Testing Lorentz invariance of Dark Matter

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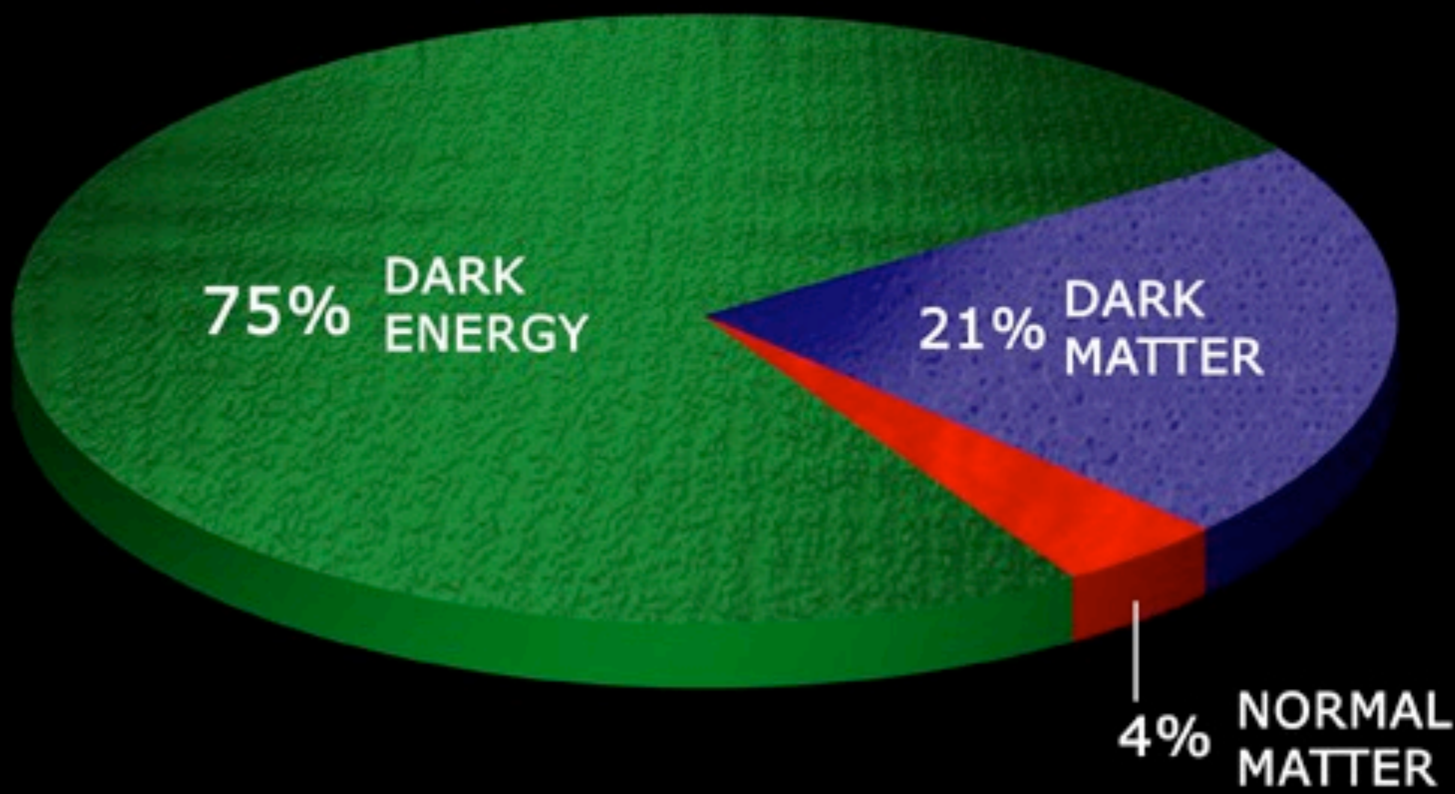
Our Universe is dark



Dark matter: present status

Theory

Plenty of candidates: neutralinos, gravitinos, sterile neutrinos, axions, wimps, wimpzillas, ...

Experiment

Nothing: no direct / indirect detection

Only information from gravitational interactions: DM clusters as non-relativistic dust

Can we learn more ?

