Title: Quantum gravity signals in cosmology and gravitational waves

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Abstract: I will highlight cosmological consequences of models inspired from string theory or non-perturbative approaches to QG. In particular, I will address the initial singularity, inflation and the late-time accelerated expansion. I will then briefly discuss how recent gravitational waves data can provide a test for some QG models.

Motivation:

Can QG theories leave a signal in astrophysical/cosmological observations and GW detections?

support/disfavor a QG theory

(*AdS/CFT, asymptotically safe gravity, causal sets, dynamical triangulations, GFT, LQG/spin foams, matrix/tensor models, NCG, string theory*)

QG motivated cosmological model

explain early/late Universe

(*initial singularity, inflation, dark energy, dark matter, ΛCDM*)

test alternative gravity models

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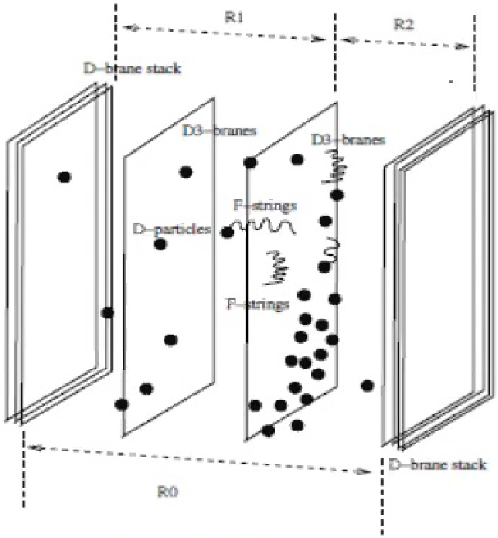
Yes !

String/Brane theory: Extra dimensions

- as brane universe moves in the bulk, D particles cross
- particle excitations (open strings) propagate in a medium of D-particles

⬇

brane-puncturing (massive) D-particles can be captured
by (electrically neutral) matter open strings



*Mavromatos, **MS** (2007)*

Lorentz invariance locally broken, leading to emergence of vector-like excitations that can lead to an era of inflation and contribute to large scale structure (enhancing DM component) and galaxy formation

*Ferreras, Mavromatos, **MS**, Yusaf (2013)*
*Elghozi, Mavromatos, **MS**, Yusaf (2016)*

String/Brane theory: Extra dimensions

Sigma model describing propagation of open strings in a FLRW background punctured by populations of fluctuating D-particles

$$S_{\text{eff 4D}} = \int d^4x \left[-\frac{1}{4}\, e^{-2\phi}\, \mathcal{G}_{\mu\nu}\, \mathcal{G}^{\mu\nu} - \frac{T_3}{g_{s0}}\, e^{-\phi}\, \sqrt{-\det\left(g + 2\pi\alpha' F\right)}\, (1 - \alpha R(g)) \right.$$
$$\left. - \sqrt{-g}\, \frac{e^{-2\phi}}{\kappa_0^2}\, \tilde{\Lambda} + \sqrt{-g}\, \frac{e^{-2\phi}}{\kappa_0^2}\, R(g) + \mathcal{O}\left((\partial\phi)^2 \right) \right] + S_m \ ,$$

$$g_{\rm s} = g_{{\rm s}0} e^{\phi} \qquad \frac{1}{\kappa_0^2} = \frac{V^{(6)}}{g_{{\rm s}0}^2}\, M_{\rm s}^2 \qquad M_{\rm s} = 1/\sqrt{\alpha'}$$

The vector field A_μ denotes the recoil velocity excitation during the string-matter/D-particle interactions and has field strength $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$

String/Brane theory: Extra dimensions

For late eras, consider populations of D-particles with fluctuating recoil velocities, which are assumed to be gaussian stochastic → macroscopically Lorentz invariance is maintained

$$\langle\langle u^m u^n \rangle\rangle = \sigma_0^2(t)\, \delta^{mn} \;, \qquad \langle\langle u^m \rangle\rangle = 0 \;, \qquad \sigma_0^2(t) = a(t)^{-3}\, |\beta| \;.$$

Find the magnitude of the statistical variance of the recoil velocity $|\beta|$ needed for the D-particle defects to play the role of dark matter candidates

$$g_{\alpha\beta}\, \mathrm{d}x^\alpha \mathrm{d}x^\beta = -e^{\nu\left(\sqrt{x^2+y^2+z^2}\right)} \mathrm{d}t^2 + e^{\zeta\left(\sqrt{x^2+y^2+z^2}\right)}\, a^2(t)(\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2)$$

deflection of light

$$\Delta\varphi = 2 \int_{r_0}^{\infty} \frac{1}{r} \left(e^{\zeta(r)-\nu(r)}\, \frac{r_0^2}{b^2} - 1 \right)^{-1/2} \mathrm{d}r - \pi \quad \xrightarrow[M_s \sim 10^4\ \mathrm{GeV}]{\text{graviton eq:}} \quad \boxed{|\beta| \leq 10^{-92}}$$

