CSL as a plausible mechanism for quantum to classical transition of primordial perturbations

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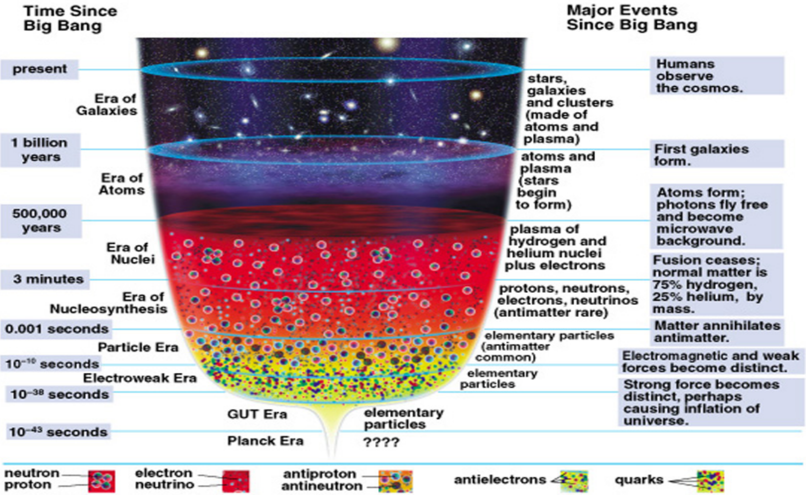
Summary

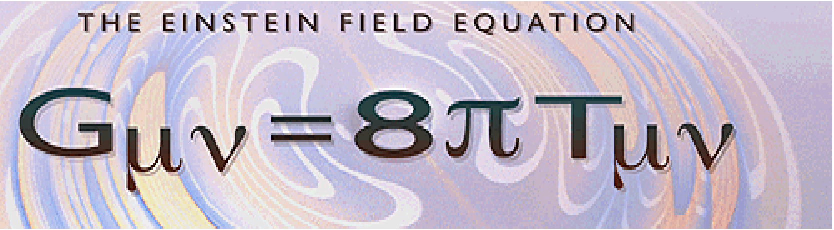
- The Problem
  - Qauntum to Classical transition problem in Cosmological context & in Laboratory System
  - Decoherence as a solution (?)
  - Issues with decoherence
  - Continuous Spontaneous Localization Model : In brief
  - Observational aspects of inflation
- Plausible Solutions with Collapse models
  - Schrödinger representation of inflationary perturbation theory
  - CSL-like modification with constant γ
  - CSL-like modification with scale-dependent γ
- Conclusion

Outline

Evolutionary history of our universe



From theoretical point of view



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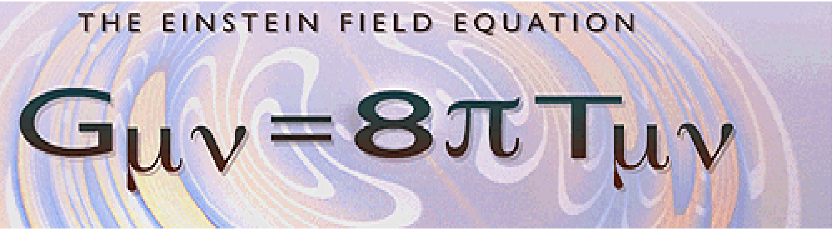
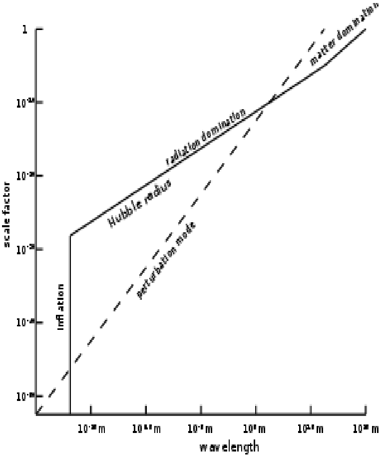


