Title: The quantum origin of the cosmological structure: an arena for quantum gravity phenomenology

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Abstract: I will review the shortcomings of the standard account of the origin of anisotropies and in-homogeneities in inflationary cosmology. I will argue that something beyond the established paradigm of physics in needed for a satisfactory explanation of the process by which the seeds of structure emerge from the inflaton vacuum and will consider the application of a generalization of the ideas of R Penrose about a quantum gravity induced dynamical collapse of the quantum mechanical state of a system as a promising avenue to address the issue. I will show i) that the proposal offers paths to test the viability of rather specific ideas about the mechanism of collapse, ii) that generically it can led to some precise features in the primordial spectrum of density fluctuations, which can in turn be looked for, in the observational data, and used to set bounds on certain aspects the quantum gravity phenomenology, and iii) that it leads to other rather robust predictions that can be confronted with experiments.

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

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

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PLAN

1) THE SHRTVOMINGS OF THE STANDARD LORE NOT SATISFYING ? .

2)THE EXTRA ELEMENT (TIED TO QG?)

3)TESTS AND PREDICTIONS

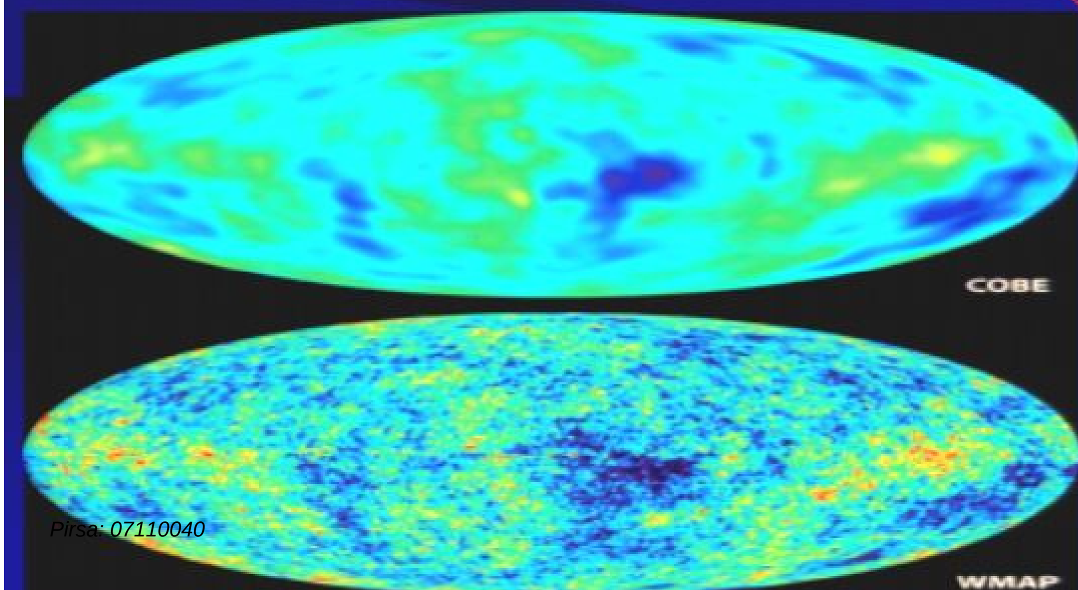
The last decade is considered as a big success, for inflationary cosmology.

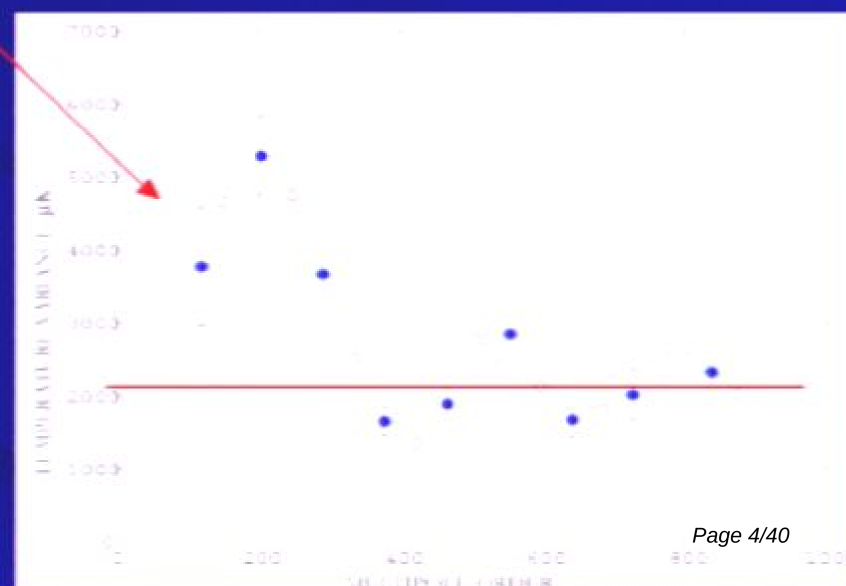
The Universe seems to be spatially flat (i.e. $\Omega \approx 1$)

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 issues

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)

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

The choice of basis problem

Diagonalization disappears upon change of basis!

