Dissipative EFTs in cosmology

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Based on
- **2509.13284** JHEP 05 (2026) 145
- **2512.21234** with Jinn-Ouk Gong

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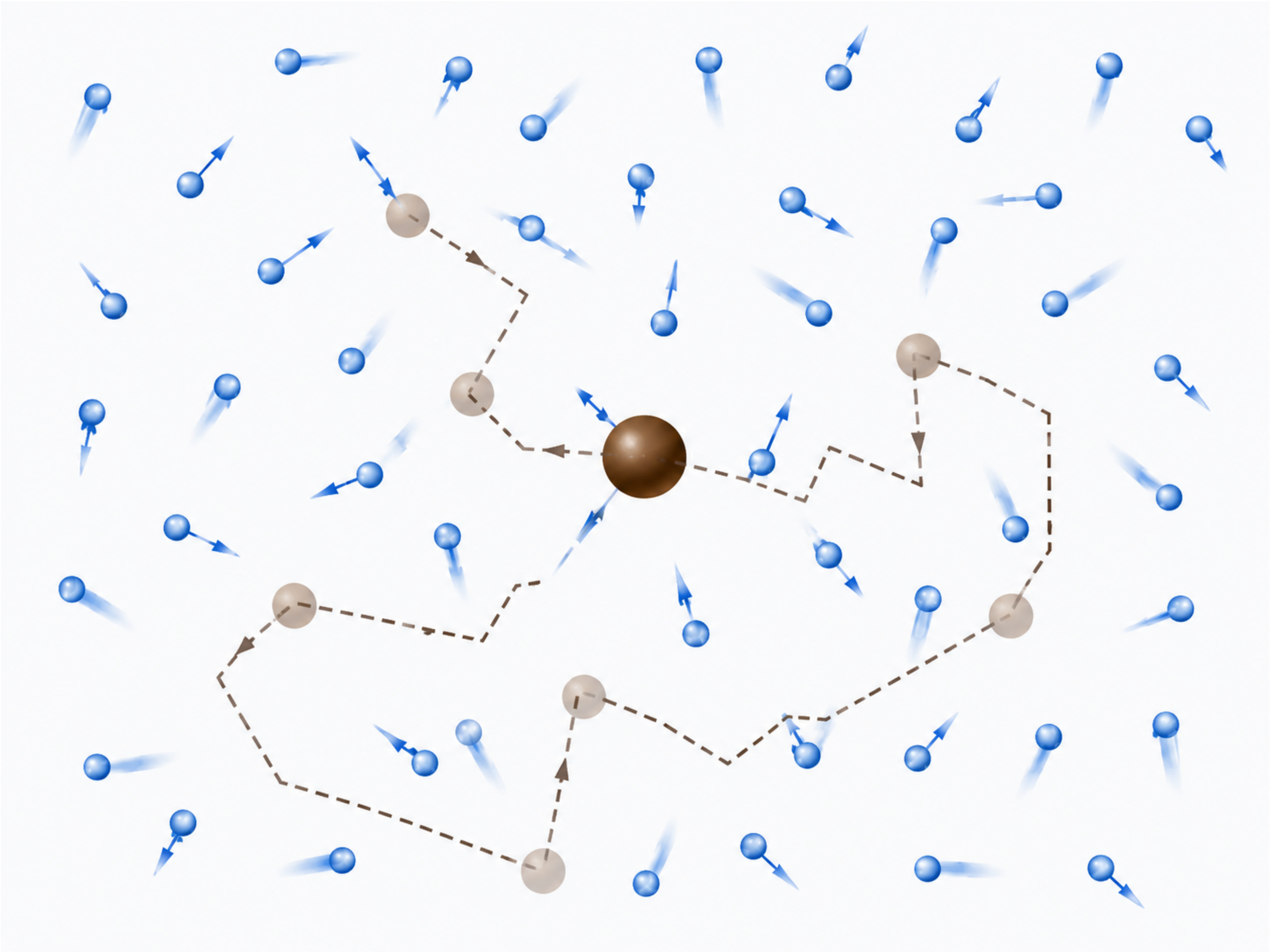
How does a pollen particle move?



