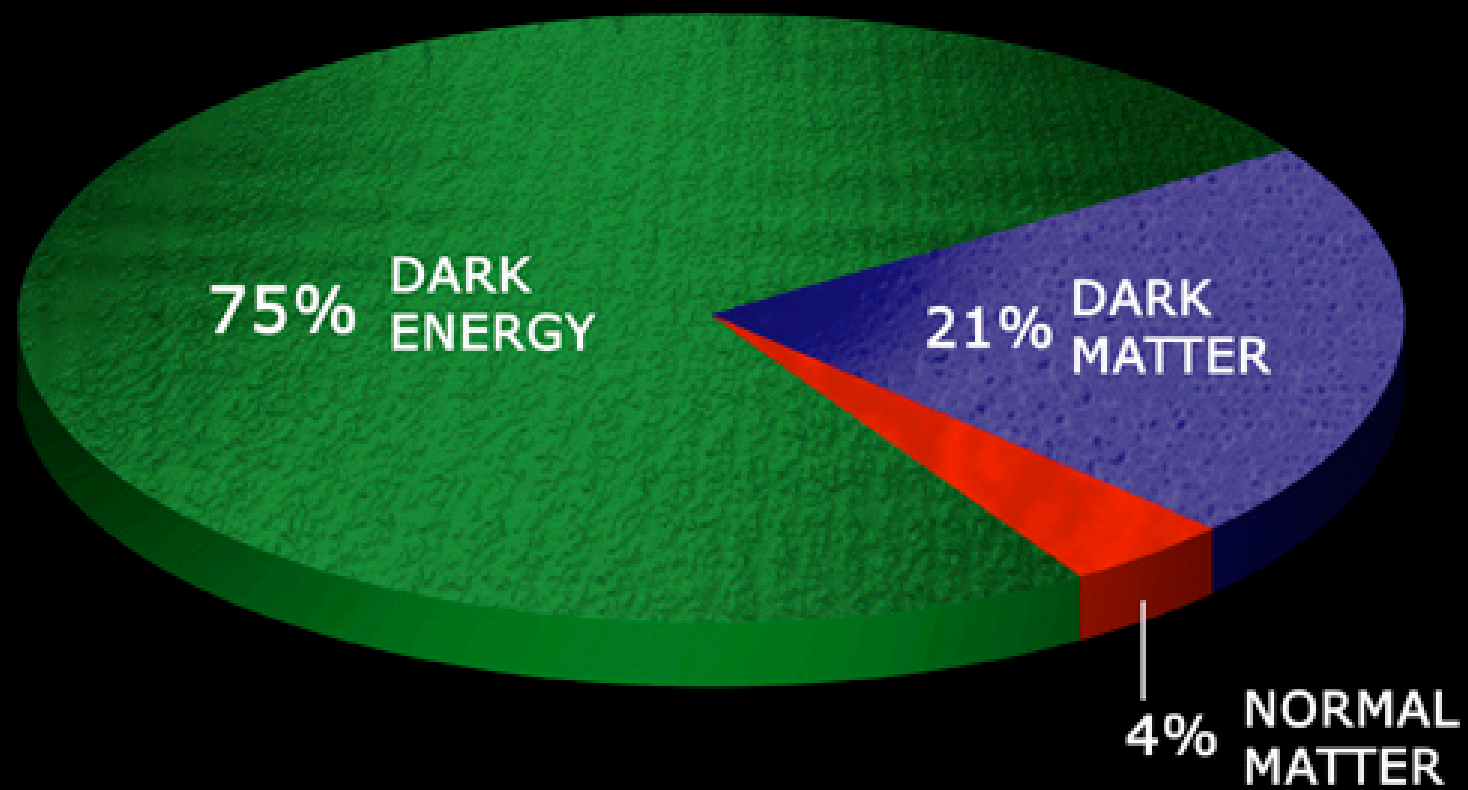


Constraining deviations from Lorentz invariance in **the Dark Sector**

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(INR RAS, Moscow)



in collaboration with **Diego Blas & Mikhail Ivanov**



The key principle tacitly assumed:

Lorentz invariance

checked with high accuracy for visible matter

Can we test *observationally* its validity in
the dark sector ?

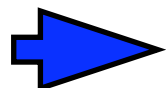
Plan

- Phenomenological description of LV in gravity
- Deviation from LI in dark matter: cosmological signatures
- A simple model of dark energy with LV: 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, ...)

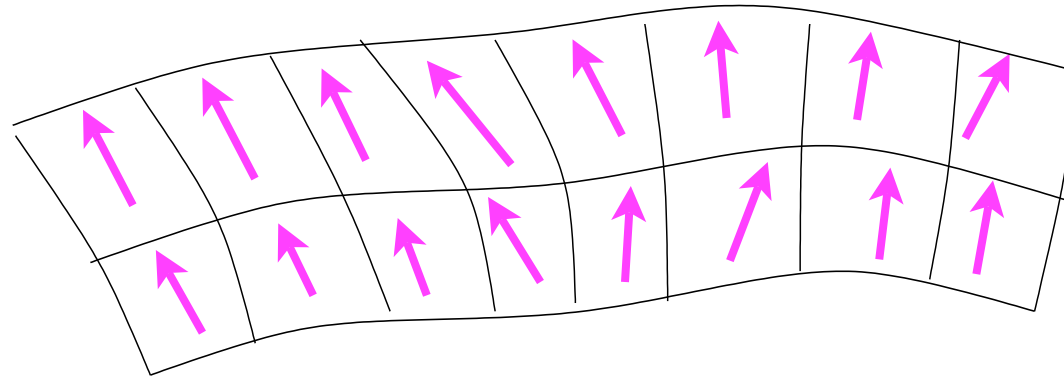
Important: violation of LI requires presence of **new light degrees of freedom**

