The Cosmological Constant the H_0 tension

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Collaborations with: A. Perez, T. Josset, J.D. Bjorken, E. Wilson-Ewing, T. Maudlin, E Okón, S. Landau & M. Benetti, as well as many other collaborators in precursor works.
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PLAN OF THE TALK:

1) Overview of our general approach to the Gravity/Quantum interface.

2) Making sense of semi-classical gravity and collapse theories.

3) Unimodular gravity as an alternative.

4) A new phenomenology tied to space-time discreteness.

5) The value of the emergent effective cosmological “constant".

6) A path for dealing with the “ H_0 tension".

We approach the exploration of the GR/ QT regime in a bottom-up approach.

Usual top-down approach: Postulates complete th. (String Theory , LQG, Causal sets, dynamical triangulations, etc.) and attempts to connect to regimes of interest of the "world out there" : Cosmology, Black Holes, etc.

The bottom-up approach, pushes existing, well tested and developed theories, to face open issues that seem to lie beyond their domain. Possible modifications can serve as clues about the nature of the more fundamental theory .

Exemplified by early studies in Quantum Gravity Phenomenolgy (QGP): search for space-time granularity in modified dispersion relations in high energy cosmic rays and cosmic photons.

Premise of QGP : the existence of a global **preferred frame** associated with a fundamental space-time granularity.

We performed an analysis taking the granular /crystal-like structure of space-time as indicating the absence of quantum field modes which, **in the preferred frame**, had wavelengths $\lambda < L_{cryst} \sim l_{Planck}$.

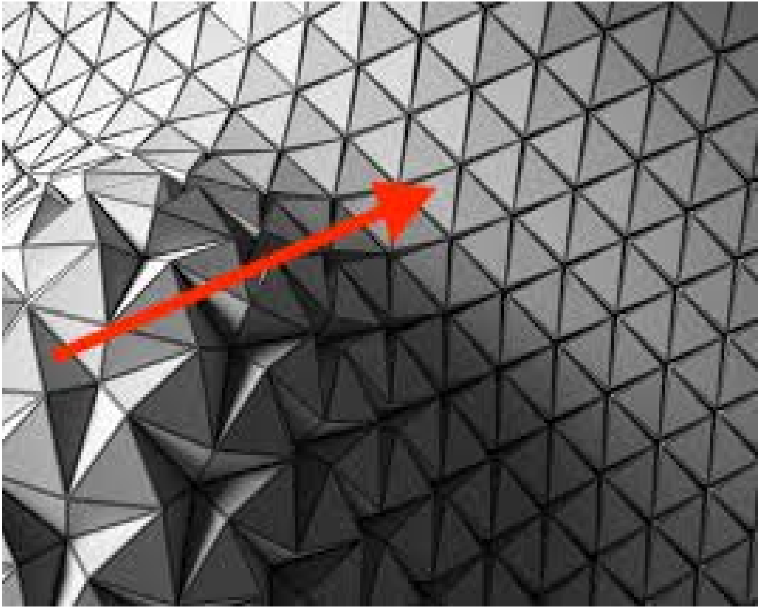
Result: such a change in the theory leads, through its impact on *radiative corrections*, to very large LIV. Would have been observed long ago.

Leading terms are independent of L_{cryst} !! The only known way to avoid them: a commitment to fine tuning of specially designed counter-terms.
(See: *" Lorentz invariance and quantum gravity: an additional fine-tuning problem?"* J. Collins, A. Perez, D. S., L. Urrutia, & H.Vucetich PRL 93 (2004) 191301).

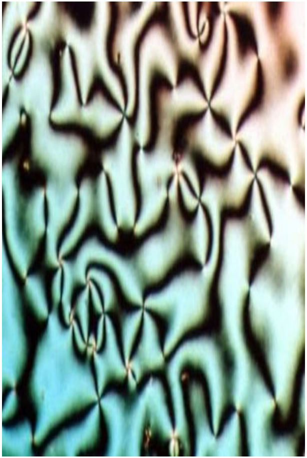
The lesson: something like a *discrete structure of spacetime* should be of a *relational type*. I.e., only present or *manifest* when the “gravitational environment" itself defines a preferential FRAME and associated SCALE, such that the physical probe can be *invariantly* characterized as moving in a specific manner with respect to such frame.

