The quantum origin of the cosmic structure: an arena for Quantum Gravity Phenomenology

Daniel Sudarsky ICN- UNAM , Mexico

Original work in collaboration with:

A. Perez (U. MARSEILLE)

H.Sahlmann (PENN STATE-UTRECHT)

gr-qc/0508100; CQG 23, 2317 (2006).

Further phenomenological studies:

my student : Adolfo de Unanue (ICN UNAM)

gr-qc/0801.4702 ; PRD78, 043510 (2008).

and recentlySusana Landau (U de BUENOS AIRES)

& her student Claudia Scoccola (U de LA PLATA)

PLAN

1) THE STANDARD LORE AND ITS SHORTCOMINGS.

2) THE EXTRA ELEMENT (TIED TO QG?).

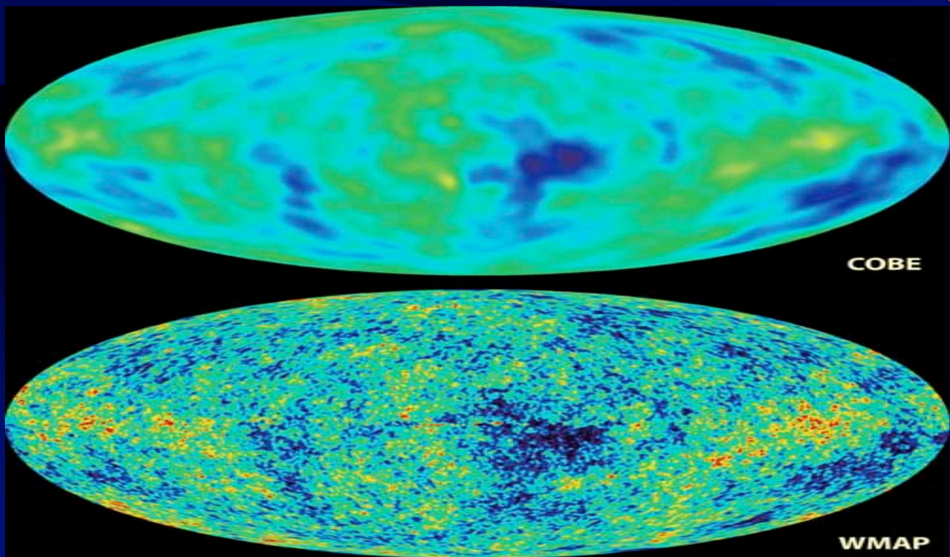
3) PHENOMENOLOGY

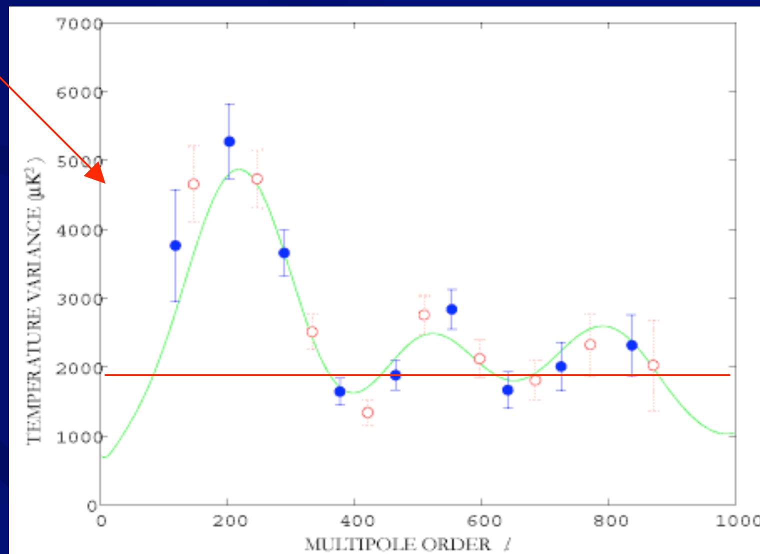
4) A PENROSE INSPIRED COLLAPSE SCHEME

5) CONCLUSIONS

The last decade is considered as a big success, for inflationary cosmology.

- The Universe seems to be spatially flat (i.e. $\Omega \approx 1$)
- Theoretical predictions of the spectrum of primordial in - homogeneities resulting from quantum fluctuations of the inflaton.
- Observational data in agreement with such predictions. AMAZING!
- Note however: The oscillations have no relation with inflation but with plasma physics (inflation alone would lead to a flat line!)





The Primordial Cosmological Spectrum

- Action $$S = \int d^4x \sqrt{-g}[\frac{1}{16\pi G} R[g] - 1/2 \nabla_a \phi \nabla_b \phi g^{ab} - V(\phi)]$$
- Metric $ds^2 = a(\eta)^2 [-(1 + 2\Psi) d\eta^2 + (1 - 2\Psi) \delta_{ij} dx^i dx^j]$
  The perturbation Ψ is called the Newtonian potential
- Scalar Field : $\phi = \phi_0 (\eta) + \delta \phi (\eta, x^i)$.
- Introduce a new combined field $V \equiv a \delta \phi + a' \phi_0 ' \Psi$ whose action (after using a further relation between V and Ψ) is that of a free filed (with time dependent mass).
- Select a vacuum and quantize:
- $V(\eta, x^i) = \int d^3k [v^*_k (\eta) e^{ikx} a_k + v_k (\eta) e^{ikx} a_k^\dagger]$
- Express Ψ in terms of V and compute the 2-p correlation function:
  $$f(x) = < 0| \Psi(\eta, 0) \Psi(\eta, x^i) |0 >$$
- Identify its Fourier transform with the Power spectrum
  $$P(k) = C k^3 \int f(x) e^{ikx} d^3x$$
- The result is independent of k, scale invariant HZ spectrum

The issues (H Shalman and A Perez)

- There is something very odd in our understanding of the problem: The Universe ``starts" as a homogeneous and isotropic space-time (H&I), and there is a scalar field (the inflaton) which is in a vacuum state, which is, of course, also H&I. How is it that we end up with a situation that is not H & I, given that the dynamics preserves these symmetries?

- Is this just Quantum Mechanics? Not exactly! The Universe is the only real example of a QM closed system. Orthodox interpretation of QM requires an external, classical, measuring apparatus (This is why J. Hartle argues for a Generalized Quantum theory applicable to cosmology).

- Nevertheless, Most Experts in the Field: "There is no problem". However. you will receive different specific answers from different cosmologists, a fact which indicates some discomfort with the views of the others !

The Most popular answer:Decoherence

(trace over environment DOF: reduced density matrix, time average)

$$\begin{pmatrix} A & B & C & \ldots \\ D & E & F & \ldots \\ G & H & I & \ldots \\ \ldots & \ldots & \ldots & \ldots \end{pmatrix} \rightarrow \begin{pmatrix} A & 0 & 0 & \ldots \\ 0 & E & 0 & \ldots \\ 0 & 0 & I & \ldots \\ \ldots & \ldots & \ldots & \ldots \end{pmatrix}$$

The choice of basis problem

Diagonalization disappears upon change of basis!

A: The Environment- System Interaction selects the basis

In our case what can play the role of the environment? Inflation has removed all matter (all fields are in the vacuum) and all local features! (That is what I. Does!!).

