 & 0 \\ 0 & 0 & 0 & a^2 \end{pmatrix}$$

$$T_{\mu\nu} = \begin{pmatrix} \rho(t) & 0 & 0 & 0 \\ 0 & P(t) & 0 & 0 \\ 0 & 0 & P(t) & 0 \\ 0 & 0 & 0 & P(t) \end{pmatrix}$$

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

$$\left(\frac{\ddot{a}}{a}\right) = -\frac{4\pi G}{3}\left(\rho + 3P\right)$$

We have two independent equations. The first one relates the expansion rate to the energy content.

The second one the relates the acceleration to energy and pressure.

We solve the system by introducing an equation of state of the form

$$P = w\rho$$

where w is usually a constant with time.

The Continuity Equation

Combining the first and second Friedmann equation we get:

$$\frac{d\rho}{\rho} = -3(1+w)\frac{da}{a}$$

We can integrate for a generic fluid with equation of state w_i obtaining:

$$\rho_i = \frac{\rho_i^{\;0}}{a^{3(1+w_i)}}$$

We can consider 4 cases:

Matter	$P = 0$	$w_m = 0$	$\rho_m = \frac{\rho_m^{\;0}}{a^3}$
Radiation	$P_r = \frac{1}{3}\rho_r$	$w_r = \frac{1}{3}$	$\rho_r = \frac{\rho_r^{\;0}}{a^4}$
Curvature	$P_k = -\rho_k / 3$	$w_k = -1/3$	$\rho_k = \rho_k^0 / a^2$
Cosmological Constant	$P_\Lambda = -\rho_\Lambda$	$w_\Lambda = -1$	$\rho_\Lambda = \rho_\Lambda^0$

Some re-definitions

The Hubble Constant: $$H_0 = \left(\frac{\dot{a}}{a}\right)\Bigg|_{t=t_0}$$

The critical density (constant): $$\rho_c = \frac{3H_0^2}{8\pi G}$$

The density parameters (computed today): $$\Omega_i = \frac{\rho_i^0}{\rho_c}$$

Some re-definitions

Suppose to have i=1,..,n energy components with equation of state w_i

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\sum_{i=1,..,n}\rho_i \qquad \left(\frac{\ddot{a}}{a}\right) = -\frac{4\pi G}{3}\sum_{i=1,..,n}(1+3w_i)\rho_i$$

$$\left(\frac{\dot{a}}{a}\right)^2 \frac{1}{H_0^2} = \sum_{i=1,..,n}\frac{\Omega_i}{a^{3(1+w_i)}} \qquad -\left(\frac{\ddot{a}}{a}\right)\frac{1}{H_0^2} = \frac{1}{2}\sum_{i=1,..,n}(1+3w_i)\frac{\Omega_i}{a^{3(1+w_i)}}$$

Curvature and the deceleration parameter

Computing the Friedmann equations today, we have

$$1 = \sum_i \Omega_i$$

Deceleration Parameter !
$q_0 > 0$ universe is decelerating
$q_0 < 0$ universe is accelerating

$$q_0 = -\left(\frac{\ddot{a}}{a}\right)\frac{1}{H_0^2}\bigg|_{t=t_0} = \frac{1}{2}\sum_i \Omega_i (1 + 3w_i)$$

In a model with curvature+matter+ cosmological constant:

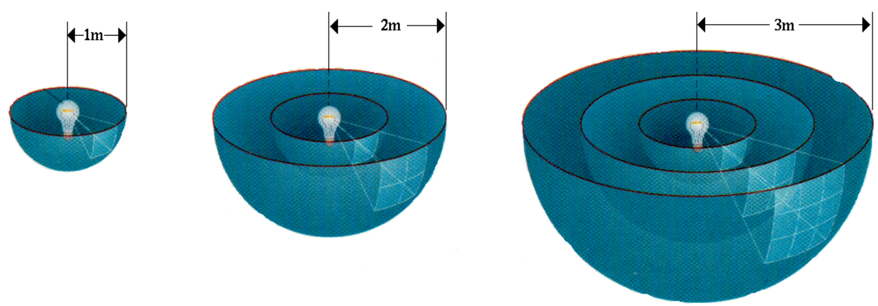
$$\Omega_k = 1 - \Omega_m - \Omega_\Lambda$$

$$q_0 = \frac{\Omega_m}{2} - \Omega_\Lambda$$

If $q_0 < 0$ then we need a cosmological constant. However we need to know the curvature to determine its precise value.

Measuring the deceleration parameter: luminosity distance.

In astronomy, given an object with known luminosity L we can measure its distance by measuring the radiative flux on earth:



$$f = \frac{L}{4\pi r^2}$$

Actually astronomers (since Hypparcos) use magnitudes

$$f \to m \quad \text{apparent magnitude}$$

$$L \to M \quad \text{absolute magnitude}$$

$$f = \frac{L}{4\pi r^2} \to m - M = 5\log_{10}\left(\frac{r}{10\,pc}\right)$$

Measuring the deceleration parameter: luminosity distance.

In cosmology, in an expanding universe, the luminosity distance is a function of the rate of expansion of the universe.

$$d_L(z) = cH_0^{-1}(1+z)\int_0^z \frac{dz'}{\left[\Omega_m (1+z')^3 + \Omega_\Lambda\right]}$$

We can expand for small values of z. At first order we get the Hubble law:

$$d_L(z) \approx cH_0^{-1} z + \ldots$$

at second order we get deviations that depends on q_0 !

$$d_L(z) \approx cH_0^{-1} z \left[1 + \frac{1-q_0}{2} z\right] + \ldots$$

The Key Equation

Measured
is equivalent to
the observed flux

Marginalized
over

Derived

$$m - M = 5\log\left(cH_0^{-1}z\left[1+\frac{1-q_0}{2}z\right]\right)+25$$

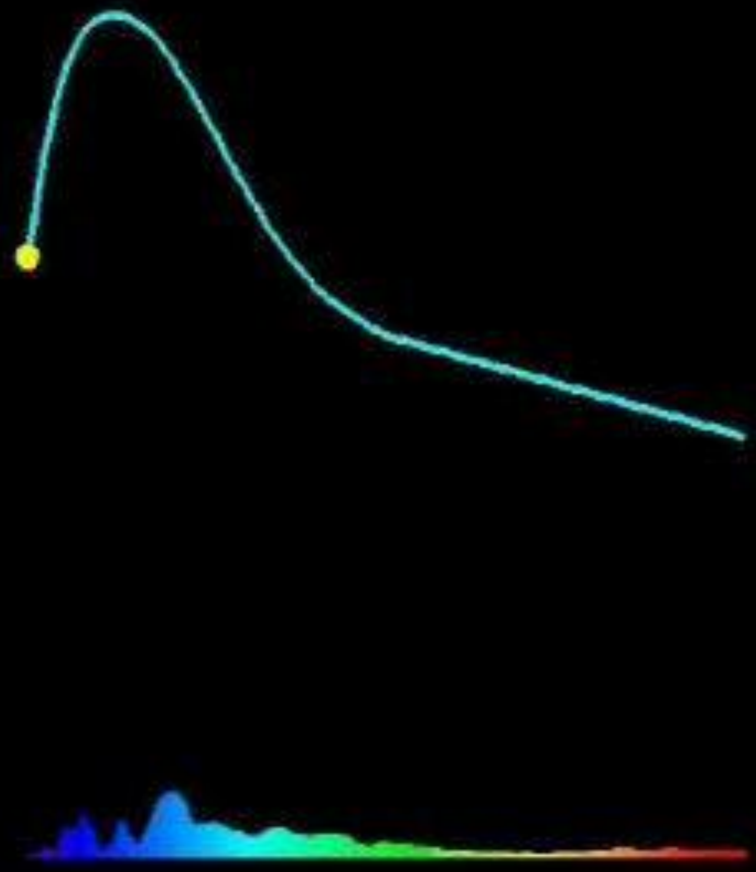
Aestimated
Equivalent to
The intrinsic
luminosity

Measured
(spectra)

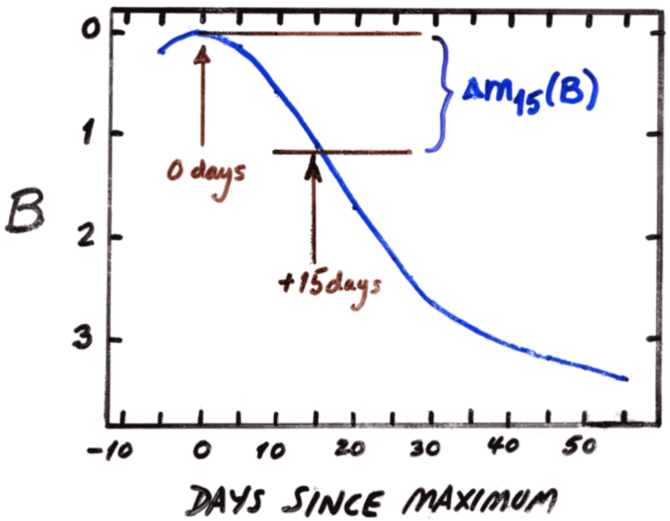
Objects with the same luminosity (or absolute magnitude) and at the same redshift will appear less luminous (or with greater apparent magnitude) if the universe is in accelerated expansion.

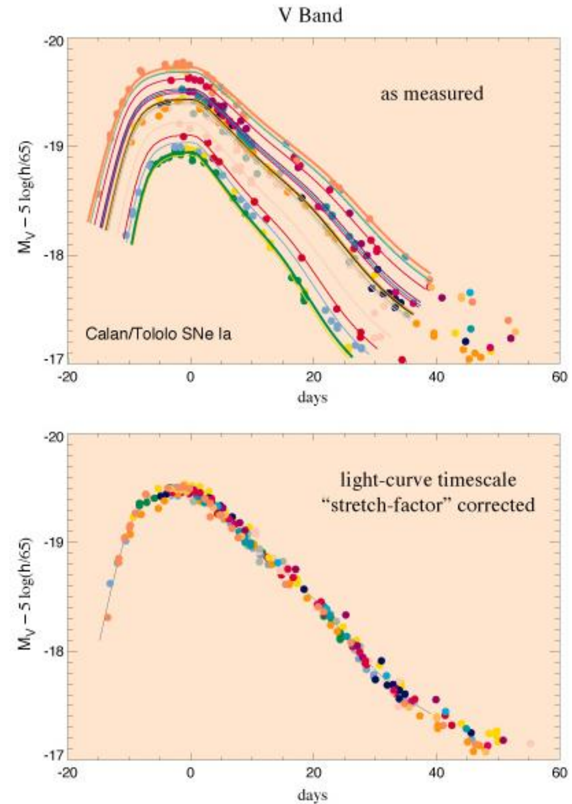
Decelerated

Accelerated



Are Supernovae type Ia standard candles ?





During the course of the Calán/Tololo Supernova Survey, Mark M. Phillips discovered that the faster the supernova faded from maximum light, the fainter its peak luminosity was.

TABLE 2

LEAST-SQUARES FITS

	$M_{\max} = a + b\,\Delta m_{15}(B)$		
BANDPASS	a	b	σ (mag)
B	−21.726(0.498)	2.698(0.359)	0.36
V	−20.883(0.417)	1.949(0.292)	0.28
I	−19.591(0.415)	1.076(0.273)	0.38

Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant

To Appear in the Astronomical Journal

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], John Tonry[11]

ABSTRACT

We present spectral and photometric observations of 10 type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-Z Supernova Search Team (Garnavich et al. 1998; Schmidt et al. 1998) and Riess et al. (1998a), this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the Universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10% to 15% farther than expected in a low mass density ($\Omega_M = 0.2$) Universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8σ

Riess et al., 1998 (submitted May 1998)

Perlmutter et al,
1999
Submitted Dec. 1998

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

S. PERLMUTTER[1], G. ALDERING, G. GOLDHABER[1], R.A. KNOP, P. NUGENT,
P. G. CASTRO[2], S. DEUSTUA, S. FABBRO[3], A. GOOBAR[4],
D. E. GROOM, I. M. HOOK[5], A. G. KIM[1,6], M. Y. KIM, J. C. LEE[7],
N. J. NUNES[2], R. PAIN[3], C. R. PENNYPACKER[8], R. QUIMBY
Institute for Nuclear and Particle Astrophysics,
E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720.
C. LIDMAN
European Southern Observatory, La Silla, Chile.
R. S. ELLIS, M. IRWIN, R. G. MCMAHON
Institute of Astronomy, Cambridge, United Kingdom.
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, Connecticut.
B. J. BOYLE
Anglo-Australian Observatory, Sydney, Australia.
A. V. FILIPPENKO, T. MATHESON
Department of Astronomy, University of California, Berkeley, CA.
A. S. FRUCHTER, N. PANAGIA[9]
Space Telescope Science Institute, Baltimore, Maryland.
H. J. M. NEWBERG
Fermi National Laboratory, Batavia, Illinois.
W. J. COUCH
University of New South Wales, Sydney, Australia.
(THE SUPERNOVA COSMOLOGY PROJECT)

Accepted for publication in The Astrophysical Journal *LBNL-41801*

ABSTRACT

We report measurements of the mass density, Ω_M, and cosmological-constant energy density, Ω_Λ, of the universe based on the analysis of 42 Type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 0.83, are fit jointly with a set of supernovae from the Calán/Tololo Supernova Survey, at redshifts below 0.1, to yield values for the cosmological parameters. All supernova peak magnitudes are standardized using a SN Ia lightcurve width-luminosity relation. The measurement yields a joint probability distribution of the cosmological parameters that is approximated by the relation $0.8\Omega_M - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$ in the region of interest ($\Omega_M \lesssim 1.5$). For a flat ($\Omega_M + \Omega_\Lambda = 1$) cosmology we find $\Omega_M^{\rm flat} = 0.28^{+0.09}_{-0.08}$ (1σ statistical) $^{+0.05}_{-0.04}$ (identified systematics). The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest inflationary universe model. An open, $\Lambda = 0$ cosmology also does not fit the data well: the data indicate that the cosmological constant is non-zero and positive, with a confidence of $P(\Lambda > 0) = 99\%$, including the identified systematic uncertainties. The best-fit age of the universe relative to the Hubble time is $t_0^{\rm flat} = 14.9^{+1.4}_{-1.1}(0.63/h)$ Gyr for a flat cosmology. The size of our sample allows us to perform a variety of statistical tests to check for possible systematic errors and biases. We find no significant differences in either the host reddening distribution or Malmquist bias between the low-redshift Calán/Tololo sample and our high-redshift sample. Excluding those few supernovae which are outliers in color excess or fit residual does not significantly change the results. The conclusions are also robust whether or not a width-luminosity relation is used to standardize the supernova peak magnitudes. We discuss, and constrain where possible, hypothetical alternatives to a cosmological constant.

Cosmology from Type Ia Supernovae

S. Perlmutter, G. Aldering, S. Deustua, S. Fabbro[1], G. Goldhaber, D. E. Groom, A. G. Kim[2], M. Y. Kim, R.A. Knop, P. Nugent, C. R. Pennypacker
Lawrence Berkeley National Laboratory and Center for Particle Astrophysics, U.C. Berkeley

A. Goobar
University of Stockholm

R. Pain
[1]LPNHE, CNRS-IN2P3 & University of Paris VI & VII

I. M. Hook, C. Lidman
European Southern Observatory

R. S. Ellis, M. Irwin, R. G. McMahon
Institute of Astronomy, Cambridge

P. Ruiz-Lapuente
Department of Astronomy, University of Barcelona

N. Walton
Isaac Newton Group, La Palma

B. Schaefer
Yale University

B. J. Boyle
Anglo-Australian Observatory

A. V. Filippenko, T. Matheson
Department of Astronomy, U.C. Berkeley

A. S. Fruchter, N. Panagia
Space Telescope Science Institute

H. J. M. Newberg
Fermi National Laboratory

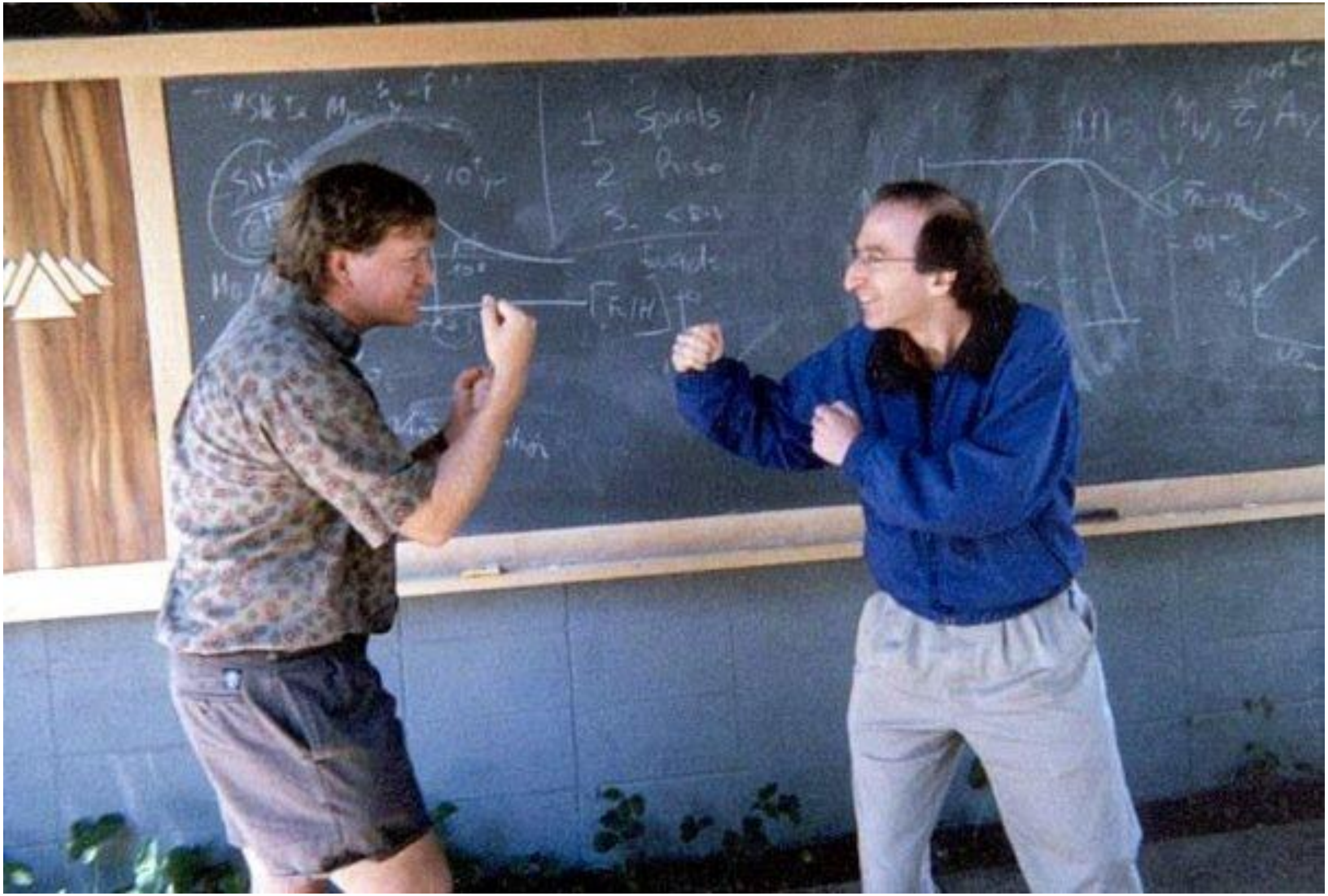
W. J. Couch
University of New South Wales

