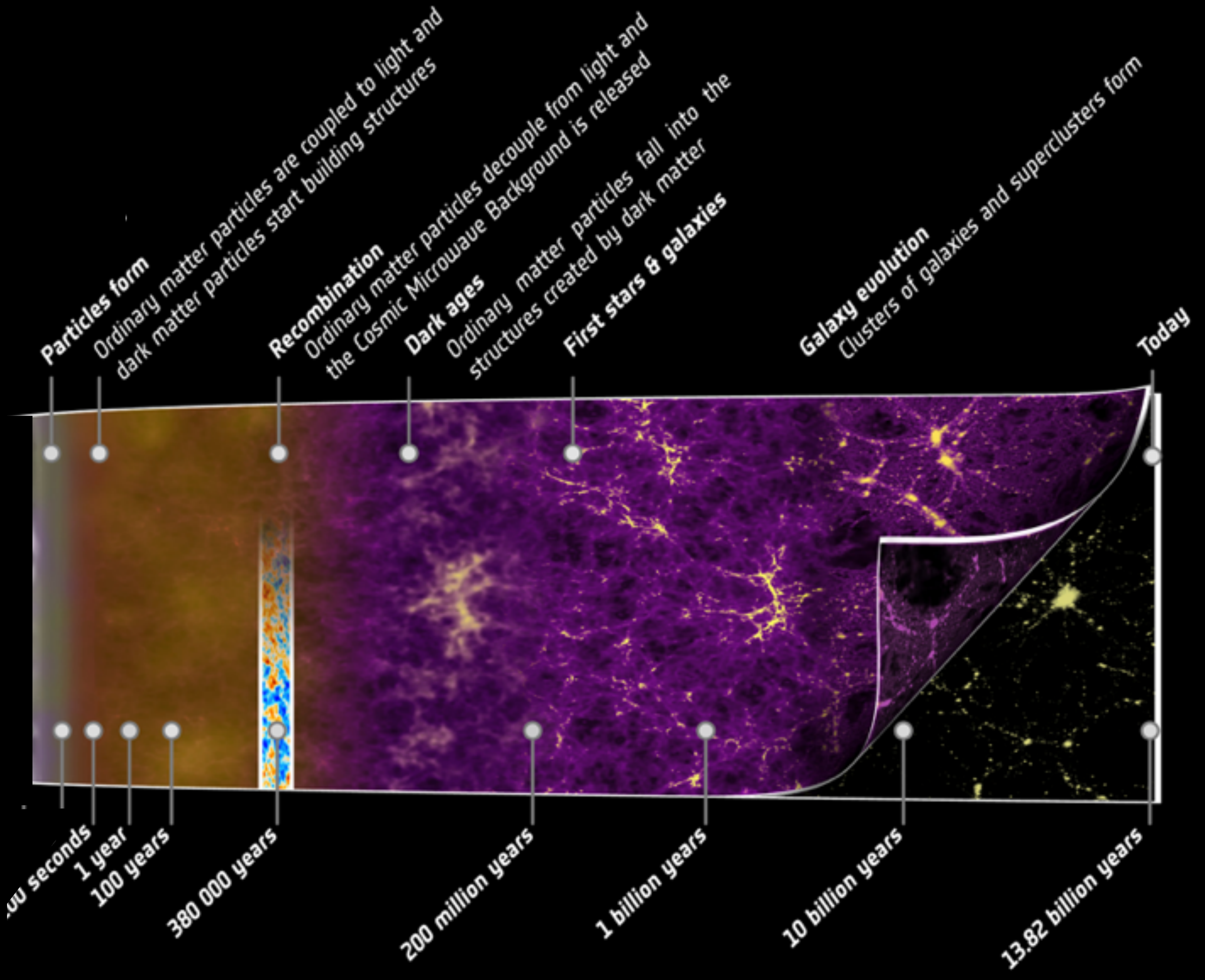
The history of our Universe: a work in progress

June 2017

The Hot Big Bang



Some history

- 1912 Henrietta Leavitt Cepheid variables in the LMC
- 1913 Vesto Slipher Redshift of Andromeda
- 1915 Harlow Shapley size of the Milky Way
- 1917 Einstein's paper applying GR to the entire Universe
- 1920 Shapley-Curtis Great debate
- 1922 Alexander Friedmann "On the curvature of space"
- 1924 Hubble Cepheids in Andromeda
- 1927 Georges Lemaître paper containing estimate of Hubble constant
- 1929 Hubble's paper with the Hubble law

- 1948 Bethe, Alpher Gamow, "The Origin of Chemical Elements", Gamow's "The Origin of Elements and the Separation of Galaxies" and Alpher and Herman's "Evolution of the Universe" with the estimate of the CMB temperature

The Hot Big Bang

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

A. A. Penzias
R. W. Wilson

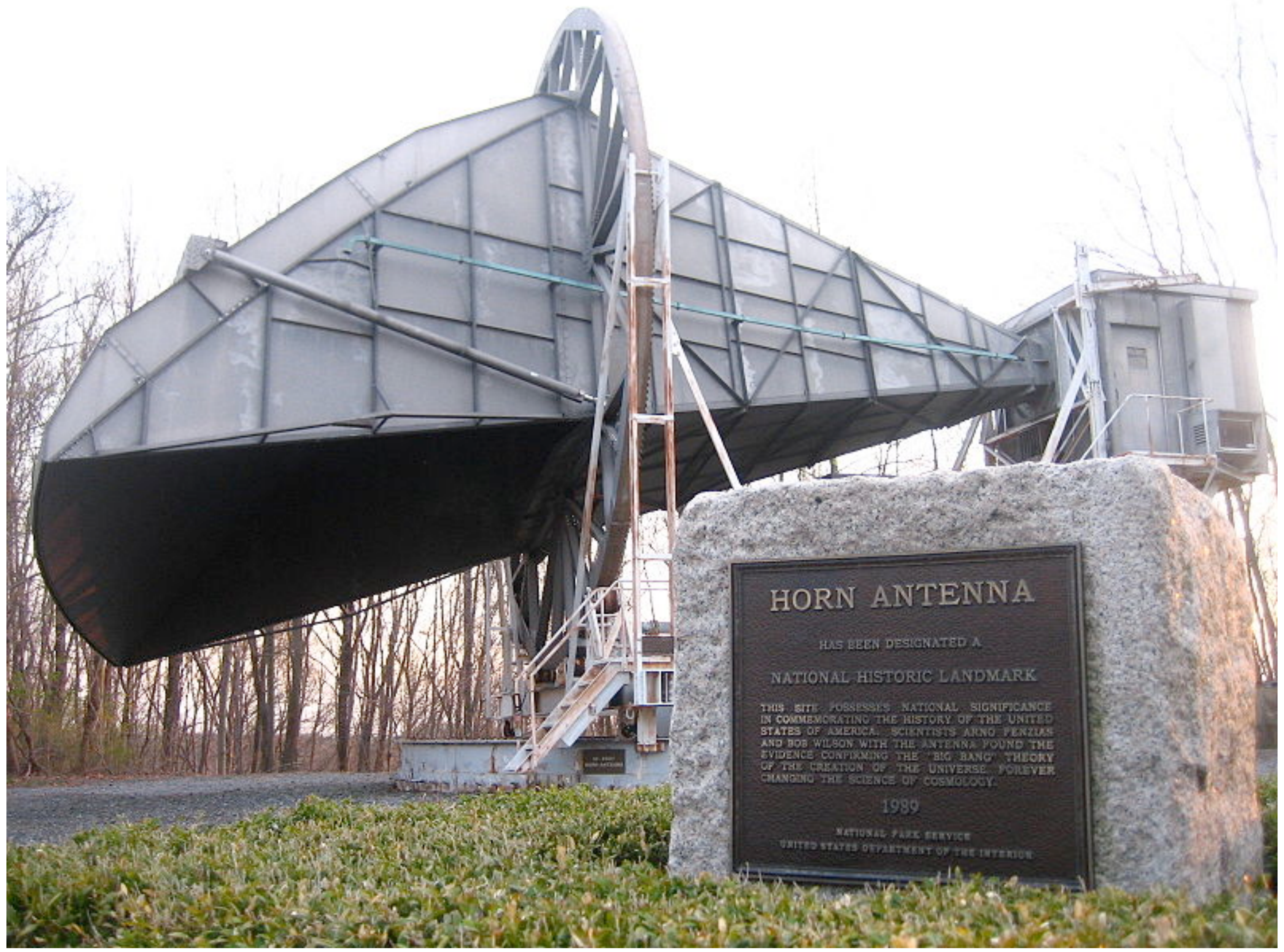
May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

COSMIC BLACK-BODY RADIATION*

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

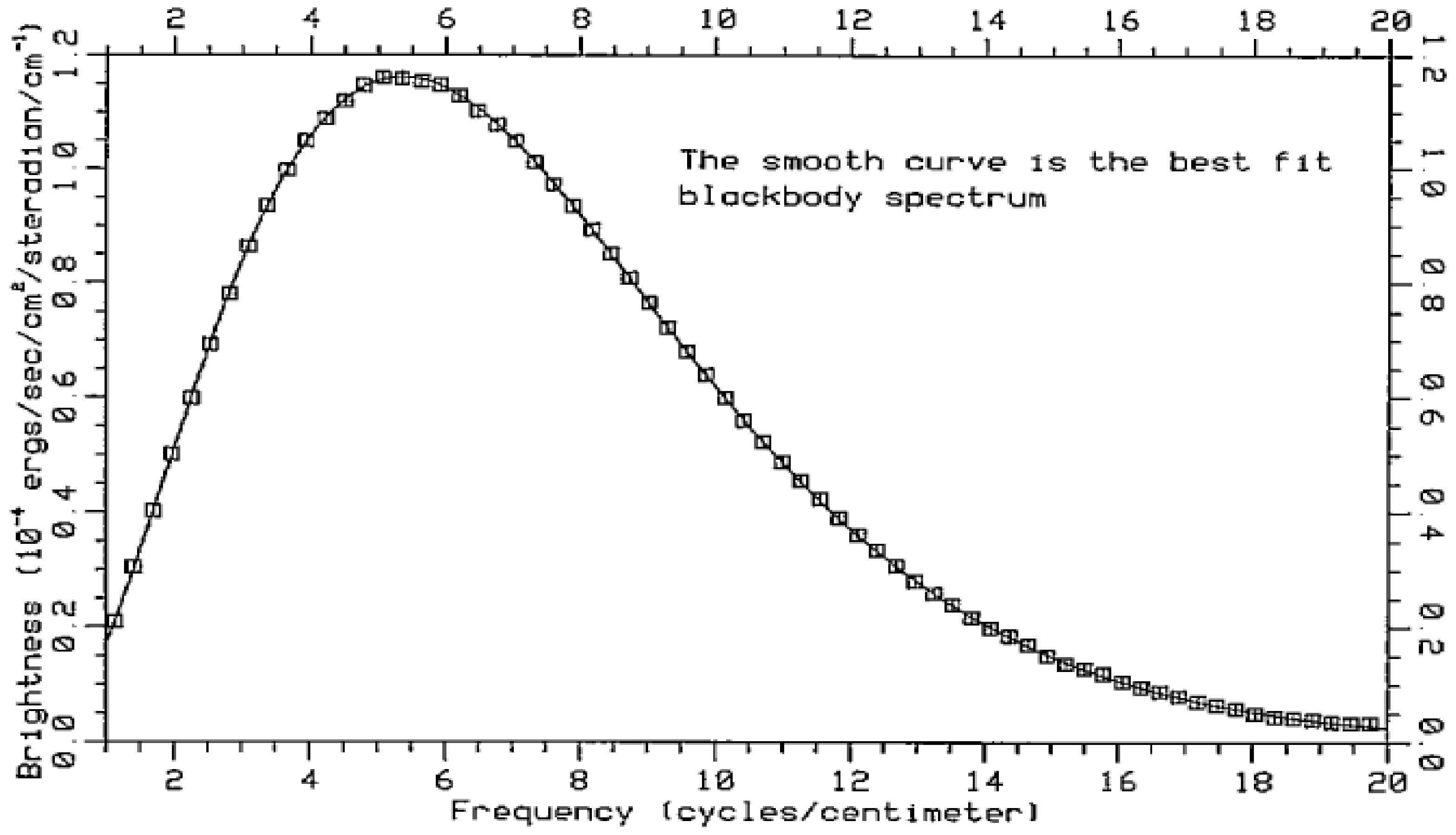
May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

Penzias & Wilson 1965

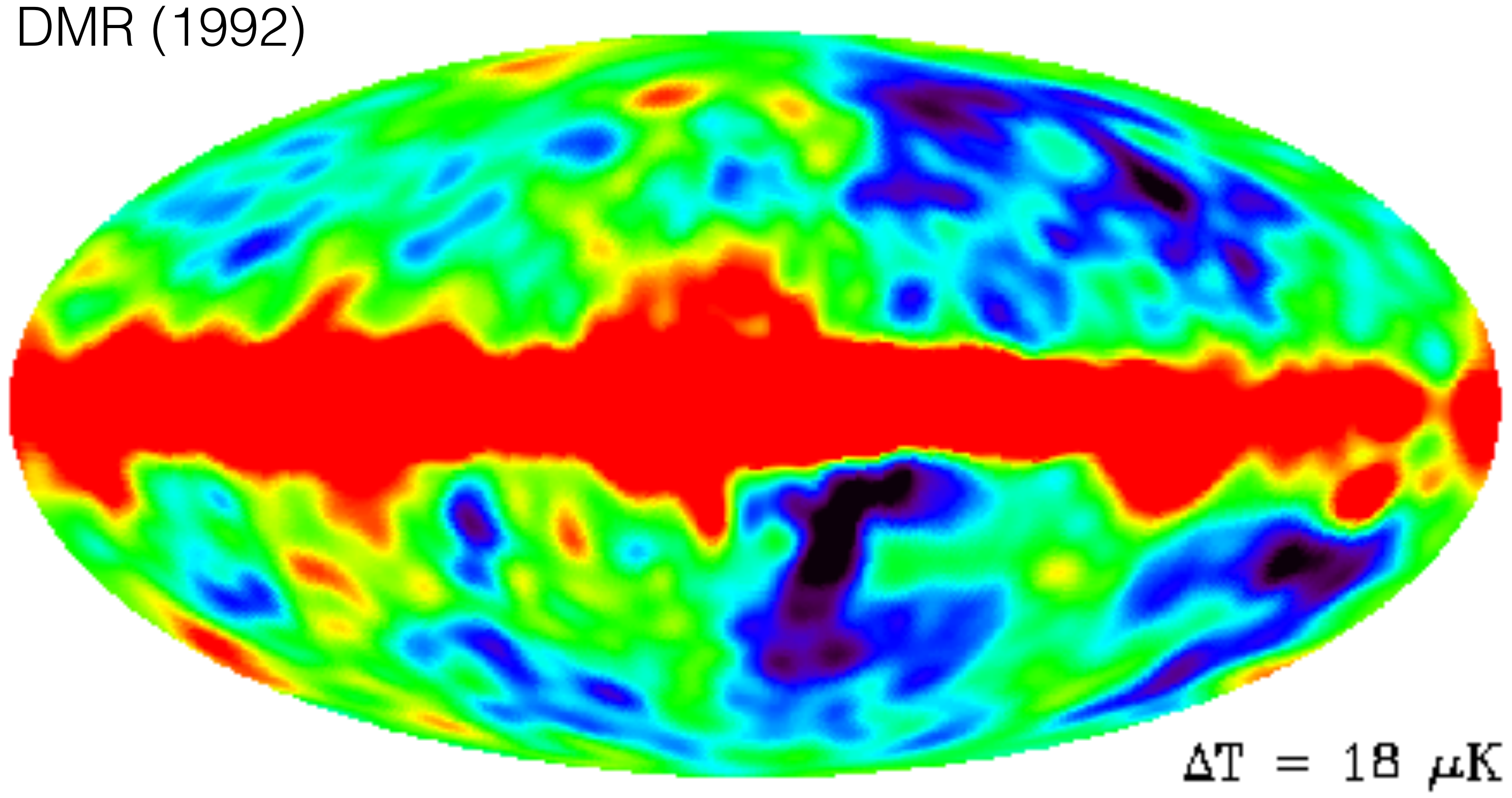


The Spectrum of the CMB

COBE FIRAS (1990)

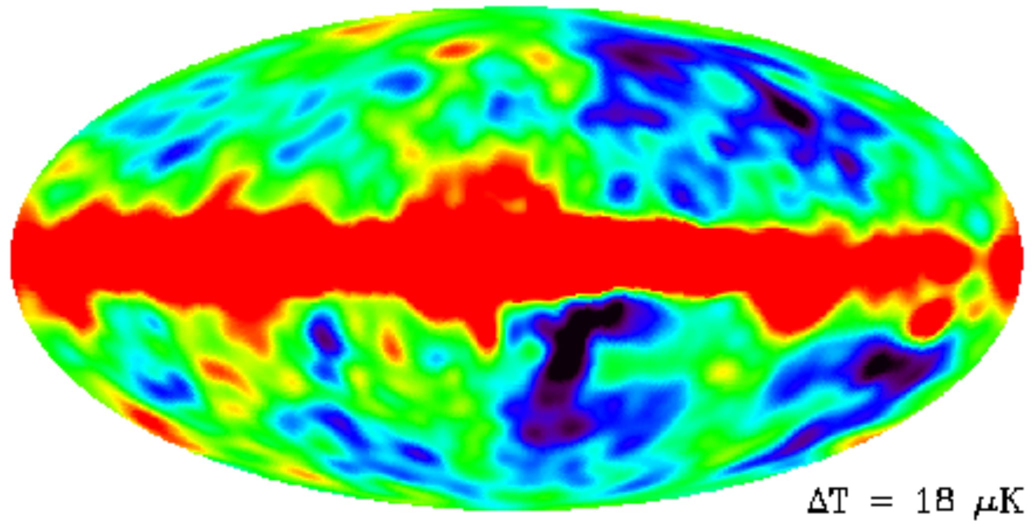


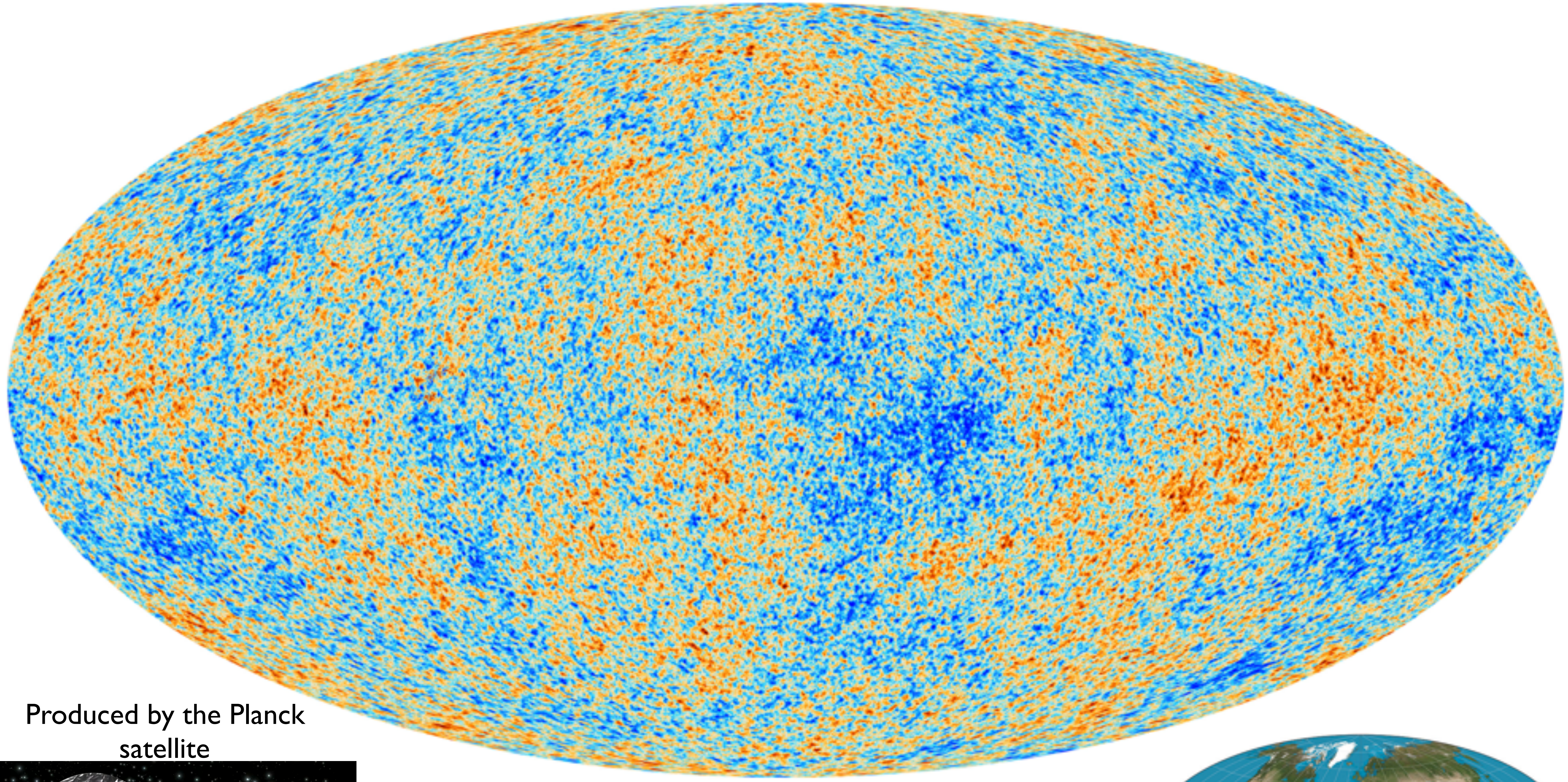
COBE DMR (1992)



