Bing Bang, new singularities, and a renormalization group improved, unified accelerating scenario

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What’s the Big Bang? – *Not what popular sources say ...*

The Universe expands (Lemaître, Hubble, ...)
Fred Hoyle $\Rightarrow$ Big Bang! $\Rightarrow$ Inflation!

Cosmological Singularities: Old & New

RG improved, unified accelerating scenario
Facts (few of them rather surprising...)

- 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

- 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
  - Zwicky discovered dark matter in the early 1930s while studying how galaxies move within the Coma Cluster
  - He was 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
FINDS SPIRAL NEBULAE ARE STELLAR SYSTEMS; Dr. Hubbell Confirms View That They Are 'Island Universes' Similar to Our Own

WASHINGTON, Nov. 22. -- Confirmation of the view that the spiral nebulae, which 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 the observatory's powerful telescopes.

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

Ernst J. Öpik, Estonian astronomer and astrophysicist (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.
Table 1: Radial velocities in km/s of 25 spiral nebulae published by VM Slipher in 1917

At large scale, the dominant movement of our Universe is dictated by the law:

\[ V = H_0 D \]

\[ H_0 = (67.8 \pm 0.9) \text{ km/s/Mpc} \quad [500 \text{ Hubble, 1929}] \]

**Interpretation:**

1. Proper movement of the galaxies
2. Movement of the reference system, of space-time

Both are right! –But the second prevails at large distances
Hubble acknowledged Slipher's seminal contribution to his own work by declaring that:

“... the first steps in a new field are the most difficult and the most significant. Once the barrier is forced further development is relatively simple.”

[Biographical Memoirs, Vol 52, National Academy of Sciences (U.S.)]
In a letter by Hubble to Willem De Sitter in 1931, he stated his thoughts about the velocities by saying

"... we use the term 'apparent velocities' in order to emphasize the empirical feature of the correlation. The interpretation, we feel, should be left to you and the very few others who are competent to discuss the matter with authority."

Sten Odenwald and Rick Fienberg, "Redshifts Reconsidered", Sky Pub Co (1993)

Einstein was convinced in `31 by Eddington, Tolman, and de Sitter (not by Hubble) of the facts that his static model was unstable and that the universe was expanding. Harry Nussbaumer, Eur Phys J H39, 37–62 (2014)
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 distances

"hypothèse de l'atome primitif" primeval atom, cosmic egg

Nature 127, 706 (1931)

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

(Translated by permission from “Annales de la Société scientifique de Bruxelles,” Tome XLVII, série A, première partie.)

1. Introduction.

According to the theory of relativity, a homogeneous universe may exist such that all positions in space are completely equivalent; there is no centre of gravity. The radius of space $R$ is constant; space is elliptic, i.e. of uniform positive curvature $1/R^2$; straight lines starting from a point come back to their origin after having travelled a path of length $\pi R$; the volume of space has a finite value $\pi^3 R^3$; straight lines are closed lines going through the whole space without encountering any boundary.

Two solutions have been proposed. That of de Sitter ignores the existence of matter and supposes its density equal to zero. It leads to a great difficulty of interpretation which will be shown...
Wikipedia webpage: "If the known laws of physics are extrapolated to the highest density regime, the result is a singularity ..."
Since Georges Lemaître first noted in 1927 that an expanding universe could be traced back in time to an originating single point, scientists have built on his idea ...
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 ..."
French Wikipedia: "De façon générale, le terme "Big Bang" est associé à toutes les théories qui décrivent notre Univers comme issu d'une dilatation rapide qui fait penser à une explosion ..."
Italian version: "La fase iniziale calda e densa è denominata "Big Bang" ..."
National Geographic: "Before the big bang, scientists believe, the entire vastness of the observable universe, including all of its matter and radiation, was compressed into a hot, dense mass just a few millimeters across."
Global Britannica: "Its essential feature is the emergence of the universe from a state of extremely high temperature and density: the so-called big bang ..."
NASA webpage: "Was the Big Bang an explosion? No, the Big Bang was not an explosion. We don't know what, exactly, happened in the earliest times, but it was not an explosion in the usual way that people picture explosions. There was not a bunch of debris that sprang out, whizzing out into the surrounding space. In fact, there was no surrounding space. There was no debris strewn outwards. Space itself has been stretching and carrying material with it."
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 Program broadcast on 28 Mar 1949: “...all matter in the universe was created in one Big Bang at a particular time...”
Hoyle is just remembered as the proposer of the discredited Steady State theory of the universe

