**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.

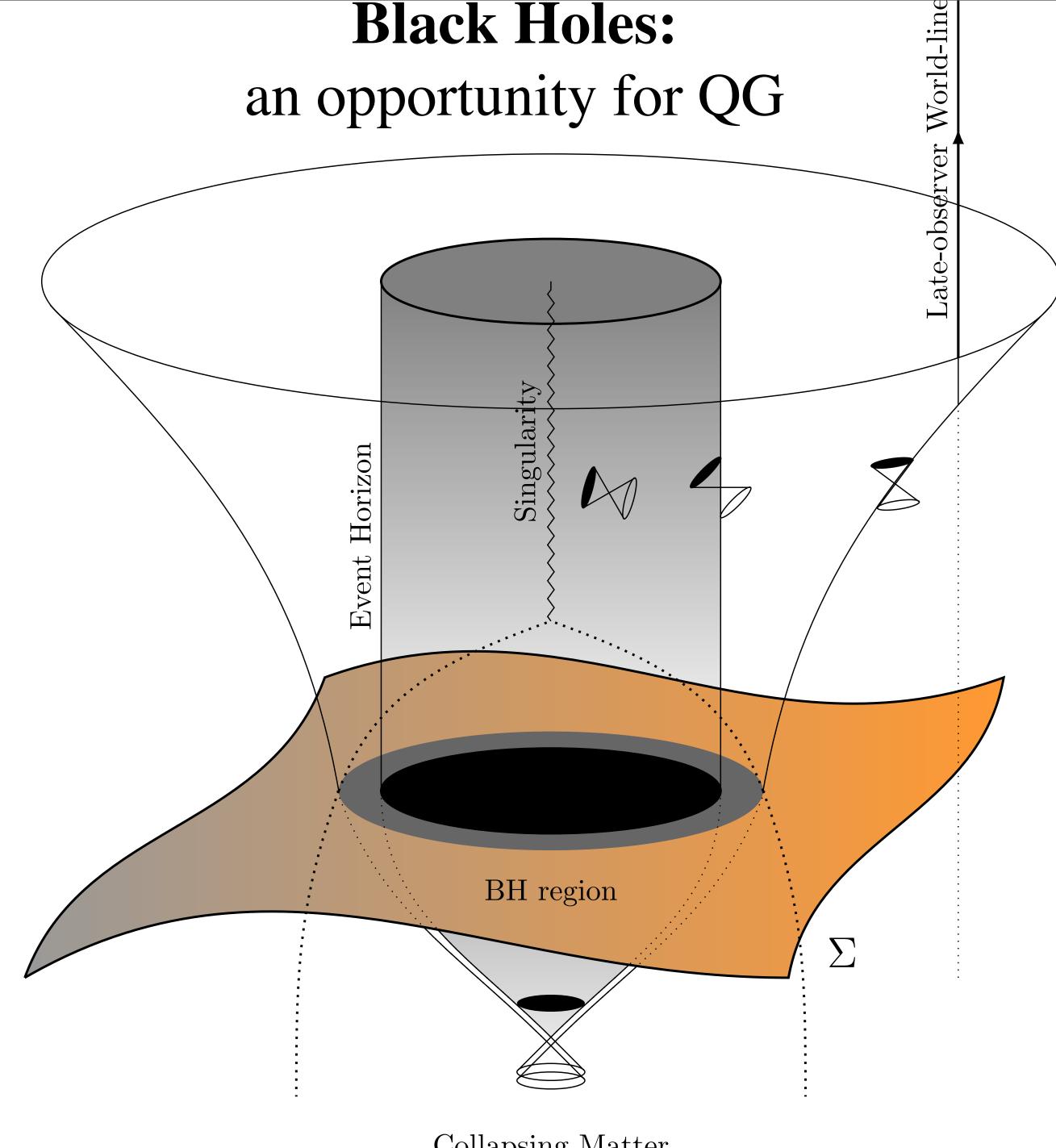
### Gravitation without energy-momentum conservation.

- 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.** 0

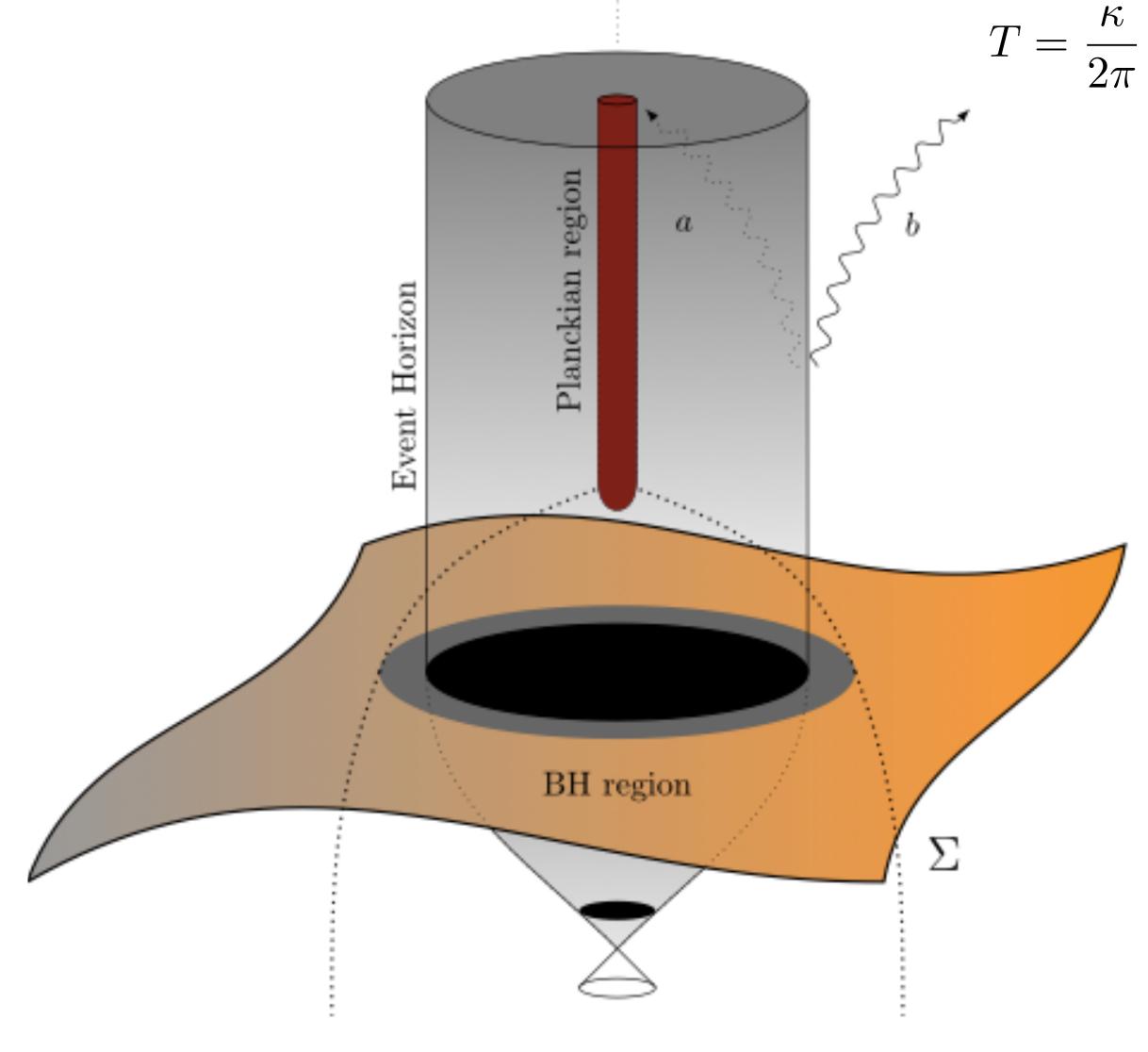
- Discreteness vs Lorentz invariance: an hypothesis.
- A phenomenological proposal.
- Implications for the dark energy problem.

