King's College London TPPC seminar 01/07/2020

CURVATURE FLUCTUATIONS FROM DISORDER DURING INFLATION

Marcos A. G. Garcia

IFT - UAM

1902.09598, 2001.09158

with M. Amin, D. Green, S. Carlsten

Instituto de Física Teórica UAM-CSIC

Universidad Autónoma de Madrid

CSIC Consejo Superior de Investigaciones Científicas

Complexity in the early universe

Credit: D. Baumann

Does the simplicity of the data reflect the simplicity of the underlying theory, or does it emerge from complexity?

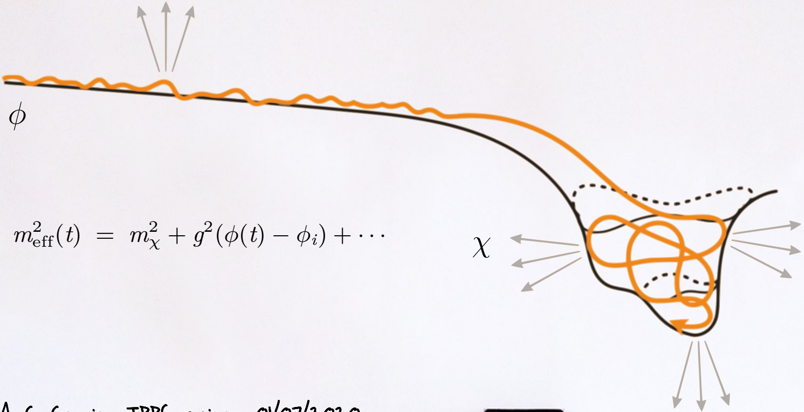
Complexity in the early universe

Inflation

- Near scale invariant: $\Delta_\zeta^2 \sim k^{n_s-1}$
- Near Gaussian
- Weak self-interaction (slow roll)

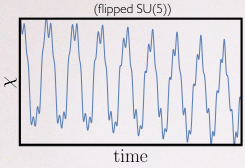
Particle theory

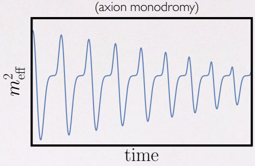
- SM UV completions $N_F \gg 1$
- Coupling to ϕ weakly constrained
- Non-trivial field manifolds

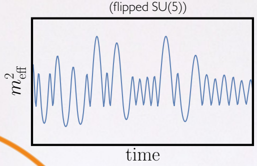


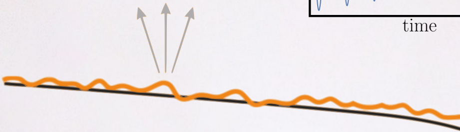
$$m_{\text{eff}}^2(t) \;=\; m_\chi^2 + g^2(\phi(t)-\phi_i) + \cdots$$

Complexity in the early universe



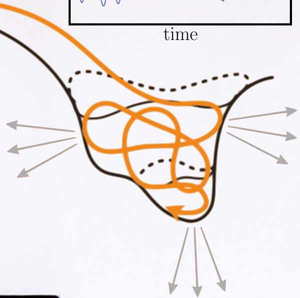






[J. Ellis, MG, N. Nagata, D. Nanopoulos, K. Olive, '17]

[R. Flauger, M. Mirbabayi, L. Senatore, E. Silverstein, '16]

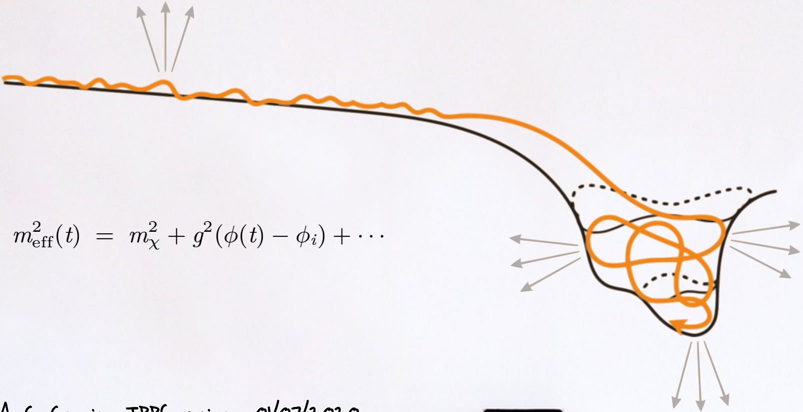


$$m^2_{\rm eff}(t) \;=\; m^2_\chi + g^2(\phi(t) - \phi_i) + \cdots$$

[R. Easther and L. McAllister, '06]
[D. Green, B. Horn, L. Senatore and E. Silverstein, '09]
[Y. Nakai, R. Namba and Z. Wang, '20]

