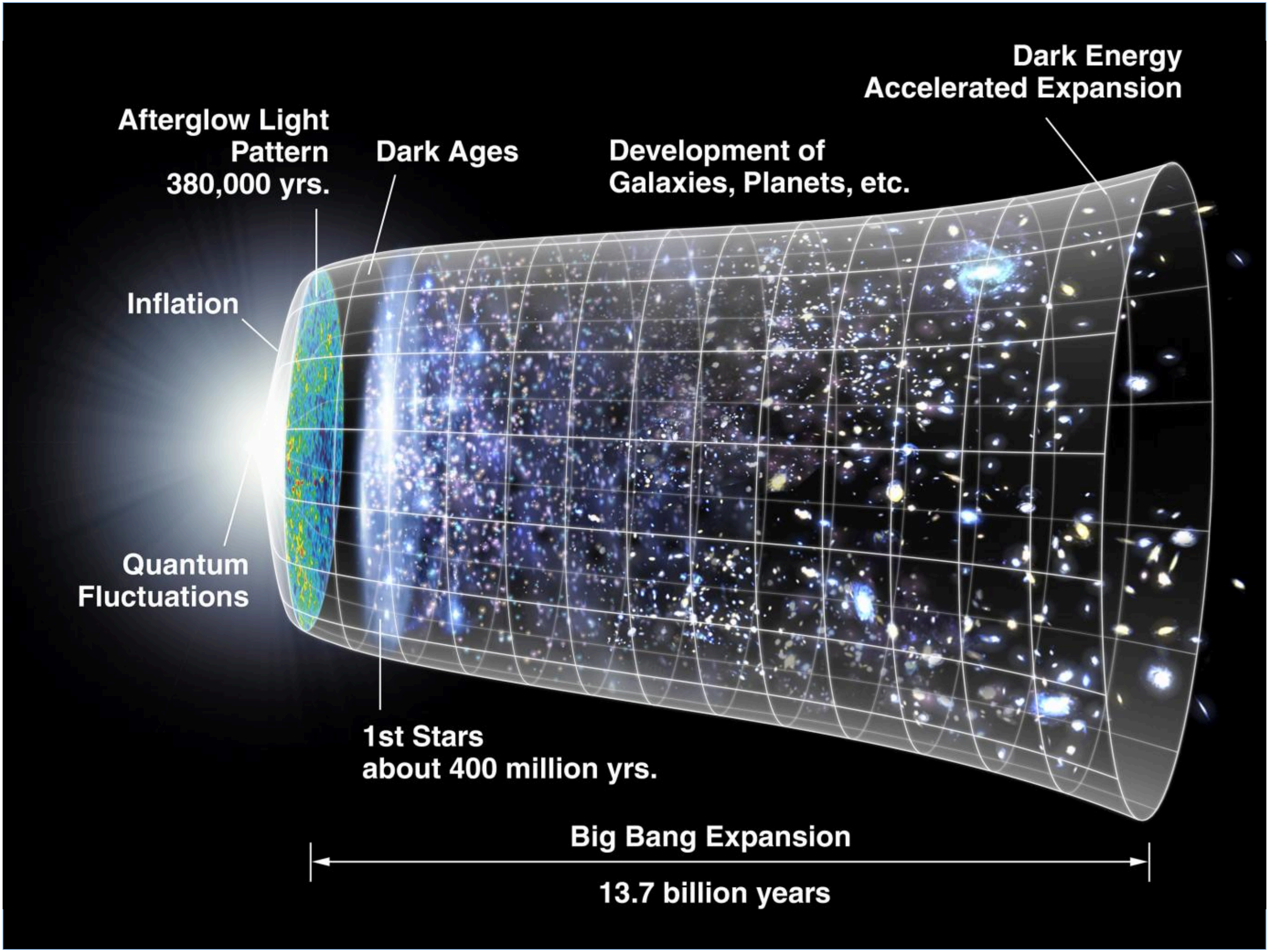
Inflation

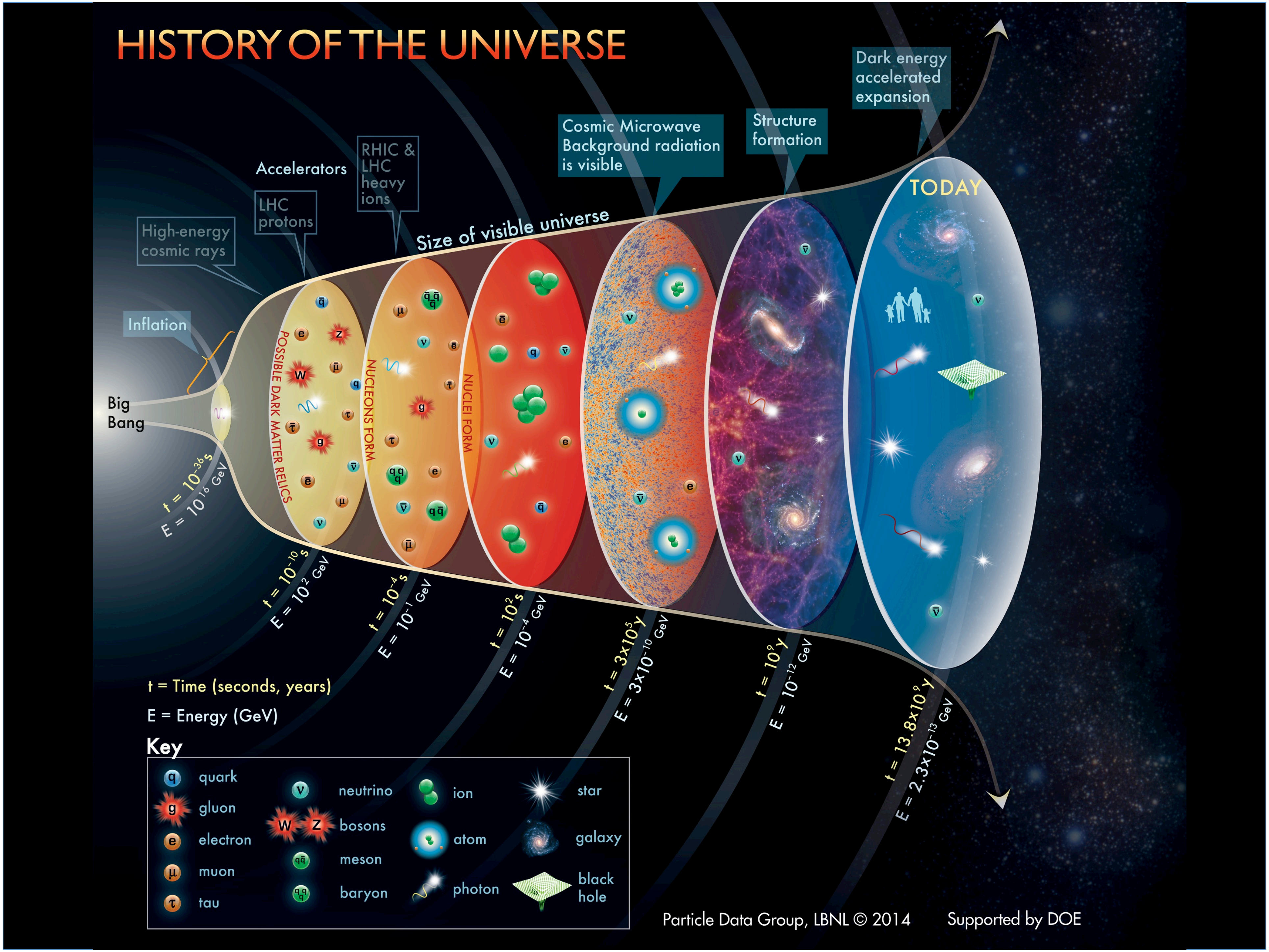
- Questions:
  - Why is the universe (close to) flat (K = 0)?
  - Why is the CMB homogeneous across the sky (no causal connection)?
  - Why is there any inhomogeneity in the CMB at all (10^{-5})?
- Answer: Inflation
  - Starting at $t = 10^{-37}$ s, Universe doubled in size every 10^{-37} s until about 10^{-35} s, growing from 10^{-30} m to about 1 cm
  - Driven by "Inflaton field" (similar to cosmological constant, constant density but expansion vastly faster)
  - Answers all 3 questions:
    - "Flattened out the wrinkles" (really: any type of Ω_Λ grows more rapidly than curvature and will completely dominate -> curvature must become zero)
    - All visible parts of the sky were in causal contact initially, but then were pushed too far apart by inflation to keep in causal contact.
    - Inhomogeneity comes from initial quantum fluctuations of size Planck length that were magnified 10^{28} times by inflation.

Inflation

- New Questions
  1. What is an Inflaton?
  2. Where are they today?
  3. Why did inflation stop after 10^{-35} s?
  4. How did all the “ordinary matter” come into being?
- Answers
