Cosmology Perspectives

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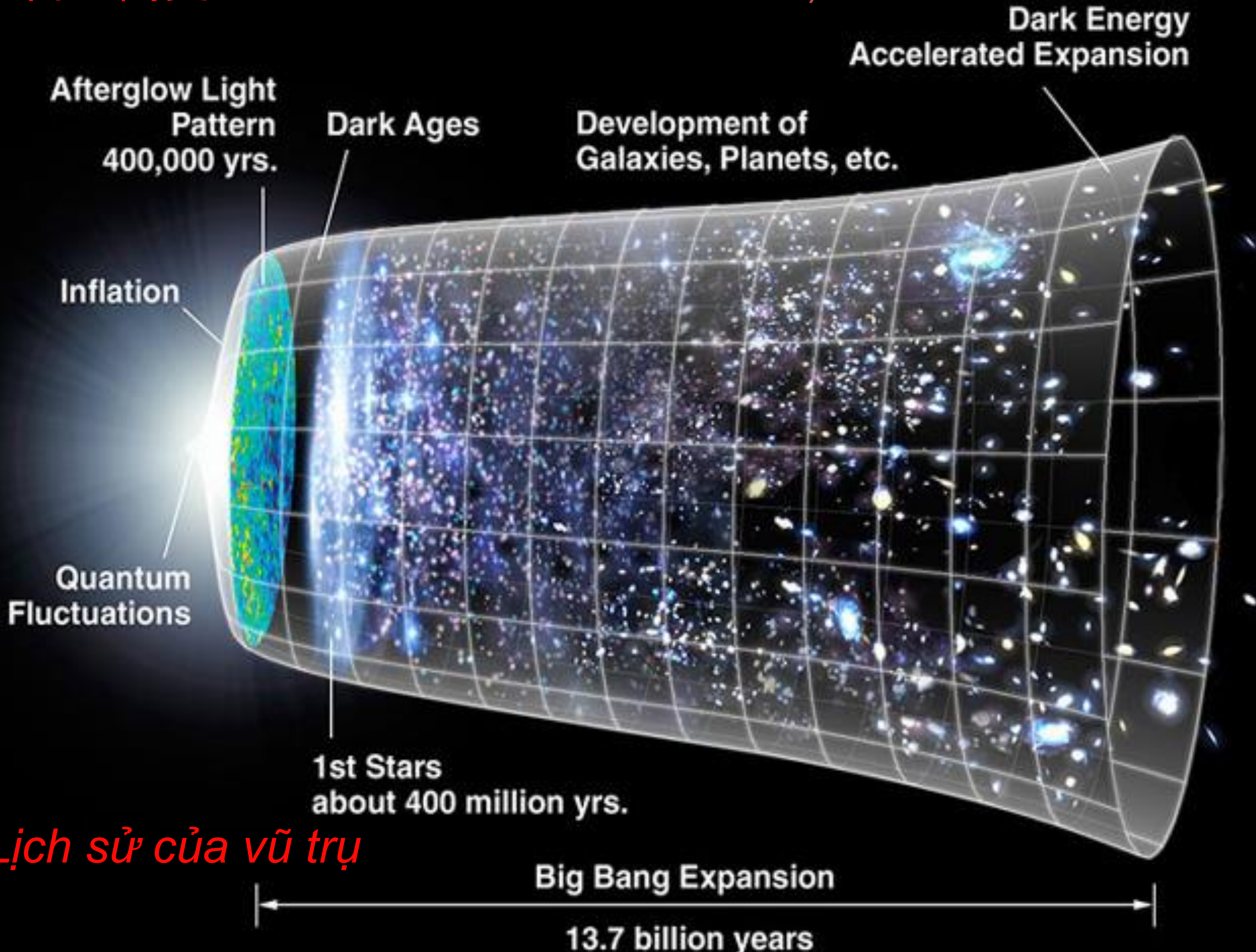
宇宙的簡史

Breve historia del universo; Brève histoire de l’univers



Lịch sử của vũ trụ

Краткая история Вселенной 우주의 간단한 병력 검사 Brief History of the Universe

THE HISTORY AND FATE OF THE UNIVERSE

The Big Bang, Inflation & the Expanding Universe

The universe has been expanding since an initial moment called the Big Bang that occurred 13.8 billion (13.8 x 10^9) years ago. The earliest expansion – called "inflation" – was extraordinarily rapid and smoothed out any wrinkles or imperfections, just as we can stretch out a wrinkled fabric. After inflation ended in a tiny fraction of a second, the universe continued to expand, becoming cooler and less dense. The expansion causes the distance between distant galaxies to increase, and thus the distance from us to them.

A Relic from the Early Universe

For the first 380,000 years the universe was so hot that hydrogen atoms had not yet formed, but were separate electrons and protons. Photons, the particles of light, bounced back and forth from collisions with the electrons. With further cooling, the electrons and protons stuck together in neutral atoms, nearly invisible to the photons, which then escaped. We can see these very same photons today. After traveling for 13.8 billion years they arrive, but with their wavelength stretched by a factor of 1100, since the universe itself has stretched by this factor during that time.

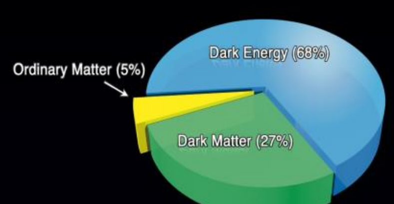
This Cosmic Microwave Background (labelled in the central figure) is nearly the same viewed in every direction. The very small variations – a part in 100,000 – are evidence of the small variations, which grew through gravitational attraction, to make the much larger variations we see today, things like galaxies and solar systems.

Dark Matter

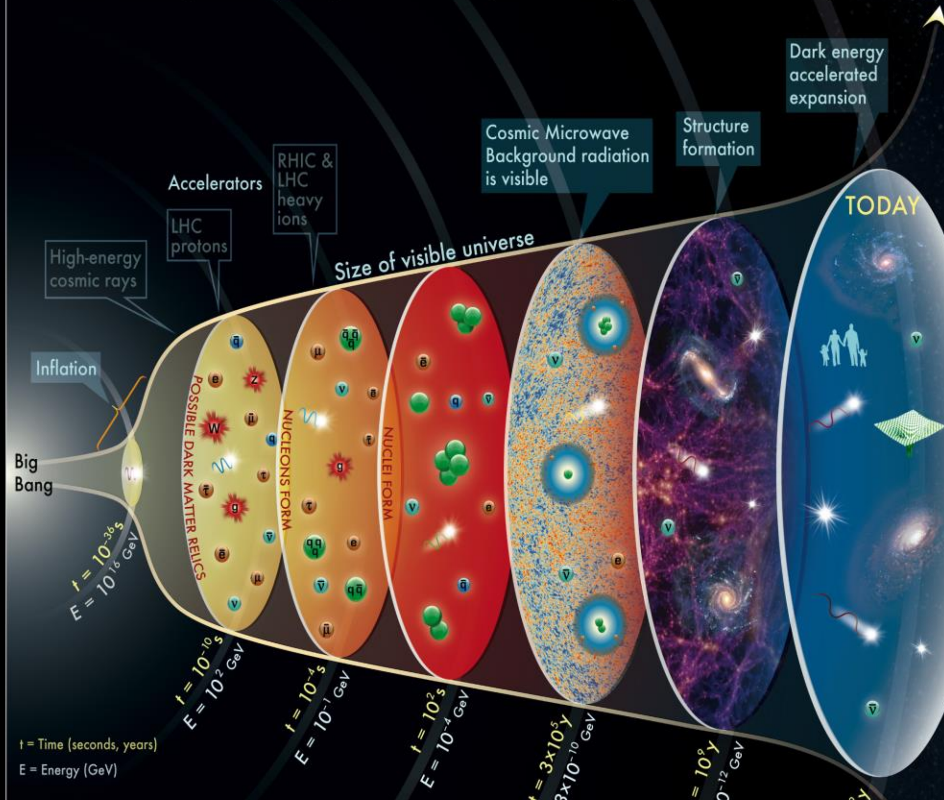
Astronomers discovered that stars far out in a rotating galaxy move just as fast as those nearer the center. This is completely unlike our solar system where the innermost planets move the fastest. This couldn't happen if the matter in the galaxy is concentrated where we see stars; there must be much more unseen matter in the galaxy. This matter doesn't emit light or reflect it, so we call it dark matter. Since dark matter doesn't clump together with ordinary matter, we believe it interacts only feebly with the matter that makes up stars, planets, and people.

