Title: Planckian discreteness and dark energy phenomenology

Speakers: Alejandro Perez

Series: Quantum Gravity

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Abstract: I will explain how dark energy in cosmology could arise from the

noisy diffusion of energy from the low energy degrees of freedom of matter (described in terms of QFT)

to the fundamental Planckian granularity (expected from quantum gravity). This

perspective leads to a natural model resolving the fine tuning problem associated to the small

value of the cosmological constant. However, recent observations suggest that the dark energy

component in our universe might not be constant and should instead have grown from the recombination time to the present.

I will present new ideas suggesting a possible explanation within the same framework.

Planckian discreteness and dark energy phenomenology

Based on work in collaboration with **D. Sudarsky, E. Wilson-Ewing** and **J. Bjorken**

Perimeter Institute

November, 2019

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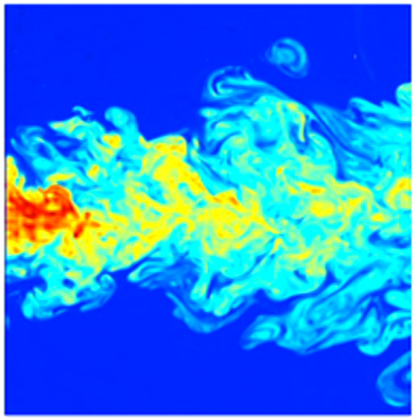
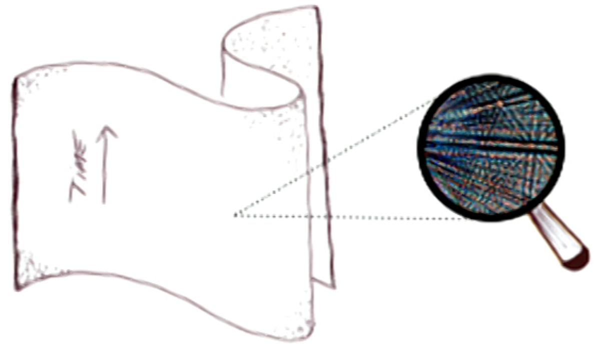
Mathematical description of fluids
(**Navier-Stokes**)



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)

Bianchi Identities

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

3) Unimodular Gravity
(1919)

Weinberg 1987

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

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

↔ **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

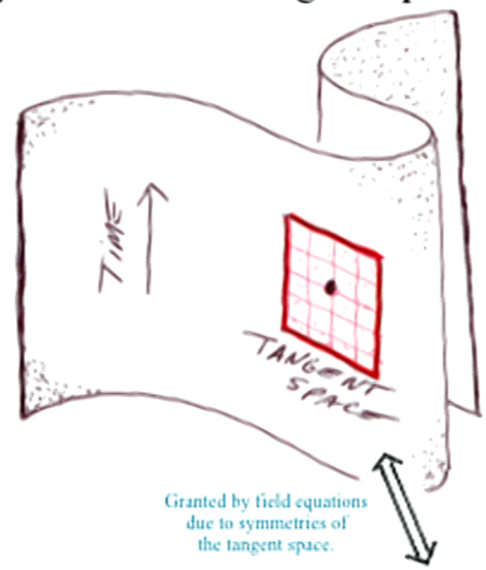
$\Uparrow$

Traceless Einstein's Equations:

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

$\Leftarrow$

Conservation of Energy:
symmetries of tangent space

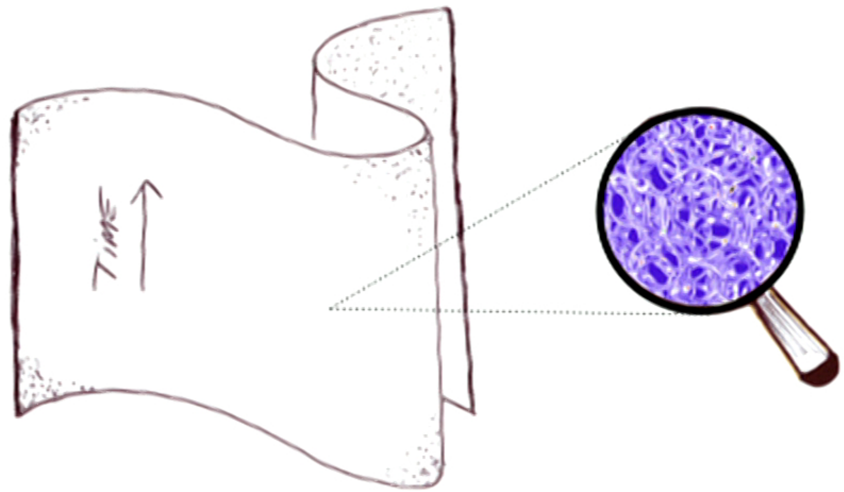


$$\nabla^a \mathbf{T}_{ab} = 0$$

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

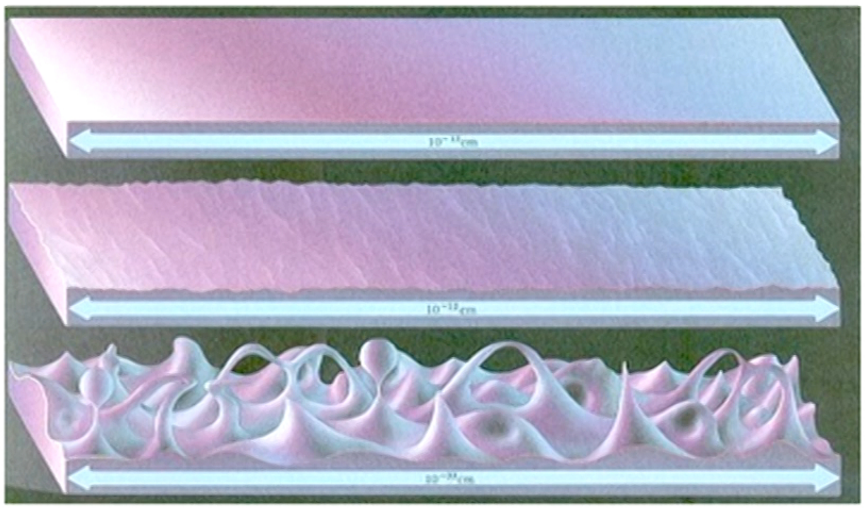
$$\mathbf{R}_{ab} - \frac{1}{4} g_{ab} \mathbf{R} = 8\pi \left(\mathbf{T}_{ab} - \frac{1}{4} g_{ab} \mathbf{T} \right)$$