 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



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

Lagrange multiplier:
enforces unit norm

$$K_{\sigma\rho}^{\mu\nu} \equiv c_1 g^{\mu\nu} g_{\sigma\rho} + c_2 \delta_\sigma^\mu \delta_\rho^\nu + c_3 \delta_\rho^\mu \delta_\sigma^\nu + c_4 u^\mu u^\nu g_{\sigma\rho}$$

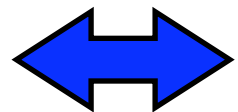
Variation: *khrono-metric* model

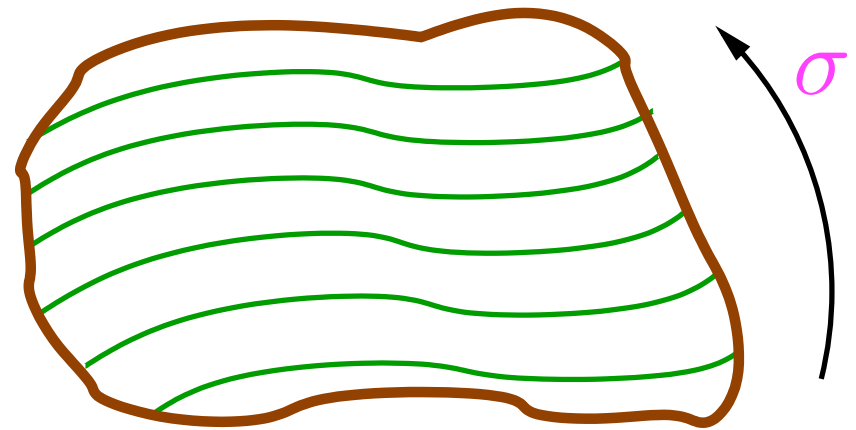
Blas, Pujolas, S.S., 2010

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



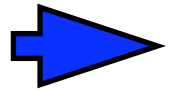
Number of couplings reduced:

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

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

Constraints from the visible sector

- LI of the Standard Model



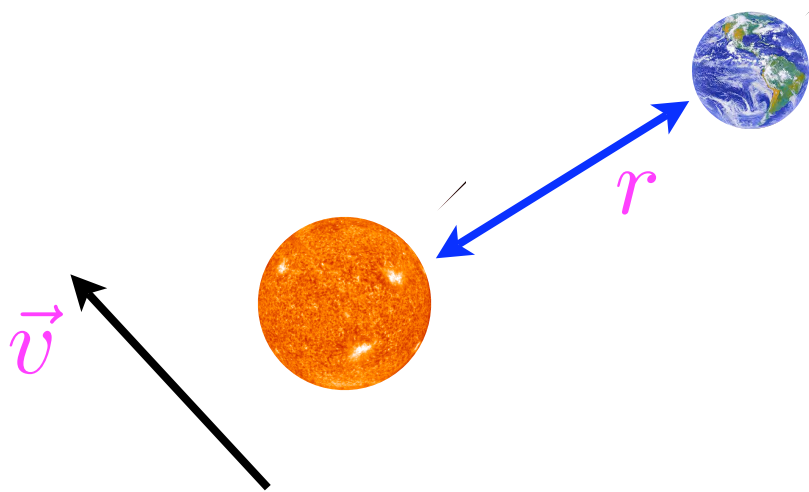
no direct coupling of aether to visible matter,
interaction only through gravity

Constraints from the visible sector

- LI of the Standard Model

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

- Post-Newtonian corrections in the Solar System



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

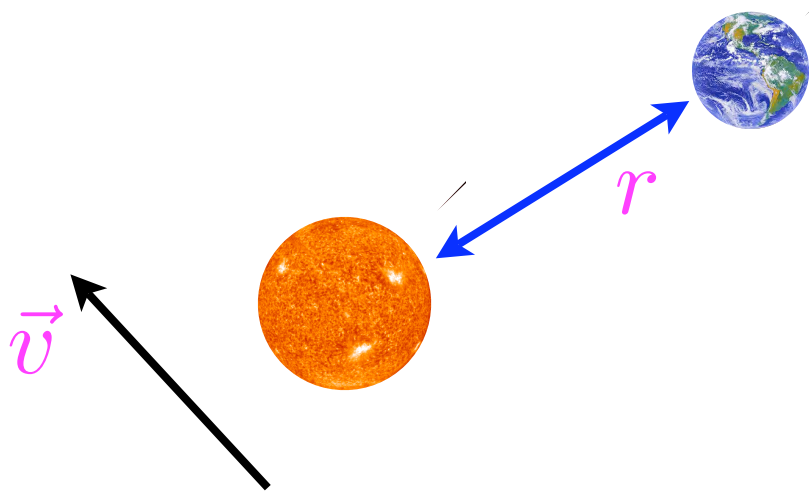
$$h_{0i} = \frac{\alpha_1^{PPN}}{2} G_N \frac{m}{r} v^i$$

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

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

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

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

- 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 MATTER

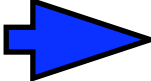
Dark matter is non-relativistic. Impossible to probe whether it is Lorentz invariant or not ?

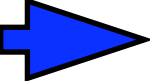
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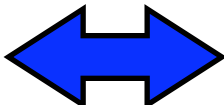
Yes, it is possible !

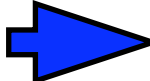
Dark matter is non-relativistic. Impossible to probe whether it is Lorentz invariant or not ?

Yes, it is possible !

