The Dark Energy of the Universe

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Niels Bohr Institute, 13 Oct., 2015

image: bornscientist.com

Dark Energy in a nutshell

In 1998, astronomers presented evidence that the primary energy density of the universe is not from particles or radiation, but of empty space—the vacuum.

Einstein had predicted it 80 years earlier, but few people believed this prediction, not even Einstein himself.

Many scientists were surprised, and the discovery was considered revolutionary.

Since then, thousands of papers have been written on the subject, many speculating on the detailed properties of the dark energy.

The fundamental origin of dark energy is the subject of intense controversy and debate amongst theorists.

Outline

Part I

- History of the dark energy
- Theory of cosmological expansion
- The observational evidence for dark energy

Part II

- What could it be?
- Upcoming observations
- The theoretical crisis !!!

Albert Einstein invents dark energy, 1917

Two years after introducing general relativity (1915), Einstein looks for cosmological solutions of his equations.

No static solution exists, contrary to observed universe at that time

He adds new term to his equations to allow for static universe, the *cosmological constant* λ:

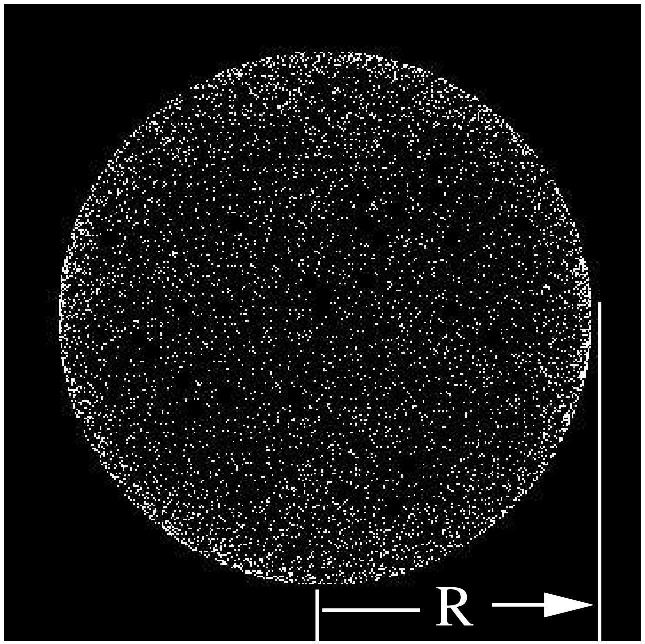
Poisson's equation given by equation (2). For on the left-hand side of field equation (13) we may add the fundamental tensor $g_{\mu\nu}$, multiplied by a universal constant, $-\lambda$, at present unknown, without destroying the general covariance. In place of field equation (13) we write

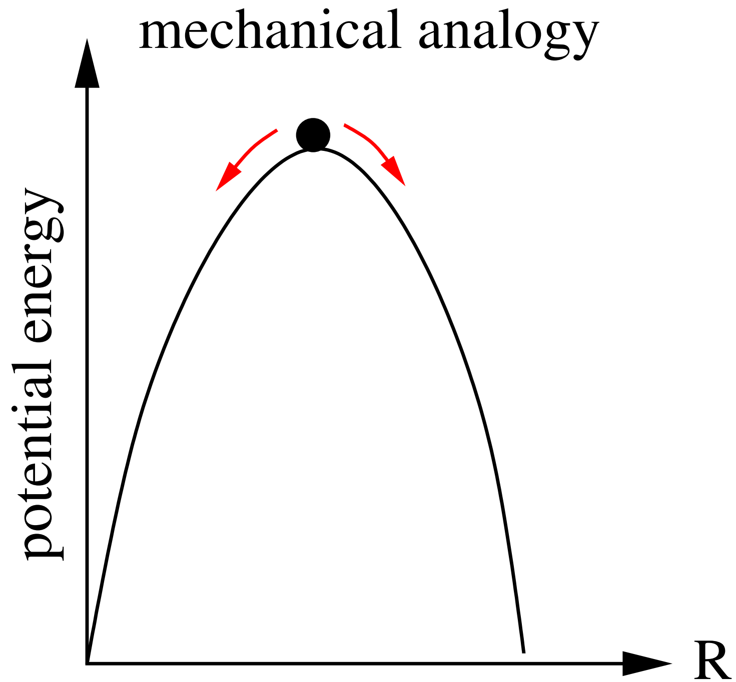
$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa(T_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} T) \quad . \quad . \quad (13a)$$

This field equation, with λ sufficiently small, is in any case also compatible with the facts of experience derived from the solar system. It also satisfies laws of conservation of

Einstein's static universe

This universe is a three-sphere with radius R and uniform mass density of stars ρ (mass per volume).



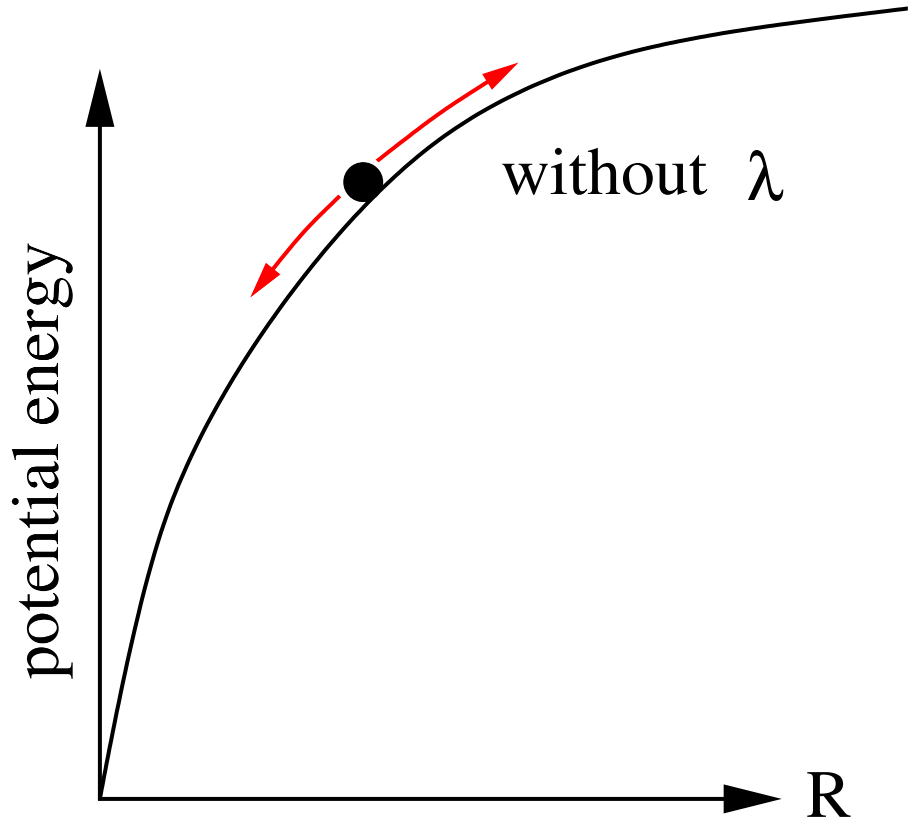


By demanding special relationships between λ, ρ and R, $\lambda = \kappa\rho/2 = 1/R^2$, a static solution can be found. ($\kappa \propto$ Newton's gravitational constant, $\kappa = 8\pi G$, appearing in force law $F = Gm_1m_2/r^2$)

Einstein did not then know that any small perturbation of R away from this value would cause the universe to collapse ($R \to 0$) or expand forever ($R \to \infty$), like a ball balanced on the top of a hill.

Why Einstein needed λ

If $\lambda = 0$, there is no point of equilibrium,



The spherical universe may expand for a while, but it reaches maximum size and then starts to collapse, as shown by Alexander Friedmann in 1922 (at first rejected by Einstein, later he agreed)

Einstein's theory with $\lambda = 0$ predicts a dynamical universe!

What is meant by dark energy?

"Dark energy" is the new terminology for the cosmological constant. λ/κ is the energy per volume of empty space!

Einstein's equations of general relativity (modern notation, $\lambda \to \Lambda$):

$$-G_{\mu\nu} - \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

curvature – c.c. = mass/energy density

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Nothing prevents us from moving Λ from one side of the equation to the other

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$$-G_{\mu\nu} = \kappa T_{\mu\nu} + \Lambda g_{\mu\nu}$$

curvature = mass/energy density + c.c.

By putting c.c. on right side of equation, it looks like a new contribution to the energy density of universe.

But it has nothing to do with stars or other kinds of known matter. It is energy of the vacuum.

Size of the dark energy density

To get his static universe, Einstein had to assume that Λ balances the effect of the universe's normal matter density,

$$\Lambda = \frac{\kappa}{2}\,\rho_m$$

so that energy density of the vacuum is

$$\rho_\Lambda = \frac{\Lambda}{\kappa} = \frac{\rho_m}{2}$$

Using modern value of ρ_m, this gives

$$\rho_\Lambda \sim 10^{-30}\,\mathrm{g/cm^3}$$

If Aud. A has volume of $(10\,\mathrm{m})^3$, it contains $\sim 10^{-9}\,\mathrm{J}$ of vacuum energy. The lighting consumes $\sim 100\,\mathrm{J/s}$.

Mass versus energy density

We talk about dark energy, but we equated it to a density of mass?

Recall Einstein's famous equivalence between mass and energy,

$$E = mc^2$$

where $c = 3 \times 10^8\,\mathrm{m/s}$, the speed of light.

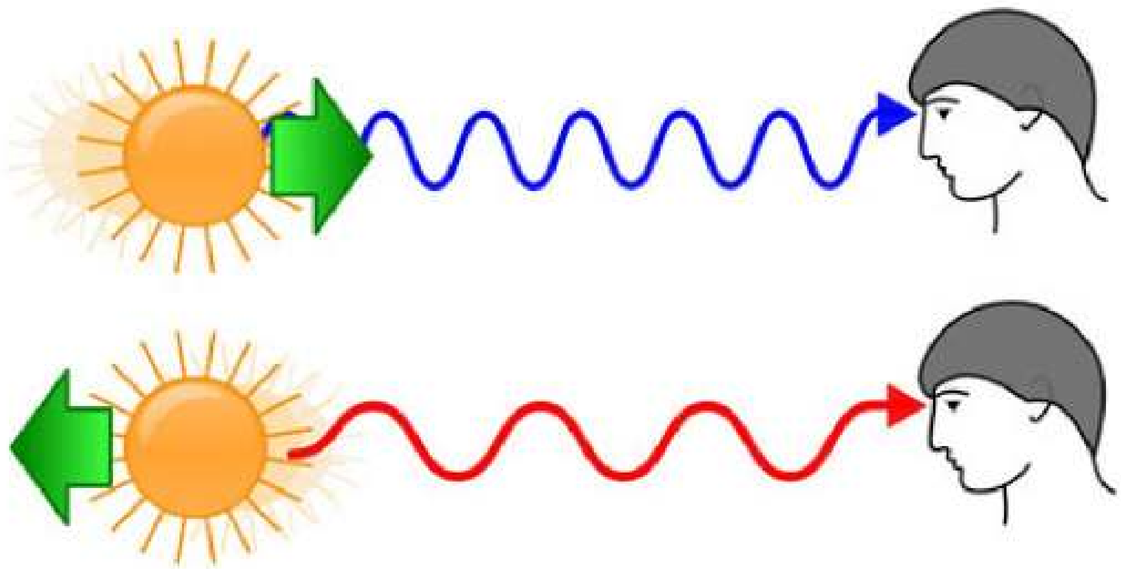
Physicists are so used to interchanging mass and energy in this way we sometimes forget to write the factors of c. ☺

These are $c = 1$ units which I will also use

Using this conversion, $1\,\mathrm{g}$ of mass $\cong 10^{14}\,\mathrm{J}$ of energy, enough to power the lighting in Aud. A for $\sim 30,000$ years.

Expansion of the universe?

1912-1924, American astronomer Vesto Slipher found the first evidence for expansion of the universe through the redshifts of galaxies (then called nebulae).



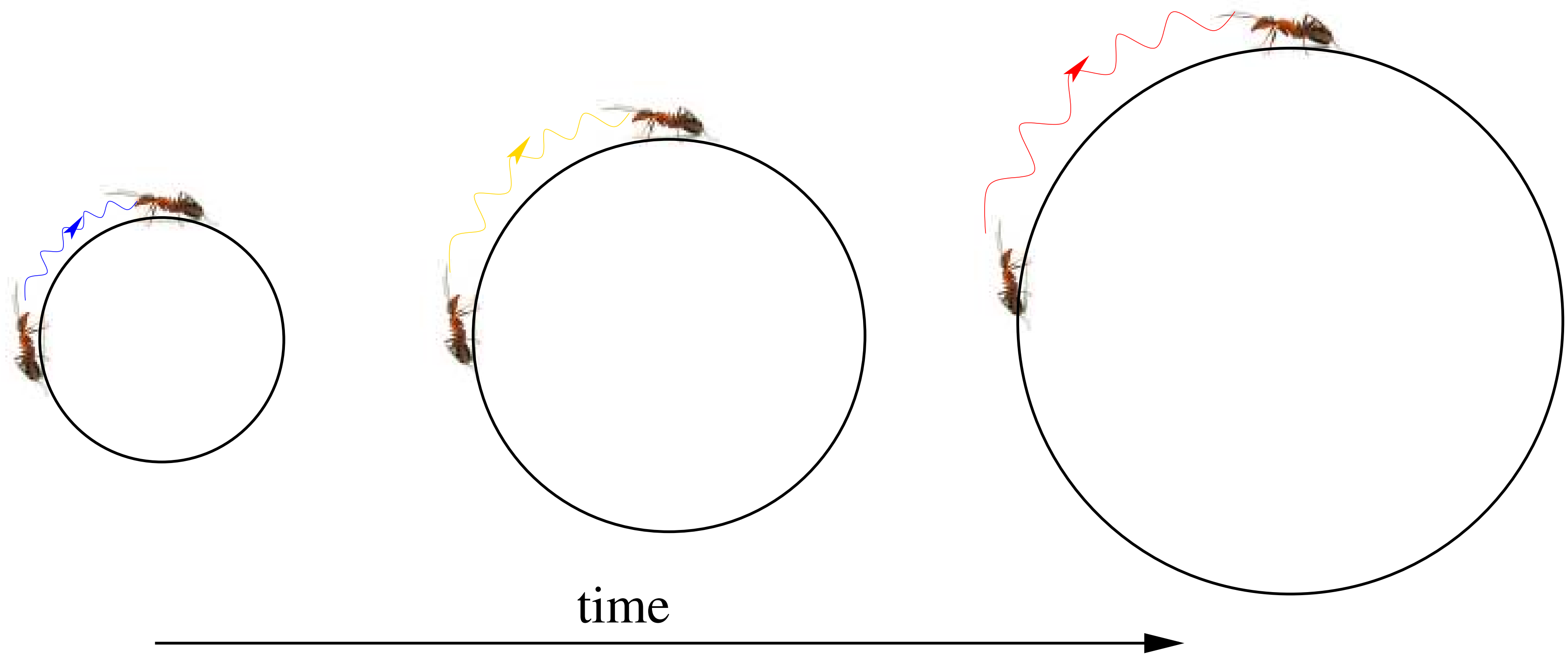
Spectral lines (light of a pure color) from atomic transitions were redshifted by the motion of the galaxies away from us.

Most galaxies were seen to be moving away, not toward us. Expansion of the universe? Not all were convinced.

(*E.g.,* Fritz Zwicky, “tired light” theory)

Expansion and redshift

Imagine universe as surface of expanding balloon. (Radial direction has no physical significance!)



Stationary observers move away from each other.

Light sent from one to the other gets stretched: *redshifted*.

Amount of redshift is exactly proportional to expansion

de Sitter's expanding universe

Using Einstein's equations, in 1917 (soon after Einstein's static universe paper) Dutch astronomer Willem de Sitter found an expanding universe with no matter, only Λ.

German mathematician / physicist / philosopher Hermann Weyl noted that light would be redshifted in such a universe (1923).

Link between universe expansion and redshift is planted in theorists minds.

Einstein writes to Weyl (1923), "If there is no quasi-static world, then away with the cosmological term"

Einstein had been reluctant to introduce Λ in the first place; he was only forced to by the perception of a static universe.

Hubble's expansion

In 1929, American astronomer (and former college basketball champion) Edwin Hubble publishes more evidence for expansion of the universe.

