The Dark Side of the Universe - I

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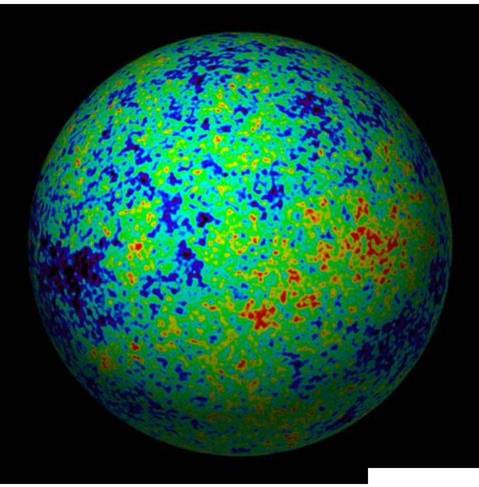
Cosmology has become a data driven science!

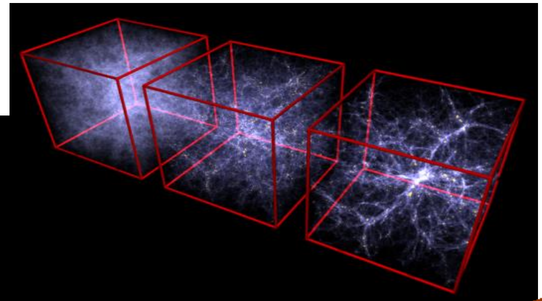
Many experiments (some in Chile) are taking a huge amount of data that are being analyzed in order to find out which model best describes the universe.

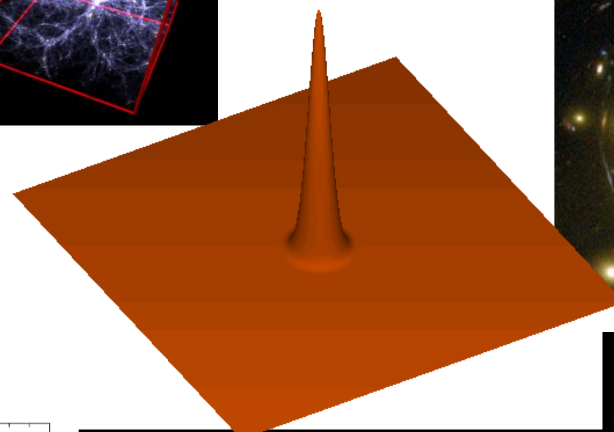
Cosmological probes

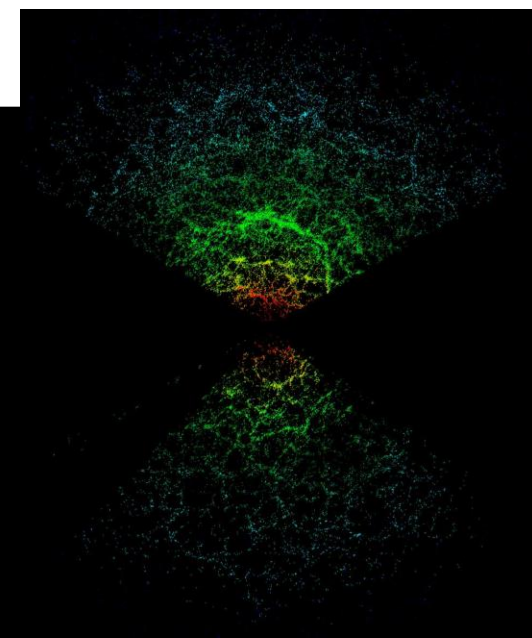
- Cosmic Microwave Background (CMB)
- Big bang nucleosynthesis (BBN)
- Supernovae (type Ia)
- Baryon acoustic oscillation (BAO)
- Gravitational lensing
- Number count of clusters of galaxies

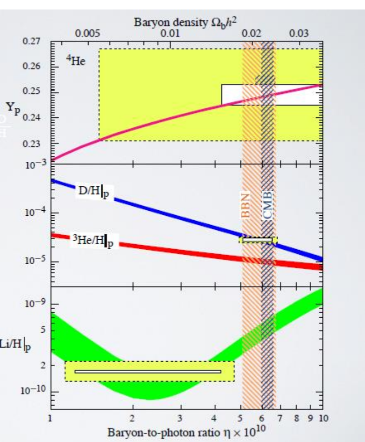
Cosmological probes

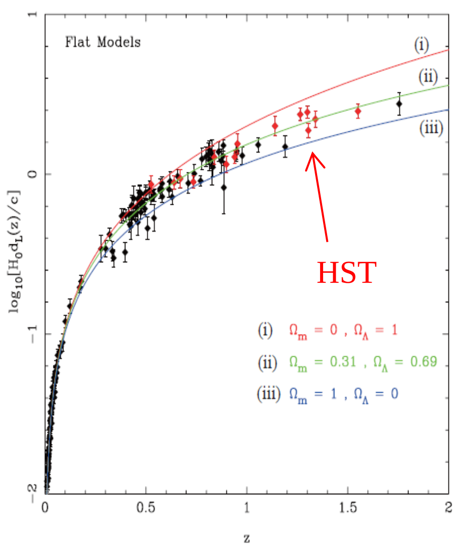


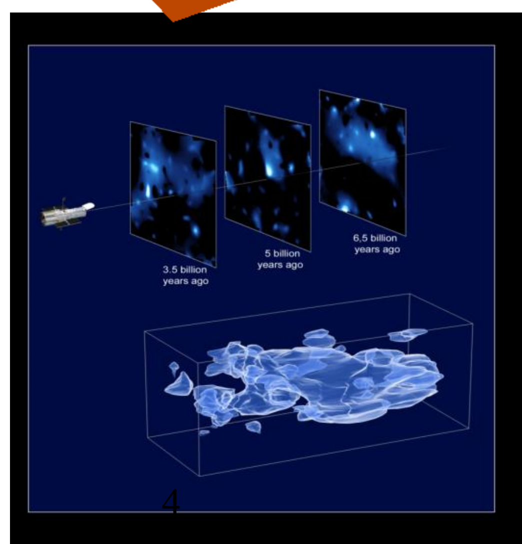




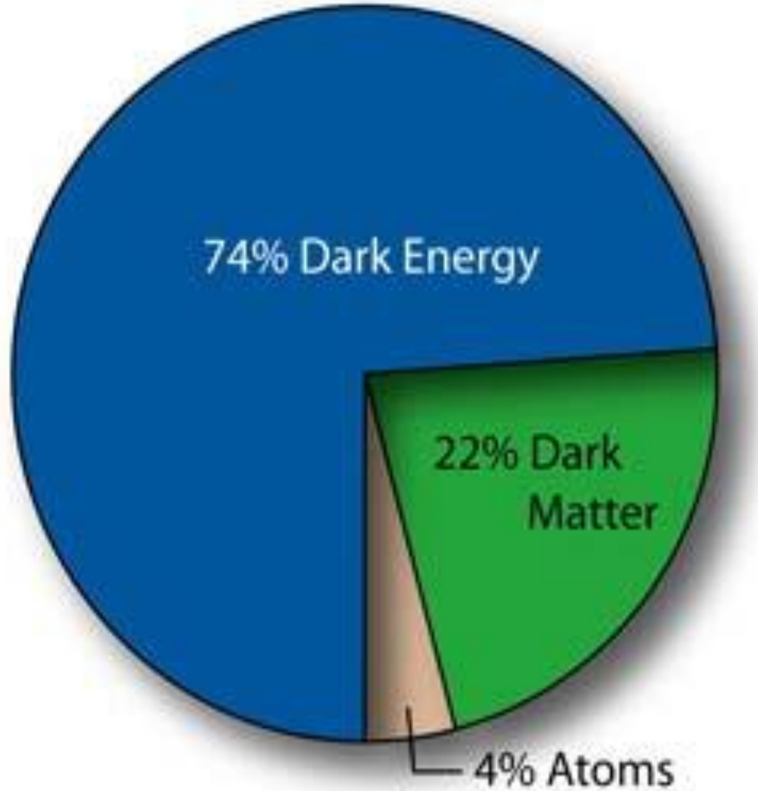








We know that we don't know what the universe is made of:



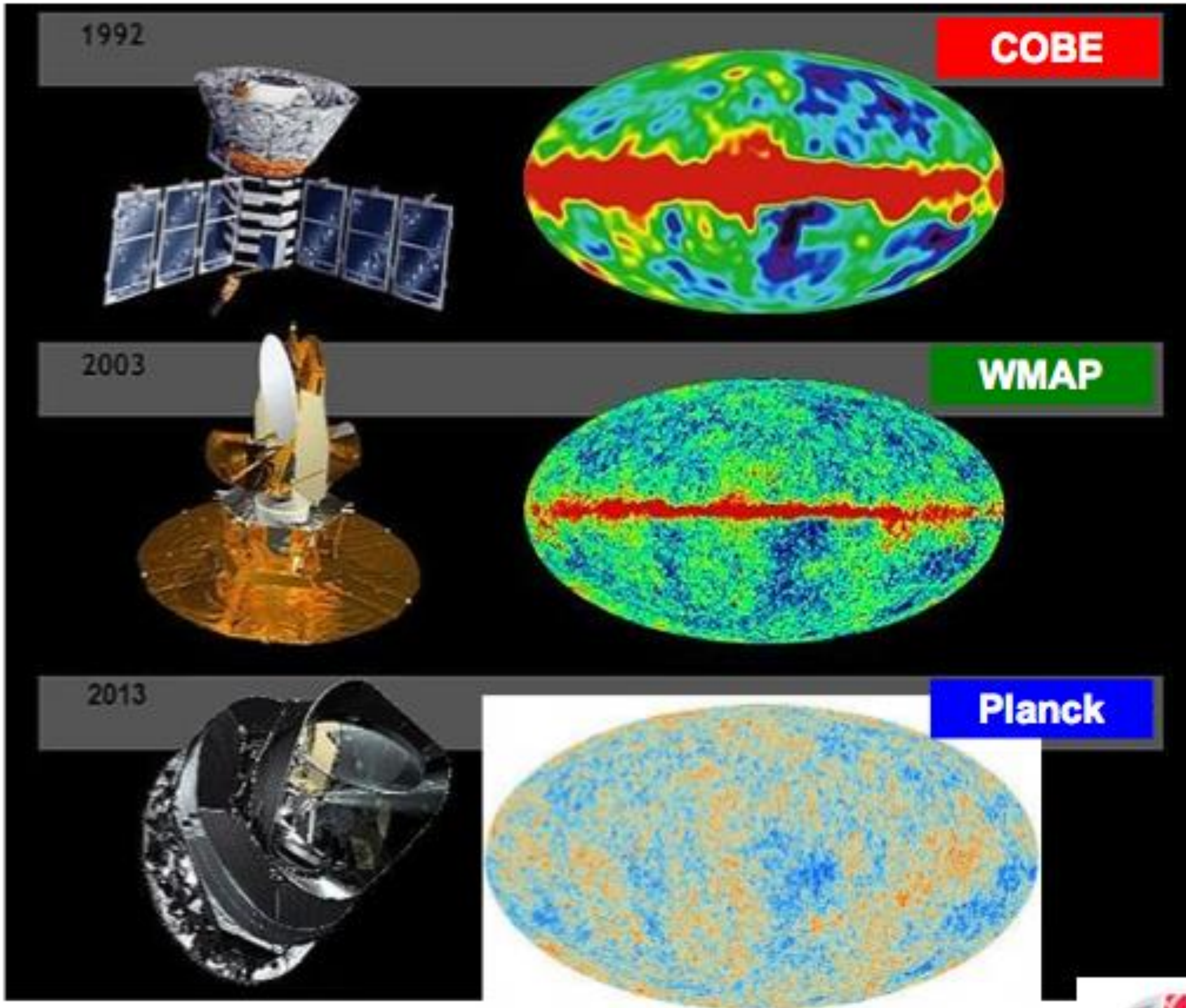
Some experiments

Cosmic Microwave Background (CMB):

