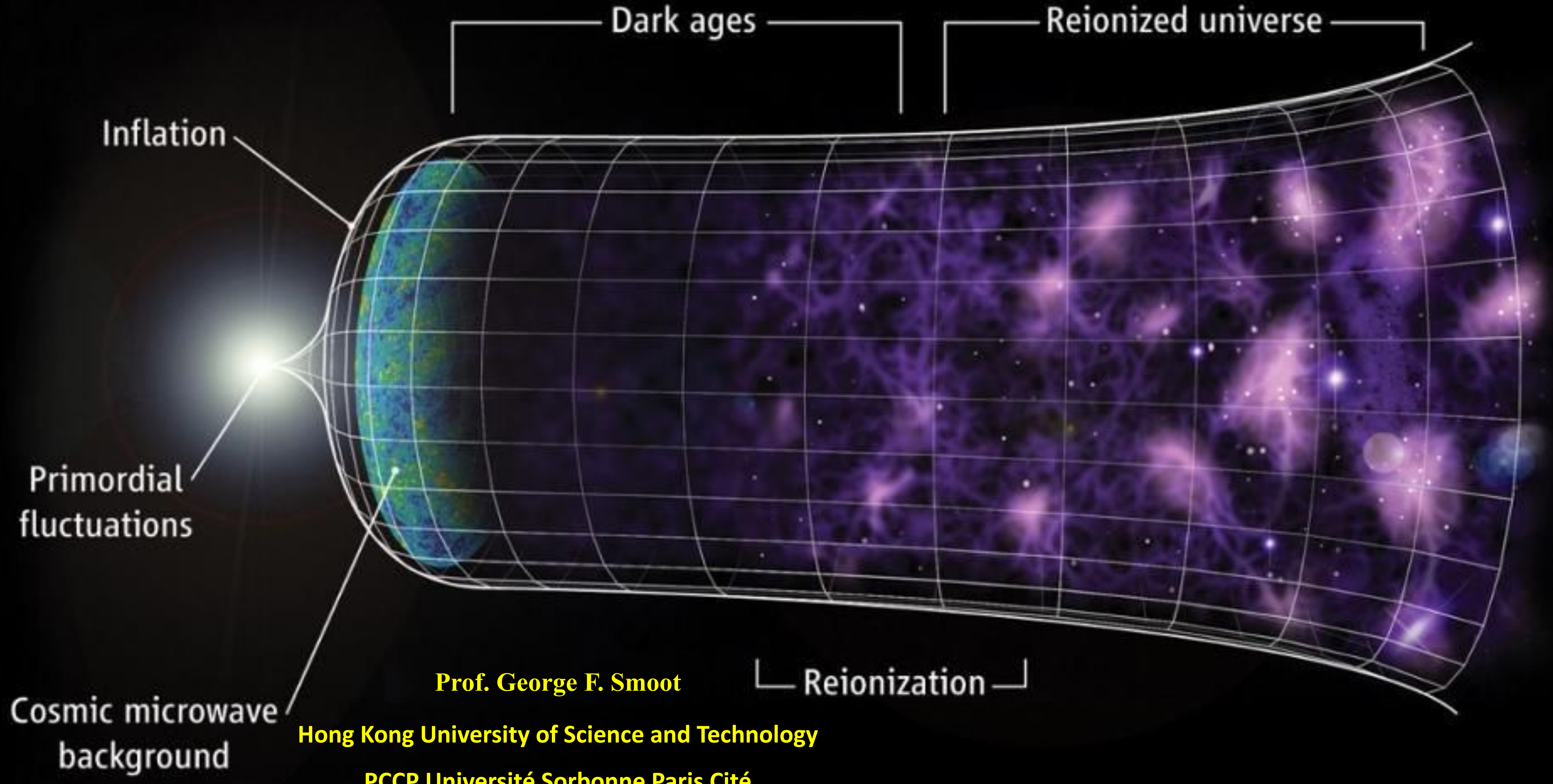
The Future of Cosmology & HEP?



Prof. George F. Smoot

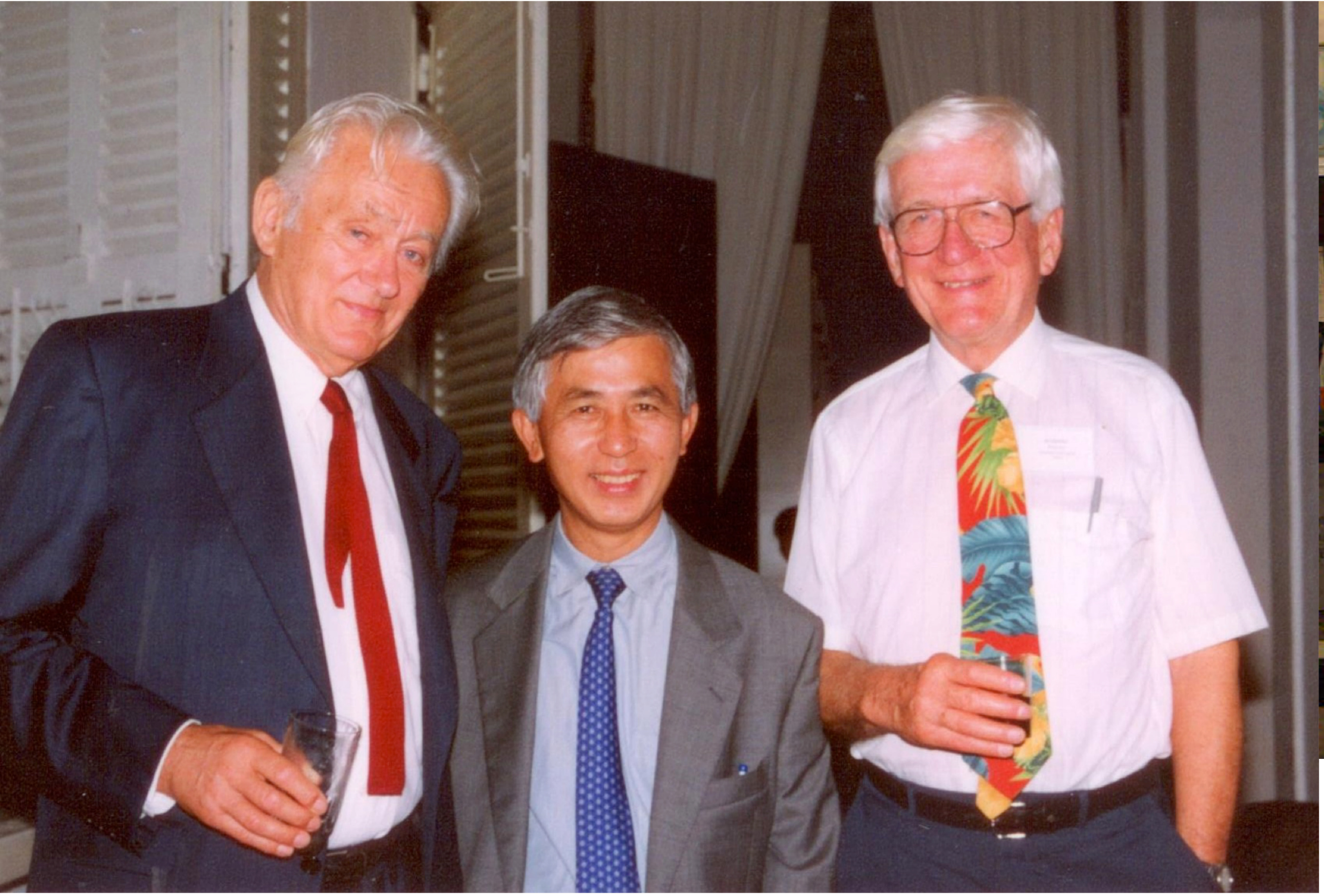
Hong Kong University of Science and Technology

PCCP Université Sorbonne Paris Cité

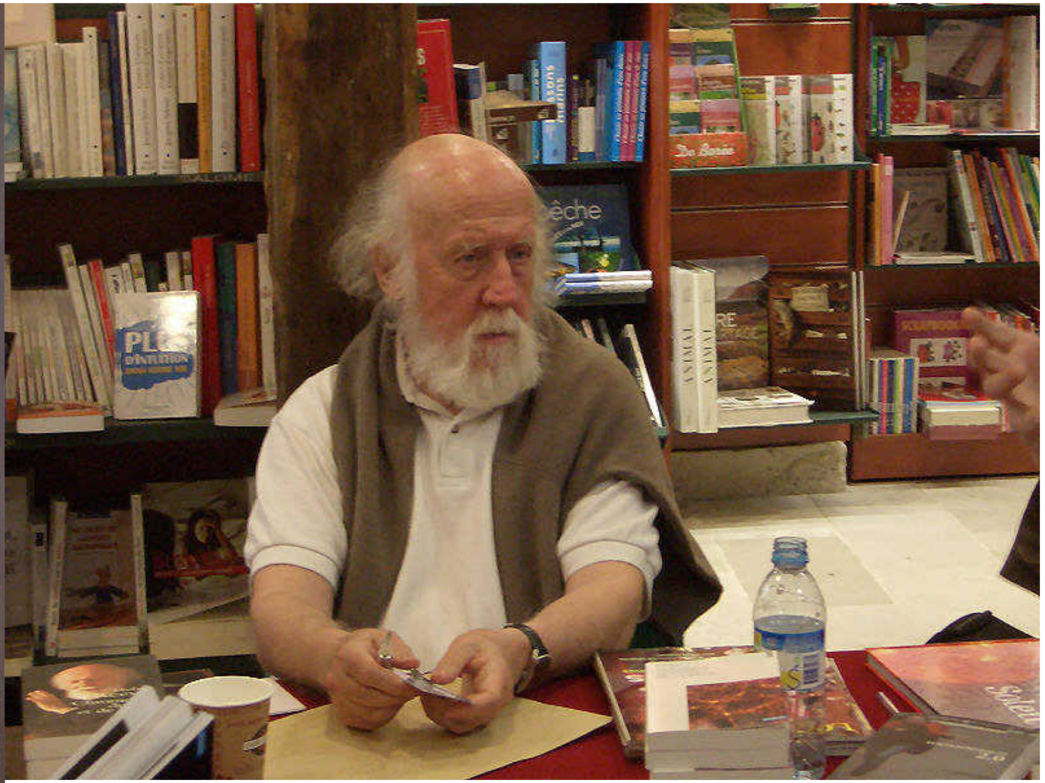
University of California at Berkeley

ECL Nazarbyaev University

Nearly 30 years of Visits to Recontres Blois, e.g. 1992

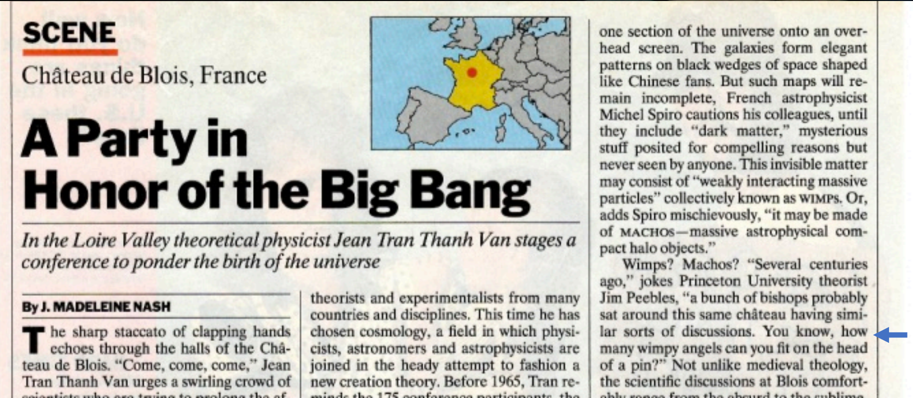


Jean Trân Thanh Vân with Georges Charpak (left), 1992 physics Nobel prize, and Norman F. Ramsey (right), 1989 physics Nobel prize



Hubert Reeves, un habitué maintenant des Rencontres de Blois

1992



SCENE

Château de Blois, France

A Party in Honor of the Big Bang

In the Loire Valley theoretical physicist Jean Tran Thanh Van stages a conference to ponder the birth of the universe

By J. MADELEINE NASH

The sharp staccato of clapping hands echoes through the halls of the Château de Blois. "Come, come, come," Jean Tran Thanh Van urges a swirling crowd of

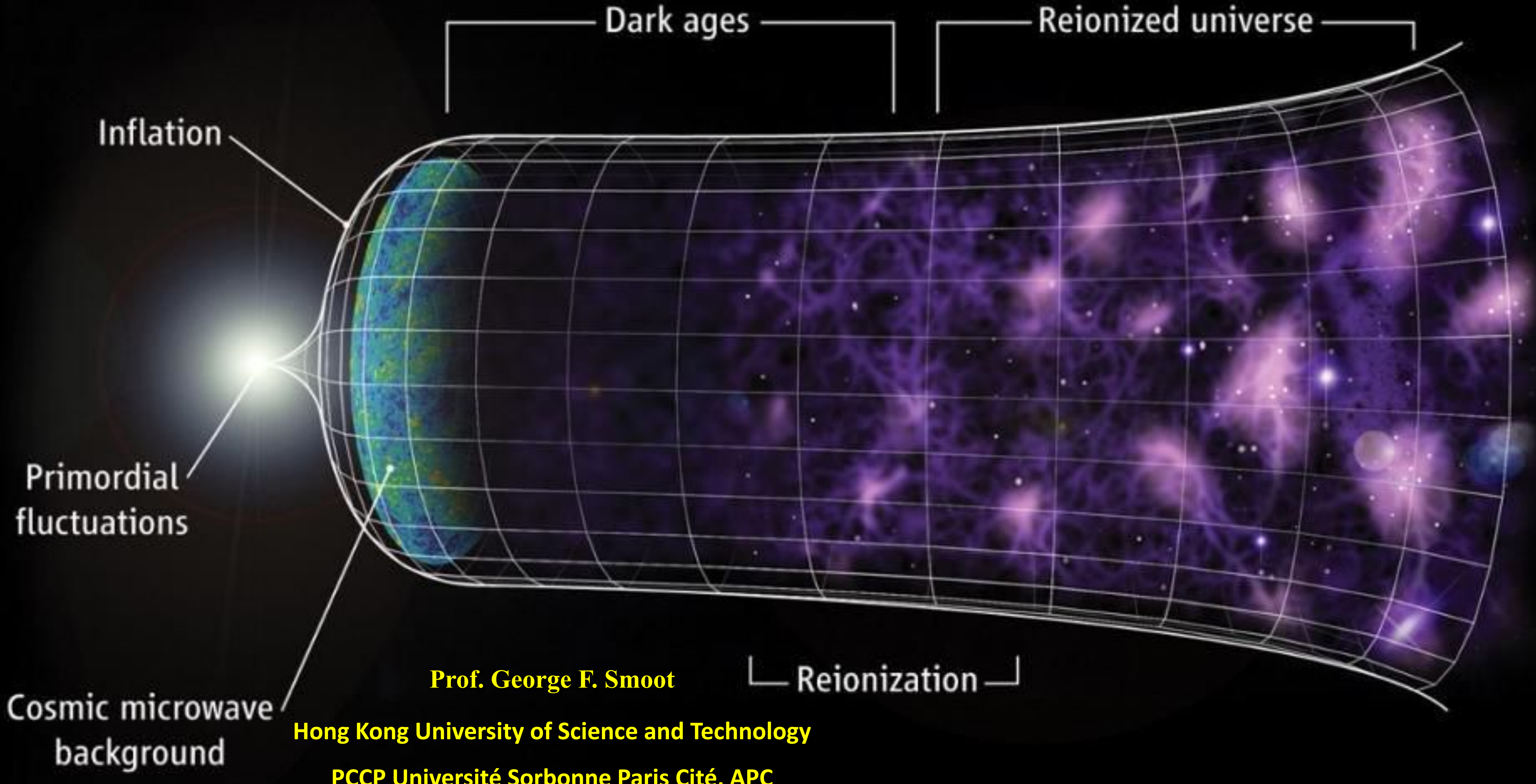
theorists and experimentalists from many countries and disciplines. This time he has chosen cosmology, a field in which physicists, astronomers and astrophysicists are joined in the heady attempt to fashion a new creation theory. Before 1965, Tran re-

one section of the universe onto an overhead screen. The galaxies form elegant patterns on black wedges of space shaped like Chinese fans. But such maps will remain incomplete, French astrophysicist Michel Spiro cautions his colleagues, until they include "dark matter," mysterious stuff posited for compelling reasons but never seen by anyone. This invisible matter may consist of "weakly interacting massive particles" collectively known as WIMPS. Or, adds Spiro mischievously, "it may be made of MACHOS—massive astrophysical compact halo objects."

Wimps? Machos? "Several centuries ago," jokes Princeton University theorist Jim Peebles, "a bunch of bishops probably sat around this same château having similar sorts of discussions. You know, how many wimpy angels can you fit on the head of a pin?" Not unlike medieval theology, the scientific discussions at Blois comfort-

1990

The Future of Cosmology & HEP?



