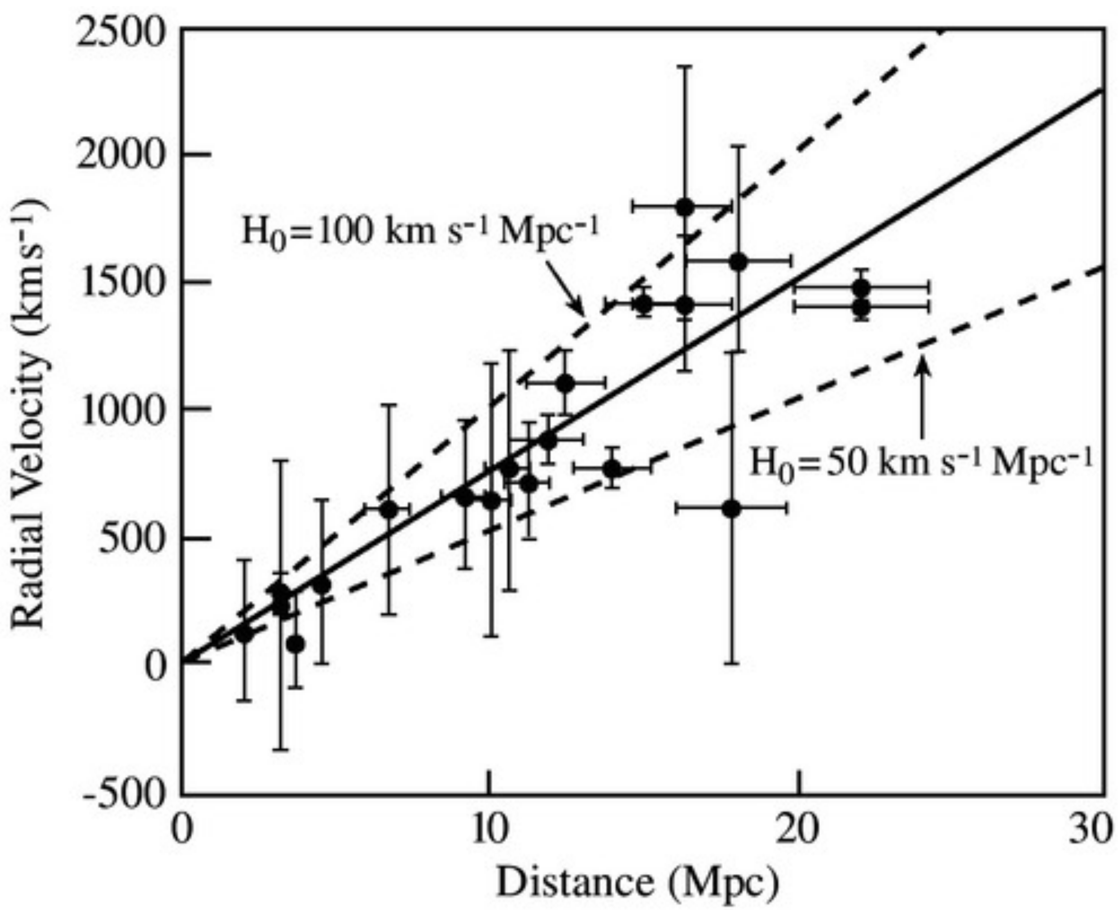
Paolo Creminelli, ICTP (Trieste)

Friedmann equation
and
the acceleration of the Universe

CERN, July 2018

Hubble diagram (cepheids)



$v = H_0 r$

1 pc ~ 3.26 light years
Milky Way ~ 50 kpc
Andromeda ~ 800 kpc

Hubble time $1/H_0$: ~ 15 billion years
Hubble length $1/H_0$: ~ 5000 Mpc

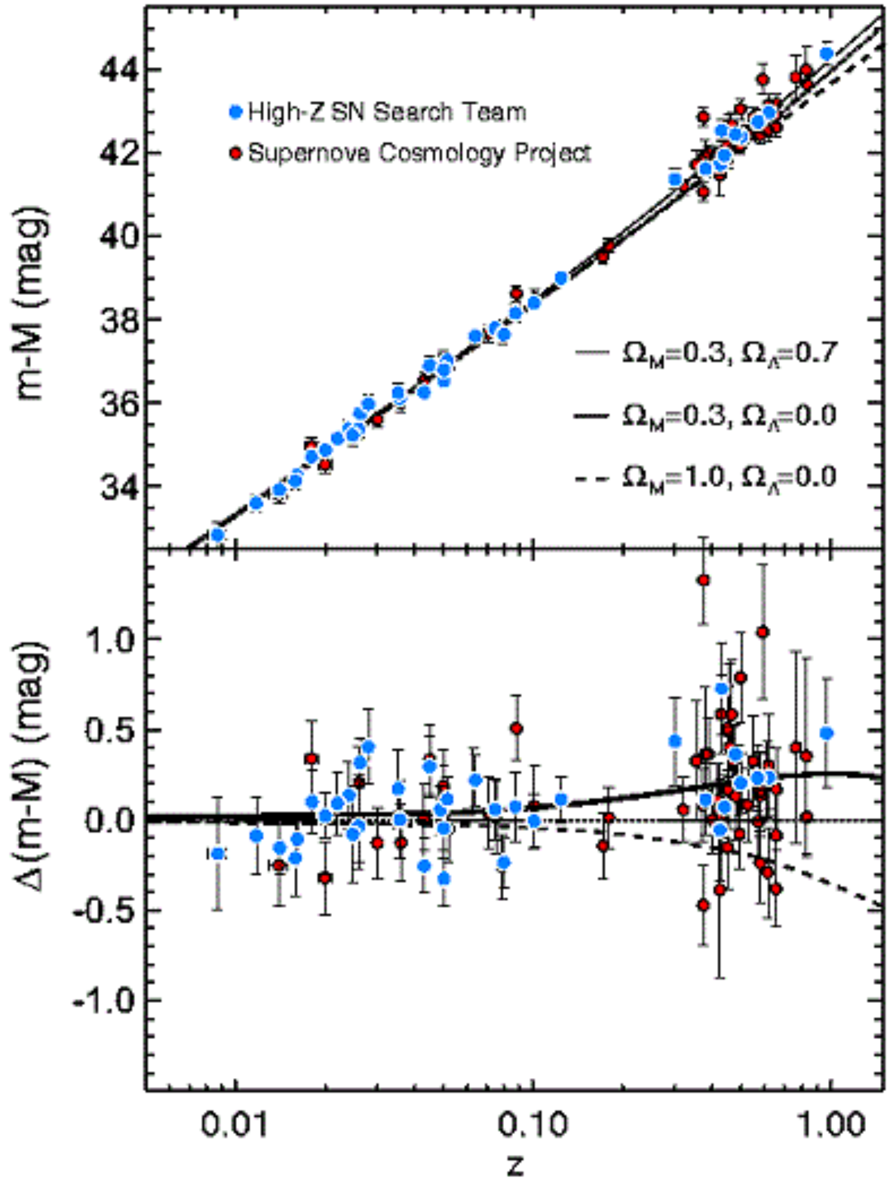
Supernovae 1A

Hubble law gets corrections at v ~ c (z ~1)

Photons travel as the Universe changes in size and probe its evolution

SURPRISE:

The Universe is now accelerating !!



Noble Prize 2011

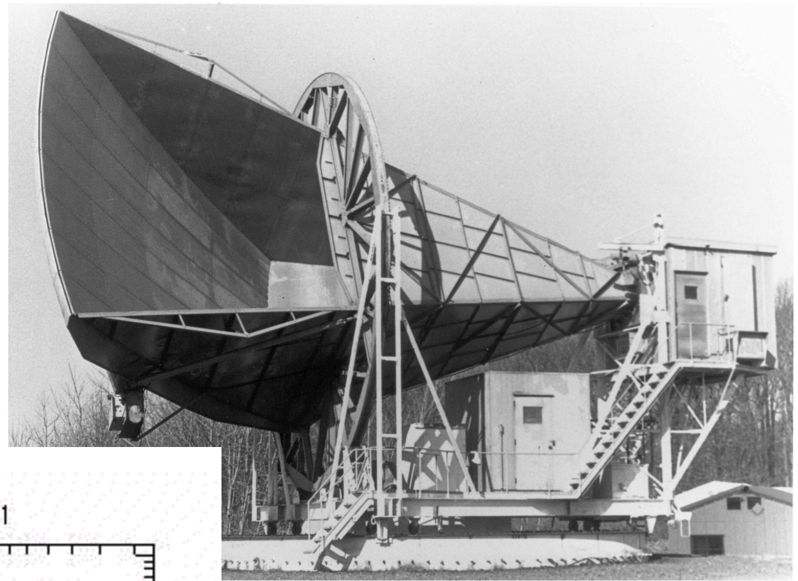
Paolo Creminelli, ICTP (Trieste)

