TOKYO METROPOLITAN UNIVERSITY
東京都立大学

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Unravelling the Darkness of the Universe

by Sergey V. Ketov

21 March 2024 Lunds Universitet, Sweden

WHO I AM

- born in Tomsk 1960, Western Siberia
- graduated from Tomsk State University 1982
- PhD(Moscow)1986,Dr.Sc.(Novosibirsk)1990
- University of Maryland, USA, 1990-1992
- Hannover University, Germany, 1992-2002
- Tokyo Metropolitan University, Japan, 2002~

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ケトフのhttps://hep-th.fpark.tmu.ac.jp/~ketov/ketov.htm

High-energy theoretical physics is fun!でも簡単ではないです。
頑張って下さい。

Cosmology

The Nobel Prize in Physics 2006 was awarded to John C. Mather and George F. Smoot "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation."

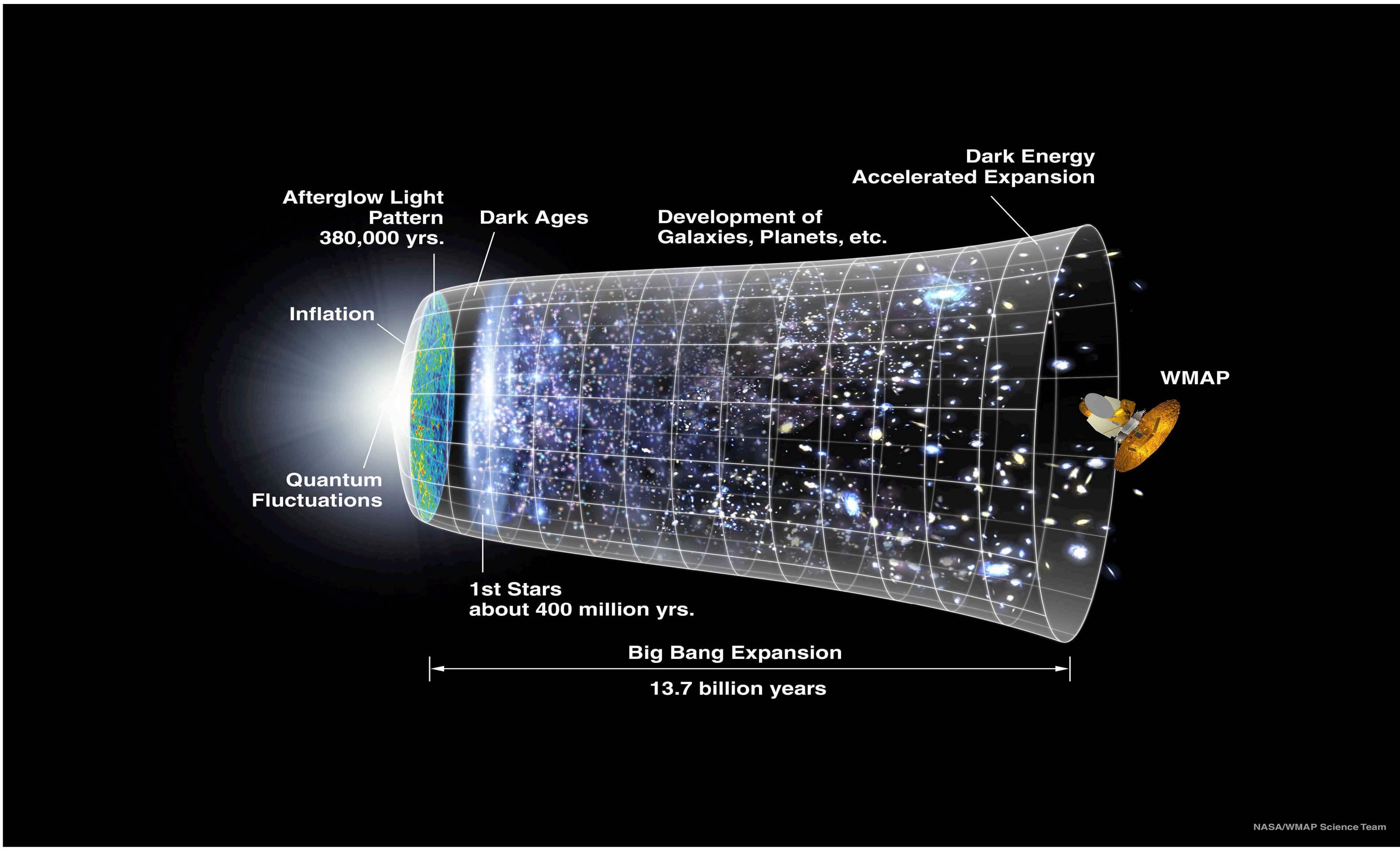
The Nobel Prize 2011 was awarded to Saul Perlmutter, Brian P. Schmid and Adam G. Riess “for the discovery of the accelerating expansion of the Universe through observations of distant supernovae”.

The Nobel Prize in Physics 2017 was awarded to Rainer Weiss, Barry C. Barish and Kip S. Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves."

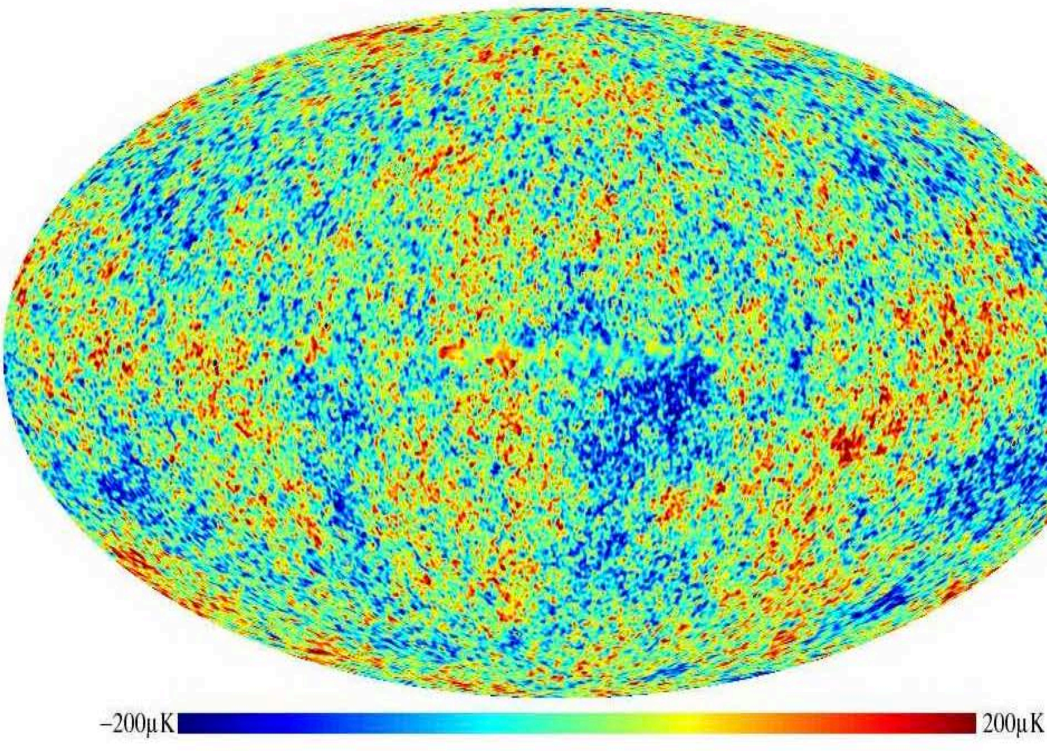
The Nobel Prize in Physics 2019 was awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos" to James Peebles "for theoretical discoveries in physical cosmology", Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."

The Nobel Prize in Physics 2020 was awarded to Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity", Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy."

The brief history of the Universe on a single slide



CMB radiation (Mona Lisa of Cosmology)



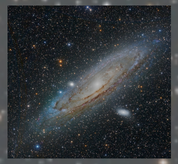
Sun

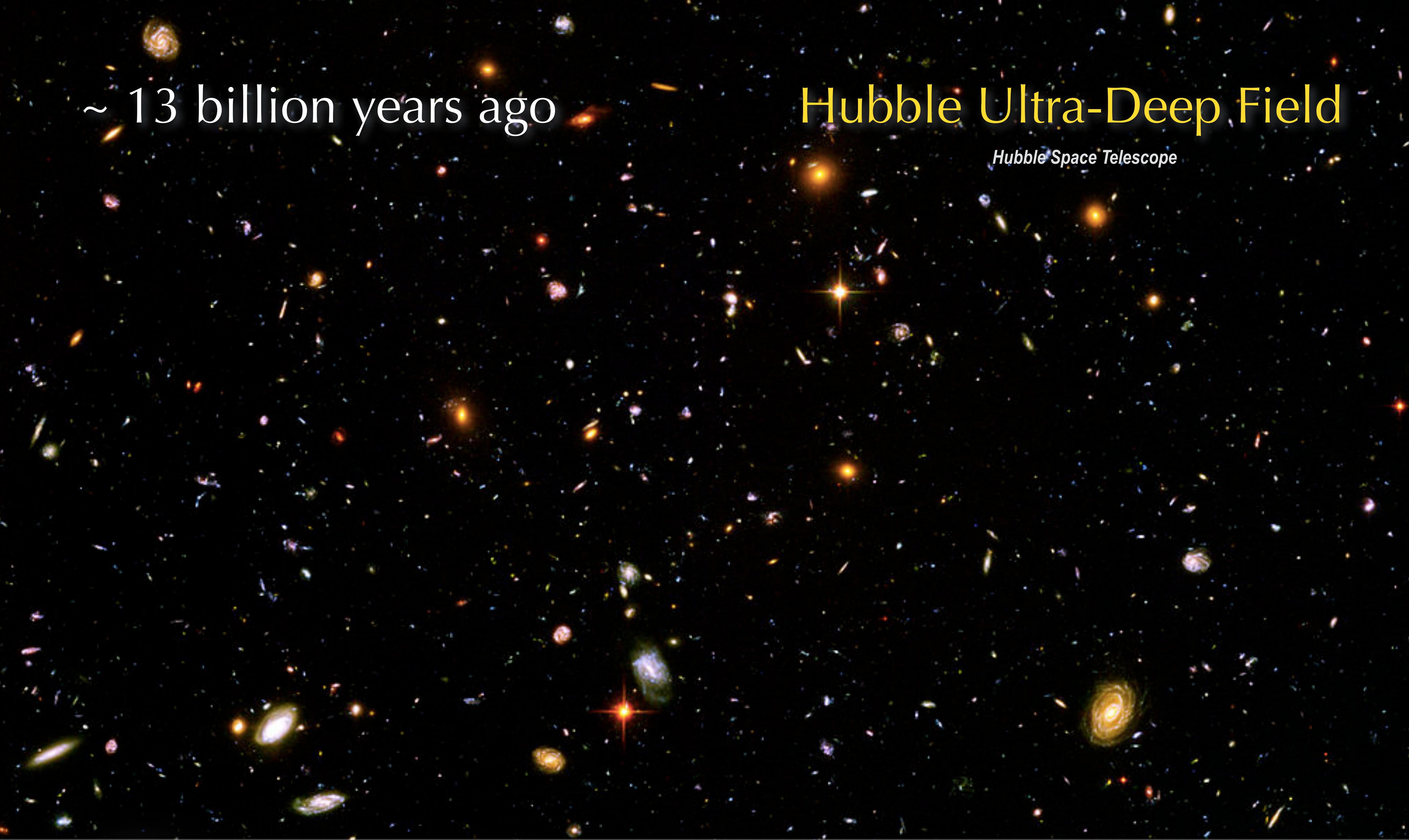
~ 8 min ago

Sun

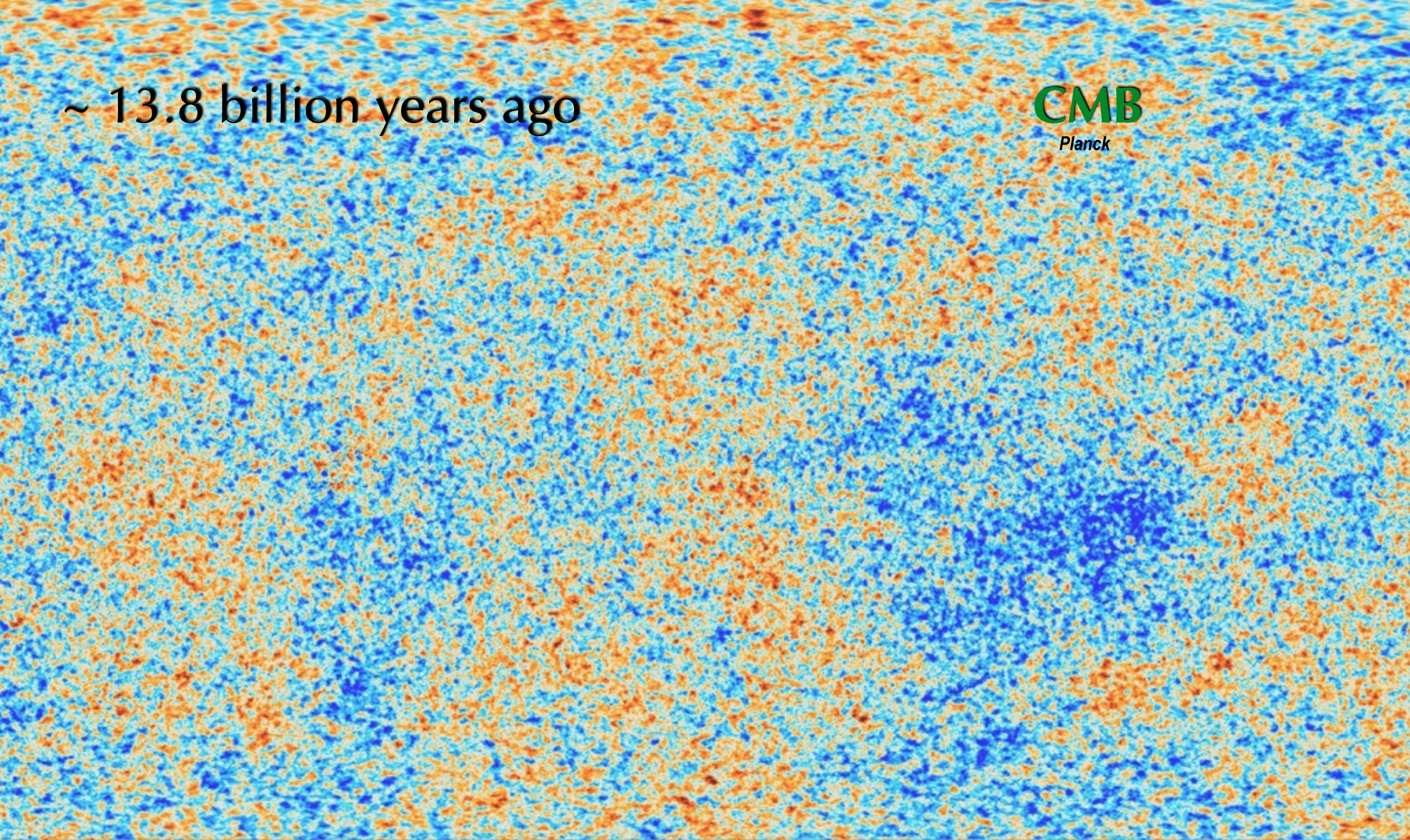

~ 4 years ago
Alpha Centauri
Digitized Sky Survey

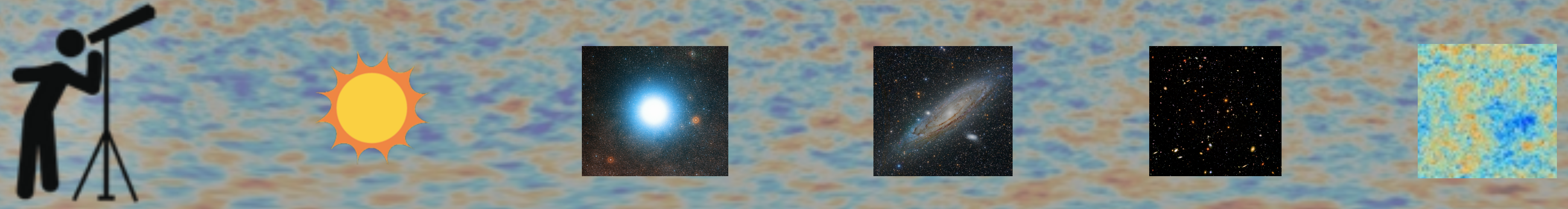

~ 2.537.000 years ago
Andromeda Galaxy
M31 - Gianni Benintende (Sicily - Italy)




~ 13 billion years ago
Hubble Ultra-Deep Field
Hubble Space Telescope

James Webb telescope first deep field (~ 13.3 billion years back)