# PART 1: A biased review on Loop Quantum Gravity.



Collapsing Matter

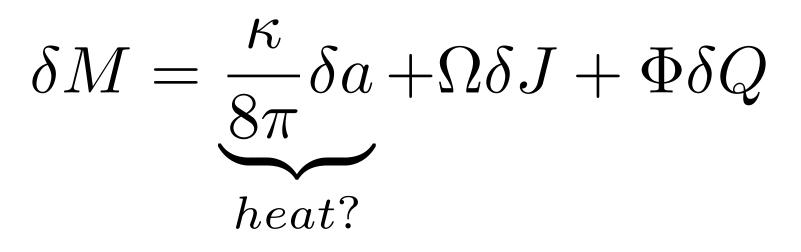
### **Black Holes:** Their thermal properties suggest micro-structure



Collapsing Matter

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

### Heat: Energy in molecular chaos



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

# Discreteness in Loop Quantum Gravity.

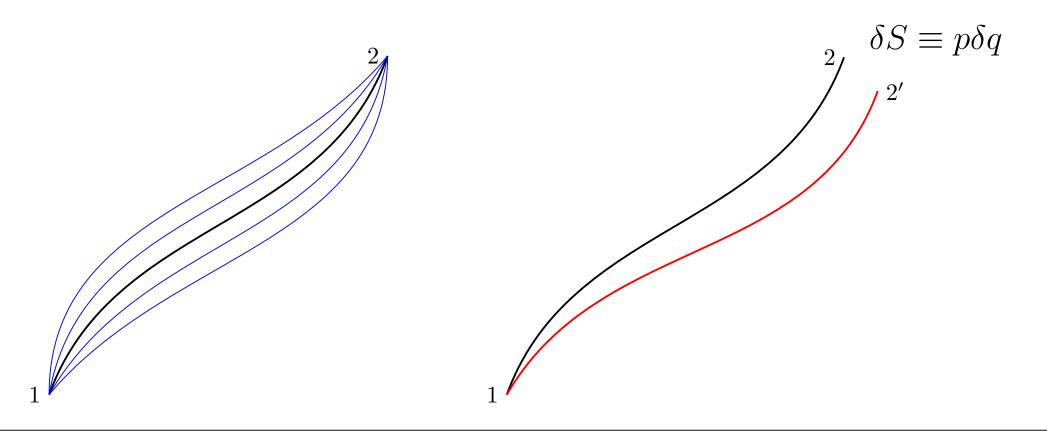
### **Pure gravity in connection variables**

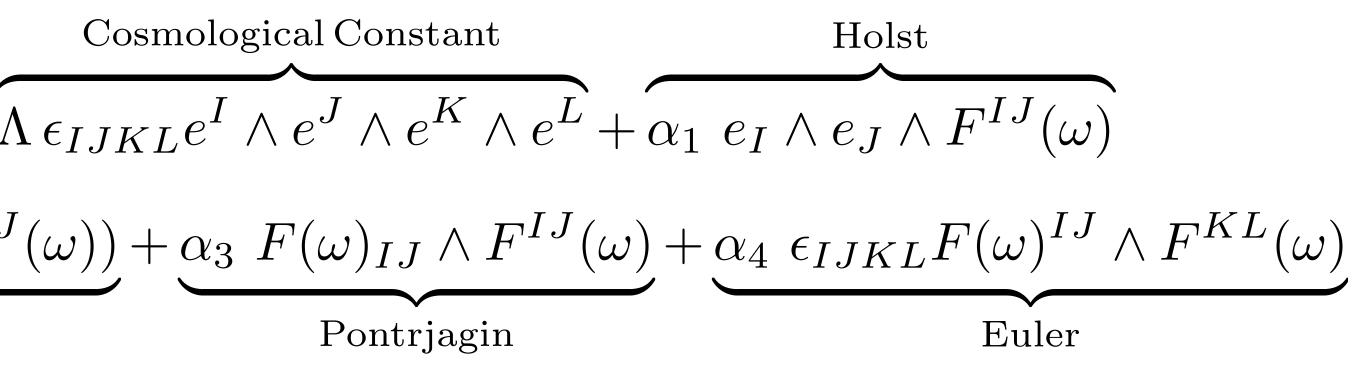
$$S[e_a^A, \omega_a^{AB}] = \frac{1}{2\kappa} \int \overbrace{\epsilon_{IJKL} e^I \wedge e^J \wedge F^{KL}(\omega)}^{\text{Einstein}} + \underbrace{\alpha_2 \ (d_\omega e^I \wedge d_\omega e_I - e_I \wedge e_J \wedge F^{IJ})}_{\text{Nieh-Yan}}$$

Simpler choice

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

### Phase space structure in a nut-shell





$$\delta S = \int_{1}^{2} \underbrace{\left[\frac{\partial L}{\partial q} - \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right)\right]}_{\text{e.o.m.}} \delta q dt + \underbrace{\frac{\partial L}{\partial \dot{q}} \delta q}_{p \delta q}\Big|_{1}^{2}$$

### Phase space structure

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

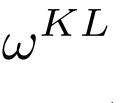
 $p_{IJKL} \equiv (\epsilon)$ 

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

### **Symplectic Potential**

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

$$\Xi_{IJKL} + \frac{1}{\gamma} \eta_{IK} \eta_{JL})$$



### Symplectic Potent

 $\Theta(\delta) = \int_{\Sigma} \frac{1}{2\kappa} [p]$ 

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

### **Poisson Brackets**

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

$$\{E^{i}(x), E^{j}(y)\} = 0 \{A^{i}(x), A^{j}(y)\} = 0 \{E^{i}(x), A^{j}(y), \} = \kappa \gamma \epsilon^{(3)} \delta^{i}$$

tial in the Time-Gauge 
$$e^{0}$$
  $e^{1}$   
 $p_{IJKL}e^{I} \wedge e^{J} ] \wedge \delta \omega^{KL}$  18  
12  
 $\wedge \delta \omega_{0i} ) - \frac{1}{\kappa} \int_{\Sigma} \left( \epsilon_{0jkl}e^{j} \wedge e^{k} \wedge \delta \omega^{l0} + \frac{1}{\gamma}e^{i} \wedge e^{j} \wedge \delta \omega_{ij} \right)$ 

 $\omega_{mn})$ 

connection

### **Constraints (EEs)**

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

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

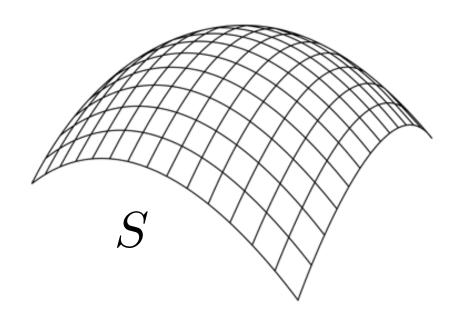
 ${}^{ij}\delta^{\scriptscriptstyle (3)}(x,y)$ 

