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

5 Fevrier, 2018

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The cosmological constant problem

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

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

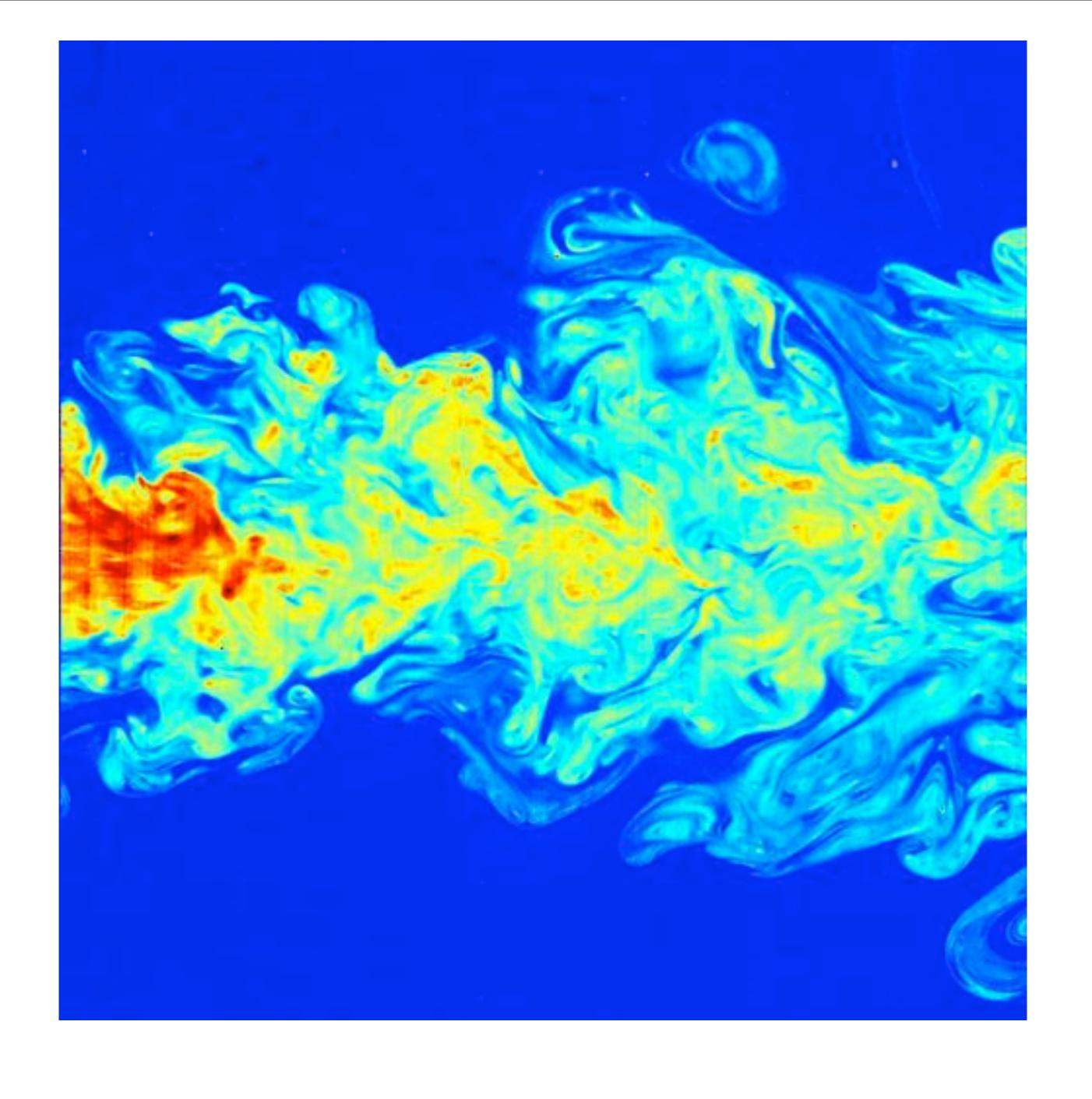
How does the vacuum gravitate?

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

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

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

Continuous fluid description breaks down at molecular scales.



SPACETIME SYMMETTRIES AND CONSERVED QUANTITIES SPACE TRANS.

