An Open System Approach to Gravity

Lennard Dufner

Based on arXiv:2507.03103

In collaboration with Santiago Agüí Salcedo, Thomas Colas & Enrico Pajer

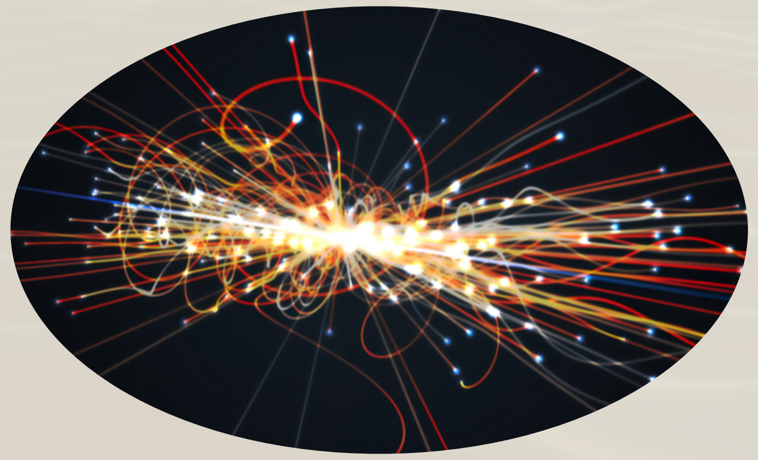
41st Annual IAP symposium on Inflation

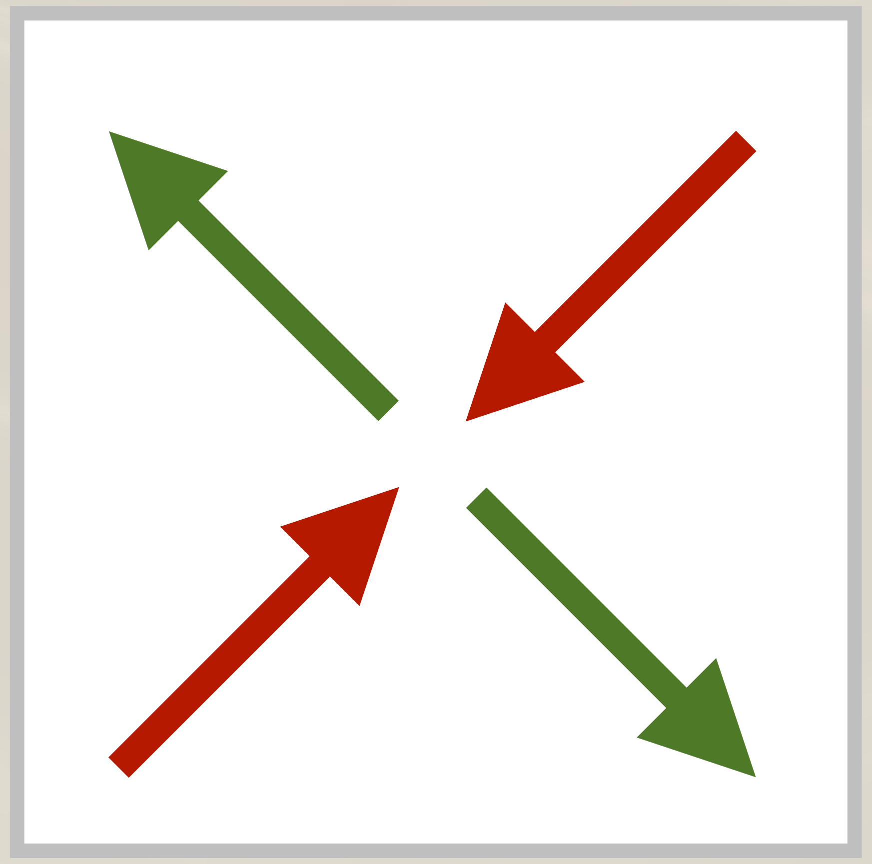
UNIVERSITY OF CAMBRIDGE

UKRI Science and Technology Facilities Council

Motivation

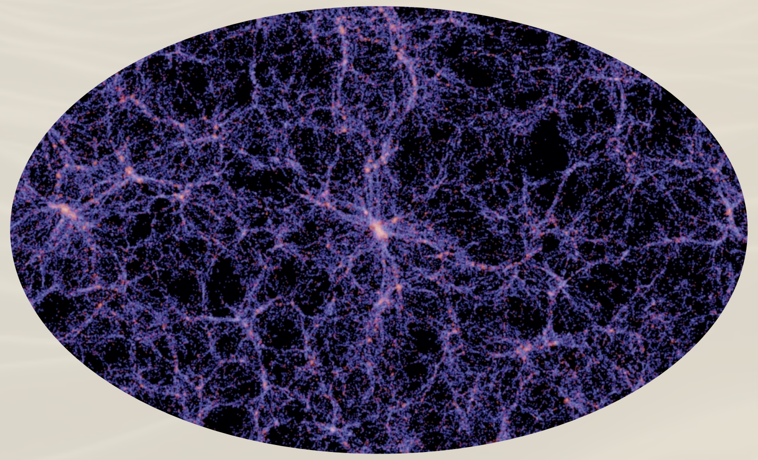
Particle Physics

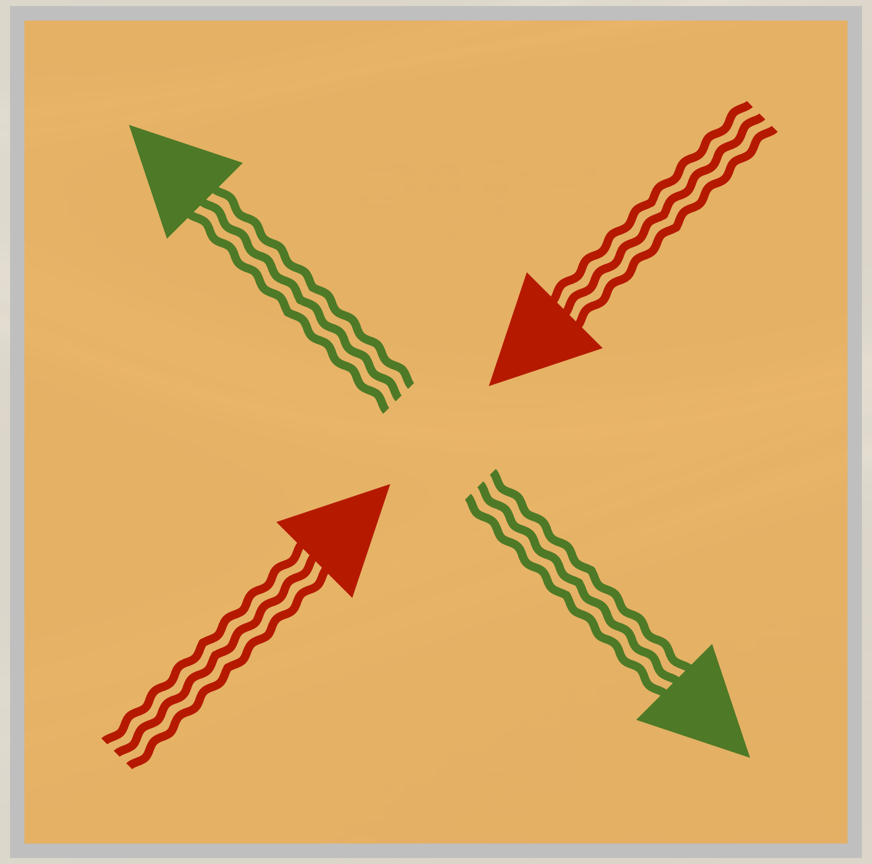




