Space-time discreteness in quantum gravity: possible consequences and a new perspective on the origin of the observed cosmological constant.

on work in collaboration with D. Sudarsky

CPPM

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The cosmological constant problem

$$R_{ab} - \frac{1}{2} g_{ab} R + \Lambda g_{ab} = 8\pi T_{ab}$$

$$\Lambda_{\text{obs}} \approx 1.19 \; 10^{-52} \; \text{m}^{-2}$$

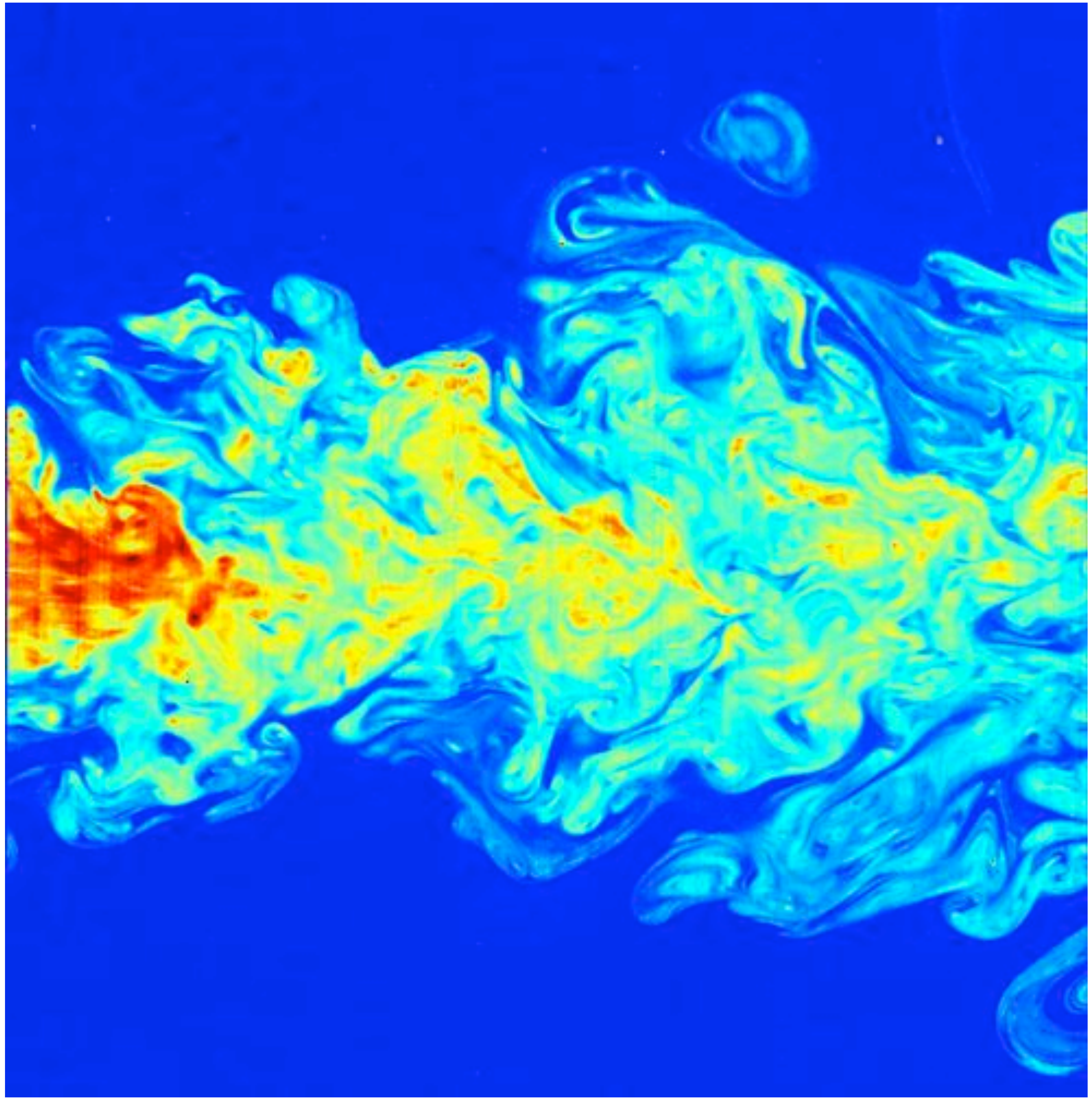
How does the vacuum gravitate?

$$\langle T_{ab} \rangle = \frac{\Lambda_{vac}}{8\pi G} \; g_{ab}$$

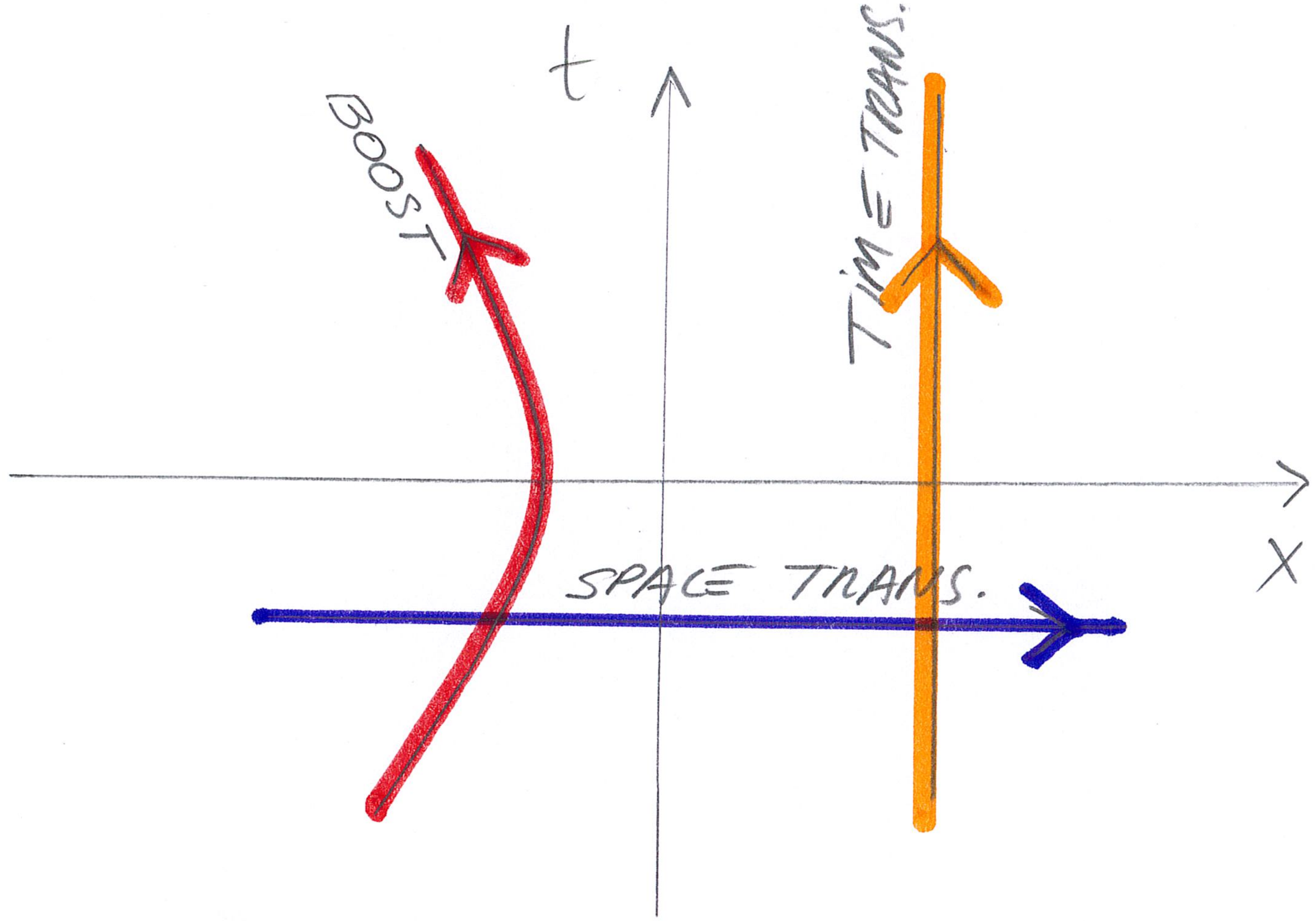
$$\rho_{vac} \equiv \frac{\Lambda_{vac}}{8\pi G} \approx m_p^4$$

$$\rho_{\Lambda_{obs}} \approx 10^{-120} m_p^4 \approx (10^{-2} eV)^4$$

Continuous fluid description breaks down at molecular scales.



SPACETIME SYMMETRIES AND CONSERVED QUANTITIES



SPACE TRANS. INVARIANCE $\Rightarrow$ MOMENTUM CONSERVATION

TIME TRANS. INVARIANCE $\Rightarrow$ ENERGY CONSERVATION

10 SYMMETRIES in the POINCARÉ GROUP $\Rightarrow$ T^{ab}

10 components of the ENERGY MOMENTUM TENSOR

$$\nabla_a v_b - \nabla_b v_a = 0$$

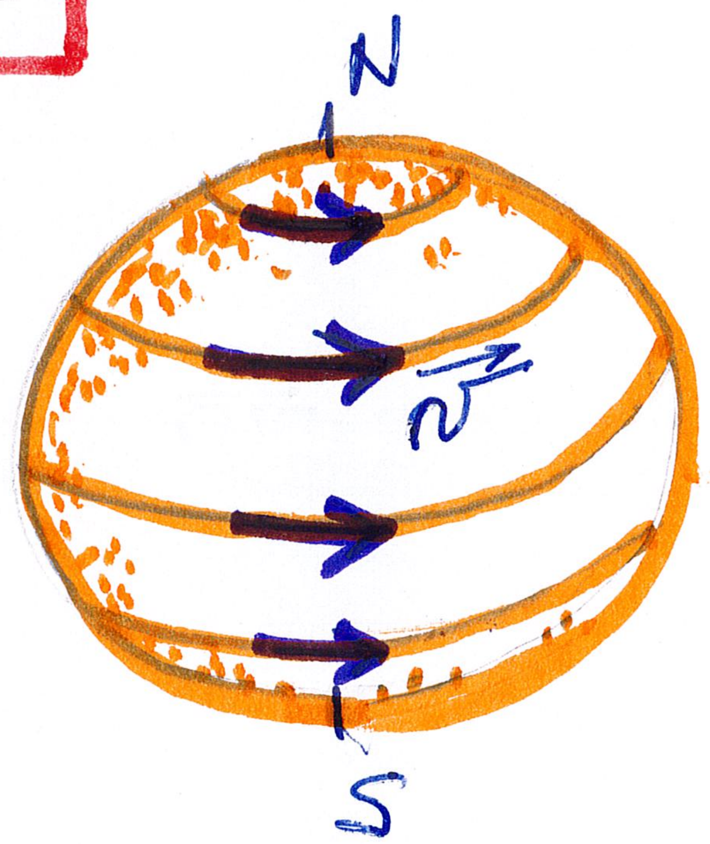
CONSERVATION $\Leftrightarrow$ $\nabla_a T^{ab} = 0$