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



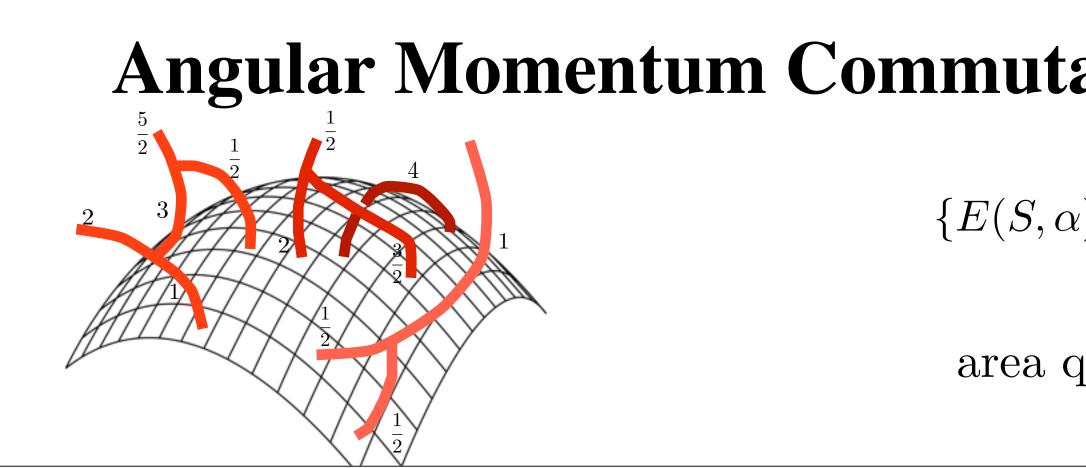
 $-\cdots = 0$ 

### **Discreteness in a nut-shell**



$$E(S,\alpha) \equiv \int_{S} \alpha_{i} E^{i}$$

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



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

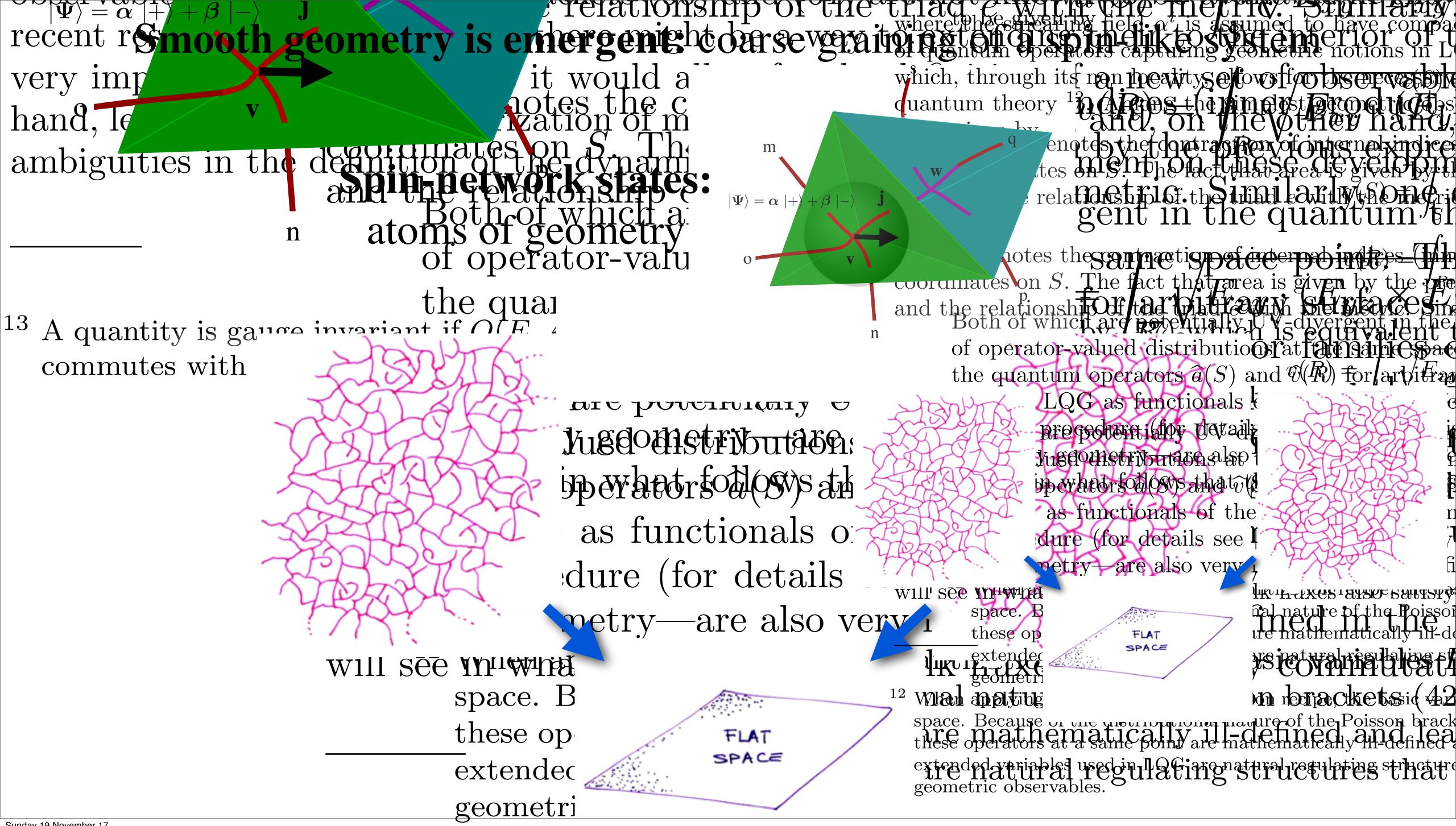
### **Angular Momentum Commutations = Angular Momentum Discreteness**

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

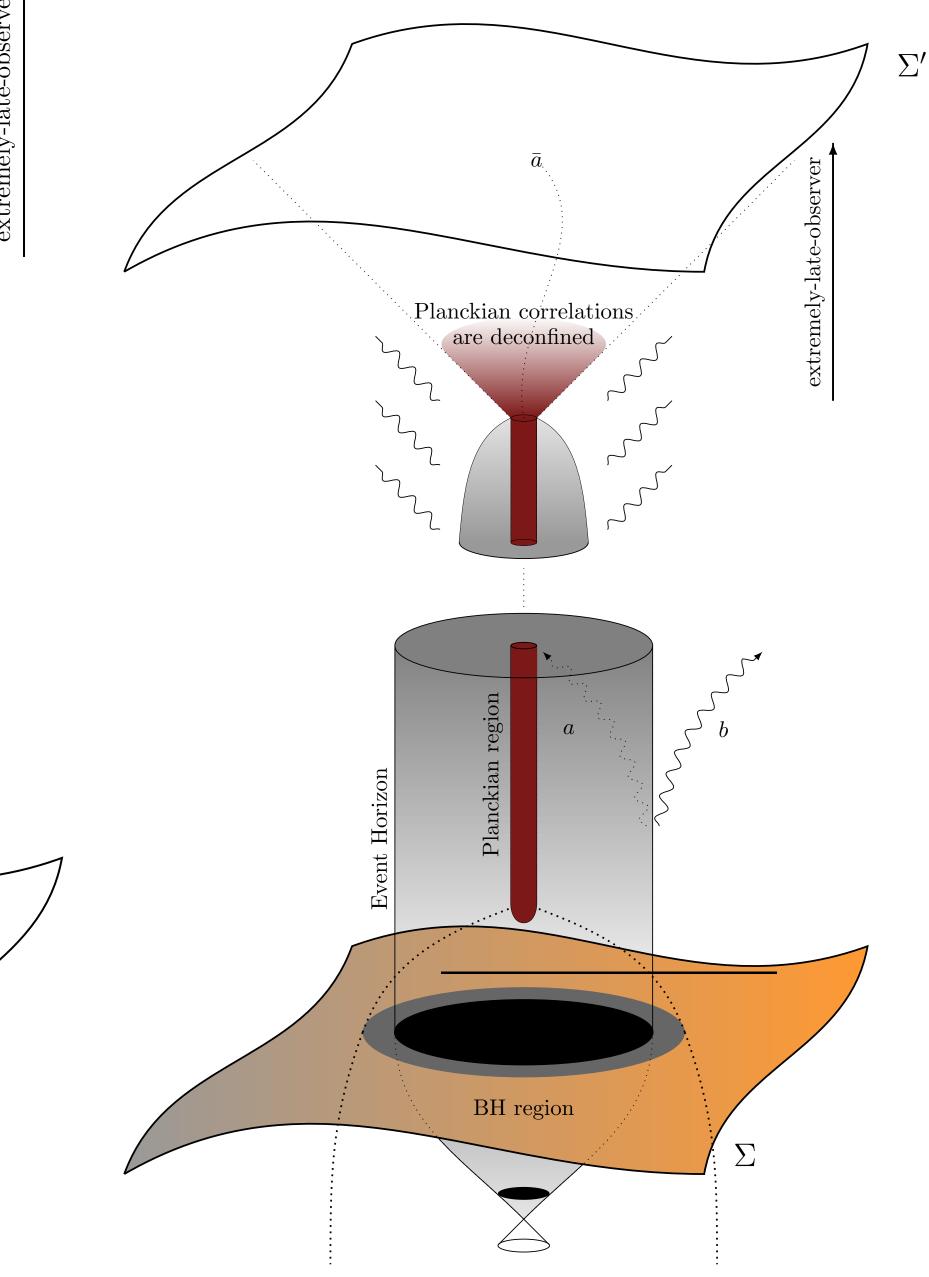
area quantum =  $\gamma \ell_p^2 \sqrt{j(j+1)}$ 