Clean vacuum - no medium

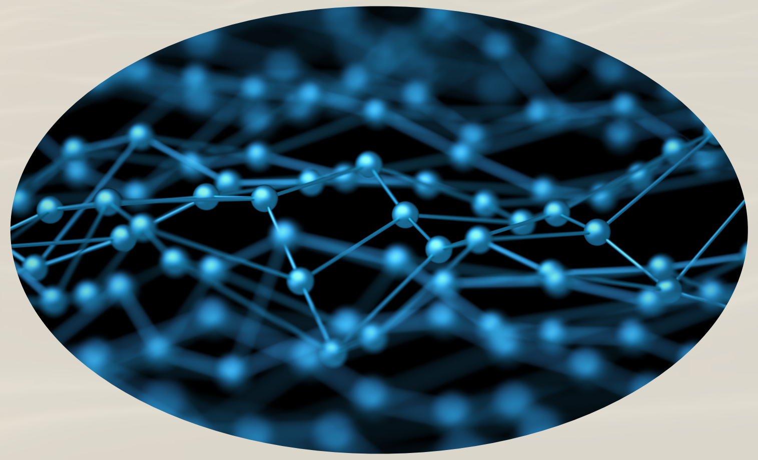
Cosmology

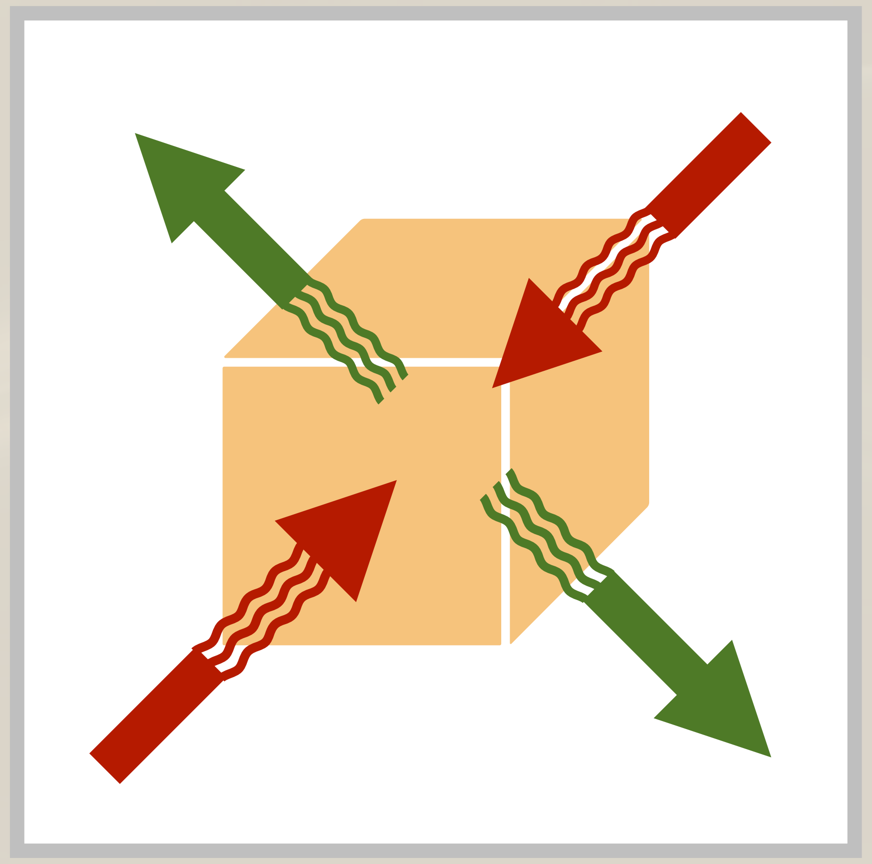




Perturbations propagate in unknown medium

Condensed matter





Medium known but intractable; medium can be manipulated

Overview

Thomas Colas' talk this morning: how to construct the "Open EFT of inflation" [Agüì-Salcedo et al. '24]
→ EFT of a single dissipative scalar on rigid inflating background

This talk: how to incorporate **dynamical gravity** in the theory?