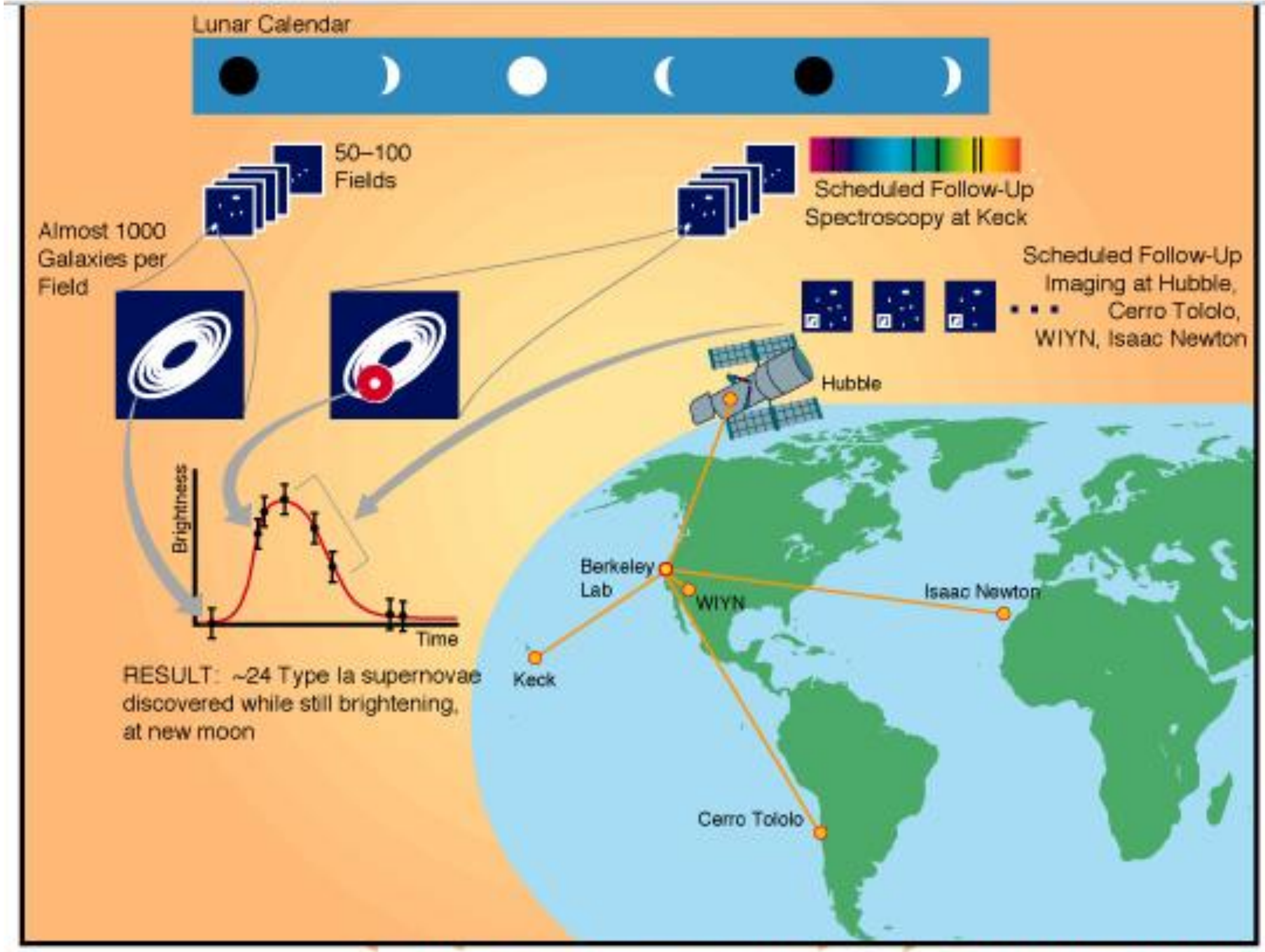
(The Supernova Cosmology Project)

ABSTRACT

This Lawrence Berkeley National Laboratory reprint is a reduction of a poster presentation from the Cosmology Display Session #85 on 9 January 1998 at the American Astronomical Society meeting in Washington D.C. It is also available on the World Wide Web at http://www-supernova.LBL.gov/ *This work has also been referenced in the literature by the pre-meeting abstract citation: Perlmutter et al., B.A.A.S., volume 29, page 1351 (1997).*

This presentation reports on first evidence for a low-mass-density/positive-cosmological-constant universe that will expand forever, based on observations of a set of 40 high-redshift supernovae. The experimental strategy, data sets, and analysis techniques are described. More extensive analyses of these results with some additional methods and data are presented in the more recent LBNL report #41801 (Perlmutter et al., 1998; Ap.J., in press), astro-ph/9812133.

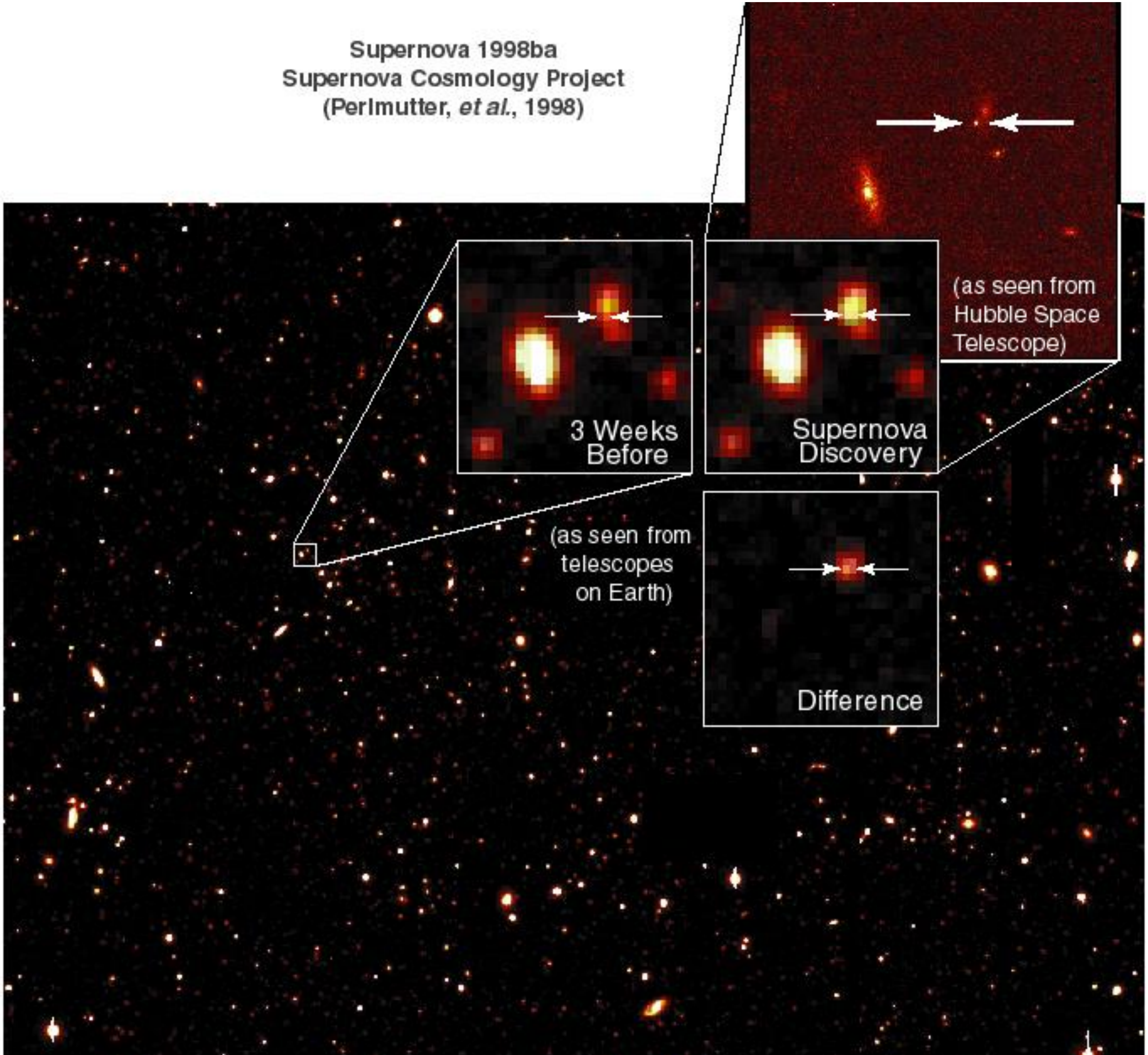

1 Spirals



Perlmutter, et al., in Thermonuclear Supernovae, NATO ASI, v. 486 (1997)

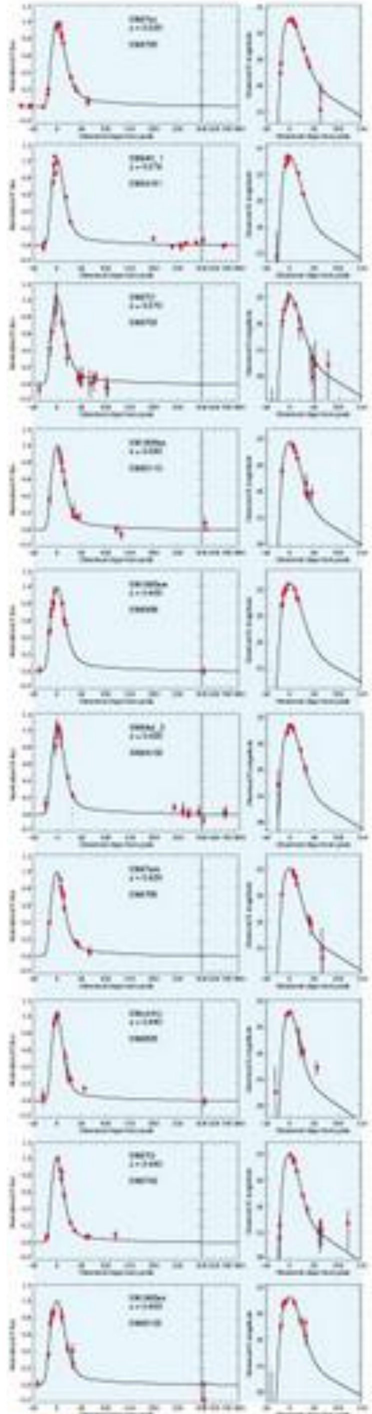
We developed a strategy to guarantee a group of supernova discoveries on a certain date. Just after a new moon, we observe some 50 to 100 high-galactic lattitute fields—each containing almost a thousand high-redshift galaxies—in two nights on the Cerro Tololo 4-meter telescope with Tyson & Bernstein's wide-field camera. We return three weeks later to observe the same fields, and then examine the images of all of the tens of thousands of galaxies. On average, some two dozen Type Ia supernovae will thus be discovered just before new moon—and while still brightening, since the three week time baseline is less than the rise time of a Type Ia supernova. We follow the supernovae, with spectroscopy at maximum light at the Keck telescope, and with photometry over the following two months at the CTIO, WIYN, INT, and (particularly for the highest redshifts) the Hubble Space Telescope.

Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)



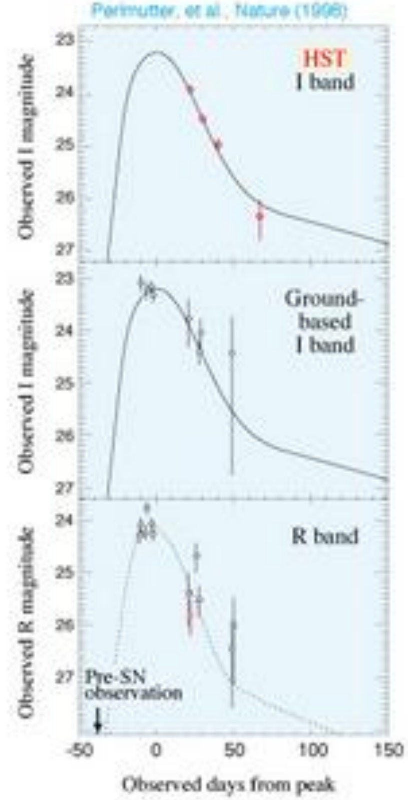
Light Curves

from z = 0.32 ...
observed from the ground



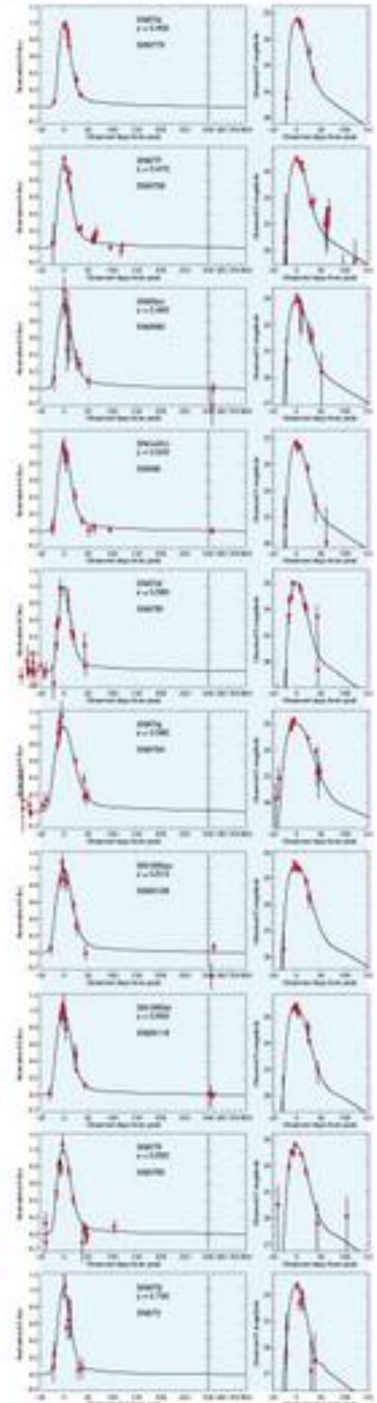
SN 1997ap at z = 0.83
observed from the
ground and with the HST

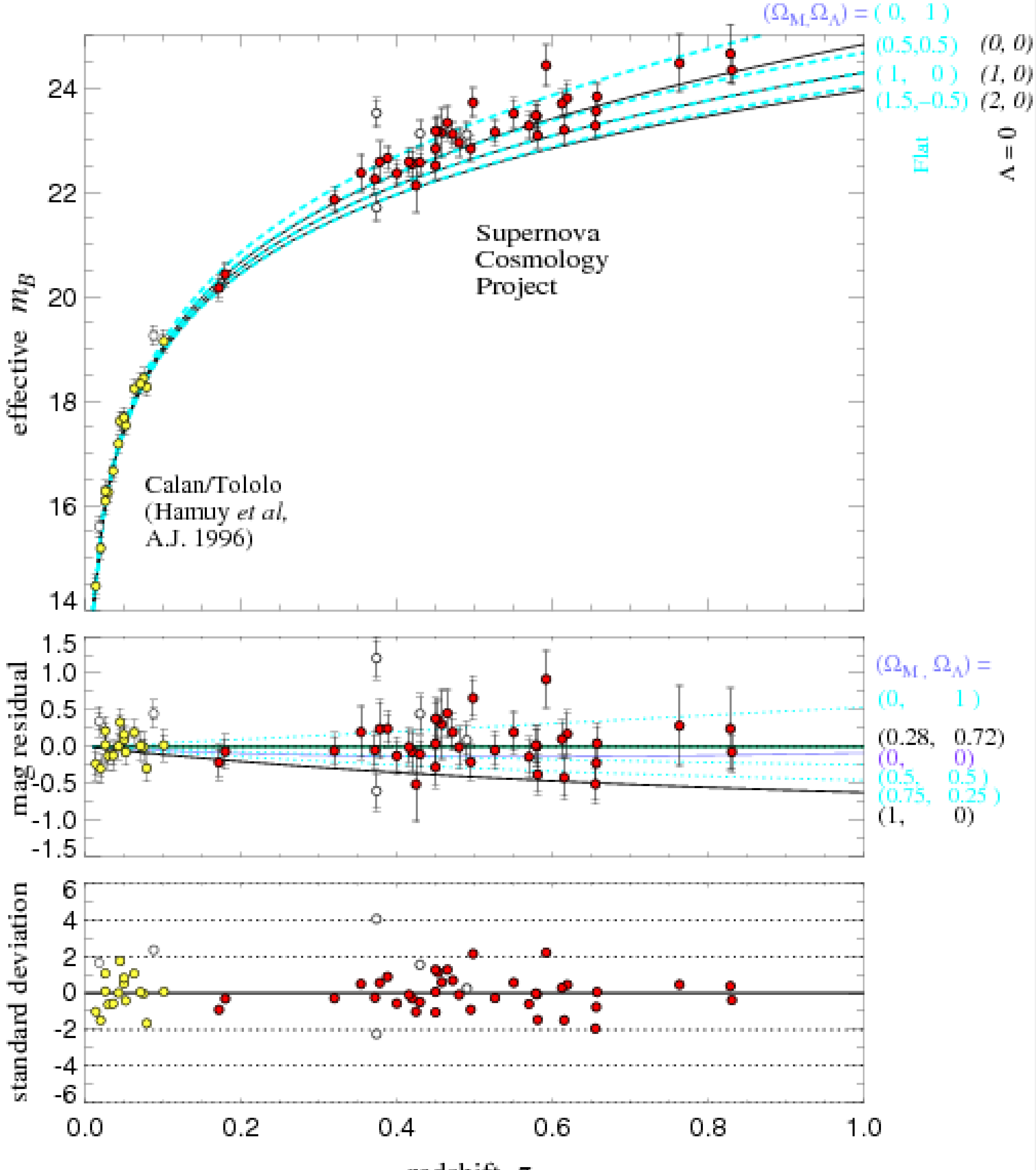
Perlmutter, et al., Nature (1998)



