Comprendre l'infiniment grand:

cosmology and large scales in the Universe

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Overview of standard cosmology

Cosmological principle, isotropy and homogeneity

Distances: Hubble law and expansion of the Universe

Abundances of light elements

Background Cosmology in General Relativity

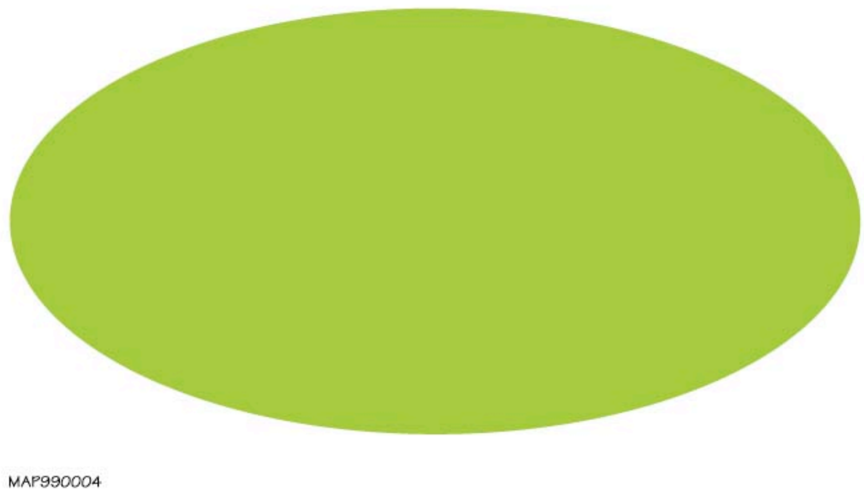
Supernovae and Cosmic acceleration

Cosmic Microwave Background

Structure formation

The Dark Universe

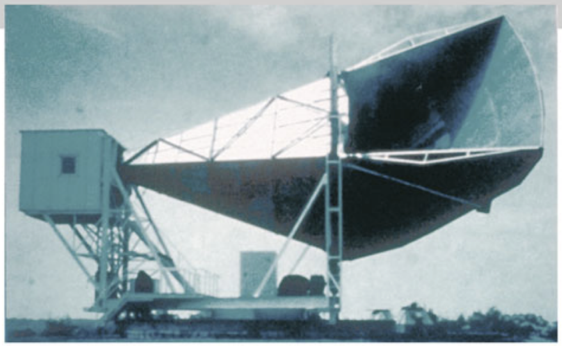
Cosmic Microwave Background: relic light from the Big Bang

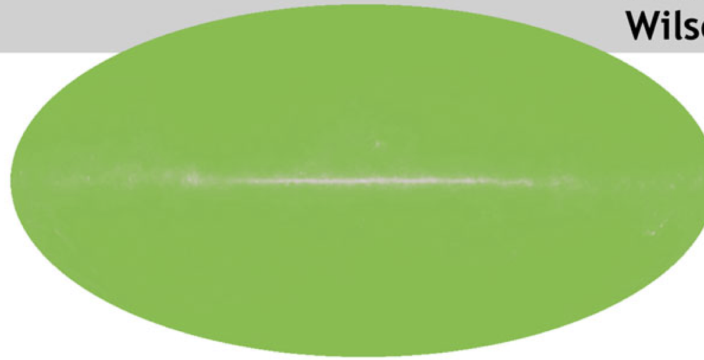


Light emitted 380.000 yrs (z = 1090) after the Big Bang, now in the microwave

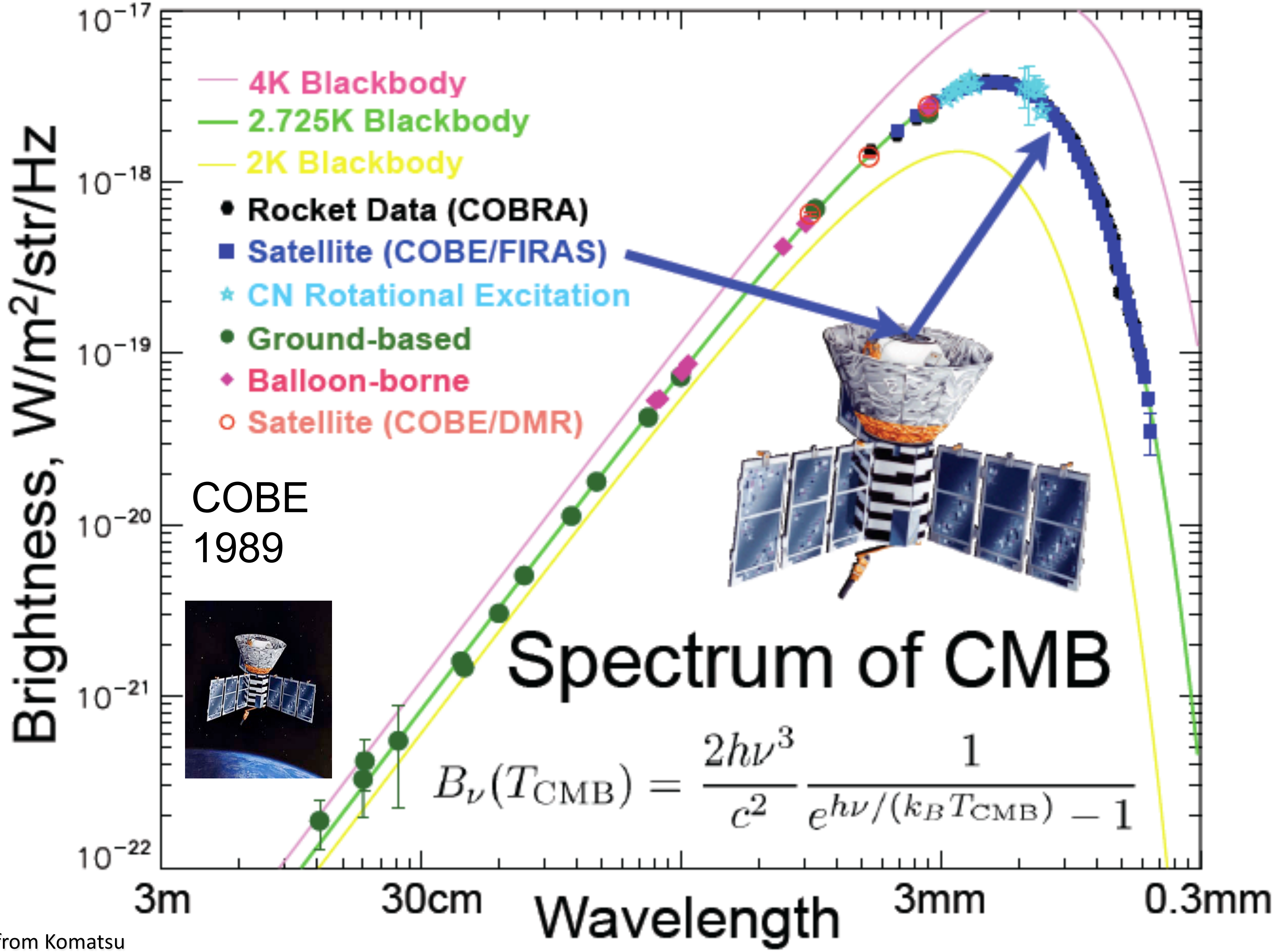
It looks (almost) the same in every direction

1965 | Penzias and Wilson

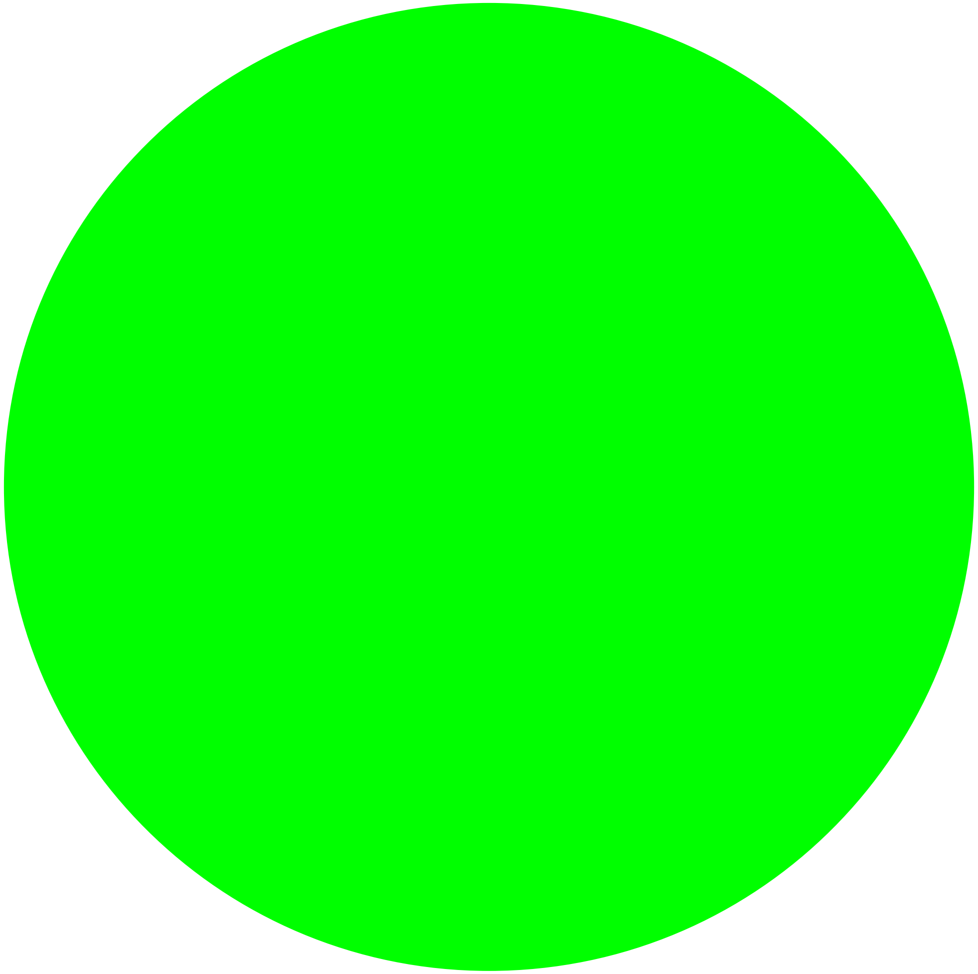




- Predicted in 1948 (Ralph lpher, Robert Herman, G. Gamow)
- First observed in 1965 by Penzias & Wilson at the Bell Telephone Laboratories in New Jersey. The radiation was acting as a source of excess noise in a radio receiver they were building.
- Researchers (Robert Dicke, Dave Wilkinson, Peebles,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