Ingredient 2

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

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

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

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

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

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

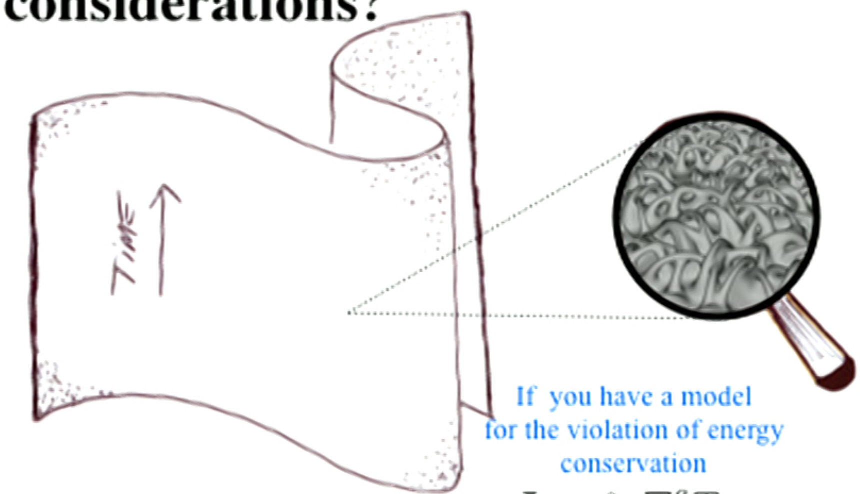
Need to satisfy the integrability condition

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

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

Can we predict J from QG considerations?

- 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

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

T. Josset, AP, D. Sudarsky. PRL 118, (2017)

AP, D. Sudarsky, J.D. Bjorken. Int.J.Mod.Phys. D27 (2018)

AP and D. Sudarsky, PRL (2019) to appear

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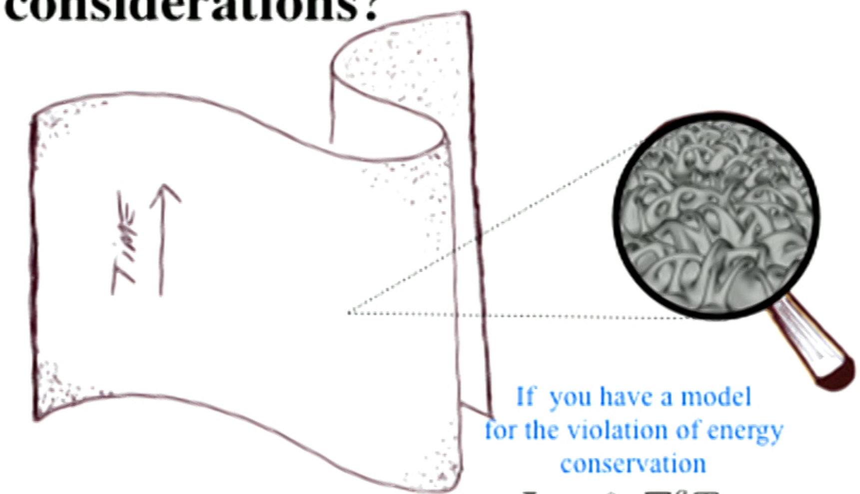

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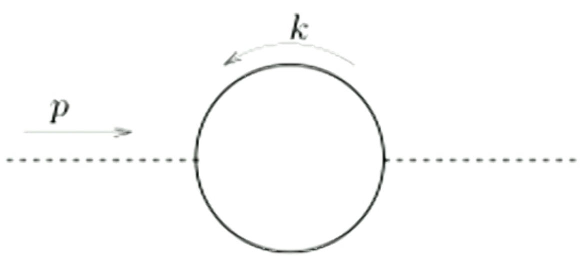
Radiative corrections make Lorentz violation percolate to low energies

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

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

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

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

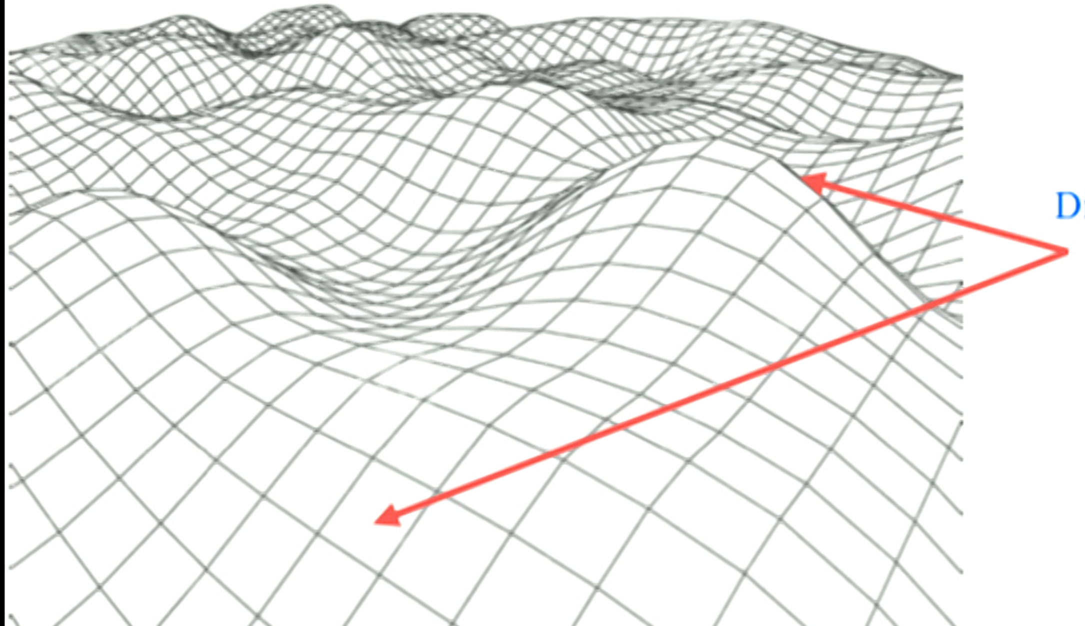


$$\Pi(p) = A + p^2 B + p^\mu p^\nu W_\mu W_\nu \tilde{\xi} + \Pi^{(\mathrm{LI})}(p^2) + \mathcal{O}(p^4/\Lambda^2)$$

