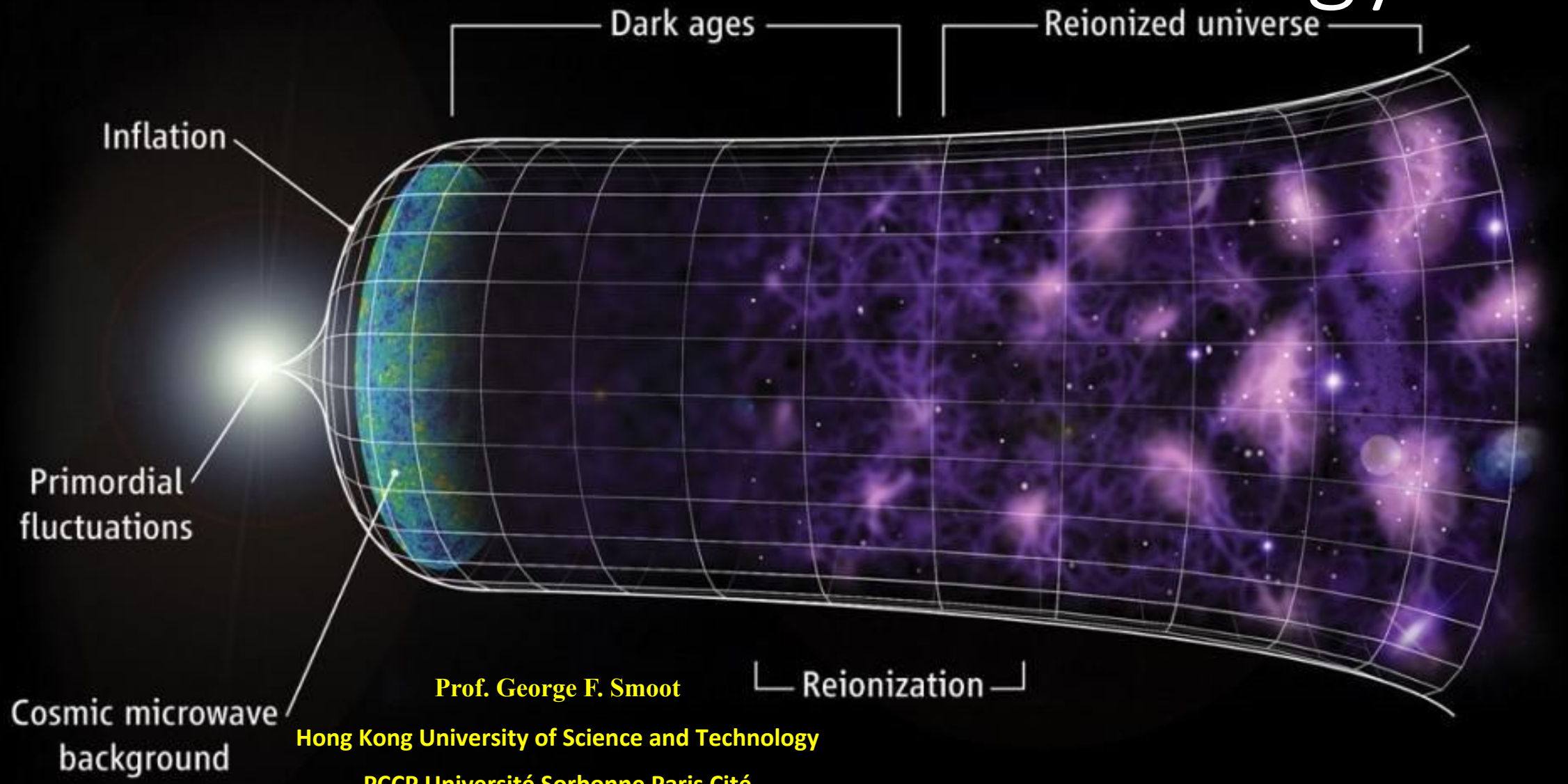
The Future of Cosmology



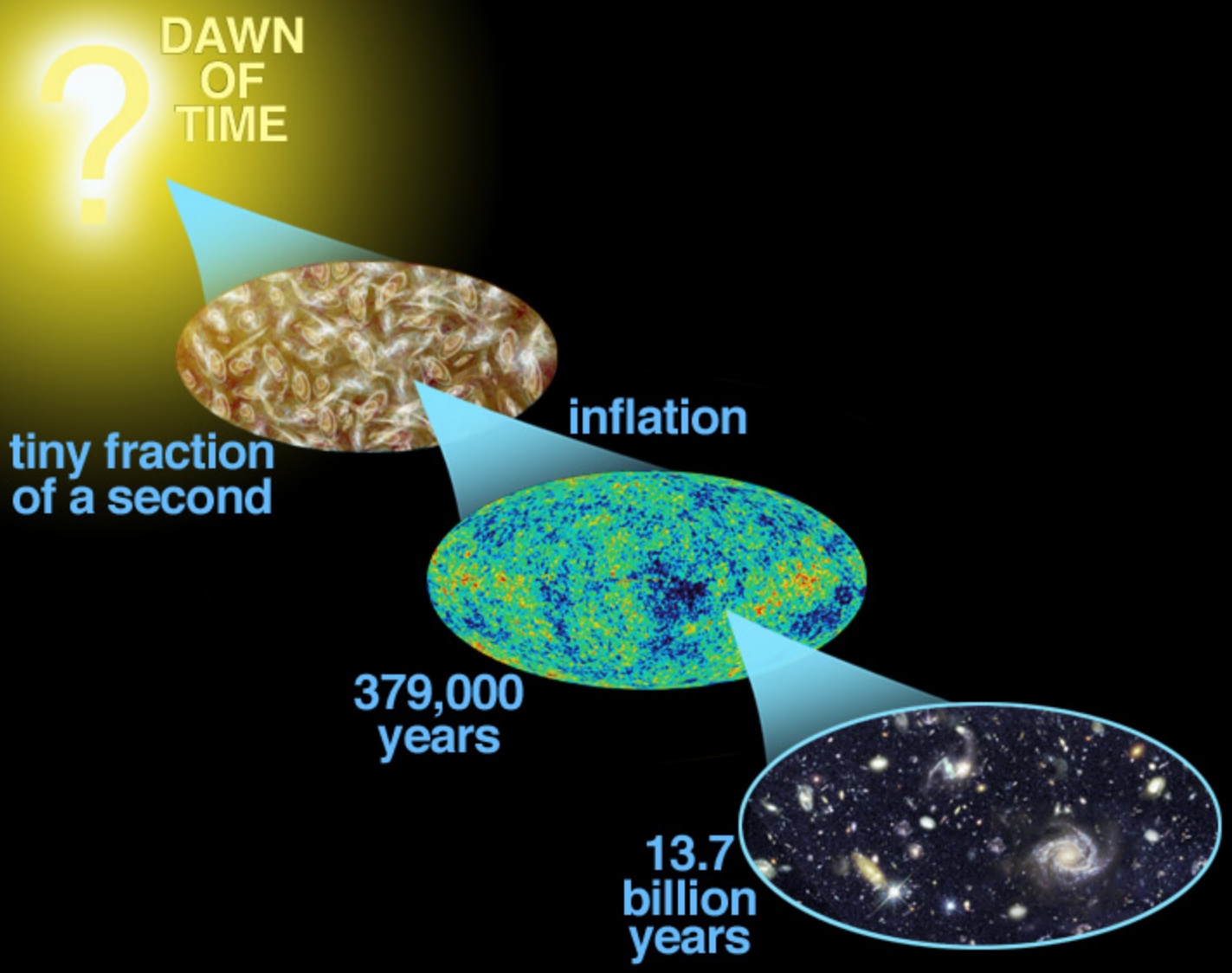
Prof. George F. Smoot

Hong Kong University of Science and Technology

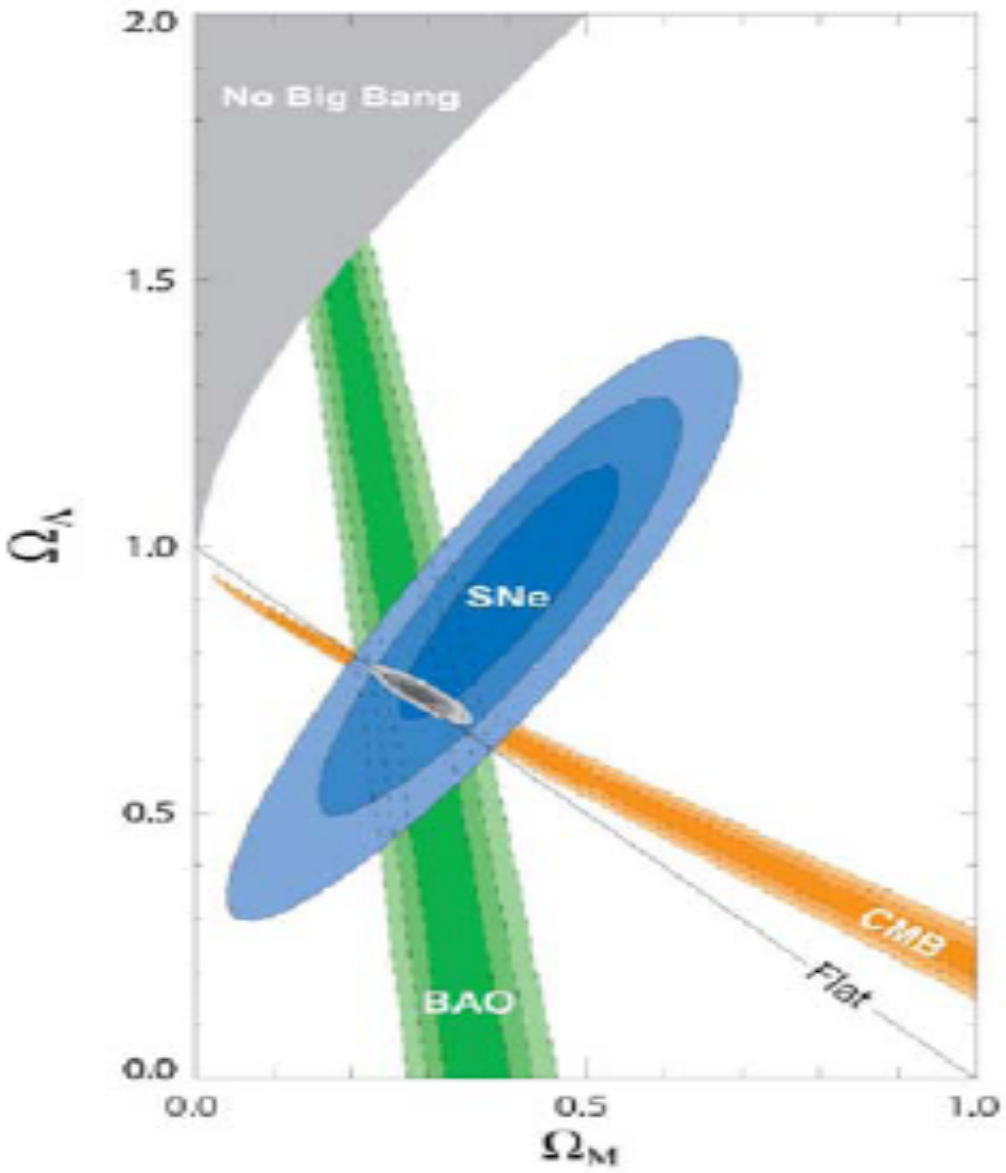
PCCP Université Sorbonne Paris Cité

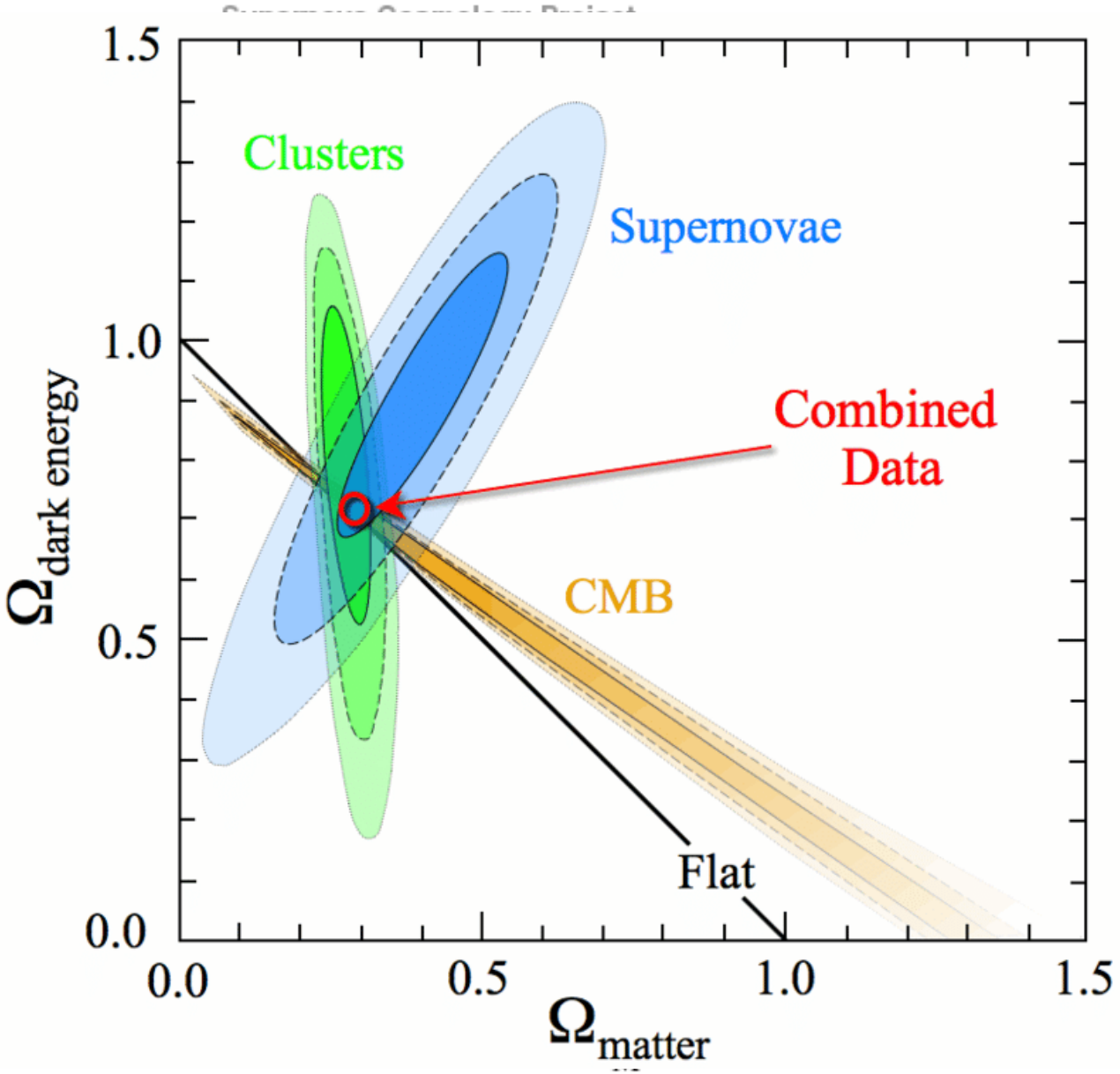
University of California at Berkeley

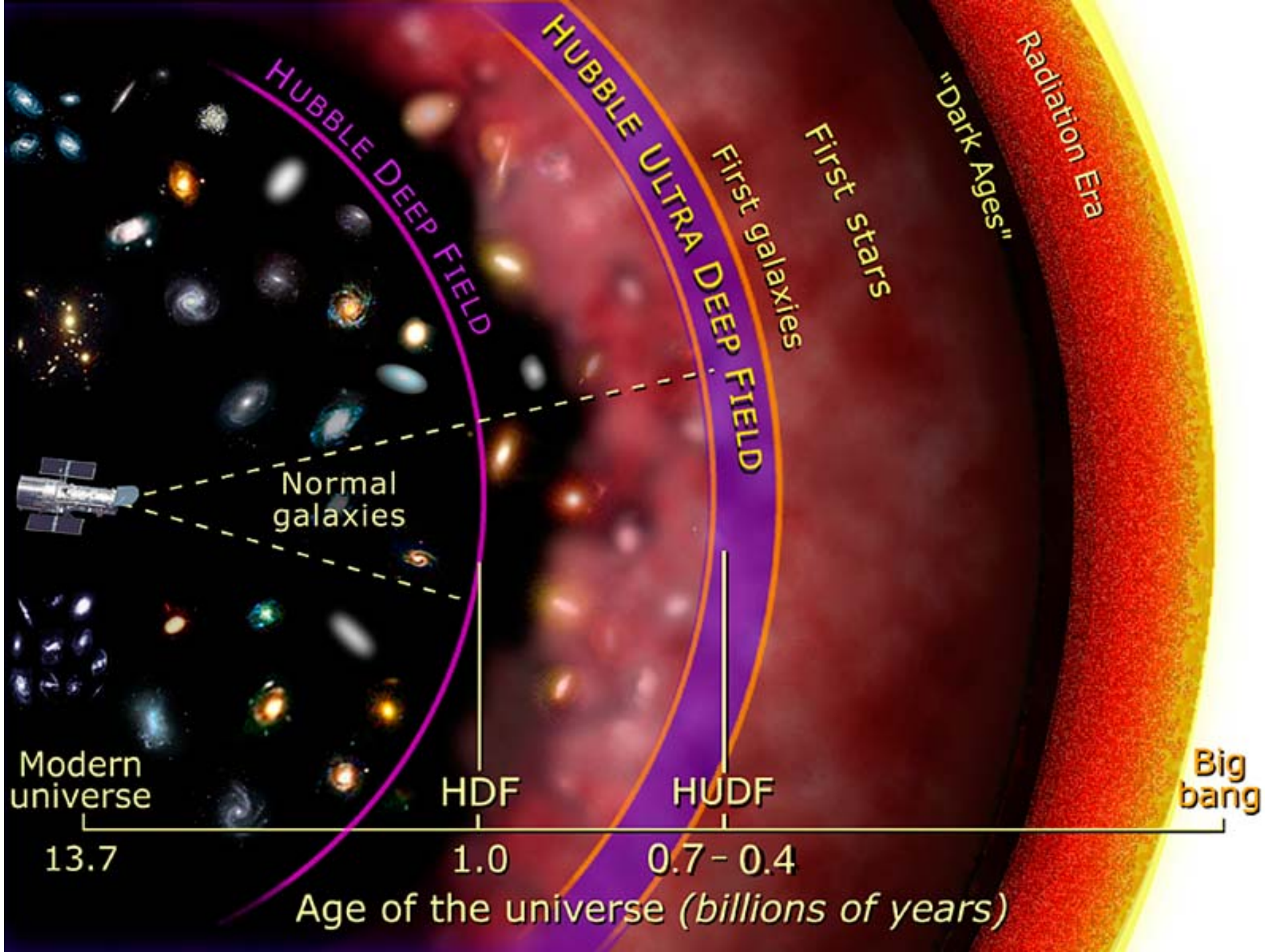
ECL Nazarbyaev University


DAWN
OF
TIME
tiny fraction
of a second
inflation
379,000
years
13.7
billion
years