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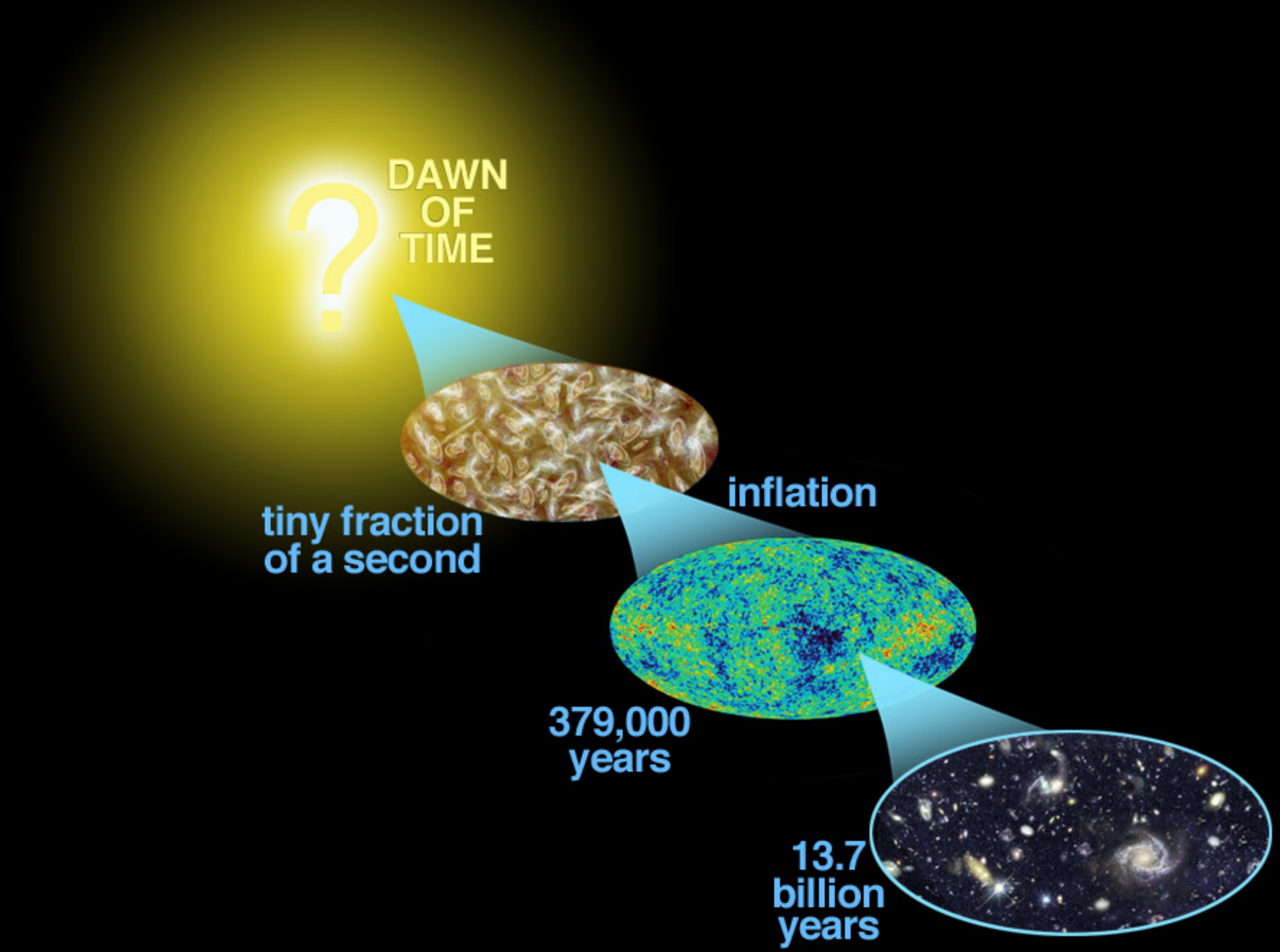
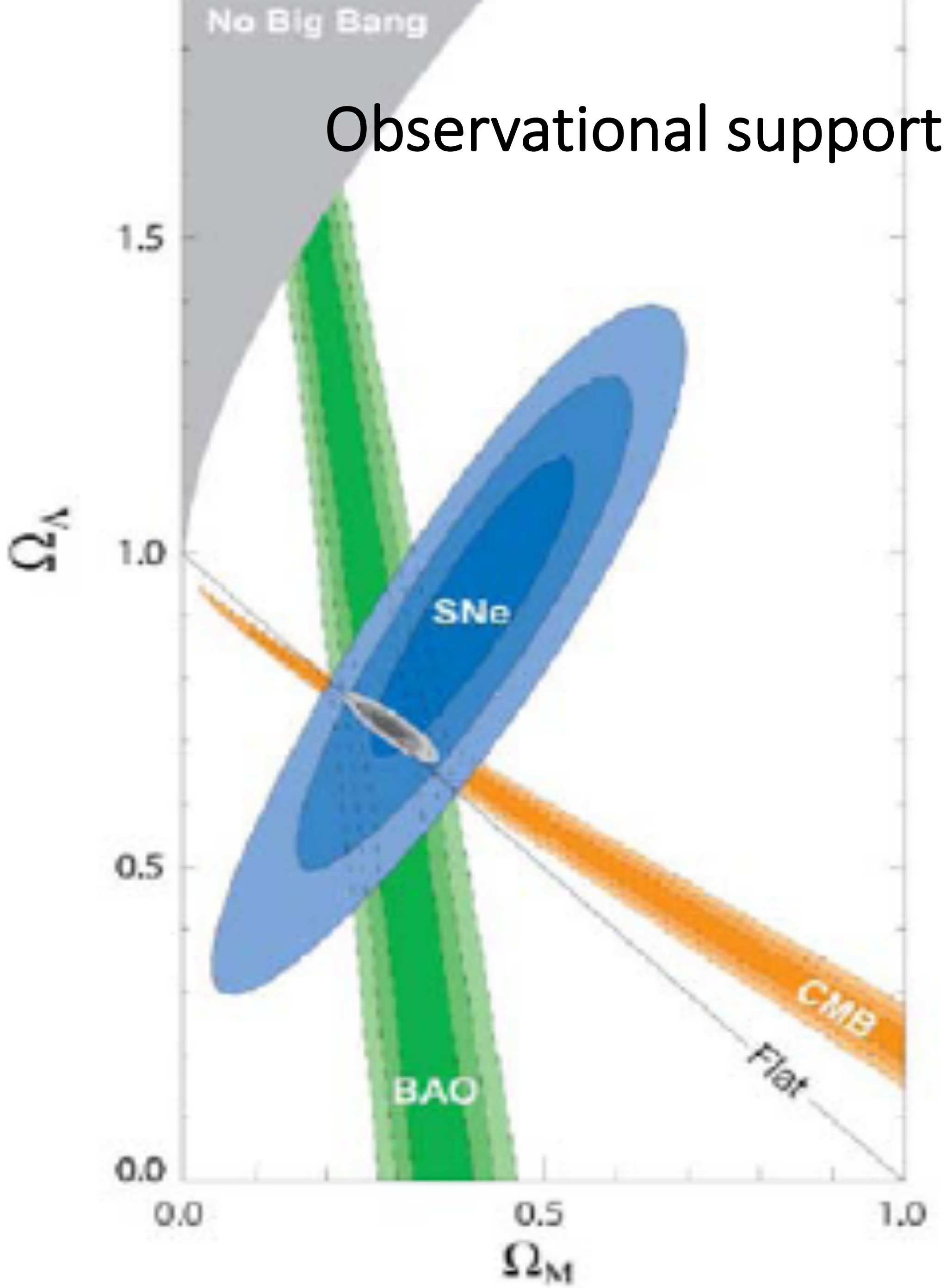
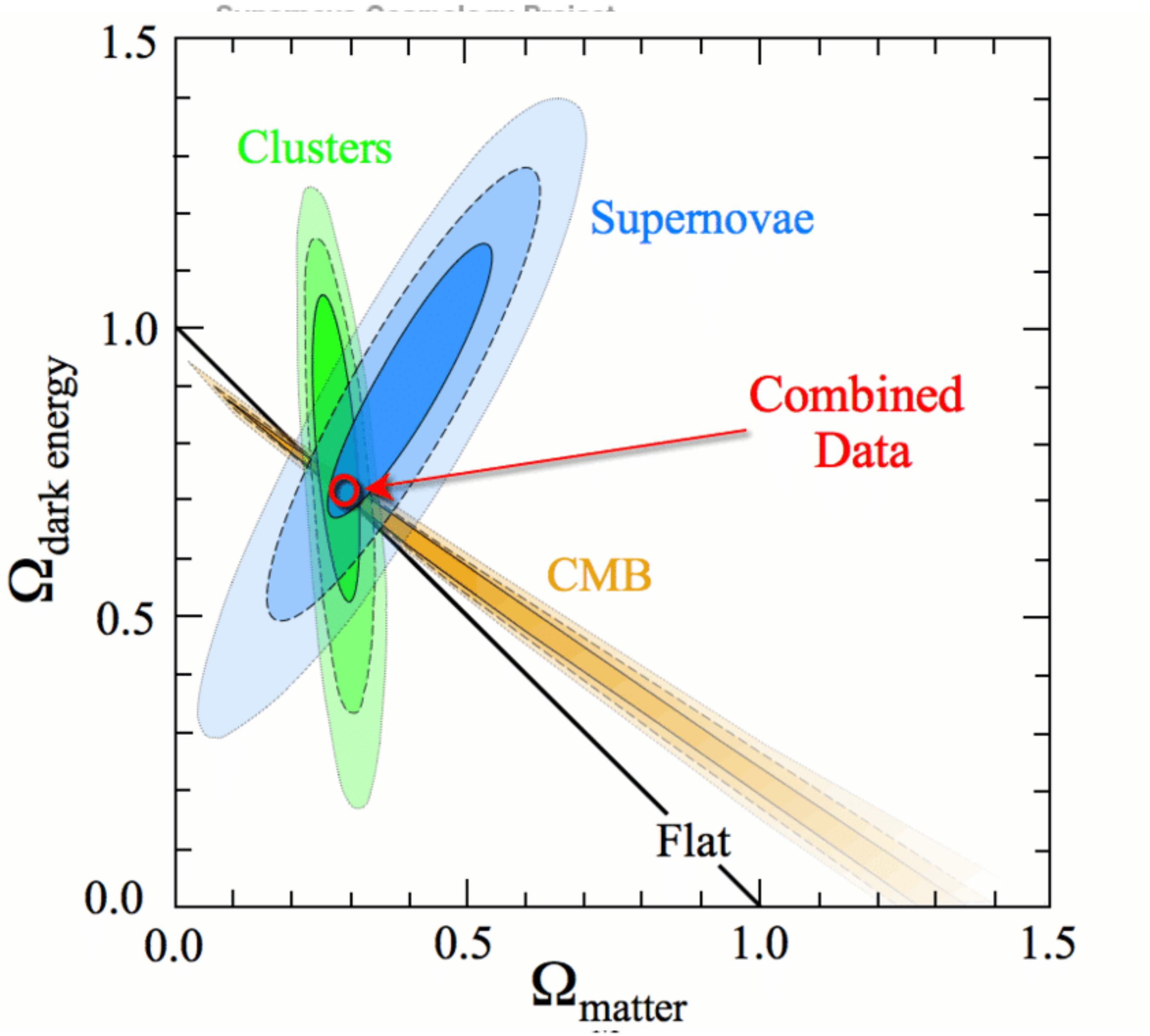
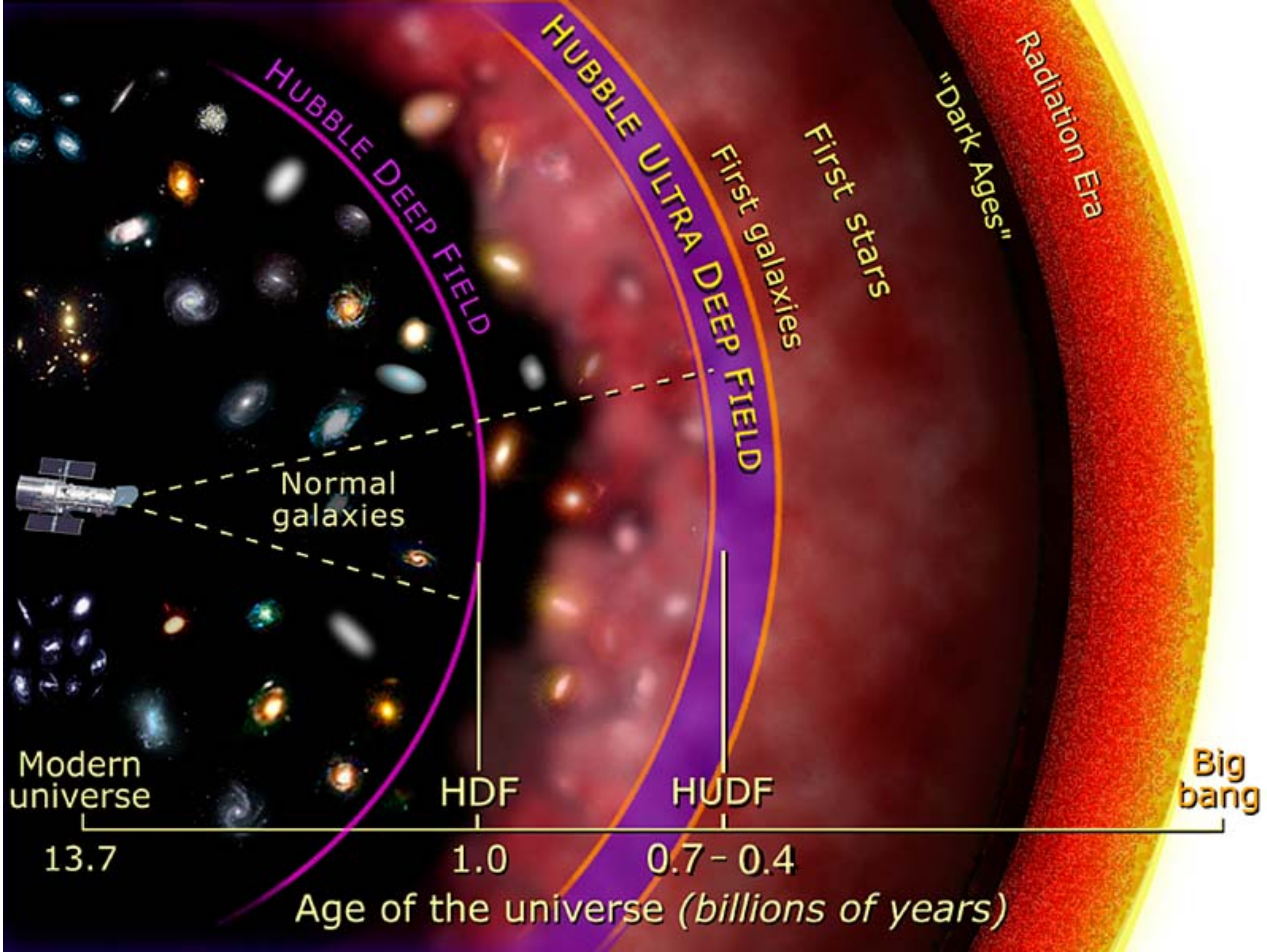

?
DAWN
OF
TIME
inflation
tiny fraction
of a second
379,000
years
13.7
billion
years

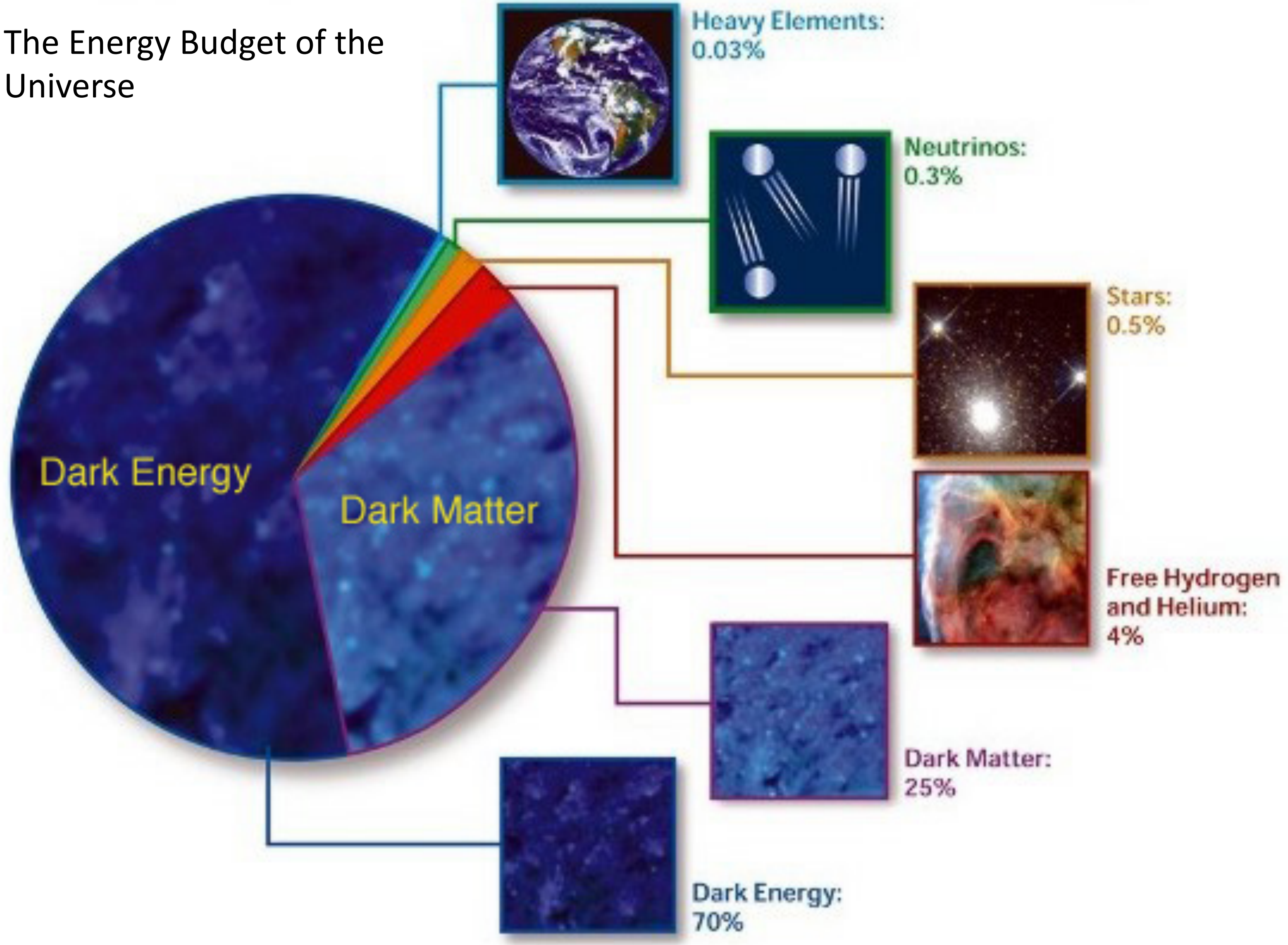
Observational support for the ΛCDM model *(http:rpp.lbl.gov)*






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)

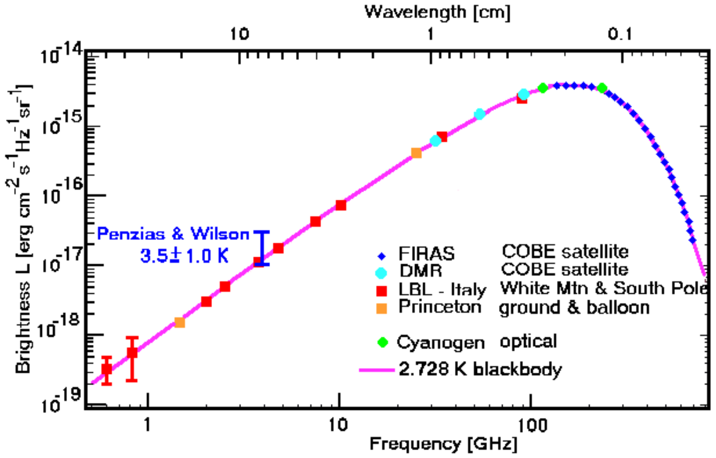
$$T_{\mu\nu} = diag(\rho, p, p, p)$$

Dynamics *(Friedmann equations from GR)*

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

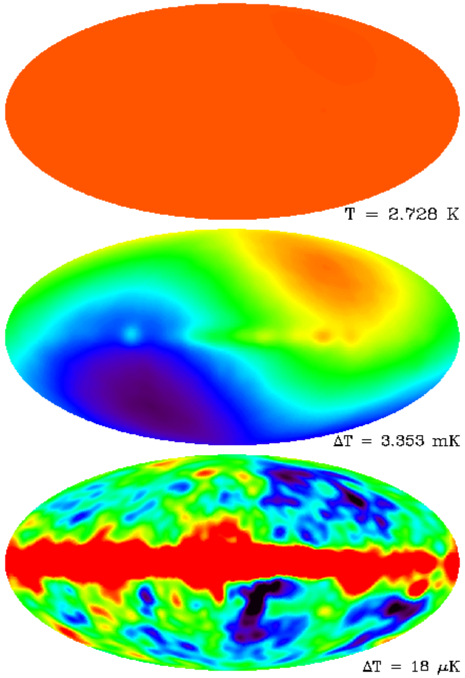
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

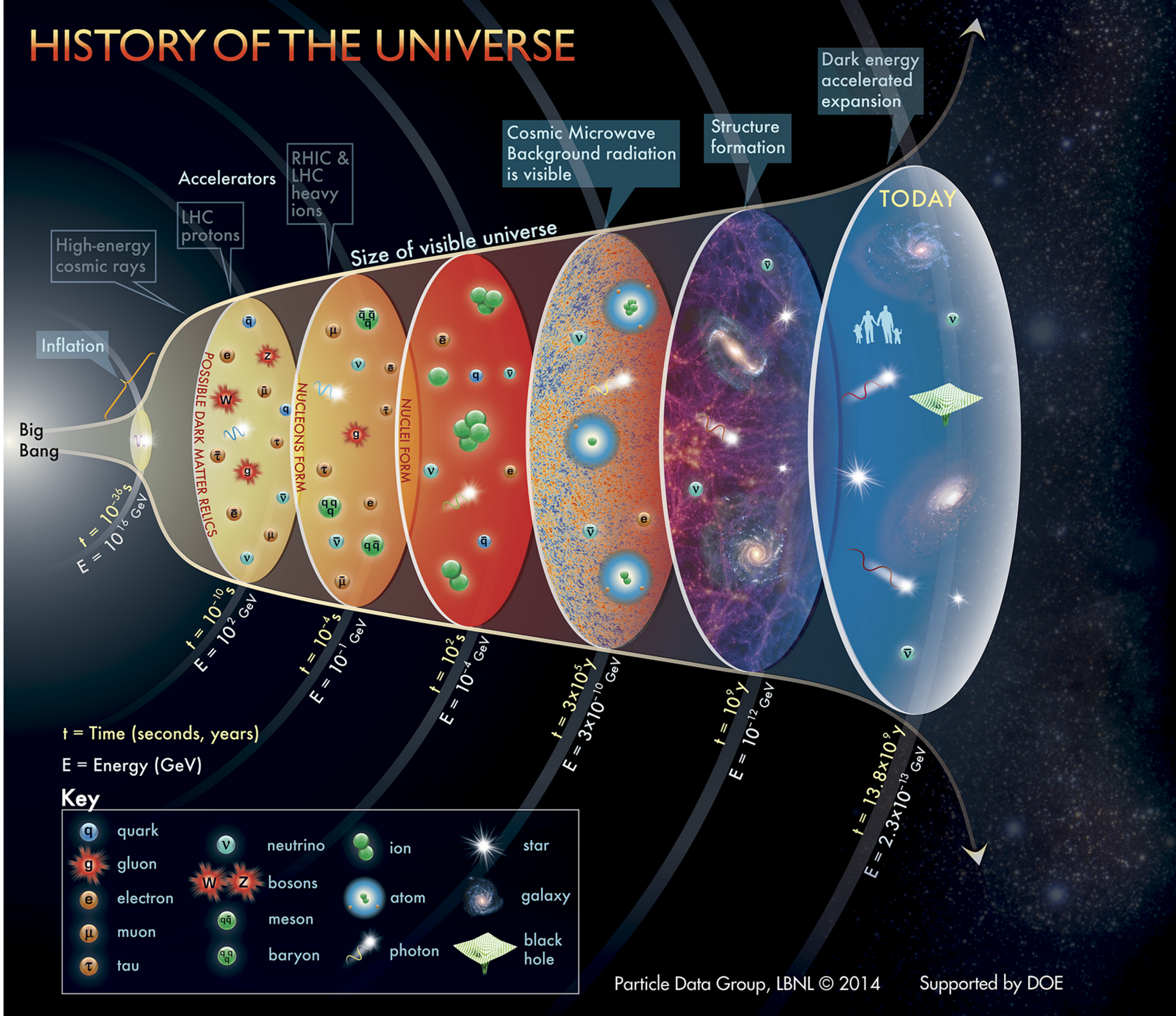
CMB discovered 55 years ago
Penzias & Wilson 1964



