κ-GRAVITY & VACUUM ENERGY

THEORY & EXPANSION OBSERVATIONS

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Based on:

D.R., O.B., CQG, 2025,

D.R & O.B PRD, 2025,

D.R & O.B, in preparation

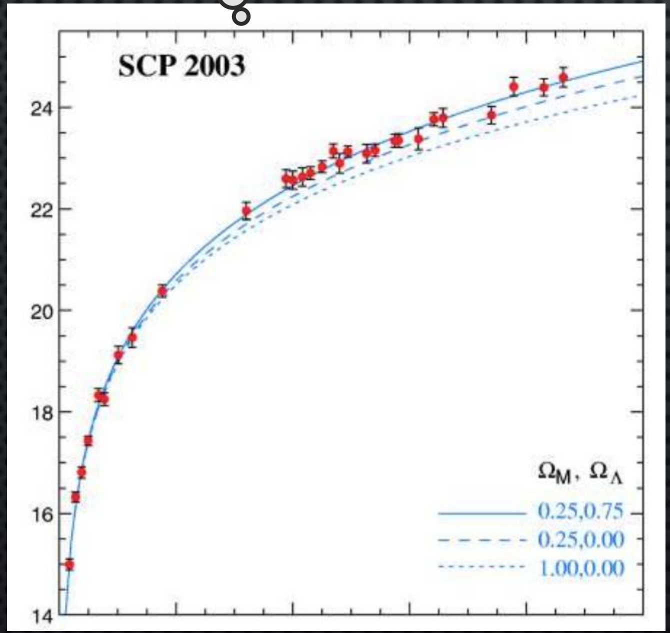
WHAT DRIVES COSMIC EXPANSION?

Expanding & accelerating universe!

Energy components ρ_i have different pressure p_i.
Cosmic acceleration occurs when
$w < -\frac{1}{3}$ in $p = w\rho$

Hubble rate: $H(t) = \frac{\dot{a}}{a}$
Recession velocity: $v \sim H(t) d_L$
Friedmann: $H^2(t) \sim \Sigma_i \rho_i(t)$

Brightness (magnitude) M



Red-shift Z (0-1)

Radiation

$$w = 1/3$$
$$a(t) \sim t^{\frac{1}{2}}$$
$$H(t) \sim \frac{1}{2t}$$

Dust (matter)

$$w = 0$$
$$a(t) \sim t^{\frac{2}{3}}$$
$$H(t) \sim \frac{2}{3t}$$

Today → Λ dominates

$$w = -1$$
$$a(t) \sim \exp[\sqrt{\Lambda}\, t]$$
$$H \sim \sqrt{\Lambda}$$

Observations show H(t) tensions

and possible **time-dependence** of Λ (e.g., DESI).

So, what is Λ? Does it really need to be Dark Energy?

A THEORY OF QUANTUM GRAVITY (BRIEF)

General Relativity

Localizing energy within $\ell \leq r_{sch}$ forms a horizon

+

QFT

Probing ℓ requires photons with $\lambda \leq \ell \rightarrow E_\lambda = \frac{\hbar c}{\ell}$

=

Quantum Gravity

For $\ell \leq \ell_p$, we get $E_\lambda \geq E_p$, but $r_{sch}\left[\frac{E_p}{c^2}\right] = 2\ell_p$!

Events (with coordinates) are now described by **operators:**

κ-Minkowski:

UV (density) scale limited by IR scale (distance) → a UV–IR coupling:

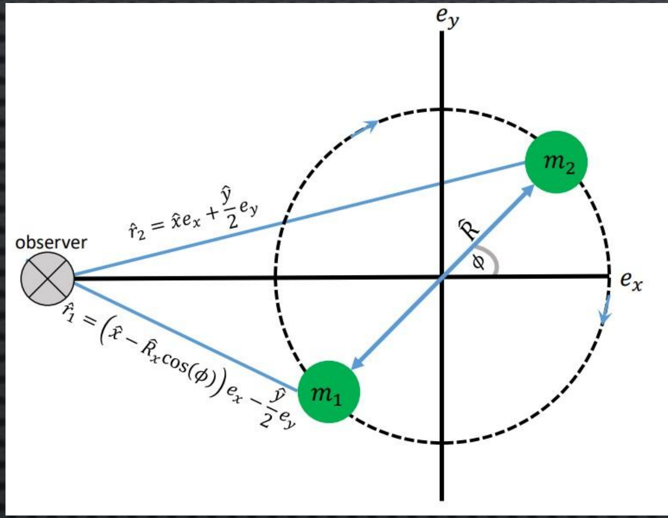
$$\left[\hat{x}^0, \hat{x}^j\right] = \frac{i\ell_p}{c} R_{caus} \Leftrightarrow \sigma_{\hat{t}}\sigma_{\hat{x}^j} \geq \frac{R_{caus}}{\omega_p}$$