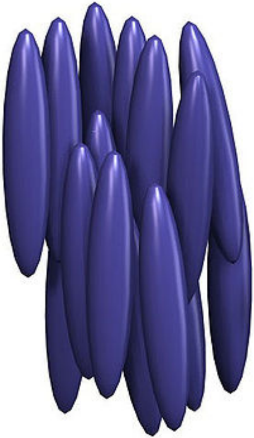
New approach to QG phenomenology :

(spacetime granularity manifest through the effects of curvature and the relative motion of the “probes"" w.r.t. the matter that “generates" the space-time curvature.) See *"Towards a new approach to quantum gravity phenomenology"* A. Corichi,& D.S. IJMP, D14 (2005) 1685 & and *"Quantum gravity phenomenology without Lorentz invariance violation: A detailed proposal"* Y. Bonder, & D.S. CQG 25 (2008) 105017), which led to an actual experiment performed by the Eöt-Wash group.



Think of the defects in the Hydrodynamic analogy : **for instance Liquid Crystals**





General idea of our bottom-up approach: to push the exploration of GR simultaneously with Quantum Theory (and, in particular, QFT in CS) beyond the usual contexts.

General program is tied to a renewed focus on **semi-classical gravity** $G_{ab} = 8\pi G \langle \hat{T}_{ab} \rangle$ considering possible (and hopefully) minimalistic modifications.

Agnostic posture regarding the full QG regime, where space-time concepts might just not be available. Space-time metric might be emergent.

Before entertaining such program we must confront objections. i.e. K. Eppley & E. Hannah 1977, challenged for instance in Carlip 2008.

The interface between QT and Gravitation needs not involve the Planck regime: (space-time associated with a macroscopic body in quantum superposition of being in two locations).

Page and Gleiker (PRL ,1981) consider such an experiment, and argued, it shows semi-classical GR is not viable.

They claim, in particular, that:

1) If there are no " Quantum Collapses", then semi-classical GR conflicts with their experiment.

2) During a Quantum Collapse generically $\nabla^a \langle \hat{T}_{ab} \rangle \neq 0$ while $\nabla^a G_{ab} \equiv 0$. Thus semi-classical GR equations are inconsistent.

A word about the “M" problem & Spontaneous Collapse Theories:

Introduced (P. Pearle, Ghirardi-Rimini-Weber) to address the measurement problem in QM:
2 rules determining the change in the quantum state: *U* and *R*.
No satisfactory rule specifying which one applies. (i.e. what exactly constitutes a measurement?)

The following 3 premises can not be held simultaneously in a self consistent manner. [Tim Maudlin (*Topoi* **14**, 1995)].

i) **The characterization of a system by its wave function is complete.** Its negation leads, for instance, to hidden variable theories.

ii) **The evolution of the wave function is always according to Schrödinger's equation.** Its negation leads, for instance, to spontaneous collapse theories.

iii)**The results, of experiments lead to definite results.** Its negation leads, for instance, to Many World/ Minds Interpretations, Consistent Histories approach, etc.

Recently “The fate of conservation laws at the interface of quantum theory and gravitation", T. Maudlin, E. Okon & D S, arXiv:1910.06473 [gr-qc]; *Stud in Hist. and Phil. of Mod. Phys* **B 69** 67-81 (2020). ALL those options led to the expectation of generic violations of “conservation laws" particularly the "Law of Conservation of Energy".

In the relativistic context this means departures from

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

Violations must be very small in the usual contexts, otherwise we would have noticed them in high precision experiments.

In accordance with our “philosophy", **we should focus on confronting the issue in the gravitational context.**

HOW CAN WE APPROACH THE PROBLEM ?

Regard semi-classical GR as an approximated description with limited domain of applicability and explore the " boundary" regime. In particular, incorporate quantum collapses to deal with Page & Gleiker. We drew on work on spontaneous collapse theories (GRW and CSL). It seems clear that during the collapse the equations can not be valid ($\nabla^a G_{ab} \equiv 0$.)