*Elghozi, Mavromatos, **MS**, Yusaf (2016)*

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Find the magnitude of the statistical variance of the recoil velocity $|\beta|$ needed for the D-particle defects to play the role of dark matter candidates and providers of large-scale structure

$$g_{\alpha\beta}\,\mathrm{d}x^\alpha \mathrm{d}x^\beta = -e^{\nu\left(\sqrt{x^2+y^2+z^2}\right)}\mathrm{d}t^2 + e^{\zeta\left(\sqrt{x^2+y^2+z^2}\right)}\,a^2(t)(\mathrm{d}x^2+\mathrm{d}y^2+\mathrm{d}z^2)$$

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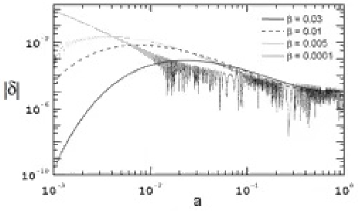
$$\boxed{|\beta| \leq 10^{-92}}$$

$$\boxed{10^{-95} \leq |\beta|}$$



There is a minimum $|\beta|$, i.e. a minimum density of D-particles, that guarantees a growing mode

*Elghozi, Mavromatos, **MS**, Yusaf (2016)*

String/Brane theory: Extra dimensions

DE contribution

Neutrinos appear as dark matter candidates that could be "captured" by D-particles

After the capture by the D-particle defect, the emerging stringy matter excitation could have a different flavor than what it had initially

- D-particle populations in galaxies act as a "medium" inducing flavor oscillations $\nu_e \leftrightarrow \nu_\mu$
- significant contribution to vacuum energy density from oscillations

compute the average of the neutrino stress tensor w.r.t. flavor vacuum $_f\langle 0|T_{\mu\nu}|0\rangle_f$

extra time-dependent dark energy contribution $\boxed{\Omega_\Lambda^{\nu_{\rm mixing}} \sim 0.24}$

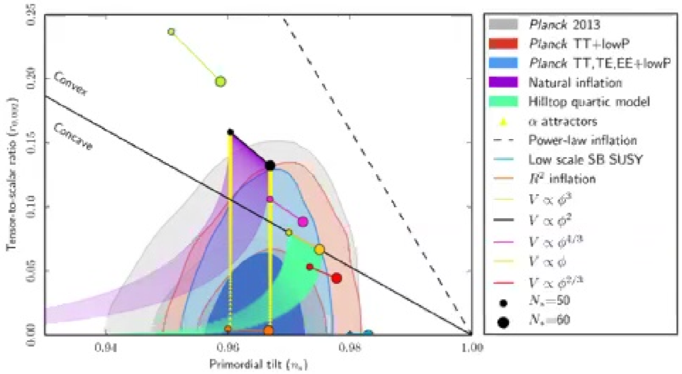
Mavromatos, ***MS*** *(2007)*

String/Brane theory: Extra dimensions

D-particles may induce inflation through condensation of their (large) recoil velocity

dense populations in the EU, but dilute today

$$M_s \ll \underbrace{H_I \sim 10^{-5}\, M_{\rm Pl}}_{\text{Planck data}} \ll M_{\rm Pl}$$