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

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

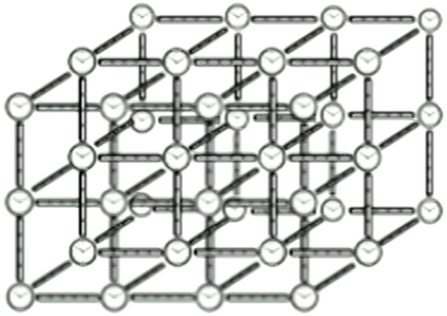
Discreteness and Lorentz invariance



Discreteness **could** manifest itself in regions of non trivial curvature

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!)**

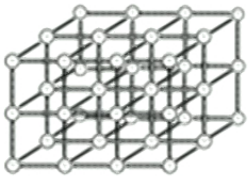


Scalar curvature is the natural "order parameter"

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

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:



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

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

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

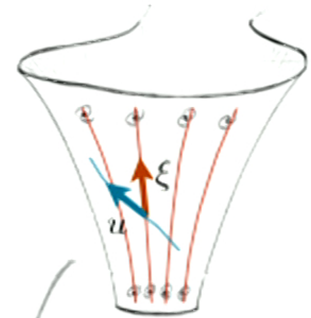
Langevin-like equation

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

On the tensor structure of the force

Langevin-Papapetrou like equation; noisy diffusion due to discreteness.

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



Massive spinning excitations = **genuine 4d probes**

Massless spinning excitations = **3d probes**

Scalar excitations = **1d probes**

Tensor structure of the RHS

$$f_\mu \propto m F_{\mu\nu} u^\nu$$

$$\boxed{F^{(1)}_{ab} = s_{[a}u_{b]}} \quad F^{(2)}_{ab} = s_{[a}\xi_{b]} \quad F^{(3)}_{ab} = \xi_{[a}u_{b]} \quad F^{(4)}_{ab} = \epsilon_{abcd}s^{[c}\xi^{d]}$$

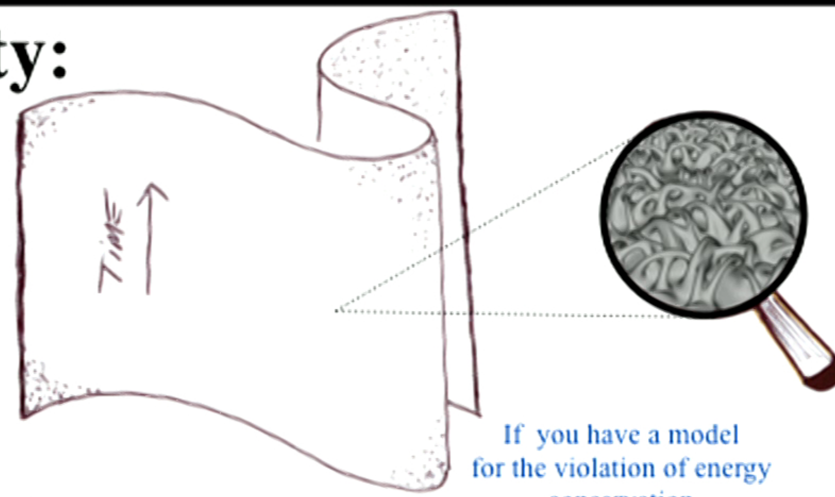
Other similar looking equations

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

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

Langevin Equation

Unimodular Gravity:



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

$\Downarrow$

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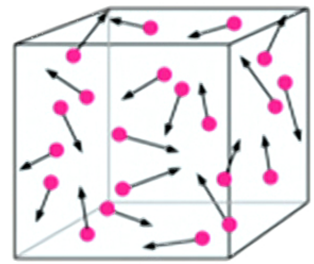


From simple relativistic kinetic theory

$$\Downarrow$$

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

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

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

Sum over species of the standard model

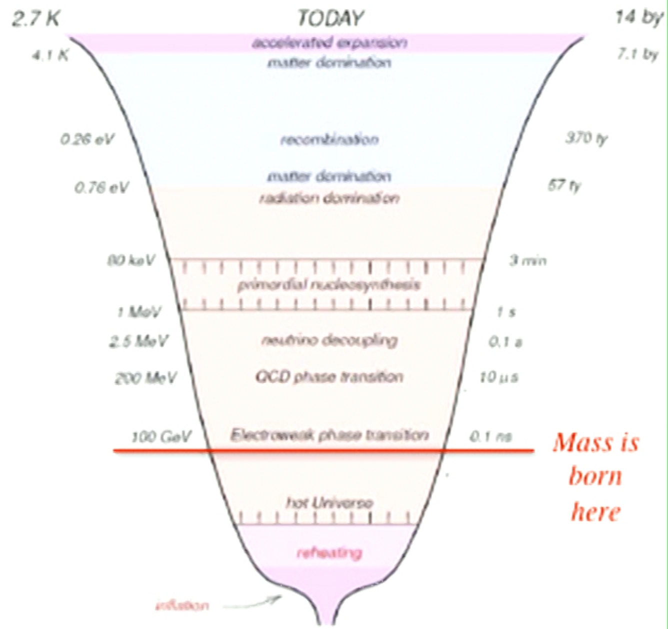
Top quark approximation

Results are in suggesting agreement with observations

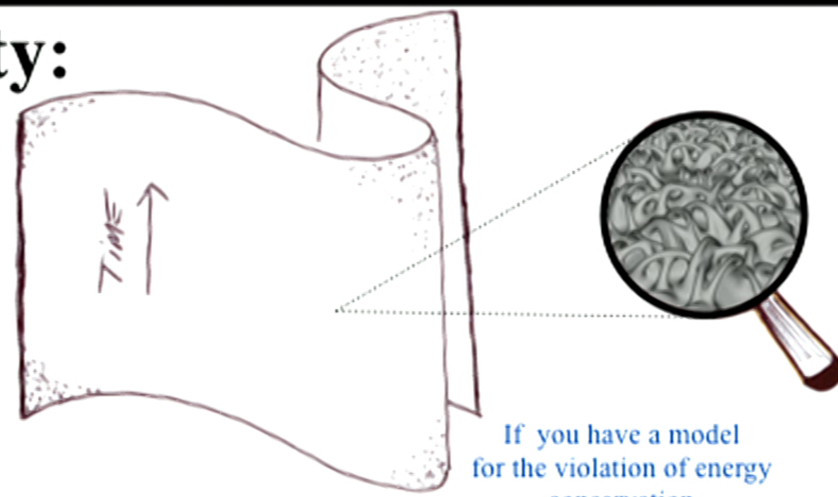
$$\mathbf{J}_b = \frac{2\pi\alpha\hbar}{m_p^2} T\mathbf{R}^2 \xi_b$$

$$\Lambda = \int \mathbf{J}_b dx^b = \frac{2\pi\alpha\hbar}{m_p^2} \int_{t_0}^{t} T\mathbf{R}^2 dt$$

