Emergent Late- and Early-Times Acceleration from Quantum Gravity

In collaboration with: T. Ladstätter and D. Oriti
(but also review of results from M. De Cesare, A. Pithis, X. Pang, M. Sakellariadou. . .)

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OIST
Kavli IPMU

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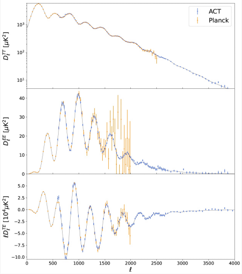
The ACT power spectra

- 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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Restriction of the parameter space for inflationary models. In particular, Starobinsky inflation disfavored at $\gtrsim 2\sigma$ for $50 < N < 60$.

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Need for a paradigm shift?

Collective states

GFT coherent states

- Collectivity: States should accommodate an infinite number of quanta. E.g.: coherent states $|\;\rangle$.
- Homogeneity: Wavefunction depends only on geometry and on a clock field , $= (g_a;\;)$.
- Isotropy: Wavefunction depends only on a single spin label, $_j(\;)$.
- Relationality: is localized in relational time (can alternatively be implemented on observables).

LM, Oriti, Pithis, Thürigen 2211.12768; LM, Oriti 2008.02774-2112.12677; Oriti, Sindoni, Wilson-Ewing 1602.05881; LM, Wilson-Ewing 2412.14622. . .

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Coarse-graining

Macroscopic dynamics = mean-field approximation

- Take simplest SD equations, i.e., the averaged quantum equations of motion: $h \; S_{\mathrm{GFT}} = \; \hat{}^{\,y} i \quad = 0$.

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Macroscopic quantities = Averaged one-body operators

- Collective behavior is captured by one-body operators $\hat{O}$, such as $\hat{N} = \hat{}^{\dagger}\ \hat{}$ and $\hat{V} = \hat{}^{\dagger}\ V[\hat{}]$.

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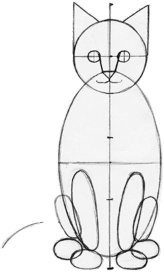
- Only need volume $V \quad h\hat{V} i \quad = \sum_j V_j \; {}^2_j$, with $_j \quad {}_j e^{i \; j}$, to describe cosmological quantities:

$$\bar{V} a^3 = V = \sum_j V_j \; {}^2_j ; \qquad H^2 = \frac{2}{9V^2} \quad \frac{V^0}{V} \quad {}^2 ; \qquad w = 3 \quad 2\frac{VV^{00}}{(V^0)^2}$$

The spherical cat model



(Pseudo)-Tensorial interactions and single-mode system

$$V[\ ;\ ] = \sum_j m_j^2 |\ _j|^2 + 2\frac{\ _j}{n_j}|\ _j|^{n_j}$$

De Cesare, Pithis, Sakellariadou 1606.00352; De Sousa, Barrau, Martineau 2305.05438.

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- (Pseudo-)Tensorial interactions: Chosen phenomenologically to depend only on $|\ _j|$ $\ _j$.
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Results

$$H^2 \underset{\text{late times}}{\to} \frac{8\ ^2}{9}\ \Lambda\ V^{\ (3\ \ n=2)}$$

- Late times dynamics: As the volume grows, grows and high-order interactions dominate.
- Emergent acceleration: If $n = 6$, emergence of a cosmological const., $\Lambda\ =\ \ V_{j_o}\ ^2 = 6$.

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- Inflation? If $\; > 0$ ($\Lambda\; < 0$), acceleration ends after $N(\;)$ e-folds.

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Bad news

Limitations

- No QG inflation: -interactions dominate and generate a recollapse: cyclic universe.
- No radiation phase (minor): For the above interactions, $H^2 \;\; / \; a \qquad$, with $\quad < 3=2 < 4$.

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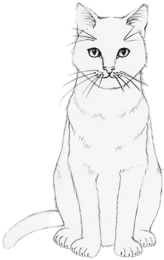
Adding details (and modes)



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A more realistic model

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- Two modes: Both $\ _{j_1}$ and $\ _{j_2}$ contribute to V, but one of them will dominate eventually.

Oriti, Pang 2105.03751 and 2502.12419.

