Title: Inflation with a Cutoff: Proposals and Problems

Date: Nov 05, 2007 02:30 PM

URL: http://pirsa.org/07110039

Abstract: The possible existence of a physical UV cutoff in dynamical spacetimes raises a number of conceptual and practical questions. If the validity of Lorentz Invariance is considered unreliable above the cutoff, the creation or destruction of quantum modes and the choice of their initial state need to be described explicitly. It has been proposed that these trans-Planckian effects might leave an oscillatory imprint on the power spectrum of inflationary perturbations. However, taking into account the fluctuations of the cutoff, the signal is smeared out beyond recognition.

Inflation with a Cutoff: Proposals and Problems

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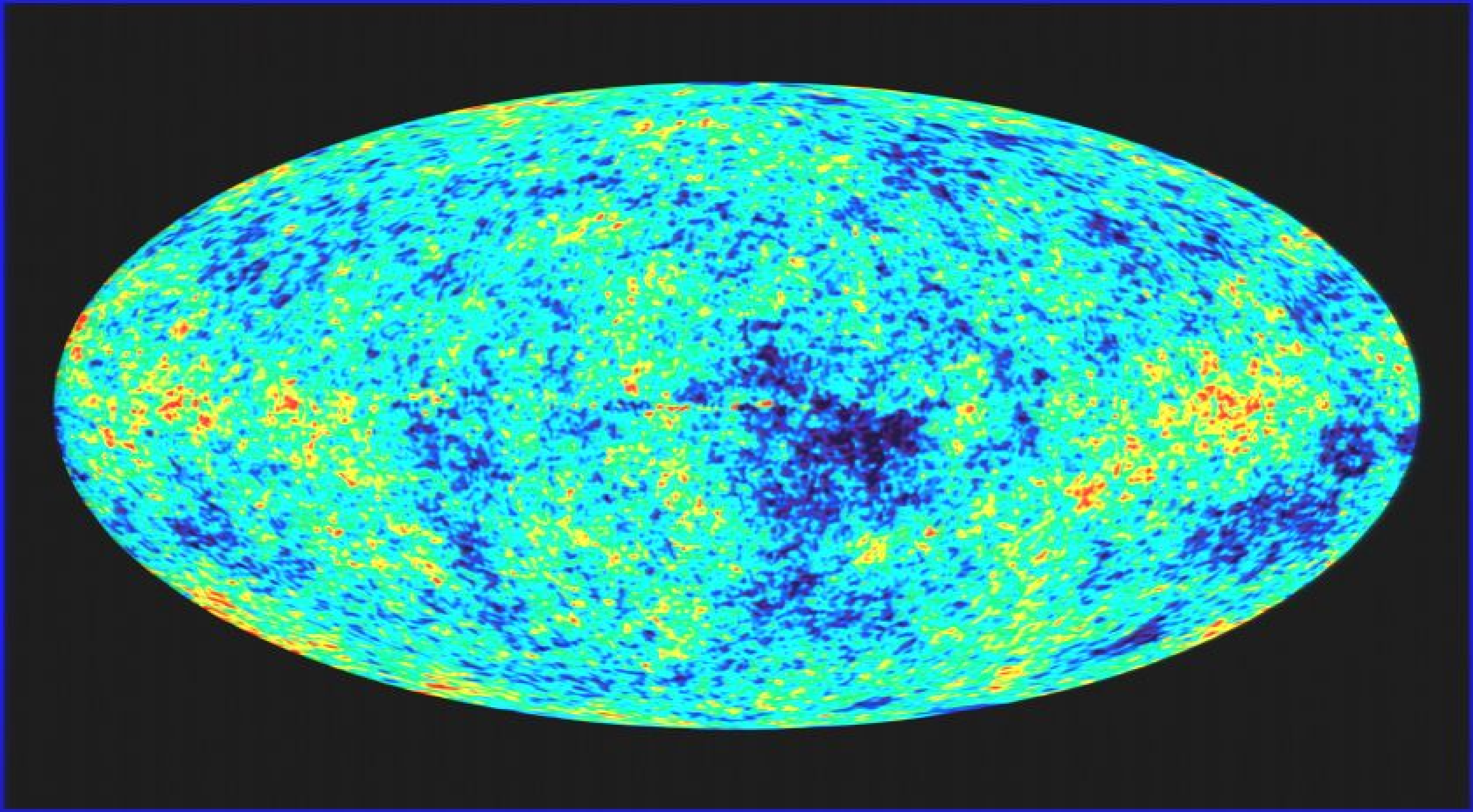
Université Paris XI, France

Experimental QG in Cosmology: Precision Measurements



WMAP-Team 2006

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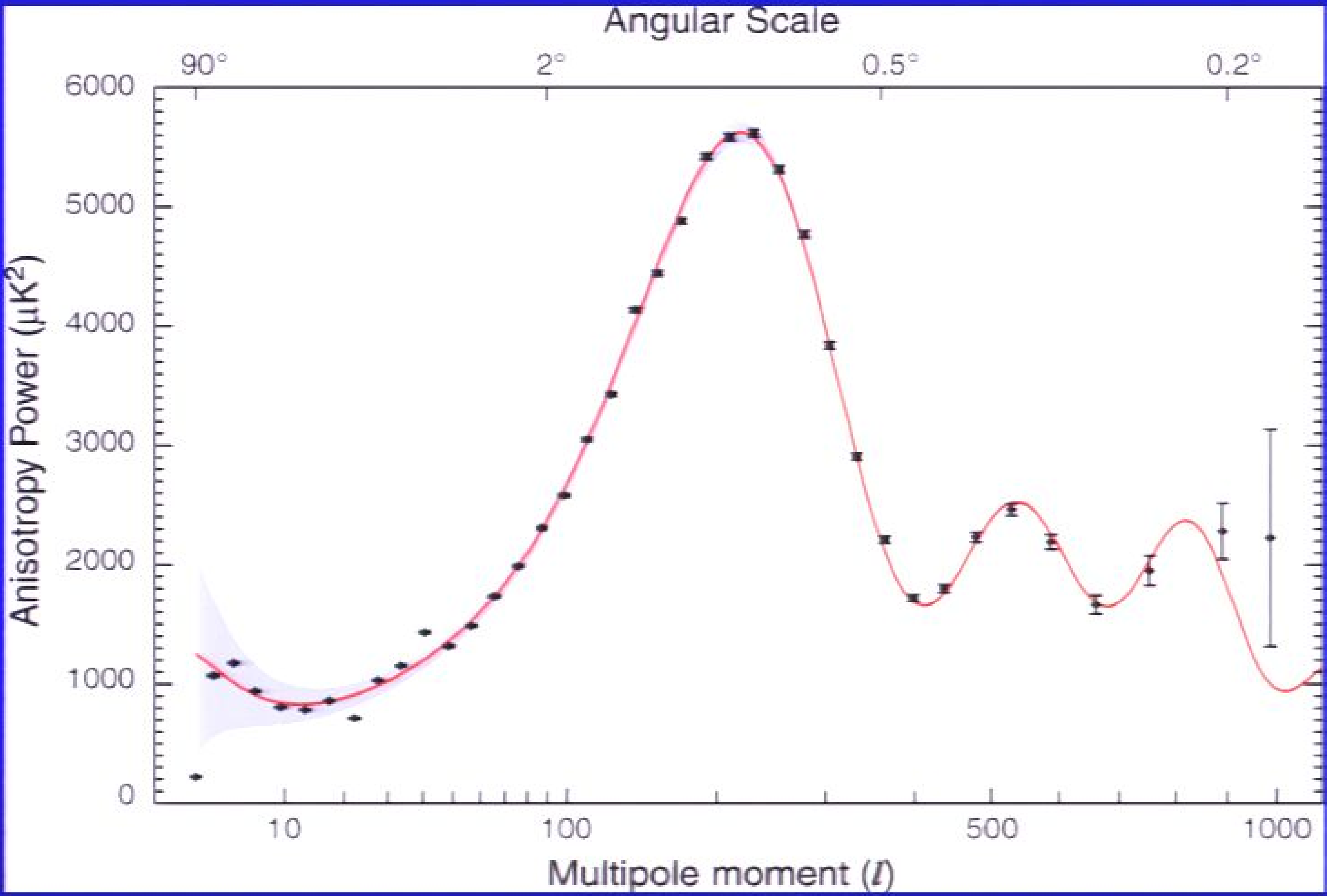

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Initial conditions in dynamical spacetimes

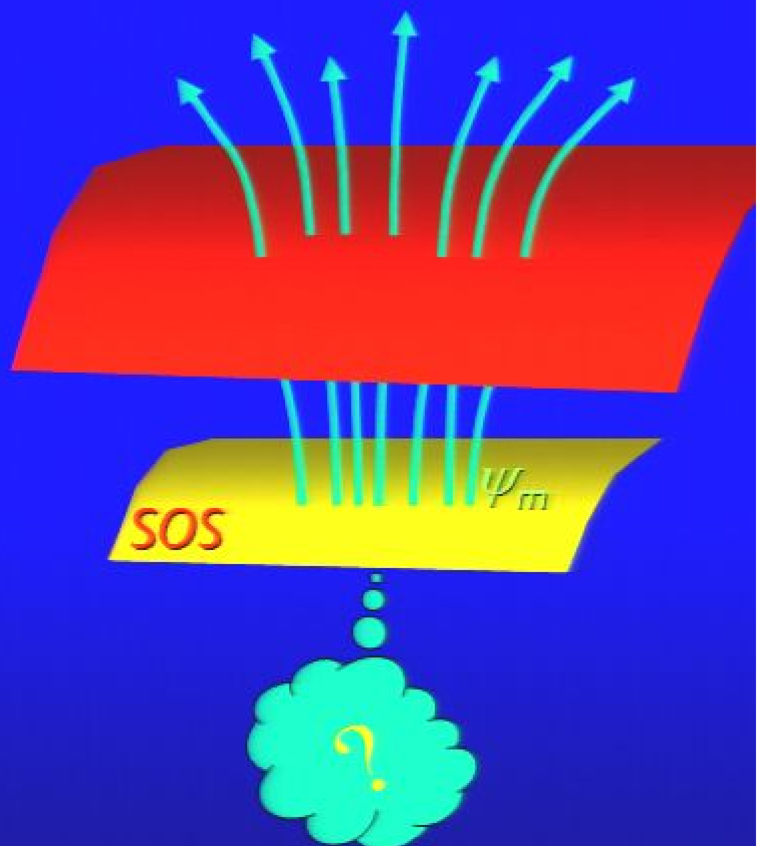
QFT in curved spacetimes = EFT, valid below cutoff $M < M_p$, lives on smooth manifold

- -initial cond.s for matter ψ_m assigned on "surface of semiclassicality (SOS)":

- -gravity → initial data needs to be arbitrarily densely spaced (density of d.o.f. infinite)

- -Lorentz invariance (LI) for arbitrary boosts → decoupling constrains choice of ψ_m (vacuum)

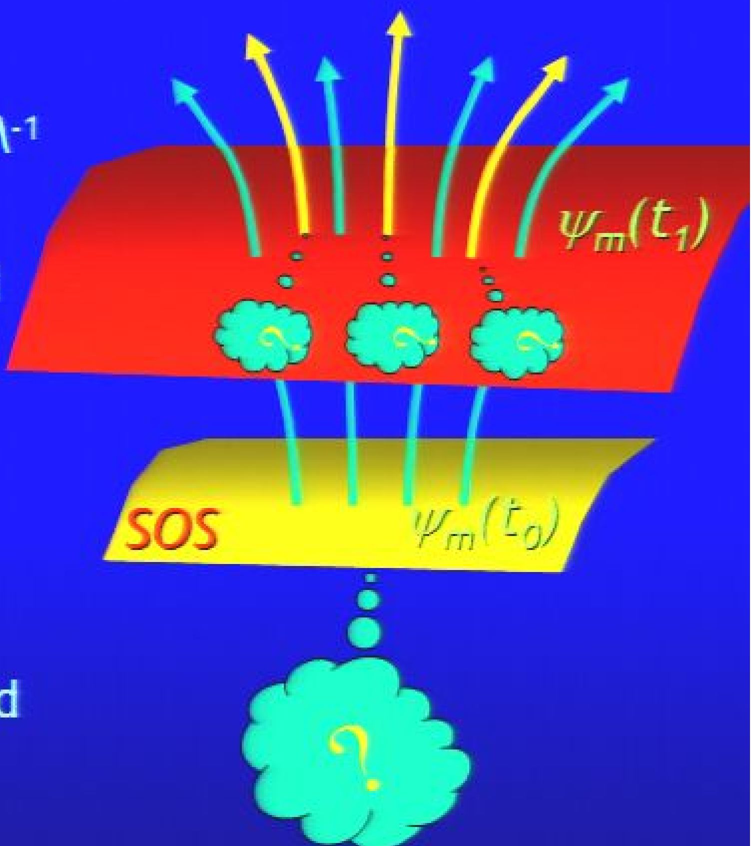
- -Q: Can selection of SOS (and hence ψ_m) be described dynamically?



Initial conditions in dynamical spacetimes

What if LI is broken (or simply meaningless) for $l < M^{-1}$?

- -SOS only well-defined for proper distances > M^{-1}
- -gravity → modes must be depleted or created (density of d.o.f. finite)
- – $\psi_m(t)$ constrained by phenomenology (backreaction, particle production)
- -Q: Can selection of SOS *and* $\psi_m(t)$ be described dynamically ("mode creation")?



