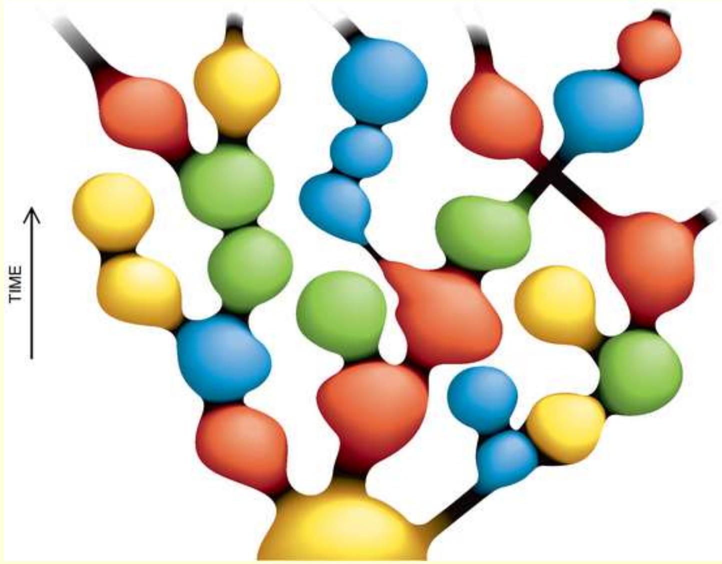
COLLÈGE DE FRANCE 1530

Chaire Galaxies et Cosmologie



History of the Universe

Françoise Combes
Observatoire de Paris

April 2022

l'Observatoire de Paris | LERMA

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

Universe size before the XXth

Disk of Nebra
Germany
1600 b JC
2kg, 32cm

Mythologies
Hindu – China
Giant turtle
Snake + elephants
Water falls

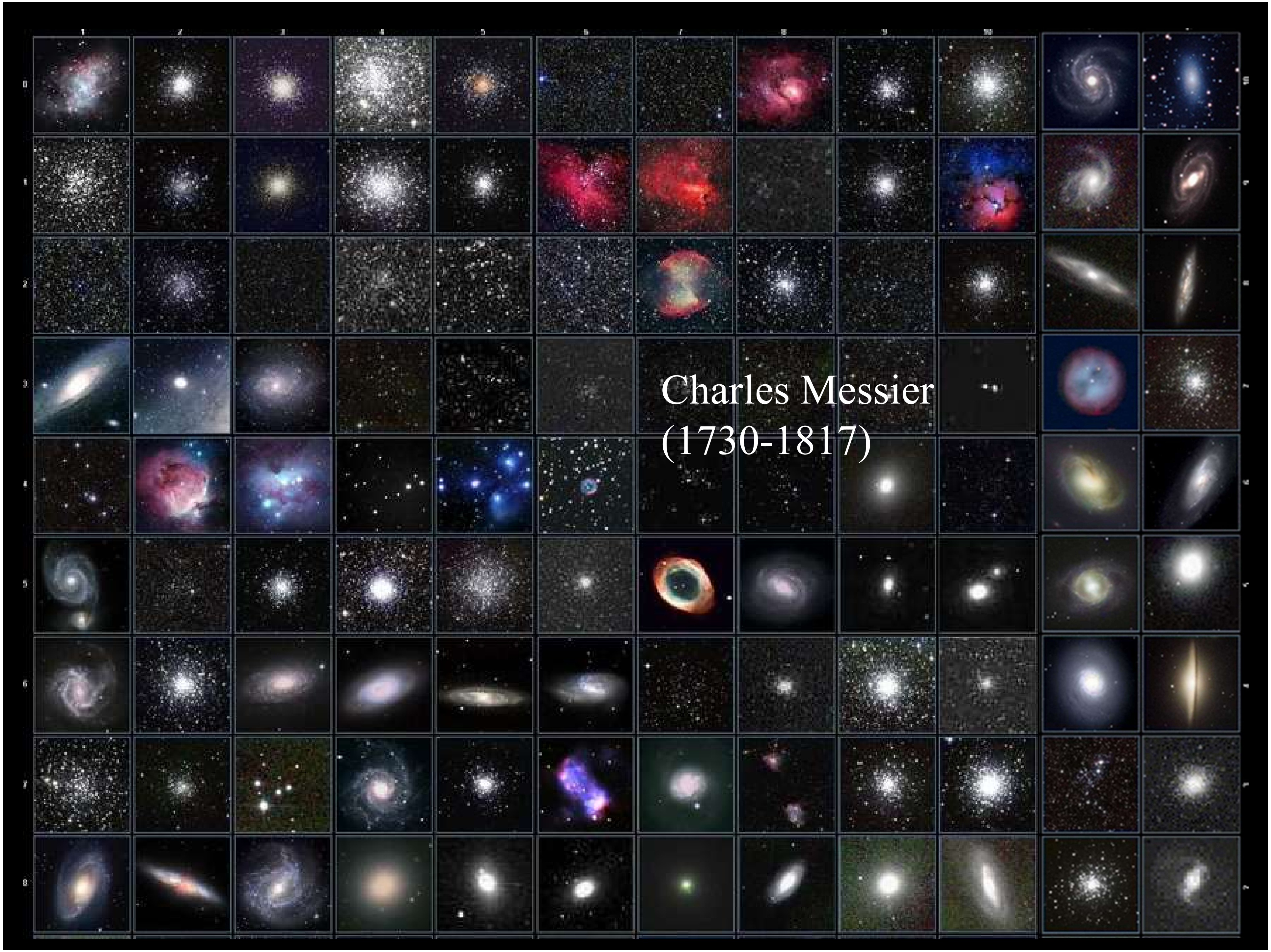
Cosmic tree
Northern
mythology

Copernic revolution

Sun at the center,
Measure of distances
of the planets

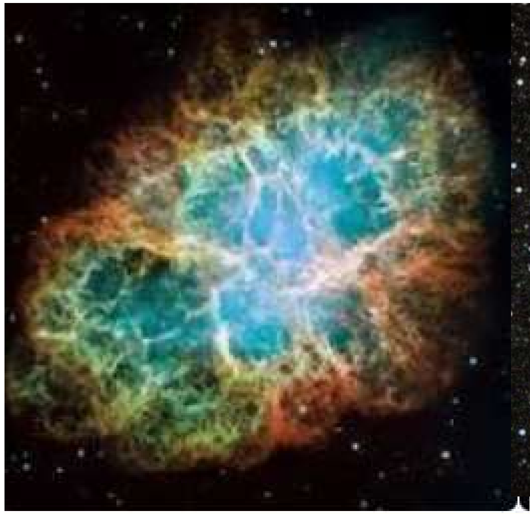
Copernician principle

We are not at the center
of the Universe!


Charles Messier
(1730-1817)

Messier

M16

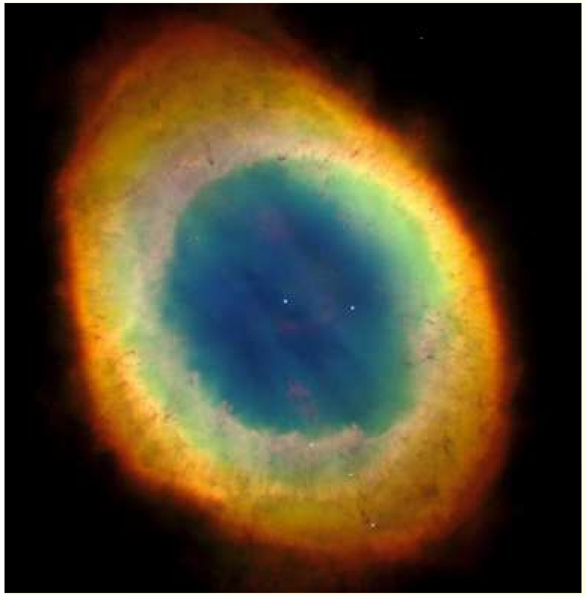


M1

M3

M51

M57

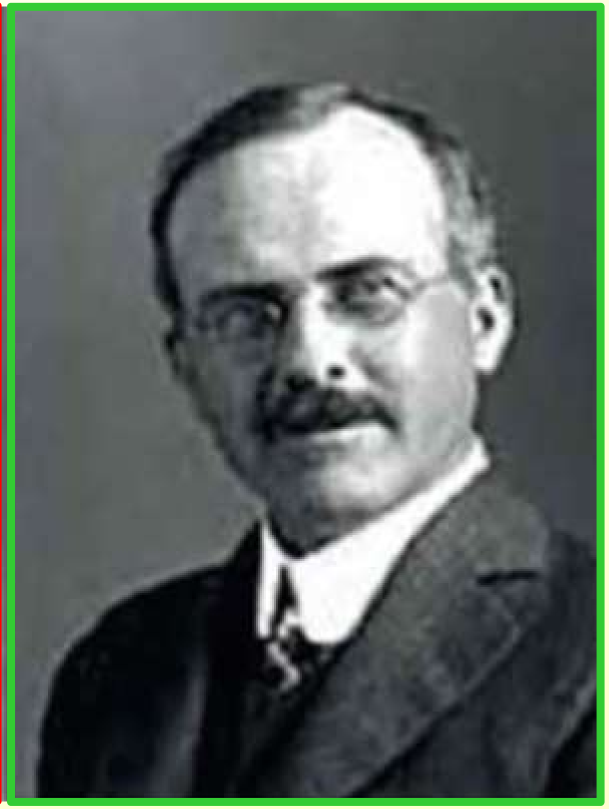


Do galaxies exist?

Early XXth century: **a great debate in 1920**
To determine our Universe size
Nebulae, stellar clusters or Galaxies?

Harlow Shapley (1885-1972)

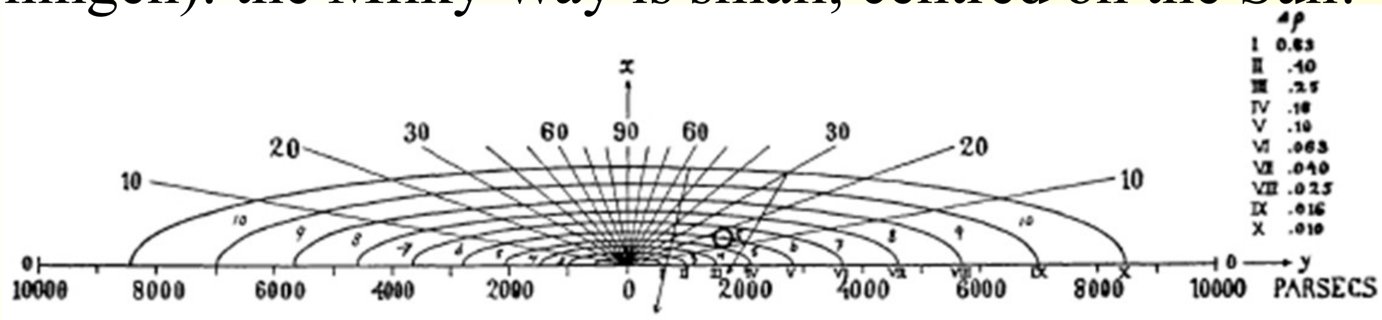
Heber Curtis (1872-1942)

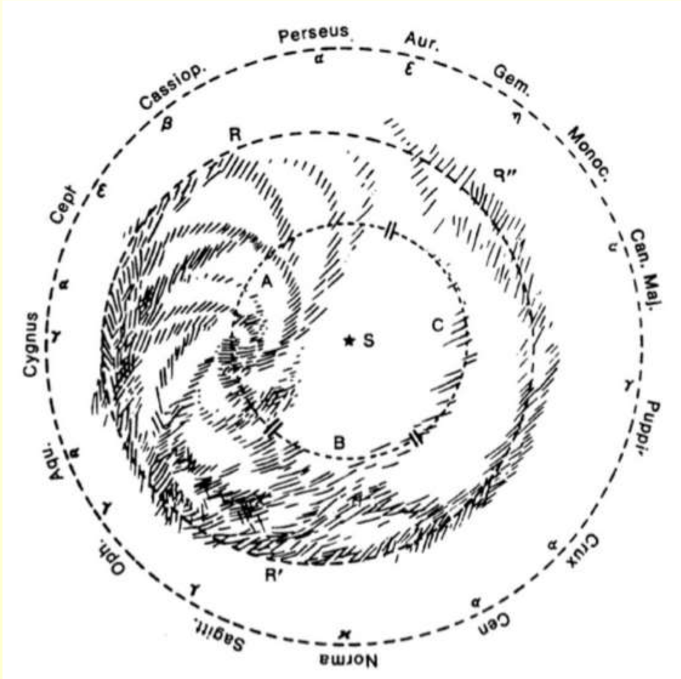


What was known in 1920

V.M.Slipher (USA) measured recession velocities of « nebulae »

J.C. Kapteyn (Groningen): the Milky Way is small, centred on the Sun!

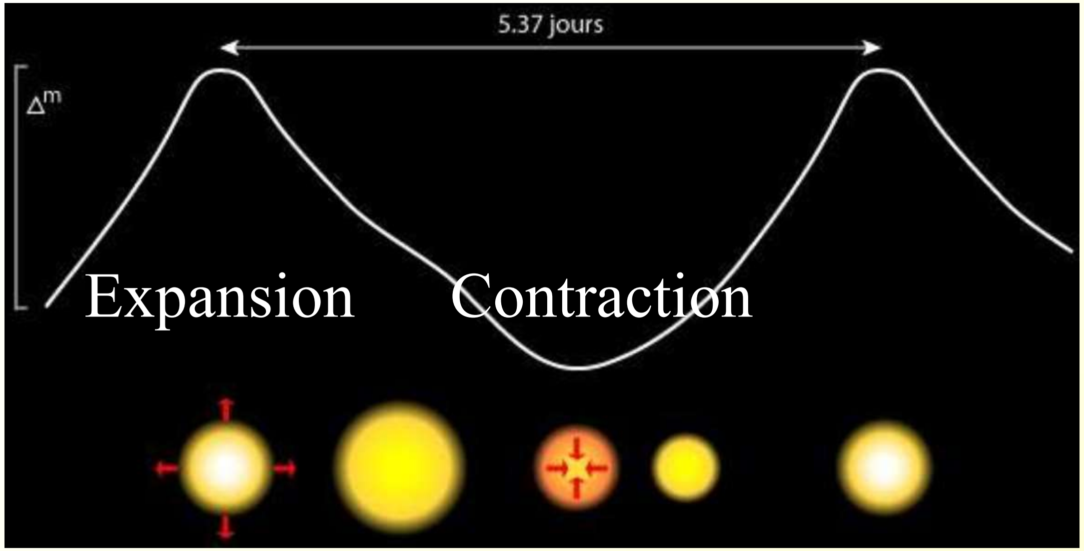




Cornelius Easton (NL): image of the Galaxy with spiral arms, in 1900
Centred on the Sun

The great debate

In 1920, relation P-L of Cépheids distance indicator (Leavitt, 1909)



