Accelerating Universe:

Dark Energy & Beyond

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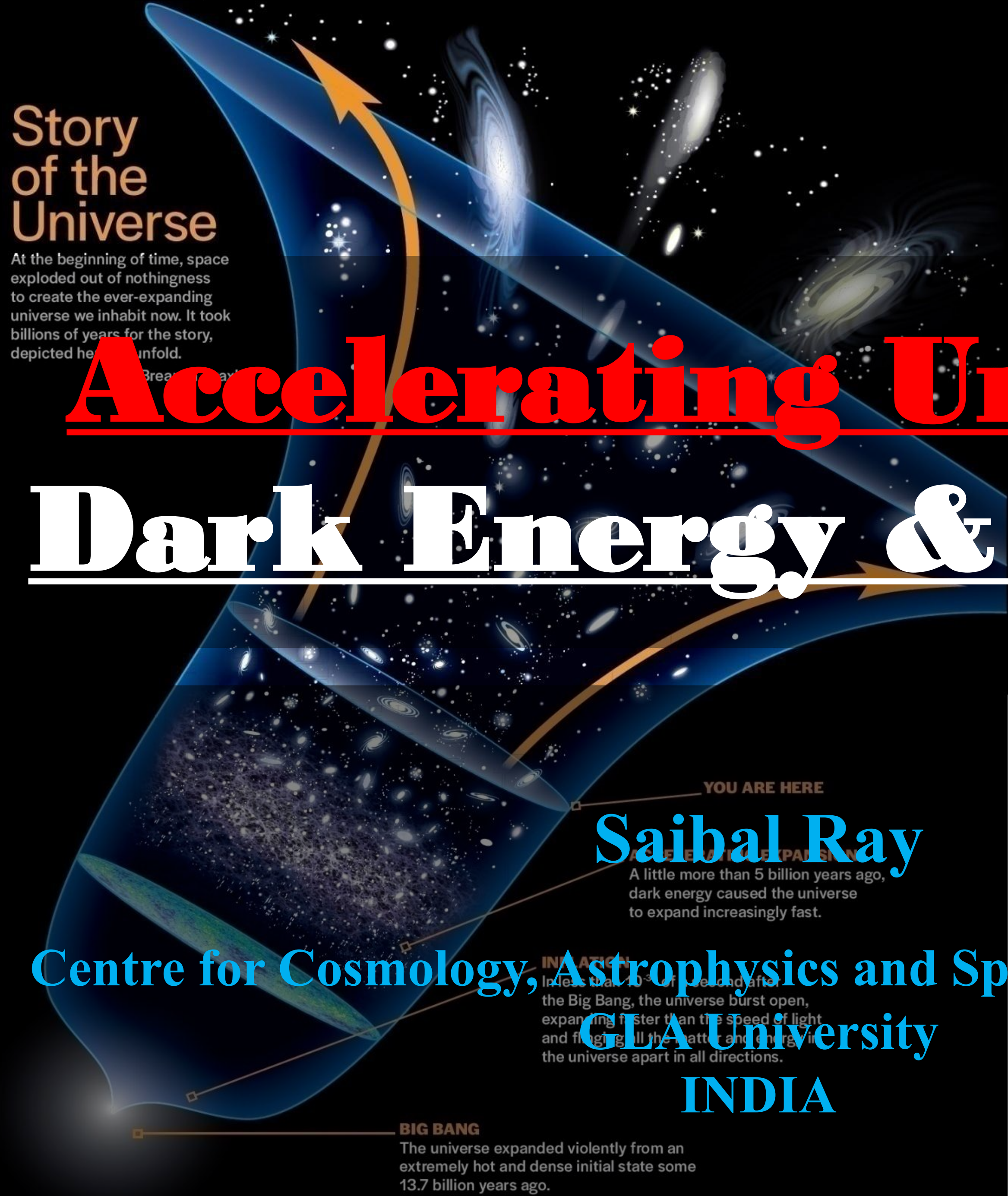
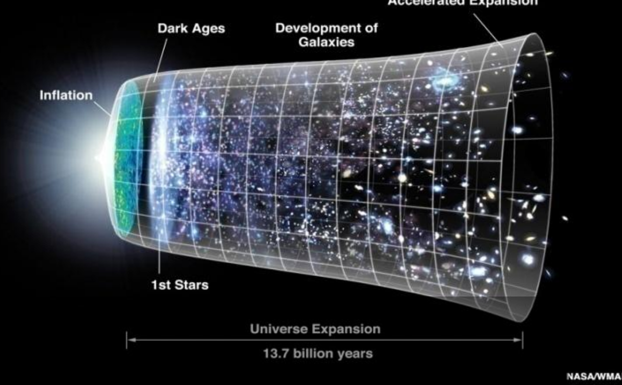
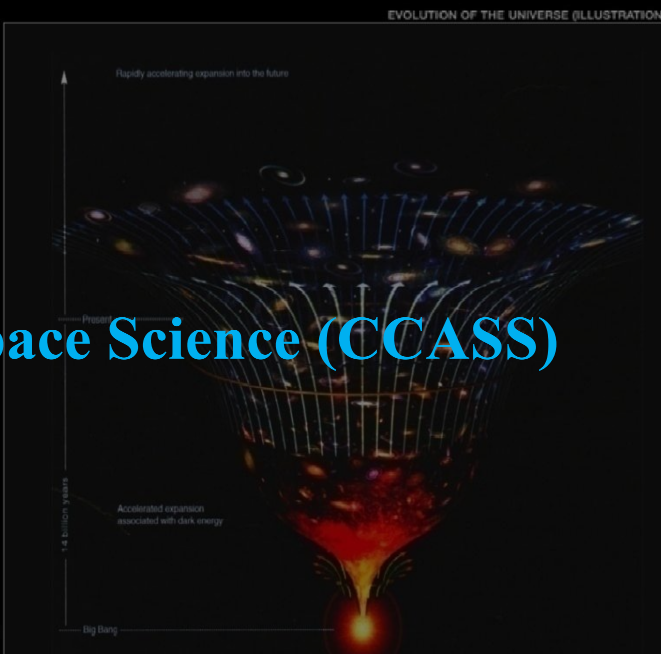






Outline

Part I: *Basic historical background*

Part II: *Technical Consideration*

Part III: *Philosophical Issues*

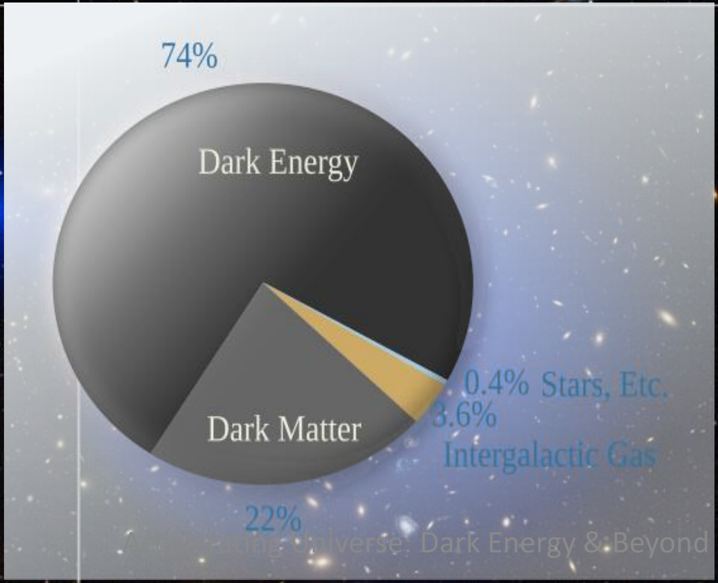
PART I

Basic historical background

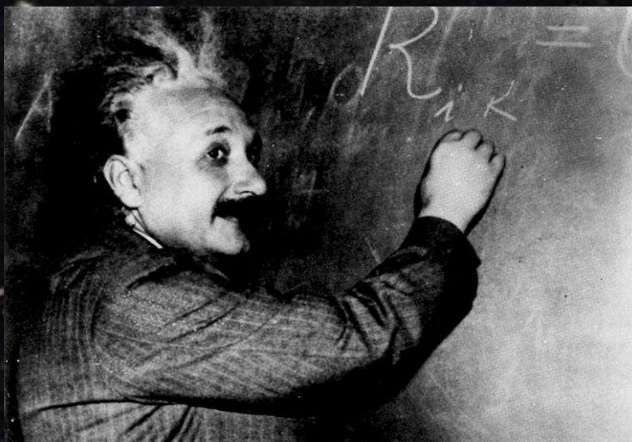
Our Issue:
To shed Light on the Dark side of the Universe