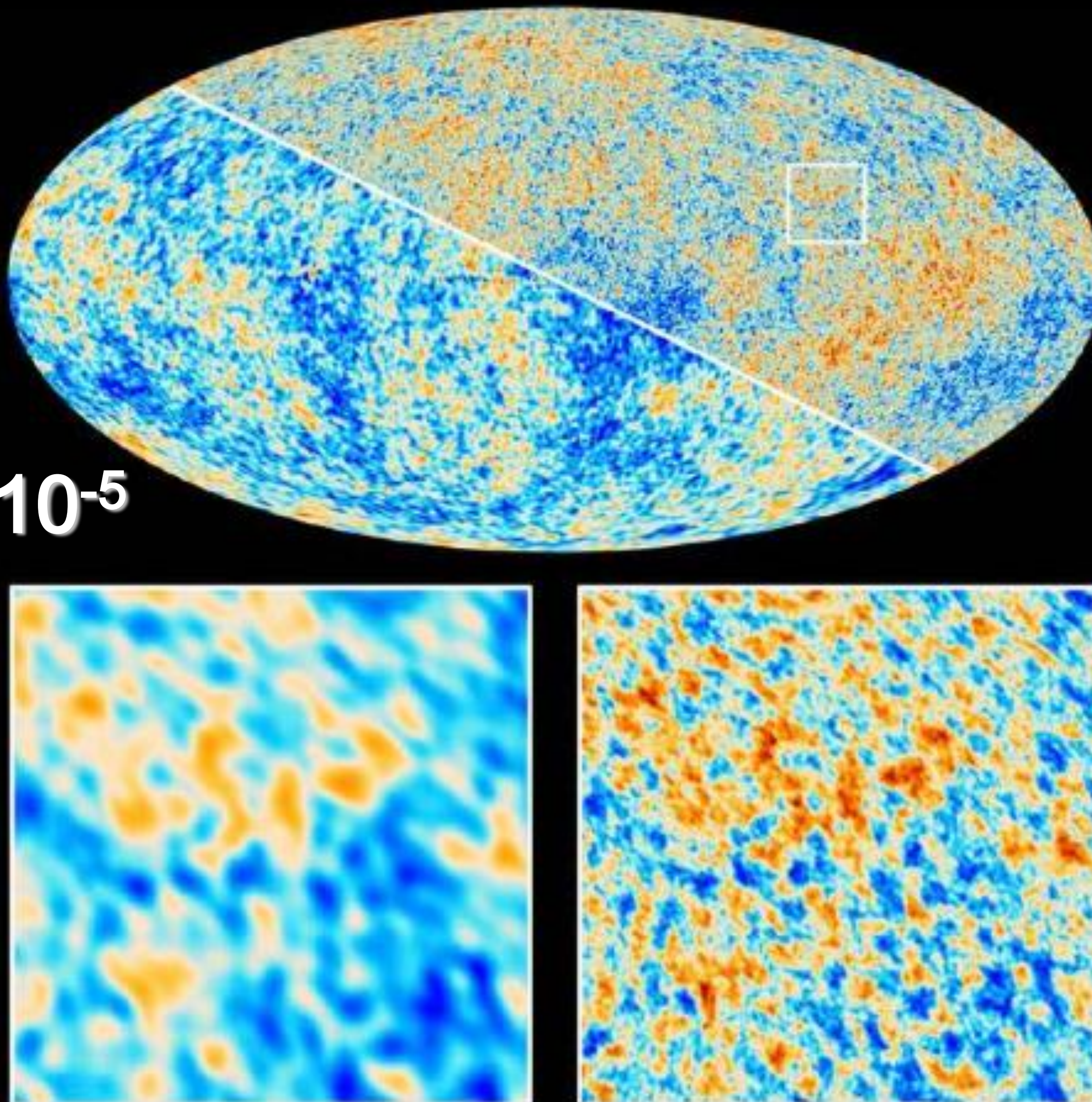
Planck satellite, South Pole Telescope, Atacama Cosmology Telescope

ACT

The Planck mission



WMAP vs Planck



$\delta T/T \sim 10^{-5}$

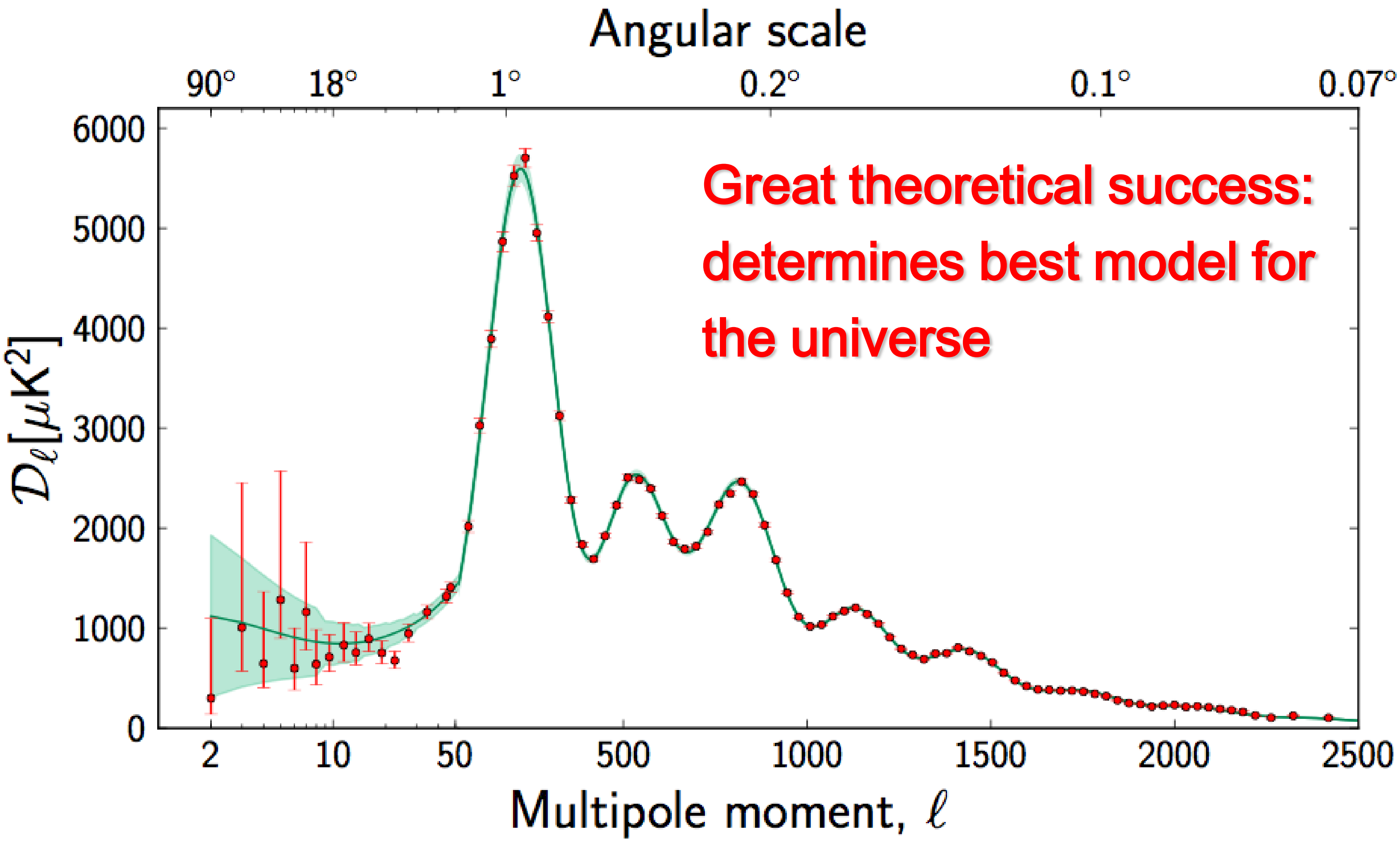


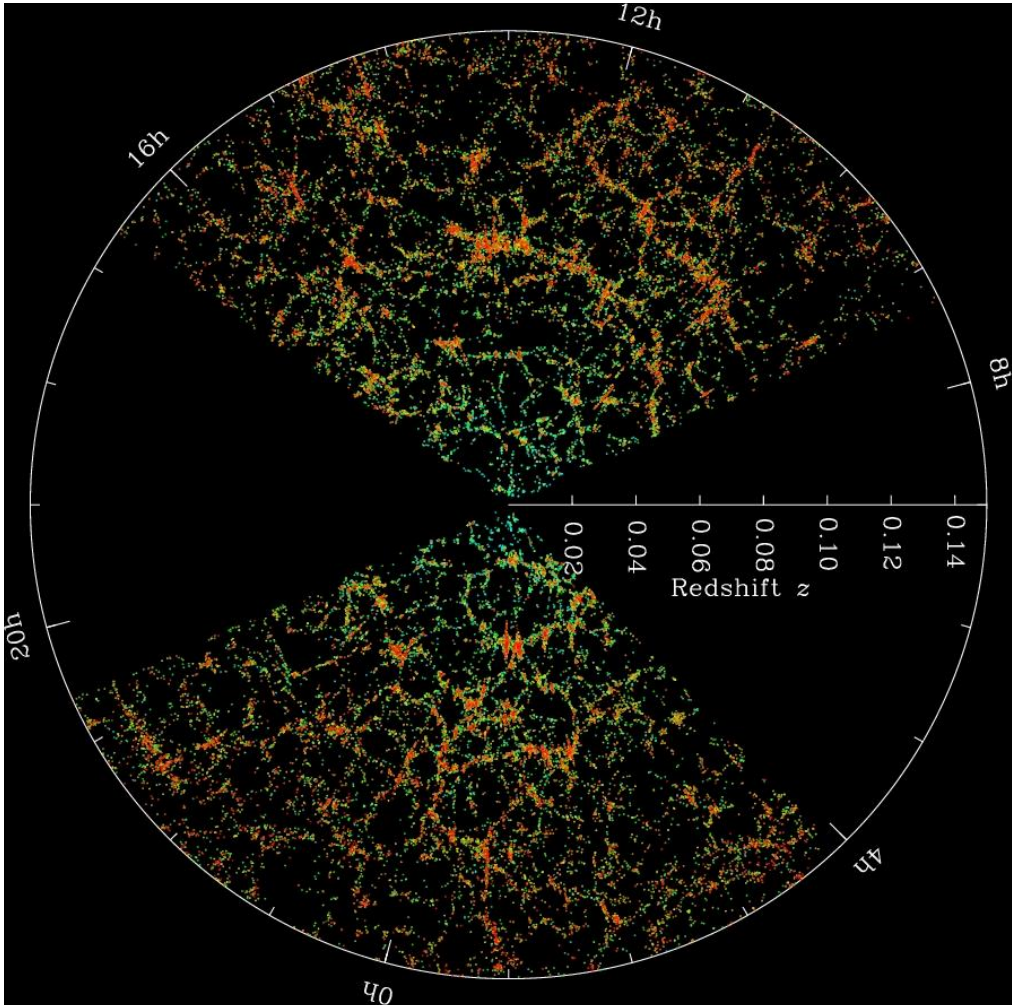
Figure 37. The 2013 *Planck* CMB temperature angular power spectrum. The error bars include cosmic variance, whose magnitude is indicated by the green shaded area around the best fit model. The low-ℓ values are plotted at 2, 3, 4, 5, 6, 7, 8, 9.5, 11.5, 13.5, 16, 19, 22.5, 27, 34.5, and 44.5.

Large galaxy surveys: probe the large scale structure (LSS) of the universe.

Sloan Digital Sky Survey (SDSS-I, 2000-2005; SDSS-II, 2005-2008, SDSS-III, 2008-2014) & Baryon Oscillation Spectroscopic Survey (BOSS) - 1.5 million Luminous Red Galaxies (LRGs) out to z~0.7 over 10,000 square degrees.

