Technically natural dark energy from Lorentz breaking

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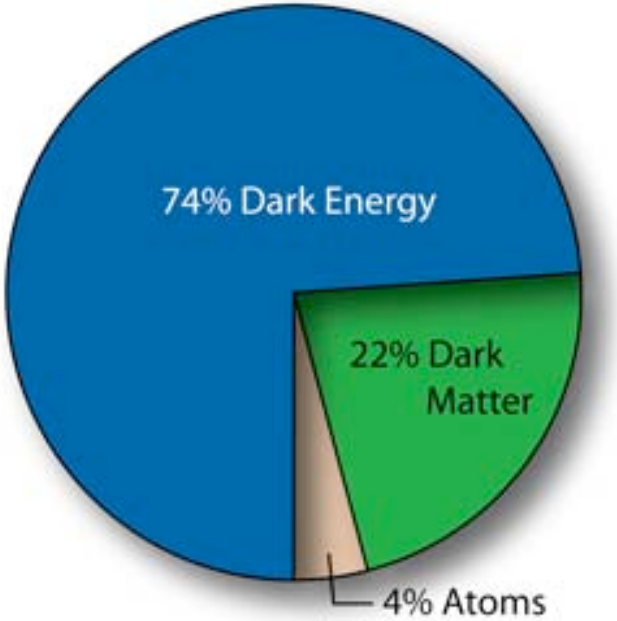
in collaboration with Diego Blas

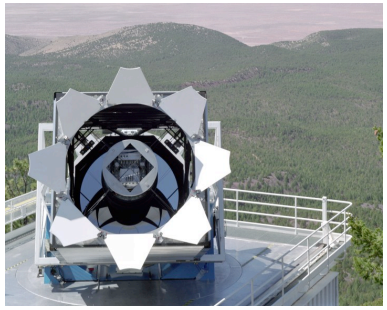


PPC2011, CERN

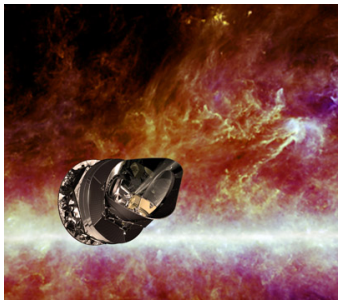
"Dark energy is not only terribly important for astronomy, it's the central problem in physics. It's been the bone in our throats for a long time."