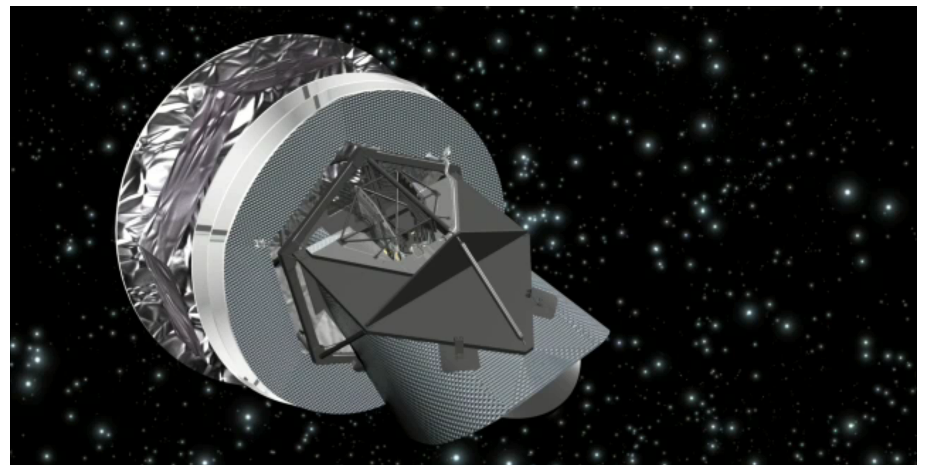
$\Delta T = 18\ \mu K$

CMB temperature in different directions



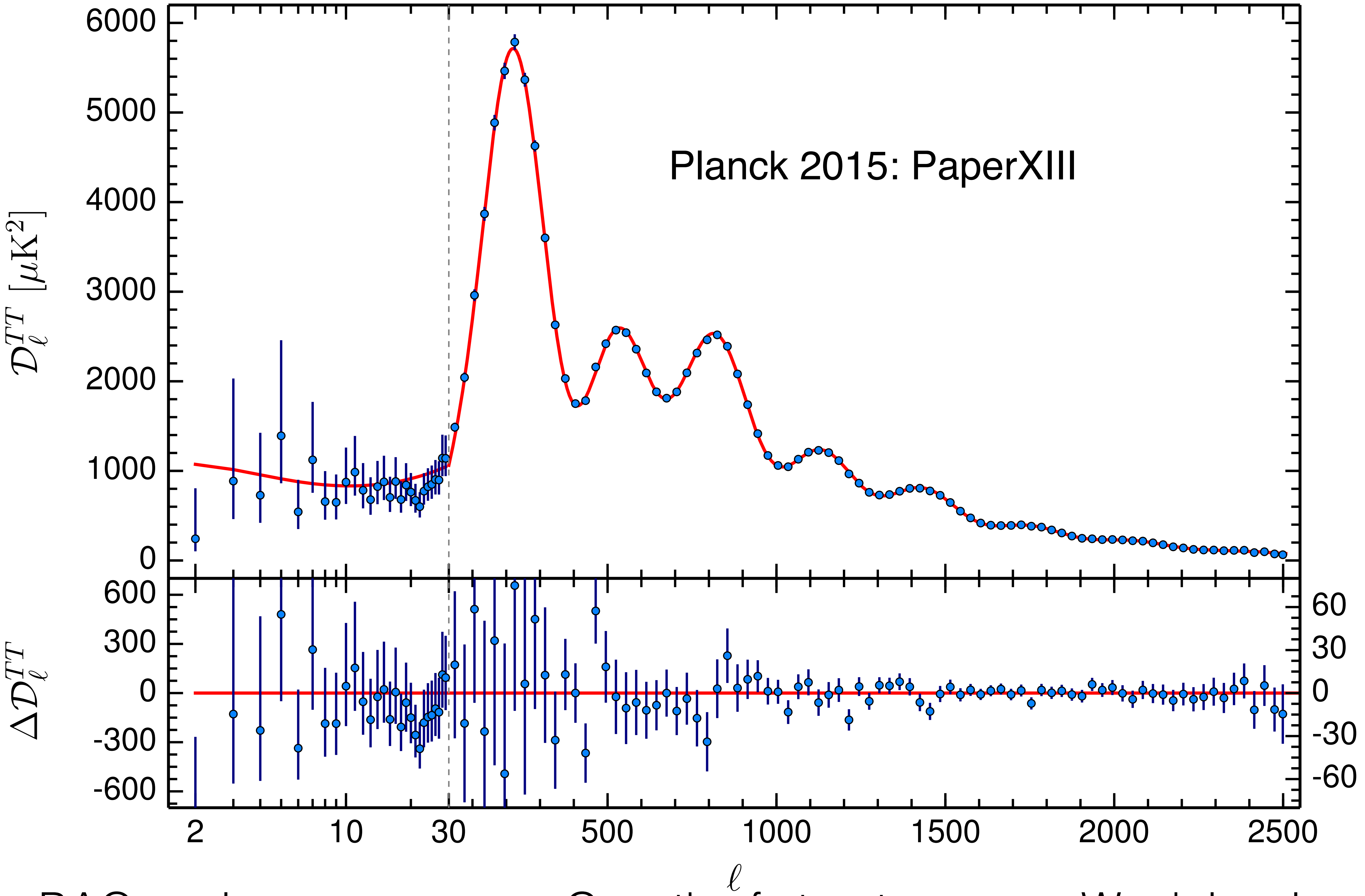


Produced by the Planck satellite

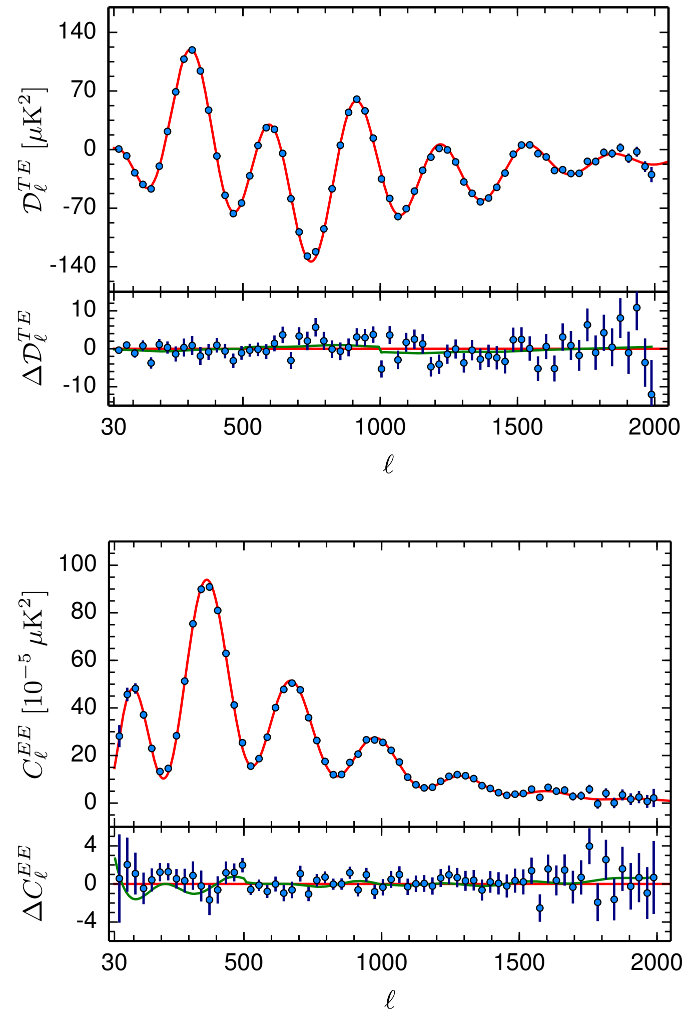


Earth in same projection

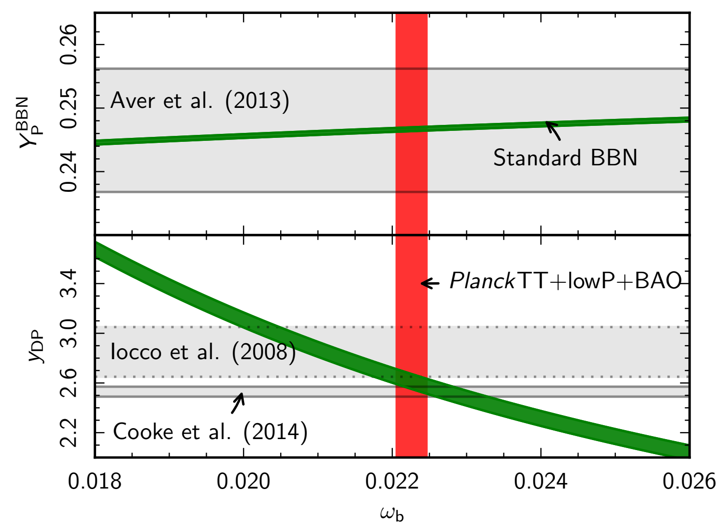
Agreement between theory and data



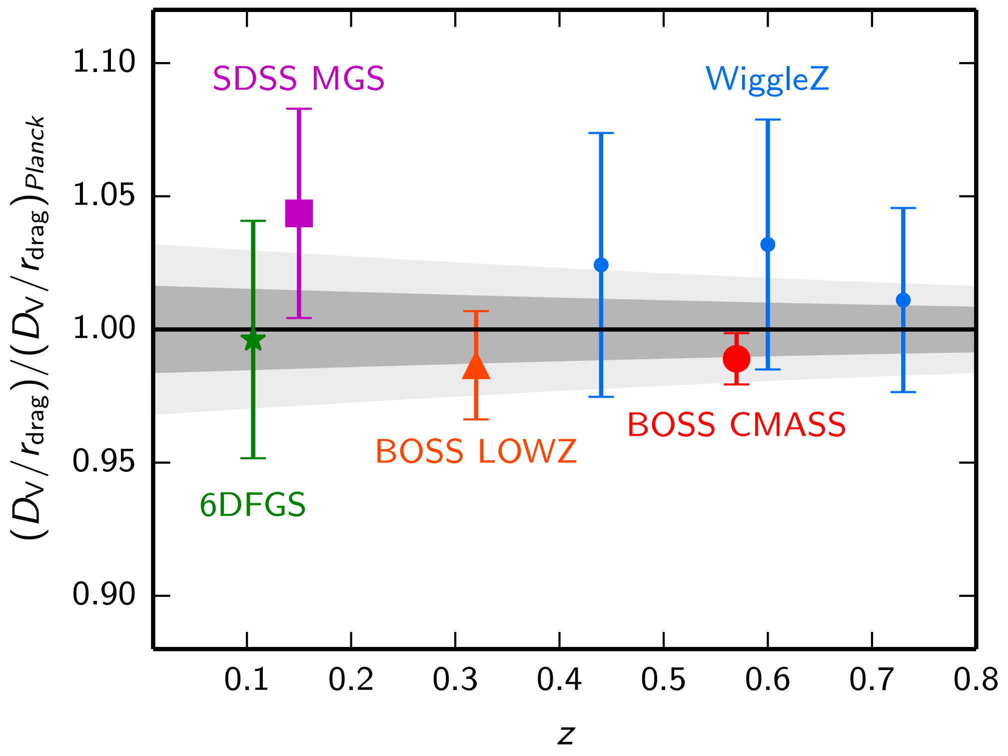
POLARIZATION



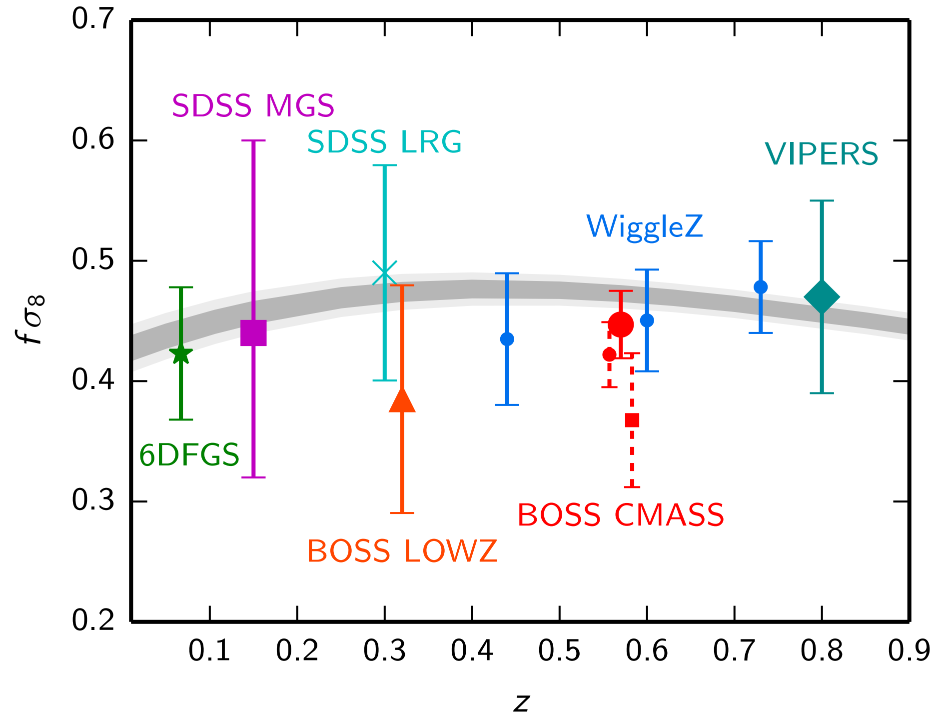
BBN



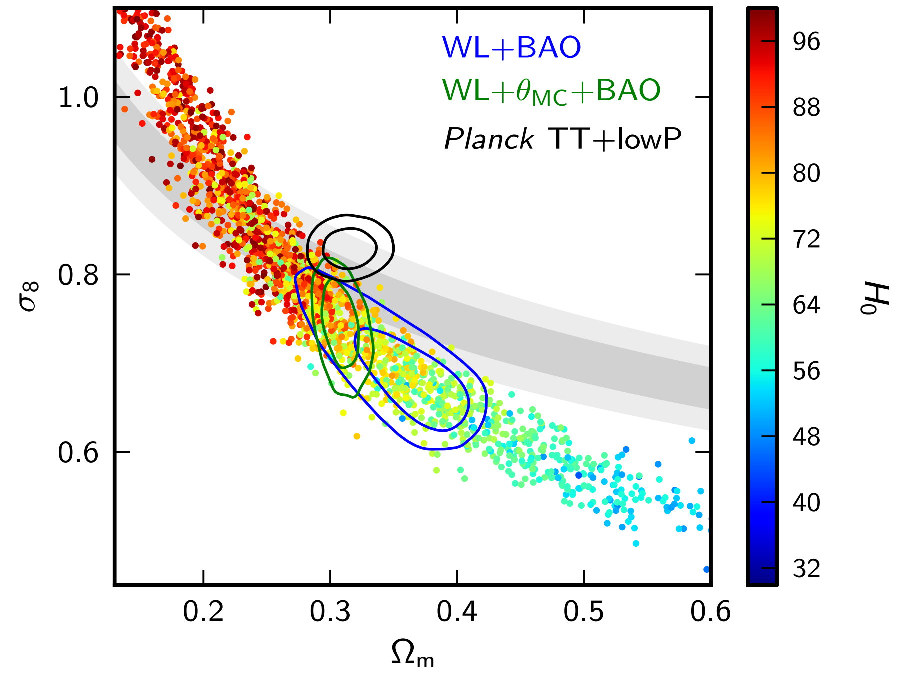
BAO scale