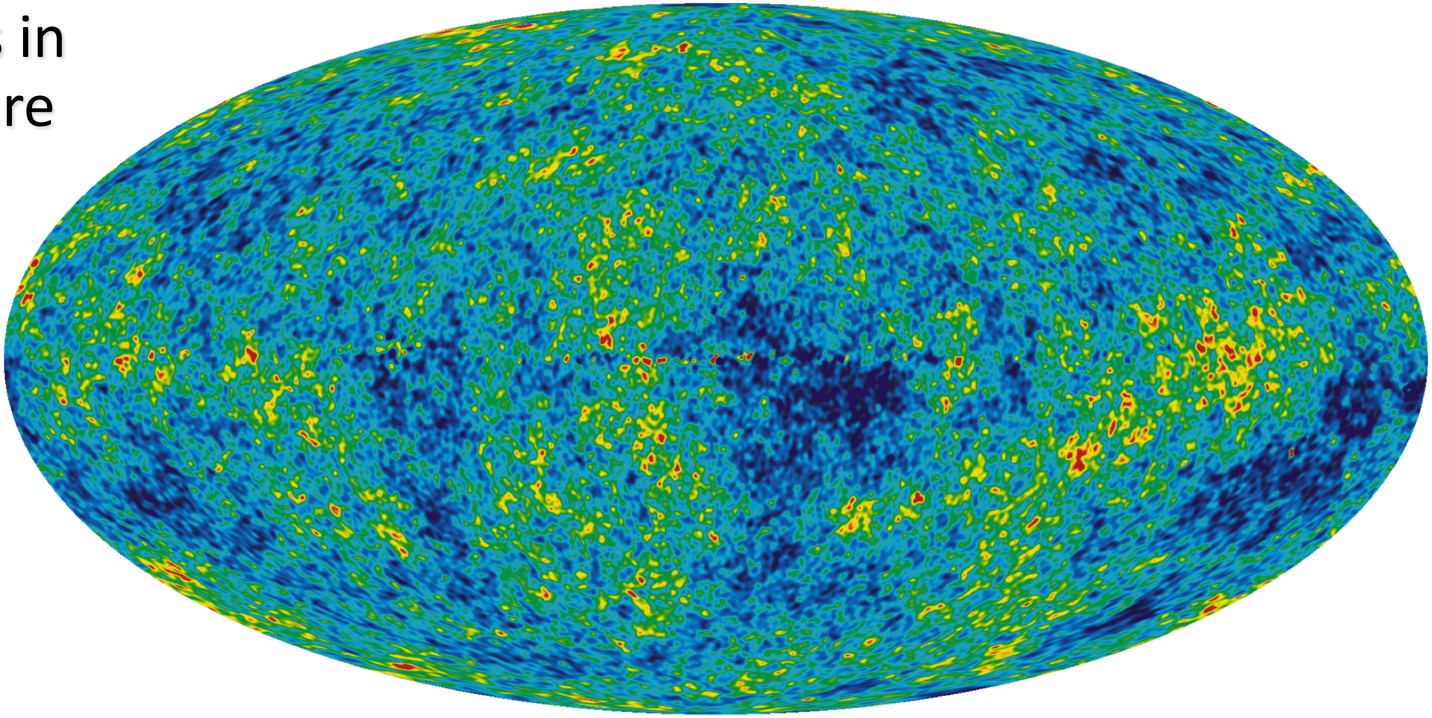


Plot from Komatsu



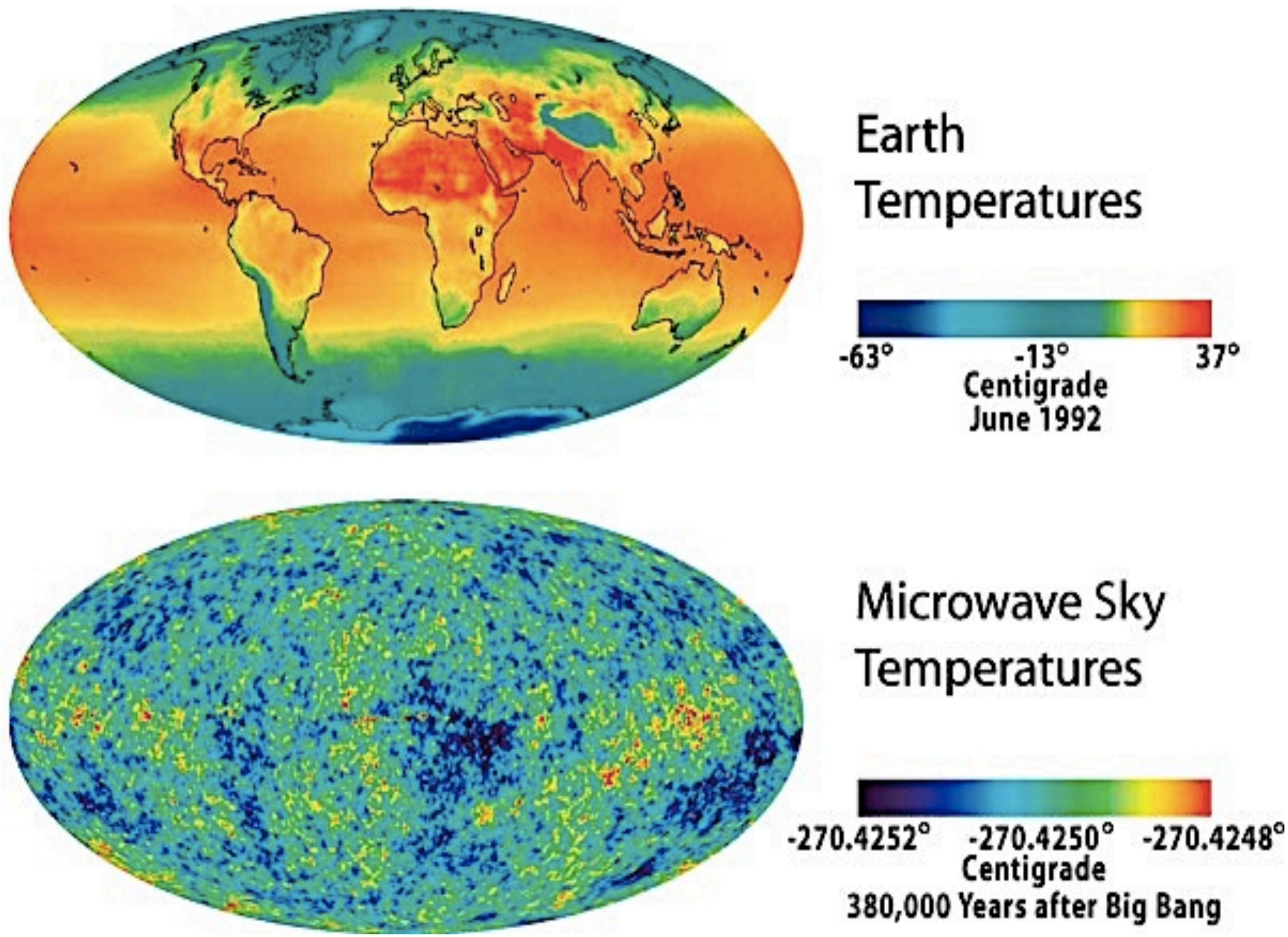
CMB anisotropies

Colours indicate differences in temperature

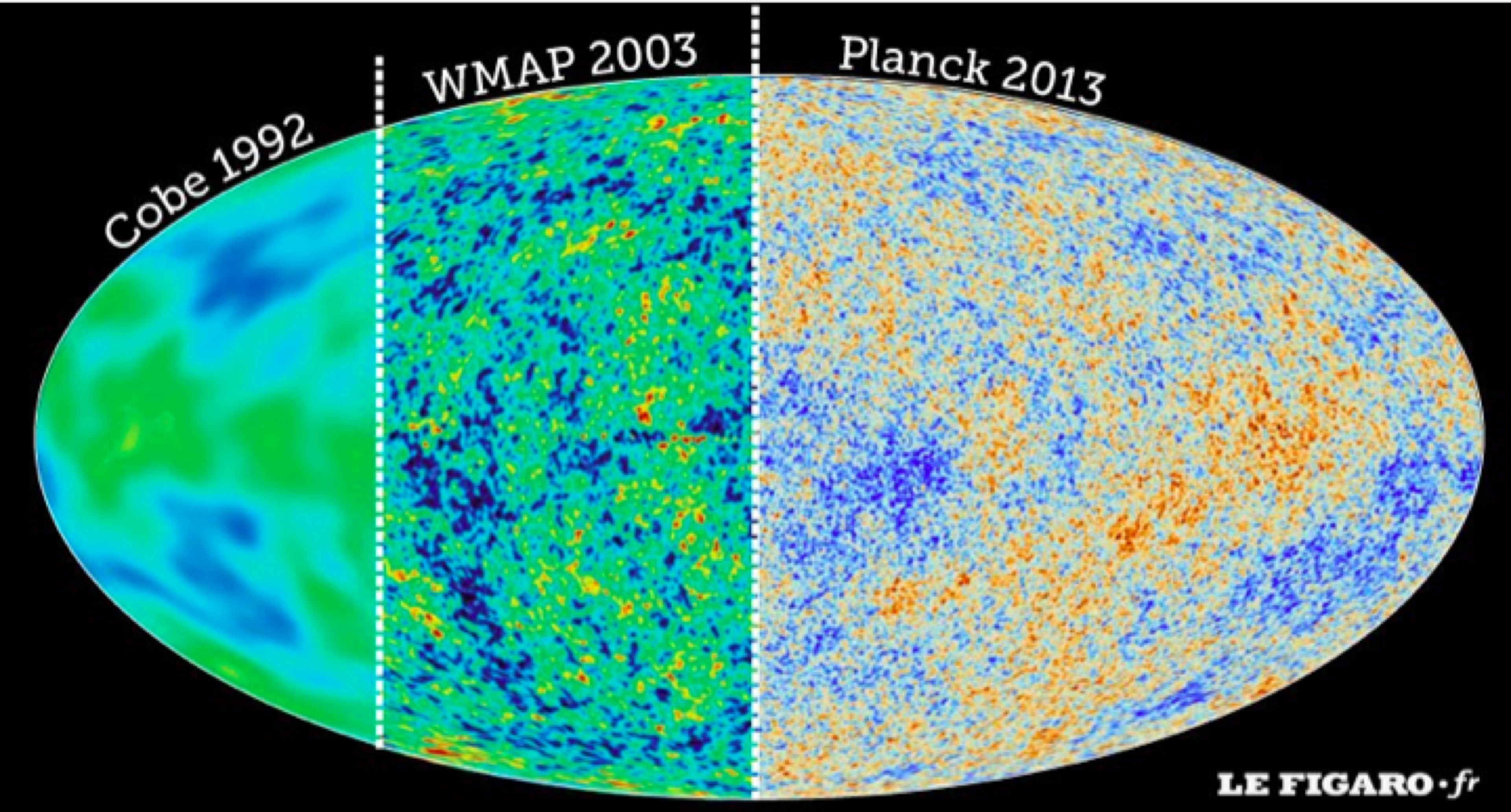


If you look at angles of about 1 degree or smaller you see anisotropies

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

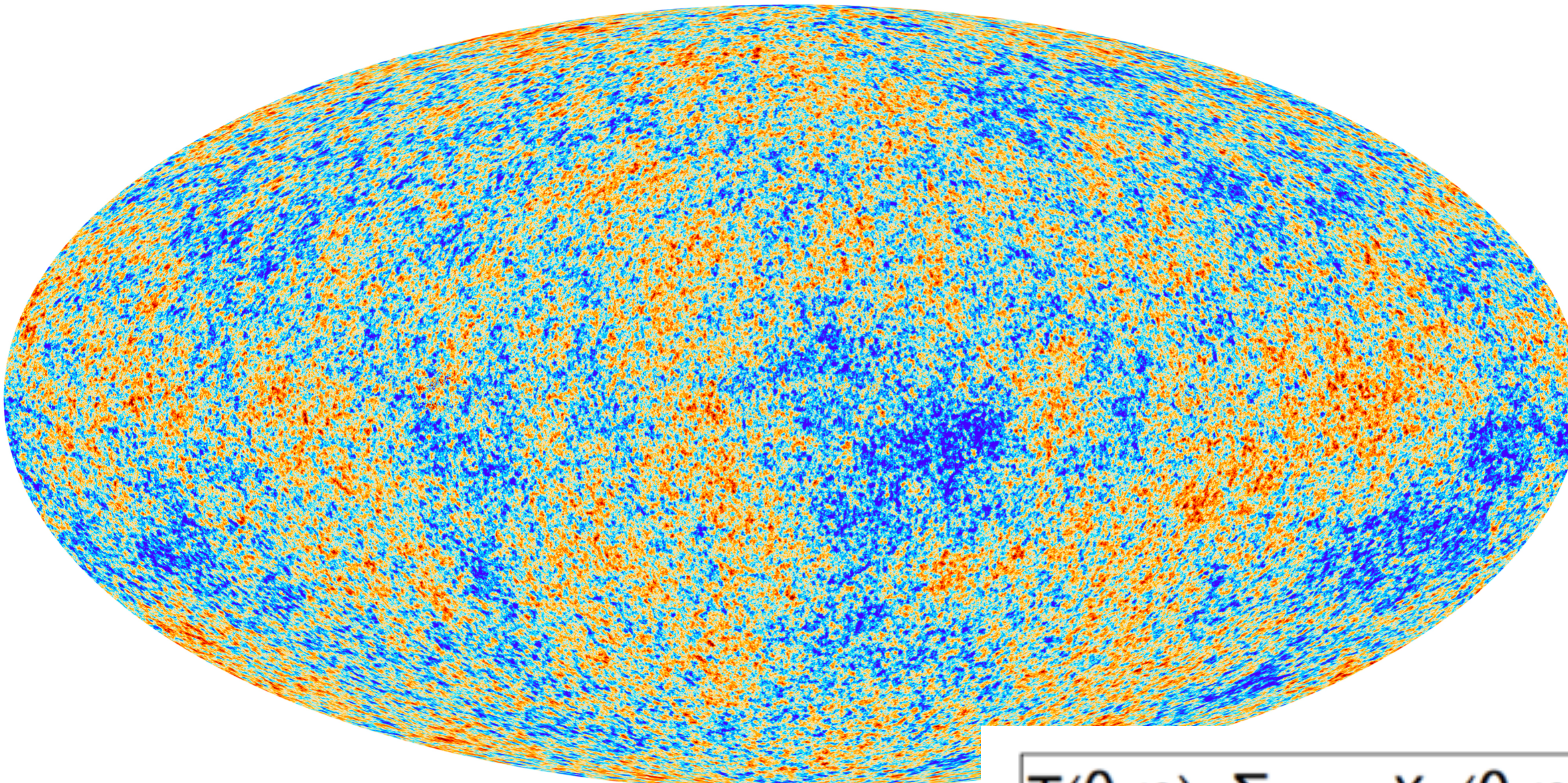


Deviations from black body are of order 10^{-5}


Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO·fr

Map of the CMB anisotropies

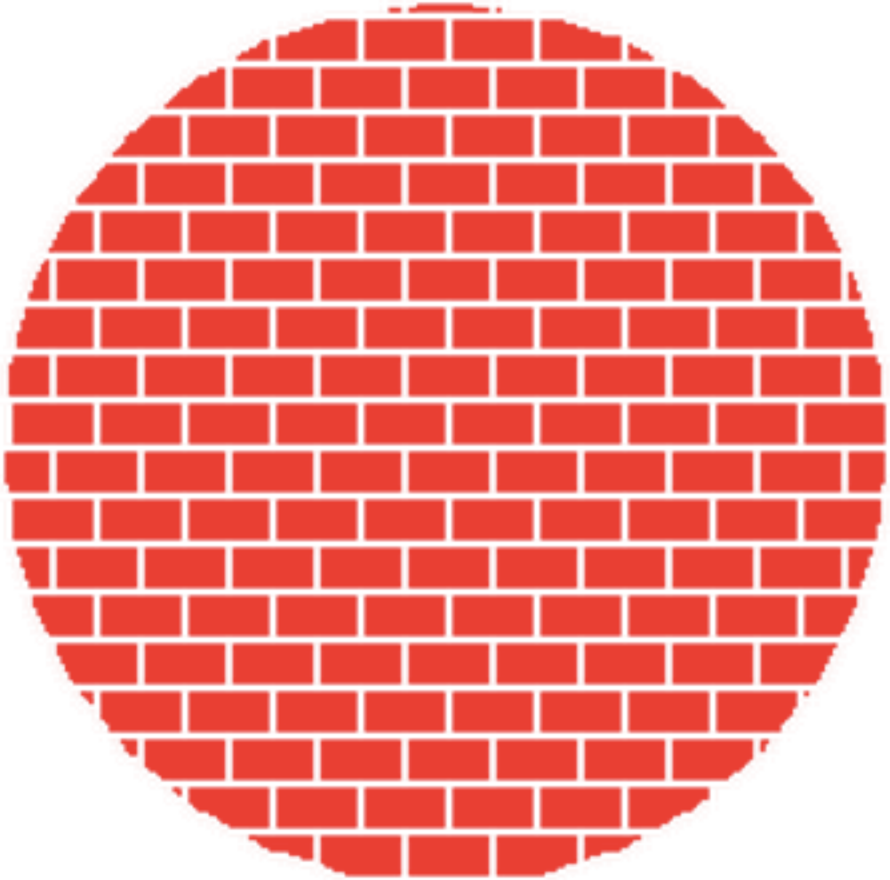
https://www.facebook.com/EuropeanSpaceAgency/photos/a.380701205666.166436.54912575666/10156276517485667/?type=3&theater

