Emergent Modified Gravity: Dynamical Dark Energy Model Without Additional Degrees of Freedom

Manuel Díaz

In collaboration with: Martin Bojowald, Erick I. Duque, and Övgü Güleryüz

Based on: arXiv:2507.08116 [Phys. Rev. D **113**, 084060 (2026)],
arXiv:2507.14358 [Phys. Rev. D **113**, 084061 (2026)],

and work in preparation.

Amherst Center for Fundamental Interactions
University of Massachusetts Amherst

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Physics at the interface: Energy, Intensity, and Cosmic frontiers
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- **Unique and New:** We use a modified gravity approach that doesn't require new degrees of freedom beyond what would be available in ΛCDM. This is because in our approach the spatial metric is not a canonical configuration variable. Instead, the metric is an emergent function of the phase space. This is in contrast to standard approaches that require new degrees of freedom/fields, have Ostrogradsky instabilities, or require higher dimensions.

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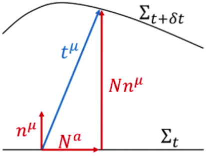
- **Implications:** The emergent metric is constrained to a form with a phenomenological **gravitational form factor** $F(\bar{p})$, analogous to a hadronic form factor, which we can fit to the required Chevallier–Polarski–Linder (CPL) parametrization curve $w(z) = w_0 + w_a\, z/(1+z)$ with $(w_0, w_a) \approx (-0.86, -0.55)$, while keeping the cosmological constant Λ non-dynamical. The phase space is *not* enlarged: no new fields, no Ostrogradsky ghosts, no new particles.

Canonical Gravity (ADM)

- **ADM decomposition**

$$ds^2 = -N^2 dt^2 + q_{ab}\left(dx^a + N^a dt\right)\left(dx^b + N^b dt\right)$$

$$t^\mu = Nn^\mu + N^a s_a^\mu$$ (Arnowitt, Deser, Misner 1962)



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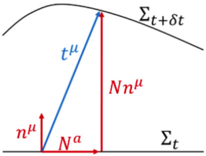

- **Einstein–Hilbert action (ADM form)**

$$S_{\rm EH}[g] = \int d^4x \sqrt{-\det g}\, R = \int dt\, d^3x \left(p^{ab}\dot{q}_{ab} - N^\mu H_\mu\right),$$

configuration: q_{ab}, Lagrange multipliers: $N^\mu = (N, N^a)$.

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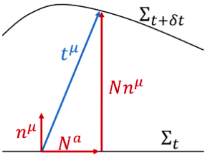

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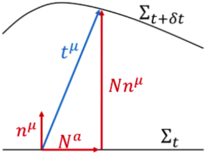

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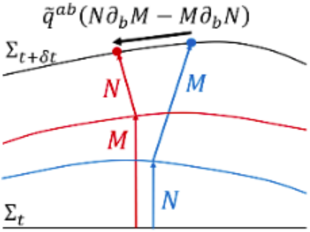
- **Total Hamiltonian and Evolution**

$$H[N] = \int d^3x\, N\, H, \qquad \dot{A} = \{A, H_\mu[N^\mu]\}, \quad \delta_\varepsilon A = \{A, H_\mu[\varepsilon^\mu]\}.$$

The Hypersurface Deformation Algebra



[ED, Bojowald 2023, arXiv:2310.06798]

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\{D_a[N_1^a], D_b[N_2^b]\} &= -D_a[N_2^b\partial_b N_1^a - N_1^b\partial_b N_2^a] \,, \\
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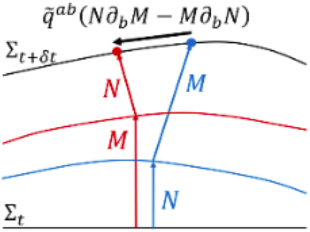

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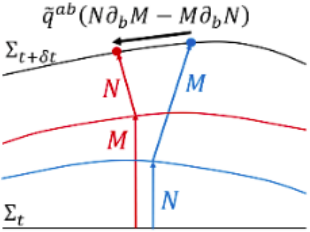
- **Covariance:** $\delta_\varepsilon g_{\mu\nu}\big|_{\text{o.s.}} = \mathcal{L}_\xi g_{\mu\nu}\big|_{\text{o.s.}}$ — the gauge flow generated by H makes $\tilde{q}^{ab}$ transform as a spatial tensor.
  - Uniqueness result: algebra $\Rightarrow$ GR [Hojman et al., 1994].
  - **Assumption:** the spatial metric q_{ab} is a configuration variable.