We have observed the results of a collision of two clusters of galaxies where the dark matter from the two clusters seems to have passed right through the other cluster, leaving behind the debris from the collision of the ordinary gas in the two clusters. Detailed measurements show that there is about six times more dark matter than ordinary matter in our universe. Detailed measurements show that there is about six times more dark matter than ordinary matter in our universe.

Composition of the Universe



Ancient light from sources billions of light-years away, such as galaxies and the cosmic background radiation, show us events occurring billions of years ago. These events map out the history of the universe and even predict its fate.



The concept for the above figure originated in a 1986 paper by Michael Turner.

Our Cosmic Address

Our sun is one of 4 x 10^{11} stars in the Milky Way galaxy, which is one of more than 10^{11} galaxies in the visible universe.

Invisible Skeleton of our Universe

Dark matter played a crucial role in the early universe creating all the structures we see today. Gravity caused the dark matter to coalesce into strands forming an invisible skeleton, as shown in the central figure (indicated by "Structure formation"). The gravity from the dark matter pulled ordinary matter to it. Then galaxies grew at the intersections of these filaments.

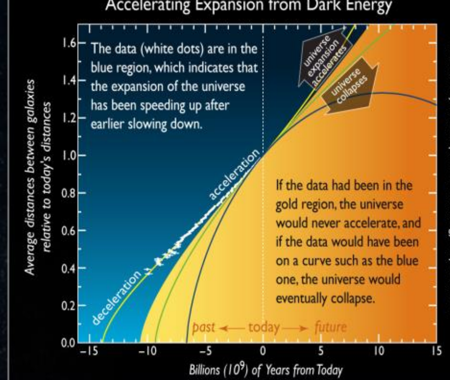
Dark Energy and the Accelerating Universe

By making detailed observations of distant supernovae, which are stars that exploded long ago, scientists discovered that the expansion of the universe is getting faster and faster instead of slowing down as would be expected from the effect of gravity pulling everything back together.

The plot shows data (white dots) from distant supernovae. From the brightness of a supernova we can infer how far away it is. By measuring the wavelengths of light from the supernova, we can determine how much the universe has expanded since the supernova explosion. Combining these gives the expansion history of the universe.

The yellow curve, with the best fit to the supernovae data, shows that about 6 billion years ago the expansion of the universe began to accelerate (the data curve upward slightly). This can only be explained by hypothesizing a new form of energy called "dark energy," which must be unlike any previously known source of energy.

Accelerating Expansion from Dark Energy



The Fate of the Universe

Whether the expansion of the universe will speed up, slow down, or even reverse into collapse depends on the types and amounts of matter and energy in it. With current observations, we believe the universe will keep expanding forever, with galaxies becoming ever more distant from one another.

We have an excellent understanding of ordinary matter and all the particles discovered at accelerators, but these account for less than 5% of the energy in the universe. The 68% in dark energy and the 27% in dark matter are two of the greatest questions facing physical science.

Learn more at
UniverseAdventure.org
and at CPEPphysics.org

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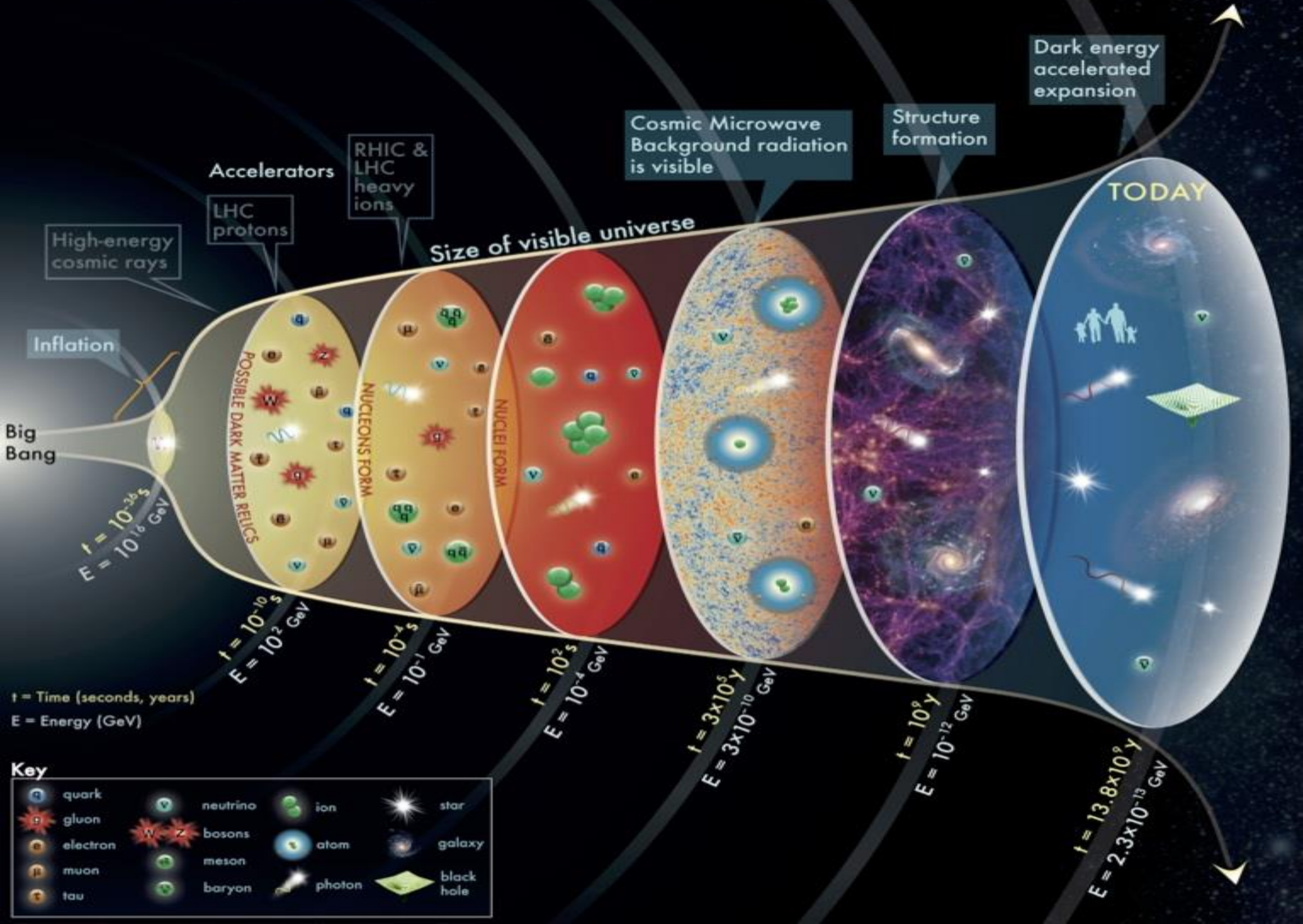