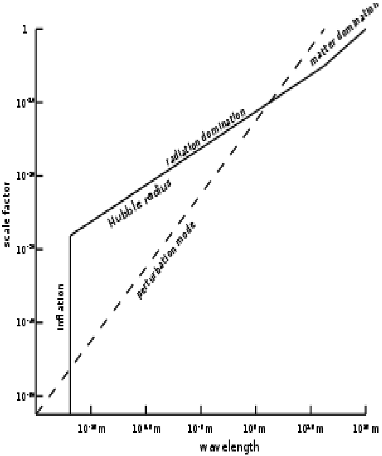
Inflation :

- $T_{\mu\nu} \Longrightarrow$ Scalar field $\Longrightarrow$ *Inflaton*
- Inflaton $\Longrightarrow$ Quantum field $\Longrightarrow \phi_0(t) + \delta\phi(t, \mathbf{x})$
- Perturbations in $T_{\mu\nu} \Longrightarrow$ Quantum perturbations in $g_{\mu\nu}$ $\Longrightarrow g^{(0)}_{\mu\nu} + \delta g_{\mu\nu}$

Inflation & the quantum to classical transition problem

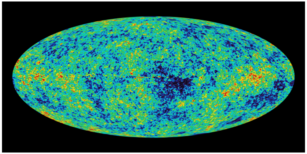


Inflation & the quantum to classical transition problem



Perturbations entering RD :

$$\delta G_{\mu\nu} = 8\pi\delta T_{\mu\nu}^{\text{Radiation}}$$



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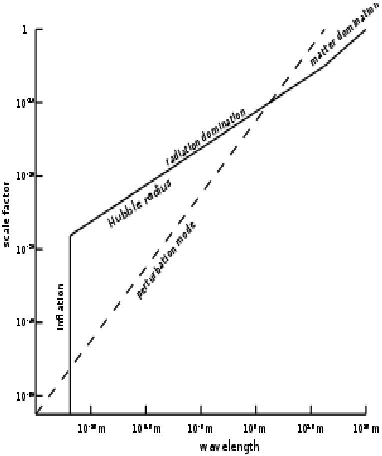

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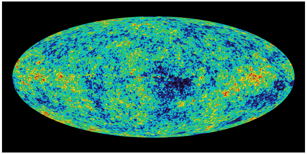
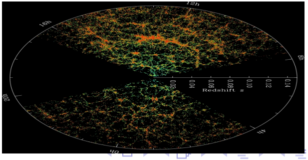


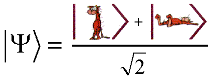
Perturbations entering MD :

$\delta G_{\mu\nu} = 8\pi\delta T_{\mu\nu}^{\text{Matter}}$



The Quantum World

$$H(t)\,|\psi(t)\rangle = i\hbar \frac{d}{dt}\,|\psi(t)\rangle$$



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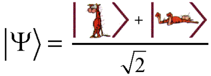
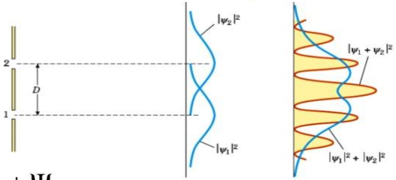


$$P = |\Psi|^2$$

probability of detecting an electron



$$\Psi = \Psi_1 + \Psi_2$$

$$P = |\Psi|^2 = |\Psi_1|^2 + |\Psi_2|^2 + 2\Psi_1\Psi_2^*$$

interference term

Outline

Decoherence in laboratory system

- Open quantum systems $\longrightarrow$ treats the effects of an uncontrollable environment on the quantum evolution
- Interactions between system and its environment $\longrightarrow$ suppression of interference between observable eigenstates