### New perspective on the information paradox



Collapsing Matter

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extremely-late-observe

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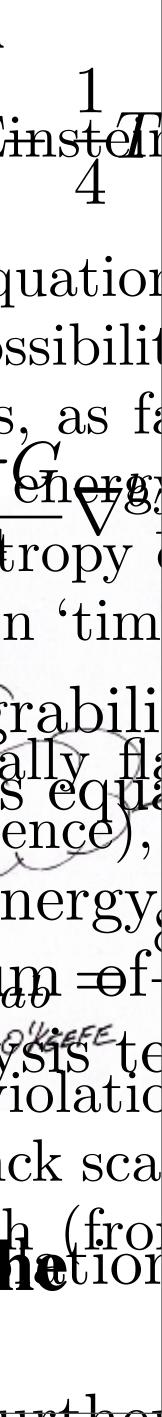
### Decoherence with discrete micro-structure imply violations of energy conservation in the smooth effective description!

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



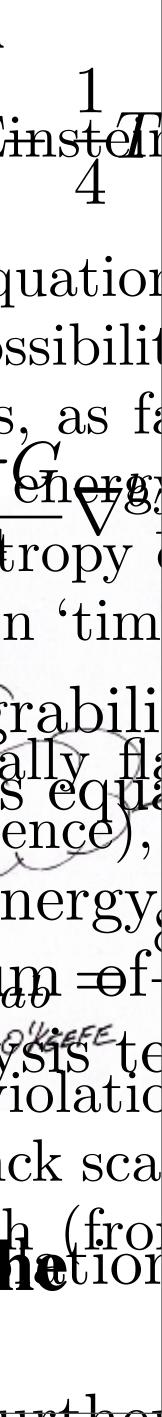


Violations of energy conservation in the effective smooth semiclassical stant of integration and we see that the therefore the stand of the expected the sequece of a term  $T_{ab}$  Einstern ng the dark energy equation of state. s the general framework where we will develop further our proposal. First, the previous equation the energy-momentum violations are the management of the matrix J the possibility of gravitational dynamics in terms of a metric theory is compromised: unimodular gravity is, as fa only relaxation of the standard general covariance requirements allowing  $\frac{8}{2}$  (violations  $\frac{3}{2}$ ) (mathematical standard general covariance requirements) allowing  $\frac{8}{2}$  (violations)  $\frac{3}{2}$ rvation. Fortunately, in applications to cosmology the a stion of homogeneity and isotropy of scales of interest, implies integrability of J (this is because in this setting J only depends on 'tim a 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 fla re-Robertson-Walker (FLRW) metric (an assumption 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 for the anticking manoscopled districter substratum = of that according to our rationale only  $\rho_m$  contributes, thus simple dimensional analysis to be a violatic determined on the spacetime formulation of the spacetime formulatin of the spacetime formulation of the spacetim tum conservation. The process is quantum gravitational so it must be contreal phintage planck sca (as argued before) by the presence of a non trivial scalar curvature or Ricci scalar which (from and we **recent the scalar which (from and we recent ance is to start the** tion and we recent the scalar which (from and we recent the s The previous the deneral manademork where we will develop further Sunday 19 November 17

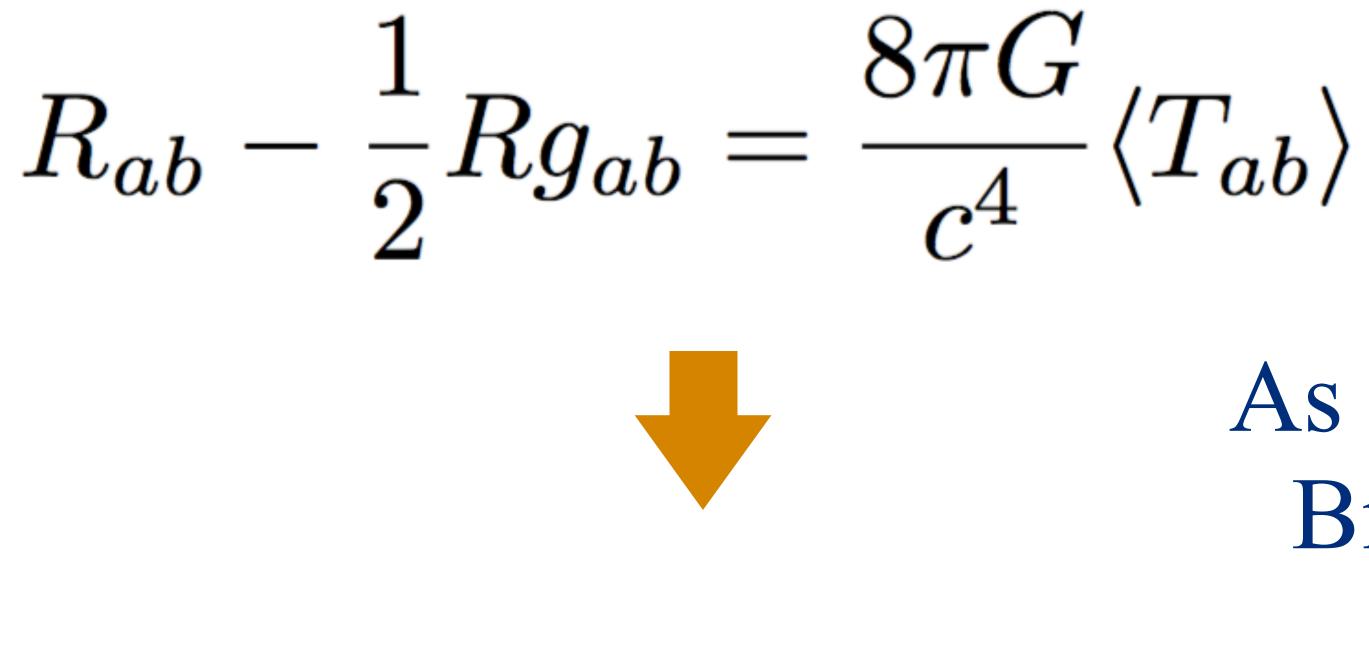


# PART 2: A phenomenological perspective on *Dark Energy*.

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### **BUT energy-momentum is conserved in general relativity**