“Everybody knows that the rival Big Bang theory won the battle of the cosmologies, but few (not even astronomers) appreciate that the mathematical formalism of the now-favoured version of Big Bang, called inflation, is identical to Hoyle's version of the Steady State model”

The original meaning of “Big Bang”

Thus:

Big Bang = Impossible blow!!

But now:

Big Bang \approx \text{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
Miracle of Physics No. 1

[Alan Guth, MIT]

“Gravity can be repulsive”
“Energies are not always positive: the gravitational field has negative energy”

[Alan Guth, MIT]
Spatial curvature: But combining the Planck data with BAO:

\[ |\Omega_K| < 0.005 \]

\[ \Omega_K = 0.000 \pm 0.005 \] (95%, Planck TT+lowP+lensing+BAO)

This is unchanged when adding JLA supernovae data (SDSS-II/SNLS3 Joint Light-curve Analysis) and the \( H_0 \) prior: \( H_0 = (70.6 \pm 3.3) \text{ km s}^{-1}\text{Mpc}^{-1} \)

Combined constraints show impressive consistency with a flat universe:

- Total Energy of the Universe is zero with a precision of more than 0.5%
- In fact, our Universe appears to be spatially flat to a 1σ accuracy of 0.25%
- Impressive confirmation of the theoretical arguments above

“The six-parameter base ΛCDM model continues to provide a very good match to the more extensive 2015 Planck data, including polarization. This is the most important conclusion of Planck 2015 results”

By combining the Planck TT+lowP+lensing data with other astrophysical data, including the JLA supernovae, the Equation of State for dark energy is constrained to: \( w = -1.006 \pm 0.045 \)

It is compatible with a cosmological constant \( \Lambda \) CDM cosmology
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)
http://www.hawking.org.uk/the-beginning-of-time.html

Extended Theorems: Arvind Borde, Allan Guth, Alexander Vilenkin


The Big Bang Cosmological Models

Cold Big Bang Model


Hot Big Bang Model

http://www.damtp.cam.ac.uk/research/gr/public/bb_home.html
https://faraday.physics.utoronto.ca/PVB/Harrison/GenRel/BigBangModel.html

Other uses for Big Bang
Acceleration: new singularities

According to the most recent and accurate astronomical observations, it is very likely that our universe had an origin from nothing (e.g., from a vacuum state of a tiny quantum system including space-time and a scalar field) some 13.8 billion years ago and is currently in accelerated expansion.

Recall the 2\textsuperscript{nd} Friedmann Eq.

\[
\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left( \rho + \frac{3p}{c^2} \right) + \frac{\Lambda c^2}{3}
\]

Fluid

\[ p = w \rho \]

Three possibilities for its fundamental parameter of state \( w \) (\( w \approx -1, \text{obs.} \))

1. \( w = -1 \) cosmological constant case, the simplest and most natural in general relativity
   - difficult to explain, need for a symmetry
   - the cosmological constant problem

2. \( w > -1 \) so-called quintessence case
   - ordinary, evolving scalar field

3. \( w < -1 \) the phantom case
   - phantom field (negative kinetic energy)
   - future singularities at finite (or infinite) time
1. If the universe is indeed in the LCDM era, it might remain in such era, becoming asymptotically de Sitter, i.e., a regular universe.

