Open systems in cosmology

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Outline of the talk

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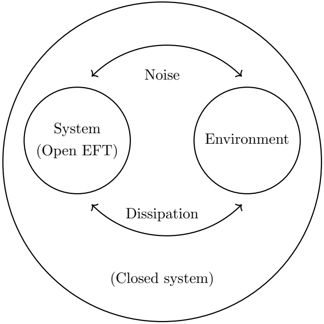
A toy model for open systems

Open systems are ubiquitous in physics. They arise whenever we are only able to track part of the degrees of freedom relevant for the dynamics under study:



An example is a pollen particle in water:

$$\ddot{x}(t) + \underbrace{\gamma(t,x)x(t)}_{\text{dissipation}} = \underbrace{\xi(t,x)}_{\text{noise}}.$$

The microscopic details of the environment are encoded in $\gamma(t,x)$ and the statistics of $\xi(t,x)$.

To derive information about the dissipation and the noise we study correlation functions of the pollen particle:

$$\langle x(t_1)x(t_2)\rangle \ , \ \langle x(t_1)x(t_2)x(t_3)\rangle \ , \ \ldots$$

Why open systems?

Cosmology is a fertile ground for open systems, where we can expect dissipation and diffusion:

$$\begin{aligned} \text{Inflation: } & \text{Inflaton} \leftrightarrow \text{Heavy fields} , \text{ Primordial gravitational waves.} \\ \text{Reheating: } & \text{Inflaton} \leftrightarrow \text{Standard model fields.} \\ \text{Photons (spin 1): } & \text{Sachs-Wolfe effect, Compton scattering...} \\ \text{Gravitons (spin 2): } & \text{Dark Energy interactions?} \end{aligned}$$

Gravity couples universally. Therefore, unless we are describing the full system, any effective description for gravity has to account for an environment.

Gauge theories and open quantum systems meet in cosmology.

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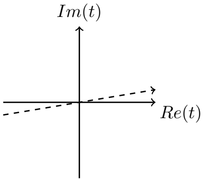
Field Theory for open systems I

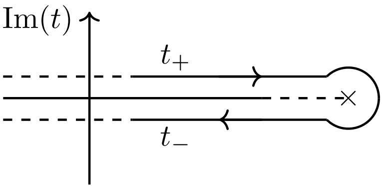
Open systems can also be studied through the lenses of field theory:

Closed systems



- Observables: Cross section.
- Functional: Action $S[\phi]$.
- Euler-Lagrange equations.

Open systems



- Observables: Correlation functions.
- Functional: Influence functional $\mathcal{I}[\phi_+, \phi_-]$.
- Langevin equation.

Dissipative dynamics are encoded in cross-branch terms in $\mathcal{I}[\phi_+, \phi_-]$:

$$\mathcal{I}[\phi_+, \phi_-] = S[\phi_+] - S[\phi_-] + i\mathcal{J}[\phi_+, \phi_-] .$$

Field Theory for open systems II

These terms arise from integrating out the environment. This can be seen from the Schwinger-Keldysh path integral:

$$\mathcal{Z}[\phi_i, \phi_f] = \int_{\phi_i}^{\phi_f} \mathcal{D}\phi_\pm \int d\chi_{i,f} \int_{\chi_i}^{\chi_f} \mathcal{D}\chi_\pm \; e^{\{iS_{\mathrm{UV}}[\phi_+,\chi_+] - iS_{\mathrm{UV}}[\phi_-,\chi_-]\}} ,$$

such that

$$e^{i\mathcal{I}[\phi_+,\phi_-]} = \int d\chi_{i,f} \int_{\chi_i}^{\chi_f} \mathcal{D}\chi_\pm \; e^{\{iS_{\mathrm{UV}}[\phi_+,\chi_+] - iS_{\mathrm{UV}}[\phi_-,\chi_-]\}}$$

this means we can express the influence functional as a product:

$$e^{i\mathcal{I}[\phi_+,\phi_-]} = \langle \chi, \phi_+ | \chi, \phi_- \rangle \, .$$