The key principle since 1905:

Lorentz invariance

Consider dispersion relation of a particle

$$E^2 = m^2 + c^2 p^2 + \sum_{n>1} a_n p^{2n}$$

LI ➡ $c = 1, a_n = 0$

Experimental bounds on deviations from LI (δc)

Standard Model	gravity	dark matter
$10^{-15} \div 10^{-22}$	$10^{-4} \div 10^{-7}$	???

Digression I

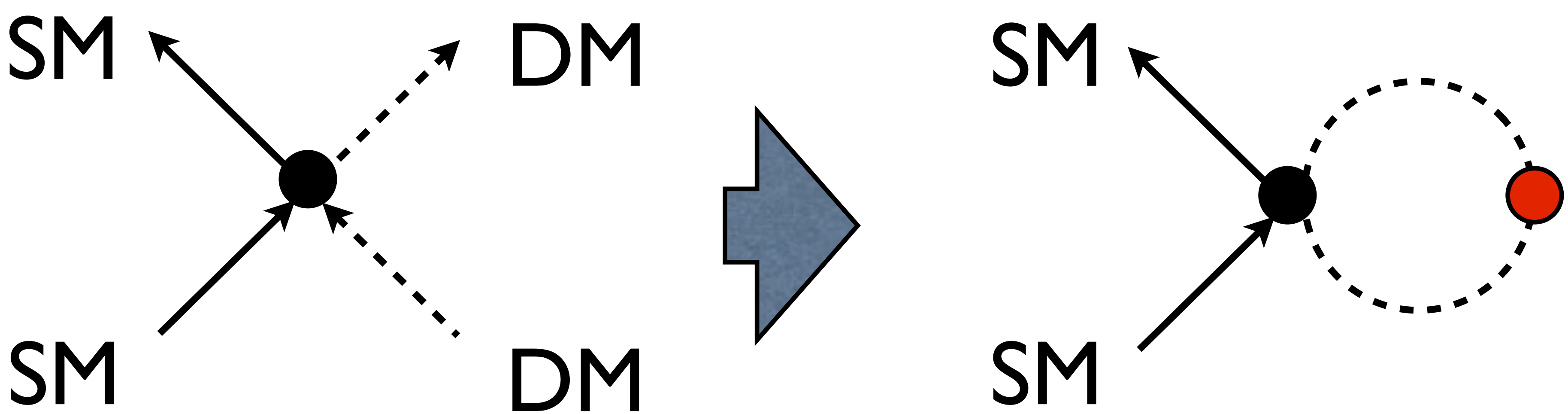
Theoretical motivations for deviation from LI

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

Digression II

If DM is directly detected

➡ very strong bounds on LV



cf. Bovy, Farrar 2009
Carroll et al. 2009

NB. These bounds are model-dependent

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

Yes, it is possible !

Violation of LI ⇨ new gravitational degrees of freedom

⇨ additional attraction between DM particles

⇔ violation of the equivalence principle

⇨ enhanced growth of structures

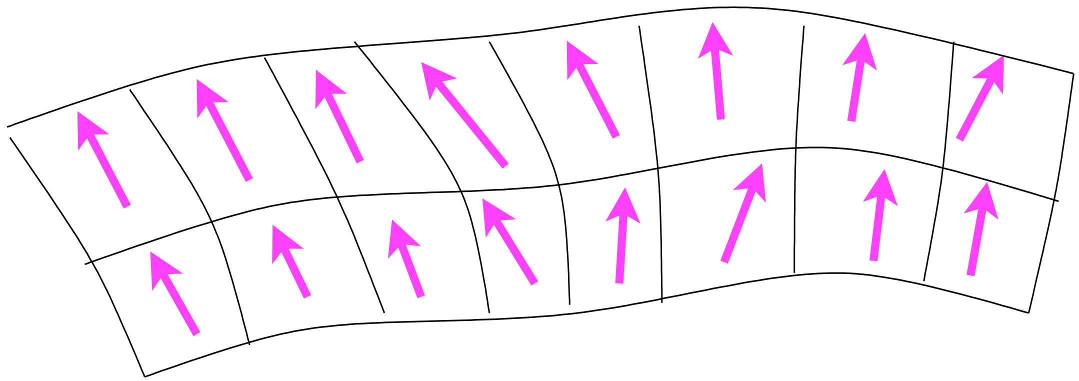
Consider the following pattern of Lorentz symmetry breaking

$$SO(3,1) \rightarrow SO(3)_{rotations}$$

Einstein - aether model

Jacobson, Mattingly, 2000

At each point of the space-time there is a preferred frame 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