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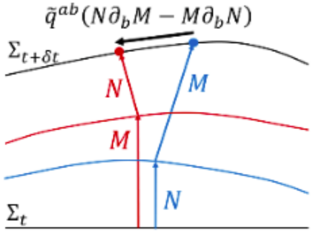
  - Uniqueness result: algebra $\Rightarrow$ GR [Hojman et al., 1994].
  - **Assumption:** the spatial metric q_{ab} is a configuration variable.
  - **Drop the assumption:** anomaly freedom of the perturbative Hamiltonian determines the emergent spacetime metric. The covariance condition guarantees the emergent metric is a valid metric.



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- DESI BAO + CMB + SNe prefer $\boxed{(w_0, w_a) \approx (-0.86,\ -0.55)}$. *Translation:* dark energy today is slightly less repulsive than Λ, which would seem to indicate **dark energy is weakening.**
- **Our approach:** modify the gravitational Hamiltonian, *not* the matter content.
  - No new degrees of freedom
  - No higher time derivatives $\Rightarrow$ no Ostrogradsky instability
  - Only a standard cosmological constant Λ

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- Spacetime metric is *not* fundamental: it **emerges** from the structure function of the $\{H, H\}$ bracket.

$$\{H[N_1], H[N_2]\} = D_a\left[\bar{\tilde{q}}^{ab}\left(\bar{N}_2\partial_b\delta N_1 - \bar{N}_1\partial_b\delta N_2\right)\right]$$

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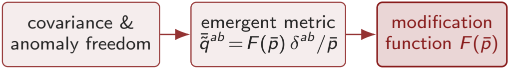

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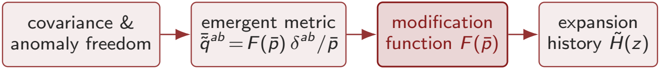

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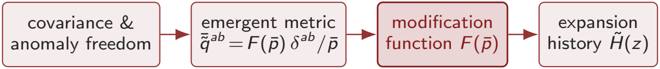

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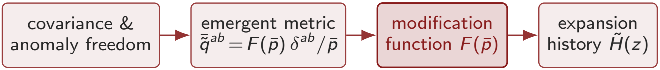

- Dropping "q_{ab} is fundamental" opens a class of covariant modified gravity theories unreachable by any metric action principle.
- This is an **EFT of the gravitational Hamiltonian:** write all operators compatible with background symmetries; the constraint algebra plays the role gauge invariance plays in the SMEFT, constraining operator coefficients.

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- In the isotropic slicing, we have

$$\bar{K}_a^i = \bar{k}\delta_a^i, \quad \bar{E}_i^a = \bar{p}\delta_i^a$$

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- All space-time metric components are perturbed including the lapse function $N = \bar{N} + \delta N$, the shift vector $N^a = \delta N^a$, and the canonical pair $K^i_a = \bar{K}^i_a + \delta K^i_a$ and $E^a_i = \bar{E}^a_i + \delta E^a_i$.

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- **Perturbed Hamiltonian**
  - $H[\bar{N}] = \int \mathrm{d}^3x \bar{N}\left[C^{(0)} + C^{(2)}\right] \quad , \quad H[\delta N] = \int \mathrm{d}^3x \delta N C^{(1)}$

Perturbative Inhomogeneity in Canonical GR

$$C^{(0)} = -6\sqrt{\bar{p}}\left(\bar{k}^2 - \frac{1}{3}\Lambda\,\bar{p}\right)\,,$$

$$C^{(1)} = \sqrt{\bar{p}}\left[-4\,\bar{k}\,\delta^c_j\,\delta K^j_c - \left(\bar{k}^2 - \Lambda\,\bar{p}\right)\frac{\delta^j_c\,\delta E^c_j}{\bar{p}} + 2\,\frac{\partial^j\partial_c\delta E^c_j}{\bar{p}}\right]\,,$$

