Space-time discreteness in quantum gravity: possible consequences and a new perspective on the origin of dark energy

on work in collaboration with D. Sudarsky and T. Josset

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The Plan

- **Motivations for discreteness of geometry at Planck scale.**

  - From Black Hole Thermodynamics.
  - From formal approaches to quantum gravity (e.g. LQG).
  - Implications for the information puzzle in BH evaporation.
  - Violations of energy-momentum for low energy degrees of freedom.

- **Gravitation without energy-momentum conservation.**

  - Unimodular gravity; a metric theory of gravity that can cope with violations of energy momentum conservations.
  - Tiny violations of energy-momentum conservation can have important effects in cosmology (two examples).

- **Energy-momentum dissipation from quantum gravity discreteness.**

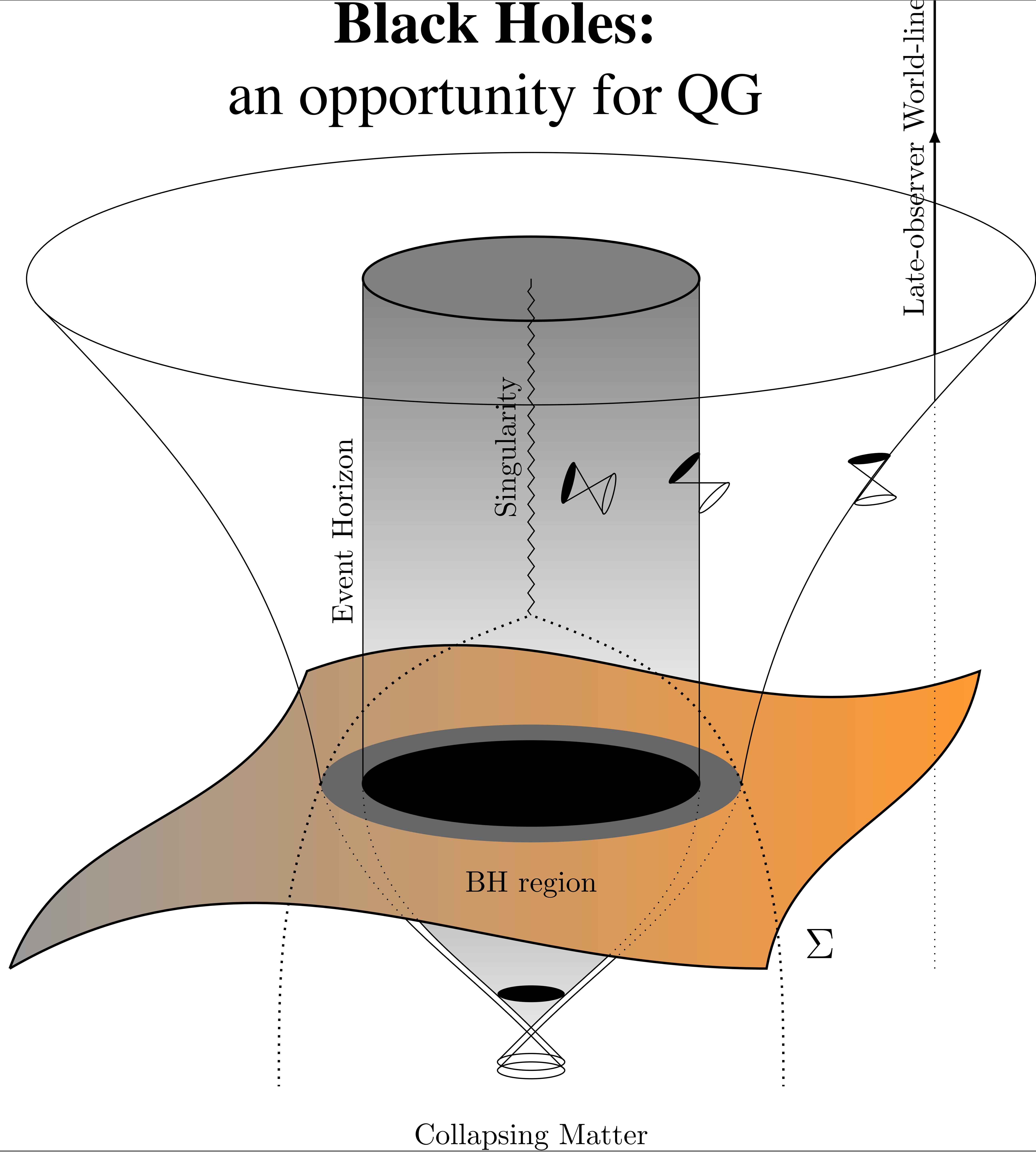
  - Discreteness vs Lorentz invariance: an hypothesis.
  - A phenomenological proposal.
  - Implications for the dark energy problem.

PART 1:

A biased review on Loop Quantum Gravity.

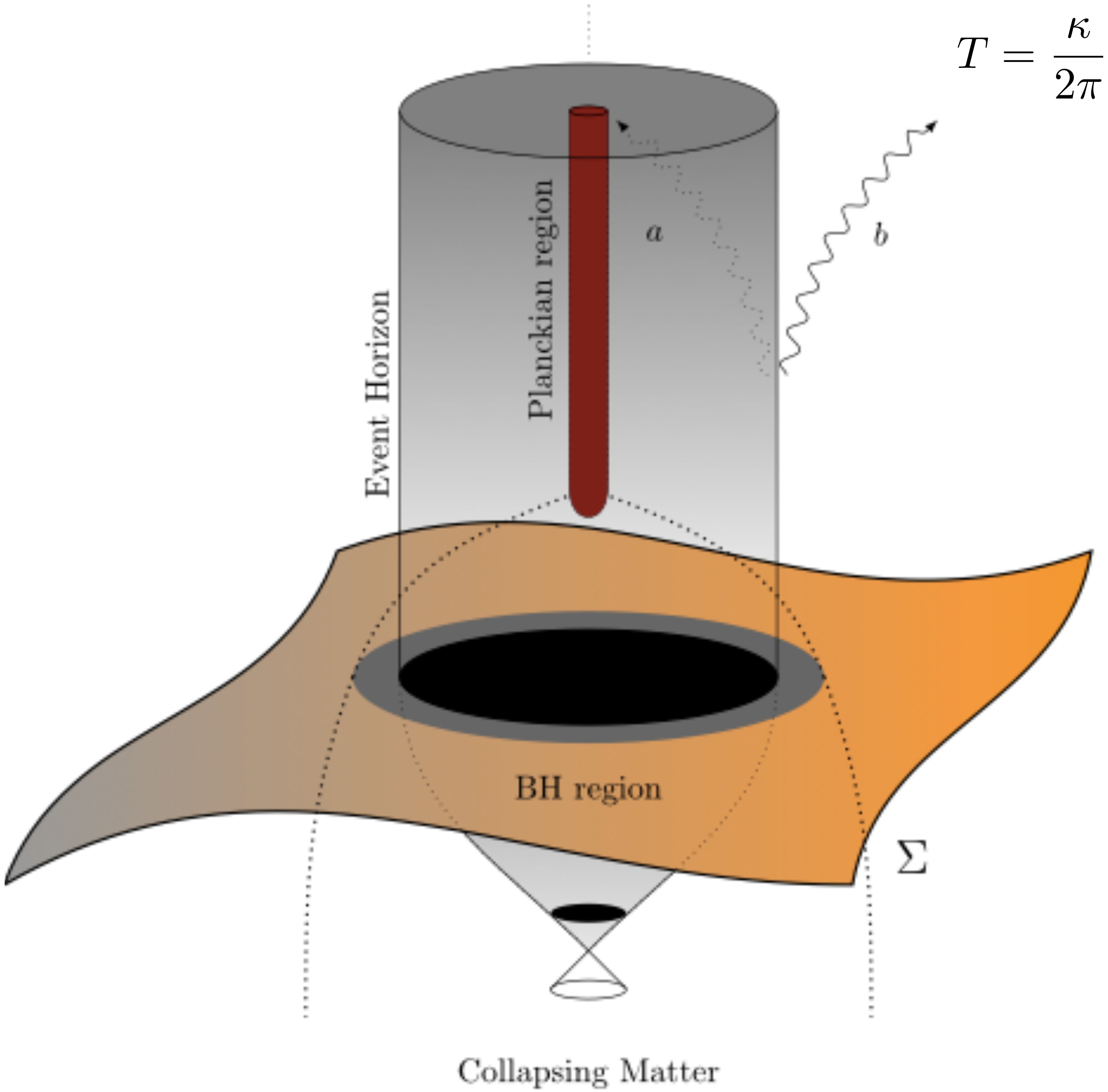
Black Holes:

an opportunity for QG



Black Holes:

Their thermal properties suggest micro-structure



$$\delta E = \underbrace{T\delta S}\, - P\delta V$$

Heat: Energy in molecular chaos

$$\delta M = \underbrace{\frac{\kappa}{8\pi}\delta a}_{heat?} + \Omega\delta J + \Phi\delta Q$$

$$S_{BH} = \frac{a}{4}$$

Discreteness in Loop Quantum Gravity.

Pure gravity in connection variables

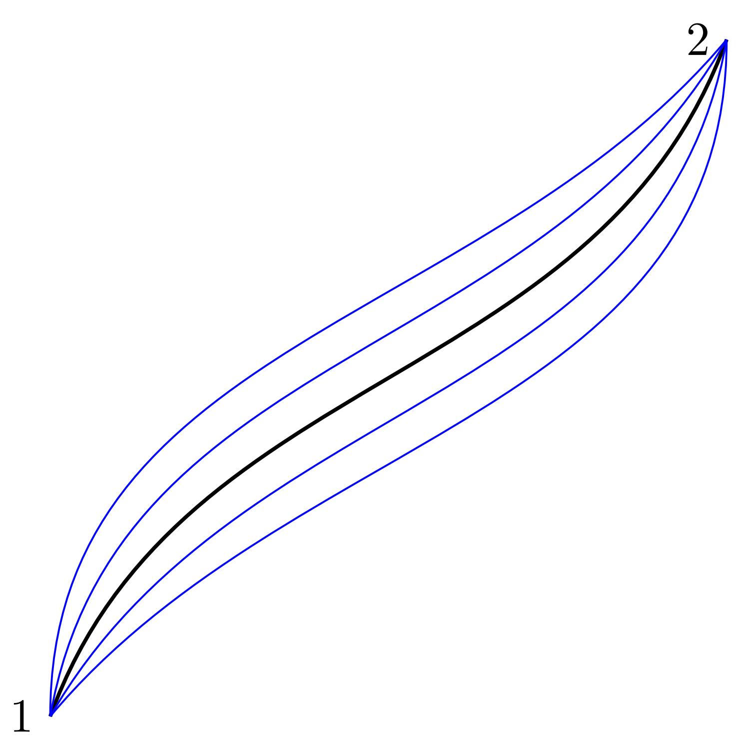
$$S[e_a^A,\omega_a^{AB}] \;=\; \frac{1}{2\kappa}\int \overbrace{\epsilon_{IJKL}e^I\wedge e^J\wedge F^{KL}(\omega)}^{\text{Einstein}} + \overbrace{\Lambda\,\epsilon_{IJKL}e^I\wedge e^J\wedge e^K\wedge e^L}^{\text{Cosmological Constant}} + \overbrace{\alpha_1\; e_I\wedge e_J\wedge F^{IJ}(\omega)}^{\text{Holst}}$$