COORDINATE INDEPENDENT CHARACTERIZATION OF SYMMETRY

KILLING VECTOR FIELD

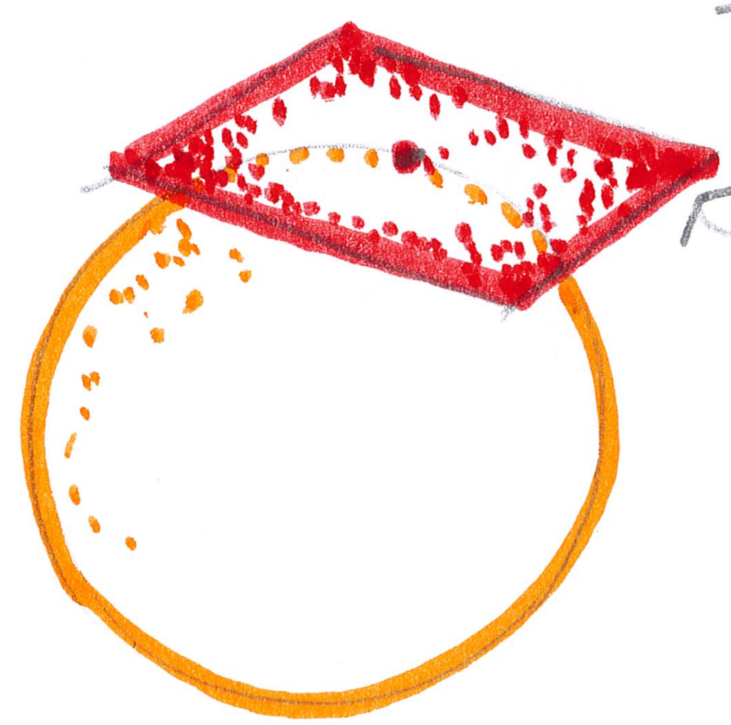
$$\nabla_a v_b + \nabla_b v_a = 0$$

WORKS ALSO FOR CURVED GEOMETRY



NO SYMMET. in general

CAN DEFINE ENERGY-MOMENTUM TENSOR IN GENERAL



10 SYMMETRIES OF TANGENT SPACE

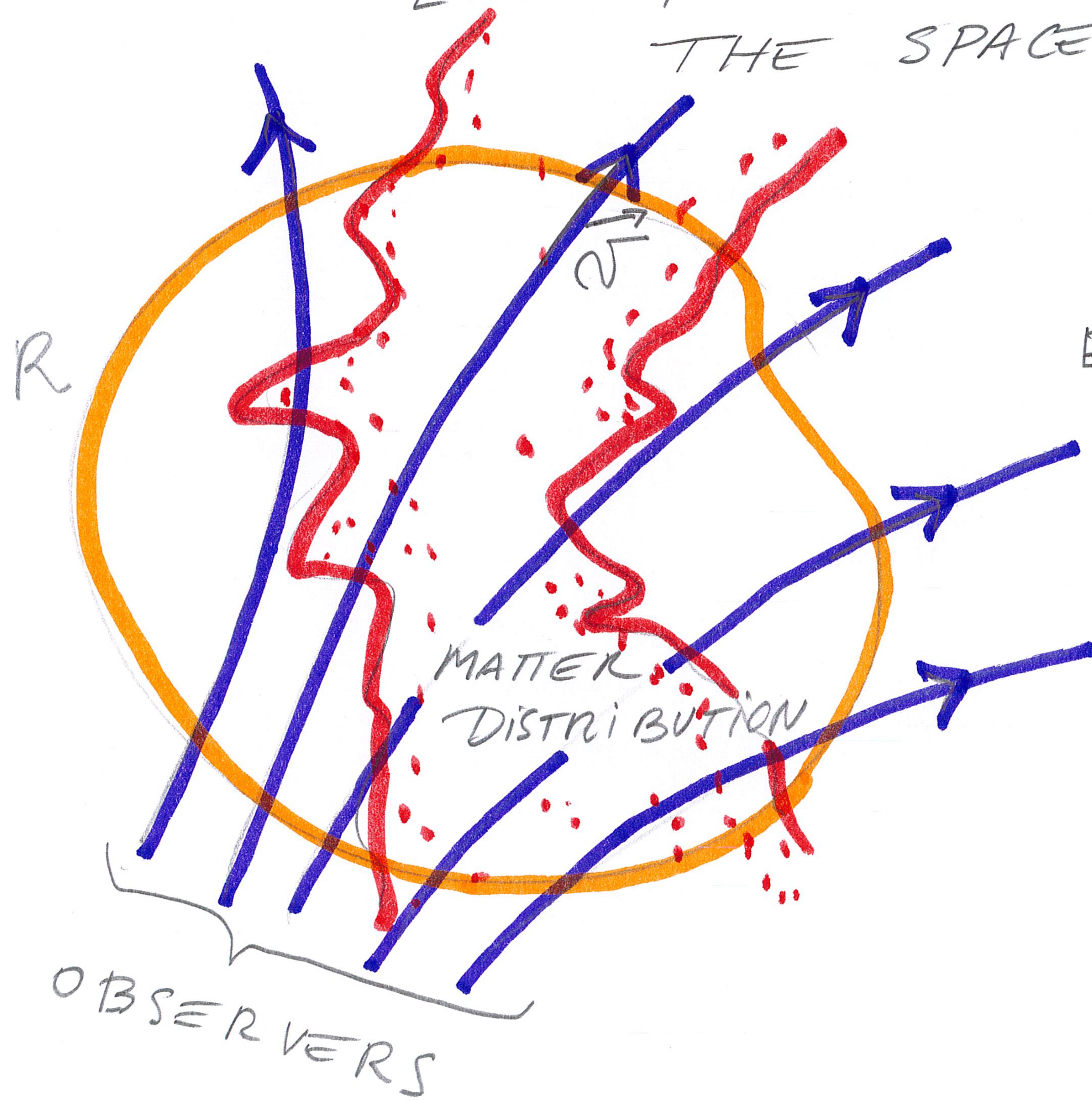
T^{ab} and $\nabla_a T^{ab} = 0$

GENERAL RELATIVITY

$$G_{ab} = \underbrace{R_{ab} - \frac{1}{2} R g_{ab}}_{\text{SPACETIME GEOMETRY}} = \underbrace{8\pi G\, T_{ab}}_{\text{ENERGY MOMENTUM TENSOR}}$$

LOCAL CONSERVATION OF ENERGY $\qquad \nabla_a T^{ab} = 0$

GRAVITATIONAL WAVES $\Longleftrightarrow$ ENERGY CARRIED BY THE SPACETIME GEOMETRY



$$p^a \equiv T^{ab} v_b$$

Energy momentum current

$$\nabla_a p^a = \nabla_a (T^{ab} v_b)$$

$$= (\nabla_a T^{ab}) v_b + T^{ab} \nabla_a v_b \neq 0$$

0

unless $\underbrace{\nabla_a v_b + \nabla_a v_a}_{\text{Killing vector field}} = 0$

Killing vector field $\Longleftrightarrow$ SPACETIME Symmetry

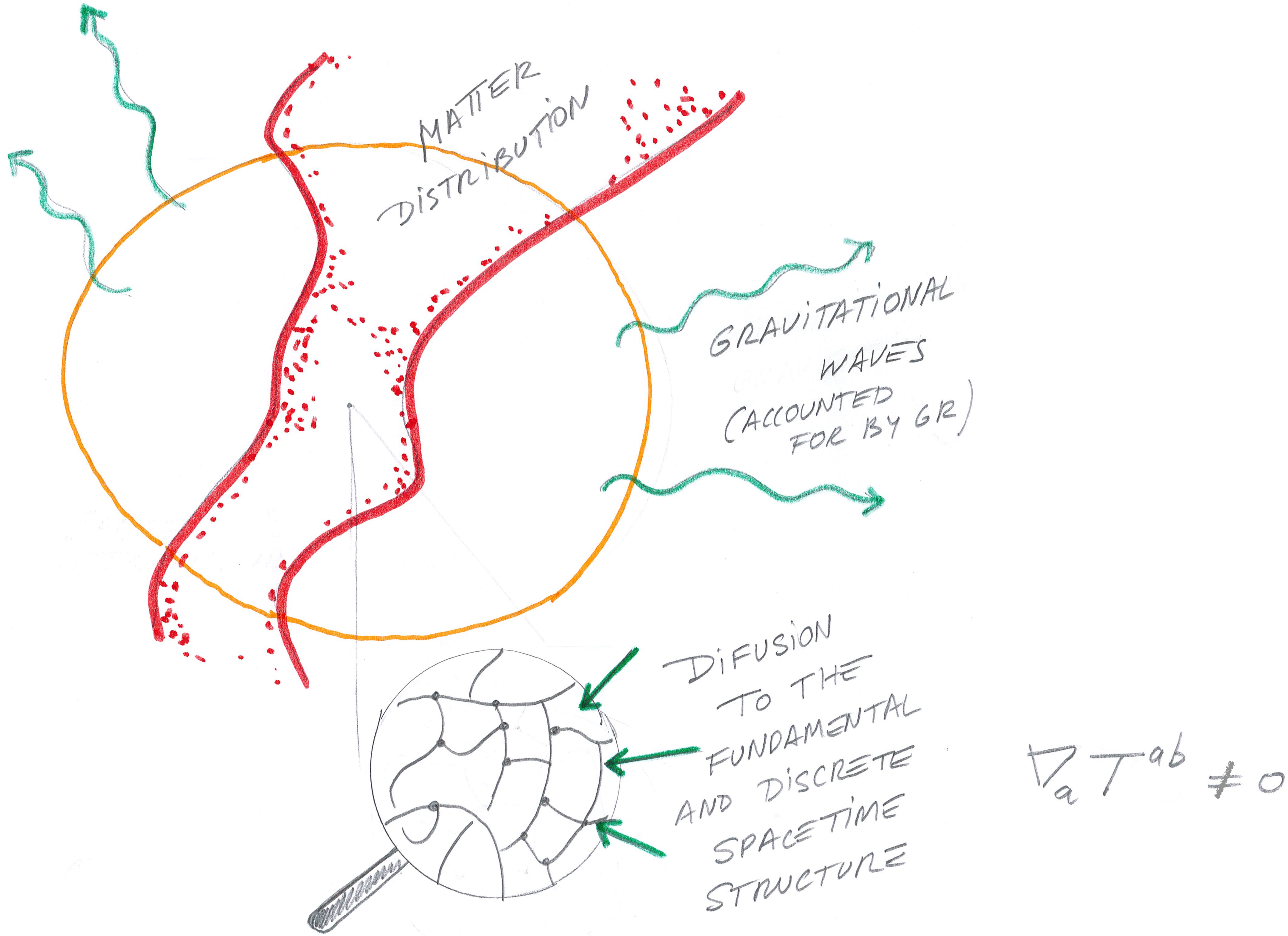
R is BIG $\Longleftrightarrow$ No conservation of matter energy unless SYMMETRIES

GRAVITY WAVES

$\tilde{R}$ is very SMALL (EQUIVALENCE PRINCIPLE)

