Towards testing quantum gravity using cosmological observations

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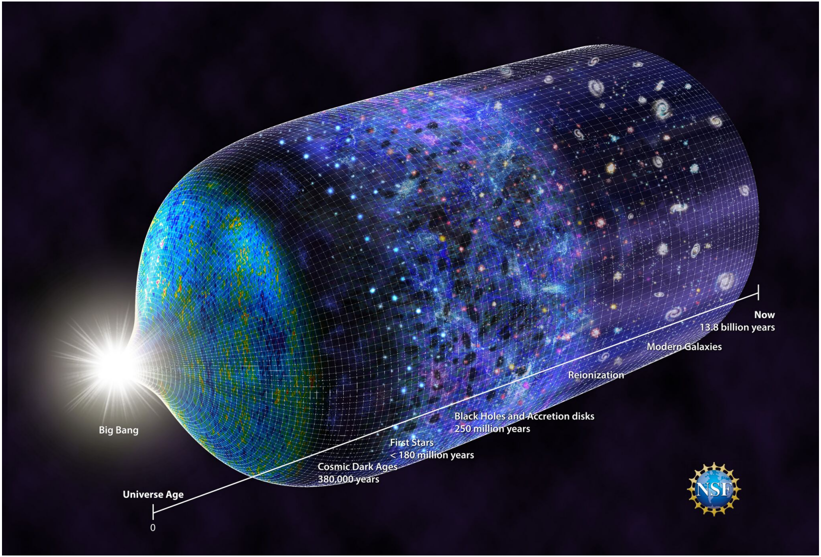
Outline


Big Bang
Universe Age
0
Cosmic Dark Ages
380,000 years
First Stars
< 180 million years
Black Holes and Accretion disks
250 million years
Reionization
Modern Galaxies
Now
13.8 billion years
NSF

- Modern cosmology started with the discovery of cosmological solutions of Einstein's equations in General Relativity.
- The only smooth solution which obeys the *cosmological principle* (spatial homogeneity and isotropy on very large scales relative to any observer) is the FLRW spacetime (Friedmann 1922 & 1924, Lemaitre 1927, Robertson & Walker 1935):

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a(t)^2 \mathrm{d}\sigma^2 \ (\textit{comoving coordinates})$$

The scale factor a is a positive function of the *cosmological time* t, while $\mathrm{d}\sigma^2$ is a Riemannian metric of constant sectional curvature on the spatial section Σ:

$$\mathrm{d}\sigma^2 = \frac{\mathrm{d}r^2}{1-\kappa r^2} + r^2(\mathrm{d}\theta^2 + \sin^2\theta \mathrm{d}\phi^2) \ , \ (\textit{comoving coordinates})$$

where (r, θ, ϕ) are *reduced circumference spherical coordinates* on Σ and $\kappa \in \{-1, 0, 1\}$. These coordinates cover only half of the 3-sphere when $\kappa = +1$. The topology of sigma is:

$$\Sigma = \Sigma_0/\Gamma \ ,$$

where $\Sigma_0 \in \{\mathrm{S}^3, \mathbb{R}^3, \mathbb{H}^3\}$ and $\Gamma \in \mathrm{Iso}(\Sigma)$ is a discrete subgroup of isometries of $(\Sigma, \mathrm{d}\sigma^2)$. Analysis of current data by the COMPACT collaboration shows that $\pi_1(\Sigma) = \Gamma$ may be nontrivial (cosmic topology). $k = +1$ corresponds to a *closed universe*.