SPACE
THANS. INVARIANCE > MOMENTUM
CONSERVATION

TIME THANS.
INVARIANCE

CONSTRYATION

10 Symmetries

in tru

Poincaré Group

To Components

of tru

ENERGY MOMENTUM

TENSOR

CONSERVATION (=) Va Tab

o

Tab

Tab

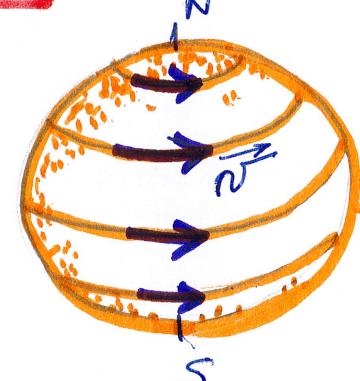
COORDINATE INDEPENDENT

CHARACTERIZATION OF SYMMETRY

KILLING VECTOR FIELD

table of the second

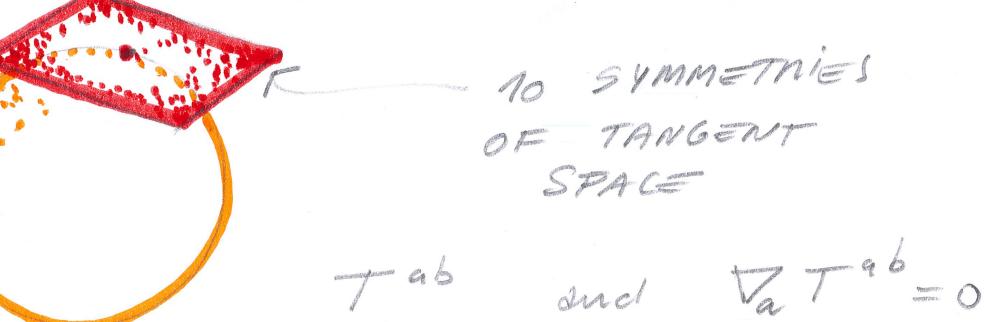
WORKS ALSO
TOR CURVED
GEOMETRY





NO SYMMET

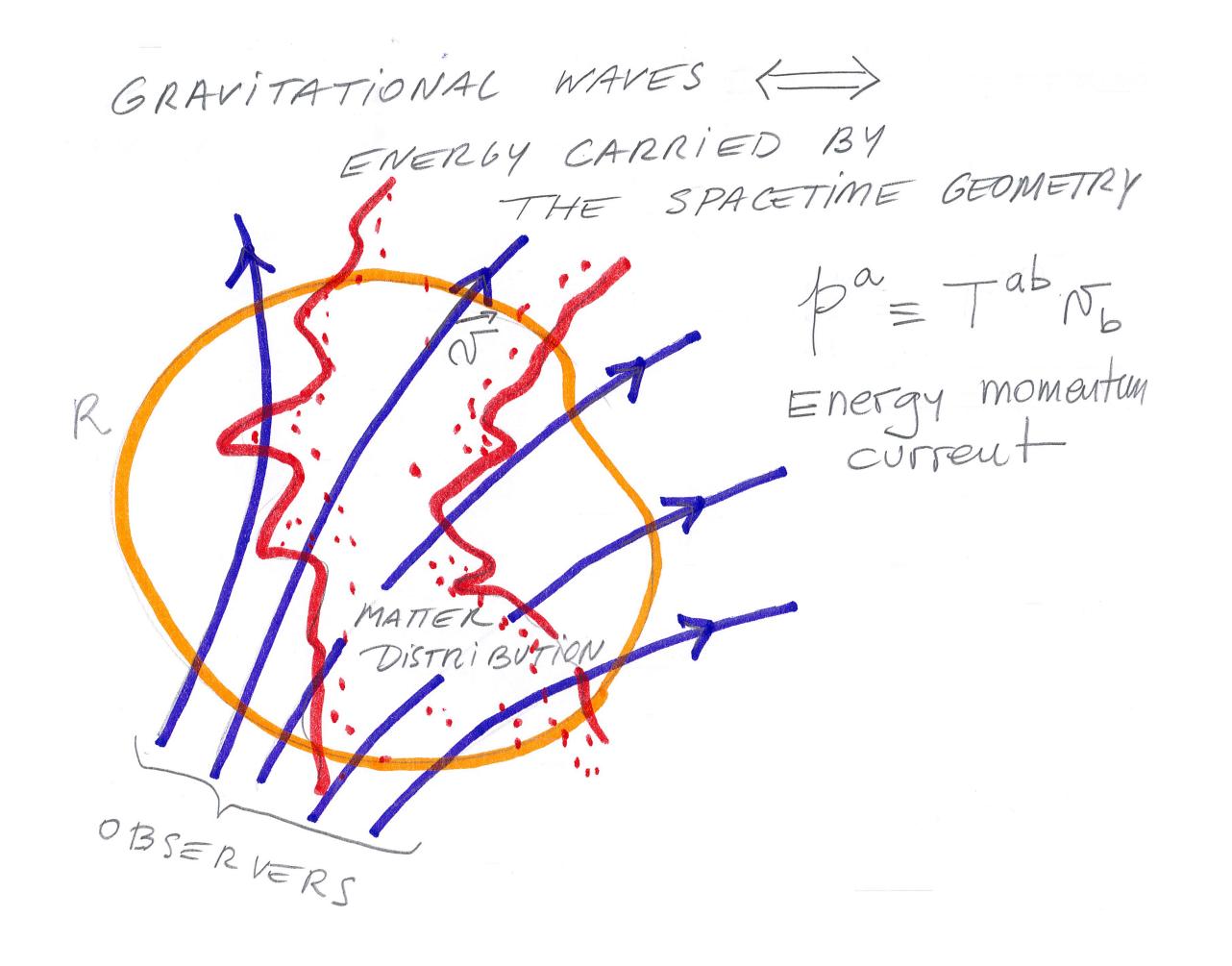
CAN DEFINE ENERGY-MOMENTUM
TENSOR IN GENERAL



GENERAL RELATIVITY

LOCAL CONSERVATION OF ENERGY

Ta 7 ab = 0



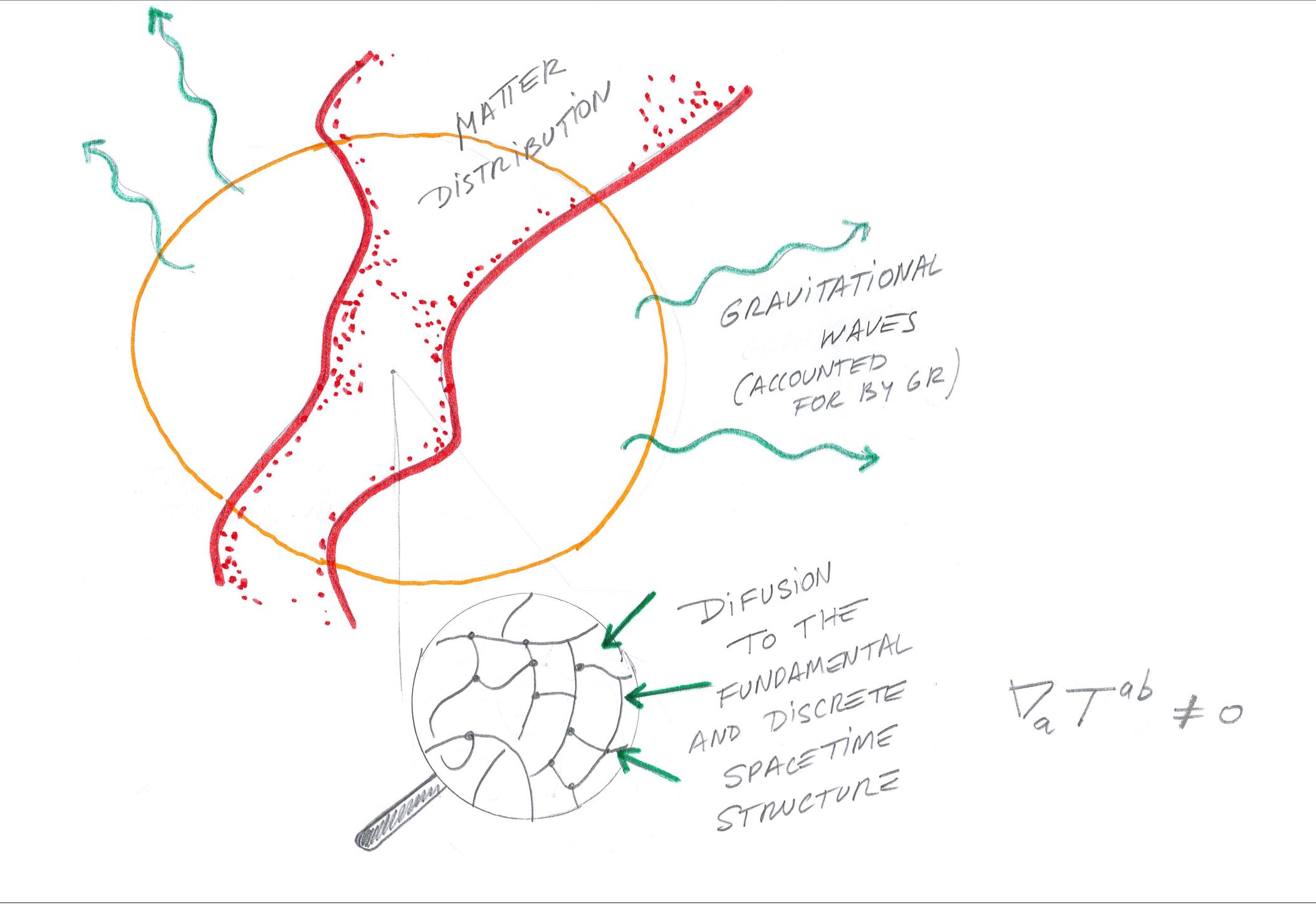
 $\nabla a \rho^a = \nabla_a (T^{ab} N_b)$ $= (\nabla_a T^{ab}) N_b + T^{ab} \nabla_a N_b \neq 0$ $\text{Unless} \quad \nabla_a N_b + \nabla_a N_a = 0$ $\text{Killing vector field} \iff \text{Spacetime}$ Symmetry