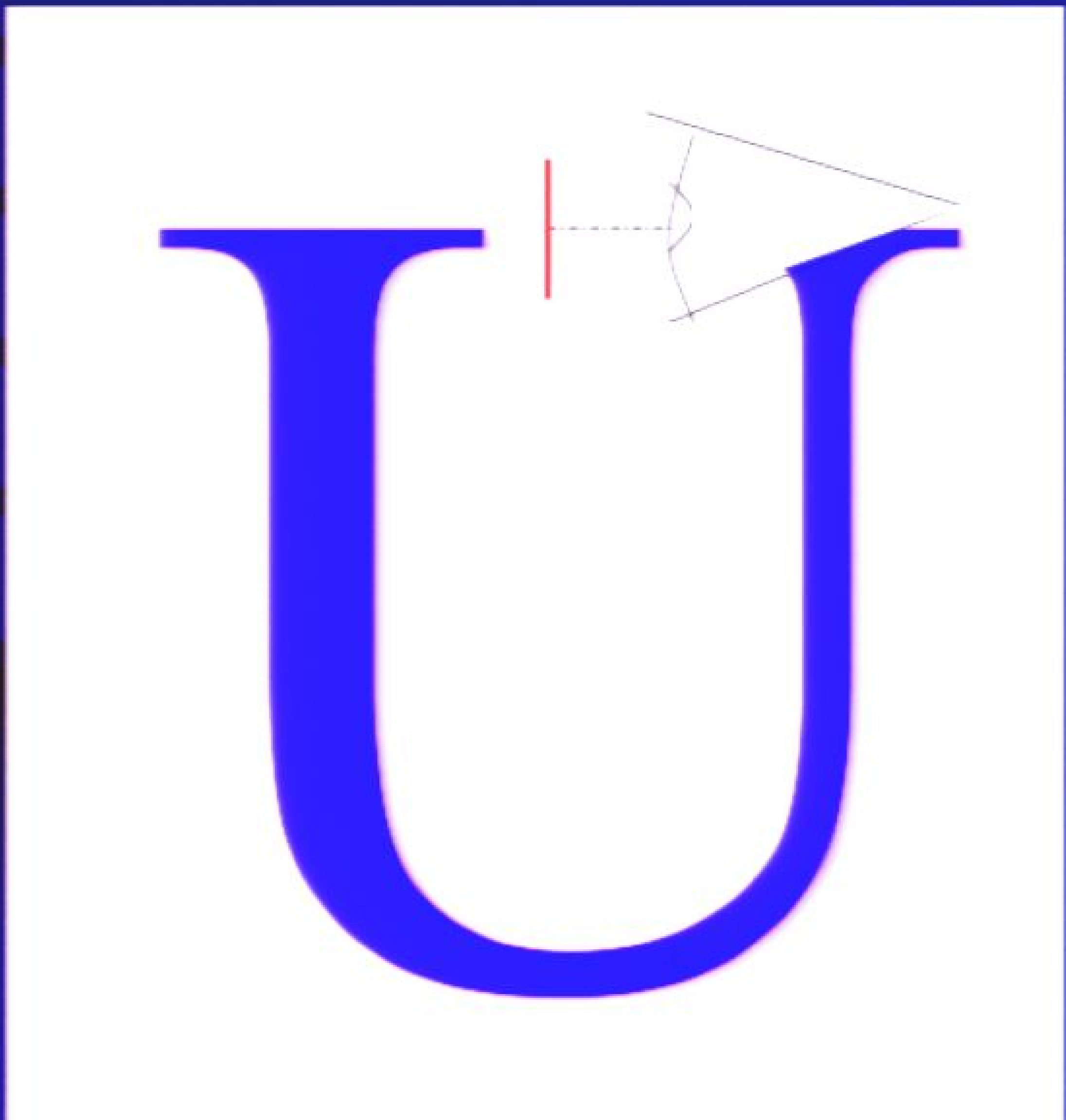
A: The Environment- System Interaction selects the basis

n our case what can play the role of the environment?

nflation has removed all matter (all fields are in the acuum) and all local features! (That is what I. Does!!).

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

The Impaired self observing Universe



Modification of picture by W. Zurek

Even if we overcome or accept this… Decoherence faces :

The problem of definite outcomes

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

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]

"The problem is that decoherence does not tell us why any particular outcome, and not one of the other possibilities, actually occurred", J Polkinghorne

"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!!

In the Cosmological Setting

- We seek a historical (time development) description of comic evolution that follows the laws of physics.
- Such description should explain how did WE arise (primordial density fluctuations, galaxies, stars, planets, living organisms, etc).
- 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).

You might instead be asked to accept:

- 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.

- That "it does not matter when the Universe stopped being H&I", without being able to even address the issues (when? , why?, due to what..?).

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

Desiderata: A scheme that

- Permits, in principle, the assignment of a Quantum State to the system, at ``every time".
- Views QM as a theory about the description of the system, and not just, of our knowledge about it.
- Allows consideration of issues such as "When did the lack of H&I at such and such scale originate?"
- Take the view that the marriage of GR and QM might involve changes in both! (R. Penrose).

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

- The marriage of Quantum Mechanics with Gravity requires changes in both. 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 is treated very differently than 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 :

$$|0\rangle \rightarrow |\Theta\rangle$$

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: $(\nabla^2 - \mu^2)\Psi = s < | \pi | >$ **Recall ***
- The Fourier Decomposition : $\Psi_k = -s < | \pi_k | > / (k^2 + \mu^2)$

The state before & after the Collapse

Before the Collapse Ψ=0:

$$< \hat{y}_k^{R,I} >_0 = 0, \qquad < \hat{\pi}_k^{(y)R,I} >_0 = 0.$$

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

Scheme 1) The symmetric :

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

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

Relatively sharp values *

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

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Scheme 2) The Gravity Coupling Preferred

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

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

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 accoustic 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 $L \to \infty$)

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

- C(k) contains information about the collapse (through F)

- Scheme1

$$C(k) = 1 + (2/z_k^2)\sin(\Delta_k)^2 + (1/z_k)\sin(2\Delta_k)$$

  - With $\Delta_k = k\eta - z_k$ $\quad z_k = \eta_k^c k.$

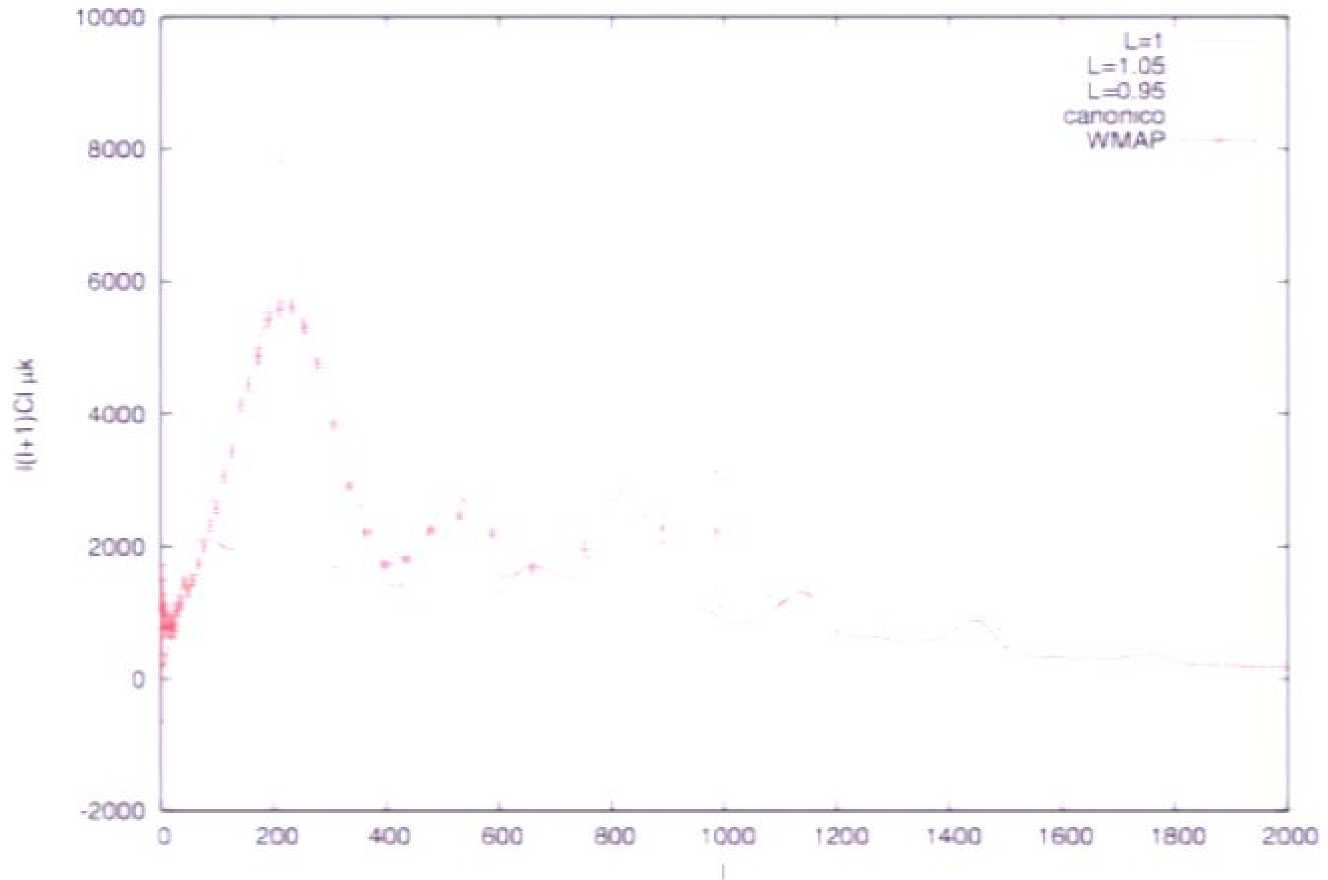
- We would get agreement with the standard form if, Δ=0 ó $z_k = \eta_k^c k.$ independent of k, (or very small corrections).