Henrietta Leavitt

Harlow Shapley

--Nebulae belong to our Galaxy + globular clusters

--Size of the Milky Way 100kpc

Heber Curtis

--Nebulae, such as Andromeda are galaxies external to Milky Way

-- Size : 10kpc in diameter

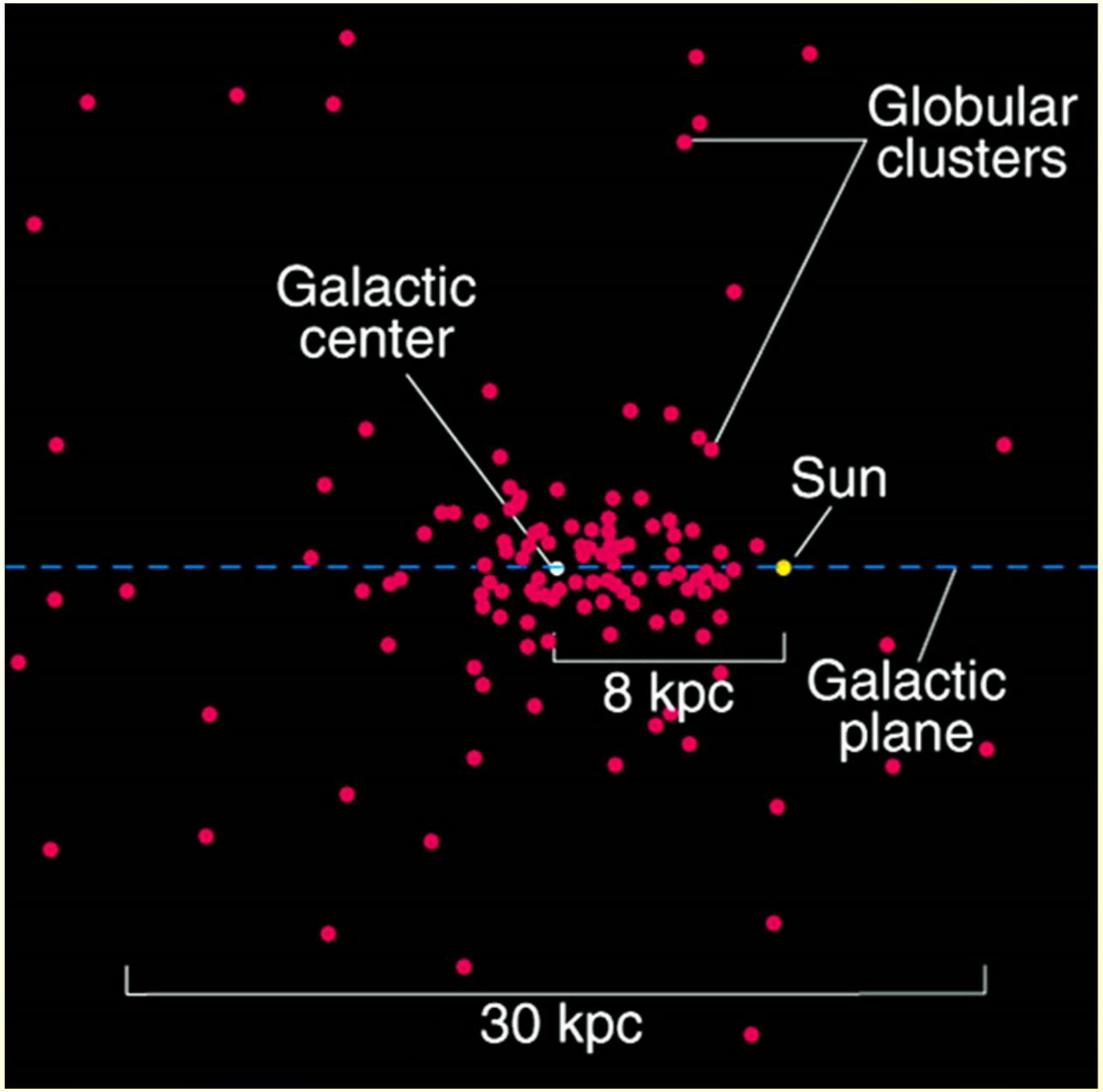
Shapley: globular clusters yield our Galaxy size

➔Sun is not centered

➔ there exists a stellar halo

The center of our Galaxy at 8kpc from Sun (>1950)

Globular clusters in our Galaxy



Actual sizes known today

End of the debate

E. Hubble

The two astronomers were both partly right

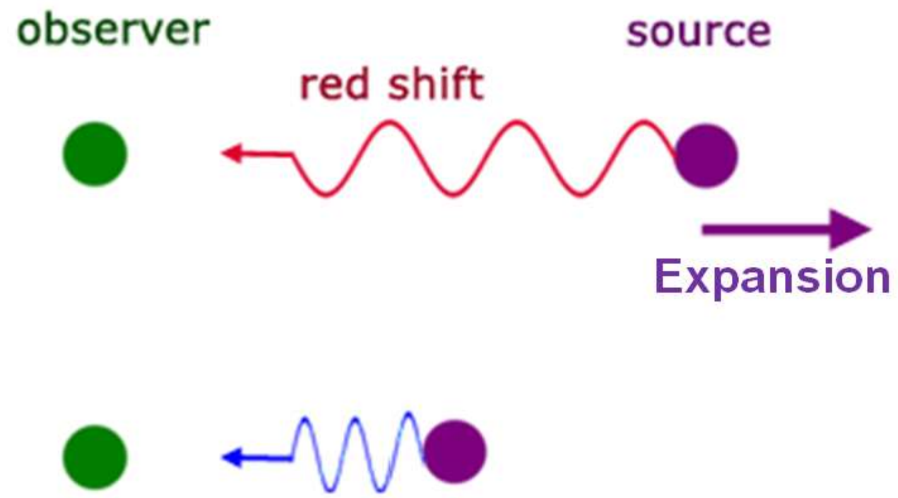
Hubble (1925, 1926) identifies Cepheids in M31, M33
They are external galaxies, distant by ~1000kpc

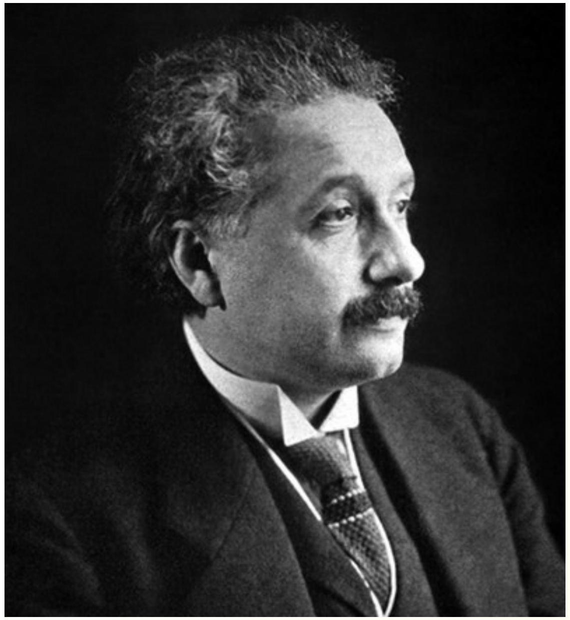
Positive velocities are interpreted as an expansion of the Universe, in 1929

1930: Globular clusters in Milky Way, not centered on the Sun

Galaxies appear to recess with Velocity $\propto$ Distance

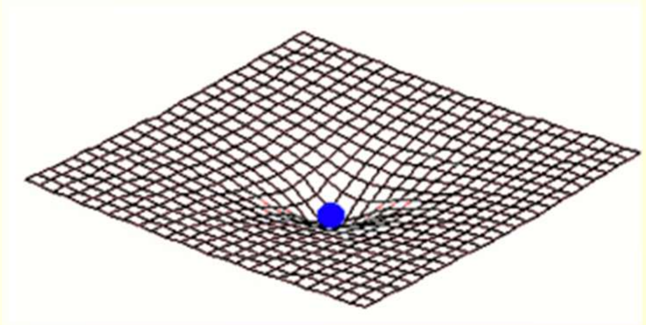
Universe in expansion





Some dates

1905: Special relativity, space-time,



1915: General Relativity

→ Gravitation as a space distortion

1917: Universe models

A **static Universe**, stable, in equilibrium

Einstein adds a **constant** Λ in the equations

➔1919: Λ is a necessity, which ruins the beauty of the theory

Big-Bang theory

1929: existence of external galaxies established
Galaxies are in recession !
velocity proportionnal to distance

E. Hubble

Space is expanding

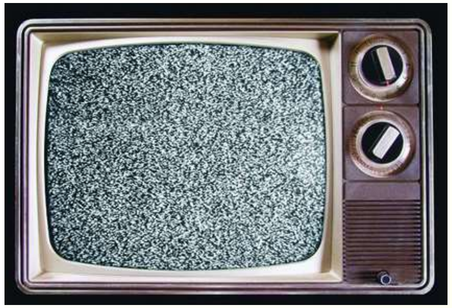
G. Lemaître

Georges Lemaître proposes the Universe beginning as very dense and hot (**1927**)

Qualified as **Big-Bang** by Fred Hoyle (BBC, **1949**!)

Cosmic microwave background (CMB)

Serendipitous discovery in 1965, as an annoying background noise!



