Cosmology

"*cosmology - the study of the universe at large, its history and its future.*"
J. Bernstein, et al (1986)

- History
- Situation in cosmology
- Assumptions and limits
- Observations
- World models
- More realistic world models
- Scenario
- Some issues

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"*There is a widespread conviction that the new teachings of astronomy and physical science are destined to produce an immense change on our outlook on the universe as a whole, and on our views as to the significance of human life. The question at issue is ultimately one for philosophic discussions.*"

Sir James Jeans (1932)

“The Case Against Cosmology”

“It is very questionable whether the study of any phenomenon that is not repeatable can call itself a science at all. It would be sad however to abandon the whole fascinating area to the priesthood.”

“It is not likely that we primates gazing through bits of glass for a century or two will dissemble the architecture and history of infinity. But if we don’t try we won’t get anywhere. Therefore we professionals do the best we can to fit the odd clues we have into some kind of plausible story. That is how science works, and that is the spirit in which our cosmological speculations should be treated. Don’t be impressed by our complex machines or our arcane mathematics. They have been used to build plausible cosmic stories before - which we had to discard afterwards in the face of improving evidence. The likelihood must be that such revisions will have to occur again and again and again.”

M. J. Disney (2000)

History

> "*Our philosophy is that the history of the Universe is infinitely more interesting than the history of the study of the Universe.*"
>
> Ya. B. Zel'dovich, et al (1983)

Can we distinguish the two?

> "*The universe evolves, but cosmology also evolves, and today's standard model of the universe is totally unlike the standard model of only a hundred years ago.*"
>
> E. Harrison (1992)

In our view, the time line of developments in modern cosmology goes as follows. Newton published Principia in 1687. However, cosmologically relevant discussion appears only in correspondences to Bentley in 1692 [1]. It was only with the advent of Einstein's general relativity in 1915 when the modern cosmological study began. Immediately after proposing the field equation Einstein applied it to a cosmological context in 1917 and noticed that it was necessary to introduce a repulsive cosmological constant Λ to make the model universe static, thus modifying his field equation. In 1917 de Sitter showed that a pure Λ leads to a model with far away objects showing more redshift. In 1922 Friedmann properly showed that cosmological model filled with pressureless matter without Λ shows dynamic behavior. In 1927 Lemaître studied radiation filled model thus showing possibility of hot early universe. In 1929 Hubble published that galaxy redshift is proportional to their distances [2]. In 1948 Alpher and Herman predicted the presence of the cosmic microwave background radiation (CMB) based on the calculation of the cosmic Helium abundance. In 1946 Lifshitz presented fully relativistic treatment of linear structures in the Friedmann world model. In 1965 Penzias and Wilson discovered the CMB. History shows many previous discoveries of the CMB without noticing its cosmological significance. It is particularly noticeable that based on the interstellar CN absorption lines observed by Adams and Dunham in the 1930s, in 1941 McKeller has clearly identified a presence of the black body bath with $2.3K$ as the source [3]. In 1967 Sachs and Wolfe showed that the presence of structures in the recombination (when the CMB photons were last scattered) anticipated in the gravitational instability picture of the structure formation necessarily implies anisotropies in the CMB temperature. It was generally known that the large-scale cosmic structure should follow a scale-invariant spectrum, often termed as a Harrison (1970) Zel'dovich spectrum (1972). In 1980 Guth has introduced the inflation stage in the early universe. History also shows that there are many simultaneous and previous studies of the advantage of such a scenario. In 1982 researchers have reached agreement that the inflation provide a natural mechanism to make a scale-invariant spectrum out of ever present quantum fluctuations. In 1992 COBE satellite mission discovered small anisotropies in the CMB temperature sky map, and showed that it has a scale-invariant spectrum.

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[1] Reprinted in p211 of Munitz (1957), and p60 of Harrison (2000).

[2] In 1908 Henrietta Leavitt discovered the period-luminosity relation of the Cepheid variable using the ones in Magellanic clouds. In 1923 Hubble has used the period-luminosity relation to the Cepheids discovered in the Andromeda and other nebulae, thus settling that these are external galaxies. Meanwhile, beginning in 1914 Vesto M. Slipher found that galaxies tend to show redshifts. Even before Hubble's publication, the redshift-distance relation of the galaxies was noticed by C. Wirtz (1924), K. Lundmark (1924), and A. Dose (1927). Hubble has used the distances measured by the Cepheid variables in the galaxies with known redshifts. In 1929 Milton L. Humason also published a galaxy with large redshift compared with the ones in Hubble's list. See chapter 3 in Hoyle, et al (2000), and Berendzen, et al (1984).

[3] The interstellar absorption lines were identified by Swings and Rosenfeld (1937), by McKellar (1940), and by Douglas and Herzberg (1941) as being due to CH and CN molecules. See W. S. Adams, ApJ., 93, 11 (1941), and chapter 8 in Hoyle, et al (2000).

Situation in Astronomy (cosmology)

1. **Single view:**

   celestial sphere, no 3D perspective available, real shapes of galaxies?

2. **Uncontrollable:**

   no controlled experiment available

3. **Unrepeatable:**

   Big bang, supernova explosion, microlensing

4. **Inaccessible:**

   finite speed of light (look back in time), last scattering surface, early universe, evolution?

   distance uncertainty

   > "*The successful measurement of the distances of unimaginably remote objects is one of the astonishing achievements of astronomy.*"
   >
   > M. Hoskin (1999)

5. **Distortion:**

   blocking, Milky way, absorption, lensing

6. **Unique:**

   our single observable universe, cosmic variance

"*Given this situation, we are unable to obtain a model of the universe without some specifically cosmological assumptions which are completely unverifiable.*"

G. F. R. Ellis (1975)

Assumptions and Limits

1. **Good luck assumption:**

   Locally discovered scientific (physics) laws are applicable beyond our planet(ary system). Unverifiable!

   > "*The normal physical laws we determine in our space-time vicinity are applicable at all other space-time points.*"
   >
   > G. F. R. Ellis (1975)

2. **Scientific policy:**

   "Ockham's razor", minimal assumption attitude. Unverifiable!

   > "*Don't multiply entities more than is absolutely necessary.*"
   >
   > M. Rees (1997)

3. **Uncertainty:**

   in both random (in measurements) and systematic (in assumptions) errors.

4. **Further loophole:**

   Any explanation may not be unique.

"*The problem [is that] there is only one universe to be observed, and we effectively can only observe it from one space-time point.*"

G. F. R. Ellis (1975)

Metaphysical assumptions:

"*All science presupposes some metaphysical system of beliefs.*"

"*As used by Aristotle the word 'metaphysics' meant 'beyond physics', that is beyond the scope of physical science.*"

"*[M]odern science is based not only on observation and experiment but also on metaphysical beliefs. [F]aith or trust is necessary for understanding the natural world.*"

J. Trusted (1991)

Theoretical World Models

◇ **Four ingredients:**

1. **Gravity:**
   Einstein gravity or generalized gravity.
2. **Spatial geometry:**
   homogeneous and isotropic, or more complicated geometries.
3. **Matter contents:**
   dust, radiation, fields, and others.
4. **Topology (global geometry):**
   undetermined in the gravity level.

Smoothed spatial geometry

◇ Radio source count, background X-ray sources, deep sky map, CMB are quite isotropic (same in all directions) around us.

◇ Do we have any evidence that the same isotropy holds in other places?
unverifiable, globally in principle, locally in practice.

◇ We need a dogma: the part we see is representative of the whole.

> "*Whatever spot anyone may occupy, the universe stretches away from him just the same in all directions without limit.*"
>
> Lucretius ($\sim$ 100-55 B.C.)

