The Universe had (probably) an origin: on the theorem of Borde-Guth-Vilenkin

Emilio Elizalde

ICE/CSIC & IEEC
Campus UAB, Barcelona

*Trento, July 26, 2016**

*XXV Years of fruitful and wonderful collaboration Trento-Barcellona

Some facts *(a few rather surprising…)*

STARMUS

- Adam Riess, NP 2011, at Starmus (Tenerife), about Hubble:
  - *"Hubble obtained the distances and redshifts of distant nebulae…"*
  - *"Hubble discovered that the Universe was expanding…"*
  - *No mention* to Vesto Slipher, an extraordinary astronomer

SHOES-Supernovae

- Brian Schmidt, NP 2011, at Starmus (Tenerife) & Lisa Randall, Harvard U, in Barcelona, about Einstein:
  - *"Einstein was the first to think about the possibility of a 'dark energy'…"*
  - *No mention* to Fritz Zwicky, another extraordinary astronomer
  - Fritz Zwicky *discovered dark matter* in the early 1930s while studying how galaxies move within the Coma Cluster
  - He was also *the first* to postulate and use nebulae as *gravitational lenses* (1937)
- How easily* brilliant astronomers get dismissed
- How easily* scientific myths arise

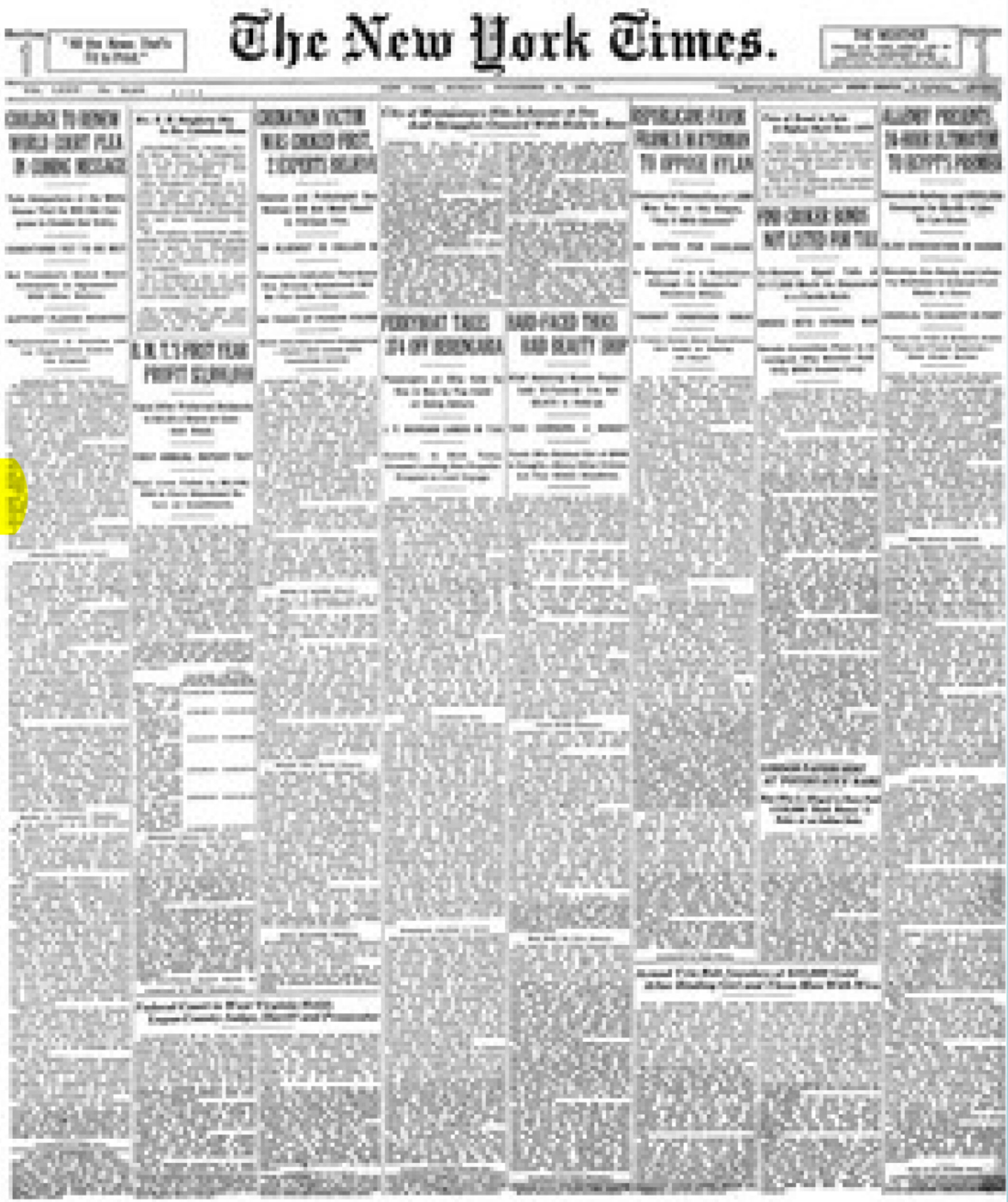
*in few decades

November 23, 1924

The New York Times

FINDS SPIRAL NEBULAE ARE STELLAR SYSTEMS; Dr. Hubbell Confirms View That They Are 'Island Universes' Similar to Our Ow