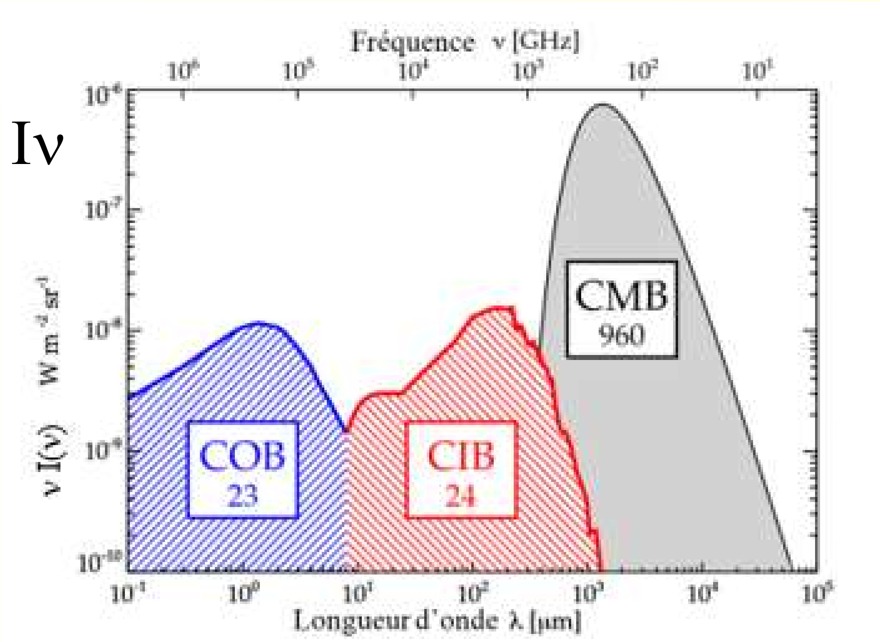
400ph/cm^3

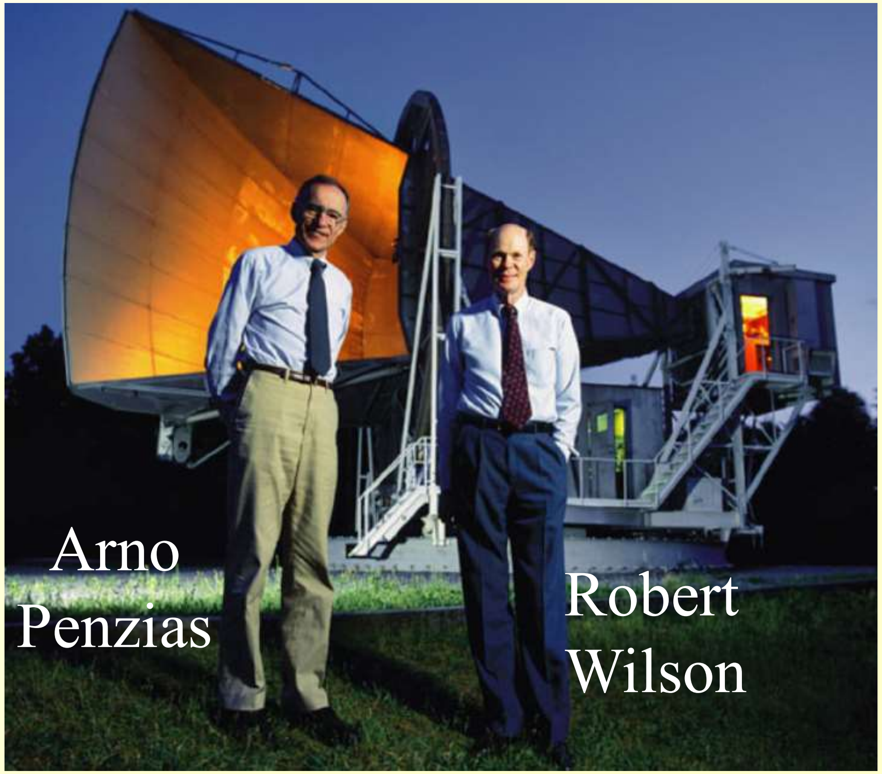
T = 2.73K

10^{13} /cm^2/s

A few % of television snow

ν Iν



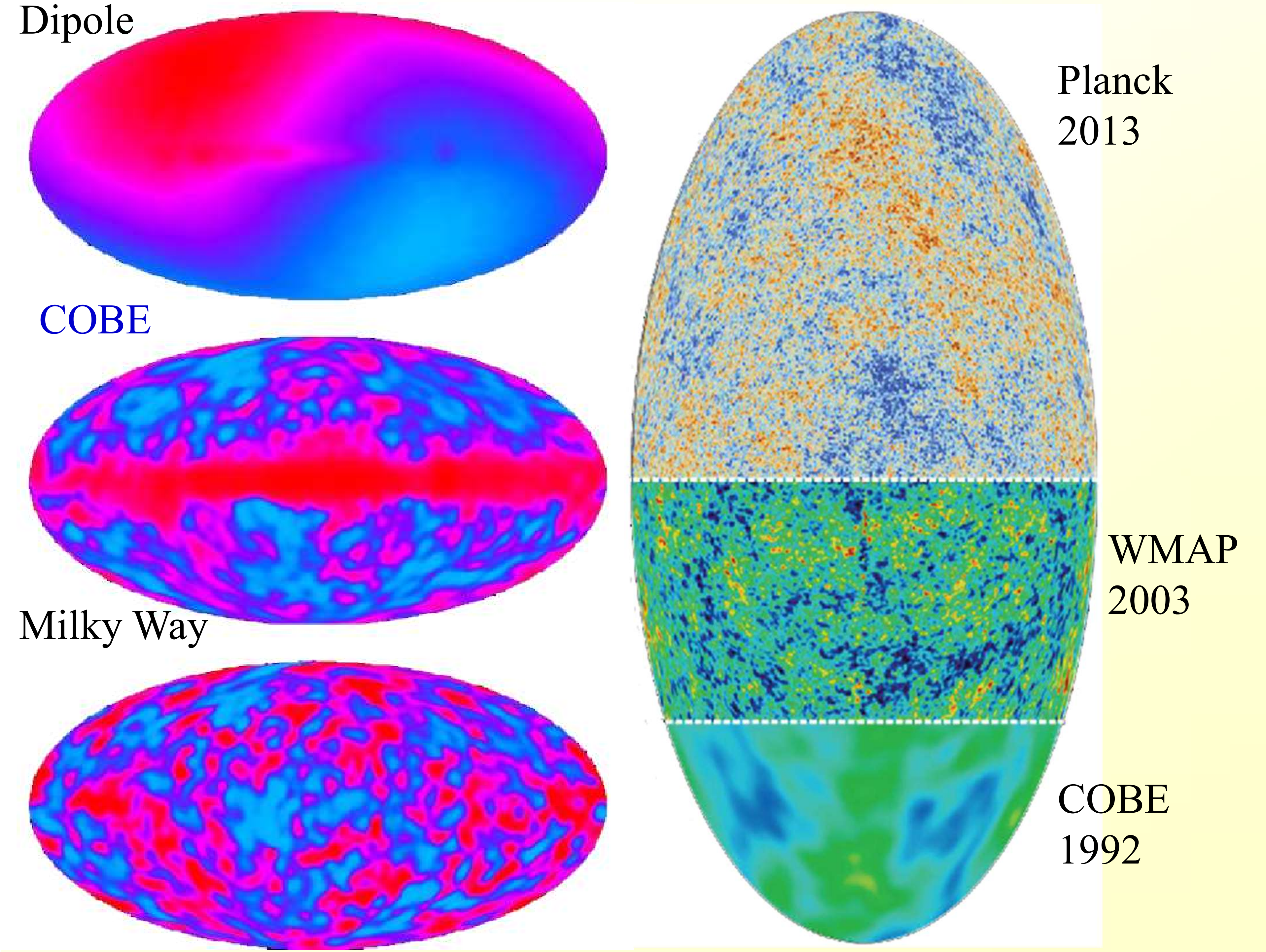


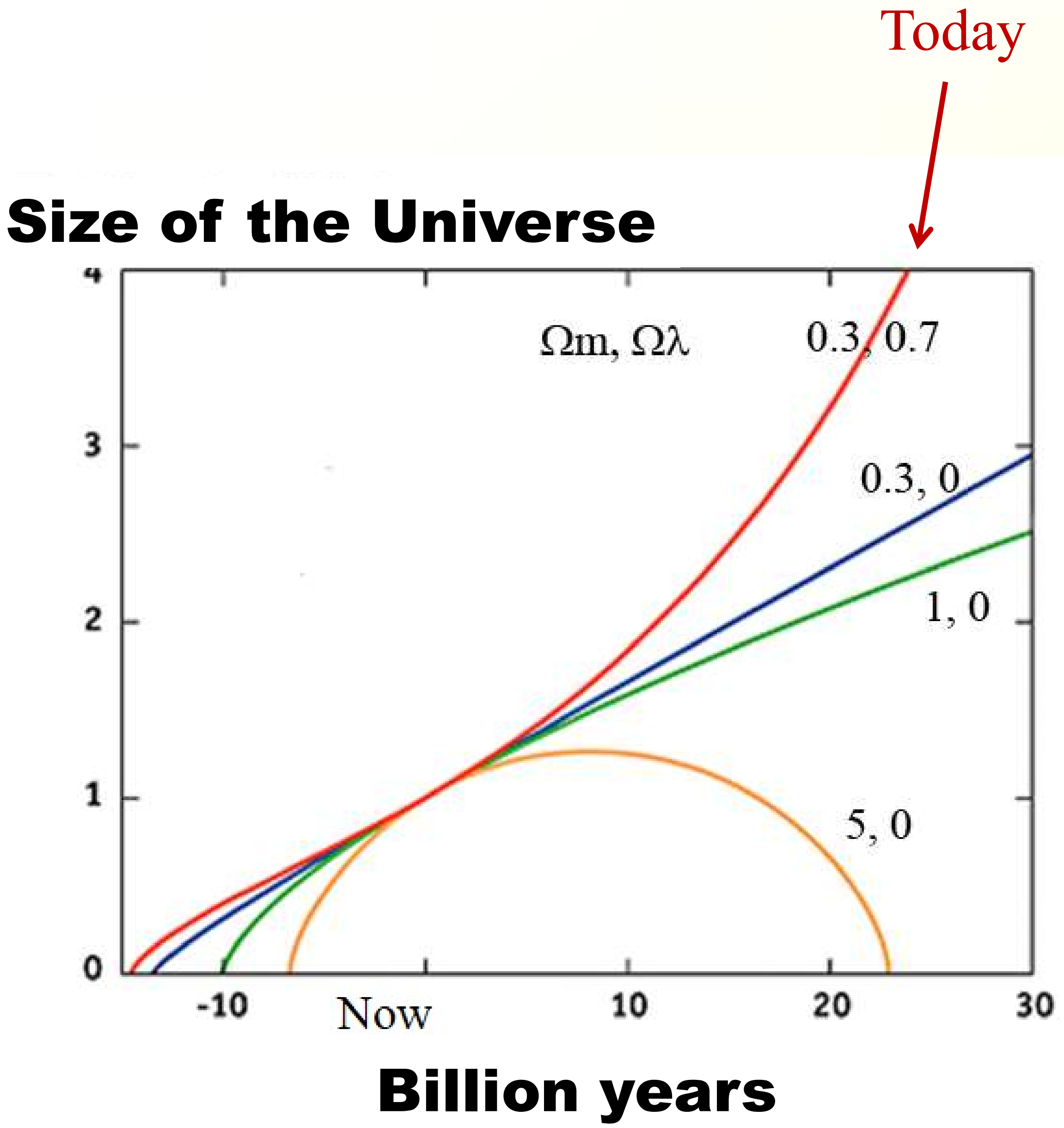
Last scattering surface

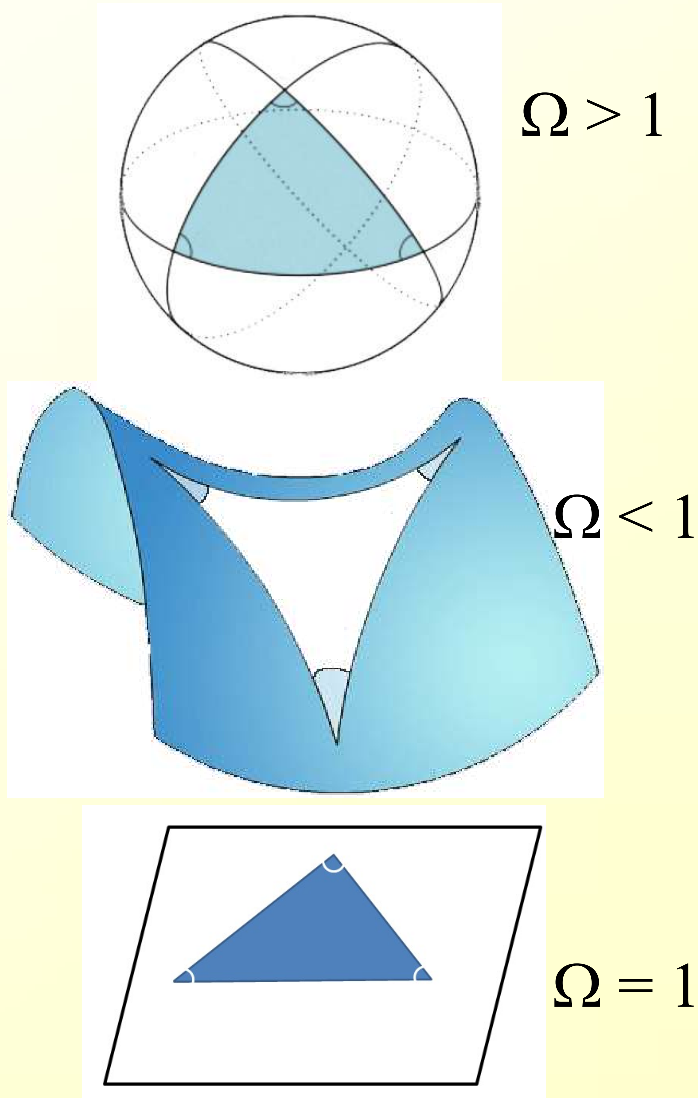
The Sun is also a plama
We see only its surface
➔Opaque inside

The photons scattered at its surface travel towards us in a straight line

Then we can derive what's happening inside!