Large scale structure: observations

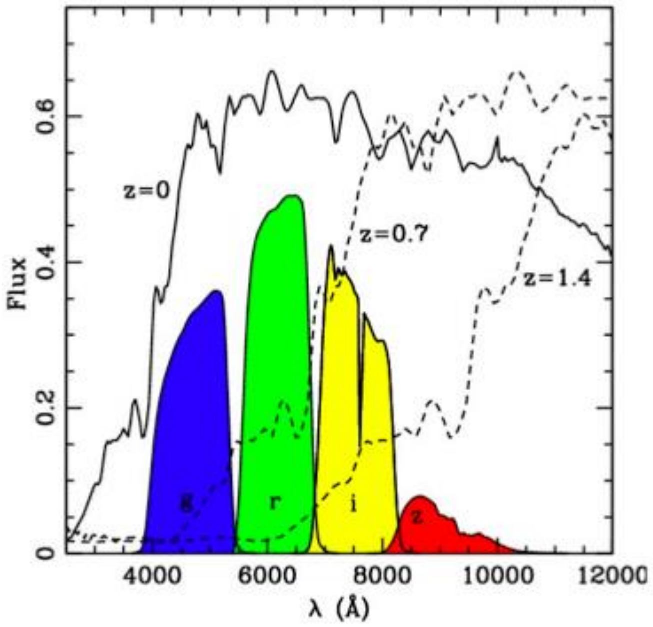
Sloan Digital Sky Survey: spectra of 930,000 galaxies



The outer circle is at a distance of two billion light years.

Dark Energy Survey

- Survey of 5000 deg^2 (~ 1/8 of the sky)
- 300 millions of galaxies up to z~1.4 (+ 100,000 clusters + 4,000 SNs)
- Photometric redshift with 5 filters
- Project initiated in 2003
- Observations from 08/2013-02/2018 (5x105 nights)



DES Project Timeline

NOAO Blanco Announcement of Opportunity 2003

DECam R&D 2004-8

Camera construction 2008-11

Final testing, integration 2011

Shipping components to Chile 2011

Installation on telescope begins early 2012

First light DECam on telescope September 2012

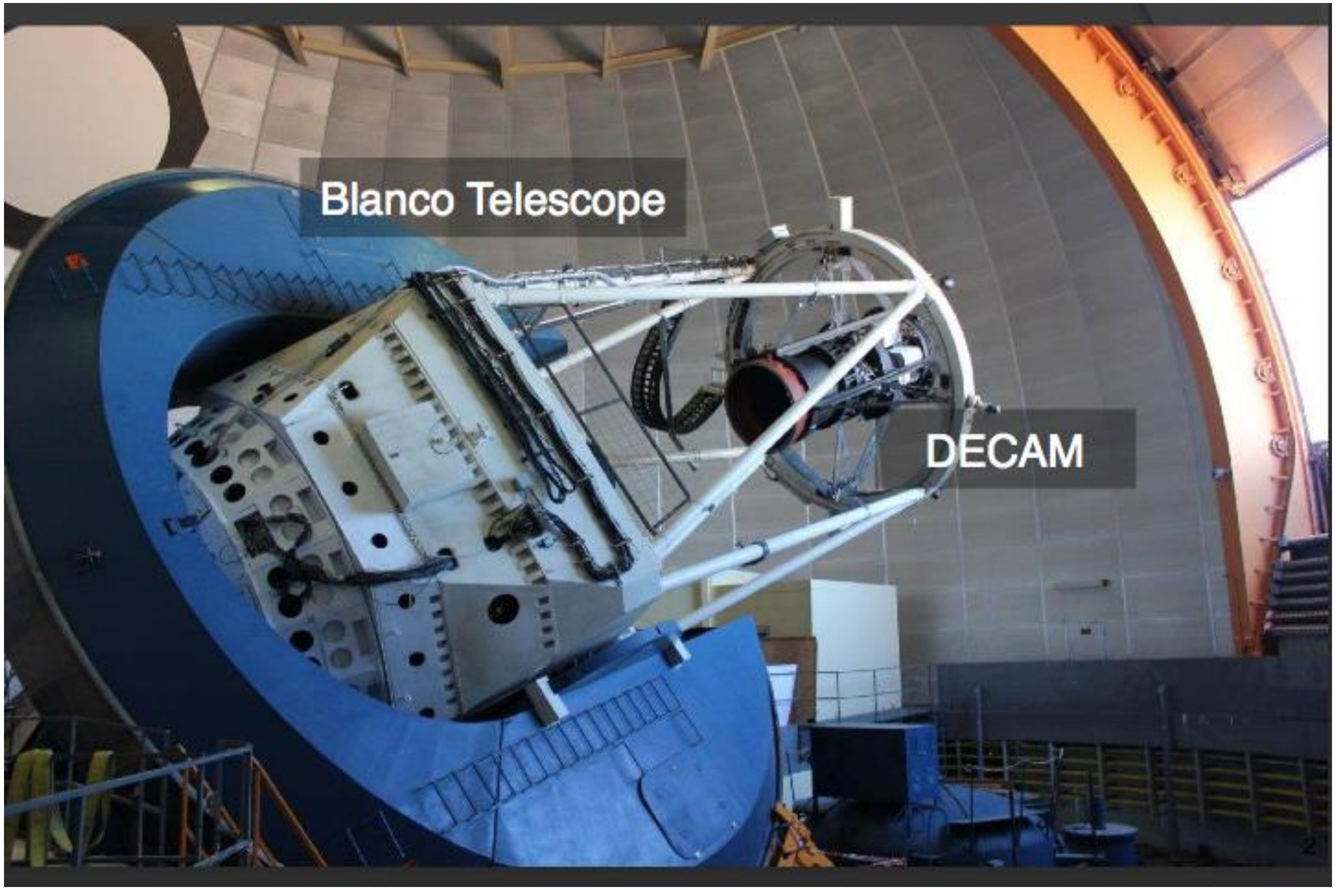
Commissioning and Science Verification: Fall 2012/Spring 2013

Survey operations begin: August 31st 2013

DES site: 4m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile

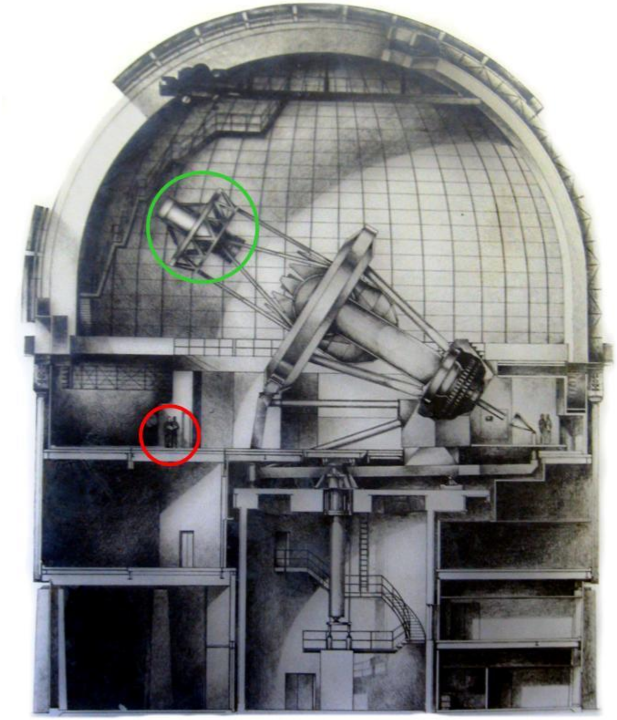
The DES Camera: the most powerful digital space camera on Earth. Weighs around 4 tons. Built at Fermilab.

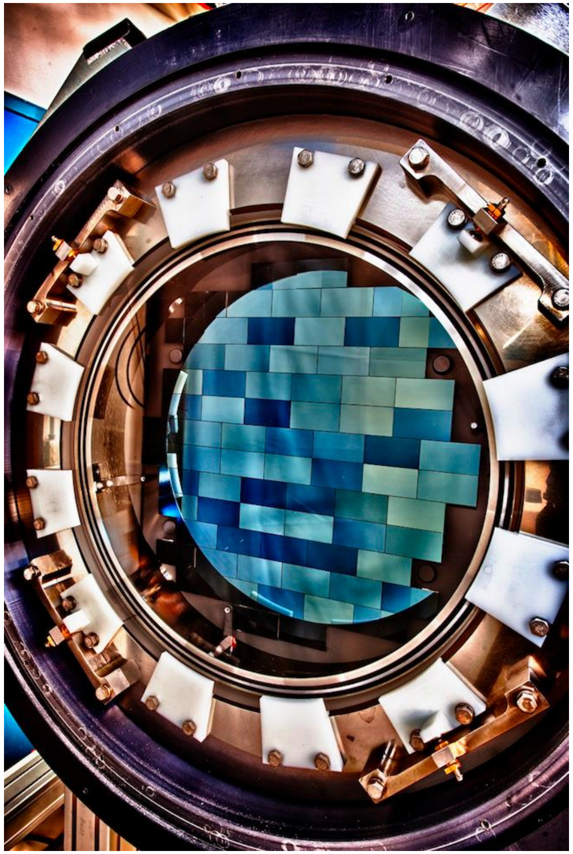
Able to see light from more than 100,000 galaxies up to 8 billion light-years away in each snapshot.

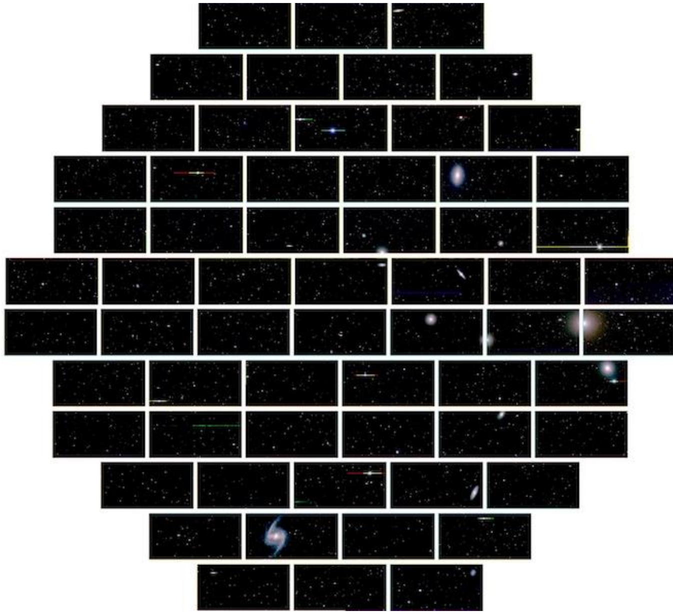


The DES Camera: 62 large CCDs – 570 megapixels.

1st light on September 12, 2012.





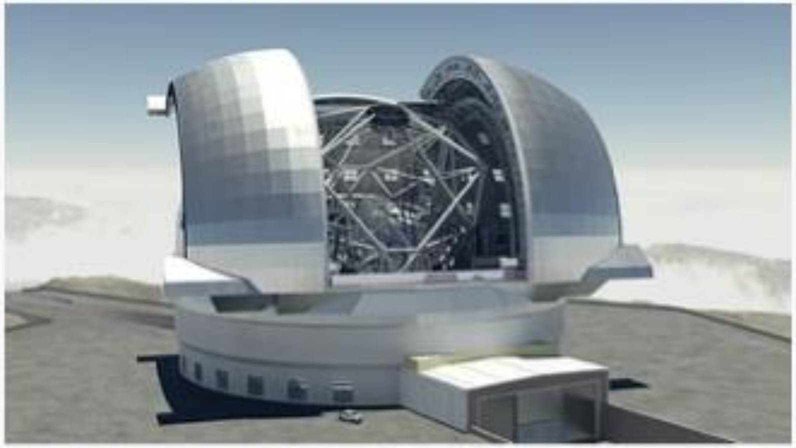


Fornax cluster of galaxies

DES image:
Barred spiral galaxy NGC 1365 in the Fornax cluster of galaxies

Future experiments

European Extremely Large Telescope (E-ELT)



An artist's impression of the E-ELT

Organization	ESO (brazilian participation?)
Location	Cerro Armazones, Chile, near Paranal Observatory
Coordinates	24°35′20″S 70°11′32″W
Altitude	3,060 m[1]
Weather	89% clear fraction,[2] 0.67″ median seeing at 500nm[3]
Wavelength	Visible, near infrared
Built	Planned completion: 2022 first light[4]
Telescope style	Reflector
Diameter	39.3 m

Future experiments: LSST

8.4-meter ground-based telescope, camera with 3200 Megapixels (will be the world's largest digital camera). First light 2020?