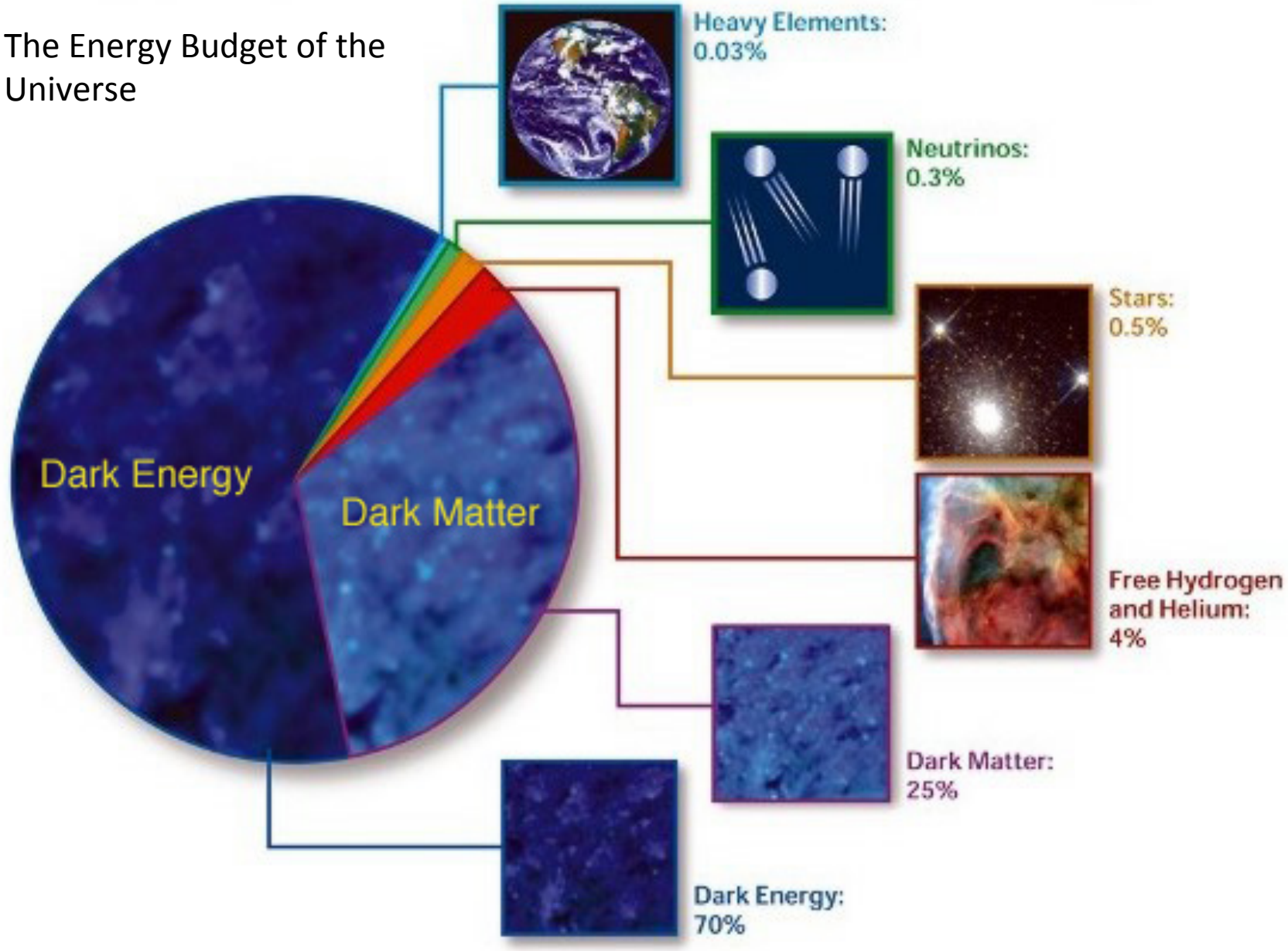
Observational support for the ΛCDM model *(http:rpp.lbl.gov)*






Hubble Deep Field
Hubble Ultra Deep Field
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 - 0.4
Age of the universe (billions of years)

The Energy Budget of the Universe



Standard cosmological model

Cosmological principle (Isotropy and homogeneity at large scales)
Friedmann-Lemaitre-Robertson-Walker metric

$$d\tau^2 = dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2\right]$$

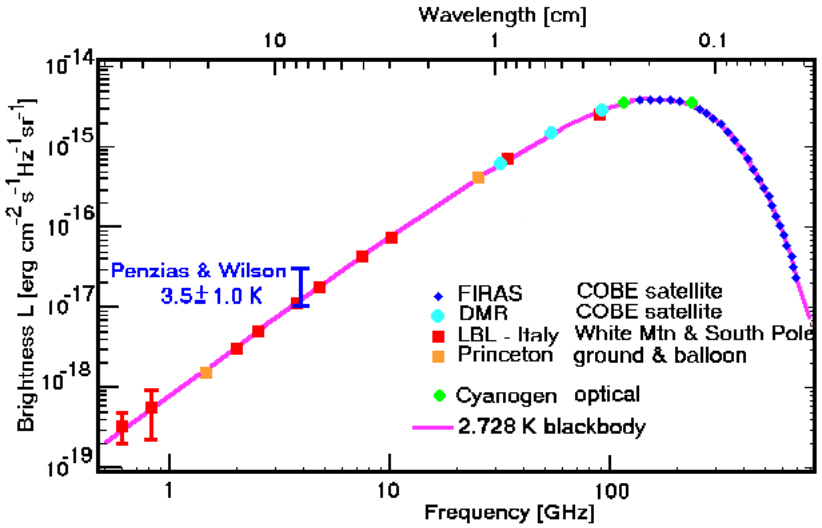
Energy-momentum (perfect fluid)

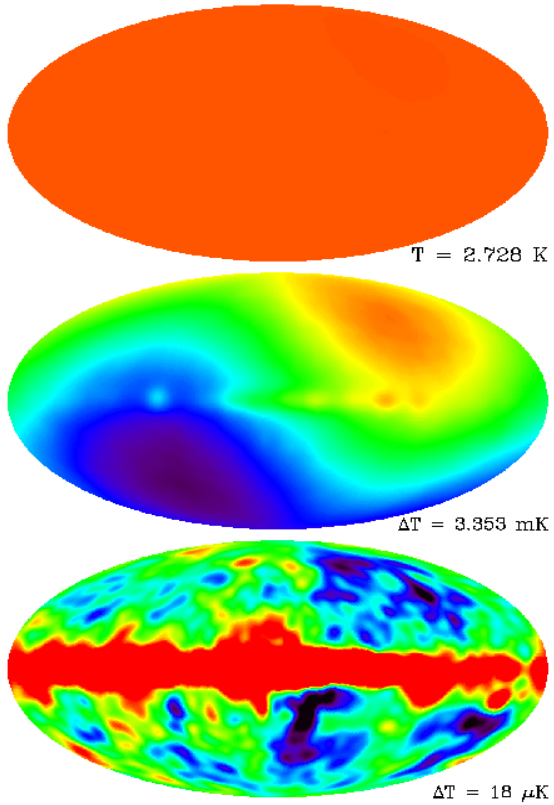
$$T_{\mu\nu} = diag(\rho, p, p, p)$$

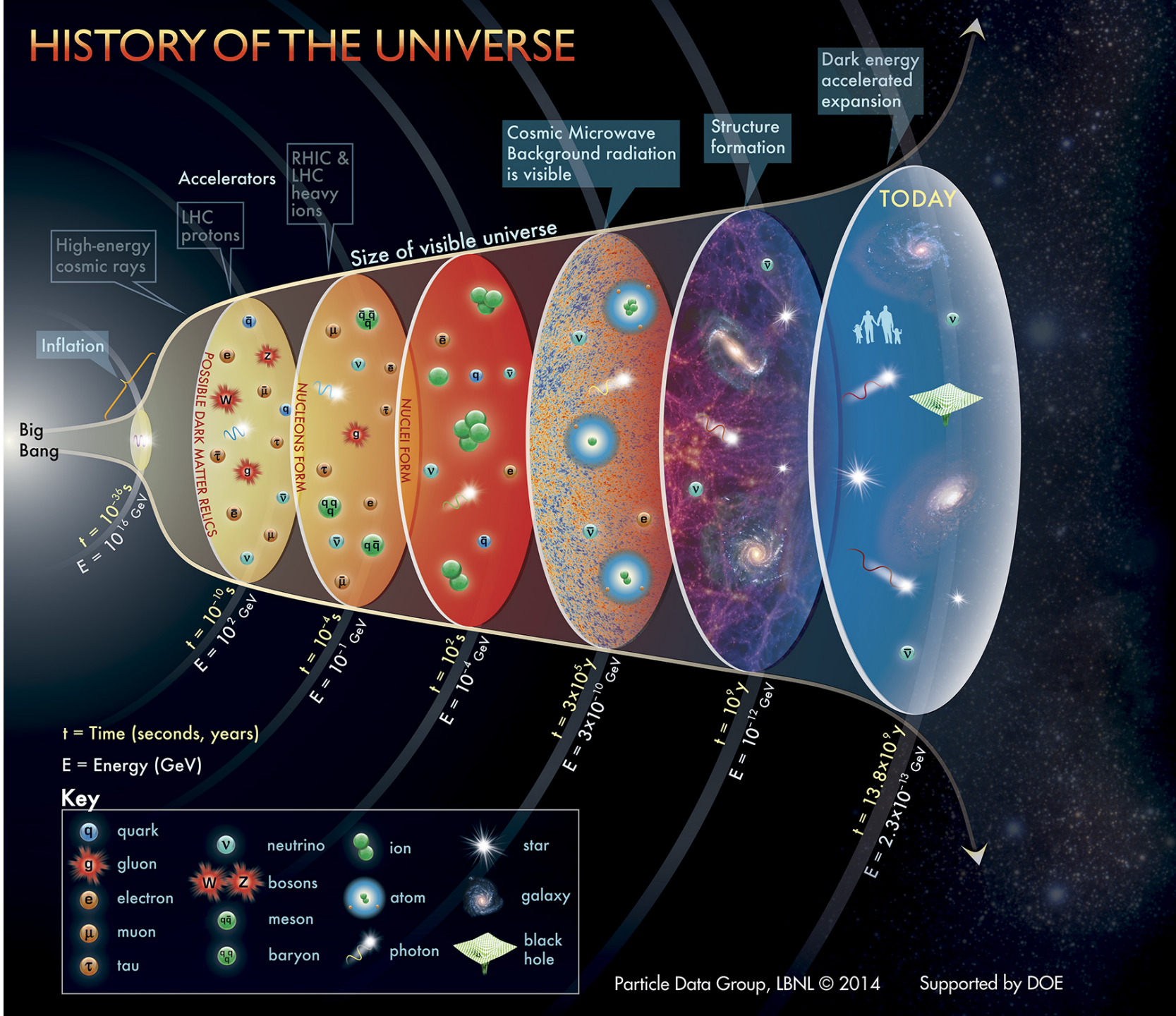
Dynamics *(Friedmann equations)*

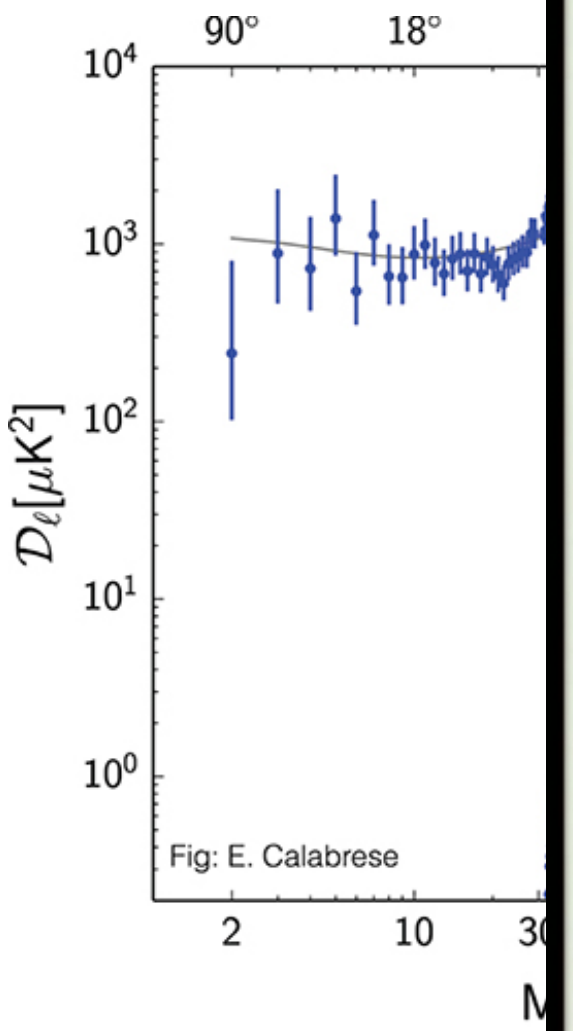
$$H^2 \equiv \left[\frac{\dot{a}}{a^2}\right] = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$


Wavelength [cm]
10
1
0.1
Brightness L [erg cm^{-2}s^{-1}Hz^{-1}sr^{-1}]
Penzias & Wilson
3.5± 1.0 K
FIRAS COBE satellite
DMR COBE satellite
LBL - Italy White Mtn & South Pole
Princeton ground & balloon
Cyanogen optical
2.728 K blackbody
Frequency [GHz]

