Different Facets of the Cosmological Bounce Phenomenon

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Main references

- R. Brandenberger and P. Peter, ``Bouncing Cosmologies: Progress and Problems,''

  Found. Phys. 47, no. 6, 797 (2017)
- M. Novello and S. E. P. Bergliaffa, ``Bouncing Cosmologies,'' Phys. Rept. 463, 127 (2008)
- ``A critical review of classical bouncing cosmologies,'' Diana Battefeld , Patrick Peter

  Phys. Rep. 571, 1 (2015)

- Prominent workers: P. J. Steinhardt , N. Turok, R. Brandenberger,

  P. Peter, J. Martin, L. Sriramkumar and many others...

Different Facets of the Cosmological Bounce Phenomenon

- Cosmological bounce non-GR models and in GR models
- Matter sector in bouncing universe
- Bounce in modified gravity
- Perturbations in bouncing models
- Power spectrum

Motivation for a bounce

- In inflationary theory the perturbations which left the horizon in the initial phase of inflation had length scales smaller than ℓ_P

  Phys.Rev.D 63:123501, (2001)

- The initial singularity problem remains in Big-Bang paradigm.
- To solve these multiple problems, the idea of a cosmological bounce turns out to be useful.
- There can be bounces induced by quantum effects and bounces purely guided by general relativity.

Non-GR quantum bounce

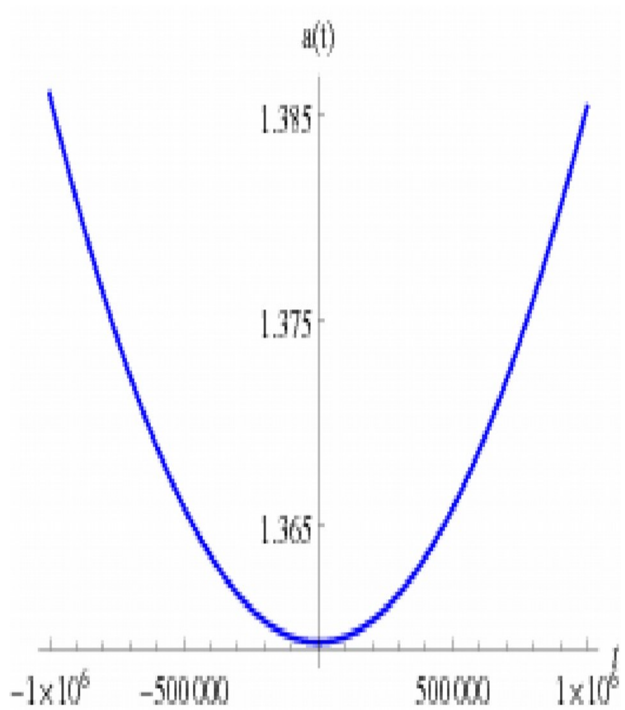
- Bounce phenomena is modular in nature – the other cosmological phases can be separated from the bouncing phase.
- The quantum bounce phenomena can be studied using Loop Quantum Cosmology. Here the Friedmann equations are modified due to Loop quantum gravity effects.
- The other framework which can study bounces is related to canonical quantum gravity. Here one works with the wave-function of the universe and sees how it evolves through a bounce.
- Bounce in the brane world. This is a 5-Dim theory, where two 4-Dim branes (one is our’s) cyclically collide in the 5^{th} extended dimension. This gives rise to cyclic – Old Ekpyrotic Universe.

  A 4-Dim GR version of the above phenomena do exist.

Non-GR quantum bounce

- Then comes bounces induced in f(R) theories of gravity. In these theories the Ricci scalar can induce negative curvature energy. These are the main branches of study in non-GR section. Except these branches there are few other branches as Horava-Lifshitz bounces.