Aspects of the problem

1. Phenomenology of mode creation in cosmology (using EFT, dispersion, boundary conditions at M, ...)
   - backreaction (Tanaka; JN & Parentani; Starobinsky; Schalm et al.; Danielsson;...)
   - particle production (Starobinsky & Tkachev; Kolb et al.; ...)
   - inflationary perturbations (Martin & Brandenberger + many more)

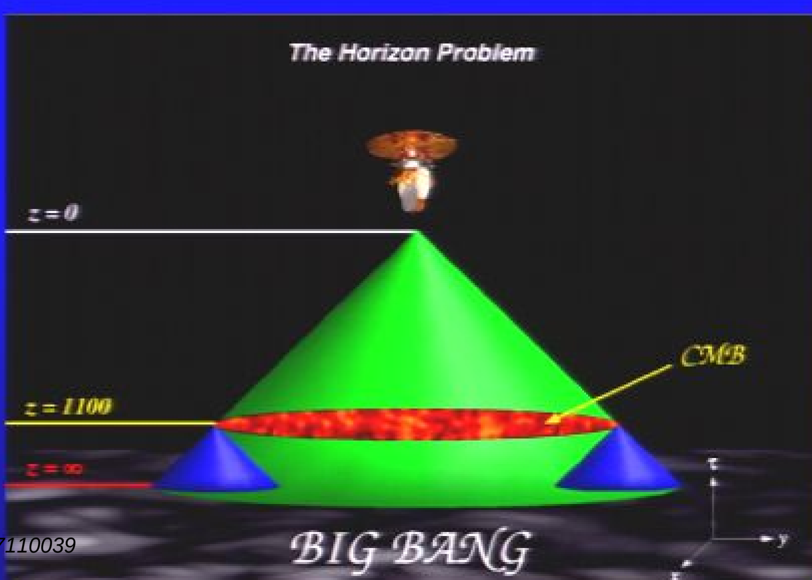
2. Models for mode creation
   - QFT on a growing lattice (Foster & Jacobson)
   - modified uncertainty relation in FRW (Kempf; Kempf & JN; Kempf & Lorentz)
   - QFT with effective dissipation (Parentani)

Horizon Dynamics: Decelerating Universe

In a decelerating (matter or radiation dominated) universe the comoving horizon grows

$\Rightarrow$ structures "enter the horizon".

Horizon problem: why is the universe uniform on super-horizon scales?



Decelerating universe, comoving coordinates:

$$
\begin{aligned}
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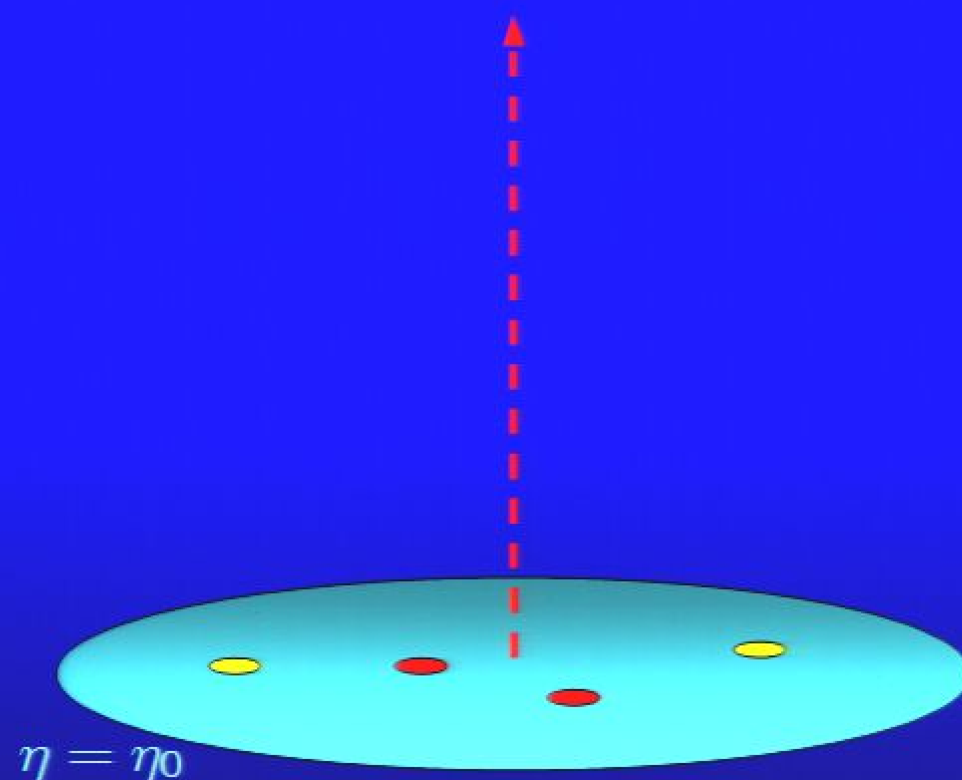

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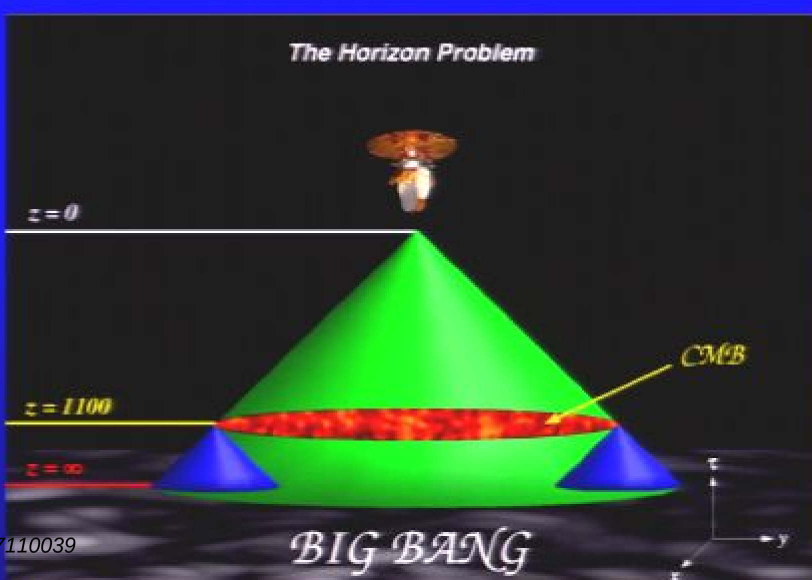

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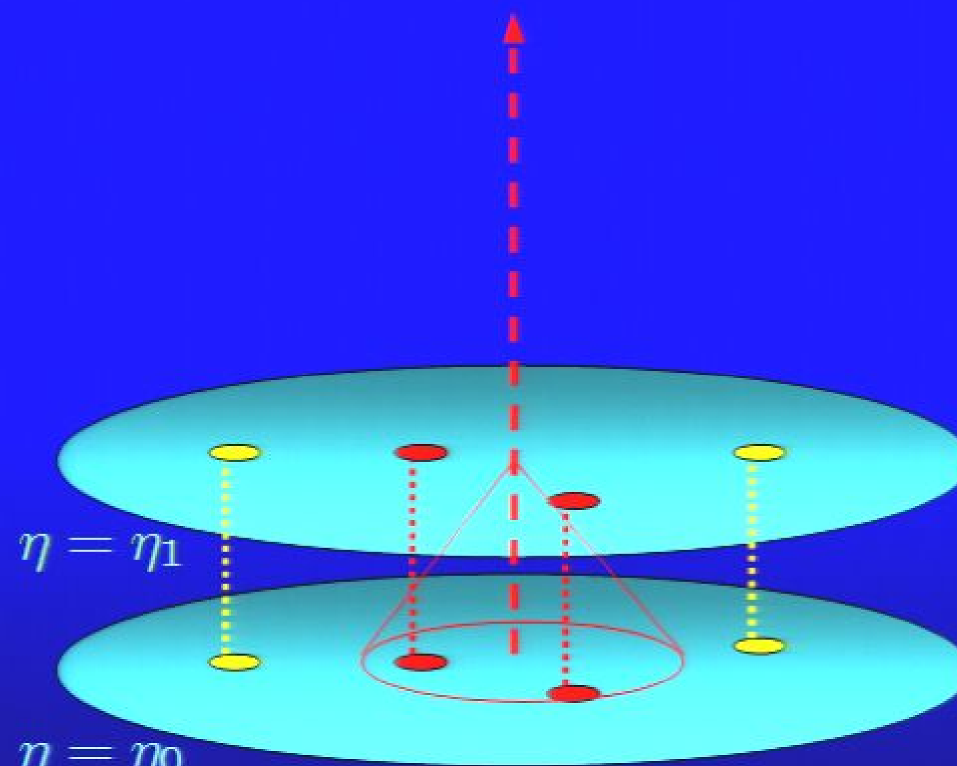

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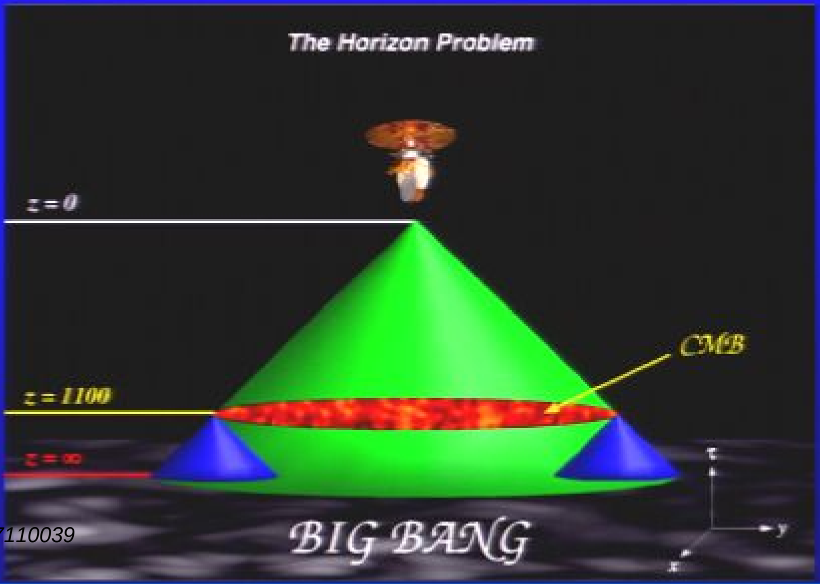

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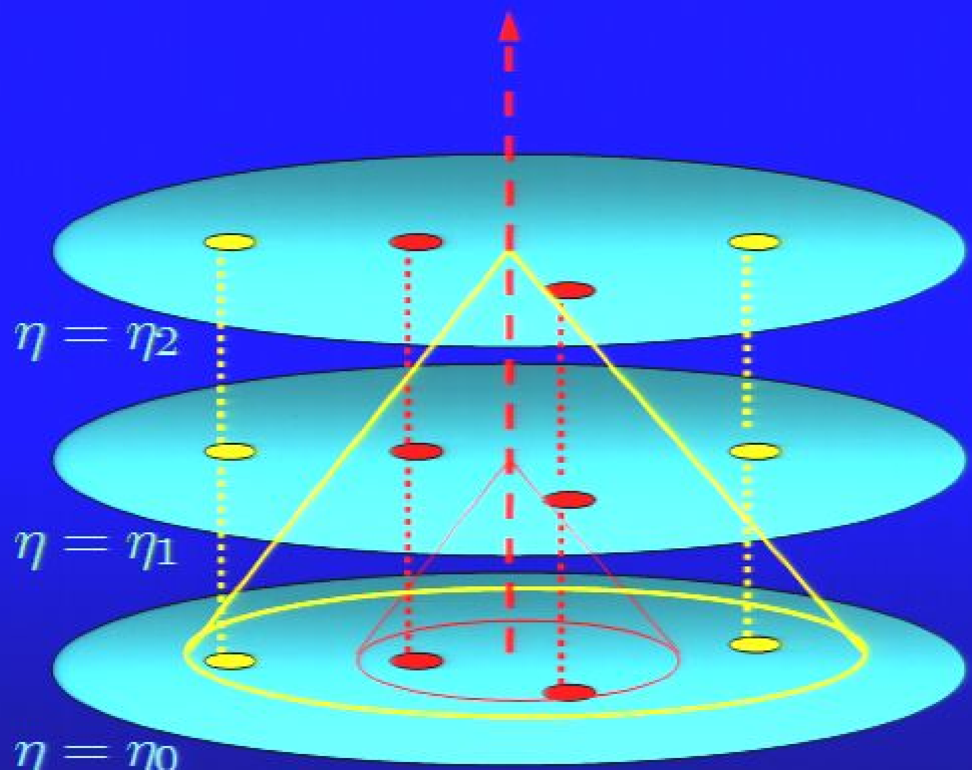

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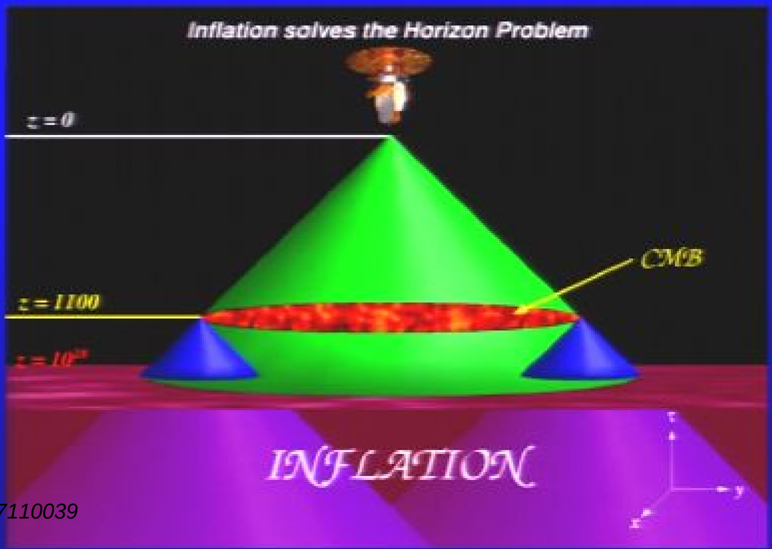
In an accelerating (vacuum dominated) universe, the comoving horizon shrinks

$\Rightarrow$ Inflation

$\Rightarrow$ structures „leave the horizon“.

