Lorentz violation in the Dark Sector: Theory and Phenomenology

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The key principle tacitly assumed:

Lorentz invariance

checked with high accuracy for visible matter

What if it is broken in the dark sector ?

Is this breaking useful for anything ?

Can we *observationally* probe the validity of LI in the dark sector ?

Plan

- Phenomenological description of LV in gravity
- A simple (and technically natural) model of dark energy with LV: cosmological signatures
- Deviation from LI in dark matter: cosmological signatures

Theoretical motivations for violation of LI

- May be a consequence of quantum gravity (emergent geometry, Horava-Lifshitz gravity, ...)
- Infrared modifications (e.g. massive gravity, ghost condensation, ...)

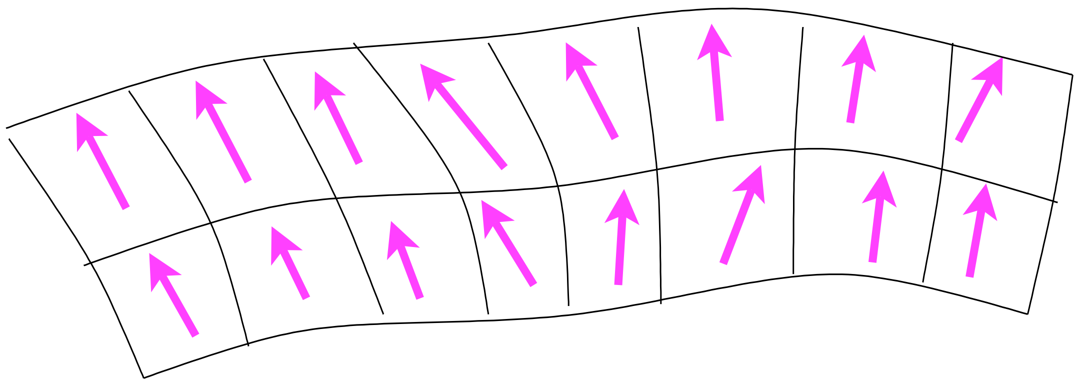
Important: violation of LI requires presence of new light degrees of freedom

⇒ LV propagates to all scales

Einstein-aether

Jacobson, Mattingly, 2000

There is a preferred frame at each point of the space-time set by a dynamical unit vector u^μ - aether



$$S = -\frac{M_P^2}{2}\int d^4x\sqrt{-g}\left[R + K^{\mu\nu}_{\sigma\rho}\nabla_\mu u^\sigma \nabla_\nu u^\rho + l(u_\mu u^\mu - 1)\right]$$

Lagrange multiplier: enforces unit norm

$$K^{\mu\nu}_{\sigma\rho} \equiv c_1 g^{\mu\nu} g_{\sigma\rho} + c_2 \delta^\mu_\sigma \delta^\nu_\rho + c_3 \delta^\mu_\rho \delta^\nu_\sigma + c_4 u^\mu u^\nu g_{\sigma\rho}$$

Variation: *khrono-metric* model

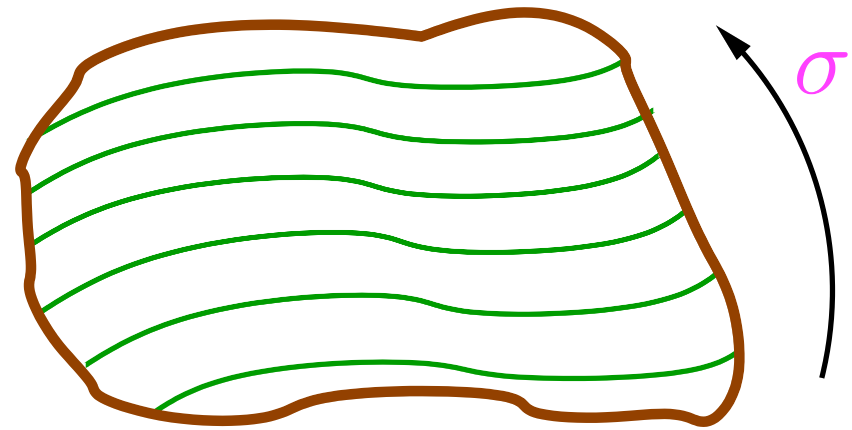
Blas, Pujolas, S.S., 2010

Aether restricted to be hypersurface-orthogonal:

$$u_\mu = \frac{\partial_\mu \sigma}{\sqrt{(\partial\sigma)^2}}$$

Scalar $\sigma(x)$ - *khronon* - defines preferred foliation of the space-time

⟺ preferred time



Number of couplings reduced:

$$\alpha = c_1 + c_4, \qquad \beta = c_1 + c_3, \qquad \lambda' = c_2$$

NB. Can be embedded into Horava-Lifshitz gravity (candidate for quantum gravity)

Constraints from the visible sector

- LI of the Standard Model

  ⇒ no direct coupling of aether to visible matter, interaction only through gravity