Complexity in the early universe

background dynamics $\longrightarrow$ particle production $\langle \chi_{\boldsymbol{k}_1} \chi_{\boldsymbol{k}_2} \cdots \rangle$ $\longleftrightarrow$ curvature fluctuations $\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \cdots \rangle$



$$m_{\rm eff}^2(t) \;=\; m_\chi^2 + g^2(\phi(t) - \phi_i) + \cdots$$

Conformal Spectator in dS

$$\mathcal{S} = \frac{1}{2}\int \sqrt{-g}\, d^4x \left[c(t+\pi)\partial_\mu\pi\partial^\mu\pi + \partial_\mu\chi\partial^\mu\chi - \left(M^2 + m^2(t+\pi)\right)\chi^2 \right]$$

$$\simeq \frac{1}{2}\int \sqrt{-g}\, d^4x \left[c(t)\partial_\mu\pi\partial^\mu\pi + \partial_\mu\chi\partial^\mu\chi - \left(M^2 + m^2(t)\right)\chi^2 - \frac{dm^2}{dt}\chi^2\pi + \cdots \right]$$

$$c = 2M_P^2|\dot{H}|$$

Conformal Spectator in dS

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$$M^2 = 2H^2$$

$$\downarrow$$

$$X_k \equiv a\,\chi_k$$

$$= \alpha_{k,j}\frac{e^{-ik\tau}}{\sqrt{2k}} + \beta_{k,j}\frac{e^{ik\tau}}{\sqrt{2k}}$$

$$m^2(t) = \textstyle\sum_j m_j \delta(t - t_j)$$

$$\langle m_j \rangle = 0$$

$$\langle m_i m_j \rangle = \sigma^2 \delta_{ij}$$

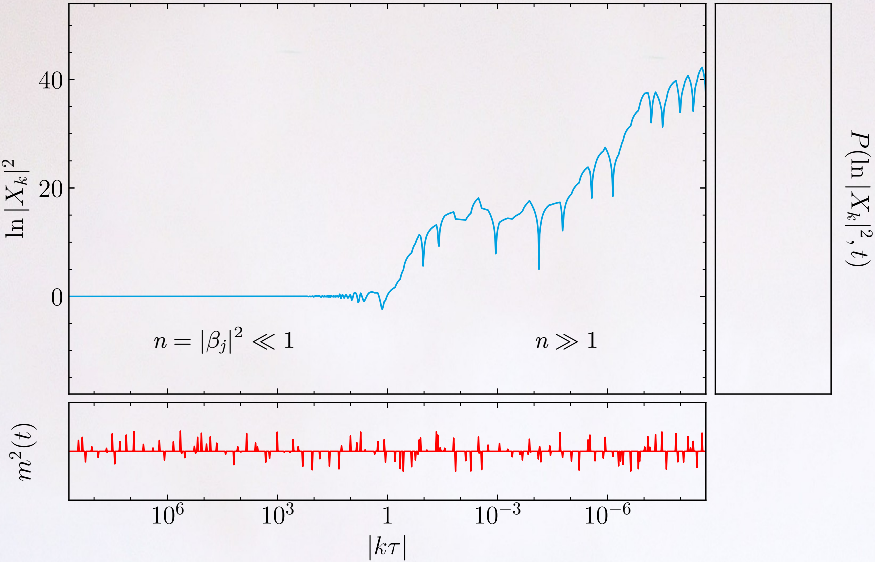
$$\mathcal{N}_s \equiv \frac{\langle N_s \rangle}{N_e}$$

$$\chi \;\underset{\not\leftarrow}{\rightarrow}\; \pi$$

$$\mathcal{O}_S \sim \langle \chi^4 \rangle$$

$$\mathcal{O}_D \sim \langle [\chi^2, \chi^2] \rangle$$

Conformal Spectator in dS



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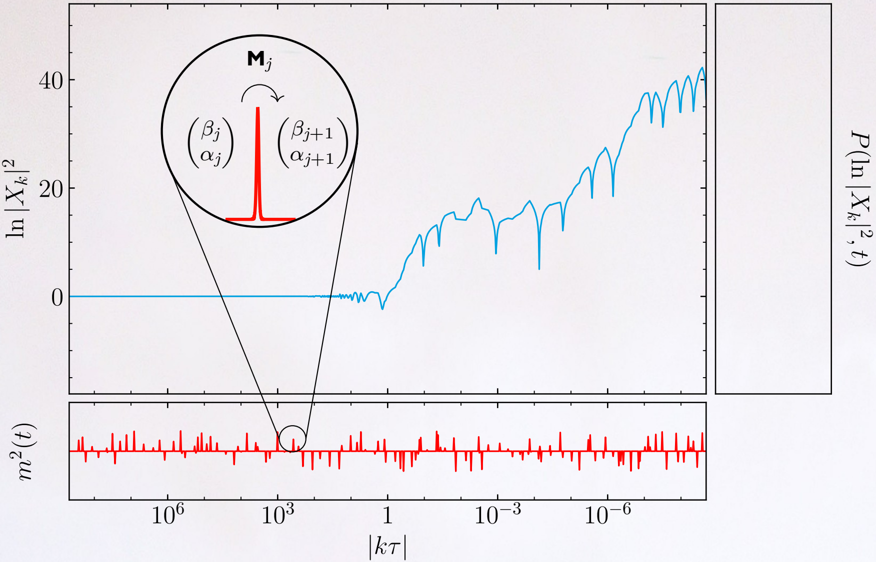