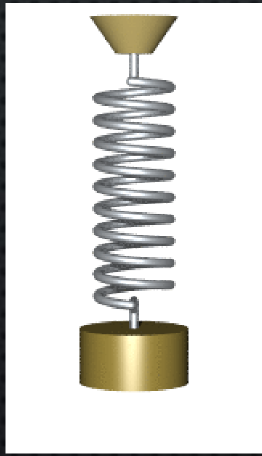
Causal radius of observers ($\sim ct$)

$$\ell_p = \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-35}[m],$$
$$\omega_p \sim 10^{43}[Hz]\,.$$

Majid, Ruegg, 1994,
Garay, 1995,
G. Amelino 2002,
J. a. Magueijo 2003
D.R., O.B., Class. Quantum Grav. 42 185006, 2025

AN EFFECT: FREQUENCY UNCERTAINTIES





Local kinematical variables (time, radius, velocity)

$$\hat{t} \equiv \frac{\hat{R}}{\hat{V}} \equiv \frac{1}{\hat{\Omega}} \Rightarrow \hat{V} = \hat{\Omega}\hat{R}$$

local time = distance / velocity

Space-time uncertainty coupling

$$\sigma_{\hat{t}} \coloneqq \hat{t} - \bar{t} = \frac{\hat{R}}{\hat{V}} - \frac{\bar{R}}{\bar{V}} \sim \hat{O}\sigma_{\hat{R}}$$

***Every oscillatory system**, with characteristic length $\bar{\ell}_{sys}$, causal radius R_{caus}, and averaged energies $(\langle|U|\rangle, \langle|T|\rangle)$, will satisfy:*

The effect

$$\frac{\sigma_{\hat{\omega}_{sys}}}{\bar{\omega}_{sys}} = \frac{1}{\sqrt{\gamma_{sys}}} \left(\frac{R_{caus}}{\ell_{sys}} \frac{\bar{\omega}_{sys}}{\omega_p} \right)^{\frac{1}{2}}$$

Ratio of potential to total energy

$$\gamma_{sys} = \frac{\langle|U|\rangle}{\langle|U|\rangle + \langle|T|\rangle}\bigg|_{sys}$$

D.R & O.B PRD **112**, 064072

VACUUM UNCERTAINTIES & DECOHERENCE

Assume vacuum modes of quantum fields as harmonic oscillators with $\ell_\phi = \frac{c}{\omega_\phi}$:

the modes will have **some uncertainty** $\sigma_{\hat{\omega}}[R_{caus} = R_{univ}]$

Modes with $\boldsymbol{\sigma_{\hat{\omega}} \geq \bar{\omega}}$ decohere: they appear random when sampled over long times.

$$\omega_\phi \sim \omega_{critic} = \sqrt{\gamma_{sys}} \left(\frac{\ell_p}{R_{univ}\,(t)} \right)^{\frac{1}{2}} \omega_p$$

$$\sigma_{\hat{\omega}} \geq \bar{\omega} \Rightarrow$$
$$T_{coh} \leq T_{osc} = \frac{1}{\omega_{critic}}$$

Cosmology: a “classical” apparatus

$$\boldsymbol{L_g \sim R_{univ}(t) \gg L_{coh},} \qquad \boldsymbol{T_g \sim \frac{R_{univ}(t)}{c} \gg \frac{1}{\omega_{critic}}}$$

Semi-classical stress–energy of decohered vacuum modes

$$\langle \hat{T}_{\mu\nu} \rangle \sim C_{\mu\nu} \times \frac{T_{coh}}{\sqrt{T_{coh}^2 + 2T_g^2}} \left(\frac{L_{coh}^2}{L_{coh}^2 + 2L_g^2} \right)^{\frac{3}{2}} \Bigg|_{T_{coh} = \frac{1}{\omega_{critic}}} \approx C_{\mu\nu} \times 10^{-113}$$