Dipole
COBE
Milky Way
Planck
2013
WMAP
2003
COBE
1992

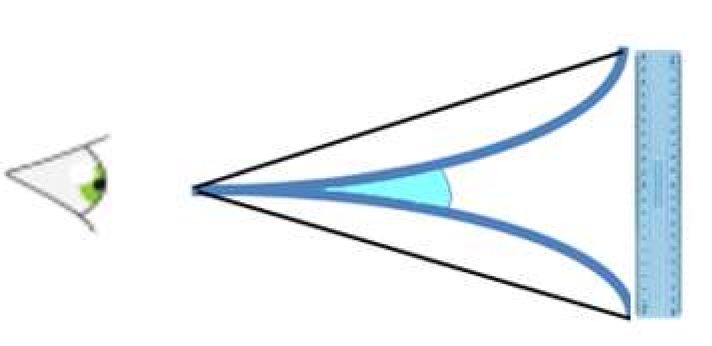


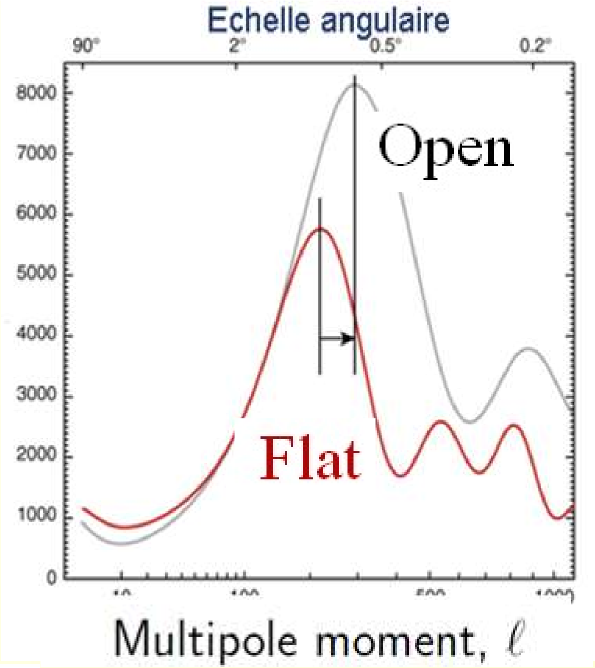


$\Omega = \rho/\rho_c$

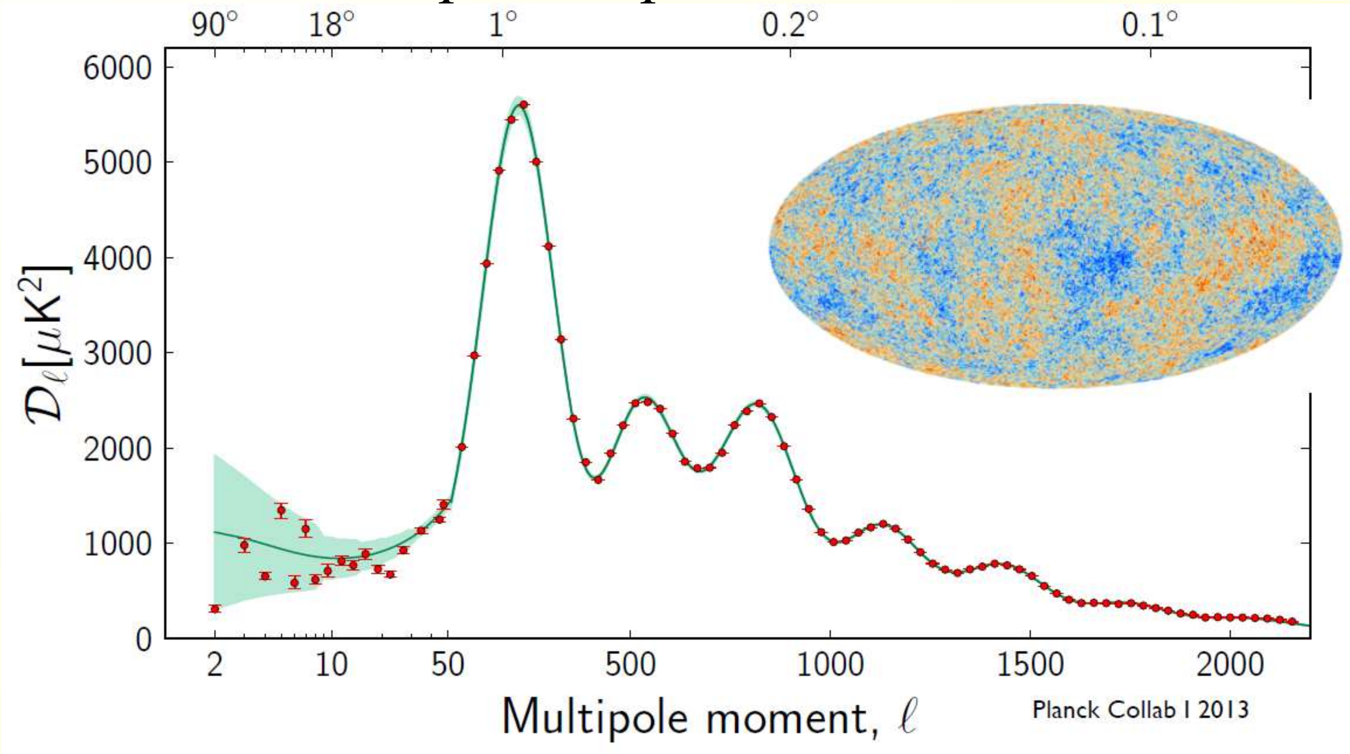
$\rho_c = 10^{-29} g/cm^3$

Flat universe



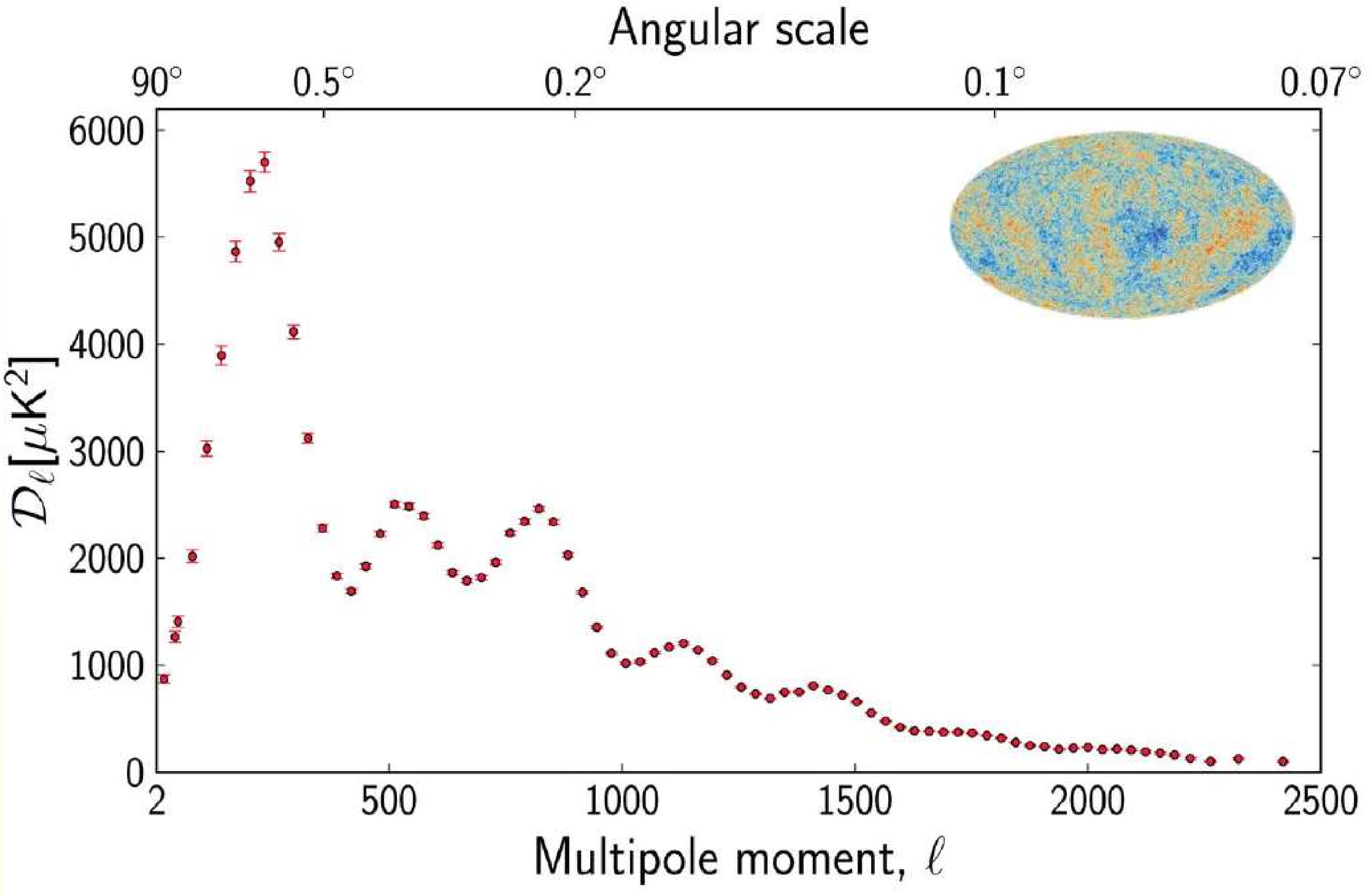


Planck : power spectrum



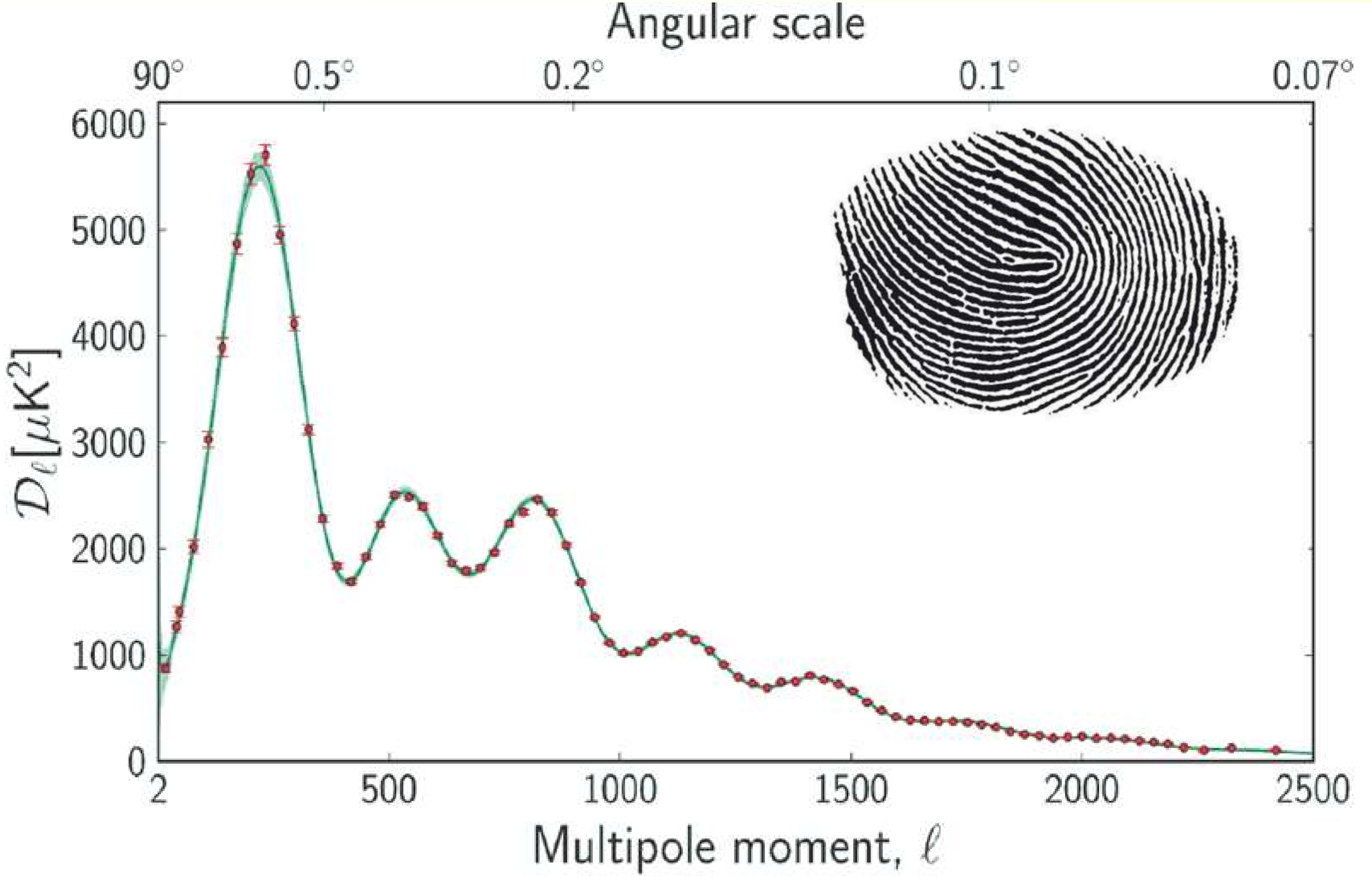
T=13,8 Gyr

Like a finger print



Like a finger print

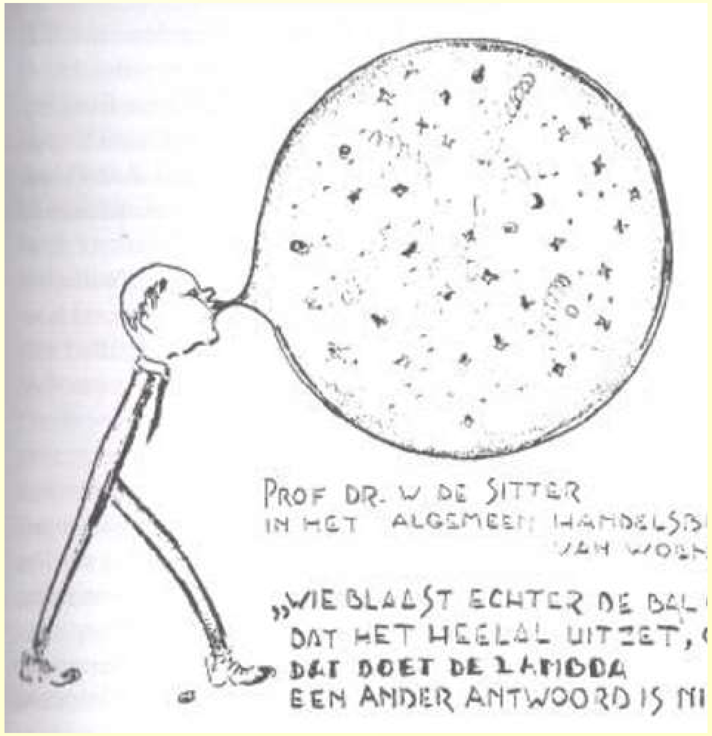
Ω_b, Ω_m, Λ, n, τ, …



Willem de Sitter model

De Sitter in **1917** develops with Λ an Universe
in expansion, completely empty, **without matter**

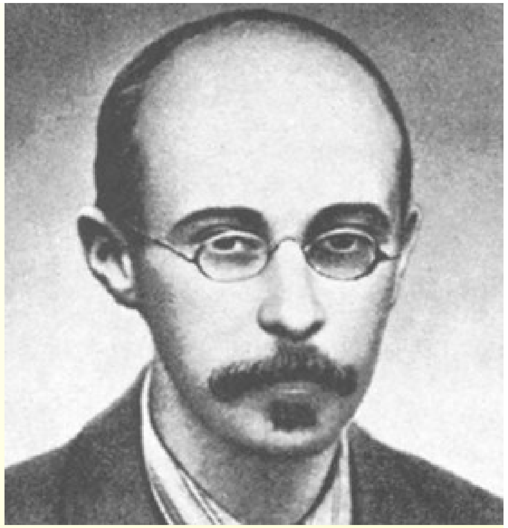
➔ Einstein makes fun of this model



Friedman & Lemaître models

Several models non-static
Alexander Friedman (**1922**)

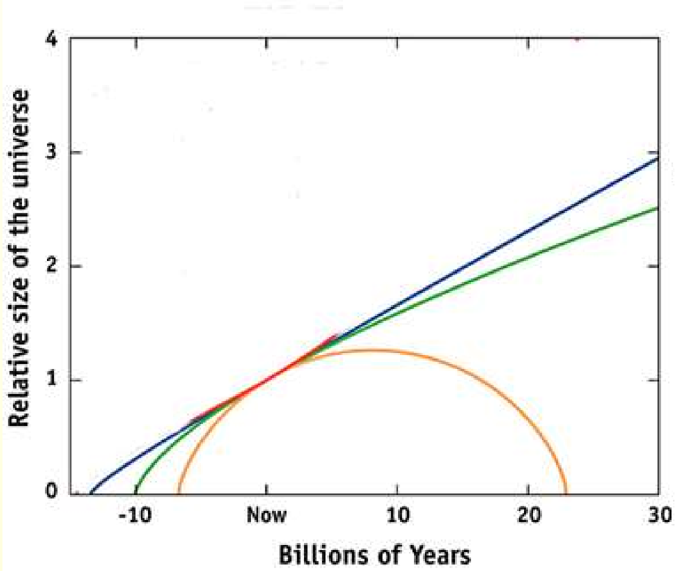
Georges Lemaître solves equations in **1927**,
With an expanding universe

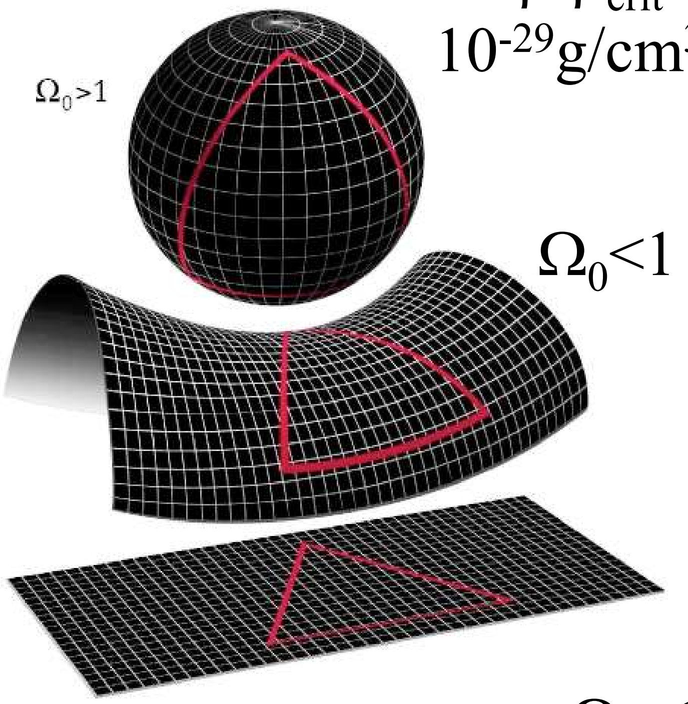


A. Friedman

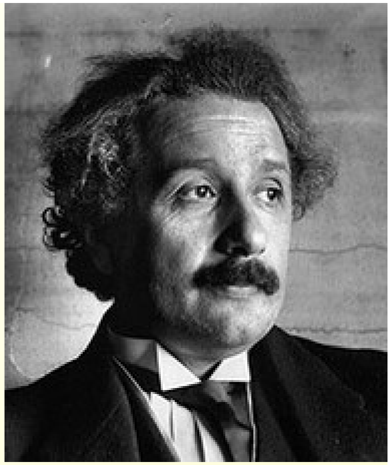
$\Omega = \rho/\rho_{crit}$
10^{-29}g/cm^3

G. Lemaître





Einstein realised his blunder



1931: after the observation of the Universe expansion Einstein writes that the Λ constant is not useful anymore

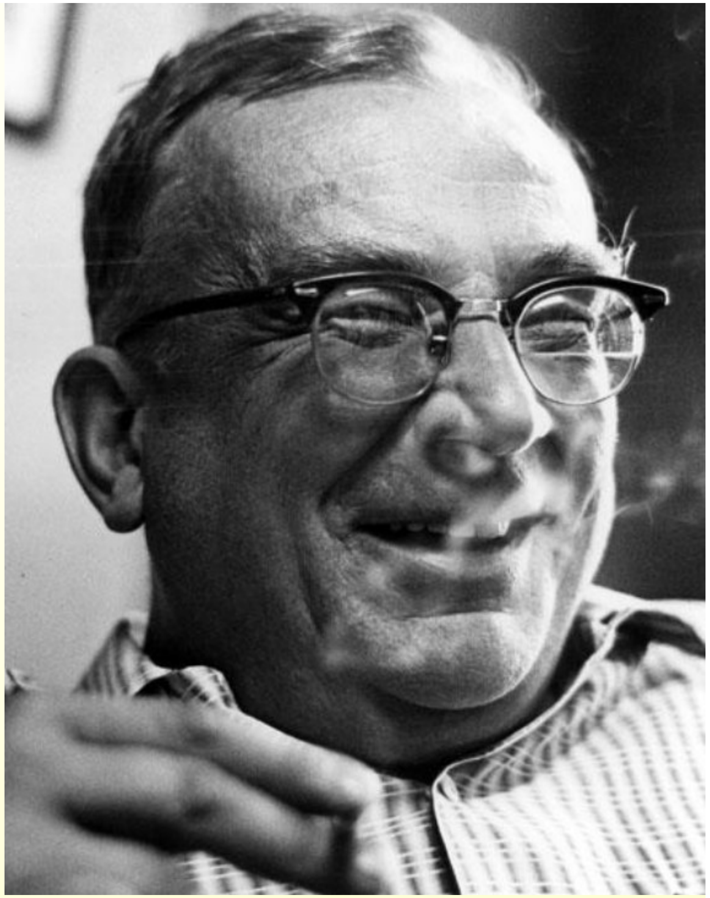
With de Sitter, he publishes in **1932** a flat model, without cosmological constant, where the Universe radius is linked to matter density

This **Einstein-de Sitter model** remained popular during the whole XXth century

What Gamow told

It is George Gamow who revealed
« the biggest blunder » recognized by
Einstein

Did Einstein actually say that?
Mario Livio (2013) doubts

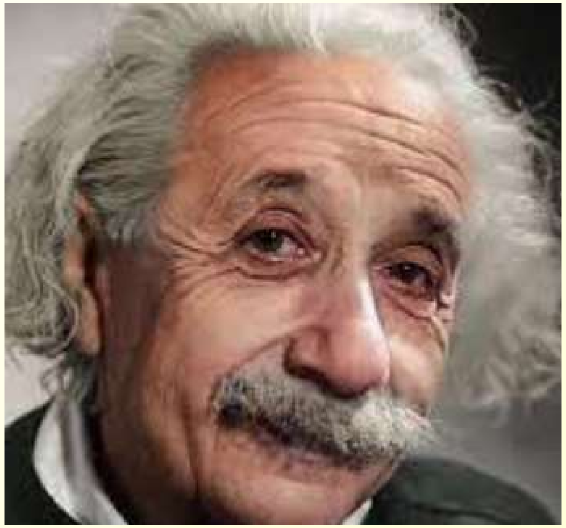


George Gamow

Gamow has a great sense of humor

He added Hans Bethe as co-author of his paper with Ralph Alpher
« Alpher, Bethe, Gamow » article on primordial nucleosynthesis

Why a cosmologic constant ?