> "*If we are concerned with the structure only on a large scale, we may represent matter to ourselves as being uniformly distributed over enormous spaces, . . .*"
>
> A. Einstein (1917)

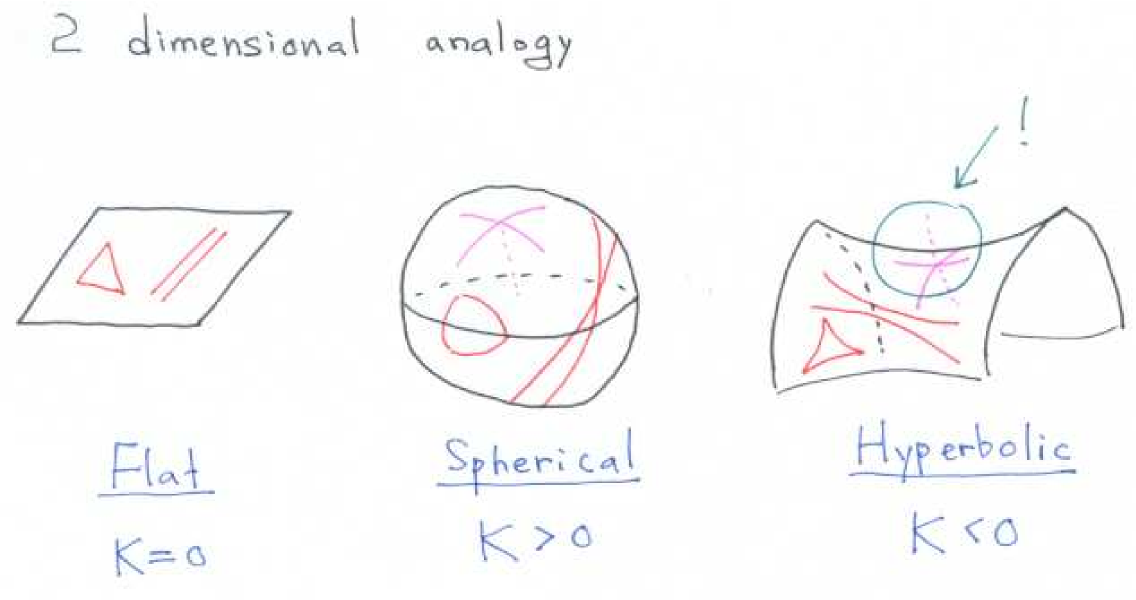
> "*dogma: a belief or set of beliefs held by a group or organization, which others are expected to accept without argument.*"
>
> The Oxford Advanced Learner's Dictionary, Sixth Edition

1. **Cosmological principle:** "*The universe is spatially homogeneous.*"
   Global assumption! Leads to a highly idealized complete world model.
   Completely unverifiable outside horizon.
2. **Copernican principle:** "*We are not at the centre of the universe.*"
   Local assumption. Leads to a model of the observed part of the universe.
   No assumption outside horizon. Still difficult to prove. (G. F. R. Ellis, 1975)

> "*"Principles" in cosmology have often connoted assumptions unsupported by evidence, but without which the subject can make no progress.*"
>
> Martin Rees (2000)

◇ Under this assumption we have **three** qualitatively different spatial geometries:

1. Flat, Euclidean
2. Spherical
3. Hyperbolic



Observations

1. **Our universe exists:**

   We know for sure.

   > *"Not how the world is, is the mystical, but that it is."*
   >
   > Ludwig Wittgenstein (1922)

   It is a philosophic statement.

   > *"Philosophy begins in wonder. And, at the end, when philosophic thought has done its best, the wonder remains."*
   >
   > A. N. Whitehead (1861-1947)

   > *"Science is what you know, philosophy is what you don't know."*
   >
   > Bertrand Russell (1872-1970)

2. **Darkness of the night sky:**

   > *"Why is the sky dark at night? The answer to this old and celebrated riddle seems deceptively simple: The Sun has set and now shines on the other side of the Earth. But, ... The riddle becomes: Why are the heavens not filled with light? Why is the universe plunged into darkness?*
   > *... Misleading trails of inquiry and strange discoveries abound in the quest for the solution to the riddle of cosmic darkness."*
   >
   > Edward Harrison (1987)

   The finite age of our observable patch plus finite speed of light resolves the issue in the standard model.

3. **Large-scale homogeneity and isotropy:**

   Observations find nothing inconsistent with these assumptions on scales larger than, say, ~ 100Mpc.

   Can we say better than that?

4. **Redshift-distance relation:**

   The redshift $z \equiv (\lambda_{\rm obs} - \lambda_{\rm emit})/\lambda_{\rm emit}$ is proportional to the distance d:

   $$zc \simeq Hd$$

   Interpreted as due to the recession of the galaxies: $v \simeq zc$ for $v \ll c$.

   It tells the expansion rate $H \equiv v/d$ and the deceleration (or acceleration).

   Currently favored value shows $H_0 = 72 \pm 7$km/sec/Mpc.

   $$H_0 \equiv 100h\text{km/sec/Mpc}$$

   Hubble age, and horizon

   $$t_H \equiv \frac{1}{H_0} = 9.778h^{-1}\text{Gyr}$$
   $$\ell_H \equiv \frac{c}{H_0} = 9.778h^{-1}\text{Gly} = 2.998h^{-1}\text{Gpc}$$

5. **CMB:**

   Has a black-body spectrum with temperature $2.725K$; thus, $\lambda_{\rm max} \sim 0.1$cm, $n_\gamma \sim 400/{\rm cm}^3$, $\varrho_\gamma \sim 5 \times 10^{-34}{\rm g/cm}^3$. It's presence with black body nature indicates 'hot' early universe. Shows dipole anisotropy at 10^{-3} level and the multipole anisotropies at 10^{-5} level. The dipole anisotropy is perhaps due to our own relative motion relative to the CMB rest frame, and the multipole anisotropies are believed to be related to the physical processes and the gravitational clustering properties at the time of its generation at last scattering epoch.

   Spectrum is consistent with the Harrison-Zel'dovich's suggestions in the 70's.

   According to the 'standard scenario' (later) we are looking at the last scattering (or recombination) surface which occurred at redshift ~ 1000 and 3×10^5yrs after the big bang.

6. **Amount of matter:**

   We have minimum amount of the baryons observed. The rotation curve of spiral galaxies, and the virial theorem in cluster of galaxies indicate presence of non-luminous dark matter. Recent observational and theoretical studies show presence of unclustered dark energy driving the universe accelerate. Current study favors dark energy (2/3), dark matter (1/3), baryons (1/25) including luminous matters (1/200), neutrinos (1/300), γ (10^{-4}), ν (10^{-4}).

   Density parameter

$$\Omega \equiv \frac{\varrho}{\varrho_{\rm crit}}, \quad \varrho_{\rm crit} \equiv \frac{3H^2}{8\pi G} = 1.88 \times 10^{-29} h^2 {\rm g/cm}^3$$
$$\Omega_{\rm DE} \sim \frac{2}{3}, \quad \Omega_{\rm DM} \sim \frac{1}{3}, \quad \Omega_{\rm baryon} \sim \frac{1}{25}, \quad \dots$$

7. **Ages:**

   We have known ages of the oldest stars which provide the minimum age of the universe. It so happened that the age estimation of the globular clusters has been reduced by $\sim 15\%$ recently. Together with recent age increase of the world model due to the acceleration, the age problem lost its urgency.

   I regard the proximity of the age of the world model and the age of the oldest stars is a big triumph of the standard world model which makes it quite credible.

   According to the cosmological estimates (flat model with 2/3 dark energy and Hubble constant stated above) the age would be around 14Gyr.

8. **Galaxy clustering:**

   The observed (thus luminous) matter, and the velocity field shows some statistical patterns of the large-scale distributions of the luminous and the gravitating matter. Spectrum is consistent with the Harrison-Zel'dovich's.

9. **Element abundances:**

   We have known range of the abundance of the Hydrogen, Helium and metals in celestial objects.

10. **Matter vs. antimatter:**

Apparently the observed universe is mainly composed of the matter instead of the antimatter.

$$\eta \equiv \frac{n_{\text{baryon}}}{n_{\text{photon}}} \sim 10^{-10}$$

11. **Existence of observers:**

One should not forget possible significance of our presence in our observed patch in the universe. Apparently one is forbidden to observe the existence of other possible patches where the presence of the observer is not allowed. This does not mean that such patches are not allowed.

The anthropic principle by Brandon Carter says:

> "*What we can expect to observe must be restricted by the conditions necessary for our presence as observers. (Although our situation is not necessarily central, it is inevitably privileged to some extent.)*"
>
> B. Carter (1974)

> "*The world is the way it is, at least in part, because otherwise there would be no one to ask why it is the way it is.*"
>
> S. Weinberg (1989)

For a balanced view:

> "*It is much better to find a simple physical resolution of the problem rather than speculate that we can live only in the universes where the problem does not exist. There is always a risk that the anthropic principle does not cure the problem, but acts like a painkiller.*"
>
> A. Linde (2002)

Still:

> "*The conditions necessary for human existence impose narrow limits on the design of the universe.*"
>
> E. Harrison (1992)

Bright daylight problem:

Considering the darkness of the sky in average place in the universe, what is rather ironic is our special location nearby a star, thus having a bright daylight. Here, the anthropic argument provide an answer: being organisms living on the surface of a planet fatally depending on the solar energy, it is necessary that we can be found only nearby a star; i.e., otherwise, there would be no one like us who can raise the question.