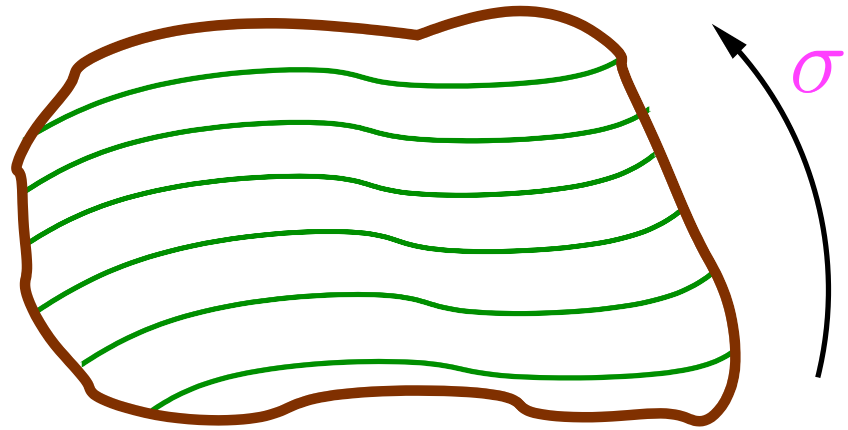
Blas, Pujolas, S.S., 2010

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:

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

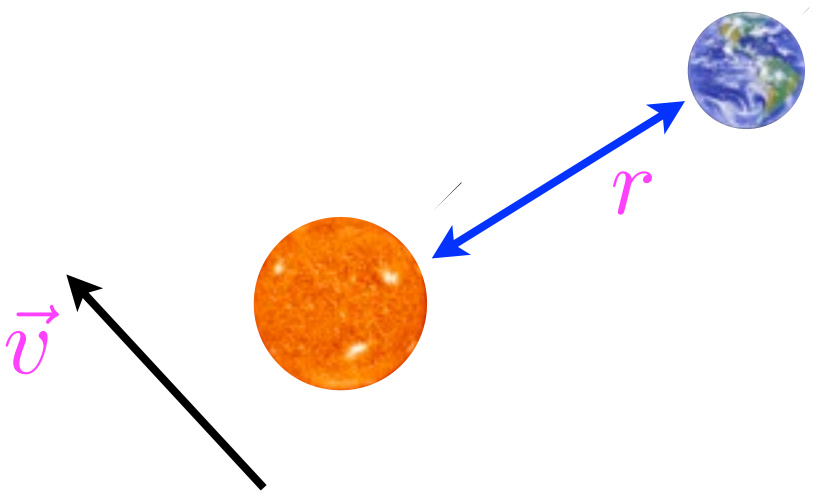
NB. Can be embedded into Horava-Lifshitz gravity (candidate for quantum gravity)

Constraints from the visible sector

- LI of the Standard Model

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

- Post-Newtonian corrections in the Solar System



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

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

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

Generalized point particle action

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

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

Connection to the dispersion relation:

$$p_i = \frac{\partial L}{\partial V^i} \qquad E = p_i V^i - L$$

$$E^2 = m^2 + (1+\xi)p^2$$

$$\Rightarrow \quad f = \sqrt{\frac{1+\xi(u_\mu v^\mu)^2}{1+\xi}} \approx 1 + \xi \frac{(u_\mu v^\mu)^2 - 1}{2}$$

Generalized point particle action

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

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

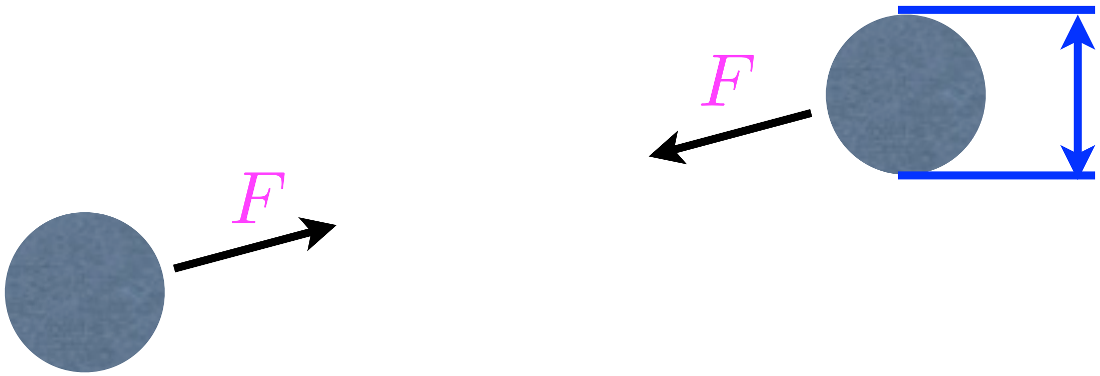
Newtonian limit: v^i , u^i -- small, $g_{00} = 1 + 2\phi$