They re-enter during the decelerating hot big bang phase.



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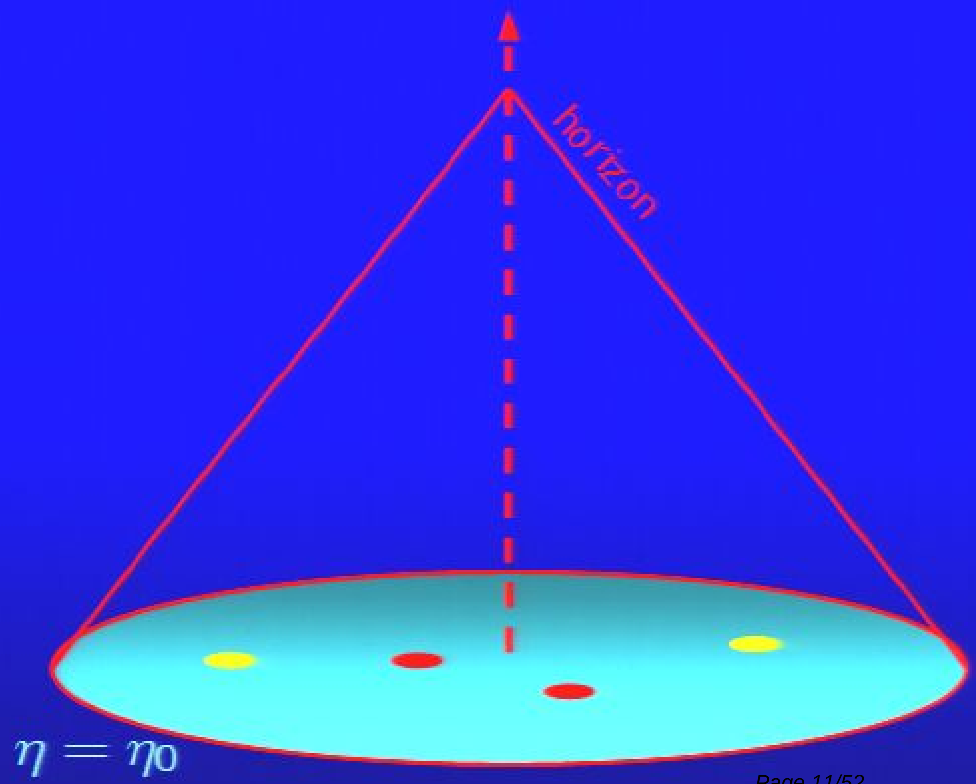

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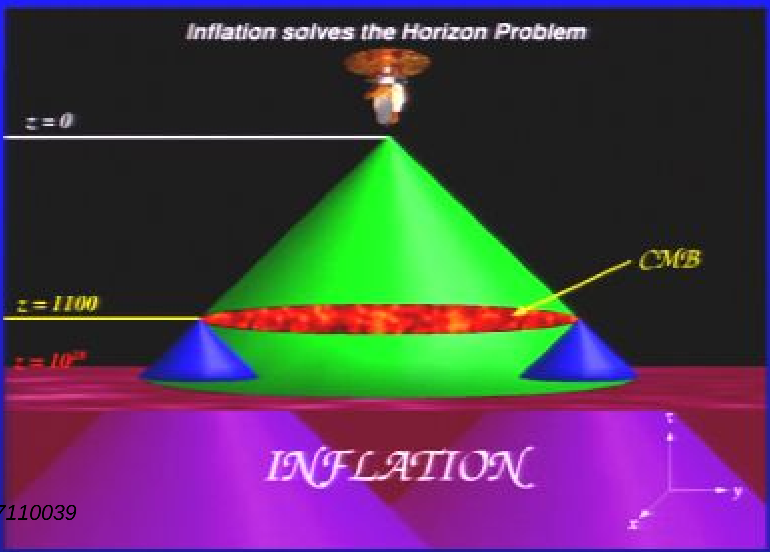

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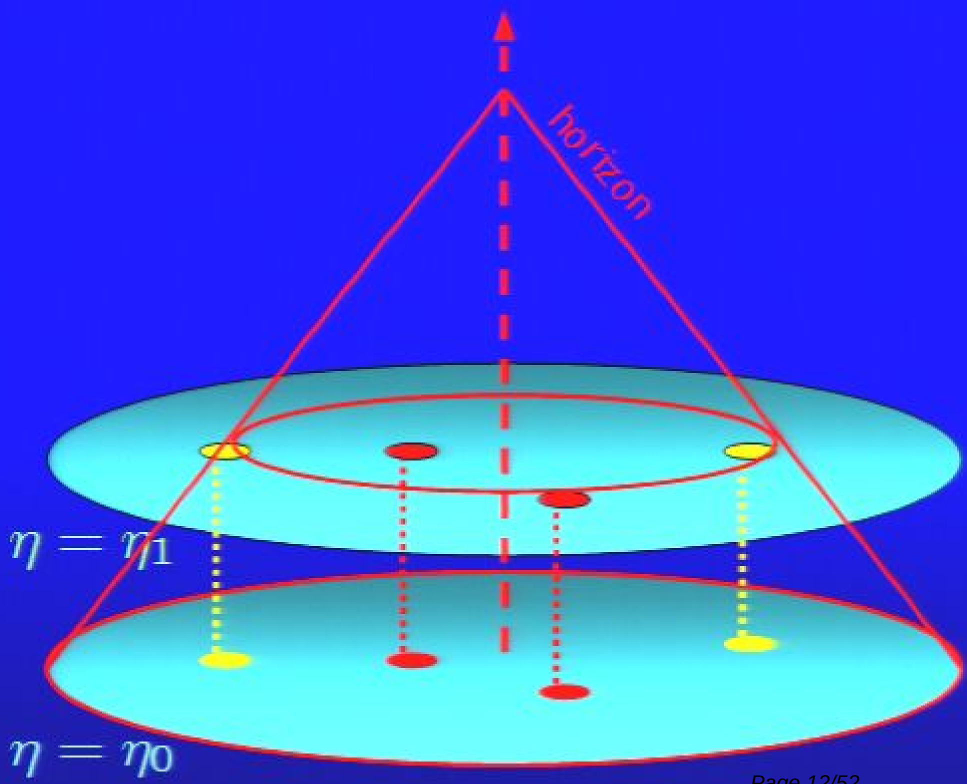

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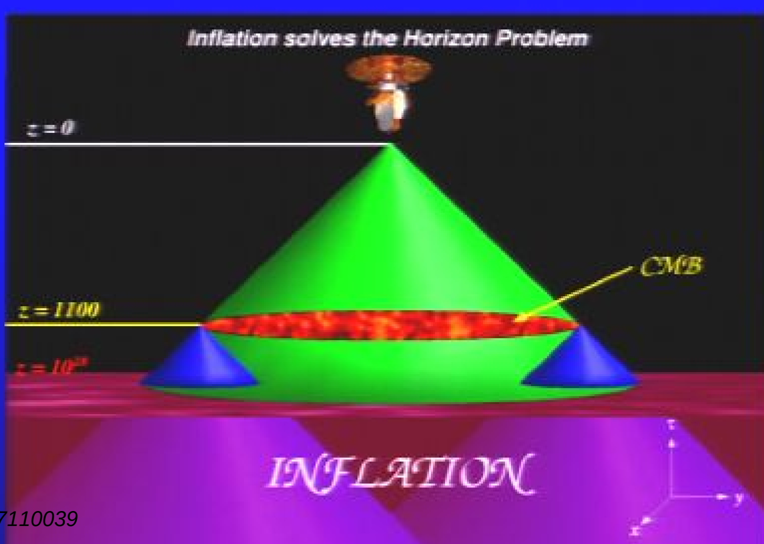

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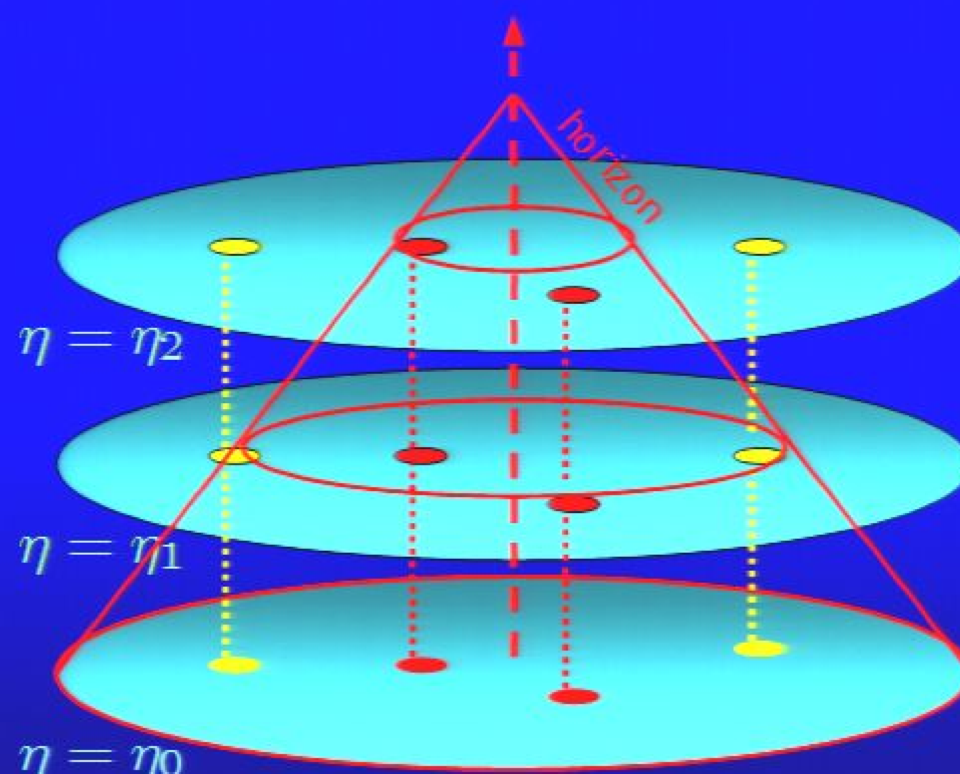

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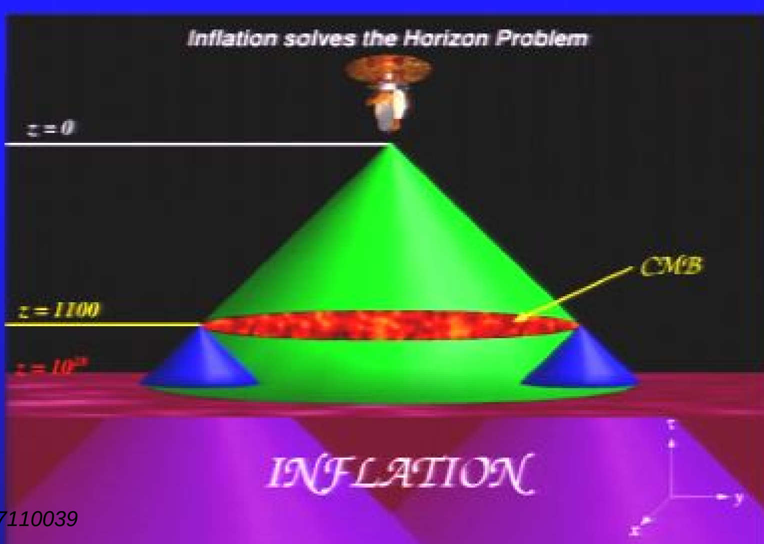
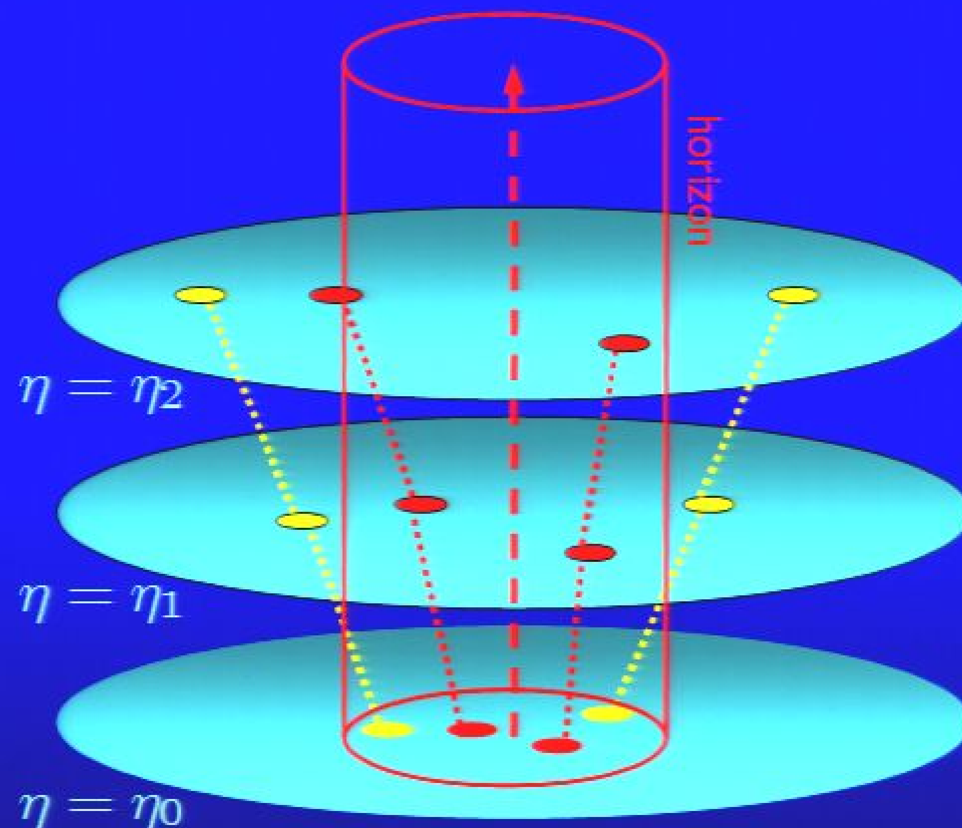


