The inflationary origin of the seeds of cosmic structure: quantum theory and the need for novel physics.

Daniel Sudarsky, Inst. for Nuclear Sciences, UNAM, México
Collaborations with: M. Castagnino (U. Buenos Aires, Arg.) , R. Laura (U. Rosario, Arg.) , H. Sahlman (U. Utrecht, Ndr.), A. Perez (U. of Marseille Fr.), A. de Unanue (ICN- UNAM), G. Garcia (ICN-UNAM), A. Diez-Tejedor (U. Guanajuato, Mx.), S. Landau (U. Buenos Aires, Arg.) & C. Sccocola (Inst. Astr. Canarias, Sp.)

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Plan: (Very condensed report of various years of work !)

1) Inflation, the usual approach, the great success.... and the problem.
2) The usual answers (Please let us leave the the discussion on this part for the end. Otherwise it can absorb the whole time!). Some people get annoyed because they see this a just philosophy. Bear with me to see it is not.
NOTE: Even if we take the standard views seriously, the relevant state is the post-selected one.
3) Our approach. A word about Dynamical Collapse Theories.
4) The formal implementation. (Very brief)
5) The practical implementation. (Brief)
6) Collapse schemes and detailed predictions. Comparing with observations.
7) Other results, The QG connection (speculations motivated by Penrose's ideas)
8) More on the usual answers. A situation were we can see analogous conceptual problems: Mini-Mott.

1) Cosmic Inflation:

Contemporary cosmology includes inflation as one of its most attractive components: The inclusion of an inflationary stage leads to a natural explanation for the seeds of cosmic structure in terms of quantum fluctuations .

Basics Inflation: A period of accelerated expansion, that takes the universe from relative generic post Plank era initial data to a stage where it is well described (with exponential accuracy in the number of e-folds) by a flat Robertson Walker space-time.

Advantages: Resolves various naturalness problems: Flatness, Horizons, and GUT relics.

But the biggest is the natural generation of the seeds of cosmic structure.

But how exactly does this happen? How do the inhomogeneities arise from the quantum uncertainties?

Let me contrast our approach with the usual one and briefly point out at this point why we feel that it is not truly satisfactory.

USUAL APPROACH: Consider the simples model where inflation is associated with a single scalar filed, where the action for the theory is : $S = \int d^4x\sqrt{-g}\{\frac{R}{16\pi G} + \nabla^\mu\phi\nabla_\mu\phi + V(\phi)\}$

Consider an inflationary background FRW space-time FRW ($K = 1$) and a background scalar filed $\phi = \phi_0(\eta)$. The relevant Einstein equation yields :

$$3\mathcal{H}^2 = 4\pi G(\dot{\phi}_0^2 + 2a^2 V_0), \tag{1}$$

$\mathcal{H} \equiv \dot{a}/a$ where " $\cdot$ " $= \frac{\partial}{\partial\eta}$, while the scalar filed satisfies the KG equation:

$$\ddot{\phi}_0(\eta) - 2\dot{\phi}_0(\eta)\mathcal{H} + \frac{\partial V}{\partial\phi} = 0 \tag{2}$$

One considers a classical background solving these equations and representing a slow rolling situation. So far everything is fine.

Next one needs to consider perturbations:
$\phi(x) = \phi_0(\eta) + \delta\phi(\eta, \vec{x})$ with $\delta\phi(\eta, \vec{x}) \ll \phi_0(\eta)$

$$ds^2 = a^2(\eta)\left[-(1+2\psi)d\eta^2 + (1-2\psi)\delta_{ij}dx^i dx^j\right], \quad \text{con} \quad \psi(\eta, \vec{x}) \ll 1. \tag{3}$$

Describe these perturbations $\delta\phi \quad \& \quad \psi$, in terms of the new variables :

$$u \equiv \frac{a\psi}{4\pi G\dot{\phi}_0}, \quad v \equiv a\left(\delta\phi + \frac{\dot{\phi}_0}{\mathcal{H}}\psi\right), \tag{4}$$

Then the dynamical equations for these take the form:

$$\Delta u = z\left(\frac{v}{z}\right)^{\cdot} \quad \text{and} \quad v = \frac{1}{z}(zu)^{\cdot}, \quad \text{with} \quad z \equiv \frac{a\dot{\phi}_0}{\mathcal{H}}. \tag{5}$$

Quantization From these one gets the evolution equation for v:

$$\ddot{v} - \nabla^2 v - \frac{\ddot{z}}{z} v = 0. \tag{6}$$

This is the evolution equation for a scalar field with a time-dependent "mass" term . Next; quantize the scalar field

$$\hat{v}(x) = \sum_{\vec{k}\neq 0} \left(\hat{a}_{\vec{k}} v_{\vec{k}}(x) + \hat{a}^{\dagger}_{\vec{k}} v^{*}_{\vec{k}}(x) \right), \tag{7}$$

with the mode functions $v_{\vec{k}}(x) = v_{\vec{k}}(\eta) e^{i\vec{k}\cdot\vec{x}}/L^{3/2}$, where :

$$v_{\vec{k}}(\eta) = \sqrt{\frac{\hbar}{2k}} \left(1 - \frac{i}{k\eta} \right) e^{-ik\eta}. \tag{8}$$

The vacuum is defined by $\hat{a}_{\vec{k}}|0\rangle = 0$. Is supposed to represent the state of the quantum field after few e-folds of inflation (up to negligible corrections of order e^{-N})
I.e. the exponential expansion takes the metric and all fields to a very simple state which in particular is highly symmetric.

It is easy to see that the state $|0\rangle$ is Homogeneous and Isotropic.

The generator of spatial translations is: $\hat{\vec{P}} = \sum_{\vec{k}} \vec{k}\, \hat{a}^{\dagger}_{\vec{k}}\, \hat{a}_{\vec{k}}$.
so a translation by $\vec{D}$ leaves the state unchanged :

$$e^{i\vec{D}\hat{\vec{P}}}|0\rangle = |0\rangle \ .$$

One can equally check that it is isotropic.