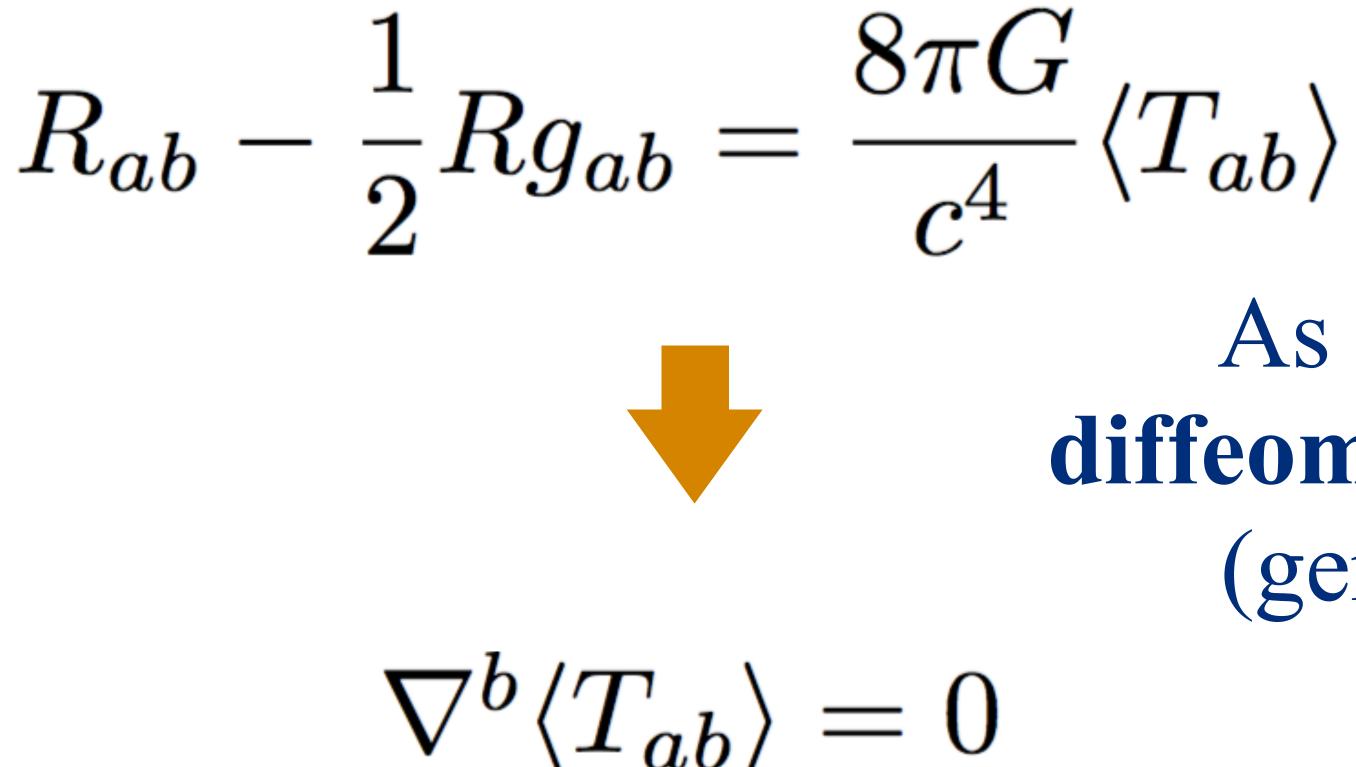


# $\nabla^b \langle T_{ab} \rangle = 0$

## As a consequence of **Bianchi identities**



### BUT energy-momentum is conserved in general relativity



As a consequence of diffeomorphism invariance (general covariance)