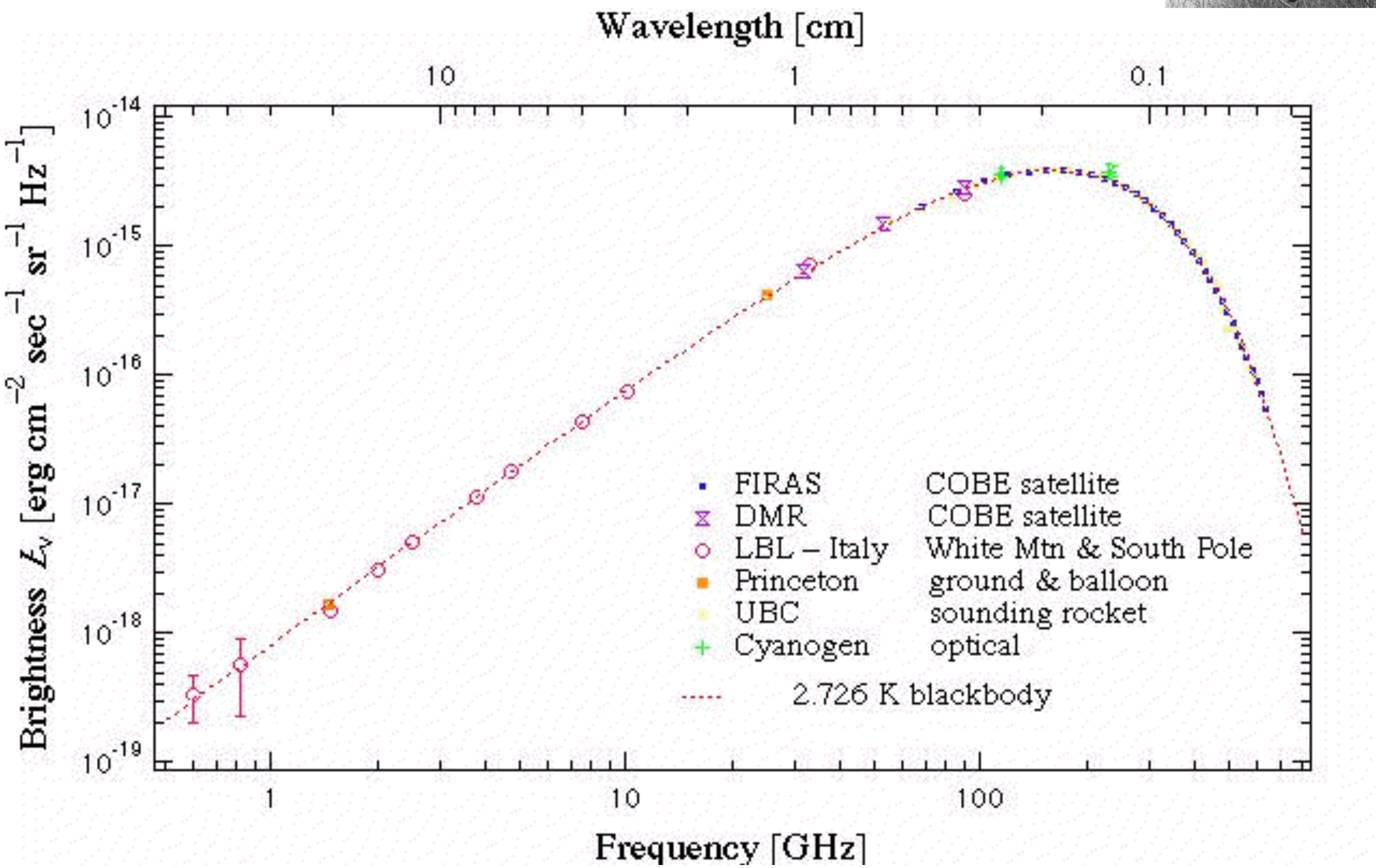
The Cosmic Microwave Background: CMB

CERN, July 2018

Detection of the CMB

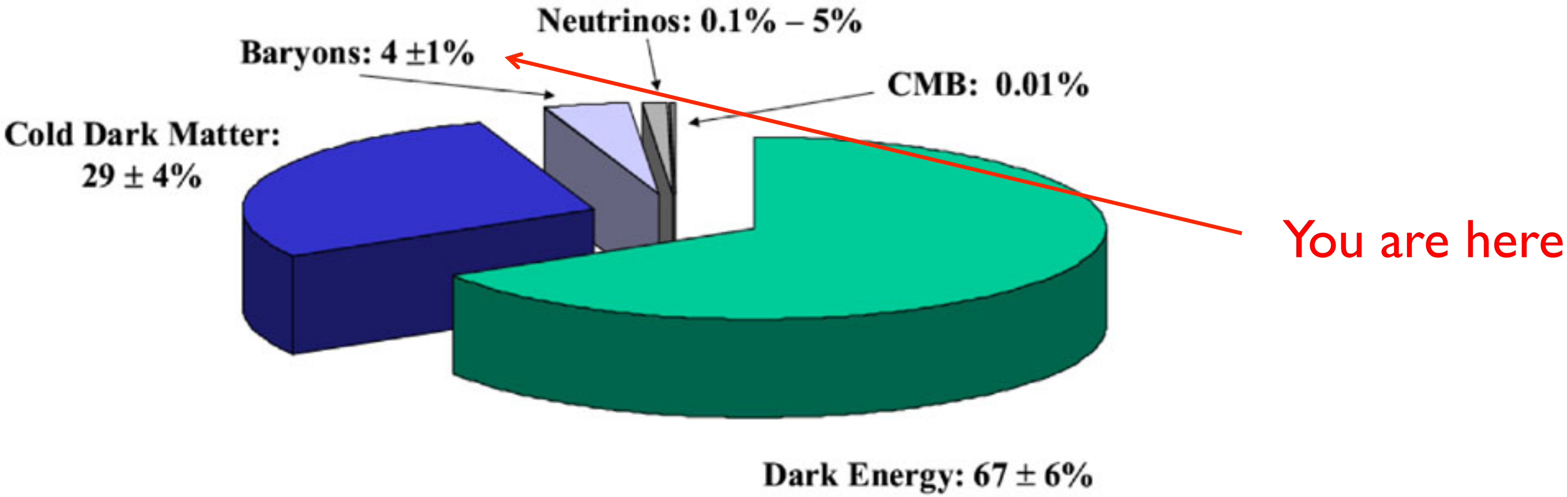
Penzias and Wilson 1965

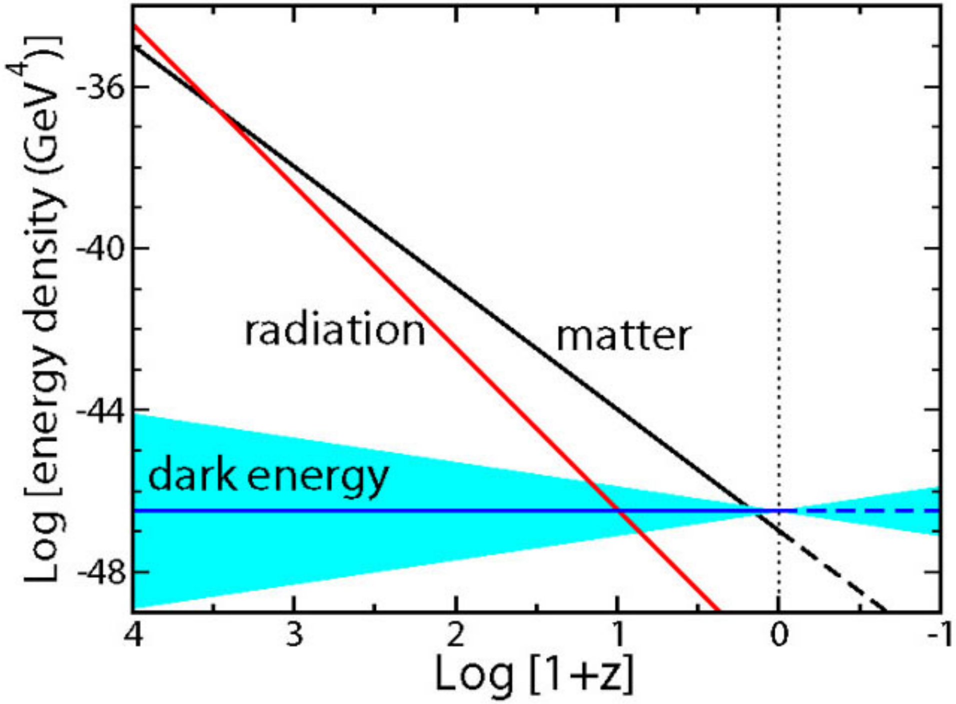




Perfect black body

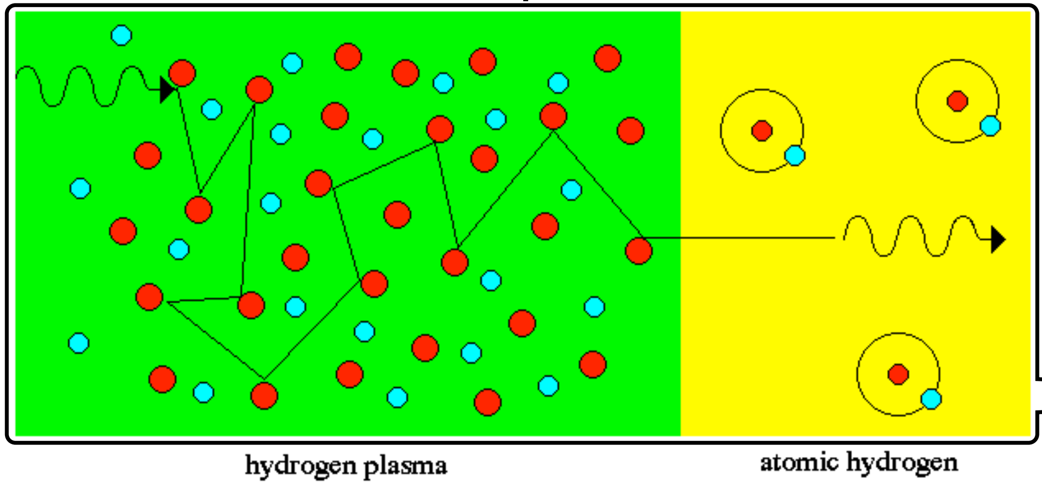
Cosmic pie: it is embarassing, isn't it?

