A possible microscopic source of the accelerating expansion of the universe

Based on work in collaboration with Daniel Sudarsky

Dark Energy, IAP

October, 2018

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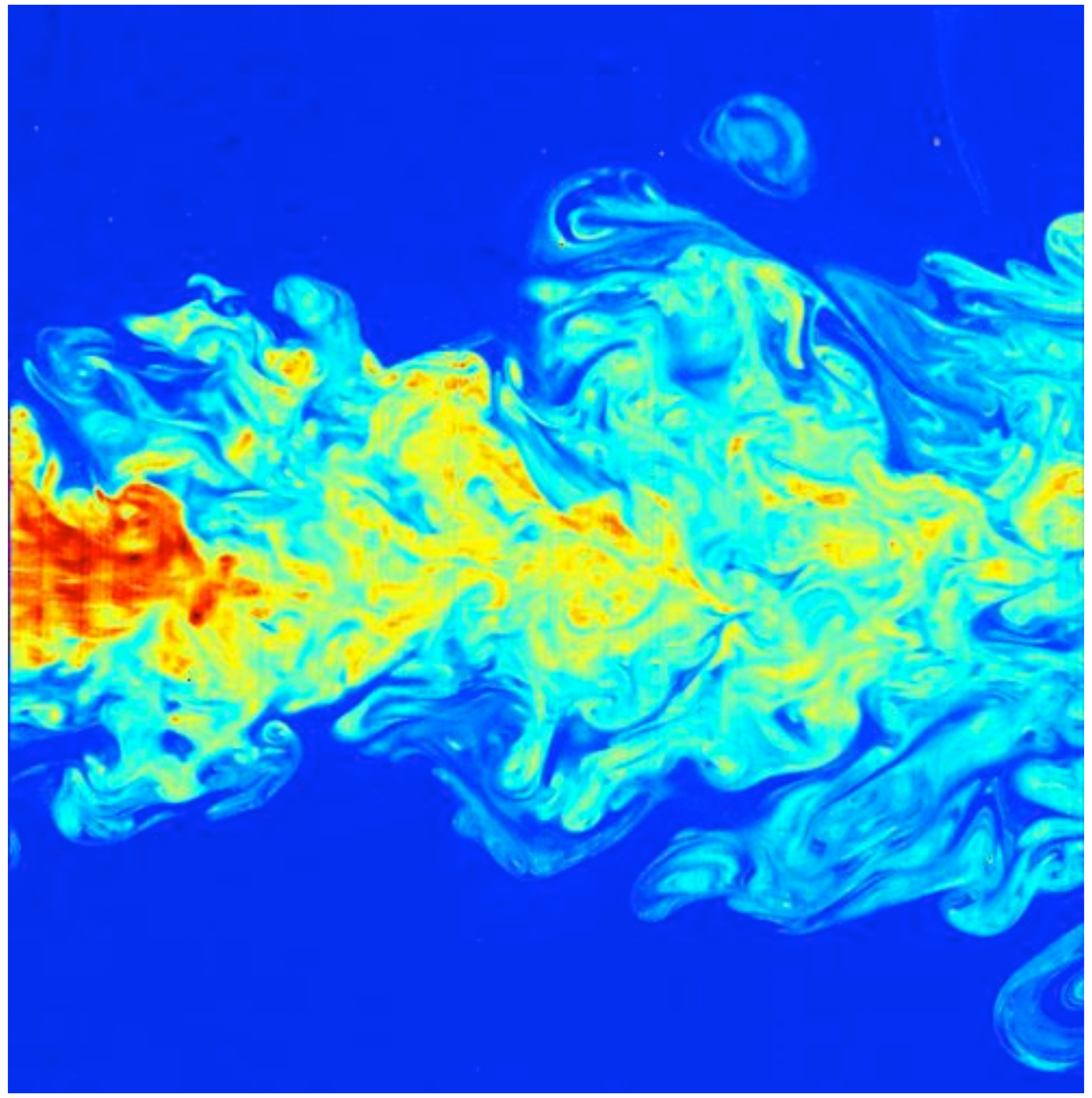
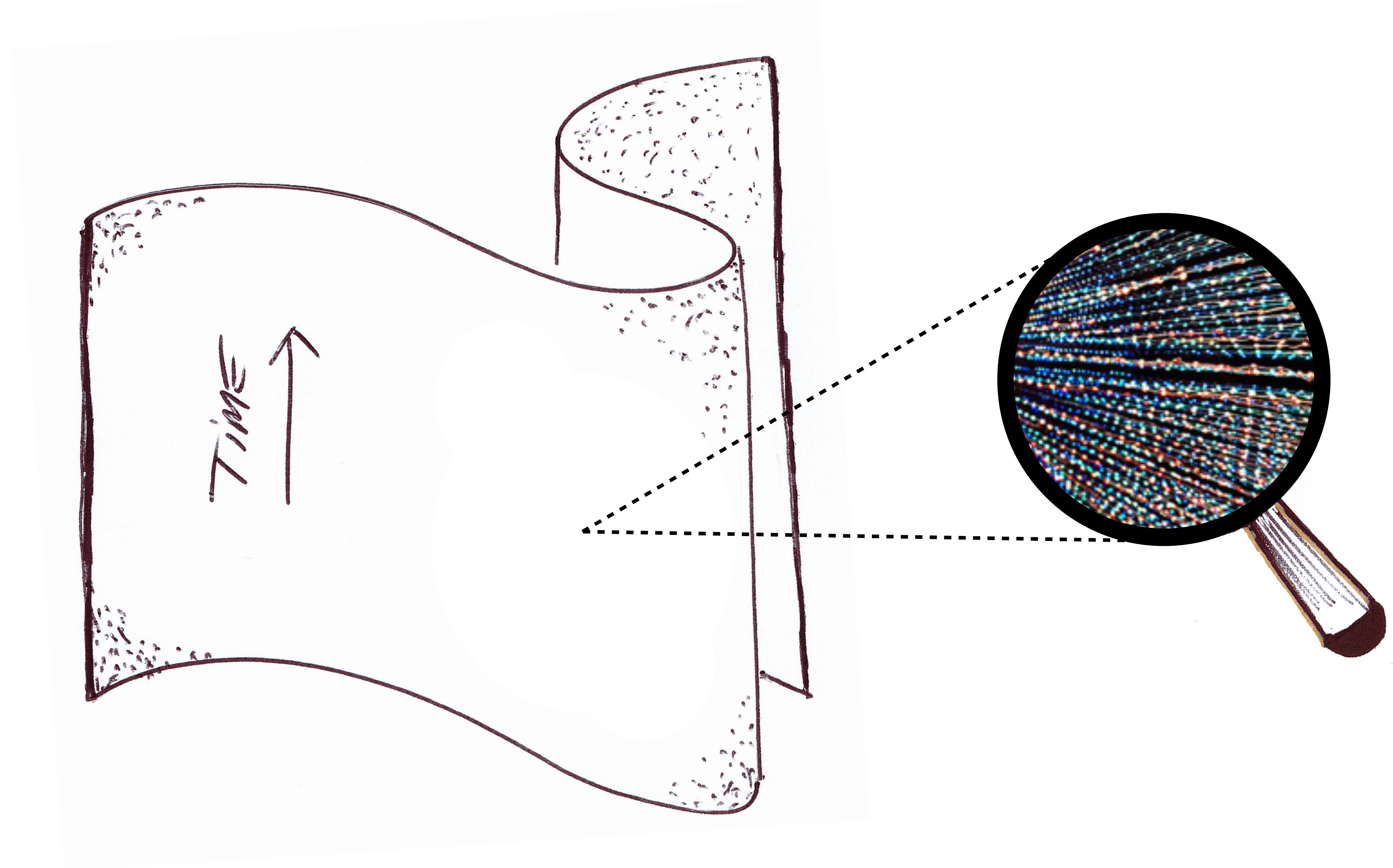
Mathematical description of fluids
(**Navier-Stokes**)



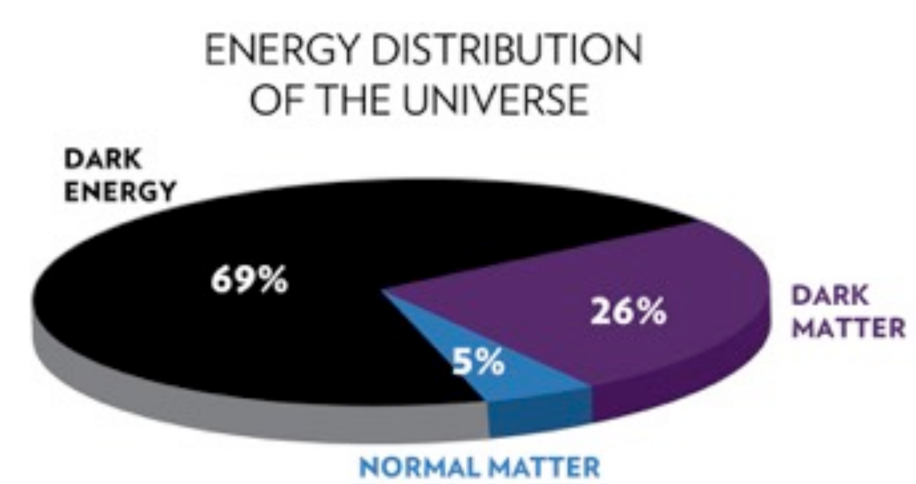
Continuous fluid description breaks down at molecular scales.

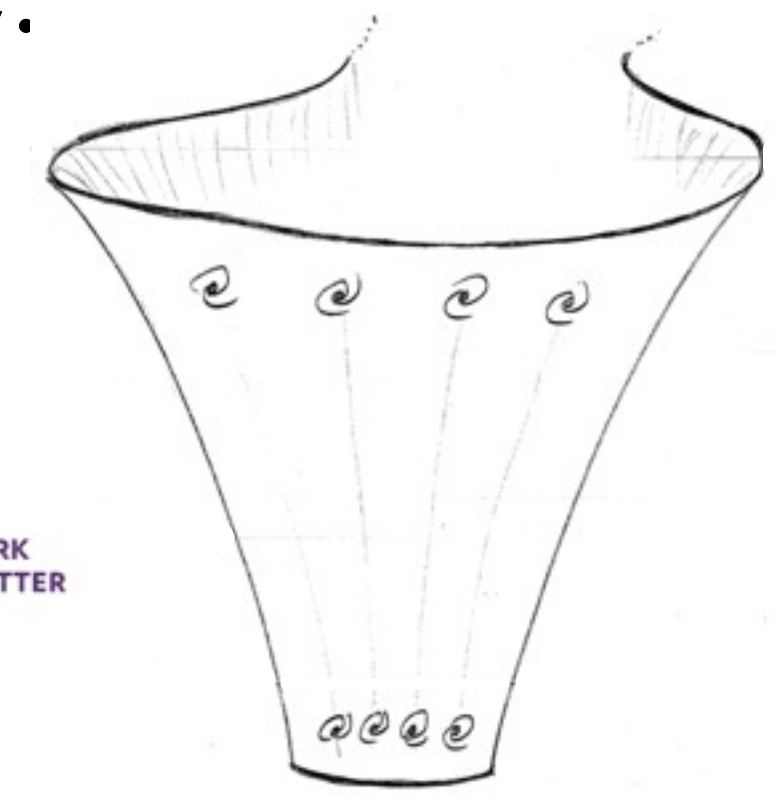
Mathematical description of gravity
General Relativity



The continuum spacetime description breaks down at the Planck scale.

Effective violation of energy conservation!





The cosmological constant problem

$$\mathbf{R}_{ab} - \frac{1}{2} g_{ab}\mathbf{R} = 8\pi \mathbf{T}_{ab} - \Lambda g_{ab}$$

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

How does the vacuum gravitate?

$$\langle \mathbf{T}_{ab} \rangle = \frac{\Lambda_{vac}}{8\pi G} \ g_{ab}$$

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

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

Three related ideas by Einstein on gravity

1) General Relativity
(1916)

$$\mathbf{R}_{ab} - \frac{1}{2} g_{ab} \mathbf{R} = 8\pi \mathbf{T}_{ab}$$

Bianchi Identities

$$\nabla^a \mathbf{T}_{ab} = 0$$

2) The cosmological constant
(1917)

$$\mathbf{R}_{ab} - \frac{1}{2} g_{ab} \mathbf{R} = 8\pi \mathbf{T}_{ab} - \Lambda g_{ab}$$

Bianchi Identities

3) Unimodular Gravity
(1919)

$$\mathbf{R}_{ab} - \frac{1}{4} g_{ab} \mathbf{R} = 8\pi \left(\mathbf{T}_{ab} - \frac{1}{4} g_{ab} \mathbf{T} \right) \quad \text{with} \quad \nabla^a \mathbf{T}_{ab} = 0$$

Weinberg 1987

$$\langle \mathbf{T}_{ab} \rangle = \frac{\Lambda_{vac}}{8\pi G} \, g_{ab}$$

The vacuum does not gravitate in UG

Unimodular Gravity:

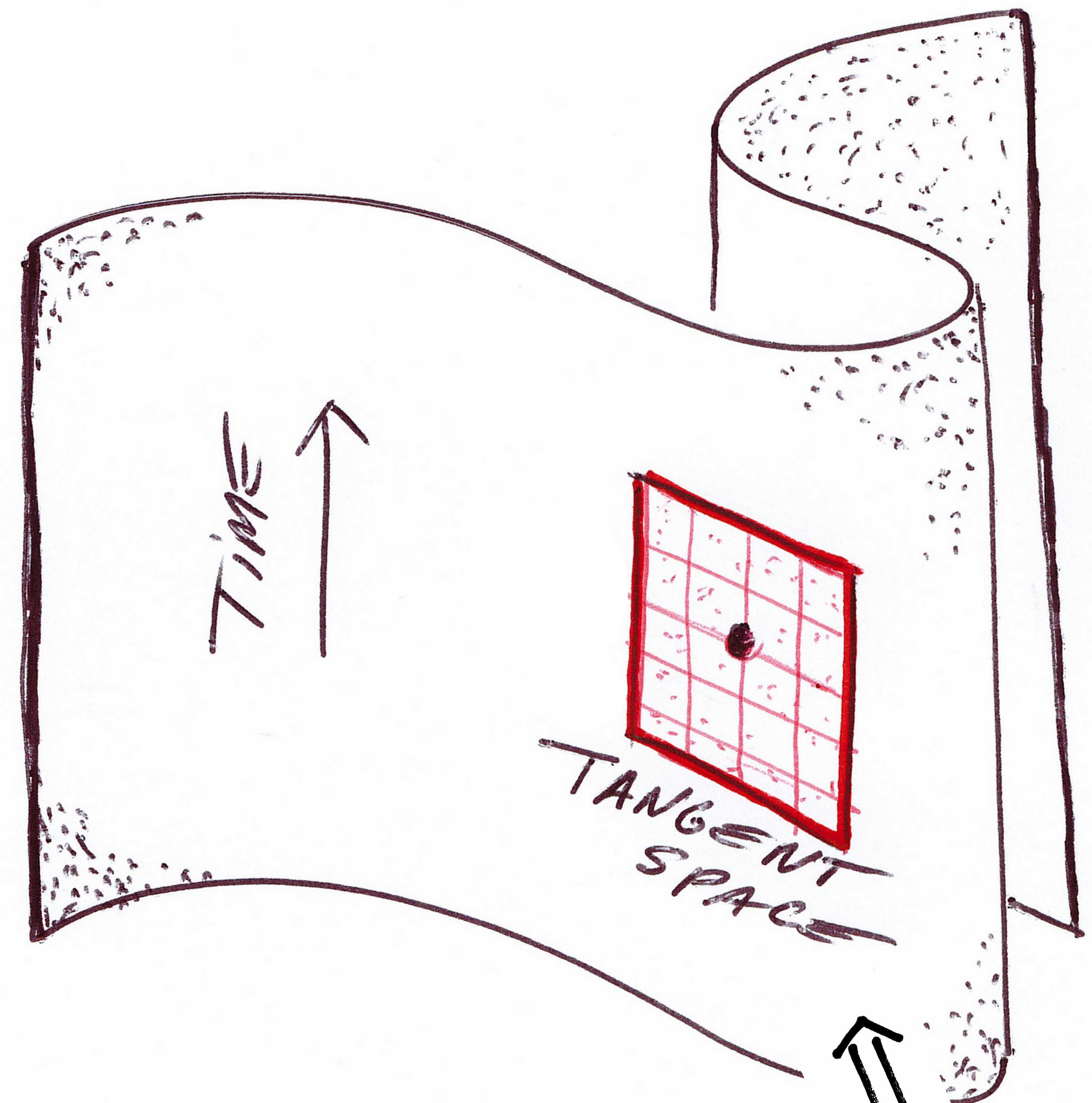
Equivalent to General Relativity:
with a cosmological constant as a constant of integration!

$$\langle \mathbf{T}_{ab} \rangle = \frac{\Lambda_{vac}}{8\pi G}\, g_{ab}$$

The vacuum does not gravitate in UG

$\Leftarrow$

Conservation of Energy:
symmetries of tangent space



Granted by field equations due to symmetries of the tangent space.