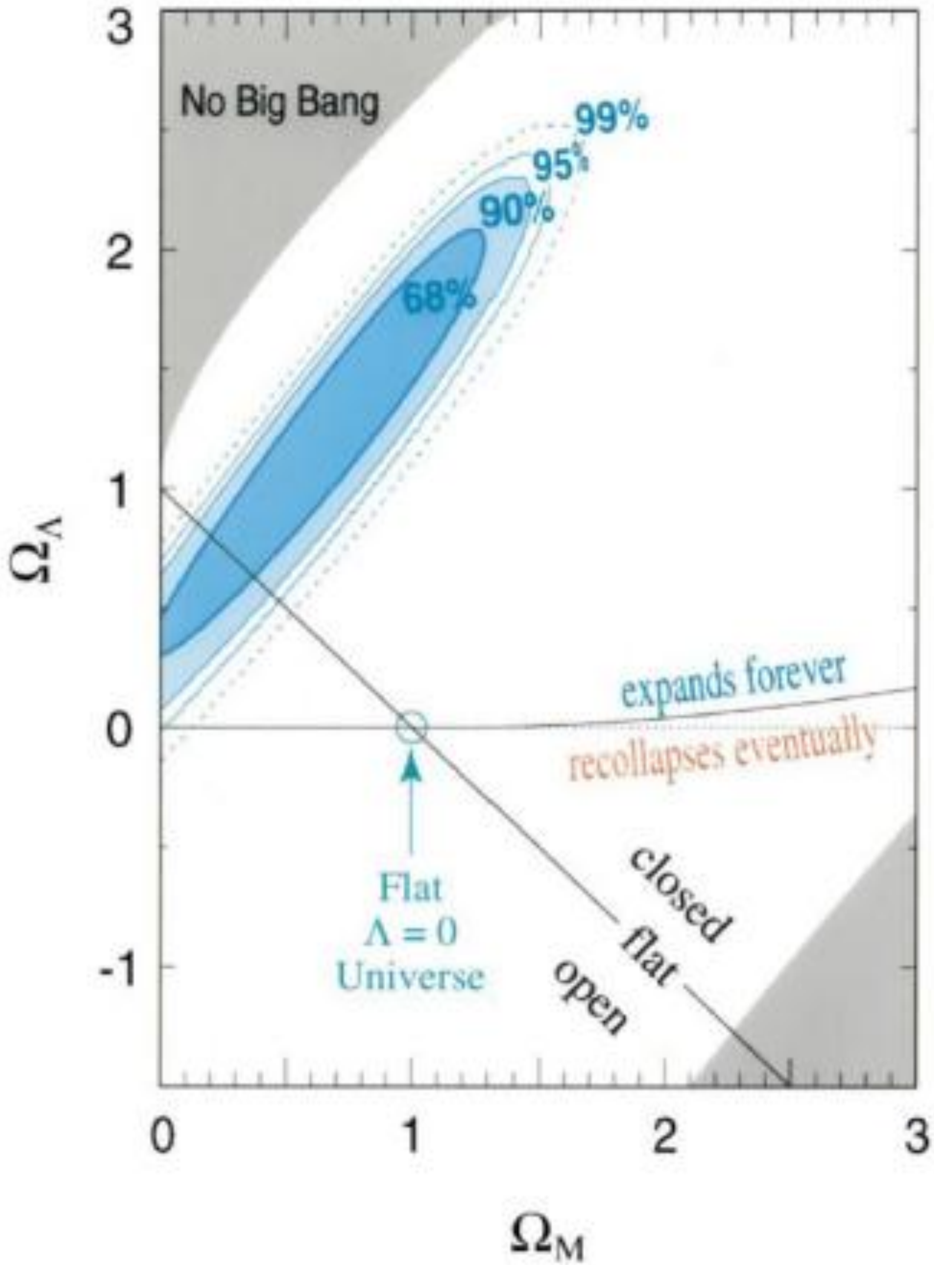
We observe most of the supernovae for approximately two months in both the R and I bands (corresponding approximately to the restframe B and V bands for the median redshift). At high redshifts, a significant fraction of this host galaxy light is within the seeing disk of the supernova, so final observations about one year later are usually necessary to observe (and subtract) the host galaxy light after the supernova has faded. The plots to the left and the right show just the R band light curves for about half of the 40 supernovae that have been completely observed and analyzed so far. The plots above show the highest redshift spectroscopically confirmed supernova, which was observed with the Hubble Space Telescope.

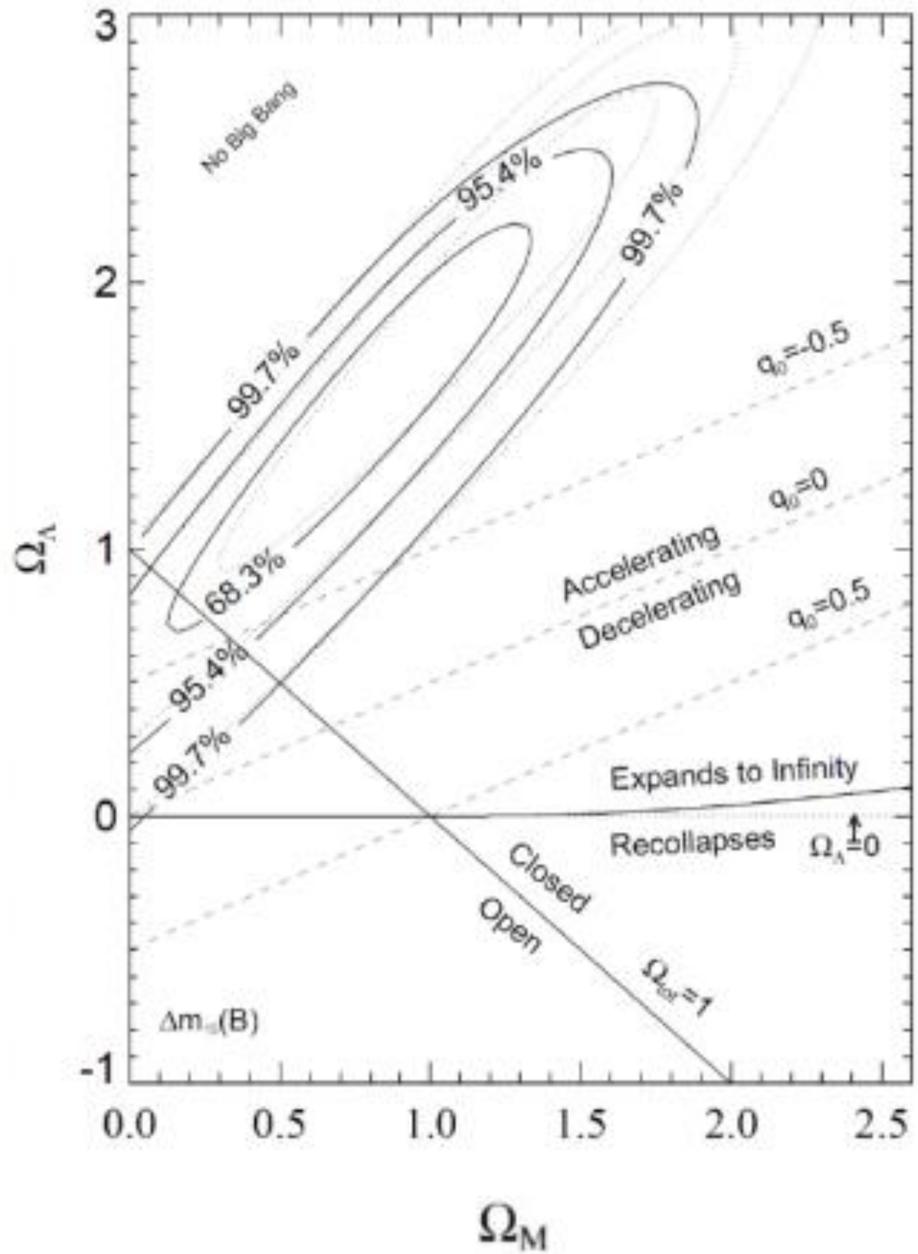
... to z = 0.75
observed from the ground

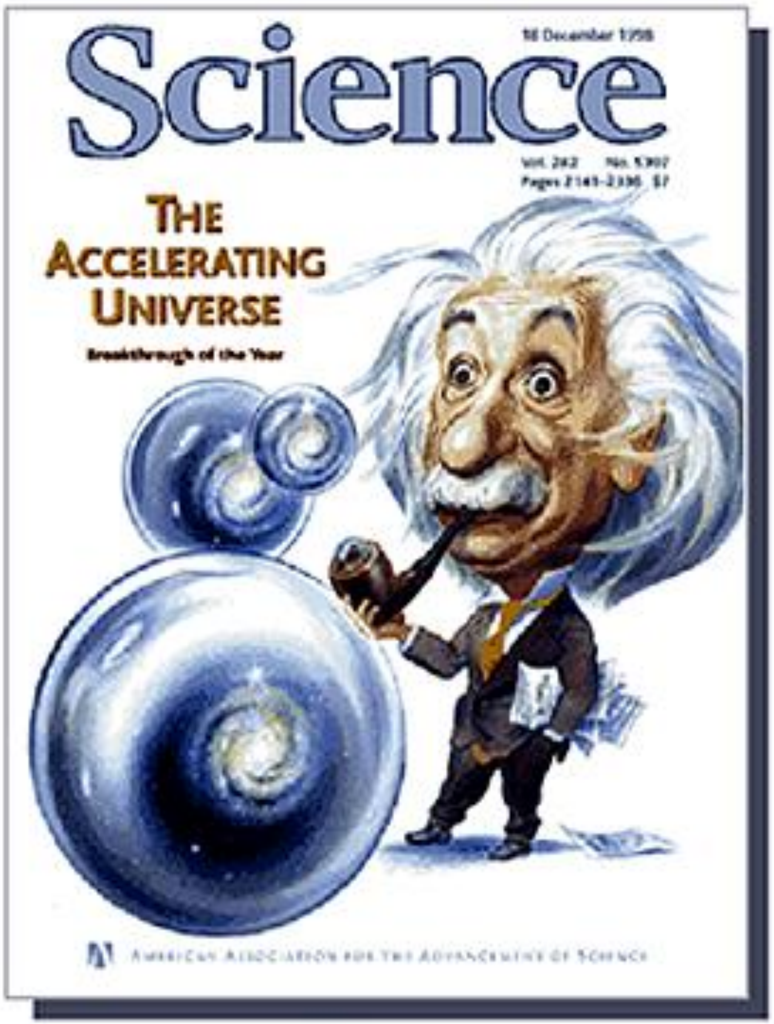




Perlmutter, *et al.* (1998)


No Big Bang
99%
95%
90%
68%
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
Ω_Λ
Ω_M


No Big Bang
95.4%
99.7%
68.3%
q_0=-0.5
q_0=0
q_0=0.5
Accelerating
Decelerating
Expands to Infinity
Recollapses
Ω_Λ=0
Closed
Open
Ω_{tot}=1
Ω_Λ
Ω_M


Science
THE ACCELERATING UNIVERSE
Breakthrough of the Year


SCIENTIFIC AMERICAN
SKY & TELESCOPE
25
Astronomy
SUPERNOVA BLAST

Top Cited Articles of All Time (2010 edition)

The 100 most highly cited papers of All Time (2010 edition)

Keep in mind that citation counts can never be exact, there is something like a 5% error in most of these numbers. Please do not fret about number 32 versus 33, as this is often not a statistically significant difference. Remember the detailed warning about the accuracy of these counts.

Also note that the counts shown, and used in the rankings, are the counts as of Wed 29-Dec-2010. Further, the counts shown by the ranking are only the cites satisfying the criteria for that list. Actual citation numbers in the database may change as corrections are made and papers are

1. 37791
Review of Particle Physics
By Particle Data Group (Claude Amsler et al.).
Citations are counted for all versions of the RPP, most recent version is:
Published in:Phys.Lett.B667:1-1340,2008
[3679 Total citations in HEP]
[37799 Total Citations to all copies of RPP in HEP]

---

2. 7328
A Model of Leptons
By Steven Weinberg (MIT, LNS).
Published in:Phys.Rev.Lett.19:1264-1266,1967
[7328 Total citations in HEP]

---

3. 7135
The Large N limit of superconformal field theories and supergravity
By Juan Martin Maldacena (Harvard U.).
Published in:Adv.Theor.Math.Phys.2:231-252,1998, Int.J.Theor.Phys.38:1113-1133,1999 (arXiv: hep-th/9711200)
[7192 Total citations in HEP]

---

4. 6168
CP Violation in the Renormalizable Theory of Weak Interaction
By Makoto Kobayashi, Toshihide Maskawa (Kyoto U.).
Published in:Prog.Theor.Phys.49:652-657,1973
[6168 Total citations in HEP]

---

5. 5920
First year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Determination of cosmological parameters
By WMAP Collaboration (D.N. Spergel et al.).
Published in:Astrophys.J.Suppl.148:175-194,2003 (arXiv: astro-ph/0302209)
[5921 Total citations in HEP]

---

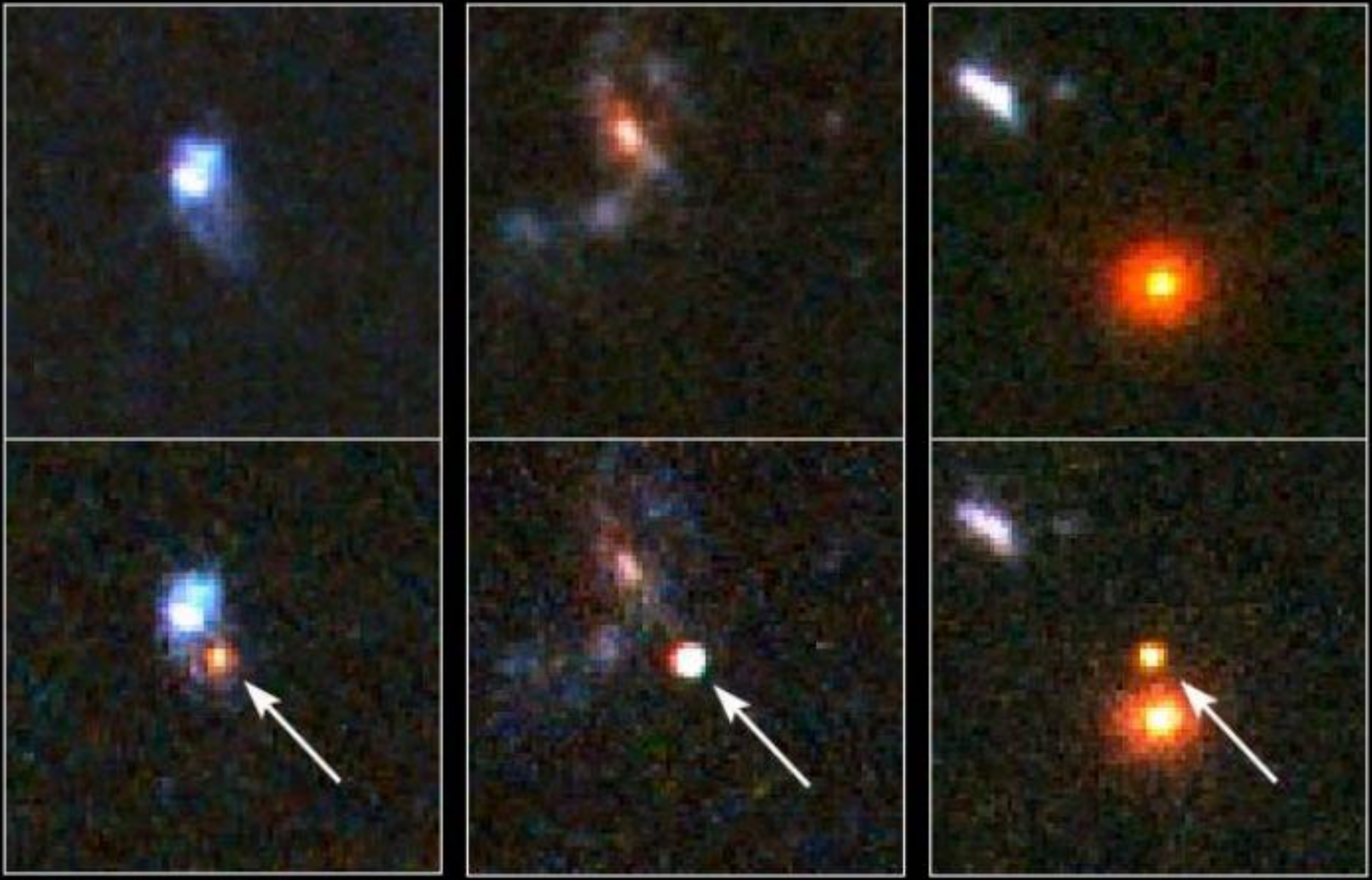
6. 5225
Measurements of Omega and Lambda from 42 high redshift supernovae
By Supernova Cosmology Project (S. Perlmutter et al.).
Published in:Astrophys.J.517:565-586,1999 (arXiv: astro-ph/9812133)
[5226 Total citations in HEP]