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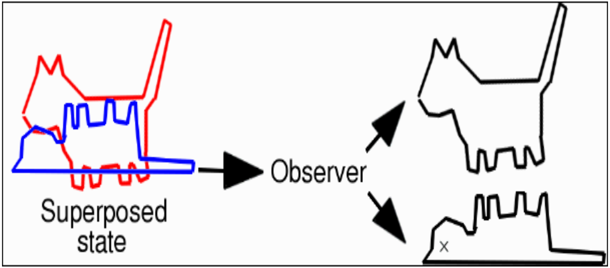
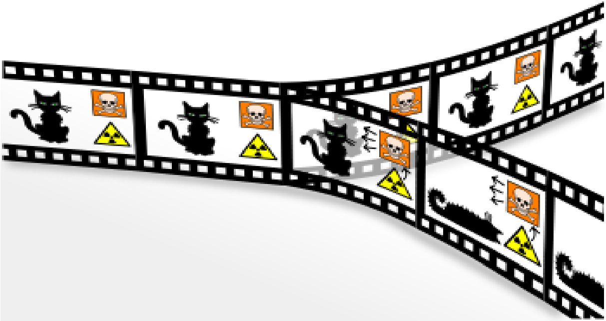


Many Worlds Interpretation for single outcome

Decohered alternatives co-exist in different branches of the Universe

$$\Psi = c_1\psi_1 A_1 O_1 + c_2\psi_2 A_2 O_2$$



Decoherence in Cosmological context

Particles : $[x, p] = i\hbar$
Fields : $[\phi, \pi] = i$

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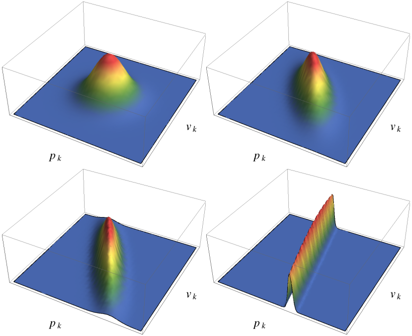
Inflation :

Squeezed in <u>momentum direction</u>

Squeezed states : Quantum but indistinguishable from classical stochastic process

Decoherence without decoherence



Decoherence in Cosmological context

- Later on $\longrightarrow$ even if the classical and quantum expectation values are indistinguishable $\longrightarrow$ the squeezed states are a quantum superposition of all possible field amplitudes $\longrightarrow$ Not an ensemble of stochastically distributed classical values

- Decoherence suppresses the interference between different members of pointer basis $\longrightarrow$ Many World Interpretation justifies the single outcome of our observed universe

Outline

Issues with decoherence in cosmological context

- Decoherence by construction requires an environment $\Longrightarrow$ Cosmology is a closed system analysis
- Small scale modes act as environment $\Longrightarrow$ Difficult to distinguish between large and small scale modes during inflation
- Many-Worlds Interpretation has its own problem as it is not observationally falsifiable
- Also the knowledge of an observer is required in this setup $\Longrightarrow$ But the observers ('We, the human beings') are the end products of the evolutionary history $\Longrightarrow$ classical structure formation starts much before any observer appears in the universe

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So let us try 'Collapse models of Quantum mechanics'

Outline

Continuous Spontaneous Localization : in brief

- Modifies Schrödinger equation by adding non-linear stochastic terms :

$$d\psi_t = \left[-\frac{i}{\hbar} H dt + \frac{\sqrt{\gamma}}{m_0} \int d\mathbf{x} (M(\mathbf{x}) - \langle M(\mathbf{x}) \rangle_t) dW_t(\mathbf{x}) - \frac{\gamma}{2m_0^2} \int d\mathbf{x} \, (M(\mathbf{x}) - \langle M(\mathbf{x}) \rangle_t)^2 dt \right]$$

- Non-linear terms breaks the superposition of wavefunctions

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- Non-linear terms breaks the superposition of wavefunctions
- Amplification mechanism :

$$\gamma(m) = \gamma_0 \left(\frac{m}{m_N} \right)^{\beta}, \qquad \gamma(m) = n^2 \gamma_0 \left(\frac{m}{m_N} \right)^{\beta}$$

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- Hamiltonian not conserved due to non-linear terms $\Longrightarrow$ Non-conservation of energy

$$\langle E\rangle = \frac{3\gamma\alpha\hbar^2}{4m}t$$

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- Relativistic (Field theoretic) version of CSL is yet to be developed