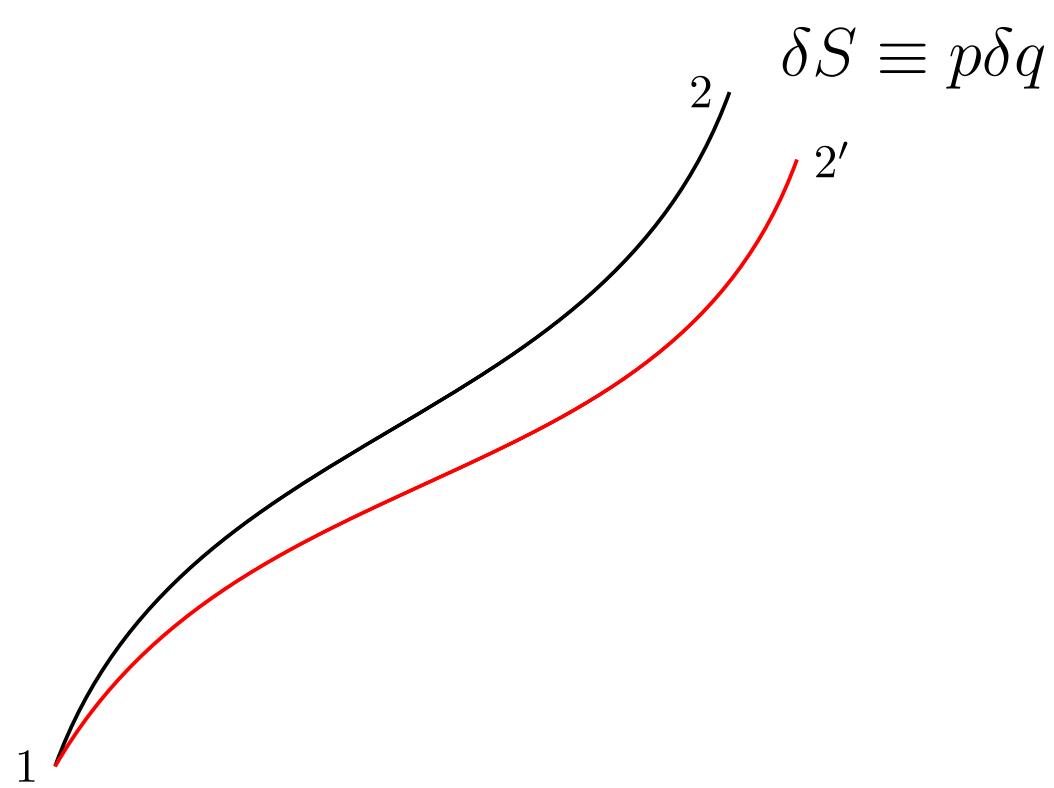
$$+\;\underbrace{\alpha_2\;(d_\omega e^I\wedge d_\omega e_I \;-\; e_I\wedge e_J\wedge F^{IJ}(\omega))}_{\text{Nieh}-\text{Yan}} + \underbrace{\alpha_3\;F(\omega)_{IJ}\wedge F^{IJ}(\omega)}_{\text{Pontrjagin}} + \underbrace{\alpha_4\;\epsilon_{IJKL}F(\omega)^{IJ}\wedge F^{KL}(\omega)}_{\text{Euler}}$$

Simpler choice

$$S=\frac{1}{2\kappa}\int\left(\epsilon_{IJKL}+\frac{1}{\gamma}\eta_{IK}\eta_{JL}\right)\left(e^I\wedge e^J\wedge F^{KL}(\omega)\right)$$

Phase space structure in a nut-shell





$$\delta S = \int_1^2 \underbrace{\left[\frac{\partial L}{\partial q}-\frac{d}{dt}\left(\frac{\partial L}{\partial \dot q}\right)\right]}_{\text{e.o.m.}}\delta q dt + \underbrace{\frac{\partial L}{\partial \dot q}\delta q\Big|_1^2}_{p\delta q}$$

Phase space structure

$$S = \frac{1}{2\kappa} \int (\epsilon_{IJKL} + \frac{1}{\gamma}\eta_{IK}\eta_{JL}) \left(e^I \wedge e^J \wedge F^{KL}(\omega)\right)$$

$$p_{IJKL} \equiv (\epsilon_{IJKL} + \frac{1}{\gamma}\eta_{IK}\eta_{JL})$$

$$\delta S = \frac{1}{2\kappa} \int_M 2p_{IJKL}\delta e^I \wedge e^J \wedge F^{KL}(\omega) + p_{IJKL}e^I \wedge e^J \wedge d_\omega(\delta\omega^{KL})$$

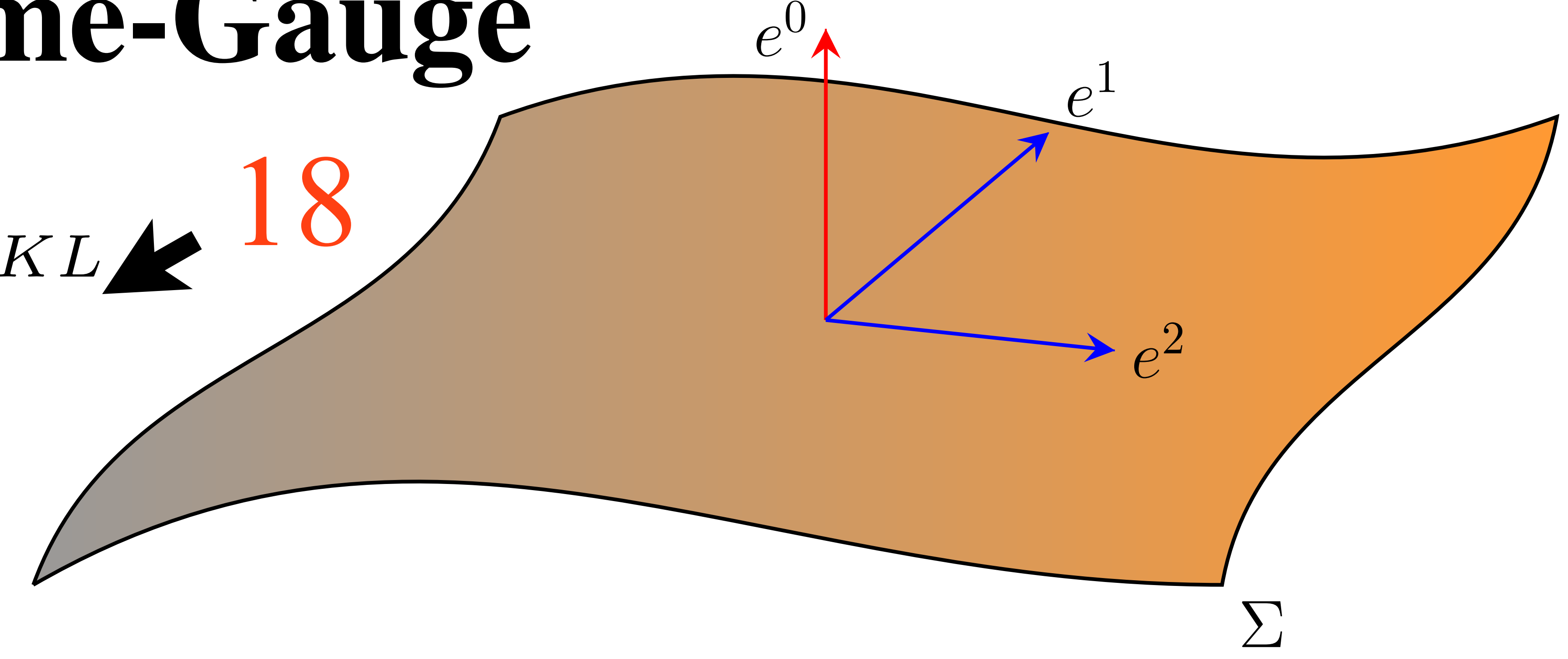
$$= \frac{1}{2\kappa} \int_M 2p_{IJKL}\delta e^I \wedge e^J \wedge F^{KL}(\omega) - p_{IJKL}d_\omega(e^I \wedge e^J) \wedge \delta\omega^{KL} + d([p_{IJKL}e^I \wedge e^J] \wedge \delta\omega^{KL})$$

$$= \frac{1}{2\kappa} \int_M \underbrace{2p_{IJKL}\delta e^I \wedge e^J \wedge F^{KL}(\omega) - p_{IJKL}d_\omega(e^I \wedge e^J) \wedge \delta\omega^{KL}}_{\text{e.o.m.}} + \int_{\partial M} \underbrace{\frac{1}{2\kappa}[p_{IJKL}e^I \wedge e^J] \wedge \delta\omega^{KL}}_{p\delta q}$$

Symplectic Potential

$$\Theta(\delta) = \int_\Sigma \frac{1}{2\kappa}[p_{IJKL}e^I \wedge e^J] \wedge \delta\omega^{KL}$$

Symplectic Potential in the Time-Gauge



$$\Theta(\delta) = \int_\Sigma \frac{1}{2\kappa}[p_{IJKL}e^I \wedge e^J] \wedge \delta\omega^{KL}$$

18

12

$$\begin{aligned}\Theta(\delta) &= \frac{1}{\kappa}\int_\Sigma \left(\epsilon_{0jkl}e^0 \wedge e^j \wedge \delta\omega^{kl} + \frac{1}{\gamma}e^0 \wedge e^i \wedge \delta\omega_{0i}\right) - \frac{1}{\kappa}\int_\Sigma \left(\epsilon_{0jkl}e^j \wedge e^k \wedge \delta\omega^{l0} + \frac{1}{\gamma}e^i \wedge e^j \wedge \delta\omega_{ij}\right) \\ &= -\frac{1}{\gamma\kappa}\int_\Sigma [\epsilon_{jkl}e^j \wedge e^k] \wedge \delta\underbrace{\left(\gamma\omega^{l0} + \epsilon^{lmn}\omega_{mn}\right)}_{\text{Ashtekar-Barbero connection}} \\ &= -\frac{1}{\gamma\kappa}\int_\Sigma [\epsilon_{jkl}e^j \wedge e^k] \wedge \delta A^l,\end{aligned}$$

Poisson Brackets

$$E^i = \epsilon^i_{jk} e^j \wedge e^k$$

$$\begin{aligned}&\{E^i(x), E^j(y)\} = 0 \\ &\{A^i(x), A^j(y)\} = 0 \\ &\{E^i(x), A^j(y),\} = \kappa\gamma\, \boldsymbol{\epsilon}^{(3)}\delta^{ij}\delta^{(3)}(x,y)\end{aligned}$$