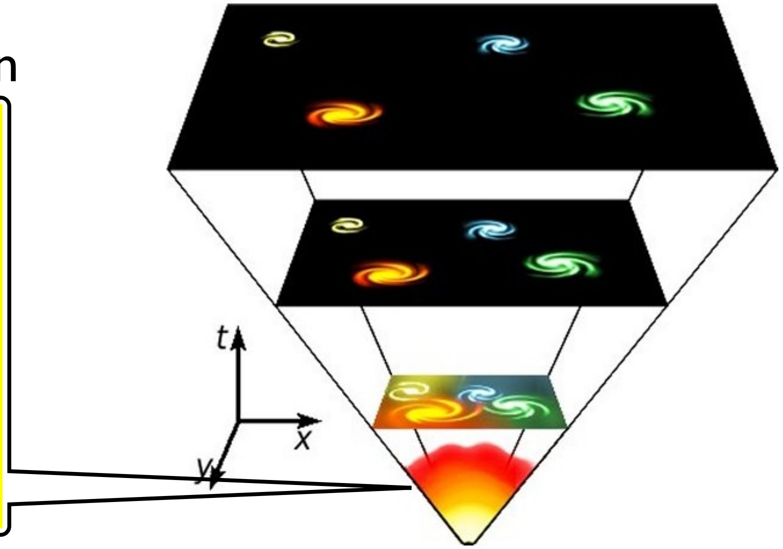




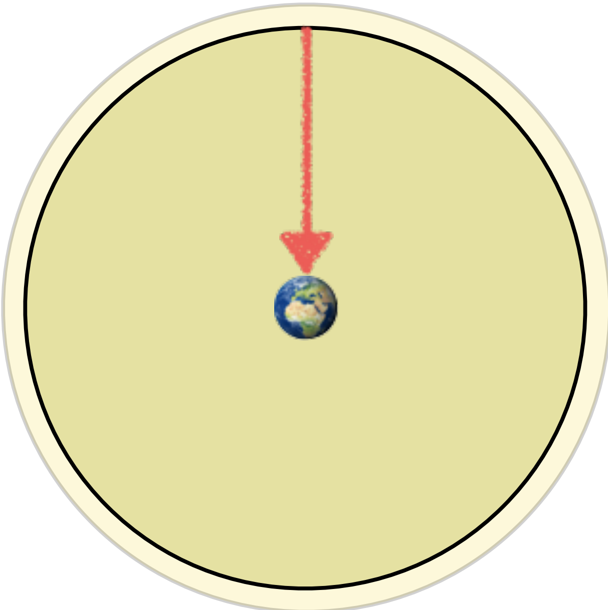
Cosmic Microwave Background

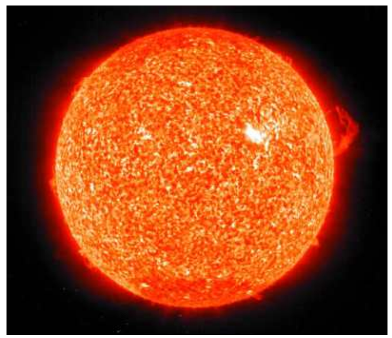
T > 3000 K: Photon/nuclei plasma - Recombination





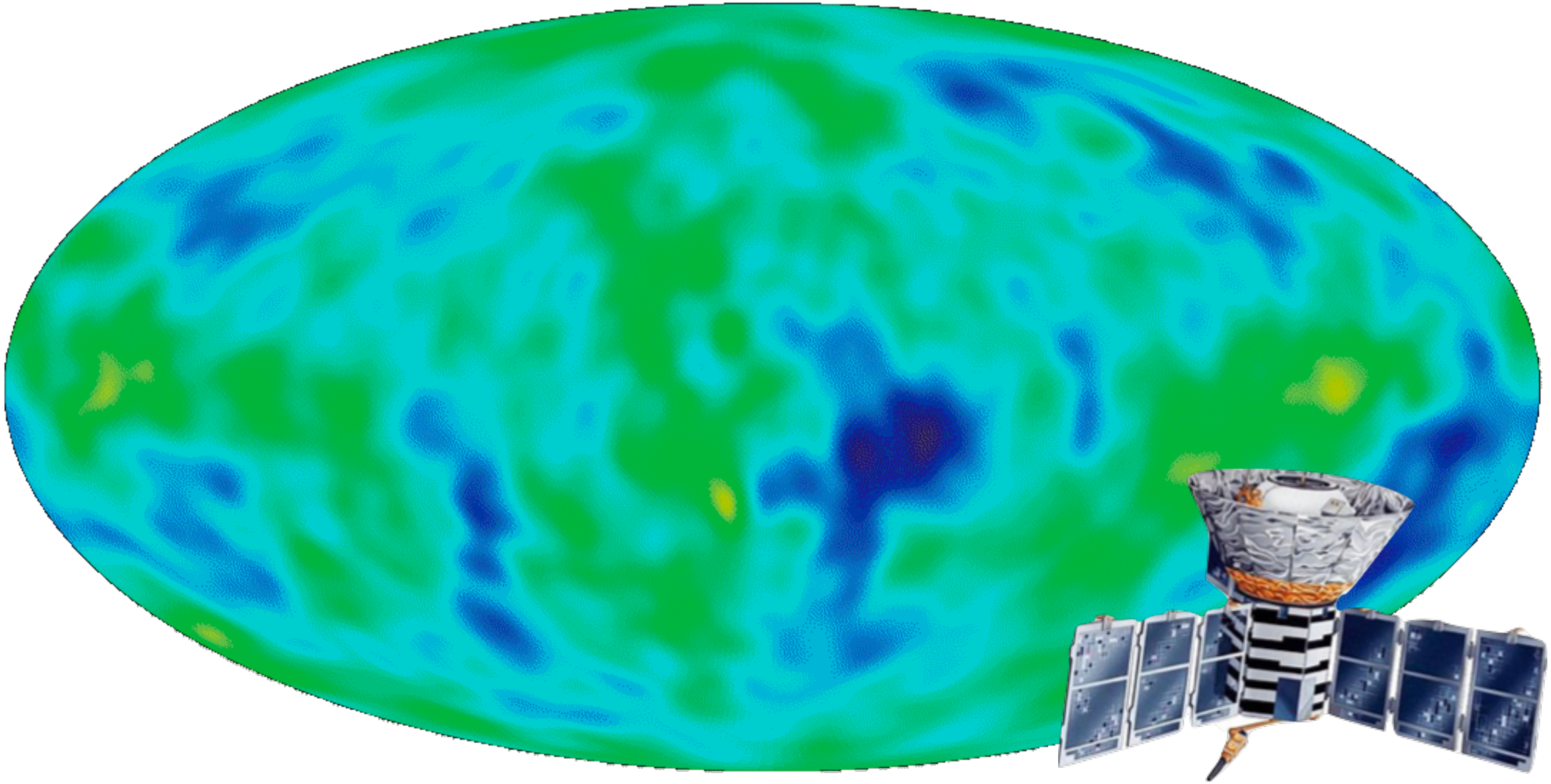
Last scattering surface:





Many years of isotropy

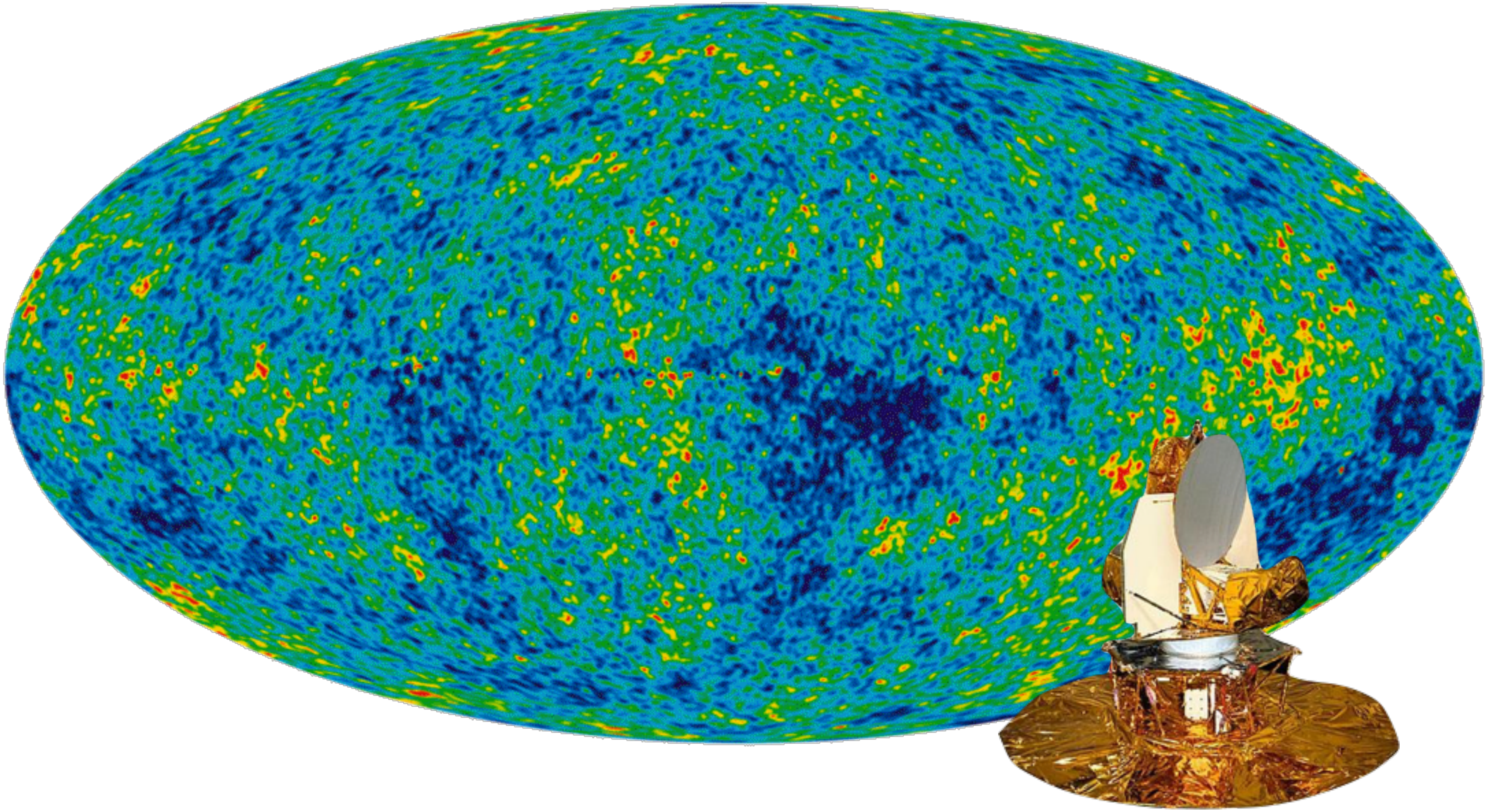
COBE (1992)