- Einstein's eqs. $R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = T_{\mu\nu}$ with $T = \mathrm{diag}(\rho, p, p, p)$ give:
$$H^2 + \frac{1}{a^2} = \frac{\Lambda + \rho}{3} \quad , \quad 2\frac{\ddot{a}}{a} + H^2 + \frac{1}{a^2} = \Lambda - p \ ,$$
where $H(t) \overset{\mathrm{def.}}{=} \frac{\dot{a}(t)}{a(t)}$ is the *Hubble parameter*. The cosmological constant is equivalent with *dark energy*, which has:
$$\rho_\Lambda = -\Lambda \ , \ p_\Lambda = \Lambda$$
and equation of state $p_\Lambda = -\rho_\Lambda$.
- The case $a = \mathrm{const}$ with $\kappa = +1$ gives *Einstein's static universe*, which is incompatible with observations; related *steady state models* (Hoyle) are ruled out since the universe is currently expanding (Hubble 1929). $H_0 = 67.4 - 70 kms^{-1}Mpc^{-1}$ (Hubble tension).
- 1950-1966. Observations increasingly supported the *big bang* (Lemaitre, Gamow), especially the discovery of the CMB (Penzias & Wilson, 1965). Theoretical developments show that positivity conditions in GR imply that the universe must have a singularity in the past (Hawking & Ellis, 1966), to be resolved by quantum effects.
- 1966-1980. Development of hot big bang model through astroparticle physics. Nucleosynthesis (Gamow, Alpher, Herman) explains He, D & Li abundances (Peebles 1966; Wagner, Fowler & Hoyle 1967). Baryogenesis (Sakharov, 1967). Progress on CMB (Sunyaev-Zeldovich 1969, detected 1983).

A brief history of modern cosmology

- 1980s. First models of inflation (Guth 1980, Starobinsky, 1980). Development of cosmological perturbation theory and models of structure formation, including the first computer simulations (1983/7). First space observatories of CMB (RELIKT-1, 1983/4, COBE, 1989/93). First models of cold dark matter (1982).
- 1990s. Development of the ΛCDM model. Observation of CMB anisotropy (1992). Discovery of present-day accelerated expansion (Supernova Cosmology Project & High-Z Supernova Search, 1998), shows that $\Lambda > 0$. Confirmation of the first acoustic peak in the CMB and hence of baryon oscillations (BOOMERanG, 1999). Observational evidence that the spatial section of the universe is almost flat.
- 2000s. Refinements of the ΛCDM model; large numerical simulations of structure formation. Precision measurements of the CMB (WMAP 2001/10). Measurement of the E-mode polarization spectrum of the CMB (DASI and CBI, 2004).
- 2010s. High precision measurements of the CMB (Planck, 2009/13). Observational confirmation of gravitational waves (LIGO & Virgo, 2016).
- 2020s. James Webb Space Telescope (2021).

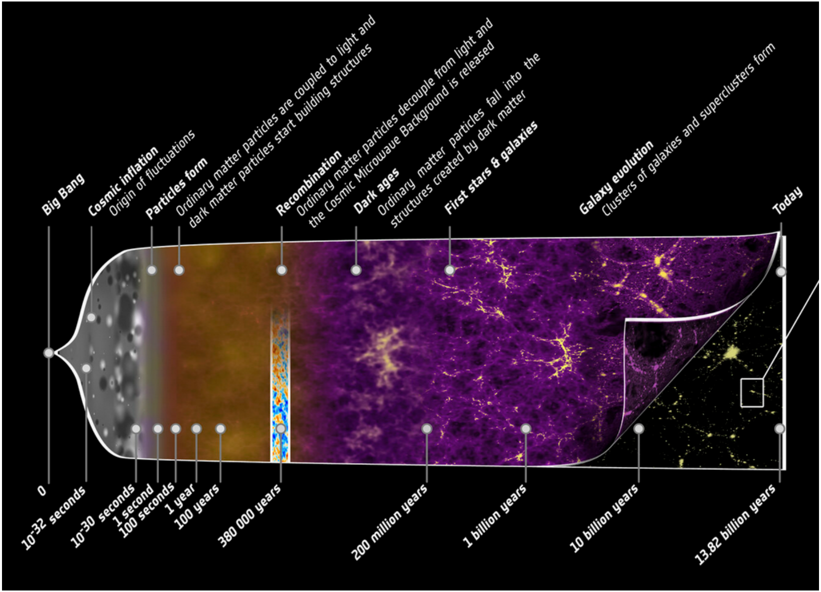
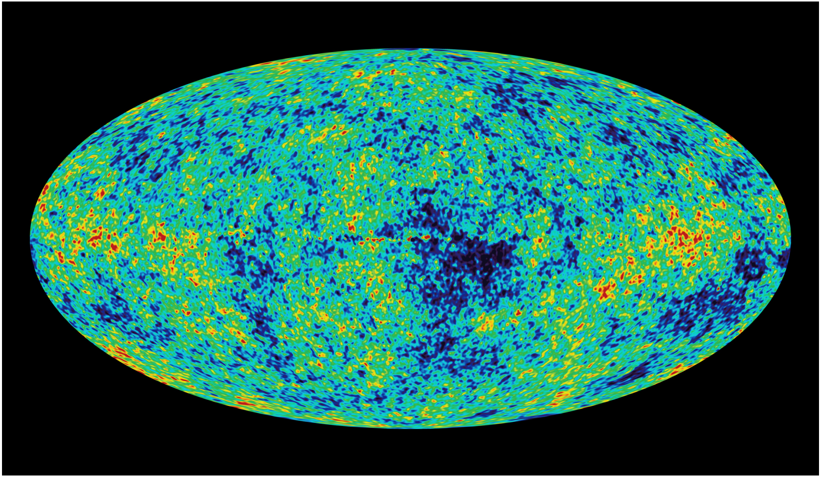

Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the
structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

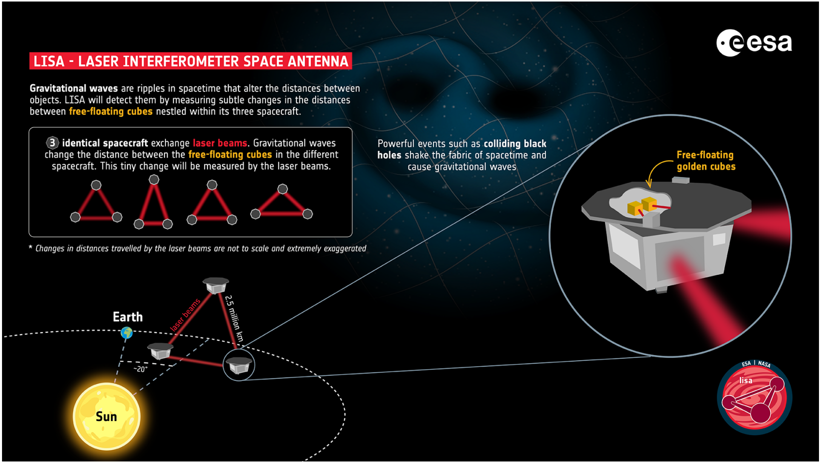
Chart of CMB anisotropies



The multi-messenger revolution in astronomy

- Observational astronomy is in the beginning stages of the multi-messenger revolution, whose start can be dated to the simultaneous observation of a neutron star merger on Aug. 17, 2017 in the gravitational wave and extended electromagnetic spectrum by the LIGO-Virgo collaboration and about 100 EM spectrum observatories worldwide.
- Multi-messenger astronomy is a nascent field of observational astronomy defined by simultaneous and correlated observations of cosmic events and data using various information messengers available: all portions of the EM spectrum, cosmic rays, gravitational waves and neutrinos. It is made possible by independent technological progress in each of these fields and by advances in computer networks which allow for real-time synchronization of detectors. Progress in neural networks enables processing of massive data produced by multi-messenger observations.
- This nascent field of observational astronomy holds great promise for the next 50 years and will provide new information about the very early universe. For example, advanced gravitational wave detectors placed in space could provide information which is not easily visible in the CMB because the universe was "opaque" to electromagnetic radiation before recombination.
- Gravitational wave astronomy is in its nascent phase, the next step being projects such as LISA. Future generations of observatories hold substantial promise for the next half century.

The planned LISA observatory (2035)



1. **What LHC experiments show and do not show**
   LHC experiments have found no evidence for supersymmetry up energies of the order of 10 TeV. However:
   - The highest collision energy attained at LHC (third run) is about 13.6 TeV $\sim 10^{13}$ eV
   - The energy scale of inflation is around 10^{13} TeV $\sim 10^{25}$ eV.
   - The Planck energy is 1.2×10^{16} TeV $= 1.2 \times 10^{28}$ eV (about $\frac{1}{1000}$ of the energy scale of inflation).