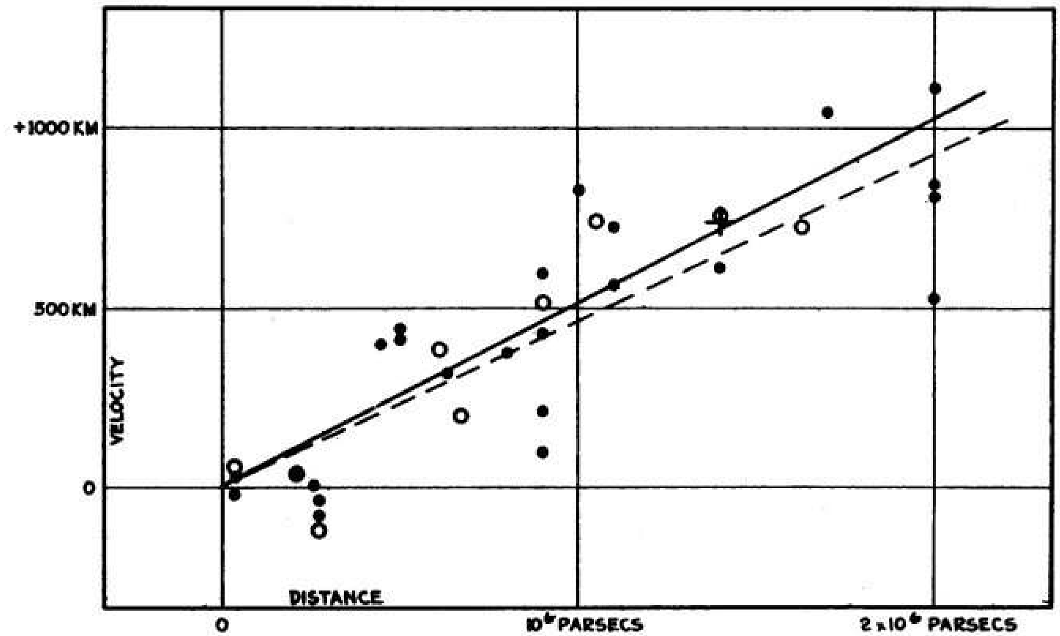


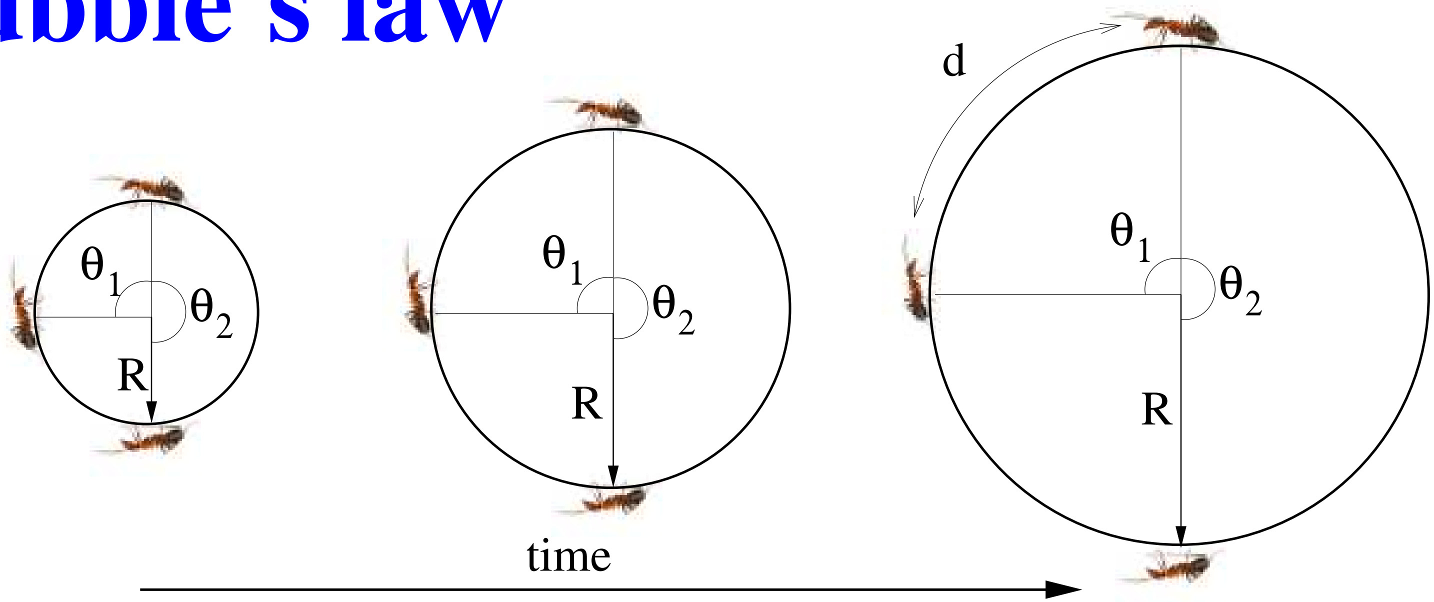
FIGURE 1

http://apod.nasa.gov/diamond_jubilee/d_1996/hub_1929.html

He showed that distant galaxies move away from us with speed proportional to their distance. (actually *redshift* $\propto d$)

This is exactly what the expanding universe picture predicts!

Hubble's law



The distance between two observers is proportional to the angle (which is constant), $d = R(t)\,\theta$

The speed at which they move away from each other has the same proportionality,

$$\dot{d} = \dot{R}\,\theta$$

Therefore

$$\dot{d} = \frac{\dot{R}}{R}\,d \equiv H\,d \qquad (H = \text{Hubble "constant"})$$

Speed of recession is proportional to distance

The Hubble parameter

H is the slope of the velocity-distance relationship, $\dot{d} = H\,d$

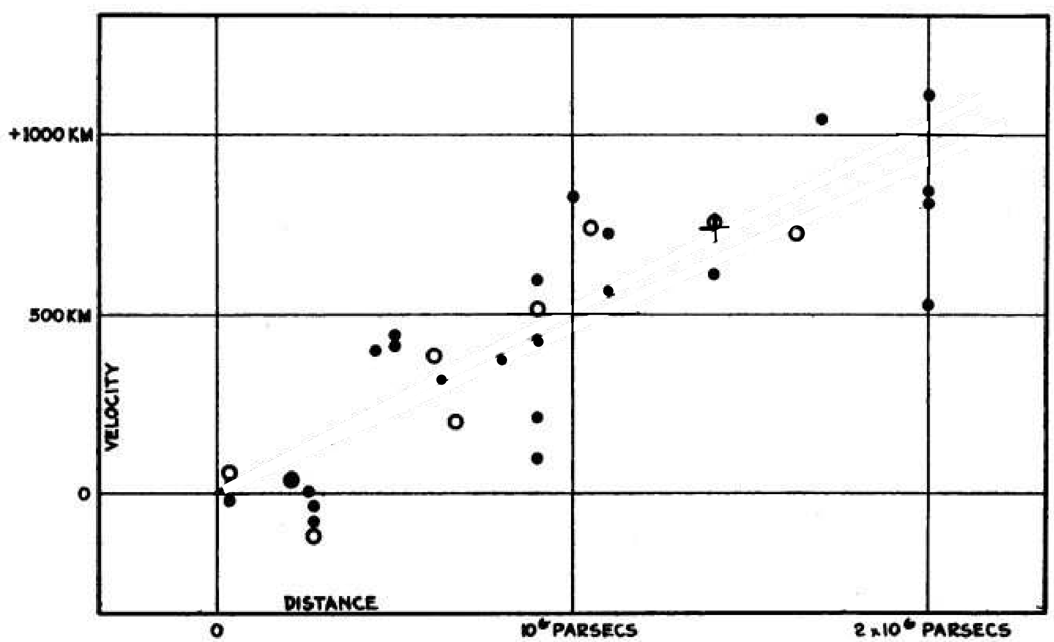


FIGURE 1

(Using redshifts determined by Slipher without giving credit!)

Modern value: $H = 67.3\,\frac{\rm km}{\rm s\cdot Mpc}$ ($1\,{\rm Mpc} \cong 3.3 \times 10^6\,{\rm light-years}$)

Most distant galaxy is $4000\,{\rm Mpc}$ away. Hubble's law says it is receding from us with velocity $67.3 \times 4000 = 267,000\,{\rm km/s}$, 0.9 times the speed of light!

Hubble's conclusions

He seems rather (falsely?) modest about the interpretation:

> New data to be expected in the near future may modify the significance of the present investigation or, if confirmatory, will lead to a solution having many times the weight. For this reason it is thought premature to discuss in detail the obvious consequences of the present results. …
>
> The outstanding feature, however, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space.

He calls the redshift from expansion the "de Sitter effect".
And ends with a prophetic remark:

> … it may be emphasized that the linear relation found in the present discussion is a first approximation representing a restricted range in distance.

The foreseen departure from linearity will play an important role for modern measurements!

Note the influence of theoretical ideas on experimental expectations

Lemaître's expansion

1927, Georges Lemaître, Belgian astronomer, physicist, priest, decorated WWI veteran, and later originator of the big bang concept, reached the same conclusions as Hubble in a paper published two years earlier!

It was written in French and published in a Belgian journal, so did not attract immediate attention. But his famous mentor Arthur Eddington promoted it.

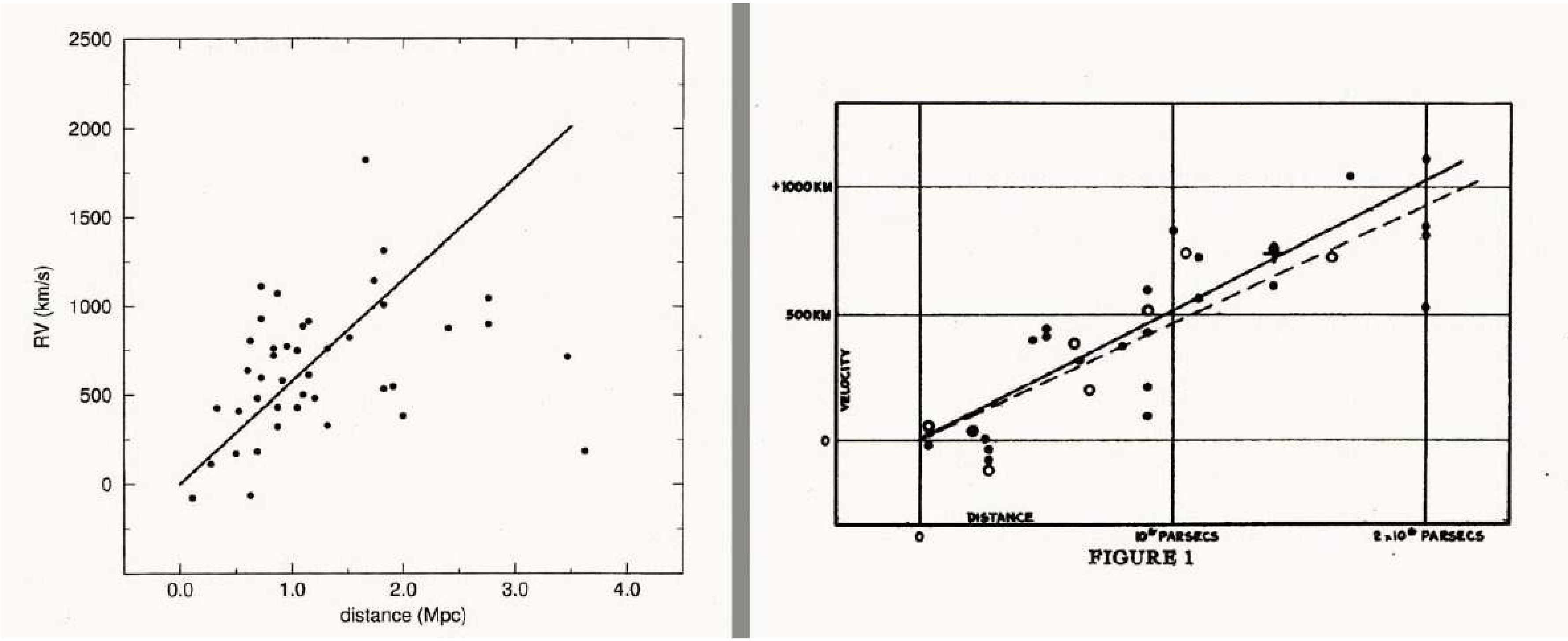
Lemaître used similar data as Hubble, derived the "Hubble Law" and estimated the "Hubble constant," getting a similar value to Hubble.

A translation of his paper into English was published in 1931, with the derivation of the Hubble constant omitted!

The influence of Hubble may be suspected in this censorship.

Lemaître versus Hubble

D. Block (2011) shows comparison of data used by Lemaître and Hubble.



http://arxiv.org/pdf/1106.3928v3.pdf

Lemaitre did not construct the left-hand plot, but these were the data he used. Hubble's data were corrected for peculiar motions of the galaxies and so look more linear.

He also gave a full theoretical explanation of "Hubble's law," completely lacking in Hubble's paper!

Lemaître censored

Block also showed which parts of Lemaître's article were not translated into English. R'/R is the "Hubble constant".

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période de la lumière reçue et δt_1 peut encore être considéré comme la période d'une lumière émise dans les mêmes conditions dans le voisinage de l'observateur. En effet, la période de la lumière émise dans des conditions physiques semblables doit être partout la même lorsqu'elle est exprimée en temps propre.

$$\frac{v}{c} = \frac{\delta t_2}{\delta t_1} - 1 = \frac{R_2}{R_1} - 1 \qquad (22)$$

mesure donc l'effet Doppler apparent dû à la variation du rayon de l'univers. *Il est égal à l'excès sur l'unité du rapport des rayons de l'univers à l'instant où la lumière est reçue et à l'instant où elle est émise.* v est la vitesse de l'observateur qui produirait le même effet. Lorsque la source est suffisamment proche nous pouvons écrire approximativement

$$\frac{v}{c} = \frac{R_2 - R_1}{R_1} = \frac{dR}{R} = \frac{R'}{R}\,dt = \frac{R'}{R}\,r$$

où r est la distance de la source. Nous avons donc

$$\frac{R'}{R} = \frac{v}{cr} \qquad (23)$$

CENSORED

Les vitesses radiales de 43 nébuleuses extra-galactiques sont données par [illegible]berg (¹).

[illegible]a gran[illegible]eur apparente m de ces nébuleuses se trouve dans le travail de [illegible]ubble. Il e[illegible]ossible d'en déduire leur distance, car Hubble a montré qu[illegible] extra-galactiques sont de grandeurs absolues sensiblement égal[illegible] (g[illegible] $-15{,}2$ à 10 parsecs, les écarts individuels pouvant atteindre [illegible]ux gra[illegible]urs [illegible] plus ou en moins), la distance r exprimée en parsecs est [illegible] do[illegible]né[illegible] pa[illegible] formule $\log r = 0{,}2m + 4{,}04$.

On trouve une dista[illegible] de l'or[illegible]e de 10^6 parsecs, variant de quelques dixièmes à 3,3 millio[illegible] de p[illegible]secs. L'erreur probable résultant de la dispersion en grandeur a[illegible]olue est d'ai[illegible]urs considérable. Pour une différence de grandeur absolu[illegible] [illegible]ux gra[illegible]leurs en plus ou en moins, la distance passe de 0,4 à 2,5 fois la distanc[illegible] ca[illegible]. De plus, l'erreur à craindre est proportionnelle à la dista[illegible] [illegible]t adm[illegible]ettre que pour une distance d'un million de parsecs, l'erreur [illegible]sult[illegible] de [illegible]ispersion en grandeur est du même ordre que celle résulta[illegible] de [illegible]a dispersion en vitesse. En effet, une différence d'éclat d'une grandeur co[illegible]spon[illegible] une vitesse propre de 300 Km. égale à la vitesse propre du soleil pa[illegible] rapport aux nébuleuses. On peut espérer éviter une erreur systé[illegible]atique [illegible]n donnant aux observations un poids proportionnel à $\frac{1}{\sqrt{1+r^2}}$, o[illegible] la distance en millions de parsecs.

(¹) Analysis of radial velocities of globular clusters and non galactic nebulae. *Ap. J.* Vol. 61, p. 353, 1925. *Mt Wilson Contr.* N° 292.

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CENSORED

Utilisant les 42 nébuleuses figurant dans les liste[illegible] Hubble et de Strömberg (¹), et tenant compte de la vite[illegible] [illegible]u [illegible]leil (300 Km. dans la direction $\alpha = 315°$, $\delta = 62°$) [illegible] u[illegible]e dis[illegible]ce moyenne de 0,95 millions de parsecs et [illegible]itess[illegible] radi[illegible]e de 600 Km./sec, soit 625 Km./sec à 10^6 par[illegible] (²).

Nous ado[illegible]s don[illegible]

$$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3{,}08 \times 10^{18} \times 3 \times 10^{10}} = 0{,}68 \times 10^{-27}\ \mathrm{cm}^{-1} \qquad (24)$$

Cette relation nous permet de calculer R_0. Nous avons en effet par (16)

$$\frac{R'}{R} = \frac{1}{R_0\sqrt{3}}\sqrt{1 - 3y^2 + 2y^3} \qquad (25)$$

où nous avons posé

$$y = \frac{R_0}{R} \qquad (26)$$

D'autre part, d'après (18) et (26),

$$R_0^2 = R_E^2\, y^3 \qquad (27)$$

et donc

$$3\left(\frac{R'}{R}\right)^2 R_E^2 = \frac{1 - 3y^2 + 2y^3}{y^3} \qquad (28)$$

Introduisant les valeurs numériques de $\frac{R'}{R}$ (24) et de R_E (19), il vient :

$$y = 0{,}0465.$$

On a alors :

$$R = R_E\sqrt{y} = 0{,}215\ R_E = 1{,}83 \times 10^{26}\ \mathrm{cm.} = 6 \times 10^{9}\ \text{parsecs}$$

$$R_0 = Ry = R_E\, y^{\frac{3}{2}} = 8{,}5 \times 10^{24}\ \mathrm{cm.} = 2{,}7 \times 10^{8}\ \text{parsecs}$$

$$= 9 \times 10^{8}\ \text{années de lumière.}$$

CENSORED

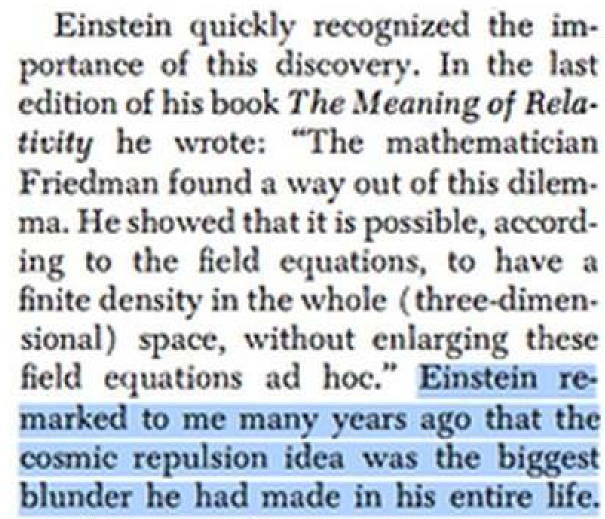
(¹) Il n'est pas tenu compte de N. G. C. 5194 qui est associé à N. G. C. 51[illegible] L'[illegible]troduction des nuées de Magellan serait sans influence sur le résultat.