Outline

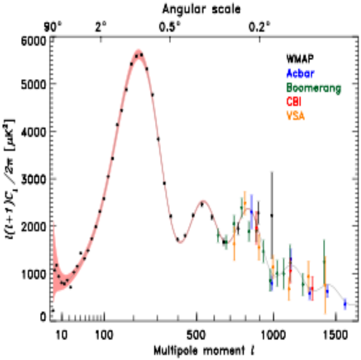
Observational aspects of inflation

Scale Invariance of power spectrum :

- Power spectrum $\longrightarrow$ Two-point correlation function of field fluctuations
- Recall $\longrightarrow$ Einstein equations $\longrightarrow \delta T_{\mu\nu} \Longrightarrow \delta G_{\mu\nu}$
- During Inflation $\longrightarrow \delta T_{\mu\nu} = \delta\phi \longrightarrow \delta g_{\mu\nu}$:
  - Scalar perturbations : Φ
  - ~~Vector perturbations~~
  - ~~Tensor perturbations~~
- Construct Gauge-invariant scalar quantity $\longrightarrow$ Comoving Curvature perturbations $\mathcal{R} \longrightarrow$ made up of $\delta\phi$ and Φ

Observational aspects of inflation

- $\mathcal{P}_{\mathcal{R}}(k) \equiv \frac{k^3}{2\pi^2} \langle \mathcal{R}(k)\mathcal{R}(k) \rangle = A_s k^{n_s - 1}$
- $\langle \mathcal{R}(k)\mathcal{R}(k) \rangle \propto \left\langle \frac{\delta T}{T} \frac{\delta T}{T} \right\rangle \Big|_{\mathrm{CMB}}$
- Experiments show $n_s \approx 1$ (WMAP : 0.971 ± 0.010, PLANCK : 0.9635 ± 0.0094)
- Any modification to inflationary dynamics should respect scale-invariance



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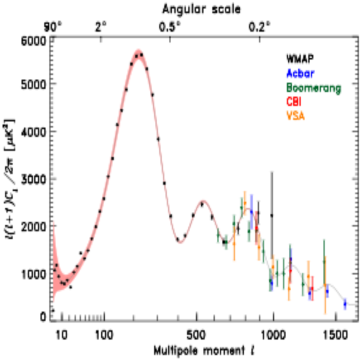
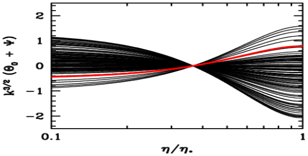


Phase Coherence : Responsible for nice peaks and troughs in the CMBR anisotropy spectrum

More on phase coherence ...

S. Dodelson, AIP Conf. Proc. **689**, 184 (2003)

Inflation predicts that modes do not evolve on super-horizon scales and re-enter the horizon with the same phase for a particular wave number $\longrightarrow$ All the modes contributing to the First peak undergo half an oscillation till last scattering surface (LSS) and so they are all at their peak $\longrightarrow$ amplitude is the sum over all of them



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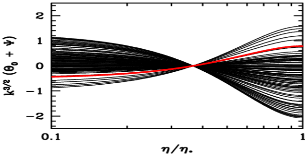
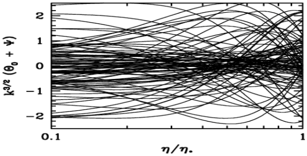


If there is no phase coherence then at re-entry different modes will be at random phases at LSS and the First peak will be washed out



Outline

Schrödinger picture analysis

- Primordial
scalar perturbations in terms of Mukhanov-Sasaki variable :

$$\zeta(\tau, \mathbf{x}) = a\left[\delta\varphi^{\mathrm{gi}} + \varphi_0' \frac{\Phi_B}{\mathcal{H}}\right]$$

- Convenient as it is related to comoving curvature perturbation

$$\zeta(\tau, \mathbf{x}) = \frac{a\varphi_0'}{\mathcal{H}} \mathcal{R}(\tau, \mathbf{x})$$

- Recall $\mathcal{R}$ freezes on super-Hubble scales $\longrightarrow$ So we need not to bother about their evolution once they are superhorizon

Schrödinger picture ...