### **Energy conservation from diff-invariance**

$$S[g_{ab},\phi] = S_{gra}$$

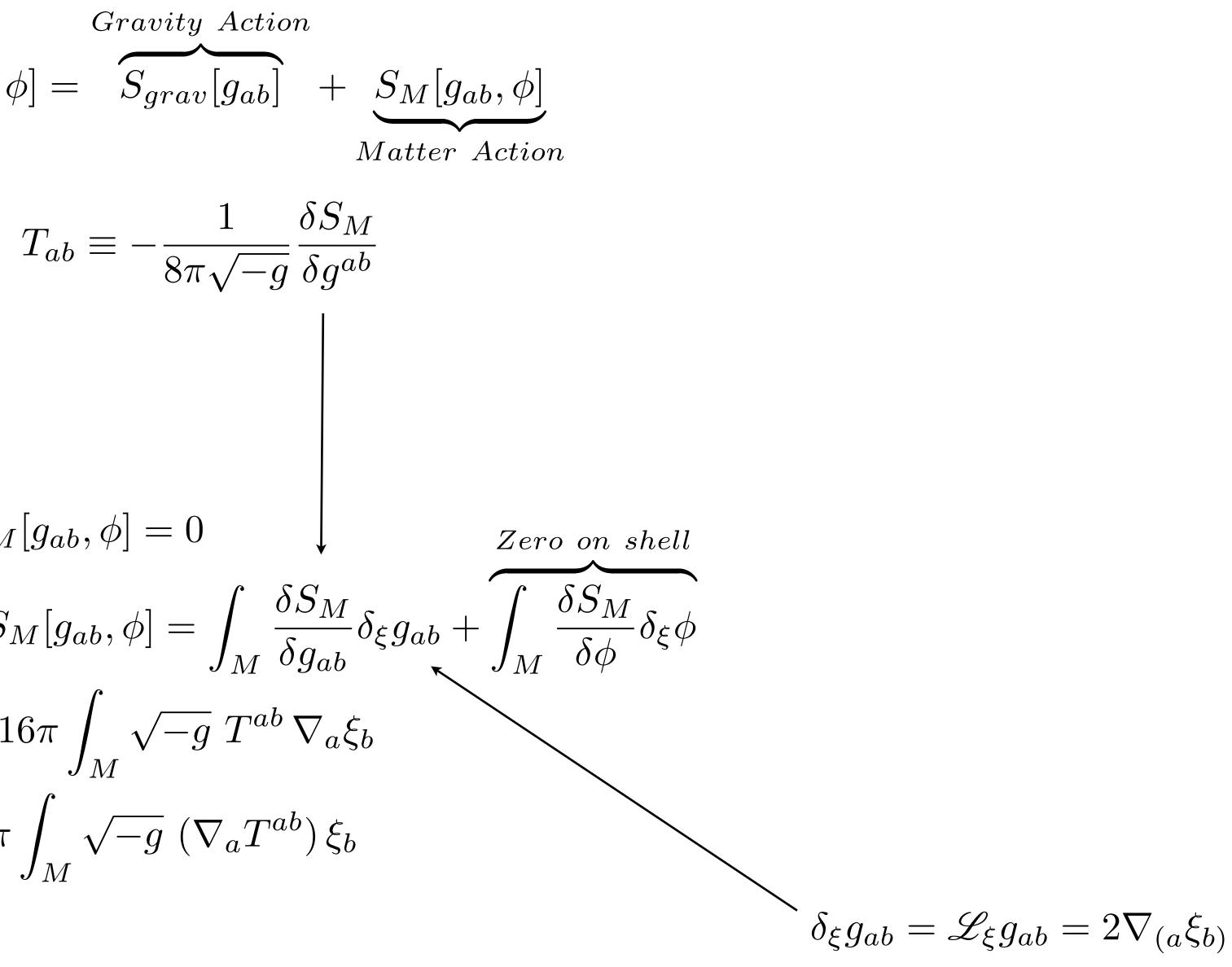
$$T_{ab} \equiv -\frac{1}{8}$$

### **Proof:**

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

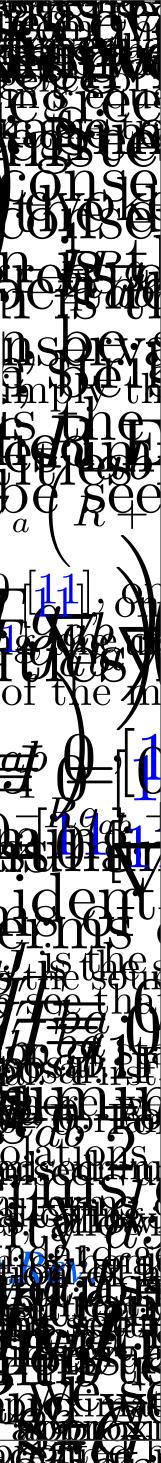
$$0 = \delta_{\xi} S_M[g_{ab}, \phi] =$$

$$= -16\pi \int_M \sqrt{-g}$$





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

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

 $S = \int \sqrt{|g|} R$  $g_{ab} \delta g^{ab} = 0$ 

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

dJ = 0

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

 $\nabla_a \xi^a = 0$ 

$$\bar{g}dx^4 = \int J_a \xi^a \sqrt{-g} dx^4 = 0$$

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

 $J_a = \nabla_a Q$ 

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

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

GR compatible stress tensor satisfying Wald axioms

### Unimodular gravity compatible stress tensor

### $\langle T_{ab} \rangle_{\rm GR} \equiv \langle T_{ab} \rangle_{\rm NO} - Qg_{ab}$ trace anomaly for CFT's!

 $\langle T_{ab} \rangle_{\text{Unimed}} \equiv \langle T_{ab} \rangle_{\text{NO}}$ NO trace anomaly! Diffeos broken down to volume preserving ones

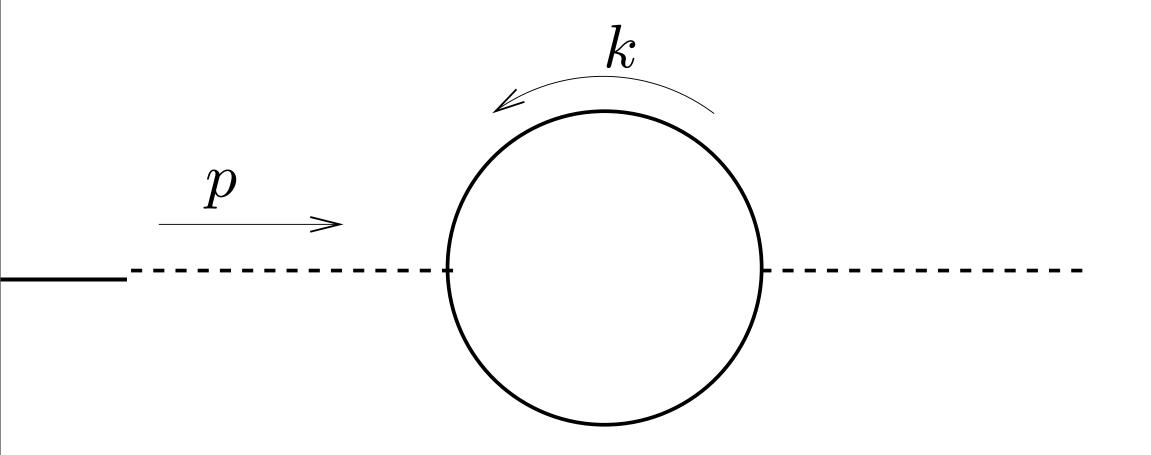
### **Discreteness and Lorentz invariance**

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**

$$\begin{aligned} \mathcal{L} &= \frac{1}{2} (\partial \phi)^2 - \frac{m_0^2}{2} \phi^2 + \bar{\psi} (i \gamma^{\mu} \partial_{\mu} - M_0) \psi + g_0 \phi \bar{\psi} \psi. \\ &\frac{i}{\gamma^{\mu} p_{\mu} - m_0 + i\epsilon} \to \frac{i f(|\mathbf{p}|/\Lambda)}{\gamma^{\mu} p_{\mu} - m_0 + \Delta(|\mathbf{p}|/\lambda) + i\epsilon}, \\ &\frac{i}{p^2 - M_0^2 + i\epsilon} \to \frac{i \tilde{f}(|\mathbf{p}|/\Lambda)}{p^2 - M_0^2 + \tilde{\Delta}(|\mathbf{p}|/\lambda) + i\epsilon}. \end{aligned}$$



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

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

$$\tilde{\xi} = \frac{g^2}{6\pi^2} \left[ 1 + 2 \int_{0}^{\infty} dx x f'(x)^2 \right]$$

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

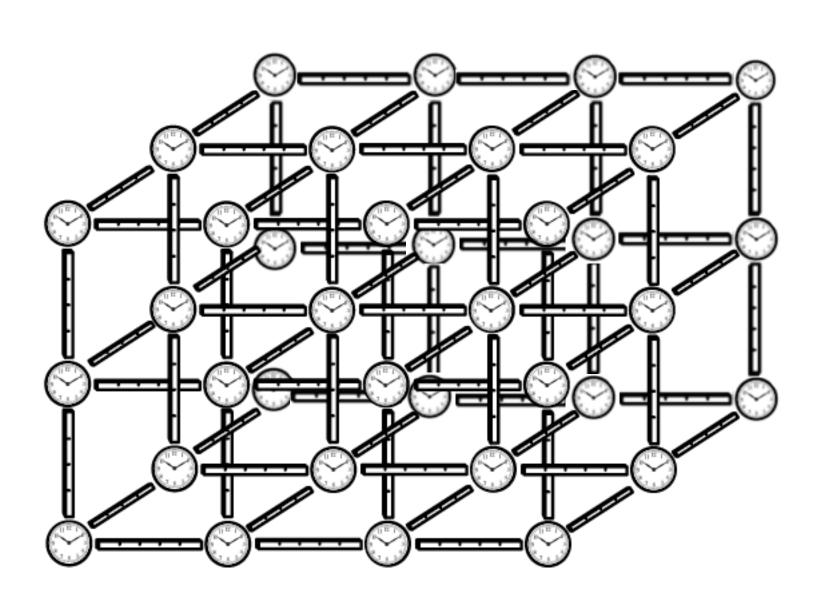


### $\Lambda^2)$

### 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"



### **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

 $g_{ab} \rightarrow$ 

### **Order parameter for** discreteness probes: scalar curvature $R = 8\pi T \neq 0$

**UG Symmetry:** Volume preserving Diffeo.

### **Broken Diffeos**

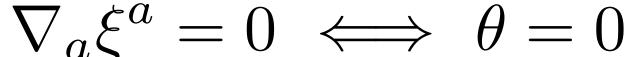
The same as Weyl transformations on shell