~ 13.8 billion years ago
CMB
Planck



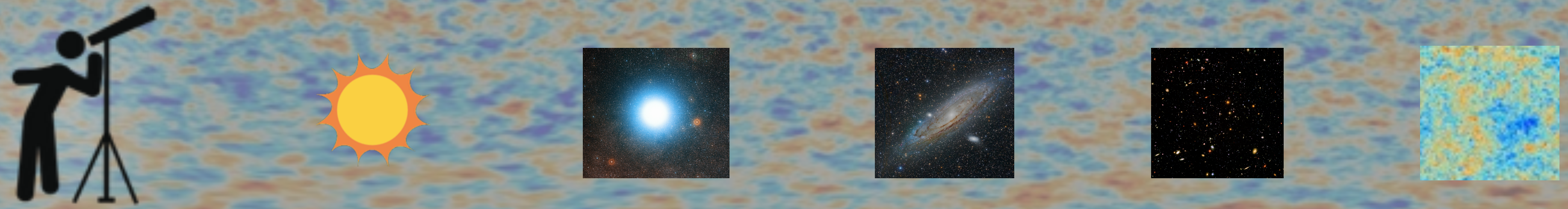
~ 13.8 billion years ago

CMB
Planck

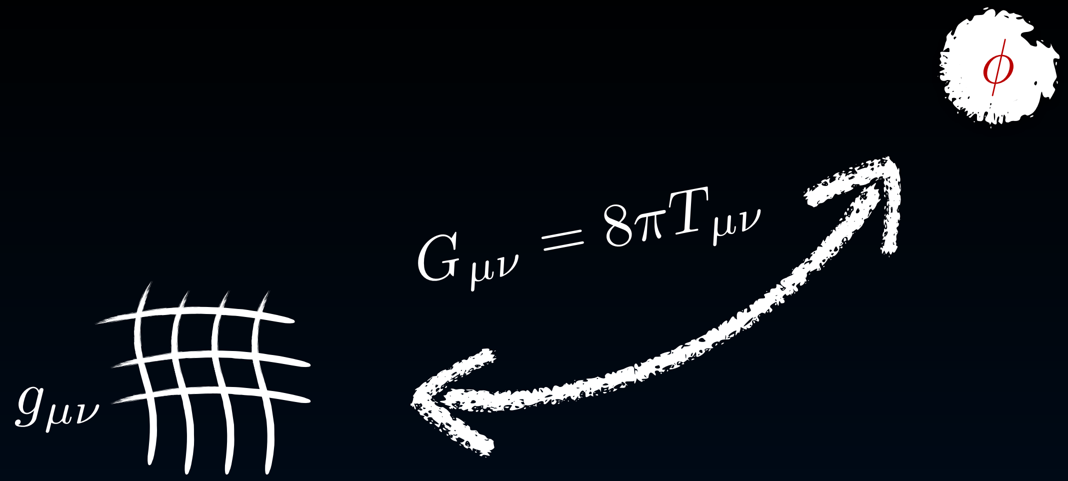
homogeneous

$T = 2.7 \pm 0.0006\ K$

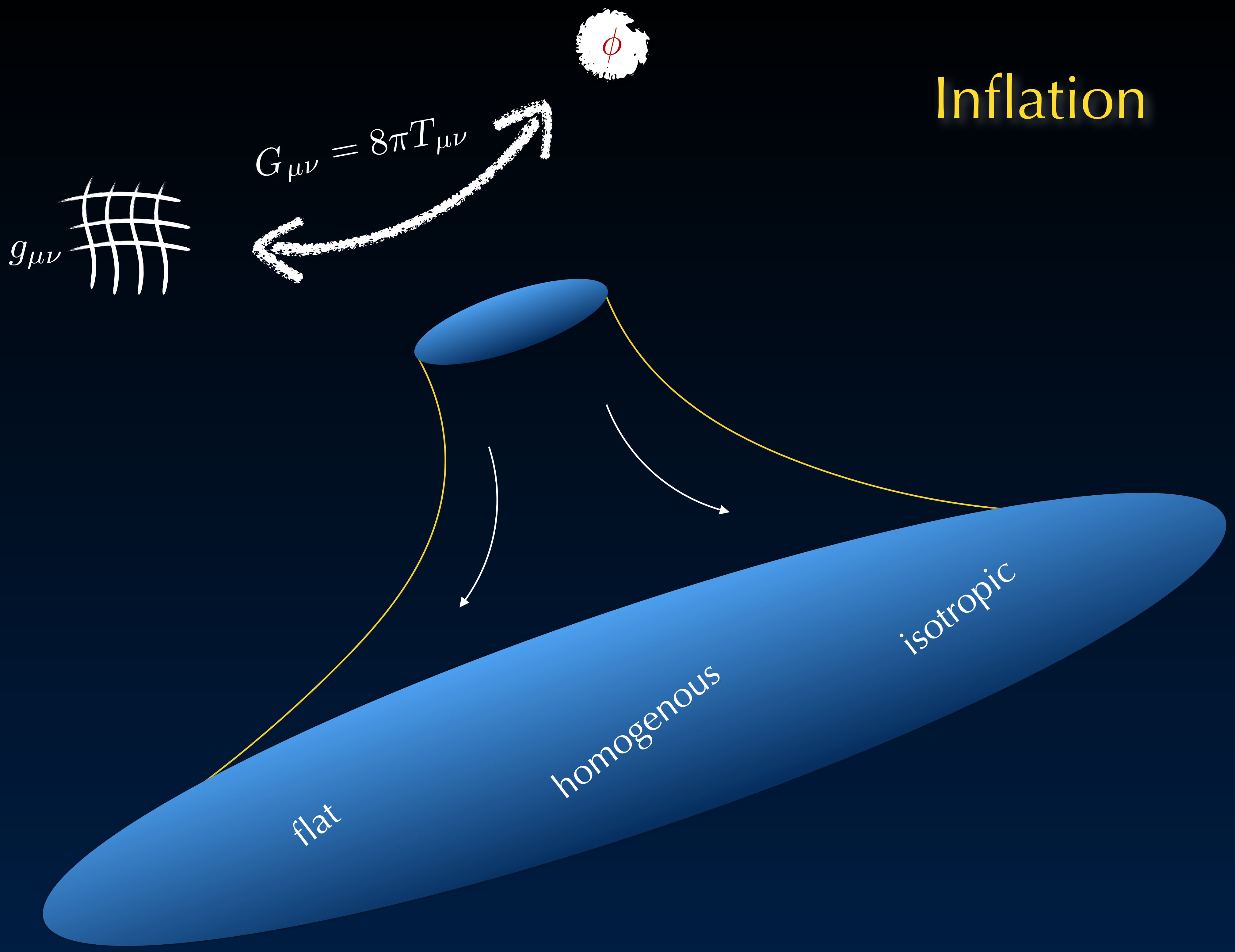
isotropic

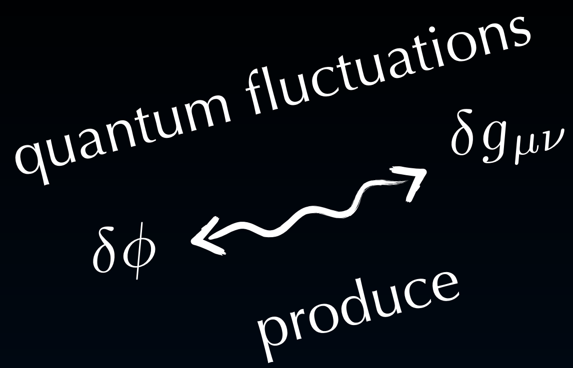


Inflation



Inflation



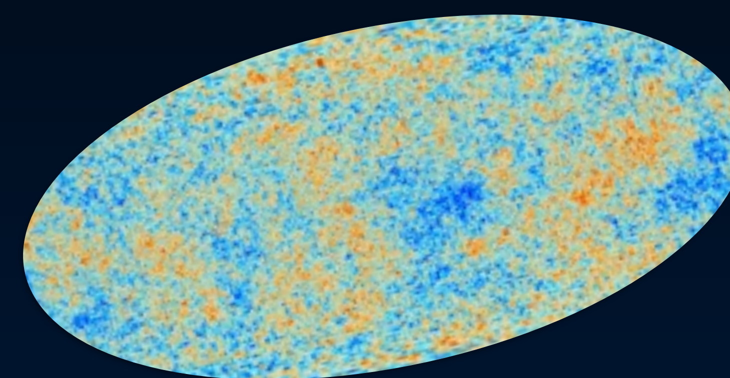

quantum fluctuations
$\delta g_{\mu\nu}$
$\delta\phi$
produce

quantum fluctuations

$\delta\phi \leftrightarrow \delta g_{\mu\nu}$

produce

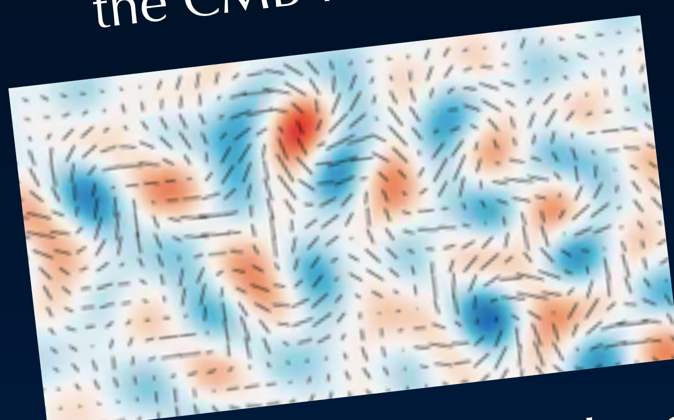
SCALAR
PERTURBATIONS
observable as temperature fluctuation in the CMB spectrum



whose **scale-dependence** is quantified by

$$n_s - 1 = \frac{d\ln\Delta_s^2}{d\ln k}$$

TENSOR
PERTURBATIONS
observable in the polarization of the CMB radiation



and usually quantified by the **ratio of the amplitude of tensor and scalar perturbations**

$$r = \frac{A_t}{A_s}$$

key predictions of inflation

$$r \neq 0$$

primordial
gravitational waves

$$n_s - 1 \approx 0$$

small deviation
from perfect
scale invariance

key predictions of inflation

$r \neq 0$

primordial
gravitational waves

$n_s - 1 \approx 0$

small deviation
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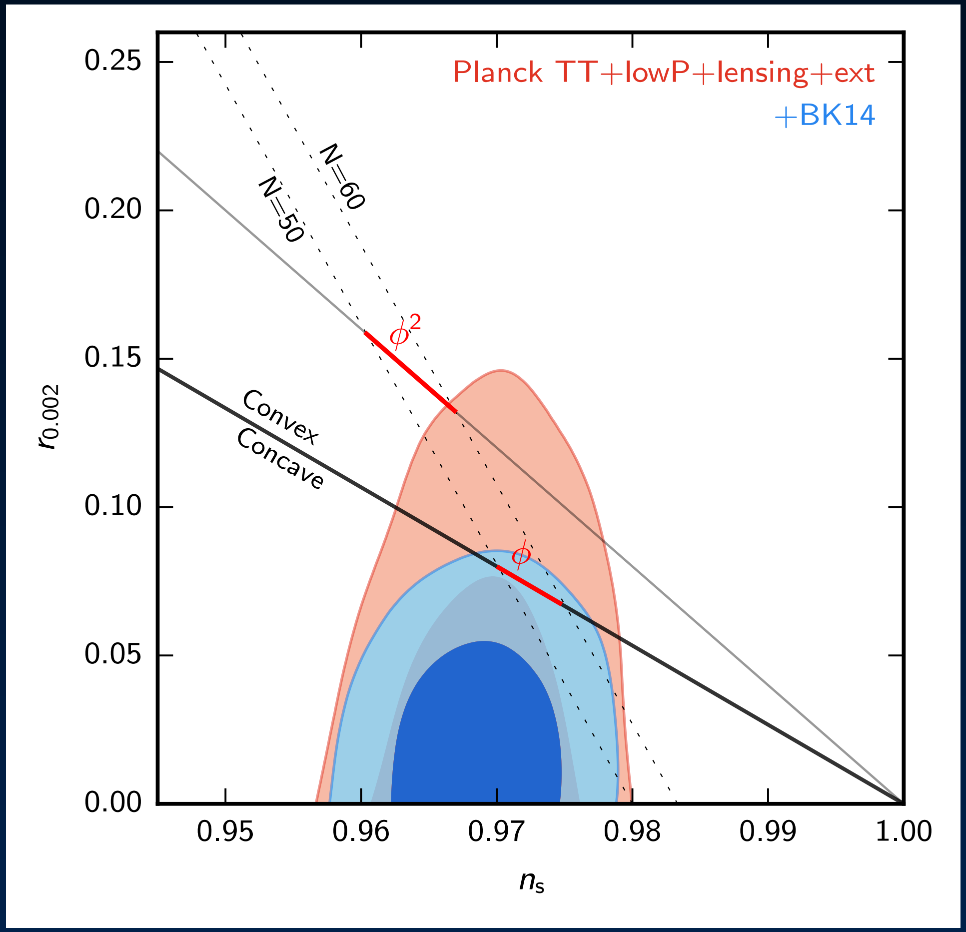
scale invariance