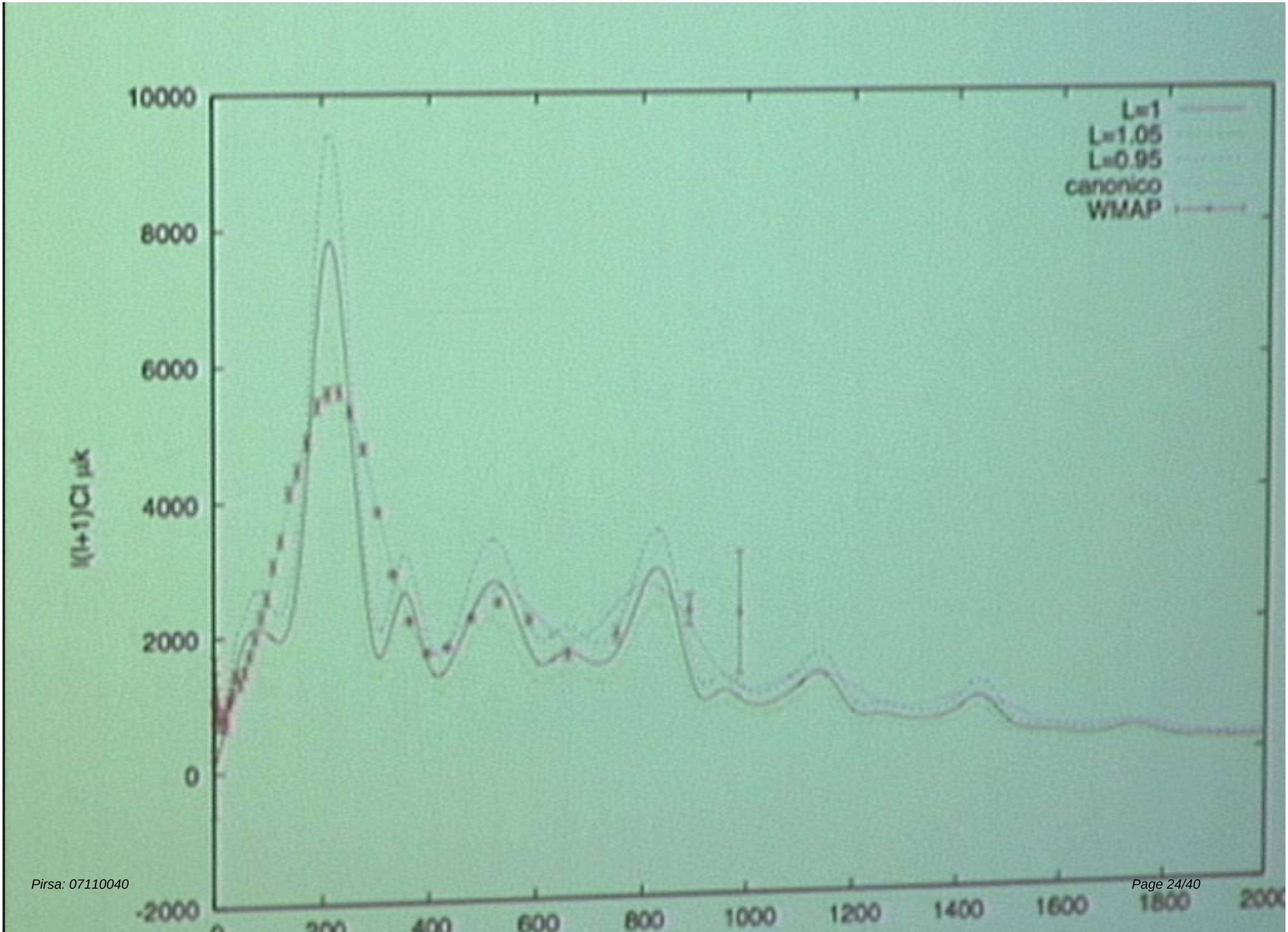
- (Ignoring U(k)), the result is independent of R_D (scale invariant) iff C(k) is independent of k , (and μ= 0 "slow roll").

- 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.

The CMB spectrum could Look

These are very preliminary but indicate that the parameters used for these simulations can be ruled out (S. Landau & C. Scoccola)