$\nabla^a T_{ab} = 0$

$\Longleftrightarrow$ conservation of energy

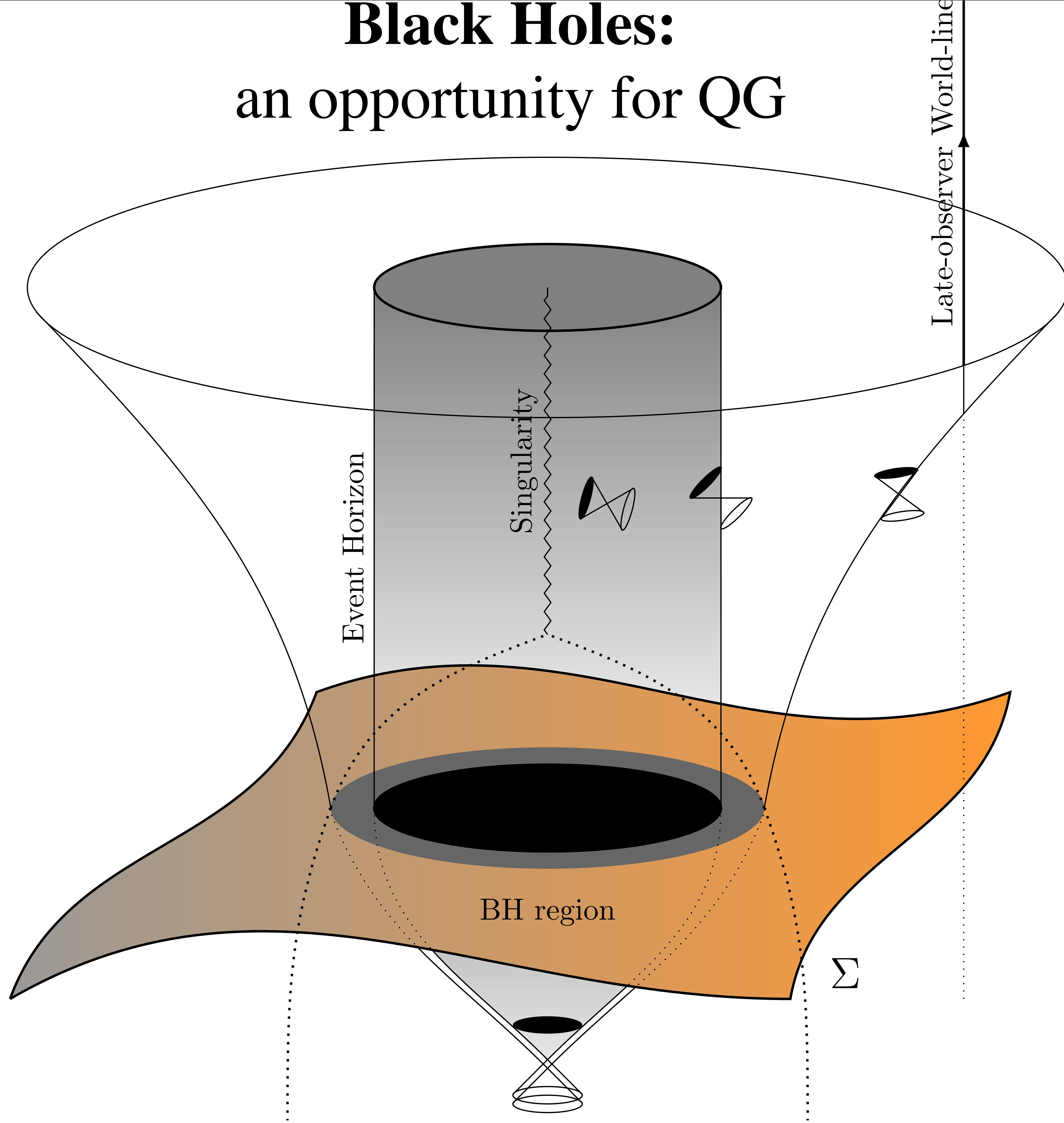


MATTER DISTRIBUTION
GRAVITATIONAL WAVES (ACCOUNTED FOR BY GR)
DIFUSION TO THE FUNDAMENTAL AND DISCRETE SPACETIME STRUCTURE
$\nabla_a T^{ab} \neq 0$

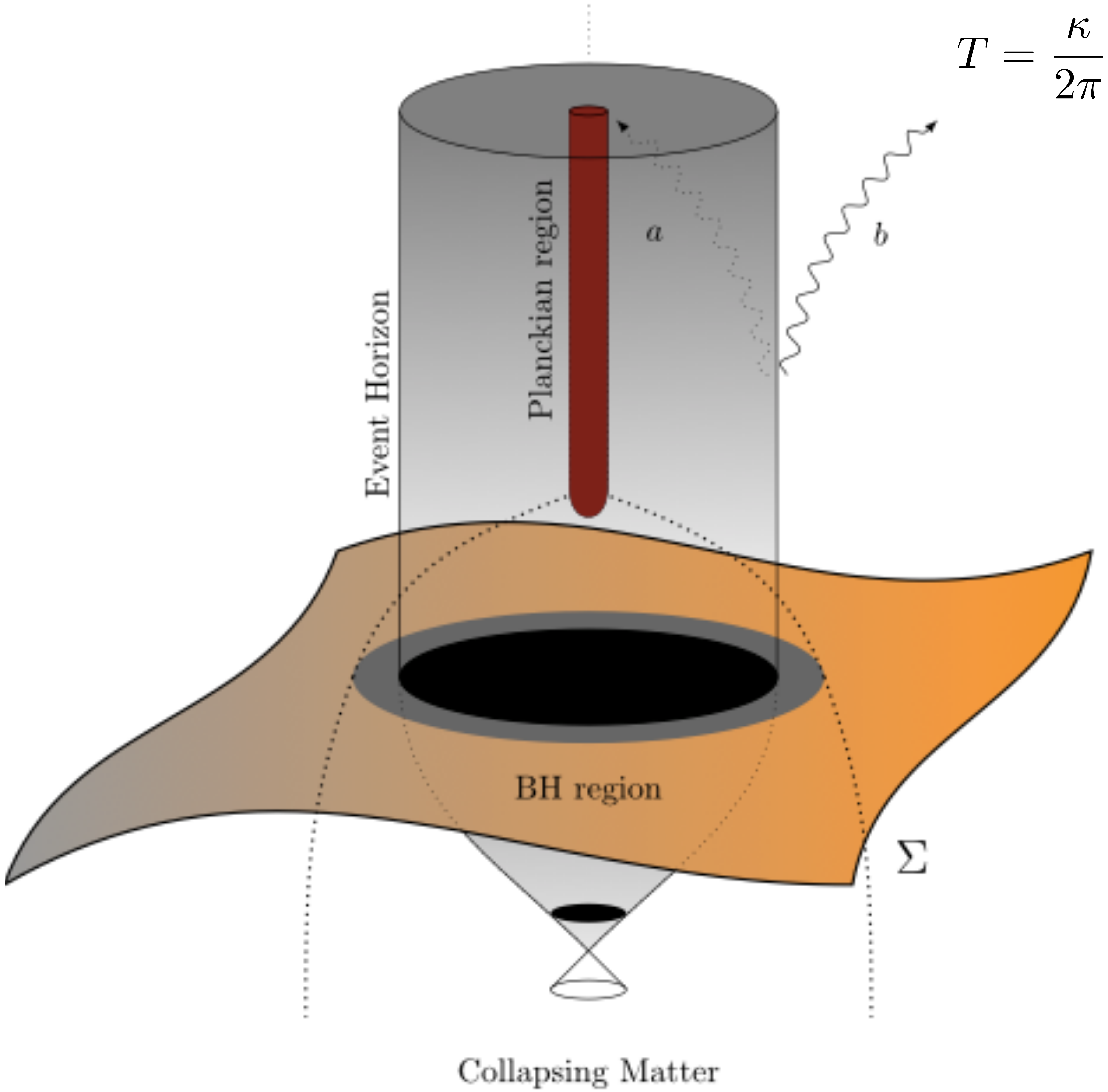
PART 1:

Spacetime es expected to be discrete
in 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

1st law: $\delta M = \underbrace{\frac{\kappa}{8\pi}\delta a}_{heat?} + \Omega\delta J + \Phi\delta Q$