(²) En ne donnant pas de poids aux observations [illegible] tr[illegible]verait 6[illegible] Km[illegible]sec à $1{,}16 \times 10^6$ parsecs, 575 Km./sec à 10^6 parsecs. Certai[illegible] aute[illegible]s [illegible] cherch[illegible] [illegible]re en évidence la relation entre v et r et n'ont ob[illegible] qu'un[illegible] faibl[illegible] corr[illegible]ation entre ces deux grandeurs. L'erreur dans la [illegible]tion des [illegible]ances [illegible]duelles est du même ordre de grandeur que l'inte[illegible]val[illegible] [illegible]ent les obs[illegible]vations et la vitesse propre des nébuleuses (en [illegible]ctio[illegible]) est gra[illegible] [illegible]m./sec. d'après Strömberg), il semble donc que ce[illegible]sultats [illegible] [illegible]pour ni contre l'interprétation relativistique de l'eff[illegible] Doppler. T[illegible]e que l'im[illegible]écision des observations permet de faire est de supposer v [illegible]oportionn[illegible] à r et d'[illegible]ssayer d'éviter une erreur systématique dans la détermination du [illegible]apport [illegible] [illegible]UNDMARK. The determination of the curvature of space time in de Sitt[illegible] [illegible] M. N., vol. 84, p. 747, 1924, et STRÖMBERG, *l. c.*

Einstein repudiates Λ

With the expanding universe, there seemed to be no need for Λ. Einstein concludes it is simpler to omit it from his equations.

Russian theorist George Gamow writes in 1956 *Scientific American* article that Einstein called Λ his "greatest blunder"



Einstein quickly recognized the importance of this discovery. In the last edition of his book *The Meaning of Relativity* he wrote: "The mathematician Friedman found a way out of this dilemma. He showed that it is possible, according to the field equations, to have a finite density in the whole (three-dimensional) space, without enlarging these field equations ad hoc." Einstein remarked to me many years ago that the cosmic repulsion idea was the biggest blunder he had made in his entire life.

Historians of science find no corroborating evidence that Einstein thought it was such a big mistake.

We will see that in fact he was right to include Λ after all!

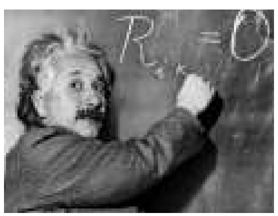
Rather than a fundamental change to his original equation, it can be seen as just a new contribution to the energy density, coming from the vacuum

Theoretical developments

Once the idea of Λ was introduced, theorists did not easily forget it, but without further experimental evidence, nothing definitive could be said.

Already in 1911, German physicist Walther Nernst showed that the new quantum theory predicts vacuum should have energy. The idea did not attract much notice at the time.

Late 1920s, German physicist Wolfgang Pauli tries to compute Λ and finds it is so big that universe would "not even reach to the moon." (Recall $\Lambda = 1/R^2$.) Dismisses vacuum energy.



1928, Einstein argues against quantum mechanical origin of vacuum energy, saying it should be zero, independently of Λ term in his gravitational equation.

1948, Dutch physicist Hendrik Casimir correctly predicts vacuum energy between conducting (metal) plates should cause them to attract each other. Nobody connects this to Λ.

1967-68, Russian physicist Yakov Zeldovich estimates Λ in quantum theory (like Pauli did) and finds it is too large. Other physicists start to pay attention.

Observational Hints of Λ

Why did some theorists start to pay more attention to Λ in the 1960's? A few astronomers were starting to think that Λ might be nonzero. This gave theorists more motivation to take it seriously.

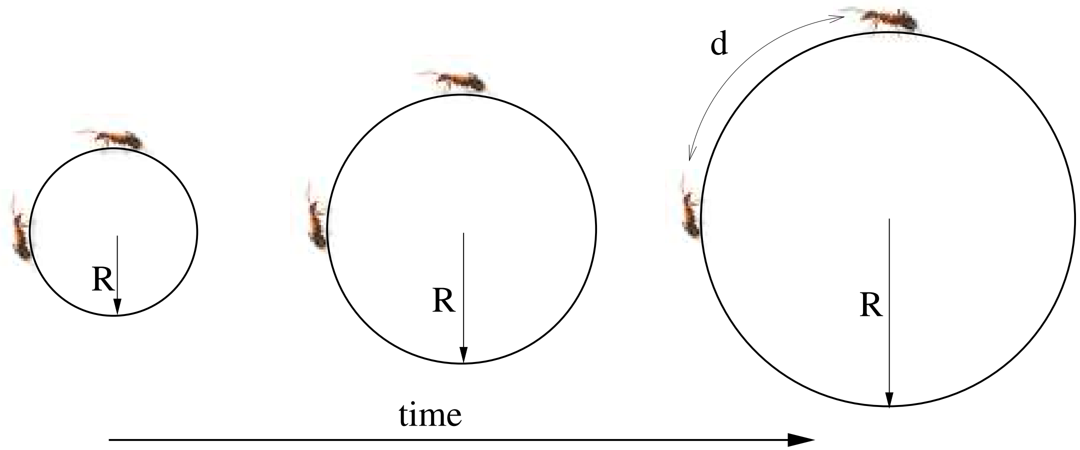
The observed rate of expansion of the universe seemed not to match expectations from Einstein's theory with $\Lambda = 0$; having $\Lambda \neq 0$ could improve the agreement.

To understand why, we need to look at the equations that determine how fast the universe expands.

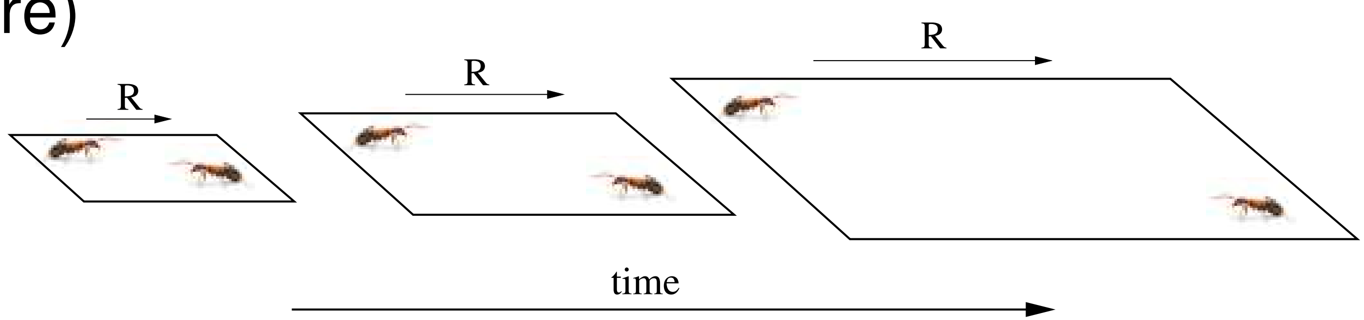
These were deduced from Einstein's equations by Alexander Friedmann in 1922. They depend upon the mass/energy density and the <u>curvature</u> of the universe.

Expansion and curvature of the universe

Our 3D universe is similar to the 2D surface of a sphere. The distance between two ants (galaxies) grows like the "scale factor" R that is like the radius of the sphere (positive curvature).



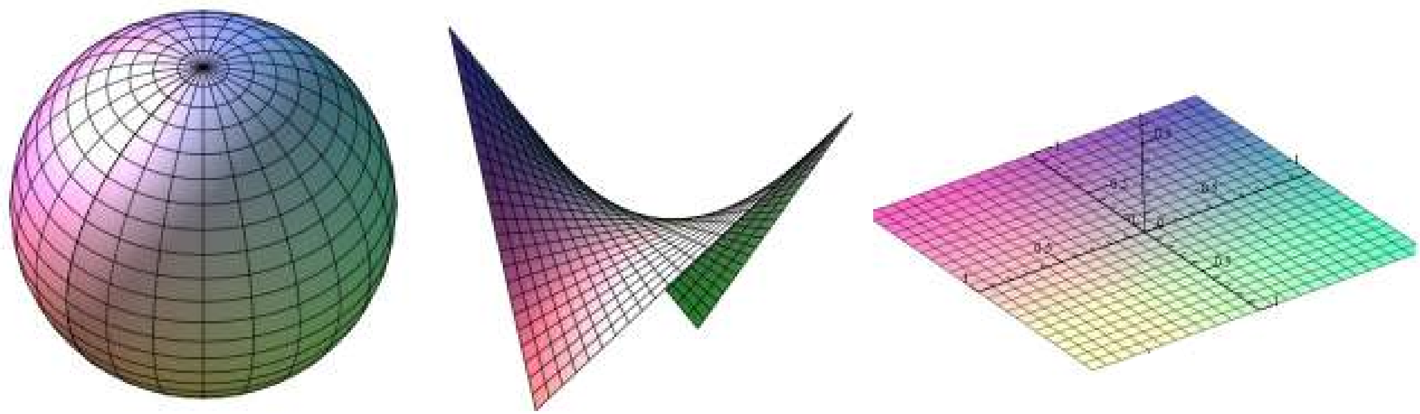
As R increases, the volume of space increases with it. A similar picture could be drawn for a flat universe (zero curvature)



(Imagine membrane being stretched.)

Expansion and curvature of the universe

Besides positive and zero curvature, it is possible for space to be negatively curved,



positive negative zero

Einstein assumed positive curvature in his static universe solution. In this case, total volume and mass of universe is finite.

If zero or negative curvature, universe is infinite.

The Friedmann equations

They are equivalent to Einstein's equations for the simplified model of a universe that is *homogeneous* and *isotropic*.

1st Friedmann equation determines relative rate of expansion (Hubble rate):

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{\kappa}{3}\rho + \frac{\Lambda}{3} - \frac{k}{R^2}$$

where $k = (\pm 1 \text{ or } 0)$ is sign of curvature,
ρ is mass/energy density of matter and radiation.

We can also write it as

$$H^2 = \frac{\kappa}{3}(\rho + \rho_\Lambda) - \frac{k}{R^2}$$

Positive energy density drives the expansion of the universe, while positive curvature tends to slow it down.

The Friedmann equations

2nd Friedmann equation determines acceleration of the universe's expansion:

$$\frac{\ddot{R}}{R} = -\frac{\kappa}{6}(\rho + 3p) + \frac{\Lambda}{3}$$

where p is the pressure due to radiation. Einstein's static solution assumed $p \cong 0$. To get static universe, he needed to balance ρ against Λ.

We can also write it in the form

$$\frac{\ddot{R}}{R} = -\frac{\kappa}{6}(\rho + \rho_\Lambda + 3p + 3p_\Lambda)$$

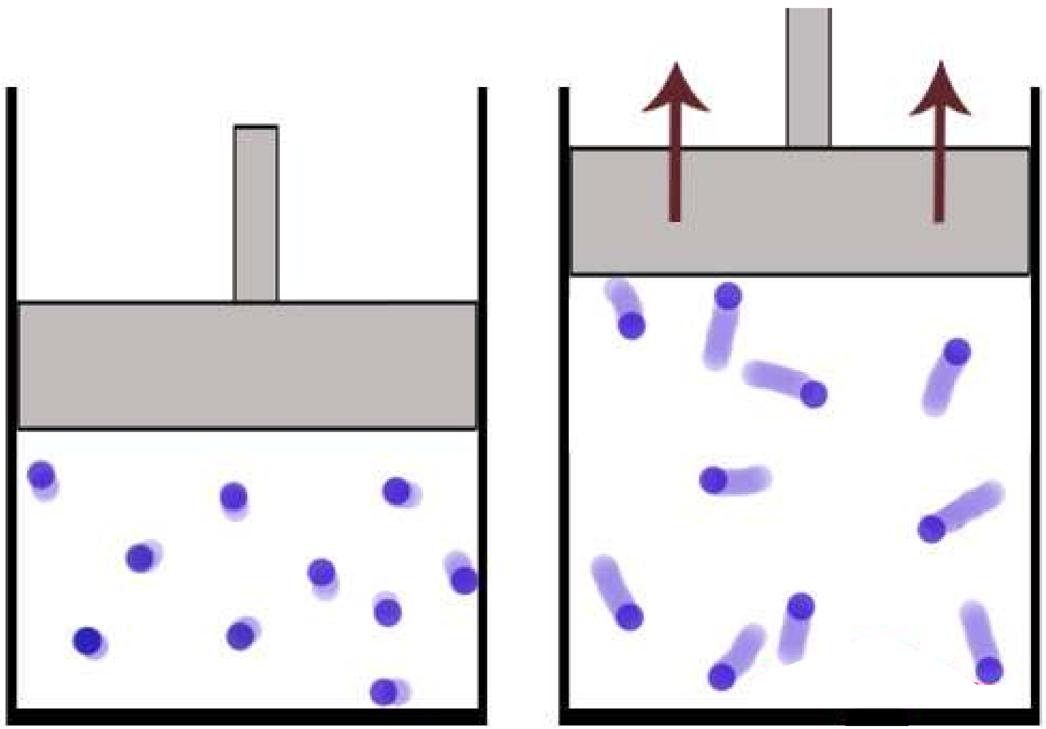
Dark energy has the curious property that $p_\Lambda = -\rho_\Lambda$:
if $\rho_\Lambda > 0$, its pressure is negative (suction)!
And this causes positive acceleration!

Negative pressure and acceleration

Why does negative pressure correspond to positive expansion?

This sounds counterintuitive, but is necessary for energy to be conserved.

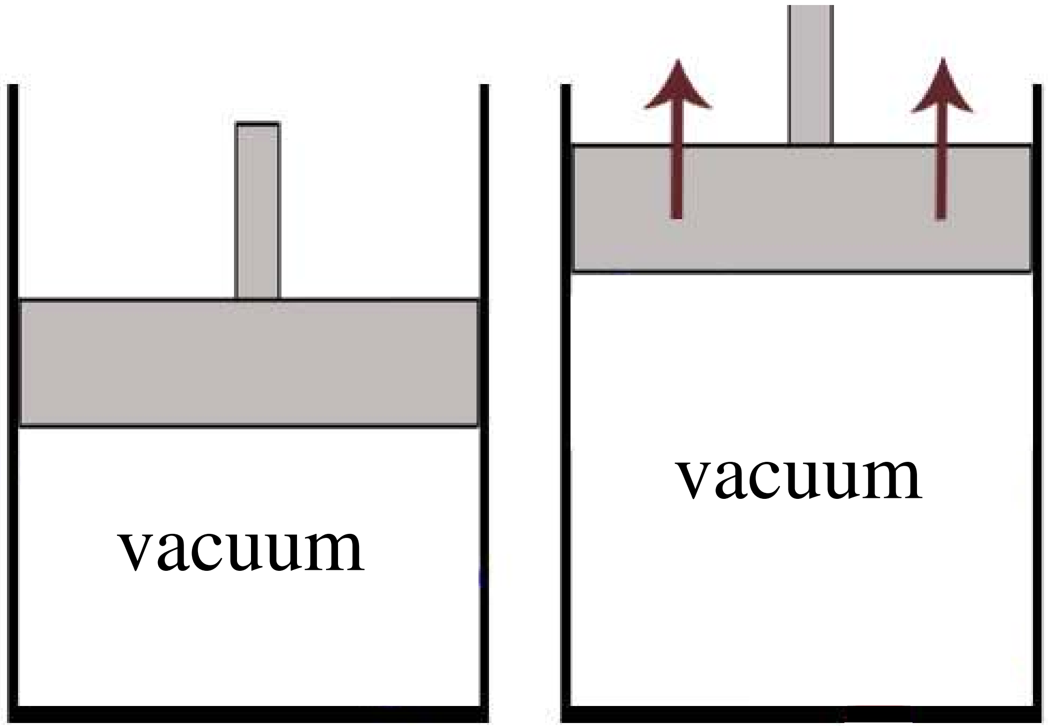
Imagine gas expanding with positive pressure in a piston:



The gas does work on something (your car), so it must lose energy: $\rho_{\rm gas}$ decreases with time.

Negative pressure and acceleration

Now imagine empty cylinder expanding like the universe:



Energy density of the vacuum ρ_Λ is constant, does not change with time.

