

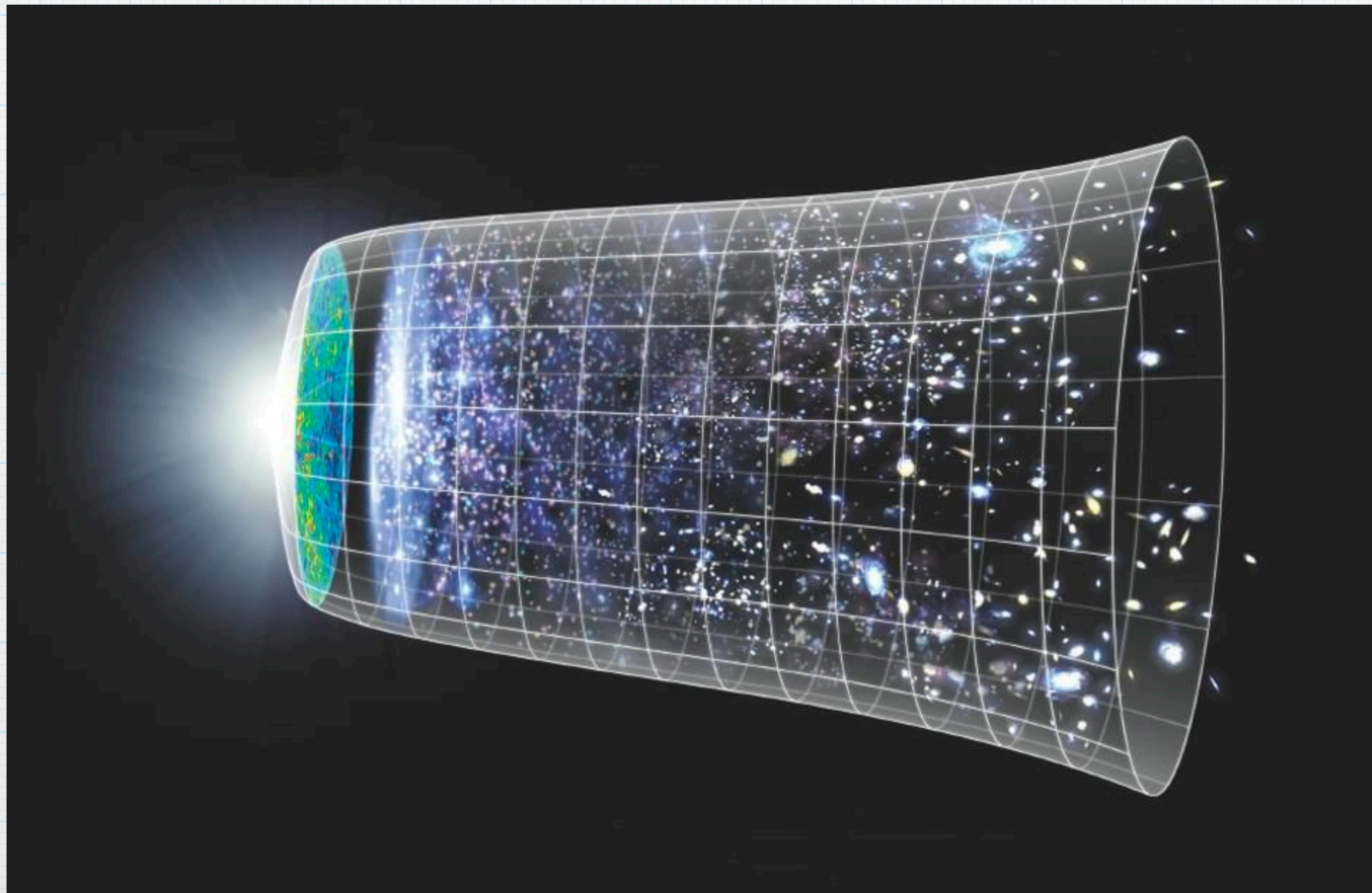
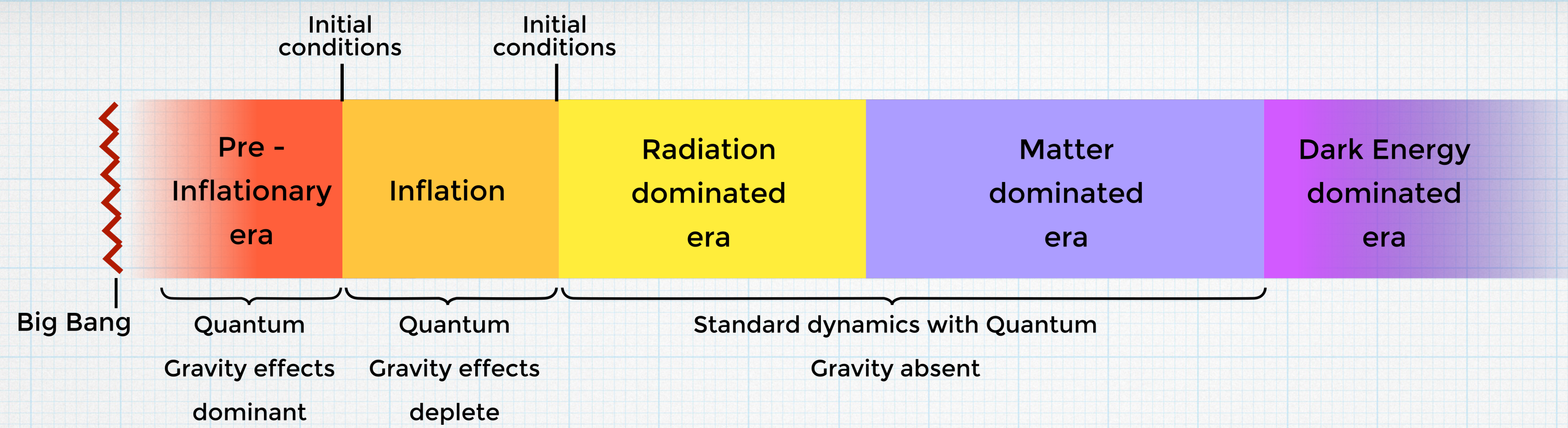
How Classical is our Universe ?

Kinjalk Lochan

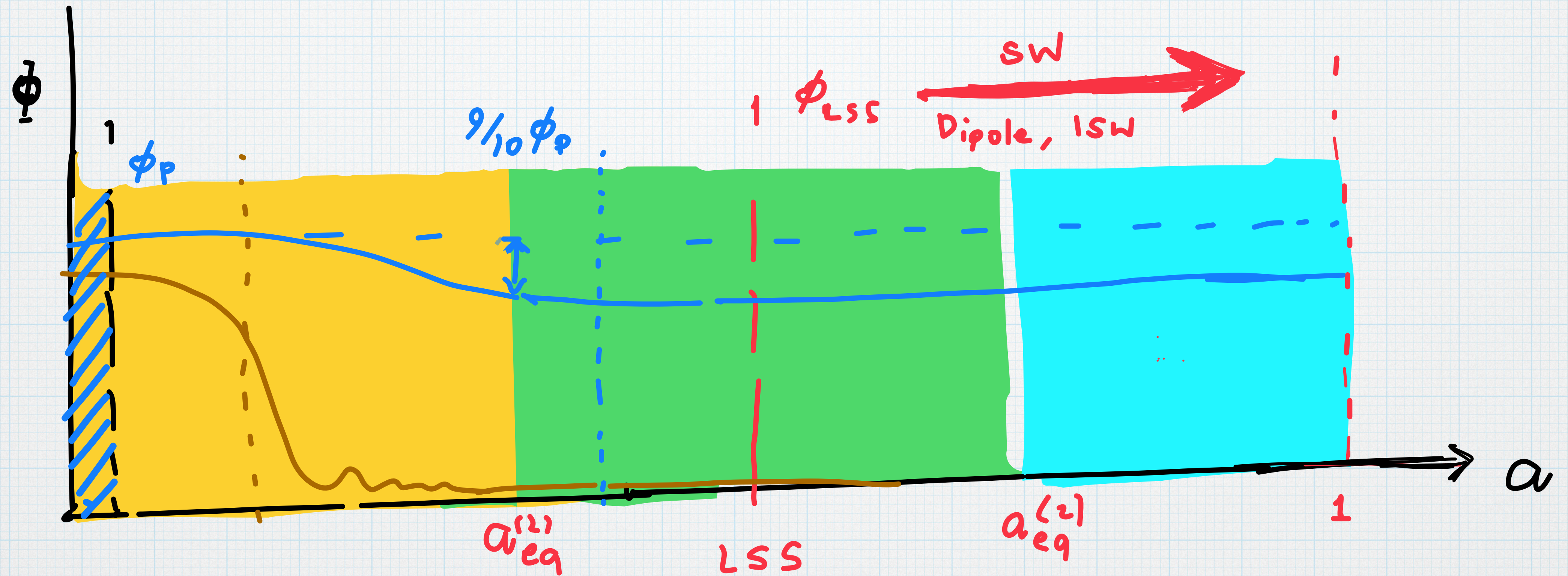


IISER Mohali

From Big Bang to Now: A Theory-Experiment Dialogue
SRM University,
25 -01 - 2025



Primordial seed!