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

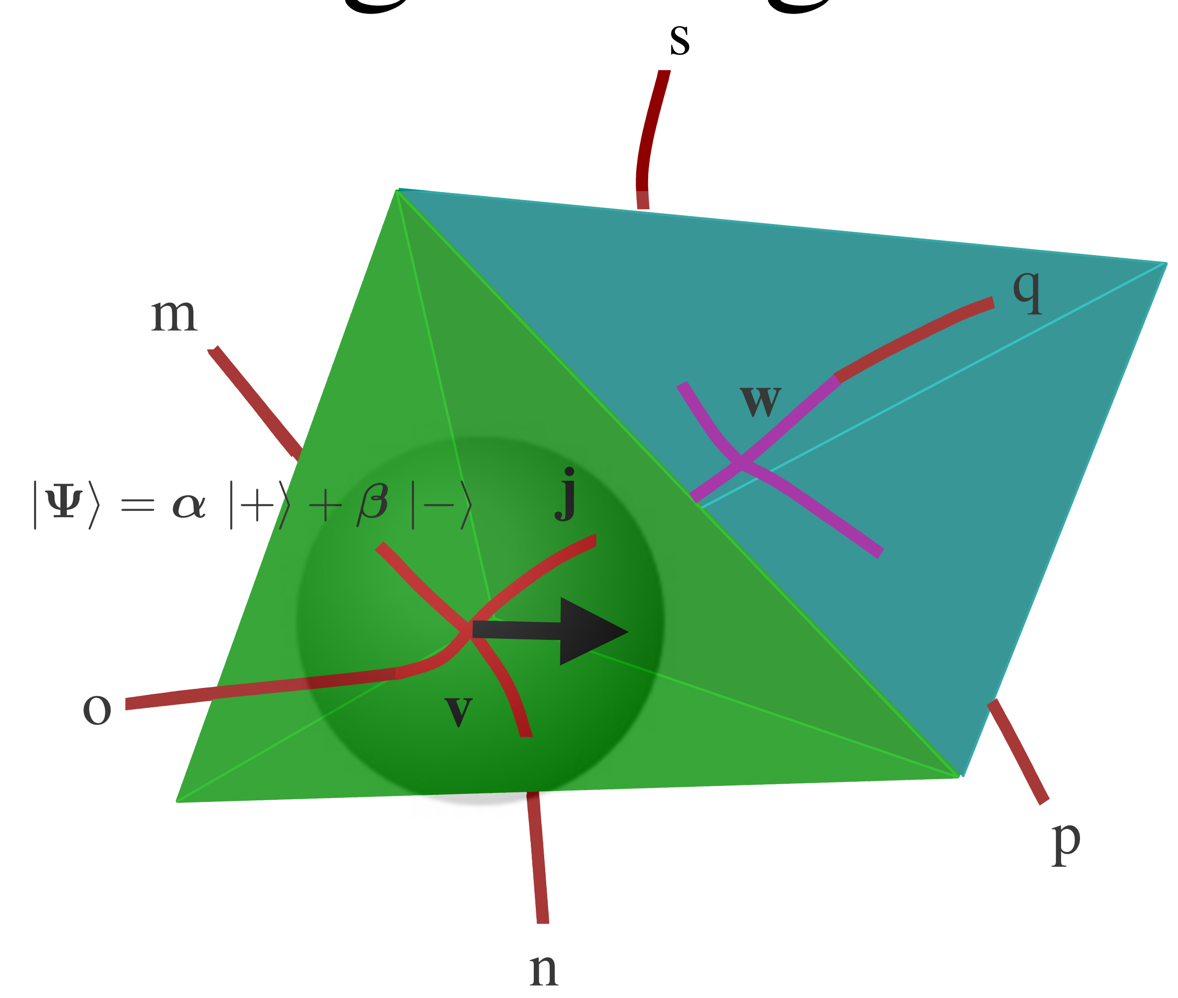
2nd law: $\delta a \geq 0$

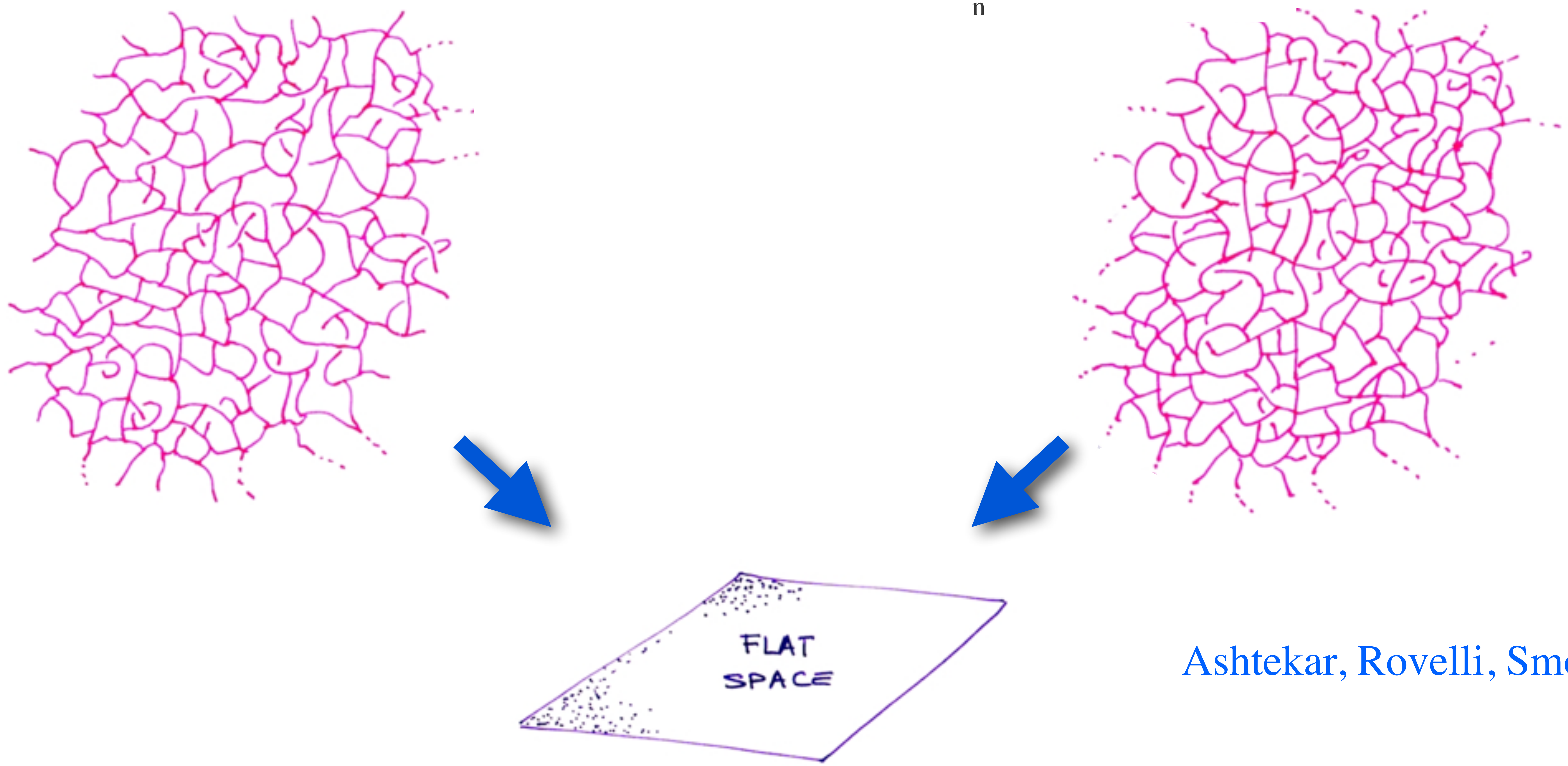
Discreteness in Loop Quantum Gravity.

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

Spin-network states:

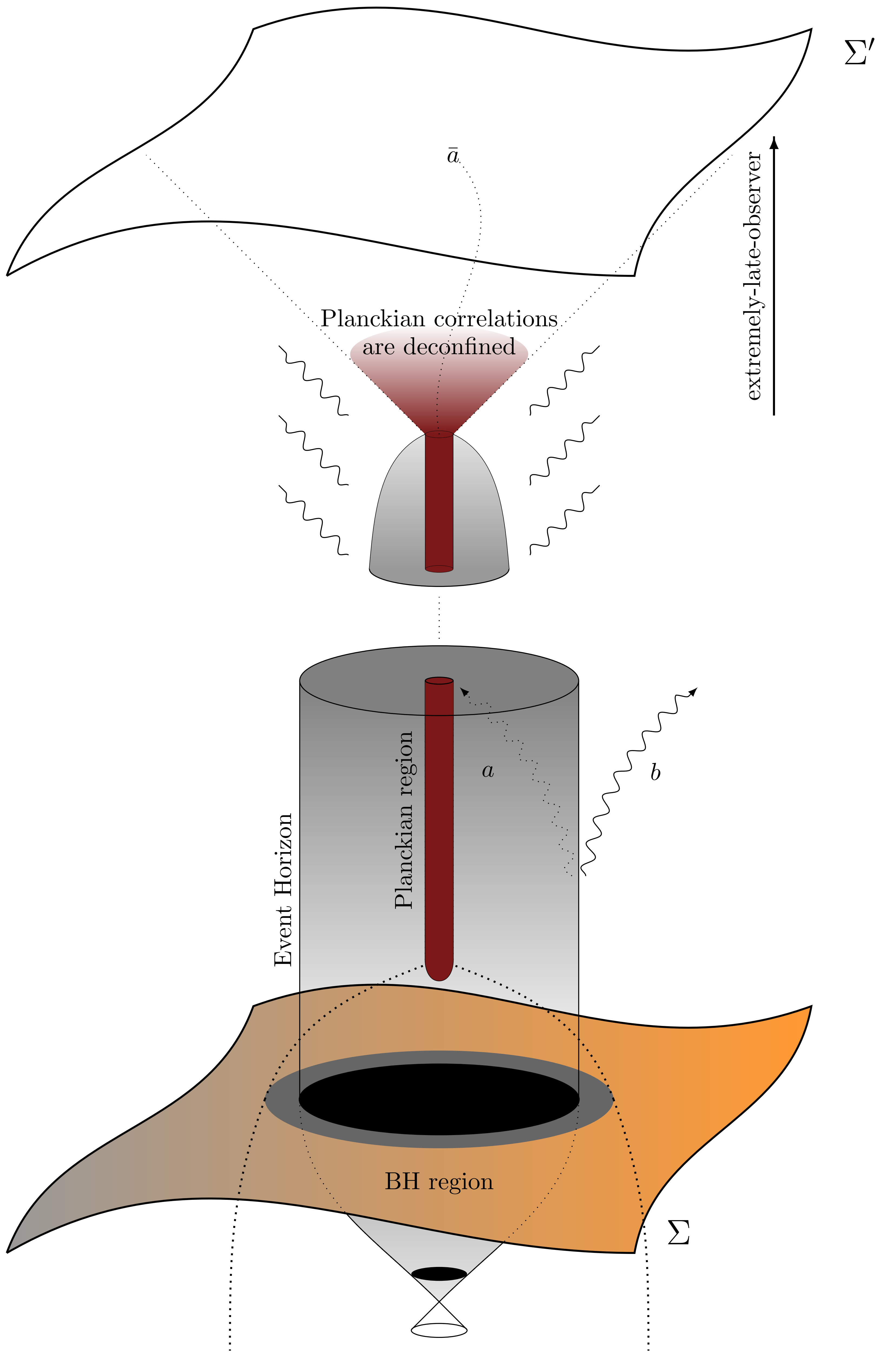
atoms of geometry



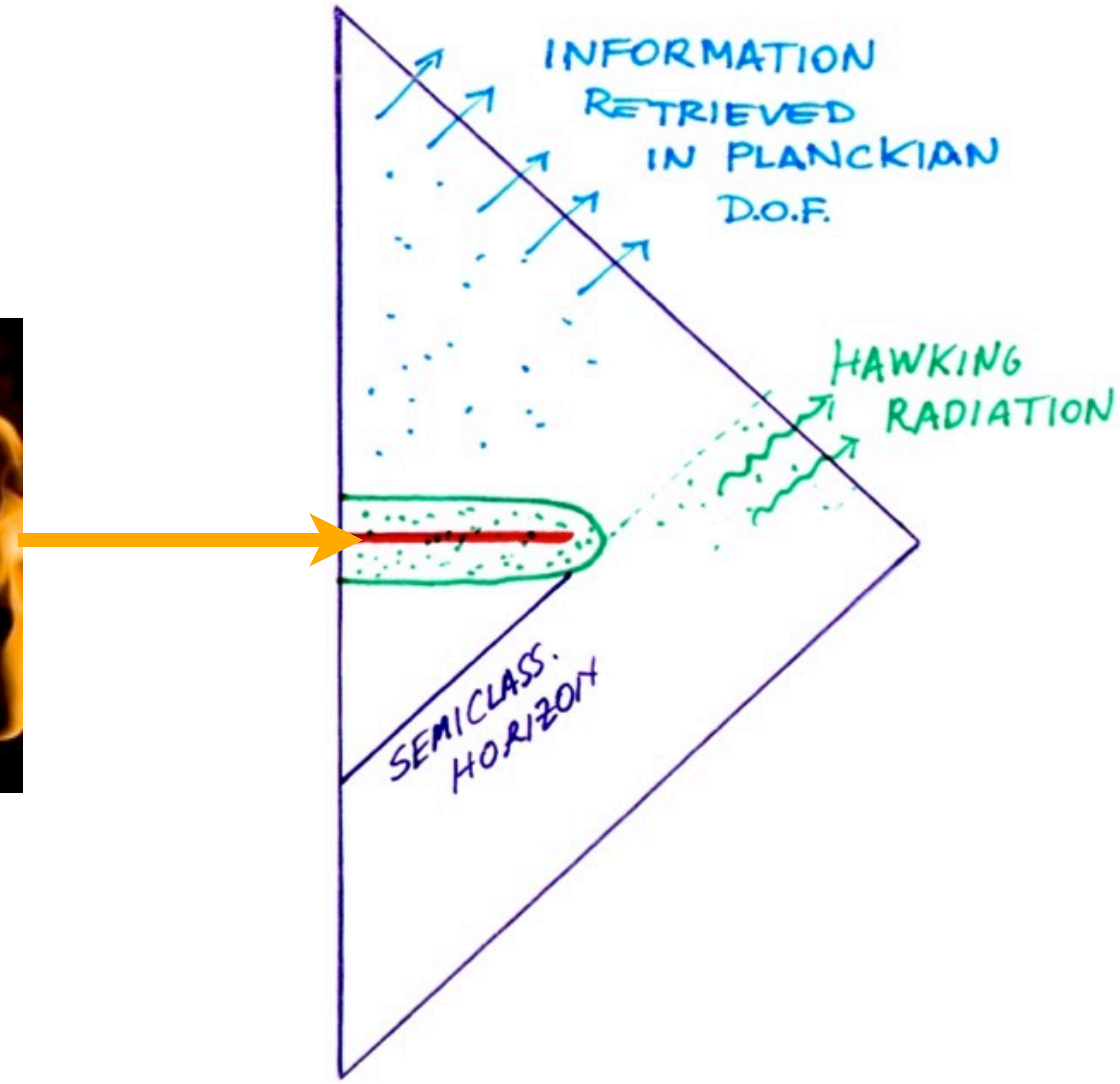


Ashtekar, Rovelli, Smolin 1992

New perspective on the information paradox



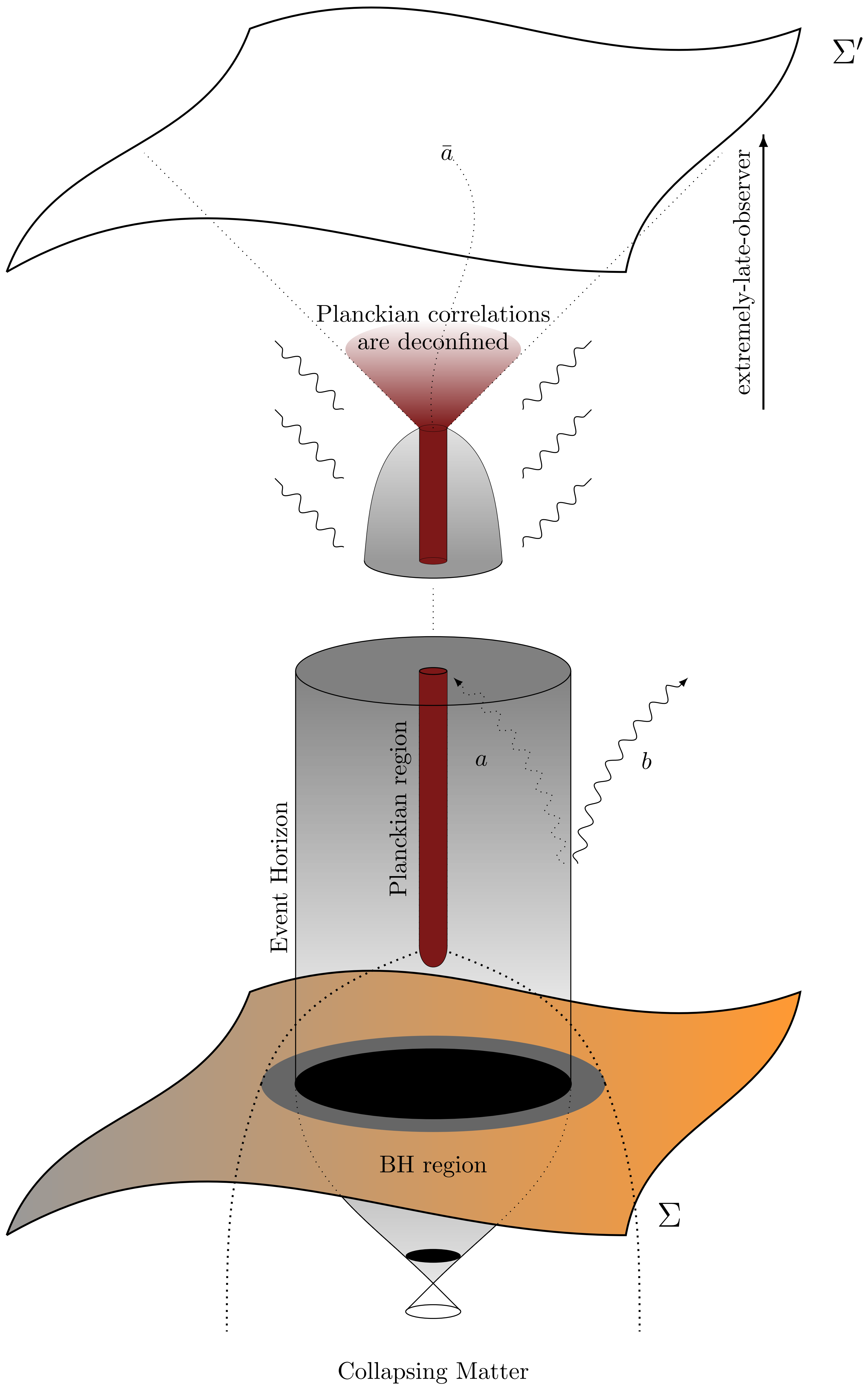
AP, *Class. Quant. Grav.* 32, 2015.



CPT **violation** in the **smooth QFT effective description**!

Wald 1980,

New perspective on the information paradox



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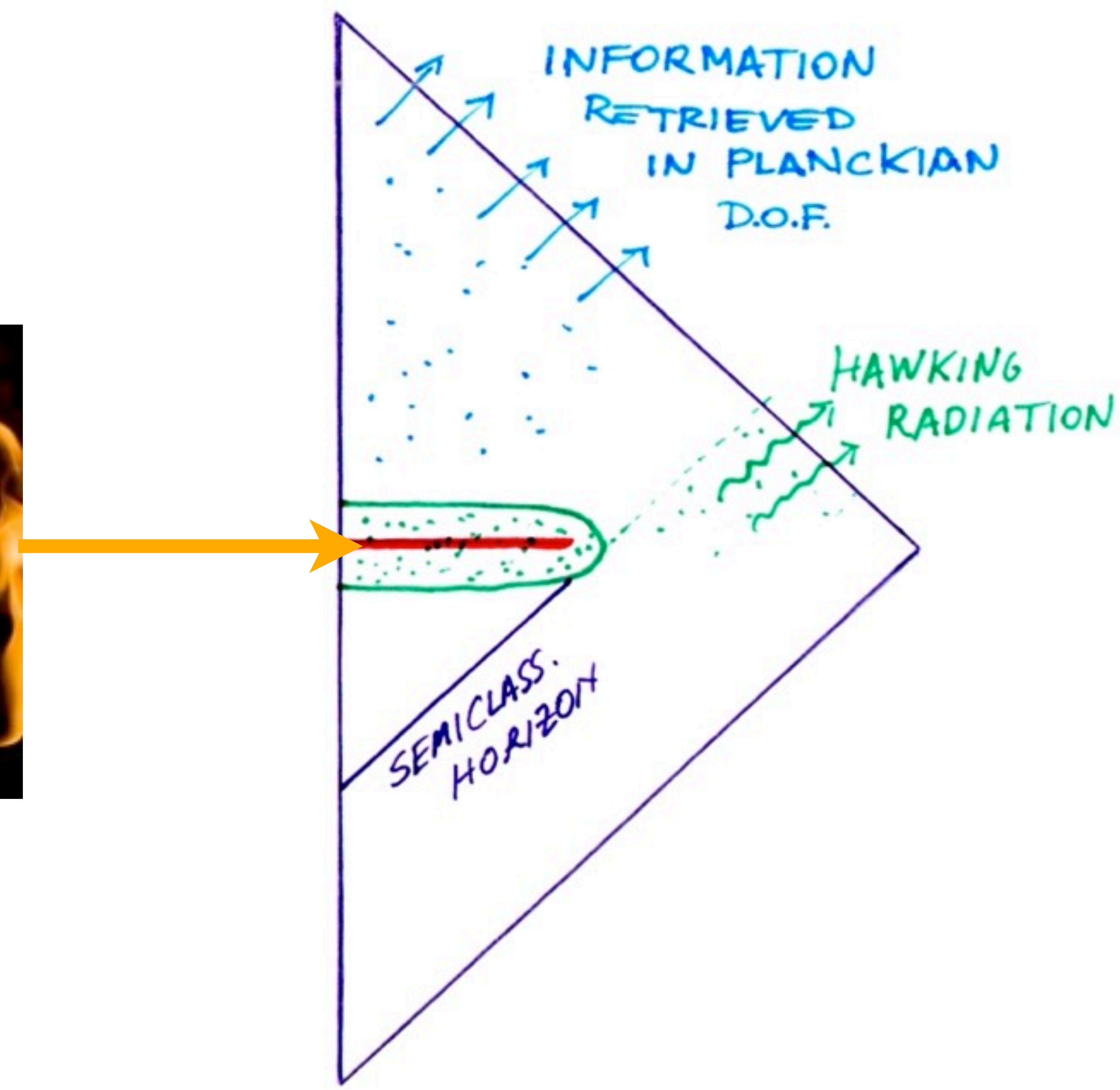
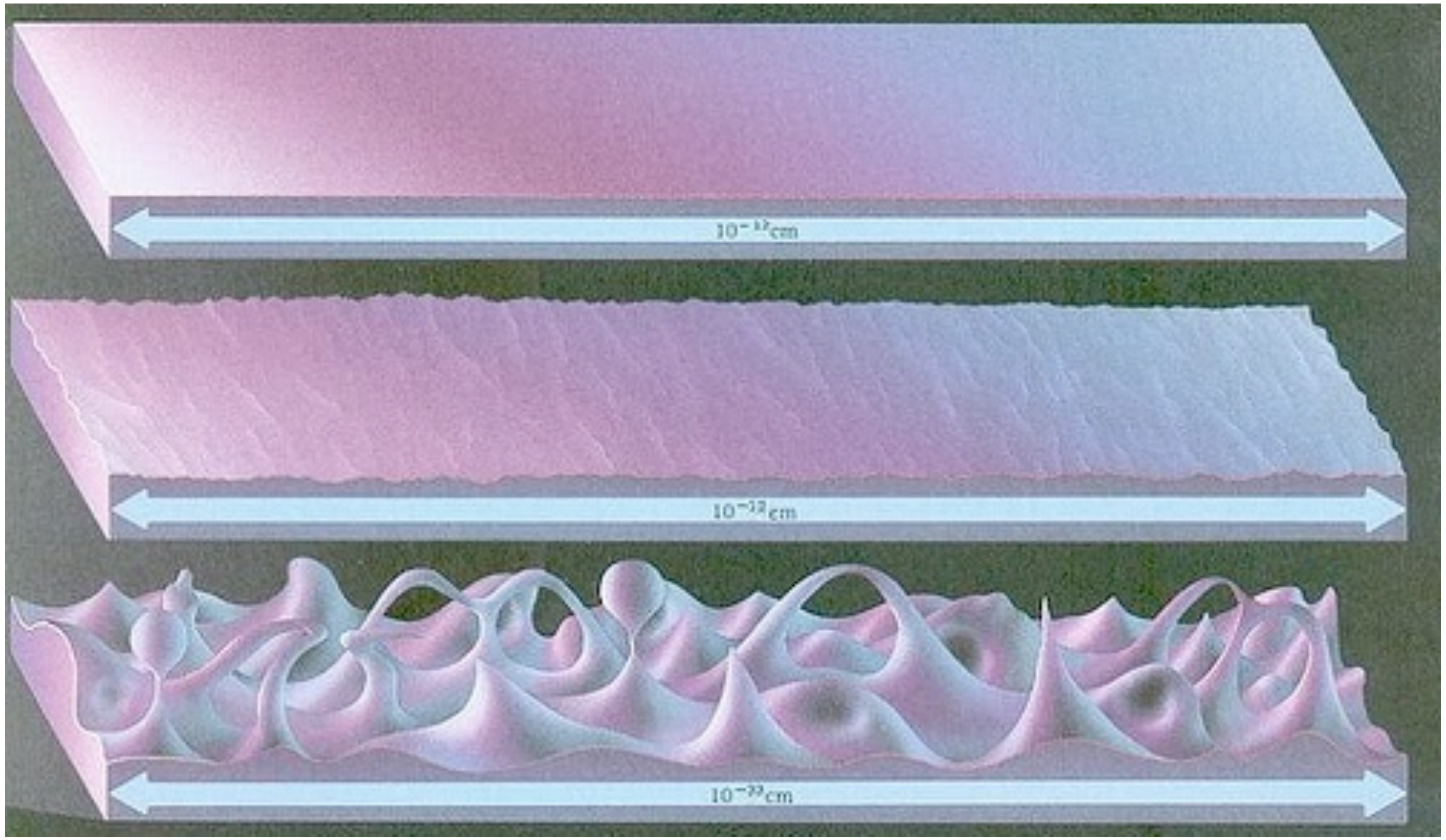