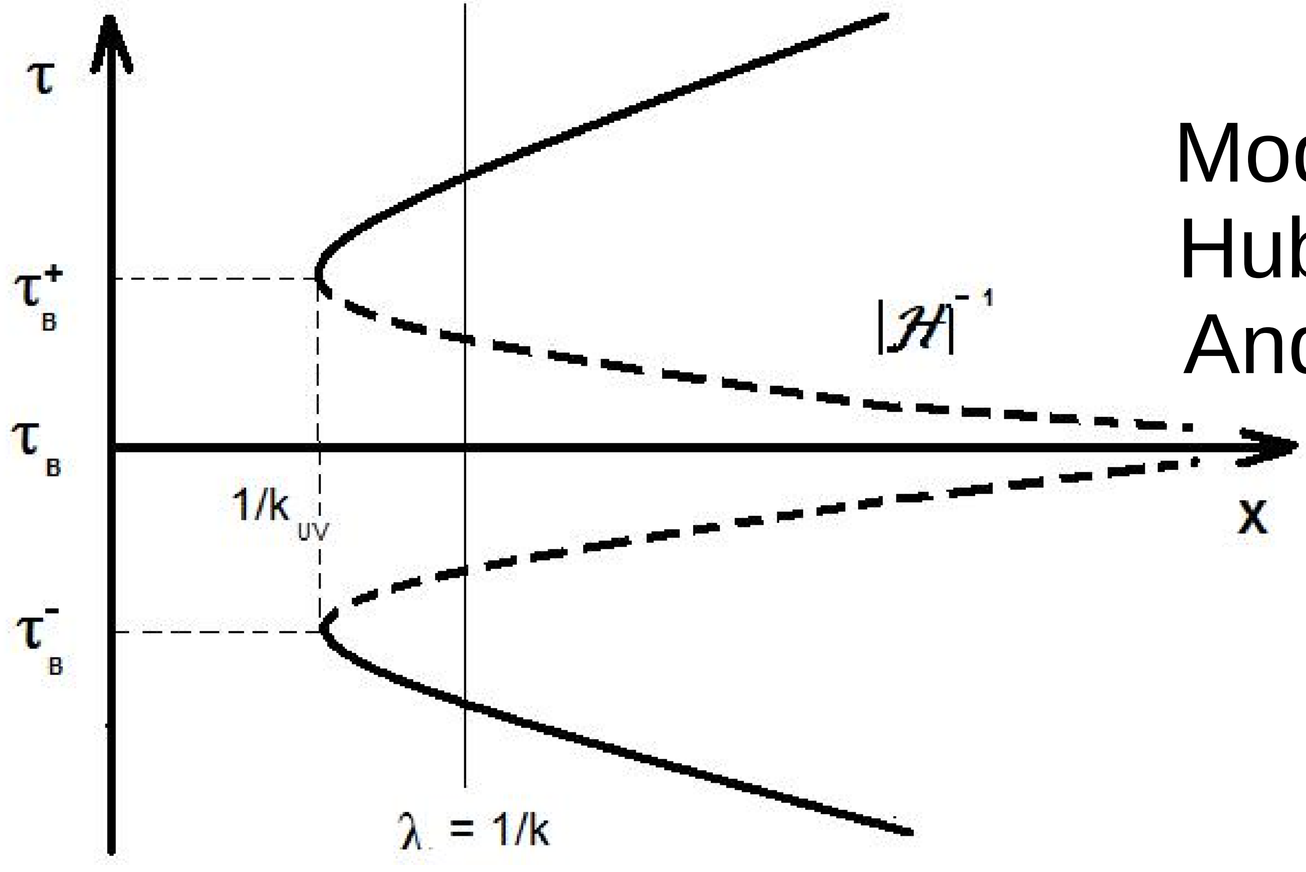
- In quantum bounces it is difficult to plot the scale-factor through bounce, but in GR based models and f(R) theories one can see how the scale-factor behaves near the bounce.



The cosmological puzzles and bounce

- The main puzzles of early universe cosmology are:
- The horizon problem, The flatness problem, Unwanted relics and so on.......

The Horizon Problem



Modes go out of
Hubble horizon
And Renter.

Flatness Problem

$$1 + \frac{\mathcal{K}}{a^2 H^2} = \frac{\rho}{3H^2}$$

- In contracting phase

  matter term scales as $a^{-3}H^{-2}$ and radiation as $a^{-4}H^{-2}$ both of which can dominate the curvature term as $\mathrm{a} \to 0$

- During bounce the curvature term can be fine-tuned to be small.
- But some models of bounce use an inflationary phase after bounce to solve this problem.

Unwanted relics

- Till now there has been no concensus on this topic. Inflation does better in sweeping out the unwanted relics as Topological defects and heavy particles which can overclose the universe.

Mattar sector in GR bounce

- Einstein equations:

$$
\begin{aligned}
H^2 &= \frac{\kappa}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3} \\
\dot{H} &= -\frac{\kappa}{2}(\rho + P) + \frac{k}{a^2}
\end{aligned}
$$

- Bouncing conditions are:

$$
\mathrm{H}(\mathrm{t}_0) = 0\,, \quad \dot{H}(t_0) > 0
$$

- The above conditions and the Einstein equations show that if there is no curvature and cosmological constant, then some exotic matter is required so that the net energy density is zero. More over the Null Energy Condition must also be violated at bounce point.

Ghost Condensate

- Here the ghost fields have wrong kinetic energy terms.
- As a result the kinetic energy of such a system can be negative.

$$\mathrm{L} = \mathrm{M}^4 P(X) - V(\phi)\,,\; X = -g_{\mu\nu}\partial^{\mu}\phi\partial^{\nu}\phi$$

- If bounce occurs purely due to ghost condensate then one can adjust the potential energy and kinetic energy to cancel each other at bounce point.
- There are instabilities because of wrong kinetic energy term. They have to be settled near the bounce point.
- The ghost condensate can olso violate NEC.

lee-wick theories

- Lee-Wick theories were introduced to make QFTs divergenceless, order by order in perturbation theory.
- These theoris require

  a Lee-Wick partner of normal fileds.