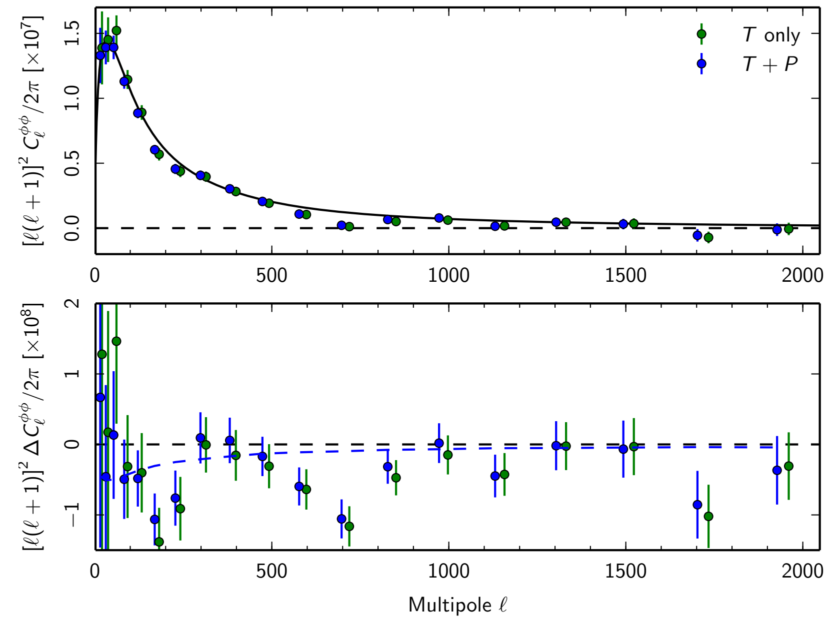
Growth of structure



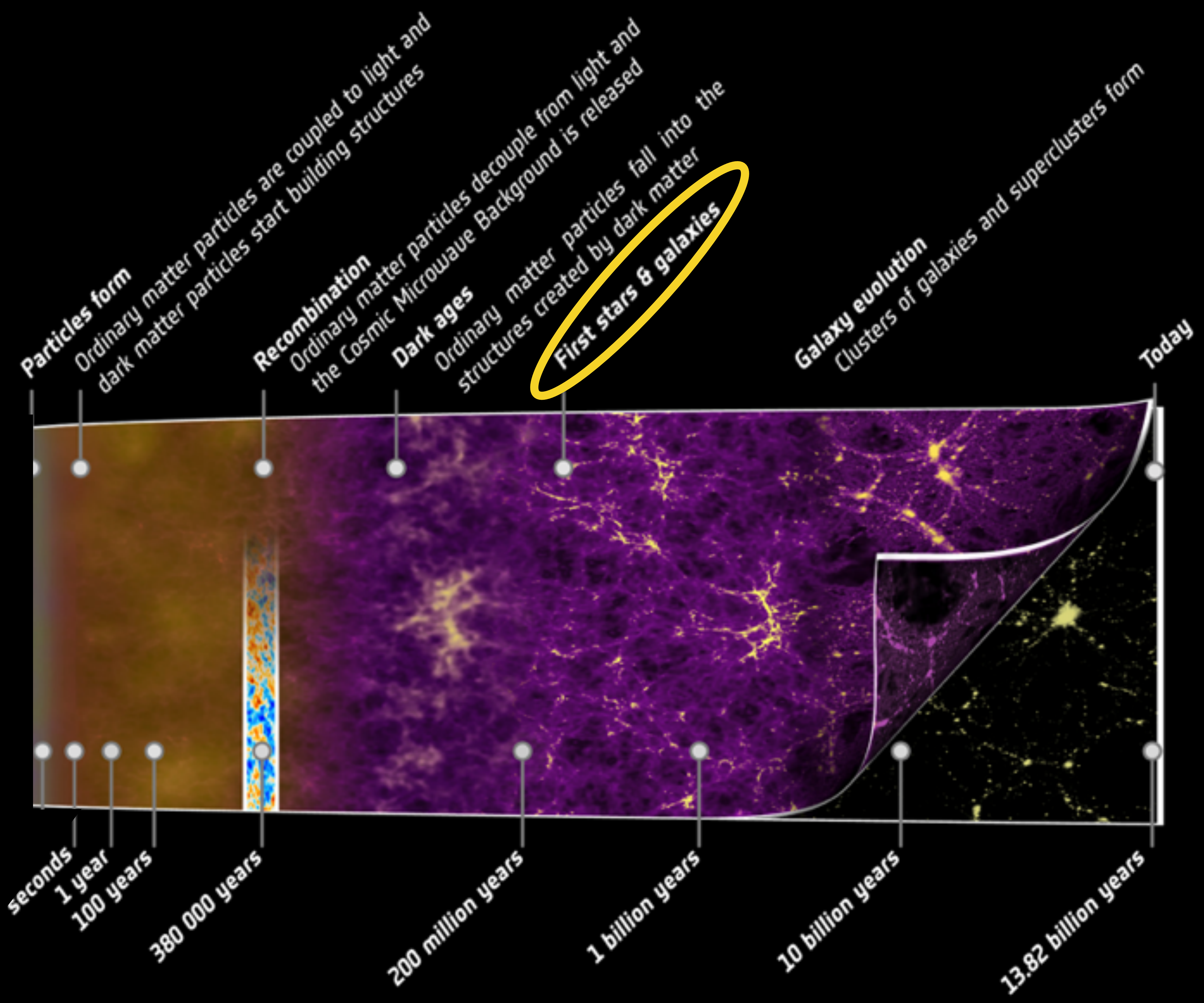
Weak lensing

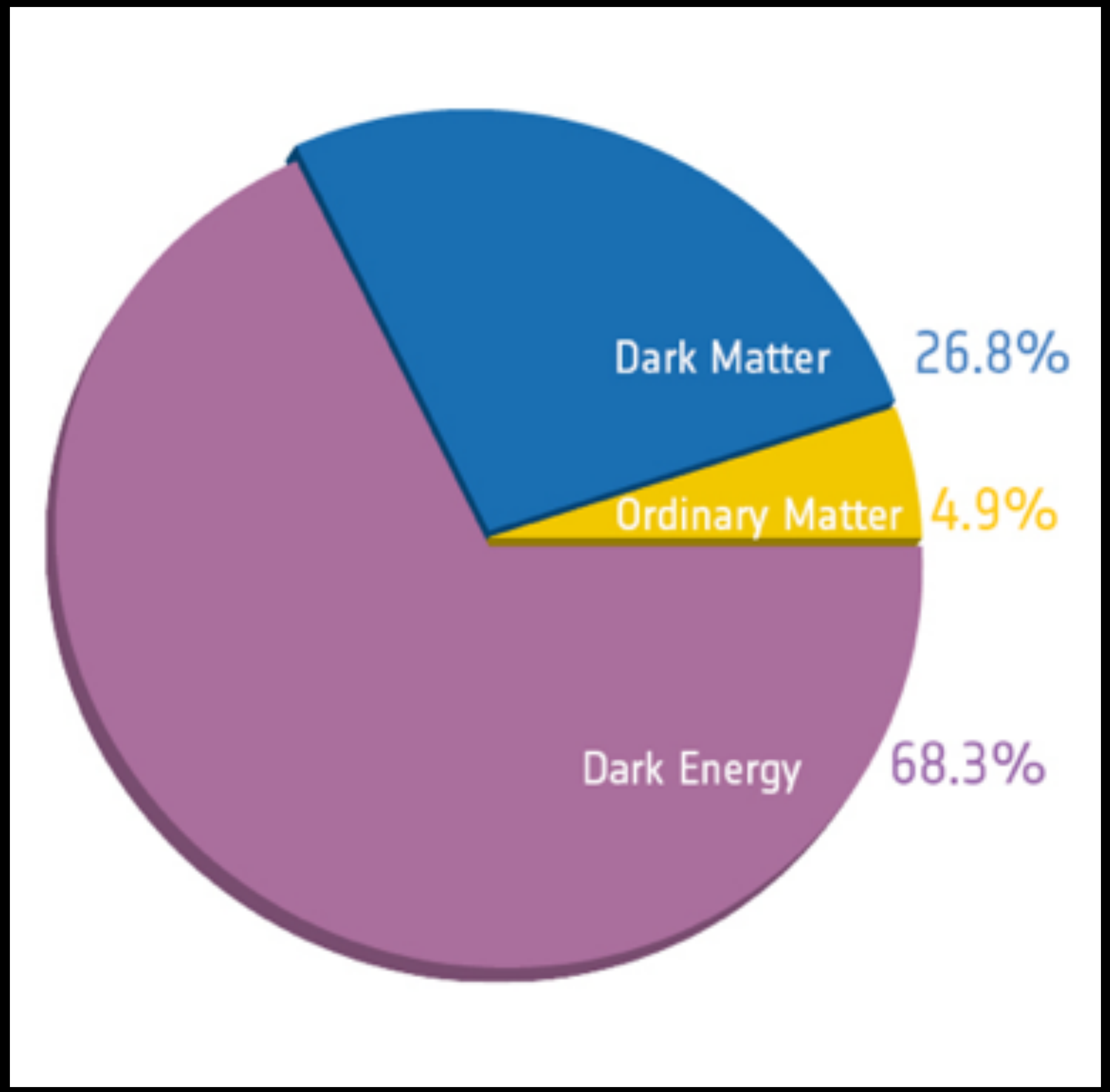


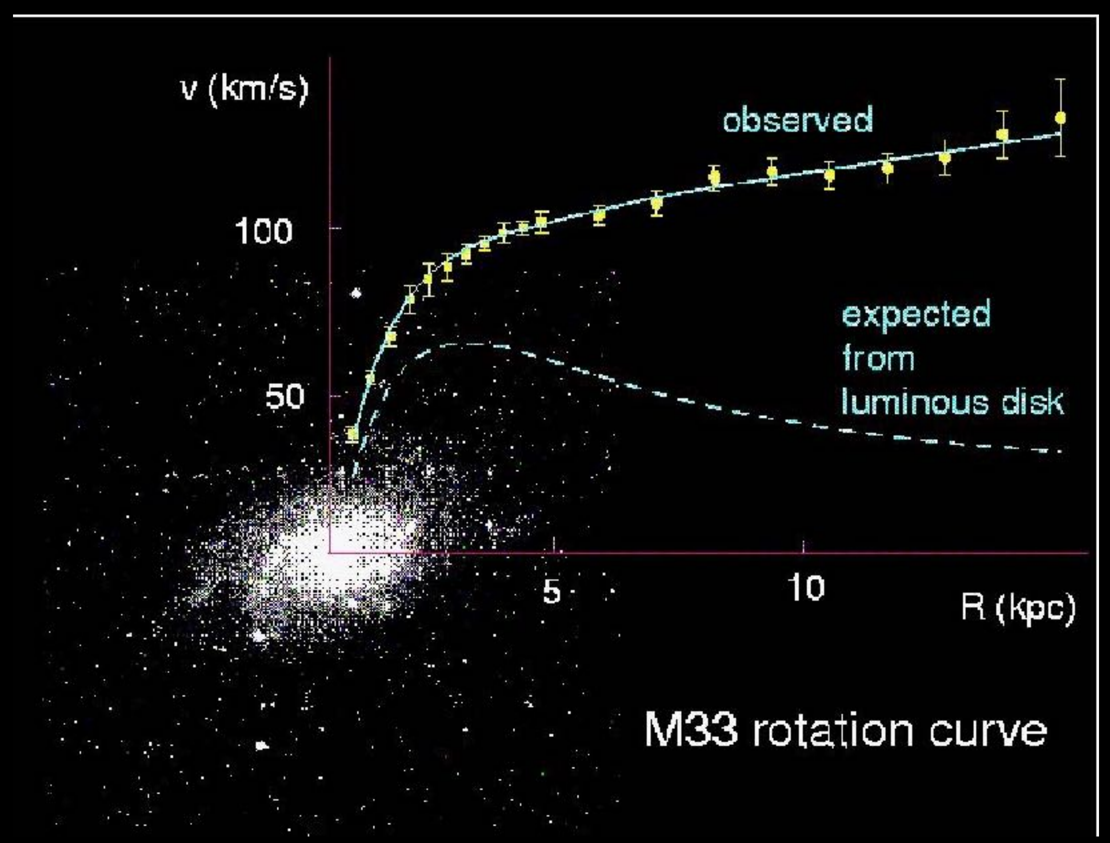
CMB lensing

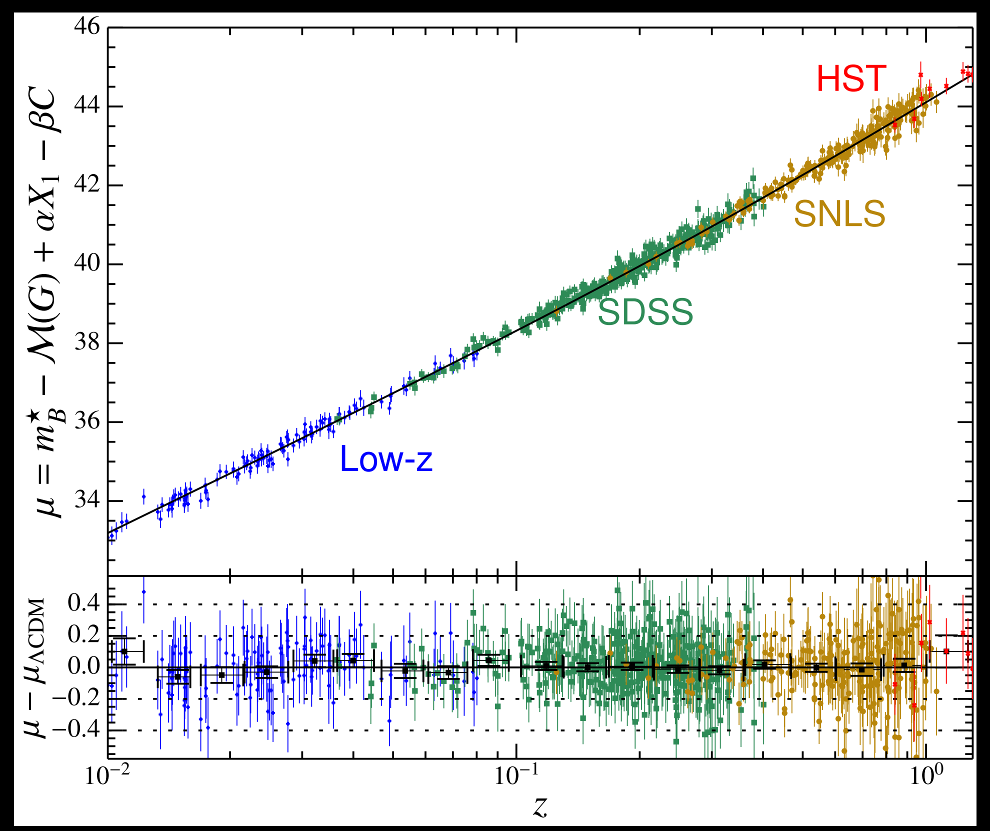


Many things are still unknown

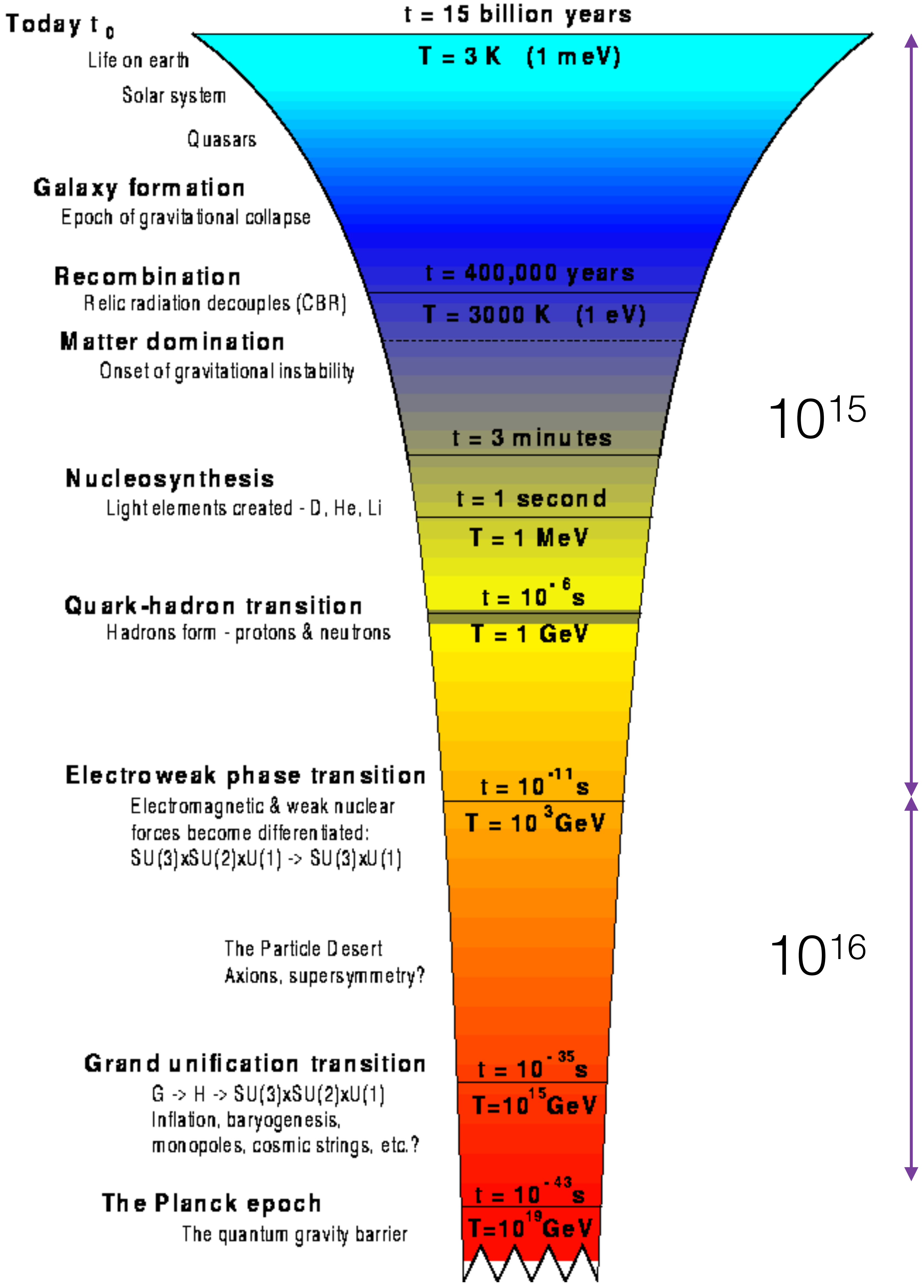


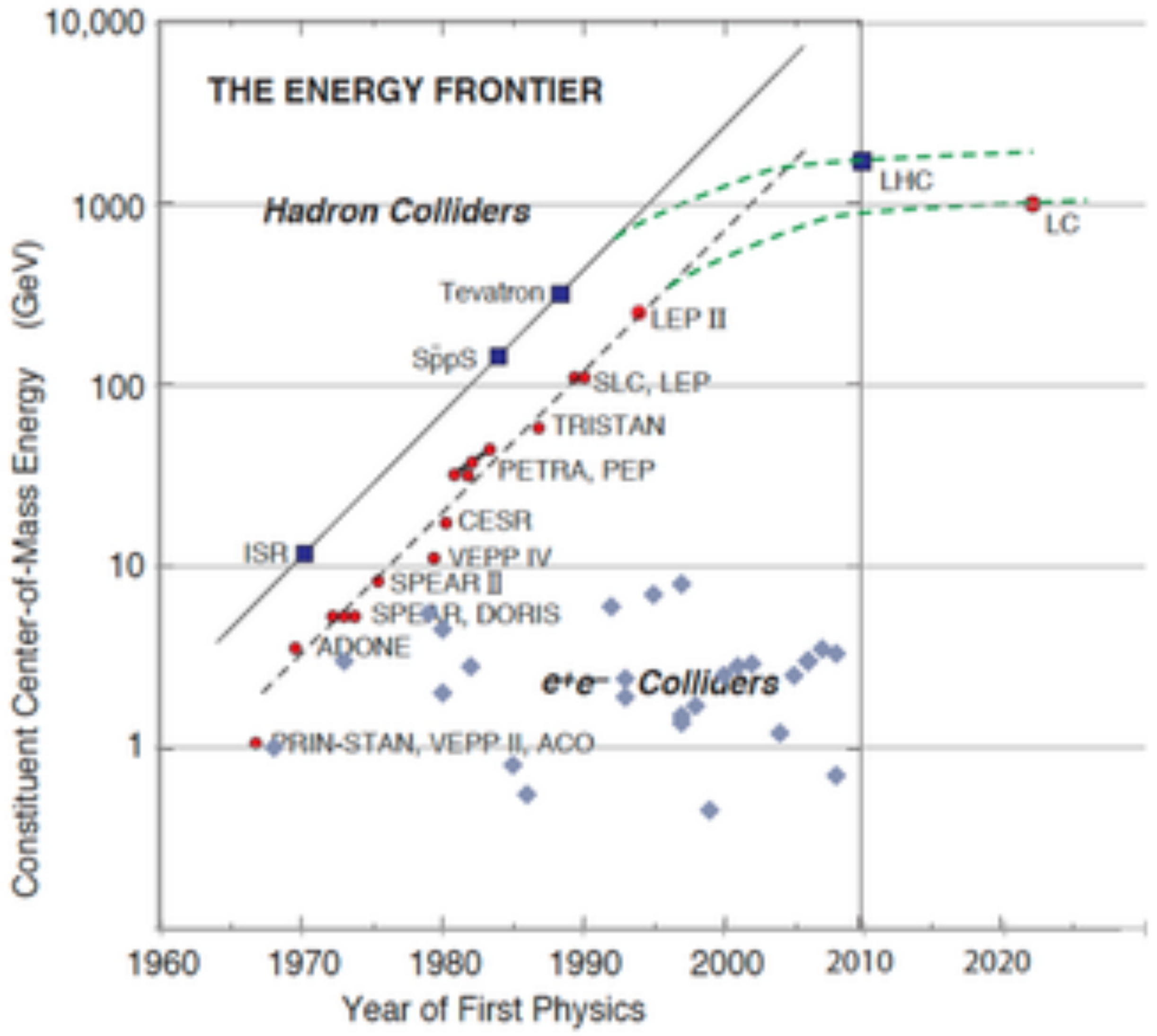


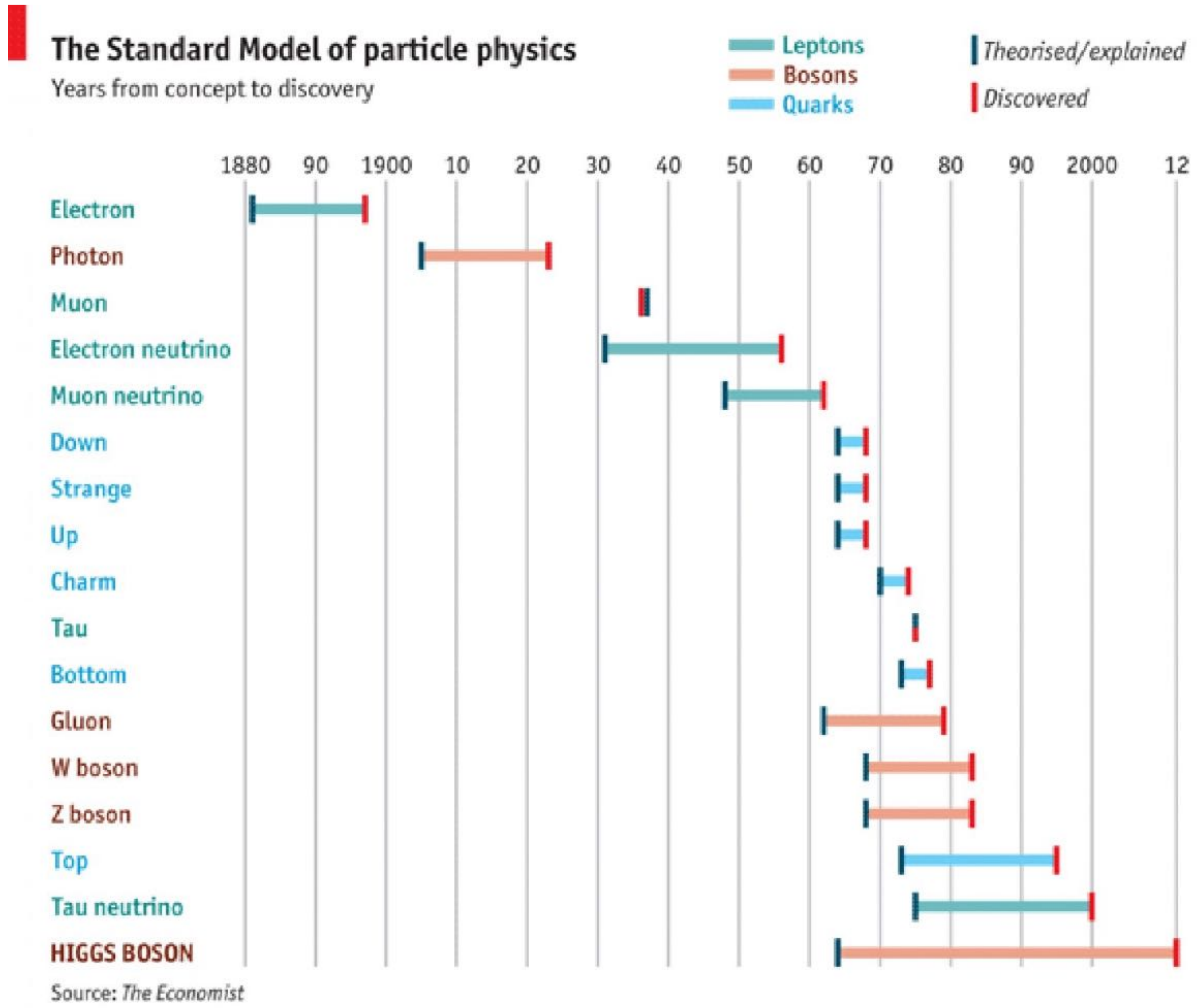




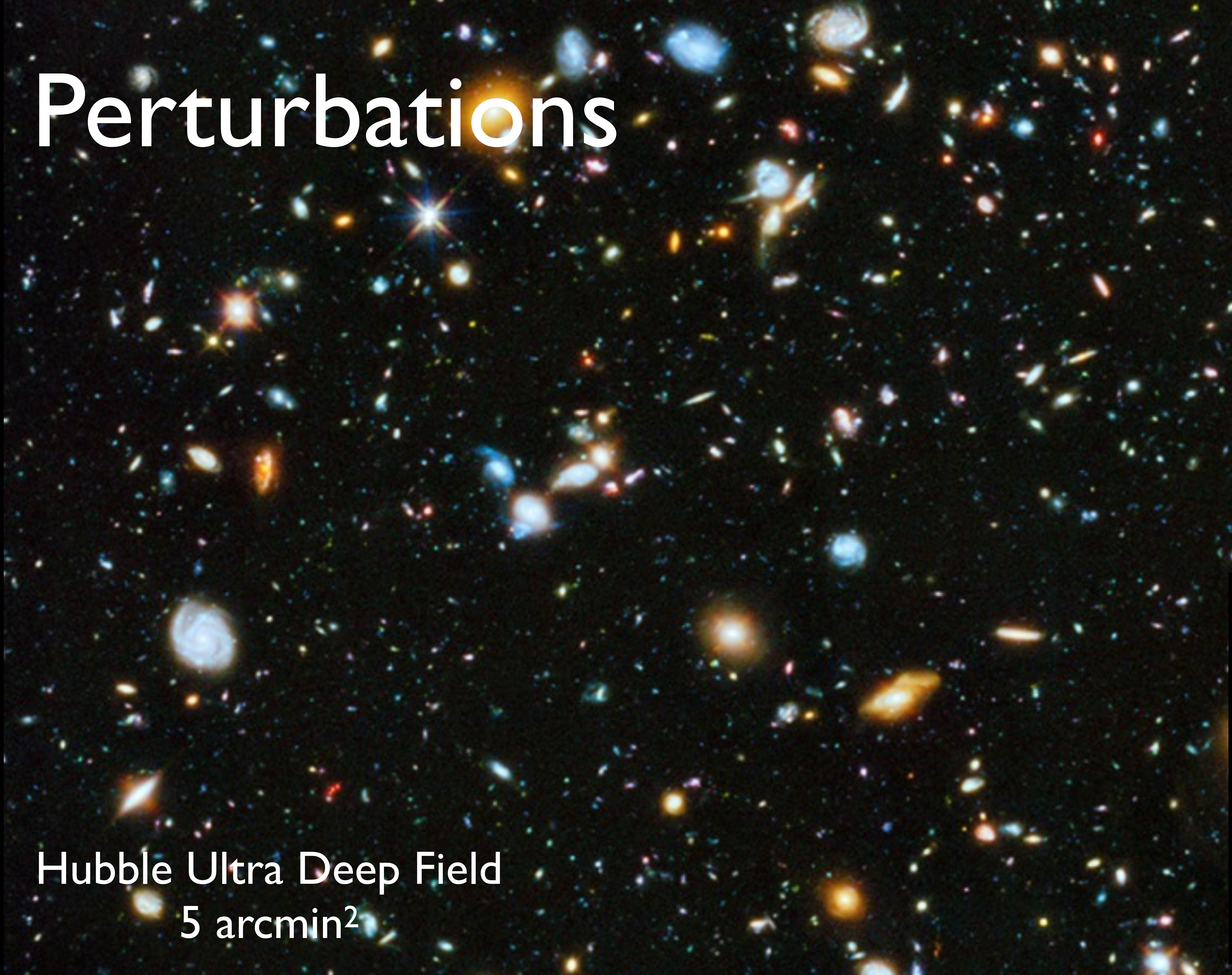
The Early Universe: probing unknown physics