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

$$S_{pp} = -m \int ds \quad \Longrightarrow \quad -m \int ds \sum_{n=0} y_n (u_\mu v^\mu)^n$$

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

Generalized point particle action

$$S_{pp} = -m \int ds \quad \Longrightarrow \quad -m \int ds \sum_{n=0} y_n (u_\mu v^\mu)^n$$

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

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

$$S = \int d^4x \left[M_P^2 \phi \Delta \phi + \frac{M_P^2 c_1}{2} u^i \Delta u^i \right] \\ + \int d^4x \rho \left[(1 + Y_2) \frac{(v^i)^2}{2} - (1 + Y_1 + Y_2) \phi + Y_1 \left(u^i v^i - \frac{(u^i)^2}{2} \right) \right]$$

DM density

$$Y_1 = \sum n y_n, \quad Y_2 = \sum (1 - n) y_n$$

Generalized point particle action

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- modified coupling to gravitational potential

Generalized point particle action

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

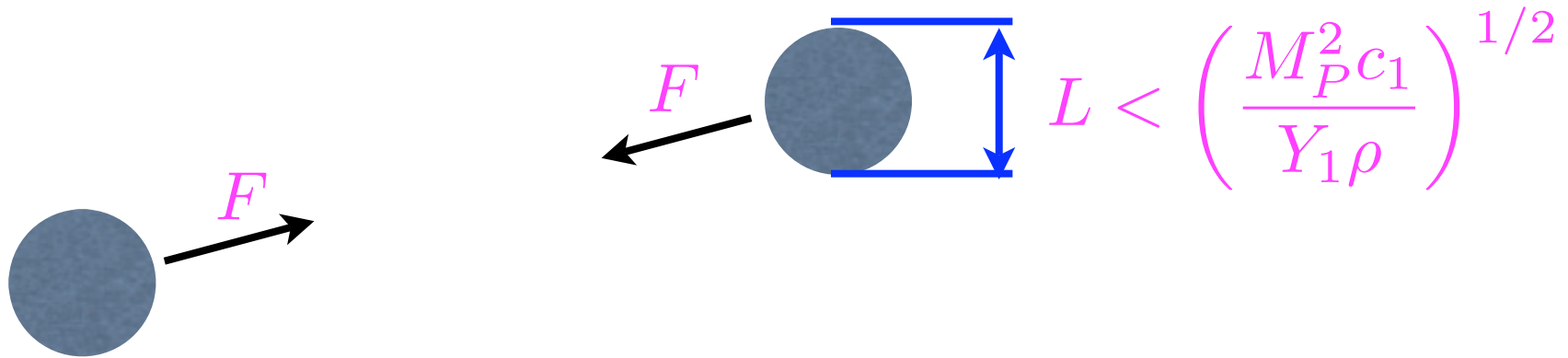
Newtonian limit: v^i , u^i -- small, $g_{00} = 1 + 2\phi$

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DM density $Y_1 = \sum n y_n$, $Y_2 = \sum (1 - n) y_n$

- modified coupling to gravitational potential
- effective potential for aether in matter

$$m_{eff}^2 \sim \frac{Y_1 \rho}{M_P^2 c_1}$$



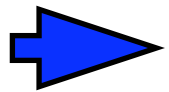
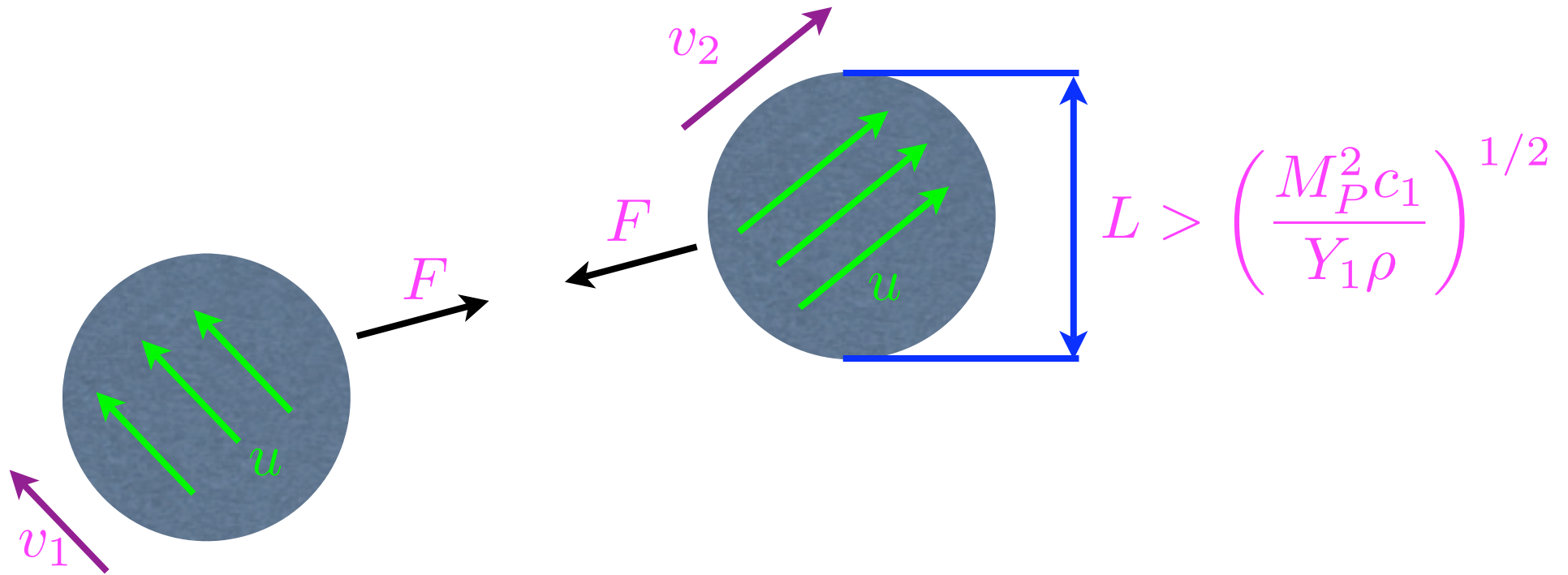
➡
$$F = F_N \left(1 + \frac{Y_1}{1 + Y_2} \right)$$

