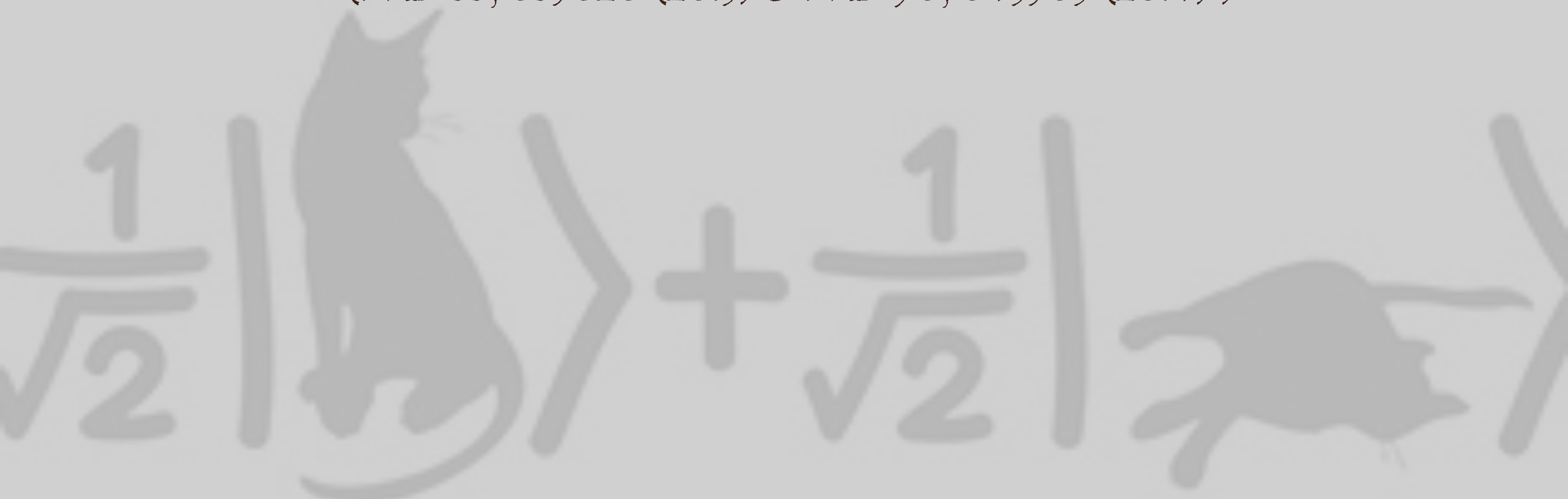
Cosmic Inflation and the measurement problem

(PRD 88, 085020 (2013) & PRD 90, 043503 (2014))