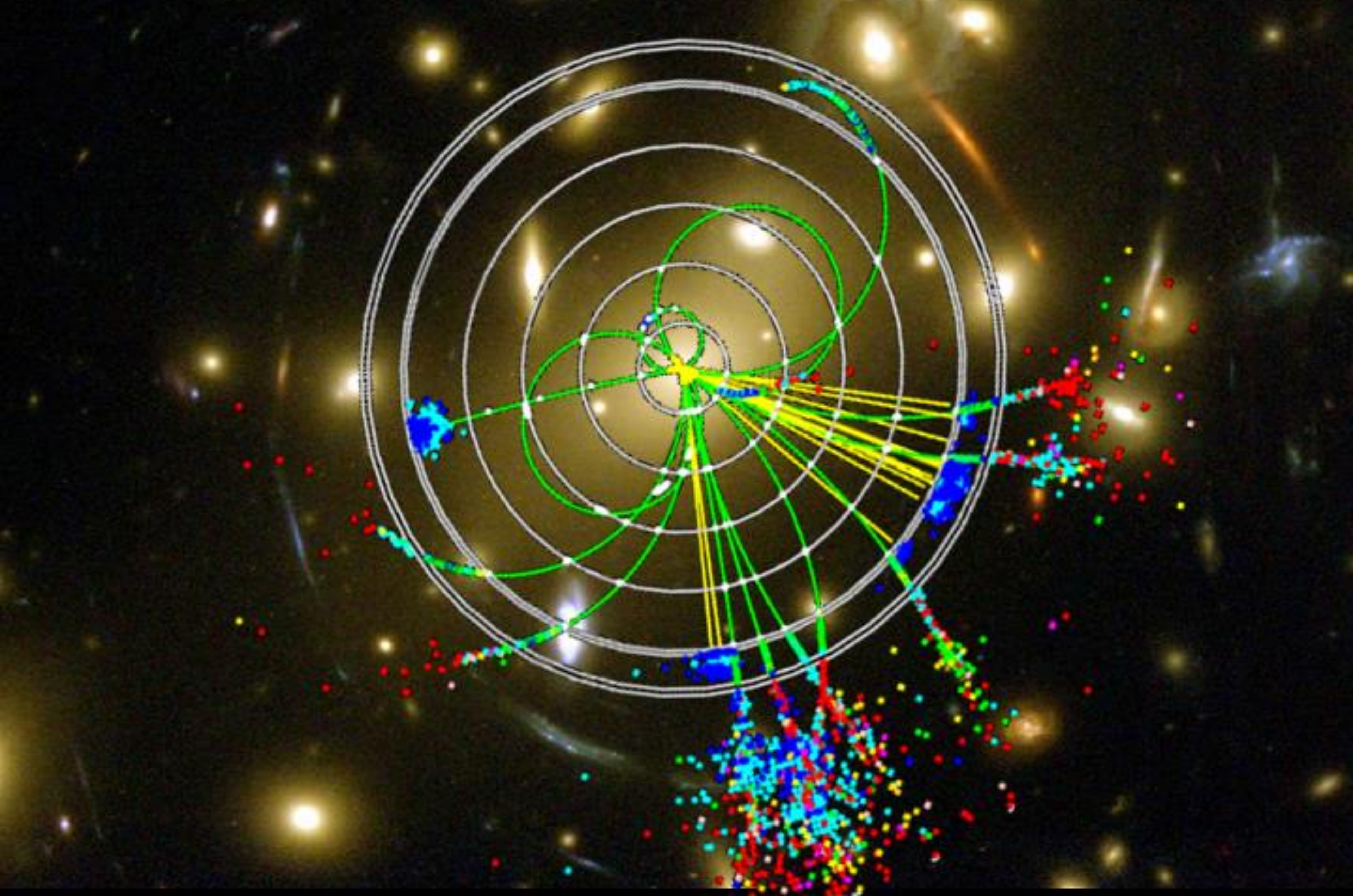
Particle (HEP) Physics vs Cosmology Beginning Three Decades Ago

- **Standard Model Particle Physics** formulation was finalized in the mid-1970s upon experimental confirmation of the existence of quarks
- top quark (1995)
- tau neutrino (2000)
- the Higgs boson (2013)
- Marked by continuing improved precision and rigour.

- Physics Beyond the SM?
- Neutrino Oscillation; mass: Solar (60's-2002), Atmospheric (1998), Reactor (2002), Beam (2000s)

- **Cosmology**
- Many things not known or at least not better than factor of 2
- CMB discovered (1965), found to be blackbody (1991), Anisotropy (1992), exploitation ever since leading towards precision and eventually to rigour.
- Baryogensis concept (1967) by Andre Sakharov
- Dark Matter suspected (70's)
- Inflation proposed (1980)
- Accelerating Universe (1998)
- Still unsolved issues