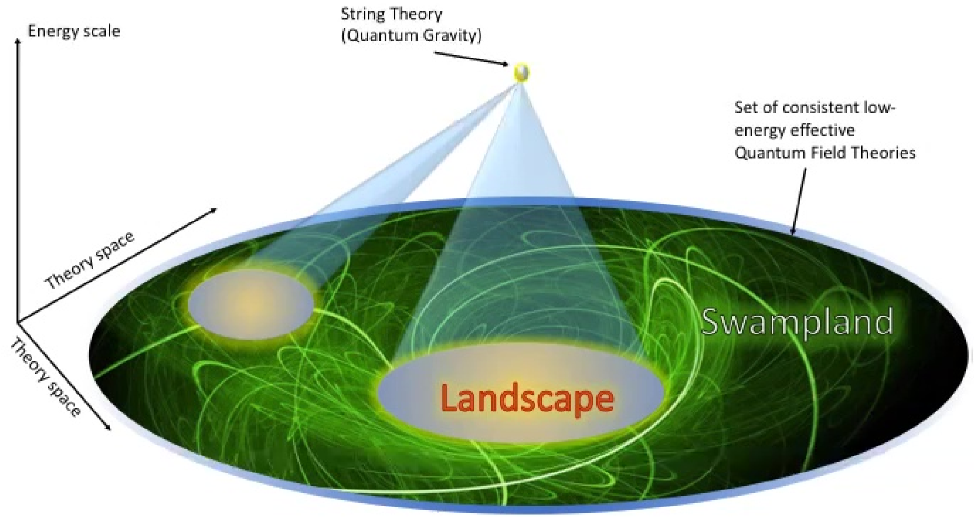
For $n_s = 0.965$ we get $N = 57.7$

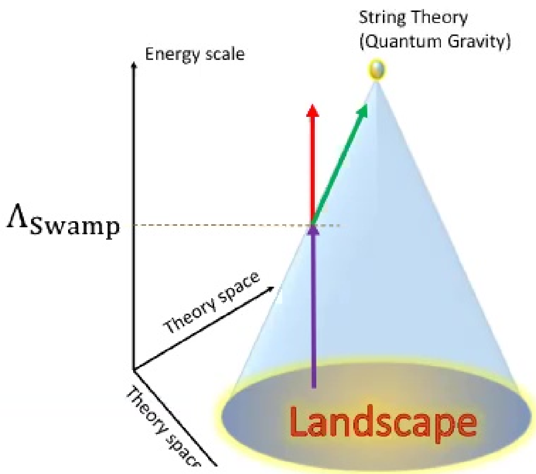
$$\Rightarrow \quad \epsilon \simeq 5.6 \cdot 10^{-5} \ll 1 \;, \qquad \eta \simeq -1.7 \cdot 10^{-2} \ll 1 \;, \qquad \xi \simeq 3.0 \cdot 10^{-4} \ll 1$$

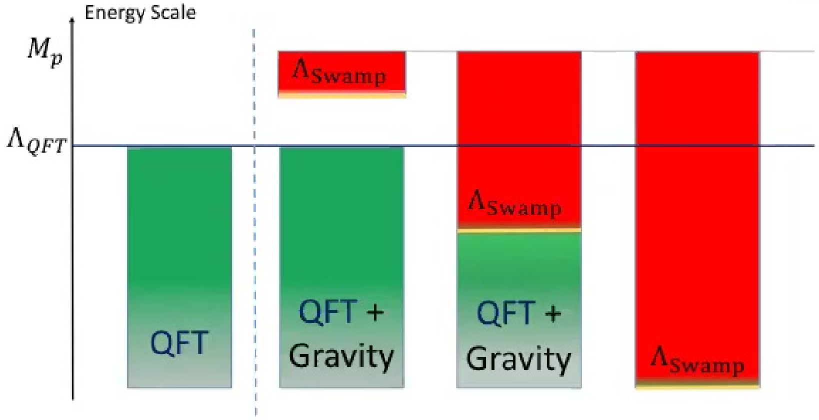
and we fix the value of the flux field condensate that induces the de Sitter phase

*Elghozi, Mavromatos, **MS**, Yusaf (2016)*

String theory: String Swampland







Palti (2019)

String theory: String Swampland

Swampland distance conjecture (*upper bound on the range traversed by scalar fields*)

$$|\Delta\phi| < \Delta \sim \mathcal{O}(1)$$ in reduced Planck units

Ooguri, Vafa (2007)

de Sitter conjecture (*lower bound on the derivatives of a scalar potential wrt scalar fields*)

$$|\nabla_\phi V|/V > c \sim \mathcal{O}(1)$$ in reduced Planck units

$$V > 0$$

Obied, Ooguri, Spodyneiko, Vafa (2018)

Trans-Planckian censorship conjecture

$$|\nabla_\phi V|/V \geq \frac{2}{\sqrt{(d-1)(d-2)}}$$

Bedroya, Vafa (2018)

➡ c, Δ unknown but close to 1: *cosmological implications?*

String theory: String Swampland

Slow-roll single-field Inflation

$$\epsilon \equiv \frac{3}{2}(1+w) \equiv \frac{3}{2}\left(1+\frac{p}{\rho}\right) \approx \frac{1}{2}\left(\frac{|\nabla_\phi V|}{V}\right)^2 \sim \frac{1}{N_e^k}$$

$$\boxed{|\Delta\phi| < \Delta \sim \mathcal{O}(1)}$$

$\Delta\phi \sim N_e\sqrt{2\epsilon} \sim \sqrt{2}N_e^{1-k/2}$ even fine-tuned “plateau models” are in tension with distance conjecture

$\Delta \geq 5$ in reduced Planck units

B-mode polarization: $r \approx 16\epsilon < 0.07 \Longrightarrow \epsilon < 0.0044 \Longrightarrow |\nabla_\phi V|/V < 0.09$

fine-tuned “plateau models” $|\nabla_\phi V|/V \lesssim 0.02$ even more in tension with de Sitter conjecture

$$\boxed{\nabla_\phi V|/V > c \sim \mathcal{O}(1)}$$

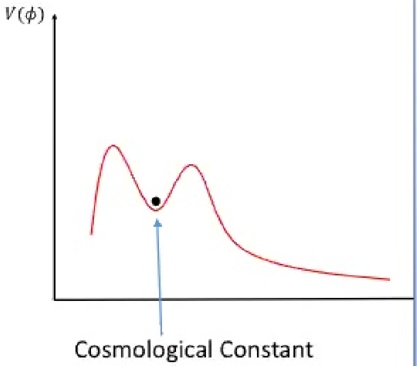
Problem: almost all inflationary models include plateau in which $|\nabla_\phi V|/V \to 0$ *at one or more points in field space*