COBE launch 1989 30 years ago

1992 Anisotropy announced





Particle Data Group, LBNL © 2014 Supported by DOE

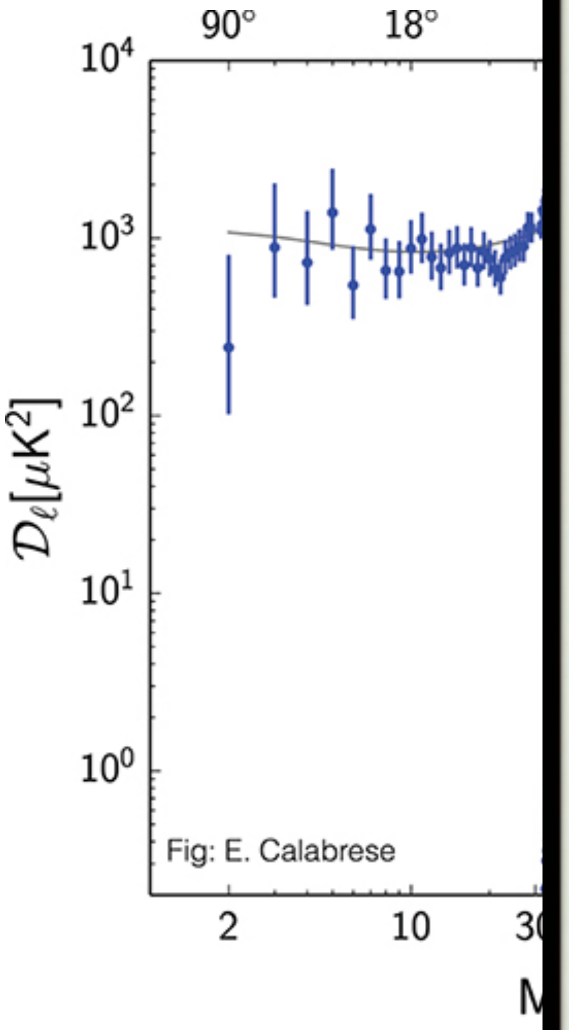
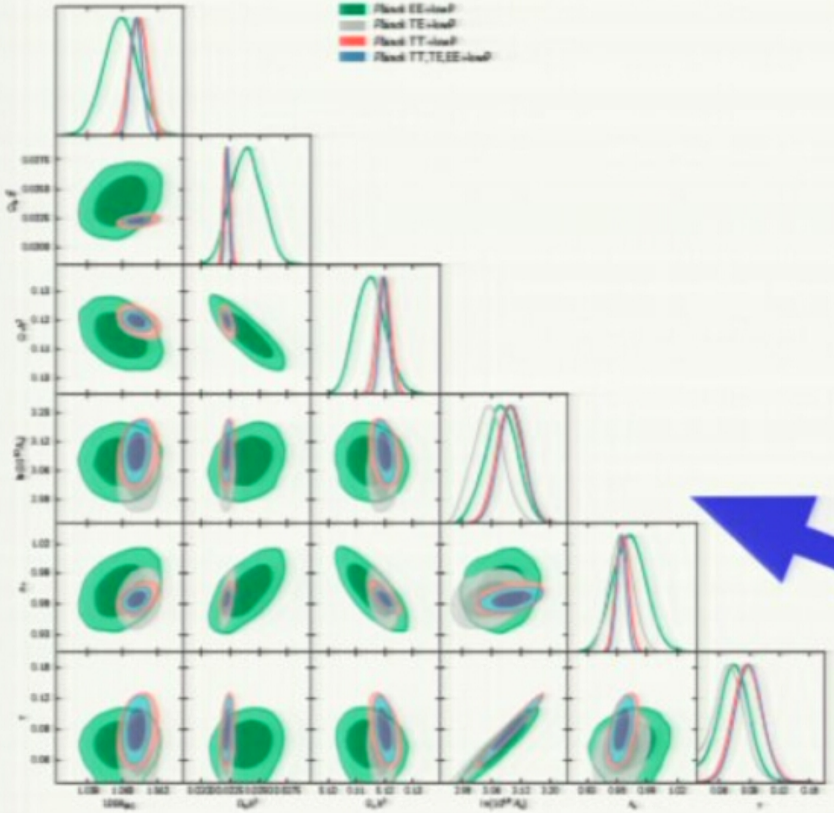
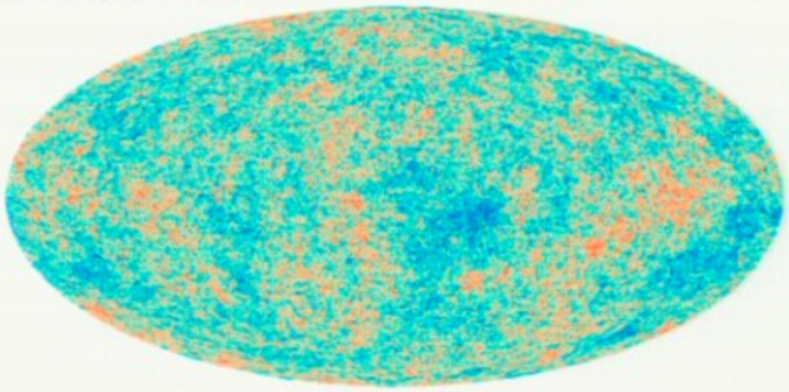


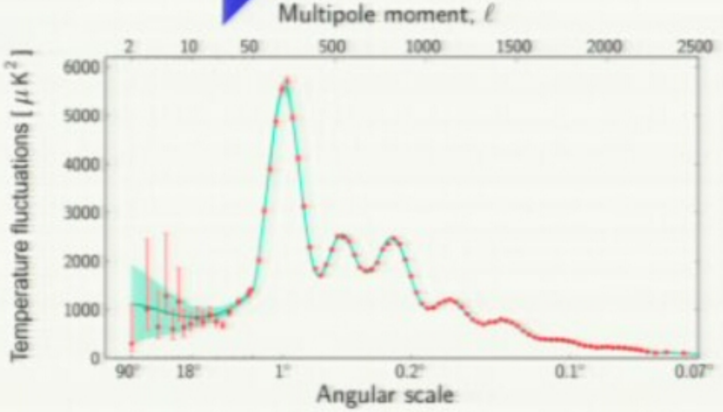
Fig: E. Calabrese

Intensity mapping: CMB

Cosmic Microwave Background, z=1100

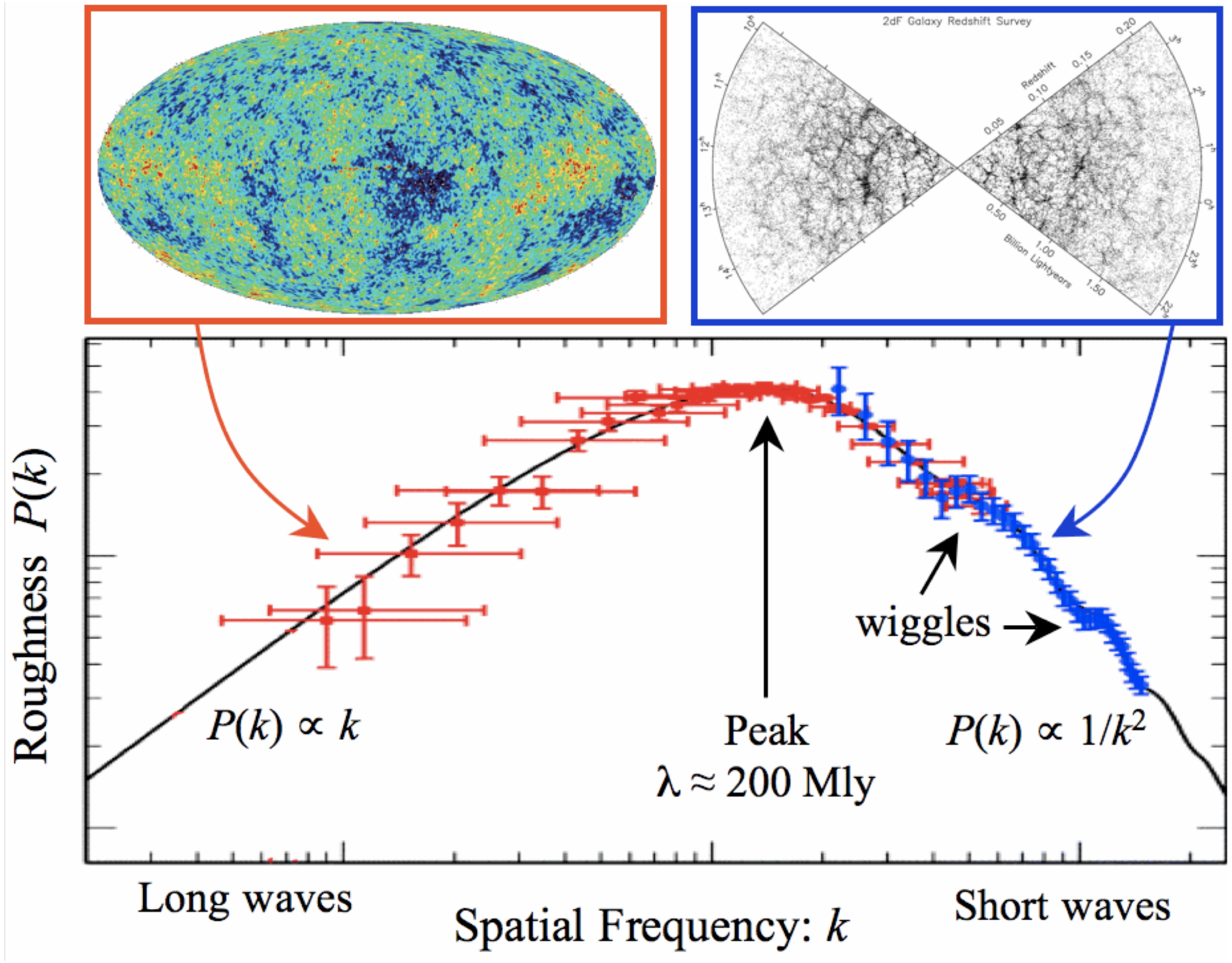


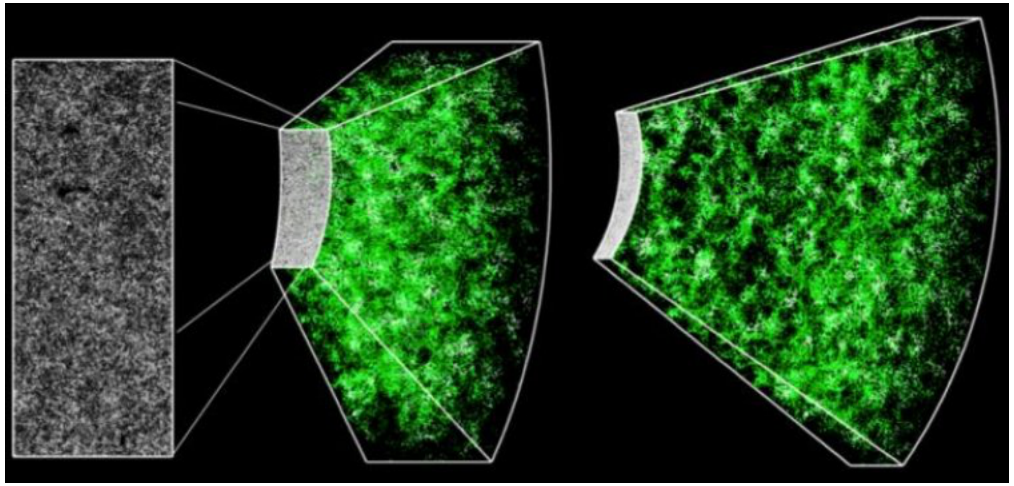




Planck 2013 results. XVI. Cosmological parameters
Planck 2015 results XIII. Cosmological parameters
Planck 2015 results IX. Diffuse component separation: CMB maps
Planck 2015 results XI. CMB power spectra, likelihoods, and robustness of parameters

Observations show very good fit to cosmology model



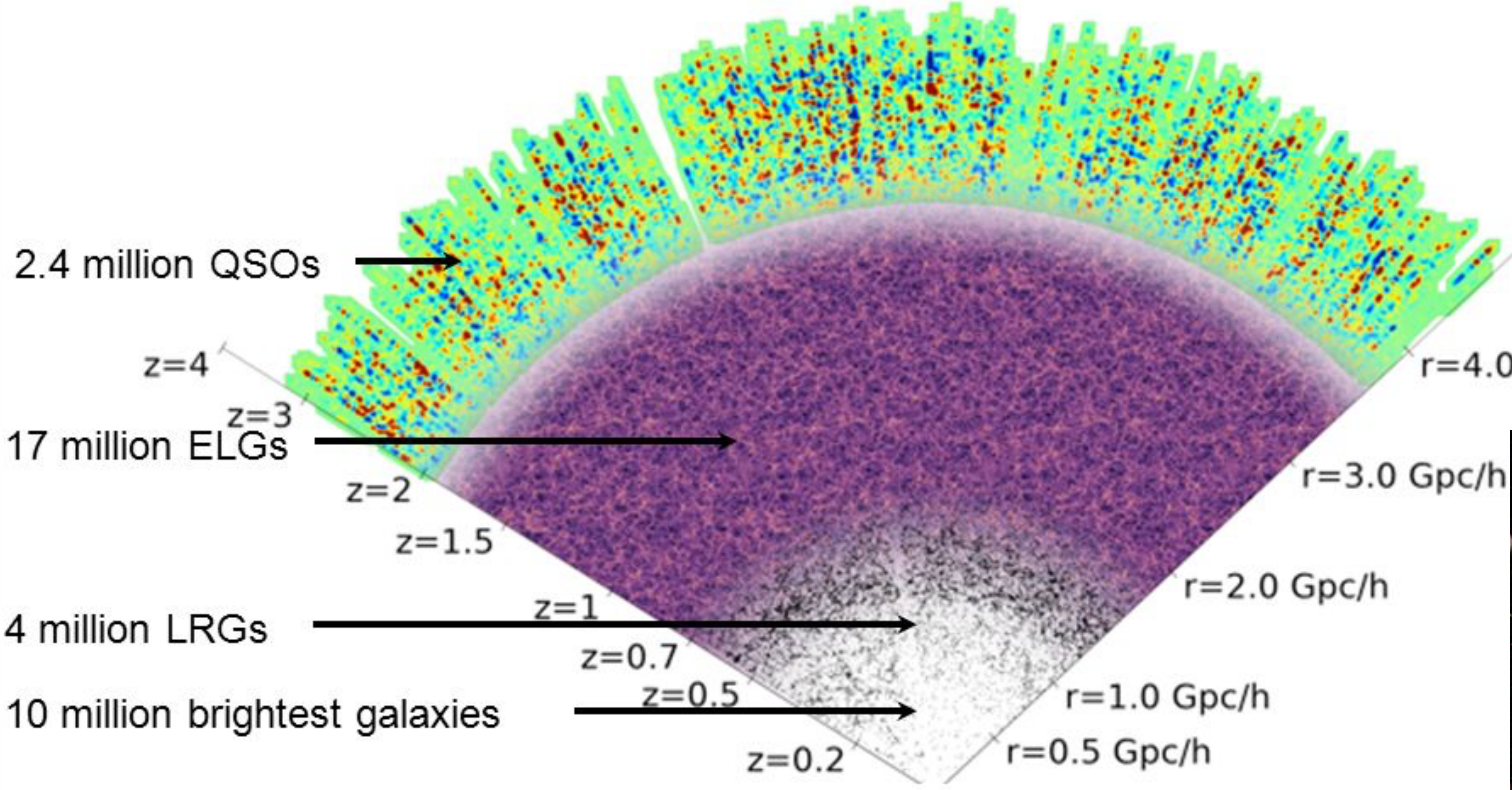


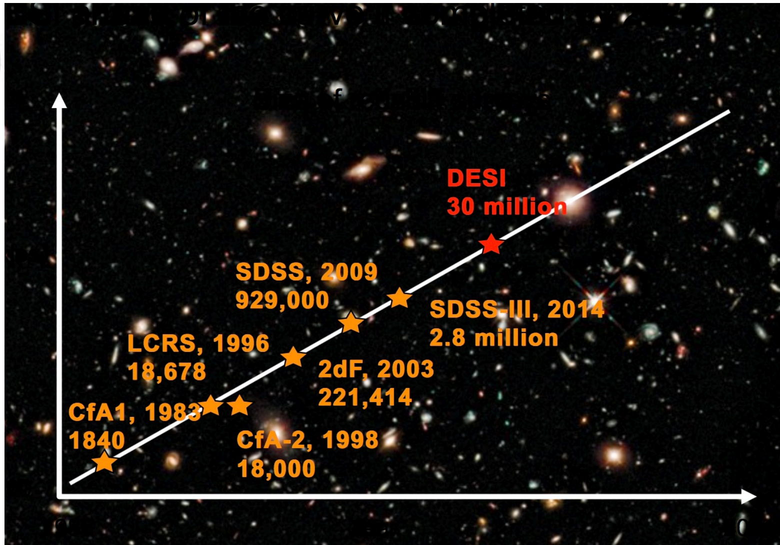
The Sloan Digital Sky Survey - Baryon Oscillation Spectroscopic Survey
has transformed a two-dimensional image of the sky (left panel)
into a three-dimensional map spanning distances of billions of light ye
shown here from two perspectives (middle and right panels).
This map includes 120,000 galaxies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

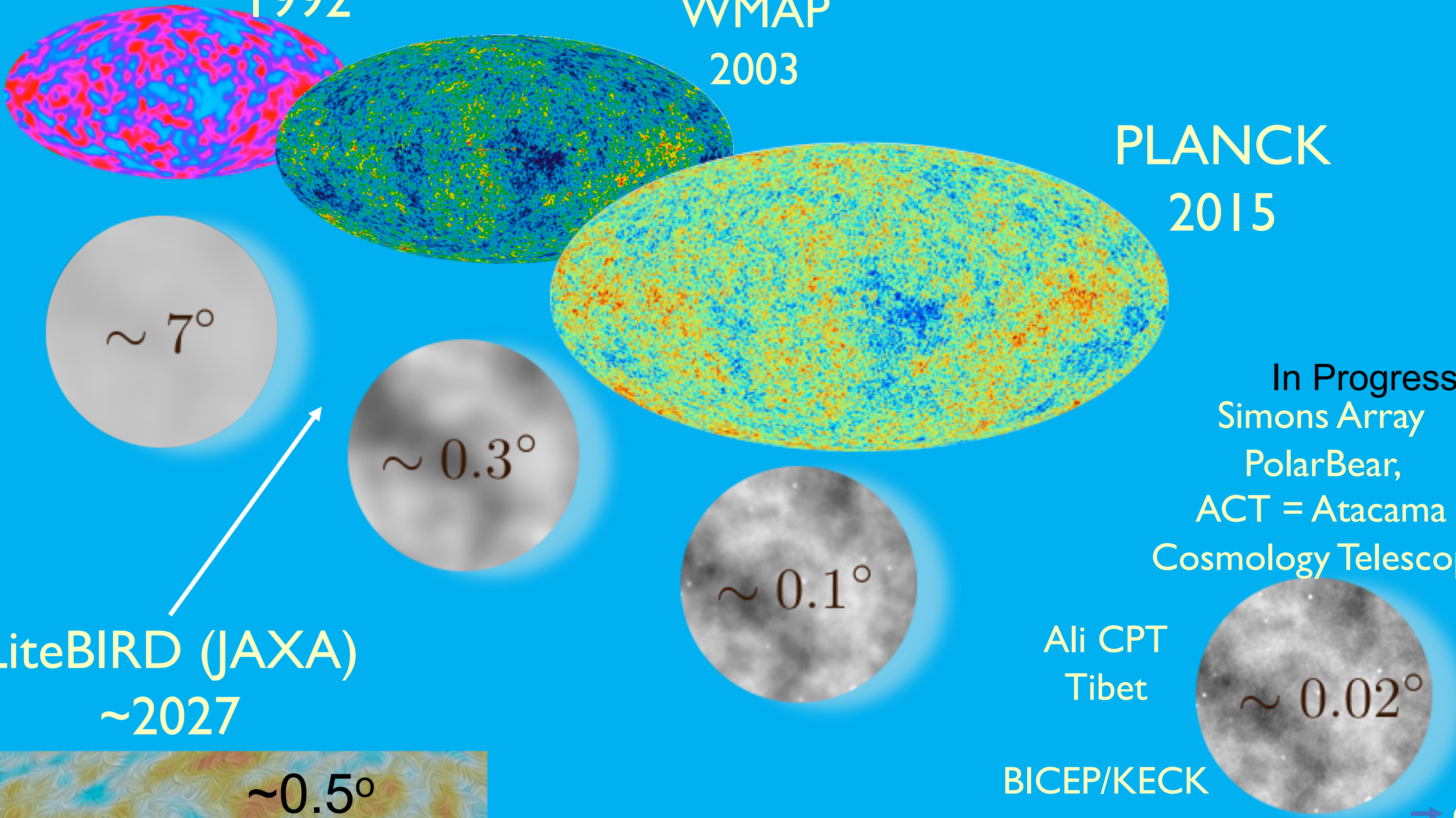
SDSS ~2h^{-3}Gpc^3 ⇨ BOSS ~6h^{-3}Gpc^3 ⇨ DESI 50h^{-3}Gpc^3