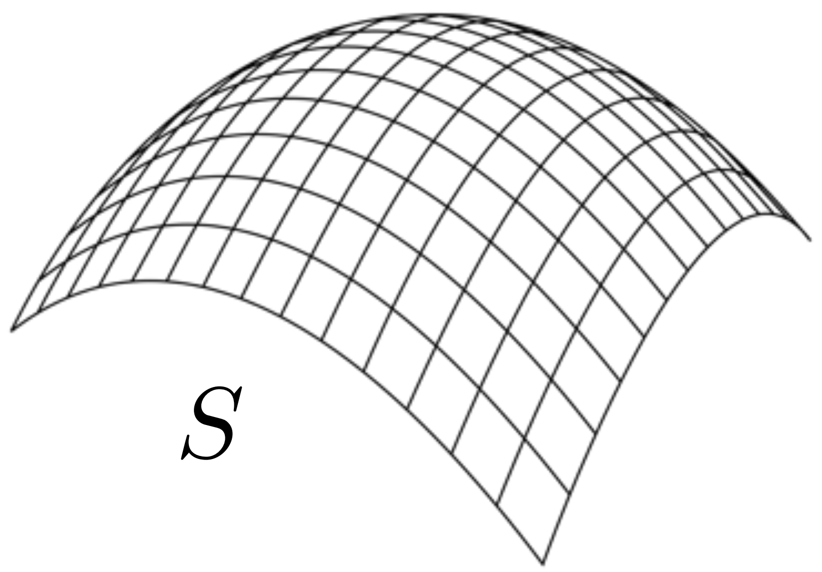
Constraints (EEs)

$$G^i(E,A) = d_A E^i = 0,$$

$$V_d(E,A) = \epsilon^{abc}E_{ab}\cdot F_{cd} = 0$$

$$S(E,A) = \frac{(E_{ab}\times E_{de})}{\sqrt{\det(E)}}\cdot F_{cf}\ \epsilon^{abc}\epsilon^{def} + \cdots = 0$$

Discreteness in a nut-shell

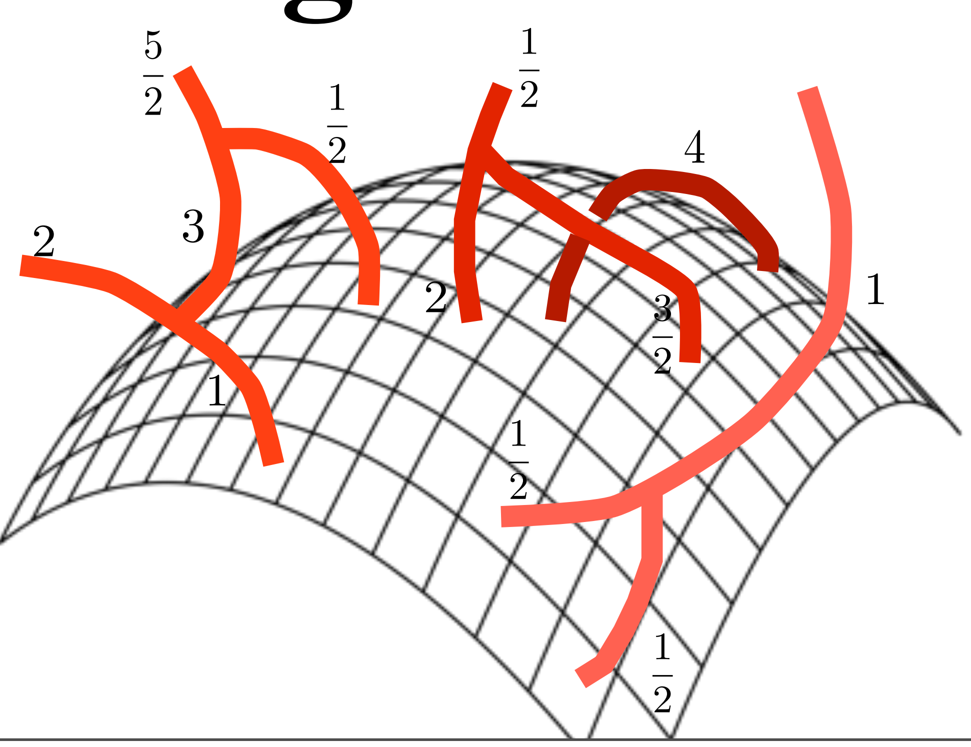


$$E(S,\alpha) \equiv \int_S \alpha_i E^i$$

$$\begin{aligned} E(S,\alpha) &= \int_{\mathrm{int}[S]} d(\alpha_i E^i) = \int_{\mathrm{int}[S]} (d_A \alpha_i) E^i + \alpha_i (d_A E^i) \\ &\approx \int_{\mathrm{int}[S]} (d_A \alpha_i) \wedge E^i, \end{aligned}$$

$$\begin{aligned} \{E(S,\alpha), E(S,\beta)\} &\approx \int\int dx^3 dy^3 \left\{ d\alpha_i \wedge E^i + \epsilon_{ijk} A^j \wedge \alpha^k \wedge E^i, d\beta_l \wedge E^l + \epsilon_{lmn} A^m \wedge \beta^n \wedge E^l \right\} \\ &\approx \int\int dx^3 dy^3 \left\{ d\alpha_i \wedge E^i, \epsilon_{lmn} A^m \wedge \beta^n \wedge E^l \right\} + \left\{ \epsilon_{ijk} A^j \wedge \alpha^k \wedge E^i, d\beta_l \wedge E^l \right\} + \left\{ \epsilon_{ijk} A^j \wedge \alpha^k \wedge E^i, \epsilon_{lmn} A^m \wedge \beta^n \wedge E^l \right\} \\ &\approx \kappa\gamma \int dx^3 \epsilon_{ijk} d\alpha^i \wedge \beta^j \wedge E^k + \epsilon_{ijk} \alpha^i \wedge d\beta^j \wedge E^k + \cdots \\ &\approx \kappa\gamma \int dx^3 d_A([\alpha,\beta])_k \wedge E^k \\ &\approx \kappa\gamma E[[\alpha,\beta],S], \end{aligned}$$

