A taste of cosmology

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Lecture 3

Cosmic Acceleration and outlook for the Future

Successes of the Big Bang model

GR+cosmological principle

Hubble’s law
CMB
Abundance of light elements

.. And problems

Flatness problem
Horizon problem
Monopole problem

Origin of perturbations

The flatness problem

$$1 - \Omega = -\frac{c^2 k}{R_0^2 a^2 H^2}$$

Remember Friedmann equations?

today $\quad |1 - \Omega_0| < 0.01$

$$1 - \Omega_0 = -\frac{kc^2}{R_0^2 H_0^2} \quad 1 - \Omega = -\frac{kc^2}{R_0^2 a(t)^2 H(t)^2} = 1 - \Omega(t) = \frac{H_o^2(1 - \Omega_0)}{H^2(t) a^2(t)}$$

For most of the life of the universe: matter+radiation only

$$\frac{H^2}{H_0^2} = \frac{\Omega_{r,0}}{a^4} + \frac{\Omega_{m,0}}{a^3} \longrightarrow 1 - \Omega(t) = \frac{(1 - \Omega_0) a^2}{\Omega_{r,0} + \Omega_{m,0} a}$$

Matter domination $\quad a \sim t^{2/3} \quad 1 - \Omega(t) = \frac{1 - \Omega_0}{\Omega_{m,0}} \left(\frac{t}{t_0}\right)^{2/3}$

Universe was flatter in the past!

Exercise: $\quad @t_{eq}? \quad z_{m,r\,eq} \sim 3000?$

Radiation dominated $\quad 1 - \Omega(t) \sim a^2 \sim t \quad 1 - \Omega(t) = (1 - \Omega(t_{eq})) \frac{t}{t_{eq}}$

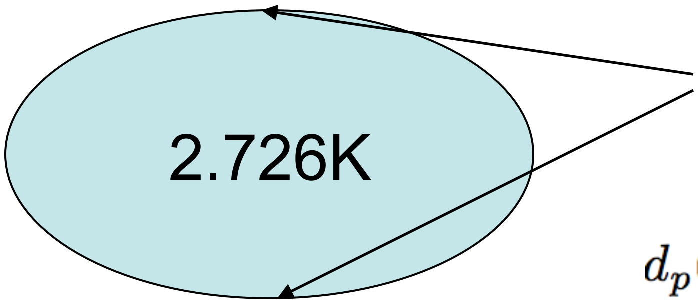
Exercise: $\quad @t = 1s?$

Very quickly you find that early on $|1-\Omega|<10^{-60}$

It is like balancing a pencil on its tip, coming back years later and still fining it balancing on its tip

The Horizon problem

The universe is homogeneous and isotropic on large scales



Consider 2 antipodal points they are separated by $2d_H$~30000 Mpc

$$d_p(t_0) = c\int_{t_{cmb}}^{t_0} \frac{dt}{a(t)} \sim d_H(t_0);\;\; t_{cmb} << t_0$$

What was the Hubble radius (horizon) back then?

$$H(z)^2 \sim H_0^2 \Omega_{m,0}(1+z)^3 \longrightarrow \frac{c}{H_{z=1000}} \simeq 0.2Mpc$$

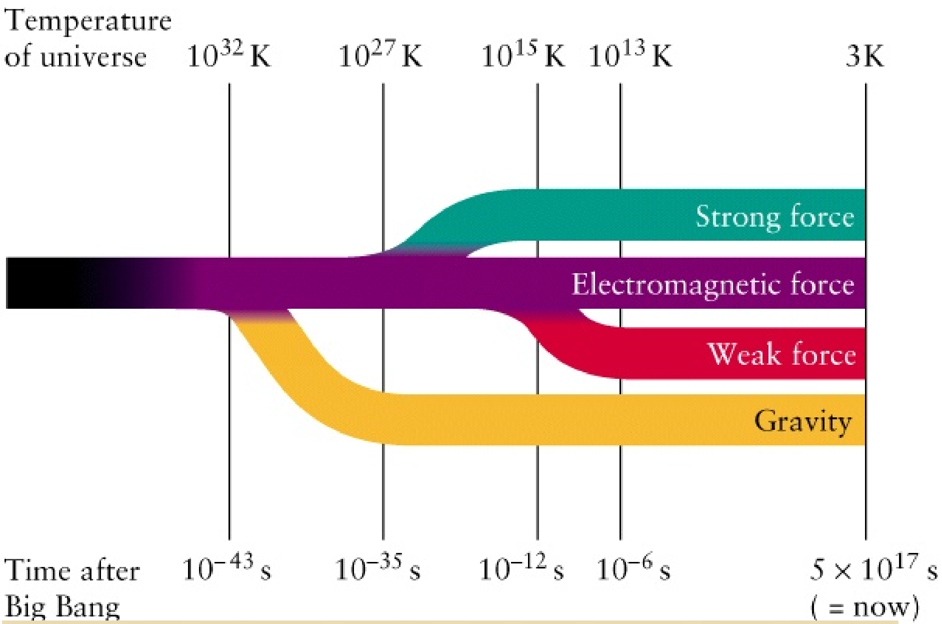
Only points at ~0.2 Mpc could have “talked”

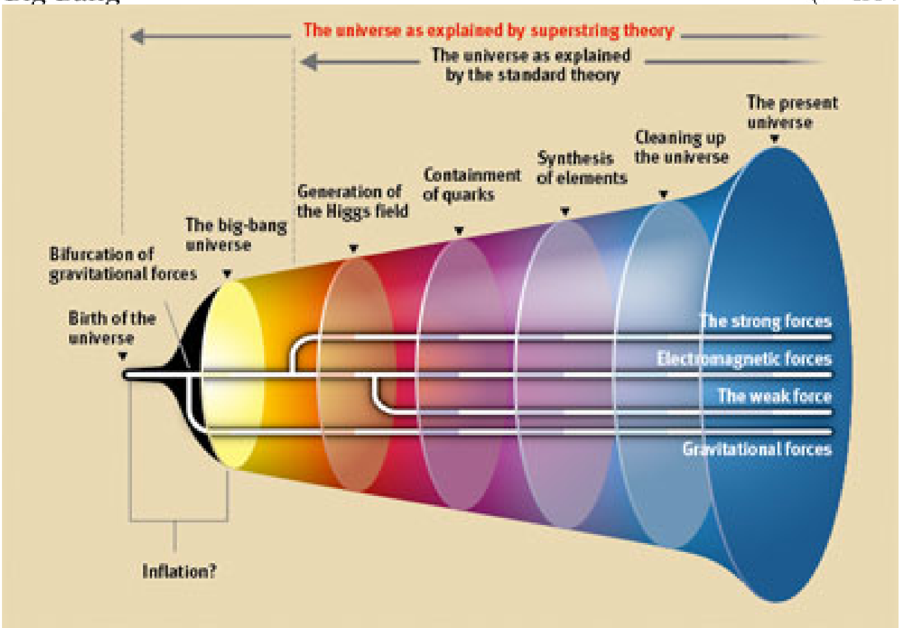
The last scattering surface can be divided in 40000 patches of degree size I.e. 40000 “horizons”….

How could they all be at 2.726K?

Imagine 40000 students taking an exam, and all returning THE SAME exam down to the commas…

The monopole problem





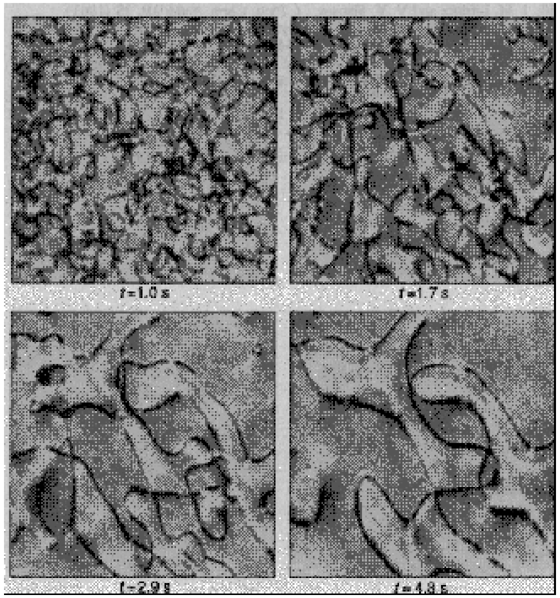
Phase transitions (water freezing, Magnetization…)

Defects….

Domain walls

Cosmic strings

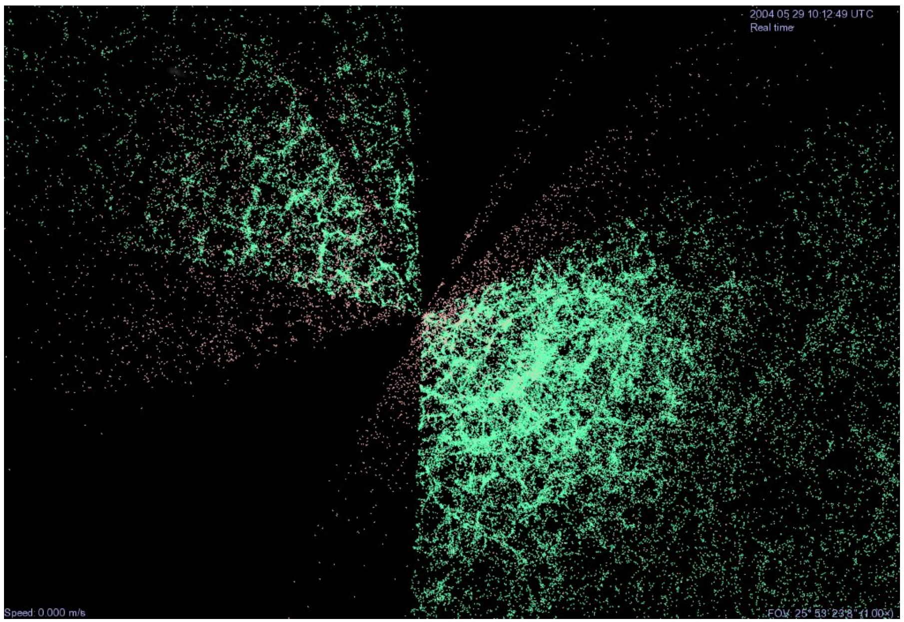
monopoles

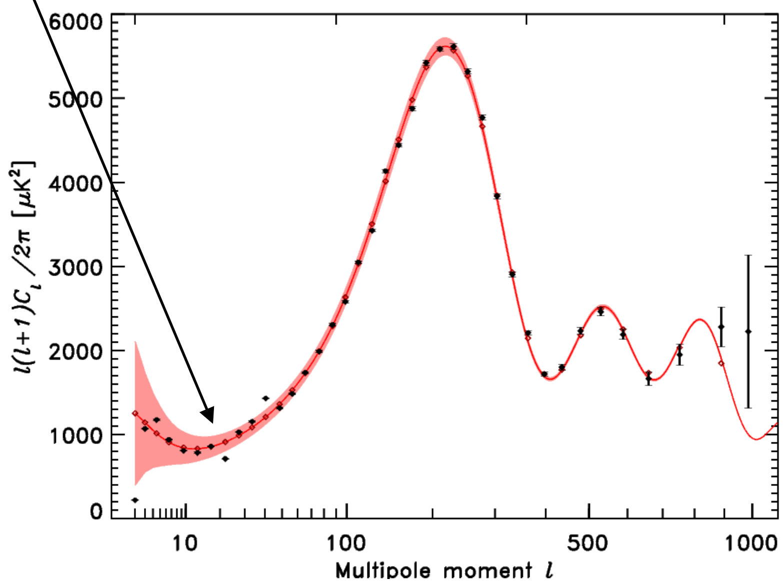


Example from a nematic liquid crystal

The most dangerous ones are the monopoles…
The fact that we are here means that at max there is one monopole in the entire observable universe….

And where the heck these perturbations come from?



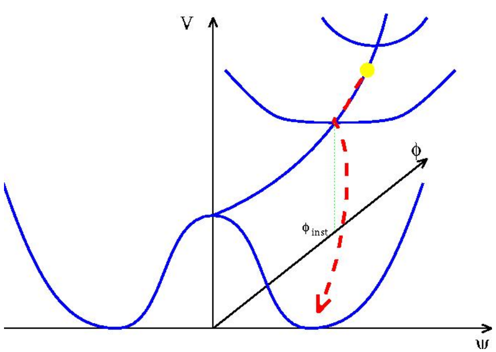


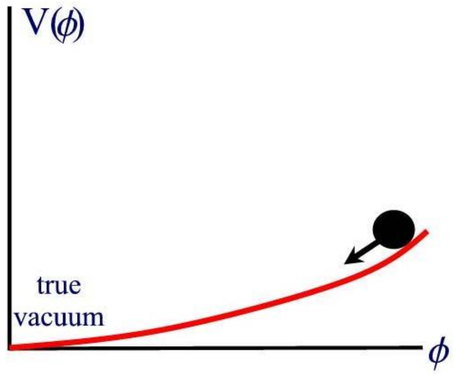
INFLATION To the rescue

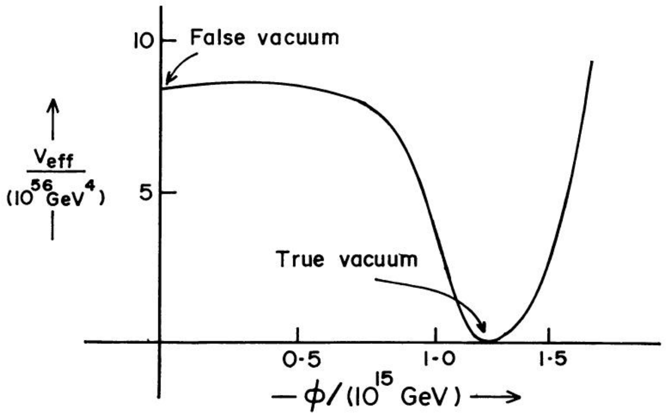
Started in the 1980 with A. Guth, active research area.
Still a “paradigm” not a proven fact…

Postulate a period of accelerated expansion
at the very beginning!
Something like a cosmological constant

Different scenarios, particle-physics motivated (?)







Why is the Universe so BIG?