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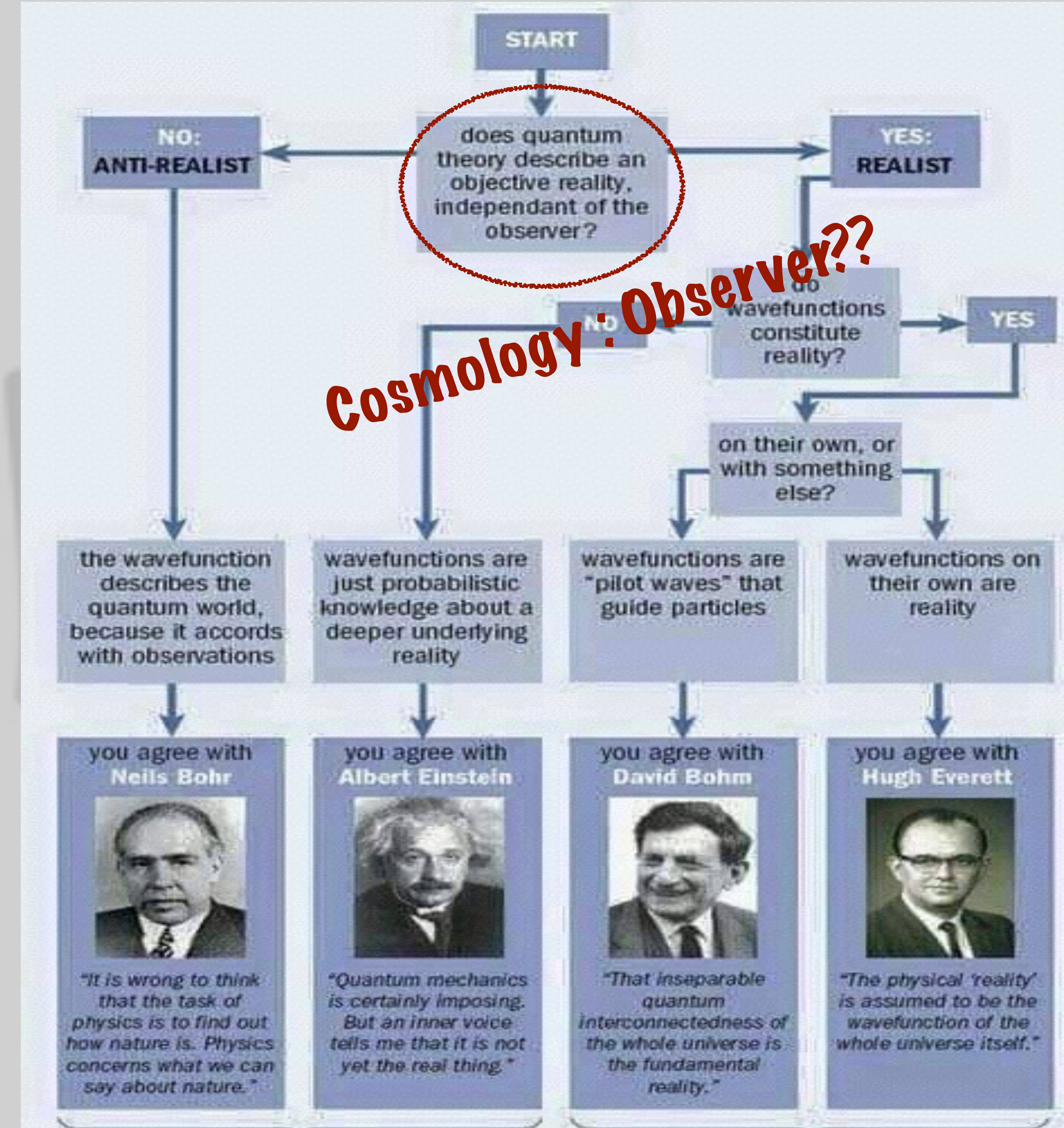
7th December, 2016, ICTS Bengaluru, India


START
does quantum theory describe an objective reality, independant of the observer?
NO: ANTI-REALIST
YES: REALIST
Cosmology : Observer??
do wavefunctions constitute reality?
NO
YES
on their own, or with something else?
the wavefunction describes the quantum world, because it accords with observations
wavefunctions are just probabilistic knowledge about a deeper underlying reality
wavefunctions are "pilot waves" that guide particles
wavefunctions on their own are reality
you agree with Neils Bohr
"It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature."
you agree with Albert Einstein
"Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing."
you agree with David Bohm
"That inseparable quantum interconnectedness of the whole universe is the fundamental reality."
you agree with Hugh Everett
"The physical 'reality' is assumed to be the wavefunction of the whole universe itself."

JEROME'S TALK

Inflationary Paradigm: Success

- Solves Big Bang pathologies
- Generates (quantum) primordial perturbations $\longrightarrow$ seeds for large scale structures, CMB anisotropy
- Predicts (Single field models):

1. Almost scale invariant scalar power spectrum: $n_s = 0.9635 \pm 0.0094$
2. Almost Gaussian distribution of primordial perturbations : $f_{NL} < 2.7 \pm 5.8$
3. Consistency relation : $r = -8n_T$

Quantum to Classical transition of primordial perturbations

Origin of perturbations are quantum but observed structures are classical

- Solutions :

1. Does not modify the basic mechanism of QM : Decoherence
2. Modifies basic mechanism of QM : Collapse models [Continuous Spontaneous Localization (CSL) Model]

   Inherent mechanism evades requirement of observer

Continuous Spontaneous Localization

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

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

- Non-linear terms break the superposition of wave functions

- Amplification Mechanism

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

- Hamiltonian not conserved due to non-Hermitian evolution $\longrightarrow$ Non-conservation of energy