A: Some DOF tied to the inflaton are unobservable (i.e. we **can not observe them).**

Even if we overcome or accept this… Decoherence faces :

The problem of definite outcomes

$$\begin{pmatrix} A & B & C & \ldots\ldots \\ D & E & F & \ldots\ldots \\ G & H & I & \ldots\ldots \\ \ldots & \ldots & \ldots & \ldots \end{pmatrix} \xrightarrow{\text{Decoherence}} \begin{pmatrix} A & 0 & 0 & \ldots\ldots \\ 0 & E & 0 & \ldots\ldots \\ 0 & 0 & I & \ldots\ldots \\ \ldots & \ldots & \ldots & \end{pmatrix} \xrightarrow{?} \begin{pmatrix} 0 & 0 & 0 & \ldots \\ 0 & E & 0 & \ldots \\ 0 & 0 & 0 & \ldots \\ \ldots & \ldots & \ldots & \end{pmatrix}$$

Decoherence

Interpretation:

i) **choice (our wish) vs.**

ii) **coexistence (QM).**

Decoherence does not solve the measurement problem.

- *"Many physicist nowadays think that decoherence provides a fully satisfying answer to the measurement problem. But this is an illusion."* Arnold Neumaier http://www.mat.univie.ac.at/~neum/physics-faq.txt.

- *"note that the formal identification of the reduced density matrix with a mixed state density matrix is easily misinterpreted as implying that the state of the system can be viewed as mixed too….. the total composite system is still described by a superposition, it follows from the rules of quantum mechanics that no individual definite state can be attributed to one of (the parts) of the system…"* M. Schlosshauer, ArXive. quant-ph/0312059, page 9]

- *“Does decoherence solve the measurement problem? Clearly not. What decoherence tells us is that certain objects appear classical when observed, But what is an observation? At some point we still have to apply the usual probability rules of Quantum Theory* Joos, in Decoherence Theoretical, Experimental and conceptual problems.

- **“ As long as we remain within the realm of mere predictions concerning what we shall observe (i.e. what will appear to us) and refrain from stating anything concerning ”things as they must be before we observe them” no break in the linearity of quantum dynamics is necessary”* D’Espagnat, Phys .Lett. A 282, 133 (2000)

BUT IN COSMOLOGY WE NEED TO TALK ABOUT PRECISELY ABOUT THOSE!!

Lately some of the Experts on Inflation have begun acknowledging the problem

For Instance, V. Mukhanov in his book Physical Foundations of Cosmology , on the issue of how do the in-homogeneities arise:

no preferred position in space? Quantum mechanical unitary evolution does not destroy translational invariance and hence the answer to this question must lie in the transition from quantum fluctuations to classical inhomogeneities. Decoherence is a necessary condition for the emergence of classical inhomogeneities and can easily be justified for amplified cosmological perturbations. However, decoherence is not sufficient to explain the breaking of translational invariance. It can be shown that as a result of unitary evolution we obtain a state which is a superposition of many macroscopically different states, each corresponding to a particular realization of galaxy distribution. Most of these realizations have the same statistical properties. Such a state is a close cosmic analog of the "Schrödinger cat." Therefore, to pick an observed macroscopic state from the superposition we have to appeal either to Bohr's reduction postulate or to Everett's many-worlds interpretation of quantum mechanics. The first possibility does not look convincing in the cosmological context. The reader who would like to pursue this issue can consult the corresponding references in "Bibliography" (Everett, 1957; De Witt and Graham, 1973).

Other postures one encounters:

- Q.M. does not describe Our Universe, as it was never H&I (the ensemble was) (Only the superposition of many U is represented by the H&I Quantum state. Beware:This is not QM!).

- Our Universe is Still H&I.

This is not ``JUST PHILOSOPHY'': The early Universe offers the "Laboratory" where some of the issues can be (at least in principle) studied.

In the Cosmological Setting

- We seek a scheme that views QM as a theory about the description of the system, and not just, of our knowledge about it.
- Provides an historical (time development) description of cosmic evolution that follows the laws of physics (Permits, in principle, the assignment of a Quantum State to the system, at ``every time").
- Such description should explain how did WE arise (primordial density fluctuations, galaxies, stars, planets, living organisms, etc). THUS it should not rely on the measurement (in) abilities of the late evolved creatures to explain the emergence of conditions that make them possible (one can not justify identifying some DOF as irrelevant environment).
- Allows consideration of issues such as "When did the lack of H&I at such and such scale originate?"

- We will take the view that the marriage of GR and QM might involve changes in both! (R. Penrose).

Quantum Gravity and the effective Description

- The fundamental theory which incorporates QG (and matter fields) is expected to be an a-temporal theory (such as LQG) .
- The states are elements in $H_G \otimes H_M$
- The effective description of space-time would require the identification of a "time" parameter, and the evolution must emerge as the result of correlations (as in recent works on LQC).
- But such effective evolution is not necessarily 100 % unitary (i.e. Realistic Clocks… PRL93;240401,2004 Gambini -Porto-Pullin). More generally, there seems to be no impediments to "jumps" or (discontinuities) in the correlations.
- In situations sufficiently close to classical, the effective evolution should take the form of semi-classical gravity coupled with a QFT for the matter (perhaps with some small modifications).

The standard scheme augmented with the ``self induced collapse” hypothesis. (Inspired by Penrose´s ideas)

- The fundamental theory describes gravity in terms of some more fundamental D.O.F. The metric description is just an effective one. QM is incomplete.
- The QM Collapse: Is the only known mechanism capable of taking a symmetric state into an asymmetric state while the dynamics preserves the symmetry.
- A NEW INGRIDIENT BROUGH INTO PHYSICS by Q&G has an effective description as a self induced collapse (which does not rely on an external agent to induce it).

- SEMICLASSICAL GRAVITY (corrected) (Note that Gravity will be treated very differently from the Matter) & coupled to the inflaton according to:

$$G_{ab} + Q_{ab} = 8\pi G < T_{ab} >$$

At least for states with relatively sharp values *

  - Quantum State subject to :

$$|0\rangle \longrightarrow |\Theta\rangle$$

- Motivation: “The QG DOF are not excited”, except at the jumps.
- Q reflects the jumps in the effective geometry that must accompany the collapse in the state. It is assumed to vanish before and after the collapse.
- Goal: To extract characteristics of the NEW PHYSICS from the observations.

Pre and Post Collapse Cosmology

- Metric $ds^2 = a(\eta)^2 [-(1 + 2\Psi) d\eta^2 + (1 - 2\Psi) \delta_{ij} dx^i dx^j]$

  The perturbation Ψ is called the Newtonian potential
- Scalar Field : $\phi = \phi_0(\eta) + \delta\phi(\eta, x^i)$
- Introduce a rescaled field $y(\eta, x^i) = a(\eta)\, \delta\phi(\eta, x^i)$ and its conjugate momentum $\pi(\eta, x^i)$.
- Einstein's Eqs.: $\nabla^2 \Psi - \mu^2 \Psi = s\, \pi$ where $s = 4\pi G \dot{\phi}_0(\eta)$
- Quantize $$\hat{y}(\eta, \vec{x}) = \frac{1}{L^3} \Sigma_{\vec{k}} \left(\hat{a}_k(\eta) e^{i\vec{k}\cdot\vec{x}} + \hat{a}_k^\dagger(\eta) e^{-i\vec{k}\cdot\vec{x}} \right),$$
- Semi-classical version: $(\nabla^2 - \mu^2)\, \Psi = s < | \pi | >$
- The Fourier Decomposition : $\Psi_k = - s < | \pi_k | > / (k^2 + \mu^2)$

The state before & after the Collapse

Before the Collapse $\Psi=0$: $<\hat{y}_k^{R,I}>_0 = 0, \quad <\hat{\pi}_k^{(y)R,I}>_0 = 0,$

Assume that at time η_k^c the mode k collapses according to various schemes:

Scheme 1) The symmetric :

$$<\hat{\pi}_k^{(y)R,I}(\eta_k^c)>_\Theta \;=\; x_{k,2}^{R,I}\sqrt{(\Delta\hat{\pi}_k^{(y)R,I})_0^2} = x_{k,2}^{R,I}|g_k(\eta_k^c)|\sqrt{\hbar L^3/2},$$

$$<\hat{y}_k^{R,I}(\eta_k^c)>_\Theta \;=\; x_{k,1}^{R,I}\sqrt{(\Delta\hat{y}_k^{R,I})_0^2} = x_{k,1}^{R,I}|y_k(\eta_k^c)|\sqrt{\hbar L^3/2},$$

Where the x's are random (around 0 and with spread 1).