Our Ever-sharpening View of the Embryo Universe …

Notre point de vue sans cesse sur l'univers embryonnaire …



COBE
1992

WMAP
2003

PLANCK
2015

In Progress
Simons Array
PolarBear,
ACT = Atacama
Cosmology Telescope

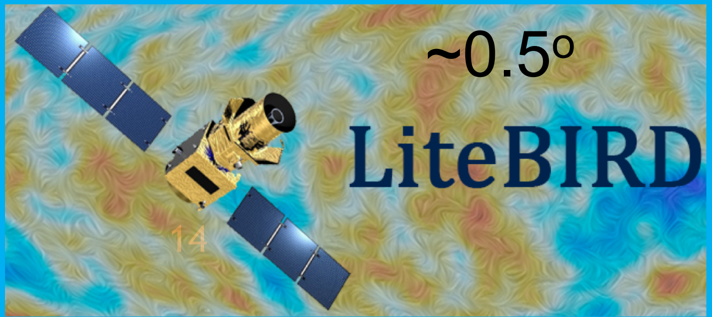
Ali CPT
Tibet

BICEP/KECK

SPT
South Pole
Telescope

→ CMB S4

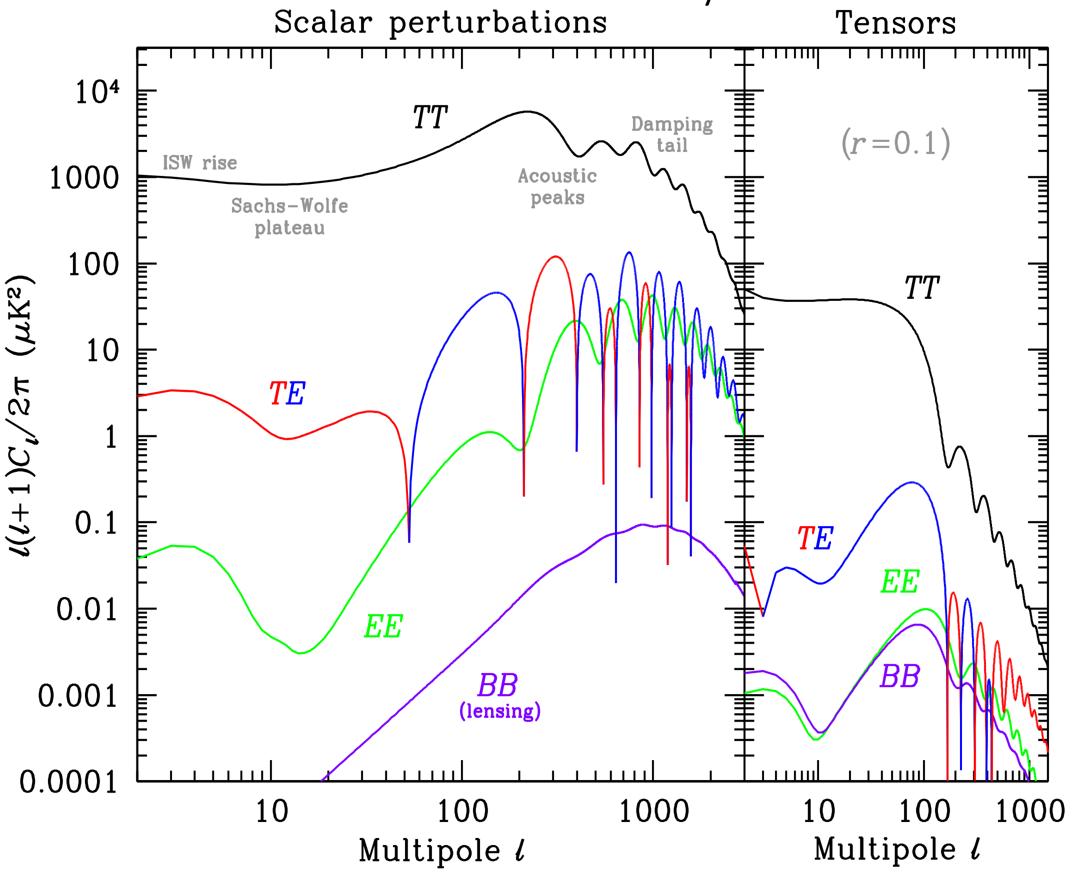
LiteBIRD (JAXA)
~2027



CMB Angular Power Spectra

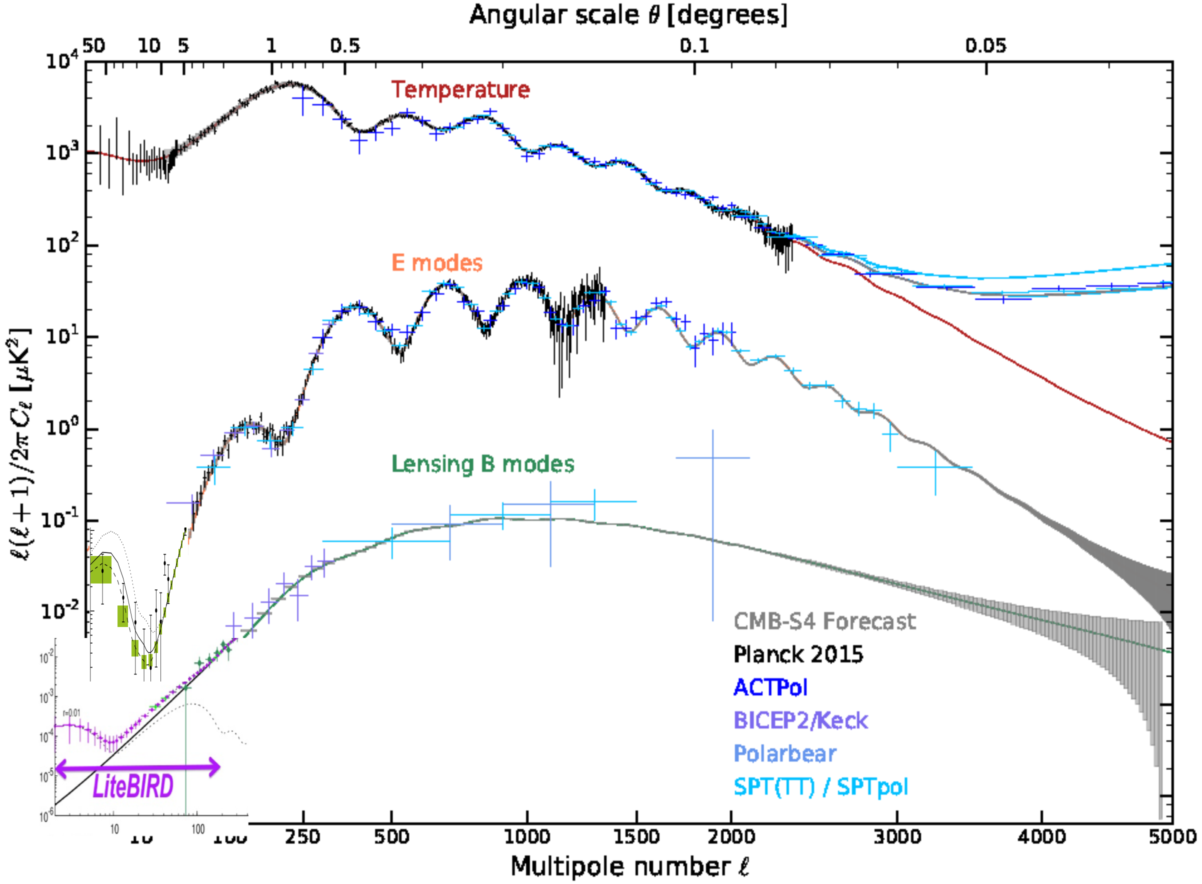
Scalar Effects Observed Very Well; Tensor Modes not seen

Theory



Scott & Smoot 2015

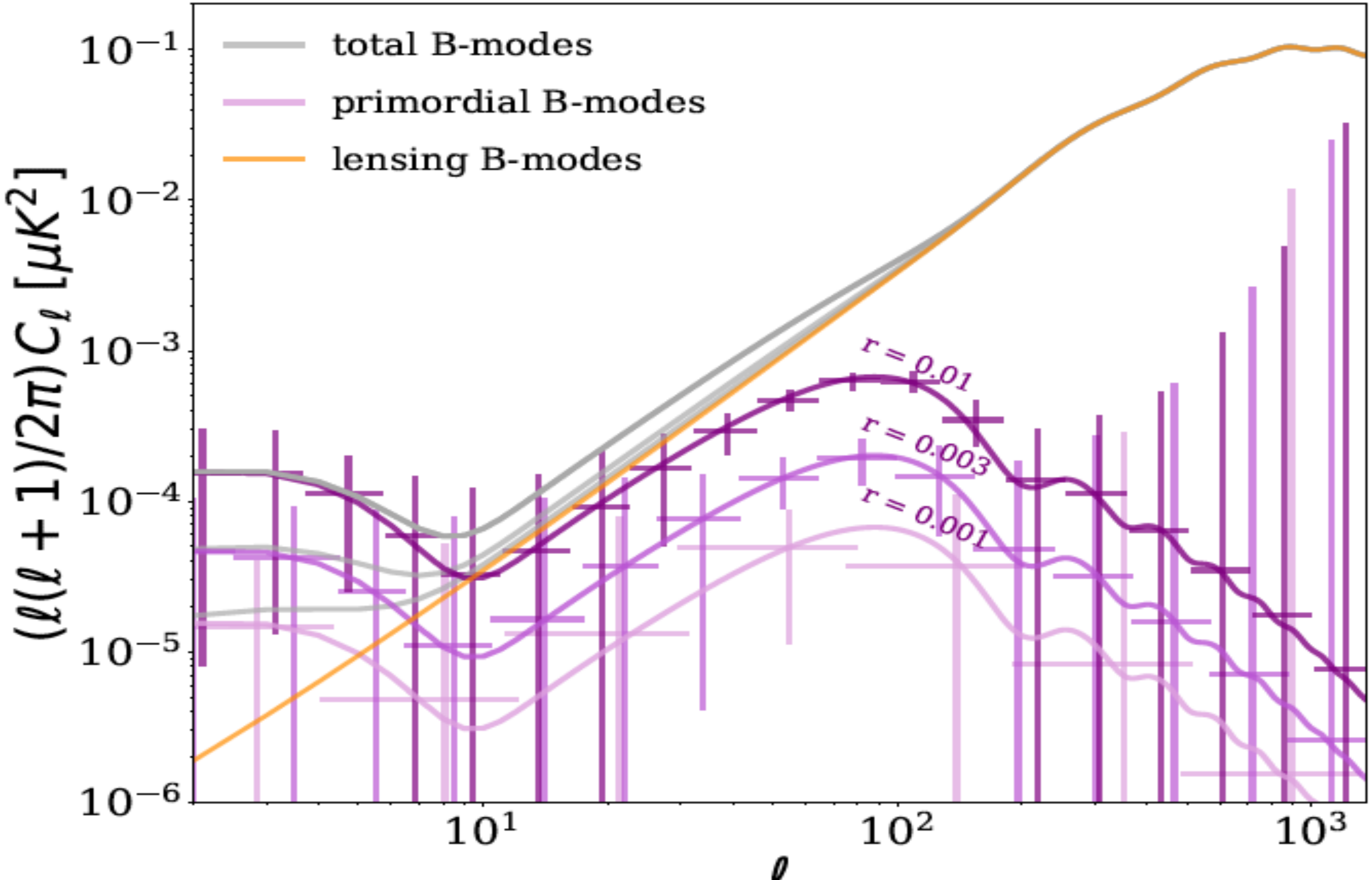
Current and Proposed Observations



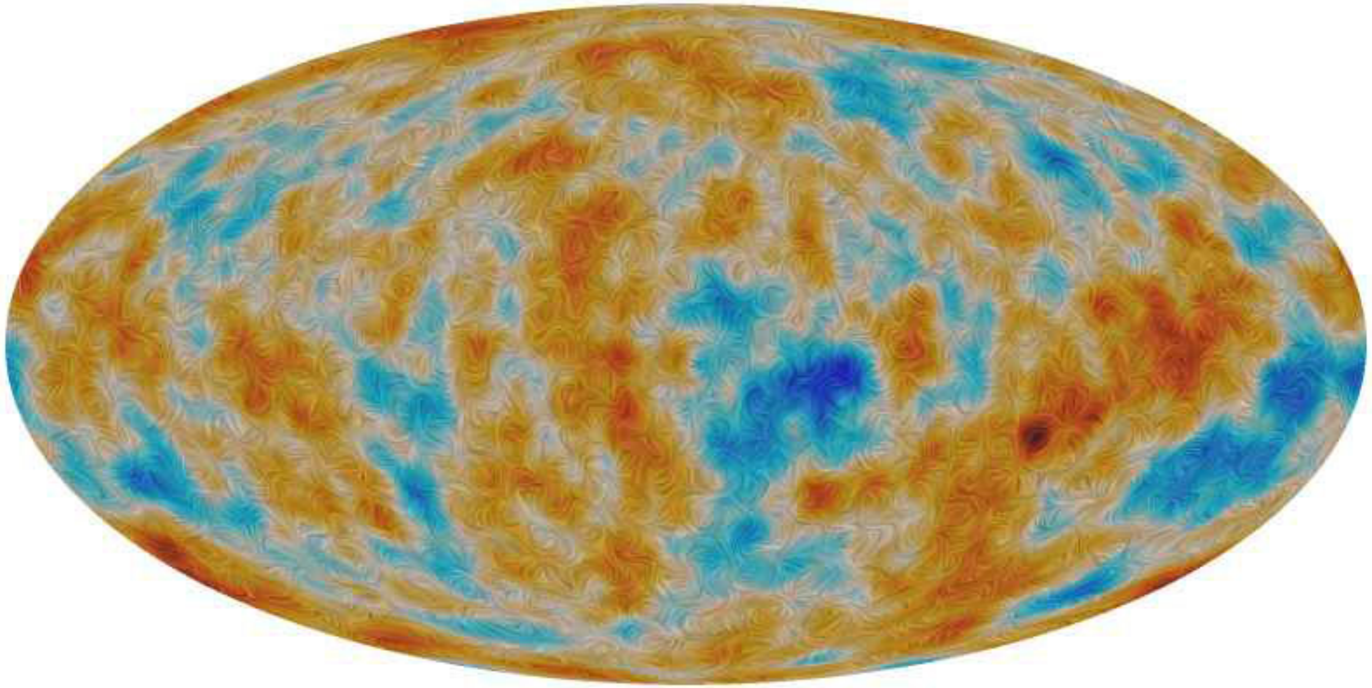
CMB S4 Science Report

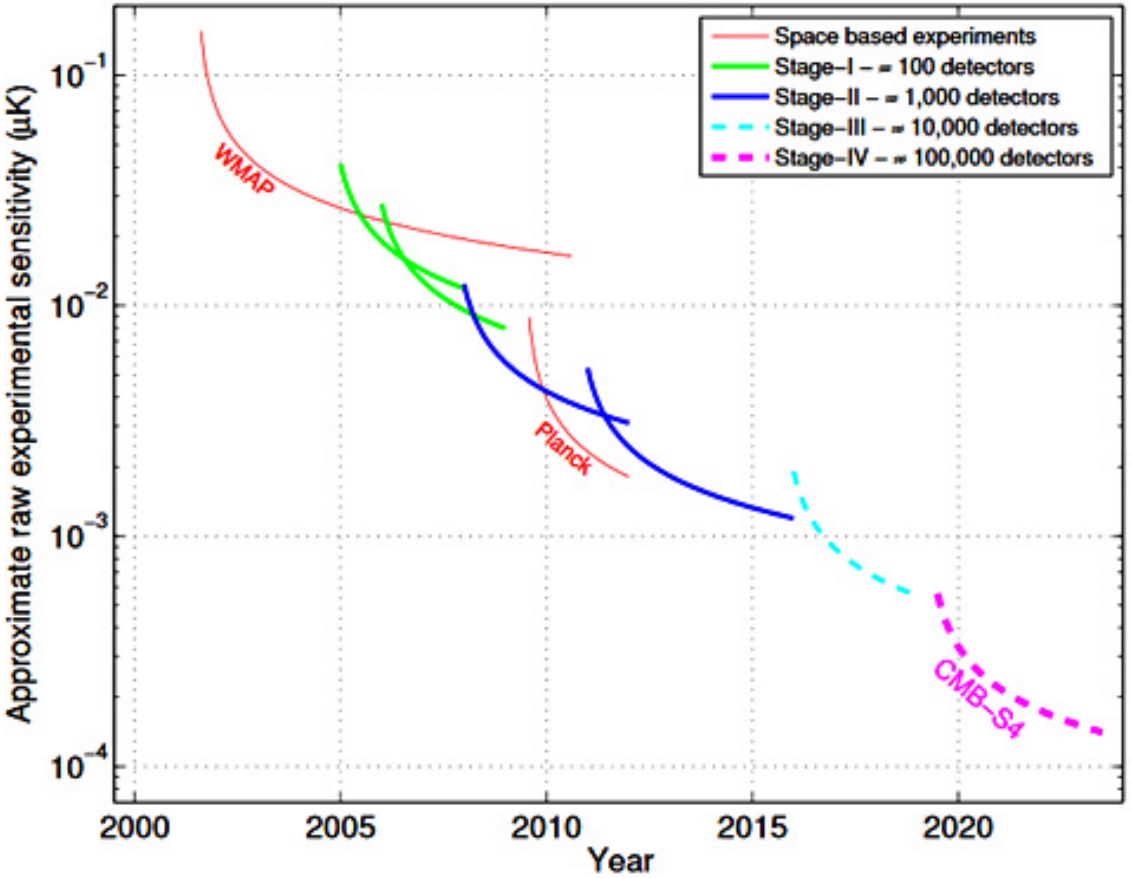
In roughly 5 years CMB observations become clean up except at large angular scales
(LiteBIRD assuming r = 0.01 in 2027+) Test of Inflation to be primodial B modes/Tensors

LiteBIRD with best delensing



Cosmic Microwave Background (CMB) Radiation



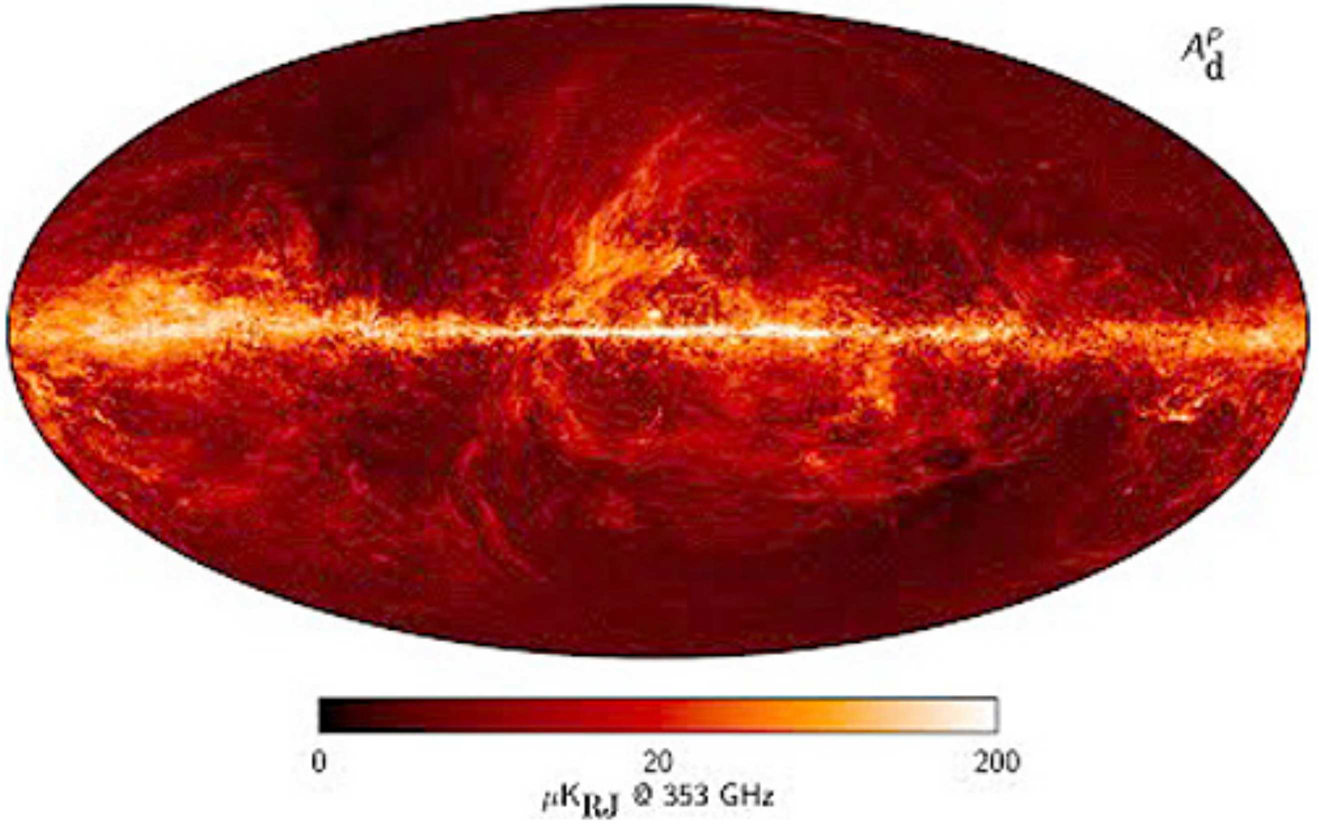


The 'Stage-4' ground-based cosmic microwave background (CMB) experiment, CMB-S4, consisting of dedicated telescopes equipped with highly sensitive superconducting cameras operating at the South Pole, the high Chilean Atacama plateau, and possibly northern hemisphere sites, will provide a dramatic leap 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.