L=1
L=1.05
L=0.95
canonico
WMAP
l(l+1)Cl μK
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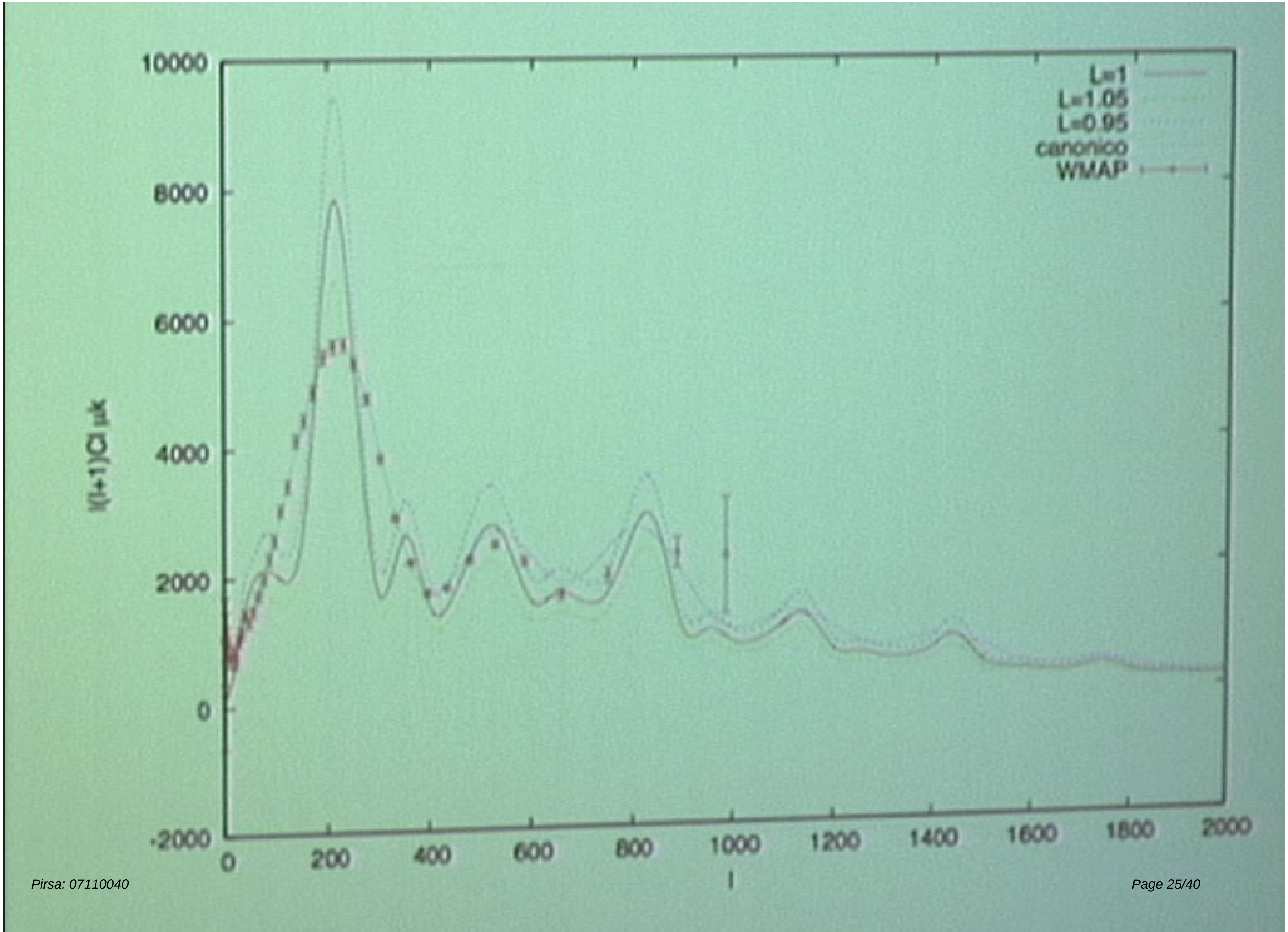

L=1
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10000
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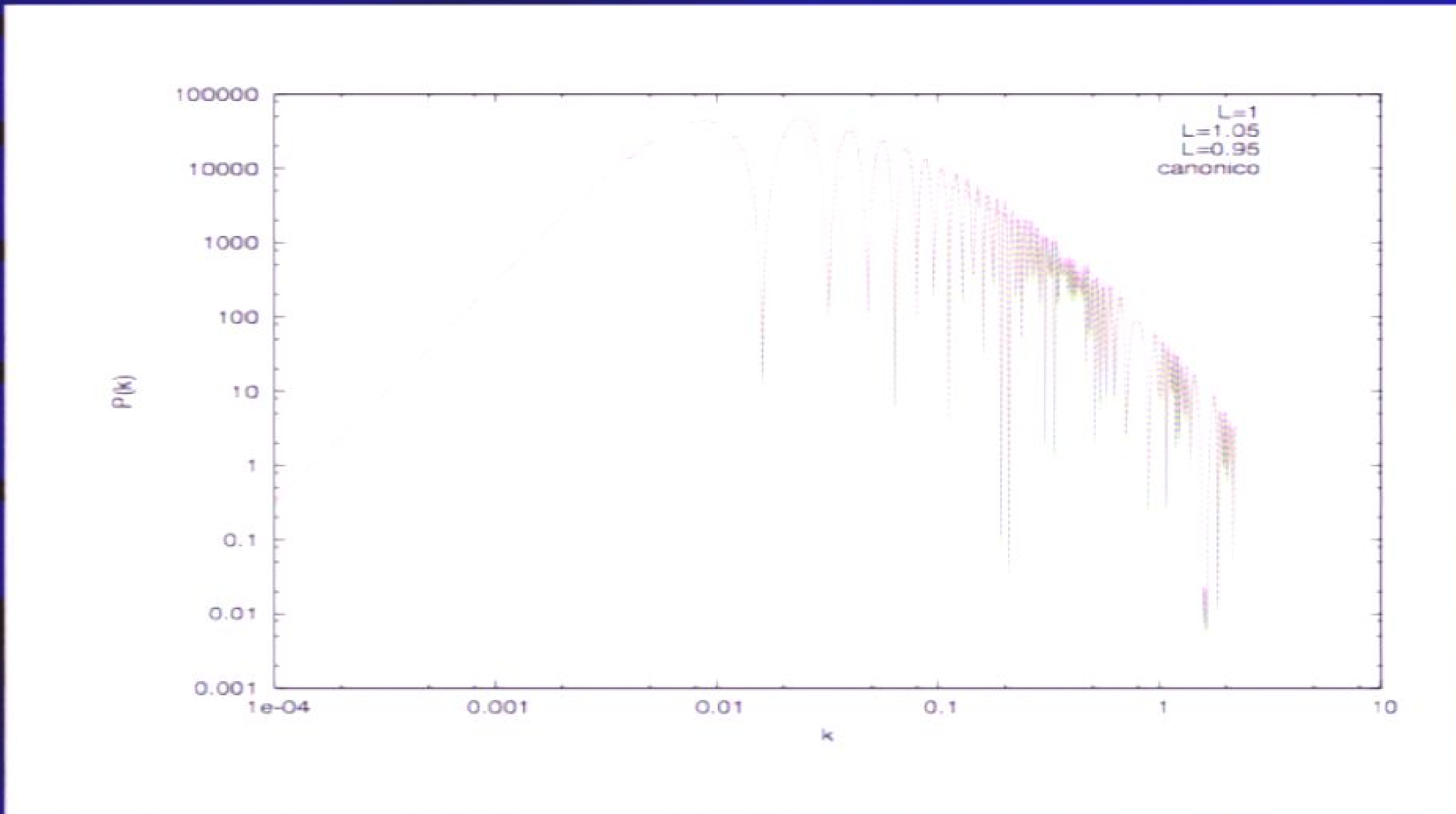
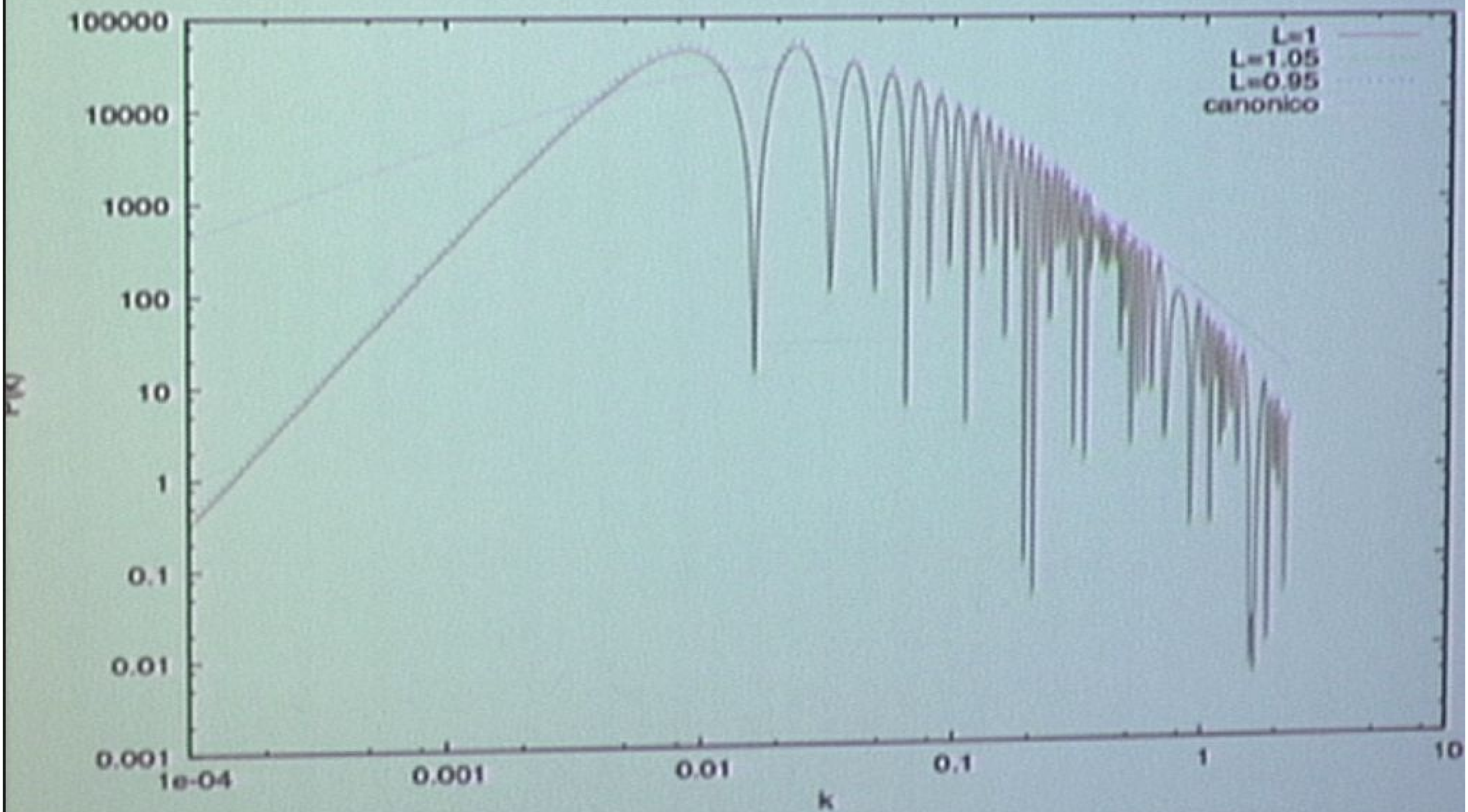
- One can also look at the effects of the nontrivial form of C(k) on the large scale structure:



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



gain 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

$$C_{wigner}(k) = \langle F(\vec{k})\overline{F}(\vec{k})\rangle = \frac{2z_k^2}{\sqrt{1-10z_k^2+9z_k^4}} \times$$

$$\frac{1}{1-5z_k^2-\sqrt{1-10z_k^2+9z_k^4}}$$

$$\left\{ \left[\sqrt{1-10z_k^2+9z_k^4} - 1 - 3z_k^2\right]\left(\cos\Delta_k - \frac{\sin\Delta_k}{z_k}\right)^2 + \right.$$

$$\left. \sin^2\Delta_k\left[\sqrt{1-10z_k^2+9z_k^4} - 3z_k^2 - 7\right] - 8z_k\cos\Delta_k\sin\Delta_k \right\}.$$

The C´s are all different.

(a) C[illegible]: the two field variables [illegible] and [illegible], collapses to a random value of the dispersion of the vacuum state independently.

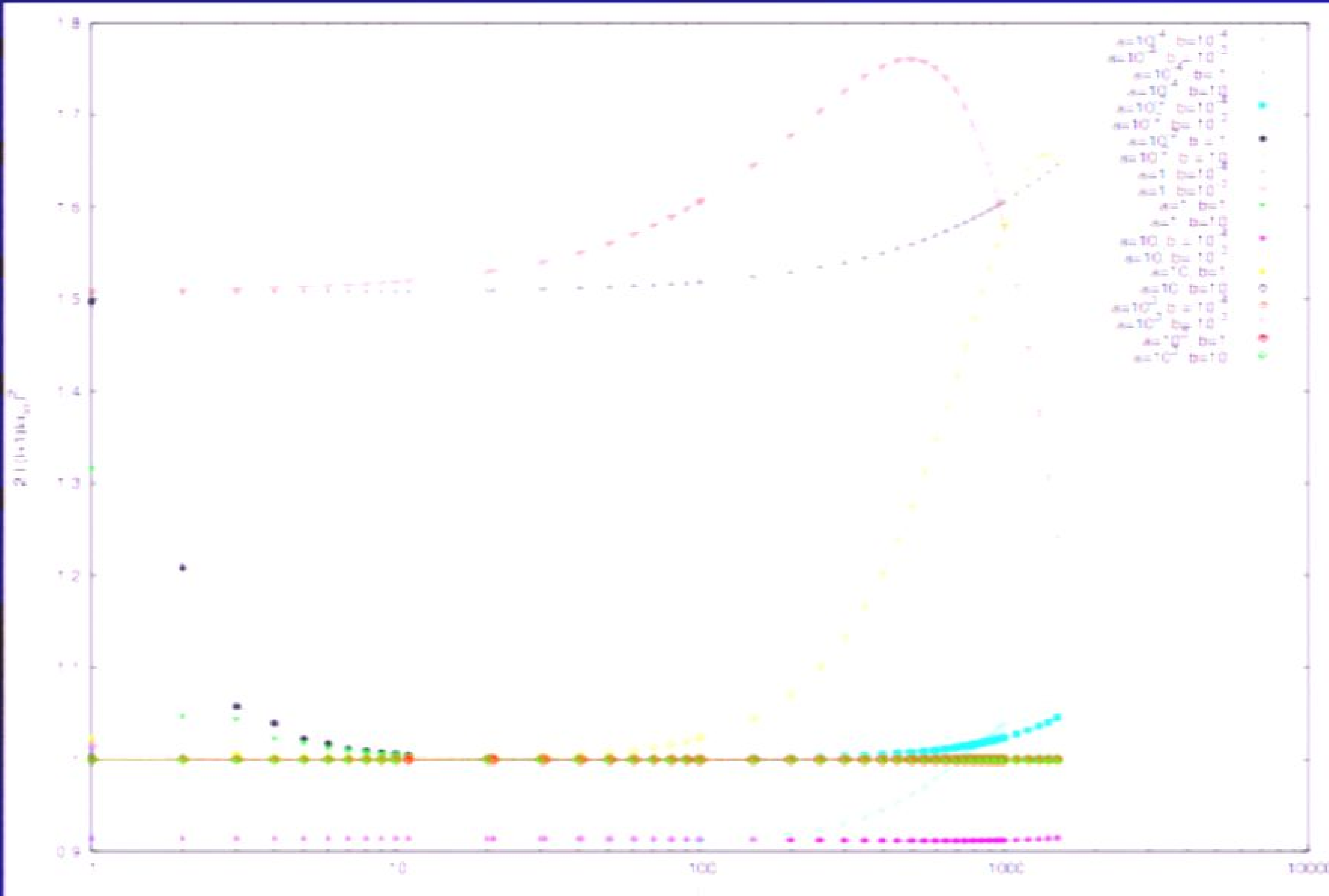
(b) C[illegible]: this scheme is proposed taking in account the fact that only [illegible] appears in the EFE at first order.