Future experiments: GMT

GIANT MAGELLAN TELESCOPE

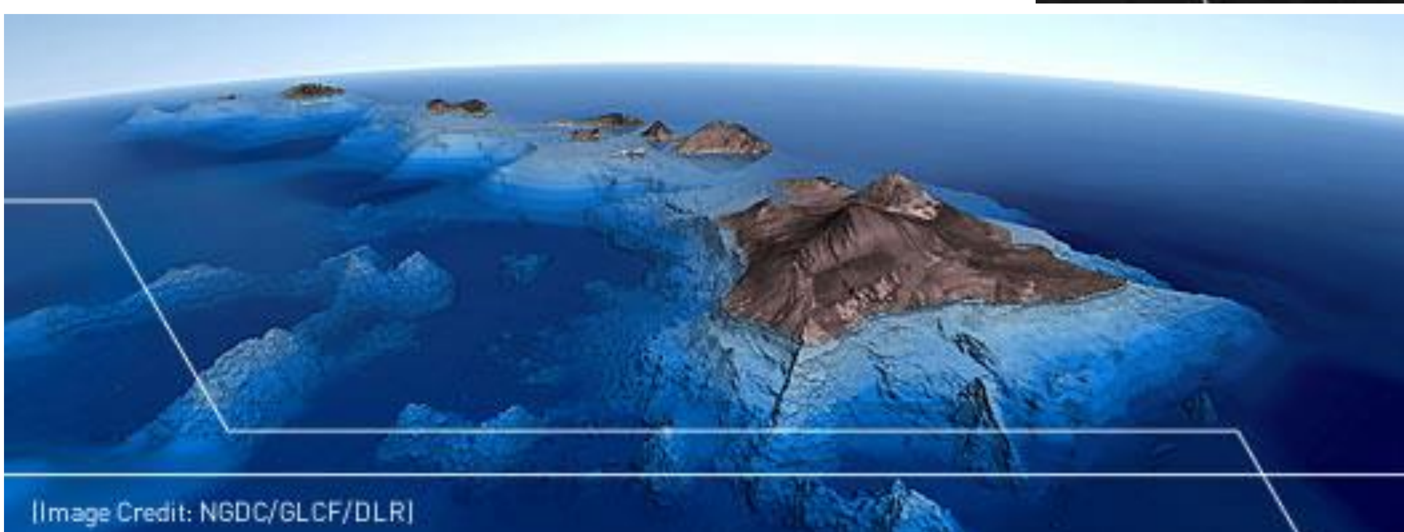
Six off-axis 8.4 meter segments surround a central on-axis segment, forming a single optical surface with an aperture of 24.5 meters in diameter. Cerro Las Campanas, Chile. Completion in 2020.

Future experiments: TMT

TMT

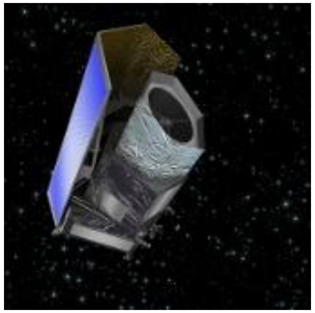
THIRTY METER TELESCOPE

Mount Mauna Kea – Hawaii. First science in 2022.



Future experiments: EUCLID

Euclid is an ESA medium class space mission selected for launch in 2020 in the Cosmic Vision 2015-2025 programme.



To achieve the Euclid's quest a satellite is under construction equipped with a 1.2 m telescope that feeds 2 instruments: a high quality panoramic visible imager (VIS), a near infrared 3-filter (Y, J and H) photometer and a slitless spectrograph (NISP). These instruments will explore the expansion history of the Universe and the evolution of cosmic structures by measuring the modification of shapes of galaxies induced by gravitational lensing effects of dark matter, and the 3-dimension distribution of structures from spectroscopic redshifts of galaxies and clusters of galaxies.

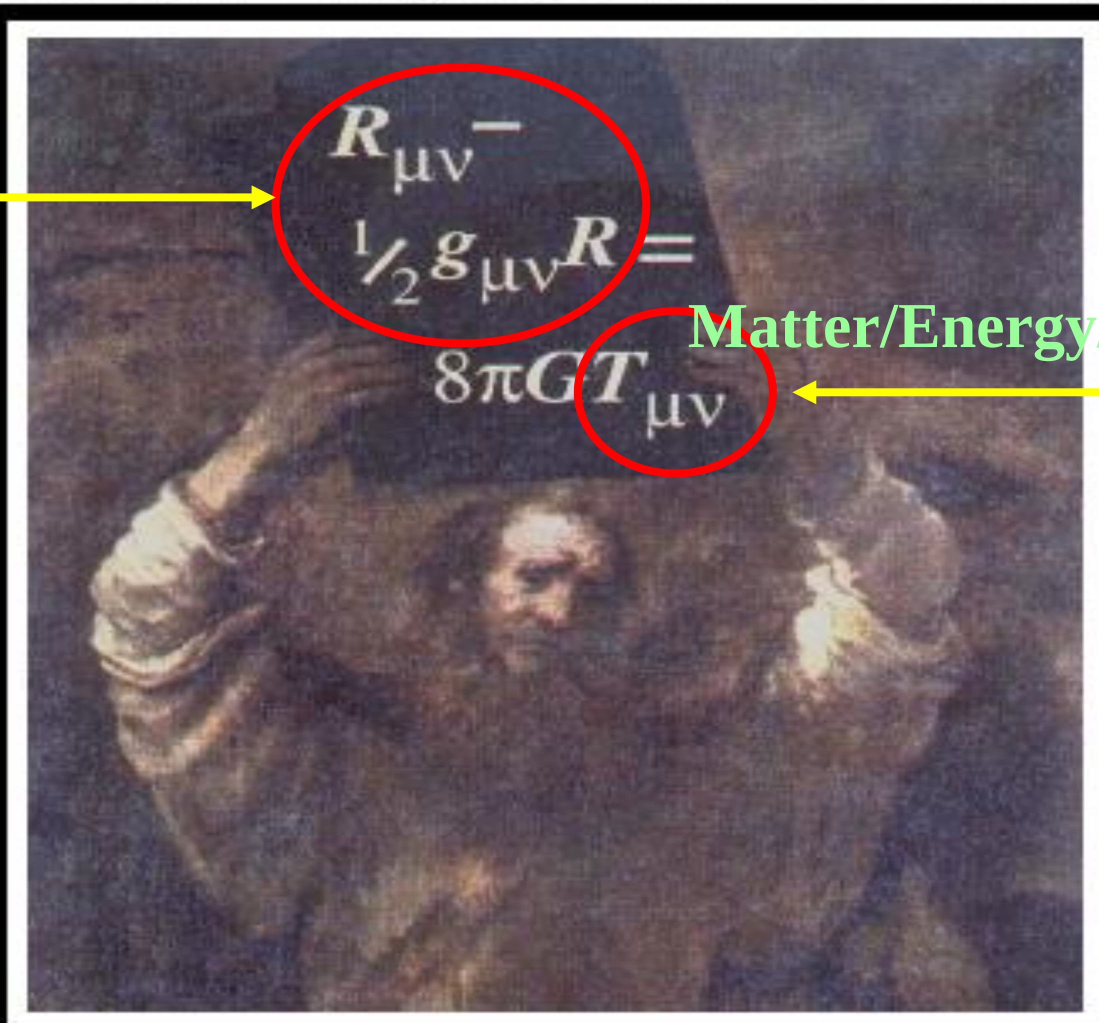
The satellite will be launched by a Soyuz ST-2.1B rocket and transferred to the L2 Lagrange point for a 6 years mission. Euclid will observe 15,000 deg2 of the darkest sky that is free of contamination by light emissions from our Galaxy and our Solar System

Standard Cosmological Model

Modern laws of Genesis

Geometry

Space tells matter how to move (J.A. Wheeler)



Matter/Energy/Pressure

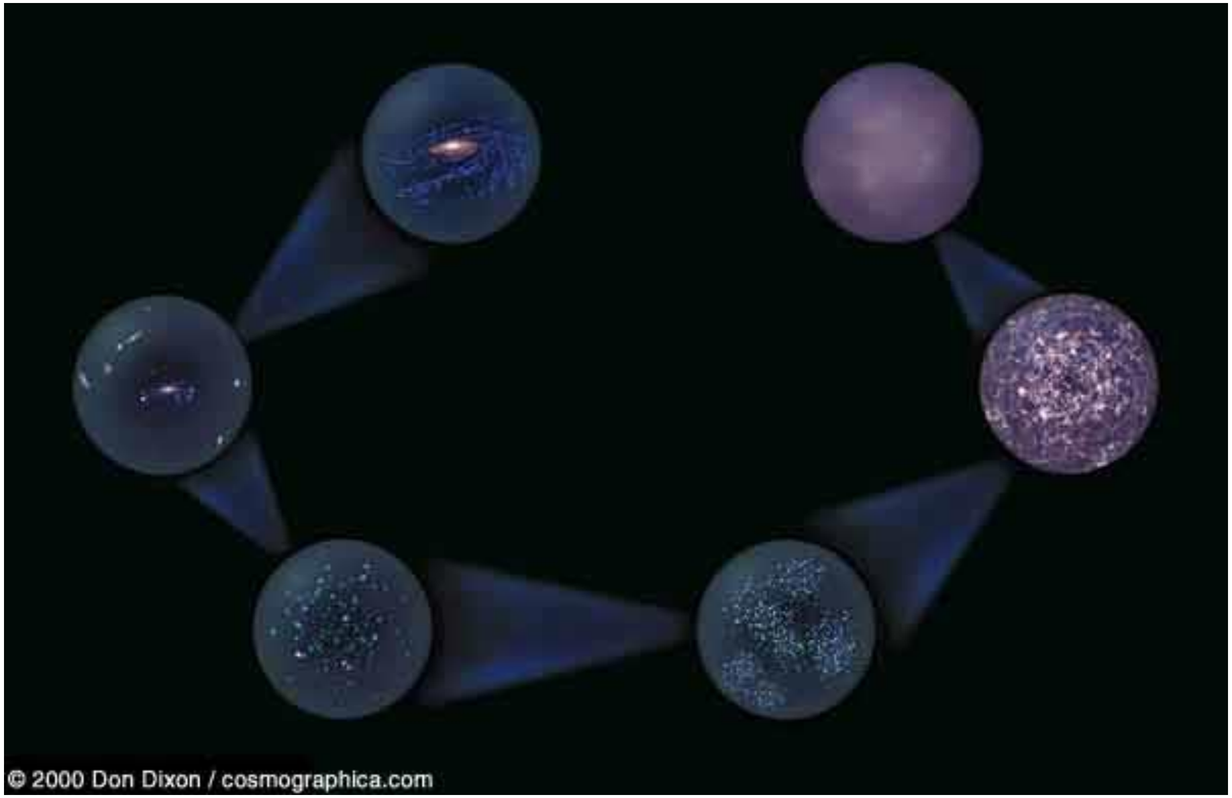
Matter tells space how to curve

Kolb

(10 nonlinear partial differential equations)

Cosmological Principle

Universe is homogeneous and isotropic at very large scales



Only small fluctuations in the CMB with $\delta T/T \sim 10^{-5}$

Geometry: left-hand side of Einstein's equation

Cosmological principle simplifies the possible geometries of the spacetime – Friedmann-Robertson-Walker metric:

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

a(t): cosmological scale factor

convention: a=1 today

physical distances: $d(t) = a(t)\, d_0$

Geometry: average evolution of the universe

- specified by <u>one function</u>: scale factor a(t)
- determines measurement of large scale distances, velocities and acceleration

$$a(t) \qquad \dot{a}(t) \qquad \ddot{a}(t)$$

- measured through standard candles (SNIa's) and standard rulers (position of CMB peak, BAO peak,...)