flat

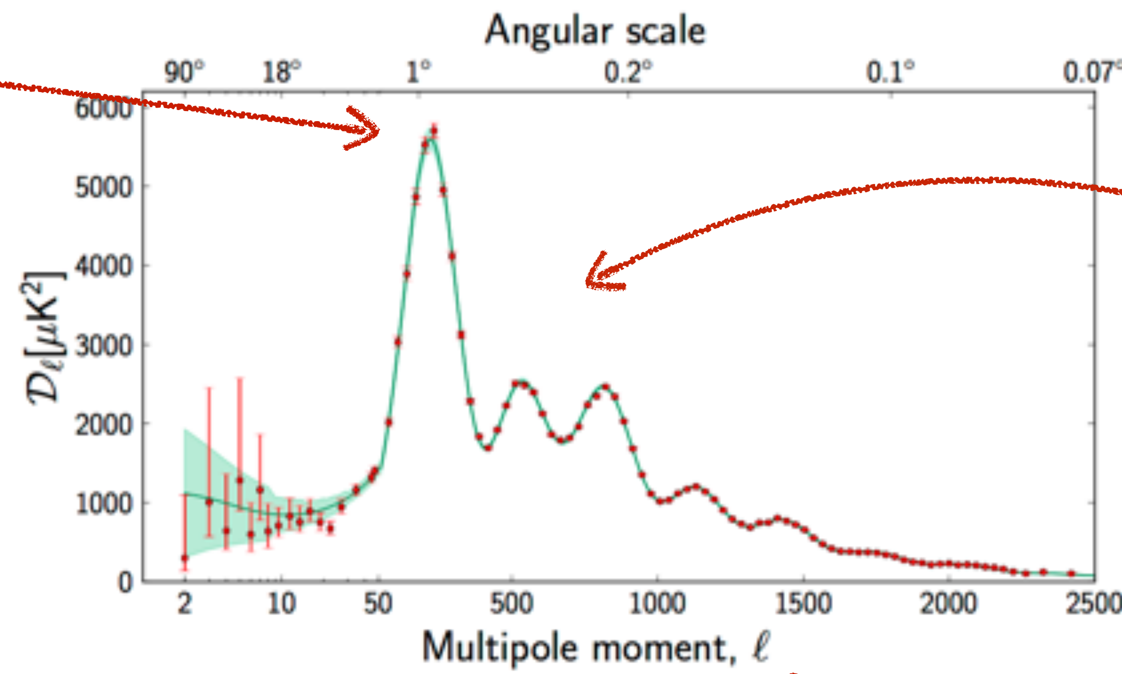
position of the first peak

$l \sim 200$

homogeneous

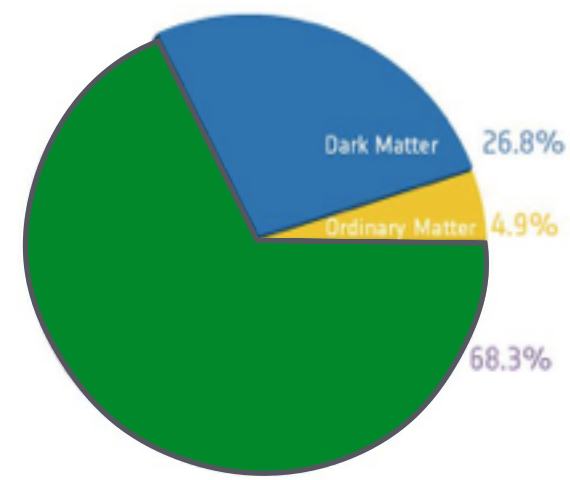
temperature fluctuations are small

$\Delta T \lesssim 10\mu K$



content of matter in the Universe

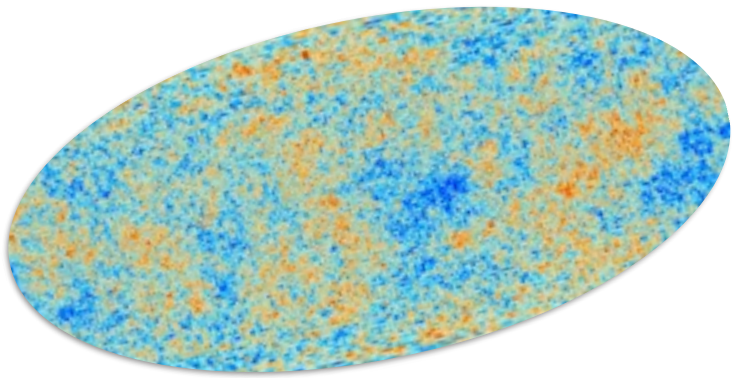
position of the first three peaks



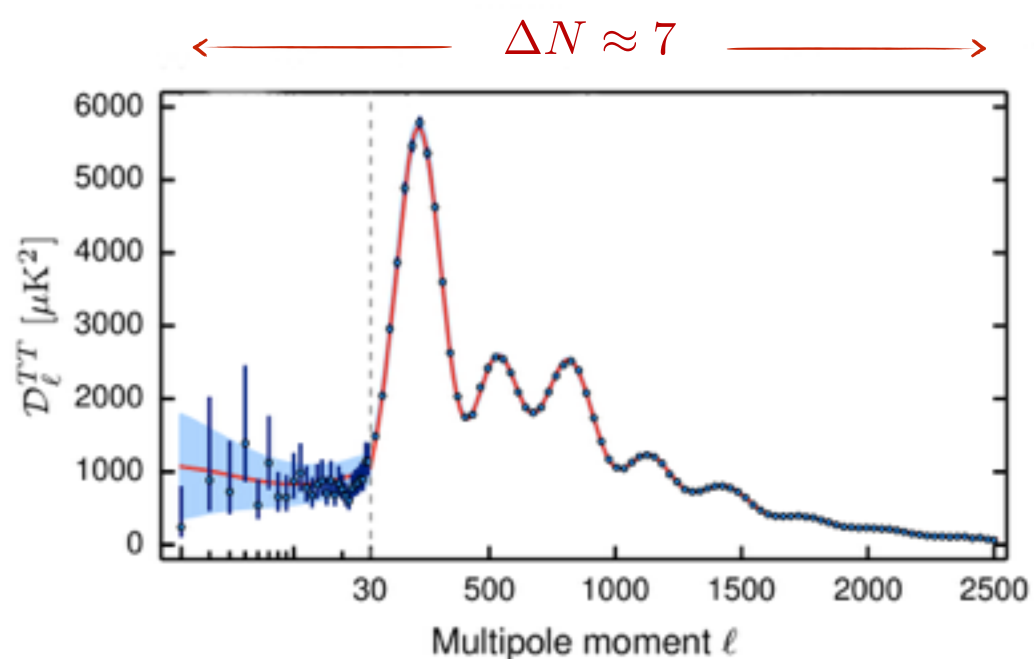
isotropic

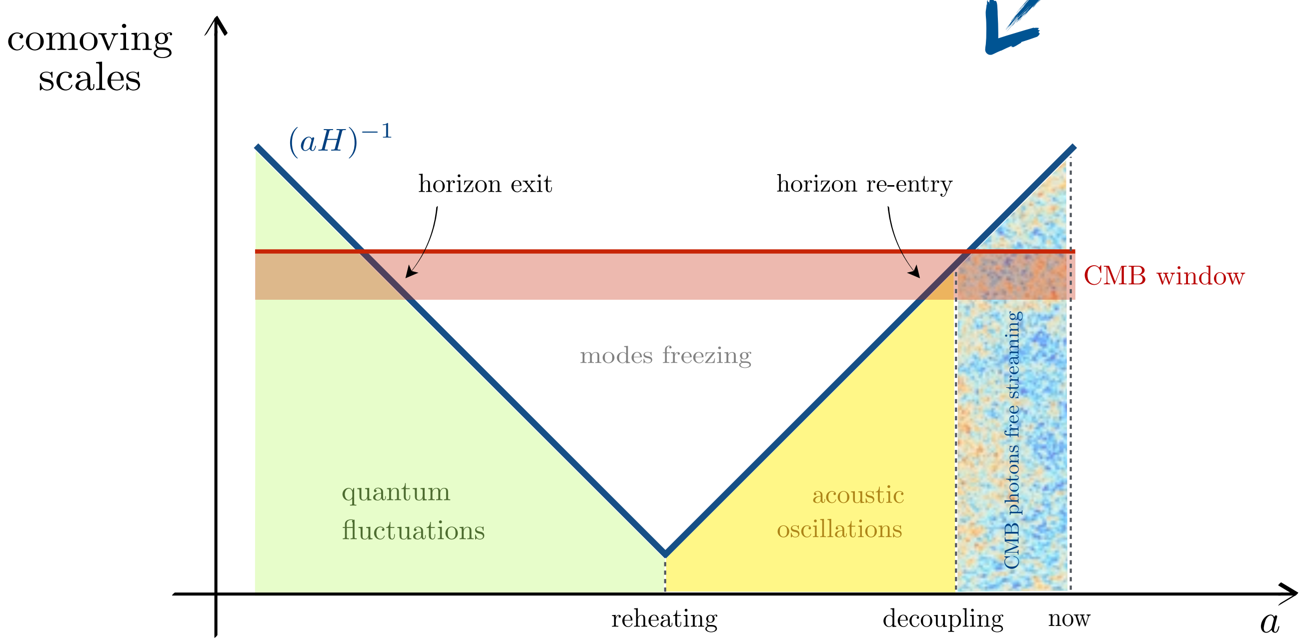
Inflation

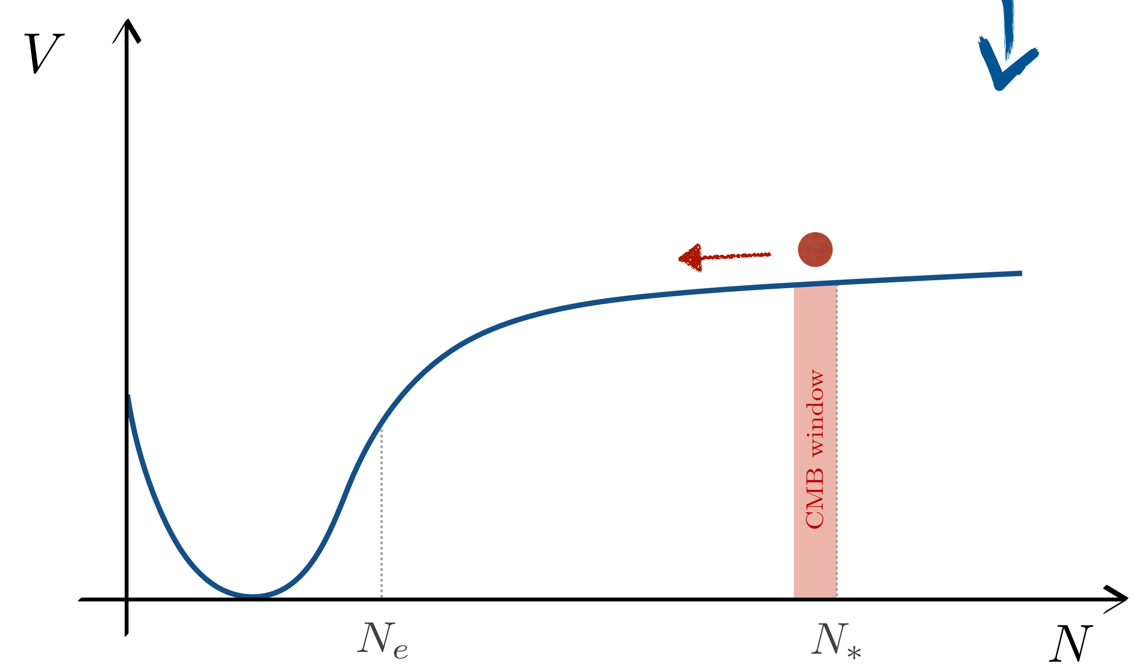
Dark Energy

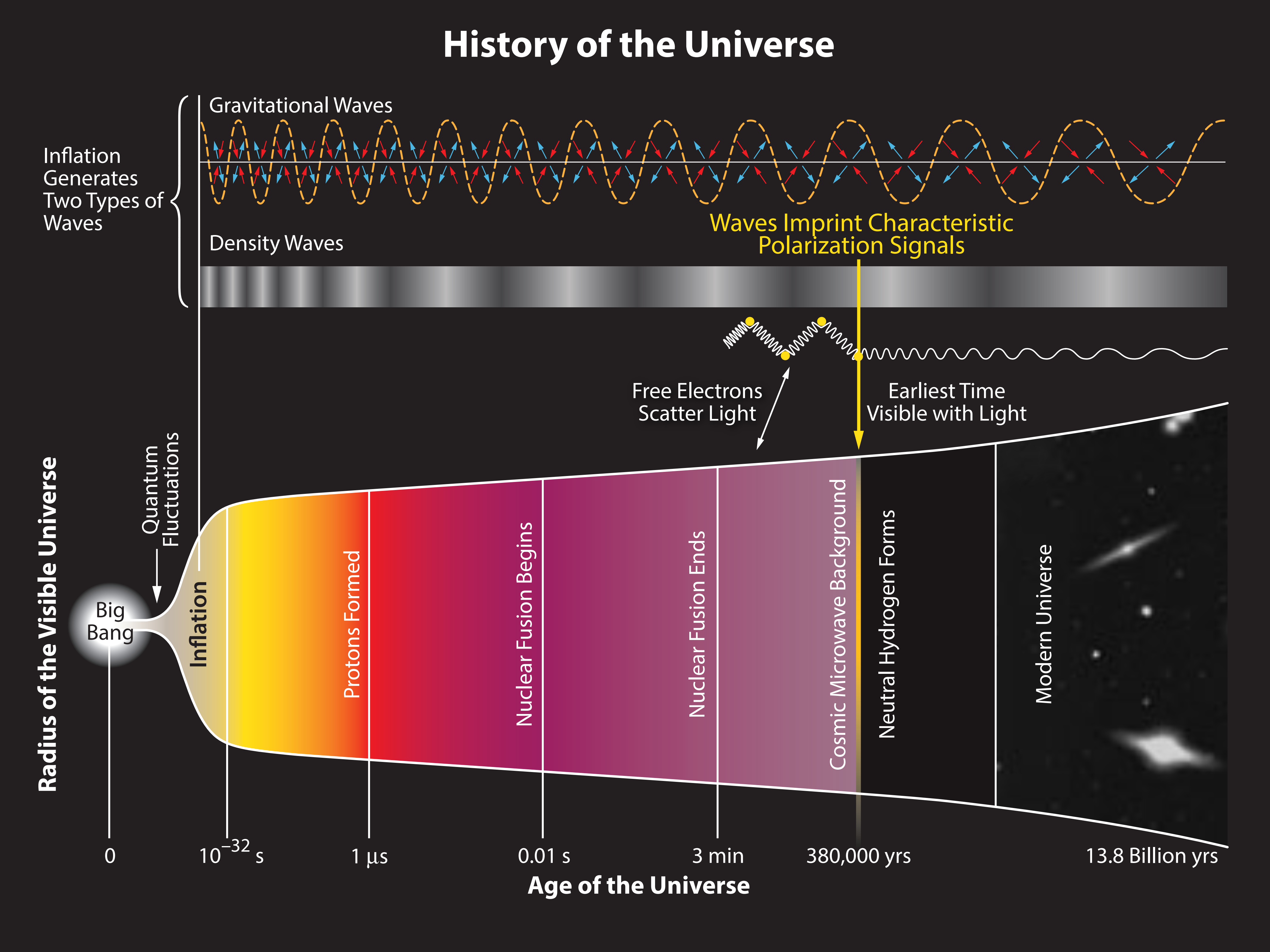


very small CMB window

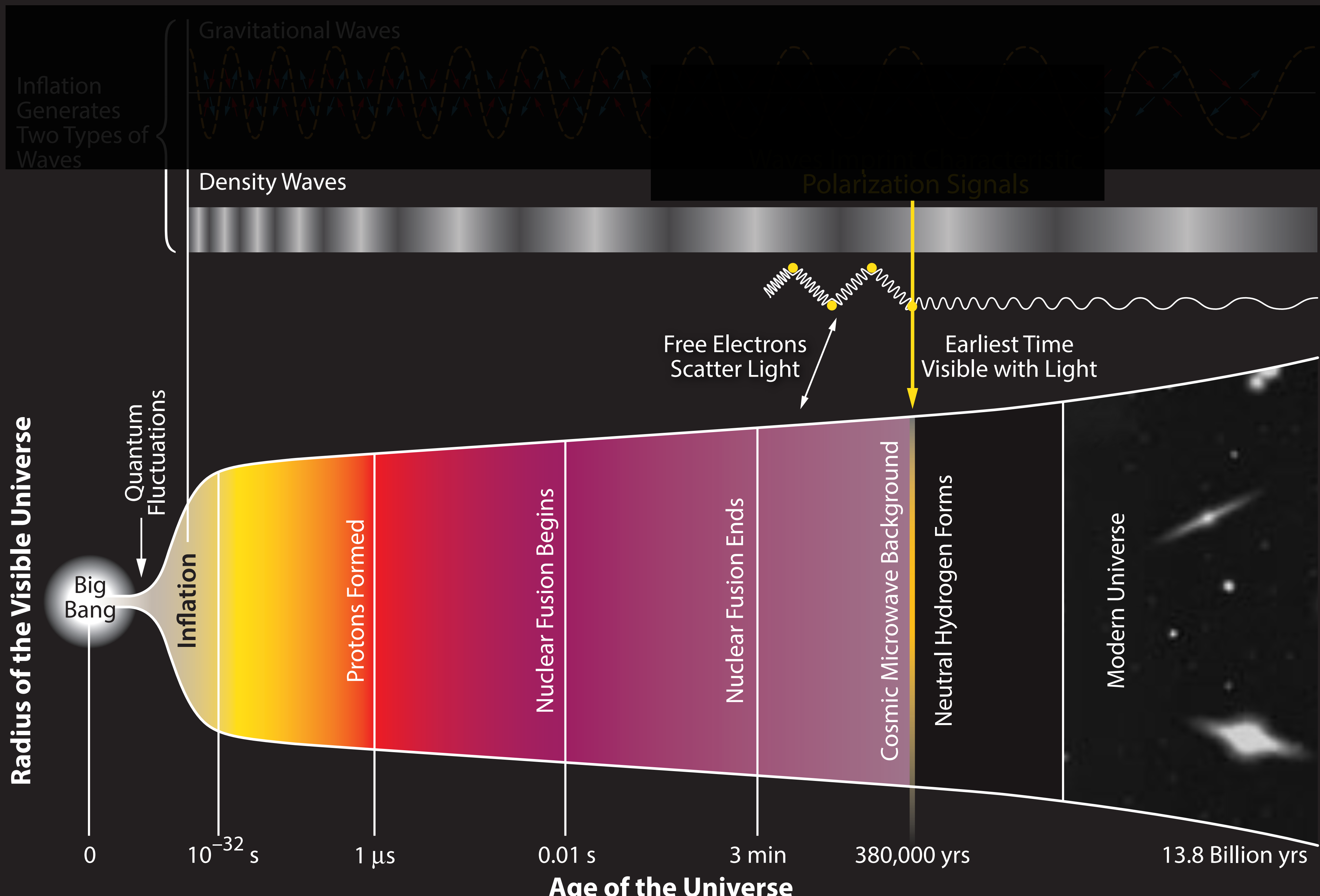




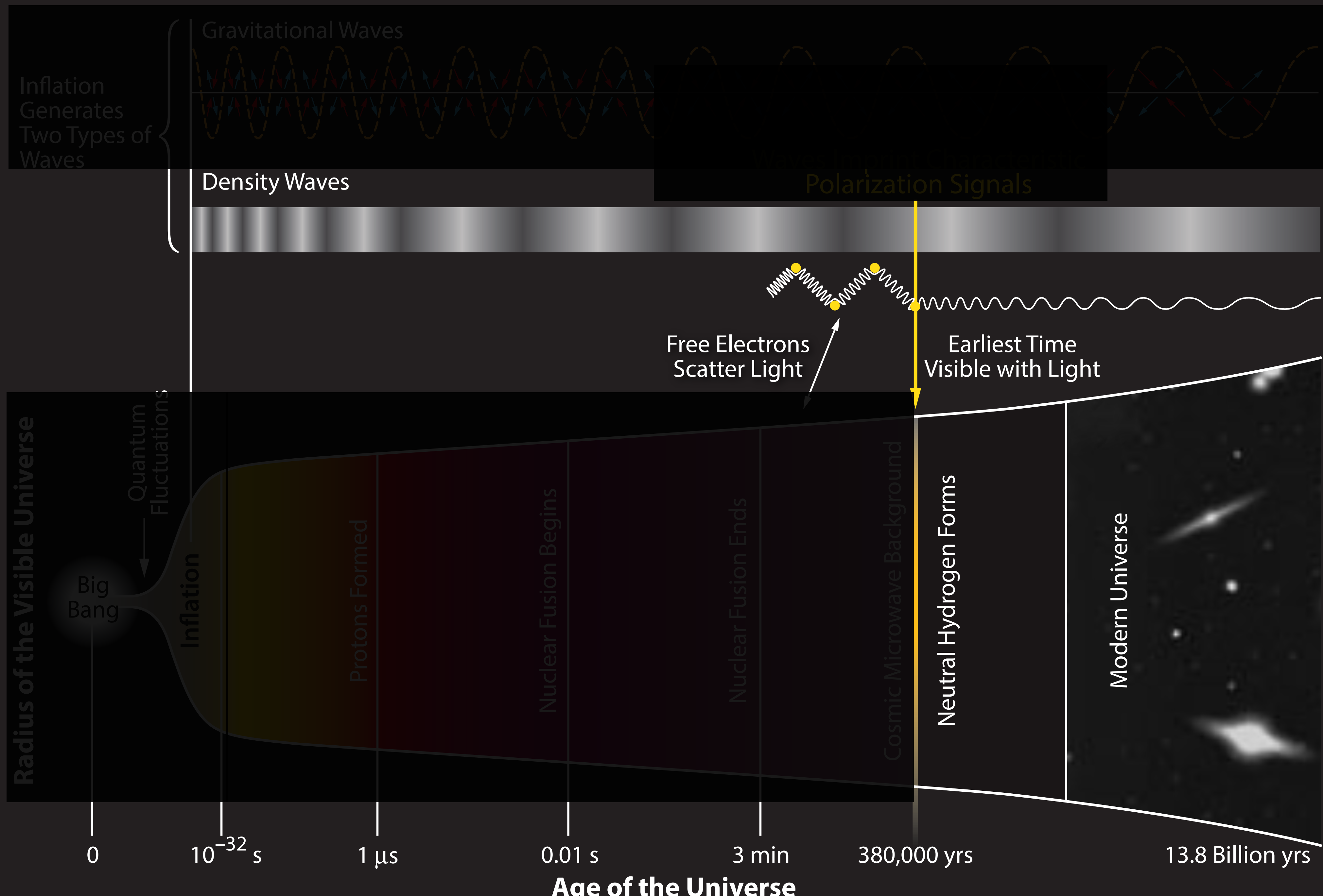



History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^{-32} s
1 μs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