Adopt an hydro-dynamical analogy: Navier-Stokes equations for a fluid (say water in the ocean), can not hold in some situations (when a wave is breaking), but they can be taken to hold before and after. Take Semi-classical GR equations to hold before and after a collapse but not during the collapse.

The approach requires a formalism providing a recipe to **join the descriptions** just before and just after the collapse: (SSC).

Incorporate collapse to GR. At the formal level we rely on the notion of *Semi-classical Self-consistent Configuration* (SSC). (work with A. Diez-Tejedor).

DEFINITION: The set $g_{\mu\nu}(x), \hat{\varphi}(x), \hat{\pi}(x), \mathcal{H}, |\xi\rangle \mathrm{in} \mathcal{H}$ represents a SSC iff $\hat{\varphi}(x)$, $\hat{\pi}(x)$ y $\mathcal{H}$ corresponds to QFT in CS over the space-time with metric $g_{\mu\nu}(x)$, and MOREOVER the state $|\xi\rangle$ in $\mathcal{H}$ is such that:

$$G_{\mu\nu}[g(x)] = 8\pi G \langle\xi|\hat{T}_{\mu\nu}[g(x), \hat{\varphi}(x), \hat{\pi}(x)]|\xi\rangle^{(Ren)}.$$

Involves self reference (is a GR version of the Schrödinger-Newton system).

Collapse: should not be looked as jumps in states but jumps of the form $....SSC1.... \rightarrow ....SSC2....$

Matching conditions: for space-time and states in the Hilbert space. Involves delicate issues.

Applied to (seeds of structure) and (BH information Puzzle). Recent works [with B. Kay, B. Juárez, T. Miramontes] have further advanced the establishment of a mathematically rigorous prescription.

Out of a fundamental QGT , one would be led to classical GR only under the most favorable conditions. In other situations (or when looking at things with more precision), some modifications will be required.
The SCC scheme seems suitable for dealing with some situations , like these confronted in the Page- Gleiker set up.Other situations will require different approximations. Eventually, a point must be reached where NO equation of similar kind applies, simply because the basic concepts underlying the scheme are no longer valid *(fluid volume element, fluid velocity, etc. in the N-S analogy)*.

The SCC scheme is too complicated for the analysis of some realistic situations : multiplicity of collapses , incorporation of a small but permanent source of energy- momentum non-conservation.

Fortunately, there is a modified version of GR where the energy momentum conservation is not so rigid: Unimodular Gravity.

The theory can be given an action principle formulation :

$$S = \int [R\epsilon^{(g)}_{abcd} + \lambda(\epsilon^{(g)}_{abcd} - \varepsilon_{abcd}) + \mathcal{L}_{Matt}\epsilon^{(g)}_{abcd}] \quad (1)$$

where ε_{abcd} is a “fixed" 4-volume element and $\epsilon^{(g)}_{abcd} = \sqrt{-g}\varepsilon_{abcd}$ is the 4-volume element associated to g_{ab}. $\lambda(x)$ is a Lagrange multiplier function.

The theory is invariant just under 4-volume preserving diffeomorphisms.
Restriction might be natural under various conditions:

1) If there is a fundamental granularity associated with space-time 4-volume, even if, as strongly indicated, it is compatible with Lorentz Invariance.

2) If there is any additional structure to space-time (such as a distribution over space-time 4-volume of discrete collapse events).

The equations of motion are:

$$R_{ab} - (1/4)g_{ab}R = 8\pi G(T_{ab} - (1/4)g_{ab}T) \quad (2)$$

Vacuum energy does not gravitate (S. Weinberg).
In uni-modular gravity, the conservation of T_{ab} is usually introduced as an extra assumption!!

However, violations i.e. $J_a \equiv 8\pi G\nabla^b T_{ab} \neq 0$ can be introduced consistently, if the integrability condition holds $dJ = 0$.

Then, simple manipulations lead to:

$$R_{ab} - (1/2)g_{ab}R + g_{ab}(\lambda_{-\infty} + \int J) = 8\pi G T_{ab} \quad (3)$$

That is : $\Lambda_{eff}(t) = \lambda_{-\infty} + \int J$

This opens very interesting possibilities.

A particularly simple situation where the integrabitity conditions are satisfied automatically (due to the symmetry) is FRW cosmology.

