Colloque national dark Energy – 2ème édition

The dark side of gravity and the acceleration of the Universe

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Dark Gravity theories are extensions of General Relativity aiming at a stable anti-gravitational sector

J.P. Petit, Twin Universe cosmology, Astrophys. Space Sci. Vol. 226, pp 273, 1995. and many other articles

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F. Henry-Couannier, Dark Gravity, GJSFR A. Vol 13, Issue 3, pp 1-53, 2013.

S. Hossenfelder, Bimetric theory with exchange symmetry Phys. Rev. D 78, 044015, 2008.

M. Milgrom, Matter and twin matter in bimetric MOND, MNRAS 405 (2), pp 1129-1139, 2010.

Laura Bernard, Luc Blanchet, Lavinia Heisenberg Bimetric gravity and dark matter 50th Rencontres de Moriond, "Gravitation: 100 years after GR", 2015

From background dependence to Dark Gravity (DG)

How far can we go ?

GR : $g_{\mu\nu}$

DG : $g_{\mu\nu}$ and $\eta_{\mu\nu}$

$$\mathrm{Riemm}(\eta_{\mu\nu}) = 0$$

⇒ $g_{\mu\nu}$ has a twin, « the inverse metric » $\tilde{g}_{\mu\nu}$

$$\tilde{g}_{\mu\nu} = \eta_{\mu\rho}\eta_{\nu\sigma}\left[g^{-1}\right]^{\rho\sigma}$$

⇒ $(g_{\mu\nu}, \tilde{g}_{\mu\nu})$ is a Janus field

From the Action to DG field equations

The Action must respect the permutation symmetry between $g_{\mu\nu}$ and $\tilde{g}_{\mu\nu}$:

$$\int d^4x(\sqrt{g}R + \sqrt{\tilde{g}}\tilde{R}) + \int d^4x(\sqrt{g}L + \sqrt{\tilde{g}}\tilde{L})$$

$$\delta g_{\mu\nu} \Rightarrow \delta S = 0$$

$$\sqrt{g}\eta^{\mu\sigma} g_{\sigma\rho} G^{\rho\nu} - \sqrt{\tilde{g}}\eta^{\nu\sigma} \tilde{g}_{\sigma\rho} \tilde{G}^{\rho\mu} + \mu \leftrightarrow \nu = -8\pi G(\sqrt{g}\eta^{\mu\sigma} g_{\sigma\rho} T^{\rho\nu} - \sqrt{\tilde{g}}\eta^{\nu\sigma} \tilde{g}_{\sigma\rho} \tilde{T}^{\rho\mu} + \mu \leftrightarrow \nu)$$

Contracted form

$$\sqrt{g}R - \sqrt{\tilde{g}}\tilde{R} = 8\pi G(\sqrt{g}T - \sqrt{\tilde{g}}\tilde{T})$$