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

Aim : Apply collapse mechanism to evolution equation of primordial perturbations

Inflationary perturbations

- Einstein Field Equations :

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

- Inflation :
  - $T_{\mu\nu}$ is determined by a slowly-rolling scalar field $\longrightarrow$ Inflaton
  - Inflaton $\longrightarrow$ Quantum Field $\longrightarrow$ $\phi_0(t) + \delta\phi(t, \mathbf{x})$
  - Perturbations in $T_{\mu\nu}$ $\longrightarrow$ Induces quantum perturbations in background metric $\longrightarrow$ $g^{(0)}_{\mu\nu}(t) + \delta g_{\mu\nu}(t, \mathbf{x})$
  - Background metric is a tensor and thus the perturbed metric will have scalar, vector and tensor type of perturbations

Scalar perturbations

Schrödinger picture of scalar perturbations

- Scalar perturbations in terms of Mukhanov-Sasaki variable

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

- Quantum state wavefunctional satisfy 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

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

- Solution of 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 & Squeezing

- Wigner function recognises the correlation between position (field) and its momentum (conjugate to field)

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

- During inflation $\longrightarrow$ on superhorizon scales $\mathrm{Re}\,\Omega_k \to 0$

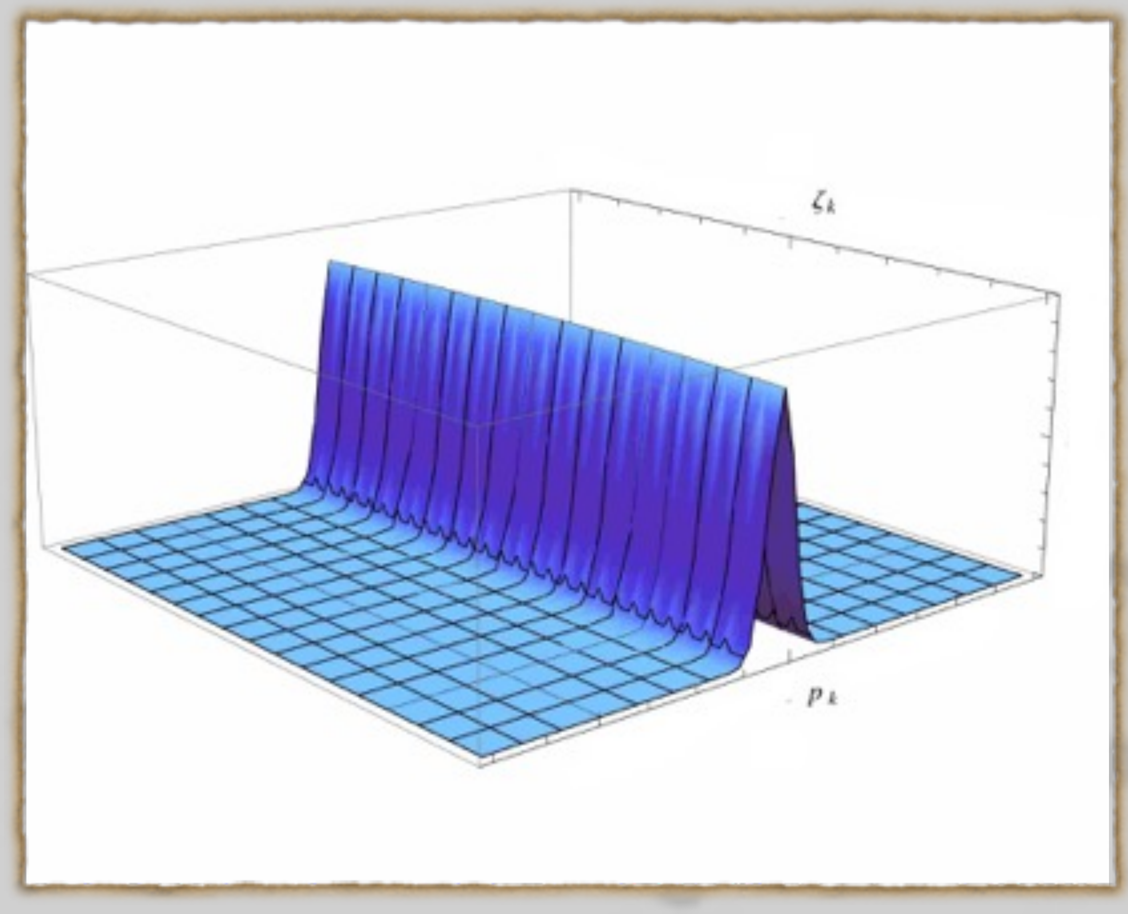
$$\mathcal{W}\left(\zeta_{\mathbf{k}}^{\mathrm{R}},\zeta_{\mathbf{k}}^{\mathrm{I}},p_{\mathbf{k}}^{\mathrm{R}},p_{\mathbf{k}}^{\mathrm{I}}\right) \to \frac{\mathrm{Re}\,\Omega_k}{\pi}e^{-\mathrm{Re}\,\Omega_k\left(\zeta_{\mathbf{k}}^{\mathrm{R}\,2}+\zeta_{\mathbf{k}}^{\mathrm{I}\,2}\right)}\delta\left(p_{\mathbf{k}}^{\mathrm{R}}\right)\delta\left(p_{\mathbf{k}}^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