R is Bi6 (=) No conservation of mother energy unless symmetries GRAVITY WAVES

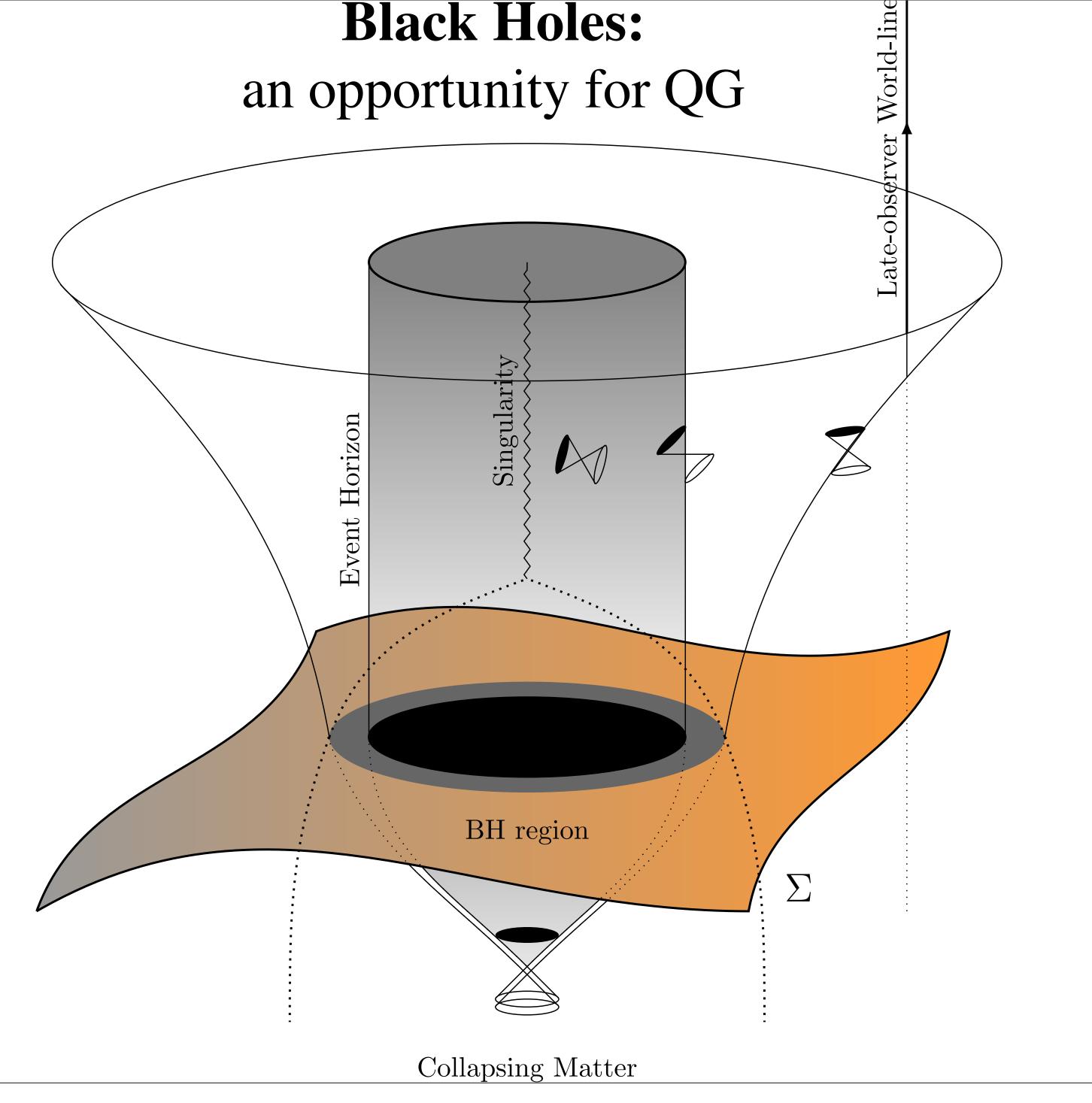
Z is very SMALL (= QVIVALENCE) PRINCIPLE)