$$\begin{aligned} C^{(2)} = \sqrt{\bar{p}}\Bigg[&\delta K^j_c\,\delta K^k_d\,\delta^c_k\,\delta^d_j - \left(\delta K^j_c\,\delta^c_j\right)^2 - 2\,\bar{k}\,\delta K^j_c\,\frac{\delta E^c_j}{\bar{p}} \\ &-\frac{1}{2}\left(\left(\bar{k}^2 + \Lambda\,\bar{p}\right)\frac{\delta^k_c\,\delta^j_d\,\delta E^c_j\,\delta E^d_k}{\bar{p}^2} - \left(\bar{k}^2 + \Lambda\,\bar{p}\right)\frac{\left(\delta^j_c\,\delta E^c_j\right)^2}{2\bar{p}^2}\right) \\ &-\frac{1}{2}\,\frac{\delta^{jk}\left(\partial_c\delta E^c_j\right)\left(\partial_d\delta E^d_k\right)}{\bar{p}^2}\Bigg]\,. \end{aligned}$$

EFT of the Gravitational Hamiltonian

The $\mathcal{K}$-function ansatz: write down **all terms compatible with background isotropy and no higher than second order derivatives**.

$$\begin{aligned}
\tilde{C}^{(0)} &= -6\sqrt{\bar{p}}\mathcal{K}^{(0)} \,, \\
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\tilde{C}^{(2)} &= \sqrt{\bar{p}}\Bigg[\mathcal{K}_1^{(2)}\delta K_c^j\delta K_d^k\delta_k^c\delta_j^d - \mathcal{K}_2^{(2)}(\delta K_c^j\delta_j^c)^2 - 2\mathcal{K}_3^{(2)}\delta K_c^j\frac{\delta E_j^c}{\bar{p}} \\
&\quad -\frac{1}{2}\left(\mathcal{K}_4^{(2)}\frac{\delta_c^k\delta_d^j\delta E_j^c\delta E_k^d}{\bar{p}^2} - \mathcal{K}_5^{(2)}\frac{(\delta_c^j\delta E_j^c)^2}{2\bar{p}^2}\right) \\
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- There are 10 coefficient functions $\mathcal{K}_I^{(n)}(\bar{p},\bar{k})$ and **general covariance constrains them to 3 independent functions.**

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- Solving the covariance conditions on the $\mathcal{K}$-functions yields the structure function in the constraint algebra:

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- What this product equals — and therefore what the emergent geometry looks like — depends on the ansatz chosen for the $\mathcal{K}$-functions. Two such ansatze follow.

From the Bounce to a General $F(\bar{p})$

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- **The bounce ansatz** (arXiv:2507.08116, 2507.14358) uses the bare LQC holonomy form $\mathcal{K}^{(0)} = \sin^2(\lambda\bar{k})/\lambda^2$. Solving the anomaly freedom conditions yields $\mathcal{K}_3^{(1)}\mathcal{K}_1^{(2)} = \cos(2\lambda\bar{k})$ for the emergent metric.

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- *Question:* what $F(\bar{p})$ describes the *low-curvature* regime — the observed cosmological expansion today?

$F(\bar{p})$ as a Gravitational Form Factor

Particle phenomenologists already know objects like $F(\bar{p})$: **form factors.** The structural parallel is exact.

	Hadronic form factor $F_p(Q^2)$	**Gravitational form factor $F(\bar{p})$**
Argument	Momentum transfer Q^2	Phase-space variable $\bar{p}$ ($\sim a^2$)
Bare interaction	Pointlike QED vertex	Einstein–Hilbert action
Physics encoded	Non-perturbative QCD substructure	Modifications beyond bare GR
Determination	Global fit to scattering data	Global fit to expansion history (CPL)
Trivial limit	$F \to 1$: pointlike charge	$F \to 1$: GR recovered (today, $\bar{p} \approx 1$)

Phenomenologists do not derive form factors from QCD; they extract them from data and use them to predict other observables. **We propose the same program for gravity.** $F(\bar{p})$ is our gravitational form factor, extracted from the expansion history, but the model can be predictive for everything else.

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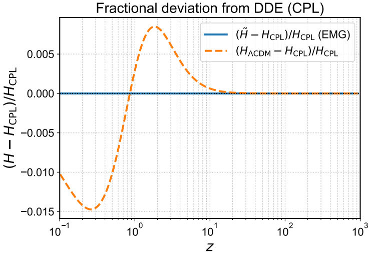
- Methodologically a **global fit:** $F(\bar{p})$ is determined by demanding the modified Friedmann equation reproduce the CPL expansion law — analogous to extracting a parton distribution from a global QCD fit.