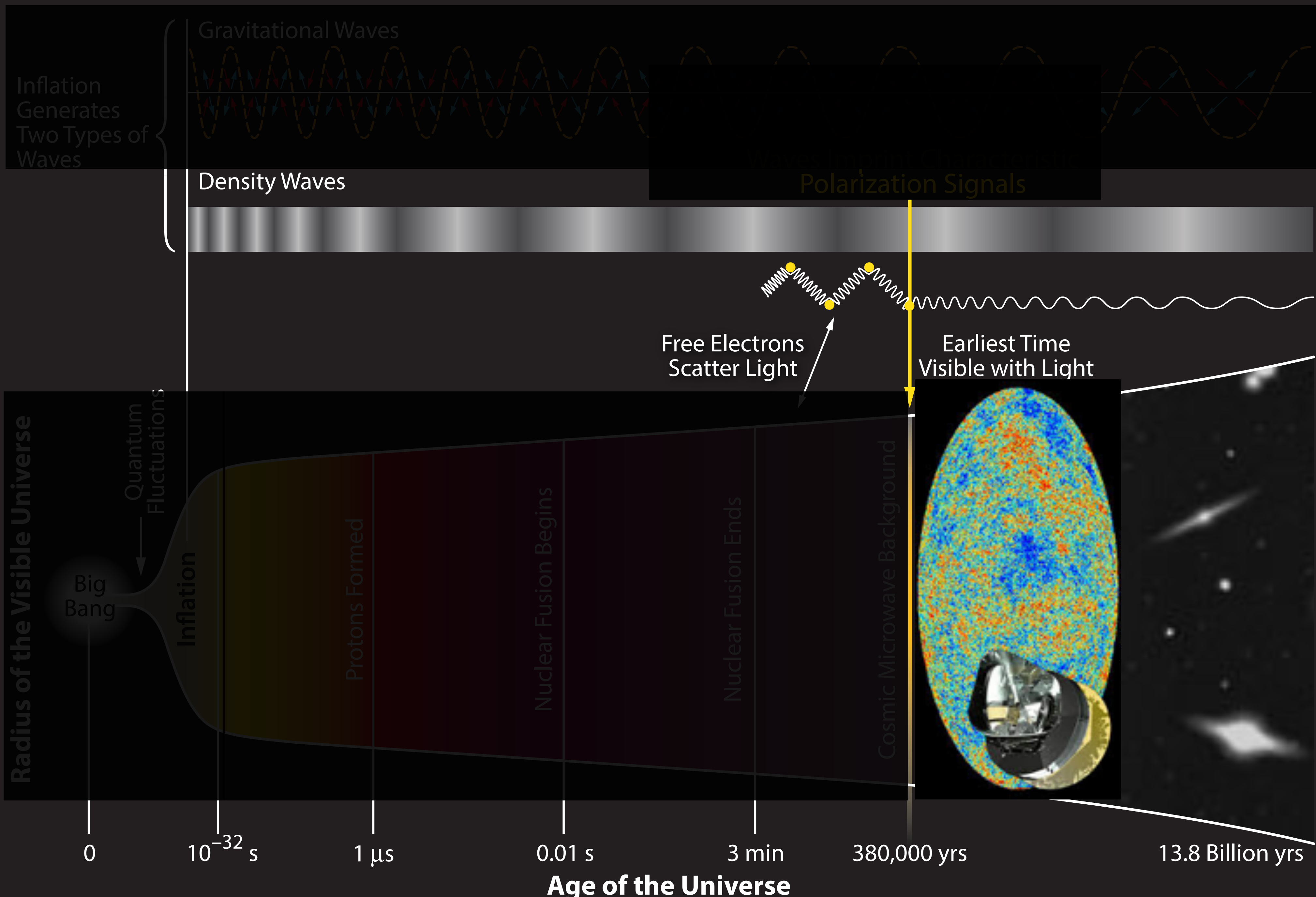
History of the Universe



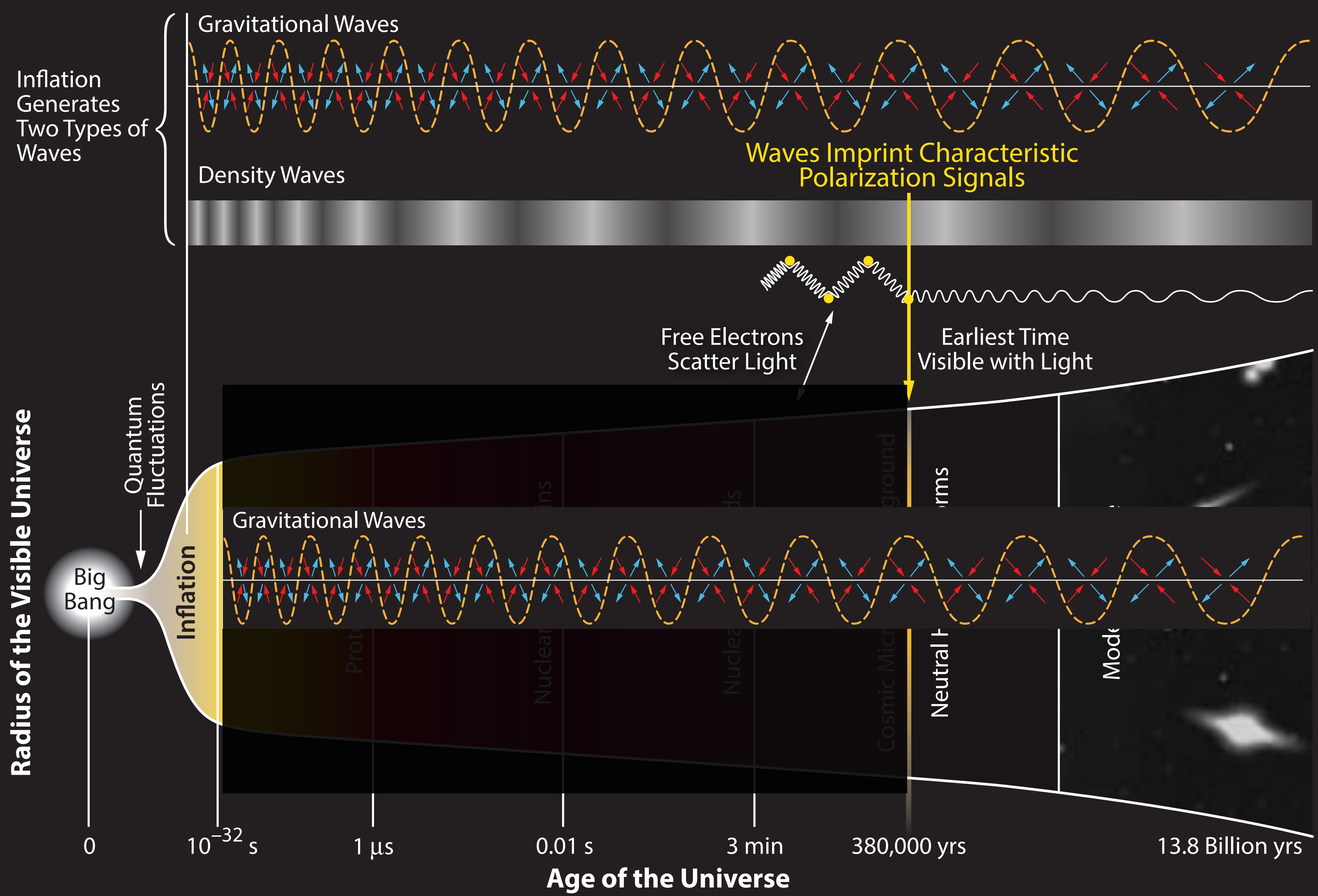
History of the Universe



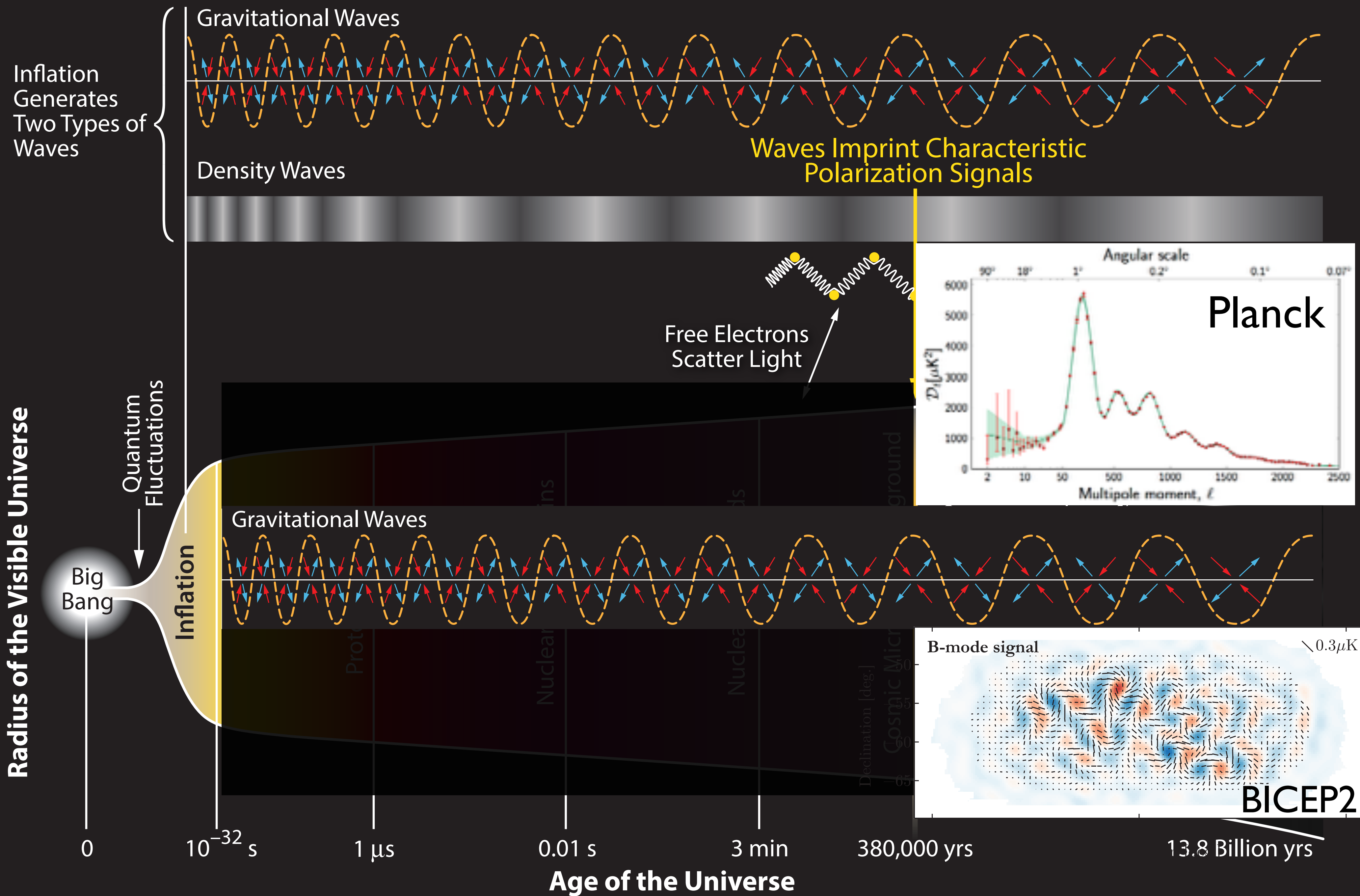
History of the Universe

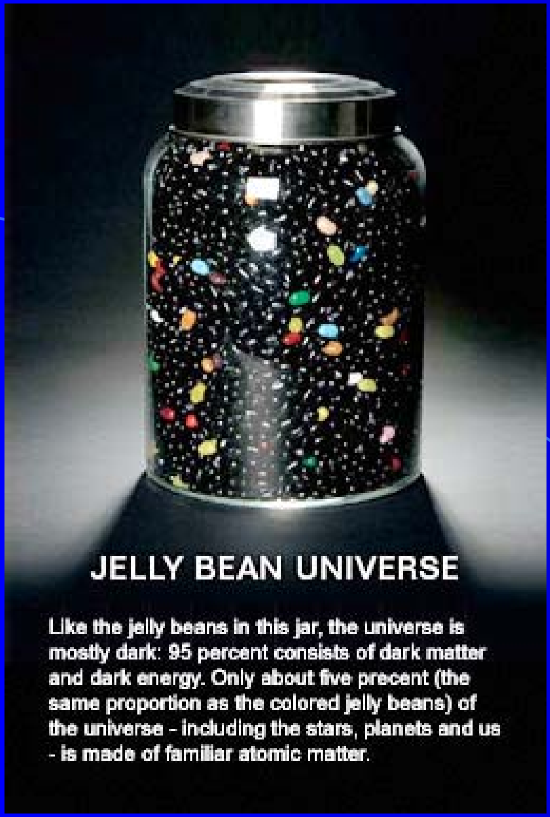


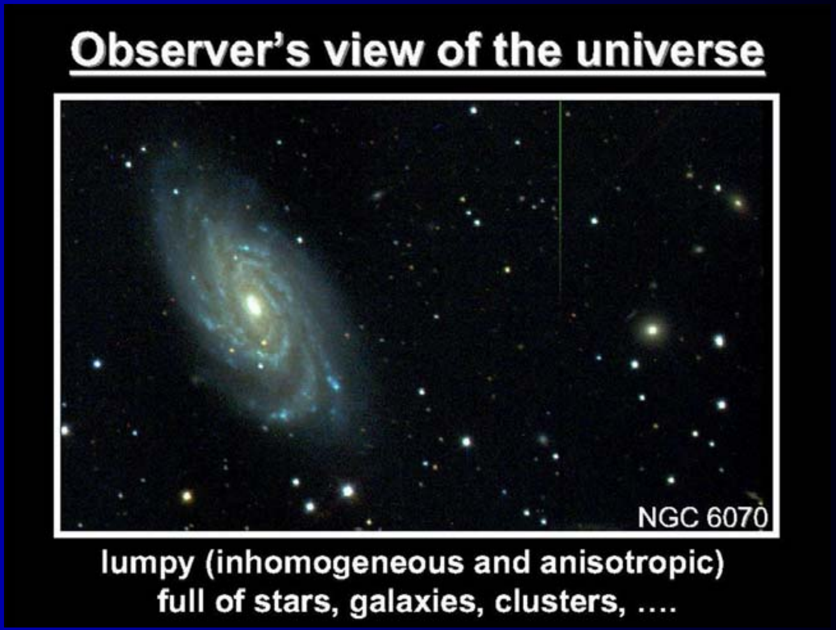
History of the Universe

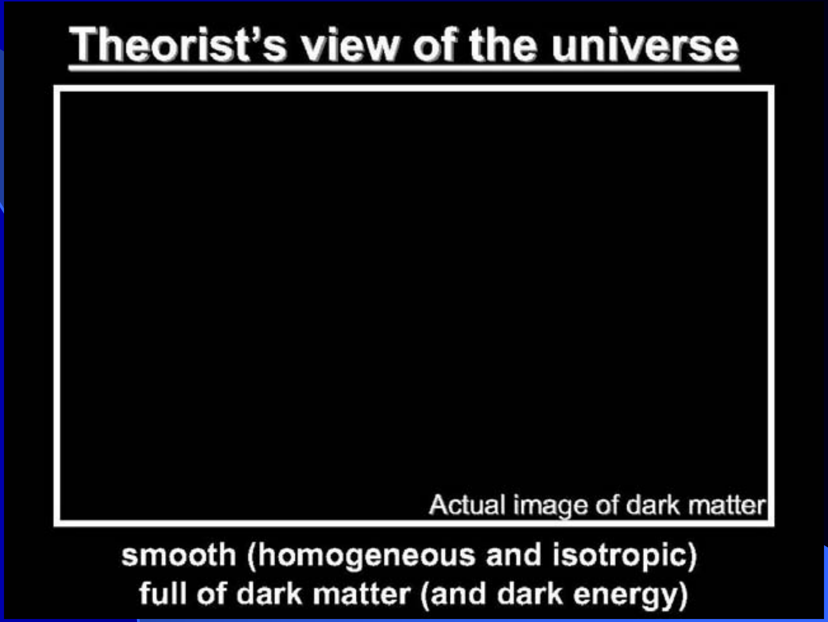


History of the Universe









宇宙の中身を例えたジェリービーン。色がついているのが通常の物質。全体の約96％の正体は未だわかっていないダークエネルギー（約73%）とダークマター（約23%）だ。