Field Theory for open systems III

UV unitarity: The union of the system and the environment form a closed system.

$$\langle \chi, \phi | \chi, \phi \rangle = 1 \rightarrow \mathcal{I}[\phi, \phi] = 0,$$
$$[\langle \chi, \phi_+ | \chi, \phi_- \rangle]^* = \langle \chi, \phi_- | \chi, \phi_+ \rangle \rightarrow \mathcal{I}[\phi_+, \phi_-] = -\mathcal{I}^*[\phi_-, \phi_+],$$
$$|\langle \chi, \phi_+ | \chi, \phi_- \rangle|^2 \leq 1 \rightarrow \mathrm{Im}[\mathcal{I}[\phi_+, \phi_-]] \geq 0.$$

It is easier to express these conditions using the Keldysh variables:

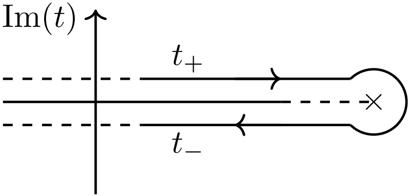
$$\phi_r = \frac{1}{2}[\phi_+ + \phi_-] \quad , \quad \phi_a = \phi_+ - \phi_-,$$

such that:

$$\mathcal{I}[\phi_r, \phi_a]\Big|_{\phi_a=0} = 0 \;\;,\;\; \mathcal{I}[\phi_r, \phi_a] \;\; = -\mathcal{I}^*[\phi_r, -\phi_a] \;\;,\;\; \mathrm{Im}[\mathcal{I}[\phi_r, \phi_a]] \geq 0.$$

Field Theory for open systems IV

The realisation of global symmetries also changes in open systems.



$$\text{Closed:} \quad \phi_\pm \to \phi_\pm + \delta\phi_\pm,$$
$$\text{Open:} \quad \phi_\pm \to \phi_\pm + \delta\phi,$$
$$\underbrace{G_+ \times G_-}_{\text{Closed}} \to \underbrace{\text{Diag}\left[G_+ \times G_-\right]}_{\text{Open}}.$$

One example is a shift symmetric scalar:

$$\text{Closed:} \quad \begin{cases} \phi_r \to \phi_r + \Delta_r \\ \phi_a \to \phi_a + \Delta_a \end{cases}, \quad \text{Open:} \quad \begin{cases} \phi_r \to \phi_r + \Delta \\ \phi_a \to \phi_a \end{cases}, \quad \Delta_i \in \mathbb{R}$$

Field Theory for open systems V

There are more terms are allowed in $\mathcal{I}[\phi_r, \phi_a]$ than in $S[\phi]$:

$$\text{Closed:} \quad S[\phi] = \int \frac{1}{2}\left[\dot{\phi}^2 - c_s^2 (\partial_i \phi)^2\right] + \text{h.d.},$$

$$\text{Open:} \quad \mathcal{I}[\phi_r, \phi_a] = \int \dot{\phi}_r \dot{\phi}_a - c_s^2 \partial_i \phi_r \partial_i \phi_a - \gamma \dot{\phi}_r \phi_a + i\beta_1 \phi_a^2 + \text{h.d.}$$

There are three types of terms :

$$\text{Unitary:} \quad \dot{\phi}_r \dot{\phi}_a = \frac{1}{2}\left[\dot{\phi}_+^2 - \dot{\phi}_-^2\right],$$

$$\text{Dissipation:} \quad \dot{\phi}_r \phi_a = \frac{1}{2}\left[\dot{\phi}_+ \phi_- - \dot{\phi}_- \phi_+\right],$$

$$\text{Noise:} \quad i\beta_1 \phi_a^2 = \beta_1 \left[\phi_+ - \phi_-\right]^2,$$

