The Open EFT of Dark Energy

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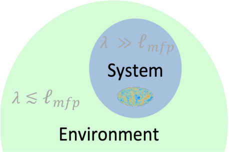
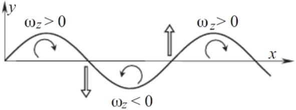
Dissipation and noise in cosmology



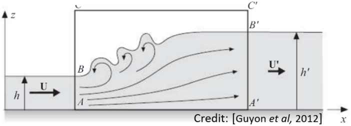
System interacts with **environment**:

Dissipation & noise = energy & information losses

Perfect fluid: Wilsonian EFT



Imperfect fluid: non-equilibrium EFT



Credit: [Guyon *et al*, 2012]

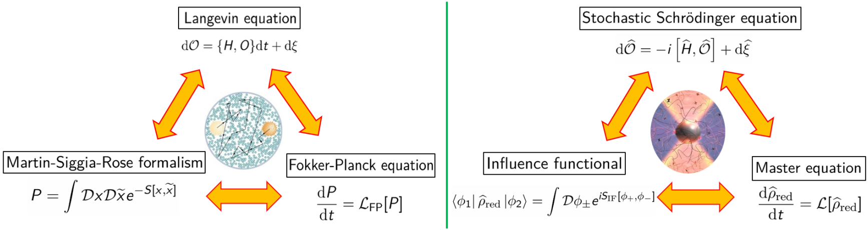
What about cosmology?

- **Observable** universe ≠ whole; 
- Continuously **evolving**; 
- Always a **medium**; 
- ∃ **fluxes** between sectors. 

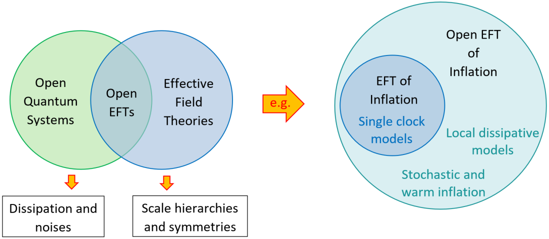
⇒ realistic experiments often **needs to model** dissipation & noise.

Goal: EFTs accounting for dissipation & noise in cosmology

Combining EFTs and Open Quantum Systems

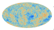


Extending the **embedding power** of EFTs:



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

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

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

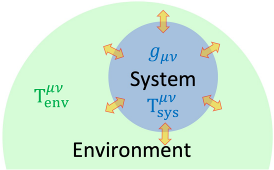
$$\mathrm{Prob}_\pi(t) = \rho_{\pi\pi}(t) = \int_\Omega^\pi \mathcal{D}\pi_+ \int_\Omega^\pi \mathcal{D}\pi_-\, e^{iS_{\mathrm{eff}}[\pi_+,\pi_-]}$$

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

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

Open gravity

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



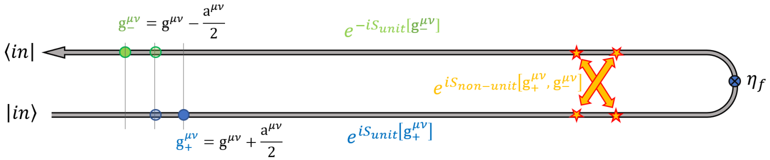
Diffeomorphisms invariance:

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

for each branch of SK path integral contour.

Keldysh basis: **retarded** $g_{\mu\nu}$ and **advanced** $a^{\mu\nu}$ metric:

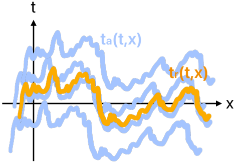
$$g = \frac{g_+ + g_-}{2} = \bar{g} + \delta g, \qquad \text{and} \qquad a = g_+ - g_- = \delta a$$



A tale of two clocks

Fluctuating clocks: $\phi_\pm(t,\mathbf{x})$, i.e.

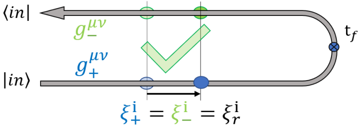
- $\phi_r(t,\mathbf{x}) \Leftrightarrow t_r(t,\mathbf{x})$: average clock;
- $\phi_a(t,\mathbf{x}) \Leftrightarrow t_a(t,\mathbf{x})$: stochasticity.

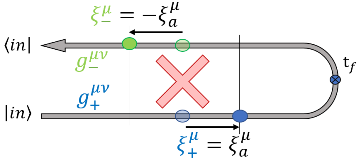


Gauge fixing. Work in *unitary gauges*: $\phi_+(t,\mathbf{x}) = \phi_-(t,\mathbf{x}) = \bar{\phi}(t)$:

$$\phi_r(t,\mathbf{x}) = \bar{\phi}(t) \quad \text{and} \quad \phi_a(t,\mathbf{x}) = 0 \qquad \text{i.e.} \qquad t_r = t \quad \text{and} \quad t_a = 0.$$

Following EFT of Inflation [Cheung *et al.*, 2008] and Dark Energy [Gubitosi, Piazza & Vernizzi, 2013]:





Most generic functional invariant under retarded spatial diffeomorphisms.

