UV-complete Ghost Inflation

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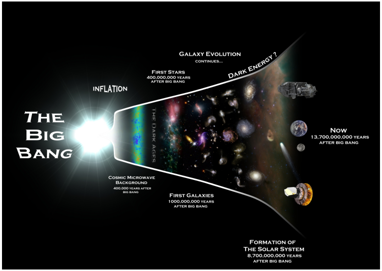
[arXiv:1310.xxxx]

7th Aegean Summer school
Paros, September 27, 2013

Why Lorentz Violation in Gravity?

Faces of Lorentz breaking:

- **Theory**. Better for quantum gravity [Horava, 09] (*emergent geometry, Horava-Lifshitz gravity, ...*)
- **Phenomonology**. Puzzles of ΛCDM cosmology: Dark matter, Dark energy and Inflation (*massive gravity, ghost condensate...*)



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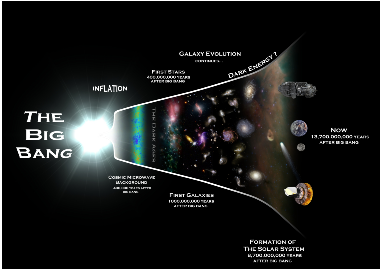
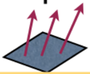


Breaking Lorentz Invariance

LI broken by a preferred **time** direction (keep rotations)

unit-timelike vector field u_μ



Generic vector

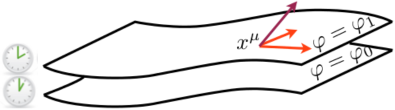
$$u_\mu u^\mu = 1$$

Einstein-aether

Scalar-vector-tensor theory

Similar scalar sector

Hypersurface orthog.



$$u_\mu \equiv \frac{\partial_\mu \varphi}{\sqrt{\partial_\alpha \varphi \partial^\alpha \varphi}} \leftarrow \textbf{Khronon}$$

scalar-tensor theory with

$$\varphi \mapsto f(\varphi) \qquad (\partial_\mu \bar{\varphi} \partial^\mu \bar{\varphi} > 0)$$

Gravity with a preferred frame

Gravitational Lagrangian

Ingredients: $u_\mu \ , \ g_{\mu\nu}$

Khronometric case $\qquad u_\mu \equiv \frac{\partial_\mu \varphi}{\sqrt{\partial_\alpha \varphi \partial^\alpha \varphi}}$

$$\mathcal{L}_{\chi GR} = \mathcal{L}_{EH} + \sqrt{-g}\left(\lambda\left(\nabla^\mu u_\mu\right)^2 + \alpha\left(u^\nu \nabla_\nu u_\mu\right)^2 + \beta \nabla_\mu u_\nu \nabla^\nu u^\mu\right)$$

- ★ Massless Spin 2 graviton $\quad \omega^2 = c_t^2\, \mathrm{k}^2$
- ★ Extra massless scalar $\quad \omega^2 = c_\chi^2\, \mathrm{k}^2$

$$\varphi = t + \chi$$

$$c_t^2 = \frac{1}{1-\beta} \qquad c_\chi^2 = \frac{\beta+\lambda}{\alpha}$$

Einstein-aether (generic u_μ): extra term

- ★ Extra vector polarizations

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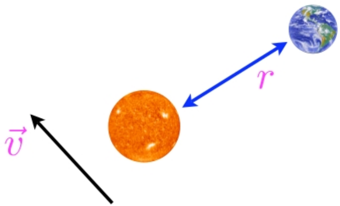
EFT with cutoff $\Lambda_{UV} \sim \sqrt{\alpha} M_P$ $\qquad$ Known UV-completion: Horava gravity!

Constraints on LV in gravity



$$h_{00} = -2G_N \frac{m}{r}\left(1 - \frac{\alpha_2^{PPN}}{2}\frac{(x^i v^i)^2}{r^2}\right)$$

$$h_{0i} = \frac{\alpha_1^{PPN}}{2} G_N \frac{m}{r} v^i$$

Observations:

$$|\alpha_1^{PPN}| \leq 10^{-4}, \quad |\alpha_2^{PPN}| \leq 10^{-7}$$

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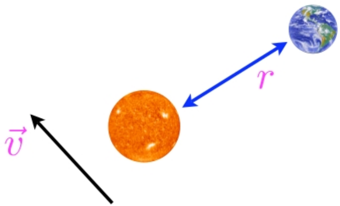

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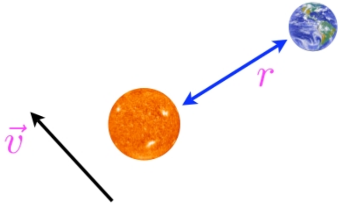

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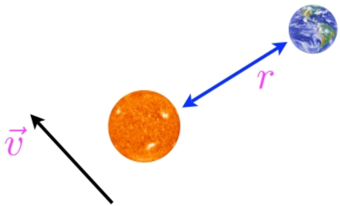