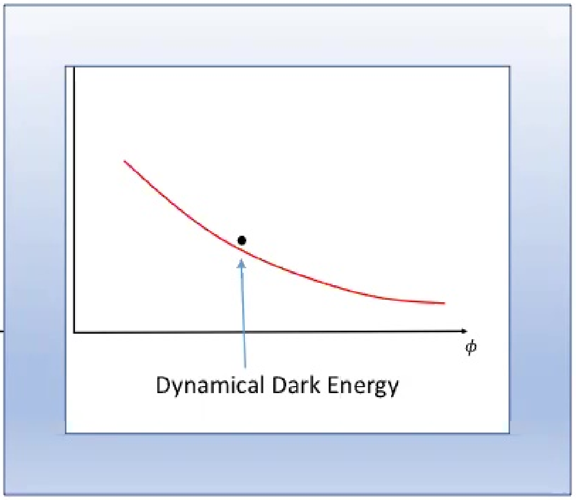
Are Swampland conjectures wrong ? Is inflation wrong?

Agrawal, Obied, Steinhardt, Vafa (2018)

String theory: String Swampland

Dark energy (current accelerated expansion)





de Sitter conjecture or. trans-Planckian conjecture: cannot be a minimum where $\nabla V = 0$

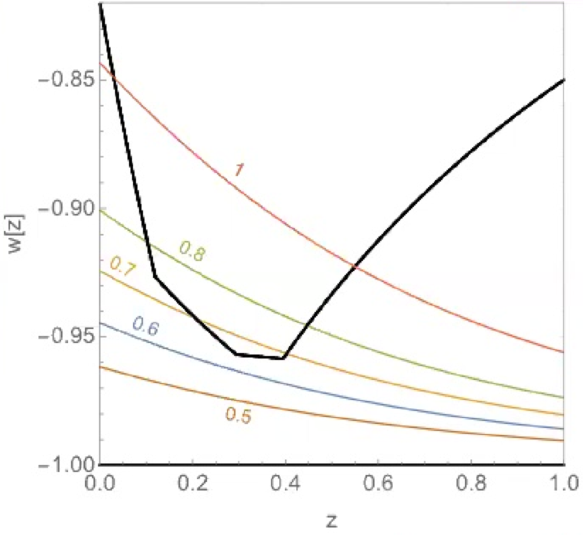
e.g., quintessence

Palti (2019)

Dark energy equation of state varies with time

$$\lambda(\phi) \equiv |\nabla_\phi V|/V$$

$$\boxed{\lambda(\phi) \geq c \sim \mathcal{O}(1)}$$



$V(\phi) = V_0 e^{\lambda\phi}$

constant

$$\boxed{c \lesssim 0.6}$$

incompatible with $c \sim \mathcal{O}(1)$

Agrawal, Obied, Steinhardt, Vafa (2018)

String theory: String Swampland

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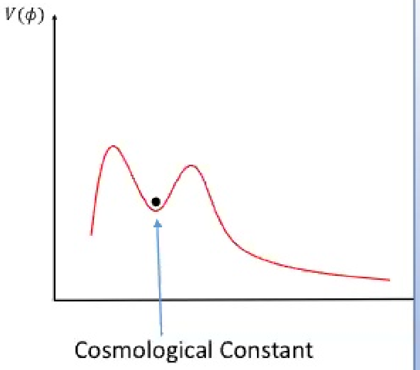

