Constraining dissipative inflation

with Open Effective Field Theories

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Inflation can be dissipative e.g. [Creminelli *et al.*, 2305.07695]

A simple model: inflaton ϕ + massive scalar field χ with softly-broken $U(1)$:

$$S = \int \mathrm{d}^4 x \sqrt{-g} \left[\frac{1}{2} M_{\mathrm{Pl}}^2 R - \frac{1}{2} (\partial\phi)^2 - V(\phi) - |\partial\chi|^2 + M^2 |\chi|^2 \right.$$
$$\left. - \frac{\partial_\mu \phi}{f} \left(\chi \partial^\mu \chi^* - \chi^* \partial^\mu \chi \right) - \frac{1}{2} m^2 \left(\chi^2 + \chi^{*2} \right) \right].$$

$\Rightarrow$ gauge sector χ plays the role of an effective bath for inflaton ϕ.

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Perturbations $\zeta = -H\pi$ controlled by **non-linear Langevin equation**:

$$\pi'' + (2H+\gamma)\, a\pi' - \partial_i^2\pi \simeq \frac{\gamma}{2\rho f}\left[(\partial_i\pi)^2 - 2\pi\xi\pi'^2\right] - \frac{a^2 m^2}{f}\left(1 + 2\pi\xi\frac{\pi'}{a\rho f}\right)\delta\mathcal{O}_S\,,$$

with **noise statistics**:

$$\langle\delta\mathcal{O}_S(\boldsymbol{k},\eta)\delta\mathcal{O}_S(\boldsymbol{k}',\eta')\rangle \simeq (2\pi)^3\delta(\boldsymbol{k}+\boldsymbol{k}')\delta(\eta-\eta')H^4\eta^4\nu_{\mathcal{O}}\,,$$

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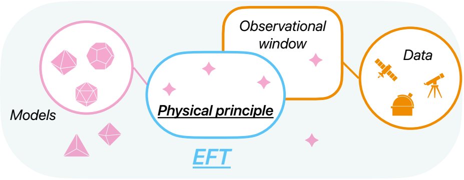
Beyond this model: *General rules*? *Universal predictions*? *Smoking gun*?

Effective Field Theories (EFTs)

EFTs explain the emergence of universality classes:



1. Degrees of freedom;
2. Principles and symmetries;
3. Hierarchies of scales.

Usually for *clean and isolated vacuum*.
Yet many systems evolve in **noisy and dissipative media**.

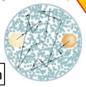
- Hydrodynamics: *imperfect fluids & viscosity*;
- Heavy ions collisions: *quark-gluon plasma*;
- Gravitational waves: *damped by relativistic neutrinos*;
- Early universe: *gauge sectors act as medium*.

Goal: *model dissipation and noise with EFTs in cosmology*

Combining EFTs and Open Quantum Systems

Langevin equation

$$\mathrm{d}\mathcal{O} = \{H, O\}\mathrm{d}t + \mathrm{d}\xi$$



Martin-Siggia-Rose formalism

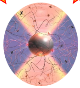
$$P = \int \mathcal{D}x\mathcal{D}\widetilde{x}\, e^{-S[x,\widetilde{x}]}$$

Fokker-Planck equation

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \mathcal{L}_{\mathrm{FP}}[P]$$

Stochastic Schrödinger equation

$$\mathrm{d}\widehat{\mathcal{O}} = -i\left[\widehat{H}, \widehat{\mathcal{O}}\right] + \mathrm{d}\widehat{\xi}$$



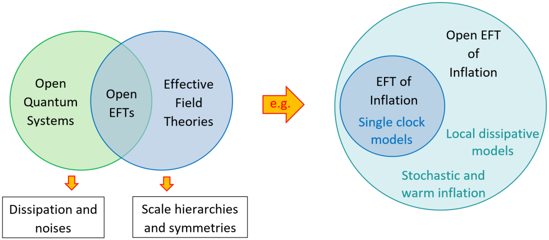
Influence functional

$$\langle\phi_1|\,\widehat{\rho}_{\mathrm{red}}\,|\phi_2\rangle = \int \mathcal{D}\phi_\pm e^{iS_{\mathrm{IF}}[\phi_+,\phi_-]}$$

Master equation

$$\frac{\mathrm{d}\widehat{\rho}_{\mathrm{red}}}{\mathrm{d}t} = \mathcal{L}[\widehat{\rho}_{\mathrm{red}}]$$

Extend the **embedding power** of EFTs:



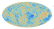
Outline

1. The Open EFT of Inflation
2. Primordial non-Gaussianities

Outline

The Open EFT of Inflation [S.A. Agüí Salcedo, T.C. & E. Pajer, 2404.15416]

Early universe: one scalar degree of freedom $\pi(\boldsymbol{x}, t)$:

Observed ⟨  ⟩ $\Leftrightarrow$ $\langle \hat{\pi}^n \rangle(t) = \int \mathrm{d}\pi \pi^n \mathrm{Prob}_\pi(t)\,.$

- EFT of Inflation [Cheung *et al.*, 2008]: most generic wavefunction

$$\mathrm{Prob}_\pi(t) = |\Psi_\pi(t)|^2 = \left| \int_\Omega^\pi \mathcal{D}\pi \; e^{iS_{\rm eff}[\pi]} \right|^2$$

- **Dissipation** & **noise**: most generic density matrix

$$\mathrm{Prob}_\pi(t) = \rho_{\pi\pi}(t) = \int_\Omega^\pi \mathcal{D}\pi_+ \int_\Omega^\pi \mathcal{D}\pi_- \; e^{iS_{\rm eff}[\pi_+,\pi_-]}$$

Physical principles restrict $S_{\rm eff}[\pi_+, \pi_-]$:

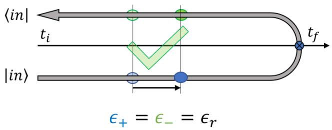
1. Unitarity: {Sys. + Env.} closed $\Rightarrow$ non-equilibrium constraints; [Liu & Glorioso, 2018]
2. Symmetries: strong-to-weak SSB & in-in coset construction; [Akyuz, Goon & Penco, 2023]
3. Locality: truncatable power counting scheme.

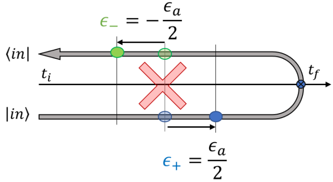
Strong-to-weak spontaneous symmetry breaking [Hongo *et al.*, 2018]

$S_{\rm unit}\left[\pi_\pm\right]$ invariant under shift$_+ \times$ shift$_-$:

$$\pi_\pm(t) \to \pi'_\pm(t) = \pi_\pm(t+\epsilon_\pm) + \epsilon_\pm,$$

but $S_{\rm non-unit}\left[\pi_+;\pi_-\right]$ **is not**: shift$_+ \times$ shift$_- \to$ shift$_r$





Retarded $\pi_r = (\pi_+ + \pi_-)/2$ and **advanced** $\pi_a = \pi_+ - \pi_-$ fields:

$$\pi_r(t) \to \pi'_r(t) = \pi_r(t+\epsilon_r) + \epsilon_r, \qquad \pi_a(t) \to \pi'_a(t) = \pi_a(t+\epsilon_r).$$

Building blocks:

$$\pi_a, \quad t+\pi_r, \quad \partial_\mu \pi_a, \quad \partial_\mu(t+\pi_r).$$

Effective functional

- *Quadratic order:* 1 $\rightarrow$ 5 EFT param (1 tadpole constraint):

$$S_{\mathrm{eff}}^{(2)} = \int \mathrm{d}^4x\sqrt{-g}\Big\{\overbrace{\dot{\pi}_r\dot{\pi}_a - c_s^2\partial_i\pi_r\partial^i\pi_a}^{\text{Kinetic term}}$$

$$\underbrace{-\gamma\dot{\pi}_r\pi_a}_{\text{Dissipation}} + i\underbrace{\left[\beta_1\pi_a^2 - (\beta_2-\beta_4)\,\dot{\pi}_a^2 + \beta_2\left(\partial_i\pi_a\right)^2\right]}_{\text{Noise}}\Big\}$$

- *Cubic order:* 1 $\rightarrow$ 13 EFT param: EFToI famous for relating operators at different orders because of **non-linearly realised boosts** [López Nacir *et al.*, 2011].

$$\text{EFToI}: \qquad \mathcal{L} \supset \left(c_s^2 - 1\right)\left[-2\dot{\pi}_r + (\partial_\mu\pi_r)^2\right]\dot{\pi}_a$$

$$\text{Dissipation}: \qquad \mathcal{L} \supset \gamma\left[-2\dot{\pi}_r + (\partial_\mu\pi_r)^2\right]\pi_a$$

$$\text{Noise}: \qquad \mathcal{L} \supset i\beta_4\left(-\dot{\pi}_a + \partial_\mu\pi_r\partial^\mu\pi_a\right)^2$$

Recover and extend EFToI construction.