$$\ddot{q} + \gamma\dot{q} + V_{,q} = \xi$$

friction

stochastic kick

When microscopic variables are not tracked their effect appears as dissipation and stochastic noise

From pollen to inflation

Brownian motion shows what happens when we observe only part of a system

System
(metric + scalar field) could be coupled to unobserved degrees

Example: Warm inflation - system coupled to a thermal bath [A. Berera 9509049]

$$\delta\ddot{\varphi}_{\mathbf{k}} + (3H + \Upsilon)\delta\dot{\varphi}_{\mathbf{k}} + \left(\frac{k^2}{a^2} + V_{\varphi\varphi}\right)\delta\varphi_{\mathbf{k}} = \xi_{\mathbf{k}} + \cdots$$

friction

noise

One-page summary

The question: Can we write a local EFT of inflation with

dissipation and noise + well-posed dynamics

see e.g. [E. Lausdei, E. Pajer 2605.23375]

(the theory should predict
at least 3 propagating DOF)

Our answer:

Yes, provided we correctly account for the constraint structure of the theory

Contents

- **Conservation laws**
- A note on diffeomorphism symmetry
- Application: dissipative inflation

Symmetries are doubled in SK: $G \to G_1 \times G_2$

Superfluid: $\boxed{S[\phi] = \int \dot{\phi}^2 - \nabla\phi \cdot \nabla\phi + \ldots}$ $\longrightarrow$ $\boxed{S_{\mathrm{SK}} = \int \dot{\phi}_{\mathrm{a}}\dot{\phi} - \nabla\phi_{\mathrm{a}}\nabla\phi + \ldots}$

$c_{\mathrm{s}}^2 = 1$

$$U(1) \to U(1) \times U(1)_{\mathrm{a}}$$

Advanced symmetries dictate conservation laws (of physical fields)

[L. M. Sieberer, M. Buchhold, S. Diehl 1512.00637]

Term proportional to ϕ_{a} gives deterministic EOM

$\mathscr{L}_{\mathrm{SK}} = \phi_{\mathrm{a}} E(\phi) + \ldots$ analogous to variation $\delta\mathscr{L}_{\mathrm{usual}} = \delta\phi$ EOM(ϕ)

Symmetry transformations of advanced fields yield conservation laws

Open system: broken (or non-trivial) global advanced symmetry

Typical open terms:

- Dissipation $u_\mu = (-1,0,0,0)$: $-\Gamma\phi_\mathrm{a}\dot{\phi}$
- Noise: $i\beta\phi_\mathrm{a}^2$

[M. Hongo, S. Kim, T. Noumi, A. Ota 1805.06240]
[L. V. Delacrétaz, B. Goutéraux, V. Ziogas 2111.13459]
[C. O. Akyuz, R. Penco 2503.22840]

Both break the advanced symmetry of closed system

$$S_\mathrm{open} = \int \left(\partial_\mu\phi_\mathrm{a} + \Gamma u_\mu\phi_\mathrm{a}\right)\partial^\mu\phi + i\beta\phi_\mathrm{a}^2$$

$$\ddot{\phi} - \nabla^2\phi + \underbrace{\Gamma\dot{\phi}}_{\text{dissipation}} - \underbrace{i\beta\phi_\mathrm{a}}_{\text{noise}} = 0$$

$$U(1)_1 \times U(1)_2 \to U(1)_\mathrm{diag}$$

$$U(1) \times U(1)_\mathrm{a} \to U(1)$$

What about gauge symmetries?

Contents

- Conservation laws
- **A note on diffeomorphism symmetry**
- Application: dissipative inflation

Diffeomorphism invariance (or the gauge issue in cosmology)

Einstein + matter

$$\mathcal{E}_{\mu\nu} = G_{\mu\nu} - \kappa T_{\mu\nu}[\psi, g_{\mu\nu}] = 0$$
$$\mathcal{E}_{\psi} = 0$$

How many DOF?