Steven Weinberg

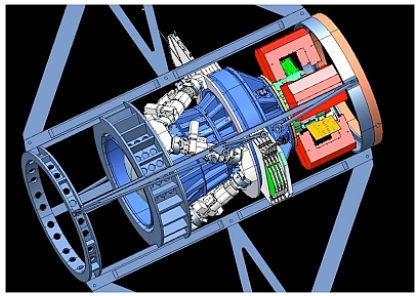
Dark energy missions



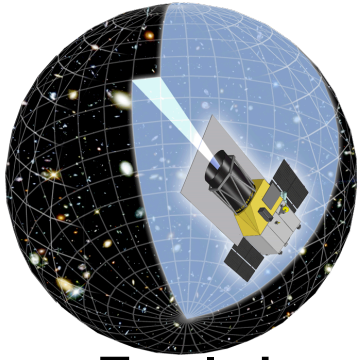
SDSS



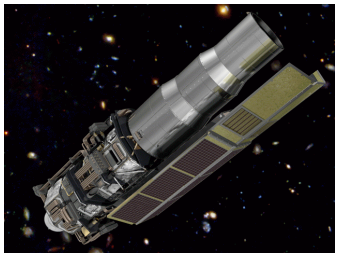
Planck



DES



Euclid



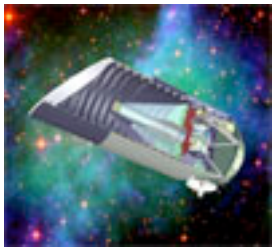
JEDI

LSST

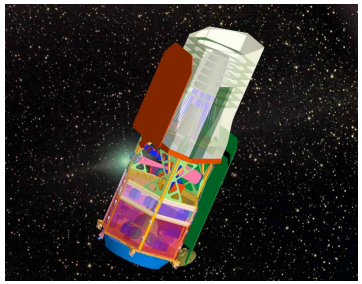
Large Synoptic Survey Telescope

HETDEX

SOUTH POLE TELESCOPE



SNAP



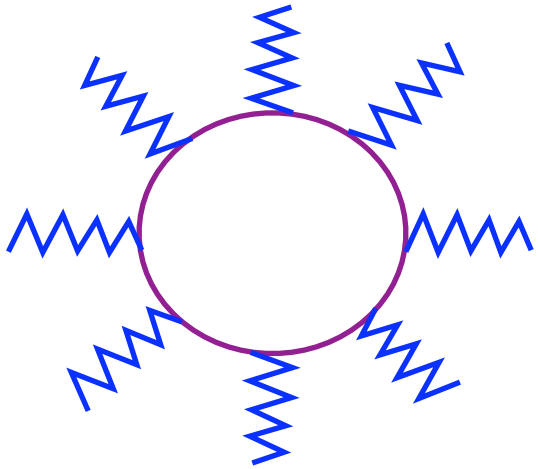
WFIRST

Theoretical problems

Cosmological constant ➡ fine-tuning

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

- loop corrections



➡ $\rho_{\Lambda,\,theor} \sim (M_{Pl})^4 \sim (10^{28}\mathrm{eV})^4$

or $(M_{SUSY})^4 \sim (10^{12}\mathrm{eV})^4$

- phase transitions in the early Universe

$\rho_{\Lambda,\,theor} \sim (M_{EW})^4 \sim (10^{11}\mathrm{eV})^4$ or $(M_{QCD})^4 \sim (10^{8}\mathrm{eV})^4$

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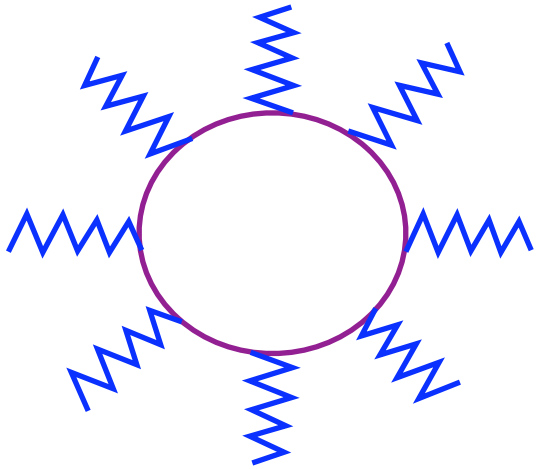

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Landscape + anthropic principle ???

Adding dynamics

Assume that CC is somehow set to zero

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

Requirements:

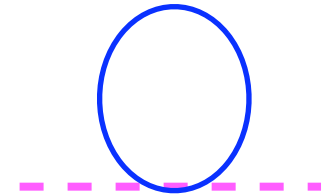
- (technically) natural
- predictive
- UV complete / valid up to high energies

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 $\delta m^2 =$  $\sim g M^2$

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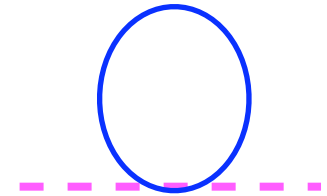
But $\delta m^2 =$  $\sim g M^2$

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

$$\boxed{\delta m^2 \propto g m^2}$$

The hierarchy between m and M is technically natural

Pseudo-Goldstone DE ?

- small mass protected by the shift symmetry +

$$\phi \mapsto \phi + const$$

- but vacuum expectation value $\gg M_P$ -
- weak predictive power -

  if $m \ll H_0$ indistinguishable from CC

DE with derivative interactions

$$\mathcal{L}_{K-ess} = K\left((\partial_\mu \phi)^2\right) = \frac{(\partial_\mu \phi)^2}{2} + \frac{(\partial_\mu \phi)^4}{2\Lambda^2} + \dots$$