Outline

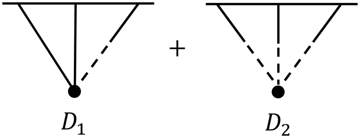
Standard observables

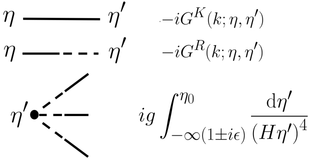
Symmetries ensure existence of nearly scale invariant power spectrum

$$\langle \zeta_{\boldsymbol{k}} \zeta_{\boldsymbol{k}'} \rangle = \frac{H^2}{f_\pi^4} \langle \pi^c_{\boldsymbol{k}} \pi^c_{\boldsymbol{k}'} \rangle \equiv (2\pi)^3 \delta(\boldsymbol{k} + \boldsymbol{k}) \frac{2\pi^2}{k^3} \Delta^2_\zeta(k).$$

$\Rightarrow \Delta^2_\zeta = 10^{-9}$ obtained by imposing hierarchies of scales.

Bispectrum computed in **perturbation theory** using standard in-in rules.

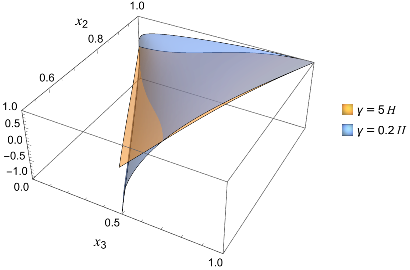




$$\langle \zeta_{\boldsymbol{k}_1} \zeta_{\boldsymbol{k}_2} \zeta_{\boldsymbol{k}_3} \rangle = -\frac{H^3}{f_\pi^6} \langle \pi^c_{\boldsymbol{k}_1} \pi^c_{\boldsymbol{k}_2} \pi^c_{\boldsymbol{k}_3} \rangle \equiv (2\pi)^3 \delta(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3) B(k_1, k_2, k_3).$$

$$S(x_2, x_3) \equiv (x_2 x_3)^2 \frac{B(k_1, x_2 k_1, x_3 k_1)}{B(k_1, k_1, k_1)}, \qquad f_{\mathrm{NL}}(k_1, k_2, k_3) \equiv \frac{5}{6} \frac{B(k_1, k_2, k_3)}{P(k_1)P(k_2) + 2 \text{ perms.}}.$$

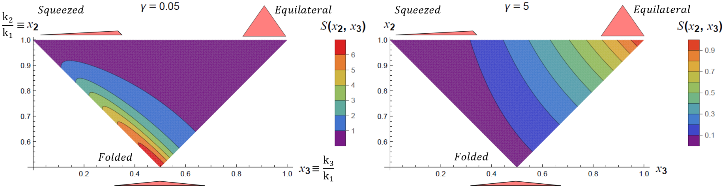
Bispectrum shapes



Main features:

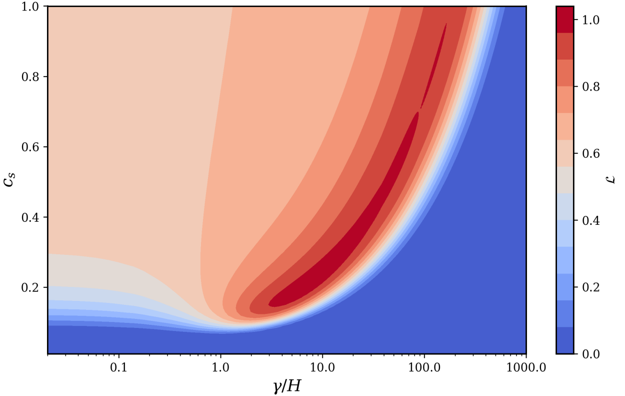
- $\gamma \gg H$: equilateral
  Dissipation suppresses unequal freeze-out times
- $\gamma \ll H$: folded
  Environmental sourcing enhances a folded signal

Shape evolution cannot be retained by a single **equilateral/orthogonal template**



Results from Planck 2018 [**Bowei Zhang**, **Petar Suman** *et al.*, 2603.13473]

$$-2\log\mathcal{L} \propto \sum_{\ell_1,\ell_2,\ell_3} \frac{\Delta_{\ell_1,\ell_2,\ell_3}}{6C_{\ell_1}C_{\ell_2}C_{\ell_3}} \left[B^{\rm th}_{\ell_1,\ell_2,\ell_3} - B^{\rm obs}_{\ell_1,\ell_2,\ell_3}\right]^2$$



$$c_s \geq 0.38, \quad \gamma \leq 383.6H \quad \text{at} \quad 2\sigma \quad \text{(with uniform priors)}$$