$\Updownarrow$

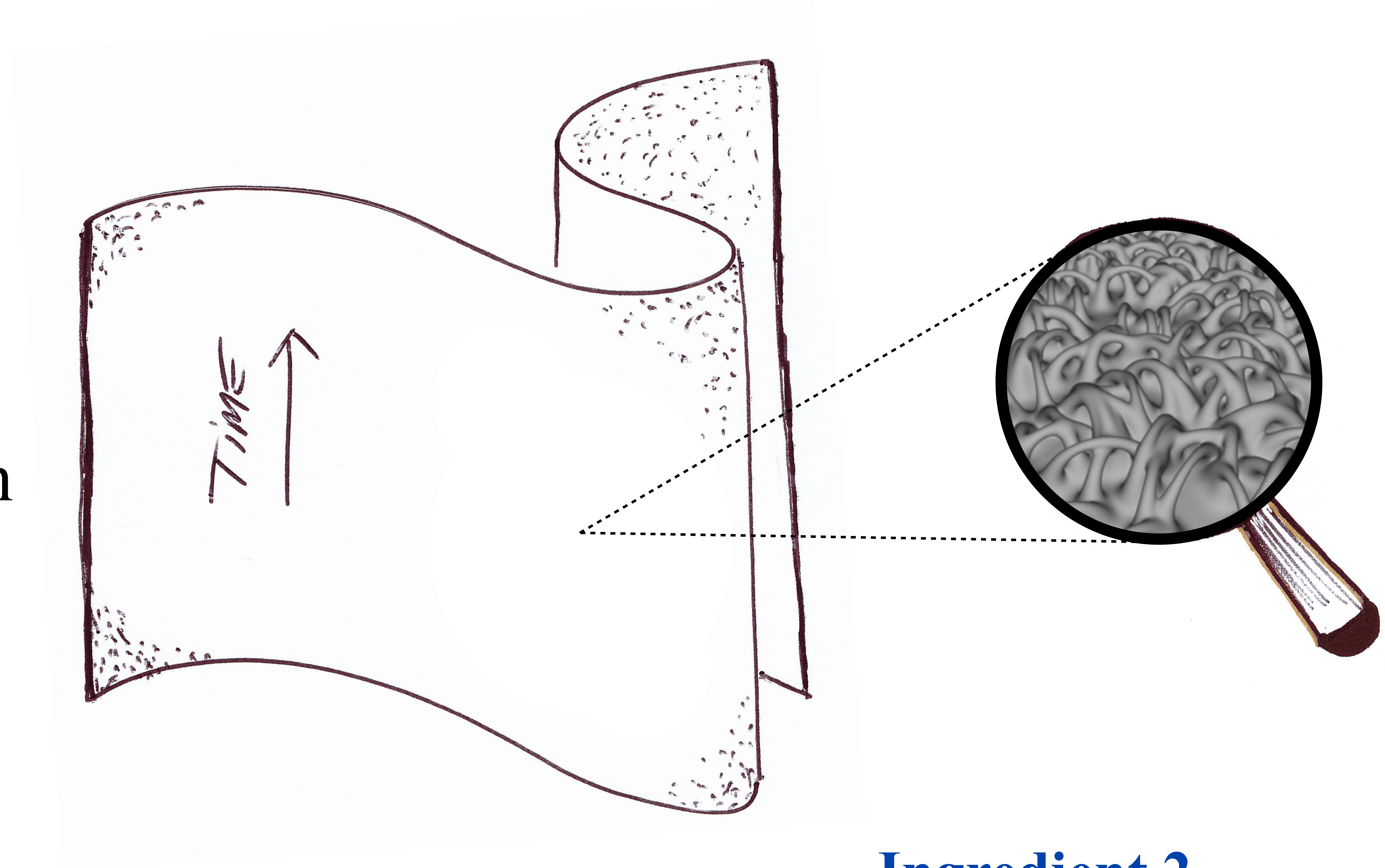
$$\nabla^a \mathbf{T}_{ab} = 0$$

$\Uparrow$

Traceless Einstein's Equations:

$$\mathbf{R}_{ab} - \frac{1}{4} g_{ab}\mathbf{R} = 8\pi \left(\mathbf{T}_{ab} - \frac{1}{4} g_{ab}\mathbf{T} \right)$$

Conservation of Energy: fails if spacetime is not smooth at the Planck scale



Unimodular Gravity

UG is a natural generalization of GR as an open system

Ingredient 1

$$\mathbf{R}_{ab} - \frac{1}{4} g_{ab} \mathbf{R} = 8\pi \left(\mathbf{T}_{ab} - \frac{1}{4} g_{ab} \mathbf{T} \right)$$

Ingredient 2

$$\nabla^a \mathbf{T}_{ab} = 0$$

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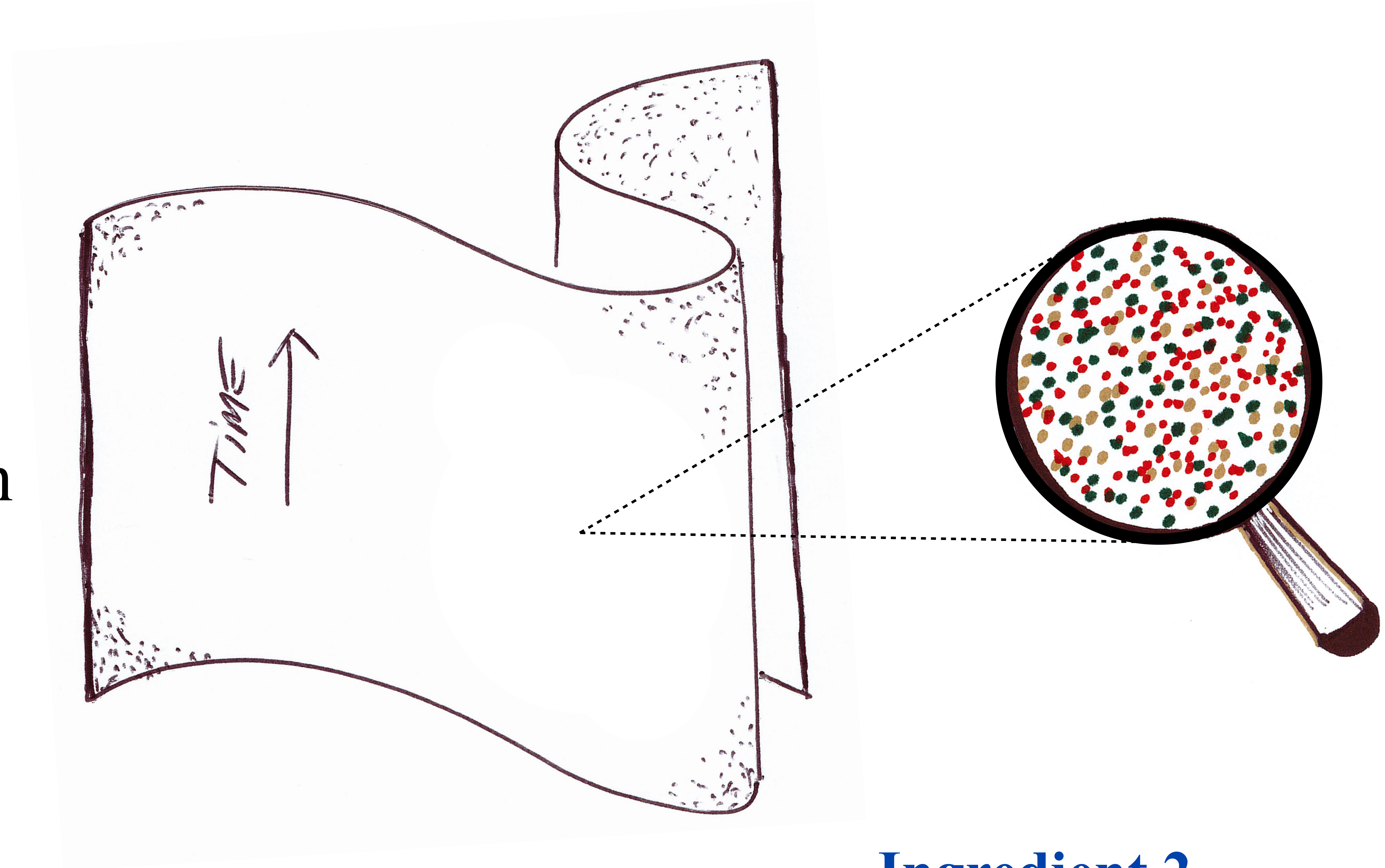

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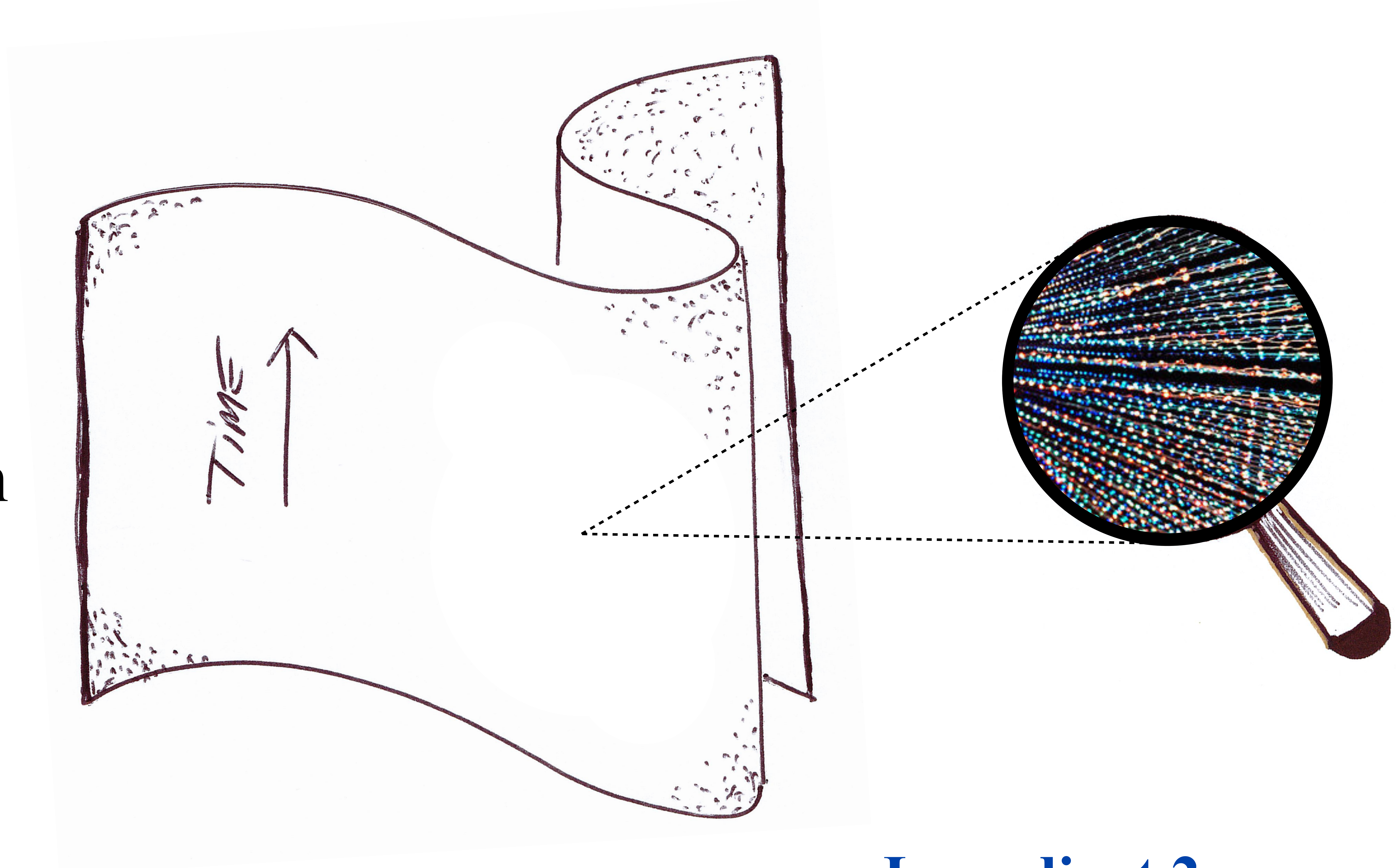

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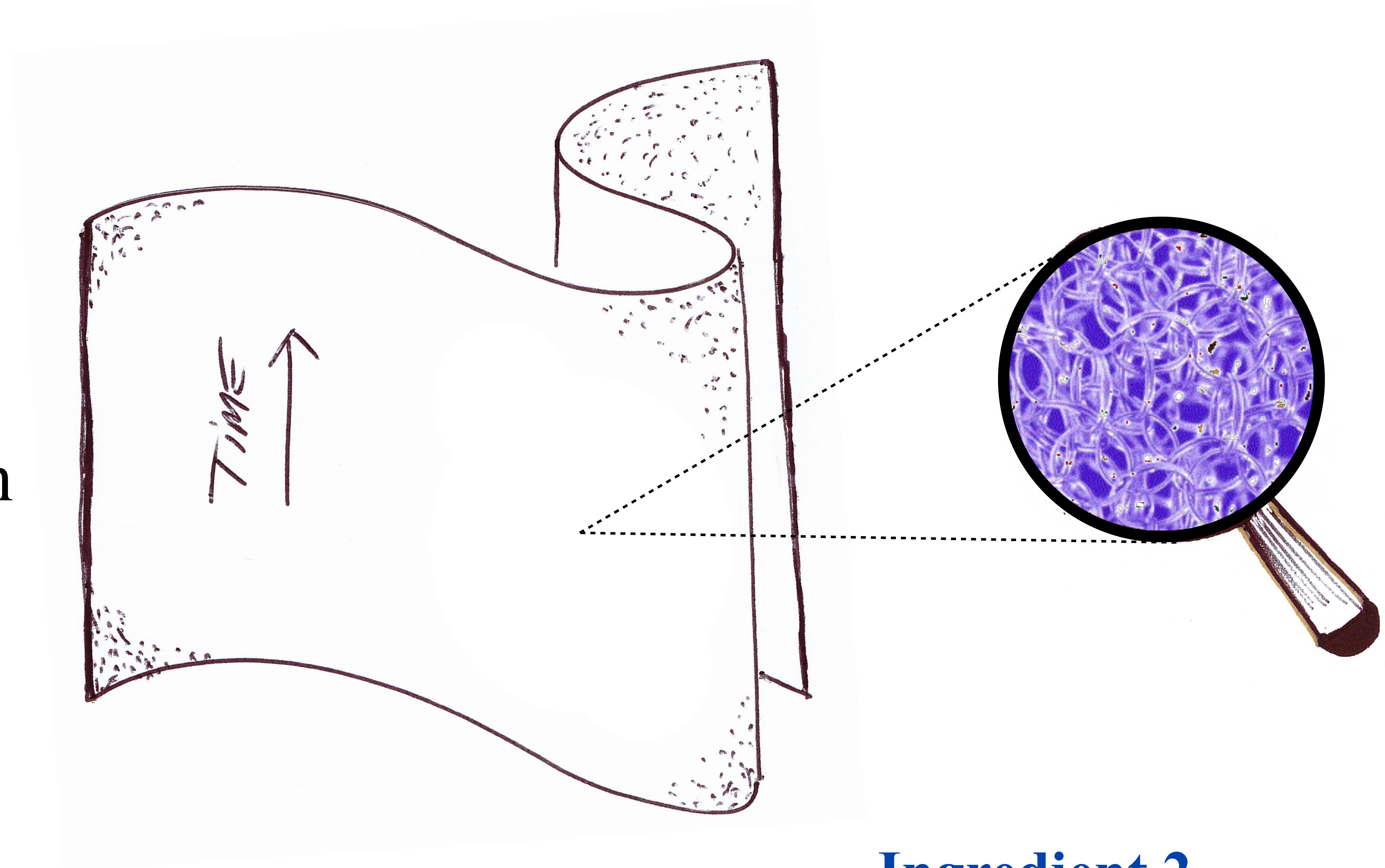

