Curvature Perturbations From Stochastic Particle Production During Inflation

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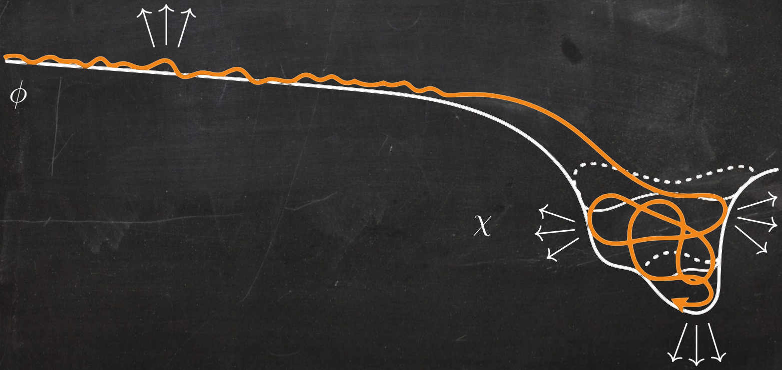
Inflation

- 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



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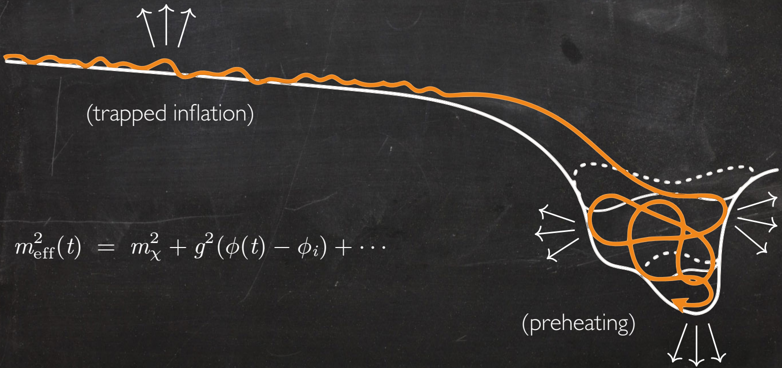

$$m^2_{\rm eff}(t) \;=\; m^2_\chi + g^2(\phi(t) - \phi_i) + \cdots$$

Spectator field in an expanding universe

$$\left(\frac{d^2}{dt^2} - \frac{\nabla^2}{a^2} + 3H\frac{d}{dt} + M^2 + m^2(t)\right)\chi(t,\mathbf{x}) = 0$$

$a = a_0\, e^{H(t-t_0)}$

(de Sitter)

$M^2 = 2H^2$ (conformal)

$M^2 = 0$ (massless)

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

(localized, non-adiabatic)

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$\frac{k}{aH} = |k\tau| \lesssim 1$ (horizon)

$M^2 = 2H^2$ (conformal)
$M^2 = 0$ (massless)

$$X_k \equiv a\,\chi_k = \alpha_{k,j} f_k(\tau) + \beta_{k,j} f_k^*(\tau)$$

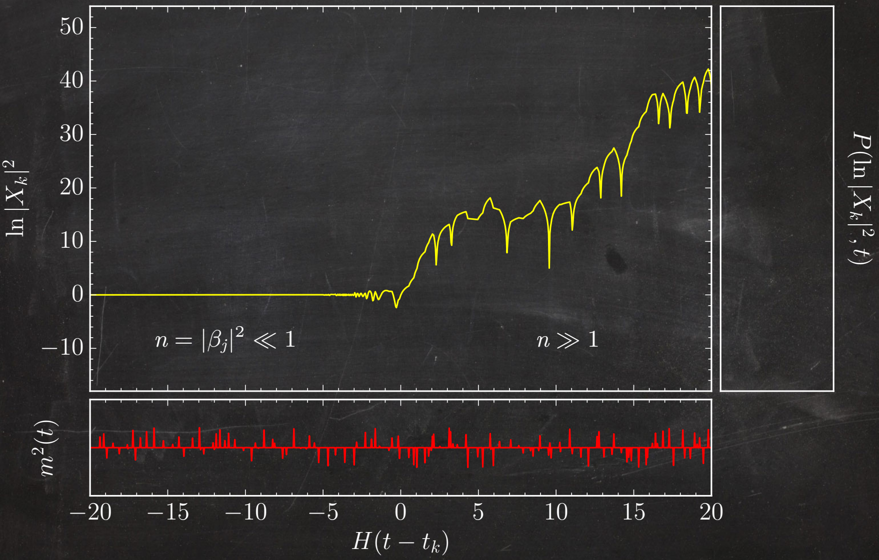
$$f_k(\tau) = \frac{e^{-ik\tau}}{\sqrt{2k}} \times \begin{cases} 1 \\ (1 - \frac{i}{k\tau}) \end{cases}$$