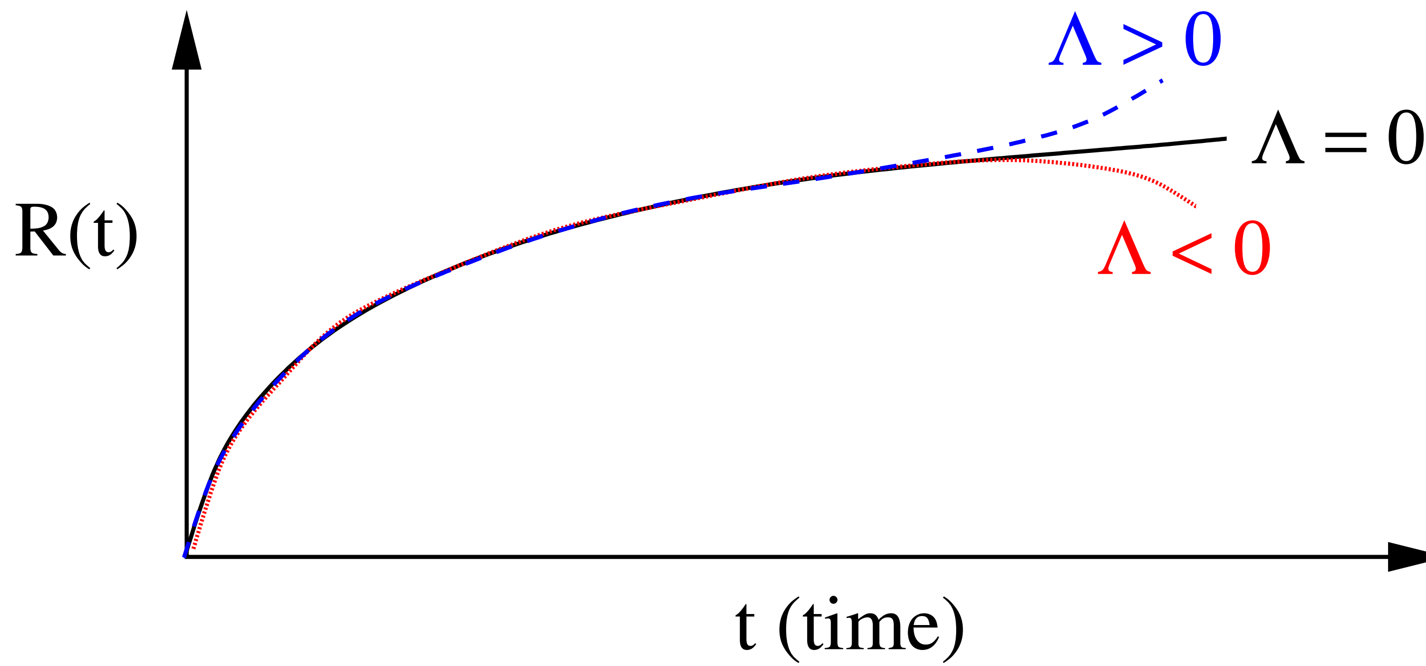
But the volume of space increased, so total energy increased, $E = \rho_\Lambda \times \mathrm{volume}$.

In this case, the cylinder did no work on the piston, rather the piston did the work (pulling to increase the volume of space), so pressure must be negative. The vacuum is like a rubber band in this respect.

But unlike a rubber band, the tension (negative pressure) does not slow the expansion, instead it increases it. Einstein's equations are not the same as the equation for a rubber band!

Effect of Λ on expansion history

We see that the value of Λ can affect the expansion of the universe as a function of time, $R(t)$,



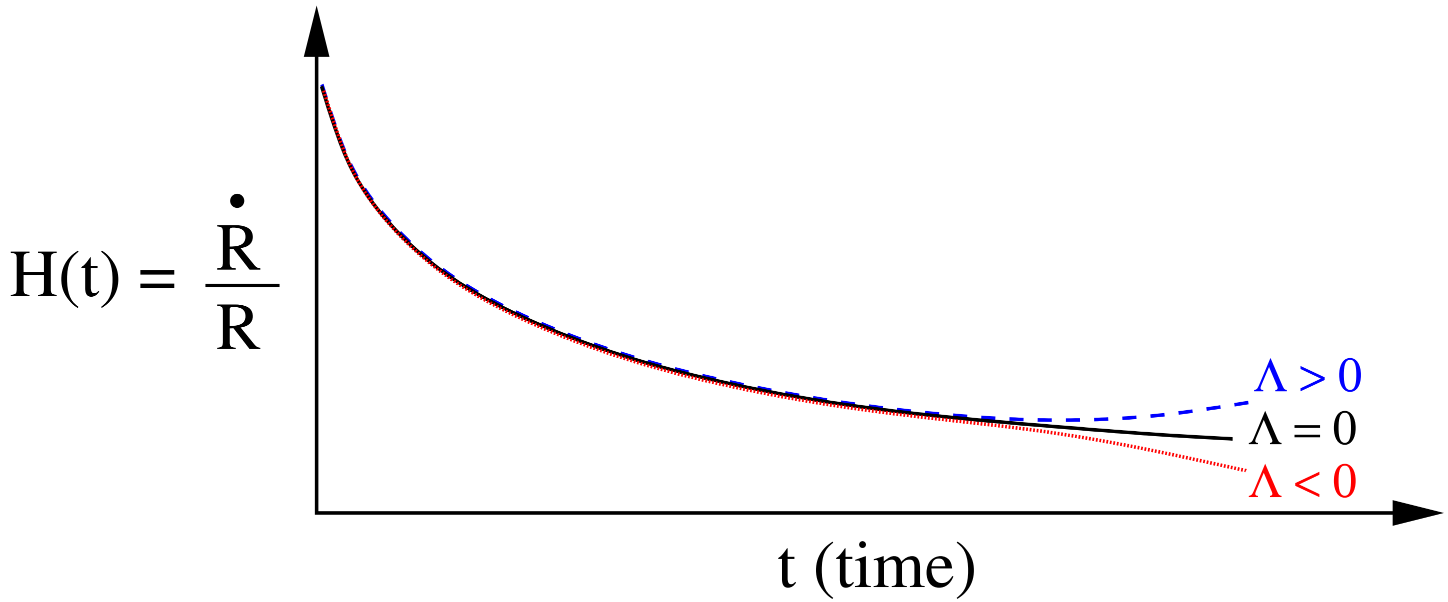
At early times after the big bang, matter and radiation was very dense, so

$$\rho \gg \rho_\Lambda, \quad p \gg p_\Lambda$$

and the effect of Λ is negligible. But ρ decreases with time as $1/R^3$ or $1/R^4$, while ρ_Λ remains constant, and comes to dominate the expansion.

Effect of Λ on expansion history

Similarly, Λ affects the Hubble rate,



Recall that Hubble deduced H by measuring the redshift of galaxies as a function of their distance. But how to measure H as a function of time?

The light from a distant galaxy takes time to reach us,

$$\Delta t = d/c$$

We see it not as it is today, but how it looked in the past, including its recession speed at the earlier time, Δt in the past!

How to measure Λ

Instead of Hubble's simple linear law for recession velocity versus distance,

$$v = Hd$$

we realize that it depends upon the time at which the light was emitted from the galaxy,

$$v(t) = H(t)d$$

where $t = d/c$. Thus v versus d is no longer a straight line but a curve with changing slope $H(d/c)$.

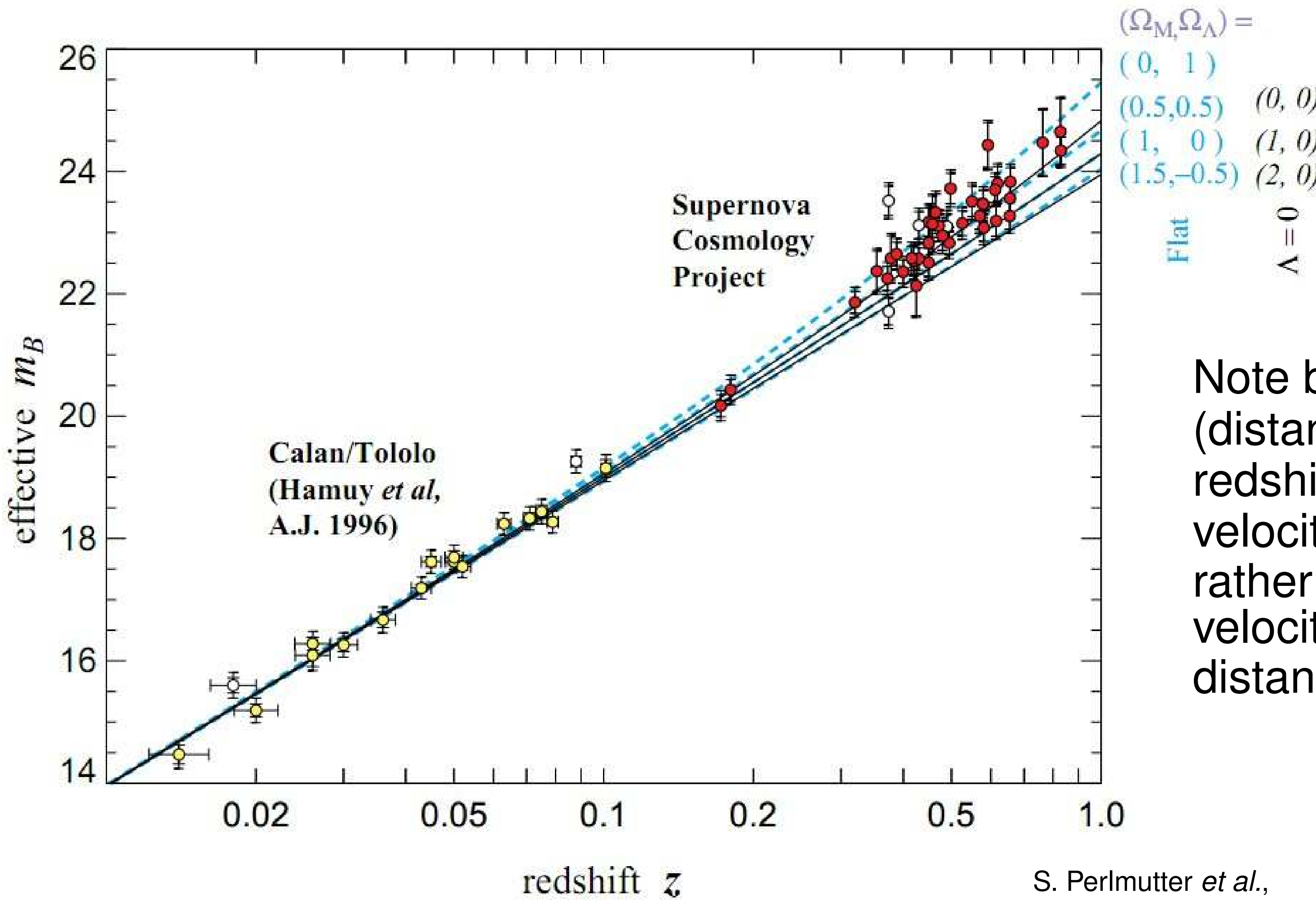
This is what Hubble meant when he said

... it may be emphasized that the linear relation found in the present discussion is a first approximation representing a restricted range in distance.

Its precise shape is sensitive to Λ.

The challenge of measuring distance

Velocity (redshift) is easy to measure, but how can we know how far away the galaxy is? This is the difficult part.



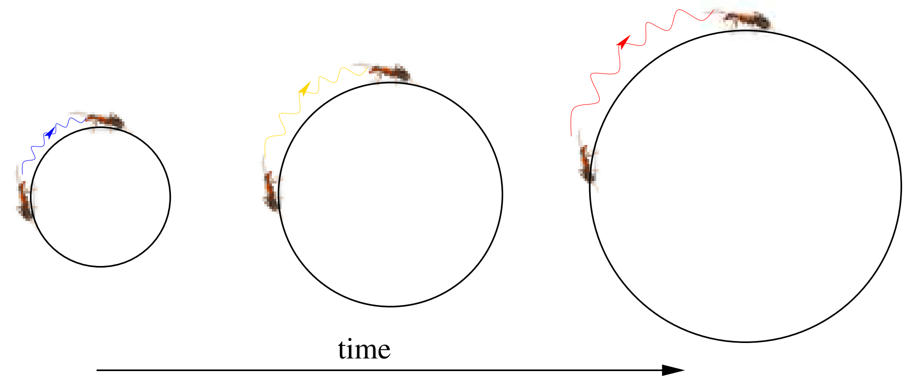
Note brightness (distance) versus redshift (recession velocity) is plotted rather than velocity versus distance

S. Perlmutter *et al.*,

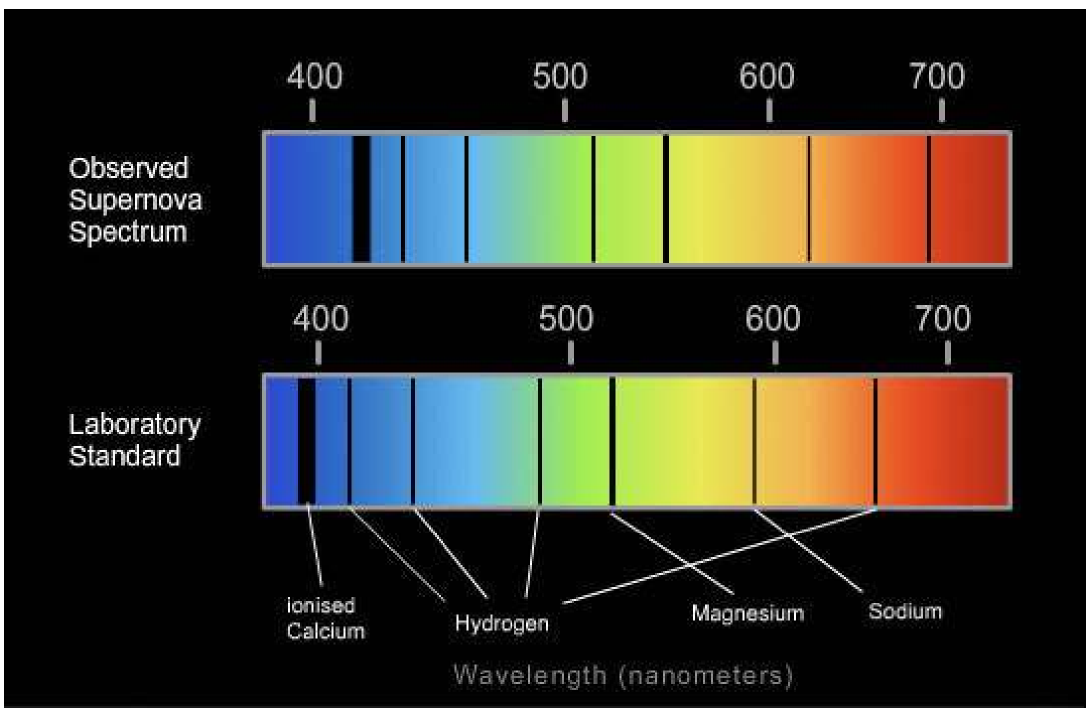
`http://arxiv.org/pdf/astro-ph/9812133.pdf`

Redshift z

Recall the expanding balloon analogy:



Light gets stretched by amount proportional to the expansion,



$$\frac{\lambda_0}{\lambda} = \frac{R_0}{R} \equiv 1 + z$$

where λ_0 and R_0 denote today's (larger) values, and λ, R refer to time when light was emitted.

At $z = 1$, universe was half of its present size

Image: `http://www.passmyexams.co.uk/GCSE/physics/the-expanding-universe-red-shift.html/`

Brightness versus distance

A distant light looks dimmer than a nearby one. Brightness (luminosity) falls with square of distance: $\mathcal{L} \propto 1/r^2$

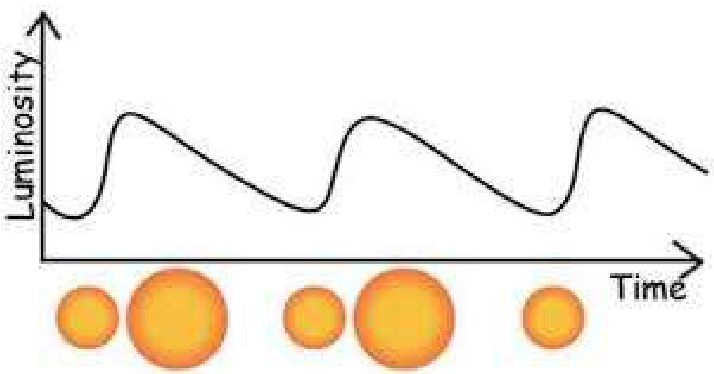
Image: http://www.shutterstock.com

If we knew the *intrinsic brightness* of the light (*e.g.,* 100 W lightbulb) we could calculate the distance from the measured brightness

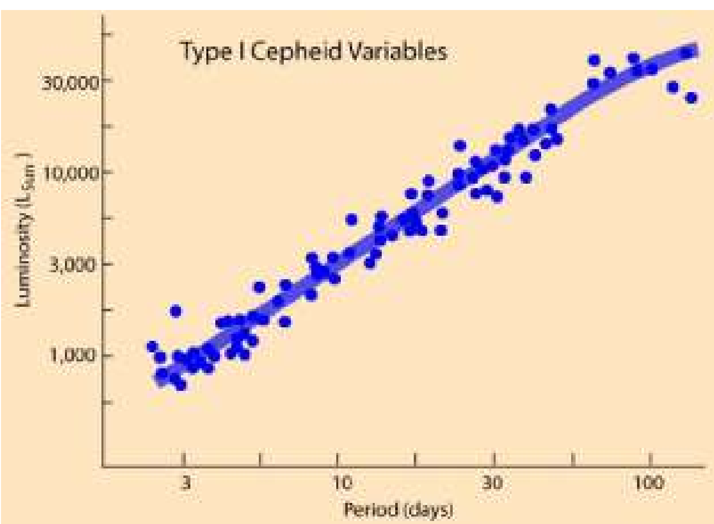
“Standard candles”

But we do *not* know the intrinsic brightness of distant galaxies.