Results: EMG Reconstructs CPL Expansion with Just Λ



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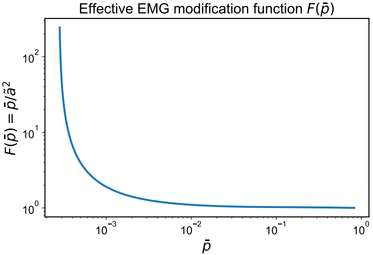

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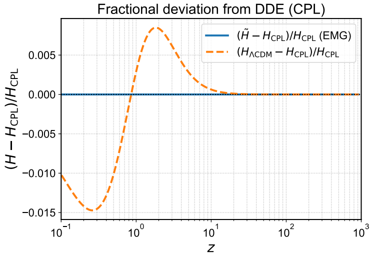

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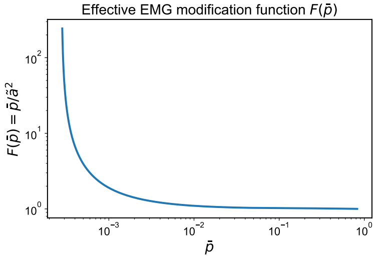

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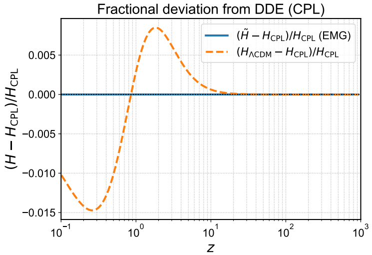

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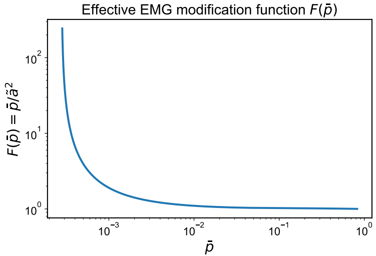

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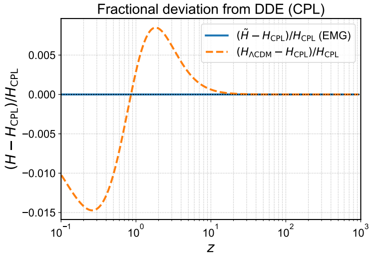

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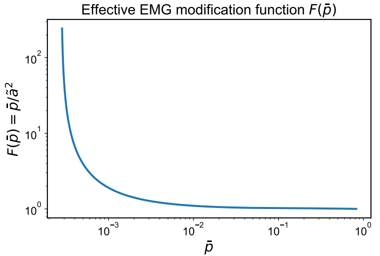

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Implications & Future Directions

Established in this work

Follow-up work in progress

Open question:

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Open question: First-principles derivation of the UV completion that produces $F(\bar{p})$ remains open, but the phenomenological implications can be explored independently of whether we have such a UV completion or not.

Thank You For Your Attention!

Feel free to approach for further discussion.

Backup Slides

The Lagrangian Question (1/2): A Lagrangian Exists

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- The question is not whether a Lagrangian *exists* — it does — but what kind of object it is. The configuration variable q_{ab} in this Lagrangian is **not the physical metric**. The physical metric is the emergent metric $\tilde{q}_{ab}$, known from the Hamiltonian analysis.

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- **Open:** The Lagrangian is covariant — the HDA guarantees it — but this covariance is with respect to the emergent geometry, not manifest in bare variables. Can it be rewritten in emergent-metric variables as a recognizable geometric action? EMG accesses theories that no bare-metric action can reach; whether an emergent-metric action exists remains under investigation.

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- The $\cos(2\lambda\bar{k})$ term was missed in a previous analysis [arXiv:1111.3535], but has profound consequences for the spacetime geometry.