---

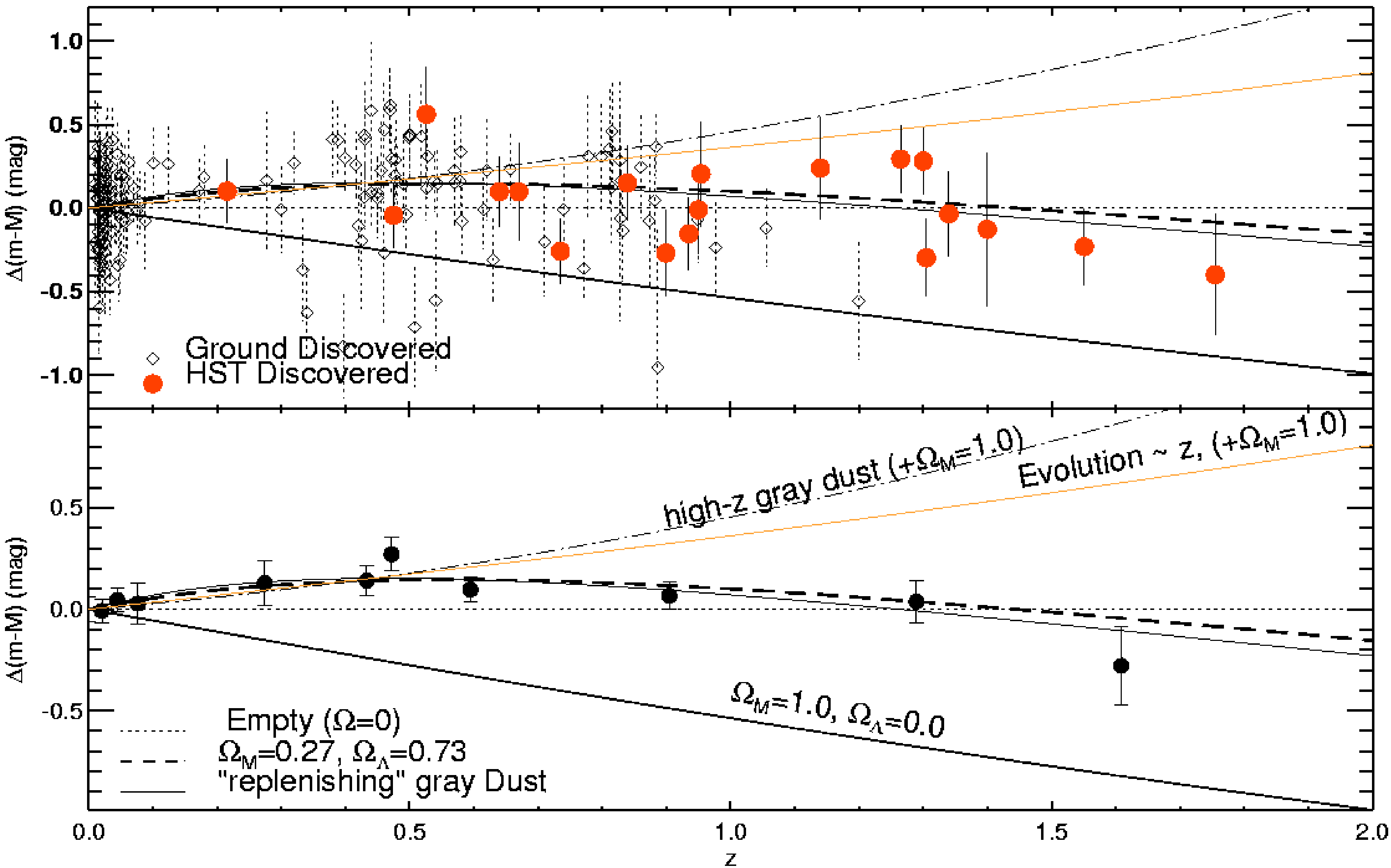
7. 5094
Observational evidence from supernovae for an accelerating universe and a cosmological constant
By Supernova Search Team (Adam G. Riess et al.).
Published in:Astron.J.116:1009-1038,1998 (arXiv: astro-ph/9805201)
[5095 Total citations in HEP]

Reasons to Believe:

1- Result confirmed by subsequent observations of high redshift SN-Ia



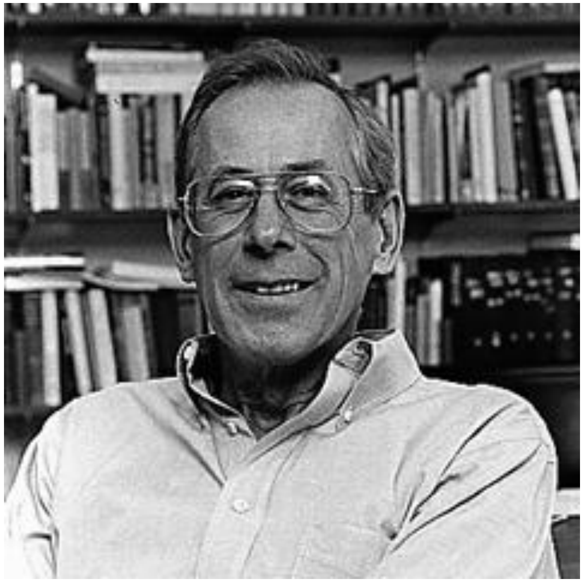
high-z SN-Ia discovered with HST



Reasons to Believe:

2- Result makes cosmology consistent with age of the Oldest objects and indication for a low density Universe.

In 1980 the most favoured model was the so-called cold dark matter model proposed by Peebles (1982) and others. This model is based on the Friedmann solution:



$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{H_0^{\ 2}}{a^3}$$

The CDM model is flat (the spatial part of the metric is euclidean) And the energy density of the universe is currently dominated by a matter component with solution:

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

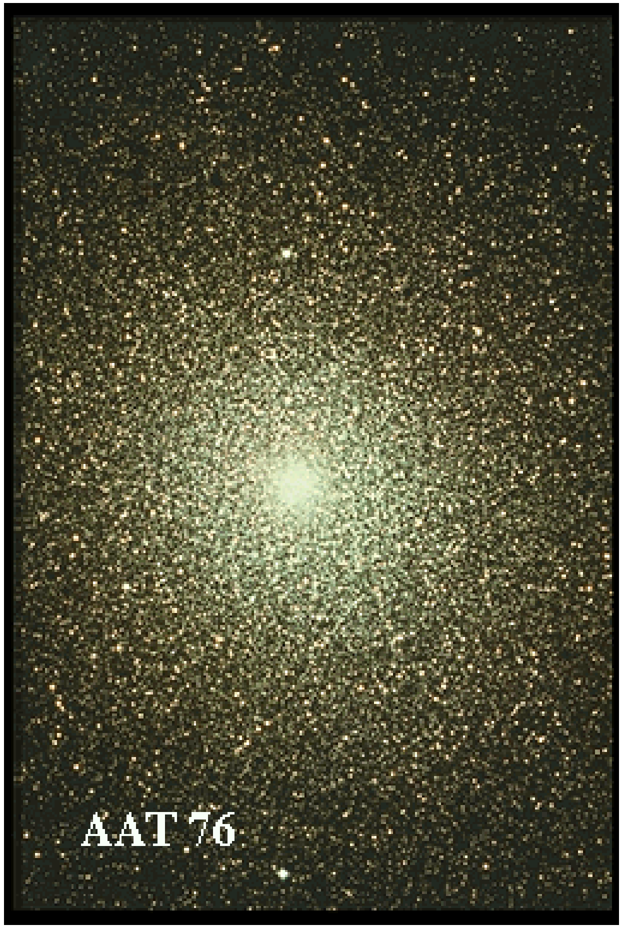
Decelerated expansion.

$$\dot{a} \approx t^{-1/3}$$

$$\ddot{a} \approx -t^{-4/3} < 0$$

Unfortunately, since the beginning of 1990, several problems for the CDM model started to emerge.

In particular the age of the universe in the CDM model was too small if compared with the age of globular clusters:



$$t_0 = \frac{2}{3} H_0 \approx 9.3\ Gyrs$$

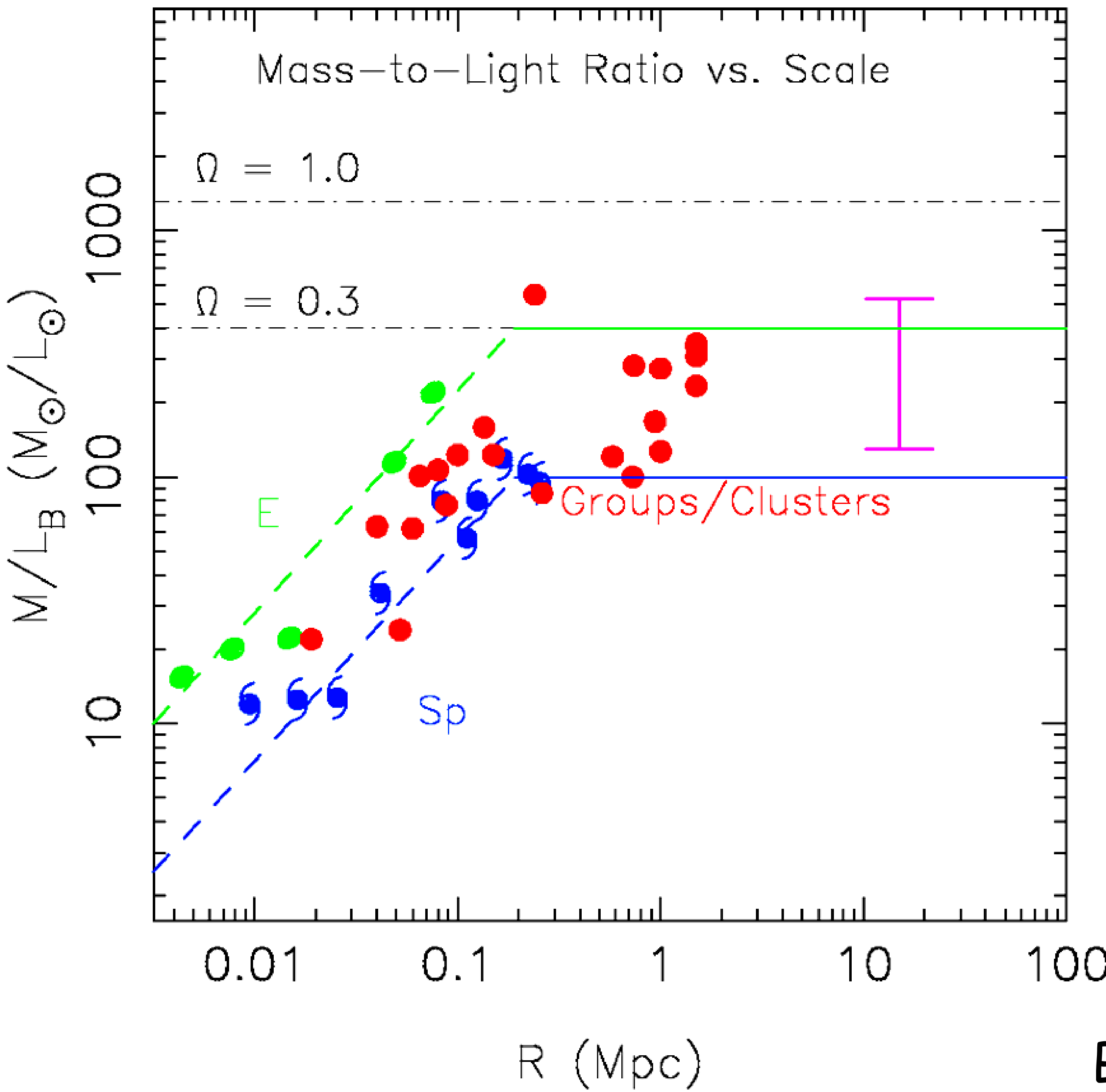
While ages for the globular clusters are in the range of 13-16 Billions of years.

Moreover, since the CDM model was flat, it was predicting an Energy density in the dark matter component equal to the critical energy density:

$$\rho_{CDM} = \rho_c = \frac{3H_0^2}{8\pi G} \rightarrow \Omega_M = \frac{\rho_{CDM}}{\rho_c} = 1$$

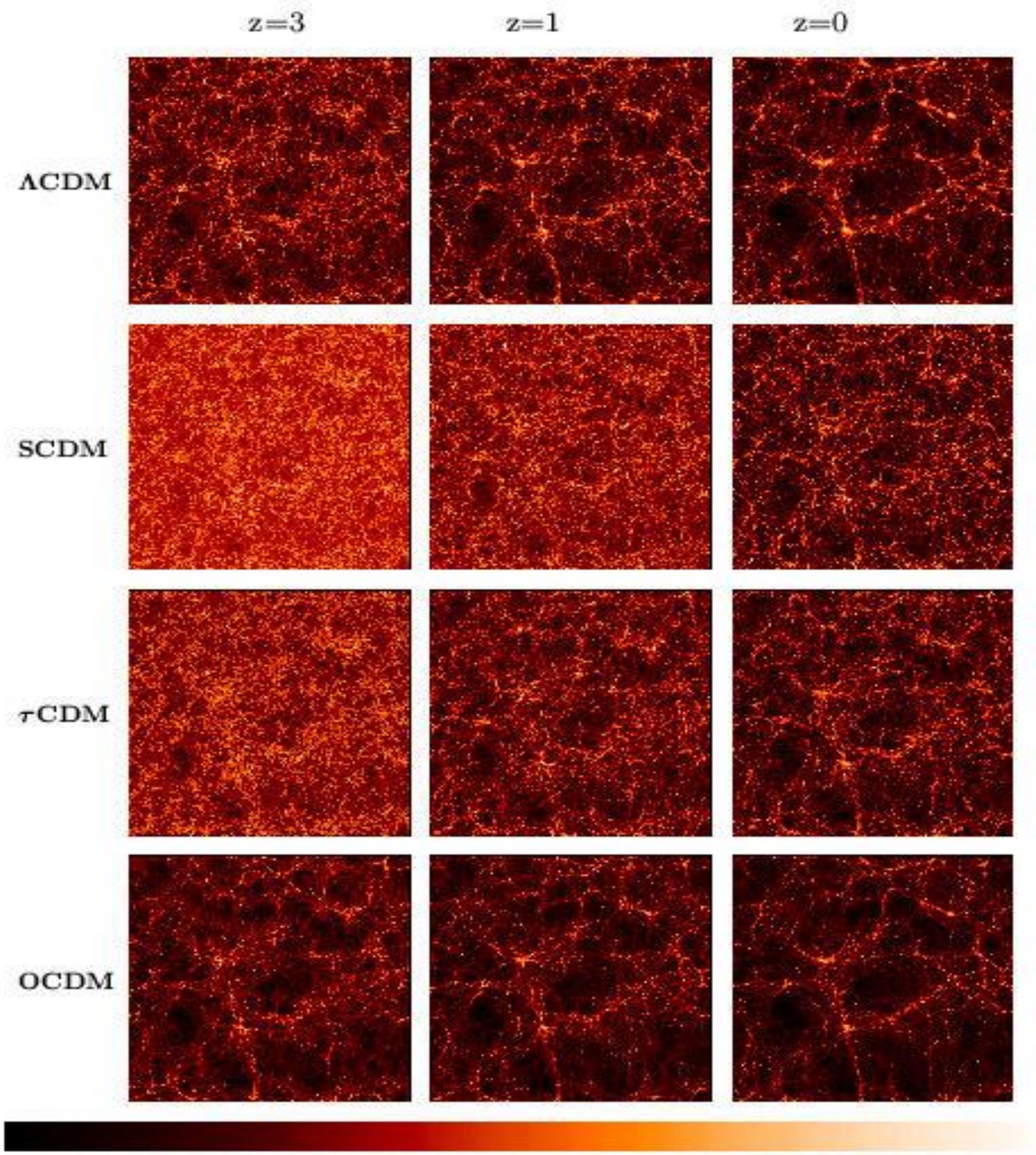
Unfortunately observations from galaxy rotation curves and velocity dispersion in cluster of galaxies were suggesting a lower value:

$$\Omega_M \approx 0.3$$



Bahcall et al, 1996

Finally the CDM model was predicting more galaxy clustering and clustering evolution than observed.



The VIRGO Collaboration 1996

In 1995 Big Bang Model was nearly dead…

nature International weekly journal of science

Search this journal go Advance

Access

To read this story in full you will need to login or make a payment (see right).

nature.com > Journal home > Table of Contents

News and Views

Nature **377**, 99 (14 September 1995) |

Big Bang not yet dead but in decline

John Maddox

The latest measurements of the Hubble constant make the Big Bang account of the origin of the Universe more dependent on the coincidence of numbers than it has so far been. But it remains the only theory in the field.

▲ Top

Is there a crisis in cosmology, or is it that the latest measurement of the Hubble constant is yet another of those numeri-cal disagreements that plague the field from time to time? That is the question inevitably prompted by last week's article by N.

To read this story in full you will need to login or make a payment (see right).

ARTICLE TOOLS

- Send to a friend
- Export citation
- Rights and permissions
- Order commercial reprints
- Bookmark in Connotea

SEARCH PUBMED FOR

- John Maddox

I want to purchase this article

Price: US$18

In order to purchase this article you
be a registered user.

Register now

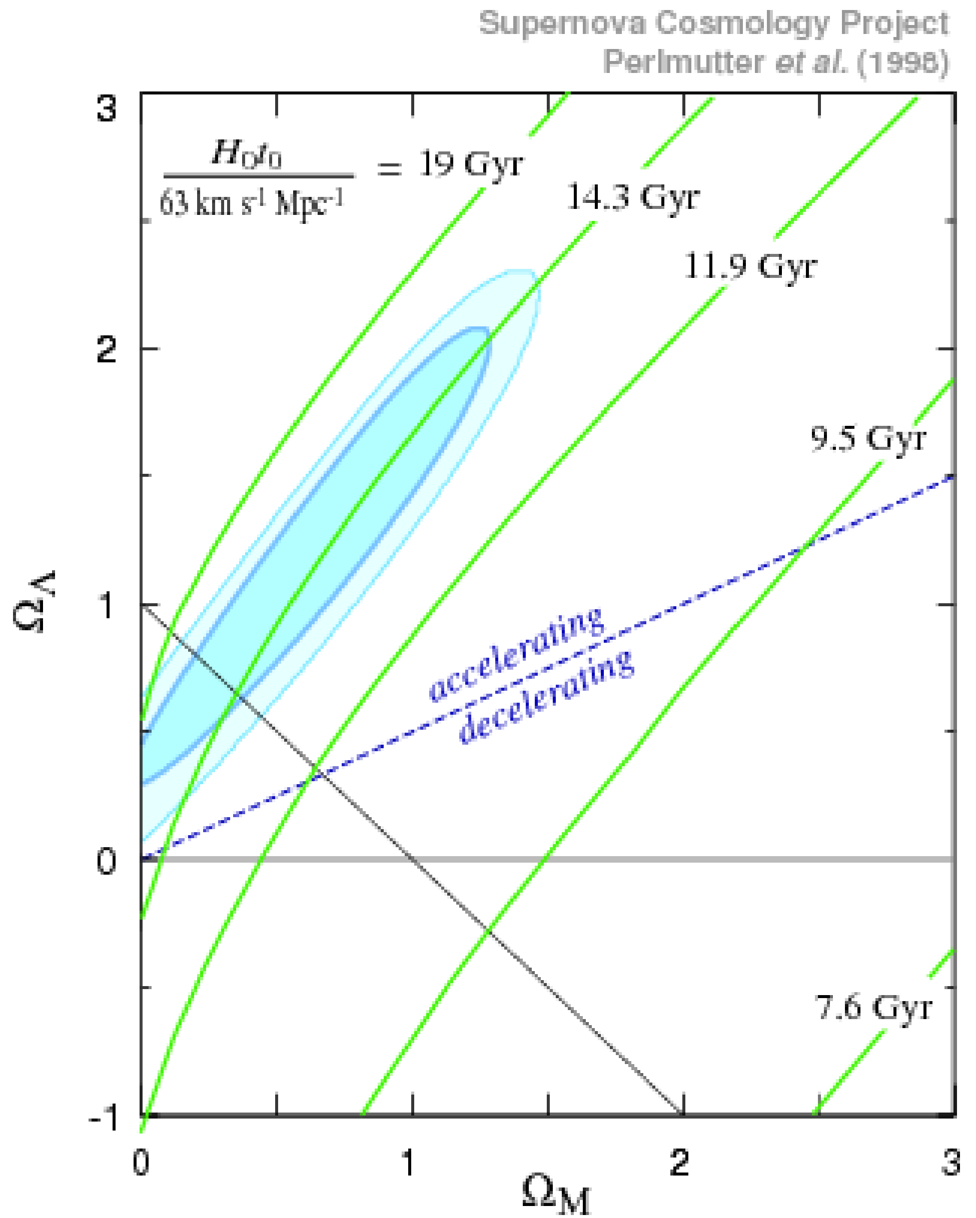
I want to subscribe to *Nature*

Price: US$199

This includes a free subscription to *N*
News together with *Nature Journal.*

Subscribe now

Personal subscribers to *Nature* can v
articles published from 1997 to the
current issue. To do this, associate y
subscription with your registration v