We need to identify some object in the galaxies whose intrinsic brightness is known, a so-called “standard candle”



Lemaître and Hubble used a kind of variable star whose brightness varies periodically with time, known as “Cepheids”



It is possible to directly measure the distances to the most nearby Cepheids.

From this it was shown that their intrinsic brightness is proportional to their frequency of variation.

Images: `http://cseligman.com/text/stars/variables.htm`, `http://hyperphysics.phy-astr.gsu.edu/hbase/astro/cepheid.html`

Measuring distance with parallax

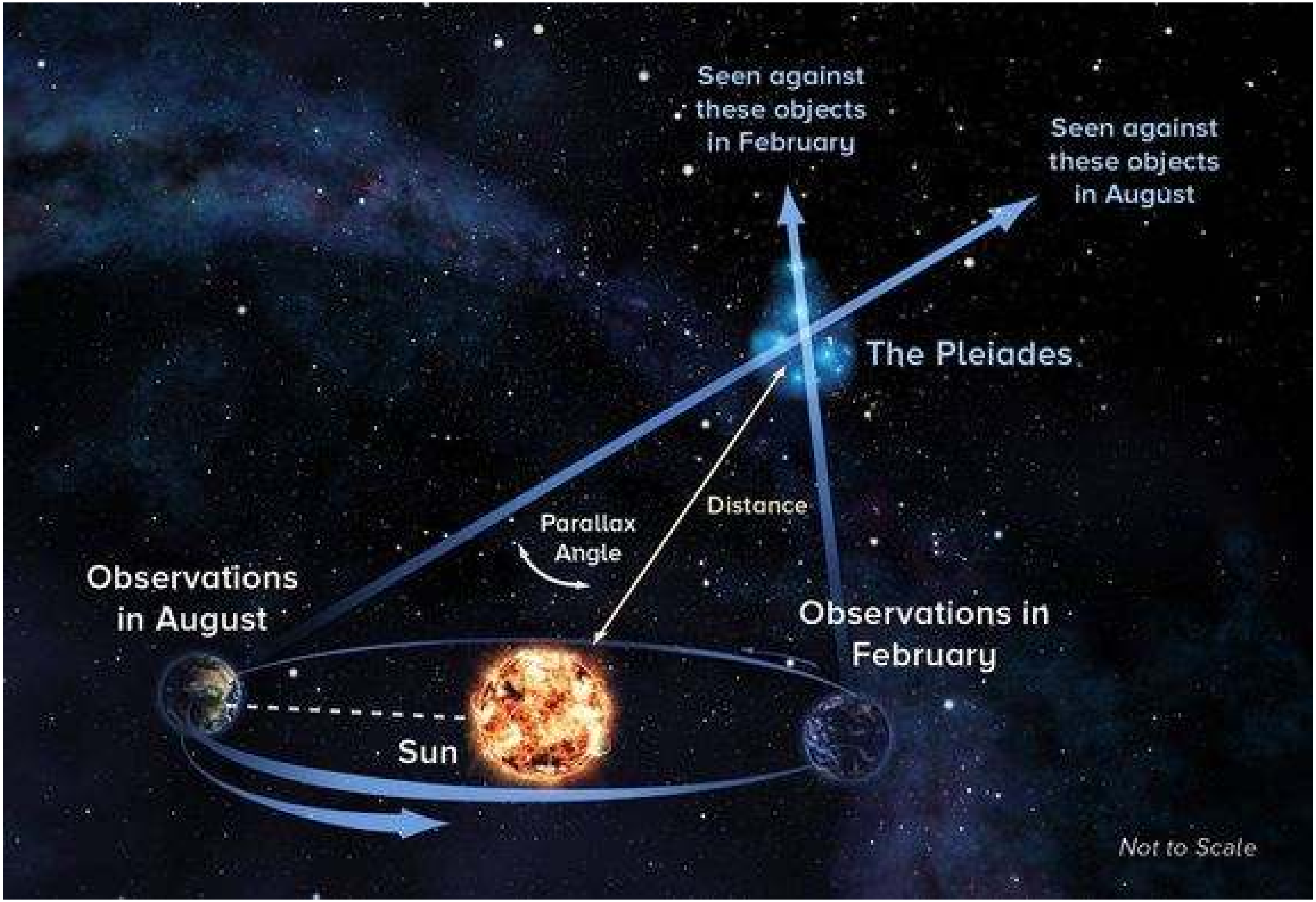


Image: `http://www.space.com/30417-parallax.html`

Note, we must first know the earth-sun distance for this.
The “cosmic distance ladder”

A more powerful candle

To go to greater distances, needed to find the small deviations from linearity in the Hubble plot, Cepheids are too dim to see.

A more powerful standard candle is required

Supernovae, stars exploding at the end of their life, are by far the brightest objects in the universe.

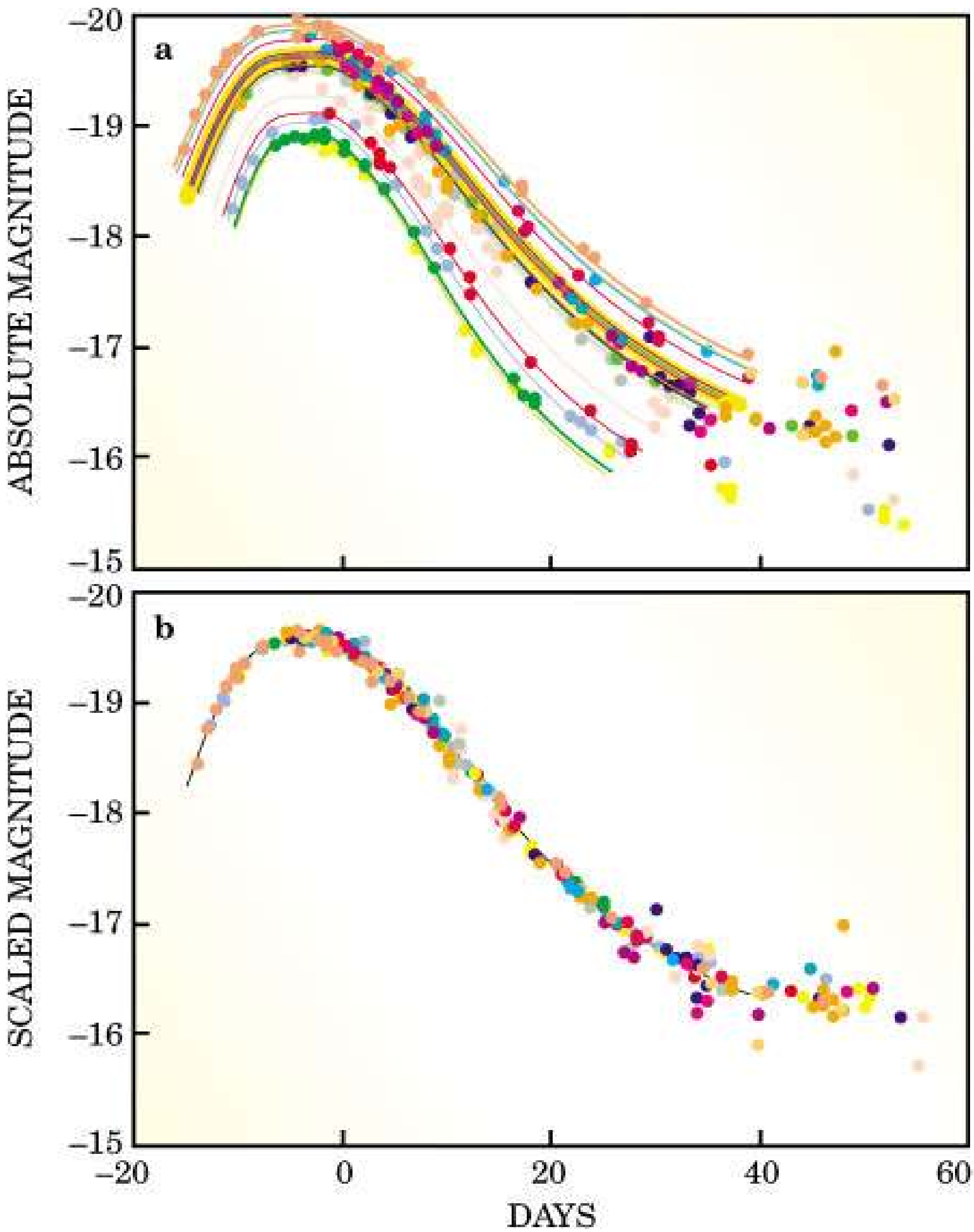
For a brief time, they outshine their entire galaxy!

Unfortunately their intrinsic brightness is not at all standard.

http://www.berkeley.edu/news/media/releases/99legacy/11-11-1999.html

But in 1993 it was proven by American astronomer M. Phillips that a certain type (called Ia) of supernovae can be standardized

Type Ia supernova light curves



Type Ia supernovae with larger intrinsic brightness ("absolute magnitude") shine longer than dimmer ones.

It was discovered that brightness versus time can be described by a single universal function by doing simple rescaling.

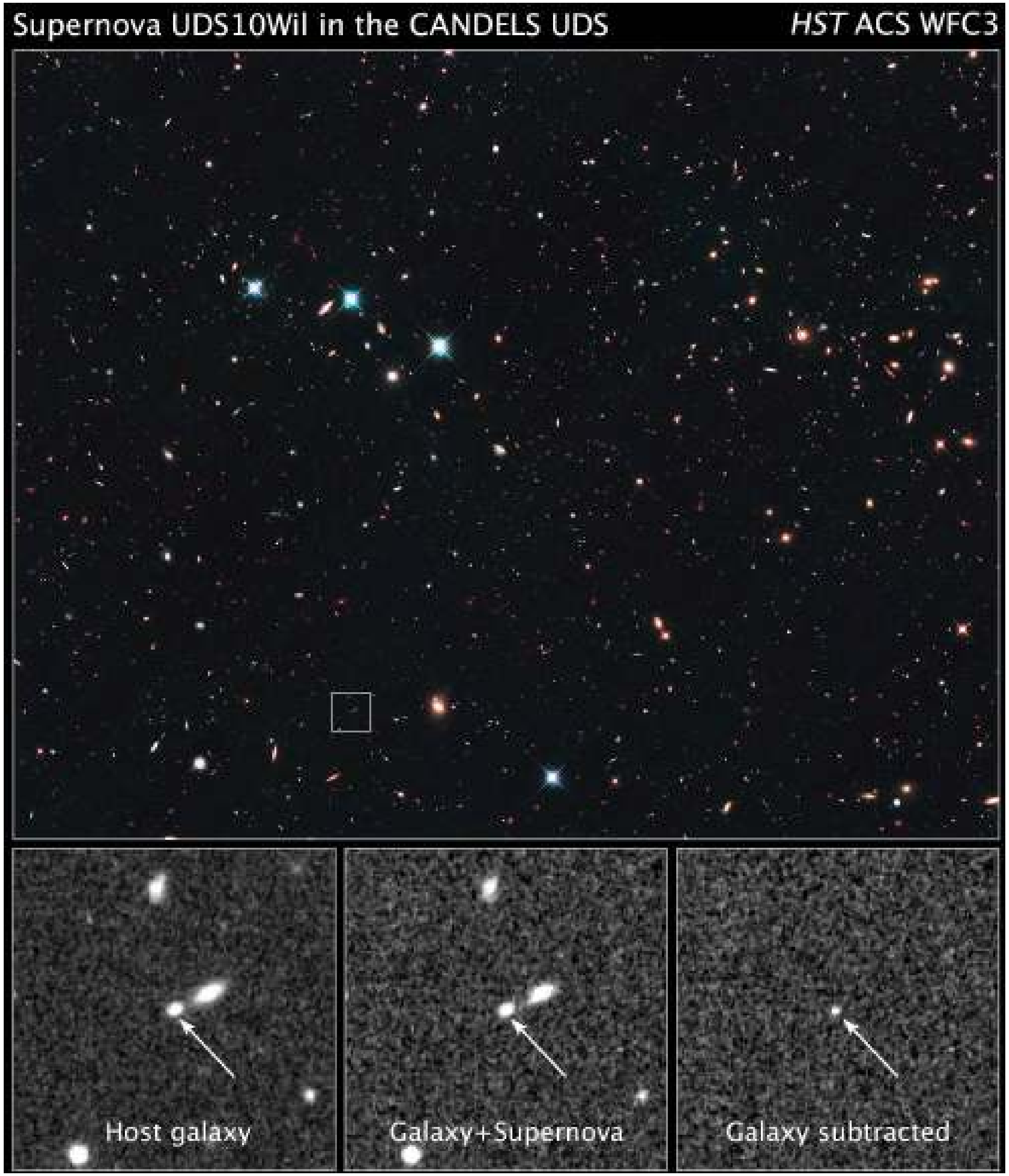
By measuring shape of light curve, the absolute brightness can be deduced.

Type 1a SNe become the new standard candle.

Note the scatter: they are not perfect. Need to observe many SNe to get a significant measurement.

Image: `https://briankoberlein.com/2015/07/22/standardizing-the-candle/`

(Most distant type Ia supernova)



In 2013, Hubble Space Telescope found the most distant type Ia SN to date, 10^{10} light-years away, 1000 times farther than Hubble's sample, at redshift $z = 1.9$

Members of the Dark Cosmology Center here at NBI were involved in the discovery.

http://www.nbi.ku.dk/english/news/news13/most-distant-type-ia-supernova-observed/

The discovery of dark energy

In 1998 two competing collaborations (High-Z and SCP) published the first evidence for nonvanishing Λ

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]

Received 1998 March 13; revised 1998 May 6

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] AND R. QUIMBY

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

(THE SUPERNOVA COSMOLOGY PROJECT)

Received 1998 September 8; accepted 1998 December 17

They got compatible results consistent with a spatially flat universe with 30% of energy density in matter and 70% in Λ.

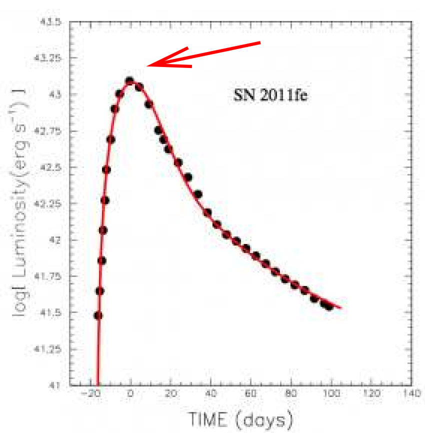
The experimental challenges

As described by SCP team member G. Goldhaber, the path to eventual success was not easy,

> During the three years we observed at this telescope, while the system worked well (and became one of the most-used instruments at the telescope for years after), there was no identified SN candidate. Unfortunately, 80% of our scheduled nights were lost due to bad weather.

> Moreover, since the observing time to confirm high redshift SNe was significant on the largest telescopes, there was a clear ‘chicken and egg’ problem: telescope time assignment committees would not award follow-up time for a SN discovery that might, or might not, happen on a given run (and might, or might not, be well past maximum) and, without the follow-up time, it was impossible to demonstrate that high redshift SNe were being discovered by the SCP

`http://arxiv.org/abs/0907.3526`

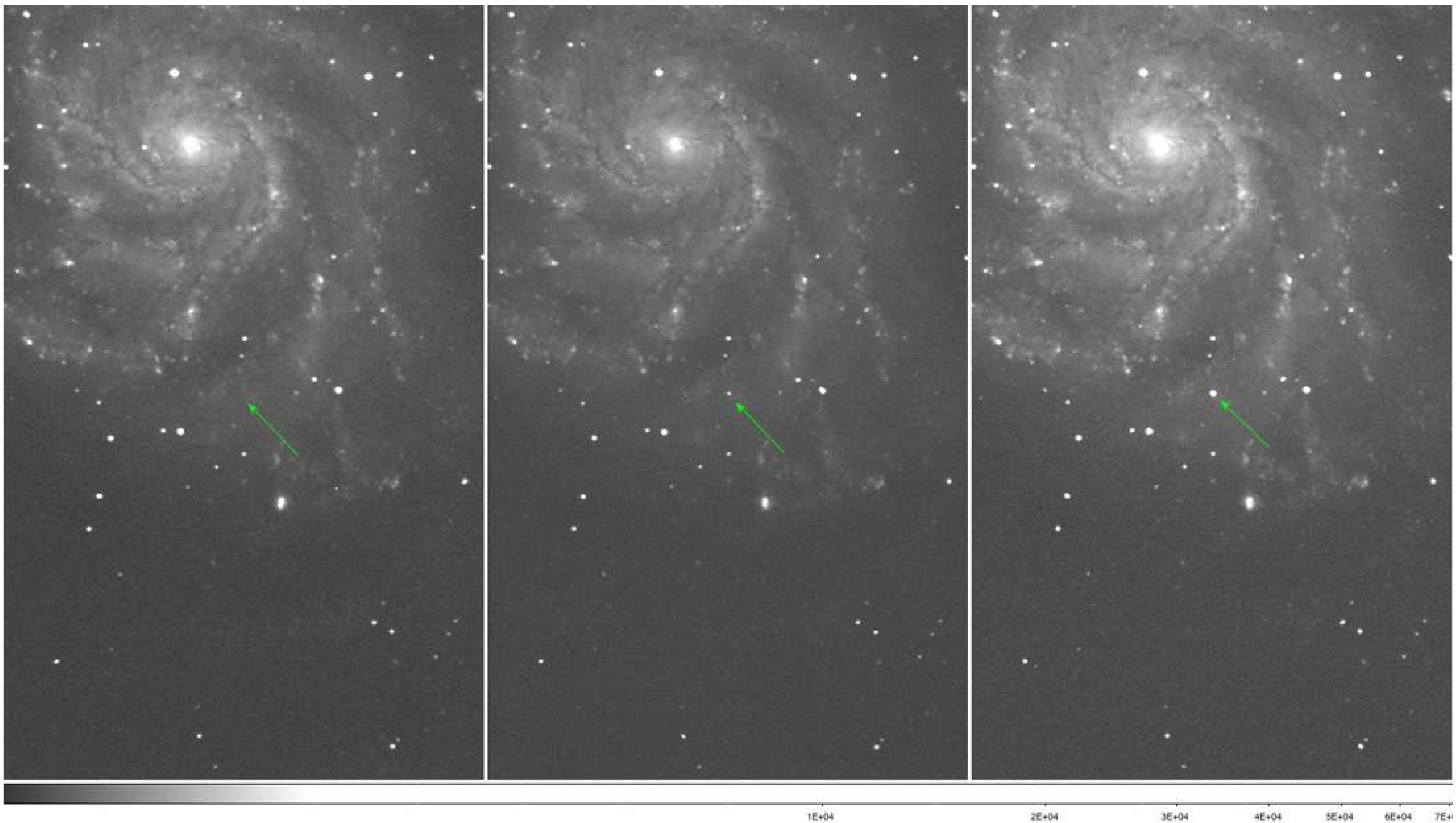


Supernova is easiest to discover when it is brightest, but by then it is too late to measure early part of light curve.

