Comprendre l'infiniment grand: cosmology and large scales in the Universe

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CosmoStat

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25th July, 2017

Some references

References:

Modern Cosmology, Dodelson

CMB physics and anisotropies: Hu & Dodelson 2002, Wayne Hu website, WMAP website: http://map.gsfc.nasa.gov/universe/

Dark Energy (Amendola & Tsujikawa)

Experiments: lambda.gfsc.nasa.gov

And references within the slides, which include work from several authors: L. Amendola, W. Hu, V. Springel, S. Dodelson, M. White, D. Weinberg, Bartelmann …

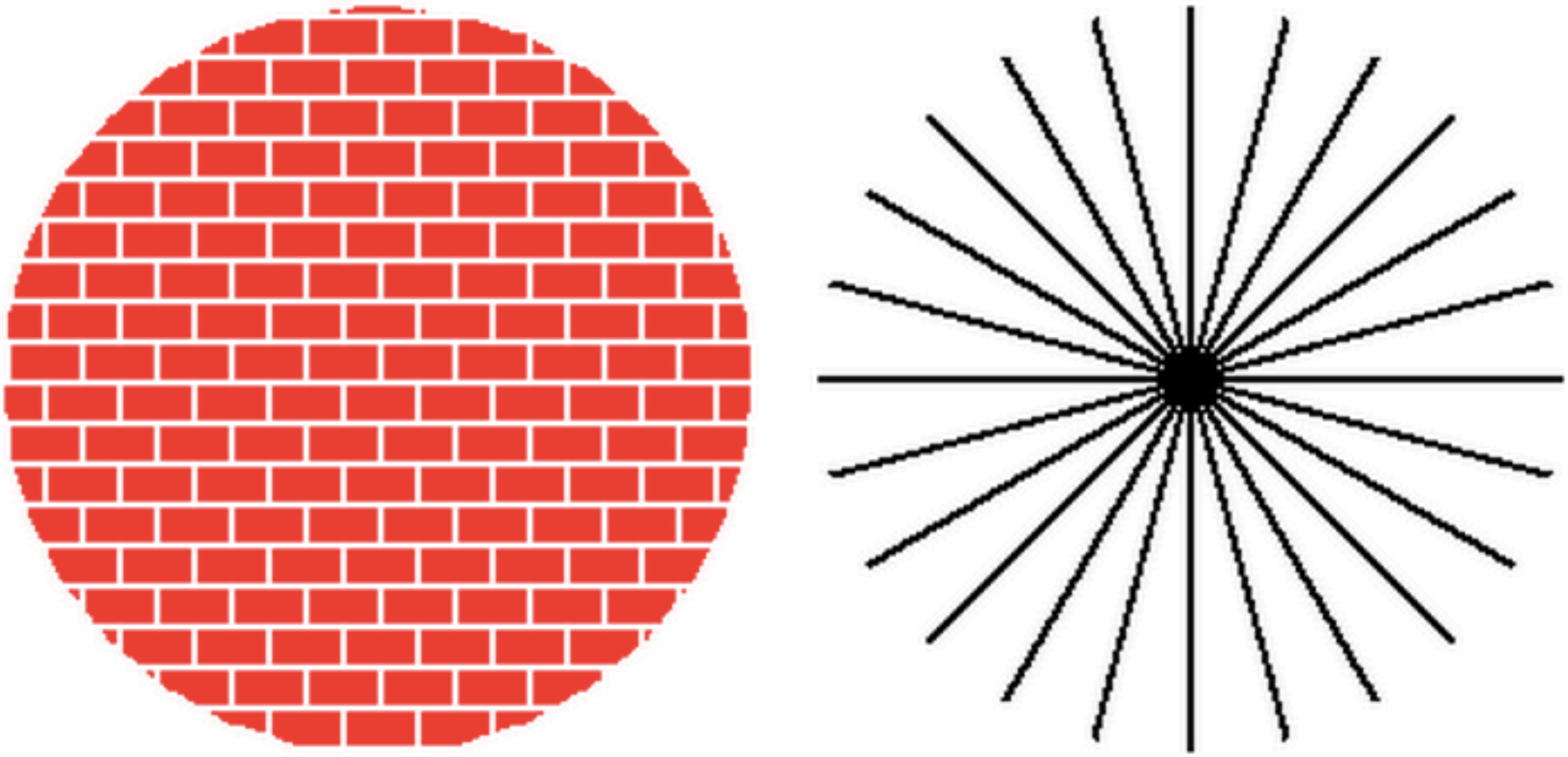
Distances: https://cosmology.carnegiescience.edu/timeline
https://telescoper.wordpress.com/2012/09/15/hubble-versus-slipher/

Other References

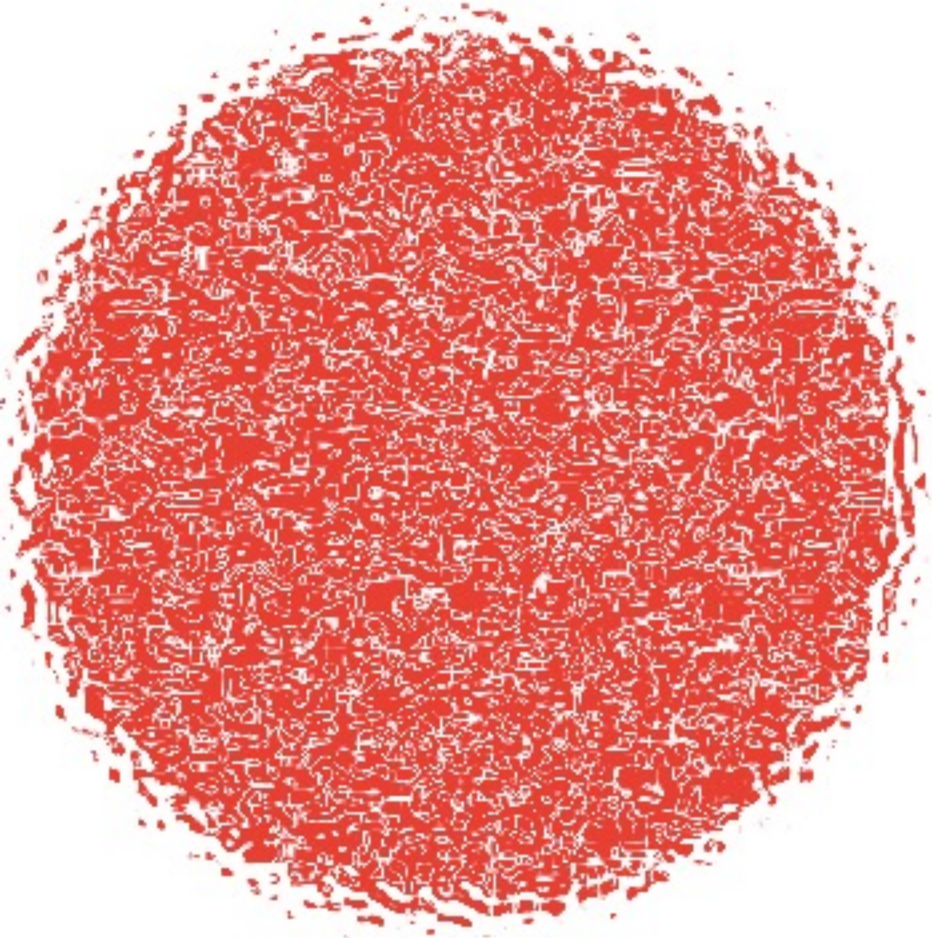
- General:
- http://arxiv.org/pdf/0904.1832v1.pdf
- http://arxiv.org/pdf/0803.0982v1.pdf
- http://www.markcwyman.com/comptonlectures/Lecture6.pdf
- http://preposterousuniverse.com/talks/decolloq06/
- http://indico.cern.ch/getFile.py/access?contribId=17&resId=0&materialId=slides&confId=104126
- http://physicsworld.com/cws/article/print/2007/dec/03/dark-energy-the-decade-ahead
- http://www-thphys.physics.ox.ac.uk/talks/oxral/Slides/mk_dark_phenomenology_oxford.pdf

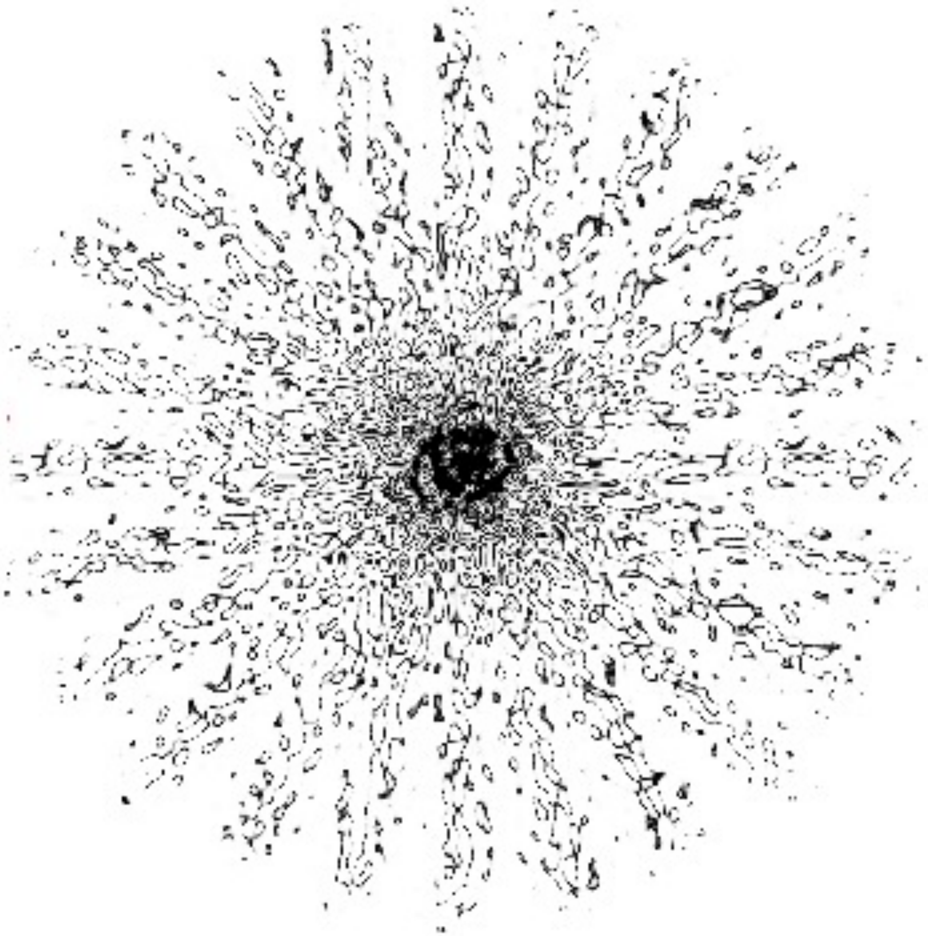
Start from a homogeneous and isotropic Universe

Study small (linear) perturbations around it for all species

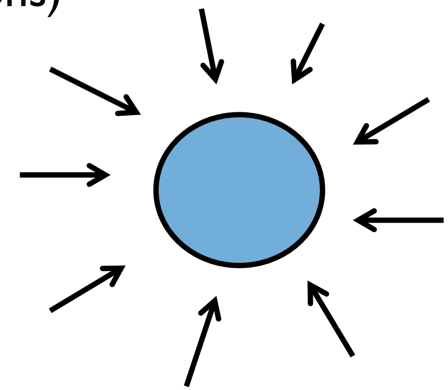


Picture from Ned Wright's Cosmology Tutorial





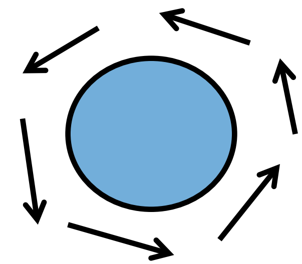
Scalar perturbations (ex. density and temperature fluctuations)



Vector perturbations:

scalar-type (ex. Infall on a cluster)

vector-type (ex. Vorticity)

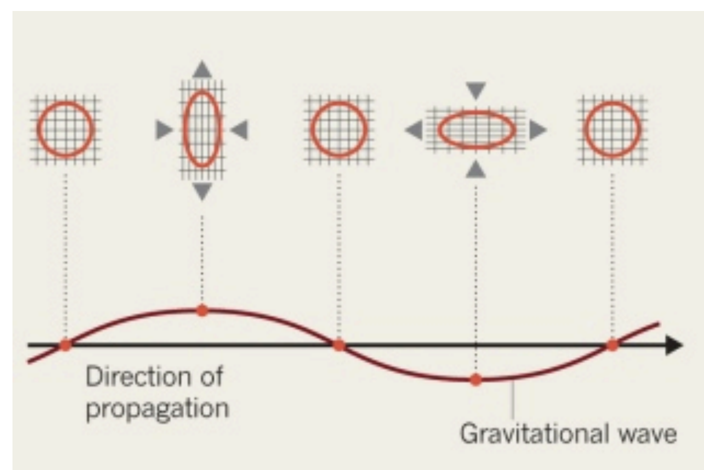


Tensor perturbations:

scalar-type (change in infall)

vector-type (change of vorticity)

tensor-type (gravitational waves)



Advantages of Linear perturbations:

Keep modes independent from each other

Separate equations for background and equations for perturbations

$$G_{\mu\nu} = 8\pi G T_{\mu\nu} \quad \begin{cases} \bar{G}_{\mu\nu} = 8\pi G \bar{T}_{\mu\nu} \\ \delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu} \end{cases}$$

$$T_{\mu\nu}^{;\nu} = 0 \quad \begin{cases} \bar{T}_{\mu\nu}^{;\nu} = 0 \\ \delta T_{\mu\nu}^{;\nu} = 0 \end{cases}$$

Stress energy tensor

Energy momentum tensor for a perfect relativistic fluid, homogeneous and isotropic

$$T^{\nu}_{\mu} \equiv \begin{pmatrix} -\rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

$$T_{\mu\nu} = (\rho + p)u_{\mu}u_{\nu} + pg_{\mu\nu}$$

Perturbing the energy momentum tensor

$$\tilde{T}_{\mu\nu} = T_{\mu\nu} + \delta T_{\mu\nu}$$

$$\longrightarrow \quad \delta T_{\mu\nu}\{\delta, v, \pi_L, \pi_T\}$$

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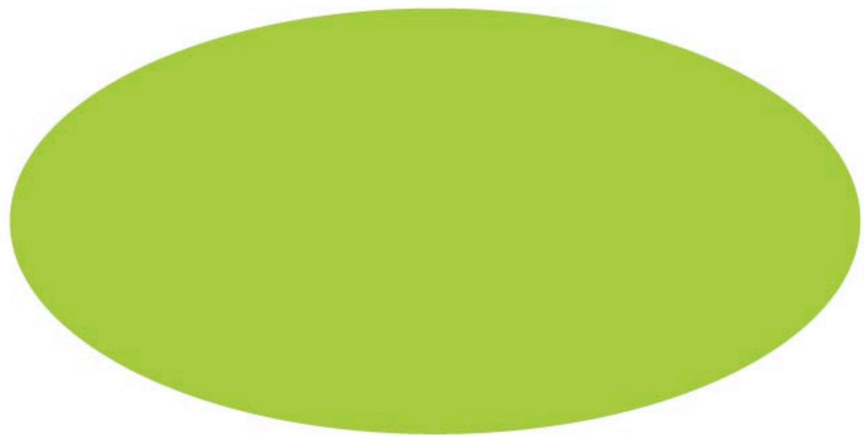
Cosmic Microwave Background: relic light from the Big Bang



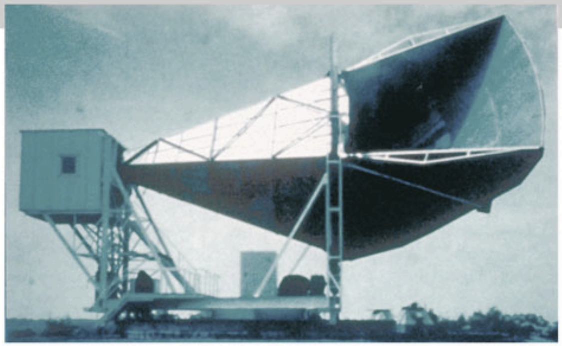
MAP990004

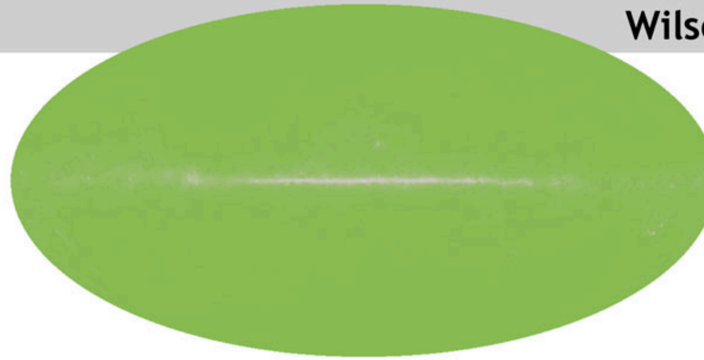
Light emitted 380.000 yrs (z = 1090) after the Big Bang, now in the microwave