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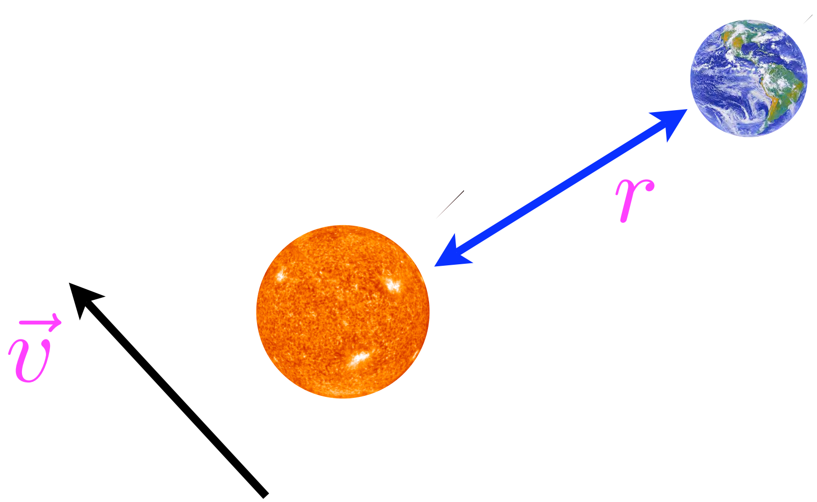

$$h_{00} = -2G_N \frac{m}{r}\left(1 - \frac{\alpha_2^{PPN}}{2}\frac{(x^i v^i)^2}{r^2}\right)$$

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

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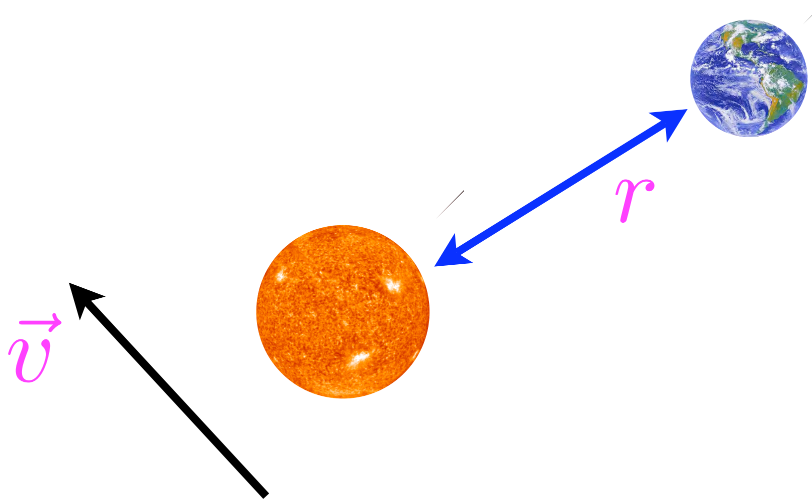

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observations: $|\alpha_1^{PPN}| \lesssim 10^{-4}\ , \qquad |\alpha_2^{PPN}| \lesssim 10^{-7}$

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

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

- no cancellations

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

- α_2^{PPN} vanishes when $\beta = 0$, $\lambda' = \alpha$

  ➡ $\alpha,\ \beta,\ \lambda' \lesssim 10^{-4}$

- both vanish if $\alpha = 2\beta$

  ➡ from gravitational wave emission and BBN

  $\alpha\ ,\ \beta\ ,\ \lambda' \lesssim 0.01$

LV 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 aether:

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

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

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

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

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

$$w = -1$$

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

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

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

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

- de Sitter solution is stable at all scales;
  at $k < k_c$ there is a slow mode

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

➡ clustering DE: 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 , $\delta \equiv \dfrac{\delta\rho_{cm}}{\rho_{cm}}$

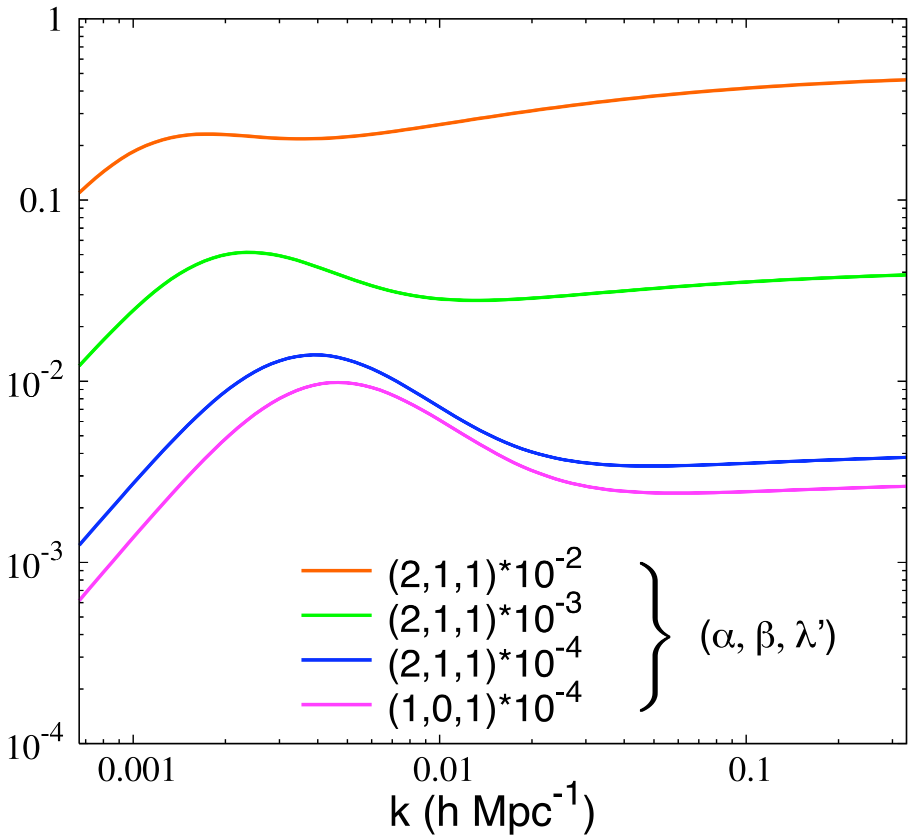
- Plot $\Delta_\phi(k) = \dfrac{P_\phi(k)}{P_{\phi_{\Lambda CDM}}(k)} - 1$