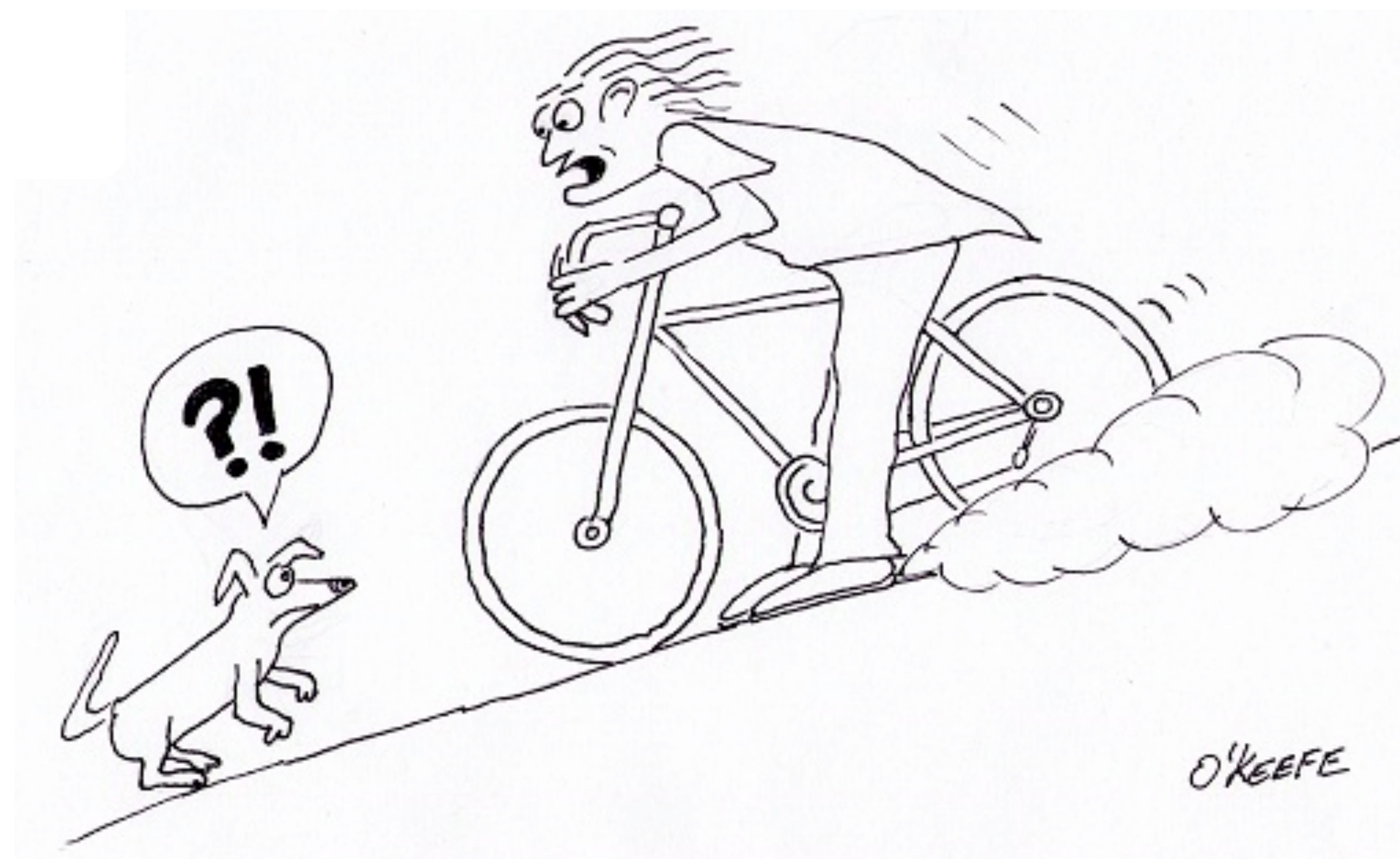
Decoherence with discrete micro-structure imply **violations** of **energy conservation** in the **smooth effective description**!

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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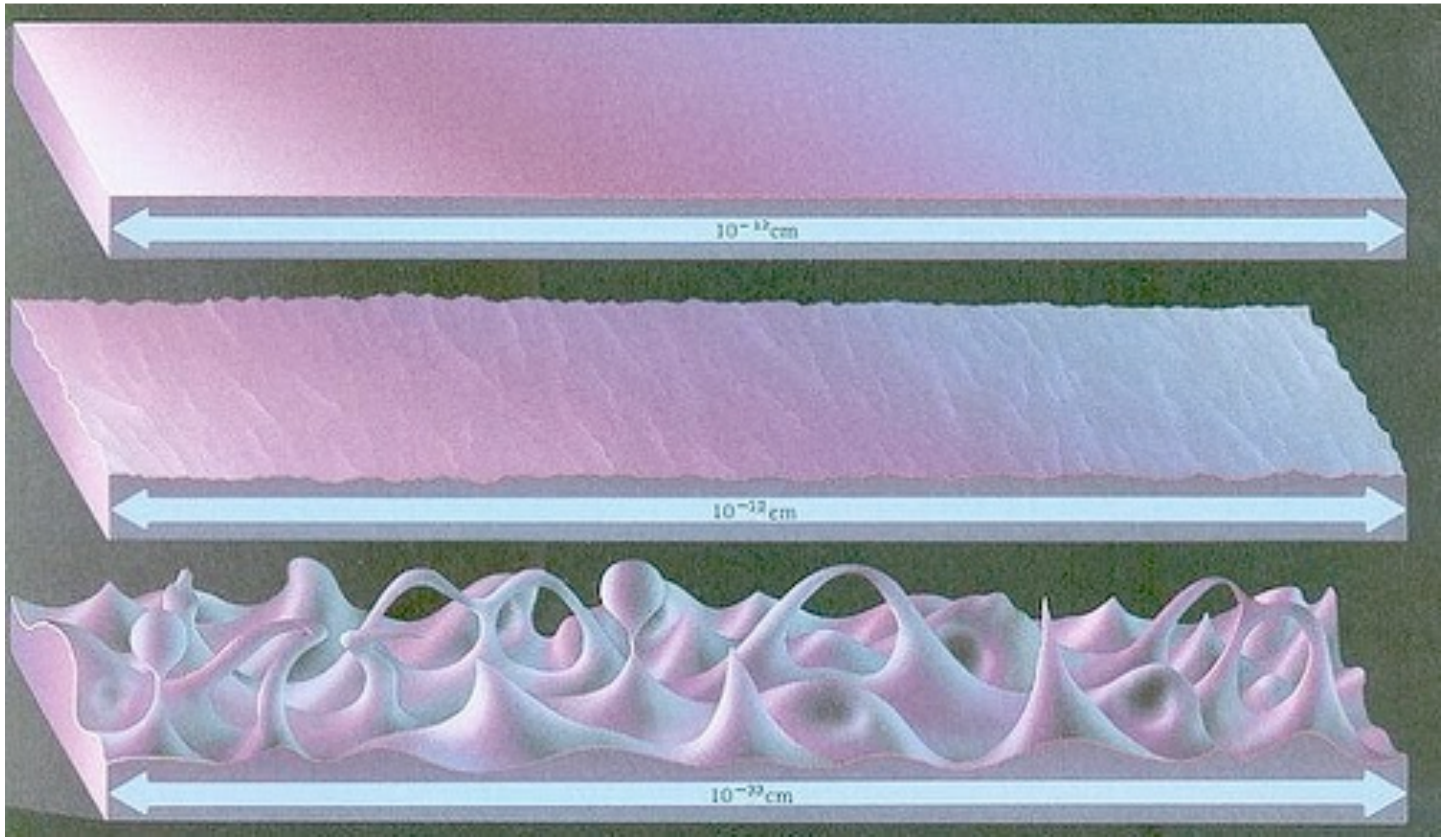

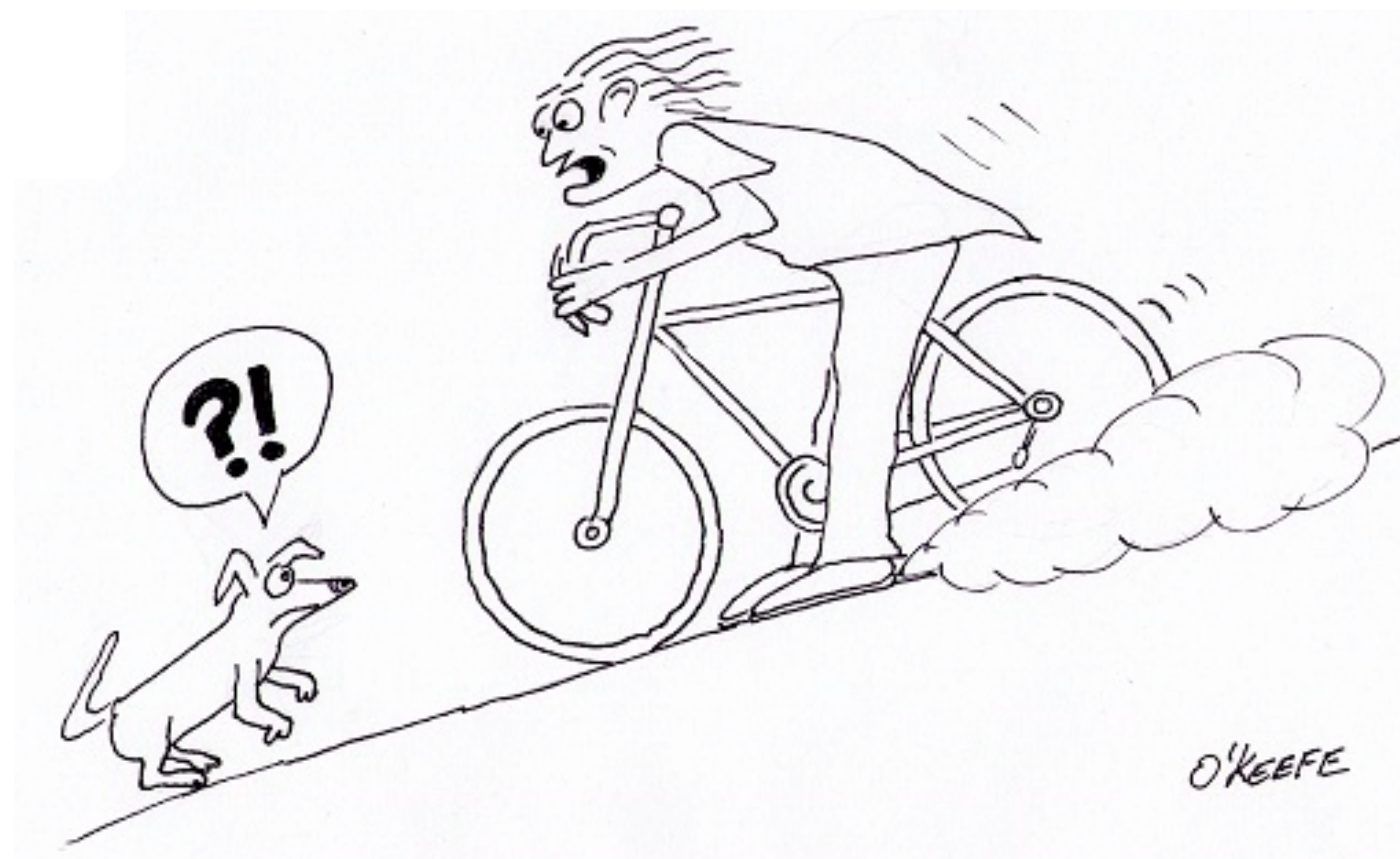

Local Poincare invariance is lost at the Planck scale

BUT energy-momentum is conserved in general relativity

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

$$\Downarrow$$

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

As a consequence of Bianchi identities

BUT energy-momentum is conserved in general relativity

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

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

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

Some violations allowed in Unimodular gravity

$$S = \int \sqrt{g}R + \lambda(\sqrt{g} - \sqrt{g_0})$$ ➡ $$R_{ab} - \frac{1}{4}Rg_{ab} = \frac{8\pi G}{c^4}\left(T_{ab} - \frac{1}{4}Tg_{ab}\right)$$

Vacuum fluctuations do not gravitate. S. Weinberg 1989

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

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

Also from Bianchi identities and the UG field equations

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

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

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

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

PART 3:

A model for ***Dark Energy*** from fundamental constants.