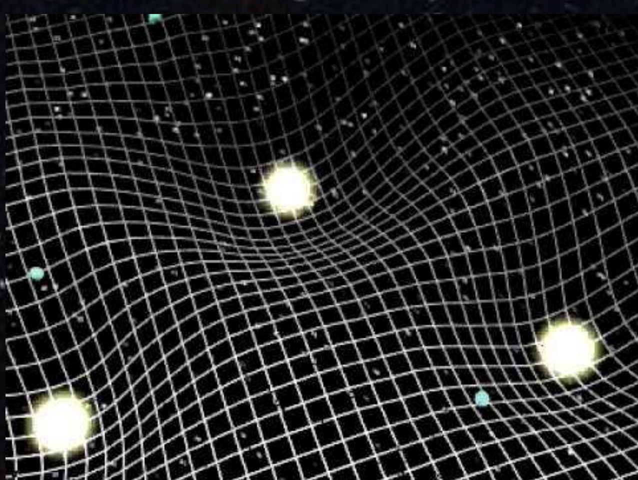
- Since the time of the ancient Greeks, scientists were searching for the constituent matter of our universe...
- Nearly over last 35 years several physicists and cosmologists became able to discover that only 4% of our universe is made up of visible matter!

So, what about other 96% !!!



General Theory of Relativity





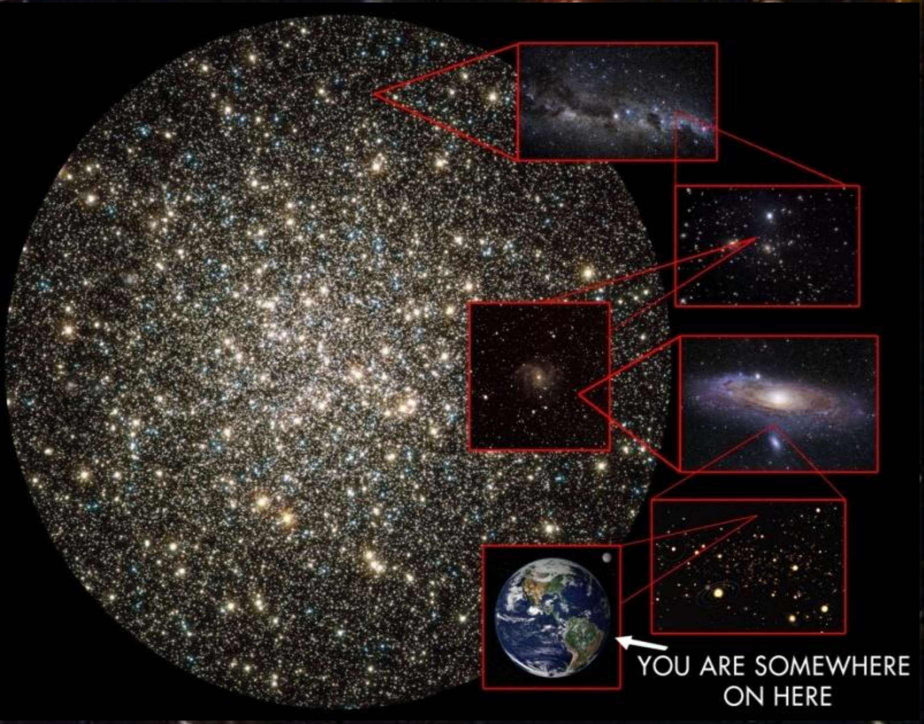
- Albert Einstein's general theory of relativity (1916) is one of the towering achievements of 20th-century physics.

- J.A.Wheeler:

  Space-time tells matter how to move; matter tells space-time how to curve.

Cosmology:

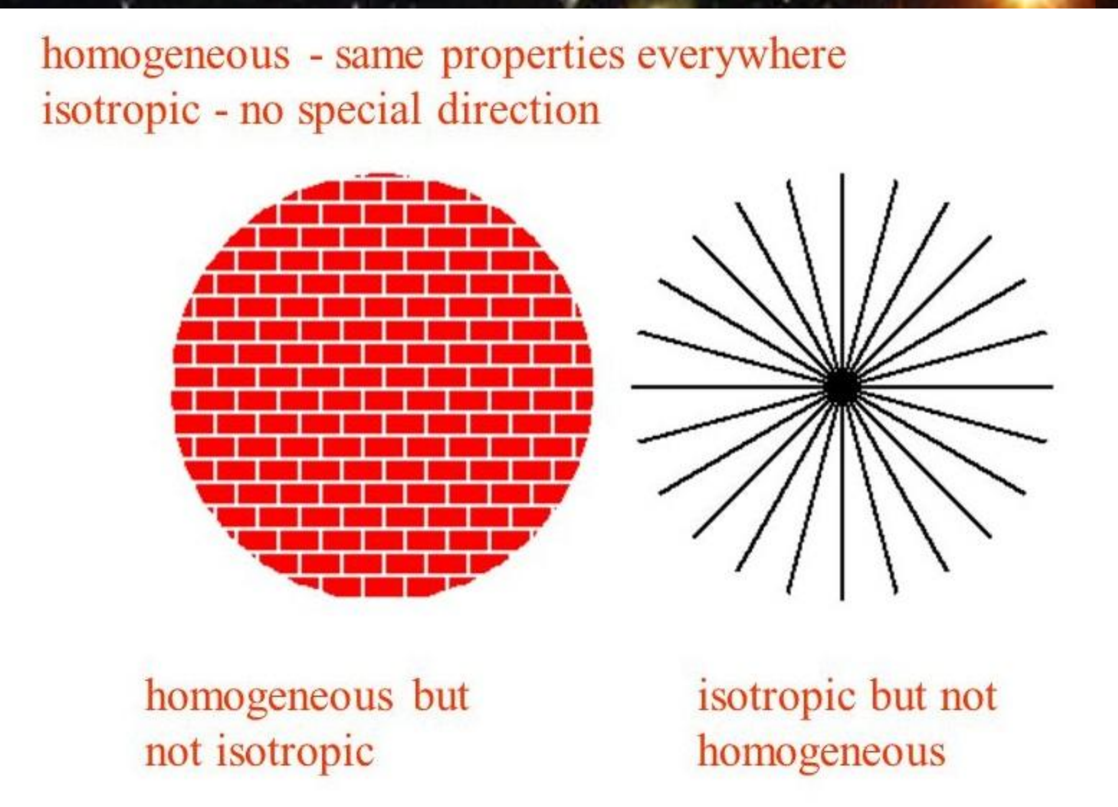
Large scale structure of the Universe



Our basic assumptions are:

- **GTR is the most promising tool to describe the Universe**
- **This requires information about how the matter in the Universe was distributed.**
- **The matter distribution of the Universe is roughly same in everywhere and in every direction.**

The Cosmological Principle



The matter in the universe is:

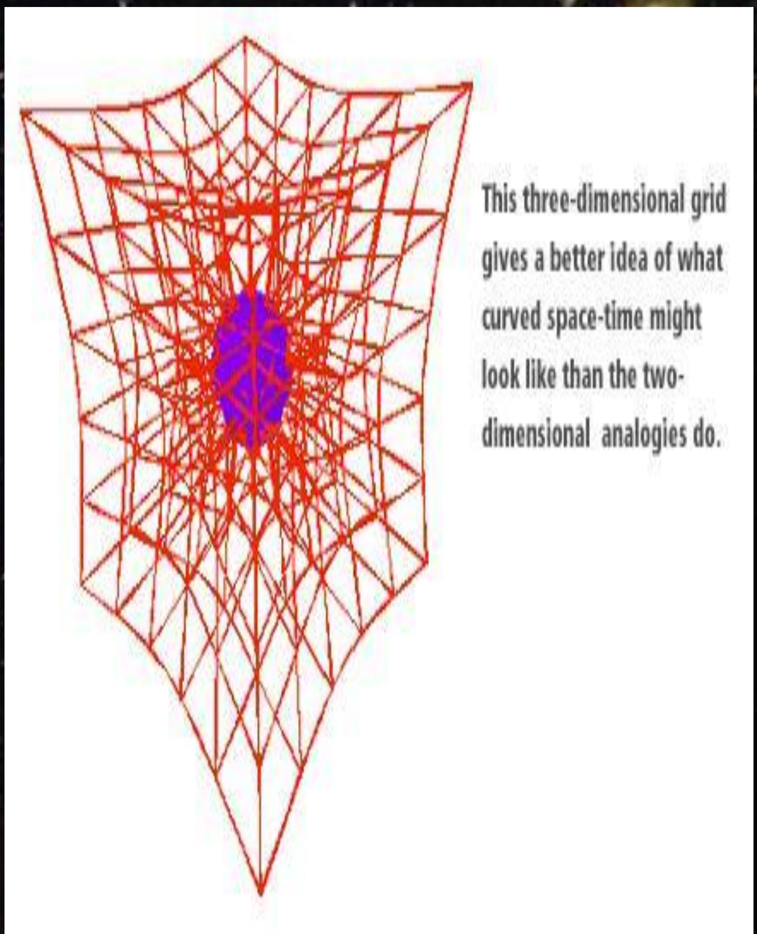
- **Homogeneous**

&

- **Isotropic**

when averaged over a very large-scale structure.

Einstein's Model of the Universe



- 1917

- **A model of a homogenous, static, spatially curved Universe**

- ***Field Equations of cosmology with the Lambda term***

Einstein's Field Equations

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- **A set of 10 equations in GTR which describe the fundamental interaction of gravitation as a result of space-time being curved by matter and energy.**
- **The expression on the left represents the *curvature of the space-time*.**
- **The expression on the right represents the *matter-energy content of the space-time*.**

Status of Einstein's Model

- Einstein believed that the universe was static and to overcome inevitable collapse due to gravity – he introduced the cosmological constant

- His two contemporaries - Alexander Friedman (1922) & Georges Lemaitre (1927) predicted that the idea of static universe were incomplete and it was in expansion phase as evident from astronomical observations

- In 1932 Einstein, along with Willem de Sitter , proposed an eternally expanding universe which since that time became a major cosmological model

The Cosmological Constant

$$\Lambda = \frac{4\pi\rho G}{c^2}$$

- Λ is that famous *Cosmological Constant*
- It was originally proposed by Einstein as a modification of his original theory *to achieve a static universe*
- It is equivalent to an *energy density of the empty space, i.e. vacuum*
- This vacuum is addressed by **Zeldovich** as *Quantum Fluctuation of Zero-Point Energy*
- This issue is connected to the *Casimir Effect*

The Shape of the Universe

- The *Friedmann–Lemaitre–Robertson–Walker (FLRW) model* has become the most accepted theoretical model of the universe

- It is sometimes called the *Standard Model* of cosmology in contrast to the *Standard Model* of particle physics

- This model describes a *curvature* of the space-time fabrics of the universe

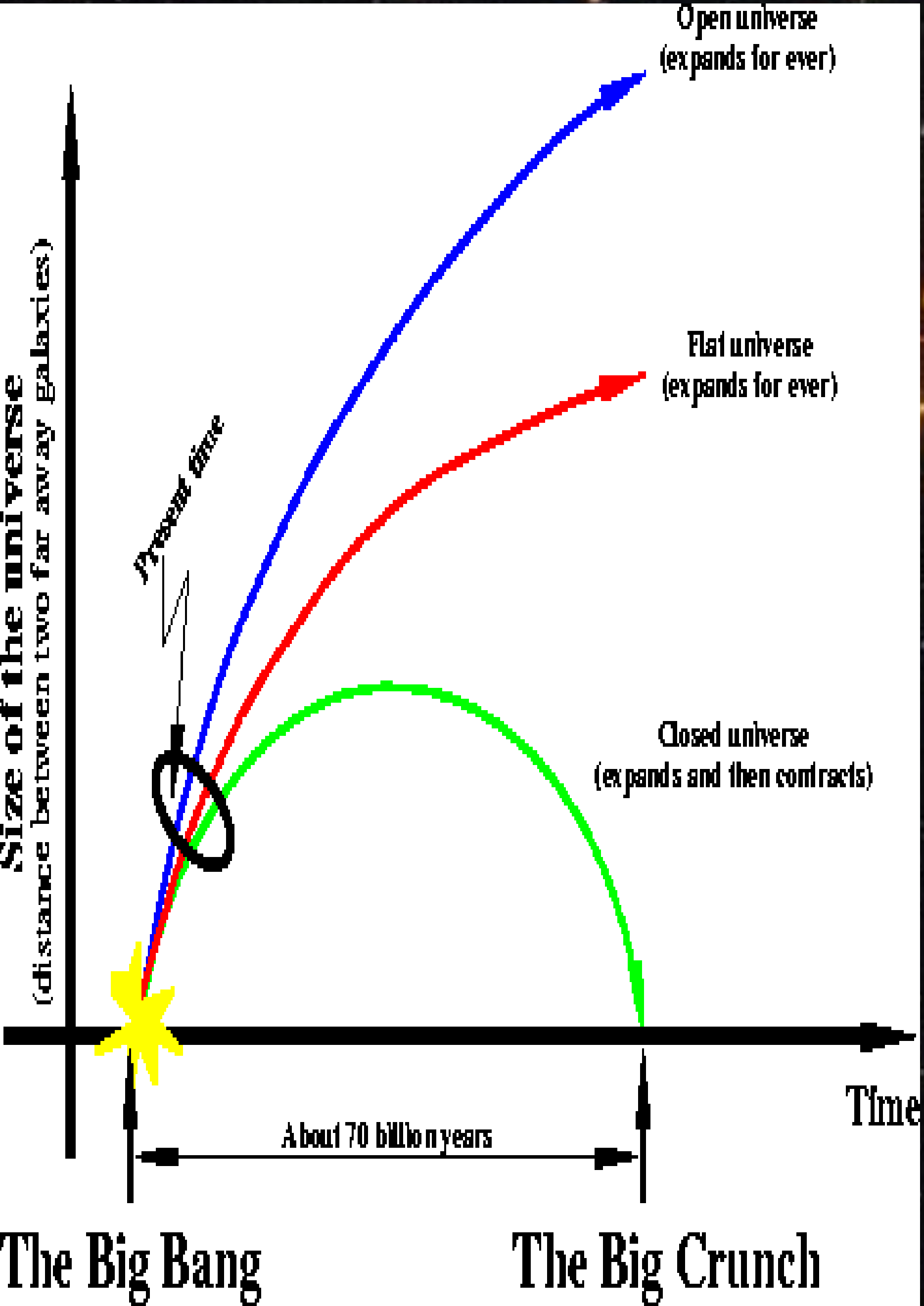
- The *curvature of space-time* depends on the value of the cosmic density parameter $\Omega := \frac{\rho}{\rho_c} = \frac{8\pi G\rho}{3H^2}$

The Cosmological parameters

The properties of the standard cosmological model are expressed in terms of various cosmological parameters such as:

- H_0 is the Hubble expansion parameter today
- $\Omega_M \equiv \rho_M / \rho_c$ is the fraction of the matter energy density to the critical density [$\rho_c \equiv \frac{3H^2}{8\pi}$]
- $\Omega_\Lambda \equiv \rho_\Lambda / \rho_c$ is the fraction of the Dark Energy density (here a cosmological constant) to the critical density.