Angular Momentum Commutations = Angular Momentum Discreteness

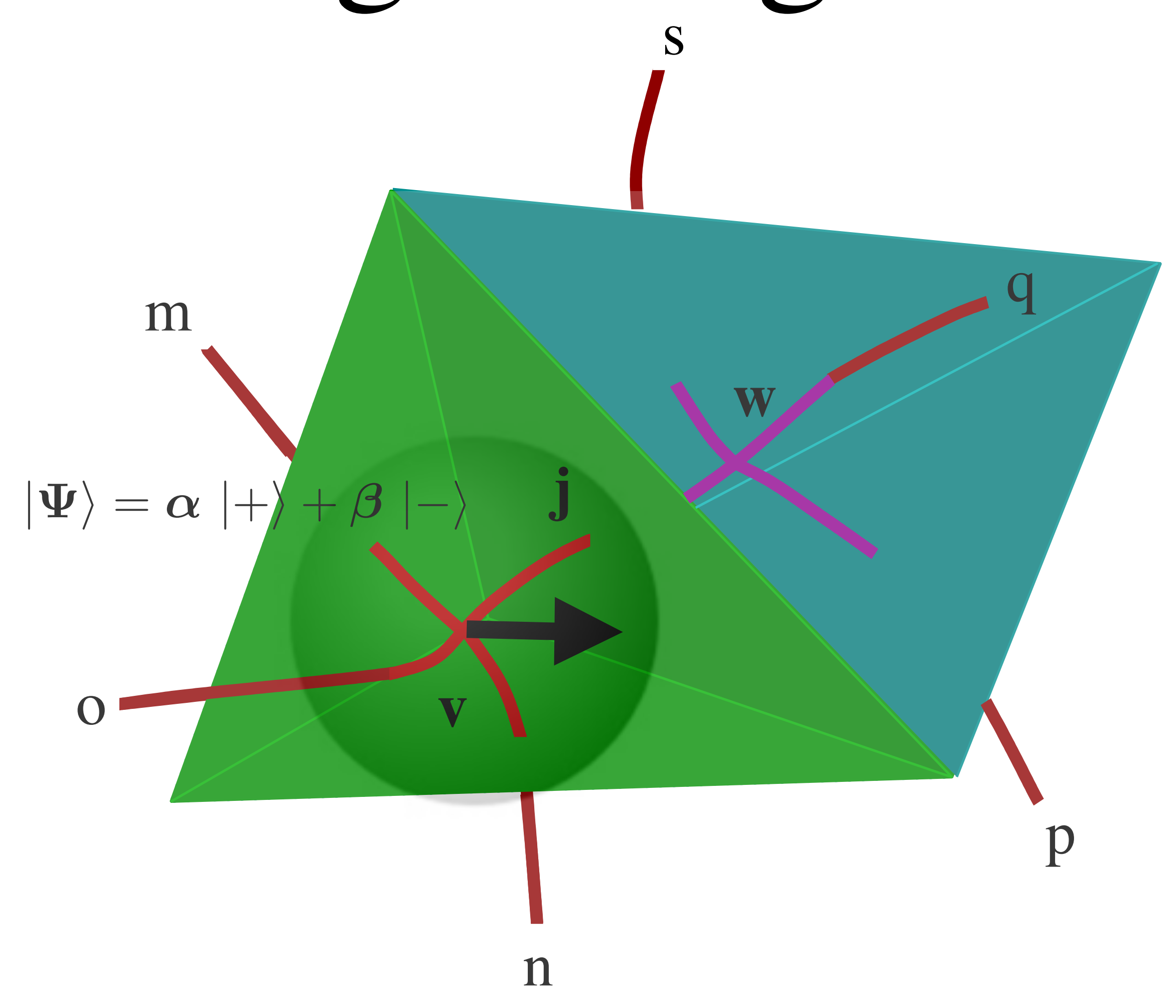


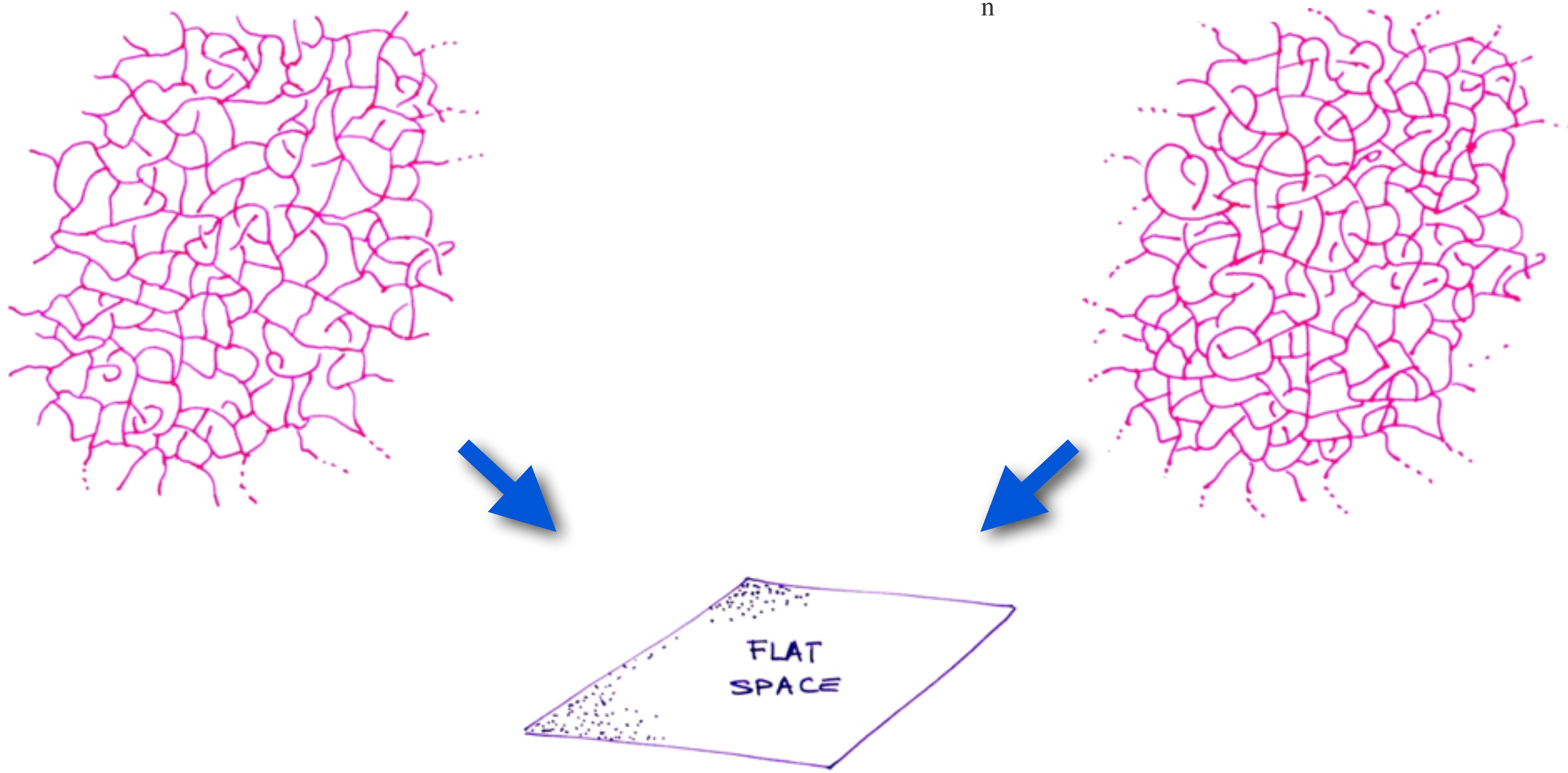
$$\{E(S,\alpha), E(S,\beta)\} \approx \kappa\gamma E[[\alpha,\beta],S]$$

$$\text{area quantum} = \gamma \ell_p^2 \sqrt{j(j+1)}$$

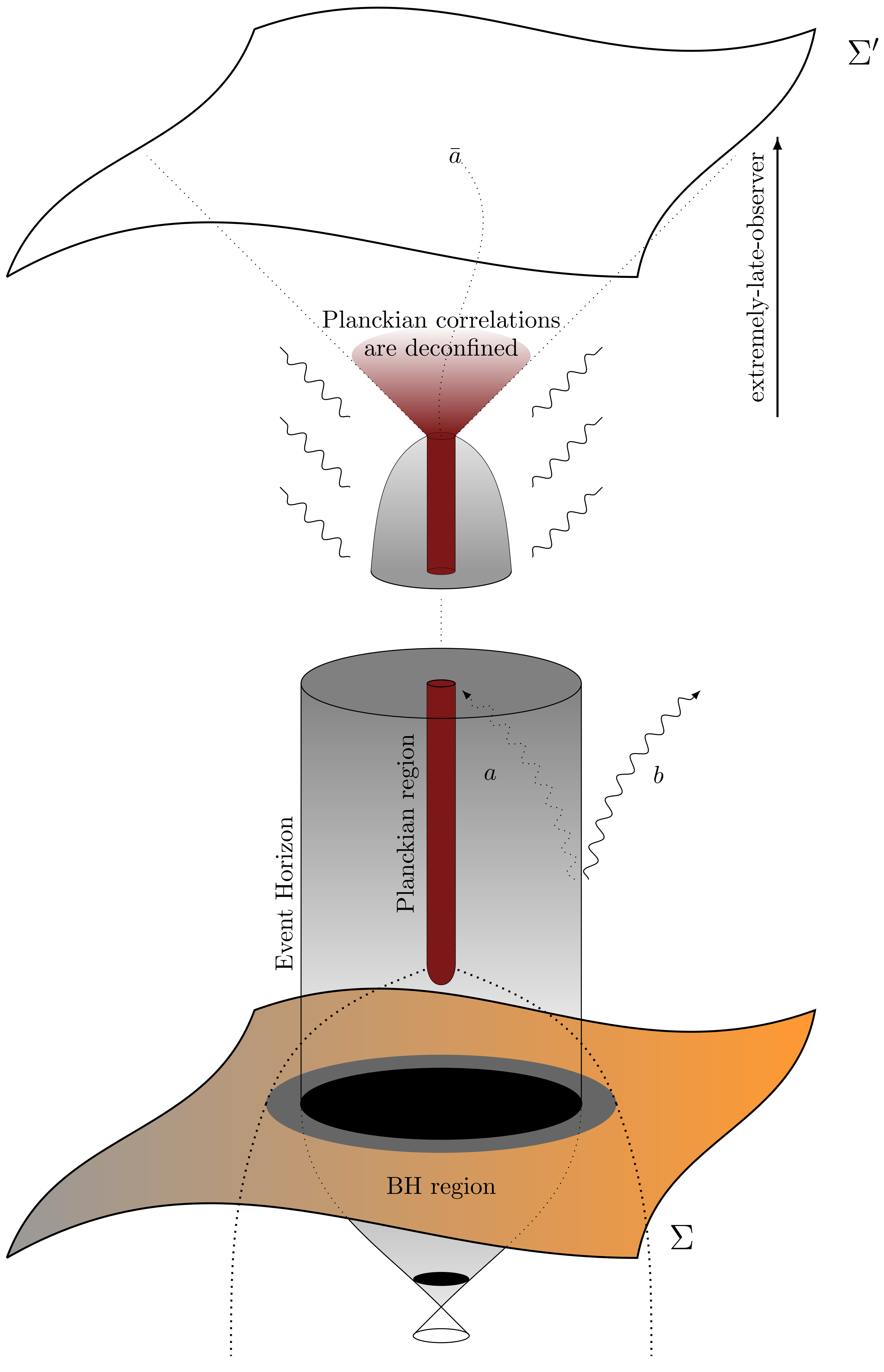
Smooth geometry is emergent: coarse graining of a spin-like system

Spin-network states:
atoms of geometry

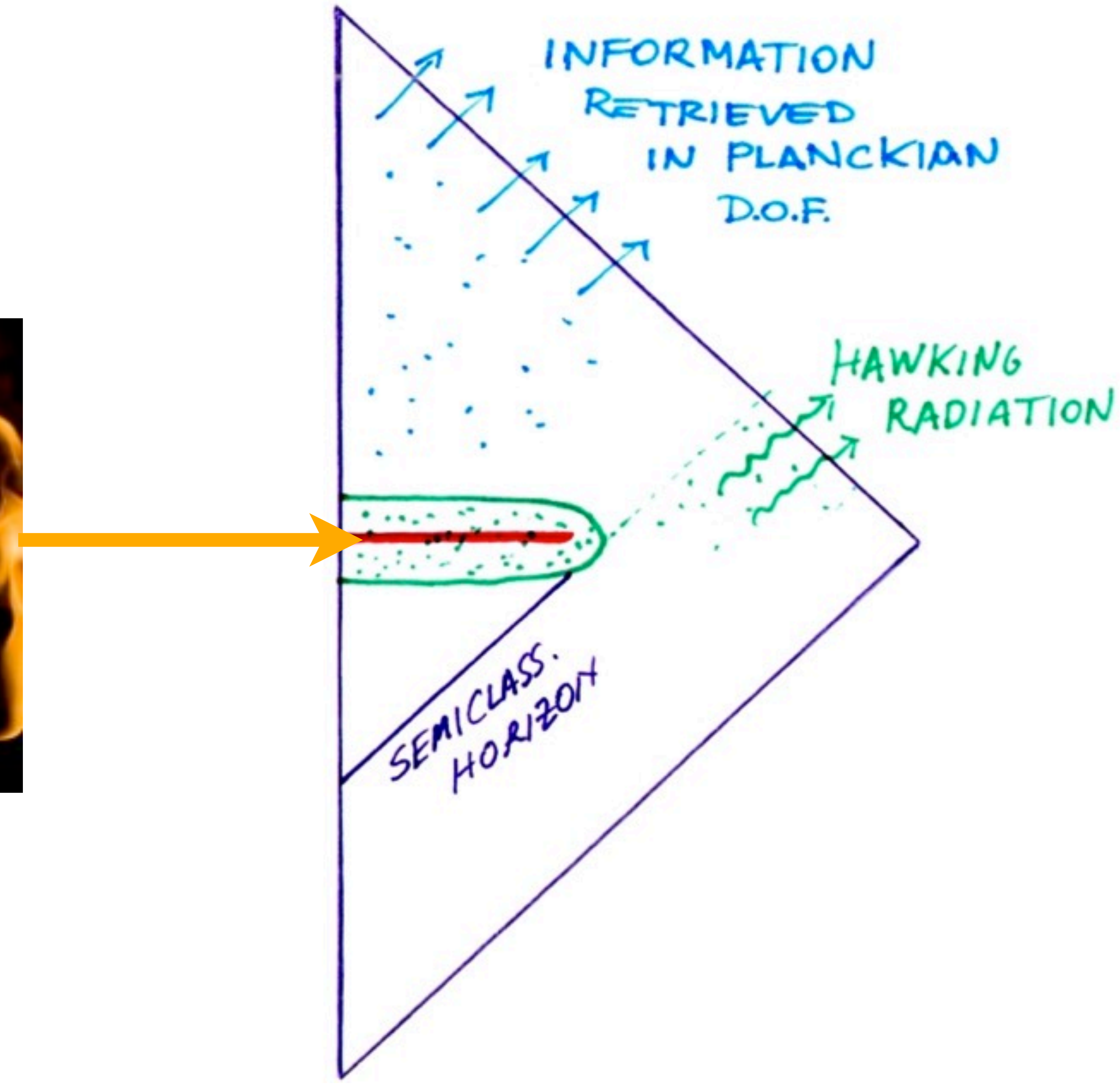




New perspective on the information paradox



AP, *Class. Quant. Grav.* 32, 2015.