Unitary gauges

$$S_{\rm eff} = \int \mathrm{d}^4 x \sqrt{-g} \sum_{\ell=0} (g^{00}+1)^\ell \left[M_{\mu\nu,\ell} a^{\mu\nu} + i N_{\mu\nu\rho\sigma,\ell} a^{\mu\nu} a^{\rho\sigma} + \cdots \right]$$

with $M_{\mu\nu,\ell}$ and $N_{\mu\nu\rho\sigma,\ell}$ rank-2 and 4 cotensors under *retarded spatial diffs*.

$$M_{00,\ell} = \gamma^{tt}_{1,\ell} + \gamma^{tt}_{2,\ell} K + \gamma^{tt}_{3,\ell} K^2 + \gamma^{tt}_{4,\ell} K_{\alpha\beta} K^{\alpha\beta} + \gamma^{tt}_{5,\ell} \nabla^0 K + \gamma^{tt}_{6,\ell} R + \gamma^{tt}_{7,\ell} R^{00} \,;$$

$$M_{0\mu,\ell} = \gamma^{ts}_{1,\ell} R^0{}_\mu + \gamma^{ts}_{2,\ell} \nabla_\mu K + \gamma^{ts}_{3,\ell} \nabla_\beta K^\beta{}_\mu \,;$$

$$\begin{aligned} M_{\mu\nu,\ell} = {} & g_{\mu\nu} \left(\gamma^{ss}_{1,\ell} + \gamma^{ss}_{2,\ell} K + \gamma^{ss}_{3,\ell} K^2 + \gamma^{ss}_{4,\ell} K_{\alpha\beta} K^{\alpha\beta} + \gamma^{ss}_{5,\ell} \nabla^0 K + \gamma^{ss}_{6,\ell} R + \gamma^{ss}_{7,\ell} R^{00} \right) \\ & + \gamma^{ss}_{8,\ell} K_{\mu\nu} + \gamma^{ss}_{9,\ell} \nabla^0 K_{\mu\nu} + \gamma^{ss}_{10,\ell} K_{\mu\alpha} K^\alpha{}_\nu + \gamma^{ss}_{11,\ell} K K_{\mu\nu} + \gamma^{ss}_{12,\ell} R_{\mu\nu} + \gamma^{ss}_{13,\ell} R_\mu{}^0{}_\nu{}^0 \\ & + \gamma^{\rm P.O.}_{1,\ell} \epsilon_\mu{}^{\alpha\beta 0} \nabla_\alpha K_{\beta\nu} + \gamma^{\rm P.O.}_{2,\ell} \epsilon_\mu{}^{\alpha\beta 0} R_{\alpha\beta}{}^0{}_\nu . \end{aligned}$$

and similarly for $N_{\mu\nu\rho\sigma,\ell}$ $\Rightarrow$ can be studied **systematically**.

Background evolution

Modified Friedmann equations:

$$3M_1^2 H^2 = c_1 + c_2 H + c_3 \dot{H},$$
$$2M_2^2 \dot{H} = c_4 + c_5 H + c_6 H^2$$

M_1, M_2, c_i: functions of EFT coefficients. **Examples**:

1. *Bulk viscosity* [Weinberg, 1971]:

$$2M_2^2 \dot{H} = -\left[\rho_\phi + (p_\phi - 3H\zeta)\right],$$

2. *Brane-world gravity*: [Dvali, Gabadadze & Porrati, 2000]:

$$3M_1^2 (H^2 \pm H/r_c) = \rho_\phi,$$

3. *Interacting dark sector*: $\bar{\nabla}^\mu \bar{T}^{(\phi)}_{\mu\nu} = -\bar{\nabla}^\mu \bar{T}^{(\mathrm{env})}_{\mu\nu}$

$$\dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = Q.$$

The clockless example

Subset that preserves retarded time-diff: **no dynamical scalar**

$$S_{\rm eff} = \int \mathrm{d}^4x\sqrt{-g}\,(f_1 R_{\mu\nu} + f_2 g_{\mu\nu} + f_3 T_{\mu\nu} + \mathrm{h.d.})\,a^{\mu\nu}.$$

$\Rightarrow$ *Very few ingredients!* To lowest order, e.o.m. takes the form:

$$G_{\mu\nu} + \tilde{f}_1 R g_{\mu\nu} = \tilde{f}_2 T_{\mu\nu} + \tilde{f}_3 T g_{\mu\nu}.$$

w.l.o.g., separating **Standard Model**, **dark matter** and **cosmological constant**:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = G_{\rm N}\left[T^{\rm SM}_{\mu\nu} + T^{\rm DM}_{\mu\nu} + (\lambda^{\rm SM} T^{\rm SM} + \lambda^{\rm DM} T^{\rm DM}) g_{\mu\nu}\right].$$