Datab = 0 Servation of energy



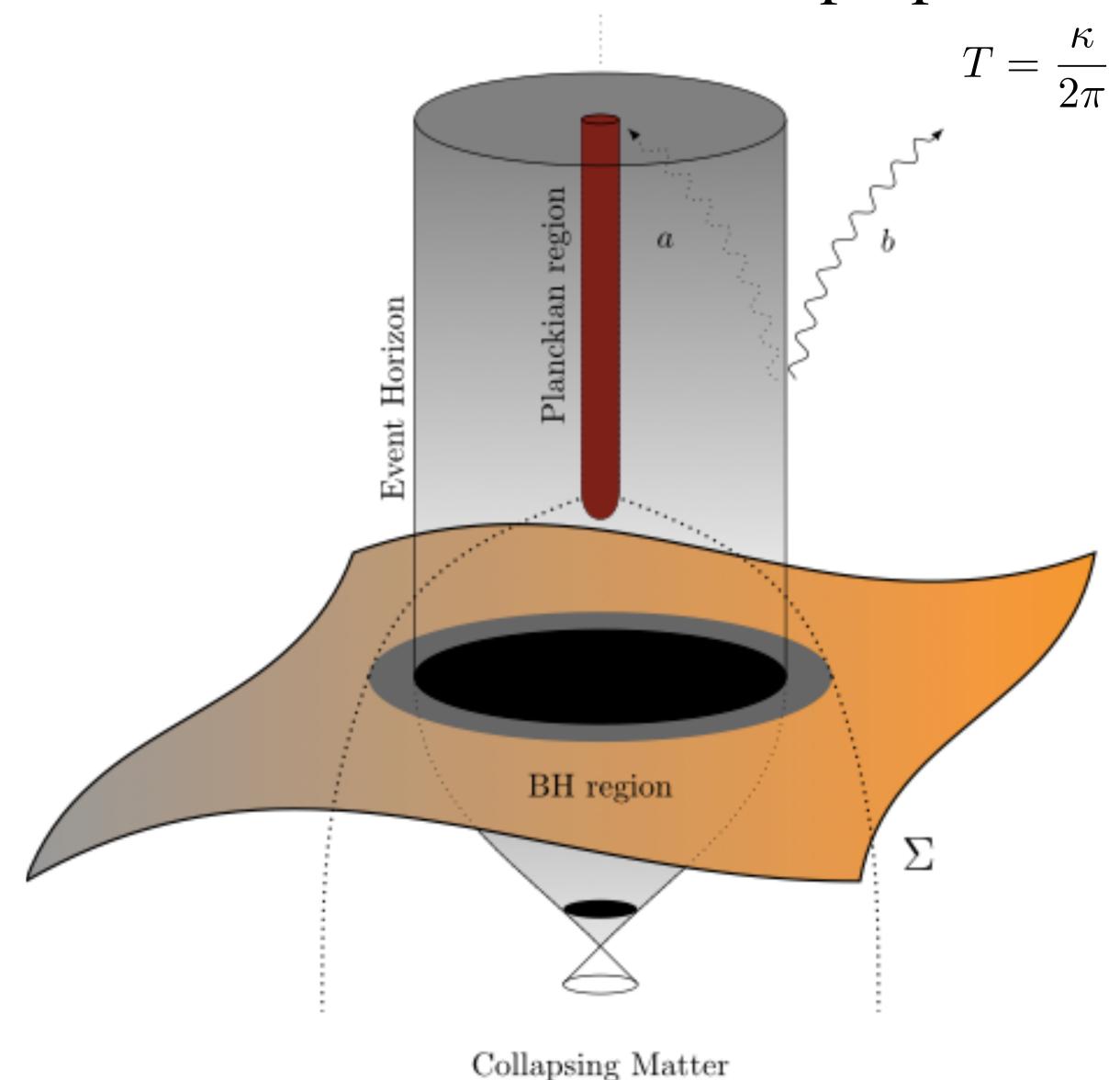
PART 1:

Spacetime es expected to be discrete in quantum gravity



Black Holes:

Their thermal properties suggest micro-structure



$$\delta E = \mathcal{I} \delta S - P \delta V$$

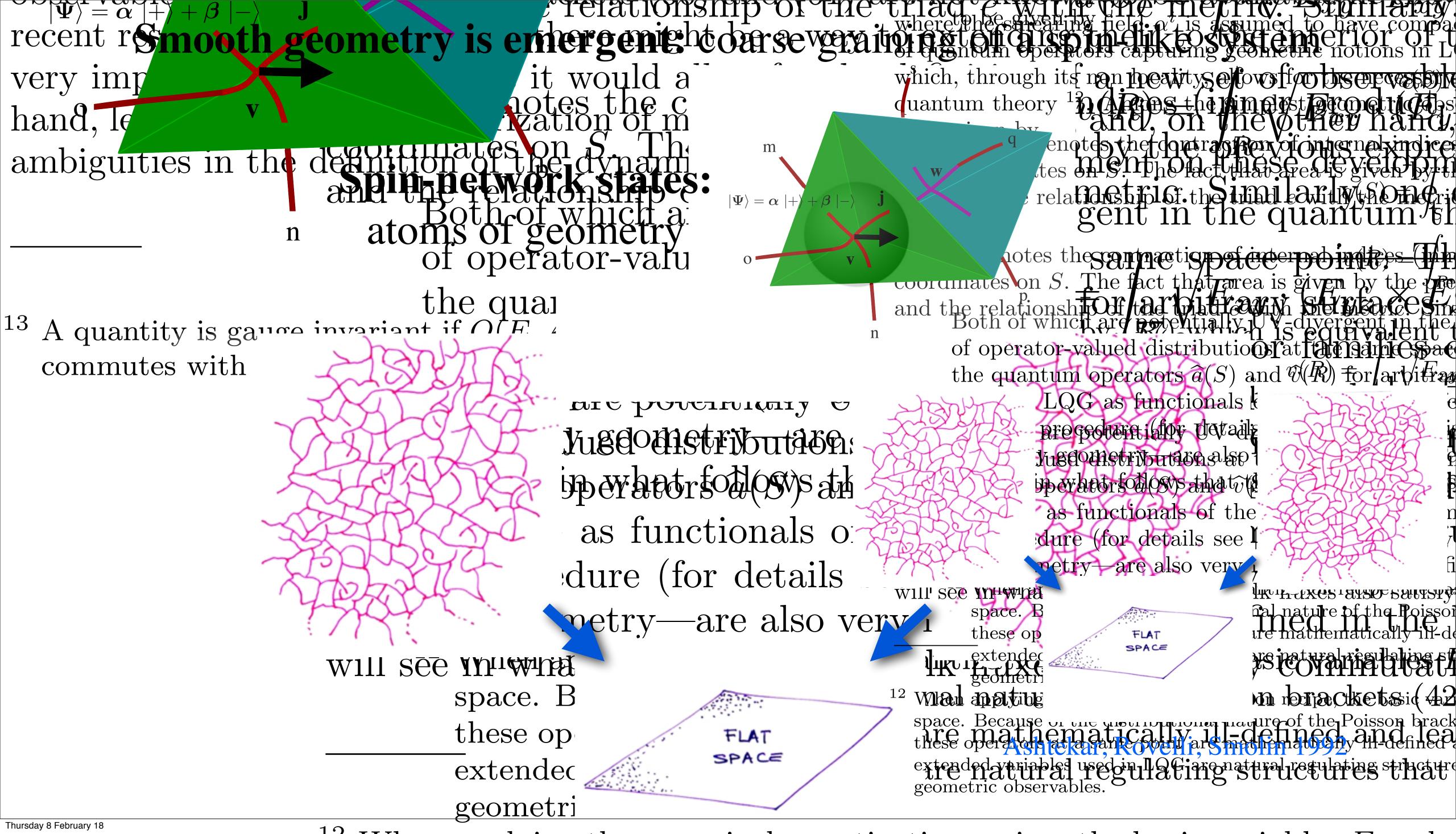
Heat: Energy in molecular chaos

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

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

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

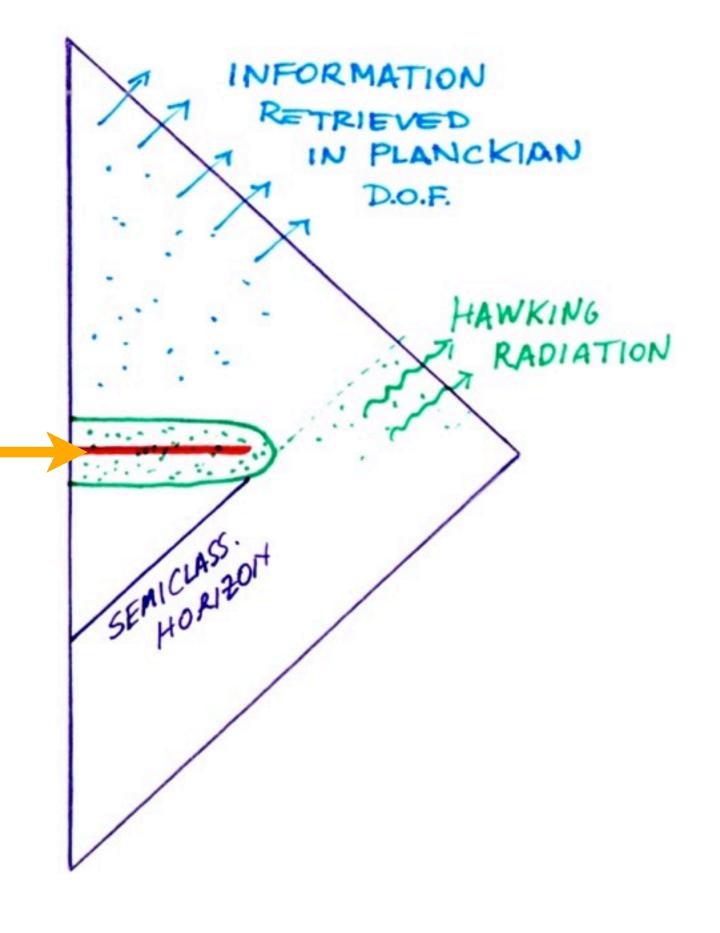
Discreteness in Loop Quantum Gravity.



New perspective on the information paradox extremely-late-observe Planckian correlations are deconfined BH region Collapsing Matter

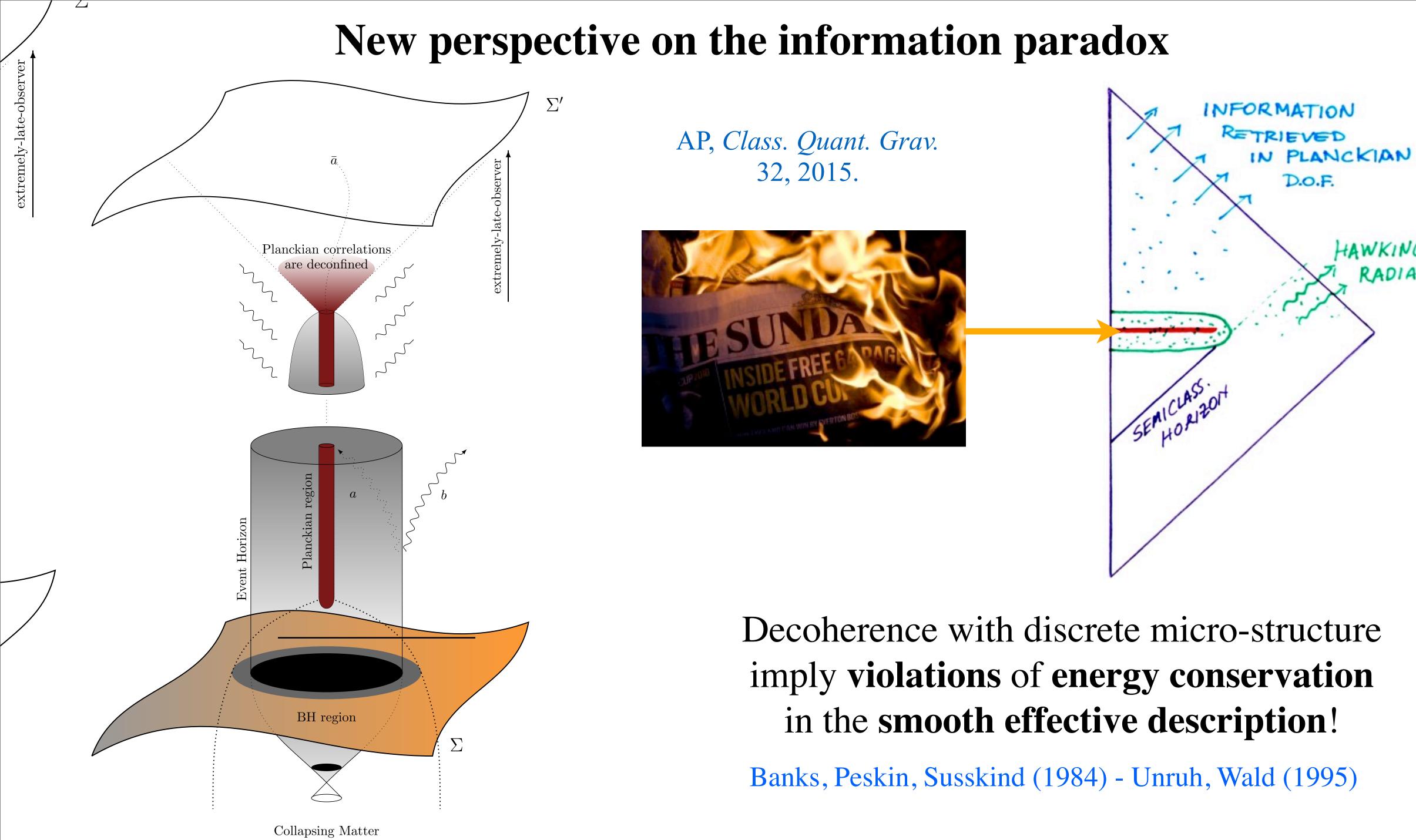
AP, Class. Quant. Grav. 32, 2015.





CPT violation in the smooth QFT effective description!