Einstein introduced a constant λ in 1917
to represent a static Universe

His model of universe was a sphere
of finite mass

Radius R(t) ➔ $\mathbf{R^2 = \Lambda / c^2}$

The vacuum energy

W. Pauli

Wolfgang Pauli in 1920: vacuum energy in quantum mechanics, could it be the origine of Λ ?

His computations showed that the Einstein universe radius was ridiculously small!

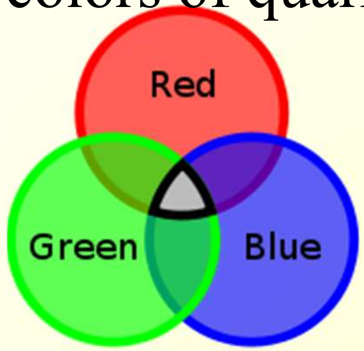
Sum of the ground state energy of each degree of freedom until frequency ν_{max} corresponding to electron radius

➔Energy density so large that the **Universe radius R(t) is 31km!**

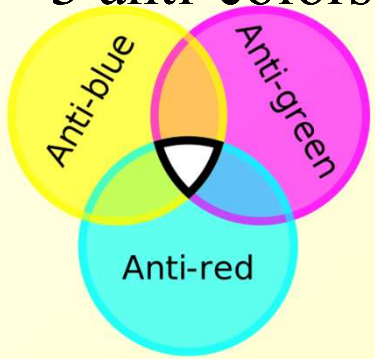
$$\Lambda = c^2/R^2$$

The quantic vacuum

3 colors of quarks



+ 3 anti-colors



- **Years 1960-70**, field theory approach, Quantum chromodynamic (QCD)

- The density of Universe (Ω=1) ~ $\mathbf{10^{-29}}$ **g/cm^3**

Σdegrees of freedom of all quantic fields

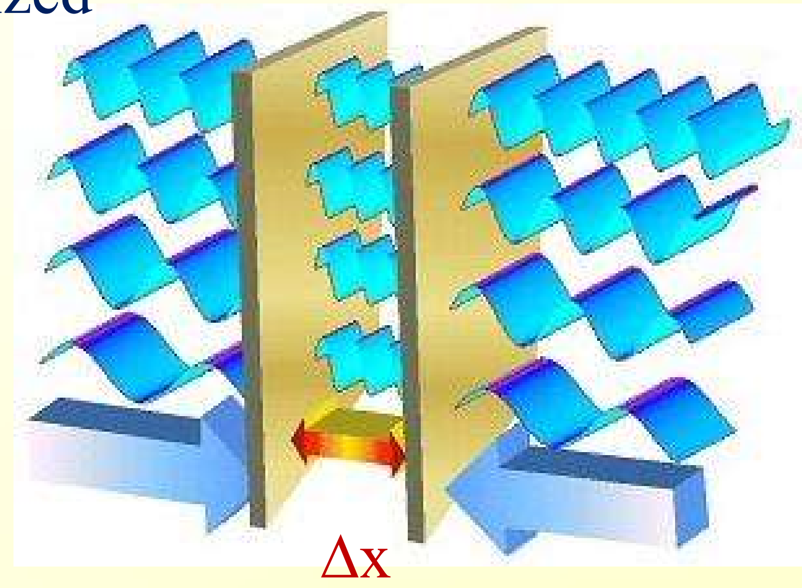
According to the cutoff scale, this gives

- scale of electroweak interaction (**10^{56} x**)
- Planck scale (**10^{119} x**)

Reality of this vacuum energy?

- **Casimir effect (1948)** between two uncharged plates
- Vacuum energy is everywhere, quantized

Virtual photons: electromagnetic field E



Between the plates:

kλ = Δx nbre of photons is limited

For Δx small ➔ less energy

Attractive force between plates, measured in several experiments, since ~30 yrs

Nobel prize in 2011 for 2 teams

- **Saul Perlmutter**, *The Supernova Cosmology Project*, Berkeley
- **Adam Riess** (Baltimore) & **Brian Schmidt** (Australia)

The High-z Supernova Search Team

In total about 50 SN Ia with a well-calibrated light curve, allowed to demontrate the acceleration of expansion of the Universe

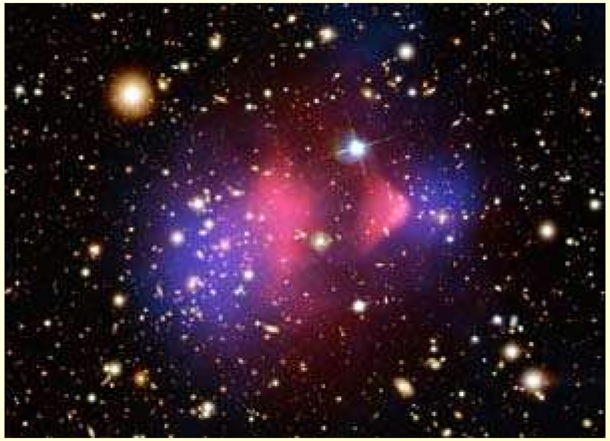
Content of the Universe

Ω_b

- Ordinary matter **5%**

Baryons (protons, neutrons)

Ω_{DM}



- Exotic dark matter **25%**

non baryonic

- Dark energy **70%**

Ω_Λ

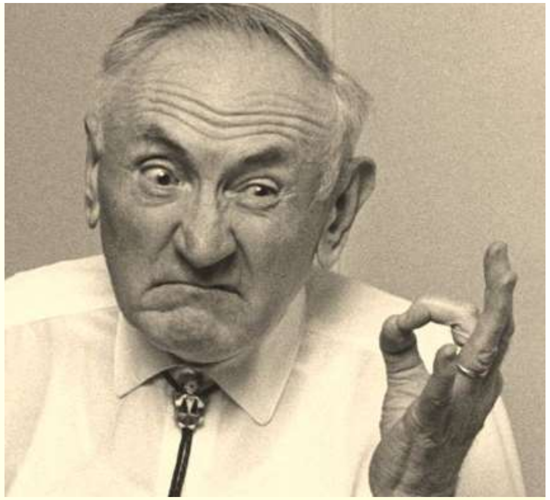
??

Or cosmological constant Λ

$$\Omega = \rho/\rho_{crit}$$

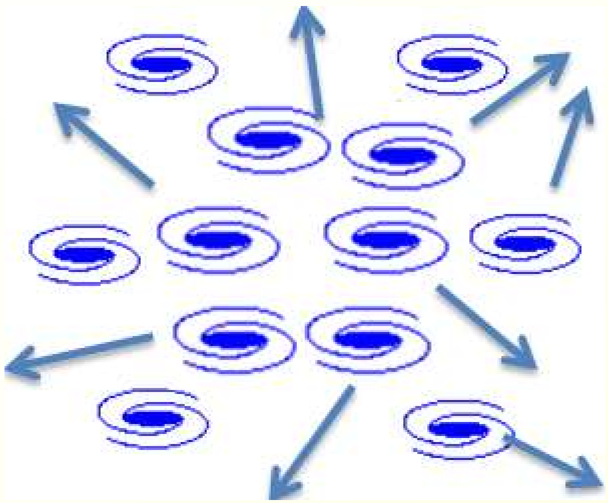
$$\rho_{crit} = 10^{-29} g/cm^3$$

Brief history of dark matter



Fritz Zwicky

1937 – Fritz Zwicky computes the mass of galaxy Clusters, using galaxy velocities



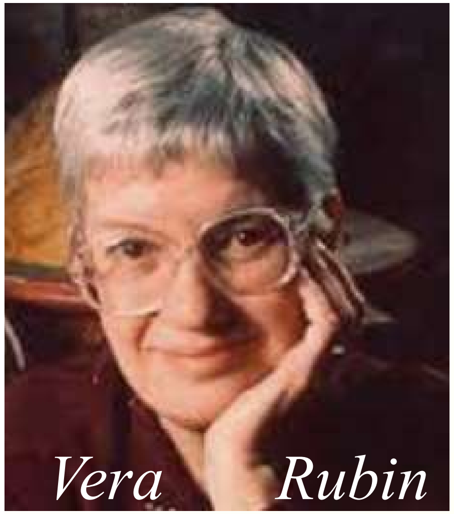
Coma cluster, V~1000km/s
M~ 5 10^{14} $M_\odot$

$M/L = 500\ M_\odot/L_\odot$

He proposes several hypotheses
-- dark matter in galaxies
-- matter in between galaxies + obscuration
-- test of Newton's law at large scale

Jan Oc

1932: Jan Oort speaks of dark matter in the solar neighborhood, in the Milky Way
➔Solids, dust, gas, dead celestial objects …

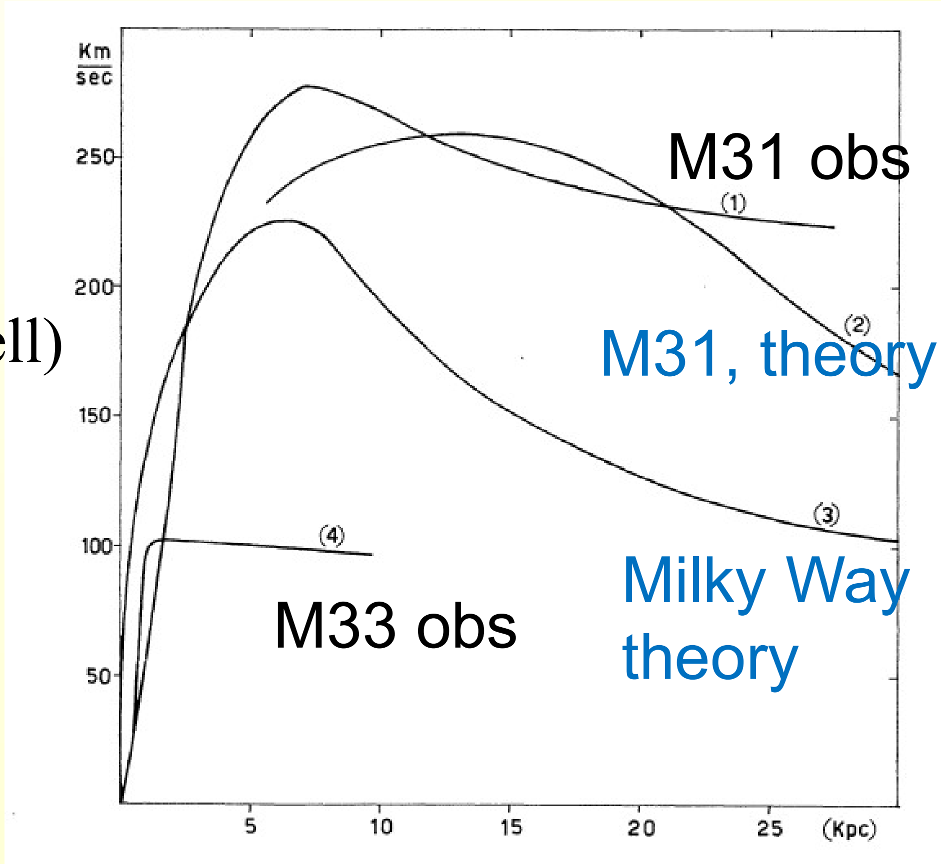


Dark matter in galaxies

Rotation curves of stars and ionized gas (Hα and [NII] 0.6μm)

Optical: Rubin, Ford et al 1978

Radio: The 21cm line of hydrogen is discovered in 1951 (Ewen & Purcell)
The first rotation curves are published at the end of 1950s



➔Flat Curves

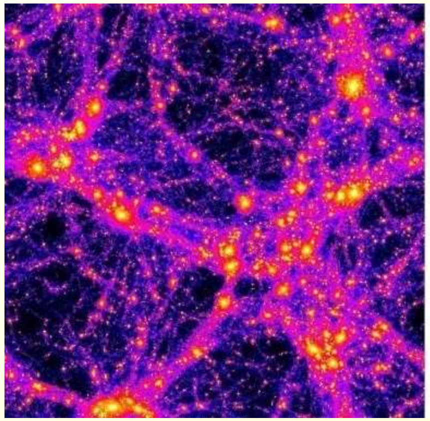
Interpretation at this epoch
M/L ratio increases with radius

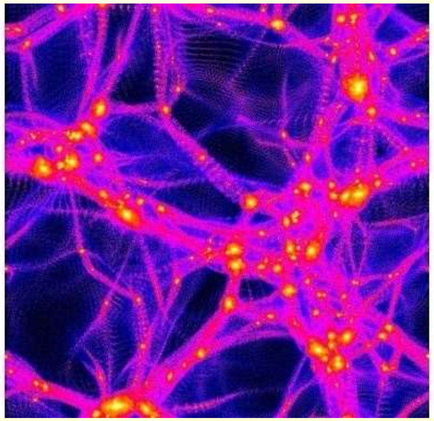
Several kinds of dark matter

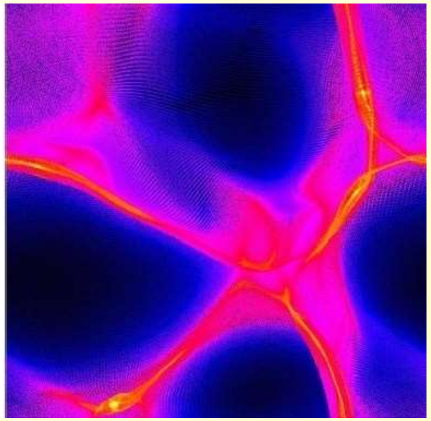
Hot (neutrinos)
Relativistic at decoupling
Cannot form the small structures, if m < 5 keV