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

DM density

$f'(1)$

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



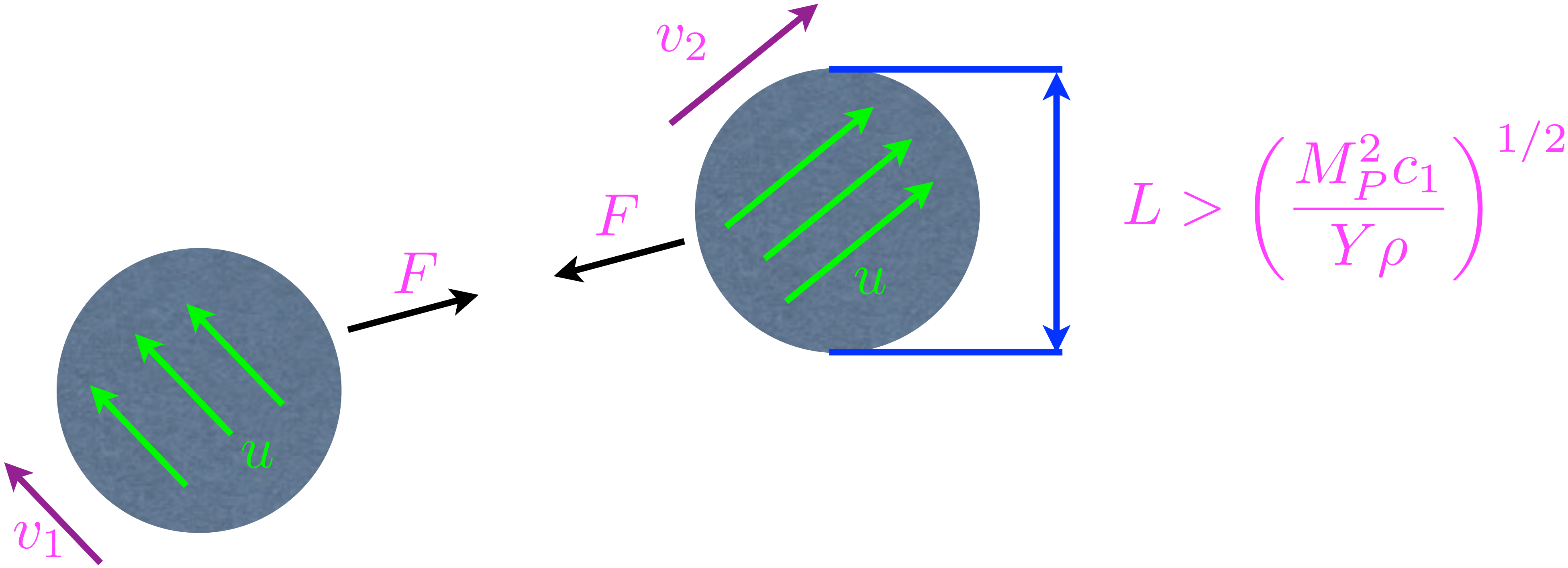
$$L < \left(\frac{M_P^2 c_1}{Y \rho} \right)^{1/2}$$