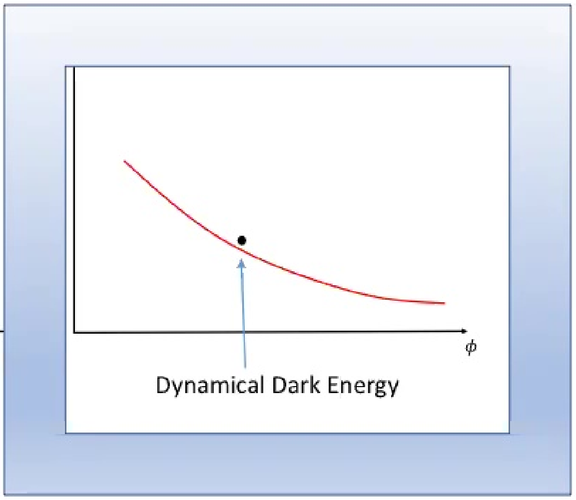

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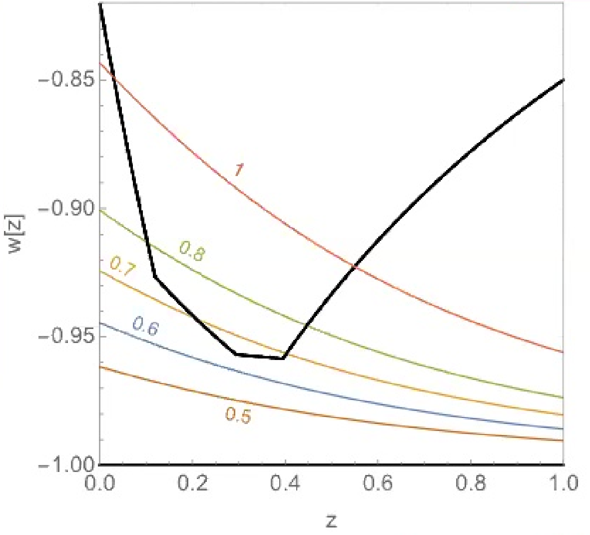

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Agrawal, Obied, Steinhardt, Vafa (2018)

Challenge: construct model with $c \lesssim 0.6$ *consistent with QG and not in the Swampland*

Group Field Theory (GFT):

spacetime and geometry should be emergent, as an effective description of the collective behaviour of different *pre-geometric* fundamental degrees of freedom

GFT models support the idea of a phase transition separating a symmetric from a broken/condensate phase, as the "mass" parameter changes its sign to negative values in the IR limit of the theory

Oriti (2007, 2014)
Gielen, Oriti, Sidoni (2013, 2014)
Gielen, Sidoni (2016)

Group Field theory Quantum Cosmology (GFC):

goal: *model homogeneous continuum 3-geometries and their cosmological evolution by means of GFT condensate states and their effective dynamics*

conjecture: a phase transition in a GFT system gives rise to a condensate phase

suitable to model spatially homogeneous geometries, whose metric is the same at every point of the space emerging from the condensate

Group Field Cosmology

- local gauge group of gravity: **SU(2)**
- **the elementary building block of 3dim space is a (quantum) tetrahedron**
- specify theory by the choice of a type of field - **complex scalar field** - and a corresponding action – **a kinetic quadratic term and a sum of interaction polynomials weighted by coupling constants** - encoding the dynamics

$$S = \int \mathrm{d}\phi \; \left(A \; |\partial_\phi \sigma|^2 + \mathcal{V}(\sigma)\right)$$

σ : complex scalar field representing the configuration of the condensate of GFT quanta as a function of relational time ϕ (massless scalar field)

$$\sigma_j(\phi) = \rho_j e^{i\theta_j}$$

$$j \in \frac{2N_0 + 1}{2}$$

ρ : modulus of the component of σ corresponding to the spin-j representation of SU(2)

$$V_j \sim \ell_{\mathrm{P}}^3 j^{3/2}$$

elementary volume determined by the chosen SU(2)-representation isotropic condensate state

GFT condensates dynamically reach a low spin phase of many quanta of geometry which are almost entirely characterised by only one spin j

*Pithis, **MS**, Tomov (2016)*

Gielen (2017)

Group Field Cosmology: resolution of the initial singularity (a bounce solution)

Assume interactions between GFT quanta as sub-dominant

$$\frac{V'}{V} = 2\frac{\rho'}{\rho} \equiv 2g(\phi)$$

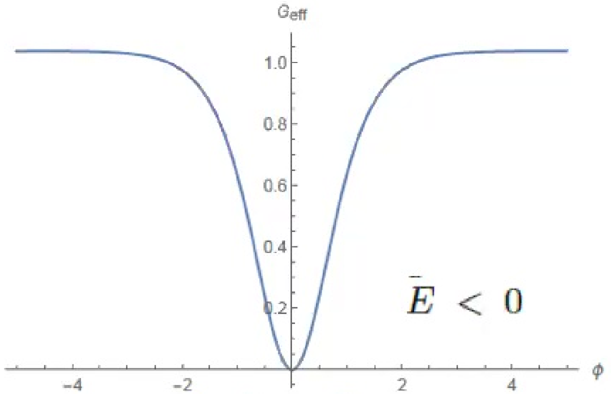
Effective Friedmann equation in the semi-classical limit:

$$H^2 = \left(\frac{V'}{3V}\right)^2 \dot{\phi}^2 = \frac{8}{9} g^2 \varepsilon.$$

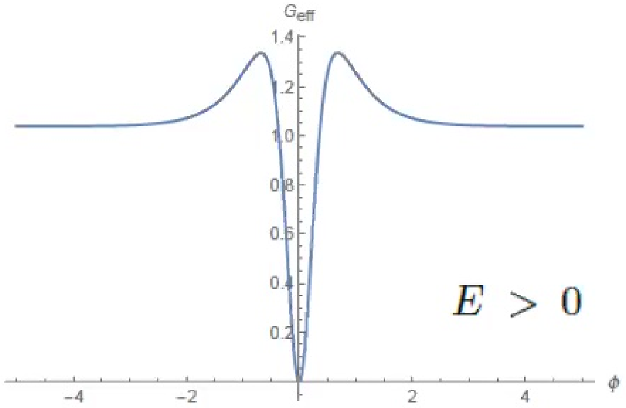
energy density

$$G_{\text{eff}} = \frac{1}{3\pi} g^2$$

Effective gravitational constant from the collective behaviour of spacetime quanta