Inflation in early Universe

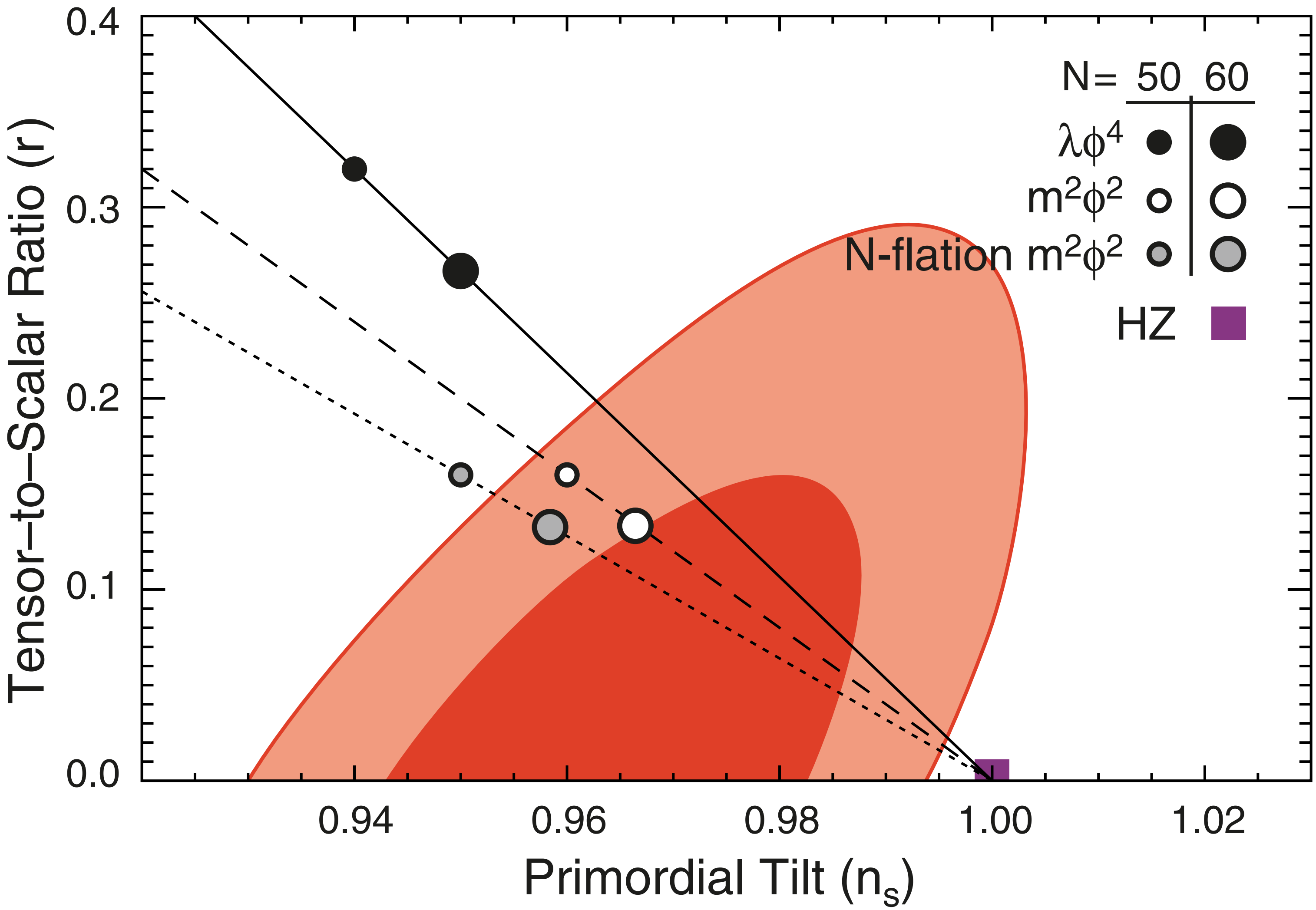
- Cosmological inflation (a phase of 'rapid' accelerated expansion) predicts homogeneity of our Universe at large scales, its spatial flatness, large size and entropy, and the almost scale-invariant spectrum of cosmological perturbations (in agreement with WMAP/PLANCK measurements of CMB radiation spectrum)!

- Inflation is a paradigm, not a theory! Usual theoretical mechanisms of inflation use a slow-roll scalar field (called inflaton) with the proper scalar potential.

- The scale of inflation is well beyond the electro-weak scale, ie. is beyond the SM. Inflationary stage in the early Universe is the most powerful HEP accelerator in Nature (about $10^{10}\ TeV$). Hence, inflation is the great window to HEP!

- The nature of the inflaton and the origin of its scalar potential are the big mysteries (eg., knowing the origin of inflaton means knowing its interactions, and, hence, details of reheating = the origin of all elementary particles).

Starobinsky vs. $m^2\phi^2$ and $\lambda\phi^4$



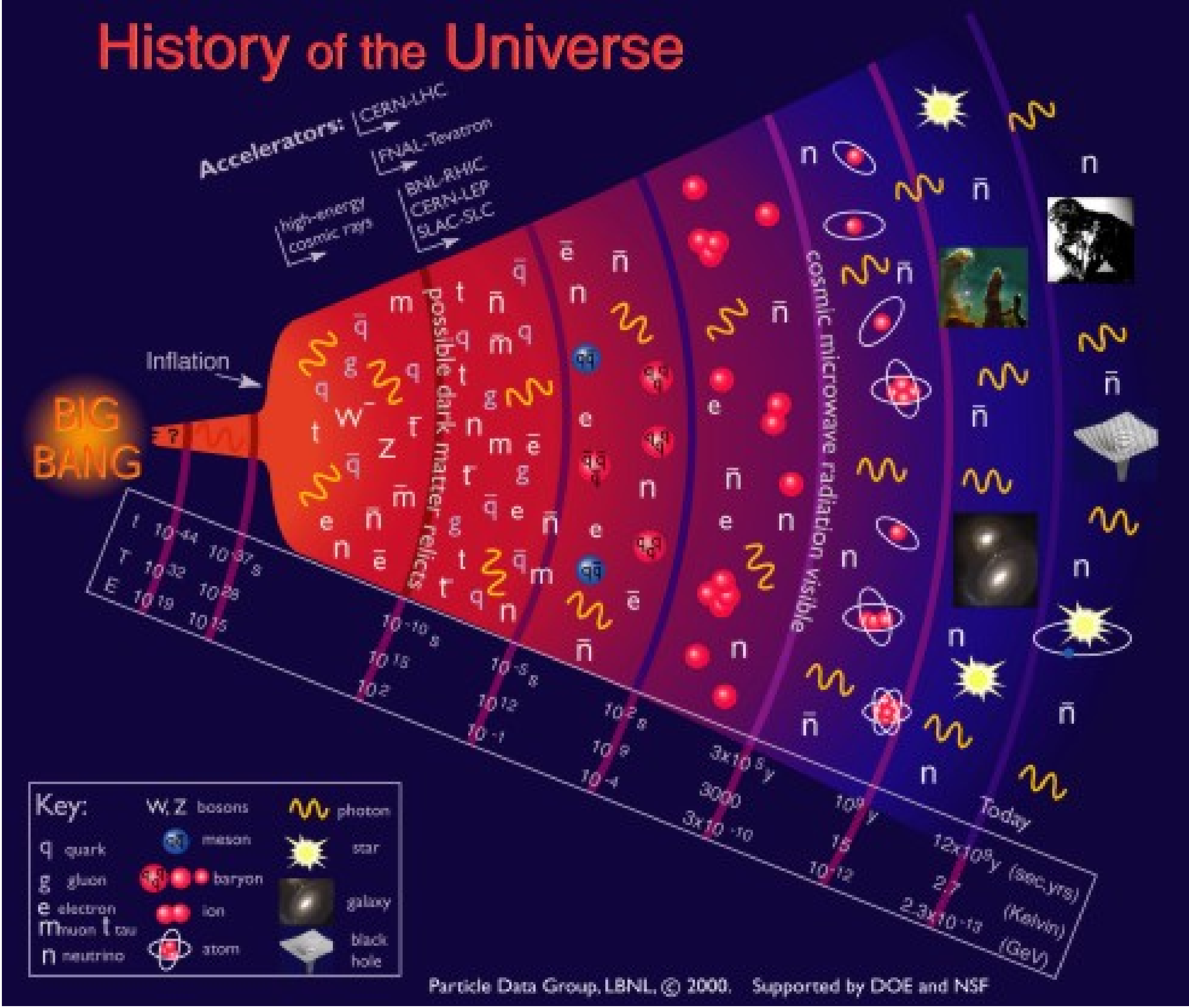
PLANCK measurements (2019)

when combined with WMAP polarization and lensing data:

$$n_s = 0.9649 \pm 0.0042$$

$$r < 0.032 \ \text{(with 95\% CL)}$$

$$f_{\mathrm{NL}} = 2.7 \pm 5.8 \ \text{(with 68\% CL)}$$


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^{-44} 10^{-37} s
T 10^{32} 10^{28}
E 10^{19} 10^{15}
10^{-10} s
10^{15}
10^{2}
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{8}
10^{-4}
3x10^{5} y
3000
3x10^{-10}
10^{9} y
18
10^{-12}
Today
12x10^{9} y (sec,yrs)
2.7 (Kelvin)
2.3x10^{-13} (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Baryonic Asymmetry Conditions

The observed part of our Universe is highly $C-$ and $CP-$asymmetric (no anti-matter). Inflation naturally implies a dynamical origin of the baryonic matter pre-dominance due to a non-conserved baryon number.

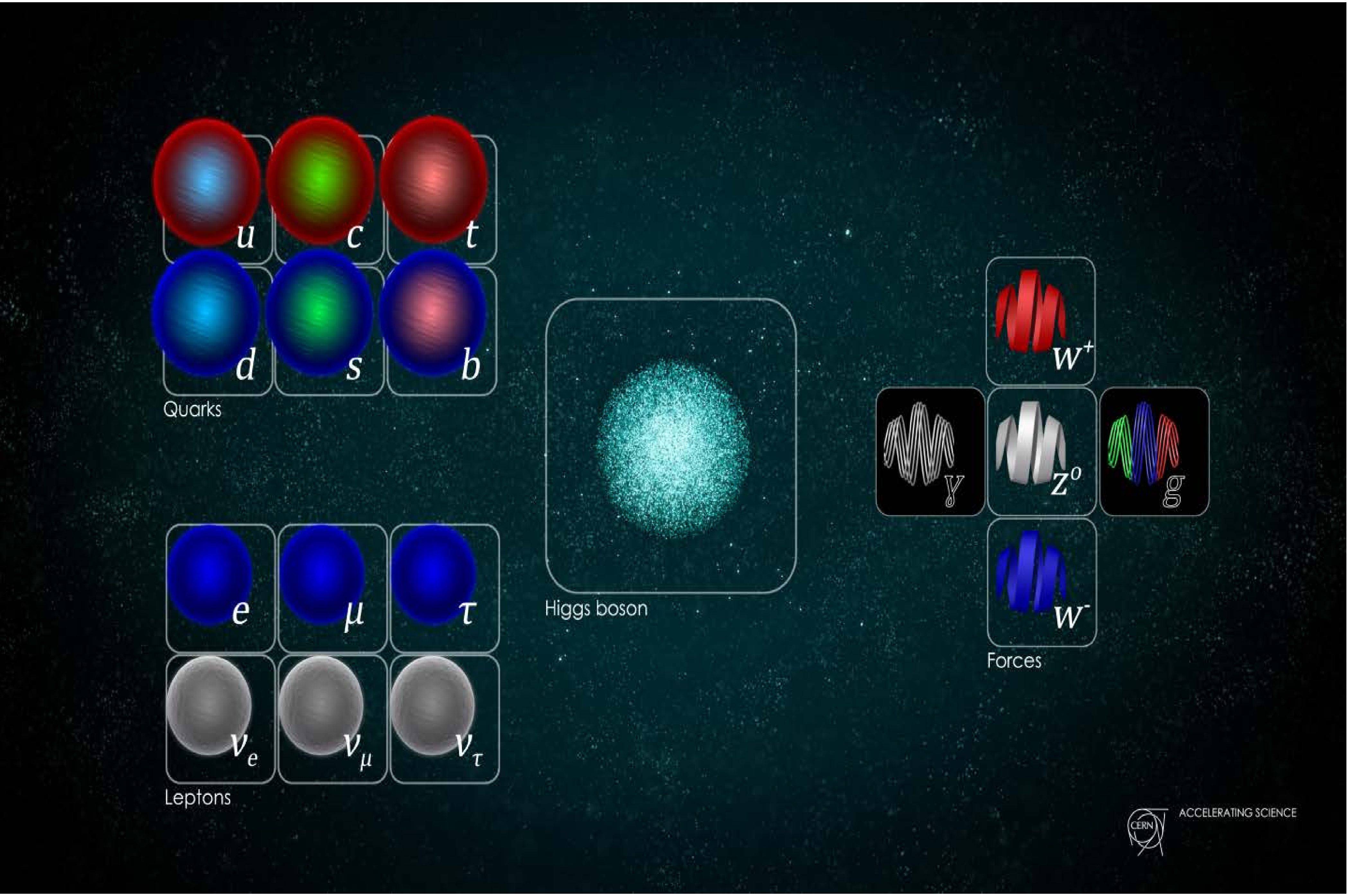
The main conditions for the dynamical generation of the cosmological baryon asymmetry in early Universe were formulated by A.D. Sakharov (1967):

1. non-conservation of baryons (*cf.* SUSY, GUT, EW theory),

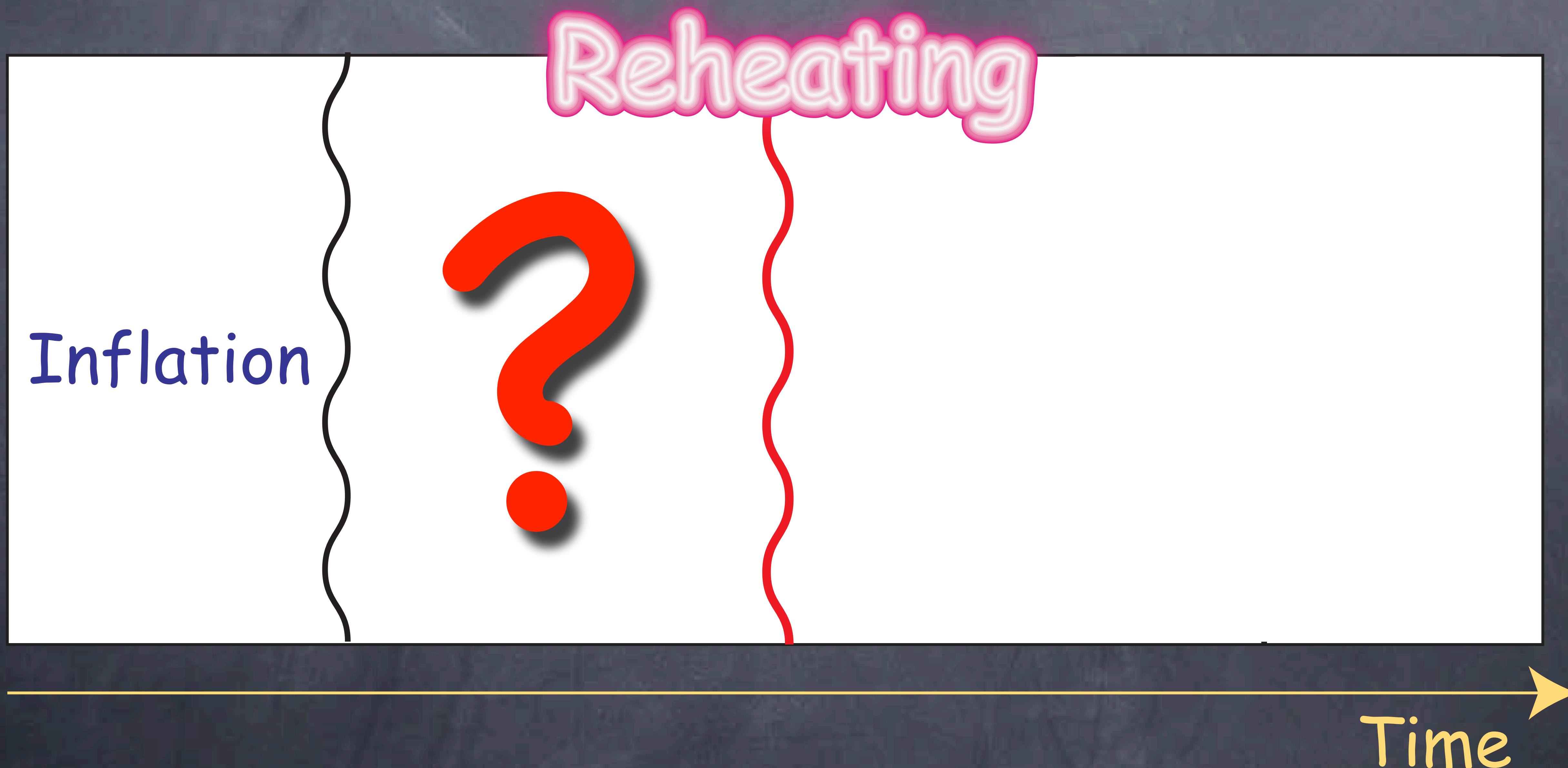
2. $C-$ and $CP-$symmetry breaking (confirmed experimentally),

3. deviation from thermal equilibrium in initial hot universe.