Implications of DG equations

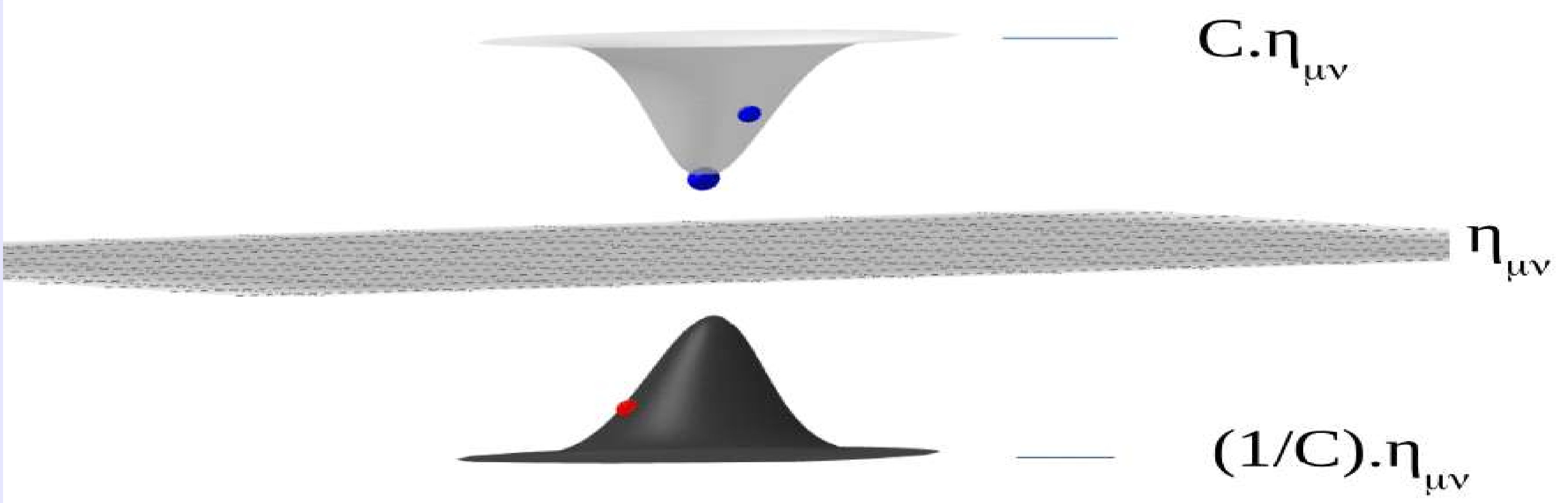
- DG is background dependent yet deviations from GR can remain arbitrarily small provided one side of the Janus Field dominates the other
- Ghost interaction between Janus and source fields but Janus field not understood to be a quantum field !
  - DG more natural than GR as a semiclassical* theory of gravity
  - Semiclassical DG stability : OK**
- New discrete (permutation) symmetry is very fundamental : will be interpreted as a global time reversal symmetry.

* https://arxiv.org/abs/0802.1978 Mark Albers, Claus Kiefer, Marcel Reginatto, Measurement Analysis and Quantum Gravity : « Despite the many physical arguments which speak in favor of a quantum theory of gravity, it appears that the justification for such a theory must be based on empirical tests and does not follow from logical arguments alone »

** https://arxiv.org/pdf/1401.4024.pdf V. A. Rubakov, page 8 : Gradient, tachyonic and ghost instabilities in scalar-tensor theories : « for ghosts, background is QM unstable but classically stable »

The static isotropic solution

Animggb



- Antigravity without run away !
- Asymptotic C matters : GR corresponds to C infinite

The static isotropic solution

C=1

DG:

$$g_{ii}(r) = A = e^{2MG/r} \approx 1 + 2\frac{MG}{r} + 2\frac{M^2G^2}{r^2}$$

$$-g_{00}(r) = \frac{1}{A} = e^{-2MG/r} \approx 1 - 2\frac{MG}{r} + 2\frac{M^2G^2}{r^2} - \frac{4}{3}\frac{M^3G^3}{r^3}$$

C=∞

RG (Schwarzschild) :

$$g_{ii}(r) = \left(1 + \frac{MG}{2r}\right)^4 \approx 1 + 2\frac{MG}{r} + \frac{3}{2}\frac{M^2G^2}{r^2}$$

$$g_{00}(r) = \frac{\left(1 - \frac{MG}{2r}\right)^2}{\left(1 + \frac{MG}{2r}\right)^2} \approx 1 - 2\frac{MG}{r} + 2\frac{M^2G^2}{r^2} - \frac{3}{2}\frac{M^3G^3}{r^3}$$