Wald 1980,



HAWKING

RADIATION

 t_{W}^{Thursday} h_{A}^{Februal} H_{A}^{S} wking particle h and its partner a

Violations of energy conservation in the effective smooth semiclassical

stant of integration and we see that the philippy are to be expected the Reguce of a term Ta_{b} Einstern ng the dark energy equation of state. s the general framework where we will develop further our proposal. First, the previous equation the energy-moment high the case the raw to the integrable type I by the transplant I the possibility of the energy-moment I the possibility I is the possibility I the possibility I is the possibility I and I and I is the possibility I and I is the poss gravitational dynamics in terms of a metric theory is compromised: unimodular gravity is, as fa only relaxation of the standard general covariance requirements allowing for ψ in ψ in ψ rvation. Fortunately, in applications to cosmology the a stion of homogeneity and isotropy scales of interest, implies integrability of J (this is because in this setting J only depends on 'tim comoving coordinates ing $J_a \equiv (8\pi G/c^4)\nabla^b T_{ba}$, and assuming the unimodular integrabili will assume that the spacetime metric at large scales is well approximated by the spatially flanteness. The spatially flanteness equation and re-write the system in terms of the modified that eins equation very well supported by empirical evidence), the amount of energy-momentum violation experienced due to the transfer of energy, s of freedom of massive matter could be and diffying magnoscopagaistrete, substilating of that according to our rationale only ρ_m contributes, thus simple dimensional analysis to letely phenomenological view that granularity associated with the spacetime form leads to a violatic tum conservation. The process is quantum gravitational so it must be centrealed by the relanck sca (as argued before) by the presence of amon trivial scalar curvature or Ricci scalar which (from a specific to the FLRW case) is given by equation of the presence of a specific curvature of the presence of t The previous the seneral manadwork where we will develop further Thursday 8 February 18

PART 2: A phenomenological perspective on Dark Energy.

Violations of energy conservation in the effective smooth semiclassical

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BUT energy-momentum is conserved in general relativity

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



As a consequence of Bianchi identities

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

BUT energy-momentum is conserved in general relativity

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



As a consequence of diffeomorphism invariance

(general covariance)

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

quation of this $g^{J}J_{a}\equiv (8\pi c)$ where $g^{J}J_{a}\equiv (8\pi c)$ is a sum of the sum of

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

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

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

GR compatible stress tensor satisfying Wald axioms

$$\langle T_{ab}
angle_{
m GR} \equiv \langle T_{ab}
angle_{
m NO} - Q g_{ab}$$
 trace anomaly for CFT's!

Unimodular gravity compatible stress tensor

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

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).

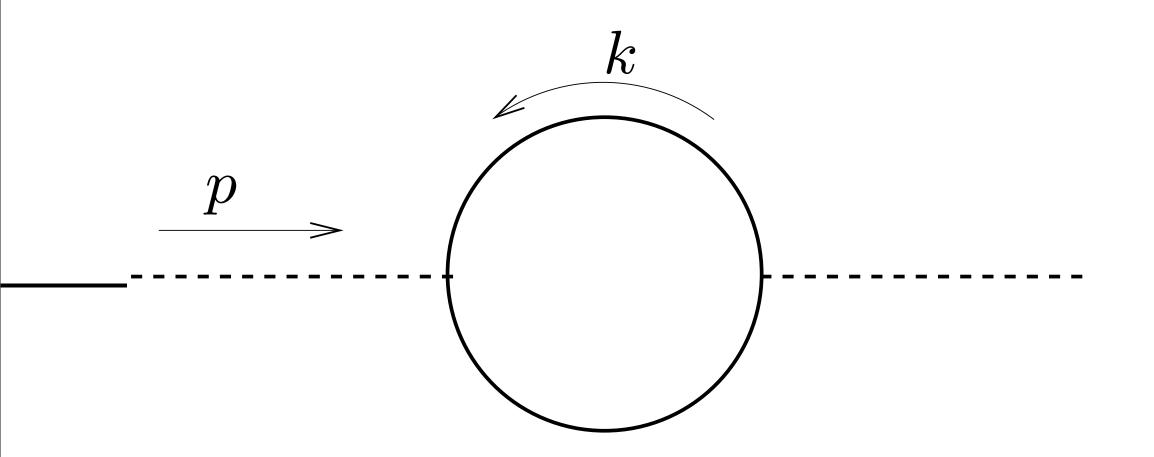
Radiative corrections make Lorentz violation percolate to low energies

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

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

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

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

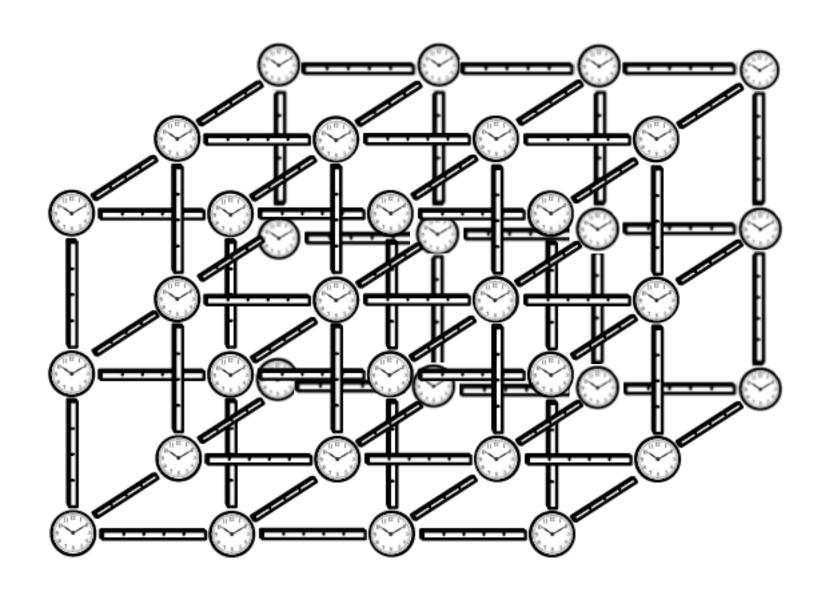


$$\Pi(p) = A + p^2 B + p^{\mu} p^{\nu} W_{\mu} W_{\nu} \tilde{\xi} + \Pi^{(LI)}(p^2) + \mathcal{O}(p^4/\Lambda^2)$$

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

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"

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

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

ext the striking consequence of such violation is the emergence of a cosmological-constate g_{ab}^{mC} . This cambe seen from the traceless field equations $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$. This cambe seen from the traceless field equations $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$. This cambe seen from the traceless field equations $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$.