Friedmann World Models

1. The spatially homogeneous-isotropic spacetime **geometry** (Robertson-Walker metric)

$$ds^2 = -c^2 dt^2 + a^2(t) \left[\frac{dr^2}{1 - Kr^2} + r^2 \left(d\theta^2 + \sin^2\theta d\phi^2 \right) \right] \tag{1}$$

2. Einstein **gravity**

$$S = \int \sqrt{-g} \left[\frac{c^4}{16\pi G} (R - 2\Lambda) + L_m \right] d^4x$$
$$G_{ab} = \frac{8\pi G}{c^4} T_{ab} - \Lambda g_{ab}, \quad T^b_{a;b} = 0$$

3. **Matter:**

   A minimally coupled scalar field:

$$L_\phi = -\frac{1}{2}\phi^{;c}\phi_{,c} - V(\phi)$$
$$T^{(\phi)}_{ab} = \phi_{,a}\phi_{,b} - \frac{1}{2} g_{ab}\phi^{;c}\phi_{,c} - V g_{ab}, \quad \phi^{;c}{}_{c} = V_{,\phi}$$

   Fluids and fields:

$$T^0_0 = -\mu, \quad T^0_\alpha = 0, \quad T^\alpha_\beta = p\delta^\alpha_\beta$$
$$\mu = \sum_i \mu_i = \mu_d + \mu_r + \mu_\phi + \dots$$
$$p = \sum_i p_i = p_d + p_r + p_\phi + \dots$$

Complete Equations

1. **Friedmann equation** ($H \equiv \frac{\dot{a}}{a}$):

$$H^2 = \frac{8\pi G}{3c^2}\mu - \frac{Kc^2}{a^2} + \frac{\Lambda c^2}{3} \tag{2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\mu + 3p) + \frac{\Lambda c^2}{3} \tag{3}$$

2. **An ideal fluid:**

$$\dot{\mu} + 3H(\mu + p) = 0 \tag{4}$$

Dust: $p = 0 \rightarrow \mu \propto a^{-3}$

Radiation: $p = \frac{1}{3}\mu \rightarrow \mu \propto a^{-4}$

Cosmological constant: $p = -\mu \rightarrow \mu = \text{constant}$

3. **A scalar field:**

$$\ddot{\phi} + 3H\dot{\phi} + c^2 V_{,\phi} = 0 \tag{5}$$

with

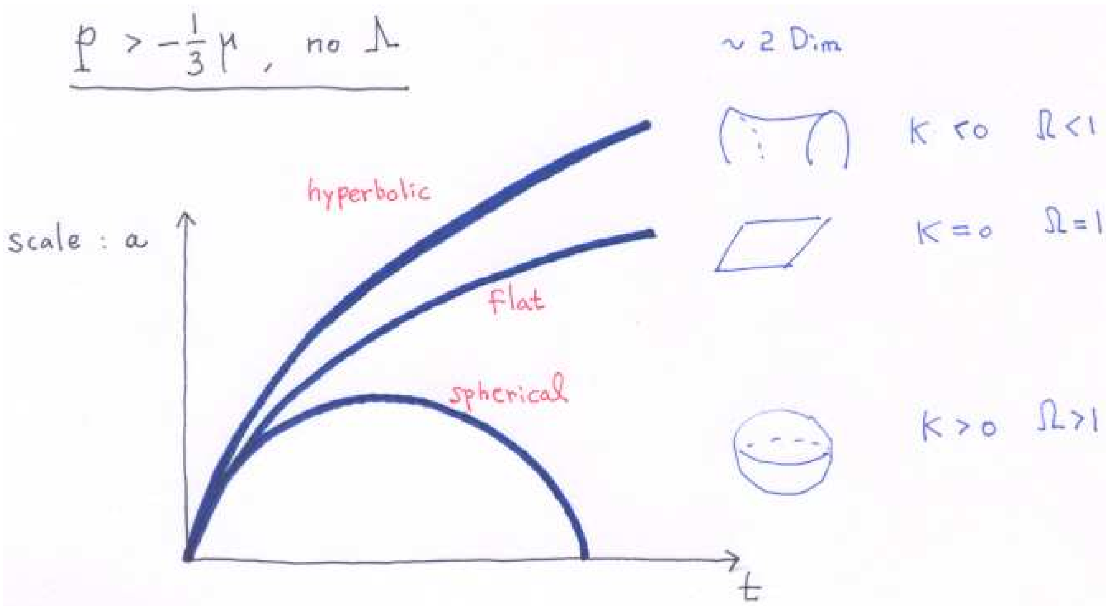
$$\mu_\phi = \frac{1}{2c^2}\dot{\phi}^2 + V, \quad p_\phi = \frac{1}{2c^2}\dot{\phi}^2 - V \tag{6}$$

4. Eqs. (1,2-6) are the **master equations** from which follow all the theoretical age, dynamics, distances, horizons, etc of the Friedmann world model.

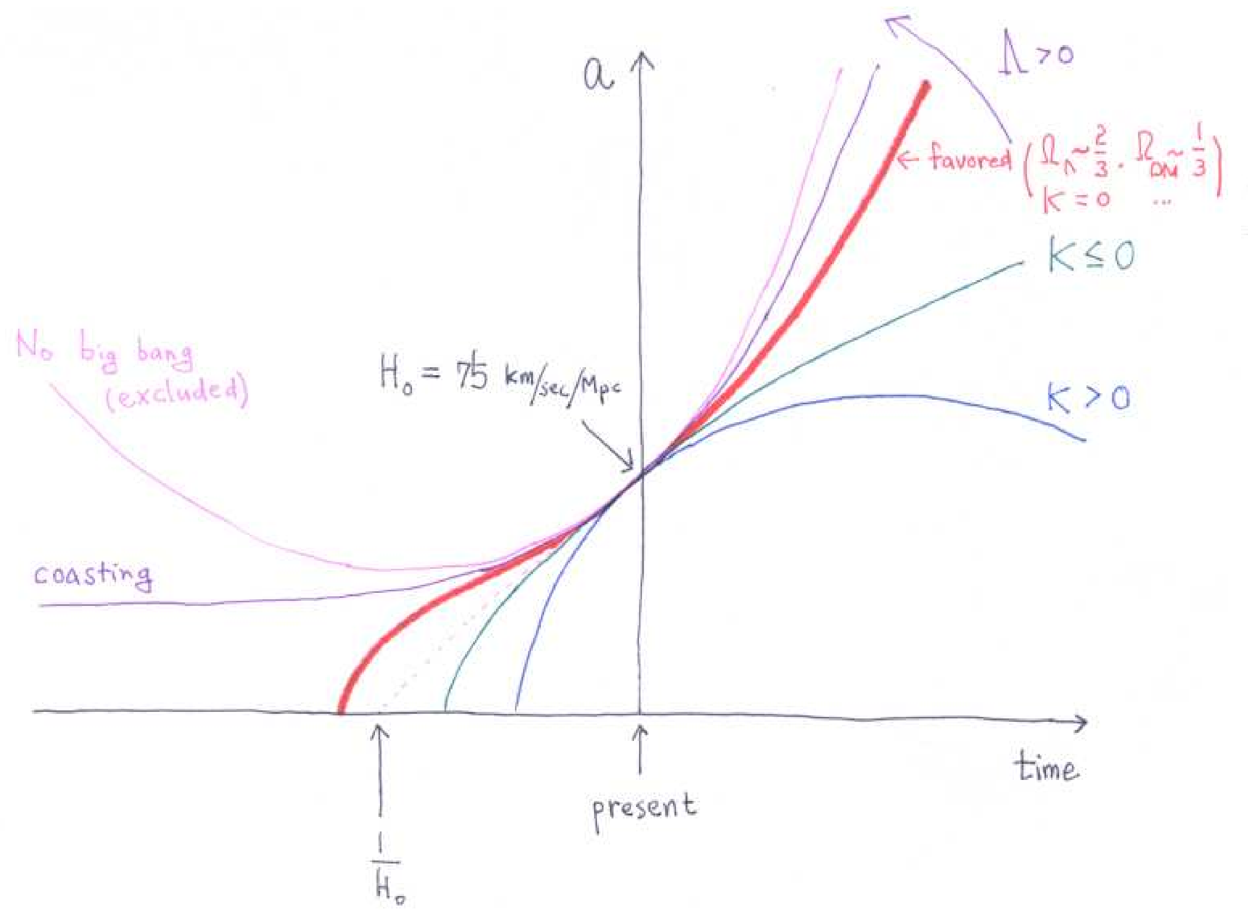
> "*Our ability to describe the universe with simple, elegant models stems in large part from our lack of data, our ignorance.*"
>
> J. Horgan (1996)