Accelerated Jeans instability

$\delta \propto \tau^\gamma,$

$$\gamma = \frac{1}{6} \left[-1 + \sqrt{25 + \frac{24Y_1}{1 + Y_2}} \right]$$

density
contrast



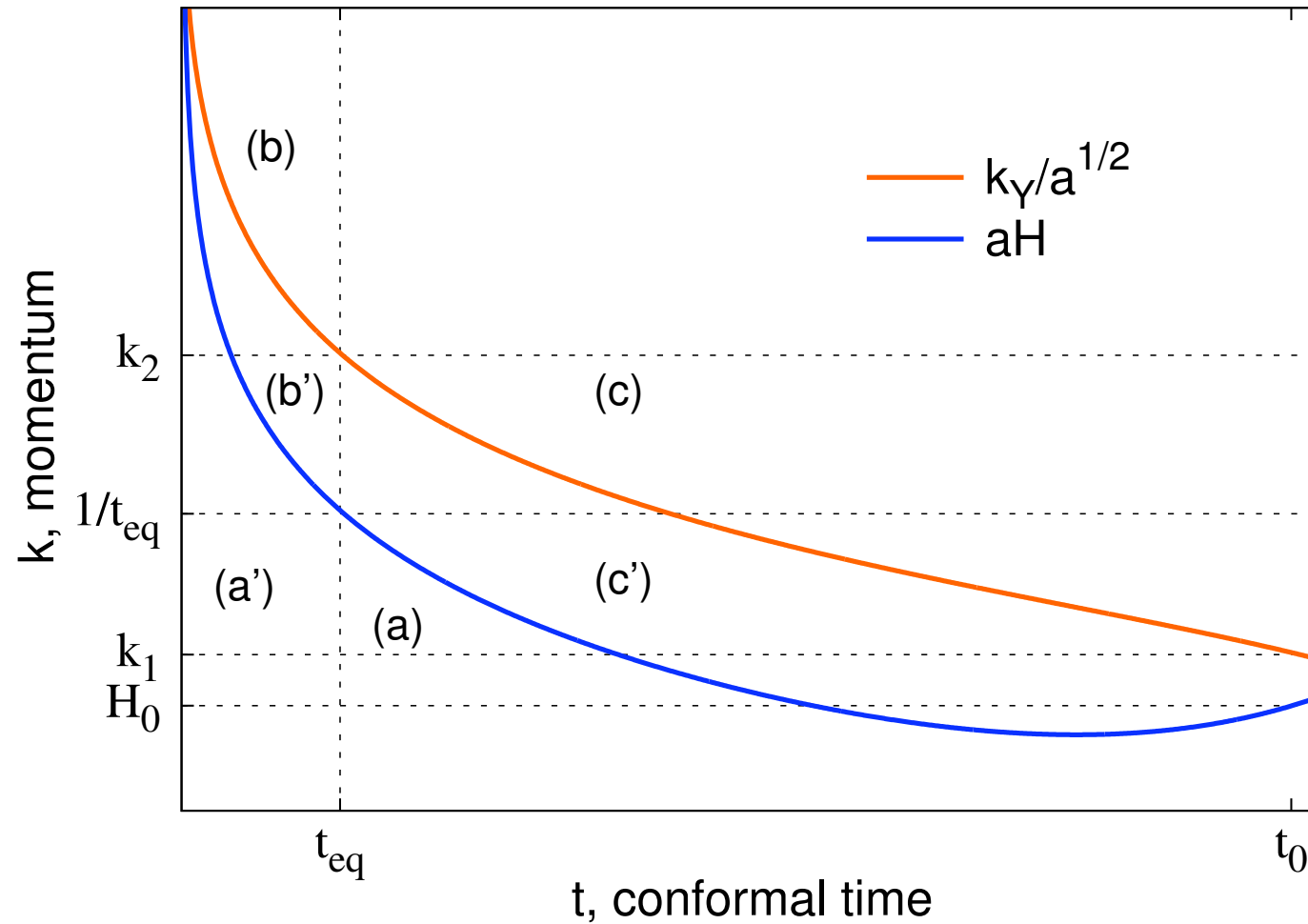
$$F = F_N$$

screening of the additional force
 $\approx$ chameleon-type mechanism