$\phi = \Phi.$



$\phi = \Phi.$

$$\varepsilon_{\text{max}} = \frac{1}{2} \frac{Q^2}{V_{\text{bounce}}^2}$$

$$V_{\text{bounce}} = \frac{V_{j_0}\left(\sqrt{E^2 + 12\pi G Q^2} - E\right)}{6\pi G}$$

E: GFT energy

Q: conserved U(1) charge

$$E_j \approx (\rho_j')^2 + \rho_j^2(\theta_j')^2 - m_j^2\rho^2$$

$$Q_j \approx \rho_j^2\,\theta_j'$$

A bounce replacing the classical singularity

*de Cesare, **MS** (2017)*

Group Field Cosmology: early phase of accelerated expansion in the absence of an inflan field with fined tuned potential

$$\ddot{a} > 0$$

classical condition for accelerated expansion within std cosmology

$$\frac{V''}{V} > \frac{5}{3}\left(\frac{V'}{V}\right)^2$$

valid also in the absence of classical spacetime and absence of proper time

$$\boxed{\underbrace{4m^2 + \frac{2E}{\rho^2}} > \frac{20}{3}g^2}$$

near bounce: positive zero

Can one get sufficiently e-folds? $N \gtrsim 60$

$$N = \frac{2}{3}\log\left(\frac{\rho_{\mathrm{end}}}{\rho_{\mathrm{bounce}}}\right)$$

It depends on type of interactions between building blocks

*de Cesare, **MS** (2017)*

Group Field Cosmology: early phase of accelerated expansion in the absence of an inflan field with fined tuned potential

Effective action for an isotropic GFT condensate $S = \int \mathrm{d}\phi \ \left(A\ |\partial_\phi \sigma|^2 + \mathcal{V}(\sigma)\right)$

Non-interacting case : $0.119 \lesssim N \lesssim 0.186$

GFT cosmology in the absence of interactions between building blocks cannot replace the standard inflationary scenario

$$\mathcal{V}(\sigma) = B|\sigma(\phi)|^2 + \frac{2}{n} w |\sigma|^n + \frac{2}{n'} w' |\sigma|^{n'}$$

$$\lambda \equiv -\frac{w}{A} < 0 \text{ and } n \geq 5 \ (n' > n)$$

GFT cosmology can lead to an inflation-like era for certain types of interactions between quanta of geometry

de Cesare, Pithis, ***MS*** *(2016)*

Noncommutative Spectral Geometry

Bottom-up approach to QG: guess small scale structure of spacetime from knowledge of EW scales

To construct a QG theory coupled to matter, gravity-matter interactions is the most important ingredient for dynamics

ST: product of a 4dim smooth compact Riemannian manifold $\mathcal{M}$ and a finite noncommutative space $\mathcal{F}$

$\mathcal{M} \times \mathcal{F}$ given by the spectral triple $(\mathcal{A}, \mathcal{H}, D)$

spectral action functional $\mathrm{Tr}(f(\mathcal{D}_A^2/\Lambda^2))$ evaluate the trace using heat kernel techniques

$$\boxed{\mathrm{Tr}\left(f\left(\frac{D_A}{\Lambda}\right)\right) \sim 2f_4\Lambda^4 a_0({D_A}^2) + 2f_2\Lambda^2 a_2({D_A}^2) + f_0\, a_4({D_A}^2) + O(\Lambda^{-1})}$$

Chamseddine, Connes (1996, 1997)

Chamseddine, Connes, Marcolli (2007)

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Chamseddine, Connes (1996, 1997)

Chamseddine, Connes, Marcolli (2007)

Noncommutative Spectral Geometry

Linear perturbations around Minkowski background

The spatial components of $h^{\mu\nu}$ in the far-field limit

$$h^{ik}(\mathbf{r},t) \approx \frac{2G\beta}{3c^4}\int_{-\infty}^{t-\frac{1}{c}|\mathbf{r}|}\frac{\mathrm{d}t'}{\sqrt{c^2(t-t')^2-|\mathbf{r}|^2}}\mathcal{J}_1\left(\beta\sqrt{c^2(t-t')^2-|\mathbf{r}|^2}\right)\ddot{D}^{ik}(t')$$

$$D^{ik}(t) \equiv \frac{3}{c^2}\int \mathrm{d}\mathbf{r}\; x^i x^k T^{00}(\mathbf{r},t)$$ quadrupole moment