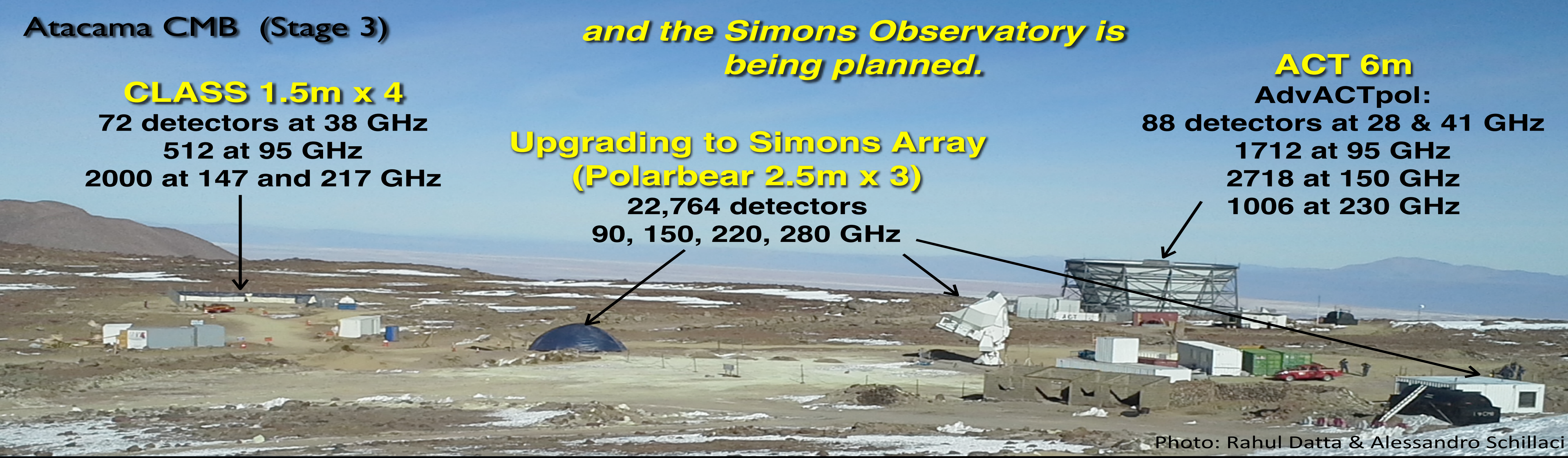
CMB-S4

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**



Atacama CMB (Stage 3)



and the Simons Observatory is being planned.

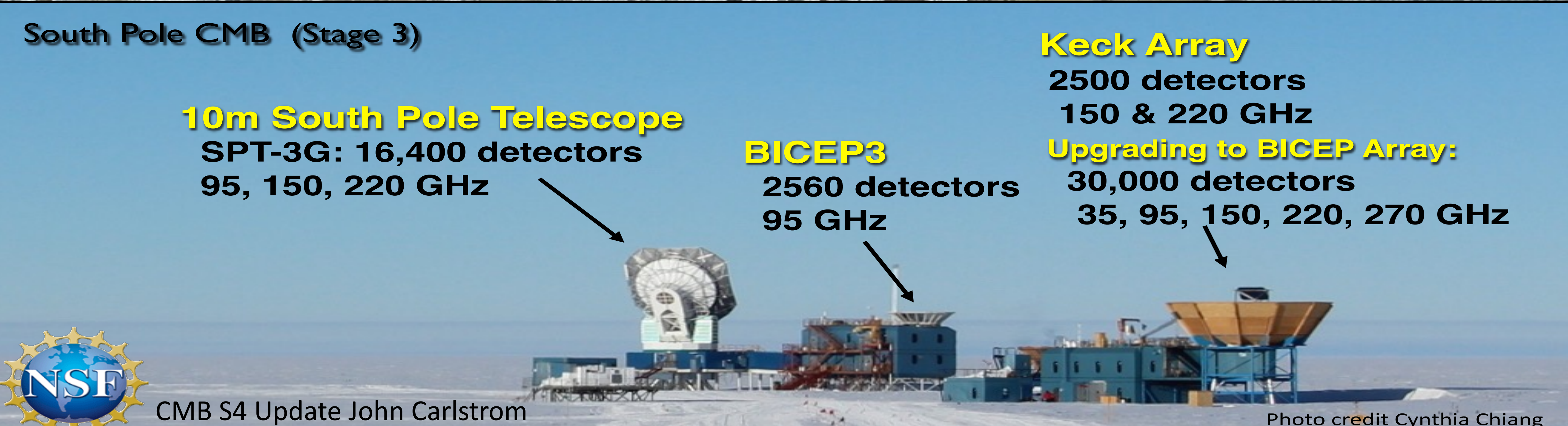
CLASS 1.5m x 4
72 detectors at 38 GHz
512 at 95 GHz
2000 at 147 and 217 GHz

Upgrading to Simons Array (Polarbear 2.5m x 3)
22,764 detectors
90, 150, 220, 280 GHz

ACT 6m
AdvACTpol:
88 detectors at 28 & 41 GHz
1712 at 95 GHz
2718 at 150 GHz
1006 at 230 GHz

Photo: Rahul Datta & Alessandro Schillaci

South Pole CMB (Stage 3)



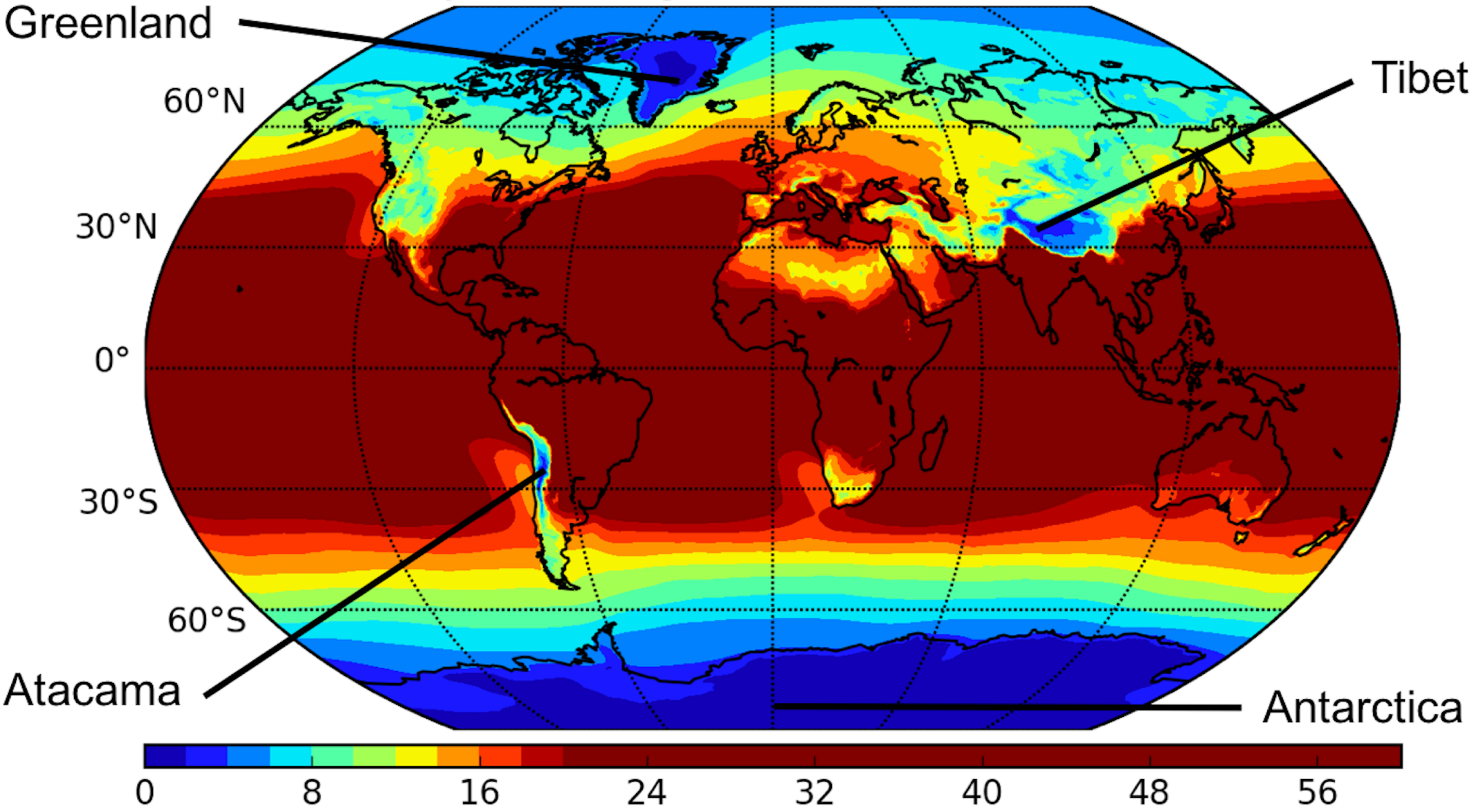
10m South Pole Telescope
SPT-3G: 16,400 detectors
95, 150, 220 GHz

BICEP3
2560 detectors
95 GHz

Keck Array
2500 detectors
150 & 220 GHz
Upgrading to BICEP Array:
30,000 detectors
35, 95, 150, 220, 270 GHz

Photo credit Cynthia Chiang

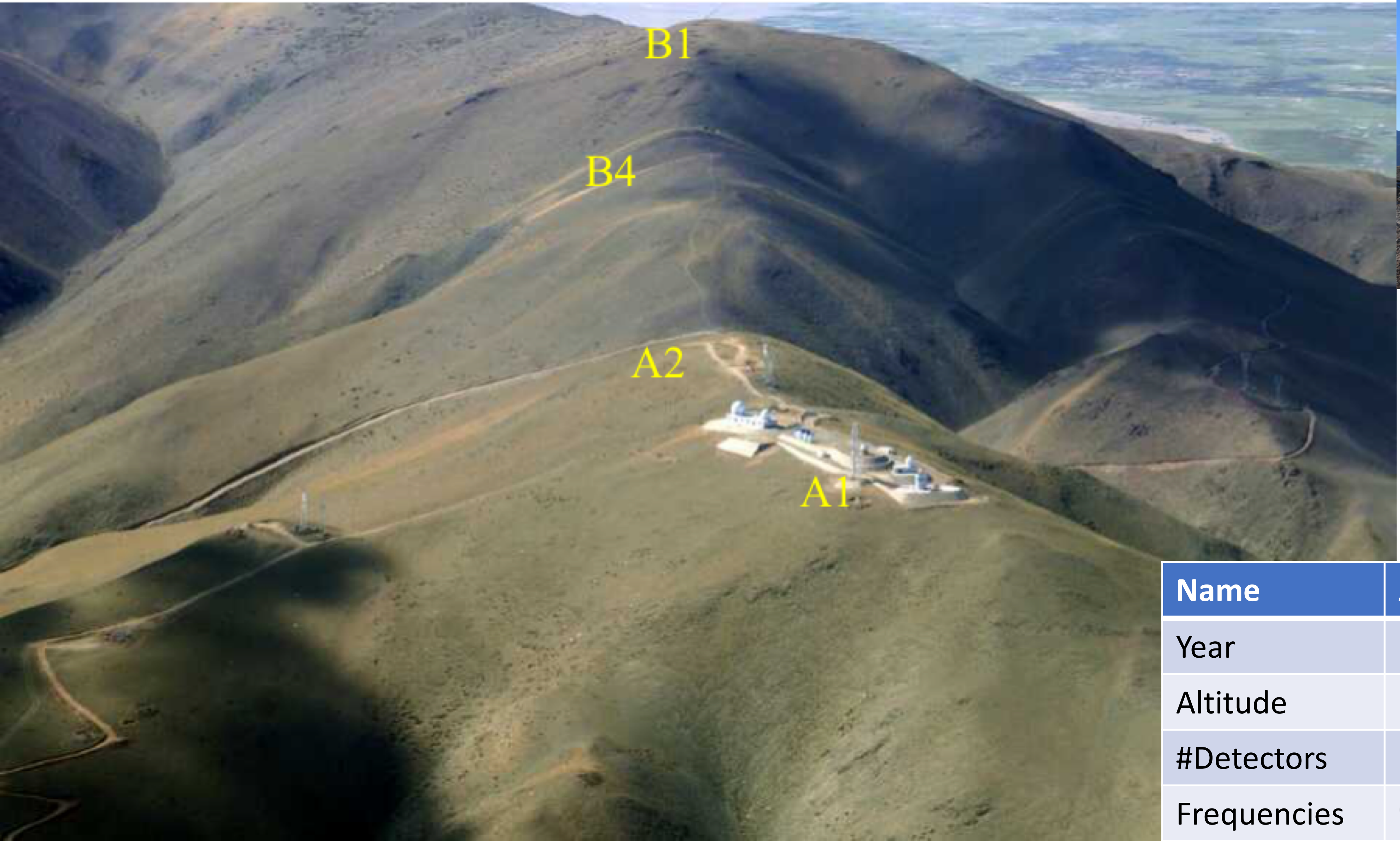
Atmospheric Precipitable Water Vapor



6-year average PWV (2011.7-2016.7)

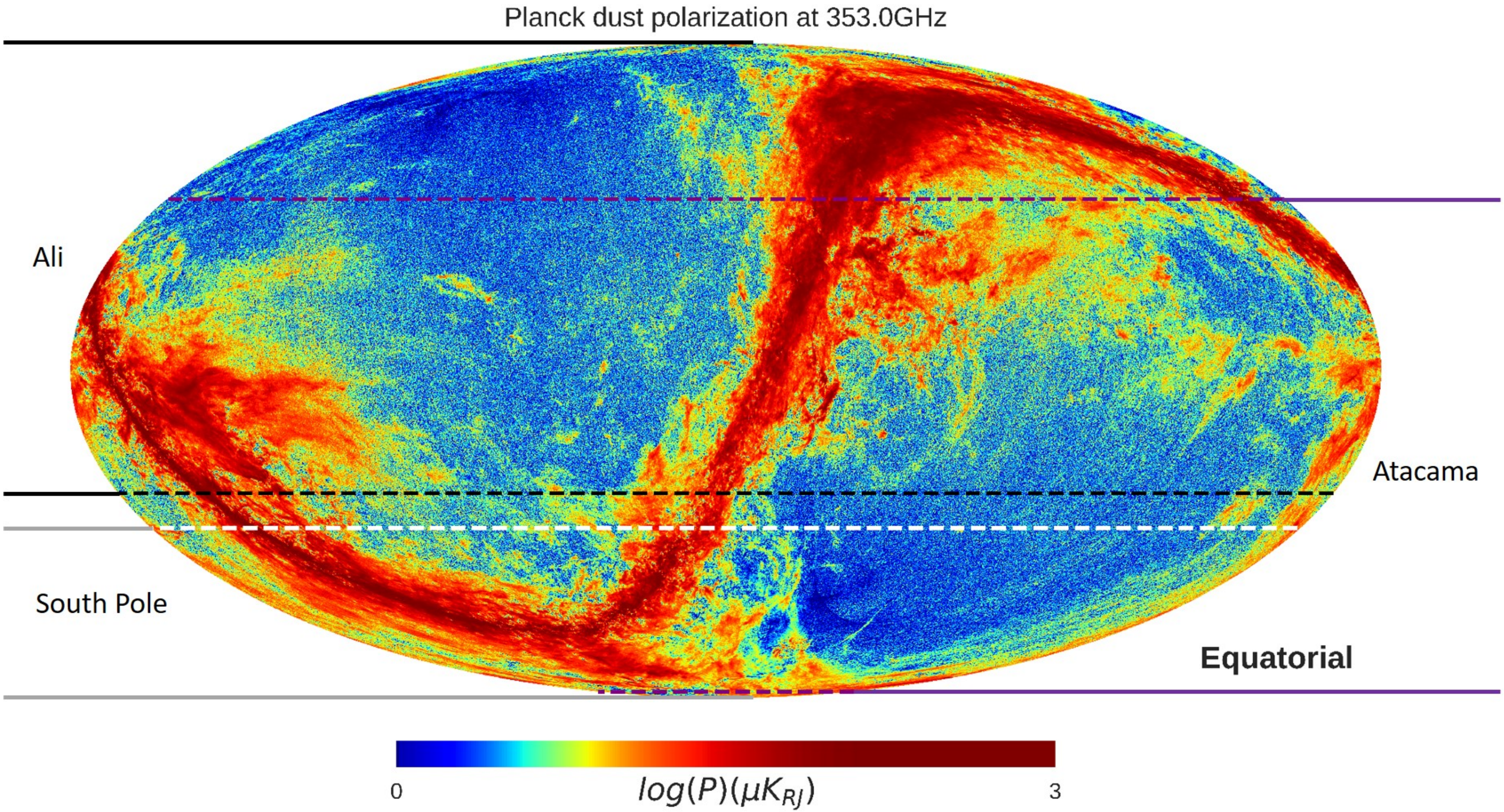

AliCPT Site
Tibetan Plateau
Himalaya Mountains

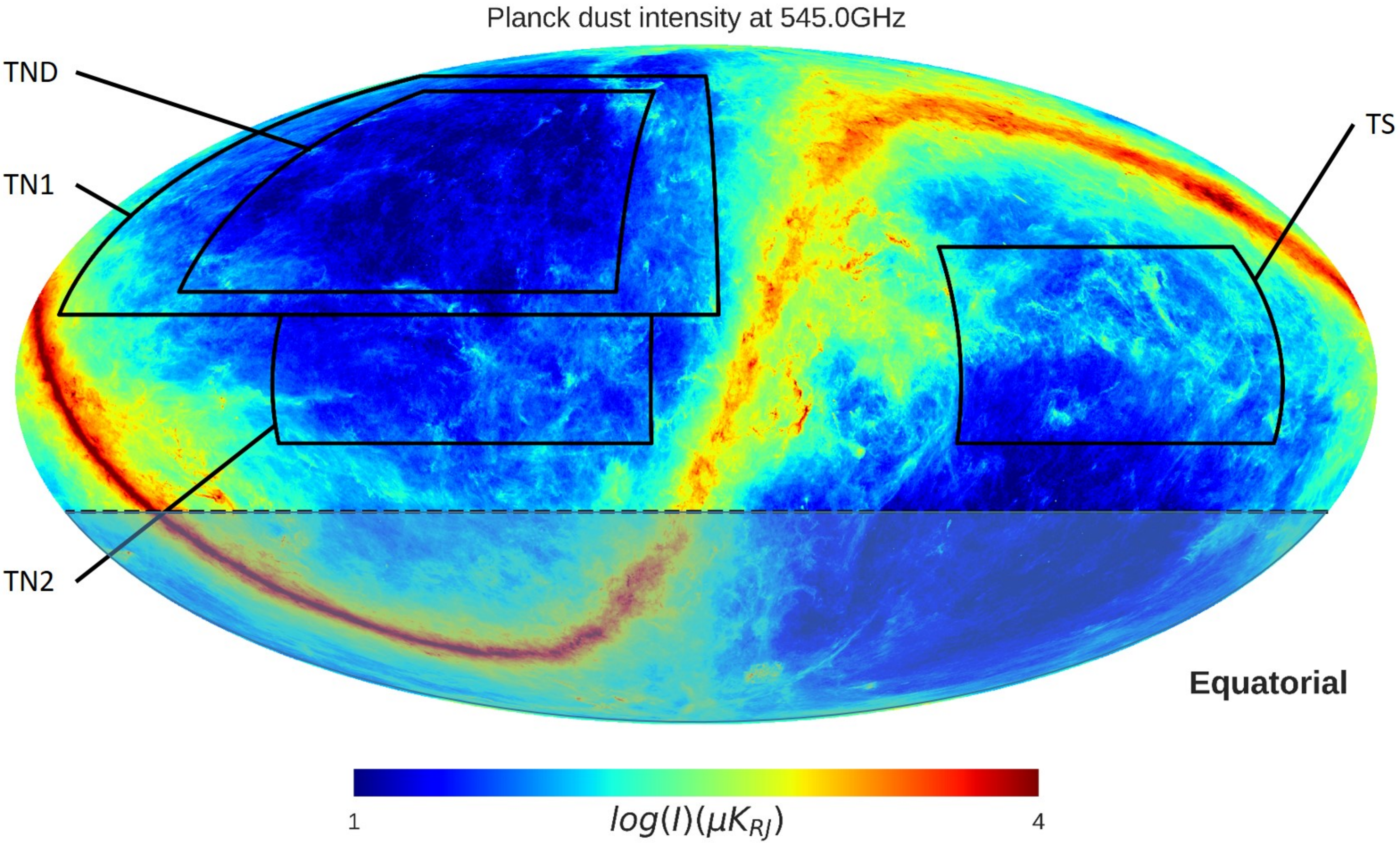
Ali CMB Program Observing Site



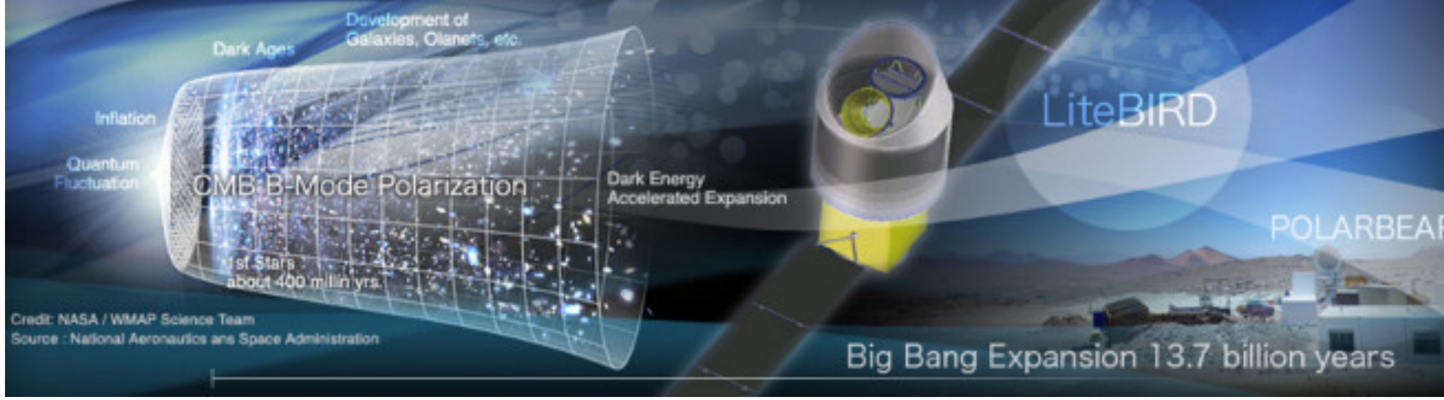
Name	Ali CPT-1	Ali CPT-2
Year	2019	2020-2022
Altitude	5250 m	6000 m
#Detectors	7,000	>20,000
Frequencies	95 & 150 GHz	95 & 150 GHz