  1. We don’t know – it’s a hypothetical particle
  2. They have a life time of only 10^{-35} s so they are all decayed now
  3. When they all decayed *), inflation stopped
  4. Ordinary matter (including dark matter etc.) is the decay product of those inflatons

*) But some pockets may have survived longer -> new baby-universes -> eternal inflation -> The Multiverse!


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
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
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→ COSMIC HISTORY

esa

10^{-32} seconds | 1 second | 100 seconds | 380 000 years | 300–500 million years | Billions of years | 13.8 billion years

Beginning of the Universe

Inflation
Accelerated expansion of the Universe

Formation of light and matter

Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures

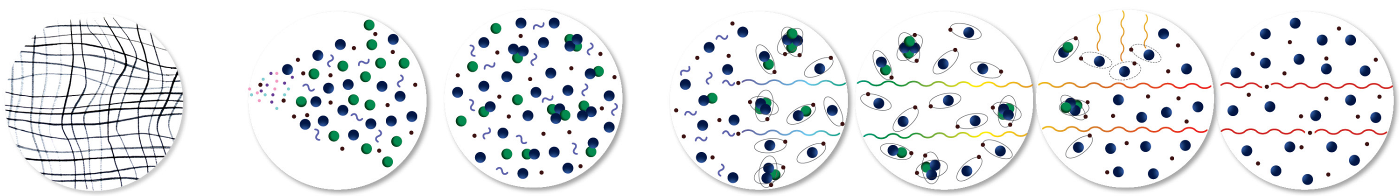
Light and matter separate
• Protons and electrons form atoms
• Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter

First stars
The first stars and galaxies form in the densest knots of the cosmic web

Galaxy evolution

The present Universe



• Tiny fluctuations: the seeds of future structures
• Gravitational waves?