Cosmological Metric

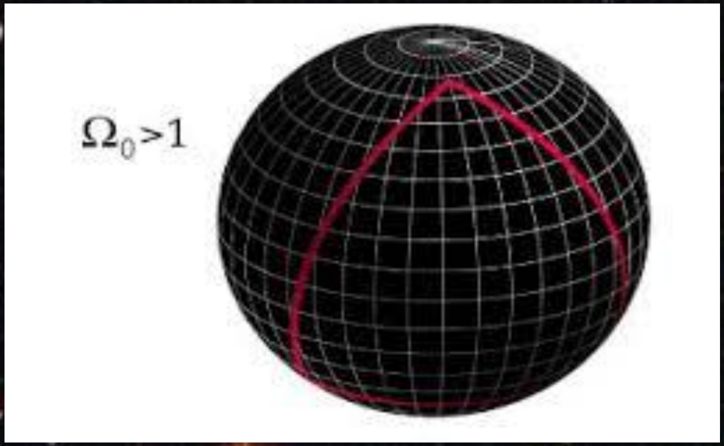


The Friedmann-Lemaitre-Robertson-Walker metric can be provided as

$$ds^2 = -dt^2 + \frac{dr^2}{1 - k\left(\frac{r}{a}\right)^2} + r^2 d\theta^2 + (r\sin\theta)^2\, d\phi^2,$$

$$k = \begin{cases} +1 & \text{positive-curvature Universe (finite, closed),} \\ 0 & \text{flat Universe (infinite, open),} \\ -1 & \text{negative-curvature Universe (infinite, open).} \end{cases}$$

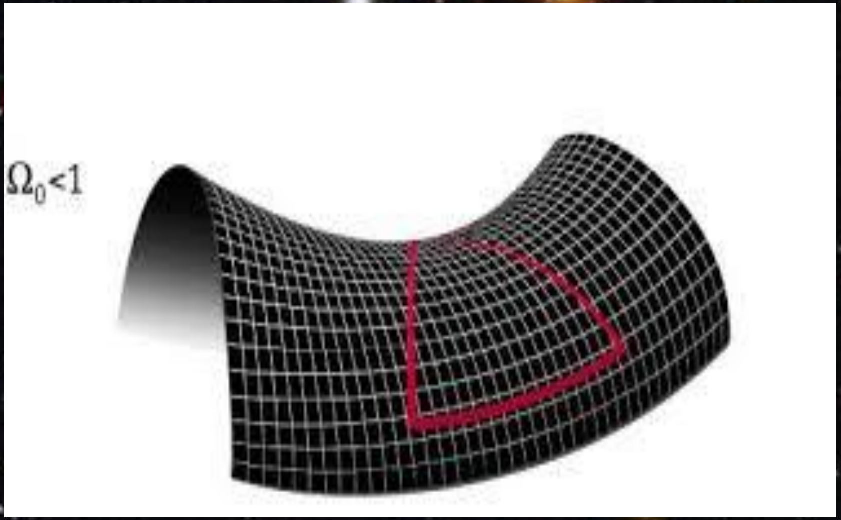
Closed Universe



If $k=1$ and $\Omega > 1$ (i.e., the density is above the critical density), the geometry of space is *closed* like the surface of a sphere and follows the Riemannian geometry of +ve curvature.

In a *closed universe*, gravity eventually stops the expansion of the universe, after which it starts to contract until all matter in the universe collapses to a point, a final singularity termed as *"Big Crunch"* – in contrary to *Big Bang!*

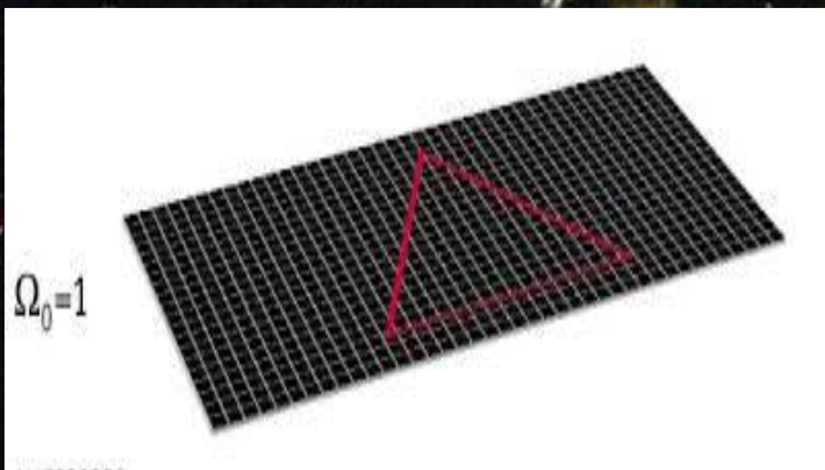
Open Universe



If *K*= *-1* and *Ω* < *1* (i.e., the density is below the critical density), the geometry of space is *open* – negatively curved like the surface of a saddle and follows the Bolyai-Lobachevskian geometry of –ve curvature.

An open universe expands forever, with gravity barely slowing the rate of expansion. The ultimate fate of an open universe is universal heat death, the *"Big Freeze"*.

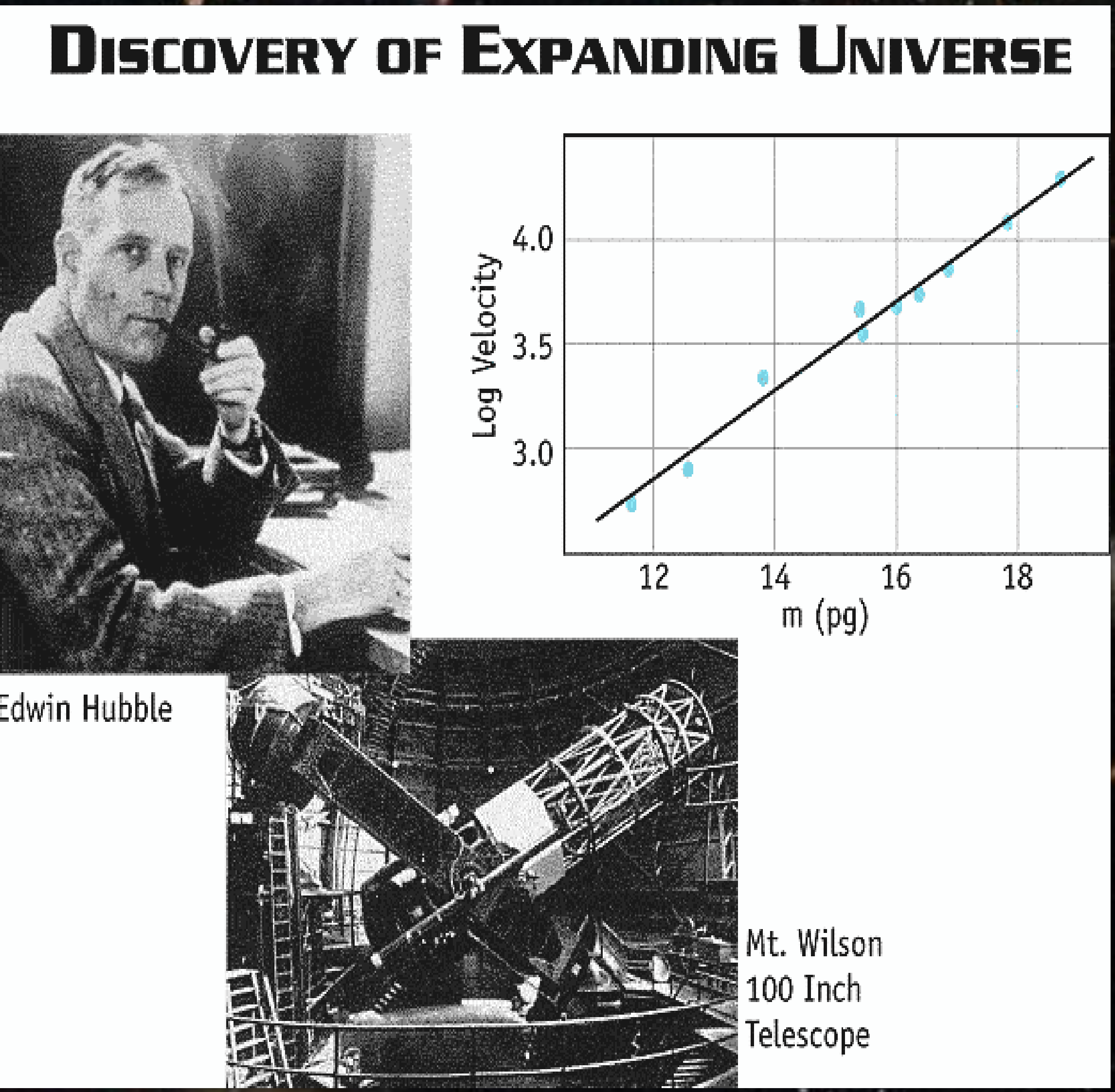
Flat Universe



If *K=0* and *Ω = 1* (i.e., the density is equal to the critical density), the geometry of space is *flat* – like a plane surface and follows the Euclidean geometry.