撸起袖子 加油干

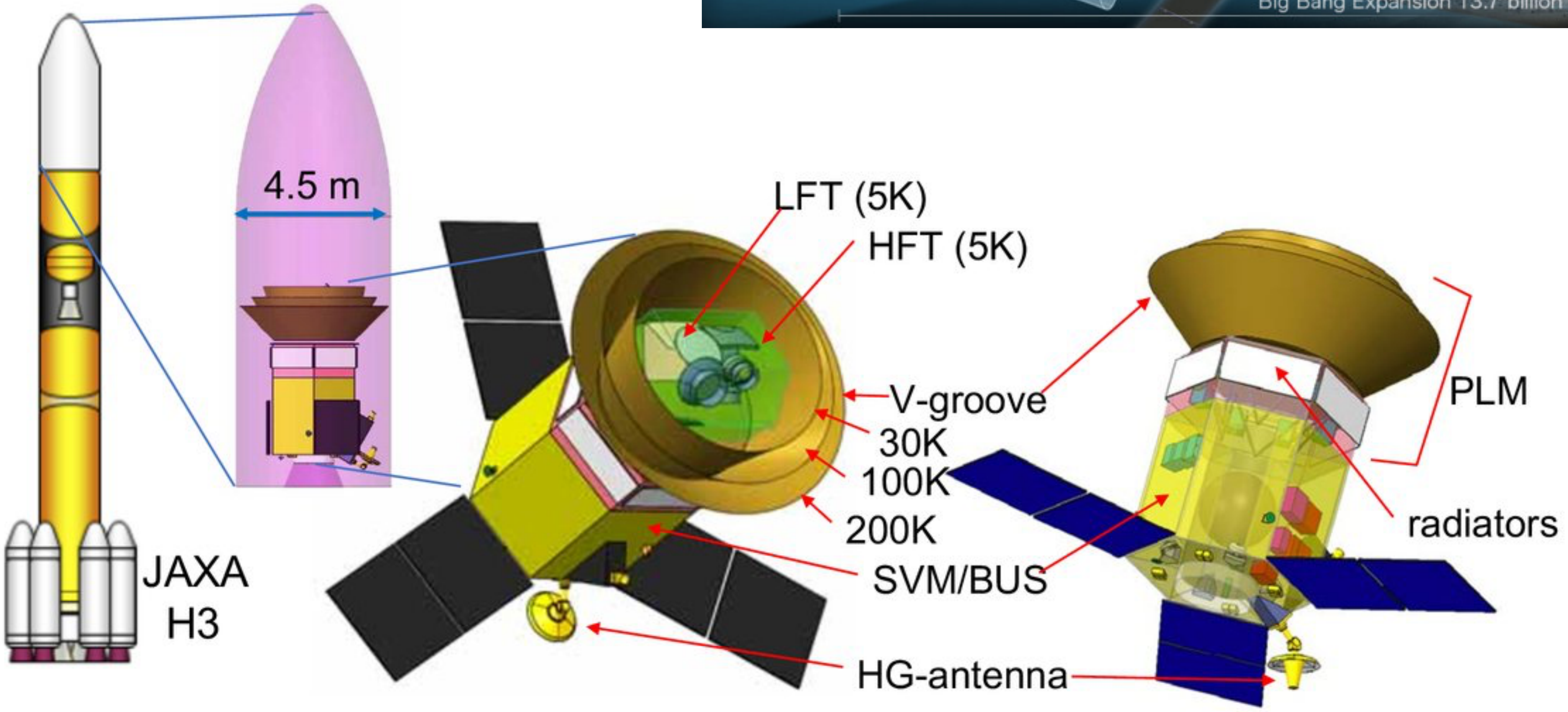

Planck dust polarization at 353.0GHz
Ali
Atacama
South Pole
Equatorial
0
$log(P)(\mu K_{RJ})$
3


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

LiteBIRD – JAXA. 2027
Clean up low-L

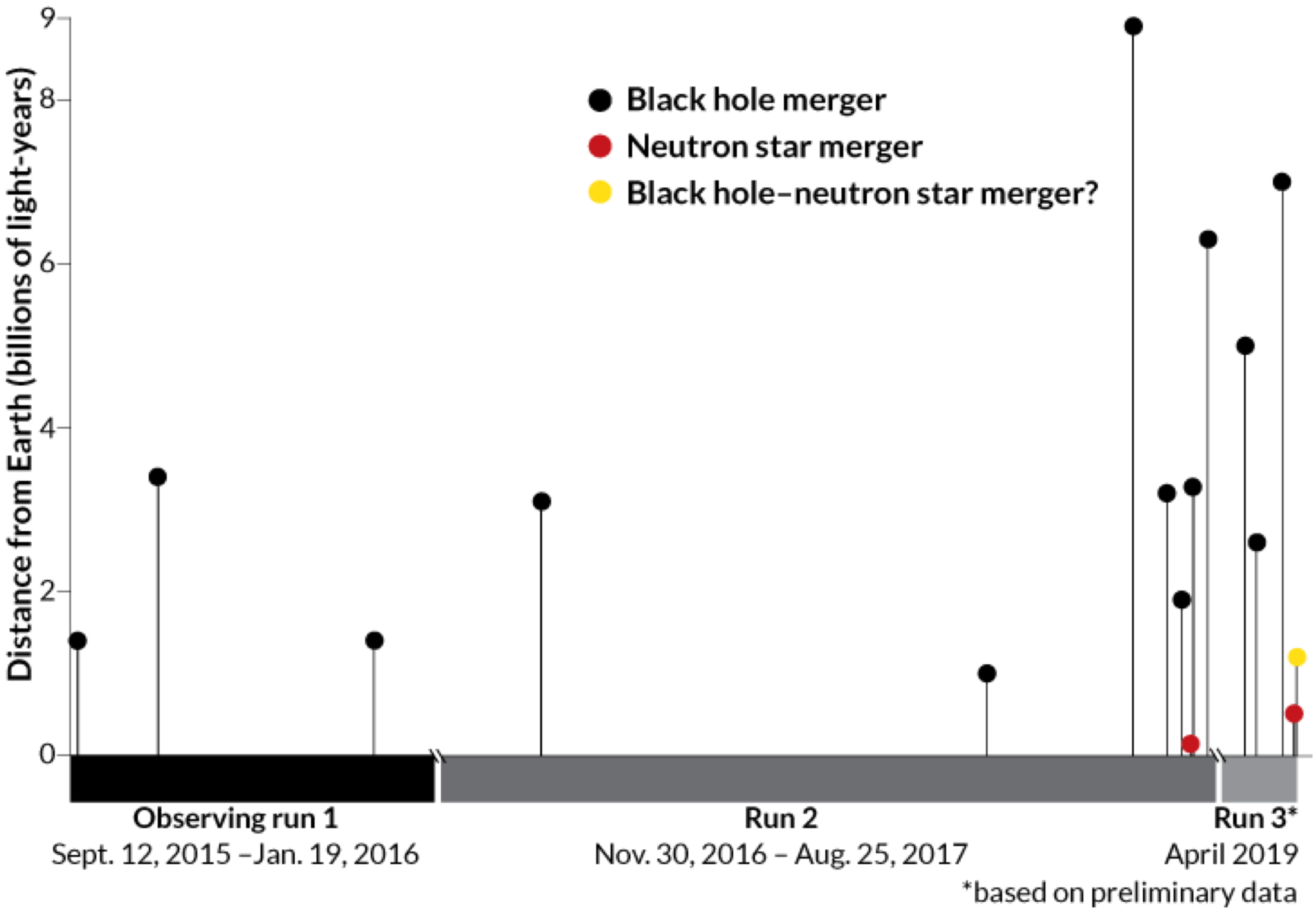


Credit: NASA / WMAP Science Team
Source : National Aeronautics ans Space Administration

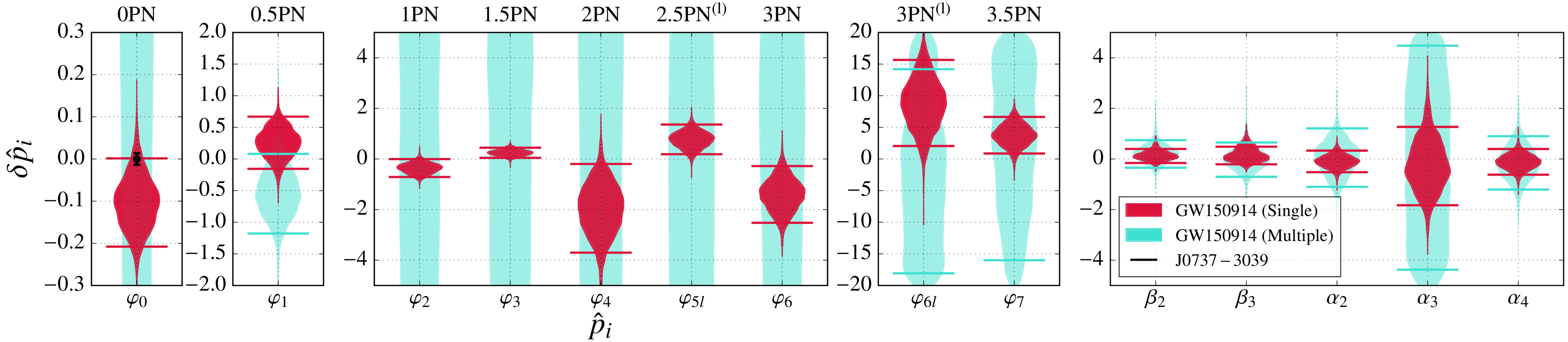


Gravitational Waves: New Kid on the Block

Observations vs. Run Number



Tests of General Relativity with GW



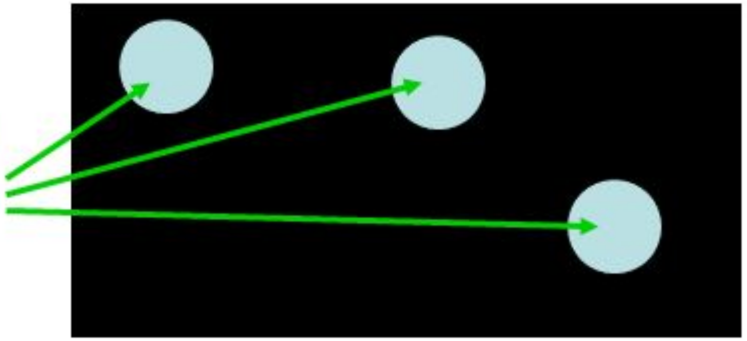
Generic metric theories of gravity predict up to six polarization modes for metric perturbations: two tensor (helicity ±2), two vector (helicity ±1), and two scalar (helicity 0) modes [76, 77]. GWs in GR, however, have only the two tensor modes regardless of the source properties; any detection of a non-tensor mode would be unambiguous indication of physics beyond GR.
Simple two tensor polarization best fit so far.

Speed of gravtitational waves is consistent with the speed of light: $\delta v/c$ <1.7 sec / 130 mLy = 4 x 10^{-10}

The Cosmological Principle

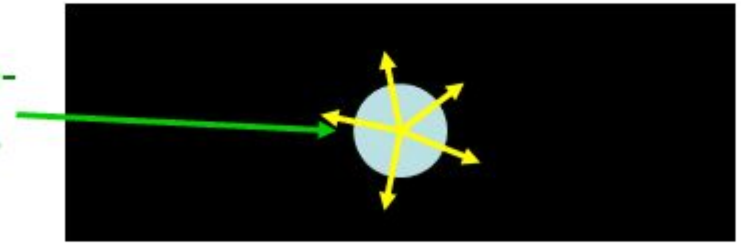
Considering the largest scales in the universe, we make the following fundamental assumptions:

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.

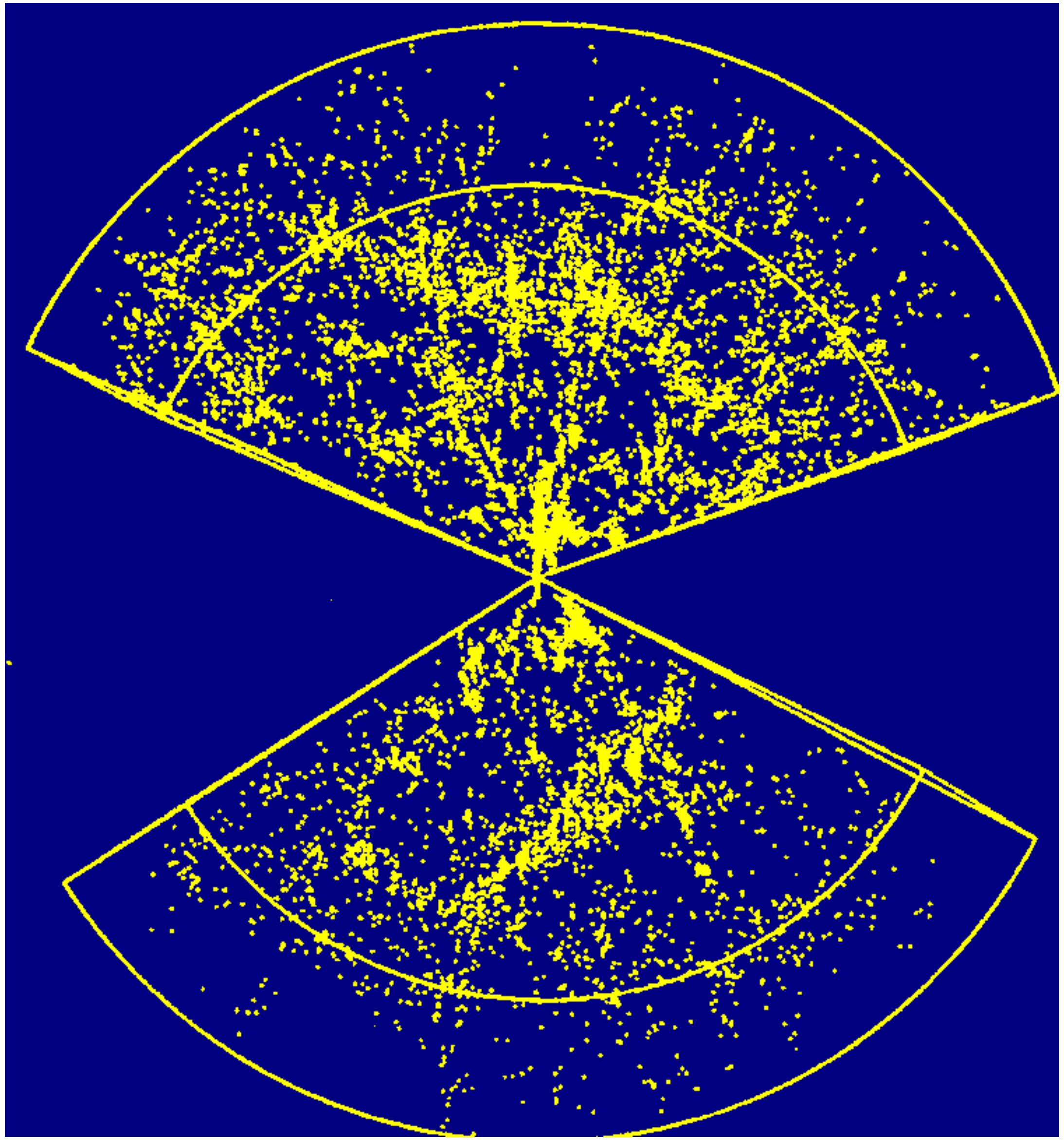


You should see the same large-scale structure in any direction.