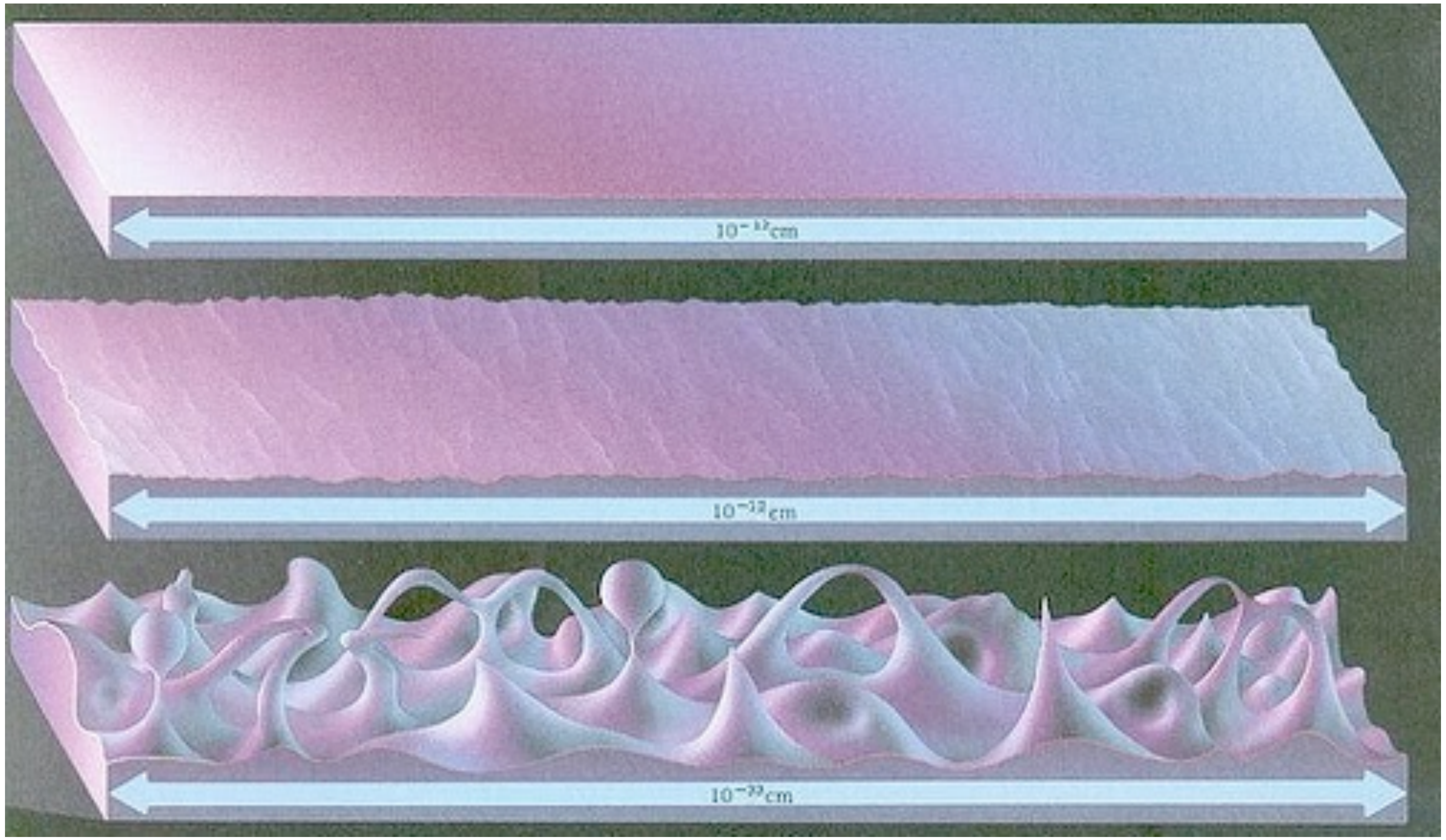


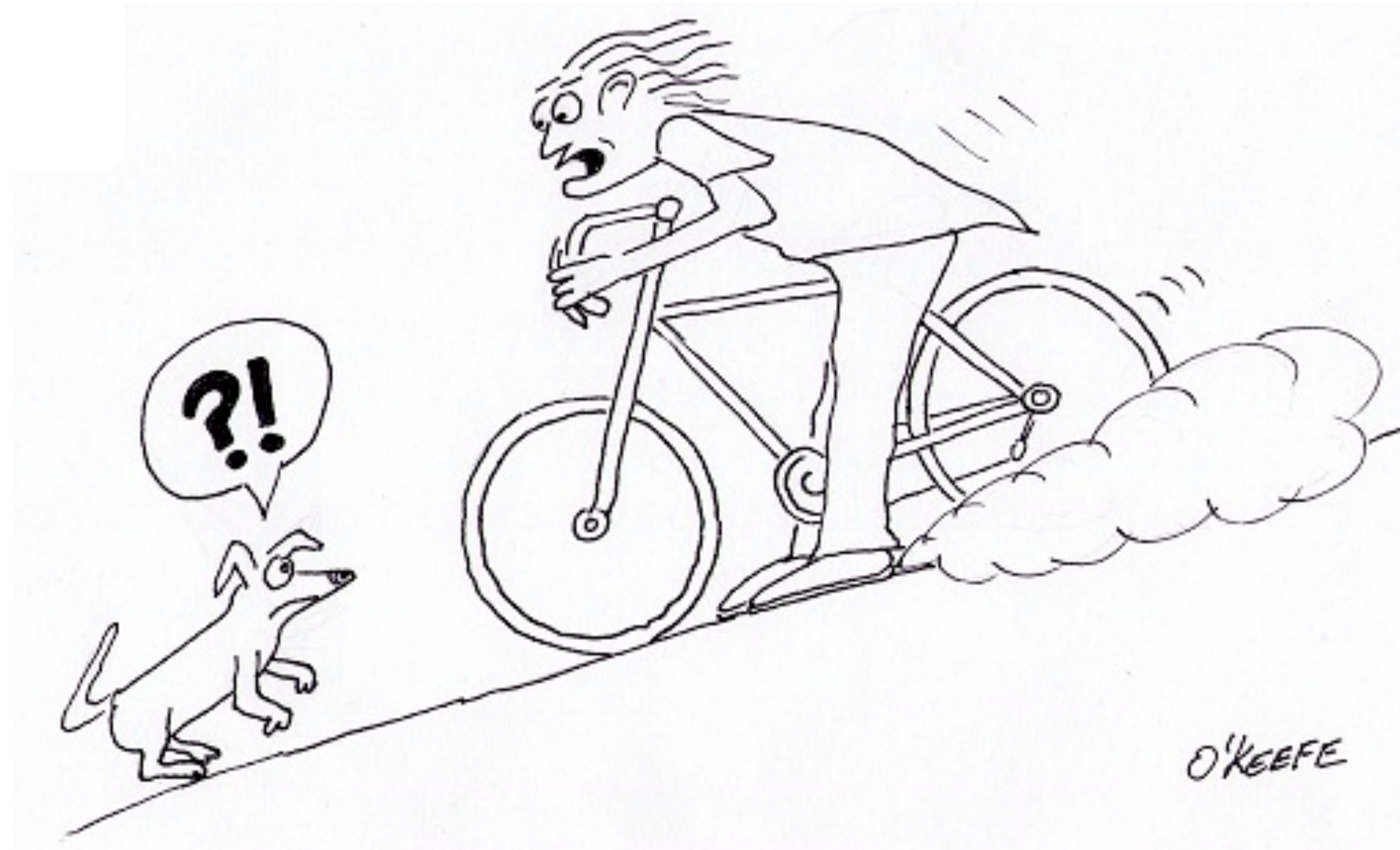
Decoherence with discrete micro-structure imply **violations** of **energy conservation** in the **smooth effective description**!

Banks, Peskin, Susskind (1984) - Unruh, Wald (1995)

Violations of energy conservation in the effective smooth semiclassical description are to be expected

$$\nabla^b \langle T_{ab} \rangle \neq 0$$





← **Local Poincare invariance is lost at the Planck scale**

PART 2:

A phenomenological perspective on

Dark Energy.