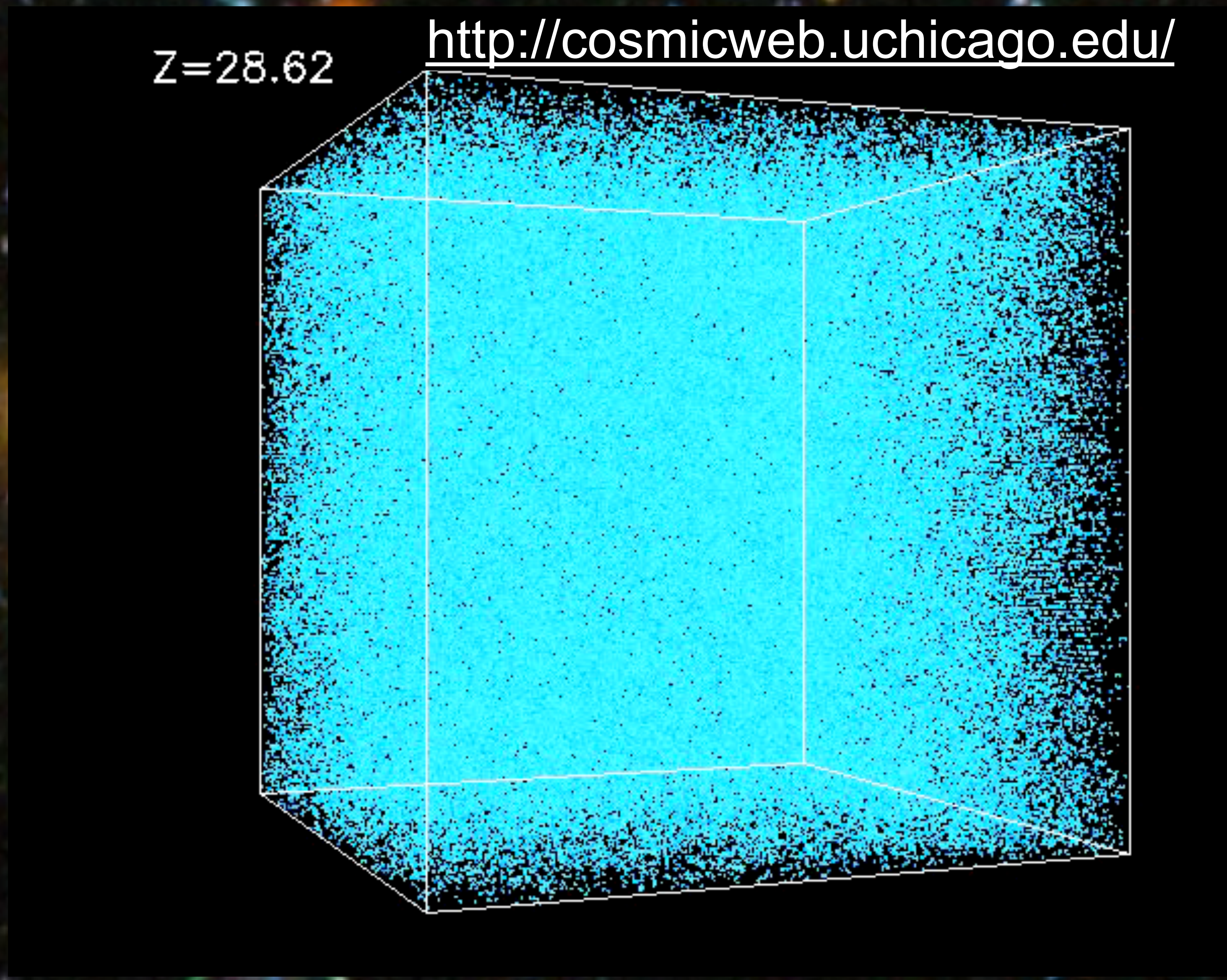




Perturbations

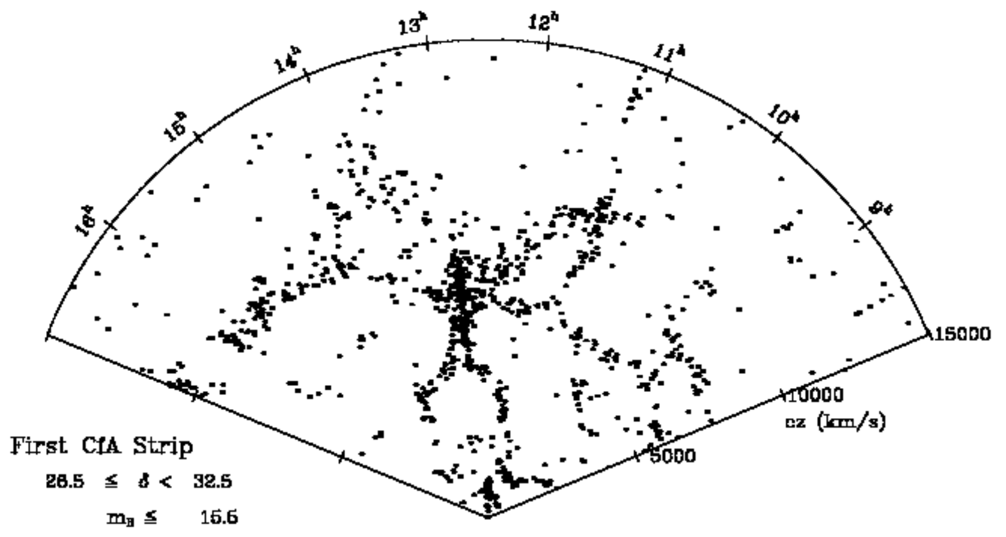


Hubble Ultra Deep Field
5 arcmin^2

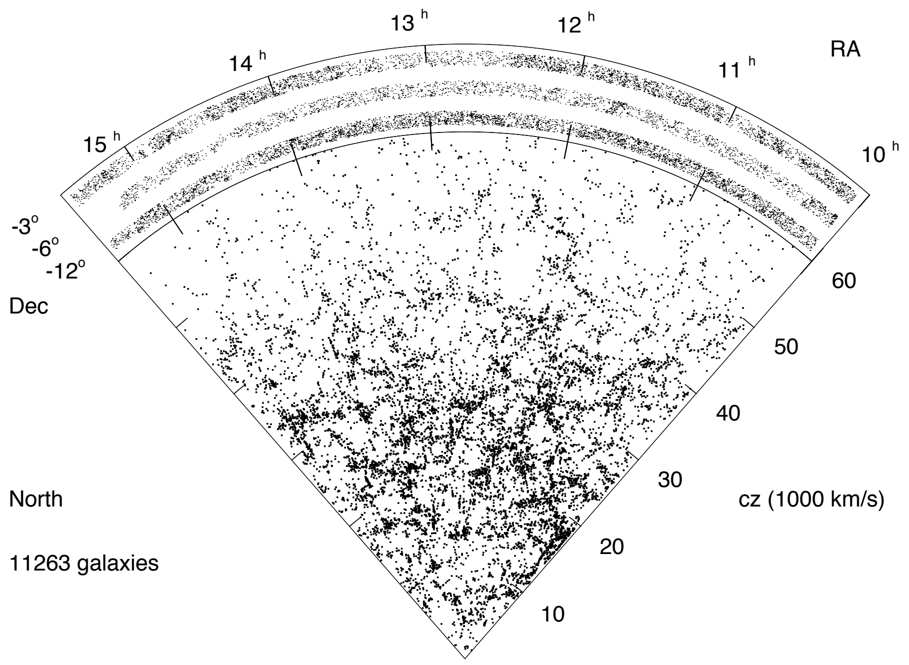


Tracing the Large Scale Structure

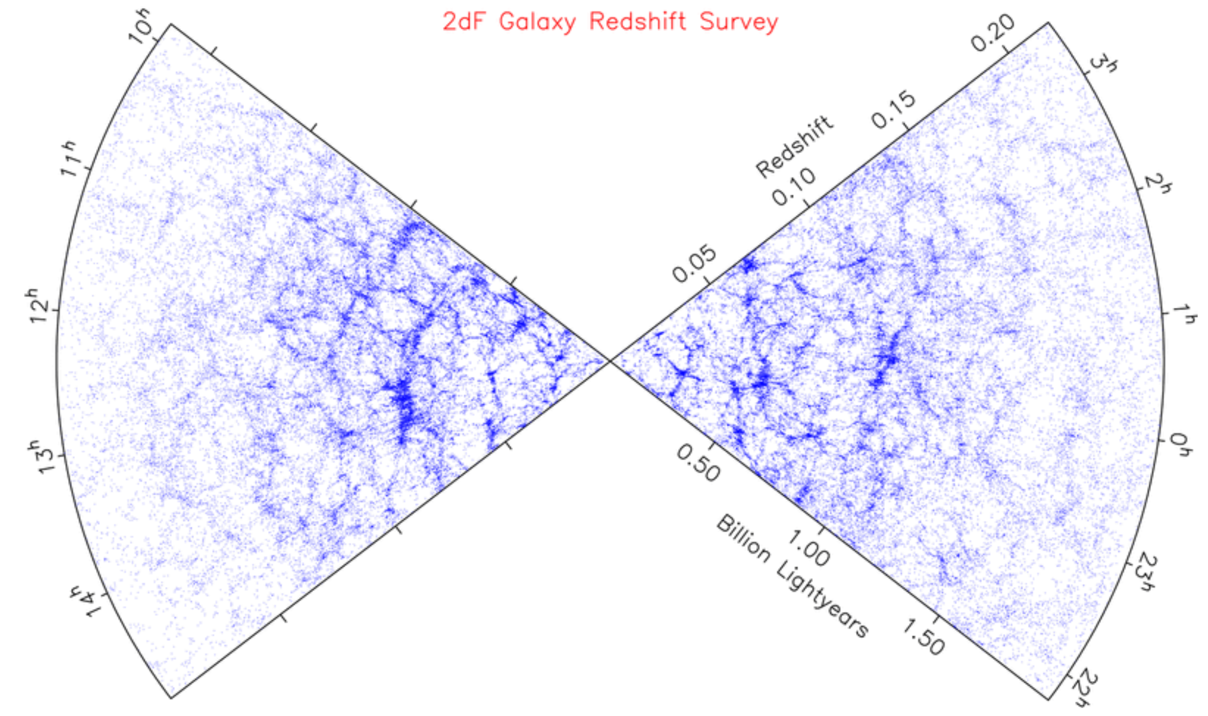
1982: CfA 1 (2000 gal redshifts)



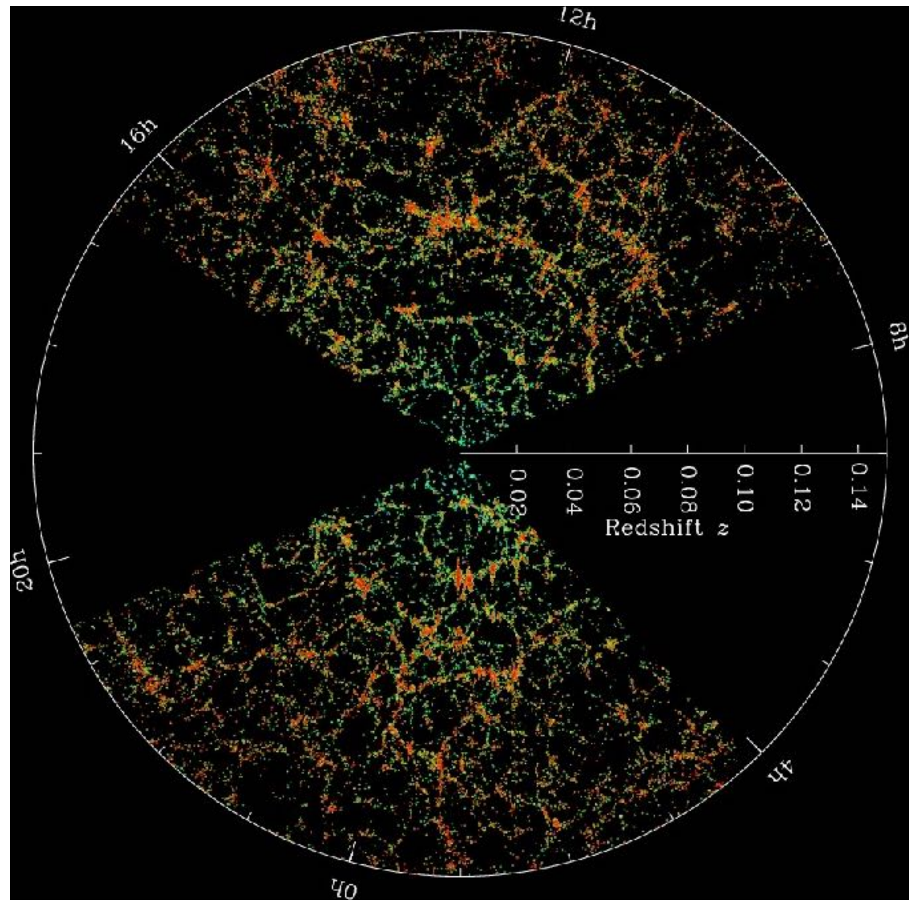
1996 Las Campanas (26000 gal redshifts)

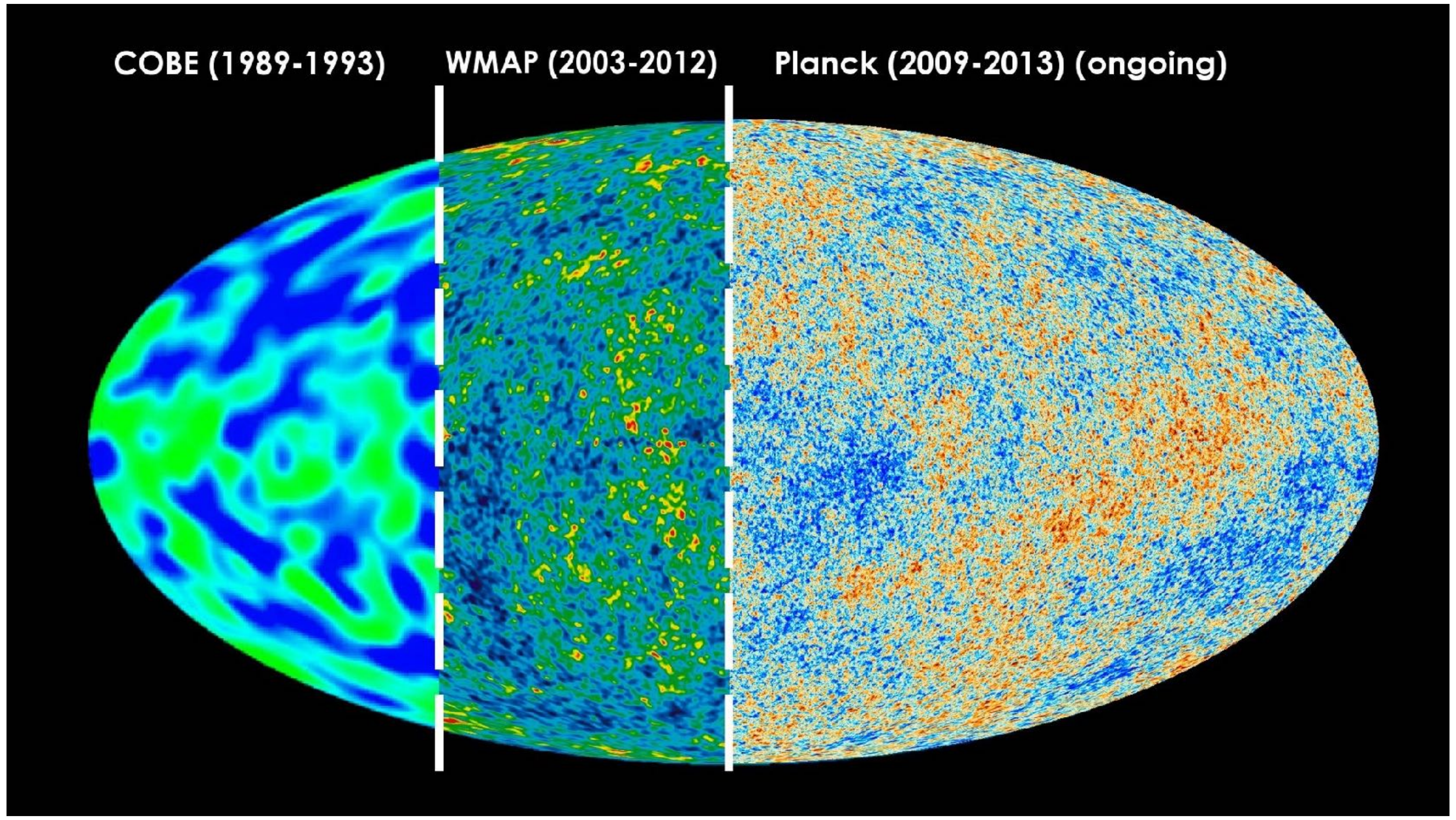


2001 2 degree Field (220000 gal redshifts)

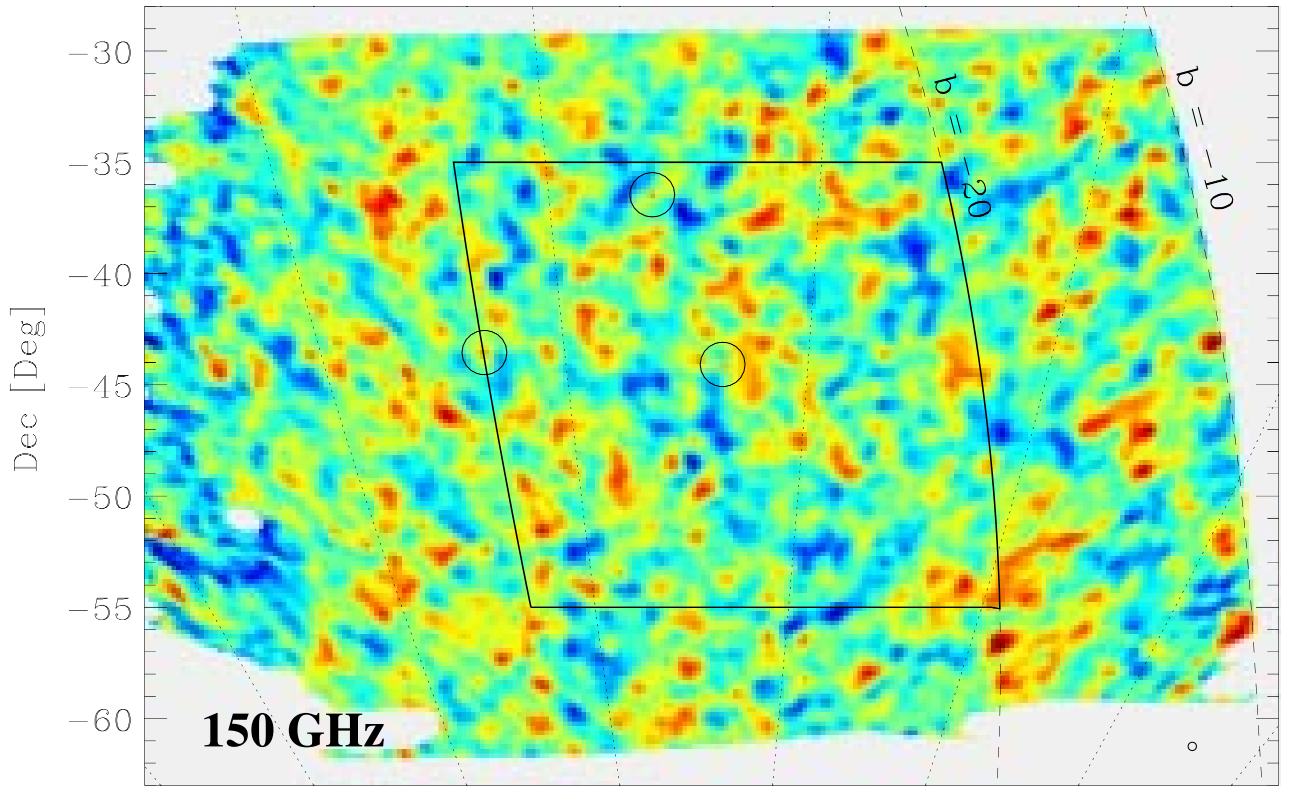


2004 2 SDSS (380000 gal redshifts)





2000 Boomerang



representative example of ground and ballon based efforts

Best constraints on Composition

Planck 2015

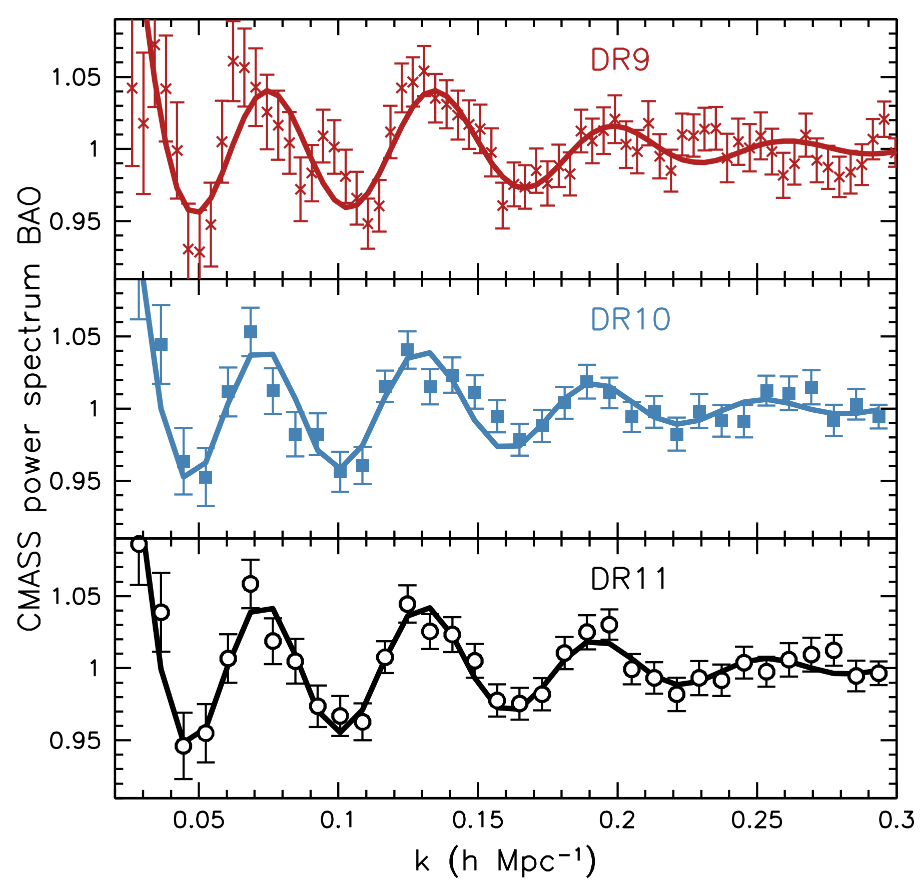
Table 18. Constraints on the basic six-parameter ΛCDM model using *Planck* angular power spectra.[a]

Parameter	PlanckTT+lowP 68 % limits	PlanckTT,TE,EE+lowP 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015

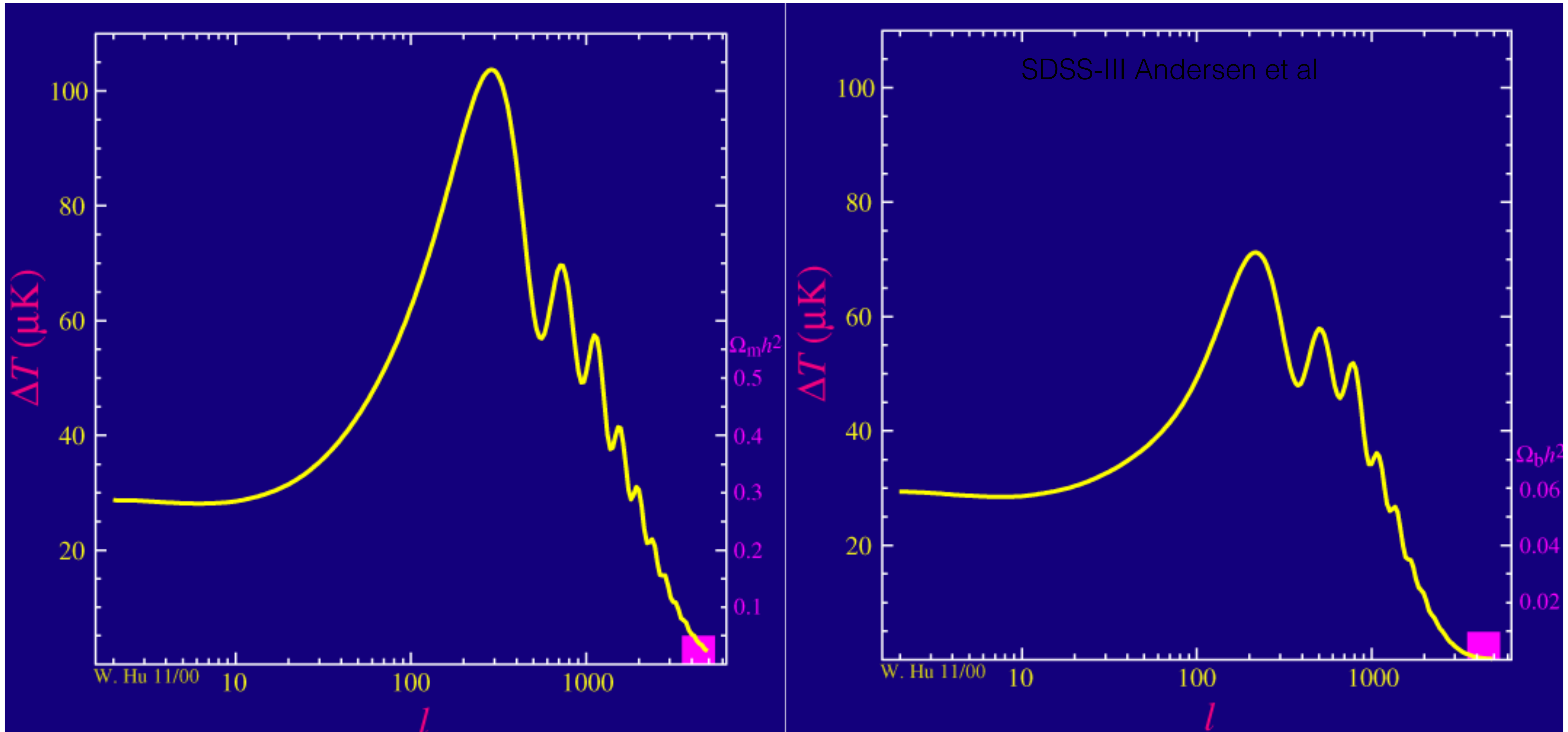
$\sim 100\sigma$

Even cosmic acceleration is now being measured by tracking these peaks in probes of the late Universe