Energy loss to gravitational radiation by orbiting binaries

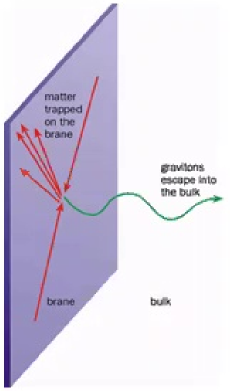
$$\boxed{-\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}t} \approx \frac{c^2}{20G}|\mathbf{r}|^2\dot{h}_{ij}\dot{h}^{ij}}$$

*Nelson, Ochoa, **MS** (2010)*

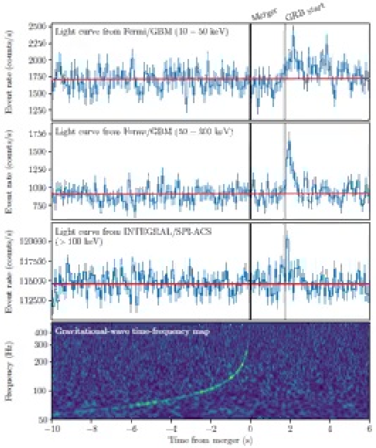
Geodesic and frame dragging effects of GR (Gravity Probe B and Laser Relativity Satellite)
Modifications to Newtonian potentials similar to those induced by a 5th force (torsion balance)

*Lambiase, **MS**, Stabile (2013)*

Brane/String theory: Extra dimensions



Constraints on the number of spacetime dimensions from GWs

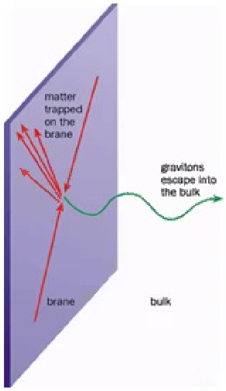


GRB 170817A and GW170817

GW event 1.7 s before γ-ray observation

BNS merger at 40 Mpc

Brane/String theory: Extra dimensions



Constraints on the number of spacetime dimensions from GWs

Damping of the waveform due to gravitational leakage into extra dim

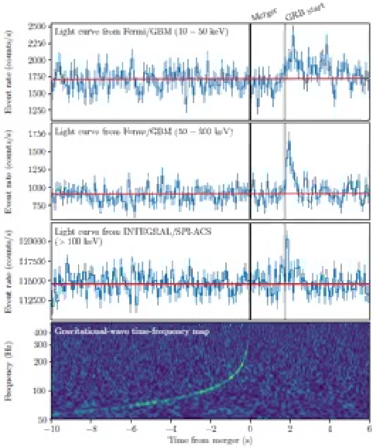
Deviation depends on the number of dimensions D and would result to a systematic **overestimation of the source** d_L^{EM} **inferred from GW data**

$$h \propto \frac{1}{d_L^{\mathrm{GW}}} = \frac{1}{d_L^{\mathrm{EM}}}\left[1+\left(\frac{d_L^{\mathrm{EM}}}{R_c}\right)^n\right]^{-(D-4)/(2n)}$$

Strain *measured in a GW interferometer* ⟷ ***Luminosity distance*** *measured for the optical counterpart of the standard siren*

- Consistency with GR in D=4 dim
- Some models (e.g. the Dvali-Gabadadze-Porrati (DGP) model) are ruled out

Abbott et al (+ ***MS****) (2018)*



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Propagation of GWs in the context of QG

Long-range nonperturbative mechanism found in most QG candidates:
Dimensional flow (change of spacetime dimensionality)

$$S = \frac{1}{2\ell_*^{2\Gamma}} \int d\varrho \sqrt{-g^{(0)}} \left[h_{\mu\nu}\mathcal{K}h^{\mu\nu} + O(h_{\mu\nu}^2) + \mathcal{J}^{\mu\nu}h_{\mu\nu}\right]$$

scaling parameter

characteristic scale of geometry

generic source term

$$\boxed{\Gamma(\ell) := \frac{d_{\mathrm{H}}(\ell)}{2} - \frac{d_{\mathrm{H}}^k(\ell)}{d_{\mathrm{S}}(\ell)}}$$

*Calcagni, Kuroyanagi, Marsat, **MS**, Tamanini, Tasinato, (2019)*

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$$h \propto \int d\varrho \, \mathcal{J} \, G$$

$$\Longrightarrow \qquad h(t,r) \sim f_h(t,r) \; (\ell_*/r)^{\Gamma}$$

In radial coordinates, and in the local wave zone

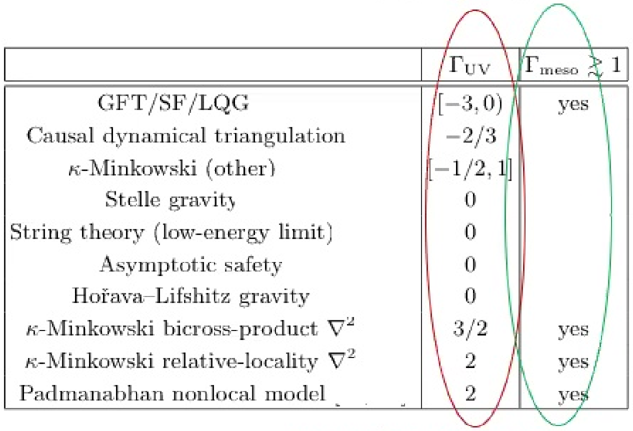
*Calcagni, Kuroyanagi, Marsat, **MS**, Tamanini, Tasinato, (2019)*