- Scheme 2) The Gravity Coupling Preferred

$$< \hat{\pi}_k^{(y)R,I}(\eta_k^c) >_{\Theta} \;=\; x_{k,2}^{R,I}\sqrt{(\Delta\hat{\pi}_k^{(y)R,I})^2_0} = x_{k,2}^{R,I}|g_k(\eta_k^c)|\sqrt{\hbar L^3/2},$$

$$< \hat{y}_k^{R,I}(\eta_k^c) >_{\Theta} = 0,$$

The point is that $< | \pi_k | >$ is the source of geometric fluctuations but $< | y_k | >$ is not.

- Scheme 3) The Wigner Functional Tracker

(Suggestion of J Garriaga, Analysis A. De Unanue)

$$\langle \hat{y}_k^{R,I} \rangle_{\Xi} = x_k^{(R,I)} \Lambda_k \cos\theta\,, \quad \langle \hat{\pi}_k^{R,I} \rangle_{\Xi} = x_k^{(R,I)} \Lambda_k k \sin\theta,$$

Where Λ & θ are determined by the inclination and major semi-axis of the ellipse characterizing the support of the Wigner function corresponding to the inflaton "vacuum" state for the mode.

In all of the cases we end up with a nontrivial expression for $<|\pi_k|>$ after the collapse, and thus for

$$\Psi_k = -s<|\pi_k|>/(k^2+\mu^2)$$

The point is that these can be used to compare with observations. There are, in fact, two pieces of information needed to do that: the collapse scheme (1,2,3 others) and the time of collapse η_k^c for the various modes.

Direct comparison with the data needs to take into account the late time physics inputs such as reheating and plasma acoustic oscillations.

The Observational quantities

- Metric perturbation :"the Newtonian potential " on the LSS is

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

identified with $\frac{\Delta T}{T}(\theta,\varphi)$

  – where U(k) late time physics , F(k) depends on details of the post collapse state .

  – The Quantity of interest $\alpha_{lm} = \int \Psi(\eta_D,\vec{x}_D)Y^*_{lm}d^2\Omega$

is then

$$\alpha_{lm} = s\sqrt{\frac{\hbar}{L^3}}\frac{1}{2a}\sum_{\vec{k}}\frac{U(k)\sqrt{k}}{k^2+\mu^2}\int F(\vec{k})e^{i\vec{k}\cdot\vec{x}}Y_{lm}(\theta,\varphi)d^2\Omega$$

- It is the result of ``a random walk".
- All we can predict is its ``most likely" magnitude: $|\alpha_{lm}|^2_{M.L.}$

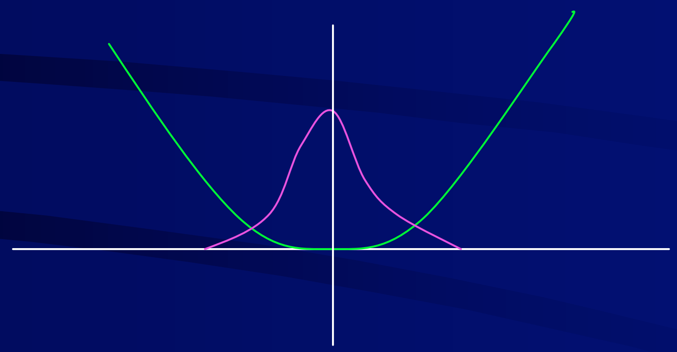
Evaluating this (in the lim L → ∞)

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

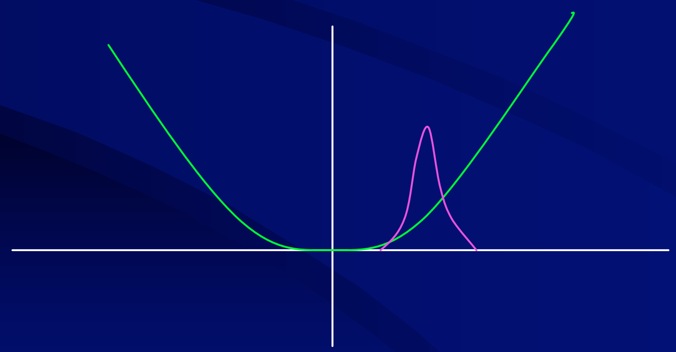
- C(k) contains information about the collapse (through F). The standard result obtains if C was a constant.
- Scheme1 $$C(k) = 1 + (2/z_k^2)\sin(\Delta_k)^2 + (1/z_k)\sin(2\Delta_k)$$
  - With $\Delta_k = k\eta - z_k$ $\quad z_k = \eta_k^c k.$
- We would get agreement with the standard form if, Δ=0 ó $z_k = \eta_k^c k.$ independent of k, (or very small corrections).
- (Ignoring U(k)), the result is independent of R_D (scale invariant) iff C(k) is independent of k , (and μ= 0 "slow roll").

Source of the Oscillations in C

- Harmonic oscillator in ground state



- After Collapse:



- By Ehrenfest Theorem it will, then, oscillate in time.