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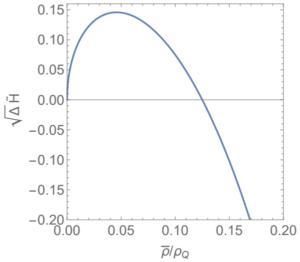

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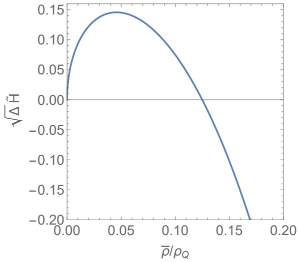

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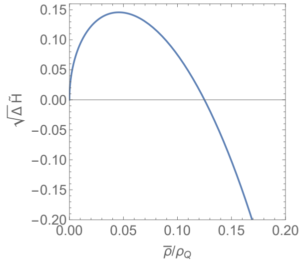

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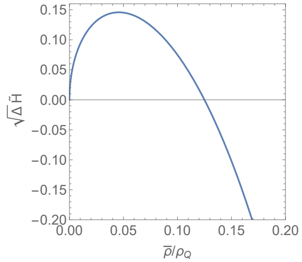
- **A New Bounce:** $\tilde{\mathcal{H}} = 0$ when $\bar{\rho} = \rho_Q/8$.

New Effective Friedmann Equation

- The modified emergent metric leads to a new effective Friedmann equation:

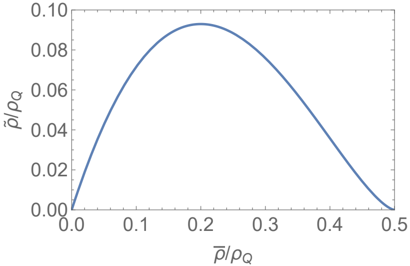
$$\tilde{\mathcal{H}}^2 = \left(\frac{\dot{\tilde{a}}}{\bar{N}\tilde{a}}\right)^2, \left(\text{where } \tilde{a} = \sqrt{\frac{\bar{p}}{\cos(2\lambda\bar{k})}}\right)$$

$$= \frac{8\pi G}{3}\bar{\rho}\left(1 - \frac{\bar{\rho}}{\rho_Q}\right)\frac{(1-8\bar{\rho}/\rho_Q)^2}{(1-2\bar{\rho}/\rho_Q)^2}$$



- **Scalar Matter:** We coupled scalar matter nonminimally.
- **A New Bounce:** $\tilde{\mathcal{H}} = 0$ when $\bar{\rho} = \rho_Q/8$.
- The maximum Hubble parameter is reached after the bounce.

Time-Reversed Big-Rip Singularity



$$\tilde{\rho} = \frac{H_\pi[1]}{V_0 \tilde{a}^3} = \bar{\rho} \cos^{3/2}(2\lambda \bar{k}) = \bar{\rho} \left(1 - \frac{2\bar{\rho}}{\rho_Q}\right)^{3/2}$$

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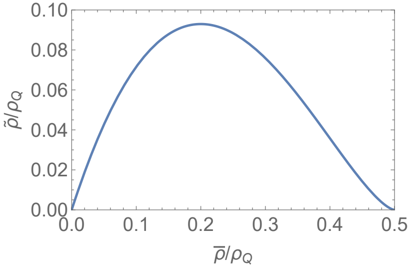

- As the universe approaches the initial rip singularity ($\bar{\rho} \to \rho_Q/2$), the emergent energy density $\tilde{\rho}$ goes to zero.

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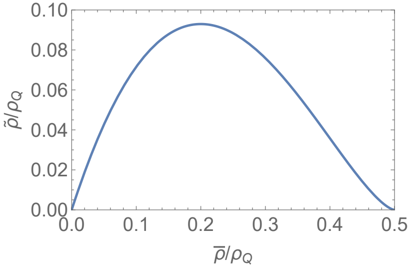
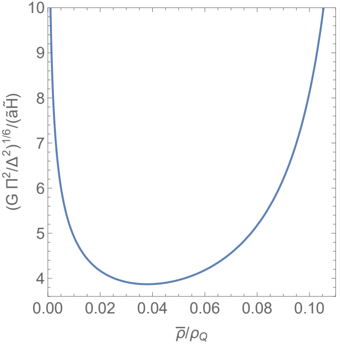


- As the universe approaches the initial rip singularity ($\bar{\rho} \to \rho_Q/2$), the emergent energy density $\tilde{\rho}$ goes to zero.
- This suggests the singularity is "tame" and may offer a more controllable starting point for cosmology than a Big Bang.

$$\tilde{\rho} = \frac{H_\pi[1]}{V_0 \tilde{a}^3} = \bar{\rho} \cos^{3/2}(2\lambda \bar{k}) = \bar{\rho}\left(1 - \frac{2\bar{\rho}}{\rho_Q}\right)^{3/2}$$