2. For a phantom or quintessence dark energy era, four finite-time futures:
      In the limit \( t = t_s \) (a finite value of time in the future) all quantities, as the scale factor, effective energy density and pressure of the universe diverge.
   b. Sudden Singularity, or Type II, discovered in J.D. Barrow, Class. Quant. Grav. 21 (2004) L79.
      In the limit \( t = t_s \) only the effective pressure of the universe becomes infinite.
   c. Type III future singularity.
      For \( t = t_s \) both effective energy density and pressure of the universe diverge.
d. Type IV future singularity

In the limit \( t = t_s \) scale factor, effective energy density, pressure do not diverge. However, higher derivatives of \( H \) become divergent, as discovered in S. Nojiri, S.D. Odintsov, S. Tsujikawa, Phys. Rev. D71 (2005) 063004 where a full classification was given. Eventually, the universe may survive the passage through a type IV singularity Sudden Singularity, or type II, discovered in J.D. Barrow, Class. Quant. Grav. 21 (2004) L79

3. Little Rip universe, where the future singularity occurs at infinite time

Typically, when the scale factor increases rapidly, as \( a(t) = \exp[\exp(t)] \) or higher exp P.H. Frampton, K.J. Ludwick and R.J. Scherrer, Phys. Rev. D84 (2011) 063003  

- Different combinations also possible, as an oscillating universe (bounce)
- Quantum gravity effects may affect this future evolution, preventing a Big Rip by quantum effects, E. Elizalde, S. Nojiri, S.D. Odintsov, Phys. Rev. D70 (2004) 043539 or by a similar Casimir-type effect
BEYOND-ONE-LOOP QG ACTION

- Unified description of early-time inflation & current cosmic acceleration
- Gravitational Lagrangian with quadratic term for inflation and including, for DE, a (phenomenologic) exponential F(R)-gravity contribution
- High-curvature corrections to Einstein’s theory well motivated by QG
- High-curvature corrections come from higher-deriv QG, yield effective action beyond the one-loop approximation
BEYOND-ONE-LOOP QG ACTION

- Viable inflation **emerges naturally**, with an e-fold number large enough to lead to the necessary thermalization of our observable Universe

- It yields also a **spectral index and tensor-to-scalar ratio** in agreement with most reliable **Planck** results

- At end of inflation, when quantum effects disappear, the **model evolves into the usual R^2 correction to GR:** gives appropriate **reheating mechanism**

"Beyond-one-loop quantum gravity action yielding both inflation and late-time acceleration"

The initial action of this theory (quadratic, higher-derivative)

\[ I = \int_M d^4x \sqrt{-g} \left( \frac{R}{\kappa_0^2} - \Lambda + a R^2 + b R_{\mu\nu} R^{\mu\nu} + c R_{\mu\nu\xi\sigma} R^{\mu\nu\xi\sigma} + d \Box R \right) \]

- \( g \) determinant of the metric tensor, \( g_{\mu\nu} \), \( M \) space-time manifold, \( \Box \equiv g^{\mu\nu} \nabla_\mu \nabla_\nu \) covariant d’Alembertian, \( \nabla_\mu \) covariant derivative associated with \( g_{\mu\nu} \)
- Hilbert-Einstein action given by the Ricci scalar \( R \), while \( R^2 \), \( R_{\mu\nu} R^{\mu\nu} \), \( R_{\mu\nu\xi\sigma} R^{\mu\nu\xi\sigma} \), \( \Box R \) higher curvature corrections to GR, \( R_{\mu\nu} \) and \( R_{\mu\nu\xi\sigma} \) Ricci and Riemann tensors
- \( 0 < \kappa_0^2 \) encodes the mass scale of the theory, \( a, b, c, d \) are constant param.
- \( \Lambda \) is a cc term, not to be confused with the cc \( \Lambda \) for DE
- If we here introduce the Gauss-Bonnet four-dimensional topological invariant, \( G \), and the square of the Weyl tensor, \( C^2 \),