- Quantum state of the system is described by wavefunctional $\Psi\left[\zeta_{\mathbf{k}}\right] \longrightarrow$ Satisfy the functional Schrödinger equation

$$i\frac{\partial \Psi_{\mathbf{k}}^{\mathrm{R,I}}}{\partial \tau} = \hat{\mathcal{H}}_{\mathbf{k}}^{\mathrm{R,I}} \Psi_{\mathbf{k}}^{\mathrm{R,I}}$$

- Hamiltonian that of harmonic oscillator

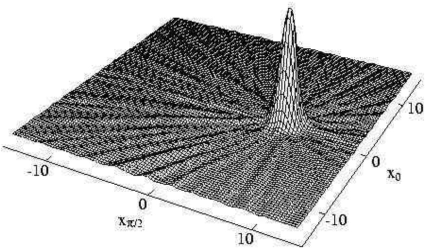
$$\hat{\mathcal{H}}_{\mathbf{k}}^{\mathrm{R,I}} = -\frac{1}{2}\frac{\partial^2}{\partial\left(\zeta_{\mathbf{k}}^{\mathrm{R,I}}\right)^2} + \frac{1}{2}\omega^2\left(\zeta_{\mathbf{k}}^{\mathrm{R,I}}\right)^2, \qquad \omega^2 \equiv k^2 - \frac{a''}{a}$$

- The solution to the functional Schrödinger equation is a functional Gaussian state

$$\Psi_{\mathbf{k}}^{\mathrm{R,I}}\left[\tau, \zeta_{\mathbf{k}}^{\mathrm{R,I}}\right] = \sqrt{N_k(\tau)}\exp\left(-\frac{\Omega_k(\tau)}{2}\left(\zeta_{\mathbf{k}}^{\mathrm{R,I}}\right)^2\right)$$

Wigner function and coherent states

- In QM $\longrightarrow$ Wigner function is a phase space probability distribution of a state
- Coherent states $\longrightarrow$ dynamics most closely resembles the oscillating behaviour of a classical harmonic oscillator



Wigner function and squeezing

- Wigner function recognizes the correlation between position (in this case the field amplitude) and momentum (canonical to the field in this case)

$$\begin{aligned}\mathcal{W}\left(\zeta_{\mathbf{k}}^{\mathrm{R}}, \zeta_{\mathbf{k}}^{\mathrm{I}}, p_{\mathbf{k}}^{\mathrm{R}}, p_{\mathbf{k}}^{\mathrm{I}}\right) &= \frac{1}{(2\pi)^2}\int dx dy \Psi^*\left(\zeta_{\mathbf{k}}^{\mathrm{R}} - \frac{x}{2}, \zeta_{\mathbf{k}}^{\mathrm{I}} - \frac{y}{2}\right) e^{-ip_{\mathbf{k}}^{\mathrm{R}}x - ip_{\mathbf{k}}^{\mathrm{I}}y}\Psi\left(\zeta_{\mathbf{k}}^{\mathrm{R}} + \frac{x}{2}, \zeta_{\mathbf{k}}^{\mathrm{I}} + \frac{y}{2}\right)\\ &= \frac{1}{\pi^2} e^{-\mathrm{Re}\,\Omega_k\left(\zeta_{\mathbf{k}}^{\mathrm{R}^2} + \zeta_{\mathbf{k}}^{\mathrm{I}^2}\right)} e^{-\frac{\left(p_{\mathbf{k}}^{\mathrm{R}} + \mathrm{Im}\,\Omega_k \zeta_{\mathbf{k}}^{\mathrm{R}}\right)^2}{\mathrm{Re}\,\Omega_k}} e^{-\frac{\left(p_{\mathbf{k}}^{\mathrm{I}} + \mathrm{Im}\,\Omega_k \zeta_{\mathbf{k}}^{\mathrm{I}}\right)^2}{\mathrm{Re}\,\Omega_k}}\end{aligned}$$