Standard Model of elementary particles



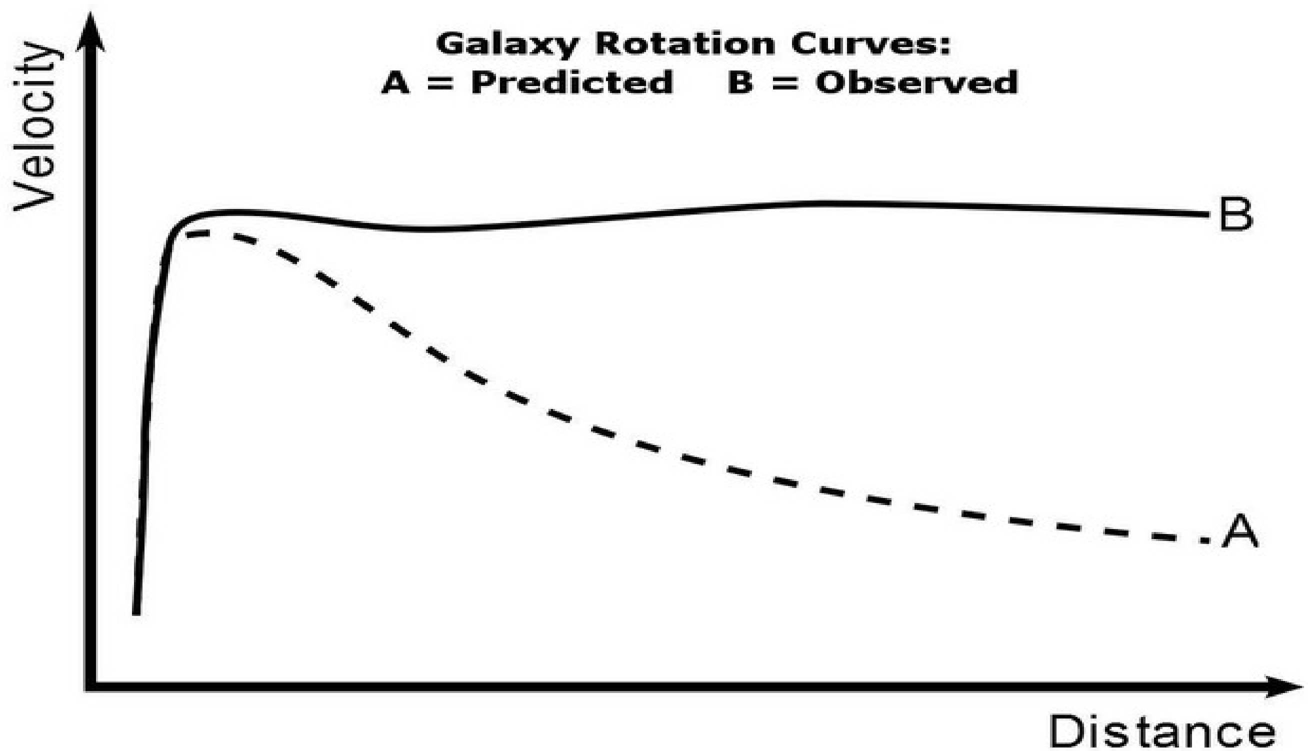
Reheating



Reheating

Reasons for Dark Matter (DM)

DM is needed to explain why stars in galaxies appeared to orbit faster than the gravitational attraction of the luminous mass would imply (Rubin, Ford. 1970):



DM does not interact electromagnetically (only gravitationally), and the new elementary particle forming DM has a mass, to get DM density of $0.3 \div 0.4\, GeV/cm^3$.

DARK MATTER IN THE SOLAR SYSTEM

The average density of dark matter near the solar system is approximately 1 proton-mass for every 3 cubic centimeters, which is roughly 6 $x10^{-28}$ kg/cm^3.

Based on this number, we can work out the total mass of dark matter within the radius of Earth's orbit around the sun: for an orbital radius of 100 million km, we get a total of $2.3x10^{12}$ kg of dark matter within the Earth's orbit. All of that dark matter only weighs 10^{-18} as much as the sun does, so we cannot detect the tiny pull of dark matter upon the Earth's orbit. The same story is true all over the solar system: the gravitational pulls of the sun and planets are always much larger than that of the dark matter.

DARK MATTER IN A GALAXY

Now consider the effect of dark matter upon the orbit of the sun around the galactic center. Let's suppose that the density of the dark matter is the same everywhere in the galaxy; this is NOT true (the density is much higher near the galactic center), so the dark matter mass will really be higher than we calculate.

The radius of the sun's orbit is about $2.5x10^{17}$ km, so the total mass of dark matter within that orbit is $6x10^{40}$ kg. This is the mass of 30 billion stars like the sun! The entire galaxy only contains ~100 billion stars, so the dark matter does have a significant effect on the sun's orbit through the galaxy. For objects farther out near the edge of the galaxy, the dark matter is actually the main thing keeping them in their orbits. This is more or less how dark matter was discovered by astronomer Vera Rubin and others: the orbital speeds of galactic stars and gas clouds don't match our expectations from the visible matter.

In other words, a galaxy is much lower in density than the solar system, so the small dark matter density becomes much more important.

What do we know about DE and DM: (very little!)

- Physical nature of DE and DM is unknown; the indirect evidence only

- DE works against gravity, to boost the expansion of the Universe. A small positive cosmological constant $(\Lambda)^{1/4} = 0.0024\, eV$ may account for the present Universe accelerated expansion, because the current (experimentally dictated) DE-equation of state should have $w = P/\rho = -0.97 \pm 0.07$

- The DM should be Cold (ie. non-relativistic), non-baryonic and stable. Possible candidates for the CDM particle include axion, gravitino and neutralino (WIMP) = Weakly Interacting Massive Particle in the MSSM =Minimal Supersymmetric Standard Model.

- The present Universe is (phenomenologically) well described by the Λ-CDM scenario = NEW Standard Cosmology.

Euclid in a nutshell

Simultaneous (i) visible imaging (ii) NIR photometry (iii) NIR spectroscopy

15,000 square degrees

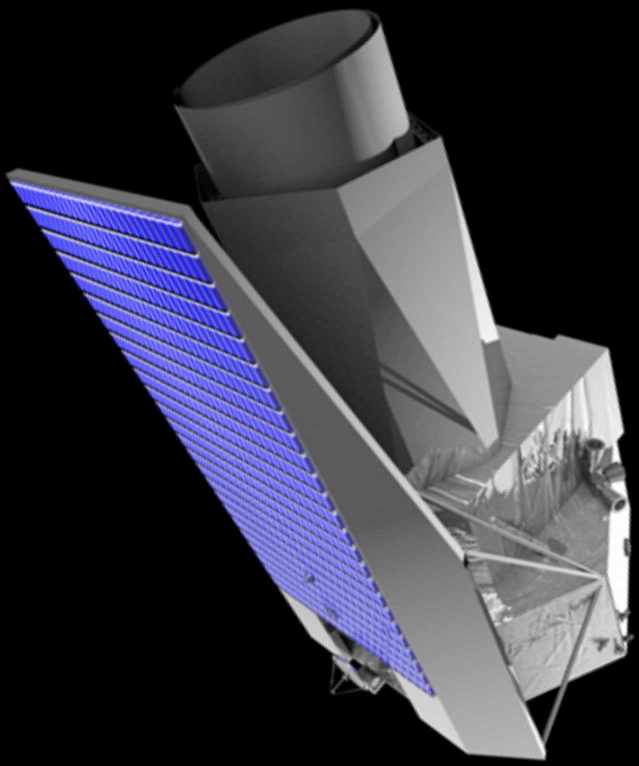
70 million redshifts, 2 billion images

Median redshift z = 1

PSF FWHM ~0.18’’