First exploration *"Dark Energy from Violation of Energy Conservation"*, T. Josset, A. Perez & D. S., PRL **118**, no 2, 021102 (2017) arXiv:1604.04183 [gr-qc] , based on:

i) a quantum treatment of matter using theories involving spontaneous collapse (Non Relativistic versions) and the corresponding non-conservation of $\langle \hat{T}_{ab} \rangle$.

We found that the contributions (taken as starting from Hadronization) could be of the right order of magnitude for parameters within the range allowed by GRW phenomenology. **The sign was wrong!**.

ii) a general model of covariant energy momentum diffusion motivated in the Causal Set approach (Philpott, Sorkin & Dowker), where again the correct order of magnitude was allowed by the existing constraints.

All those depend on dimension-full parameters, with values we are almost free to set, and uncertain order of magnitude.

In [“Dark energy from quantum gravity discreteness ", A. Perez & D.S. arXiv:1711.05183 [gr-qc] *Phys. Rev. Lett.* **122**, 221302 (2019).] we consider an effect of QG origin. Consider that:

1) Non-conservation might be associated with interaction of matter with **spacetime granular features or defects.**

Recalling the general outlook:

2) A spatio-temporal discreteness of a relational type: the gravitational environment itself defies a preferential frame and associated scale(so motion of physical probes can be given invariant sense). Effects tied to curvature and depend on the relative motion of the matter that *“experiences"* the granularity to that which *“generates"* the space-time curvature.

And adding that,

3) probes of granularity should have both **mass**, so as to *“carry with them a length scale"*, and **spin**, so as to be sensitive to *“directionality" in their rest frame*.

Modeling (effective) : Interaction with granular structure $\rightarrow$ an otherwise free particle deviates from geodesic motion. The effect should be proportional to **R**, depend on the mass m, the 4-velocity u^μ, the spin s^μ of the classical particle (the only intrinsic features defining a particle), and a time-like unit vector ξ^μ specifying the local frame defined by the matter that "curves space-time". The simplest (essentially unique) option is

$$u^\mu \nabla_\mu u^\nu = -\alpha \frac{m}{m_p^2} \operatorname{sign}(s \cdot \xi) \mathbf{R}\, s^\nu, \tag{4}$$

where $\alpha > 0$ is a dimensionless parameter of order 1. The $\operatorname{sign}(s \cdot \xi)$ ensures the effect is dissipative.
Self-Consistency requires the modification of evolution equation for the spin

$$u^\mu \nabla_\mu s^\nu = \alpha \frac{m}{m_{\mathrm{p}}^2} \operatorname{sign}(s \cdot \xi) \mathbf{R}\, (s \cdot s)\, u^\nu \tag{5}$$

For $\alpha \sim 1$ the effect is completely insignificant in all situations of experimental interest (i.e. there are so far no known relevant bounds). Note that particles with no spin are not affected.

Analogy

Note the similarity with the Mathisson-Papapetrou-Dixon equations describing the dynamics of idealized *extended objects* in GR,

$$u^\nu \nabla_\nu P_\mu = -\frac{1}{2} R_{\mu\nu\rho\sigma} u^\nu S^{\rho\sigma}, \tag{6}$$

Also, the characterization of WKB-trajectories of the Dirac theory in a spacetime with **torsion** (J. Audretsch PRD 24, 1470 (1981)).

I.e. writing $\psi = Re^{iS}$ in the Dirac equation and setting $p_\mu \equiv \partial_\mu S, \& \; u_\mu = p_\mu / m$ the lowest order correction to the evolution is given by

$$m u^\nu \nabla_\nu u_\mu = -\frac{1}{2} \tilde{R}_{\mu\nu\rho\sigma} u^\nu \langle S^{\rho\sigma} \rangle, \tag{7}$$

Were $\tilde{R}$ is the curvature of a connection involving **torsion**.

Application to the Cosmological setting

Specializing to cosmology $ds^2 = -dt^2 + a^2(t)d\vec{x}^2$, the local frame $\xi = \partial_t$ is identified with co-moving observers.

We have further assumed that a protective symmetry enforces $\lambda_{-\infty} = 0$.