- During Inflation $\Longrightarrow$ on superhorizon scales $\mathrm{Re}\,\Omega_k \to 0$

$$\mathcal{W}\left(\zeta_{\mathbf{k}}^{\mathrm{R}}, \zeta_{\mathbf{k}}^{\mathrm{I}}, p_{\mathbf{k}}^{\mathrm{R}}, p_{\mathbf{k}}^{\mathrm{I}}\right) \to \frac{\mathrm{Re}\,\Omega_k}{\pi} e^{-\mathrm{Re}\,\Omega_k\left(\zeta_{\mathbf{k}}^{\mathrm{R}^2} + \zeta_{\mathbf{k}}^{\mathrm{I}^2}\right)} \delta\left(p_{\mathbf{k}}^{\mathrm{R}}\right) \delta\left(p_{\mathbf{k}}^{\mathrm{I}}\right)$$

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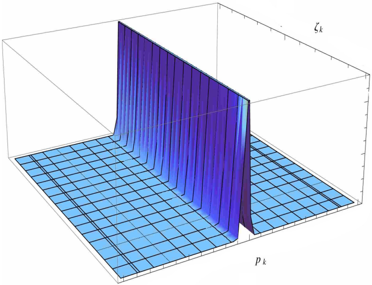
- The power spectrum :

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{k^3}{8\pi^2\epsilon M_{\mathrm{Pl}}^2}\frac{1}{a^2\mathrm{Re}\Omega_k}$$

Wigner function and squeezing

Highly squeezed in momentum direction and spread in field direction



Observation shows classicality in field direction $\longrightarrow$ Expect 'collapse models' to squeeze the modes in field direction

Outline

CSL-like modification with constant γ

- Recall : Functional Schrödiner equation in Inflation :

$$i\frac{\partial \Psi_{\mathbf{k}}^{\mathrm{R,I}}}{\partial \tau} = \hat{\mathcal{H}}_{\mathbf{k}}^{\mathrm{R,I}} \Psi_{\mathbf{k}}^{\mathrm{R,I}}$$

- Modify with 'CSL-like' terms where constant γ

$$d\Psi_{\mathbf{k}}^{\mathrm{R,I}} = \left[-i\hat{\mathcal{H}}_{\mathbf{k}}^{\mathrm{R,I}} d\tau + \sqrt{\gamma}\left(\hat{\zeta}_{\mathbf{k}}^{\mathrm{R,I}} - \left\langle \hat{\zeta}_{\mathbf{k}}^{\mathrm{R,I}} \right\rangle\right) dW_\tau - \frac{\gamma}{2}\left(\hat{\zeta}_{\mathbf{k}}^{\mathrm{R,I}} - \left\langle \hat{\zeta}_{\mathbf{k}}^{\mathrm{R,I}} \right\rangle\right)^2 d\tau\right]$$

- In generic Inflation $\longrightarrow \omega^2 = k^2 - \frac{a''}{a}$
- Now it becomes also complex :

$$\omega^2 = k^2 - 2i\gamma - \frac{a''}{a}$$

Constant γ case : Main results

All quantities calculated depends upon a scale $2\gamma/k^2$

- Smaller scale modes ($2\gamma \ll k^2$)

$$\mathrm{Re}\,\Omega_k \approx 2k(-k\tau)^2 \to 0, \qquad \mathcal{P}_{\mathcal{R}}(k) = \frac{1}{16\pi^2 \epsilon M_{\mathrm{Pl}}^2}$$

  - Not affected by γ
  - Squeezing in momentum direction (can't explain classicality)
  - Power spectrum scale-independent (good for observation)

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- Larger scale modes ($2\gamma \gg k^2$)

$$\mathrm{Re}\,\Omega_k \approx \frac{2\gamma}{k}(-k\tau) \to 0, \qquad \mathcal{P}_{\mathcal{R}}(k) = \frac{k^3}{16\pi^2\epsilon M_{\mathrm{Pl}}^2\gamma k_0} e^{-\Delta N}$$

  - Affected by γ (which we wanted !!)
  - Squeezing in momentum direction (can't explain classicality)
  - Power spectrum scale-dependent (bad for observation)

So far ...