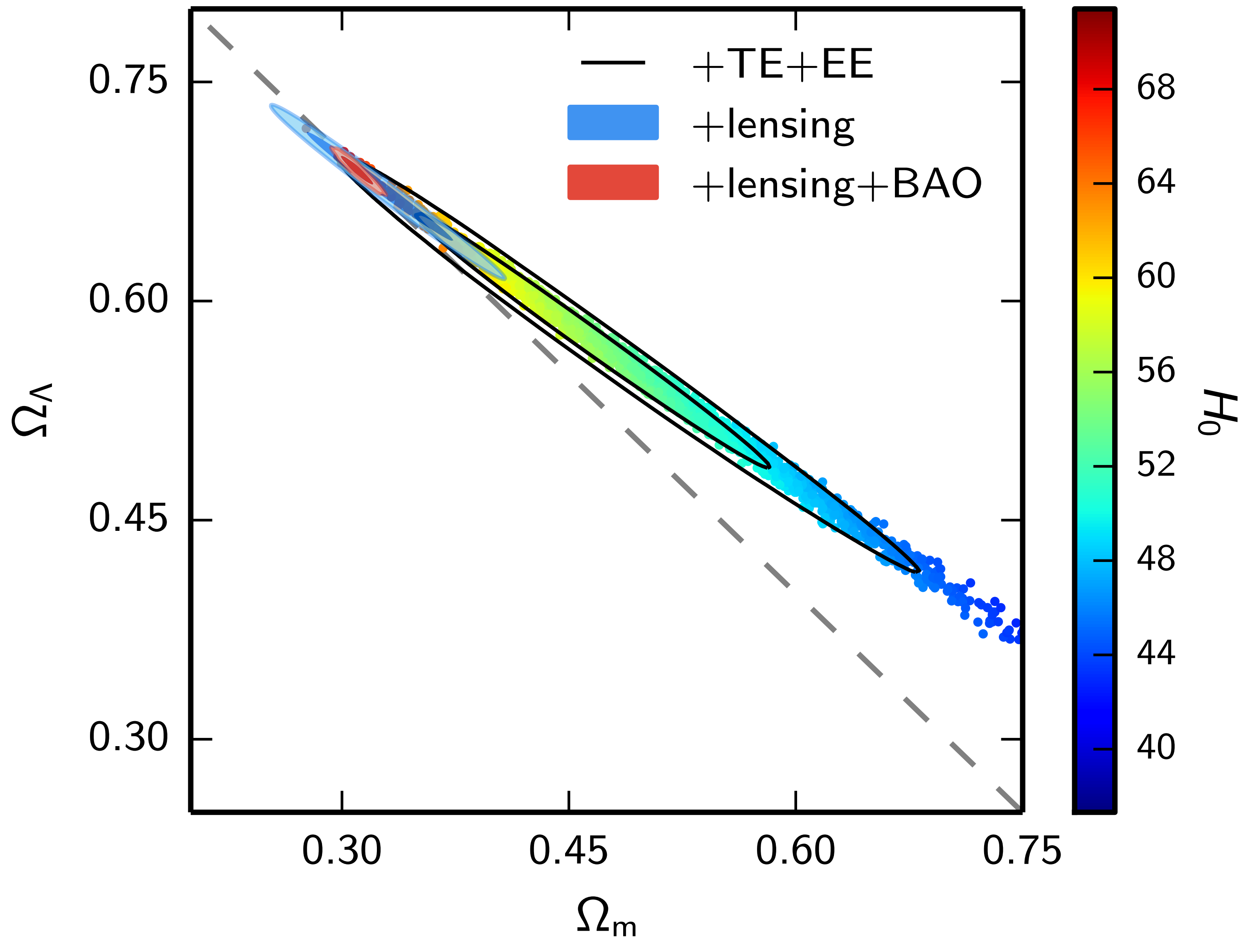
SDSS-III Andersen et al



Wayne Hu

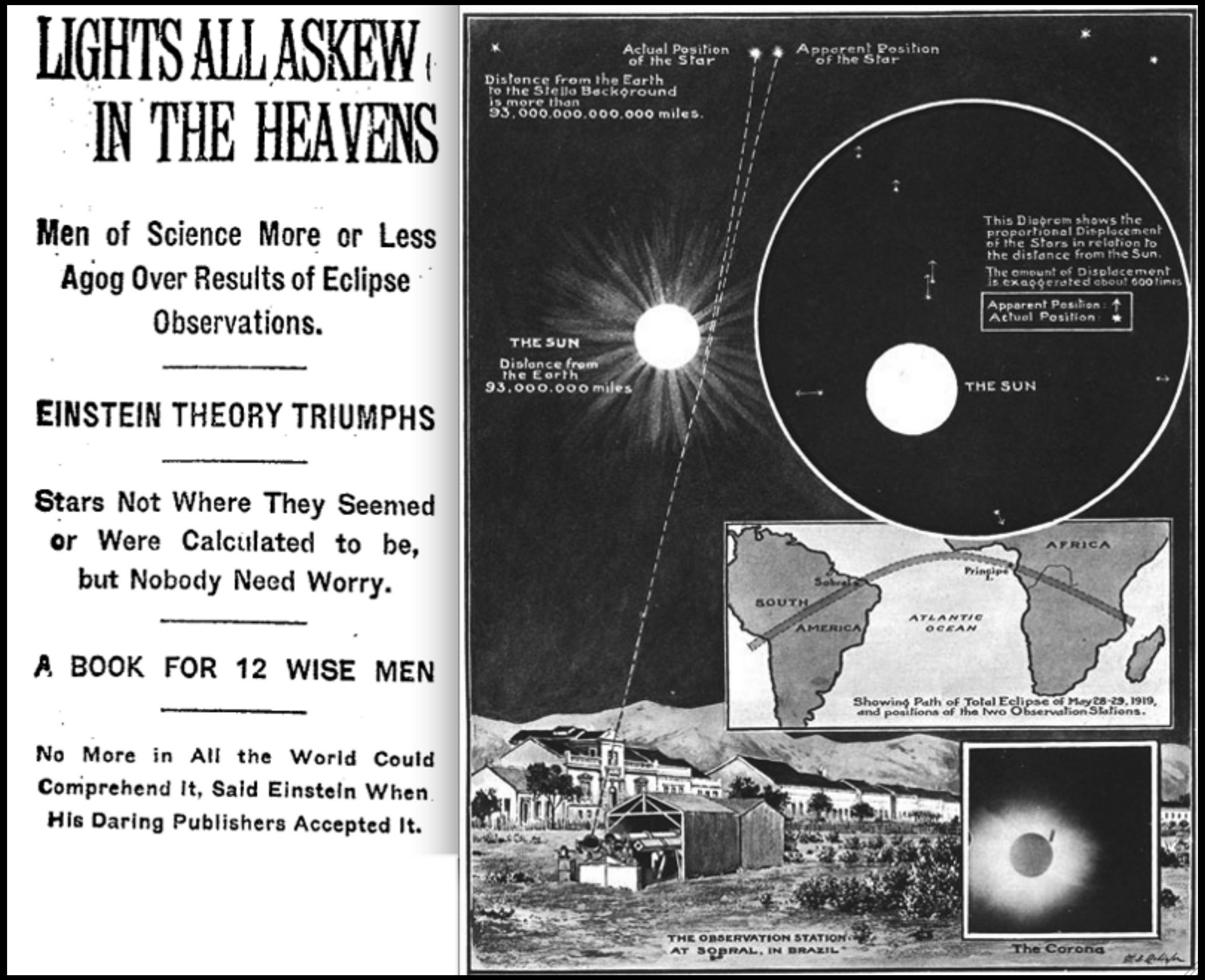


Planck 2015



Photon trajectories

The 1919 Solar Eclipse



LIGHTS ALL ASKEW IN THE HEAVENS

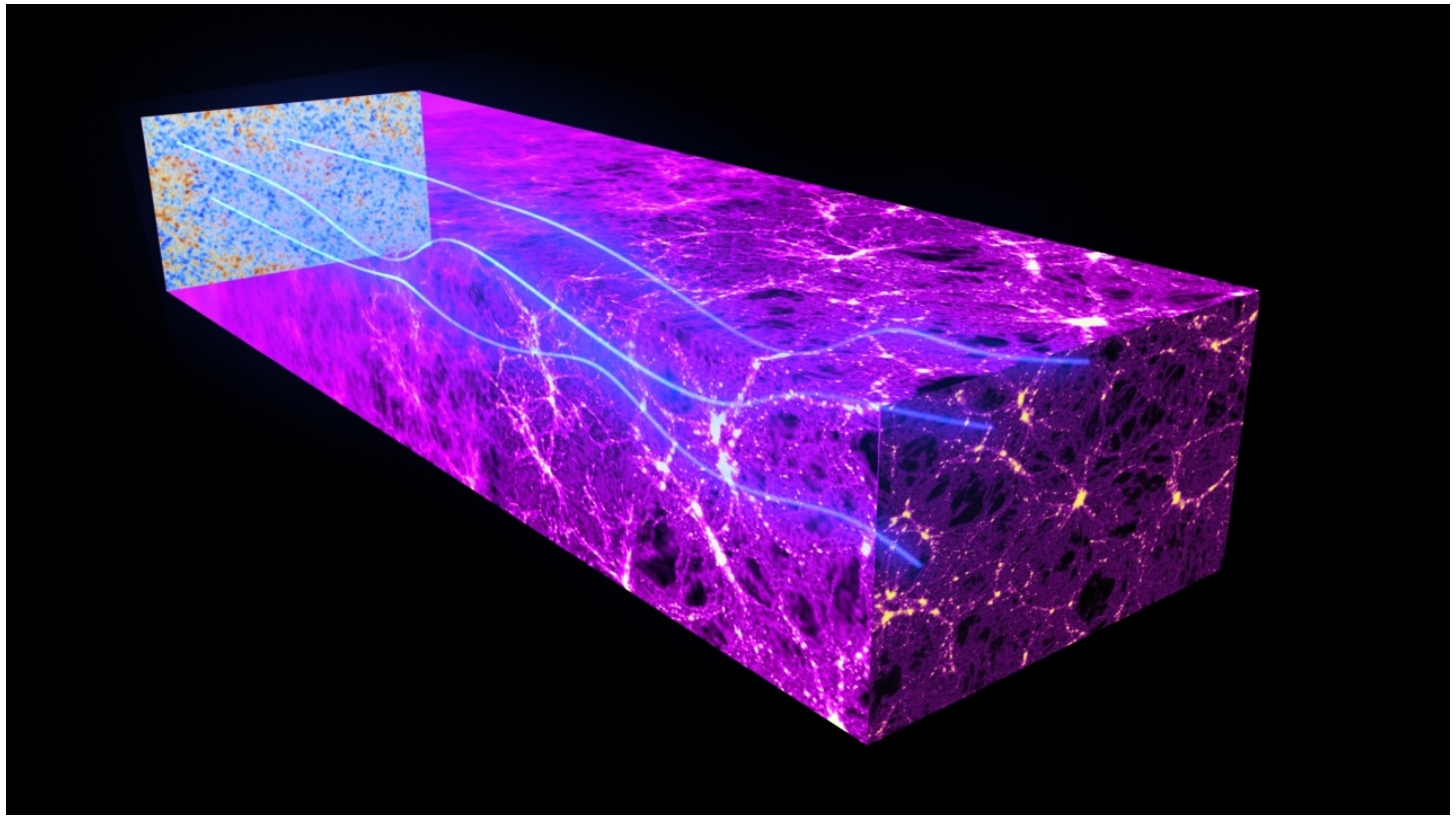
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

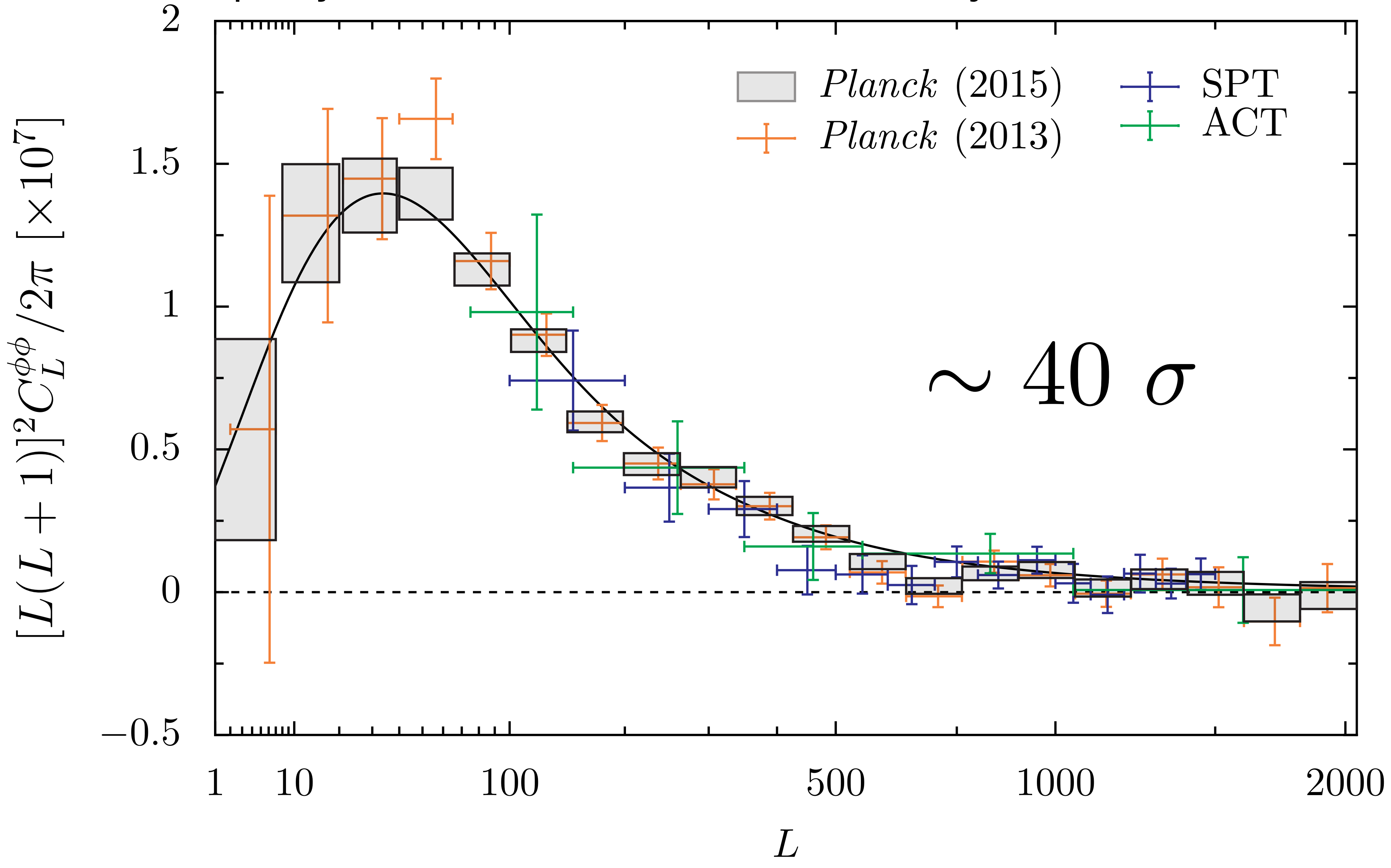
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.



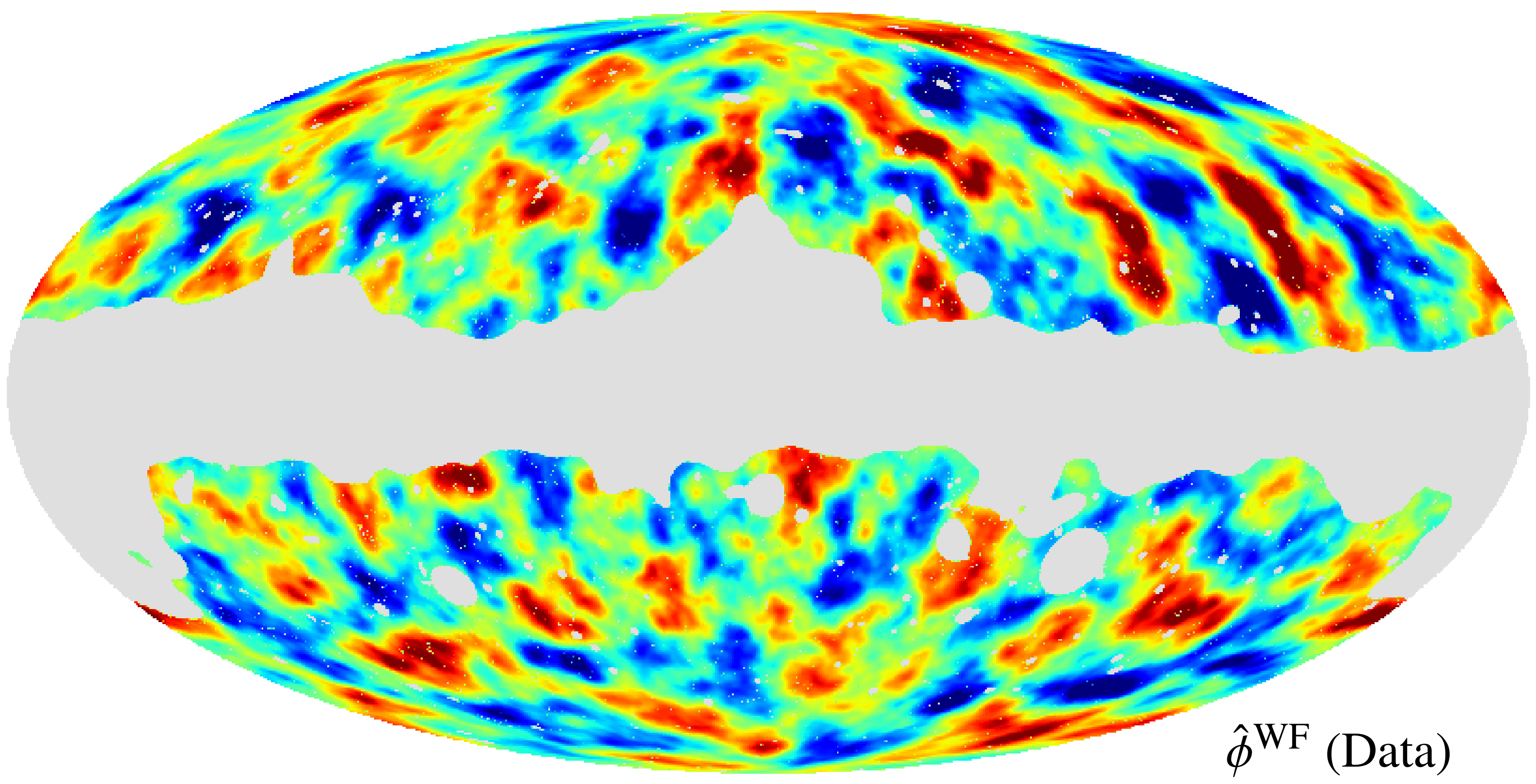
Lensing distorts the anisotropies and can be recovered statistically

Future measurements of this effect should allow us to determine the mass of the neutrinos.

Measurement of the power spectrum of the projected mass measured by Planck.

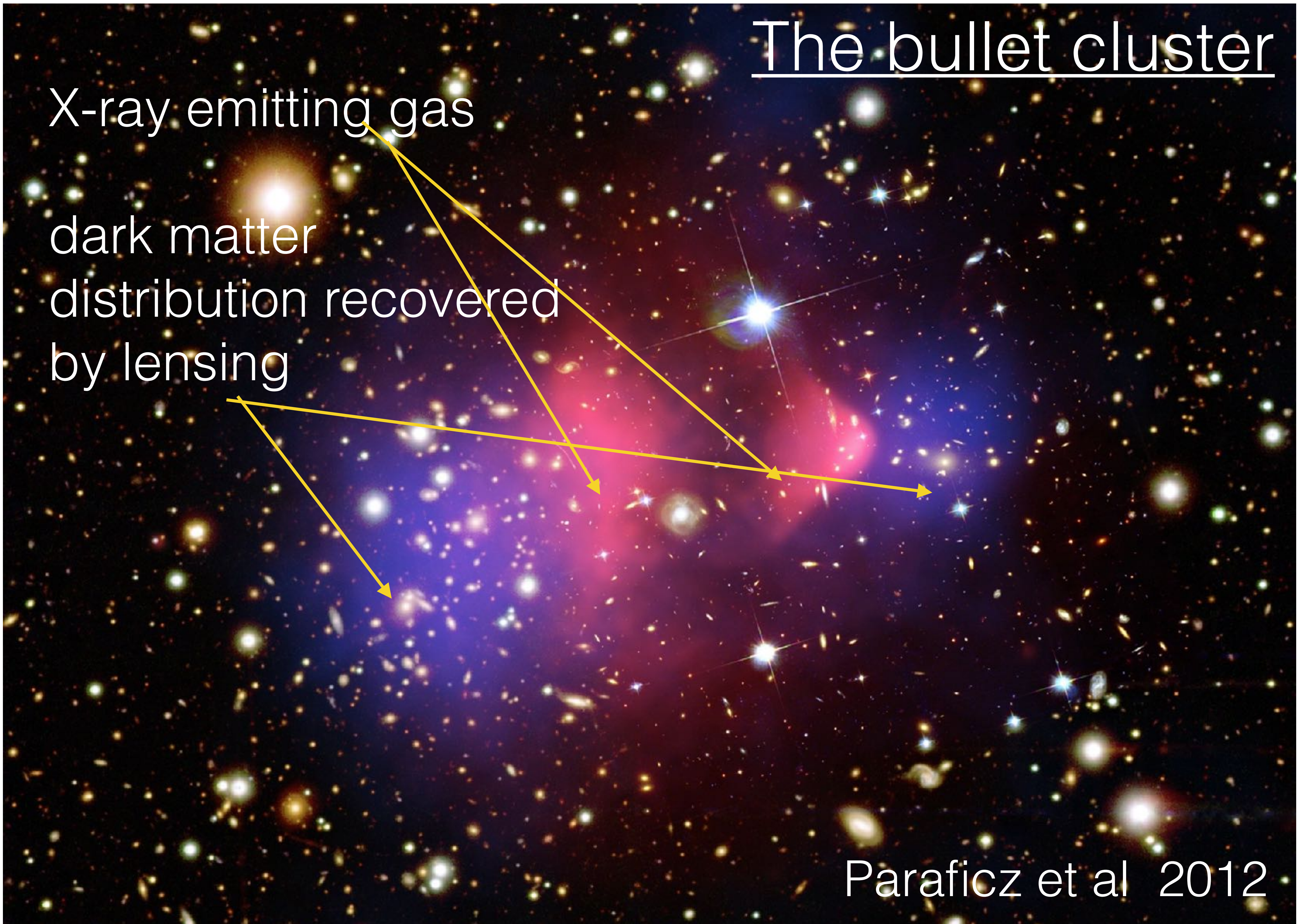


Map of the mass projected along the line of sight reconstructed by Planck.