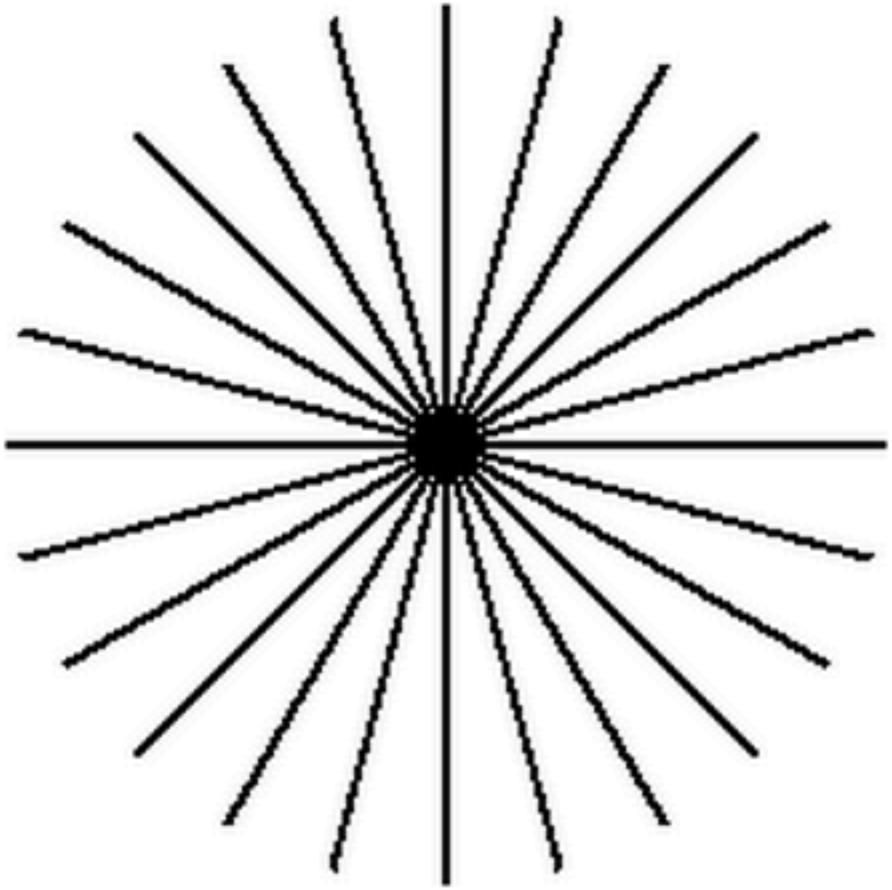


$$T(\theta,\varphi)=\sum_{lm} a_{lm} Y_{lm}(\theta,\varphi)$$

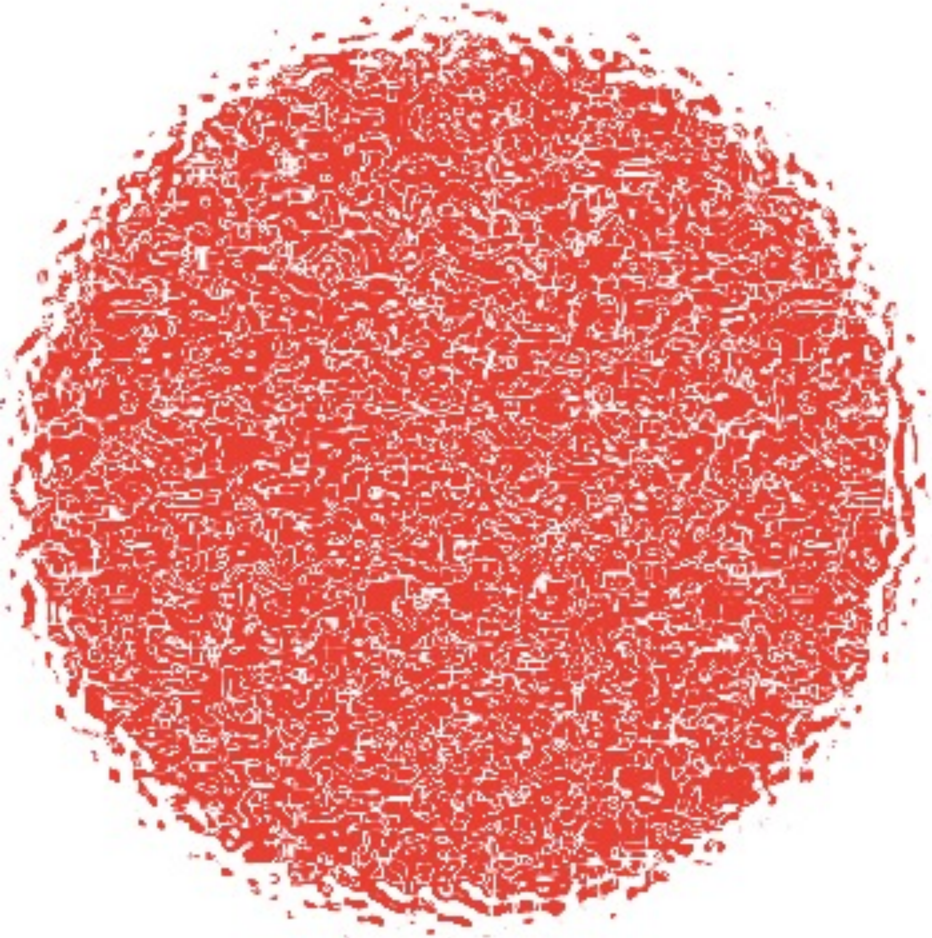
Start from a homogeneous and isotropic Universe

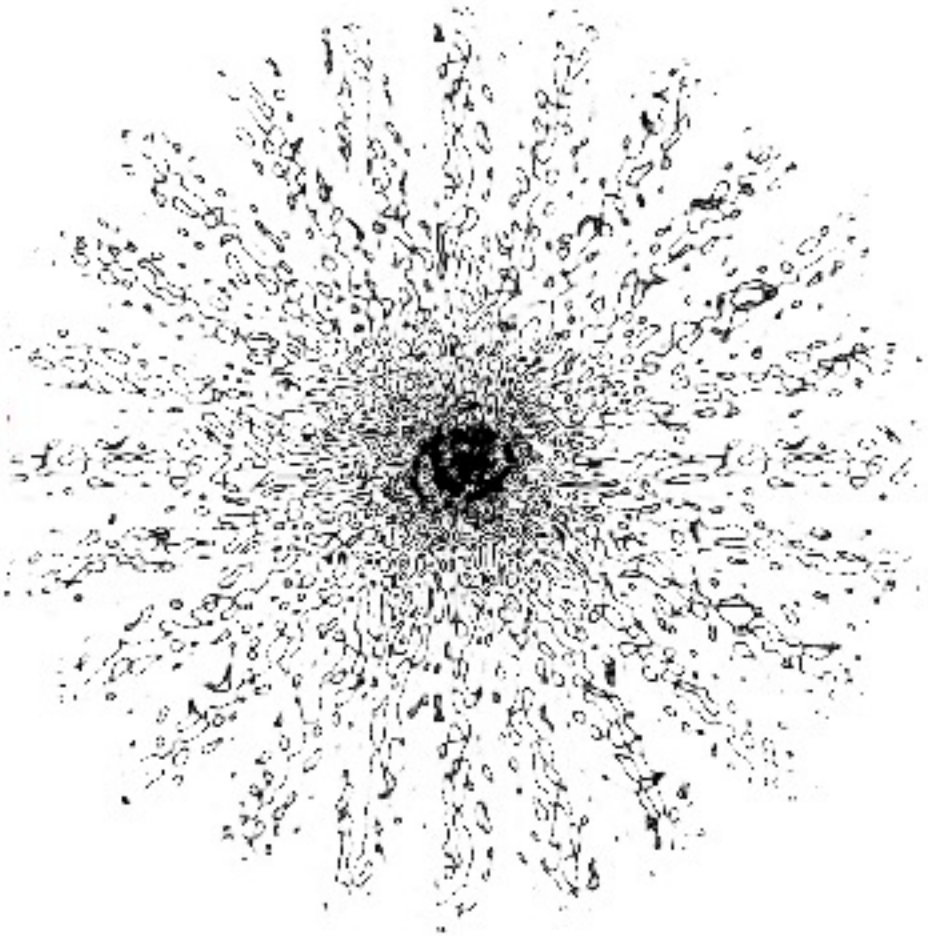
Study small (linear) perturbations around it for all species



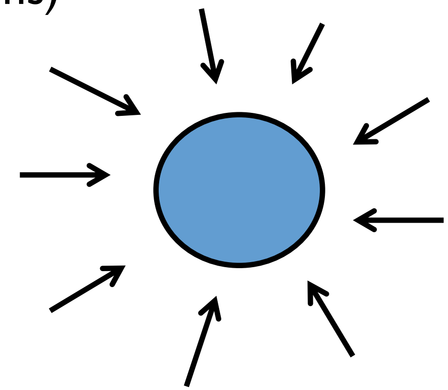


Picture from Ned Wright's Cosmology Tutorial



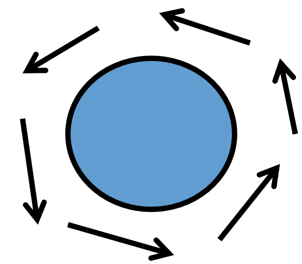


Scalar perturbations (ex. density and temperature fluctuations)



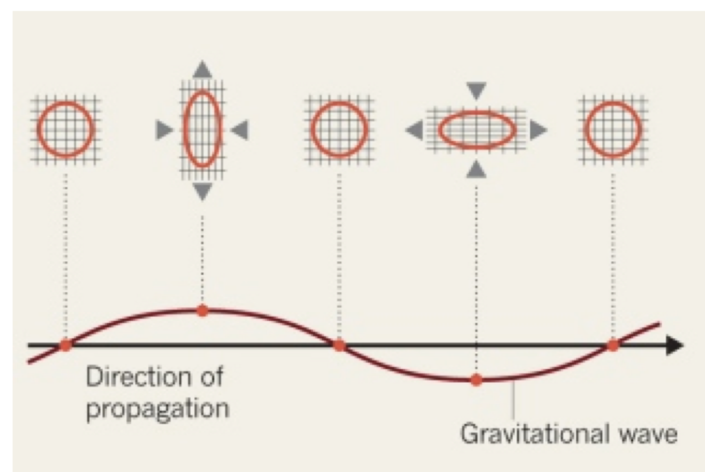
Vector perturbations:

- 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

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

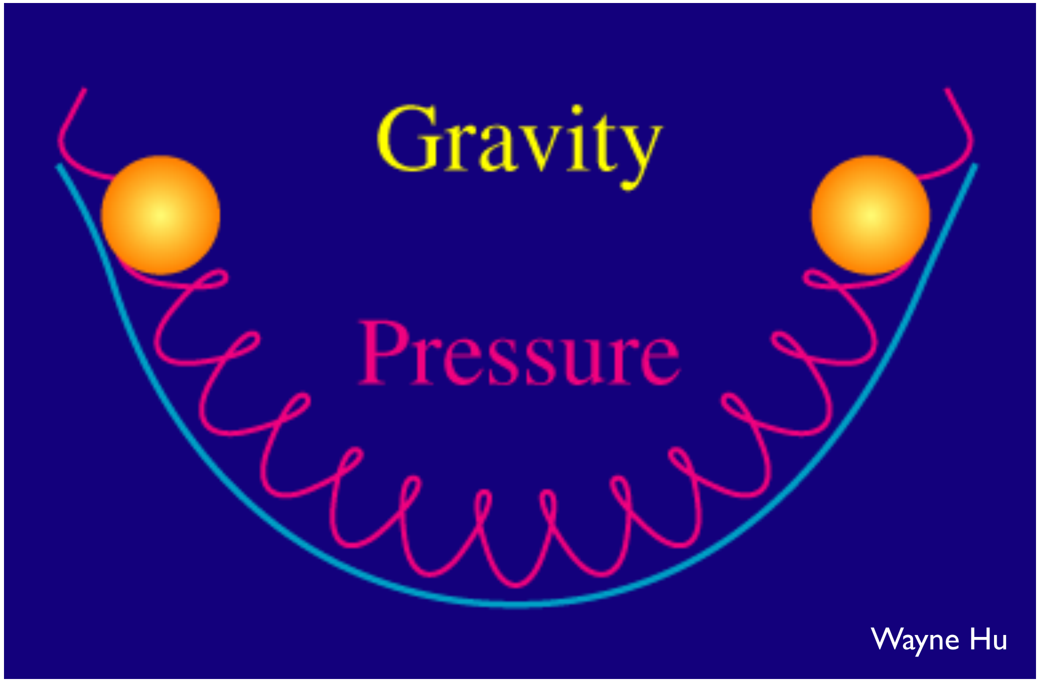
$$T_{\mu\nu}^{;\nu} = 0 \quad \begin{cases} \bar{T}_{\mu\nu}^{;\nu} = 0 \\ \delta T_{\mu\nu}^{;\nu} = 0 \end{cases}$$

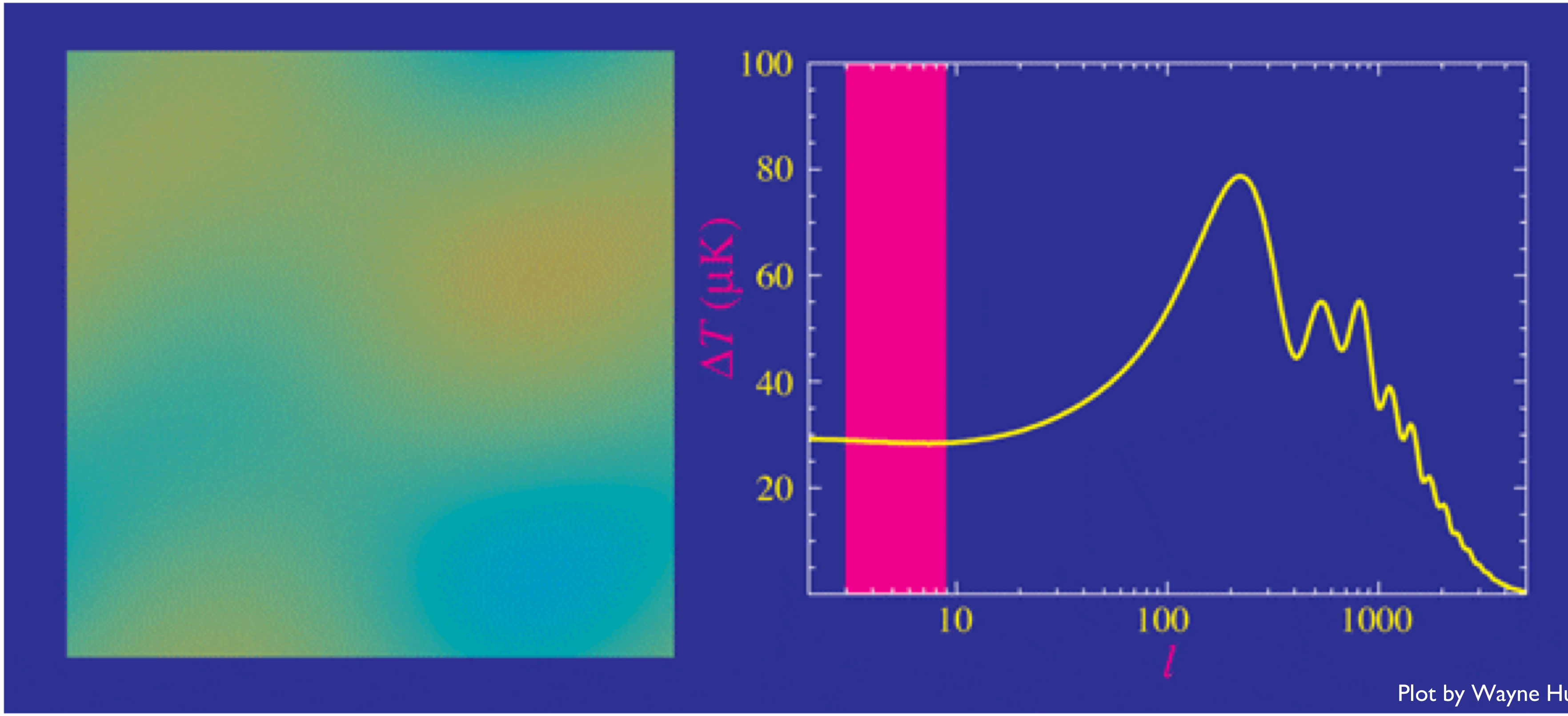
Sound waves

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

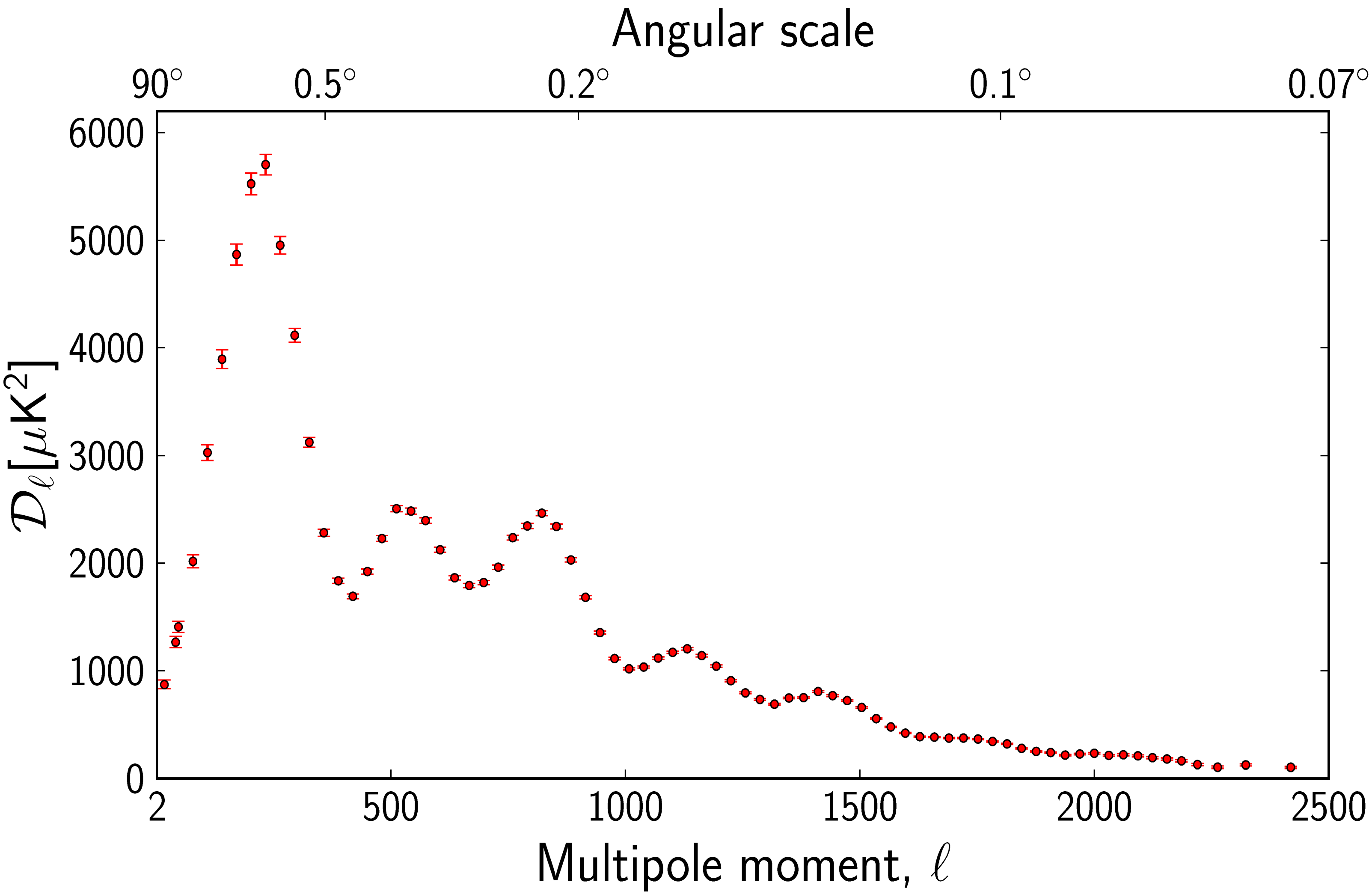
The tight coupling between baryons and photons produce oscillations in the plasma.