$m^2(t) = \sum_j m_j \delta(t - t_j)$ (localized, non-adiabatic)

$m_j,\ t_j$ random

$$\langle m_j \rangle = 0$$
$$\langle m_i m_j \rangle = \sigma^2 \delta_{ij}$$
$$\frac{\langle N_s \rangle}{H(t_i - t_f)} \equiv \mathcal{N}_s$$

Numerical solution



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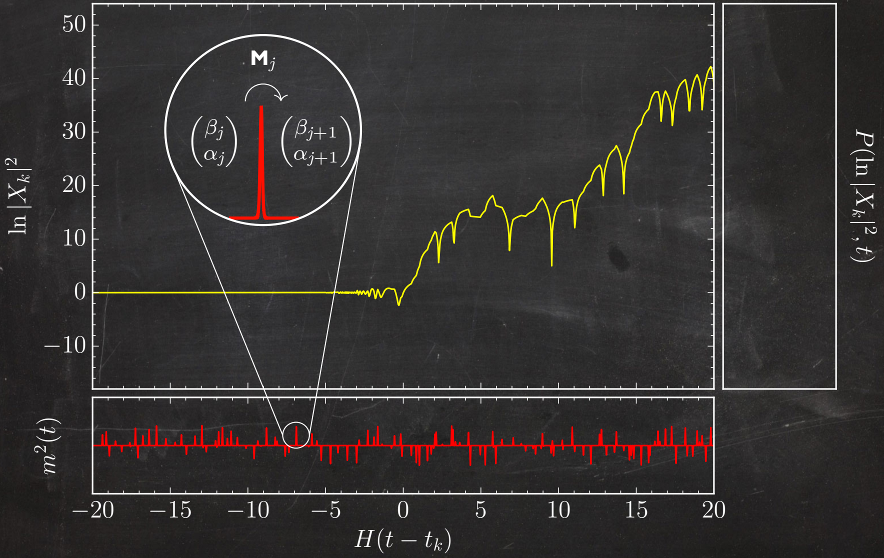

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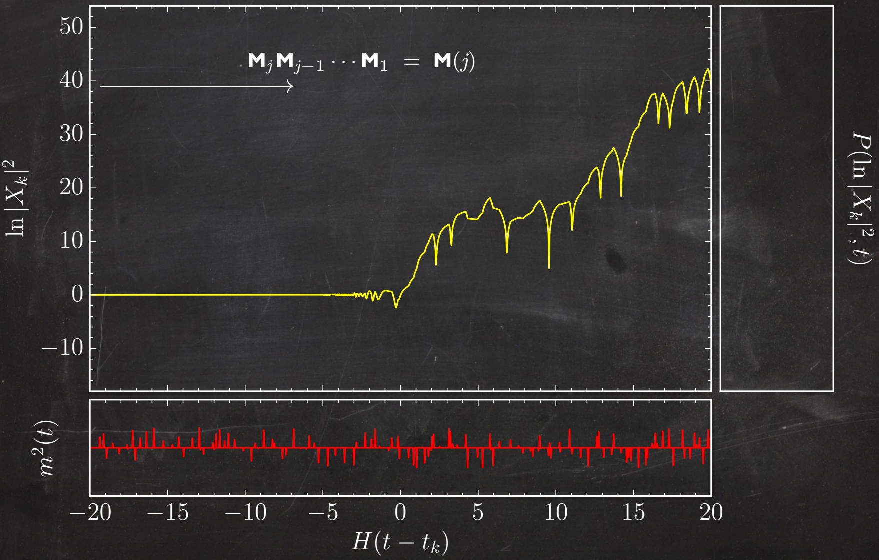