WASHINGTON, Nov. 22. -- Confirmation of the view that the spiral nebulae, whic appear in the heavens as whirling clouds, are in reality distant stellar systems, or "island universes," has been obtained by Dr. Edwin Hubbell of the Carnegie Institution's Mount Wilson observatory, through investigations carried out with tl observatory's powerful telescopes.


The New York Times.

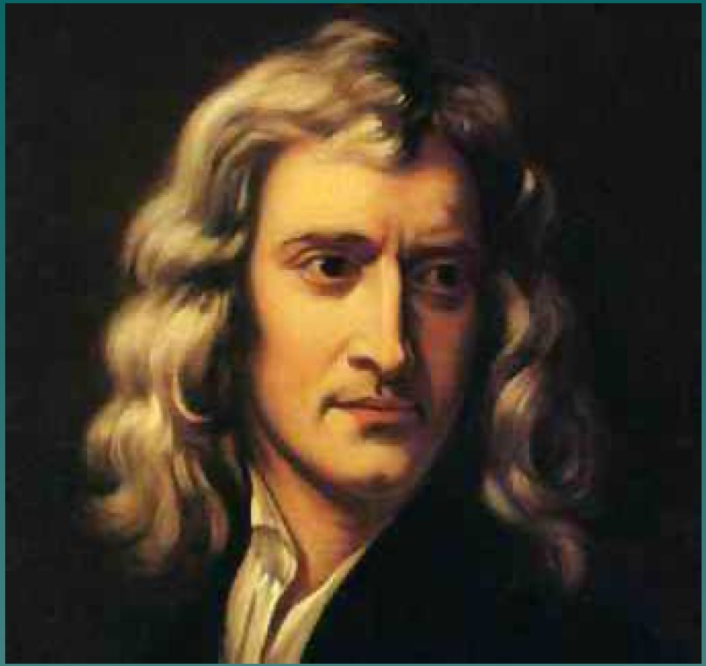
In 1929 Hubble formulated the Redshift Distance Law, Hubble's law

Edwin Hubble (1929), *"A relation between distance and radial velocity among extra-galactic nebulae"*, PNAS 15, 168–173

Ernst J. Öpik

Estonian astronomer and astrophys. (1893-1985) worked at the Armagh Observatory in Northern Ireland. In 1922 published a paper estimating the distance to Andromeda using an original method based on observed rotational velocities of the galaxy: 450 kpc. Was the first to calculate the density of a white dwarf.

His result was closer to recent estimates (775 kpc) than Hubble's result (285 kpc) of Nov 23, 1924; E Öpik, ApJ 55, 406, 1922.



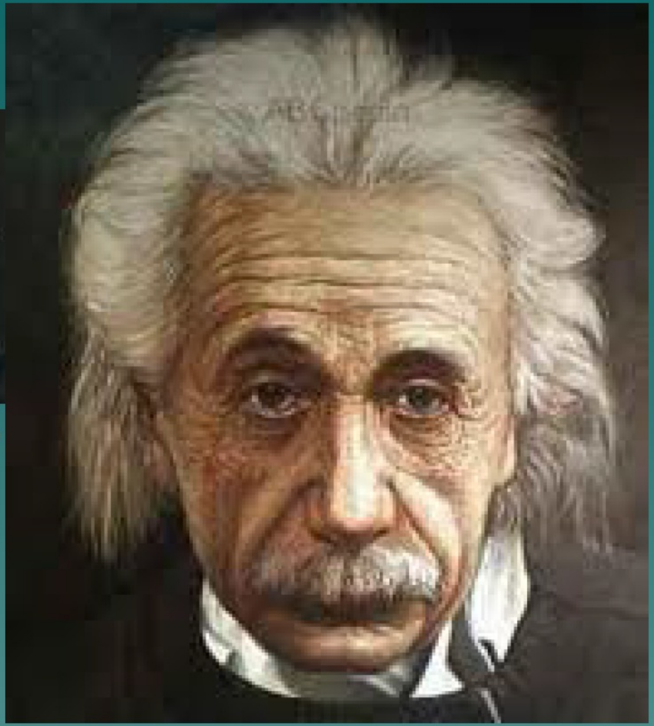
Isaac Newton (1642–1727)

Leibniz (1646–1716)

$$F = G\frac{Mm}{r^2}$$

Galileo (1564–1642)

$$E = mc^2$$



Albert Einstein (1879-1955)