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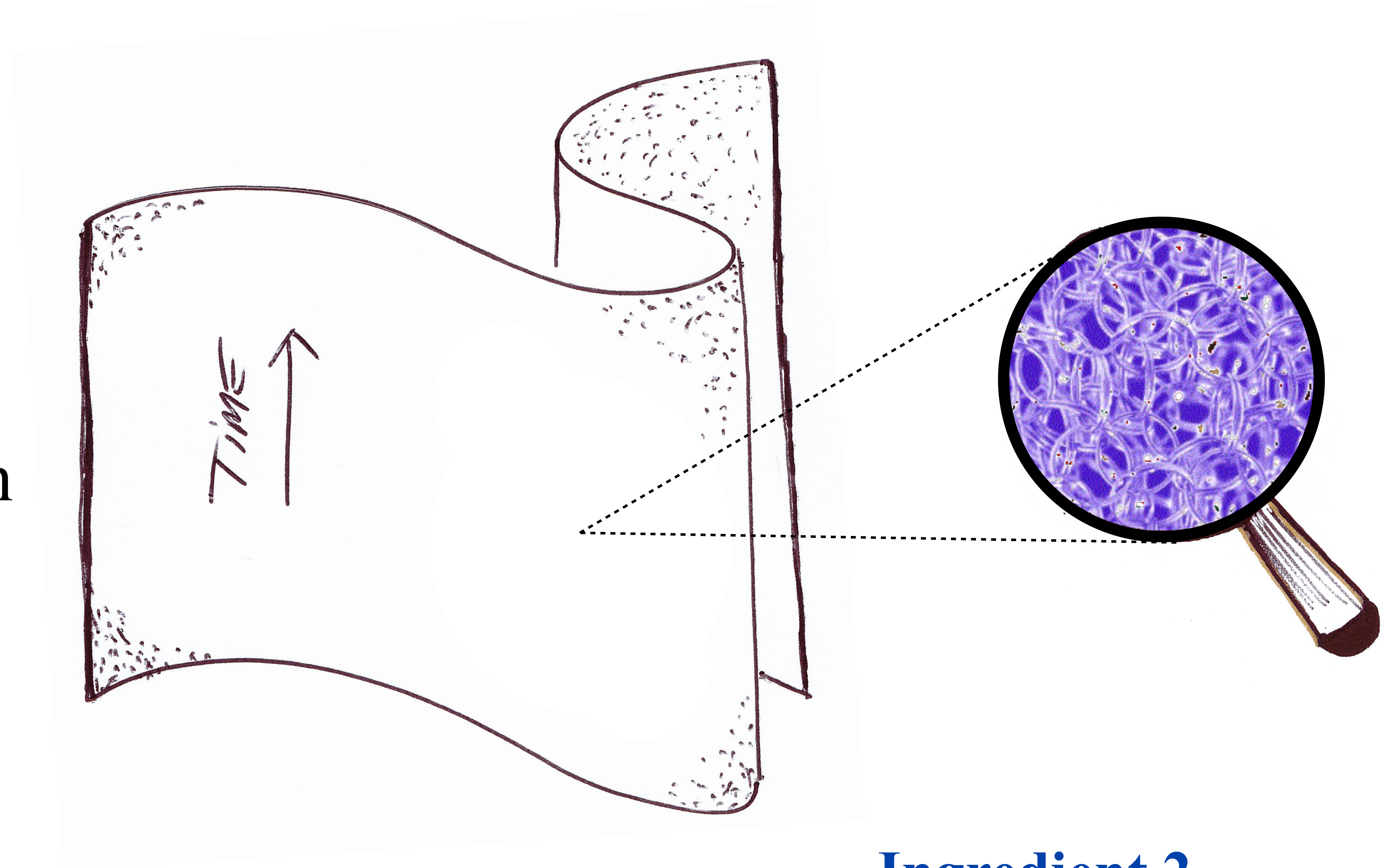

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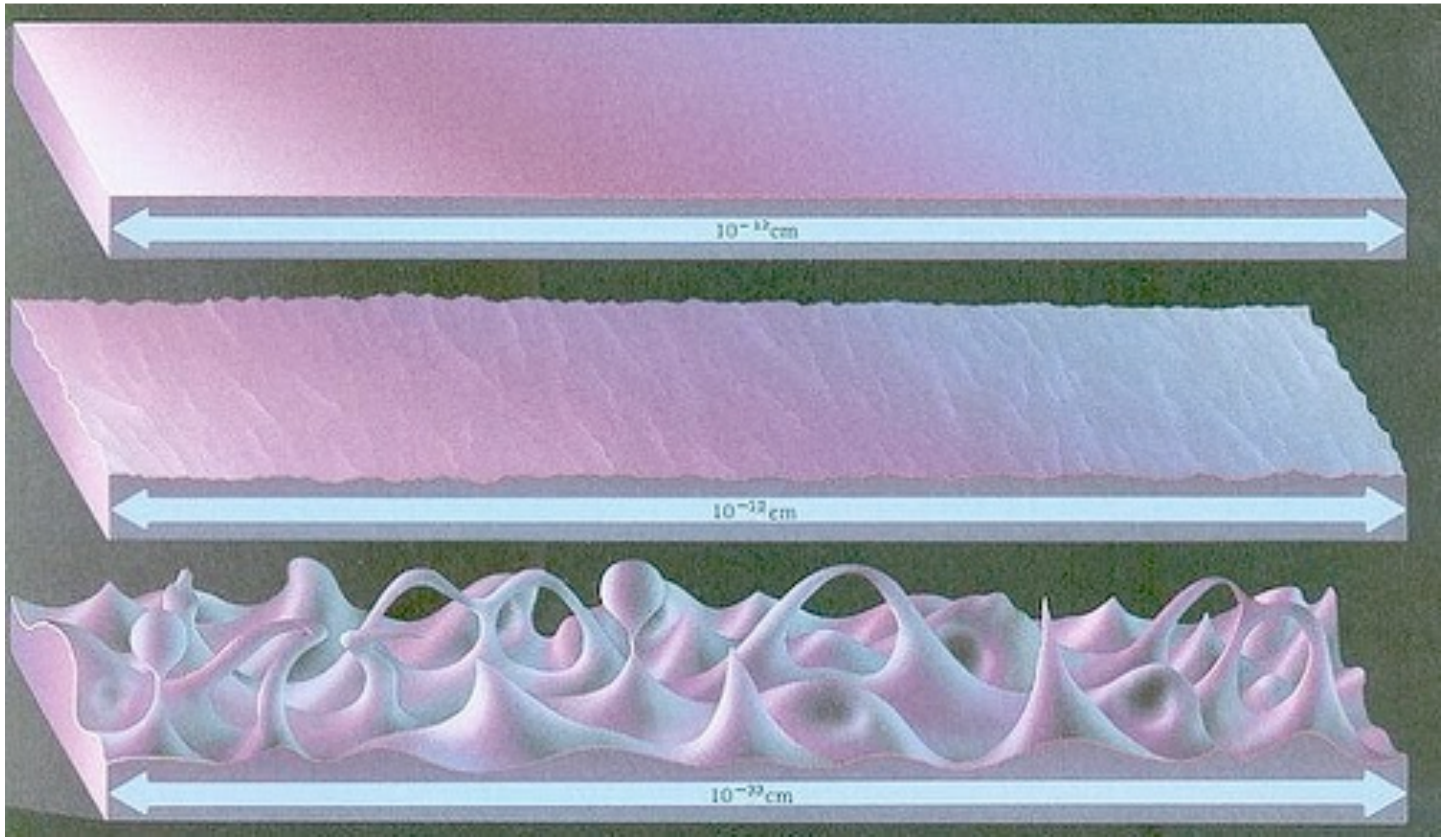
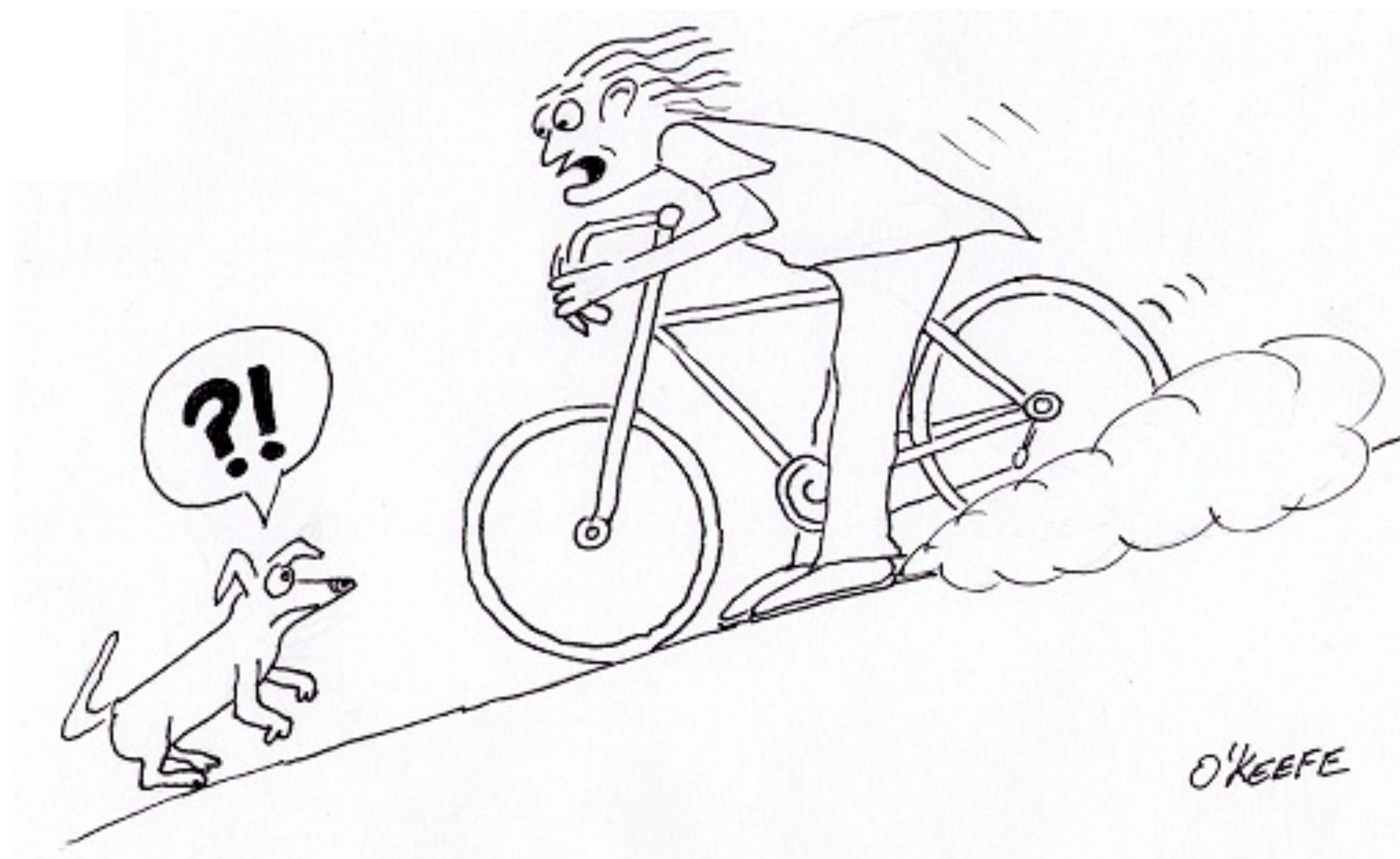
Ingredient 2

$$\nabla^a \mathbf{T}_{ab} = 0$$

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

Unimodular Gravity without energy conservation

Trace free Einstein's equations

$$\mathbf{R}_{ab} - \tfrac{1}{4}\mathbf{R}g_{ab} = 8\pi\left(\mathbf{T}_{ab} - \tfrac{1}{4}\mathbf{T}g_{ab}\right)$$

$$\underbrace{\mathbf{R}_{ab} - \frac{1}{2}\mathbf{R}g_{ab}}_{\mathbf{G}_{ab}} + \tfrac{1}{4}\mathbf{R}g_{ab} = 8\pi\left(\mathbf{T}_{ab} - \tfrac{1}{4}\mathbf{T}g_{ab}\right)$$

$$\tfrac{1}{4}\nabla_b\left(\mathbf{R} + 8\pi\mathbf{T}\right) = 8\pi\nabla^a\mathbf{T}_{ab}$$

$$\mathbf{J}_b \equiv 8\pi\nabla^a\mathbf{T}_{ab}$$

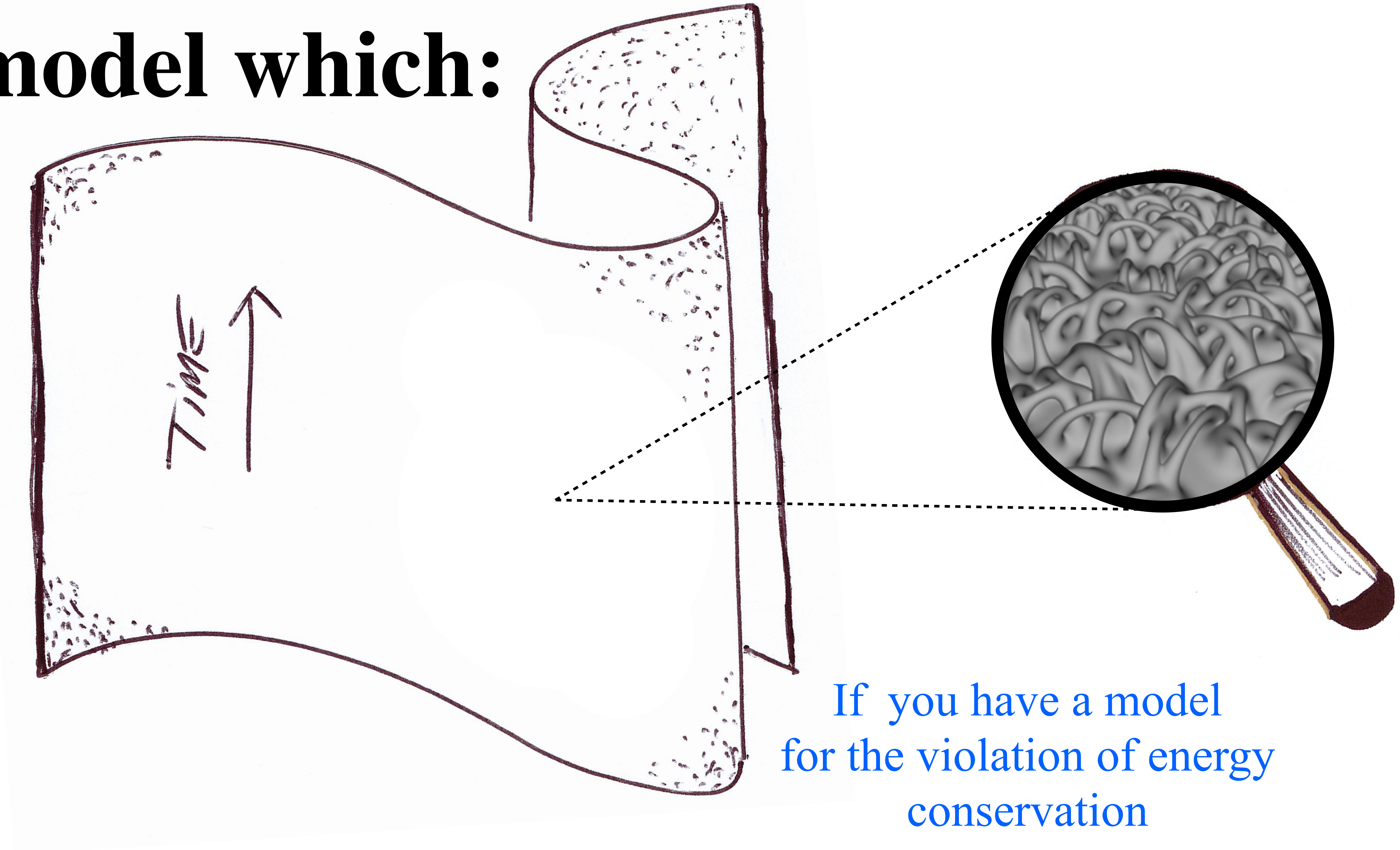
Need to satisfy the integrability condition

$$d\mathbf{J} = 0$$

$$\mathbf{R}_{ab} - \frac{1}{2}\mathbf{R}g_{ab} = 8\pi\mathbf{T}_{ab} - \underbrace{\left[\Lambda_0 + \int_\ell \mathbf{J}\right]}_{\text{Dark Energy } \Lambda} g_{ab}$$

Need a phenomenological model which:

- Only depends on fundamental constants.
- Does not require one to arbitrarily set an initial time for diffusion.