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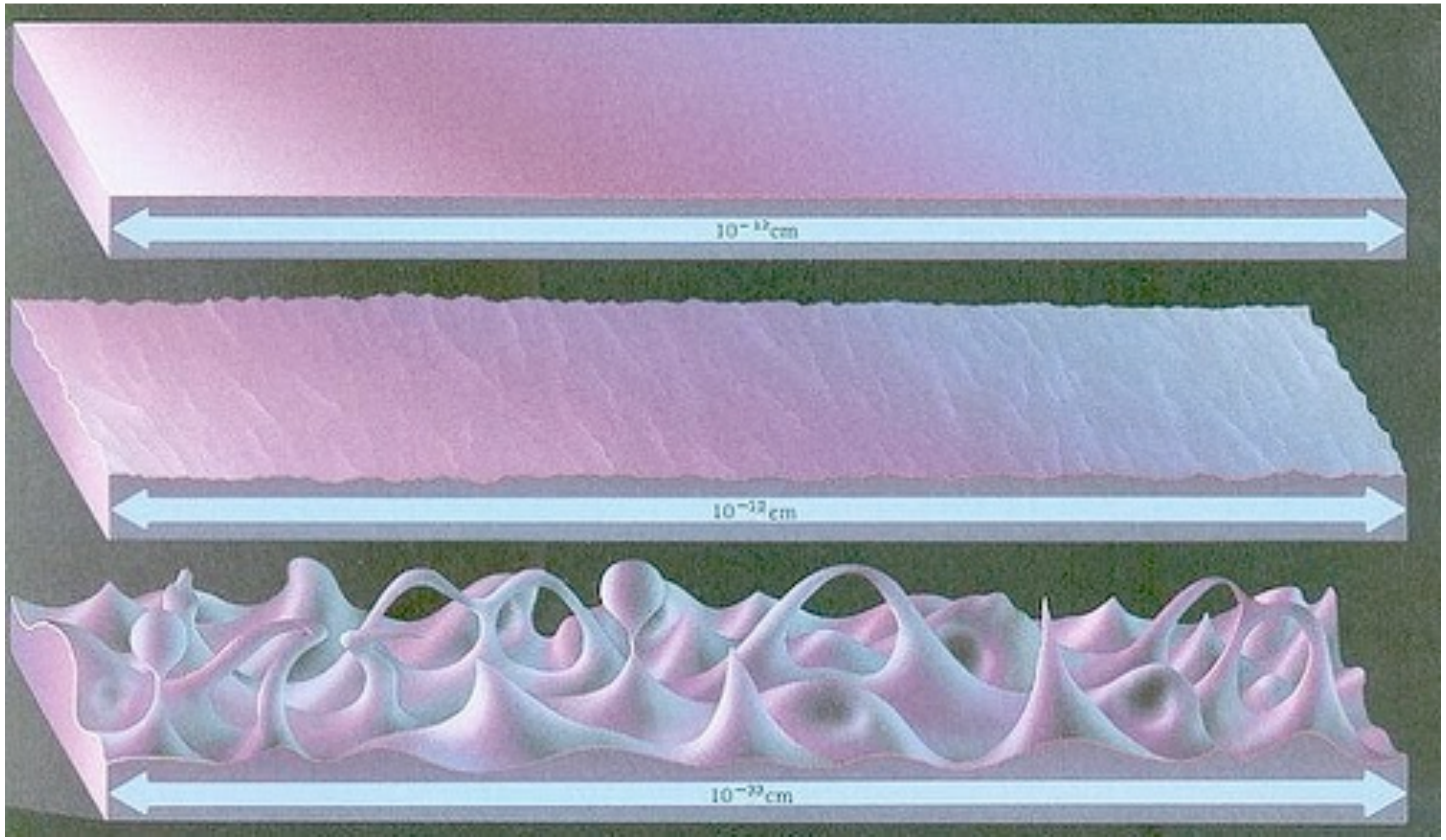
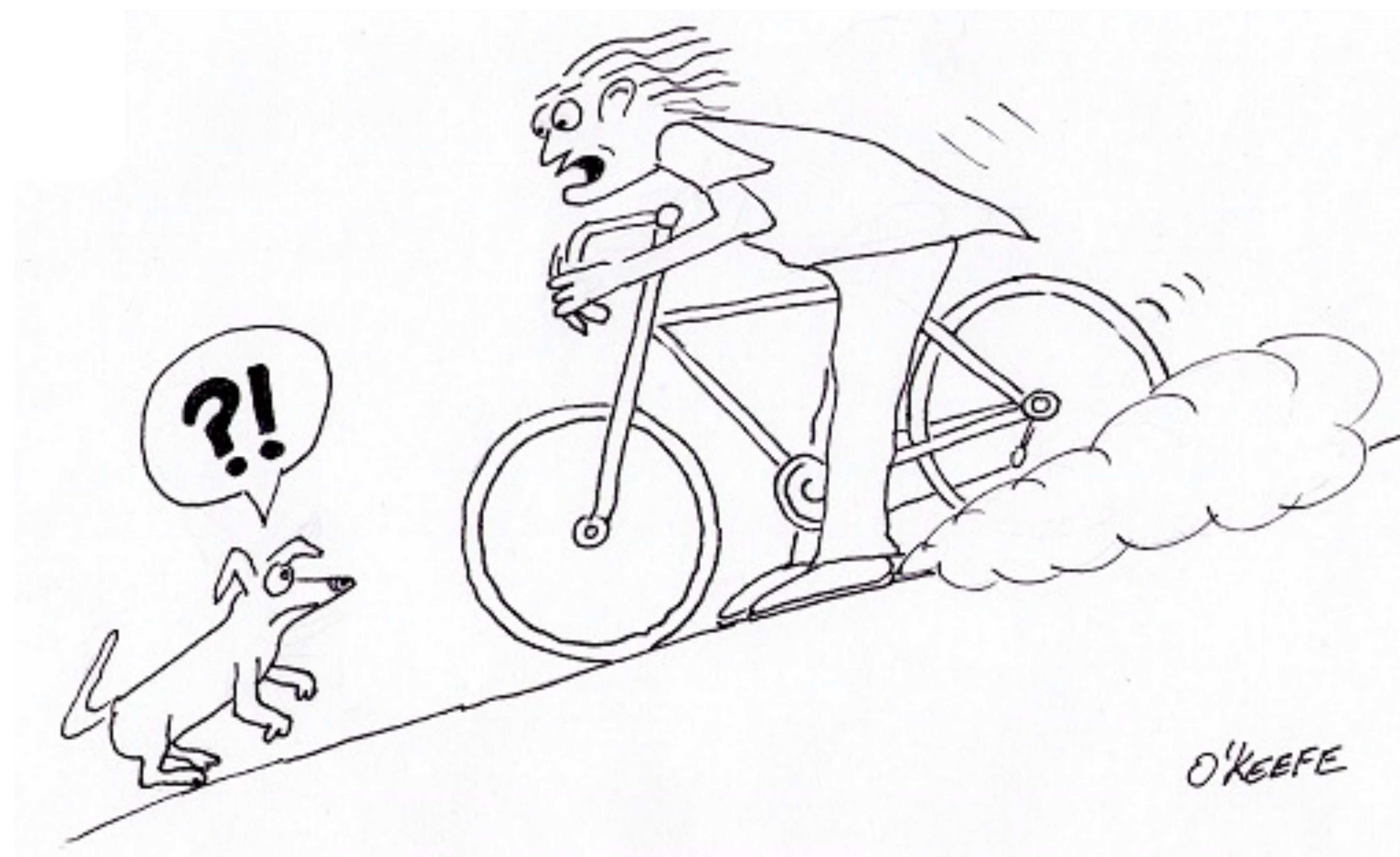
$$\nabla^b \langle T_{ab} \rangle \neq 0$$





Local Poincare invariance is lost at the Planck scale

BUT energy-momentum is conserved in general relativity

$$R_{ab} - \frac{1}{2} R g_{ab} = \frac{8\pi G}{c^4} \langle T_{ab} \rangle$$

$$\nabla^b \langle T_{ab} \rangle = 0$$

As a consequence of Bianchi identities

BUT energy-momentum is conserved in general relativity

$$R_{ab} - \frac{1}{2} R g_{ab} = \frac{8\pi G}{c^4} \langle T_{ab} \rangle$$

$$\Downarrow$$

$$\nabla^b \langle T_{ab} \rangle = 0$$

As a consequence of **diffeomorphism invariance** (general covariance)

Energy conservation from diff-invariance

$$S[g_{ab},\phi] = \overbrace{S_{grav}[g_{ab}]}^{Gravity\ Action} + \underbrace{S_M[g_{ab},\phi]}_{Matter\ Action}$$

$$T_{ab} \equiv -\frac{1}{8\pi\sqrt{-g}}\frac{\delta S_M}{\delta g^{ab}}$$

Proof:

$$\delta_\xi S[g_{ab},\phi] = 0 \iff \delta_\xi S_M[g_{ab},\phi] = 0$$

$$\begin{aligned} 0 &= \delta_\xi S_M[g_{ab},\phi] = \int_M \frac{\delta S_M}{\delta g_{ab}}\delta_\xi g_{ab} + \overbrace{\int_M \frac{\delta S_M}{\delta\phi}\delta_\xi\phi}^{Zero\ on\ shell} \\ &= -16\pi\int_M \sqrt{-g}\ T^{ab}\,\nabla_a\xi_b \\ &= 16\pi\int_M \sqrt{-g}\ \left(\nabla_a T^{ab}\right)\xi_b \end{aligned}$$

$$\delta_\xi g_{ab} = \mathscr{L}_\xi g_{ab} = 2\nabla_{(a}\xi_{b)}$$

Some violations allowed in Unimodular gravity

$$S = \int \sqrt{|g|} R$$

$$g_{ab} \delta g^{ab} = 0$$

$$\Rightarrow \quad R_{ab} - \frac{1}{4} R g_{ab} = \frac{8\pi G}{c^4} \left(T_{ab} - \frac{1}{4} T g_{ab} \right)$$

Vacuum fluctuations do not gravitate. S. Weinberg 1989

Symmetry reduced down to **volume-preserving-diffeos**

$$J_a \equiv (8\pi G / c^4) \nabla^b T_{ba} \quad \Rightarrow \quad dJ = 0$$

Also from Bianchi identities and the UG field equations

$$\nabla_a \left(R + \frac{8\pi G}{c^4} T \right) = \frac{32\pi G}{c^4} \nabla^b T_{ba}$$

$$R_{ab} - \frac{1}{2} R g_{ab} + \underbrace{\left[\Lambda_0 + \int_\ell J \right]}_{\text{Dark energy term}} g_{ab} = 8\pi G T_{ab}$$

AP, D. Sudarsky, *Phys.Rev. Lett*. 118 (2017).

Unimodular Gravity:
an effective low energy description where diffeomorphism invariance can be mildly broken

$$S = \int \sqrt{|g|}R$$

$$g_{ab}\delta g^{ab} = 0$$

General covariance can be broken down to 4-volume preserving diffeomorphism

$$\nabla_a \xi^a = 0$$

$$\xi^a = \epsilon^{abcd}\nabla_b \omega_{cd}$$

$$\delta S_m = \int T_{ab}\nabla^a \xi^b \sqrt{-g} dx^4 = \int J_a \xi^a \sqrt{-g} dx^4 = 0$$

$$J_a \equiv \nabla^b T_{ba}$$

⇩

$$dJ = 0 \qquad J_a = \nabla_a Q$$

Breaking diffeomorphism invariance down to **volume preserving diffeomorphism:** standard in QFT on curved spacetimes

Hadamard regularization

$$\nabla^a \langle T_{ab} \rangle_{\rm NO} = \nabla_b Q$$

GR compatible stress tensor satisfying Wald axioms

$$\langle T_{ab} \rangle_{\rm GR} \equiv \langle T_{ab} \rangle_{\rm NO} - Q g_{ab}$$

trace anomaly for CFT's!

Unimodular gravity compatible stress tensor

$$\langle T_{ab} \rangle_{\rm Unimed} \equiv \langle T_{ab} \rangle_{\rm NO}$$

NO trace anomaly! Diffeos broken down to volume preserving ones

Discreteness and Lorentz invariance

Quantum spacetime cannot be interpreted in analogy with a lattice choosing a preferred rest frame. Lorentz violation at the Planck scale is not suppressed by the Planck scale. It percolates via radiative corrections to large violations at low energies.

Collins, AP, Sudarsky, Urrutia, Vusetich;
Phys. Rev. Letters. 93 (2004).