It looks (almost) the same in every direction

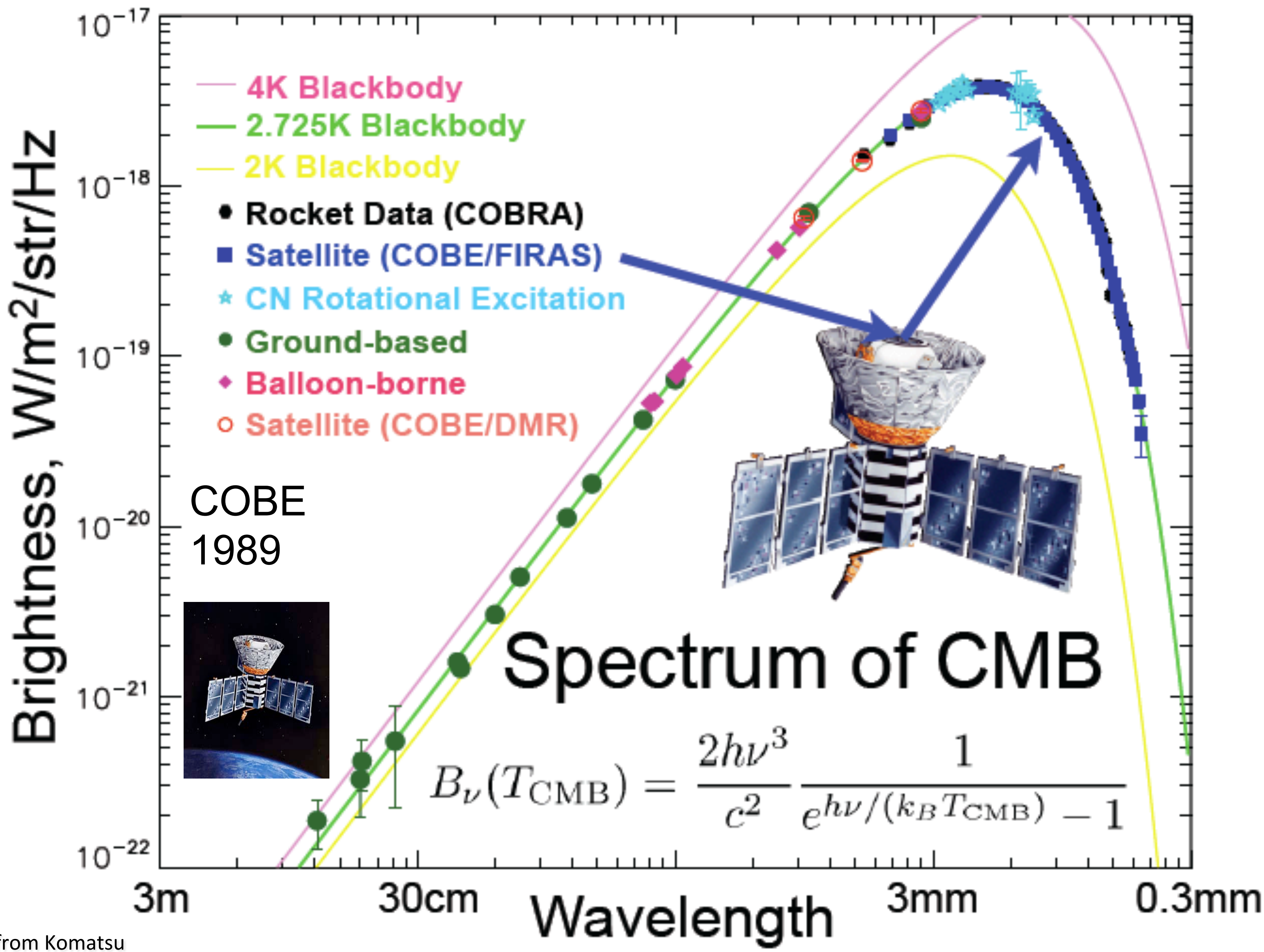
History

1965 **Penzias and Wilson**



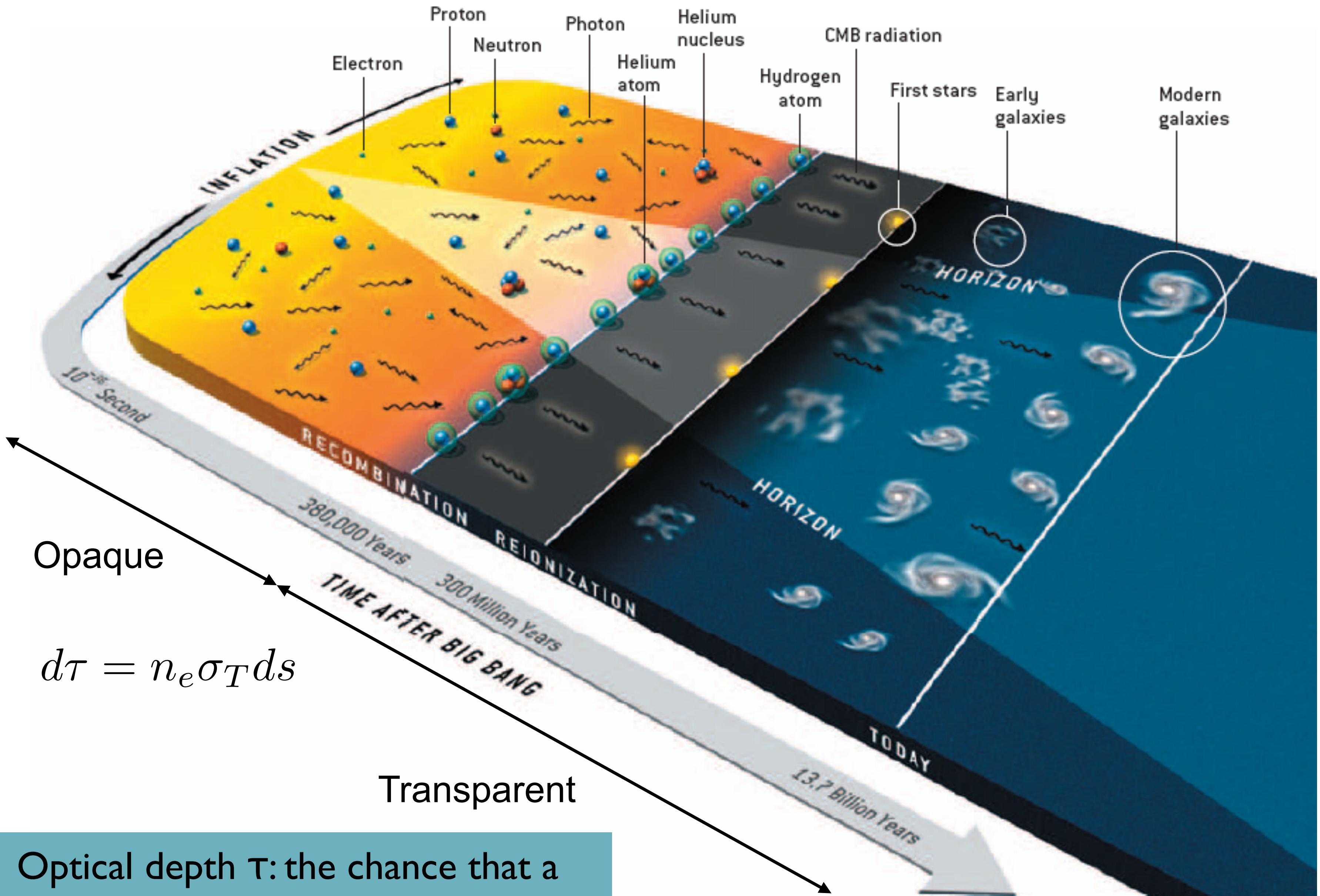


- Predicted in 1948 (Ralph lpher, Robert Herman, G. Gamow)
- First observed in 1965 by Penzias & Wilson at the Bell Telephone Laboratories in New Jersey. The radiation was acting as a source of excess noise in a radio receiver they were building.
- Researchers (Robert Dicke, Dave Wilkinson, Peebles, Roll) realised it was CMB
- Nobel Prize in 1978 to Penzias & Wilson for the discovery



Plot from Komatsu

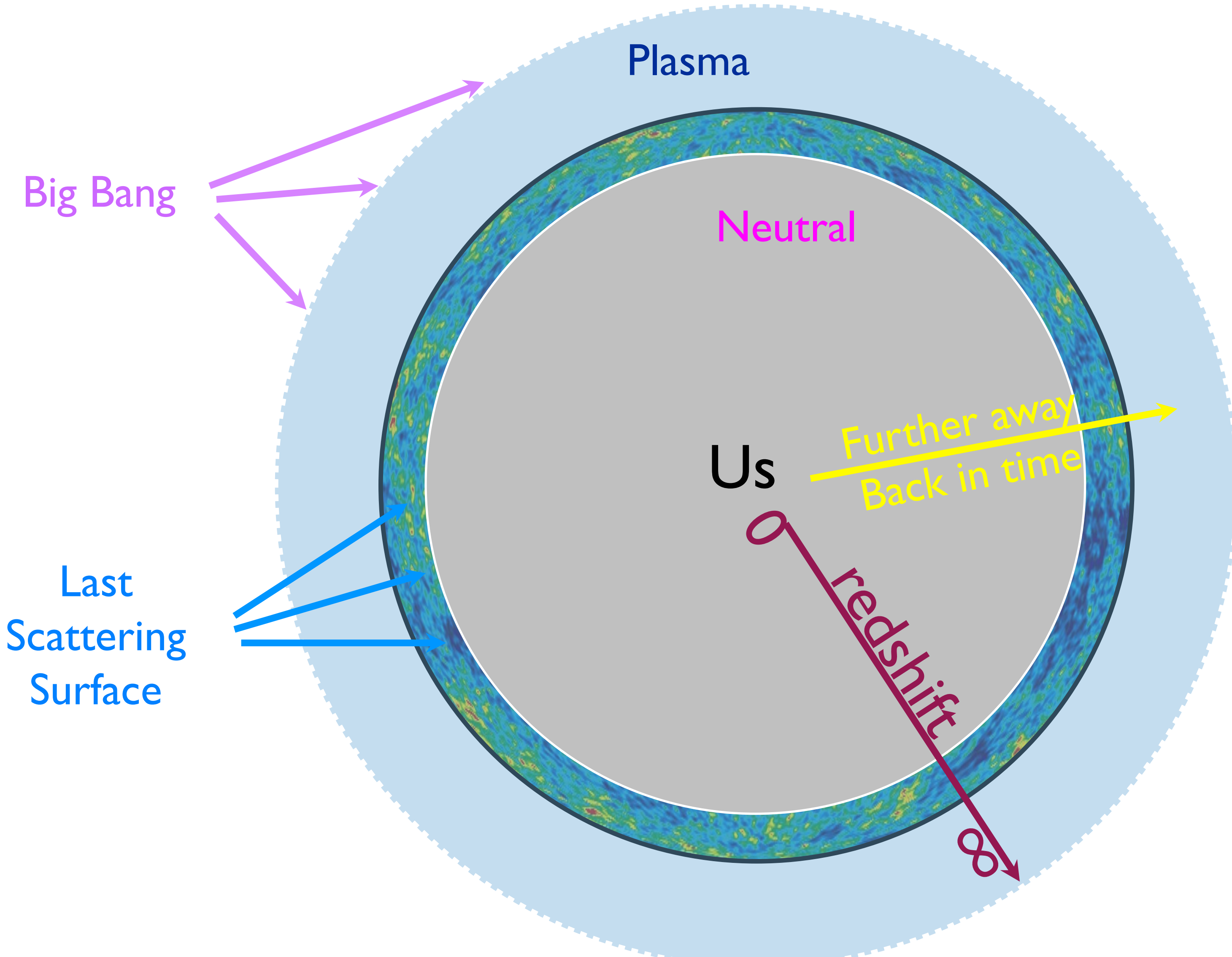
Evolution of the universe



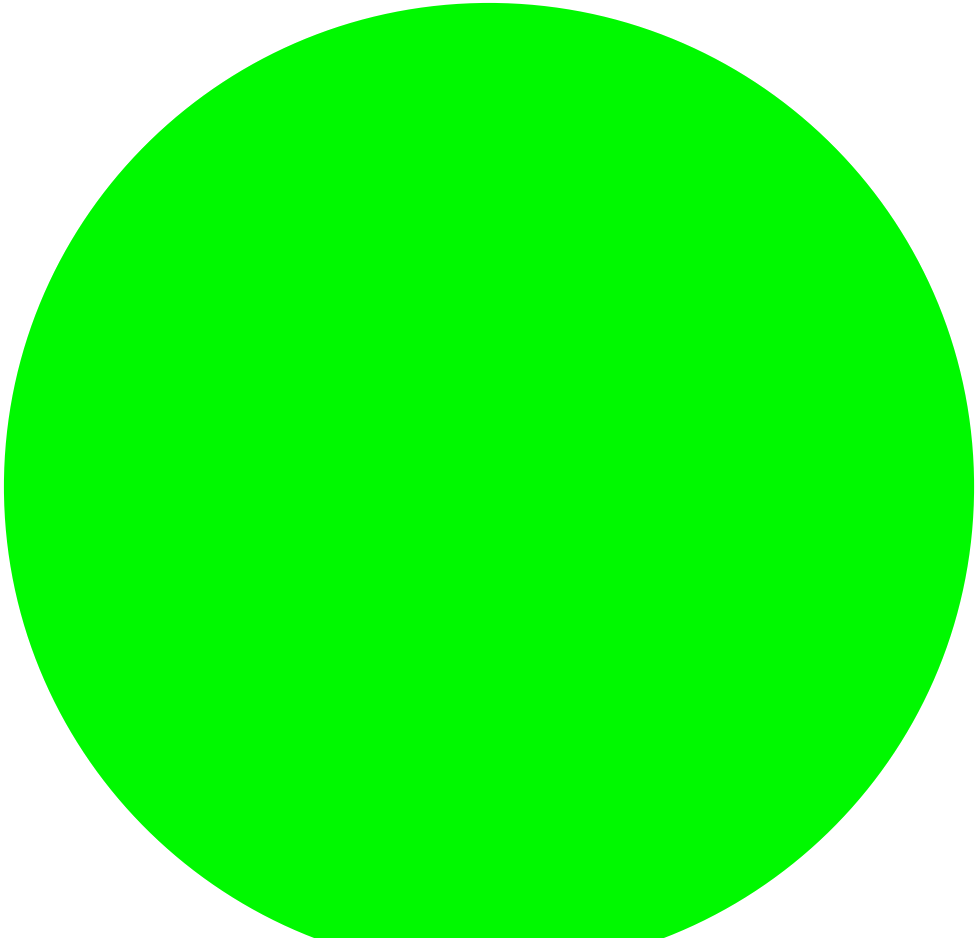
$$d\tau = n_e \sigma_T ds$$

Optical depth τ: the chance that a photon is scattered within a given interval of length ds

Electrons combined with protons to form neutral hydrogen and CMB photons travelled freely until detection (first in 1965, Penzias and Wilson)