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

Accelerated Jeans instability

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

density contrast



$F = F_N$

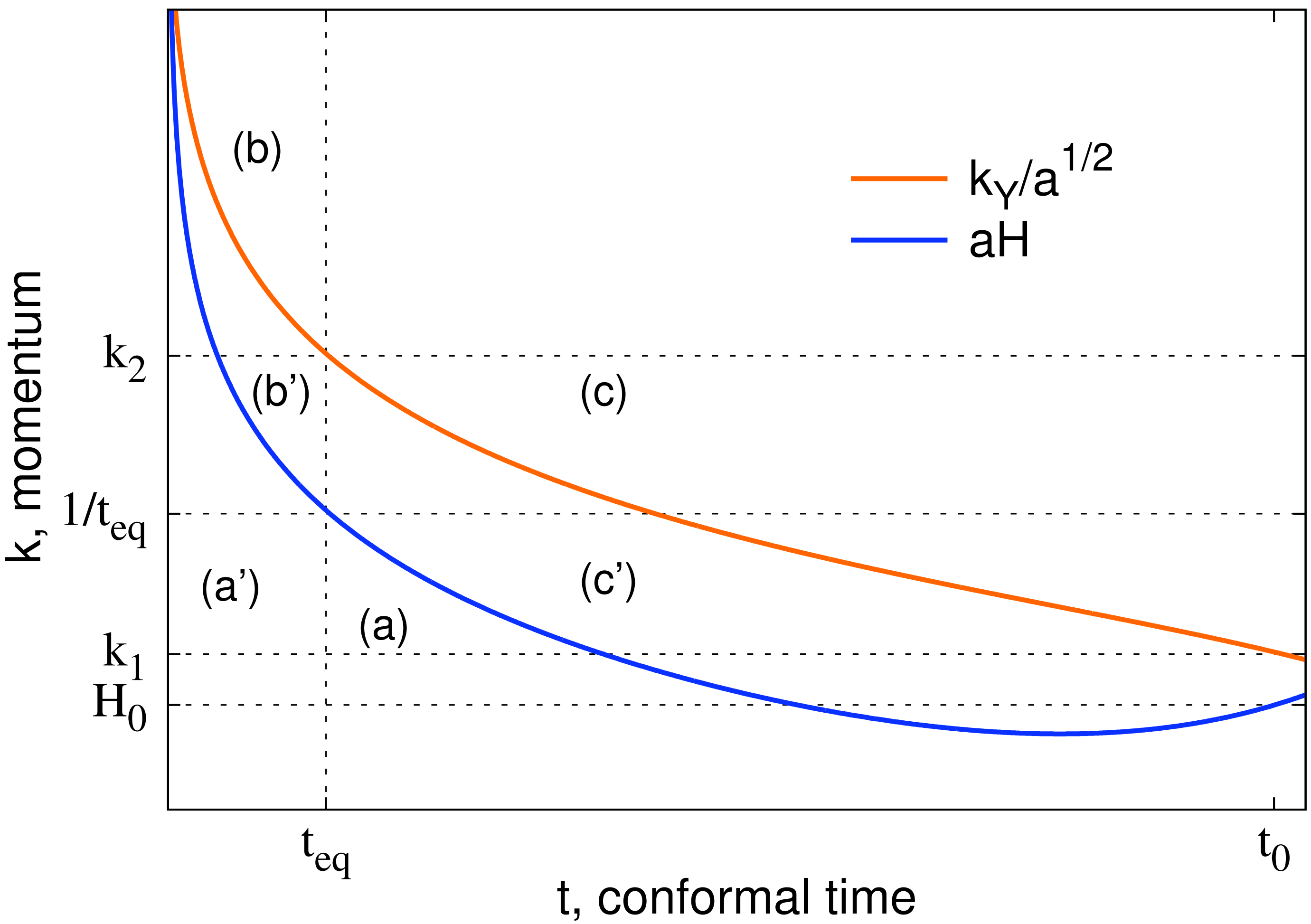
screening of the additional force

$\approx$ chameleon-type mechanism

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

NB. Standard homogeneous cosmology

Screening scale vs. Hubble



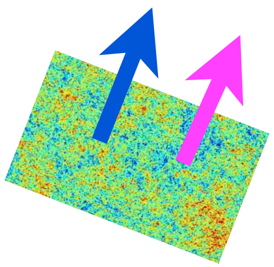
$$k_Y^2 \equiv \frac{3H_0^2 \Omega_{dm} Y}{(\beta + \lambda')(1 - Y)}$$

Relativistic cosmology

$$G_{\mu\nu} = \frac{1}{M_P^2} T^{m}_{\mu\nu} + \frac{1}{M_P^2} T^{fluid}_{\mu\nu} + \frac{1}{M_P^2} T^{aether}_{\mu\nu} + \Lambda\, g_{\mu\nu}$$

baryonic matter minimally coupled to gravity

Background: Homogeneous and isotropic (preferred foliation aligned with CMB frame)



$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = dt^2 - a(t)^2 dx^i dx^i$$

$$u_\mu = (u_0(t), 0, 0, 0) = v_\mu \quad , \quad \rho(t)$$

Friedmann equations almost not modified!