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

Cosmological perturbations in ΘCDM vs ΛCDM

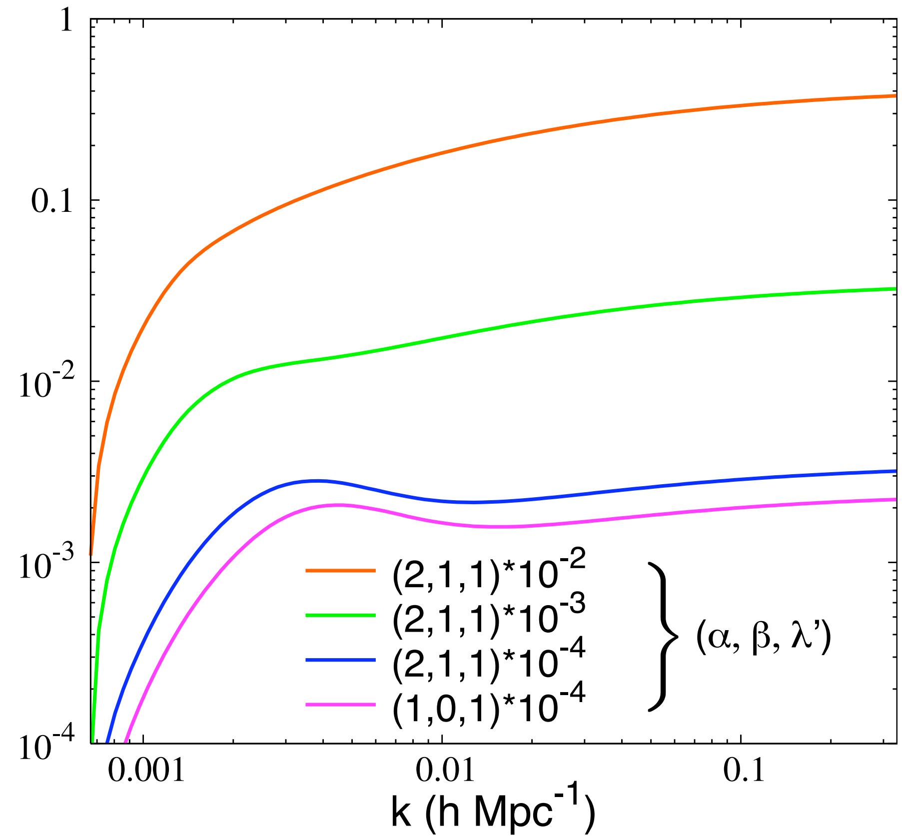
Newton potential:

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



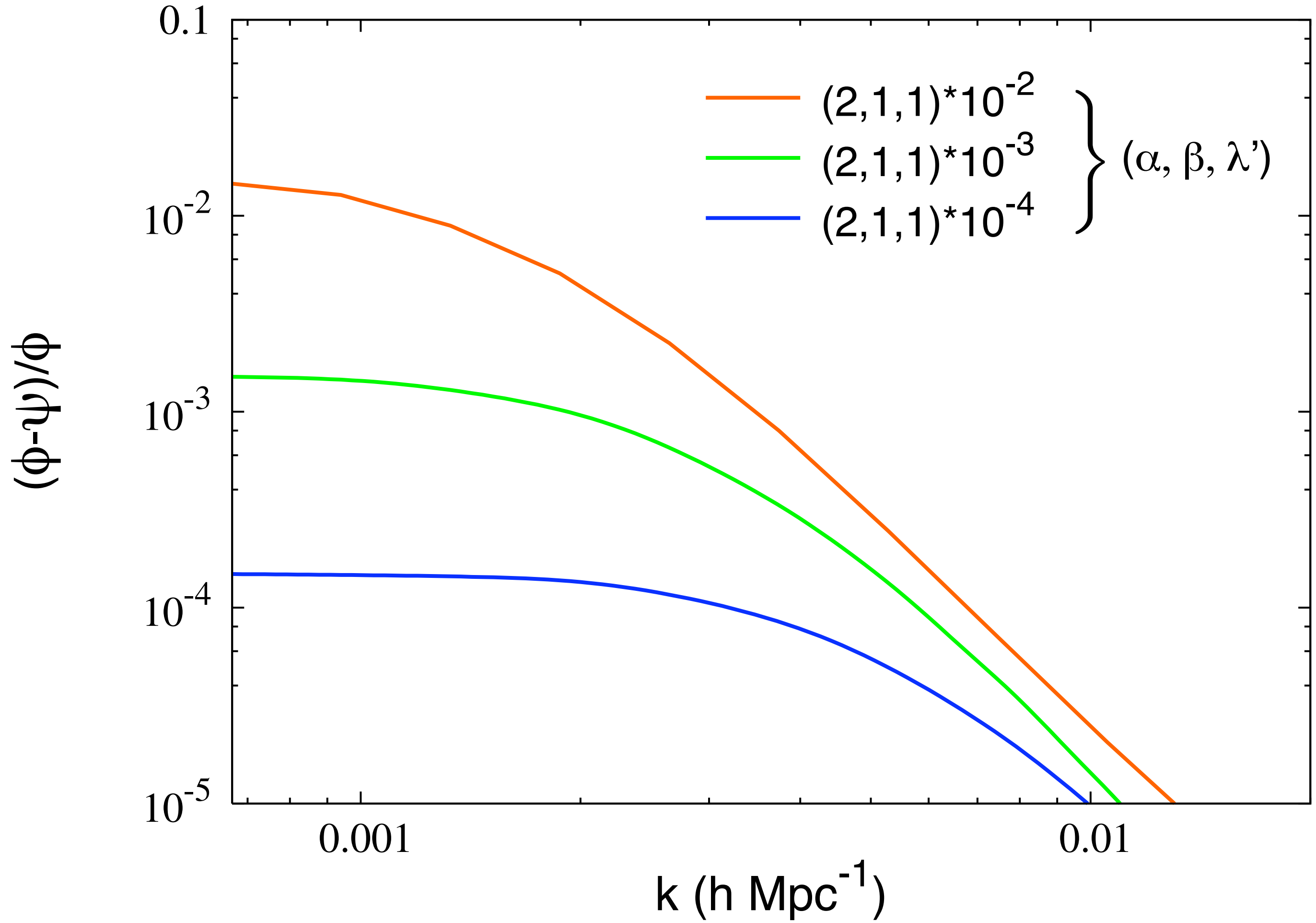
Matter density contrast:

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

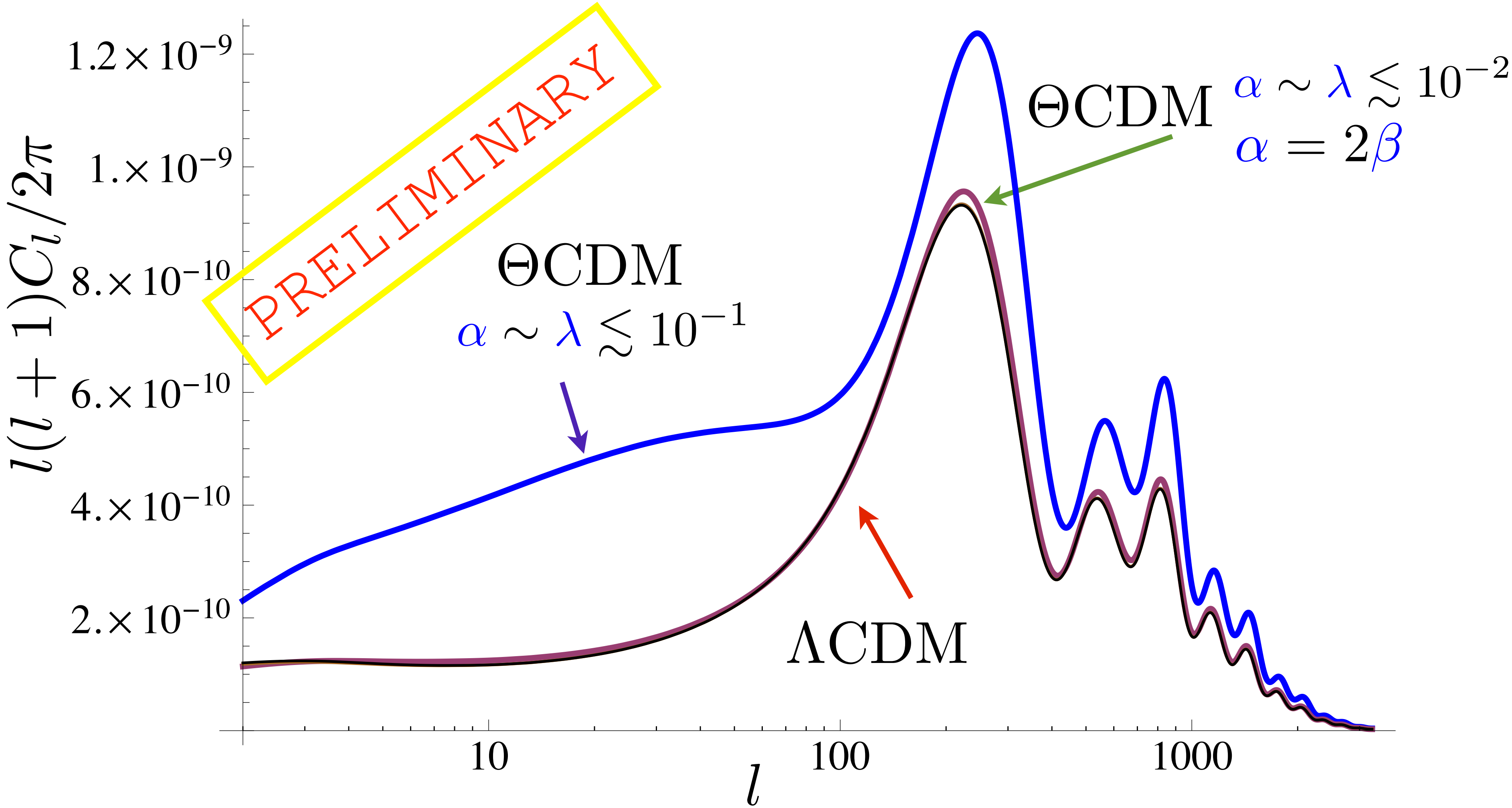


Peaks $\sim \sqrt{\alpha}$ at $k_{1/2} = \sqrt{k_c H_0}$ + logarithmic tails

Anisotropic stress in ΘCDM



Towards realistic simulation



http://class-code.net

LV DARK MATTER

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Yes, it is possible !