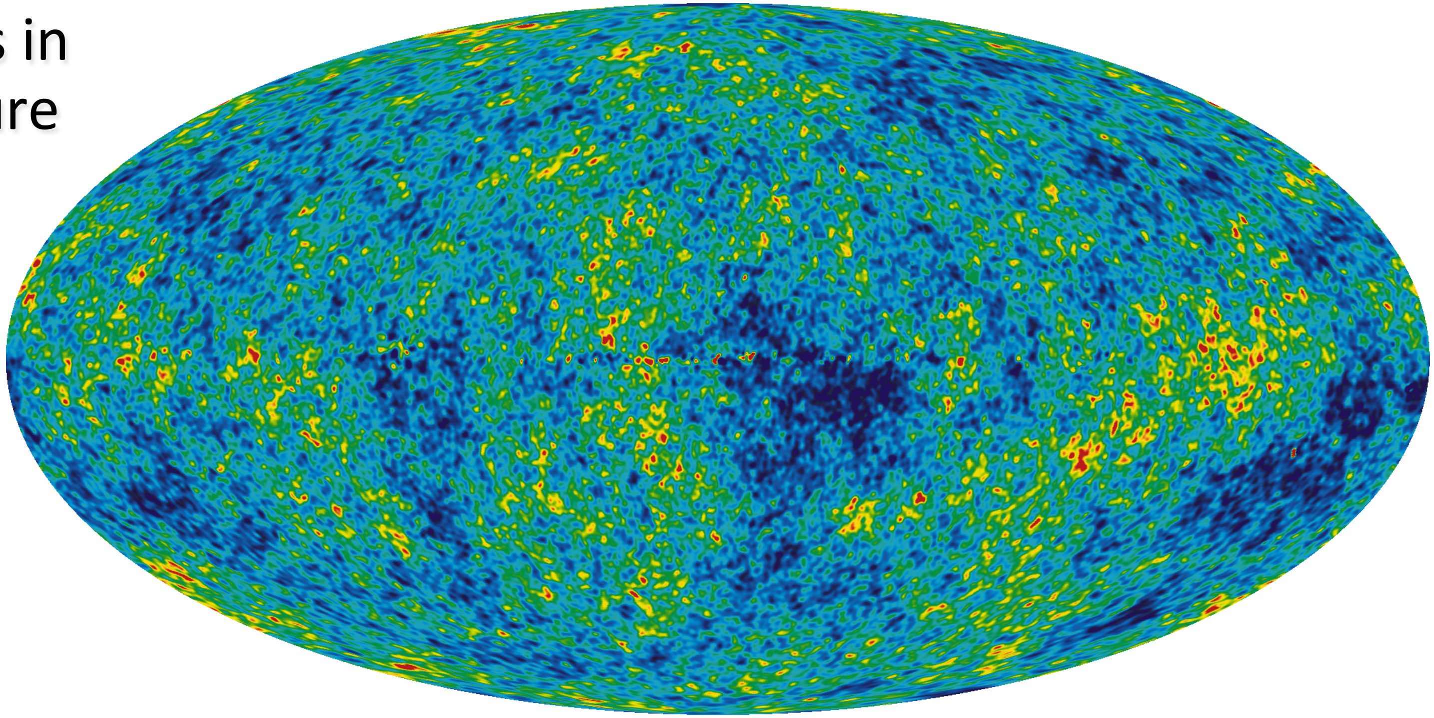


Crowe, Moss & Scott (2008)



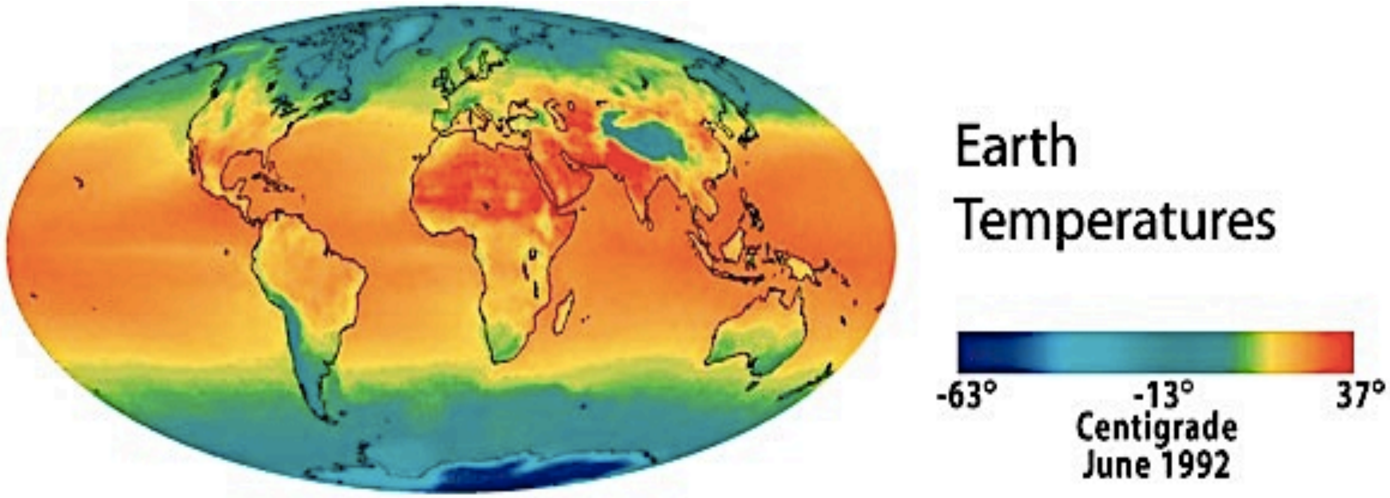
CMB anisotropies

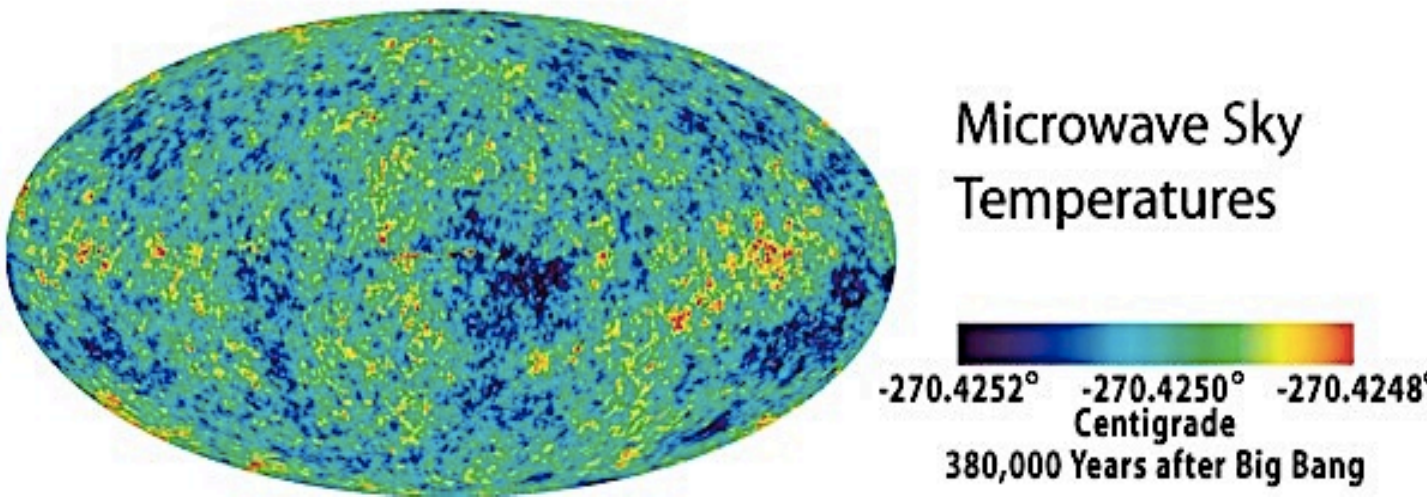
Colours indicate differences in temperature



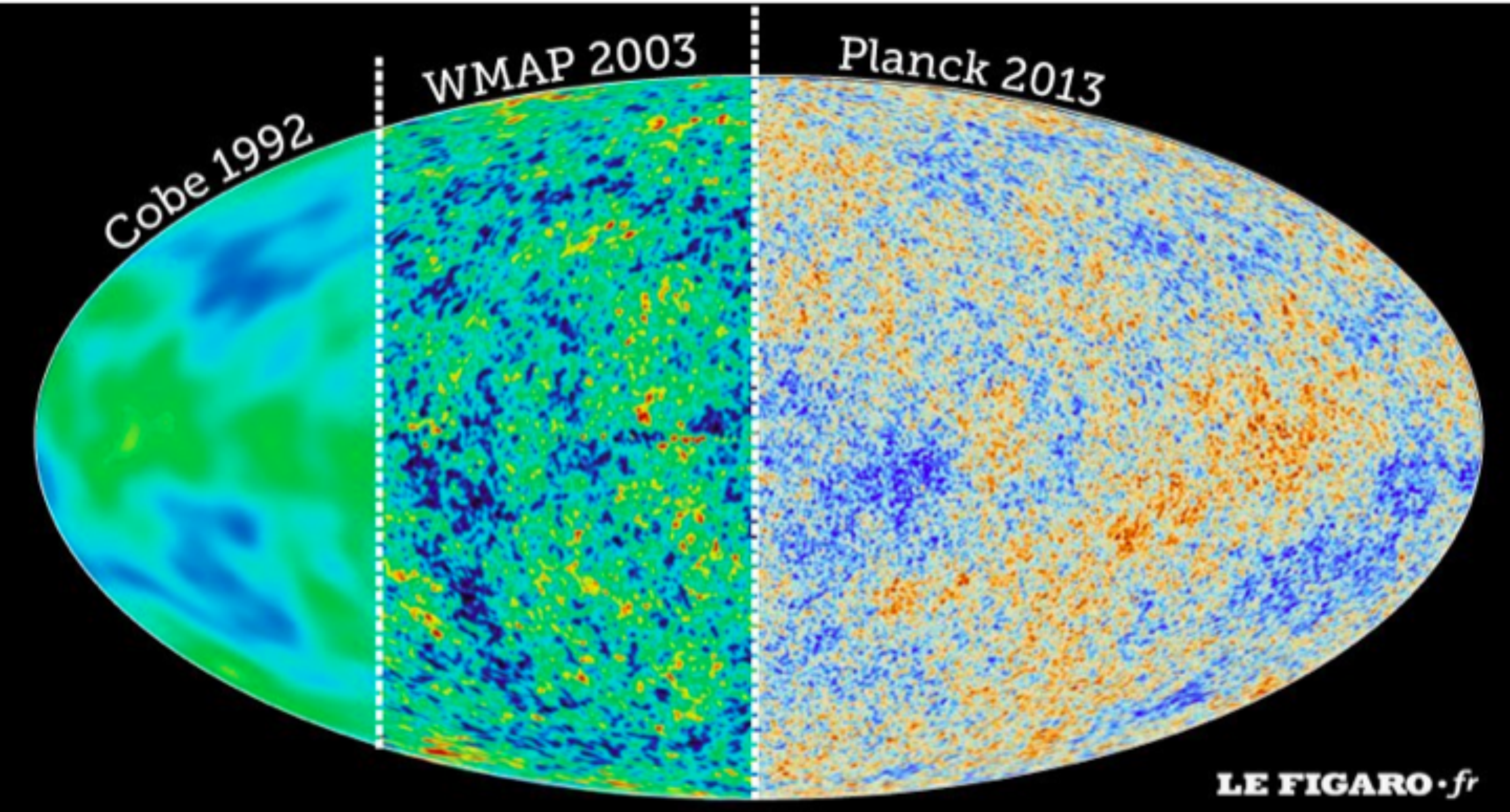
If you look at angles of about 1 degree or smaller you see anisotropies

The fluctuations in temperature across the sky are the precursors of the large scale structures that we see around us today.

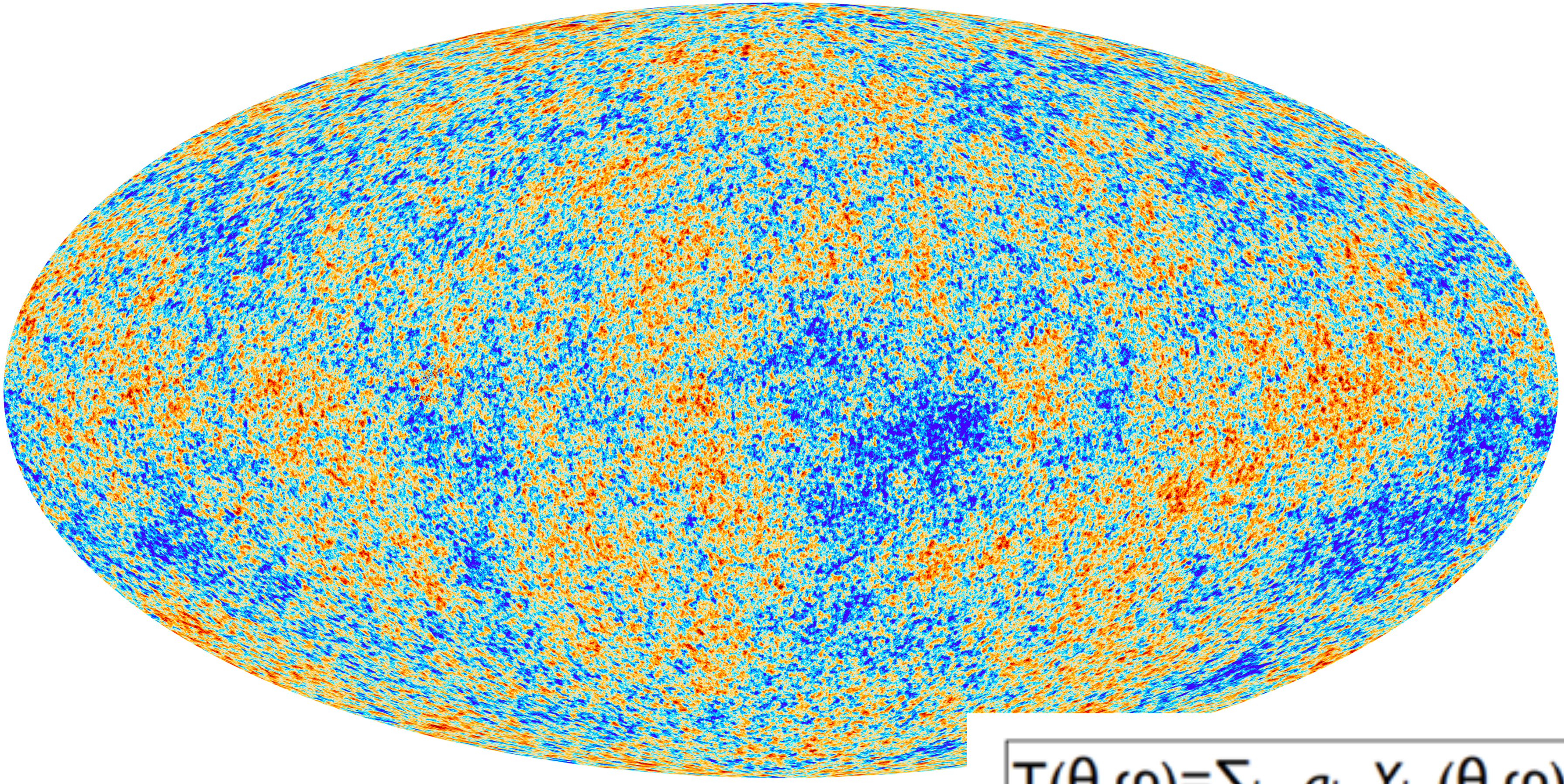




Deviations from black body are of order 10^{-5}


Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO·fr

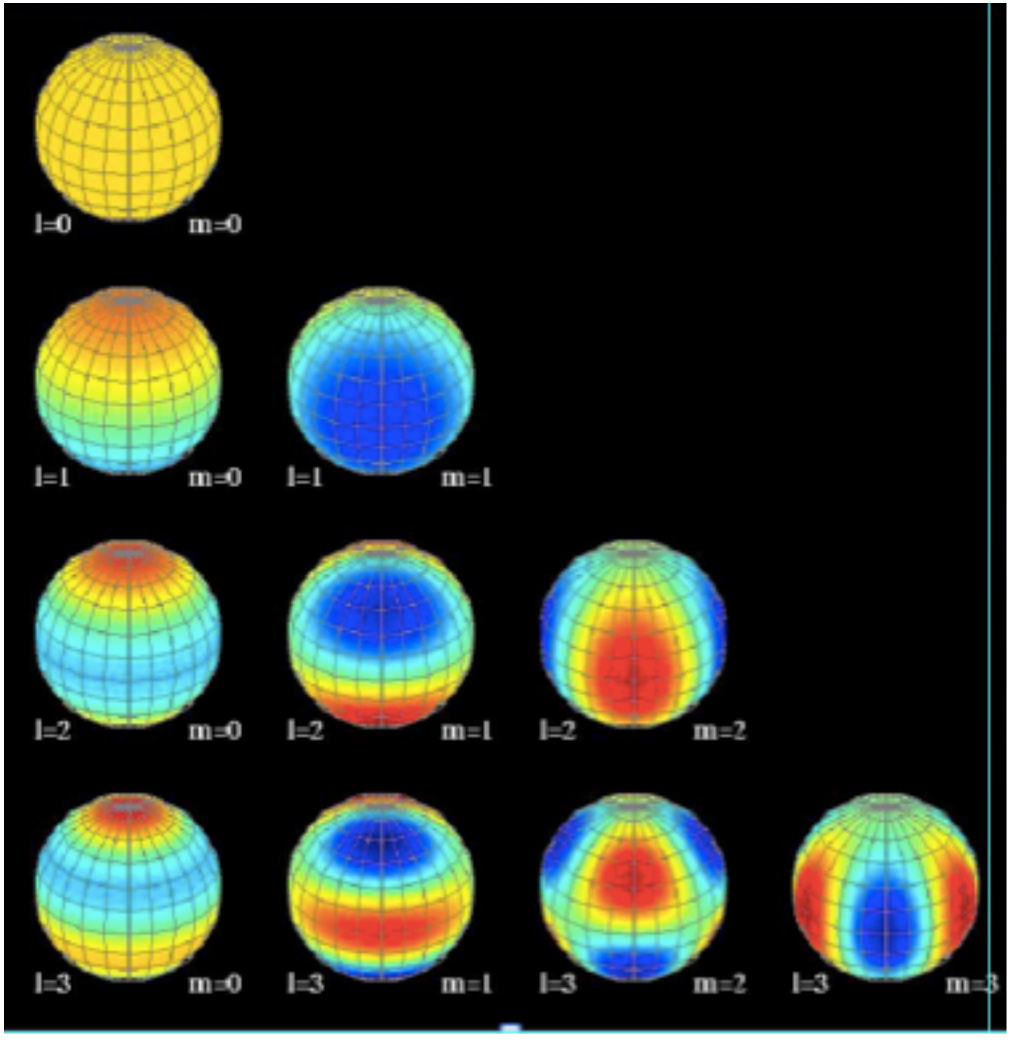
Map of the CMB anisotropies



$$T(\theta,\varphi)=\sum_{lm} a_{lm} Y_{lm}(\theta,\varphi)$$

Mapping temperature fluctuations into spherical harmonics.