Inflation to the rescue: an accelerated expansion

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3} \longrightarrow a \propto e^{H_\Lambda t}$$

t_i Inflation begins

t_f Inflation ends

$$a(t) = \begin{cases} a_i \left(\frac{t}{t_i}\right)^{1/2} & t < t_i \\ a_i e^{H_i(t-t_i)} & t_i < t < t_f \\ a_i e^{H_i(t_f - t_i)} \left(\frac{t}{t_f}\right)^{1/2} & t > t_f \end{cases}$$

$$\frac{a(t_f)}{a(t_i)} = e^N \quad N = H_i(t_f - t_i) \quad \text{number of e-foldings}$$

Example: $t_i = T_{GUT} = 10^{-36} s \quad H_i \sim t_{GUT}^{-1} \sim 10^{36} s^{-1}$ $\quad N \sim 100$

Even if inflation lasts for $\Delta t \sim 10^{-34} s$

$$\frac{a(t_f)}{a(t_i)} \simeq 10^{43}$$

NOT BAD!

Any weirdness like monopole

Would be diluted away!

Inflation solves the Flatness problem

Something like a Λ

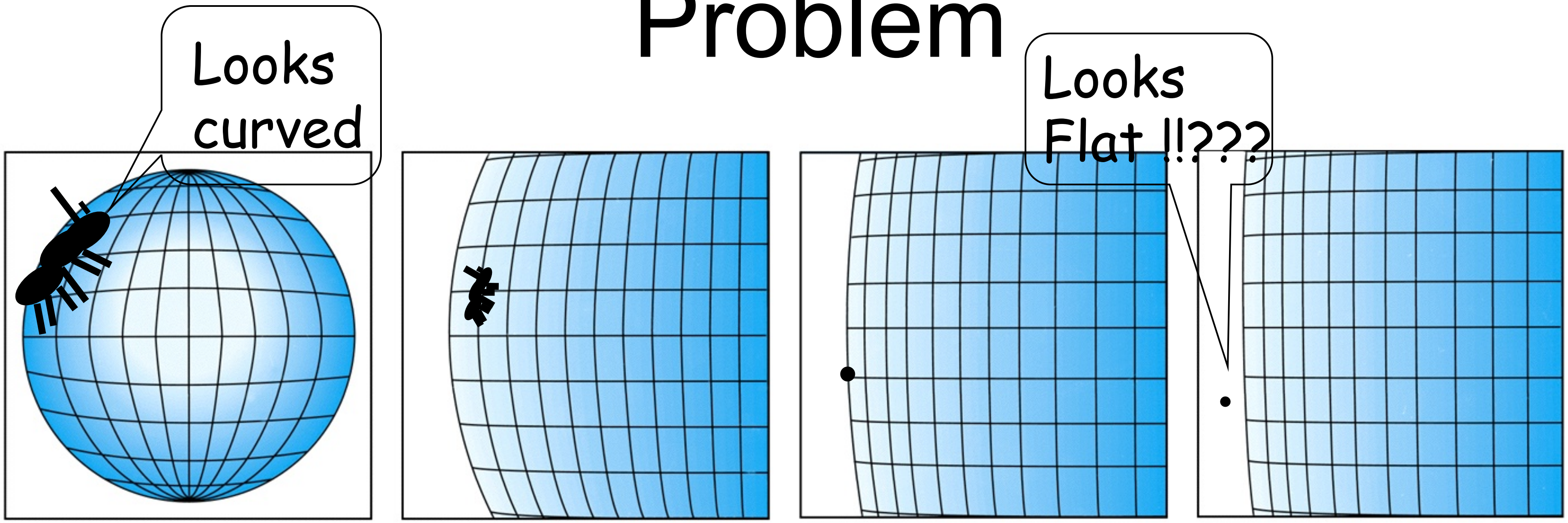
$$H = const\,; \quad a \sim \exp(H_I t)$$

$$1 - \Omega(t) = \frac{c^2}{R_0^2 a^2 H^2}$$

$$|1 - \Omega(t_f)| = \exp(-2N)|1 - \Omega(t_i)|$$

For N~100 NOT BAD!

Inflation Solves the Flatness Problem



What made the Universe so flat?

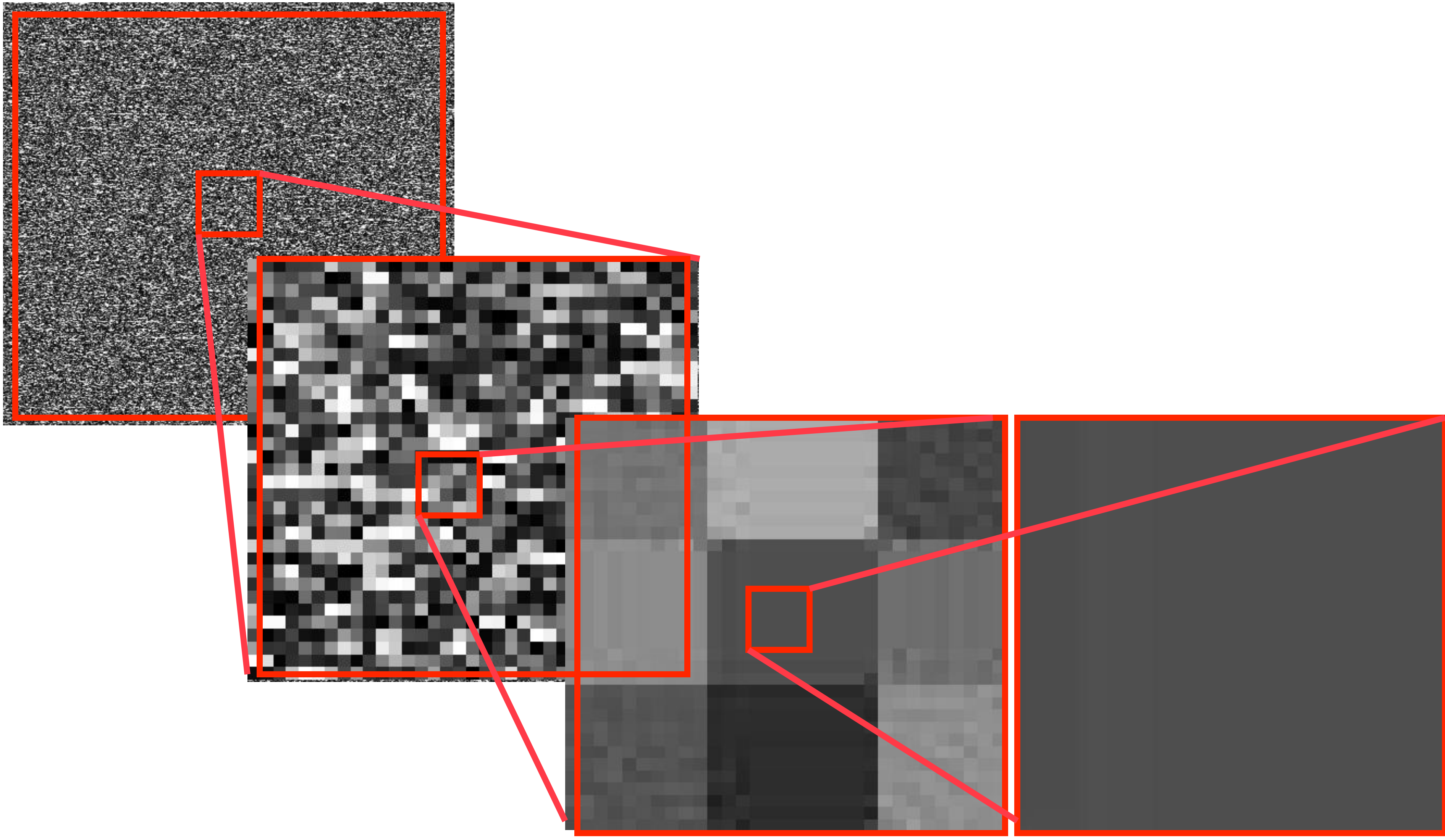
What made the Universe so big?

What made the universe so uniform?

What seeded the galaxies?

Why is the Universe so uniform?

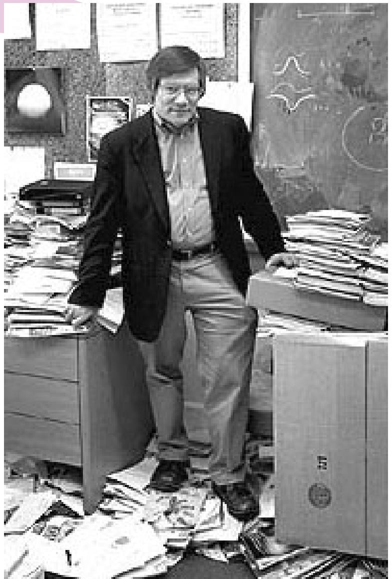
Inflation solves that

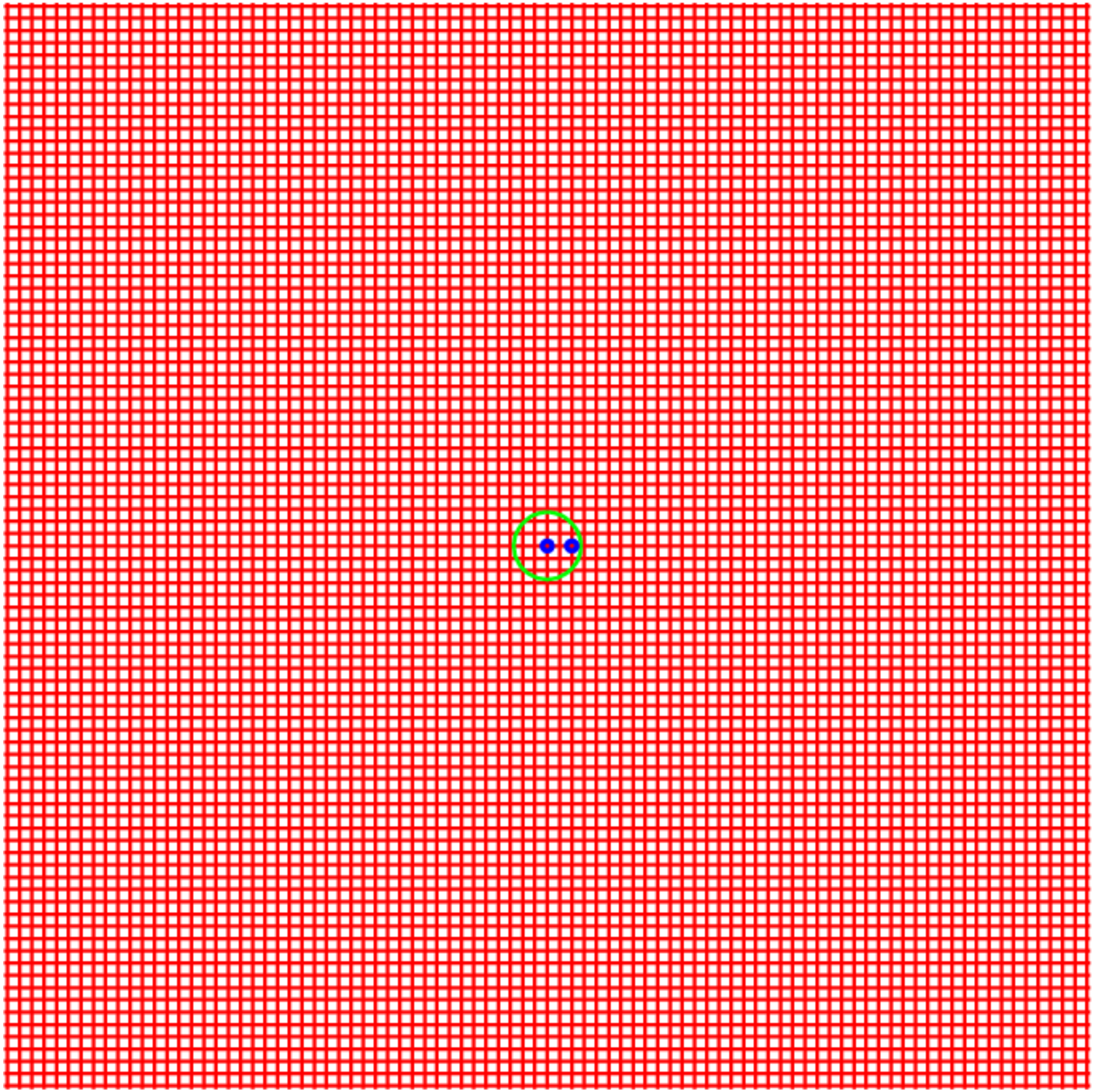


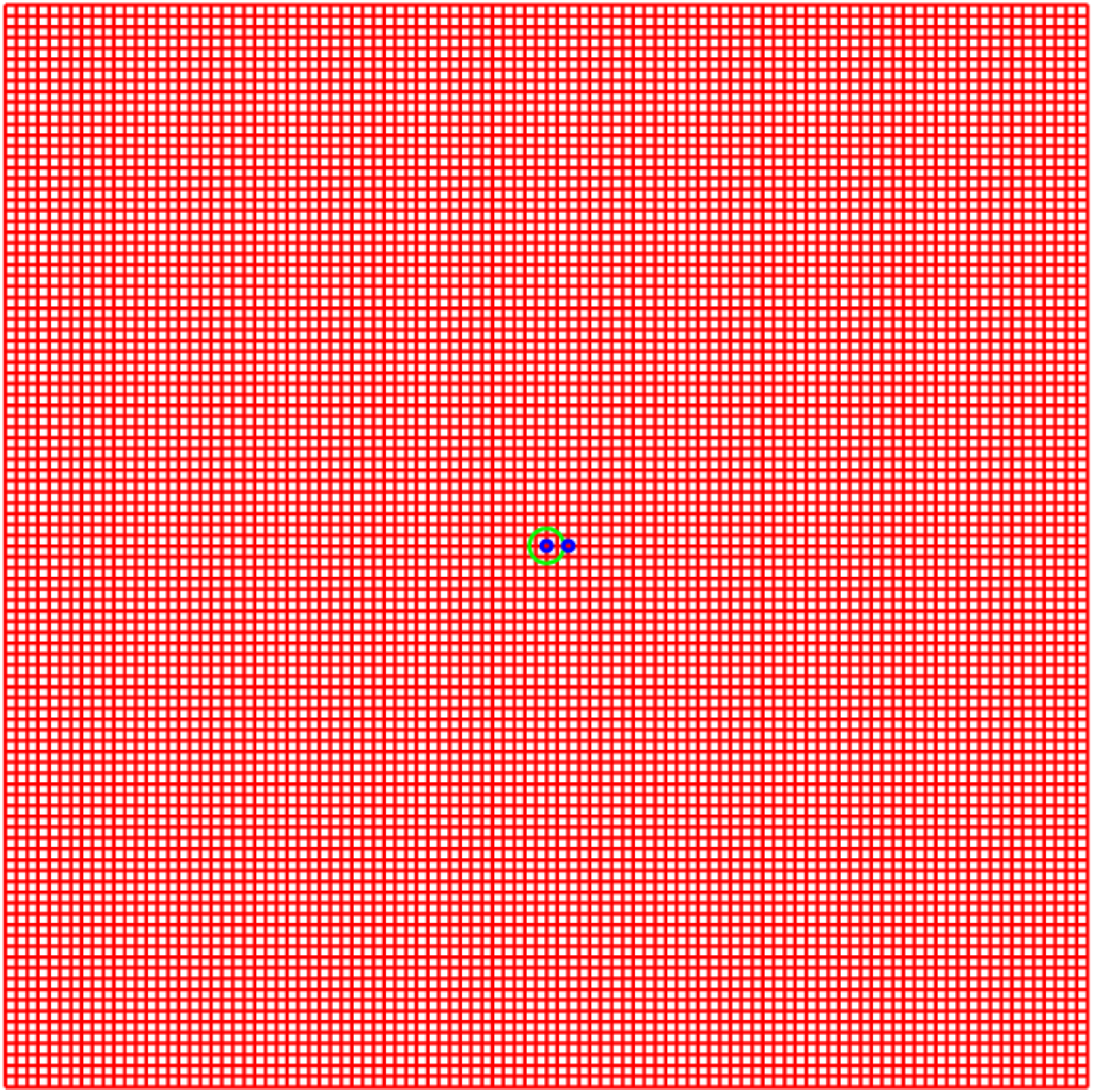
Inflation solves the Horizon problem

In an accelerated expansion the particle horizon and the Hubble horizon can be VERY DIFFERENT

Given the same dt, dp can be very different if a(t) is weird!