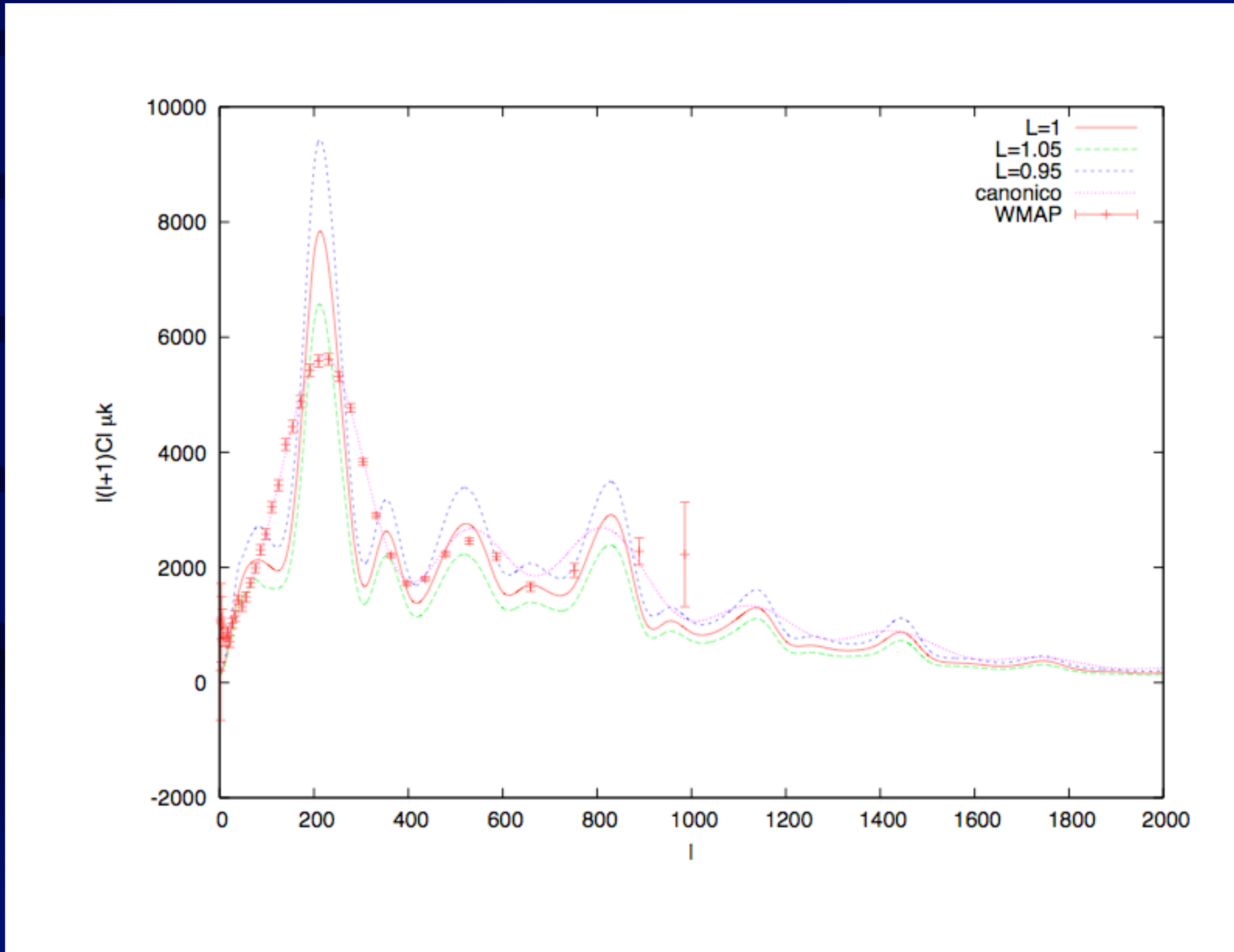
- The nontrivial form of C(k) could, in principle, and depending on the collapse parameters, lead observational effects whose absence could be used to bound them.

If we take scheme 1 with

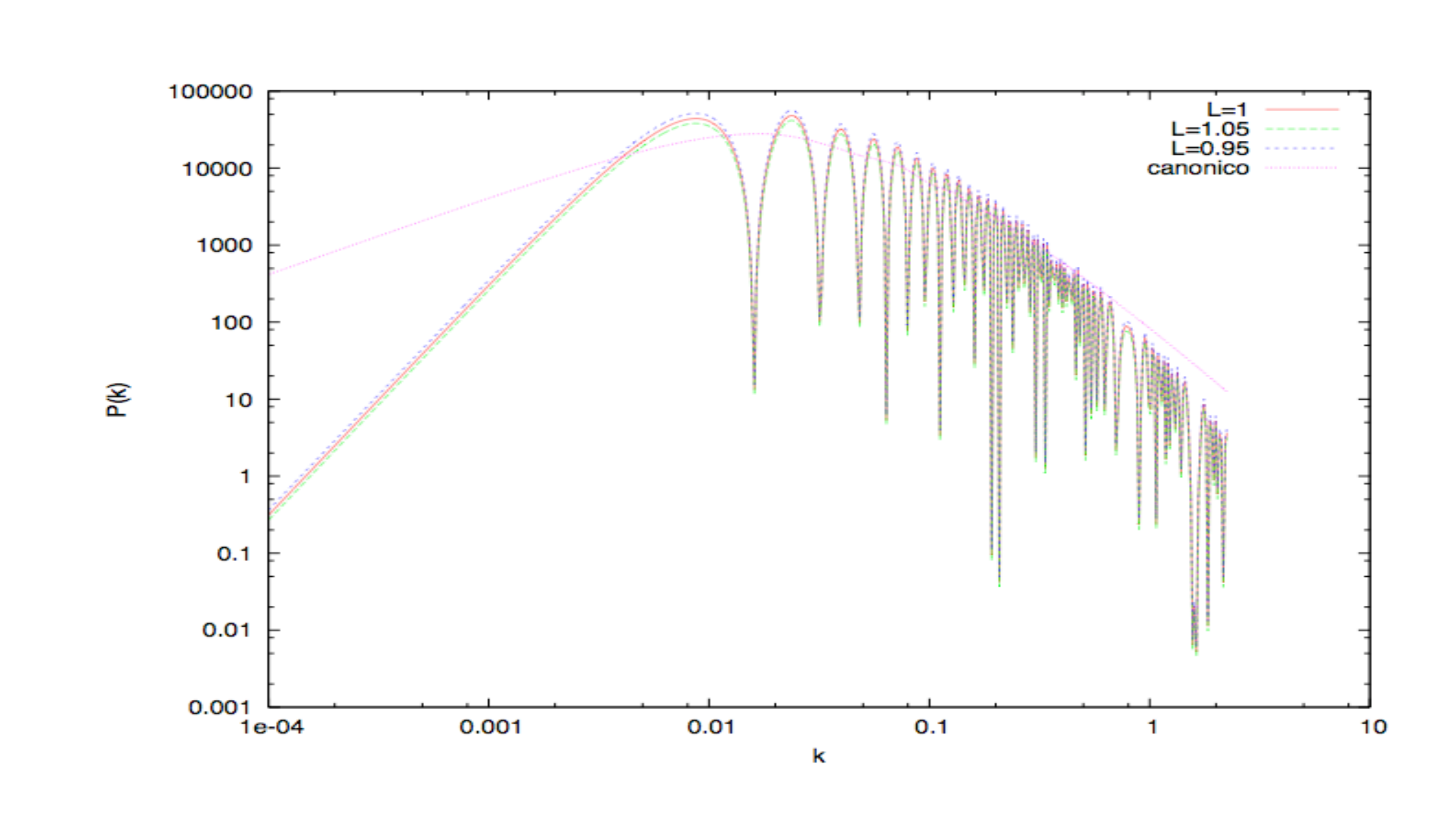
$\eta_k{}^c$ = cte

the CMB spectrum would Look like:

Preliminary results but indicate that the parameters used for these simulations can be ruled out (S. Landau & C. Scoccola)



- One can also look at the effects of the nontrivial form of C(k) on the large scale structure. The mater distribution spectrum would be:



- Again very preliminary (S. Landau & C. Scoccola)

- Scheme 2 gives

$$C'(k) = [1 + \sin^2(\Delta_k)(1 - (1/z_k^2)) - (1/z_k)\sin(2\Delta_k)]$$

- Scheme 3 gives

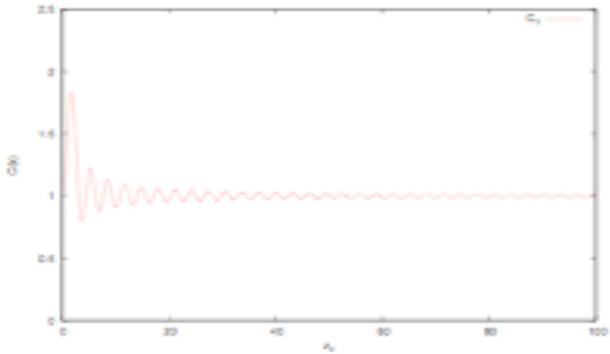
$$C_{wigner}(k) = \langle F(\vec{k})\overline{F}(\vec{k})\rangle = \frac{2z_k^2}{\sqrt{1+10z_k^2+9z_k^4}} \times \frac{1}{1+5z_k^2-\sqrt{1+10z_k^2+9z_k^4}} \left\{ \left[\sqrt{1+10z_k^2+9z_k^4} - 1 + 3z_k^2\right]\left(\cos\Delta_k - \frac{\sin\Delta_k}{z_k}\right)^2 + \sin^2\Delta_k\left[\sqrt{1+10z_k^2+9z_k^4} - 3z_k^2 - 7\right] + 8z_k\cos\Delta_k\sin\Delta_k \right\},$$

The C (z)´s are all different.