Planckian microstructure

$$R_{ab} - \frac{1}{2}Rg_{ab} + 4Rg_{ab} + 4Rg_{ab} = 8\pi G$$

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further our proposal. First, the previous equations ignable identities imply that trary J the possibility

neory is compromise Darkienergy term ty is, as far nee requirements, allowing for violence 32 frequency of some of homogeneity and isotropy of a.

s is because in this setting Jonly depends on 'time'

 T_{ba} , and assuming the unimodular integrability dJ = 0 [1], one can integrate the previous system in terms of the invented by empirical evidence), $= \alpha \ell_p \left[8\pi G (\rho - 3P) \right]^2 d\eta_p$, and assuming the unimodular integrability dJ = 0 [1], one can integrate the previous system in terms of the invented by empirical evidence),

ion experienced due to the transfer of energy from the the distrete, substilation of qualitym ntributes, thus simple dimensional analysis tell us that sociated with the spacetime foam leads to a violation

In FLRW cosmology:

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

$$\begin{cases} \frac{1}{2} \left[\frac{8\pi G}{5} \nabla_{p}^{b} T_{bq} dx_{q}^{a} \right] = \alpha \ell_{p} \left[8\pi G(\rho - 3P) \right]^{2} d\eta_{p}, \end{cases}$$

$$\alpha \equiv$$
 dimensionless constant

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

itational so it must be controlled by the Planck scale

Results are in remarkable agreement with observations

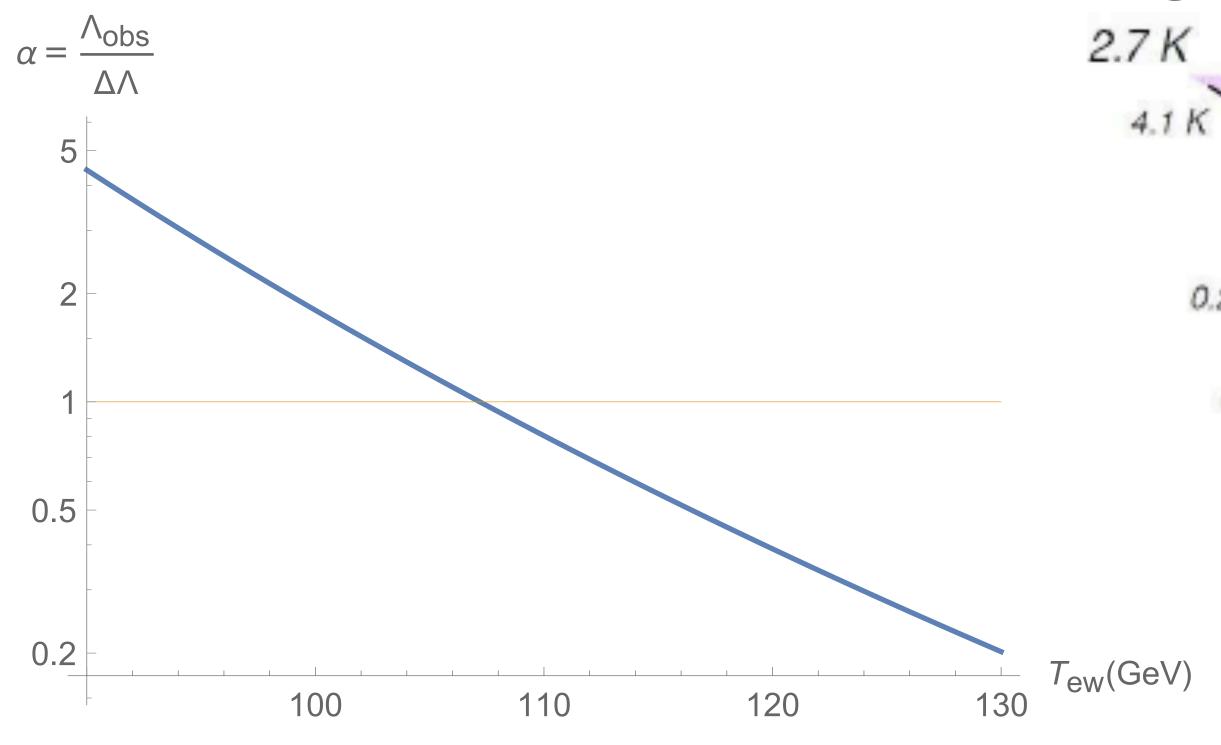
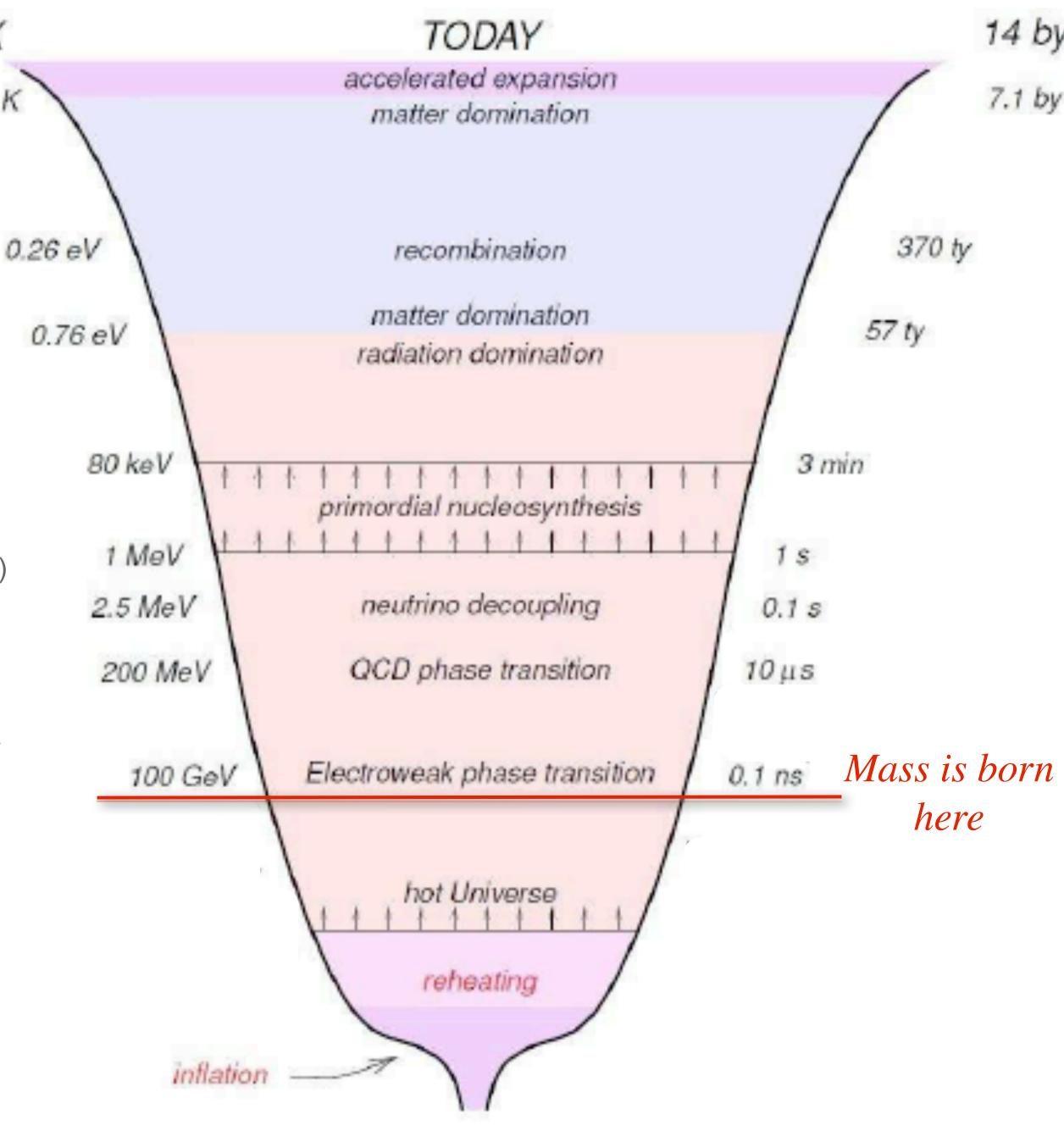
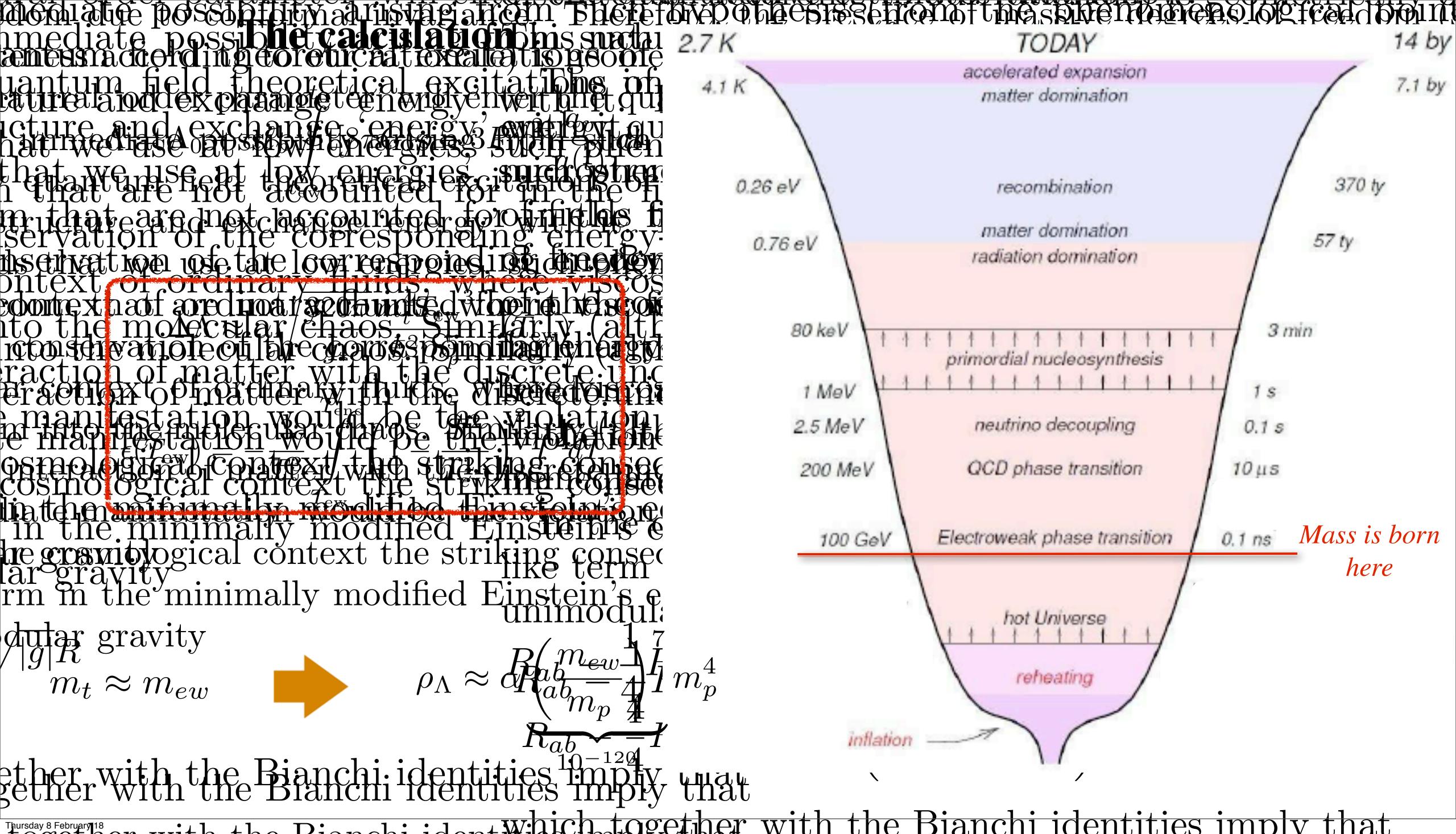


