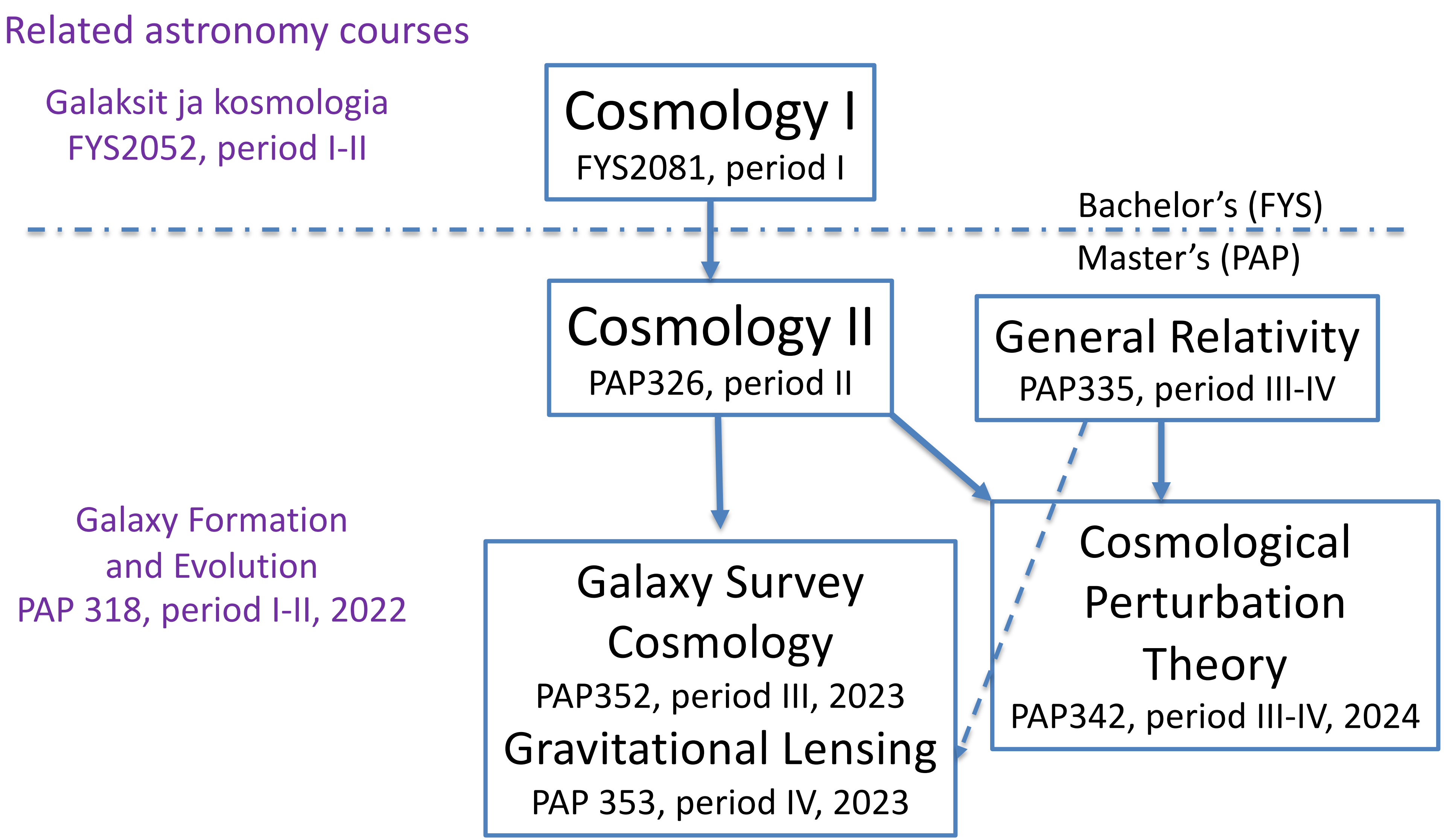
PAP 352 Galaxy Survey Cosmology

Introduction

Cosmology curriculum



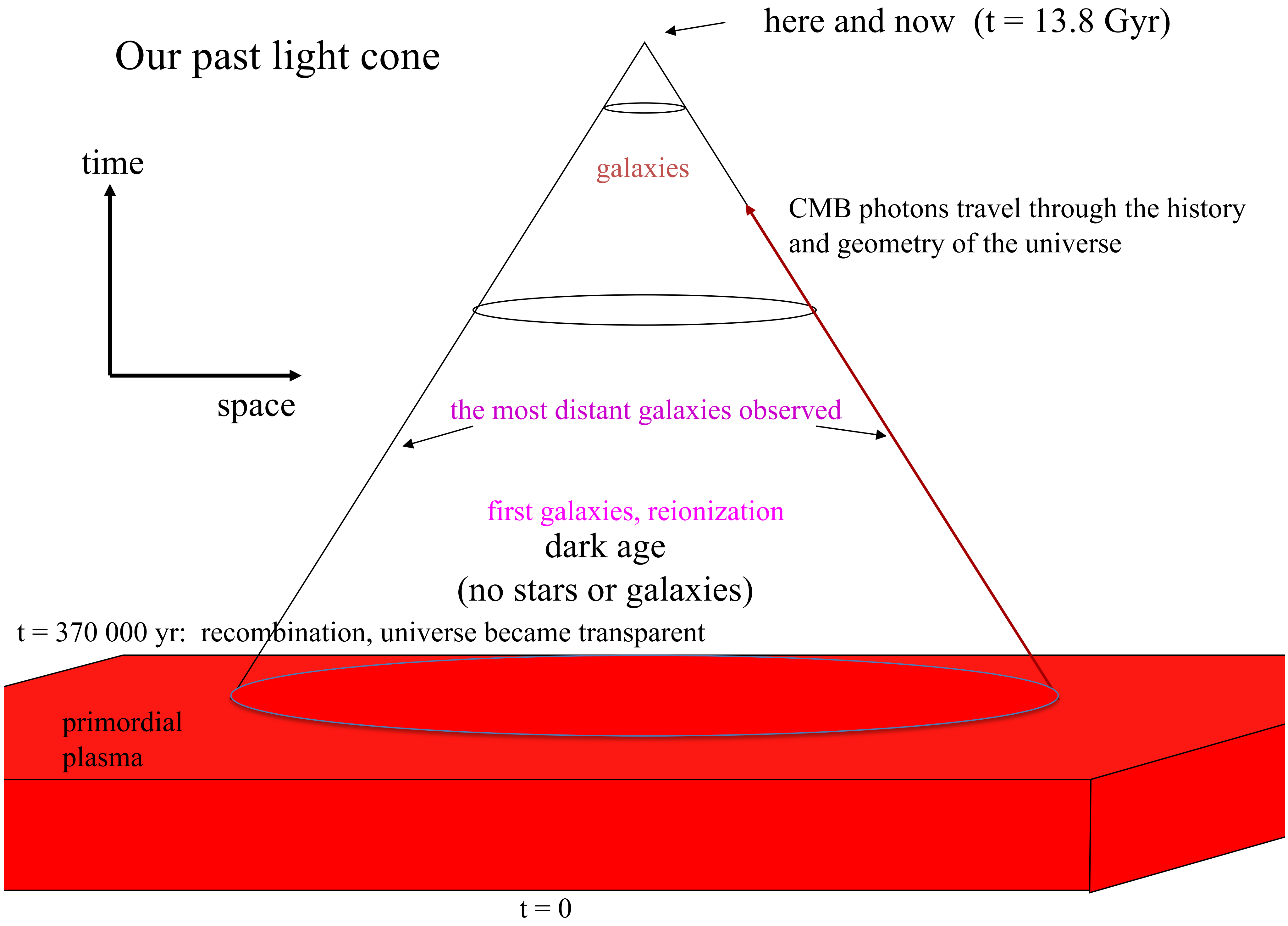
Galaxy Survey Cosmology

- **PAP352 Galaxy Survey Cosmology 18.1 – 3.3**
- https://moodle.helsinki.fi/course/view.php?id=56110
- **Lecture notes**
  - **Homework problems**
- Lecturer: Hannu Kurki-Suonio
  Assistant: Kimmo Kiiveri
- Lectures : We 12-14, Th 12-14 **?**
- Homework problem sets given out on Wednesdays
- Exercise session: Fr 14-16
- The course is lectured in English (I take questions also in Finnish)
- No exam, grade 100% from homework

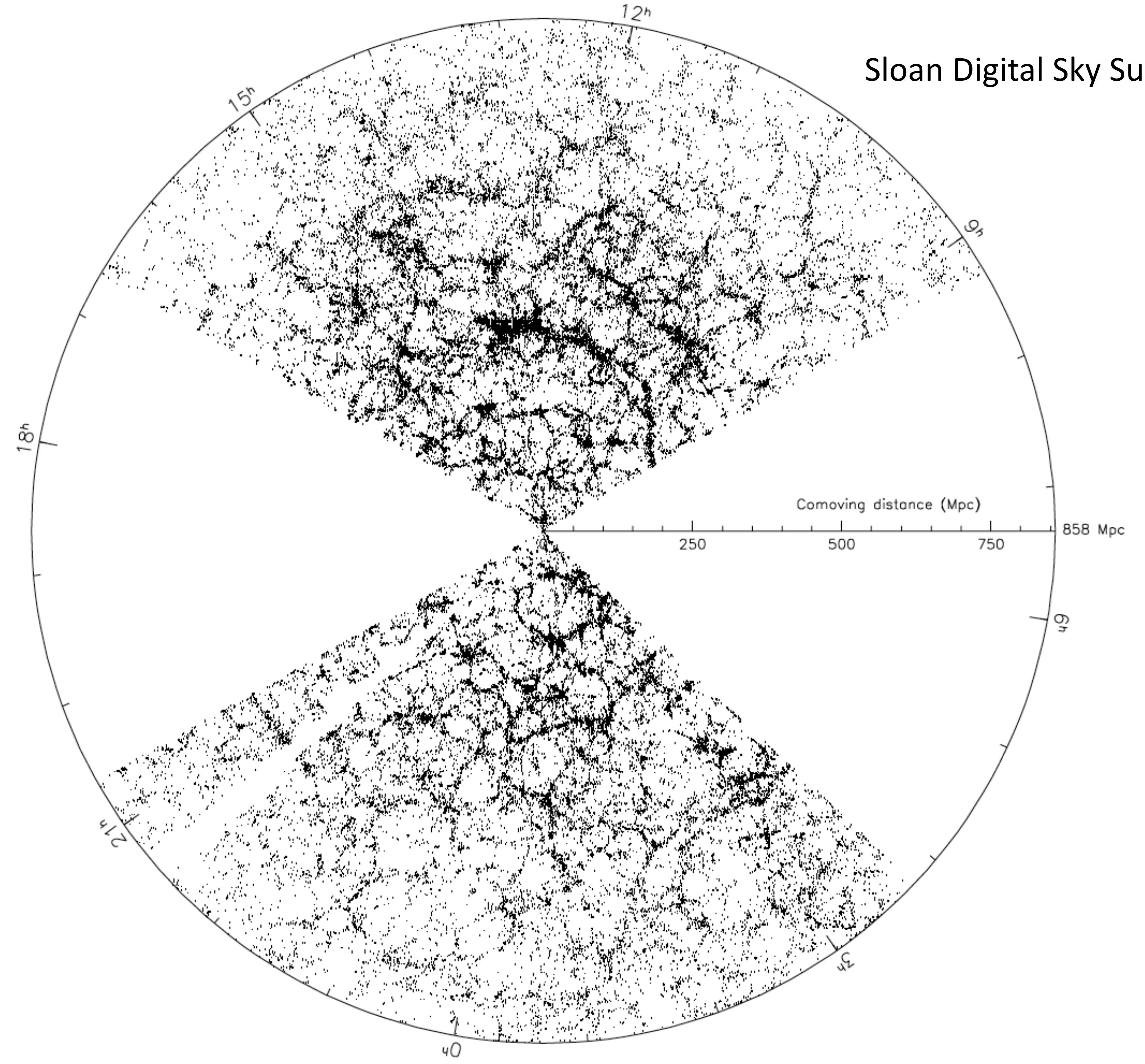
HIP SEMINAR ROOM A315 RESERVATIONS SPRING 2023 (16.1.-5.3.2023)