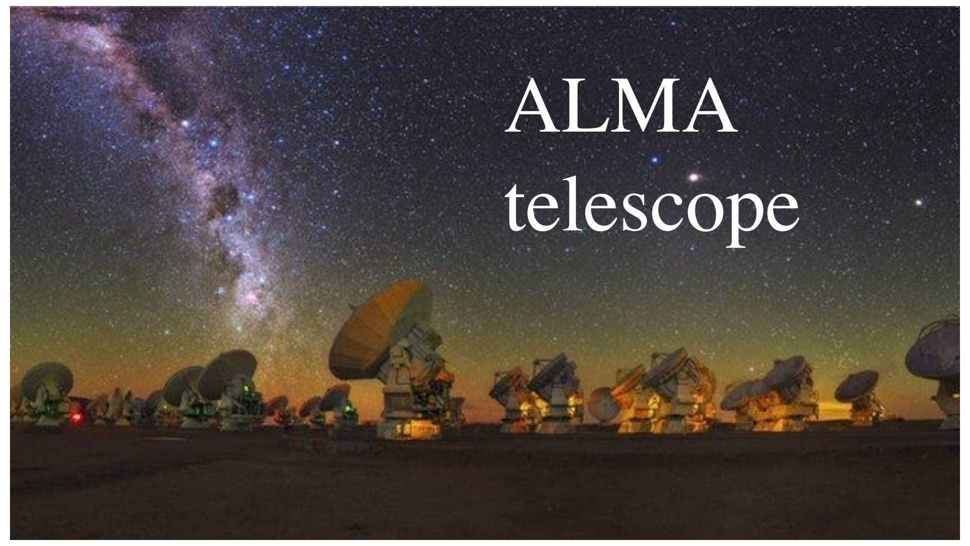


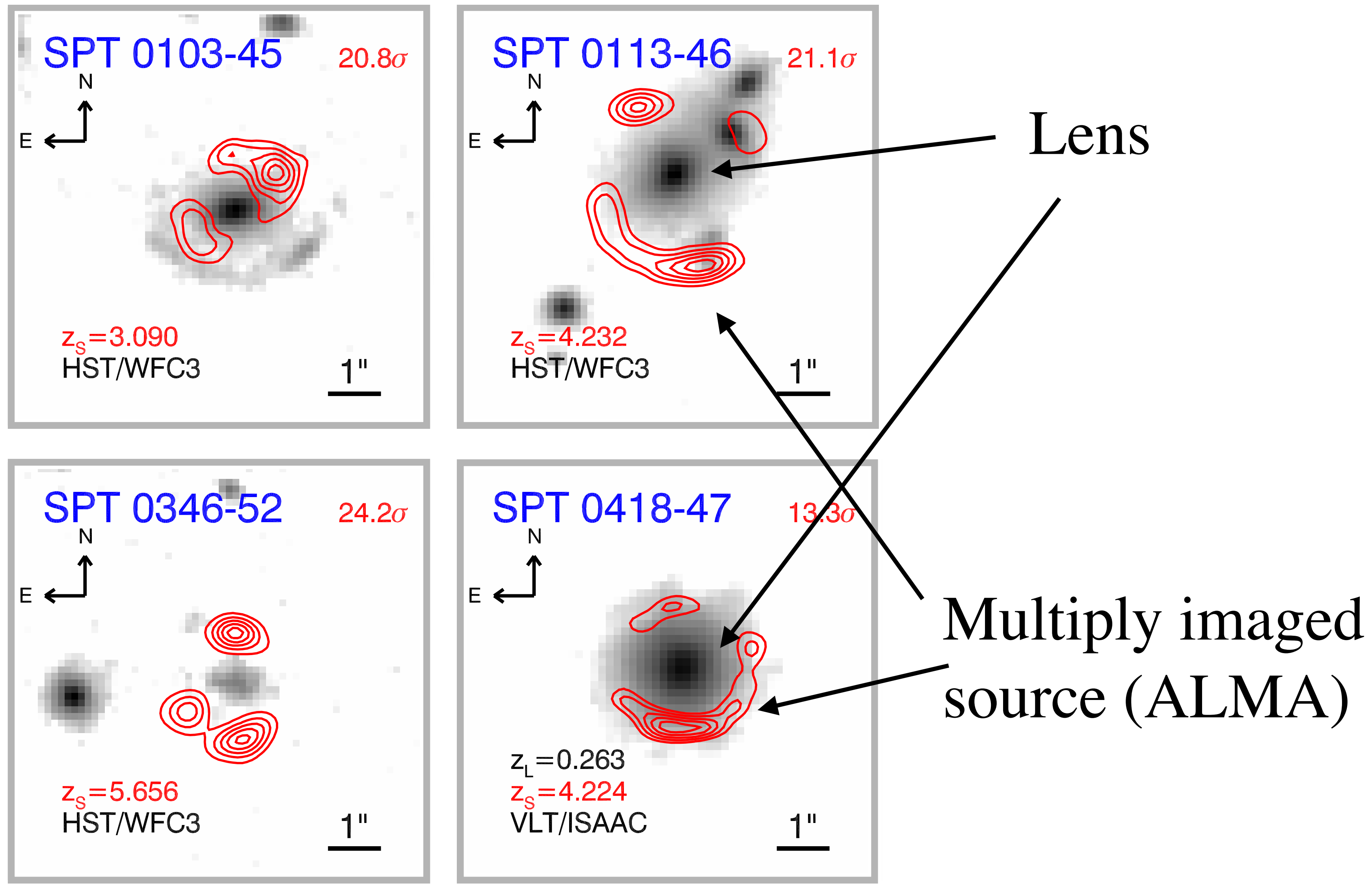
Lensing to determine masses

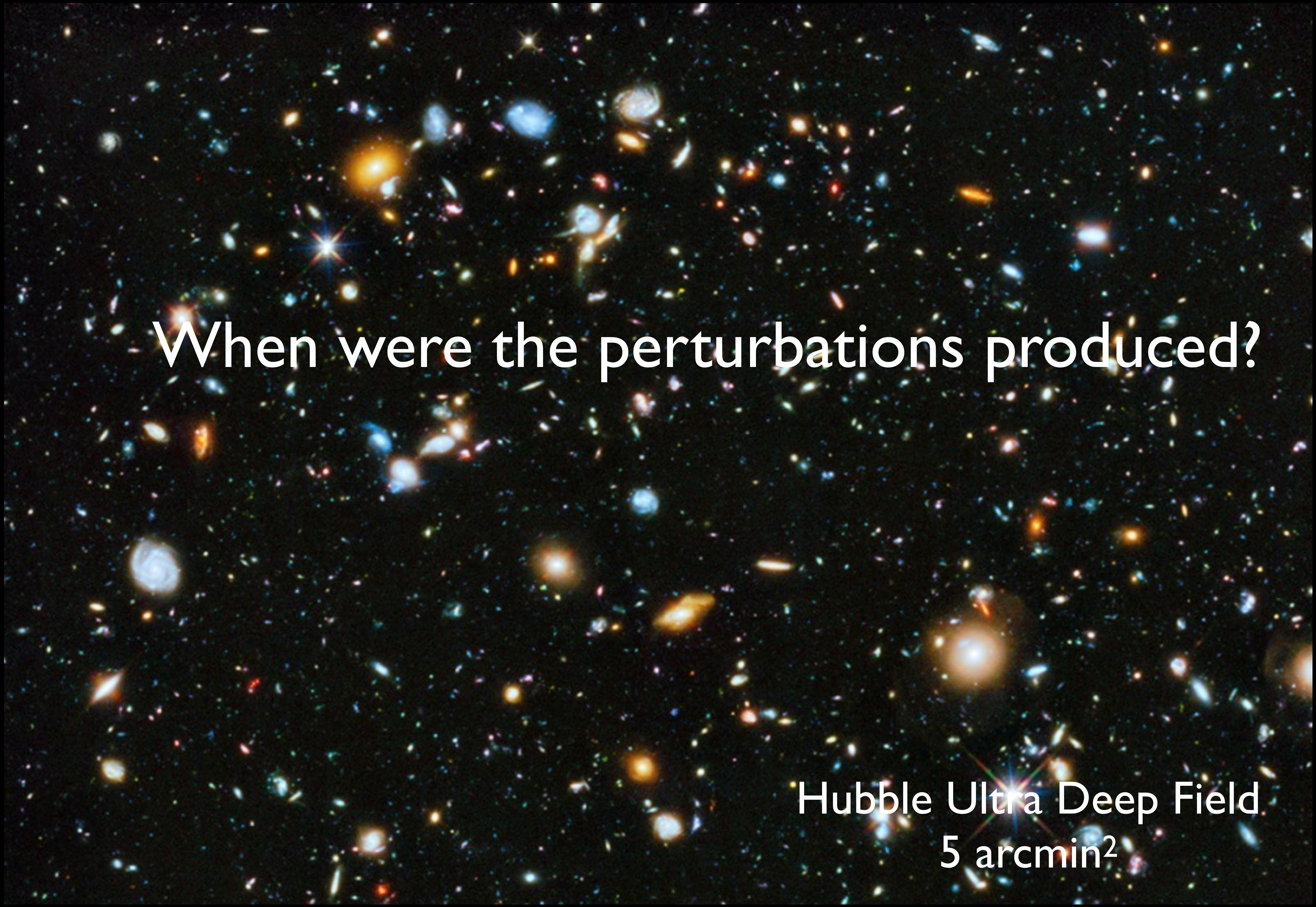
The bullet cluster



Dark matter substructure in gravitational lenses



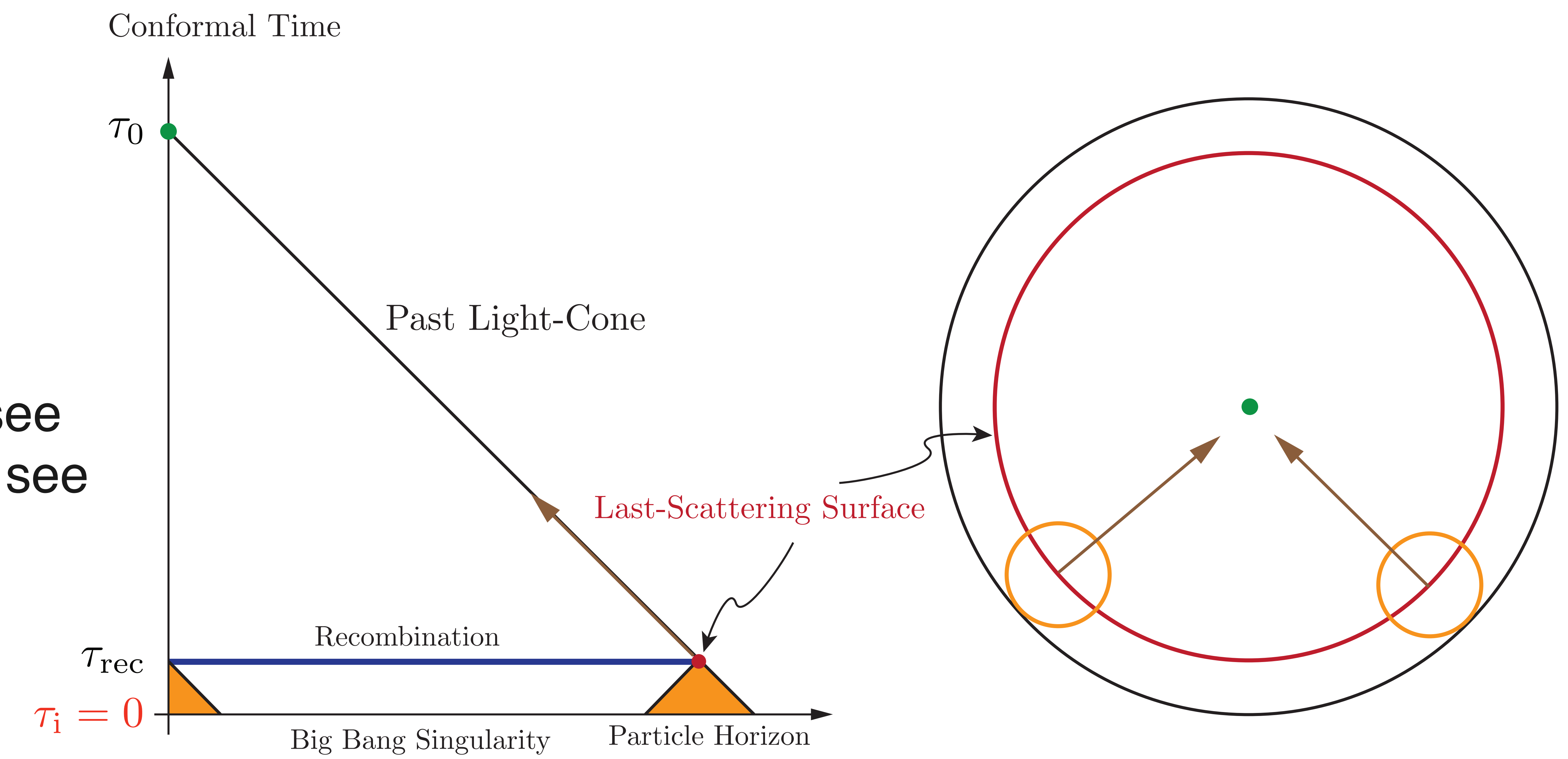



When were the perturbations produced?
Hubble Ultra Deep Field
5 arcmin²

Cosmological Horizons

Our Horizon volume is the part of the Universe we can currently observe.

The Horizon volume was smaller in the past. We can see regions which could not see each other at the time we see them.



D. Baumann 0907.5424

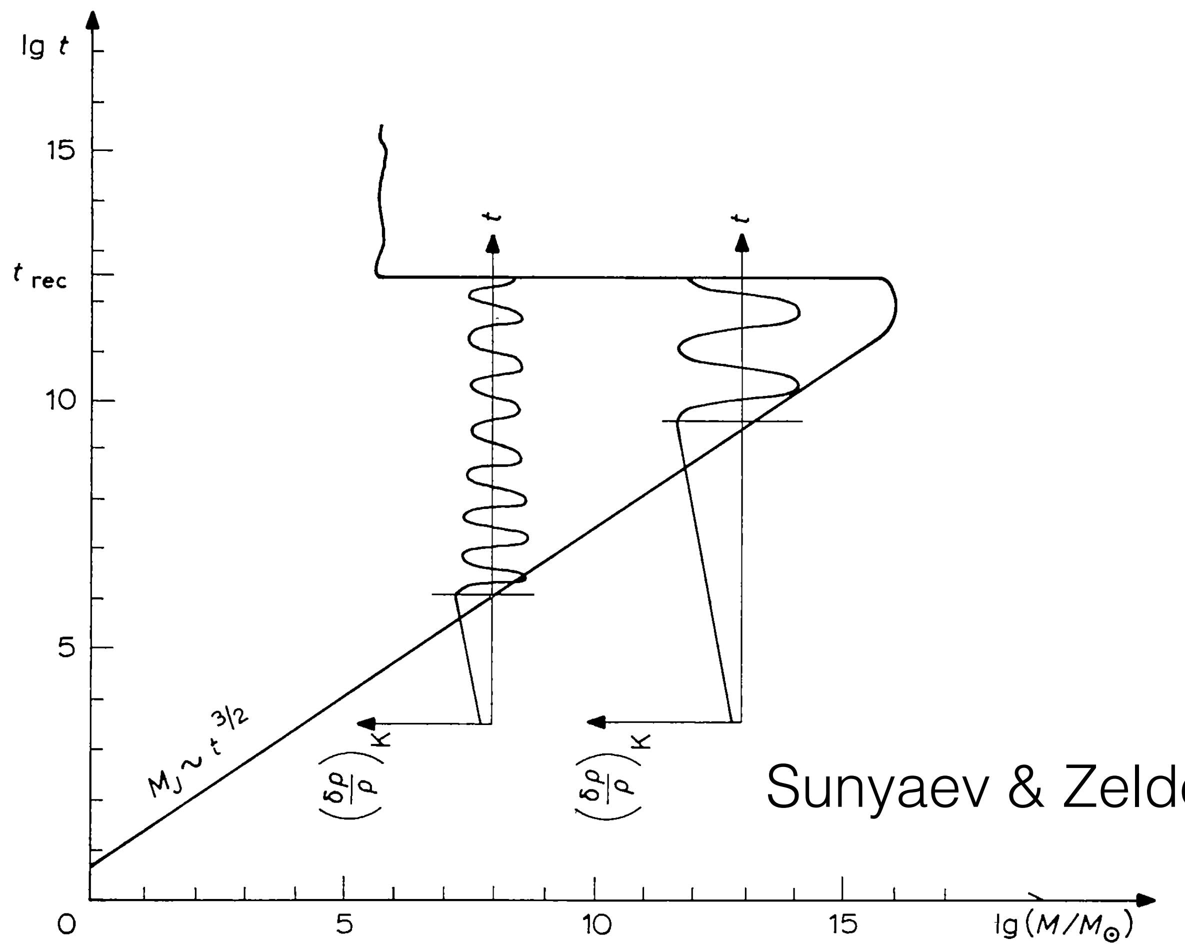
today: 10^{10} years after BB   we can observe: 10^{28} cm   containing 10^{21} solar masses

BBN 1 sec after the BB one could observe 1 light-sec but the size at that time of the part of the Universe we can currently observe is 2 light years. Inside of the light-second there are only 0.01 solar masses of material.

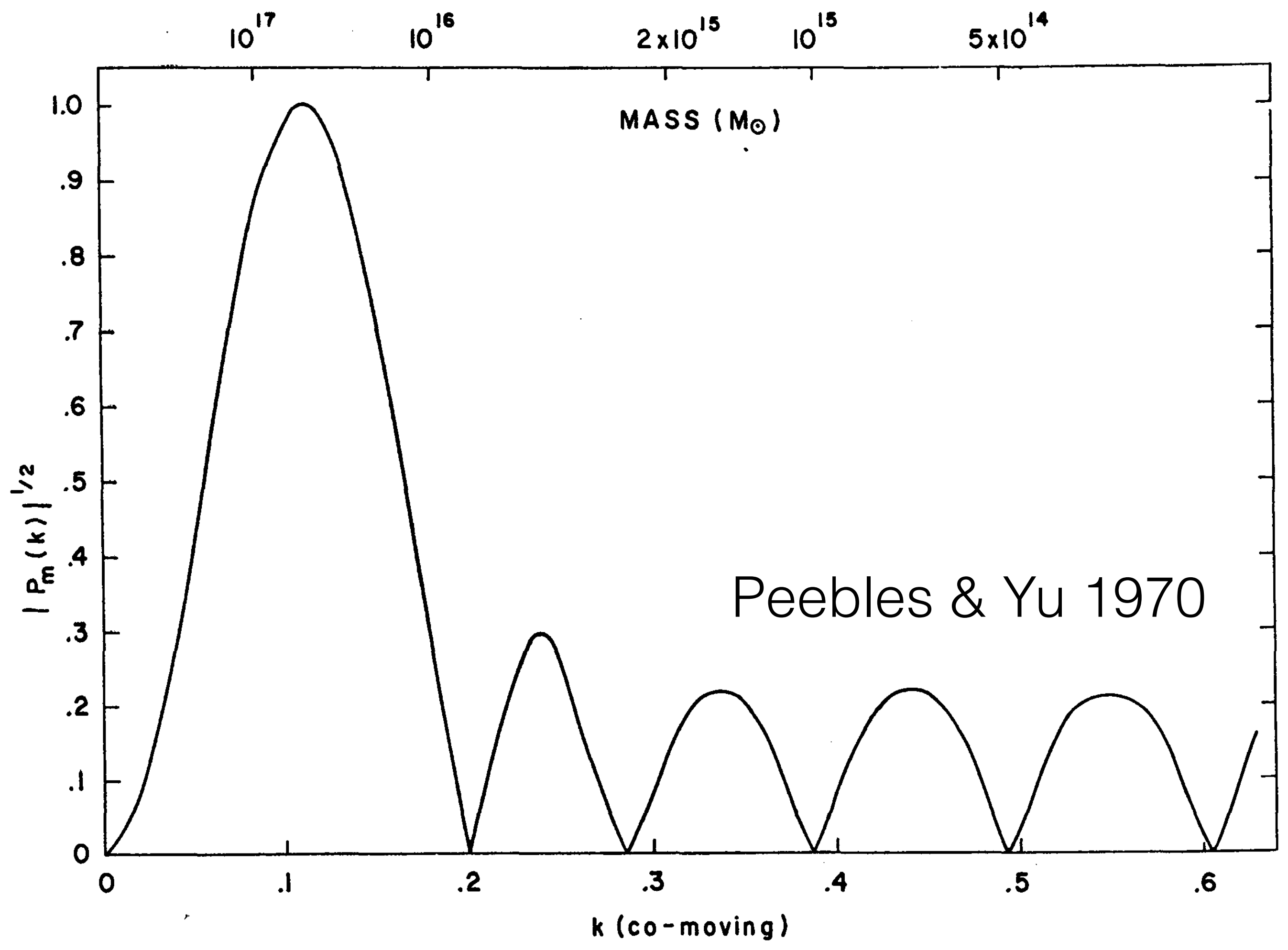
At the time when the energy of particles was comparable to that of the LHC, the time was 10^{-12} seconds. In that time light can travel roughly a millimeter. That region only contains the mass of hundreds of large buildings. The size at that time of the part of the Universe we can currently observe is 10^{12} cm.

When were the seeds of structure created?

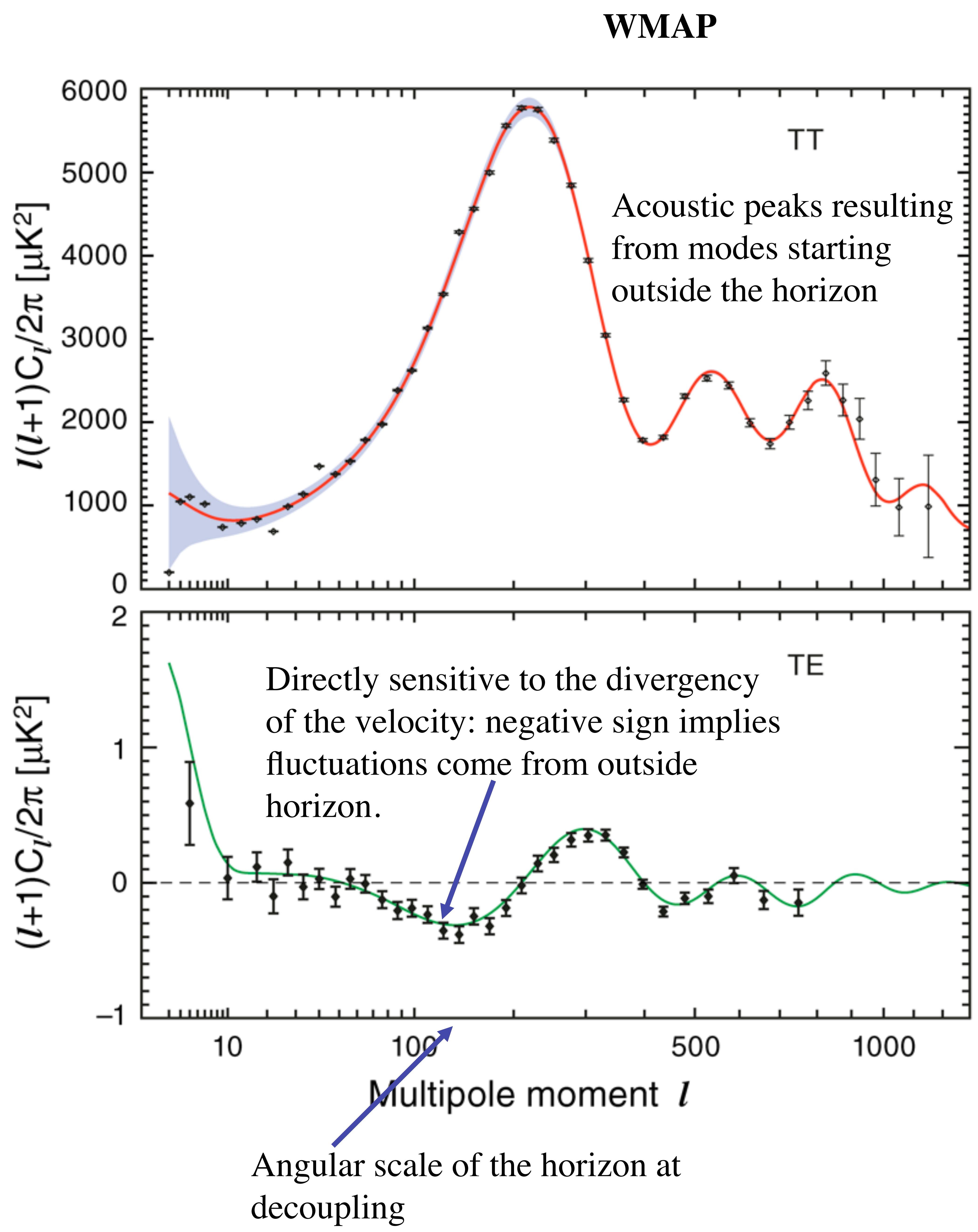
Perturbations already present at the beginning of the hot big bang phase. Although the theory for the origin of the fluctuations is bound to be speculative this fact is robust.