As an added bonus:

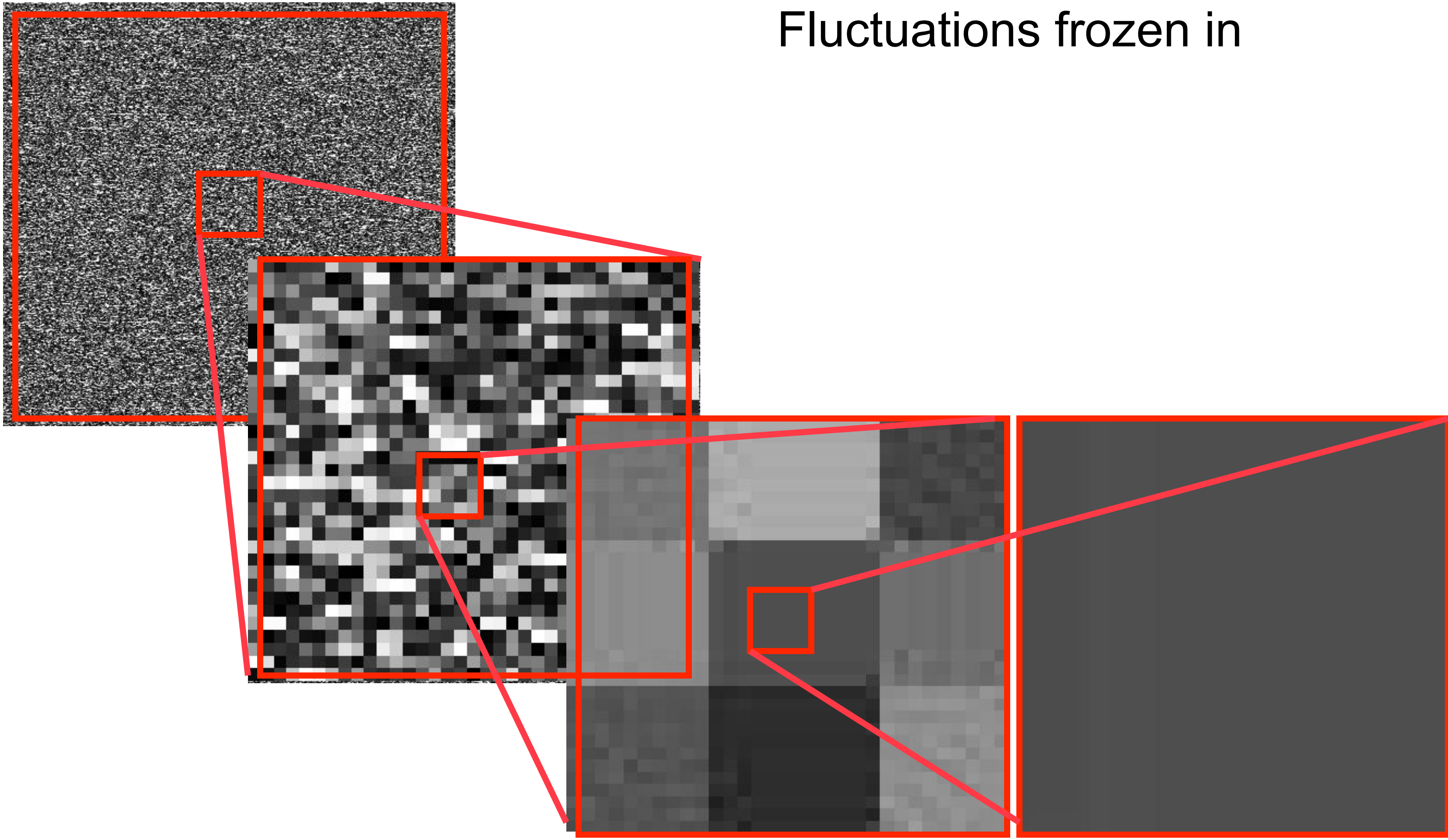
Inflation generates Gaussian perturbations:
quantum fluctuations stretched to become classical
by the expansion. The mechanism is similar to Hawkings
radiation. (The event horizon being the complementary
concept to the particle horizon…)

Turns out that the power spectrum of these perturbations will be
a power law: different model of inflation predict slightly different
power laws, but all close to "scale invariant"..

Perturbations outside the Horizon?

Inflation solves that

Fluctuations frozen in



CAN THIS BE TESTED?

flatness 

Power law primordial power spectrum 

Can even hope to distinguish specific models

Super horizon fluctuations (polarization) 

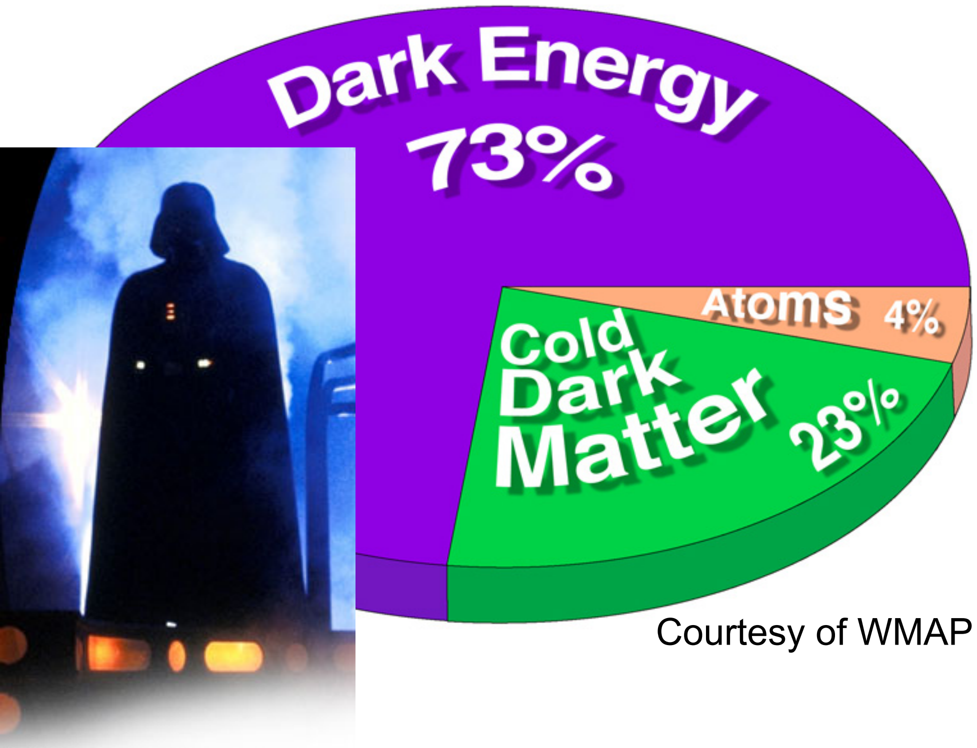
gaussianity 

Can even hope to distinguish specific models

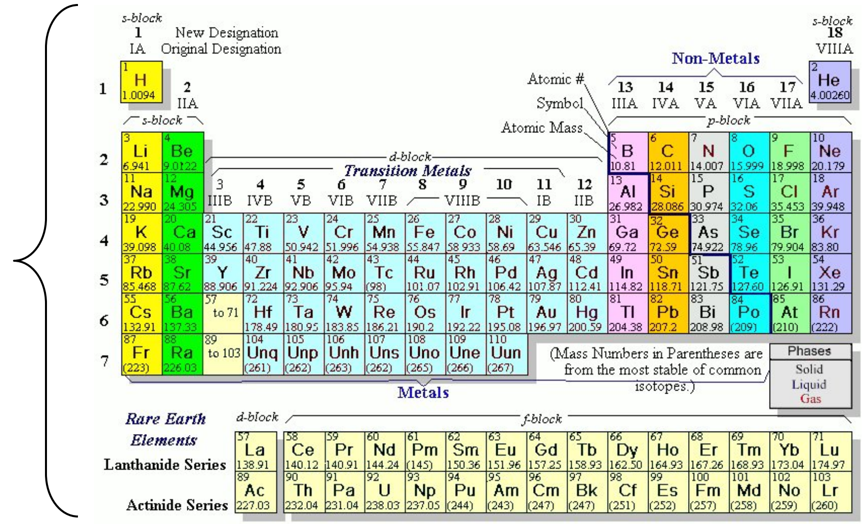
Stochastic background of gravity waves

(polarization)

We (and all of chemistry) are a small minority in the Universe.



Courtesy of WMAP team



In brief

Last Judgment, Vasari, Florence Duomo

Einstein's Greatest Blunder

1909: Einstein's general theory of relativity *predicts the expansion of the universe!*

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

Courtesy of W.Kinney

Einstein's Greatest Blunder

1909: Einstein's general theory of relativity
predicts the expansion of the universe!

$$G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda\delta_{\mu\nu}$$

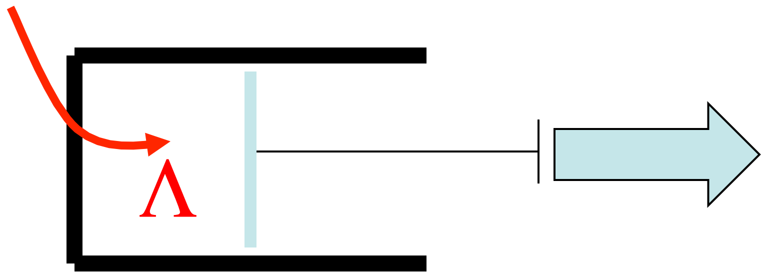
Einstein introduced a fudge factor to make the universe static: the *cosmological constant,*
Λ = the energy of empty space.

Courtesy of W.Kinney

Vacuum energy Λ

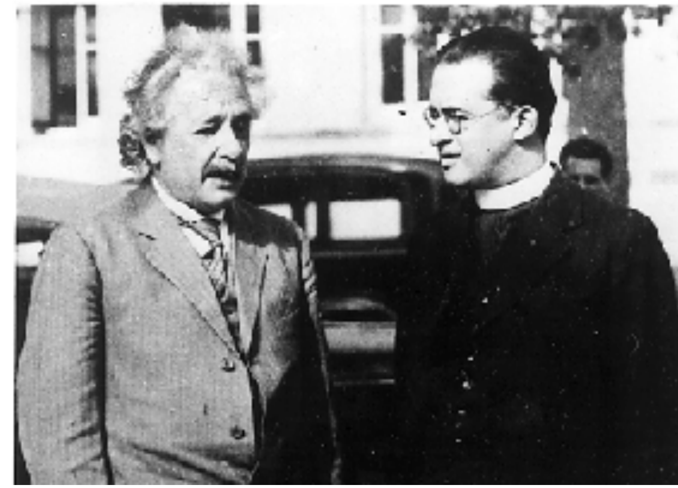
(also known as dark energy or cosmological constant)