The NEQ constraints mean:

$$\mathcal{I}[\phi_r, \phi_a] \sim \mathcal{O}(\phi_a),$$

$$\mathcal{O}\left(\phi_a^{2n+1}\right) \to \text{Real coefficients},$$

$$\mathcal{O}\left(\phi_a^{2n}\right) \to \text{Imaginary coefficients},$$

$$\beta > 0.$$

Field Theory for open systems VI

The influence functional can be recasted as a Langevin equation.

$$\langle\hat{\phi}^n\rangle = \int d\phi \int_{\phi_i}^{\phi} \mathcal{D}\phi_r \int_{\phi_i}^{0} \mathcal{D}\phi_a e^{i\mathcal{I}[\phi_r,\phi_a]}\phi_r^n,$$

$$\mathcal{I} = \int \phi_a \left[-\ddot{\phi}_r - \gamma\dot{\phi}_r + c_s^2\nabla^2\phi_r\right] + i\beta_1\phi_a^2,$$

to perform the saddle point approximation we introduce a random field ξ:

$$\exp\left[-\int \beta\phi_a^2\right] = \int \mathcal{D}\xi \exp\left[-\frac{\xi^2}{4\beta} + i\phi_a\xi\right],$$

such that:

$$\ddot{\phi} + \gamma\dot{\phi} - c_s^2\nabla^2\phi = \xi \quad , \quad \langle\xi^2\rangle \sim \beta.$$

The resulting Langevin equation is well-posed and allows for a solution in terms of Green's function.

Summary

- Open systems can be described through an influence functional.

$$\text{Closed}: \quad S[\phi] \to \text{Open}: \quad \mathcal{I}[\phi_r, \phi_a].$$

- UV unitarity leads to the NEQ constraints,

$$\mathcal{I}[\phi_r, \phi_a]\Big|_{\phi_a=0} = 0 \;\;,\;\; \mathcal{I}[\phi_r, \phi_a] \;\; = -\mathcal{I}^*[\phi_r, -\phi_a] \;\;,\;\; \mathrm{Im}\left[\mathcal{I}[\phi_r, \phi_a]\right] \geq 0.$$

- Global symmetries are broken to its diagonal components.

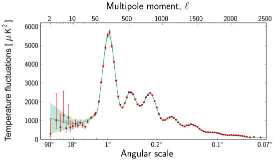
$$\text{Closed}: \quad G_+ \times G_- \to \text{Open}: \quad \mathrm{Diag}\left[G_+ \times G_-\right].$$

- There is a map between an influence functional and a Langevin equation.

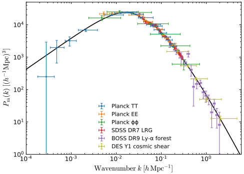
$$\mathcal{I}[\phi_r, \phi_a] \to \ddot{\phi} + \gamma\dot{\phi} - c_s^2 \nabla^2 \phi = \xi \quad , \quad \langle \xi^2 \rangle \sim \beta.$$

First application: Open PNGs I

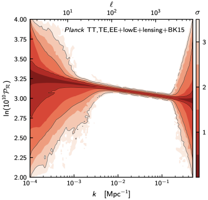
Different cosmological probes point to a common primordial seed:



(a) CMB power spectrum



(b) LSS power spectrum



(c) Primordial power spectrum

This primordial seed is generated during inflation. Among different inflation models there are several that present dissipative dynamics:

Warm inflation , Axion inflation , Temporary instabilities.

[SAS, Colas & Pajer, 2404.15416] presents a bottom-up approach to local dissipative dynamics in inflation.