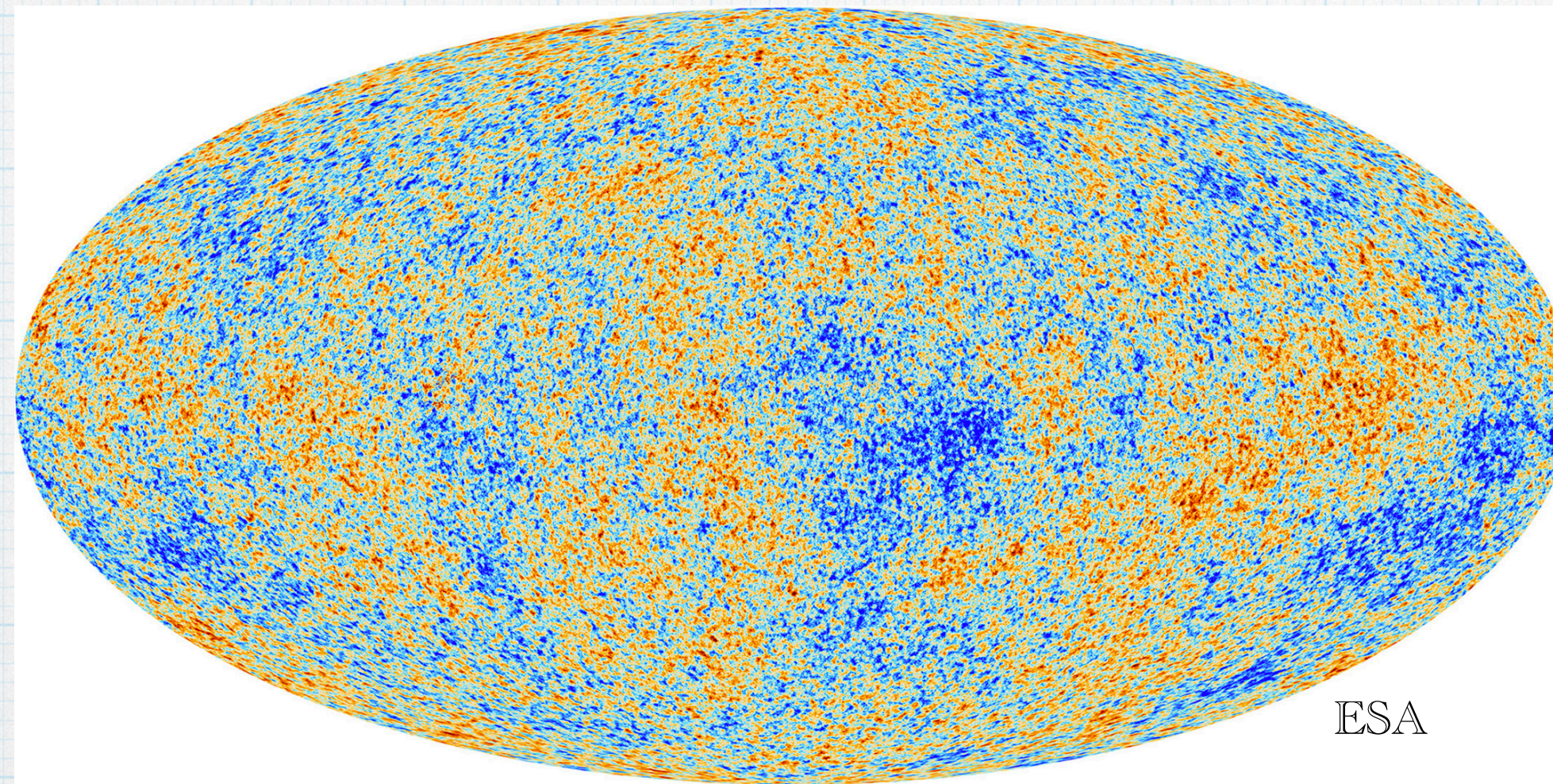


$$\theta_l(k\eta_0) = \left(\theta_0(k\eta_*) + \psi(k\eta_*) \right) j_l(k(\eta_0 - \eta_*))$$

$$\theta_0(k\eta_0) \sim \frac{5}{6} \theta_0(k\eta_*) \sim \frac{5}{9} \Phi(k\eta_*) \sim \frac{\Phi_P}{2}$$

Universe : Post Born Quantum

- * Past tracking inevitably takes the universe into the quantum domain
- * How do we know if the universe was ever quantum ?



- * Primordial seed $\rightarrow$ large wavelength $9/10 \rightarrow$ Freezing of Modes

Puzzle at hand !

The Universe (homogeneous and isotropic) expands and accelerates !

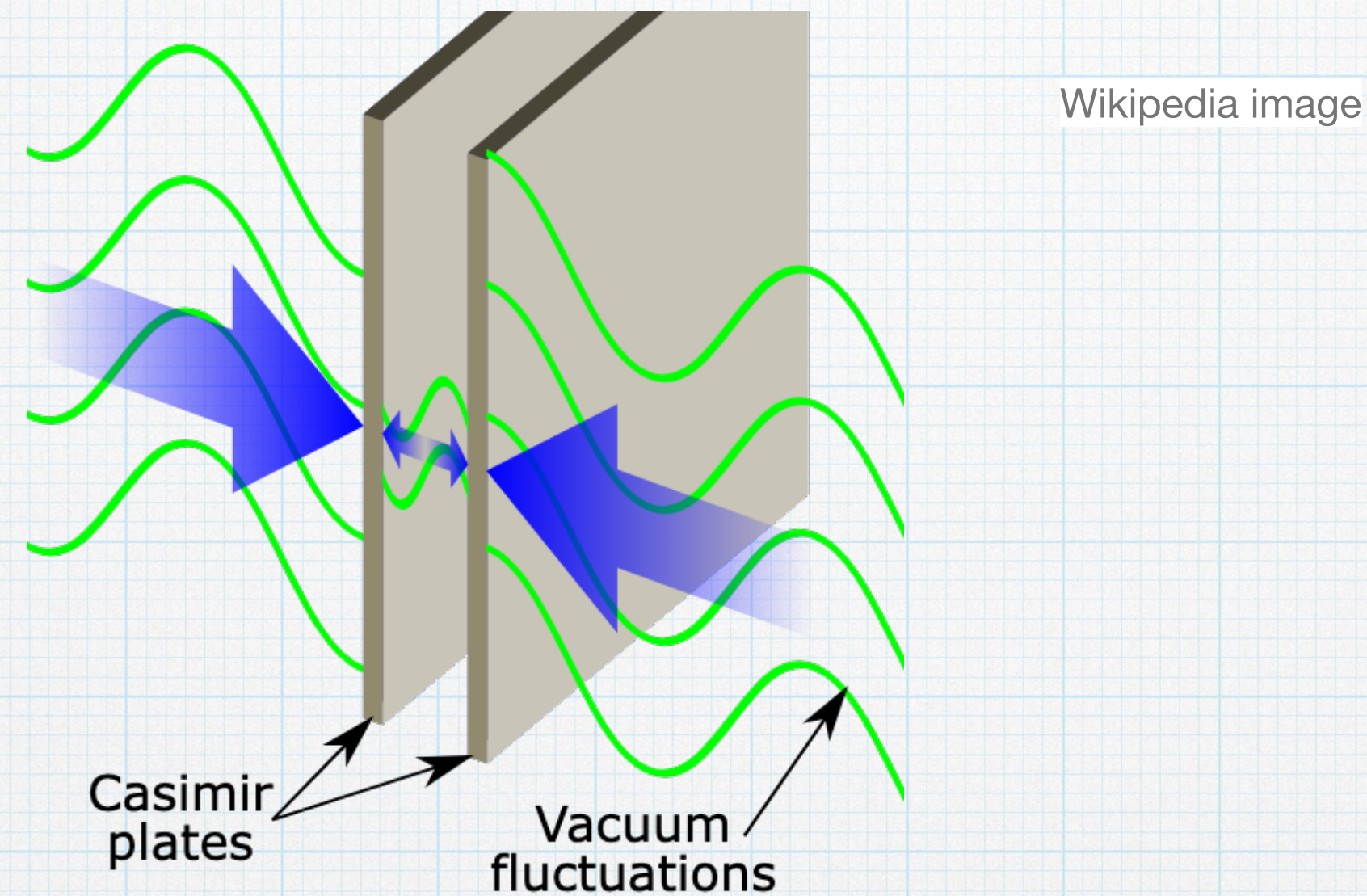
For that to happen : $\rho + 3P < 0$

Normal matters do not do that !