If you have a model for the violation of energy conservation

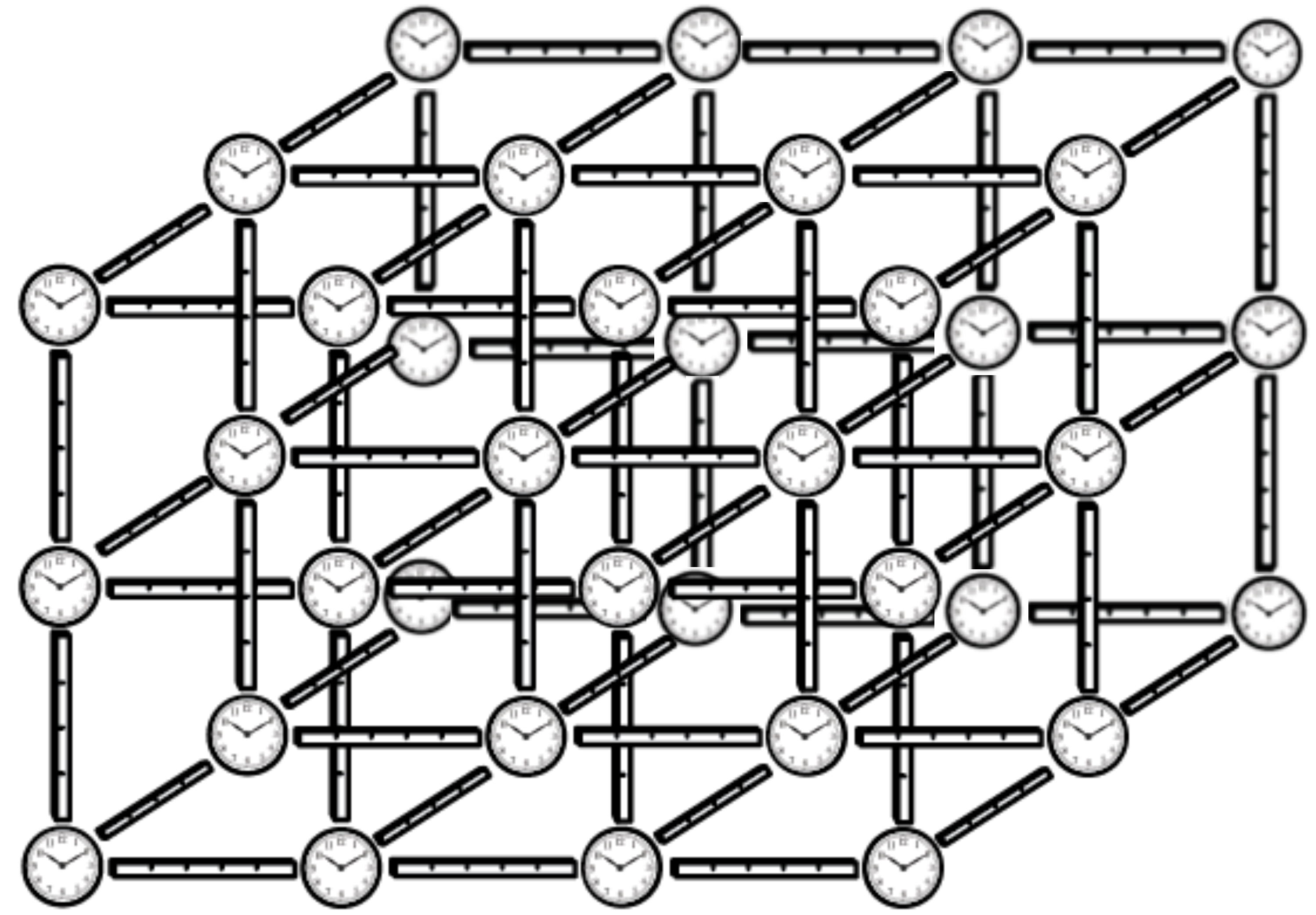
$$\mathbf{J}_b \equiv 8\pi \nabla^a \mathbf{T}_{ab}$$

$$\Downarrow$$

$$\mathbf{R}_{ab} - \frac{1}{2}\mathbf{R} g_{ab} = 8\pi \mathbf{T}_{ab} - \underbrace{\left[\Lambda_0 + \int_\ell \mathbf{J}\right]}_{\text{Dark Energy } \Lambda} g_{ab}$$

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

To probe **Planck scale**
we need a **breaking of**
scale invariance
(need a ruler!)



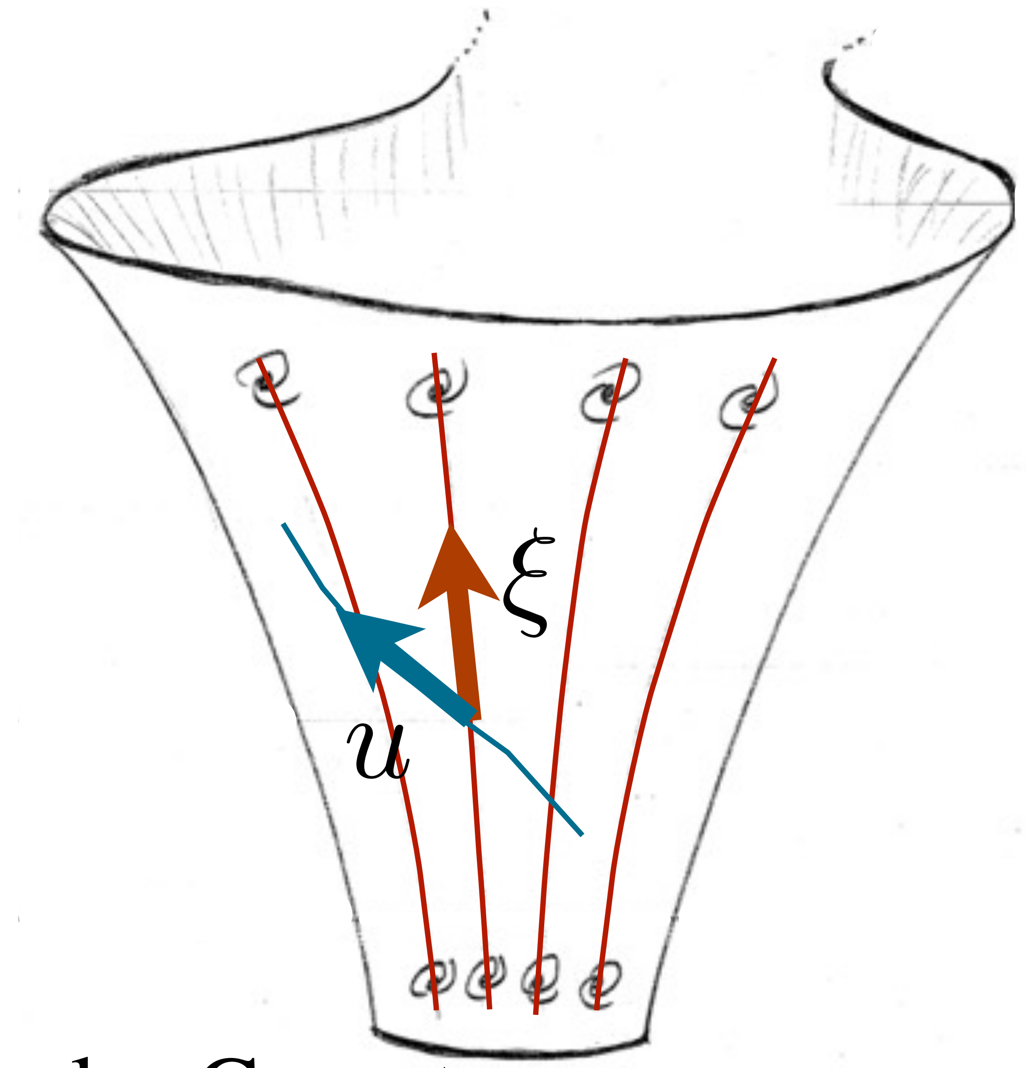
Scalar curvature is the natural "order parameter"

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

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

A mesoscopic model for Planckian friction:

The effect on a test particle



particle mass

$$a^b = u^a \nabla_a u^b = -\alpha \, \mathrm{sign}(s \cdot \xi) \frac{m\mathbf{R}}{m_p^2} s^b$$

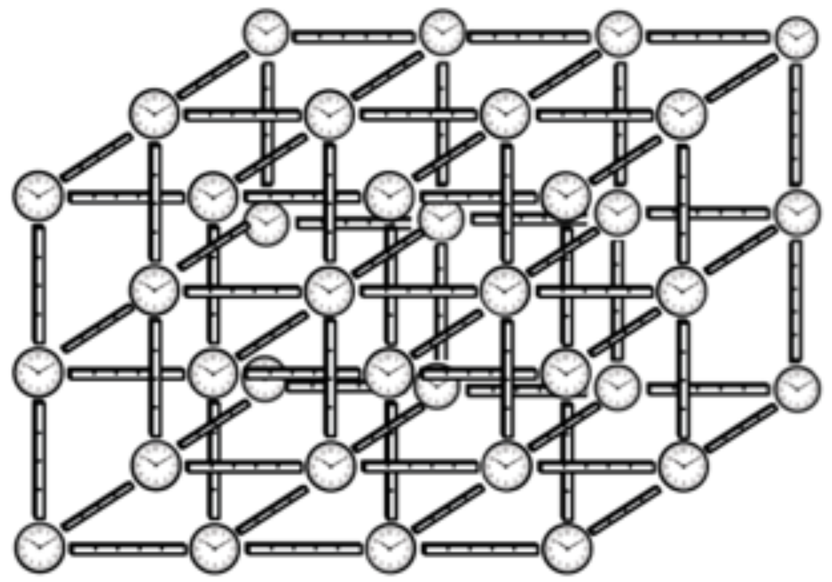
Scalar Curvature

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

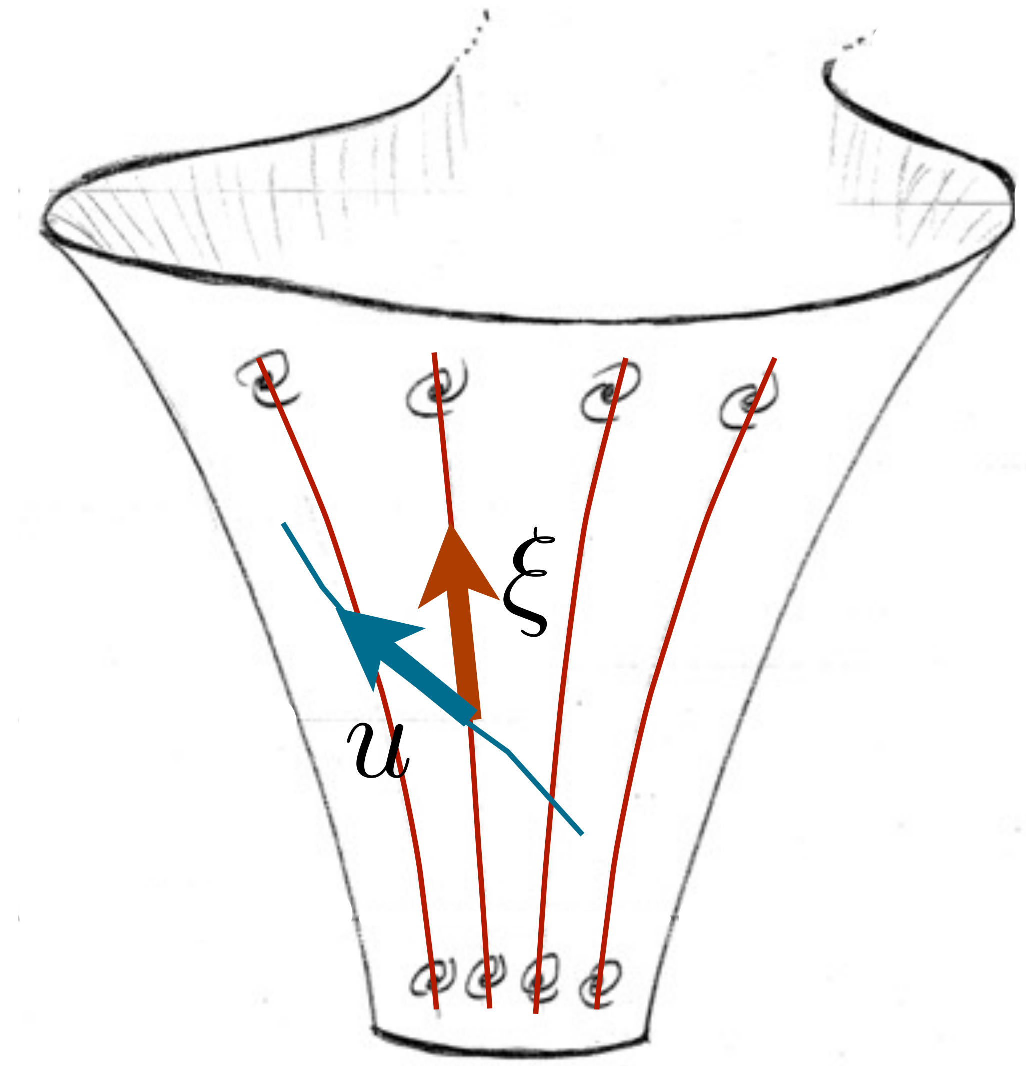
dimensionless constant

particle spin

A mesoscopic model for Planckian friction:



Relational nature of discreteness in quantum gravity $\Longrightarrow$ Scale invariant matter does not **suffer** nor **sources** friction force



$$a^b = u^a \nabla_a u^b = \alpha\, \mathrm{sign}(s\cdot\xi)\, \frac{m\mathbf{R}}{m_p^2}\, s^b$$

$$\ddot{X} = -\gamma \dot{X} + \xi(t)$$

Langevin-like equation

$$\dot{E} \equiv -m u^\mu \nabla_\mu (u^\nu \xi_\nu) = -\alpha \frac{m^2}{m_p^2} |(s\cdot\xi)| \mathbf{R} - m u^\mu u^\nu \nabla_{(\mu}\xi_{\nu)}$$

Other similar looking equations

$$a^b = u^a \nabla_a u^b = \alpha \, \mathrm{sign}(s \cdot \xi) \frac{m\mathbf{R}}{m_p^2} \, s^b$$

$$u^\nu \nabla_\nu P_\mu = -\frac{1}{2} \mathbf{R}_{\mu\nu\rho\sigma} u^\nu S^{\rho\sigma}$$

Achille Papapetrou, Proc. Roy. Soc. Lond.,A209:248–258, 1951.