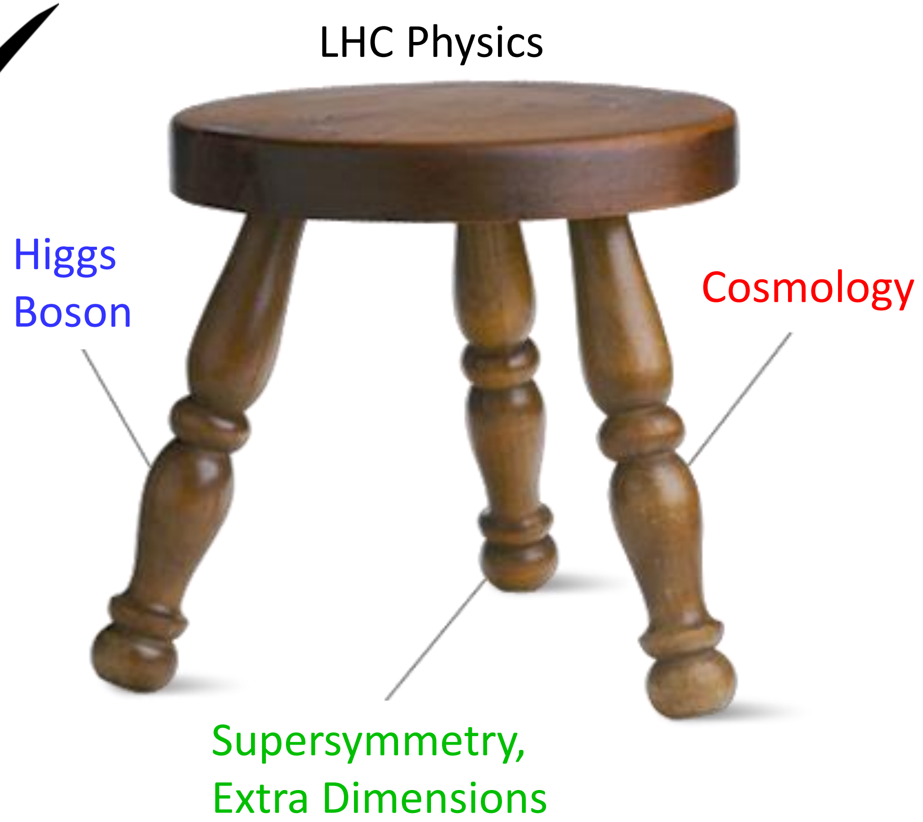
COLLIDER PHYSICS AND COSMOLOGY



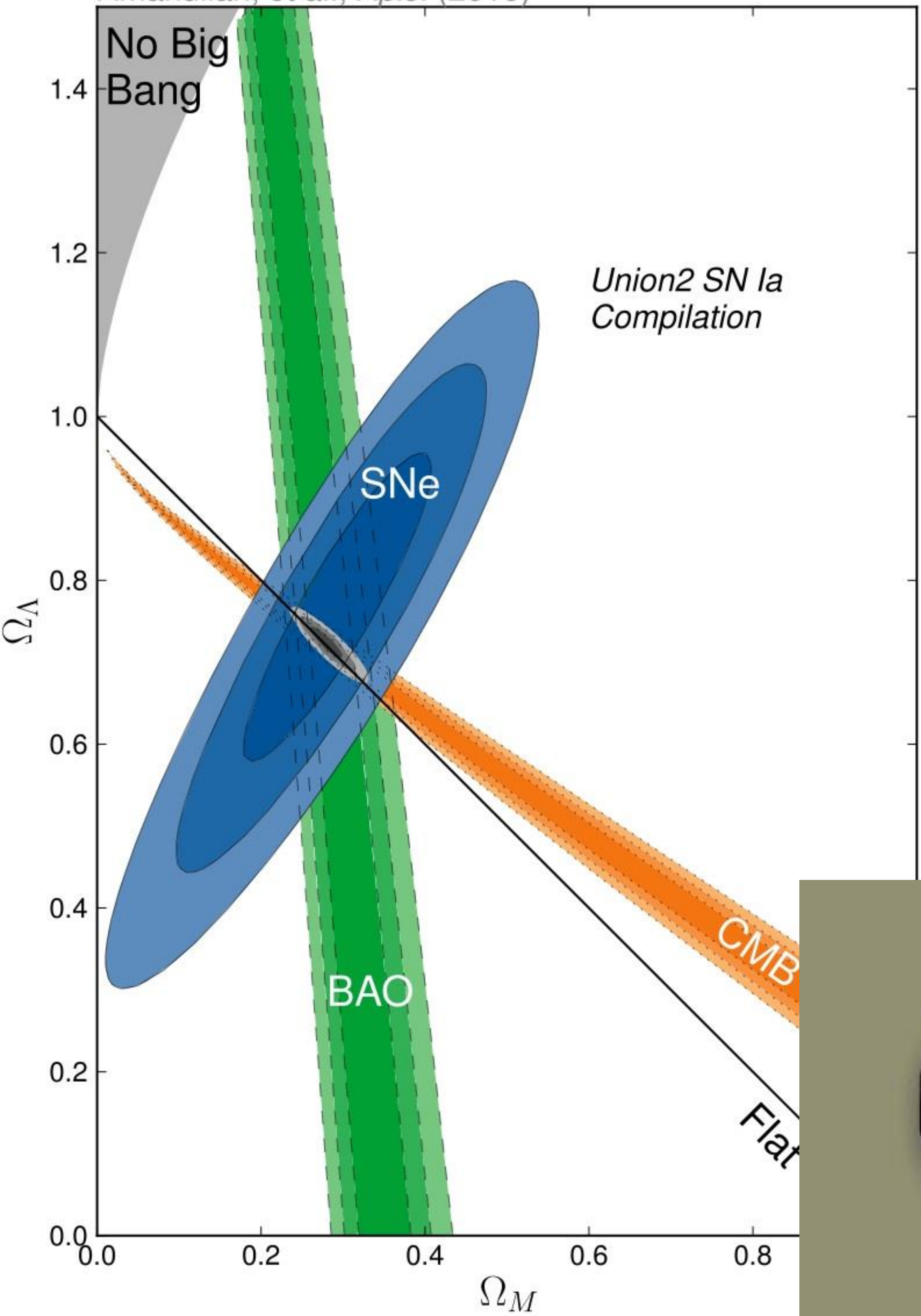
Understanding Physics with LHC

Based on three legs:

- Finding the Higgs ✓
- Supersymmetry (& extra dimensions)
- Cosmology
  - Dark Matter
  - Baryogenesis
  - Inflation / extra d
  - Dark Energy



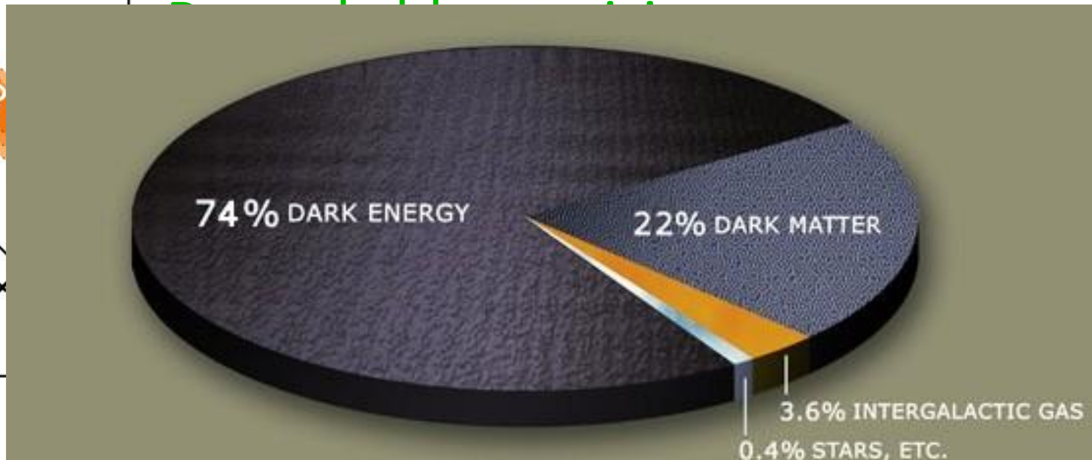
Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)



COSMOLOGY NOW

Remarkable agreement

Dark Matter: 23% ± 4%
Dark Energy: 70% ± 4%
Baryons: 4.5% ± 0.4%
Neutrinos: 2% (Σm_ν/eV)



OPEN QUESTIONS

DARK MATTER

- What is its mass?
- What are its spin and other quantum numbers?
- Is it absolutely stable?
- What is the symmetry origin of the dark matter particle?
- Is dark matter composed of one particle species or many?
- How and when was it produced?
- Why does Ω_{DM} have the observed value?
- What was its role in structure formation?
- How is dark matter distributed now?

DARK ENERGY

- What is it?
- Why not $\Omega_\Lambda \sim 10^{120}$?
- Why not $\Omega_\Lambda = 0$?
- Does it evolve?

BARYONS

- Why not $\Omega_B \approx 0$?
- Related to neutrinos, leptonic CP violation?
- Where are all the baryons? Anti-baryons

THE DARK UNIVERSE

The problems appear to be completely different

DARK MATTER

- No known particles contribute
- Probably tied to $M_{\text{weak}} \sim 100$ GeV
- Several compelling solutions

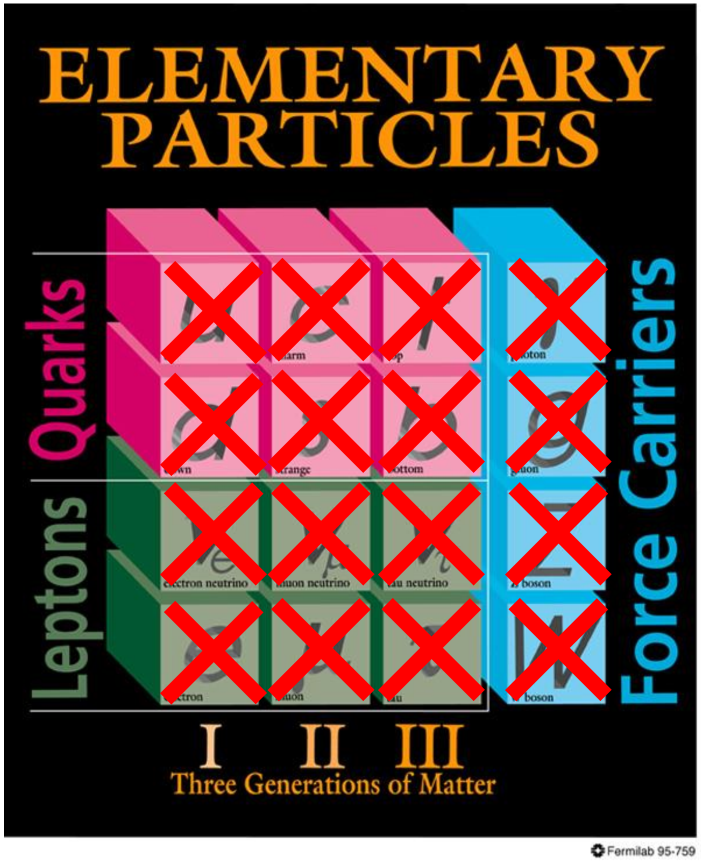
DARK ENERGY

- All known particles contribute
- Possibly tied to $M_{\text{Planck}} \sim 10^{19}$ GeV
- No compelling solutions

INFLATION

- Apparently no known particles contribute
- Probably tied to $M_{\text{Planck}} \sim 10^{19}$ GeV
- No compelling solutions