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Phantom dark energy

$$w \xrightarrow{\text{late times}} \; 1 \;\; \frac{b}{V}$$

- Emergent phantom dark energy with no field theoretical issue.
- Fast transition: End of Friedmann phase, phantom crossing, and minimal value of w are close to each other.
- Recent crossing: If we are in a phantom phase, the crossing must have happened recently.
- Increased H_0 with respect to single-mode.

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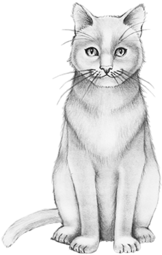

Emergent dynamical dark energy

$$V[\;;\;] = \sum_j m_j^2 j\;{}_j j^2 + \;{}_j e^{i\#}\;{}_j^{l} + \text{c.c}$$

Ladstätter, LM, Oriti (to appear).

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$$ {}^{00}_{j} \quad [({}^{0}_{j})^2 + m_j^2] \; {}_{j} \qquad {}_{j} \cos {}'_{j} \; {}^{l}_{j} = 0 \qquad {}_{j} \; {}^{00}_{j} + 2 \; {}^{0}_{j} \; {}^{0}_{j} \qquad {}_{j} \sin {}'_{j} \; {}^{l}_{j} = 0 $$

Pseudosimplicial: Good News

Model and Assumptions

- (Pseudo-)Simplicial interactions: Less symmetric, but more easily connected to simplicial gravity.
- Phase dependence: Equations depend on $_j$ and $_j$ (also in $'_j \quad \#_j \quad n \; _j$, $n = l + 1$).
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Evolving Dark Energy

- Asymptotically autonomous system: standard stability analysis possible.

$$x = \;; \quad y = {}^0 = {}^3; \quad z = {}^0 :$$

$$\begin{aligned} x^0 &= z\,; \\ y^0 &= 3\,{}^2 y^2 + (z^2 + m^2) = {}^2 + {}^l\,{}^3 \cos{}'(x)\,; \\ z^0 &= 2\,{}^2 yz + {}^l\,{}^1 \sin{}'(x) : \end{aligned}$$

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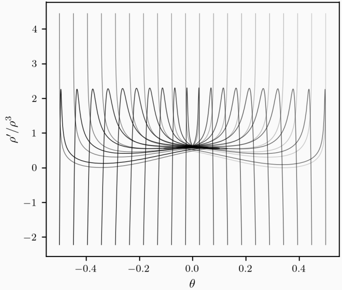
Late-times de Sitter attractor!



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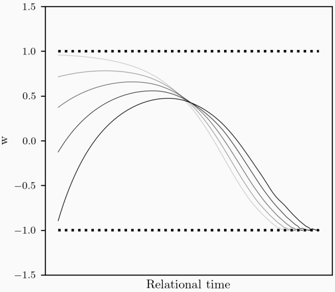

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Pseudosimplicial: Even Better News

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Inflaton description

- One can construct a with potential $V(\ )$ driving the inflationary dynamics $_1(N)$.

GFT inflation as emergent SFI!

- No analytic form for $V(\ )$, but numerically well approximated by a Mexican-hat potential.

Ladstätter, LM, Oriti (to appear); Mukhanov 1409.2335.

Dynamical Dark Energy

- Order 6 GFT interactions generate acceleration, both in pseudo-tensorial/-simplicial models.
- Asymptotically de Sitter is an attractor, with Λ depending on GFT parameters.
- Emergent description is that of a dynamical dark energy, with $w = w(a)$ depending on the microscopic dynamics.

Late Times

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Early Times

Emergent Inflation

- Slight modification of the pseudo-simplicial dynamics leads to instability in de Sitter solution.
- QG interactions produce **emergent inflation**: persistent acceleration and graceful exit.
- This emergent inflation is quasi-**slow-roll** ($_2$ large).
- **No inflaton needed!** Still, the emergent scenario can be described as single-field inflation.
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Outlook

Model Building and Phenomenology

- What is the simplicial gravity interpretation of the emergent inflationary models?
- Impact of additional modes in pseudo-tensorial/-simplicial models?
- Evolving dark energy affects H_0. Can QG alleviate cosmological tensions?
- 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?
- ...