If dark matter $\simeq$ perfect fluid, absorb $\lambda^{\rm DM} T^{\rm DM} g_{\mu\nu}$ into equation of state $w^{\rm DM}$:

Minimal Open GR:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = G_{\rm N}\left[T^{\rm SM}_{\mu\nu} + T^{\rm DM}_{\mu\nu} + \lambda^{\rm SM} T^{\rm SM} g_{\mu\nu}\right].$$

Minimal Open GR

- Does not come from an action $\Rightarrow$ **evade** **[Lovelock, 1971]** **theorem**;
- Dissipative dark matter:

$$\nabla^\mu T^{\mathrm{SM}}_{\mu\nu} = 0\,, \qquad \nabla^\mu T^{\mathrm{DM}}_{\mu\nu} + \lambda \partial_\nu T^{\mathrm{SM}} = 0\,.$$

- To **UV complete**, need to find sector s.t. $\langle T^{\mathrm{env}}_{\mu\nu} \rangle = \lambda^{\mathsf{SM}} T^{\mathsf{SM}} g_{\mu\nu}$;
- One-parameter extension of Λ-CDM $\Rightarrow$ data-analysis CMB + BAO.

Background: change expansion history (*Hubble tension*?)

$$3H^2 = \Lambda + G_{\mathrm{N}} \left[\rho^{\mathsf{SM}} + \rho^{\mathsf{DM}} + \lambda^{\mathsf{DM}} (\rho^{\mathsf{SM}} - 3p^{\mathsf{SM}}) \right]$$

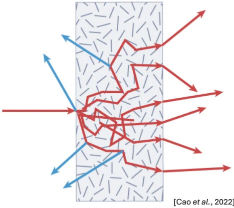
Perturbations: modify matter clustering (S_8 *tension*?)

$$\dot{\delta}_c = -\theta_c + 3\dot{\phi} + \lambda \frac{\delta \dot{T}^{\mathrm{SM}}}{\rho_c}, \qquad \dot{\theta}_c = -H\theta_c + k^2\psi + \frac{\lambda k^2}{1+w} \frac{\delta T^{\mathsf{SM}}}{\rho_c}$$

Primordial gravitational waves

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

$$S^{(2)} = \int \mathrm{d}^4x \sqrt{-g}\, \frac{M_{\mathrm{P}l}^2}{4c_T^2}\, h^a_{ij} \left\{ \ddot{h}_{ij} - c_T^2 \frac{\nabla^2}{a^2} h_{ij} + \left(\Gamma + 3c_T^2 H\right) \dot{h}_{ij} + \frac{\chi}{a} \epsilon_{imn} \left(\partial_m \dot{h}_{nj} + 2H\partial_m h_{nj}\right) + i \frac{\beta_T}{M_{\mathrm{P}l}^2} h^a_{ij} \right\}.$$



[Cao *et al.*, 2022]

1. Speed of propagation c_T^2;
2. Dissipation Γ;
3. Birefringence χ;
4. Noise β_T.

Tensor-to-scalar ratio r: at low dissipation, setting $\chi = 0$:

$$\Delta_h^2 \propto \frac{\beta_T}{M_{\mathrm{P}l}^4}, \quad \Delta_\zeta^2 = 10^{-9}, \quad r < 0.036 \quad \Rightarrow \quad \beta_T \lesssim (0.002 M_{\mathrm{P}l})^4.$$

Summary: A glimpse on what to expect

- Dissipative and stochastic Einstein Equations: $G_{\mu\nu} + \Gamma \mathcal{D}_{\mu\nu} = T_{\mu\nu} + \xi_{\mu\nu}$
- Non-conserved stress-energy tensor: $\nabla_\mu T^{\mu\nu} \neq 0$

Phenomenology:

- **Background**: Interacting DE/DM sectors

$$\dot{\rho}_{DE} + 3H(\rho_{DE} + p_{DE}) = \Gamma \quad \text{and} \quad \dot{\rho}_m + 3H(\rho_m + p_m) = -\Gamma$$

- **Clustering** $\Rightarrow$ redshift space distortion (RSD) and weak lensing (WL)

$$k^2 \langle \psi \rangle = -4\pi G \mu(a,k) a^2 \rho_m \langle \delta \rangle, \qquad k^2 \frac{\langle \psi + \phi \rangle}{2} = -4\pi G \Sigma(a,k) a^2 \rho_m \langle \delta \rangle$$

- **Gravitational waves** $\Rightarrow$ GW production, propagation and dissipation

$$\ddot{h}_{ij} + \Gamma \dot{h}_{ij} + c_T^2 h_{ij} + \chi \epsilon_{ilm} k_m h_{jl} = T_{ij} + \xi_{ij}$$

Rich phenomenology to explore,
*eventually **already constrained from data**.*