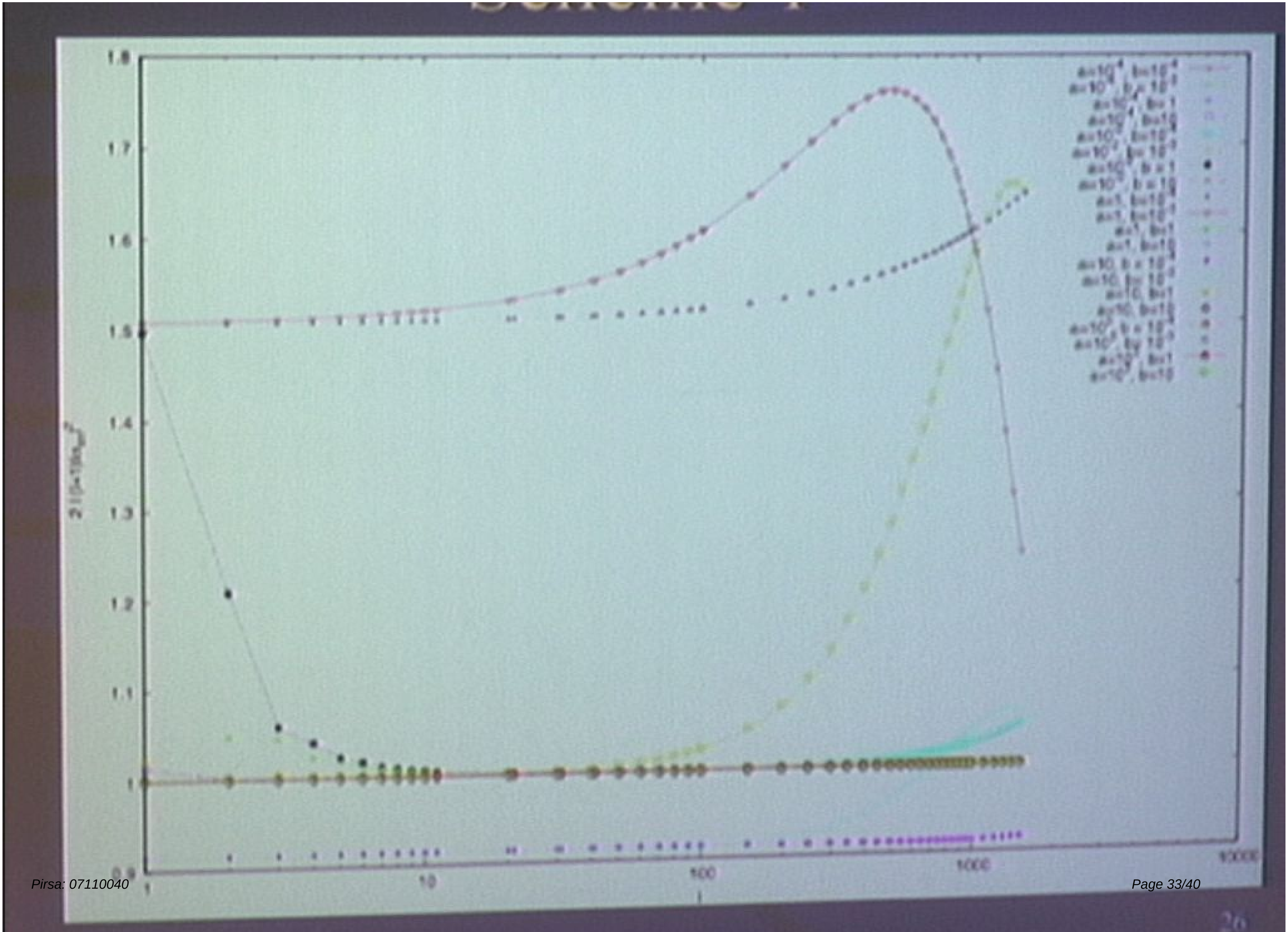
(c) C[illegible]: this scheme proposes a kind of correlation between the post-collapse values taking the Wigner functional of the vacuum state as an indicator of this correlation.