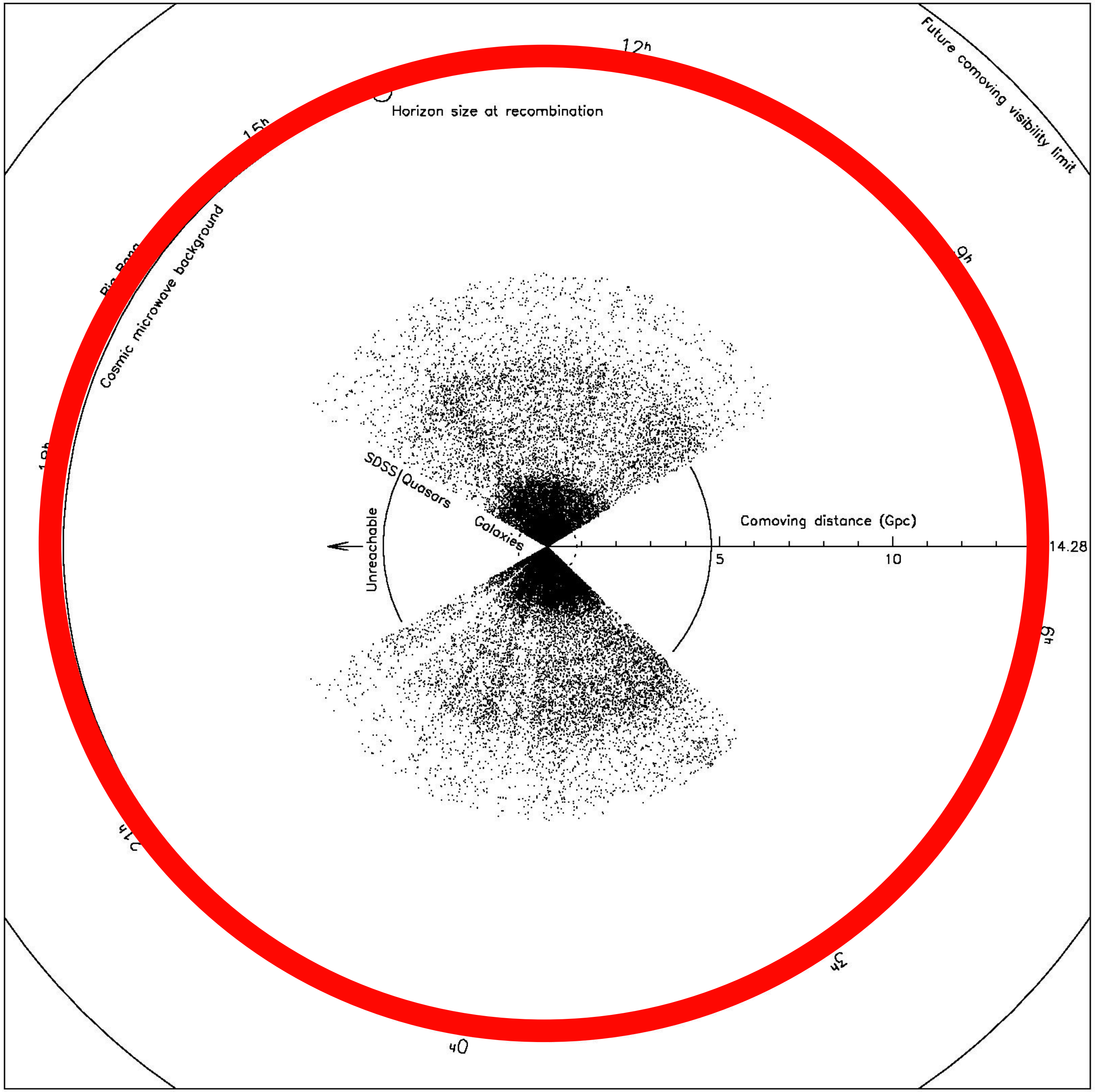
	Monday	Tuesday	Wednesday	Thursday	Friday
8.00 – 9.00					
9.00 – 10.00					
10.00 – 11.00	┌ **TFT**	┌ **HIP**	┌ **Quantum**	┌ **HIP**	
11.00 – 12.00	**Vuorinen** ┘	**Seminar** ┘	**mechanics IIa** **Keski-Vakkuri** ┘	**Seminar** ┘	
12.00 – 13.00	┌ **Statistical**	┌ **Statistical**	┌ **Galaxy Survey**	┌ **Galaxy Survey**	
13.00 – 14.00	**Mechanics** **Kerminen** ┘	**Mechanics** **Kerminen** ┘	**Cosmology** **Kurki-Suonio** ┘	**Cosmology** **Kurki-Suonio** ┘	
14.00 – 15.00	┌ **Gen. relativity**	┌ **Gen. relativity**	┌ **Astroparticle**		┌ **Galaxy Survey**
15.00 – 16.00	**Räsänen** ┘	**Räsänen** ┘	**Seminar** ┘		**Cosmology** **Exercises** ┘
16.00 – 17.00	┌ **Quantum**		┌ **Gen. relativity**		
17.00– 18.00	**Mechanics IIa** **Keski-Vakkuri** ┘		**Exercises** ┘		
18.00 – 19.00					
19.00 – 20.00					

FOR RESERVATIONS PLEASE CONTACT TARJA H. (tarja.heikkila@helsinki.fi) 16.01.2023


Our past light cone
here and now (t = 13.8 Gyr)
time
space
galaxies
CMB photons travel through the history
and geometry of the universe
the most distant galaxies observed
first galaxies, reionization
dark age
(no stars or galaxies)
t = 370 000 yr: recombination, universe became transparent
primordial
plasma
t = 0

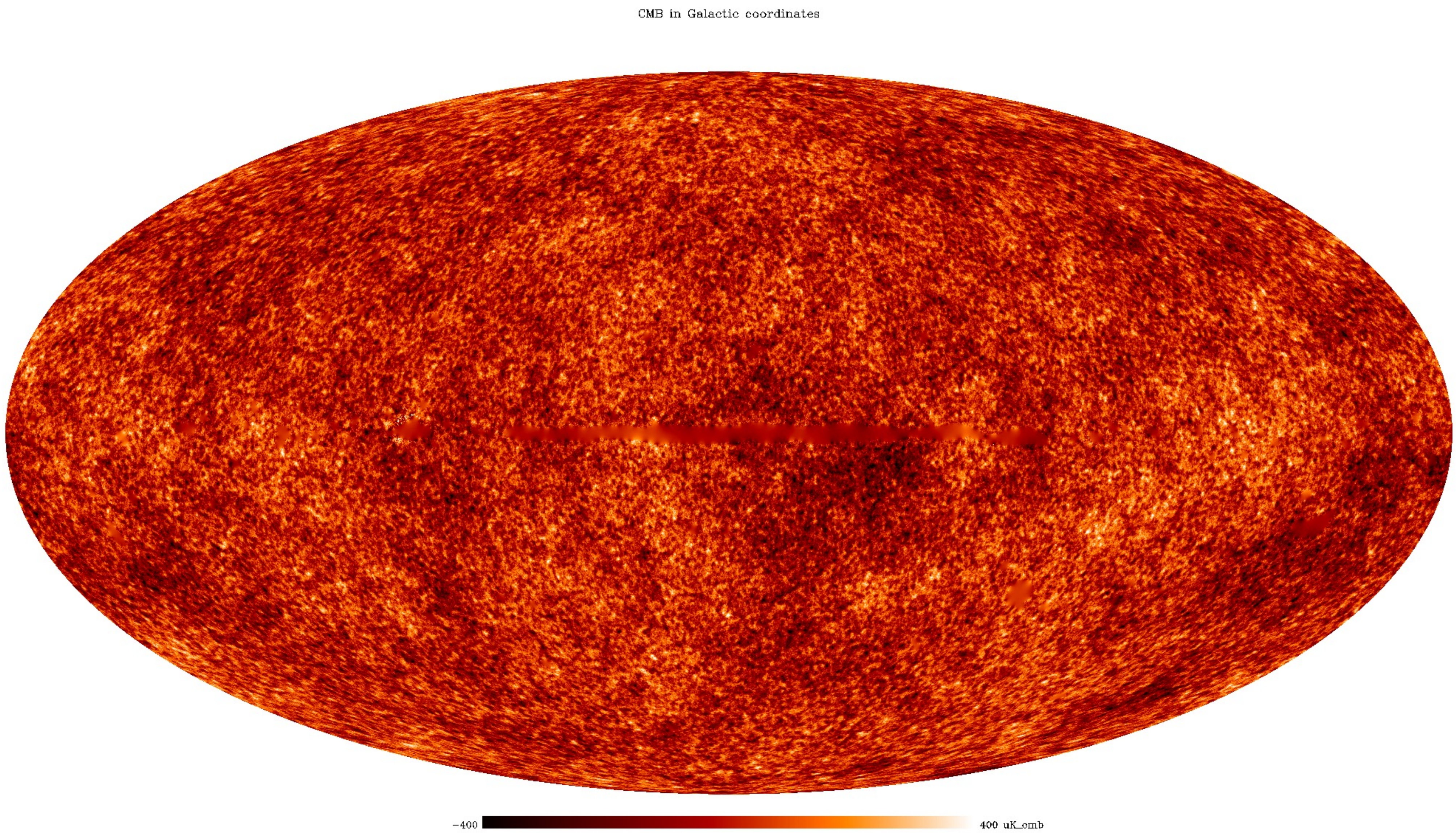
Sloan Digital Sky Survey





12h
Future comoving visibility limit
Horizon size at recombination
15h
Big Bang
Cosmic microwave background
9h
18h
SDSS
Quasars
Galaxies
Unreachable
Comoving distance (Gpc)
5
10
14.28
6h
21h
3h
0h

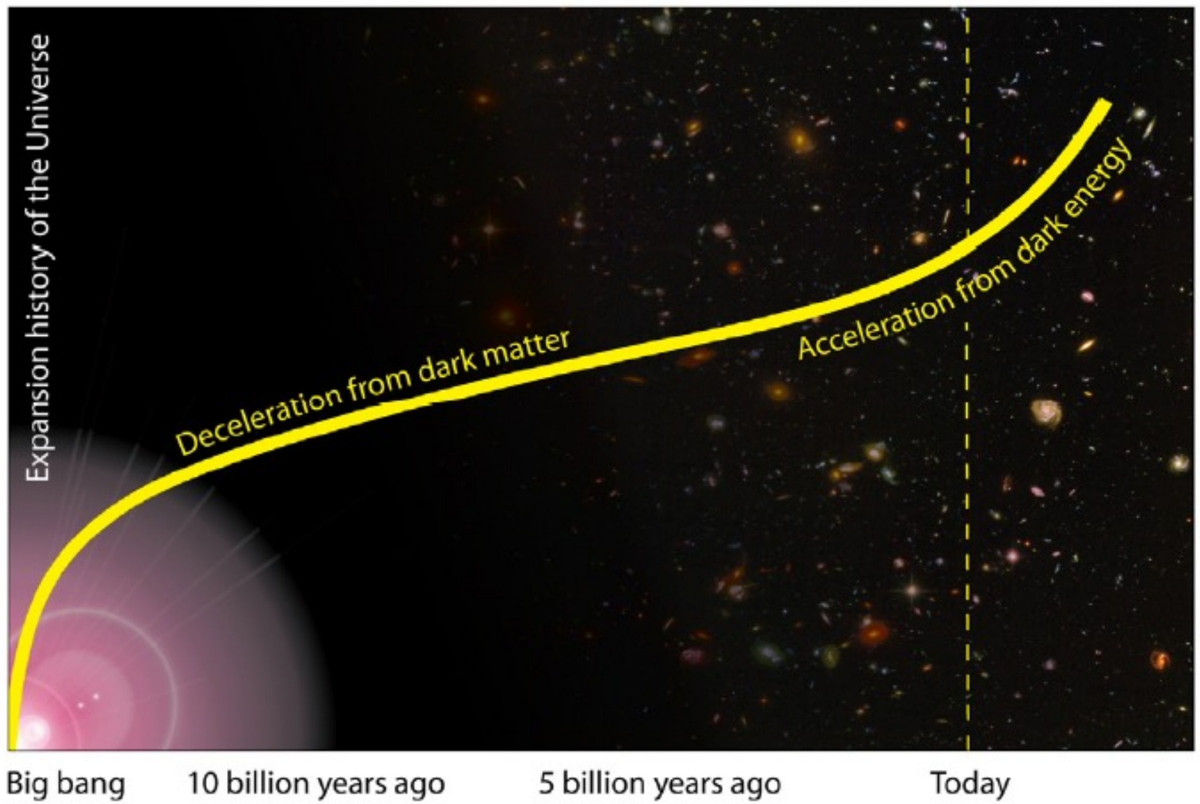
The CMB shows us the early universe at t ≈ 370 000 years



