Technically natural dark energy from Lorentz breaking

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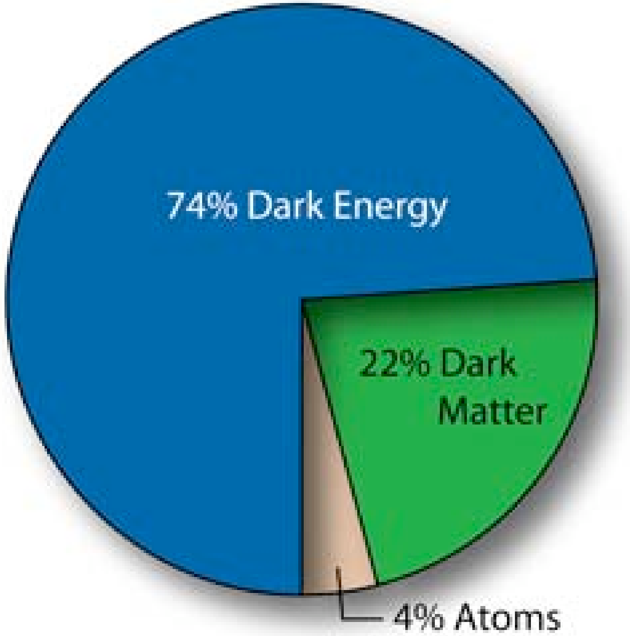
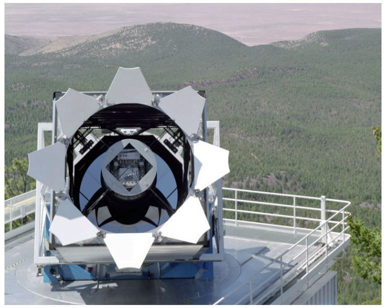
in collaboration with Diego Blas



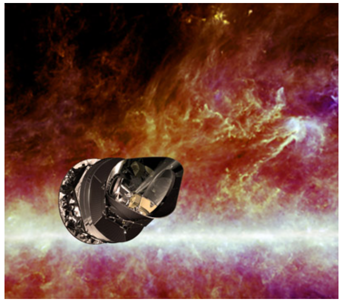
“Dark energy is not only terribly important for astronomy, it’s the central problem in physics. It’s been the bone in our throats for a long time.”

Steven Weinberg

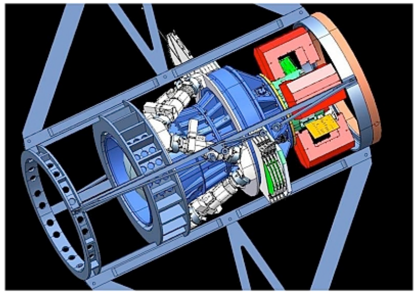
Dark energy missions



SDSS



Planck

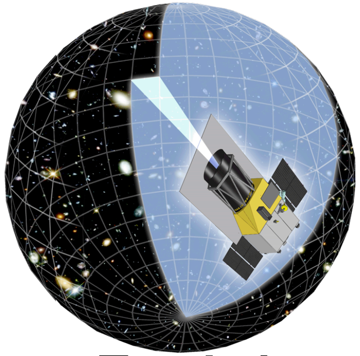


DES

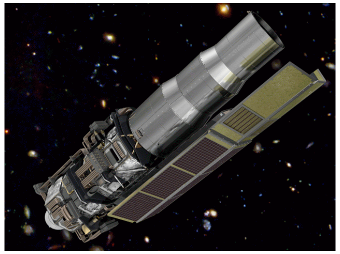
LSST

Large Synoptic Survey Telescope

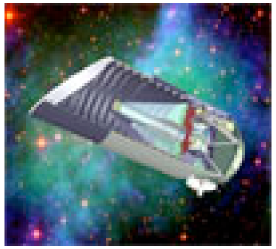
HETDEX



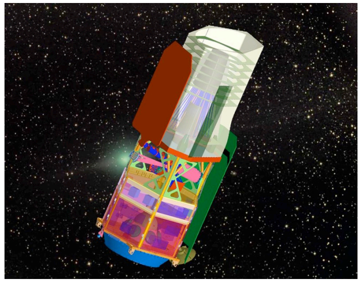
Euclid



JEDI



SNAP



WFIRST

Theoretical problems

Cosmological constant ➡
- fine-tuning

Dynamical dark energy (assume that CC is somehow set to zero) ➡
- fine-tuning
- low cutoff
- lack of predictive power