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

$$\Omega_{tot} = \Omega_r + \Omega_m + \Omega_k + \Omega_\lambda$$

Big Bang

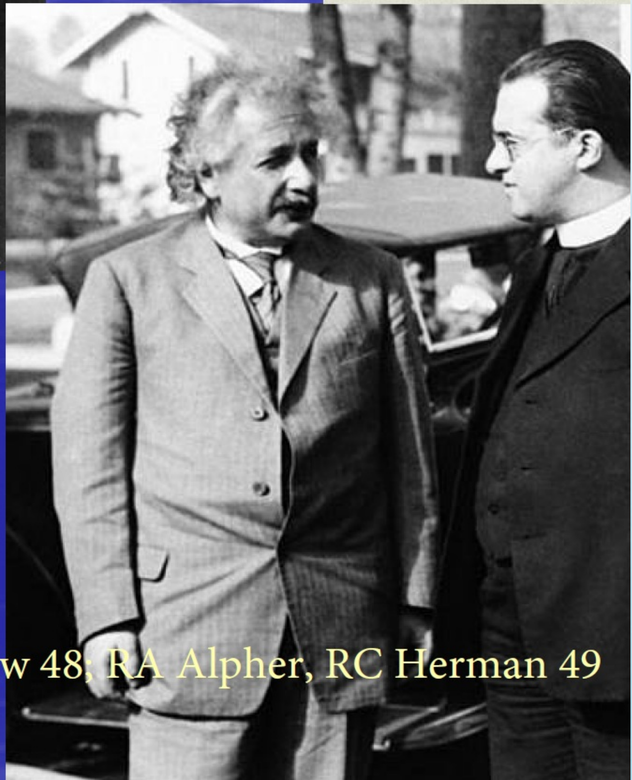
"Condició primigènia en la qual existien unes condicions d'una infinita densitat i temperatura" [Wikipedia CAT]

"At some moment all matter in the universe was contained in a single point" [Wikipedia]

Georges Lemaître (1894-1966)

Theory, 1927: Solution (Friedmann's) of Einstein's Eqs

Annales Société Scientifique Bruxelles **47**, 49 (1927), Eddington *MNRAS* (1930)



Observational evid.: V. Slipher redshifts + E. Hubble distancies

"hypothèse de l'atome primitif" *Nature* **127**, 706 (1931)

primeval atom, cosmic egg

WS Adams i T Dunham Jr 37-41; G Gamow 48; RA Alpher, RC Herman 49

James Peebles: *"The discovery that the U is expanding"*, Madrid 21/4/15

How did the “Big Bang” get its name ?

http://www.bbc.co.uk/science/space/universe/scientists/fred_hoyle

- Sir Fred Hoyle (1915–2001) English astronomer noted primarily for the theory of stellar nucleosynthesis (1946,54 groundbreaking papers)
- Work on Britain's radar project with Hermann Bondi and Thomas Gold
- William Fowler NP’83: *“The concept of nucleosynthesis in stars was first established by Hoyle in 1946”*
- He found the idea universe had a beginning to be *pseudoscience*, also arguments for a creator, *“…for it's an irrational process, and can't be described in scientific terms“; “…belief in the first page of Genesis"*
- Hoyle-Gold-Bondi 1948 steady state theory, "creation or C-field"
- BBC radio's Third Programme broadcast on 28 Mar 1949: *“… for this to happen you would need such a Big Bang!”*

Thus:

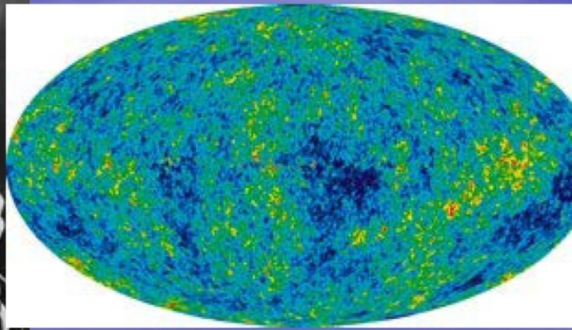
Big Bang = Impossible !!

But now:

Big Bang ≈ Inflation !

- Same underlying physics as in steady state theory, “creation or C-field”
- Richard C. Tolman, 1934: *Relativity, Thermodynamics, and Cosmology.* Explained how a closed universe could equal zero energy: how all mass/energy is positive and all gravitational energy is negative and how they may cancel each other out, leading to a universe of zero energy
- Tolman–Oppenheimer–Volkoff (TOV) equation: constrains in GR the structure of a spherically symmetric body of isotropic material in static equilibrium