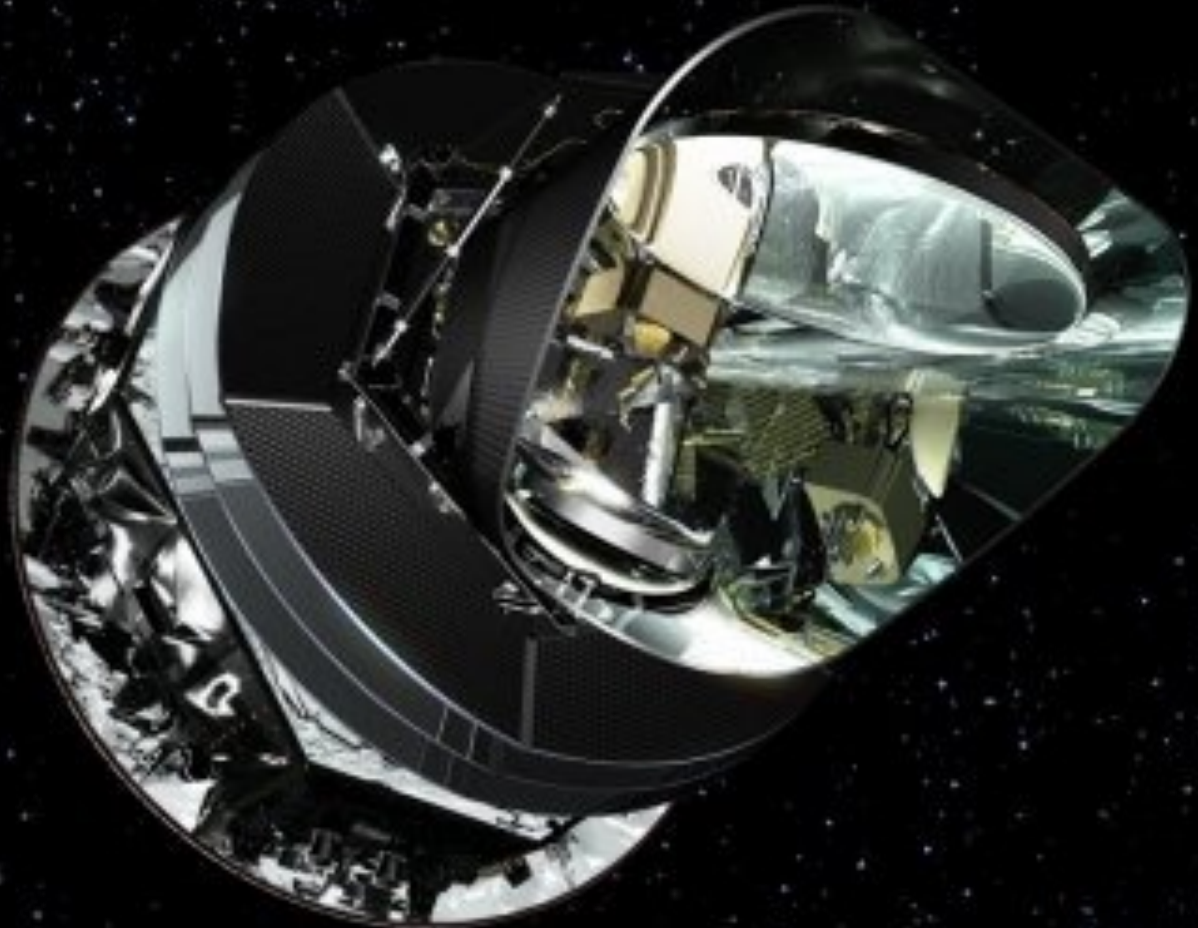
Planck 2013

Composition and fate of the universe

- Expansion of the universe appears to be accelerating
- This may eventually lead the universe to be very empty
- General relativity => energy component with negative pressure
- This is called "dark energy": $p = w\rho$, $w < 0$ ($w = -1$ cosmological const.)
- Alternative explanation: modify general relativity (at very large scales)



Planck satellite



Launch 2009, observations 2009-13, final results 2018

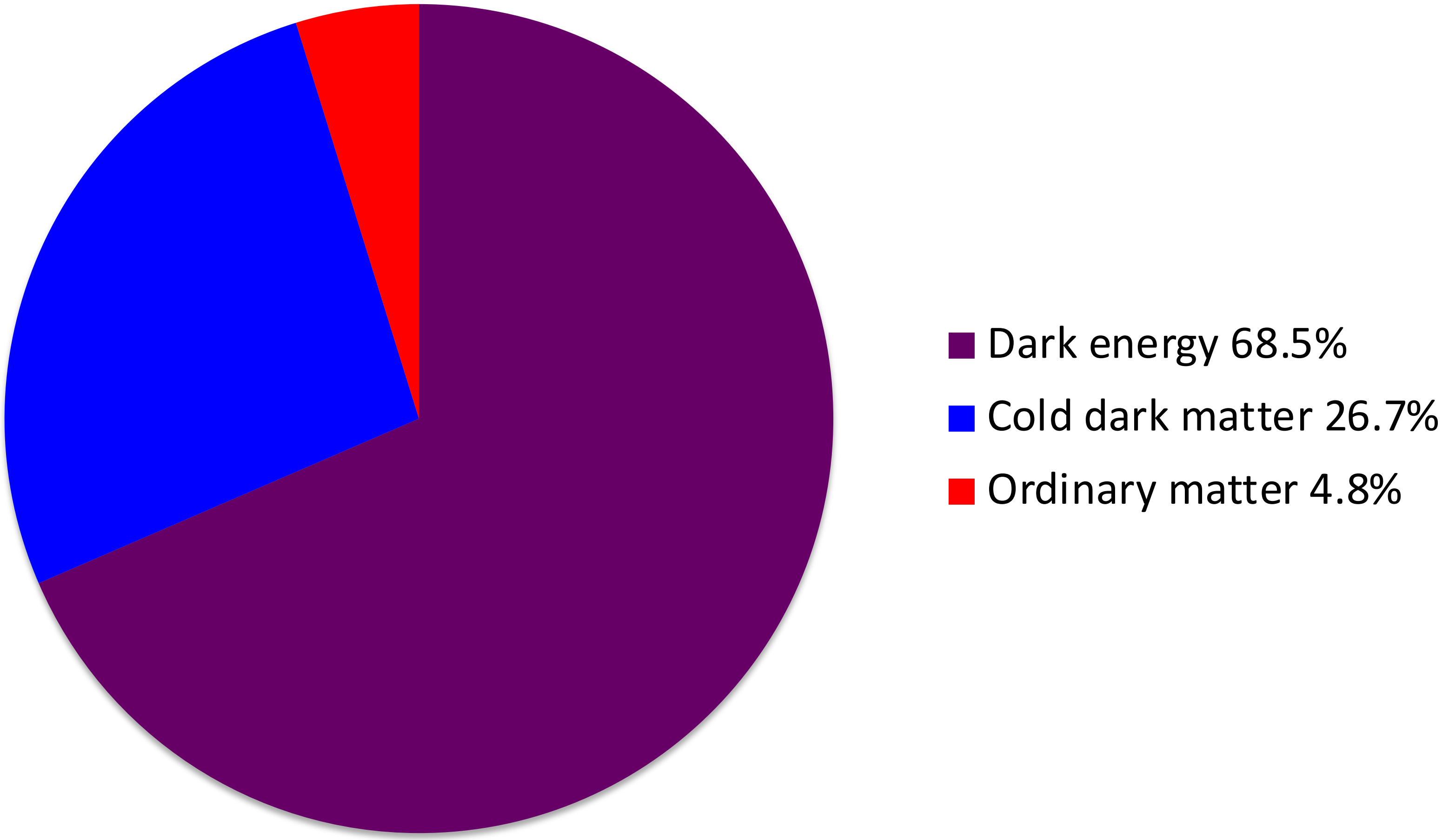
Standard ΛCDM parameters

Parameter	Planck 2018	+ other data
$\Omega_b h^2$	0.02237±15	0.02242±14
$\Omega_c h^2$	0.1200±12	0.1193±9
$100\theta_*$	1.04110±31	1.04119±29
τ	0.054±7	0.056±7
n_s	0.9649±42	0.9665±38
$\ln(10^{10} A_s^{\ 2})$	3.044±14	3.047±14

(68% CL errors are for the least significant digits, $h = H_0$ in units of 100 km/s/Mpc)

Ω_Λ	0.685±7	0.689±6
$\Omega_{\rm m}$	0.315±7	0.311±6
H_0	67.4±5	67.7±4
Age/Gyr	13.797±23	13.787±20

Recipe for the universe



Limits to extended models

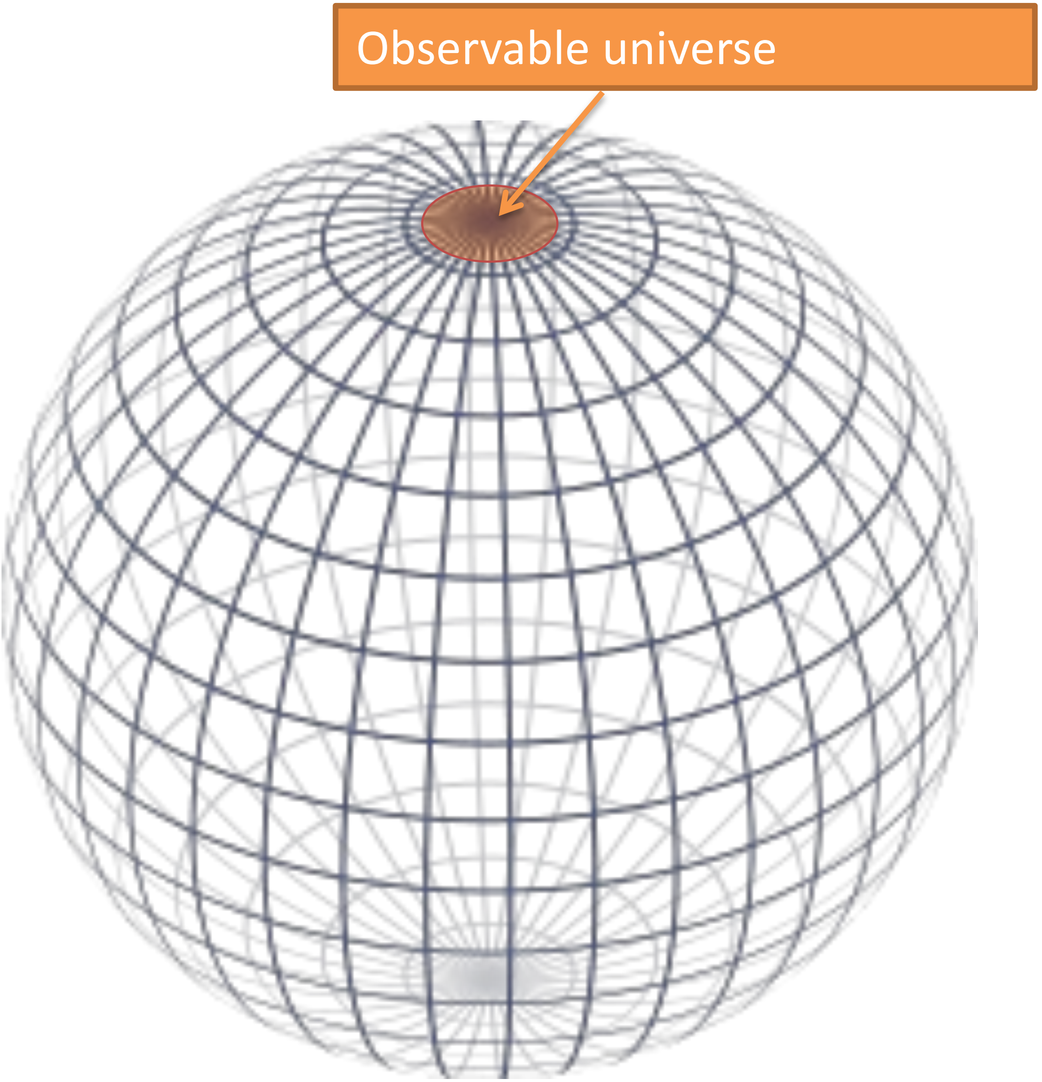
ΛCDM + one extra feature (parameter):