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



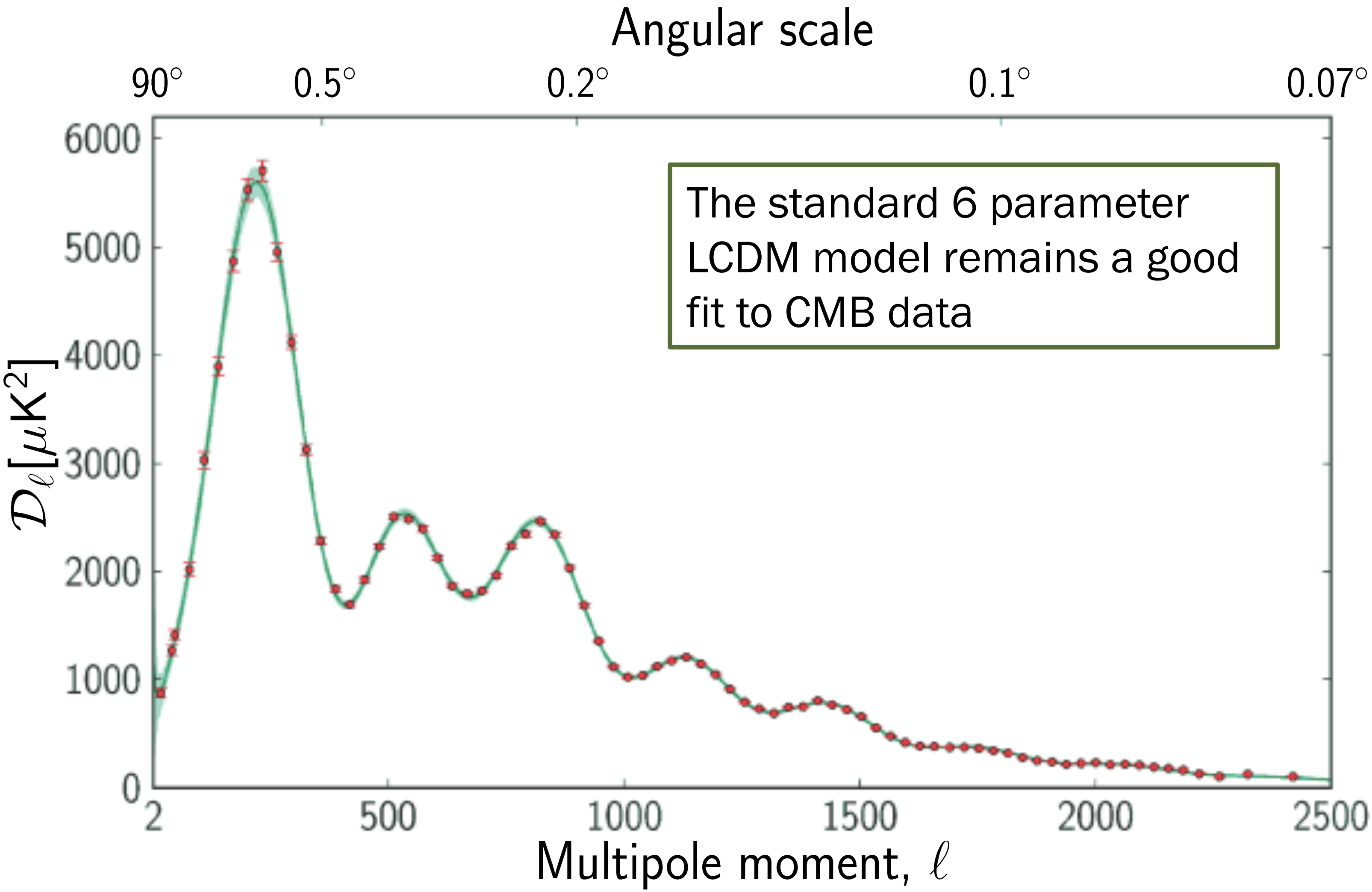

100
80
60
40
20
ΔT (μK)
10
100
1000
l
Plot by Wayne Hu

Power spectrum



ΛCDM is a very good fit

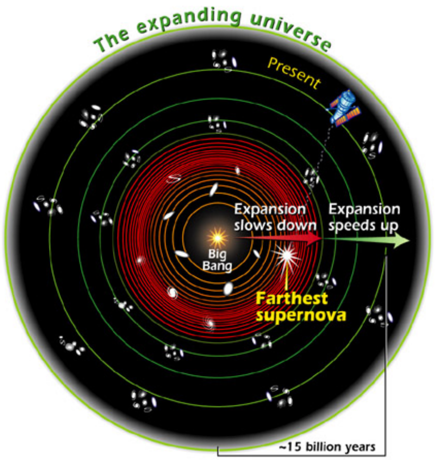
https://map.gsfc.nasa.gov/resources/camb_tool/



Quite impressive. From terabytes of data to 6 parameters

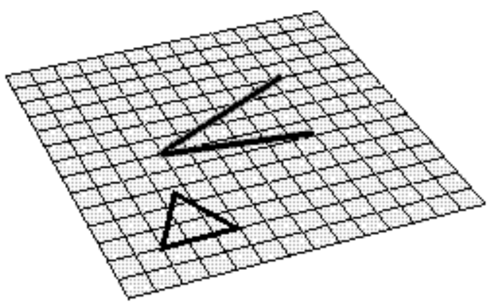
Ingredients of the Universe

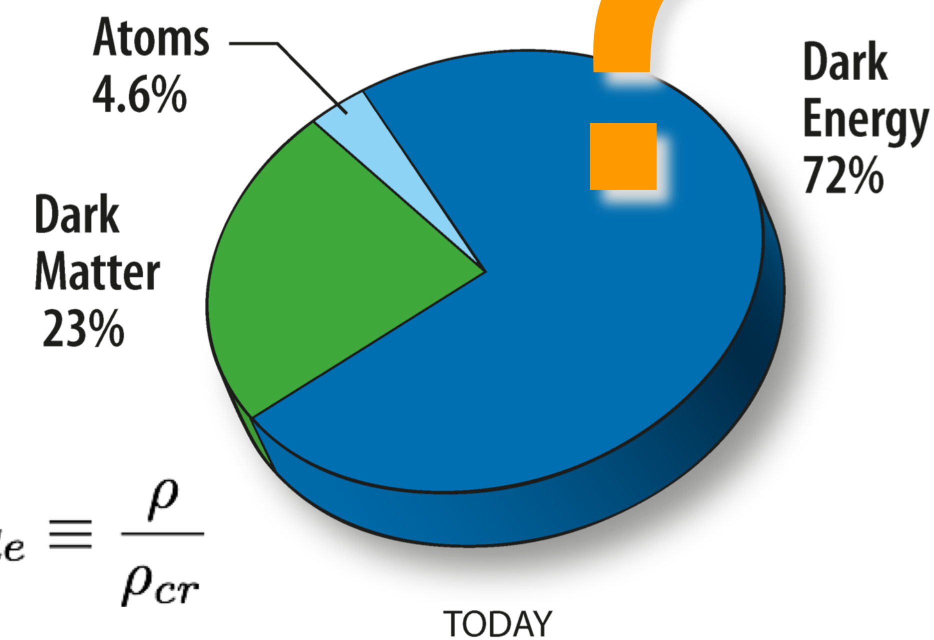
$$\Omega_i \equiv \frac{\rho_i}{\rho_{cr}}$$



Accelerated expansion

Flatness





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

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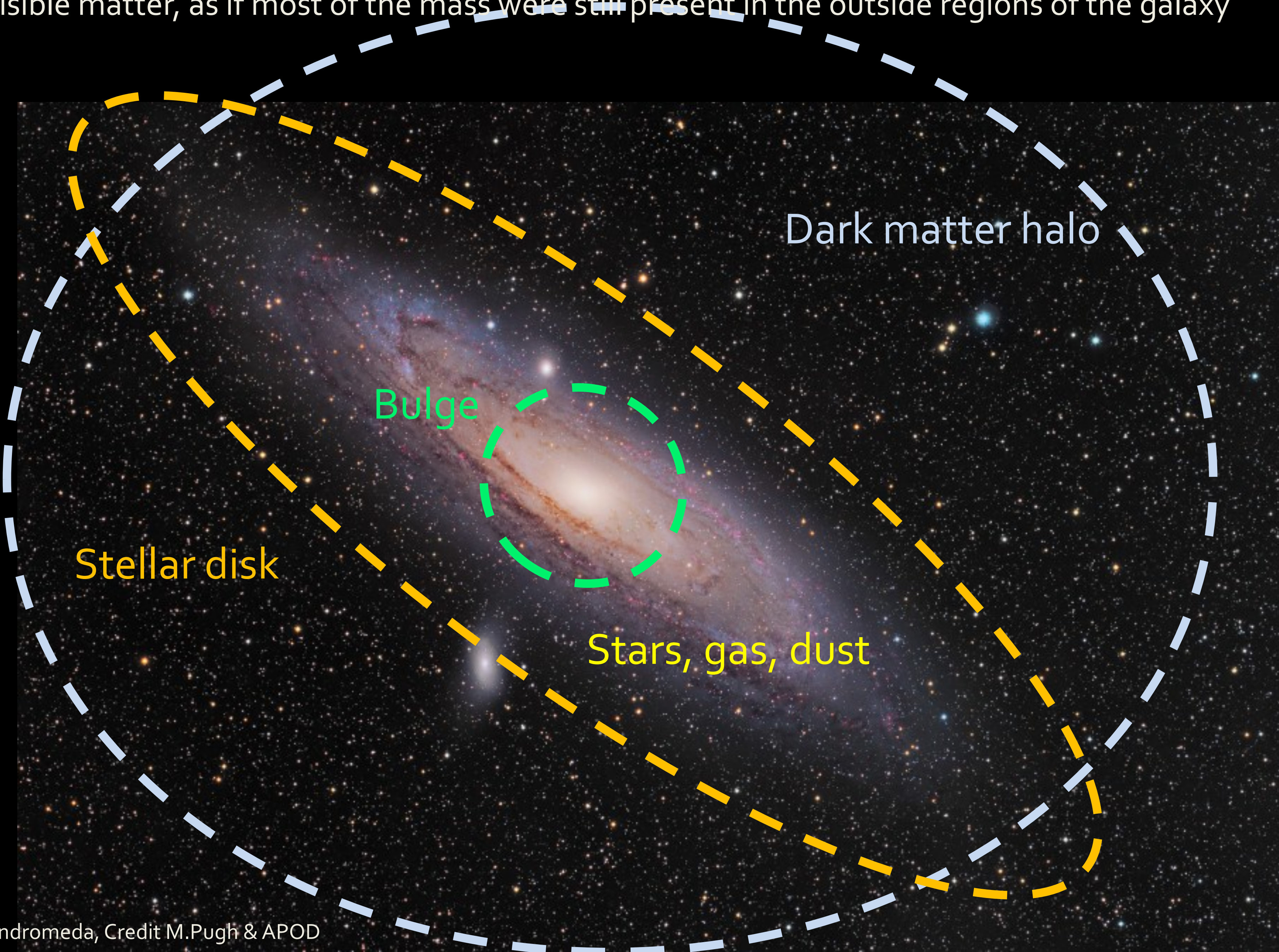
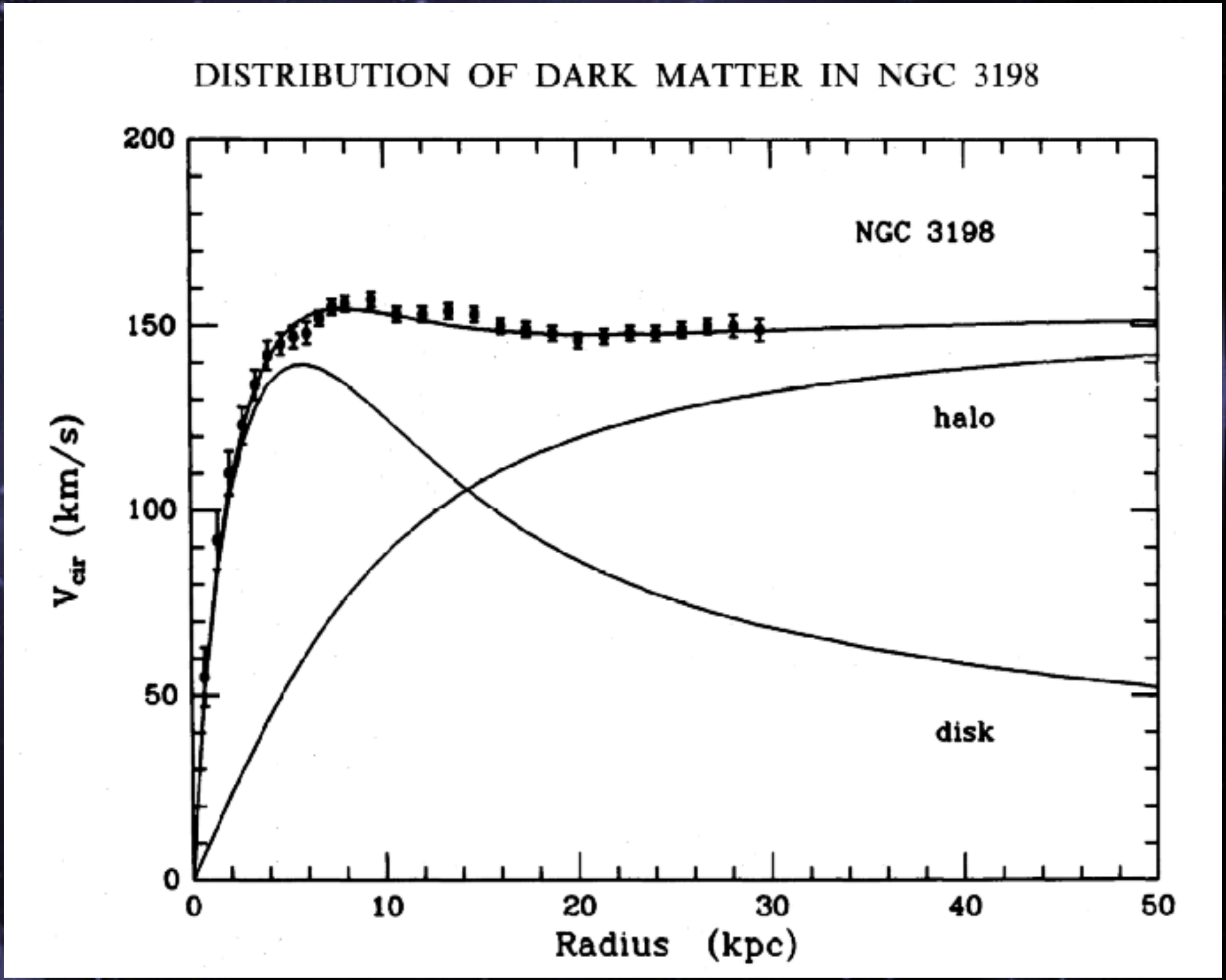
Spiral galaxies: at large radial scales, they keep rotating fast; faster than if there were only visible matter, as if most of the mass were still present in the outside regions of the galaxy