In this case, using standard relativistic kinetic theory, we can evaluate the effect on T_{ab} and obtain :

$$J_\nu \equiv (8\pi G)\, \nabla^\mu T_{\mu\nu} = 4\pi\alpha \frac{T}{m_p^2} \mathbf{R} \left[8\pi G \sum_i |s_i| \mathbf{T}^i \right] \xi_\nu \approx -2\pi\alpha \frac{T}{m_p^2} \mathbf{R}^2 \xi_\nu \tag{8}$$

where T is the fluid's temperature. Last step specializes to cases in which a single $s = 1/2$ fermion species dominates.

We now estimate the effective cosmological constant $\Lambda_{eff}(t)$ predicted by our model.

The modification of the cosmological evolution is negligible during most of the Universe's history (including the relevant part, when $\int Jdt$ is generated).

It is only very late that the $\Lambda_{eff}(t)$ becomes dominant because everything else has been diluted with the expansion.

Thus we can take the standard cosmological expressions for $T(t)$ and $R(t) = -8\pi G g^{ab} T_{ab} = -8\pi G(\rho - 3P)$ (the corrections at this stage are absolutely insignificant) to evaluate:

$$\Lambda_{eff}(t_0) = \frac{2\pi\alpha}{m_p^2} \int_{t_{\rm ew}}^{t_0} R(t)^2 T(t)\, dt, \qquad (9)$$

with t_0 the present time.

Note: as only massive particles with spin are involved, the diffusion mechanism in cosmology starts when particles acquire mass i.e. the (EW) transition epoch.

It turns out that the dominant contribution comes from the top quark very close to the electro-weak transition.

In the relativistic regime, standard thermodynamics leads to the expression:

$$\rho - 3P \approx \frac{m_t^2 T^2}{2} \tag{10}$$

where m_t is the Top mass. Evaluating the integral we find:

$$\Lambda^{\text{eff}} = 16\alpha \sqrt{\frac{5\pi^3}{g_*}} \frac{m_t^4 {T_{\text{ew}}}^3}{m_p^5} \epsilon(T_{ew}) \tag{11}$$

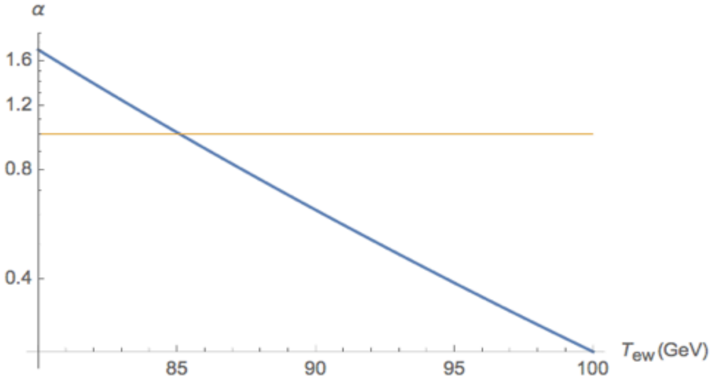
g^* is the effective degeneracy factor for the temperatures of interest (and enters the analysis because standard cosmology is used in writing $a(t)$ (and everything else) as a function of t). $\epsilon(T_{ew})$ is a factor taking into account the T dependence of the top quark's mass.
The order of magnitude is easy to see:

$$\Lambda^{\text{eff}} \sim (m_t/m_p)^7 m_p^2 = 10^{-119} m_p^2 \tag{12}$$

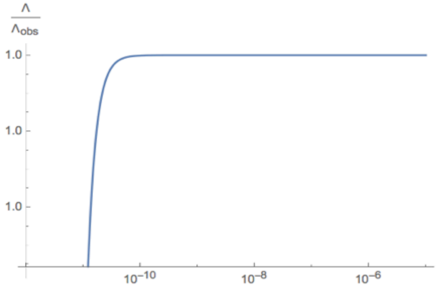
Including all factors and the corrections coming from the W's and Z's, we find (taking $T_{EW} = 90 GeV$)

$$\Lambda^{\text{eff}} \approx 1.6\, \alpha\, \Lambda_{\text{obs}} \tag{13}$$

Or in more generality, the value of α that fits Λ_{obs} is :



It saturates rapidly to the “present value"



We note that its effect in ordinary situations (even in, say, at the center of neutron stars) is exceedingly small and impossible to detect with present experimental accuracy.