Big Bang: Evidences

- Expansion according to Hubble’s law
- CMB Radiation 1964 A Penzias R Wilson

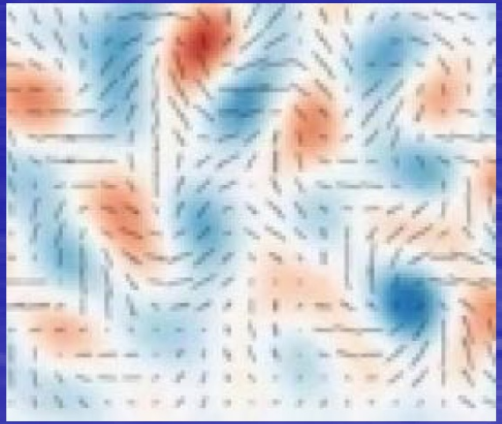
  WS Adams i T Dunham Jr 37-41; G Gamow 48; RA Alpher, RC Herman 49
- Abundancy of primordial elements

  helium-4, helium-3, deuterium, litium-7

- Evolution & distribution of galaxies
- Primordial gas clouds

  distant quasars
- Detection of primordial gravitational waves ?

  17 March 2014



Gravitational Waves, as Einstein predicted

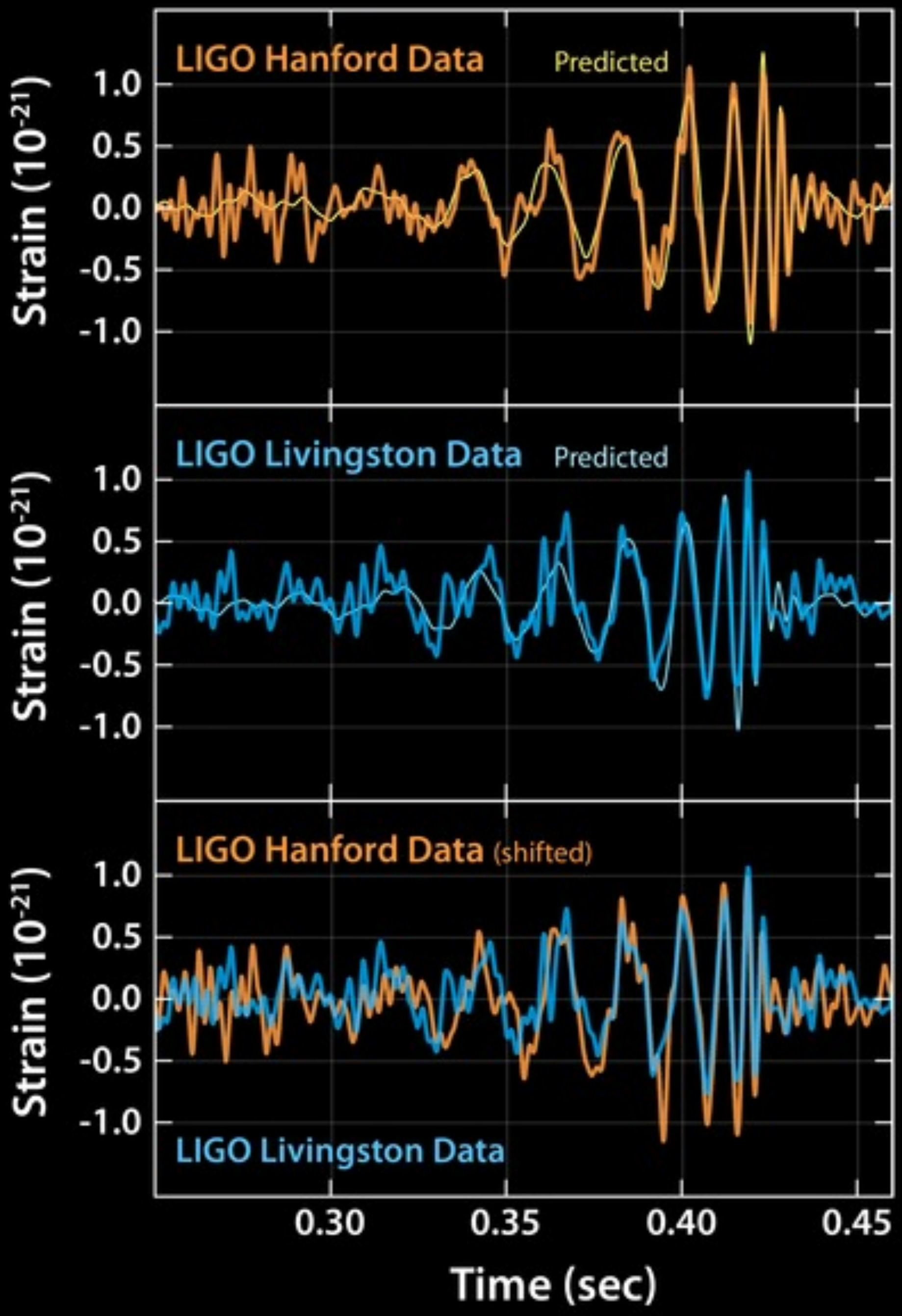
Febr 11, 2016; detected on Sept 14, 2015

…and Dec 2015 !