Motivation:

- Describe gravitons propagating through unknown medium
- Interactions between graviton and scalar
- Applications to late-time cosmology

Goal:

How to describe gravitational systems in the Schwinger-Keldysh formalism?

Outline

1. Gravity in the Schwinger-Keldysh formalism

2. Dissipative gravitational waves during inflation

3. Summary and outlook

Outline

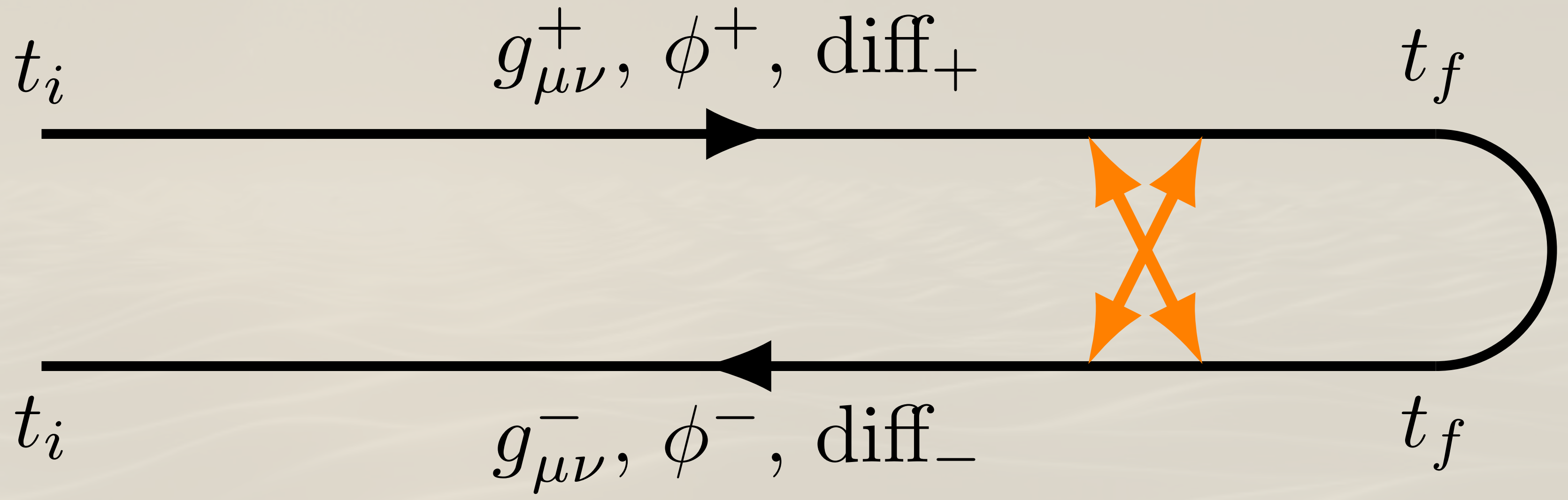
1. **Gravity in the Schwinger-Keldysh formalism**

