Dissipative effects of Planckian discreteness: *"the thermal bath of QG-defects"*

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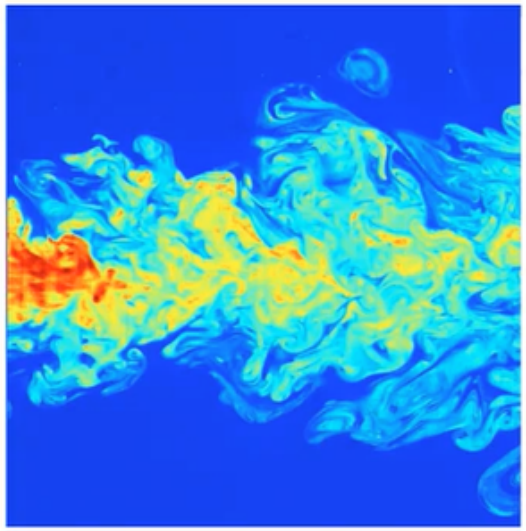
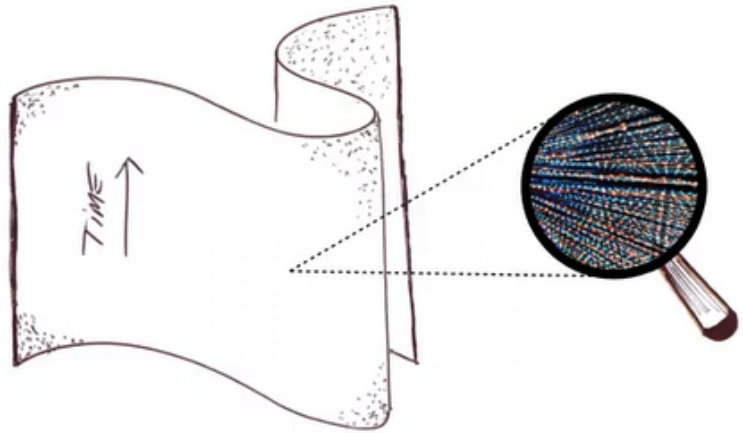
Diffusion from Planckian discreteness

Mathematical description of fluids
(Navier-Stokes)



Continuous fluid description breaks down at molecular scales.

Mathematical description of gravity
General Relativity



The continuum spacetime description breaks down at the Planck scale.

Effective violation of energy conservation!

Unimodular Gravity

UG is a mild modification of GR,[1] energy conservation not guaranteed $J_\mu \equiv \nabla^\nu T_{\mu\nu} \neq 0$

- UG (1919)

$$\boxed{R_{\mu\nu} - \frac{1}{4} g_{\mu\nu} R = T_{\mu\nu} - \frac{1}{4} g_{\mu\nu} T}$$

The equations of UG can be rearranged in an Einstein-like fashion:[2] a Λ_{eff} emerges

- UG+J$\neq$0 (2016)

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R + \underbrace{\left[\Lambda_0 + \int_\ell J\right]}_{\Lambda_{eff}} g_{\mu\nu} = T_{\mu\nu}$$

That's ***Unimodular Gravity with diffusion***: energy dissipation feeds a dynamical Λ_{eff}

- if no *diffusion mechanism* is at play it reduces to GR with a CC not put by hand
- new interpretation of *dark energy*: register of energy non-conservation in the past
- another nice feature: in UG vacuum fluctuations do not gravitate

[1] A. Einstein, "Do gravitational fields play an essential role in the structure of elementary particles?" (1919)
[2] T. Josset, A. Perez, D. Sudarsky "Dark Energy from Violation of Energy Conservation" (2016)

Unimodular Cosmology

In cosmology UG predicts a **time-dependent cosmological constant**:

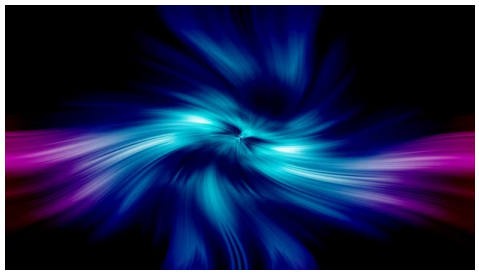
$$\boxed{\Lambda(\tau) \equiv \Lambda_{in} + \int_{\tau_{in}}^{\tau} J_0(t)dt}$$

UG gives two **cosmological equations** in 3 unknown functions $\rho(\tau), a(\tau), \Lambda(\tau)$

$$\boxed{\begin{cases} 3\left(\frac{a'}{a}\right)^2 = \rho + \Lambda(\tau) & \textit{unimodular Friedmann eq.} \\ \rho' + 3(1+\omega)\frac{a'}{a}\rho = \Lambda'(\tau) & \textit{unimodular continuity eq.} \end{cases}}$$

To obtain a specific model of **Unimodular Cosmology** we need info about *dissipation*

- **diffusion equation** $J_0 = ??$ (i.e. $\Lambda' = ??$)
- some phenomenological models have been proposed
- *CC problem*,[3] *H_0-tension*,[4] *inflation without inflaton* [5]



[3] A. Perez, D. Sudarsky, "Dark energy from quantum gravity discreteness" (2019)
[4] A. Perez, D. Sudarsky, E. Wilson-Ewing, "Resolving the H0 tension with diffusion" (2021)
[5] L. Amadei, A. Perez, "Planckian discreteness as seeds for cosmic structure" (2022)

Formalizing dissipation: *the thermal bath of quantum-gravity defects*

Hamiltonian formulation of unimodular cosmology

The effective CC is related to the total energy of the 'matter+geometry' system

- *Parameterization in volume-Hubble-rate variables:* $x \equiv a^3, \quad dt \equiv x d\tau$

  geometry $S_{geo} = V_0 \int 3a^4 \dot{a}^2 dt$

  matter $S_{mat} = -\frac{1}{2} V_0 \int a^6 \dot{\phi}^2 dt$

$$H = \underbrace{\left(\frac{1}{3} V_0 \dot{x}^2\right)}_{H_{geo}} - \underbrace{\left(\frac{1}{2} V_0 x^2 \dot{\phi}^2\right)}_{H_{mat}}$$

- *Proper definition of effective cosmological constant:*

  Friedmann eq. $H = E \iff 3\left(\frac{a'}{a}\right)^2 = \rho + \Lambda_{eff} \iff$

$$\boxed{\Lambda_{eff} \equiv \frac{E}{V_0}}$$

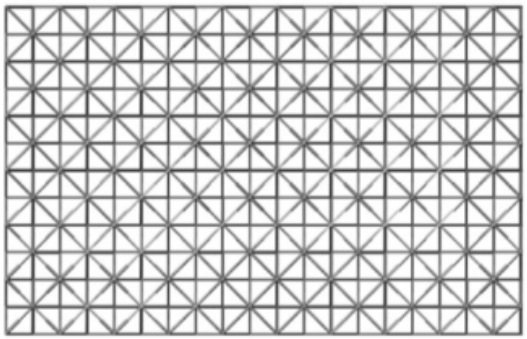
If we want a dynamical Λ_{eff} we need extra terms in the Hamiltonian

Hidden degrees of freedom: the QG-defects

We must postulate **hidden degrees of freedom**:

- *Tot Hamiltonian* $H_T = H_{geo} + H_{mat} + H_{hidden}$
- *Hidden Hamiltonian* $H_{hidden} = \underbrace{H_{hid}}_{\text{store energy}} + \underbrace{V_{mat\leftrightarrow hid}}_{\text{interaction}} + \underbrace{V_{geo\leftrightarrow hid}}_{\text{interaction}}$
- *Effective lambda* $\Lambda_{eff} \equiv \frac{1}{V_0}(E - H_{hidden})$