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



Unimodular Gravity:



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⇘ ⇙

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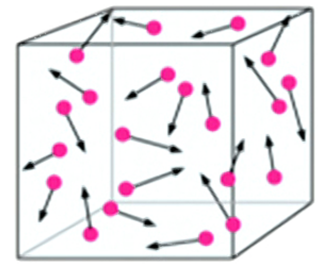
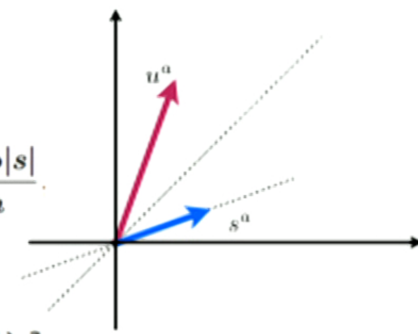


From probability distribution evolution

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



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

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

Results are in suggesting agreement with observations

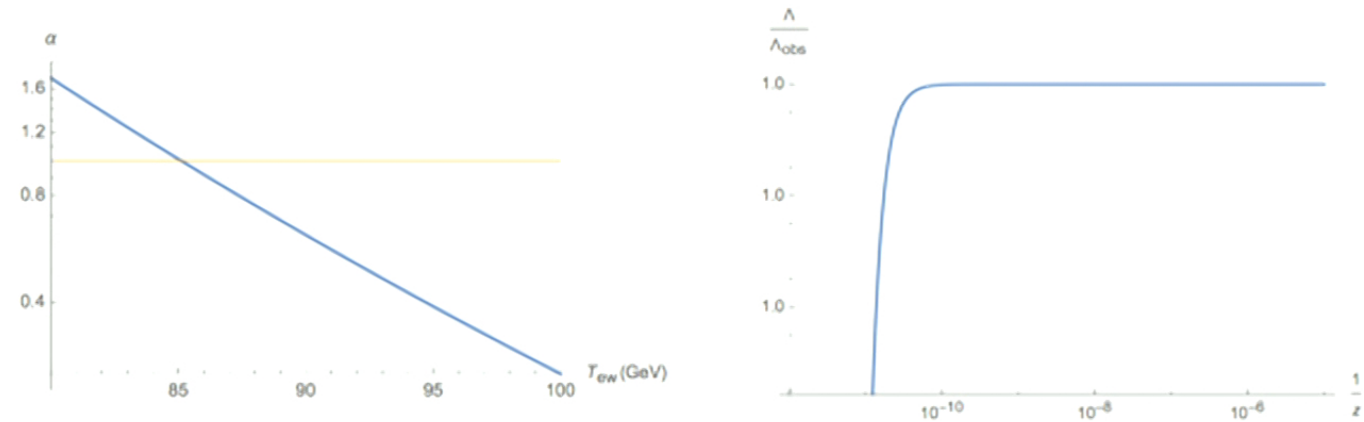


Figure 1: **Left:** The value of the phenomenological parameter α that fits the observed value of Λ_{obs} as a function of the EW transition scale $T_{\rm ew}$ in GeV. We see that for $T_{\rm ew} \approx 100GeV$ $\alpha \approx 1$. **Right:** The time dependence of Λ expressed in terms of the inverse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

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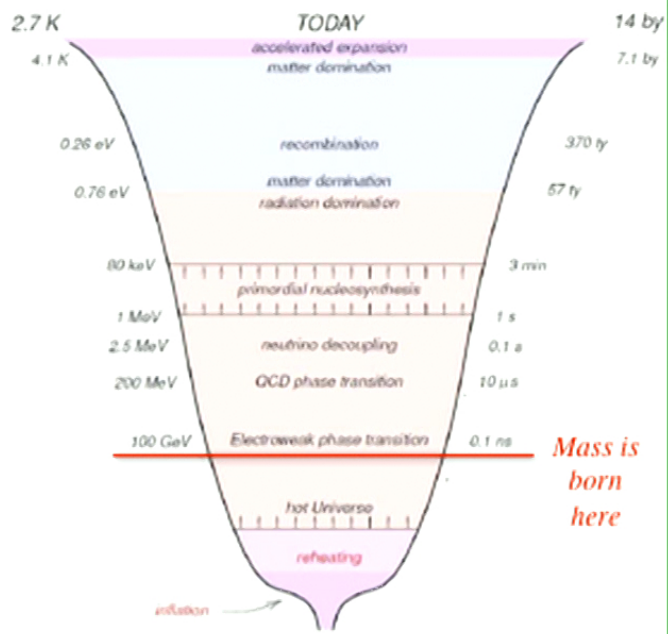

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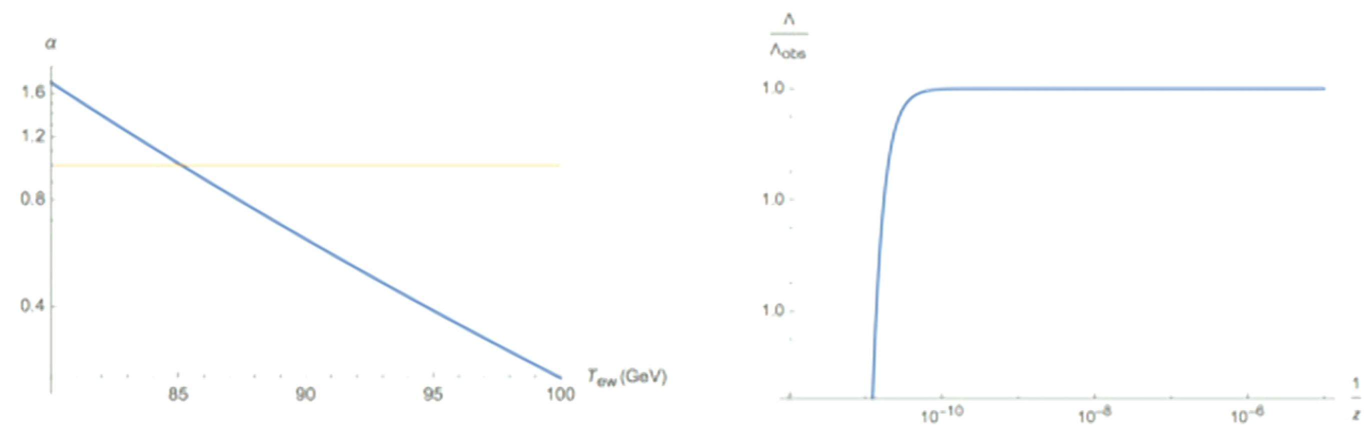