- No Horizon
- Zero Gravitational Waves

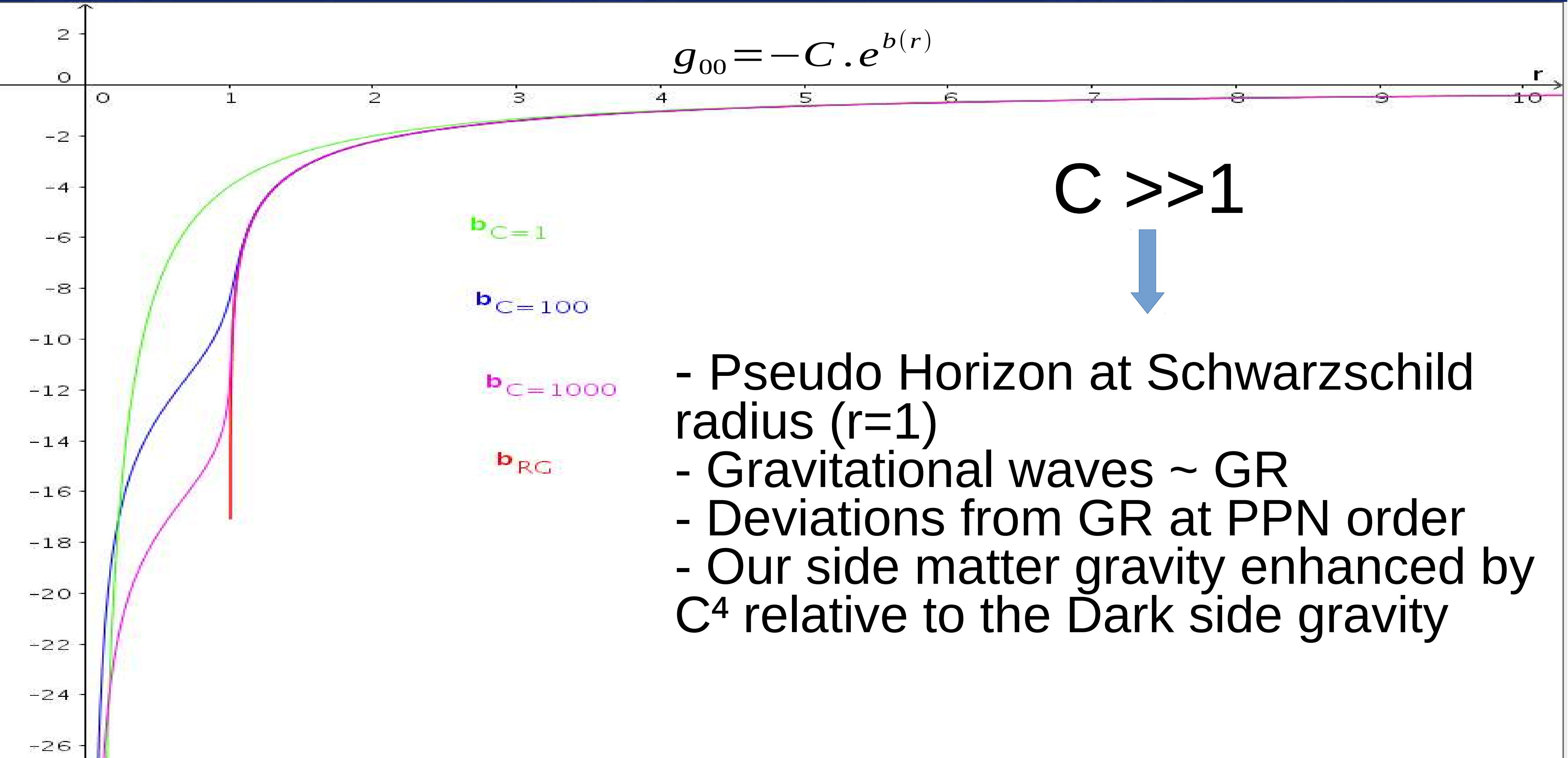
$$\tilde{h}_{\mu\nu} = -h_{\mu\nu} + O(h^2)$$

$$2(R^{(1)}_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}R^{(1)\lambda}_{\lambda}) = -8\pi G(T_{\mu\nu} - \tilde{T}_{\mu\nu} + t_{\mu\nu} - \tilde{t}_{\mu\nu})$$

$t_{\mu\nu} - \tilde{t}_{\mu\nu} \to 0$

- Deviations from GR at PPN order only

The static isotropic solution



C >>1

- Pseudo Horizon at Schwarzschild radius (r=1)
- Gravitational waves ~ GR
- Deviations from GR at PPN order
- Our side matter gravity enhanced by C^4 relative to the Dark side gravity

Cosmological equation

- Homogeous & isotropic Janus solution is flat and static : C was indeed a constant !