Using statistics, power spectrum, correlation functions to describe the temperature fluctuations

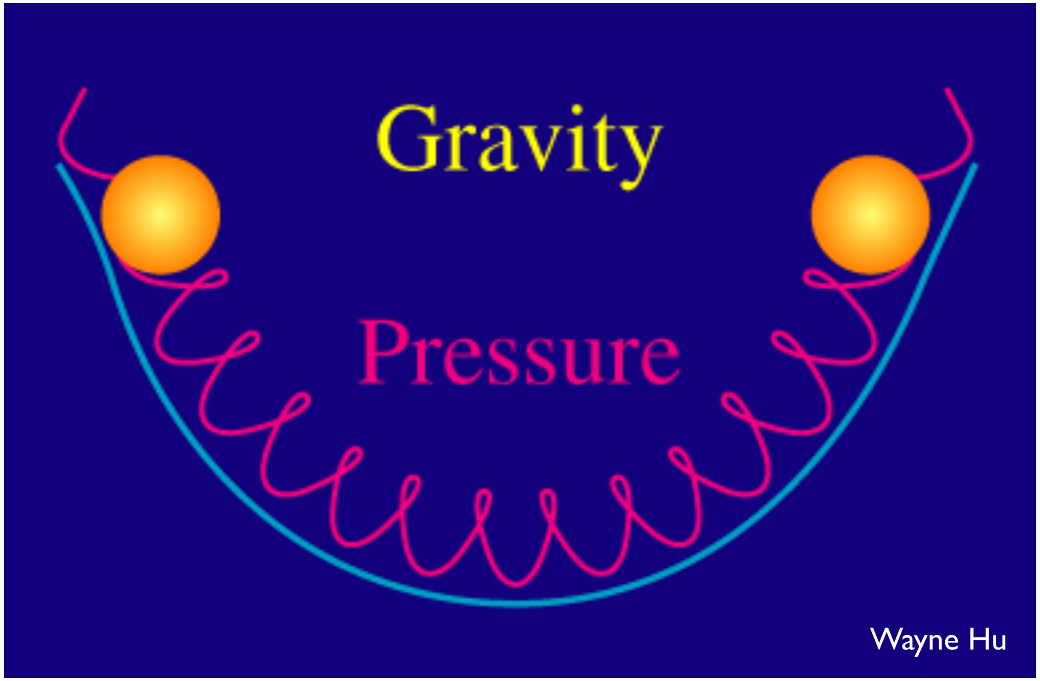


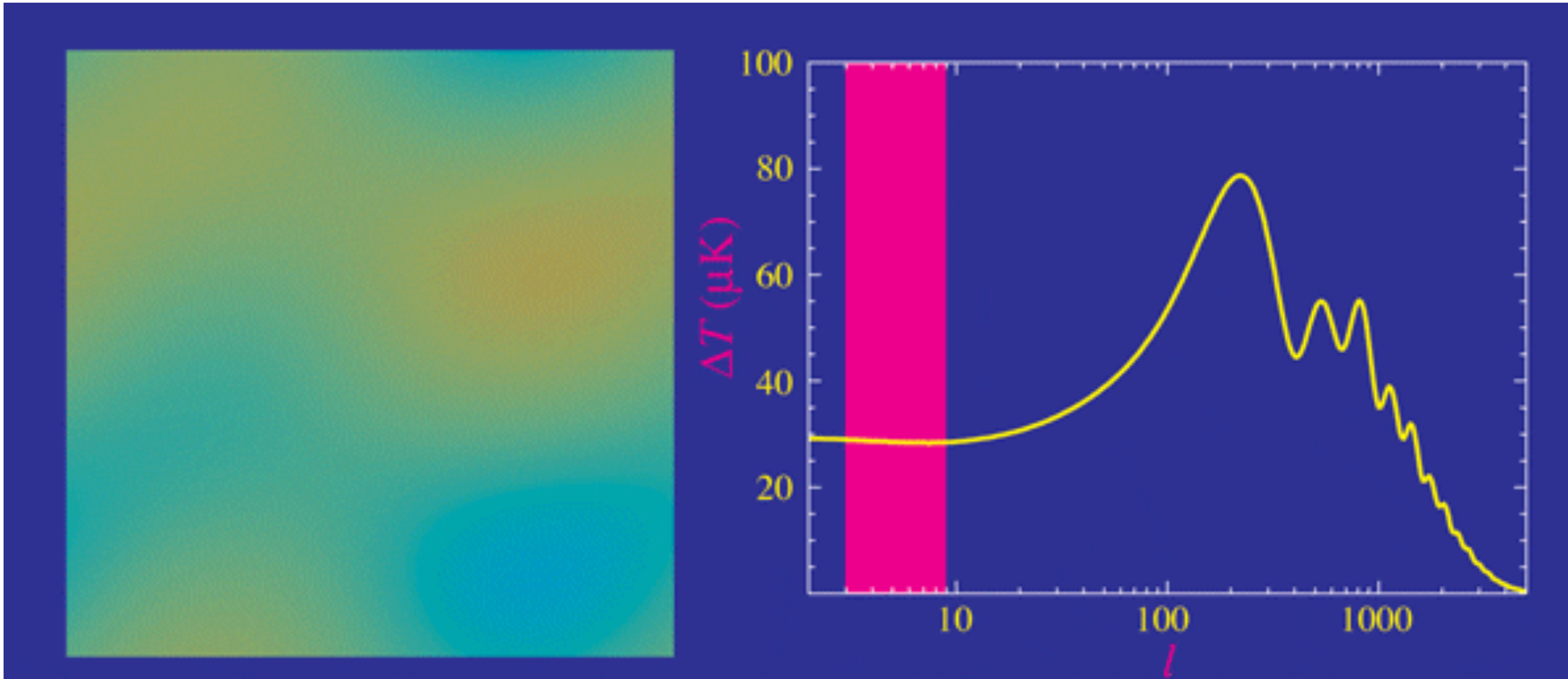
Sound waves

Before last scattering, photons, electrons and protons behave as a single fluid.

The tight coupling between baryons and photons produce oscillations in the plasma.

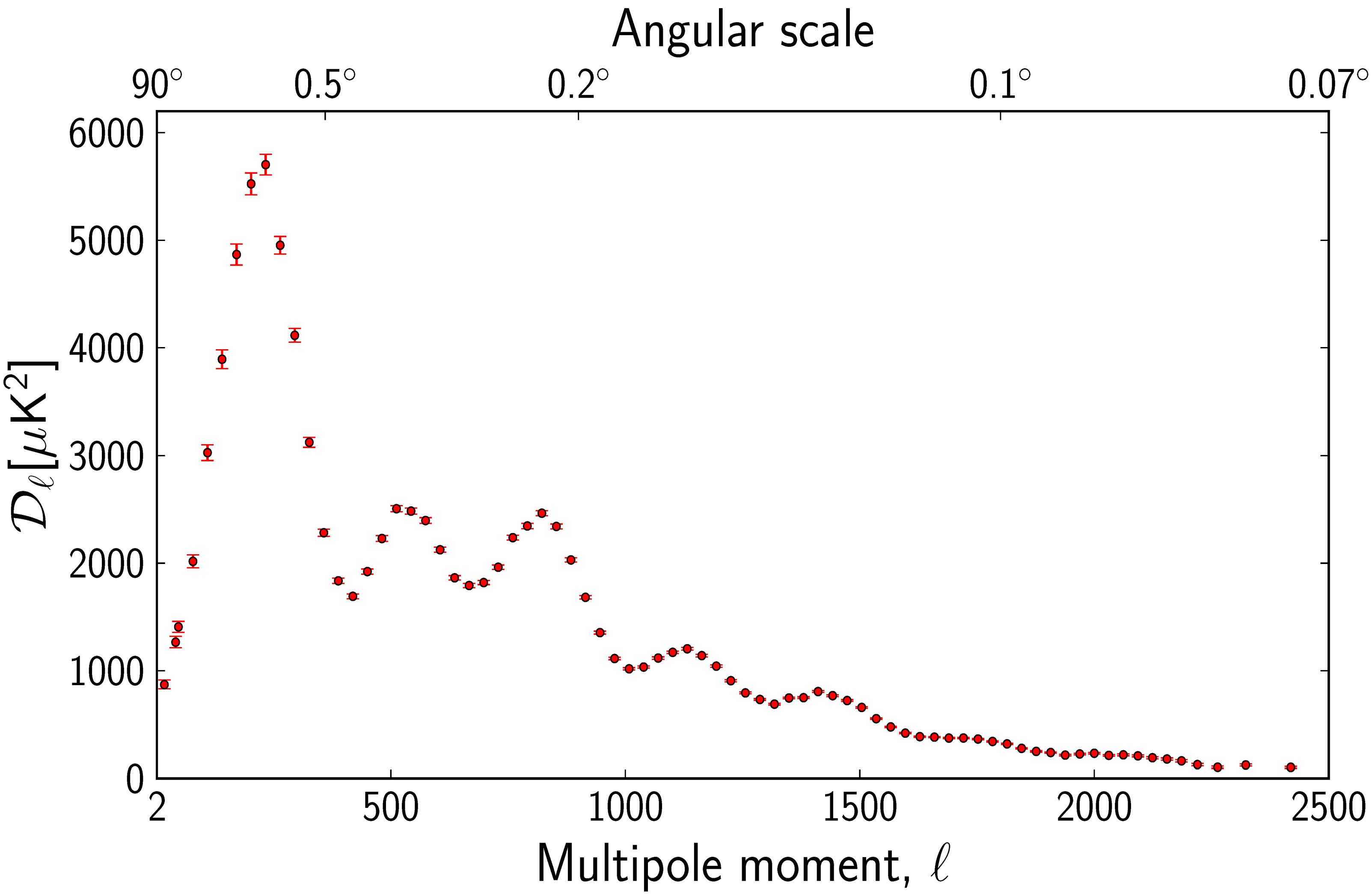
Sound waves of the baryon-photon fluid, gravity/pressure, compressions/ rarefactions.





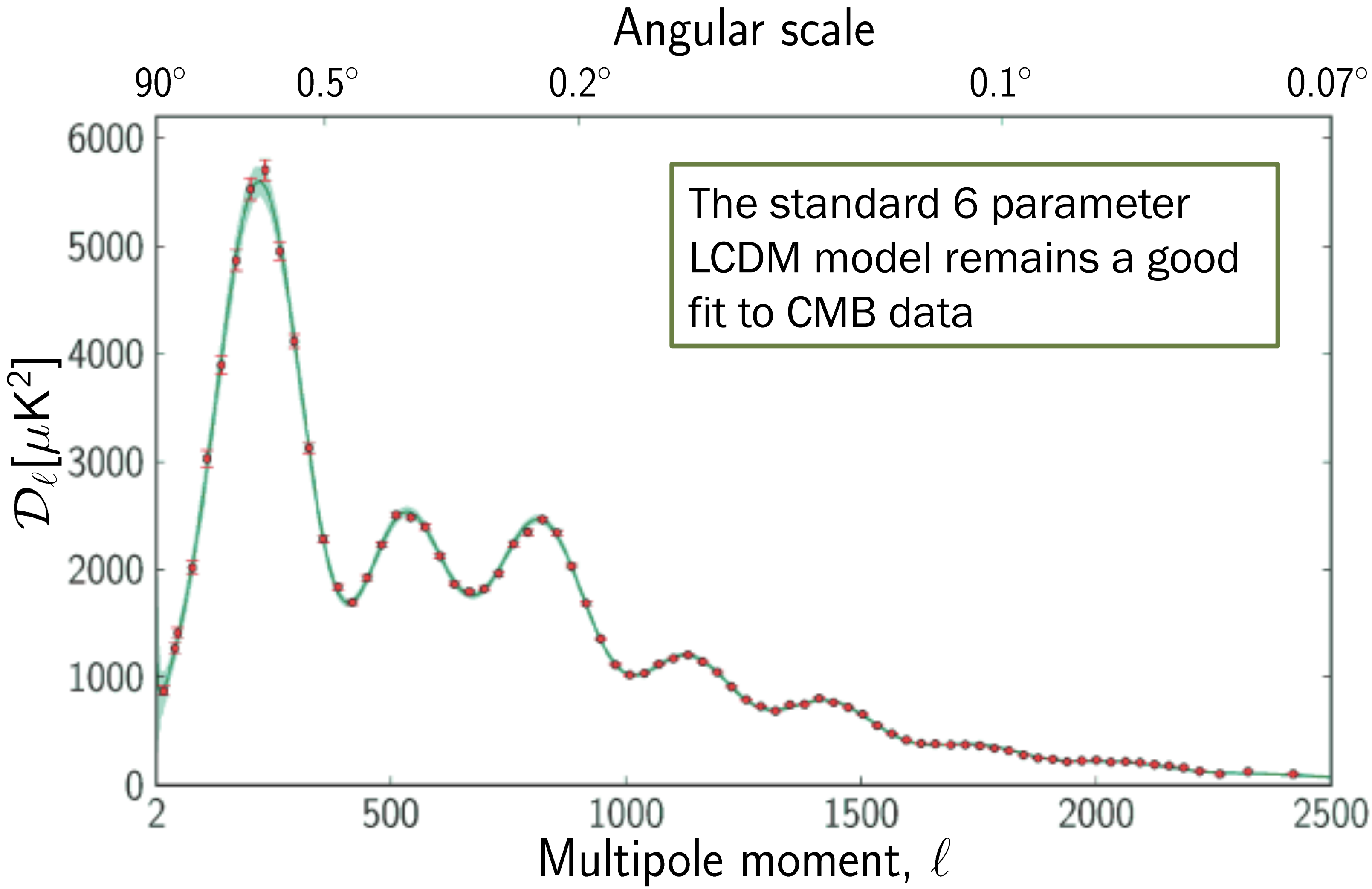
Plot by Wayne Hu

Power spectrum



ΛCDM is a very good fit

http://map.gsfc.nasa.gov/resources/camb_tool/index.html

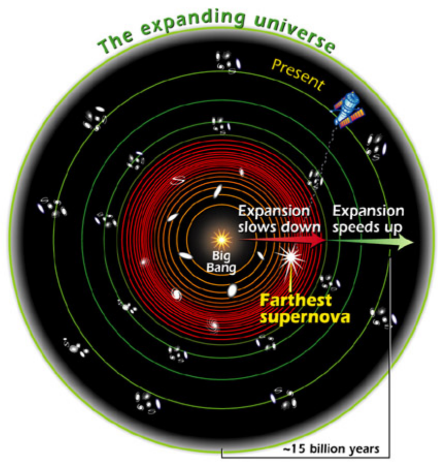


The standard 6 parameter LCDM model remains a good fit to CMB data

Quite impressive. From terabytes of data to 6 parameters

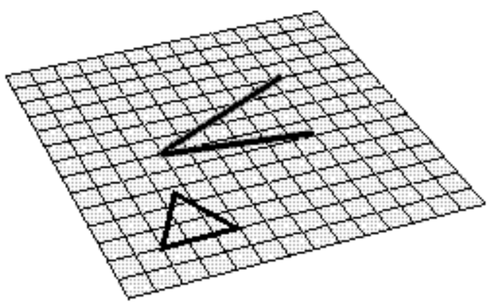
Ingredients of the Universe

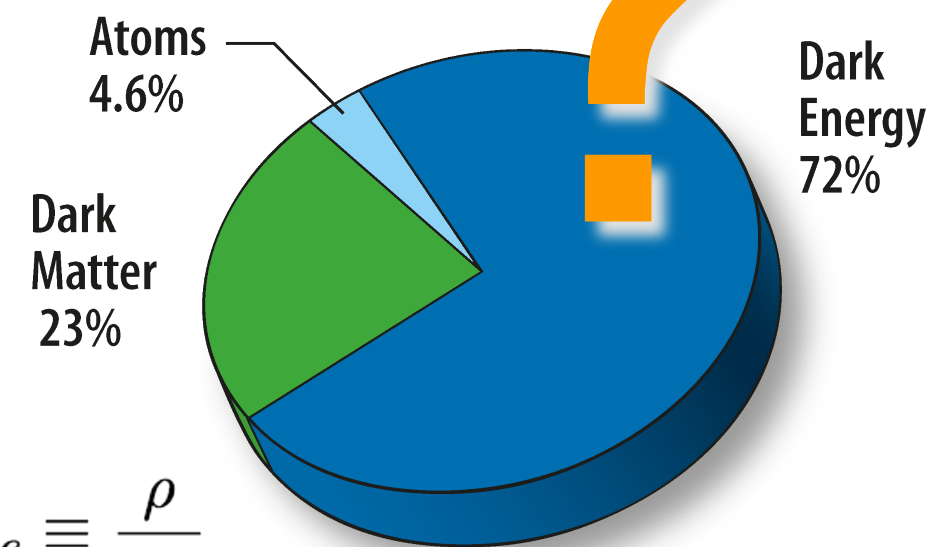
$$\Omega_i \equiv \frac{\rho_i}{\rho_{cr}}$$



Accelerated expansion

Flatness





$$\Omega_{de} \equiv \frac{\rho}{\rho_{cr}}$$

TODAY

Dark Matter interacts gravitationally and forms structures in which baryons fall.