A flat universe expands forever but at a continually decelerating rate. The ultimate fate of the universe is the same as an open universe – a *"Big Freeze"*.

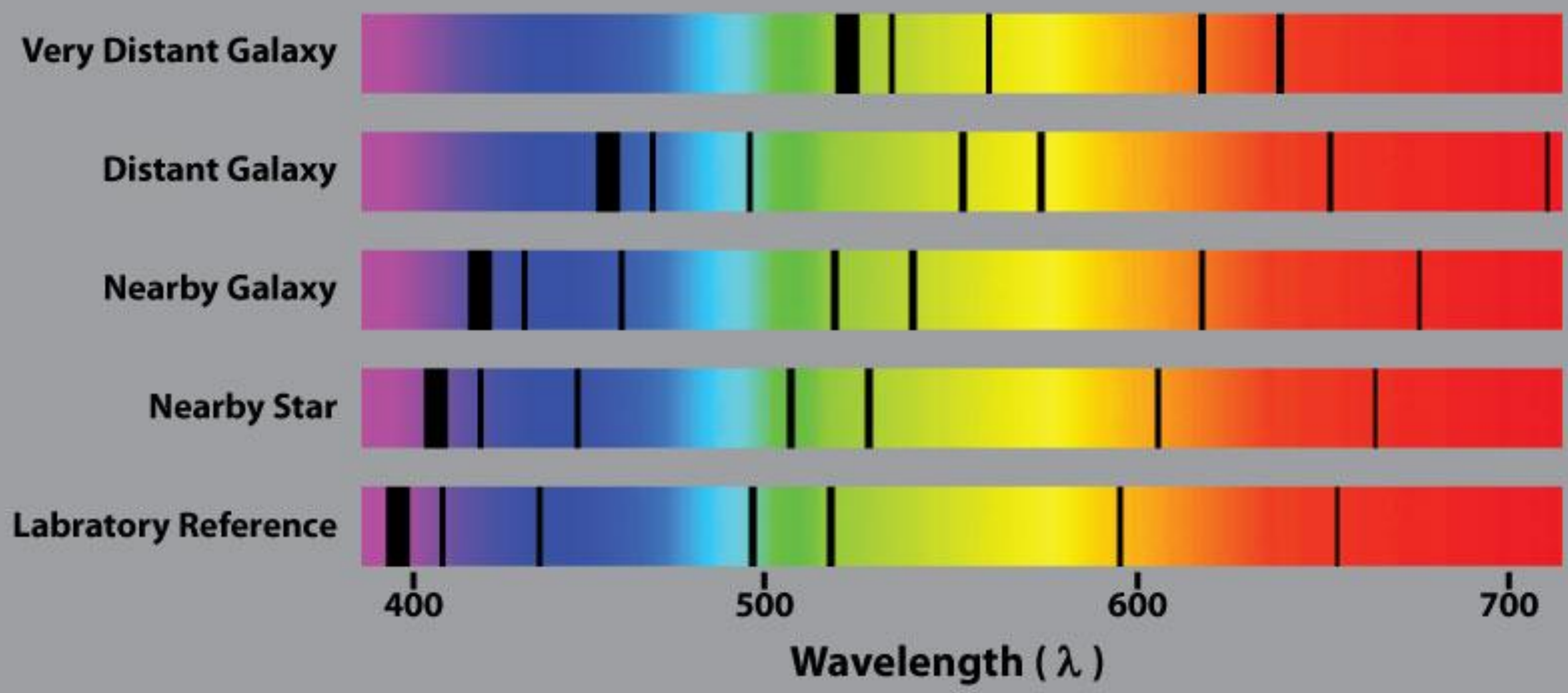
Hubble's Discovery



In 1928, *Edwin Hubble* found that the further the distance to a nebula, the greater the receding velocity of that nebula.

He used *Cepheid variable stars* as the *“standard candles”* to estimate their distance, and measured their *redshifts* to estimate velocity.

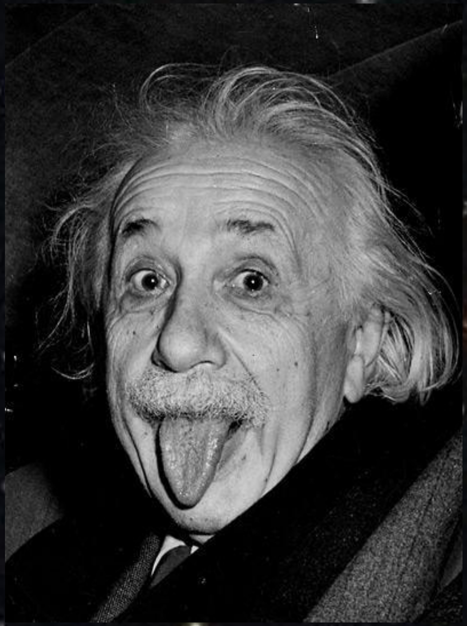
Galactic Redshifts



Here are some examples …

how spectral lines are shifted in stars and galaxies

Einstein's "Biggest Blunder"?

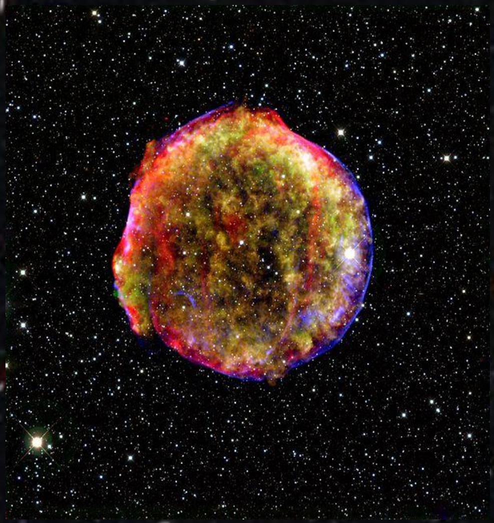


- ➢ **Evidence mounted that the universe was not static, but expanding...**
  This was consistent with the original Einstein model; who could have predicted it, but had assumed the static universe.

- ✓ **Einstein later remarked that *introduction of the cosmological constant was the biggest blunder of his life!***

- ○ **But was it really a blunder?**

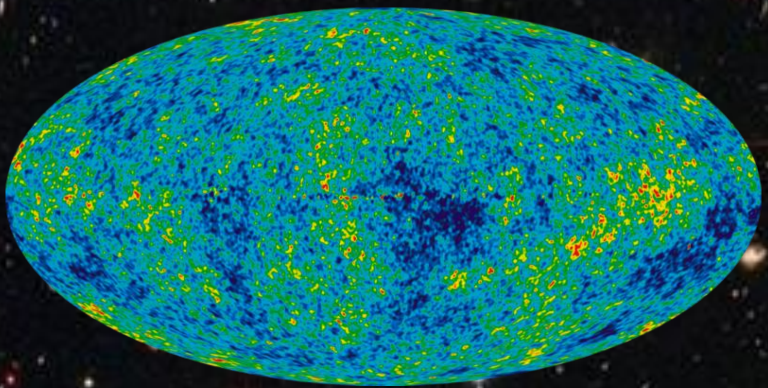
Type Ia Supernova



Multi-wavelength X-ray / infrared image of SN 1572 or Tycho's Nova, the remnant of a Type Ia supernova

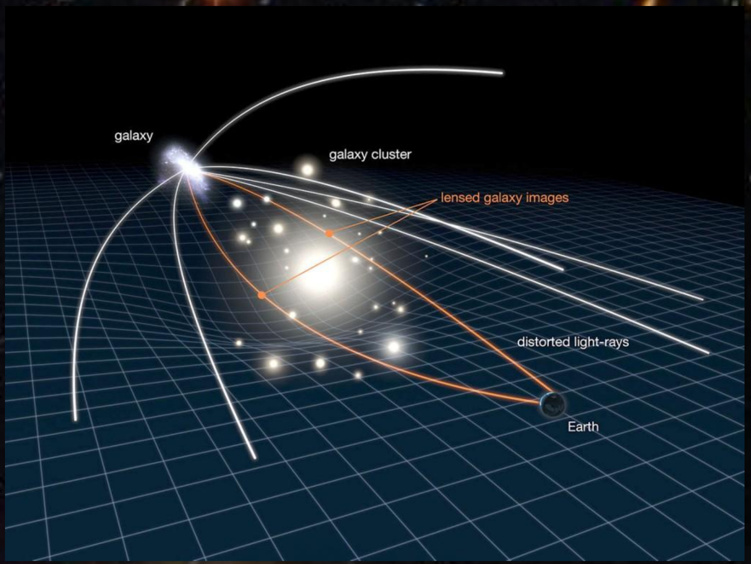
- It was discovered that these supernovae had a smaller redshift than would be expected.
- The fact that the redshift was smaller than expected means that they were moving slower in the past.
- These supernovae act as Standard Candle and distance ladder due to their constant luminosity.