Dynamics

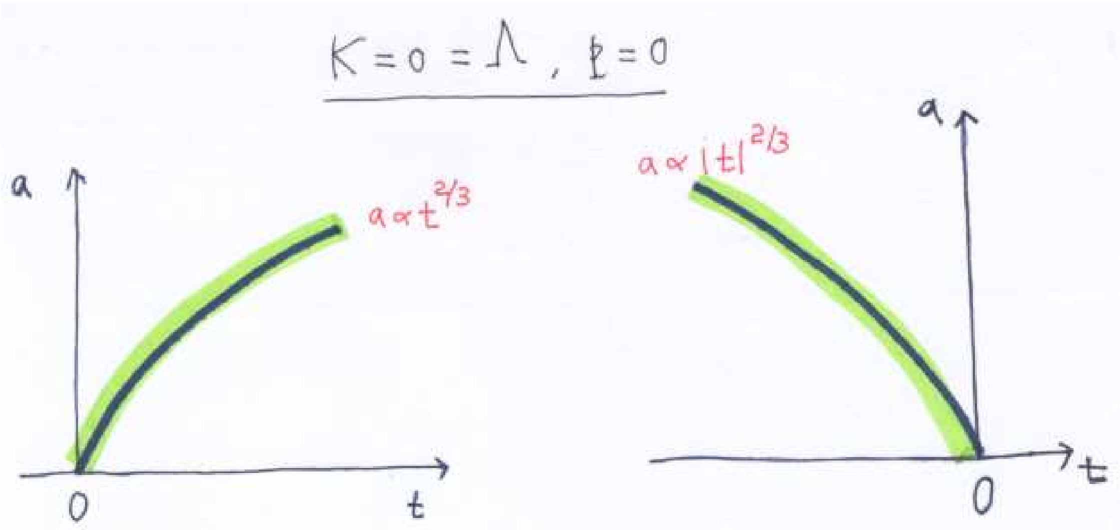
◇ $p > -\frac{1}{3}\mu (< -\frac{1}{3}\mu)$ → decelerated (accelerated) expansion



Diverse scenarios

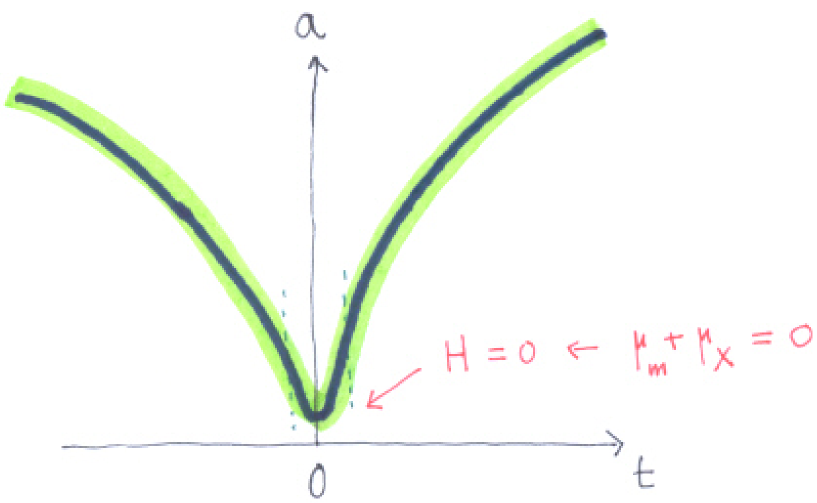


Expansion and collapse



Bounce

◇ An additional exotic matter with $\mu_X < 0$, $p_X > \frac{1}{3}\mu_X$ $\quad\rightarrow\quad$ bounce



More realistic world models

"Do I dare disturb the universe?"
T. S. Eliot (1888-1965)

1. Superimpose **small amplitude perturbations** on the Friedmann world model. Perturbed Friedmann world model (E. M. Lifshitz, 1946).

$$g_{ab} = \bar{g}_{ab} + \delta g_{ab}$$
$$T_{ab} = \bar{T}_{ab} + \delta T_{ab}$$

2. Evolution of the Friedmann world model (Λ absorbed in T_{ab}):

$$\bar{G}_{ab} = \frac{8\pi G}{c^4} \bar{T}_{ab}$$

Evolution of the structures:

$$\delta G_{ab} = \frac{8\pi G}{c^4} \delta T_{ab}$$

3. Perturbations are described by an **action** of the form

$$\delta^2 S = \frac{1}{2} \int a^3 Q \left(\dot{\Phi}^2 - c_A^2 \frac{1}{a^2} \Phi^{|\alpha} \Phi_{,\alpha} \right) dt d^3 x$$

Φ is the perturbed curvature ($\sim \delta g_{\alpha\beta}$) in certain hypersurface (gauge).

4. **Valid** for (i) a fluid, (ii) a field, and (iii) the gravitational wave.
5. From it follow the **quantum generation** and **classical evolution**. [4]

[4] See gr-qc/9607059, astro-ph/9909150, astro-ph/0107069.

Evolution of structures

1. This still idealized world model with small structures is supposed to be a good approximation in the early stage of the evolution and in the large-scale at present.
2. The initially small amplitude structures grow due to gravity (Jeans-Lifshitz instability) and later develop into the present day large-scale structure.
3. These also cause fluctuations in the recombination era which can be viewed as temperature anisotropies in the CMB.
4. Gravity can "grow" the structure, but not generate it.
5. We need other mechanism to "generate" it:

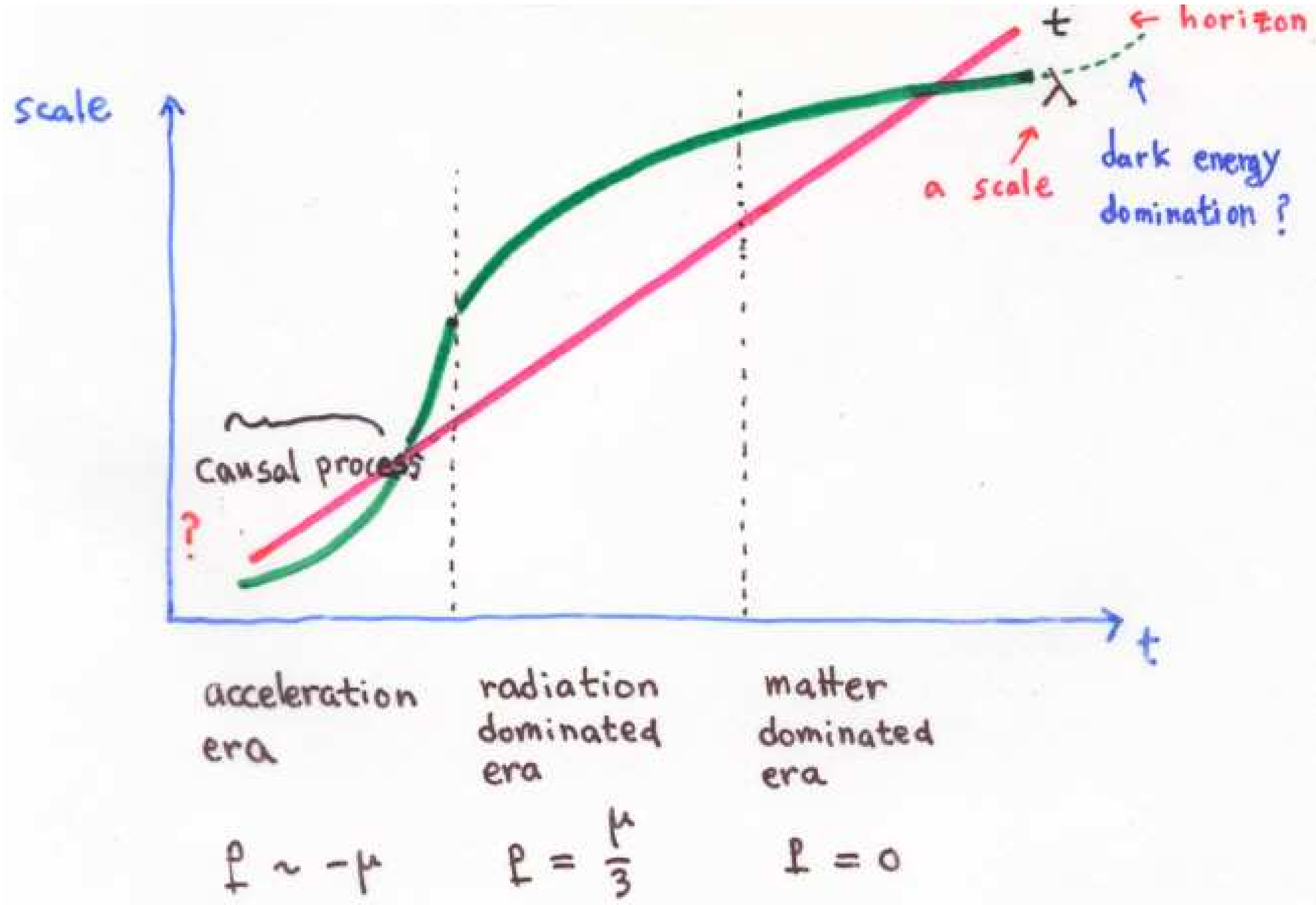
Origin of structures

1. Quantum fluctuations amplified by inflation mechanism
2. Topological defects
3. Statistical fluctuations
4. Other unknown mechanism?