Some early steps into the phenomenological analysis

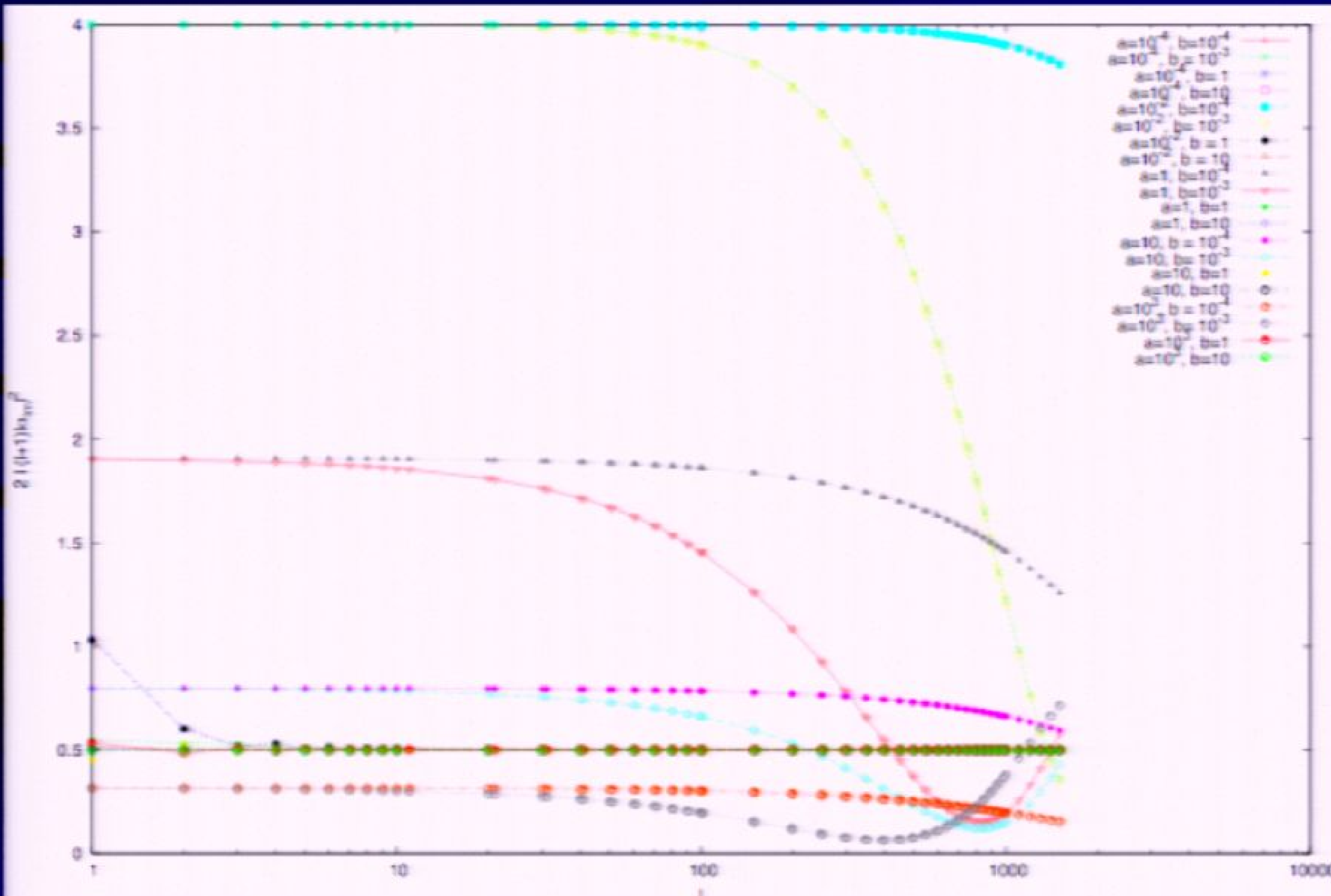
- We want to compare the different collapse schemes, various possibilities for the collapse time and, eventually, other parameters.
- We know that if $\eta^c_k \approx A/k$ we recover the standard form of the spectrum, we will assume that $\eta^c_k \approx A/k + B$ and try to obtain bounds on A & B.

Scheme 1





Scheme 2



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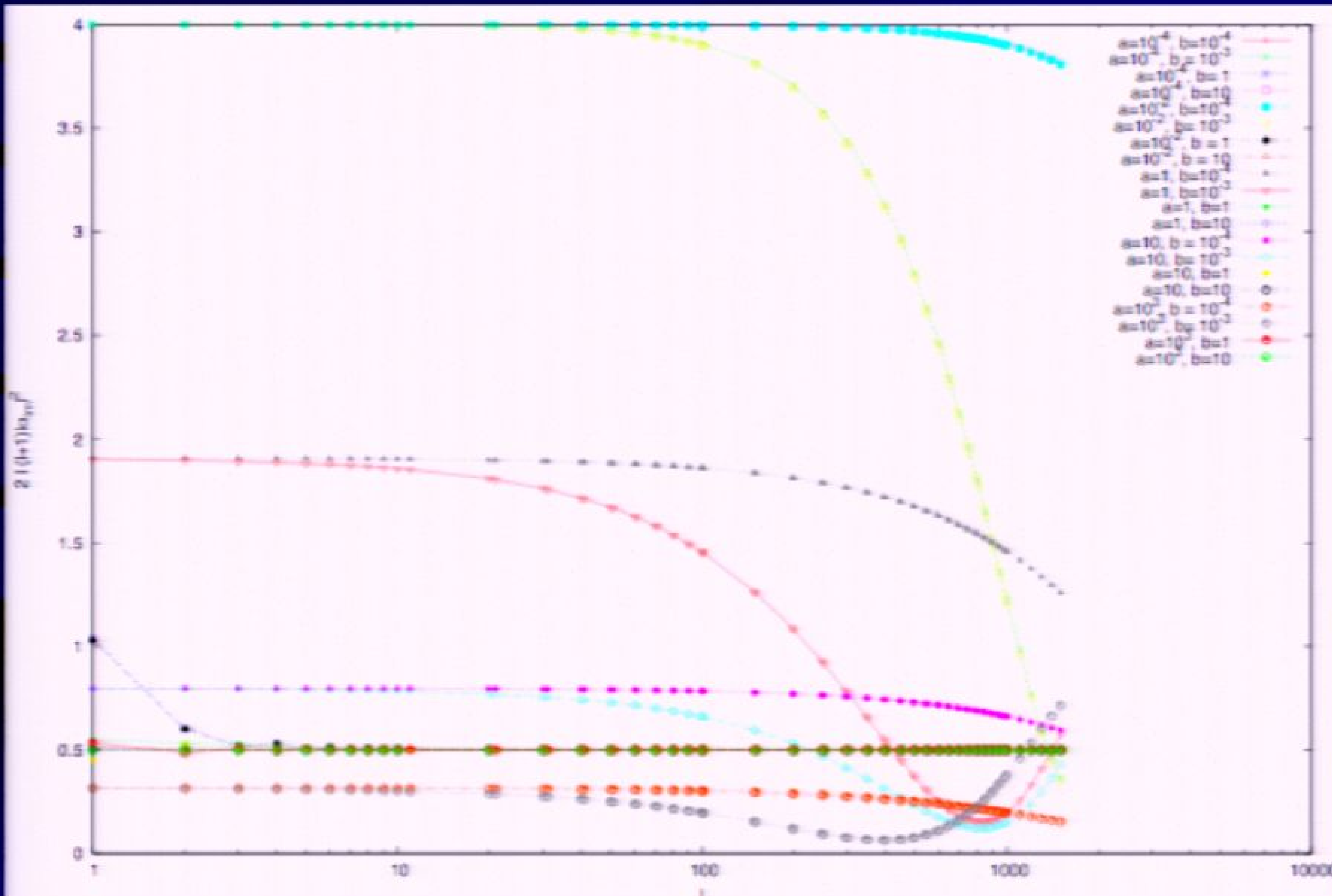
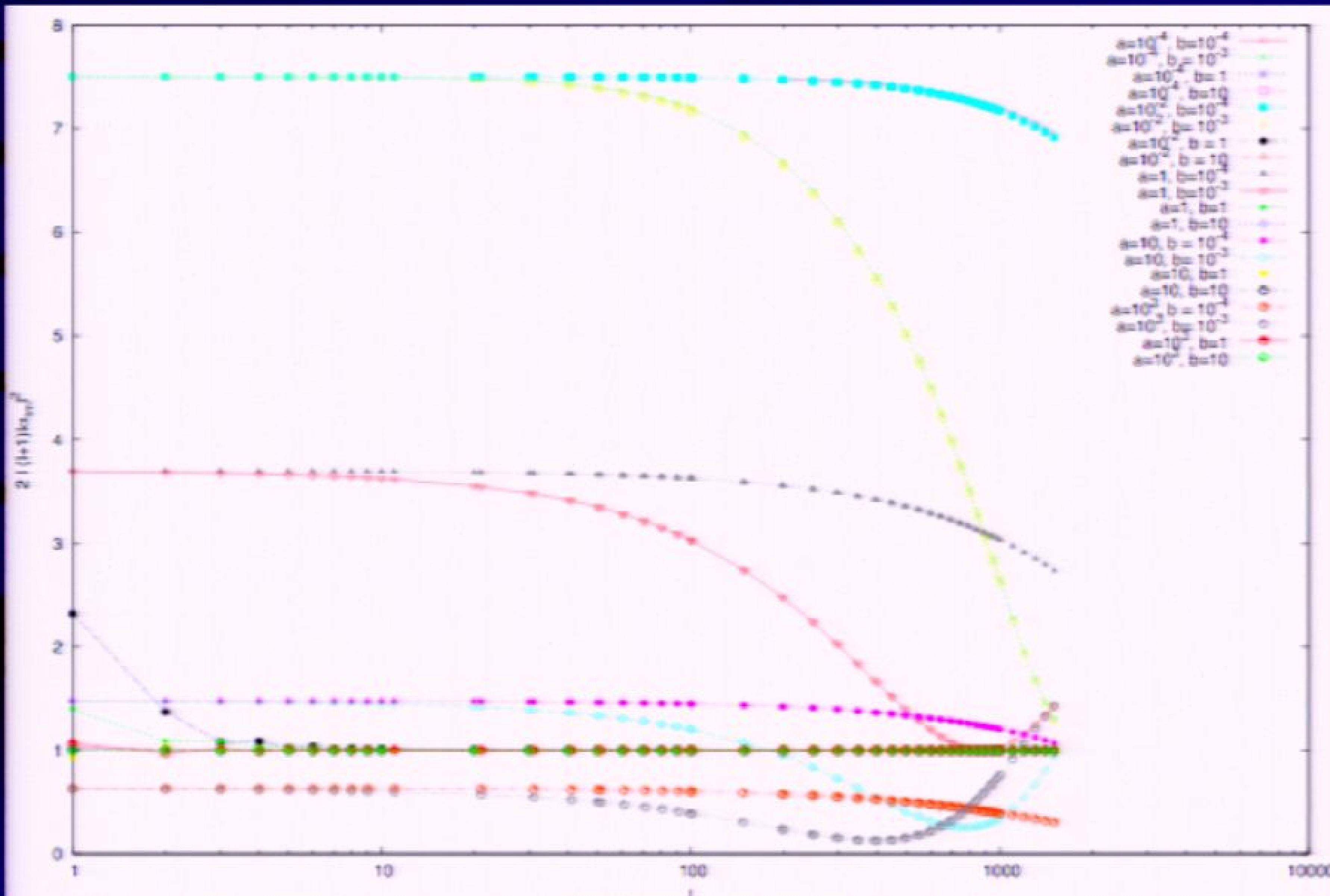