Parameter	Planck 2018	+ other data
$\Omega_K = 1 - \Omega$	-0.011±13	0.001±4
Σm_ν [eV]	< 0.241	< 0.120
$N_{\rm eff}$	2.89±0.38	2.99±0.34
$r = T/S$	< 0.101	< 0.065
w = DE p/ρ	-1.57±0.50	-1.04±0.10
nonG $f_{\rm NL}$	-0.9±10.2	
α_T (matter)	< 1.3%	
α_T (neutrinos)	< 1.7%	

(95% confidence limits)

Flatness of the universe

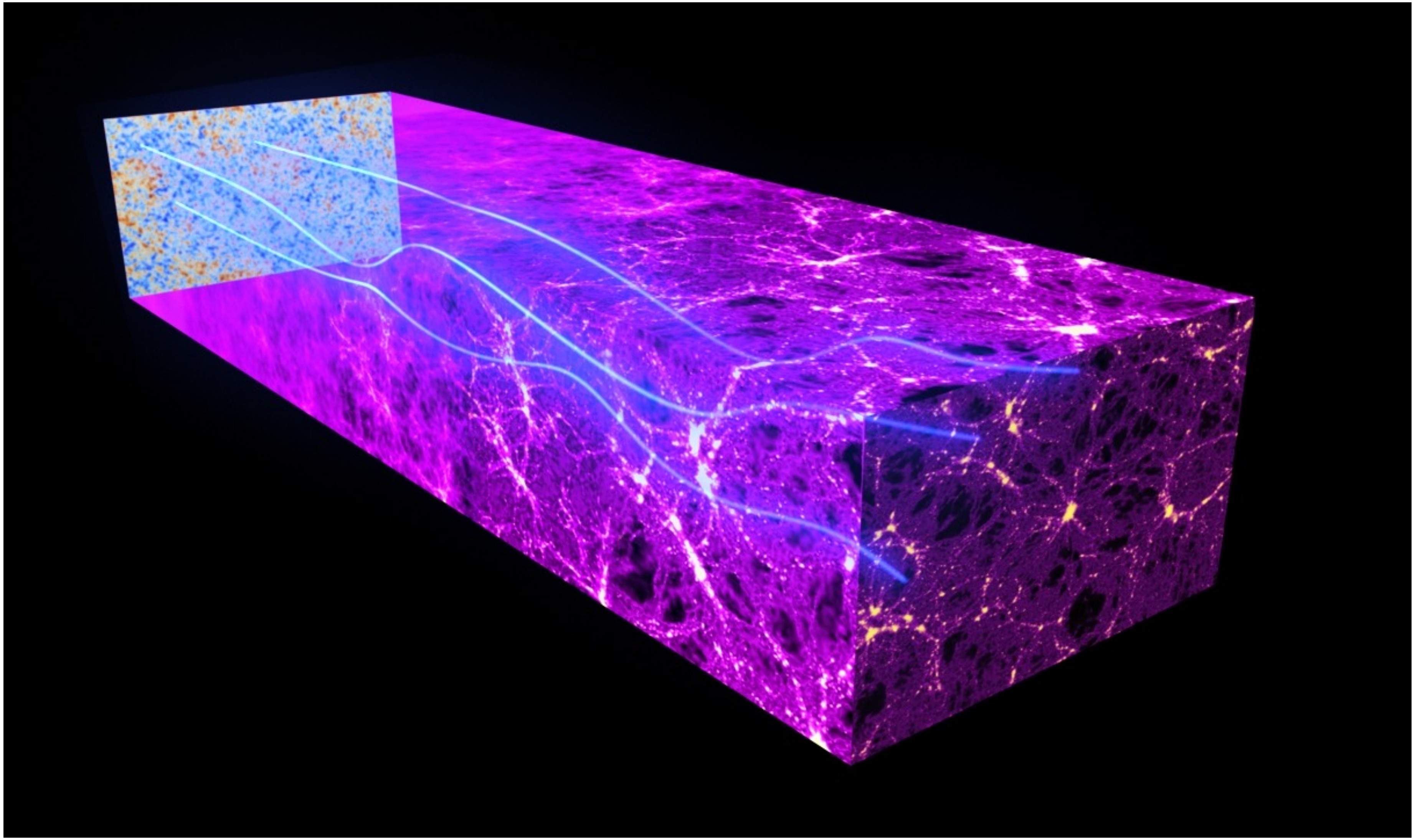
- Planck data agrees with a flat universe
- No sign of background curvature
- Deviation from critical density < 0.5%
- Curvature radius > 5.9 x distance to the horizon (from where CMB comes)



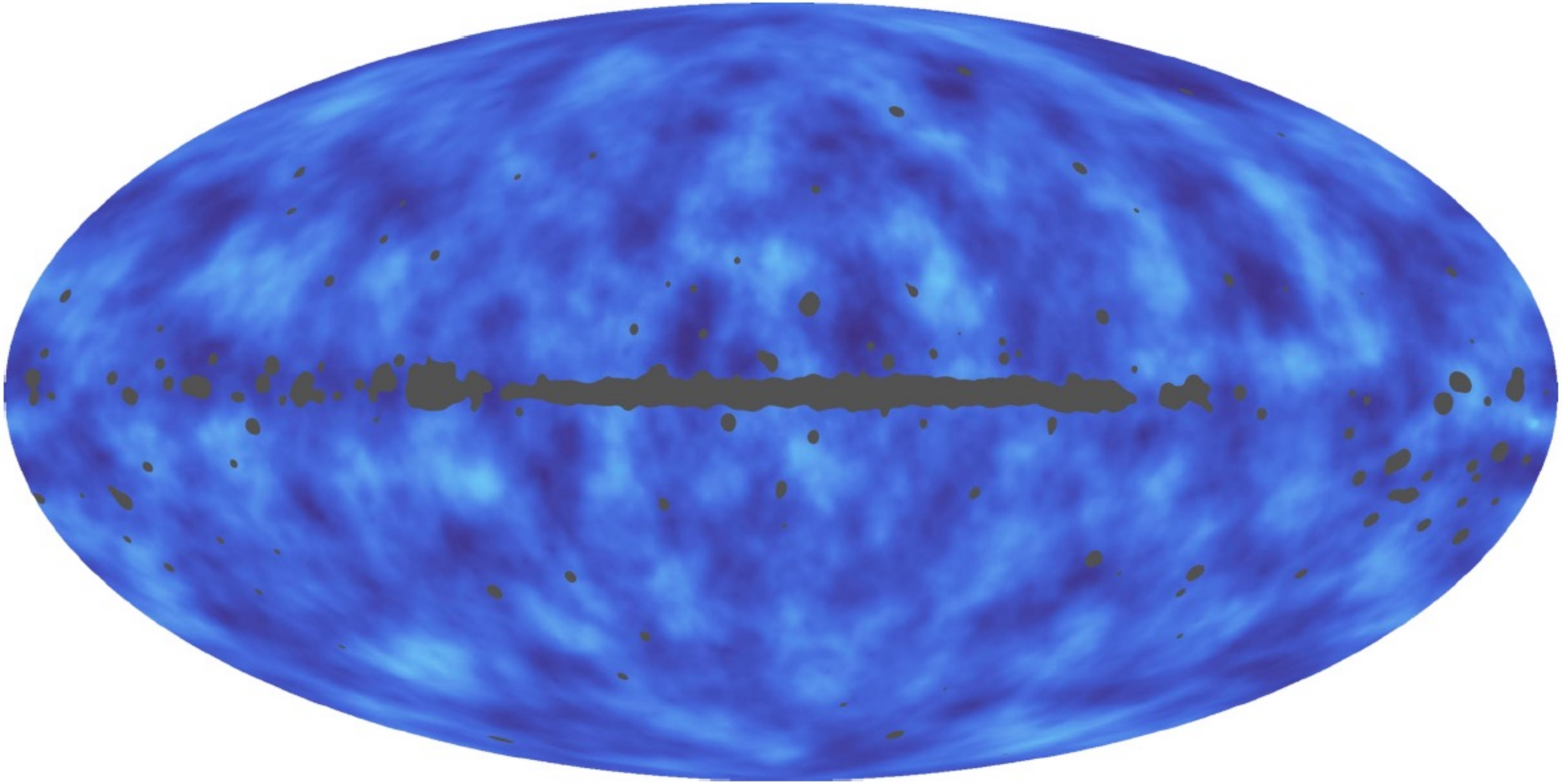
Smallest allowed closed (3-sphere) universe

Lensing of the CMB

$$T(\hat{\boldsymbol{n}}) = T^{\mathrm{unl}}(\hat{\boldsymbol{n}} + \nabla\phi(\hat{\boldsymbol{n}})),$$



Lensing Potential ≈ Distribution of Dark Matter



Planck 2015

Lighter color = more dark matter

Summary

- We have a working cosmological model that agrees with observations:
  - The universe is flat (Ω = 1)
  - Expands according to the laws of general relativity
  - Energy content:
    - ≈ 69% dark energy (cosmological constant, vacuum energy)
    - ≈ 26% cold dark matter
    - ≈ 5% ordinary (“baryonic”) matter
    - < 0.6 % neutrinos
    - 0.005% photons
  - Structure (galaxies, their clustering) formed by gravitational attraction starting from small primordial seed density variations,
  - which were created by some random process in the very early universe (consistent with quantum fluctuations during inflation)

- Primordial perturbations:
  - almost scale invariant ($n = 0.965 \pm 0.004$)
  - no gravitational waves observed so far ($r < 6.5\%$)
  - no deviations from Gaussianity observed so far ($f_{\mathrm{NL}} < 11$(≈ 0.2%))
  - no deviations from adiabaticity observed so far ($\alpha_T < 1.7\%$)
  - agrees with predictions from the simplest inflation models
    - but we would like to observe primordial gravitational waves
- Open questions:
  - Nature of dark energy ? (New ESA mission Euclid, launch 2023)
  - What is the cold dark matter particle ? (LHC)

Galaxy survey cosmology

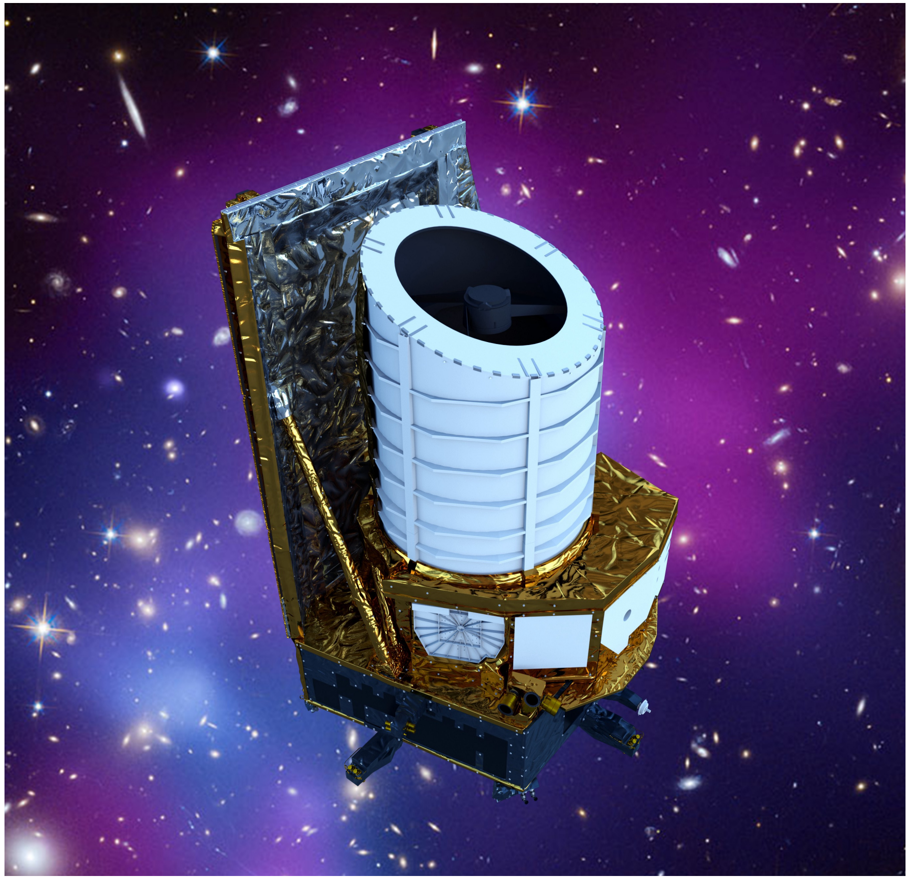
- Current observational information on cosmology is dominated by the cosmic microwave background (z ~ 1000)
  - WMAP and Planck space missions
- Focus on the early universe
- Constraints on evolution from then to now are weak
- Attention now turning to large galaxy surveys
- Focus on the evolution during the last ¾ of the history
  - z ~ 2 to 0

Ground-based surveys

- Current (or past)
  - Sloan Digital Sky Survey (SDSS)
    - Baryon Oscillation Spectroscopic Survey (BOSS)
  - Kilo-Degree Survey (KiDS)
  - Dark Energy Survey (DES): 3-year results published
- Future
  - Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST), first light 2023

Space missions

- Euclid (ESA), launch 2023



- Nancy Grace Roman Space Telescope (NASA), launch after 2025 (2026-27 ?)