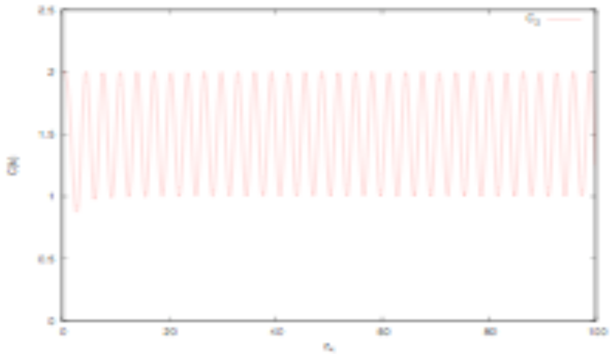
(A. de Unanue)

Recall one still needs to specify

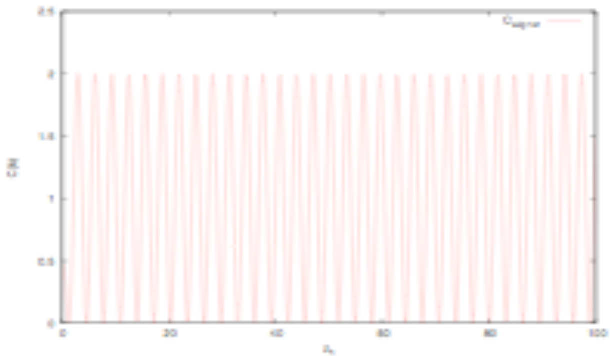
Z=Z(k)



(a) C_1, the two field variables $\langle\hat{y}_k\rangle$ and $\langle\hat{\pi}_k\rangle$, collapses to a random value of the dispersion of the vaccum state independently



(b) C_2, this scheme is proposed taking in account the fact that only $\langle\hat{\pi}_k\rangle$ appears in the EFE at first order.

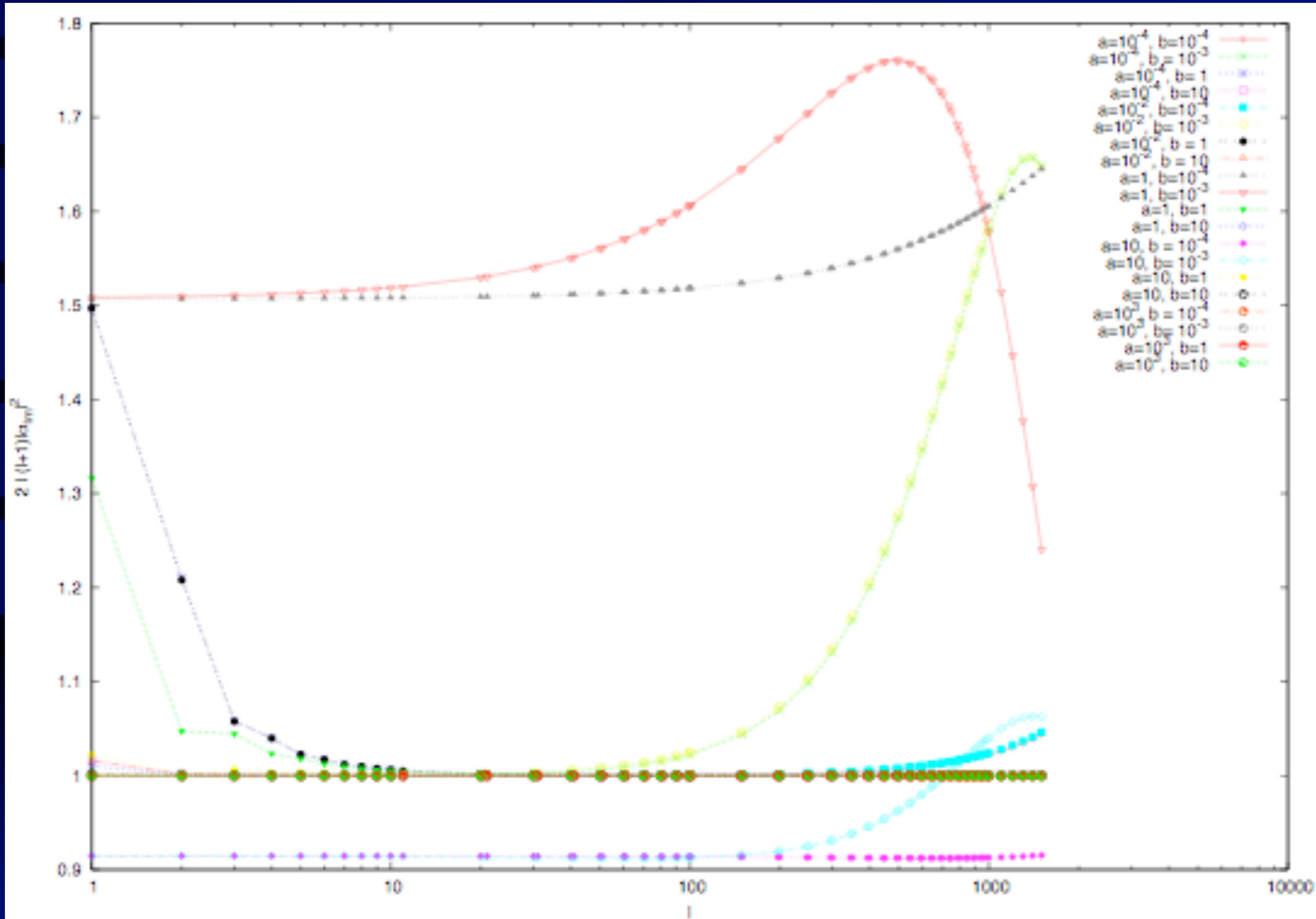


(c) C_{wigner}, this scheme proposes a kind of correlation between the post-collapse values taking the Wigner functional of the vaccum state as an indicator of this correlation.