>1000 peoples, >10 countries

launched July 1st, 2023

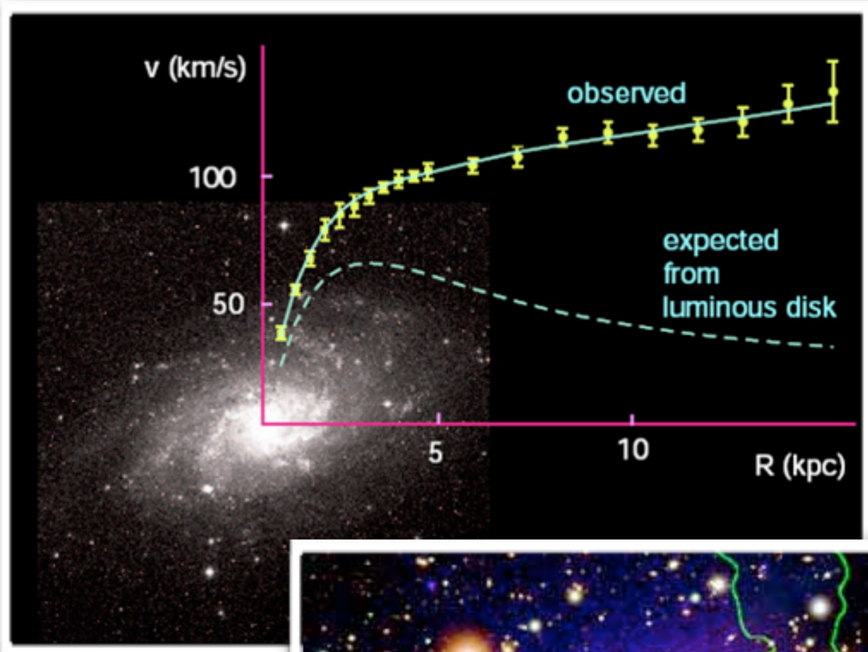


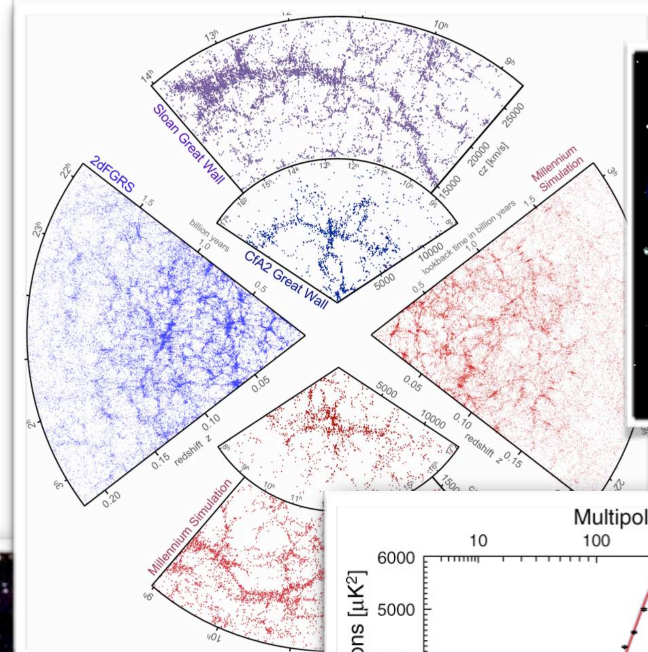
Euclid satellite

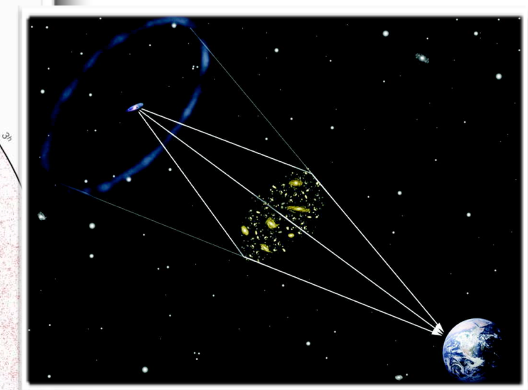
arXiv Red Book 1110.3193

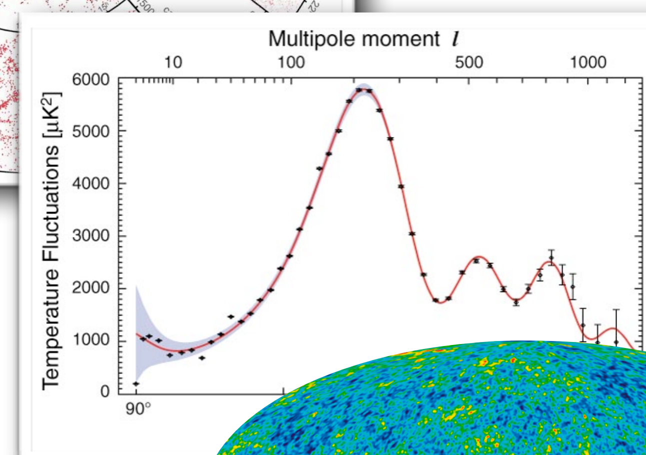
arXiv Theory Review 1206.1225

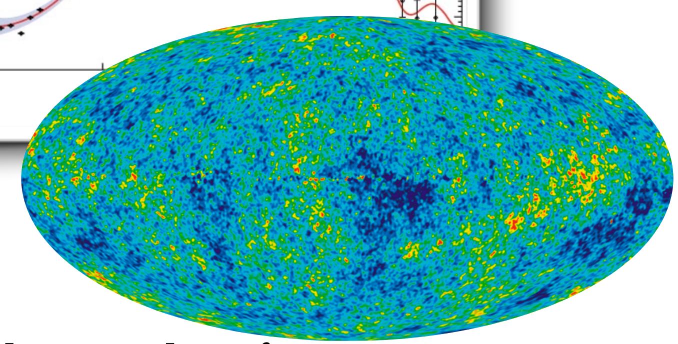
Dark matter all around





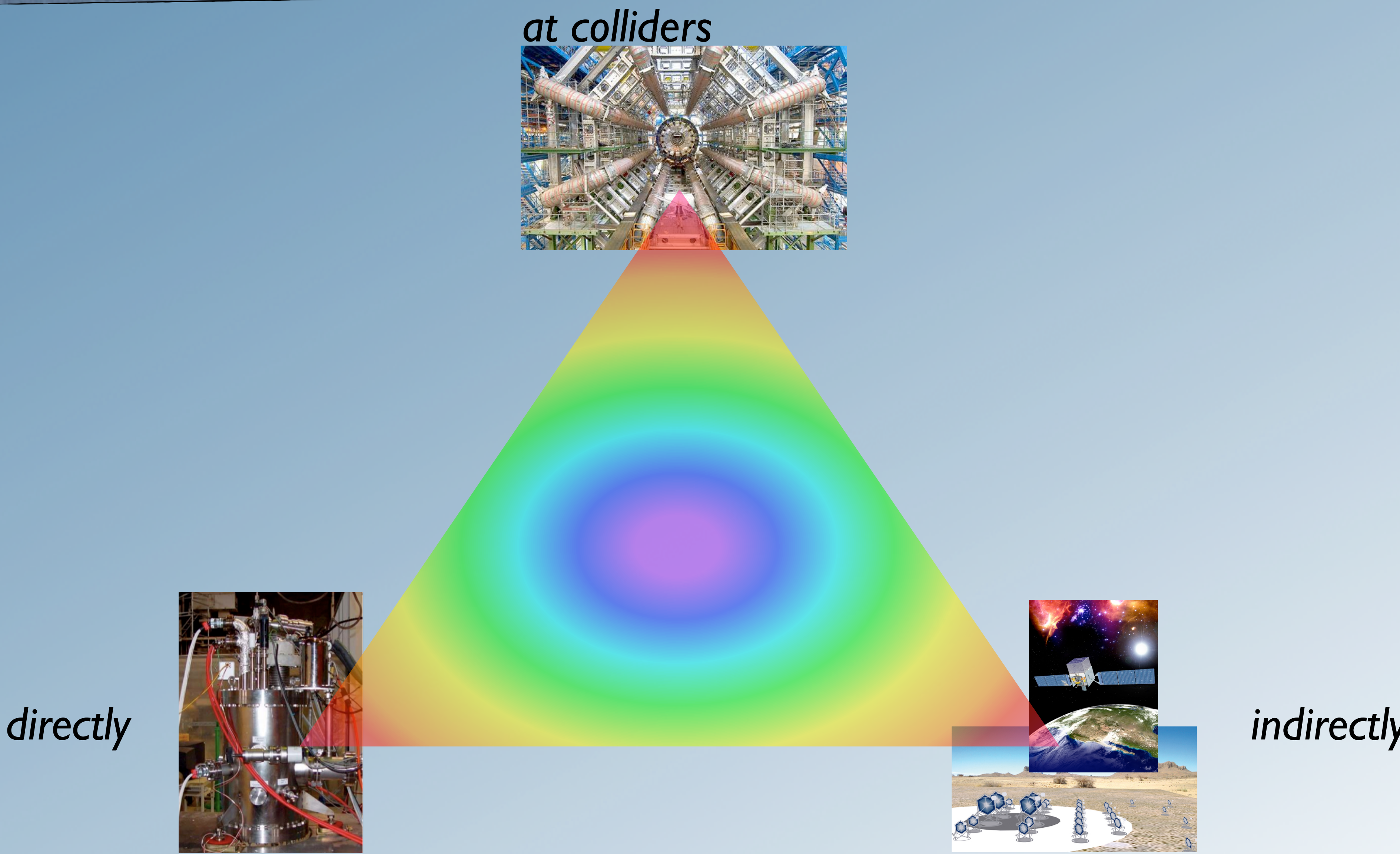






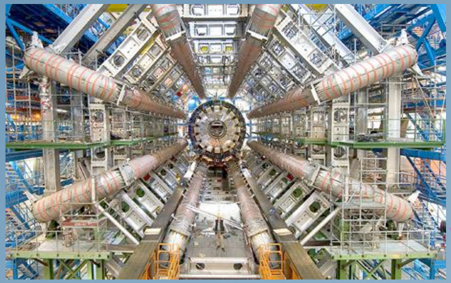
overwhelming evidence on all scales!

Strategies for WIMP searches

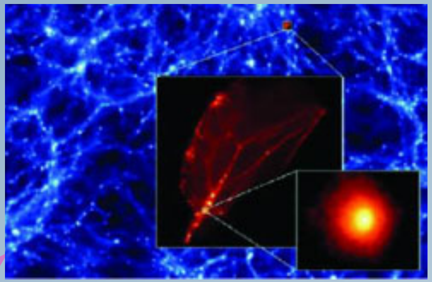


➩ *all complementary!*

Strategies for WIMP searches

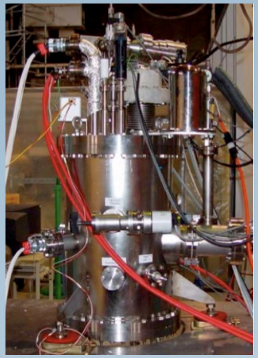


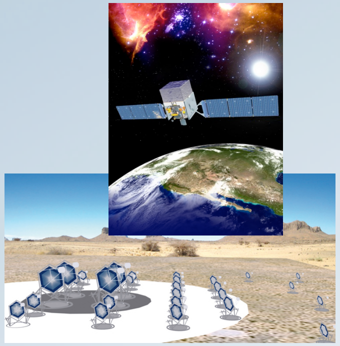
at colliders



astrophysical probes of matter distribution

directly



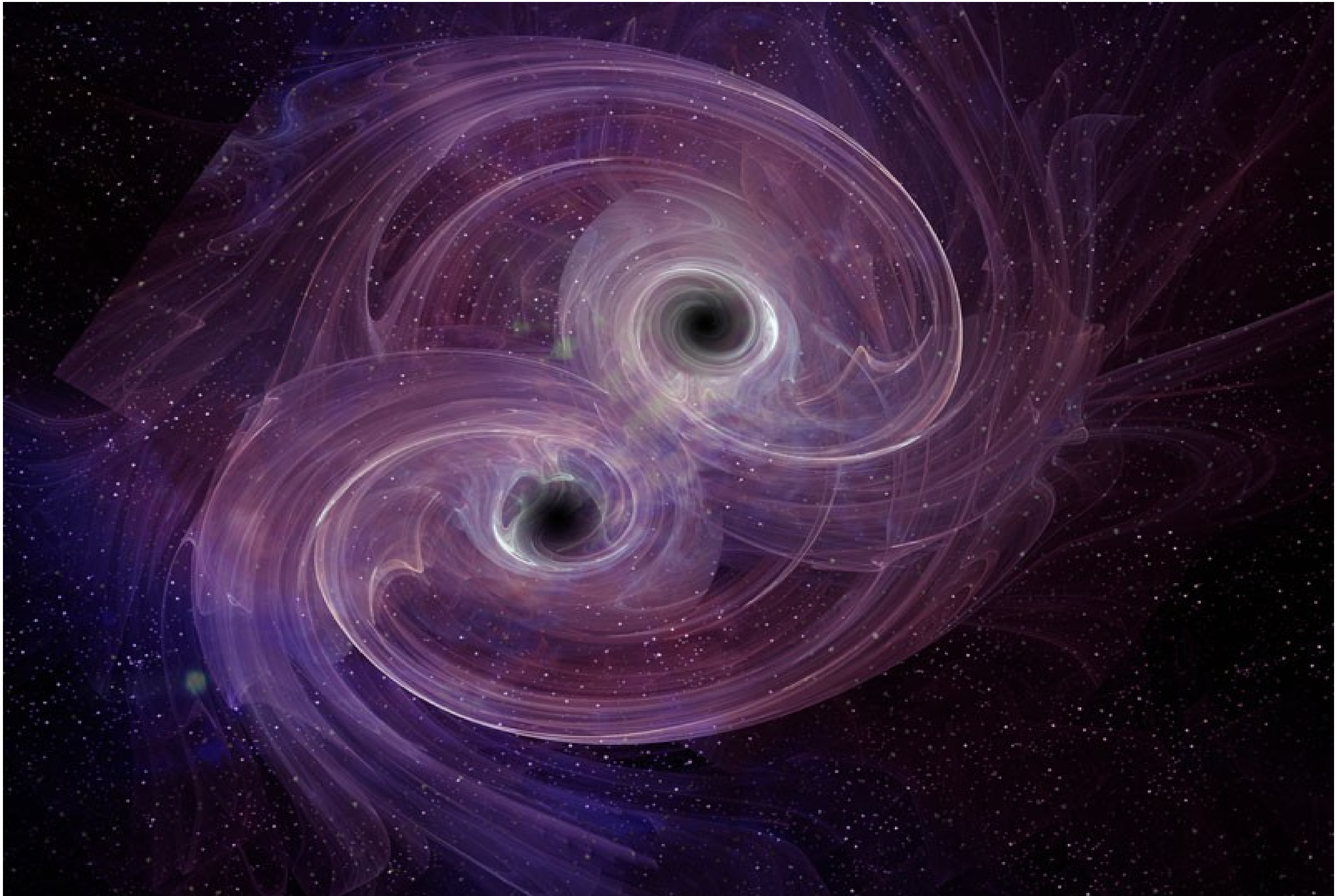


indirectly

➩ *all complementary!*

The Laser Interferometer Gravitatational-wave Observatory (LIGO) in the USA

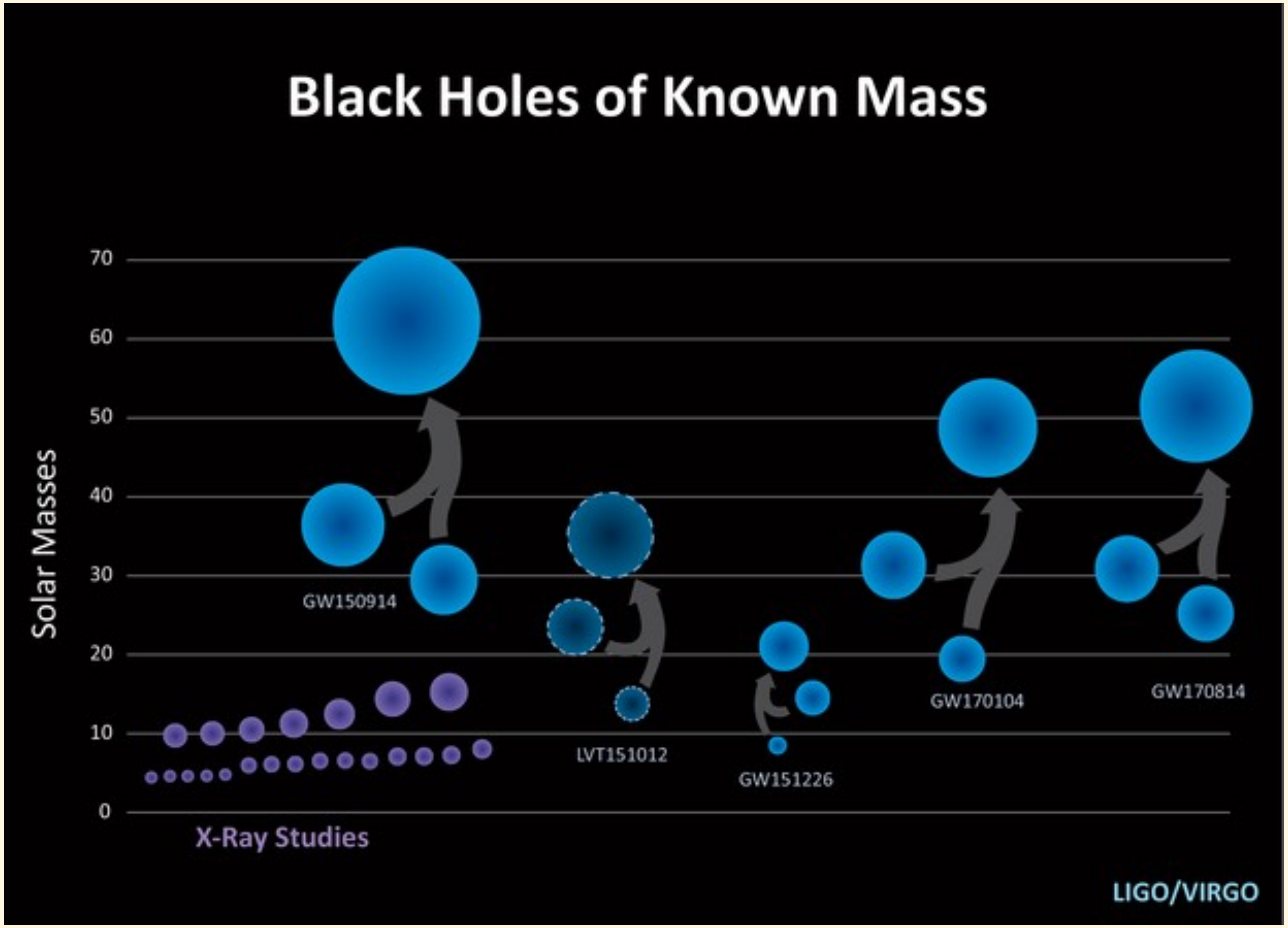
Binary black hole merger (LIGO)



Outlook of LIGO events

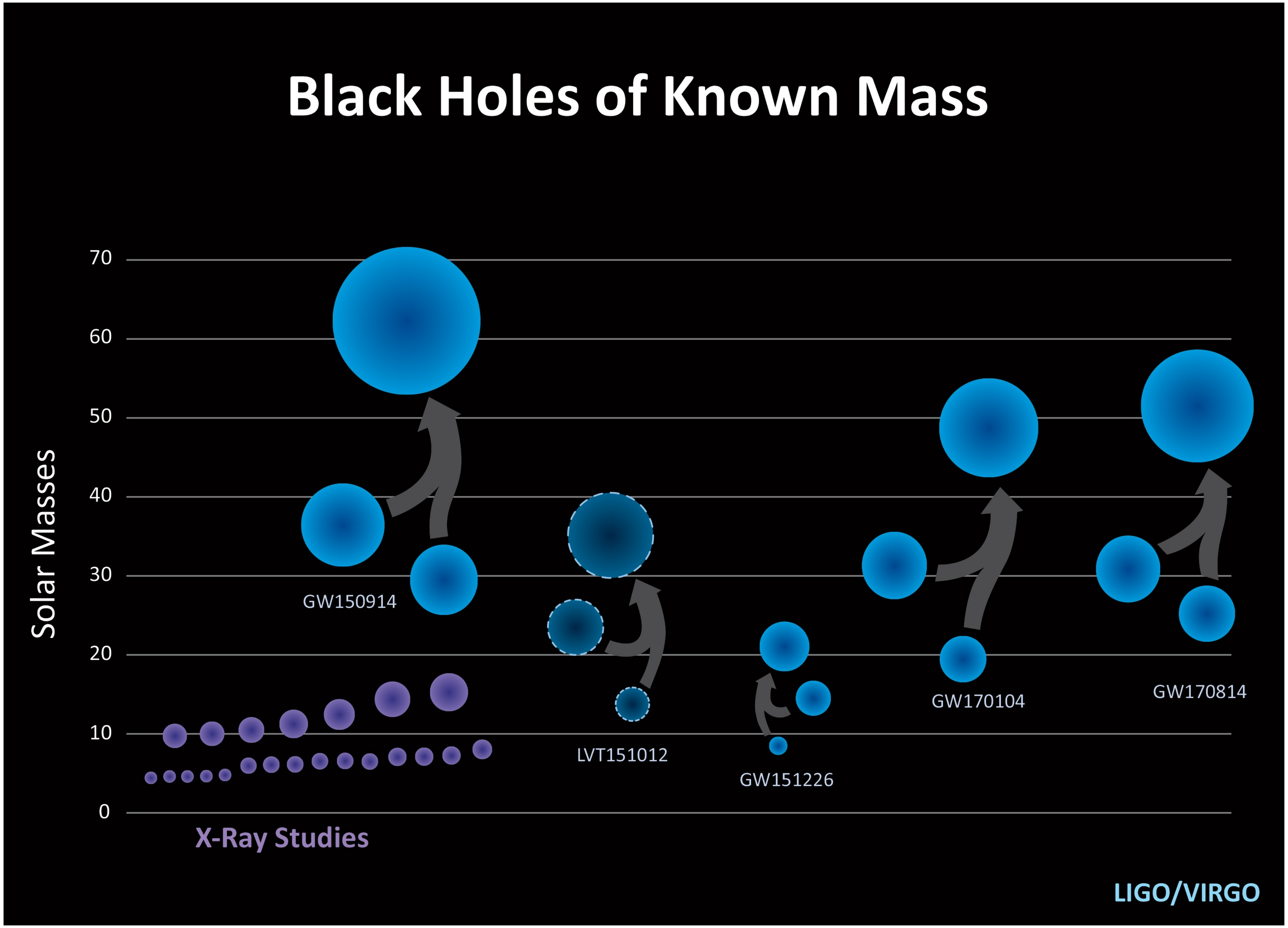
Merging of **Binary BH** observed by LIGO

- Estimated event rate **O1**: $9-240\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$, **Total**: $12-213\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$



