Emergent Acceleration from Quantum Gravity: Dynamical Dark Energy and Inflation

In collaboration with: T. Ladstätter and D. Oriti

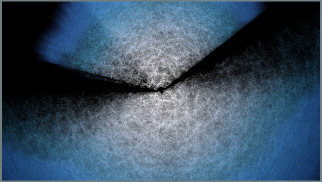
Luca Marchetti

13 Tux Winter Workshop on Quantum Gravity

Tux

Feb 12, 2026

OIST
Kavli IPMU



The DESI galaxy survey

- BAOs create features in galaxy clusters of the size of the sound horizon at recombination.
- This is used as a ruler to determine the distance to different galaxies.
- In turn, this determines the Universe's evolution.

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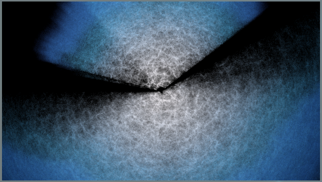

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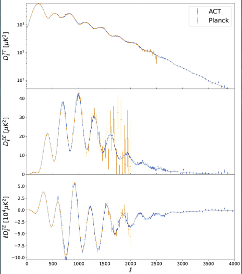
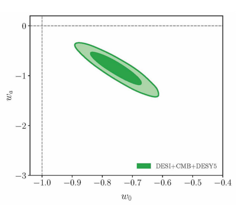
The ACT power spectra

- Ground based CMB observations.
- Higher angular resolution and targeted observation when compared to Planck.
- In practice: much smaller noise levels at small scales and extension to larger multipoles.





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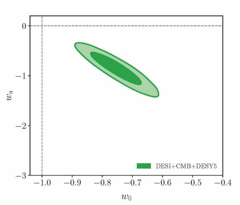

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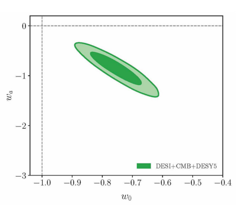

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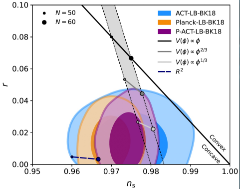

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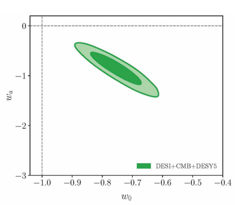

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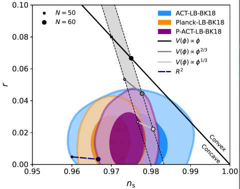

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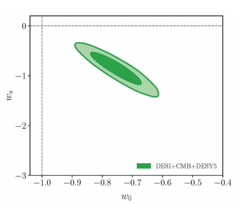

Phantom dark energy models

- Fluid: violates NEC: which "matter"?
- Fundamental (k-essence): classical (gradient) & quantum instability (vacuum decay, ghosts).

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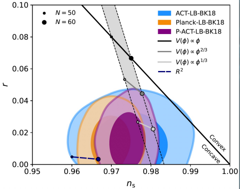

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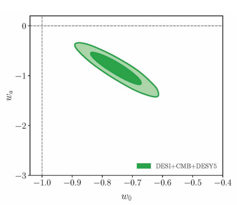

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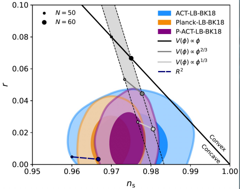
- Fundamental: which guiding principles? Which models admit an UV completion?



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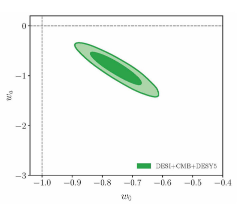

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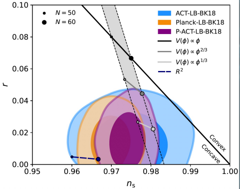

Need for a paradigm shift?