Two-point correlation function ξ

- Measure of clustering of galaxies
- ξ(r) = excess probability of finding another galaxy a separation r from a randomly chosen galaxy

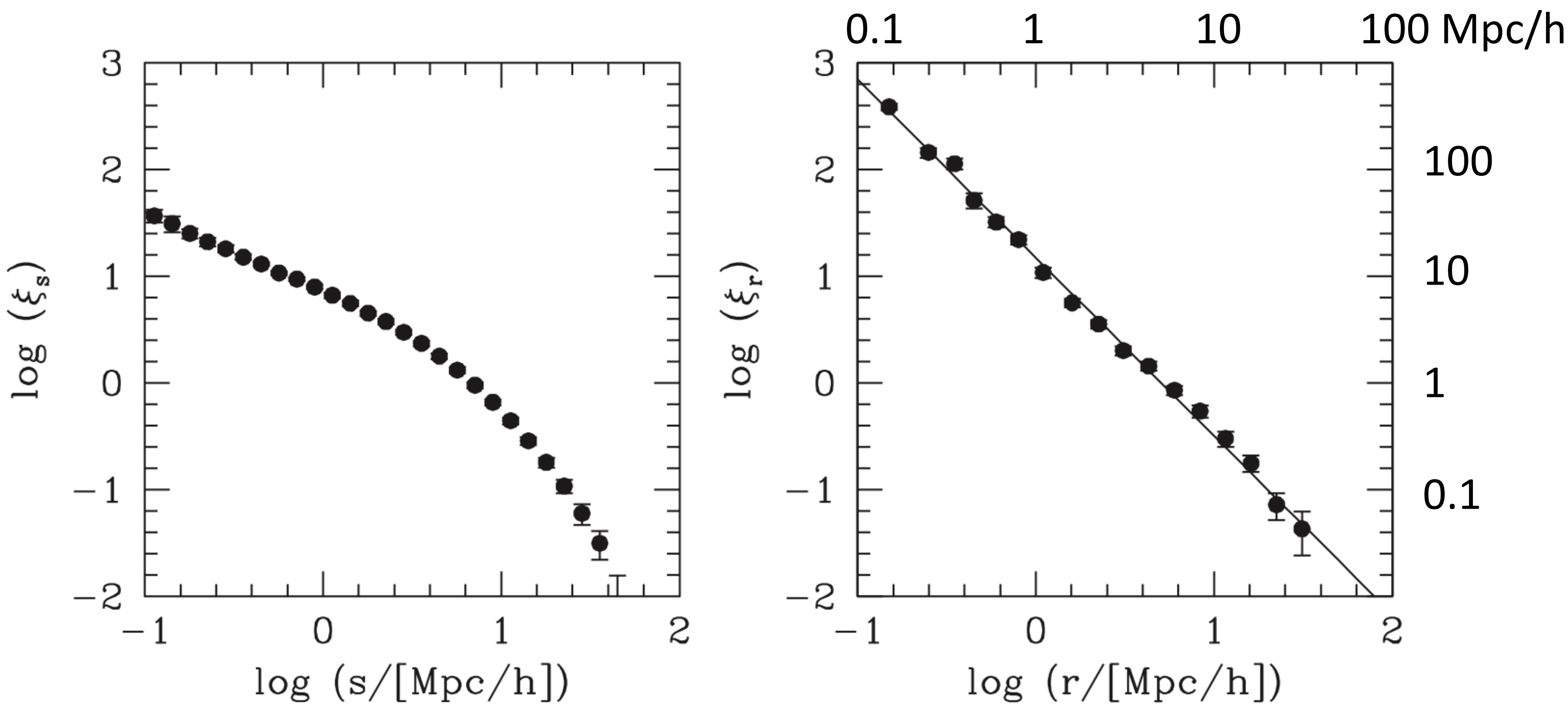
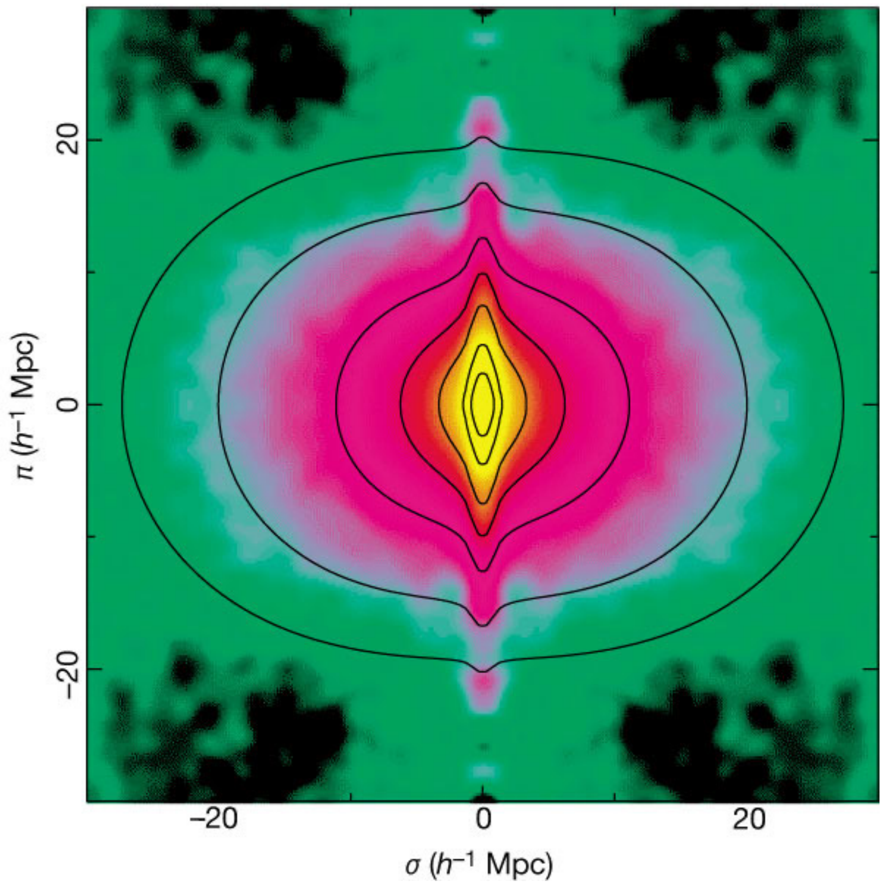


Fig. 2.37. The two-point correlation function of galaxies in redshift space (left) and real space (right). The straight line is a power law, $\xi(r) = (r/r_0)^{-\gamma}$, with $r_0 = 5.05\,h^{-1}$Mpc and $\gamma = 1.67$. [Based on data published in Hawkins et al. (2003)]

[MBW p. 83]

Redshift-space distortions (RSD)

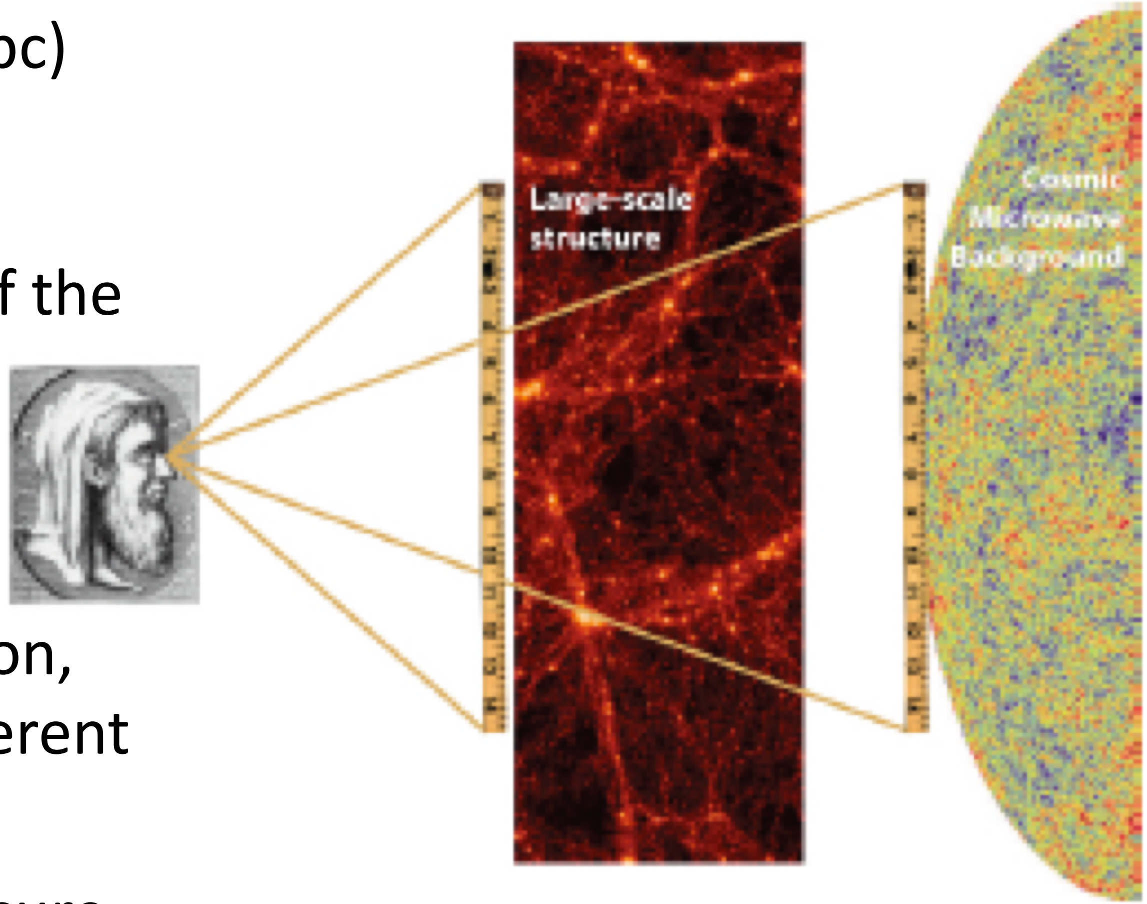
- Distance to the galaxy determined from redshift
  - Affected by peculiar velocity
- Affects radial component of position
  - Transverse component (position on sky) not affected