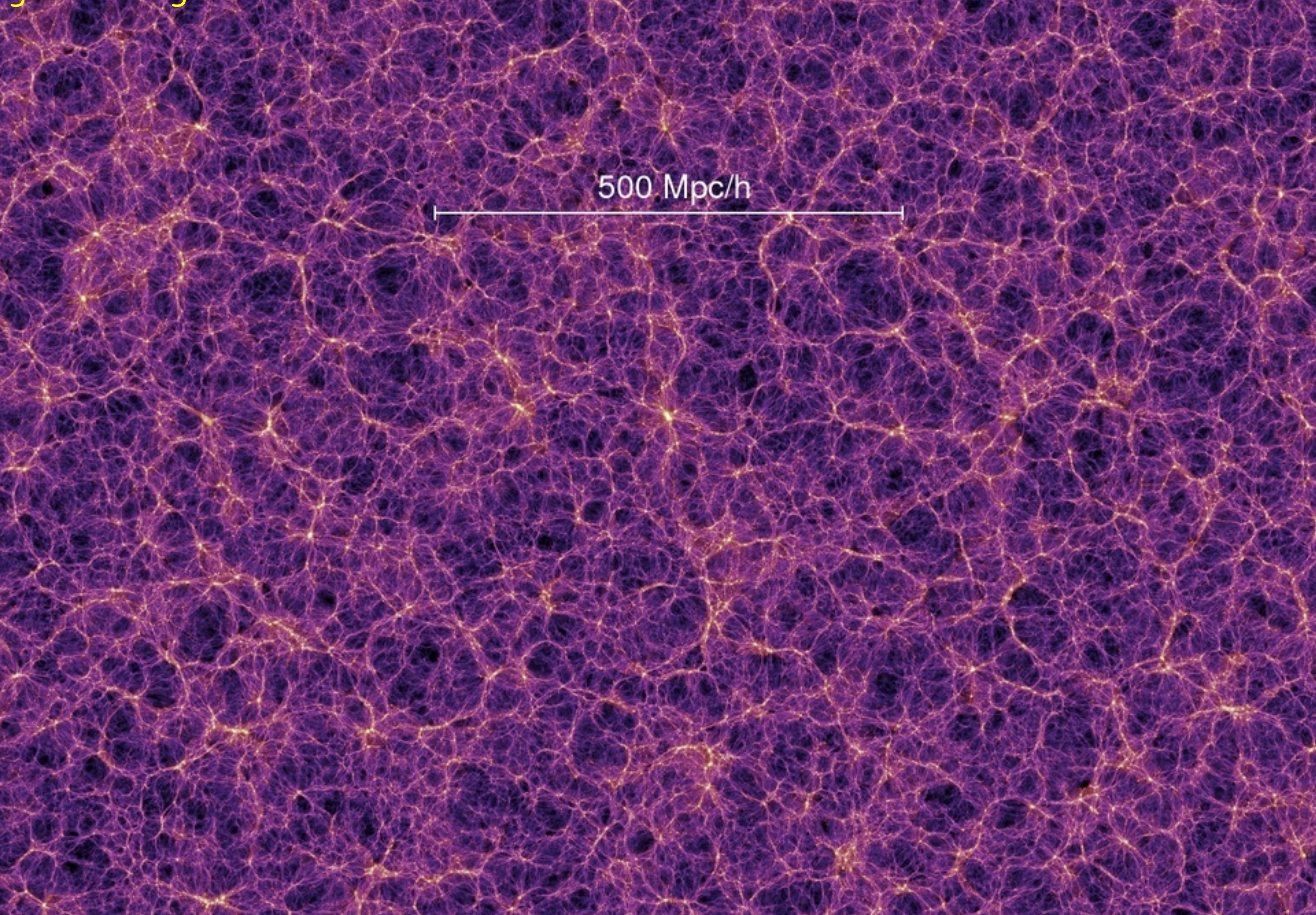
Andromeda, Credit M.Pugh & APOD

Rotation curves

Typical rotation speed 200 km/s

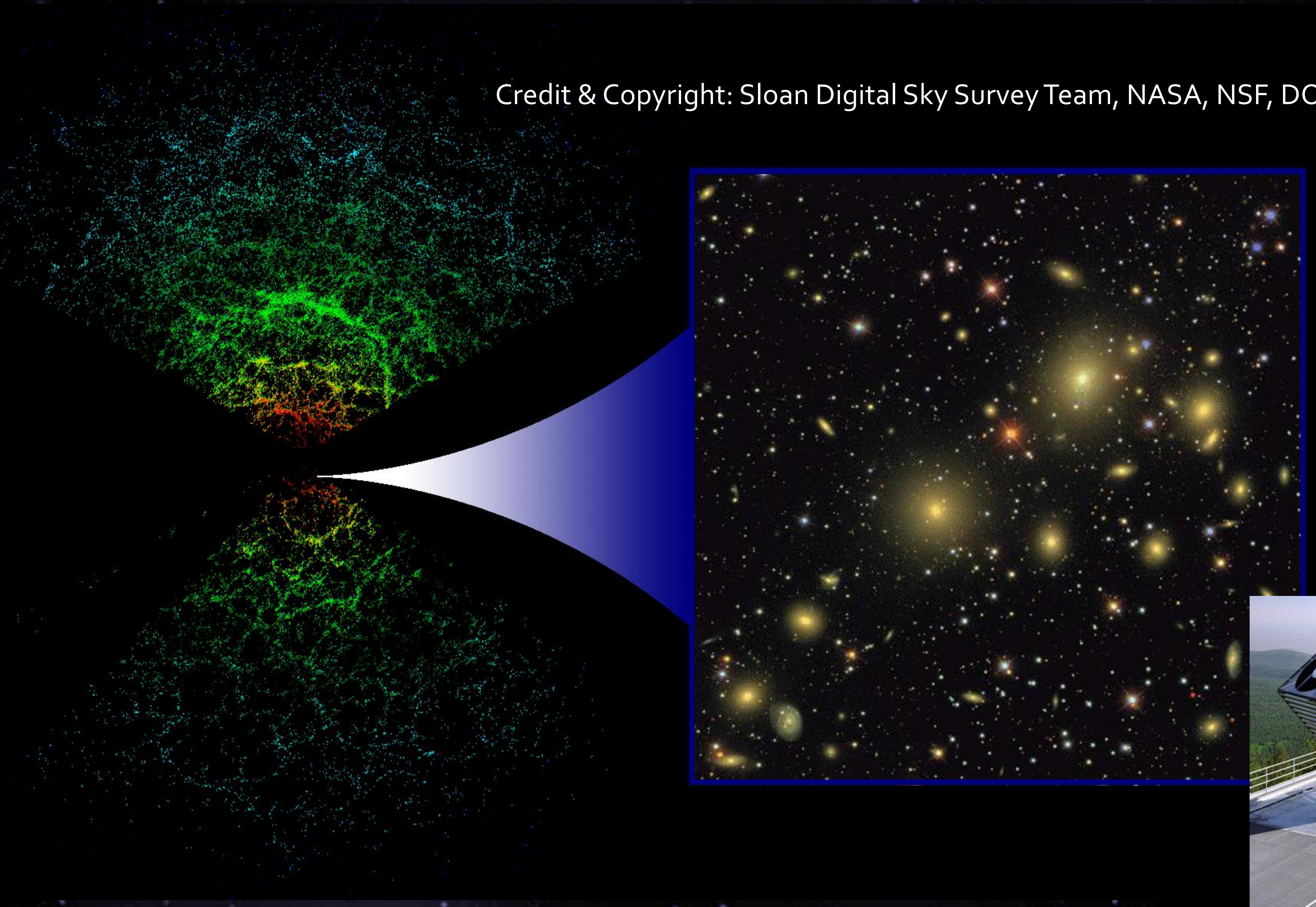


Dark matter is the web network in which visible matter stays. The glue that keeps galaxies together.



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

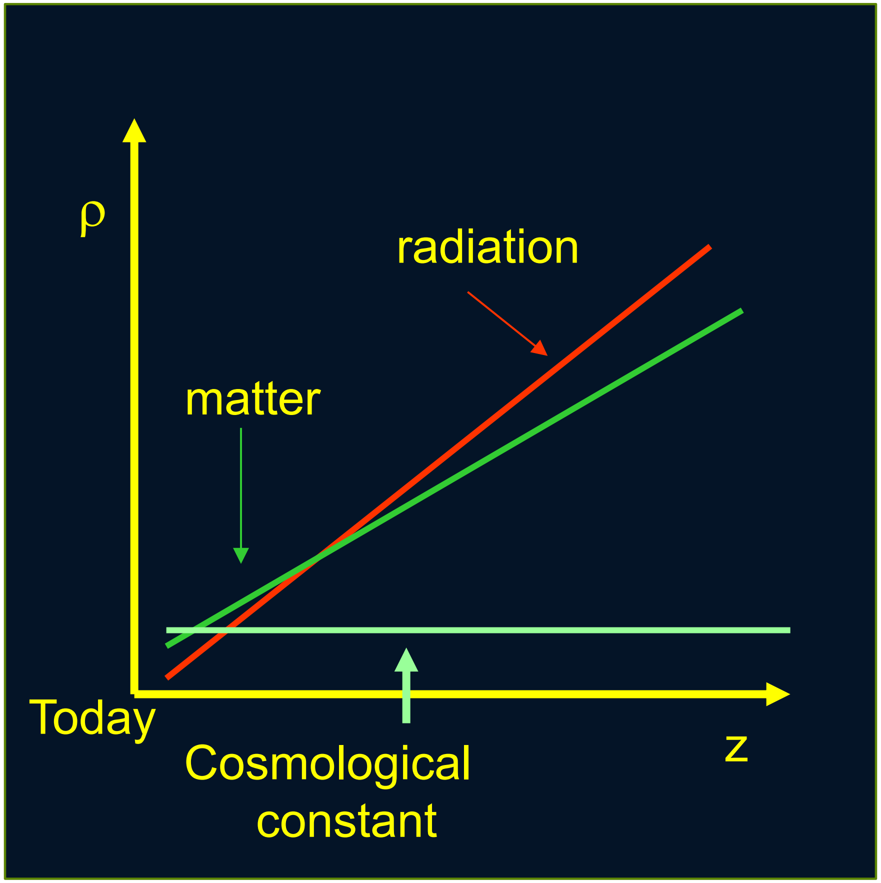
Axions

Sterile Neutrinos

Hidden Dark Matter

SuperWIMPS

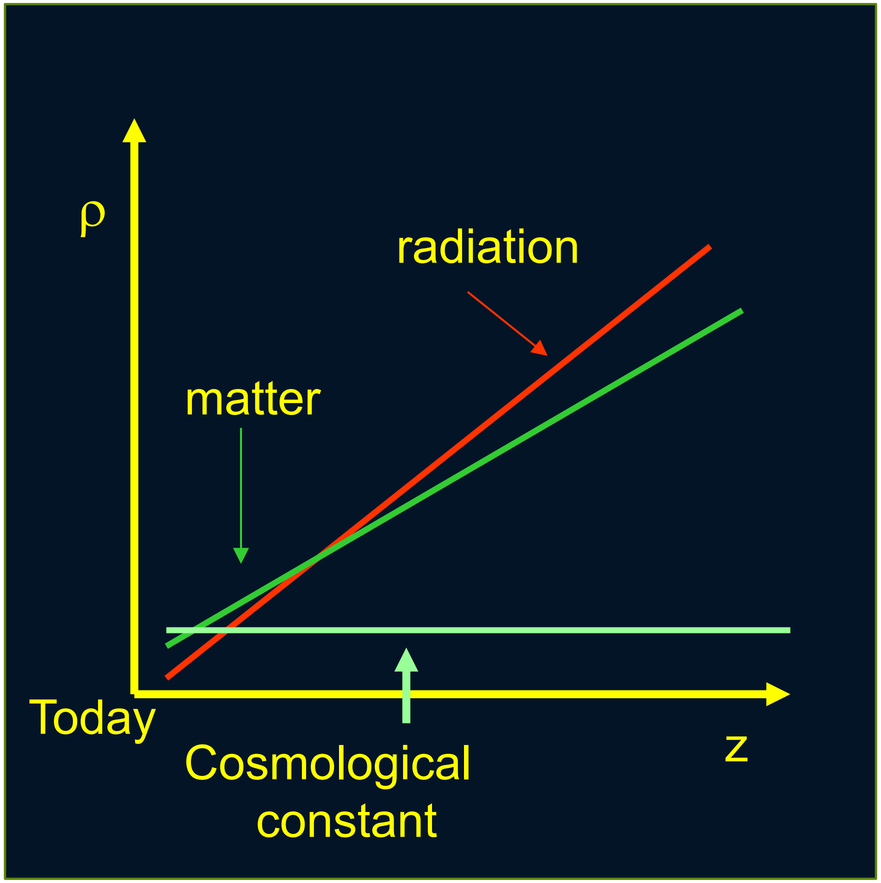
Cosmological constant



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

Introduced by Einstein to avoid expansion

Cosmological constant



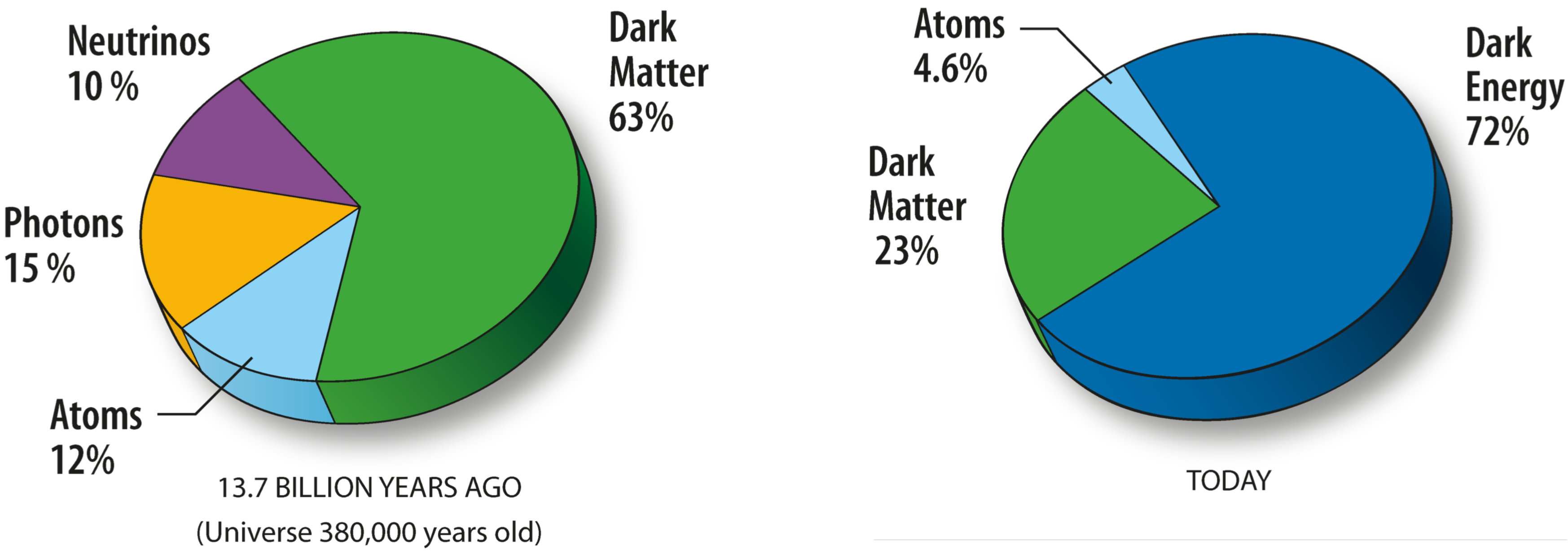
$$\rho_\Lambda = (10^{-3} eV)^4$$

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)