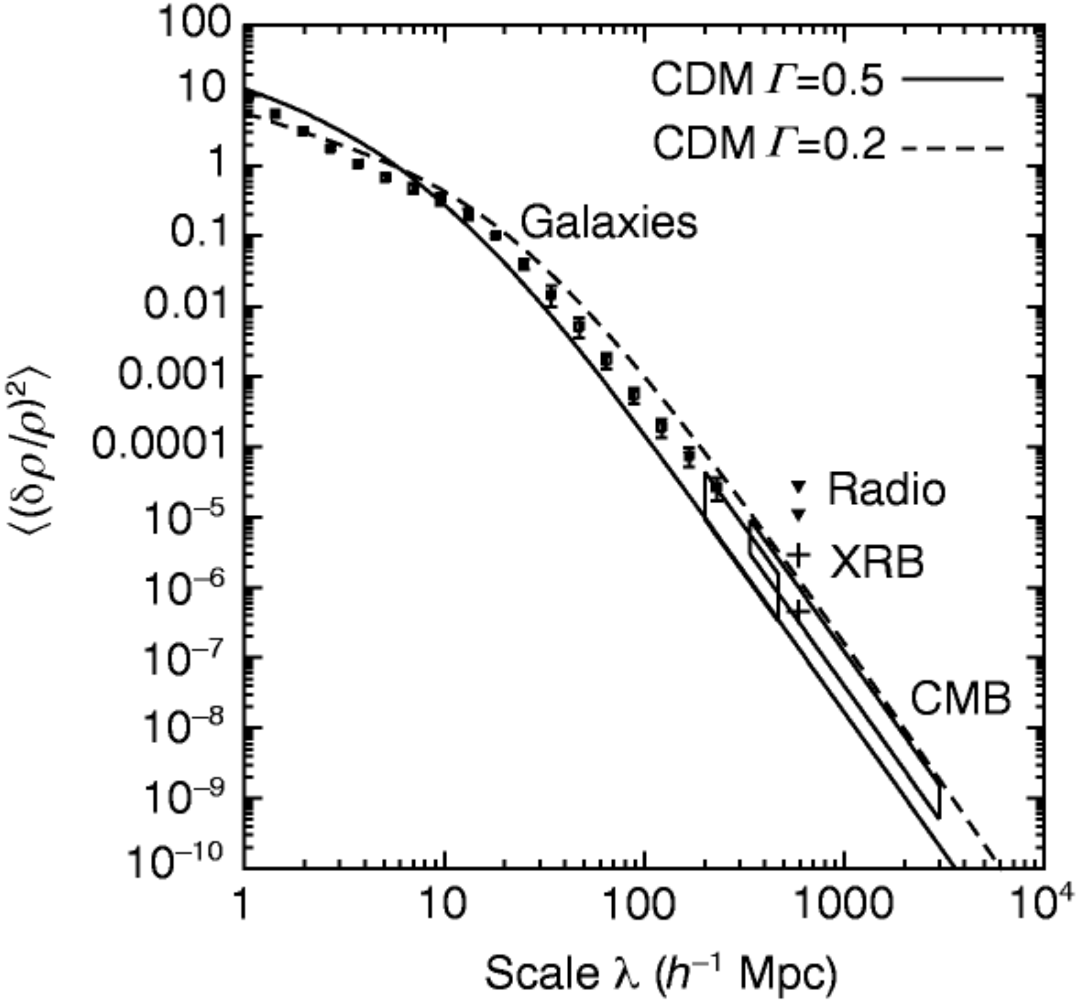
Implies Robertson-Walker Metric

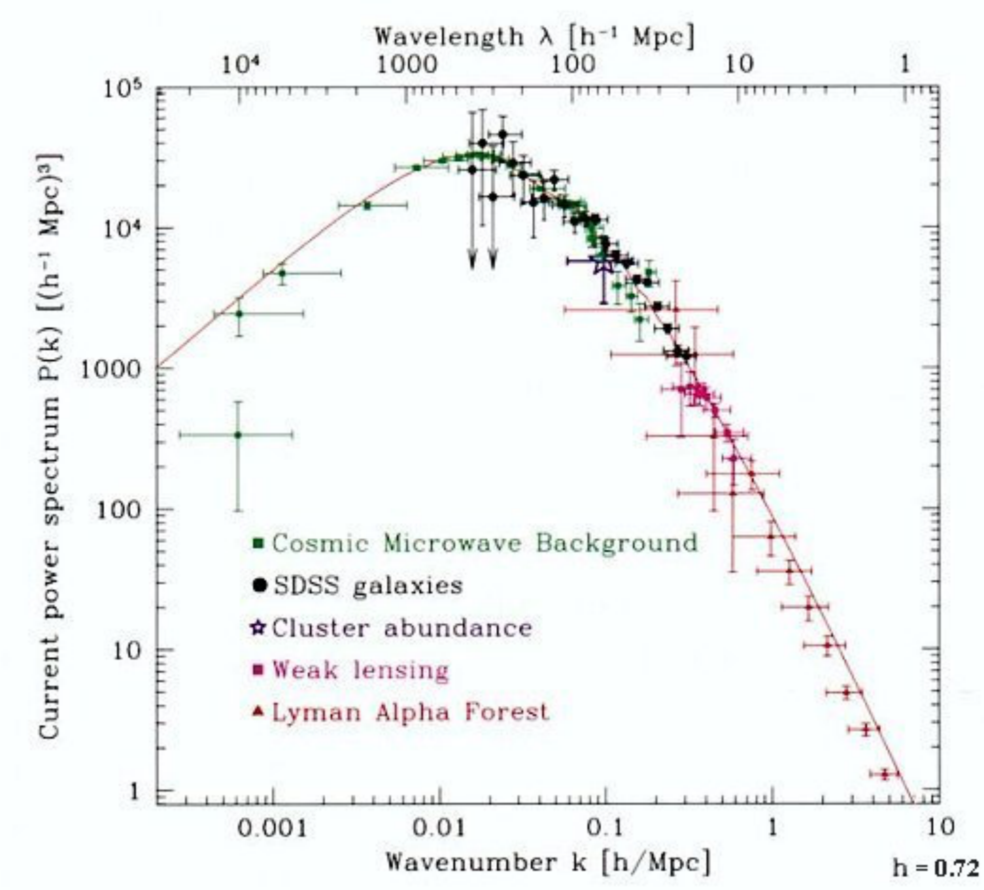
3) Universality: The laws of physics are the same everywhere in the universe.

Observed Distribution of Galaxies

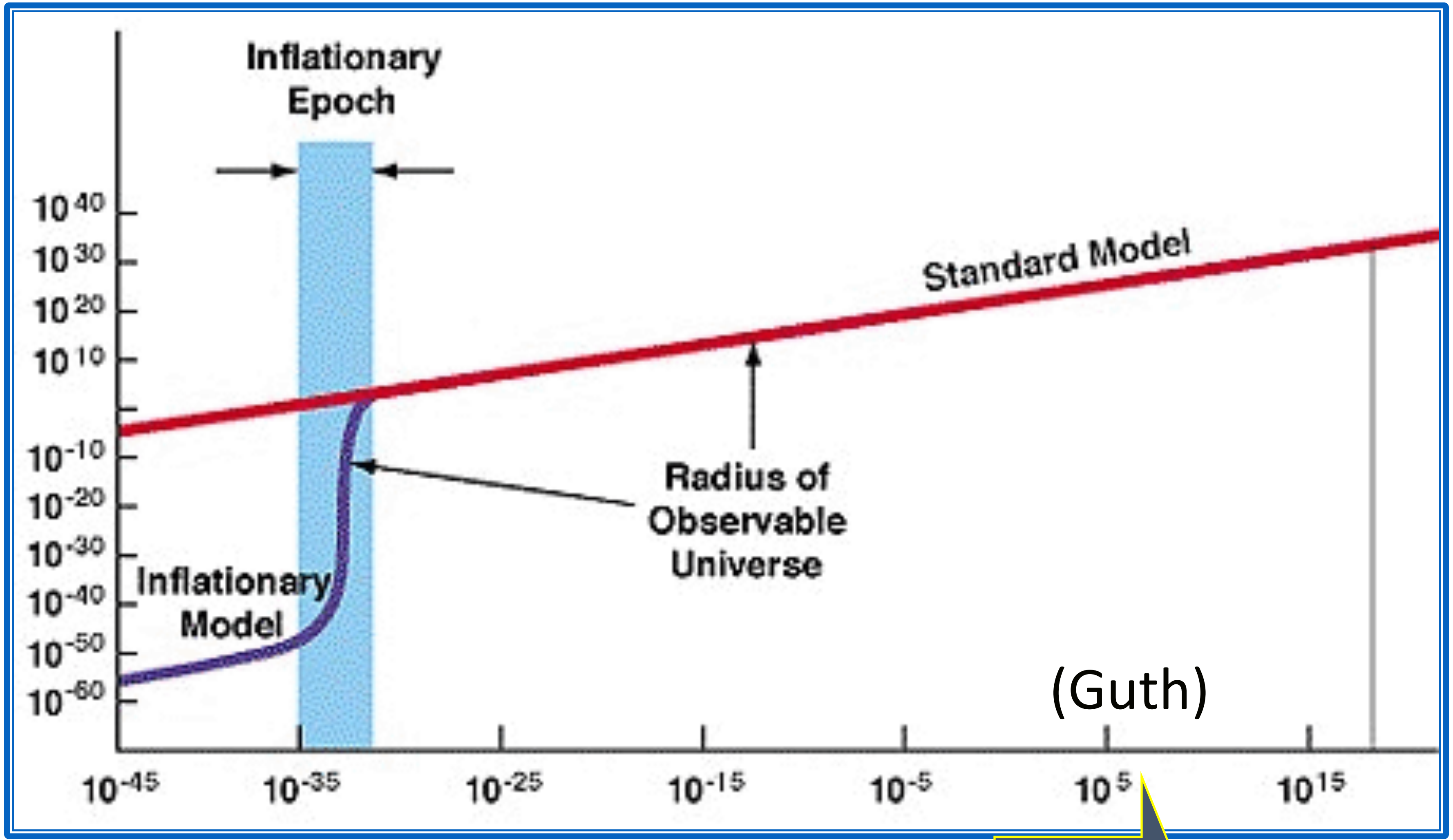


Cosmological Principle Re-Interpreted Currently





The Inflationary Universe



(Guth)

Time in seconds

Broken Symmetries

Cosmological Principles

- The Copernican Principle:

  We do not occupy a special place in the Universe
- The Cosmological Principle:

  The Universe is homogeneous and istotropic (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:

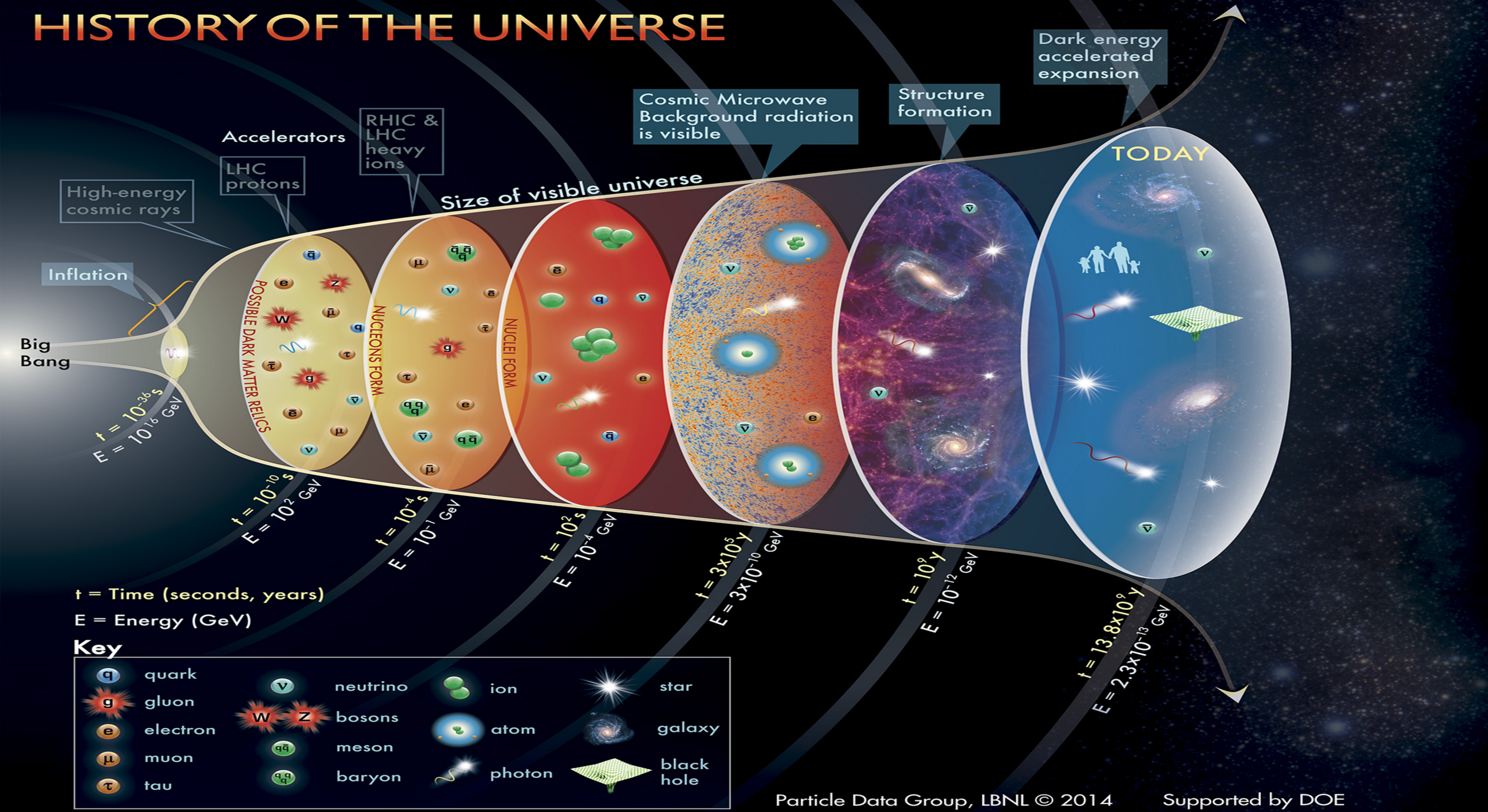
  Life can exist only in the Universe as it is.
- The Strong Anthropic Principle:

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

Observations

- Well Earth is pretty special for light years. There is no Planet B.
- The Universe is homogeneous only on very large scales and more in the past than now. Seems isotropic on large scales.
- Clearly wrong on the homogeneity of time on even largest observed scales.
- No clear observations supporting this concept.
- Not necessarily well defined statement.

HISTORY OF THE UNIVERSE



Big Bang

Inflation

High-energy cosmic rays

Accelerators

LHC protons

RHIC & LHC heavy ions

Cosmic Microwave Background radiation is visible

Structure formation

Dark energy accelerated expansion

Size of visible universe

POSSIBLE DARK MATTER RELICS

NUCLEONS FORM

NUCLEI FORM

TODAY

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 = 3×10^{5} y
E = 3×10^{-10} GeV

t = 10^{9} y
E = 10^{-12} GeV

t = 13.8×10^{9} y
E = 2.3×10^{-13} GeV

t = Time (seconds, years)

E = Energy (GeV)

Key

- q quark
- g gluon
- e electron
- μ muon
- τ tau
- ν neutrino
- W Z bosons
- $q\bar{q}$ meson
- qqq baryon
- ion
- atom
- photon
- star
- galaxy
- black hole

Supported by DOE

What comes after the Standard Model?

- The standard model (SM) of elementary particles involves particle symmetry and the mechanism of its breaking. There areno contradictions with experiments, but calls for extensions to solutions of its internal problems and in view of its evident incompleteness.

- The paradigm of the modern cosmology is based on inflationary models with baryosynthesis and dark matter/energy each involving physics beyond the standard model (BSM) of elementary particles. However, studies of the BSM physical basis of the modern cosmology inevitably reveals additional particle model dependent cosmological consequences that go beyond the modern Standard cosmological model. The mutual relationship of the BSM particle physics basis of the key future directions.

BSM physics and its cosmological reflections

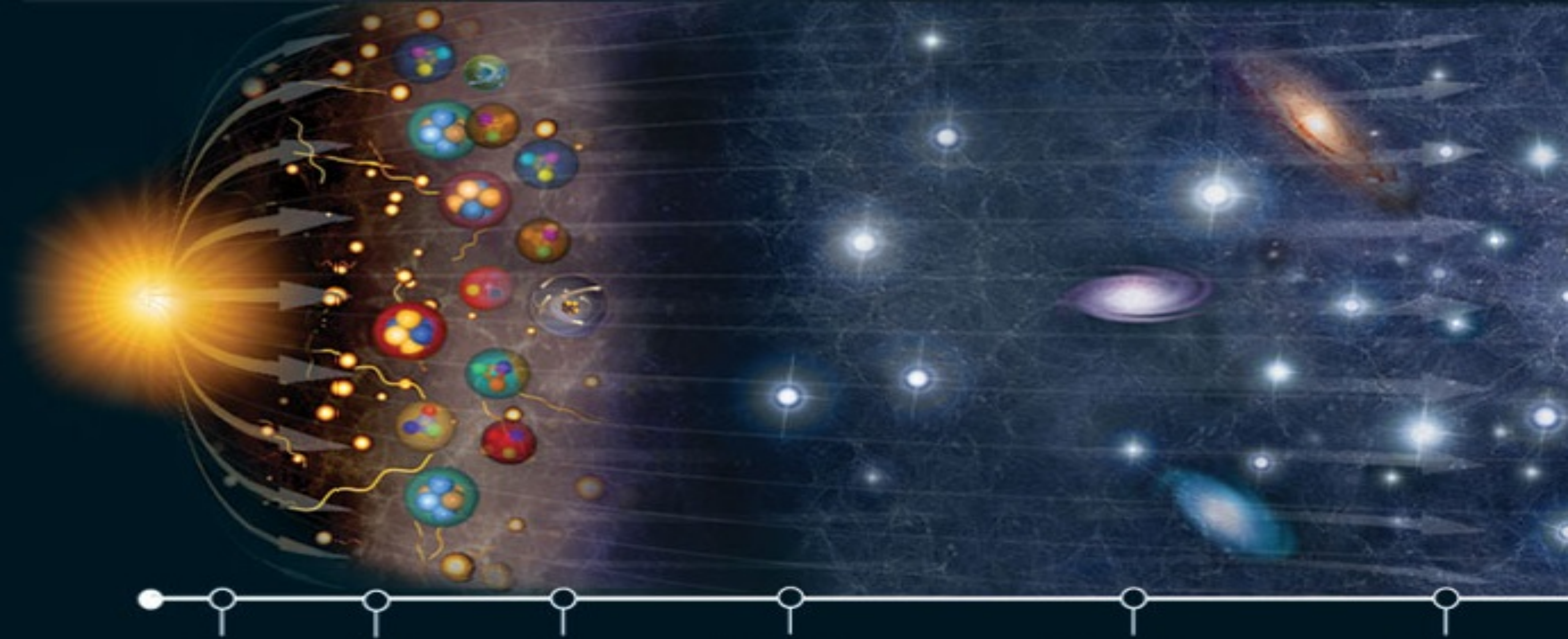
- Arguments for extension of the Standard model of particle physics
- BSM physics of the mass of neutrino
- Supersymmetry
- Composite Higgs boson
- Axion and pseudo Nambu-Goldstone models
- BSM physics of the quark-lepton families
- Mirror and Shadow Worlds
- Unification of fundamental forces
- Unification of all the four fundamental forces, including gravity

Emergent Symmetry

- A key difference between spontaneously broken symmetries and emergent symmetries is that emergent symmetries are never exact (as opposed to broken symmetries prior to breaking).
- For example, could lepton number and baryon number be only approximately conserved especially at lower energies?
- Is it possible that in the low energy ground state one has symmetries arise including Lorentz symmetry? Seems unlikely and thus it would be a fundamental property of the more basic `Lagrangian’. However there are a couple of Condensed matter examples where it does occur.
- Dynamical generation of a gauge symmetry

Theorem – S. Weinberg 1979

- The quantum field theory generated by the most general Lagrangian with some assumed symmetries will produce the most general S matrix, incorporating quantum mechanics, Lorentz invariance, unitarity, cluster decomposition, and those symmetries with no further physical content.
- it isn’t any good just to present the formalism and say that it agrees with experiment
- it is very likely that any quantum theory that at sufficiently low energy and large distances looks Lorentz invariant and satisfies the cluster decomposition principle will also at sufficiently low energy look like a quantum field theory



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

The Einstein-Hilbert action

$$\delta \int \mathcal{L} \mathrm{d}^4 x = 0$$

Variational Principle

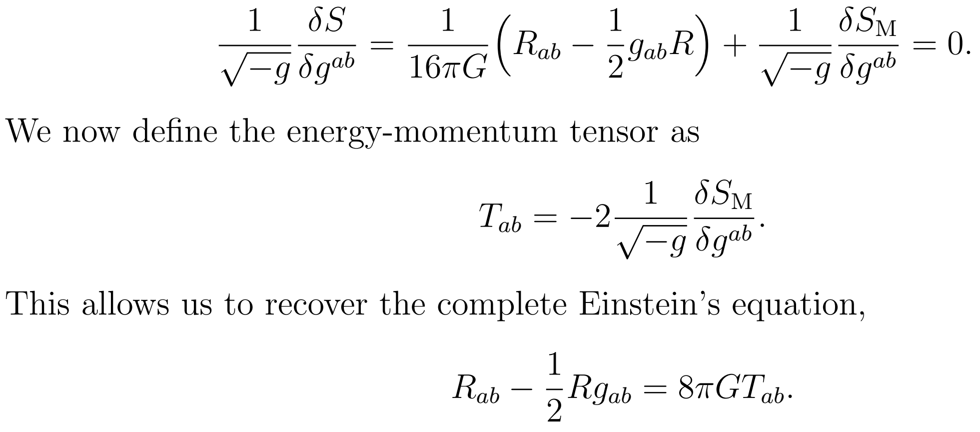
EH gravitational Lagrangian

$$\mathcal{L} = \sqrt{-g} R, \text{ therefore} \quad S_{\mathrm{EH}} = \int \sqrt{-g} R \, \mathrm{d}^4 x$$