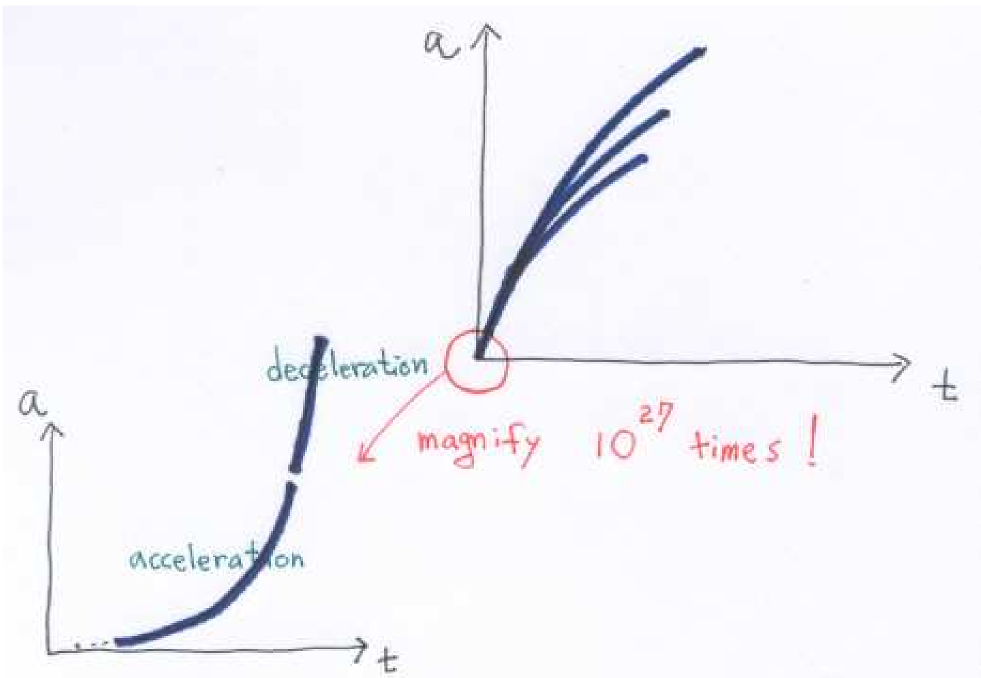
"*The universe was brought into being in a less than fully formed state, but was gifted with the capacity to transform itself from unformed matter into a truly marvellous array of structure and life forms.*"

Saint Augustine (354-430)

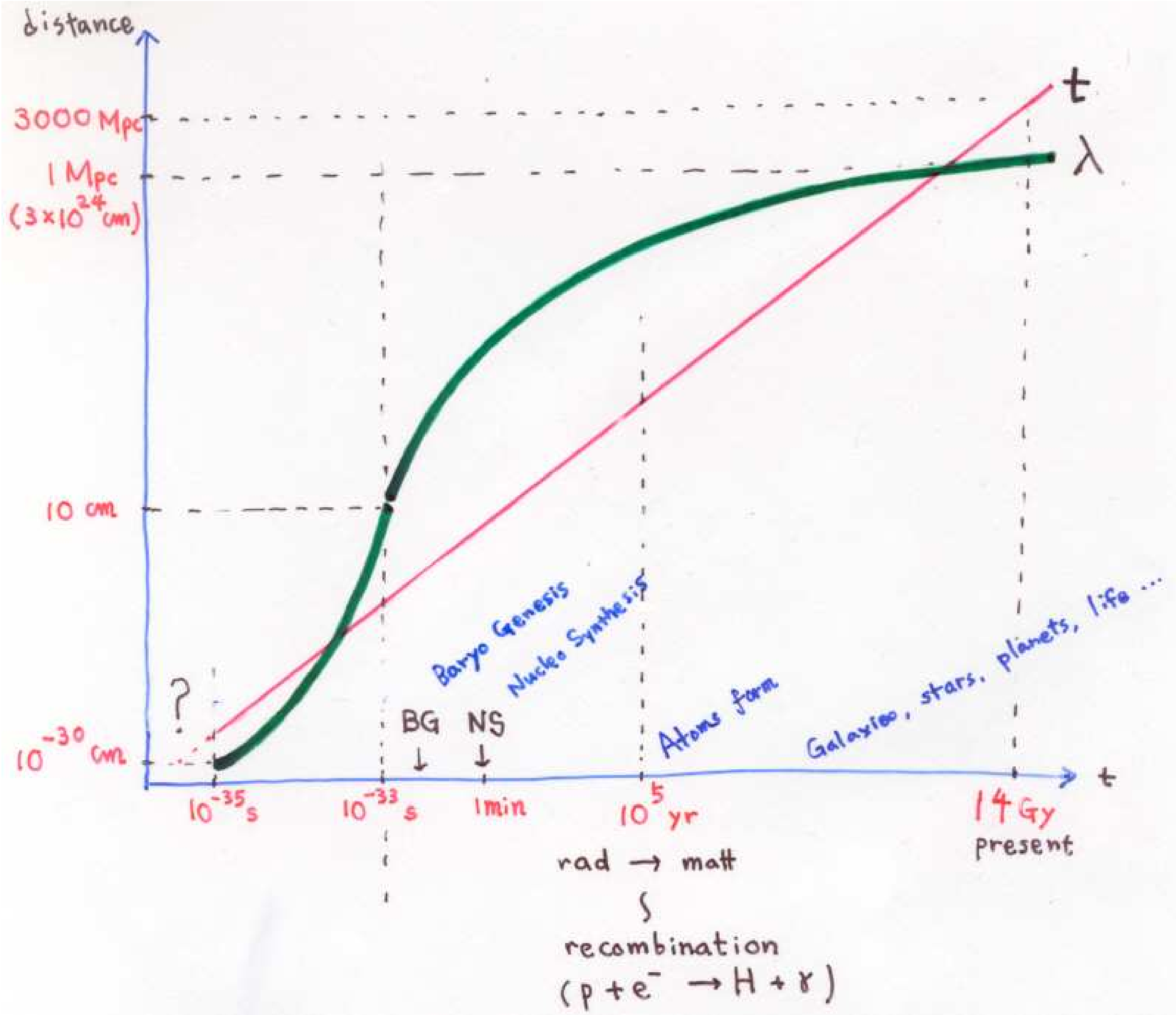
Early acceleration phase



Scale



Scenario

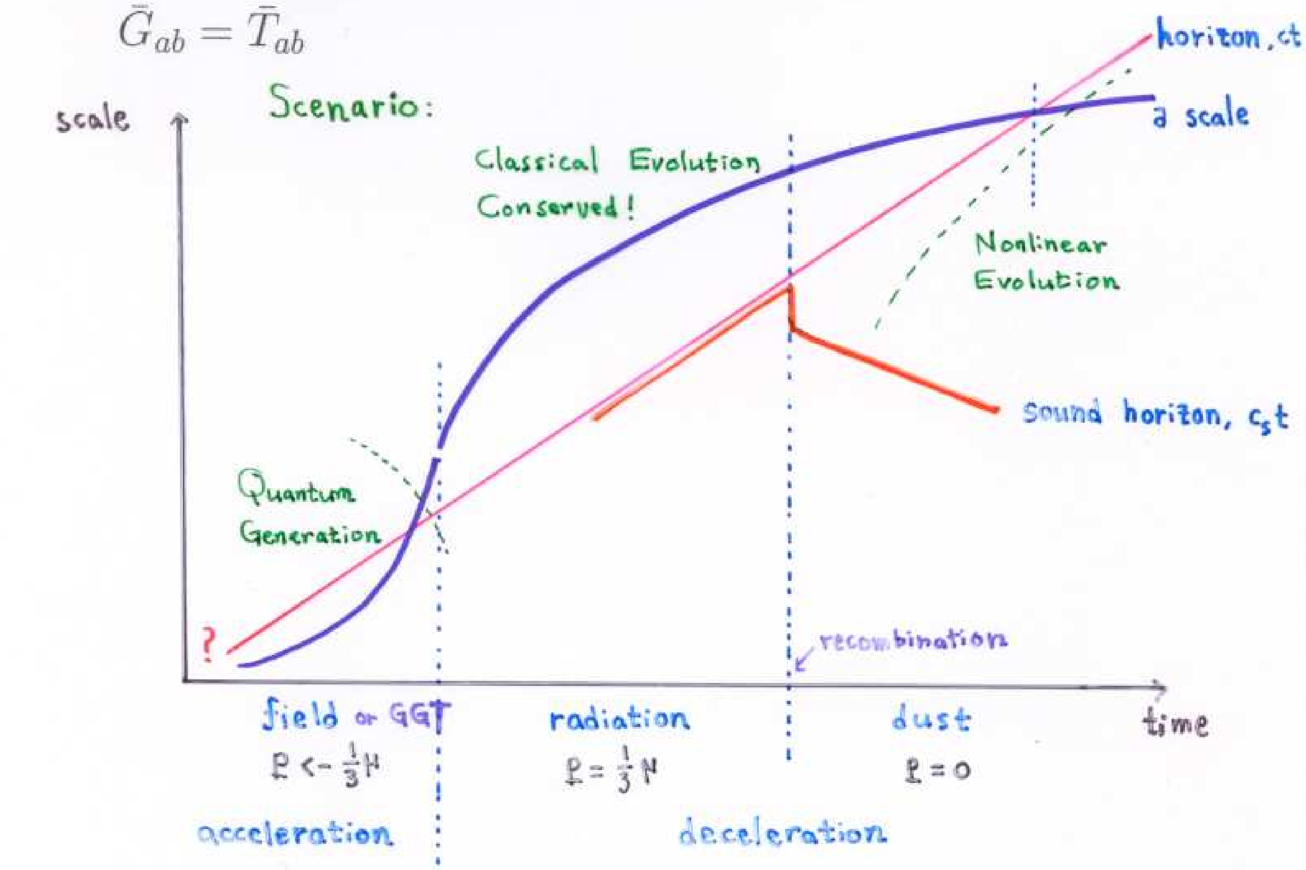


distance
3000 Mpc
1 Mpc
(3×10^24 cm)
10 cm
10^-30 cm
?
t
λ
Baryo Genesis
Nucleo Synthesis
Atoms form
Galaxies, stars, planets, life ...
BG
NS
10^-35 s
10^-33 s
1min
10^5 yr
14 Gy
present
rad → matt
recombination
(p + e^- → H + γ)