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 repul… …mponent to the stress energy tensor

Dark energy

- Or Modify the geometry (an… …ity), mainly at large scales

Modified gravity

- We keep GR and a Matter Dominated Universe but drop the assumption that … …iverse is spatially homogeneous on large scales, … …g large scale structure to induce some apparent a… …ation

Backreaction, voids, …

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

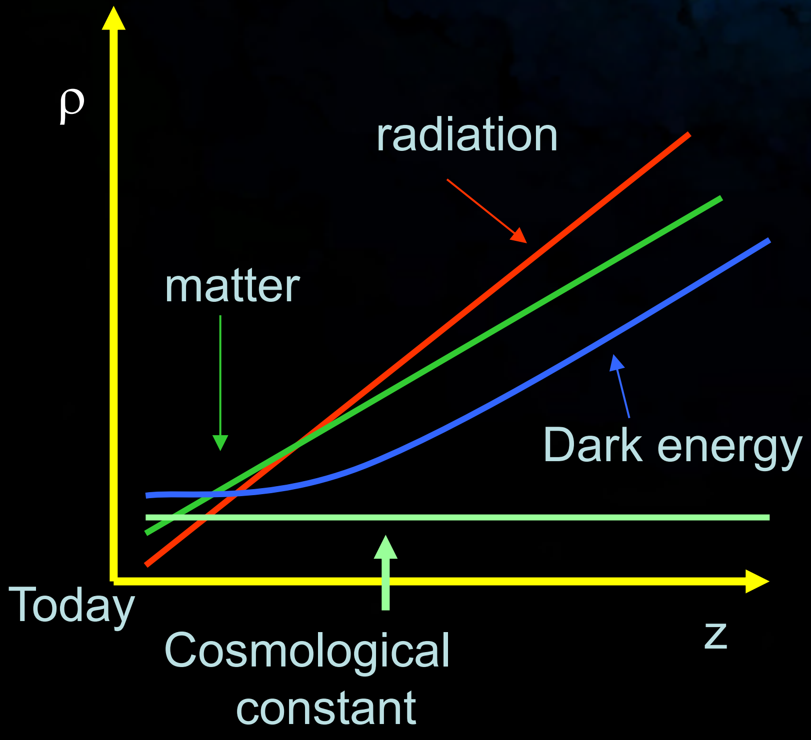
$$\rho_{DE}/M^4 \sim 75 \times 10^{-120}$$

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

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

Why so small?

Why important just today?



Wetterich 1988, Ratra & Peebles 1988

… to dynamical dark energy

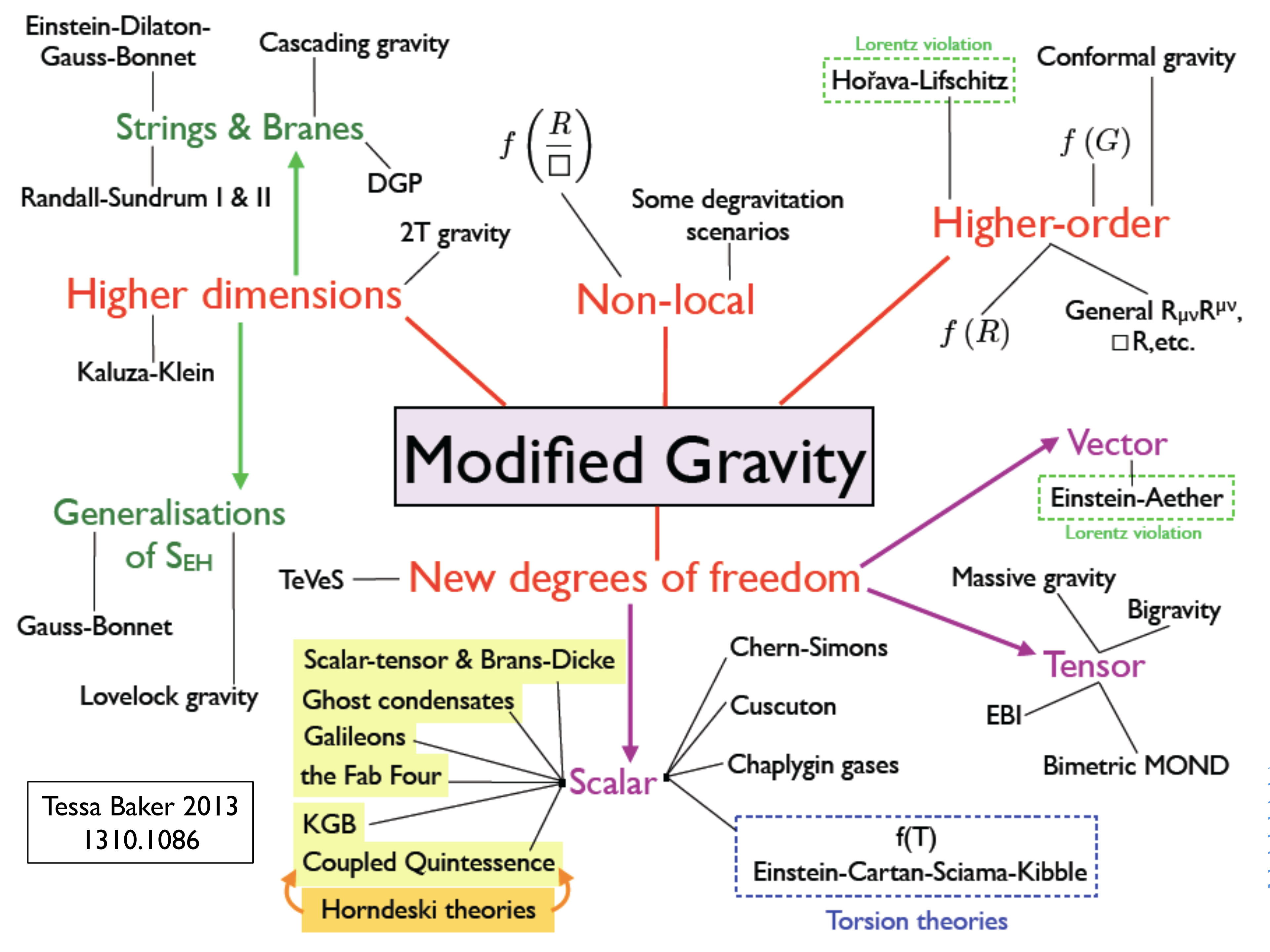
It can be thought of as a fluid with negative pressure that contrasts gravity and delays the formation of gravitational structures or equivalently as a modification of gravity

Challenge

$$\Lambda$$

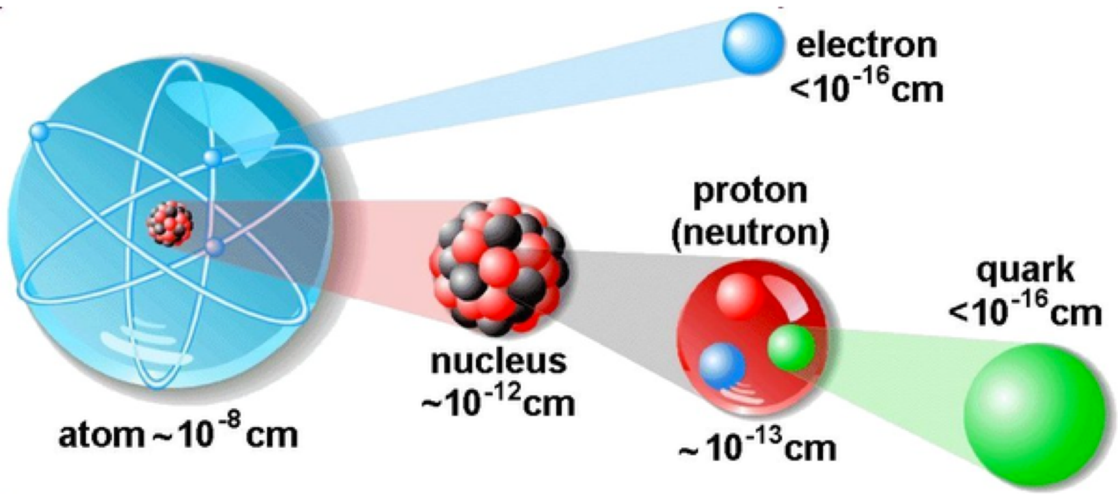
Can we falsify or verify a cosmological constant?

Can we distinguish among the models present in literature?



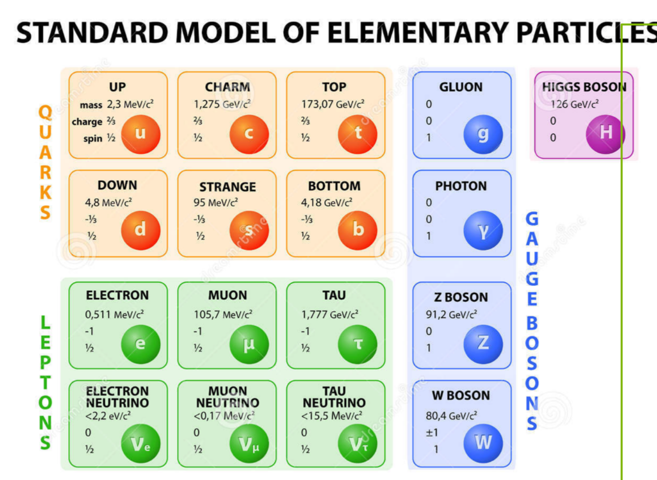
Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Strings & Branes
DGP
Randall-Sundrum I & II
2T gravity
Higher dimensions
Kaluza-Klein
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
$f\left(\frac{R}{\Box}\right)$
Some degravitation scenarios
Non-local
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
Higher-order
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Modified Gravity
Vector
Einstein-Aether
Lorentz violation
TeVeS
New degrees of freedom
Massive gravity
Bigravity
Tensor
EBI
Bimetric MOND
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Scalar
Chern-Simons
Cuscuton
Chaplygin gases
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
Tessa Baker 2013
1310.1086

A Dark person looking at 4% of its Universe



Fundamental Force Particles

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	*g* (gluon)	short range	much stronger



We are much more exotic

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?

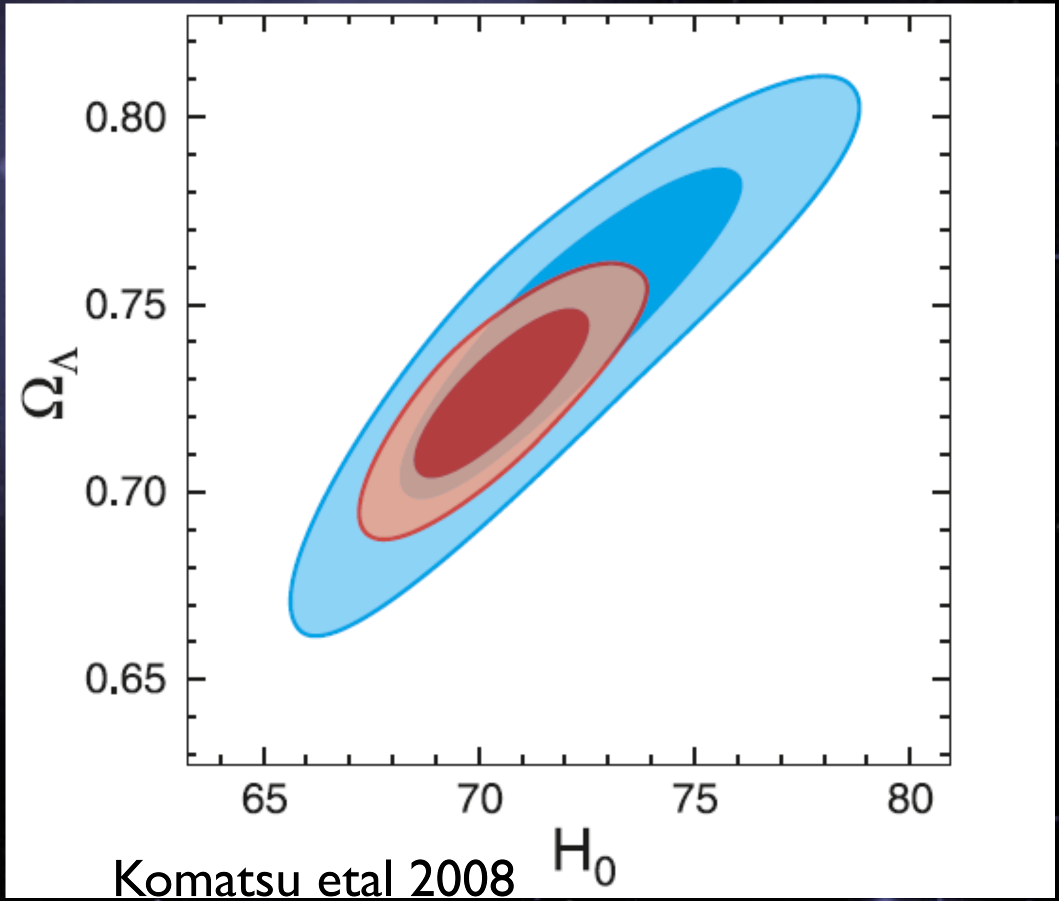
1. Theory: model building and equations that describe the evolution of expansion and perturbations in that model