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

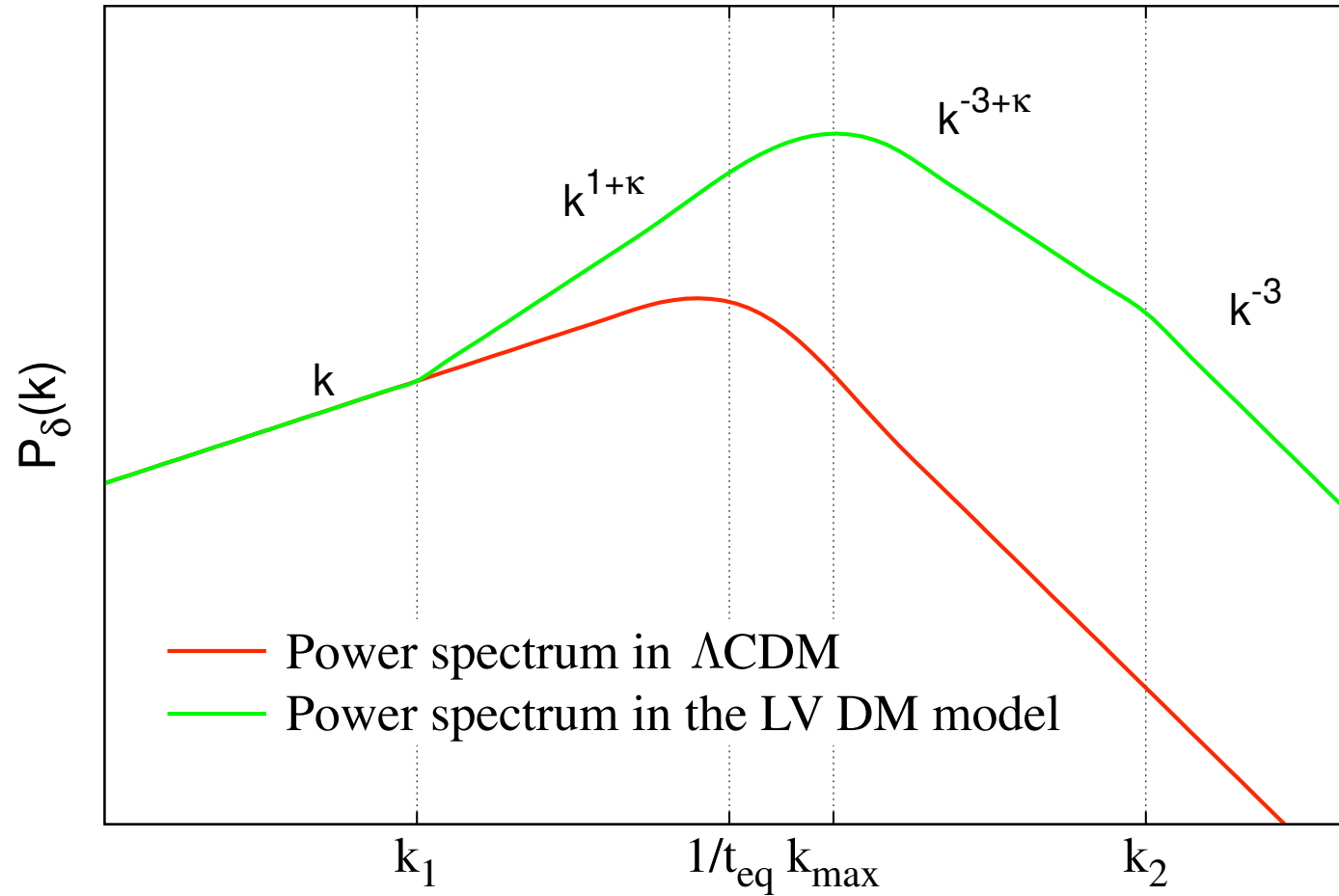
NB. Standard homogeneous cosmology

Screening scale vs. Hubble



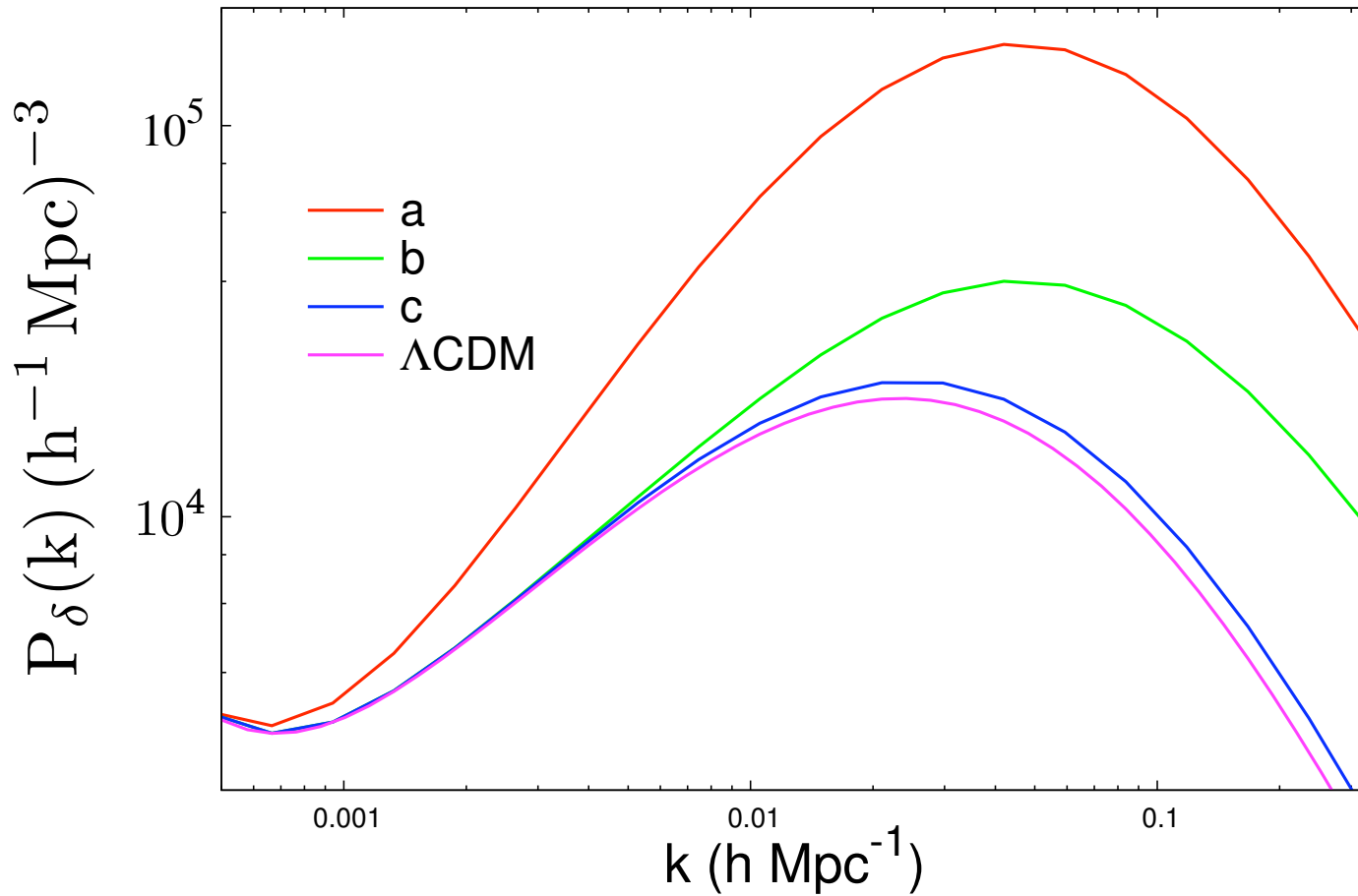
$$k_Y^2 \equiv \frac{3H_0^2 \Omega_{dm} Y_1}{(\beta + \lambda')(1 + Y_2)}$$

