Primordial Universe and Cosmic Inflation

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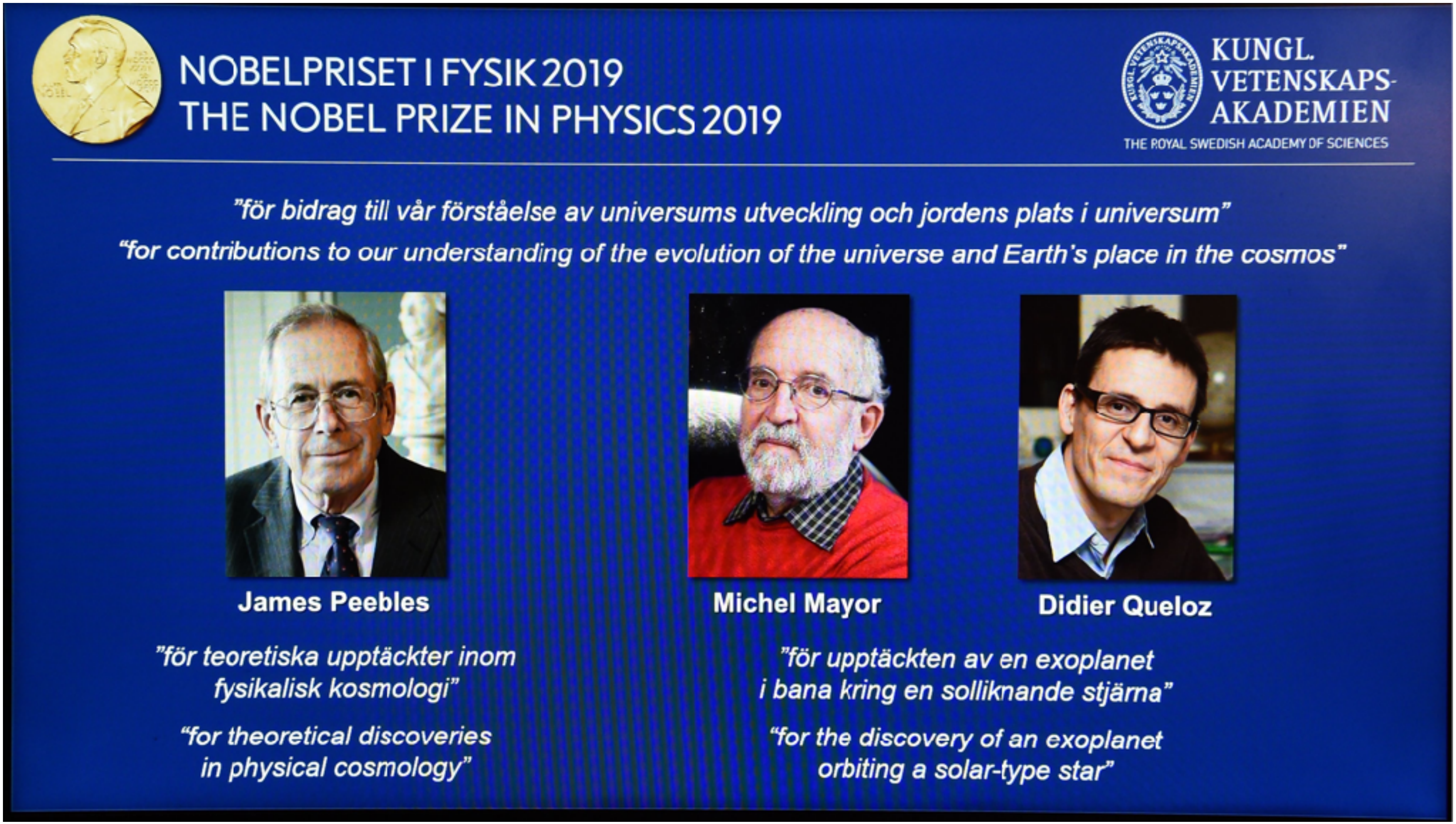
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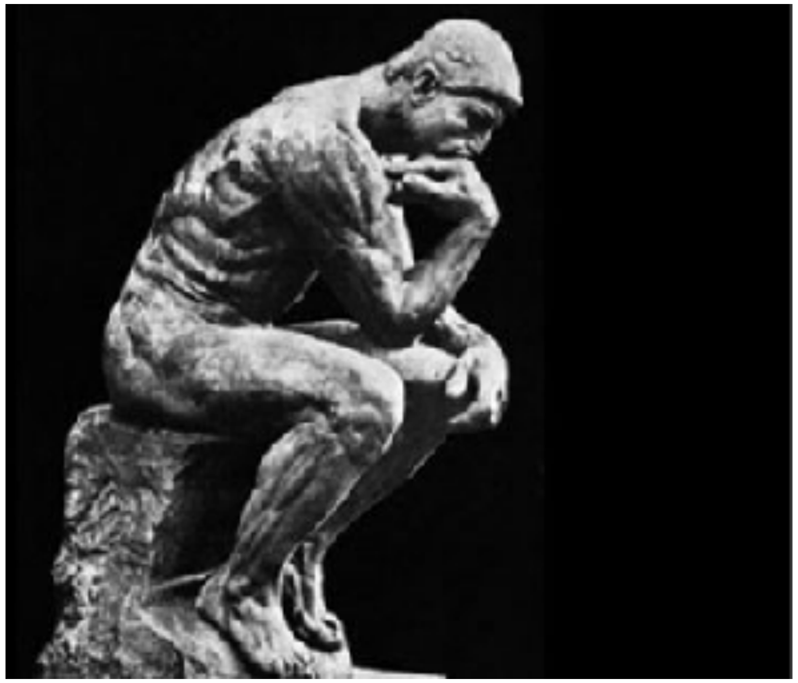
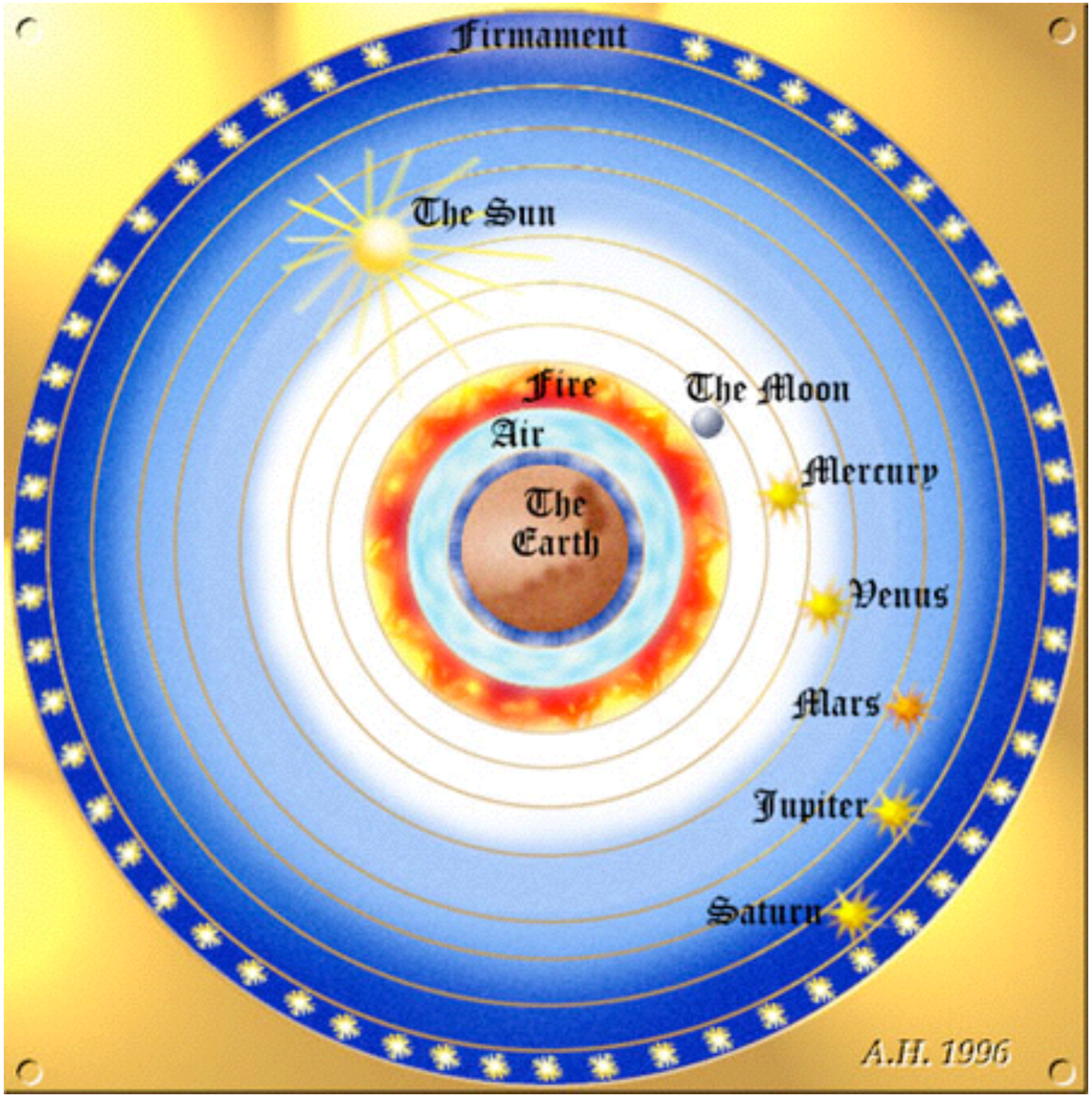
KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES
”för bidrag till vår förståelse av universums utveckling och jordens plats i universum”
“for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos”
James Peebles
Michel Mayor
Didier Queloz
”för teoretiska upptäckter inom fysikalisk kosmologi”
“for theoretical discoveries in physical cosmology”
”för upptäckten av en exoplanet i bana kring en solliknande stjärna”
“for the discovery of an exoplanet orbiting a solar-type star”

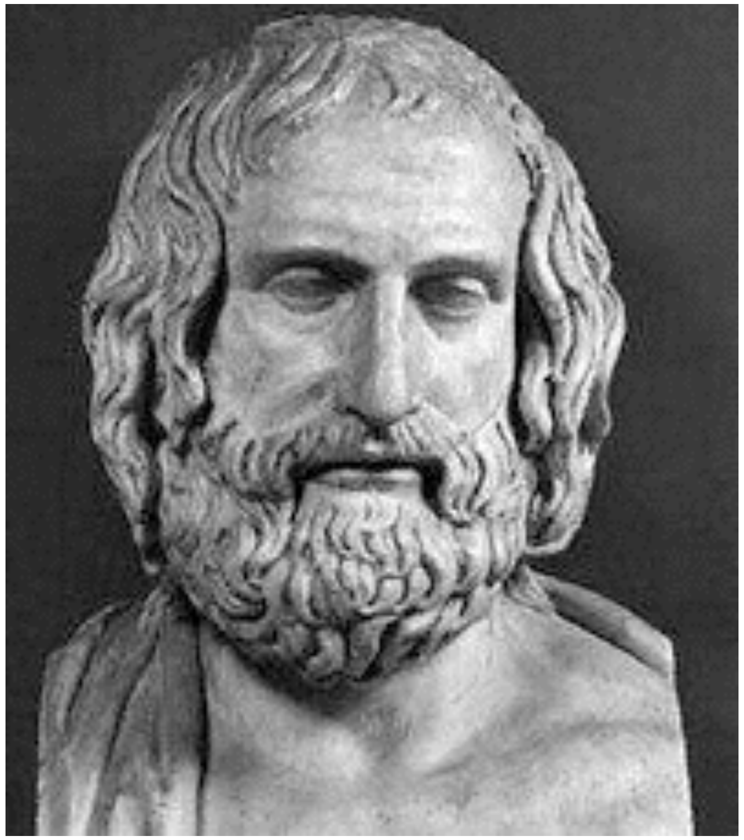
Cosmology: The science of the Universe as a whole

- Nature is written in the mathematical language (Galileo).
- The laws of physics are the same in all Universe.
- We (the observers) do not occupy specific location in space and time (The Copernicus principle).
- The Universe is comprehensible by human.
- The laws of physics at the smallest scales are the building blocks to uncover the dynamics of Universe on largest scales.
- Cosmology is a God-given laboratory to understand the laws of physics at the deepest level. Not to mention a lot of philosophical insights!

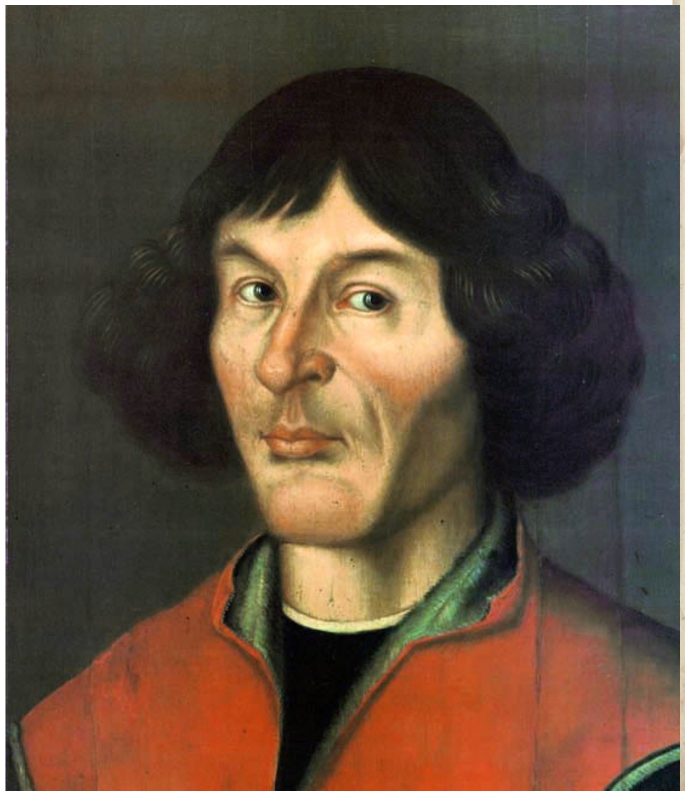


اولین مدل کیهان شناسی

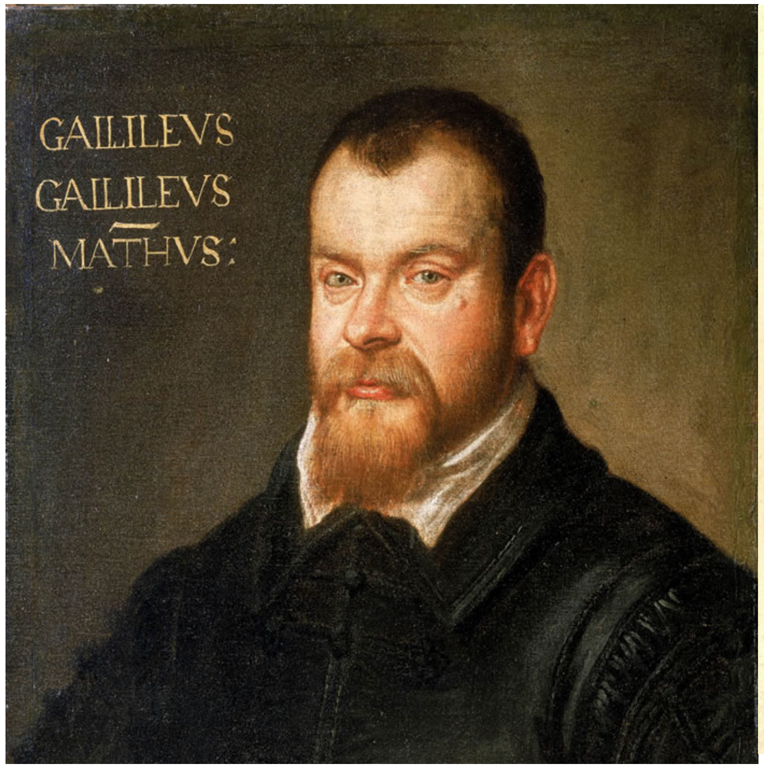


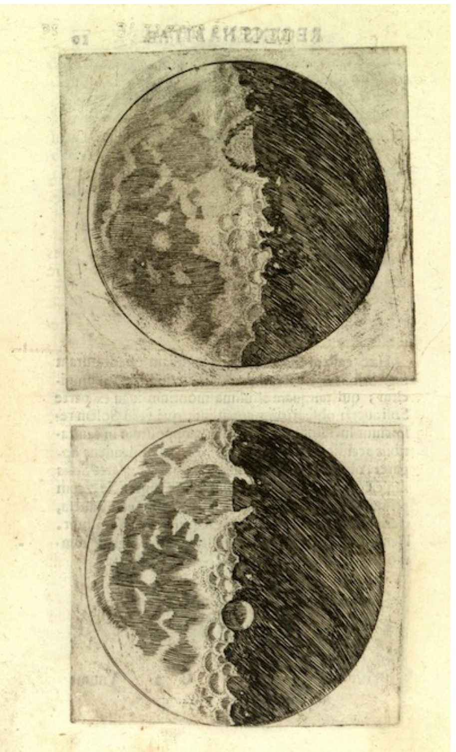


Copernicus:
De Revolutionibus Orbium Coelestium (1543)

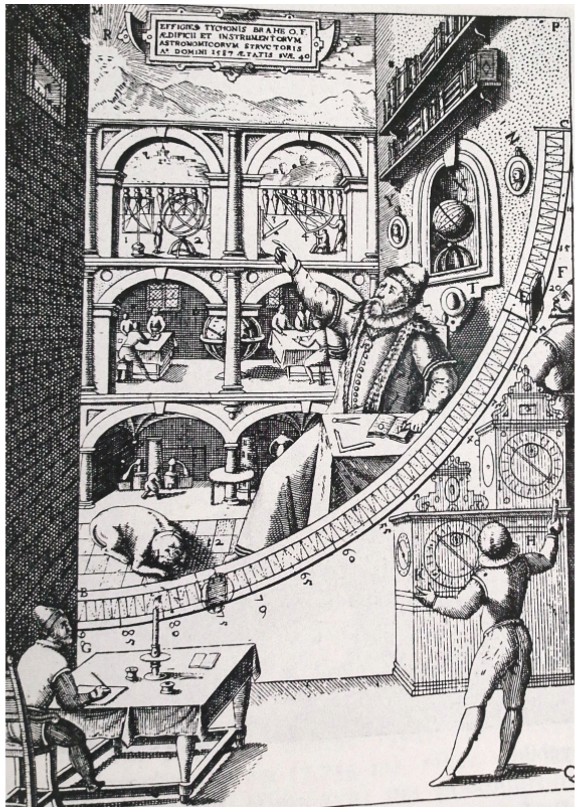


Galileo: Starry Messenger (1610), Dialogue Concerning the Two Chief World Systems(1632)