Cold (massive particles)
Non relativistic at decoupling
WIMPS
("weakly interactive massive particles")
Neutralinos: particle **m~100GeV**
The lightest supersymmetric particle

Cold model (CDM) ***Warm*** ***Hot model (HDM)***





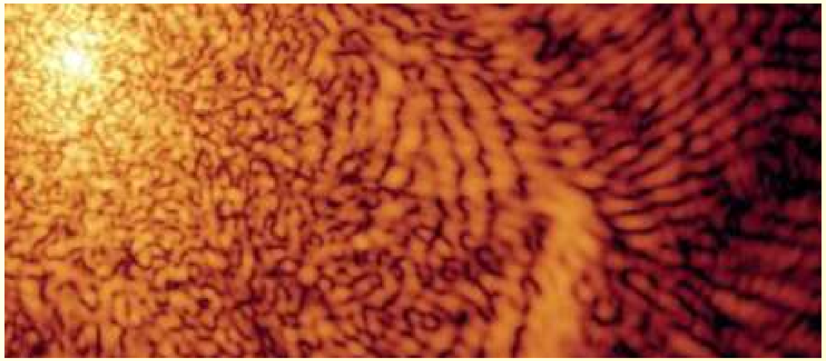


Alternatives to standard CDM

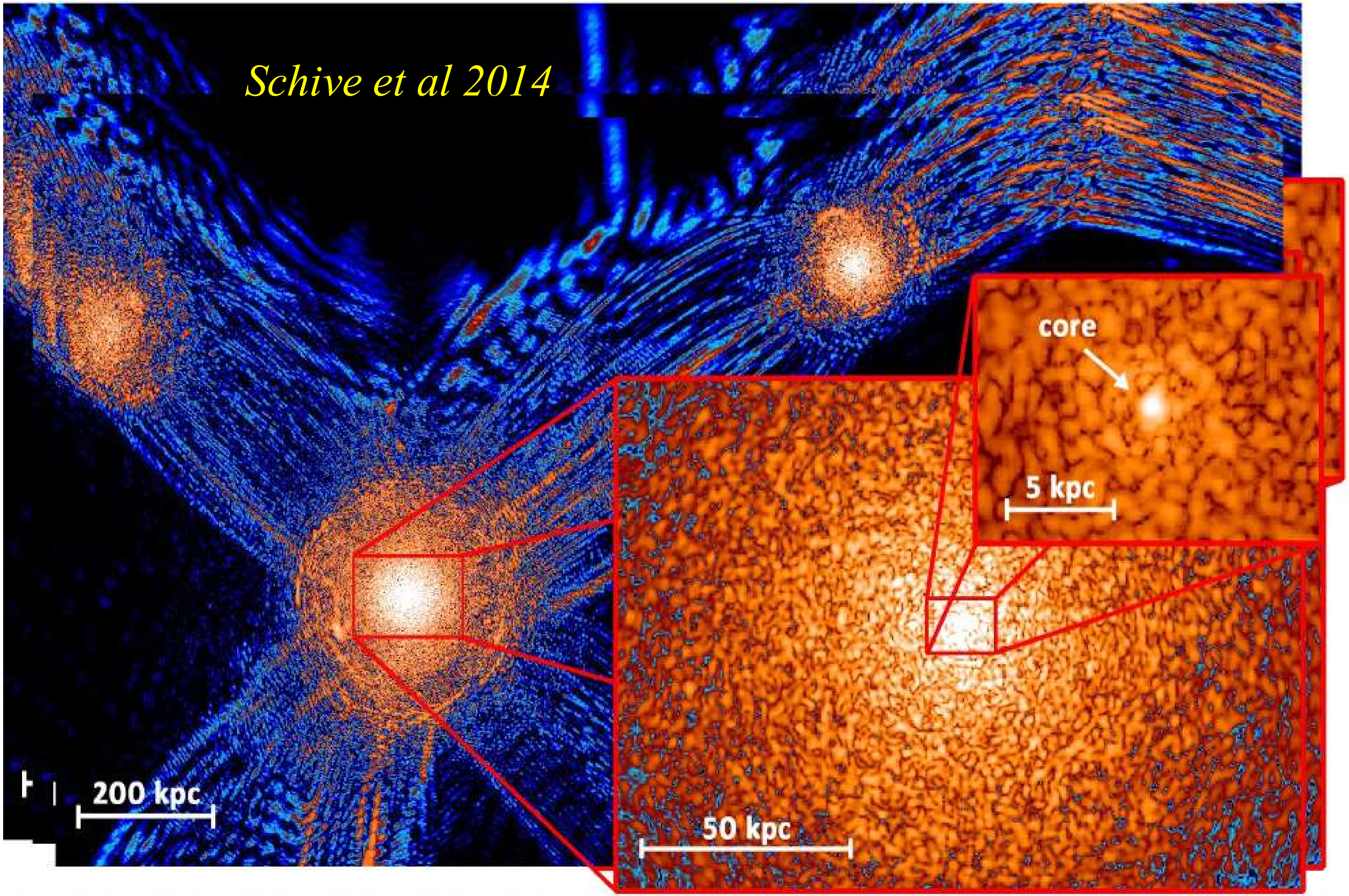
WDM: lukewarm, reduces small scale structures
SIDM: "Self-Interacting Dark Matter" *(Spergel & Steinhardt 2000)*

DM which annihilates, or decaying DM

Axions: invented in quantum chromodynamic (CP violation)
Fuzzy CDM 10^{-33} GeV $\ll M_{axion}$, Condensed Bosons *(Hu et al 2000)*



Quantum interferences: 9 orders of magnitude



Modified gravity: MOND

At weak acceleration

$a << a_0$ MOND regime $a = (a_0 \, a_N)^{1/2}$

$a >> a_0$ Newtonian $a = a_N$

Milgrom (1983)

M. Milgrom

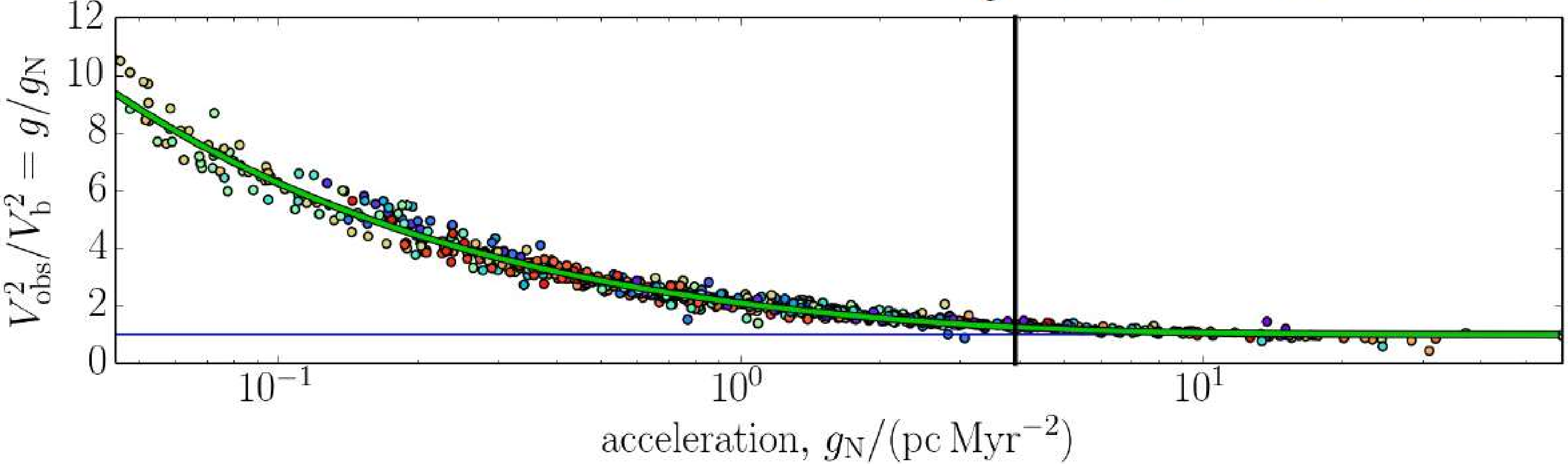
$$\nabla \cdot [\mu(|\nabla \phi|/a_0)\nabla \phi] = 4\pi G\rho$$

New Poisson equation

$a_0 = 10^{-11}$ g(earth)

M_{dyn}/M_{vis}

$a_0 \sim \Lambda^{1/2} c^2 \sim 10^{-10}\ m/s^2$

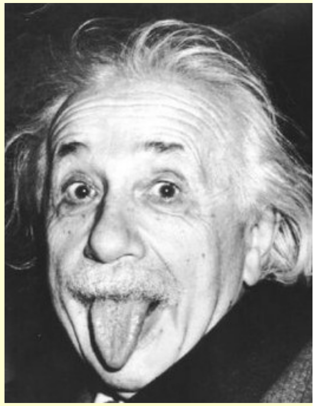


Theories Einstein - aether

The theories "Einstein æther", ou æ-theories, are covariant théories with modified general relativity

Tensor + vector (or scalar) field, of time regime, called aether

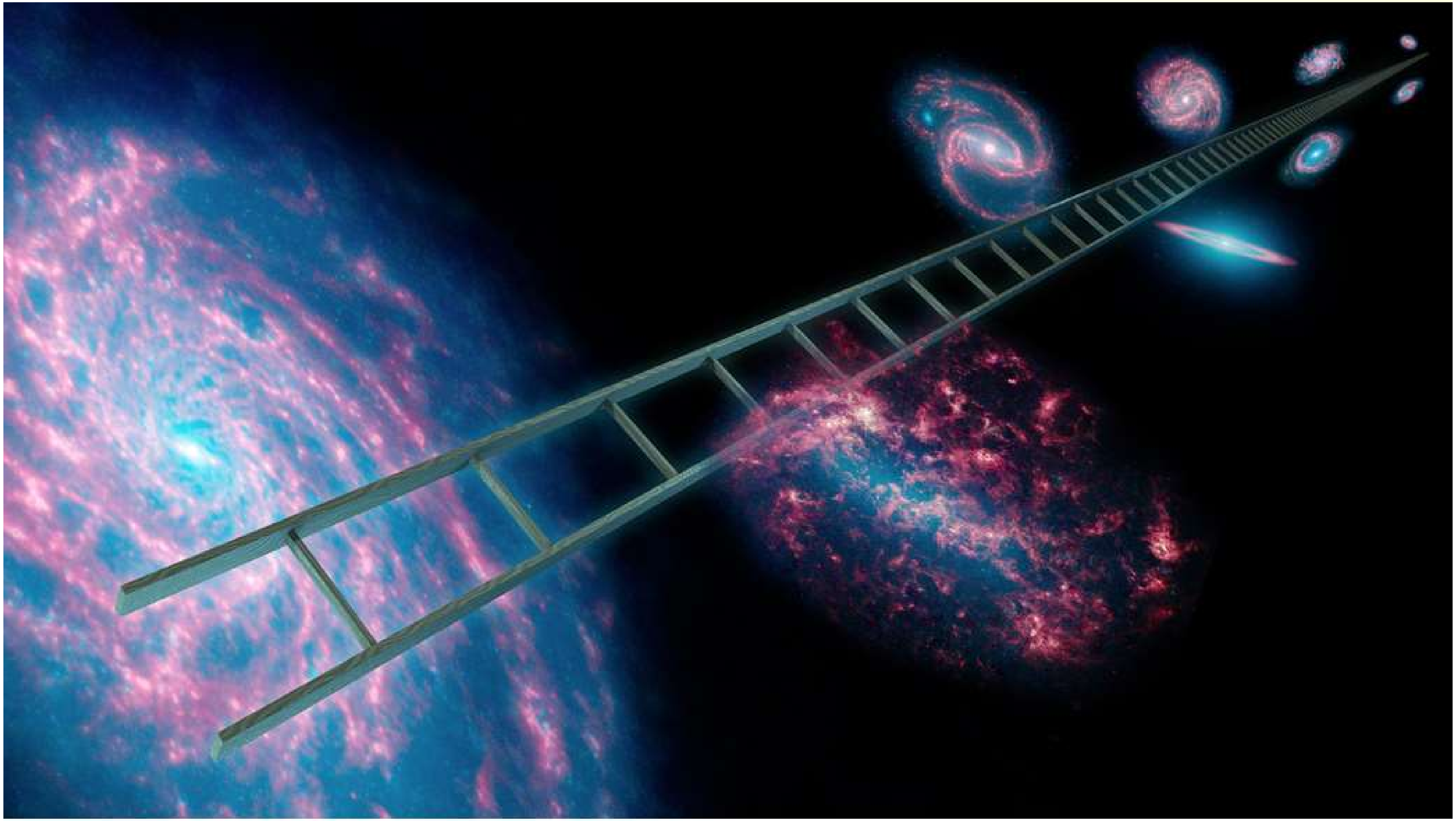
A revival of gravitational ether of 19th century!



Existence of a privileged frame, rest-frame of ether
these theories violate Lorentz invariance

Cosmic distance scale

Cepheids, RR Lyrae, Tully-Fischer relation, HII regions, SN-Ia, ….