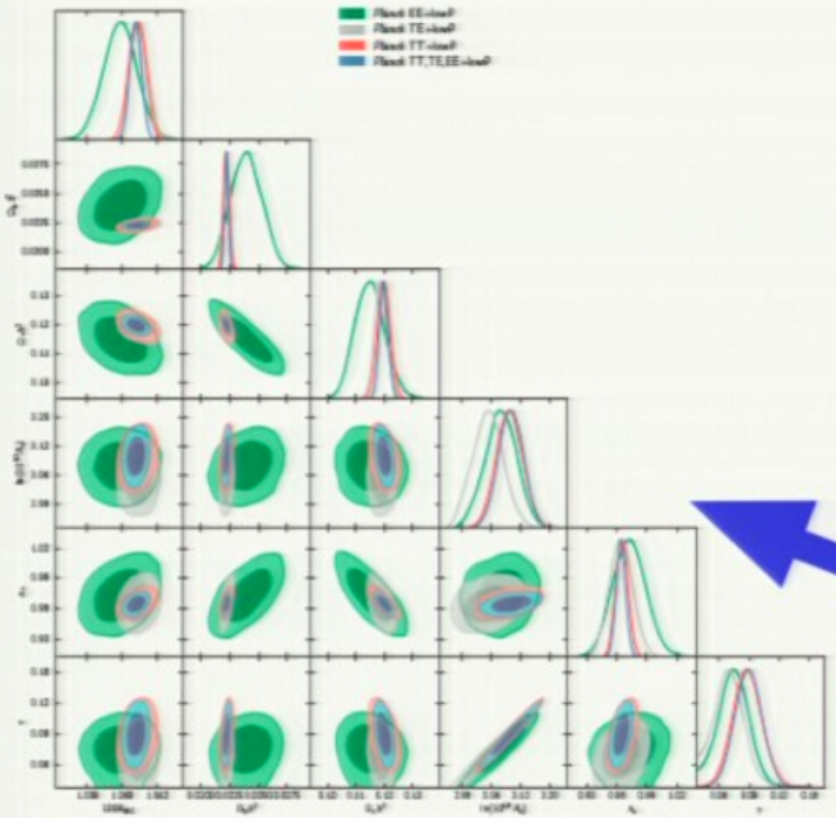

T = 2.728 K
ΔT = 3.353 mK
ΔT = 18 μK

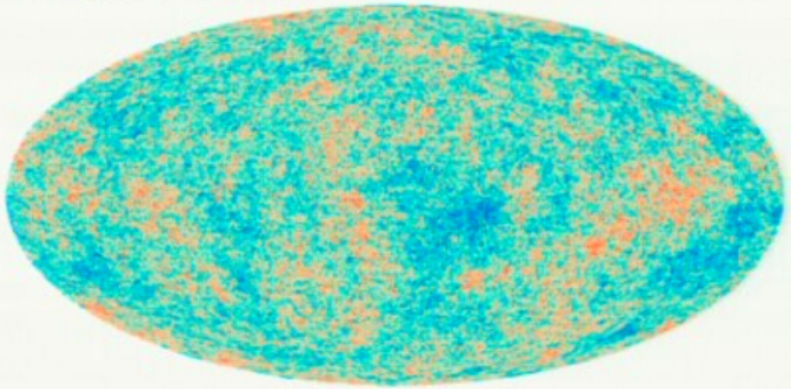

HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

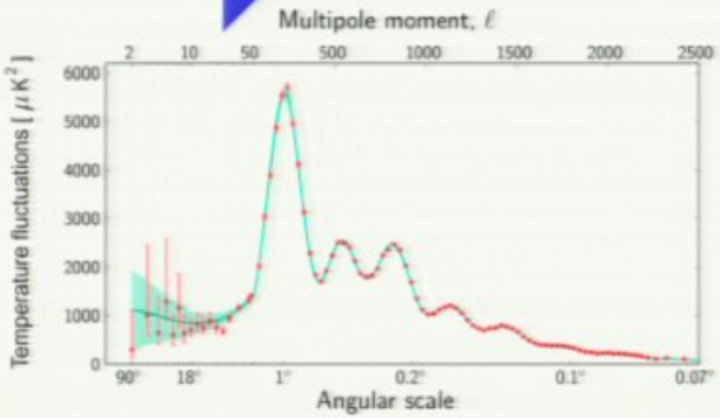


Intensity mapping: CMB

Cosmic Microwave Background, z=1100

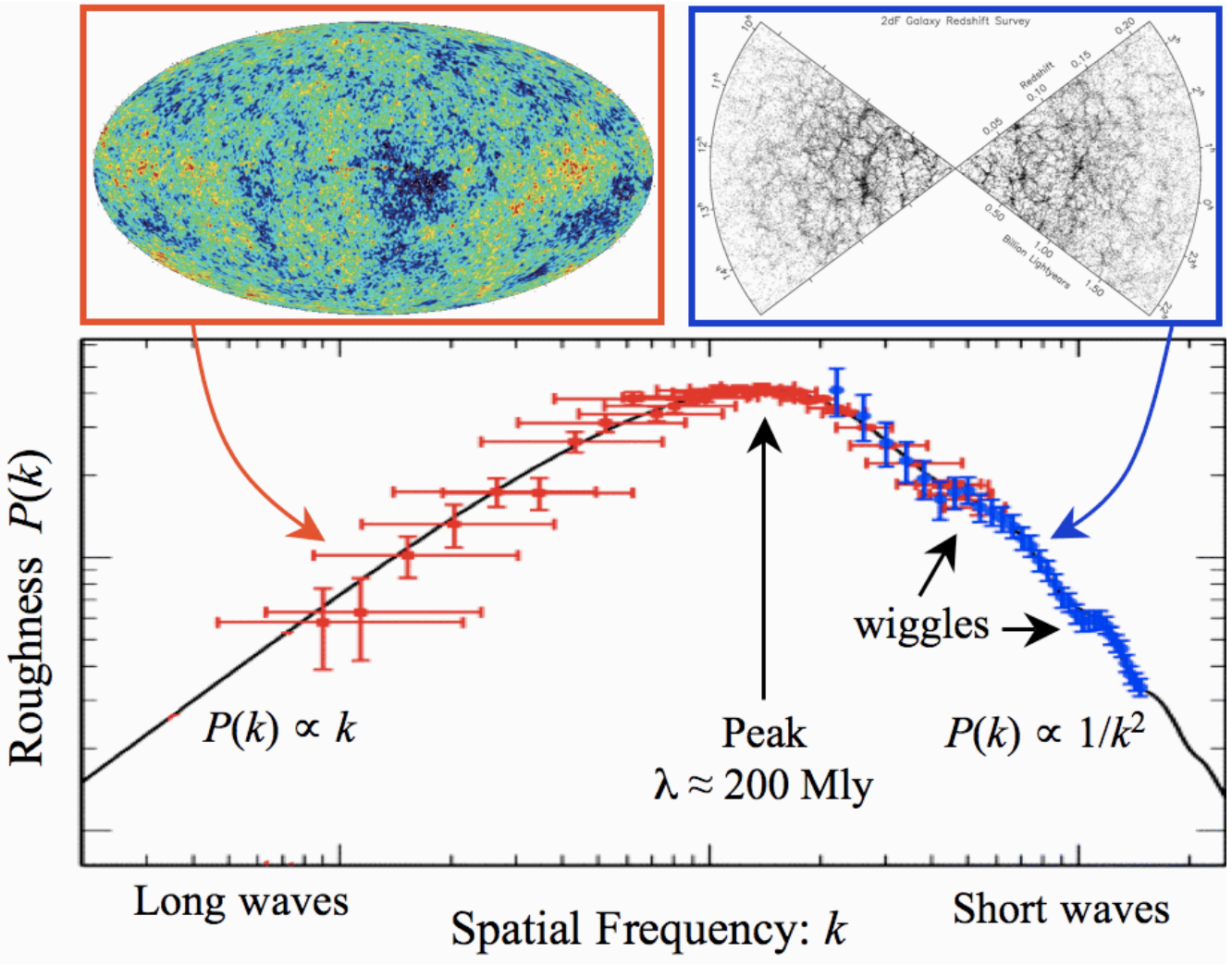


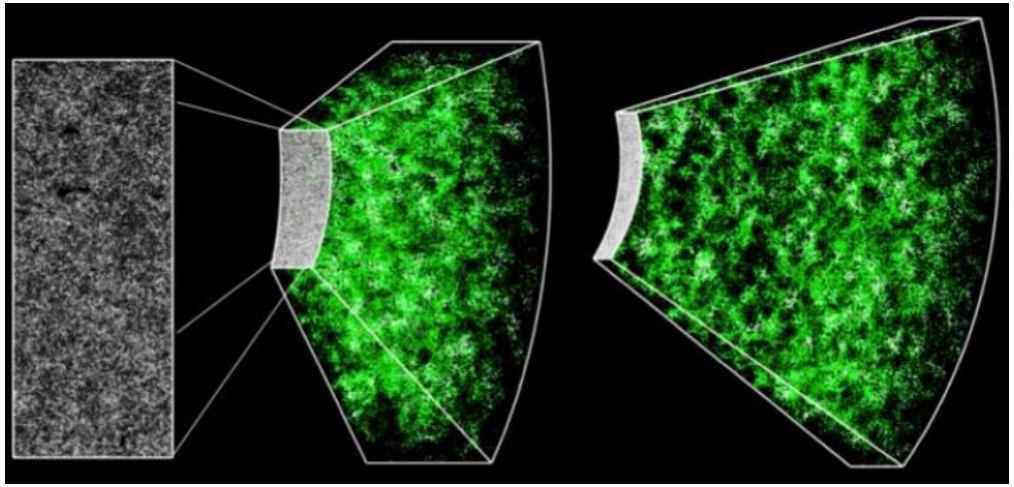




Planck 2013 results. XVI. Cosmological parameters
Planck 2015 results XIII. Cosmological parameters
Planck 2015 results IX. Diffuse component separation: CMB maps
Planck 2015 results XI. CMB power spectra, likelihoods, and robustness of parameters

Observations show very good fit to cosmology model



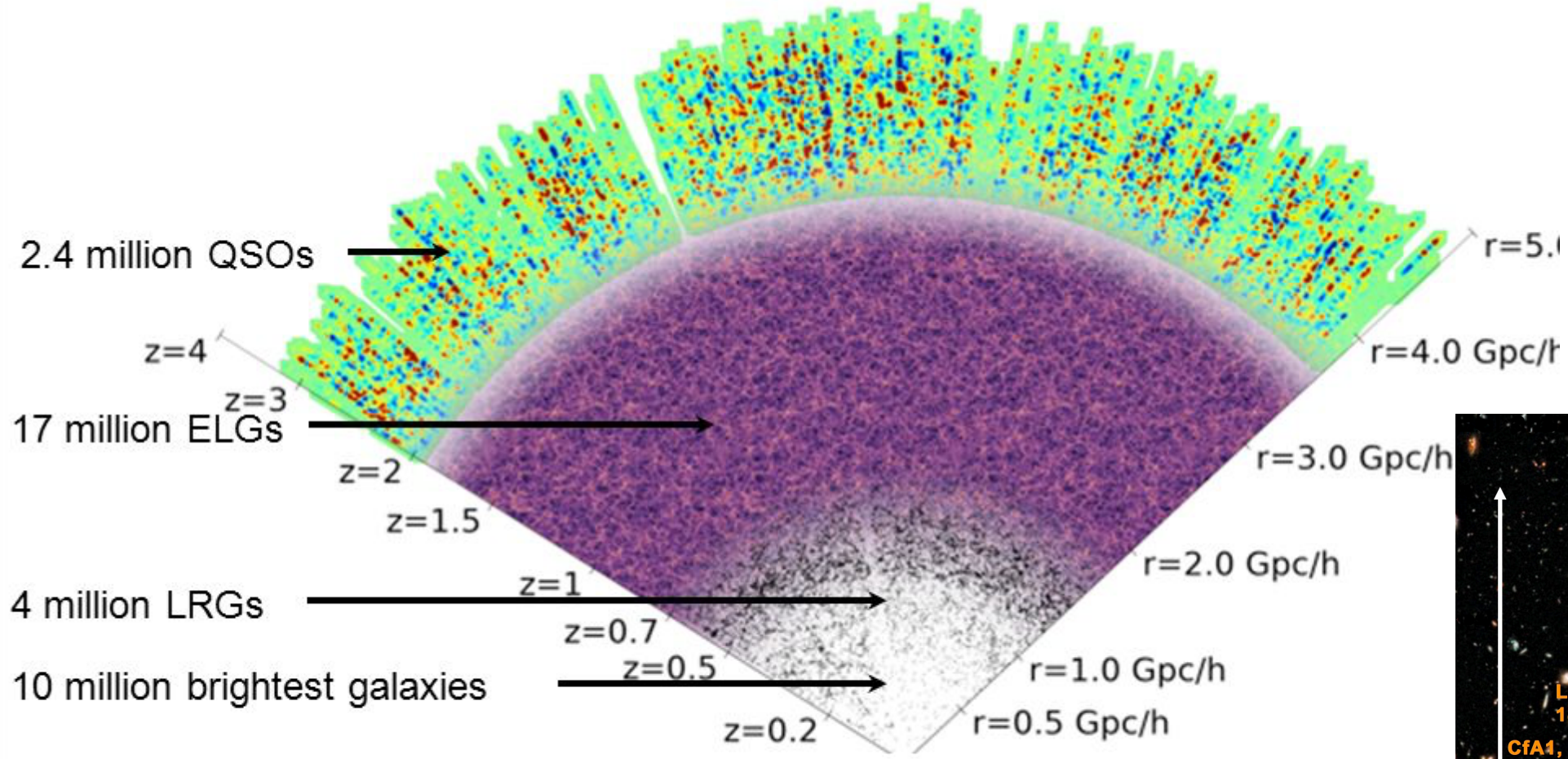


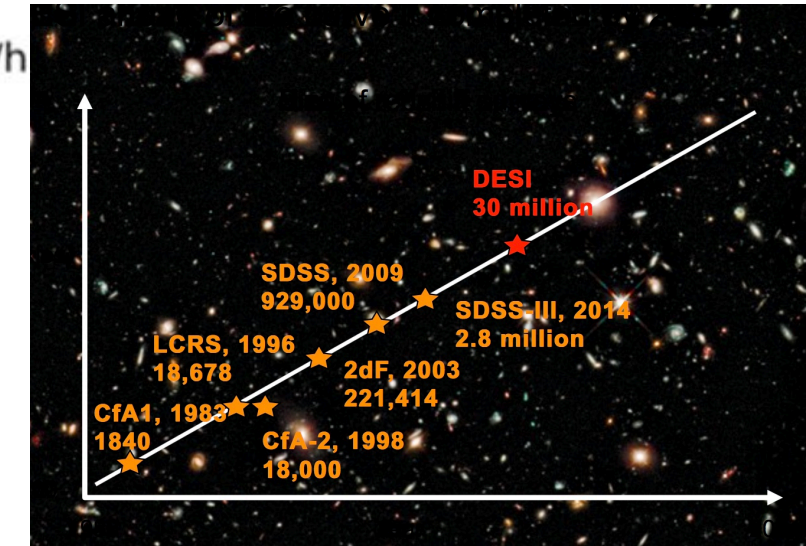
The Sloan Digital Sky Survey - Baryon Oscillation Spectroscopic Survey has transformed a two-dimensional image of the sky (left panel) into a three-dimensional map spanning distances of billions of light ye shown here from two perspectives (middle and right panels). This map includes 120,000 galaxies over 10% of the survey area. The brighter regions correspond to the regions of the Universe

What is the DESI survey?

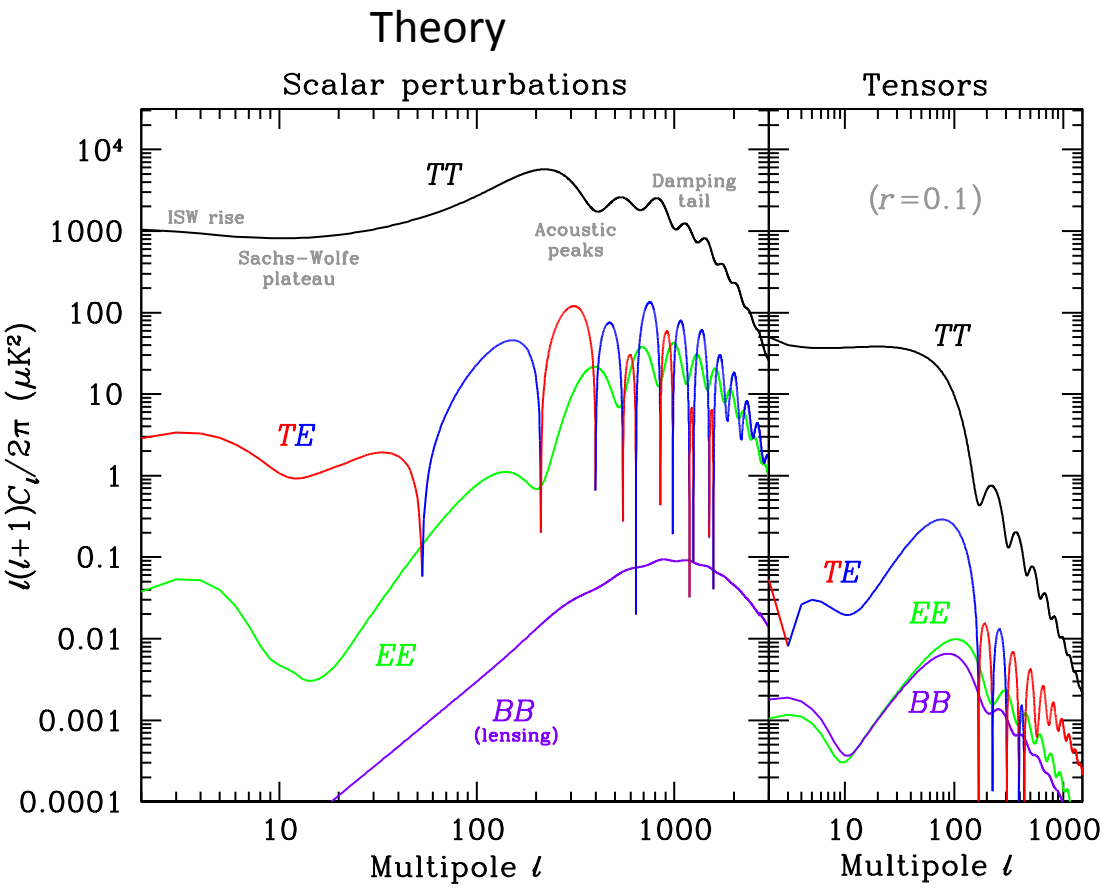
The largest spectroscopic survey for dark energy