$$\Delta T \sim 3K \times 10^{-5}$$

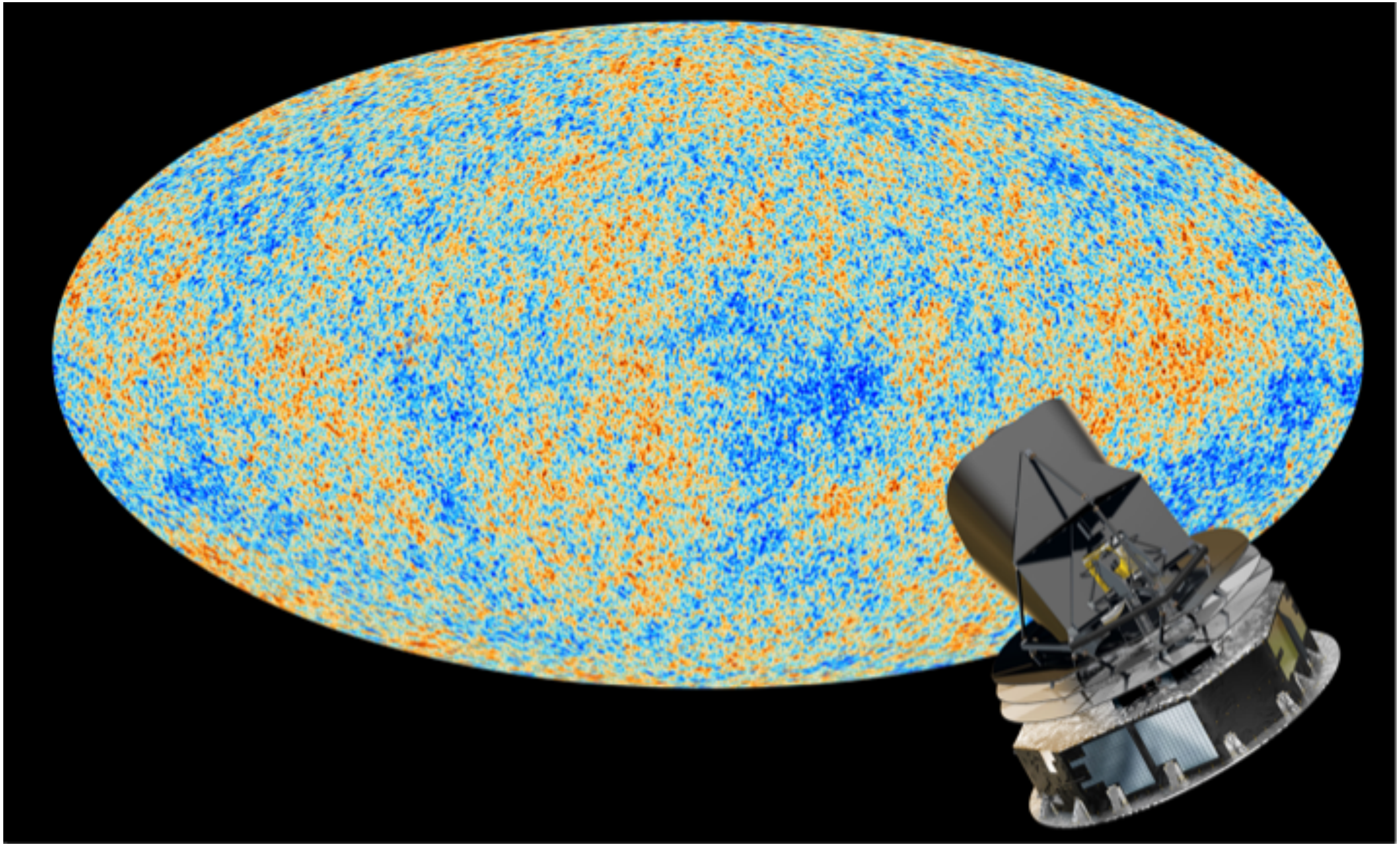
150 million $ glasses

WMAP (2003)

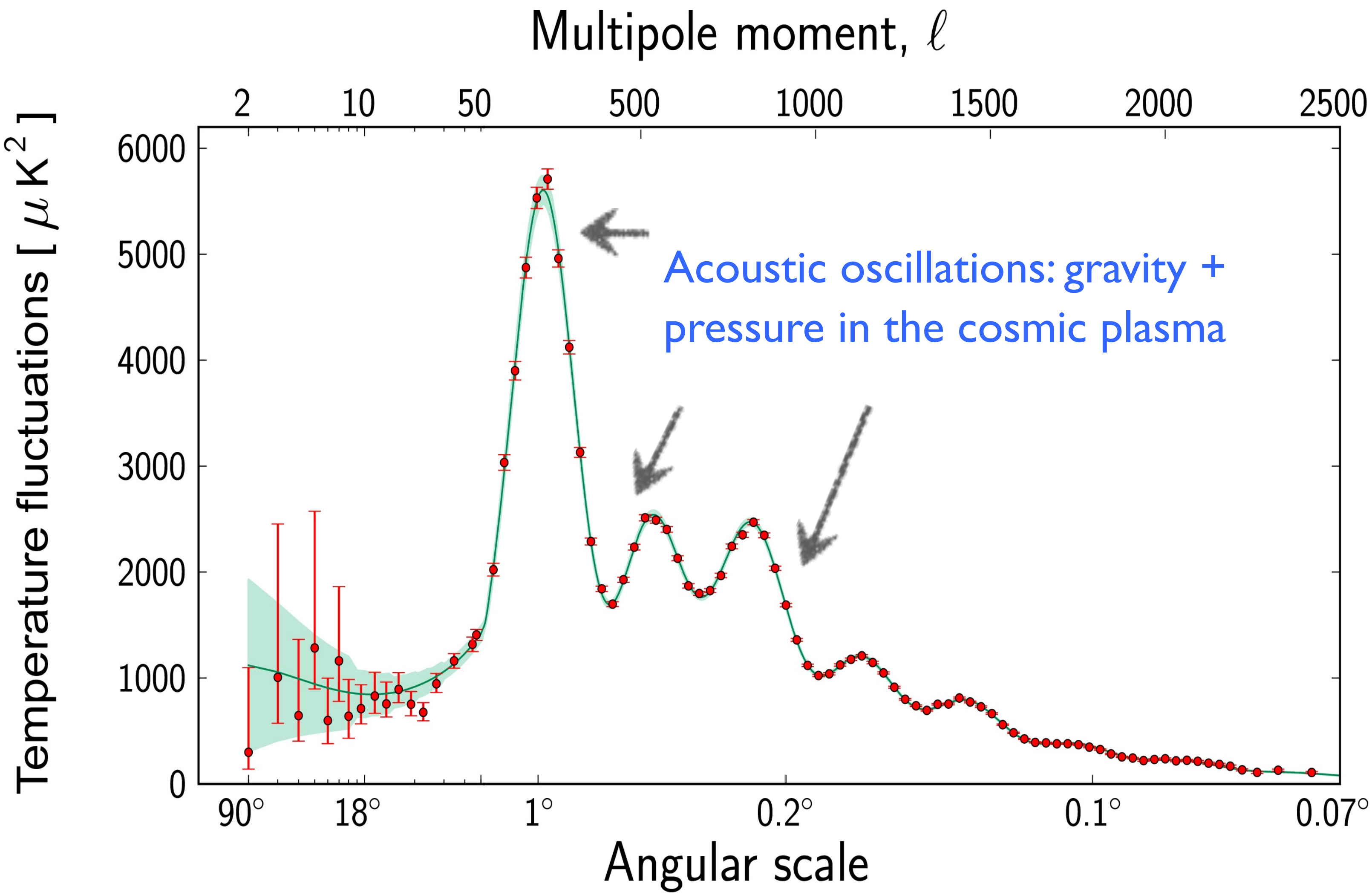


700 million $ glasses

Planck (2013)