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Violation of LI ⇒ direct coupling to the aether

⇒ additional attraction between DM particles

⇔ violation of the equivalence principle

⇒ enhanced growth of structures

Generalized point particle action

$$S_{pp} = -m \int ds \quad \Longrightarrow \quad -m \int ds\, f(u_\mu v^\mu)$$

$$v^\mu = \frac{dx^\mu}{ds}$$

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v^μ ← $\dfrac{dx^\mu}{ds}$

Newtonian limit: v^i, u^i -- small, $g_{00} = 1 + 2\phi$

$$S = \int d^4x \left[M_P^2 \phi \Delta \phi + \frac{M_P^2 c_1}{2} u^i \Delta u^i \right] + \int d^4x\, \rho \left[\frac{(v^i)^2}{2} - \phi - Y \frac{(u^i - v^i)^2}{2} \right]$$

ρ ← DM density

Y ← $f'(1)$

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$$\frac{dx^\mu}{ds}$$

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DM density

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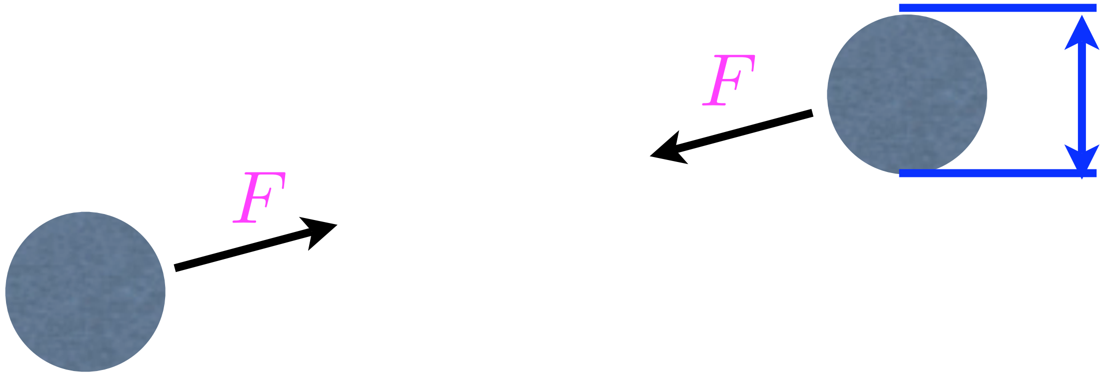
ρ: DM density

Y: $f'(1)$

- modified the inertial mass = violation of the equivalence principle
- effective potential for aether in matter $\quad m_{eff}^2 \sim \dfrac{Y\rho}{M_P^2 c_1}$



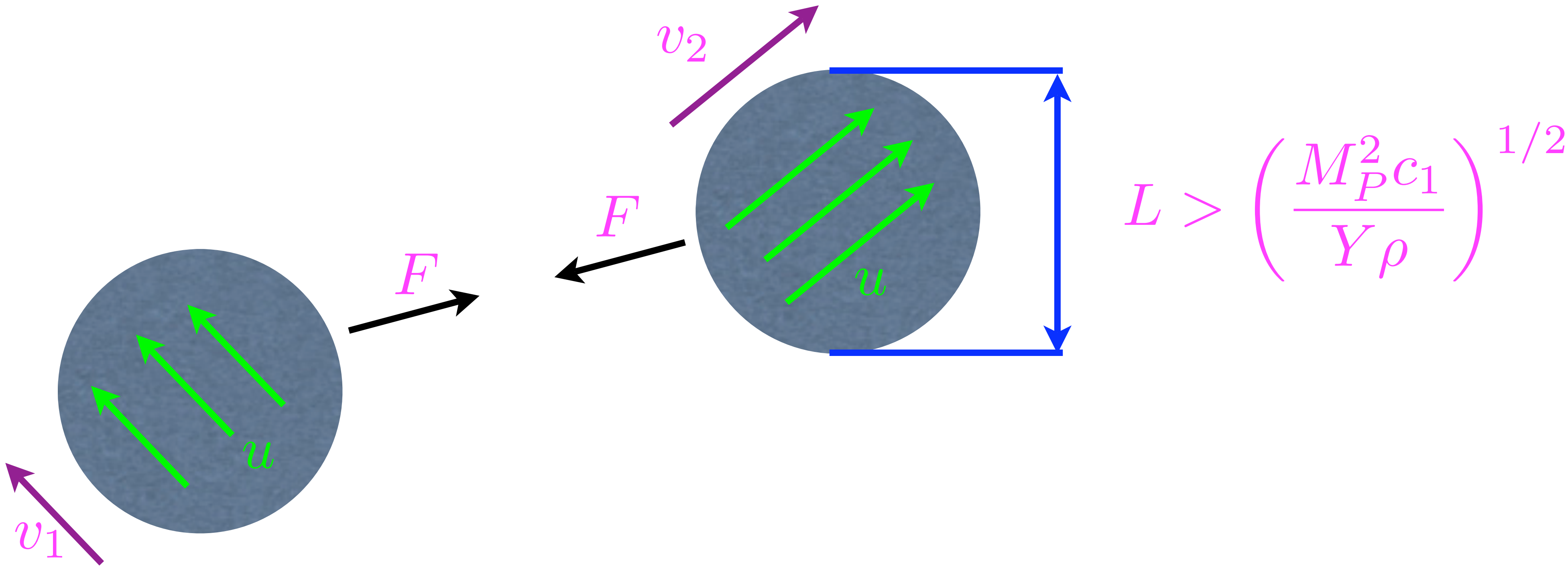
$$L < \left(\frac{M_P^2 c_1}{Y \rho} \right)^{1/2}$$

$$F = \frac{F_N}{(1 - Y)}$$

Accelerated Jeans instability

$$\delta \propto \tau^{\gamma}, \qquad \gamma = \frac{1}{6}\left[-1 + \sqrt{\frac{25 - Y}{1 - Y}} \right]$$