Frequent collisions between normal matter and light

As the Universe expands, particles collide less frequently

Last scattering of light off electrons
→ Polarisation

The Universe is dark as stars and galaxies are yet to form

Light from first stars and galaxies breaks atoms apart and "reionises" the Universe

Light can interact again with electrons
→ Polarisation

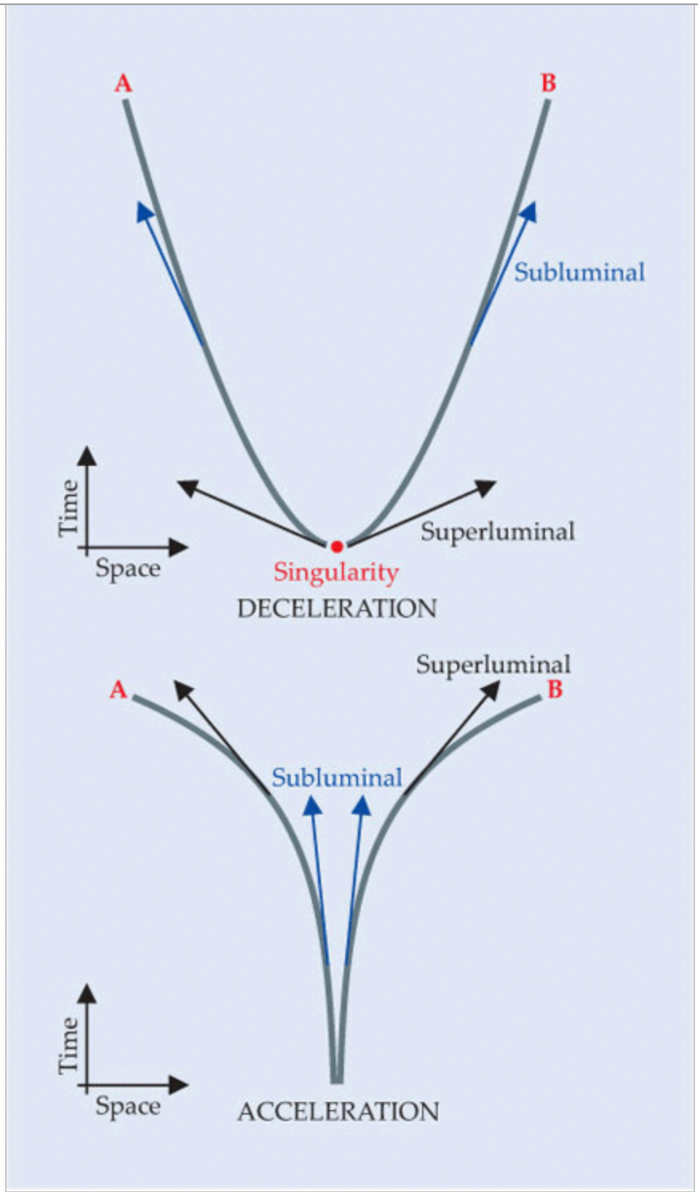
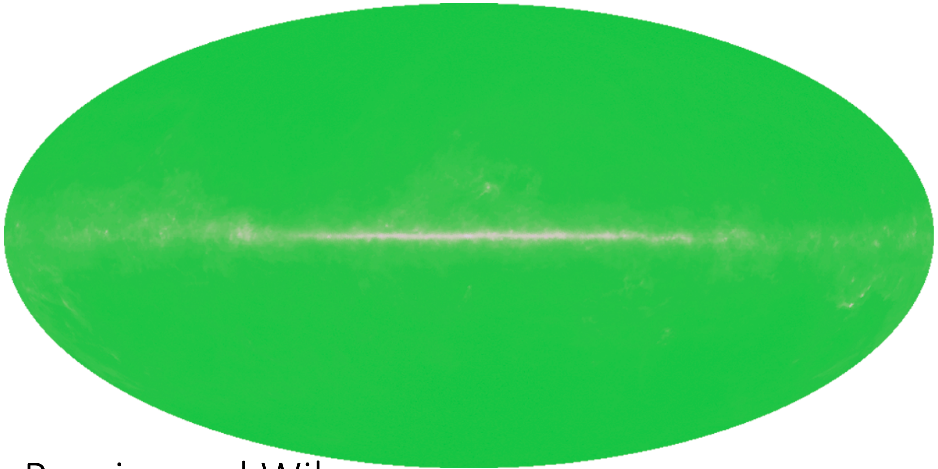


Figure 1. In an expanding universe, the distance between two separated points increases over time, simply due to the expansion of the space between them. The two panels here show the spacetime trajectories of two points, A and B. For the decelerating expansion illustrated in the top panel, the separation rate is greater in the past and even exceeds the speed of light at sufficiently early time. Thus A and B go from being out of causal contact—unable to influence each other—to being in causal contact. In an accelerating cosmos, the separation rate is smaller in the past; the two points go from being in causal contact to being out of causal contact. In the inflationary universe scenario, an early epoch of acceleration—the inflationary era—smoothly maps onto a long period of deceleration. Thus two points can go from being in causal contact to out of causal contact and, much later, back into causal contact. (Courtesy of Marius Millea.)