So we invoke **Dark energy** : Entity with negative pressure

Have we ever seen such a thing ?

Vacuum Fluctuations : Also do that



A mysterious cosmological constant does that and so does a slowly evolving homogeneous field !

But they preserve some quantumness of matter riding atop !

Negative Pressure providers are not known to suppress quantum properties !

Can acceleration of the universe be achieved without having quantum effects ?

What happened to universe's quantumness ?

T. Padmanabhan, Phys. Rev. D (1989)

J. Halliwell, Phys. Rev. D (1989)

PHYSICAL REVIEW D

VOLUME 39, NUMBER 10

15 MAY 1989

Decoherence in the density matrix describing quantum three-geometries and the emergence of classical spacetime

T. Padmanabhan

Astrophysics Group, Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India

(Received 1 December 1988)

PHYSICAL REVIEW D

VOLUME 39, NUMBER 10

15 MAY 1989

Decoherence in quantum cosmology

Jonathan J. Halliwell

Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

(Received 27 January 1989)

- * Tracing out unobserved matter d.o.f results in decoherence for gravitational d.o.f.
- * Once the "Classical" geometry has emerged, for observable matter d.o.f. one can do semi classical analysis.
- * Yet primordial seeds are required to turn classical, preferably by the time inflation ends

Decoherence without Decoherence

Polarski, Starobinsky; Class.Quant.Grav. (1996)

Lesgourgues, Polarski, Starobinsky; Nucl. Phys. B(1997)

* Primordial perturbations : Vacuum State gets squeezed

$$y''(\mathbf{k}) + \left(k^2 - \frac{a''}{a} \right) y(\mathbf{k}) = 0.$$

$$u_k = e^{-i(k\eta + \delta_k)} \cosh r_k \quad v_k = e^{i(k\eta + \frac{\pi}{2})} \sinh r_k$$

$$\sinh r_k = \frac{1}{2k\eta} \quad \varphi_k = \frac{\pi}{4} - \frac{1}{2} \arctan \frac{1}{2k\eta}$$

$$f_k = \frac{u_k + v_k^*}{\sqrt{2k}}, \quad |f_k|^2 = \frac{1}{2k} (\cosh 2r_k + \cos 2\varphi_k \sinh 2r_k),$$

$$g_k = \sqrt{\frac{k}{2}} (u_k - v_k^*) = i \left(f'_k - \frac{a'}{a} f_k \right).$$

Squeezing + Decoherence

Kiefer, Polarski; Adv. Sci. Lett. (2009)

Why do cosmological perturbations look classical to us?

Claus Kiefer*

Institut für Theoretische Physik, Universität zu Köln, Zùlpicher Strasse 77, 50937 Köln, Germany

David Polarski†

*Laboratoire de Physique Théorique et Astroparticules, CNRS,
Université de Montpellier II, 34095 Montpellier, France*

$$y''(\mathbf{k}, \eta) + \left(k^2 - \frac{a''}{a} \right) y(\mathbf{k}, \eta) = 0$$

$$y(\mathbf{k}, \eta) = \sqrt{2k} f_{k1}(\eta) y_{\mathbf{k}} - \sqrt{\frac{2}{k}} f_{k2}(\eta) p_{\mathbf{k}}$$
$$p(\mathbf{k}, \eta) = \sqrt{\frac{2}{k}} g_{k1}(\eta) p_{\mathbf{k}} + \sqrt{2k} g_{k2}(\eta) y_{\mathbf{k}}$$

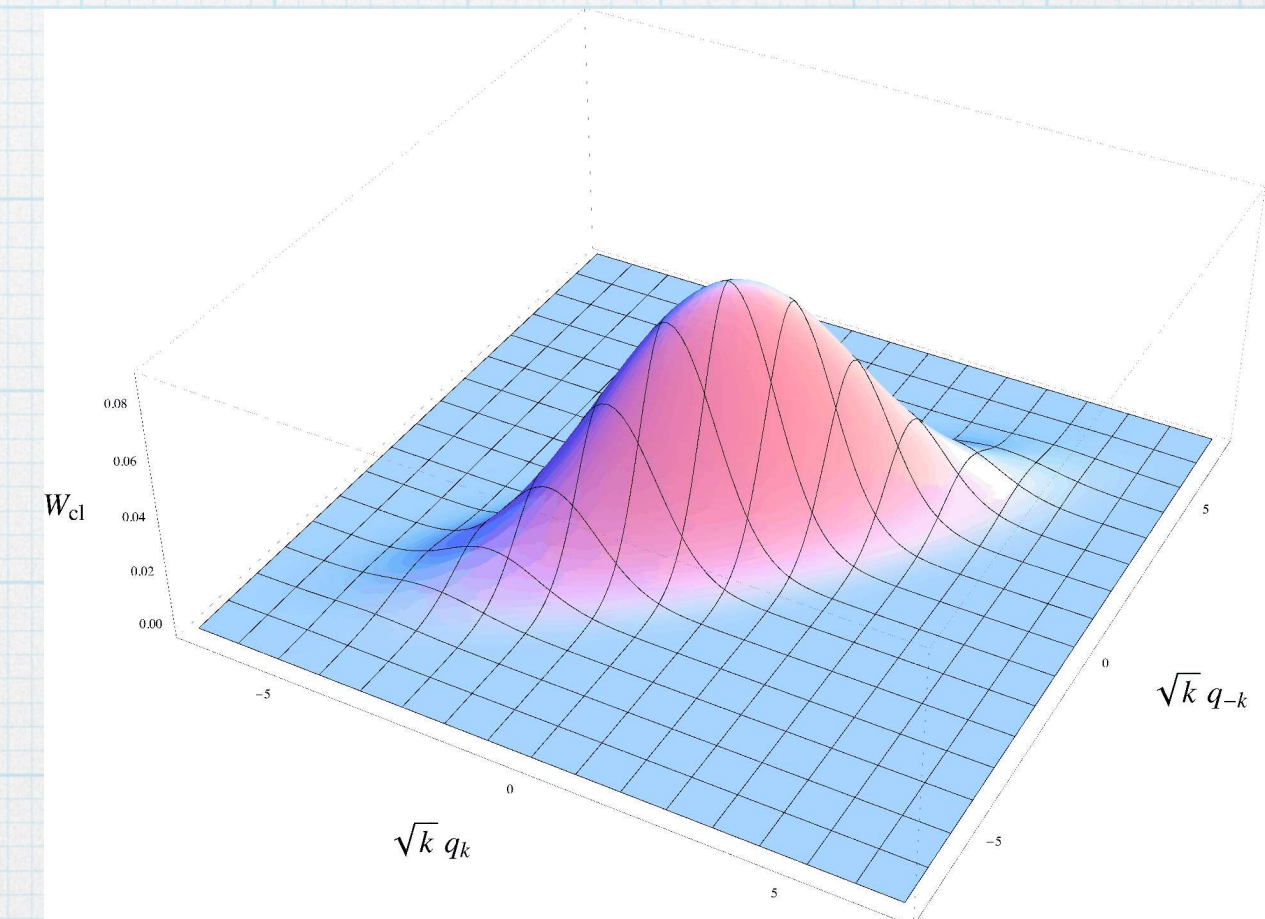
Quantum Character becomes irrelevant
If (f1,g2) or (f2,g1) pair diminish