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Energy lost in a Hubble time

$$\frac{\Delta\rho_{\mathrm{diffusion}}}{\rho} < 10^{-51}$$

Dynamical effect of the diffusion is **negligible.**

Entropy production in FLRW cosmology:

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

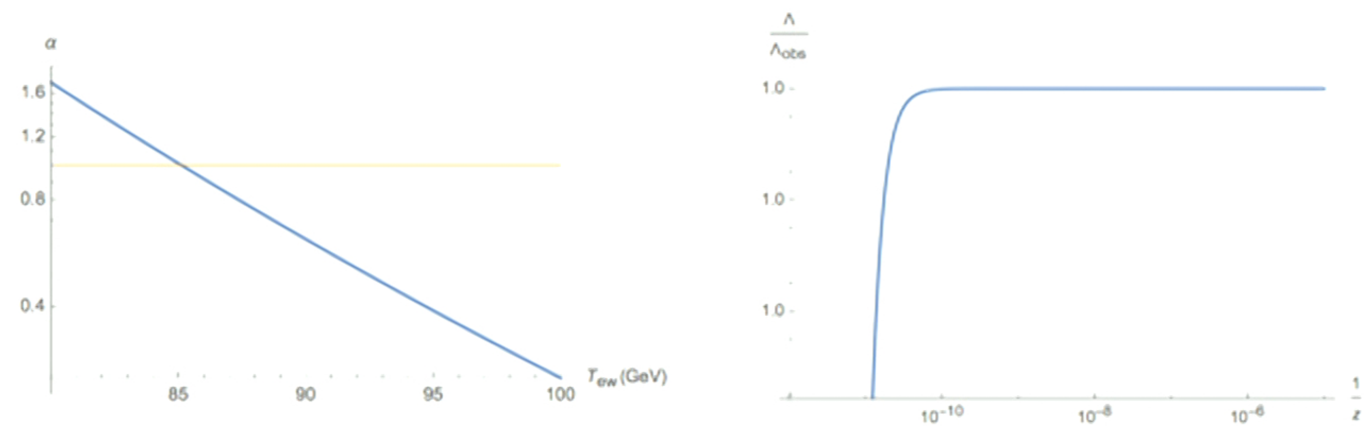
$$d(\rho a^3) + Pd(a^3) = \frac{J_0 a^3}{8\pi G}dt$$

From the first law (thermal equilibrium)

$$Td(sa^3) = d(\rho a^3) + Pd(a^3) - \mu d(na^3)$$

$$\frac{\Delta s}{s} \approx 10^{-19}$$

Results are in suggesting agreement with observations



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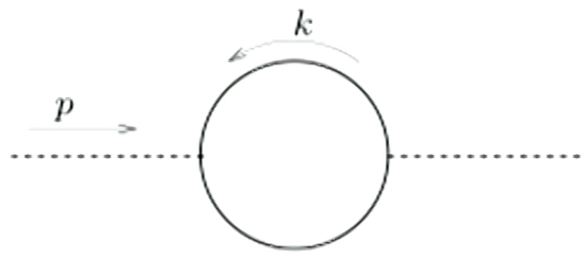
What effects could be observable after the EW era?

Lorentz violating operators in EQFT must be suppressed by the scalar curvature. The leading operators dimensionally allowed are:

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

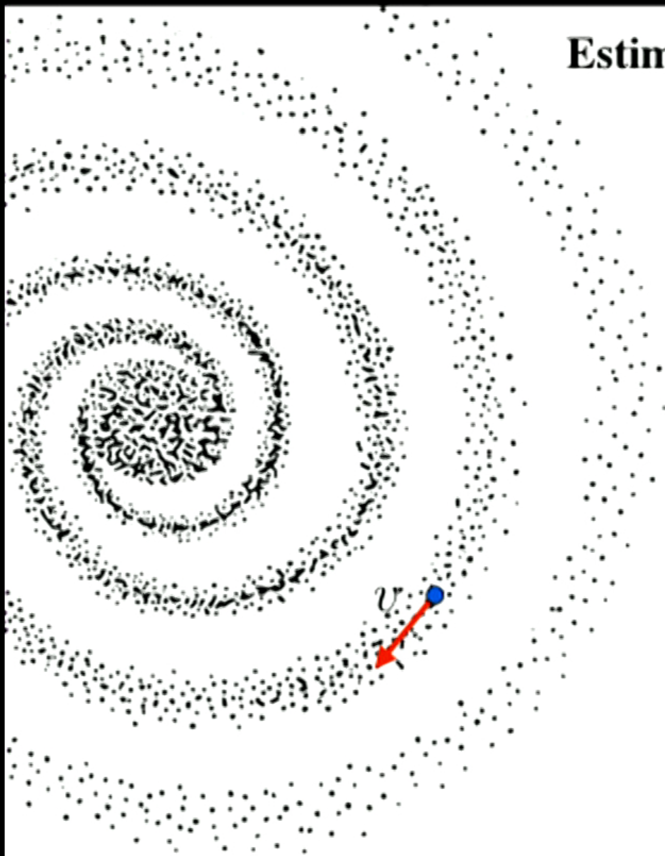
$$O_2 = \lambda_2 \xi^\mu \bar{\psi} \gamma_\mu \psi \frac{\mathbf{R}}{m_p}$$



Constraints from present experiments and observations

$$T > 10^{-8} T_p = 10^{11} \mathrm{GeV}$$

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



Estimate of the force in astrophysical objects

(e.g. Neutron stars)

$$u^\mu \nabla_\mu u^\nu = \alpha \frac{m}{m_{\rm p}^2}\, \text{sign}(s\cdot\xi)\mathbf{R}\, s^\nu$$

$$|F| \leq \alpha \frac{mM}{m_{\rm p}^2}\mathbf{R} = \alpha \frac{mM}{m_{\rm p}^2}\frac{8\pi\rho}{m_{\rm p}^2} = \alpha 8\pi \frac{mM}{m_{\rm p}^2}\frac{m^4}{m_{\rm p}^4} m_{\rm p}^2$$

$$|F_{\rm g}| = \frac{GMM_{\rm g}}{R^2} = \frac{Mv^4}{GM_{\rm g}} = \frac{Mv^4}{M_{\rm g}} m_{\rm p}^2$$

$$\left|\frac{F}{F_{\rm g}}\right| \leq 2\alpha \times 10^{-32}$$

What effects could be observable after the EW era?