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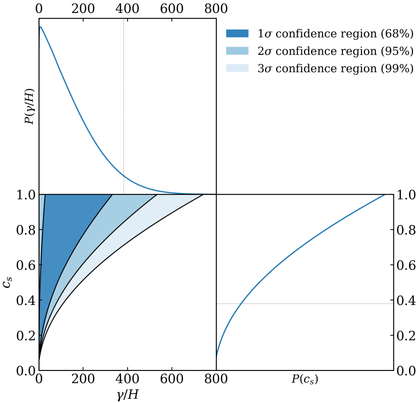

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Constraining UV models (*WIP*) [with **Bowei Zhang**, **Petar Suman** *et al.*]

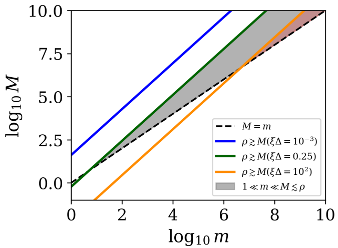
Dissipative inflation via scalar production [Creminelli *et al.*, 2305.07695]

$$S = \int \sqrt{-g}\left[\frac{1}{2}M_{\rm Pl}^2 R + \mathcal{L}(\phi) - |\partial\chi|^2 + M^2|\chi|^2 - \frac{\partial_\mu\phi}{f}\left(\chi\partial^\mu\chi^* - \chi^*\partial^\mu\chi\right) - \frac{1}{2}m^2\left(\chi^2+\chi^{*2}\right)\right].$$

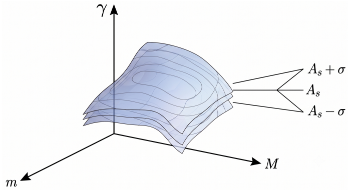
1. **Scale hierarchy**: with $\rho f \equiv \dot{\phi}$

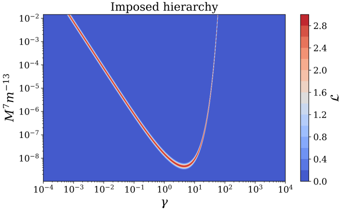
$$f \gg \rho \gtrsim M \gg m \gg H$$

$\Rightarrow$ *constrains parameter space*

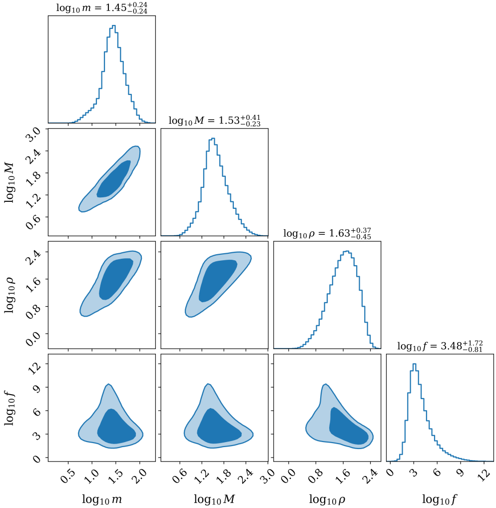


2. **Power spectrum A_s**:





Posteriors from joint likelihood (*preliminary*)



1. Bispectrum only *marginally improves* the constraints;
2. Bispectrum helps to *break degeneracy* in (γ, ξ) plane.

Conclusion

Open EFT of Inflation:

1. Unitarity, locality, scale invariance: dissipative shift symmetric scalar in dS;
2. Capture some gauge-inflation models with a **scale hierarchy**.

Power counting & radiative stability, dynamical gravity & GWs

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Primordial non-Gaussianities:

1. Smoking gun near folded triangles in **primordial non-Gaussianities**;
2. Shape evolution needs to go beyond **equilateral/orthogonal template**

CMB and LSS constraints on EFT coefficients

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Constraining UV models:

1. Combined constraints from **scale hierarchy**, **power spectrum** & **PNG**;
2. So far, PNG add **marginal information** but may break degeneracy.