* Rotate in Phase space and squeeze

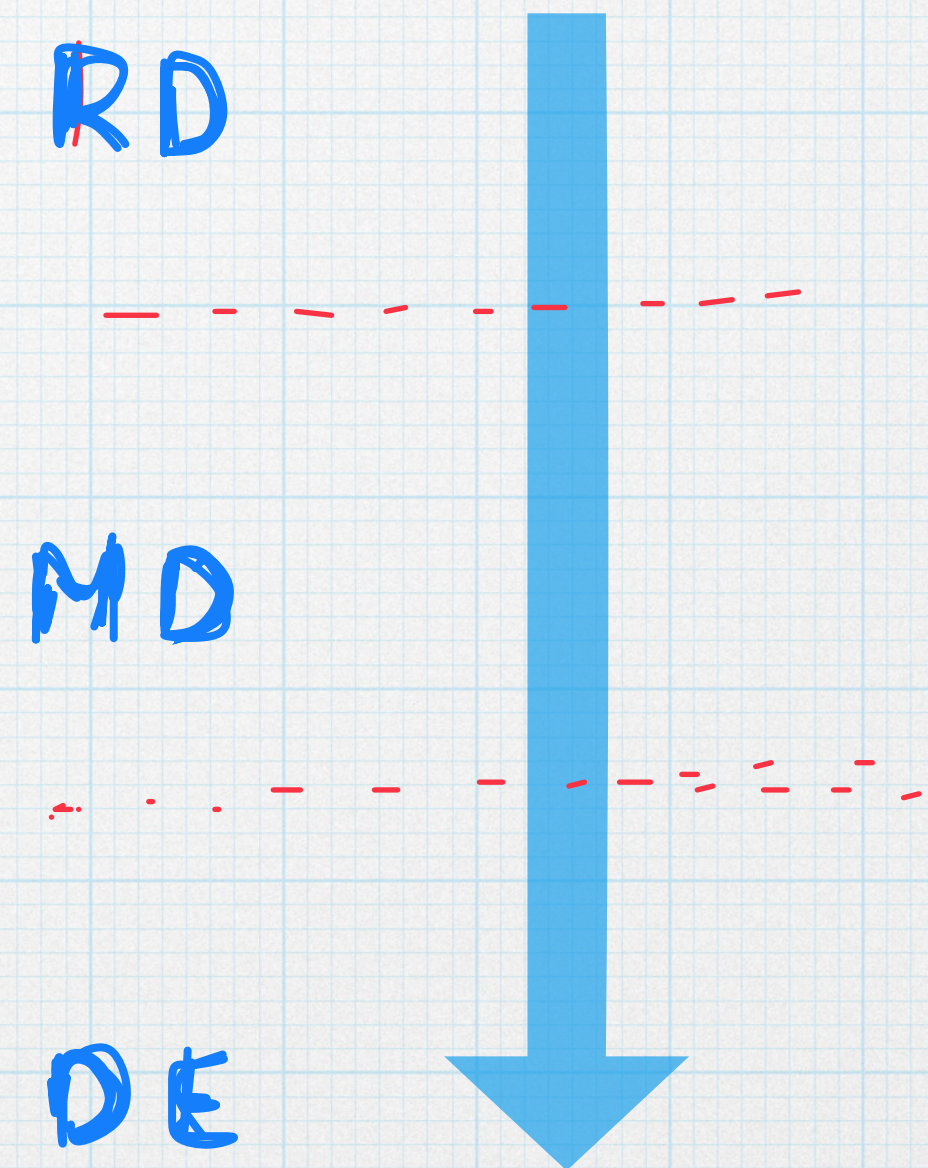
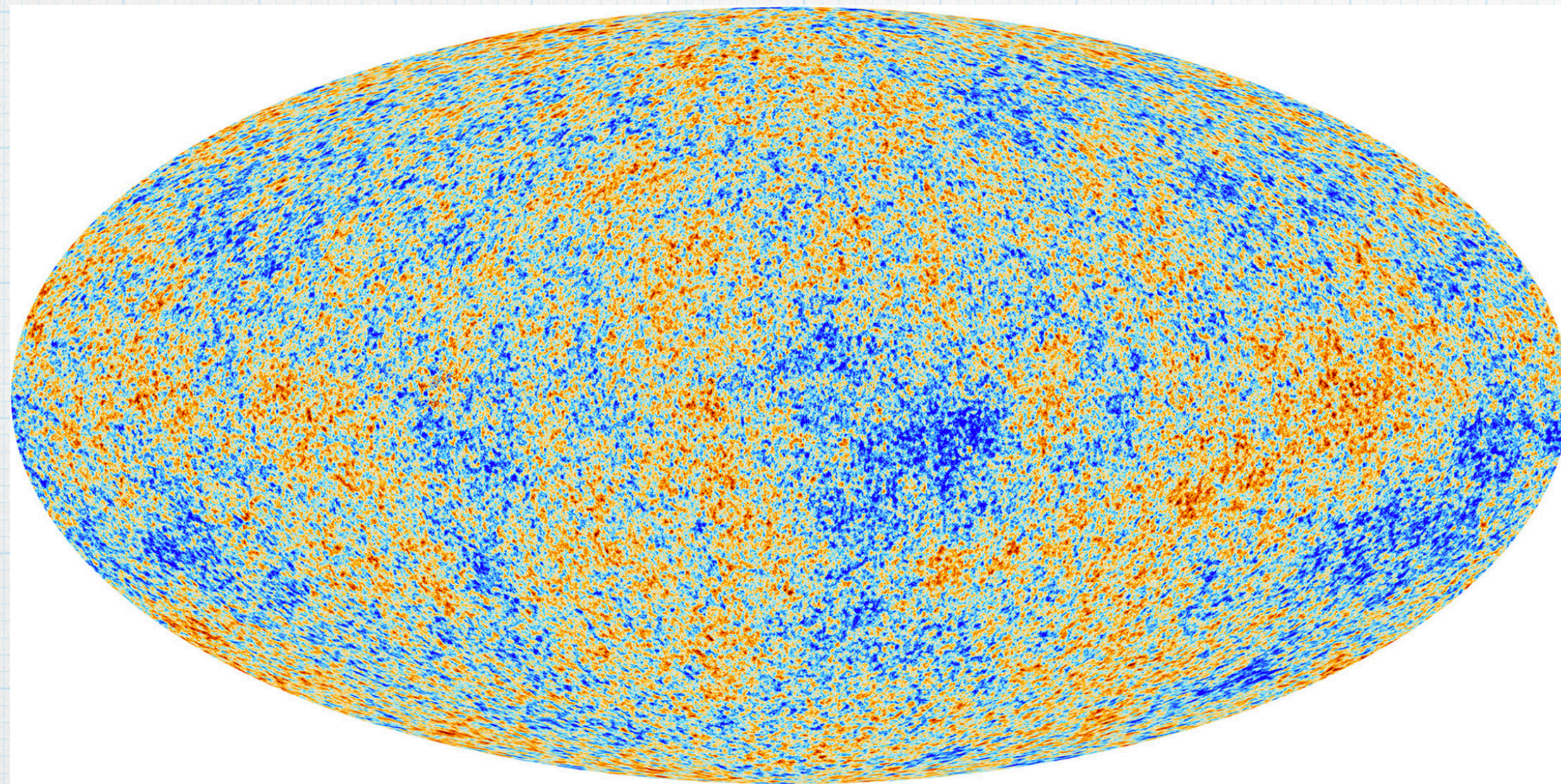
$${}_H \langle 0, \eta_0 | G(y(\mathbf{k})) G^\dagger(y(\mathbf{k})) | 0, \eta_0 \rangle_H = \int \int dy_1(\mathbf{k}) dy_2(\mathbf{k}) \rho(|y(\mathbf{k})|) |G(y(\mathbf{k}))|^2$$