Papapetrou-Dixon equation: motion of a spinning body in curved spacetimes

Other similar looking equations

$$a^b = u^a \nabla_a u^b = \alpha \, \mathrm{sign}(s \cdot \xi) \frac{m\mathbf{R}}{m_p^2} \, s^b$$

$$u^\nu \nabla_\nu (m u_\mu) = -\frac{1}{2} \tilde{\mathbf{R}}_{\mu\nu\rho\sigma} u^\nu \langle S^{\rho\sigma} \rangle + \mathscr{O}(\hbar^2)$$

J. Audretsch, Phys. Rev., D24:1470–1477, 1981.

WKB trajectories: fermions in curved spacetimes with torsion

Other similar looking equations

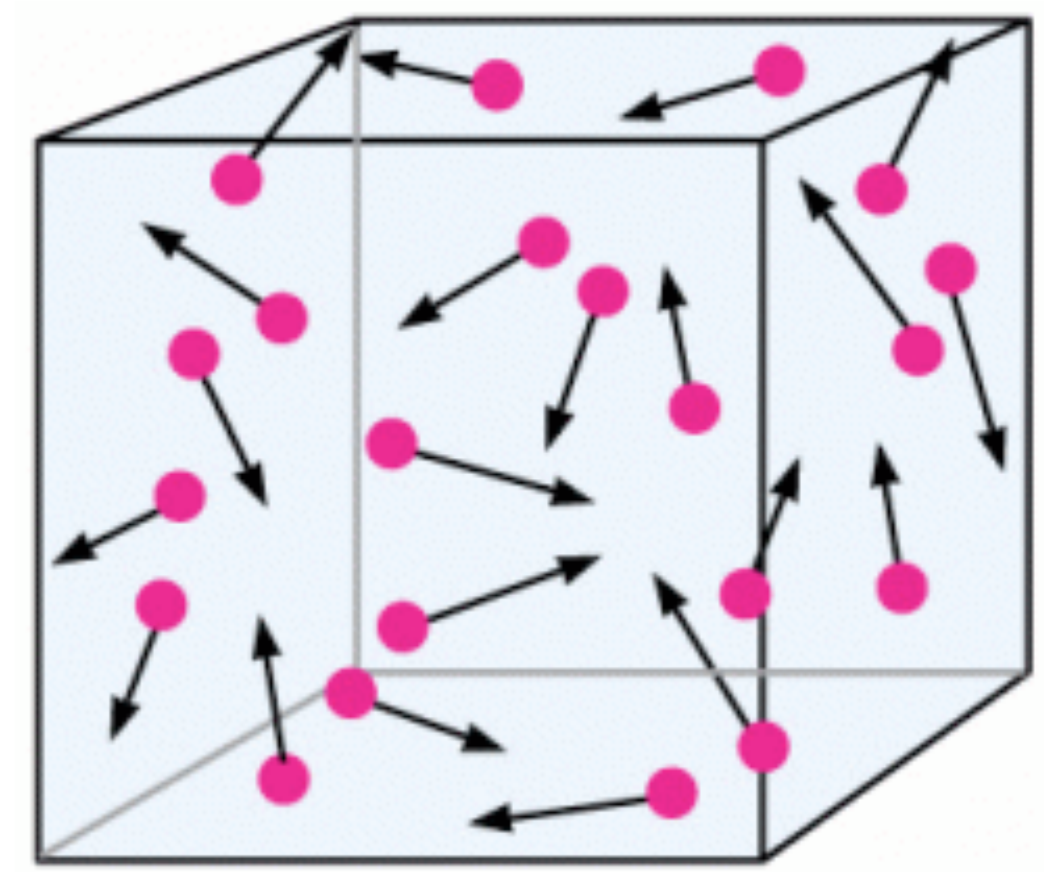
$$a^b = u^a \nabla_a u^b = \alpha\, \mathrm{sign}(s \cdot \xi)\, \frac{m\mathbf{R}}{m_p^2}\, s^b$$

$$\ddot{X} = -\gamma \dot{X} + \xi(t)$$

Langevin Equation

From simple relativistic kinetic theory

$$\mathbf{T}^i_{\mu\nu}(x) \equiv \int p_\mu p_\nu \, f^i(x,p,s_r)\mathrm{D}p\mathrm{D}s_r$$

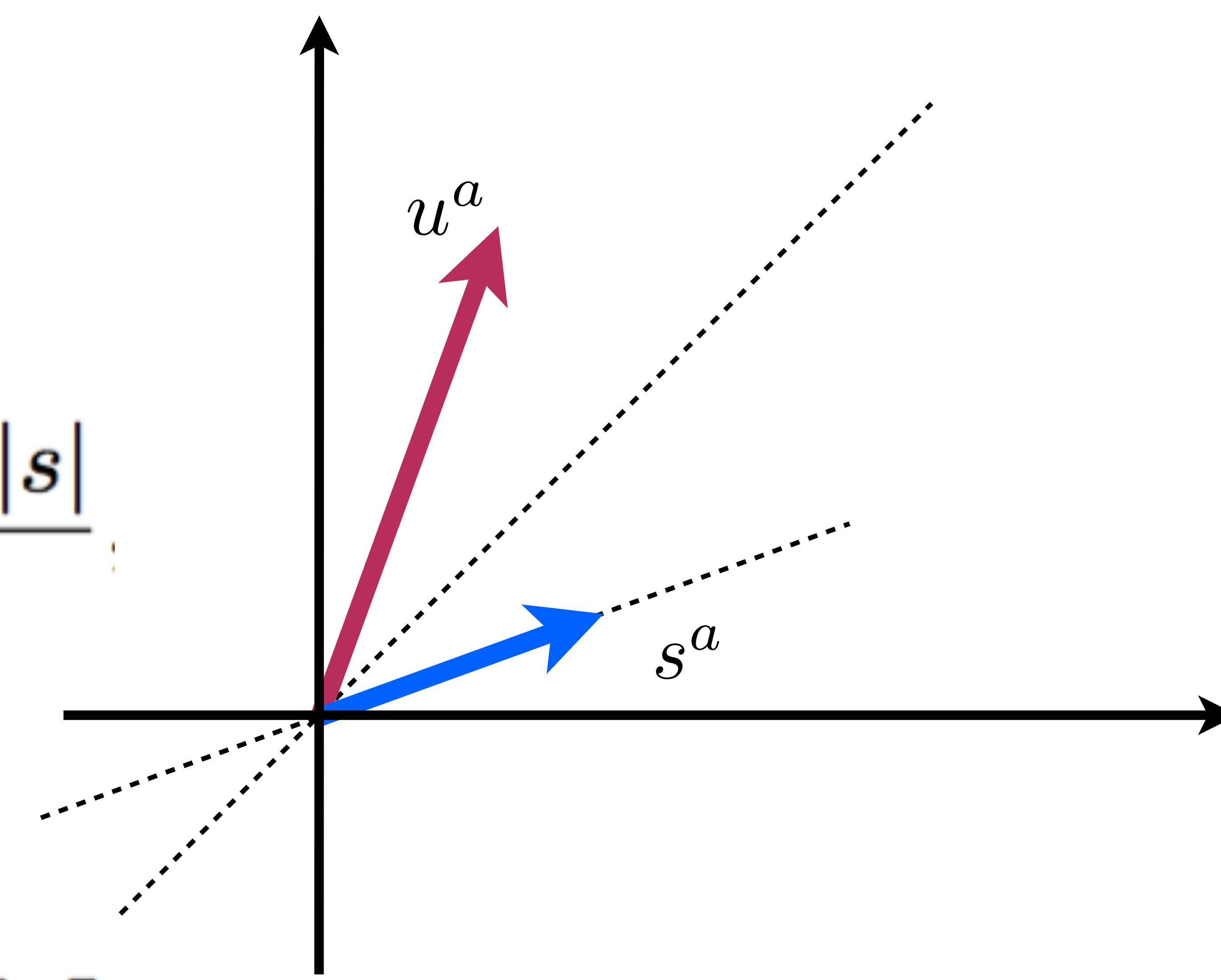


$$a^b = u^a \nabla_a u^b = \alpha \, \mathrm{sign}(s\cdot\xi) \frac{m\mathbf{R}}{m_p^2} \, s^b$$

From probability distribution evolution

$$\frac{\nabla^\mu \mathbf{T}^i_{\mu\nu}}{\mathbf{T}^i} = -\frac{\int m_i F_\nu f^i(x,p,s_r)\mathrm{D}p\mathrm{D}s_r}{m_i^2 \int f^i(x,p,s_r)\mathrm{D}p\mathrm{D}s_r}$$

$$= -\alpha \frac{m_i}{m_p^2}\mathbf{R} \frac{\int \left[\frac{s_\nu s_0}{|s_0|}\right] f^i(x,p,s_r)\mathrm{D}p\mathrm{D}s_r}{\int f^i(x,p,s_r)\mathrm{D}p\mathrm{D}s_r}$$



Isotropy in the spin distribution

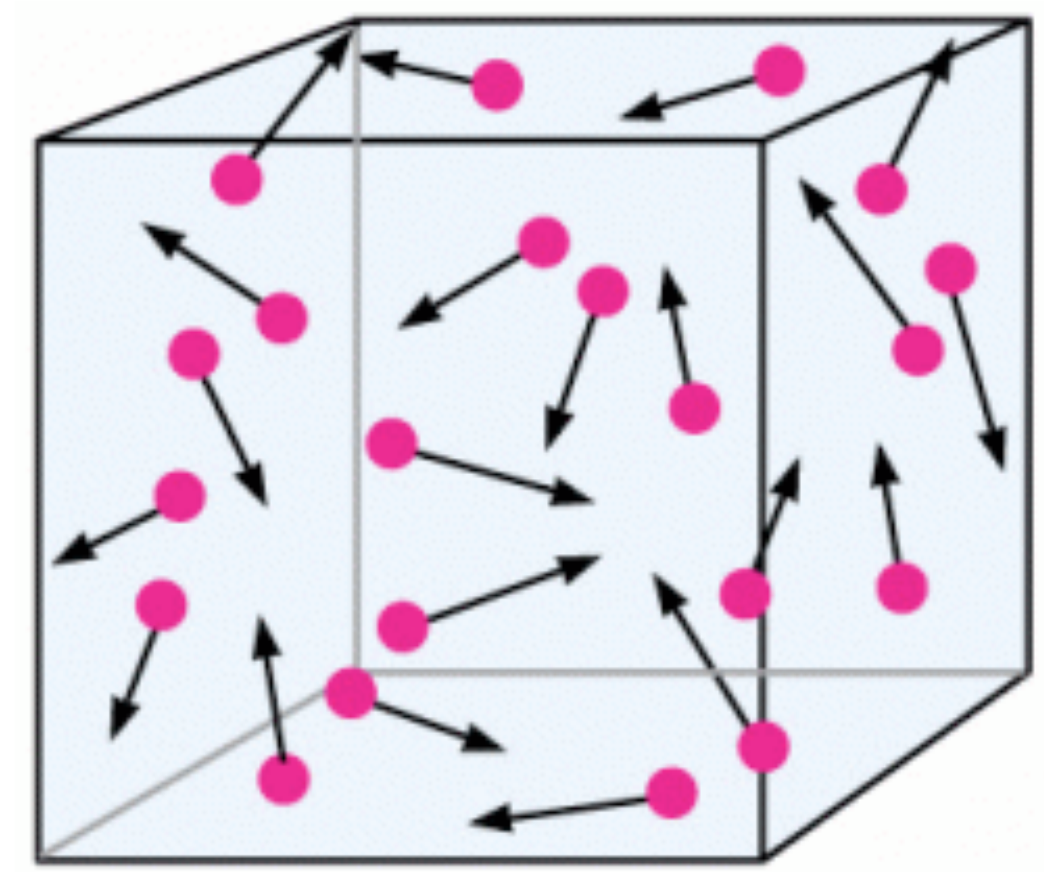
$$\int |s_0|\mathrm{D}s_r = \frac{2\pi\mathbf{p}|s|}{m}\int |\cos(\theta)|\sin(\theta)d\theta = \frac{2\pi\mathbf{p}|s|}{m}$$

Thermal average

$$\frac{\int \left[\frac{2\pi\mathbf{p}|s|}{m}\right] f_T(p)\mathrm{D}p}{\int f_T(p)\mathrm{D}p} = 4\pi|s|\frac{T}{m}\left[1+\mathscr{O}\left(\log\left(\frac{m}{T}\right)\frac{m^2}{T^2}\right)\right]$$

From simple relativistic kinetic theory

$$\mathbf{T}^i_{\mu\nu}(x) \equiv \int p_\mu p_\nu \, f^i(x,p,s_r) \mathrm{D}p \mathrm{D}s_r$$



$$a^b = u^a \nabla_a u^b = \alpha \,\mathrm{sign}(s\cdot\xi) \frac{m\mathbf{R}}{m_p^2}\, s^b$$

$$\Downarrow$$

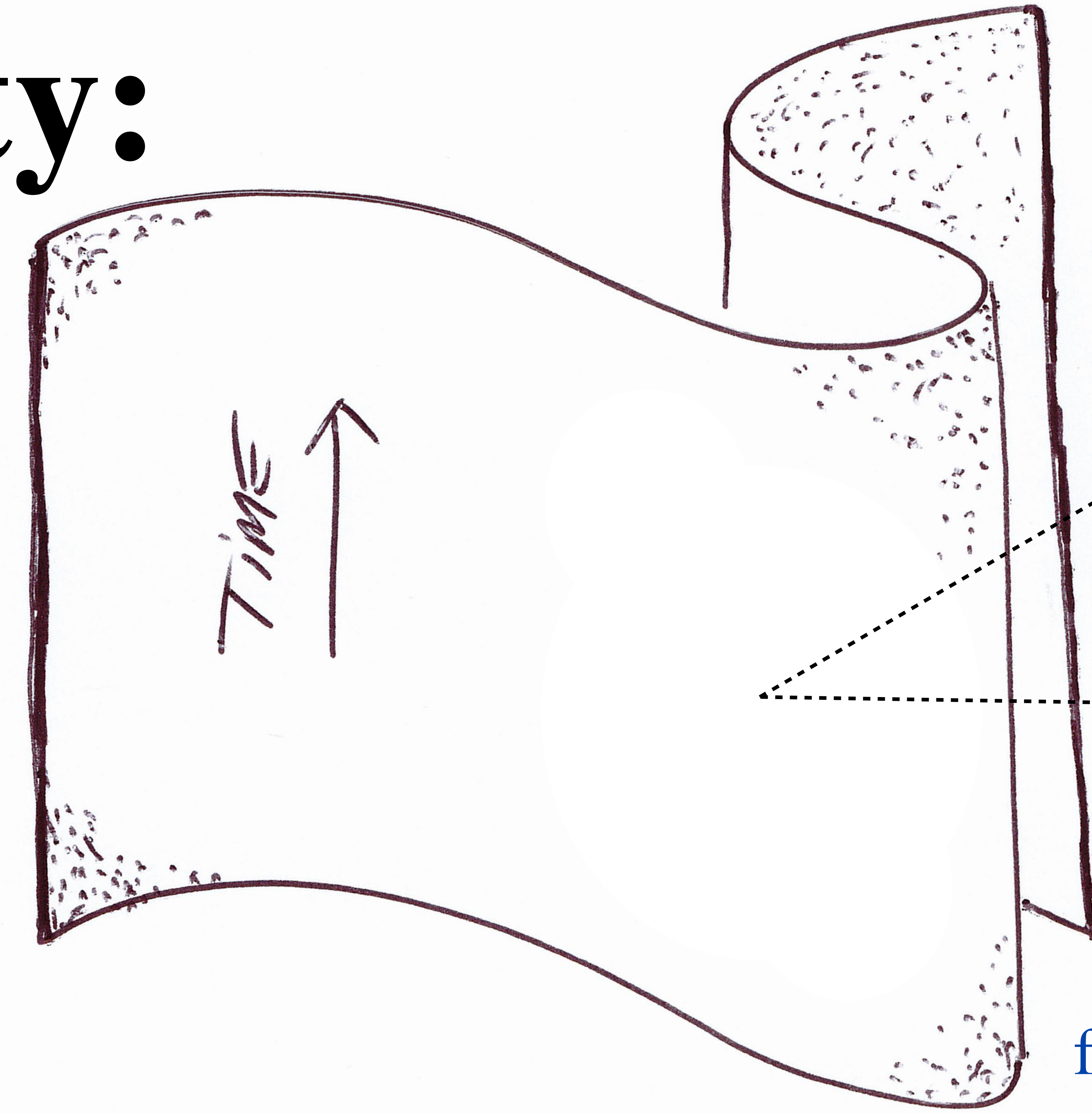
$$\mathbf{J}_b \equiv 8\pi \nabla^a \mathbf{T}_{ab} = -4\pi\alpha\hbar \frac{T\mathbf{R}}{m_p^2} \left[8\pi G \sum_i |s^i| \mathbf{T}_i \right] \xi_b$$