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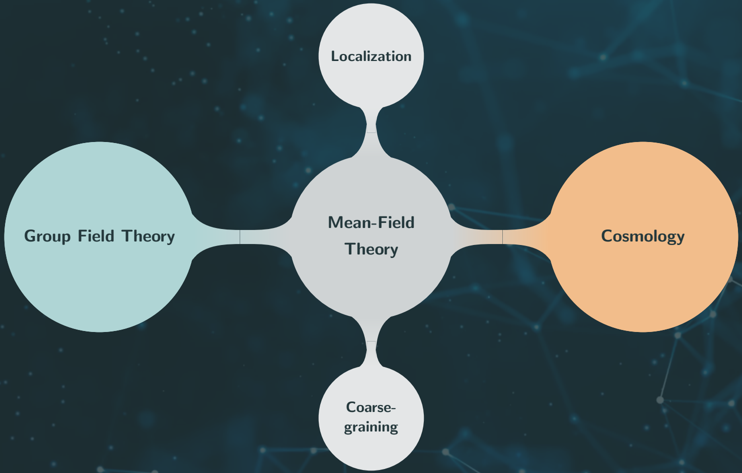
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Group Field Theory
Mean-Field Theory
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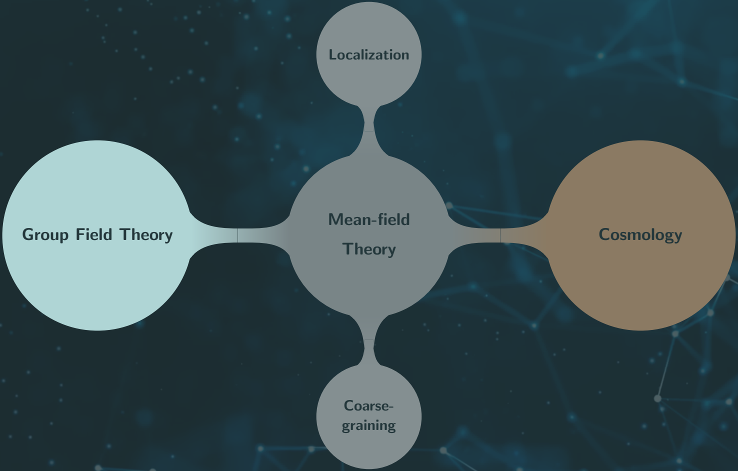
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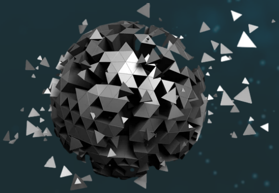

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Kinematics: GFT quanta

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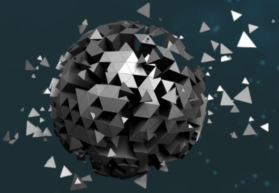
Reisenberger, Rovelli 2001; Freidel 0505016; Oriti 1408.7112; Oriti, Ryan, Thürigen 1409.3150; Sahlmann, Sherif 2302.03612; LM, Mehmood, Husain 2412.09851



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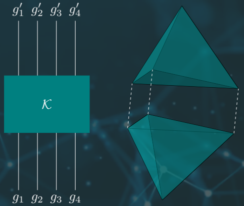

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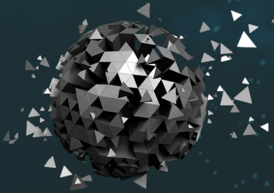

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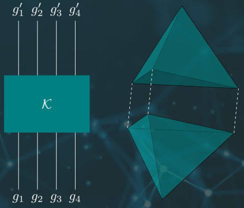

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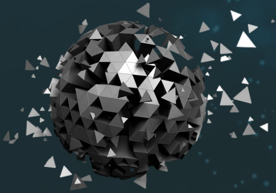

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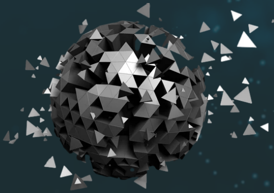

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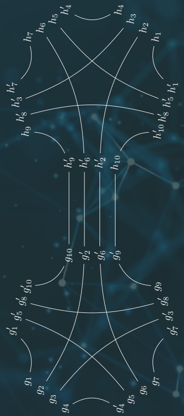

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$$Z_{\text{GFT}} = \sum_\Gamma w_\Gamma \mathcal{A}_\Gamma = \text{complete spinfoam model.}$$

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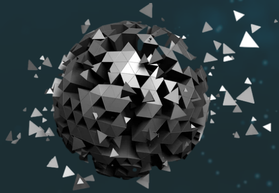