DARK MATTER



Known DM properties

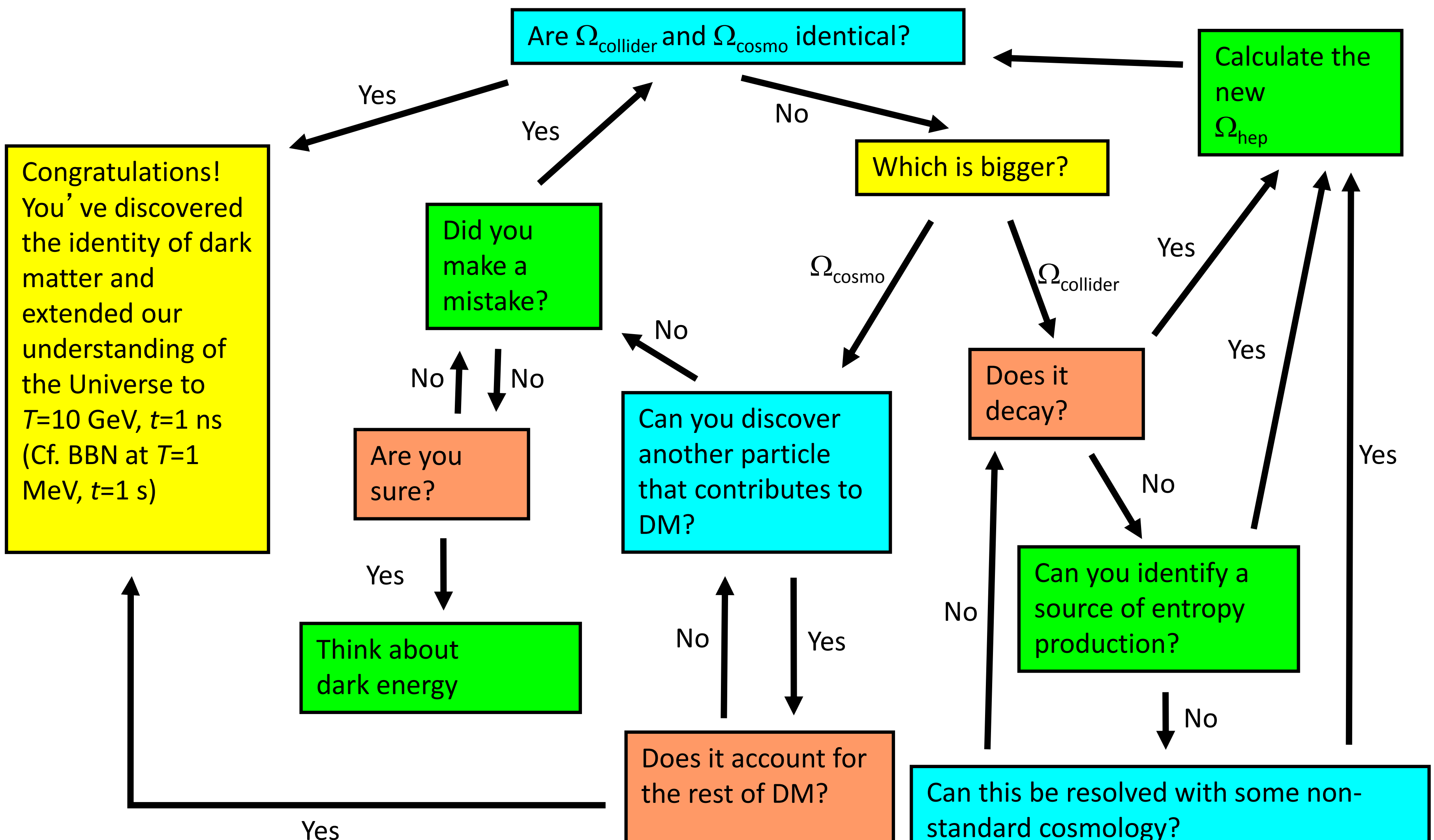
- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

Unambiguous evidence for new physics

DARK MATTER CANDIDATES

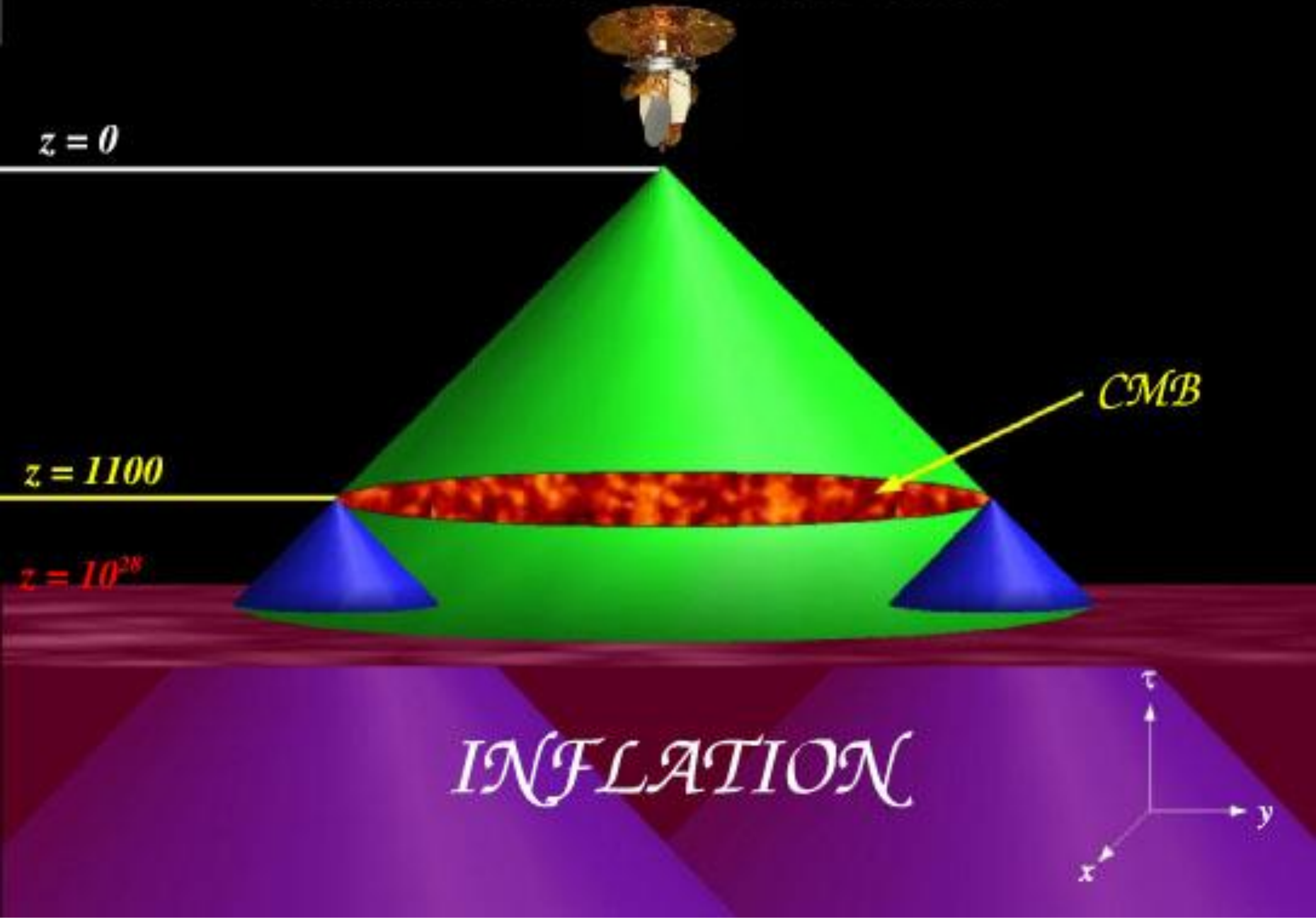
- The observational constraints are no match for the creativity of theorists
- Candidates: primodial black holes, axions, warm gravitinos, neutralinos, sterile neutrinos, Kaluza-Klein particles, Q balls, wimpzillas, superWIMPs, self-interacting particles, self-annihilating particles, fuzzy dark matter,…
- Masses and interaction strengths span many, many orders of magnitude, but not all candidates are equally motivated

