Technically natural dark energy from Lorentz breaking

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74% Dark Energy
22% Dark Matter
4% Atoms

PPC2011, CERN
“Dark energy is not only terribly important for astronomy, it’s the central problem in physics. It’s been the bone in our throats for a long time.”

Steven Weinberg
Dark energy missions

- SDSS
- Planck
- DES
- Euclid
- JEDI
- HETDEX
- SNAP
- WFIRST
Theoretical problems

Cosmological constant $\rho_\Lambda, \text{obs} \sim (10^{-3}\text{eV})^4$

- loop corrections

\[ \rho_\Lambda, \text{theor} \sim (M_{Pl})^4 \sim (10^{28}\text{eV})^4 \]
or \[ (M_{SUSY})^4 \sim (10^{12}\text{eV})^4 \]

- phase transitions in the early Universe

\[ \rho_\Lambda, \text{theor} \sim (M_{EW})^4 \sim (10^{11}\text{eV})^4 \]
\[ \text{or} \quad (M_{QCD})^4 \sim (10^{8}\text{eV})^4 \]
Theoretical problems

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Landscape + anthropic principle ???
Adding dynamics

Assume that CC is somehow set to zero

Dynamical dark energy (quintessence, K-essence, tracking DE, modified gravity, ...)

Requirements:

• (technically) natural
• predictive
• UV complete / valid up to high energies
Fine-tuning versus technical naturalness

\[ \mathcal{L}_{Q-ess} = \frac{(\partial_\mu \phi)^2}{2} - \frac{m^2 \phi^2}{2} \]

for DE \( m \lesssim H_0 \) present Hubble rate

But \( \delta m^2 = \cdots \sim gM^2 \)
Fine-tuning versus technical naturalness

\[ \mathcal{L}_{Q-ess} = \frac{(\partial_{\mu}\phi)^2}{2} - \frac{m^2\phi^2}{2} \]

for DE \( m \lesssim H_0 \)

But \( \delta m^2 = \cdots \sim gM^2 \)

\textbf{NB.} Would not be a problem if \( m = 0 \) corresponds to a new symmetry (example: electron mass in SM)

\[ \delta m^2 \propto gm^2 \]

The hierarchy between \( m \) and \( M \) is \textit{technically natural}
Pseudo-Goldstone DE?

- small mass protected by the shift symmetry
  \[ \phi \mapsto \phi + \text{const} \]
  \[ m \ll H_0 \]

- but vacuum expectation value \[ \gg M_P \]

- weak predictive power

  \[ m \ll H_0 \] indistinguishable from CC
DE with derivative interactions

\[ \mathcal{L}_{K-ess} = K((\partial_\mu \phi)^2) = \frac{(\partial_\mu \phi)^2}{2} + \frac{(\partial_\mu \phi)^4}{2\Lambda^2} + \ldots \]

\[ \propto \frac{E^2}{\Lambda^2} \]

at \( E > \Lambda \) the system enters into strong coupling

\[ \Lambda \sim (\rho_{\Lambda, obs})^{1/4} \]

low cutoff
Can we do better?
Reasons to consider Lorentz violation in gravity

• Infrared modifications (e.g. massive gravity, ghost condensation, Einstein-aether)

• Approaches to quantum gravity (*Horava, 2009*)

• Interesting on its own right (what if ...)
Effective description of LV

preferred time = foliation of the manifold by space-like surfaces

introduce a field $\sigma(x, t)$ to parametrize the foliation surfaces

choosing the gauge $t = \sigma$ sets global time

KHRONON
Effective description of LV

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introduce a field $\sigma(x, t)$ to parametrize the foliation surfaces

choosing the gauge $t = \sigma$ sets global time

NB. Foliation preserving transformations

symmetry $\sigma \mapsto \tilde{\sigma} = f(\sigma)$
Constructing KHRONO-METRIC action

- Invariant object -- unit normal to the foliation surfaces:
  \[ u_\mu = \frac{\partial_\mu \sigma}{\sqrt{(\partial \sigma)^2}} \]