Qualitative power spectrum



$$k_1 = H_0 \sqrt{\frac{3Y_1 \Omega_{dm}}{(\beta + \lambda')(1 + Y_2)}}, \quad k_2 = k_1 \sqrt{1 + Z_{eq}}, \quad \kappa = \sqrt{25 + \frac{24\Omega_{dm} Y_1}{\Omega_{cm}(1 + Y_2)}} - 5$$

Numerical power spectrum



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

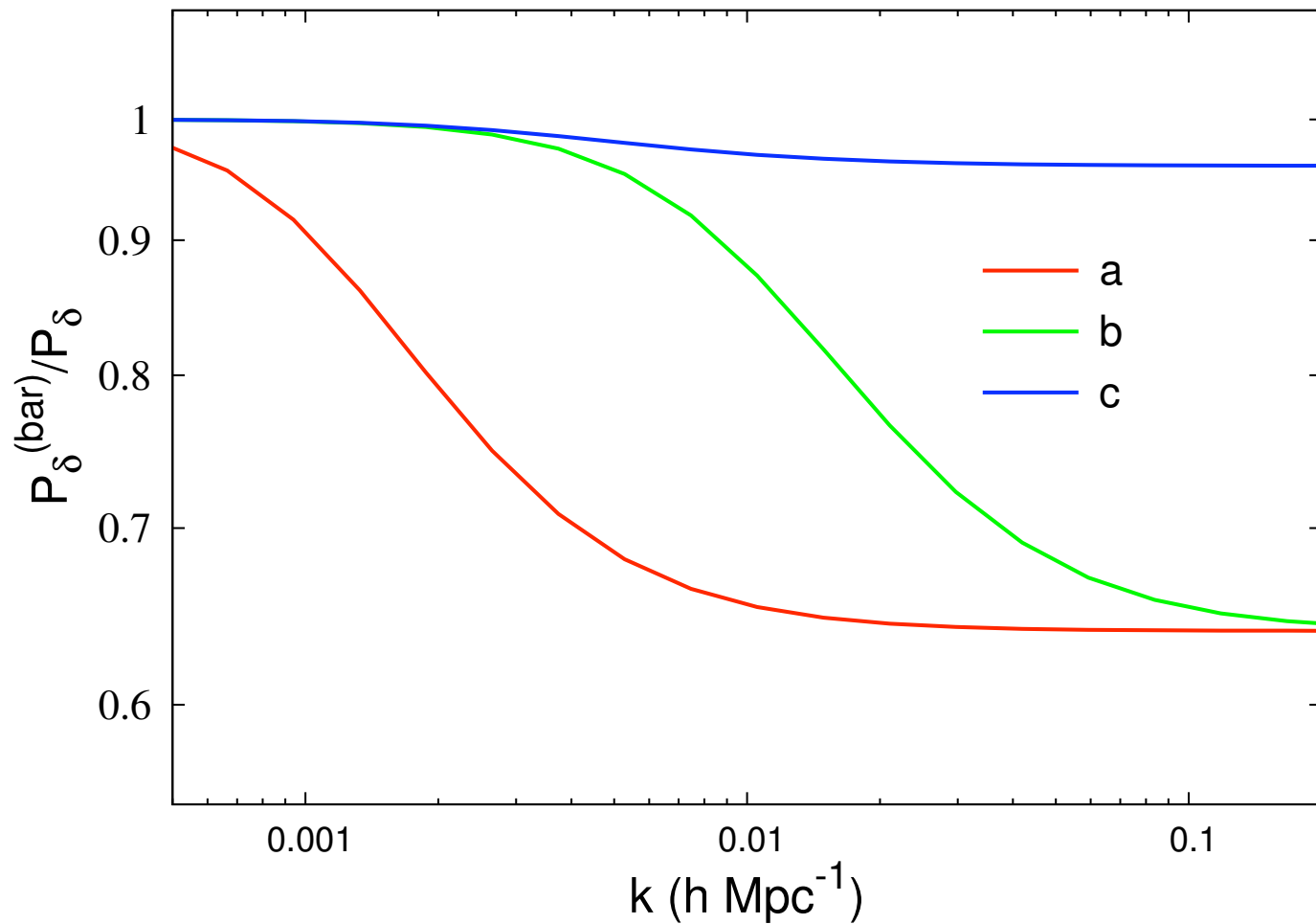
$$\Omega_{cm} = 0.25$$

$$\Omega_{dm} = 0.2$$

$$\Omega_\Lambda = 0.75$$

	α	β	λ	Y_1	Y_2	$k_Y (h \text{Mpc}^{-1})$
a	$2 \cdot 10^{-2}$	10^{-2}	10^{-2}	$2 \cdot 10^{-1}$	$-2 \cdot 10^{-1}$	$1.02 \cdot 10^{-3}$
b	$2 \cdot 10^{-4}$	10^{-4}	10^{-4}	$2 \cdot 10^{-1}$	$-2 \cdot 10^{-1}$	$1.02 \cdot 10^{-2}$
c	$2 \cdot 10^{-4}$	10^{-4}	10^{-4}	$2 \cdot 10^{-2}$	$-2 \cdot 10^{-2}$	$2.9 \cdot 10^{-3}$