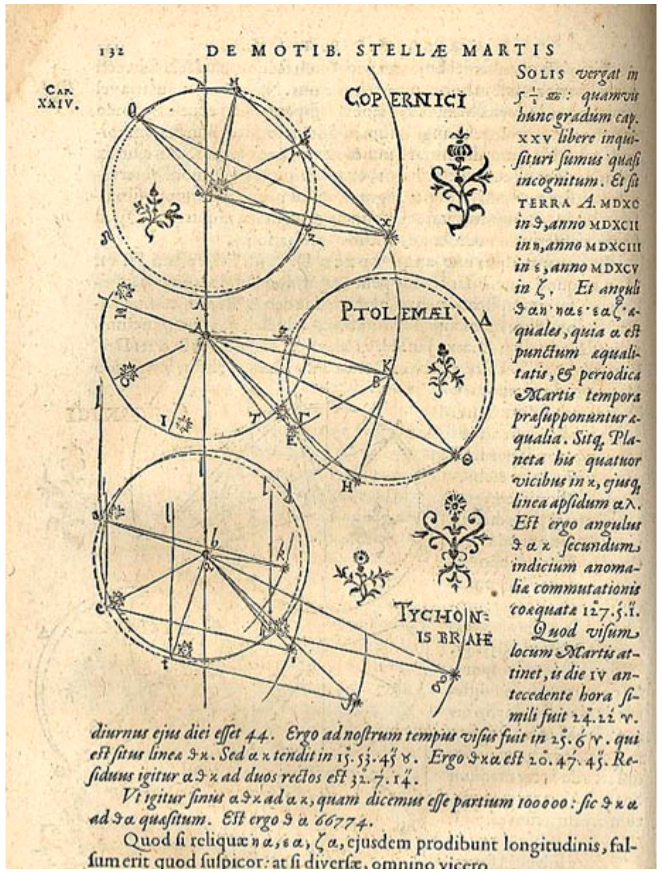




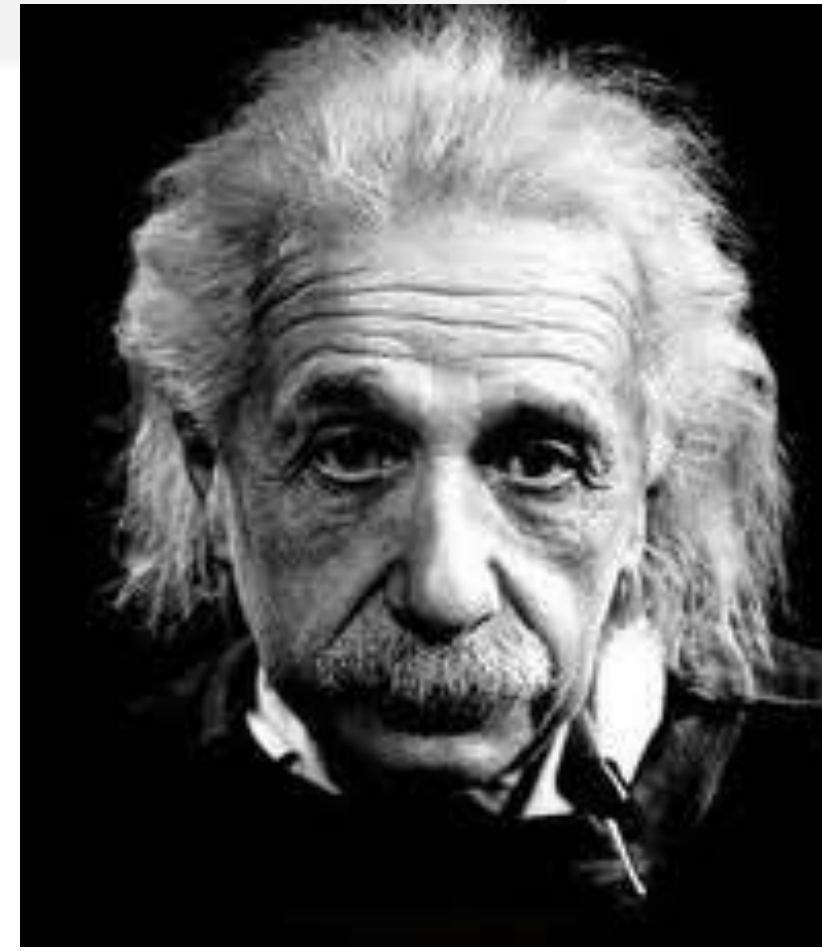
Tycho Brahe



Kepler: Astronomia Nova (1609)



Einstein Gravity



There is no separate notion of " space" and " time.

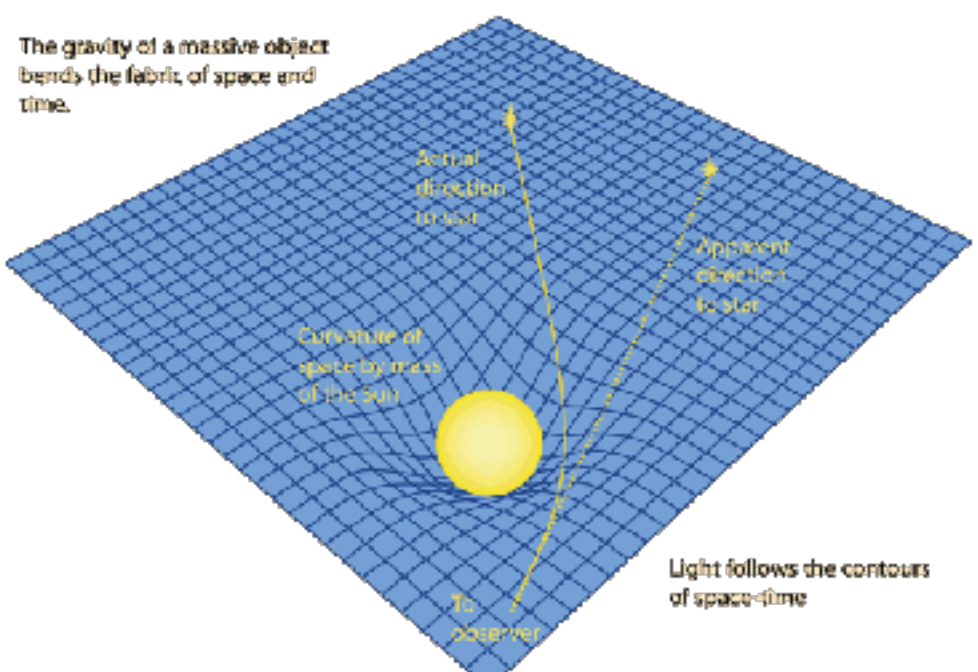
We have the spacetime as the 4-dimensional manifold.

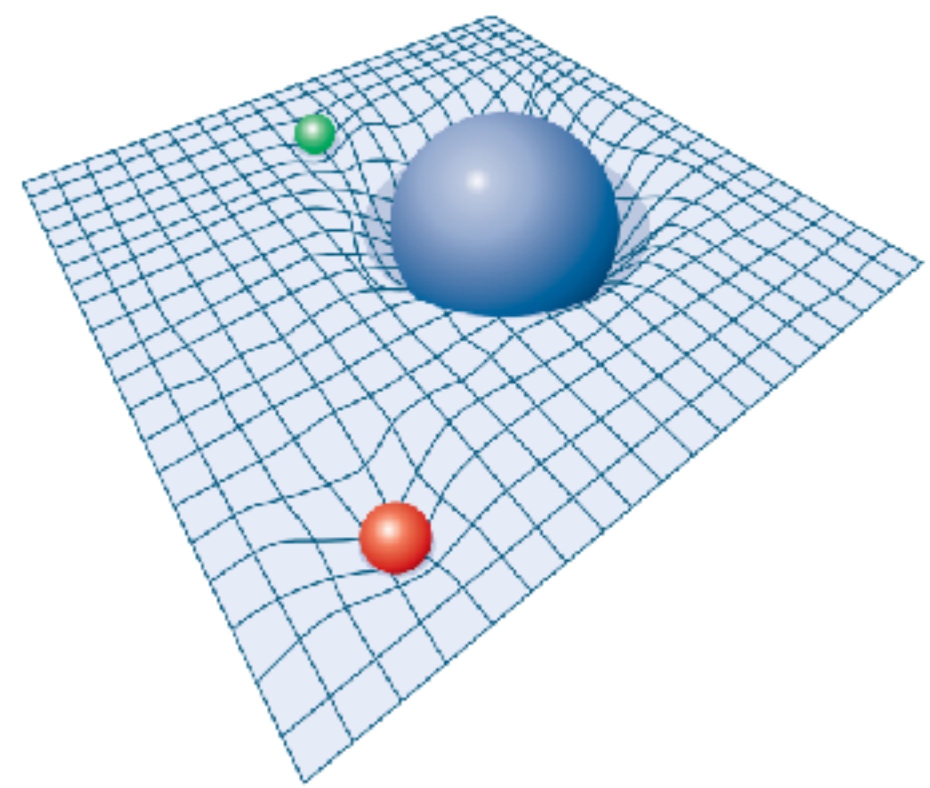
The dynamics of the spacetime is determined by the distribution of matter.

"Spacetime tells matter how to move, and
matter tells spacetime how to curve and twist."

The whole Universe is studied as a physical system under Einstein gravity!

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G T_{\mu\nu}$$





New units of measure

For distance, we use pc, Kpc & Mpc

$$1\ \mathrm{pc} = 3.086 \times 10^{16}\mathrm{m}$$

$$1\ \mathrm{Mpc} = 3.086 \times 10^{22}\mathrm{m}$$

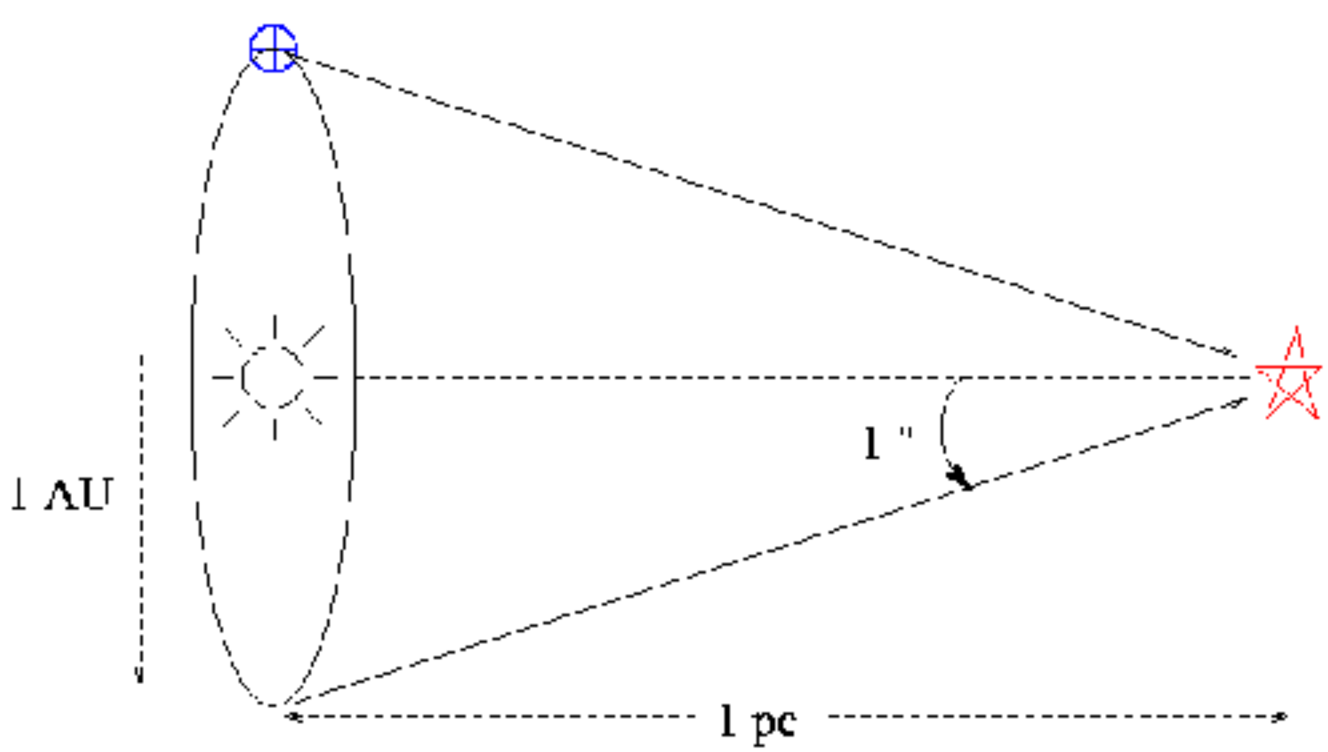
For comparison, mean Earth-Sun distance (Astronomical Unit):

$$1\ \mathrm{AU} = 1.496 \times 10^{11}\mathrm{m}$$

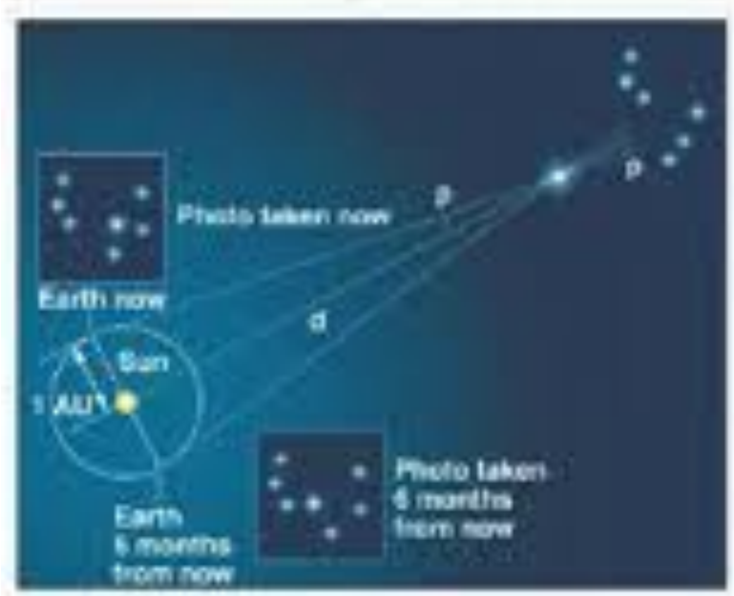
$$1\ \mathrm{pc} = 2.1 \times 10^{5}\mathrm{AU}$$

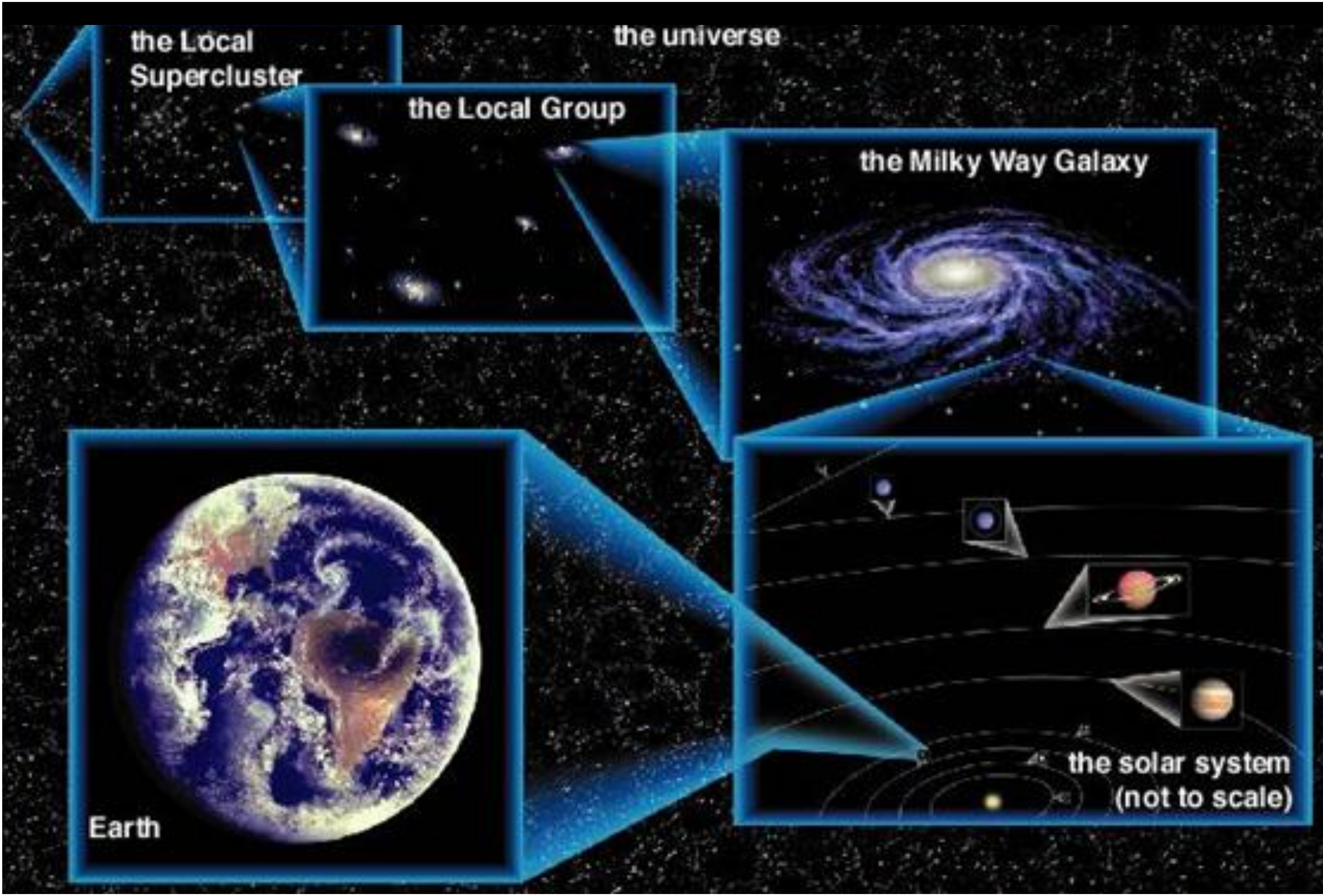
- Cosmologists often express masses
- in units of the solar mass:

$$1\ \mathrm{M}_{\odot} = 1.99 \times 10^{30}\mathrm{kg}$$



In 1838, Bessel announced that 61 Cygni had a parallax of 0.314 arcseconds; which, given the diameter of the Earth's orbit, indicated that the star was about 3 parsecs (9.8 light years) away.