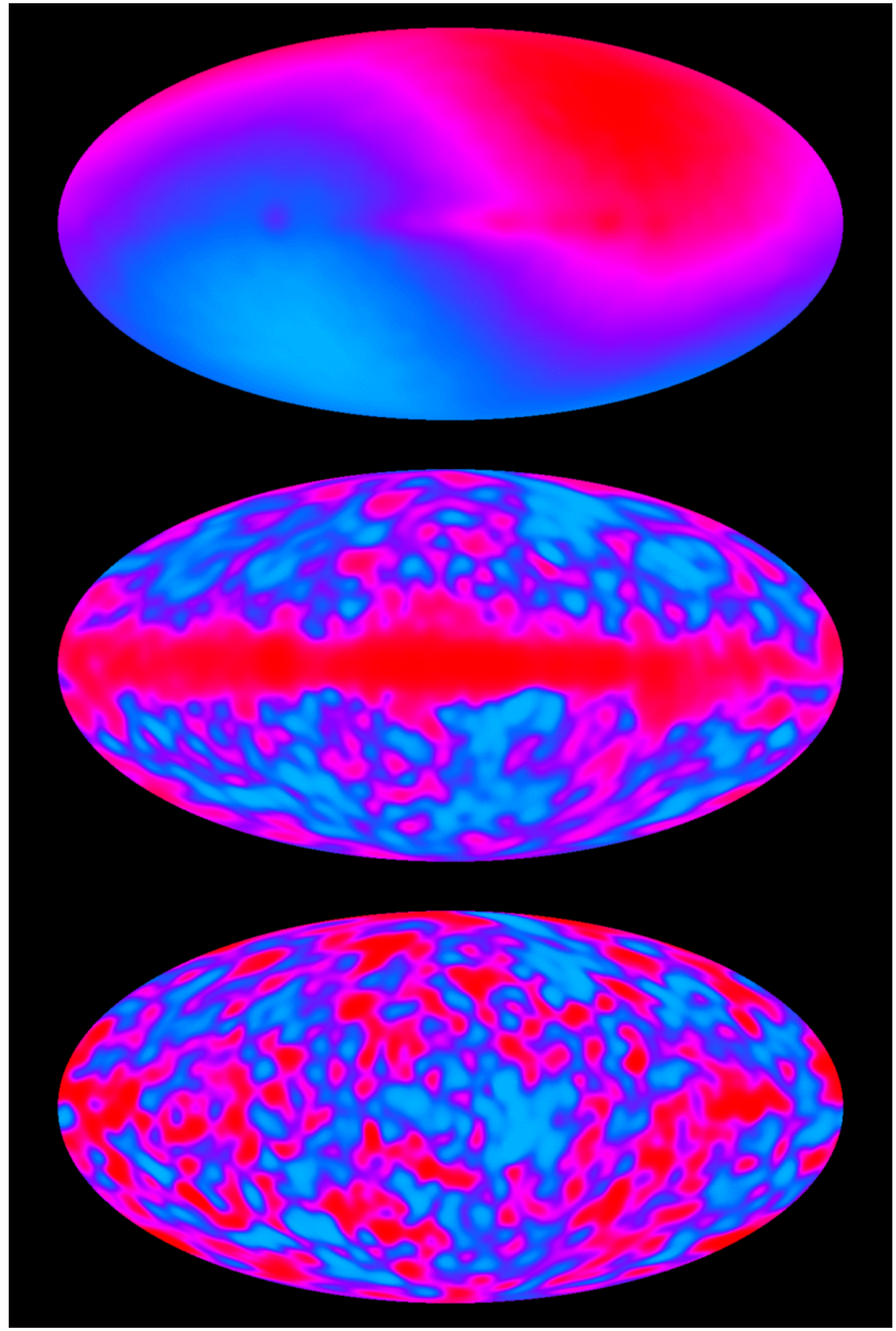


Penzias and Wilson
(simulated)