First application: Open PNGs II

The presence of non-linearly realised symmetries lead to a relation between the quadratic and the cubic theory:

$$\mathcal{I}^{(2)} = \int \dot{\phi}_r \dot{\phi}_a - c_s^2 \partial_i \phi_r \partial_i \phi_a - \gamma \dot{\phi}_r \phi_a + i\beta_1 \phi_a^2,$$

$$\mathcal{I}^{(3)} = \int \underbrace{\frac{c_s^2 - 1}{2f_\pi^2}\left[(\partial_i \pi_r)^2 \dot{\pi}_a + 2\dot{\pi}_r \partial_i \pi_r \partial^i \pi_a - 3\dot{\pi}_r^2 \dot{\pi}_a\right]}_{\text{speed of sound}} + \underbrace{\frac{\gamma}{2f_\pi^2}\left[(\partial_i \pi_r)^2 - \dot{\pi}_r^2\right]\pi_a}_{\text{dissipation}}.$$

[SAS, Colas et al. 2603.13473] compares the predictions with CMB data. This analysis places a constraint on the dissipation and the speed of sound:

$$c_s \geq 0.38 \quad , \quad \gamma \leq 384H.$$

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Open Electromagnetism I

The simplest case to study is a spin 1 gauge field:

$$\text{Field content} \rightarrow \begin{cases} \text{Retarded: } A^\mu = \frac{1}{2}\left(A_+^\mu + A_-^\mu\right), \\ \text{Advanced: } a^\mu = A_+^\mu - A_-^\mu. \end{cases}$$

$$\text{Symmetries} \rightarrow \begin{cases} \text{Background: Lorentz } \rightarrow \text{ Rotations,} \\ \text{Gauge: } A^\mu \rightarrow A^\mu + \partial^\mu \lambda. \end{cases}$$

These conditions give a list of gauge invariant elements:

$$a^0 \ , \ a^i \ , \ F^{0i} \ , \ F^{ij} \ , \ \partial_\mu t \ , \ + \text{derivatives...}$$

We focus on the quadratic theory:

$$\mathcal{I} = \int d^4x \left[a^\mu M_{\mu\nu} A^\nu + i a^\mu \tilde{M}_{\mu\nu} a^\nu\right].$$

Open Electromagnetism II

A general result for $M_{\mu\nu}$ is:

$$M_{\mu\nu} + M^*_{\nu\mu} \to \text{Unitary}\ ,\ M_{\mu\nu} - M^*_{\nu\mu} \to \text{Dissipation.}$$

The most general action that we can write at $\mathcal{O}(A \times a)$ is:

$$a^\mu M_{\mu\nu} A^\nu = a^0 ik_i F^{0i} + a_i \left(\gamma_2 F^{0i} + \gamma_3 ik_j F^{ij} + \gamma_4 \epsilon^i{}_{jl} F^{jl}\right).$$

The Maxwell equations are:

$$M_{\mu\nu} A^\nu = \begin{pmatrix} \mathbf{k}^2 & -\omega k_i \\ -i\gamma_2 k_i & i\gamma_2\omega\delta_{ij} + \gamma_3(\mathbf{k}^2\delta_{ij} - k_i k_j) - 2i\gamma_4\epsilon_{ijl}k_l \end{pmatrix} \begin{pmatrix} A^0 \\ A^j \end{pmatrix}.$$

To recover the Maxwell equations in the vacuum we set:

$$\gamma_2 = -i\omega\ ,\ \gamma_3 = -1\ ,\ \gamma_4 = 0,$$

$$M_{\mu\nu} A^\nu = \left(k^2\eta_{\mu\nu} - k_\mu k_\nu\right) A^\nu = \begin{pmatrix} \mathbf{k}^2 & -\omega k_j \\ -\omega k_i & \omega^2\delta_{ij} - (\mathbf{k}^2\delta_{ij} - k_i k_j) \end{pmatrix} \begin{pmatrix} A^0 \\ A^j \end{pmatrix}$$

Open Electromagnetism III

To analyse the degrees of freedom we study the eigenvalues of M:

$$M_{\mu\nu} = \begin{pmatrix} \mathbf{k}^2 & -\omega k_i \\ -i\gamma_2 k_j & i\gamma_2\omega\delta_{ij} + \gamma_3(\mathbf{k}^2\delta_{ij} - k_i k_j) - 2i\gamma_4\epsilon_{ijl}k_l \end{pmatrix},$$

whose eigenvalues are:

$$(0, \underbrace{\mathbf{k}^2 + i\gamma_2\omega}_{\text{ghost}}, \underbrace{\mathbf{k}^2\gamma_3 - 2|\mathbf{k}|\gamma_4^2 + i\gamma_2\omega, \mathbf{k}^2\gamma_3 + 2|\mathbf{k}|\gamma_4^2 + i\gamma_2\omega}_{\text{Propagating}}).$$