Who rang the bell of Acceleration!

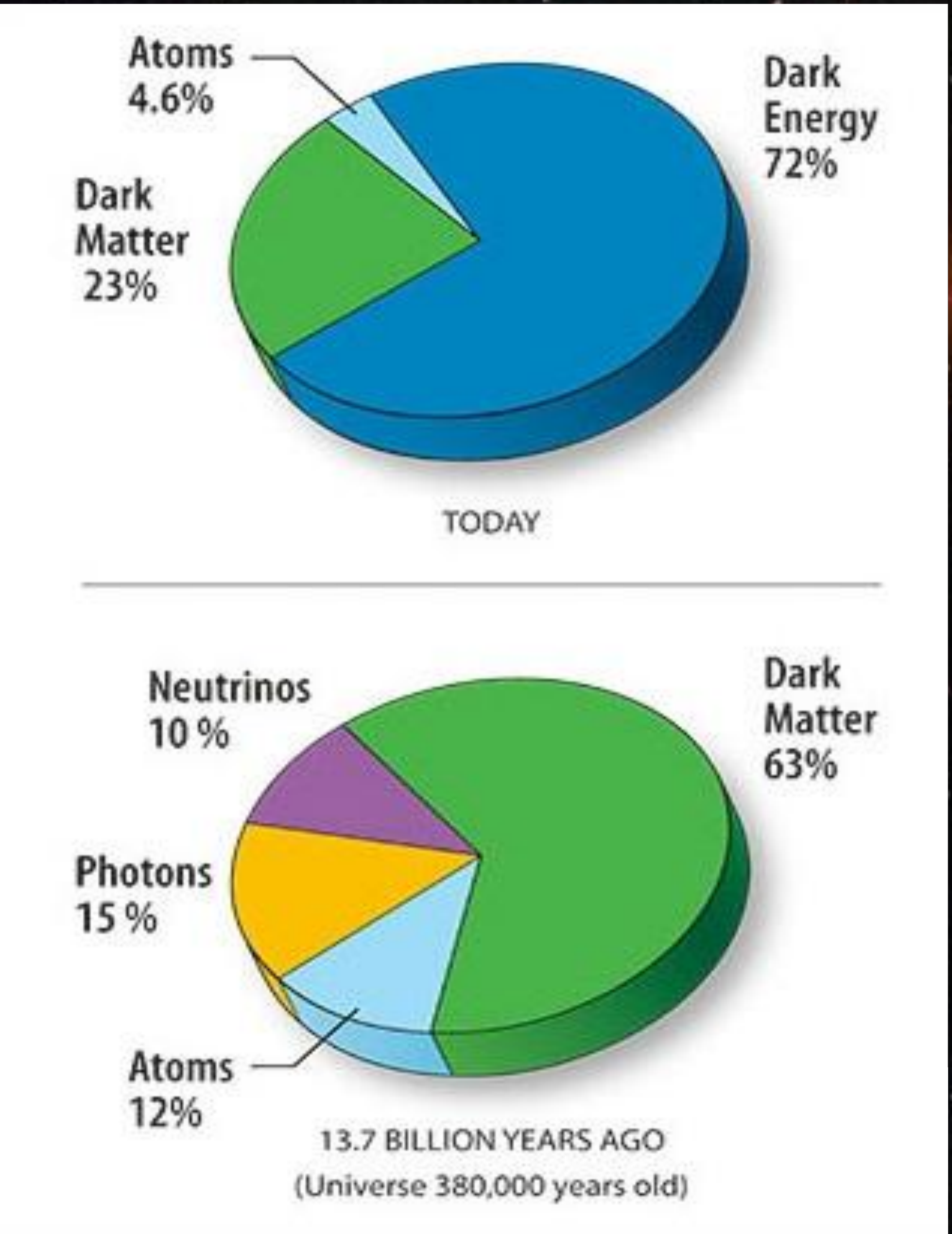


Since then, these observations have been corroborated by several independent sources:

- ***Cosmic Microwave Background Radiation***
- ***Gravitational Lensing***
- ***Large scale structure of the cosmos***
- ***Improved measurements of supernovae***

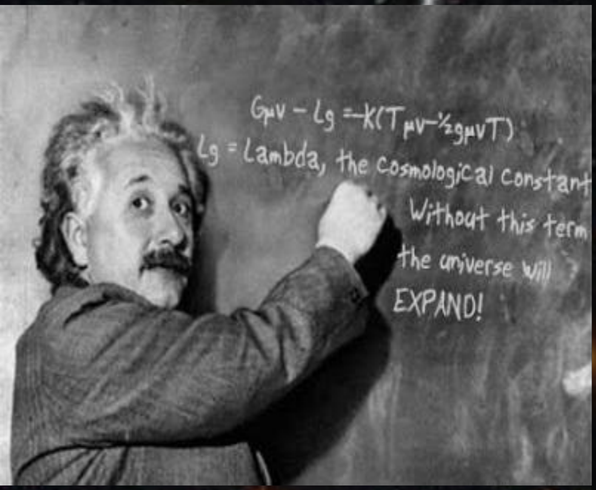


Contents of the universe



- Evidence for Dark Matter and Dark Energy has accumulated, and it is now estimated that only about 4% of the matter/energy in the universe is 'ordinary matter'.
- In other words, we have no real clue what the other 96% consists of !!!

Cosmological Constant?



- ***The story line:***

Einstein knew the universe was expanding…so he adopted Λ to get a static model…after Hubble's discovery he discarded the cosmological constant…he later on called it as the "biggest blunder of his life".

- **The *Cosmological Constant* has returned, and is the leading candidate for a Dark Energy explanation**