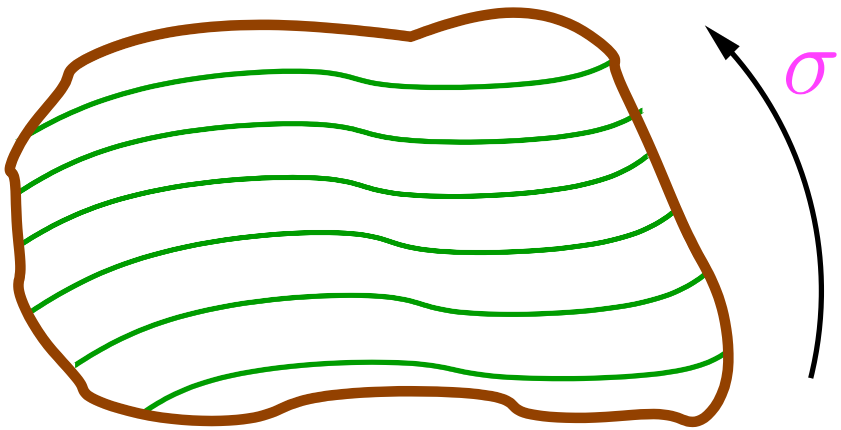
Can we do better ?

Reasons to consider Lorentz violation in gravity

- Infrared modifications (e.g. massive gravity)
- 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 $\sigma(\mathbf{x}, t)$ to parametrize the foliation surfaces

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

KHRONON

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 limit = Lagrangian with lowest number of derivatives

$$S_{kh\text{-}m} = -\frac{M_P^2}{2}\int d^4x\sqrt{-g}\Big[{}^{(4)}R + \beta\nabla_\mu u_\nu \nabla^\nu u^\mu + \lambda'(\nabla_\mu u^\mu)^2 + \alpha u^\mu u^\nu \nabla_\mu u_\rho \nabla_\nu u^\rho\Big]$$

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

ΘCDM

Consider a scalar Θ with shift symmetry $\Theta \mapsto \Theta + const$
(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 μ is technically natural !

Has high UV cutoff $M_\alpha \equiv M_{Pl}\sqrt{\alpha}$
(and can be UV completed by Horava gravity)

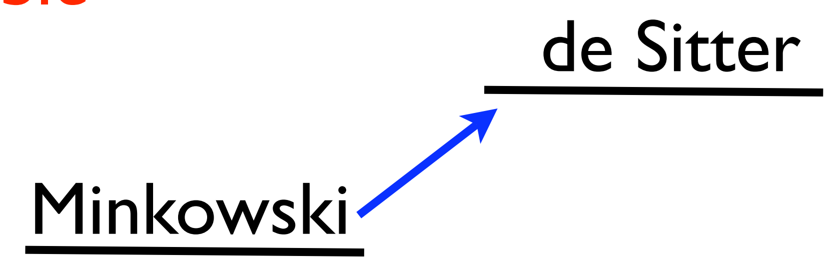
Homogeneous cosmology

$$ds^2 = dt^2 - a^2(t)dx^2 \,, \qquad \Theta = \Theta(t)$$

$$\frac{d}{dt}\left(a^3\dot{\Theta} + \mu^2 a^3\right) = 0 \quad \Rightarrow \quad \dot{\Theta} = -\mu^2 + \frac{C}{a^3}$$

$$H^2 = \frac{8\pi G_{cosm}}{3}\left(\frac{\dot{\Theta}^2}{2} + \rho_{mat}\right) \quad \Rightarrow \quad \rho_\Theta \to \mu^4/2, \quad w = -1$$

NB. If and only if $\rho_{mat} = 0$ 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