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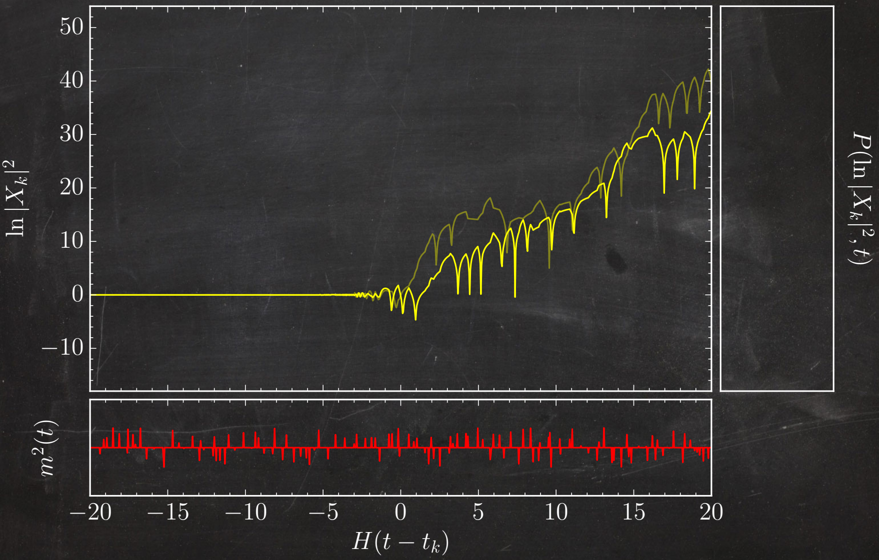