All effects seem extremely tiny as matter densities go down when the universe grows. Nothing remarkable or interesting seems to happen after the EW era.

However, observations strongly suggest an anomalous behavior of the expansion of rate of the universe near present times (the so-called H0 tension). Dark energy would need to grow from the CMB time to today to account for supernova data. Riess et al. 2019 find a **4.4 sigma** separation between the value of H0 determined from supernovae and the one from the CMB (Planck 2018)

Could our ideas say something about that? Maybe, notice there is a entirely new thing happening after recombination leading to **high densities again**: this is the formation of structure and the possibility of gravitational collapse, i.e., **black holes form.**

Generalizing the friction effects to black holes treated as effective particles

Model for fundamental particles

$$u^\mu \nabla_\mu u^\nu = \alpha \frac{m}{m_{\rm P}^2}\, \mathrm{sign}(s\cdot\xi)\mathbf{R}\, s^\nu$$

$$u^\mu \nabla_\mu s^\nu = \alpha \frac{m}{m_{\rm P}^2}\, \mathrm{sign}(s\cdot\xi)\mathbf{R}\,(s\cdot s)\, u^\nu$$

Model for black holes

$$u^\mu \nabla_\mu u^\nu = \bar\alpha_{\rm bh} \frac{M}{m_{\rm P}^2}\, \mathrm{sign}(s\cdot\xi)\tilde{\mathbf{R}}\, s^\nu$$

$$u^\mu \nabla_\mu s^\nu = \bar\alpha_{\rm bh} \frac{M}{m_{\rm P}^2}\, \mathrm{sign}(s\cdot\xi)\tilde{\mathbf{R}}\,(s\cdot s)\, u^\nu - \bar\beta_{\rm bh}\frac{M}{m_{\rm P}^2}\,\tilde{\mathbf{R}}_{\rm BH}\, s^\nu$$

Black holes are simple systems with the same 'quantum-numbers' (mass, spin, gyromagnetic ratio) as point particles (**no-hair theorem**).

$$\tilde{\mathbf{R}}_{\rm BH} \approx \frac{1}{r_{\rm bh}^2}$$

Generalizing the friction effects to black holes treated as effective particles

Model for fundamental particles

$$u^\mu \nabla_\mu u^\nu = \alpha \frac{m}{m_{\rm p}^2}\, \mathrm{sign}(s\cdot\xi)\mathbf{R}\, s^\nu$$

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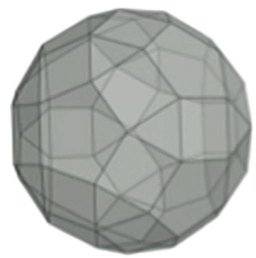
Rotational invariance is might not be an exact symmetry in quantum gravity. The ground for exact **conservation of spin** is lost.



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Generalizing the friction effects to black holes treated as effective particles (work in progress with D. Sudarsky)

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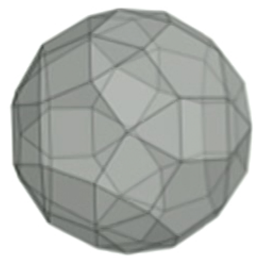
For a given mass, **spin-less** black holes **maximize** their Bekenstein-Hawking entropy. This term is opening a **channel for 'thermalization'**



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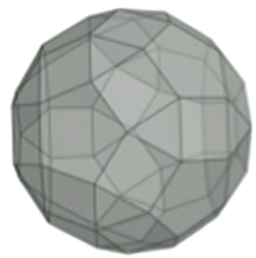

$$\tilde{\mathbf{R}}_{\rm BH} \approx \frac{1}{r_{\rm bh}^2}$$

Phenomenology of the translational term

$$u^\mu \nabla_\mu u^\nu = \bar{\alpha}_{\rm bh} \frac{M}{m_{\rm p}^2} \operatorname{sign}(s\cdot\xi)\bar{\mathbf{R}}\, s^\nu$$

$$u^\mu \nabla_\mu s^\nu = \bar{\alpha}_{\rm bh} \frac{M}{m_{\rm p}^2} \operatorname{sign}(s\cdot\xi)\bar{\mathbf{R}}\,(s\cdot s)\, u^\nu - \bar{\beta}_{\rm bh} \frac{M}{m_{\rm p}^2}\, \bar{\mathbf{R}}_{\rm BH}\, s^\nu$$

$$\left|\frac{F}{F_{\rm BHC}}\right| \leq 4\bar{\alpha}_{\rm bh} \left(\frac{M}{m_{\rm p}}\right)^4 \frac{\bar{\mathbf{R}}}{m_{\rm p}^2} = 4\bar{\alpha}_{\rm bh} 10^{32} \left(\frac{M}{M_\odot}\right)^4$$

$$\bar{\alpha}_{\rm BH} \approx \frac{1}{\sqrt{\mathcal{N}}}$$

For a macroscopic system like a BH these coupling need not be order 1. e.g., could be suppressed the square root of the number of a suitable number of quanta involved.

'Area quanta' model

$$\bar{\alpha}_{\rm bh} = \bar{\alpha}_{\rm bh}^{01} \frac{m_{\rm p}}{M} \quad \Longrightarrow \quad \left|\frac{F}{F_{\rm BHC}}\right| \leq 4\bar{\alpha}_{\rm bh}^{01} 10^{-6} \left(\frac{M}{M_\odot}\right)^3$$

$$\left|\frac{F}{F_g}\right| \leq \bar{\alpha}_{\rm bh}^{01} 10^{15-6n} \left(\frac{M}{M_\odot}\right)^2$$

'Mass quanta' model

$$\bar{\alpha}_{\rm bh} = \bar{\alpha}_{\rm bh}^{02} \sqrt{\frac{m_{\rm p}}{M}} \quad \Longrightarrow \quad \left|\frac{F}{F_{\rm BHC}}\right| \leq 4\bar{\alpha}_{\rm bh}^{02} 10^{13} \left(\frac{M}{M_\odot}\right)^{\frac{7}{2}}$$

$$\left|\frac{F}{F_g}\right| \leq \bar{\alpha}_{\rm bh}^{02} 10^{34-6n} \left(\frac{M}{M_\odot}\right)^{\frac{5}{2}}$$

Phenomenology of the translational term

$$u^\mu \nabla_\mu u^\nu = \bar{\alpha}_{\rm bh} \frac{M}{m_{\rm p}^2} \, {\rm sign}(s \cdot \xi) \bar{\mathbf{R}} \, s^\nu$$

But the **sign function** needs to a regularization near zero. This regularization has no effect in the ultrarelativistic limit where Lambda was calculated.