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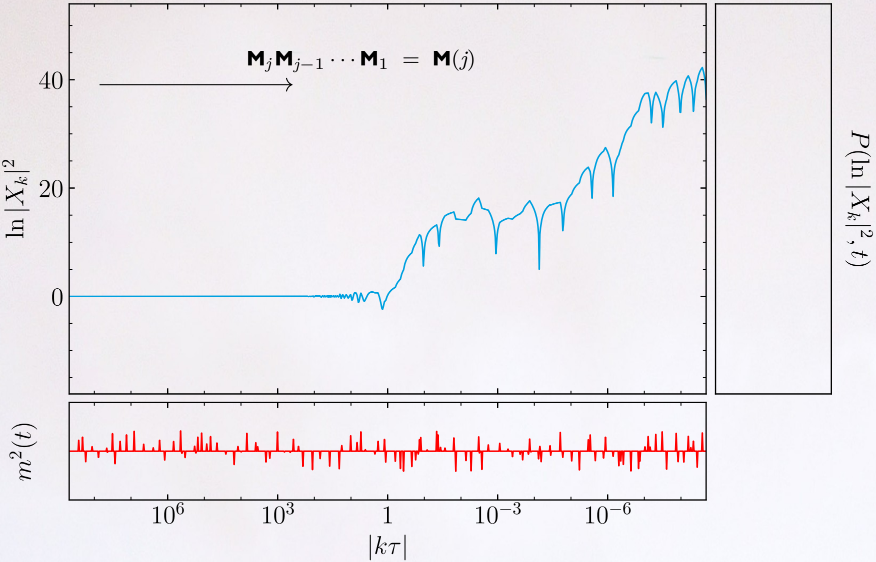
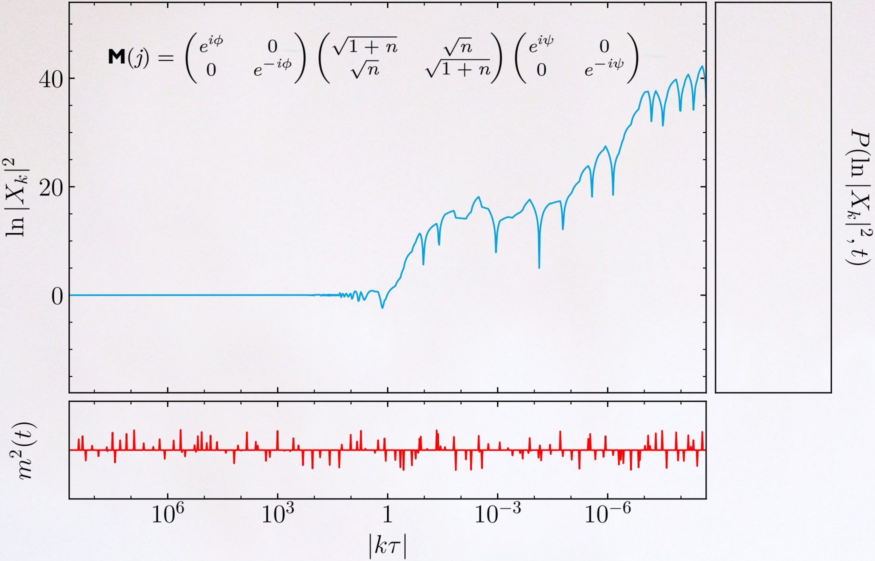


Conformal Spectator in dS

$$\mathbf{M}(j) = \begin{pmatrix} e^{i\phi} & 0 \\ 0 & e^{-i\phi} \end{pmatrix} \begin{pmatrix} \sqrt{1+n} & \sqrt{n} \\ \sqrt{n} & \sqrt{1+n} \end{pmatrix} \begin{pmatrix} e^{i\psi} & 0 \\ 0 & e^{-i\psi} \end{pmatrix}$$



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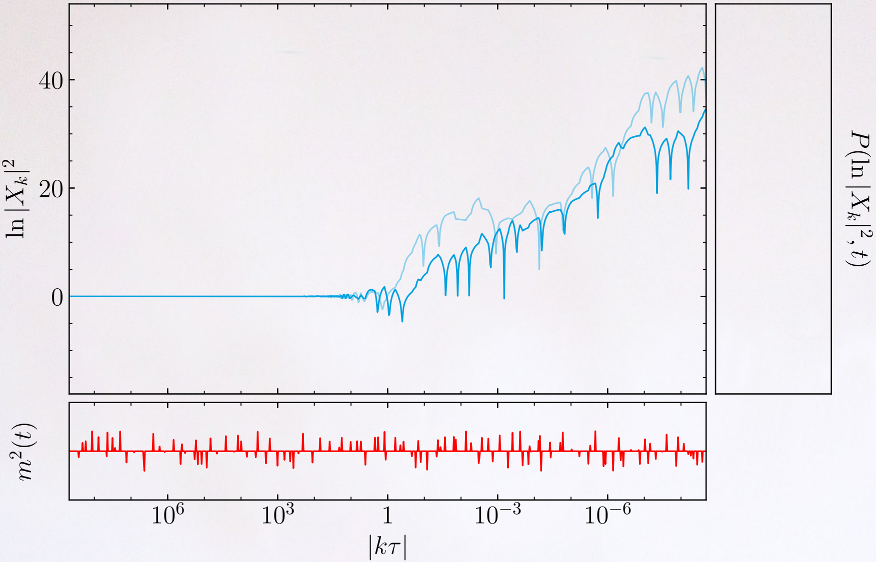