- Highly squeezed in momentum direction and spread in field

- Observation shows classicality in field direction

Expect `collapse models' to squeeze the modes in field direction

$$\mathrm{Re}\,\Omega_k \to \infty$$



CSL-like modification with constant γ

- Modify functional Schrödinger equation with `CSL-like' terms

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

- Frequency of the Harmonic Oscillator Hamiltonian becomes time dependent and complex

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

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

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

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

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

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

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

Jerome Martin, Vincent Vennin, Patrick Peter (Phys. Rev. D86 (2012) 103524)

Modification by scale-dependent γ

- Modes 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

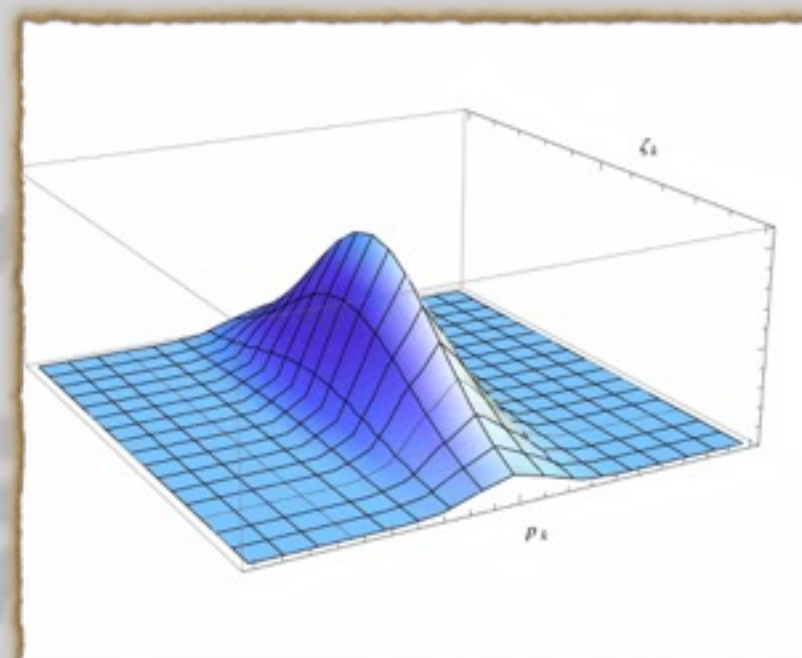
$$\gamma = \frac{\gamma_0(k)}{(-k\tau)^\alpha}\,, \qquad 0 < \alpha < 2$$