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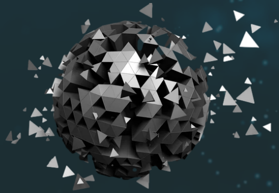

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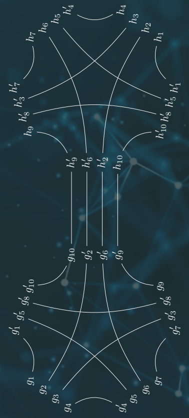

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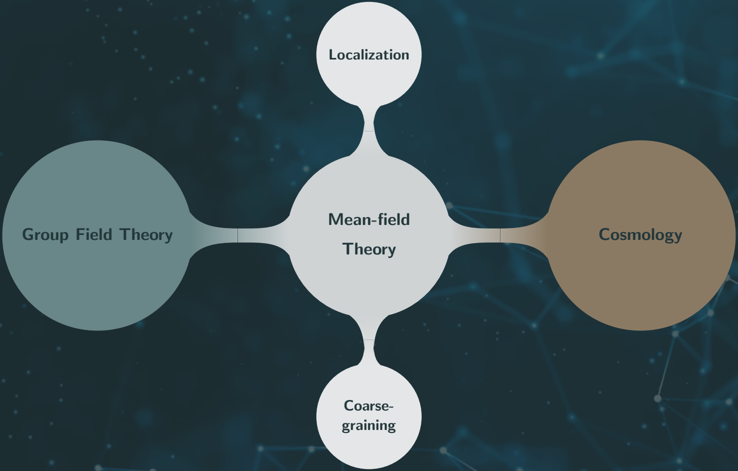
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Macroscopic Physics and Mean-Field Theory

Emergence

Extracting physics

- Locality

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LM, Wilson-Ewing 2412.14622; Aguilar, Ferrero, Höhn, LM (to appear); Oriti, Sindoni, Wilson-Ewing 1602.05881; LM, Oriti 2008.02774-2112.12677;. . .

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Macroscopic quantities = Collective averages

notation: $\varphi\cdot\psi = \int_{\mathcal{G}} \mathrm{d}\mathbf{g}\,\varphi\psi$

- Hydrodynamic: Macroscopic quantities $\sim O_\sigma \sim \sigma$-"hydrodynamic" averages of collective obs.
- Microscopic picture: Collective observables are one-body operators $\hat{\mathcal{O}}$ in $\mathcal{F}_{\mathrm{GFT}}$: $\mathcal{O}_\sigma = \langle\hat{\mathcal{O}}\rangle_\sigma$.
- E.g. number $\hat{N} = \varphi^\dagger\cdot\hat{\varphi}$ and volume $\hat{V} = \hat{\varphi}^\dagger\cdot V[\hat{\varphi}]$, with $N_\sigma = \sigma^*\cdot\sigma$ and $V_\sigma = \sigma^*\cdot V[\sigma]$.

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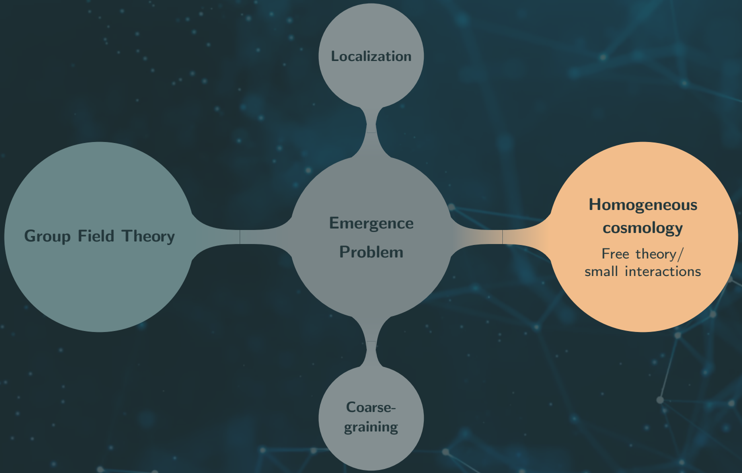
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Homogeneous cosmology
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Effective FLRW cosmological dynamics