  ⇒ We need to introduce a separate scalar-η Janus field for cosmology :

$$g_{\mu\nu} = \Phi \eta_{\mu\nu} \text{ and } \tilde{g}_{\mu\nu} = \frac{1}{\Phi}\eta_{\mu\nu} \qquad \Phi(t) = a^2(t)$$

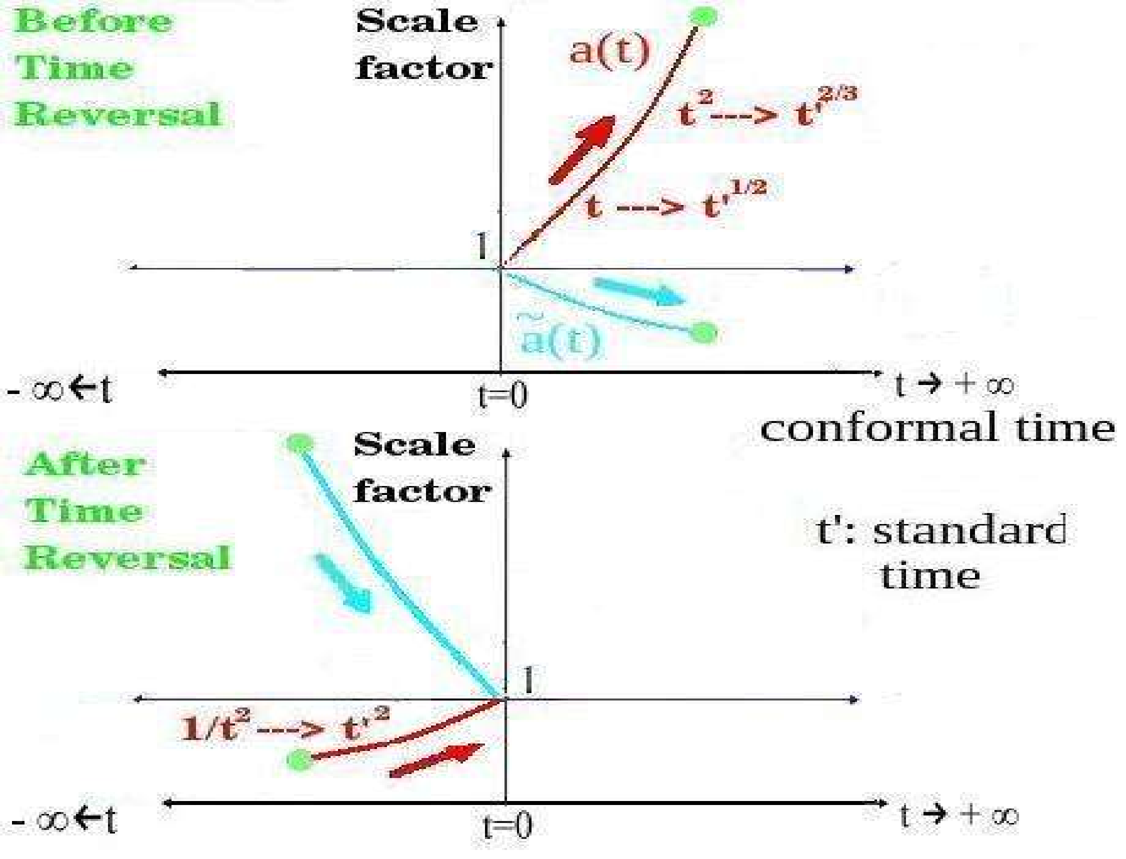
- Single scale factor equation :

$$a\ddot{a} - \tilde{a}\ddot{\tilde{a}} = \frac{4\pi G}{3}\left(a^4(\rho - 3p) - \tilde{a}^4(\tilde{\rho} - 3\tilde{p})\right)$$