* “Late time final data” can be used as stochastic classical initial data

* A Classical description is apt thereafter



* Primordial seed → large wavelength $9/10$ → Freezing of Modes



* Temperature anisotropy

Expectation versus correlation

- * For independent events

$$P(A \cap B) = P(A) P(B)$$

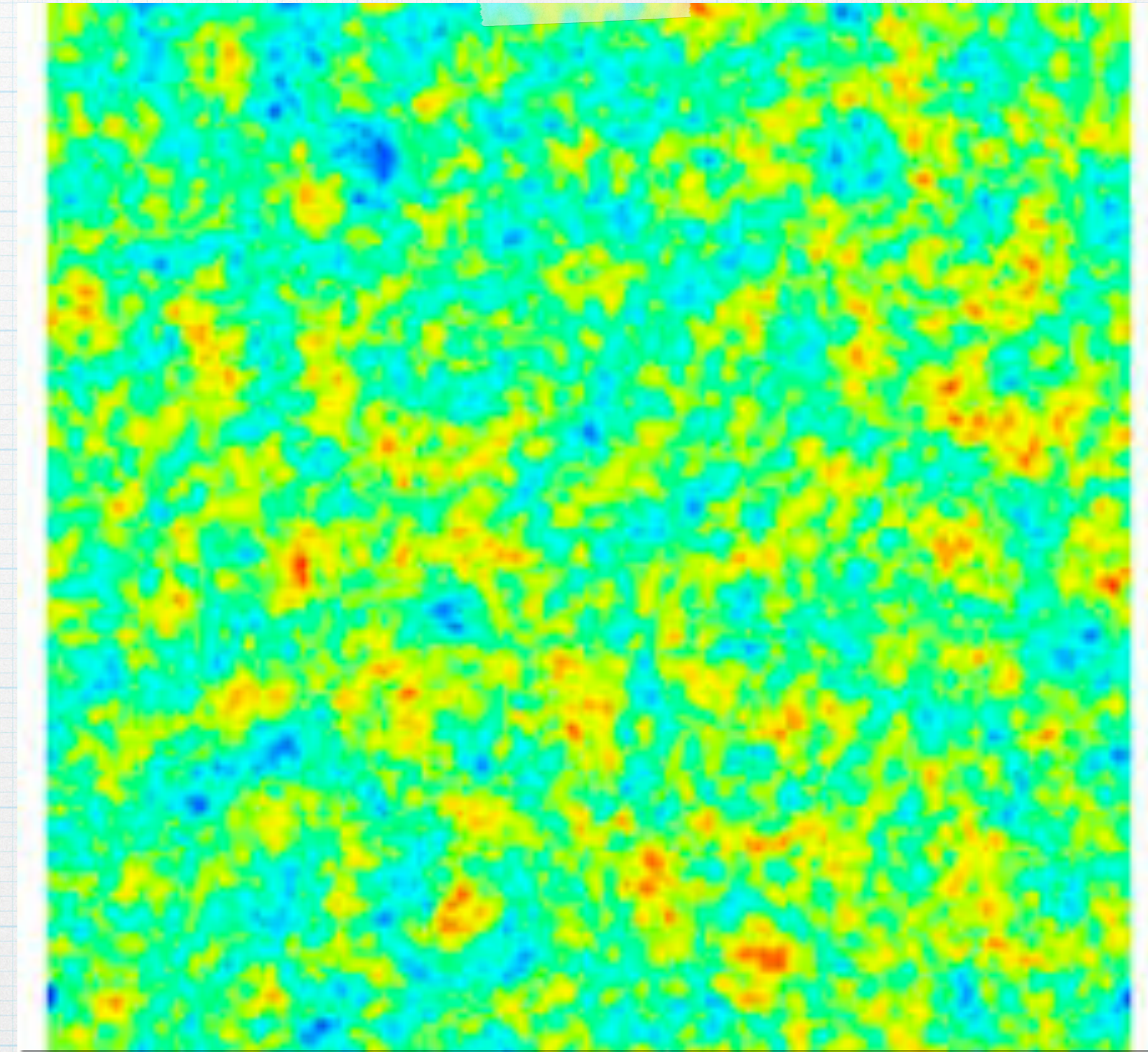
- * For Quantum processes

$$\langle \phi(x)\phi(y) \rangle \neq \langle \phi(x) \rangle \langle \phi(y) \rangle$$

Reminiscent Quantumness

- * Initial quantumness persists. Correlation persists. Entanglement persists.
- * To dub CMBR data completely classical is probably too early !
- * Observable : Quantum interaction with environment leads to Non Gaussianities in primordial perturbations

Martin, Vennin; JCAP (2018)



! Yet Not classical at heart

* Quantum Entanglement : Bell's test

Kanno, Soda; Phys. Rev. D (2017)

Martin, Vennin; Phys. Rev D (2016)

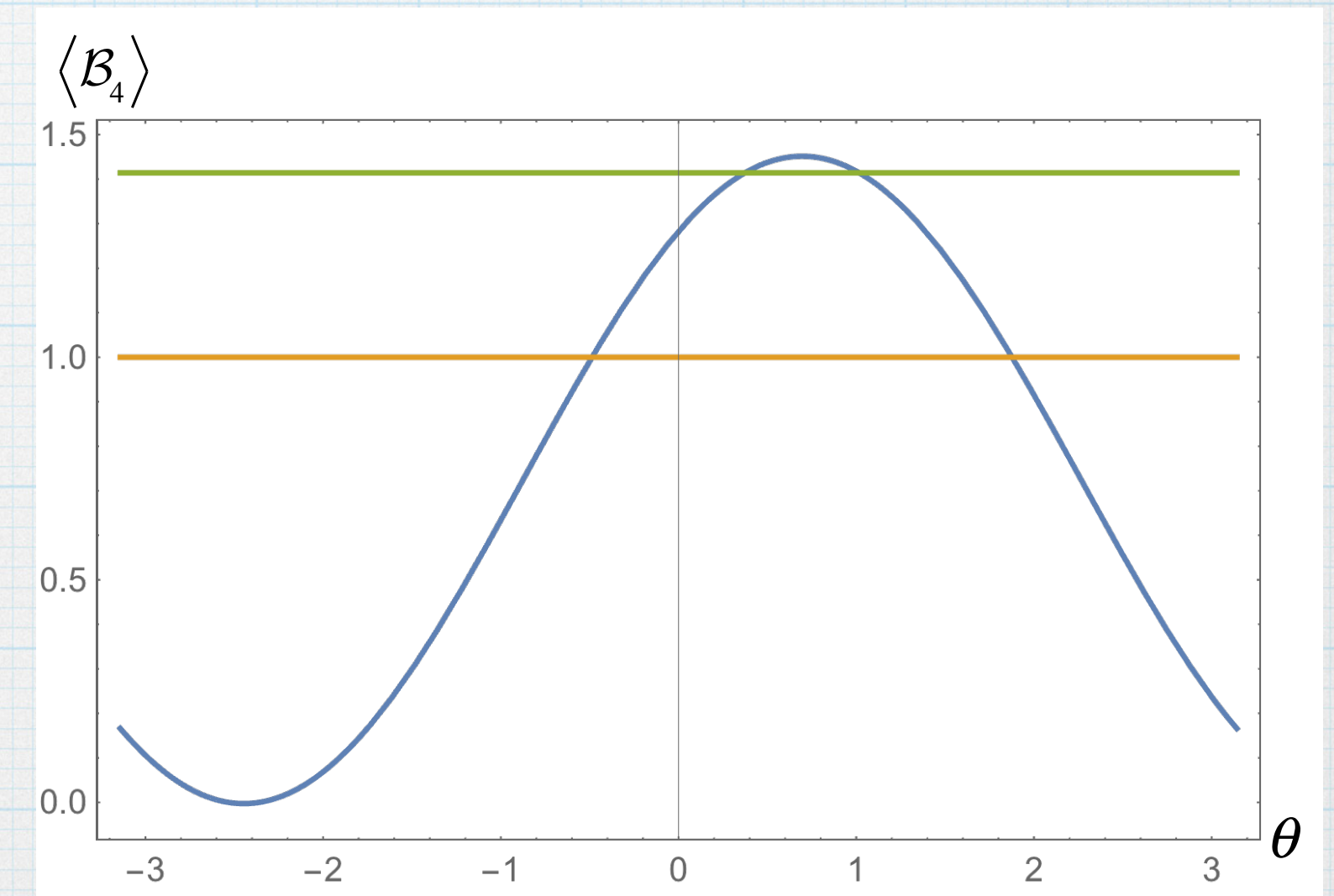
Two-mode squeezed state

$$|0_{\mathbf{k}}^{\text{in}}\rangle = \sum_{n=0}^{\infty} \frac{\tanh^{2n} r_k}{\cosh r_k} |2n_{\mathbf{k}}^{\text{out}}\rangle \otimes |2n_{-\mathbf{k}}^{\text{out}}\rangle + \sum_{n=0}^{\infty} \frac{\tanh^{2n+1} r_k}{\cosh r_k} |(2n+1)_{\mathbf{k}}^{\text{out}}\rangle \otimes |(2n+1)_{-\mathbf{k}}^{\text{out}}\rangle$$

$$\langle 0_{\mathbf{k}}^{\text{in}} | \mathcal{B}_2 | 0_{\mathbf{k}}^{\text{in}} \rangle = \sqrt{1 + \tanh^2 2r_k} \leq \sqrt{2}.$$

$$\begin{aligned} \delta(\mathbf{k}, -\mathbf{k}) &= \cosh^2 r_k \log_2 (\cosh^2 r_k) \\ &\quad - \sinh^2 r_k \log_2 (\sinh^2 r_k) \end{aligned}$$

$$S[\hat{\rho}(\mathbf{k})] = (1 + \langle \hat{n}_k \rangle) \log_2 (1 + \langle \hat{n}_k \rangle) - \langle \hat{n}_k \rangle \log_2 \langle \hat{n}_k \rangle$$



Is the lingering quantumness harmless ?

* Semiclassical treatment

Hu, Verdaguer; Liv. Rev. Relat. (2008)

$$G_{ab}[g] + \Lambda g_{ab} - 2(\alpha A_{ab} + \beta B_{ab})[g] = 8\pi G \langle \hat{T}_{ab}^R[g] \rangle$$

* Second order effect

$$G_{ab}[g+h] + \Lambda(g_{ab} + h_{ab}) - 2(\alpha A_{ab} + \beta B_{ab})[g+h] = 8\pi G \left(\langle \hat{T}_{ab}^R[g+h] \rangle + \xi_{ab}[g] \right)$$

* Stochastic field. Quantum Fluctuations

$$\langle \xi_{ab}[g; x] \xi_{cd}[g; y] \rangle_s = N_{abcd}[g; x, y]$$

* Noise Kernel : Stress Tensor fluctuations

$$N_{abcd}[g; x, y] = \frac{1}{2} \langle \{ \hat{t}_{ab}[g; x], \hat{t}_{cd}[g; y] \} \rangle \quad \hat{t}_{ab}[g; x] \equiv \hat{T}_{ab}[g; x] - \langle \hat{T}_{ab}[g; x] \rangle$$

Noise Kernel in FRW

$$N_{abcd}(x, x') = 2 \lim_{\substack{y \rightarrow x \\ y' \rightarrow x'}} P_{ab}(x, y) P_{cd}(x', y') G(x, x') G(y, y').$$

Dhanuka, KL; Phys. Rev. D (2020)

$$P_{ab}(x, y) = \left(\delta_{(a}^c \delta_{b)}^d - \frac{1}{2} \eta_{ab} \eta^{cd} \right) \nabla_c^x \nabla_d^y - \frac{1}{2} \left(\frac{a(\eta) + a(\eta')}{2} \right)^2 \eta_{ab} m^2$$

* The correlators of the fields decide !