Accelerating universe, proper coordinates:

$$l_{\rm phys} = a\,x \quad , \quad H \simeq {\rm const}$$



Inflationary Perturbations

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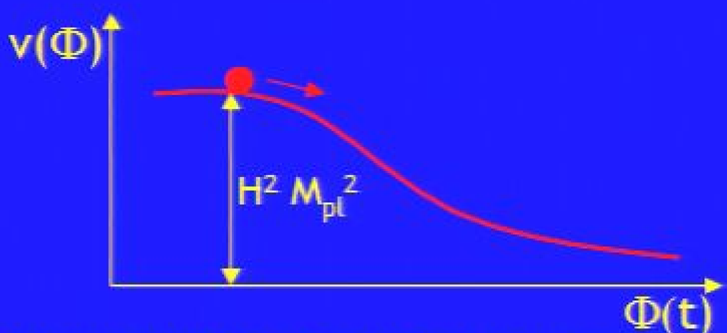

Separate into classical zero mode and quantum flucuation:

$$\Phi(\eta, x) = \phi_0(\eta) + \hat{\varphi}(\eta, x)$$

(physical d.o.f. for metric fluctuations essentially equivalent)

Vacuum modes of φ obey oscillator equation with time-dependent mass:

$$\partial_\eta^2 \varphi_q + [q^2 - \chi(\eta)]\varphi_q = 0$$

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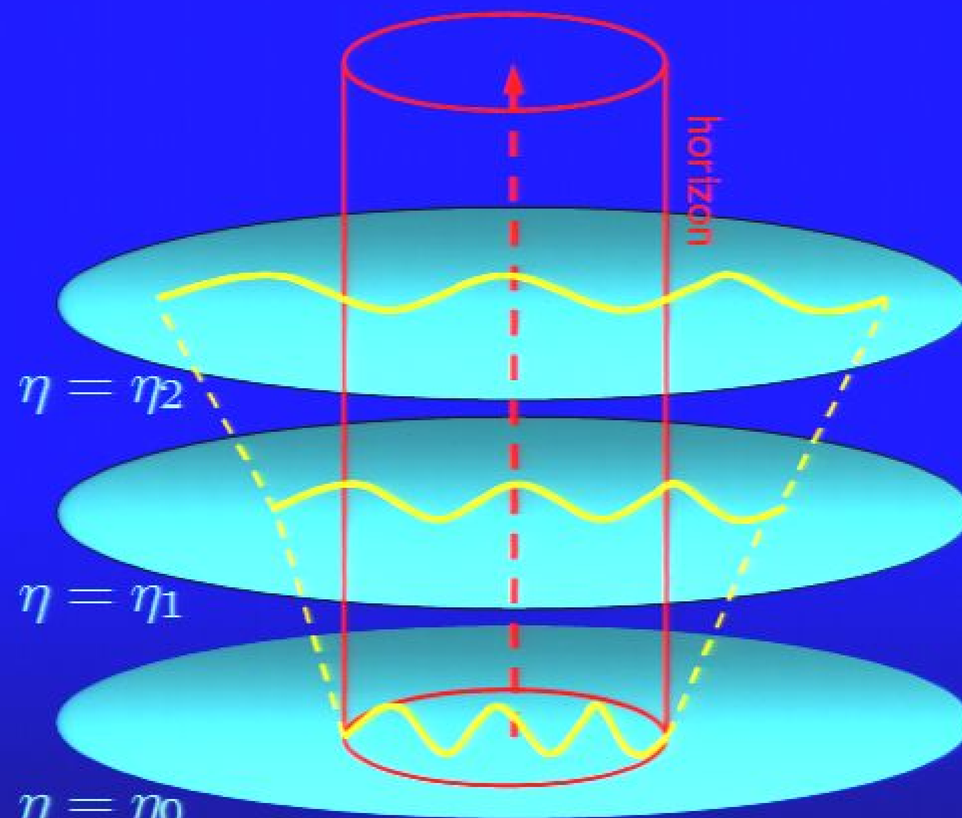

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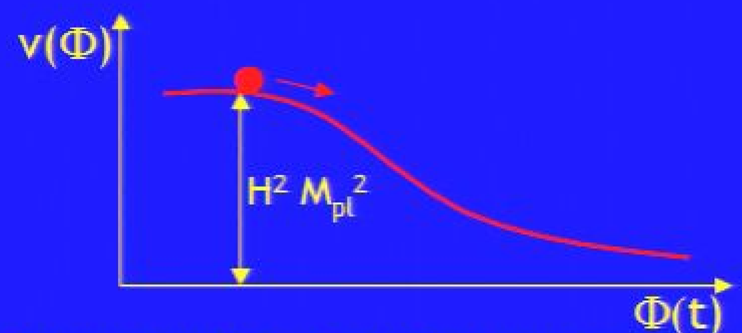

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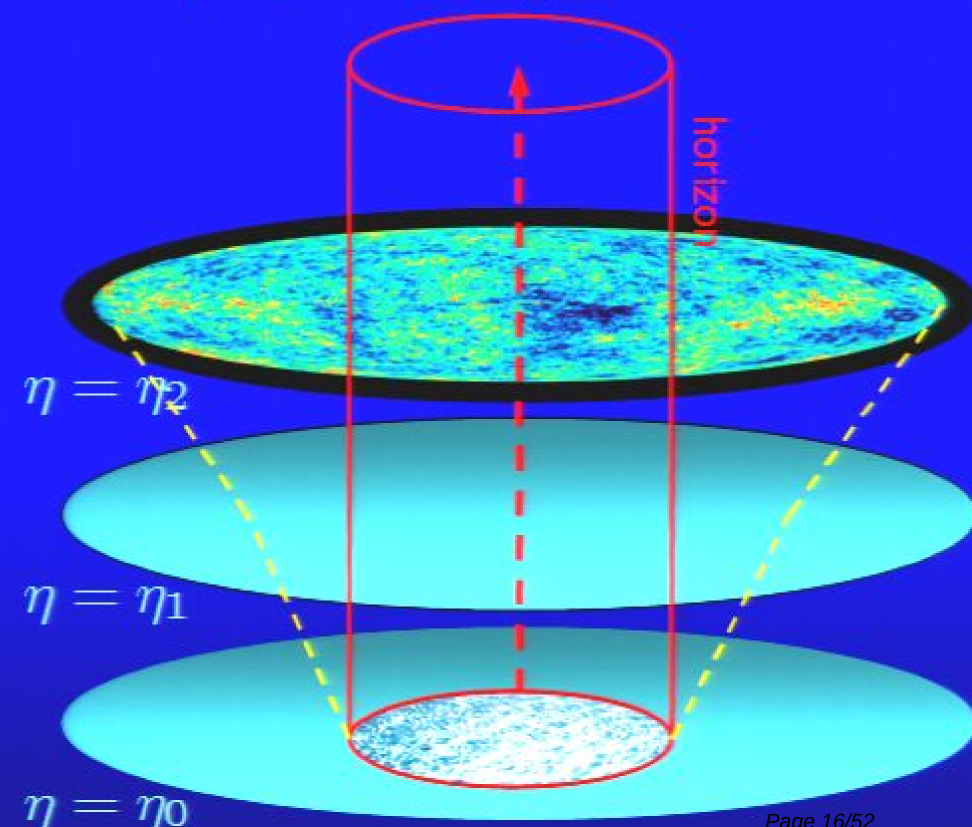
On super-horizon scales, $\chi > q^2 \Rightarrow$ the modes are overdamped.

They become the seeds for CMBR anisoptropies and large scale structure.



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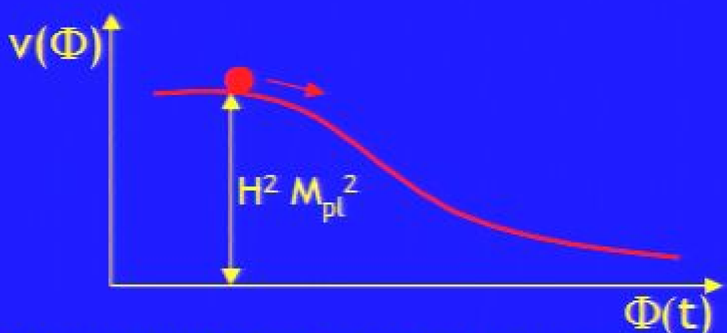

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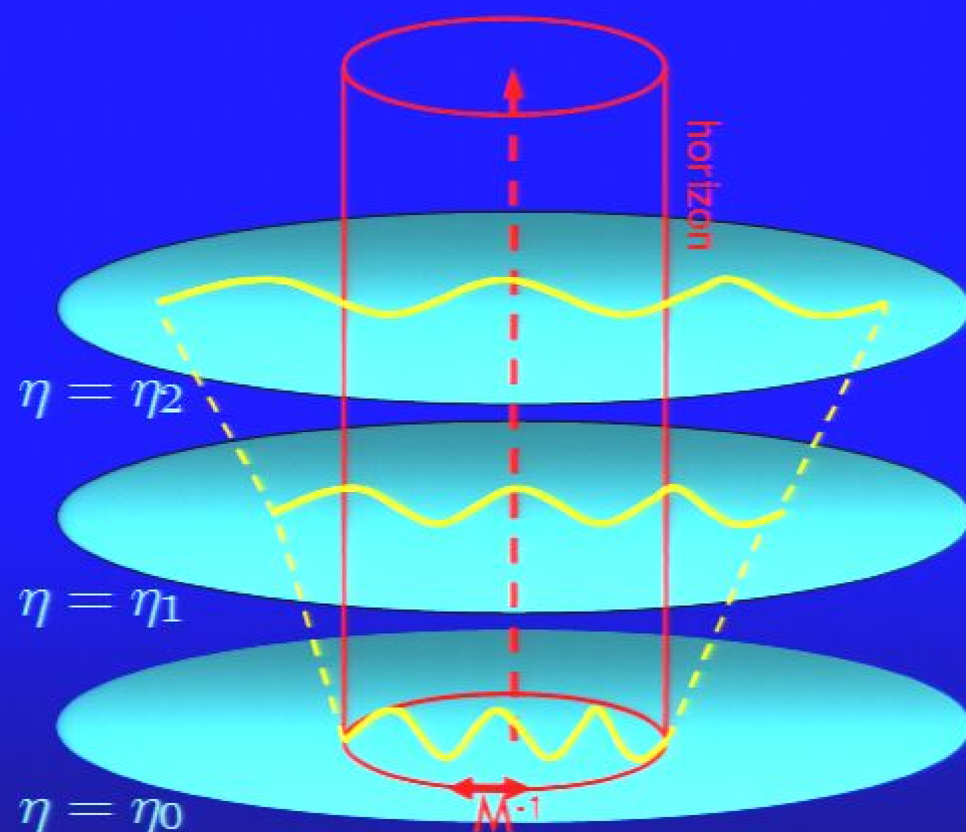

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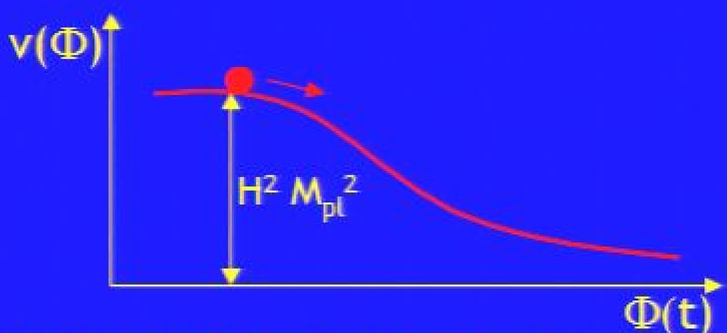