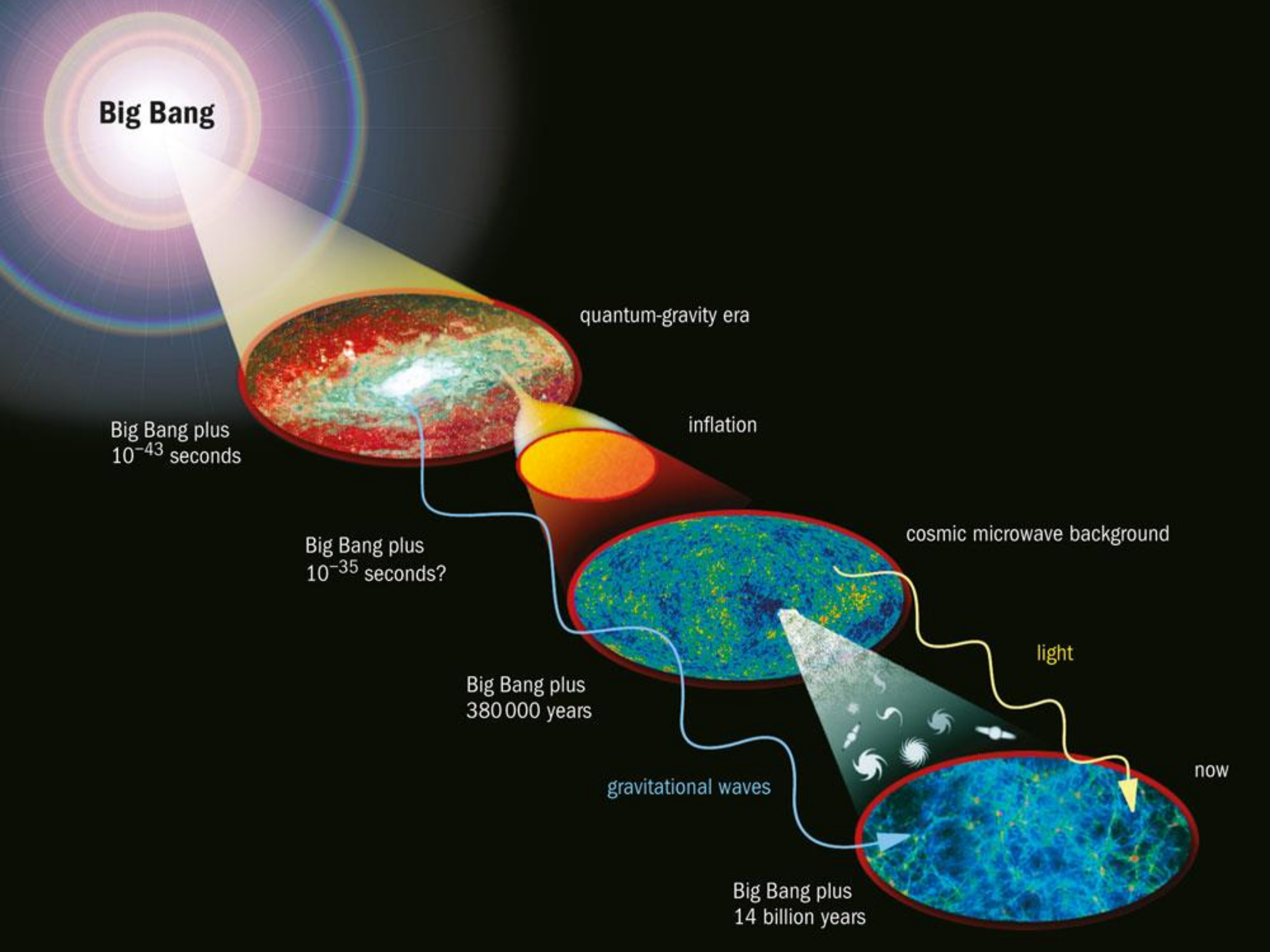
IDENTIFYING DARK MATTER




Inflation

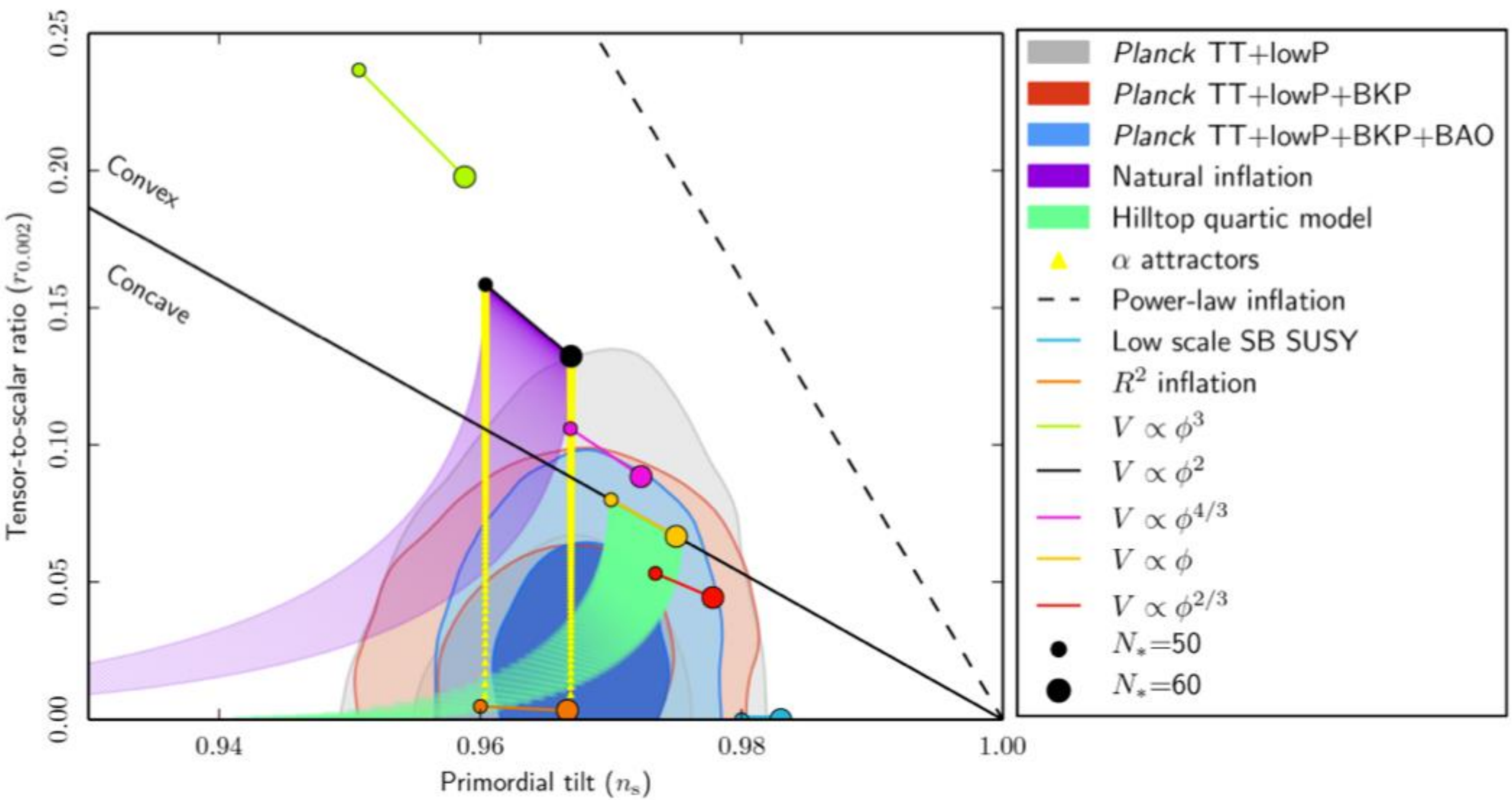
Inflation solves the Horizon Problem



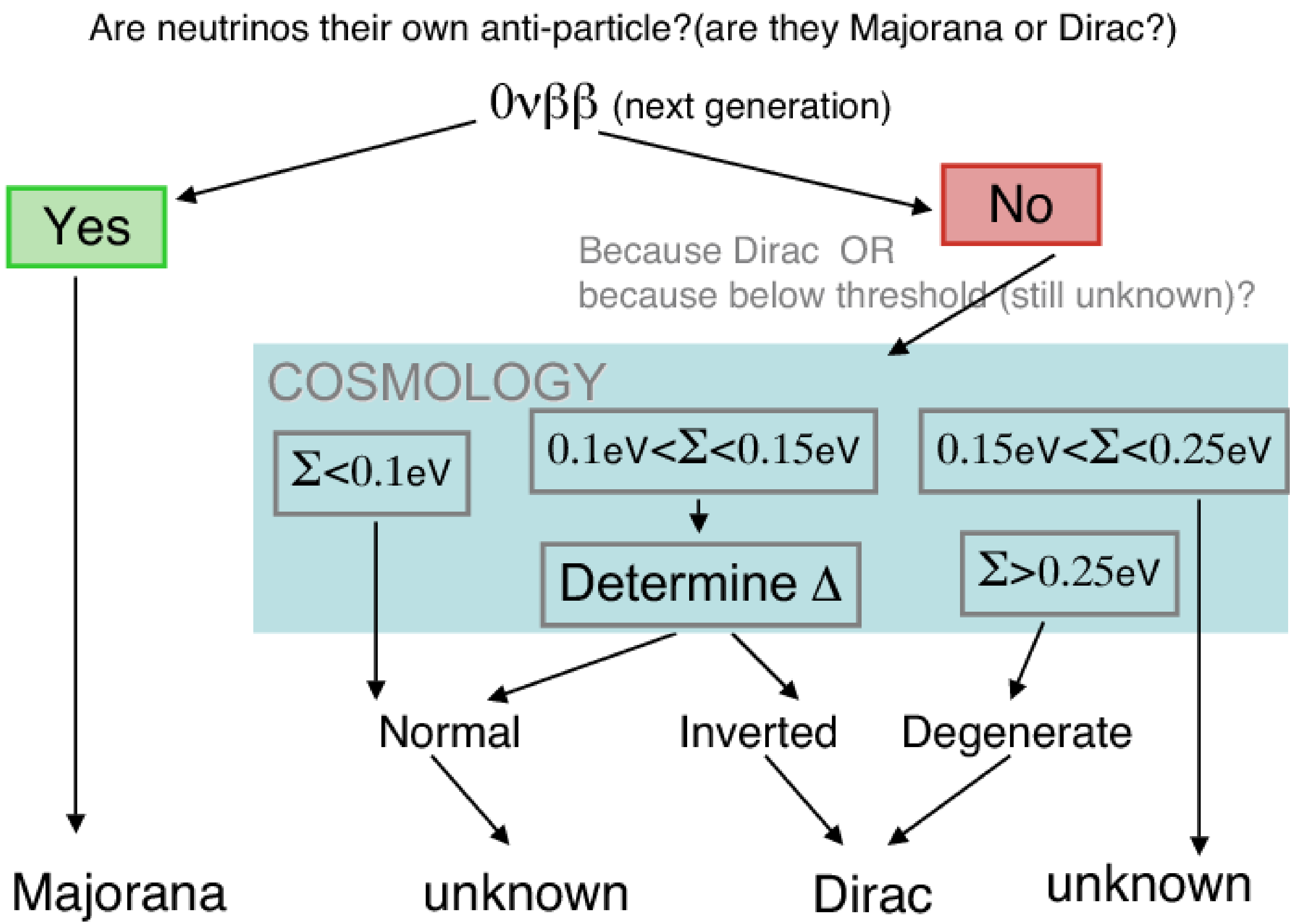

Big Bang
quantum-gravity era
Big Bang plus
10^{-43} seconds
inflation
Big Bang plus
10^{-35} seconds?
cosmic microwave background
light
Big Bang plus
380 000 years
gravitational waves
now
Big Bang plus
14 billion years