Comoving Hubble Radius vs. Density



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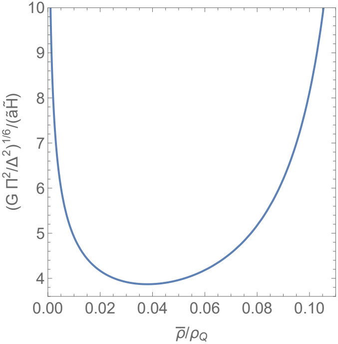
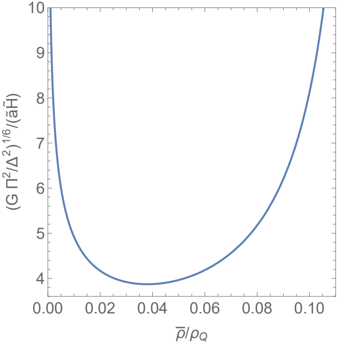


- The Hubble radius reaches a minimum shortly after the bounce, at a density of $\bar{\rho} \approx 0.038\rho_Q$.

Comoving Hubble Radius vs. Density



- The Hubble radius reaches a minimum shortly after the bounce, at a density of $\bar{\rho} \approx 0.038\rho_Q$.
- This rapid change in the Hubble radius at sub-Planckian densities could have important implications for early universe physics.

Constraints from Anomaly Freedom

$$
\begin{aligned}
\mathcal{K}_2^{(2)} &= \mathcal{K}_1^{(2)}\,, \quad \mathcal{K}_3^{(2)} = \frac{\partial \mathcal{K}^{(0)}}{\partial \bar{k}} - \bar{k}\mathcal{K}_1^{(2)}\,, \\
\mathcal{K}_4^{(2)} &= 2\bar{k}\mathcal{K}_3^{(2)} - \mathcal{K}^{(0)} - 2\bar{p}\frac{\partial \mathcal{K}^{(0)}}{\partial \bar{p}}\,, \quad \mathcal{K}_5^{(2)} = \mathcal{K}_4^{(2)}\,, \\
2\mathcal{K}_1^{(1)}\mathcal{K}_6^{(2)} &= \frac{\partial \mathcal{K}^{(0)}}{\partial \bar{k}}\left(\mathcal{K}_3^{(1)}\frac{\partial \mathcal{K}^{(0)}}{\partial \bar{k}} + 2\bar{p}\frac{\partial \mathcal{K}_3^{(1)}}{\partial \bar{p}}\right) - \frac{\partial \mathcal{K}_3^{(1)}}{\partial \bar{k}}\left(\mathcal{K}^{(0)} + 2\bar{p}\frac{\partial \mathcal{K}^{(0)}}{\partial \bar{p}}\right) \\
-3\mathcal{K}^{(0)}\mathcal{K}_1^{(2)} &= 2\bar{p}\frac{\partial \mathcal{K}_1^{(1)}}{\partial \bar{p}}\frac{\partial \mathcal{K}^{(0)}}{\partial \bar{k}} - \frac{\partial \mathcal{K}_1^{(1)}}{\partial \bar{k}}\left(\mathcal{K}^{(0)} + 2\bar{p}\frac{\partial \mathcal{K}^{(0)}}{\partial \bar{p}}\right) - \mathcal{K}_1^{(1)}\frac{\partial \mathcal{K}^{(0)}}{\partial \bar{k}}\,, \\
\mathcal{K}_2^{(1)} &= 3\mathcal{K}^{(0)} - 2\bar{k}\mathcal{K}_1^{(1)}\,.
\end{aligned}
$$

DESI: Anticipated Questions

- **Q1.** *"$w_0 + w_a \approx -1.41$ corresponds to phantom dark energy, doesn't it?"*
  In a fluid description with a fundamental scalar, that early-universe value is phantom and pathological. In EMG there is *no* fundamental scalar driving dark energy — the modification is geometric, encoded in $F(\bar{p})$. The phantom-versus-canonical distinction does not apply. What matters is whether the modified Friedmann equation reproduces the observed $H(z)$, which it does.

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- **Q2.** *"How robust is the CPL parametrization itself?"*
  CPL is a phenomenological choice — a two-parameter expansion in scale factor. The DESI collaboration also reports tension with ΛCDM in non-parametric reconstructions, so the dynamical preference is not solely an artifact of CPL. Our framework reproduces whatever expansion history the data prefer; a different parametrization would yield a different $F(\bar{p})$ but the methodology would be identical.