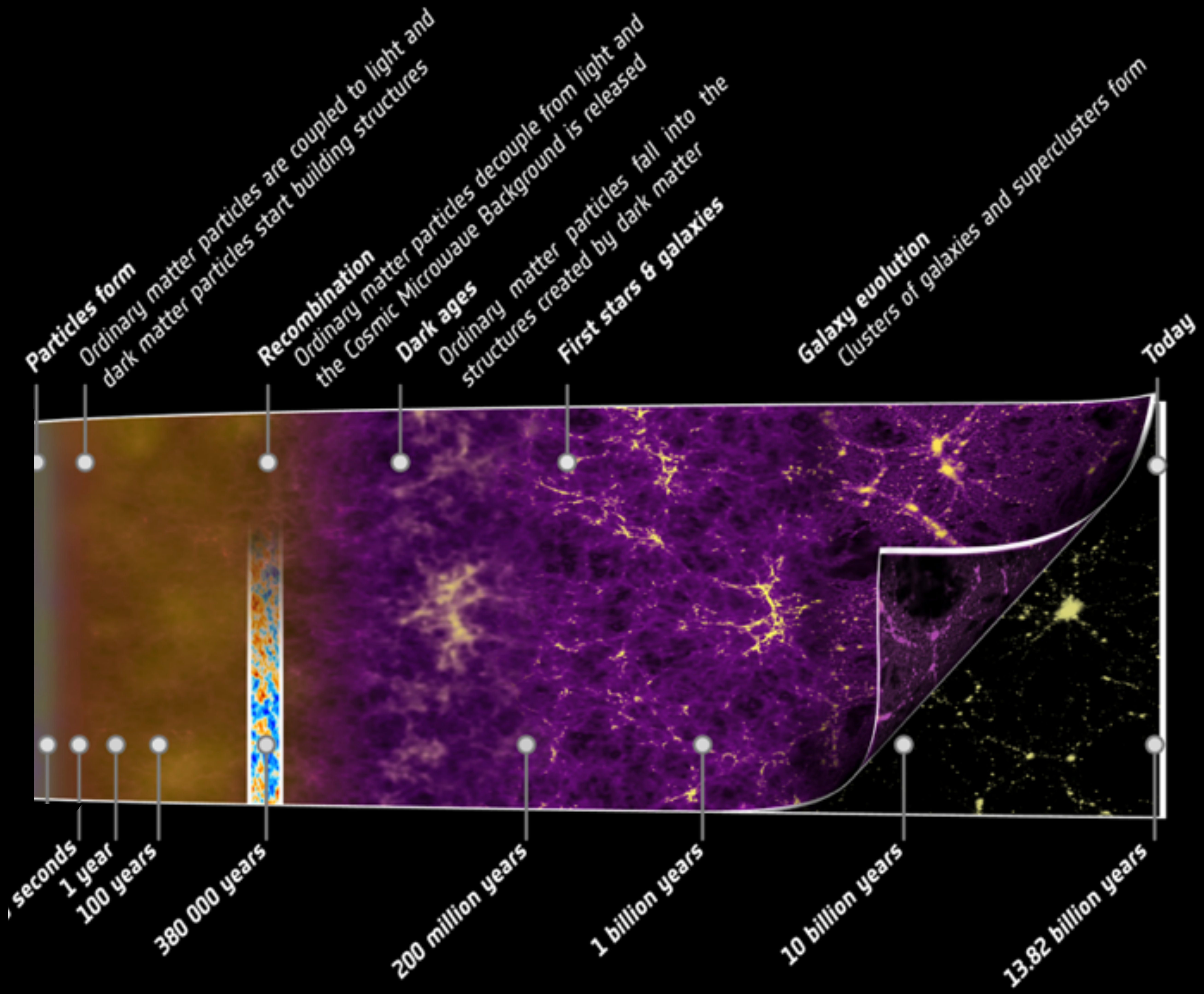
Sunyaev & Zeldovich 1970



Peebles & Yu 1970



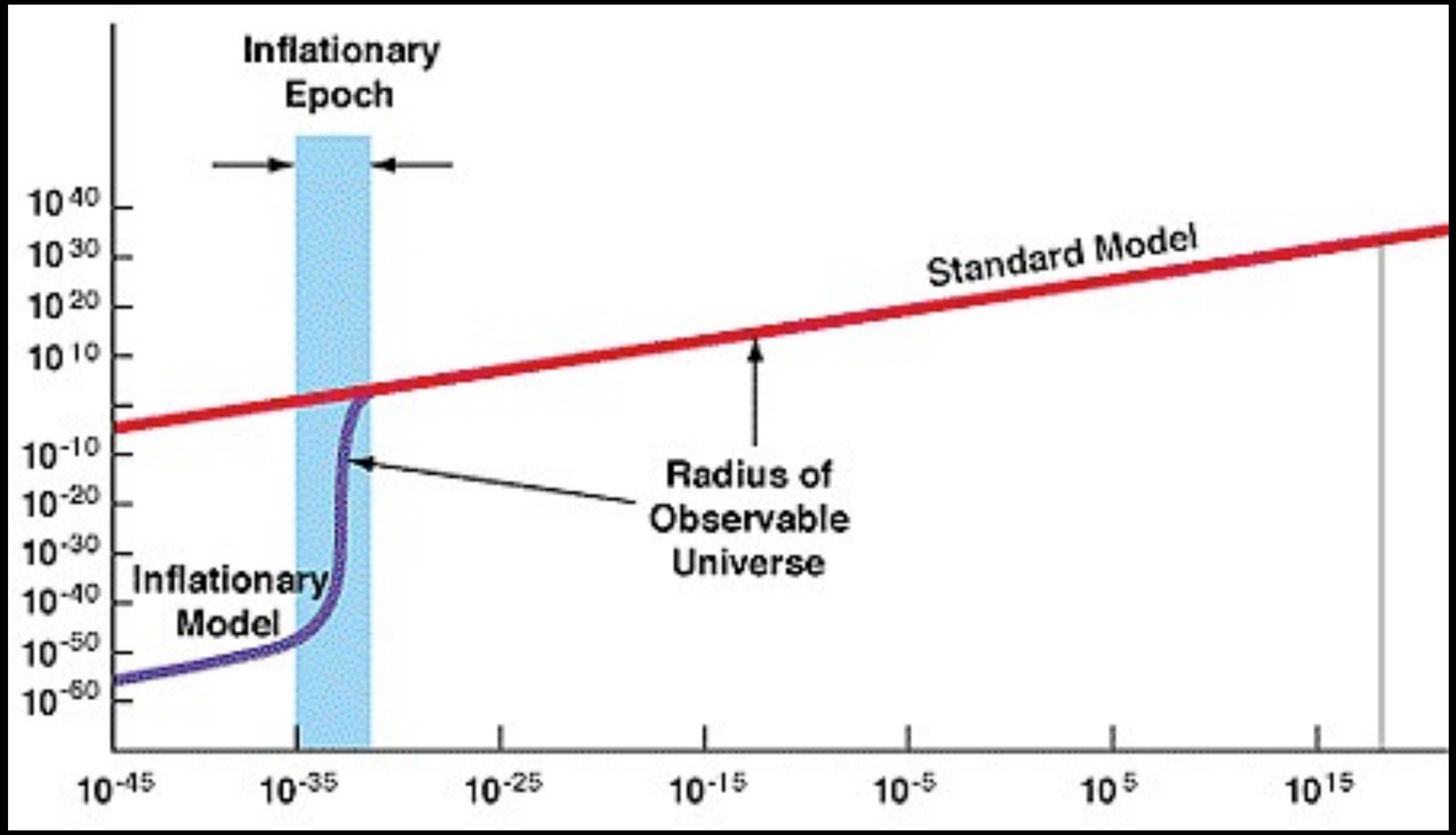
Before the Hot Big Bang



The peculiar initial condition of our Universe

Why is the Universe so large/old?
Why is the Universe so homogeneous/synchronized?
What is the origin of the primordial fluctuations?

Can these questions be answered in the context of known physical principles?



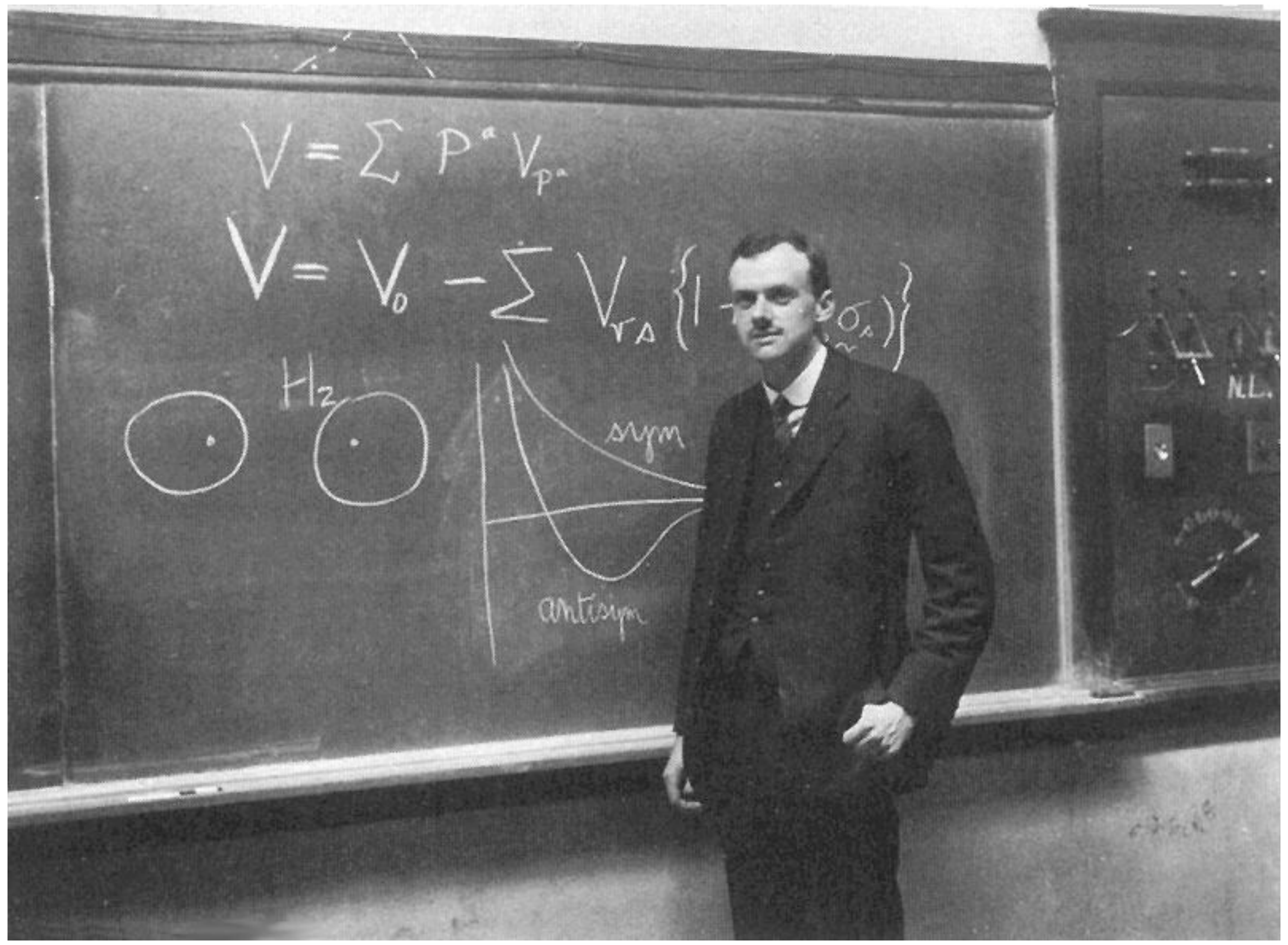
Slow-roll inflation

Almost exponential expansion
Only small departures from Cosmological Constant (Inflation has to end)
During this period the Universe must have expanded by at least 60 enfolds

$$\text{size} \times e^{H_{\text{inf}} \Delta t} \qquad H_{\text{inf}} \times \Delta t \sim 60 \qquad H_{\text{inf}} \sim 10^{-38} \text{ sec}$$

The initial conditions for structure

How did the initial seeds for structure come about? Quantum Mechanics

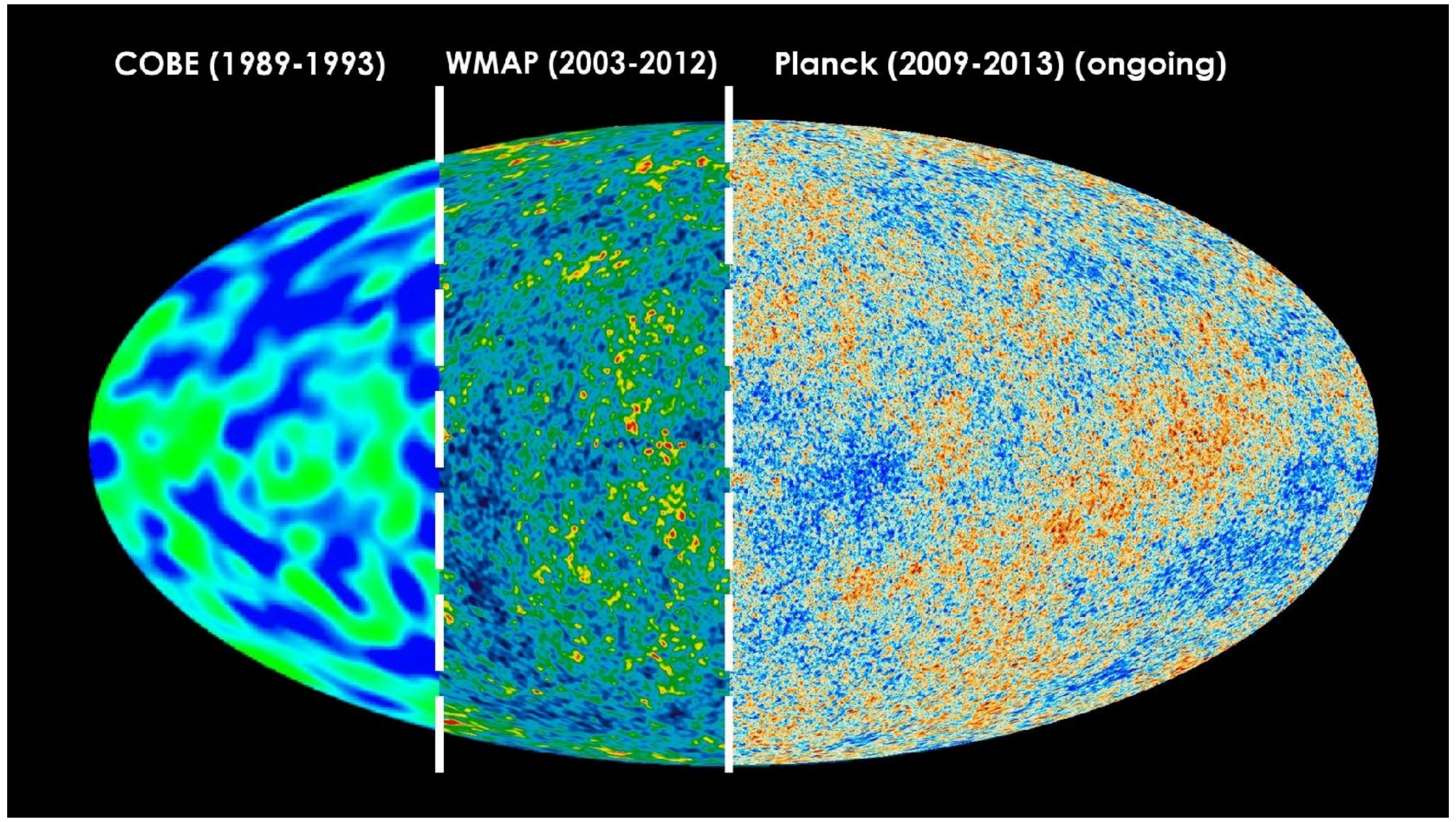


Paul A. M. Dirac
1939 Lecture

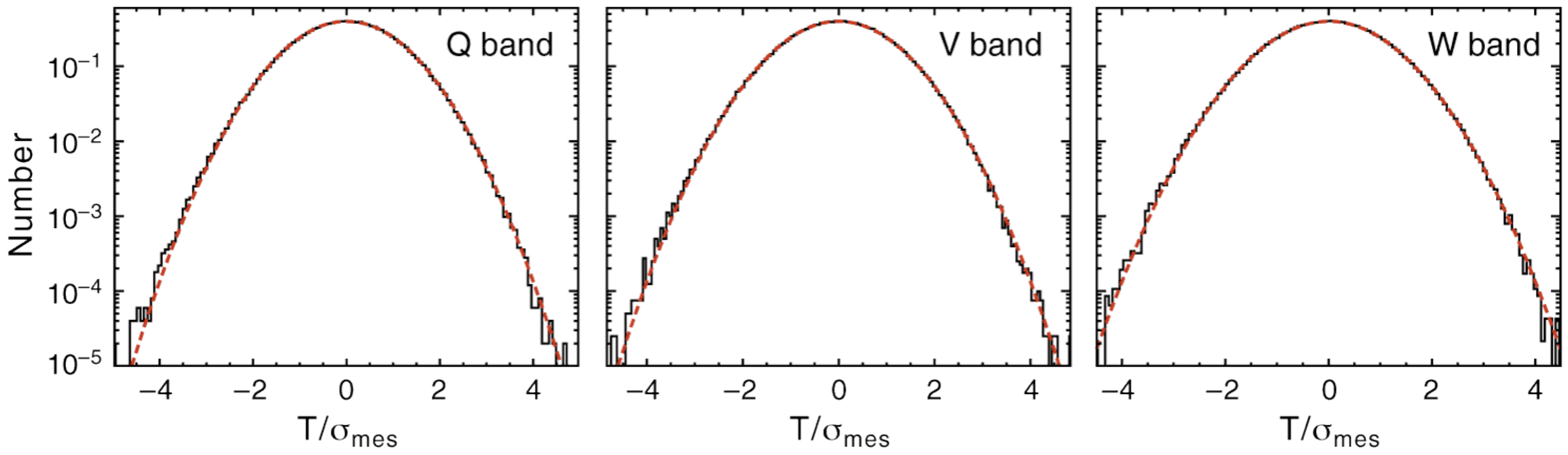
"Let us return to dynamical questions. With the new cosmology the universe must have started off in some very simple way. What, then, becomes of the initial conditions required by dynamical theory? Plainly there cannot be any, or they must be trivial. We are left in a situation which would be untenable with the old mechanics. *If the universe were simply the motion which follow from a given scheme of equations of motion with trivial initial conditions, it could not contain the complexity we observe. Quantum mechanics provides an escape from the difficulty. It enables us to ascribe the complexity to the quantum jumps, lying outside the scheme of equations of motion.*"

- Inflation needs a clock
- Quantum mechanics implies that the clock must fluctuate.
- The Universe cannot be perfectly homogeneous.
- Properties of the fluctuations are consistent with our best observations.
- Potentially there is an additional fossil, a stochastic background of gravitational waves.
- Calculations are under control.

Origin is quantum mechanical. We can only calculate a probability distribution for the primordial seeds.

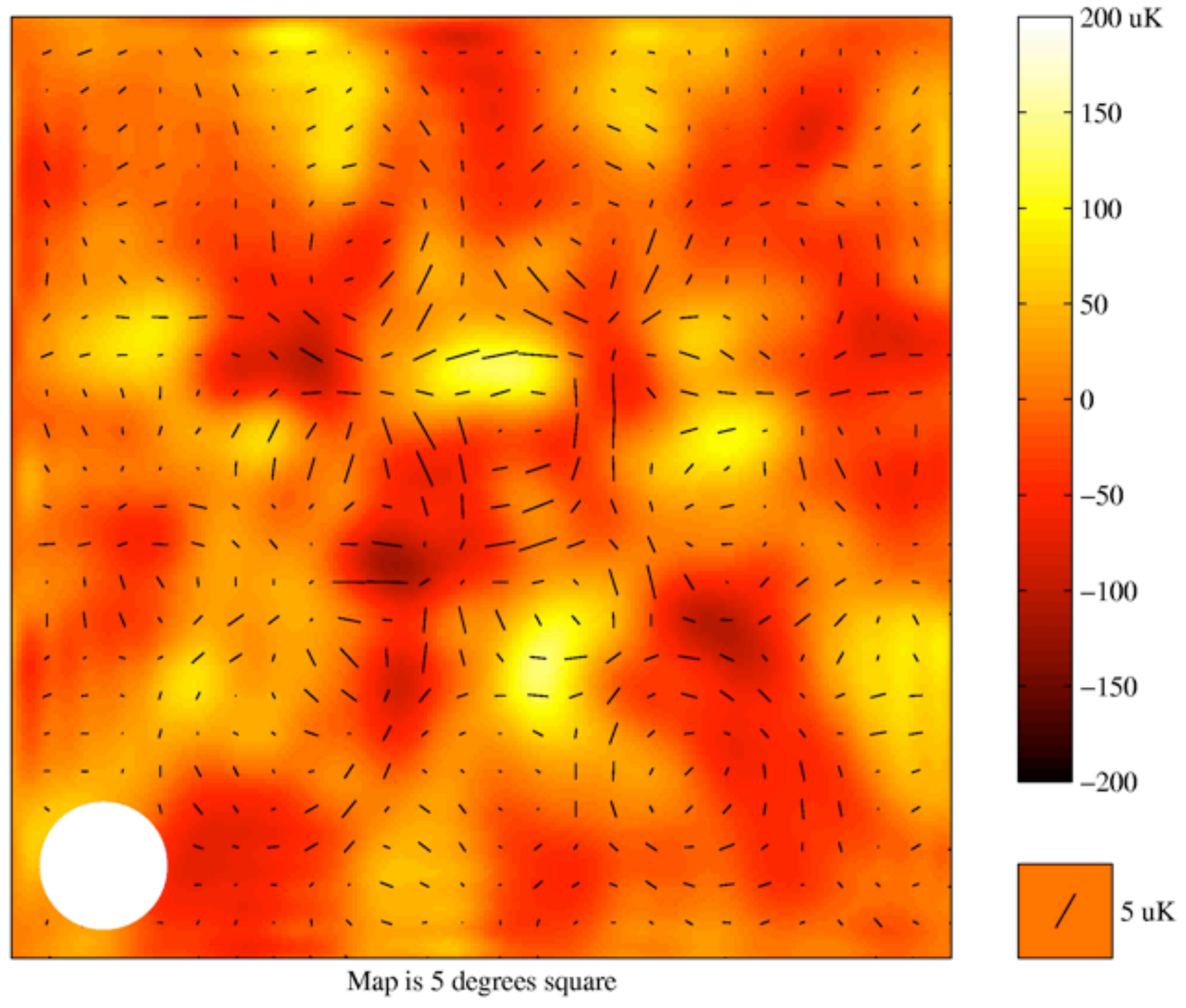


- Amplitude almost scale invariant
- No fluctuations in composition of the Universe
- Almost perfectly Gaussian distribution