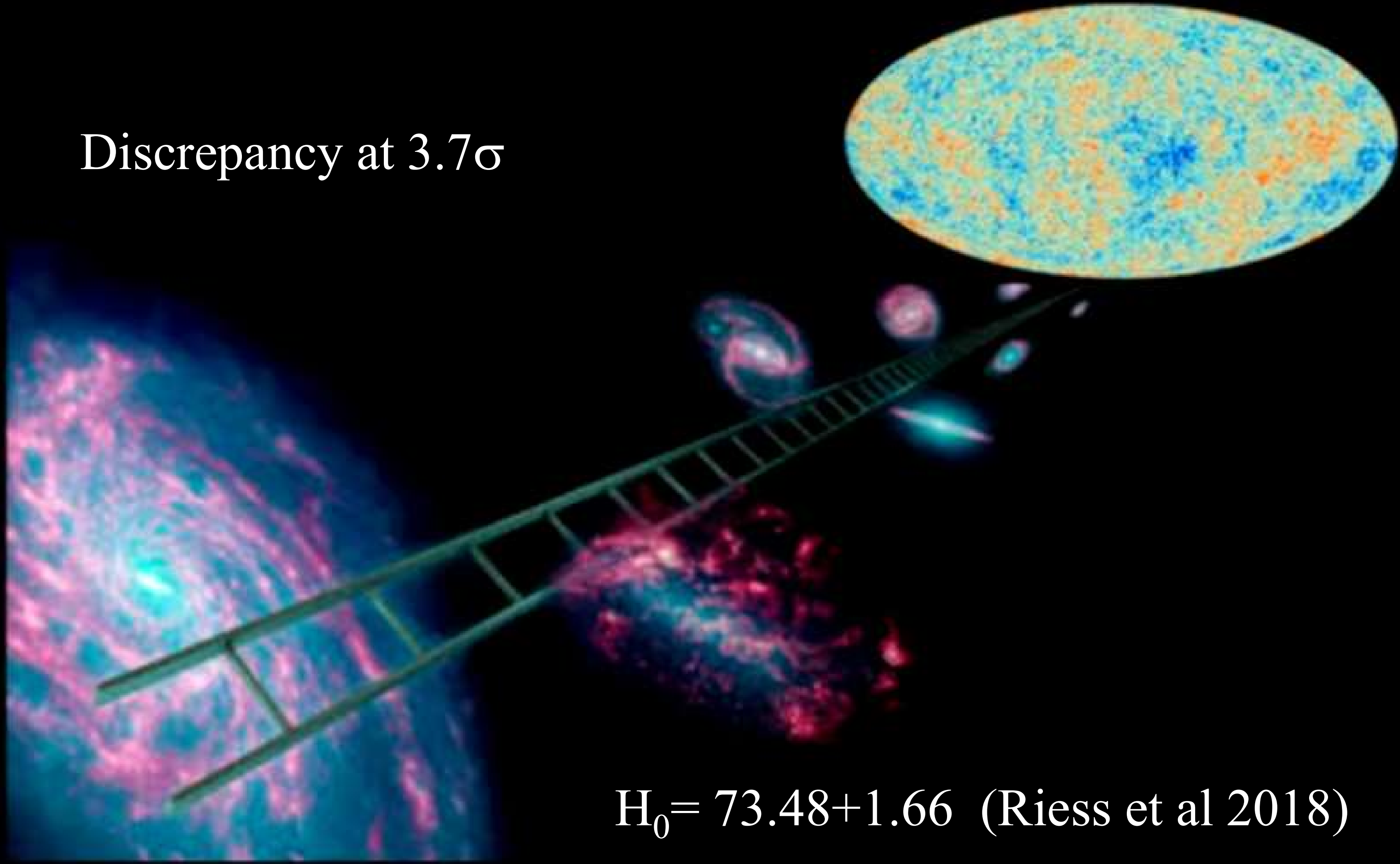


Spitzer 3.6 microns (blue), 4.5 microns (green), et 8.0 microns (red)

H_0= 67.8+0.9 (Planck coll 2016)

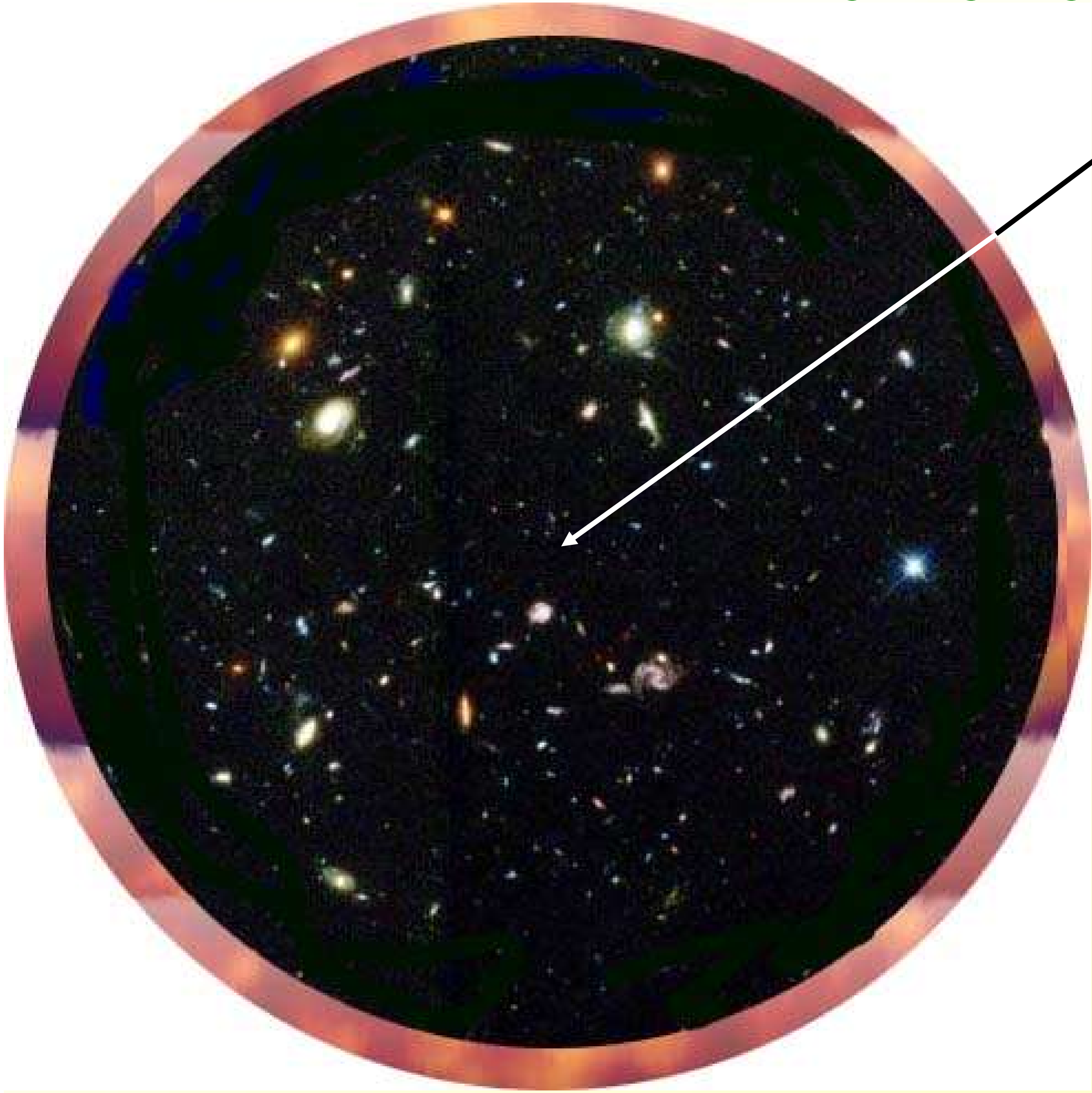
The H_0 challenge

Discrepancy at 3.7σ



H_0= 73.48+1.66 (Riess et al 2018)

Horizon of the Universe

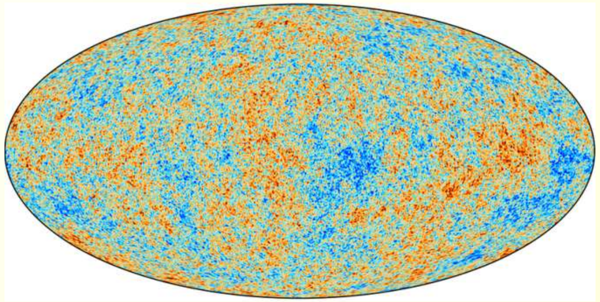


You are HERE

Looking far
is looking back in
time

**To the Big-Bang
there are 13.7 billion
years**

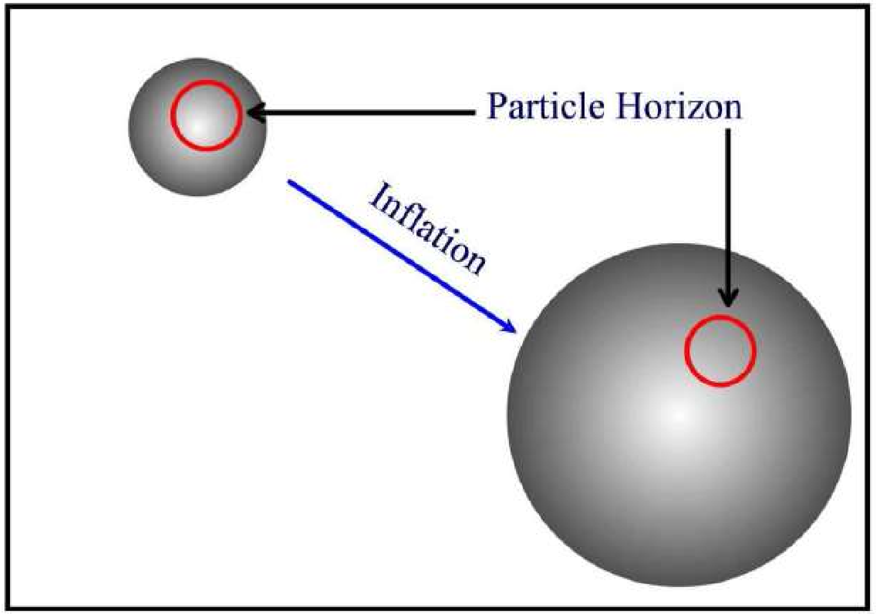
Inflation theory:
Problem of the horizon



- The horizon at CMB epoch was < 2°
- How can T_{CMB} be the same everywhere within 10^{-5} ?

(regions non causally linked)

Homogeneity

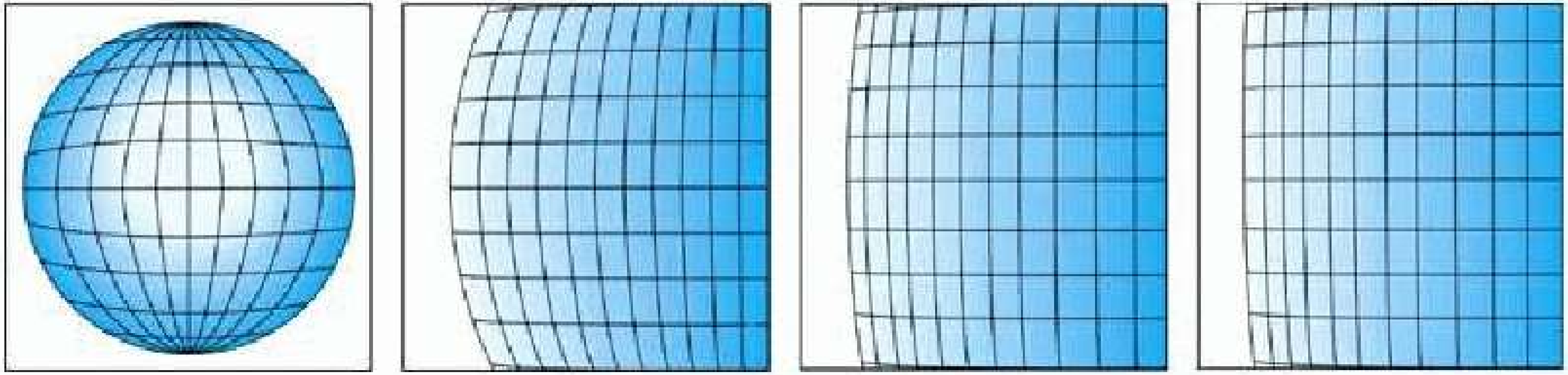


Rest frame

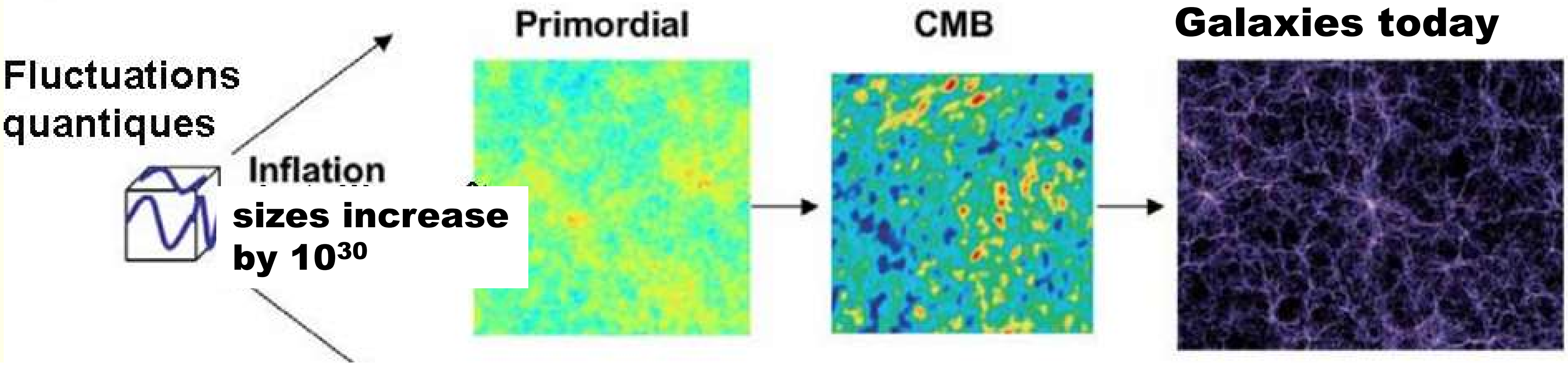
The observer follows
the inflation of space
The horizon is constant

Sizes increase by 10^{30} in 10^{-32}s

Inflation solves the flatness problem



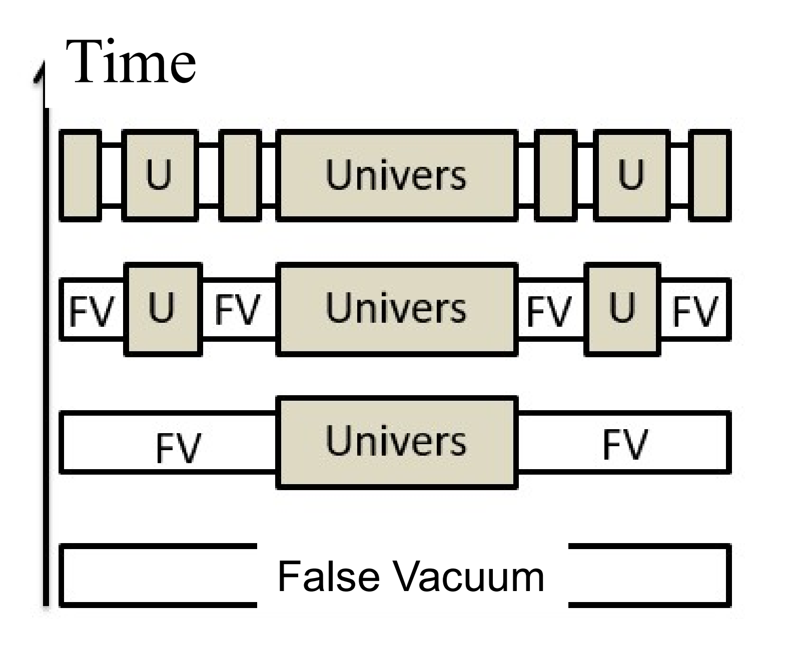
Inflation = origin of fluctuations at $t < 10^{-32}$s