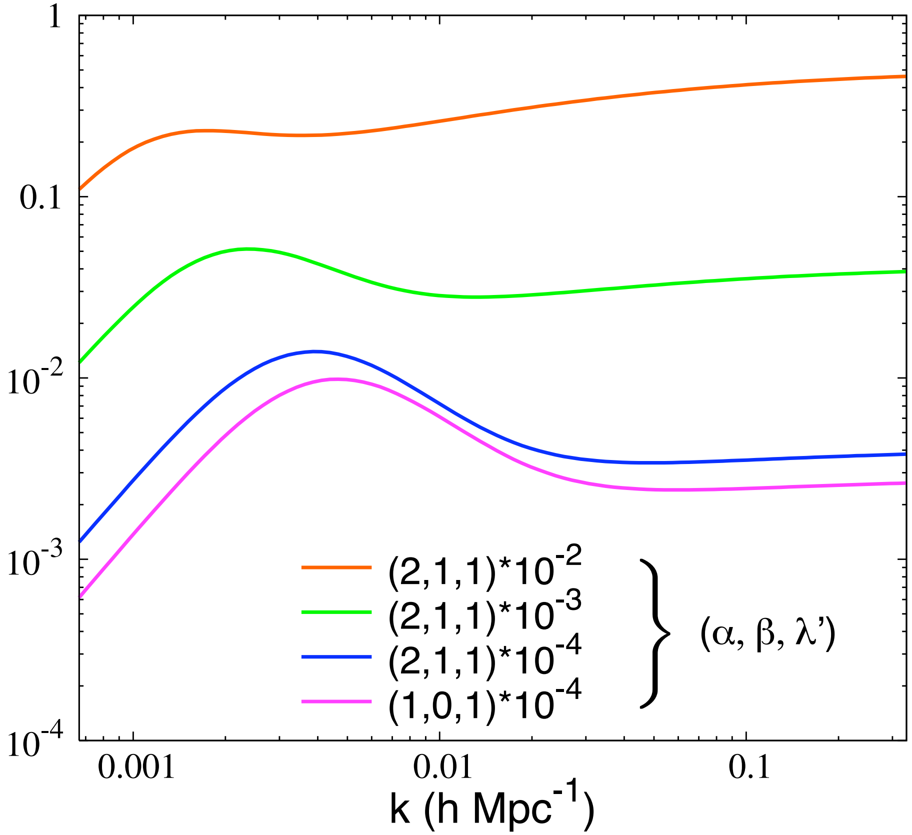
$$\omega \propto k^2/k_c$$

➡ expect enhancement of structure formation at large scales

Cosmological perturbations in ΘCDM vs ΛCDM

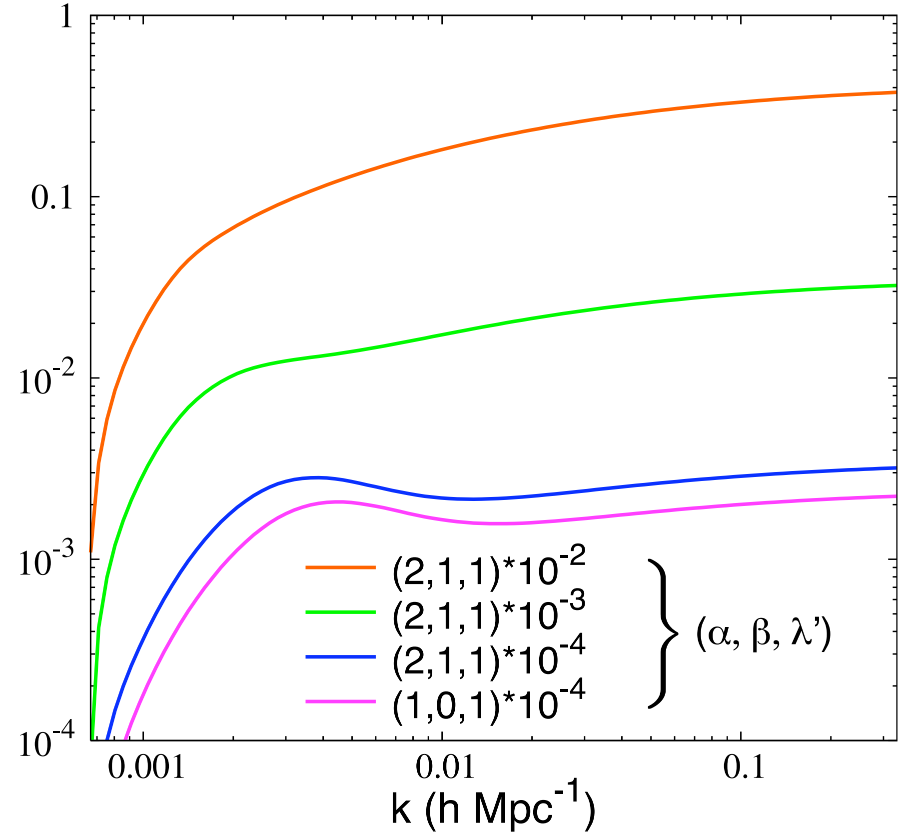
Newton potential:

$$\Delta_\phi(k) = \frac{P_\phi(k)}{P_{\phi_{\Lambda CDM}}(k)} - 1$$



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

CONCLUSIONS

- Breaking of Lorentz invariance + scalar with shift symmetry = technically natural dark energy (ΘCDM) with high cutoff
- 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
- Bounds on possible Lorentz violation in the dark matter sector