SDSS ~2h^{-3}Gpc^3 ➡ BOSS ~6h^{-3}Gpc^3 ➡ DESI 50h^{-3}Gpc^3

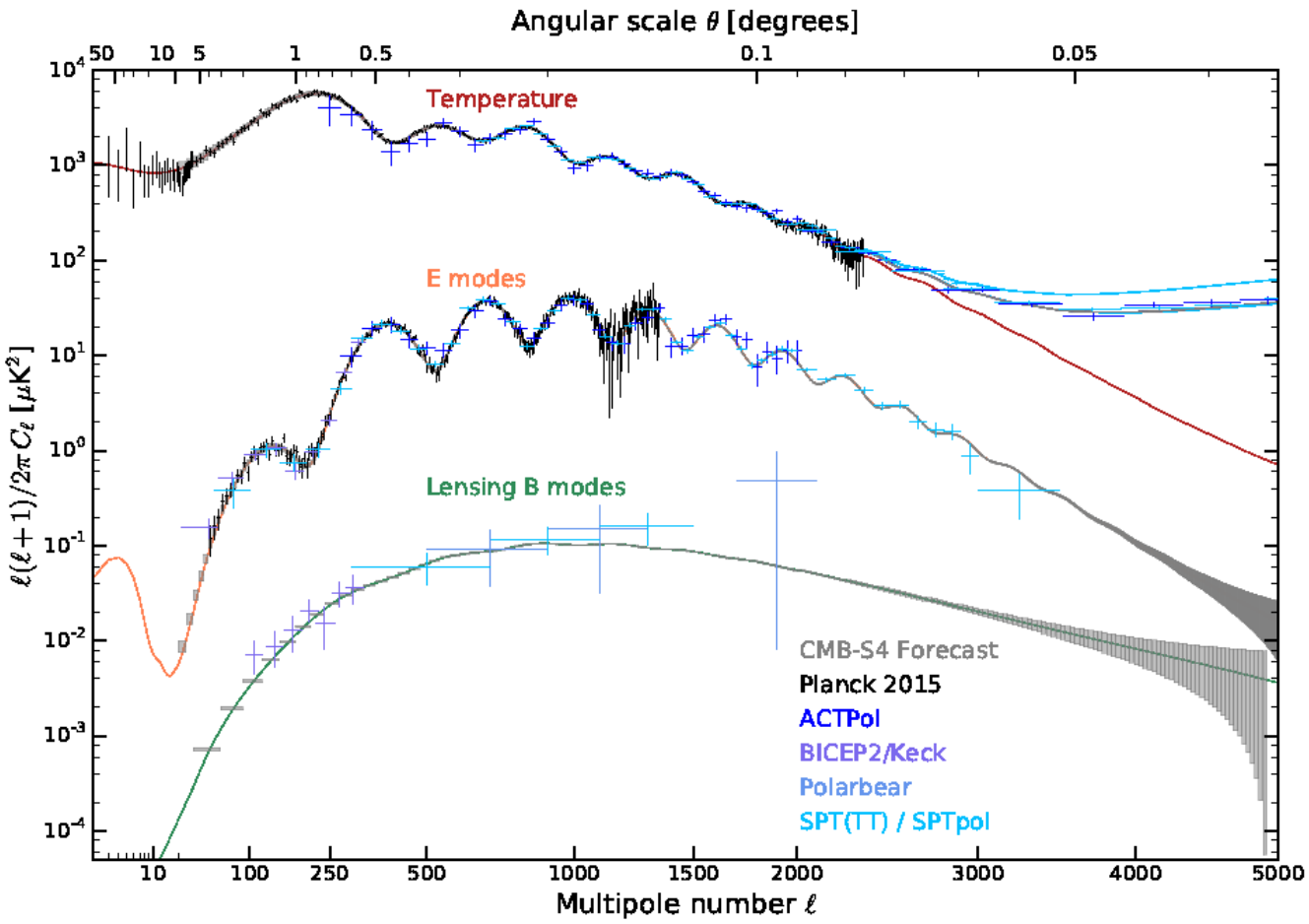




CMB Angular Power Spectra

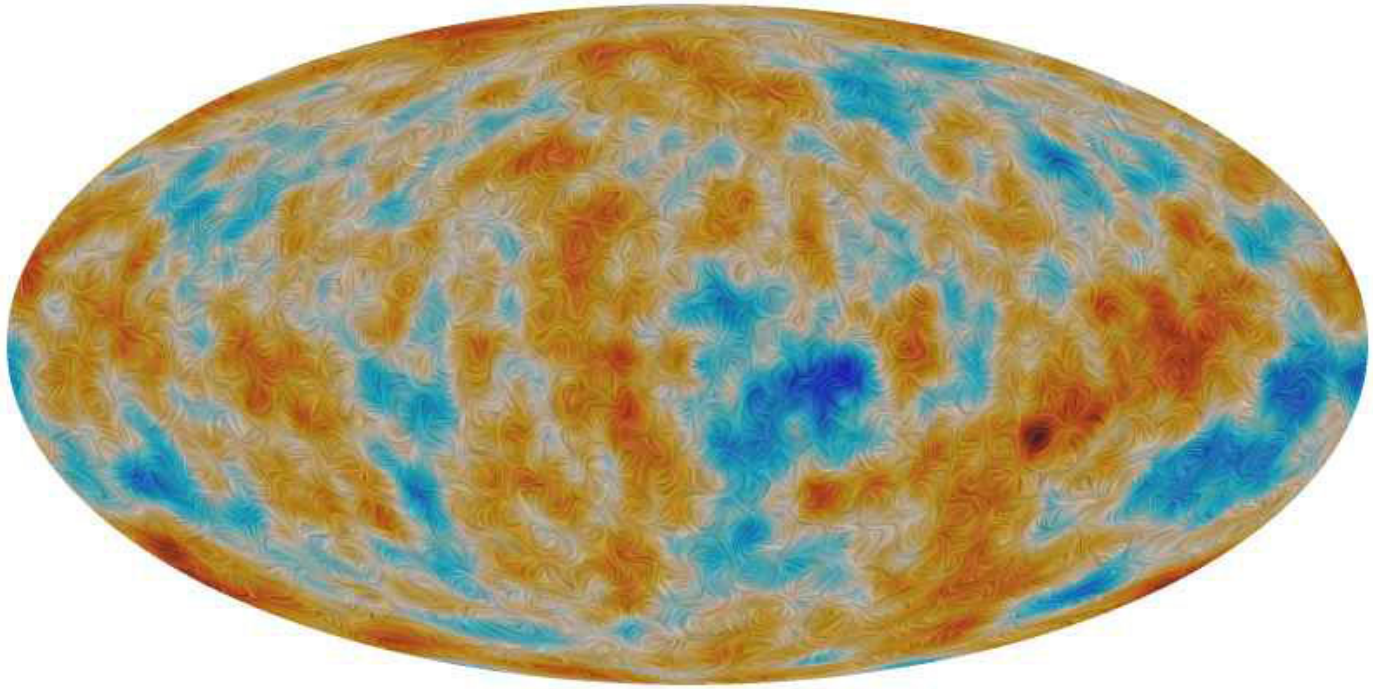


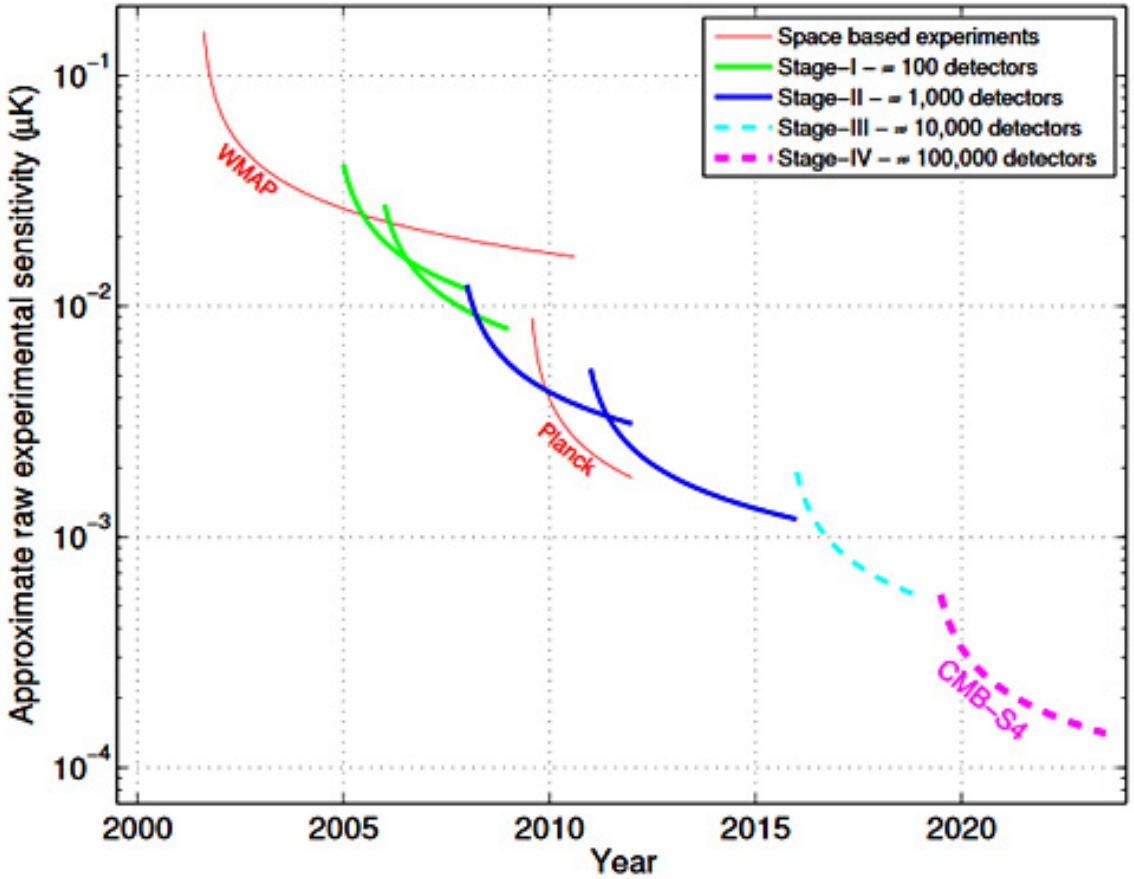
Scott & Smoot. 2016



CMB S4 Study Report 2017

Cosmic Microwave Background (CMB) Radiation



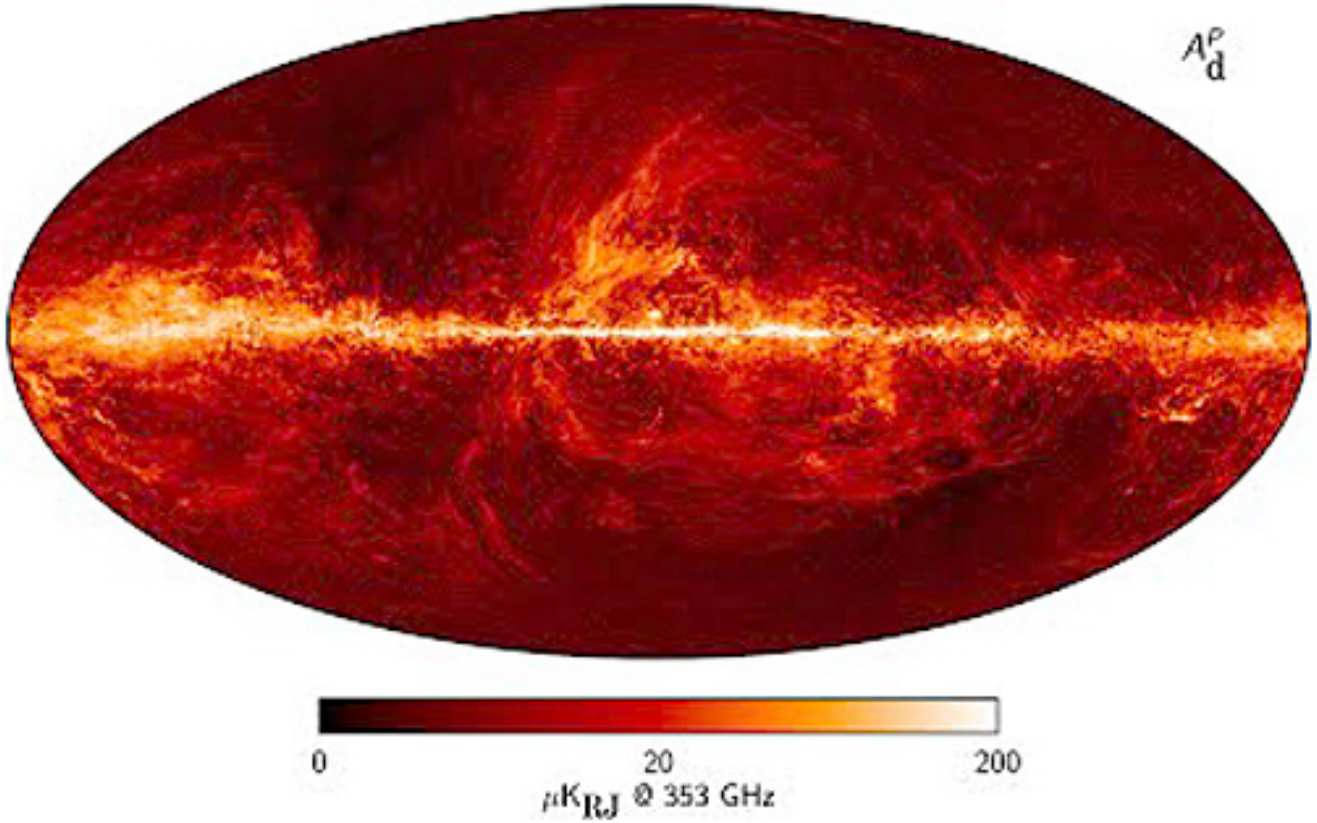


The 'Stage-4' ground-based cosmic microwave background (CMB) experiment, CMB-S4, consisting of dedicated telescopes equipped with highly sensitive superconducting cameras operating at the South Pole, the high Chilean Atacama plateau, and possibly northern hemisphere sites, will provide a dramatic leap forward in our understanding of the fundamental nature of space and time and the evolution of the Universe. CMB-S4 will be designed to cross critical thresholds in testing inflation, determining the number and masses of the neutrinos, constraining possible new light relic particles, providing precise constraints on the nature of dark energy, and testing general relativity on large scales.

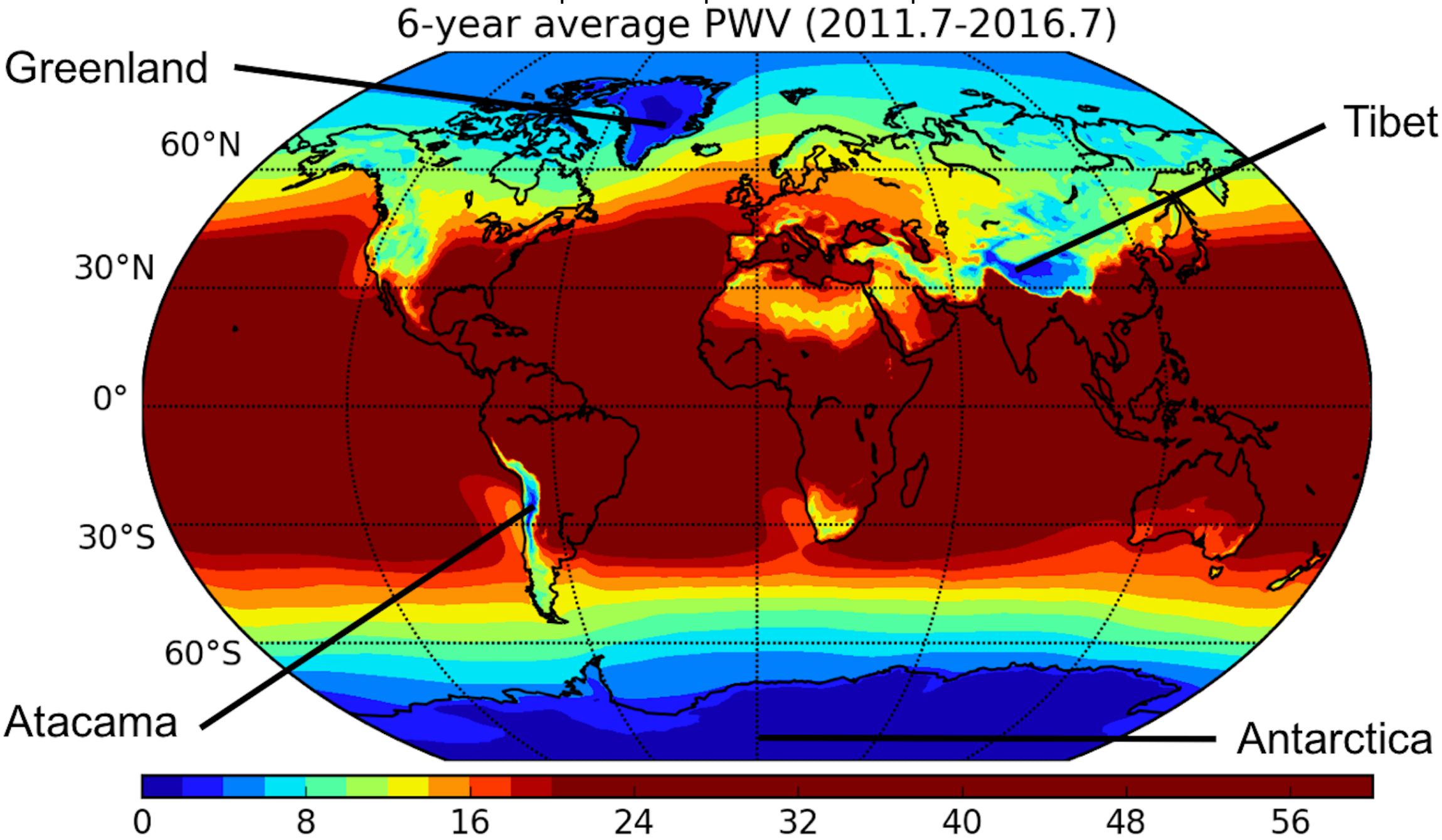
CMB-S4

Next Generation CMB Experiment

		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015	Stage 2 1000 detectors				Boss BAO prior	DES+BOSS SPT clusters
2016		$\gtrsim 10^{-5}$	0.035	0.14	0.15eV	~180
2017	Stage 3 10,000 detectors					
2018						
2019					Boss BAO prior	DES + DESI SZ Clusters
2020		10^{-6}	0.006	0.06	0.06eV	~300-600
2021	Stage 4 CMB-S4 ~500,000 detectors					
2022						
2023					DESI BAO $+\tau_e$ prior	DESI +LSST S4 Clusters
Target		**10^{-8}**	**0.0005**	**0.027**	**0.015eV**	**1250**