Dark energy is enough for the Universe to be spatially flat, responsible for the accelerated expansion of the Universe

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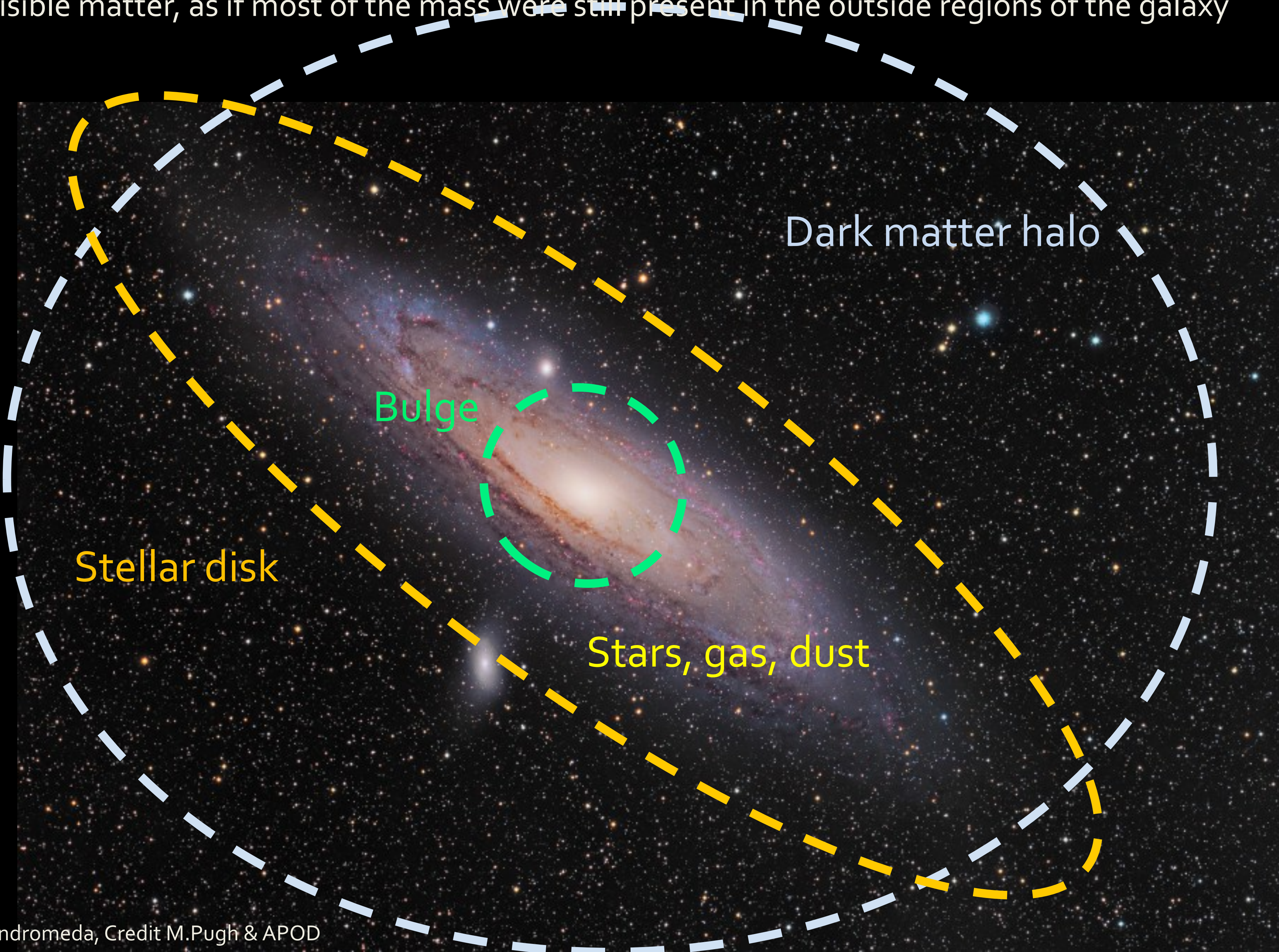
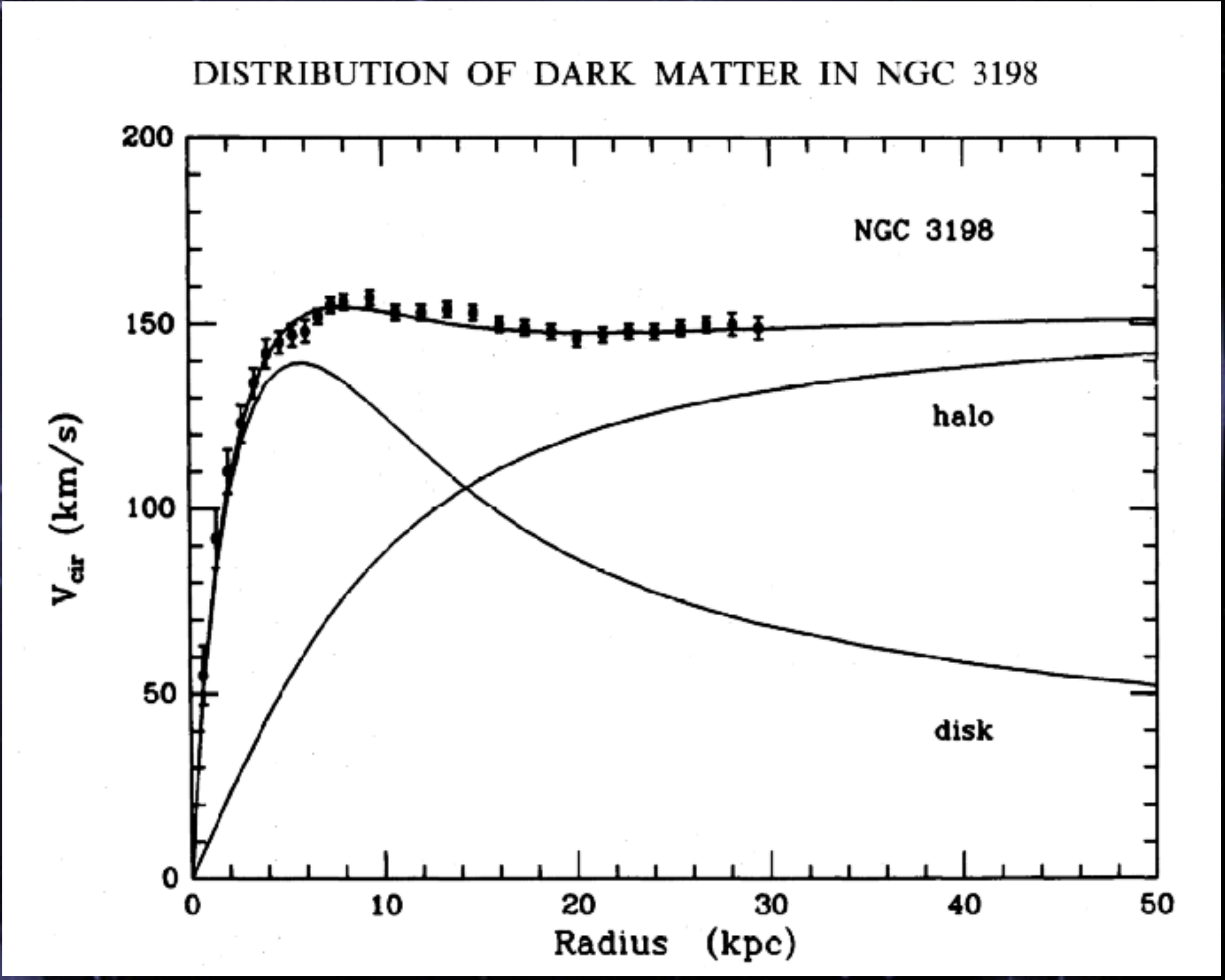
Spiral galaxies: at large radial scales, they keep rotating fast; faster than if there were only visible matter, as if most of the mass were still present in the outside regions of the galaxy



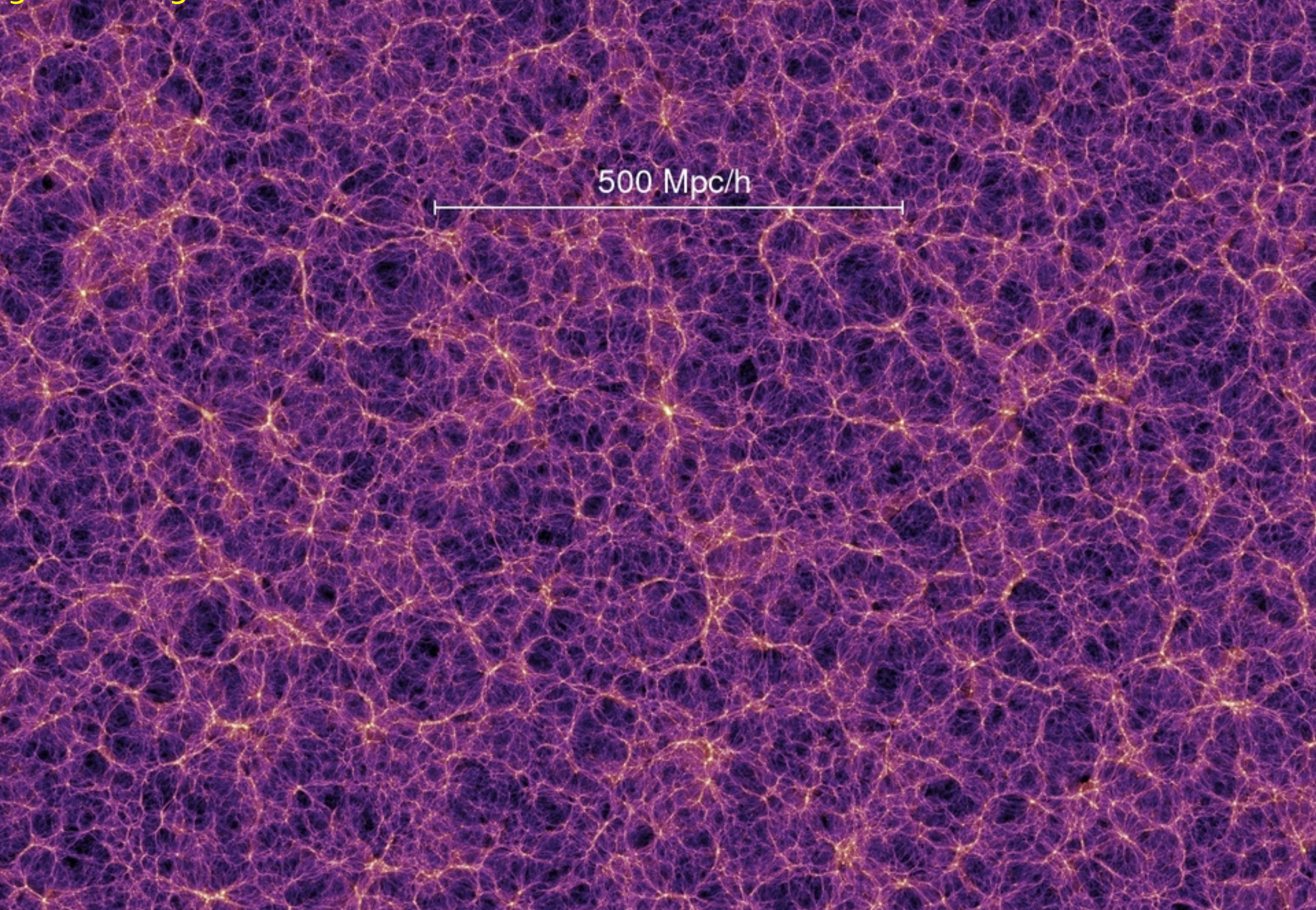
Andromeda, Credit M.Pugh & APOD

Rotation curves

Typical rotation speed 200 km/s

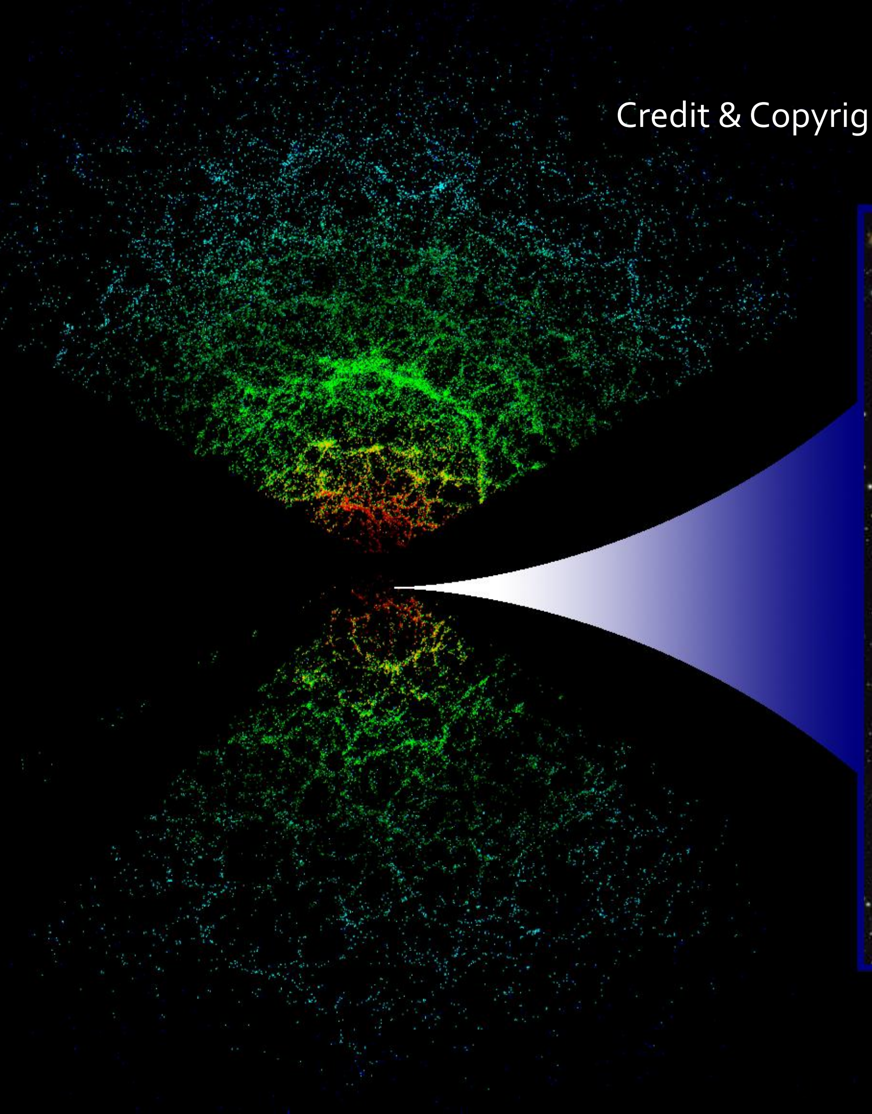


Dark matter is the web network in which visible matter stays. The glue that keeps galaxies together.