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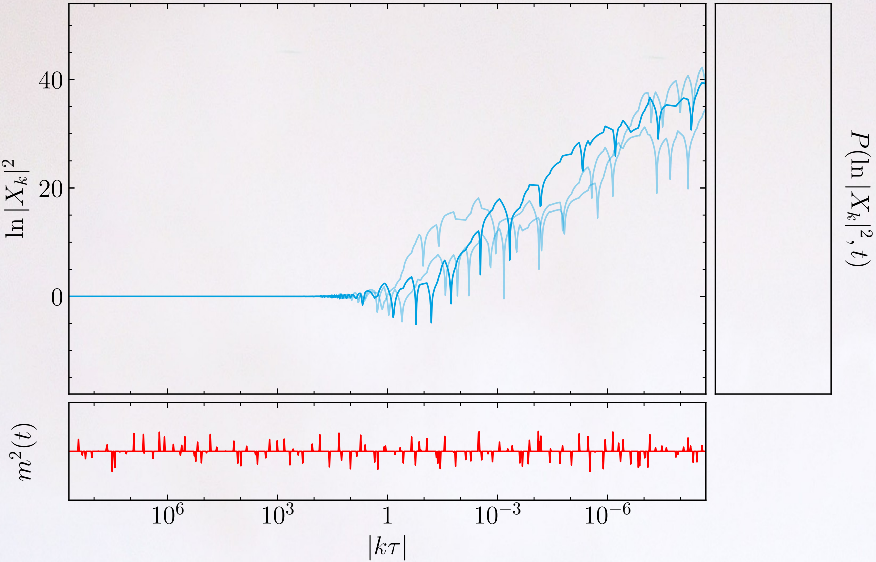

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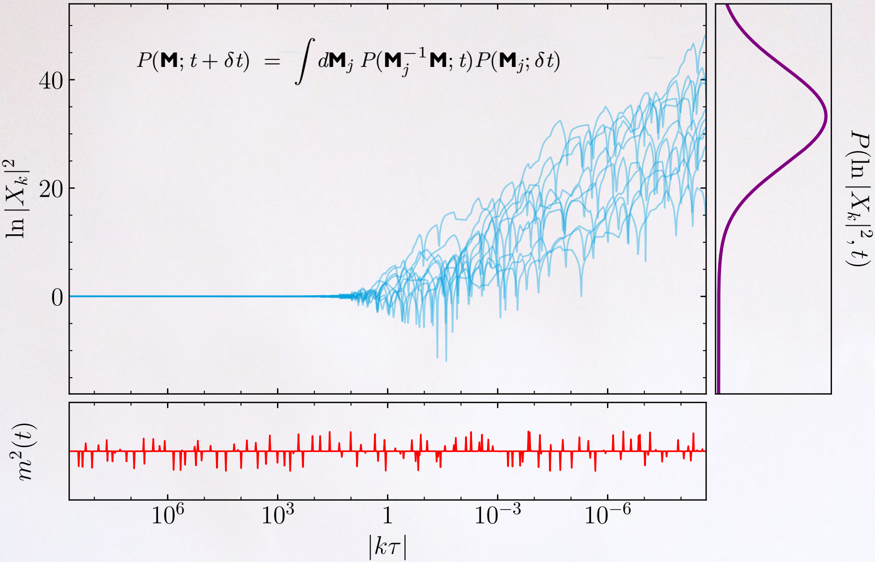

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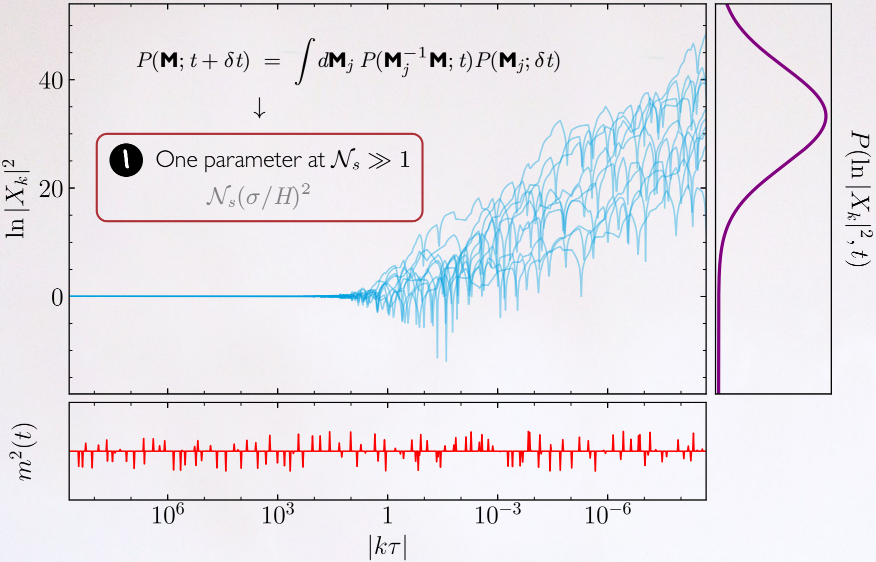