¿What do we measure?

Basically the CMB photons emitted by the LSS. They are essentially at a local a $T \approx 3000K^0$. but are subjected to the redshift by the cosmological expansion down to $T \approx 2.7K^0$. However, besides that, there is an extra red shift associated with their emergence from the local well in the Newtonian potential.

Then:
$\frac{\delta T}{T_0}(\theta, \varphi) = \frac{1}{3}\psi(\eta_D, \vec{x}_D)$, gives us a picture of Newtonian Potential on the LSS.

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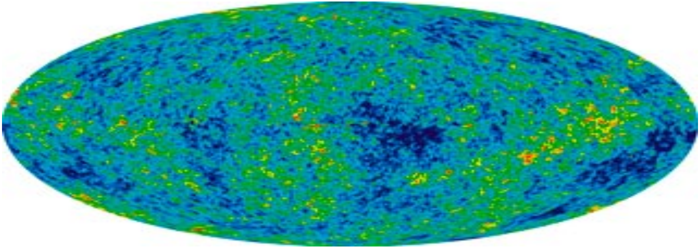

We characterize this map in terms of the spherical harmonic functions, and write: $\frac{\delta T}{T_0}(\theta, \varphi) = \sum_{lm} \alpha_{lm} Y_{lm}(\theta, \varphi)$.
The coefficients are thus :

$$\alpha_{lm} = \frac{1}{3} \int d\Omega^2 \psi(\eta_D, \vec{x}_D) Y^*_{lm}(\theta, \varphi) \quad (9)$$

This is what is measured. (Please do not confuse the fact that the satellite rotates, with the notion that one only extracts an average: The measurements allow us to extract the detailed map we saw and from which we extract the α_{lm}).
The quantity that is often the focus of the analysis is:

$$C_l = \frac{1}{2l+1} \sum_m |\alpha_{lm}|^2. \quad (10)$$

The calculation in the standard approach:
Write the Newtonian Potential in a Fourier decomposition $\psi(\eta,\vec{x}) = \sum_{\vec{k}} \psi_{\vec{k}}(\eta) e^{i\vec{k}\cdot\vec{x}}/L^{3/2}$. Substituting, one finds:

$$C_l = \frac{16\pi^2}{9L^3(2l+1)} \sum_m \sum_{\vec{k}\vec{k}'} \psi_{\vec{k}}(\eta_R)\psi_{\vec{k}'}(\eta_R) j_l(kR_D) j_l(k'R_D) Y^*_{lm}(\hat{k}) Y_{lm}(\hat{k}'). \tag{11}$$

However the central step is to replace $\psi_{\vec{k}}(\eta_R)\psi_{\vec{k}'}(\eta_R)$ by $\langle 0|\hat{\psi}_{\vec{k}}(\eta_R)\hat{\psi}_{\vec{k}'}(\eta_R)|0\rangle$.

Using the expression for the Newtonian potential in terms of the filed and $\hat{v}$, and its conjugate momentum $\hat{\pi}$:

$$\hat{\psi}_{\vec{k}} = -\left(\frac{\sqrt{4\pi G\epsilon}H}{k^2}\right)\left(\hat{\pi}_{\vec{k}} - \frac{\dot{z}}{z}\hat{v}_{\vec{k}}\right). \tag{12}$$

When doing this one finds remarkable agreement with observations:

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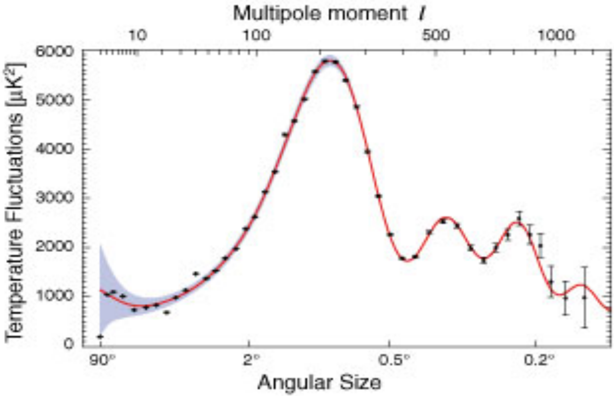


These are supposed to represent the primordial inhomogeneities which evolved into all the structure in our Universe: galaxies, stars planets, etc... AND THE THEORY FITS VERY WELL WITH THE OBSERVATIONS. One is then very tempted to say "well that is it. What else do we want". An attitude that is hard to blame.

However let us consider the following: The Universe was H&I, (both in the part that could be described at the "classical level", and the quantum level) as a result inflation. But we end with a situation which is not: Contains the primordial inhomogeneities which will result in our Universe structure and the conditions that permit our own existence.

How does this happen if the dynamics of the closed system does not break those symmetries.? I would say we might want to understand this, and answer the above question in a fully satisfactory way. If our theory really does it, then fine. If not we can take this as a starting point to further inquiry.

After all, Inflation resulted from demanding more from cosmology that what the Old Big Bang Theory was providing (like naturalness).

2) THE USUAL ANSWERS: See also Penrose's "Shadows of the Mind" Ch 6

a) We measure.

The problem with this view, is that the conditions that made possible our own existence would be said to result of our actions.

b)Environment-induced decoherence + many worlds Interpretations (MWI). i) Requires identification of D.O.F as an " environment" (and traced over). That would entail using our on limitations to measure things, as part of the argument. ii) Does not tell us that the situation is now described by one element of the diagonal density matrix, but by all, and as such the situation is still symmetric. Need something like MWI. iii) But MWI relies on a mind whose state of consciousness determines the alternatives into which the word splits.

c) Consistent (or de-cohering) Histories. Answer depends on the questions we ask.

d) This is just Philosophy.

One would have thought so. However as we will see it is not, as it leads in principle to predictions that depend on the answers.