These plots show the signals of gravitational waves detected by the twin LIGO observatories at Livingston, Louisiana, and Hanford, Washington.

The signals came from two merging black holes, of about 36 and 29 times the mass of our Sun, lying 1.3 billion light-years away. The top two plots show data received at Livingston and Hanford, along with the predicted shapes for the waveform.

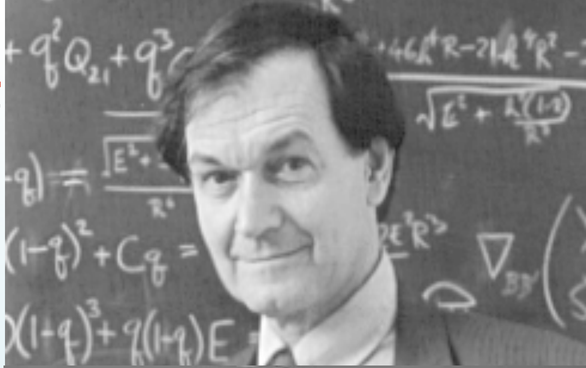
As the plots reveal, the LIGO data very closely match Einstein's predictions.



But there is another meaning for BB:

The Big Bang Singularity !!

Singularity Theorems: Roger Penrose, Stephen Hawking, …



R Penrose, *"Gravitational collapse and space-time singularities"*, Phys Rev Lett **14** (1965) 57
S Hawking, GFR Ellis, "*The Large Scale Structure of Space-Time*" (Cambridge U P, 1973)
RM Wald, *"General Relativity"* (U Chicago P, 1984); R Geroch, Ann Phys **48** (1968) 526
http://www.hawking.org.uk/the-beginning-of-time.html

Theorem 1 (Big Bang). Let (M,g) a global hyperbolic spacetime satisfying $R_{ab} \chi^a\chi^b \geq 0$ for all temporal vectors χ^a (Einstein's Eqs. with the strong energy condit.) If there exists a spatial Cauchy C^2 hypersurface, Σ, for which the trace of the intrinsic curvature satisfies $K<C<0$, C const., then no temporal curve starting from Σ and going towards the past can have a length that is larger than $3/|C|$.
All temporal geodesics to the past are incomplete.

[This is to say, under the conditions observed in our Universe (Hubble's law) and admitting the validity of General Relativity, our Universe had a begining]

Theorem 2 (Black Holes). Let (M,g) a global hyperbolic space-time satisfying $R_{ab}\, k^a k^b \geq 0$ for all lightlike vectors k^a (Einstein's Eqs. with the strong or the weak energy condit's.). Let us assume that there exists a spatial Cauchy C^2 hypersurface, Σ, and a trapped surface, and let θ_o be the maximum value of the expansion over it. If $\theta_o < 0$, then there exists at least a lightlike geodesic, which cannot be extended to the future, and which is orthogonal to the trapped surface. Moreover, the value of the affine parameter, up to the point where the geodesic is no further extensible, is less than $2/|\theta_o|$.
[The existence of a non-extensible lightlike geodesic implies that there will be a photon which, starting from that surface and after a time of travel proportional to $2/c|\theta_o|$, will fall into a future time singularity.
In absence of a theory of quantum gravity we cannot know the physical nature of the singularity.]

On the very origin ?

A mathematical singularity.

Extrapolation of the expansion of the universe backwards in time using General Relativity yields an infinite density and temperature at a finite time in the past [Hawking and Ellis, *The Large-Scale Structure of Space-Time* (Cambridge U.P., 1973)]

$$\ell_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^3}} \approx 1.616\,199(97) \times 10^{-35}\ \mathrm{m}$$

$$t_P \equiv \sqrt{\frac{\hbar G}{c^5}} \approx 5.39106(32) \times 10^{-44}\ \mathrm{s}$$

$\hbar$ = 1.054571726(47)×10^{-34} J s

= 6.58211928(15)×10^{-16} eV s

inside Planck region ?

Creation of the Universe

… out of nothing !

What's 'nothing' ??

- In fundamental classical physics, GR:

  de Sitter sol. is the zero-energy sol. of Einstein's Eqs.

- In quantum physics:

  The vacuum state of a quantum system

  - Of quantum spacetime   Krauss-Wilczek '15, nope!
  - Of a scalar field Hamilt (Higgs, inflaton, …)

Inflation

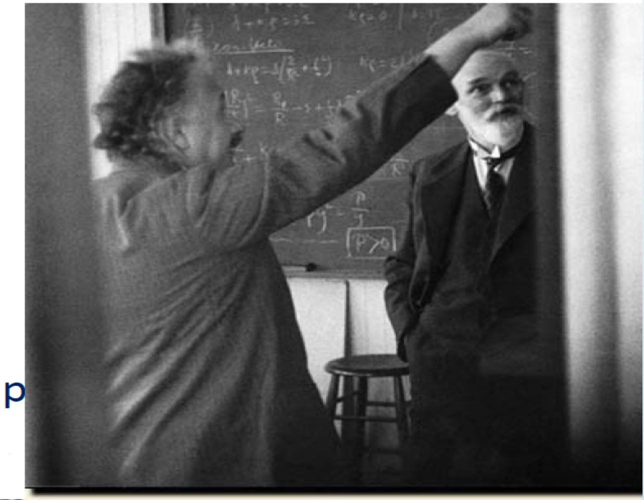
App. 10^{-36} seconds after the origin, a phase transition caused a cosmic inflation, during which the universe grew very quickly