Redshift z: $$a(t) = \frac{1}{1+z}$$ z=0 today.

Expansion of the universe

Hubble parameter:

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

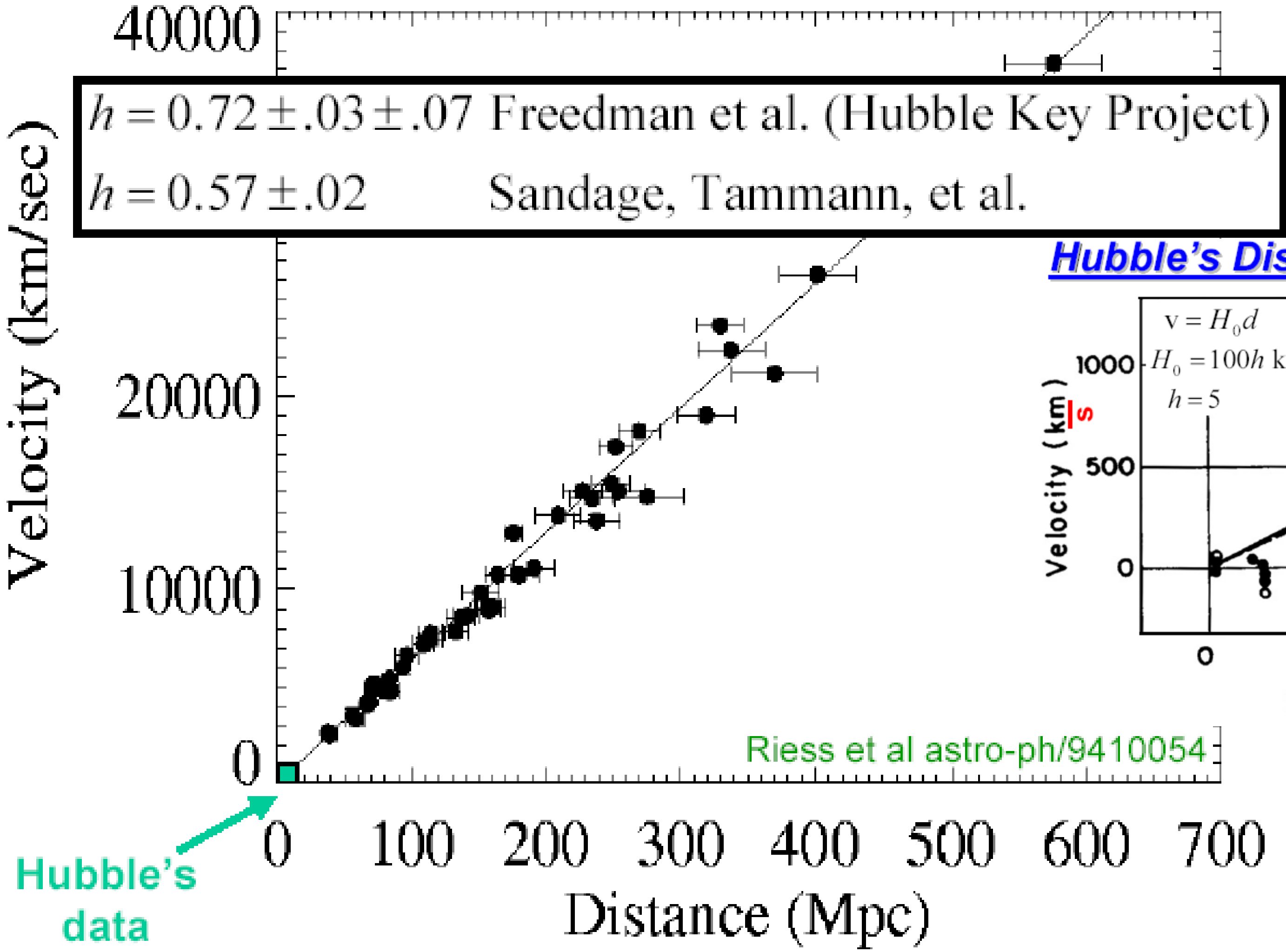
Expansion rate of the universe

Hubble constant: Hubble parameter today (H_0)

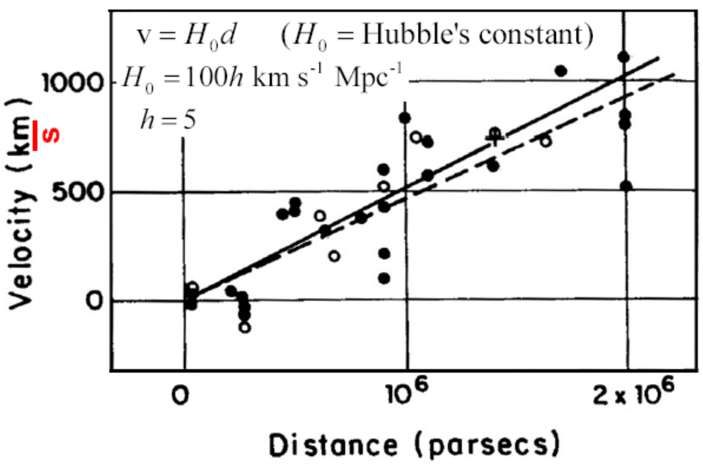
Analogy of the expansion of the universe with a balloon:

Space itself expands and galaxies get a free “ride”.

Expansion of the universe



Hubble's Discovery Paper - 1929



Universe has a history!

Energy and matter: right-hand side of Einstein's equation

All forms of matter and energy in the universe are described by the energy-momentum tensor.

Homogeneity and isotropy:

$$\rho = \sum_i \rho_i$$

$$p = \sum_i p_i$$

$$T^{\mu\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

i= matter (baryonic or dark), radiation, neutrinos, cosmological constant, quintessence, ...

DM and DE in the universe

Dark matter and dark energy affect:

• Expansion history of the universe
(evolution of the "average")

• History of structure formation
(evolution of perturbations)

Dynamics of the universe

Follow from Einstein's equation

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

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

Expansion rate

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

$$q = -\frac{\ddot{a}}{aH^2}$$

Deceleration parameter

Critical density

The universe is spatially flat (k=0) if:

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

This critical density is time-dependent.

Today $H_0 \cong 70 \frac{km}{s\,Mpc}$ and

$$\rho_c \cong 5 \text{ protons/m}^3$$

Density parameter

Different contributions to the density of the universe:

$$\Omega_i = \frac{\rho_i}{\rho_c}$$

i= matter, radiation, dark energy, neutrinos...

Flat universe: $\sum_i \Omega_i = 1$

Dynamics of the universe

Need to determine how density of different fluids changes as a function of the scale in order to close the system of equations.

Choose an equation of state for each component:

$$p_i = \omega_i \rho_i$$

ω = 1/3 (radiation)

ω=0 (non-relativistic matter)

ω=-1 (cosmological constant)

ω = w(a) (general case)

Dynamics of the universe

1st law of thermodynamics:

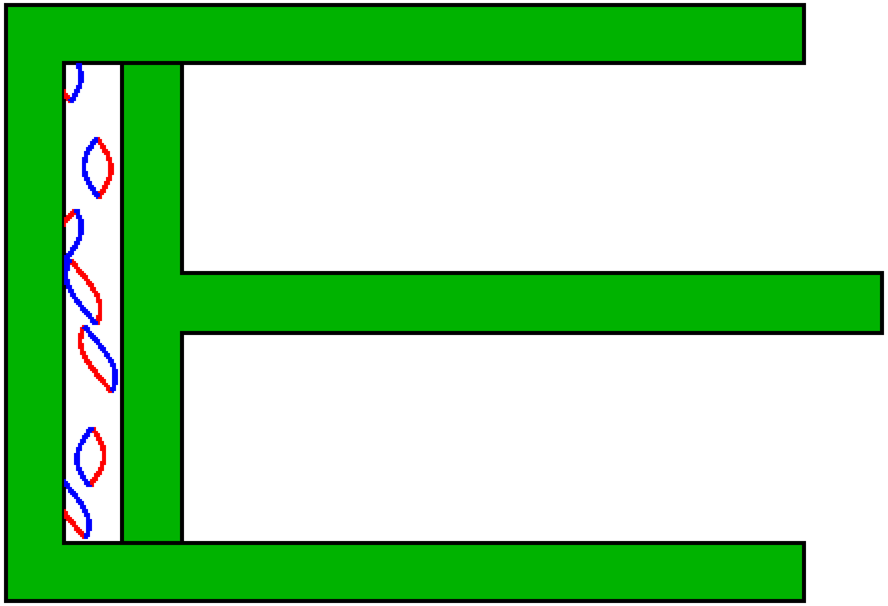
$$dE = -pdV \Rightarrow d(\rho V) = -\omega \rho dV$$

Therefore:

$$\rho \propto a^{-3(1+\omega)} \Rightarrow \begin{cases} a^{-3} (\omega_M = 0) \\ a^{-4} (\omega_R = 1/3) \\ a^{0} (\omega_\Lambda = -1) \end{cases}$$

Vacuum energy

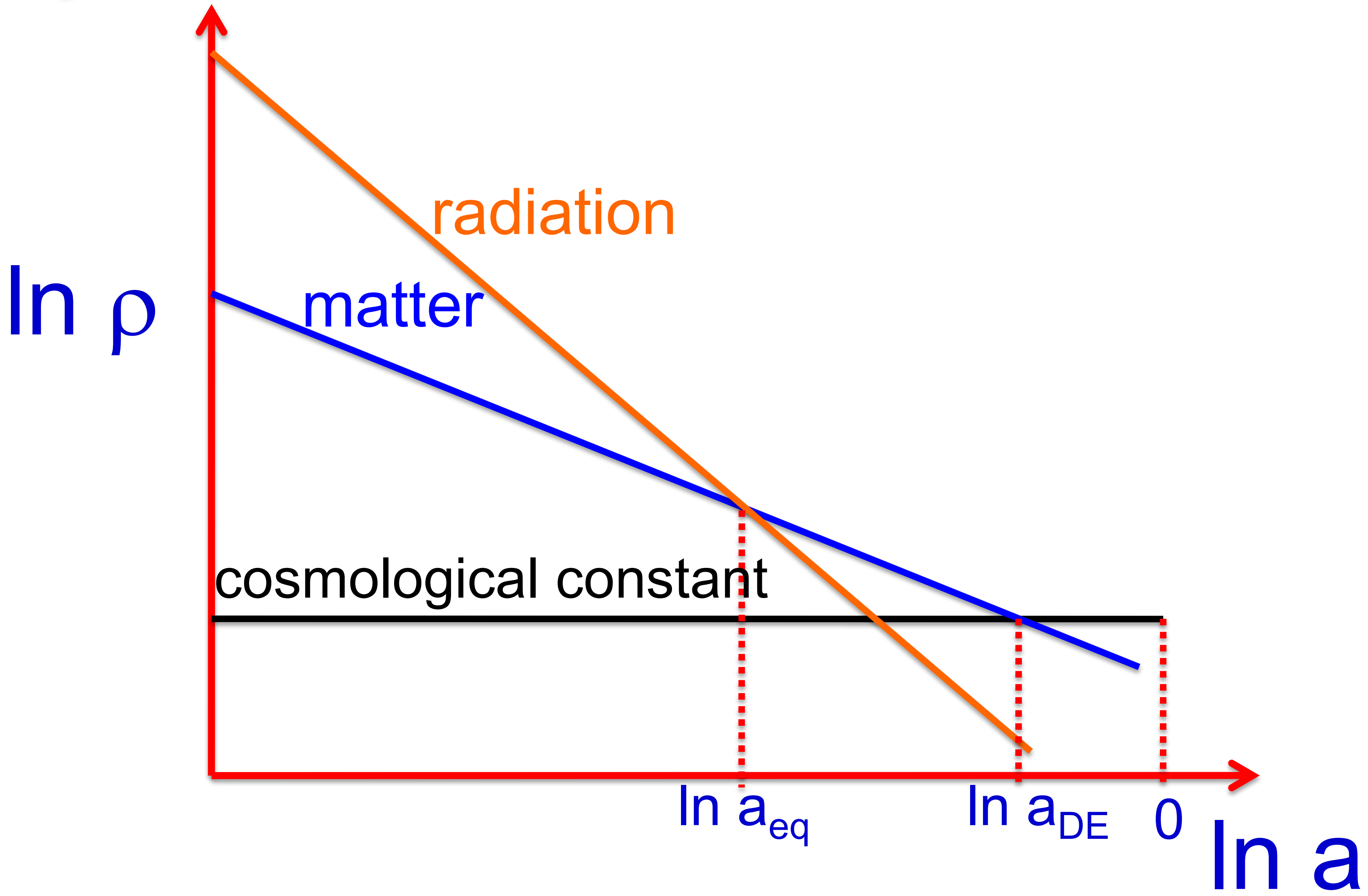
$$\rho_\Lambda \propto \text{constant}$$