Radiative corrections make Lorentz violation percolate to low energies

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{m_0^2}{2}\phi^2 + \bar{\psi}(i\gamma^\mu\partial_\mu - M_0)\psi + g_0\phi\bar{\psi}\psi.$$

$$\frac{i}{\gamma^\mu p_\mu - m_0 + i\epsilon} \to \frac{if(|\mathbf{p}|/\Lambda)}{\gamma^\mu p_\mu - m_0 + \Delta(|\mathbf{p}|/\lambda) + i\epsilon},$$
$$\frac{i}{p^2 - M_0^2 + i\epsilon} \to \frac{i\tilde{f}(|\mathbf{p}|/\Lambda)}{p^2 - M_0^2 + \tilde{\Delta}(|\mathbf{p}|/\lambda) + i\epsilon}.$$

Collins, AP, Sudarsky, Urrutia, Vusetich;
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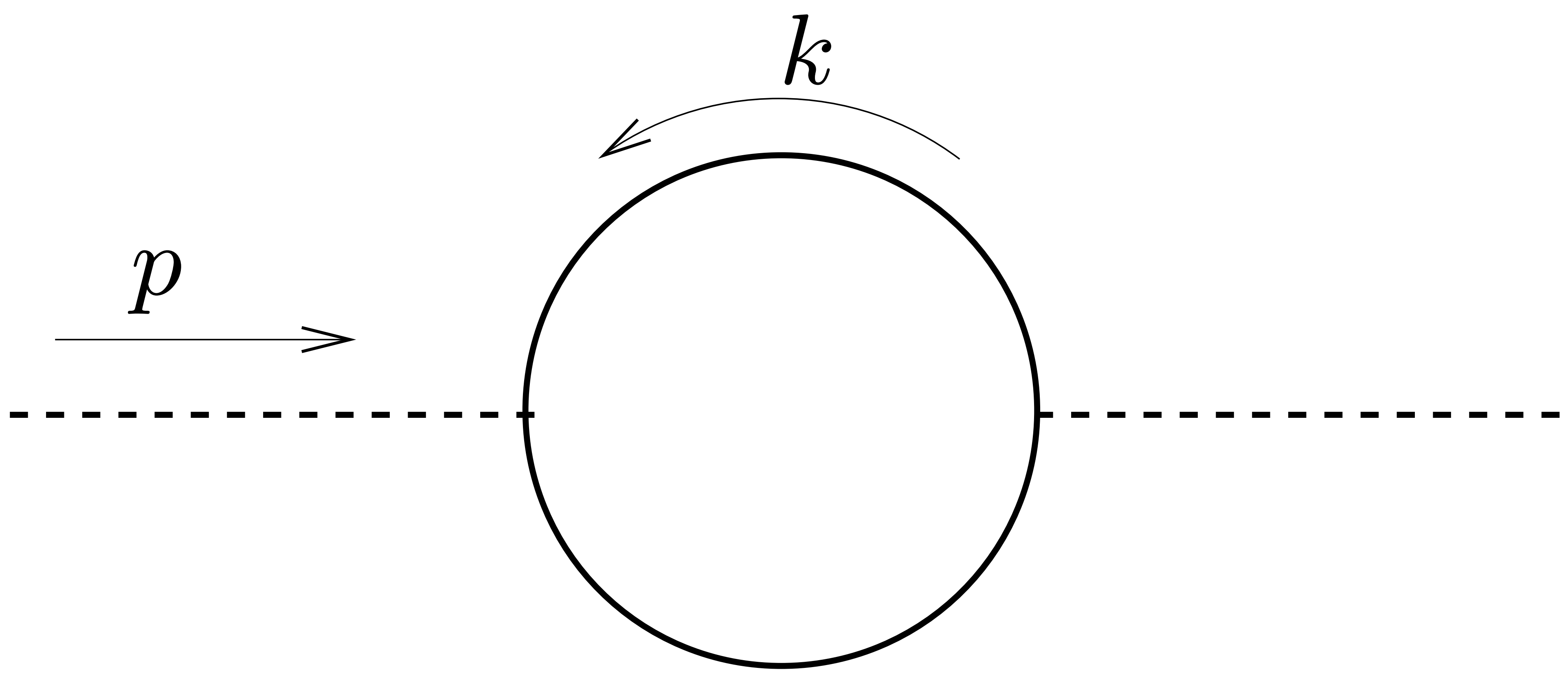


$$\Pi(p) = A + p^2 B + p^\mu p^\nu W_\mu W_\nu \tilde{\xi} + \Pi^{(\mathrm{LI})}(p^2) + \mathcal{O}(p^4/\Lambda^2)$$

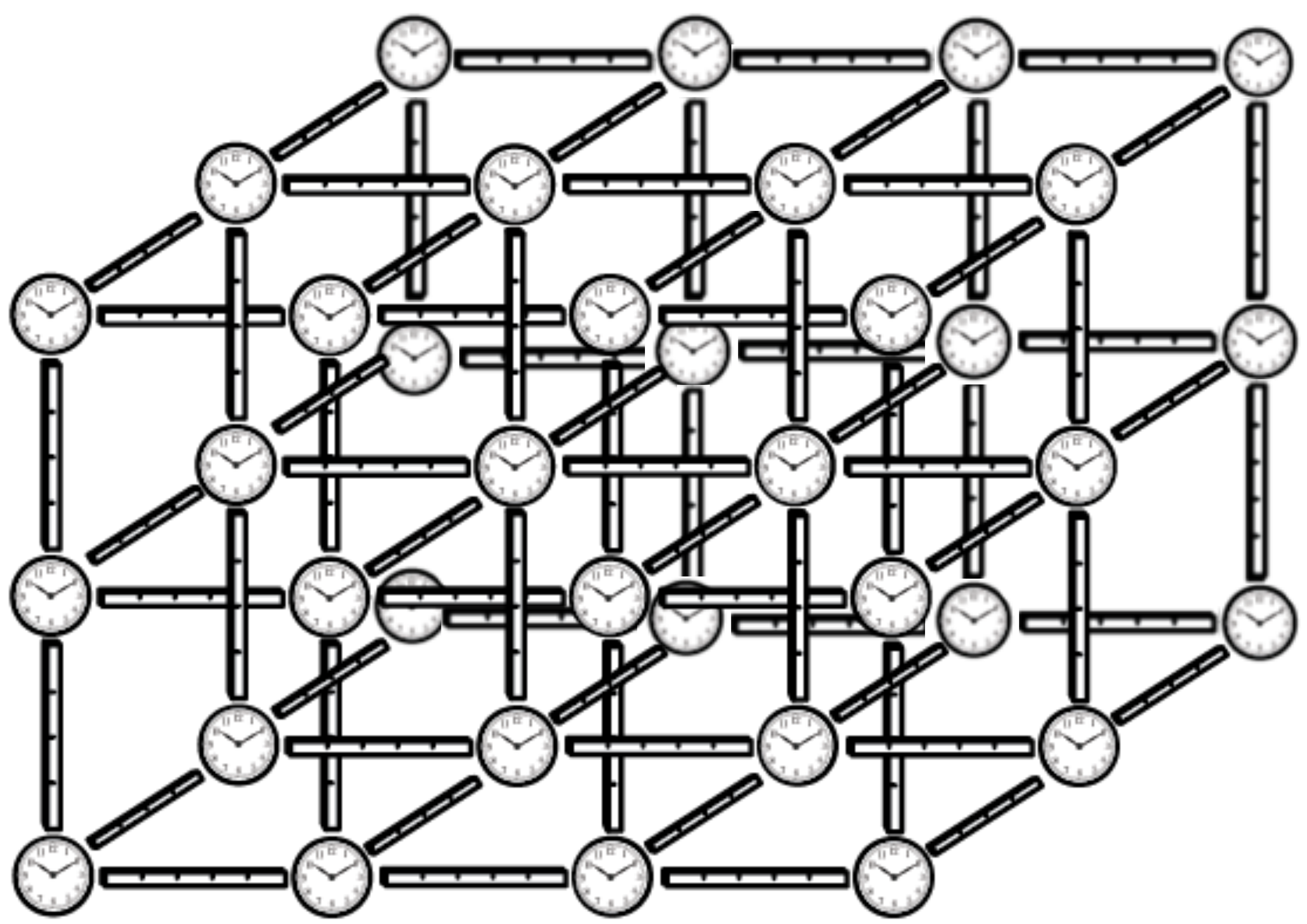
$$\tilde{\xi} = \frac{g^2}{6\pi^2}\left[1 + 2\int_0^\infty dx x f'(x)^2\right]$$

WAY OUT: Observables in QG are relational,
discreteness must be relational

Meaningful geometric observables must be Dirac observables.

Dirac observables are hard to construct explicitly but it seems clear that, when it comes to geometry, matter degrees of freedom need to be invoked in order to achieve gauge invariance. **Relational geometric notions are the key for reconciling discreteness and Lorentz invariance.**

Discreteness manifest itself via interactions with the matter that probes it.



From this perspective, the discrete aspects of quantum spacetime would arise primarily via interactions of the degrees of freedom of gravity and matter which by themselves select a preferential rest frame at the fundamental level; a setting where the Planck length lp would acquire an invariant sense. In other words, and within the **relational approach we are advocating**, it is clear that in order to be directly sensitive to the discreteness scale lp, the probing degrees of freedom must themselves carry their intrinsic scale. These ideas would seem to rule out massless (scale invariant) degrees of freedom as leading probes of discreteness simply because massless particles cannot be associated with a single local preferential rest frame.

Scalar curvature is the natural "order parameter"

Modeling the diffusion from low energy field theory degrees of freedom to Planckian microstructure

GR Symmetry:
General Diffeo.

$$\mathscr{L}_\xi g_{ab} = 2\nabla_{(a}\xi_{b)}$$

$$\nabla_{(a}\xi_{b)} = \frac{\theta}{4} g_{ab} + \sigma_{ab}$$

We relax diff-invariance to accommodate violations of energy conservation

UG Symmetry:
Volume preserving Diffeo.

$$\nabla_a \xi^a = 0 \iff \theta = 0$$

Broken Diffeos
The same as Weyl transformations on shell

$$g_{ab} \rightarrow (1 + \tfrac{\theta}{4}) g_{ab}$$

Order parameter for discreteness probes:
scalar curvature

$$R = 8\pi T \neq 0$$

Preferred volume structure in UG:
Preferred conformal structure in cosmology

$$ds^2 = a(\eta)^2 \left[-d\eta^2 + d\vec{x}^2\right]$$

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In fact this is the most general relaxation
when it comes to cosmology

$dJ = 0$
trivially true in FLRW

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Broken Diffeos
The same as Weyl transformations on shell

$$g_{ab} \to (1 + \tfrac{\theta}{4}) g_{ab}$$

This is the same as a preferred 4-volume of UG

Order parameter for discreteness probes:
scalar curvature

$$R = 8\pi T \neq 0$$

Preferred volume structure in UG:
Preferred conformal structure in cosmology

$$ds^2 = a(\eta)^2 \left[-d\eta^2 + d\vec{x}^2\right]$$

Modeling the diffusion from low energy field theory degrees of freedom to Planckian microstructure

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Broken Diffeos
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Order parameter for discreteness probes:
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Both **R** the preferred volume structure are natural ingredients of the **Planckian** phenomenology we are exploring