- The partners enter the Lagrangian with a wrong sign of kinetic energy.

- Thermal Lee-Wick theories are also there where the Lee-Wick partners have negative energy-density.
- The negative energies can compensate the positive energies to produce a bounce.

f(R) theories

- In these theories: $$G^{\mu}{}_{\nu} = \frac{\kappa}{f'(R)}\left[T^{\mu}{}_{\nu} + T^{\mu}{}_{\nu\,(\mathrm{curv})}\right],$$
- The energy-momentum from the curvature terms can be negative and this may ultimately give rise to bounces.
- In f(R) theories there may be bounces in the absence of any matter, purely curvature driven bounce.
- The energy conditions do not play very important part as in modified gravity theories the energy conditions are not that well defined.

Galileons

- One can also introduce scalar fields with the property, $$\phi \to \phi + b^\mu x_\mu$$ these are called the galileon fields.
- They can have various scalar derivative couplings in the Lagrangian, but ultimately they give rise to second order field equations.
- These fields can also produce bouncing conditions in GR based models.

Perturbations

- The scalar perturbation:

$$\mathrm{ds}^2 = -a^2[-(1+2\phi)d\eta^2 + (1-2\psi)d\mathbf{x}^2]$$

- From this one defines the Bardeen potentials Φ, Ψ. Without anisotropic stress these potentials are equal.
- Then one gets a differential equation for Φ and tries to match the solutions across the bounce.
- The main intention being whether the solutions can be smoothly matched across the bounce.

Perturbations

- The potentials in general form a second order differential equation which contains two different mode functions:

$$\Phi(k,\eta) = A_{b\,,\,a}(k)\ \mathrm{f}_{b\,,\,a}(k,\eta) + B_{b\,,\,a}(k)\ \mathrm{g}_{b\,,\,a}(k,\eta)$$

- Here b and a stands for before bounce and after bounce. The main task is to see how the coefficients A and B match at the bounce.
- Work along these lines have been done and perturbations can be matched.
- Vector perturbations naturally get suppressed in the expanding phase of the universe and never becomes out of bound in a non-singular bounce.
- Brandenberger, Patrick Peter and Jerome Martin have done various works along these lines.

Tensor perturbations

- In this case $\mathrm{ds}^2 = -dt^2 + (\delta_{ij} + h_{ij})dx^i dx^j$
- In this case also one can solve for the tensor perturbation modes which, comes in two polarization states: $\mathrm{h}_{ij} = h(t)\, e_{ij}^{+,\times}(\mathbf{x})$
- The h(t) function satisfies a second order differential equation and that is solved in the contracting phase and matched with the expanding phase at the bounce.

Ekpyrotic Phase

- If the contracting universe has shear,i.e., anisotropic dynamics, then this shear can grow rapidly as it scales as $1/\mathrm{a}^6$. If not restricted it will lead to BKL instability.
- To solve this issue one uses a slow contraction process called the ekpyrotic phase which is dominated by ultrastiff matter component with $\omega > 1$
- This ultrastiff matter can conteract the shear energy growth.
- Most modern models of bounce now use this ekpyrotic phase of contraction.

Scalar power spectrum

- It is very difficult to obtain scale-invariant scalar power spectrum for $\mathrm{R} = \psi + \frac{H}{\dot{\phi}} \delta\phi$ by adiabatic perturbations in bouncing cosmologies. Here we use only one scalar field during bounce.
- To solve this issue multifield bounce models through ekpyrosis has been proposed.
- Two field ekpyrotic models do produce isocurvature perturbations which has to be converted to adiabatic perturbations via some mechanism, as curvaton mechanism in inflation.

Power spectra

- In reality bounce models still require more accurate calculations of scalar power spectra.
- The most successful ones are two field ekpyrotic models where both the adiabatic and isocurvature modes requires to be carried out to the expanding phase.
- In the contracting phase the adiabatic modes do show blue tilt. The isocurvature modes are also blue tilted. It is assumed that some mechanism will convert the isocurvature modes to a nearly scale-invariant spectrum.

Tensor power spectrum

- The tensor power spectrum turns out to be blue tilted in two field ekpyrotic bounce models .
- The cyclic/ekpyrotic models leads to small amounts of gravitational wave production.
- These models do not have anything dramatic about tensor modes and unobservability of cosmological gravitational waves favours these models.

Non-Gaussianities

- Larger non-Gaussianities are expected in bouncing models, since models are of the fast-roll type,
- Entropy perturbations are present,
- And the non-trivial bounce physics may affect the computation.
- Computing non-Gaussianity in bounce models are challenging because preheating and reheating may change these results.

Open questions

- Many, many questions ....
- The matter component which produces bounce?
- The horizon problem requires more elaborate solution.
- Preheating and reheating models of bounce are in their infancy. If there is no inflation after bounce then these topics require to be studied.
- More refined methods of calculation of power spectrum.
- Non-Gaussianity
- New modified models of gravity may become useful.

Many ways to proceed.................