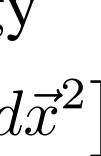
$$(1+\frac{\theta}{4})g_{ab}$$

**Preferred volume** structure in UG: Preferred conformal

structure in cosmology

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





# degrees of freedom the

### **GR Symmetry:** General Diffeo.

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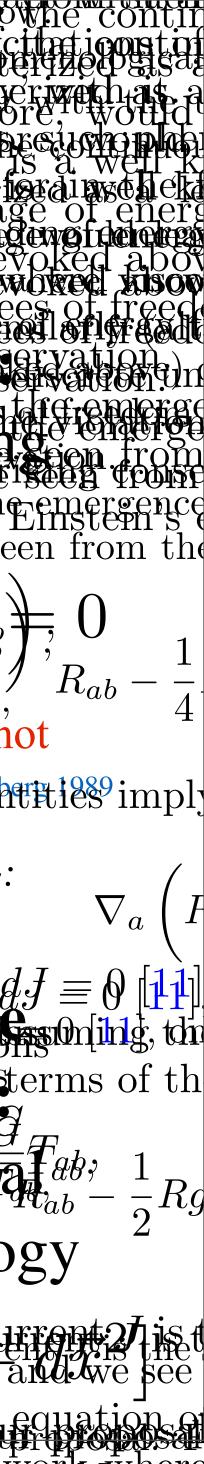
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which toget

Modeling the diffusion the transferrence of the second of gravity gical context the striking consequences no the minimally modified tutar gravity en Diffeos  $R_{ab}$  – with grev Baanchi Weenerties imply which together with the Bianchi identities in place that transformations on shell  $\nabla_{a}$  ( $R_{B} + \frac{87}{2}$ n and re-write the system in termation structure in cosmology  $\mathbf{2}$ 

$$g_{ab} \rightarrow D_{gab}$$

### **Order parameter for** discreteness probes: scalar curvature $R = 8\pi T \neq 0$

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**Broken Diffeos** The same as Weyl transformations on shell  $g_{ab} \rightarrow (1 + \frac{\theta}{4})g_{ab}$ 

**Order parameter for** discreteness probes:

scalar curvature

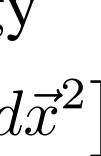
$$R = 8\pi T \neq 0$$

### **UG Symmetry:** Volume preserving Diffeo. $\nabla_a \xi^a = 0 \iff \theta = 0$

**Preferred volume** structure in UG: Preferred conformal structure in cosmology

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





### **GR Symmetry:** General Diffeo.

$$\mathscr{L}_{\xi}g_{ab} = 2\nabla_{(a}\xi_{b)}$$
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Order parameter for  
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scalar curvature  
$$R = 8\pi T \neq 0$$



### **UG Symmetry:** Volume preserving Diffeo.

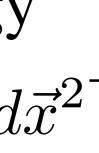
 $\nabla_a \xi^a = 0 \iff \theta = 0$ 

### **Broken Diffeos** The same as Weyl transformations on shell $g_{ab} \to (1 + \frac{\theta}{4})g_{ab}$

**Preferred volume** structure in UG: Preferred conformal structure in cosmology

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**Order parameter for** discreteness probes: scalar curvature  $R = 8\pi T \neq 0$ 

**UG Symmetry:** Volume preserving Diffeo.

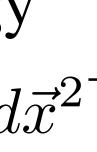
**Broken Diffeos** The same as Weyl transformations on shell  $g_{ab} \to (1 + \frac{\theta}{4})g_{ab}$ 

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

> **Preferred volume** structure in UG: Preferred conformal structure in cosmology

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





### **GR** Symmetry: General Diffeo.

$$\mathscr{L}_{\xi}g_{ab} = 2\nabla_{(a}\xi_{b)}$$
$$\nabla_{(a}\xi_{b)} = \frac{\theta}{4}g_{ab} + \sigma_{ab}$$