Baryonic bias



	α	β	λ	Y_1	Y_2	$k_Y \text{ (h Mpc}^{-1}\text{)}$
a	$2 \cdot 10^{-2}$	10^{-2}	10^{-2}	$2 \cdot 10^{-1}$	$-2 \cdot 10^{-1}$	$1.02 \cdot 10^{-3}$
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c	$2 \cdot 10^{-4}$	10^{-4}	10^{-4}	$2 \cdot 10^{-2}$	$-2 \cdot 10^{-2}$	$2.9 \cdot 10^{-3}$

Rough constraint on LV in dark matter:

$$Y_1, Y_2 < 10^{-2}$$

LV DARK ENERGY

Θ CDM

Consider a scalar Θ 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 aether:

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

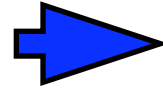
stable under radiative corrections:
breaks $\Theta \mapsto -\Theta$
Small μ is technically natural !

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

Homogeneous cosmology

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

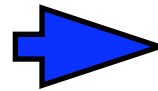
$$\frac{d}{dt}(a^3 \dot{\Theta} + \mu^2 a^3) = 0$$



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



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



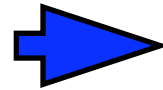
$$\rho_{\Theta} \rightarrow \mu^4/2$$

$$w = -1$$

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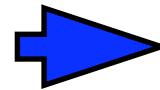
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$$\rho_{\Theta} \rightarrow \mu^4/2$$

$$w = -1$$

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

Minkowski



de Sitter

Perturbations of $\sigma - \Theta$ system

- For short waves: two decoupled relativistic excitations

$$\omega \propto k$$

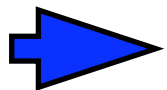
- Minkowski background is unstable at long distances

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

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

- 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 Θ CDM vs Λ CDM

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

- 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 , $\delta \equiv \frac{\delta\rho_{cm}}{\rho_{cm}}$

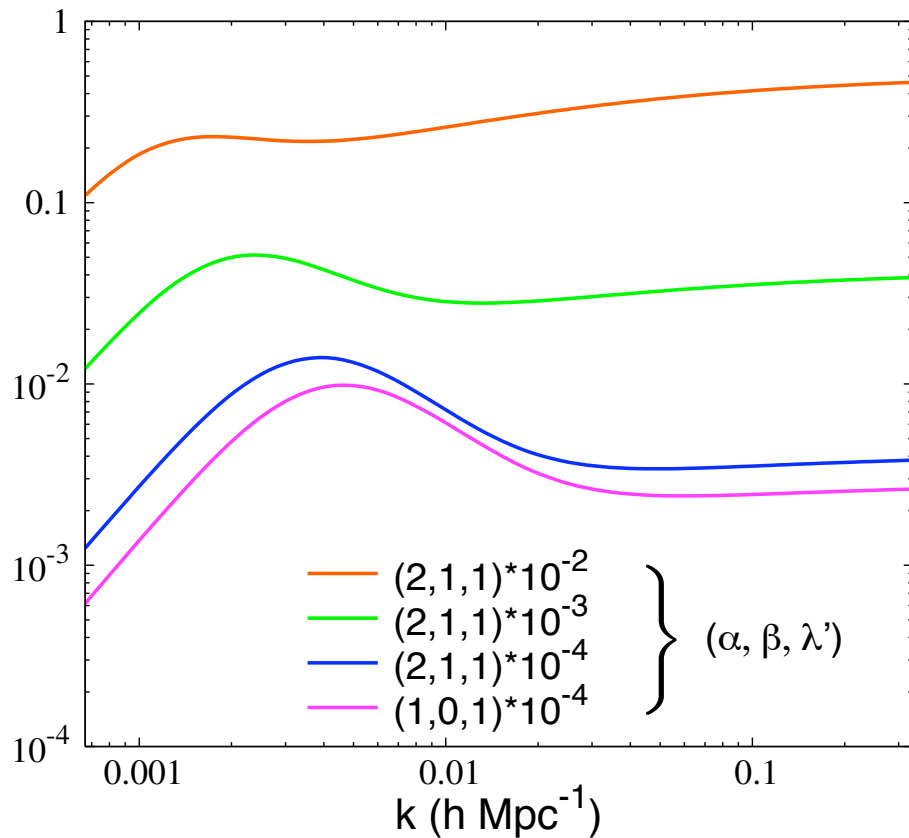
- Plot $\Delta_\phi(k) = \frac{P_\phi(k)}{P_{\phi\Lambda CDM}(k)} - 1$