$$\tilde{a}(t) = \frac{1}{a(t)}$$

Cosmological solutions

Anim ggb



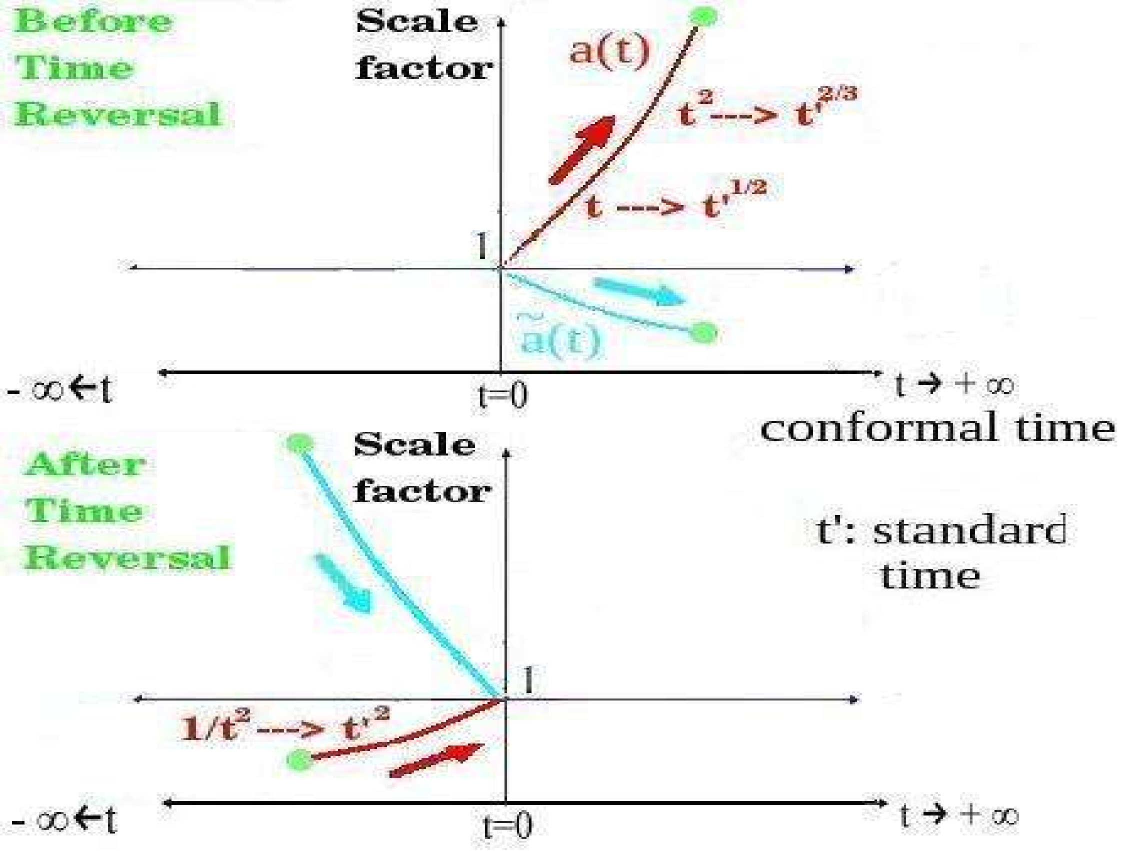
- Janus scale factors are related by a global conformal time reversal symmetry T : $\tilde{a}(t) = \frac{1}{a(t)} = a(-t)$
- Both continuous evolution and discontinuous permutation T allowed when $\rho - 3p = \tilde{\rho} - 3\tilde{p}$

Global time reversal : not going backward in time, but jumping to the opposite time !

A cyclic Universe ?