In **4D** $\boxed{\text{\# metric components}} = \boxed{\text{\# } G_{\mu\nu} \text{ components}} = 10$

Can we determine 10 metric components uniquely?

NO! Not every metric component is physical

Can always perform 4 coordinate transf. to set 4 metric components to zero

$g_{\mu\nu} \Leftrightarrow A_{\mu}$

coordinate freedom $\rightarrow$ 4 should remain undetermined $\Rightarrow$ system should be degenerate $\Leftrightarrow$ not all equations can be independent

From Noether's 2nd theorem, EOM of a diff-invariant action satisfy: $\boxed{\nabla^{\mu}\mathscr{E}_{\mu\nu} = 0}$ $\left(\text{for } \frac{\delta S}{\delta \psi} = 0\right)$

6 linearly independent EOM $\longrightarrow$ can determine 6 components

Consistent $T_{\mu\nu}$: covariantly conserved **off-shell** (when matter EOM are satisfied) $\boxed{\nabla^{\mu}T_{\mu\nu} = 0}$

Emmy Noether called this type of conservation law improper

SK formulation of gravity

Simplest gravitational action is the E-H term

$$S_{\mathrm{SK}}[g_1, g_2] = \int \left(\sqrt{-g_1} R[g_1] - \sqrt{-g_2} R[g_2] \right)$$

Action invariant under two diffeomorphims: Diff$(4)_1 \times$ Diff$(4)_2$

In Keldysh basis $\quad S_{\mathrm{SK}}[g, g_{\mathrm{a}}] = S\left[g + \frac{1}{2} g_{\mathrm{a}}\right] - S\left[g - \frac{1}{2} g_{\mathrm{a}}\right]$

Highly non-linear + Physical content of 2 independnent metrics? $\longrightarrow$ Motivates working in semi-classical limit $g_{\mathrm{a}}^{\mu\nu} \to 0$

Advanced metric becomes a matter field living on physical spacetime

$$S_{\rm SK} = \int \left[\sqrt{-g}\, G_{\mu\nu} g_{\rm a}^{\mu\nu} + \mathcal{O}\left(g_{\rm a}^3\right) \right]$$

Action invariant under **diagonal** diffs

$$\boxed{\delta g_{\mu\nu} = -\mathcal{L}_\xi g_{\mu\nu}\,, \quad \delta g_{\rm a}^{\mu\nu} = -\mathcal{L}_\xi g_{\rm a}^{\mu\nu}\,, \ldots}$$

To find advanced diffs recall in the classical limit $\delta g^{\mu\nu} \sim g_{\rm a}^{\mu\nu}$

$$\delta S = \int \sqrt{-g}\, G_{\mu\nu} \delta g^{\mu\nu}$$

$\boxed{\delta g_{\rm a}^{\mu\nu} = -\mathcal{L}_{\xi_{\rm a}} g^{\mu\nu}}$ implies $\nabla^\nu G_{\mu\nu} = 0$ (identities between EOM)

$\text{Diff}(4)_1 \times \text{Diff}(4)_2 \longrightarrow \boxed{\text{Diff}(4) \quad \times \quad \text{Advanced Diffs}(4)}$

Ordinary diffs (physical)

Shifts acting only on advanced metric

[P. Glorioso, H. Liu 1805.09331]

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- **Application: dissipative inflation**

Lightning review of **EFT of inflation**

Inflationary background depends on t	Action for perturbations is time dependent $S_2[\delta\phi] = S[\phi] - S[\bar{\phi}]$	Invariant only under spatial diffeomorphisms $\tilde{x}^i = \tilde{x}^i(t, x^j)$	EFT: most general action invariant under 3D diffeomorphisms