2. Dissipative gravitational waves during inflation

3. Summary and outlook

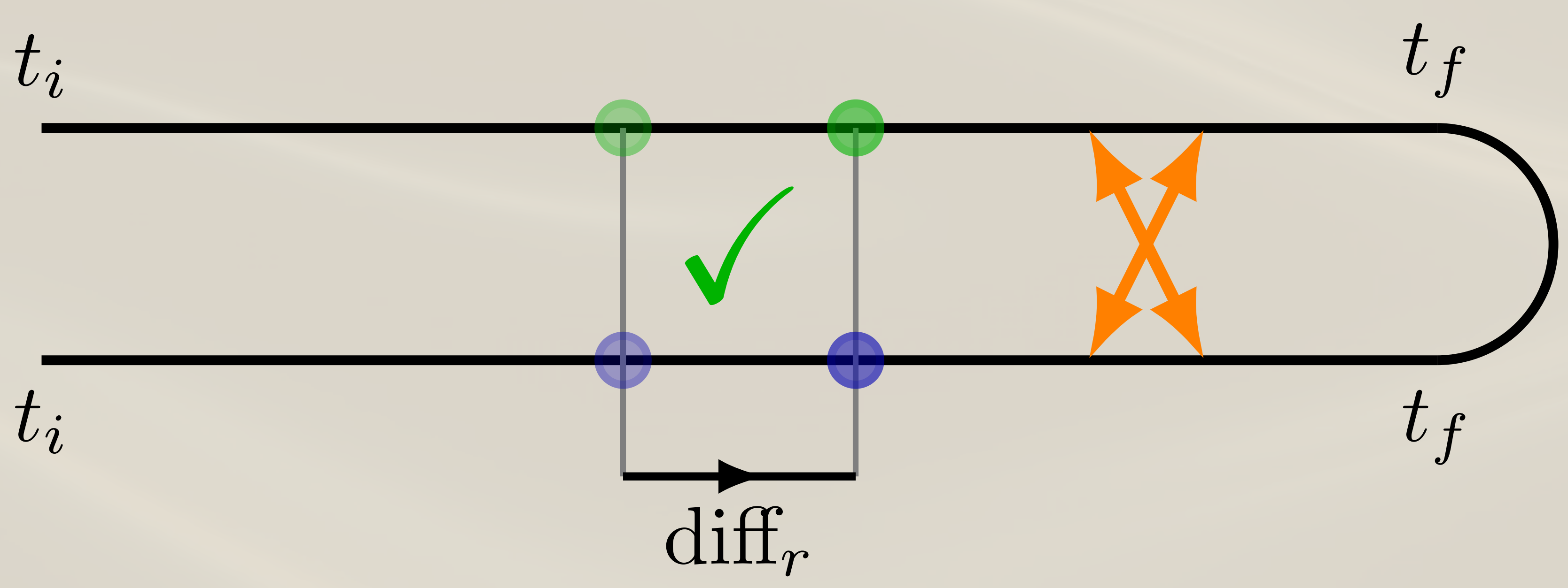
Gauge symmetries in open gravity

In "single clock" cosmologies:

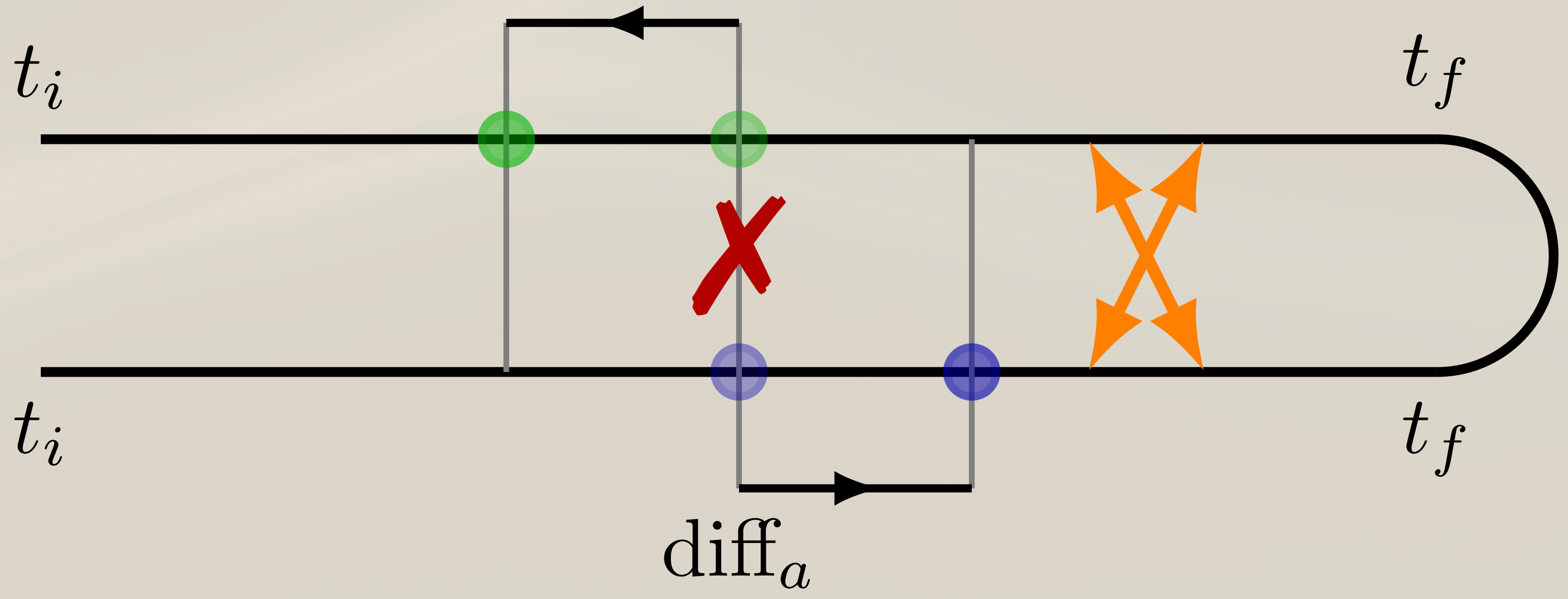


Work with $\begin{pmatrix}\text{diff}_+\\ \text{diff}_-\end{pmatrix} \to \begin{pmatrix}\text{diff}_r\\ \text{diff}_a\end{pmatrix}$: [Agüi-Salcedo et al. 24]