Chaotic or eternal inflation

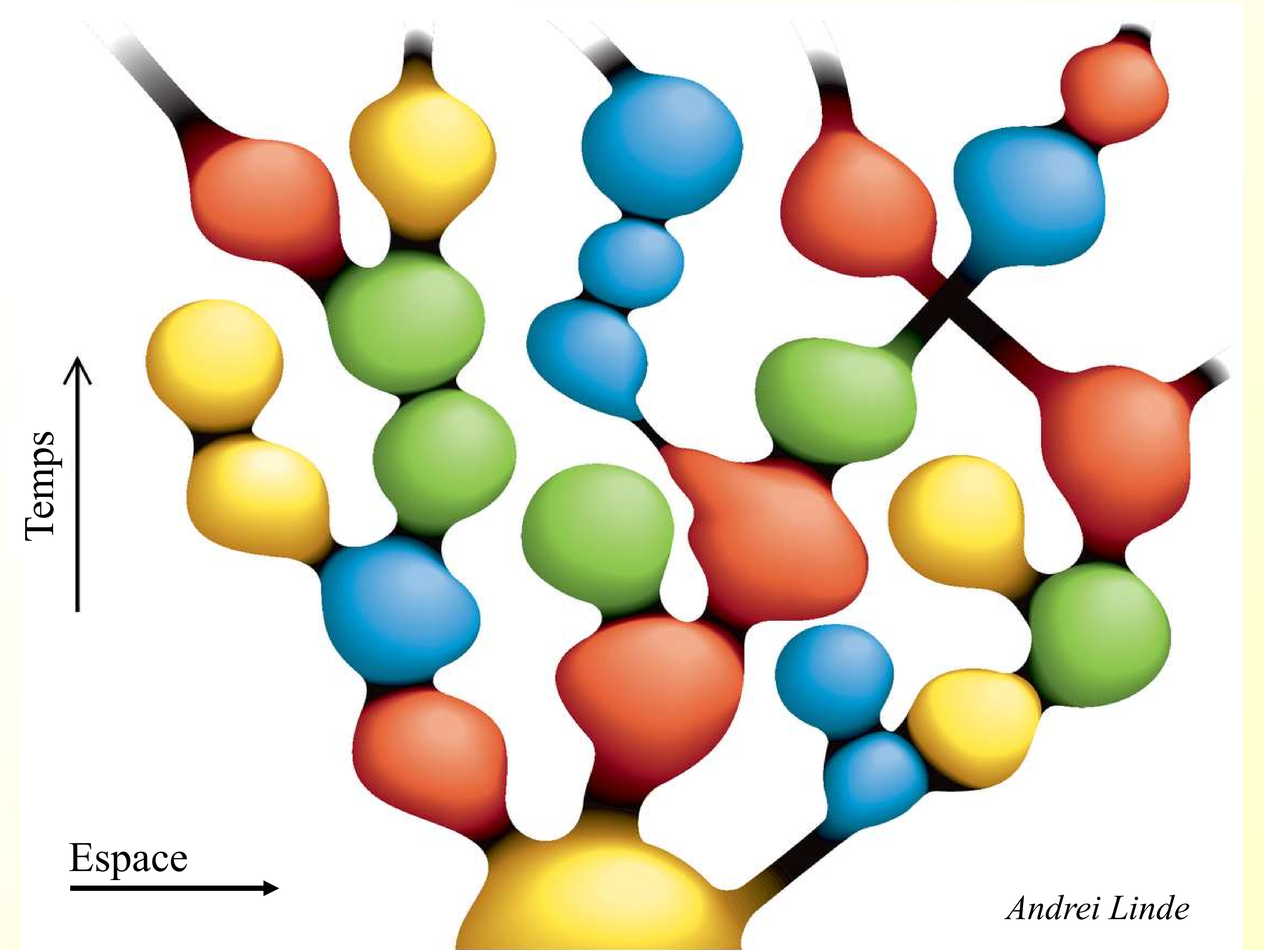
Impossible to stop inflation everywhere: in one bubble only with a re-heating, and creation of matter particles but **space continues to expand elsewhere**

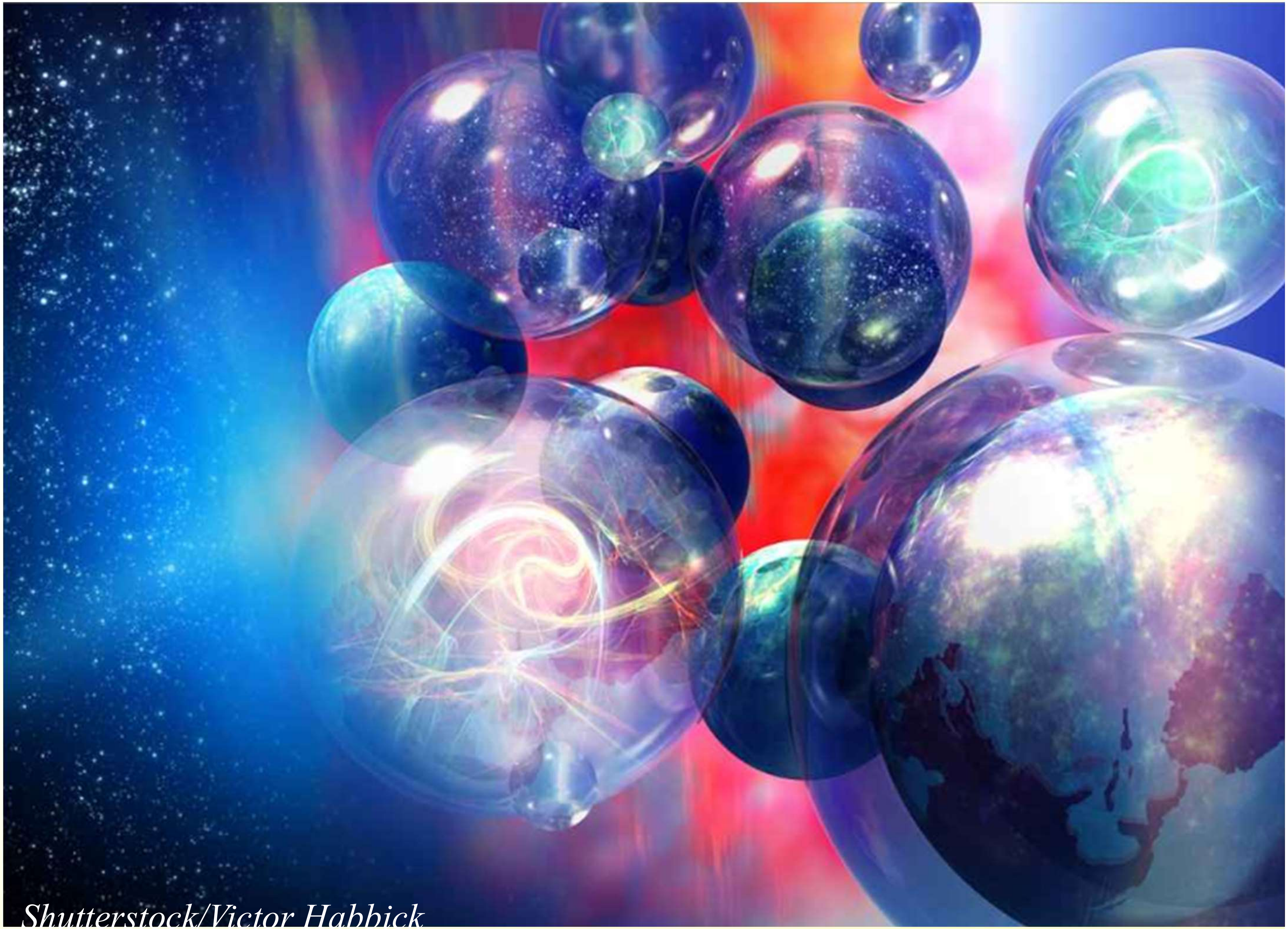
Inflation is self-maintained, on a chaotic way
No beginning, no end ➔ eternal inflation (Linde 1986)



Inevitable!

Guth 2007

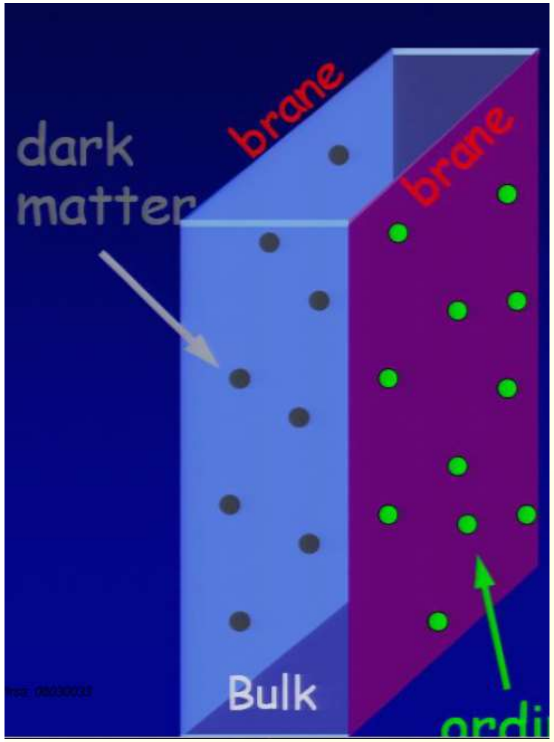

Temps
Espace
Andrei Linde



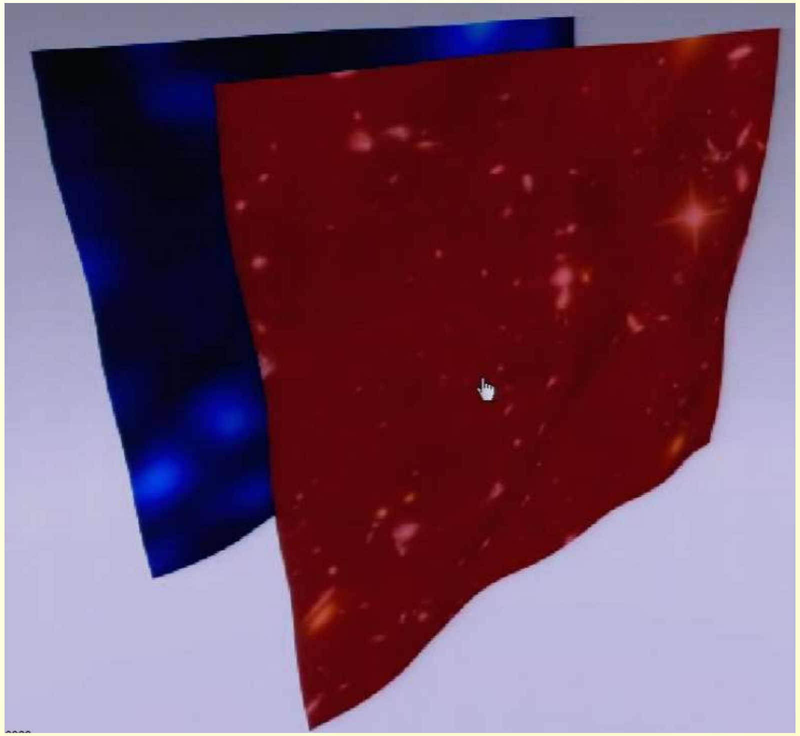
Shutterstock/Victor Habbick

Alternatives: cyclic models

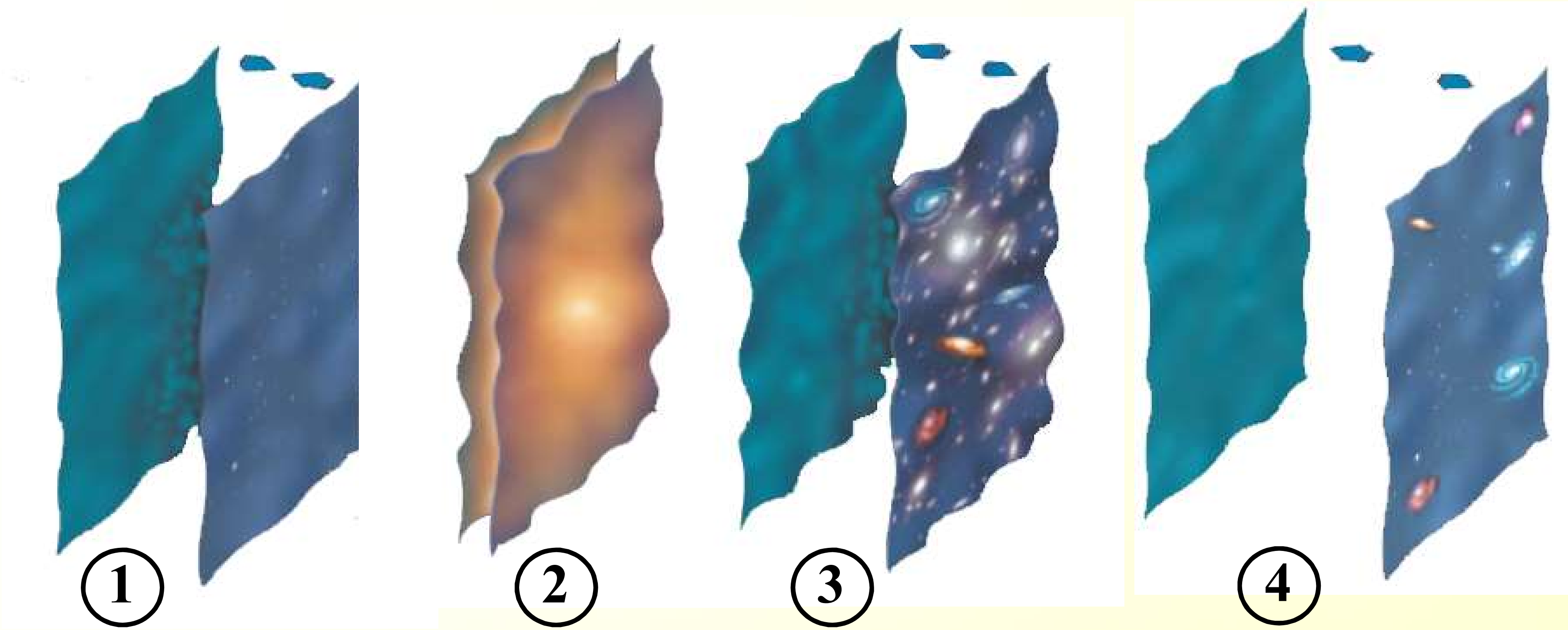
Ekpyrotic model, from colliding branes
Cyclic, with rebound (Turok & Steinhardt 2005)
The cyclic model still needs dark energy Λ



String theory
10, 11 or
26 dimensions



Gravity propagates outside the 3-brane



Cyclic theory of ekpyrotic Universe

(1) 2 branes move toward each other (space contracting)

(2) they collide: kinétic energy ➔ matter & radiation

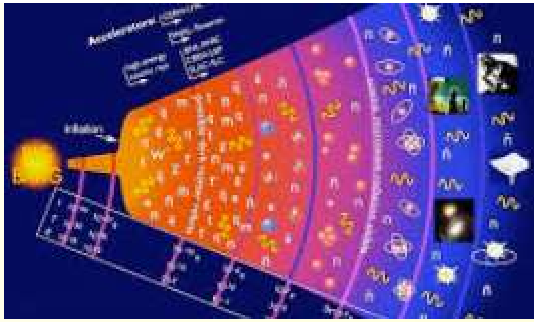
(3) rebound : space in decelerated expansion

(4) Attraction between branes slows them

➔Inverse motion ➔ (1)

G. Veneziano (2006)

The history is not finished !



Inflation is **favored** by observations

-- solves problems of flatness, horizon, homogeneity
-- provides initial quantic fluctuations ➔ Structures

Problems: eternal inflation, multiple universes

Observations: one field inflation favored by **Planck**

➔Future: observations of primordial gravitational waves
As a proof of inflation