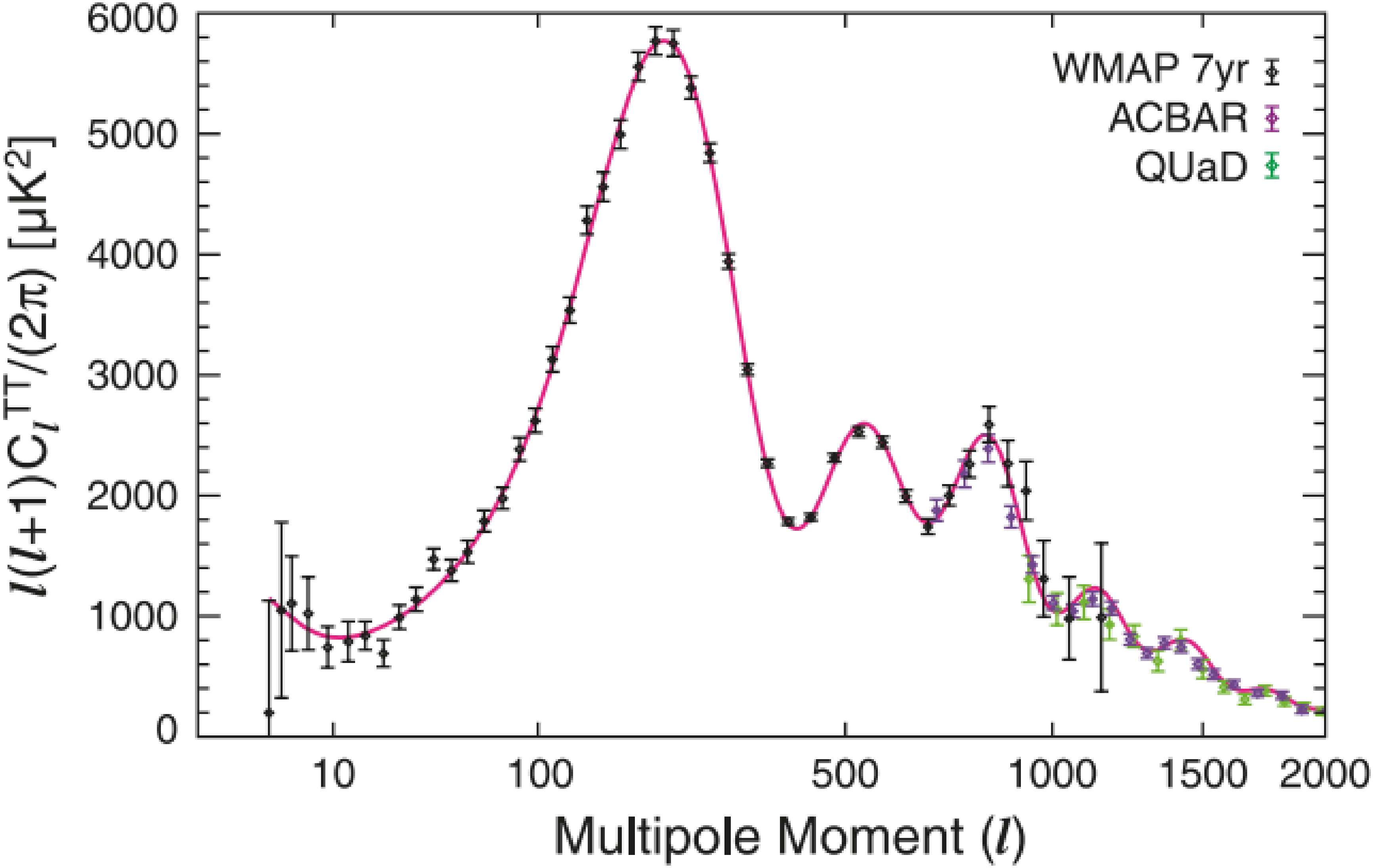


Best fit age of universe: $t_o = 14.5 \pm 1 \ \ (0.63/h)$ Gyr

Best fit in flat universe: $t_o = 14.9 \pm 1 \ \ (0.63/h)$ Gyr

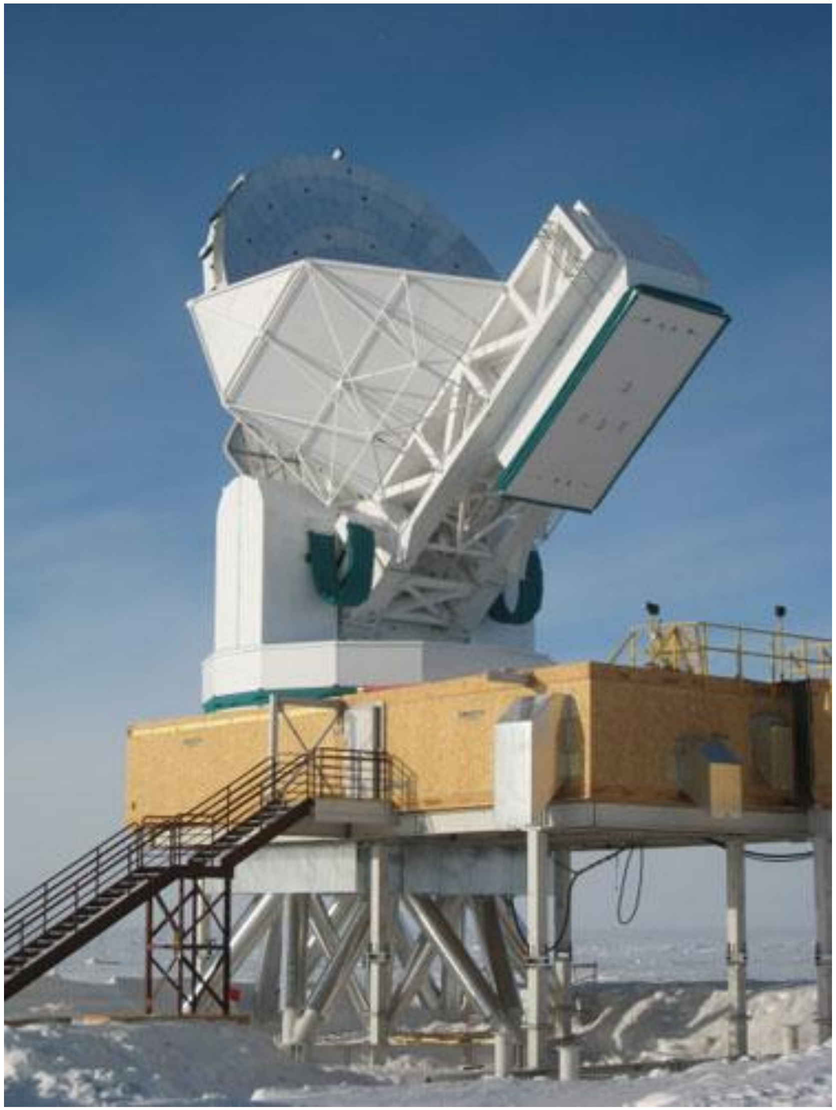
Reasons to Believe:

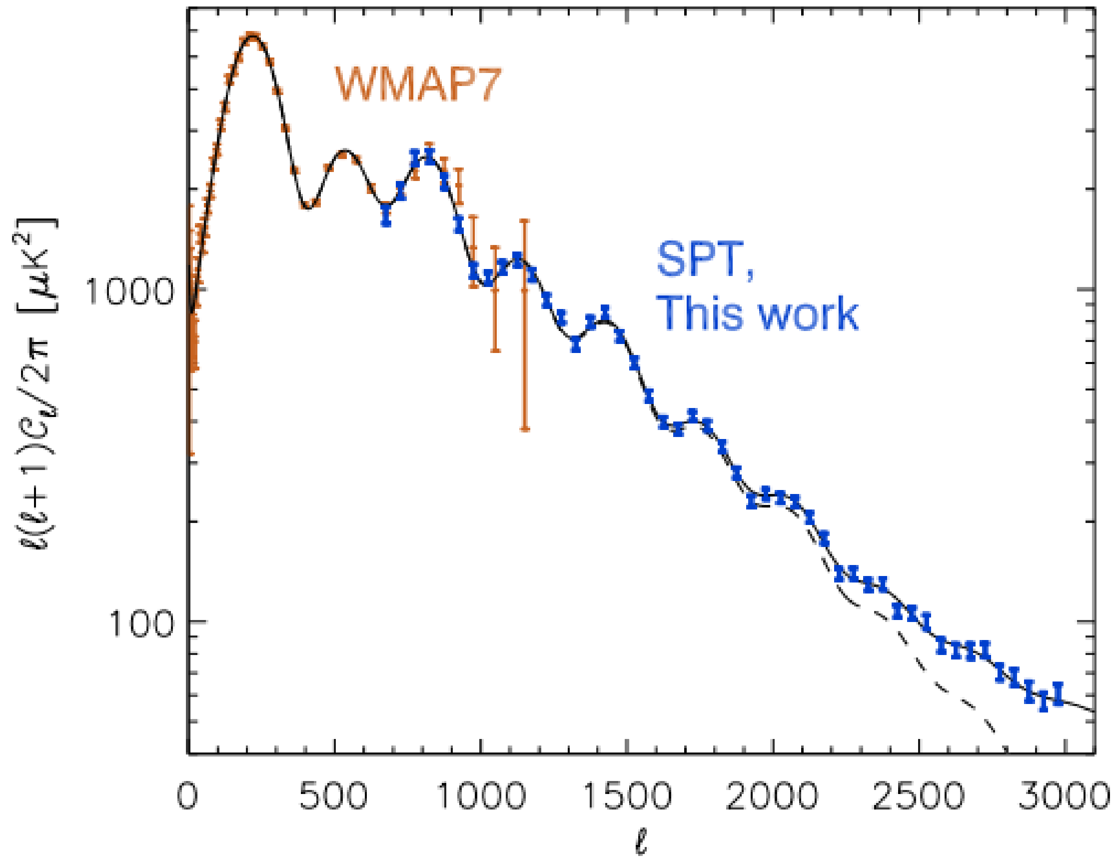
3- Other observables as CMB anisotropies are consistent with an accelerating universe.



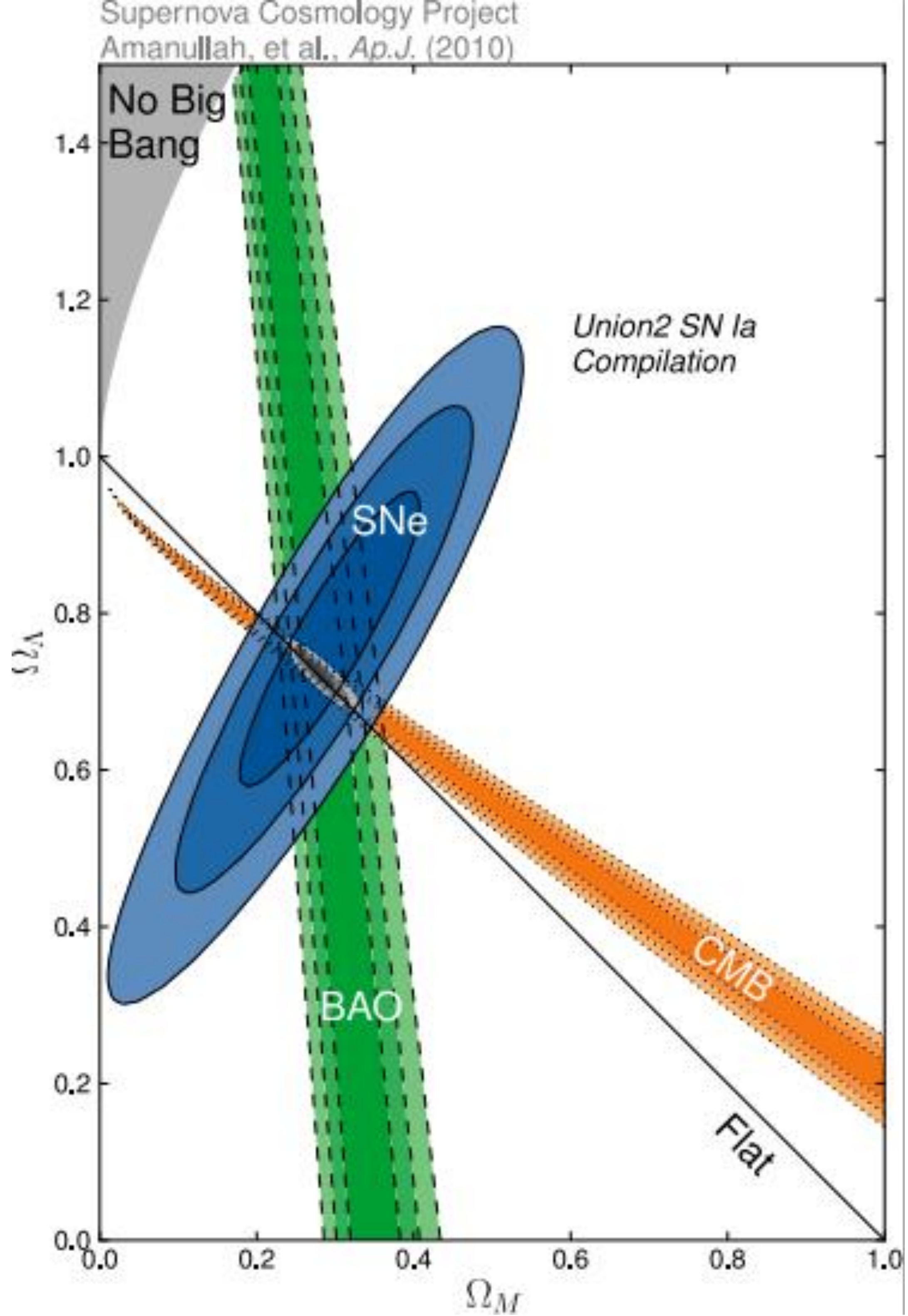
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
2000
WMAP 7yr
ACBAR
QUaD
$l(l+1)C_l^{TT}/(2\pi)$ [μK²]
Multipole Moment (l)

South Pole Telescope

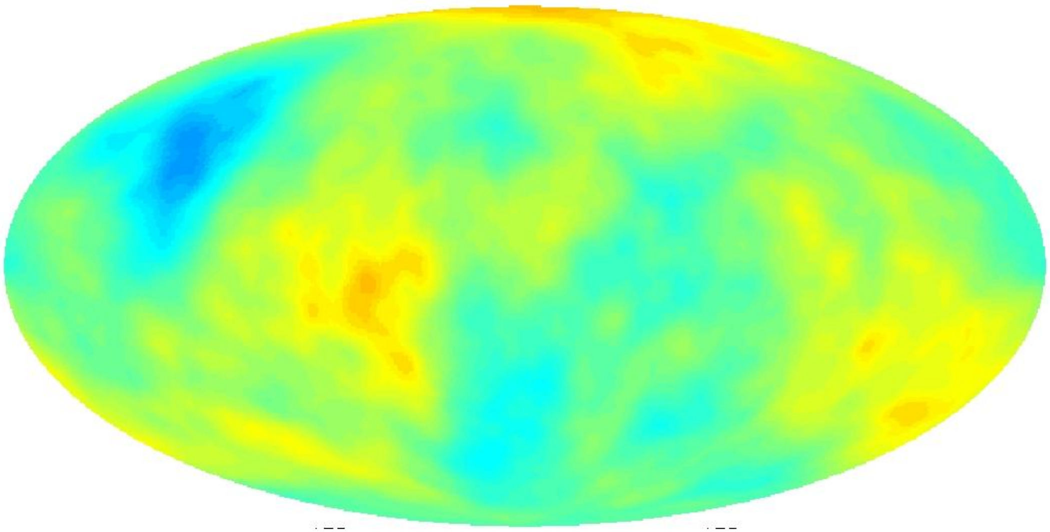




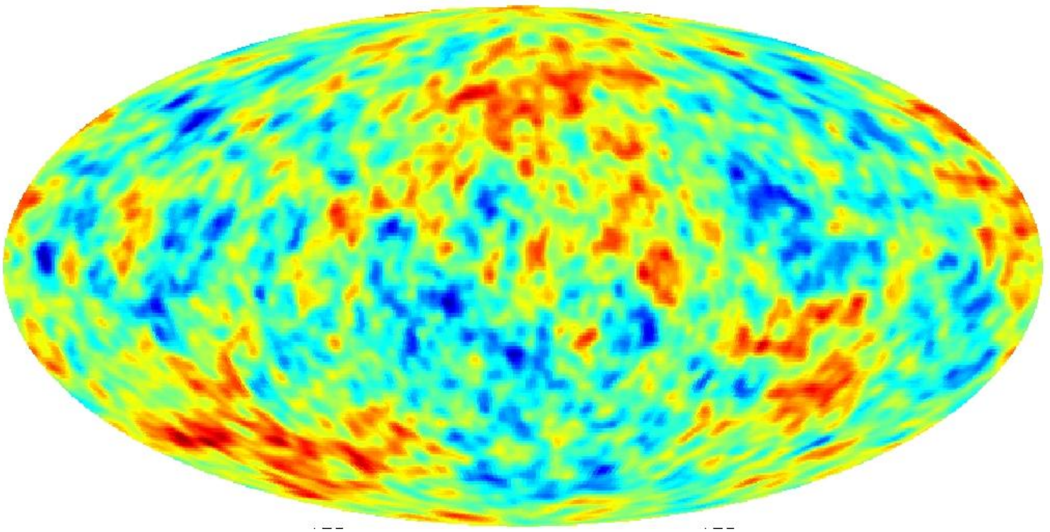
R. Keisler et al, 2011, arXiv:1105.3182


Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)
No Big Bang
Union2 SN Ia Compilation
SNe
BAO
CMB
Flat
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Ω_Λ
Ω_M