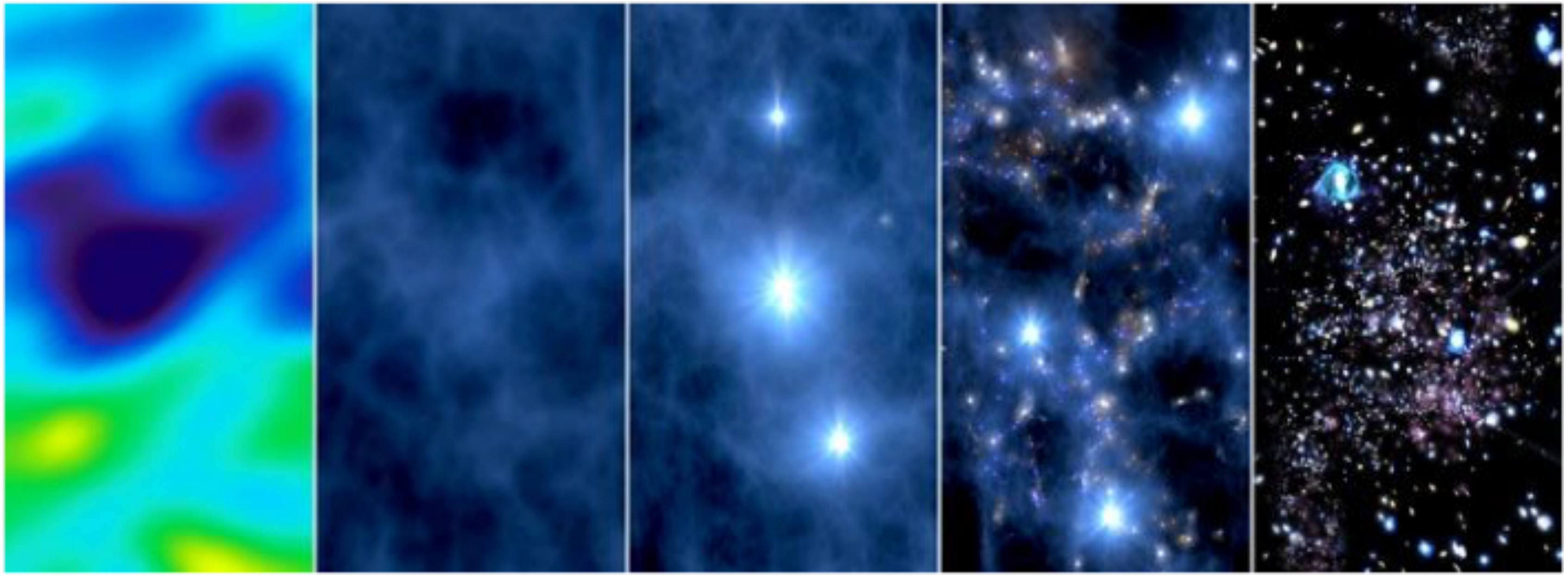
Acoustic oscillations

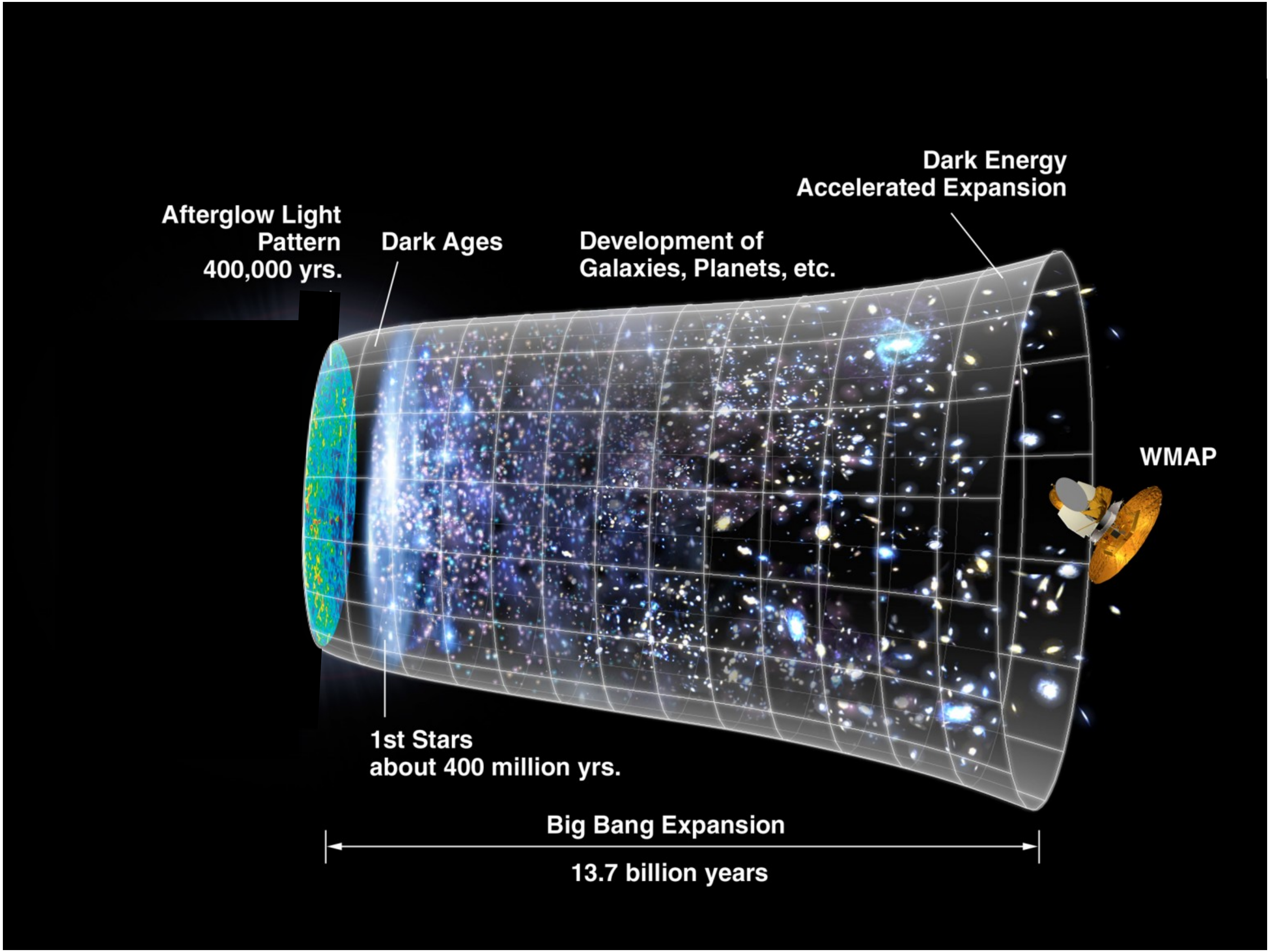


Initial seeds

Inhomogeneities are acoustic oscillations due to some initial (primordial) seeds

Homogeneities then grow to give rise to all the structures we see





Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
WMAP
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

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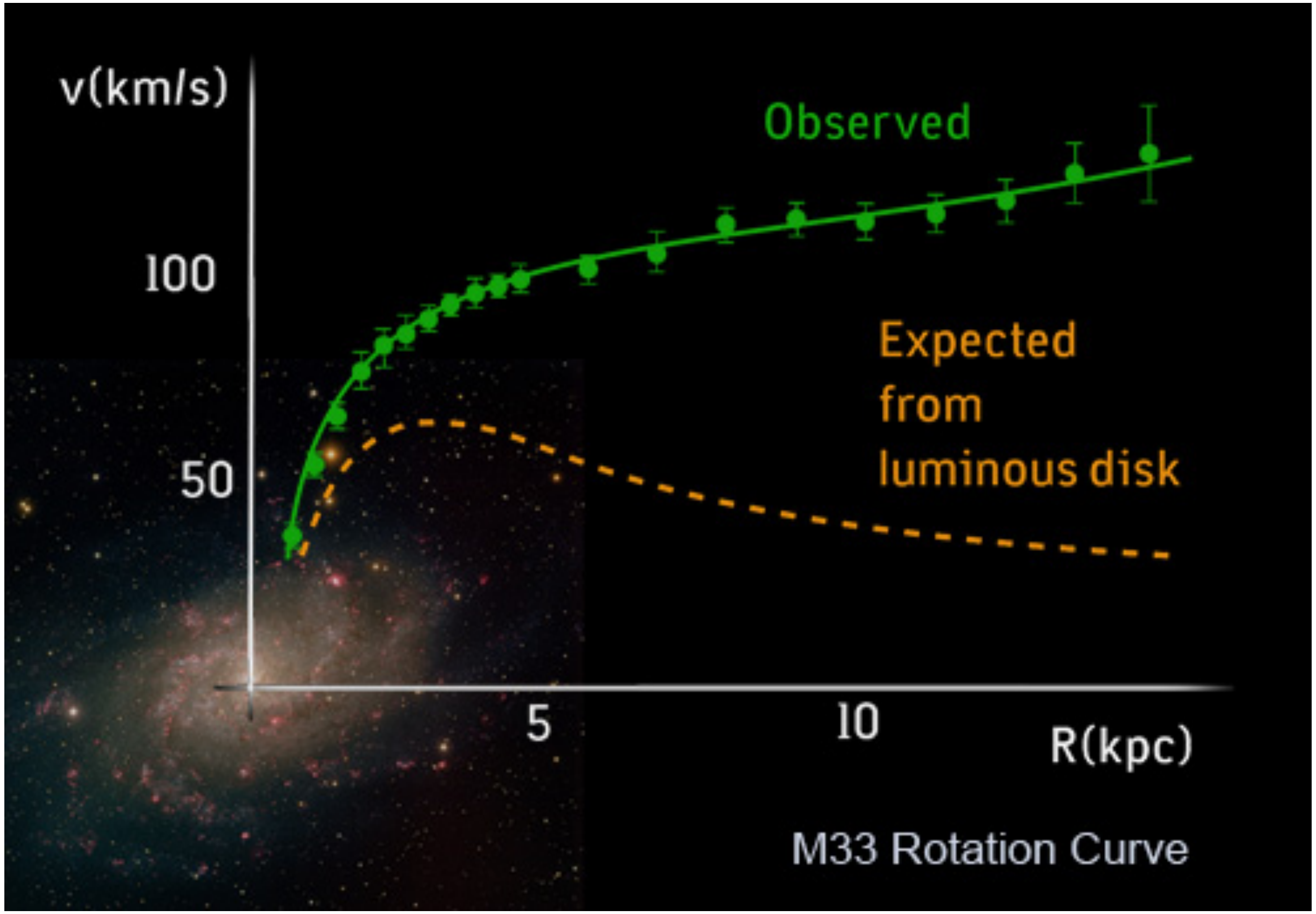
Dark Matter