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

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

```
pphix=phidotant**2/2-y(1)**2*Vofphi(phiant,0)
wcomb=(pnux+pphix)/(rhonux+rhophix)

antrhophi=0.5_dl*phidotant*phidotant/y(1)**2+Vofphi(phiant,0)
antrhophidot=phidotant*(-3._dl*adotoa*phidotant/y(1)**2-1._dl*betatemp*(rhonux-3._dl*pnux)/y(1)**2)


dnu=clxnuant*grhormass*rhonuant/y(1)**2
dcdm=y(3)*grhoc/y(1)          ! deltarhoc*a^2   !vale
db=y(4)*grhob/y(1)            ! deltarhob*a^2   !vale
dg=y(6)*grhog/y(1)**2         ! deltarhog^a^2   !vale
dr=grhornomass*y(7+EV%lmaxg)/y(1)**2
dphi=phidotant*y(EV%w_ix+1)+y(EV%w_ix)*y(1)**2*Vofphi(phiant,1)
dgrho=db+dcdm+dg+dr+dnu+dphi
call Nu_derivs(y(1)*avarmnu(phiant,0),adotoa,betatemp,rhonuant,pnuant,phidotant,rhonudot,shearnudot,y(EV%iq2),dummy)
dpnuant=dpnuant*grhormass/y(1)**2
rhophidot=phidotant*(betatemp*-1_dl*(rhonuant-3*pnuant)*grhormass/(y(1)**4)-3*adotoa*phidotant/y(1)**2)
rhonudot=(rhonudot-4*adotoa*rhonuant) ! *grhormass/(y(1)**4*1.677004778d-9
rhonudot=rhonudot*grhormass/(y(1)**2)

pnudot=-ix*(betatemp*phidotant+adotoa)*grhormass/(3*y(1)**2)-4*adotoa*pnux
!pnudot=-4*adotoa*pnux


rhocdmdot=-3*adotoa*grhoc/(y(1))
scdmphi=-3*adotoa*(dcdm/rhocdmdot-dphi/rhophidot)
snuphi=-3*adotoa*(dnu/rhonudot-dphi/rhophidot)
scdmnu=-3*adotoa*(dcdm/rhocdmdot-dnu/rhonudot)
qnuant=qnuant*grhormass/y(1)**2      !+alpha*EV%k_buf**2*eightpig*y(1)**2
dgqtotal=grhob*y(5)/y(1)+(grhog*y(7)+grhornomass*y(8+EV%lmaxg))/y(1)**2+qnuant
dgqtotal=dgqtotal+EV%k_buf*phidotant*y(EV%w_ix)
dgpitotal=grhog/y(1)**2*y(8)+grhornomass/y(1)**2*y(9+EV%lmaxg)+grhormass/y(1)**2*shearx*1.5_dl
zant=(0.5_dl*dgrho/EV%k_buf+y(2))/adotoa
sigmaant=(zant+1.5_dl*dgqtotal/EV%k_buf**2)
alpha=sigmaant/EV%k_buf
philong=y(2)*EV%k_buf-adotoa*alpha*EV%k_buf**2     !=Phi*k**2  (=-Phi*k^2 K&S)
philongcheck=-(dgrho+3*adotoa*dgqtotal/EV%k_buf)/2._dl
```

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



Komatsu etal 2008

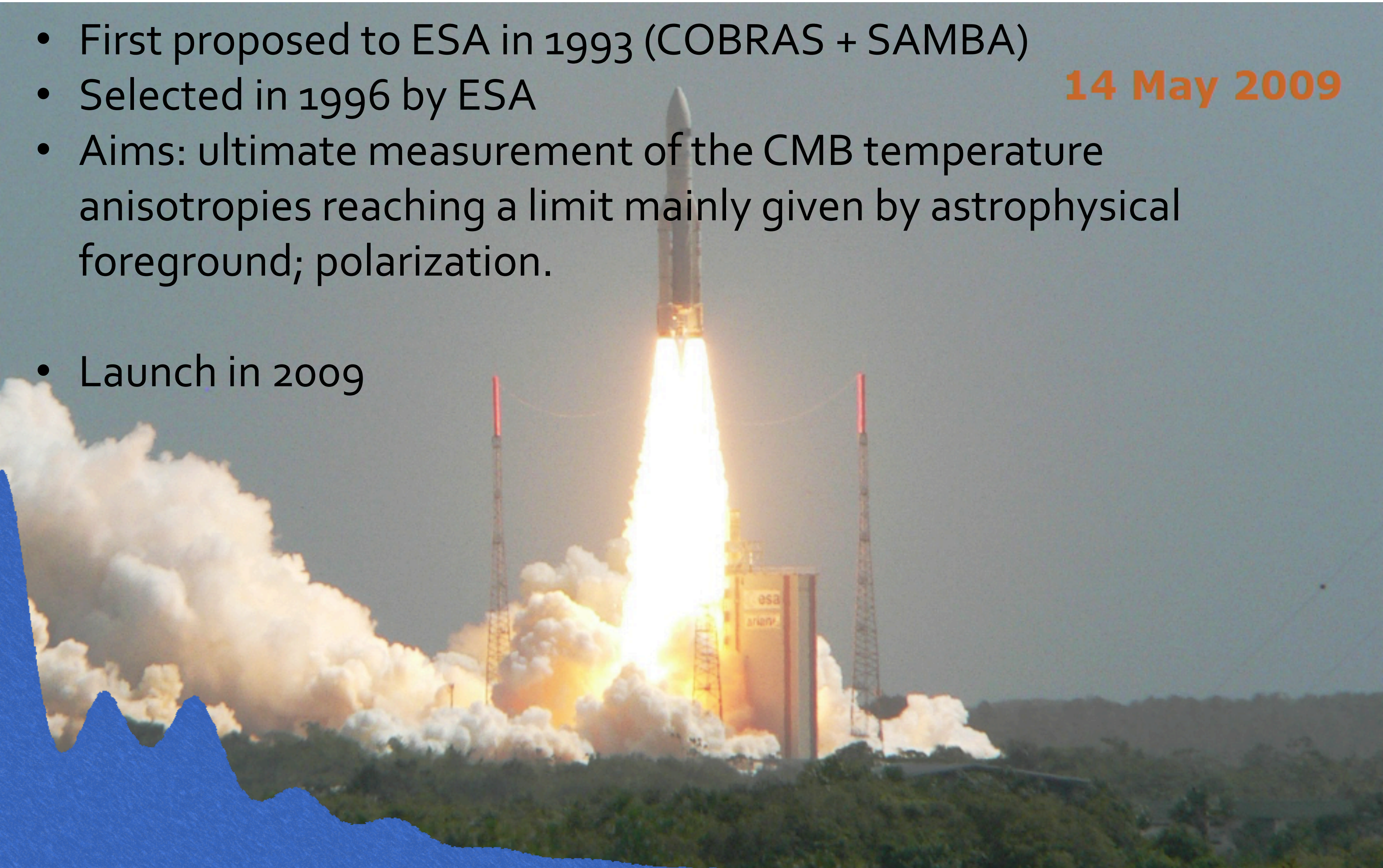
Experiments

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

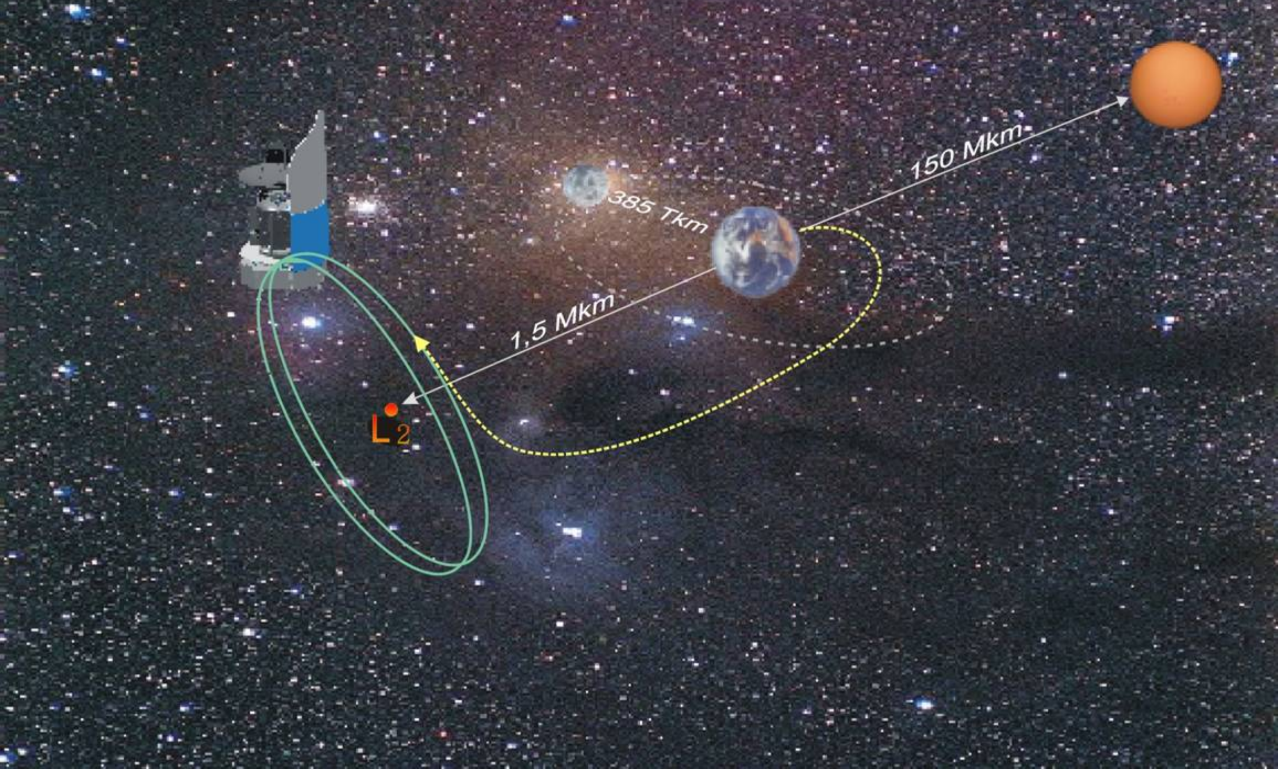
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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



The Planck project

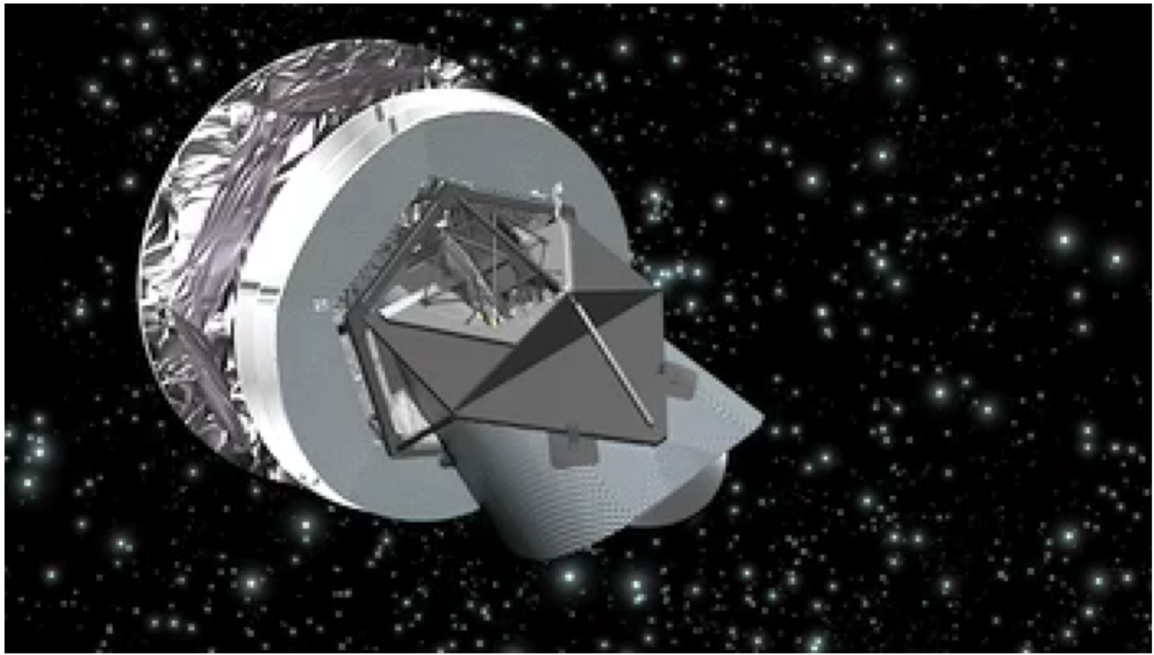


- Nominal mission completed in November 2010 (15.5 months). In practice, twice the nominal mission (full surveys: 5 HFI; 8 LFI)

(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.

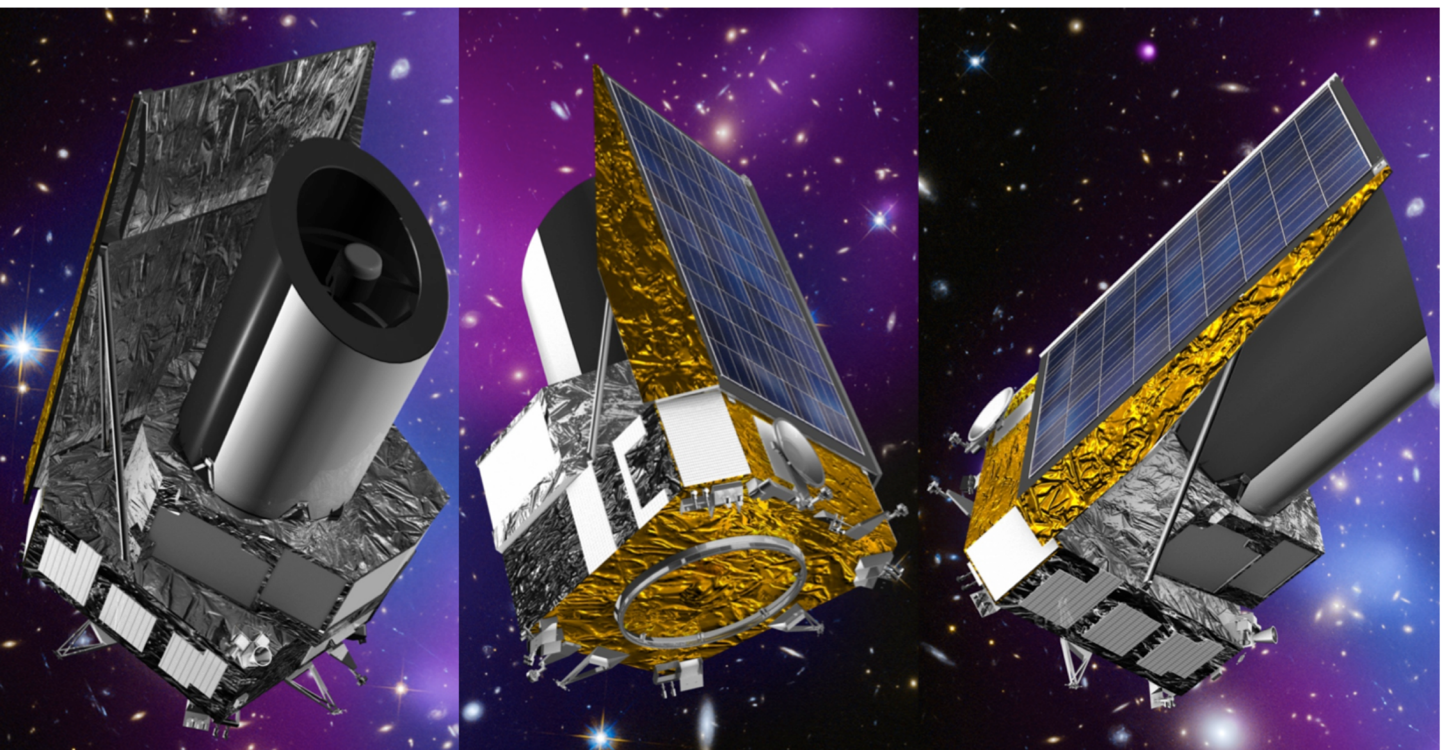
Multiple passes over same sky by each detector at each position of the axis.