\[ G = R^2 - 4 R_{\mu\nu} R^{\mu\nu} + R_{\mu\nu\xi\sigma} R^{\mu\nu\xi\sigma}, \quad C^2 = \frac{1}{3} R^2 - 2 R_{\mu\nu} R^{\mu\nu} + R_{\mu\nu\xi\sigma} R^{\mu\nu\xi\sigma} \]
Get

\[ R_{\mu\nu}R^{\mu\nu} = C^2 / 2 - G / 2 + R^2 / 3, \quad R_{\mu\nu\xi\sigma}R^{\mu\nu\xi\sigma} = 2C^2 - G + R^2 / 3 \]

* The Gauss-Bonnet and surface term \( \Box R \) do not contribute to the dynamical field Eqs; can drop them from the action, which will result in terms of \( R/\kappa_0^2, \bar{\Lambda}, R^2, C^2 \) only

* Using results of one-loop calculations, we proceed with its RG improvement, in analogy with RG-improved calculations carried out in QFT in curved space-time [EE+SDO '90s]: we obtain a RG-improved action for higher-derivative QG

\[
I = \int_M d^4x \sqrt{-g} \left[ \frac{R}{\kappa^2(t')} - \bar{\Lambda}(t') + \omega(t')R^2/3\lambda(t') + C^2/\lambda(t') + f_{DE}(R) + L_m \right]
\]

* To the RG-improved action we added \( L_m \), Lagrangian corresponding to standard matter, and the function of the Ricci scalar \( f_{DE}(R) \), introduced by hand to support late-time cosmic acceleration (details Sect V of paper)

\[
f_{DE}(R) = -2 \bar{\Lambda} g(R) \left( 1 - e^{-aR/\bar{\Lambda}} \right) / \kappa_0^2
\]
Exponential gravity reproduces the cosmological constant at large curvature when
\[ f_{\text{DE}}(R) \simeq -2 \Lambda g(R) / \kappa_0^2, \quad \Lambda \ll R \]

--- Usually singularities avoided by introduction of a \( R^{1/3} \)-term in the gravitational action
--- Here compensating term included in the dark energy function \( f_{\text{DE}}(R) \) through \( g(R) \)
--- We propose the following form of \( g(R) \)

\[ g(R) = [1 - b (R / 4\Lambda) \log (R / 4\Lambda)], \quad b > 0 \]

\( b \) a constant positive parameter. Motohashi-Starobinsky-Yokoyama ‘11

--- RG-improved effective action follows from the solution of the RG equation applied to the complete effective action of the multiplicatively renormalizable theory

--- cc expressed in terms of the log term of a characteristic mass scale in the theory

\[ t' = \left( \frac{t'_0}{2} \right) \log \left( \frac{R}{R_0} \right)^2, \quad 0 < t'_0, \]

with \( t'_0 > 0 \) and \( R_0 \) curvature at which QG effects disappear
As exponential gravity, for DE, must be stabilized during matter and radiation eras, we introduce this term to avoid nonphysical singularities in the effective EoS parameter.

Hilbert-Einstein action for GR is non-renormalizable: compulsory to consider an effective improved action with an ultraviolet completion at high-E scale, might lead to a renormalizable theory.

We show our model can be naturally extended to include in the action Gauss-Bonnet and $\Box R$ terms, with corresponding running coupling constants.

The new set of RG Eqs for the coupling constants correspond to this case have been derived.

Results confirmed by accurate numerical simulations.
To be studied:

- In conformally invariant theory, contribution of the Weyl tensor vanishes in the primordial scalar power spectrum — constant terms in spectra of vector & tensor perturbations

- Not clear what happens in a more involved theory. In our case, Weyl tensor is coupled with Ricci scalar: — change of curvature rate of model during exit from inflation

- See if spectra of perturbations left at the end of inflation is still realistic
Thank You

Gracias