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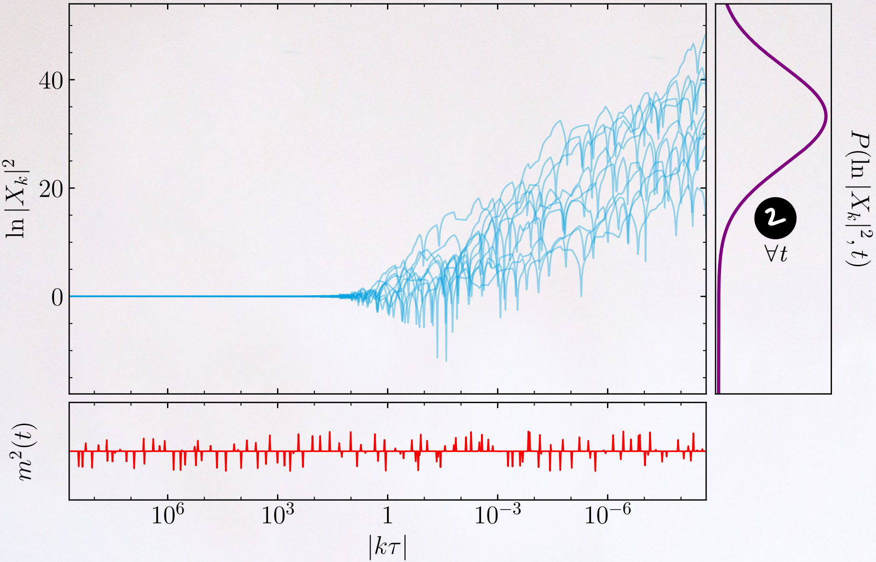

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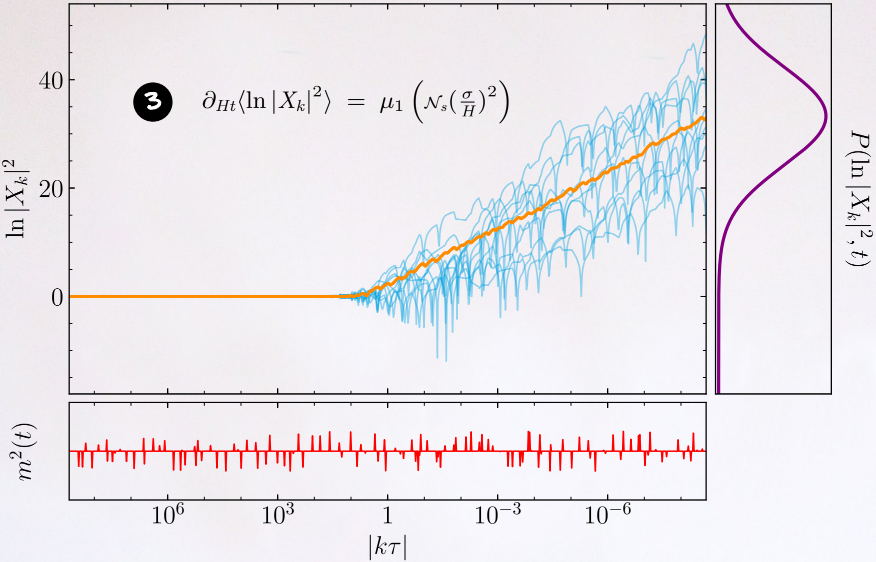

Conformal Spectator in dS

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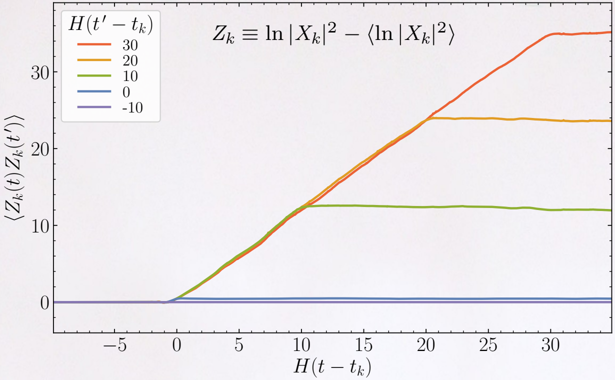
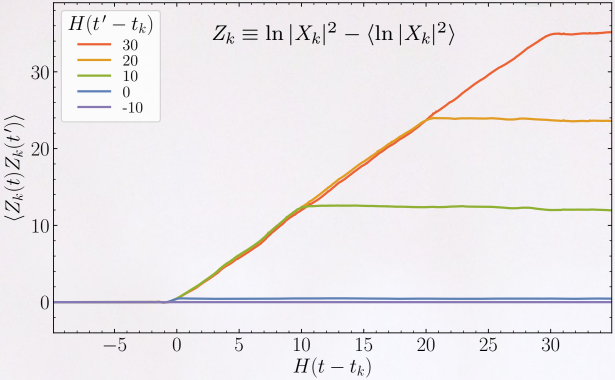


$$\langle Z_k(t) Z_{k'}(t') \rangle \;=\; \mu_2 \left(\mathcal{N}_s \left(\tfrac{\sigma}{H}\right)^2 \right) H \min\left[t - t_k, t - t_{k'}, t' - t_k, t' - t_{k'}\right]$$

Conformal Spectator in dS

1 + 2 + 3 + 4 = geometric (Brownian) random walk of $|X_k|^2$



$$\left\langle |X_{k_1}(t_1)|^2 \cdots |X_{k_n}(t_n)|^2 \right\rangle = \exp\left[\sum_{i=1}^{n} \langle \ln|X_{k_i}(t_i)|^2\rangle + \frac{1}{2}\sum_{i,j=1}^{n} \langle Z_{k_i}(t_i) Z_{k_j}(t_j)\rangle\right]$$