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

Cosmological perturbations in Θ CDM vs Λ CDM

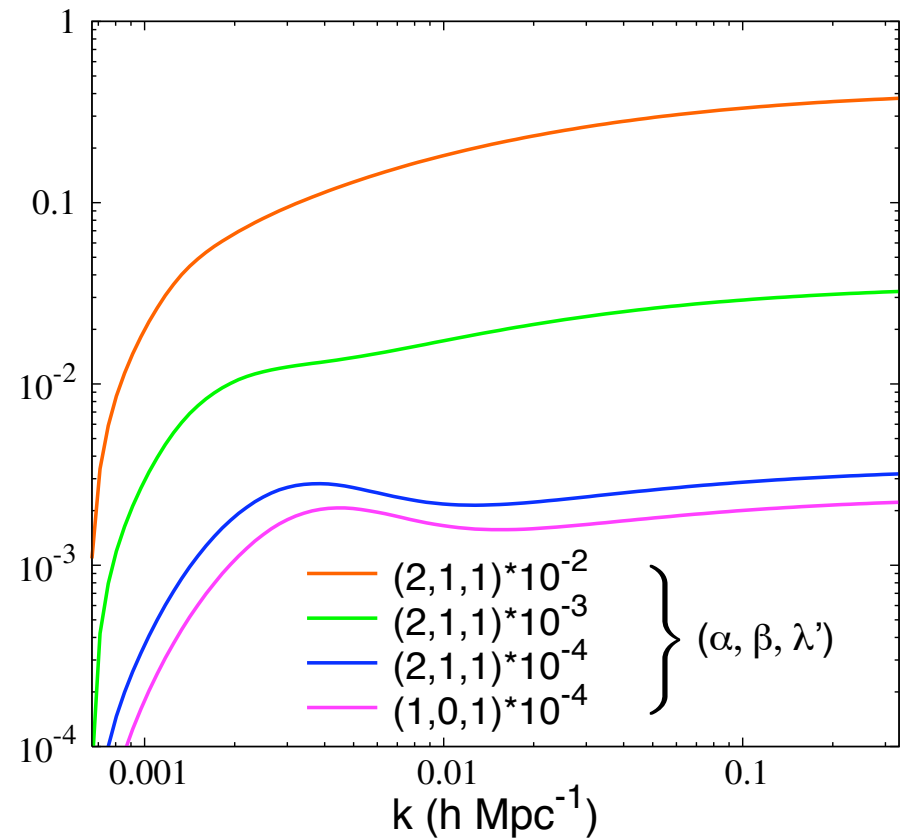
Newton potential:

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



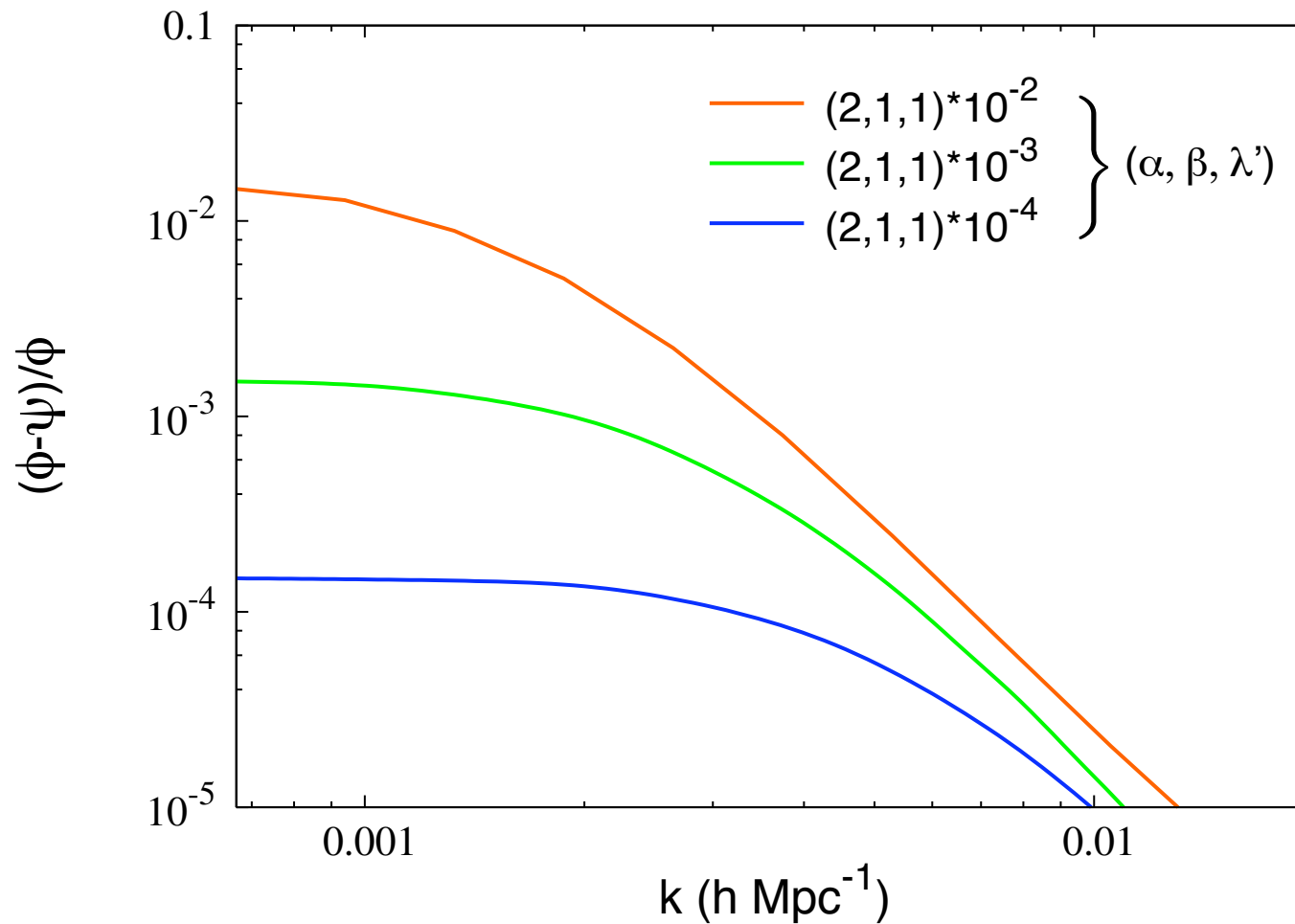
Matter density contrast:

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



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

Anisotropic stress in Θ CDM



Summary

- 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
- Breaking of LI + scalar with shift symmetry = technically natural dark energy (Θ CDM) with high cutoff
- Predictions of Θ CDM: $w = -1$, growth of structure is enhanced and effective anisotropic stress appears at scales of a few hundred Mpc
- Cosmological perturbations provide a sensitive probe of LV in the dark sector