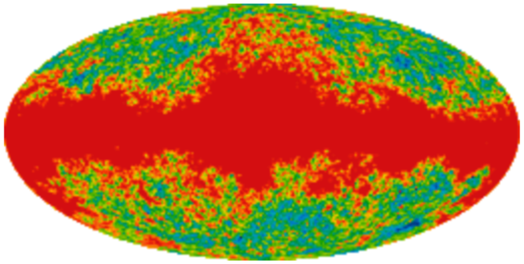
1) Dipole

2) Galactic µwave BG

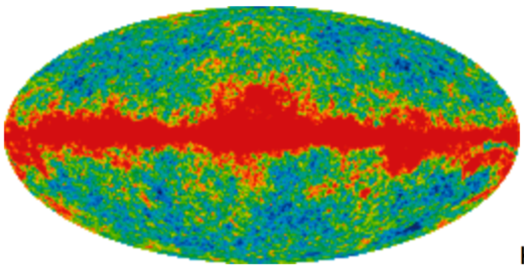
3) CMB



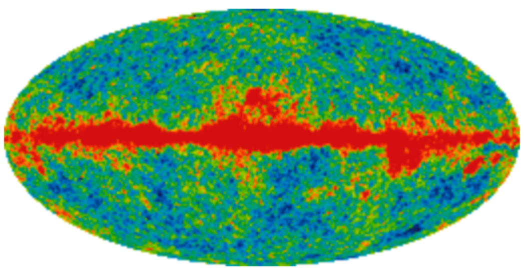
WMAP



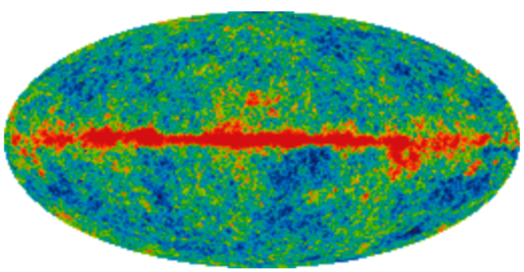
K band



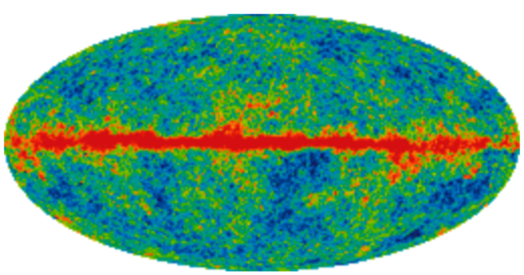
Ka band



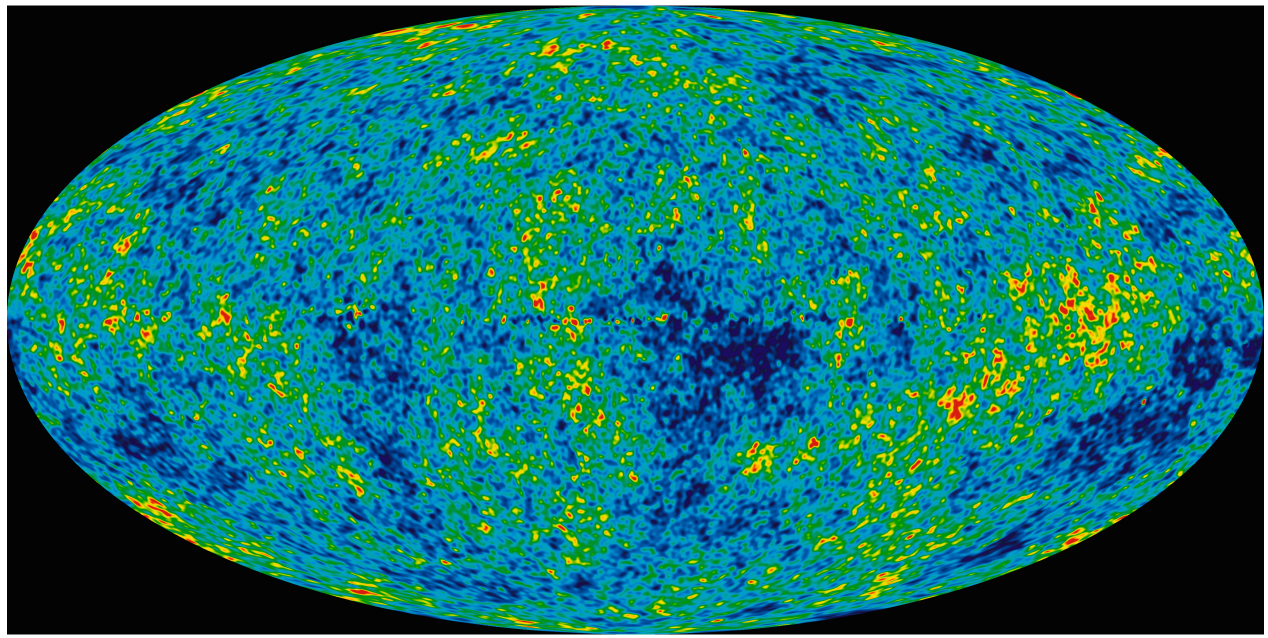
Q band

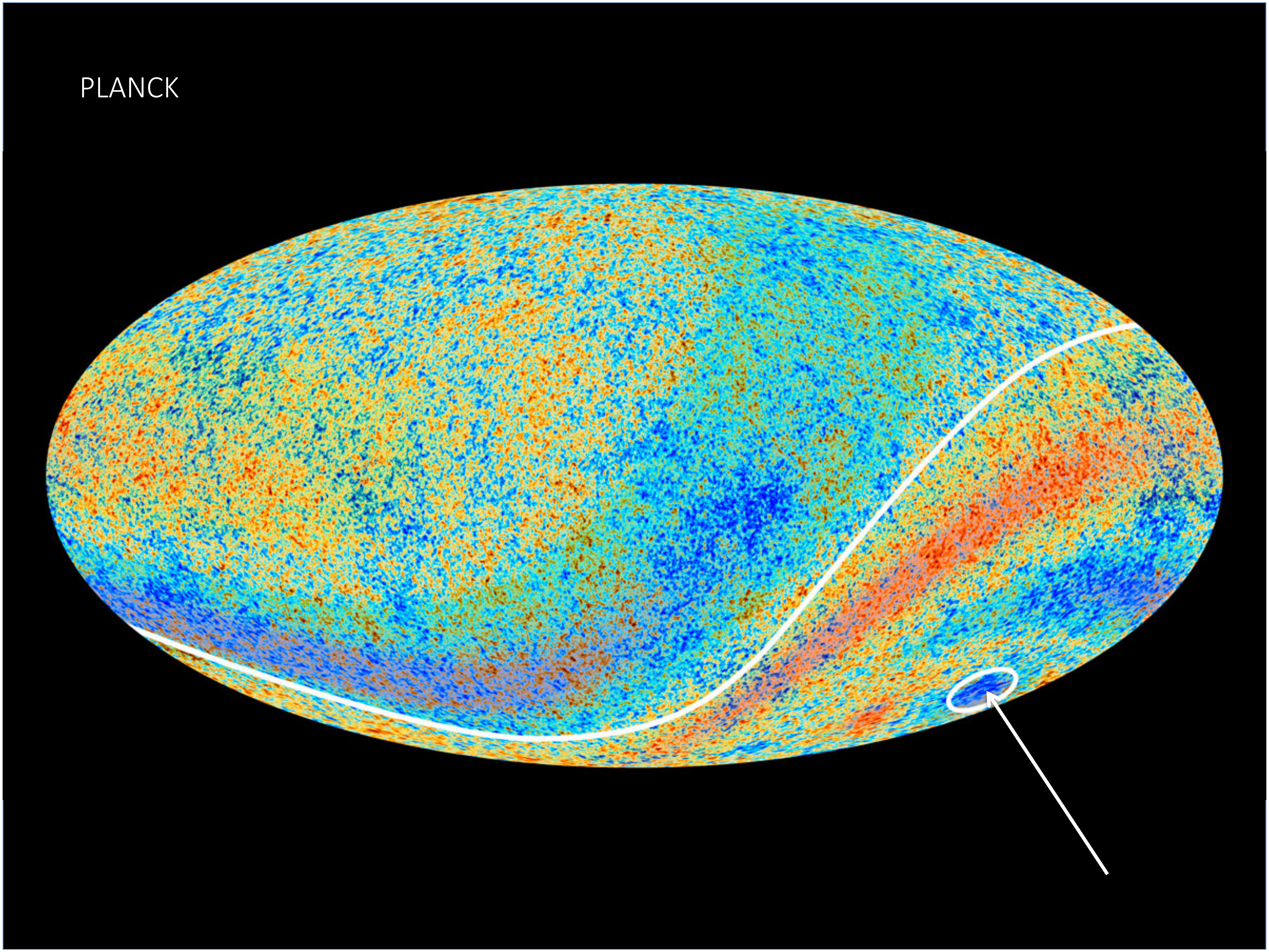


V band

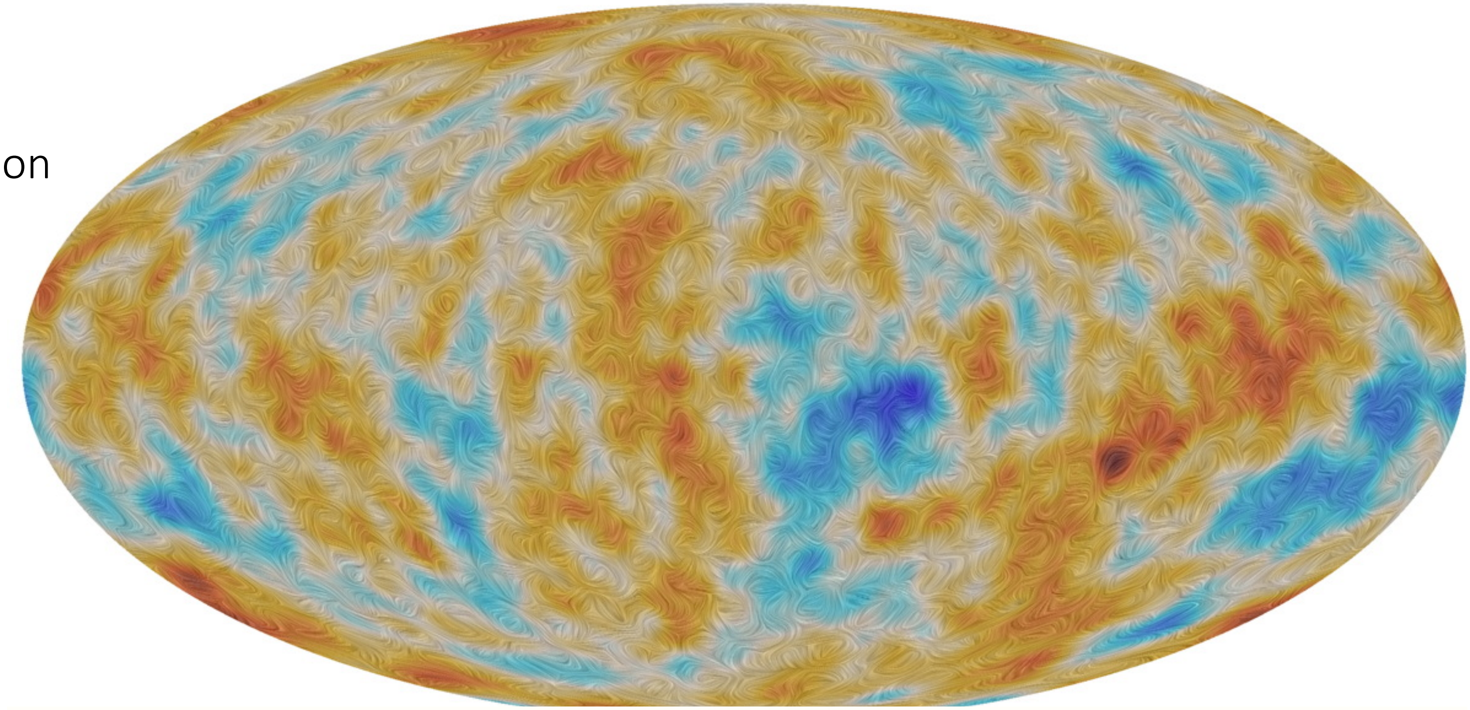


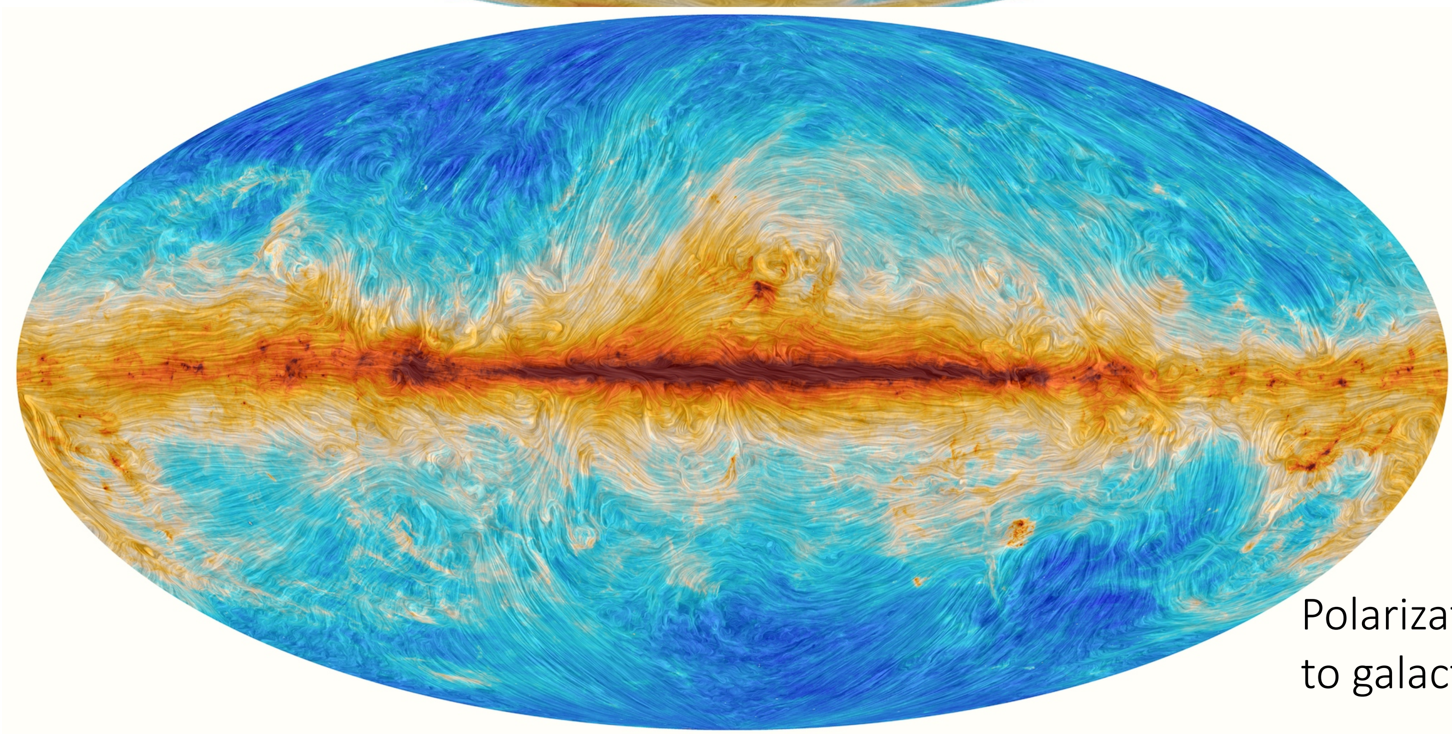
W band




PLANCK

BICEP2
Polarization





PLANCK
Polarization due
to galactic dust

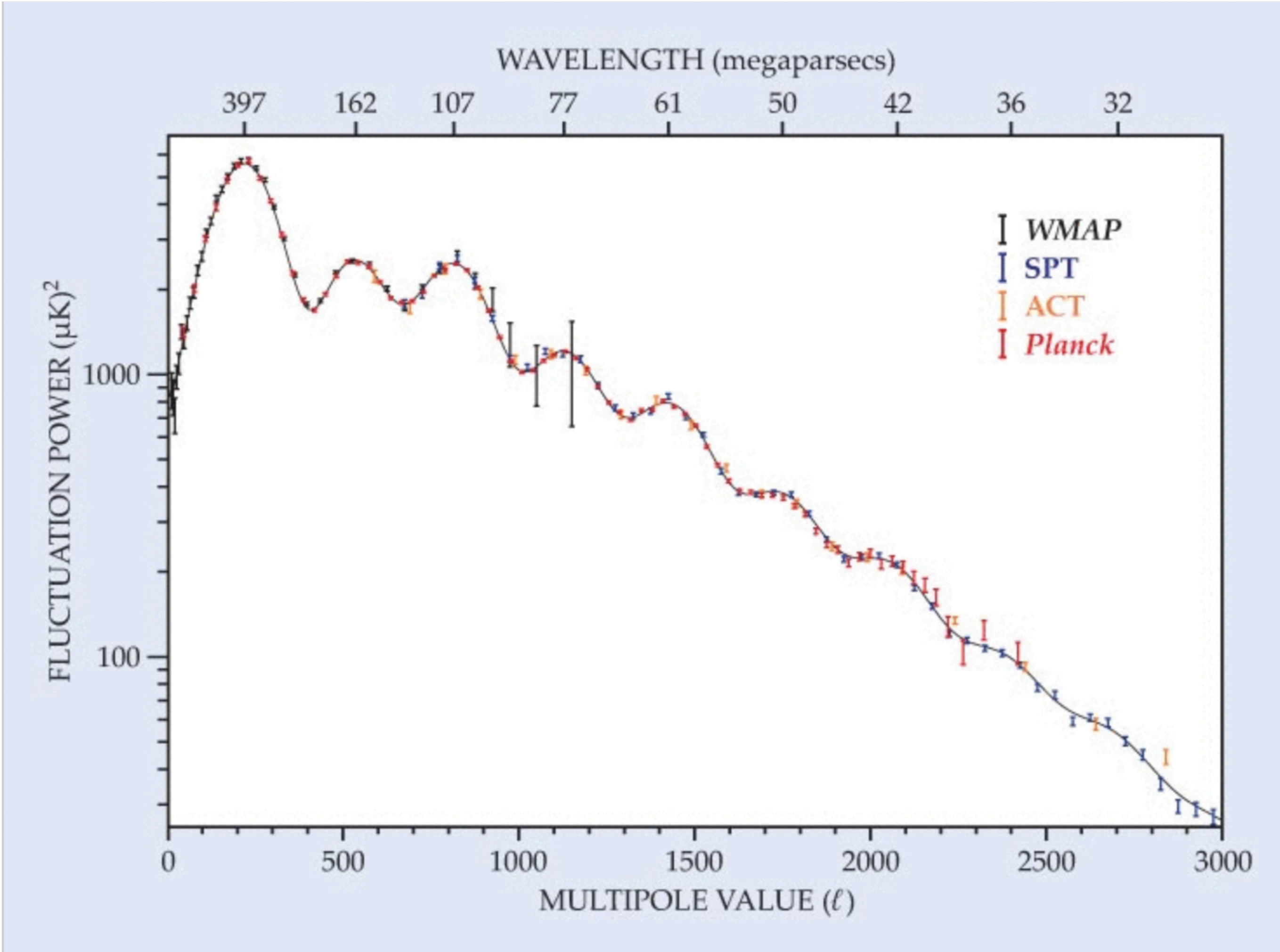