E. L. Wright

$$dE = -pdV \Rightarrow p_\Lambda < 0$$

Dynamics of the universe



Model for the smooth universe

- Einstein's equation

- Different components and their densities

$$\Omega_i = \frac{\rho_i}{\rho_c}$$

- Equation of state for each component

$$p_i = w_i \rho_i$$

- Hubble's constant $H_0(h_0)$

$$H_0 = 100\, h_0 \frac{km}{s\, Mpc}$$

Ex.1: Estimate how many photons exist in a cm^3 today given that the CMB temperature is approx. 2.7 K

Ex.2: Estimate the fraction of photons to protons today, given that $\Omega_b = 0.04$

Ex.3: Estimate the fraction of energy in photons to protons today.

Ex.4: Estimate the redshift at which photons and matter have equal energy density.

Ex.5: Estimate the redshift at which photons decouple from atoms (last scattering surface).

Ex.6: estimate the age of the universe

$$t_0 = \int_0^{t_0} dt = \int_0^{a_0=1} \frac{da}{\dot{a}}$$

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\rho_\gamma + \rho_m + \rho_\phi\right) =$$

$$H_0^2\left(\Omega_\gamma a^{-3(1+\omega_\gamma)} + \Omega_m a^{-3(1+\omega_m)} + \Omega_\phi a^{-3(1+\omega_\phi)}\right)$$

$$t_0 = \frac{1}{H_0}\int_0^1 \frac{da}{a}\frac{1}{\sqrt{\left(\Omega_\gamma a^{-3(1+\omega_\gamma)} + \Omega_m a^{-3(1+\omega_m)} + \Omega_\phi a^{-3(1+\omega_\phi)}\right)}}$$

Age of the universe:

Hubble time:

$$t_H = H_0^{-1} = 3.09 \times 10^{17} h^{-1} \text{ sec} = 9.78 \times 10^9 h^{-1} \text{ yr.}$$

```
In[14]:= Ωm = 0.315; Ωr = 8.24 × 10^-5; ΩL = 1 - Ωm - Ωr; h0 = 0.7; wm = 0; wr = 1 / 3; wL = -1;
         tH = 9.78 × 10^9 h0^-1;
```

$$\text{In[8]:= tU = tH NIntegrate}\left[\frac{1}{a} * \frac{1}{\sqrt{\Omega m\, a^{-3*(1+wm)} + \Omega L\, a^{-3*(1+wL)} + \Omega r\, a^{-3*(1+wr)}}}, \{a, 0, 1\}\right]$$

Out[8]= 1.32818×10^{10}

Ex.7: Estimate the redshift at which the universe starts to be dominated by dark energy (= Λ).

Calculate the redshift where dark energy and matter have equal energy density (Ωm=0.315)

- **Equal densities:** $\rho_\Lambda = \rho_m a^{-3}$, $a_\Lambda = \left(\frac{\rho_m}{\rho_\Lambda}\right)^{1/3} = \left(\frac{\Omega_m}{\Omega_\Lambda}\right)^{1/3}$

In[1]:= $a_\Lambda = \left(\frac{0.315}{1 - 0.315}\right)^{1/3}$

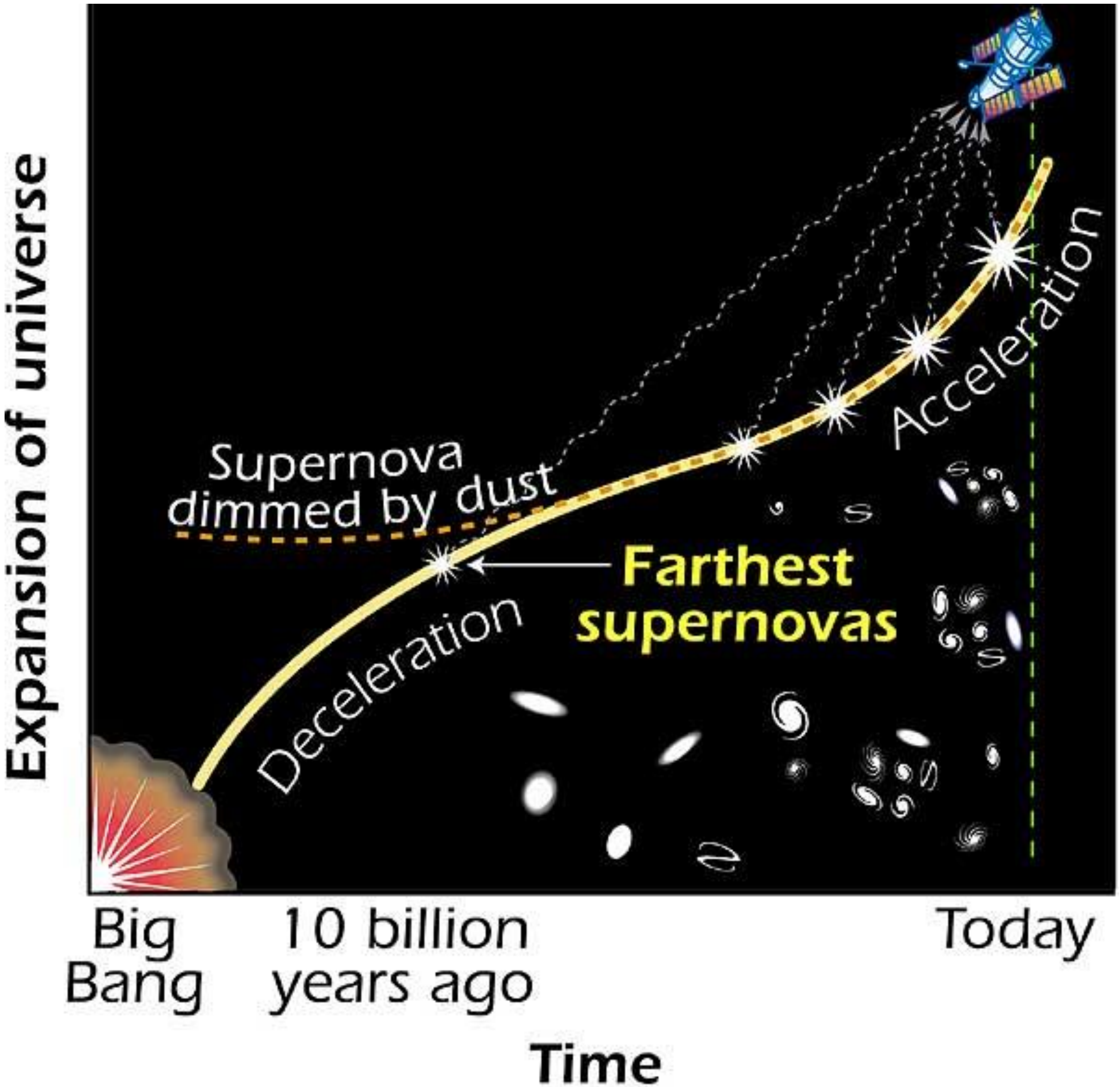
Out[1]= 0.771863

In[2]:= $z_\Lambda = \frac{1}{a_\Lambda} - 1$

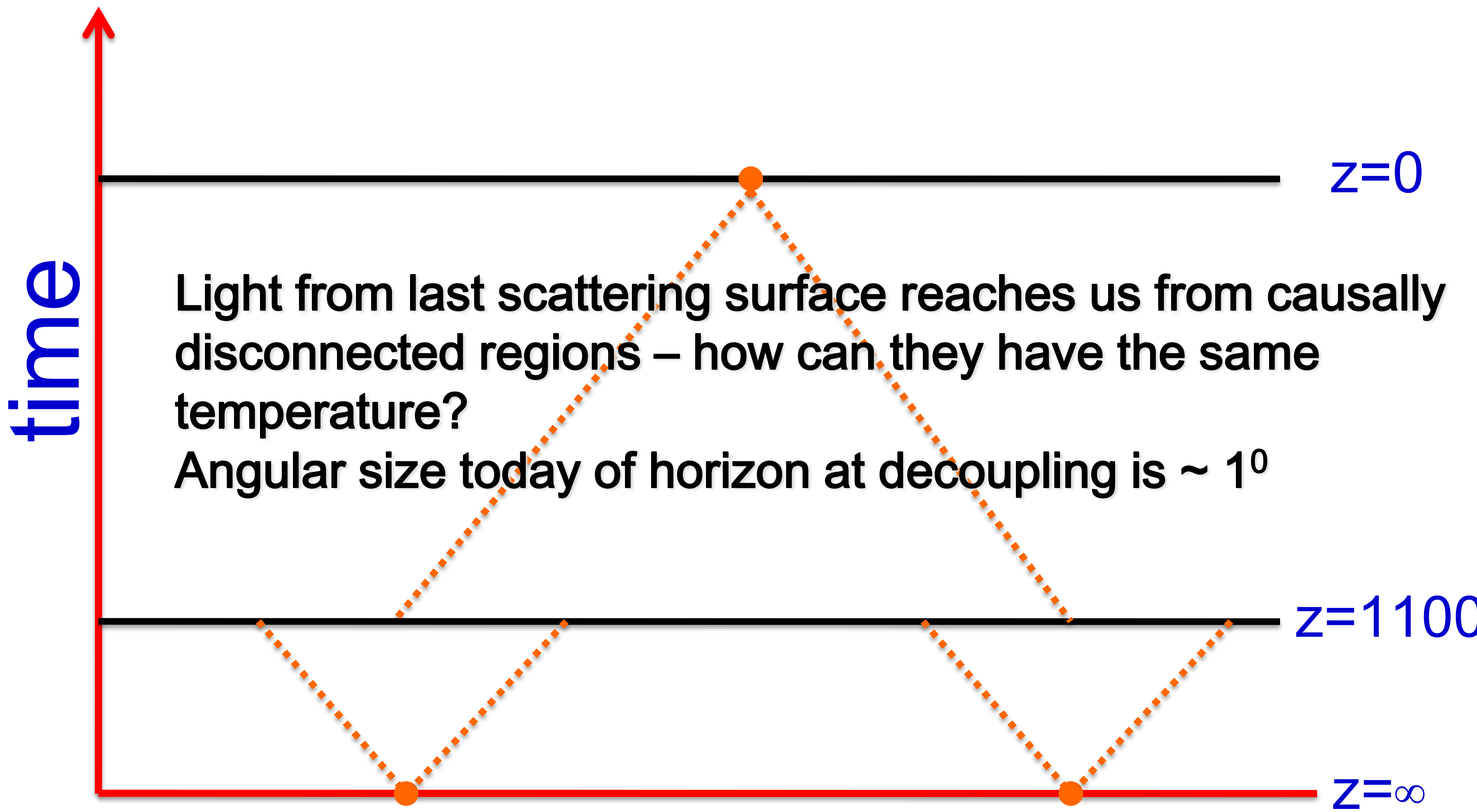
Out[2]= 0.295567

Cosmological coincidence problem

Why now?