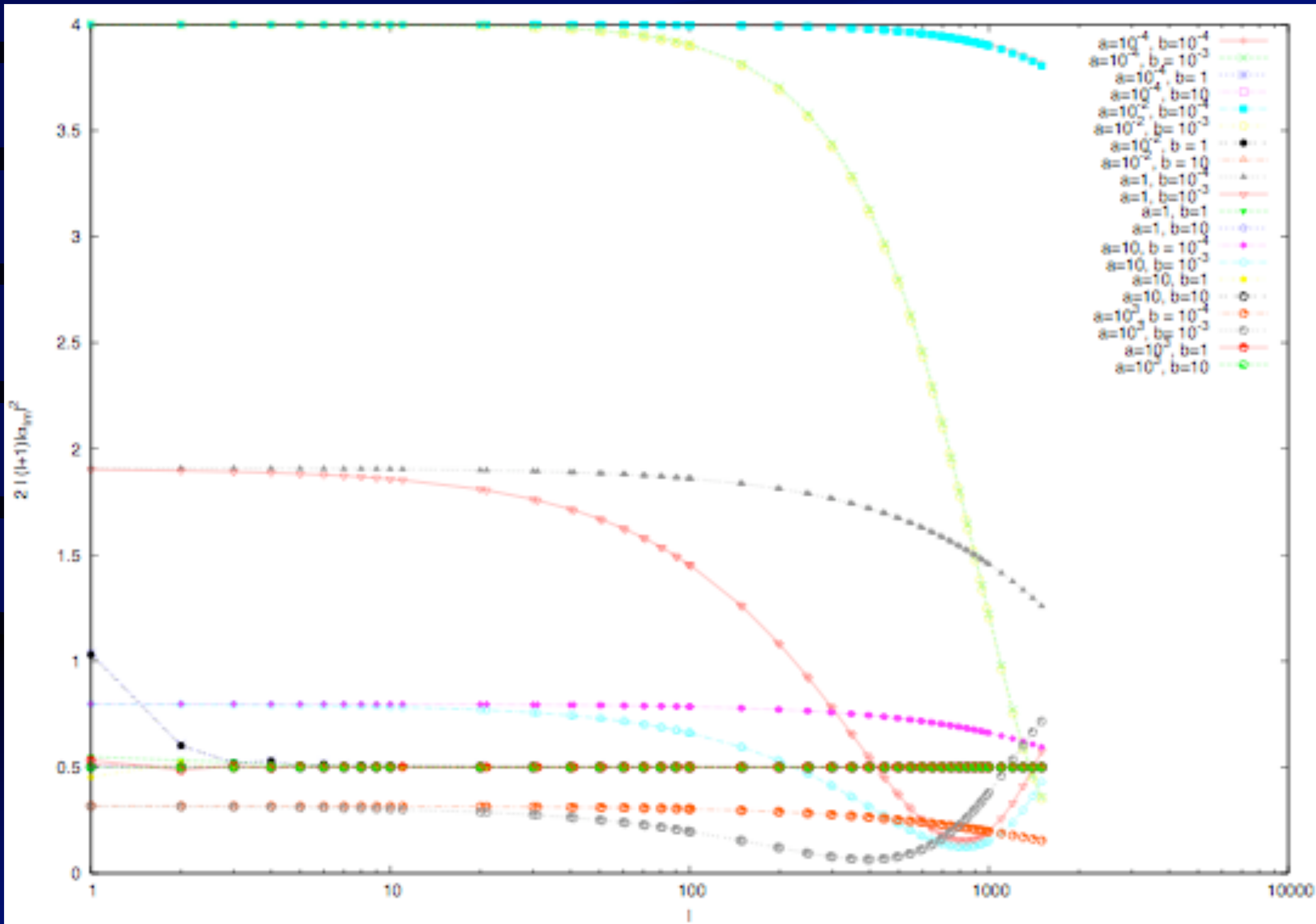
Some early steps into the phenomenological analysis

- We want to compare the different collapse schemes, various possibilities for the collapse time and, eventually, other parameters.
- We know that if $\eta^c_k \approx A/k$ we recover the standard form of the spectrum, we will assume that $\eta^c_k \approx A/k + B$ and try to obtain bounds on A & B.

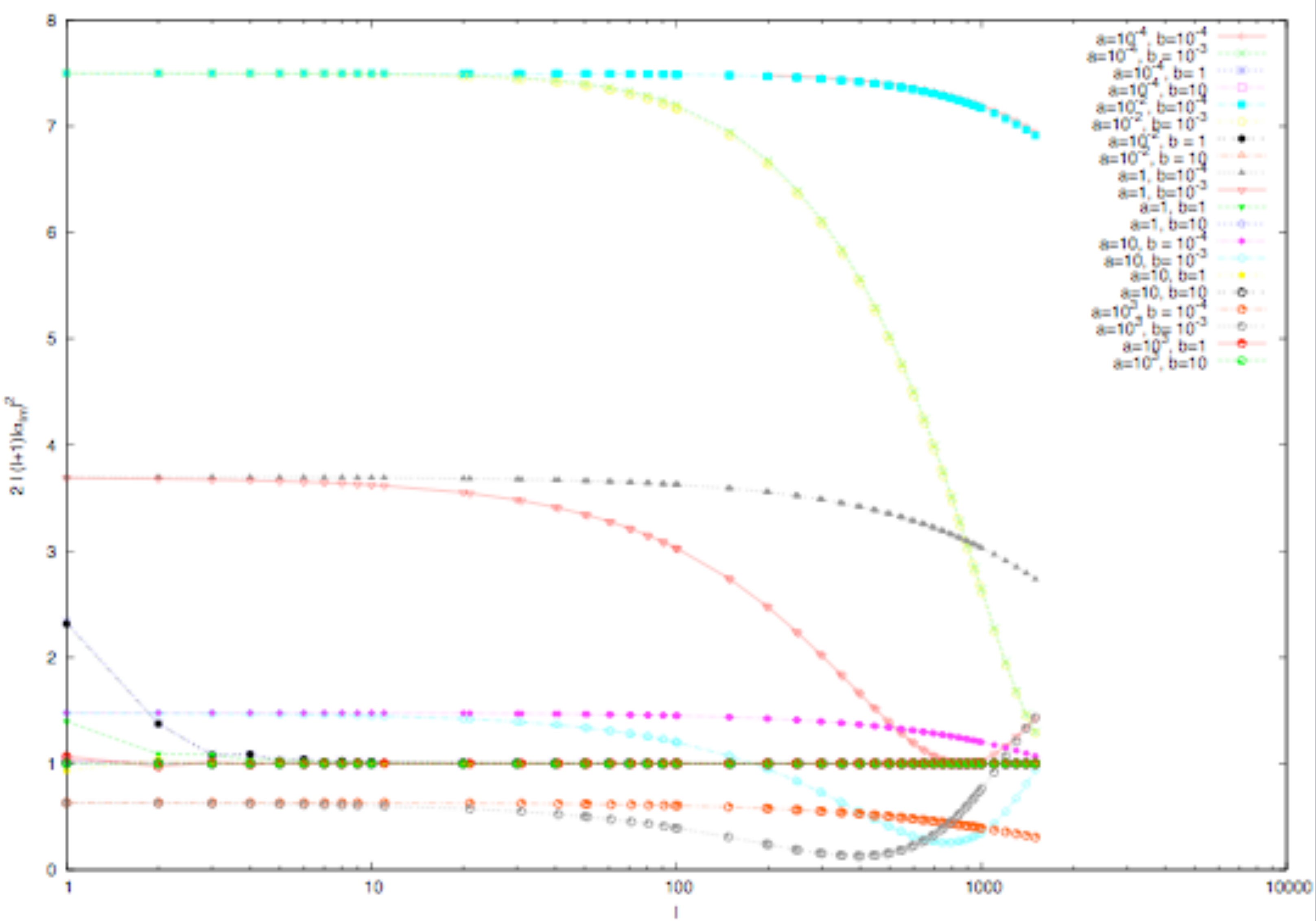
Scheme 1 (A. de Unanue)