Structures on large scales

Credit & Copyright: Sloan Digital Sky Survey Team, NASA, NSF, DOE



3D - SDSS

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Dark matter candidates

WIMPS

Neutralinos

Gravitino

Kaluza Klein Dark Matter

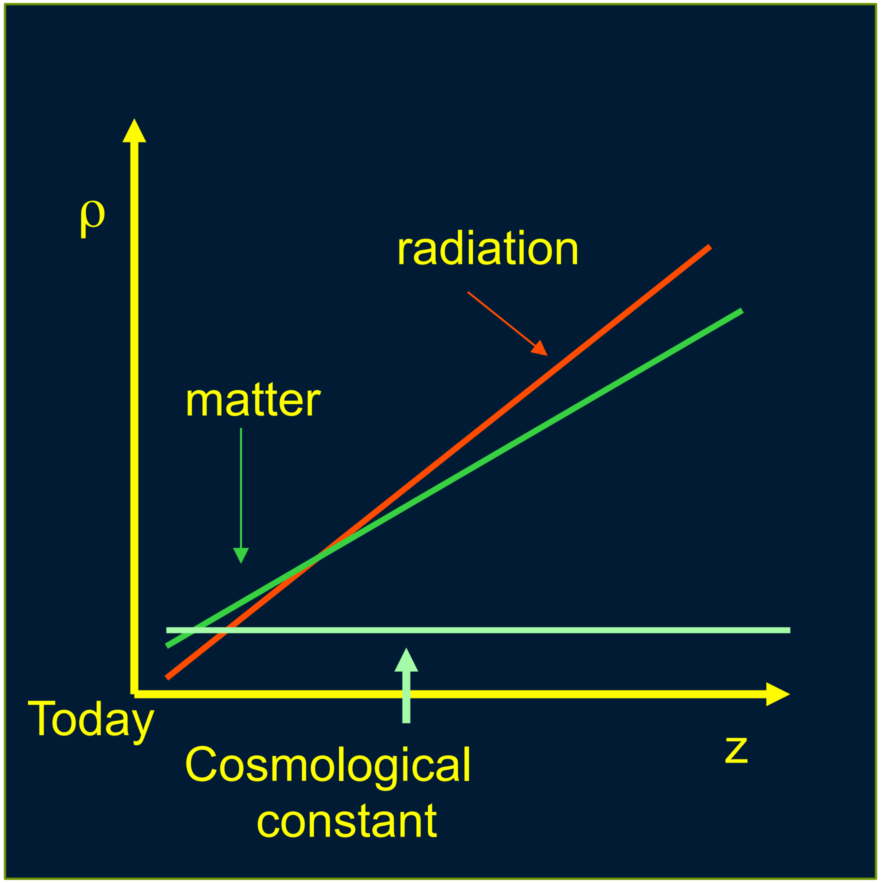
Axions

Sterile Neutrinos

Hidden Dark Matter

SuperWIMPS

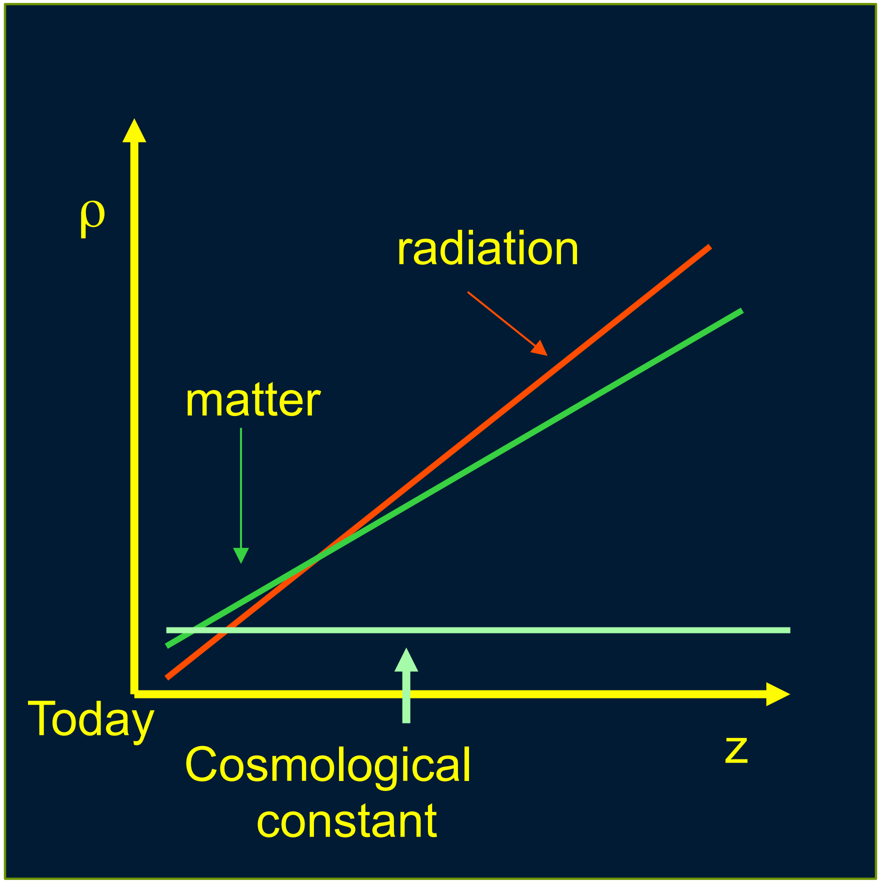
Cosmological constant



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

Introduced by Einstein to avoid expansion

Cosmological constant



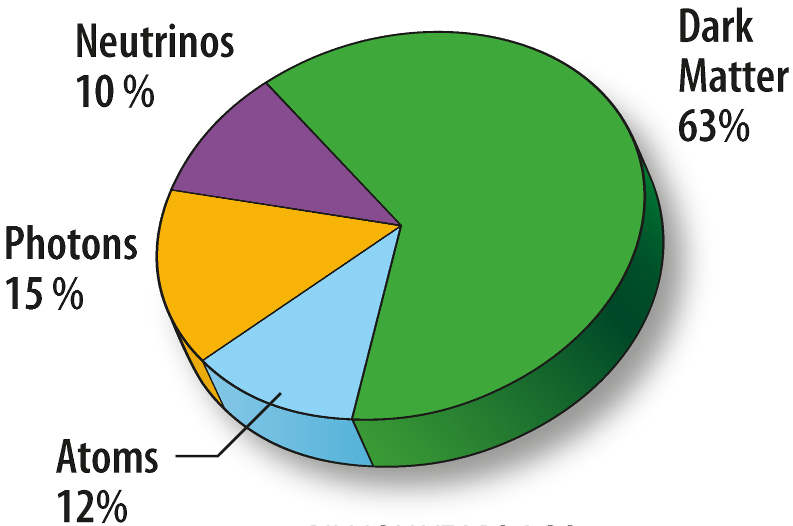
$$\rho_\Lambda = (10^{-3} eV)^4$$

Contribution from quantum zero-point vacuum fluctuations of each field of the standard model. It is necessary to introduce a cutoff and hope that a more complete theory will hold at higher energies. If the cutoff is at the Planck scale,

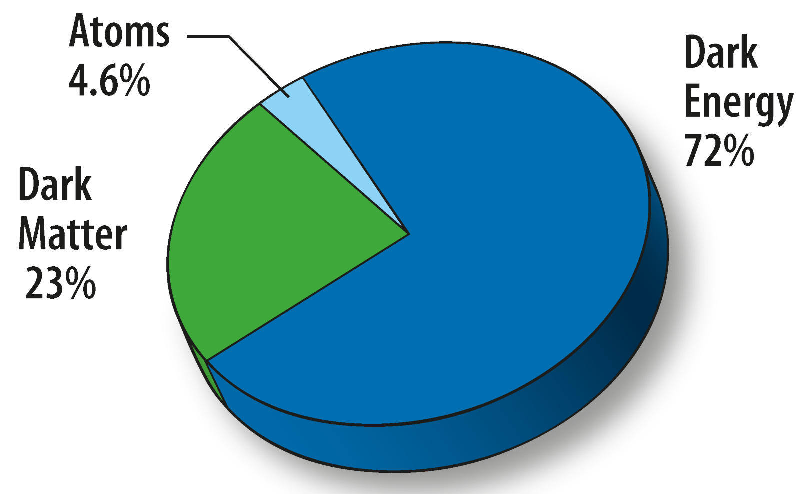
$$\rho_{vac} = (10^{18} GeV)^4$$

$$\rho_\Lambda^{(theory)} \sim 10^{120} \rho_\Lambda^{(obs)}$$

From present to past (in a LCDM)



13.7 BILLION YEARS AGO
(Universe 380,000 years old)



TODAY

How did the transition between the two pies happen? Was causes cosmic acceleration? Was Dark Energy really negligible in the past?

Approaches to the dark energy problem

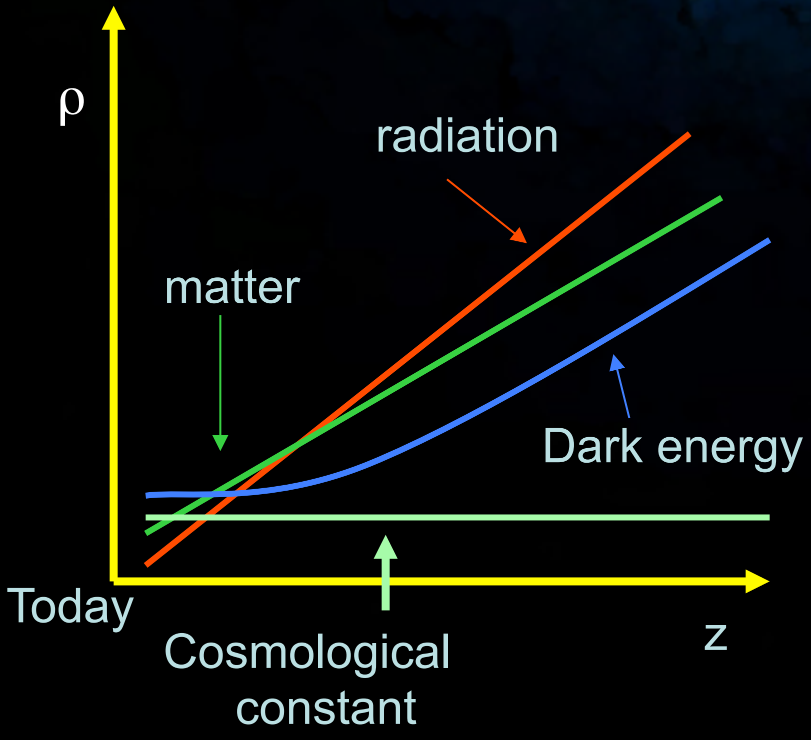
- Form of 'gravitationally repuls Dark energy omponent to the stress energy tensor
- Or Modify the geometry (an Modified gravity ity), mainly at large scales
- We keep GR and a Matter Dominated Universe but drop the assumption that Backreaction, voids, … iverse is spatially homogeneous on large scales, i g large scale structure to induce some apparent a tion

No real strict distinction: the important is to find a solution to the *dark energy problem*

What is dark energy?

From a cosmological constant…

agrees with experiments, but theoretically not understood



$\rho_{DE}/M^4 \sim 75 \times 10^{-120}$

$\rho_m/M^4 \sim 25 \times 10^{-120}$

$M = 2.44 \times 10^{18}$ GeV

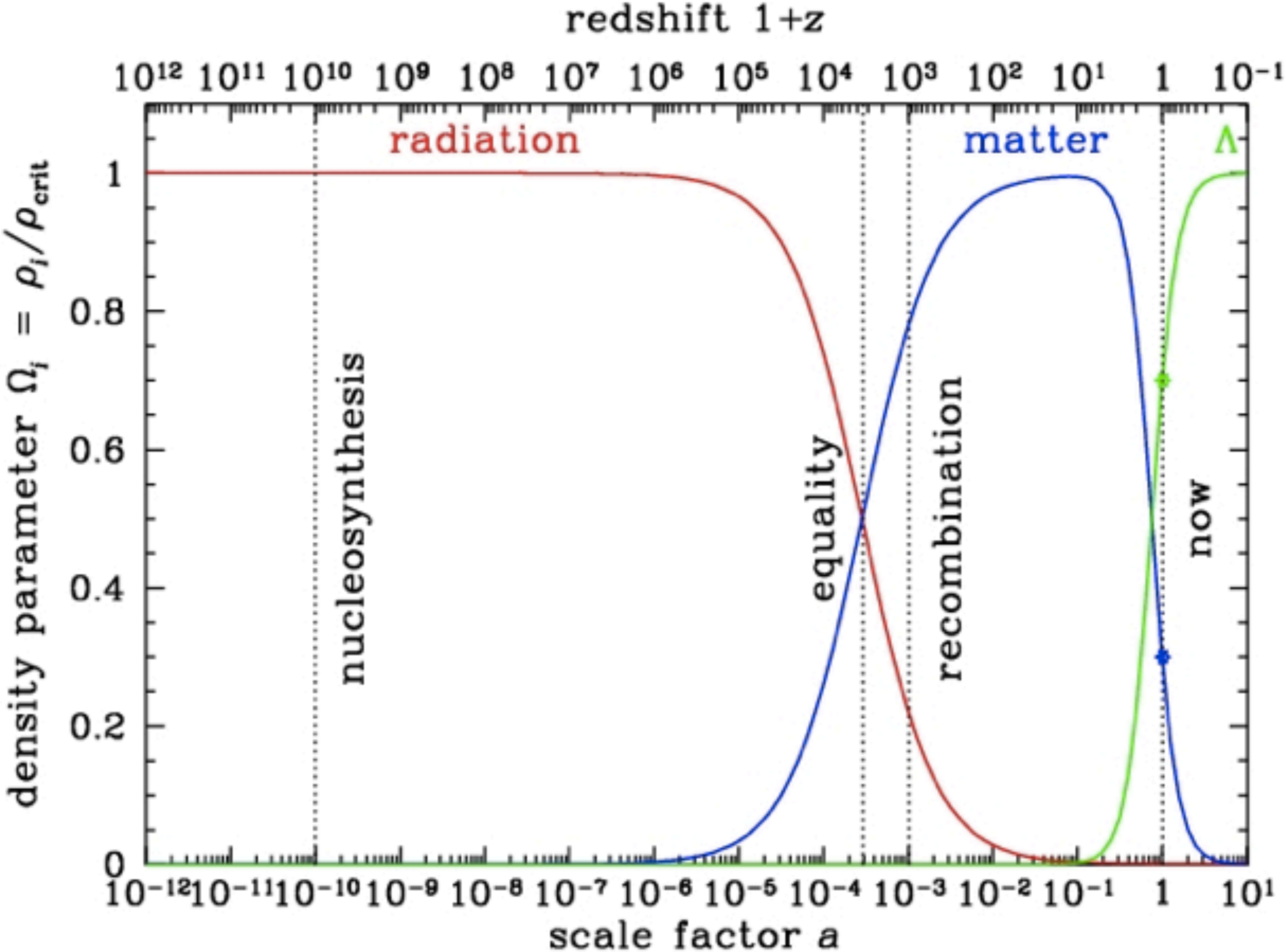
Why so small?

Why important just today?

Wetterich 1988, Ratra & Peebles 1988

… to dynamical dark energy

It can be thought of as a fluid with negative pressure that contrasts gravity and delays the formation of gravitational structures or equivalently as a modification of gravity



Plot by B. Fields

Challenge

$$\Lambda$$

Can we falsify or verify a cosmological constant?

Can we distinguish among the models present in literature?