In the case of Maxwell in the vacuum:

$$(0, \mathbf{k}^2 + \omega^2, -\mathbf{k}^2 + \omega^2, -\mathbf{k}^2 + \omega^2),$$

$$\gamma_2 + i\omega \rightarrow \text{ dissipation }, \gamma_3 \rightarrow \text{ speed of light }, \gamma_4 \rightarrow \text{ birefringence}$$

The zero eigenvalue corresponds to the gauge transformations $A^\mu \rightarrow A^\mu + k^\mu\lambda$.

Open Electromagnetism IV

The diffusion terms are encoded in $\tilde{M}$. It is symmetric:

$$\tilde{M}_{(\mu\nu)} = \tilde{M}_{\mu\nu} .$$

It has to be positive definite from the non-equilibrium constraint:

$$\mathrm{Im}(\mathcal{I}[A, a]) > 0 \to a^\mu \tilde{M}_{\mu\nu} a^\nu > 0 \ , \ \forall a^\mu .$$

There is an analogous Hubbard-Stratonovich trick:

$$\exp\left(-\int d^4x a^\mu \tilde{M}_{\mu\nu} a^\nu\right) = \int [\mathcal{D}\xi_\mu] \exp\left(\int d^4x \left[-\frac{1}{2}\xi_\mu (\tilde{M}^{-1})^{\mu\nu}\xi_\nu + i\xi_\mu a^\mu\right]\right) .$$

This leaves the dissipative Maxwell equations to be:

$$\begin{pmatrix} \mathbf{k}^2 & -\omega k_i \\ -i\gamma_2 k_j & i\gamma_2\omega\delta_{ij} + \gamma_3(\mathbf{k}^2\delta_{ij} - k_i k_j) - 2i\gamma_4\epsilon_{ijl}k_l \end{pmatrix} \begin{pmatrix} A^0 \\ A^j \end{pmatrix} = \begin{pmatrix} \xi_0 \\ \xi_i \end{pmatrix} \ , \ \langle \xi_\mu \xi_\nu \rangle = 2\tilde{M}_{\mu\nu} .$$

The question is how do we solve these equations, as we can fix a gauge in the retarded sector but we cannot do it in the advanced sector.

New advanced symmetry.

The existence of a zero eigenvector to the right implies the existence of a zero eigenvector to the left:

$$M_{\mu\nu} k^{\nu} = 0 \to \exists v^{\mu} : \; v^{\mu} M_{\mu\nu} = 0 \; , \; v^{\mu} = (i\gamma_2, k^i).$$

This has consequences for the sourced Maxwell equations:

$$M_{\mu\nu} A^{\nu} = \xi_{\mu} \to v^{\mu} \xi_{\mu} = 0.$$

This is a modified conservation equation that accounts for dissipation. The symmetry breaking pattern is deformed:

$$\text{Closed: } G_+ \times G_- \to \text{Open: } \underbrace{\text{Diag}\left[G_+ \times G_-\right]}_{\text{retarded}} \times \underbrace{\text{Def}\left[G_+ \times \bar{G}_-\right]}_{\text{advanced}}$$

We can use this transformation to fix the gauge in advanced sector. The existence of this transformation guarantees the well posedness of the Maxwell equations in a conductor.