Structures

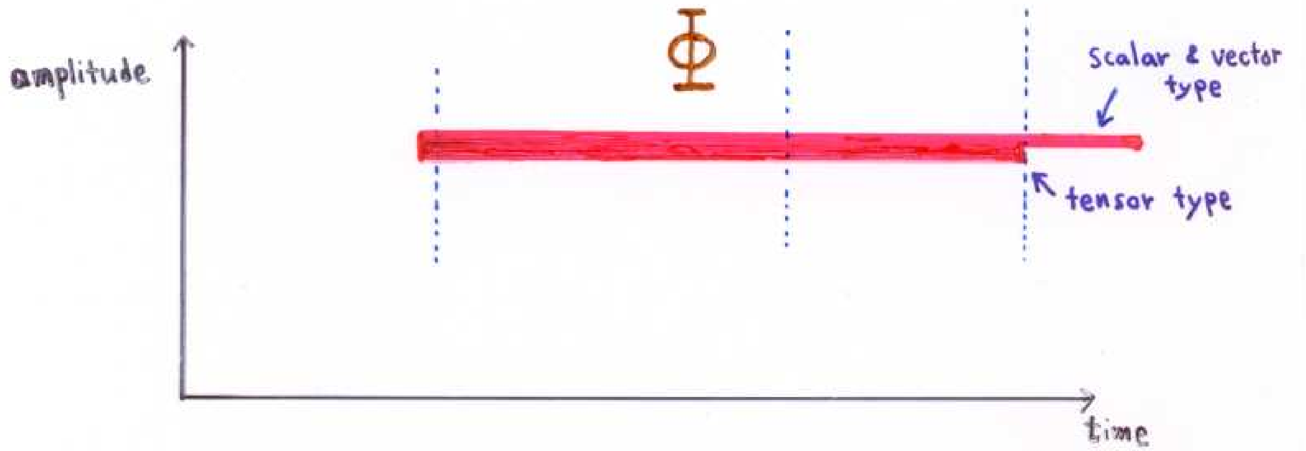
Background Evolution

$\bar{G}_{ab} = \bar{T}_{ab}$

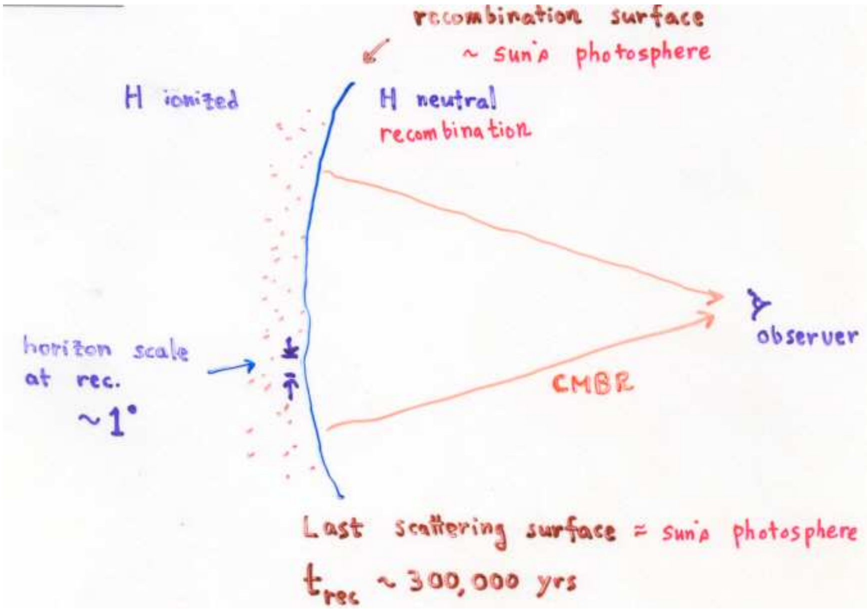


Perturbation: conserved evolutions

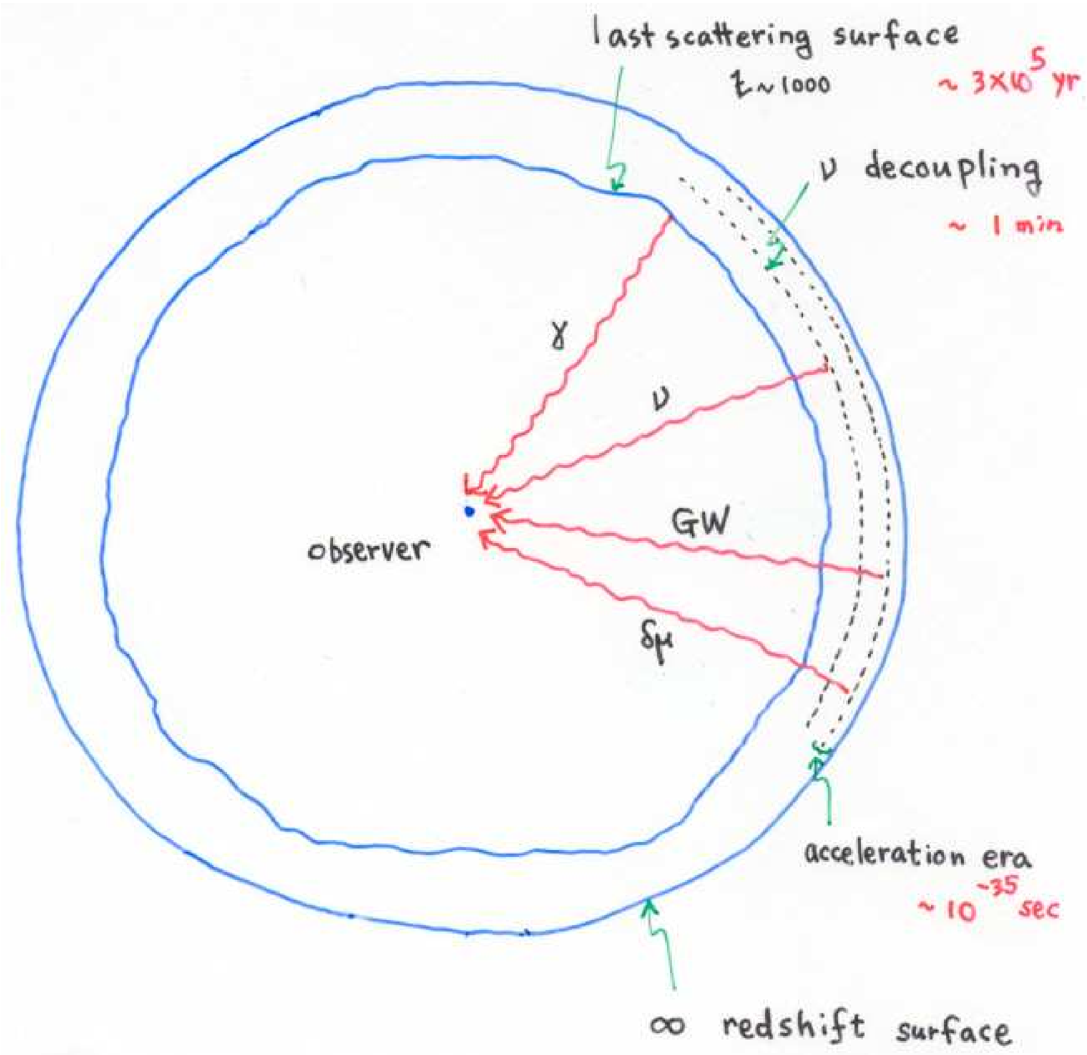
$\delta G_{ab} = \delta T_{ab}$



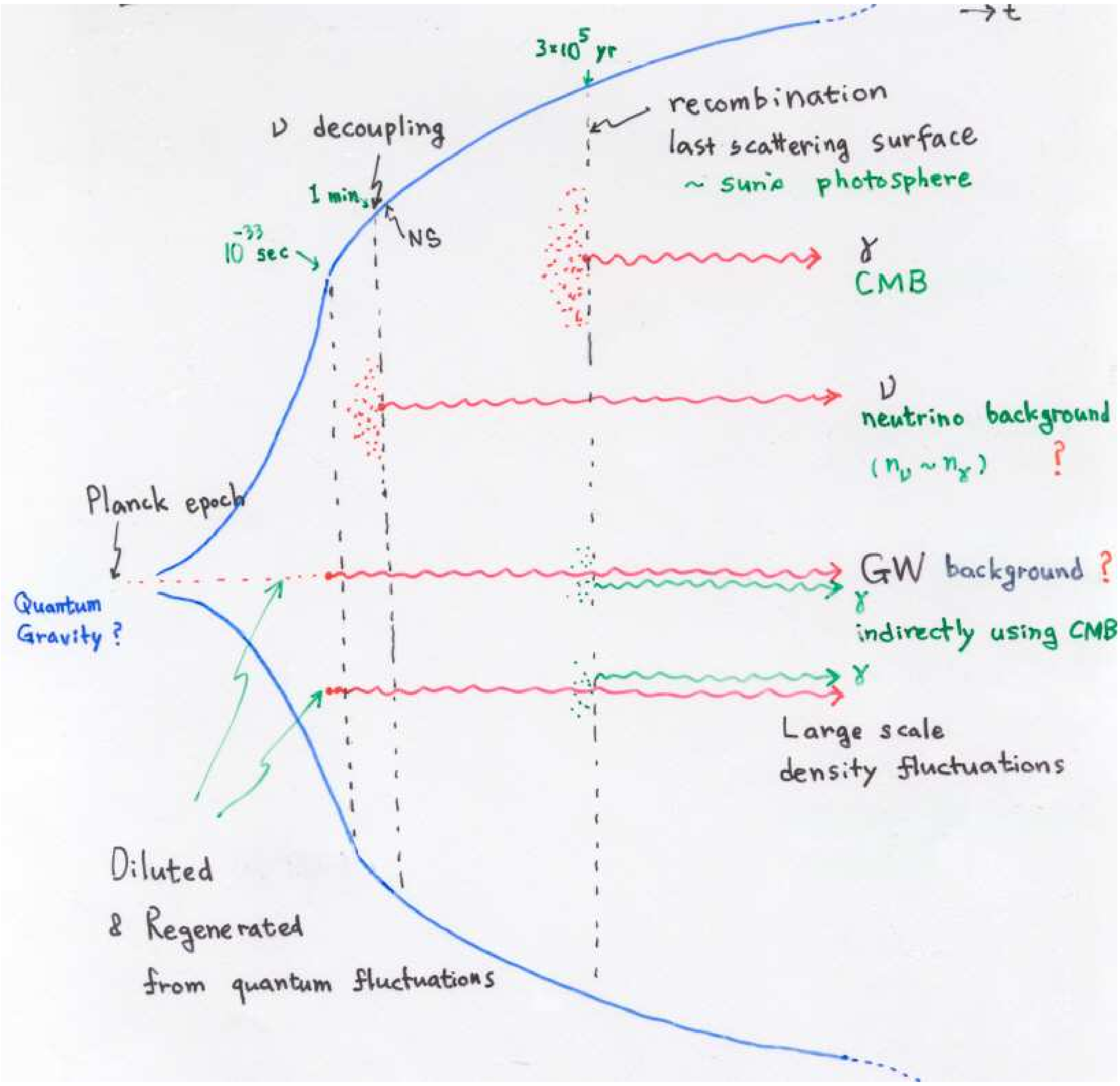
CMB



Observer's view



Observational tools



Some Issues

1. **Cosmological redshift:**

   Caused by the expansion of the world model during the photon travel. The wavelength of a freely propagating photon is stretched according to the expansion of the world model.

   $$1 + z \equiv \frac{\lambda_{obs}}{\lambda_{emit}} = \frac{a(t_{obs})}{a(t_{emit})}$$

   This differs from the Fizeau-Doppler effect which is caused by the relative velocity difference between the observed and emitted epochs.

2. **Expansion: the space or galaxies?:**

   It looks not possible to distinguish. If you could, it means we could use the expansion relation to "test" the relativistic gravity relative to the Newtonian one.

3. **Does Hubble's Law imply expansion?:**

   Plausible. But, difficult to prove. Need non-expansion-caused-redshift model and compare the difference.

   > "*It is always good to know which ideas cannot be checked directly, but it is not necessary to remove them all. It is not true that we can pursue science completely by using only those concepts which are directly subject to experiment.*"
   >
   > R. Feynman (1964)

4. **Is CMB cosmological?**

   Plausible. But, do we have any proof? Perhaps high-redshift-objects with certain line excitations caused by higher CMB temperature at that time would make the situation 'more' plausible. Similarly, the CN absorption lines were the first evidence of the presence of CMB.

5. **Homogeneity and isotropy:**

   Difficult to prove observationally. Homogeneity, in particular.

   CMB is quite isotropic around us.

6. **Does CMB imply cosmic rest frame (ether)?:**

   No. Our assumption of spatial homogeneity and isotropy implies a frame (spatial hypersurface) where the matter and geometry look homogeneous and isotropic. In that frame the CMB should look isotropic.

7. **Is CMB dipole due to our motion?**

   Can we show that the observed dipole anisotropy of CMB is due to our motion rather than a characteristic of our observable patch of the universe? This is an interesting question which looks very difficult (or, rather impossible) to settle observationally. Notice the current curious situation: the direction of CMB dipole axis differs significantly from the net observed direction of our (Local Group) motion relative to our neighbouring large-scale structures.

8. **Light elements and baryon density:**

   The nucleosynthesis model for the origin of light elements (H, He^4, He^3, D and Li^7) seems to require the amount of baryons to be less than that needed to account for the dynamics of the galaxies.

9. **Flatness problem:**

   In a decelerating expansion phase ($p > -\frac{1}{3}\mu$) the Friedmann world model diverges from near flat case. Then, why is the observed patch still near flat at the age of $\sim 14Gyr \sim 10^{61} t_{Pl}$ ($t_{Pl} \equiv \sqrt{\frac{G\hbar}{c^5}}$)?

   A plausible solution (inflation):

   If we had an accelerated expansion phase ($p < -\frac{1}{3}\mu$) in the early stage the world model dynamically converges to near flat model.