$$\propto \frac{E^2}{\Lambda^2}$$

at $E > \Lambda$ the system enters into strong coupling

$\Lambda \sim (\rho_{\Lambda,\ obs})^{1/4}$ low cutoff

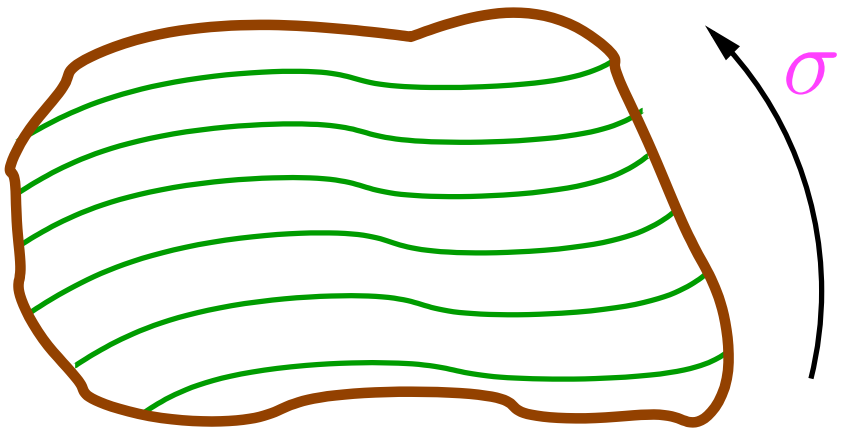
Can we do better ?

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 $\sigma(\mathbf{x}, t)$
to parametrize
the foliation
surfaces

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

KHRONON

Effective description of LV

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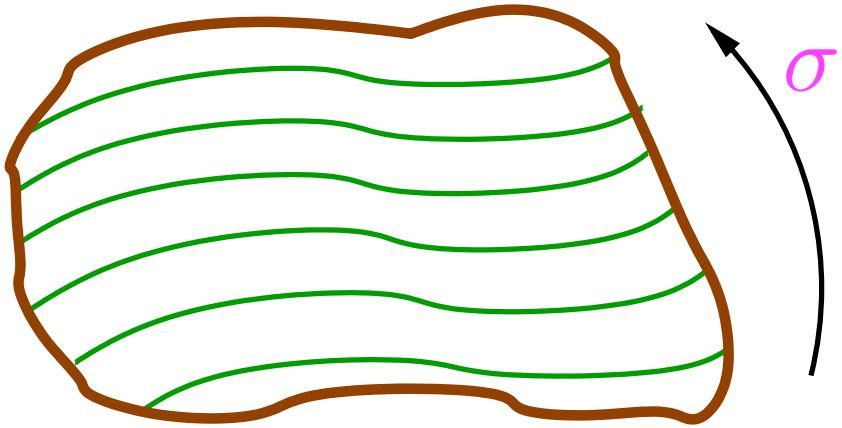

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KHRONON

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 EFT = 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

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

$$c_g \ , \ c_\sigma \geq 1 \quad \Rightarrow \quad \boxed{\beta \geq 0 \ , \quad \frac{\lambda' + \beta}{\alpha} \geq 1}$$

- 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:

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

$$\Rightarrow \quad \boxed{\alpha \ , \ \beta \ , \ \lambda' \lesssim 0.1}$$

PPN parameters

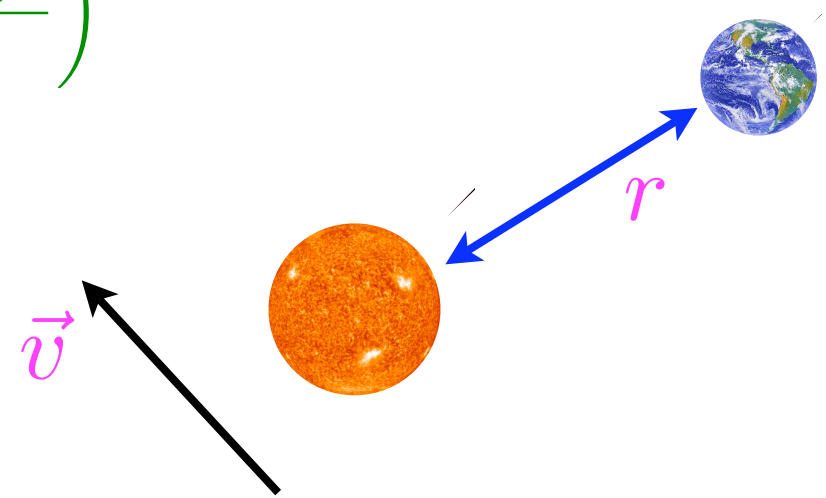
Spherically symmetric solutions the same as in Einstein-aether