A puzzle

There is a puzzle for the sourced Maxwell equations:

$$M_{\mu\nu} A^{\nu} = \xi_{\mu} \rightarrow \begin{cases} \text{Conservation: } v^{\mu}\xi_{\mu} = 0, \\ \text{HS: } \langle \xi_{\mu}\xi_{\nu} \rangle = 2\tilde{M}_{\mu\nu}. \end{cases}$$

How can there be a conservation equation for ξ_{μ} if its two-point function is $\tilde{M}_{\mu\nu}$ and $\tilde{M}_{\mu\nu}$ is supposed to be a positive definite square matrix?

Solution to the puzzle

The key is to do the path integral for a^μ with care:

$$a^\mu = a^\mu_\perp + a^\mu_{||}\ ,\ a^\mu_\perp v_\mu = 0,$$

which divides the path integral over a^μ

$$a^\mu(M_{\mu\nu}A^\nu - \xi_\mu) = a^\mu_\perp(M_{\mu\nu}A^\nu - P^\nu_\mu \xi_\nu) + a^\mu_{||}\left(\xi_\mu - P^\nu_\mu \xi_\nu\right).$$

The integral over $a^\mu_\perp$ yields our original sourced Maxwell equation and the integral over $a^\mu_{||}$ leaves a constrain on the noise:

$$M_{\mu\nu}A^\nu = P^\nu_\mu \xi_\nu\ ,\ \xi_\mu = P^\nu_\mu \xi_\nu.$$

The puzzle is solved because the noise is dressed by the projectors:

$$\langle P^\alpha_\mu \xi_\alpha P^\beta_\nu \xi_\beta \rangle = 2 P^\alpha_\mu P^\beta_\nu \tilde{M}_{\alpha\beta}.$$

Summary

- The Schwinger-Keldysh formalism can be applied to electromagnetism in a conductor [SAS, Colas & Pajer, 2412.12299].
- Dissipation deforms advanced gauge transformations

$$\text{Closed: } G_+ \times G_- \to \text{Open: } \underbrace{\text{Diag}\left[G_+ \times G_-\right]}_{\text{retarded}} \times \underbrace{\text{Def}\left[G_+ \times \bar{G}_-\right]}_{\text{advanced}}.$$

- The well-posedness of the equations of motion rely on this advanced gauge transformation:

$$M_{\mu\nu} A^{\nu} = \xi_{\mu} \ , \ v^{\mu} M_{\mu\nu} = 0 \to v^{\mu} \xi_{\mu} = 0.$$

What about gravity? I

The extension to gravity changes the gauge symmetry [SAS, Colas et al. 2507.03103

$$\text{E\&M: } U(1) \to \text{Gravity: } \text{Diff}_4 \to \text{Cosmology: } \text{Diff}_3.$$

A closed system follows the usual Bianchi-identity:

$$\text{Closed: } E_{\mu\nu} = G_{\mu\nu} - 8\pi \left[T^{\phi}_{\mu\nu} + T^{\chi}_{\mu\nu} \right] \to \nabla^{\mu} \left[T^{\phi}_{\mu\nu} + T^{\chi}_{\mu\nu} \right] = 0,$$

dissipative dynamics lead to a non-standard conservation law:

$$\text{Open: } E_{\mu\nu} = G_{\mu\nu} - 8\pi \left[T^{\phi}_{\mu\nu} + \langle T^{\chi}_{\mu\nu} \rangle (\phi, g) \right] \to \nabla^{\mu} T^{\phi}_{\mu\nu} \neq 0.$$

The main constraint for an open theory of gravity is finding the set of operators that yield well-posed equations of motion.

What about gravity? II

In [Christodoulidis & Gong, 2512.21234] a consistent operator was presented:

$$\Delta_{\mu\nu} = \sqrt{-g^{00}}\left[K_{\mu\nu} - K\left(g_{\mu\nu} + n_\mu n_\nu\right)\right],$$

which can be included into the equations of motion:

$$E_{\mu\nu} = G_{\mu\nu} - \Gamma\Delta_{\mu\nu} - T_{\mu\nu}.$$

This operator modifies the conservation law:

$$P_i^\nu \nabla^\mu T_{\mu\nu} = \Gamma\sqrt{-g^{00}} P_i^\mu T_{\mu\nu} n^\nu.$$