Similar to Higgs, can perform a time redefinition to set inflationary fluctuations to zero
$\delta\phi = 0 \Leftrightarrow$ unitary gauge

Minimal ingredients of EFT in unitary gauge

- Arbitrary time-dependent functions $f(t)$
- Basis one-form $\mathrm{d}t = \delta^0_\mu \mathrm{d}x^\mu$
- Spacetime metric $g_{\mu\nu}$ to construct scalars, ∇_μ

Invariant objects include: $g^{00}, \delta^0_\mu \nabla^\mu, K^{ij} g_{ij}, \dots$

$\delta g^{00} \equiv g^{00} - g^{00}_{\mathrm{FRW}}$

$K_{\mu\nu} \equiv P^\alpha_\mu \nabla_\alpha n_\nu$

$$\boxed{\mathscr{L}_{\mathrm{EFT}} = \underbrace{R + c_1(t) + c_2(t)\delta g^{00}}_{\text{universal part}} + \underbrace{c_3(t)\left(\delta g^{00}\right)^2 + c_4(t)\delta K^2 + \dots}_{\text{theory specific}}}$$

[C. Cheung, P. Creminelli, A. L. Fitzpatrick, J. Kaplan, L. Senatore 0709.0293]

Broken time diffs $\rightarrow$ Reduced identities between EOM $\rightarrow$ $P^\nu_i \nabla^\mu E_{\mu\nu} = 0$

No derivatives of lapse and shift: **Hamiltonian** and **Momentum** constraints are preserved

10 - 3 diffs - 4 constraints = 3 **propagating DOF**

Dissipative inflation

Assumption: environment relaxes much faster than H^{-1} $\Rightarrow$ Local EFT

Strategy: break advanced diffeomorphism symmetry to write terms belonging to S_{IF}

Can we write arbitrary terms allowed by physical 3D diffs?

Is the problem similar to open E/M? [S. A. Salcedo, T. Colas, E. Pajer 2412.12299]
[See also talk by S. A. Salcedo]

No! We can only write terms that do not over/under constrain the EOM

Allowed terms $\Leftrightarrow$ existence of deformed advanced diffs

[See talk by A. Tolley for related argument from top down]

One consistent term:
[**PC** 2509.13284]

$$\left(K_{\mu\nu} - KP_{\mu\nu}\right)\sqrt{-g^{00}}$$

$$\pi_{ij}/\sqrt{-g}$$

$$P_i^{\nu} \equiv \delta_i^{\nu} + n^{\nu} n_i$$
$$g^{00} = -\mathcal{N}^{-2}$$

$$E_{\mu\nu} = \underbrace{G_{\mu\nu} + \left(\bar{c}_{\delta} + M^2 \delta g^{00}\right) \delta_{\mu}^{0} \delta_{\nu}^{0} + \left[\bar{c}_{\mathrm{g}} - \frac{1}{2}\bar{c}_{\delta}\delta g^{00} - \frac{1}{4}M^2 \left(\delta g^{00}\right)^2\right] g_{\mu\nu}}_{\text{closed part}}$$
$$+ \underbrace{\Gamma(K_{\mu\nu} - KP_{\mu\nu})\sqrt{-g^{00}}}_{\text{open part}}$$

$$M \equiv \sqrt{2} M_2(t)^2 / m_{\mathrm{pl}}$$

Why does it work?

The deterministic EOM satisfy the deformed identity [PC 2509.13284]

$$P_i^\nu \nabla^\mu E_{\mu\nu} = \frac{\Gamma}{\mathcal{N}} P_i^\nu E_{\mu\nu} n^\mu \qquad \left[\delta g_{\rm a}^{\mu\nu} = -2\nabla^{(\mu}\xi_{\rm a}^{\nu)} - 2\Gamma n^{(\mu}\xi_{\rm a}^{\nu)} \quad \text{with} \quad \xi_{\rm a}^\mu n_\mu = 0\right]$$

EFT of inflation building blocks → freedom to perform 3 spatial coordinate transformations

Deformed advanced diffs → 3 relations between 10 components of EOM

they match!