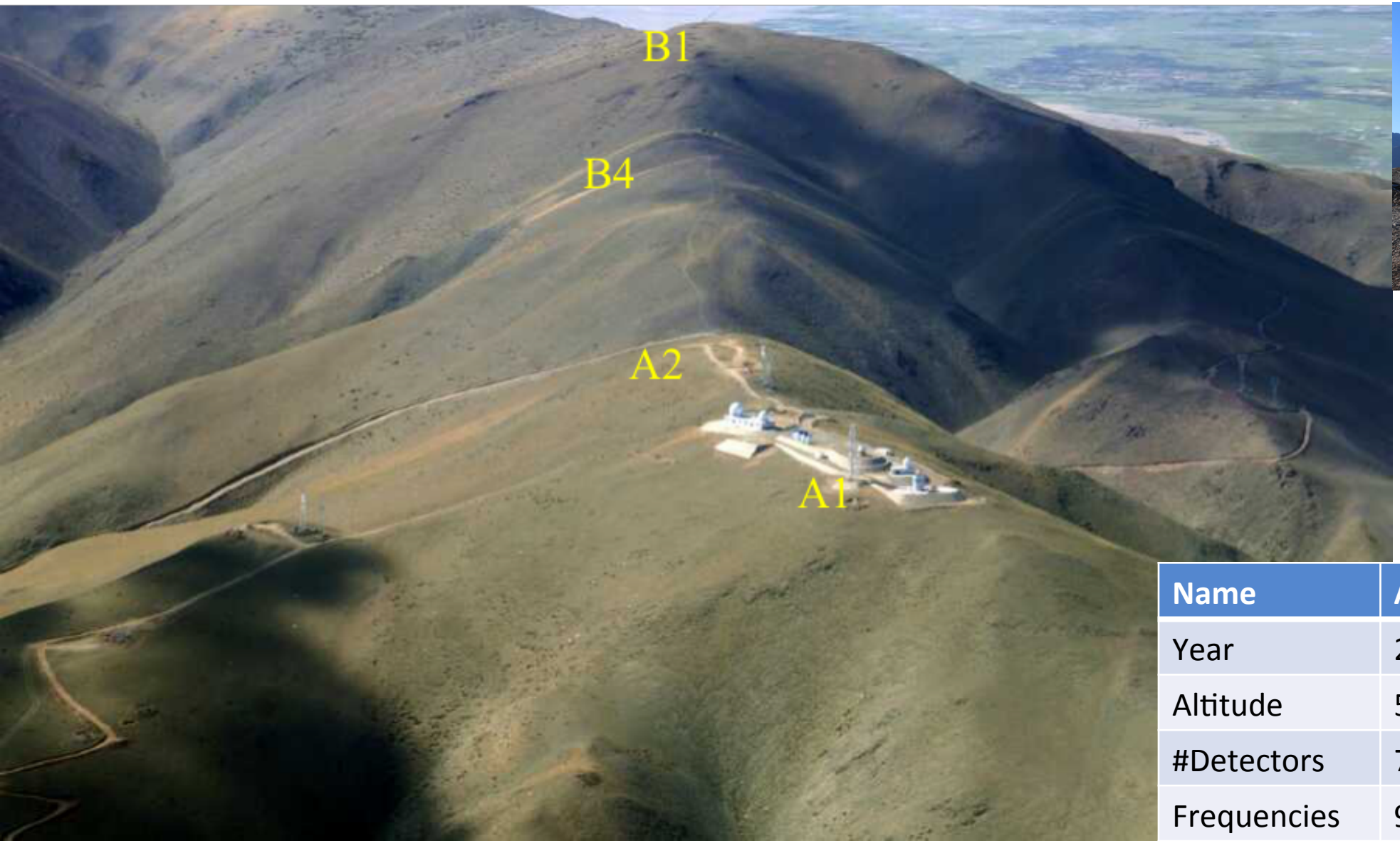


Atmospheric Precipitable Water Vapor



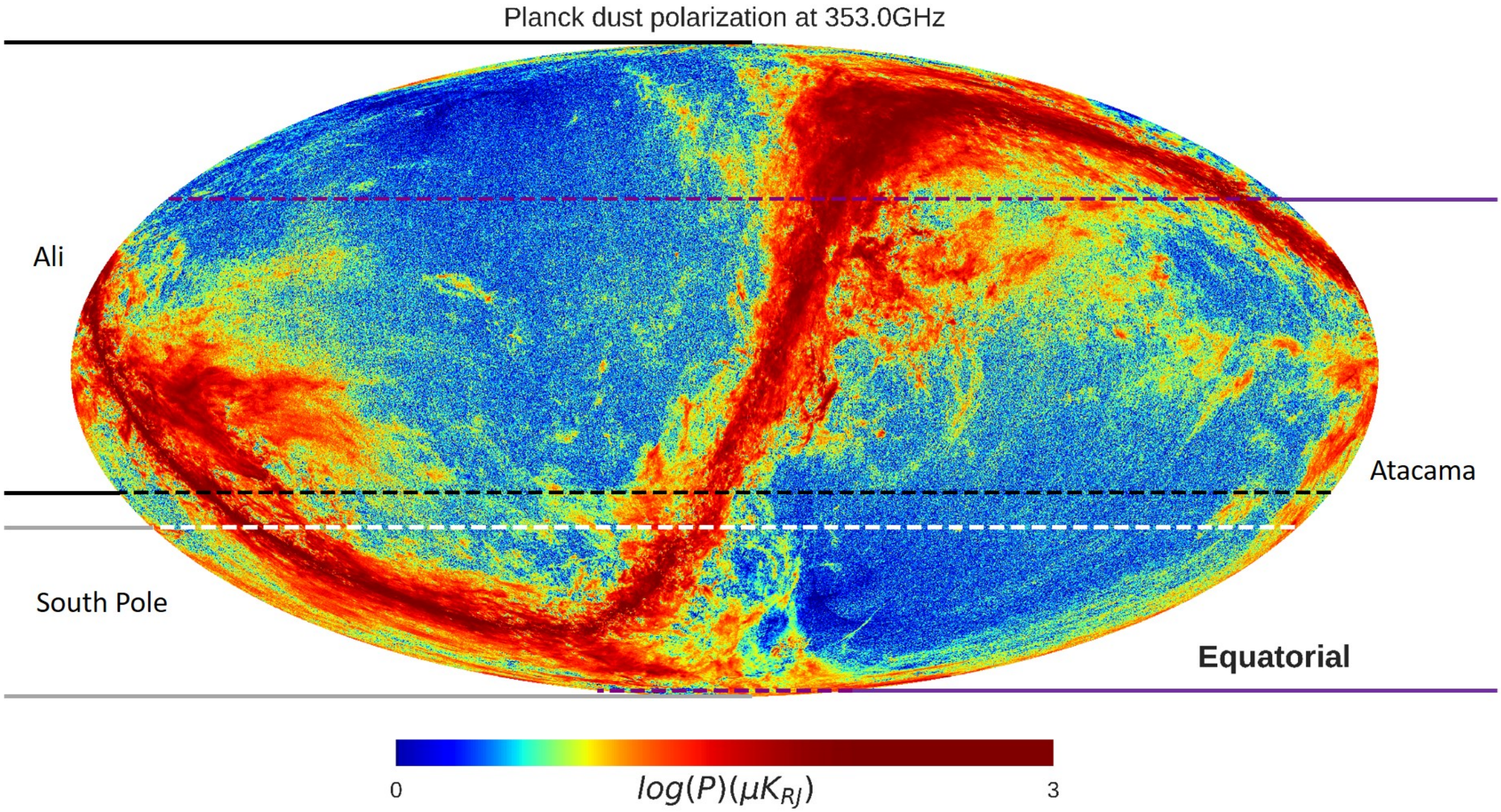

AliCPT Site
Tibetan Plateau
Himalaya Mountains

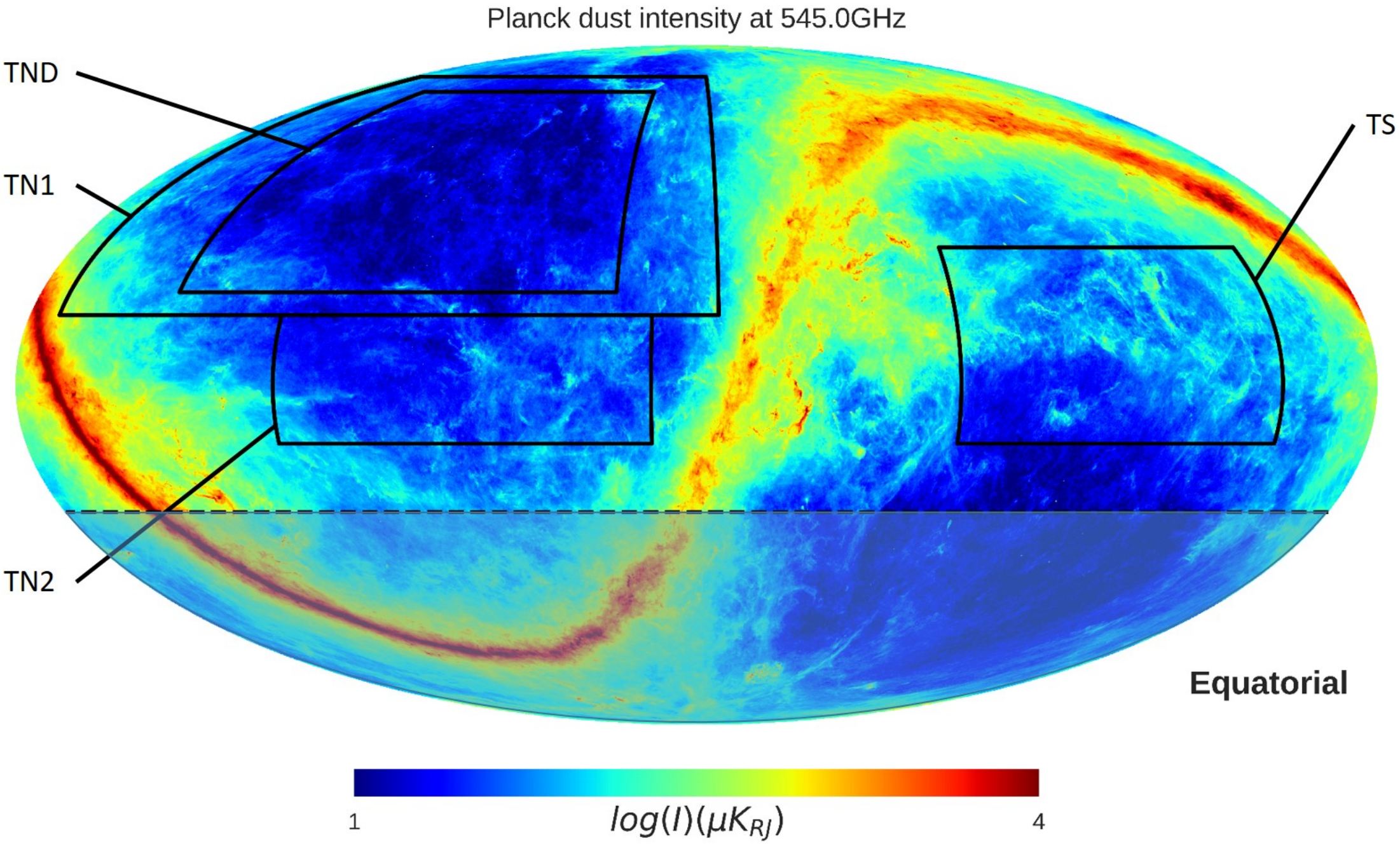
Ali CMB Program Observing Site



Name	Ali CPT-1	Ali CPT-2
Year	2019	2020-2022
Altitude	5250 m	6000 m
#Detectors	7,000	>20,000
Frequencies	95 & 150 GHz	95 & 150 GHz


撸起袖子 加油干


Planck dust polarization at 353.0GHz
Ali
Atacama
South Pole
Equatorial
0
$log(P)(\mu K_{RJ})$
3


Planck dust intensity at 545.0GHz
TND
TN1
TN2
TS
Equatorial
1
$log(I)(\mu K_{RJ})$
4

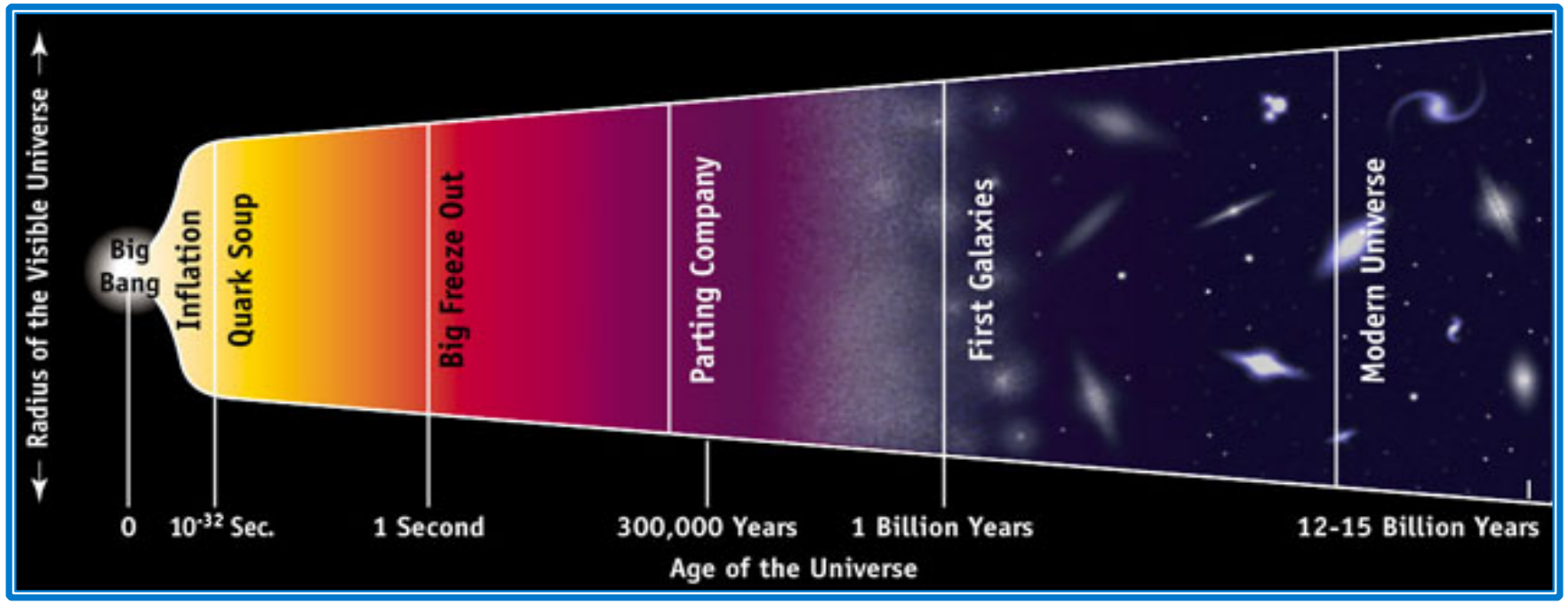
The Copernican Time Principle

The current cosmological epoch has no special significance.

Interesting physics processes will continue to take place in the future, despite very decreased energy levels.

Can we get Cosmological Principle in Time?
Will that define the future of cosmology?

Cosmic Timeline



Five Ages of the Universe

- Primordial Era n < 6
- Stelliferous Era n = 6 - 14
- Degenerate Era n = 14 - 40
- Black Hole Era n = 40 - 100
- Dark Era n > 100

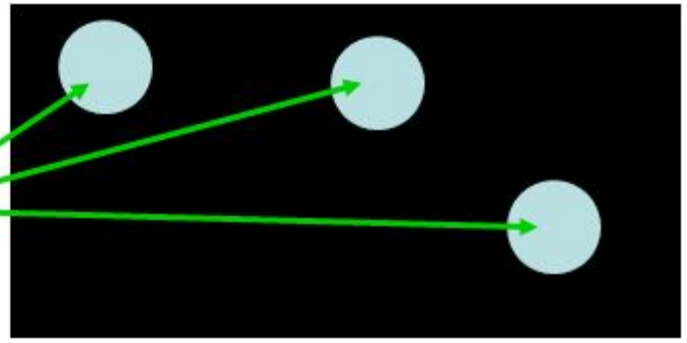
Fred Adams 10^n years

The Cosmological Principle

Considering the largest scales in the universe, we make the following fundamental assumptions:

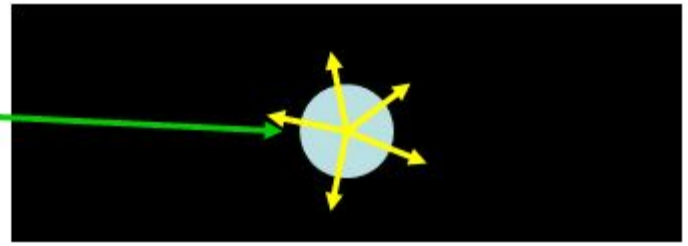
1) Homogeneity: On the largest scales, the local universe has the same physical properties throughout the universe.

Every region has the same physical properties (mass density, expansion rate, visible vs. dark matter, etc.)



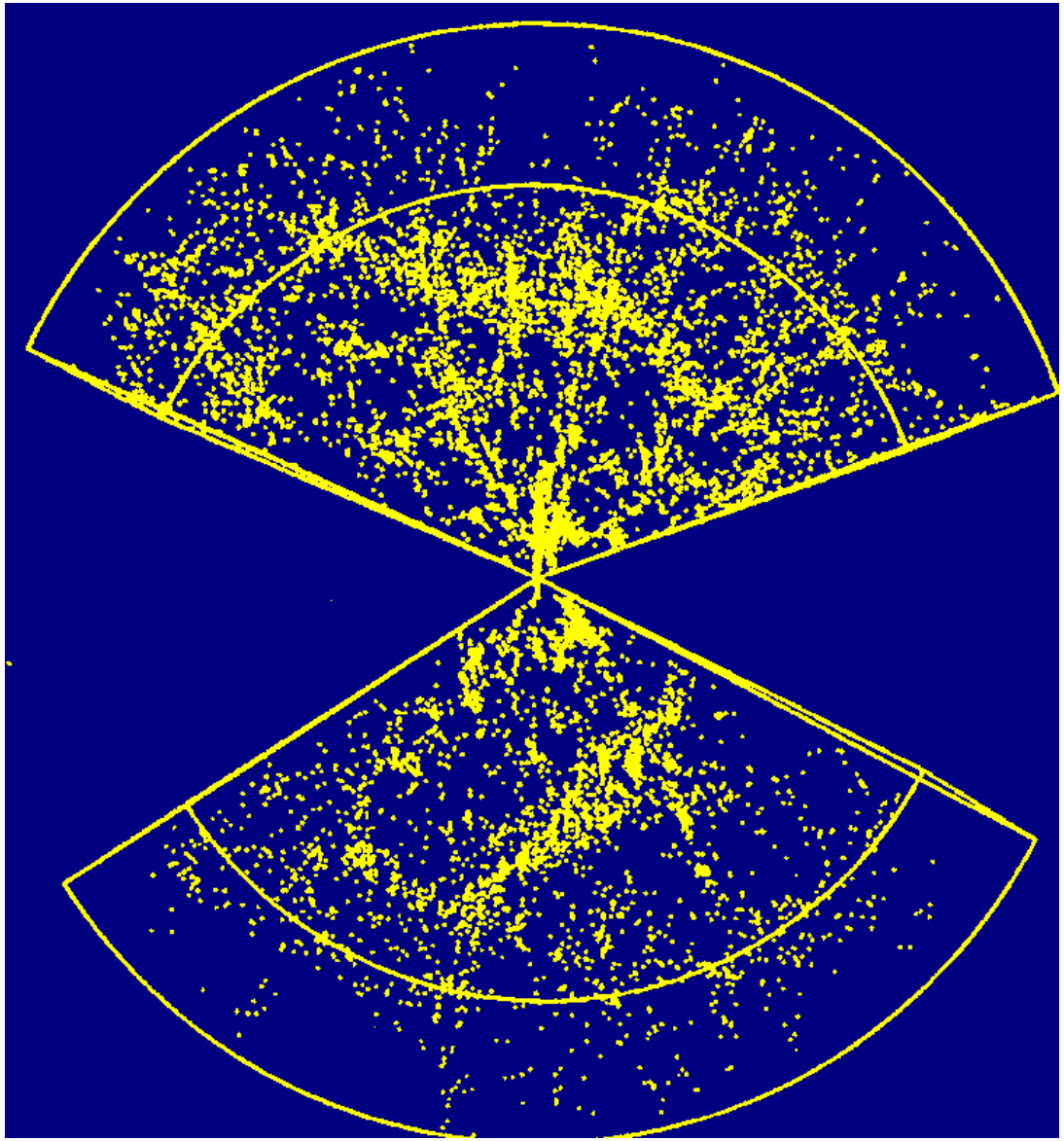
2) Isotropy: On the largest scales, the local universe looks the same in any direction that one observes.

You should see the same large-scale structure in any direction.