$$g_{ab} \rightarrow$$

### **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

### **UG Symmetry:** Volume preserving Diffeo.

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

### **Broken Diffeos**

The same as Weyl transformations on shell

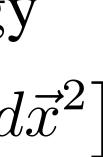
$$(1+\frac{\theta}{4})g_{ab}$$

**Preferred volume** structure in UG: Preferred conformal

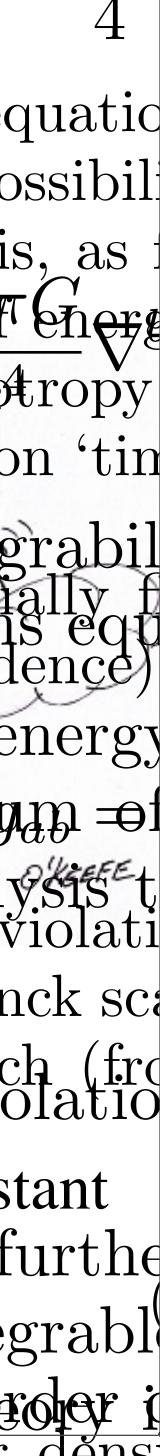
structure in cosmology

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



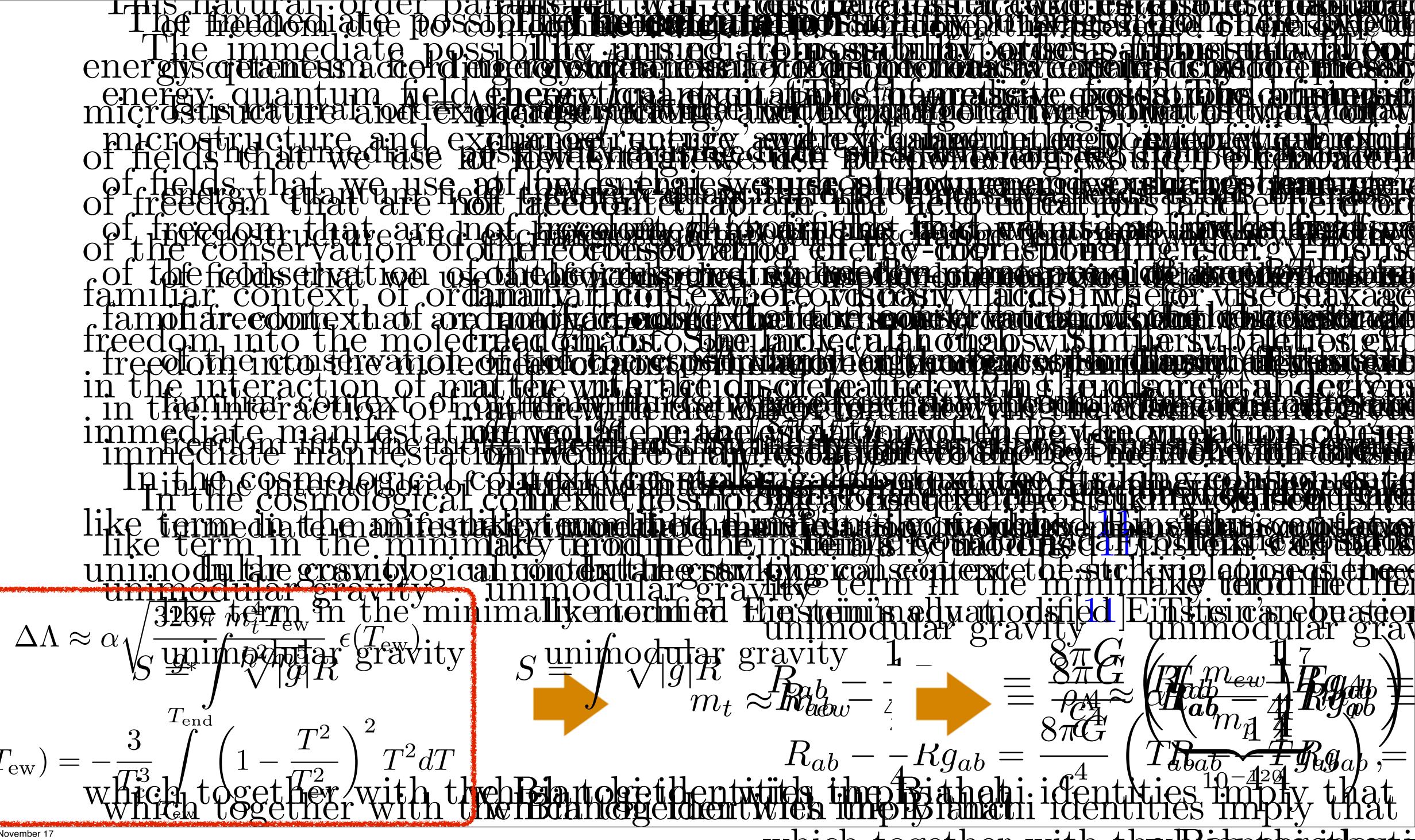


ing the dark energy equation of state the diffusion from low energy is the general framework where we will develop further our proposal. First, the previous equation for the energy-momentum violations are the diffusion from low energy J the possibility of the energy-momentum violations are the diffusion from low energy J the possibility of the energy-momentum violations are the diffusion from low energy J the possibility of the energy-momentum violations are the energy of the ener gravitational dynamics in terms **Planckian microstructure**sed: unimodular gravity is, as : only relaxation of the standard general covariance requirements, all by ing  $\delta T = \delta T =$ e scales of interest. implies integrability of d f =In comoving coordinates  $J_a \equiv (8\pi G/c^4) \nabla^b T_{ba}$ , and assuming the unimodular integrabil will assume that the spacetime metric at large scales is well approximated by the spatially for tre-Robertson-Walker (FLBW) metric (an assumption very well supported by empirical evidence) te the amount of energy-momentum violation experienced due to the presser of energy es of freedom =ofahassice(phater) to the quitering manoscople discrete, substratum =of that according to our rationale only  $\rho_m$  contributes, thus simple dimensional analysis to pletely phenomenological view that granularity associated with the spacetime form leads to a violation but ion should be -. bution should be full conservation. The process is quantum gravitational so it must be controlled by the Planck sca d (as argued before), by the presence of an on trivial scalar curvature or Ricci scalar which (fro ons applied to the PLANE HARMED Structure of Silver to match tegration and we see that the energy violatio co-moving time at Plans, toged ark energy equation of atmensionless constant The previous pis toged for a Phanetwork where we swill develop furthe date on the deful of the energy-momentum violations are of the integrable sumersenter and the universe the institute of the institute of the includes the baryonic matter dens



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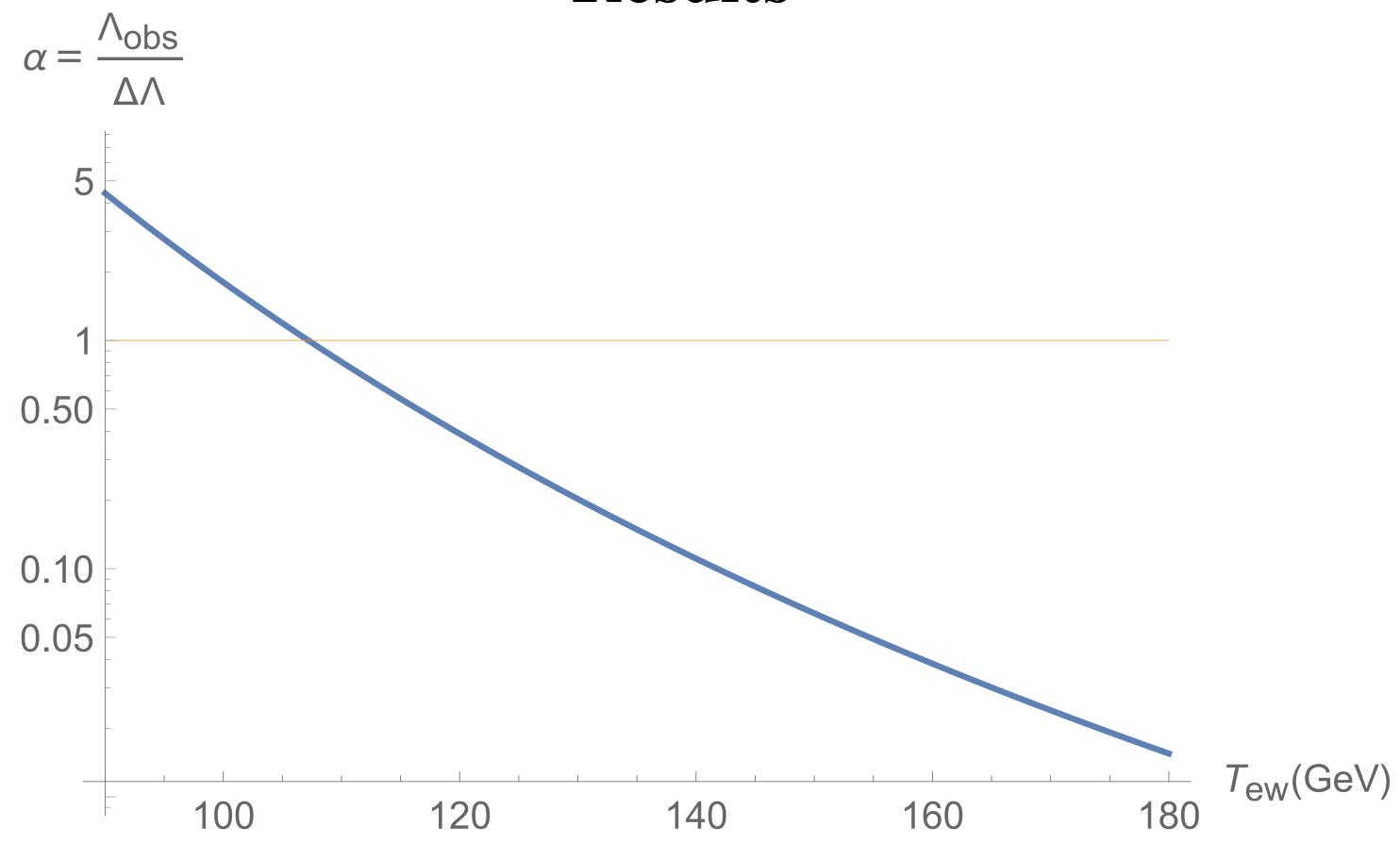


Figure 1. The value of the phenomenological parameter  $\alpha$ , see eq. (6), that fits the observed value of  $\Lambda_{obs}$  as a function of the electro-weak transition scale  $T_{ew}$  in GeV.

### Results

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

### Discussion

- on smooth spacetime geometry.
- feed a dark energy term in the Einsteins equations.
- scription of this type of diffusion in cosmology.
- Vacuum energy does not gravitate in UG.
- tant cosmological influence.
- beyond the standard model.
- Can one find another (independent) implication of these ideas?

• Violations of energy momentum conservation are natural in an effective description of a fundamentally discrete physics in terms of smooth fields

• When integrable such violations can be describe in terms of UG, and they

• Integrability is trivial in FLRW spacetimes. UG is the most general de-

• Tiny violations (hard to detect in local experiments) can have an impor-

• 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

Merci Beaucoup!

### \begin{itemize}

\item 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. \item When integrable such violations can be describe in terms of UG, and they feed a dark energy term in the Einsteins equations. \item Integrability is trivial in FLRW spacetimes. UG is the most general description of this type of diffusion in cosmology.  $\pm$  vacuum energy does not gravitate in UG.

\item Tiny violations (hard to detect in local experiments) can have an important cosmological influence.

\item 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. \item Can one find another (independent) implication of these ideas?

\end{itemize}