Key is variation of the metric

Obtain the full field equations by adding the matter Lagrangian and vary the action

$$S = \frac{1}{16\pi G} S_{\mathrm{EH}} + S_{\mathrm{M}}$$



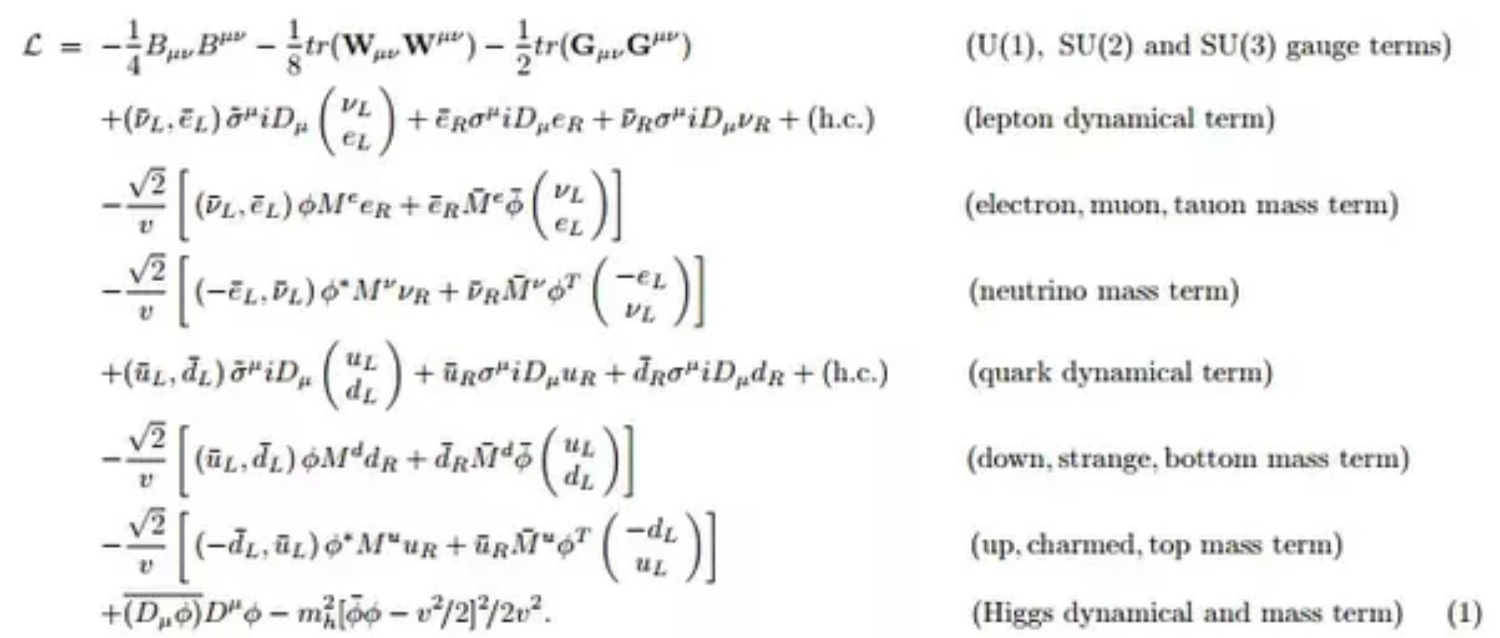
$$\frac{1}{\sqrt{-g}} \frac{\delta S}{\delta g^{ab}} = \frac{1}{16\pi G} \left(R_{ab} - \frac{1}{2} g_{ab} R \right) + \frac{1}{\sqrt{-g}} \frac{\delta S_{\mathrm{M}}}{\delta g^{ab}} = 0.$$

We now define the energy-momentum tensor as

$$T_{ab} = -2 \frac{1}{\sqrt{-g}} \frac{\delta S_{\mathrm{M}}}{\delta g^{ab}}.$$

This allows us to recover the complete Einstein's equation,

$$R_{ab} - \frac{1}{2} R g_{ab} = 8\pi G T_{ab}.$$



$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

(U(1), SU(2) and SU(3) gauge terms)

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$

(lepton dynamical term)

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R\bar{M}^e\bar{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}\right]$$

(electron, muon, tauon mass term)

$$-\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R\bar{M}^\nu\phi^T\begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}\right]$$

(neutrino mass term)

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L \\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$

(quark dynamical term)

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R\bar{M}^d\bar{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}\right]$$

(down, strange, bottom mass term)

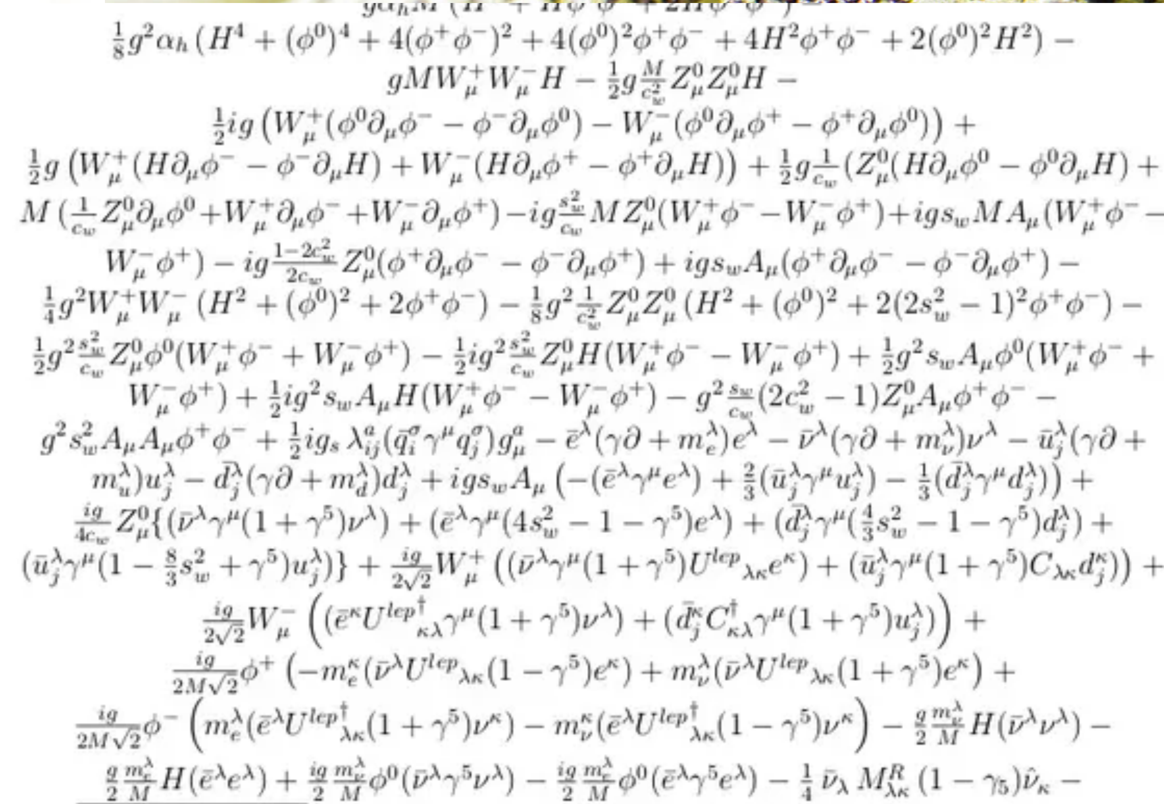
$$-\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R\bar{M}^u\phi^T\begin{pmatrix}-d_L \\ u_L\end{pmatrix}\right]$$

(up, charmed, top mass term)

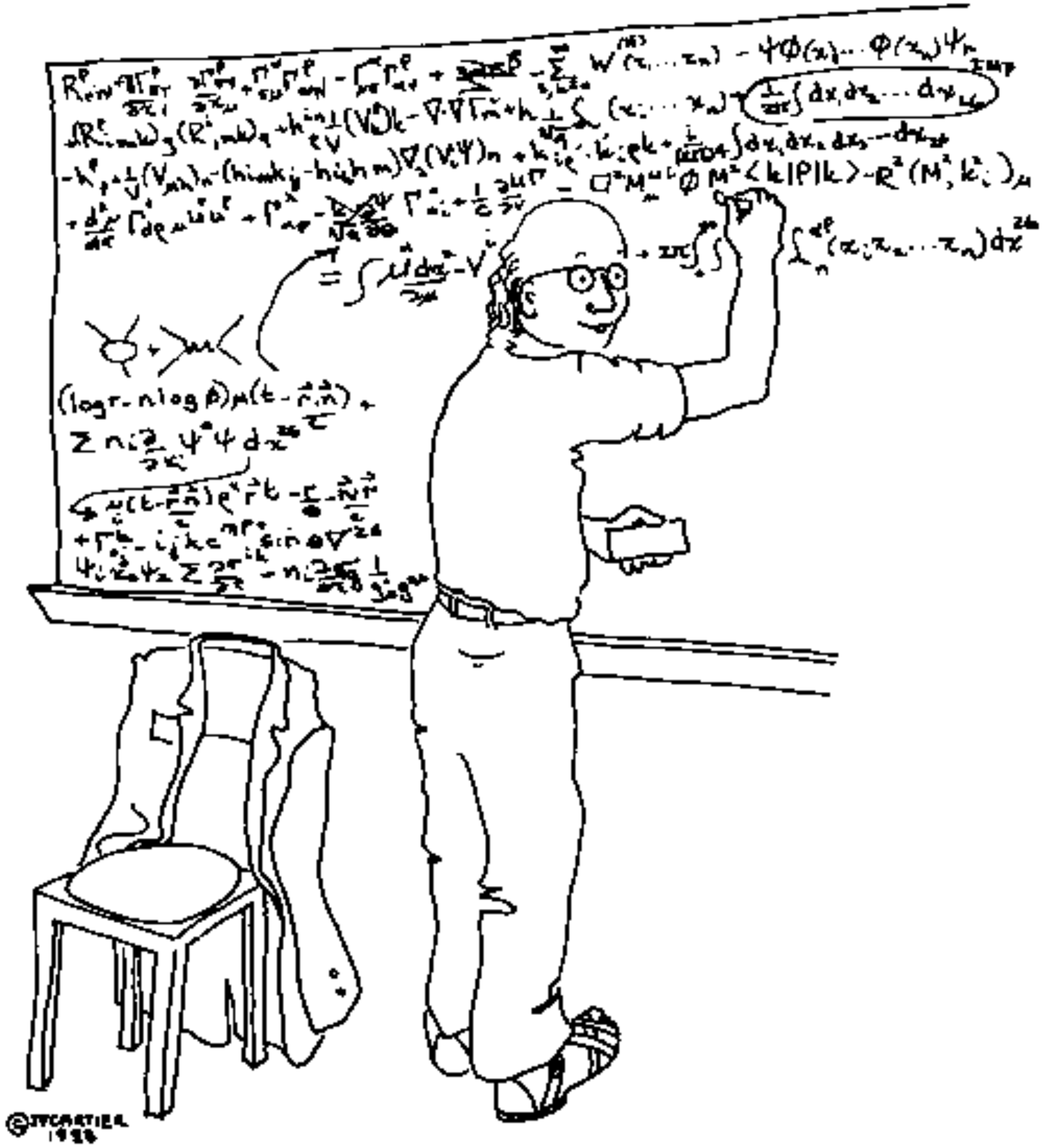
$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. \tag{1}$$

(Higgs dynamical and mass term)

Variation of matter Lagrangian components
To provide the extrememum of the action
Including space time



$$\frac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) -$$
$$gMW_\mu^+W_\mu^-H - \frac{1}{2}g\frac{M}{c_w^2}Z_\mu^0Z_\mu^0H -$$
$$\frac{1}{2}ig\left(W_\mu^+(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W_\mu^-(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$
$$\frac{1}{2}g\left(W_\mu^+(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W_\mu^-(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac{1}{2}g\frac{1}{c_w}(Z_\mu^0(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) +$$
$$M\,(\frac{1}{c_w}Z_\mu^0\partial_\mu\phi^0 + W_\mu^+\partial_\mu\phi^- + W_\mu^-\partial_\mu\phi^+) - ig\frac{s_w^2}{c_w}MZ_\mu^0(W_\mu^+\phi^- - W_\mu^-\phi^+) + igs_wMA_\mu(W_\mu^+\phi^- -$$
$$W_\mu^-\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z_\mu^0(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\frac{1}{4}g^2W_\mu^+W_\mu^-\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \frac{1}{8}g^2\frac{1}{c_w^2}Z_\mu^0Z_\mu^0\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) -$$
$$\frac{1}{2}g^2\frac{s_w^2}{c_w}Z_\mu^0\phi^0(W_\mu^+\phi^- + W_\mu^-\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z_\mu^0H(W_\mu^+\phi^- - W_\mu^-\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W_\mu^+\phi^- +$$
$$W_\mu^-\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W_\mu^+\phi^- - W_\mu^-\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z_\mu^0A_\mu\phi^+\phi^- -$$
$$g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \frac{1}{2}ig_s\,\lambda_{ij}^a(\bar{q}_i^\sigma\gamma^\mu q_j^\sigma)g_\mu^a - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m_\nu^\lambda)\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial +$$
$$m_u^\lambda)u_j^\lambda - \bar{d}_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)\right) +$$
$$\frac{ig}{4c_w}Z_\mu^0\{(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}_j^\lambda\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)d_j^\lambda) +$$
$$(\bar{u}_j^\lambda\gamma^\mu(1 - \frac{8}{3}s_w^2 + \gamma^5)u_j^\lambda)\} + \frac{ig}{2\sqrt{2}}W_\mu^+\left((\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}_j^\lambda\gamma^\mu(1 + \gamma^5)C_{\lambda\kappa}d_j^\kappa)\right) +$$
$$\frac{ig}{2\sqrt{2}}W_\mu^-\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger\gamma^\mu(1 + \gamma^5)u_j^\lambda)\right) +$$
$$\frac{ig}{2M\sqrt{2}}\phi^+\left(-m_e^\kappa(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1 - \gamma^5)e^\kappa) + m_\nu^\lambda(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1 + \gamma^5)e^\kappa\right) +$$
$$\frac{ig}{2M\sqrt{2}}\phi^-\left(m_e^\lambda(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1 + \gamma^5)\nu^\kappa) - m_\nu^\kappa(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1 - \gamma^5)\nu^\kappa\right) - \frac{g}{2}\frac{m_\nu^\lambda}{M}H(\bar{\nu}^\lambda\nu^\lambda) -$$
$$\frac{g}{2}\frac{m_e^\lambda}{M}H(\bar{e}^\lambda e^\lambda) + \frac{ig}{2}\frac{m_\nu^\lambda}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m_e^\lambda}{M}\phi^0(\bar{e}^\lambda\gamma^5e^\lambda) - \frac{1}{4}\bar{\nu}_\lambda\,M_{\lambda\kappa}^R\,(1 - \gamma_5)\hat{\nu}_\kappa -$$



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

In a modern understanding of particle physics,
global symmetries are approximate and
gauge symmetries may be emergent. - Ed Witten 2017

If we want to generate gravity as an emergent phenomenon, we must go farther and generate spacetime itself as an emergent phenomenon.

Conclusion

- Interesting observations coming in Cosmology
- Possible there will be no great surprises only improved constraints and confirmations of the Standard Model of Cosmology
- Cosmology motivates a lot of HEP program

- Possible BSM could have big surprises
- Also possible emergent spacetime and symmetries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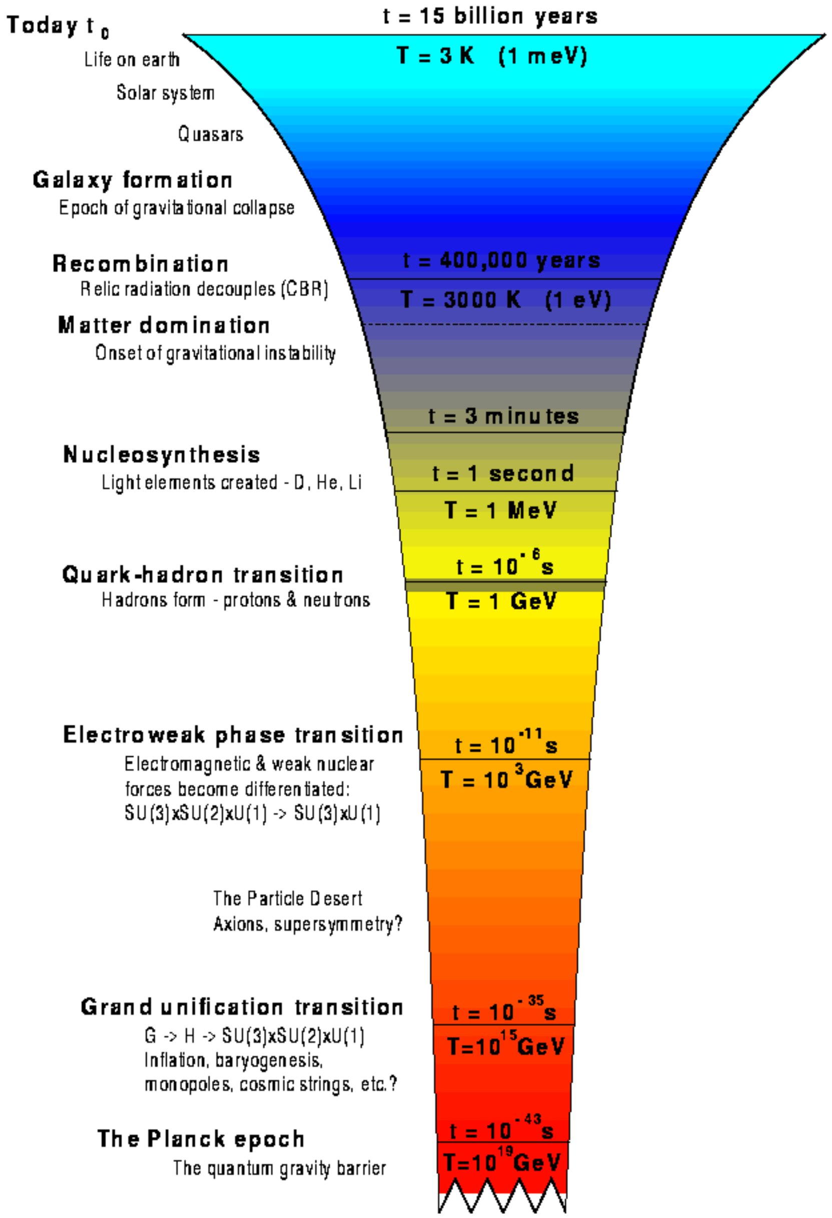

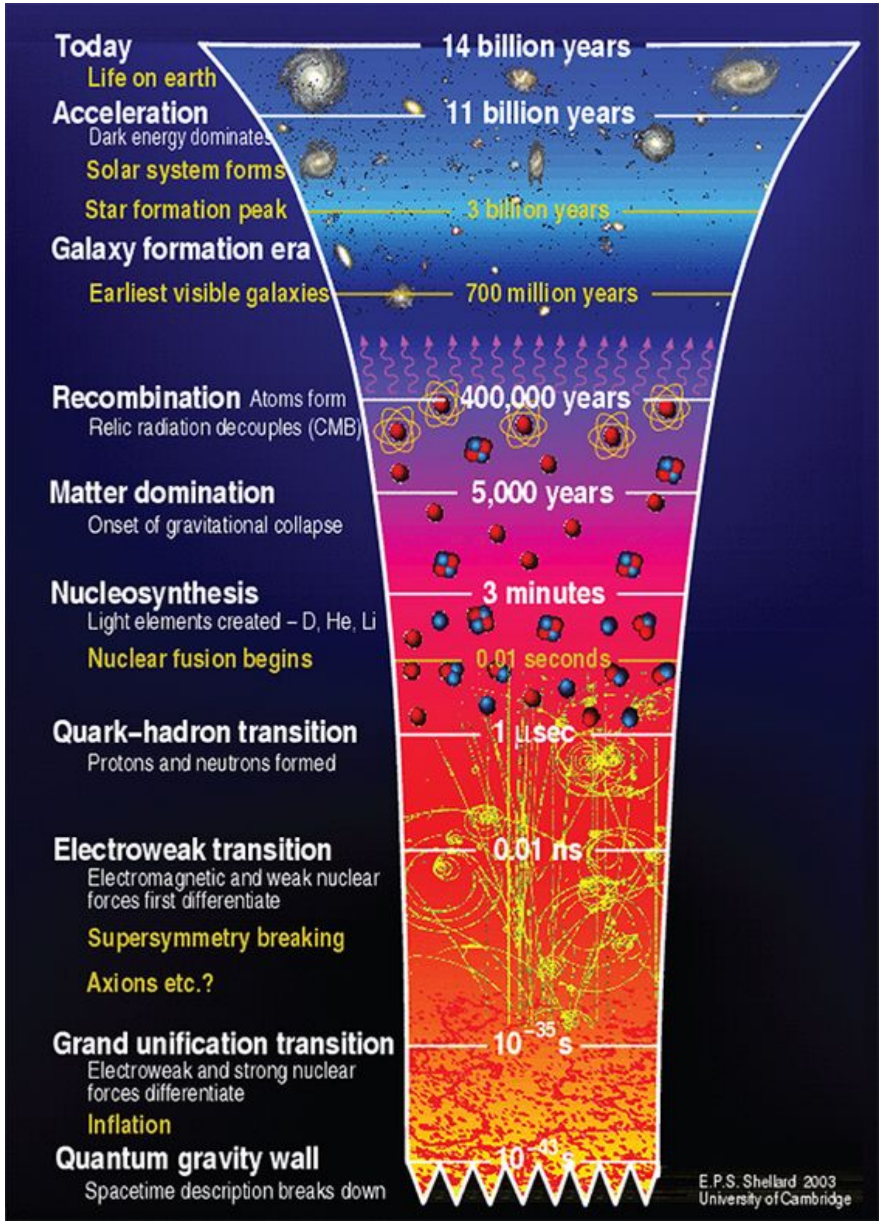

Examples of more epochs
Or major transitions

One can imagine this
Going on into the future
To energy scale 10^{-22} eV

However now we see
Issues at 10^{19} GeV (10^{28} eV
And at 10^{-22} eV but
Perhaps lower much later.

We can make it so that
Every time is within
A decade of an important
Universe epoch.
Seems arbitrary but is
Predictive