Figure 5. The angular power spectrum of the cosmic microwave background (CMB) displays a series of acoustic peaks, as predicted by inflation theory. A peak at a multipole value of ℓ means that the fluctuations in the CMB include a significant component of hot spots and cold spots separated by $180/\ell$ degrees. The first peak corresponds to acoustic oscillations (defined in the text, which also gives a precise definition of the fluctuation power) that reached their first extremum about 370 000 years after the Big Bang, when the universe decoupled, or became transparent to photons. As indicated on the upper axis, those modes now have a wavelength of about 400 megaparsecs (1.3×10^9 light-years). Modes with a current wavelength of 162 Mpc oscillated faster and achieved their second extremum at decoupling. Between those two wavelengths are modes with $\ell \approx 400$ that hit a null in their oscillations at decoupling; those modes are responsible for the trough at 213 Mpc. The data shown here were obtained by the *Wilkinson Microwave Anisotropy Probe* (*WMAP*), the South Pole Telescope (SPT), the Atacama Cosmology Telescope (ACT), and the *Planck* satellite. The curve is the prediction of a representative inflationary model. (Courtesy of Zhen Hou.)

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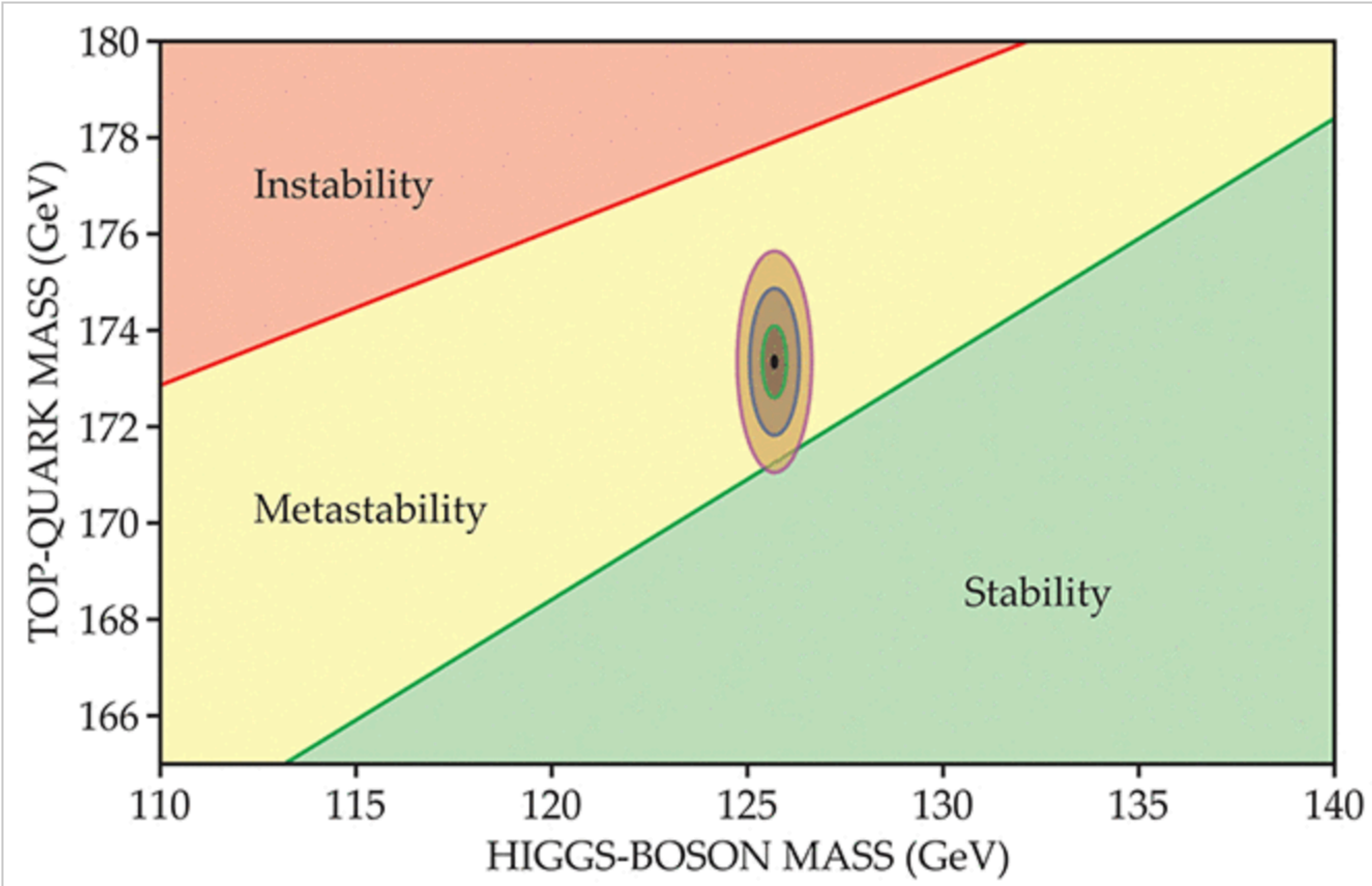

Figure 6. The universe is metastable, long-lived but not eternal, for certain combinations of top-quark and Higgs-boson masses. Given the current determination of the top-quark mass, the Higgs-boson mass of about 125 GeV is close to the boundary for stability, but a definitive answer will require a much more precise measurement of the top-quark mass. The three ellipses represent 1-σ, 2-σ, and 3-σ confidence areas for the mass determinations. (Adapted from ref. 10 , which uses a somewhat different Higgs-boson mass than we cited in the main text.)

Citation: Phys. Today **68**, 4, 46 (2015); http://dx.doi.org/10.1063/PT.3.2749