The inflationary epoch lasted from 10^{-36} to 10^{-35} seconds after the origin to some 10^{-33} to 10^{-32} s

de Sitter space (1917) is the analog in Minkowski space (spacetime) of a sphere in ordinary, Euclidean space. It is the maximally symmetric, vacuum solution of Einstein's eqs, corresp. to a positive vacuum energy density and negative pressure

De Sitter space can be defined as a submanifold of a Minkowski space of one higher dimension. Take Minkowski space $\mathbf{R}^{1,n}$ with the standard metric:

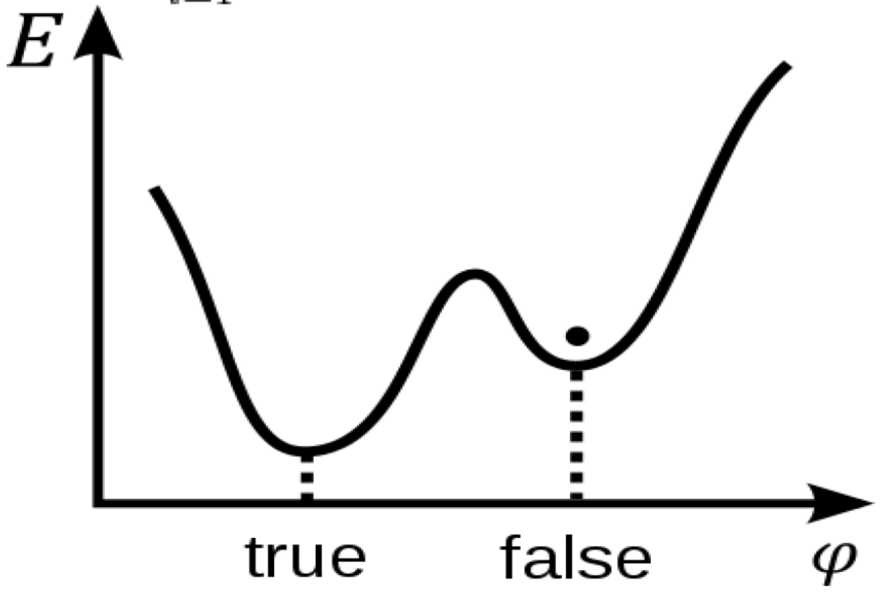
$$ds^2 = -dx_0^2 + \sum_{i=1}^{n} dx_i^2.$$



De Sitter space is the submanifold described by the hyperboloid of one sheet

$$-x_0^2 + \sum_{i=1}^{n} x_i^2 = \alpha^2$$

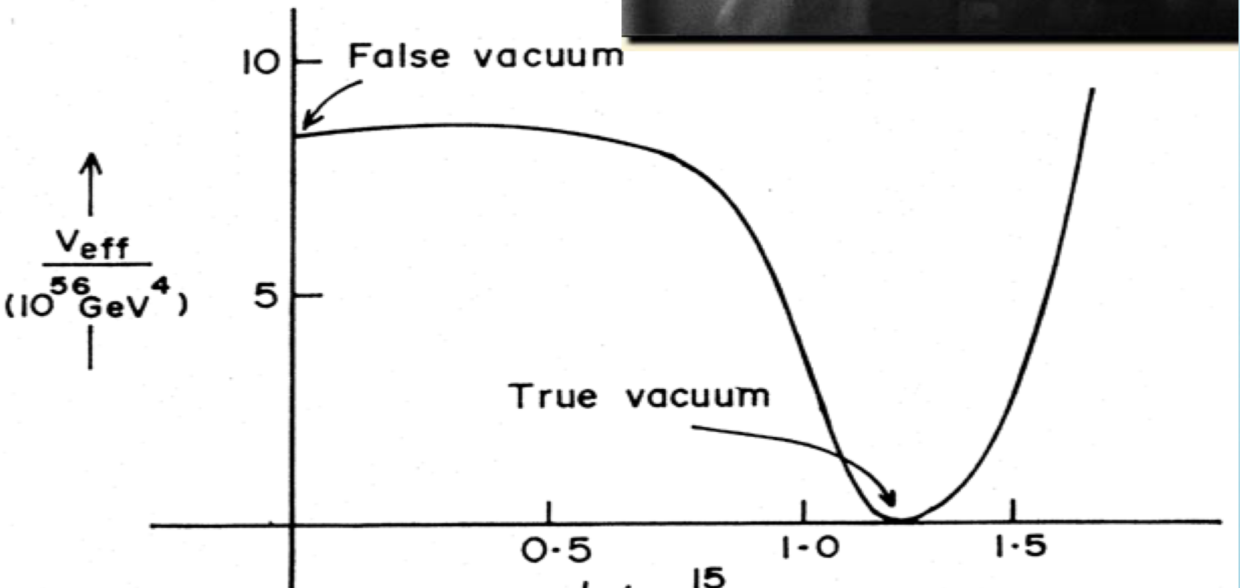
where α is some positive constant with dimensions of length