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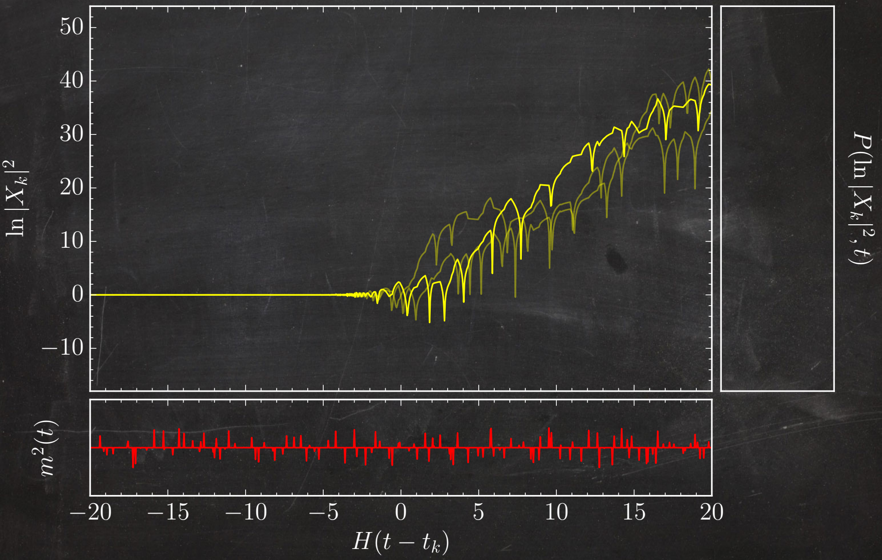
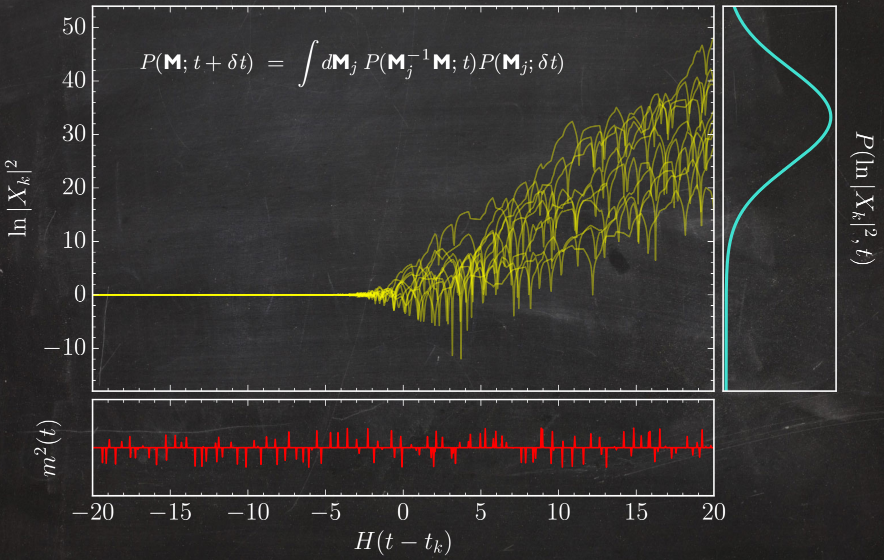
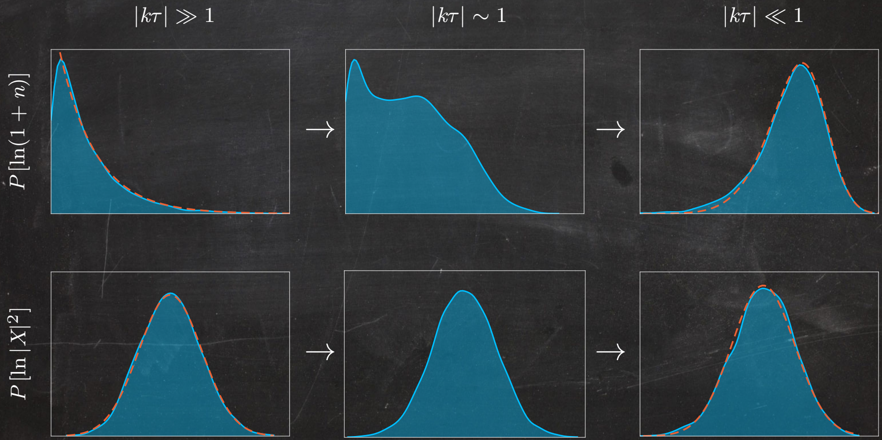


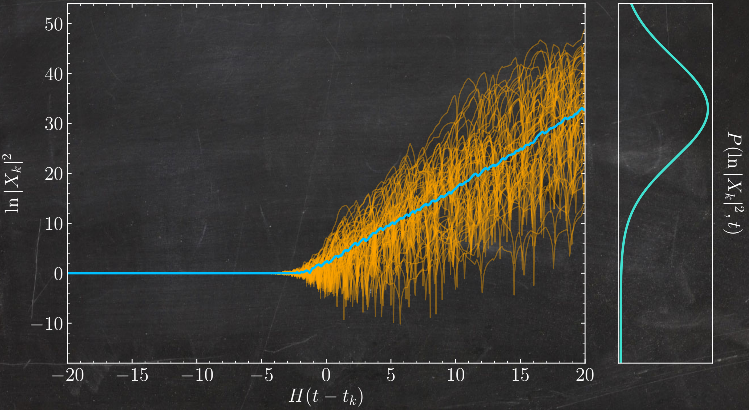
Numerical *and analytical* solution



1. Strength of non-adiabaticity is quantified by: $\frac{N_s}{H\Delta t}\frac{\mathrm{Var}\,[m_j]}{H^2} \equiv \mathcal{N}_s\left(\frac{\sigma}{H}\right)^2$
2. Distributions:



3. Mean of $\ln|X_k|^2$ grows linearly with time outside the horizon



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$$\partial_{Ht}\langle \ln|X_k|^2 \rangle = \mu_1 \left(\mathcal{N}_s \left(\frac{\sigma}{H}\right)^2 \right)$$