What next?

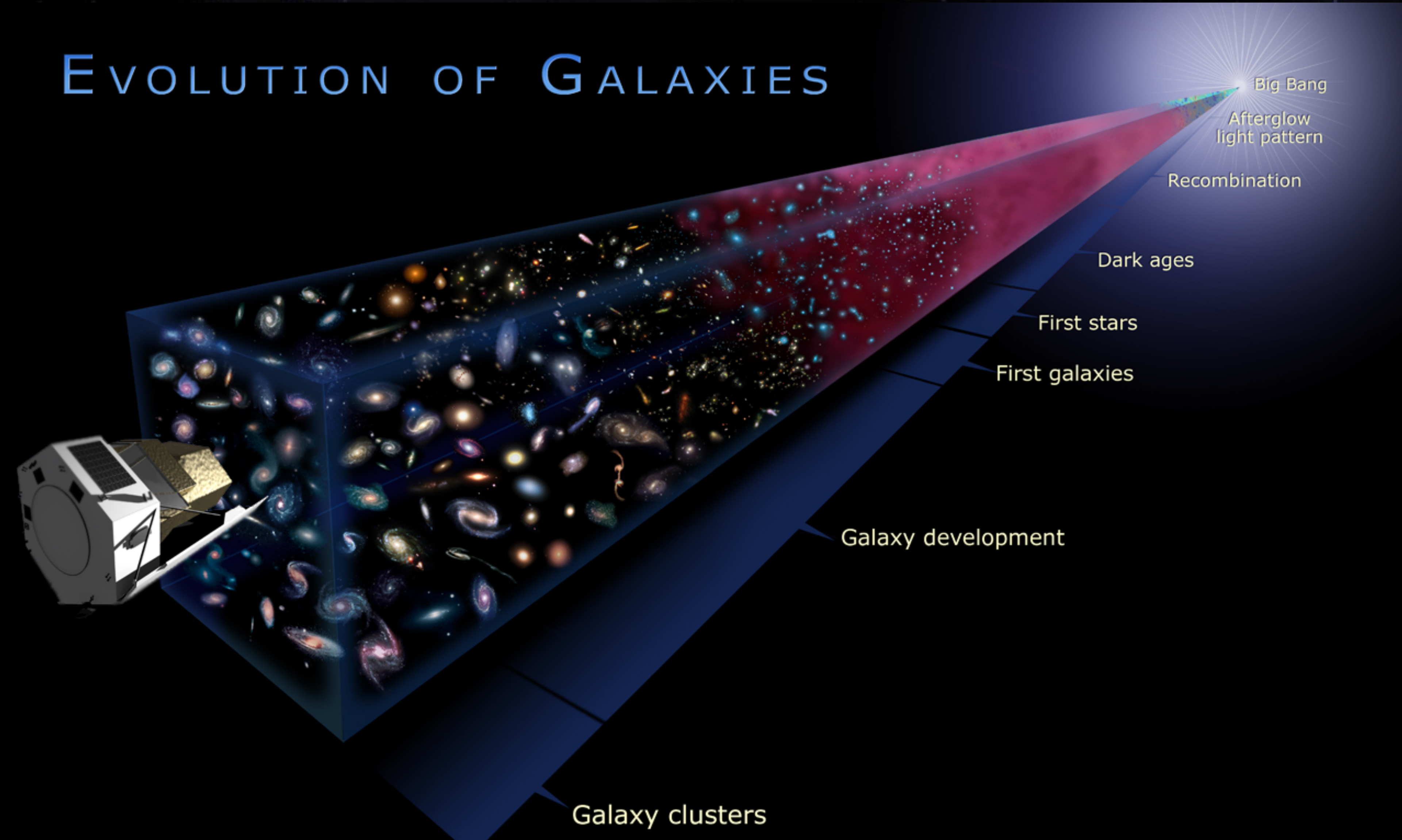
What is Euclid?

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



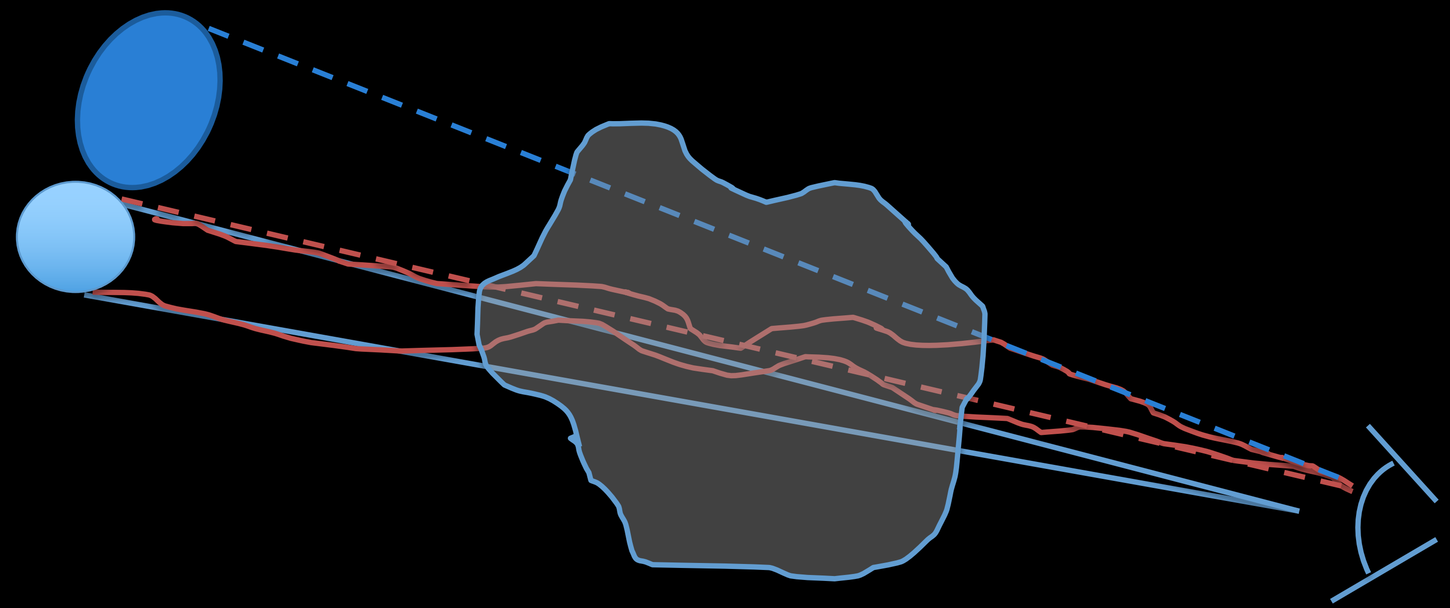
Launch in 2022: measures 1.5 billion shapes of galaxies and distances (z) of millions of galaxies
Telescope of 1.2 m with a detector in the visible and one in the infrared

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

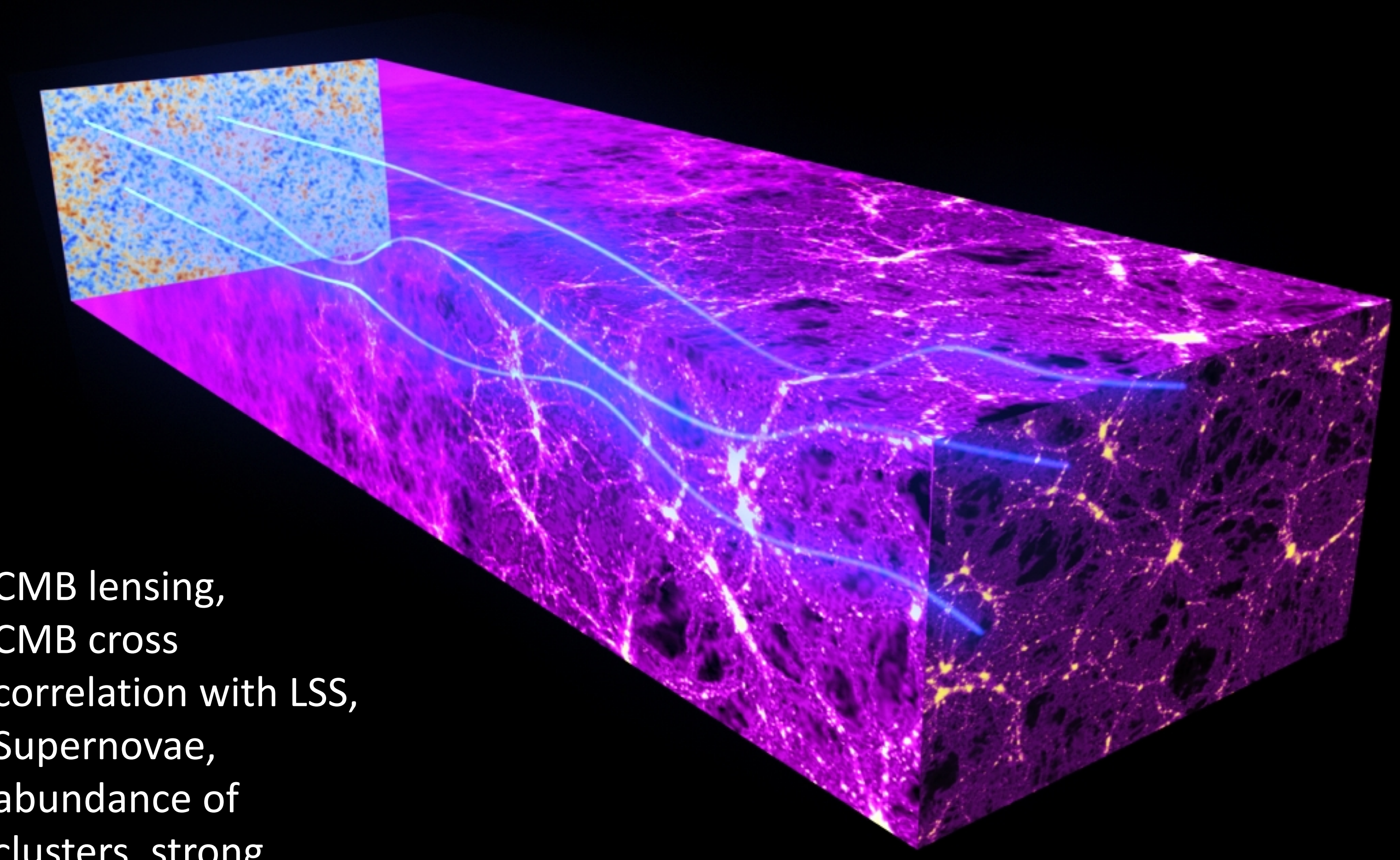
Weak lensing



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

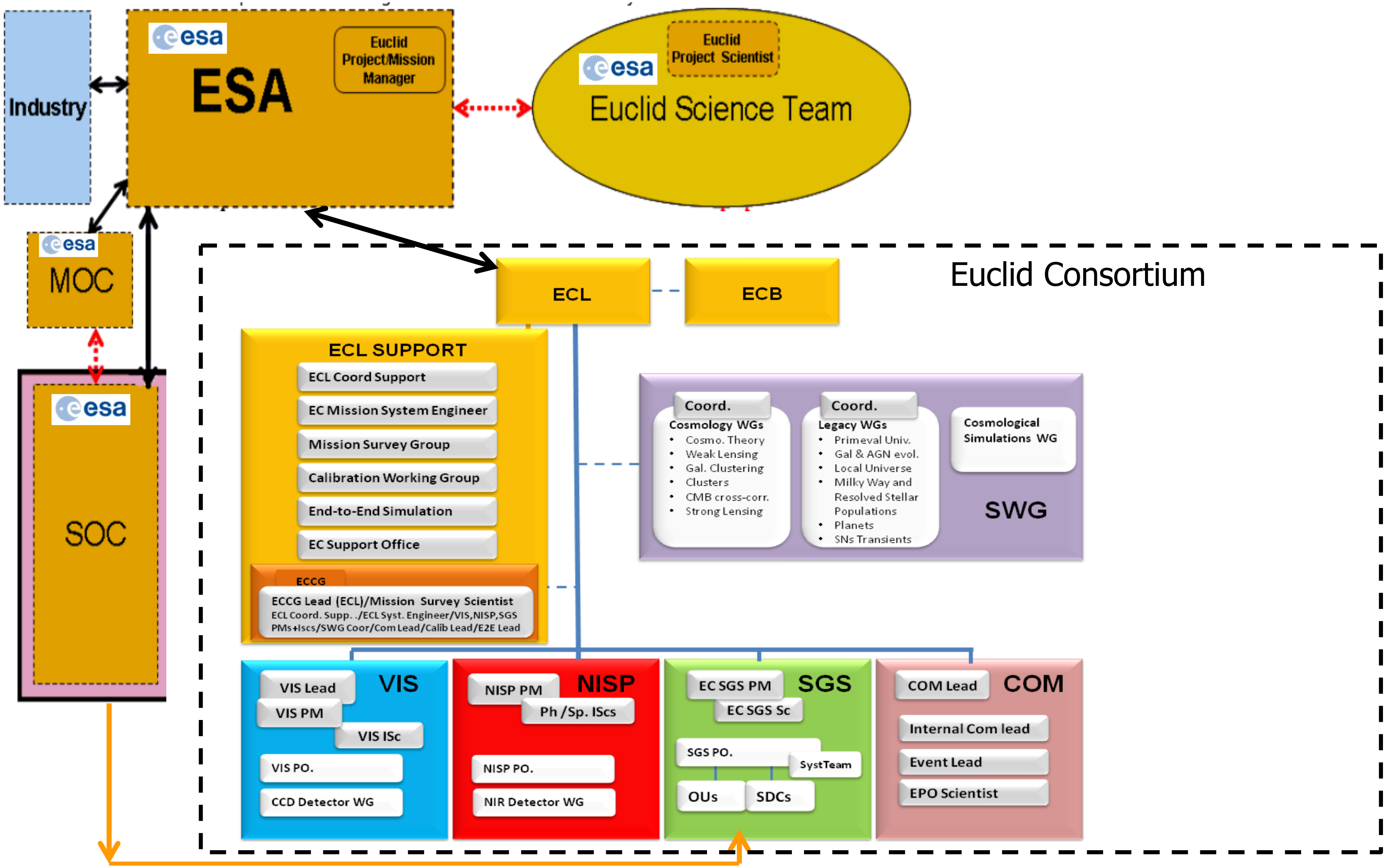
Related to the two gravitational potentials and used to test gravity

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

www.euclid-ec.org

> 1500 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 Bonn, June 2018

Supernova Foundation

Worldwide remote mentorship program for women in science (entirely free)

http://supernovafoundation.org/

The Supernova Foundation aims to:

- Connect women undergraduates in Physics, with a focus on students from developing countries, to established female physicist role models.
- Provide support for women undergraduate students as they transition to postgraduate studies, in the form of personal mentoring.
- Provide guidance on various topics including: career choices, application process, CVs, work-life balance and gender-specific harassment.
- Provide generally useful advice in form of regular webinars that anyone can attend but which are focused on women in science.
- Create a resource of recorded webinars with useful advice and interesting discussion that will be publicly available.