In the early 1970s Zeldovich: flatness and horizon p

In the late 1970s, Si
Polyakov et al to stu
Like a metastable p
temperature or abc
large enough bubbl

(In QFT, a false vacu
perturbative vacuu
to a lower energy st
or the creation of h
first-order phase tra



On the BGV Theorem: Introduction

- Inflationary cosmological models are generically eternal in their future evolution [1981-83: Guth, Linde, Albrecht, Steinhardt, Vilenkin]
- In inflation one cannot in principle conclude for any future time that the whole Universe will reach thermal equilibrium
- We could ask ourselves if it would be possible to construct a model with the Universe being eternal towards the past, without ever ocurring an initial singularity
- In this case the Universe would not be created at a certain moment, it would have always existed
- This possibility was already discussed in the 80's, but a specific model starting from an exact dS solution could not be formulated

- What could be proven is a theorem which states that inflationary spacetimes are past geodesically incomplete [1994: Borde, Vilenkin] → an initial singularity

- Key assumption: the energy-momentum tensor obeys the weak energy condition (WEC)

- But: quantum corrections to inflationary models seem to violate such condition

- This happens when quantum fluctuations result in an increase of the Hubble parameter: $dH/dt > 0$

- And this point is essential for chaotic inflation to be eternal !

- Therefore, the WEC must be generically violated in those models !

- What opens the door to a scape from the BV theorem, and from the initial singularity

- This was the motivation for Borde, Guth & Vilenkin: *"Inflationary Spacetimes Are Incomplete in Past Directions,"* *PRL 90 (2003) 151301*

- As the title clearly indicates, they eventually recovered the same result of BV'94

- In few words, they proved that the situation is very similar to the case of an initial (classical) de Sitter space

- The intuitive reason why de Sitter inflation cannot be past eternal is that in dS space exponential inflation is always preceded by an exponential contraction
- But an exponential contraction is not consistent with the physics of inflation: it thermalizes the Universe in the past infinity and prevents the appearance of inflation itself
- In the work, initial inflation is saved by imposing an "almost dS" space together with a minimal condition of "averaged expansion": $H_{av} > 0$
- The authors proved that the condition of averaged expansion implies, again, past incompleteness
- The theo can be extended to cosmologies with extra dimensions

- To finish, a comment about ciclic models [2002: Steinhardt-Turok]
- It is *not* true that ciclic models do no require initial conditions
- Most usual is that $H_{av} > 0$ is fulfilled and, then the BGV theorem applies
- As a consequence, also in these models one gets initial geodesic incompleteness ! → an origin

Recent work:

- INFLATIONARY UNIV. WITH A VISCOUS FLUID AVOIDING SELF-REPRODUCTION, I Brevik, EE et al, 2016
- Self-reproduction of the universe means that the inflationary process has no way to finish; it can be also seen as a major problem: inflation would never end
- Recently, an inflationary scenario which avoids the self-reproduction problem has been proposed in:

V. Mukhanov, Fortschritte der Physik 63, 1 (2014), arXiv:1409.2335

- We have considered what we believe is the simplest possibility for inflation without self-reproduction
- We consider in the paper a universe with a bulk viscous cosmic fluid in flat FLRW
- We derive the conditions for the existence of inflation, and those which at the same time prevent the occurrence of self-reproduction
- Our theoretical model gives results which are in agreement with data from BICEP2 and PLANCK

Thank You

Mille Grazie

Age of the universe

- In the context of the ΛCDM model

$$t_0 = \frac{1}{H_0} F(\Omega_r, \Omega_m, \Omega_\Lambda, \ldots)$$

- Three density parameters Ω_m, Ω_r, Ω_Λ + the Hubble parameter H_0

Cosmological parameters from 2015 Planck results

Parameter	Symbol	TT+lowP 68% limits	TT+lowP +lensing 68% limits	TT+lowP +lensing+ext 68% limits	TT,TE,EE+lowP 68% limits	TT,TE,EE+lowP +lensing 68% limits	TT,TE,EE+lowP +lensing+ext 68% limits
Age of the universe (Ga)	t_0	13.813±0.038	13.799±0.038	13.796±0.029	13.813±0.026	13.807±0.026	13.799±0.021
Hubble constant (km/Mpc•s)	H_0	67.31±0.96	67.81±0.92	67.90±0.55	67.27±0.66	67.51±0.64	67.74±0.46