Accurate distance determination requires both parts of the light curve

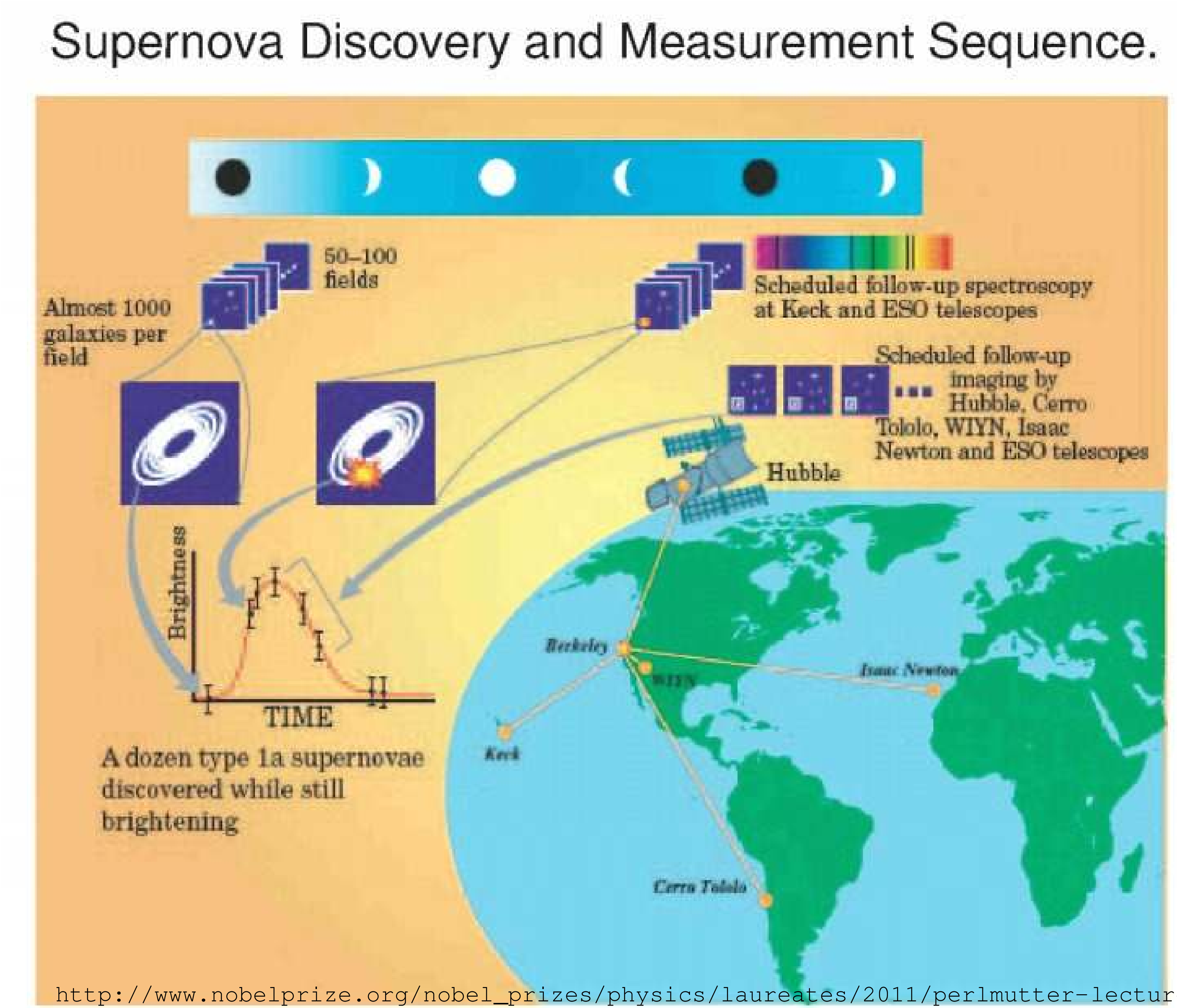
Supernovae on demand

SCP leader Saul Perlmutter developed an automated way to discover many supernova much faster. Many patches of sky were photographed and compared by computer at intervals of one month.



http://www.ia.ucsb.edu/pa/image.aspx?pkey=2550&Position=1

Perlmutter describes the process in this diagram:

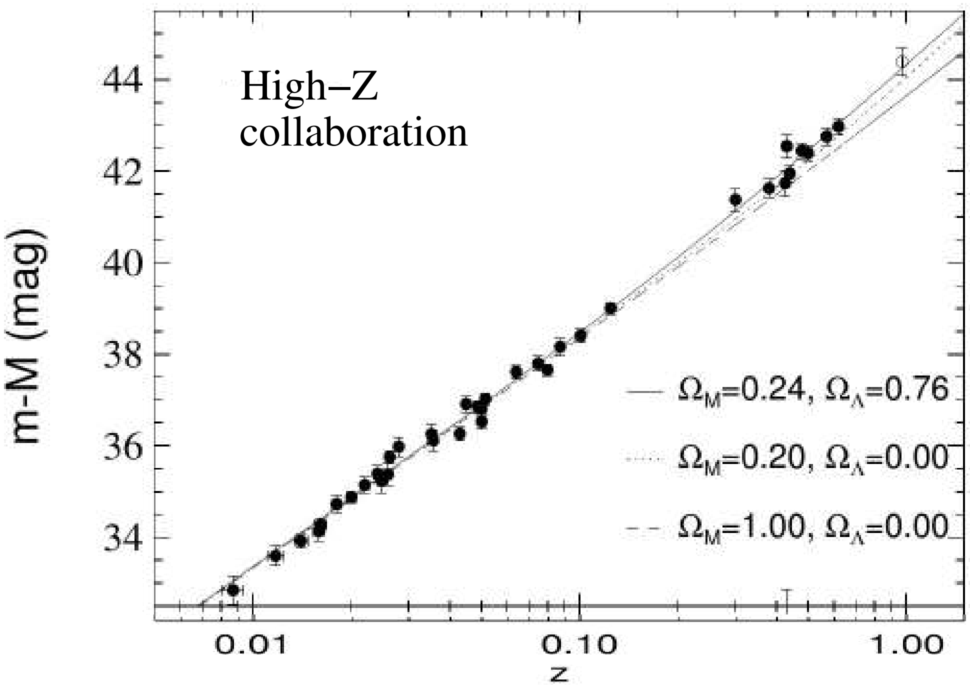


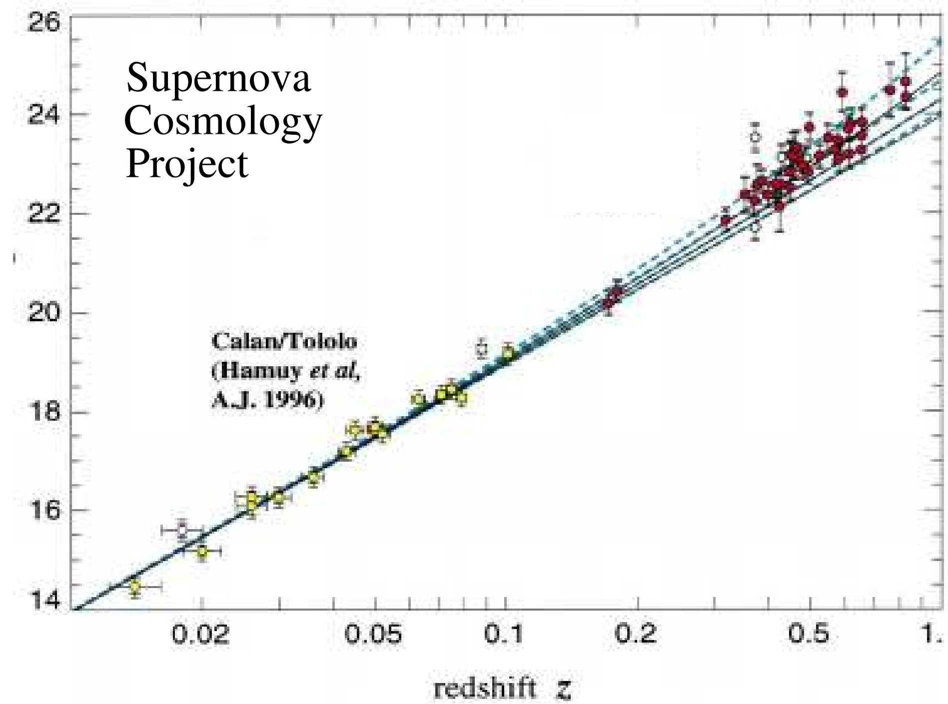
http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.pdf

http://arxiv.org/abs/0907.3526

The Hubble plots

Based on 16 (High-Z) and 42 (SCP) distant supernovae





http://arxiv.org/abs/astro-ph/9805201

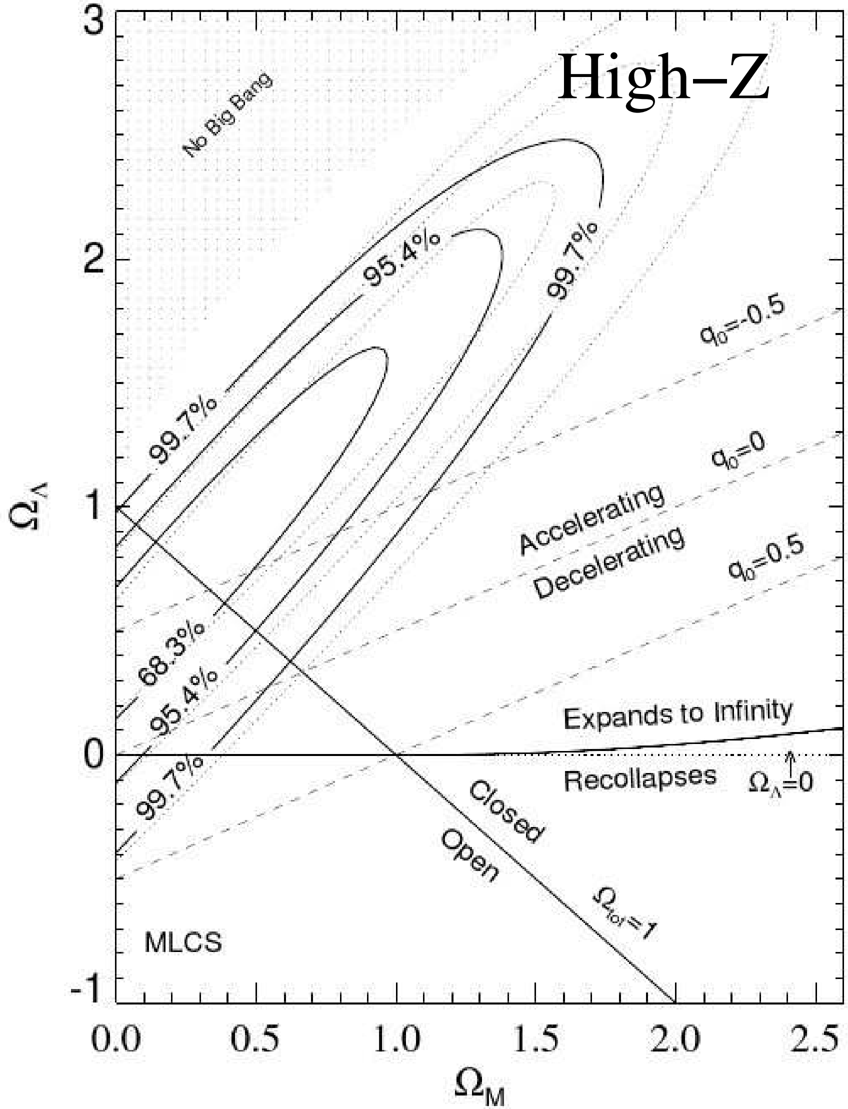
http://arxiv.org/abs/astro-ph/9812133

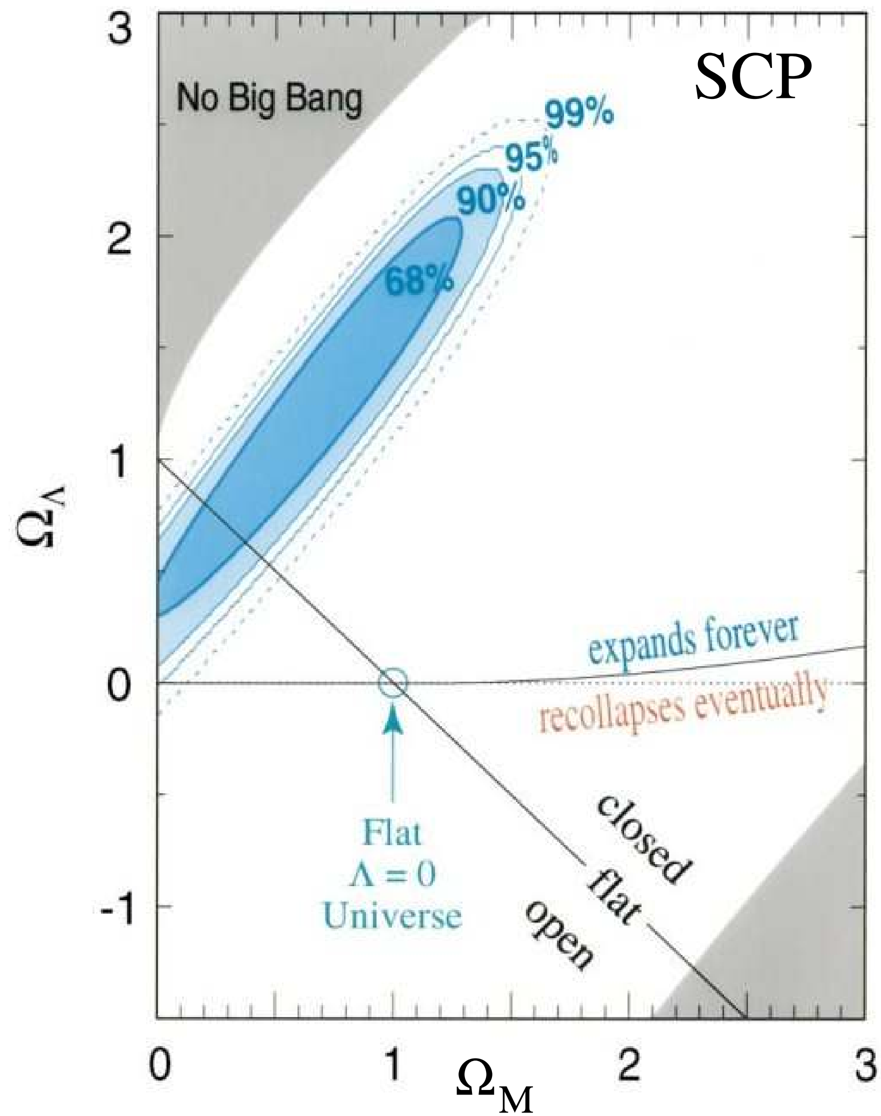
Data is shown along with theoretically predicted curves, assuming different values of

Ω_M : fraction of energy density in matter

Ω_Λ : fraction of energy density in Λ

Λ versus matter density





Note <u>degeneracy</u> (a linear combination of Ω_Λ and Ω_M is determined)

But regardless, $\Omega_\Lambda = 0$ is inconsistent unless $\Omega_M = 0$ also!