density contrast



$F = F_N$

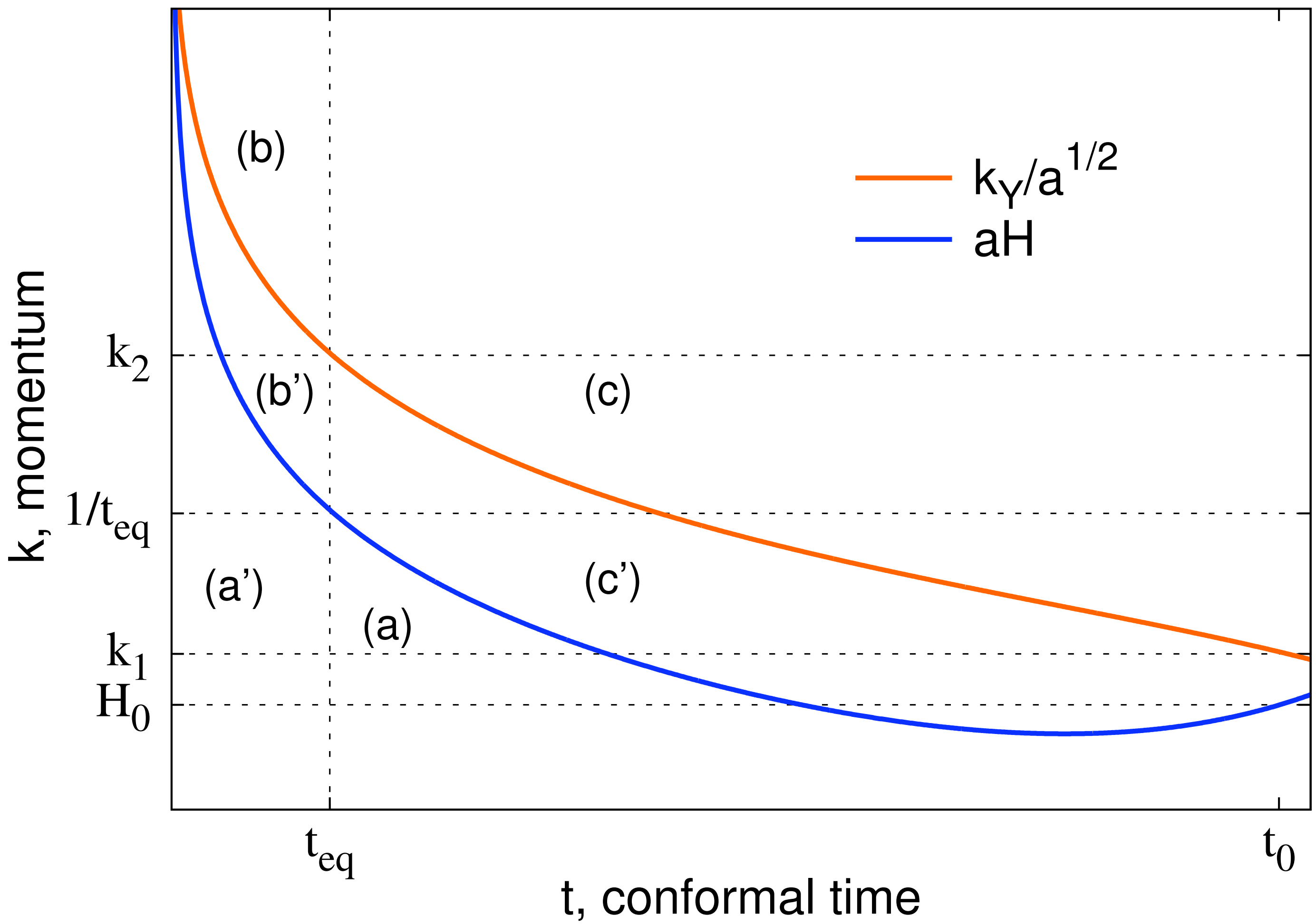
screening of the additional force

$\approx$ chameleon-type mechanism

Standard Jeans instability $\delta \propto \tau^{2/3}$