DG Cosmology

Animggb



Hyp : $\rho \simeq \rho - 3p = \tilde{\rho} - 3\tilde{p} \simeq \tilde{\rho}$ occured at transition redshift triggering T and a'(t')~ t'²

With H(t) continuous at the transition and assuming same universe age as in LCDM:

$$\text{a'(t')} \sim t'^{\alpha} \implies z_{\text{tr}} = \left(\frac{2/3 - \alpha}{1 - \alpha}\right)^{\alpha} - 1$$

⇒ z_{tr} = 0.78 vs observed z_{tr} =0.67+- 0.1

- ~ Same scale factor evolution as in LCDM
- Without DE
- Inflation not needed to get k=0
- Without Big Bang singularity
- Cosmological DM still needed
- Dark side effects only since t_{tr} or near t=0

Problem statement

- We have two separate theories :
  - Asymptotically static DG correctly describes all aspects of gravity except expansion
  - Scalar-η Janus field only correctly describes expansion
- How to get expansion effects on the largest scales and differential eoms non trivially mixing background and perturbations (GR like) as needed to reproduce CMB phenomenology ?

Conclusion and outlooks

- DG avoids Big-Bang singularity and BH horizon very naturally
- Acceleration, k=0, large scale homogeneity, matter/antimatter asym
- Likely to cancel the gravity of vacuum energy
- Outlook :

Unification ⇒ New rich and effective phenomenology

(DM candidate, …)

www.darksideofgravity.com/DG.pdf

How far could we go ?

Background dependent ⇒  EP violating

+ Ghost ⇒ OK* ⇒  Quantum unstable

+ Semiclassical ⇒ OK ⇒ OK** ⇒  Unbounded

+ Discontinuous ⇒ OK ⇒ OK ⇒ OK ⇒  Incomplete

+ Emerging dynamics ⇒ OK ⇒ OK ⇒ OK ⇒ OK

* EP violations (η effects) usually small, **harmless classical instabilities

⇒ Fascinating phenomenological and theoretical implications !

Dynamical discrete symmetries

- Standard view :

Symmetries (cont & disc) ⇒ Action

Extreme action principle ⇒ Eoms & conservation equations

No dynamical processes associate with discrete symmetries

- Extended view :

Symmetries (cont & disc) ⇒ Action

Extreme action principle ⇒ Eoms & conservation equations

Discrete symmetries ⇒ Discontinuous processes

Dynamical discrete symmetries

1) Discrete (permutation) symmmetry and continuous symmetries already unified in DG framework
2) Just as discrete (T&P) and continuous spacetime symmetries already unified in the Lorentz group

1) and 2) turn out to be related : global T symmetry is permutation symmetry !

Dynamical discrete symmetries ⇒ discontinuous transitions in addition to usual continuous evolution processes deduced from differential eoms.

⇒ Fills the gap between the discrete and the continuous

⇒ Hopefully opens the way to a genuine unification (understanding) of QM discrete and non local laws to the rest of physics !

Vacuum energy terms in DG equations

DG vacuum source term :

$$(\sqrt{g}\Lambda - \sqrt{\tilde{g}}\tilde{\Lambda})\, g^{\mu\nu}$$

Cancels for $g_{\mu\nu}$ = $\tilde{g}_{\mu\nu}$ = $\eta_{\mu\nu}$ and $\Lambda = \tilde{\Lambda}$ (natural)

⇒ Might remain zero when Janus field starts to evolve, may be through the auto-adjustment of cut-offs to preserve compensation.

DG unification with adiabatic particles exchange?

*** adapted from original idea by Prigogin et al**

- Matter and radiation fields conservation equations including adiabatic gravitationnally induced* transfers occuring between the two metrics :

$$\nabla_\nu T^\nu_\mu \neq 0 \implies \frac{\dot\rho}{H} = (\frac{\Gamma}{H} - 3)(\rho + p)$$

$$\tilde\nabla_\nu \tilde T^\nu_\mu \neq 0 \implies \frac{\dot{\tilde\rho}}{\tilde H} = (\frac{\tilde\Gamma}{\tilde H} - 3)(\tilde\rho + \tilde p)$$