Effects on OBSERVATIONS

Background

- Expansion
- Non negligible dark energy at early times (EDE)

Linear

- Shift of the peaks
- Change in baryon/DM ratio and BAO peaks
- Integrated Sachs-Wolfe (ISW)
- CMB-lensing

Non-linear

- Structure formations and halo number
- Galaxy and shape of voids distribution
- Density profiles
- Cross-correlation with CMB

Working in cosmology

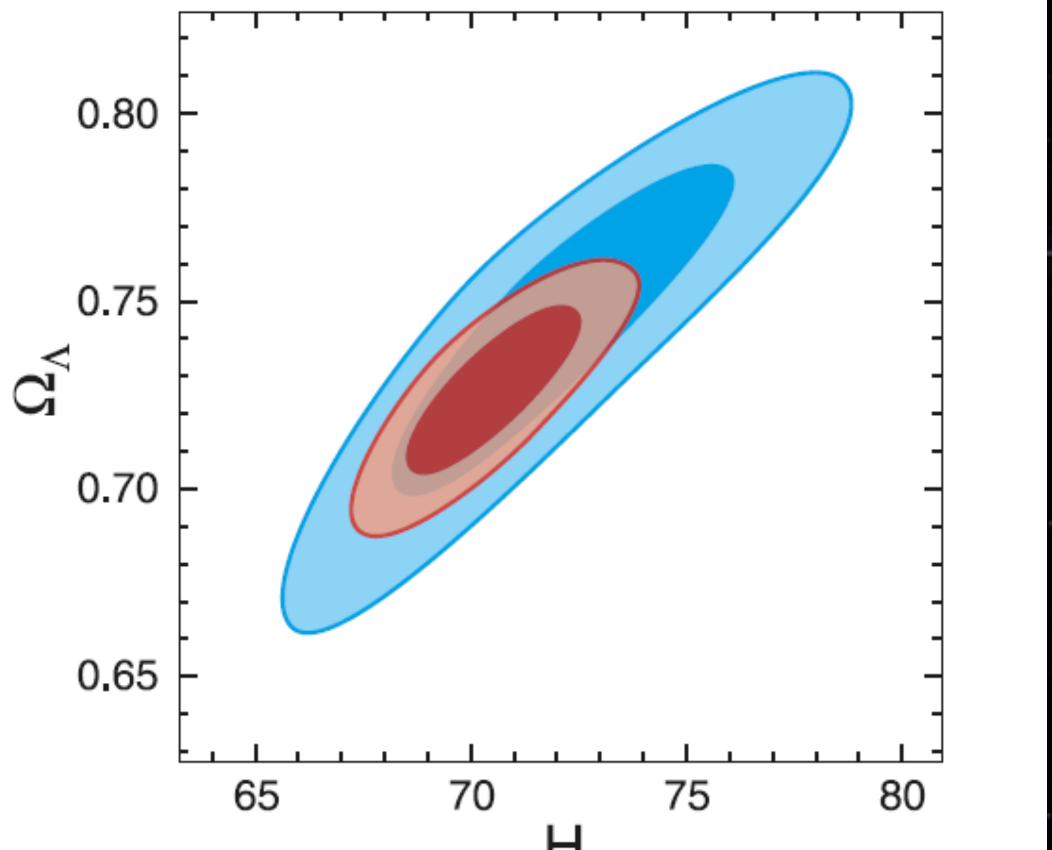
In practice, what do cosmologists do?

1. Theory: model building and equations that describe the evolution of expansion and perturbations in that model

$$
\begin{aligned}
\delta\rho_c' + 3\mathcal{H}\delta\rho_c + \bar{\rho}_c k v_c + 3\bar{\rho}_c\Phi' &= -C_c(\bar{\rho}_c\delta\phi' + \bar{\phi}'\delta\rho_c) \quad , \\
v_c' + (\mathcal{H} - C_c\bar{\phi}')v_c &= -k(\Phi + C_c\delta\phi) \quad , \\
\delta\rho_\phi' + 3\mathcal{H}(\delta\rho_\phi + \delta p_\phi) + k\bar{h}_\phi v_\phi + 3\bar{h}_\phi\Phi' &= C_c(\bar{\rho}_c\delta\phi' + \bar{\phi}'\delta\rho_c) \quad , \\
\bar{h}_\phi v_\phi' + (\bar{h}_\phi' + 4\mathcal{H}\bar{h}_\phi)v_\phi &= k\delta p_\phi - k\bar{h}_\phi\Phi + C_c k\bar{\rho}_c\delta\phi \\
\delta\rho_r' + 4\mathcal{H}\delta\rho_r + k\frac{4}{3}\bar{\rho}_r v_r + 4\bar{\rho}_r\Phi' &= 0 \quad , \\
\bar{\rho}_r v_r' - \frac{k}{4}\delta\rho_r &= -k\bar{\rho}_r\Phi \quad ,
\end{aligned}
$$

2. Phenomenology and programming: numerically solve the equations to estimate the prediction of model on observables

3. Statistical analysis and comparison of predictions with different data sets



Komatsu etal 2008

Experiments

In practice, what do cosmologists do?

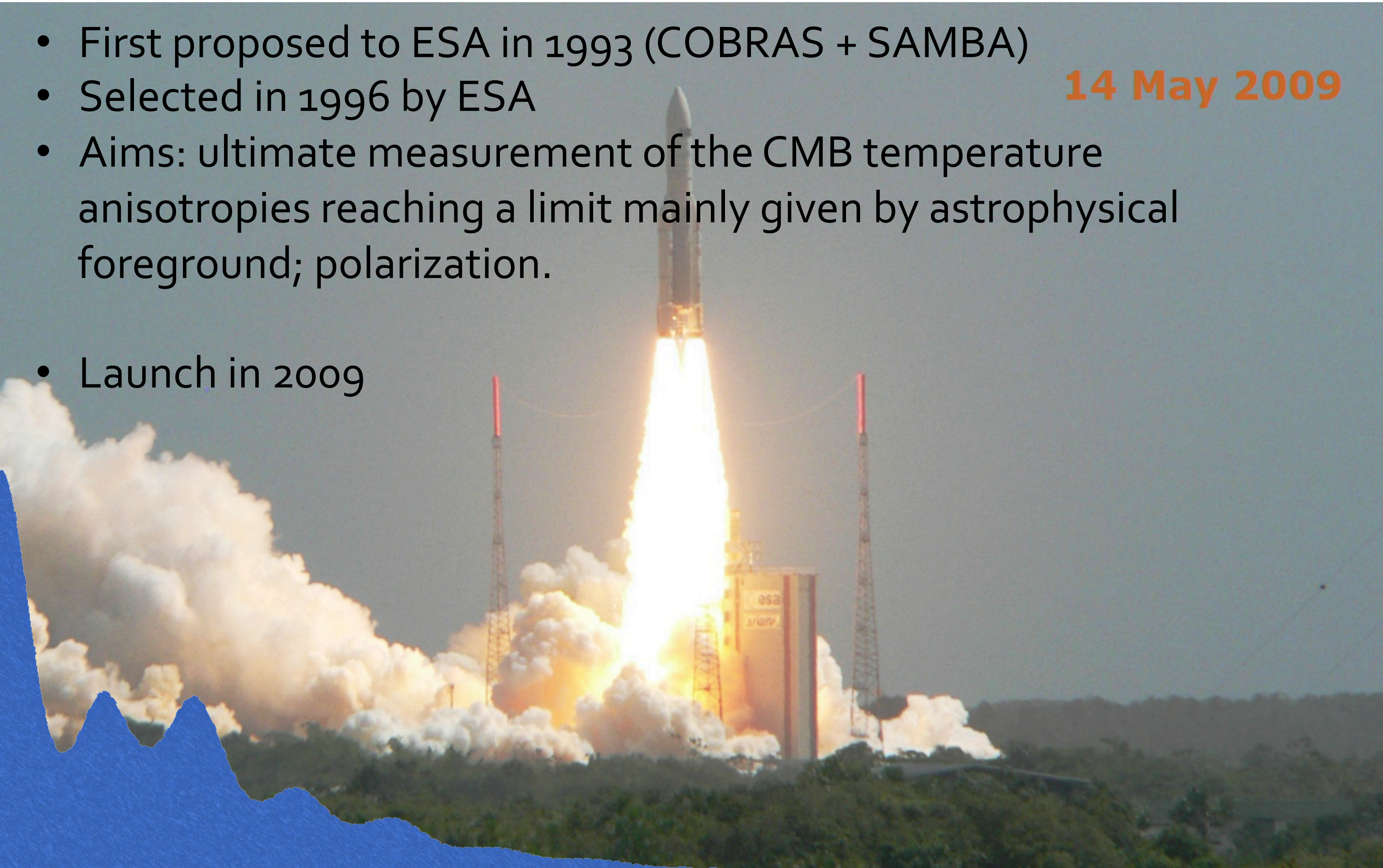
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

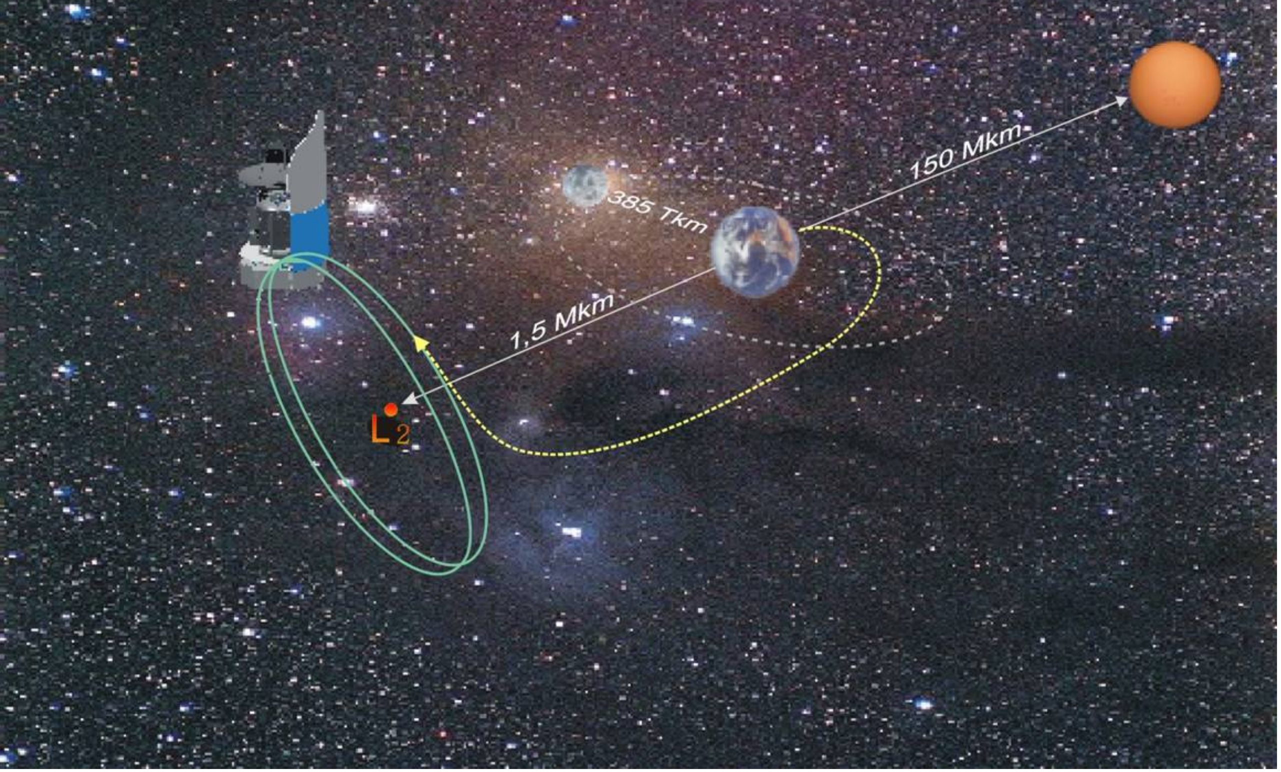
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

The Planck project

- First proposed to ESA in 1993 (COBRAS + SAMBA)
- Selected in 1996 by ESA
- Aims: ultimate measurement of the CMB temperature anisotropies reaching a limit mainly given by astrophysical foreground; polarization.

- Launch in 2009



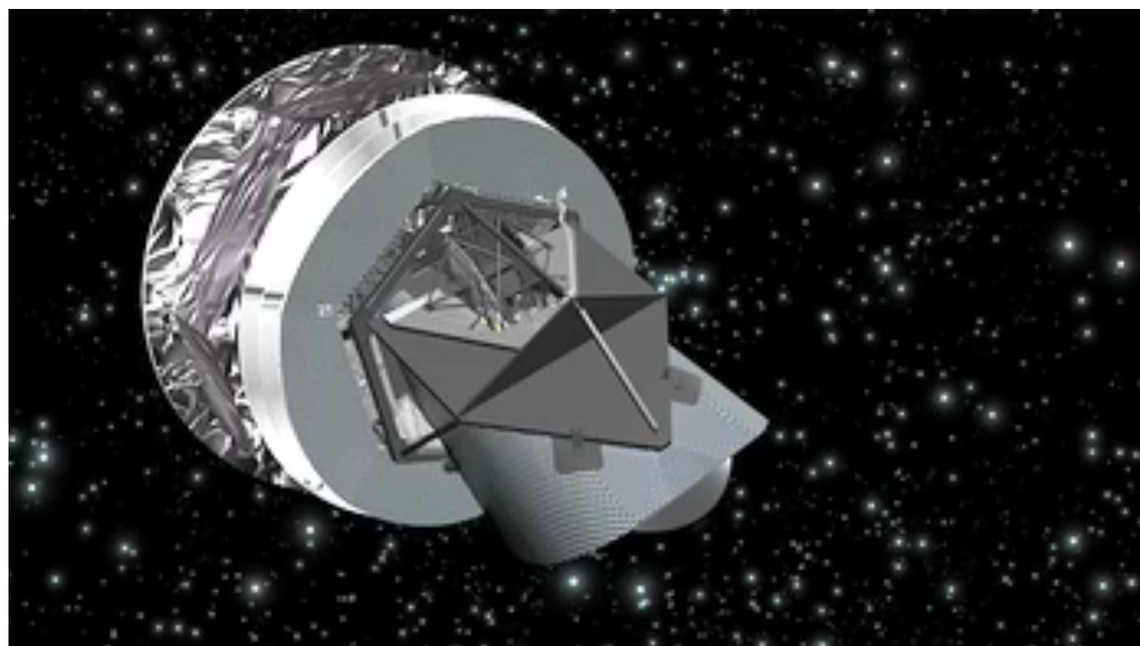


- Nominal mission completed in November 2010 (15.5 months). In practice, twice the nominal mission (full surveys: 5 HFI; 8 LFI)

(2013 data release is based on the nominal mission)

Placed in orbit around L2. Scans the entire sky twice per year.
The spacecraft spins with 1 rotation per minute, tracing circles on the celestial sphere.

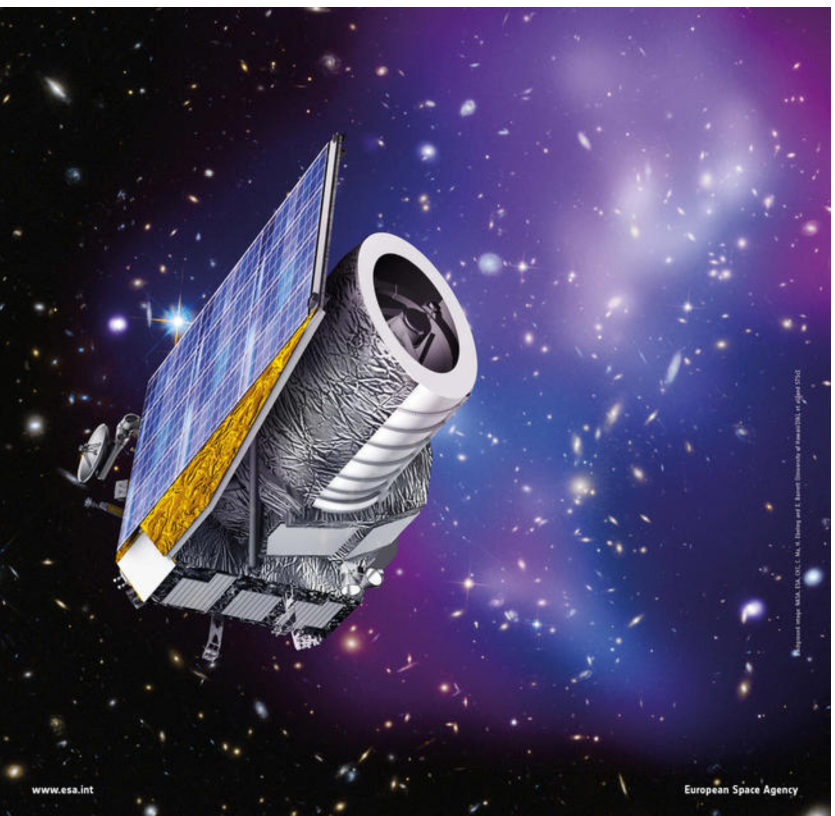
Multiple passes over same sky by each detector at each position of the axis.



What next?