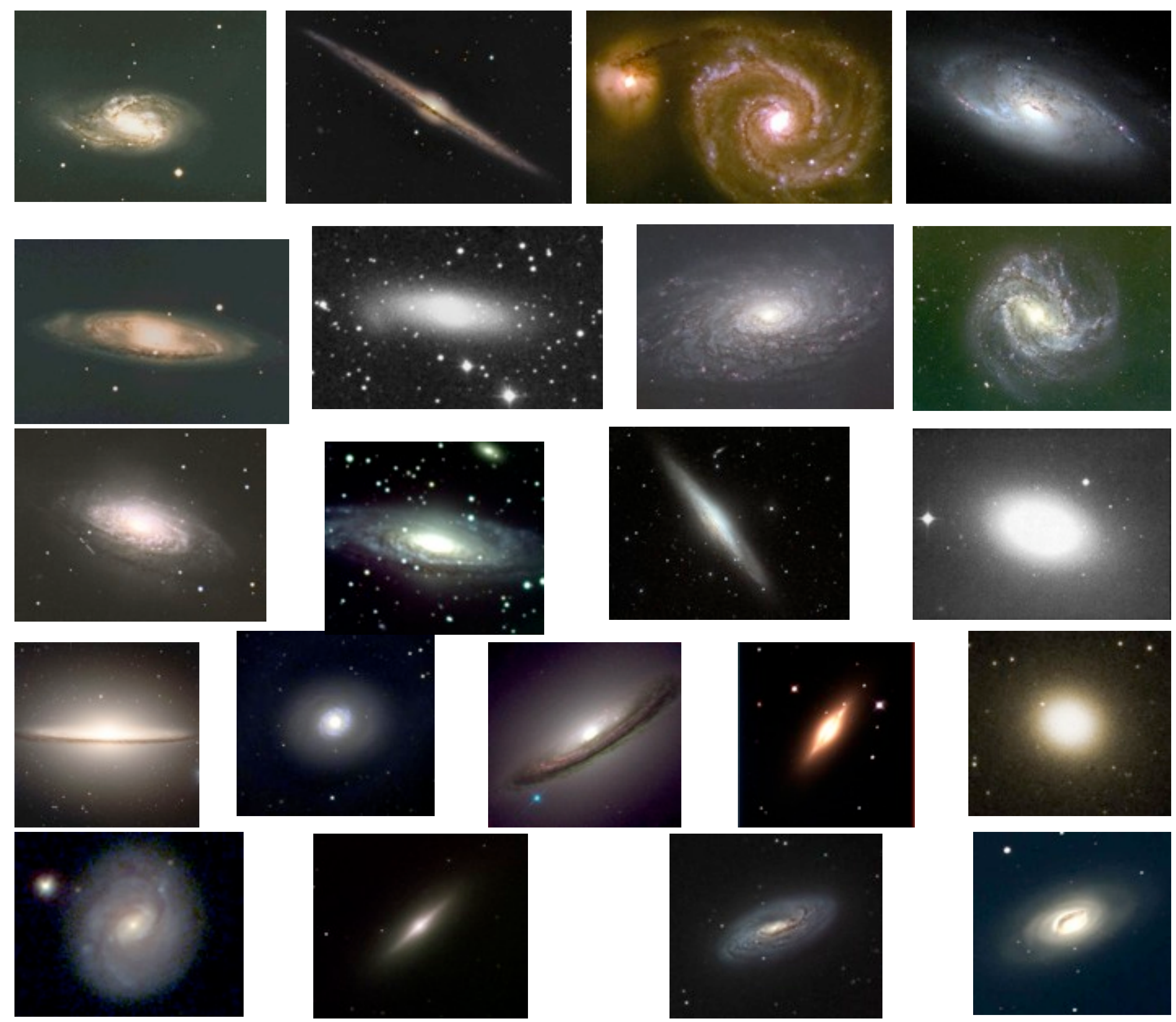



the universe
the Local Supercluster
the Local Group
the Milky Way Galaxy
the solar system (not to scale)
Earth

تصویر ما از کیهان

مجادله شاپلی و کرتس ۱۹۲۰

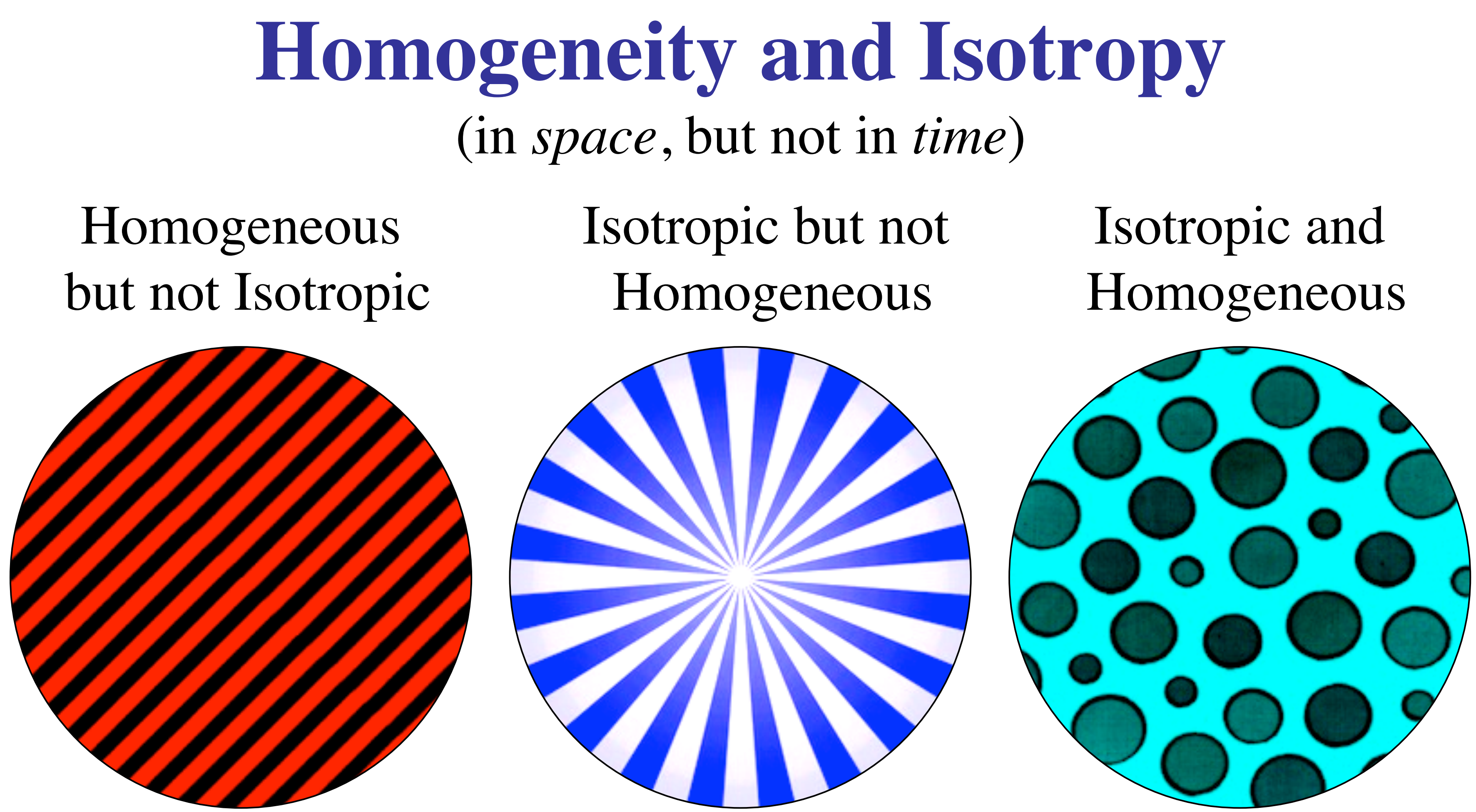
جزیره های دوردست از ساحل ما دور می شوند ...



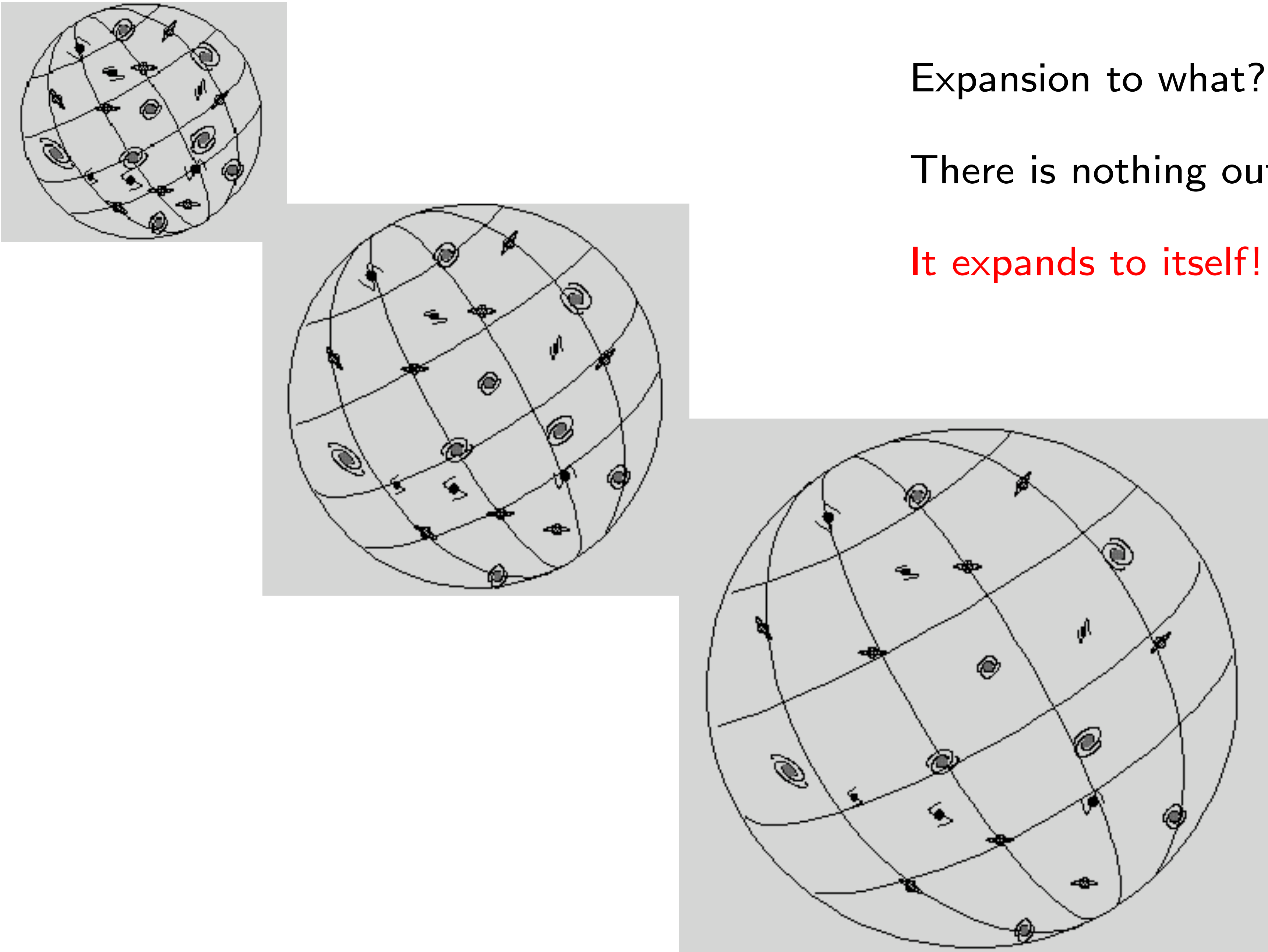
We need some symmetry assumptions in to study the Universe.

The cosmological Principle:

The Universe is the same in all locations and in all directions, except for local irregularities.



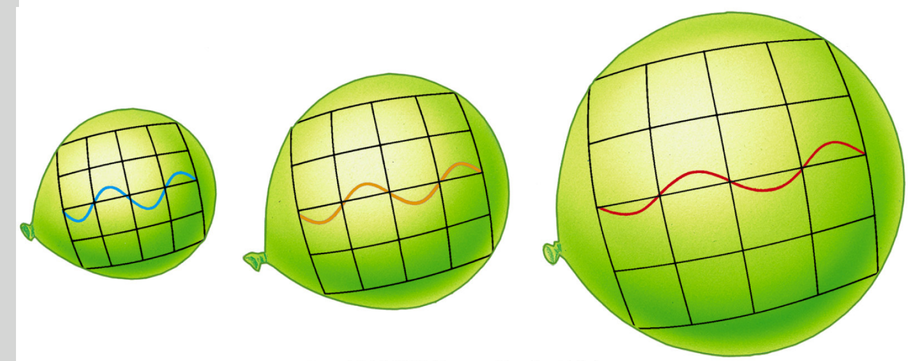
Observationally, the Universe is homogeneous and isotropic on scales larger than 100 Mpc.



Expansion to what?

There is nothing outside the Universe to expand to!

It expands to itself!!



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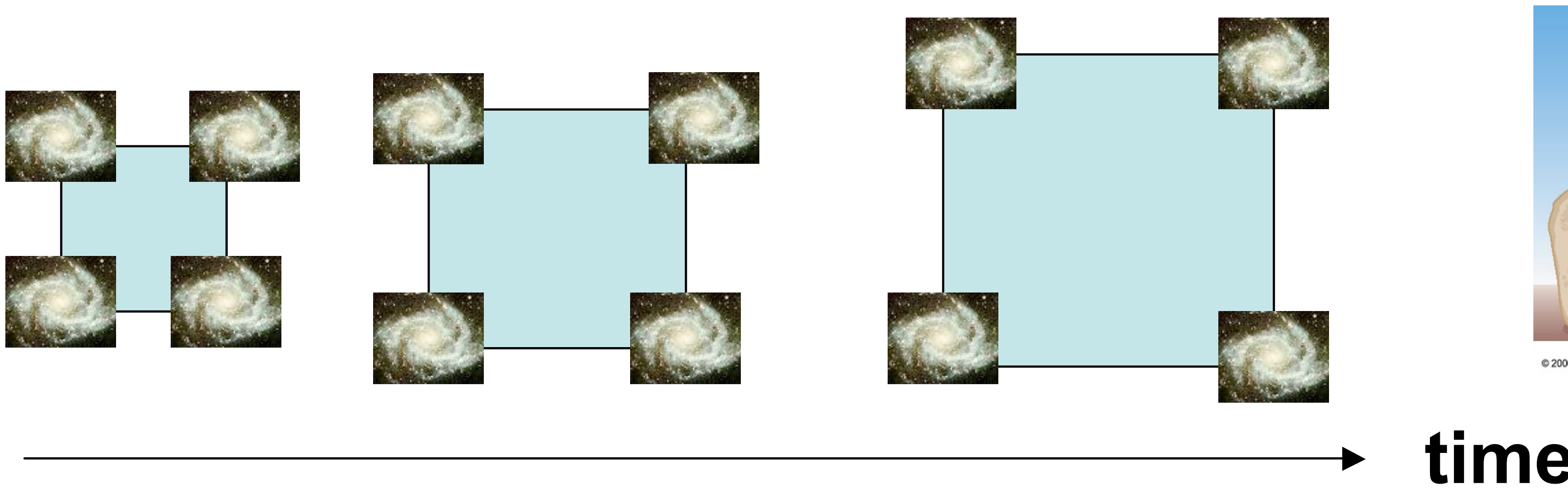