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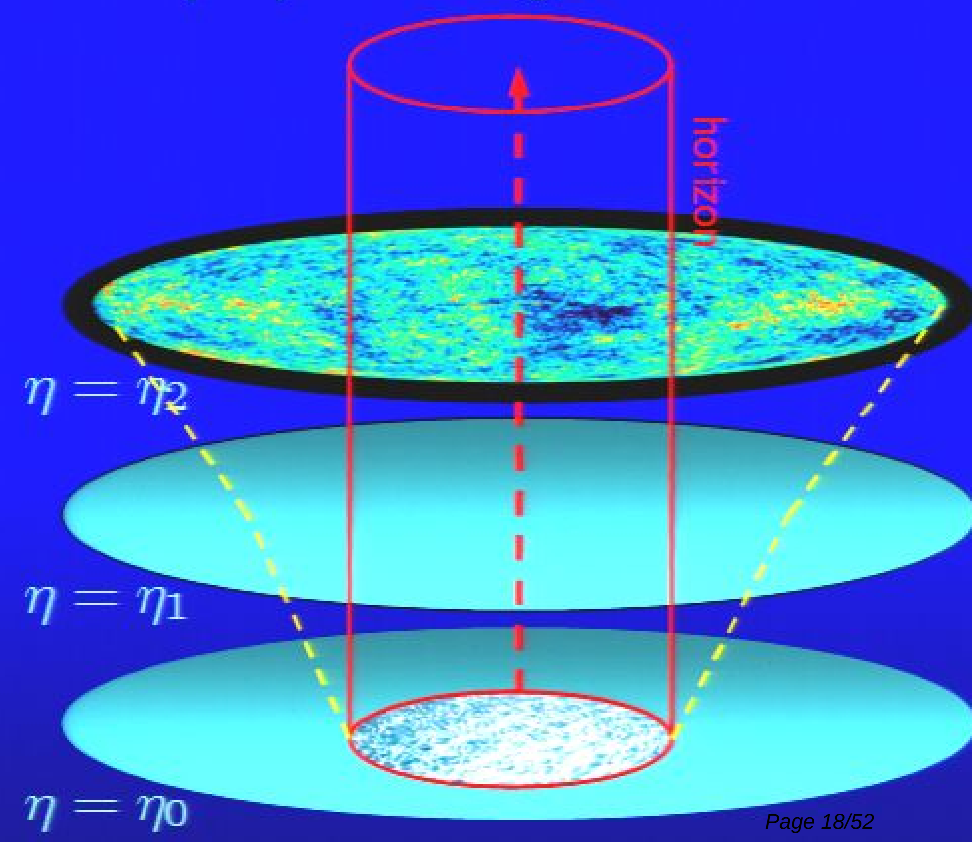
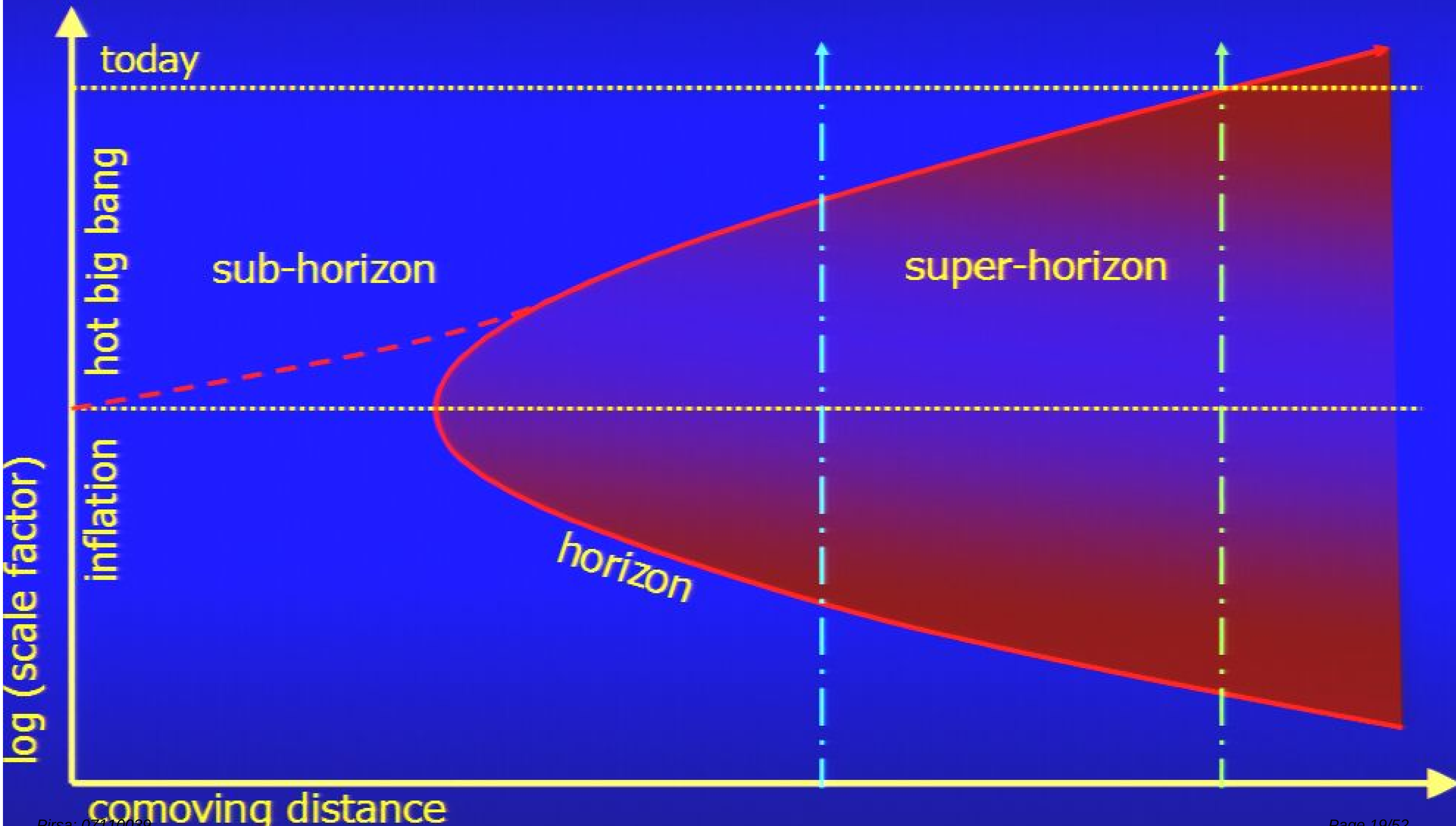


Cosmological evolution of scales



Standard Procedure

Power spectrum: $\langle \Psi_M | \hat{\varphi}(t,\mathbf{x}) \hat{\varphi}(t,\mathbf{y}) | \Psi_M \rangle = \int_0^{+\infty} \frac{dq}{q} \frac{\sin(qr)}{qr} \mathcal{P}_M(q,t)$

hence $\mathcal{P}_M(q,t) = \frac{q^3}{2\pi^2} |\varphi_q(t)|^2$

where φ_q is solution of $\left(\partial_\tau^2 + \omega_q^2(\tau)\right) \varphi_q = 0$

and $\omega_q^2(\tau) = q^2 - \chi(\tau) \simeq q^2 - \frac{f}{\tau^2}$

Vacuum choice:

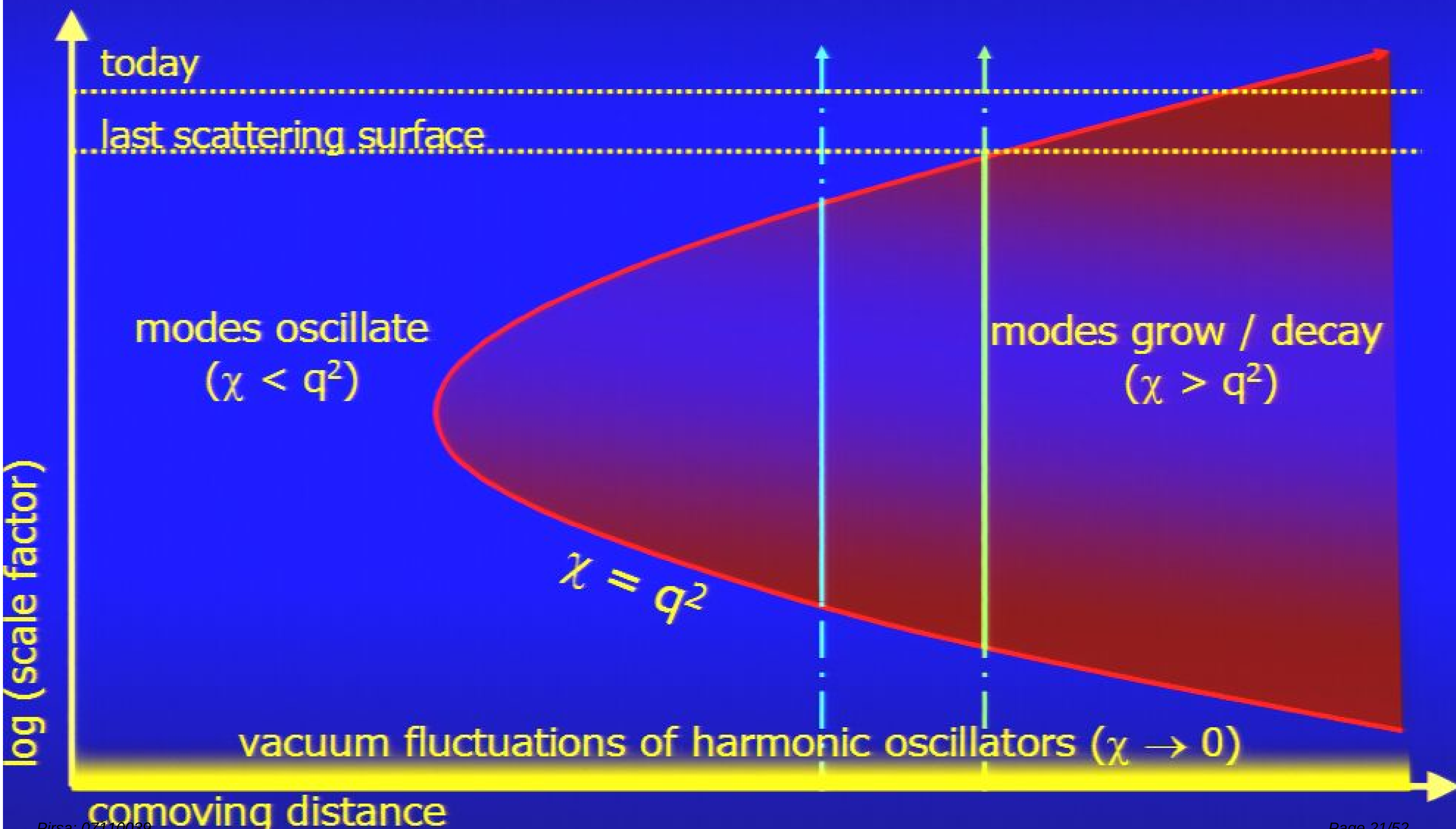
"Bunch-Davies" (BD) vacuum = positive frequency mode at $\tau \to -\infty$:

$$(i\partial_\tau - q)\, \varphi_q^{-\infty}|_{\tau \to -\infty} = 0$$

so that:

$$\boxed{\mathcal{P}_{-\infty}(q,t) = \frac{q^3}{2\pi^2} |\varphi_q^{-\infty}(t)|^2 \propto \frac{H_q^2}{M_{\rm Pl}^2}}$$

Perturbations without cutoff



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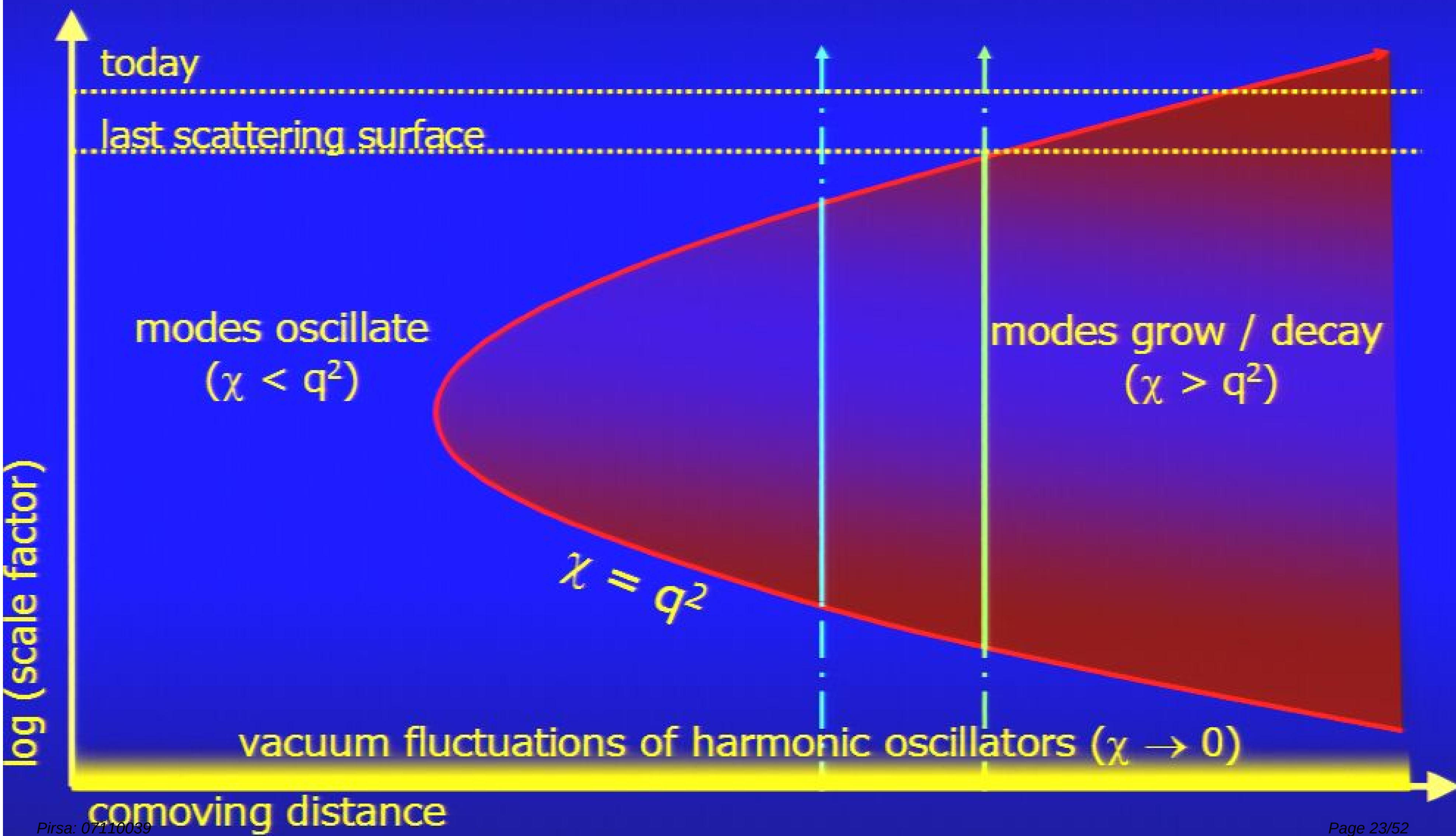