This operator relates the dissipation in the scalar sector and the tensor sector:

$$\text{Scalar: } \ddot{\psi} + \left[3H(t) + \Gamma\right]\dot{\psi} - \frac{c_s^2\nabla^2\psi}{a^2(t)} = \xi^s,$$

$$\text{Tensor: } \ddot{\gamma}_{ij} + \left[3H(t) + \Gamma\right]\dot{\gamma}_{ij} - \frac{\nabla^2}{a^2(t)}\gamma_{ij} = \xi_{ij}^{\mathrm{TT}}.$$

Second application: Dark Energy I

Current surveys show a preference for dynamical dark energy.

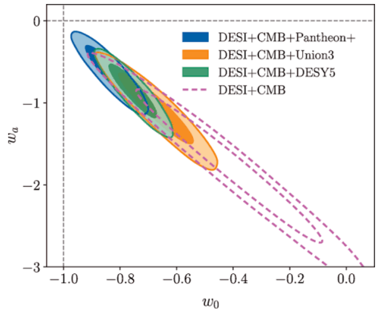


Figure: DESI results

This problem can be solved by considering unified DE-DM models.

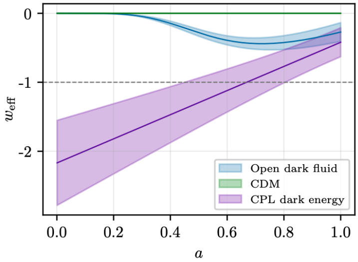


Figure: $w_{\rm eff}$

The preference is for phantom crossing:

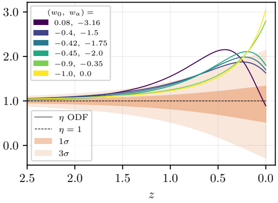
$$w_{\rm DE} \leq -1.$$

$$\nabla^\mu T_{\mu\nu}^{\rm DM} = -\nabla^\mu T_{\mu\nu}^{\rm DE}.$$

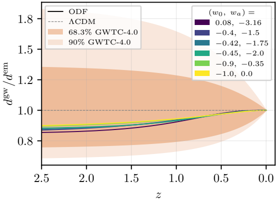
In [SAS, Colas et al 2603.12321] these unified scenarios were modelled through Open Gravity. The dissipation is fixed through the Friedman equations:

$$G_{\mu\nu} + \Gamma\Delta_{\mu\nu} + \underbrace{T_{\mu\nu}(g)}_{\text{singleclock}} = 0 \rightarrow \begin{cases} 3M_{\rm pl}^2 H^2 = \rho, \\ 2M_{\rm pl}^2 \dot{H} = -(\rho + P) - 2M_{\rm pl}^2 \Gamma H. \end{cases}$$

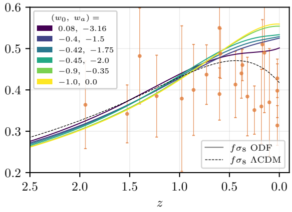
This analysis can be extended to probe different effects of dissipation.



(a) Weak lensing probe



(b) GW propagation



(c) LSS formation

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Conclusions & Outlook

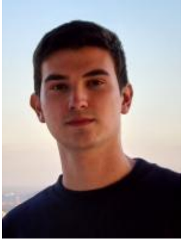
- Open systems are ubiquitous in cosmology.
- The Schwinger-Keldysh formalism allows for a field theoretic treatment of open systems. This is fundamental to develop effective field theories.

$$\text{UV unitarity} \to \text{NEQ constraints} \quad , \quad \text{Dissipation} \to \text{coset construction.}$$

- It is possible to test for open systems in cosmology:

$$\text{Inflation} \to \text{Dissipative non-gaussianities,}$$
$$\text{Dark Energy} \to \text{Open gravity.}$$

(a) Lennard Dufner



(b) Petar Suman

(c) Bowei Zhang