vacuum

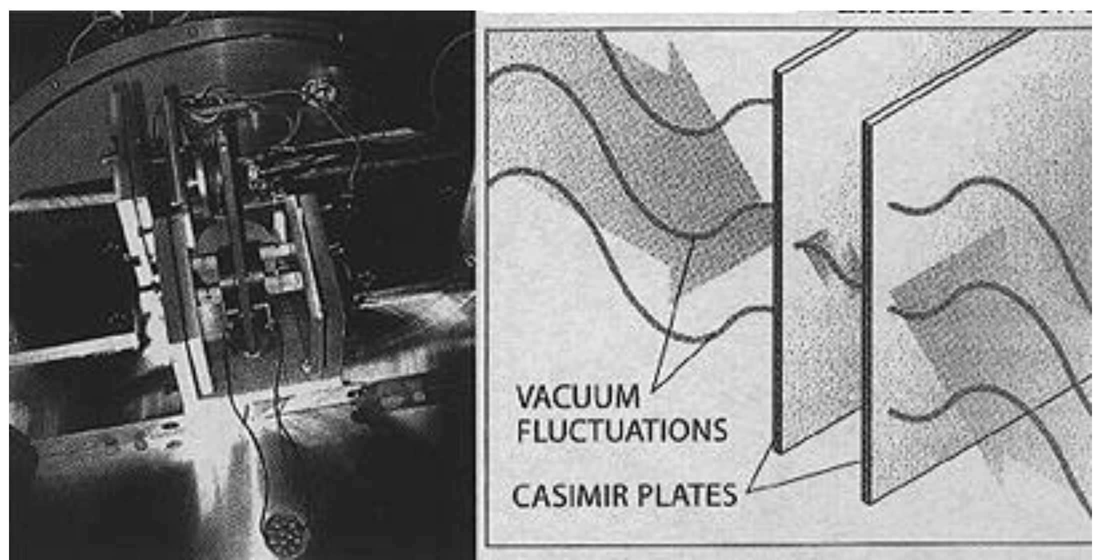


V_1

1917

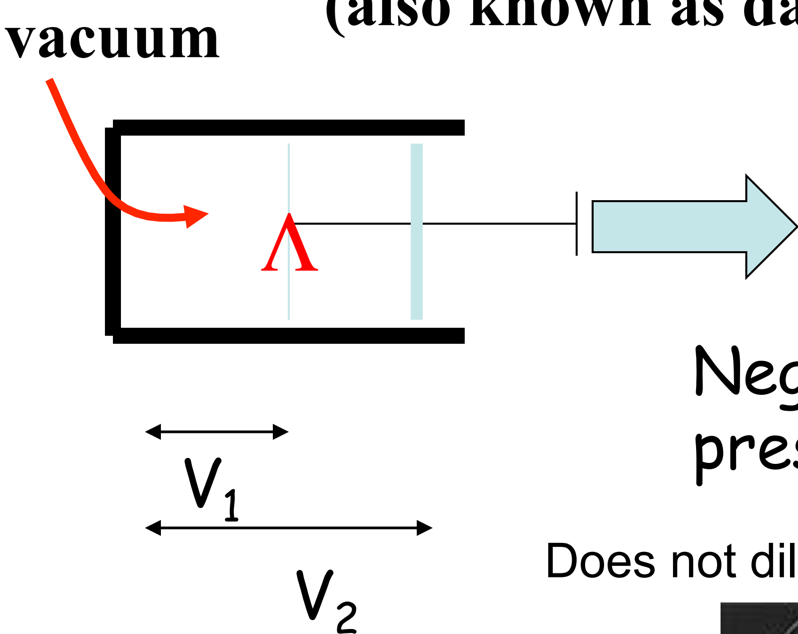


$E_1 = \rho_V V_1$



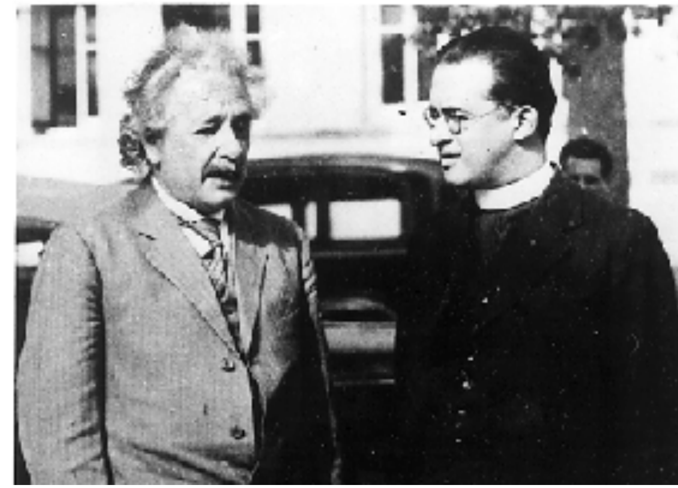
Vacuum energy Λ

(also known as dark energy or cosmological constant)



Negative pressure!

1917

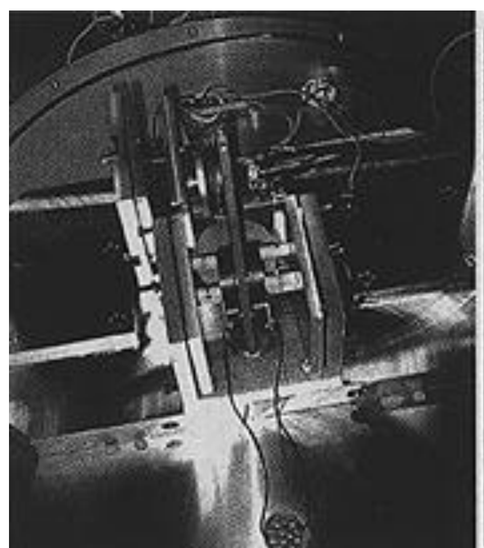


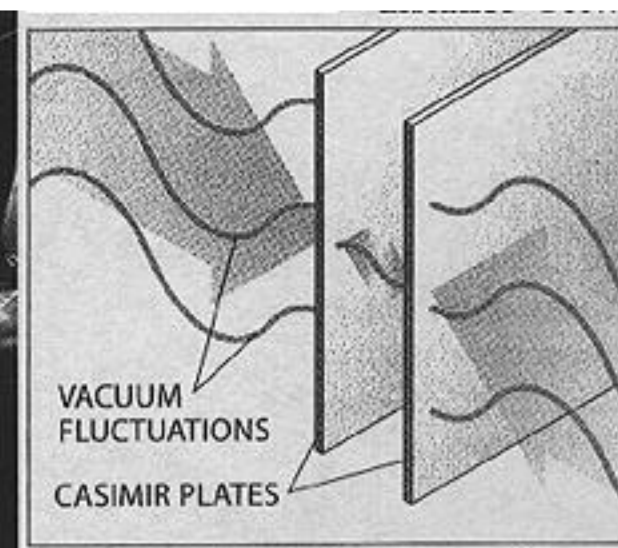
Does not dilute!

$E_1 = \rho_V V_1$

$E_2 = \rho_V V_2$

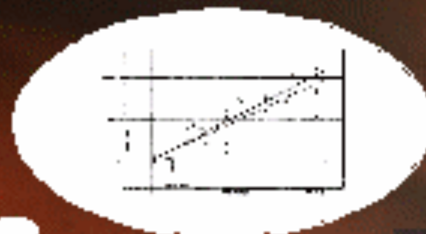
$E_2 > E_1$

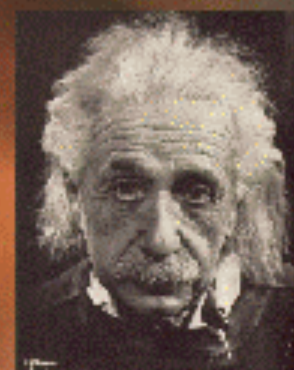




Einstein's Greatest Blunder

1929: Hubble discovers the cosmological expansion.





Courtesy of W. Kinney

It's the amount of "stuff" in the Universe that determine its geometry

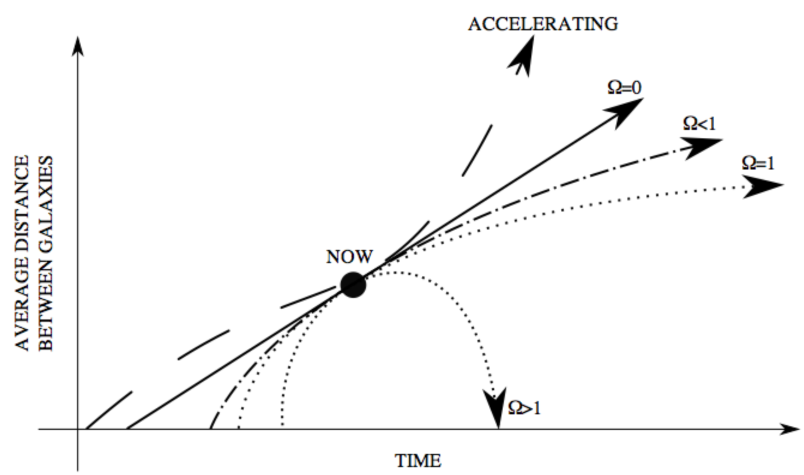
The galaxy distribution
and gravitational lensing
and galaxy rotation curves (see Vera Rubin's approach)
and galaxy clusters (remember Zwiky)
tell us…

that there is not enough matter to make the Universe flat

$$\Omega_m << 1$$

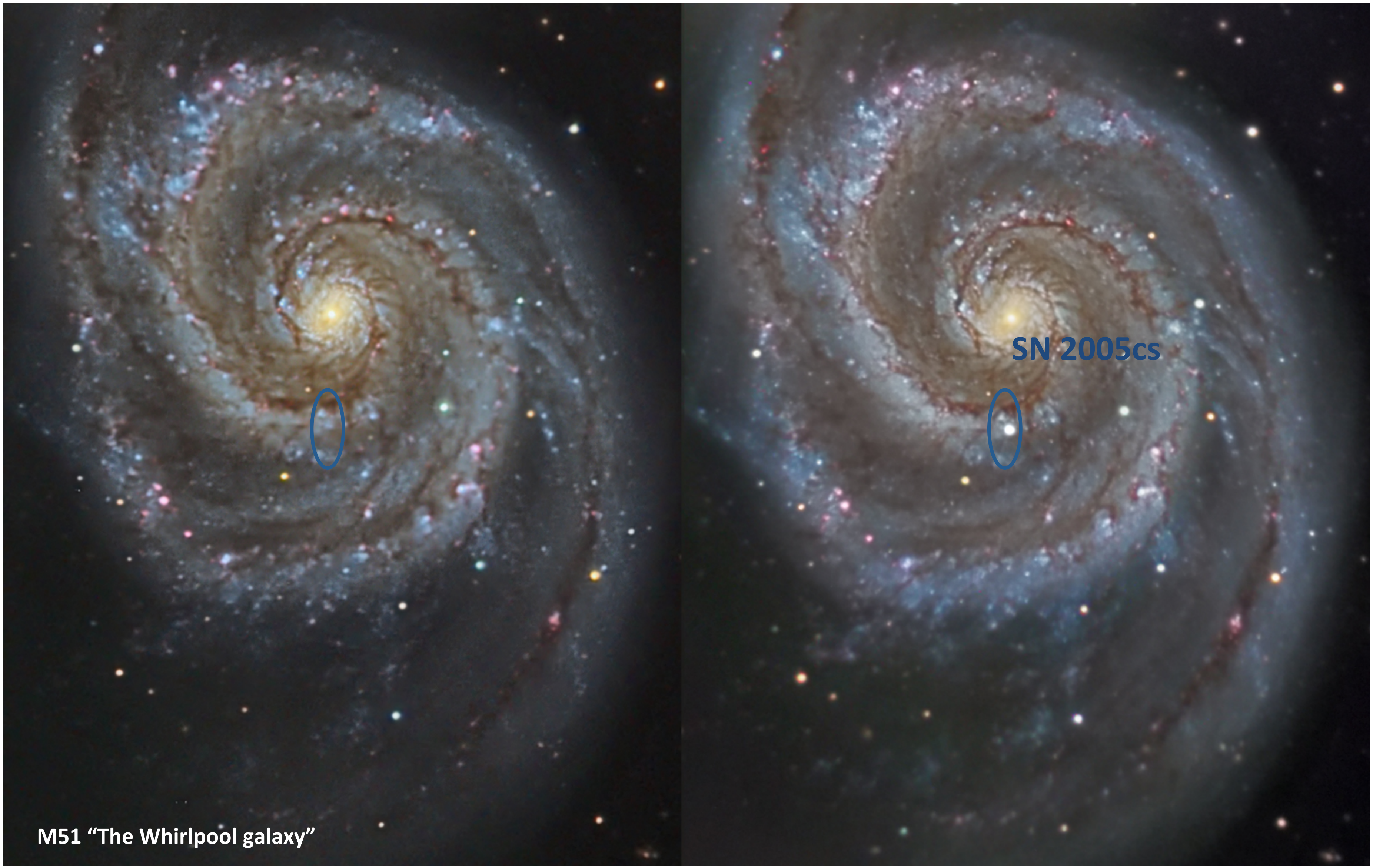
What?

The nagging problem of the age of the universe…



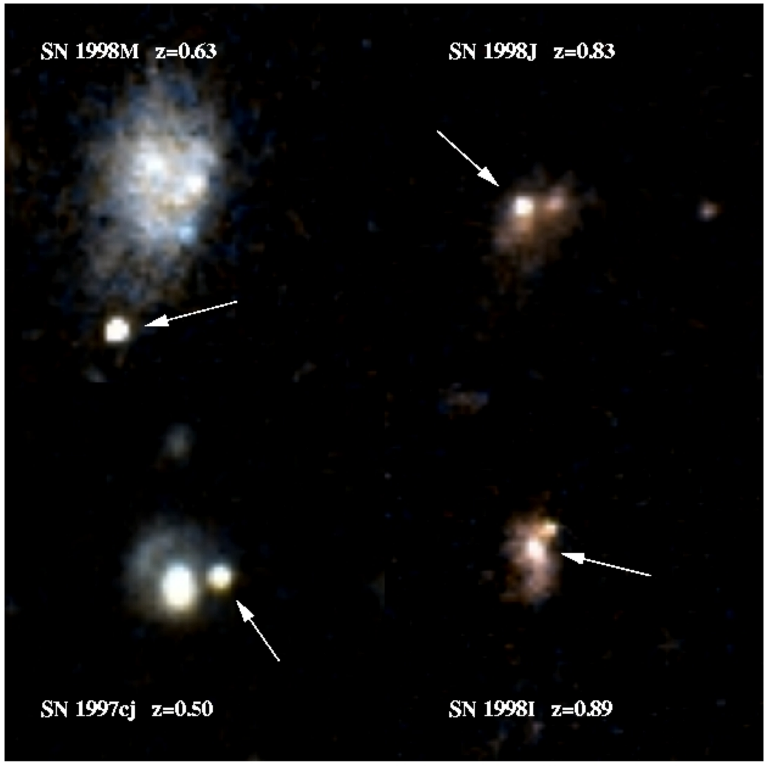
Just give me a standard candle....

Do you have a sharp eye for Supernova explosions?