Correlators in early universe

- * The quantum correlations of massless fields do not decay with the growth of scale factor in De Sitter
- * Reflected by infrared divergence for small masses

$$G_{dS}(x, x') = \left(\frac{H^2}{16\pi^2} \right) \left(\frac{2}{\delta} + \frac{4}{y} - 4 - 2\ln(y) + 4\ln 2 + O(\delta) \right)$$

Ford, Parker; Phys. Rev D (1977), Allen; Phys. Rev. D (1985), Ford; Phys. Rev. D (1985), Antoniadis, Tsamis, Woodard; J Math. Phys. (1986), Allen, Follacci; Phys. Rev. D (1987), ..., Tsamis, Woodard ; CQG (1994), ..., Marolf, Morrison; Phys Rev. D (2010), Page, Wu; JCAP (2012), Anderson, Mottola; Phys. Rev. D. (2014), Higuchi, Rendell; JCAP(2018),...

$$G_{BD}(\eta, \eta'; \mathbf{R}) = \frac{H^2}{(2\pi)^2} \int_0^\infty \frac{dk}{2iR} \left[\eta\eta' - \frac{i}{k}(\eta' - \eta) + \frac{1}{k^2} \right] \left(e^{-ik(\Delta\eta - R)} - e^{-ik(\Delta\eta + R)} \right)$$

Parker and Toms, Cambridge (2007), KL; GRG (2022)

- * Genesis of the scale invariant power spectrum.. Still semiclassical analysis is safe under back reaction

Correlators in late time era : Omnipresent de Sitter

KL, Rajeev, Vikram, Padmanabhan; Phys. Rev. D (2018)

$$\begin{aligned} S &\equiv -\frac{1}{2} \int d^4x \sqrt{-g} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi \\ &= -\frac{1}{2} \int d^4x a^4 (a^{-2} \eta^{\mu\nu} \partial_\mu \phi \partial_\nu \phi) \end{aligned}$$

$$a(\eta) = (H\eta)^{-q}$$

$$\phi(x) = (H\eta)^{-1+q} \psi(x)$$

$$\begin{aligned} S &\equiv -\frac{1}{2} \int d^4x \sqrt{-g} g^{\mu\nu} [\partial_\mu \psi \partial_\nu \psi - m_{eff}^2 \psi^2] \\ &= -\frac{1}{2} \int d^4x \tilde{a}^4 (\tilde{a}^{-2} \eta^{\mu\nu} \partial_\mu \psi \partial_\nu \psi - m_{eff}^2 \psi^2) \end{aligned}$$

$$\tilde{a}(\eta) = 1/H\eta = -1/H\tilde{\eta} \text{ where } \tilde{\eta} = -\eta$$

$$m_{eff}^2 = H^2(1-q)(2+q)$$

*** FRW**

de Sitter

- * Mode functions of these universes are similarly conformally related
- * Thus the correlators in their individual vacua will also be conformally connected
- * QFT structure in these universes are related to each other!

Omnipresent de Sitter

KL, Rajeev, Vikram, Padmanabhan; Phys. Rev. D (2018)

$$\begin{aligned}
 S &\equiv -\frac{1}{2} \int d^4x \sqrt{-g} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi \\
 &= -\frac{1}{2} \int d^4x a^4 (a^{-2} \eta^{\mu\nu} \partial_\mu \phi \partial_\nu \phi) \quad \phi(x) = (H\eta)^{-1+q} \psi(x)
 \end{aligned}$$

$$\begin{aligned}
 S &\equiv -\frac{1}{2} \int d^4x \sqrt{-g} g^{\mu\nu} [\partial_\mu \psi \partial_\nu \psi - m_{eff}^2 \psi^2] \\
 &= -\frac{1}{2} \int d^4x \tilde{a}^4 (\tilde{a}^{-2} \eta^{\mu\nu} \partial_\mu \psi \partial_\nu \psi - m_{eff}^2 \psi^2)
 \end{aligned}$$

* **FRW** $a(\eta) = (H\eta)^{-q}$

de Sitter $\tilde{a}(\eta) = -(H\eta)^{-1}$

$$m_{eff}^2 = H^2(1 - q)(2 + q)$$

$$G^{FRW}(x_1, x_2) = (H\eta_1)^{q-1} (H\eta_2)^{q-1} G^{dS}(x_1, x_2)$$

* Inflationary Era $q = 1$ $m = 0$

* Radiation Dominated $q = -1$ $m = \sqrt{2} H$

* Matter Dominated $q = -2$ $m = 0$

* Dark Energy Dominated $q = 1$ $m = 0$

Conformal; Trivial

Particularly interesting

- * Massless fields in de Sitter have divergent correlations

$$G_{dS}(x, x') = \left(\frac{H^2}{16\pi^2} \right) \left(\frac{2}{\delta} + \frac{4}{y} - 4 - 2\ln(y) + 4\ln 2 + O(\delta) \right)$$

- * Massless fields in matter dominated era conformally share the divergence (hence scale invariance)

Wands; Phys. Rev. D (1999)

$$\underline{\underline{G^{matter}(x(\eta_1), x(\eta_2))}} = (H^2 \eta_1 \eta_2)^{-3+\delta} \left(\frac{H^2}{16\pi^2} \right) \left(\frac{2}{\delta} + \frac{4}{y} - 4 - 2\ln(y) + 4\ln 2 + O(\delta) \right)$$

Late time Back reaction

Dhanuka, KL; Phys. Rev. D (2020)

$$a(\eta) = (H\eta)^{-q}$$

$$q \in (0, 1) :$$

$$\langle \hat{t}_{00}(\eta, \vec{x}) \hat{t}_{00}(\eta, \vec{x}') \rangle_{P.L.}$$

$$\lim_{\eta \rightarrow 0} \frac{(H\eta)^{4q-4}}{(\Delta \vec{x})^4} \left[\frac{H^4 \eta^{4-4q} (\Delta \vec{x})^{4q-4}}{8\pi^5} \left((11 - 12q + 4q^2)(\Gamma(2 - q))^2 (\Gamma(0.5 + q))^2 \right) \right. \\ \left. + \frac{4^{4q} \eta^{4q+4} H^4}{32\pi^5 (\Delta \vec{x})^{4+4q}} \left((1 + 2q)^4 (\Gamma(2 + q))^2 (\Gamma(-0.5 - q))^2 \right) + O(\eta^{6-4q}) \right].$$