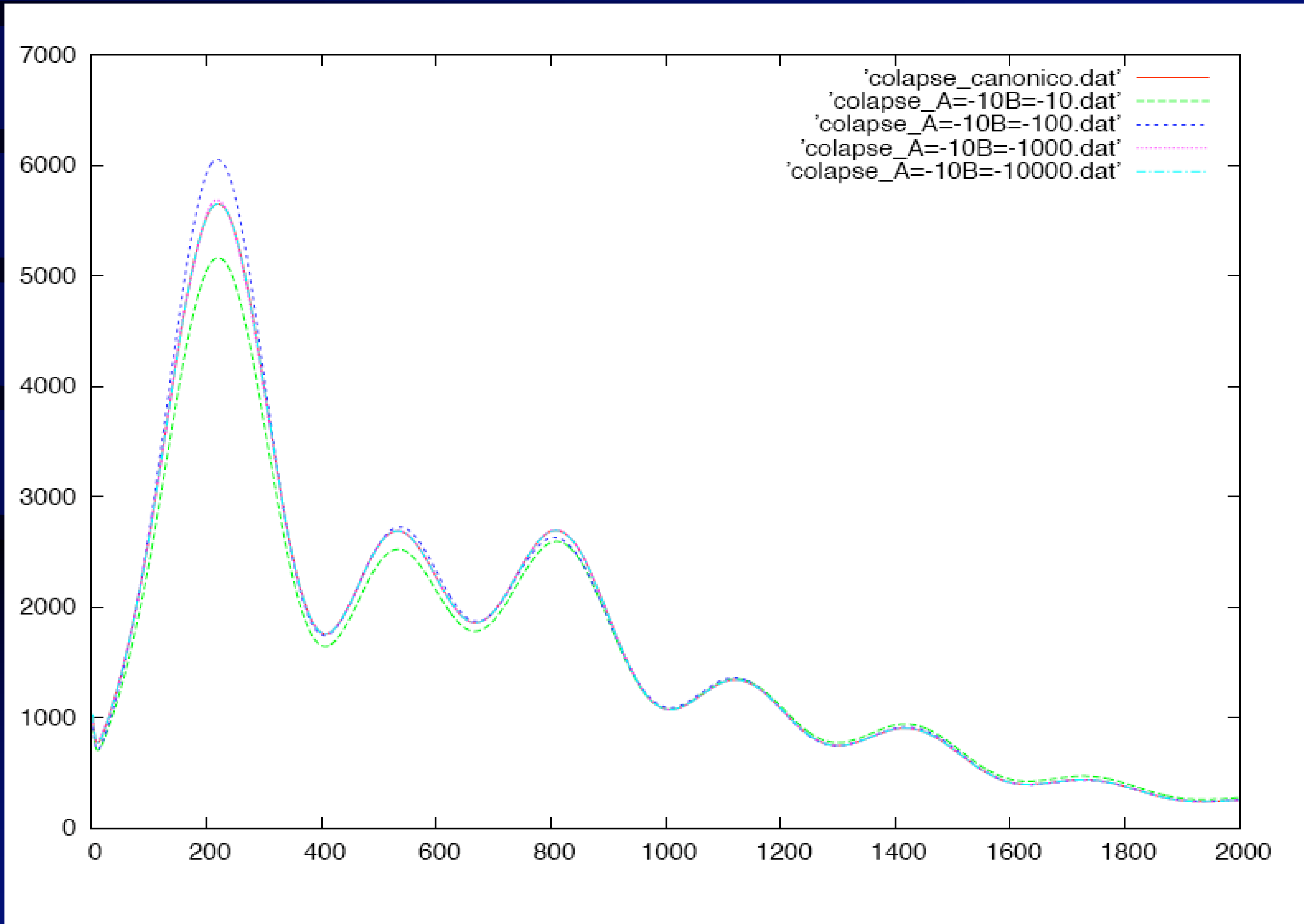
Scheme 2 (A. de Unanue)



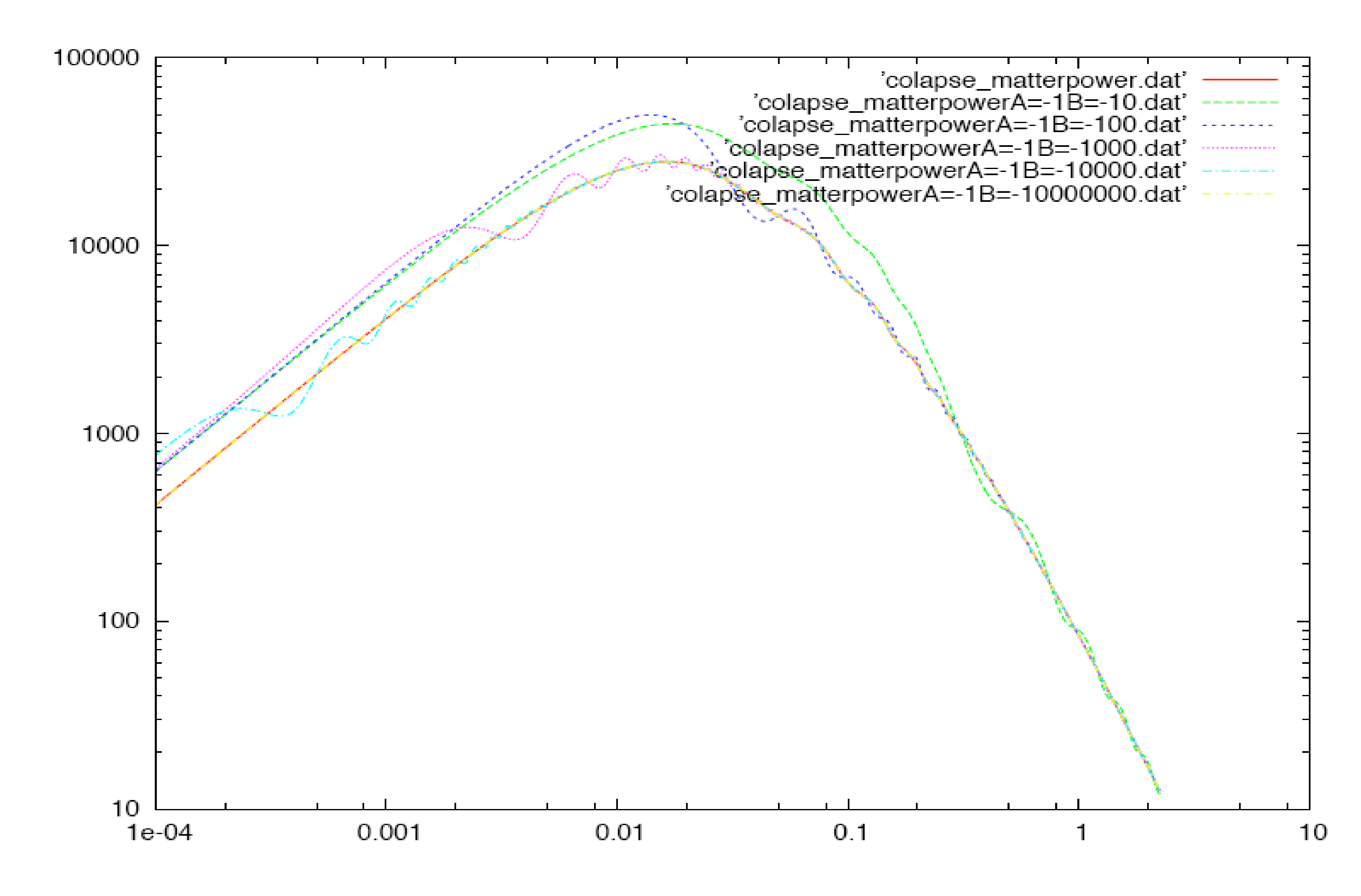
Scheme 3 (A.de Unanue)



They can be compared directly with actual data.
(Scheme 1, S. Landau & C. Sccocola preelimnary)



Also the large scale matter power spectrum
(Scheme 1, S. Landau & C. Sccocola preelimnary)



A Penrose Inspired Model (H Shalmann & A Perez) :

Collapse occurs when the energy of gravitational interaction among alternatives reaches M_{PLANCK}.