$$\tilde\Gamma = -\Gamma, \tilde H = -H$$

- Replacing in DG_Friedmann equations

$$a\ddot a - \tilde a\ddot{\tilde a} = K(a^4(\rho - 3p) - \tilde a^4(\tilde\rho - 3\tilde p))$$
$$\dot a^2 - \dot{\tilde a}^2 = 2K(a^4\rho - \tilde a^4\tilde\rho)$$

$$\Rightarrow$$

$$a\ddot a = K(a^4(\rho - 3p) + \frac{1}{2}(C + \tilde C))$$
$$\tilde a\ddot{\tilde a} = K(\tilde a^4(\tilde\rho - 3\tilde p) + \frac{1}{2}(C + \tilde C))$$

$$C = a^4\frac{\Gamma}{H}(\rho + p)$$
$$\tilde C = \tilde a^4\frac{\Gamma}{H}(\tilde\rho + \tilde p)$$

⇒ ~ usual solutions valid provided $\Gamma \approx 2H\frac{a\ddot a}{\tilde a\ddot{\tilde a}}$ (for $a \ll \tilde a$)

DG unification with Emerging Dynamics (ED)

As the universe evolves new dynamical dofs are released :

- Non dynamical

$$\eta_{\mu\nu}$$

- Homogenous scalar-eta

$$\varphi(t)\eta_{\mu\nu}$$

- Scalar-eta + non dynamical fluctuation

$$\varphi(t)\eta_{\mu\nu}+\Delta g_{\mu\nu}$$

- Separate dynamics

$$\varphi(t)\eta_{\mu\nu} \qquad \Delta g_{\mu\nu}$$

$a^2(t)$ C

ED : Early DG unification

- For a²(t) < Fundamental Threshold,

$$g_{\mu\nu} = \varphi(t)\eta_{\mu\nu} + \Delta g_{\mu\nu}$$

  but only the scalar φ(t) is dynamical ⇒ we again get a single equation

- Symmetries related to our privileged coordinate system (rather than isometries related to the sources) force the primordial metrics in the Newtonian Gauge form :

$$d\tau^2 = a^2(t)((1 + 2\Psi)dt^2 - (1 - 2\Psi)d\sigma^2)$$

- ⇒ We get the same scale factor (order 0) and potential (order 1) eoms as in GR but rotational and radiative modes should be absent from the CMB.

ED : Late DG unification

- $a^2(t)$ > Fundamental Threshold breaks the primordial symmetries

  ⇒ $\varphi(t)\eta_{\mu\nu}$ and $\Delta g_{\mu\nu}$ start to play their dynamics independently

  ⇒ Late DG unification required to account for expansion effects

- In the Linear domain, C (integration constant of $\Delta g_{\mu\nu}$) is driven step by step by the scale factor from $\varphi(t)\eta_{\mu\nu}$:

  ⇒ expansion effects through discrete rules

  ⇒ rich new and effective phenomenology related to field discontinuities

- In the Non Linear domain (solar system), we are asymptotically Minkowskian: C strictly constant !

Classical stability issues

- Background remains bounded thanks to global time reversal
- Linear inhomogeneous perturbations unstable in contracting phase

  but gravity from these is negligible : suppressed by C^4 factor (~scale_factor^8) before transition to acceleration.
- Linear inhomogeneous perturbations from the dark sector can start to grow under their own gravity after transition
- Strong gravity inhomogeneous pertubations presumably always stable on both sides thanks to C >1 at our side structures while C<1 at dark side structures

Problems with semiclassical Gravity

- Case I : Classical gravity triggers quantum collapses ⇒ no Energy-momentum conservation violation, nor violation of uncertainty relations contrary to popular argument by Eppley & Hannah ...

  https://arxiv.org/pdf/0802.1978.pdf

  otherwise :

- Case 2A : No collapse interpretation of QM (MWI, decoherence …) ruled out because classical gravity would see the uncollapsed superpositions
- Case 2B : Realistic collapse interpretation of QM leads to possible faster than light signaling. Either specific more local model of quantum collapse can solve this or … DG : instantaneous signaling is not anymore a menace to causality as soon as there exists a unic privileged instantaneity frame for any collapse !