on superhorizon scales

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

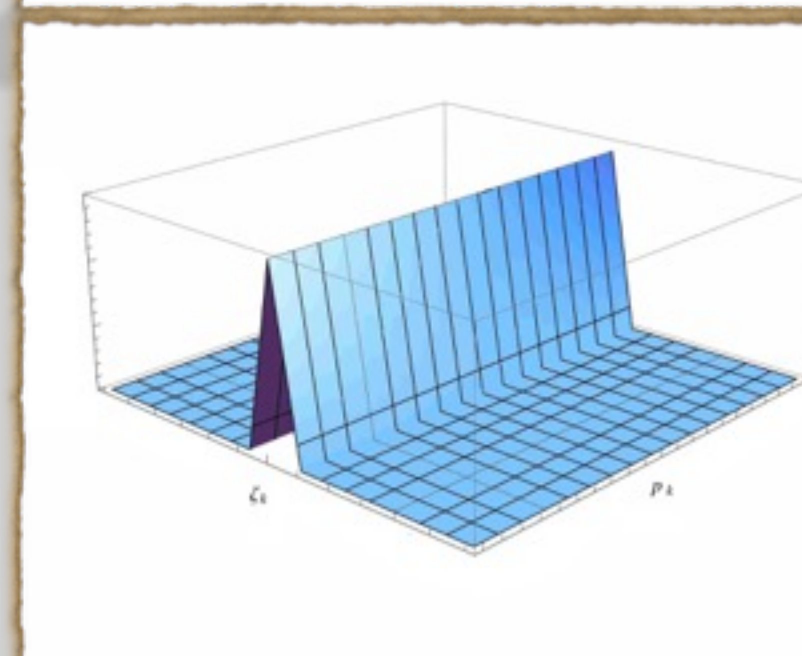
$$0 < \alpha < 1 \quad \longrightarrow \quad \mathrm{Re}\,\Omega_k \to 0$$

No macro-objectification



$$1 < \alpha < 2 \quad \longrightarrow \quad \mathrm{Re}\,\Omega_k \to \infty$$

Macro-objectification occurs



Scale-invariance of power spectrum

- To obtain a scale-invariant power spectrum make γ mode dependent

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

- The power spectrum becomes

$$\mathcal{P}_{\mathcal{R}}(k) \propto k^{3+\alpha-\beta}$$

- $\beta = 3 + \alpha$ yields scale-invariant power spectrum

Vector perturbations $\longrightarrow$ Decay

during inflation $\longrightarrow$ Not Important

Tensor perturbations

Macro-objectification of tensor modes

- Tensor modes $\longrightarrow$ Traceless and transverse part of metric fluctuations $\longrightarrow$ associated with two helicity states $+$ and $\times$
- Each helicity states identical to a massless scalar in de Sitter space
- Previous analysis of scalar perturbations applicable to each helicity states to obtain macro-objectification of tensor modes
- Assumption : CSL-modified dynamics is essentially same for gravitons and inflatons

Observables

- Scalar power spectrum

$$\begin{aligned}\mathcal{P}_{\mathcal{R}} &= \frac{1}{8\pi\epsilon M_{\rm Pl}^2}\frac{k_0^2 H^2}{\tilde{\gamma}_0} e^{-(1+\alpha)\Delta N}\left(\frac{k_*}{k_0}\right)^{3+\alpha-\beta}\left(\frac{k}{k_*}\right)^{3+\alpha-\beta+2\eta-3\epsilon} \\ &\equiv A_s(k_*)\left(\frac{k}{k_*}\right)^{n_s-1}\end{aligned}$$

- Tensor power spectrum

$$\begin{aligned}\mathcal{P}_h &= \frac{2}{\pi^2 M_{\rm Pl}^2}\frac{k_0^2 H^2}{\tilde{\gamma}_0} e^{-(1+\alpha)\Delta N}\left(\frac{k_*}{k_0}\right)^{3+\alpha-\beta}\left(\frac{k}{k_*}\right)^{3+\alpha-\beta-2\epsilon} \\ &\equiv A_T(k_*)\left(\frac{k}{k_*}\right)^{n_T}\end{aligned}$$

- Scalar spectral index

$$n_s - 1 = \delta + 2\eta - 4\epsilon \qquad (\delta = 3 + \beta - \alpha)$$

- δ can be of the order of slow-roll parameters
- Tensor spectral index

$$n_T = \delta - 2\epsilon$$

- Tensor-to-Scalar ratio

$$r = -8n_T + 8\delta$$

- Accurate measurements of r and n_T would be able to distinguish this scenario with the generic one

Summary

- Scale dependent collapse parameter can yield micro-objectification of modes, both scalar and tensor
- Wave-number dependence of collapse parameter yield nearly scale-invariance of power spectrum
- Collapse dynamics changes the consistency relation of single-field model
- Accurate measurement of tensor-to-scalar ratio and tensor spectral index can distinguish this dynamics from the generic scenario

Thank You