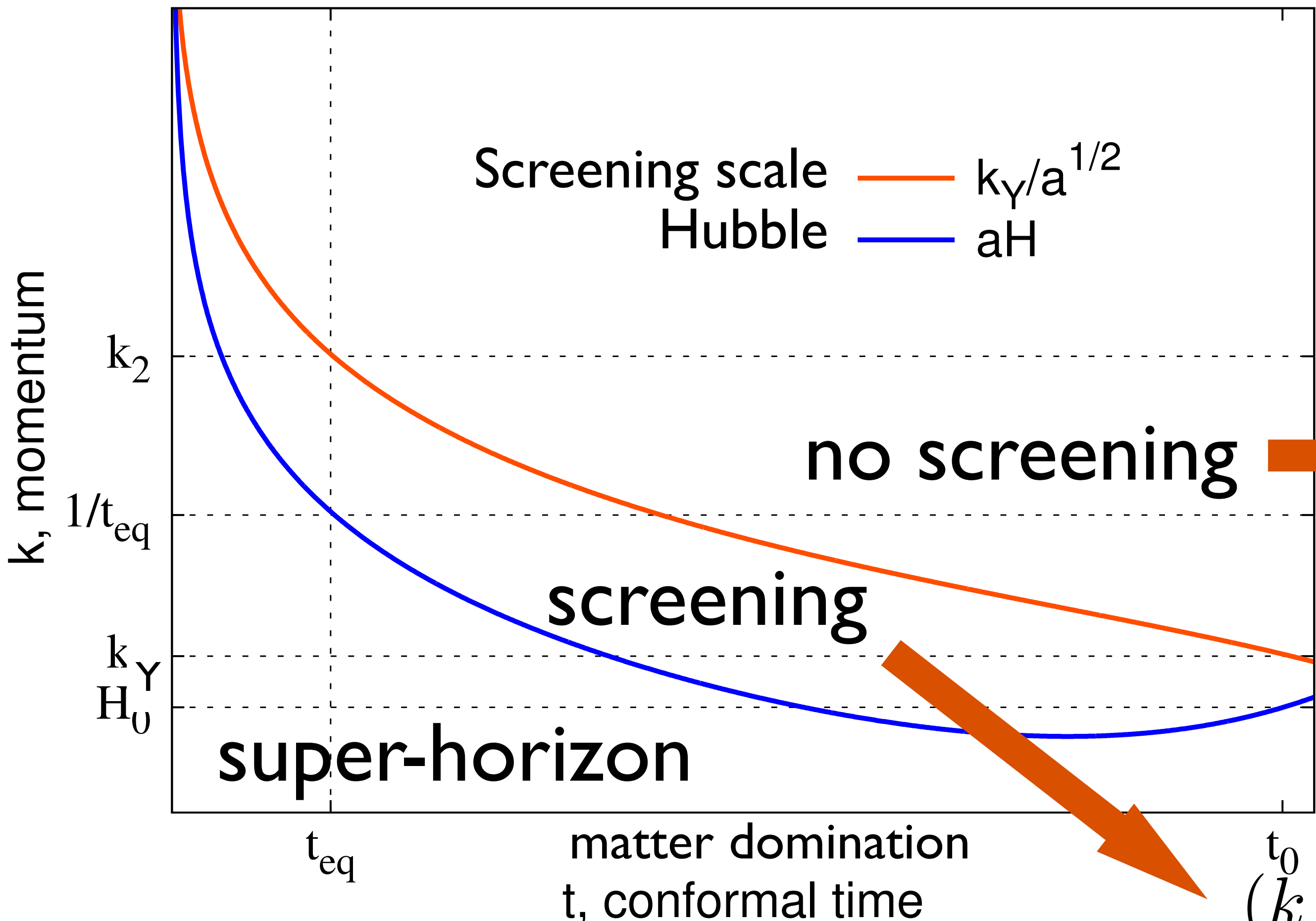
$$\left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G_c}{3}\rho_m \qquad G_c = \frac{1}{8\pi M_P^2 [1 + 3\lambda/2 + \beta/2]}$$