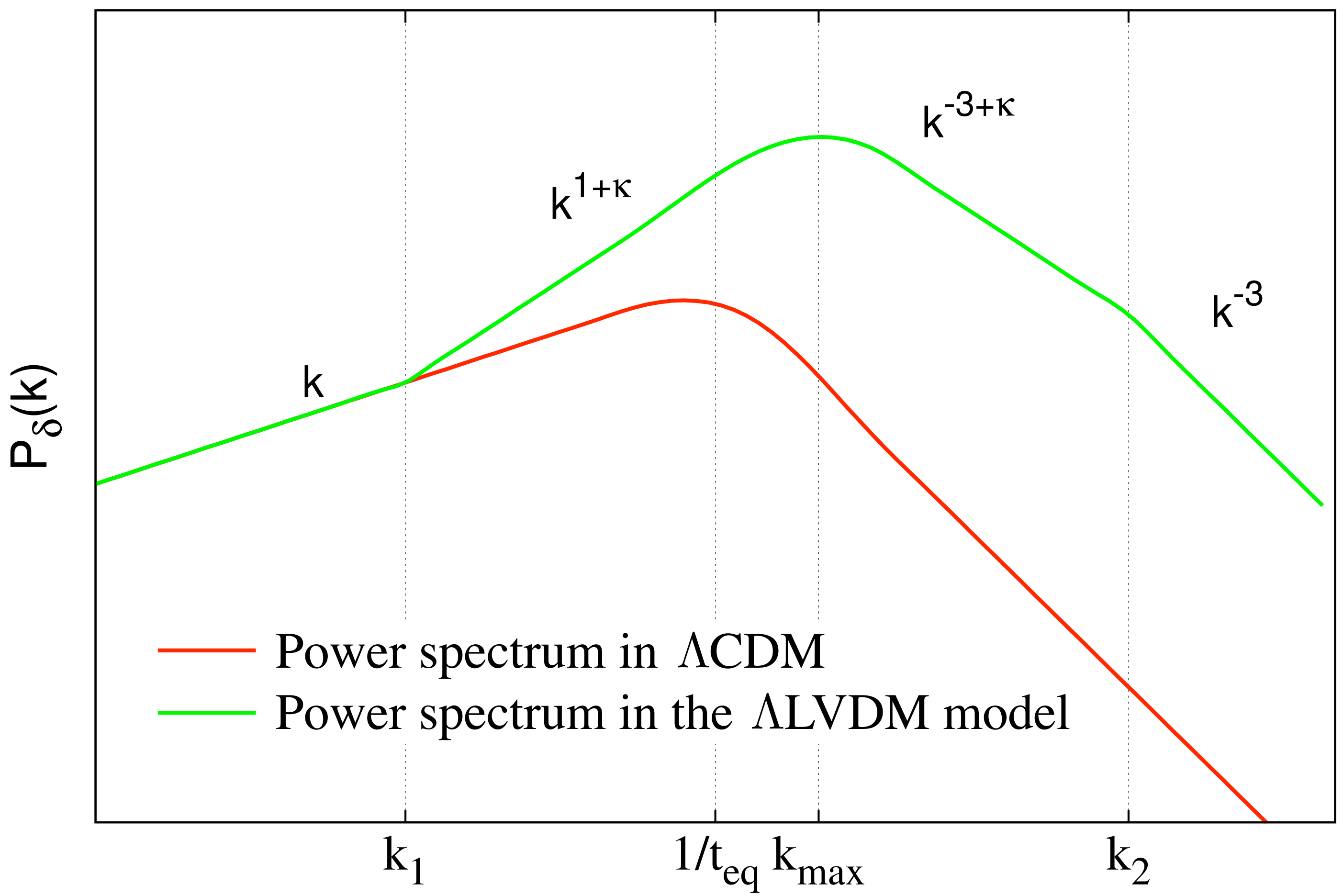
NB. Standard homogeneous cosmology

Screening scale vs. Hubble



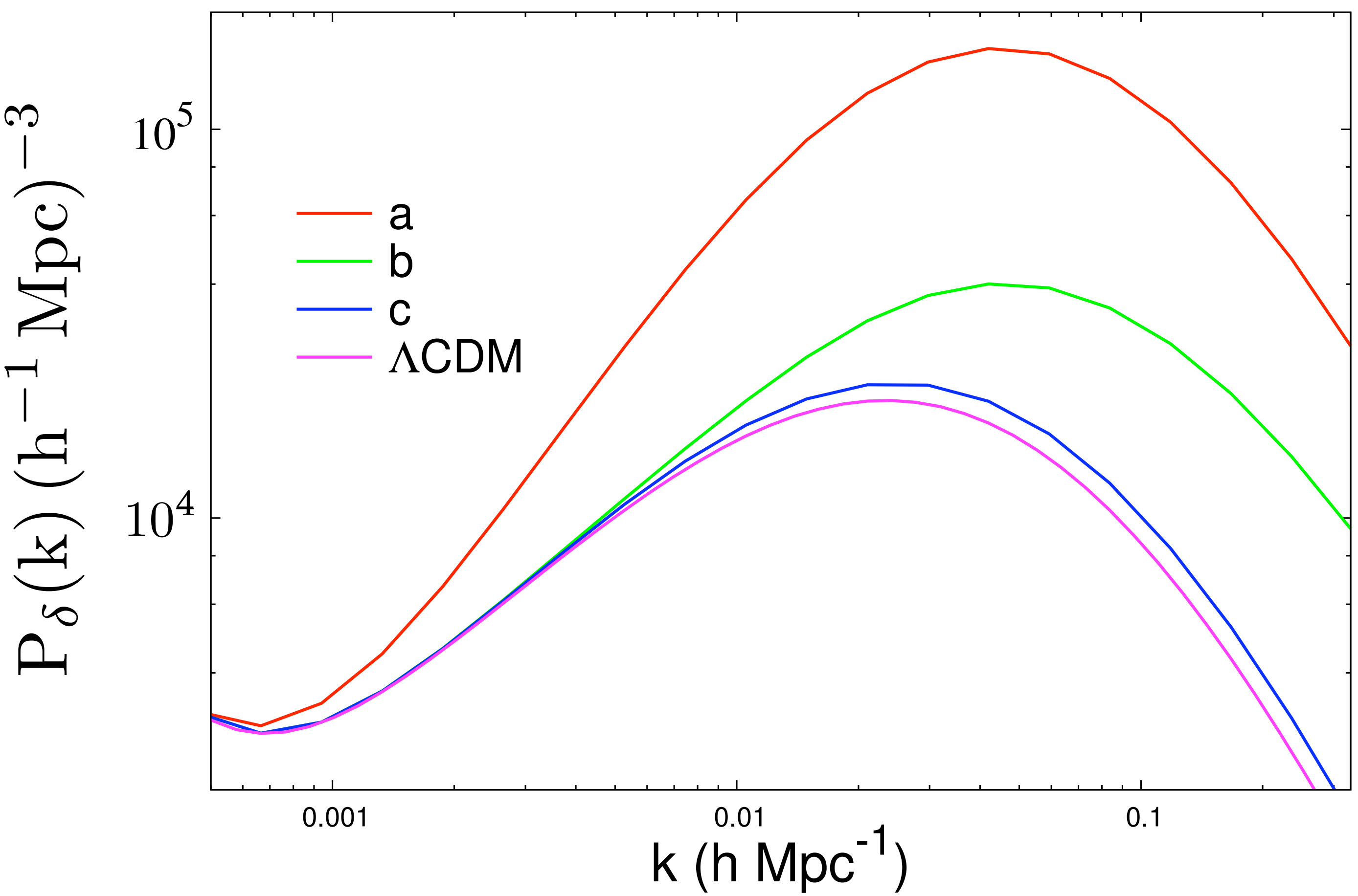
$$k_Y^2 \equiv \frac{3H_0^2\Omega_{dm}Y}{(\beta+\lambda')(1-Y)}$$