Dealing with the "H_0" tension

The Λ-CDM model is currently under pressure by the H_0 tension (*CMB* and SNI-a determinations give different values).

Could something like our proposal help to account for this? The kind of effect we have in mind becomes significant only in very early times (the EW-Transition) when densities and curvatures are very high, and once that era is over the effect should become insignificant.

Note that the effect, as characterized by our equation:

$$u^\mu \nabla_\mu u^\nu = -\alpha \frac{m}{m_p^2} \operatorname{sign}(s \cdot \xi) \mathbf{R}\, s^\nu, \tag{14}$$

could not satisfy " simple scaling and composition properties". It cannot be applied to, say, a composite body like a star, among other reasons, because its spin is not simply the sum of the spins of the constitutive particles, while, at least in simple enough situations, the total force must be (close to) the sum of the forces.

There are now two observations 1) that at late cosmological times something took place again, involving **high curvatures and densities**: the formation of BH's, and 2), that in a certain *effective level* sense, a BH might be taken to be *more like a fundamental particle* than a composite object: for instance its complete (equilibrium) characterization by just M, Q, J ; the impossibility to assigning it (*locally*) a CoM.

We considered the idea that a similar *friction-like* effect may *"diffuse"* translational and **rotational** energies of rotating BH's (with parameters $\overline{\alpha}_{\rm bh} \& \overline{\beta}_{\rm bh}$ respectively).

Note that unlike a fundamental particle the black hole spin can also be affected via the friction with the fundamental granularity.

$$u^{\mu}\nabla_{\mu}s^{\nu} = \overline{\alpha}_{\rm bh}\frac{M}{m_{\rm p}^2}\,{\rm sign}(s\cdot\xi)\tilde{\mathbf{R}}\,(s\cdot s)\,u^{\nu} - \overline{\beta}_{\rm bh}\frac{M}{m_{\rm p}^2}\,\tilde{\mathbf{R}}_{\rm BH}\,s^{\nu}, \quad (15)$$

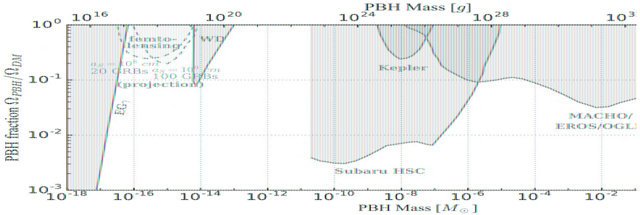
Here $\tilde{\mathbf{R}}_{\rm BH}$ is a suitable measure of curvature around the BH.

In “Black holes, Planckian granularity, and the changing cosmological constant", A.P. & D.S. GRG **53** 40(2021), arXiv:1911.06059 [gr-qc])) we have investigated the phenomenology of such terms and have shown that for reasonable values of the coupling parameters (specifically, $\overline{\beta}_{\rm bh} \sim \sqrt{m_p/M}$) the effects could become important over cosmological times for BH's with large J's. The effect can lead, for instance to the dissipation of up to 30% of the total mass of an **extremal** black hole in such times.

Phenomenological consequences include a tendency to drive all black holes far away from extremality over long times (fits well with general thermodynamic expectations: **minimization of free energy**). Increased rate of accretion of stellar type BH towards the galactic centers (perhaps even a role in the formation of super-massive BH's ?). This might be testable with LISA.

In order to explore in detail the cosmological consequences of the proposal we would need to have a solid understanding of the cosmic BH abundances as function of M, J and cosmic time ($f(M, J, t)$). Something we unfortunately do not have.

Existing studies offering interesting and relevant bounds:



Note that the bounds concern individual mass ranges, and there seems to be no global bound.

One can explore simple model the diffusion idea by writing an effective modified evolution for $\rho_{matter}(z)$ (and the corresponding $\Lambda_{eff}(z)$).