Planck 2015 Constraints on Inflation

Calls for quite flat potential

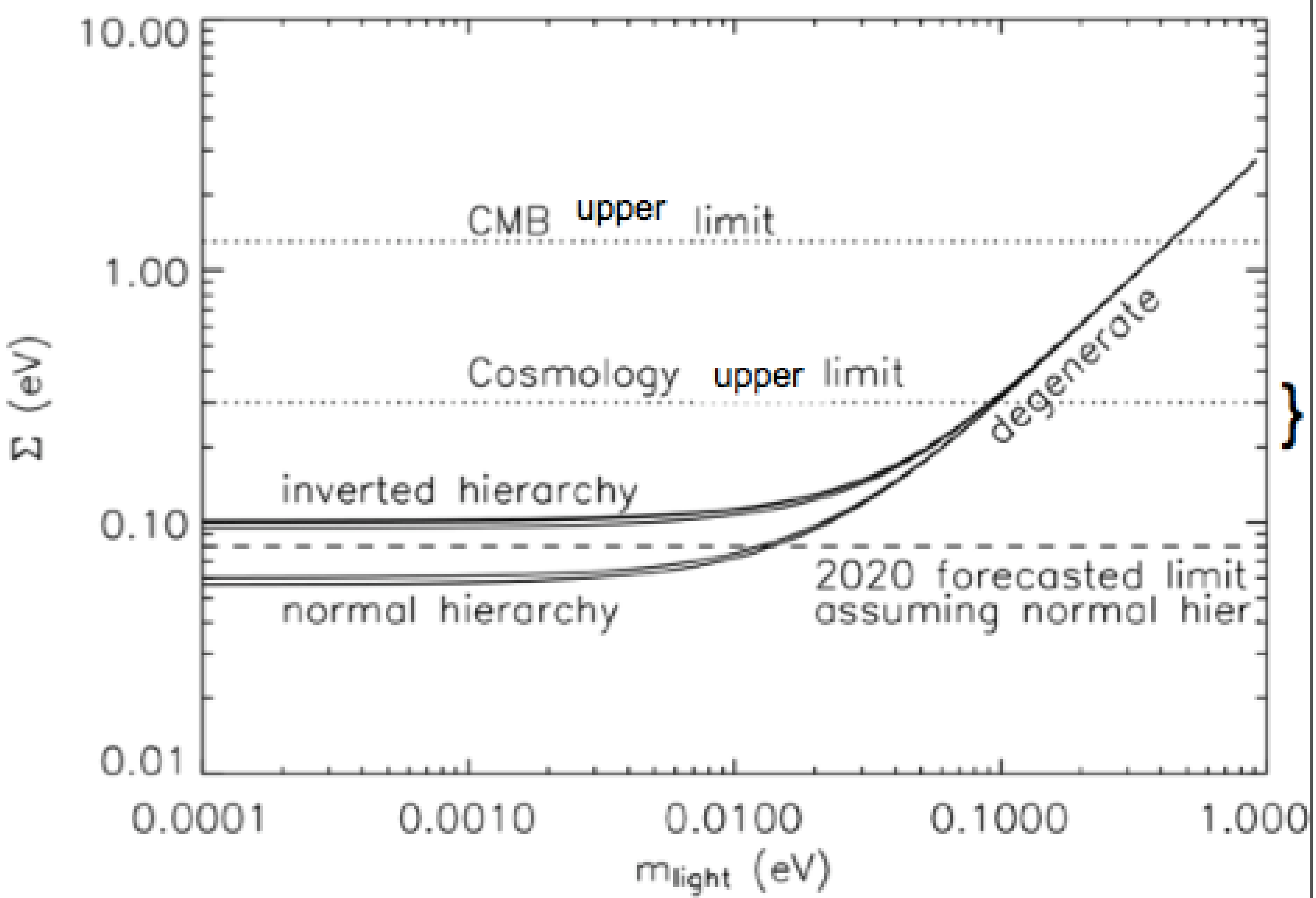



NEUTRINO



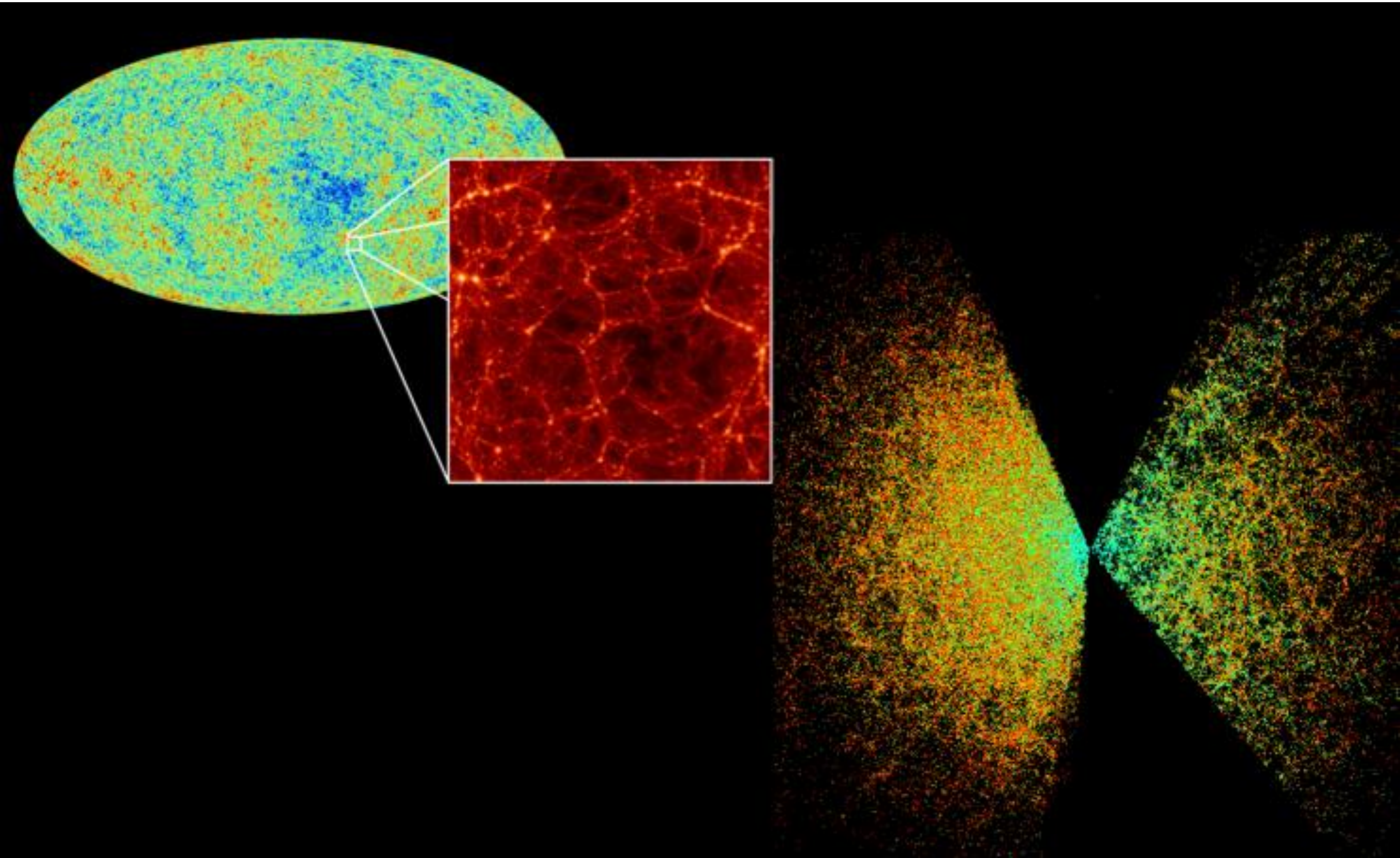
From Raul Jimenez

CMB and Cosmology Limits on Neutrinos



From Lucia Verde

Cosmology Limits on Neutrinos

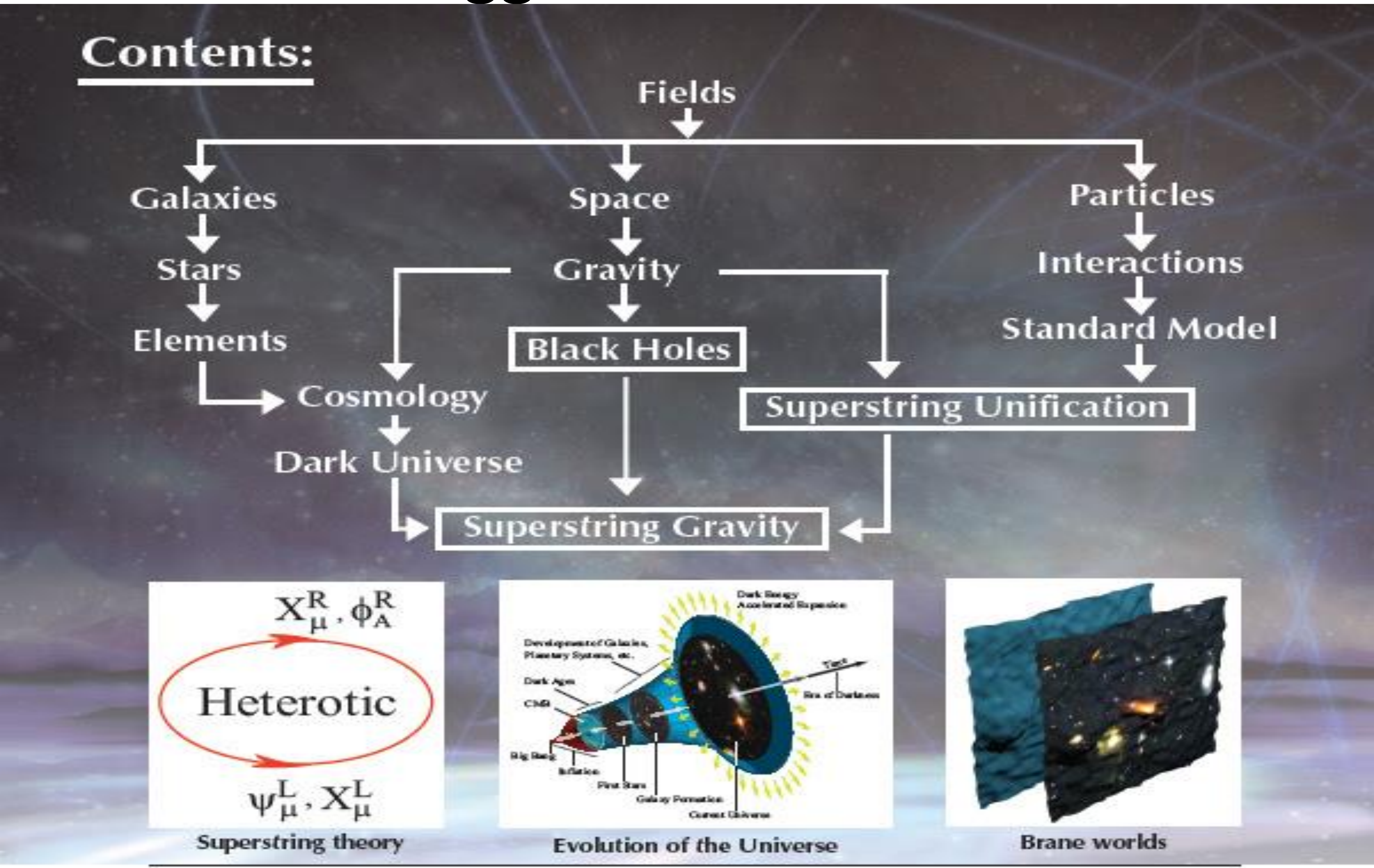


Cf. Ph.D. Forum talks

Baryogenesis

EXTRA DIMENSIONS

Movie: What to do with LHC now that the Higgs is discovered?



Conclusions Cosmology Perspectives

- The joining of cosmology and HEP has been fruitful; especially in terms of motivating new physics and concepts
- Most of the flow for new physicshas been from cosmology to HEP; however, we can hope that it will also soon flow the other way and HEP will give ideas and observations that point the way for cosmology
- Note: that standard model of cosmology is based upon General Relativity (100 yrs old) and SM Particle Physics (~40 yrs) both for calculations and ideas of how to add mechanisms & components