$$\mathrm{sign}(\xi \cdot \mathrm{s}) \to \left(\frac{\xi \cdot s}{\xi \cdot u} \right)^{2n+1}$$

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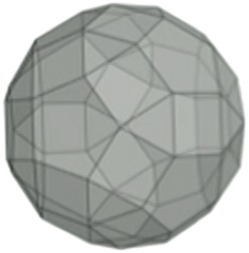
Phenomenology of the spin friction term

$$u^\mu \nabla_\mu (s\cdot s) = -2\overline{\beta}_{\rm bh}\frac{M}{m_{\rm p}^2}\,\tilde{\mathbf{R}}_{\rm BH}\,(s\cdot s)$$



$$\overline{\beta}_{\rm bh} \equiv \overline{\beta}^0_{\rm bh}\sqrt{\frac{m_p}{M}}$$

$$\tau_s = 2\sqrt{\frac{M}{M_\odot}}10^{19-5}s \approx \frac{1}{158}\sqrt{\frac{M}{M_\odot}}\text{byrs}$$

$$\tilde{\mathbf{R}}_{\rm BH} \approx \frac{1}{r_{\rm bh}^2}$$

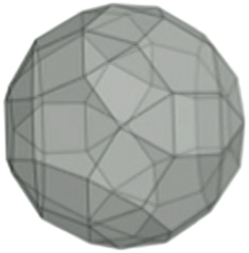
B. P. Abbott *et al.* (LIGO Scientific, Virgo), (2018), arXiv:1811.12940 [astro-ph.HE].

Caveat: in the previous solution we neglected the fact that the mass of the BH changes as spin is slowed down (a process that we assume, for concreteness, to be 'adiabatic').

Energy available (rotation dominates)

$$u^\mu \nabla_\mu (s \cdot s) = -2\overline{\beta}_{\rm bh} \frac{M}{m_{\rm p}^2} \tilde{\mathbf{R}}_{\rm BH} (s \cdot s)$$

$$\tilde{\mathbf{R}}_{\rm BH} \approx \frac{1}{r_{\rm bh}^2}$$



Translational energy in a galactic BH

$$E \approx \frac{1}{2} M v^2$$

$$\frac{E}{M} \approx 10^{-6}$$

Galactic BHs are highly non relativistic

Rotational energy in a maximally rotating BH

$$M = \frac{A}{8\pi} \frac{1}{\sqrt{\frac{A}{4\pi} - a^2}}$$

$$\Delta M = \frac{2-\sqrt{2}}{2} \sqrt{\frac{A}{8\pi}} \approx 0.3 \sqrt{\frac{A}{8\pi}} = 0.3\, M_{\rm ext}$$

30% of the initial energy is available!

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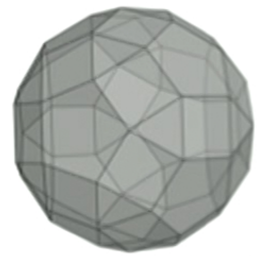

Rotational energy in a maximally rotating BH

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Spin BH friction, if present, could significantly contribute to the growth of dark energy in cosmology at late times that is needed to resolve the H0 tension.

30% of the initial energy is available!

The H0 tension

Riess et al. 2019 finds a **4.4 sigma** separation between the value of H0 determined from supernovae and the one from the CMB (Planck 2018),

"A new feature in the dark sector of the Universe appears increasingly necessary to explain the present difference in views of expansion from the beginning [CMB times] *to the present."*

It is claimed that the problem can be alleviated if **w < -1** for the dark energy component (phantom dark energy). This is very problematic because such equation of state violates the dominant energy condition (faster than light energy propagation).

Our scheme can accommodate a **growing dark energy component** without violating the dominant energy condition. The equation of state of dark energy is strictly **w = -1.**

The basic idea (work in progress with D. Sudarsky and E. Wilson-Ewing)

Measured angular scale in the CMB

The sound horizon (inferred from local physics at the CMB)

$$\theta = \frac{r_s}{R_{\rm LS}}$$

Radius of last scattering surface (calculated using a cosmological model for **H(z)**)

$$R_{\rm LS} = \int_{t_{ls}}^{t_0} \frac{dt}{a(t)} = \int_{z_0=0}^{z_{\rm LS}=1090} \frac{dz}{H(z)}$$

A poor-man determination of H0 from observations

the complete analysis uses all data from the CMB observations and BAO physics to determine H0

Our paradigm

The input is a **dark-energy component growing with time** at the expenses of energy diffusion from the **matter sector**.

$$\dot{\rho}_m + 3H\rho_m = -\frac{\dot{\Lambda}(t)}{8\pi G}$$

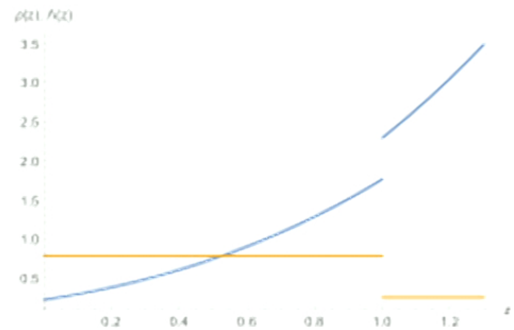
$$(1+z)^3 \frac{d}{dz}\left(\frac{\rho_m(z)}{(1+z)^3}\right) = -\frac{1}{8\pi G}\frac{d\Lambda(z)}{dz}$$

Model A: The sudden jump of dark energy

$$\omega_\Lambda(z) \equiv \frac{\Lambda(z)}{3H_0^2} \qquad \omega_m(z) \equiv \frac{8\pi G}{3H_0^2}\rho_m(z)$$

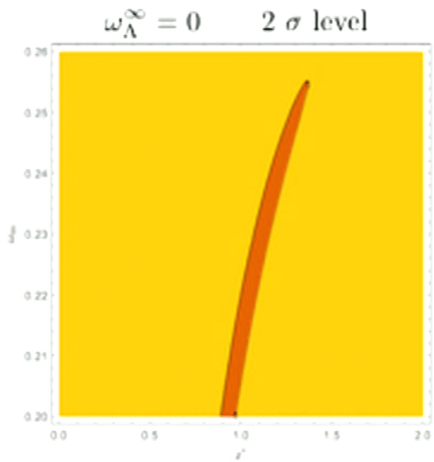
$$\boxed{\omega_\Lambda(z) = \omega_\Lambda^\infty + (1 - \omega_\Lambda^\infty - \omega_m^0)\theta[z^\star - z]}$$