- **May be Einstein didn't commit any blunder!**

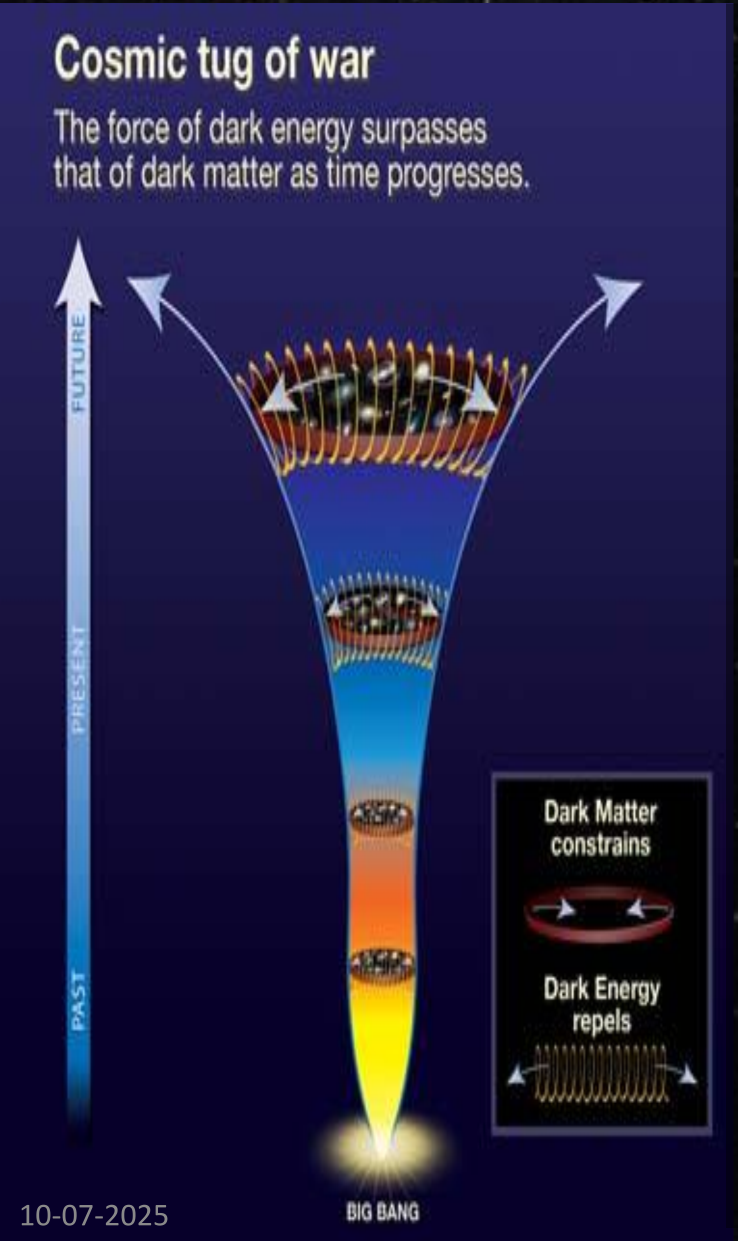
A Slight Problem...

- The *Cosmological Constant* being nonzero means that the vacuum can contain energy!

- However, when physicists calculate the vacuum energy using our best theory, the Standard Model, they come up with an estimate that is 120 orders of magnitude (10^{120}) .

- **This is too large & embarrassing!**

Implications



- Cosmologists estimate that the acceleration began roughly 5 billion years ago.
- Before that, it is thought that the expansion was decelerating, due to the attractive influence of dark matter and baryons.
- The density of dark matter in an expanding universe decreases quickly than dark energy, and eventually dark energy dominates.

PART II

Technical Consideration

Case studies : 1

Λ as a dynamic factor

$$\Lambda = \Lambda(t)$$

- S. Ray, U. Mukhopadhyay and X.-H. Meng, *Gravit. Cosmo.* 13, 142 (2007)
- A.A. Usmani, P.P. Ghosh, U. Mukhopadhyay, P.C. Ray and S. Ray, *MNRAS*, 386 L92 (2008)

Λ AS A DYNAMIC FACTOR (1)

- To accommodate the present status of the accelerating and flat Universe, some specific *dynamical models of the cosmological term* are useful for investigating the nature of dark energy.

- Connecting the *free parameters of the models* with the *cosmic matter and vacuum energy density parameters*, it can be shown that the models are equivalent.

- Using the *selected models*, the present values of some of the physical parameters can be estimated, and a glimpse of the *past decelerating* and *present accelerating universe* can be shown.

Λ AS A DYNAMIC FACTOR (2)

The matter and radiation energy densities of the expanding Universe fall off as a^{-4} and a^{-3} respectively, where *a* is the scale factor of the universe, while *Λ* remains constant.

For this reason, at present *Λ with a dynamical character is preferred over a constant Λ*, especially a time dependent *Λ*.

Λ AS A DYNAMIC FACTOR (3)

$$\Lambda \sim \left(\frac{\dot{a}}{a}\right)^2$$

It was proposed from dimensional arguments by Carvalho et al. [1] & Waga [2].

$$\Lambda \sim \frac{\ddot{a}}{a}$$

This model was dealt by Arbab [3] & Overduin and Cooperstock [4].

$$\Lambda \sim \rho$$

Using dimensional arguments, Vishwakarma [5] suggested this model.

Λ AS A DYNAMIC FACTOR (4)

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

The Einstein field equations are given by

$$R^{ij} - \frac{1}{2} R g^{ij} = -8\pi G \left[T^{ij} - \frac{\Lambda}{8\pi G} g^{ij} \right] \quad (2)$$

Here Λ to be assumed time-dependent, i.e. $\Lambda = \Lambda(t)$.

Using Eqs. (1) & (2) with a time-dependent cosmological constant yield the two equations, (i) the Friedmann equation and (ii) the Raychaudhuri equation.

Λ AS A DYNAMIC FACTOR (5)

Friedmann equation > $$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} \qquad (3)$$

Raychaudhuri equation > $$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \qquad (4)$$

The energy conservation law can be written as

$$8\pi G(p+\rho)\frac{\dot{a}}{a} = -\frac{8\pi G}{3}\dot{\rho} - \frac{\dot{\Lambda}}{3} \qquad (5)$$

The equation of state $$p = w\rho \qquad (6)$$

where the parameter ω can take the constant values 0, 1/3, −1 and +1 for dust, radiation, vacuum fluid and stiff fluid, respectively.

Λ AS A DYNAMIC FACTOR (6)

Using Eqs. (4) & (6) >

$$\frac{\ddot{a}}{a} + \frac{4\pi G}{3}(1+3w)\rho = \frac{\Lambda}{3} \quad (7)$$

Differentiating Eq. (3) w.r.t. '*t*' and using Eqs (4)–(7) >

$$\left(\frac{\dot{a}}{a}\right)^2 + \left[3\left(\frac{1+w}{1+3w}\right) - 1\right]\frac{\ddot{a}}{a} + \frac{k}{a^2} = \left(\frac{1+w}{1+3w}\right)\Lambda \quad (8)$$

This is the dynamical equation relating the cosmic scale factor *a* to a known value of the dynamic cosmological term

$$\Lambda = \frac{4\pi\rho G}{c^2}$$

A case study with Λ as a DYNAMIC FACTOR (7)

$$\Lambda = 3\alpha(\dot{a}/a)^2 = 3\alpha H^2$$

$$2a\ddot{a} + (1 + 3w - 3w\alpha - 3\alpha)\dot{a}^2 = 0$$

$$a(t) = C_1 t^{2/3(1-\alpha)(1+w)}$$

$$\rho(t) = \frac{1}{6\pi G(1-\alpha)(1+w)^2} t^{-2}$$

$$\Lambda(t) = \frac{4\alpha}{3(1-\alpha)^2(1+w)^2} t^{-2}$$

A case study with Λ as a DYNAMIC FACTOR (8)

$$\Lambda \sim (\dot{a}/a)^2$$

$$\Lambda = 3\alpha(\dot{a}/a)^2 = 3\alpha H^2$$

$$\Lambda = \beta(\ddot{a}/a)$$

$$\Lambda = 8\pi G\gamma\rho$$

A case study with Λ as a DYNAMIC FACTOR (9)

$$\alpha = \Omega_\Lambda$$

$$\beta = \frac{6\Omega_\Lambda}{2\Omega_\Lambda - \Omega_m(1+3w)}$$

$$\gamma = \frac{\Omega_\Lambda}{\Omega_m}$$

$$\alpha = \frac{\beta(1+3w)}{3(\beta w + \beta - 2)} = \frac{\gamma}{1+\gamma}$$

We find an interesting result that starting from any of our *Λ*-models, since they are equivalent, we can arrive at the Friedmann field equation without any special assumption.

A case study with Λ as a DYNAMIC FACTOR (10)

Forms of EOS parameter:

$$\omega(z) = \omega_o + \omega' z,$$

$(d\omega/dz)_{z=0}$ (Huterer & Turner 2001; Weller & Albrecht 2002)

$\omega(z) = \omega_o + \omega_1 z/(1+z)$ (Polarski & Chevallier 2001; Linder 2003)

Results show Universe is Accelerating

$$\Omega = \Omega_m + \Omega_\Lambda = 1$$

$$q = -\frac{a\ddot{a}}{\dot{a}^2} = \frac{3(1-\alpha)(1+w)}{2} - 1$$

$$\alpha > \frac{1+3w}{3(1+w)}$$

Conclusion

- We note that the cosmic vacuum density parameter from our model fits an Accelerating Universe since the modern accepted value of $\Omega_{\Lambda 0}$ is about 0.7 [5,6,7,8].