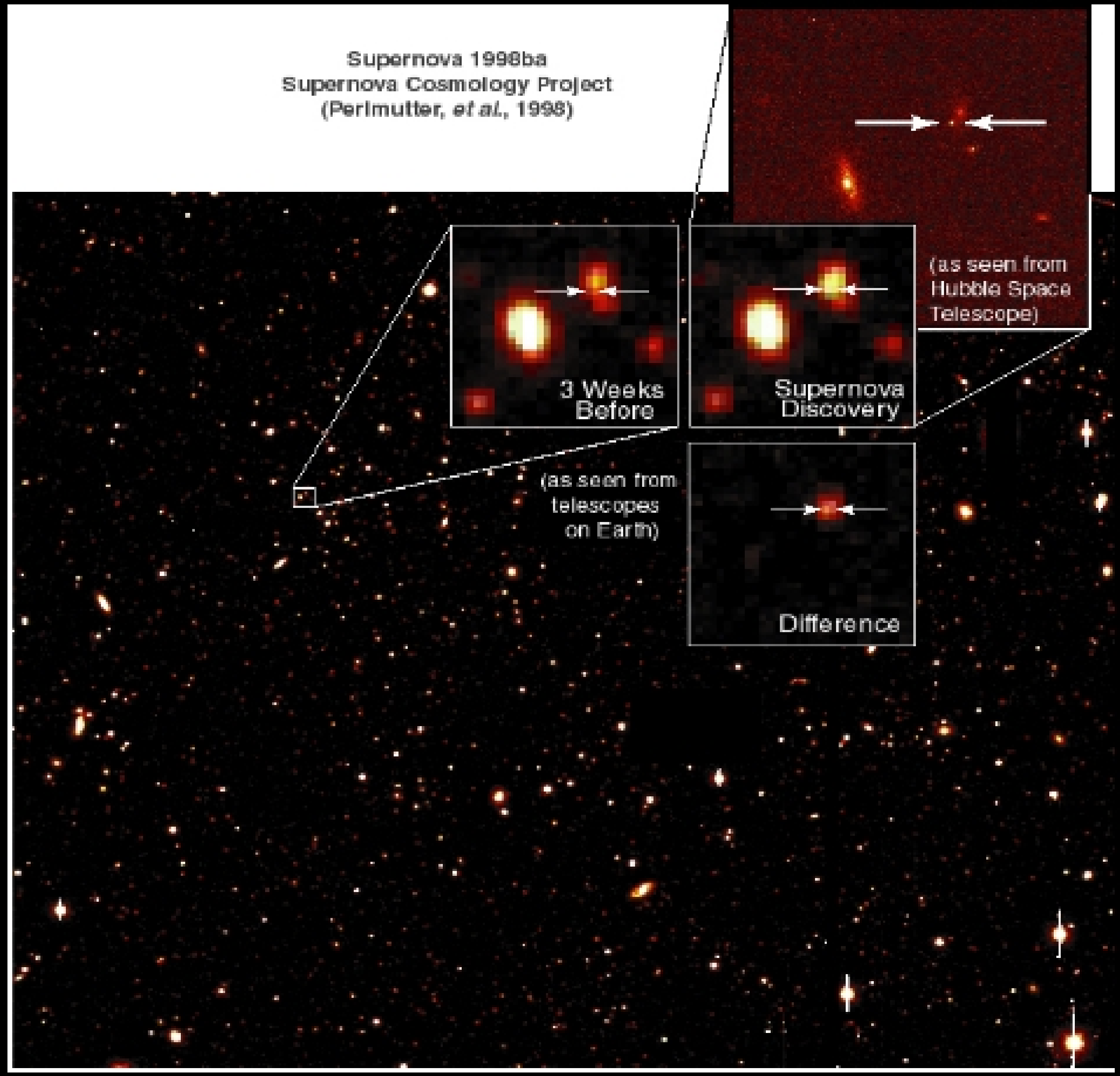
A particular type of Supernovae are STANDARD CANDLES

- The program:
  - Search for SN1a in distant galaxies
  - Compare expected power with observed power to determine distance
  - Measure velocity using redshift
- “Low redshift” galaxies give measurement of H_0
- “High redshift” galaxies allows you to look for deceleration of universe



Standard candles

Strategy: stare at one patch of the sky for a long time, waiting for a star to blow up.



In practice: Magnitudes

Apparent magnitude $$m \equiv -2.5\log_{10}(f/f_x)$$

Note the - sign: larger number=fainter

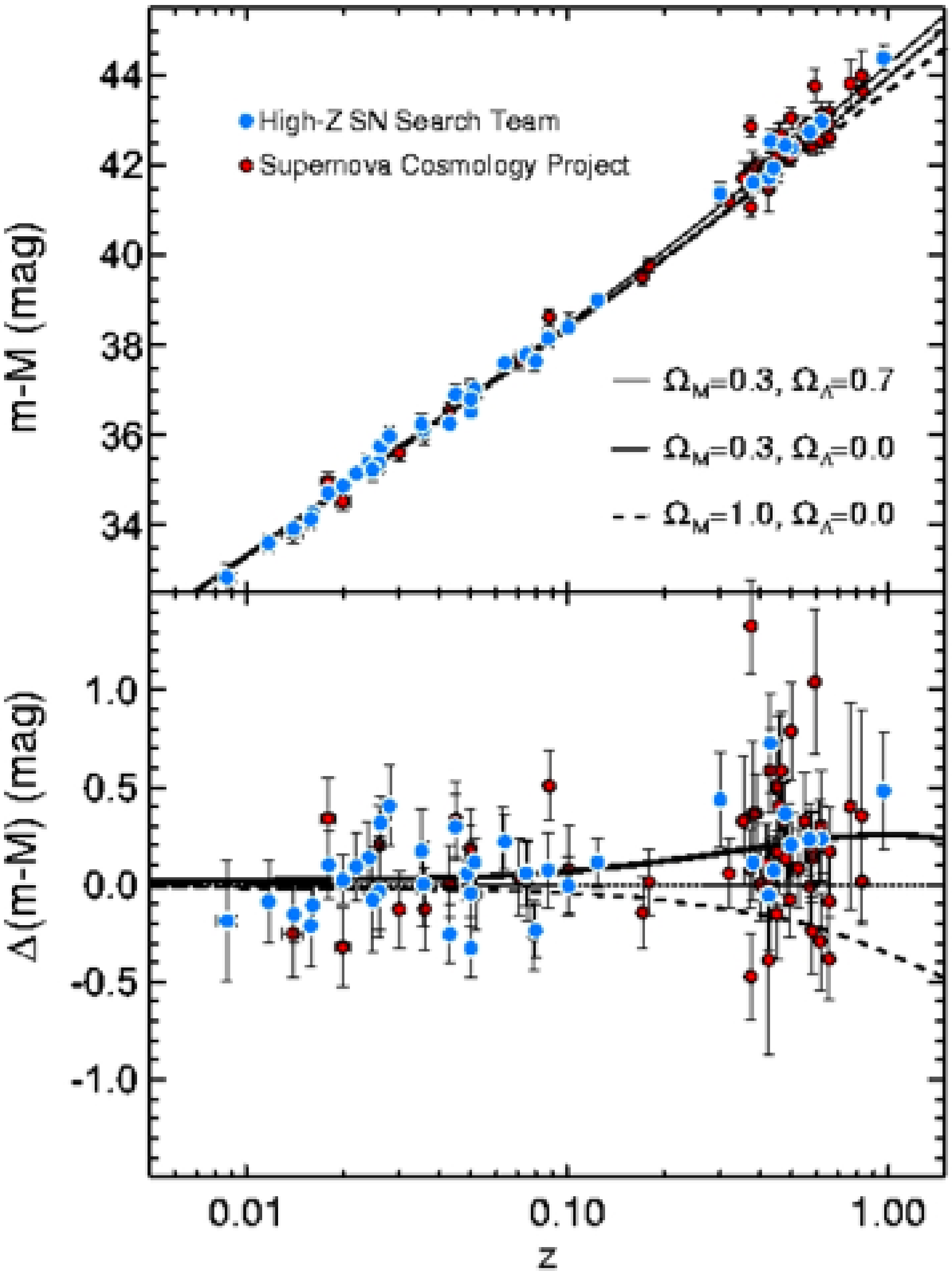
$$f_x = 2.53 \times 10^{-8} W/m^2$$

Absolute magnitude $$M = -2.5\log_{10}(L/L_x)$$

$$L_x = 78.7 L_\odot$$ As if x was at 10pc

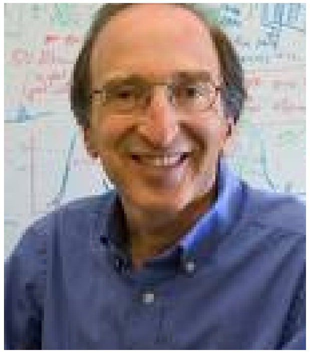
$$M = m - 5\log_{10}\left(\frac{d_L}{1Mpc}\right) - 25$$

$$\mu = M - m$$



- This program gives most accurate value for Hubble's constant
  - H=74.2 km/s/Mpc, error<4%
- Find acceleration, not deceleration!
  - Very subtle, but really is there in the data!
  - Profound result!

1998!



Humm the expansion seems to accelerate…

What the heck!

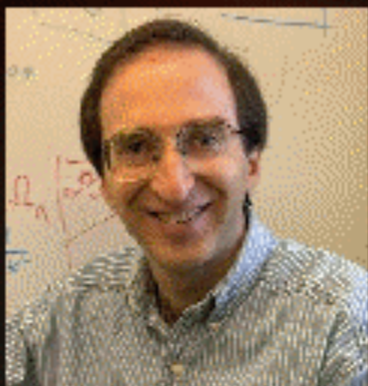
Nobel prize in Physics 2011

Saul Perlmutter, Brian P. Schmidt and Adam G. Riess
"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".

Einstein's Greatest Blunder

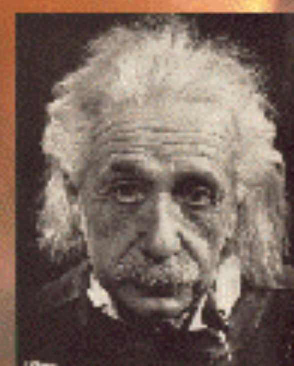
1998: Accelerating expansion

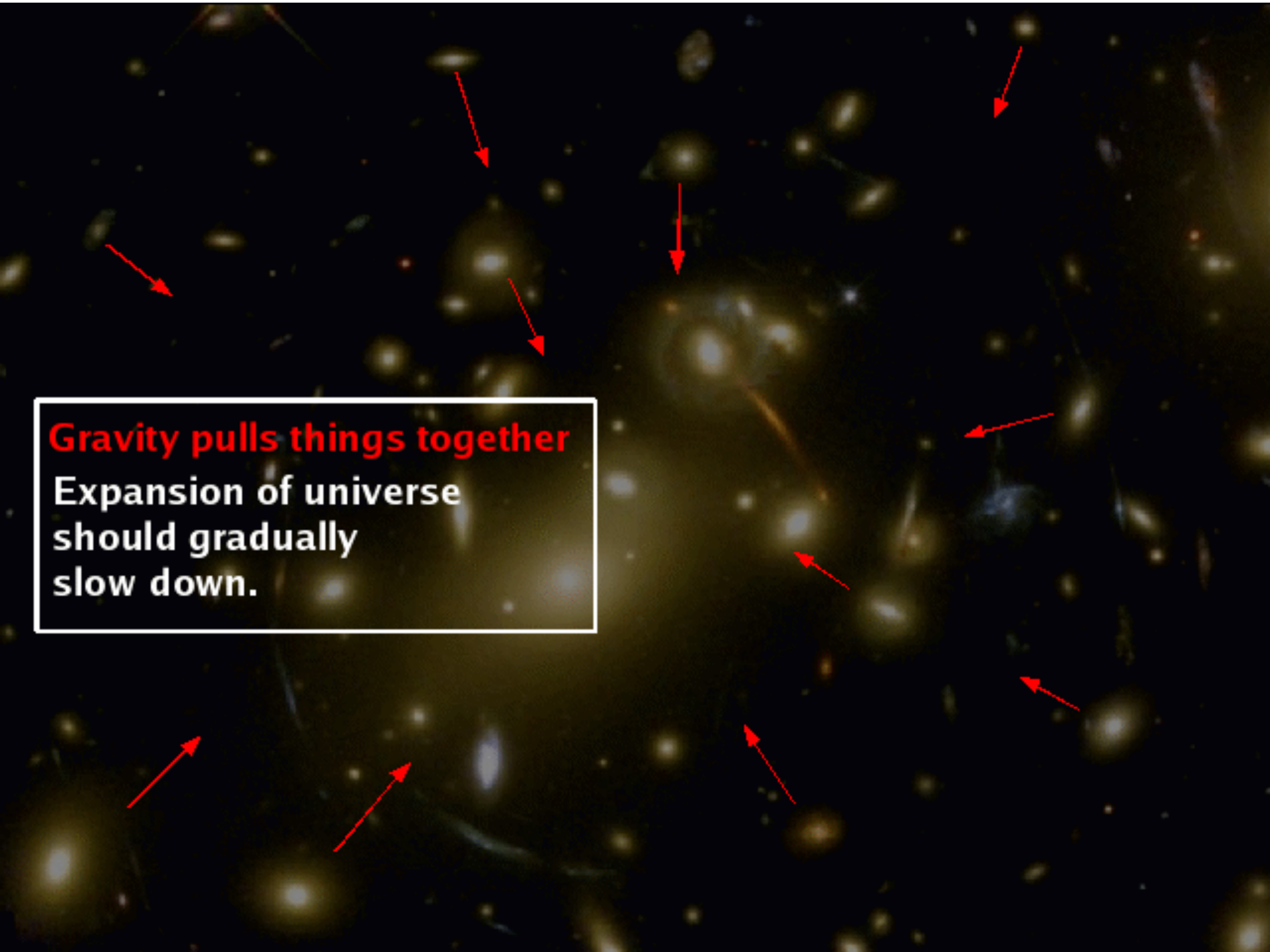
Λ



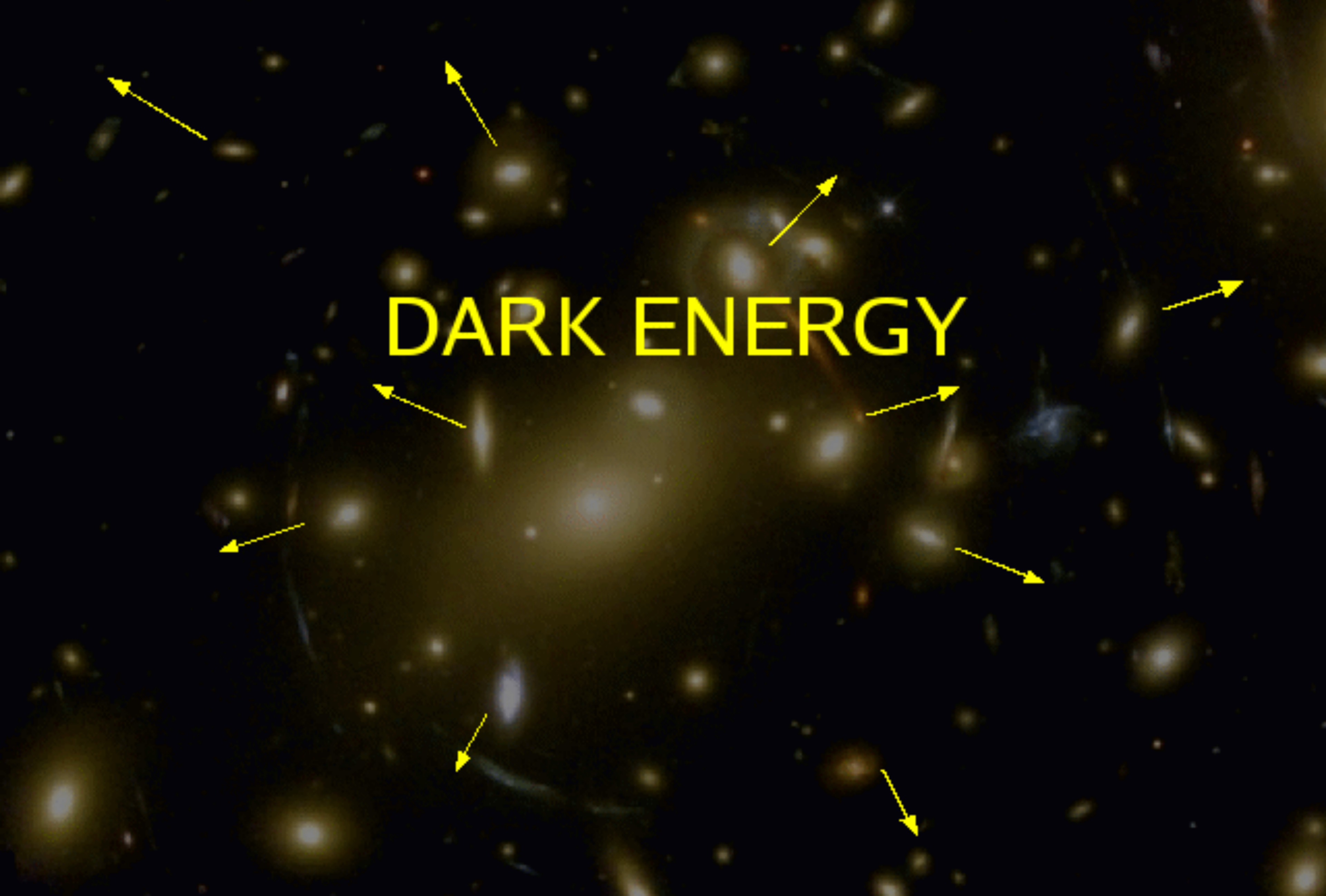
D'oh!