QG-defects: not the fundamental ones, just another type of emergent low-energy dofs



Fundamental Discreteness

Quantum Gravity Defects

Smooth Spacetime

"Collective deviations from perfect smoothness, capture only effectively underlying discreteness"

The formal recipe of diffusion

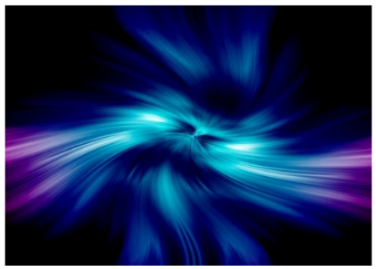
Theorem

Diffusion in UG requires a hidden Hamiltonian, but this can, at most, be of the form

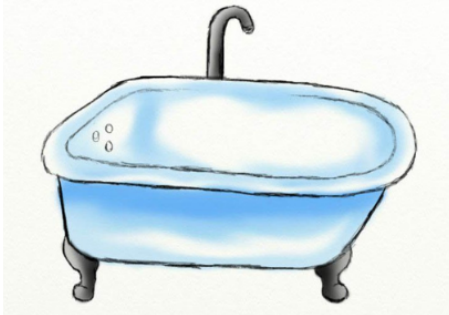
$$H_{hidden}(\cancel{x, \dot{x}}, \phi, \dot{\phi}, Q_\alpha, \dot{Q}_\alpha, t) = H_{hid}(Q_\alpha, \dot{Q}_\alpha) + \\ + V_{hid \leftrightarrow mat}(Q_\alpha, \dot{Q}_\alpha, \phi, \dot{\phi}, t) + \\ + \cancel{V_{hid \leftrightarrow geo}(Q_\alpha, \dot{Q}_\alpha, x, \dot{x}, t)}$$

To obtain a specific model of **Unimodular Cosmology** we need info about *dissipation*

specifying dissipation mechanism, J_0



modeling the bath, H_{hidden}

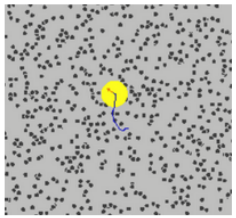


The toy model of ohmic diffusion

Ideal model used in complex systems to study Brownian motion and diffusion

- defects as a ***bath of harmonic oscillators*** for matter

$$H_{hidden} = \sum_{\alpha} \left(\frac{1}{2} \dot{Q}_{\alpha}^2 + \frac{1}{2} \omega_{\alpha}^2 Q_{\alpha}^2 \right) + \sum_{\alpha} b_{\alpha}(t) \ \phi \ Q_{\alpha}$$



- the EoM for ϕ is Langevin-like $\Rightarrow$ ***diffusion equation***

$$x^2 \ddot{\phi} + 2x\dot{x}\dot{\phi} - m_p \beta \dot{\phi} + M^2 \phi = \xi(t)$$