A Penrose Inspired Model (H Shalmann & A Perez) : Collapse occurs when the energy of gravitational interaction among alternatives reaches M_{PLANCK}.

$$E_I(\eta) = \int \Psi^{(1)}(x,\eta)\rho^{(2)}(x,\eta)dV$$

Naive generalization

- For individual modes $E_I(k,\eta) = (\pi hG / 9H_I^2)(a/k)(V')^2$

A Penrose Inspired Model (H Shalmann & A Perez) : Collapse occurs when the energy of gravitational interaction among alternatives reaches M_{PLANCK}.

-
- $$E_I(\eta) = \int \Psi^{(1)}(x,\eta)\rho^{(2)}(x,\eta)dV$$ Naive generalization

- For individual modes $E_I(k,\eta) = (\pi hG / 9H_I^2)(a/k)(V')^2$
- Then $\eta_k^c = Z/k$ with $Z = (\pi / 9 M_P^3 H_I^3)(hV')^2$ indep of k

AMAZING!

The collapse for the physically relevant modes occurs about 80 e-folds before the end of inflation (for standard V parameters).

In fact, the relation between the scale factor at the time of Horizon exit, of a mode to its size at the time of collapse is a constant

$$a_k^c / a_k^H = (16/\varepsilon)\,(6\pi^3)^{(1/2)}(V\,h^3/M_P^4)^{(-1/2)}$$

In general, a large number, so in this scheme collapse occurs long after horizon exit of the mode.

Conclusions

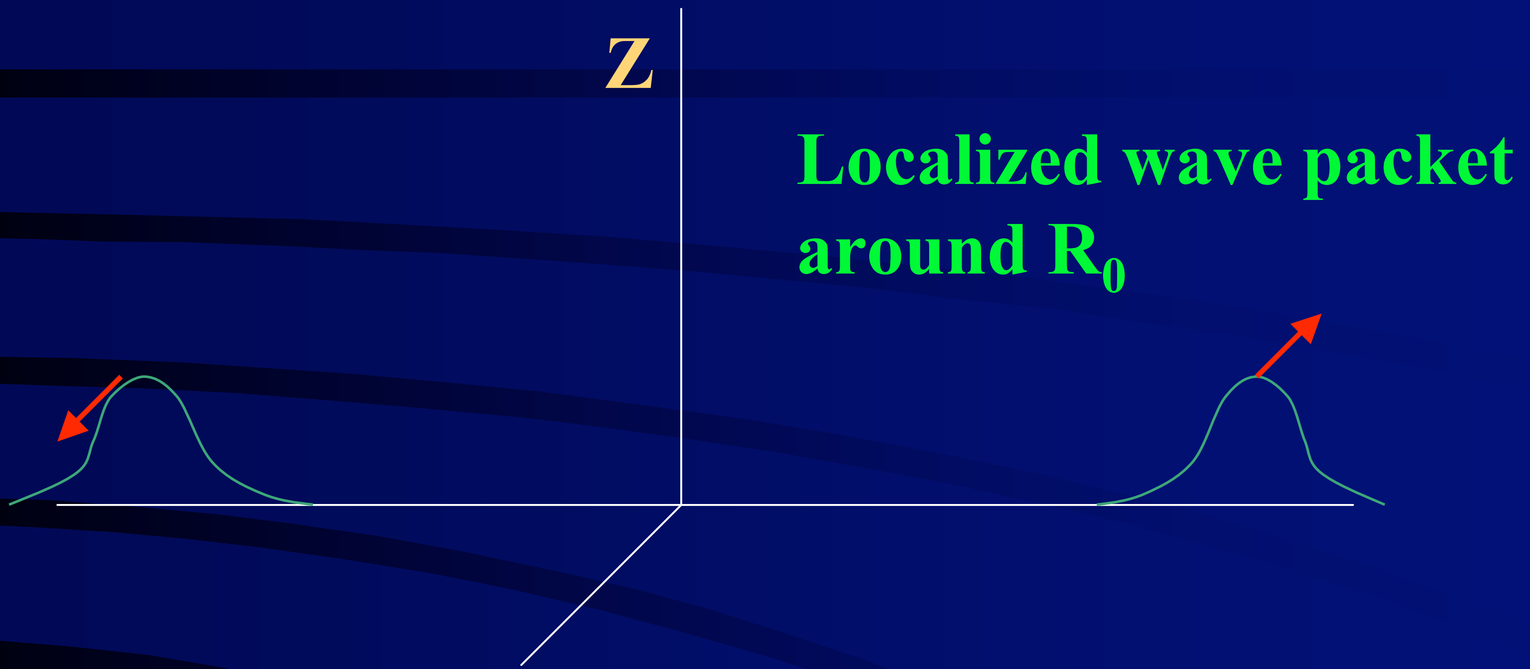
- Something (related to QM) is missing in our understanding of the origin of cosmic structure, & something like a self induced collapse is required to take us from a H&I state to another one lacking such symmetry.
- The Present Proposal has the required features.
- It also leads to phenomenological predictions.
- It offers a path to alleviate the need of fine tuning.
- In this scheme there would not be Tensor Modes (GW) contributions to the CMB anisotropies (except secondary ones)!
- NEW PHYSICS seems to be there, just waiting to be explored!

End

Some tools for dealing with common questions

Example

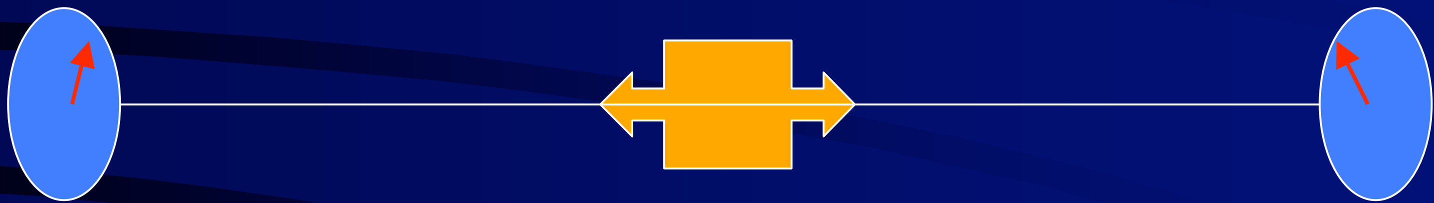
State symmetric under rotations by π around Z



Now consider taking the trace over the spin DOF.
The resulting density matrix is diagonal.
Is the situation classical? Is the state still invariant?
Can a mathematical manipulation with no physical process counterpart ever change the state of the system?

Does focusing on quantum correlations resolves the problem ?

- Some people argue that failure to consider the fact that one is studying the two point correlation function is what lies behind the "confusion".
- Consider an EPR experiment with 1/2 spin particles:



- Let $\vec{N}_1 . \vec{S}_1$ & $\vec{N}_2 . \vec{S}_2$ be the two observables.

If the initial state has $J=0$, the correlation in these observables is $\text{Cos}\,\theta = N_1 . N_2$, but the state remains invariant under rotations, until a measurement!