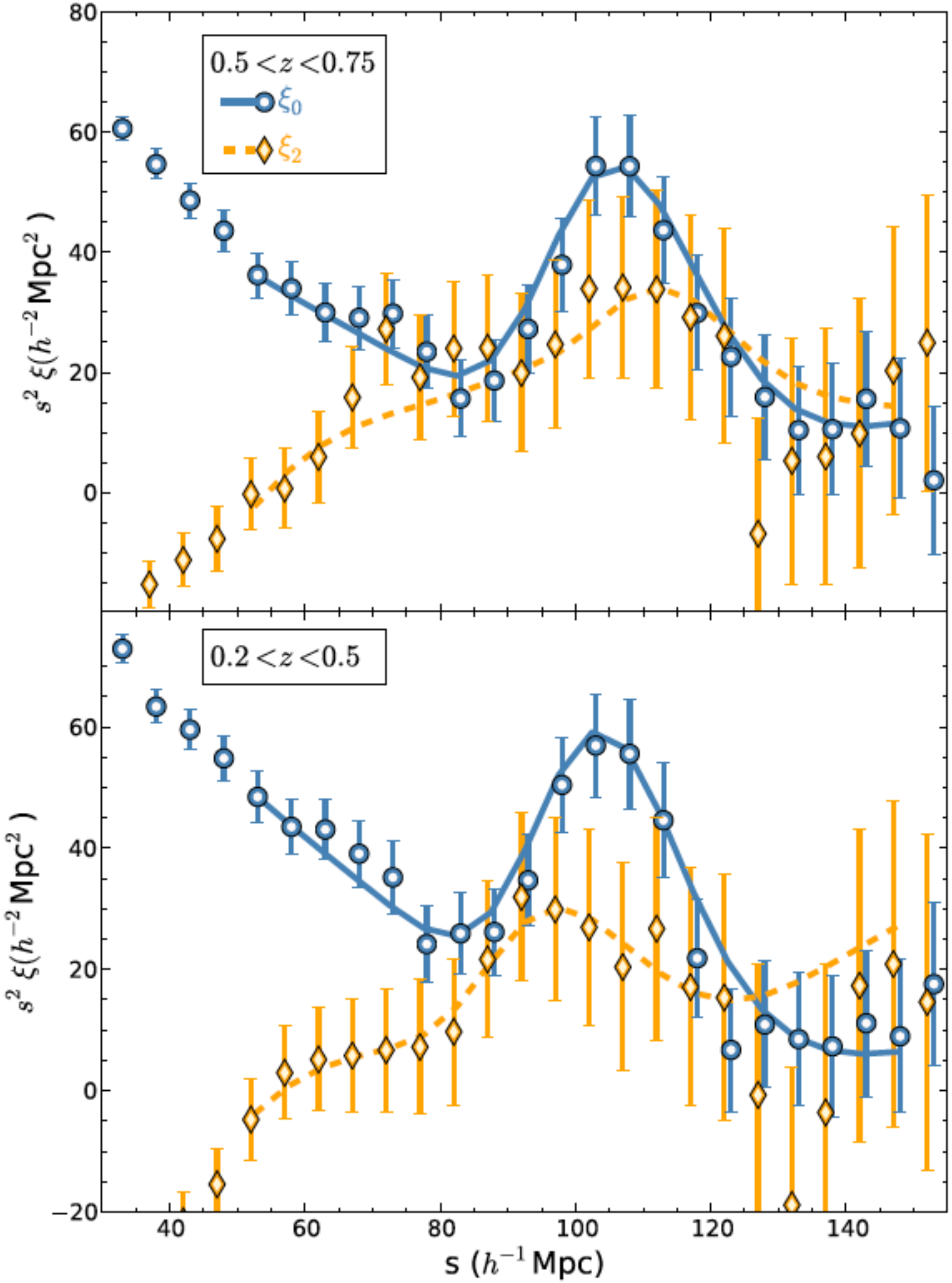


[Peacock et al, Nature 410, 169 (2001)]

Baryon Acoustic Oscillation scale

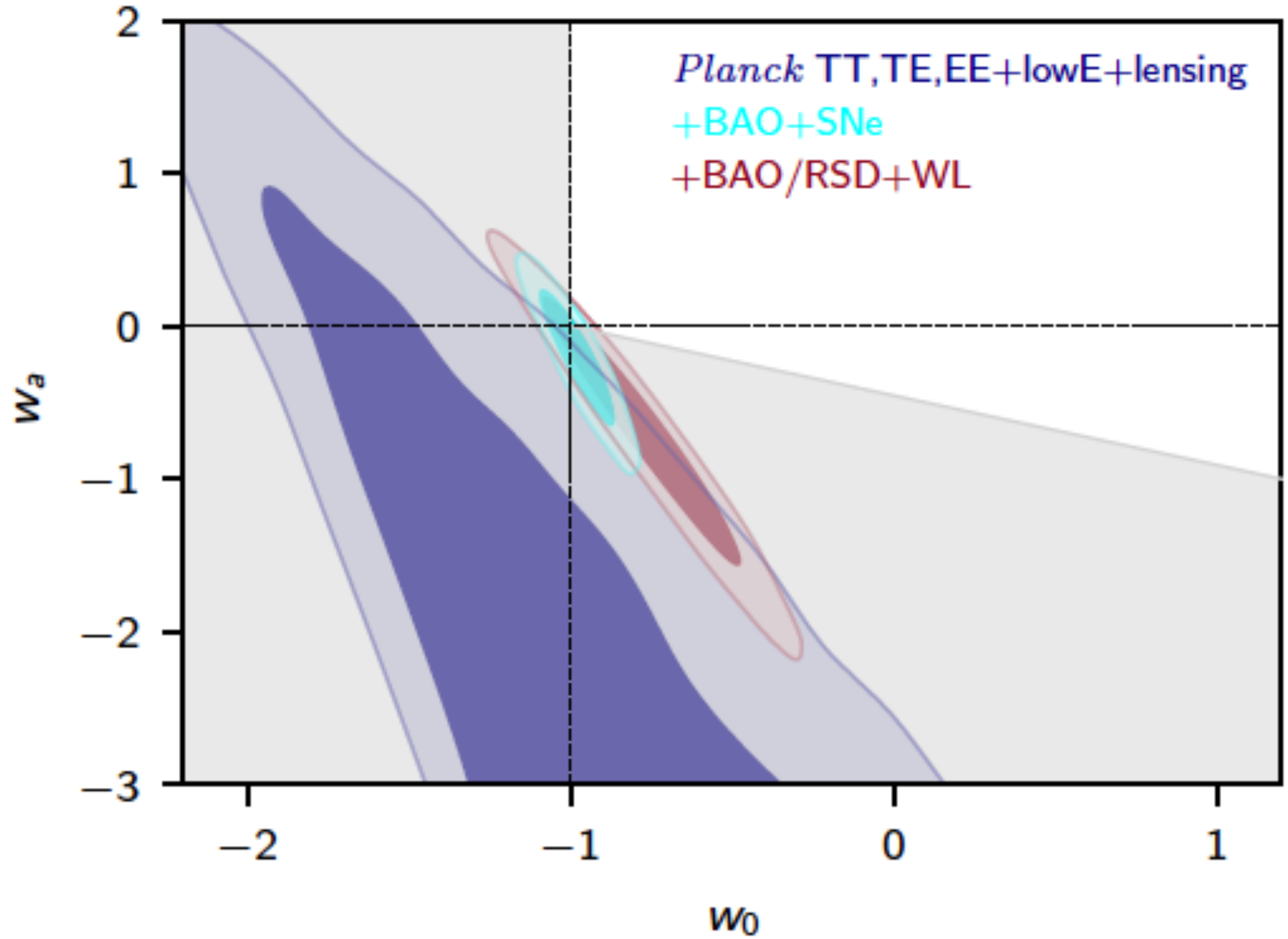
- Distance scale (~ 140 Mpc) imprinted on matter distribution in the early universe by oscillation of the baryon-photon fluid
- Prominent in the CMB anisotropy (z = 1090)
- Faint in galaxy distribution, can be measured at different redshifts z
- A standard ruler to measure expansion





Ross et al. arXiv:1607.03415
MNRAS 464, 1168 (2017)

Two-parameter dark energy equation of state: $p = [w_0+w_a(a-a_0)]\rho$

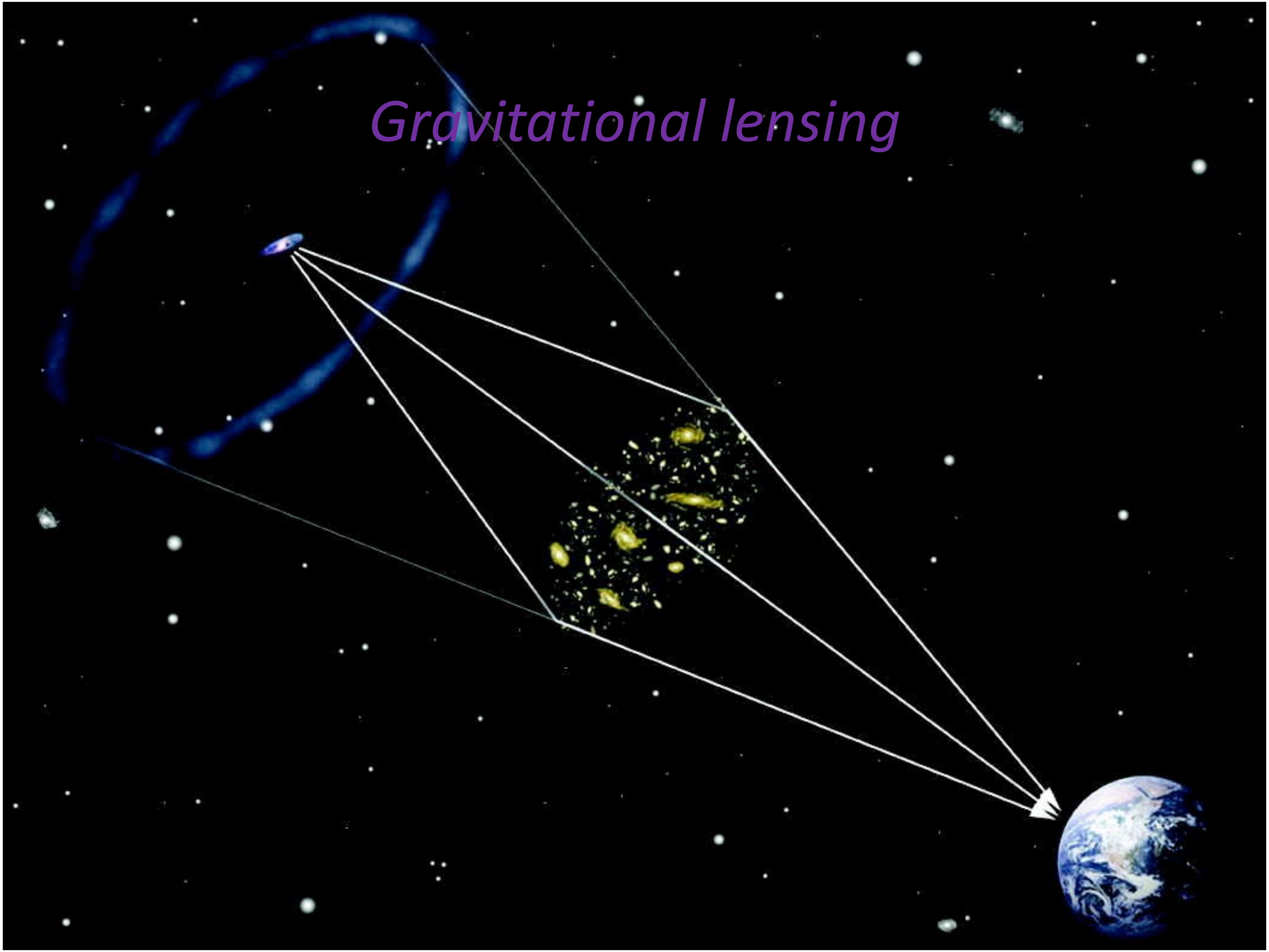


[Planck Collaboration, arXiv:1807.06209]