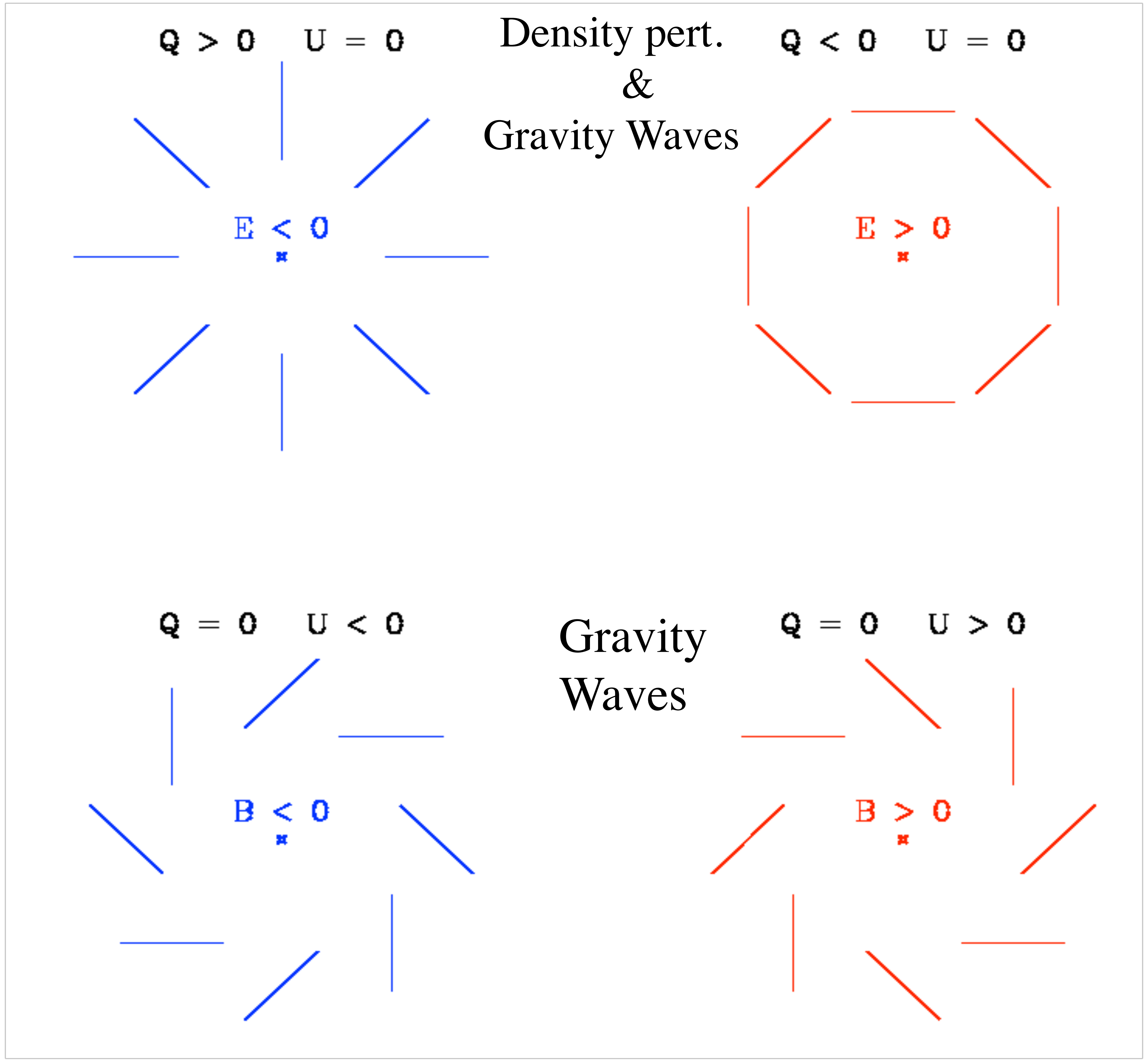


- Temperature histogram

A second fossil: tensor modes



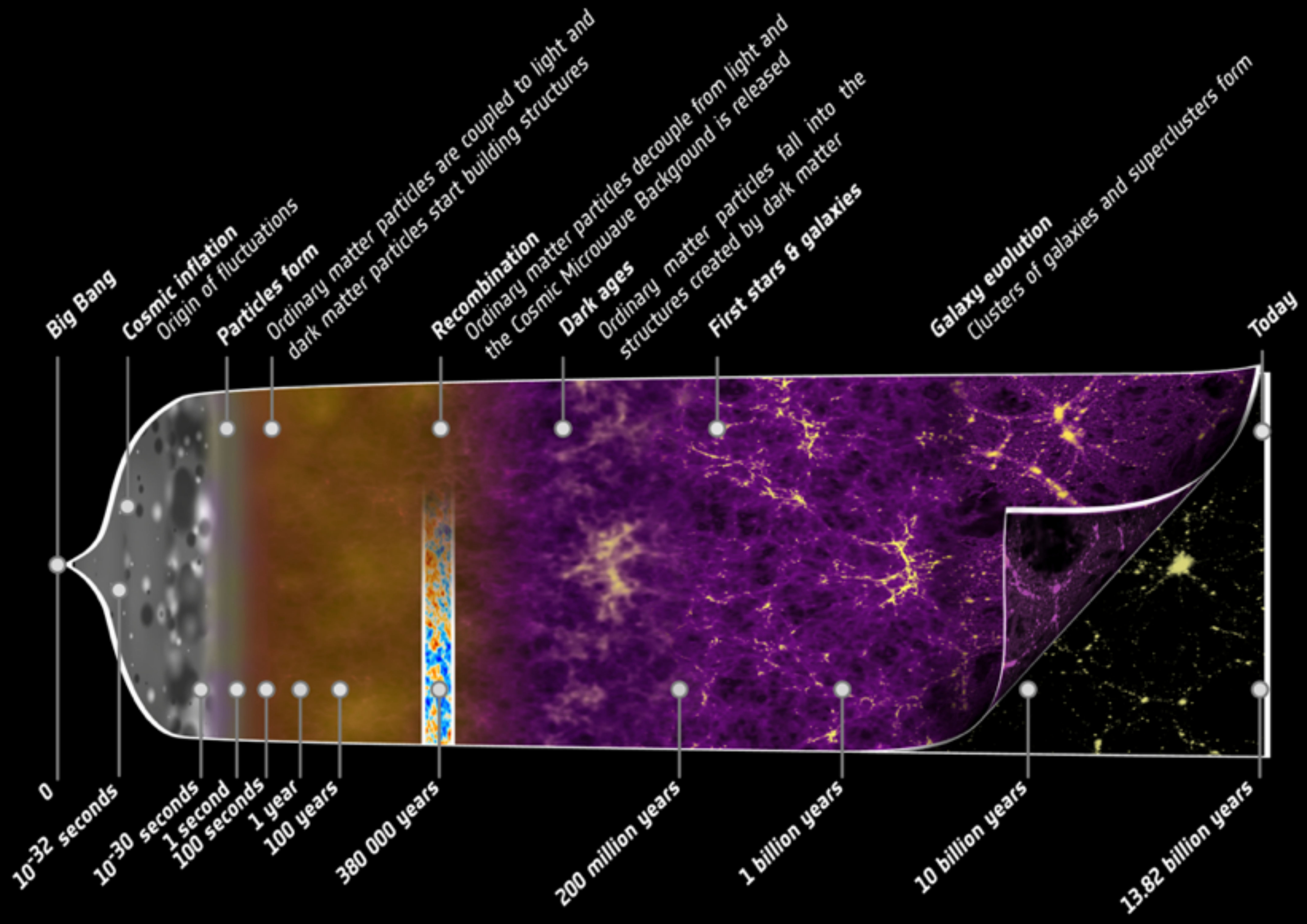
Potentially there is an additional fossil, a stochastic background of gravitational waves.



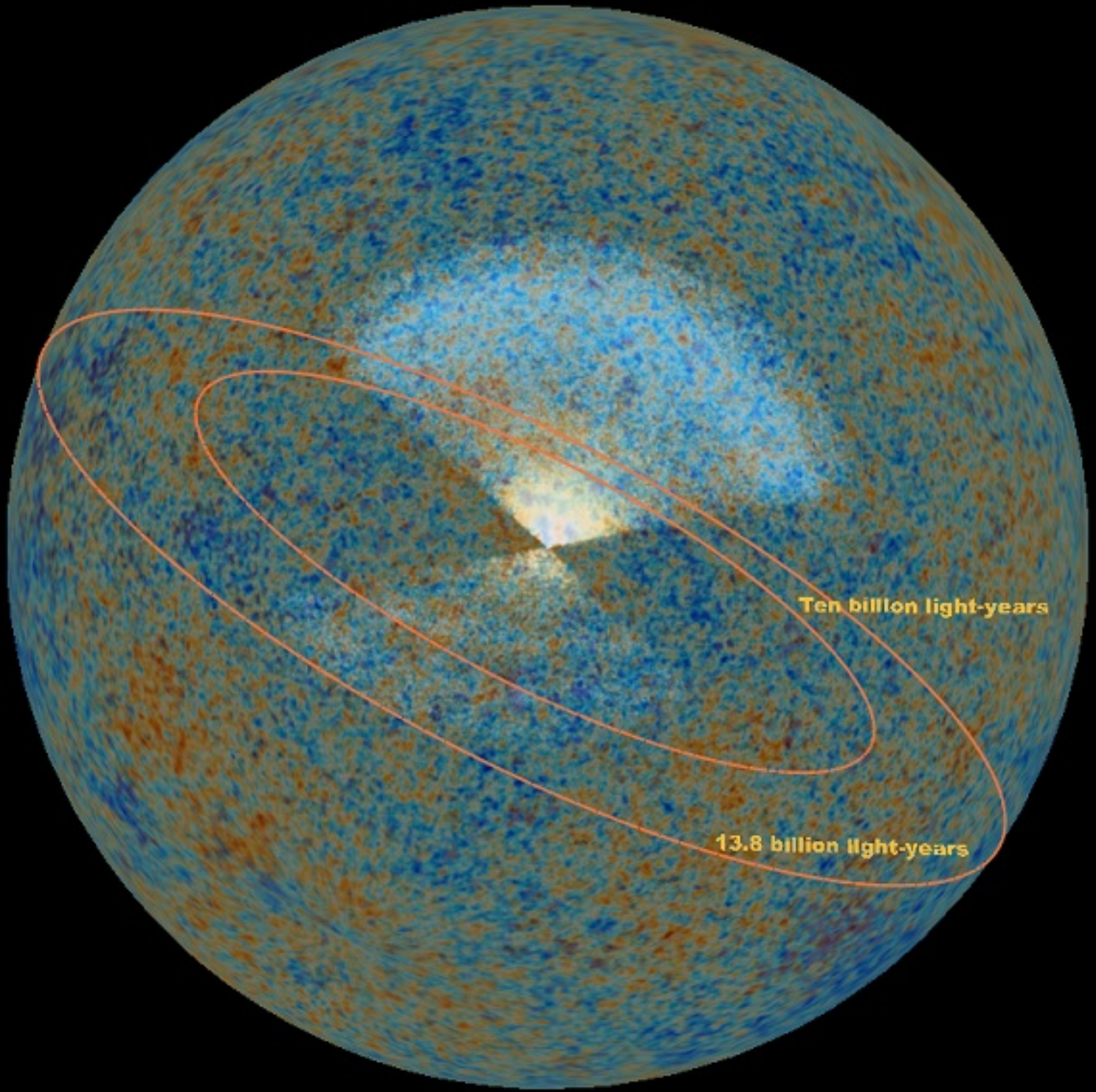
Gaussian distribution of amplitudes with amplitude set by the Hubble scale during Inflation

Experiments are testing very interesting values.
"Simple" textbook examples of inflation mostly ruled out.
We can expect significant improvements in the near future.

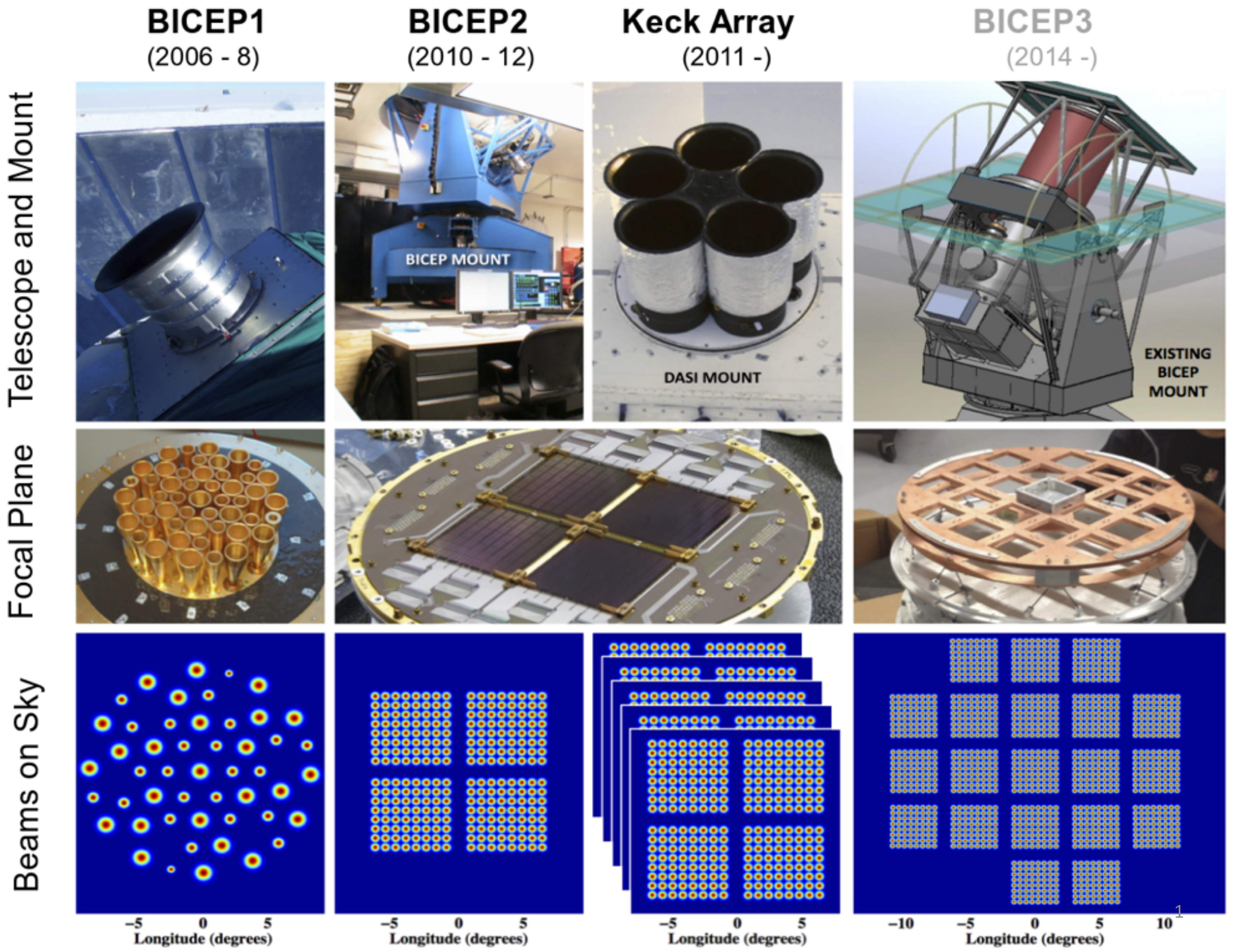
Is slow-roll inflation the last necessary ingredient ?

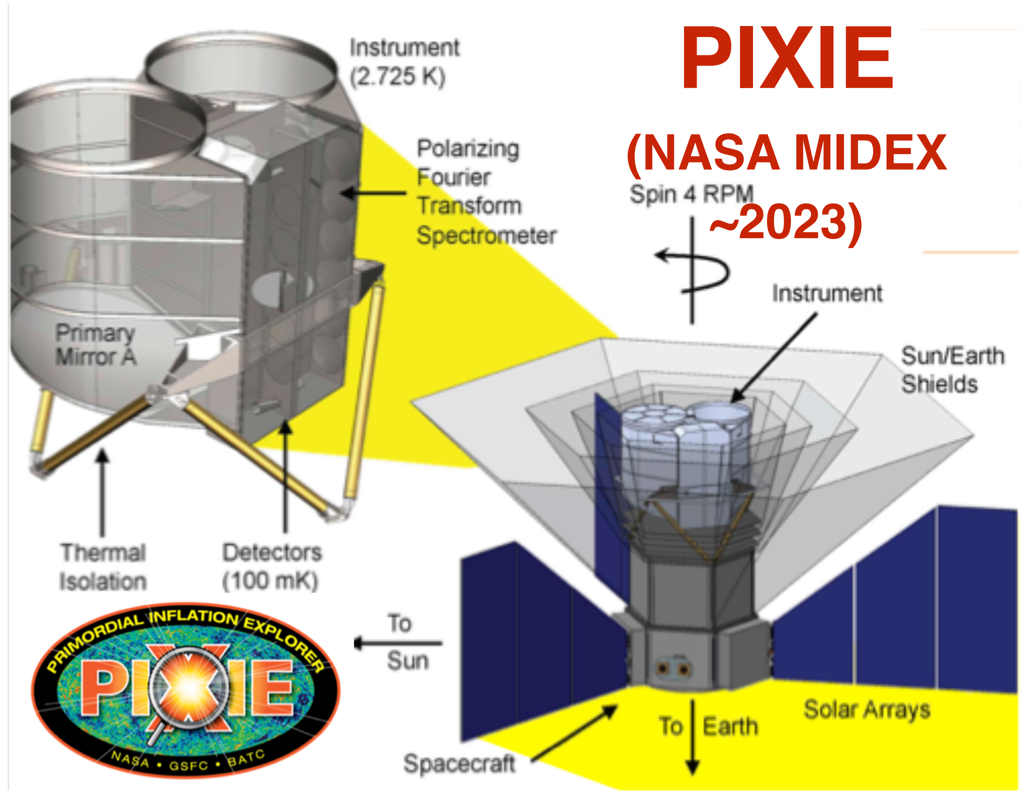


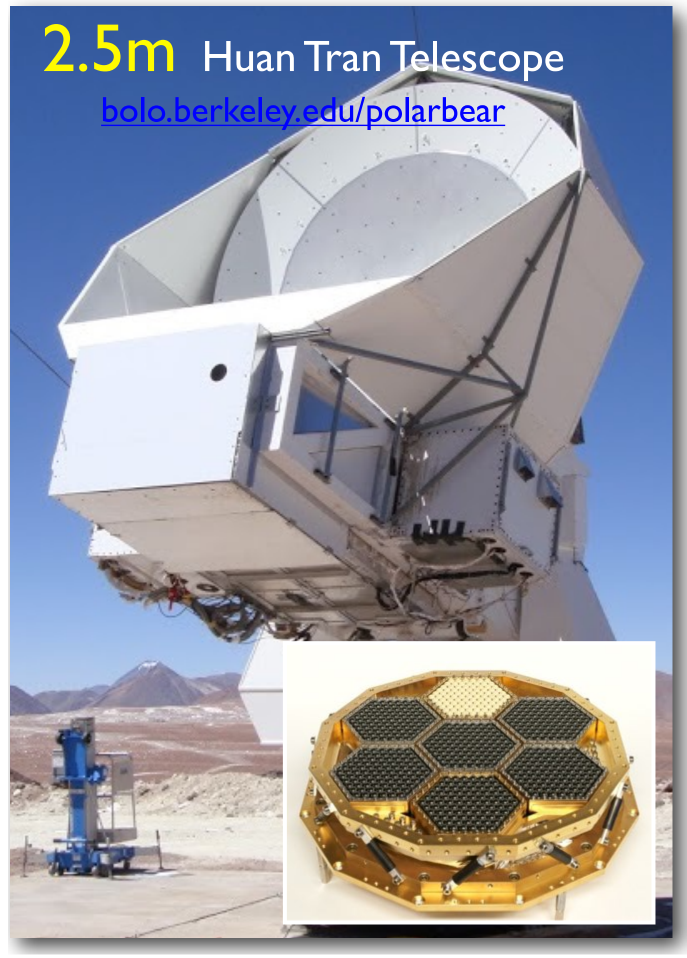
Better maps to make a better history

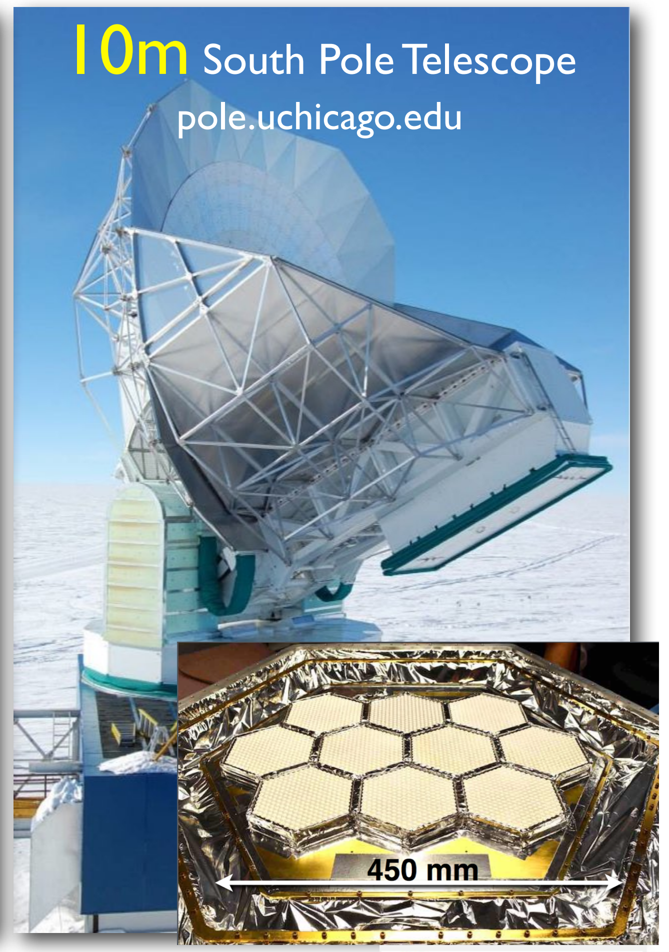


The Cosmic Microwave Background

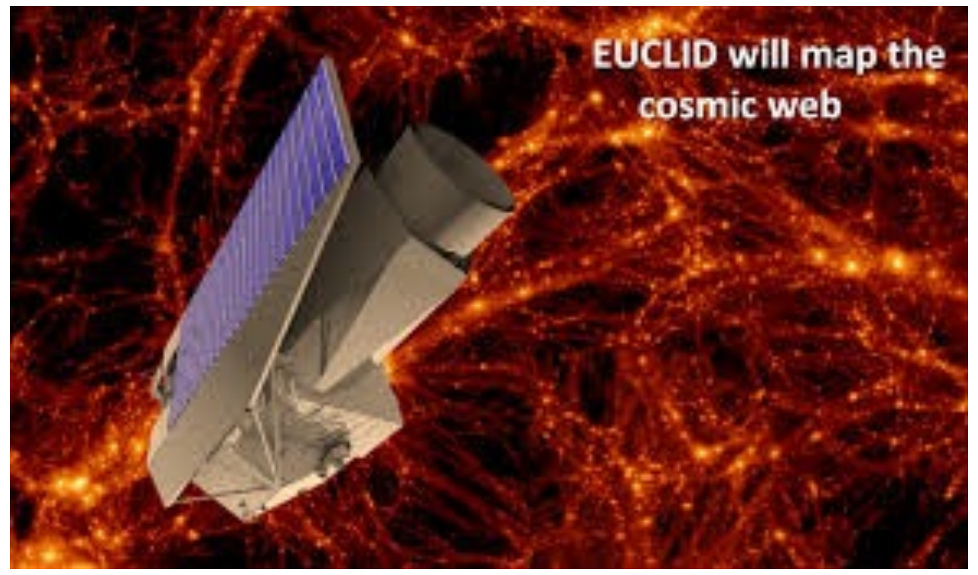








Large Scale Structure



	LSST	DESI	Euclid	SPHEREx	CHIME
Survey type	photo	spectro	photo+spectro	low-res spectro	21-cm
Ground or space	ground	ground	space	space	ground
Previous surveys	CFHTLS, DES, HSC	BOSS, eBOSS, PFS	no direct precursor	PRIMUS, COMBO-17, COSMOS	GBT HIM
Survey start	2020	2020	2018	2020	2016
Redshift-range	$z < 3$ (1% sources above 3)	$z < 1.4$, $2 < z < 3.5$ (Lya)	$z < 3$	$z < 1.5$	$0.75 < z < 2.5$
Survey area [deg^2]	20k	14k	15k	40k	20k
Approximate number of objects	2×10^9 (WL sources)	$22{\times}10^6$ gal., $\sim 2.4 \times 10^5$ QSOs	40×10^6 redshifts, 1.5×10^9 photo-zs	15×10^9 pixels	10^7 pixels
Galaxy clustering	✓✓°	✓	✓	✓	✓
Weak lensing	✓		✓		✓
RSD		✓	✓	✓✓	✓✓
Multi-tracer	✓✓	✓✓	✓✓	✓	

Table 2. A selection of currently funded or planned surveys. Other important surveys not included in the table are PFS, JPAS, PAU, EMU. Relevant survey links [LSST],[DESI],[Euclid], [UBC],[PFS], [JPAS],[PAU], [EMU]. °Galaxy clustering is possible, but very strong radial degradation.

The End