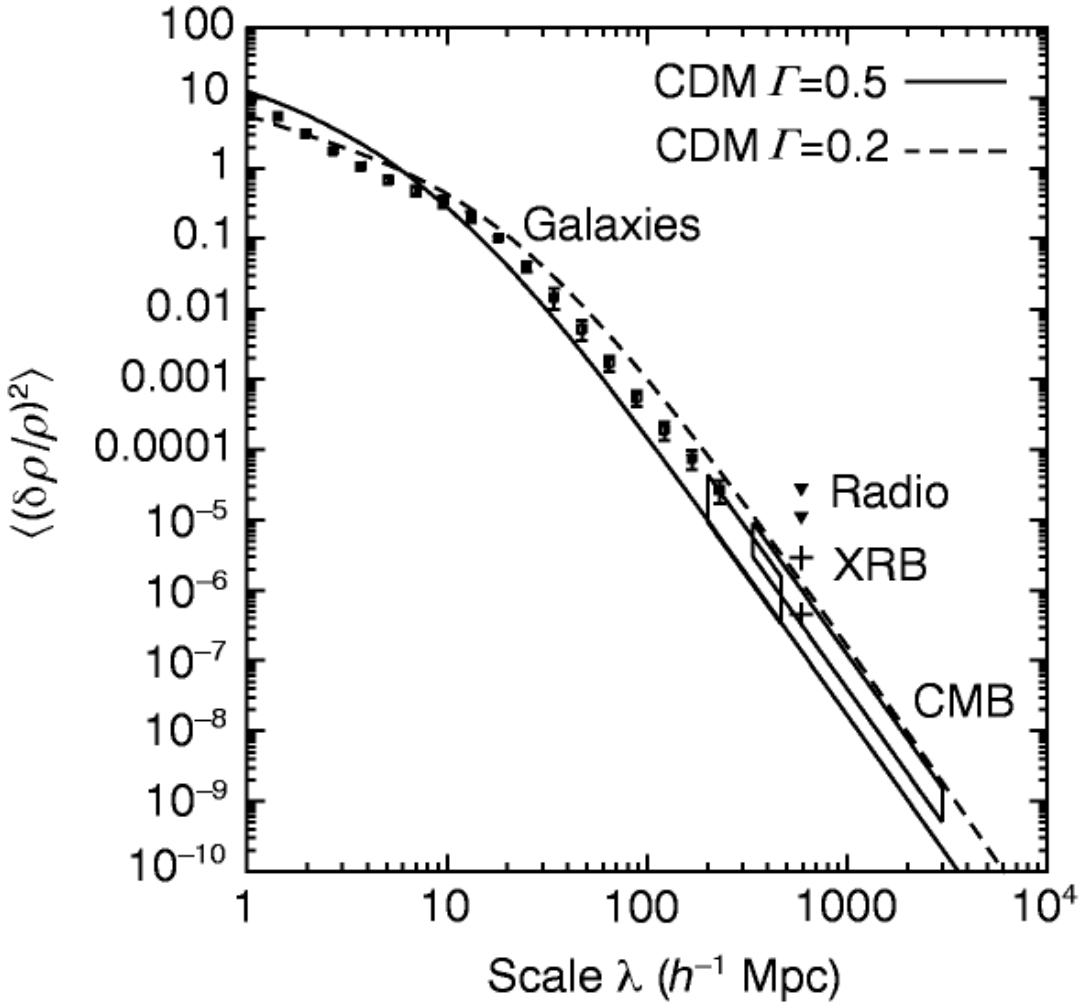


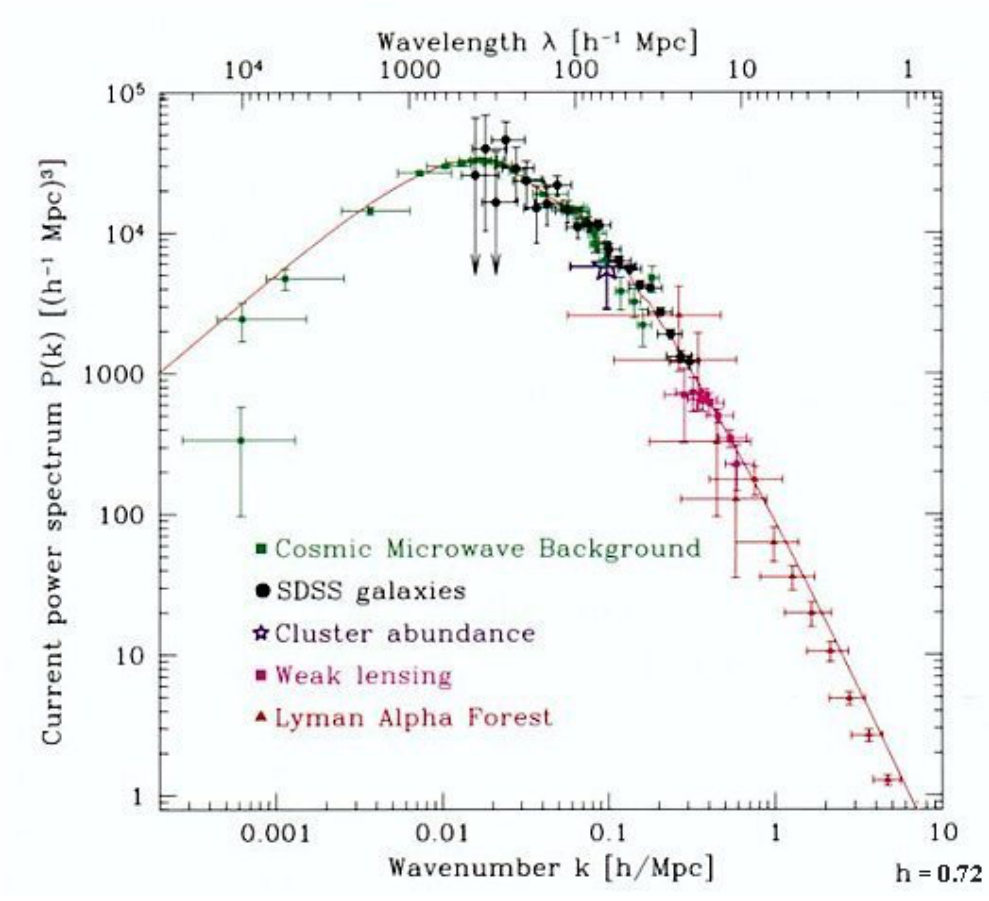
3) Universality: The laws of physics are the same everywhere in the universe.

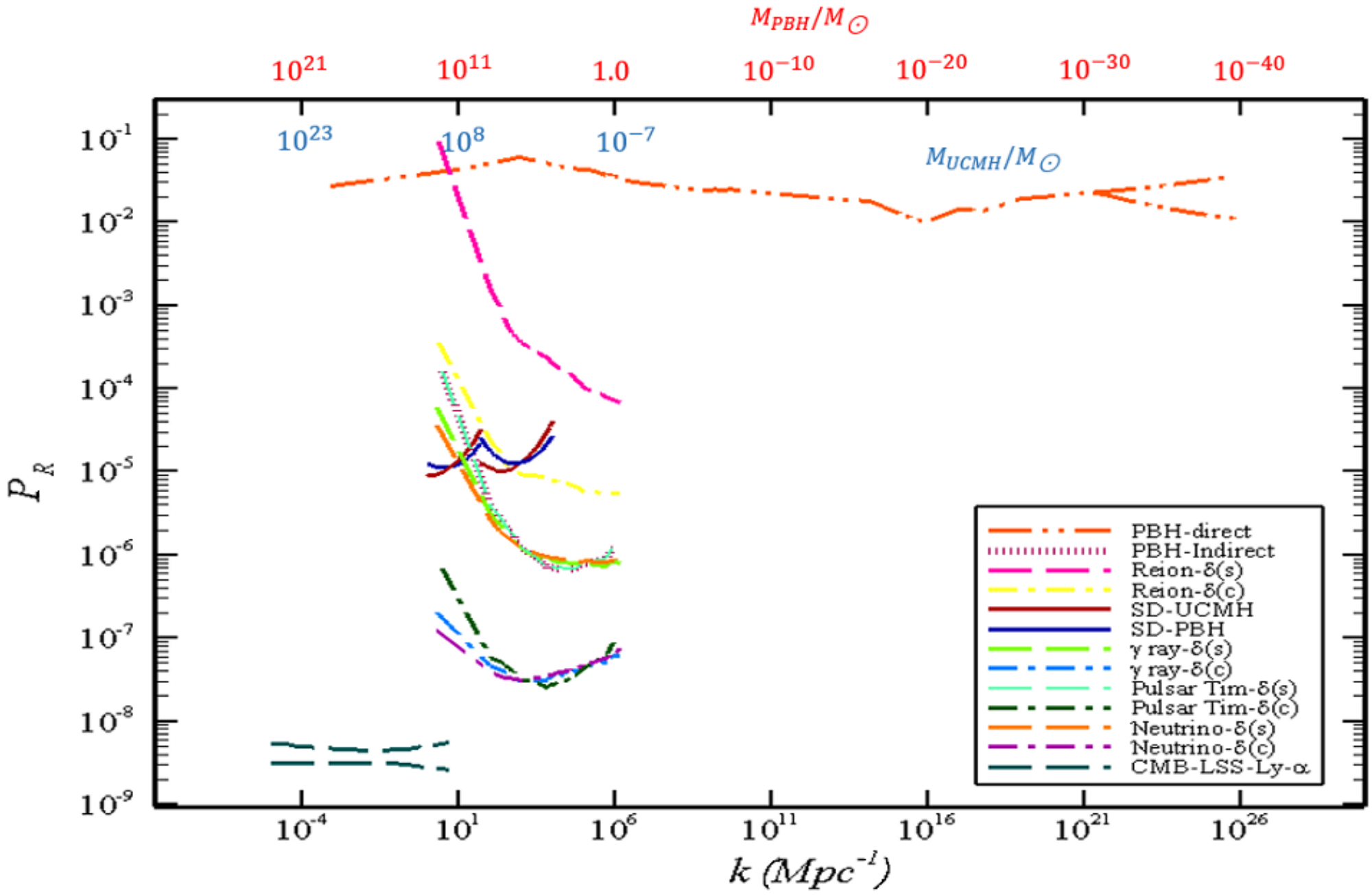
Observed Distribution of Galaxies



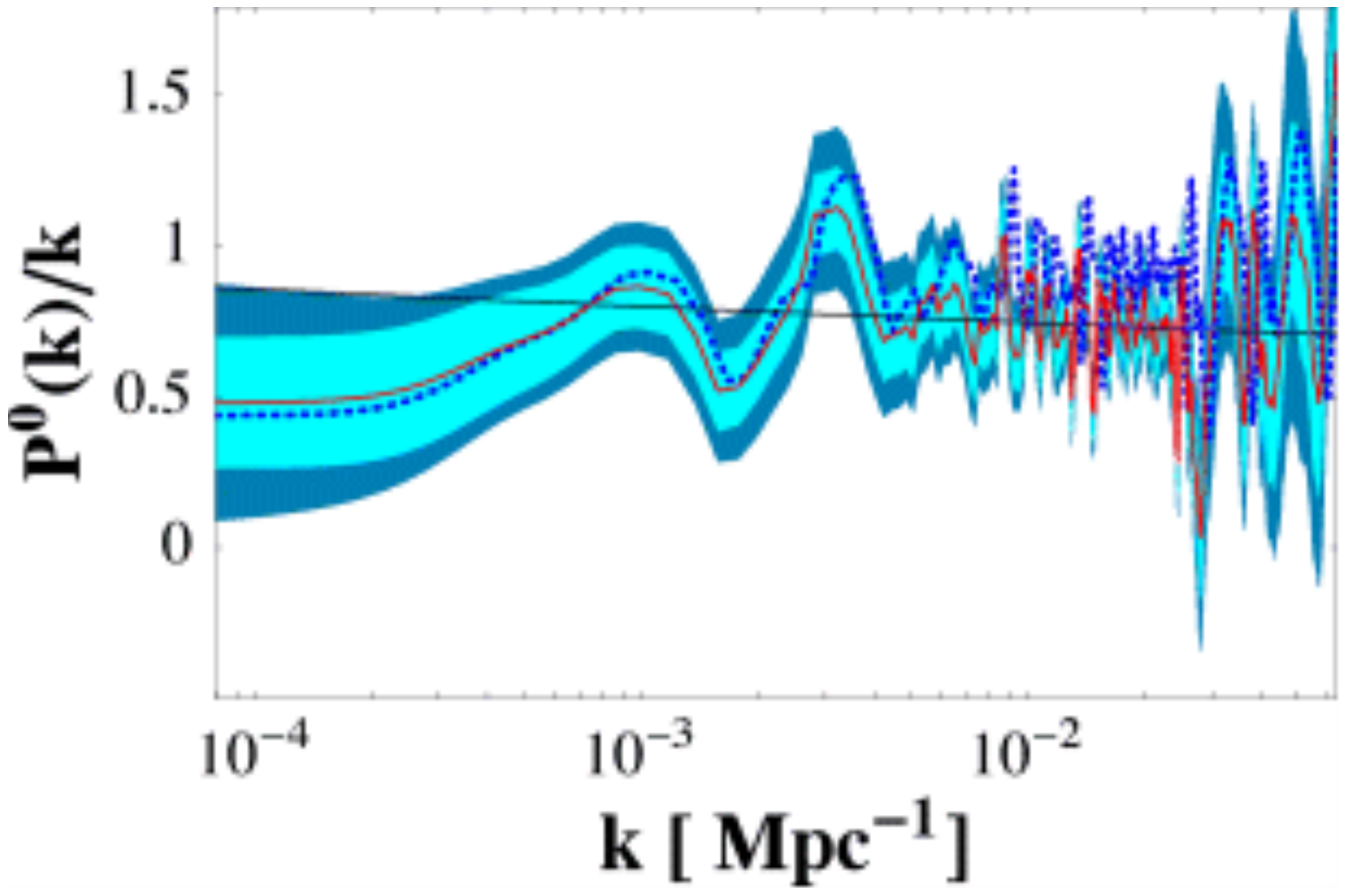
Cosmological Principle Re-Interpeted Currently







Observational Constraints on the Primordial Curvature Power Spectrum -
Emami, Razieh & George F. Smoot. JCAP 1801 (2018) no.01, 007 arXiv:1705.09924 [astro-ph.CO]



From: Non-parametric reconstruction of the primordial power spectrum at horizon scales from WMAP data
Mon Not R Astron Soc. 2006;367(3):1095-1102. doi:10.1111/j.1365-2966.2006.10031.x

Cosmological Principles

- **The Copernican Principle:**

We do not occupy a special place in the Universe.

- **The Cosmological Principle:**

The Universe is homogeneous and isotropic (no special place or direction).

- **The Perfect Cosmological Principle:**

The Universe is homogeneous in space and time, and is isotropic in space.

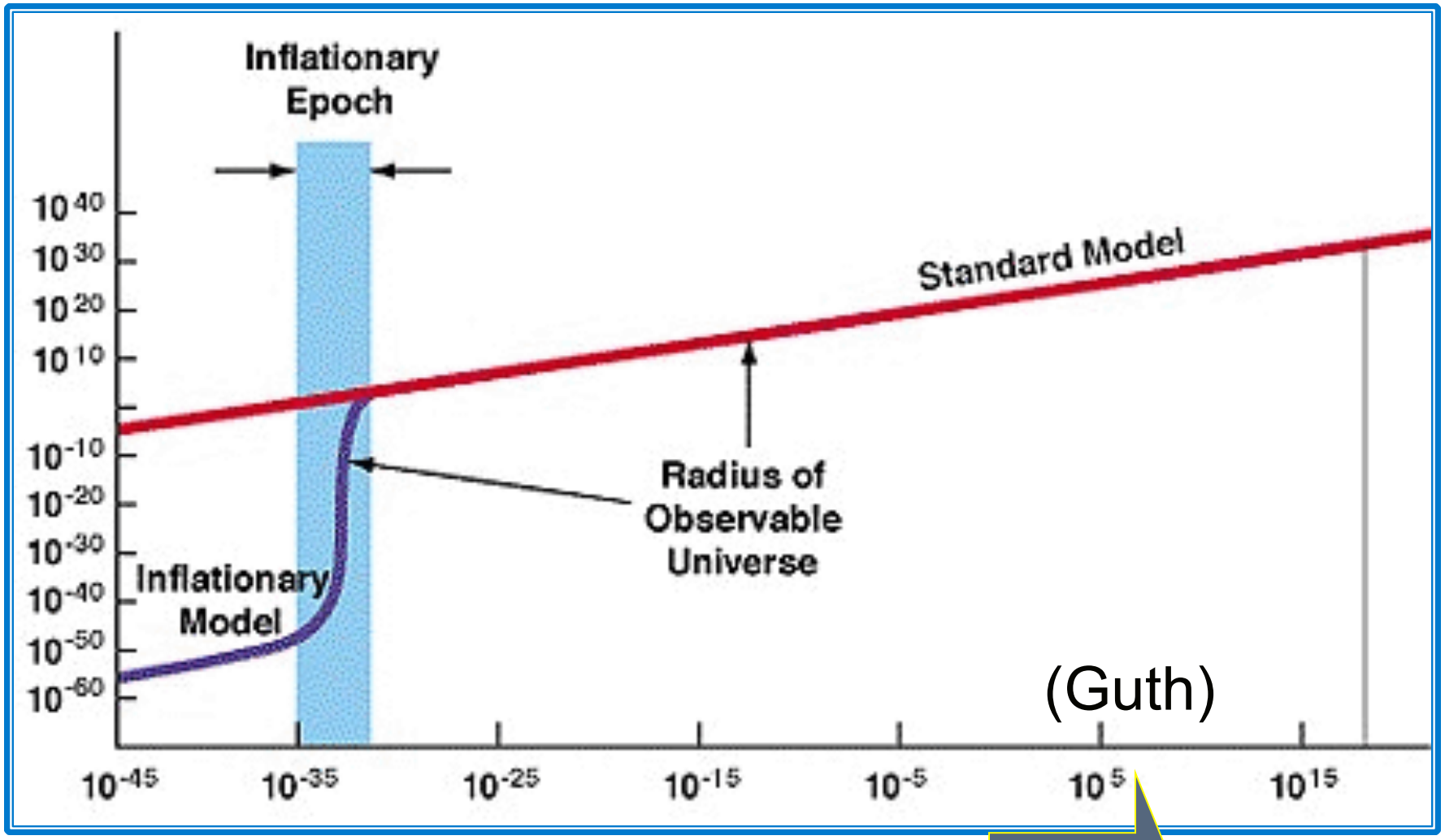
- **The Weak Anthropic Principle:**

Life can exist only in the Universe as it is.

- **The Strong Anthropic Principle:**

The Universe is such as it is because its purpose is to create life.