3) OUR APPROACH: The situation we face here is unique (Quantum + Gravity + Observations).

We want to be able to point to a physical process that occurs in time as the explaining the emergence of the seeds of structure. After all emergence means : Something that was not there at a time, is there at a latter time.

We thus propose to add to the standard inflationary paradigm a quantum collapse of the wave function as as self induced processes.

NOTE HOWEVER THAT EVEN IGNORING THE PROBLEMS AND ACCEPTING ONE OF THE ALTERNATIVES a) b) or c) , what they say is that the relevant state is not the H& I vacuum state but some other state. Thus one should characterize such state and extract the spectrum from it. Not from the vacuum. I think even the advocates of such postures would have to agree with us on this point .

However the basic assumption of most people working in the filed seems to be that that this does not mater as the results are the same. We find this is generically not a correct assumption.

Collapse Theories: GRW, Pearle, Diosi, Penrose and now Weinberg.

4) The Proposal:

The idea is that at the quantum level gravity is VERY different, and at large scales leaves something that looks like a collapse of the quantum wave function matter fields. (Inspired by Penrose and Diosi's ideas).

Thus the inflationary regime is one where gravity already has a good classical description but matter fields might still require a full quantum treatment.

The setting will thus naturally be semiclassical Einstein's gravity (with the extra element: THE COLLAPSE): i.e., besides U we have sometimes, spontaneous jumps:

$$....|0\rangle_{k_1} \otimes |0\rangle_{k_2} \otimes |0\rangle_{k_3} \otimes .... \rightarrow ....|\Xi\rangle_{k_1} \otimes |0\rangle_{k_2} \otimes |0\rangle_{k_3} \otimes .....$$

There is an underlying Quantum Theory of Gravity, (probably with no notion of time as in LQG) . By the "time" we recover space-time concepts, the semiclassical treatment is a very good one, its regime of validity includes the inflationary regime as long as $R << 1/l^2_{Plank}$.

More precisely we will rely on the notion of *Semiclassical Self-consistent Configuration* (SSC).

DEFINITION: The set $g_{\mu\nu}(x), \hat{\varphi}(x), \hat{\pi}(x), \mathcal{H}, |\xi\rangle \in H$ represents a SSC if and only if $\hat{\varphi}(x)$, $\hat{\pi}(x)$ and $\mathcal{H}$ correspond a to quantum field theory constructed over a space-time with metric $g_{\mu\nu}(x)$ and the state $|\xi\rangle$ in $\mathcal{H}$ is such that:

$$G_{\mu\nu}[g(x)] = 8\pi G\langle\xi|\hat{T}_{\mu\nu}[g(x), \hat{\varphi}(x), \hat{\pi}(x)]|\xi\rangle.$$

It is the general relativistic version of Shrödinger-Newton eq..

This however can not describe the transition from a H&I SSC to one that is not. For that we need to add a collapse: A collapse will be a transition from one SSC to another.
So instead of just “state jumps” we need: $....SSC1.... \rightarrow ....SSC2....$

In particular they will describe a transition form an H&I SSC o to one that is not. That involves changing the state and thus the space-time and thus the Hilbert space where the state “lives” and is a bit complex.

Space-time is thus treated as classical and in our case (working in a specific gauge and ignoring the tensor perturbations):

$$ds^2 = a^2(\eta)\left[-(1+2\psi)d\eta^2 + (1-2\psi)\delta_{ij}dx^i dx^j\right], \psi(\eta,\vec{x}) \ll 1$$

The scalar filed is treated at the level of quantum filed theory on a curved space-time, so we write:

$$\hat{\phi}(x) = \sum_{\alpha}\left(\hat{a}_{\alpha}u_{\alpha}(x) + \hat{a}^{\dagger}_{\alpha}u^{*}_{\alpha}(x)\right), \tag{13}$$

with the functions $u_{\alpha}(x)$ a complete set of normal modes orthonormal with respect to the symplectic product.

Working up to the first order in the Newtonian potential the equations for the normal modes simplify to

$$(1-2\psi)(\ddot{u}_{\vec{k}}+2\mathcal{H}\dot{u}_{\vec{k}})-(1+2\psi)\Delta u_{\vec{k}}-4\dot{\psi}\dot{u}_{\vec{k}}+a^2m^2u_{\vec{k}}=0, \quad (14)$$

$$\int_{\eta=\text{const.}}\left[u_{\vec{k}}(\partial_\eta u^*_{\vec{k}'})-(\partial_\eta u_{\vec{k}})u^*_{\vec{k}'}\right](1-4\psi)d^3x=i\hbar a^{-2}\delta_{\vec{k}\vec{k}'}. \quad (15)$$

Construct the modes for a "generic" ψ and then look for a state in the Hilbert space leading to a self consistent solution for the equations controlling $a(\eta)$ and ψ. This is nontrivial, but is a well defined problem. We have constructed explicitly the SSC for the H& I case where $\psi=0$ and, for the case involving the excitation of just one nontrivial mode $\psi=F(\eta)Cos(\vec{k_0}.\vec{x})$ and studied the transition from one SSC to the other.
In practice, and while working just to first order perturbation, we can work with a single QFT construction.

5) PRACTICAL TREATMENT:

We have checked that this is equivalent at the lowest order in perturbation theory.
We again split the treatment into that of a classical homogeneous ('background') part and an in-homogeneous part ('fluctuation'), i.e.$g = g_0 + \delta g$, $\phi = \phi_0 + \delta\phi$.
The background is taken again to be Friedmann-Robertson universe, and the homogeneous scalar field $\phi_0(\eta)$. In the previous more precise treatment this corresponds to the zero mode of the quantum filed.
The big difference will be in the spatially dependent perturbations. Here the theory indicates we should quantize the scalar filed but not the metric perturbation. (We will have something to say about this in 7).
We will set $a = 1$ at the "present cosmological time", and assume that inflationary regime ends at a value of $\eta = \eta_0$, negative and very small in absolute terms.