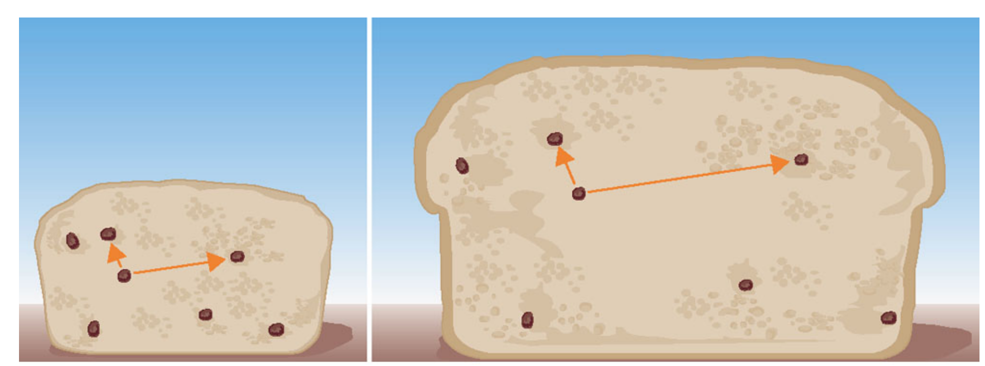

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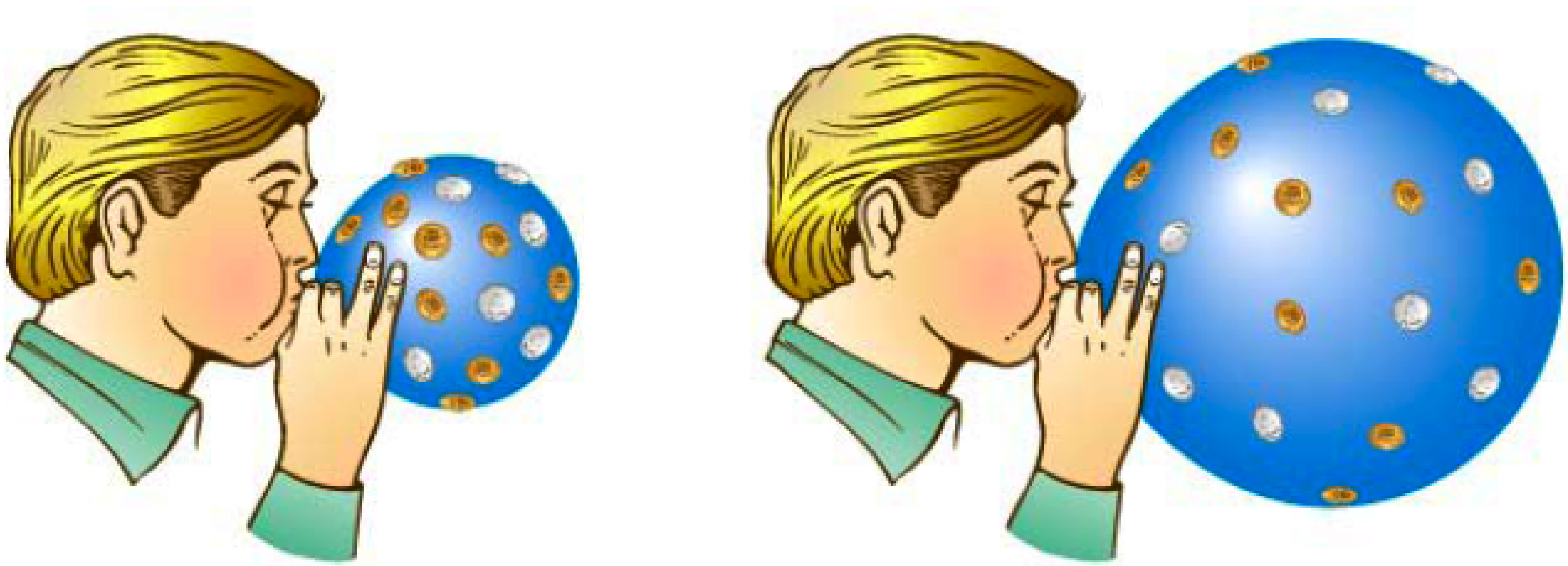
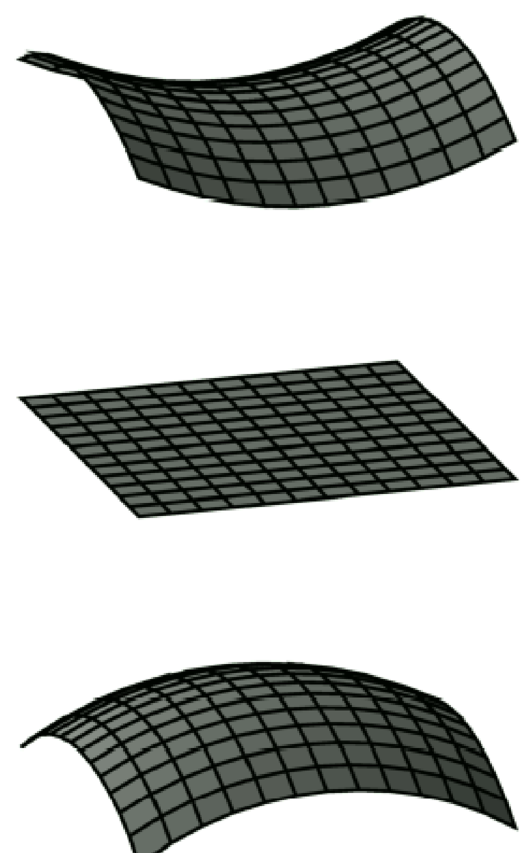
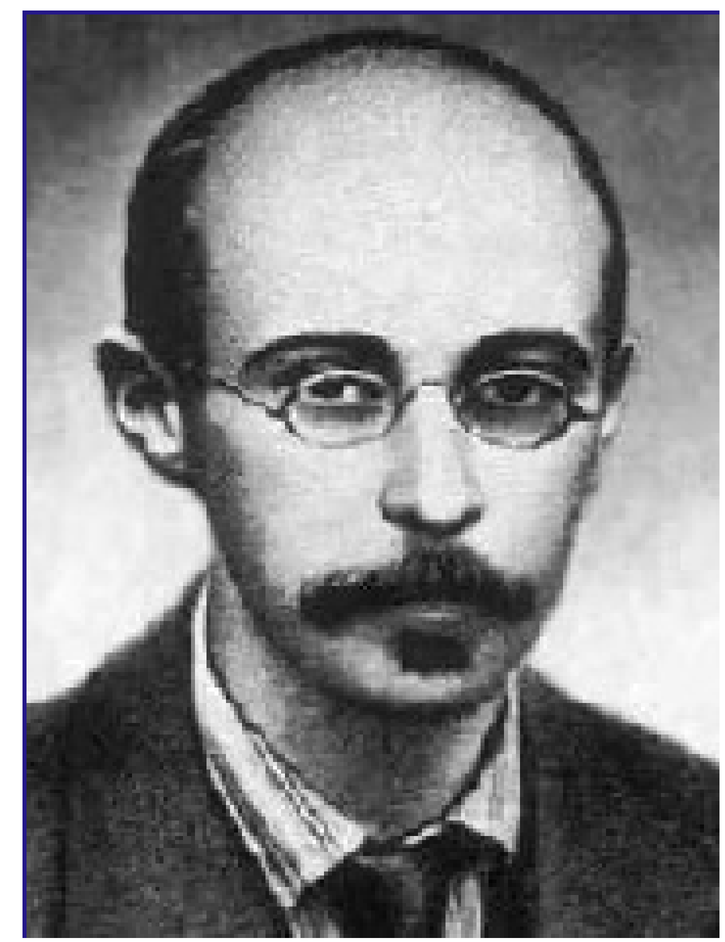
Standard Big Bang Cosmology :







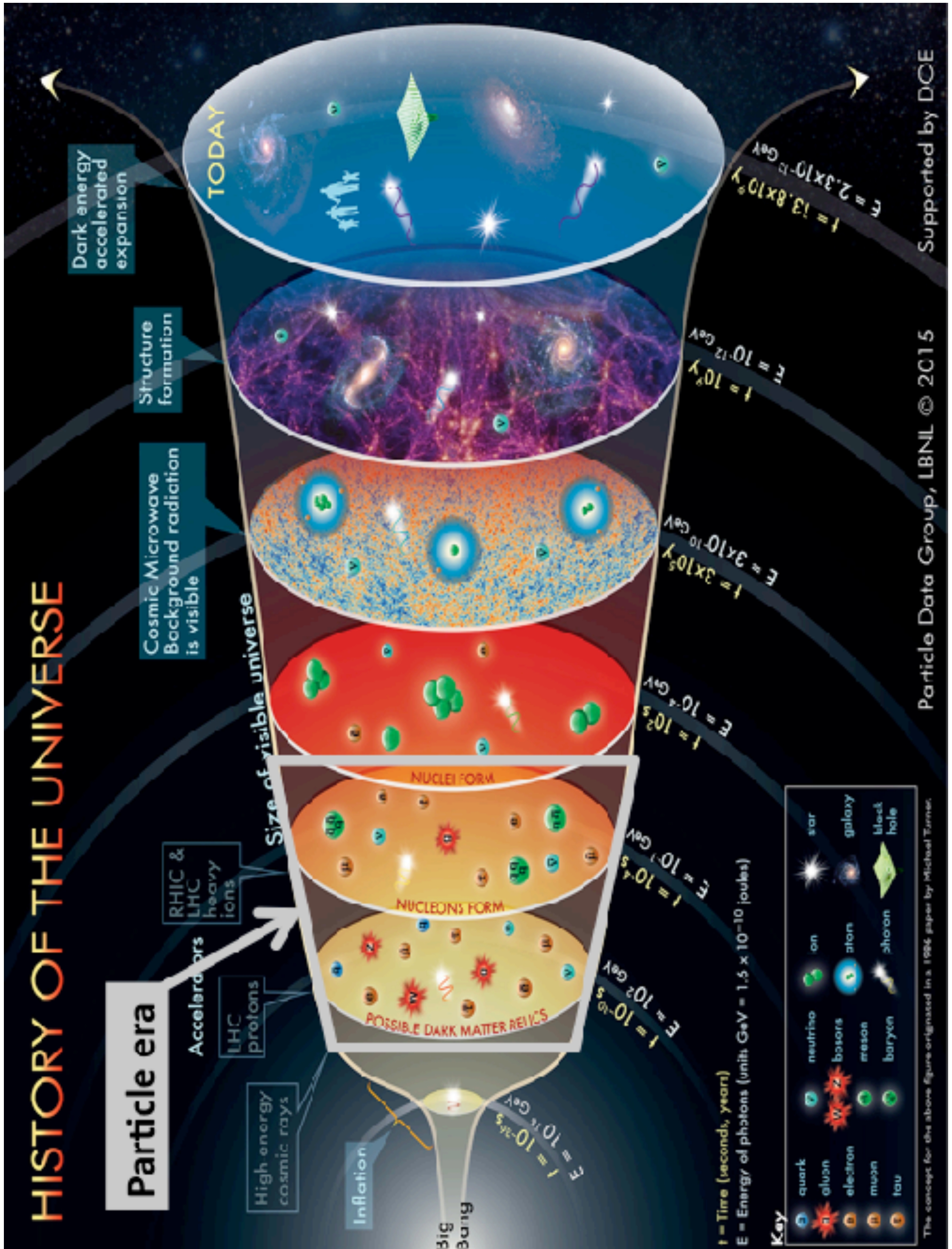
http://www.astro.ucla.edu/~wright

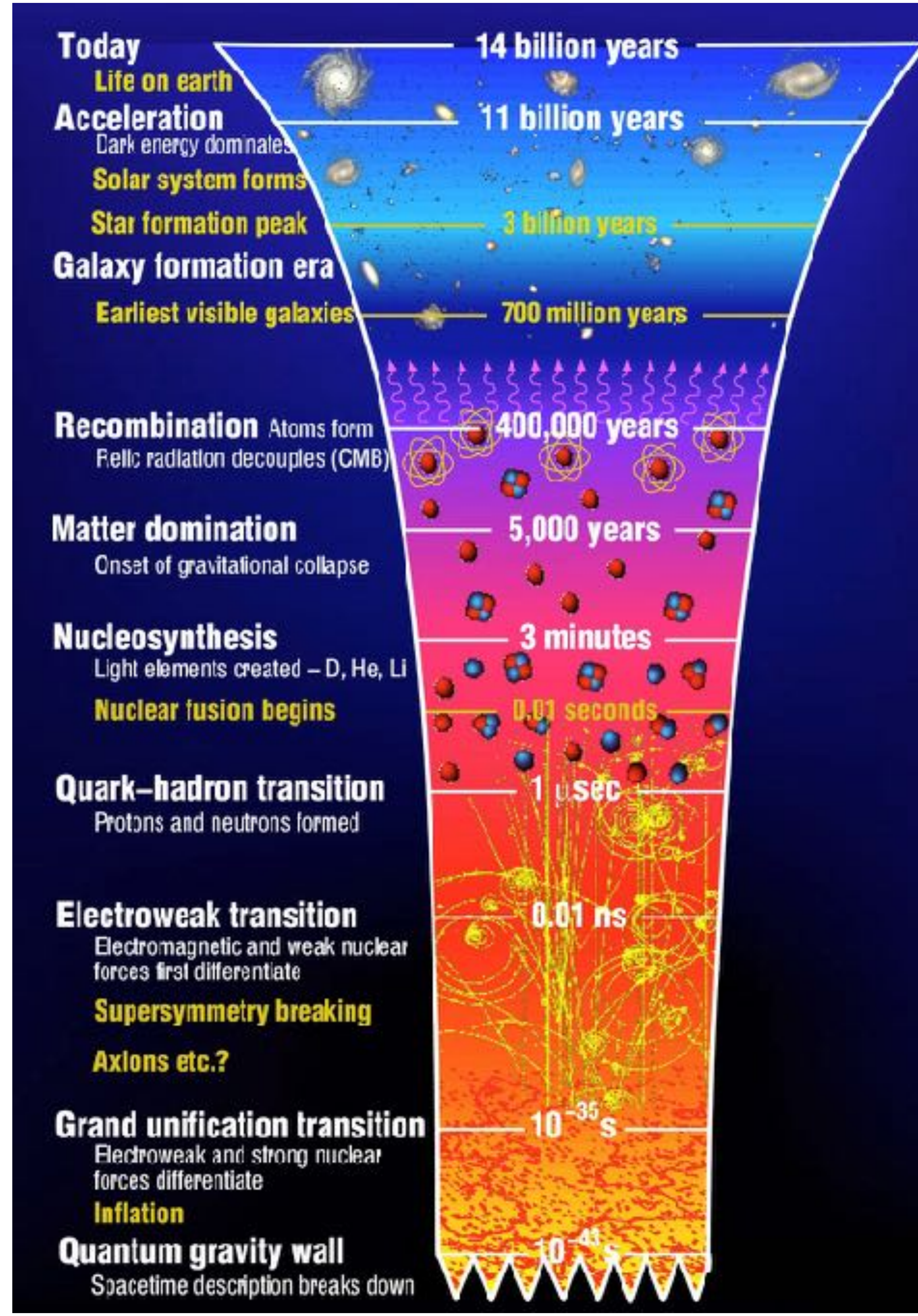
$$ds^2 = dt^2 - a(t)^2\, d\vec{x}^{\,2}$$

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

ρ : Total energy density including ordinary matter(atoms), dark matter, dark energy,...

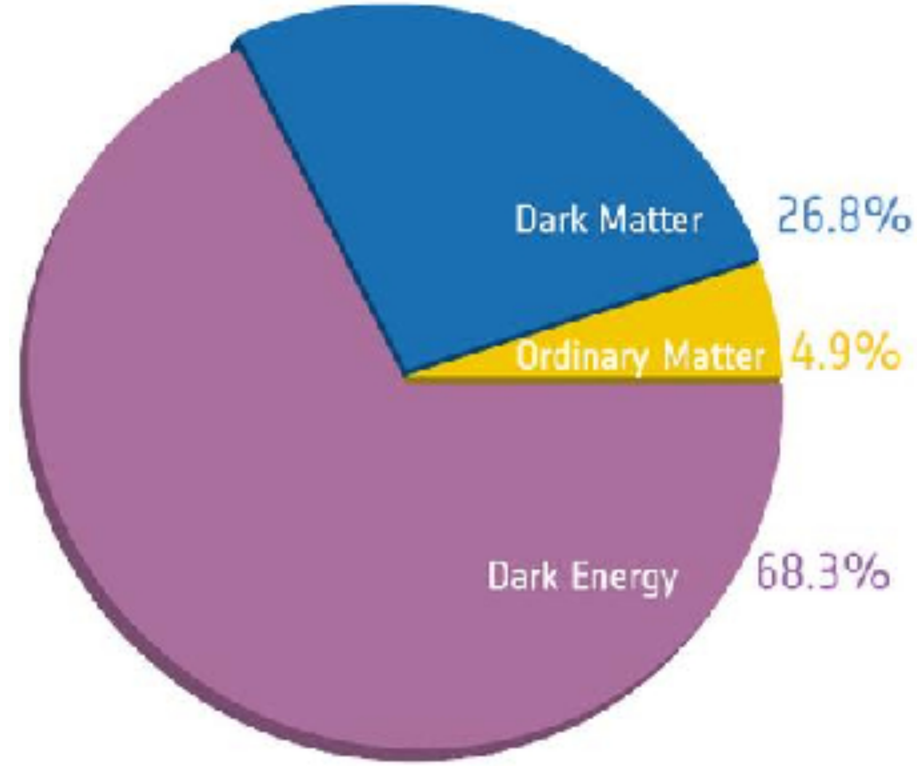
A Brief History of Universe

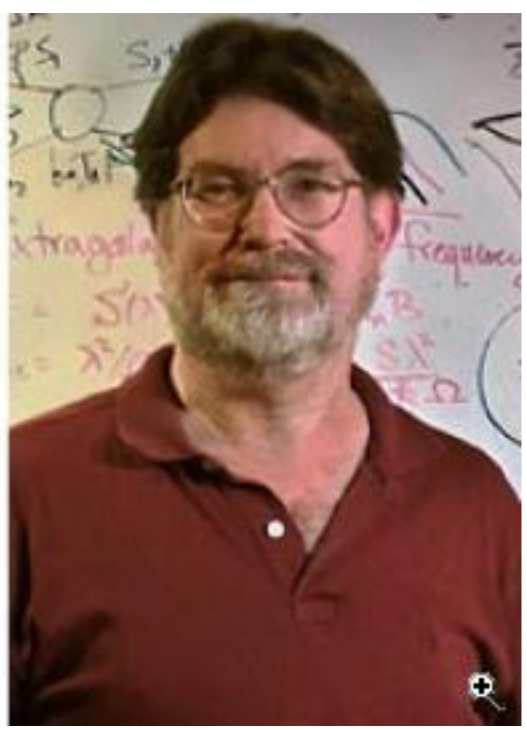




The Standard Model of Cosmology

- Ordinary Atoms:(Baryons) 5%
- Dark Matter: 26%
- Dark Energy: 69%
- Spatial Curvature ~ 0





Nobel 2006 (CMB)

Photo: Lawrence Berkeley National Lab

Saul Perlmutter

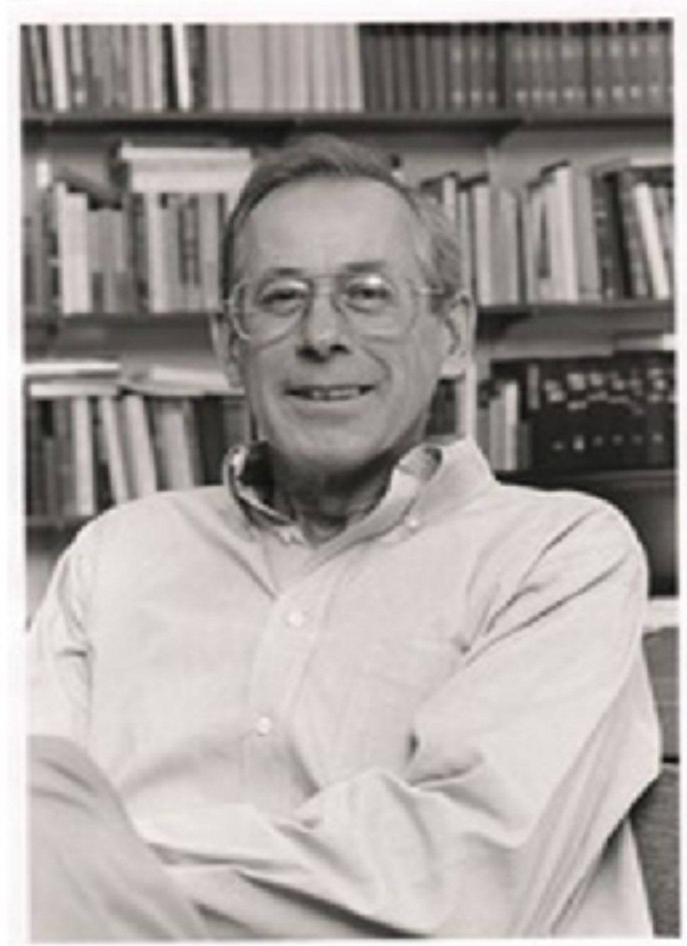
Photo: Belinda Pratten, Australian National University