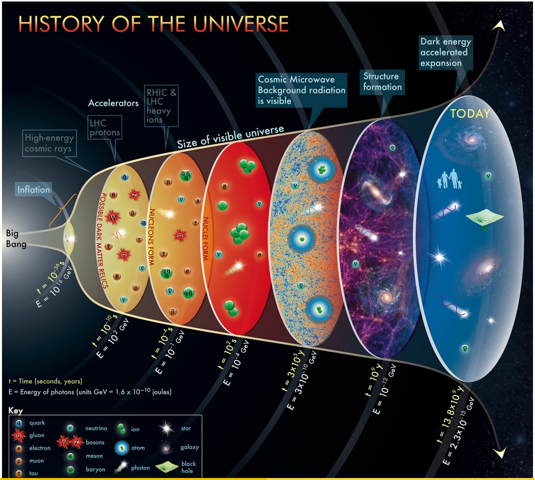
   Thus LHC energies are 12 orders of magnitude below the energy scale of inflation and 15 orders of magnitude below the Planck energy.
2. While LHC experiments practically rule out certain models of low energy supersymmetry (such as the MSSM, which used to be the remaining leading candidate), it is impossible to draw conclusions about what happens at inflation or Planck energy scales using negative results obtained at LHC.
3. In particular, LHC experiments cannot invalidate super-string theory or supergravity, which are intended to describe the behavior of gravity and matter at energies over 10 orders of magnitude higher than those probed at the LHC.
4. **Naturalness arguments** have often been used in ways that are unwarranted by renormalization theory. They can and have been criticized on epistemic grounds. Such arguments are incompatible with Popper's epistemic standards for a theory of physics.

What we could learn from LHC experiments about cosmology

LHC sheds light on aspects relevant to the **post-inflationary** epoch:

- Quark-gluon plasma (ALICE) – relevant to the radiation-dominated era.
- CP violation (LHCb) – relevant to origin of baryon number asymmetry.
- Precision measurements of SM parameters; new physics ? (ATLAS).
- Neutrino physics (SND).

Unlikely that we'll learn about the very early universe from LHC.

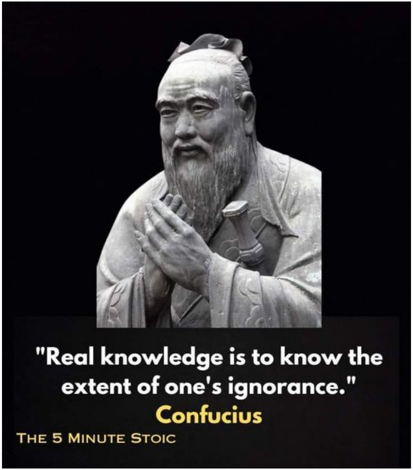


The assault against string theory and supergravity

- A furibund attack against string theory started about 5 years ago as experimental bounds began to rule out supersymmetry at LHC. This involves mass media, blogs and internet "influencers".
- The criticism often resorts to pseudo-science and even scientific nonsense.
- Numerous false or exaggerated claims were made about what LHC experiments show, about what string theory states and about the actual status of development of alternative proposals to string theory.
- A systematic attempt is being made to mislead young people regarding the current status of scientific knowledge.
- Naive approaches are presented as science, despite failing to pass basic requirements of plausibility.

Some **common sense reminders**:

1. Proper science is not done in the mass media, on blogs, youtube or tick-tock but through papers published in reputable scientific journals that are subject to rigorous peer review.
2. Internet influencers are unlikely to be competent in quantum gravity.
3. It is not likely that naive ideas pushed by people whose mathematics education stopped at second year undergraduate level can contribute anything serious to the subject.
4. Reviving old proposals while failing to address the reasons why they were discarded in the first place is unlikely to lead to scientific progress.



String theory says:

Rumors of my death were greatly exaggerated !