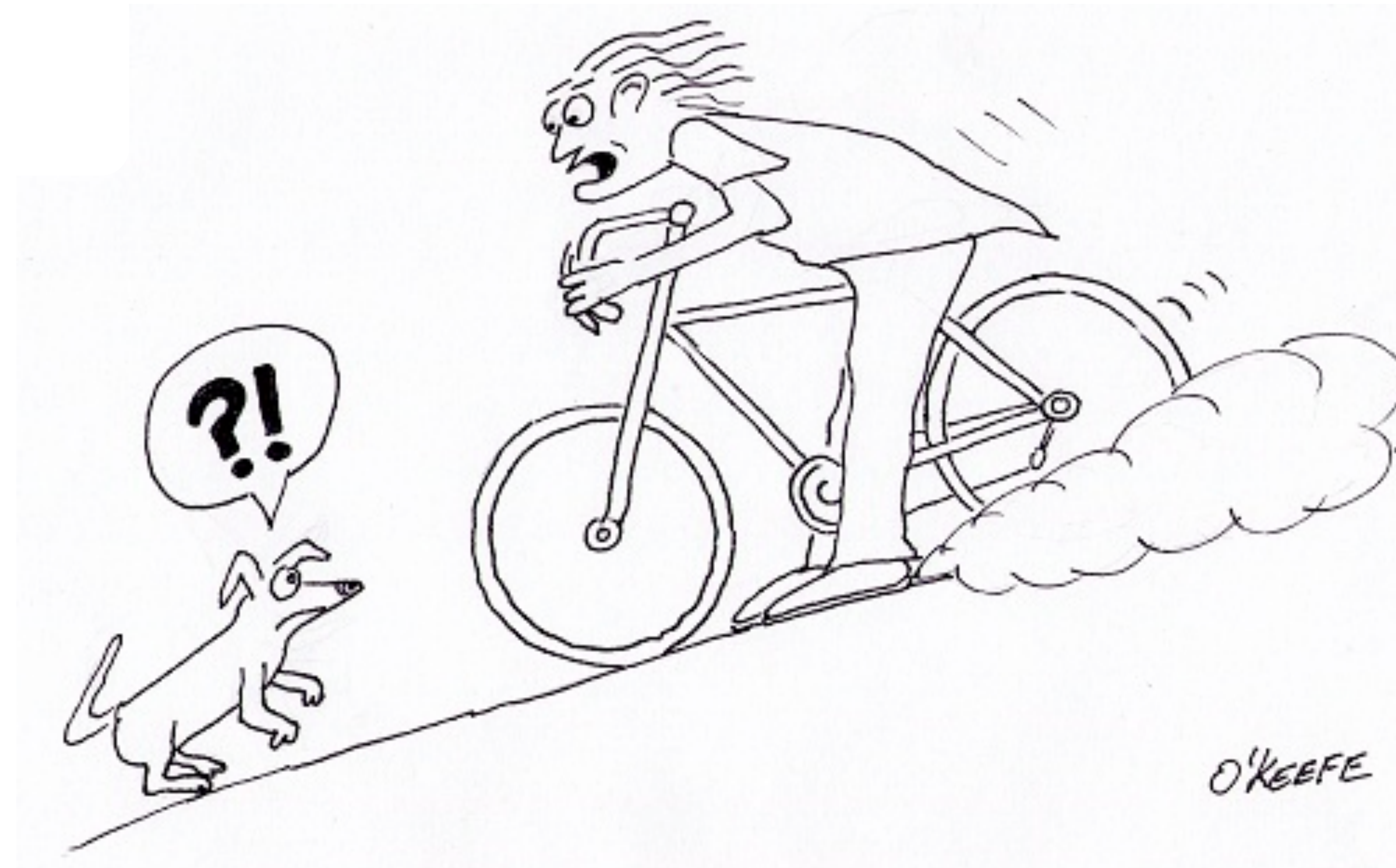
Preferred volume structure in UG:
Preferred conformal structure in cosmology

$$ds^2 = a(\eta)^2 \left[-d\eta^2 + d\vec{x}^2\right]$$

Modeling the diffusion from low energy field theory degrees of freedom to Planckian microstructure

$$ds^2 = a(\eta)^2 \left[-d\eta^2 + d\vec{x}^2\right]$$

$$J \equiv (8\pi G)\nabla^b T_{ba} dx^a = \alpha \ell_p R^2 \, d\eta_p$$
$$= \alpha \ell_p \left[8\pi G(\rho - 3P)\right]^2 \, d\eta_p,$$



Preferred volume structure in UG:
conformal time normalized to match co-moving time at Planck scale

$$d\eta_p = a_p d\eta = a_p \frac{dt}{a(t)}$$

$\alpha \equiv$ dimensionless constant

The calculation

$$\Lambda = \Lambda_0 + \alpha \ell_p \int_{t_{\rm ew}}^{t_0} \left[8\pi G(\rho - 3P)\right]^2 \frac{a_p}{a(t)}\, dt$$

$$\rho = \pi^2 g_* T^4/(30\hbar^3)$$

$$\rho - 3P \approx \frac{m_t^2 T^2}{2\hbar^3}$$

$$\frac{dT}{T} = -\frac{da}{a} = -\underbrace{T^2\sqrt{\frac{8\pi G}{3}\frac{\pi^2 g_*}{30\hbar^3}}}_{H(a)}\, dt$$

$$\equiv \dot{a}/a$$

$$\Delta\Lambda \approx \alpha\sqrt{\frac{320\pi}{g_*}\frac{m_t^4 {T_{\rm ew}}^3}{\hbar^2 m_p^5}}\ \epsilon(T_{\rm ew})$$

$$\epsilon(T_{\rm ew}) = -\frac{3}{T_c^3}\int_{T_{\rm ew}}^{T_{\rm end}} \left(1 - \frac{T^2}{T_{\rm ew}^2}\right)^2 T^2 dT$$

$\Rightarrow$

$$m_t \approx m_{ew}$$

$\Rightarrow$

$$\rho_\Lambda \approx \alpha \underbrace{\left(\frac{m_{ew}}{m_p}\right)^7}_{10^{-120}} m_p^4$$

The calculation

$$\Lambda = \Lambda_0 + \alpha \ell_p \int_{t_{\rm ew}}^{t_0} \left[8\pi G(\rho - 3P)\right]^2 \frac{a_p}{a(t)}\, dt$$

$$\rho = \pi^2 g_* T^4/(30\hbar^3)$$

$$\rho - 3P \approx \frac{m_t^2 T^2}{2\hbar^3}$$

$$\frac{dT}{T} = -\frac{da}{a} = -\underbrace{T^2\sqrt{\frac{8\pi G}{3}\frac{\pi^2 g_*}{30\hbar^3}}}_{H(a)}\, dt$$

$$\equiv \dot{a}/a$$

$$\Delta\Lambda \approx \alpha \sqrt{\frac{320\pi}{g_*}\frac{m_t^4 {T_{\rm ew}}^3}{\hbar^2 m_p^5}}\ \epsilon(T_{\rm ew})$$

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Results

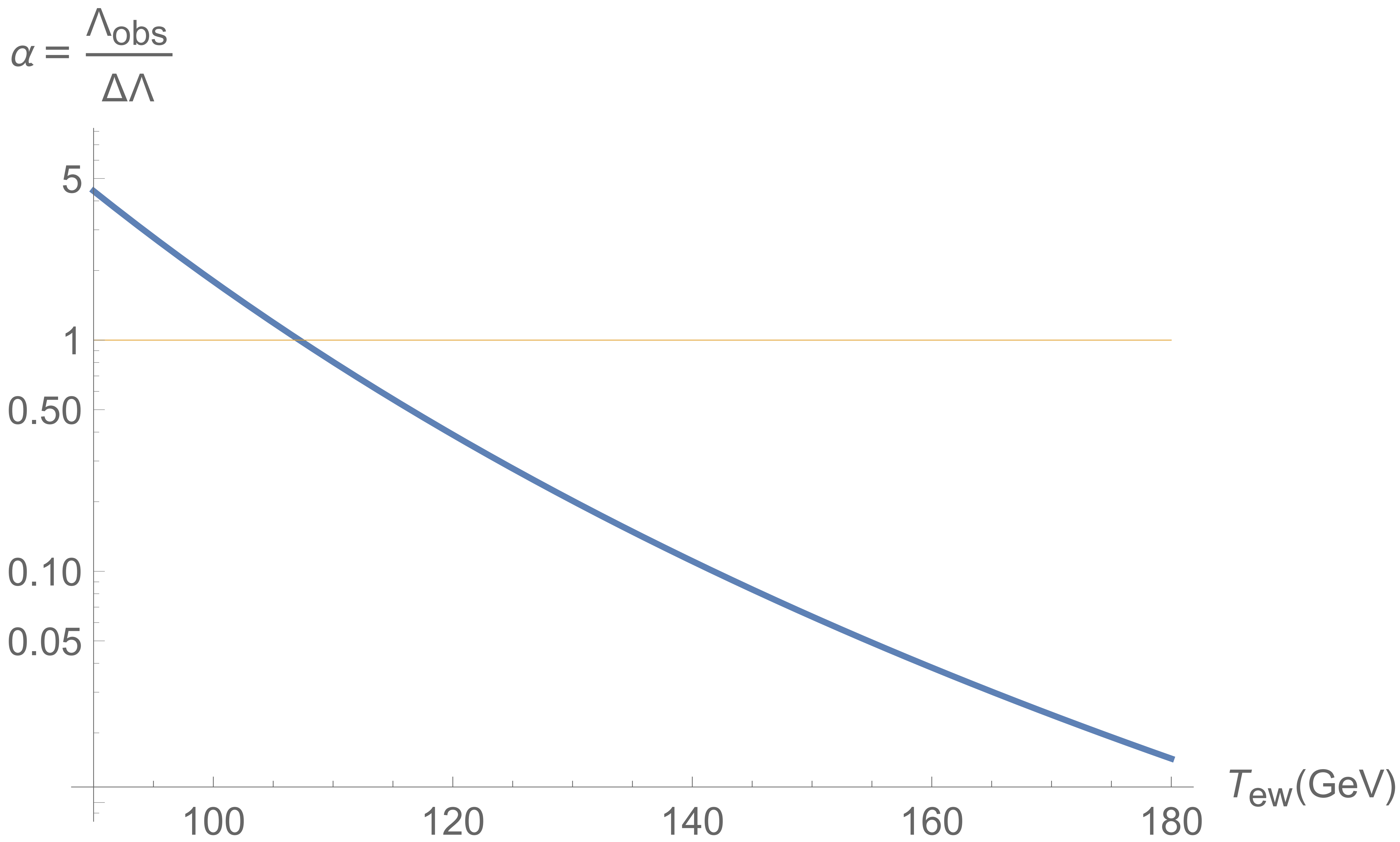

Figure 1. The value of the phenomenological parameter α, see eq. (6), that fits the observed value of Λ_{obs} as a function of the electro-weak transition scale T_{ew} in GeV.

$$T_{\text{ew}} \approx 100 \text{ GeV} \qquad \Delta\Lambda \approx 0.6\,\alpha\,\Lambda_{\text{obs}}$$

Discussion

- Violations of energy momentum conservation are natural in an effective description of a fundamentally discrete physics in terms of smooth fields on smooth spacetime geometry.
- When integrable such violations can be describe in terms of UG, and they feed a dark energy term in the Einsteins equations.
- Integrability is trivial in FLRW spacetimes. UG is the most general description of this type of diffusion in cosmology.
- Vacuum energy does not gravitate in UG.
- Tiny violations (hard to detect in local experiments) can have an important cosmological influence.
- We predict the correct order of magnitude for dark energy using: the structure of UG, the idea that only massive fields are main probes of discreteness (Lorentz invariance), and some assumptions on the physics beyond the standard model.
- Can one find another (independent) implication of these ideas?


Merci
Beaucoup!

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