10. **Horizon problem:**

    > "*The history of astronomy is a history of receding horizons.*"
    >
    > Edwin Hubble (1936)

    Horizon is a light-travel distance during the age of a world model. So, the present day horizon is about 14 Gly, and at the recombination the horizon was about 3×10^5 ly. If we observe the CMB we are observing it at the last scattering surface. The horizon at that time subtends about $1 \sim 2$ arc-degree. Thus, if the universe has been decelerating after the big bang, two spots in the CMB separated more than 2 arc-degree has never been in causal contact. However, they show remarkably the same temperature.

    Acceleration phase in the early stage could make the observed CMB in all sky generated from a causal domain.

11. **Inflation as a solution:**

    An acceleration phase in the early expansion stage could solve (or relax) the flatness and the horizon problems.

    More importantly, an accelerated expansion provides a natural mechanism to generate the seeds fluctuation (by magnifying the ever present quantum fluctuations) with the Harrison-Zel'dovich spectrum which can later develop into the large-scale structures.

12. **Can we show inflation as a fact?:**

    Inflation provides a needed ingredient in the current paradigm of cosmology. The near flatness of the space curvature, and future detection of the right amount of gravitational wave signature in CMB could reinforce its reality (or plausibility). However, considering the energy scale it is supposed to be realized, I doubt whether it can be shown in near future.

    > "*When a feature of a model is ascertained through imposition rather than by experimental or observational check it is unscientific because it is only based on personal choices. In other words, a certainty achieved that way becomes a dogma.*"
    >
    > M. R. Ribeiro, etal (1998)

13. **Curvature:**

    The observed location of the first peak in CMB anisotropy favors the spatial flatness. The angular size of first peak corresponds to the horizon size at the recombination. In the spherical (hyperbolic) geometry the angle should be larger (smaller) than the one in the flat geometry.

14. **Dark matter problem:**

    The presence of nonluminous (measured by light) but gravitating (measured by dynamics) matter in clusters of galaxies was known from the 30's by Jan Oort and Fritz Zwicky. We also have similar problem in the galaxy level (Vera Rubin and Kent Ford, 1970): flat rotation curve of spiral galaxies. Their identities are still unknown (a scandal?). Does it indicate a missing matter problem or imply non-Newtonian gravity in such scales?

    Perhaps, it is fair to point out, though, that pure baryonic model has problem in the large-scale structure formation due to the lack of time after the recombination (only thousand times of the expansion factor after the recombination, thus thousand times of the linear growth factor of the density fluctuation) and the low degrees of anisotropy (10^{-5}) of CMB. Before recombination the baryonic fluctuation in linear stage is tightly coupled with the radiation and cannot grow. Whereas, the collision-free dark matter could grow even before recombination as soon as the dark matter dominates the universe.