D'oh!



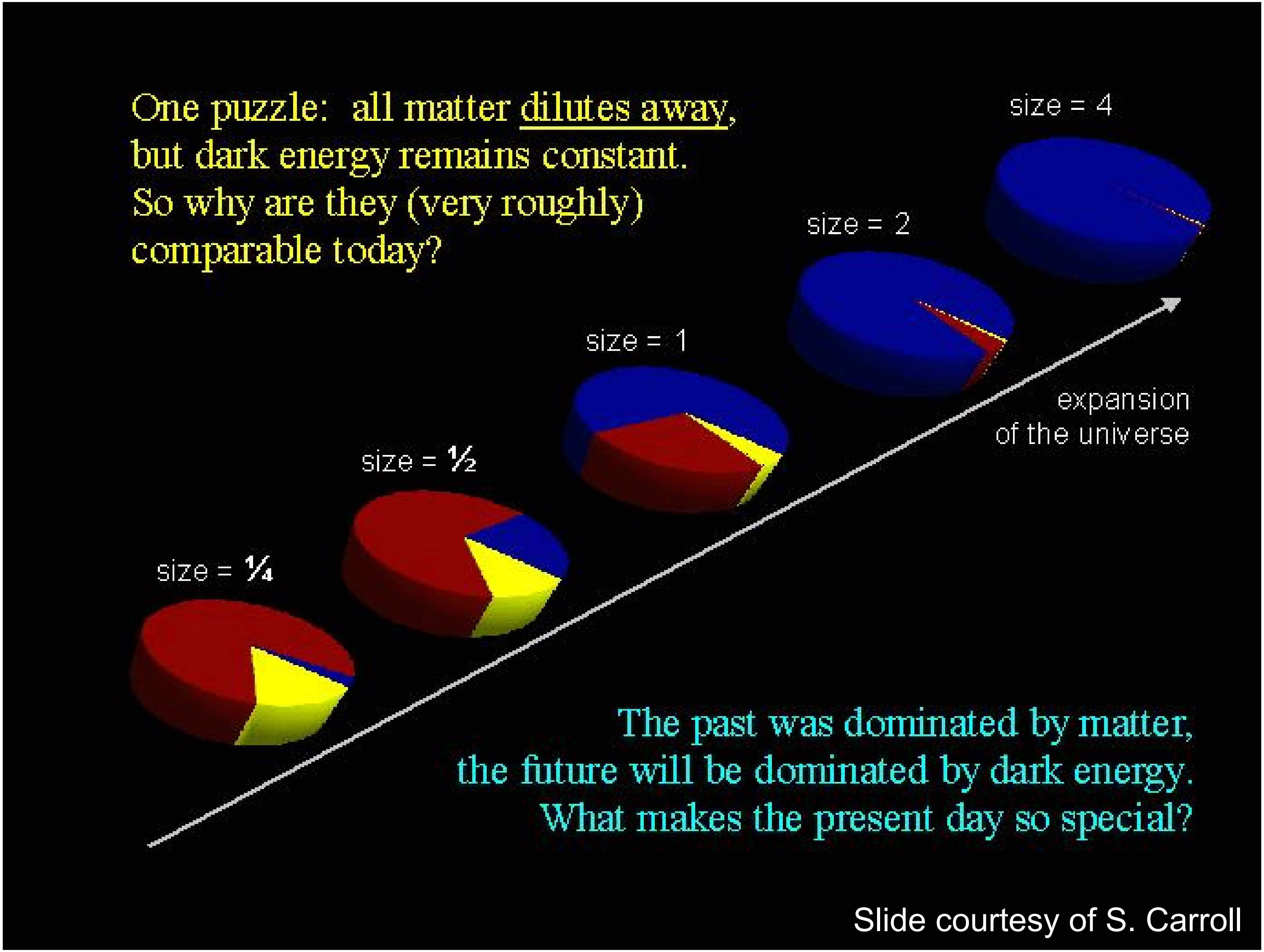

Gravity pulls things together
Expansion of universe
should gradually
slow down.

Something is pushing the galaxies apart



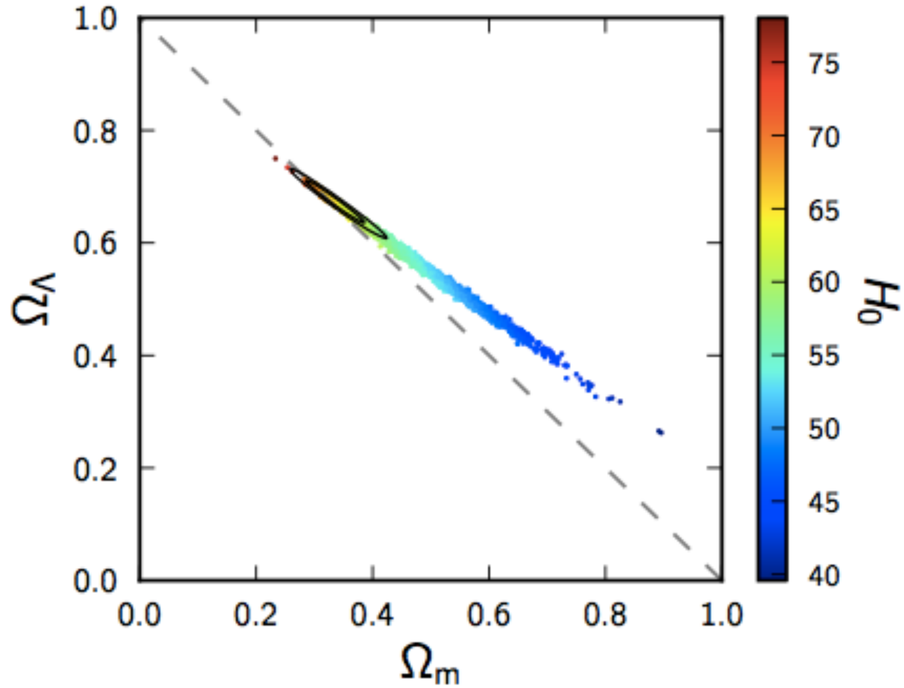
What is the dark energy?

Nothing.



One puzzle: all matter dilutes away,
but dark energy remains constant.
So why are they (very roughly)
comparable today?
size = 4
size = 2
size = 1
size = ½
size = ¼
expansion
of the universe
The past was dominated by matter,
the future will be dominated by dark energy.
What makes the present day so special?
Slide courtesy of S. Carroll

The latest results!



Planck collaboration paper XVI

This is a preposterous universe.

- Why is the vacuum energy density so much smaller than it should be? Naive expectation:

$$\rho_{DE}^{(theory)} = 10^{120} \rho_{DE}^{(obs)}$$

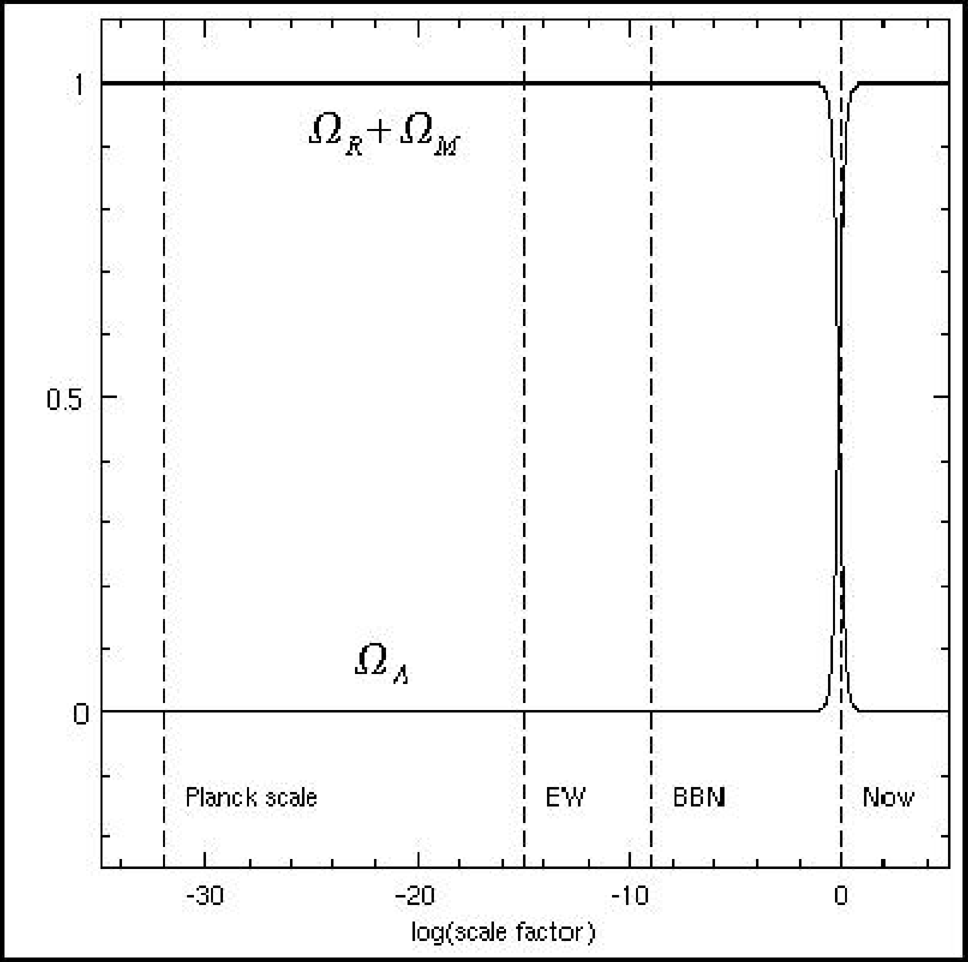
- What is the nonzero dark energy? A tiny vacuum energy, a dynamical field, or something even more dramatic?

- Why <u>now</u>? Remember $\rho_{DE} / \rho_M \sim a^3$. So why are they approximately equal today?

Slide courtesy of S. Carroll

And it's moving quickly:

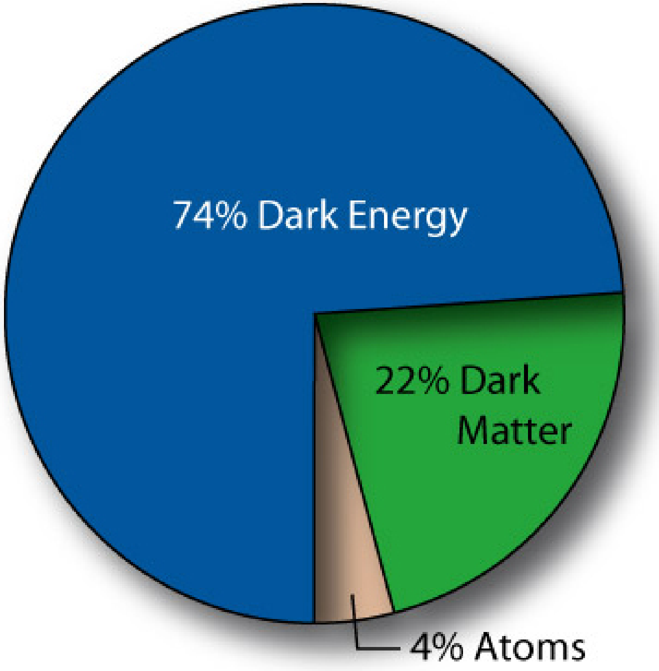
$$\frac{\Omega_\Lambda}{\Omega_M} \sim a^3$$



The standard cosmological model

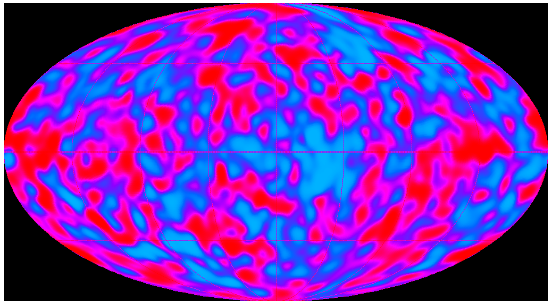
96% of the Universe is missing!!!

↓



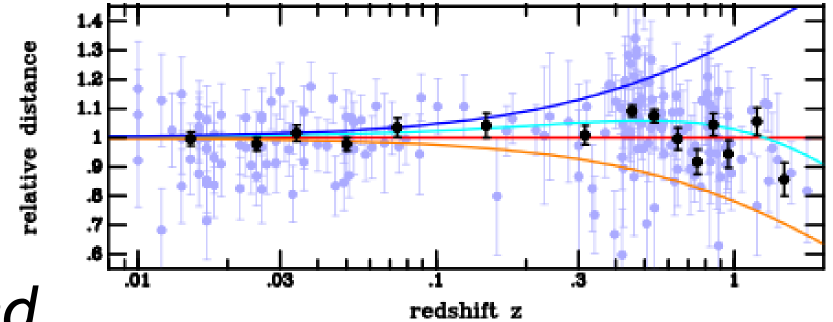
Major questions :

Questions that can be addressed exclusively by looking up at the sky



1)What created the primordial perturbations?

2) What makes the Universe accelerate?