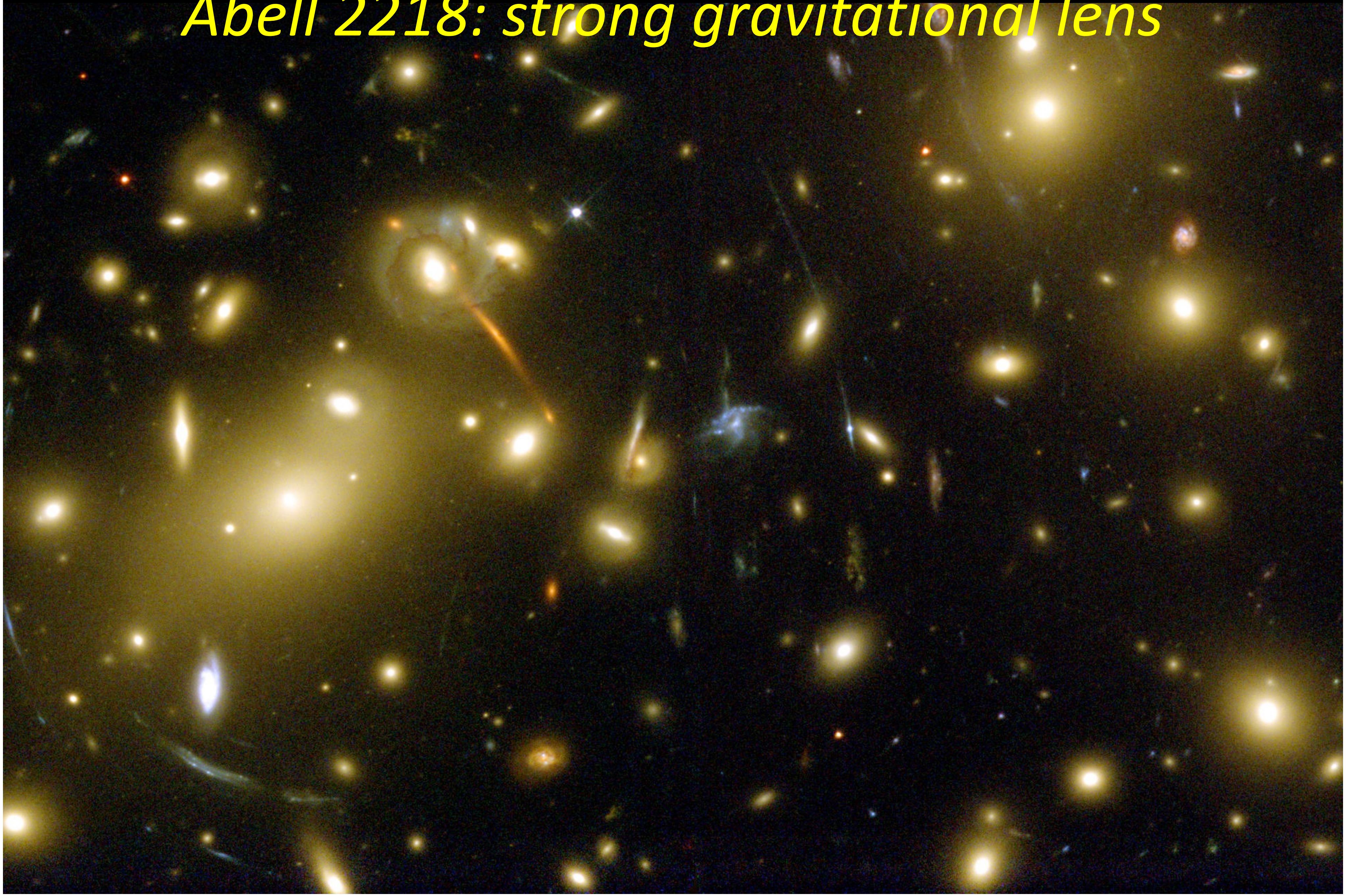
Dark energy vs modified gravity

- Both can give the same expansion history
- But they affect growth of structure (formation of galaxies and galaxy clusters) differently
- Expansion slows down formation of structure
- Modifying gravity has an additional effect
- Most of the structure is in the distribution of dark matter; galaxies provide only a crude measurement
- How to see dark matter structures?
  - Gravitational lensing

Gravitational lensing

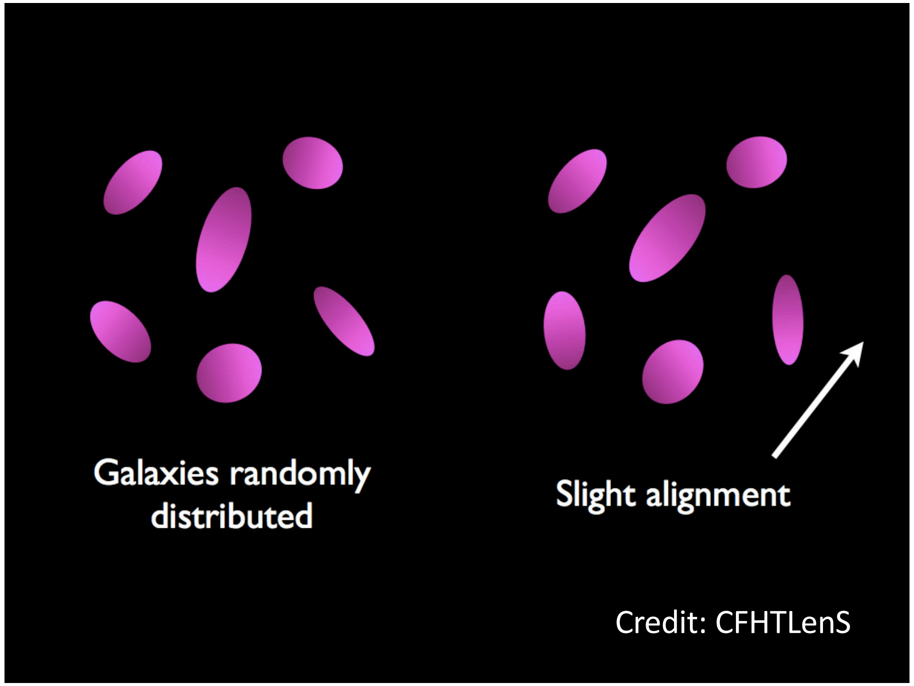


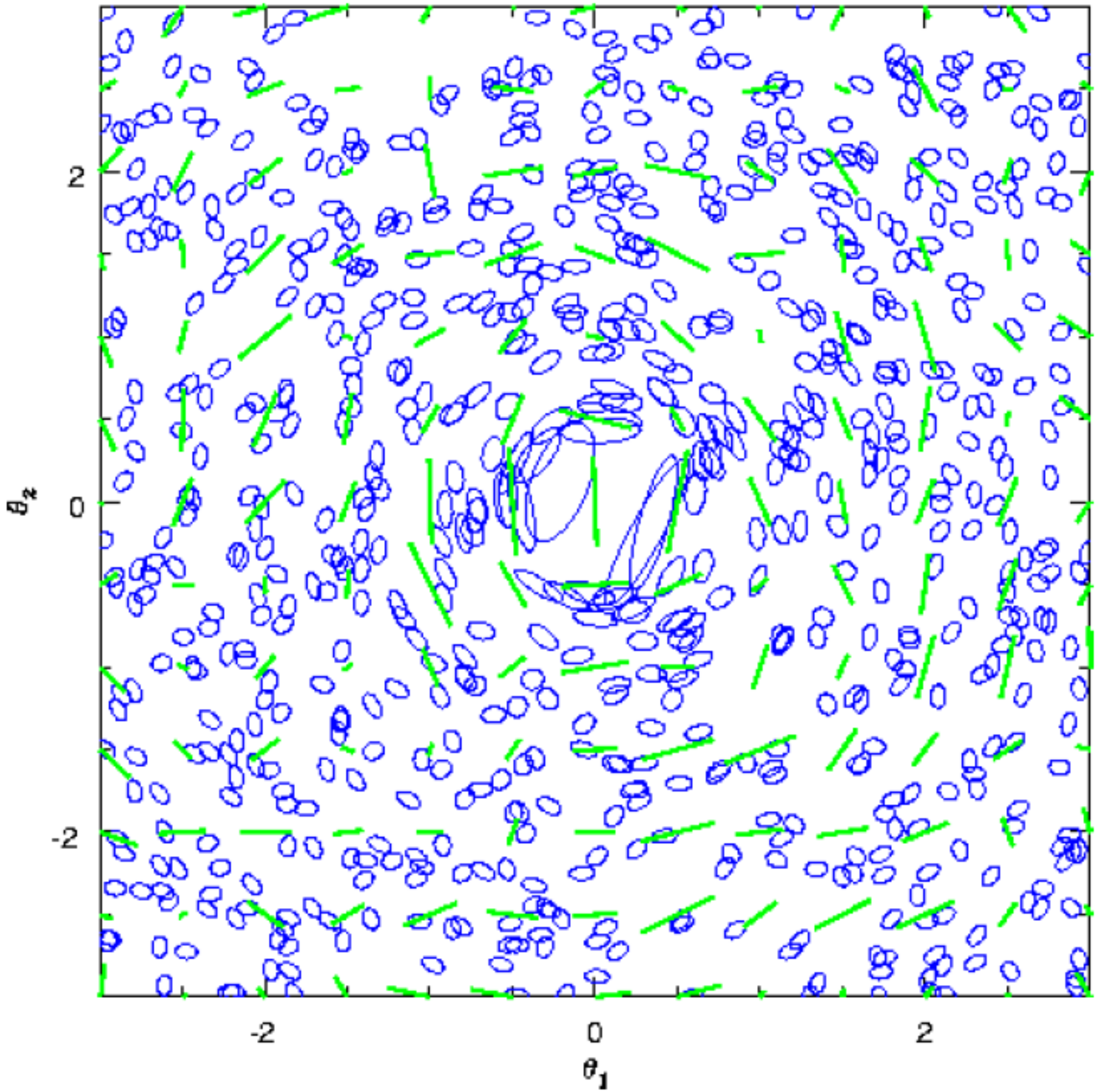
Abell 2218: strong gravitational lens



All galaxies are lensed

- For most galaxies the effect is small (weak lensing)
  - Image stretched by a few %
- But large enough to be measured
- If we only knew the true shape of the galaxy!
- Statistical method
  - Fit an ellipse to each galaxy image
  - Assume galaxies oriented randomly
  - If galaxies in the same small region of sky appear elongated in the same direction on average; conclude this is due to lensing