15. **Dotty cosmology:**

    Do you believe we could 'simulate' the universe in the computer using mere millions of dots, or even 10^{12} dots?

16. **Cosmological constant problem:**

    Recently introduced unclustered component in the largest scale which causes the observed patch accelerating is yet another cosmological conundrum. If Λ dominates the current expansion

    $$\Lambda \sim 10^{-123}/l_{Pl}^2,$$

    where $l_{Pl} = ct_{Pl}$. Why Λ so small so that only by now (at $t \sim 10^{60} t_{Pl}$) it starts dominating the dynamics? Once Λ dominates, in few dynamical time scale, the world model should enter the de Sitter phase which expands exponentially.

17. **Dark energy?:**

    If Λ is dynamic, it is no longer the cosmological "constant": dark energy. To achieve such a dynamics we can play with either an exotic fluid with $p < -\frac{1}{3}\mu$ or a scalar field with suitable potential (quintessence).

    Even with this, the problem present in Λ ('why now?' problem) is not addressed properly.

18. **Is Einstein's gravity correct?:**

    Einstein's gravity, the general theory of relativity, has been tested in the weak gravity limit (in the solar system). Whether it is valid in the untested arena of strong gravity (cosmology!) is based on our belief. There are indications that the theory itself breaks down near (cosmological) singularity. Perhaps, yet unavailable quantum gravity is desperately needed to make any conclusion. At least, we anticipate the quantum effects will become important near singularity (early universe) where curvature or the energy scale diverges.

    If we have to resort to cosmology because our theory cannot be examined by other experiments, after all, we should be aware that cosmology itself (in the large scale and in the early stage) is very loosely related to experimental ground.

19. **Cosmic joke?:**

> "*. . . we will establish the cosmological model as securely as the Standard Model of elementary particles. We will then know as much, or even more, about the early Universe and its contents as we do about the fundamental constituents of matter.*"
>
> quoted in Disney (2000)

> "*Cosmologists are often in error, but never in doubt.*"
>
> L. D. Landau (1908-1968)

20. **Before the big bang?:**

> "*Nothing can ever be created by divine power out of nothing.*"
>
> Lucretius (A Roman citizen, $\sim$ 100-55B.C.)

> "*What was God doing before the creation of the world? Some people say that before He made the Heaven and Earth, God prepared Gehenna (hell) for those who have the hardihood to inquire into such high matters. . . . There was no time before creation, and hence the question was not cogent. Simultaneously with time the world was made.*"
>
> "Confessions" Saint Augustine (354-430)

> "*The universe is created with time, not in time.*"
>
> J. D. Barrow (1999)

I believe it is rather a far-fetched interpretation. As we approach the singularity we no longer able to depend on the classical gravity, and, I believe it is fair to say that, we do not have better suggestions yet.

> "*. . . danger of strongly believing in ideas not confirmed by observation, . . . without this confirmation we lose the only way we can distinguish science from metaphysics.*"
>
> M. R. Ribeiro, etal (1998)

21. **Boundary of the universe?:**

> "*Many of today's problems awaiting solution are more sophisticated versions of puzzles discussed by the philosophers and mathematical astronomers of ancient Greece over two thousand years ago. They too worried about the limits of time and space, the elements that make up the whole, how (or if) the universe began, and whether cosmic events are random or meaningful, chaotic or maintained by balance and order.*"
>
> M. R. Wright (1995)

> "*Learn, therefore, that* the universe is not bounded in any direction. *If it were, it would necessarily have a limit somewhere. But clearly a thing cannot have a limit unless there is something outside to limit it, ... Since you must admit that there is nothing outside the universe, it can have no limit and is accordingly without end or measure.*"
>
> Lucretius ($\sim$ 100-55 B.C.)

Expanding Friedmann world model has a finite horizon, the light travel distance during the age of the universe, thus about $14Gly$. In this world model we do not need to assume anything which encompass beyond the horizon from the outset.

> "*In the search for truth there are certain questions that are not important. Of what material is the universe constructed? Is the universe eternal? Are there limits or not to the universe? ... If a man were to postpone his search and practice for Enlightenment until such questions were solved, he would die before he found the path.*"
>
> Gautama Buddha (563-483 B.C.)

> "*Socrates didn't spend his time discussing the nature of everything as most others did, wondering about what the experts call the* kosmos *and the reasons for all the things in the sky necessarily coming about as they do; on the contrary he pointed out the foolishness of those who were concerned with such matters.*"
>
> Xenophon, cited in M. R. Wright (1995)

22. **What's beyond the horizon, anyway?:**

What's beyond the present horizon is, by definition, beyond our recognition at present.

> "*Because we wish to talk about regions we cannot directly influence or experiment on, our theory is at the mercy of the assumptions we make.*"
>
> G. F. R. Ellis (1975)

> "*When our models give predictions of the nature of the Universe on a larger scale than the Hubble radius, these are strictly unverifiable, however appealing they may be.*"
>
> G. F. R. Ellis (1993)

23. **Future of the universe?:**

> "*Definite predictions may be made for finite (though very large) intervals of time only, as well as in other branches of science. . . . we see that the future of our Universe may be not simply* very *complicated but even* infinitely *complicated.*"
>
> A. A. Starobinsky (2000)

> "*The charm and importance of a study of the heavens was matched only by the uncertainty of the knowledge produced.*"
>
> Aristotle (384-322 B.C.)

24. **Future of the cosmology?:**

> "*The progress of astronomical science during the last five-and-twenty or thirty years has been so rapid as almost to approach the marvellous.*"
>
> E. Ledger (1882)

> "*Some genuine progress in cosmology has come mostly from advances in observational astronomy leading to new information being obtained at an increasing rate . . . .*"
>
> F. Hoyle, et al (2000)

Golden ages? or gloomy situation?:

> "*There is a special reason for believing that the twentieth-century universe is* the *universe; that further discoveries will add much in detail but will not alter the general picture.*"
>
> D. W. Sciama (1961)

> "*What if cosmologists already had, in the big bang theory, the major answer to the puzzle of the universe? What if all that remained was tying up loose ends, those that could be tied up? One does not become a cosmologist to fill in the details left by the pioneers.*"
>
> J. Horgan (1996)

> "*On the blurred boundaries of ancient maps, cartographers wrote 'There be dragons'. After the pioneer navigators had encircled the globe and delineated the main continents and oceans, later explorers filled in the details. But there was no longer any hope of finding a new continent, or any expectation that the Earth's size and shape would ever be drastically reappraised.*
>
> *At the start of the twenty-first century we have, remarkably, reached the same stage in mapping our universe: the grand outlines are now coming into focus.*"
>
> Martin Rees (2000)

> "*Given this possibility, it is no wonder that 'strong' scientists such as Hawking have vaulted past the big bang theory into postempirical science.*"
>
> J. Horgan (1996)

Only hope?:

> "*Prediction is very hard, particularly of the future.*"
>
> Neils Bohr (1885-1962)

25. **The ultimate question?:**

> "*On the ultimate origination of things: why there is a world at all? Why is there something rather than nothing?*"
>
> Gottfried Wilhelm Leibniz (1646-1716)

> "*I wonder at the existence of the world: how extraordinary that anything should exist, or, how extraordinary that the world should exist.*"
>
> Ludwig Wittgenstein (1889-1951)

> "*Why is there any Being at all - why not far rather Nothing?*"
>
> Martin Heidegger (1889-1976)

These are metaphysical questions.

26. **More tractable ones, perhaps?:**

> "*Where do we come from? What are we? Where are we going?*"
>
> Paul Gauguin (1897)

These must belong to the most profound questions raised by humankind,

especially the middle one.

Meanwhile, we also have

> "*It is better to inquire about 'light' things, finding some truth, than keeping to wonder about the 'maximal questions' without reaching anything.*"
>
> Galileo Galilei (1564-1642)

27. **Pointlessness:**

> "*The more the universe seems comprehensible, the more it also seems pointless.*"
>
> S. Weinberg (1977)

It seems to me: physics is not the right vehicle if one is interested in the "point (purpose or meaning) of the universe". Although, modern sciences have been trying to avoid the term "purpose" intentionally, still perhaps, cosmo'bio'logy would provide better perspective on such a matter, not physical cosmology.

> "*Physical cosmology confines its attention to the "how" of the universe and does not deal with the "why".*"
>
> R. A. Alpher et al (2001)

All interesting fundamental questions are metaphysical ones then.

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"it is ironic science, science that is not experimentally testable or resolvable even in principle ... Its primary function is to keep us awestruck before the mystery of the cosmos. ... Ironic cosmology will continue, of course, as long as we have poets as imaginative and ambitious as Hawking, Linde, Wheeler, ... Their visions are both humbling, in that they show the limited scope of our empirical knowledge, and exhilarating, since they also testify to the limitlessness of human imagination. ... But it is not science."

J. Horgan (1996)

"cosmology itself, like all arts and sciences, is a construct of human intelligence, subject to social and linguistic conditioning and dubious means of communication."

M. R. Wright (1995)