Scheme 3



A Penrose Inspired Model : 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 η_k^c =Z/k with $Z = (\pi / 9 M_P^3 H_I^3)(hV')^2$ indep of k

AMAZING!

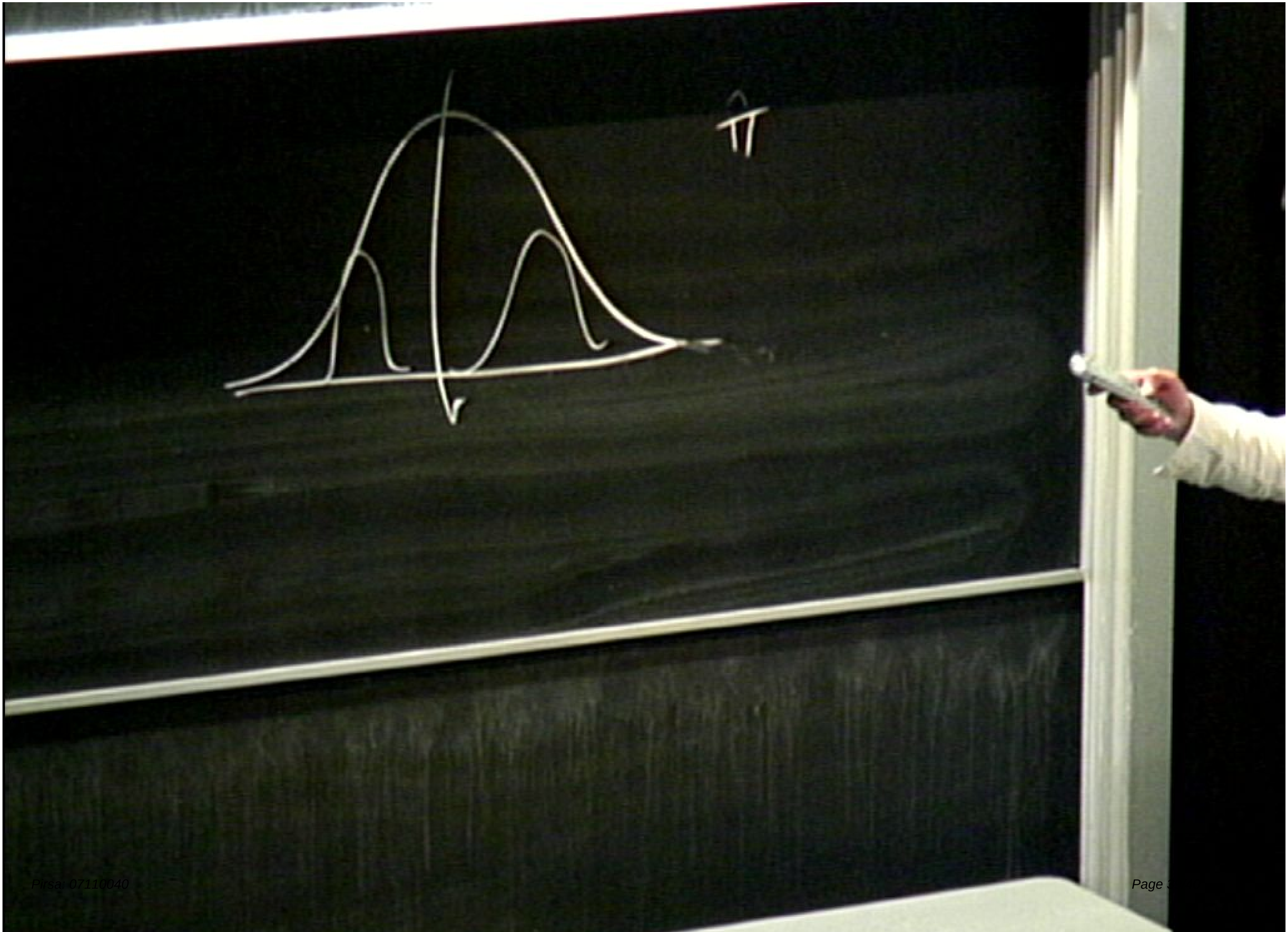
The collapse for the physically relevant modes occurs about 80 e-folds before the end of inflation (for standard V parameters).

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.

[redacted]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