Title: The exponential expansion of the universe from unrenormalised energy momentum tensor

Date: Aug 03, 2017 11:00 AM

URL: http://pirsa.org/17080016

Abstract: <p>The unrenormalised energy momentum tensor is both huge and fluctuating from point to point. Taking this seriously we (Qingdi Wang, Zhen Zhu, and myself) argue that the slow exponential expansion of the universe (on time scales of 10^10 years) comes from a very weak parametric resonance induced by the fluctuating energy mementum tensor on the rapidly fluctuating scale factor (on time scales much shorter than the Planck scale). We see only the slow exponential growth because we avarage over the scale factor squared.</p>

Cosmological Constant from Vacuum Energy

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Einstein-1919 – introduced cosm const into his field equations to get around dynamic solutions (Friedman)

Solution (Einstein Universe) was static, spherical universe

DeSitter and Eddington showed that the solution was unstable-- Exponential expansion, or collapse to singularity

Hubble-Universe IS dynamic, expanding. “Biggest Mistake”.

1980s evidence from observational cosmology that “cosm const” was not zero. (eg age of universe too old for standard models-- models had expansion increase into past younger universe)

Is cosm const simply an unknown parameter or is it determined by something else? Why so small?

Particle Physics and cosmology → Modes of quantum fields each have vacuum energy--
Harmonic oscillator has $\frac{1}{2}\hbar\omega$ energy

Divergent contribution to energy and to pressure

Divergence horrible – Huge energy and pressure.

Symmetries: Homogeneity should have same effect everywhere
Lorentz symmetry-- Should have energy momentum tensor be proportional to metric-- Ie, cosm constant.

Still divergent-- Use ideas from QED-- renormalisation
Cosm const is free parameter-- bare constant cancels contribution from matter fields.

(Einstein gravity is not renormalizable theory)

Neglects fluctuations.
Energy momentum tensor at different points does not commute with total energy and momentum

Entanglement of quantum fields means fluctuations are not independent.

Do the effects of the quantum field obey the symmetries?

Should one take seriously the divergent energy and divergent fluctuations of the matter vacuum energy momentum tensor? (Crazy idea-- obviously divergent energy would drive divergent fluctuations of gravity while cosmology is smooth on huge scales (10^{65} times Planck scales)

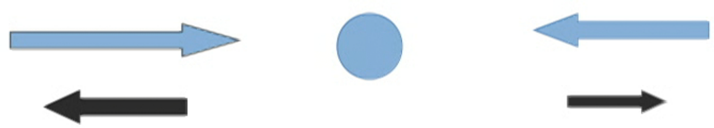
Take large energy density seriously. Take Planck scale dynamics seriously.

History:

QW- Master's thesis

Consider particle in 1+1 dimensional spacetime interacts with scalar field
Scalar field in vacuum state.

Pressure on particle will average to zero.
Huge vacuum fluctuations of scalar field will not be zero—scalar field impinging on particle will be uncorrelated on the two sides.



Momentum carried by scalar field $T^{tx}_{R,L} = \frac{1}{2}T^{tt}$

Diverges (as Λ^2 in 1+1 dim)

To make the effect on particle finite, make the particle reflect part (high energy parts) of the field.

$$S = \frac{1}{2}\int[\dot\phi^2 - \phi'^2$$
$$+2\int\{(\epsilon\phi\dot q) + M + \frac{dq}{d\tau}^2\}\delta(X(\tau)-x)\delta(T(\tau)-t)d\tau]dtdx$$

At high frequencies the particle becomes transparent to the field, and field exerts no force on the particle. Ie, only low energy modes of the field exert a force.
But the cutoff (determined by ϵ) means the force does not diverge, but can be huge.

While fluctuations in velocity are of order of c, fluctuations in position are small and bounded.
They are not Brownian (growing with time) but constant in time.

Reason is that the forces are anti-correlated in time, and effect of the first tends to cancel the next.
(Ford and collaborators)

Energy of oscillator with derivative coupling diverges logarithmically so still need cutoff.

Alternative:
Use non-derivative coupling to remove this divergence

$$S = \frac{1}{2}\int[\dot\phi^2 - \phi'^2 + m^2\phi^2$$
$$+2\int\{(\epsilon\phi q) + M + \frac{dq}{d\tau}^2\}\delta(X(\tau)-x)\delta(T(\tau)-t)d\tau]dtdx$$

m needed to get rid of IR instability of model

Qingdi then decided to see if this idea-- taking the energy of the vacuum seriously, and not something to be regularized or renormalised-- could be applied to cosmology.