"Retarded" diffs - same direction:



"Advanced" diffs - opposite direction:



Overall: $(\text{4d-diff}_+ \times \text{4d-diff}_-) \simeq (\text{4d-diff}_a \times \text{4d-diff}_r) \xrightarrow{\text{open}} (\text{4d-diff}_r) \xrightarrow{\text{clock}} (\text{3d-diff}_r)$

$\Rightarrow$ **S_{eff} most generic action invariant under 3d-diff$_r$**

Construction of S_{eff} for open gravity

Retarded and advanced metric:

$$g_{\mu\nu} = \frac{(g_+)_{\mu\nu} + (g_-)_{\mu\nu}}{2} \qquad a^{\mu\nu} = (g_+)^{\mu\nu} - (g_-)^{\mu\nu}$$

Tensors under diff$_r$
More involved transformation under diff$_a$
[Lau et al. '24]

Construct S_{eff} in **"unitary" gauge** [Cheung et al. '08], in which the "clock" is absorbed in the metric (n_μ: clock foliation; $K_{\mu\nu}$: extrinsic curvature):

$$S_{\text{eff}} = \int d^4x\sqrt{-g}\left[M_{\mu\nu}a^{\mu\nu} + iN_{\mu\nu\rho\sigma}a^{\mu\nu}a^{\rho\sigma} + \mathcal{O}(a^3)\right]$$

$$M_{\mu\nu} \equiv n_\mu n_\nu M^{tt} + n_{(\mu}M^{ts}_{\nu)} + M^{ss}_{\mu\nu}$$

$$M^{tt} = \sum_{\ell=0}(g^{00}+1)^\ell[\gamma^{tt}_1 + \gamma^{tt}_2 K + \gamma^{tt}_3 K^2 + \gamma^{tt}_4 K_{\alpha\beta}K^{\alpha\beta} + \gamma^{tt}_5 \nabla^0 K + \gamma^{tt}_6 R + \gamma^{tt}_7 R^{00}]$$

$$M^{ts}_\mu = \sum_{\ell=0}(g^{00}+1)^\ell[\gamma^{ts}_1 R^0{}_\mu + \gamma^{ts}_2 \nabla_\mu K + \gamma^{ts}_3 \nabla_\beta K^\beta{}_\mu]$$

$$M^{ss}_{\mu\nu} = \sum_{\ell=0}(g^{00}+1)^\ell[g_{\mu\nu}\big(\gamma^{ss}_1 + \gamma^{ss}_2 K + \gamma^{ss}_3 K^2 + \gamma^{ss}_4 K_{\alpha\beta}K^{\alpha\beta} + \gamma^{ss}_5 \nabla^0 K + \gamma^{ss}_6 R + \gamma^{ss}_7 R^{00}\big)$$

$$+\gamma^{ss}_8 K_{\mu\nu} + \gamma^{ss}_9 \nabla^0 K_{\mu\nu} + \gamma^{ss}_{10} K_{\mu\alpha}K^\alpha{}_\nu + \gamma^{ss}_{11} K K_{\mu\nu} + \gamma^{ss}_{12} R_{\mu\nu} + \gamma^{ss}_{13} R_\mu{}^0{}_\nu{}^0 + \gamma^{PO}_{1,\ell}\epsilon_\mu{}^{\alpha\beta 0}\nabla_\alpha K_{\beta\nu} + \gamma^{PO}_{2,\ell}\epsilon_\mu{}^{\alpha\beta 0}R_{\alpha\beta}{}^0{}_\nu]$$

Classical regime: expansion in advanced fields

Derivative expansion (up to 2 ∂'s)

Similar expansion for noise $N_{\mu\nu\rho\sigma}$

Open EFT of inflation

$$S_{\text{eff}} = \int d^4x\sqrt{-g}\left[M_{\mu\nu}a^{\mu\nu} + iN_{\mu\nu\rho\sigma}a^{\mu\nu}a^{\rho\sigma} + \mathcal{O}(a^3)\right]$$

Contains **1 scalar dof**, which can be made explicit by restoring 3d-diff$_r$ → 4d-diff$_r$ via Stückelberg trick:

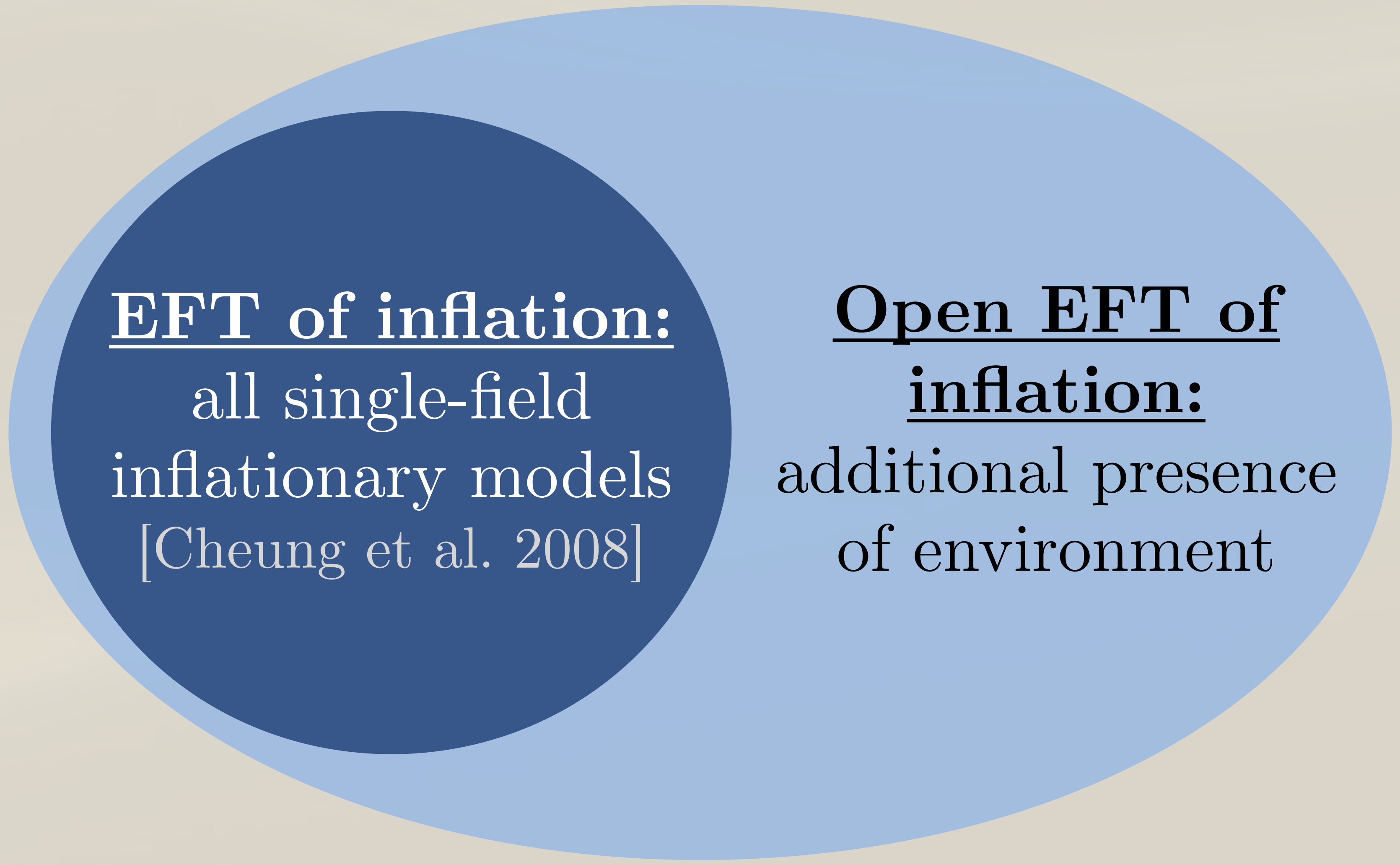
$$t \rightarrow t + \pi(t, \mathbf{x})$$

Decoupling limit: at high energy π decouples from fluctuations of $g_{\mu\nu}$ → EFT of inflation
[Cheung et al. '08, Baumann and Green '11]

In that limit our theory reduces to the "Open EFT of inflation" [Agüì-Salcedo et al. '24] - EFT of a single dissipative scalar on rigid inflating background → covered in Thomas Colas' talk this morning

But our construction is more general than that:

- additionally **2 tensor dof's**
- **Away from decoupling limit** (important for applications to late-time cosmology)



Outline

1. Gravity in the Schwinger-Keldysh formalism

2. **Dissipative gravitational waves during inflation**

3. Summary and outlook

Application: Open EFT of Inflation

Expand around inflating FRW spacetime: $g_{\mu\nu} = \bar{g}_{\mu\nu} + \delta g_{\mu\nu}$ $\quad a^{\mu\nu} = \delta a^{\mu\nu}$

Restrict to transverse traceless (TT) perturbations: $\delta g_{ij} = a^2 h_{ij}$ $\quad a^{ij} = a^{-2} h^a_{ij}$

with $\partial_i h_{ij} = 0 = \partial_i h^a_{ij}$ and $\delta^{ij} h_{ij} = 0 = \delta^{ij} h^a{}_{ij}$

S_{eff} to second order in TT perturbations:

$$S^{(2)}_{\text{eff}} = \int \mathrm{d}^4x \sqrt{-g}\, \frac{\mathrm{M}^2_{\text{Pl}}}{4c_T^2}\, h^a_{ij} \left[\ddot{h}_{ij} - c_T^2 \frac{\nabla^2}{a^2} h_{ij} + \left(\Gamma_T + 3H\right) \dot{h}_{ij} + \frac{\chi}{a} \epsilon_{imn} \partial_m \dot{h}_{nj} + i c_T^2 \frac{4\beta_6}{\mathrm{M}^2_{\text{Pl}}} h^a_{ij} \right]$$