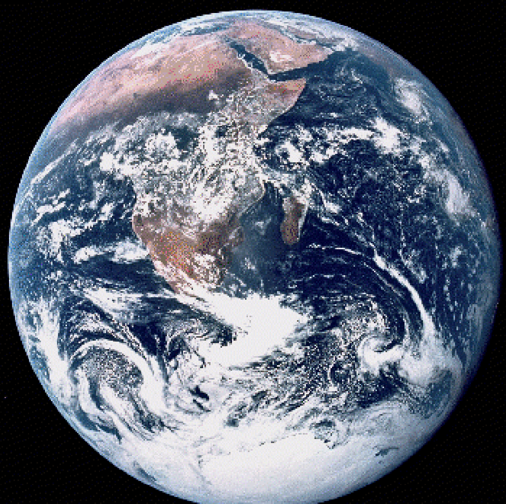
These questions may not be unrelated

Problems with dark energy:

Theoretical physicists study the vacuum and tell us that:

A cosmological constant should be
10000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000
00000000000000 larger than observed

Vacuum Energy is uniformly distributed



If we could transform all the energy of the vacuum enclosed in the volume of the Earth in electricity, this would correspond to the quantity of electricity that an American uses in one day!

Burt we can't: as it is uniformly distributed,
dark energy is completely useless.

Courtesy of S. Carroll

Dark Energy: have you seen it?

Smoothly distributed: does not fall into galaxies and clusters

Affects the Universe only at its largest scales

Almost constant density: does not really dilute as the Universe expand

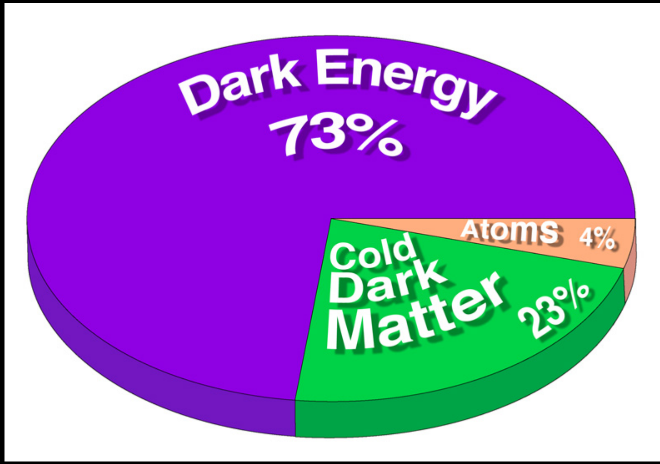
Invisible:
only visible through its effects on the expansion and geometry of the Universe

Possibly associated with vacuum (I.e. nothing)

What is it? Honestly… …We haven't got a clue

So.. Where do we go from here?

We have an inventory of what makes up the Universe but no understanding.



Connections with fundamental physics!

What may be going on?

Options include:

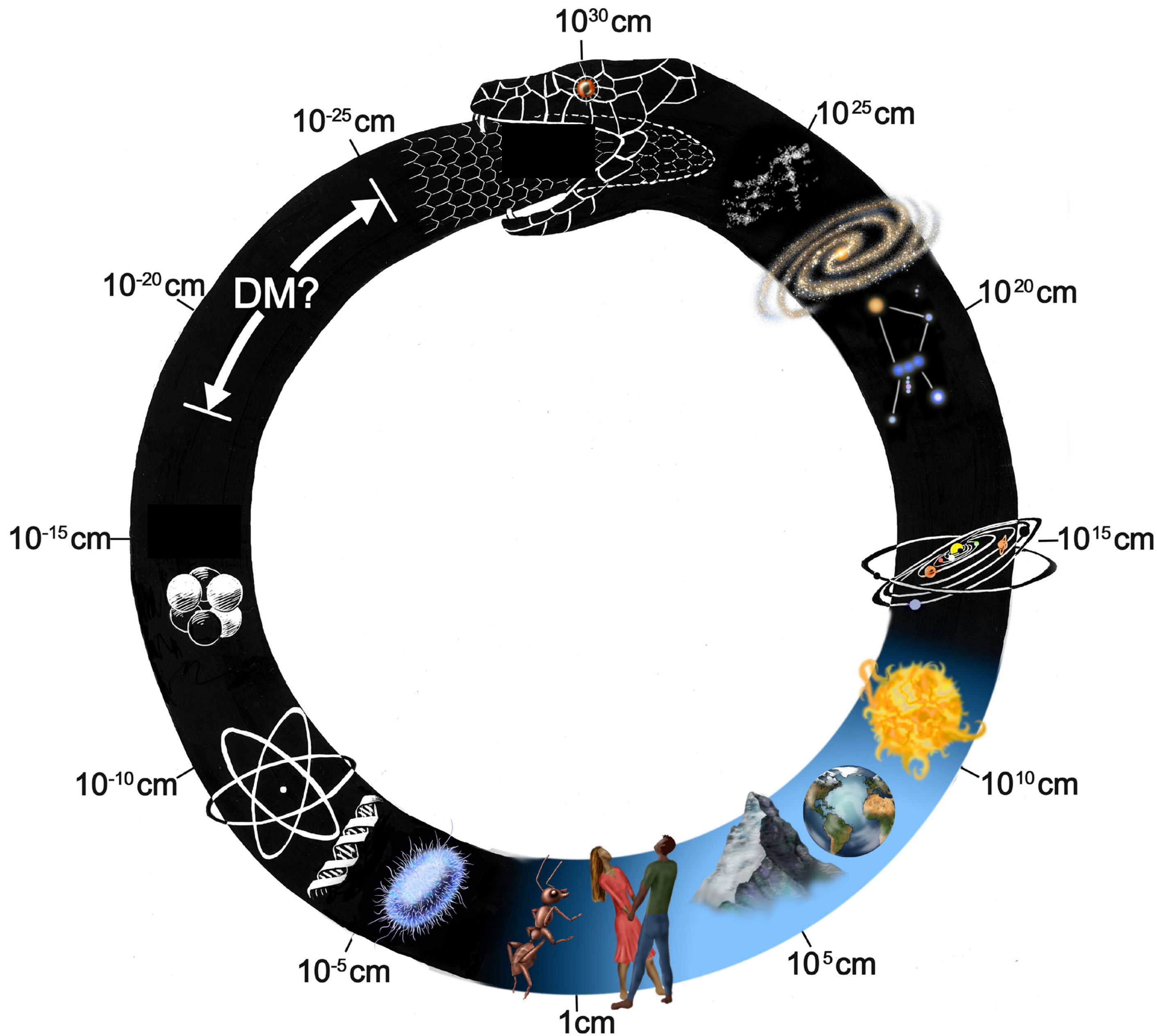
The vacuum energy is very different in other far far away parts of the Universe

We just got lucky…

A slowly varying dynamical component taking over (and it may not even be the first time)

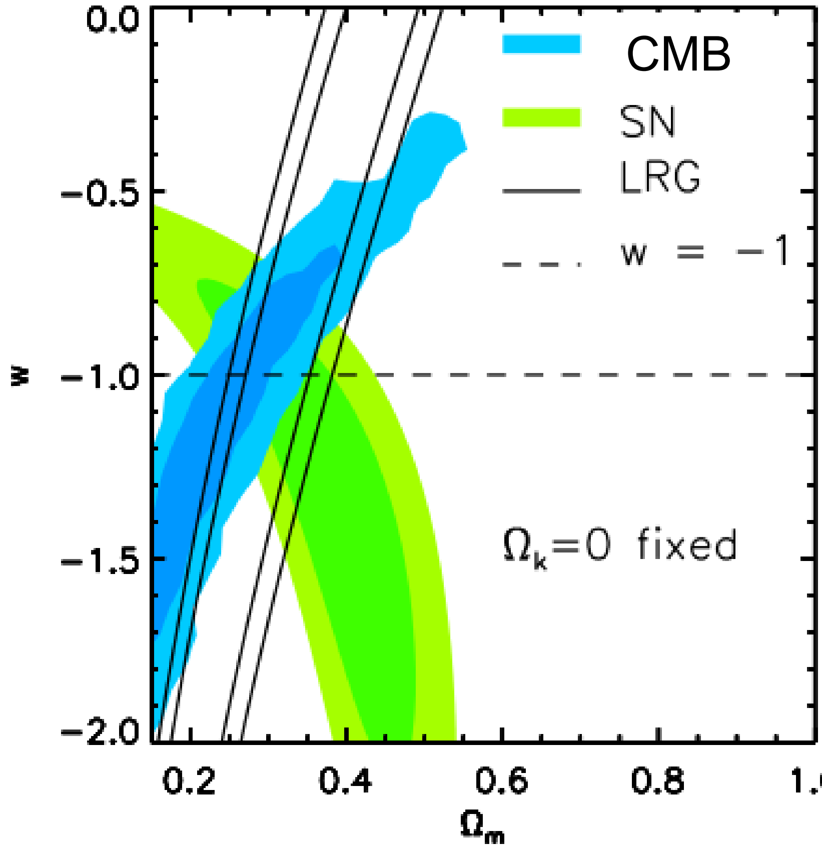
Einstein was wrong

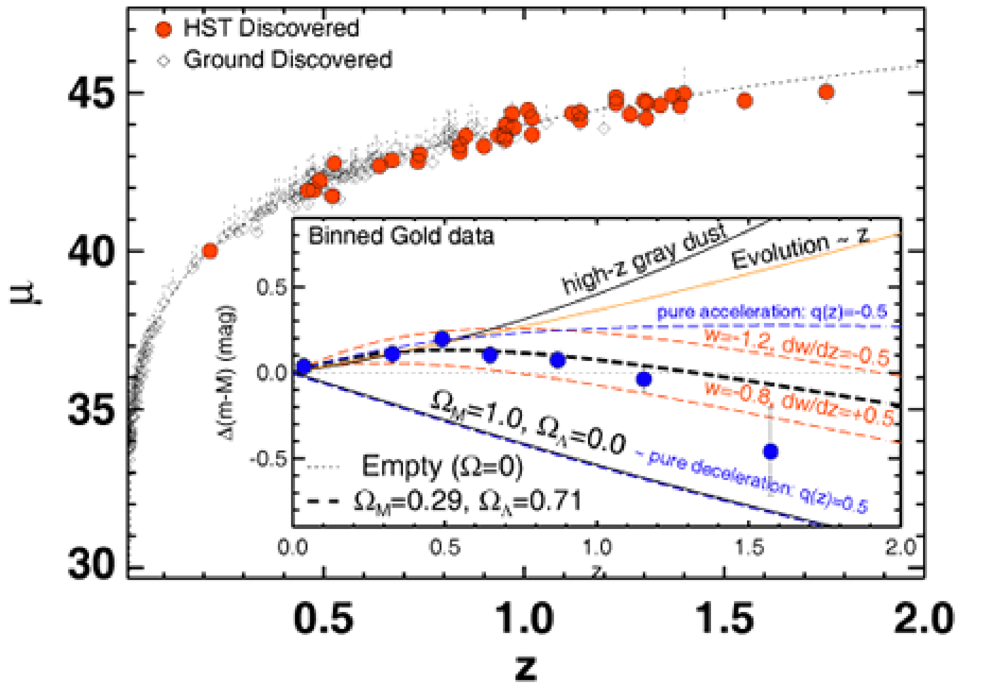
String theory?


10^{30} cm
10^{25} cm
10^{20} cm
10^{15} cm
10^{10} cm
10^{5} cm
1cm
10^{-5} cm
10^{-10} cm
10^{-15} cm
10^{-20} cm
10^{-25} cm
DM?

Dark energy: is it a cosmological constant?

Is w=-1? If not we expect it to vary in time….





Coupling in the dark sector?

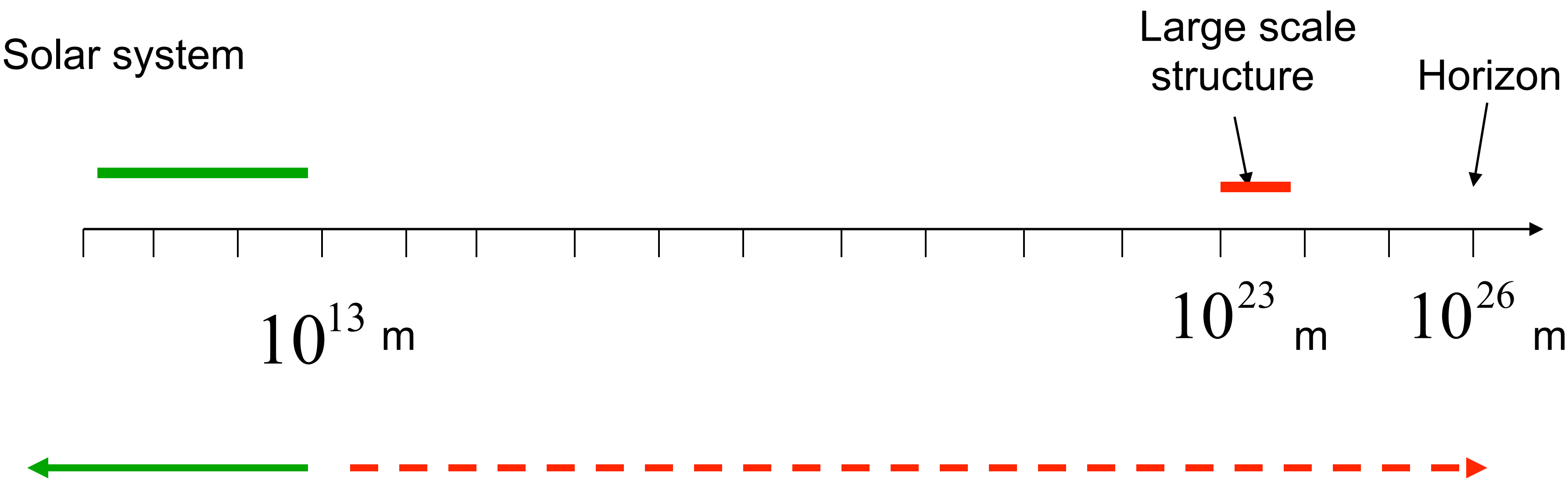
Variation of fundamental constants?

Was Einstein wrong?