Expansion of universe
Supernova
dimmed by dust
Farthest
supernovas
Deceleration
Acceleration
Big
Bang
10 billion
years ago
Today
Time

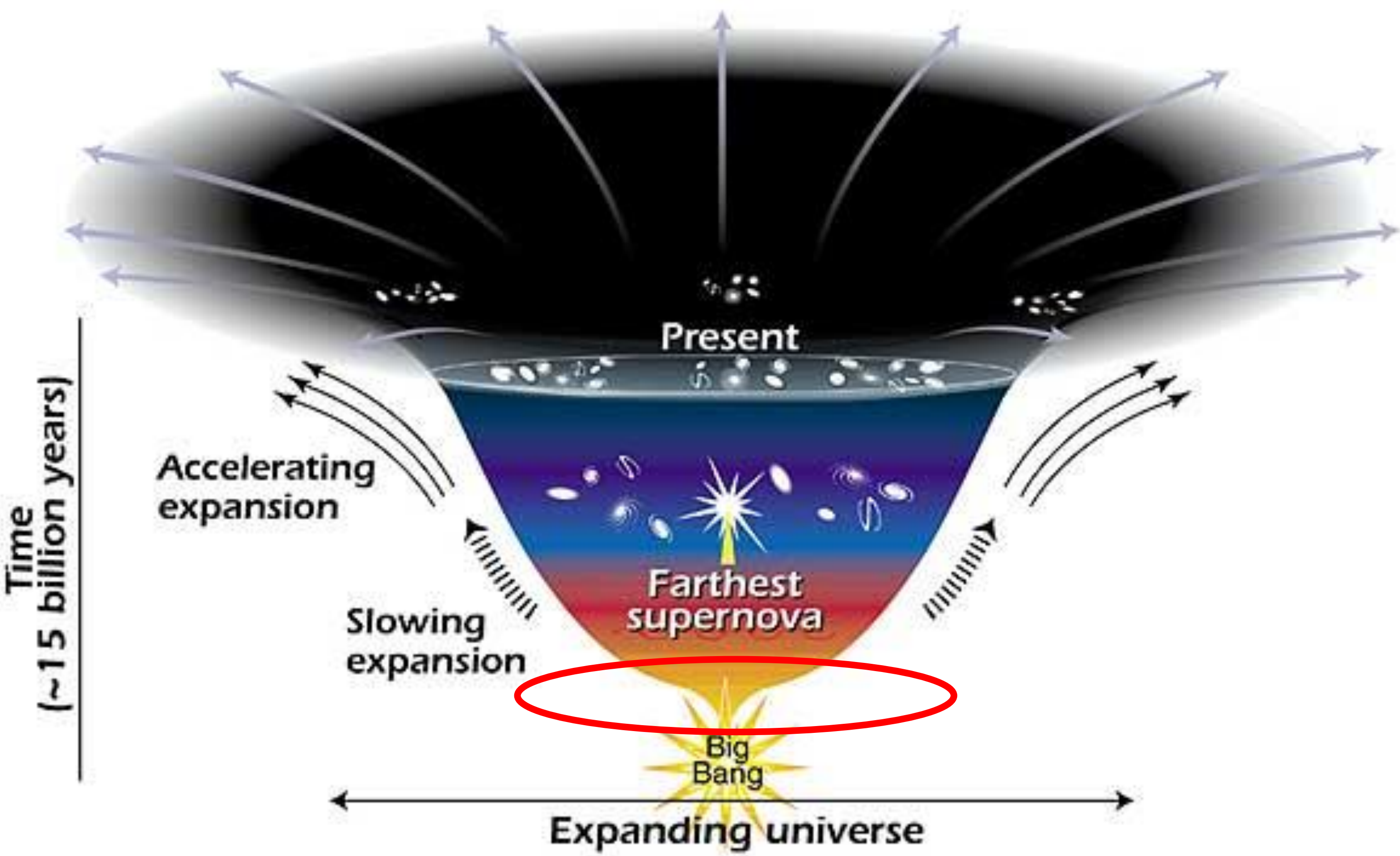
The causality problem

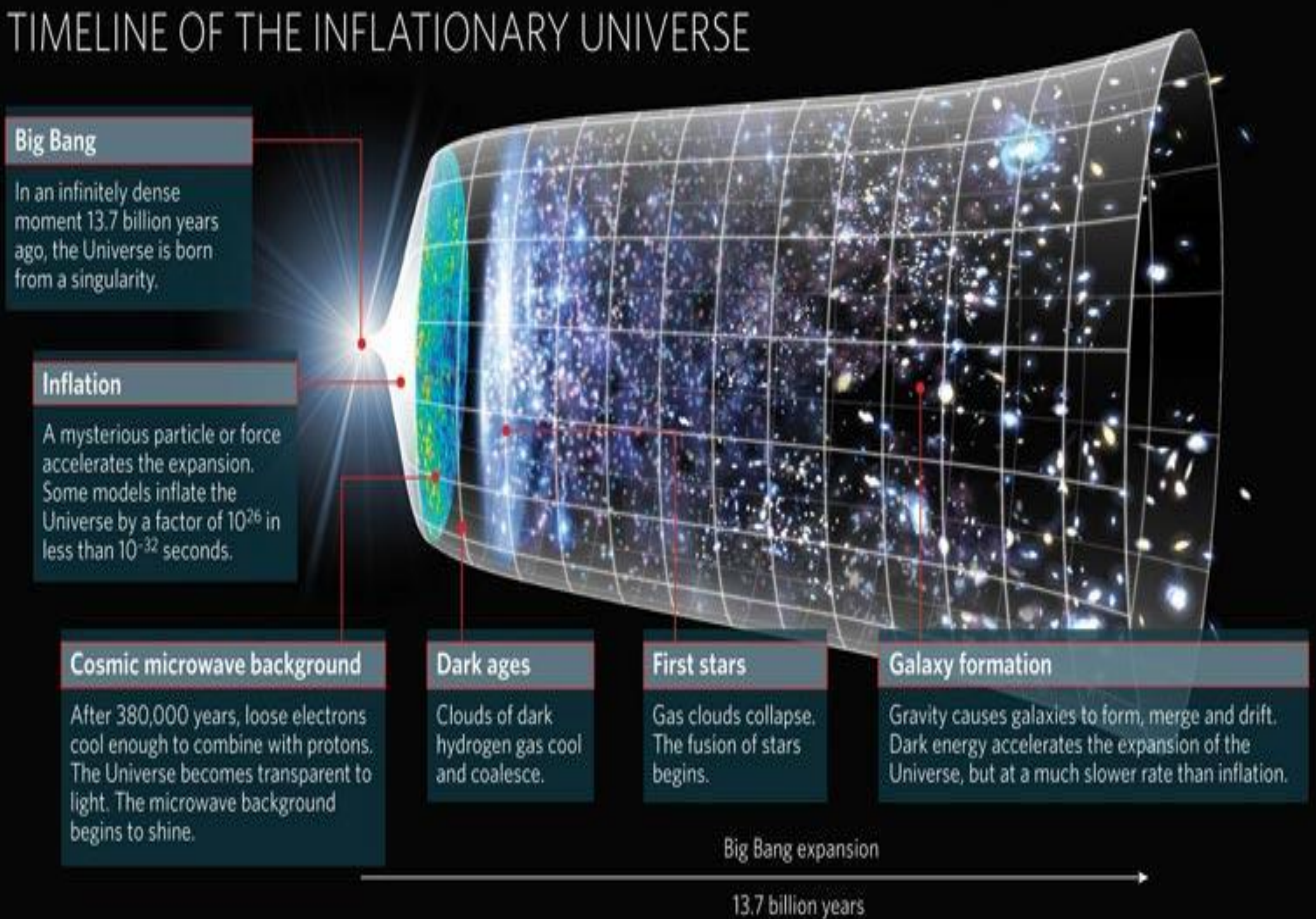


Light from last scattering surface reaches us from causally disconnected regions – how can they have the same temperature?

Angular size today of horizon at decoupling is ~ 1^0

Solution: inflation




TIMELINE OF THE INFLATIONARY UNIVERSE
Big Bang
In an infinitely dense moment 13.7 billion years ago, the Universe is born from a singularity.
Inflation
A mysterious particle or force accelerates the expansion. Some models inflate the Universe by a factor of 10^26 in less than 10^-32 seconds.
Cosmic microwave background
After 380,000 years, loose electrons cool enough to combine with protons. The Universe becomes transparent to light. The microwave background begins to shine.
Dark ages
Clouds of dark hydrogen gas cool and coalesce.
First stars
Gas clouds collapse. The fusion of stars begins.
Galaxy formation
Gravity causes galaxies to form, merge and drift. Dark energy accelerates the expansion of the Universe, but at a much slower rate than inflation.
Big Bang expansion
13.7 billion years

Solution: inflation

Exponential growth of the universe.

For instance, if a flat universe is dominated by a vacuum energy:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_\Lambda = H^2 = const \Rightarrow$$

$$a(t) \propto e^{Ht}$$

Solution: inflation

- Solves causality (horizon) problem

- Explains why $\Omega_{TOT} = 1$ (flatness problem)

- Generates small perturbations from quantum fluctuations that become seeds for the large scale structure of the universe

Encyclopædia Inflationaris

http://arxiv.org/1303.3787

Jérôme Martin,[a] Christophe Ringeval[b] and Vincent Vennin[a]

Dark energy

The universe today is again dominated by some sort of vacuum energy – dark energy – and the expansion is accelerated.

Is this vacuum energy today related to the vacuum energy that generated inflation?

What is dark energy?

Some sort of vacuum energy – a huge embarassment!

Quantum mechanics:"zero point energy"

$$E = \hbar\omega(n + 1/2)$$

In Quantum Field Theory, the energy density of the vacuum is (free scalar field of mass m):

$$\rho_{vac} = \int \frac{d^3k}{(2\pi)^3} \frac{1}{2} \sqrt{k^2 + m^2}$$

It is infinite!!

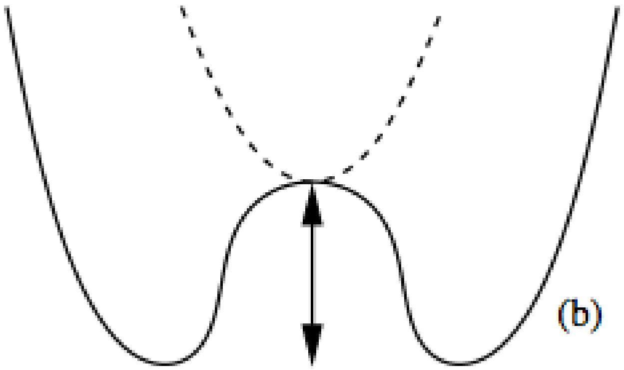
If integral is cutoff at the Planck scale, disagreement of ~ 10^{120} with data.

Cosmological constant problem

What is dark energy?

Vacuum energy modelled by a scalar field:

. Field at the minimum of its potential, such as the Higgs field (indistinguishable from a cosmological constant).



(b)

. Field not yet at the minimum – still rolling down its potential – "quintessence" or dynamical dark energy. Requires a very light field ($m \sim H_0 \sim 10^{-33}$ eV).