Semiclassical Einstein's equations, at lowest order lead to

$$\nabla^2\Psi = 4\pi G\dot{\phi}_0\langle\delta\dot{\phi}\rangle = s\langle\delta\dot{\phi}\rangle, \tag{16}$$

where $s \equiv 4\pi G\dot{\phi}_0$.

Now we consider the quantum theory of the field $\delta\phi$. It is convenient to work with the rescaled field variable $y = a\delta\phi$ and its conjugate momentum $\pi = \delta\dot{\phi}/a$. Set the problem in a box of side L, which can be taken to ∞ at the end of all calculations.

We decompose the field and momentum operators as:

$$y(\eta,\vec{x}) = \frac{1}{L^3}\sum_{\vec{k}} e^{i\vec{k}\cdot\vec{x}}\hat{y}_k(\eta),$$
$$\pi_y(\eta,\vec{x}) = \frac{1}{L^3}\sum_{\vec{k}} e^{i\vec{k}\cdot\vec{x}}\hat{\pi}_k(\eta),$$

$\vec{k}$ satisfying $k_iL = 2\pi n_i$.

Here $\hat{y}_k(\eta) \equiv y_k(\eta)\hat{a}_k + \bar{y}_k(\eta)\hat{a}^{+}_{-k}$

and $\hat{\pi}_k(\eta) \equiv g_k(\eta)\hat{a}_k + \bar{g}_k(\eta)\hat{a}^{\dagger}_{-k}$

with the usual choice of modes: $y_k(\eta) = \frac{1}{\sqrt{2k}}\left(1 - \frac{i}{\eta k}\right)\exp(-ik\eta)$

$g_k(\eta) = -i\sqrt{\frac{k}{2}}\exp(-ik\eta)$, which leads to what is known as the Bunch Davies vacuum: the state defined by $\hat{a}_k|0\rangle = 0$.

The collapse will modify the state and thus expectation values of the operators $\hat{y}_k(\eta)$ and $\hat{\pi}_k(\eta)$.

Now we need to specify the rules according to which collapse happens. That is: the state $|\Theta\rangle$ after the collapse. This is thought to be controlled by novel physics so we must try to make and “educated guess”, and hopefully then contrast with data.

We will assume that after the collapse, the expectation values of the field and momentum operators in each mode, will be related to the uncertainties of the pre-collapse state (recall that the expectation values in the vacuum state are zero).

In the vacuum state, $\hat{y}_k$ and $\hat{\pi}_k$ characterized by Gaussian wave functions centered at 0 with spread Δy_k and $\Delta \pi_{y_k}$, respectively.

6)

We will want to consider various possibilities for the detailed form of this collapse. Thus, for their generic form, associated with the ideas above, we assume that at time η_k^c the part of the state corresponding to the mode $\vec{k}$ undergoes a sudden jump so immediately afterwards:

$$\langle \hat{y}_k(\eta_k^c) \rangle_\Theta = A \;\; x_{k,1}\sqrt{\Delta \hat{y}_k}$$
$$\langle \hat{\pi}_k(\eta_k^c) \rangle_\Theta = B \;\; x_{k,2}\sqrt{\Delta \hat{\pi}_k^y}$$

where $x_{k,1}, x_{k,2}$ are selected randomly from within a Gaussian distribution centered at zero with spread one. Here A and B are parameters that characterize specific types of collapse.
At this point, we must emphasize that our universe corresponds to a single realization of these random variables, and thus each of these quantities has a single specific value.

Model 1): *the symmetric model*. In this case we do not want to distinguish one operator over the other and assume that the collapse leads to independent and uncorrelated expectation values for the two operators involved. This we do by choosing $A = B = 1$.

Model 2):*the Newtonian model*. In this case we take the view that what is relevant as source of the gravitational effect is $\hat{\pi}_k$. It is thus natural, (in following Penrose´s ideas) to assume that it is only this latter operator which is involved in the collapse and that it is the only one whose expectation value changes in that process. This we represent by choosing $A = 0$, $B = 1$.

Finally for each model we obtain the information giving the relevant expectation values of the field operators in the post collapse state $|\Theta\rangle$. That is, from the equations above and using the result in the evolution equations for the expectation values (i.e. using Ehrenfest's Theorem) we obtain $\langle \hat{y}_k(\eta) \rangle$ and $\langle \hat{\pi}_k(\eta) \rangle$ for the state that resulted from the collapse for all later times.

Analysis of the Phenomenology

The semi-classical version of the perturbed Einstein's equation that, in our case, leads to equation
The Fourier components at the conformal time η are given by:

$$\Psi_k(\eta) = -(s/ak^2)\langle\hat{\pi}_k(\eta)\rangle$$

Prior to the collapse, the state is the vacuum and $\langle 0|\hat{\pi}_k(\eta)|0\rangle = 0$ so we have:

$$\Psi_k(\eta) = 0$$

But after the collapse we have:

$$\Psi_k(\eta) = -(s/ak^2)\langle\Theta|\hat{\pi}_k(\eta)|\Theta\rangle \neq 0$$

And thus

$$\Psi(\eta, \vec{x}) = \frac{1}{L^3}\sum_{\vec{k}} e^{i\vec{k}\cdot\vec{x}}\Psi_k(\eta)$$

The measured quantity is the "Newtonian potential" on the surface of last scattering: $\Psi(\eta_D, \vec{x}_D)$, where η_D is the conformal time at decoupling and $\vec{x}_D$ are co-moving coordinates of points on the last scattering surface corresponding to us as observers

This quantity is identified with the temperature fluctuations on the surface of last scattering. Thus $\alpha_{lm} = \int \Psi(\eta_D, \vec{x}_D) Y^*_{lm} d^2\Omega$.