E.o.m.: $$\ddot{h}_{ij} - c_T^2 \frac{\nabla^2}{a^2} h_{ij} + \left(\Gamma_T + 3H\right) \dot{h}_{ij} + \frac{\chi}{a} \epsilon_{imn} \partial_m \dot{h}_{nj} = \xi_{ij}$$

c_T^2 : Speed of propagation
Γ_T : Dissipation
χ : Dissipative Birefringence
ξ_{ij} : Noise

(All given as combination of EFT coefficients γ's)

Dissipation and noise

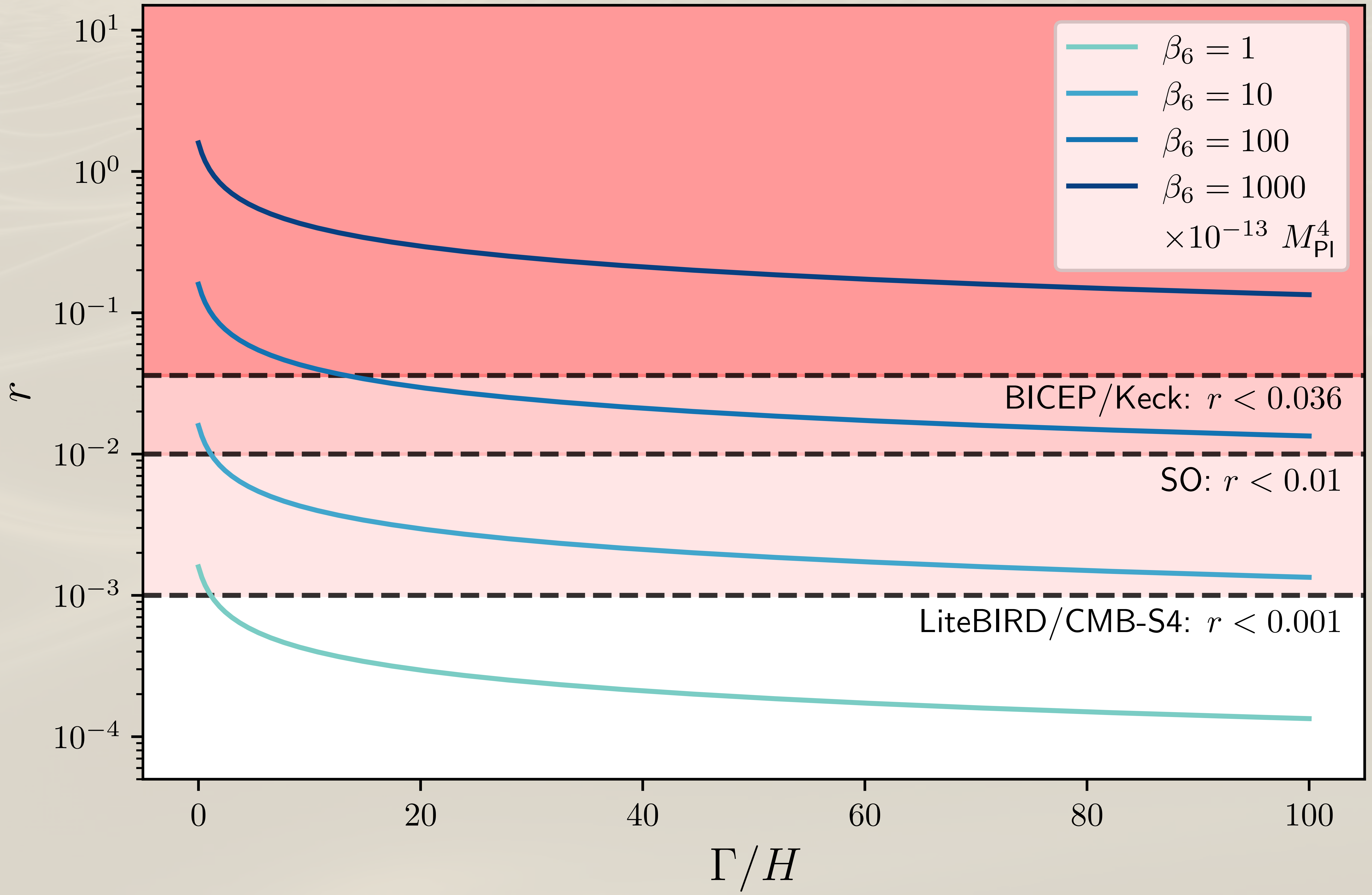
Power spectrum for $c_T = 1$, $\chi = 0$:

$$\Delta_h^2(k) = \frac{4\beta_6}{M_{Pl}^4} 2^{2\nu_\Gamma} \frac{\Gamma(\nu_\Gamma - 1)\Gamma(\nu_\Gamma)^2}{\Gamma(\nu_\Gamma - \frac{1}{2})\Gamma(2\nu_\Gamma - \frac{1}{2})}$$

$$\nu_\Gamma \equiv \frac{3}{2} + \frac{\Gamma_T}{2H}, \quad r = \frac{\Delta_h^2}{\Delta_\pi^2}, \; \langle \xi_{ij}(x)\xi_{ij}(y)\rangle = \beta_6\, \delta^4(x-y)$$