Curvature power spectrum

To lowest order in π, with $\zeta \simeq H\pi$ and $\langle\zeta(\mathbf{k})\zeta(\mathbf{k}')\rangle = \frac{2\pi^2}{k^3}\Delta_\zeta^2(k)\,\delta^{(3)}(\mathbf{k}+\mathbf{k}')$,

$$\hat{\pi}''(\mathbf{x},\tau) + 2\mathcal{H}\hat{\pi}'(\mathbf{x},\tau) - \nabla^2\hat{\pi}(\mathbf{x},\tau) \;=\; -\frac{a(\tau)}{2c(\tau)}\frac{dm^2(\tau)}{d\tau}\hat{\chi}^2(\mathbf{x},\tau)\,,$$

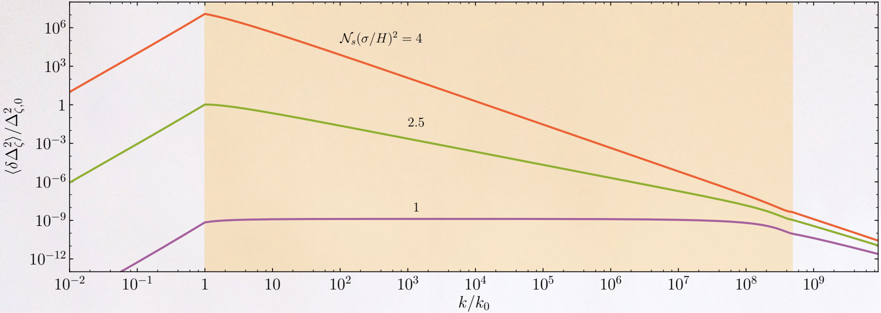
$$\downarrow$$

$$\boxed{\begin{aligned}\delta\Delta_\zeta^2(k) \;=\; & 4\pi^2(\Delta_{\zeta,0}^2)^2\frac{k^3}{H^4}\int d\tau'\,d\tau''\,\tau'\tau''\,G_k(\tau,\tau')\,G_k(\tau,\tau'')\frac{dm^2(\tau')}{d\tau'}\frac{dm^2(\tau'')}{d\tau''}\\ & \times\int^{\Lambda(\tau)}\frac{d^3\mathbf{p}}{(2\pi)^3}\left[X_p(\tau')X_p^*(\tau'')\right]_{\rm AS}\left[X_{|\mathbf{p}-\mathbf{k}|}(\tau')X^*_{|\mathbf{p}-\mathbf{k}|}(\tau'')\right]_{\rm AS}\end{aligned}}$$

- $\mathcal{O}_{\rm AS} \;\equiv\; \mathcal{O} - \mathcal{O}_{\rm vac}$
- $\Lambda(\tau) \;\equiv\; (Hw\tau)^{-1}$
- Start: $|k_0\tau| = 1$. End: $|k_f\tau| = 1$

Curvature power spectrum

$$\left\langle \delta\Delta_\zeta^2(k)\right\rangle = \left(\Delta_{\zeta,0}^2\right)^2 \mathcal{N}_s \left(\frac{\sigma}{H}\right)^2 e^{\mathcal{F}\left(k,N_e,\mathcal{N}_s(\sigma/H)^2\right)}$$



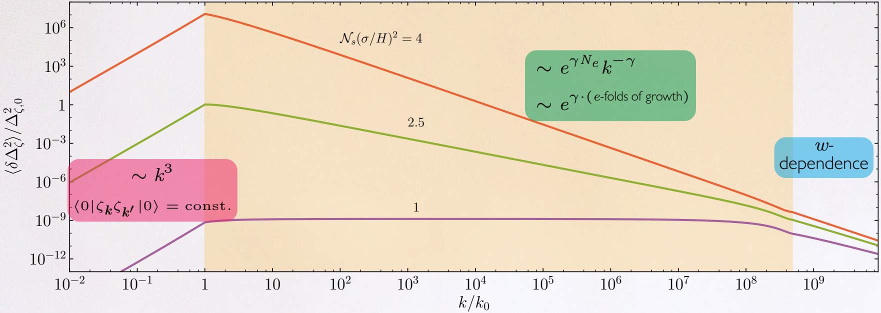
always super-horizon

cross horizon during scatterings

always sub-horizon

Curvature power spectrum

$$\left\langle \delta\Delta_\zeta^2(k) \right\rangle = \left(\Delta_{\zeta,0}^2\right)^2 \mathcal{N}_s \left(\frac{\sigma}{H}\right)^2 e^{\mathcal{F}\left(k, N_e, \mathcal{N}_s(\sigma/H)^2\right)}$$



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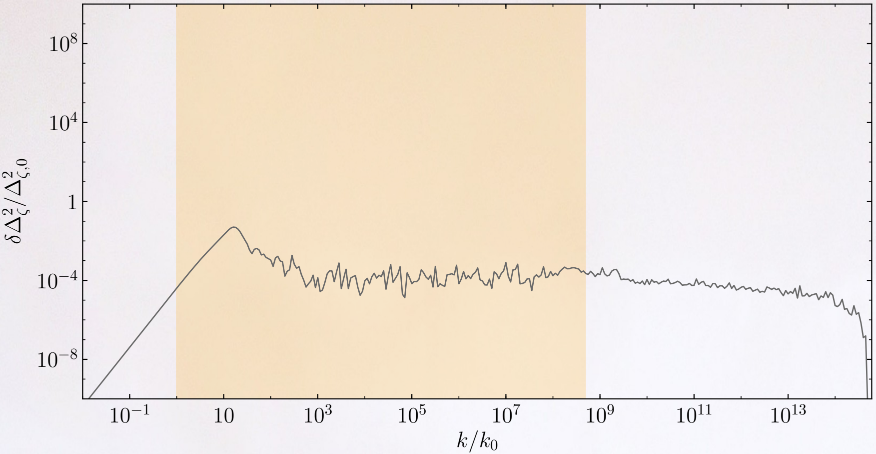
Curvature power spectrum