⇒ all PPN parameters the same as in GR except $\underbrace{\alpha_1^{PPN}, \alpha_2^{PPN}}_{\text{preferred frame effects}}$

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:

$$|\alpha_1^{PPN}| \lesssim 10^{-4}\ , \qquad |\alpha_2^{PPN}| \lesssim 10^{-7}$$

$$\alpha_1^{PPN} = -4(\alpha - 2\beta)$$

$$\alpha_2^{PPN} = \frac{(\alpha - 2\beta)(\alpha - \lambda' - 3\beta)}{2(\lambda' + \beta)}$$

- no cancellations

  ➡ $\alpha\ ,\ \beta\ ,\ \lambda' \lesssim 10^{-7} \div 10^{-6}$

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

- α_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

$$M_\alpha \equiv M_P \sqrt{\alpha} \sim 10^{15} \div 10^{17} \mathrm{GeV}$$

which sets the UV cutoff

Above M_α can be embedded into Horava gravity

Blas, Pujolas, S.S., 2010

Back to Dark Energy

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

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

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

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

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NB. If and only if $\rho_{mat} = 0$ there is Minkowski solution with $\dot{\Theta} = 0$. But it is unstable

de Sitter

Minkowski

Perturbations of $\sigma - \Theta$ system

- For short waves: two decoupled relativistic excitations

$$\omega \propto k$$

- Minkowski background is unstable at long distances

$$L > \frac{2\pi}{k_c}$$

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

- 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 ϕ , ψ , $\delta \equiv \dfrac{\delta\rho_{cm}}{\rho_{cm}}$

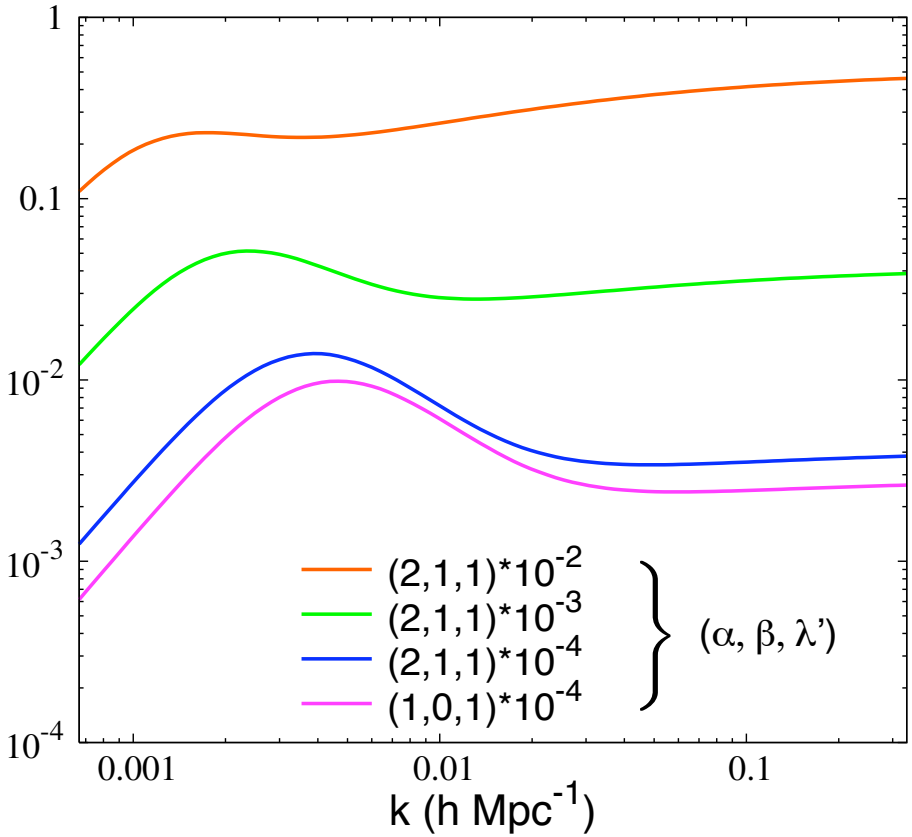
- Plot $\Delta_\phi(k) = \dfrac{P_\phi(k)}{P_{\phi_{\Lambda CDM}}(k)} - 1$