In “Resolving the H_0 tension with diffusion", A.P., D.S., &, E. Wilson-Ewing , GRG **57** 7 (2021), arXiv:2001.07536 [astro-ph.CO] we carried out a preliminary analysis on the cosmological effect of that kind of energy dissipation and have seen that, with as little as a few % of the matter density in the universe appearing as black holes, and a reasonable fraction of them having sufficiently high J, it is possible to eliminate the H_0 tension through the corresponding “dissipation".

A detailed modeling involving an attempt to characterize ($f(M, J, t)$) is underway (Sebastien Fromenteau Diago A Ruiz García).

In the meantime a slightly more realistic model assumes a fixed period of linear change with scale a, in the dark energy , namely using $\rho_\Lambda \equiv \frac{\Lambda}{8\pi G}$ and assuming:

$$\rho_\Lambda(a) = \rho_\Lambda(t_{\rm rad}) + f(a)\Delta\rho \tag{16}$$

with

$$f(a) = \begin{cases} 0 & a \,\mathrm{in}\, (\mathrm{a_{rad}}, \mathrm{a}^* - \delta/2)\,, \\ \dfrac{a - a^* + \delta/2}{\delta} & a \,\mathrm{in}\, (\mathrm{a}^* - \delta/2, \mathrm{a}^* + \delta/2) \\ 1 & a \,\mathrm{in}\, (\mathrm{a}^* + \delta/2, \mathrm{a_0})\,. \end{cases} \tag{17}$$

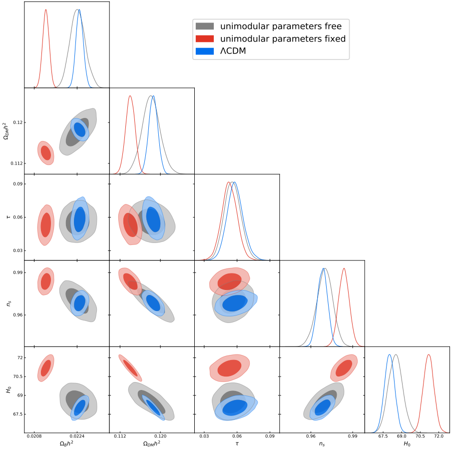
Note the matter density is then determined from the UM equation:

$$\dot\rho_M + 3\frac{\dot a}{a}\rho_M = -\dot\rho_\Lambda \tag{18}$$

In [Cosmological constraints on unimodular gravity models with diffusion S.L., M.B., A.P., D.S. PRD 108 (4), 043524] we have analyzed (using the package CosmoMC) the resulting model, looking for collective best fit of the usual cosmological parameters, together with $(a^*, \delta, \& \Delta\rho)$, taking into account both CMB data from *Planck 2018*, data from BAO (*6dFGS, BOSS*), a well as supernova surveys (*Patheon compilation*).

In order to optimize statistical aspects of the analysis the Supernova data are included via a direct use of the locally obtained prior on the supernova absolute magnitude, rather than using a prior on H_0 (following Camarena et. al.).

In order to use the analysis as a basis for constraining the model based on our BH friction hypothesis, together with the modeling of $(f(M, J, t))$, a different type of analysis would be advantageous.



The analysis confirms that even this very simplified model leads to a reduction in the discrepancy of best fit values for H_0 without generating conflict with other relevant data.

There is a degeneration that allows this model to “adjust" higher H_0 values (see red line).

In " A clarification on prevailing misconceptions in unimodular gravity", G. Bengochea, G León, A Perez, D.S. JCAP 2023 (11), 011 we have clarified a widespread misconception ($det[g_{\mu\nu}] = -1$) regarding the appropriateness of the use of arbitrary "gauge conditions" in the analysis of cosmological perturbation theory in the context of UG.

Various related proposals have been recently studied in detail by local colleagues "Revisiting Cosmological Diff. Models in U.G. and the H_0 tension" F.X. Linares & Nucamendi , *Phys. Dark Univ. 32 (2021) 100807*. The Universe acceleration from the Unimodular gravity view point: Background and linear perturbations M. A. García-Aspeitia, A. Hernández-Almada , J. Magaña & V. Motta *Phys. Dark Univ. 32 (2021) 100840*. Several other studies by colleagues abroad.

Much more needs to be done. THANKS .