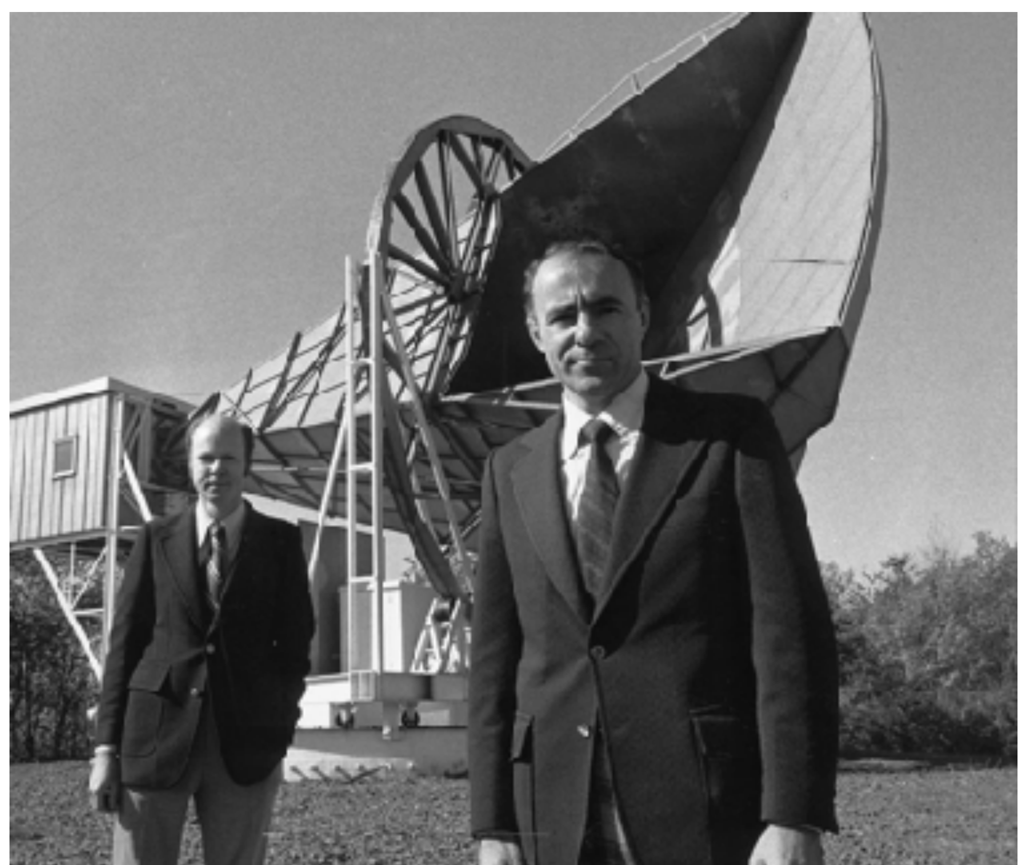
Brian P. Schmidt

Photo: Scanpix/AFP

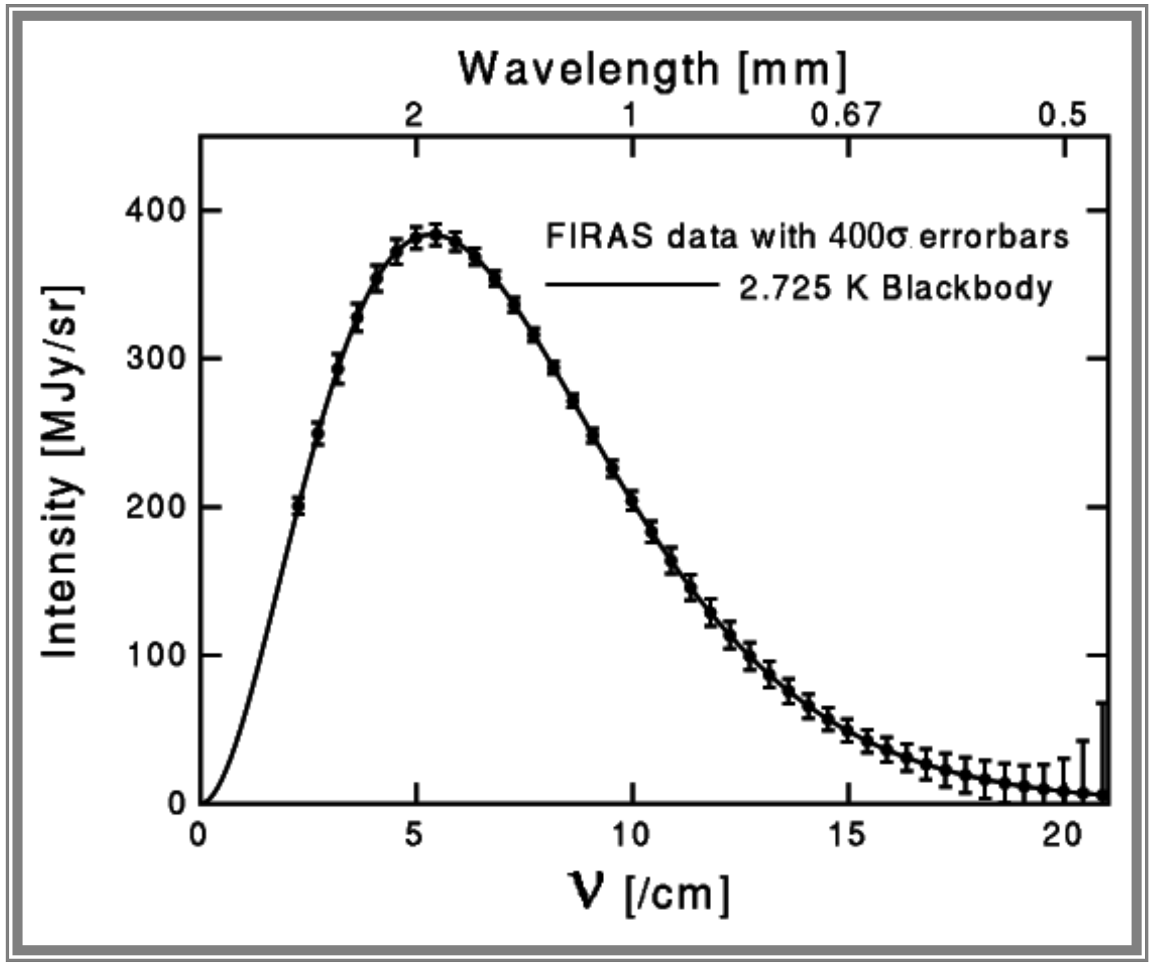
Adam G. Riess

Nobel 2008 (dark energy)