Qualitative power spectrum



$$k_1 = H_0 \sqrt{\frac{3Y\Omega_{dm}}{(\beta+\lambda')(1-Y)}}\,, \quad k_2 = k_1\sqrt{1+Z_{eq}}\,, \quad \kappa = \sqrt{25 + \frac{24\Omega_{dm}Y}{\Omega_{cm}(1-Y)}} - 5$$

Numerical power spectrum



$\Omega_\gamma = 5 \cdot 10^{-5}$

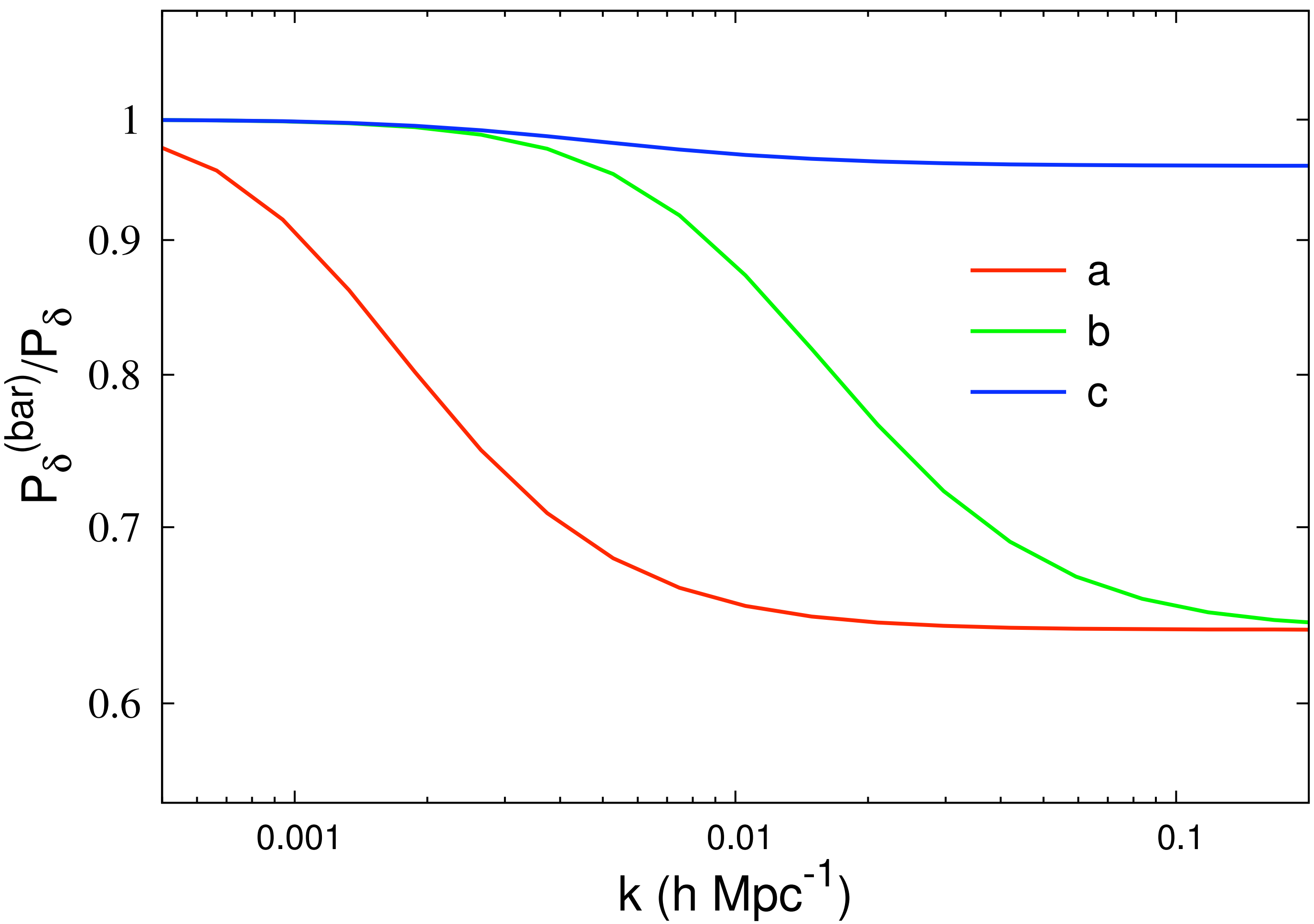
$\Omega_{cm} = 0.25$

$\Omega_{dm} = 0.2$

$\Omega_\Lambda = 0.75$

	α	β	λ	Y	k_Y (h Mpc^{-1})
a	$2 \cdot 10^{-2}$	10^{-2}	10^{-2}	$2 \cdot 10^{-1}$	$1.02 \cdot 10^{-3}$
b	$2 \cdot 10^{-4}$	10^{-4}	10^{-4}	$2 \cdot 10^{-1}$	$1.02 \cdot 10^{-2}$
c	$2 \cdot 10^{-4}$	10^{-4}	10^{-4}	$2 \cdot 10^{-2}$	$2.9 \cdot 10^{-3}$

Baryonic bias



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Rough constraint on LV in dark matter:

$$Y < 10^{-2}$$

Summary

- Breaking of LI + 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
- Deviation from LI in dark matter accelerates growth of structures at short to intermediate lengths
- Bounds on Lorentz violation in DM at the level 10^{-2} or better
- Cosmological perturbations provide a sensitive probe of LV in the dark sector