$(N_e = 20, \mathcal{N}_s(\sigma/H)^2 = 25)$



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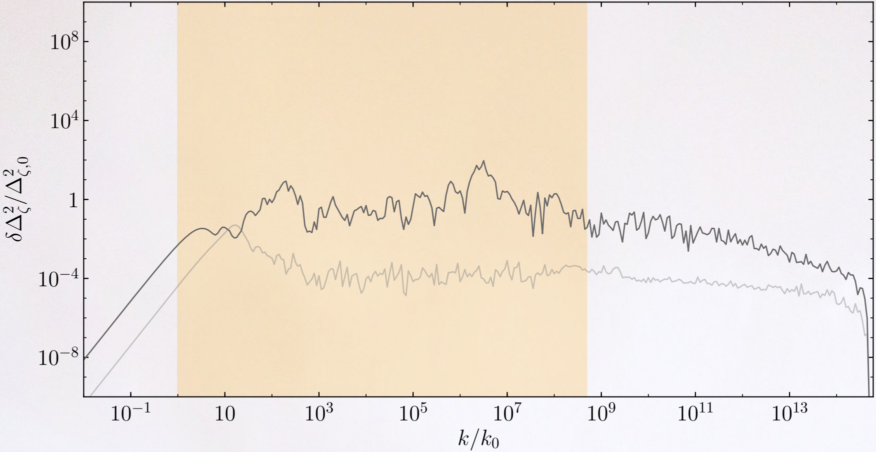

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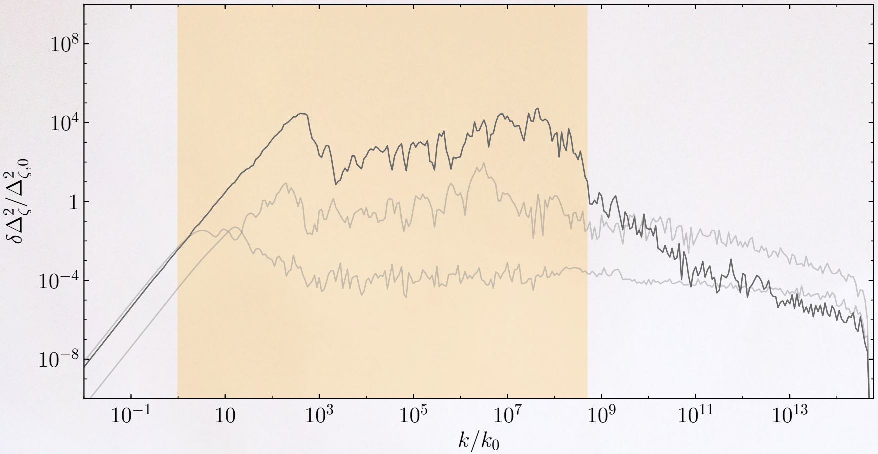

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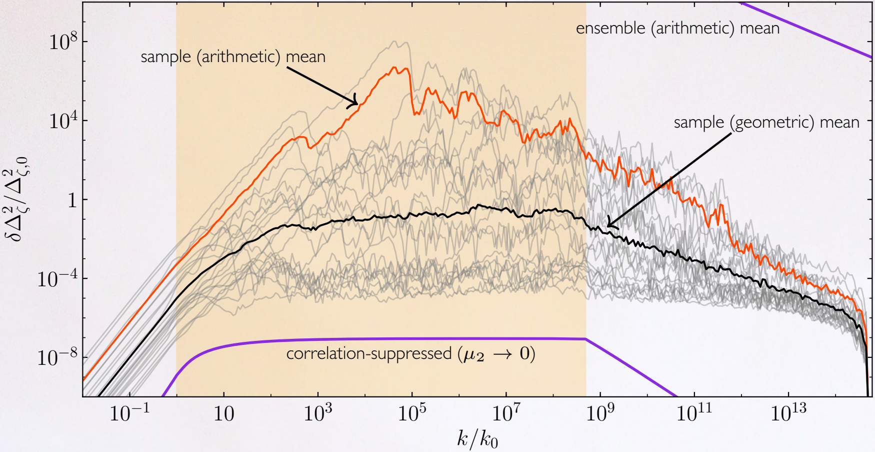