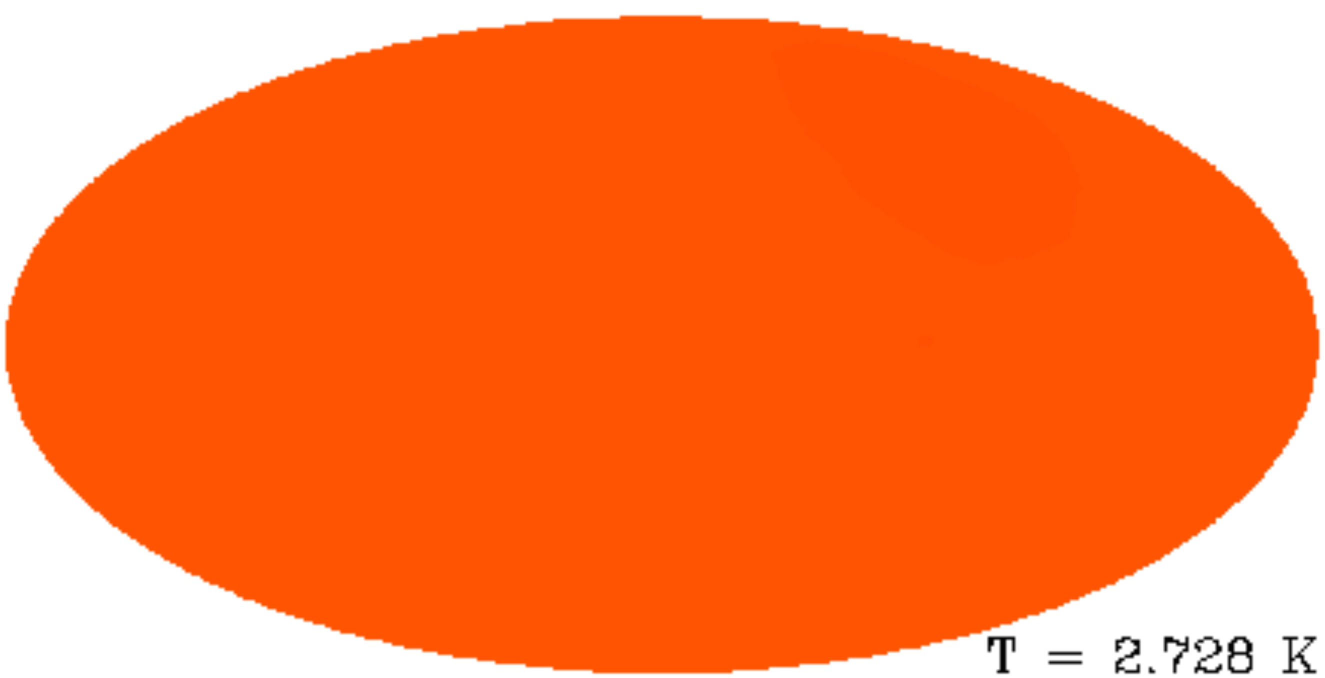



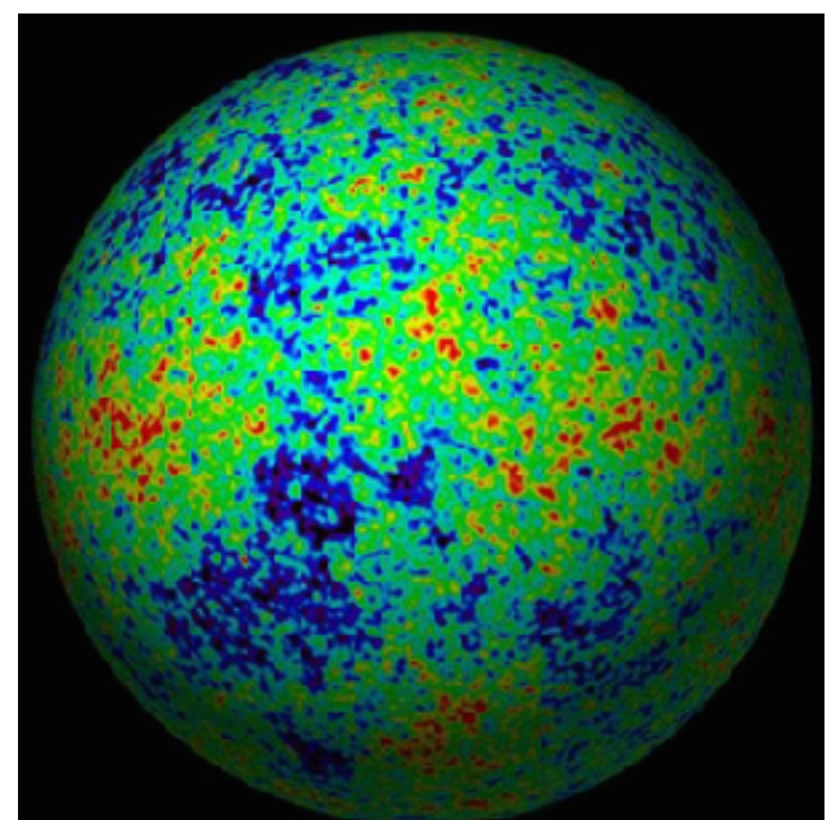


تابش زمینه کیهانی

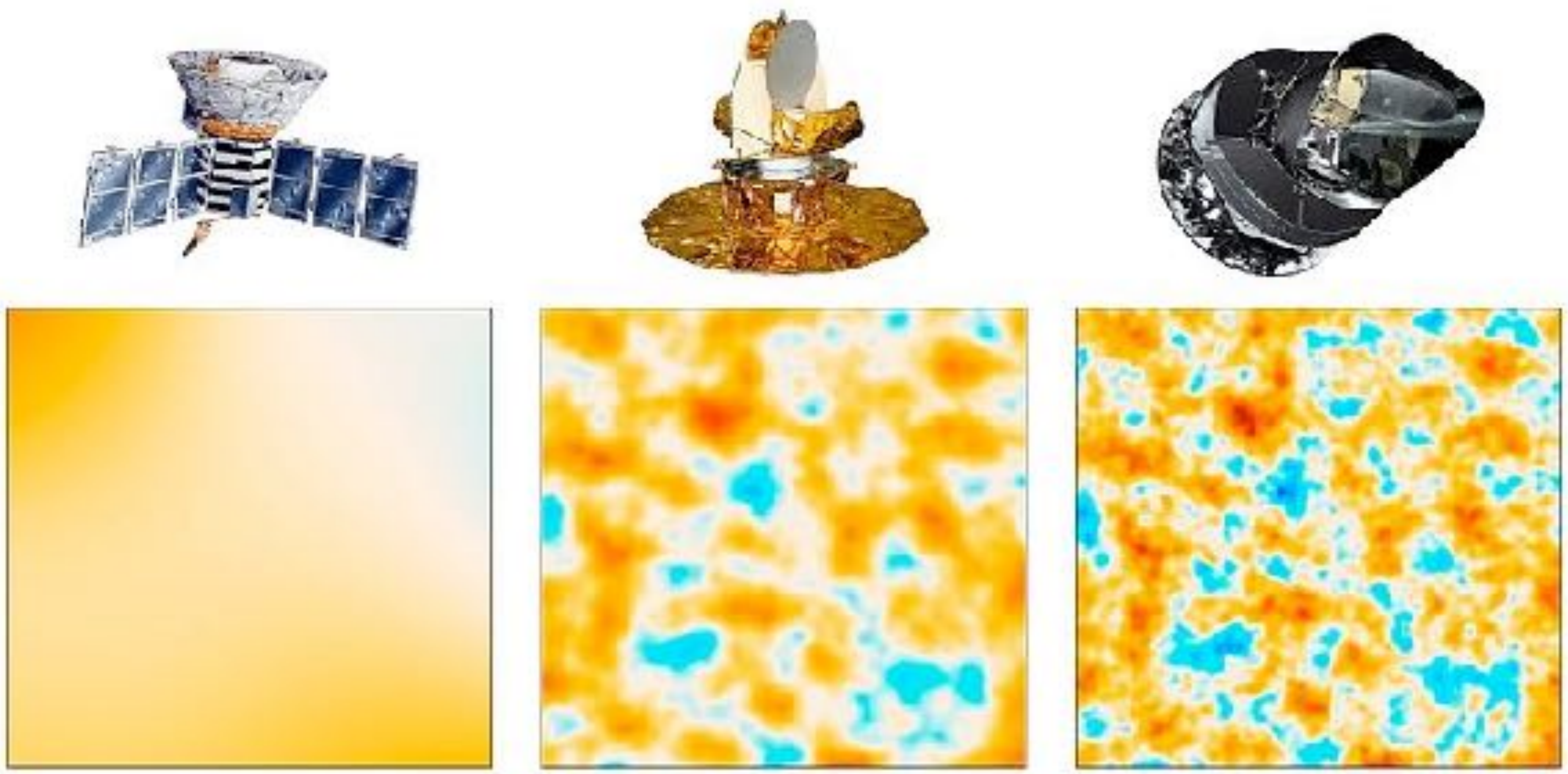


پنزیاس و ویلسون ۱۹۶۵



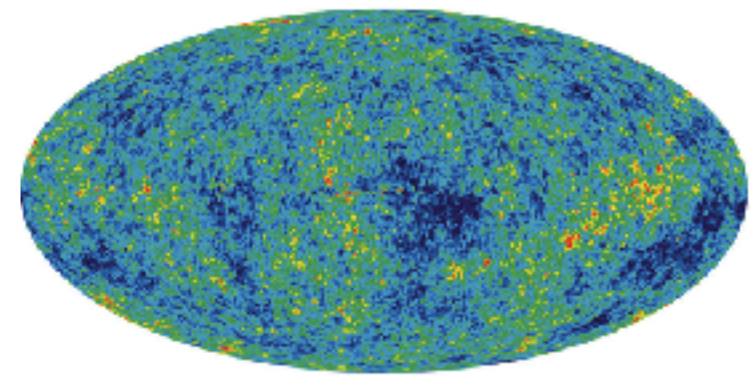


space-based cosmological observations

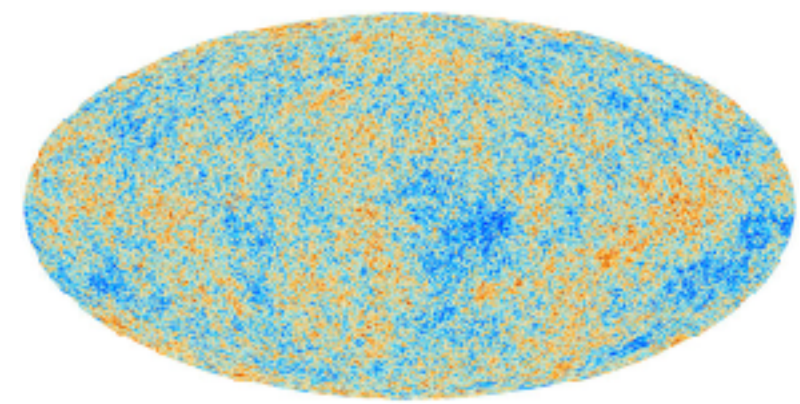


COBE WMAP Planck

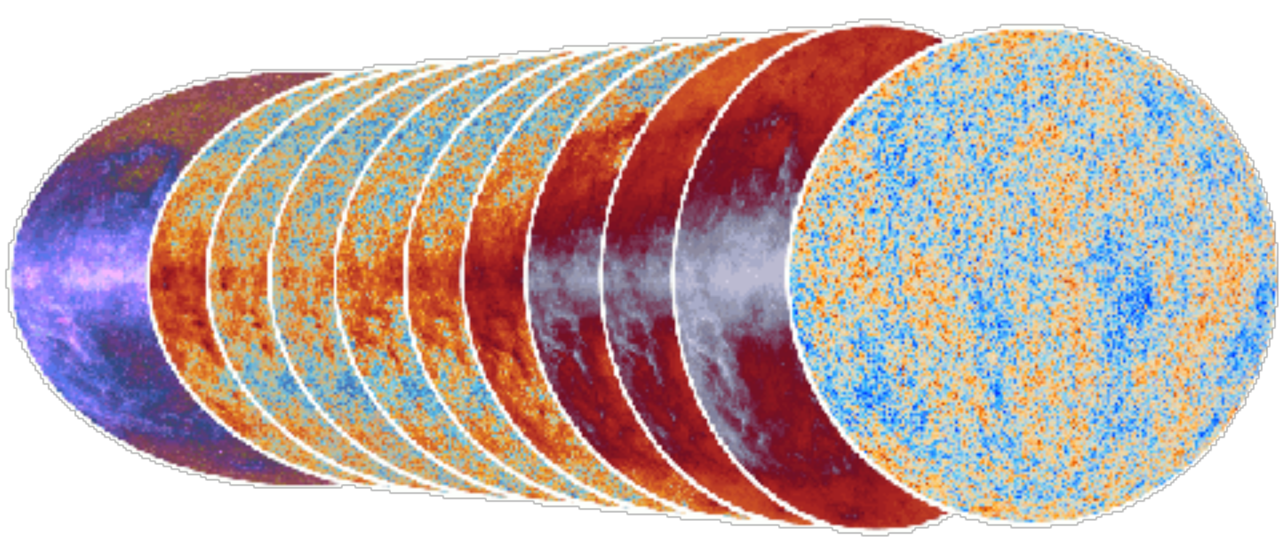
1992 2003 2013



WMAP

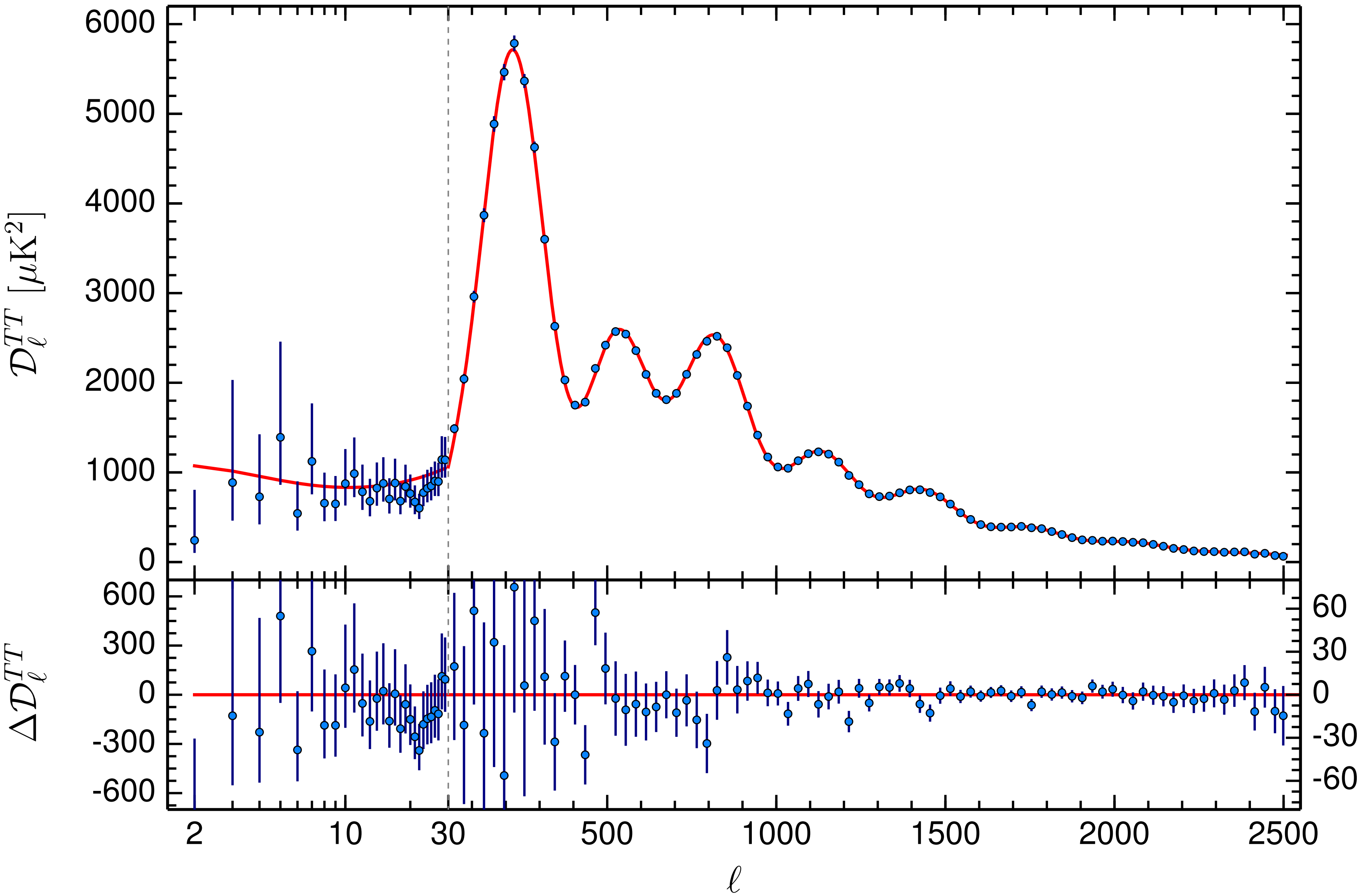


Planck



Planck used 9 frequency bands

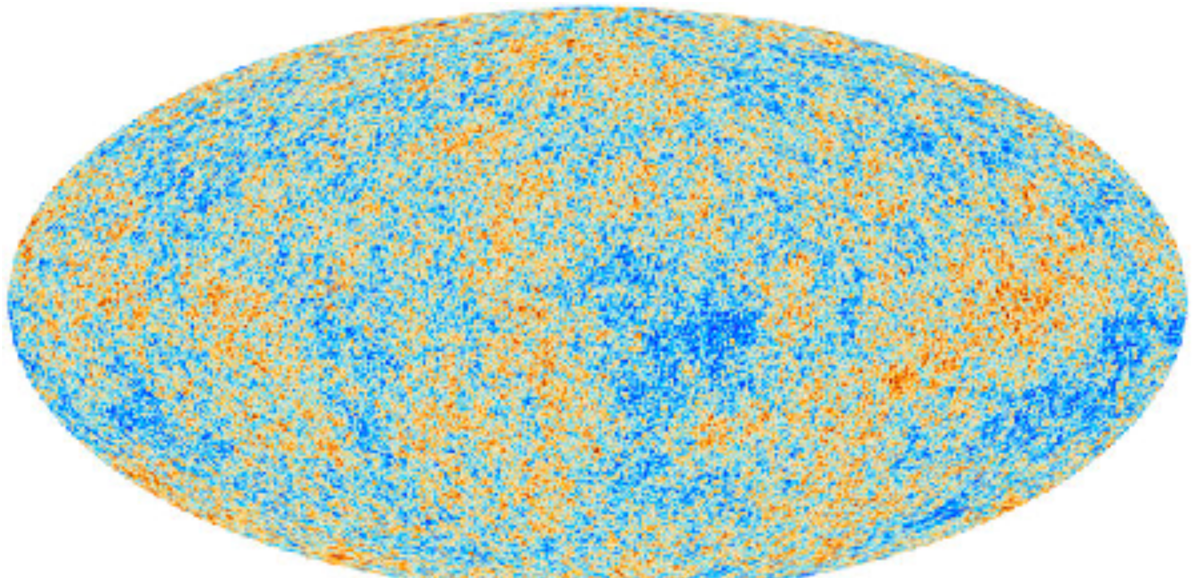
Temperature anisotropy power spectrum



$$\Delta T(\hat{n}) \equiv T(\hat{n}) - T_0 = \sum_{\ell m} a_{\ell m} Y_\ell^m(\hat{n})$$

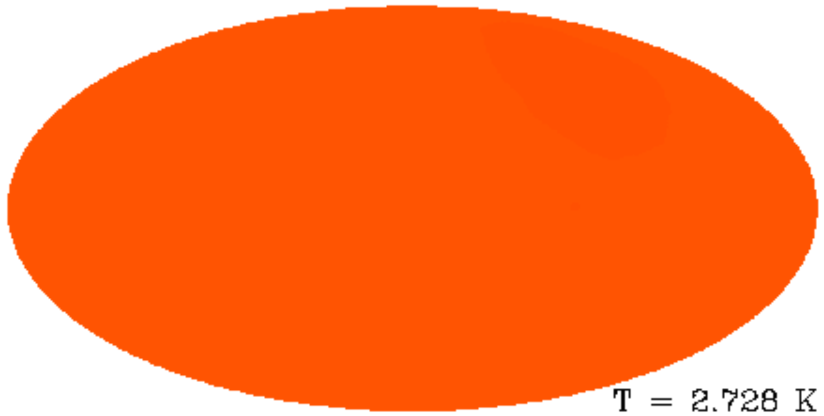
$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell\ell'}\delta_{mm'} C_\ell$$

$$\langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle = \sum_{\ell m} C_\ell Y_\ell^m(\hat{n}) Y_\ell^{-m}(\hat{n}')$$

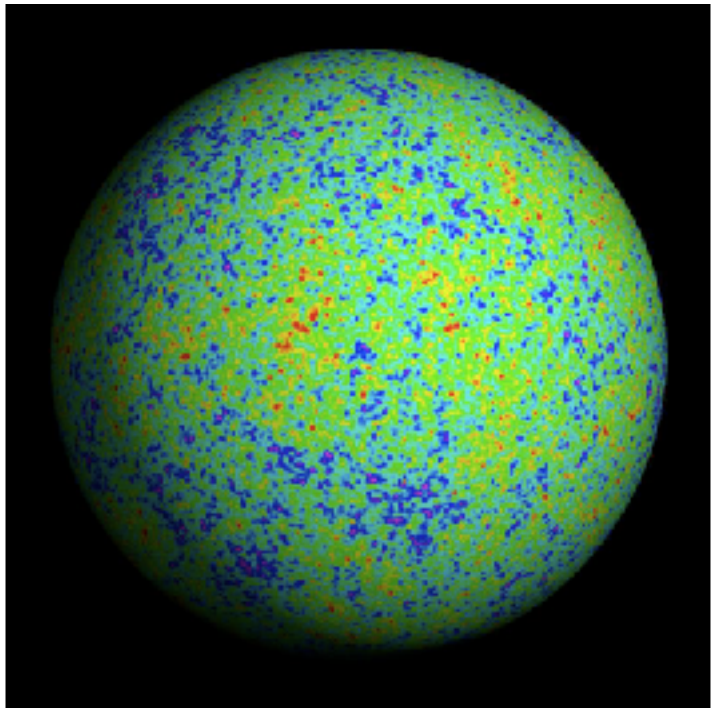


The Initial Conditions Puzzles

Despite the successes of the big bang cosmology, there are initial conditions problems:

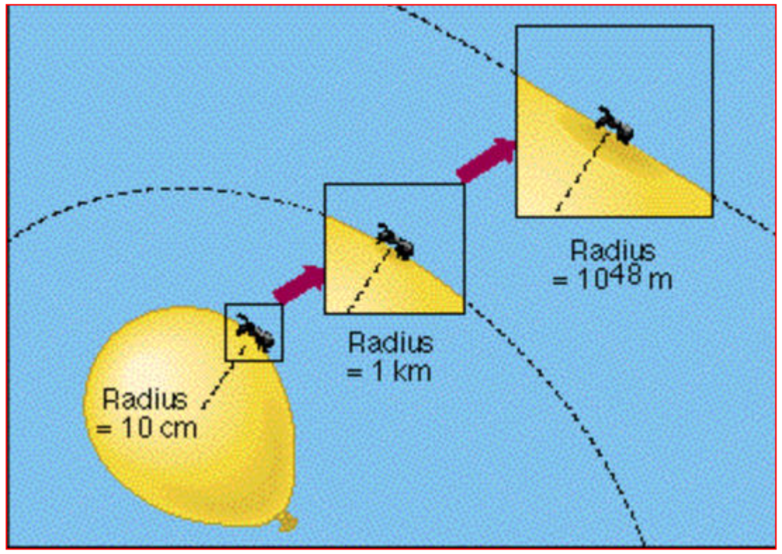


- The Horizon Problem: Why is the Universe so homogeneous and isotropic? During its evolution, the Universe did not have enough time to become so isotropic and homogeneous.



- The Flatness Problem: Why is the Universe so flat? If $\Omega \sim 1$ today, then extrapolating back to very early Universe at Planck time we find $|\Omega - 1| \sim 10^{-60}$.

- There are tiny fluctuations at the level of 10^{-5} on the smooth CMB background, which are almost scale invariant, adiabatic and Gaussian. What mechanism can create these perturbations ?



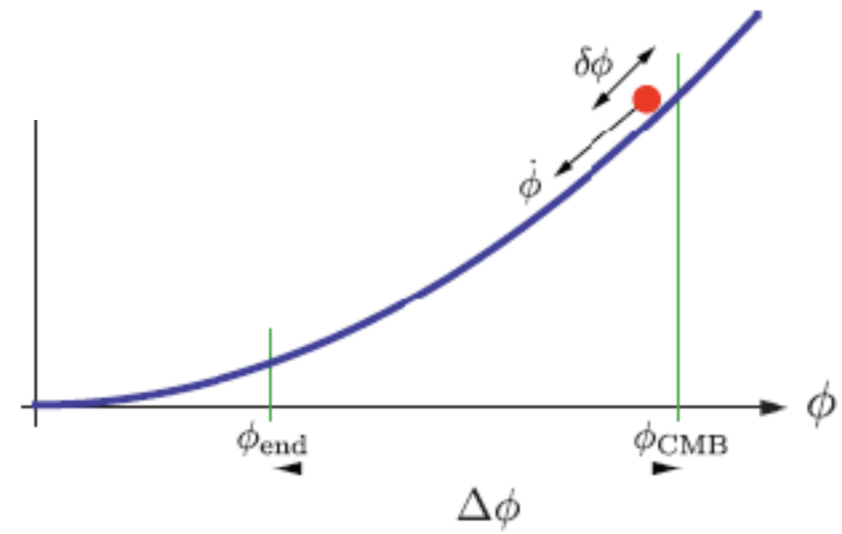
A short period of acceleration in very early Universe will provide all these necessary initial conditions and flattens the Universe. In addition, quantum fluctuations during inflation source the structure in cosmos!

Slow-Roll Inflation

The simplest models of inflation are based on a scalar field dynamics:

The Slow-Roll Models.

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{8\pi G} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right]$$



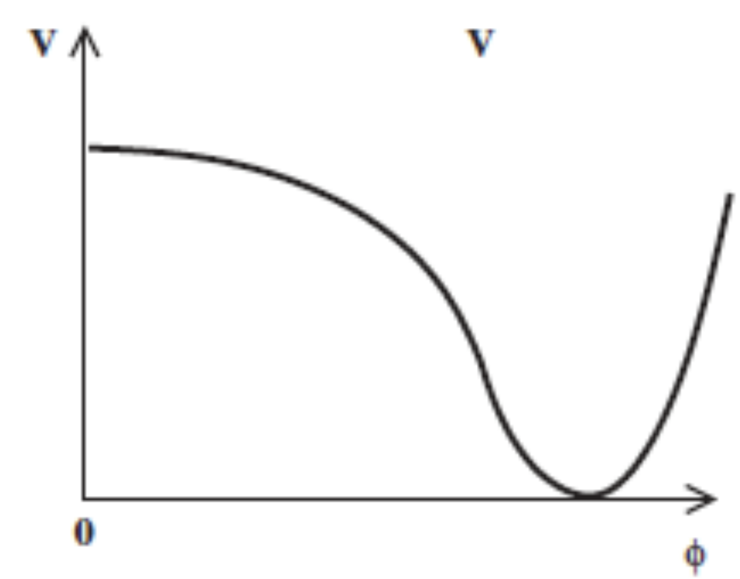
Large field inflation:

$$V = \frac{1}{2}m^2\,\phi^2 \qquad \phi_i \sim 15\,M_P$$

$$V = \frac{\lambda}{4}\phi^4 \qquad \lambda \sim 10^{-14} \qquad \phi_i \sim 22\,M_P$$

Small field inflation:

$$V(\phi) = V_0\left[1 - \left(\frac{\phi}{\mu}\right)^2\right]^2 .$$
$$= V_0 - \frac{1}{2}m^2\phi^2 + \ldots .$$

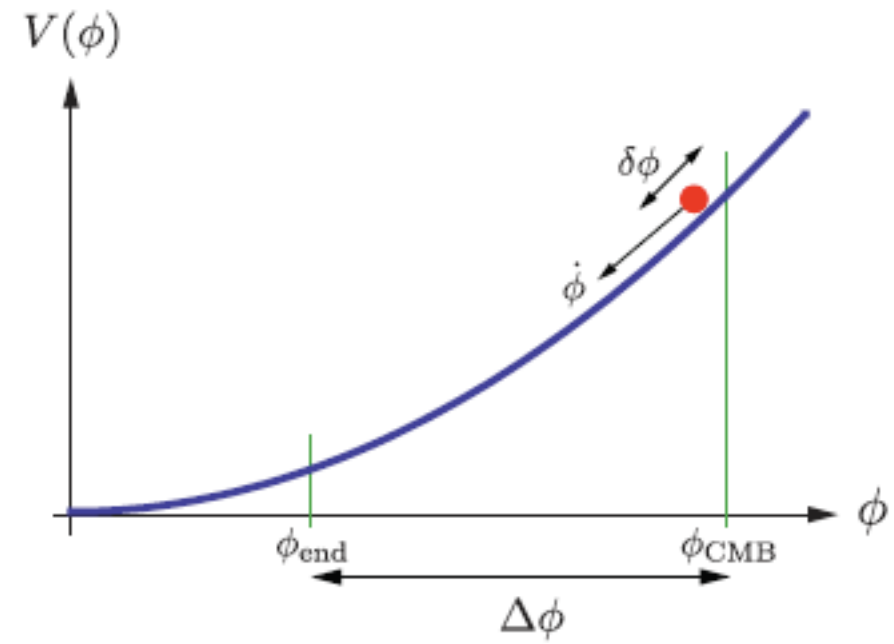


Inflation, a brief review

The necessary condition for inflation

$$\ddot{a} = -\frac{4\pi G}{3}(\rho + 3p) > 0 \qquad \rightarrow \qquad p < -\frac{\rho}{3}$$

In most models, inflation is derived by a scalar field, the inflaton.