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New inflationary model

Assume that LI is broken (by Khronon)

Add a field with shift symmetry

$$\Theta \to \Theta + \text{const}\,,$$

$$\mathcal{L}_{[\Theta]} = \frac{(\partial_\mu \Theta)^2}{2} + \mu^2 u^\nu \partial_\nu \Theta\,.$$

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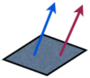
Slightly **broken** by potential and (or) derivative coupling

$$\mathcal{L}_{[\Theta]} = \frac{(\partial_\mu \Theta)^2}{2} + \mu^2(\Theta) u^\nu \partial_\nu \Theta - V(\Theta)\,.$$

Homogeneous Cosmology

Homogeneous and isotropic ansatz
(preferred foliation aligned with CMB preferred frame)



$$ds^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = \mathrm{d}t^2 - a(t)^2 \mathrm{d}x^i \mathrm{d}x^i$$
$$u_\mu = (u_0(t), 0, 0, 0)$$

Friedman equation

$$H^2 = \frac{1}{3M_P^2(1+\frac{\beta+3\lambda}{2})}\left(\frac{\dot{\Theta}^2}{2} + V\right),$$

Inflaton equation

$$\ddot{\Theta} + 3H(\dot{\Theta} + \mu^2) + V' = 0\,.$$

Slow rolling and slow acceleration

$$\dot{\Theta} = -\mu^2 \simeq \text{const}\,, \quad V \simeq \text{const}\,.$$

Homogeneous Cosmology: different regimes of evolution

Kinetic driven Inflation

$$V \ll \mu^4 \,,$$

Friedman eq.

$$3M_P^2 H^2 \simeq \frac{\dot{\Theta}}{2} = \frac{\mu^4}{2}$$

Shift-symmetry of Inflation is a good approximation

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Shift-symmetry of Inflation is a good approximation

Potential-driven Inflation

$$\mu^4 \lesssim V \,,$$

Shift-symmetry is strongly broken.

$$\mu^4 \ll V$$

recovers slow-roll inflation.

$$\dot{\Theta} = -\mu^2 + \dot{\Theta}^{(1)} = -\mu^2 - \frac{V' + (\mu^2)'\mu^2}{3H} \,,$$

Slow-roll corrections:

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \sim \frac{\mu^2 \dot{\Theta}^{(1)}}{M_P^2 H^2} \ll 1 \,.$$

Perturbations

In a fixed expanding background
$\Theta(t) = \bar{\Theta}(t) + \theta(t,\vec{x}) \qquad \varphi = t + \chi(t,\vec{x}).$

A new scale appears

$$H_\alpha \equiv \frac{\mu^2}{\sqrt{\alpha} M_P} \sim \frac{H}{\sqrt{\alpha}} \gg H \, .$$

* Spectrum $k \gg H_\alpha$ $\boxed{\omega_\Theta^2 = k^2 \, , \quad \omega_\chi^2 = c_\chi^2 k^2}.$

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* Spectrum $k \ll H_\alpha$:

$$\omega_+^2 = H_\alpha^2 + (c_\chi^2 + 1)k^2\,, \qquad \text{Massive mode}$$

$$\omega_-^2 = \frac{c_\chi^2}{H_\alpha^2} k^4 + \delta^2 k^2\,, \quad \delta^2 \ll 1 \qquad \text{Slow mode.}$$

Perturbations

* Spectrum $k \ll H_\alpha$: action for metric fluctuations (ζ is the Bardeen parameter)

$$S^{(2)}_{[\zeta]} = \int d^4x \, \frac{a^3}{2} \frac{\mu^4}{H^2} \left[\dot{\zeta}^2 - \frac{\delta^2}{a^2} (\partial_i \zeta)^2 - \frac{c_\chi^2 (\Delta\zeta)^2}{a^4 H_\alpha^2} \right] ,$$

where effective sound speed

$$\delta^2 = -\frac{\dot{H}}{H^2} \frac{2M_P^2 H^2}{\mu^4} \simeq \frac{\epsilon}{3} \ll 1 \quad \text{Kinetic driven case.}$$

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$$\frac{k^2}{H_\alpha} > \delta \cdot k \quad \text{at Horizon crossing} \quad \Rightarrow \quad \boxed{\alpha > 10^{-4}}$$

Perturbations

Two different regimes,

- Quadratic dispersion relation $\omega \sim k^2/H_\alpha$.
  Takes place for

  $$\boxed{\alpha > 10^{-4}}$$

  Power spectrum $P_\zeta \sim \frac{1}{\alpha^{3/4}} \cdot \frac{H^2}{M_P^2}$
  Tilt $n_s - 1 = -2\epsilon = -6\delta^2$,
  Scalar-tensor ratio $r \simeq 6.5 \cdot 10^{-3} \left(\alpha/10^{-4}\right)^{3/4}$.

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- Linear dispersion relation $\omega = \delta \cdot k$. Takes place in the potential driven case and where the above inequality breaks.