Figure 1. The value of the phenomenological parameter α , see eq. (6), that fits the observed value of Λ_{obs} as a function of the electro-weak transition scale $T_{\rm ew}$ in GeV.

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





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 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

- 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!



GR Symmetry:

General Diffeo.

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

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

Order parameter for discreteness probes:

scalar curvature

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

We relax diff-invariance to accommodate violations of energy conservation

Broken Diffeos

The same as Weyl transformations on shell

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

UG Symmetry:

Volume preserving Diffeo.

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

Preferred volume structure in UG:

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

The the minimally modified Einstein's equations unimodular gravit

Modeling the diffisher that we use at low operation of the difficulty of the continue of the c

degrees of freedom that we use the few chief the stations of the feducation of the feducation of the low responsition of the feducation of the feducation of the low responsition of the feducation of the feducation of the feducation of the feducation of the low responsition of the feducation of the feducation of the low responsition of the feducation of the feducation of the low responsition of the feducation of the feducation of the low responsition of the least the l

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 $S \stackrel{\text{unimodular}}{=} \text{gravity}$

which together with the Bianchi identifies the transformations on shell ∇

$$\begin{array}{c} g_{ab} \rightarrow (1 + \theta) g_{ab} \\ \text{Defining} J_{a} = (8\pi G/c) \sqrt{g_{ab}}, \\ \text{equation in the event of the system} \end{array}$$

equation and re-write the system in terms of the model

where A is a separate of integration and we see that the energy violation current of integration and we see

equations a statisfying the characteristic of integration and we see

The operations is the equation of the winds with the characteristic of integration and we see

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Thursday 8 February 18

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Preferred volume structure in UG:

Preferred conformal structure in cosmology

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



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

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

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Preferred volume structure in UG:

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\begin{itemize}

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