Baumann.

At the background inflation we turn on the quantum fluctuations

$$\phi(t, \mathbf{x}) = \bar{\phi}(\mathbf{t}) + \delta\phi(\mathbf{t}, \mathbf{x})$$

The curvature perturbation is $\quad \zeta = \psi + \frac{H}{\dot{\phi}}\delta\phi$

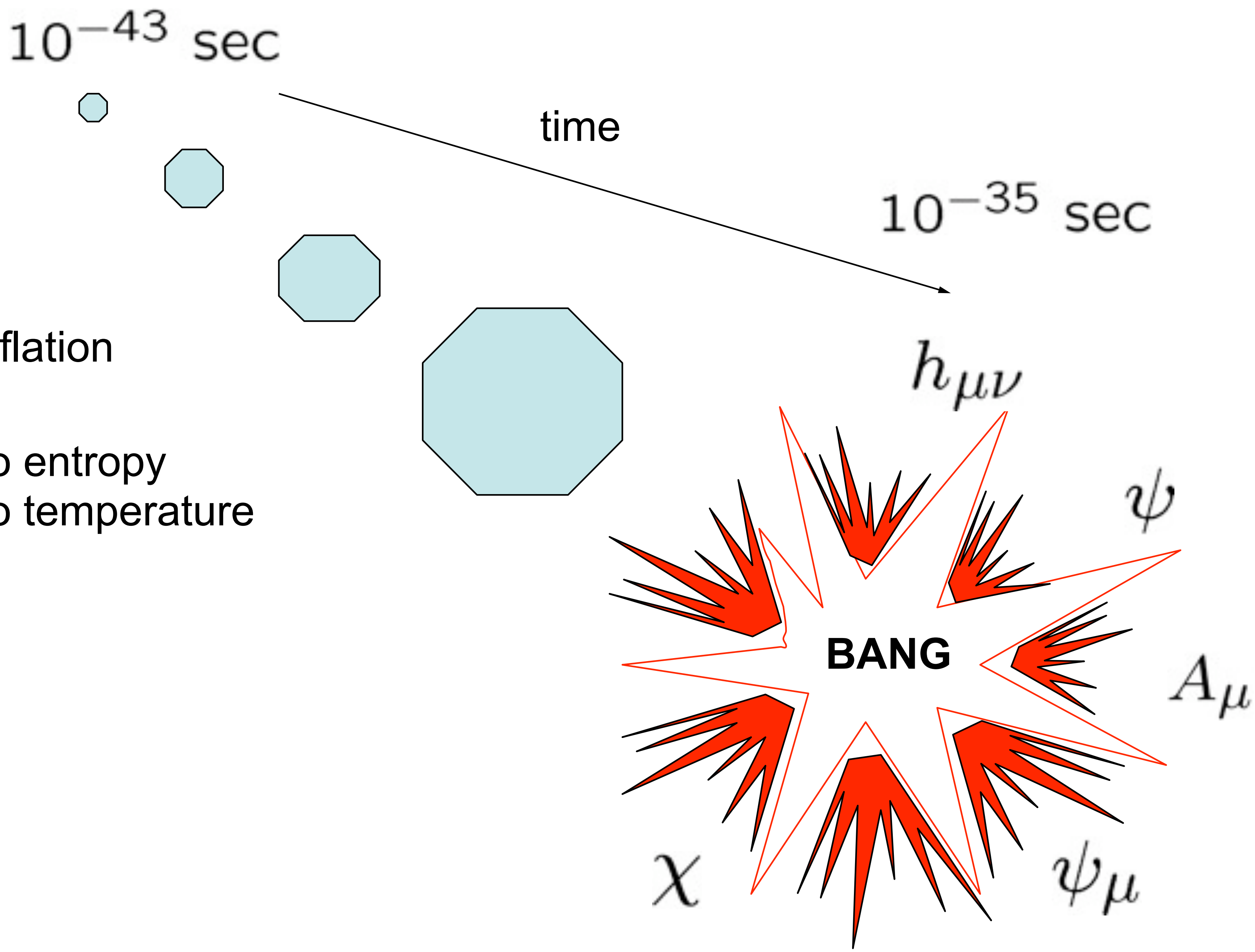
The curvature perturbation power spectrum is

$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\rangle = \frac{P_\zeta}{2k_1^3}(2\pi)^5\delta^3(\mathbf{k}_1 + \mathbf{k}_2) \longrightarrow \langle \Delta T(\hat{n})\Delta T(\hat{n}')\rangle$$

The perturbations are almost scale invariant,
almost Gaussian and almost adiabatic

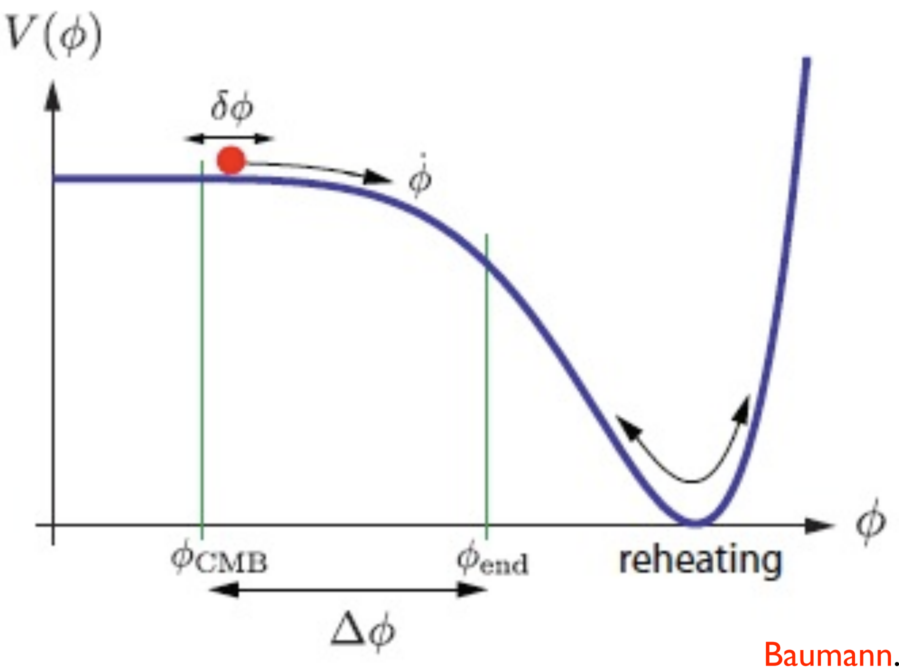
Reheating

Lev Kofman



Inflation

no entropy
no temperature

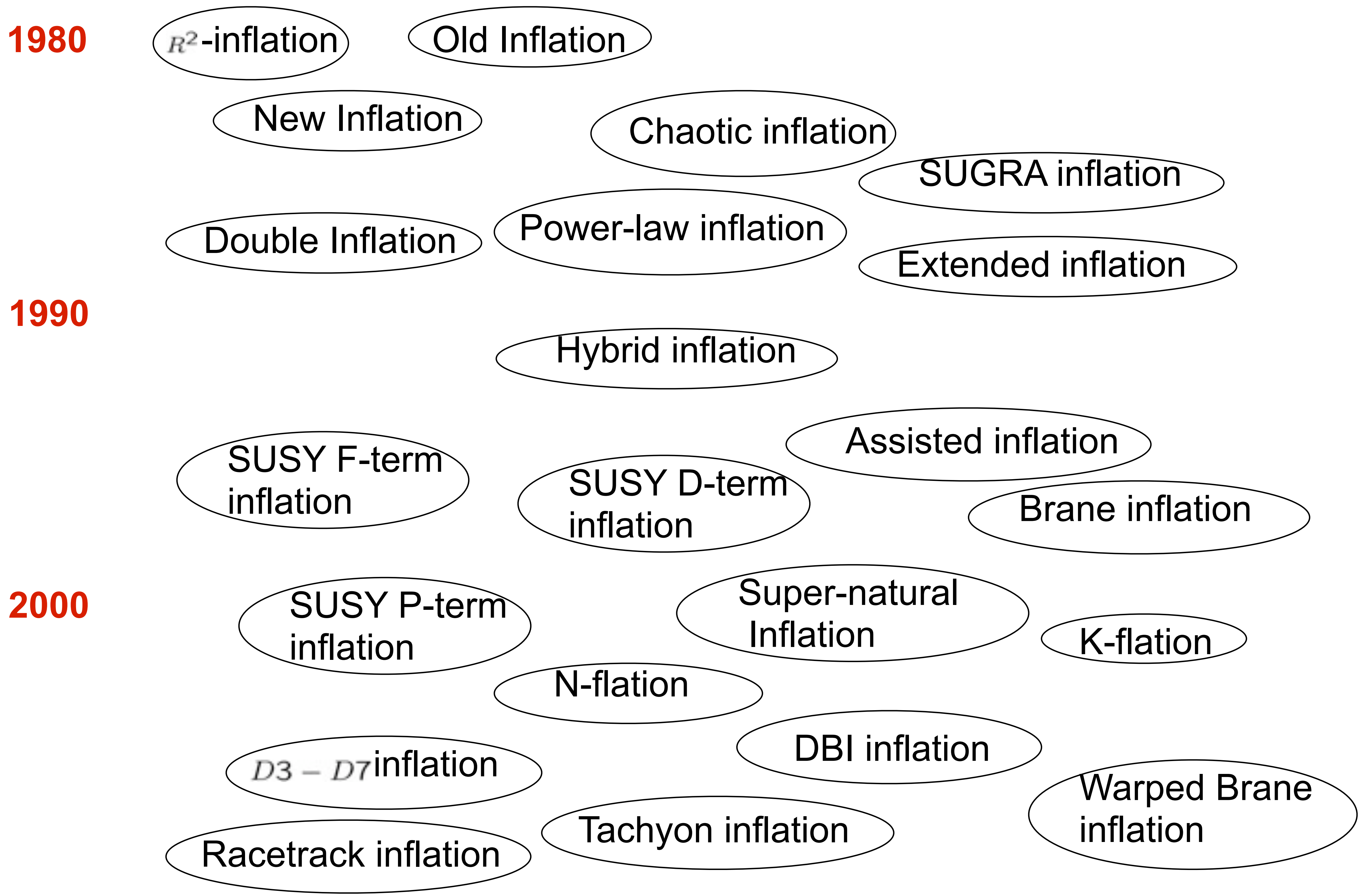


Baumann.

$$\mathcal{L}(\phi, \chi, \psi, A_\mu, \psi_\mu, h_{\mu\nu})$$

The Standard Big Bang Cosmology Starts after Inflation !

Inflation in the context of ever changing fundamental theory



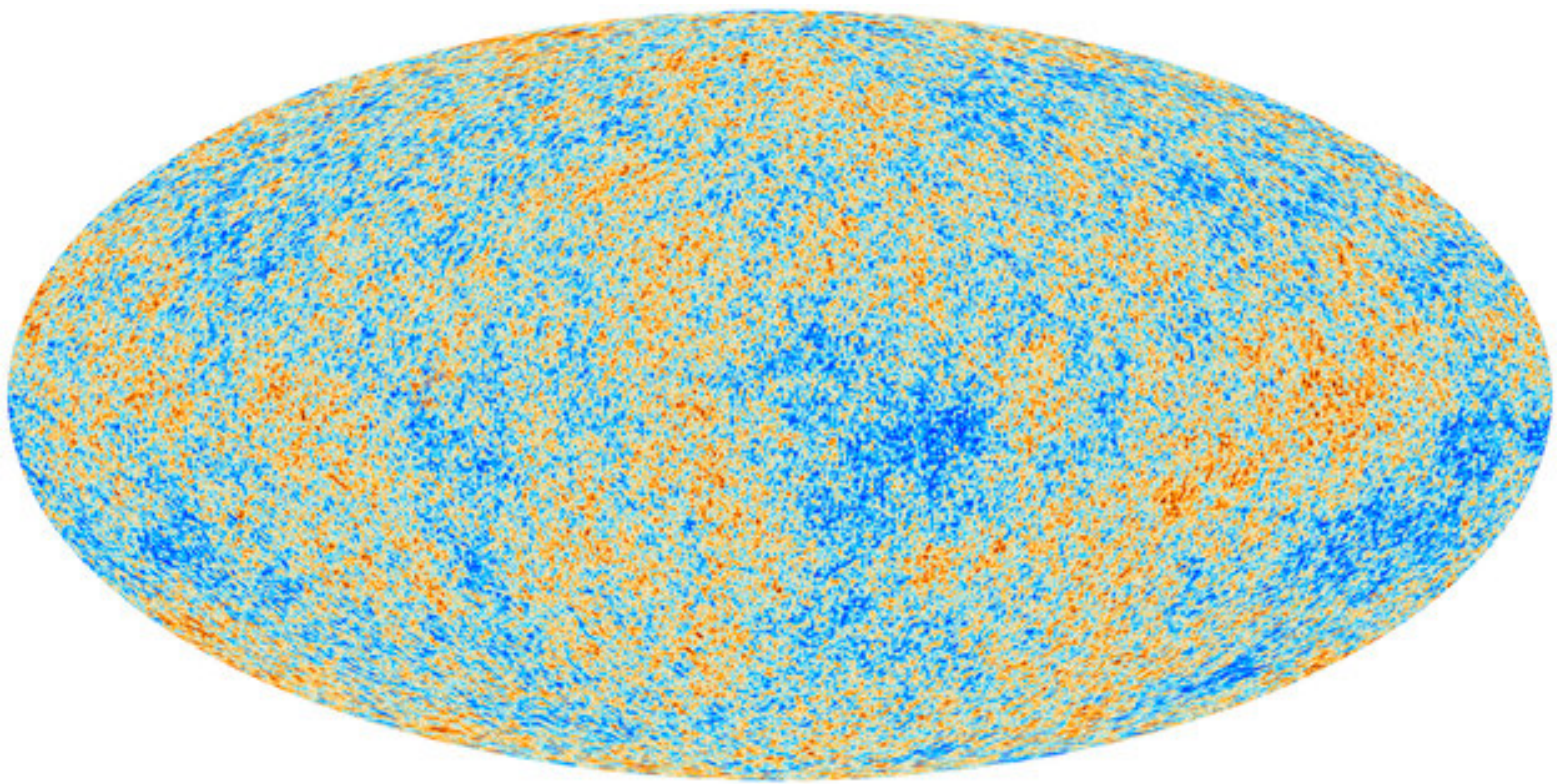
Borrowed from Lev. Kofman

Inflation and Observations

All observations (WMAP, Planck,...) strongly support inflation.

The basic predictions of inflation are that the primordial perturbations are nearly scale invariant, nearly adiabatic and nearly Gaussian.

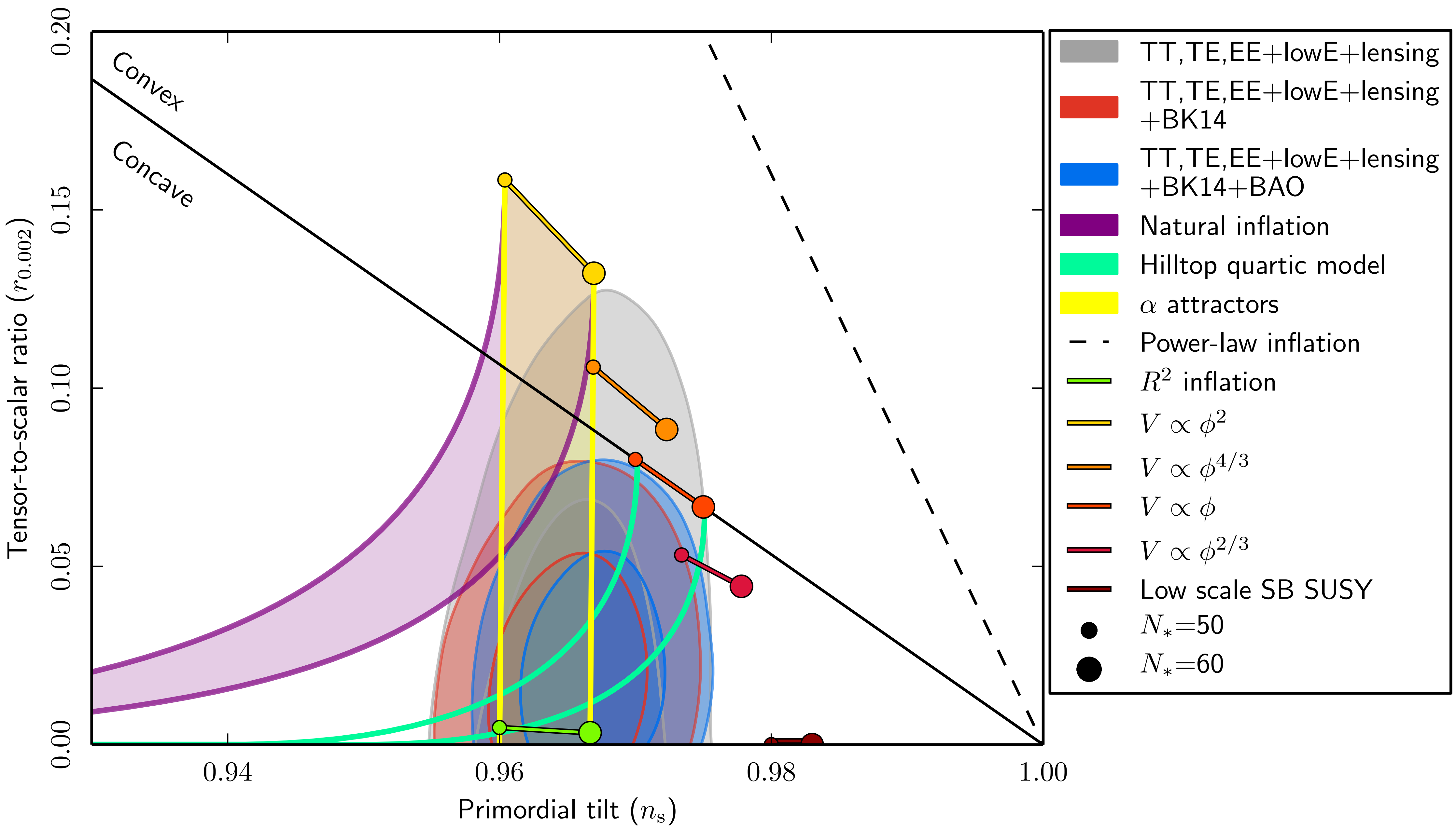
In CMB perturbations we observe the quantum vacuum fluctuations.