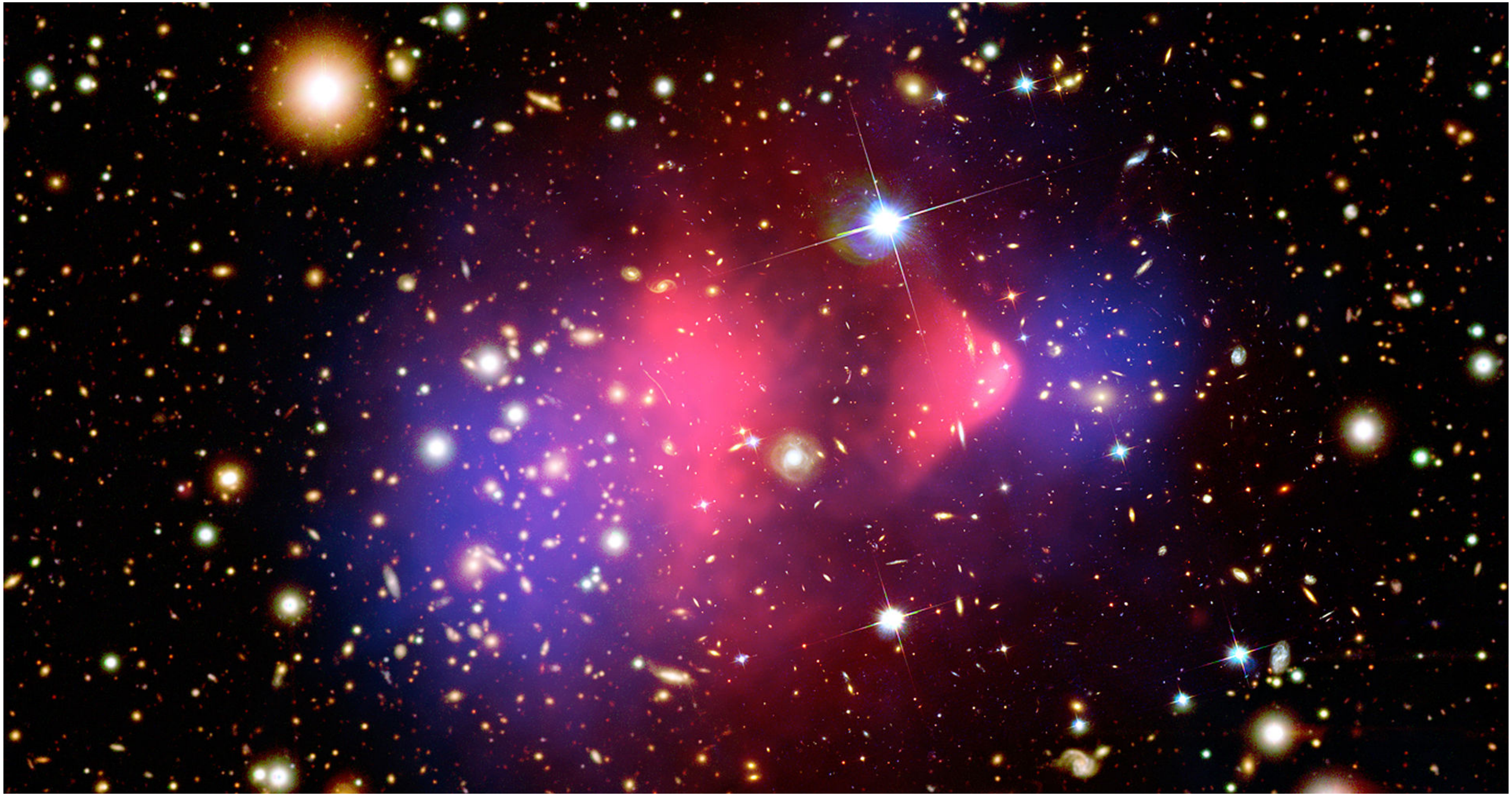
CERN, July 2018

Rotational curves



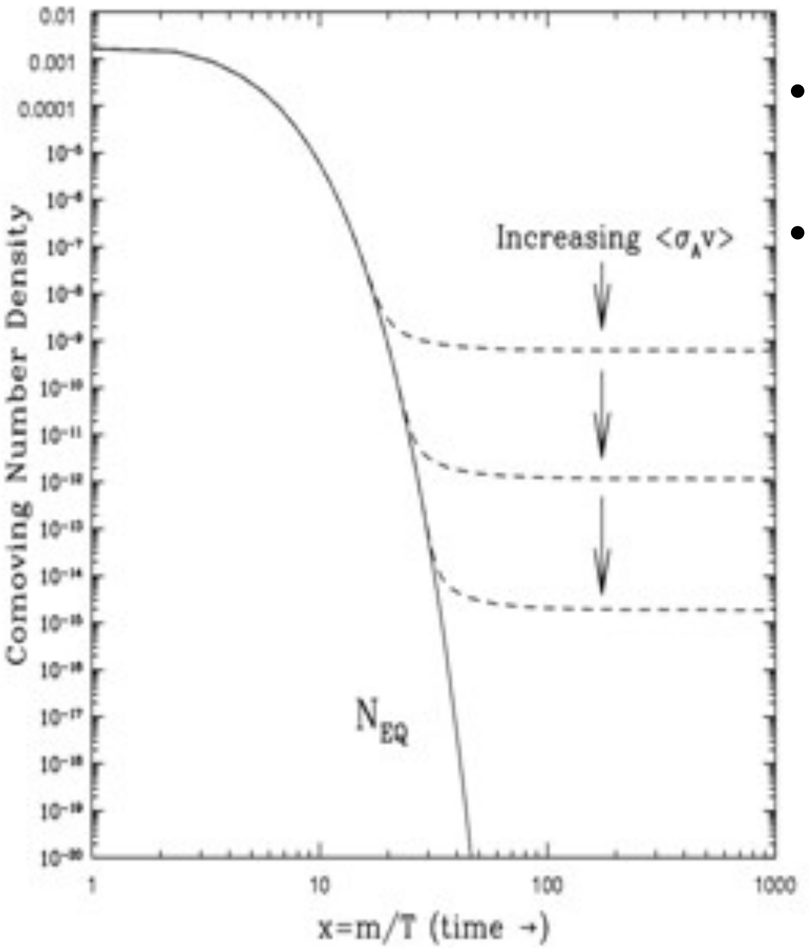
An order of magnitude larger than the disk!