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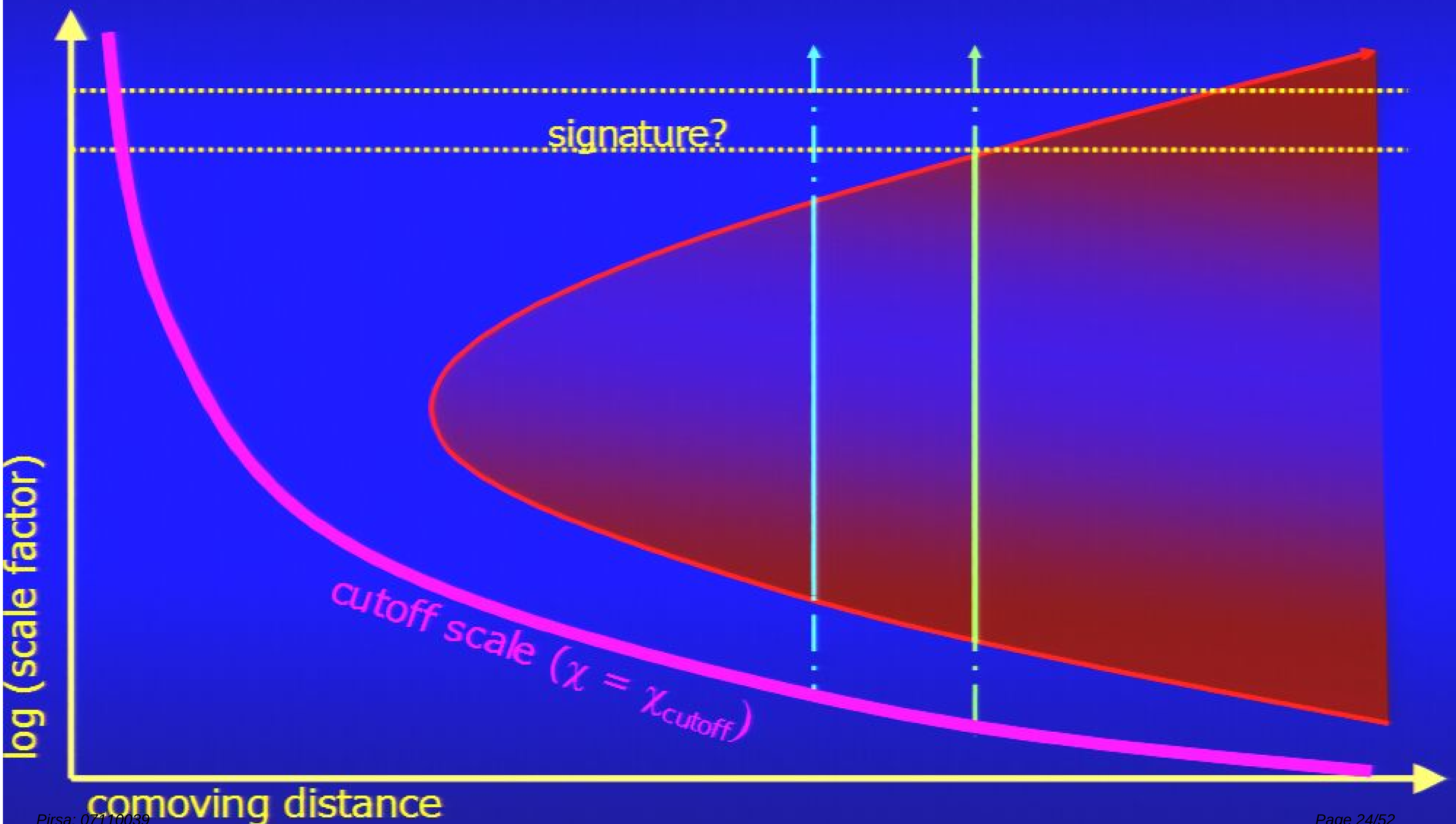
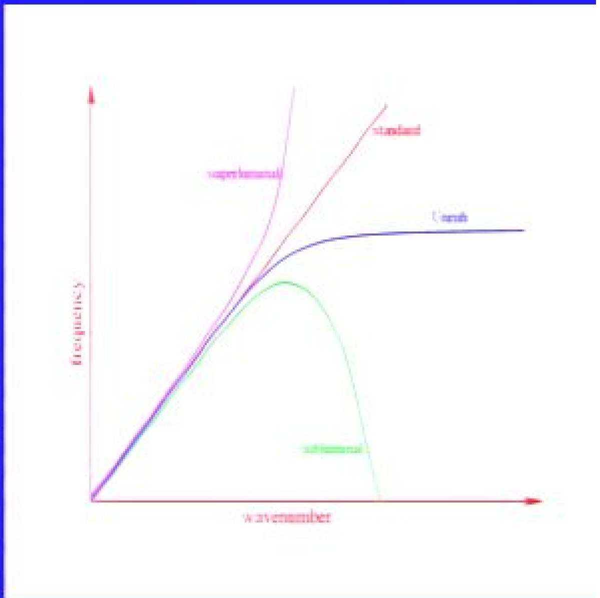


Modification I: Dispersion

(Brandenberger & Martin, JN &Parentani, many others)

Following Unruh and others in the black hole community, break LI with nonlinear dispersion relation.

Replace ω_q/a with $F_M(p=q/a) \rightarrow \omega_q/a$ for $q << a\,M$, where F_M is chosen phenomenologically:



Correction to power spectrum small if the evolution is adiabatic, i.e. if

$$\left|\frac{\omega'}{\omega^2}\right| \leq \left|\frac{H}{F}\right| + \left|\frac{H\,p}{F^2}\frac{dF}{dp}\right| \ll 1$$

$\Rightarrow$ scale separation ($\sigma_q = H_q/M << 1$) suppresses modifications (same as for Hawking radiation)

Modification II: mode creation with sharp cutoff

(Jacobson; Danielsson; Easther et al., JN, Campo, Parentani, ...)

Fix the state for each mode φ_q^M at M-crossing time: $q = Ma(t_M)$

Relation to standard modes: $\varphi_q^M(\tau) = \alpha_q \varphi_q^{-\infty}(\tau) + \beta_q \varphi_q^{-\infty *}(\tau)$

where $\alpha_q = (\varphi_q^{-\infty})^* \, i\overleftrightarrow{\partial}_\tau \varphi_q^M$, $\beta_q = -\varphi_q^{-\infty} \, i\overleftrightarrow{\partial}_\tau \varphi_q^M$

Power spectrum:

$$\mathcal{P}_M(q) = \mathcal{P}_{-\infty}(q) \times |\alpha_q|^2 \left\{ 1 + 2\mathrm{Re}\left(\frac{\beta_q^*}{\alpha_q^*} \frac{(\varphi_q^{-\infty})^2}{|\varphi_q^{-\infty}|^2} \right) + \frac{|\beta_q|^2}{|\alpha_q|^2} \right\}$$

Properties of the corrections

Amplitude: $|\beta_q|^2 = O\left(\sigma_q^{2p}\right)$, $|\alpha_q|^2 = 1 + |\beta_q|^2$

where p = 1 for $(i\partial_\tau - q)\,(\varphi_q^M/a) = 0$ (Danielsson)

p = 2 for $(i\partial_\tau - q)\,\varphi_q^M = 0$ (Martin & Brandenberger)

p = 3 for $(i\partial_\tau - \omega_q(\tau))\,\varphi_q^M = 0$ (JN, Campo, Parentani)

If $\sigma = O(10^{-3})$, there is essentially no hope to detect the steady contribution.

Oscillatory correction potentially observable for p = 1.

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Properties of the corrections

Oscillations

Generic form of oscillatory term: $$\frac{\beta_q^*}{\alpha_q^*}\frac{\left(\varphi_q^{-\infty}\right)^2}{|\varphi_q^{-\infty}|^2} \propto \sigma_q^p\left(1+O\left(\sigma_q\right)\right) e^{i2q\tau_M}$$

with $$q\tau_M = \frac{\tau_M}{\tau_H} \simeq \frac{(aH)_{\tau_H}}{(aH)_{\tau_M}} \simeq \frac{a(\tau_H)}{a(\tau_M)}$$

i.e., the redshift between creation and horizon crossing.

In the slow-roll approximation (H_q ~ ln q): $$q\tau_M = \frac{1}{\sigma_0}\left(1+\epsilon_1+\epsilon_1\ln\left(\frac{q}{q_0}\right)\right)$$

and $$\boxed{\Delta \ln q = \frac{\pi\sigma_0}{\epsilon_1}}$$

$\Rightarrow$ signature: superimposed oscillation in ln q with amplitude ~ σ_q^p

Signatures of sharp cutoffs

eplace mode creation with boundary condition

. boundary cond. at $q/a(\eta_M) = M$

)anielsson; JN, Campo, Parentani; Easther, Greene, Kinney, Shiu)

› characteristic signature in power spectrum:

$$\Delta P(q) \propto \left(\frac{H(q)}{M}\right)^n \sin\left(2\frac{M}{H(q)} + \Theta\right)$$

/here *n* depends on degree of non-adiabaticity;

ut: signal strongly damped if cutoff fluctuates

ampo, JN, Parentani)

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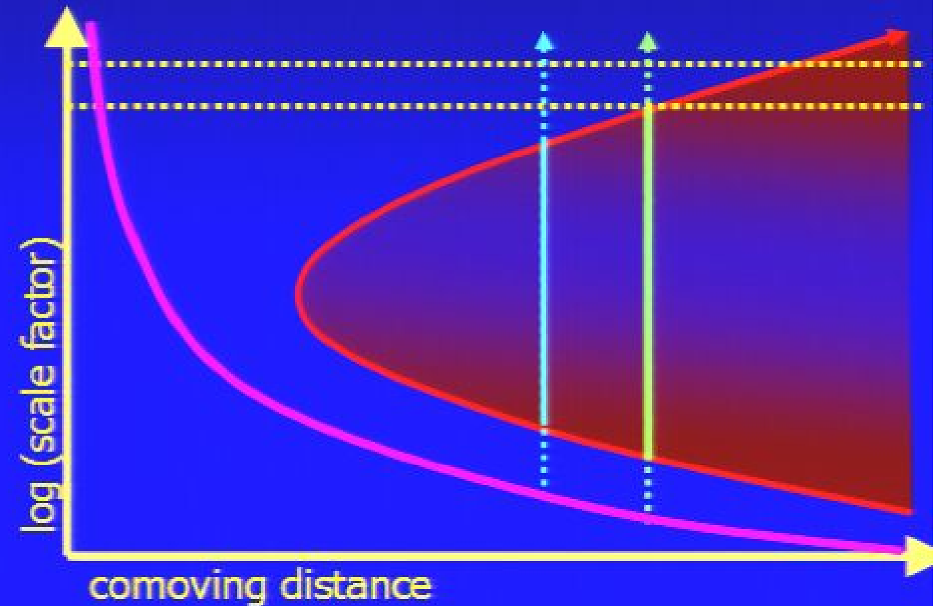