New long-range forces when coupled to normal stuff? Ways to shield this forces (chameleon models)?

Some examples of dark energy models:

Cosmological Constant $p_\Lambda = -\rho_\Lambda$

Canonical Scalar Field:
Quintessence $\mathcal{L}_Q = \frac{1}{2}\partial^\mu\varphi\partial_\mu\varphi - V(\varphi)$

Perfect Fluid $p_0 = w\rho_0$ $\delta p = c_{\text{eff}}^2 \delta\rho$

Chaplygin Gas $\rho_{Ch} = -A\rho_{Ch}^{-\alpha}$

K-essence $\mathcal{L} = F(X, \varphi)$ $X = \frac{1}{2}\partial^\mu\varphi\partial_\mu\varphi$

e.g. Tachyon,
Born-Infeld $\mathcal{L}_T = V(\varphi)\sqrt{1 - \partial^\mu\varphi\partial_\mu\varphi}$

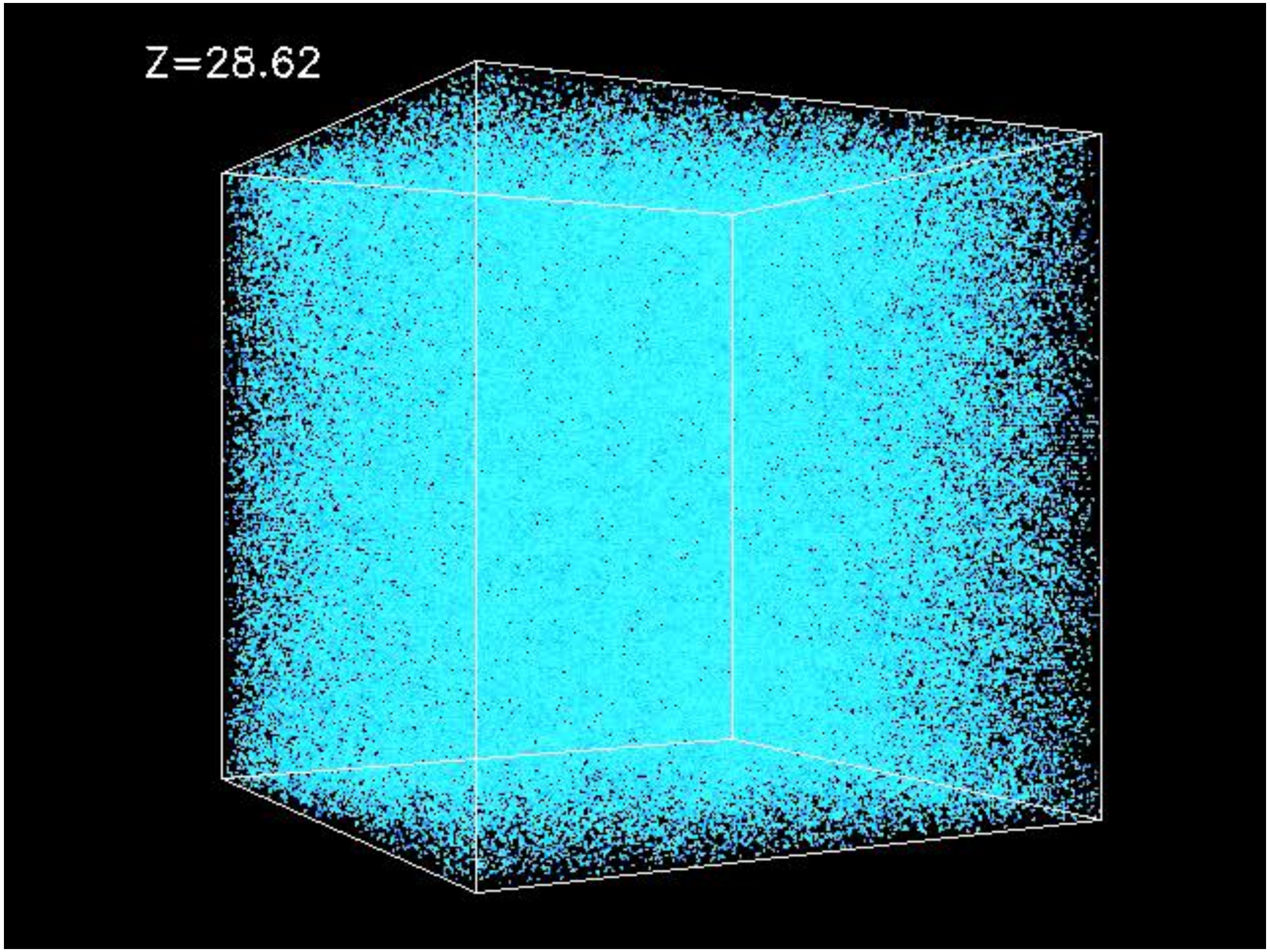
Dark energy and structure formation

Dark energy impacts the formation of structures (galaxies, cluster, etc) in the Universe.

Universe started out very homogeneous with small perturbations generated at Inflation that grew under grav. instability.

Large scale structure: N-body simulations

Universe in a box (A. Kravtsov)



The movie illustrates the formation formation of clusters and large-scale filaments in the Cold Dark Matter model with dark energy. Evolution of structures in a 43 Mpc box from redshift of 30 to the present epoch . At the initial epoch (z=30), when the age of the Universe was less than 1% of its current age, distribution of matter appears to be uniform. As time goes on, the fluctuations grow resulting in a wealth of structures from the smallest bright clumps which have sizes and masses similar to those of galaxies to the dark large filaments.

Evolution of small perturbations:

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

It is not possible to fully describe the non-linear regime in RG:
large numerical simulations are necessary (Millenium, MareNostrum, etc…)

Linear growth of perturbation δ

linearized equation:

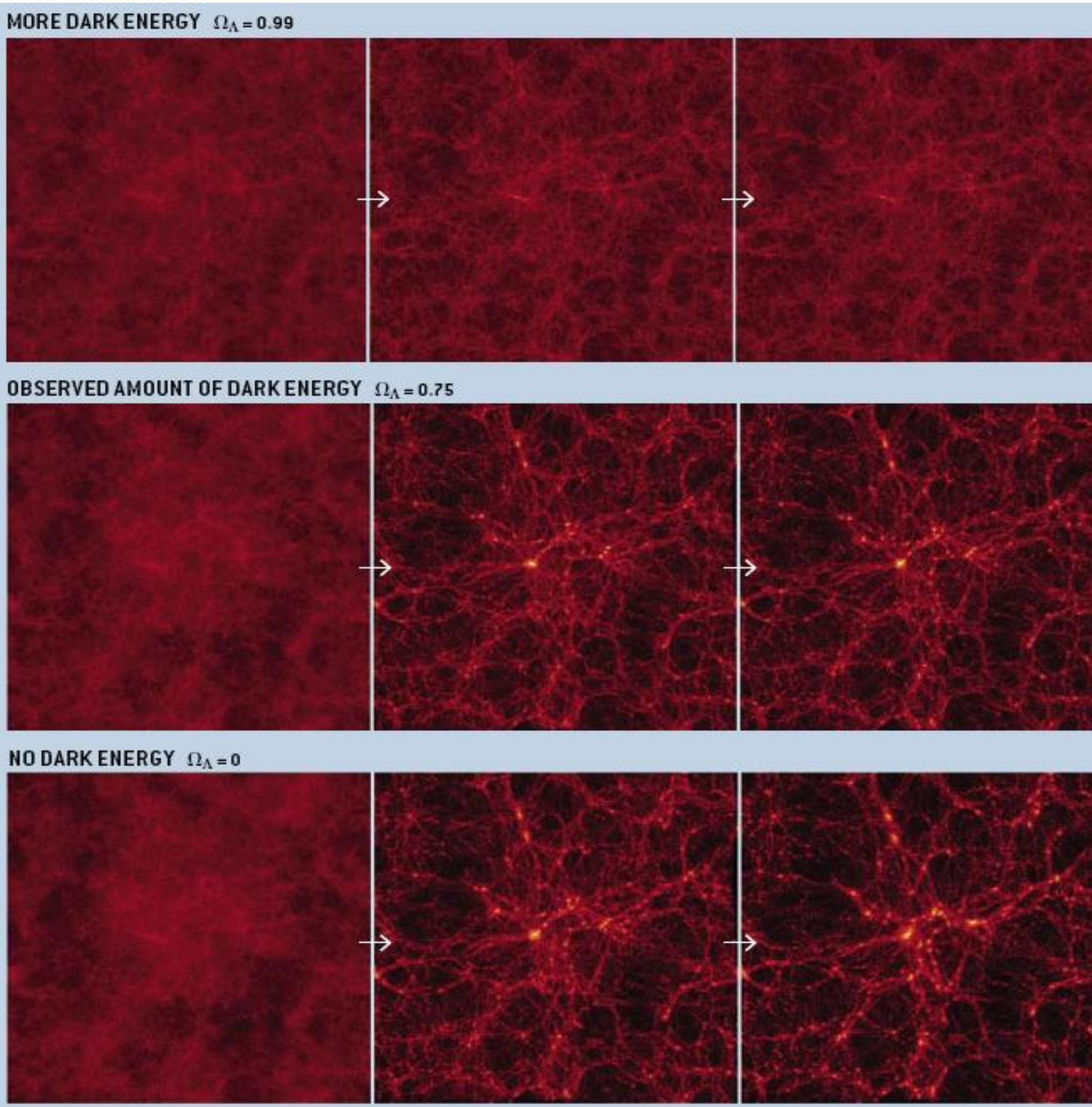
$$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}} = \frac{\delta\rho}{\bar{\rho}}$$

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho\,\delta = 0$$

$$\delta(a) \propto a = \frac{1}{1+z}$$ dark matter dominated universe

$$\delta(a) \propto a^0$$ dark energy dominated universe

Dark energy suppresses structure formation
(Weinberg's anthropic argument)



EARLY UNIVERSE: When the universe is a sixth of its current size, matter is evenly distributed in all three scenarios. Dark energy has not yet exerted its influence.

TRANSITION PERIOD: When the universe is 75 percent of its current size, the effects of dark energy are stark. In the high dark energy scenario (*top*), the universe looks amorphous. In the other two scenarios, structure formation still continues, producing a cobweb pattern.

TODAY: In a universe with the observed amount of dark energy (*middle*), large-scale structure formation has ended, leaving the cobweb frozen in place. In a zero dark energy scenario (*bottom*), the cobweb continues to develop.

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Dark energy and Modified Gravity

Maybe Einstein's equations need to be Modified ("left-hand side" is the culprit) in order to describe the evolution of the Universe.

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} + L_m \right]$$

Modified gravity: $R \rightarrow f(R)$

Tests of Dark energy and Modified Gravity

Novel Probes of Gravity and Dark Energy

1309.5389

Test	Observations	Telescopes and Facilities
Consistency of growth and expansion	Planned dark energy program with imaging and spectroscopic surveys	DES, BOSS, DESI, LSST, Euclid, WFIRST
Lensing vs. Dynamical mass	Imaging and spectroscopic observations	Fraction of time on planned surveys + $O(100)$ nights on 4-m class spectroscopic telescopes
Astrophysical Tests	Multi-wavelength observations of nearby galaxies	2-4m class IFU spectroscopic telescopes; High resolution optical imaging; High resolution radio (21cm) observations
Lab and Solar System Tests	Sensitivity improvements to torsion pendulum, neutron, and lunar laser ranging experiments; adaptations to axion experiments	Eöt-Wash, NIST, JLab, CAST

Table 3. *Resources needed for experimental tests of gravity in the next decade. See Figure 5 and Table 2 for information on the tests.*

Conclusions on Dark energy

- There are many models to describe dark energy

- All observations so far can be explained by a simple model with a cosmological constant: ΛCDM

- Any deviations will be revolutionary

- New instruments to continue measuring what the universe is made of!