Quick counting

2 tensor
4 vector
4 scalar
− **3** physical diffs/ **3** deformed identities
1 Hamiltonian + **3** momentum constraints
= **3** propagating DOF

Expand in metric perturbations, solve the constraints to obtain the EOM for $\psi = -\mathscr{R}$

[**PC** , J-O Gong 2512.21234]

$$\boxed{\ddot{\psi} + \left\{(3+\gamma)H + \partial_t\left[\log\left(\frac{2\epsilon + 2\gamma}{c_s^2}\right)\right]\right\}\dot{\psi} - c_s^2\frac{\nabla^2\psi}{a^2} = \Xi_\psi}$$

$$\boxed{\begin{aligned} \gamma &\equiv \frac{\Gamma}{H} \\ c_s^2 &\equiv \frac{\epsilon + \gamma}{\epsilon + M^2/H^2 - \gamma} \end{aligned}}$$

This matches expressions obtained in the decoupling limit in previous

[D. Lopez Nacir, R.A. Porto, L. Senatore, M. Zaldarriaga 1109.4192]

[P. Creminelli, . Kumar, B. Salehian, L. Santoni 2305.07695]

[S.A. Salcedo, T. Colas, E. Pajer 2404.15416]

Tensor modes can be treated analogously, see also [P. H. C. Lau, K. Nishii, T. Noumi 2412.21136] [S. A. Salcedo, T. Colas, L. Dufner, E. Pajer 2507.03103]

Compute power spectrum under some assumptions:

- The EFT is not valid for arbitrary scales $\Leftrightarrow \gamma$ becomes significant after some time τ_0 [D. Lopez Nacir, R.A. Porto, L. Senatore, M. Zaldarriaga 1109.4192]
- Similarly, c_s can differ after τ_0. Usually set $(\tilde{c}_s = 1)$
- Initially factorisable state + Bunch-Davies for the scalar/tensor degrees (convenience)

$$\boxed{\mathcal{P}_{\mathcal{R}} = \left\{1 + \left[\frac{8(c_s - \tilde{c}_s) - \gamma\tilde{c}_s(6+\gamma)}{8\tilde{c}_s\gamma\omega_0}\right]^2\right\}\left(\frac{2}{\gamma\omega_0}\right)^{\gamma}\left[\frac{2}{\sqrt{\pi}}\Gamma\left(\frac{3+\gamma}{2}\right)\right]^2\frac{\tilde{c}_s}{c_s}\mathcal{P}_0 + \sum_i \mathcal{P}^i_{\text{noise}}}$$

$$\mathcal{P}_0 \equiv \frac{H^2}{8\pi^2\epsilon c_s}$$ - standard single-field power spectrum

$$\omega_0 \equiv -c_s k\tau_0/\gamma$$

Previous has the correct limits for small/large dissipation or noise

- Closed EFT limit: $\gamma \to 0$ and noise $\to 0$: $\mathscr{P}_{\mathscr{R}} \to \mathscr{P}_0$
- Strong dissipation limit: $\mathscr{P}_{\mathscr{R}}$ is dominated by noise

Decoupling limit is straightforward - study of higher correlators

Performing an advanced field redefinition, identity becomes

$$P_i^{\nu} \nabla^{\mu} \left(e^{\Gamma\theta} E_{\mu\nu} \right) = 0 \quad \left[n^{\mu} \equiv \partial^{\mu}\theta \right]$$

Similar to what happens in open e/m [G. Kaplanek,M. Mylova, A-J. Tolley 2512.17089]

Conclusion

Physical gauge symmetries require the existence of (possibly deformed) advanced gauge symmetries. Otherwise EFT is inconsistent

Future directions

- Classify all open terms in the EFT of inflation
- Better understand the openness of dissipative terms
- Construct explicitly the noise sector
- Implement stochastic inflation in this framework [See talk by S. Cespedes]