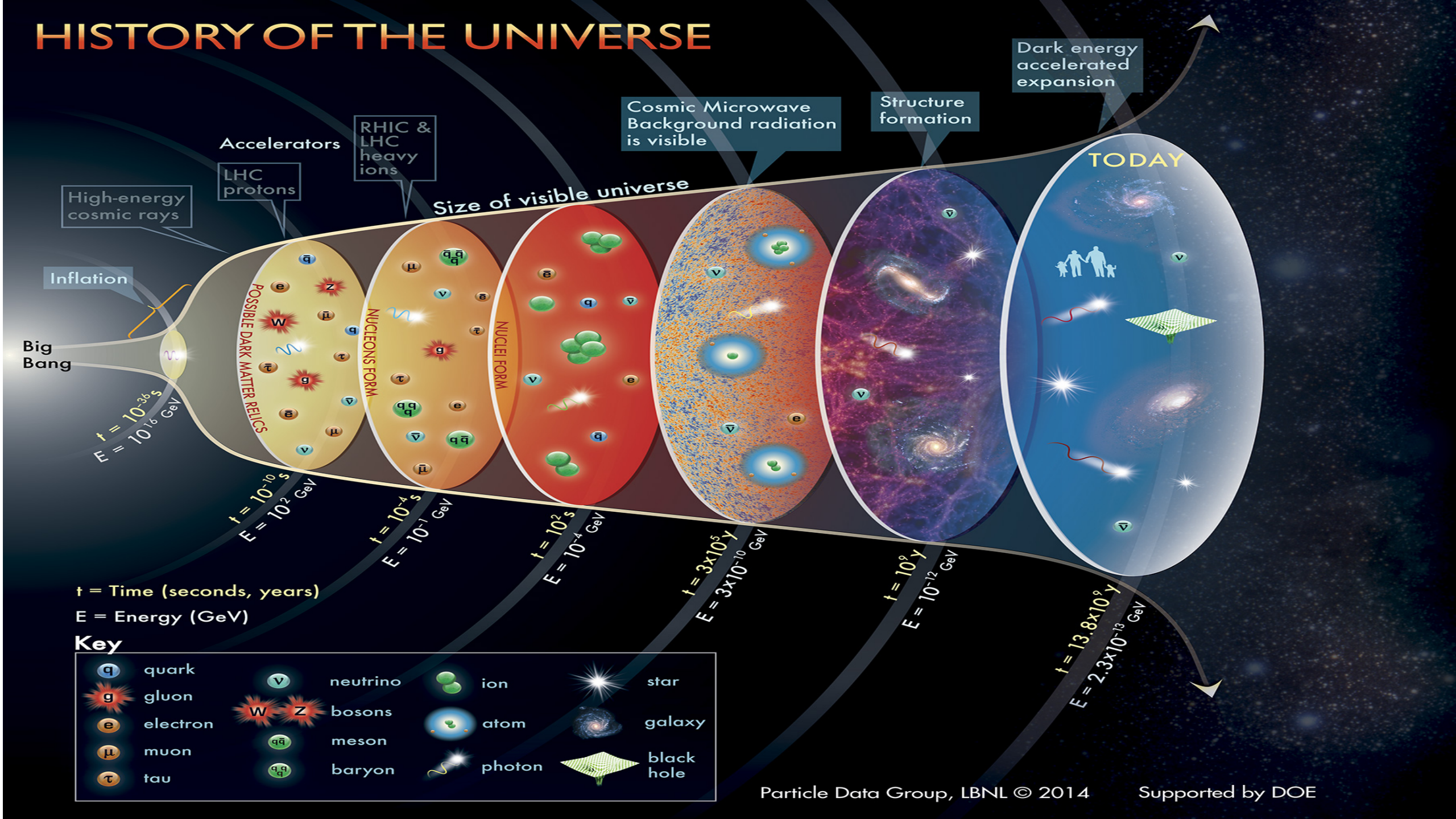
The Inflationary Universe

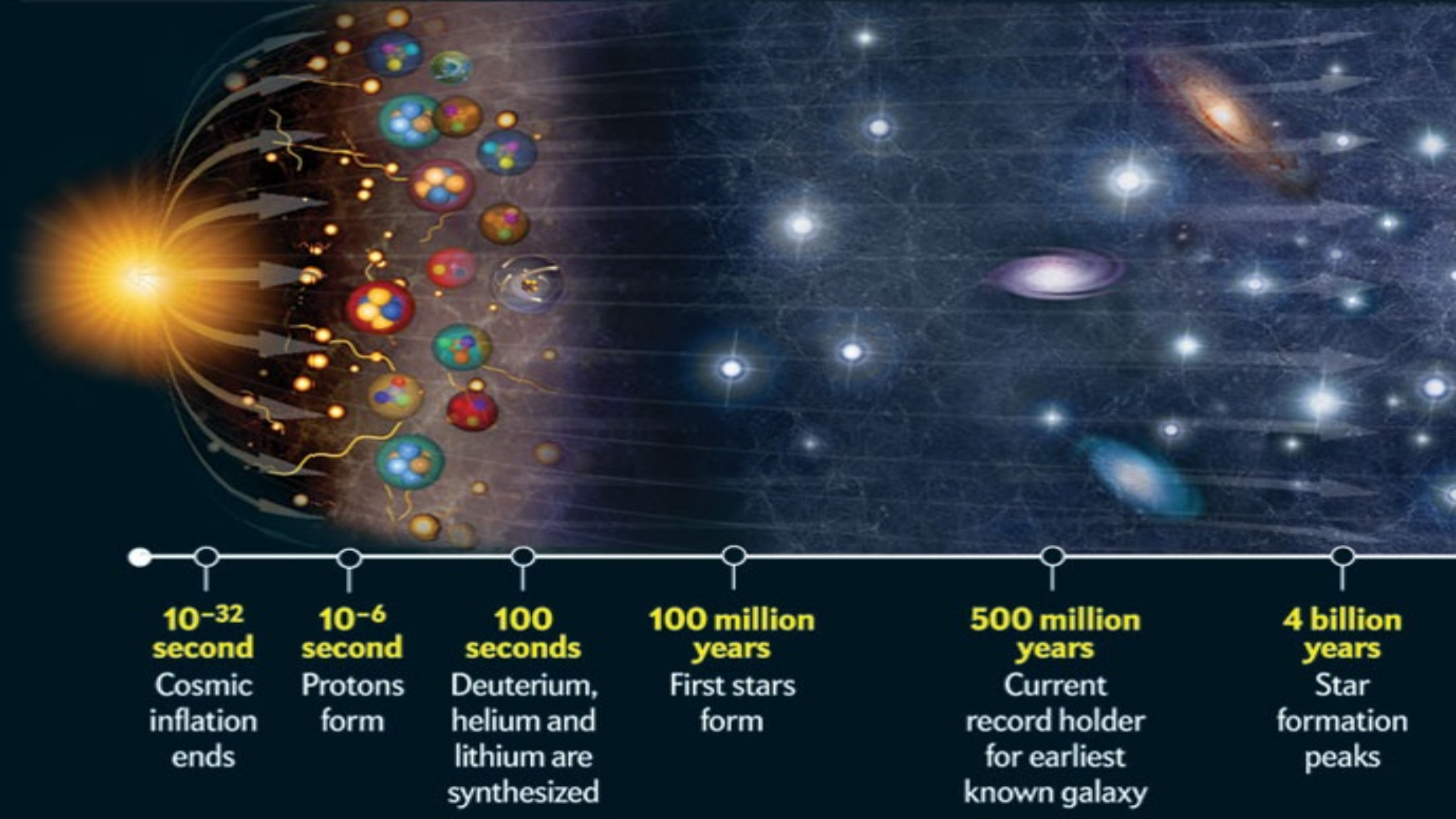


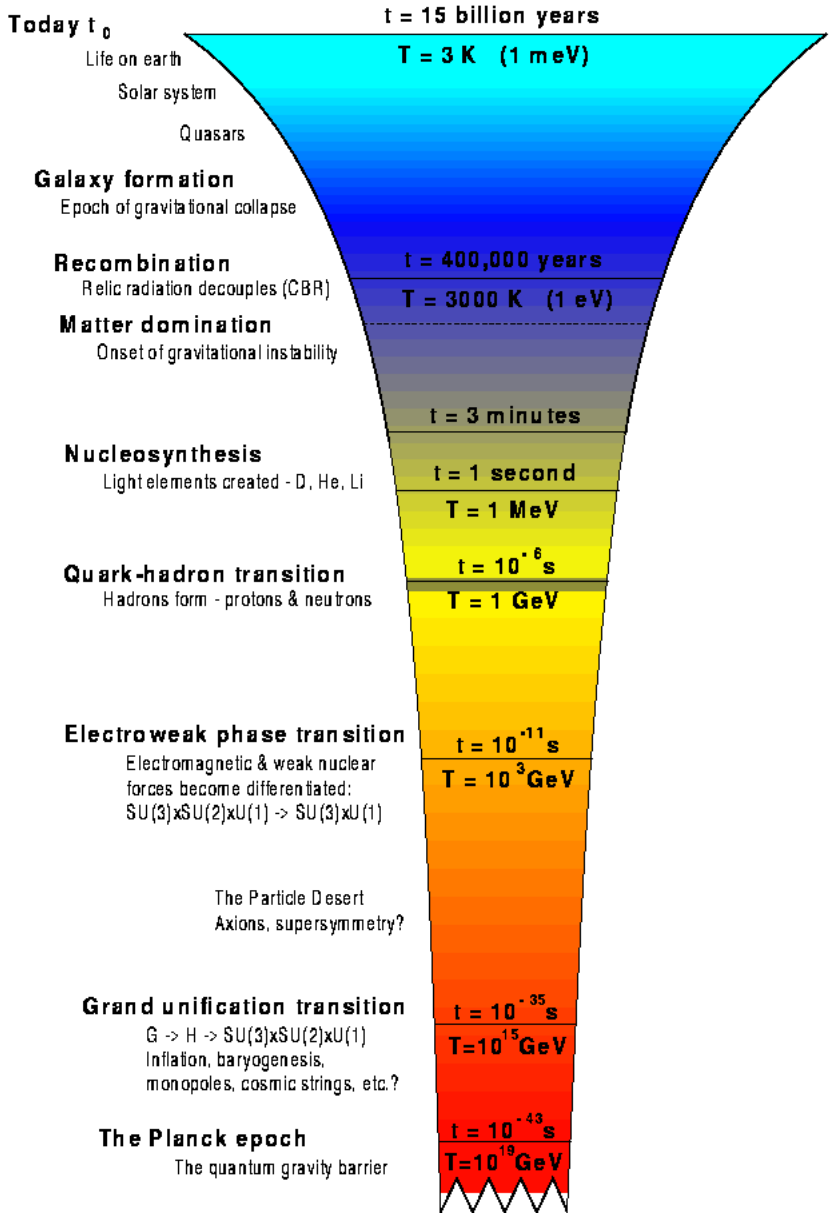
(Guth)

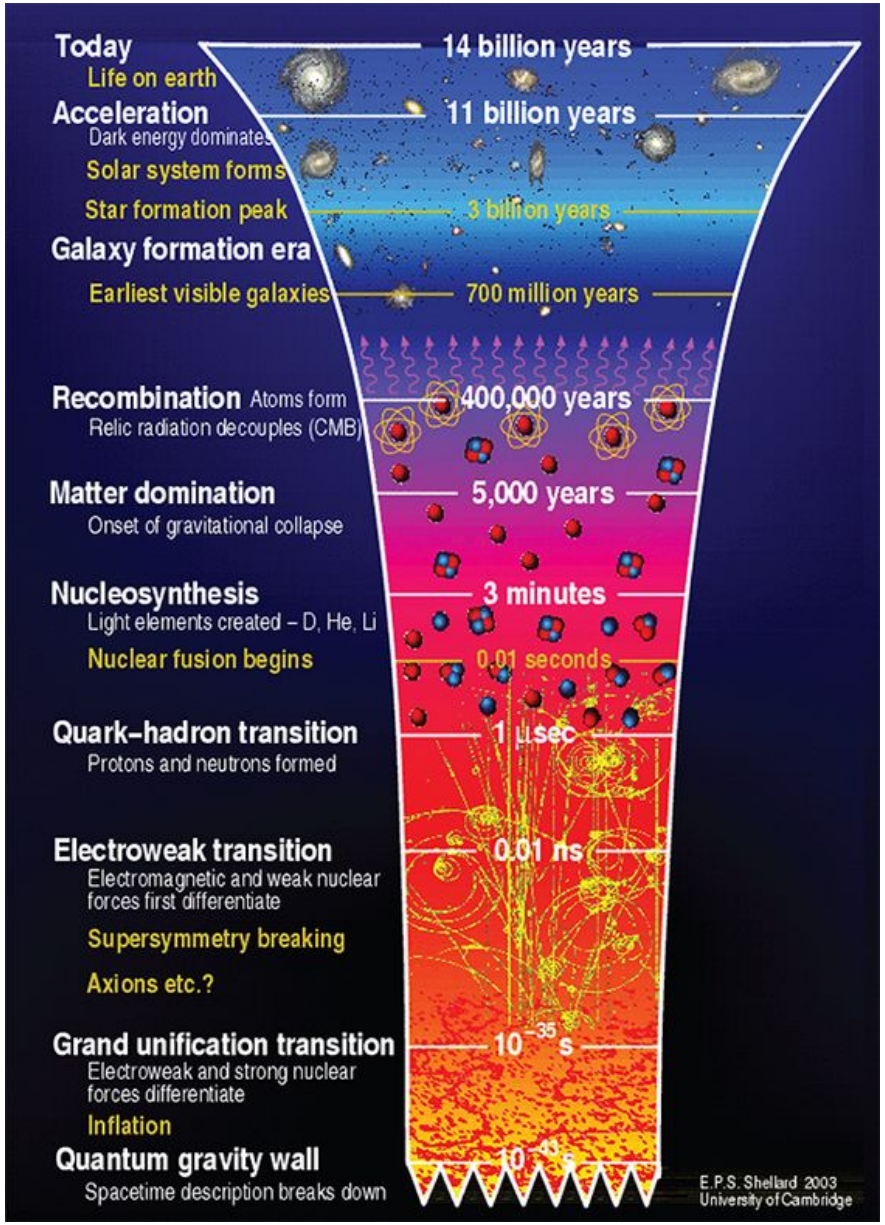
Time in seconds

HISTORY OF THE UNIVERSE




10^{-32} second
Cosmic inflation ends
10^{-6} second
Protons form
100 seconds
Deuterium, helium and lithium are synthesized
100 million years
First stars form
500 million years
Current record holder for earliest known galaxy
4 billion years
Star formation peaks


Today t_0
Life on earth
Solar system
Quasars
t = 15 billion years
T = 3 K (1 meV)
Galaxy formation
Epoch of gravitational collapse
Recombination
Relic radiation decouples (CBR)
t = 400,000 years
T = 3000 K (1 eV)
Matter domination
Onset of gravitational instability
t = 3 minutes
Nucleosynthesis
Light elements created - D, He, Li
t = 1 second
T = 1 MeV
Quark-hadron transition
Hadrons form - protons & neutrons
$t = 10^{-6}$s
T = 1 GeV
Electroweak phase transition
Electromagnetic & weak nuclear forces become differentiated:
SU(3)xSU(2)xU(1) -> SU(3)xU(1)
$t = 10^{-11}$s
$T = 10^{3}$GeV
The Particle Desert
Axions, supersymmetry?
Grand unification transition
G -> H -> SU(3)xSU(2)xU(1)
Inflation, baryogenesis, monopoles, cosmic strings, etc.?
$t = 10^{-35}$s
$T=10^{15}$GeV
The Planck epoch
The quantum gravity barrier
$t = 10^{-43}$s
$T=10^{19}$GeV


Today
Life on earth
14 billion years
Acceleration
Dark energy dominates
11 billion years
Solar system forms
Star formation peak
3 billion years
Galaxy formation era
Earliest visible galaxies
700 million years
Recombination Atoms form
Relic radiation decouples (CMB)
400,000 years
Matter domination
Onset of gravitational collapse
5,000 years
Nucleosynthesis
Light elements created – D, He, Li
3 minutes
Nuclear fusion begins
0.01 seconds
Quark–hadron transition
Protons and neutrons formed
1 μsec
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
0.01 ns
Supersymmetry breaking
Axions etc.?
Grand unification transition
Electroweak and strong nuclear forces differentiate
10^{-35} s
Inflation
Quantum gravity wall
Spacetime description breaks down
10^{-43} s
E.P.S. Shellard 2003
University of Cambridge

Cosmic Energy/Time

Kind of global see-saw mechanism

At any time in the universe there is a "special" time transition nearby on an approximately log scale

Time	Time (s)	Event			
-43		Planck Time	10^19 GeV	28	
-35		Grand Unification Transition	10^15 GeV	24	
-33		Inflation		23	
-32		End of Inflation		21	
-11		Electroweak phase transition	10^3 GeV	12	
-6		protons form/ quark-gluon phase transition	1 GeV	9	
2		D, He, Li light element synthesis	1 MeV	6	
	10000	Matter Domination structure formation begins			
12.5	400000 years	Recombination, CMB freed	10eV	1	
15.5	10^8 years	First stars			
16	5*10^8 years	first galaxies			
17	4*10^9 years	star formation peaks			
	10 *10^9 years	Dark Energy begins accel	1 meV	-3	
17.5	14*10^9 years	Present	1 meV	-3	
		ALP 1		-18	
		ALP 2		-22	
		ALP 3		-28	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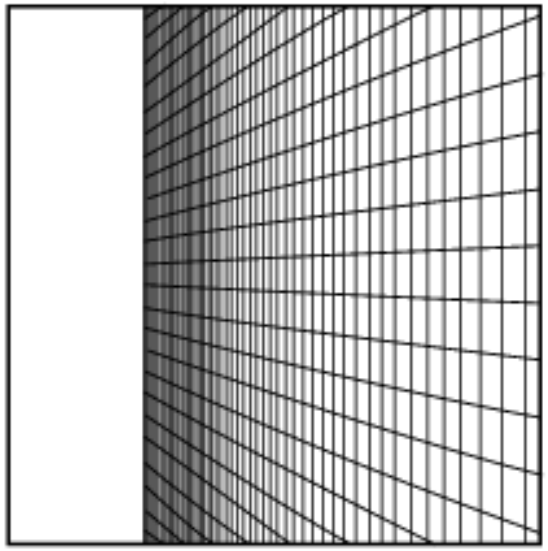
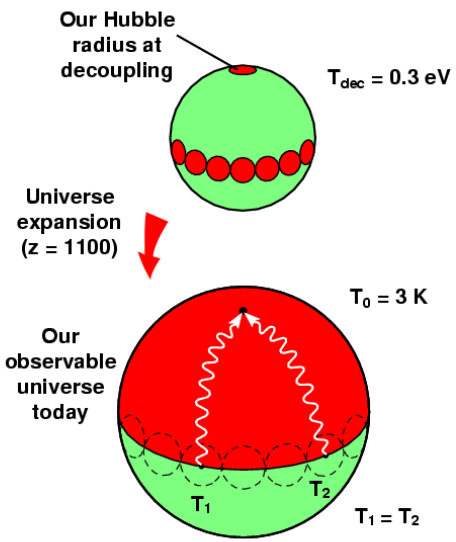
What about
Super-
symmetry?
S. Harris

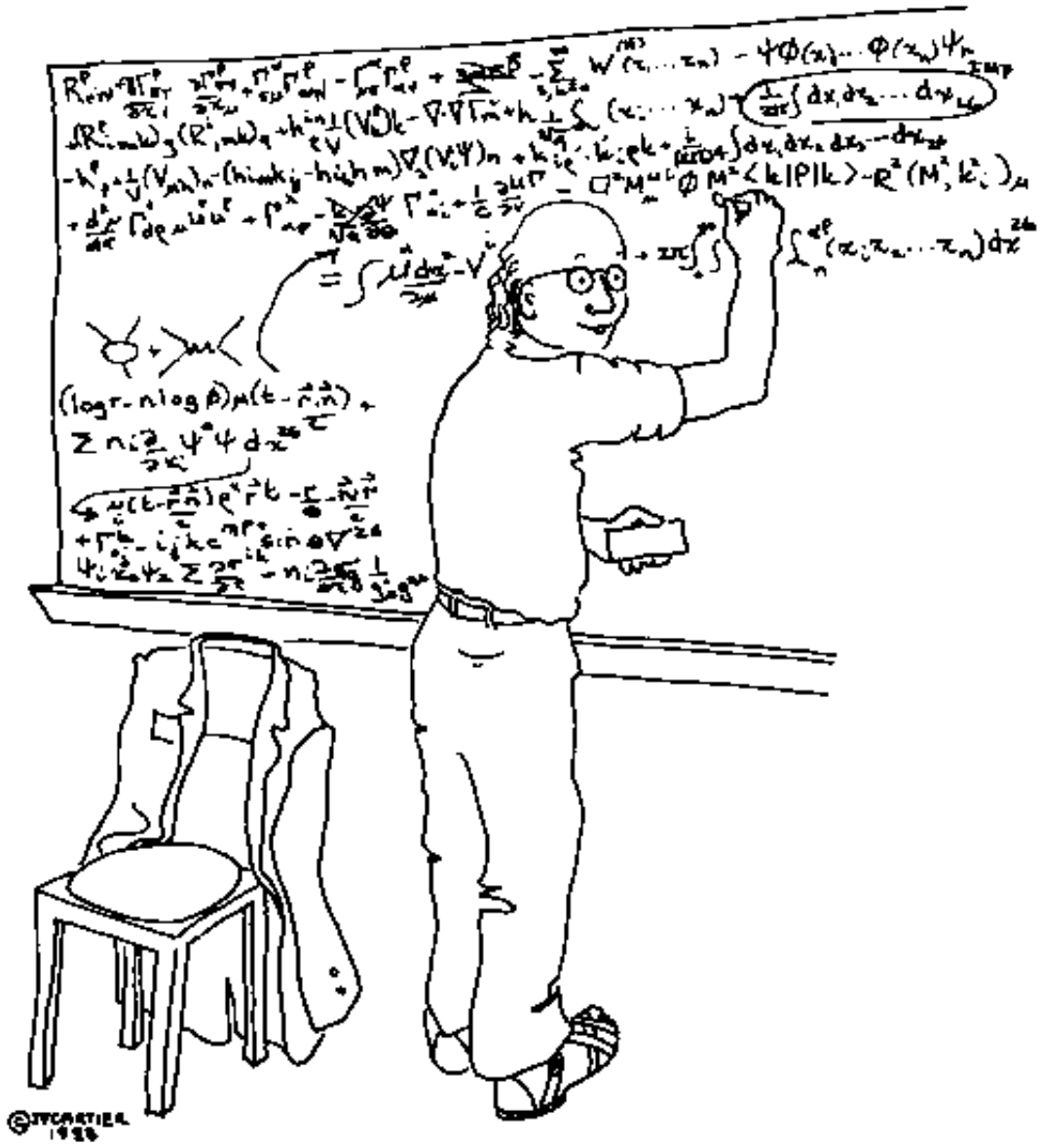
But what **else** has SUSY ever done for us?