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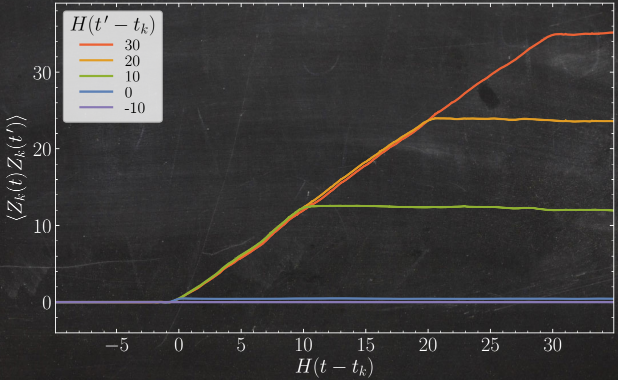
4. The two-point function of $Z_k \equiv \ln|X_k|^2 - \langle \ln|X_k|^2\rangle$ is also linear



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

$|X_k|^2$ performs a geometric (Brownian) random walk ourside the horizon

$$\downarrow$$

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

The quasi-de Sitter Goldstone π couples to the spectator field χ,

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

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To lowest order in π, with $\zeta \simeq H\pi$

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

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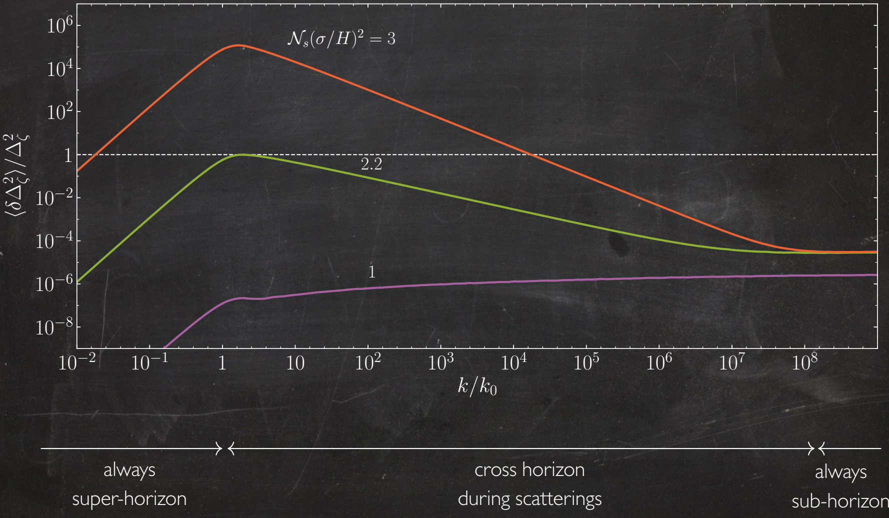
$$\times \int \frac{d^3\mathbf{p}}{(2\pi)^3}\, \left[X_p(\tau')X_p^*(\tau'')\right]_{\rm AS} \left[X_{|\mathbf{p}-\mathbf{k}|}(\tau')X^*_{|\mathbf{p}-\mathbf{k}|}(\tau'')\right]_{\rm AS}$$

$$\downarrow$$

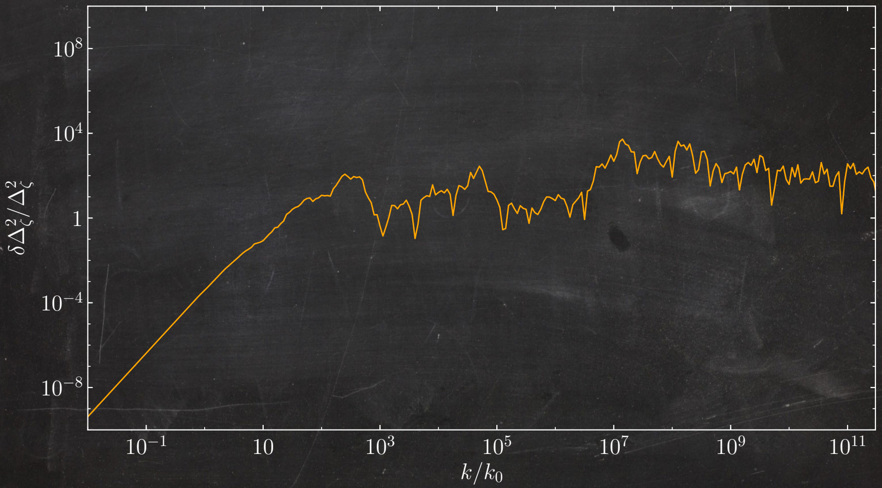
$$\left\langle \delta\Delta_\zeta^2(k)\right\rangle = \left(\Delta^2_{\zeta,0}\right)^2 \mathcal{N}_s \left(\frac{\sigma}{H}\right)^2 e^{\mathcal{F}\left(k, N_e, \mathcal{N}_s(\sigma/H)^2\right)}$$