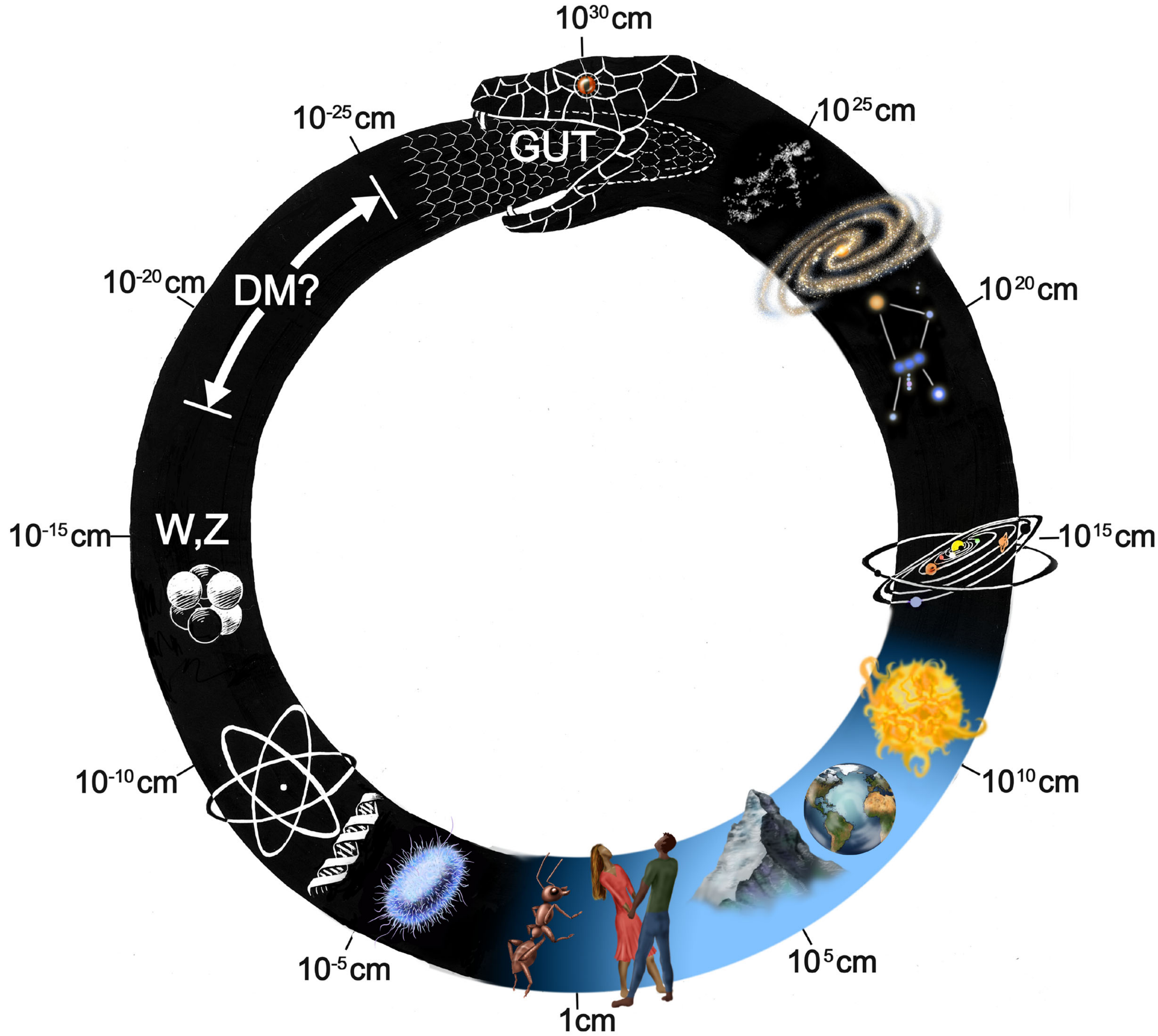
Something on large scales?

Dark energy shows its effects on scales comparable to the horizon… 10^{26} m

Precision test of the law of gravity have been carried out on scales< 10^{13} m



An enormous extrapolation is required



10^{30}cm
10^{-25}cm
GUT
10^{25}cm
10^{-20}cm
DM?
10^{20}cm
10^{-15}cm
W,Z
10^{15}cm
10^{-10}cm
10^{10}cm
10^{-5}cm
10^{5}cm
1cm

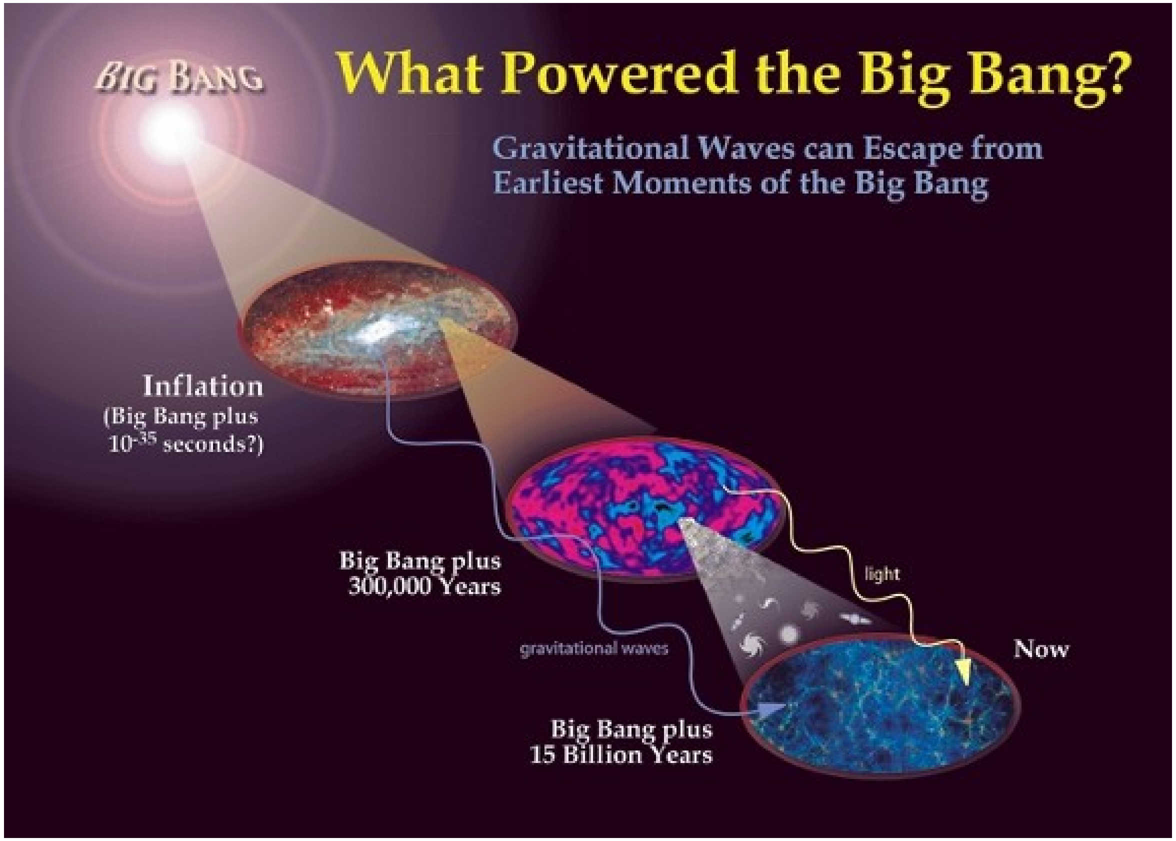
The blessing and the curse of cosmology

We only have one observable Universe

We can make “ultimate experiments”

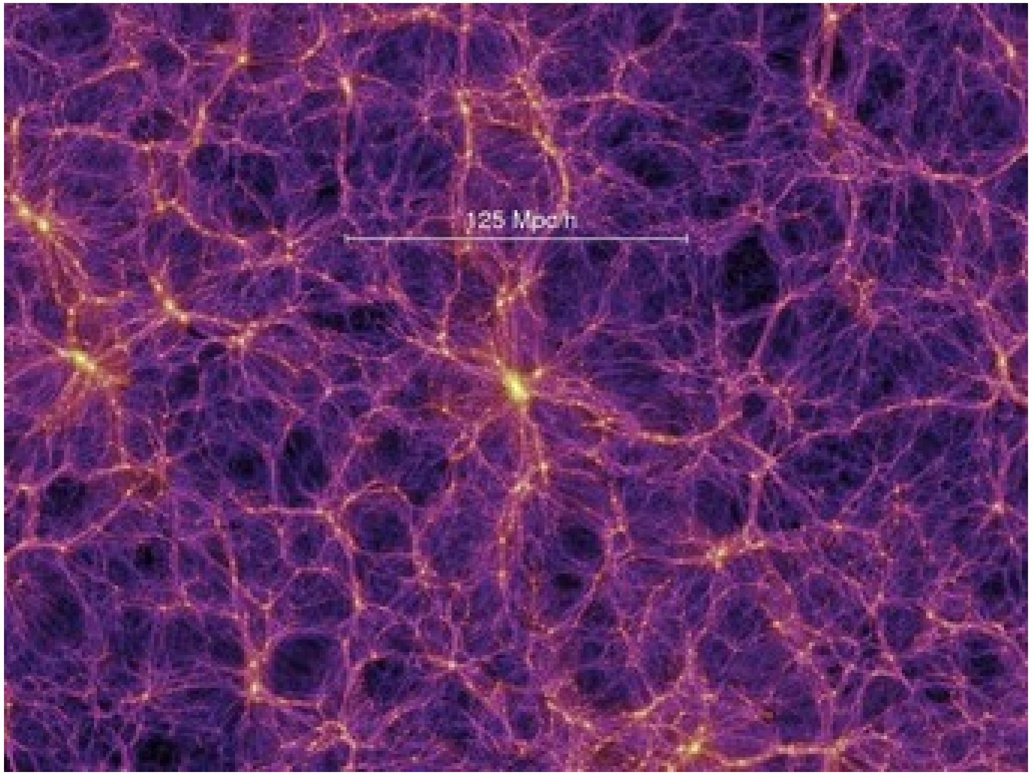
(CM)Bpol/PRISM (proposal stage)

Different inflationary models leave their signature in the CMB.
In particular in the polarization patterns of the CMB light.



The ultimate primary CMB polarization experiment

Euclid



Chasing dark energy: expansion history and growth of structures

An analogy: the theory of gravitation at the time of N. Copernicus (1473-1543)

“ I believe that gravity is nothing but a certain natural desire, which the divine providence of the Creator of all things has implanted in parts, to gather as a unity and a whole by combining in the form of a globe. This impulse is present, we may suppose, also in the sun, in the moon, and in the other brilliant planets, so that through its operation they remain in that spherical shape which they display. Nevertheless, they swing round their circles in diverse ways…”

De Revolutionibus Orbitum Coelestium

The theory of gravitation after Isaac Newton (1643-1727)

- All objects in the universe attract each other with the force $F=G\, m_1\, m_2 / d^2$
- That's now quantitative… it can predict the orbital period of the Moon, Kepler's laws of planet motion, planet perturbations from Kepler's laws, precession of the Moon's orbit, ocean tides, deviation of Earth's shape from a perfect sphere…

A (personal) perspective on the future of cosmology

- Our ideas on cosmology are somewhat like Copernicus' ideas on gravity.
- We need a new Isaac Newton (or Einstein) who will explain why not just how gravity works…

How long will that take?

It took ~ 150 years from Copernicus to Newton

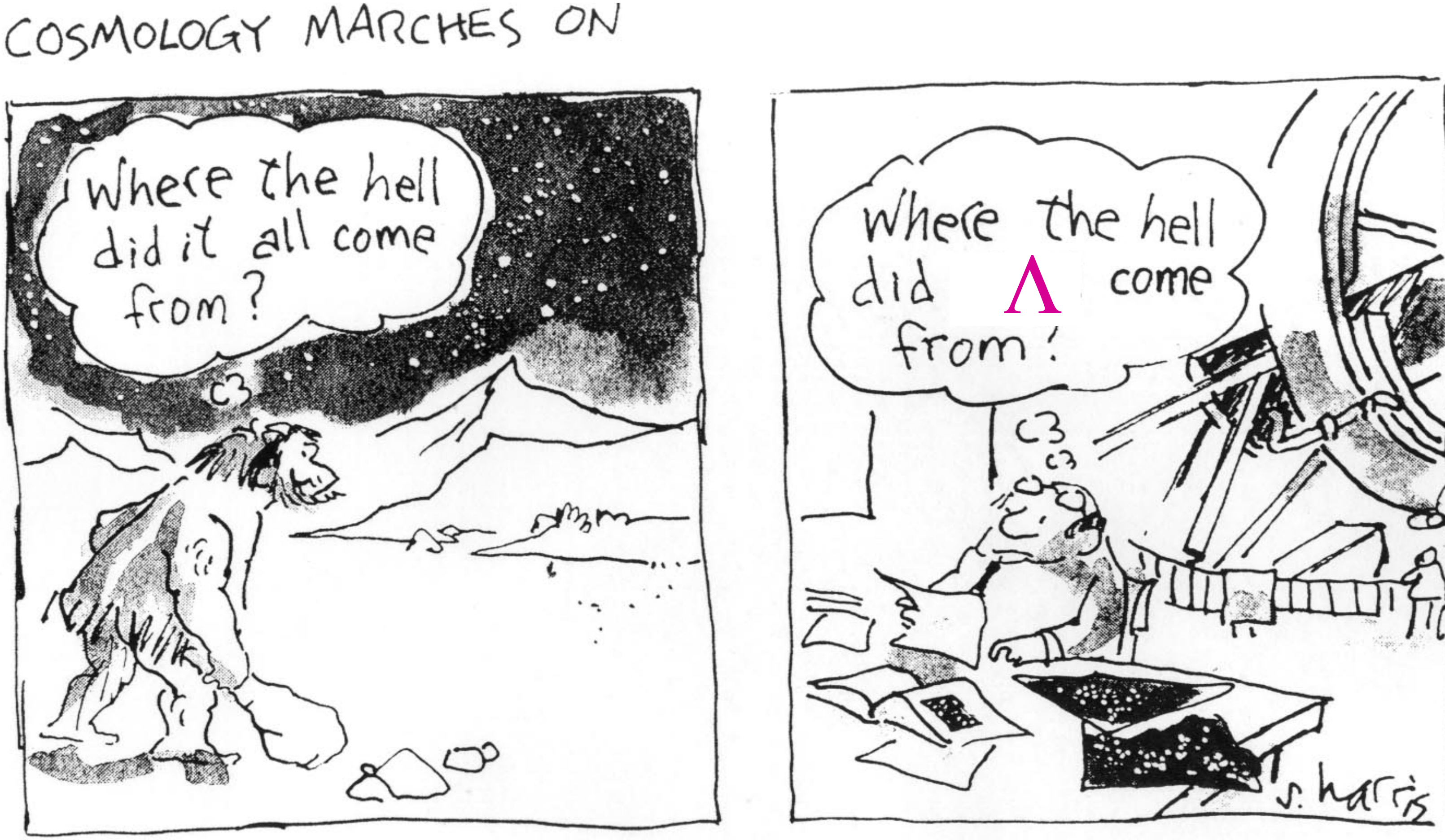
and another ~230 years from Newton to Einstein.

Will it be longer or shorter than that?

Maybe one of YOU….

Something really funny

“Nothing” really funny



END

Lecture slides (and additional material) at
http://icc.ub.edu/~liciaverde/cernlectures.html