Effective dynamics

Mean-field approximation

- Homogeneity: σ depends on geometry + clock χ^0.
- Isotropy: $\sigma_\upsilon \equiv \rho_\upsilon e^{i\theta_\upsilon}$ ($\upsilon_{\text{EPRL}} \in \mathbb{N}/2$, $\upsilon_{\text{BC}} \in \mathbb{R}$).
- Mesoscopic regime: negligible interactions.
- V_σ (thus a) increases as ρ_υ (thus N_σ) increases.

$$
\begin{aligned}
0 &= \mathcal{K}[\sigma], \\
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&= \bar{V}_0 a^3 \quad \longrightarrow \quad \{\mathcal{H}(V_\sigma), w(V_\sigma)\}\,.
\end{aligned}
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LM, Oriti 2008.02774-2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881; Jercher, Oriti, Pithis 2112.00091; Gielen, Polaczek 1912.06143.

Effective FLRW cosmological dynamics

Effective dynamics

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$$\left(\frac{V'_\sigma}{3V_\sigma}\right)^2 = \left(\frac{2\sum_\upsilon V_\upsilon \rho_\upsilon \operatorname{sgn}(\rho'_\upsilon)\sqrt{\mathcal{E}_\upsilon - Q_\upsilon^2/\rho_\upsilon^2 + \mu_\upsilon^2\rho_\upsilon^2}}{3\sum_\upsilon V_\upsilon \rho_\upsilon^2}\right)^2, \quad \frac{V''_\sigma}{V_\sigma} = \frac{2\sum_\upsilon V_\upsilon\left[\mathcal{E}_\upsilon + 2\mu_\upsilon^2\rho_\upsilon^2\right]}{\sum_\upsilon V_\upsilon \rho_\upsilon^2}$$

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Late/early times

Large/small number of quanta

- ✓ Volume quantum fluctuations under control.
- ✓ If one υ_o is dominating and $\mu_{\upsilon_o}^2 = 3\pi G$, matching with relational GR dynamics:

$$(V_\sigma'/3V_\sigma)^2 \simeq 4\pi G/3 \longrightarrow \text{flat FLRW}$$

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- For a large range of initial conditions (at least one $Q_\upsilon \neq 0$ or one $\mathcal{E}_\upsilon < 0$)
- Same type of bouncing dynamics as in LQC.

Singularity res. into quantum bounce!

LM, Oriti 2008.02774-2010.09700; Oriti, Sindoni, Wilson-Ewing 1602.05881; Jercher, Oriti, Pithis 2112.00091; Gielen, Polaczek 1912.06143.

Effective FLRW cosmological dynamics

Overview

Assumptions

- Homogeneity: $\sigma(g_A, \chi^0, \psi)$; ψ interacting scalar.
- Isotropy: $\sigma_\upsilon \equiv \rho_\upsilon e^{i\theta_\upsilon}$.
- Weak interactions: perturbative analysis.
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Dynamics

$$S[\phi, \phi^*] = \phi^* \cdot \mathcal{K}[\phi] + U[\phi, \phi^*]$$

$$\mathcal{K} = \mathcal{K}((\chi_1^0 - \chi_2^0)^2; (\psi_1 - \psi_2)^2)$$

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LM, Ladstätter 2508.16194; Li, Oriti, Zhang 1701.08719; De Cesare, Pithis, Sakellariadou 1606.00352

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$$\begin{array}{ccccccc} V_\sigma & \xrightarrow{\phantom{\text{mean-field dyn.}}} & \mathcal{H}_{\text{GFT}}[V_\sigma, \psi_\sigma] & \xrightarrow{\phantom{\text{recast as}}} & \mathcal{H}_{\text{cl}}[a, \psi] & \searrow & \\ & \text{mean-field dyn.} & & \text{recast as} & & & \text{Effective quantities: } G,\ V_{\text{eff},\psi}, \ldots \\ \psi_\sigma & \longrightarrow & E_{\text{GFT}}[V_\sigma, \psi_\sigma] & \longrightarrow & E_{\text{cl}}[a, \psi] & \nearrow & \end{array}$$