Curvature power spectrum

(conformal, $N_e = 20$)



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



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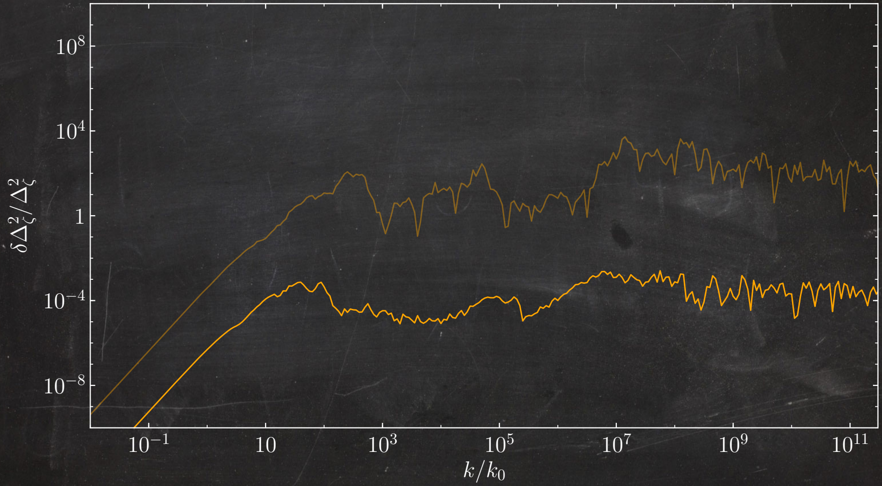

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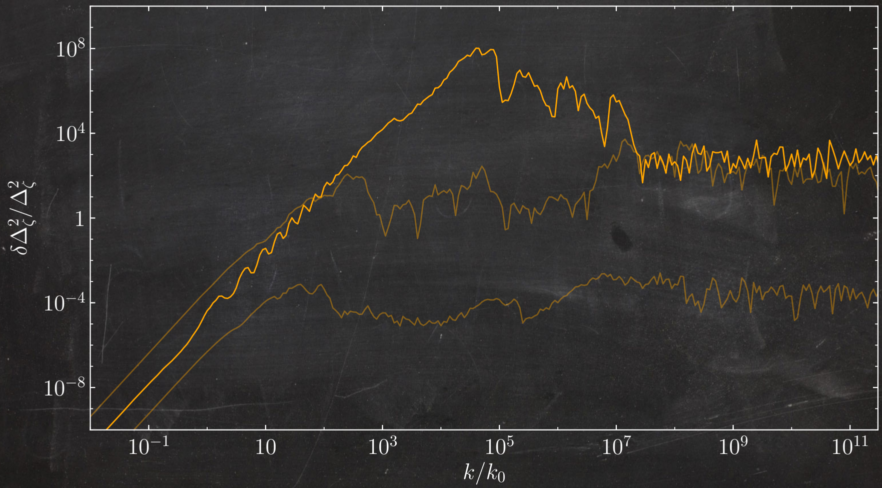