SUSY provides the basis for cosmological theories in which the Universe naturally inflates to its present size, and explain how the microwave background radiation appears isotropic

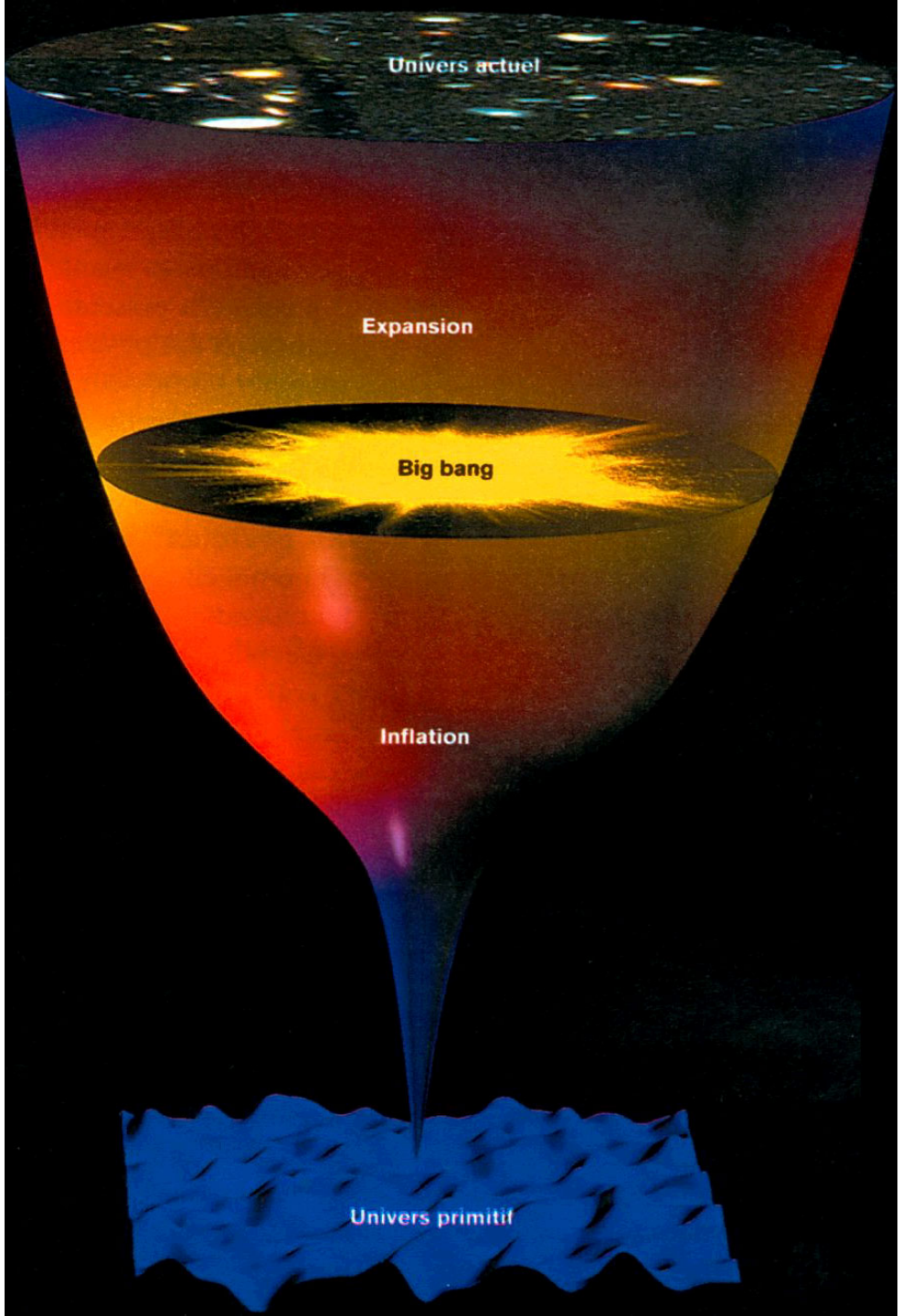


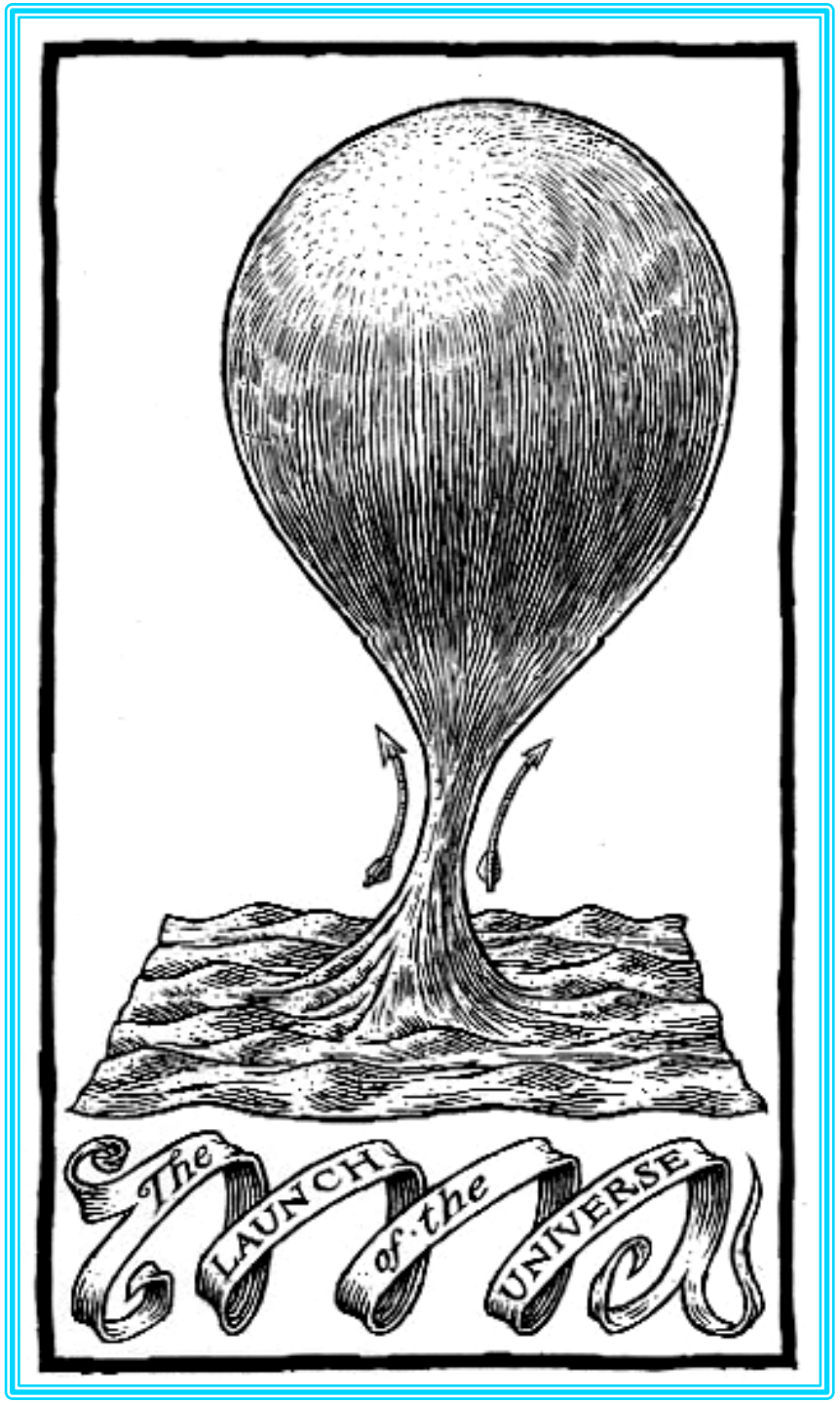


For example a SUSY version of the Standard Model with extra Higgs singlets has been constructed that explains inflation, large scale structure, the origin of Higgs mass, and the origin of right-handed neutrino mass (Bastero-Gi,SFK, Di Clemente)

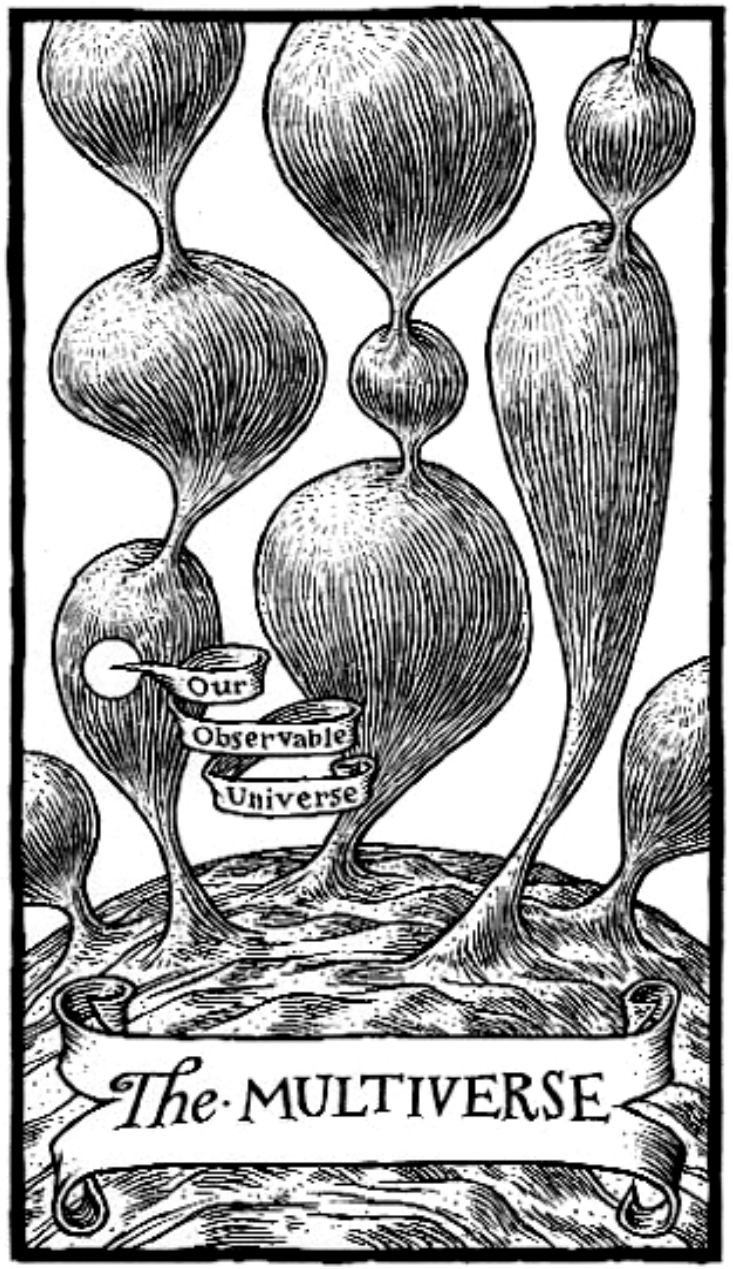


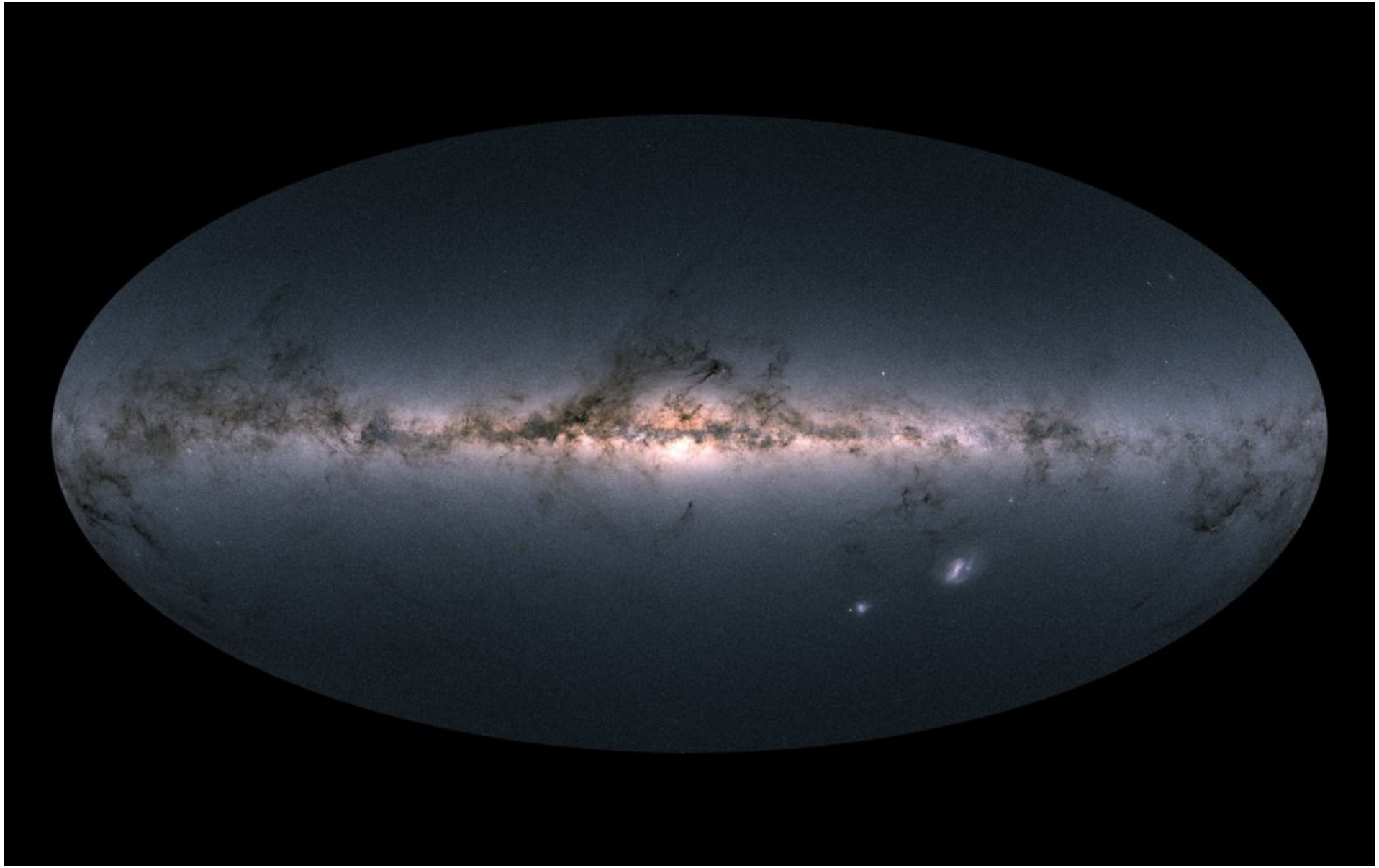
"At this point we notice that this equation is beautifully simplified if we assume that space–time has 92 dimensions."

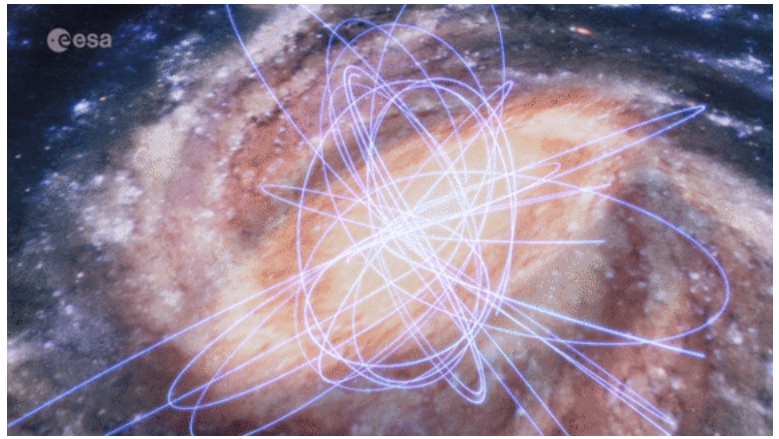

Univers actuel
Expansion
Big bang
Inflation
Univers primitif


The LAUNCH of the UNIVERSE

As our own universe experiences its time-line, other parts of the global space-time (other universes) can live through their own lifetimes, as part of a cosmic archipelago sometimes called the MULTIVERSE.



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