two independent maps

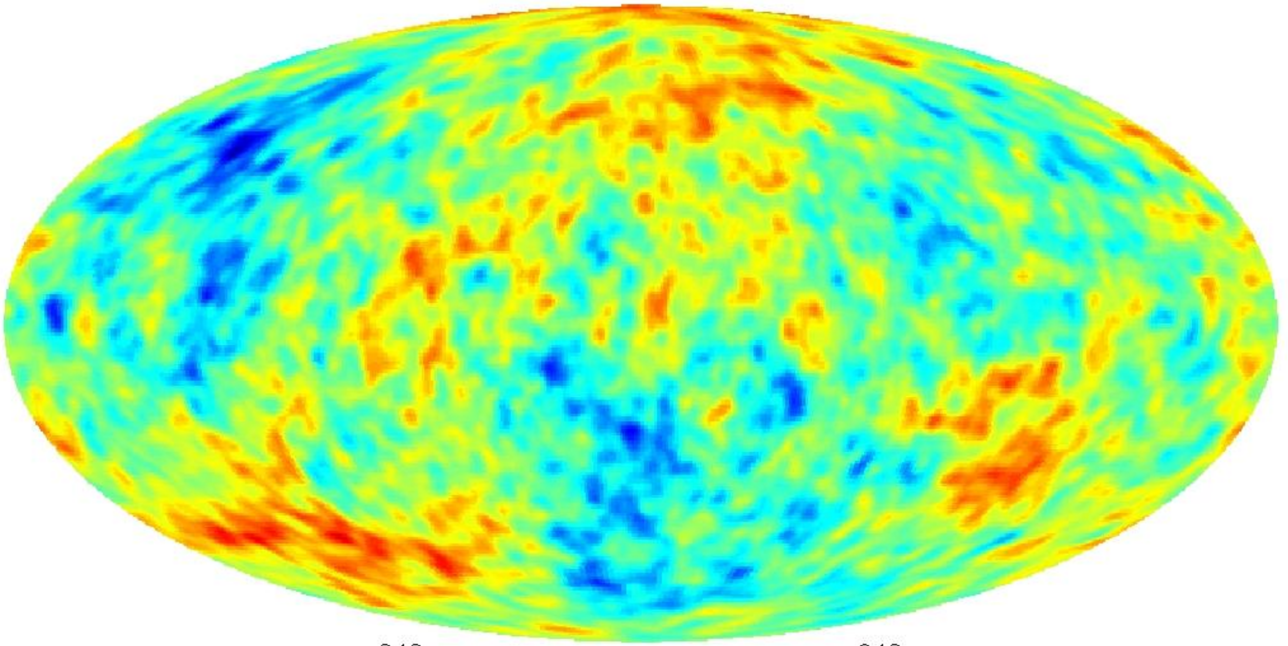


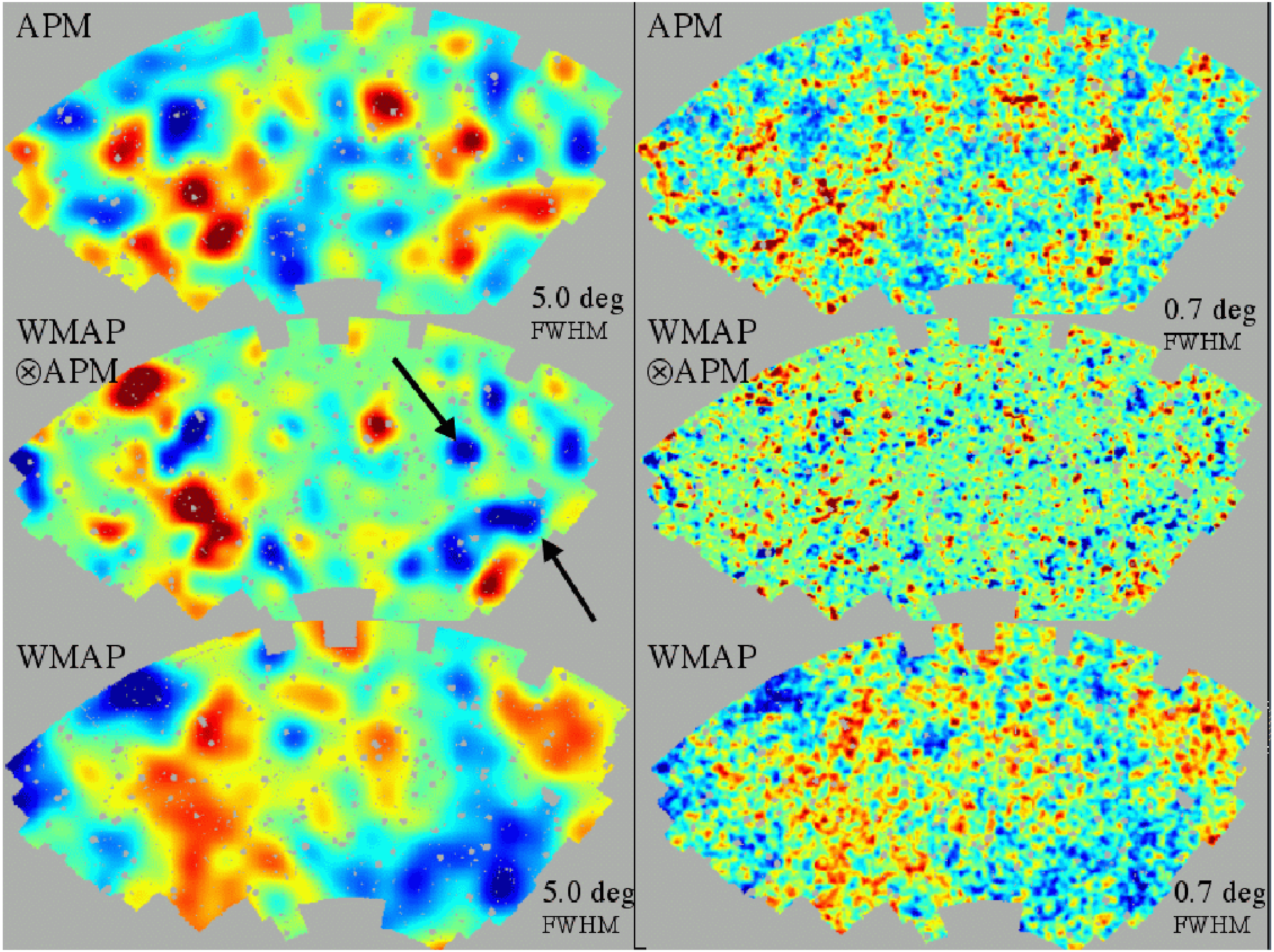
Integrated Sachs-Wolfe map
Mostly large angular features



Early time map (z > 4)
Mostly from last scattering surface

Observed map is total of these, and has features of both (3 degree resolution)



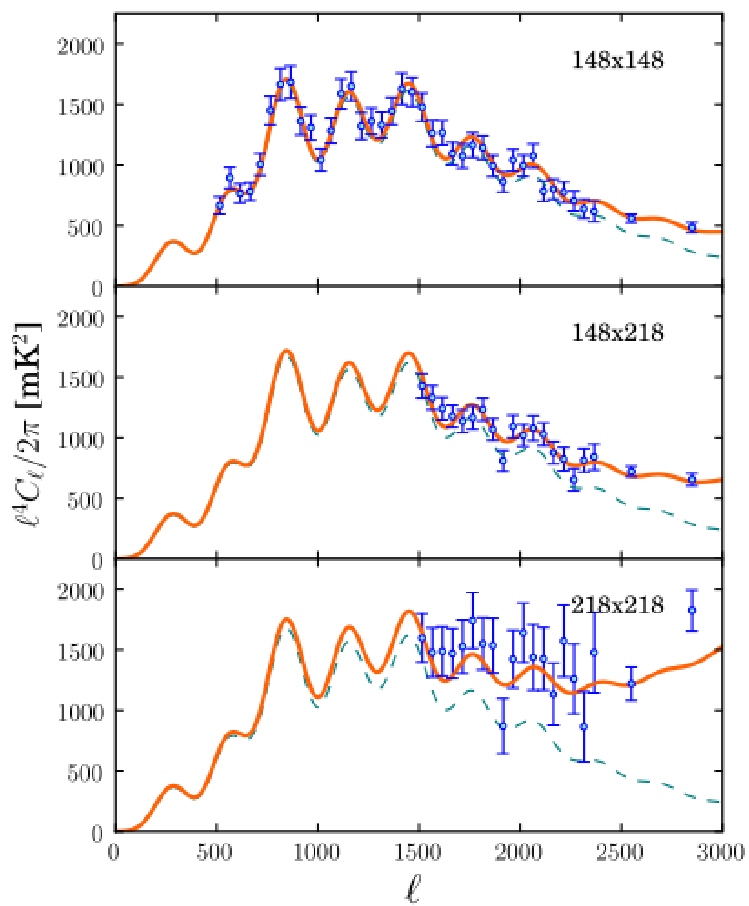


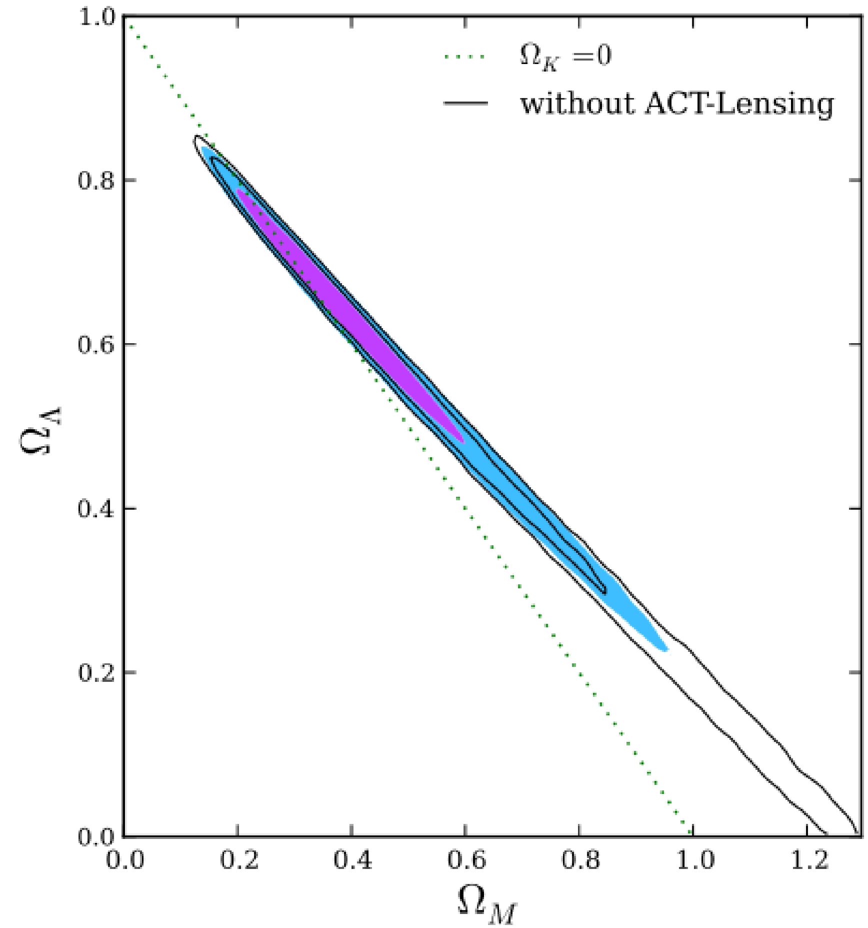
Fosalba, Gaztanaga 2004

More than 5 ISW detections!

Mean redshift	Signal (μK)	Bias	Catalog Band	Reference	
0.1	0.70 pm 0.32	1.1	2MASS, infrared	Afshordi et al. 2004	
0.15	0.35 pm 0.17	1.0	APM, optical	Scranton et al, 2004	
0.3	0.26 pm 0.14	1.0	SDSS, optical	Fosalba et al. 2004	
0.5	0.216 pm 0.1	1.8	SDSS high z, optical	Padmanabhan et al. 2004	
0.9	0.04 pm 0.02	1-2	NVSS+ HEAO, Radio, X-Rays	Boughn & Crittenden 2004	

Recent CMB data from ACT are sensitive to lensing and break geometrical degeneracy.





Sherwin et al, Phys.Rev.Lett.107:021302,2011

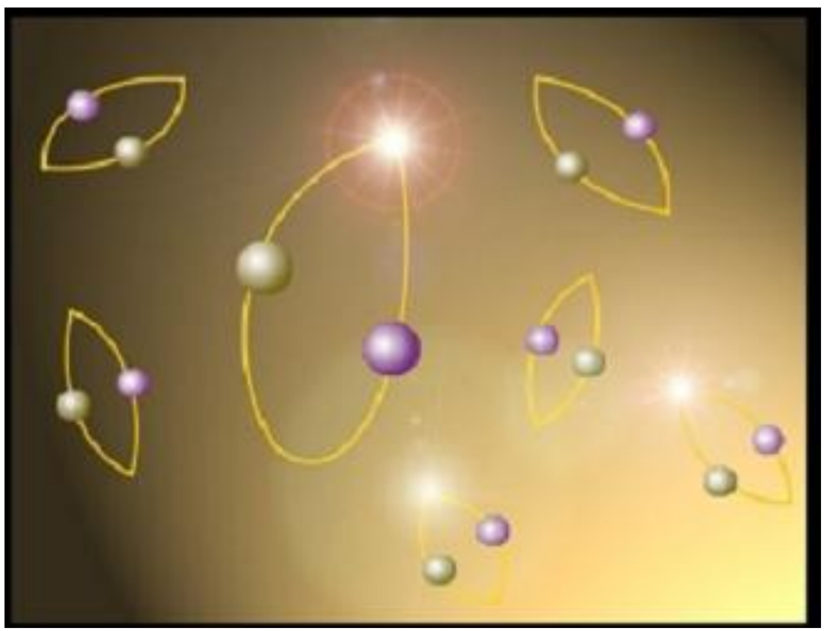
$$\Omega_{\Lambda} = 0.73 \pm 0.04$$

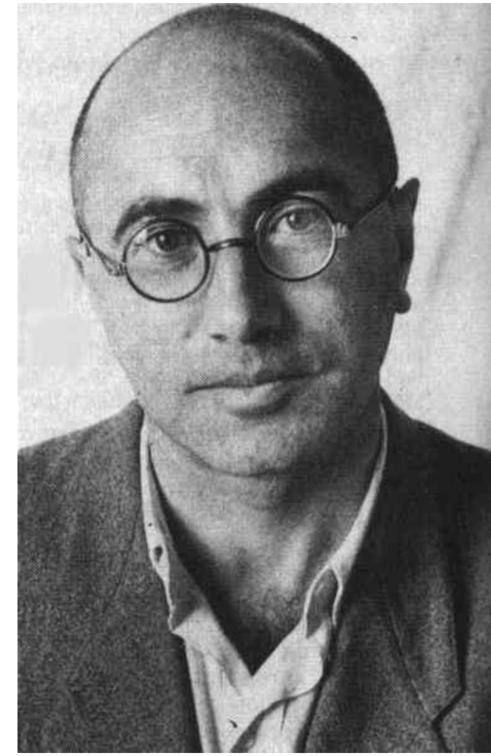
A model without cosmological constant is now ruled out at more than 18 sigma!

The problem of the Cosmological Constant

Already in 1968 Zeldovich noticed that the vacuum energy in particle physics could be a source for a cosmological constant.

"The genie (Λ) has been let out of the bottle"





Zeldovich

"A new field of activity arises, namely the determination of Λ"

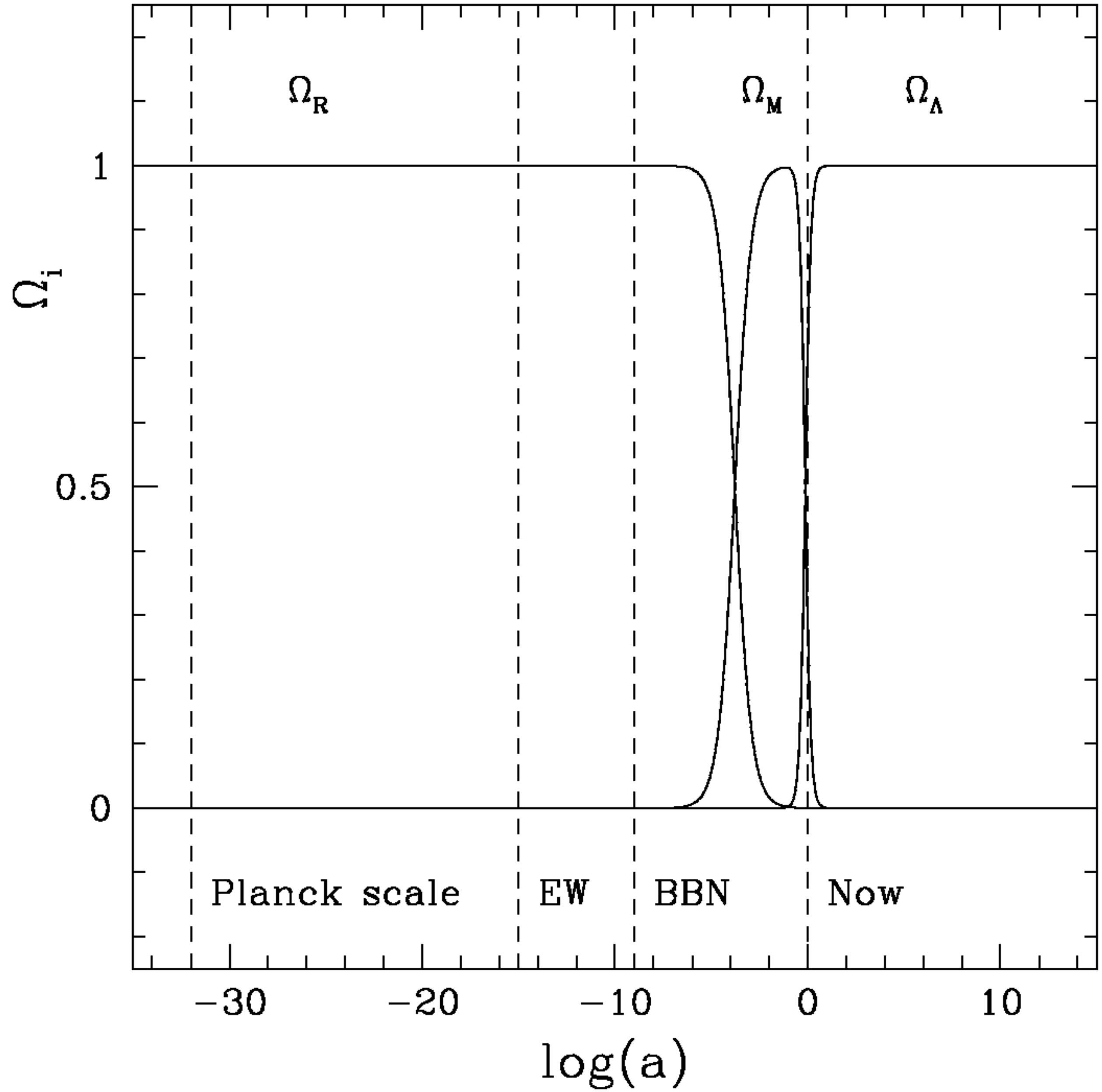
This anyway would lead to a great problem. The vacuum energy in particle physics is infinite. We may stop at Planck Scale but still we have a discrepancy of 120 orders of magnitude:

$$\rho_{vac} \approx \int_0^{M_P} \sqrt{k^2 + m^2}\, d^3k \approx M_p^4 \approx 10^{120} \rho_\Lambda$$

If we consider supersimmetry we go in the right direction but we are still 60 orders of magnitude away !

$$\rho_{vac} \approx \rho_{susy} \approx M_{susy}^4 \approx 10^{60} \rho_\Lambda$$

But there is a second problem, why the universe is accelerating Today ? ?