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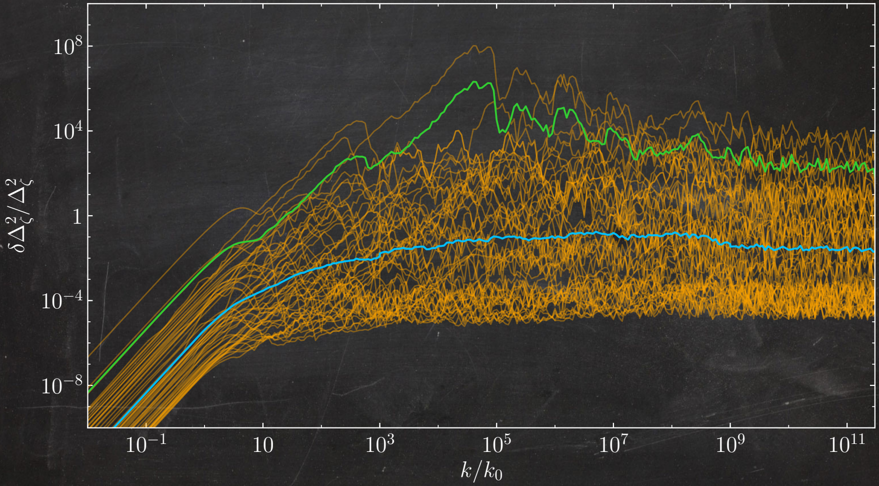

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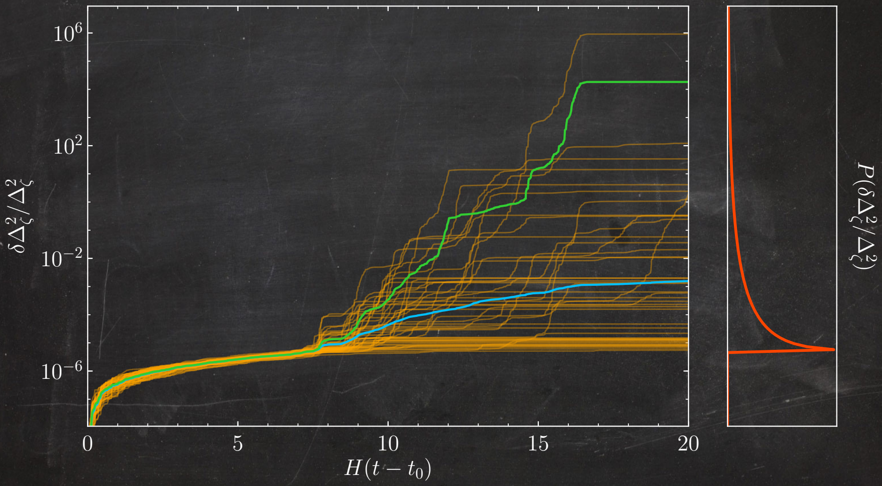


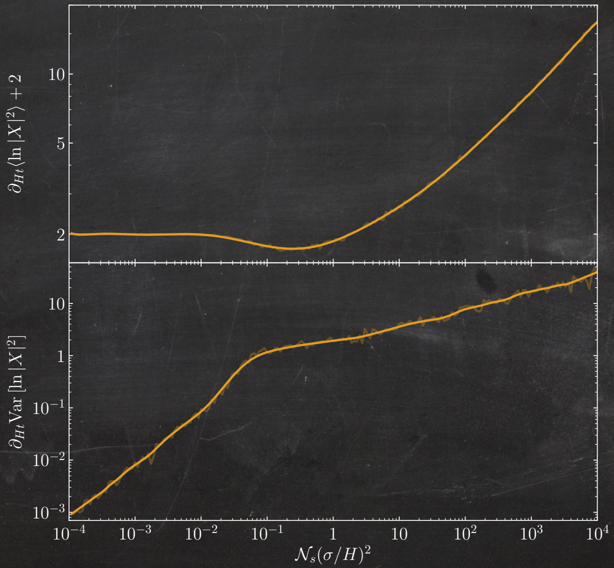
- Stochastically excited spectator fields undergo geometric random walks
- Lead to features in the curvature power spectrum → constraints
- Look for enhancement in the N-point function

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

- Higher spin spectators / higher spin observables
- Stochastic preheating
- Backreaction regime → dissipation

Thank You

Moment rates



Plenty of available parameter space