Usual (closed) EFToI: $\Delta_h(k) \sim (H/M_{pl})^2$
→ scale fixed by H [Creminelli et al '14]

Here: $\Delta_h(k) \sim \beta_6/M_{pl}^4$
→ scale set by environment
→ perturbations can be of classical origin



Birefringence

For $\chi \neq 0$ dispersion relation for $k \gg aH$: $\omega = -\frac{1}{4}i\chi sk \pm \frac{1}{2}k\sqrt{4-\chi^2}$ with $s = \pm 2$

- **dissipative effect** → term not present in closed (conservative) EFT
- one polarisation enhanced (instability), one damped → also known as amplitude birefringence
- instability can be cured by including higher derivative operators and/or non-linearities
- alternatively cure by choosing a time-dependence of coupling χ
  (realised in some concrete theories, e.g. in Chern-Simons gravity where time-dependence of this term is realised through coupling $R\tilde{R}$-term to the inflaton [Alexander and Martin '04, Dyda et al. '12, Creque-Sarbinowski '23])

No term $\sim \epsilon_{imn}\partial_m h_{nj}$ (velocity birefringence) in eom → would violate retarded diffs

Different from electromagnetism in a medium — here such a term $\sim \epsilon_{ijk}\partial_j A_k$ appears as leading one in eom for gauge field A_i [Agüì-Salcedo et al. '24]

Outline

1. Gravity in the Schwinger-Keldysh formalism
2. Dissipative gravitational waves during inflation
3. **Summary and outlook**

Summary and outlook

Summary:

- We developed a general framework for open gravitational dynamics based on General Relativity and the Schwinger–Keldysh formalism
- As an application, we use this framework to extend the Open EFT of Inflation to include dynamical gravity
- In the dynamical-gravity sector, we find that:
  - The tensor power spectrum is determined by the properties of the environmental sector, rather than the scale of inflation
  - Leading-order gravitational birefringence is dissipative in nature — opposite to, for example, birefringence in electromagnetism

Outlook:

- The framework of open gravity can readily be applied to settings beyond inflation, in particular:
  - Late-time cosmology, e.g. dark energy
  - Modified GW luminosity distance
  - Black hole perturbation theory (quasi-normal modes) and binary mergers
- Can we derive bounds on various EFT operators from physical principles (e.g. causality, locality, unitary UV)?

Thank you!

Backup slides

Dissipative fluids in our model

Map EFT to dissipative fluid:

Two fluids:

$$S = \int \mathrm{d}^4x\sqrt{-g}\,\frac{1}{2}a^{\mu\nu}\left(M_{\mathrm{pl}}^2 G_{\mu\nu} - T_{\mu\nu} - T_{\mu\nu}^{\mathrm{dissip}}\right)$$

$$T_{\mu\nu}^{\mathrm{dissip}} = \rho n_\mu n_\nu + \left(P - \zeta\nabla_\lambda n^\lambda\right)\Delta_{\mu\nu} + \eta\Delta_\mu^\alpha\Delta_\nu^\beta\left(\nabla_{(\alpha}n_{\beta)} - \frac{1}{3}\Delta_{\alpha_\beta}\nabla_\lambda n^\lambda\right) + \ldots$$

$\Delta_{\alpha\beta}$: projector on 3d hyper surfaces, ζ bulk viscosity, η shear viscosity

$\nabla_\lambda n^\lambda = K$, $\Delta_\mu^\alpha\Delta_\nu^\beta\nabla_{(\alpha}n_{\beta)} = K_{\mu\nu}$ so the above action is equivalent to

$$S = \int \mathrm{d}^4x\sqrt{-g}\,\frac{1}{2}a^{\mu\nu}\left(M_{\mathrm{pl}}^2 G_{\mu\nu} - T_{\mu\nu}^{\mathrm{sys}} + \gamma_1 K_{\mu\nu} + \gamma_2\Delta_{\mu\nu}K + \ldots\right)$$

Here $\Delta_{\mu\nu} = g_{\mu\nu} + n_\mu n_\nu$, our model even breaks tuning between these two terms

Could include terms at higher order in ∂'s by expanding $T_{\mu\nu}^{\mathrm{dissip}}$ to higher order

Modified Friedmann equations

Open:

$$3M_{\text{pl}}^2H^2 = \alpha_1 + \alpha_2 H\,,$$
$$2M_{\text{pl}}^2\dot{H} = \alpha_3 + \alpha_4 H$$

Closed:

$$3M_{\text{pl}}^2H^2 = \rho\,,$$
$$2M_{\text{pl}}^2\dot{H} = -\left(\rho + P\right)$$

Where α_i are combinations of the EFT coefficients γ_i

Bulk viscosity [Weinberg '71]: $\alpha_4 = 3\zeta$

$$2M_{\text{pl}}^2\dot{H} = -\left(\rho + (P - 3H\zeta)\right)$$

Brane-world gravity [Dvali, Gabadadze & Porrati '00]: $\alpha_2 = \pm 3M_{\text{pl}}^2/r_c$

$$3M_{\text{pl}}^2\left(H^2 \pm H/r_c\right) = \rho$$