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

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

$$\frac{i}{\gamma^\mu p_\mu - m_0 + i\epsilon} \rightarrow \frac{if(|\mathbf{p}|/\Lambda)}{\gamma^\mu p_\mu - m_0 + \Delta(|\mathbf{p}|/\lambda) + i\epsilon},$$

$$\frac{i}{p^2 - M_0^2 + i\epsilon} \rightarrow \frac{i\tilde{f}(|\mathbf{p}|/\Lambda)}{p^2 - M_0^2 + \tilde{\Delta}(|\mathbf{p}|/\lambda) + i\epsilon}.$$

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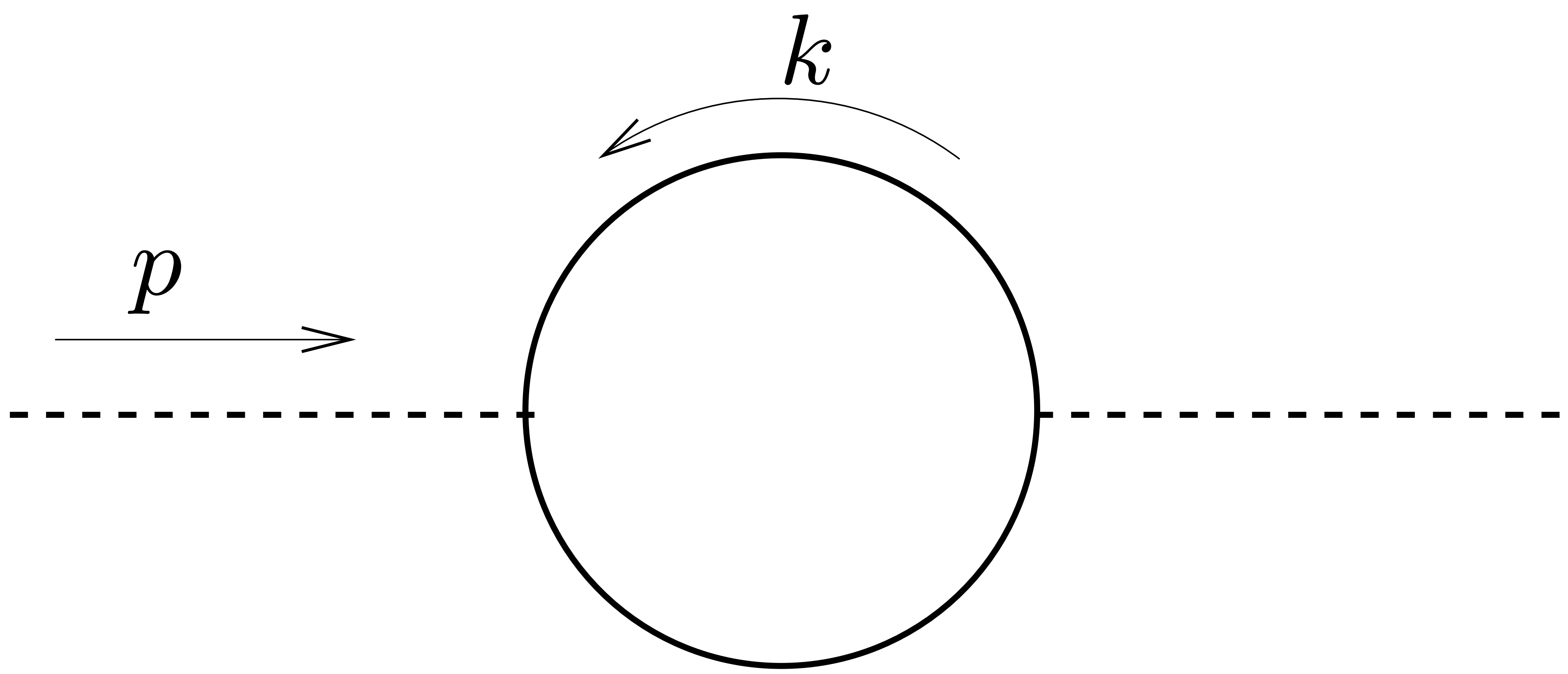
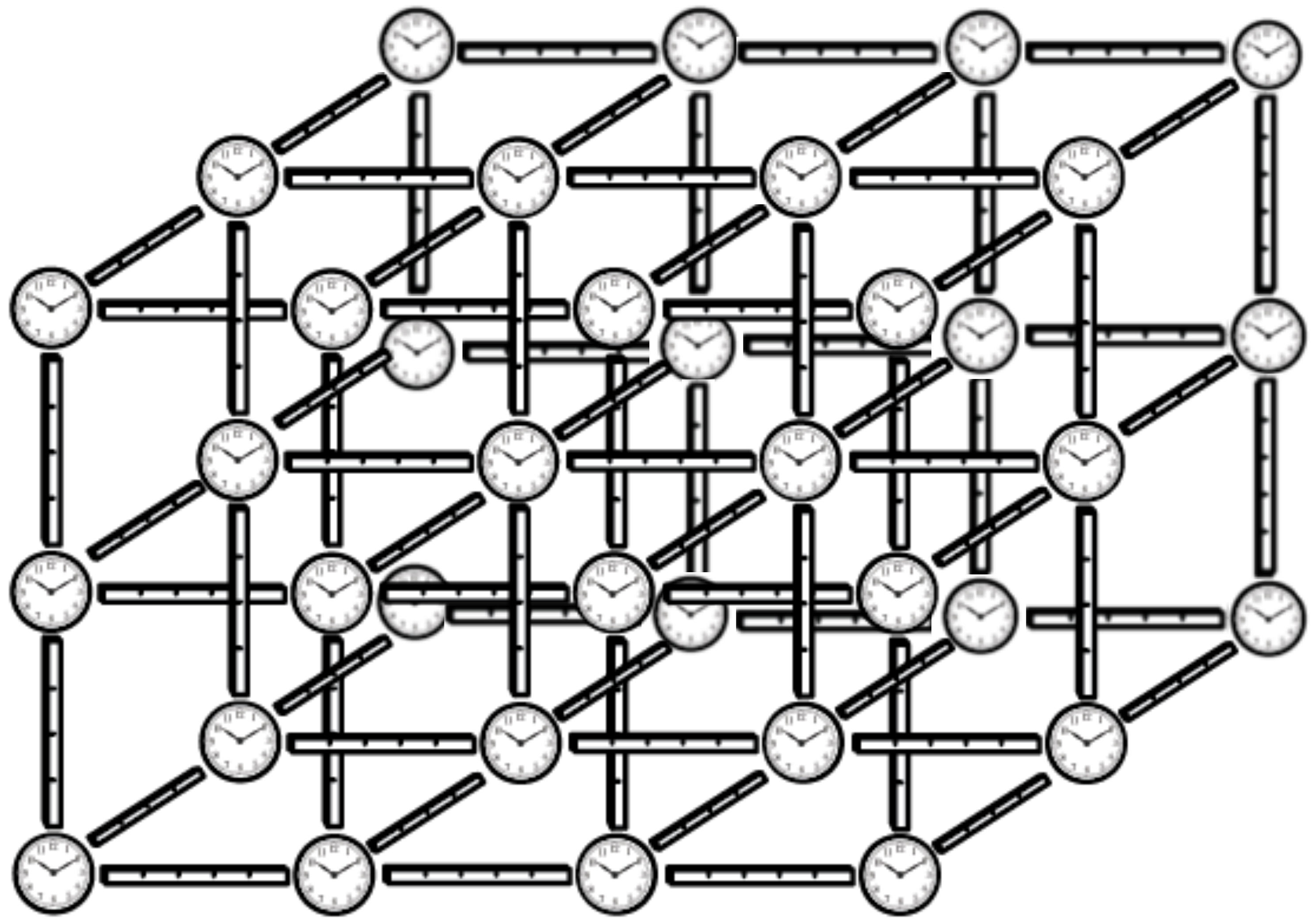


$$\Pi(p) = A + p^2 B + p^\mu p^\nu W_\mu W_\nu \tilde{\xi} + \Pi^{(\mathrm{LI})}(p^2) + \mathcal{O}(p^4/\Lambda^2)$$

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

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

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"

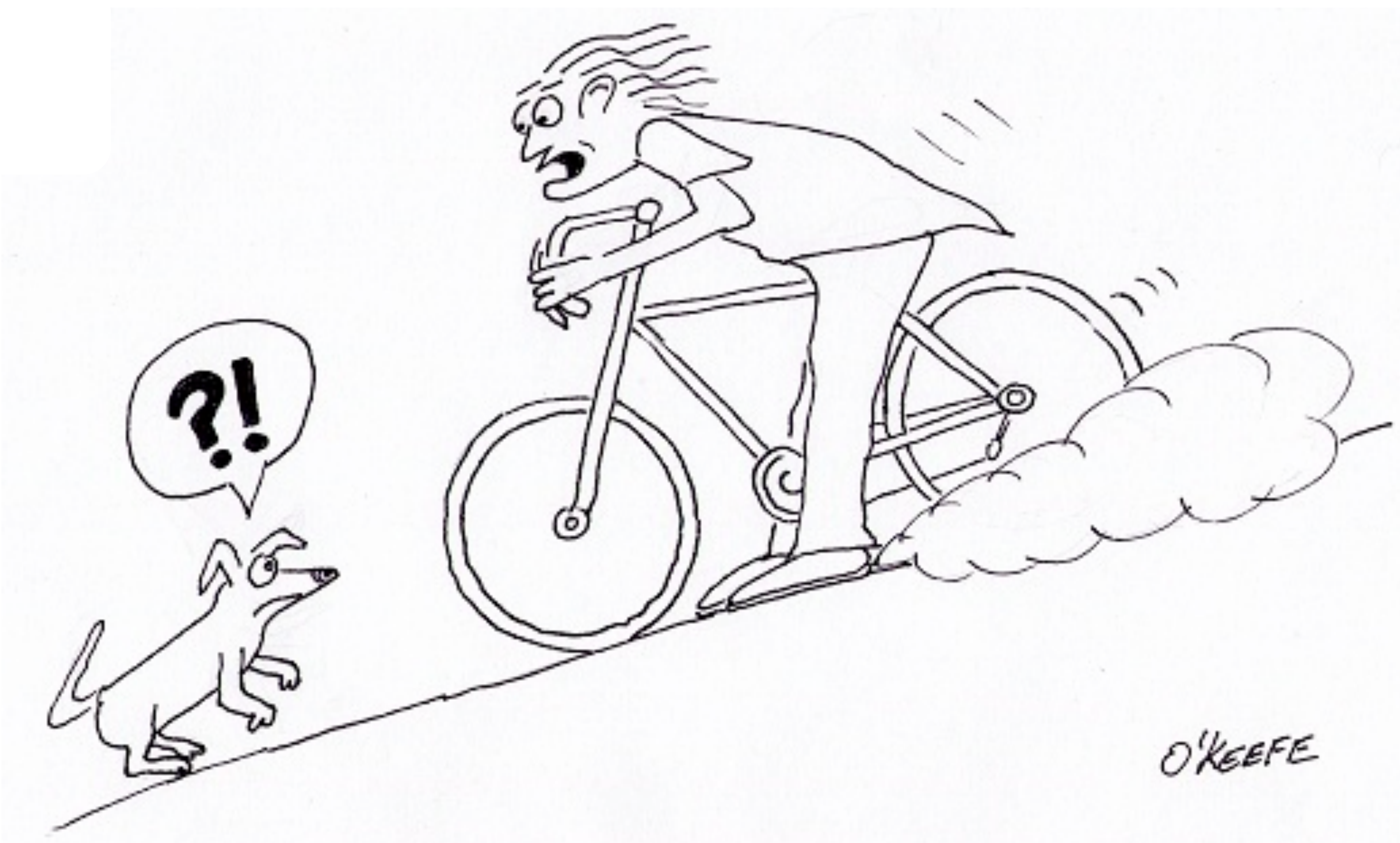
$$R = 8\pi G T = 8\pi G(\rho - 3P)$$

This notion encodes in a MEAN FIELD manner the interaction of the matter degrees of freedom with fundamental discreteness

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

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

Dark energy term



In FLRW cosmology:

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

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

$\alpha \equiv$ dimensionless constant

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

Results are in remarkable agreement with observations

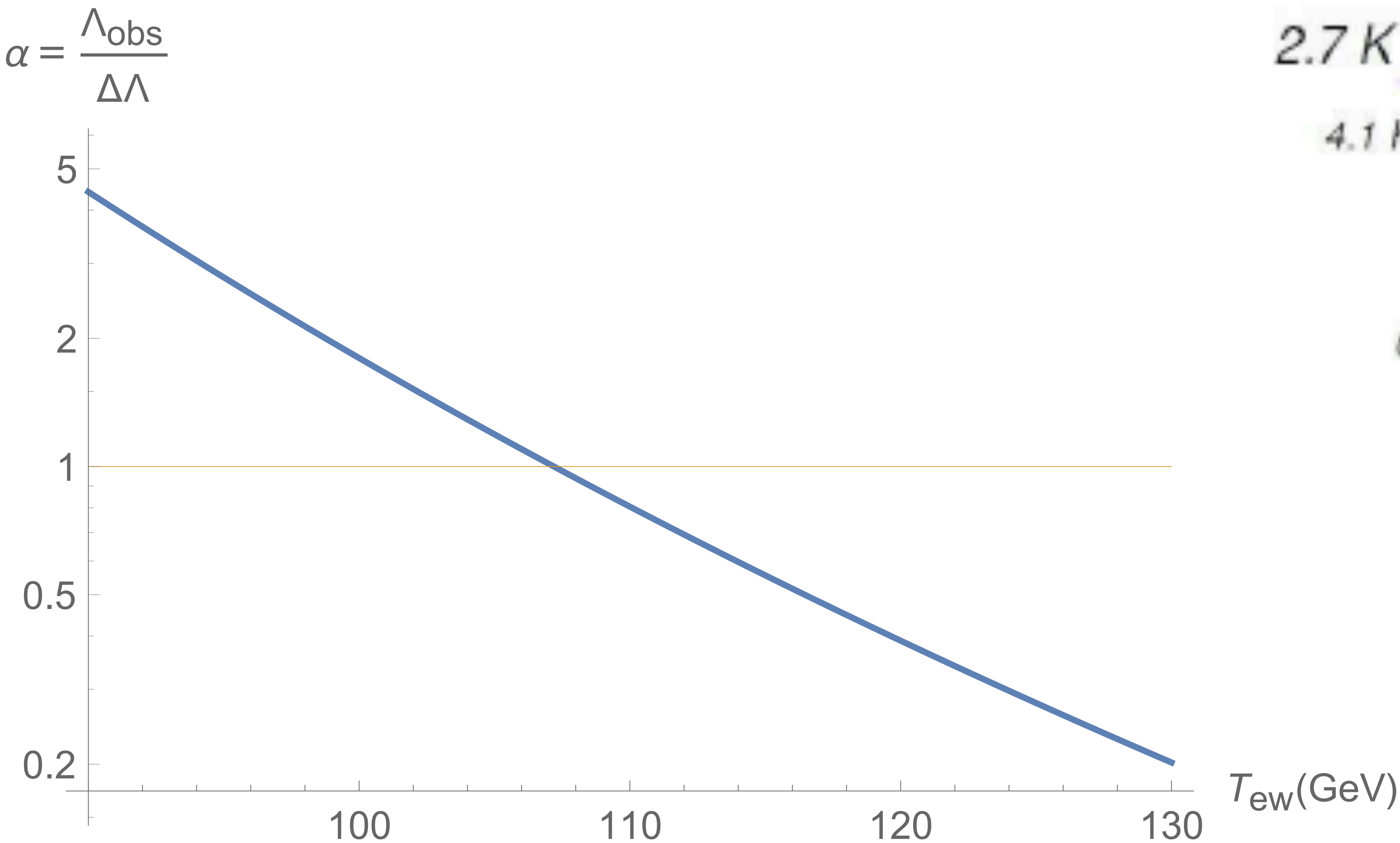
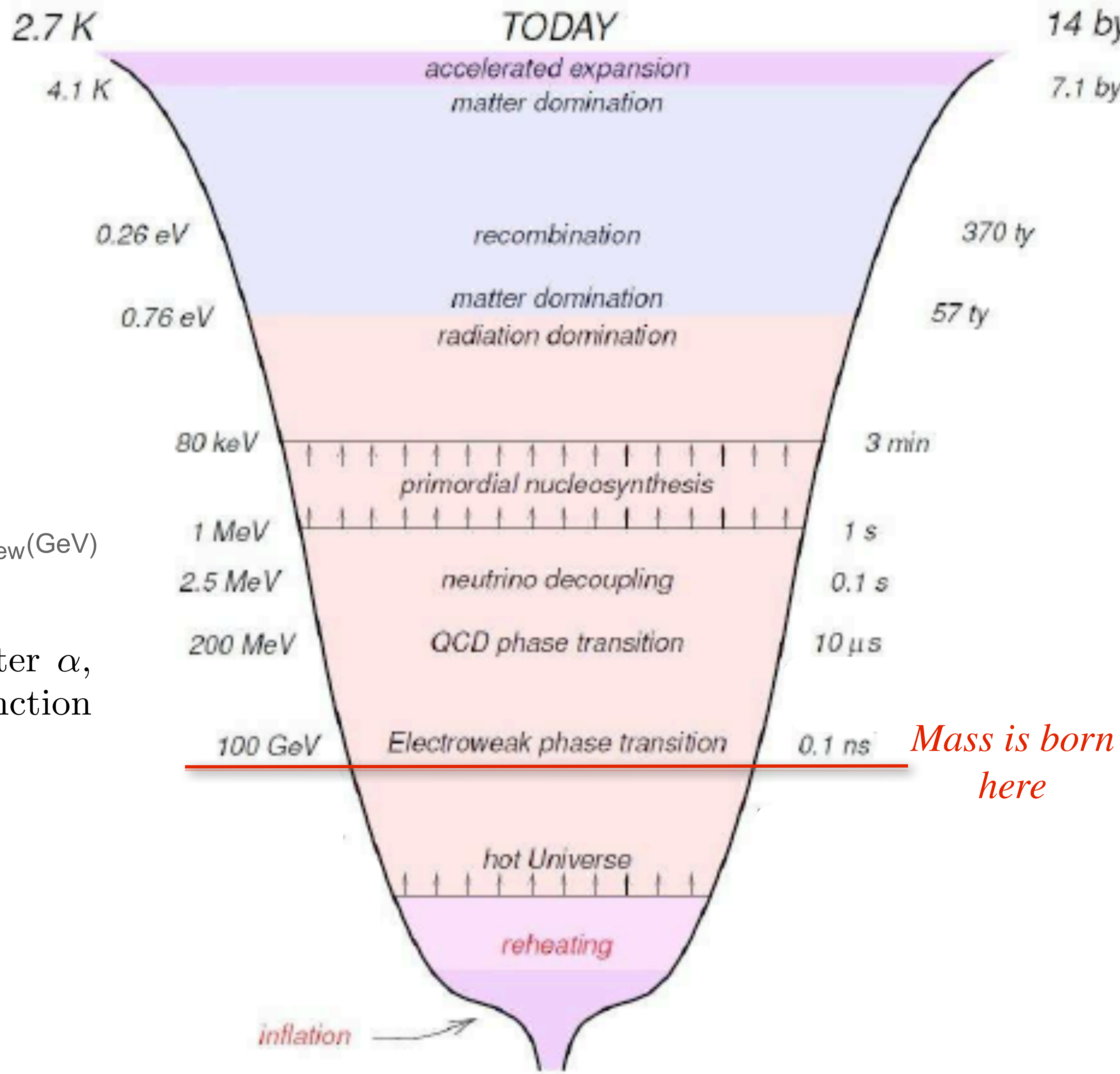


Figure 1. The value of the phenomenological parameter α, see eq. (6), that fits the observed value of Λ_{obs} as a function of the electro-weak transition scale $T_{\rm ew}$ in GeV.

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



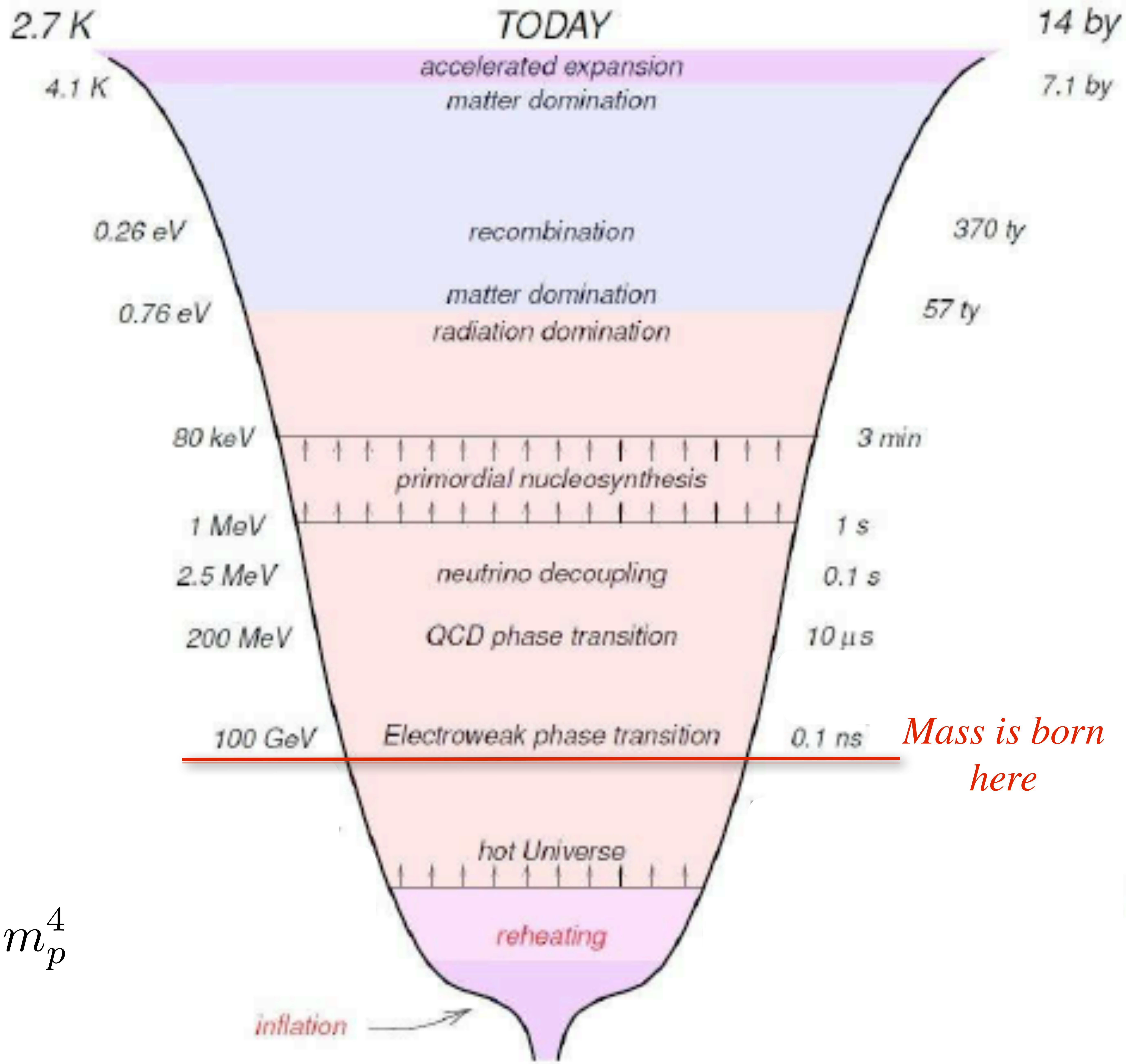
The calculation

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

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

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

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



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 described 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?

Outlook

Conditions for Baryogenesis: A.D. Sakharov 1967

1. Baryon number is not conserved.
2. CP violation
3. Out of equilibrium process (thermal equilibrium makes CPT symmetry undo what was built by (1) and (2)).

New possible mechanism

The EW transition triggers CP violation as well as the QG effect presented here!

1. Baryon number is not conserved.
2. CP violation
3. CPT is violated by QG discreteness.


Merci
Beaucoup!

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

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

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

Order parameter for discreteness probes:
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Preferred conformal structure in cosmology

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Order parameter for discreteness probes:
scalar curvature

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

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

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

```
\begin{itemize}

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