I was extremely skeptical-- kept telling him I thought this was a blind alley, that there was no way that it could work. For example, the effect at the expectation value level was not zero not only the fluctuations were huge, but so was the zeroth order effect. I strongly advised him that he should find another topic for his PhD. He refused and kept coming back with more answers to my objections.

Finally, I felt that there was enough of an unusual enough result and argument that it was worth putting out into the community.

We both expected severe problems with the referee, who instead “got it” and recommended publication as a novel idea in a field which was rather bereft of them. The editors decided to make it an editor’s selection!

Far from a fully worked out scenario-- rather a suggestion of a possible direction to go.

Usual idea-- Vacuum energy must be constant, and Lor invar. Must be proportional to the metric (large negative pressure).

However, mode by mode, for scalar field for example, pressure is positive, as is the energy.

Energy density does not commute with the total energy and components of the energy Momentum tensor do not commute with each other. Ie, huge fluctuations in the energy density and pressures from point to point.

Lets take these seriously. (Stochastic gravity)

Wheeler in 70's: Spacetime foam. Metric on small (Planck) scale all higgledy piggledy.

Our approach is very much along that idea.

Problem-- no more solvable than full quantum gravity.

Simplified model.

$$ds^2 = dt^2 - a(t, \mathbf{x})^2(dx^2 + dy^2 + dz^2)$$

with quantum scalar field as source of energy momentum

Cannot solve all of Einstein equations. (If we chose the scale factor and the scalar field to be functions of time alone can solve all of them, but not if they are functions of space as well-- generally inconsistent) .

Must choose one of Einstein equations to solve for scale factor.

Lamppost principle: A man comes across a drunk on his hands and knees searching the ground. “I lost my contact lenses”. After searching for a while the man says “Where did you lose them?” “ I don’t know” . “Why are you looking here?” “This is where the light is!”

Note-- special foliation-- space and time. Not gen covar.

Will also choose time specially-- cutoff in energy.

$$G_{tt} + \frac{1}{a^2}\left(G_{11} + G_{22} + G_{33}\right) = -6\frac{\ddot{a}}{a}$$

$$\ddot{a} + \Omega^2(t,x)a = 0$$

$$\Omega^2 = \frac{8\pi G}{3}(\rho + \sum_i T_{ii})$$

$$\Omega^2 > 0$$

Harmonic oscillator with a stochastic frequency.

Note that a will oscillate – but only a^2 is physically significant.

What is Ω^2 ?

Take it to be given by flat (a constant) stress energy tensor.

Each mode of the field contributes $\frac{1}{2}\hbar\omega$ to the total energy

and to the energy density. No normal ordering. No regularization or renormalization. Note that the energy density does not commute with the total energy, so even in vacuum huge vacuum fluctuations.

a will oscillate on extremely short scales-- much less than cutoff scales of the field phi. Thus phi will average a^2 over a wavelength which averagewill be constant over space and (roughly) time.

(Note this is like sound waves on an atomic fluid-- the long wavelengths do not see the fluctuations-- they simply average over them. Or like light waves in glass which average over the fluctuating index of refraction of the glass due to the atoms).

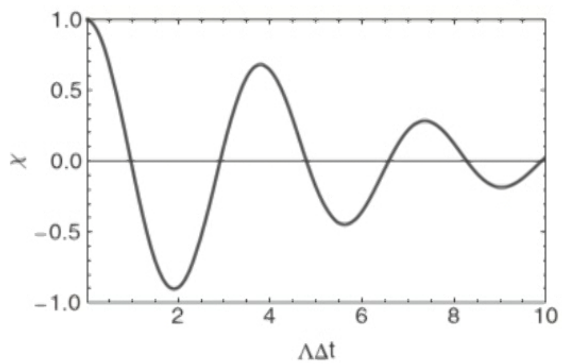
Ω^2 is fluctuating. If it were periodic, you would get parametric resonanace.

$$a(t,x) = c_1 e^{H_x t} P_1(t,x) + c_2 e^{-H_x t} P_2(t,x)$$

Exponentially growing and decaying periodic modes with period T

Ω^2 is not strictly periodic, but is quasi periodic.

$$\chi(\Delta t) = \frac{< (\Omega^2(t) - < \Omega^2 >)(\Omega^2(t+\Delta t) - < \Omega^2 >) >}{< (\Omega^2 - < \Omega^2 >)^2 >}$$



$$<\Omega^2>\approx<T^{tt}>\approx\Lambda^4$$

So a oscillates on time scale of 1/cutoff squared.
While the oscillation frequency oscillates on time period of 1/cutoff. Ie, the oscillation of the frequency occurs on a scale much less than the oscillation time scale (assuming the cutoff is above the Plack scale).
oscillation of a is an adiabatic process.