- low-energy EFT = Lagrangian with lowest number of derivatives
  \[ S_{kh-m} = -\frac{M_P^2}{2} \int d^4x \sqrt{-g} \left[ (4)R + \beta \nabla_\mu u_\nu \nabla^\nu u^\mu \right. \]
  \[ \left. + \lambda' (\nabla_\mu u^\mu)^2 + \alpha u^\mu u^\nu \nabla_\mu u_\rho \nabla^\nu u^\rho \right] \]
  cf. with Einstein-aether theory (Jacobson & Mattingly, 2001): a LV theory of a unit vector

- matter sector is Lorentz invariant at low energies
  direct coupling of the khronon to SM fields is forbidden
Observational constraints

Exploit known bounds for Einstein - aether (beware: in our case there are no helicity-1 modes)

- Absence of gravitational Cherenkov losses by UHECR

\[ c_g, c_\sigma \geq 1 \]

- Newton law vs Friedman equation

\[ G_N = \frac{1}{8\pi M_P^2(1 - \alpha/2)} \neq G_{cosm} = \frac{1}{8\pi M_P^2(1 + \beta/2 + 3\lambda'/2)} \]

\[ H^2 = \frac{8\pi}{3} G_{cosm} \rho \]

BBN bound:

\[ |G_{cosm}/G_N - 1| \leq 0.13 \]

\[ \alpha, \beta, \lambda' \lesssim 0.1 \]
PPN parameters

Spherically symmetric solutions the same as in Einstein-aether

all PPN parameters the same as in GR except $\alpha_1^{PPN}$, $\alpha_2^{PPN}$

preferred frame effects
Definition of $\alpha_{1,2}^{PPN}$

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

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

Solar system bounds:

\[ |\alpha_1^{PPN}| \lesssim 10^{-4} \ , \quad |\alpha_2^{PPN}| \lesssim 10^{-7} \]
\[ \alpha_1^{PPN} = -4(\alpha - 2\beta) \]
\[ \alpha_2^{PPN} = \frac{(\alpha - 2\beta)(\alpha - \lambda' - 3\beta)}{2(\lambda' + \beta)} \]

- no cancellations

\[ \alpha, \beta, \lambda' \lesssim 10^{-7} \div 10^{-6} \]

- vanish if \( \alpha = 2\beta \) (hidden symmetry ?)

- \( \alpha_2^{PPN} \) vanishes when \( \beta = 0, \lambda' = \alpha \) \( (c_g = c_\sigma = 1) \)

\[ \alpha, \beta, \lambda' \lesssim 10^{-4} \]
Cutoff scale and UV completion

Khrono-metric model -- a theory with derivative interactions suppressed by

\[ M_\alpha \equiv M_P \sqrt{\alpha} \sim 10^{15} \div 10^{17} \text{GeV} \]

which sets the UV cutoff

Above \( M_\alpha \) can be embedded into Horava gravity

*Blas, Pujolas, S.S., 2010*
Back to Dark Energy
Consider a scalar $\Theta$ with shift symmetry $\Theta \mapsto \Theta + \text{const}$ (e.g. Goldstone boson of a broken global symmetry).

In general it will have dim 2 coupling to the khronon:

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

stable under radiative corrections: breaks $\Theta \mapsto -\Theta$

Small $\mu$ is technically natural!