L. H. Ford, et,al. The Effects of stress tensor fluctuations upon focusing. R.M.Wald, et,al. Local Wick Polynomials

COHERENT VACUUM AS THE EXPANSION ENERGY

For cosmological gravity with $L_{grav} \sim R_{univ}$:
$$\rho_\phi|_{Vac} \sim \rho_\phi[\omega < \omega_{critic}]|_{Vac} + 0$$

Only coherent modes gravitate

The **gravitationally relevant** energy density:
$$\rho_i^{QFT} \sim \frac{\hbar}{c^3}\omega_{crit,i}^4 \sim \frac{\hbar}{c^3}\gamma_i^2\left(\frac{\ell_p}{R_{uni}}\right)^2\omega_p^4 = \gamma_i^2\frac{c}{\hbar}\left(\frac{M_p}{R_{uni}}\right)^2$$

$\boldsymbol{\alpha_{bare}}$: renormalization bare term

$$\rho_{gravity}^{QFT} = (\alpha + \alpha_{bare})\sum_i \gamma_i^2\left(\frac{M_p}{R_{uni}}\right)^2 \Rightarrow \rho_{coh}^{QFT}(t = t_0) \sim A \cdot 10^{-10}\left[\frac{J}{m^3}\right]$$

Dynamical: $\frac{d}{dt}\rho_{coh} \neq 0$

No fine–tuning: $\frac{\alpha_{bare}}{\alpha} \sim O(1)$

Similar form as in **CKN-bound**!

Decoherent modes are still there!

Cohen, Kaplan, & Nelson. Phys. Rev. Lett. **82**, 4971

SUMMARY & WHAT NOW

- THE UNIVERSE EXPANDS AND ACCELERATES $\Rightarrow$ THERE IS A Λ-TERM: WHAT IS IT?
- THE QG EFFECT IN OSCILLATIONS (ℓ_{sys}, R_{caus}): $\frac{\sigma_{\hat{\omega}}}{\overline{\omega}} \sim \frac{1}{\sqrt{\gamma_{sys}}}\left(\frac{R_{caus}}{\ell_{sys}}\frac{\overline{\omega}_{sys}}{\omega_p}\right)^{\frac{1}{2}}$
- GRAVITATION & NON-COHERENCE: $\frac{\rho^{QFT}[\omega>\omega_c]}{\rho^{QFT}[\omega<\omega_c]} \sim 10^{-120}$
- GRAVITY-RELEVANT QFT-VACUUM: $\rho^{QFT}_{coh} \sim \sum_i \gamma_i^2 \left(M_p H(t)\right)^2 \sim \rho_{obs}(t_0)$

Thanks for listening!
Any Questions?

Cosmic expansion might be driven by the **small subset of vacuum modes** that remain coherent in the sampling scale of the universe.

Show the model's consistency for the past/future evolution:
using the κ-GR deformed equations & comparing with data (DESI!)

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BACKUP SLIDE: WHY QUANTUM GRAVITY

The scale at which General Relativity and Quantum Mechanics become incompatible

General Relativity

Masses held by gravity with wavelength ℓ_{grav}

+

Quantum Mechanics

Masses with uncertainty of $\Delta X \Delta P \geq \hbar/2$

=

Quantum Gravity

Energy so dense that $\ell_{grav} \sim \Delta X \sim r_{sch} = \frac{2GM}{c^2}$

General Relativity

Mass/Energy forms a horizon when localized within $\ell \leq r_{sch}$

+

QFT

Probing ℓ requires photons with $\lambda \leq \ell$: with energy of $E_\lambda = \frac{\hbar c}{\ell}$

=

Quantum Gravity

For $\ell \leq \ell_p$, we get $E_\lambda \geq E_p$, but $r_{sch}\left[\frac{E}{c^2}\right] = 2\ell_p$!

$$\ell_p = \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-35}[m],\ \mathrm{M_p} = \frac{\mathrm{E_p}}{\mathrm{c^2}} = \frac{\hbar c}{\ell_p} \cdot \frac{1}{c^2} = \sqrt{\frac{\hbar c}{G}} \sim 10^{-8}[kg]\ ,\ \epsilon_p \equiv \rho_p c^2 \equiv \frac{M_p c^2}{\ell_p^3} \sim 10^{113}\left[\frac{J}{m^3}\right]$$

Mead, 1964

J. F. Donoghue (1994).