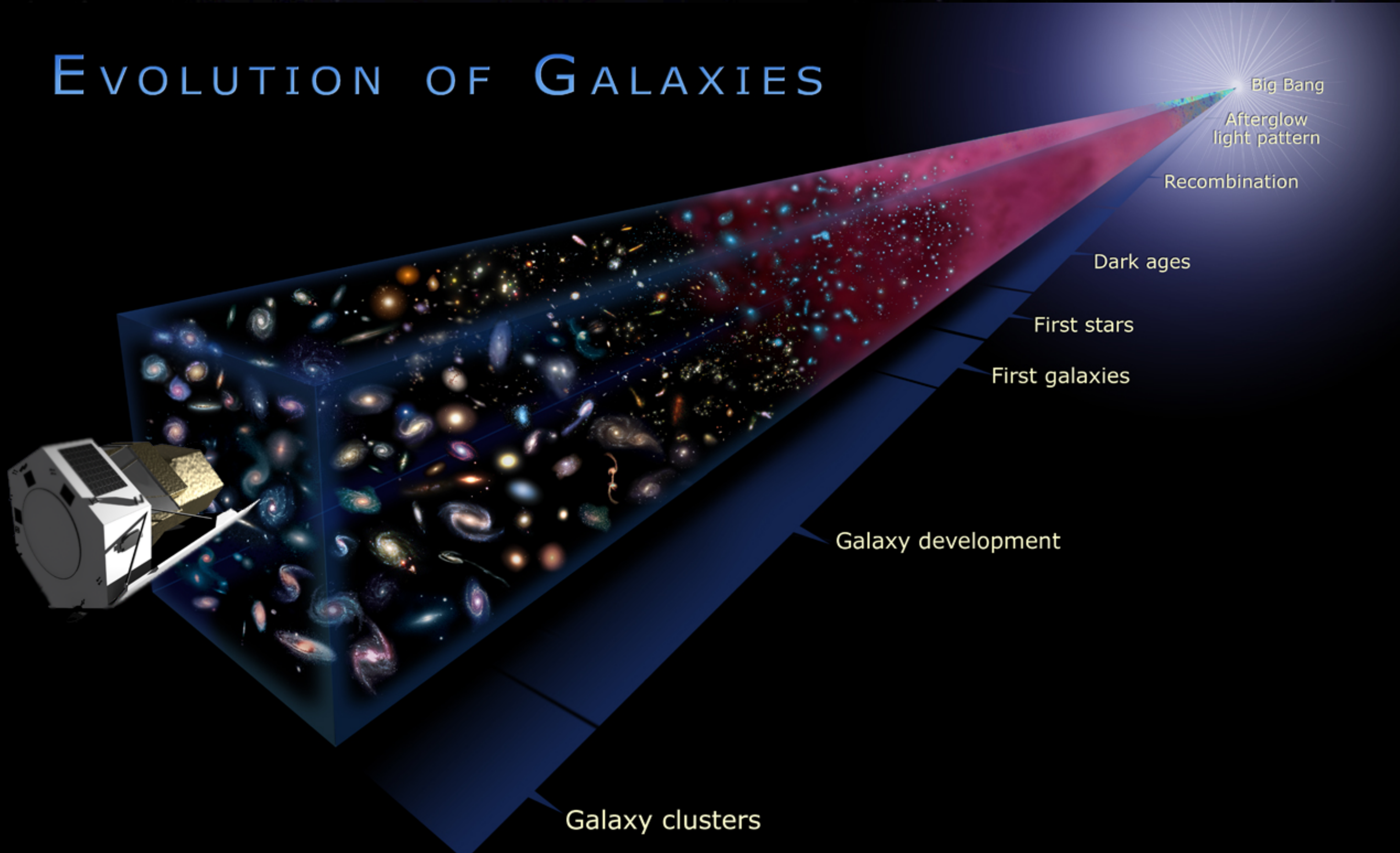
What is Euclid?

ESA medium class space mission selected in the program
Cosmic Vision 2015-2025



Launch in 2021: measures 1.5 billion shapes of galaxies and distances (z) of millions of galaxies
Telescope of 1.2 m with a detector in the visible and one in the infrared

Laureijs etal 2011, Refregier 2009, Cimatti etal 2009



two complementary cosmological probes to capture signatures of the expansion rate of the Universe and the growth of cosmic structures: weak gravitational Lensing and Galaxy Clustering

Euclid primary probes

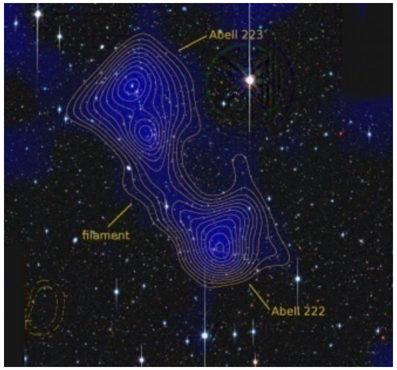
HST/ACS credit NASA/ESA

Galaxy halos

HST/ACS; credit NASA/ESA

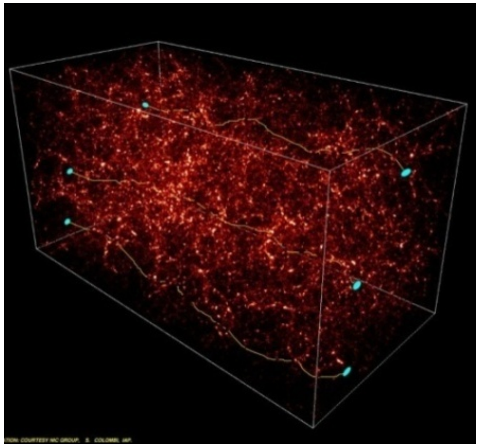
Clusters of galaxies

Dietrich et al 2012



Filaments between clusters

Colombi/Mellier



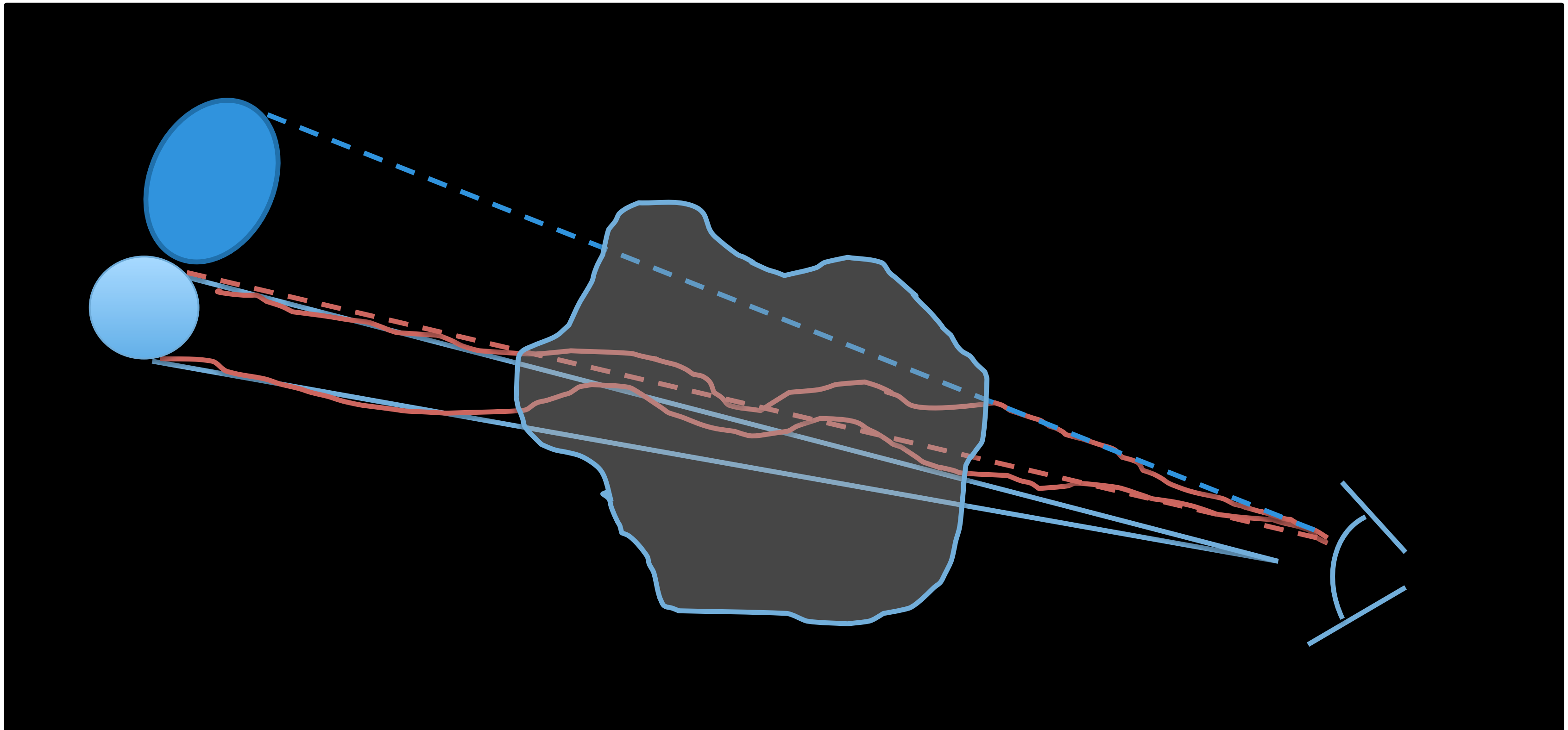
Cosmic shear

CMB cross correlation with LSS, Supernovae, abundance of clusters, strong lensing, simulations

Galaxy clustering

Weak Lensing

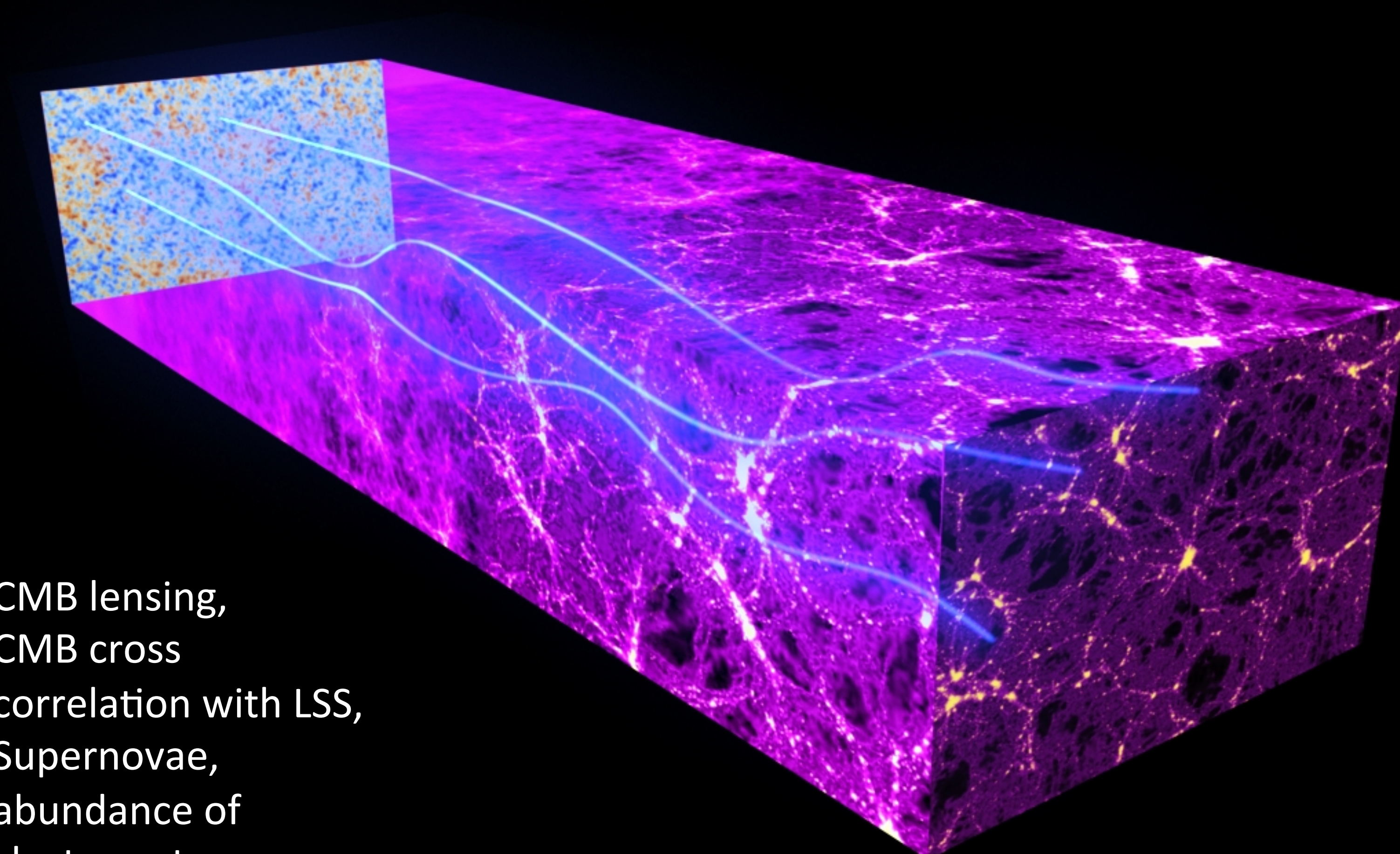
Weak lensing



The image of the galaxy is related to its true shape via convergence (modifies the size) and shear (distorts the shape)

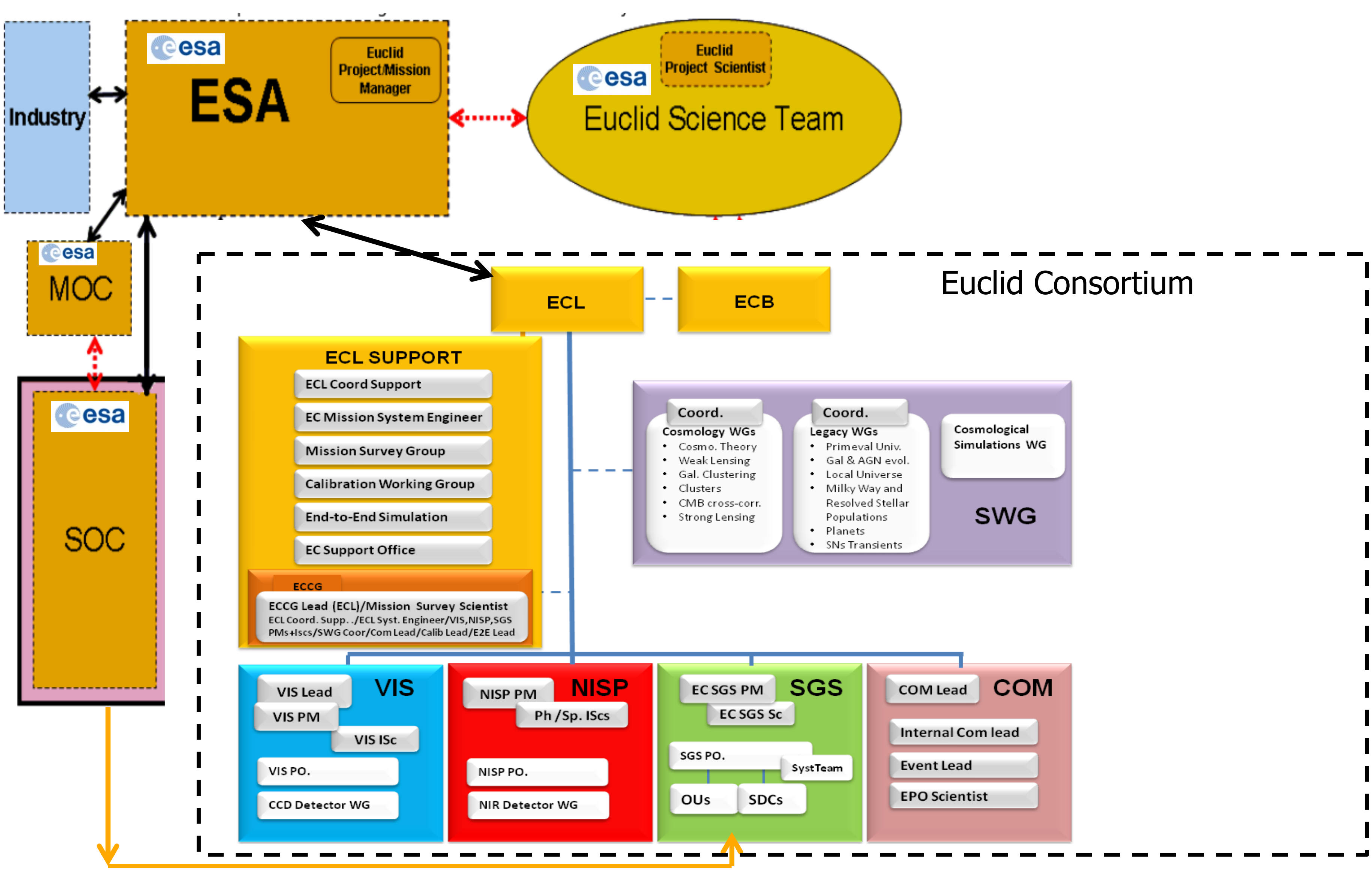
Related to the two gravitational potentials and used to test gravity

Gravitational lensing of the CMB



CMB lensing,
CMB cross
correlation with LSS,
Supernovae,
abundance of
clusters, strong
lensing, simulations

Euclid Consortium



Courtesy of Yannick Mellier

https://www.euclid-ec.org

> 1400 members, > 120 Labs

- 13 European countries: Austria, Denmark, France, Finland, Germany, Italy, The Netherlands, Norway, Portugal, Romania, Spain, Switzerland, UK + US/NASA and Berkeley labs, …

(updated list on the Consortium Website)

Consortium Meeting in London, May 2017

Polarization spectra