The non-adiabaticity leads to a slow exponential growth in the oscillations of a

$$a\approx a_0 cos(\Lambda T+\psi)e^{Ht}$$

$$H\approx\alpha\Lambda e^{-\beta\Lambda}$$

Ie, the exponential expansion is exponentially small in the cutoff above the Planck scale.
The expansionof the universe is about 10^{70} times longer than Planck scale, which gives what the cutoff must be.

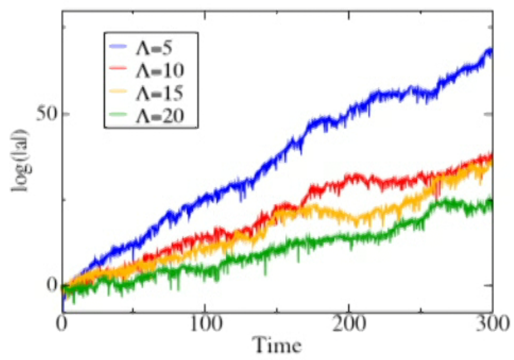


FIG. 4. Numeric result for $\log|a_o(t)|$ for a single real massless scalar field. It shows that as Λ increases, the slope of $\log|a_o(t)|$ decreases.

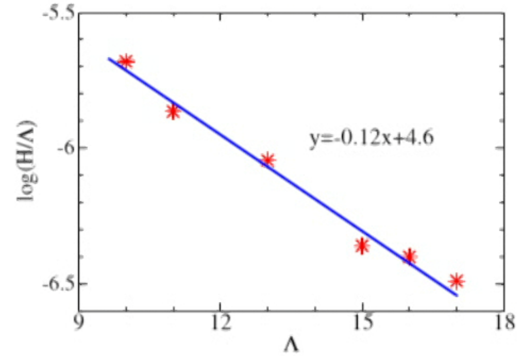


FIG. 6. The plot of $\log(H/\Lambda)$ over Λ. The fitting result shows that $\alpha = e^{4.6} \approx 100$ and $\beta = 0.12$ in this two-field case.

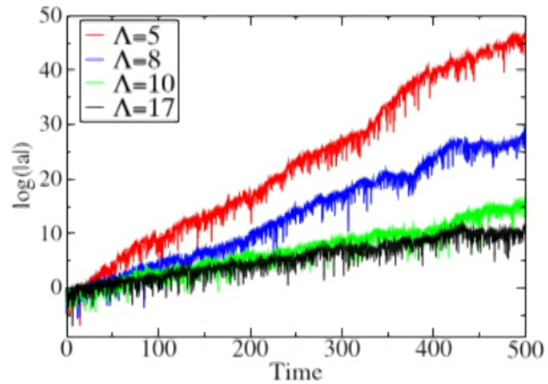


FIG. 5. Numeric result for $\log|a_o(t)|$ when two scalar fields are present and it shows that as Λ increases, the slope of $\log|a_o(t)|$ decreases.

cutoff plays a crucial role in this model. The matter fields must have a cutoff scale. What provides that cutoff I do not know

Note that the gravity sector does not have the same cutoff. gravity oscillates much faster than does the matter. Ie, gravity being universal does not recognize the same cutoff as does the matter. [What does this mean about gravity waves and the quantunization of gravity waves, and their contribution to the expansion of the universe? I have no idea.]

Open Questions:

Can this be extended to the full metric rather than just the scale factor?

Do neglected Einstein equations destroy effect? (eg, go singular in non-removable way)

Where does the cutoff come from and why cutoff only for matter not for gravity?

Do gravity waves have cutoff?

What about fermions? Their vacuum energy is usually negative mode by mode. If Ω^2 negative, a does not oscillate but exponentially expand. (if more bosons than fermions, Ω^2 should on average be positive. What about brief negative fluctuations?)

Argument is all in stochastic gravity framework. What about quantum gravity?

Special time chosen (metric is NOT conformally invariant and time has special role). Can equations be made covariant or is there a special cosmological time?

a goes to through 0. (not globally but point by point). Not a problem for the equation used, but is it a problem for other Einstein equations after full metric used?

What about low energy Einstein equations? Do they decouple from these high energy equations? If not--problems with gravity waves from Ligo? Or planetary motion?

Can this argument be extended to inflation? Is inflation extra low energy equations, or is inflation also by same mechanism (change in cutoff in early universe?)
Maybe this process solves old cosm const probem (0 when cutoff goes to infinity) and other exponential expansions are extra low energy effect?

Lots of open questions: opportunities or death knell?