Planck Observation

$$\left\langle \frac{\delta T^2}{T^2} \right\rangle \propto \left\langle \mathcal{R}^2 \right\rangle = \left(\frac{H^2}{2\pi\dot{\phi}} \right)^2$$

Constraint on Single Field Inflation



- The joint data analysis from Planck/BICEP2/Keck Array indicates $r < 0.1$.
- The data prefers concave potential with $\partial^2 V < 0$.
- Simple potential such as ϕ^2 and ϕ^4 are disfavored.

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_s} \right)^{n_s - 1}$$

انرژی تاریک

Supernova Observations1998

Using type Ia supernova as standard candles, two teams, independently concluded that the expansion of the Universe is speeding up

Photo: Lawrence Berkeley National Lab

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

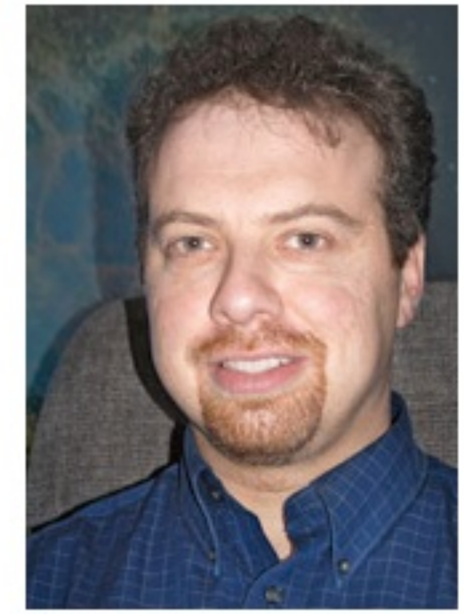


Photo: Scanpix/AFP

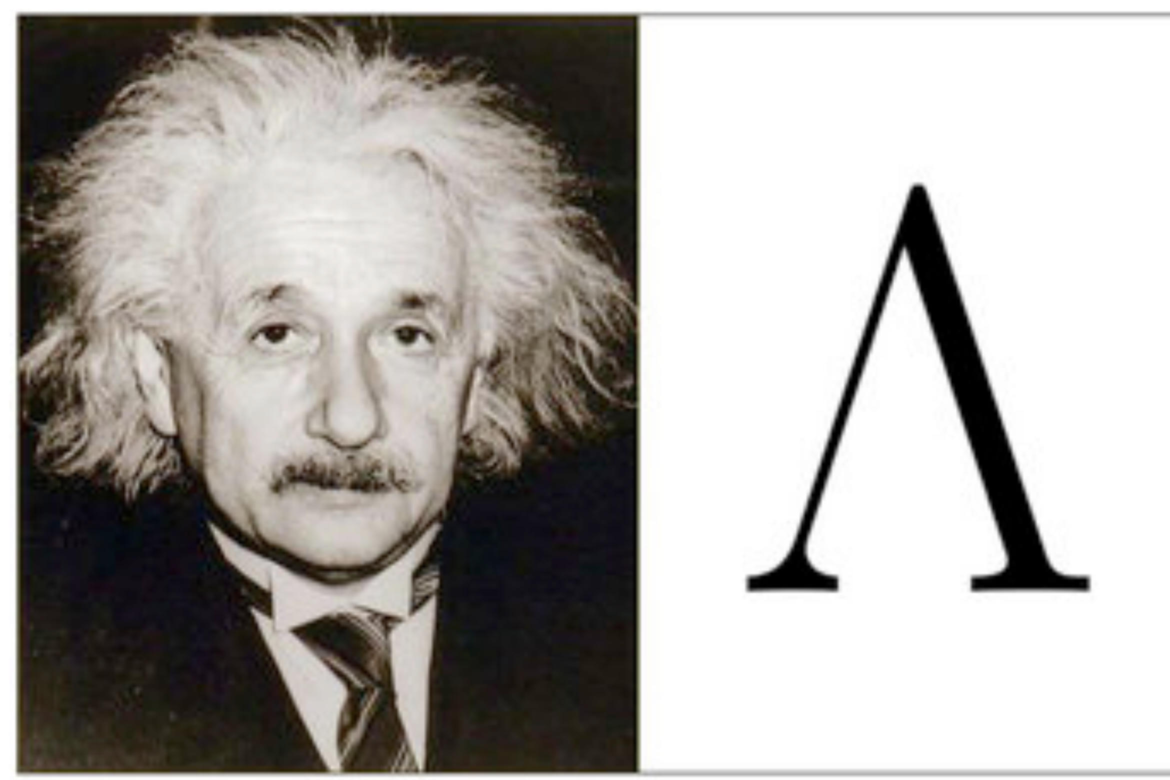
Adam G. Riess

Question: Can one trust type Ia Supernova as standard candles?

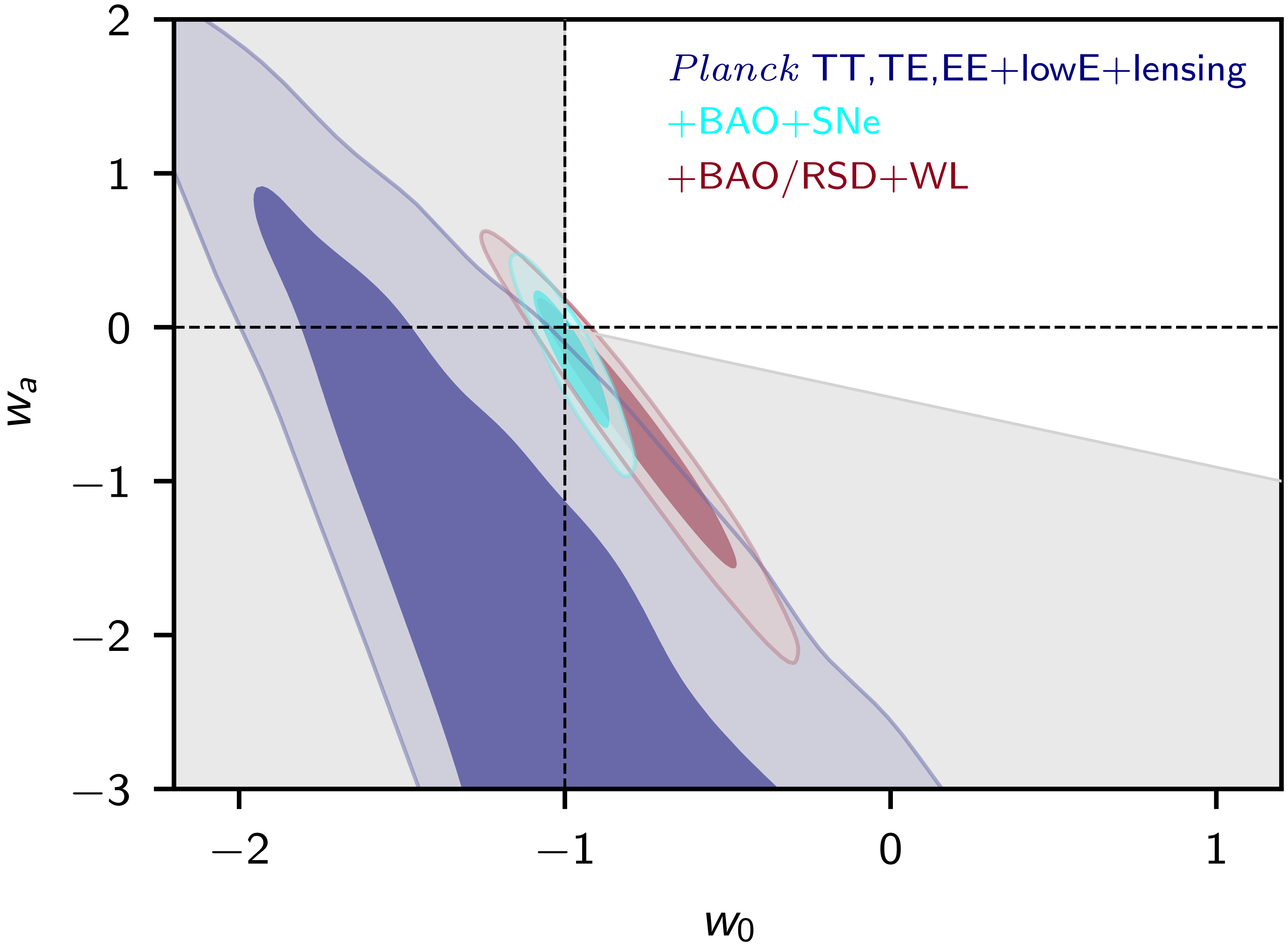
Problem with dark energy and cosmological constant

$$\left(R_{\alpha}{}^{\beta} - \frac{1}{2} g_{\alpha}{}^{\beta} R \right) + \Lambda\, g_{\alpha}{}^{\beta} = \frac{8\pi G}{c^4} T_{\alpha}{}^{\beta}$$

$$\boxed{\rho_{vac} \sim 10^{120} \rho_{obs}}$$

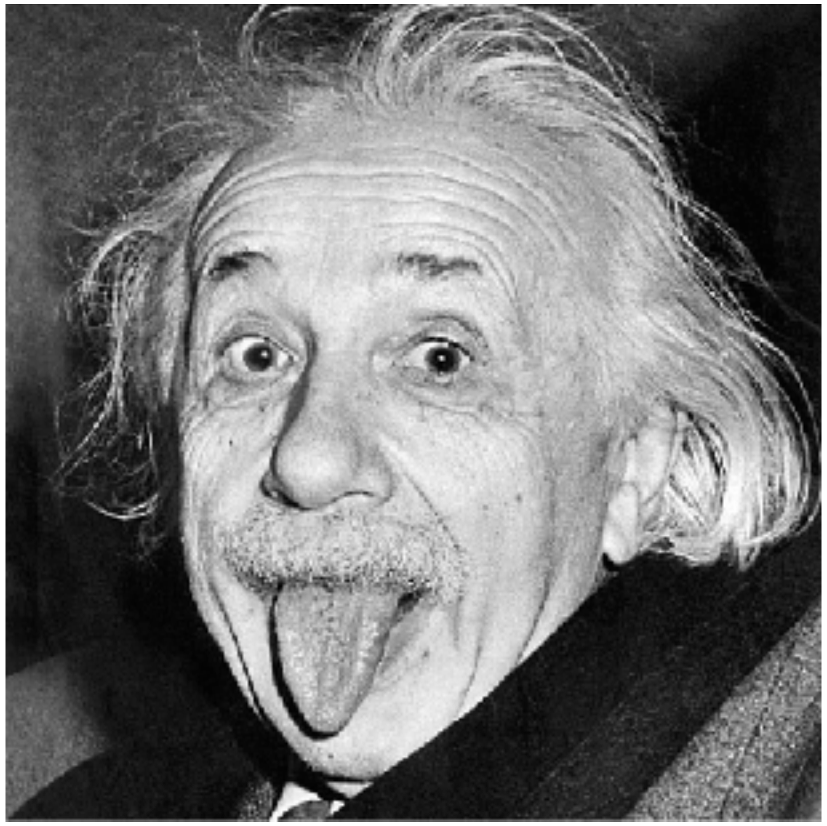


Dark Energy



$$w = w_0 + (1 - a)w_a$$

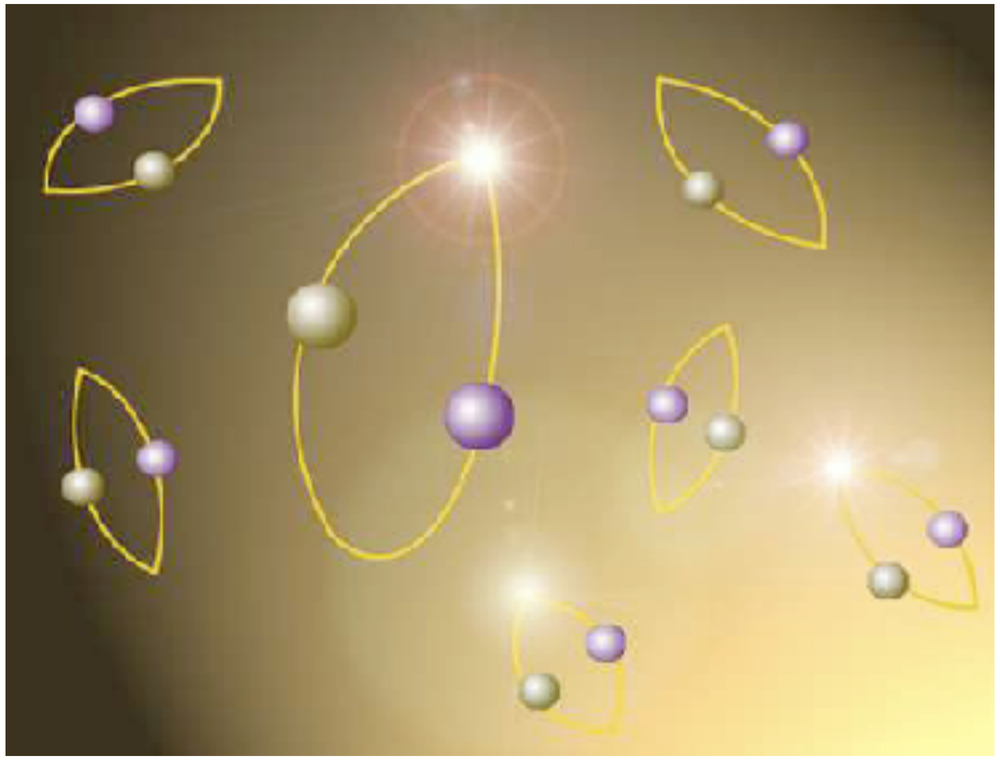
Cosmological constant
is a very good fit !



Planck 2018

$$w_0 = -1.028 \pm 0.032 \quad \text{(68 \%, \textit{Planck} TT,TE,EE+lowE +lensing+SNe+BAO),}$$

Problems with the Dark Energy



S. Carroll

Gravity is repulsive rather than attractive!

A form of energy that exists even in empty space.

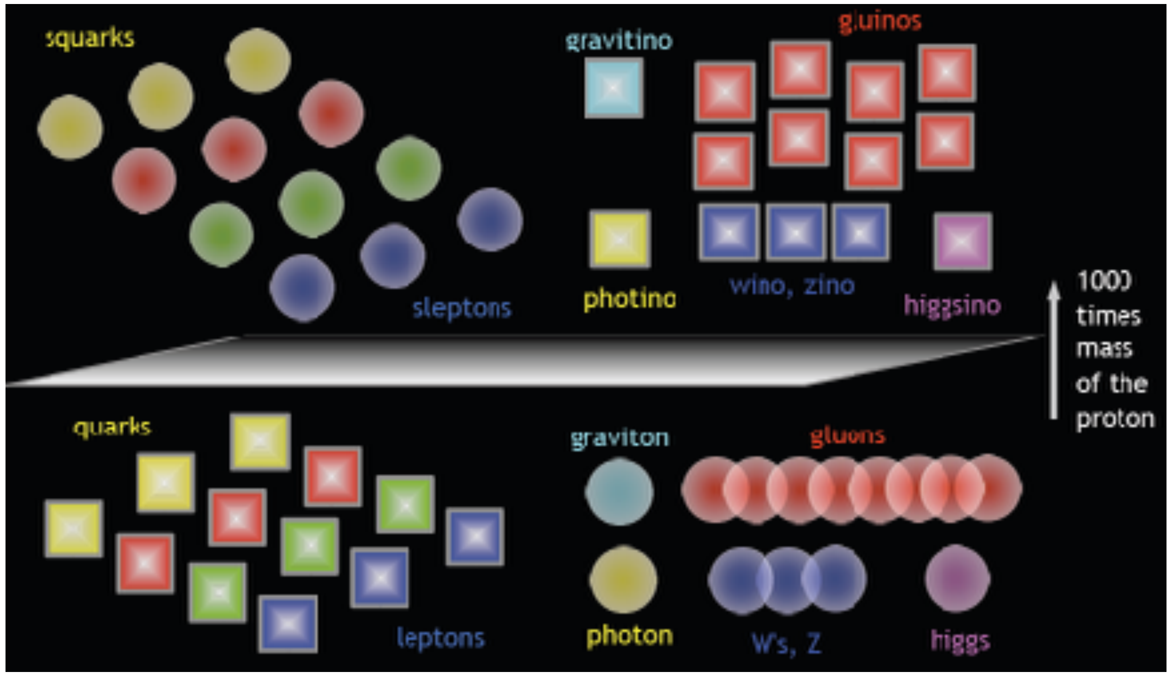
It does not cluster. It is invisible to ordinary matter, it acts only gravitationally.

Good news from Quantum Mechanics:

The vacuum is not empty. The vacuum is full of quantum fluctuations (the Casimir effect).

Adding up the QFT vacuum energy leads to

theoretical prediction = 10^{120} times bigger than observation.



Can Supersymmetry help with Dark Energy?

Bosons have positive vacuum energy. Fermions have negative vacuum energy. In SUSY these two adds up to zero.

However, SUSY is broken, perhaps at the TeV scale

supersymmetry prediction = 10^{60} times bigger than observation.

String Theory Landscape

Linde

Conclusions

- We are in golden age of cosmology.
- The Standard Model of cosmology is well described by the 6 parameter LCDM model.
- Inflation is the leading paradigm for early universe and generating perturbations on CMB and seeds of large scale structure.
- The cosmological data strongly support the LCDM model with the initial conditions set by a period of inflation.
- There are important open questions in LCDM model:

What are the nature of dark energy and dark matter?

What is the fundamental physics behind inflation?