- We find the value of Ω_m is 0.3, which provides q_0 $=-0.50 \pm 0.05$ for the dust case which can nicely accommodate the currently accepted value related to the Accelerating Universe [9,10,11].

- Again, q will be positive if it is less than 0.3. Thus, for a decelerating universe, the cosmic vacuum density parameter should be smaller than 0.3, which is also consistent with the modern ideas.

- Therefore, we find that, within our models, one can investigate accelerating as well as decelerating phases of the cosmic expansion since q depends on ω.

Opponent Gravity Theories

1) **GR can not explain properly the late time acceleration of the universe.**

2) **To explain the acceleration the erstwhile Λ is to be invoked on the podium!**

3) **Gravity Theories can explain the effect without assuming any exotic agent**

Case studies : 2

Francisco Lobo …

- D. Deb, S.V. Ketov, S.K. Maurya, M. Khlopov, P.H.R.S. Moraes, S. Ray, Exploring physical features of anisotropic strange stars beyond standard maximum mass limit in *f(R,T)* gravity, *Mon. Not. R. Astron. Soc.* **485,** 5652 (2018)
- D. Deb, S.V. Ketov, M. Khlopov and S. Ray, Study on charged strange stars in *f(R,T)* gravity, *J. Cosmol. Astropart. Phys.* **10**, 070 (2019).
- V.K. Bhardwaj and **S. Ray**, Cosmological model in the framework of $f(R,L_m)$ gravity with quadratic equation of state parameter, *Phys. Dark Univ.* **48** (2025) 101930
- V.C. Dubey, U.K. Sharma, **S. Ray** and A. Sanyal, Study of cosmological dark energy models under $f(Q)$ gravity, *Phys. Dark Univ.* **47** (2025) 101736

PART III

Philosophical Issues

A FEW PHILOSOPHICAL ISSUES (1)

WHAT IS THE STATUS OF DARK ENERGY:

- **DOES IT EXIST OR NOT?**
- **IF DOES EXIST THEN**
  (i) WHETHER \`Λ' IS THE PROPER CANDIDATE OR SOMETHING ELSE IS WAITING FOR US?
  (ii) WHAT ARE THE FATES OF THE MODIFIED GRAVITY THEORIES?
- **IF Λ DOES NOT EXIST THEN WHAT?**

A FEW PHILOSOPHICAL ISSUES (2)

Newly discovered cosmic megastructure challenges theories of the universe:

1.3 bn light year-sized ring discovered by **Alexia Lopez**, a PhD student in the University of Central Lancashire appears to defy the cosmological principle assumption.

[The Guardian, Hannah Devlin (11 January 2024)]

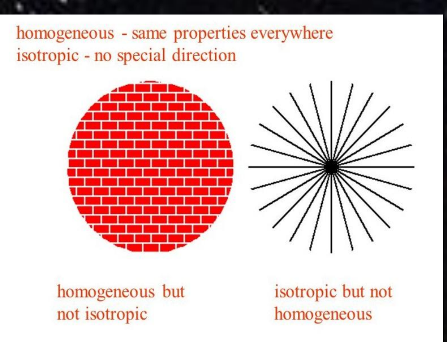
A FEW PHILOSOPHICAL ISSUES (3)

The inference of this discovery is that

the Cosmological Principles, i.e.

the matter in the universe is Homogeneous & Isotropic *when averaged over a very large-scale structure…*

DOES NOT HOLD GOOD!!!



A FEW PHILOSOPHICAL ISSUES (4)

What about the status of the Big Bang…

A few photographs by **JWST** and inference from those observation is as follows:

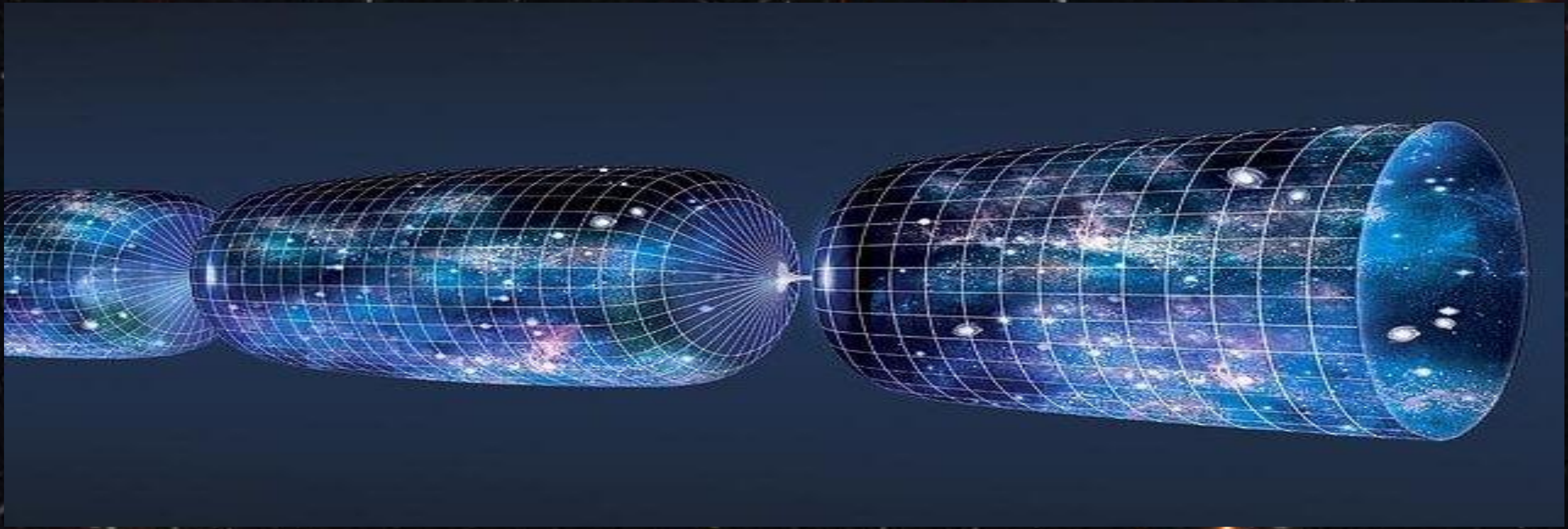
A few **QUASARS** suggest that they are much older than the so-called age of the universe, i.e. 13.8 bn years based on the Big Bang theory…

A FEW PHILOSOPHICAL ISSUES (5)

Breaking the Big Bang Barrier:

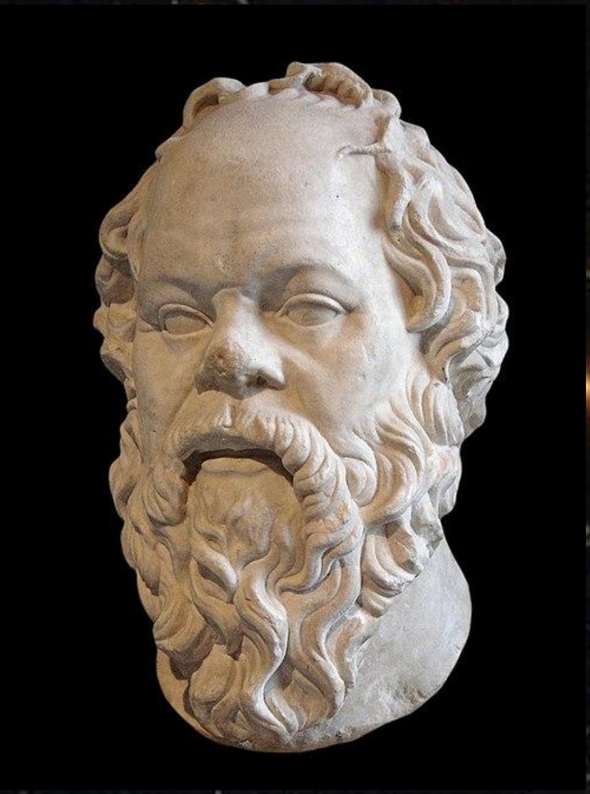
(i) Penrose's Vision for a Cyclic Universe

(ii) Hoyle-Narlikar's Steady State Universe



“All I know is that

I know nothing”



: *Socrates*

(470 – 399 BC)

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THANK YOU FOR YOUR KIND PATIENCE !