$$q = 0 :$$

$$\frac{3}{2\pi^4 (\Delta \vec{x})^8}.$$

$$q \in (-2, 0) :$$

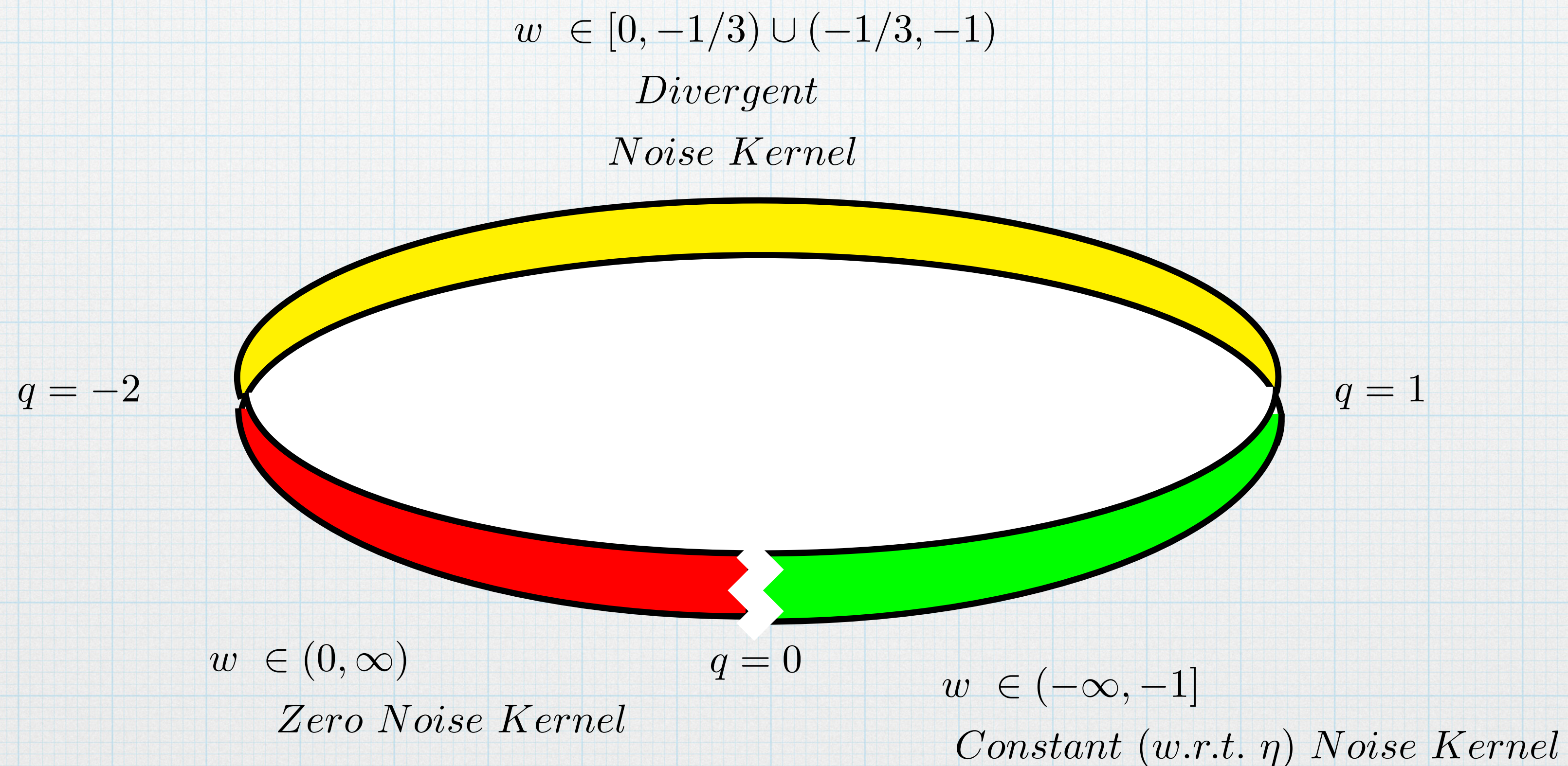
$$\lim_{\eta \rightarrow \infty} (H\eta)^{4q-4} \left[\frac{3H^4 \eta^4}{2\pi^4 (\Delta \vec{x})^8} + \frac{\eta^2 H^4 (3q + 4q^2)}{8\pi^4 (\Delta \vec{x})^6} + \frac{H^4 q}{64\pi^4 (\Delta \vec{x})^4} \left((-4 - 7q + 6q^2 + 11q^3) \right. \right. \\ \left. \left. + 2(1 + q)(-1 + q)^2 \left[2\gamma + \log\left(\frac{(\Delta \vec{x})^2}{4\eta^2}\right) + \psi^{(0)}(1 - q) + \psi^{(0)}(2 + q) \right] \right) + O(\eta^{-2}) \right]$$

$$q = -2 + \epsilon$$

$$\lim_{\eta \rightarrow \infty} \lim_{\epsilon \rightarrow 0} H^{-12} \left[\frac{3H^4}{2\pi^4 \eta^8 (\Delta \vec{x})^8} + \frac{4}{(\Delta \vec{x})^6 \eta^{10}} \left(\frac{5H^4}{16\pi^4} + O(\epsilon) \right) + \frac{1}{\eta^{12} (\Delta \vec{x})^4} \left(\frac{9H^4}{16\pi^4 \epsilon} + \frac{9(6H^4 + H^4 \log(\frac{(\Delta \vec{x})^2}{4\eta^2}))}{16\pi^4} + O(\epsilon) \right) \right. \\ \left. + \frac{1}{4(\Delta \vec{x})^2 \eta^{14}} \left(-\frac{27H^4}{8\pi^4 \epsilon} - \frac{27(7H^4 + 2H^4 \log(\frac{(\Delta \vec{x})^2}{4\eta^2}))}{16\pi^4} + O(\epsilon) \right) + \frac{1}{16\eta^{16}} \left(\frac{81H^4}{8\pi^4 \epsilon^2} + \frac{27H^4(10 + 3\log(\frac{(\Delta \vec{x})^2}{4\eta^2}))}{4\pi^4 \epsilon} + O(\epsilon^0) \right) + O(\eta^{-18}) \right]$$

Back reaction cart wheel

- * Scalar Back reaction : Some epochs are susceptible to strong back reaction



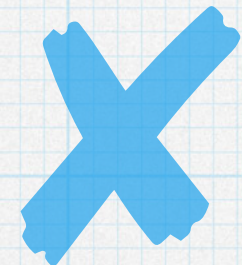
Massless field back reaction growth FRW catalogue

* Scalar



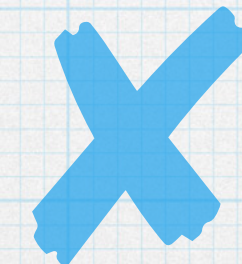
Dhanuka, KL; Phys. Rev. D (2020)

* Spinor



Dhanuka; Phys. Rev. D (2022)

* Vector



Conformally flat in 3+1, flat space correlation

* Tensor



KL; GRG (2022)

* Facilitated by uncontrolled growth of correlators

Quantum Gravitons : a la Unruh DeWitt Detector Route

- * Hydrogen atom perturbed by curvature

$$(i\frac{\partial}{\partial t} - m)\psi = (-\frac{1}{2m}\nabla^2 - \frac{e^2}{r} + \frac{1}{2}mR_{0l0m}x^lx^m)\psi$$

Parker; Phys. Rev. Lett. (1980)

Pimentel, Parker; Phys. Rev. D (1982)

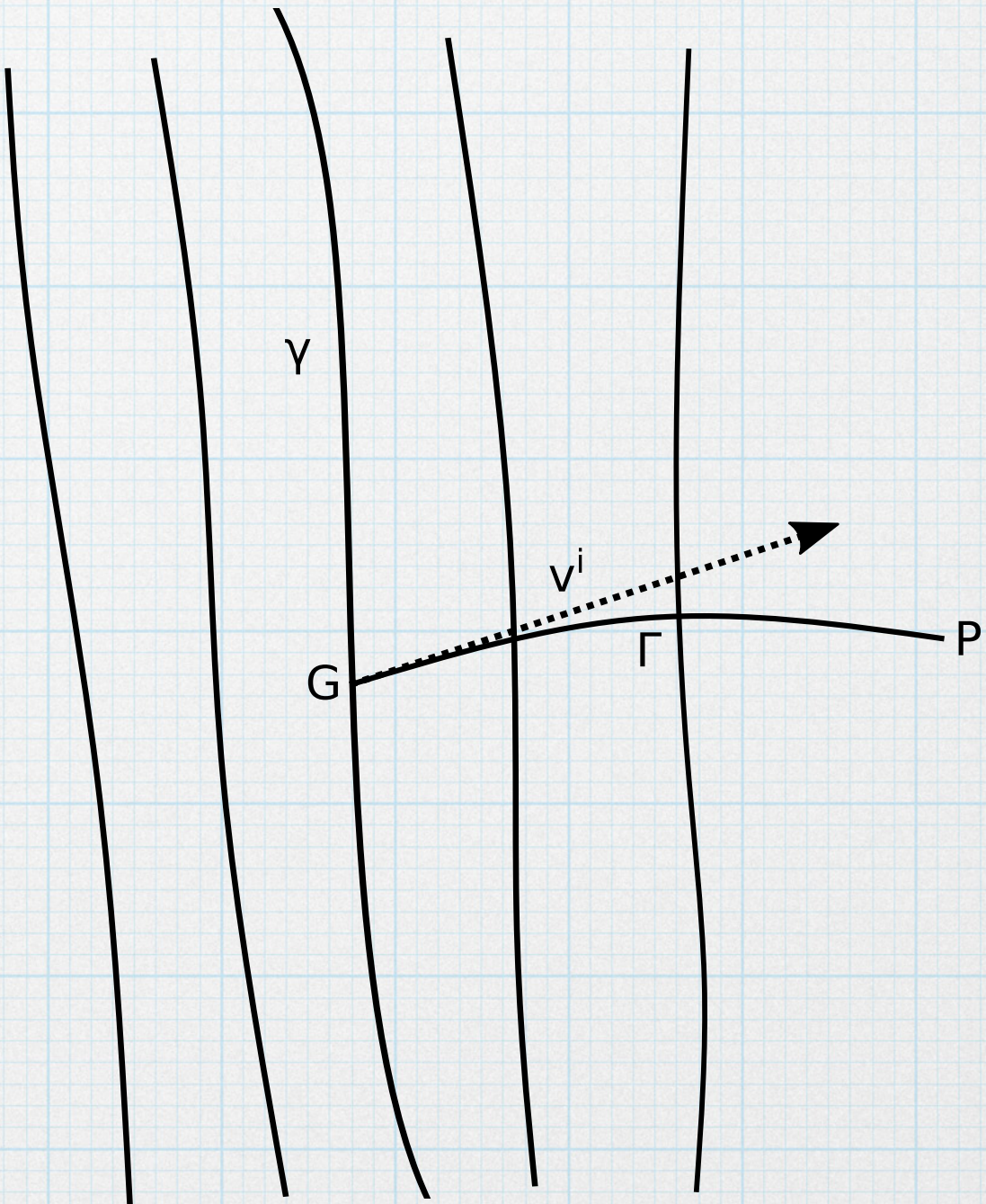
- * Specialize to perturbed Friedmann universe

$$H_I = \frac{m}{2}\left(-\delta_{lm}\frac{\ddot{a}}{a} - \frac{\dot{a}}{a}\dot{h}_{lm} - \frac{1}{2}\ddot{h}_{lm}\right)x^lx^m = \frac{m}{2}H_{lm}x^lx^m$$