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Models and Results

Matching procedure

$$V_\sigma \xrightarrow{\text{mean-field dyn.}} \mathcal{H}_{\mathrm{GFT}}[V_\sigma, \psi_\sigma] \xrightarrow{\text{recast as}} \mathcal{H}_{\mathrm{cl}}[a,\psi]$$

$$\psi_\sigma \longrightarrow E_{\mathrm{GFT}}[V_\sigma, \psi_\sigma] \longrightarrow E_{\mathrm{cl}}[a,\psi]$$

$\longrightarrow$ Effective quantities: $G,\ V_{\mathrm{eff},\psi}, \ldots$

Pseudo-tensorial

$$U_{\mathrm{T}}[\phi,\phi^*,V_\psi] = \mathrm{Tr}\{\mathcal{U}_{\mathrm{T}}[V_\psi]\phi^{\frac{l+1}{2}}(\phi^*)^{\frac{l+1}{2}}\}$$

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- Geometry: matching $+ \Lambda$ for $l = 5$.

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LM, Ladstätter 2508.16194; Li, Oriti, Zhang 1701.08719; De Cesare, Pithis, Sakellariadou 1606.00352

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- QG-Higgs: Emergence of (constant) ψ-mass.
- Potential: Matching only for a class of V_ψ.

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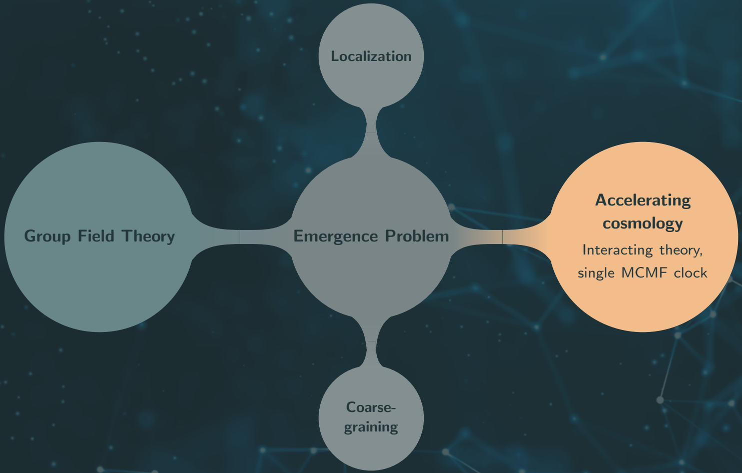
LM, Ladstätter 2508.16194; Li, Oriti, Zhang 1701.08719; De Cesare, Pithis, Sakellariadou 1606.00352


Localization
Group Field Theory
Emergence Problem
Accelerating cosmology
Interacting theory, single MCMF clock
Coarse-graining

Emergent acceleration I: Stability

Mean-field model

Model and Assumptions

$$\underbrace{\mathcal{K}_\upsilon[\sigma_\upsilon]}_{\text{kinetic kernel}} + \underbrace{\mathcal{V}_\upsilon[\sigma_\upsilon,\sigma_\upsilon^*]}_{\text{interaction kernel}} = 0\,, \qquad \mathcal{K}_\upsilon = \partial_\chi^2 - E_\chi^2\,, \qquad \mathcal{V}_\upsilon[\sigma_\upsilon,\sigma_\upsilon^*] = -\lambda_\upsilon\,\rho_\upsilon^{l}\,e^{i((m+1)\theta_\upsilon+\vartheta_\upsilon)}\,,$$

int. order $\in \mathbb{N}^+$

$\in \mathbb{R}$

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Dynamical system

Fixed points and dynamical stability

- First order for $x=\theta$, $y=\rho'/\rho^3$, $z=\theta'$.
- FP_∞: $l=5$, $\bar{y}^2=|\lambda|/3$, $\bar{x}=(n\pi-\vartheta)/m$, $z=0$.
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LM, Ladstätter, Oriti 2512.11712; Ladstätter, LM 2508.16194; Oriti, Pang 2105.03751-2502.12419; De Cesare, Pithis, Sakellariadou 1606.00352...

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$$H^2 \propto y^2\,, \qquad w = -[(1 + y'/(\rho^2 y^2)]$$

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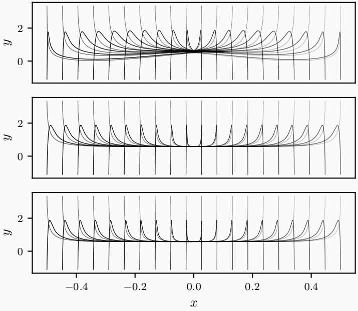
Emergent dS cosmological attractor for $m \leq 0$.