Has high UV cutoff $M_\alpha \equiv M_{Pl} \sqrt{\alpha}$

(and can be UV completed by Horava gravity)
Homogeneous cosmology

\[ ds^2 = dt^2 - a^2(t)dx^2, \quad \sigma = t, \quad \Theta = \Theta(t) \]

\[ \frac{d}{dt}(a^3 \dot{\Theta} + \mu^2 a^3) = 0 \]

\[ H^2 = \frac{8\pi G_{\text{cosm}}}{3} \left( \frac{\dot{\Theta}^2}{2} + \rho_{\text{mat}} \right) \]

\[ \rho_{\Theta} \rightarrow \frac{\mu^4}{2} \]

\[ w = -1 \]
Homogeneous cosmology

\[ ds^2 = dt^2 - a^2(t)dx^2 , \quad \sigma = t , \quad \Theta = \Theta(t) \]

\[ \frac{d}{dt}(a^3 \dot{\Theta} + \mu^2 a^3) = 0 \]

\[ \dot{\Theta} = -\mu^2 + \frac{C}{a^3} \]

\[ H^2 = \frac{8\pi G_{\text{cosm}}}{3} \left( \frac{\dot{\Theta}^2}{2} + \rho_{\text{mat}} \right) \]

\[ \rho \Theta \rightarrow \mu^4 / 2 \]

\[ w = -1 \]

**NB.** If and only if \( \rho_{\text{mat}} = 0 \) there is **Minkowski solution** with \( \dot{\Theta} = 0 \). But it is **unstable**
Perturbations of $\sigma - \Theta$ system

- For short waves: two decoupled relativistic excitations
  $\omega \propto k$

- Minkowski background is unstable at long distances
  $$L > \frac{2\pi}{k_c}$$

  $k_c \equiv \mu^2 / M \alpha \sim H_0 / \sqrt{\alpha}$

- de Sitter solution is stable at all scales;
  at $k < k_c$ there is a slow mode
  $\omega \propto k^2 / k_c$

  expect enhancement of structure formation
  at large scales
Cosmological perturbations in ΘCDM vs ΛCDM

\[ ds^2 = a^2(t)[(1 + 2\phi)dt^2 - (1 - 2\psi)\delta_{ij}dx^i dx^j] \]

- Solve linear equations numerically with
  \[ \Omega_\gamma = 5 \cdot 10^{-5}, \quad \Omega_{cm} = 0.25, \quad \Omega_{DE} = 0.75 \]
  (assuming Lorentz-invariant dark matter)

- Find \( \phi, \psi, \delta \equiv \frac{\delta \rho_{cm}}{\rho_{cm}} \)

- Plot \( \Delta_\phi(k) = \frac{P_\phi(k)}{P_{\phi_{\Lambda CD M}}(k)} - 1 \)
  \( \Delta_\delta(k) = \frac{P_\delta(k)}{P_{\delta_{\Lambda CD M}}(k)} - 1 \)
Cosmological perturbations in $\Theta CDM$ vs $\Lambda CDM$

Newton potential:
$$\Delta \phi(k) = \frac{P_\phi(k)}{P_{\phi_{\Lambda CDM}}(k)} - 1$$

Matter density contrast:
$$\Delta \delta(k) = \frac{P_\delta(k)}{P_{\delta_{\Lambda CDM}}(k)} - 1$$

Peaks \( \sim \sqrt{\alpha} \) at \( k_{1/2} = \sqrt{k_c H_0} \) + logarithmic tails
Anisotropic stress in $\Theta$CDM

$$(\phi - \psi)/\phi, k (h \text{ Mpc}^{-1})$$

$$(\alpha, \beta, \lambda')$$

$$(2,1,1)^*10^{-2}, (2,1,1)^*10^{-3}, (2,1,1)^*10^{-4}$$
Time dependence of cosmological perturbations

\[ k/H_0 = 4 \]

\[ k/H_0 = 15 \]

\[ \alpha = 0.02 , \quad \beta = 0.01 , \quad \lambda' = 0.01 \]
CONCLUSIONS

- Breaking of Lorentz invariance + scalar with shift symmetry = technically natural dark energy (ΘCDM) with high cutoff

- Can be embedded in UV into Horava gravity

- Predictions of ΘCDM: $w = -1$, growth of structure is enhanced and effective anisotropic stress appears at scales of a few hundred Mpc

OUTLOOK

- Detailed simulations with comparison against current and future data

- Consequences of possible Lorentz violation in the dark matter sector