- Constant $\gamma \longrightarrow$ No 'amplification mechanism'
- Squeezing occurs in the momentum direction $\longrightarrow$ same as in generic inflationary scenario
- Longer modes $\longrightarrow$ affected by CSL term $\longrightarrow$ yields scale dependent power $\longrightarrow$ better to keep them outside present horizon
- Shorter modes $\longrightarrow$ not affected by CSL term $\longrightarrow$ produce scale invariant power $\longrightarrow$ but not classicalized

Outline

Scale-dependent γ

- Modes to behave more classically as they start crossing the horizon
- γ should discriminate between different modes according to their physical length scales $\longrightarrow$ grow stronger as a mode starts crossing the horizon during inflation
- γ should be a function of time

Scale-dependent γ

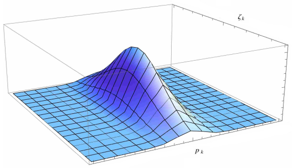
- Modes to behave more classically as they start crossing the horizon
- γ should discriminate between different modes according to their physical length scales $\longrightarrow$ grow stronger as a mode starts crossing the horizon during inflation
- γ should be a function of time
- Phenomenological ansatz :

$$\gamma = \frac{\gamma_0(k)}{(-k\tau)^{\alpha}}, \qquad 0 < \alpha < 2$$

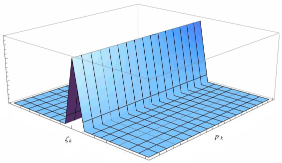
Scale-dependent γ & macro-objectification

- $$\mathrm{Re}\,\Omega_k \approx \frac{k}{2}(-k\tau)^{1-\alpha}\left(\frac{2\gamma_0(k)}{k^2}\right)$$

- $0 < \alpha < 1 \longrightarrow \mathrm{Re}\,\Omega_k \to 0 \longrightarrow$ no macro-objectification
- $1 < \alpha < 2 \longrightarrow \mathrm{Re}\,\Omega_k \to \infty \longrightarrow$ macro-objectification occurs



$\alpha = 0.5$



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Scale-dependent γ & scale-invariance of Power spectrum

- Use k dependence of γ

$$\gamma_0(k) = \tilde{\gamma}_0 \left(\frac{k}{k_0}\right)^{\beta}$$

- $\mathcal{P}_{\mathcal{R}}(k) \propto k^{3+\alpha-\beta}$
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- $4 < \beta < 5$ for $1 < \alpha < 2$

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- This scenario satisfies two observations : Single value of the field consistent with the classical behaviour of the observation and scale invariant power spectrum for a certain range of parameter values.

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- The evolution of the mode function is such that if δ_k is constant for superhorizon scales then the amplitude of the comoving curvature pertubation $\mathcal{R}_k$ is also constant and does not evolve in time
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Phase coherence contd

- Cosntant γ case for larger modes:

$$\frac{d|\mathcal{R}_k|}{d\tau} \propto 1/\sqrt{-\tau}$$

  Amplitude grows and do not freeze
- Constant γ case for smaller modes:

$$\frac{d|\mathcal{R}_k|}{d\tau} \propto \text{constant}$$

  Amplitude freezes
- Scale-deendent γ case

$$\frac{d|\mathcal{R}_k|}{d\tau} \propto (-\tau)^{\alpha-1}/2$$

  For $\alpha > 1$ the amplitude freezes

Conclusion

- Scale-dependent γ modification can yield macro-objectification of modes
- Range should be $1 < \alpha < 2$
- For scale-invariant spectrum γ should be function of wavenumber
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Thank you for your attention !!