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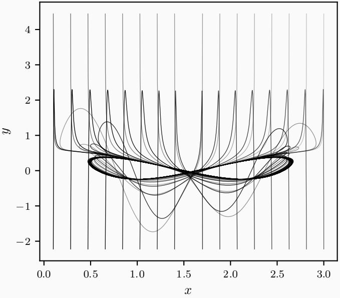

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Asymptotics

Asymptotic Λ

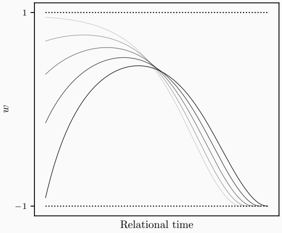
- Emergent DE: For $m \leq 0$ asymptotic dS attractor.

GFT coupling

Clock momentum

$$\bar{w} = -1, \qquad \bar{\Lambda} = |\lambda| \frac{4\pi_\chi^2}{9\mathfrak{v}^2}$$

Volume eigenvalue



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Emergent acceleration II: Dynamical Dark Energy

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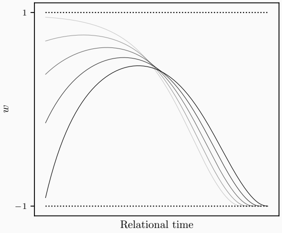

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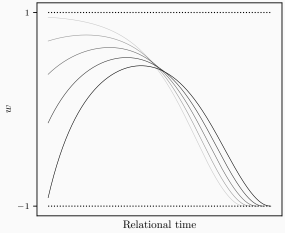


Dynamical behavior

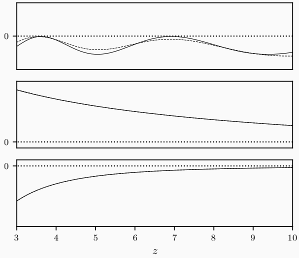
EoS dynamics

$(1+z_q)/(1+z)$ $\qquad$ $\propto \mathcal{T}(z)$

$$\delta w(z) = \begin{cases} [\mathcal{T}(z)]^{-6}(\delta w_0 + \delta w_1 \cos 2\Phi(z) + \delta w_2 \sin 2\Phi(z)) \\ \delta w_0 [\mathcal{T}(z)]^{6(\sqrt{1+3m/4}-1)} \\ \delta w_0 [\mathcal{T}(z)]^{-6} \log^2[\mathcal{T}(z)] \end{cases}$$

Solutions depend on $\mathrm{sgn}(1+3m/4)$.

- Quantum features: $z_q \sim \#$ of QG atoms today.



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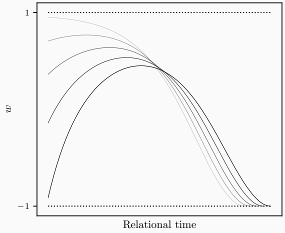
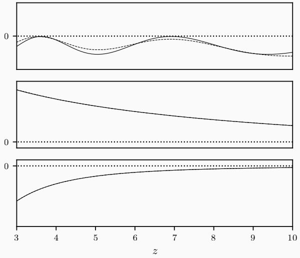


Dynamical behavior

EoS dynamics

$$\delta w(z) = \begin{cases} [\mathcal{T}(z)]^{-6}(\delta w_0 + \delta w_1 \cos 2\Phi(z) + \delta w_2 \sin 2\Phi(z)) \\ \delta w_0 [\mathcal{T}(z)]^{6(\sqrt{1+3m/4}-1)} \\ \delta w_0 [\mathcal{T}(z)]^{-6} \log^2[\mathcal{T}(z)] \end{cases}$$

- Quantum features: $z_q \sim \#$ of QG atoms today.
- Phantom behavior for $m \leq -6$ and $-1.27 \lesssim m \leq 0$



LM, Ladstätter, Oriti 2512.11712; Ladstätter, LM 2508.16194; Oriti, Pang 2105.03751-2502.12419; De Cesare, Pithis, Sakellariadou 1606.00352. . .