Axion inflation, warm inflation, dissipative Cosmological Collider

Backup

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Outline

Details of matching with [Creminelli *et al.*, 2305.07695]

	Parameters:						
UV completion	M	m	f	ρ	ξ	γ	$\nu_{\mathcal{O}}/\nu_{\mathcal{O}^3}$
Open EFT	f_π^2	c_s	γ	γ_2	β_1	β_5	δ_1

Matching:	$f_\pi^2 = \rho f$
$\xi = \frac{m^4}{8H\rho M^2}$	$\gamma = \frac{\xi m^4}{\pi M f^2} e^{2\pi\xi}$
$\Gamma = \pi\xi\gamma$	$\beta_1 = \frac{\nu_{\mathcal{O}}}{2\rho f}\frac{m^4}{f^2}$
$\beta_5 = 2\pi\xi\beta_1$	$\delta_1 = \frac{\nu_{\mathcal{O}^3}}{6\sqrt{\rho f}}\frac{m^6}{f^3}$

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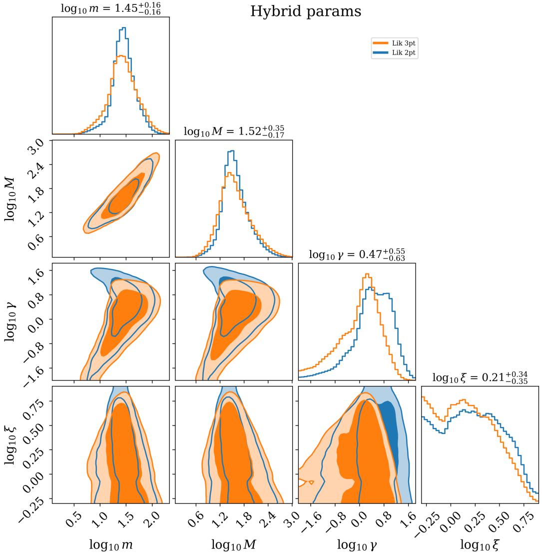
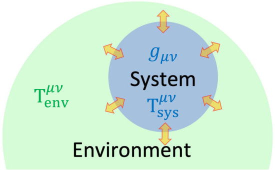


Outline

Open gravity [S.A. Agüí Salcedo, T.C. , L. Dufner & E. Pajer, 2507.03103]

Dissipative theory for a **massless spin** 2 **graviton**: theory of gravity in a medium.

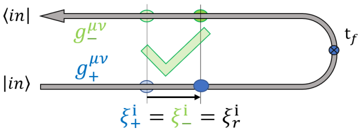


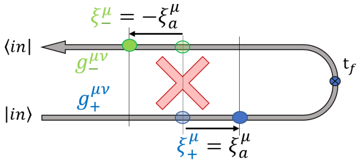
Diffeomorphisms invariance:

$$g^{\mu\nu}_{\pm}(x) \to \frac{\partial(x^\mu + \xi^\mu_\pm)}{\partial x^\alpha}\frac{\partial(x^\nu + \xi^\nu_\pm)}{\partial x^\beta} g^{\alpha\beta}_{\pm}(x)$$

for each branch of SK path integral contour.

Dissipation & noise: *strong-to-weak* SSB [Sieberer *et al.*, 2016]





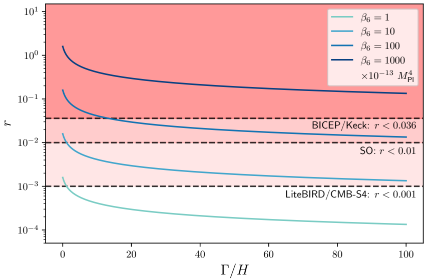
$$\mathrm{ISO}(3,1)_+ \times \mathrm{ISO}(3,1)_- \to \mathrm{ISO}(3)_{\rm r} \times \mathbb{R}_{\rm r}$$ [Crossley, Liu & Glorioso, 1511.03646]

Gravitational waves in a medium

Transverse and traceless (TT) sector: $g_{ij} = a^2(t)\,(\delta_{ij} + h_{ij})$:

$$\ddot{h}_{ij} - c_T^2 \frac{\nabla^2}{a^2} h_{ij} + (\Gamma + 3H)\,\dot{h}_{ij} + \frac{\chi_T}{a}\epsilon_{imn}\left(\partial_m \dot{h}_{nj} + 2H\partial_m h_{nj}\right) = \xi_{ij}$$

1. Speed of propagation c_T^2;
2. Dissipation Γ;
3. Birefringence χ_T;
4. Noise $\beta_6 \propto \langle \xi_{ij}\xi^{ij}\rangle$.



For $\chi_T = 0$ (no birefringence):

BICEP/Keck bound:

$$r < 0.036 \;\Rightarrow\; \beta_T \lesssim (0.002 M_{\rm Pl})^4$$

SGWB and PTA data?