Now, $\Psi(\eta, \vec{x}) = \sum_{\vec{k}} \frac{sU(k)}{k^2} \sqrt{\frac{\hbar k}{L^3}} \frac{1}{2a} F(\vec{k}) e^{i\vec{k}\cdot\vec{x}}$

where $F(\vec{k})$ contains the information about the type of collapse scheme one is considering as well as the time at which the collapse of the wave function for the mode $\vec{k}$ occurs, and the factor $U(k)$ represents known physics like others, the acoustic oscillations of the plasma (i.e. are transfer functions).

Putting all this together we find,

$$\alpha_{lm} = s\sqrt{\frac{\hbar}{L^3}} \frac{1}{2a} \sum_{\vec{k}} \frac{U(k)\sqrt{k}}{k^2} F(\vec{k}) 4\pi i^l j_l((|\vec{k}|R_D) Y_{lm}(\hat{k}),$$

where $j_l(x)$ is the spherical Bessel function of the first kind, $R_D \equiv ||\vec{x_D}||$, and $\hat{k}$ indicates the direction of the vector $\vec{k}$.

Thus α_{lm} is the sum of contributions from all the harmonic oscillators, each one contributing with a complex number to the sum, i.e. the equivalent to a two dimensional random walk, whose total displacement corresponds to the observational quantity.

We then evaluate the most likely value:

$|\alpha_{lm}|^2_{M.L.} = \frac{s^2\hbar}{2\pi a^2} \int \frac{U(k)^2 C(k)}{k^4} j_l^2((|\vec{k}|R_D) k^3 dk$ where some of the information contained in $F(k)$ has become encoded in the function $C(k)$ which for each one of the models has a slightly different functional form:

For Model 1) we have $C(k)^{(1)} = 1 + \frac{2}{z_k^2}\sin^2\Delta_k + \frac{1}{z_k}\sin(2\Delta_k)$, where $\Delta_k = k\eta - z_k$, $z_k = \eta_k^c k$ with η representing the conformal time of observation, and η_k^c the conformal time of collapse of the mode k.

For Model 2) we find: $C(k)^{(2)} = 1 + \sin^2\Delta_k\left(1 - \frac{1}{z_k^2}\right) - \frac{1}{z_k}\sin(2\Delta_k)$,

These expressions differ, and at the same time affect our prediction of the exact form of the spectrum, indicates clearly that we could in principle empirically determine which, if any, is favored by the data.

The last expression for $|\alpha_{lm}|^2_{M.L.}$ can be made more useful by changing the variables of integration to $x = kR_D$ leading to

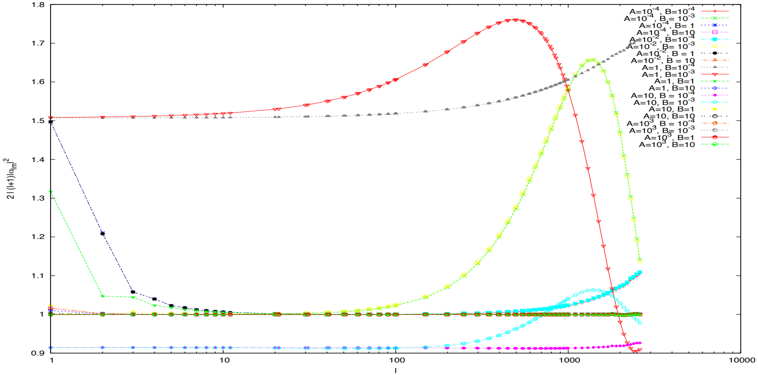
$$|\alpha_{lm}|^2_{M.L.} = \frac{s^2\hbar}{2\pi a^2}\int \frac{U(x/R_D)^2 C(x/R_D)}{x^4} j_l^2(x) x^3 dx.$$

This expression reveals that, if one ignores late time physics processes represented by U and the remaining signatures of the collapse process represented by C, the observational spectrum should have no dependence on the size of the surface of last scattering R_D.

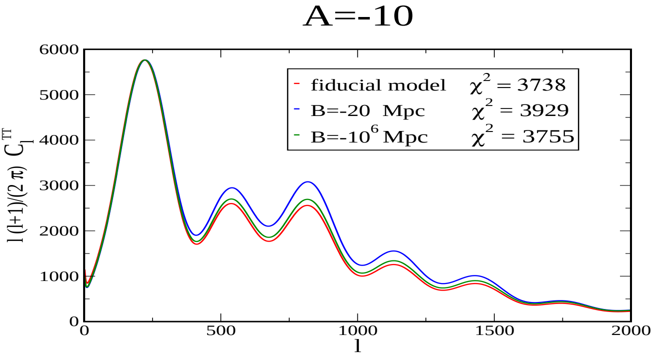
In order to get a reasonable spectrum, we have one single simple option: z_k must be almost independent of k, That is: $\eta_k^c = z/k$. (Recall that formally $\eta \to 0^-$ as $a \to \infty$).

However the important aspect in this result is it also shows that in principle the details of the collapse can have observational consequences.

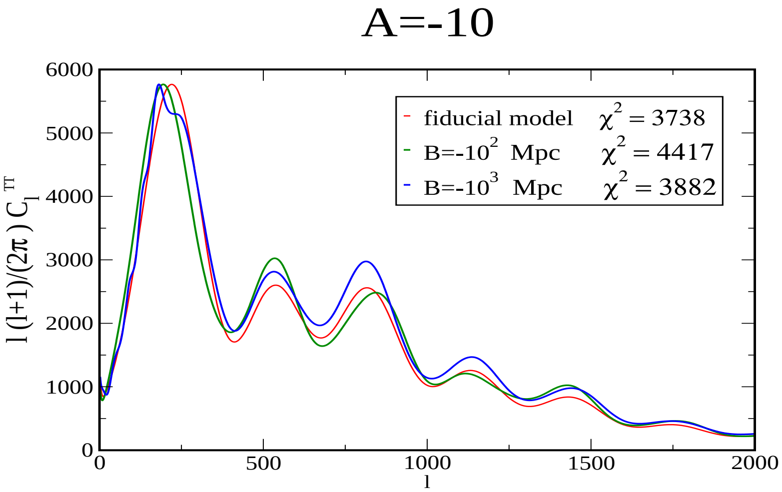
We have carried out preliminary exploration (with A de Unanue, PRD 2008) of the effects of departures from the pattern $\eta^c_k = z/k$, but assuming $\eta^c_k = A/k + B$. This first analysis simply ignores the effects of late physics and compares the predicted spectrum with a flat one.