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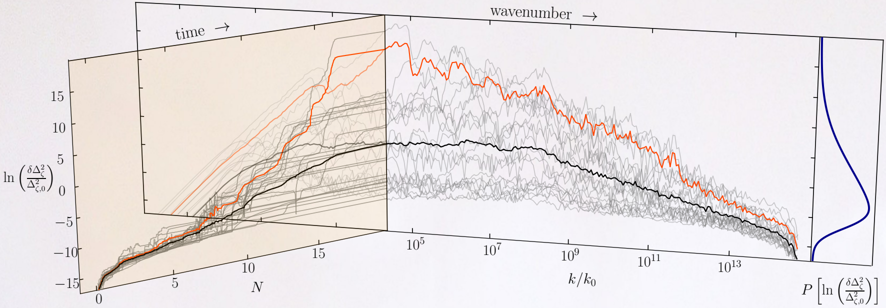
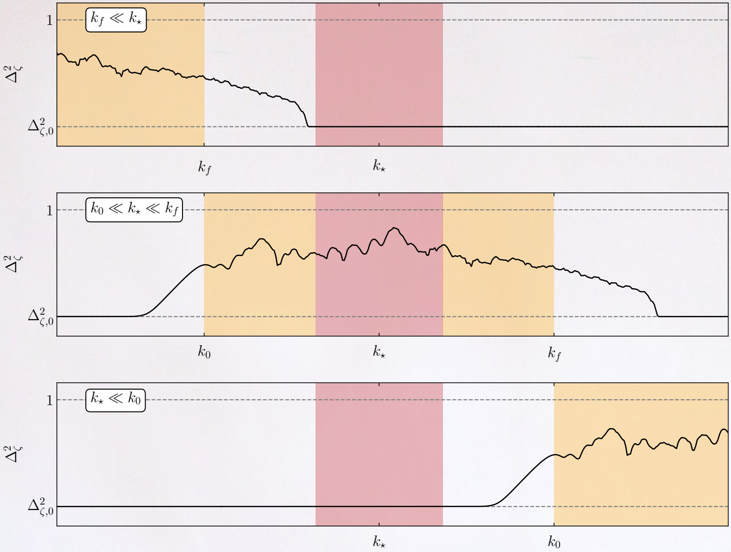


Observational implications



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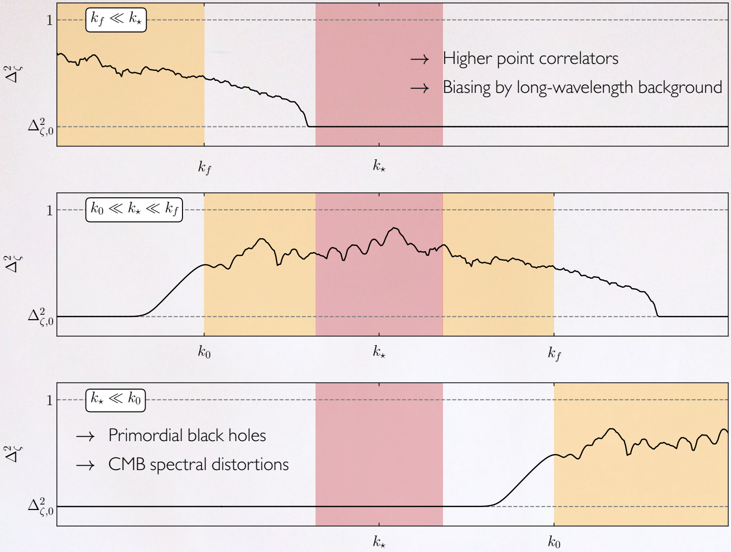
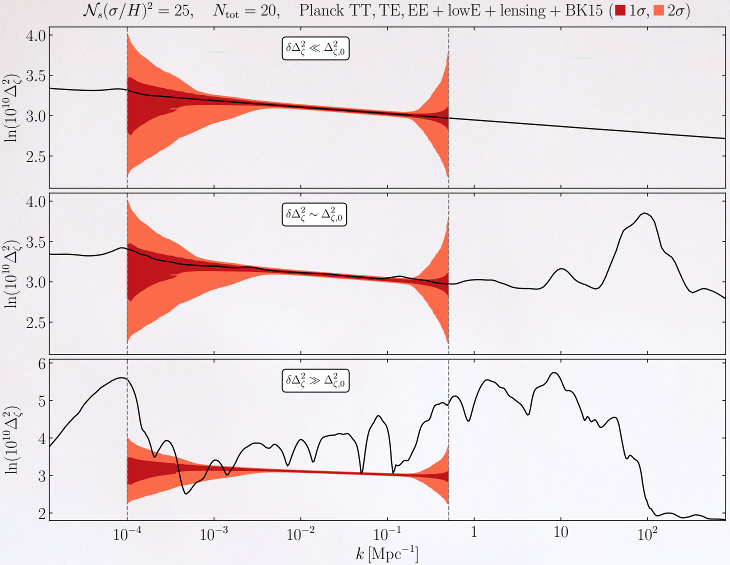


Observational implications



Conclusions

- Stochastically excited spectator fields undergo geometric random walks
- Lead to features in the curvature power spectrum $\rightarrow$ constraints
- Look for enhancement in the N-point function

$$\langle\zeta^n\rangle - \langle\zeta^n\rangle_{\chi=0} \;\sim\; \langle\zeta^2\rangle^n_{\chi=0} \times \exp\left[\frac{n^2}{2}F\left(\mathcal{N}_s\frac{\sigma^2}{H^2}\right)\right]$$

- Higher spin spectators / higher spin observables
- Stochastic preheating
- Backreaction regime $\rightarrow$ dissipation
- Applications to landscape models
  (e.g. J. J. Blanco-Pillado, K. Sousa and M. A. Urkiola, '19)

Thank You