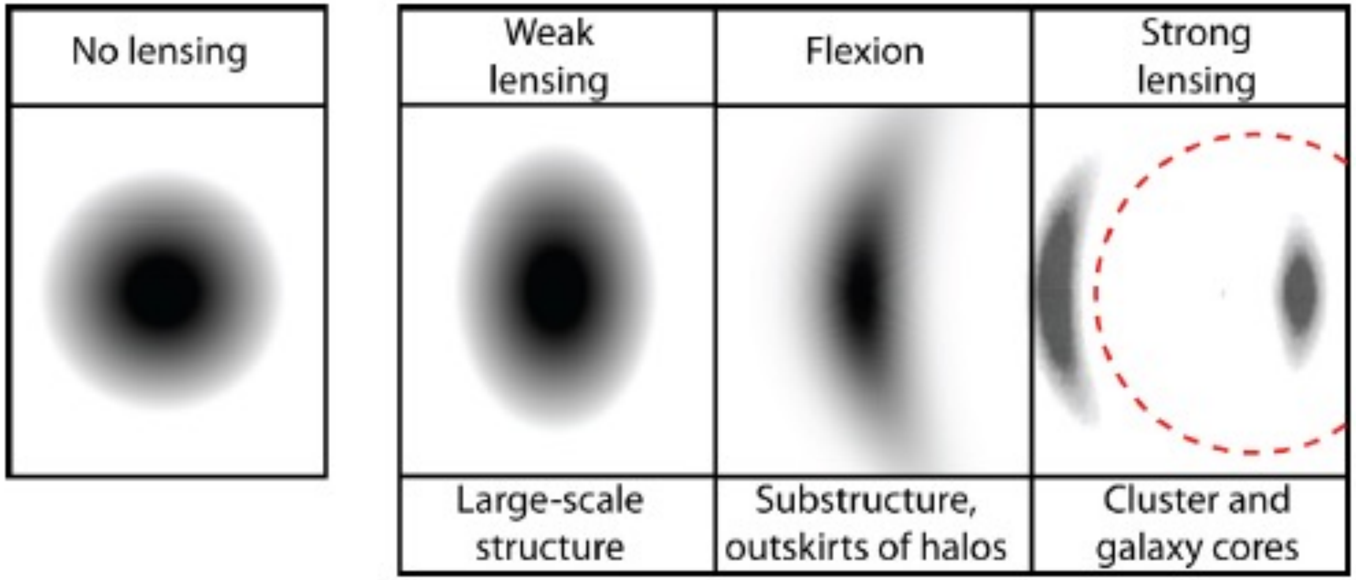


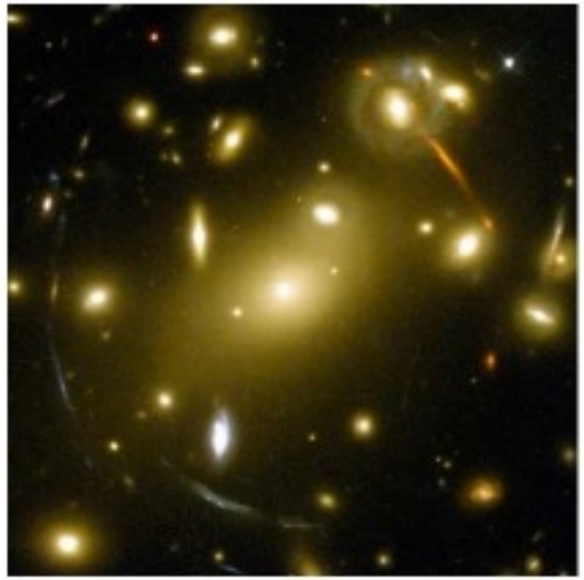


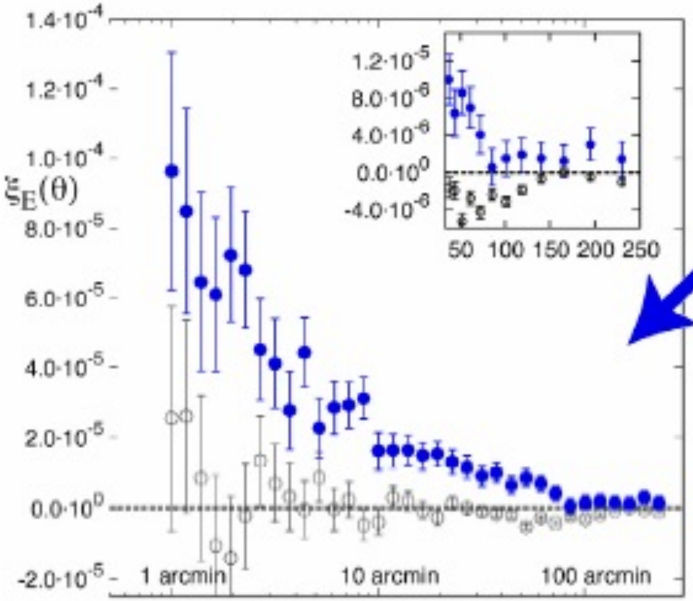
Shear (lensing) field

C. Seitz, dissertation (1996)

Gravitational lensing maps dark matter

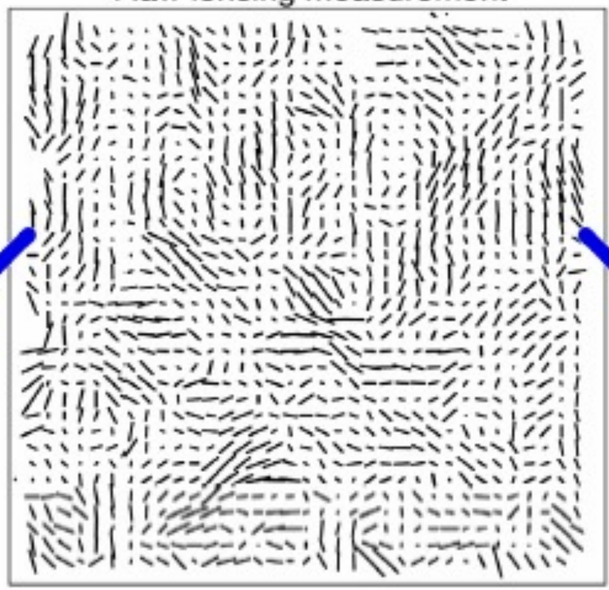


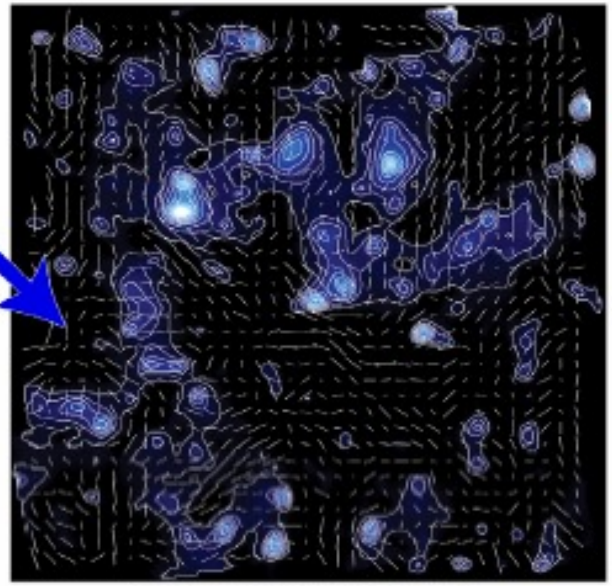




Correlation function

Raw lensing measurement

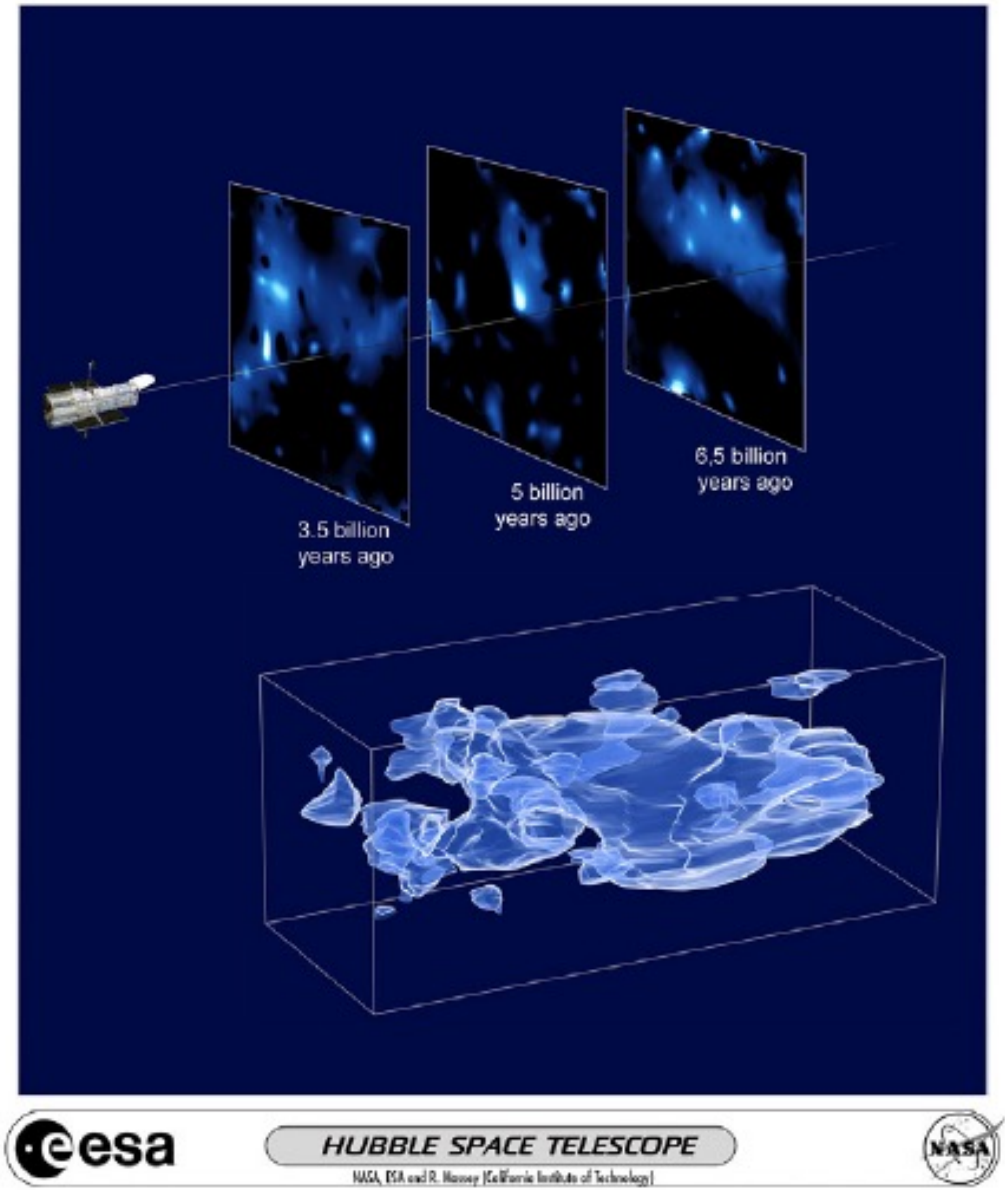


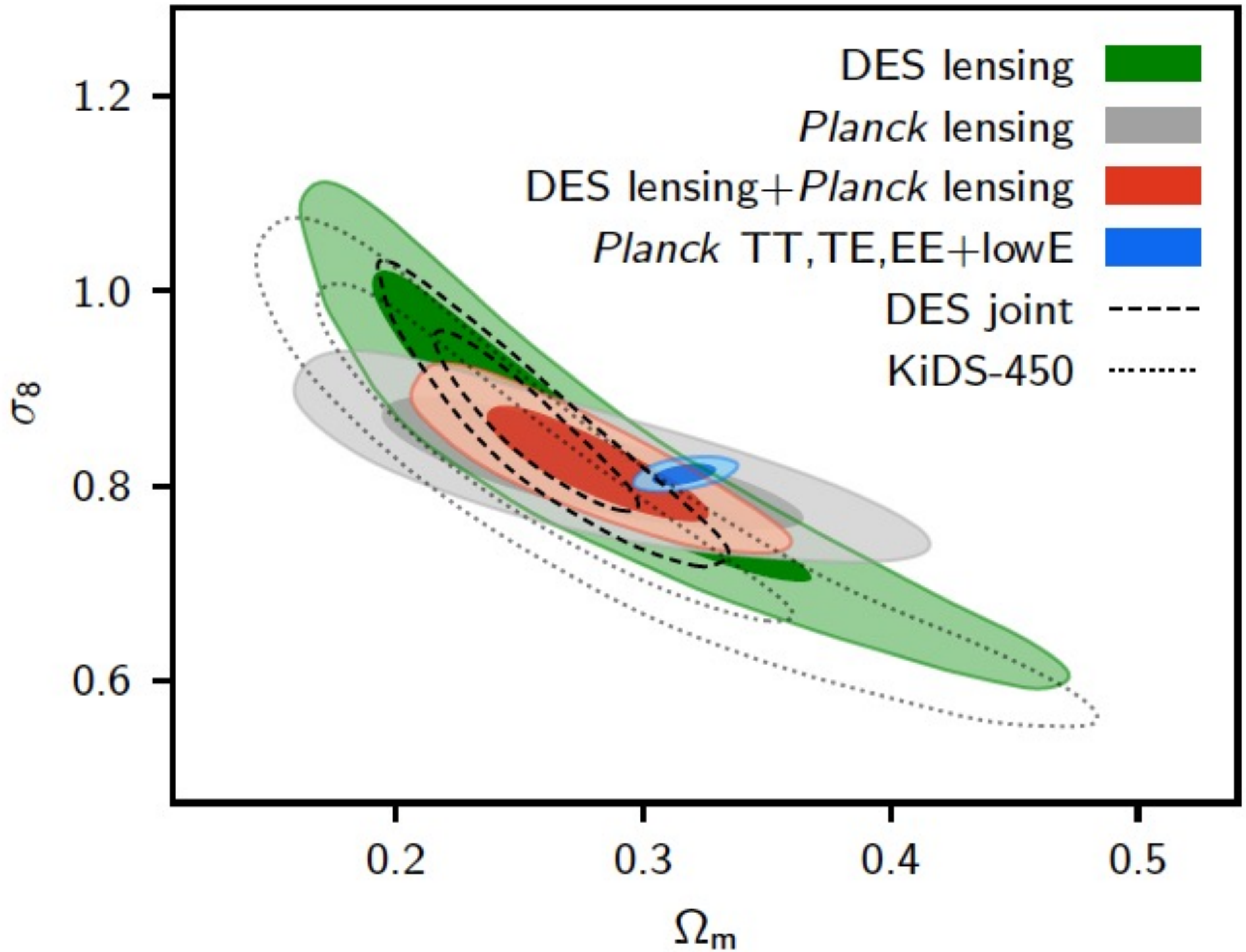


Dark matter distribution

Structure in dark matter

HST COSMOS survey of 2 square deg





[Planck Collaboration, arXiv:1807.06209]

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