We are now finishing (with S, Landau & C. Sccocola) a much more detailed analysis incorporating the well understood late time physics (acoustic oscillations, etc) and comparing directly with the observational data.



For Model 2


A=-10
fiducial model $\chi^2 = 3738$
B=-10^2 Mpc $\chi^2 = 4417$
B=-10^3 Mpc $\chi^2 = 3882$
l (l+1)/(2π) C_l^{TT}
l
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1000
2000
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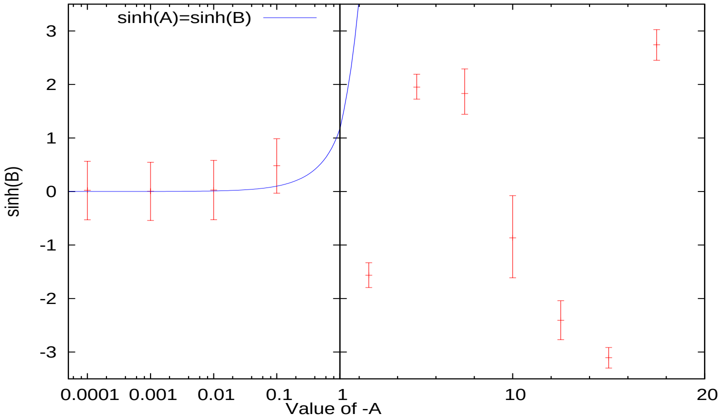
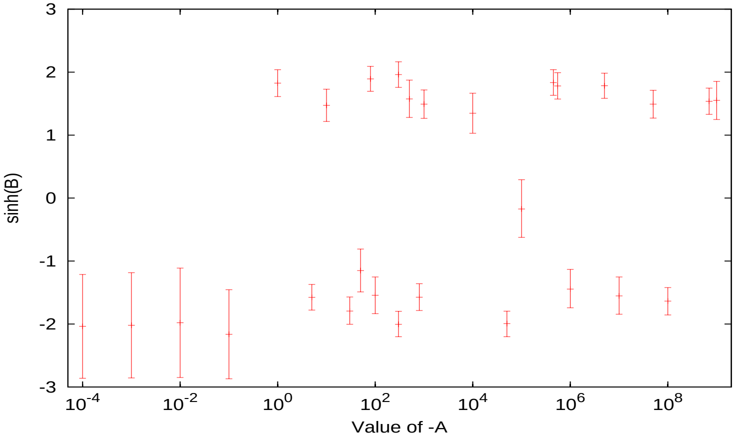
1500

For Model 1



For Model 2



A version of 'Penrose's mechanism' for collapse in the cosmological setting

Penrose has advocated the idea of a collapse of the wave functions as a dynamical process related to gravitational interaction. The suggestion… collapse into one of two quantum mechanical alternatives would take place when the gravitational interaction energy between them exceeds a certain threshold.
A very naive realization of Penrose's ideas in the present setting could be obtained as follows: each mode would collapse by the action of the gravitational interaction between its own possible realizations. In our case, one could estimate the interaction energy $E_I(k, \eta)$ by considering two representatives of the possible collapsed states on opposite sides of the Gaussian associated with the vacuum. We will denote the two alternatives by the indices (1) and (2).

We interpret Ψ as the Newtonian potential and, the matter density $\rho = a^{-2}\dot{\phi}_0\dot{\delta}\phi = a^{-3}\dot{\phi}_0\pi^y$.

Then the relevant energy is given by :

$$E_I(\eta) = \int \Psi^{(1)}\rho^{(2)}dV = \int \Psi^{(1)}(x,\eta)\rho^{(2)}(x,\eta)a^3d^3x = \int \Psi^{(1)}(x,\eta)\dot{\phi}_0(\pi^y(x,\eta))^{(2)}d^3x$$

where $\Psi^{(1)}$ is Newtonian potential that would have arisen if the system had collapsed into the alternative (1), and $\rho^{(2)}$ represents the density perturbation associated with a collapse into the alternative (2).

Viewing each mode's collapse as occurring independently, the trigger for the collapse of mode k would be the condition that this energy $E_I(k,\eta) = (\pi\hbar G/ak)(\dot{\phi}_0)^2$ reaches the value of the Planck Mass M_p.

This leads to:

$$z_k = \eta_k^c k = \frac{\pi}{9}(\hbar V')^2(H_I M_p)^{-3} = \frac{\epsilon}{8\sqrt{6\pi}}(\tilde{V})^{1/2} \equiv z^c$$

which is independent of k, and, thus, as we have seen this leads to a roughly scale invariant spectrum of fluctuations in accordance with observations. TEST OF CONCEPT.

7) MORE ON THE COLLAPSE MODELS AND IDEAS.

i) No tensor modes. (In the semiclassical approach we favor. This can also be tested.)

ii) Might offer a solution to the Fine Tuning problem for the inflaton Potential. (CQG, 27, 225017 (2010).

iii) Multiple collapses. More information about the post-collapse states .(CQG, 28, 155010 (2011))

iv) New views on the study of Non-Gaussianities. Novel possibilities, and approaches. (arXiv:1107.3054 [astro-ph.CO].)

v) Very Speculative Ideas connecting with QG and the problem of time: Wheeler de Witt or LQG are timeless theories. To recover time we must resort to identifying an observable that acts as a physical clock. When the evolution of the state for other variables is cast in terms of a physical clock an approx Schrëdinger eq. is recovered. But is not 100% Unitary. Can this be the place where a collapse fits with the rest of our theories?