Lensing

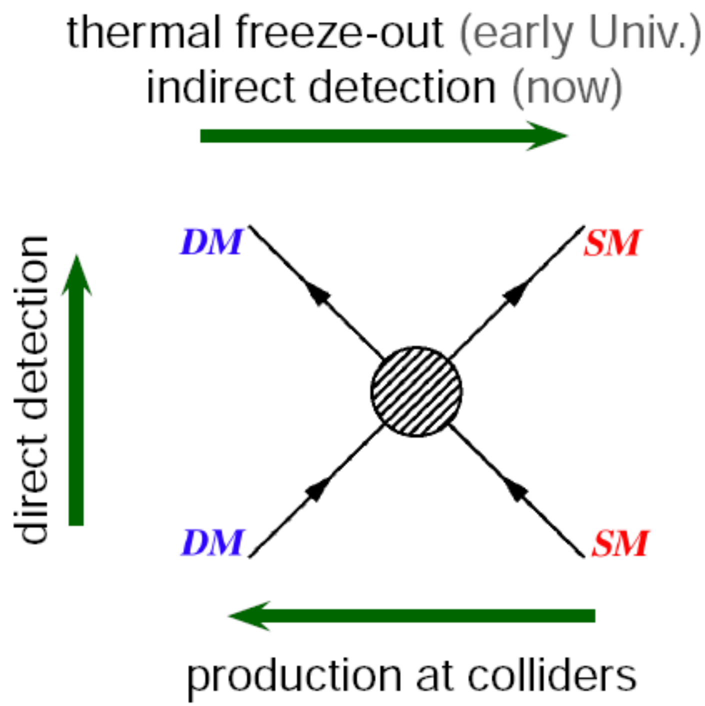


Bullet cluster

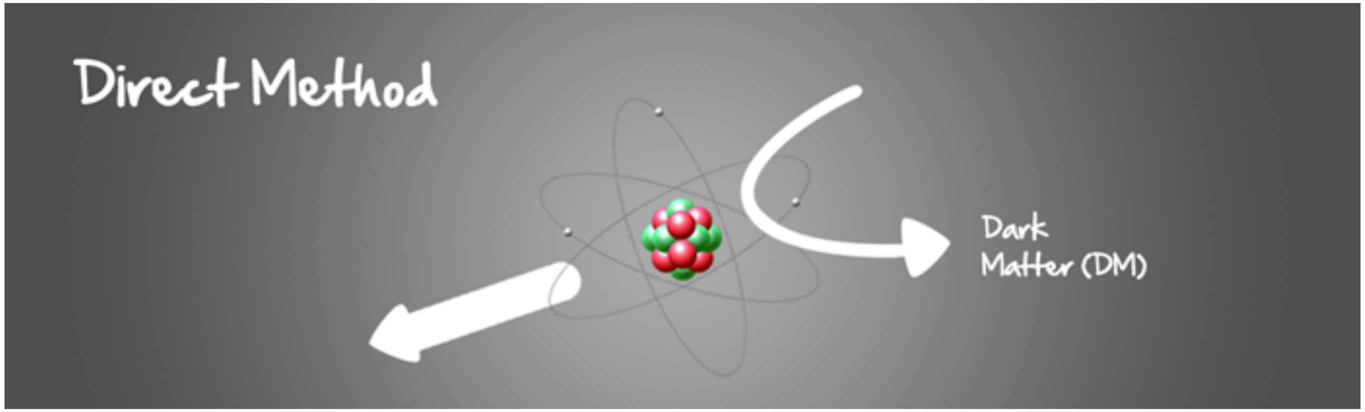
WIMP: Weakly Interacting Massive Particle



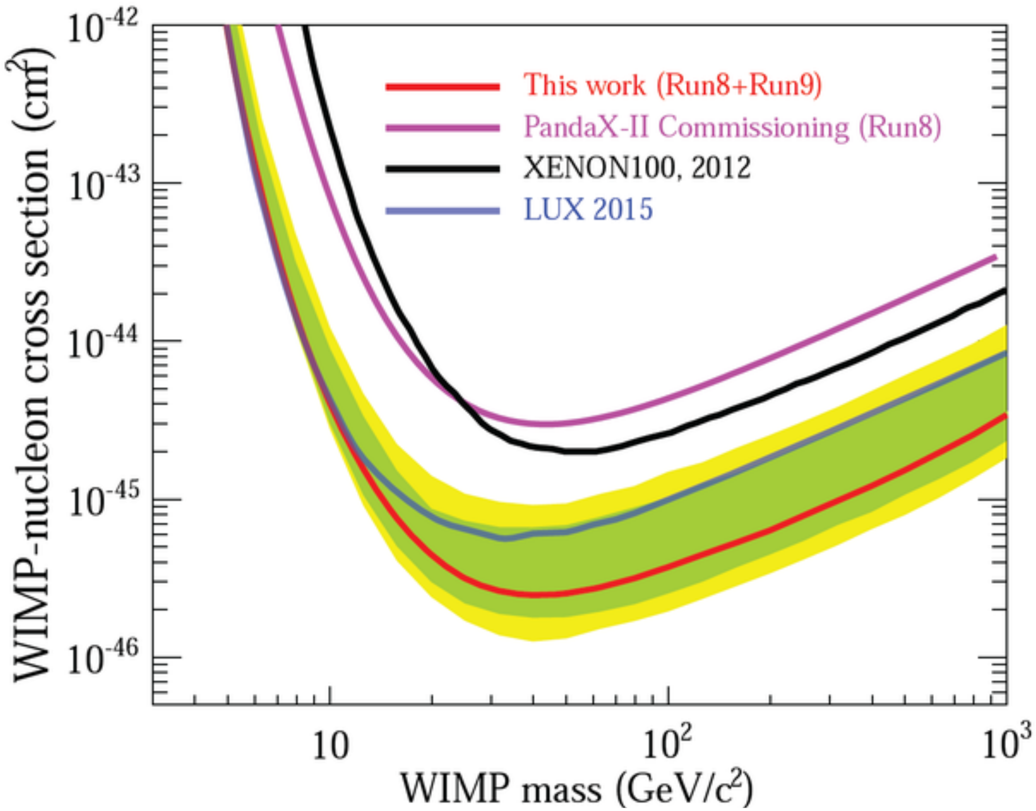
- Stable particle that interacts with SM: in equilibrium at high T
- If m ~ 100 GeV and weak interactions:
  correct relic abundance (WIMP miracle)



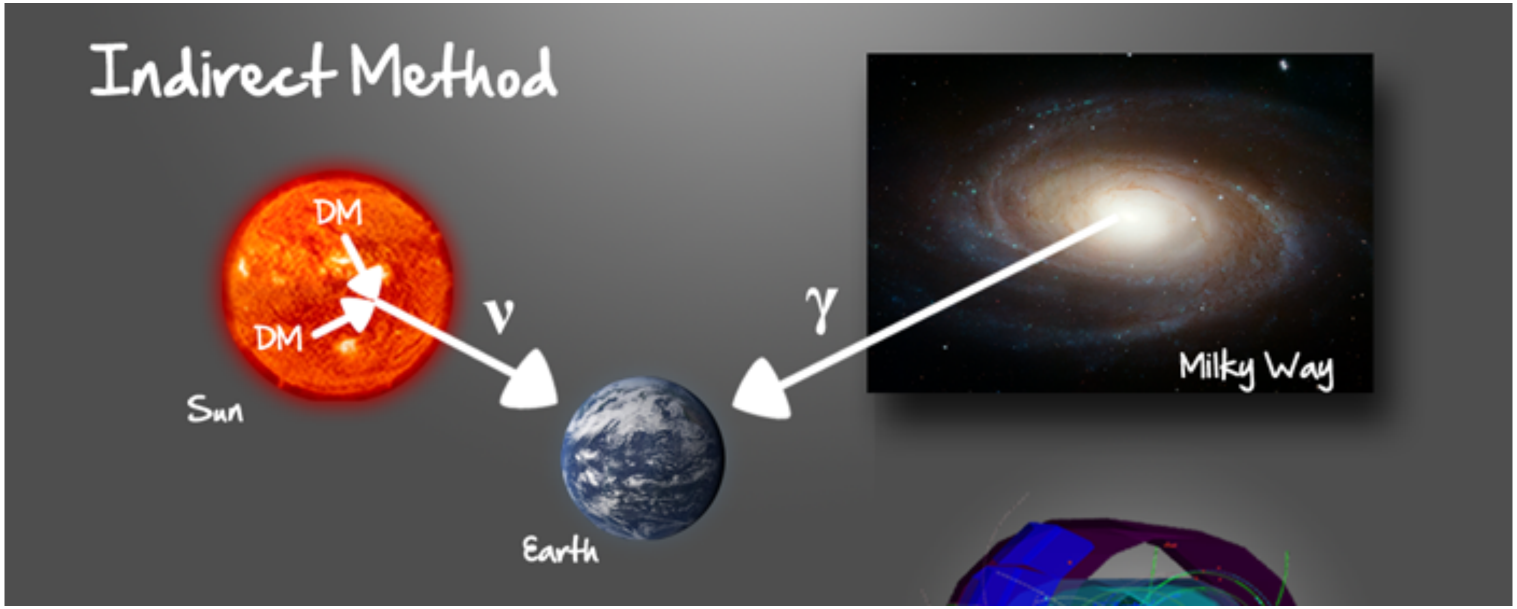
Direct detection



Scattering on nucleons



Indirect detection



Many signals but very challenging to distinguish from messy astrophysics

Astroparticle physics: see Montaruli's lectures

Q&A: July 2020

Q1: What is the difference between cosmology, astrophysics and astronomy

A1: Astrophysics and astronomy are interested in studying objects in the Universe, like planets, stars, galaxies, clusters, supernovae...
How does a star form and die? Why some galaxies have a spiral shape? How frequent are planetary systems like ours? Why a supernova IA emits always a certain quantity of light?

Cosmology is interested in the Universe as a whole, its evolution, its birth, its large-scale structure, its fate..
How old is the Universe? When photons decoupled from the other particles? Why is the Universe accelerating today? How much dark matter is there?

(Notice most of the objects of interest in astrophysics formed recently, $z<5$, while cosmology mostly focusses on when the Universe was much younger)
(The distinction astrophysics/astronomy is not sharp: astronomy is a bit old fashioned and refers to study the motion of celestial objects)

Q2: What is the difference between radiation and matter? Alpha radiation is a helium nucleus and this is also matter

A2: In cosmology, matter = non-relativistic particles
radiation= relativistic particles

A massless particle (e.g photon) is always relativistic (radiation), a massive particle (e.g proton) will be relativistic at high temperature (T >> m), non-relativistic at low temperature (T << m).