Asymptotics

Asymptotic Λ

- Emergent DE: For $m \leq 0$ asymptotic dS attractor.

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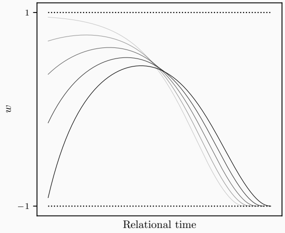

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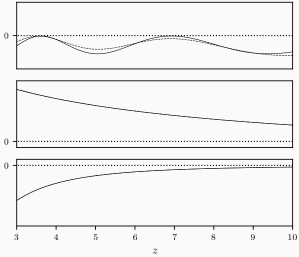
Emergent dynamical (typically phantom) dark energy!



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Emergent acceleration III: Emergent Inflation

Quasi dS phase

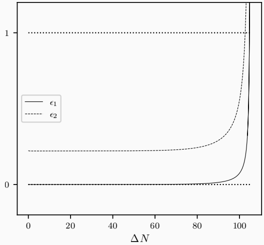
Slow-Roll Inflation

- Quasi dS: For $m > 0$ FP_∞ repulsive; acceleration ends.

$$\epsilon_1(N) = \exp[-\epsilon_2(N_{\text{end}} - N)]$$

$$\epsilon_2(N) = 6(\mu - 1)$$

$(1 + 3m/4)^{1/2}$



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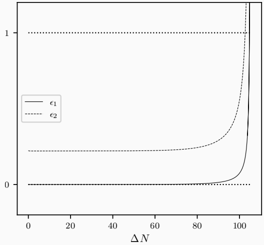

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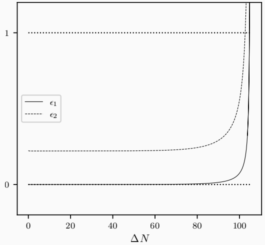


Single-field description

Emergent Inflaton

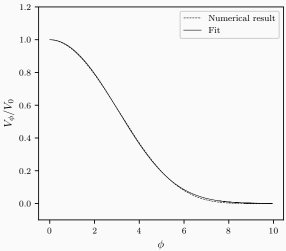
- SFI: GFT inflation can be described by emergent ϕ:

$$\delta\theta(\phi) \propto \phi - \phi_0$$

GFT phase

$\in [\phi_0, \phi_0 + 1]$

$$V(\phi) = V_0 \left(1 - \frac{(\phi - \phi_0)^2}{3}\right) e^{-2(\phi-\phi_0)^2/\epsilon_2},$$



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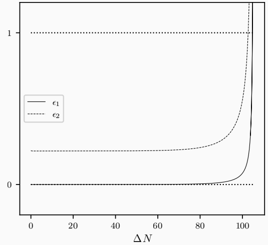

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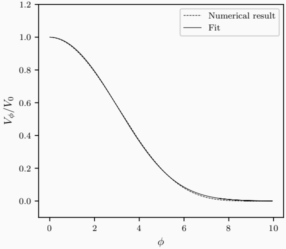
Emergent slow-roll single-field inflation!



LM, Ladstätter, Oriti 2512.11712;

Dynamical Dark Energy

- Order 6 GFT interactions generate acceleration, both in pseudo-tensorial/-simplicial models.
- For $m \leq 0$ de Sitter is an asymptotic attractor, with Λ depending on GFT parameters.
- Emergent dynamical dark energy, with $w = w(z)$ depending on the microscopic parameters.
- Dark energy is phantom for a large set of models (including pseudo-simplicial)!

Late Times

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- Emergent inflaton: dynamics can be described as SFI; inflaton associated with condensate phase.
- Inflaton potential: in this description, the emergent inflaton potential is a polynomial-Gaussian..
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Outlook

Model Building and Phenomenology

- ⚠ How do predictions on $w(z)$ compare with data?
- How do primordial cosmological perturbations emerge from QG? (No inflaton in this picture!)
- ⚠ In this scenario, what can cosmological power spectra tell us about QG?
- ⚠ Can a similar mechanism also produce a dark matter component? Emergent tracking solutions?
- Constraining effective theory space: map between SFI models and GFT mean-field theory models?
- Impact of additional modes on emergent dynamical dark energy behavior?
- ...