8) MORE ON THE INTERPRETATIONAL PROBLEM:

In fact we could have decided to compute directly the quantities most directly observed: our specific CMB map (characterized by its coefficients):

$$\alpha_{lm} = \frac{1}{3}\int d\Omega^2 \psi(\eta_D, \vec{x}_D) Y^*_{lm}(\theta, \varphi)$$

Identifying $\psi(\eta_D, \vec{x}_D)$ con $\langle 0|\hat{\psi}_{\vec{k}}(\eta_R)|0\rangle$, we find that $\alpha_{lm} = 0$. THIS SEEMS LIKE A PROBLEM, OR DOES IT NOT?.

One could dismiss this by saying: Well that is only the average value over universes. That is one would take the view that the vacuums state (i.e its unitary evolution) does not represent the state of our universe. That is just " like when we measure anything"... perhaps but then, we musk acknowledge that there must be same measurement involved. What measurement? By whom?

Perhaps the view is that the vacuums state does not represent our Universe but some ensemble. If so what is the state that represents our universe? And why should we not use that state in analyzing the spectrum?

In any way we should not trust the analysis that lead to $\alpha_{lm} = 0$.
¿ Why should we trust some predictions of the formalism and not others ?
In fact to be able to trust the analysis we need to find the physical reason behind the breakdown of the initial symmetry. (even if the symmetry was broken in one part in e^{80} that is not relevant). Often this issue is hidden from view by the fact that one is dealing with complex situations involving large numbers of D.O.F.

But this does not means that the conceptual problem simply goes away.

What helps us focus here on the issue despite the large number of D.O.F. is the symmetry, People often refer to so call analogous situations:

Example 1 Radioactive α Decay of an spherically symmetric atomic nucleus in a bubble chamber.

How is it that the outgoing spherical wave function characterizing such decay, could be reconcile wit the observational fact that the emitted α particles lead to straight tracks in the bubble chambers ?

Problem considered by Sir. N. F. Mott in 1929 in the following manner:

Initially we have the unstable nucleus located at ($\vec{X} = \vec{0}$) in the state $|\Psi^+\rangle$ (spherically symmetric). Decays to the nuclear ground state $|\Psi^0\rangle$, plus an α particle in the sate $|\Xi_\alpha\rangle$, which also spherically symmetric . One considers then two hydrogen atoms with nuclei fixed at $\vec{a}_1$ and $\vec{a}_2$, while the electrons are in the corresponding ground states . The analysis focuses on the degree of alignment of he origin and the points ($\vec{a}_2 \approx c\vec{a}_1$) if both atoms become excited by the interaction with the α particle.

The result is that the probability of both atoms to be excited is $\neq 0$ sonly if here is a large degree of alignment which then explains the experimental finding of straight α tracks in the bubble chamber.

At first sight this seems like clear example of an initial state with a given un symmetry ($|\Psi^+\rangle$) evolving to a final state lacking it, despite the fact that the Hamiltonian (governing the decay $|\Psi^+\rangle \rightarrow |\Psi^0\rangle|\Xi_\alpha\rangle$ and the dynamics of of the α particle) preserves that symmetry.

A second look reveals, to start, that the localization the hydrogen nuclei, break the symmetry. The discussion in fact is based not just in what we said before but also by Hamiltonian for the joint evolution of the α particle and the 2 electrons (of the localized hydrogen atoms). In fact the analysis by Mott relies, implicitly, on the projection postulate in connection with measurement: This is employed while computing probabilities, by projecting on the sub-space corresponding to both atoms being exited.
If we were to replace such atoms by some hypothetical detectors having spherical wave functions (say spherical shells with radius r_i), a similar calculation would not yield straight lines but spherical patterns of excitation. We would find that with a certain probability the shells $i^{th}\& j^{th}$ would be excited, but symmetry would remain intact. In our problem with the inflationary cosmology the situation is closer to the later than the former.

Simplified Model: Mini-Mott:

Consider two, double level detectors $|-\rangle$ (ground) y $|+\rangle$ (excited) located in $x = x_1$ y $x = -x_1$: Initially they are in their ground states, and there is a particle with an initial sate corresponding to a wave packet $\psi(x, 0)$ centered at the origin and symmetric under $x \to -x$.
El Hamiltonian for the free particle:

$$\hat{H}_P = \hat{p}^2/2M \tag{17}$$

while that for each detector is

$$\hat{H}_i = \epsilon \hat{I}_p \otimes \{|+\rangle^{(i)}\langle+|^{(i)} - |-\rangle^{(i)}\langle-|^{(i)}\}. \tag{18}$$

where $i = 1, 2$. The hamiltonian for particle -detector 1 interaction is:

$$\hat{H}_{P1} = \frac{g}{\sqrt{2}}\delta(x - x_1\hat{I}_p) \otimes (|+\rangle^{(1)}\langle-|^{(1)} + |-\rangle^{(1)}\langle+|^{(1)}) \otimes I_2 \tag{19}$$

analogously for detector 2.

Then we consider Schrödinger's equation for the initial condition:

$$\Psi(0) = \sum_x \psi(x,0)|x\rangle \otimes |-\rangle^{(1)} \otimes |-\rangle^{(2)}$$

Thus after some time t we have:

$$\Psi(t) = \sum_x \psi_1(x,t)|x\rangle \otimes |+\rangle^{(1)} \otimes |-\rangle^{(2)} + \sum_x \psi_2(x,t)|x\rangle \otimes |-\rangle^{(1)} \otimes |+\rangle^{(2)}$$

$$+ \sum_x \psi_0(x,t)|x\rangle \otimes |-\rangle^{(1)} \otimes |-\rangle^{(2)} + \sum_x \psi_D(x,t)|x\rangle \otimes |+\rangle^{(1)} \otimes |+\rangle^{(2)}$$

The first 2 terms seem be easily interpreted, while the last two represent the failure of detection and double detection (or bounce) usually very small amplitude g^2.