When did Cosmic acceleration start?

Dataset WMAP+	z_{eq}	$t_0 - t_{eq}$ [Gyrs]	z_{acc}	$t_0 - t_{acc}$ [Grys]	t_0 [Gyrs]
Alone	$0.47^{+0.09}_{-0.09}$	$4.7^{+0.5}_{-0.5}$	$0.86^{+0.11}_{-0.12}$	$7.0^{+0.4}_{-0.4}$	$13.8^{+0.3}_{-0.3}$
+SDSS	$0.40^{+0.08}_{-0.07}$	$4.3^{+0.5}_{-0.5}$	$0.77^{+0.10}_{-0.10}$	$6.7^{+0.3}_{-0.3}$	$13.8^{+0.3}_{-0.2}$
+2dF	$0.48^{+0.06}_{-0.05}$	$4.8^{+0.3}_{-0.3}$	$0.87^{+0.07}_{-0.07}$	$7.1^{+0.2}_{-0.3}$	$13.8^{+0.2}_{-0.2}$
+GOLD	$0.38^{+0.06}_{-0.06}$	$4.1^{+0.4}_{-0.4}$	$0.74^{+0.08}_{-0.08}$	$6.6^{+0.3}_{-0.3}$	$13.8^{+0.2}_{-0.2}$
+SNLS	$0.45^{+0.07}_{-0.06}$	$4.6^{+0.4}_{-0.4}$	$0.83^{+0.08}_{-0.08}$	$6.9^{+0.3}_{-0.3}$	$13.8^{+0.1}_{-0.1}$
+all	$0.40^{+0.04}_{-0.04}$	$4.3^{+0.3}_{-0.3}$	$0.76^{+0.05}_{-0.05}$	$6.7^{+0.2}_{-0.2}$	$13.9^{+0.1}_{-0.2}$

TABLE I: Constraints on z_{eq}, t_{eq}, z_{acc} and t_{acc}, at 68% c.l., in comparison with various datasets for ΛCDM.

Model	z_{eq}	$t_0 - t_{eq}$ [Gyrs]	z_{acc}	$t_0 - t_{acc}$ [Grys]	t_0 [Gyrs]
$w \neq -1$	$0.48^{+0.07}_{-0.07}$	$4.9^{+0.4}_{-0.5}$	$0.81^{+0.06}_{-0.06}$	$6.9^{+0.2}_{-0.2}$	$13.9^{+0.1}_{-0.2}$
$\Omega_{tot} \neq 1$	$0.32^{+0.10}_{-0.10}$	$3.9^{+0.8}_{-0.8}$	$0.68^{+0.10}_{-0.10}$	$6.9^{+0.3}_{-0.3}$	$15.1^{+0.8}_{-0.9}$
$dn/d\ln k \neq 0$	$0.37^{+0.05}_{-0.05}$	$4.1^{+0.3}_{-0.3}$	$0.72^{+0.06}_{-0.10}$	$6.6^{+0.2}_{-0.2}$	$14.1^{+0.1}_{-0.2}$
$N^{\nu}_{eff} \neq 3$	$0.40^{+0.05}_{-0.06}$	$4.3^{+0.5}_{-0.4}$	$0.77^{+0.06}_{-0.06}$	$6.8^{+0.6}_{-0.6}$	$14.0^{+1.2}_{-1.4}$
$\Sigma m_\nu > 0$	$0.37^{+0.04}_{-0.04}$	$4.2^{+0.3}_{-0.3}$	$0.73^{+0.05}_{-0.05}$	$6.7^{+0.2}_{-0.2}$	$14.1^{+0.2}_{-0.2}$

TABLE II: Constraints on z_{eq}, t_{eq}, z_{acc} and t_{acc}, at 68% c.l., under differing theoretical assumptions for the underlying cosmological model.

Model	z_{eq}	$t_0 - t_{eq}$ [Gyrs]	z_{acc}	$t_0 - t_{acc}$ [Grys]	t_0 [Gyrs]
$w \neq -1$	$0.43^{+0.07}_{-0.06}$	$4.5^{+0.5}_{-0.5}$	$0.79^{+0.07}_{-0.07}$	$6.8^{+0.3}_{-0.3}$	$13.8^{+0.1}_{-0.2}$
CPL	$0.44^{+0.11}_{-0.10}$	$4.5^{+0.7}_{-0.6}$	$0.80^{+0.16}_{-0.17}$	$6.8^{+0.6}_{-0.7}$	$13.9^{+0.2}_{-0.2}$
HM	$0.45^{+0.10}_{-0.10}$	$4.6^{+0.6}_{-0.7}$	$0.79^{+0.14}_{-0.14}$	$6.7^{+0.6}_{-0.5}$	$13.9^{+0.2}_{-0.3}$
SQ	–	–	$0.80^{+0.08}_{-0.08}$	$6.8^{+0.3}_{-0.3}$	$13.8^{+0.2}_{-0.2}$

TABLE III: Constraints on z_{eq}, t_{eq}, z_{acc} and t_{acc}, at 68% c.l., for different theoretical assumptions about the nature of the dark energy component.

AM, Luca Pagano, Stefania Pandolfi arXiv:0706.131
Phys. Rev. D **76**, 041301 (2007)

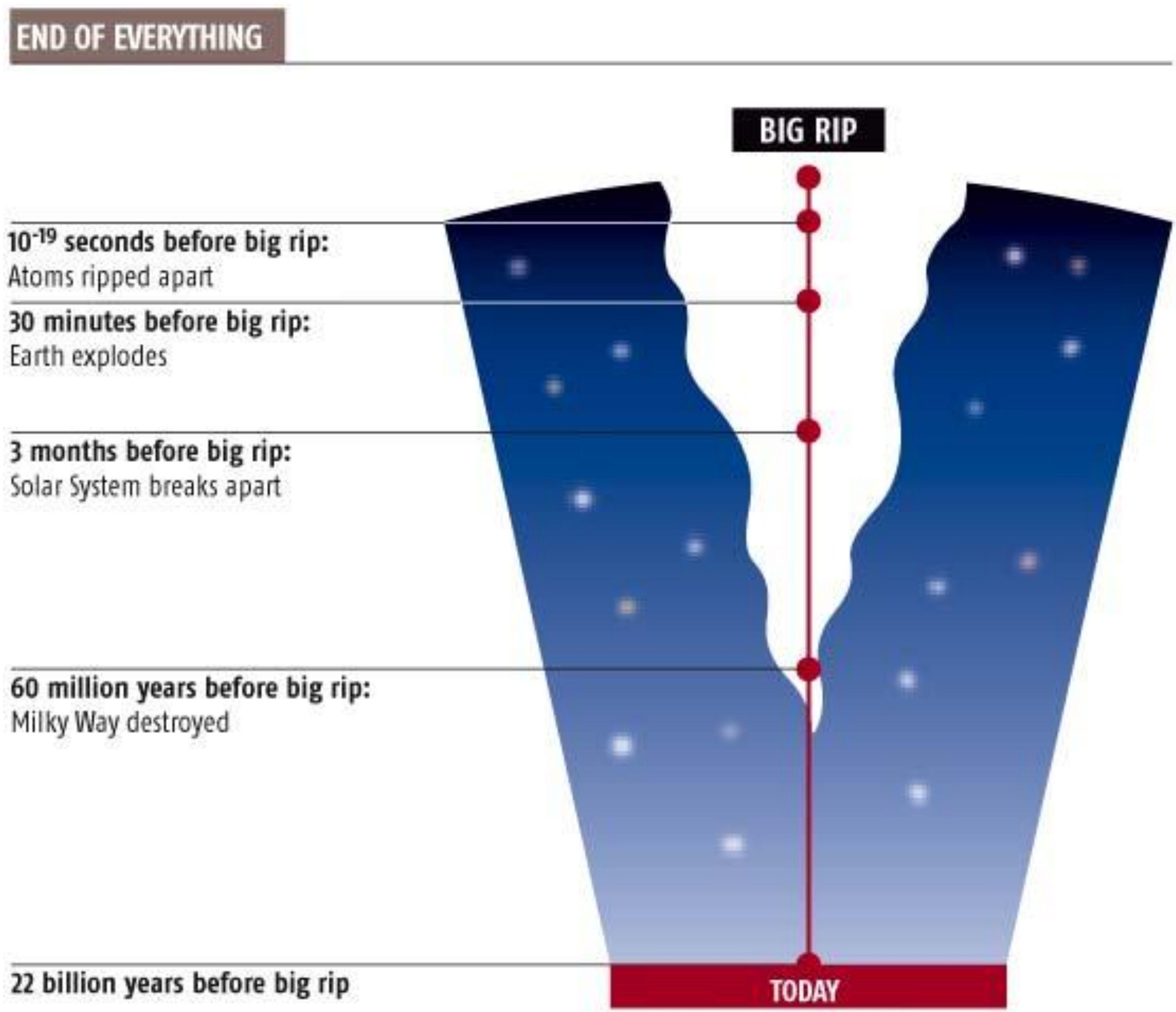
Alternatives to Lambda

- Scalar field: it can track the dominant component. Solves the «Why Now ?» problem. Mass of the field too small (ultralight and dark particle).

- Modified Gravity: needs to «mimic» Lambda. Few models survive local constraints on deviation from GR.

- Non homogeneous Universe: disomogeneities should decelerate the expansion not decelerate (Choudury theorem). No consistent picture present at the moment.

- Anthropic principle. Landscape scenario....


END OF EVERYTHING
BIG RIP
10^{-19} seconds before big rip:
Atoms ripped apart
30 minutes before big rip:
Earth explodes
3 months before big rip:
Solar System breaks apart
60 million years before big rip:
Milky Way destroyed
22 billion years before big rip
TODAY

COSMOLOGICAL COSTANT vs "Something else"

$$\rho_\Lambda \equiv const$$

$$p_\Lambda = -\rho_\Lambda$$

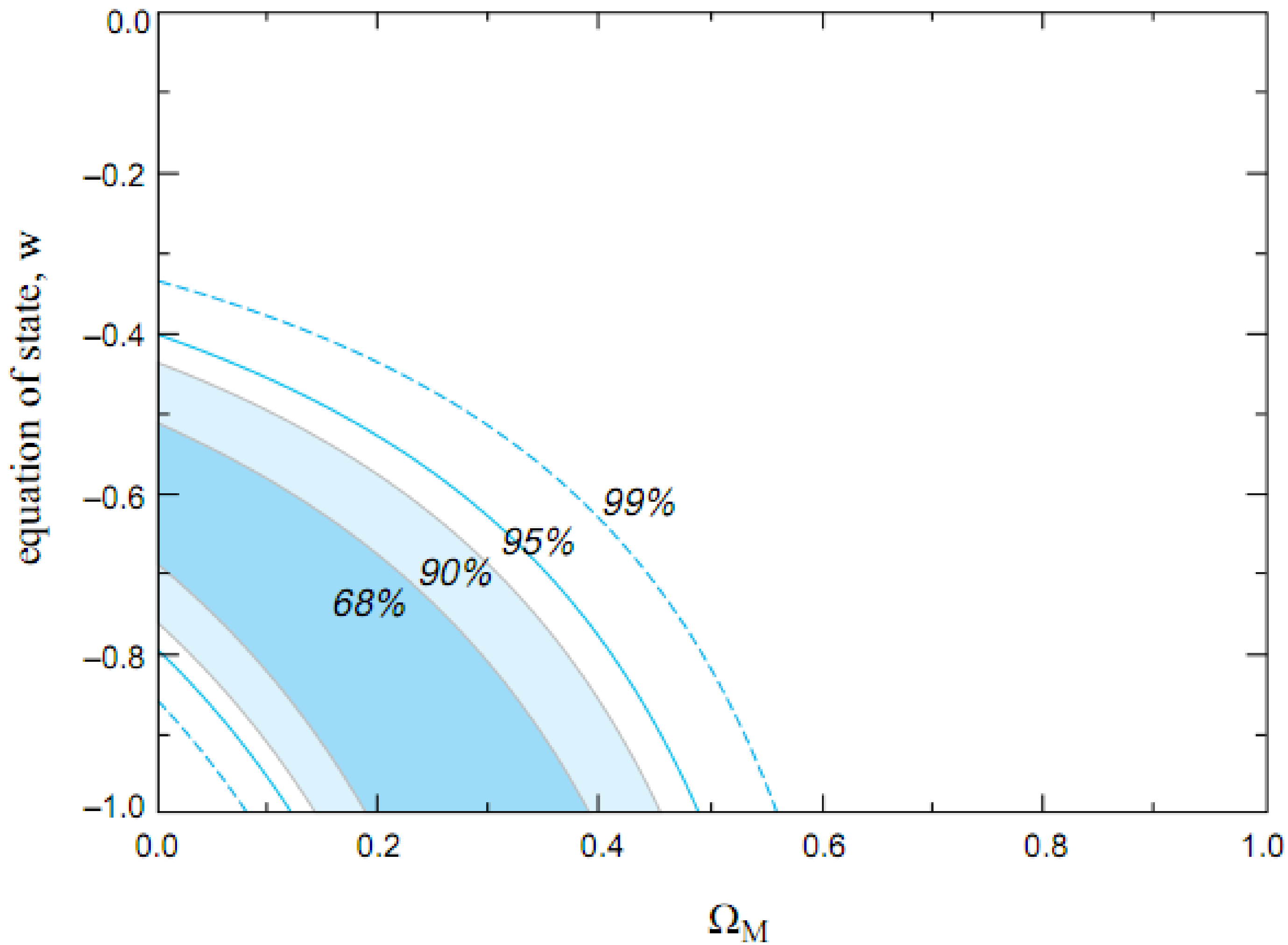
$$\delta\rho_\Lambda = 0$$

Vs.

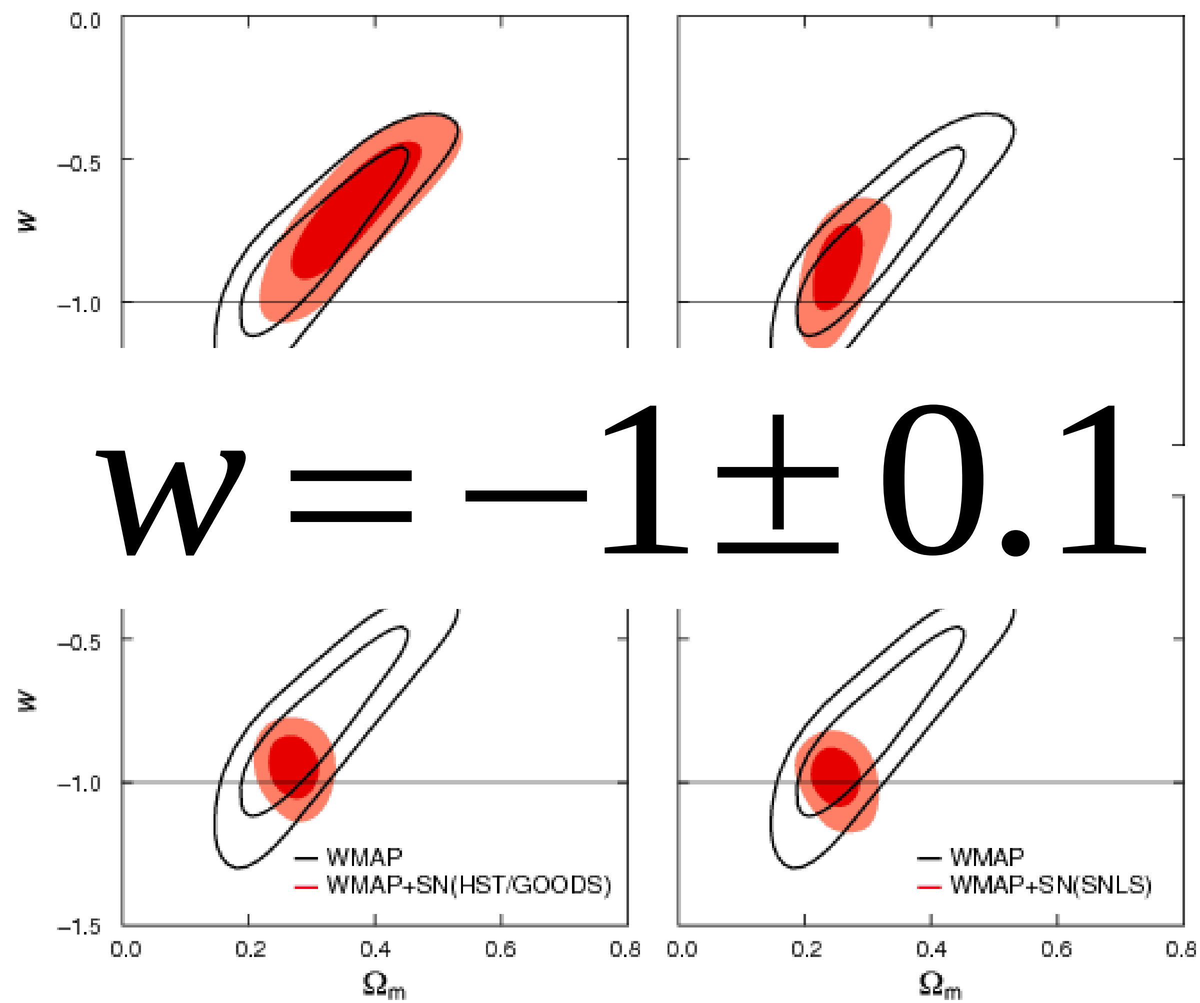
$$\rho_X(z) \equiv \rho_X(0)\exp\left(3\int_0^z dz'\frac{1+w(z')}{1+z'}\right)$$

$$p_X = w(z)\rho_X$$

$$\delta\rho_X \neq 0$$



Perlmutter et al, 1998



$$w = -1 \pm 0.1$$

WMAP Cosmological Parameters, Spergel et al., 2007

Bayesian Model Selection

Current cosmological data are in agreement with more complicated Dark energy parametrizations, but do we need more parameters ? More complicated models should give better fits to the data. In model selection we have to pay the larger number of parameters (see e.g. Mukherjee et al., 2006):

$$E = P\left(\vec{D} \mid H\right) = \int P\left(\vec{D} \mid \vec{\theta}, H\right) P\left(\vec{\theta}, H\right)$$

Evidence

Likelihood

Prior

Jeffrey(1961):

$$1 < \Delta \ln(E) < 2.5 \quad \text{Substantial}$$

$$2.5 < \Delta \ln(E) < 5 \quad \text{Strong}$$

$$5 < \Delta \ln(E) \quad \text{Decisive}$$

f_0

Δ

Constraints	$\Delta \ln E$	χ^2_{Min}	Model
$\Omega_m = 0.28 \pm 0.03$ $H_0 = 64.5 \pm 0.09$	0.0	24.39	I
$\Omega_m = 0.27 \pm 0.03$ $H_0 = 63.4 \pm 1.1$ $w < -0.84$ at 1σ $w < -0.73$ at 2σ	-0.222 ± 0.005	22.43	II
$\Omega_m = 0.27 \pm 0.03$ $H_0 = 63.4 \pm 1.1$ $w = -0.86 \pm 0.1$	-1.027 ± 0.002	22.43	III
$\Omega_m = 0.28 \pm 0.04$ $H_0 = 63.8 \pm 1.4$ $w_0 = -1.03 \pm 0.25$ $w_a = 0.76^{+--}_{-0.91}$	-1.118 ± 0.015	21.47	IV
$\Omega_m = 0.27 \pm 0.03$ $H_0 = 63.5 \pm 1.1$ $w_0 = -0.85 \pm 0.12$ $w_1 = -0.81 \pm 0.21$ a_s unconstrained q unconstrained	-1.059 ± 0.008	21.38	V
$\Omega_m = 0.30 \pm 0.05$ $H_0 = 63.5^{+1.8}_{-1.2}$ $w_0 = -1.08^{+0.24}_{-0.30}$ $w_1 = 0.78^{+0.83}_{-0.57}$	-1.834 ± 0.006	21.52	VI

More Parameters

Current data:
"Substantial"
Evidence
for a cosmological
constant...