Friedmann equations again

We can understand this degeneracy by rewriting Friedmann's equations in terms of the Ω's. Recall

$$\text{rate of expansion: } \left(\frac{\dot{R}}{R}\right)^2 \propto (\rho_M + \rho_\Lambda) - \text{curvature term}$$

$$\text{acceleration: } \frac{\ddot{R}}{R} \propto -\rho_M + 2\rho_\Lambda$$

Dividing both sides by H_0^2, the square of the Hubble rate today, these can be written in the form

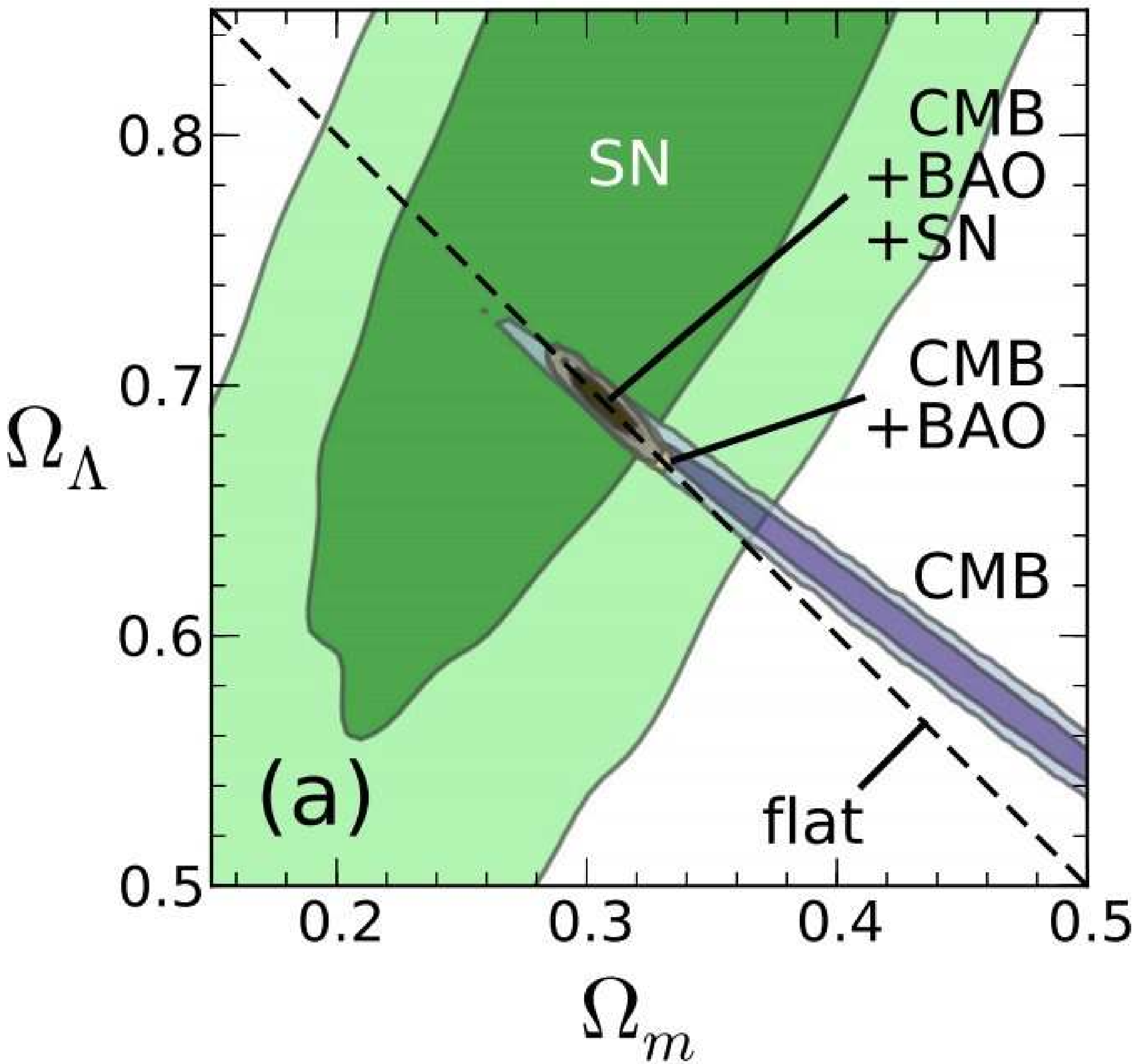
$$\begin{aligned} \Omega_M (1+z)^3 + \Omega_\Lambda + \Omega_k (1+z)^2 &= 1 \\ -\Omega_M (1+z)^3 + 2\,\Omega_\Lambda &= \epsilon \end{aligned}$$

We have two equations in three unknowns, so a linear relation between Ω_M and Ω_Λ can be deduced

in fact just the second equation, with $z \cong 0.6$, giving $\Omega_M \cong \Omega_\Lambda/2 - 0.25$

Other measurements remove ambiguity

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-dark-energy.pdf



Today we have more than just the supernova measurements to pin down the value of Ω_Λ.

Cosmic microwave background (CMB) and baryon acoustic oscillations (BAO) depend differently upon the parameters, allowing a complete determination.

Current values: $\Omega_m = 0.315 \pm 0.017$, $\Omega_\Lambda = 0.685 \pm 0.017$.
Cosmology has become (more of) a precision science!

The reaction to Λ's discovery

A few theorists had anticipated this discovery already in 1995, based on previous data from cosmology.

General Relativity and Gravitation, Vol. 27, No. 11, 1995

The Cosmological Constant Is Back†

Lawrence M. Krauss[1] and Michael S. Turner[2,3]

A diverse set of observations now compellingly suggest that the universe possesses a nonzero cosmological constant. In the context of quantum-

LETTERS TO NATURE

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

J. P. Ostriker* & Paul J. Steinhardt†

Received 16 May; accepted 13 September 1995.

VOLUME 59, NUMBER 22 PHYSICAL REVIEW LETTERS 30 NOVEMBER 1987

Anthropic Bound on the Cosmological Constant

Steven Weinberg
Theory Group, Department of Physics, University of Texas, Austin, Texas 78712
(Received 5 August 1987)

But most astronomers had resisted Λ, since it was such a strange concept.

Even members of the SN discovery teams had thought they would find $\Lambda = 0$, and at first worried there was some mistake in the data analysis.

After sufficient scrutiny, the data proved to be convincing.

The 1991 Nobel Prize in Physics

After an unusually short interval following discovery, the Nobel prize in physics was awarded to leaders of both teams

http://www.space.com/13866-nobel-prize-physics-accelerating-universe-dark-energy.html

The theoretical conundrum

Following Zeldovich, theorists had become concerned about why Λ was not extraordinarily larger than observed.

Estimates based on quantum theory were $\sim 10^{120}$ times too large!

This was considered by many to be the most serious conceptual problem in theoretical physics:

The cosmological constant problem*

Steven Weinberg

Theory Group, Department of Physics, University of Texas, Austin, Texas 78712

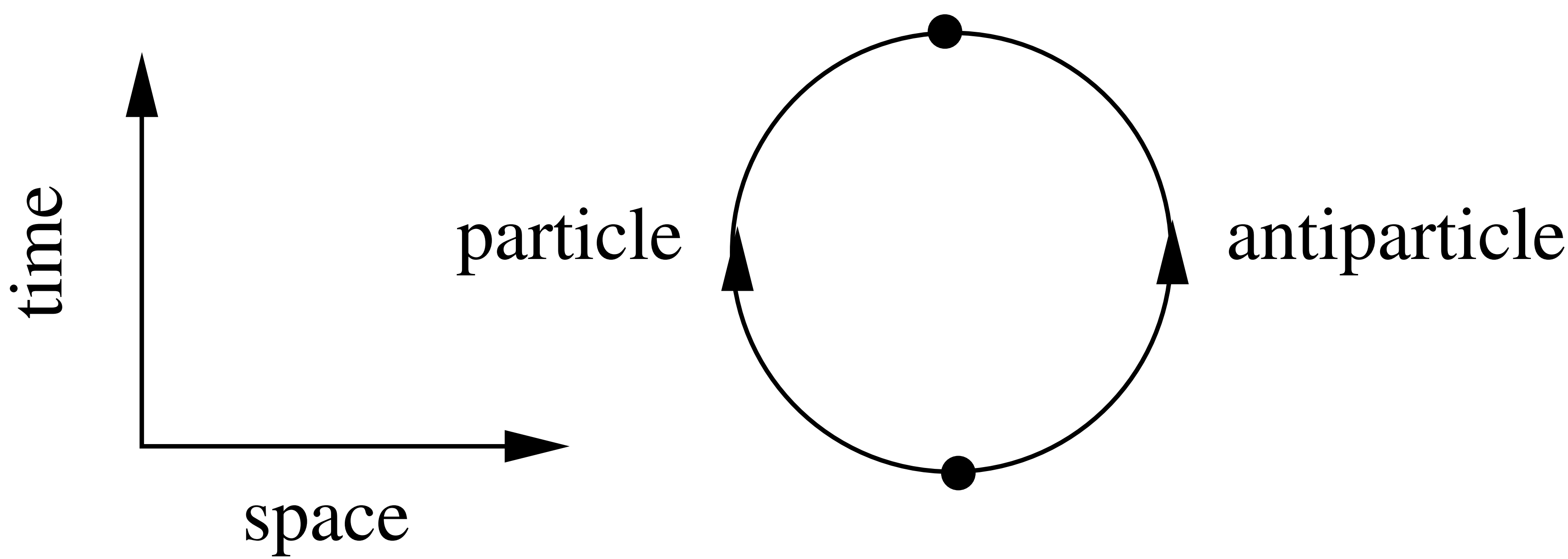
Astronomical observations indicate that the cosmological constant is many orders of magnitude smaller than estimated in modern theories of elementary particles. After a brief review of the history of this problem, five different approaches to its solution are described.

Reviews of Modern Physics, Vol. 61, No. 1, January 1989

`http://journals.aps.org/rmp/abstract/10.1103/RevModPhys.61.1`

The quantum vacuum

From the quantum mechanical viewpoint, the vacuum is not just empty space. It can be thought of as being filled with virtual particle/antiparticle pairs that appear and disappear at random.



Energy of the quantum vacuum

An estimate gives the vacuum energy density

$$\rho_\Lambda \sim \frac{M_p}{L_P^3} \sim 10^{100}\,\mathrm{g/m^3}$$

M_p is the "Planck mass" derived from Newton's gravitational constant, $M_p = 1/\sqrt{G} \cong 10^{-5}\,\mathrm{g}$

L_p is the "Planck length," also derived from Newton's constant, $L_p = \sqrt{G} \cong 10^{-35}\,\mathrm{m}$ (in particle physics units $\hbar = c = 1$).

The measured value is

$$\rho_\Lambda \sim 10^{-23}\,\mathrm{g/m^3}$$

Off by 123 orders of magnitude. The worst prediction in the history of science!

How to explain such a small Λ?

Before 1998, a popular idea was that for some as yet unknown reason, $\Lambda = 0$ exactly.

Zero sounds much simpler to explain than 10^{-123}, compared to the natural value.

For example it was known that particles with spin 1/2 (fermions) contribute negatively to Λ, while those with spin 0 or 1 (bosons) contribute positively.

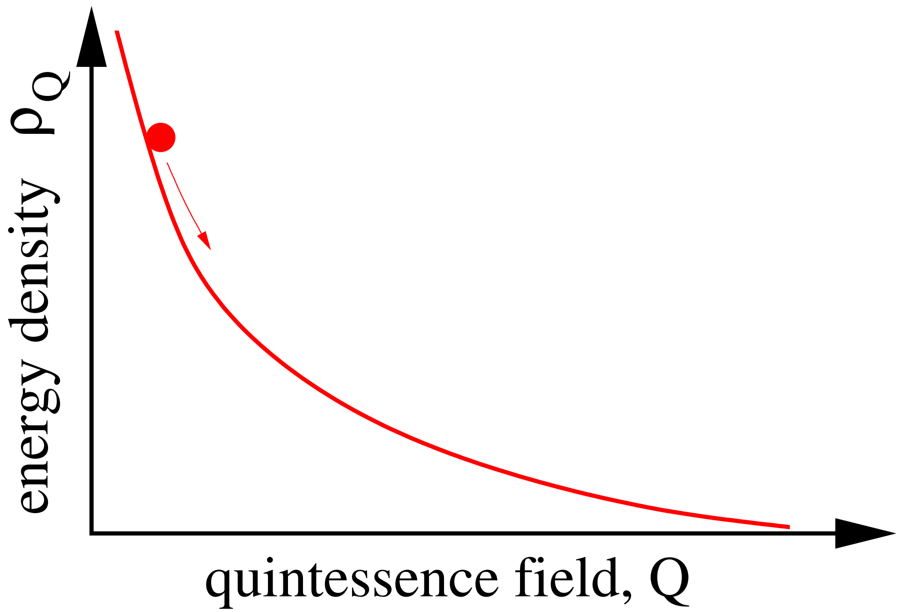
But the 1998 measurement of $\Lambda \neq 0$ disproved this elegant possibility.

Many theorists have tried, but no convincing mechanism to produce such a small value has been proposed.

(With perhaps one exception)

Perhaps dark energy is not constant?

Many theorists have studied models where dark energy is not constant but can vary with time: "quintessence"



ρ_Q can be pictured as the height of a ball rolling down a shallow hill.

These theories don't explain why the hill goes down to "sea level" instead of nonzero elevation — why is there no Λ in addition to ρ_Q?

Pressure is no longer simply $-\rho$, instead

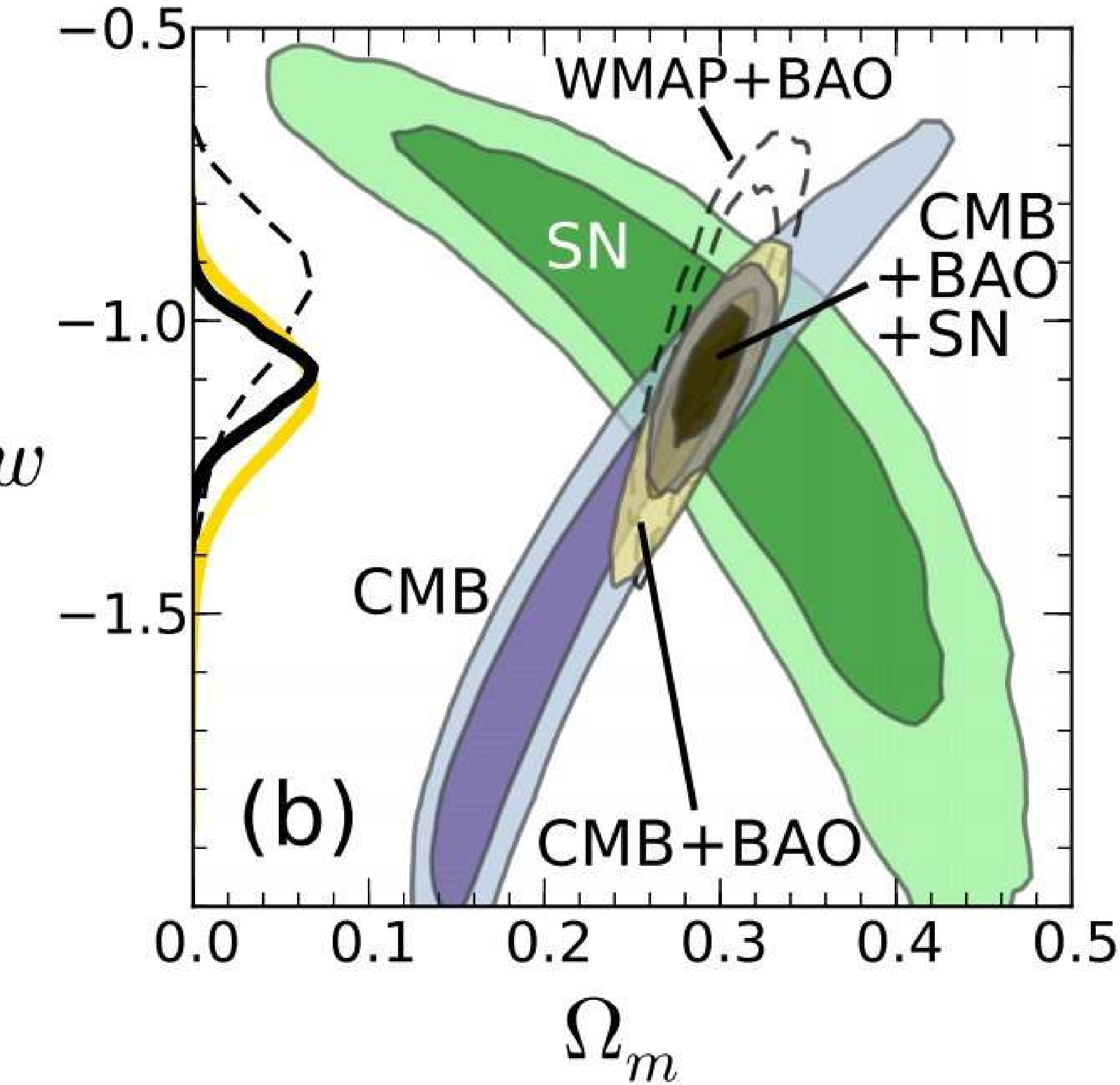
$$p_Q = w\rho_Q, \qquad -1 < w < -1/3$$

Acceleration is reduced, relative to constant Λ with $w = -1$.

w is called "equation of state" parameter

No evidence for time variation

Current observations constrain w only very weakly.