$$\Delta_\delta(k) = \frac{P_\delta(k)}{P_{\delta_{\Lambda CDM}}(k)} - 1$$

Cosmological perturbations in ΘCDM vs ΛCDM

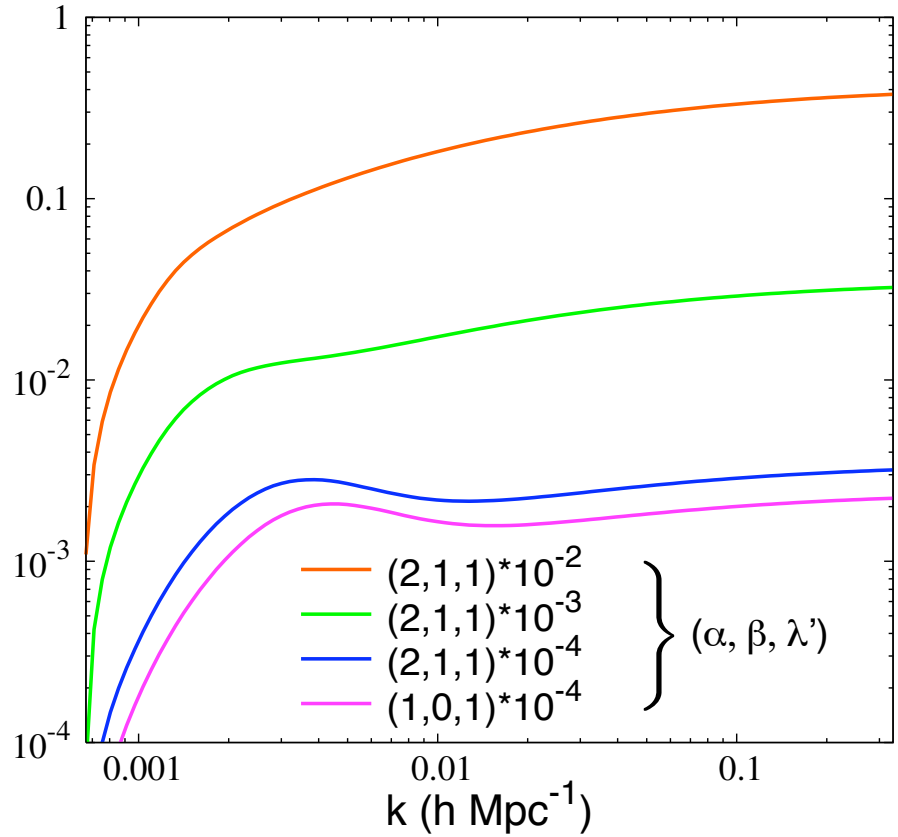
Newton potential:

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



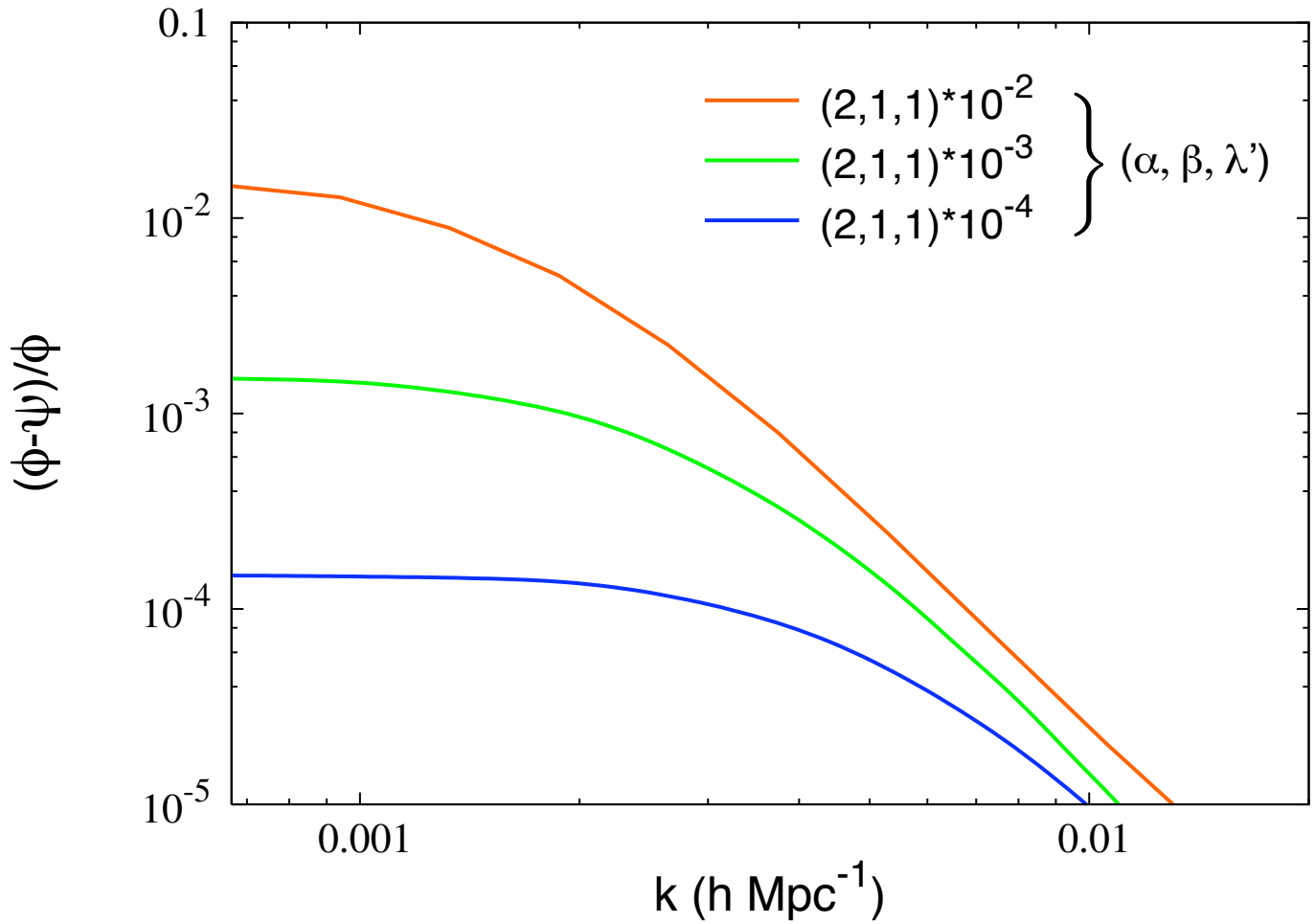
Matter density contrast:

$$\Delta_\delta(k) = \frac{P_\delta(k)}{P_{\delta_{\Lambda CDM}}(k)} - 1$$



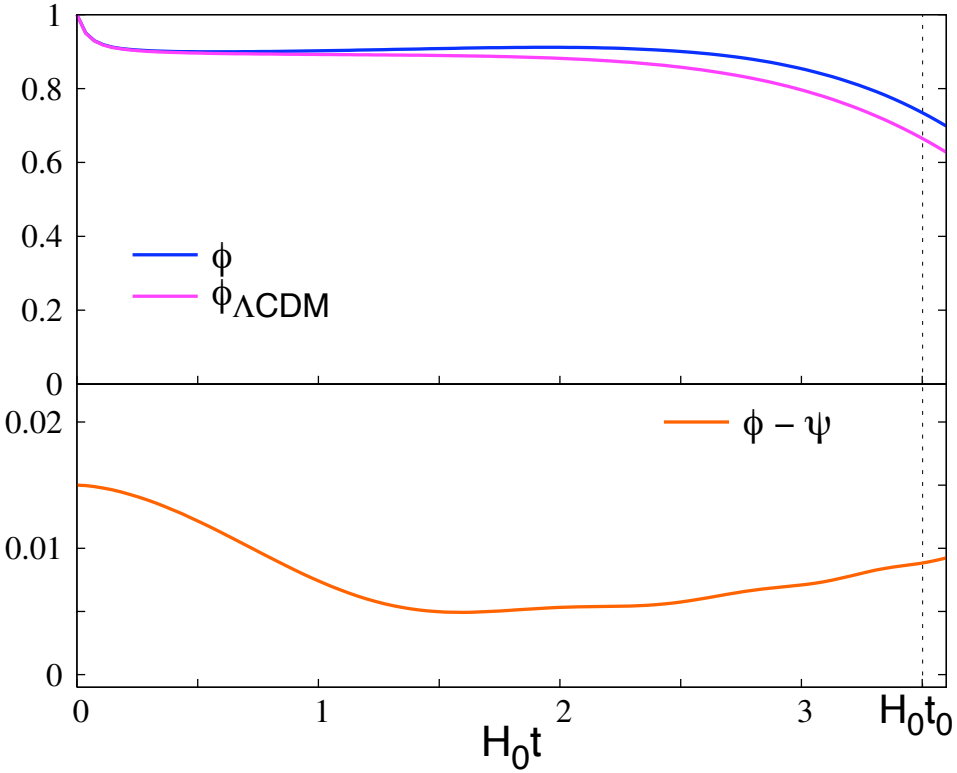
Peaks $\sim \sqrt{\alpha}$ at $k_{1/2} = \sqrt{k_c H_0}$ + logarithmic tails

Anisotropic stress in ΘCDM

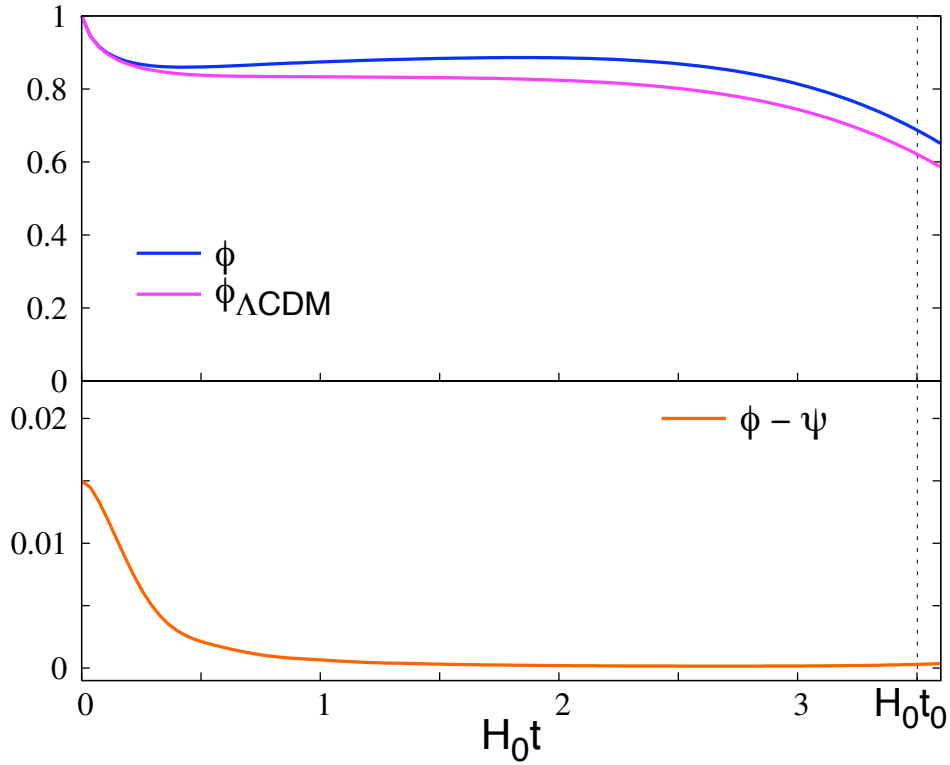


Time dependence of cosmological perturbations

$k/H_0 = 4$



$k/H_0 = 15$



$$\alpha = 0.02 \ , \quad \beta = 0.01 \ , \quad \lambda' = 0.01$$

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