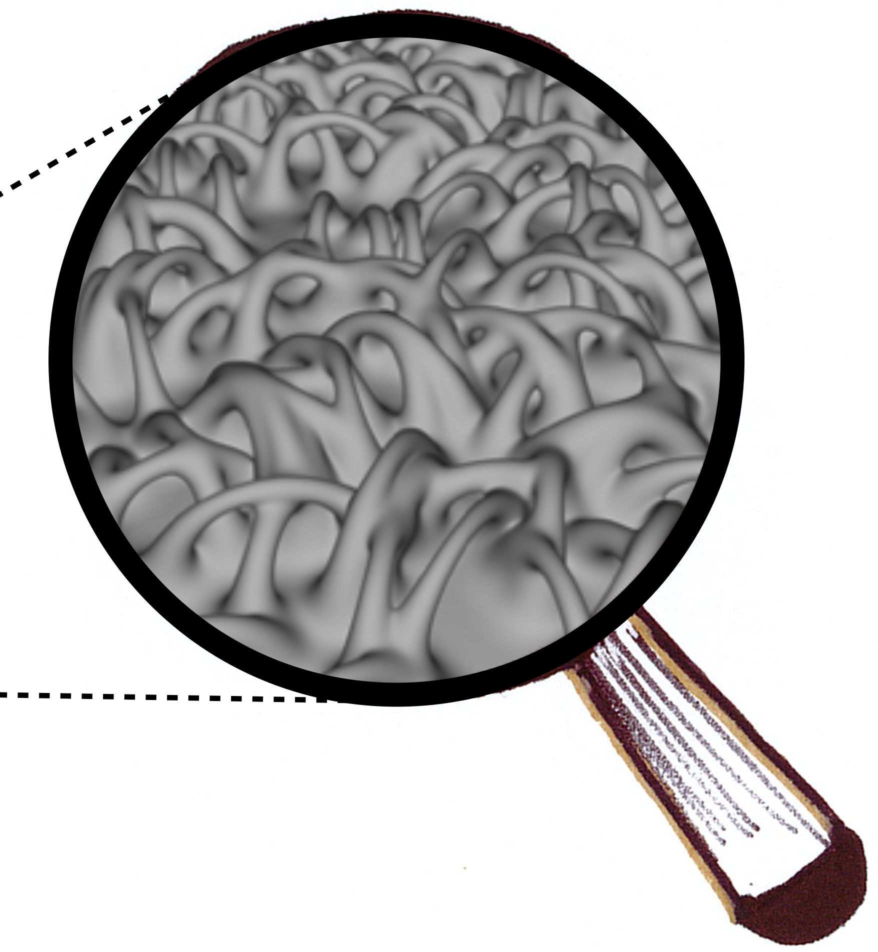
$$\approx 2\pi\alpha\hbar \frac{T\mathbf{R}^2}{m_p^2} \xi_b$$

Sum over species of the standard model

Top quark approximation

Unimodular Gravity:





If you have a model for the violation of energy conservation

$$\mathbf{R}_{ab} - \frac{1}{4} g_{ab} \mathbf{R} = 8\pi \left(\mathbf{T}_{ab} - \frac{1}{4} g_{ab} \mathbf{T} \right)$$

$$\mathbf{J}_b \equiv 8\pi \nabla^a \mathbf{T}_{ab}$$

$$\Downarrow$$

$$\mathbf{R}_{ab} - \frac{1}{2} \mathbf{R} g_{ab} = 8\pi \mathbf{T}_{ab} - \underbrace{\left[\Lambda_0 + \int_\ell \mathbf{J} \right]}_{\text{Dark Energy } \Lambda} g_{ab}$$

Results are in suggesting agreement with observations

$$\Lambda = \frac{2\pi\alpha\hbar}{m_p^2}\left(\int_{t_0}^{t} T(t)\mathbf{R}^2(t)dt\right)$$

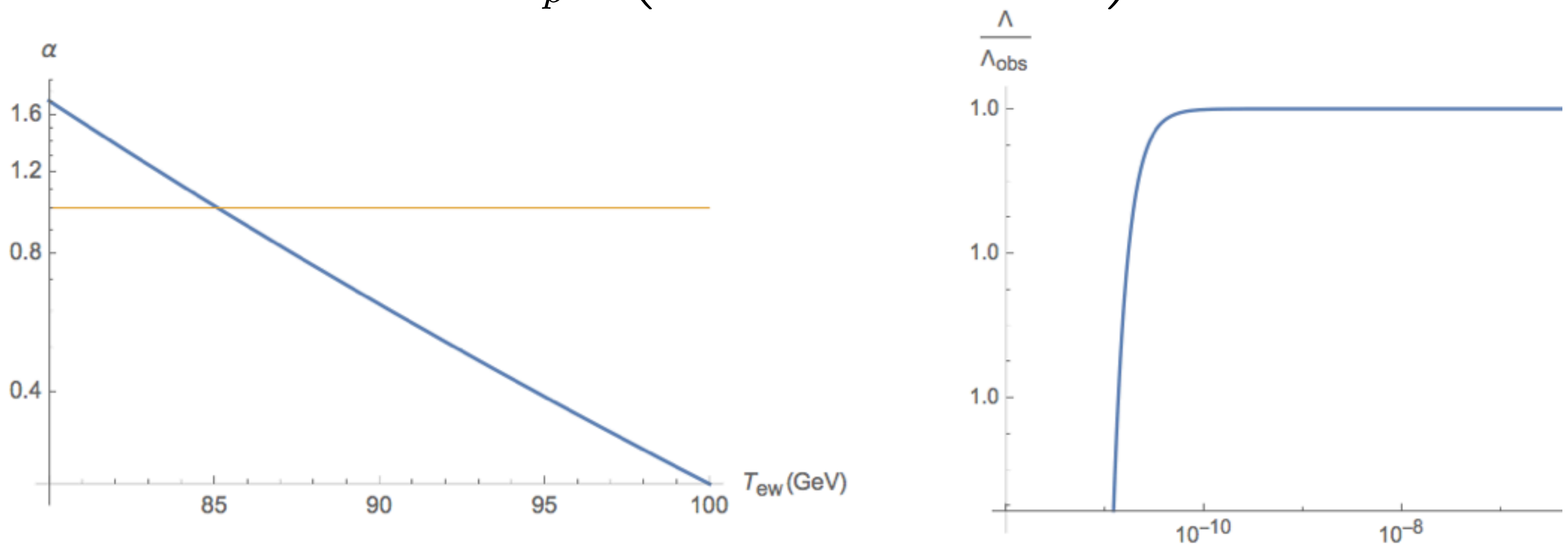
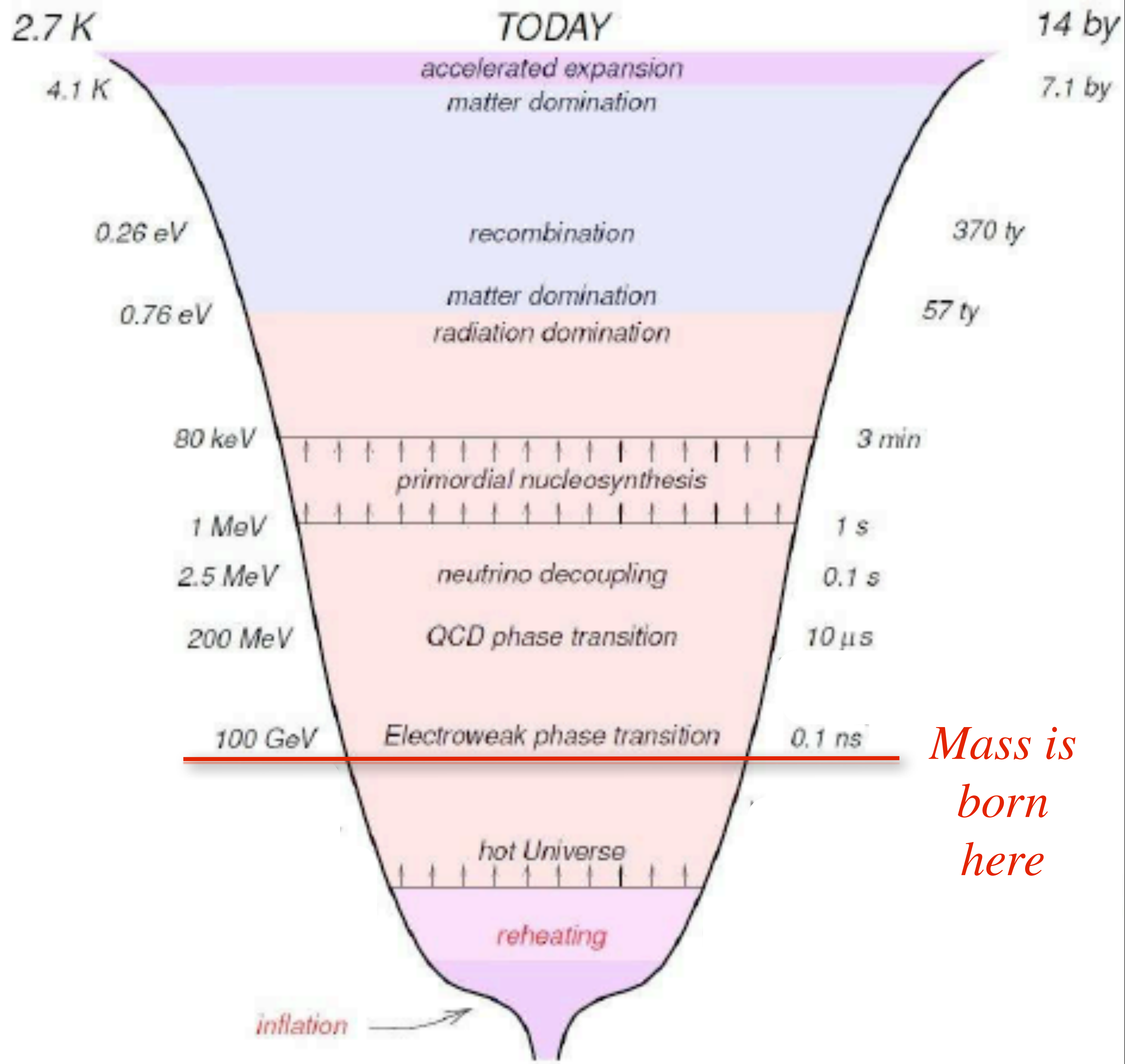


Figure 1: **Left:** The value of the phenomenological parameter α that fits the observe
Λ_{obs} as a function of the EW transition scale $T_{\rm ew}$ in GeV. We see that for $T_{\rm ew} \approx 100G$
Right: The time dependence of Λ expressed in terms of the inverse redshift factor $1/z$.

$$\Lambda \approx \frac{\overline{m}_t^4 T_{ew}^3}{m_p^7} m_p^2 \approx \underbrace{\left(\frac{T_{ew}}{m_p}\right)^7}_{10^{-120}} m_p^2$$



Discussion

- Violations of energy momentum conservation are natural in an **effective description** in terms of smooth fields of a physics that is **fundamentally discrete (quantum gravity)**.
- When they satisfy suitable integrability conditions they can be described in terms of **unimodular gravity** and they feed a **dark energy component.**
- In absence of a fundamental theory a phenomenological approach is justified. The constraints from low energy Lorentz invariance determined an essentially **unique leading contribution** to the nosy diffusion on standard model particles (analogy with Brownian motion).
- **The effects are tiny** in laboratory experiments. They are also tiny (when maximal) in cosmology: they affect the cosmological dynamics in a negligible way.
- Such tiny effect produces **the cosmological constant** during the electroweak transition. It becomes dominant today **once the universe has sufficiently diluted.**
- **If all this is correct, the cosmological constant would be the first observable manifestation of Planckian discreteness expected from quantum gravity.**

Possible independent signals:

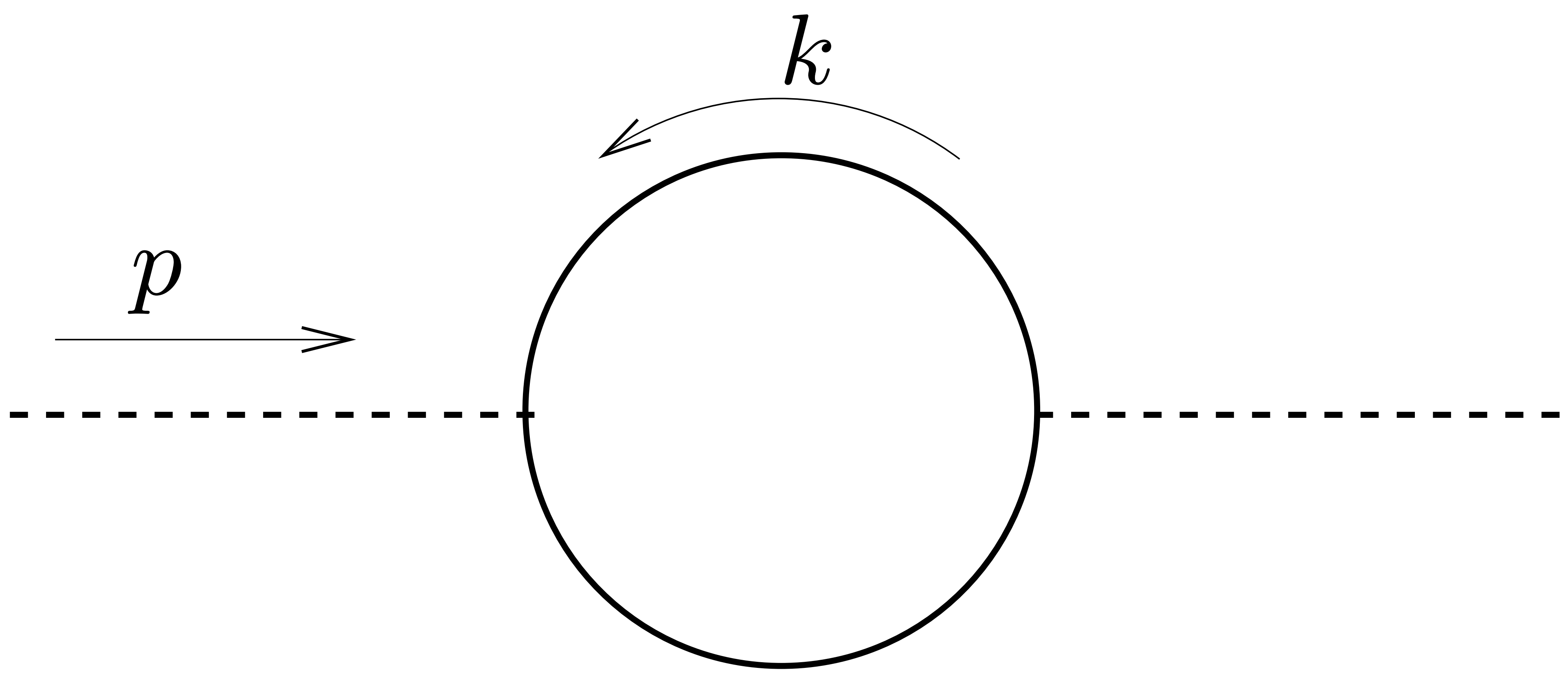
radiative corrections in QFT

Radiative corrections make Lorentz violation percolate to low energies

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

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

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



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

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

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

Leading operators dimensionally allowed

$$O_1 = \lambda_1 \, \xi^\mu \nabla_\mu \phi \mathbf{R} = \lambda_1 \dot{\phi} \mathbf{R}$$