Matter particles move slowly (v<<c) and this implies pressure is small.
Radiation particles move ~ at the speed of light: sizeable pressure

This difference (see lectures) gives:

$$\rho_{\rm matter} \propto a^{-3} \qquad \rho_{\rm radiation} \propto a^{-4}$$

Today more matter than radiation, but going back they are the same when Universe is ~3600 times smaller. Equality

Q3: How is the region that the Universe expands into perceived? Does the fact that the Universe is expanding imply it has an edge/boundary

The Universe does not expand INTO anything

$$\Delta s^2 = -\Delta t^2 + \Delta x^2 + \Delta y^2 + \Delta z^2$$

$$\rightarrow \Delta s^2 = -\Delta t^2 + a^2(t)(\Delta x^2 + \Delta y^2 + \Delta z^2)$$

It does not have an edge/boundary (probably, for sure it there is a boundary it is very far away and unobservable)

Universe is an infinite Panettone!

As the panettone raises in the oven the distance between two raisins increase.
If the panettone is infinite there is no boundary and no elsewhere

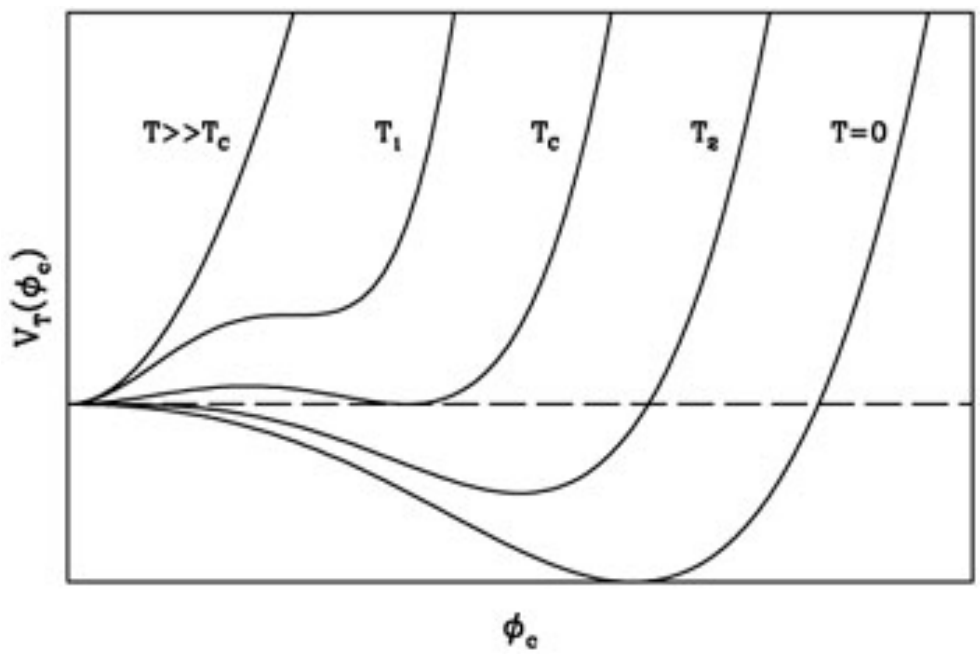
Q4: How do recent findings in particle physics influence our picture of the Universe? What about the Higgs?

In general unfortunately not all details of the SM (or BSM) Lagrangian are important for the cosmological evolution. Thermal equilibrium erases most of the information (i.e. the mass of the Higgs, its quartic coupling...)

In cosmology we are only sensitive to some events that leave some imprint today (like fossils), while we are ignorant about other phases that leave no fossil

Electroweak phase transiton

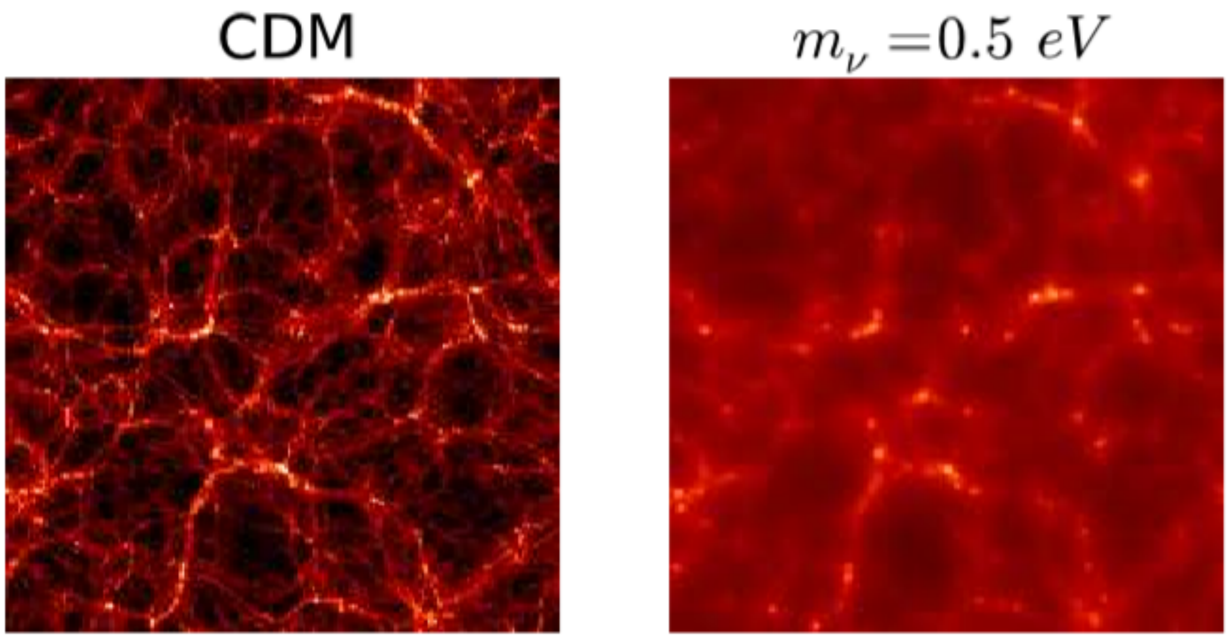
if violent enough it could leave inprint of Gravitational Waves



Neutrinos

Neutrinos are stable particles and like CMB photons, they are around us.
Difficult to detect (only weak interactions) but relevant cosmologically

Laboratory experiments (oscillations, neutrinoless double beta decay) and cosmology are both sensitive to their mass



Q5: Can the Universe undergoes cycles between Big Bang and Big Crunch?

The present Universe is accelerating so we do not expect a Big Crunch

Q6: The universe is constantly expanding, and therefore its temperature decreases due to its increasing expansion. Does the universe reach a point where it becomes cold enough to not allow life to continue?

The physics of bound objects does not cool down following the expansion of the Universe. Ask an astrophysicist! :)

Q7: What are acoustic oscillations?

Q8: Dark matter sensitivity

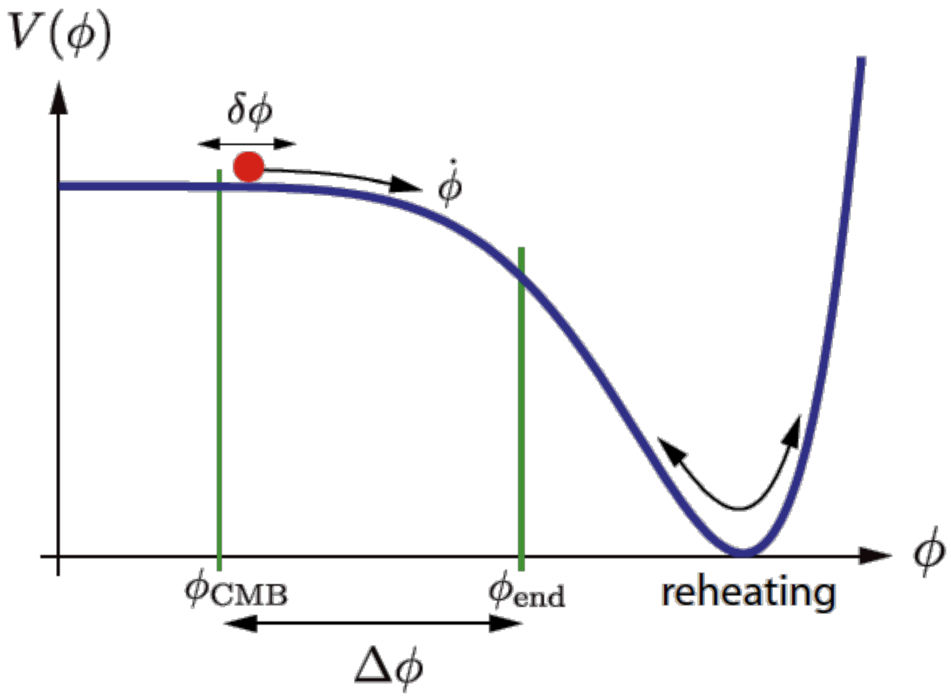
Q9: Derivation of Friedmann equations

Q10: What is slow-roll inflation? Did we detect Gravitational Waves from Big Bang?

Q11: If photons cannot escape from a Black Hole, can BHs have charge?

(Slow-roll) inflation

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



$$\ddot\phi + 3H\dot\phi + V'(\phi) = 0$$

friction is dominant

$$\epsilon = \frac{1}{2}M_P^2\left(\frac{V'}{V}\right)^2$$

$$\eta = M_P^2\frac{V''}{V}$$

$$\epsilon, \eta, \ldots \ll 1$$

$$\dot a^2 = \frac{\Lambda(t)}{3}a^2$$

$$H \equiv \frac{\dot a}{a}$$

Hubble rate

$$\epsilon \equiv -\frac{\dot H}{H^2} \ll 1$$