Propagation of GWs in the context of QG

Scaling parameter

$$\boxed{\Gamma(\ell) := \frac{d_{\rm H}(\ell)}{2} - \frac{d_{\rm H}^k(\ell)}{d_{\rm S}(\ell)}}$$

QG corrections are important



	$\Gamma_{\rm UV}$	$\Gamma_{\rm meso} \gtrsim 1$
GFT/SF/LQG	$[-3, 0)$	yes
Causal dynamical triangulation	$-2/3$	
κ-Minkowski (other)	$[-1/2, 1]$	
Stelle gravity	0	
String theory (low-energy limit)	0	
Asymptotic safety	0	
Hořava–Lifshitz gravity	0	
κ-Minkowski bicross-product ∇^2	$3/2$	yes
κ-Minkowski relative-locality ∇^2	2	yes
Padmanabhan nonlocal model	2	yes

Contributions to GR small but non-negligible

*Calcagni, Kuroyanagi, Marsat, **MS**, Tamanini, Tasinato, (2019)*

Propagation of GWs in the context of QG

*The **strain** measured in a GW interferometer* ↔ *The **luminosity distance** measured for the optical counterpart of the standard siren*

$$\boxed{h \propto \frac{1}{d_L^{\rm GW}}, \qquad d_L^{\rm GW} = d_L^{\rm EM}\left[1+\varepsilon\left(\frac{d_L^{\rm EM}}{\ell_*}\right)^{\gamma-1}\right], \qquad \gamma \neq 0,}$$

$$\varepsilon = \pm(\gamma - 1)$$

If there is only one fundamental scale, $\ell_* = \mathcal{O}(\ell_{\rm Pl})$, the equation is exact and $\gamma = \Gamma_{\rm UV}$

If ℓ_* is a mesoscopic scale, then the equation is valid only near the IR regime and $\gamma = \Gamma_{\rm meso} \approx 1$

Calcagni, Kuroyanagi, Marsat, **MS**, Tamanini, Tasinato, (2019)

Propagation of GWs in the context of QG

When $\gamma = \Gamma_{\rm UV}$ we cannot constrain the deep UV limit of QG, since $\ell_* = \mathcal{O}(\ell_{\rm Pl})$.
(*deviations from classical geometry occur at microscopic scales unobservable in astrophysics*)

The only theories that can be constrained in this way are those with $\Gamma_{\rm meso} > 1 > \Gamma_{\rm UV}$

$$0 < \Gamma_{\rm meso} - 1 < 0.02$$

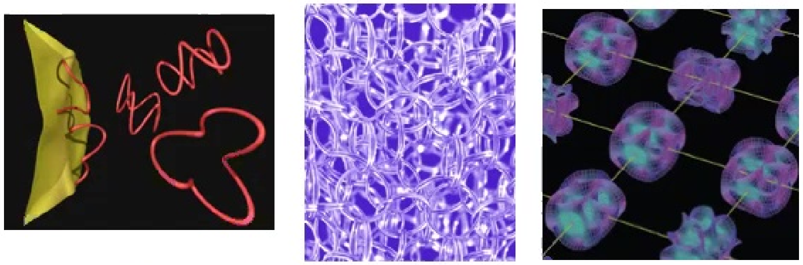
Only GFT, SF or LQG *could* generate a signal detectable with standard sirens

Look for realistic quantum states of geometry giving rise to such a signal

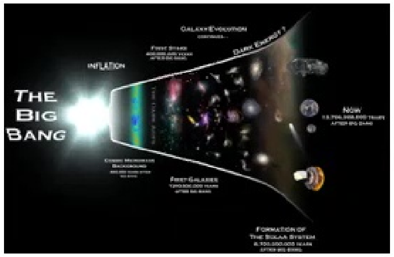
*Calcagni, Kuroyanagi, Marsat, **MS**, Tamanini, Tasinato, (2019)*

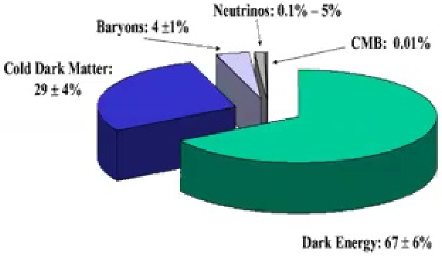
Conclusions

Cosmological models built on quantum gravity theories



can provide mechanisms to explain observations for which ad hoc phenomenological models have been proposed.





Astrophysical observations and gravitational wave detections offer tests to support or disfavor quantum gravity theories and, in some cases, assist in model building.