Thus we could think that the first 2 terms indicate the high probability of breakdown of the symmetry: Either detector 1 or 2 became exited. Just using a Bohr-like interpretation we are done. However we can that besides indicating that these are detectors, we must specify how are they used. In other words one must determine which basis (or observable) is the appropriate one to describe their behavior.

Let us focus on the ambiguities by considering an

Alternative description

Simply work with the basis:

$$|U\rangle \equiv |+\rangle^{(1)} \otimes |+\rangle^{(2)} \tag{20}$$

$$|D\rangle \equiv |-\rangle^{(1)} \otimes |-\rangle^{(2)} \tag{21}$$

$$|S\rangle \equiv \frac{1}{\sqrt{2}}[|+\rangle^{(1)} \otimes |-\rangle^{(2)} + |-\rangle^{(1)} \otimes |+\rangle^{(2)}] \tag{22}$$

$$|A\rangle \equiv |\frac{1}{\sqrt{2}}[|+\rangle^{(1)} \otimes |-\rangle^{(2)} - |-\rangle^{(1)} \otimes |+\rangle^{(2)}] \tag{23}$$

These are more convenient to discuss the symmetry issues .

In terms of the new states:

The Hamiltonian for the detectors:

$$\hat{H}_1 + \hat{H}_2 = 2\epsilon \hat{I}_p \otimes \{|U\rangle\langle U| - |D\rangle\langle D|\}. \tag{24}$$

(the other eigen-states correspond to he eigenvalue 0.)

The interaction Hamiltonian

$$\hat{H}_{P1} + \hat{H}_{P2} = \frac{g}{\sqrt{2}}[\{\delta(x - x_1\hat{I}_p) + \delta(x - x_2\hat{I}_p)\} \otimes (|U\rangle + |D\rangle)\langle S| \tag{25}$$

$$+\{\delta(x - x_1\hat{I}_p) - \delta(x - x_2\hat{I}_p)\} \otimes (|U\rangle + |D\rangle)\langle A|] + h.c. \tag{26}$$

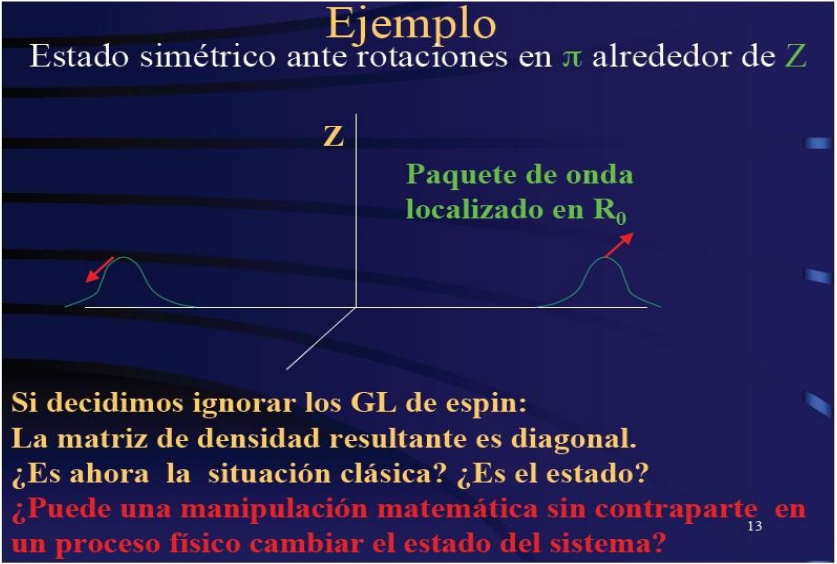
This structure revels that a wave function that is symmetric $x \to -x$ and $1 \to 2$ can not excite the antisymmetric sate of the detectors. In particular the second term wold give no contribution.
In fact we can write the solution to the problem as :

$$\Psi(t) = \sum_x \psi_s(x,t)|x\rangle \otimes |S\rangle + \sum_x \psi_0(x,t)|x\rangle \otimes |D\rangle + \sum_x \psi_D(x,t)|x\rangle \otimes |U\rangle$$

Here the question is: why would it be wrong to consider this picture involving the full Hilbert space and the particle- detectors interactions, in terms of this basis where we view the two detectors a simply a more complex single one.

In this way we see that the initial symmetry is not broken when the detectors are considered at the quantum level and are initially also in a symmetric state. At least not, without the introduction of some additional postulate.

How do we explain the breakdown of the symmetry? Decoherence?



In the case of our cosmological problem, the environment would corresponds to the DOF of other fields, or some particular modes of the inflaton field deemed to be ”non observable”. The point is however that the whole state involving the full set of modes is symmetric
as inflation is supposed to drive all fields to their vacuum state (why would the geometric accelerated expansion affect the inflaton and other fields in a different matter?)..

Most people working on this topic compute the so called decoherence functionals, apparently without focussing too much on these issues ...

”The interpretation based on the ideas of decoherence and ein-selection has not really been spelled out to date in any detail. I have made a few half-hearted attempts in this direction, but, frankly, I was hoping to postpone this task, since the ultimate questions tend to involve such “anthropic” attributes of the “observership” as “perception,” “awareness,” or “consciousness,” which, at present, cannot be modeled with a desirable degree of rigor.” W Zurek.

We can not use our own technological and observational limitations as part of the argument para argument (i.e. the appeal to an unobservable set of DOF we declare to constitute the environment) which through decoherence explains the very conditions that lead to us..

In any even in our case the things mentioned by Zurek, do not seem to help. We need to understand the breakdown of the initial homogeneity and isotropy if we really want to understand the source of the seeds of the cosmic structure (which eventually lead to galaxies stars and planets, where we can find the conditions for the emergence of life and eventually intelligent :-) .., beings like ourselves.)