Current measurements indicate $w = -1.10 \pm 0.09$

Consistent with constant Λ, $w = -1$

$w < -1$ is theoretically disfavored ("phantom" dark energy)

Phantom dark energy is incompatible with quantum mechanics, but many theorists continue to consider it nonetheless

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-dark-energy.pdf

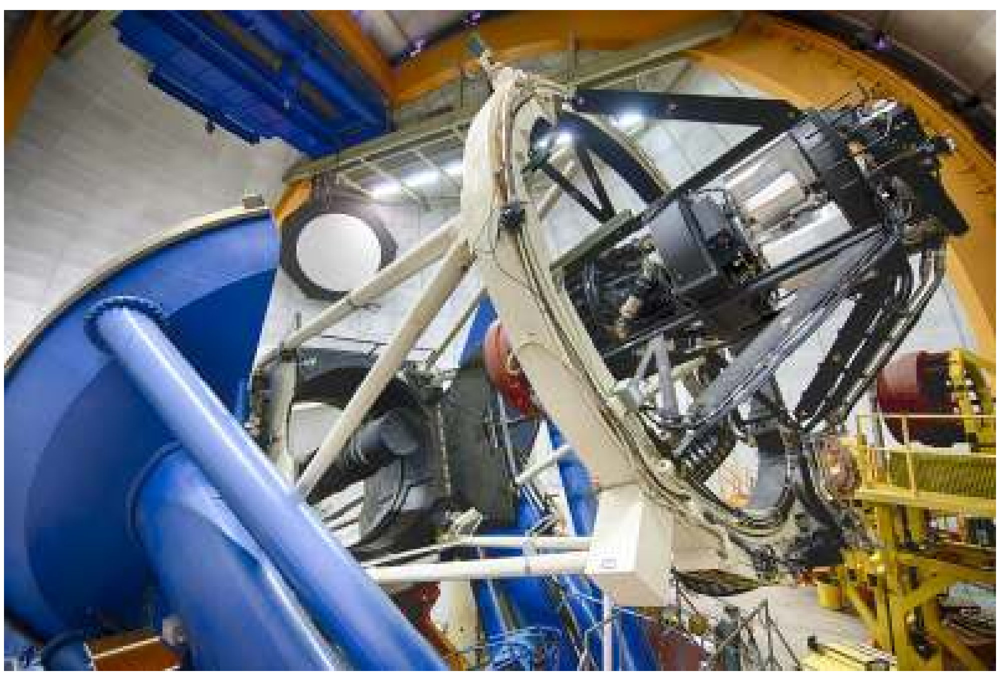
The Dark Energy Survey

International collaboration with telescope in Chile since 2013

Plans to discover 3000 distant supernovae and observe 300,000,000 galaxies

But will they significantly improve determination of w?

iopscience.iop.org/article/10.1088/1742-6596/259/1/012080/pdf



http://www.fnal.gov/pub/presspass/press_releases/2013/DES-2013-images.html

The Large Synoptic Survey Telescope

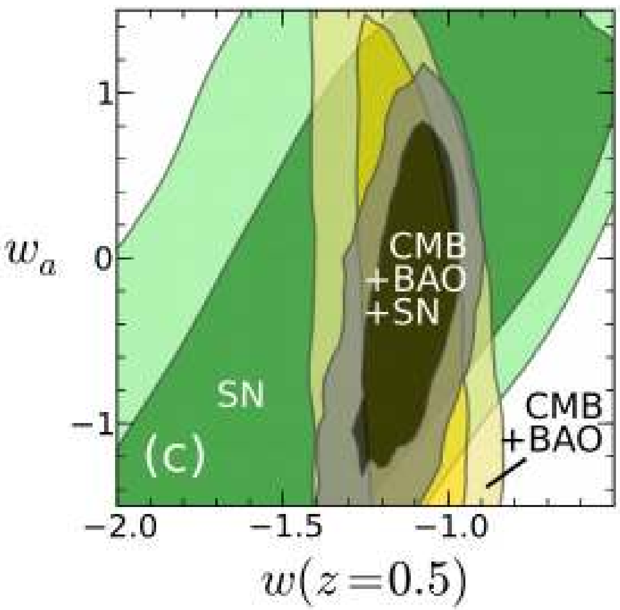
Another international collaboration, building telescope in Chile for 2019

Also observing billions of galaxies

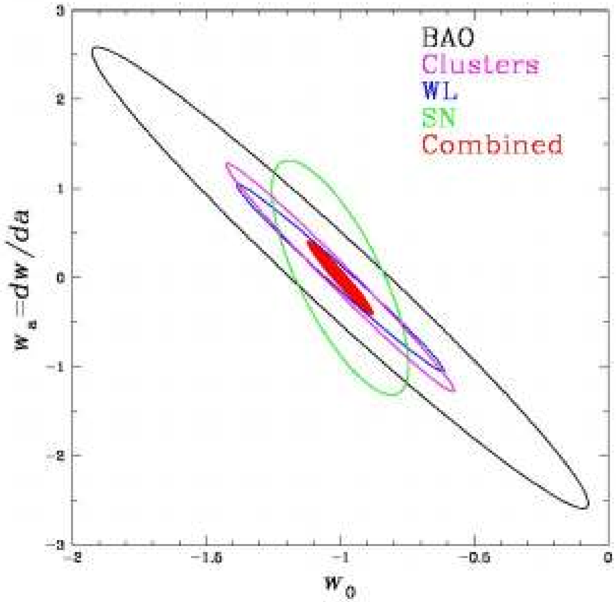
But will *they* significantly improve determination of w?

Present and forecasted constraints on w

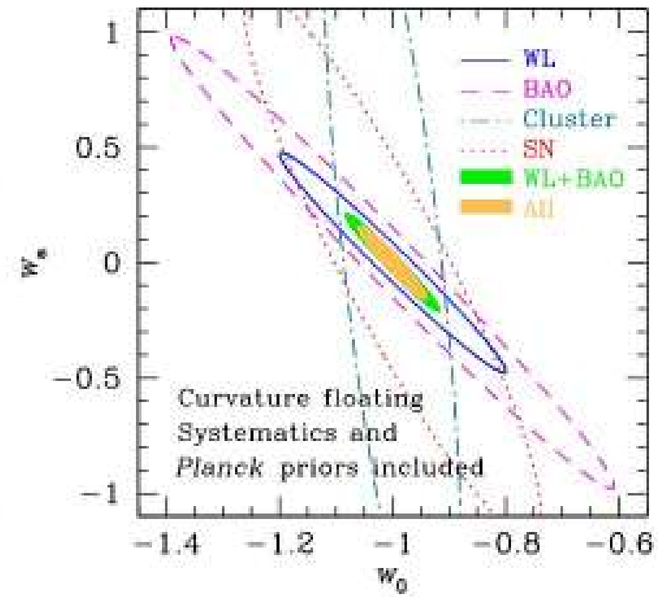
Showing w_a (rate of change of w) versus w:



current constraint



DES projected



LSST projected

Even after measuring 1000s of supernovae and billions of galaxies, w will not be determined to much better than 10%

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-dark-energy.pdf
http://iopscience.iop.org/article/10.1088/1742-6596/259/1/012080/pdf
http://arxiv.org/pdf/1211.0310v1.pdf

Modified gravity

Another popular approach is to modify Einstein's equations to get acceleration without Λ (in the hope that for some reason $\Lambda = 0$), or to explain why even very large Λ does not give acceleration.

$$
\begin{aligned}
S_{\rm pre} = & \frac{M_{\rm P}^2}{2}\int d^4x\sqrt{-g}\,\mathcal{R}[g_{\mu\nu}] \\
& + \frac{M_{\rm P}^2}{2} m^2 \int d^4x \left[\frac{c_0}{24}\epsilon_{\mathcal{ABCD}}\epsilon^{\alpha\beta\gamma\delta} E^{\mathcal{A}}{}_{\alpha} E^{\mathcal{B}}{}_{\beta} E^{\mathcal{C}}{}_{\gamma} E^{\mathcal{D}}{}_{\delta} \right. \\
& + \frac{c_1}{6}\epsilon_{\mathcal{ABCD}}\epsilon^{\alpha\beta\gamma\delta} E^{\mathcal{A}}{}_{\alpha} E^{\mathcal{B}}{}_{\beta} E^{\mathcal{C}}{}_{\gamma} e^{\mathcal{D}}{}_{\delta} \\
& + \frac{c_2}{4}\epsilon_{\mathcal{ABCD}}\epsilon^{\alpha\beta\gamma\delta} E^{\mathcal{A}}{}_{\alpha} E^{\mathcal{B}}{}_{\beta} e^{\mathcal{C}}{}_{\gamma} e^{\mathcal{D}}{}_{\delta} \\
& + \frac{c_3}{6}\epsilon_{\mathcal{ABCD}}\epsilon^{\alpha\beta\gamma\delta} E^{\mathcal{A}}{}_{\alpha} e^{\mathcal{B}}{}_{\beta} e^{\mathcal{C}}{}_{\gamma} e^{\mathcal{D}}{}_{\delta} \\
& \left. + \frac{c_4}{24}\epsilon_{\mathcal{ABCD}}\epsilon^{\alpha\beta\gamma\delta} e^{\mathcal{A}}{}_{\alpha} e^{\mathcal{B}}{}_{\beta} e^{\mathcal{C}}{}_{\gamma} e^{\mathcal{D}}{}_{\delta} \right]
\end{aligned}
$$

Einstein gravity

modified gravity

These theories tend to be very complicated, and to create more problems than they solve (*e.g.*, making wrong predictions for properties of gravity as measured in the solar system).

The cosmological constant is by far the simplest explanation of cosmic acceleration.

But why is it so small?

The anthropic explanation

In 1987, S. Weinberg noted that if Λ was too large, we could not be here to measure it. The universe would expand too fast for galaxies and stars to form if $\rho_\Lambda > 500\,\rho_m$.

http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.59.2607

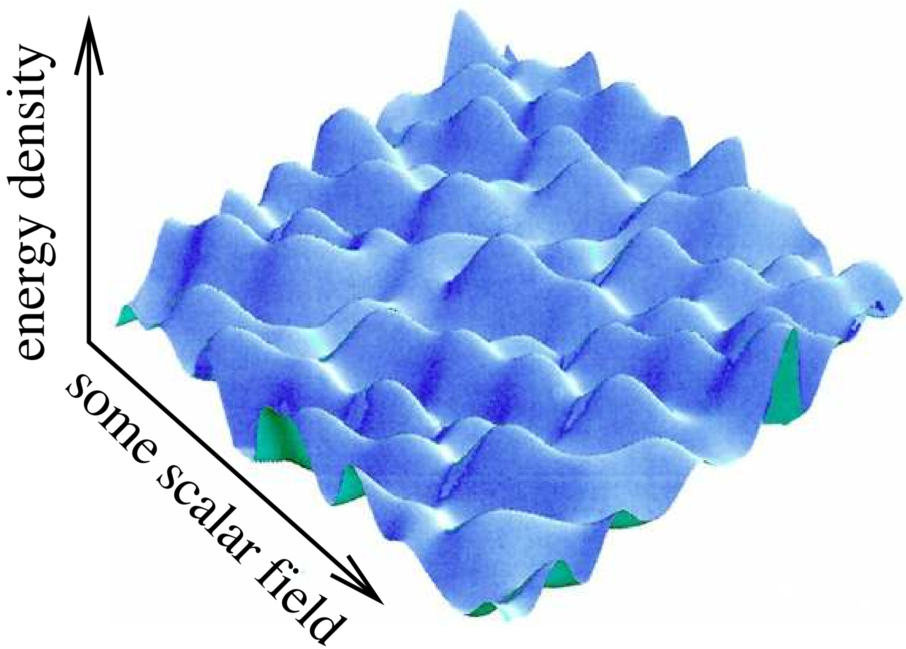
Suppose there were many universes with different values of Λ; then we would only consider those that are compatible with life. (String theory and cosmic inflation provide such a framework.)

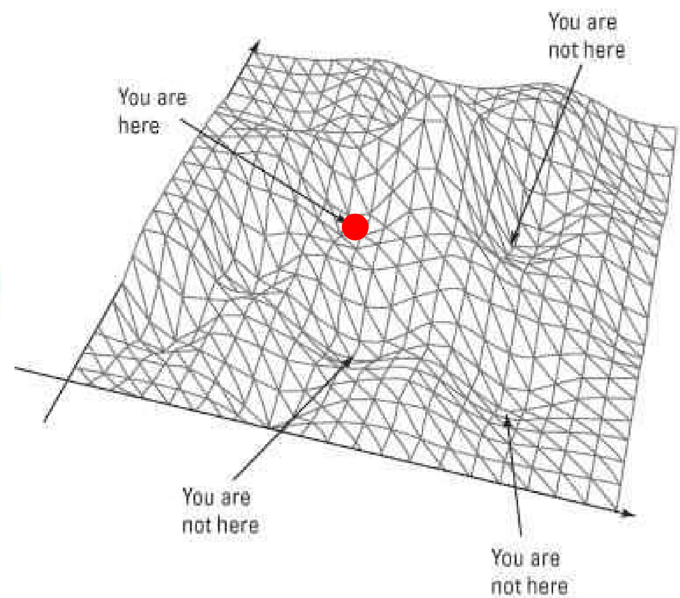
This vastly reduces the severity of the cosmological constant problem. Now the observed ρ_Λ is only ~ 100 times smaller than its maximum expected value, rather than 10^{120}. Events with probability $1/100$ happen to us all the time.

Many scientists view this as just giving up on a real explanation. My personal view is that it is the most likely explanation that has been proposed so far.

The multiverse

A candidate theory for unifying gravity with the other forces of nature, string theory, is thought to predict a huge range of possible values for the dark energy, depending on where we happen to settle in the energy landscape.



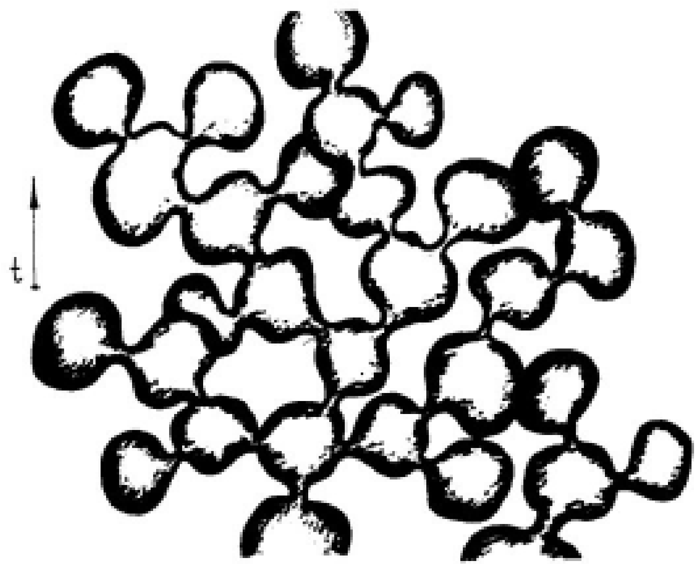


Different regions in the universe settle into separate minima with different values of Λ. In this context, anthropic principle makes sense.

http://what-when-how.com/string-theory/understanding-the-current-landscape-a-multitude-of-theorie
https://community.emc.com/people/ble/blog/2011/10/13/landscape-multiverse

Eternal inflation

While the scalar field rolls down the hill, it has a large vacuum energy and gives accelerated expansion in the early universe. This framework of cosmological "inflation" at the time of the big bang has wide theoretical and experimental validation.



Many theorists believe that inflation continues forever in distant parts of the universe, continually spawning new subuniverses falling into different minima of the landscape.

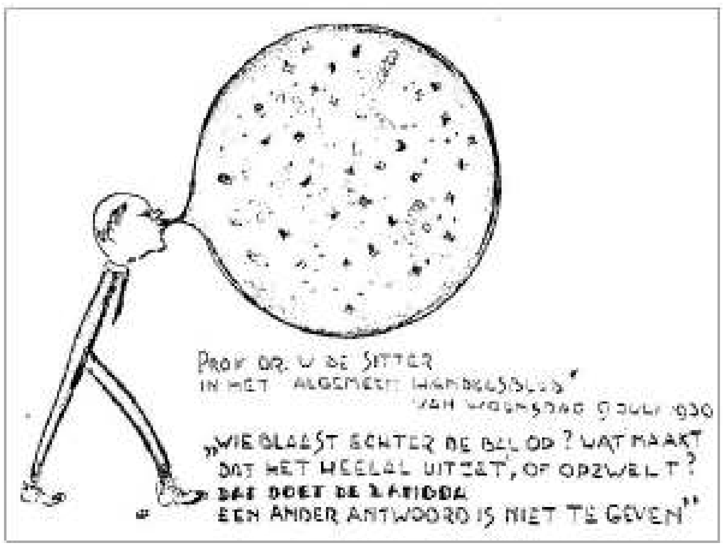
This gives a mechanism for populating the different minima.

A.D. Linde, `http://iopscience.iop.org/article/10.1088/0031-8949/1987/T15/024/pdf`

Is dark energy mysterious?

Many scientists preface talks about dark energy by saying “it is a complete mystery, . . . we have no idea what it is.”

I have argued that we have a very good idea: it is vacuum energy from quantum fluctuations, giving rise to Einstein’s cosmological constant Λ. (Understanding its size is another matter.)



http://arxiv.org/abs/1111.4623

de Sitter seems to have anticipated this discussion in a popular article (1930):

“What, however, blows up the ball? What makes the universe expand or swell up? That is done by Λ. No other answer can be given. . . . To some it may sound unsatisfactory that we are not able to point out the mechanism by which Λ contrives to do it. But there it is, we cannot go beyond the mathematical equations and . . . the behavior of Λ is not more strange or mysterious than that of the gravitational constant κ, to say nothing of the quantum constant h, or the velocity of light c.”

Conclusions

The concept of dark energy continues to intrigue and confound many physicists.

Einstein invented it but could never accept it, and some today still can't.

Why it is so small compared to theoretical expectations persists as an outstanding problem.

Big experimental resources are aimed at measuring its properties better, but they may only prove with slightly better accuracy that it is constant Λ rather than something more exotic.

Mila (commercial break)

My friend Mila is looking for a home

She is a wonderful cat who would make a very nice and affectionate companion.

I wish I could take her myself but I already have two and it's a long trip to Montreal.

http://www.dyrevaernet.dk/dyr.aspx?id=54db411d-fce4-48ea-a45f-297d989786a3