P. Serra, A. Heavens,
A. Melchiorri
Astro-ph/0701338
MNRAS, 379, 1,169
2007

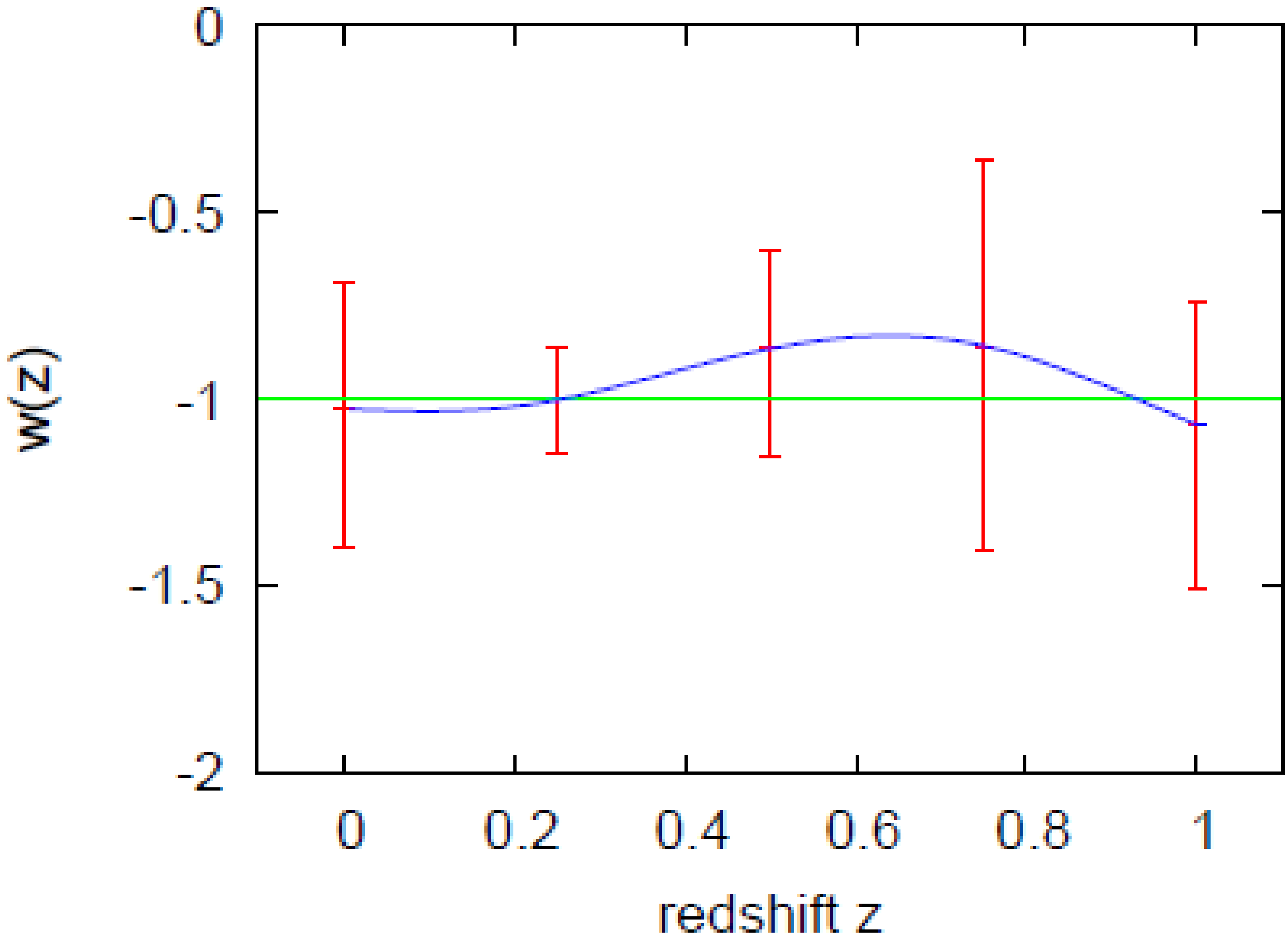
Dark Energy- a recent analysis for w(z)

- We sample w(z) in 5 redshift bins up to z=1:

$$w(z) = \begin{cases} w(z=1), & z > 1; \\ w_i, & z \le z_{max}, z \in \{z_i\}; \\ \text{spline}, & z \le z_{max}, z \notin \{z_i\}. \end{cases}$$

- We use CMB (WMAP5,QUAD, ACBAR) data, BAO DR7, Weak Lensing from CFHFTLS, ISW data, Supernovae from UNION and CONSTITUTION datasets.

Serra, Cooray, Holtz, Melchiorri, Pandolfi, Sarkar, Phys.Rev.D80:121302,2009



CMB+WL+BAO+UNION+ISW

Serra, Cooray, Holtz, Melchiorri, Pandolfi, Sarkar,
Phys.Rev.D80:121302,2009

Parameter	WMAP+UNION+BAO	WMAP+Constitution+BAO	all dataset	future datasets
$\Omega_b h^2$	0.02281 ± 0.00057	0.02278 ± 0.00058	0.02304 ± 0.00056	0.02270 ± 0.00015
$\Omega_c h^2$	0.1128 ± 0.0059	0.1144 ± 0.0060	0.1127 ± 0.0018	0.1100 ± 0.0012
Ω_Λ	0.728 ± 0.018	0.715 ± 0.017	0.728 ± 0.016	0.751 ± 0.008
n_s	0.964 ± 0.014	0.963 ± 0.014	0.971 ± 0.014	0.962 ± 0.004
τ	0.085 ± 0.017	0.084 ± 0.016	0.088 ± 0.017	0.084 ± 0.05
Δ^2_R	$(2.40 \pm 0.10) \cdot 10^{-9}$	$(2.40 \pm 0.10) \cdot 10^{-9}$	$(2.40 \pm 0.10) \cdot 10^{-9}$	$(2.40 \pm 0.10) \cdot 10^{-9}$
$w(z = 1.7)$	$--$	$--$	$--$	$-1.55^{+0.46}_{-0.44}$
$w(z = 1)$	$-1.72^{+0.73}_{-0.81}$	$-1.68^{+0.73}_{-0.85}$	$-1.07^{+0.21}_{-0.20}$	-1.03 ± 0.10
$w(z = 0.75)$	$-0.71^{+0.44}_{-0.47}$	$-0.47^{+0.34}_{-0.33}$	$-0.86^{+0.025}_{-0.26}$	-0.98 ± 0.08
$w(z = 0.5)$	$-0.65^{+0.29}_{-0.30}$	$-1.06^{+0.41}_{-0.40}$	-0.86 ± 0.14	-1.00 ± 0.05
$w(z = 0.25)$	-1.05 ± 0.10	-1.04 ± 0.07	-1.00 ± 0.07	-1.00 ± 0.02
$w(z = 0)$	-0.97 ± 0.22	-0.86 ± 0.13	$-1.02^{+0.17}_{-0.18}$	-0.99 ± 0.05
σ_8	0.814 ± 0.055	0.815 ± 0.057	0.810 ± 0.024	0.811 ± 0.012
Ω_m	0.272 ± 0.018	0.285 ± 0.017	0.272 ± 0.016	0.249 ± 0.008
H_0	70.7 ± 2.0	69.4 ± 1.7	70.8 ± 2.0	73.1 ± 1.0
z_{reion}	10.8 ± 1.4	10.8 ± 1.4	11.0 ± 1.5	10.7 ± 0.4
t_0	13.65 ± 0.14	13.67 ± 0.15	13.67 ± 0.13	13.60 ± 0.06

No evidence from current data for deviations from a cosmological constant

Serra, Cooray, Holtz, Melchiorri, Pandolfi, Sarkar, Phys.Rev.D80:121302,2009

Media Centre
- Press Releases
- ESA Television
- Launch Media Corner
- Exhibitions

Services
- Calendar
- Publications
- Frequently asked questions
- ESA-sponsored Conferences
- Help
- Site Credits
- Portal terms of use
- Comments

Cosmic Vision 2015-2025

Dark and bright: ESA chooses next two science missions

4 October 2011

ESA PR 25 2011 - The powerful influence of the Sun and the nature of the mysterious 'dark energy' motivate ESA's next two science missions. Solar Orbiter and Euclid were selected today by ESA's Science Programme Committee for implementation, with launches planned for 2017 and 2019.

These two missions are medium-class missions and are the first in ESA's Cosmic Vision 2015-2025 Plan.

More about ESA's Cosmic Vision...
- Defining the Cosmic Vision
- Missions beyond imagination

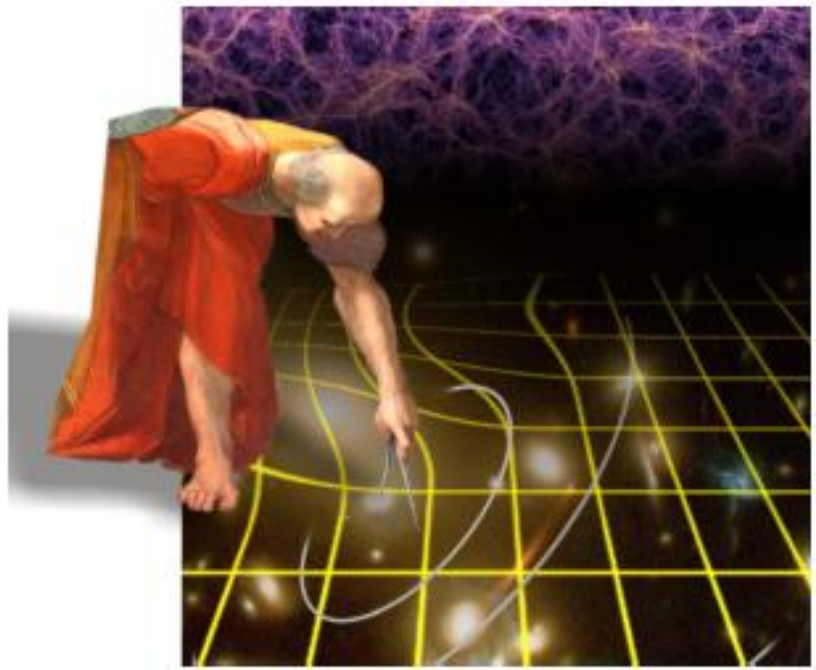
Related articles
- ESA's Cosmic Vision workshop 2004
- Plans for the future
- IAA's vision for the next steps in exploring deep space
- How a mission is chosen

Related links
- More on Cosmic Vision 2015-2025

ESA/SRE(2011)12
July 2011

Euclid

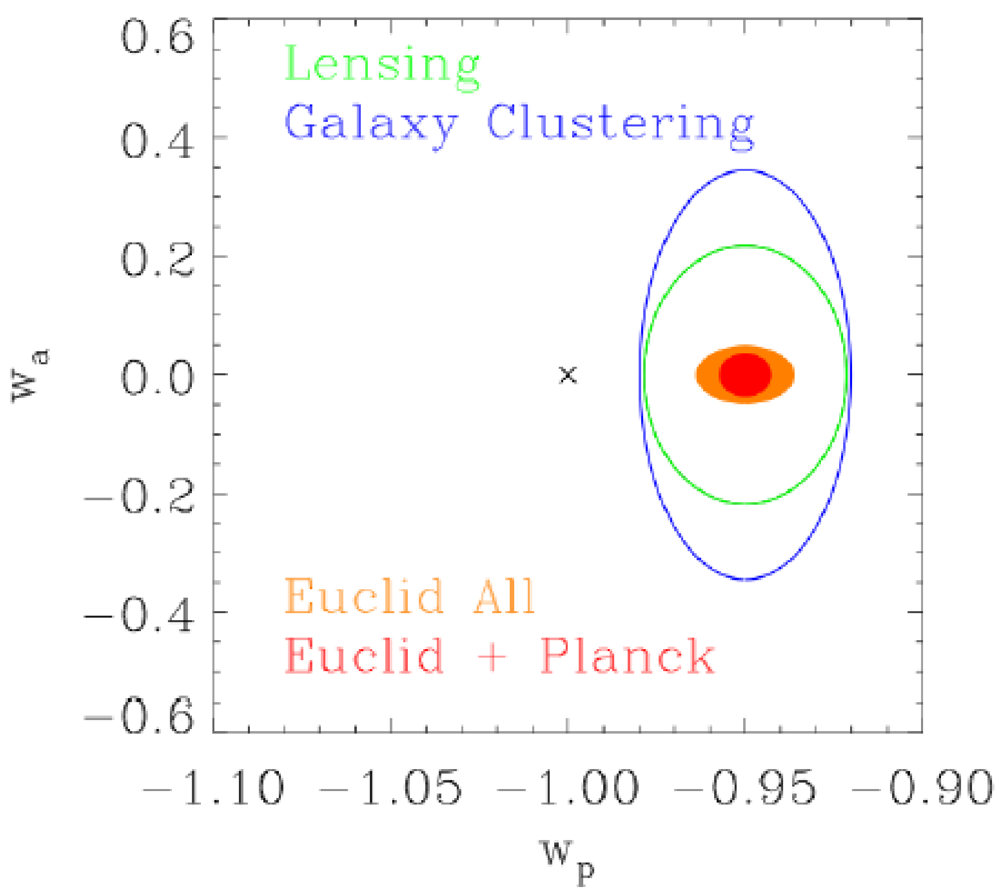
Mapping the geometry of the dark Universe

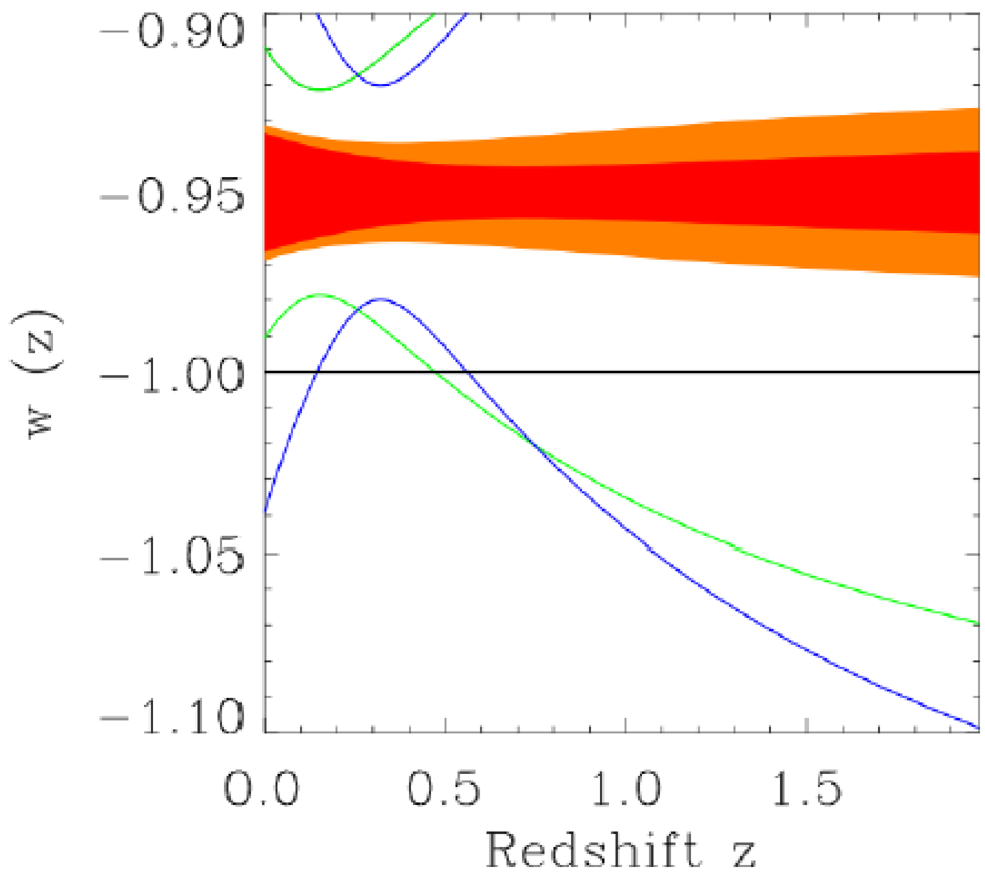


Definition Study Report

European Space Agency

http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=48983#





http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=48983#

KUNGL. VETENSKAPS-AKADEMIEN

THE ROYAL SWEDISH ACADEMY OF SCIENCES

For almost a century, the Universe has been known to be expanding as a consequence of the Big Bang about 14 billion years ago. However, the discovery that this expansion is accelerating is astounding. If the expansion will continue to speed up the Universe will end in ice.

The acceleration is thought to be driven by dark energy, but what that dark energy is remains an enigma - perhaps the greatest in physics today. What is known is that dark energy constitutes about three quarters of the Universe. Therefore the findings of the 2011 Nobel Laureates in Physics have helped to unveil a Universe that to a large extent is unknown to science. And everything is possible again.

COSMOLOGY MARCHES ON