68% limits: Parameter 68% confidence limits for the base ΛCDM model
TT, TE, EE: Planck Cosmic microwave background (CMB) power spectra
lowP: Planck polarization data in the low-ℓ likelihood
lensing: CMB lensing reconstruction
ext: External data (BAO+JLA+H0). BAO: Baryon acoustic oscillations, JLA: Joint Light-curve Analysis, H0: Hubble constant

Null energy condition

The null energy condition stipulates that for every future-pointing null vector field k,

$$\rho = T_{ab}\, k^a\, k^b \geq 0.$$

Each of these has an averaged version, in which the properties noted above are to hold only on average along the flowlines of the appropriate vector fields. Otherwise, the Casimir effect leads to exceptions. For example, the averaged null energy condition states that for every flowline (integral curve) C of the null vector field k, we must have

$$\int_C T_{ab}\, k^a\, k^b\, d\lambda \geq 0.$$

Weak energy condition

The weak energy condition stipulates that for every timelike vector field X, the matter density observed by the corresponding observers is always non-negative:

$$\rho = T_{ab}\, X^a\, X^b \geq 0.$$

Dominant energy condition

The dominant energy condition stipulates that, in addition to the weak energy condition holding true, for every future-pointing causal vector field (either timelike or null) Y, the vector field $-T^a{}_b Y^b$ must be a future-pointing causal vector. That is, mass-energy can never be observed to be flowing faster than light.

Strong energy condition

The strong energy condition stipulates that for every future-pointing timelike vector field X, the trace of the tidal tensor measured by the corresponding observers is always non-negative:

$$\left(T_{ab} - \frac{1}{2} T\, g_{ab}\right) X^a X^b \geq 0$$

There are many matter configurations which violate the strong energy condition, at least from a mathematical perspective. It is not clear whether these violations are physically possible in a classical regime. For instance, a scalar field with a positive potential can violate this condition. Moreover, it is violated in any cosmological inflationary process. However, it is clear that such a violation would violate the classical regime of general relativity, and one would be required to use an alternative theory of gravity.

ρ is the energy density and p is the pressure

The energy conditions can then be reformulated in terms of these eigenvalues:

The weak energy condition stipulates that

$\rho \geq 0, \rho + p \geq 0$

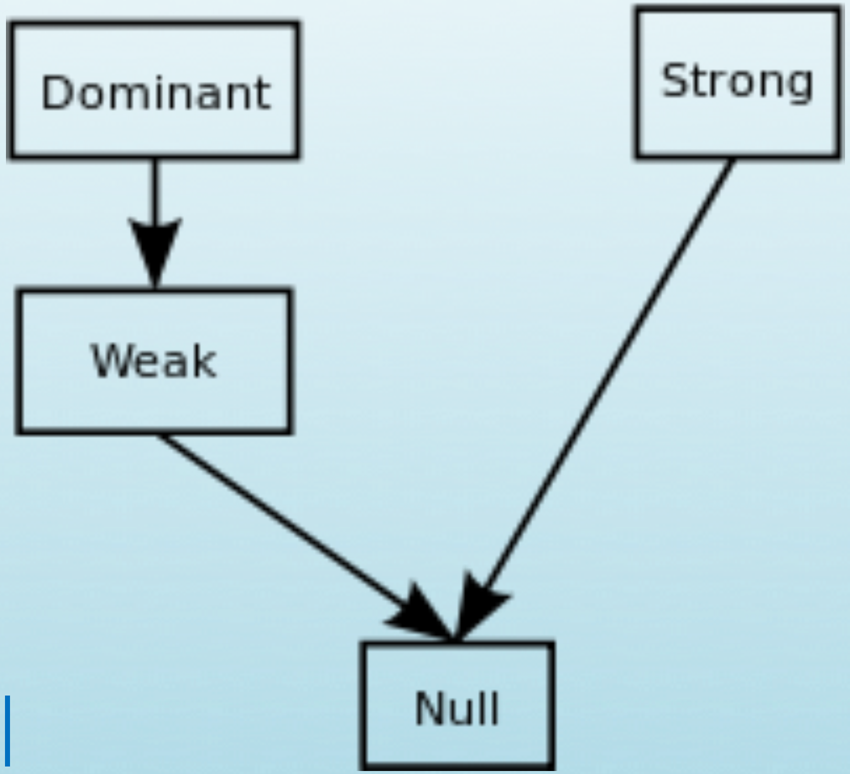
The null energy condition stipulates that

$\rho + p \geq 0$

The strong energy condition stipulates that

$\rho + p \geq 0, \quad \rho + 3p \geq 0$

The dominant energy condition stipulates that $\rho \geq |p|$



Despite the names the strong energy condition does not imply the weak energy condition *even in the context of perfect fluids*.