- * UDD Detector structure

Dhanuka, KL; Phys. Rev. D (2022)

Dhanuka, KL; arXiv: 2212.09784



x^2, y^2, xy, yx		xz, yz		z^2	
Δl	Δm	Δl	Δm	Δl	Δm
-2,0,2	-2,0,2	-2,0,2	-1,1	-2,0,2	0

Graviton mediated transition

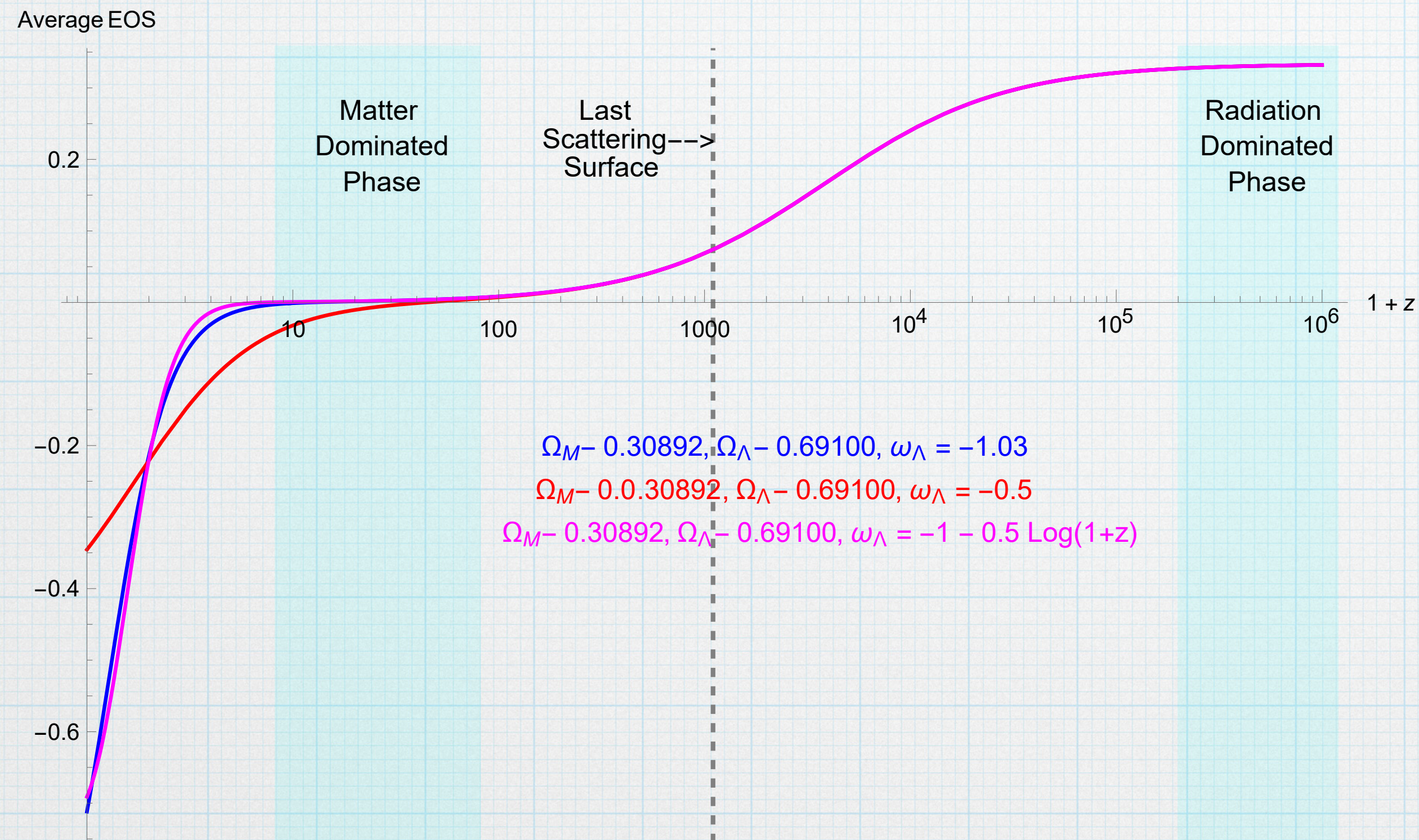
$$\lim_{\vec{y}_1 \rightarrow \vec{y}_2} \langle 0 | \hat{H}_{ij}(\vec{y}_1, \eta_1) \hat{H}_{pk}(\vec{y}_2, \eta_2) | 0 \rangle = \lim_{\vec{y}_1 \rightarrow \vec{y}_2} \frac{1}{a_1^4} \left(\frac{a_1 a_1'}{2} \frac{\partial}{\partial \eta_1} - \frac{a_1^2}{2} \nabla_{\vec{y}_1}^2 \right) \frac{1}{a_2^4} \left(\frac{a_2 a_2'}{2} \frac{\partial}{\partial \eta_2} - \frac{a_2^2}{2} \nabla_{\vec{y}_2}^2 \right) \underbrace{\langle 0 | \hat{h}_{ij}(\vec{y}_1, \eta_1) \hat{h}_{pk}(\vec{y}_2, \eta_2) | 0 \rangle}_{G_{ijpk}}$$

* Derivatively coupled UDD in matter dominated era

$$P_{\psi_{nlm} \rightarrow \psi_{n'l'm'}} = \frac{m^2}{4} \langle \psi_{n'l'm'} | \hat{x}^i \hat{x}^j | \psi_{nlm} \rangle^* \langle \psi_{n'l'm'} | \hat{x}^p \hat{x}^k | \psi_{nlm} \rangle \lim_{\vec{y}_1 \rightarrow \vec{y}_2} \int_{\eta_i}^{\eta_f} d\eta_1 \int_{\eta_i}^{\eta_f} d\eta_2 e^{-i\Omega(t(\eta_1) - t(\eta_2))} \\ \frac{1}{a_1^3} \left(\frac{a_1 a_1'}{2} \frac{\partial}{\partial \eta_1} \right) \frac{1}{a_2^3} \left(\frac{a_2 a_2'}{2} \frac{\partial}{\partial \eta_2} \right) \left(\delta_{ip} \delta_{jk} + \delta_{ik} \delta_{jp} - \delta_{ij} \delta_{pk} \right) \boxed{(H^2 \eta_1 \eta_2)^{-3+\delta} \frac{H^2}{32\pi^2 \delta}} + \text{Subdominant terms.}$$

* EM transitions are distinct and relatively suppressed

Quantum Gravity at doorstep ?



$$\left(\frac{RR_e}{RR_g}\right)_{flat} \propto \frac{d^2}{m^2(Q)^2\Omega^2} \sim 10^{39}$$

$$\left(\frac{RR_e}{RR_g}\right)_{curved} \propto \frac{d^2}{m^2(Q)^2\Omega^2} \left(\frac{H}{\Omega}\right)^{-\frac{2q}{1-q}}$$

$$\left(\frac{RR_e}{RR_g}\right)_\delta \propto \delta \frac{d^2}{m^2Q^2\Omega^2} \left(\frac{H}{\Omega}\right)^{\frac{4}{3}} \sim 10^{-12}$$

* Singular time in history when gravitons beat photons

Other hints of late time quantum revival

* Quantum Cosmology Spill Over

Sahota, KL; EPJC (2024)

* Quantum Gravity

Alexandre, Magueijo; Phys. Rev. D (2022)

* Bouncing/Collapsing dual

Mukherjee, Jassal, KL; EPJC(2024)

Take home

- * Classical Appearance of the universe is perplexing !
- * Inflation tried preserves quantum seed. Hands it over to following phases
- * Radiation dominated epoch : Sympathetic towards heading to classical
- * Matter dominated to matter driven era : Quantum revival possible
- * Late time epoch may not be as innocent as we would have thought it to be !

Thank You !