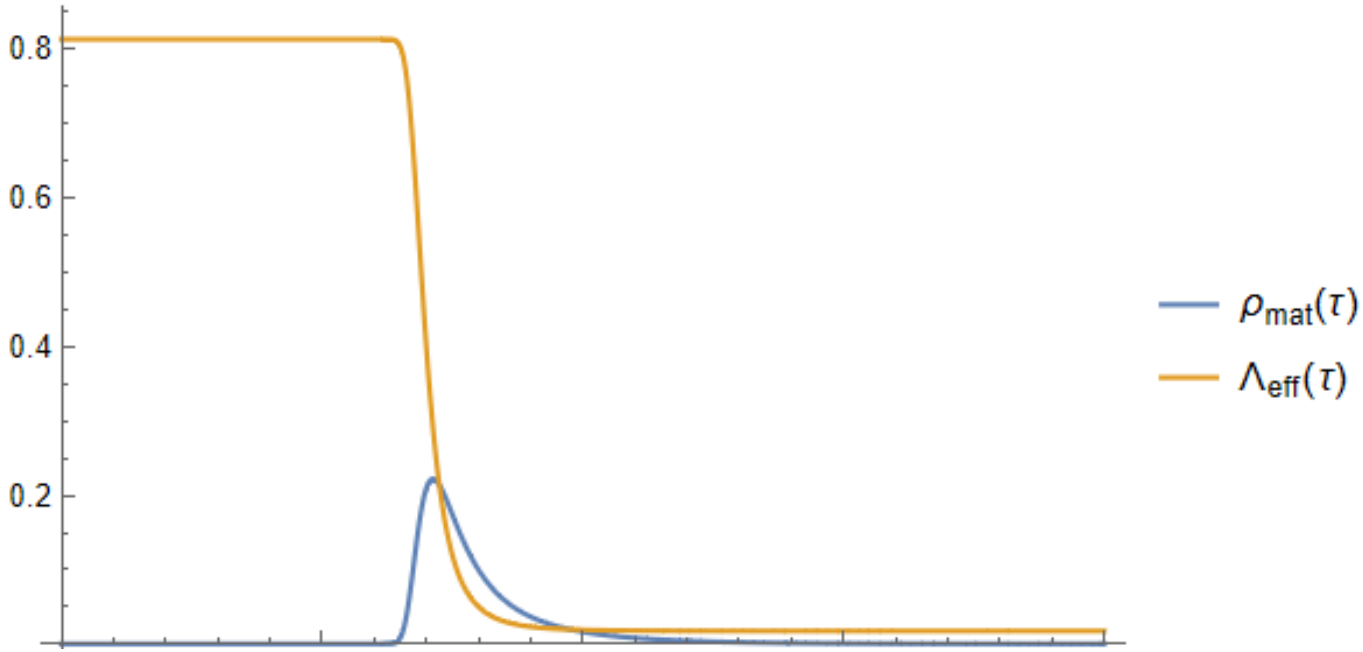
The ohmic model yields a ***well defined set of equations for unimodular cosmology***!

- *Diffusion equation* $\boxed{\Lambda'_{eff} = -\beta \ \rho / a^3}$
- *Diffusion parameter* $\beta \sim$ *friction strength*

'de Sitter de better': inflation and late-time acceleration

The solutions suggest a relaxation of the cosmological constant

- **Inflation with no inflaton**: Λ_{eff} pre-relaxation gives an inflationary era
- **Late-time acceleration**: the dynamics reduces to the standard one
- **No singularity?**: $a(\tau) \to 0$ in the past only asymptotically



Further study of solutions and general idea QG-defects in a work-in-progress paper [6]

[6] P. Pellecchia, A. Perez "Dissipative effects of Planckian discreteness: the thermal bath of the QG-defects" (expected July 2024)

Recap and conclusions

Three motivations of **Unimodular Gravity with diffusion**:

- ***New interpretation of dark energy*** register non-conservation in the past history
- ***New cosmology*** $\Lambda(t)$***-CDM*** potentially fixes issues of Λ-*CDM*
- ***New channels QG-phenomenology*** small local effects, important changing CC

$$\boxed{\textit{QG discreteness} \longrightarrow \textit{effective dissipation} \longrightarrow \textit{dynamical } \Lambda \longrightarrow (\Lambda_{obs}, j_0, H_0, ..)}$$

The thermal bath of the **Quantum-Gravity defects**:

- ***Formalism for dissipative UG*** total Hamiltonian $H_T = H_{geo} + H_{mat} + H_{defects}$
- ***Low energy limit*** $\boxed{\textit{QG dof} \longrightarrow \textit{GEO dof} + \textit{MAT dof} + \textit{DEF dof}}$
- ***Ohmic toy model*** explains the general idea, work in progress ;)

Thanks for your attention