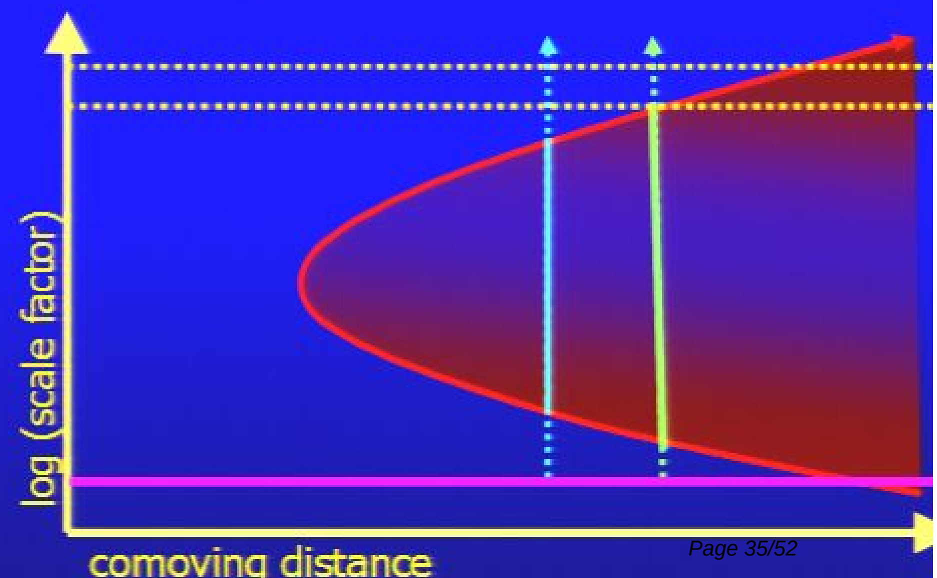

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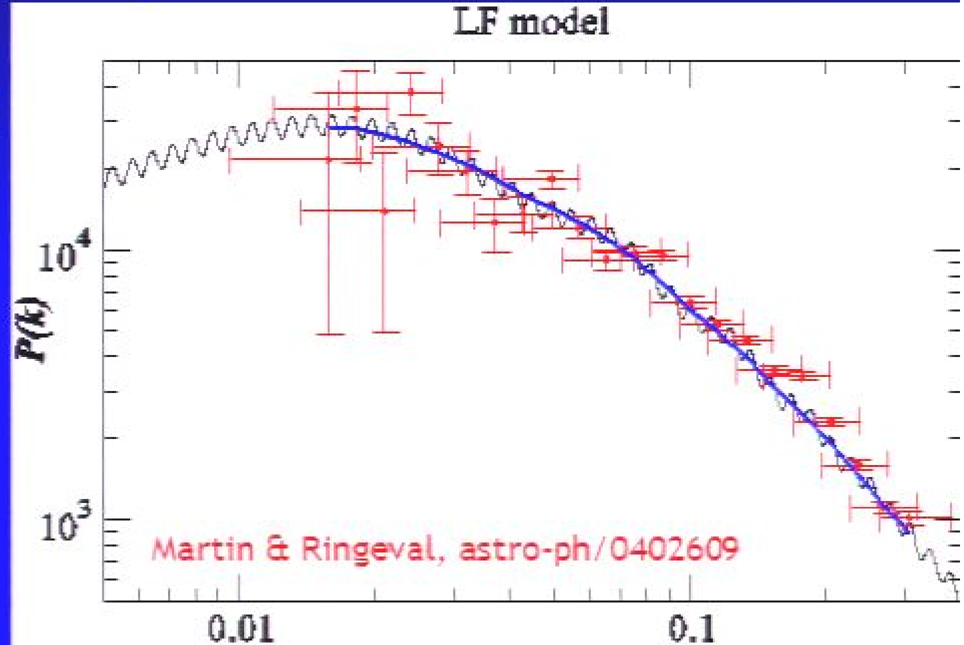

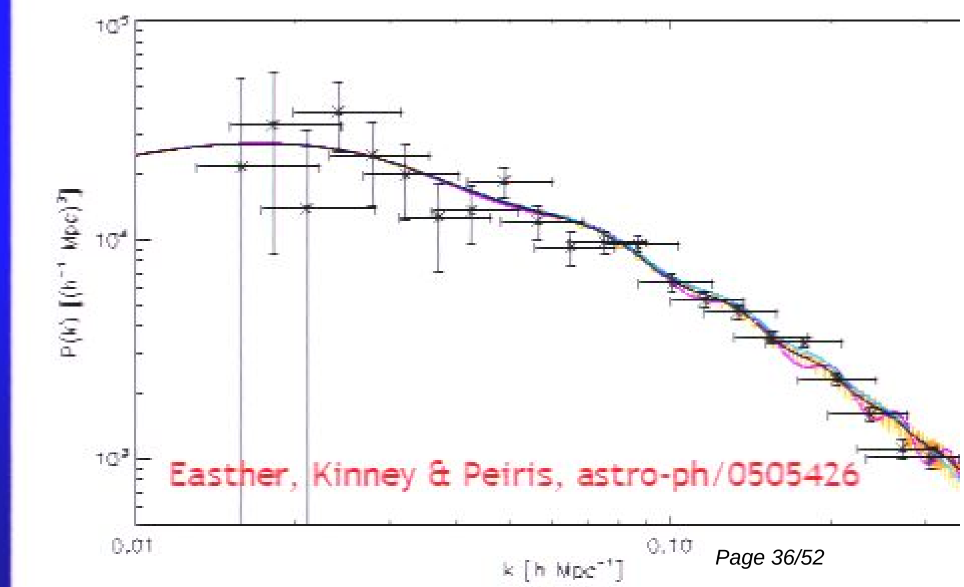

Modification III: fluctuating cutoff
(Campo, JN & Parentani, PRD 07)

Treat M as stochastic variable with fluctuations (of unspecified origin)

$$\langle\langle\, M \,\rangle\rangle = \bar{M} \quad , \quad \langle\langle\, (M - \bar{M})^2 \,\rangle\rangle^{1/2} = \Sigma \qquad \text{and} \qquad \Sigma \ll \bar{M}$$

For $\Sigma_n \equiv H_M \left(\frac{\bar{M}}{H_M} \right)^n$ this means $n - 1 < \frac{3}{\ln(\bar{M}/H)}$

and

$$\boxed{\langle\langle\, \sigma_q^p \, e^{i2/\sigma_q} \,\rangle\rangle = \bar{\sigma}_q^p \, e^{i2/\bar{\sigma}_q} \times \exp\left[-4 \frac{H_M^2}{H_q^2} \left(\frac{\bar{M}}{H_M} \right)^{2n} \right]}$$

$\Rightarrow$ the oscillatory term becomes exponentially suppressed, the steady term becomes the leading order correction.

Modification IV: Dissipation

(Parentani, arXiv:0710.4664)

Goal

Effective dissipation of φ_q above scale M while preserving unitarity

$\Rightarrow$ coupling to heavy "environment field" Ψ : $S_T = S_\varphi + S_\psi + S_{\varphi,\psi}$

Power spectrum $$P_p(t) = 4\pi p^3 \int \left(\frac{dx}{2\pi}\right)^3 e^{i\mathbf{px}}\, G_a(t,\mathbf{x};t,\mathbf{0})$$

computed from 2pt function instead of mode functions, where G_a is the symmetric part of $G_W(x,y) = \mathrm{Tr}\left[\hat{\rho}_T\, \hat{\phi}(x)\, \hat{\phi}(y)\right]$

Properties

- G_a determined by noise kernel N $\Rightarrow$ largely generic, insensitive to detailed dynamics of ψ and ϕ-ψ coupling
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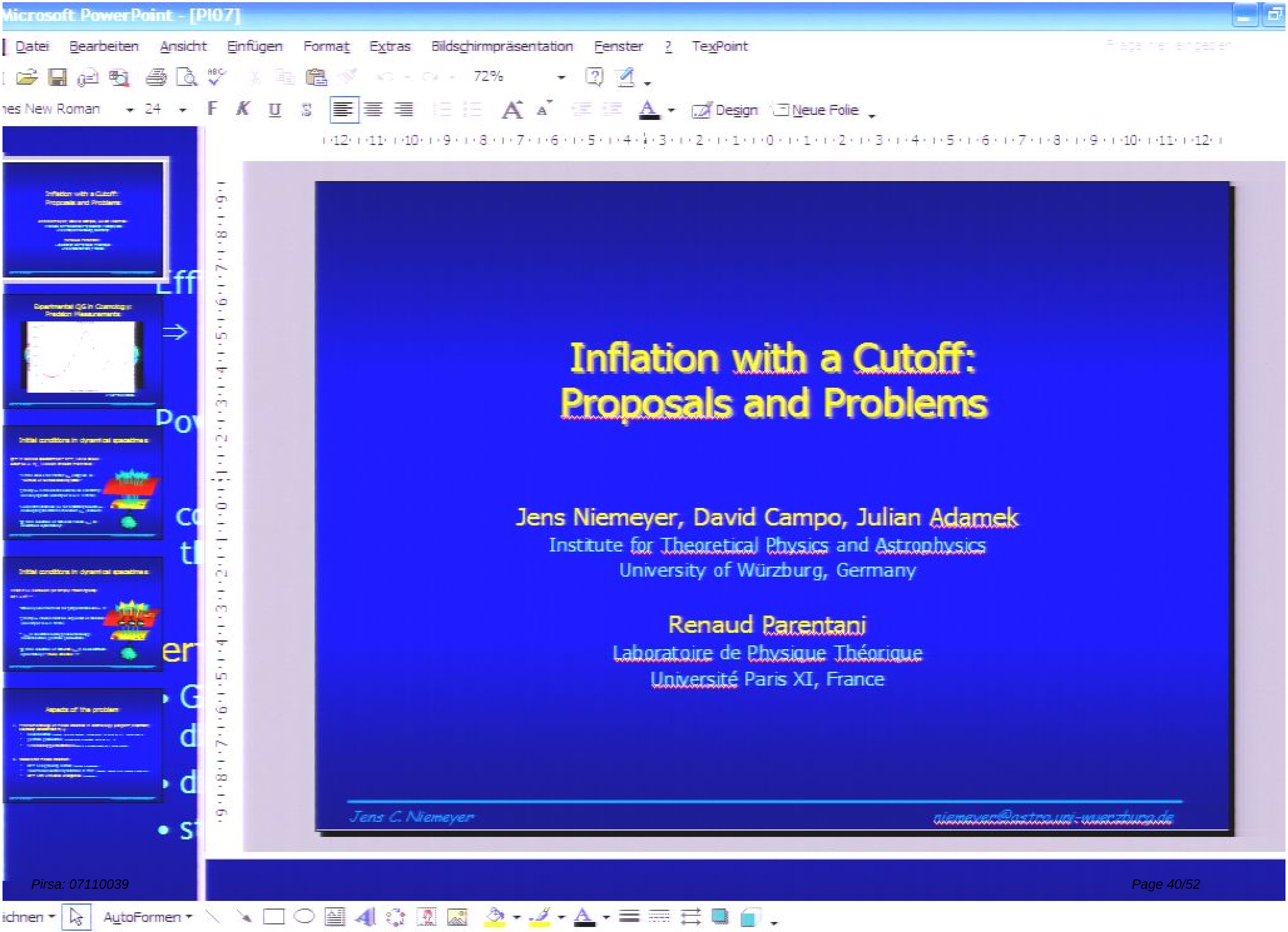
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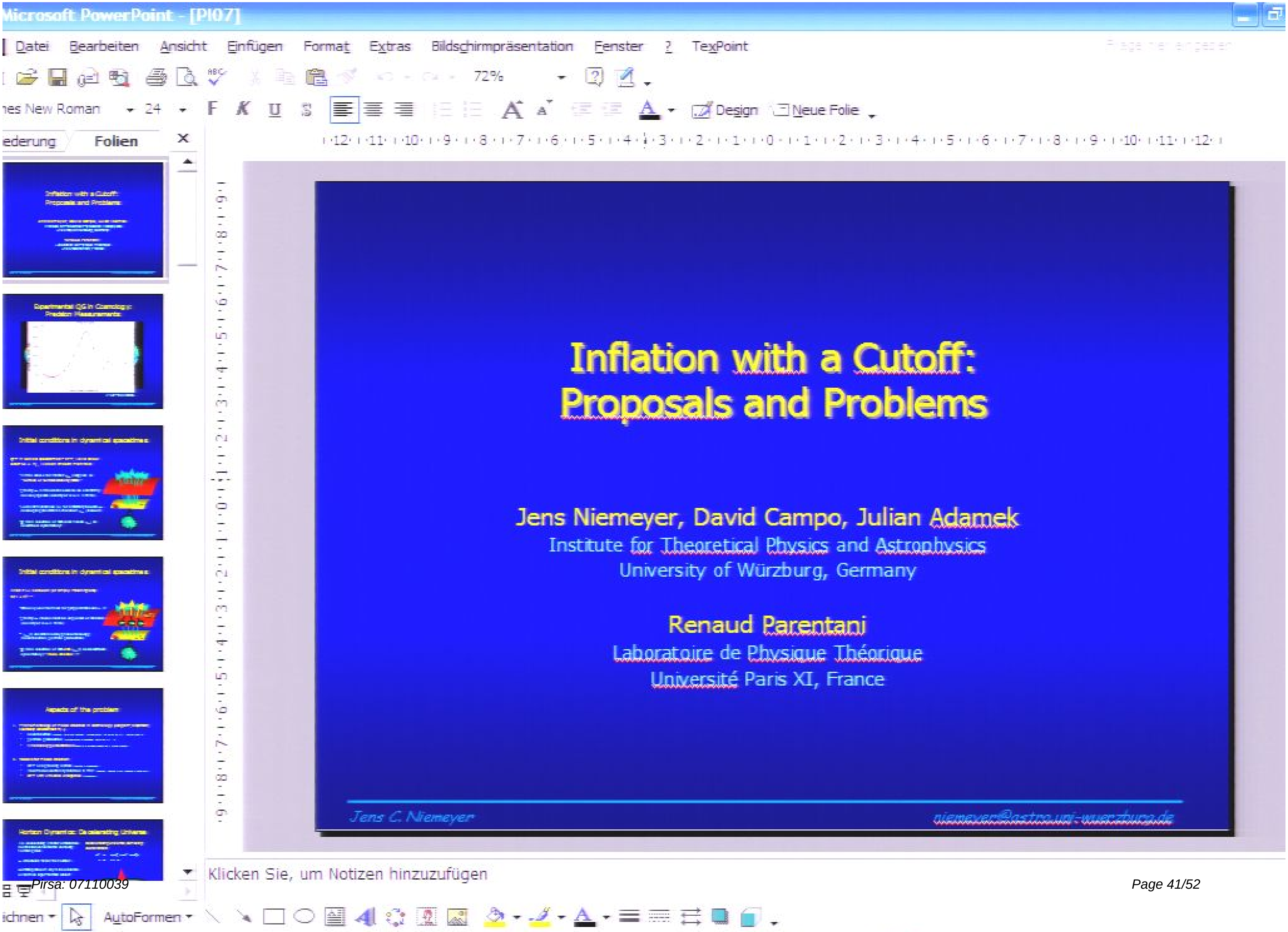
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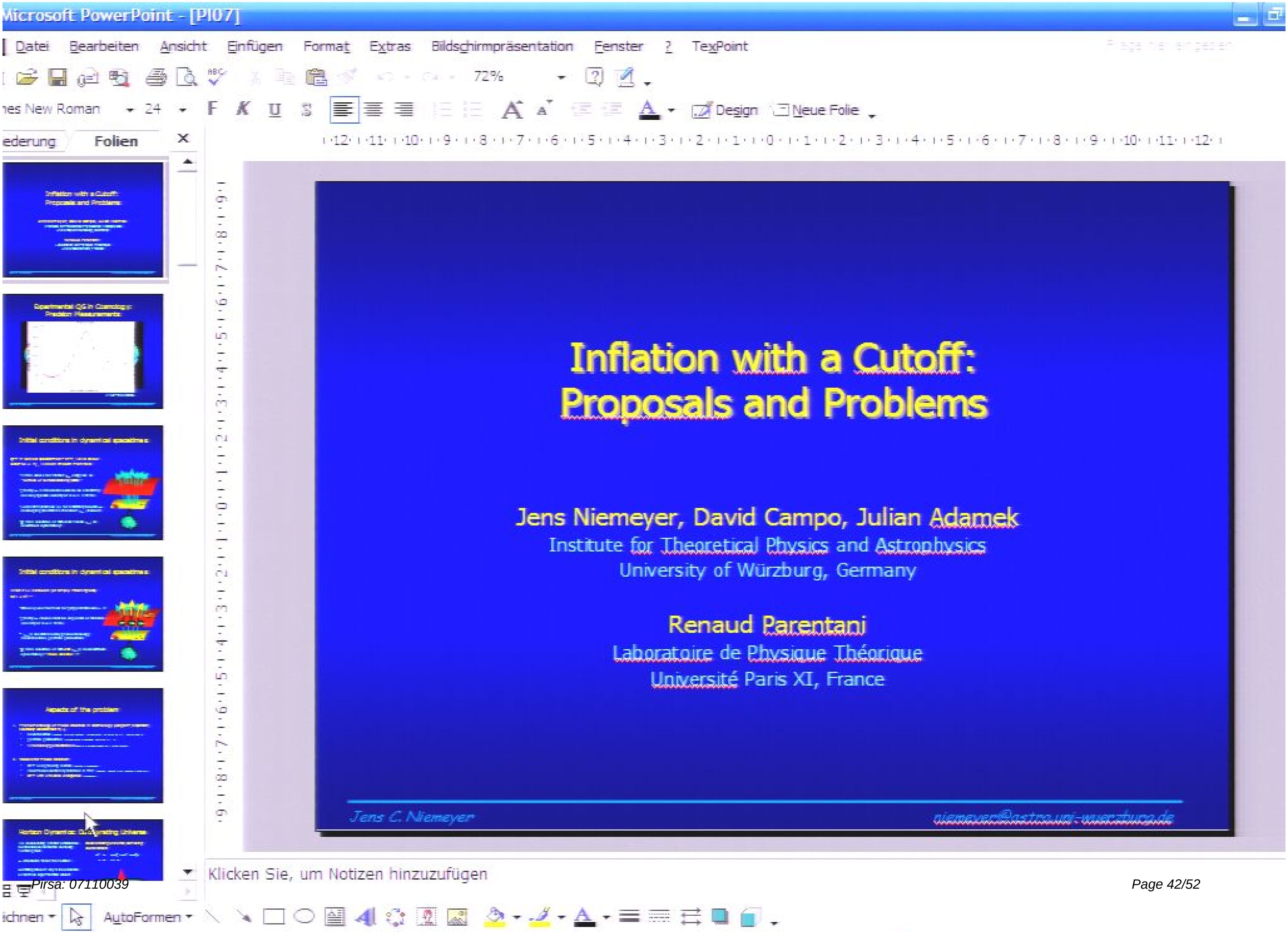
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1. flat space, time dependent formulation with interaction chosen so that G_r obeys local equation of motion:

$$S_T^{(n)}(\mathbf{p}) = \frac{1}{2}\int dt\ \phi_{\mathbf{p}}^*(-\partial_t^2 - \omega_p^2)\phi_{\mathbf{p}} + \frac{1}{2}\int dt \int_{-\infty}^{\infty} dk\ \Psi^*(\mathbf{p},k)(-\partial_t^2 - (\pi M k)^2)\Psi(\mathbf{p},k)$$
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$$\Rightarrow \quad [\partial_t^2 + \frac{g_n^2}{M}\partial_t + \omega_p^2] G_r(t,t',p) = \delta(t-t')$$

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Dissipation and Inflation

Dissipation regimes

1. p/a >> M : ϕ is overdamped, strongly coupled to ψ
2. p/a = M : ϕ decouples, becomes underdamped
3. p/a << M : ϕ propagates as free field in the BD vacuum if ψ is in the ground state and the evolution is adiabatic $\Rightarrow$ standard power spectrum for $H/M << 1$ (while $P \sim H^2 T_\psi/M$ for $T_\psi/H >> 1$)

Numerical analysis (Adamek et al., in progress):

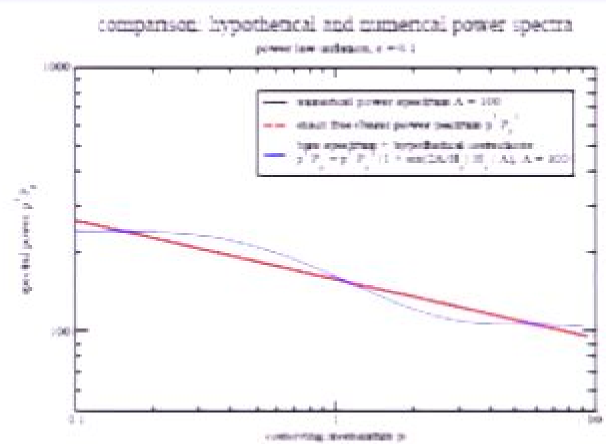

Figure 2: Numerical power spectrum for power law inflation in the zero temperature limit. Again no deviation from the standard result (bare spectrum of a free field). We also included a hypothetical power spectrum featuring some oscillations, typical for some other models.

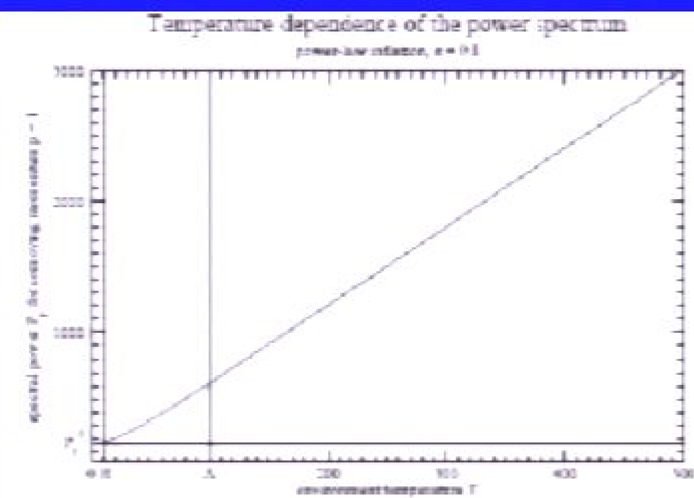

Figure 3: Temperature dependence of the power spectrum for power law inflation. The numerical result smoothly asymptotes to the two analytic limits.

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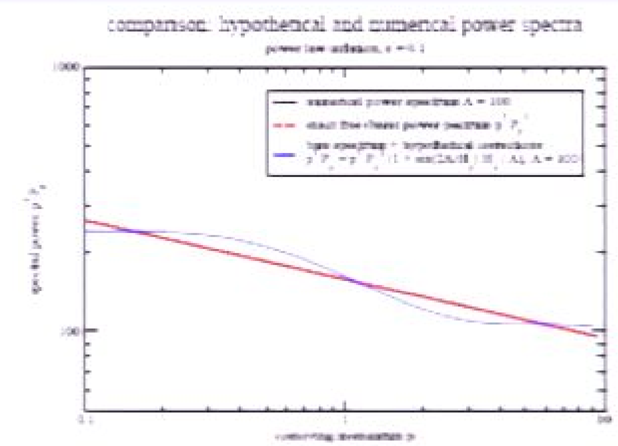

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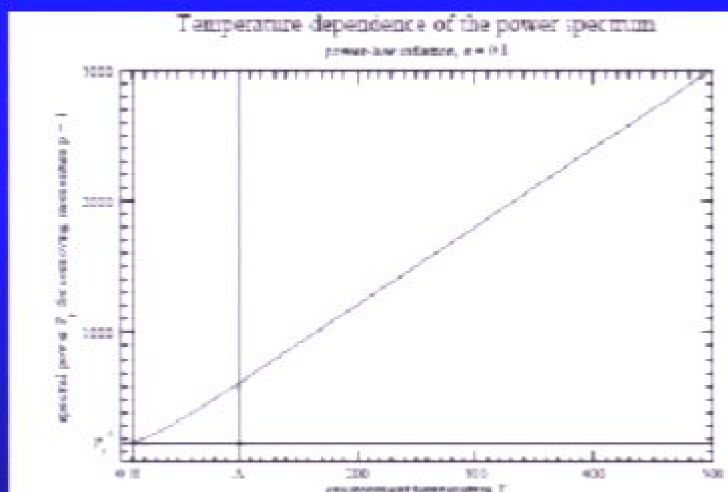

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Summary and Conclusions

LIV in cosmology (re-)raises the problem of mode generation in curved spacetimes

- Interesting and largely unsolved practical and conceptual questions.

Various models for LI-breaking modifications to the production of inflationary perturbations have been analyzed

- Dispersion: modifications of power spectrum suppressed by adiabatic evolution
- Hard mode creation at fixed boundary: potentially observable, oscillatory signature
- Soft mode creation at finite-width boundary: oscillations suppressed

"Parentani model" for dissipation provides generic framework for mode generation

- Application to inflation confirms the absence of oscillations in the power spectrum.

Dissipation and Inflation

Dissipation regimes

1. $p/a \gg M$: ϕ is overdamped, strongly coupled to ψ
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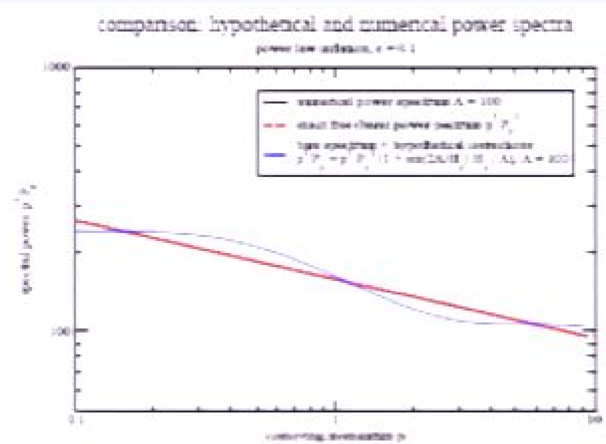

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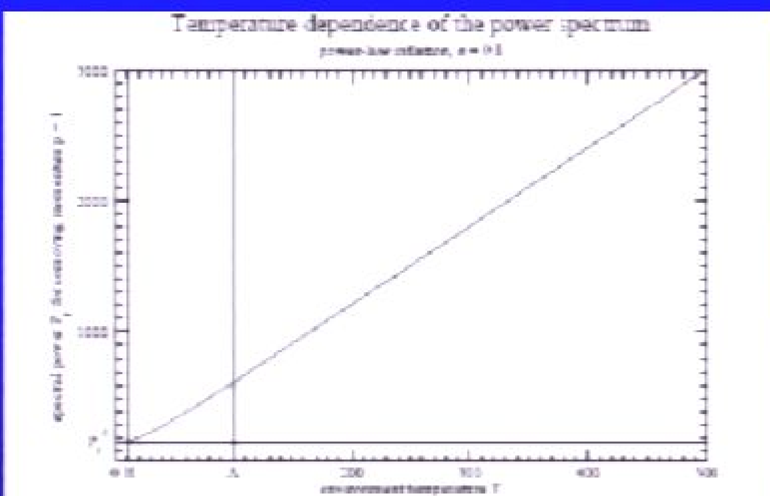

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