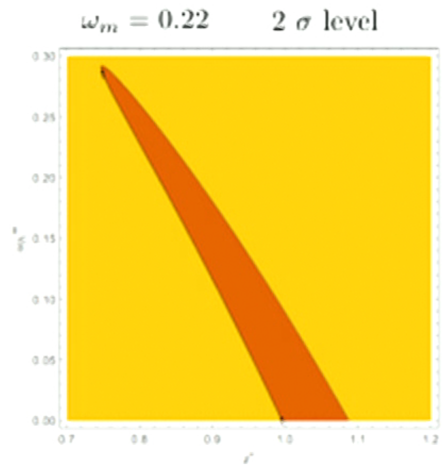
$$\omega_m(z) = (z+1)^3 \left[\frac{(1 - \omega_m^0 - \omega_\Lambda^\infty)\theta[z - z^\star]}{(z^\star + 1)^3} + \omega_m^0 \right]$$



Model A: The sudden jump of dark energy

$$\chi^2_{nm} \equiv \frac{1}{2}\left(\frac{H_0^{\rm sn} - H_0^{\rm model}}{n\sigma_H H_0^{\rm sn}}\right)^2 + \frac{1}{2}\left(\frac{\rho_m^{\Lambda{\rm CDM}}(z_{\rm CMB}) - \rho_m^{\rm model}(z_{\rm CMB})}{m\sigma_\rho \rho_m^{\Lambda{\rm CDM}}(z_{\rm CMB})}\right)^2$$





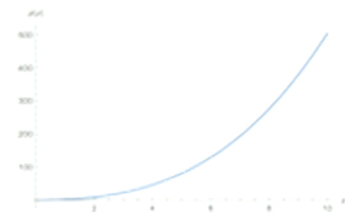
Model B: Dark energy growth as a power of the scale factor

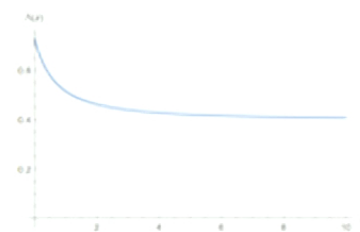
$$\Lambda(z) = \frac{\Lambda_0}{(1+z)^\alpha} + \Lambda_\infty \qquad w = -1 - \frac{\alpha}{3}$$

$$\omega_\Lambda(z) \equiv \frac{\Lambda(z)}{3H_0^2} \qquad \omega_m(z) \equiv \frac{8\pi G}{3H_0^2}\rho_m(z)$$

$$\boxed{\omega_\Lambda(z) = \frac{1-\omega_m^0-\omega_\Lambda^\infty}{(1+z)^\alpha} + \omega_\Lambda^\infty}$$

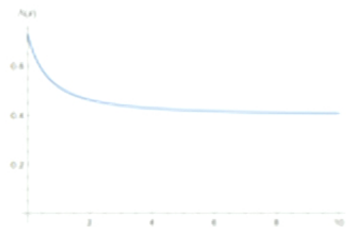
$$\omega_m(z) = \frac{(z+1)^3}{\alpha+3}\left[\alpha(1-\omega_\Lambda^\infty) + 3\omega_m^0 + \alpha\frac{\omega_\Lambda^\infty+\omega_m^0-1}{(z+1)^{\alpha-3}}\right]$$



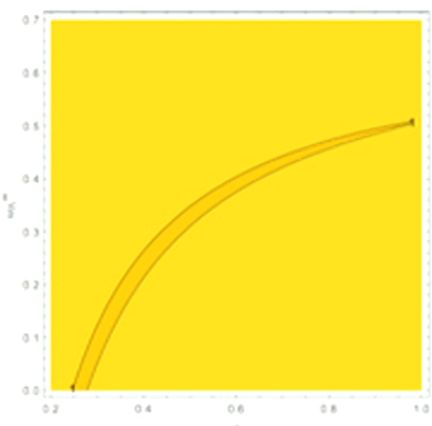


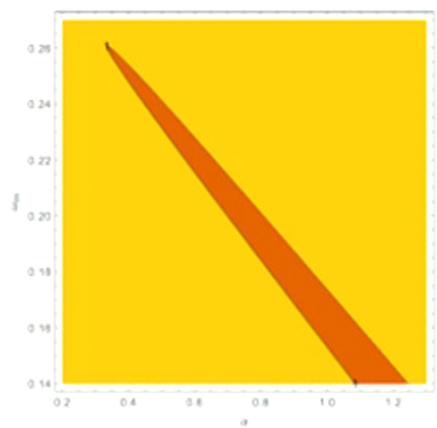
Dark energy growth as a power of the scale factor

$$\chi^2_{nm} \equiv \frac{1}{2}\left(\frac{H_0^{\rm sn} - H_0^{\rm model}}{n\sigma_H H_0^{\rm sn}}\right)^2 + \frac{1}{2}\left(\frac{\rho_m^{\Lambda{\rm CDM}}(z_{\rm CMB}) - \rho_m^{\rm model}(z_{\rm CMB})}{m\sigma_\rho \rho_m^{\Lambda{\rm CDM}}(z_{\rm CMB})}\right)^2$$



$\omega_m = 0.25$ $\quad$ $2.5\ \sigma$ level $\quad$ $\omega_\Lambda^\infty = 0.25$





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 lead to an essentially **unique leading contribution** to the nosy diffusion on standard model particles.
- **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.**

Discussion

- But observations suggest that dark energy is growing again in the recent history of the universe.
- After the recombination, densities become large again in gravitational collapse. Black holes might be an important part of the matter in galaxies. Black holes 'interact' directly with the Planck scale (singularities, non-locality of QM) and are simple as point particles in some respects.
- Applying our effective equations for fundamental particles to the case of black holes a whole and wide range of phenomenological implications opens up.
- In particular, energy loss associated associated to the slowing down of BHs seem sufficient to alleviate (perhaps solve (work in progress)) the H_0 tension.
- This offers a channel for thermalisation of BHs to their maximum entropy state which would be compatible with what is so far seen in gravitational wave detections.

Written in the stars (last paragraph of the press release 2011 Nobel Prize in Physics for S. Perlmutter, B. Schmidt, and A. Riess.)

The acceleration is thought to be driven by dark energy, but what that dark energy is remains an enigma – perhaps the greatest in physics today. What is known is that dark energy constitutes about three quarters of the Universe. Therefore the findings of the 2011 Nobel Laureates in Physics have helped to unveil a Universe that to a large extent is unknown to science. ***And everything is possible again.***

Thank you very much!