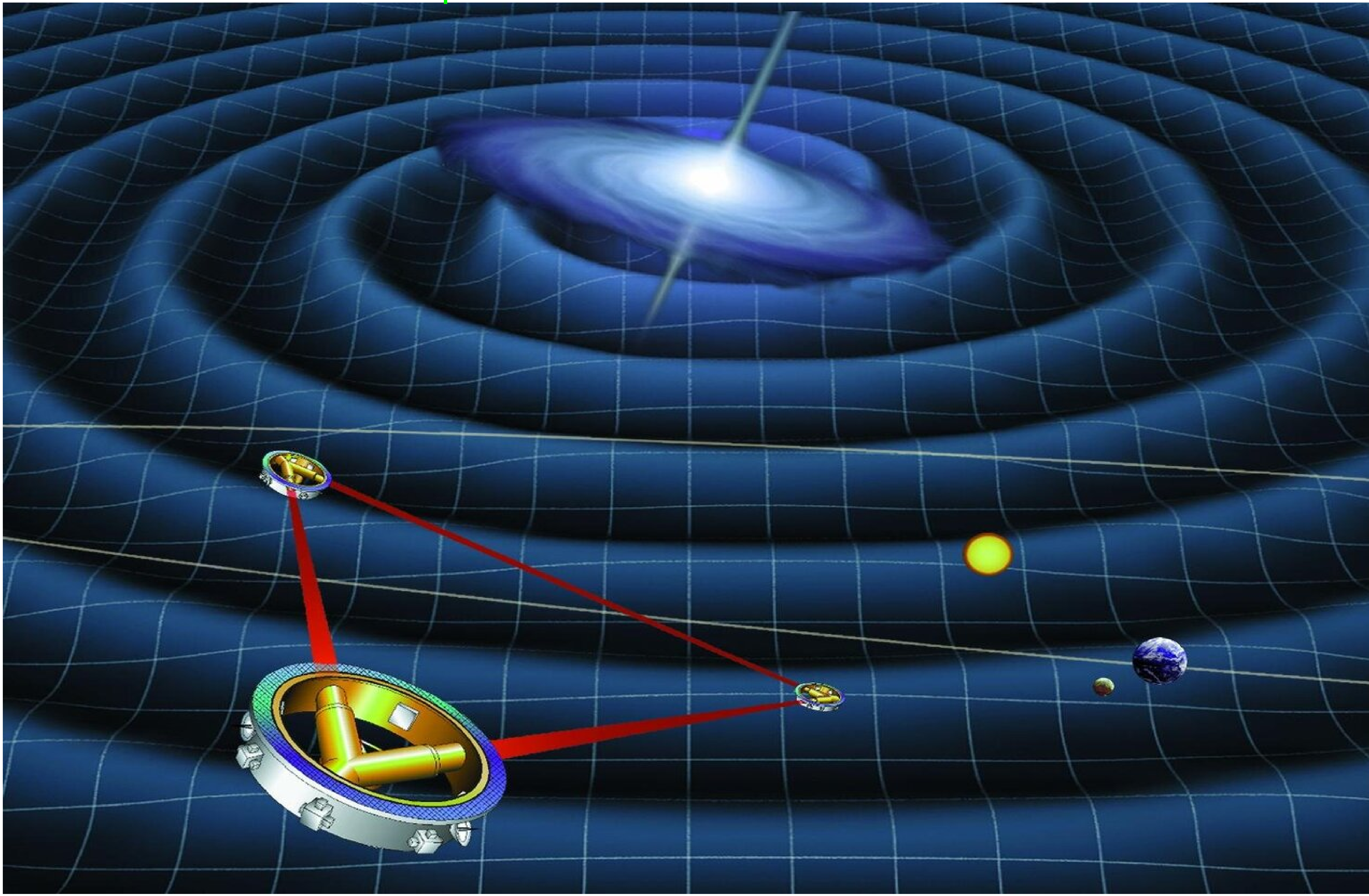
[Ref. https://www.ligo.caltech.edu]

- LIGO-VIRGO events: $\mu_{\rm PBH} \sim (0.01 - 100)\, M_{\odot}$

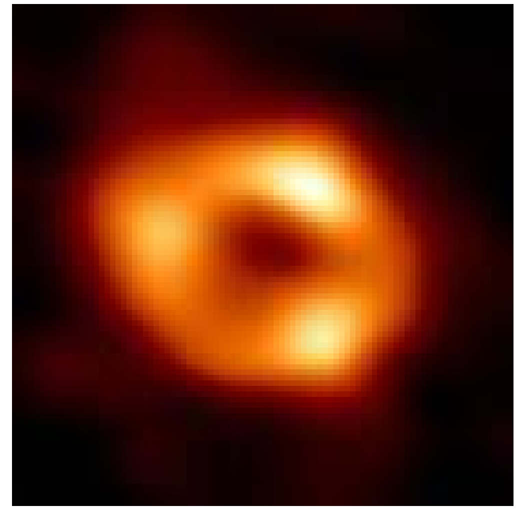


Laser Interferometer Space Antenna (LISA)

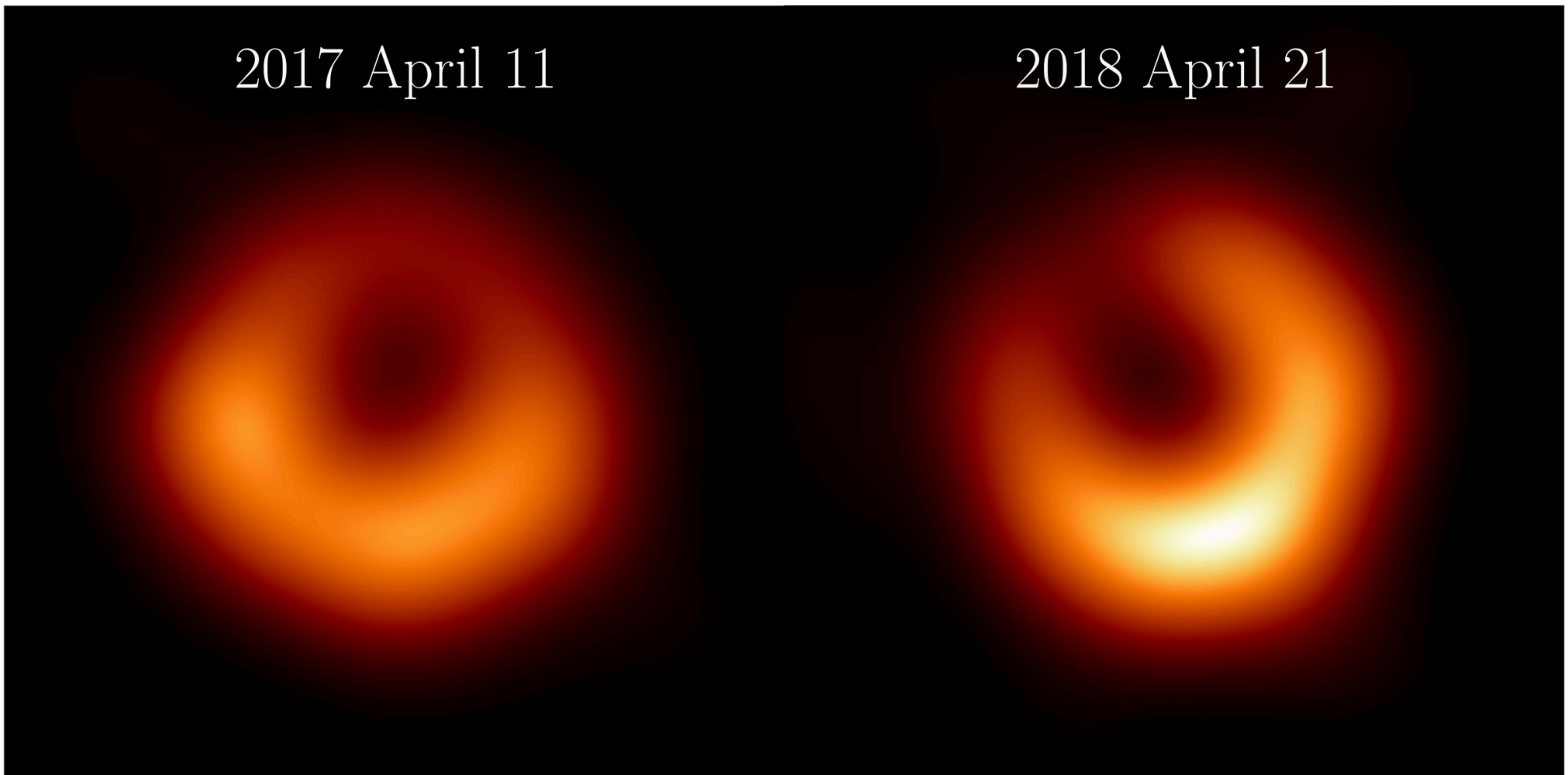
expected to launch in 2035



How to see a black hole?



Images from the Event Horizon Telescope



The Smithsonian Associates

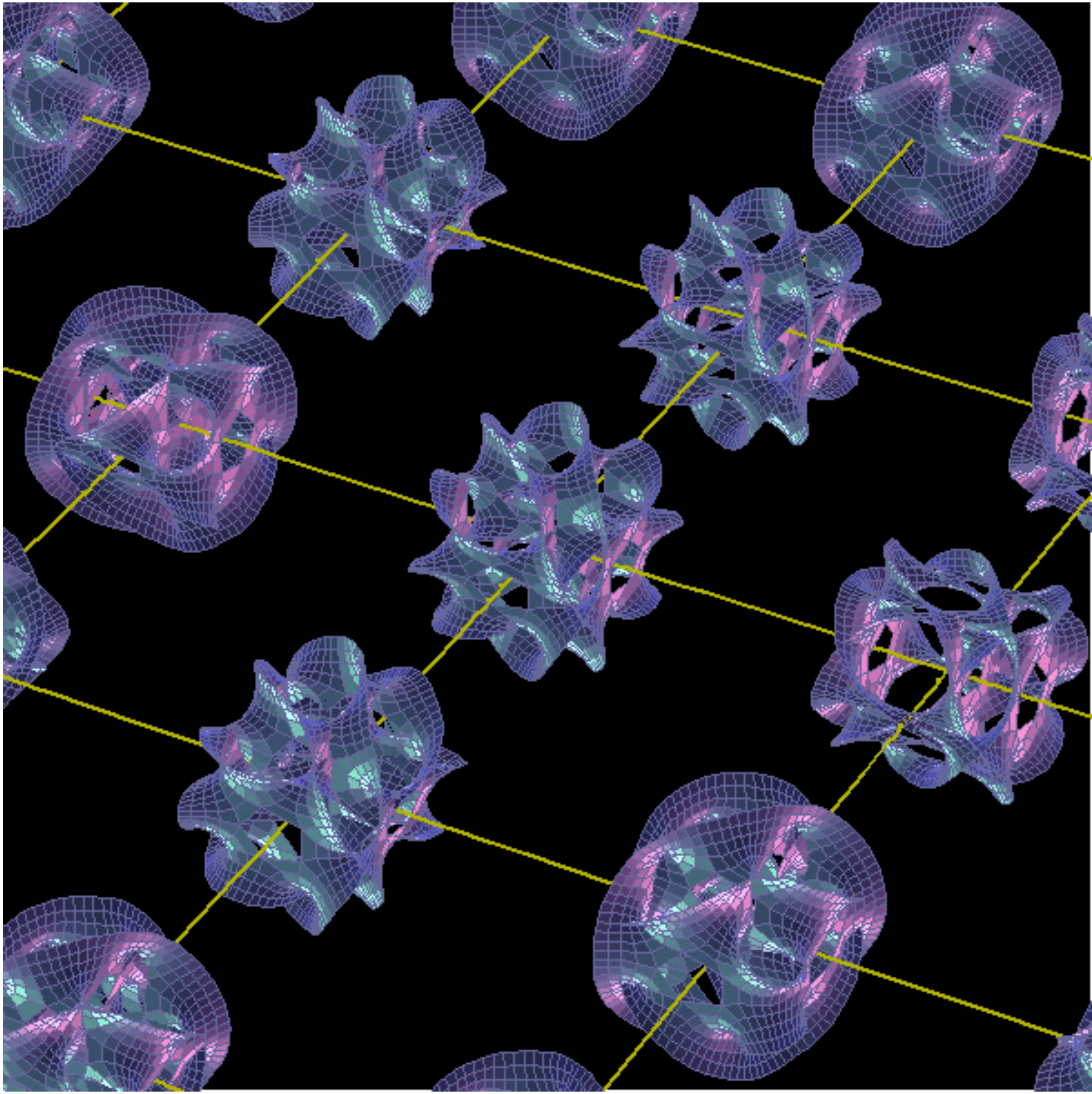
Office of Science
U.S. Department of Energy

String Theory Landscape may explain the incredibly small value of the cosmological constant

$$\Lambda \sim 10^{-120}$$

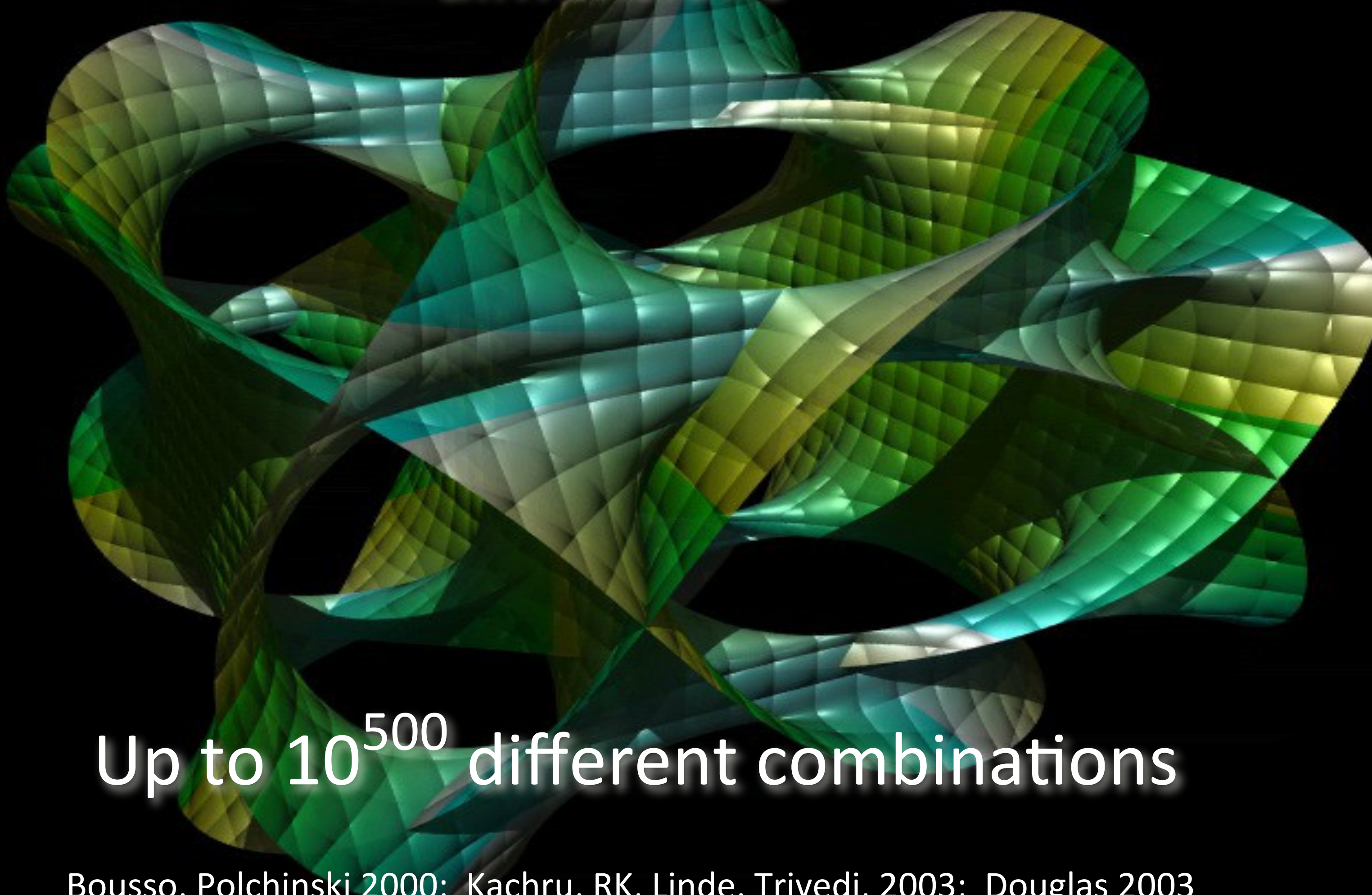
if the total number of such vacua is huge,

$$N \gg 10^{120}$$



Stable supersymmetric anti de Sitter vacua (under water, negative cosmological constant) and Minkowski vacua (sea level, vanishing cosmological constant) can be easily constructed. However, de Sitter vacua (over water, positive cosmological constant) break supersymmetry, very difficult to avoid tachyons and achieve stability.

In string theory, genetic code is written in properties of compactification of extra dimensions



Up to 10^{500} different combinations

Bousso, Polchinski 2000; Kachru, RK, Linde, Trivedi, 2003; Douglas 2003

Conclusion

The physics of the Universe can be more exciting than science-fiction, but it is real.

Cosmology, astro-particle and astro-physics deal with the
Large Scale Structure of the Universe!

There are many scientific puzzles there: Dark Energy, Dark Matter, Inflation, Black Holes, origin of Structure, origin of elementary particles, etc.

You can also contribute to this great scientific endeavour!

However, your ideas and thoughts must be consistent with ALL physics that we already now. It is not easy! Therefore, you may need to learn a lot!