$$O_2 = \lambda_2 \, \xi^\mu \bar{\psi} \gamma_\mu \psi \frac{\mathbf{R}}{m}$$

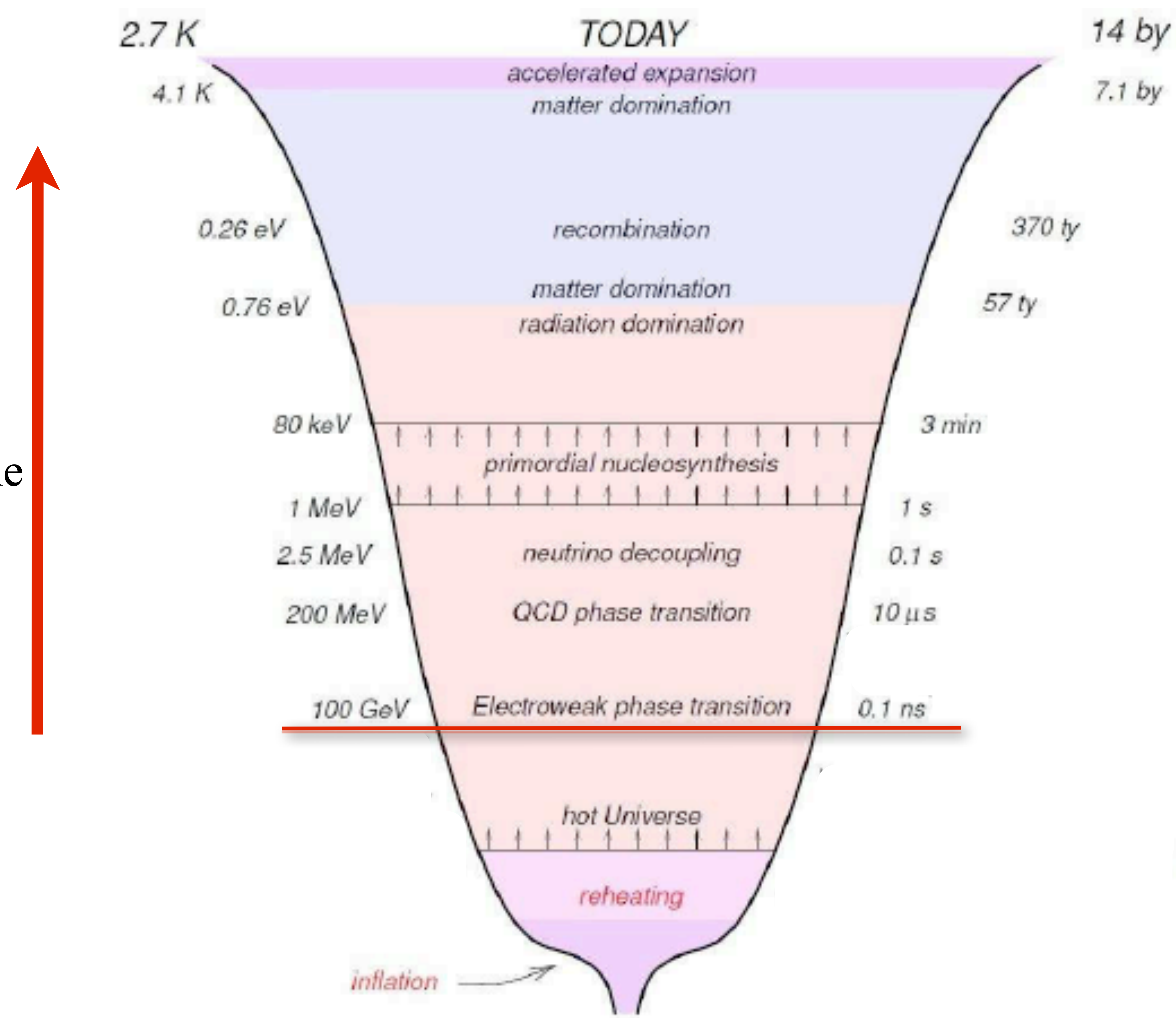
Constraints from present experiments and observations

$$\mathbf{T} = \frac{\mathbf{R}}{8\pi G} > 10 \, \mathrm{GeV}^4 \approx 10^{-2} \mathbf{T}_{ew}$$

V. Alan Kostelecky and Neil Russell. Data Tables for Lorentz and CPT Violation. Rev. Mod. Phys., 2011.

Leading operators dimensionally allowed

Lack of energy conservation has a negligible effect on the dynamics of the background



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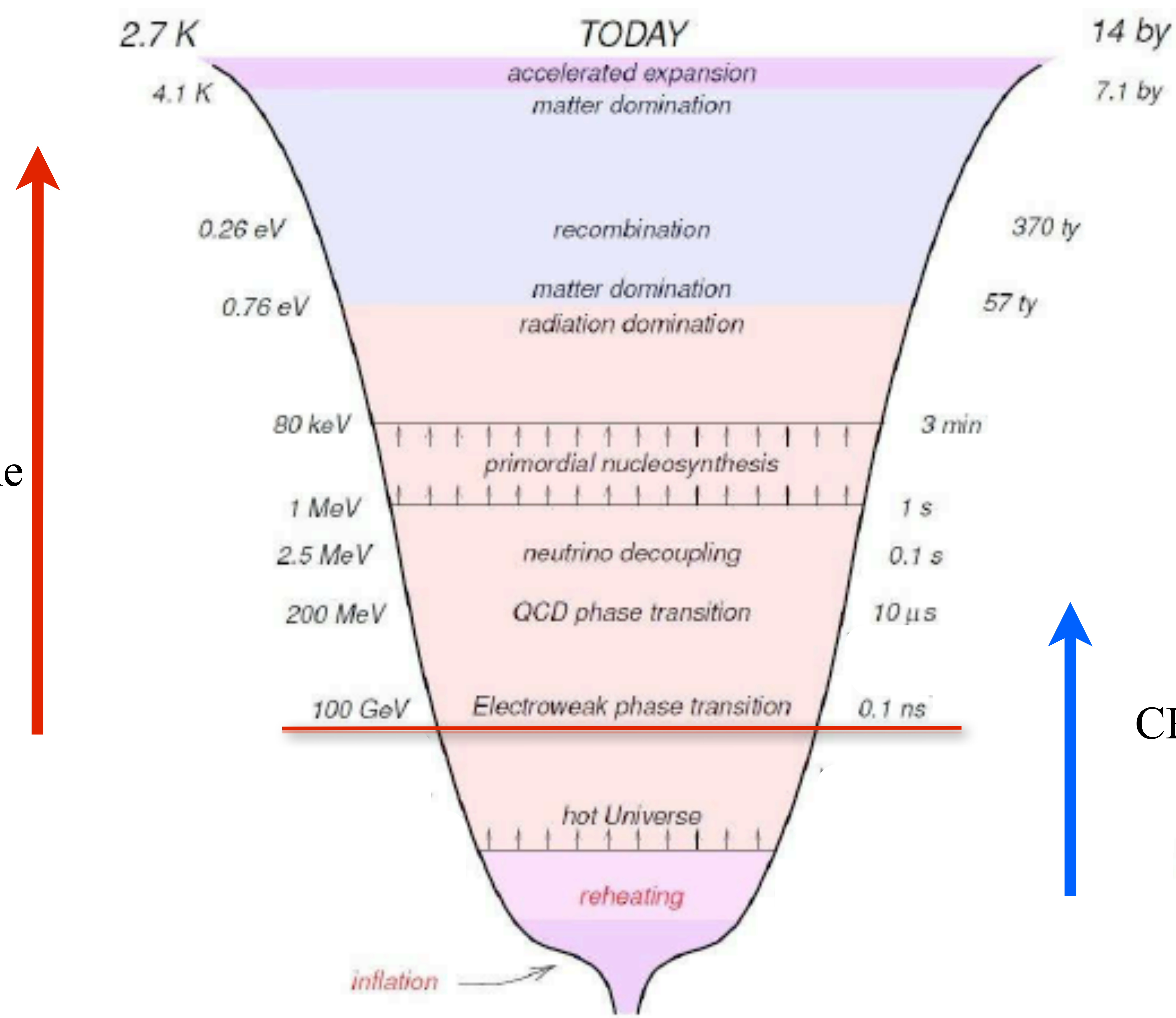

CPT violation and baryogenesis

Leading operators dimensionally allowed

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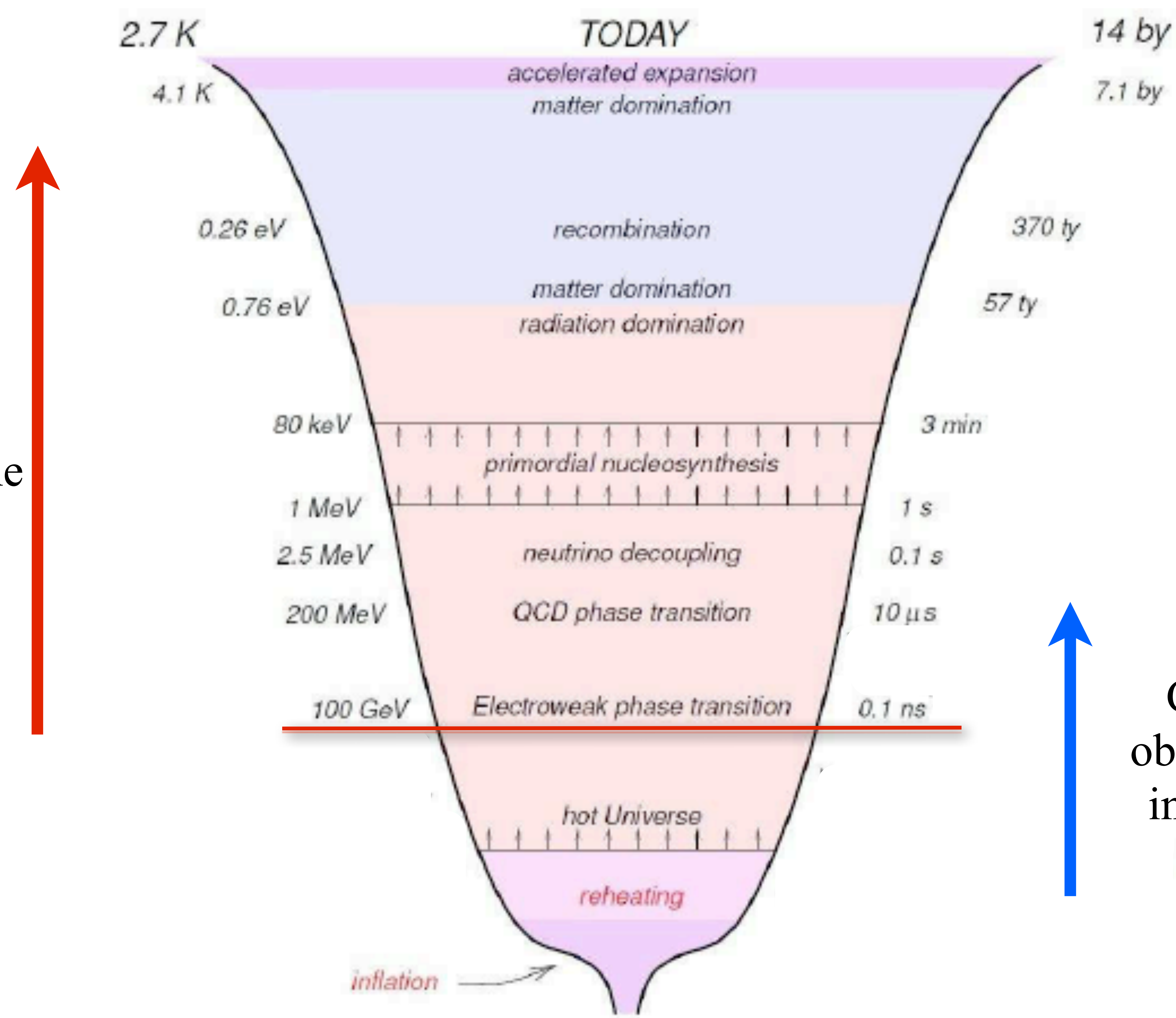


Can it leave an observable imprint in perturbations?

Other formal implications

Entropy production in FLRW cosmology:

$$\nabla^a T_{ab} = J_b/(8\pi G)$$

$$\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + P) = \frac{J_0}{8\pi G} \qquad d(\rho a^3) + P d(a^3) = \frac{J_0 a^3}{8\pi G} dt$$

$$T d(s a^3) = d(\rho a^3) + P d(a^3) - \mu d(n a^3)$$

$$\boxed{d(s a^3) = \frac{J_0 a^3}{8\pi G T} dt - \frac{\mu}{T} d(n a^3)}$$

$$\frac{\Delta S}{(a_f^3/\ell_p^3)} \approx 10^{-116}$$

Other formal implications

Unitarity loss in the QFT effective description

$$\nabla^b \langle T_{ab} \rangle \neq 0 \quad \Longleftrightarrow \quad \text{decoherence with the Planckian microscopic environment}$$

Entropy production in general: decoherence in a Planckian discrete environment

$$a^b = u^a \nabla_a u^b = \alpha\,\mathrm{sign}(s \cdot \xi)\,\frac{m\mathbf{R}}{m_p^2}\,s^b$$

Hongguang Liu, *work in progress*

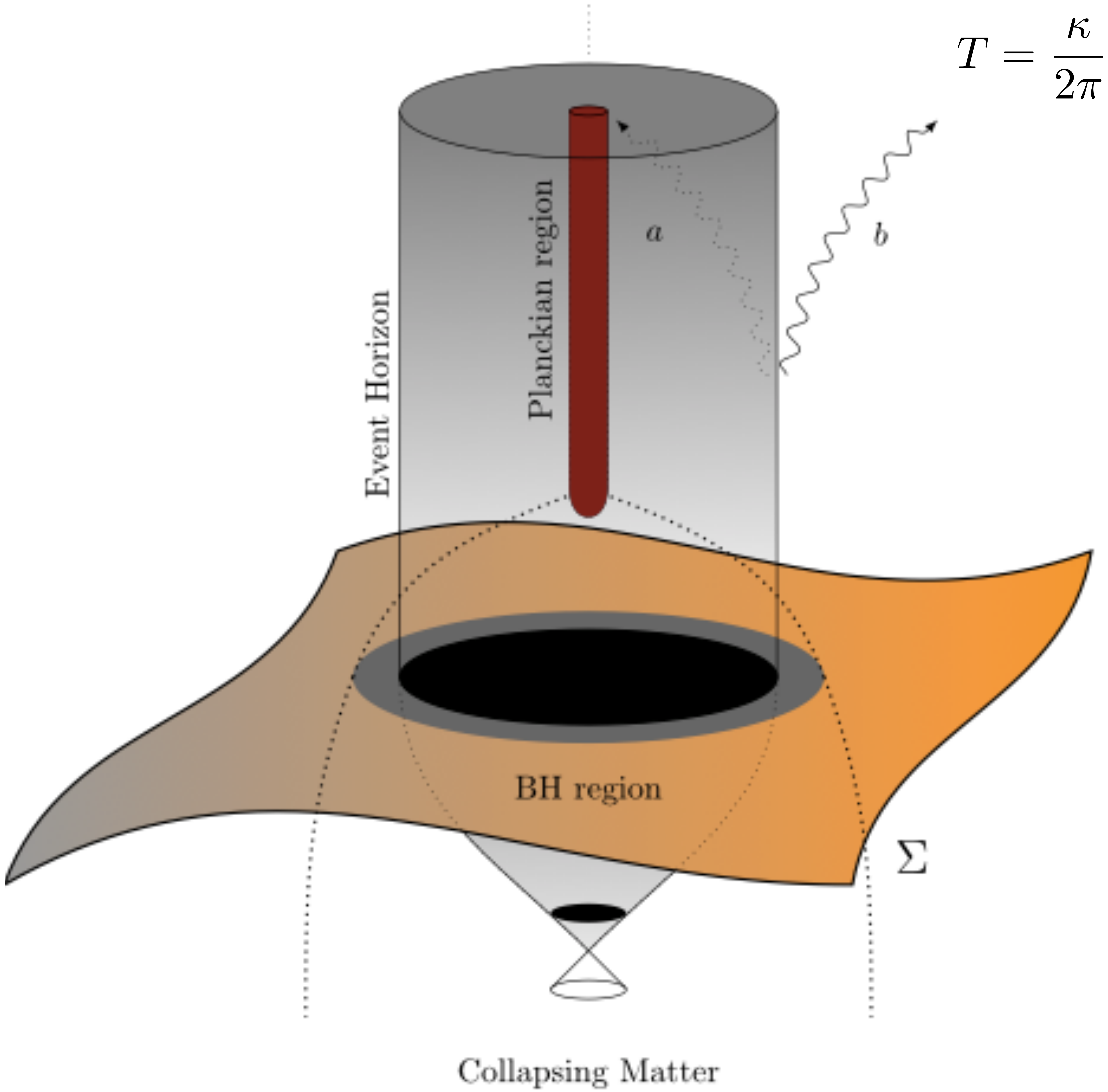
$$i\hbar\gamma^\mu\partial_\mu\Psi(x) - m\Psi(x) = \int d^4y D(x,y)\Psi(y)$$

Bei-Lok Hu, Esteban Calzetta, *Nonequilibrium QFT*.

$$i\hbar\gamma^\mu\partial_\mu\Psi(x) - m\Psi(x) = F(x)\Psi(x)$$

Black Holes:

Their thermal properties suggest micro-structure



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

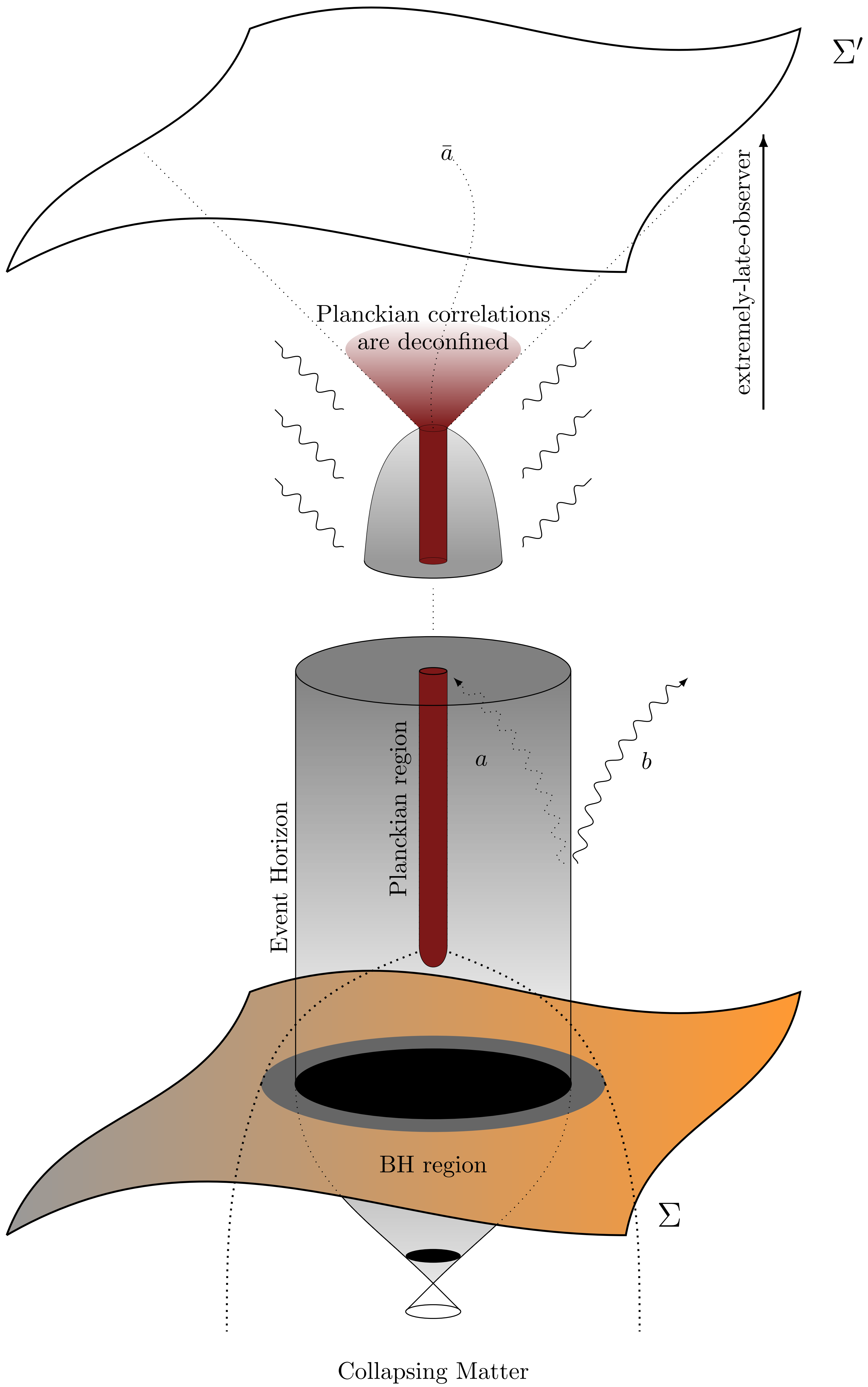
Heat: Energy in molecular chaos

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

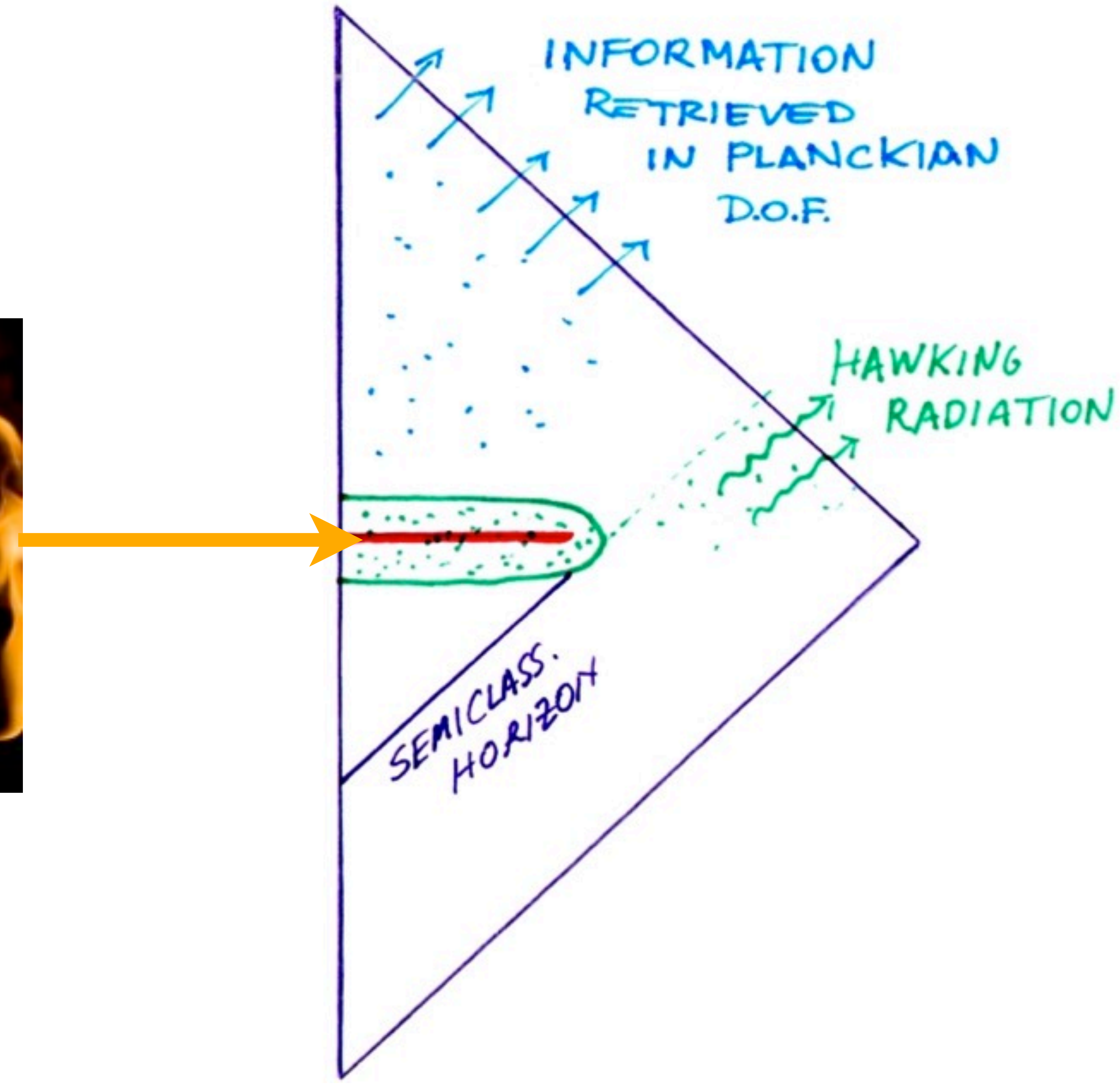
$$S_{BH} = \frac{a}{4}$$

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

New perspective on the information paradox



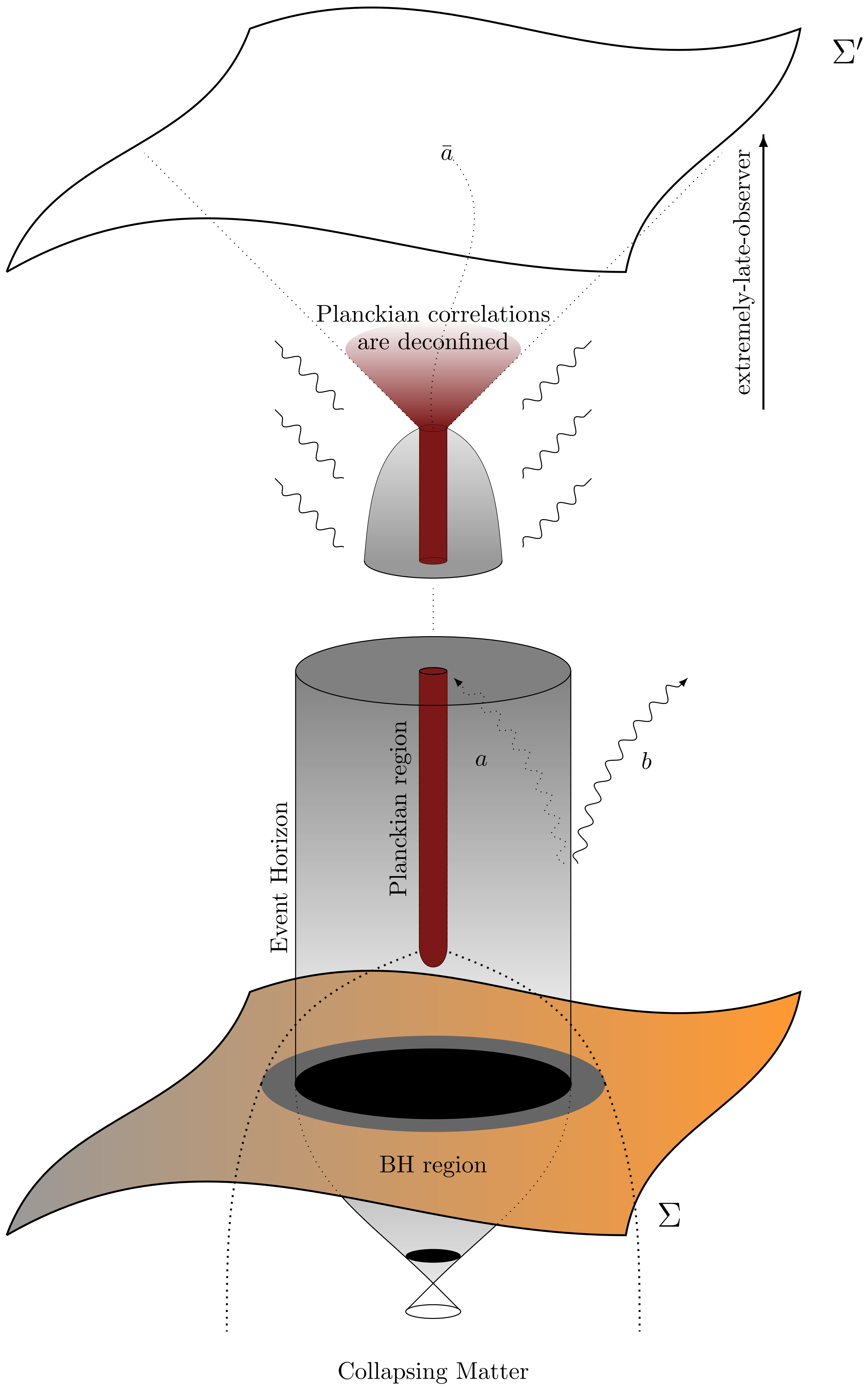
AP, *Class. Quant. Grav.* 32, 2015.



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

Wald 1980,

New perspective on the information paradox



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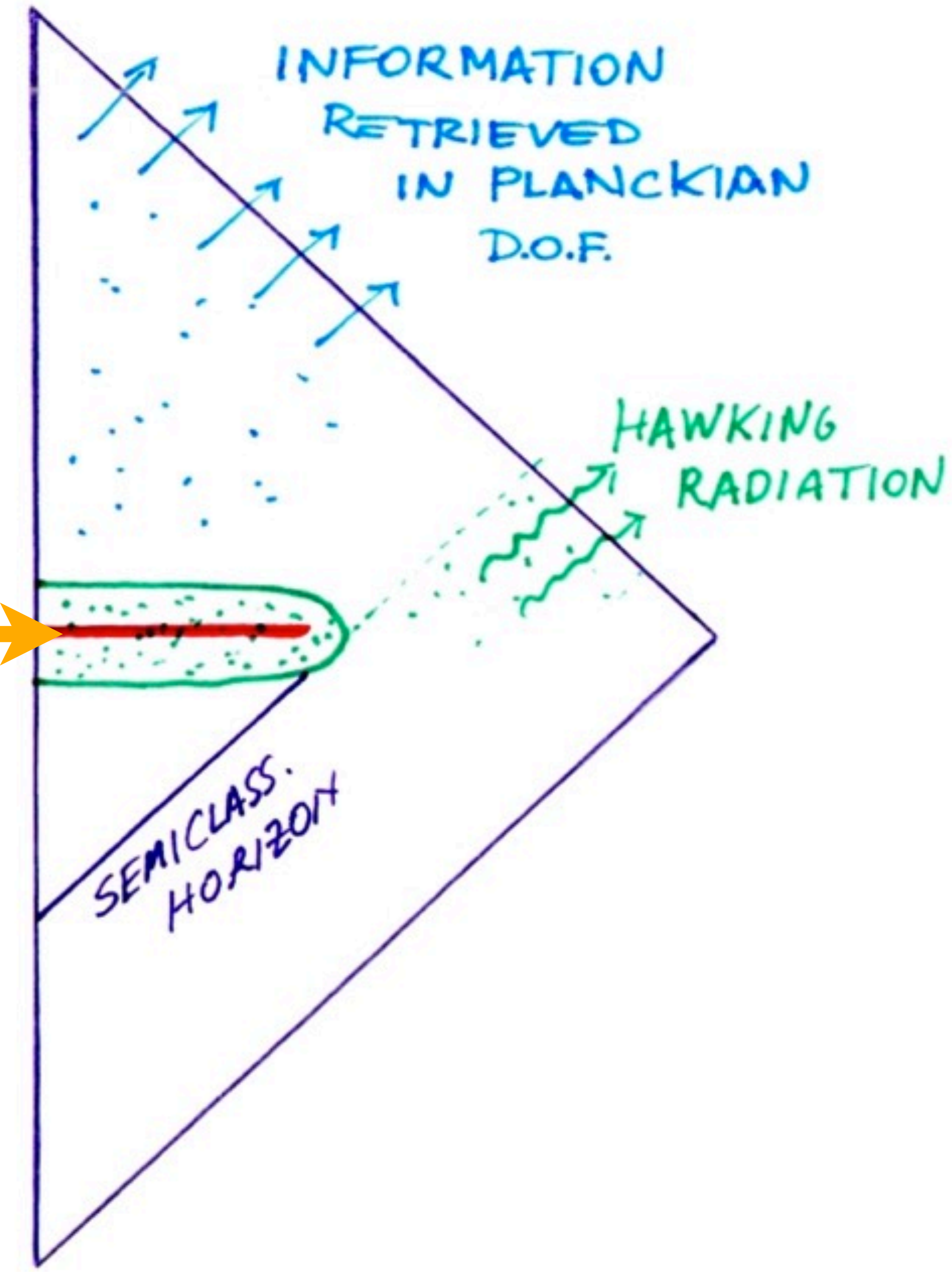

Decoherence with discrete micro-structure imply **violations** of **energy conservation** in the **smooth effective description**!

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

Outlook: Lambda, okay. But what else?

$$\frac{\mathbf{R}_{\text{Iron}}}{\mathbf{R}_{EW}} \approx 10^{-24}$$

1. Violations of energy conservation in local experiments (too tiny!)
2. Violations of the equivalence principle in local experiments (too tiny)
3. Violations of Lorentz invariance of the week type we propose (too tiny)
4. Violations of unitarity: nice perspective for the information paradox.
5. Early cosmology is the natural arena where to test additional effects (baryogengesis, leptogenesis, structure formation, etc)


NGC 4526 with SN 1994D
Thank you!

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

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

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

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

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

Order parameter for discreteness probes:
scalar curvature

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

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$dJ = 0$
trivially true in FLRW

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Vacuum fluctuations do not gravitate. S. Weinberg 1989

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Both **R** the preferred volume structure are natural ingredients of the **Planckian** phenomenology we are exploring

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