Power spectrum $P_\zeta \sim \frac{1}{\delta^3} \cdot \frac{H^2}{M_P^2}$
Tilt $n_s - 1 = -2\epsilon = -6\delta^2$,
Scalar-tensor ratio $r \simeq 24\delta^3$.

All in agreement with Planck data

Remarkable similarity with Ghost Inflation (Arkani-Hamed et. al. 2004, Senatore, 2008)

	Kinetic-Driven	Ghost	Tilted Ghost
Background	$\dot{\Theta} = -\mu^2$	$\dot{\phi} = M^2$	$\dot{\phi} = M^2$
Quadratic d.r.	$\omega \sim k^2/H_\alpha$	$\omega \sim k^2/M$	-
Linear d.r.	$\omega \sim \delta \cdot k$	-	$\omega \sim \delta \cdot k$

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Linear d.r.	$\omega \sim \delta \cdot k$	-	$\omega \sim \delta \cdot k$

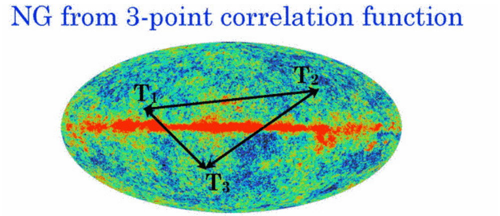
But! Scale of Ghost Inflation: $H < 10$ Mev

In our model may be big, even close to the Planck mass!

Kinetic driven inflation = UV-completion of Ghost Inflation.

Even with the tilt!

Non-gaussianities



Data analysis:

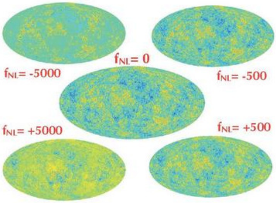
$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle =$$
$$(2\pi)^7 \delta^3 \Big(\sum_i \vec{k}_i \Big) B_\zeta(\vec{k}_1, \vec{k}_2, \vec{k}_3)$$

$$B_\zeta(k, k, k) = (3/5) \cdot 6\, f_{NL} P_\zeta^2 / k^6$$

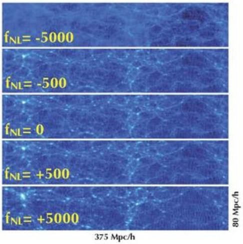
Theory: $\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle =$

$$\langle U_{int}^{-1} \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} U_{int}(t, t_0) \rangle$$

$$U_{int} = T \exp\Big(\int_{t_0}^{t} H_{int}(t') dt' \Big)$$



CMB

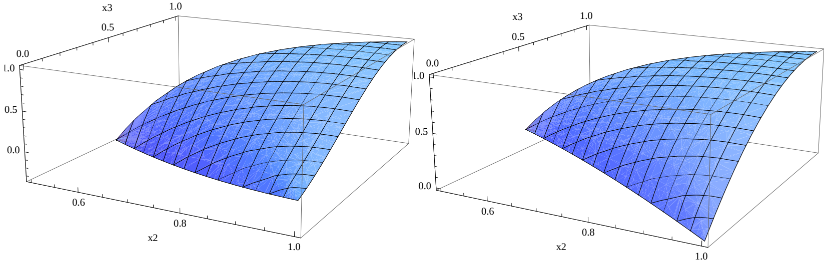


LSS

Non-gaussianities

Interaction Hamiltonian $H_{int} = -\frac{a}{2\mu^2}[\dot{\theta}(\partial_i\theta)^2]$

The same with Ghost inflation!



Shapes of Non-gaussianities $B(1, x_2, x_3)x_2^2x_3^2$.
Left panel: quadratic dispersion relation. Right panel: linear dispersion relation.

Non-gaussianities

$$f_{NL}^{\text{Ghost, q.d.r.}} \simeq \frac{0.1}{\sqrt{\alpha}} = 10 \times \left(\frac{10^{-4}}{\alpha}\right)^{1/2} , \quad f_{NL}^{\text{equil, l.d.r}} \simeq \frac{0.07}{\delta^2} = 10 \times \left(\frac{0.02}{\epsilon}\right) .$$

Planck data: $f_{NL}^{\text{Ghost}} = -23 \pm 88\,, \qquad f_{NL}^{\text{equil}} = -42 \pm 75.$

Summary

- We propose an UV-complete Inflationary theory in the context of khronometric gravity (Inspired by Horava-Lifshitz theory). If HL-gravity is indeed renormalizable, then it is consistent and fully UV-complete inflationary theory.

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- We propose an UV-complete Inflationary theory in the context of khronometric gravity (Inspired by Horava-Lifshitz theory). If HL-gravity is indeed renormalizable, then it is consistent and fully UV-complete inflationary theory.
- At the Inflation energies the theory behaves as the Ghost inflation and its Tilted extension.

OUTLOOK:

What if $u_\mu \neq (1,0,0,0)$?

Thank you for your attention!