From BBN $\quad G_c = G_N + O(.01)$

Cosmological perturbations

$$\rho(x,t) \equiv \rho(t)(1+\delta(x,t))$$

Scalars: All effects summarized in $Y \equiv \tilde{f}'(1)$



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

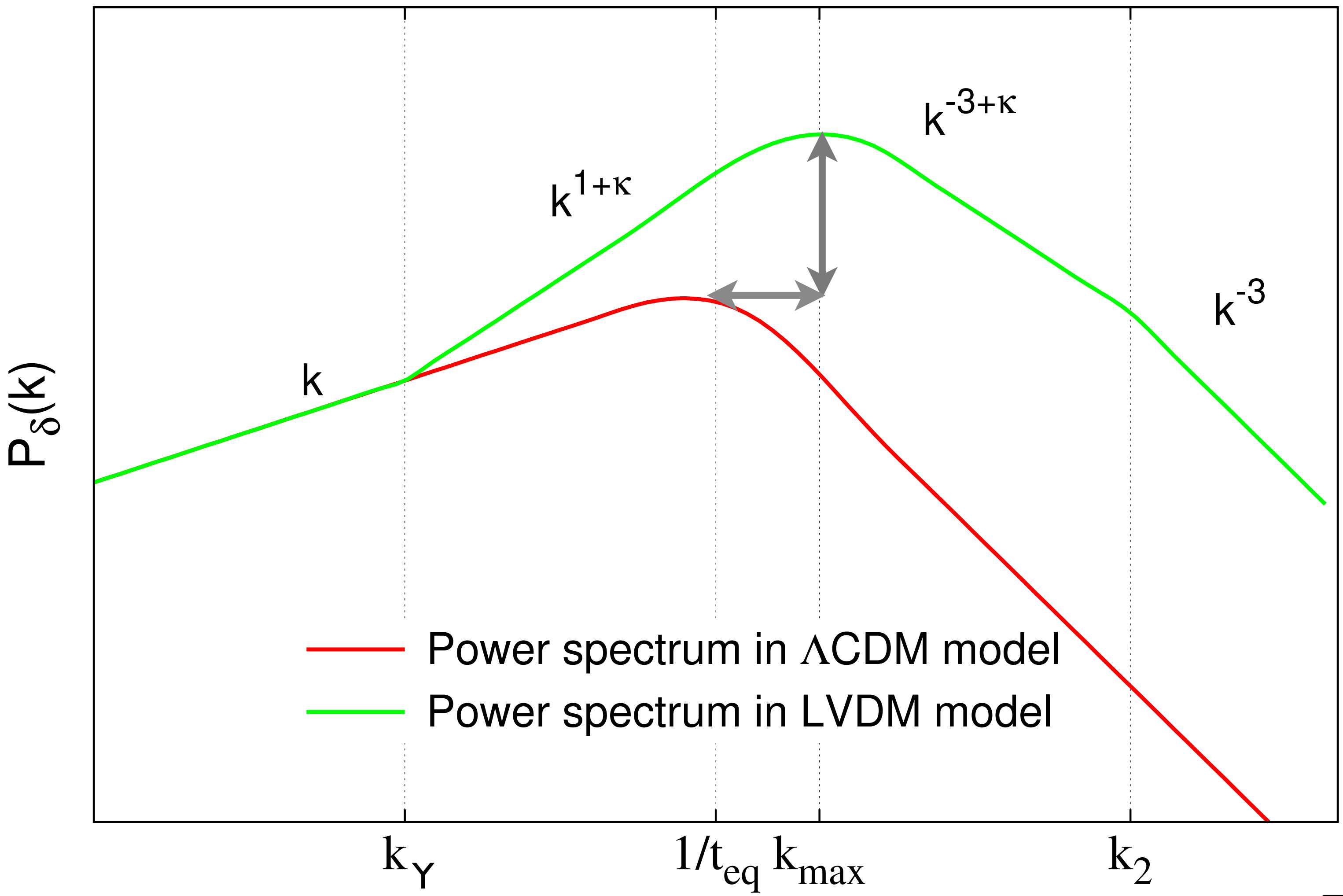
$$\delta \sim \frac{(k\,t)^2}{6(1-Y)}t^{\kappa}$$

$$\kappa = \sqrt{25+\frac{24\Omega_{dm}Y}{\Omega_{cm}(1-Y)}}-5$$

$$\delta \sim \frac{(k\,t)^2}{6}$$

Matter power spectrum: qualitative

$$\langle\delta(k)\delta(k')\rangle \equiv \delta^{(3)}(k+k')P(k)k^3$$

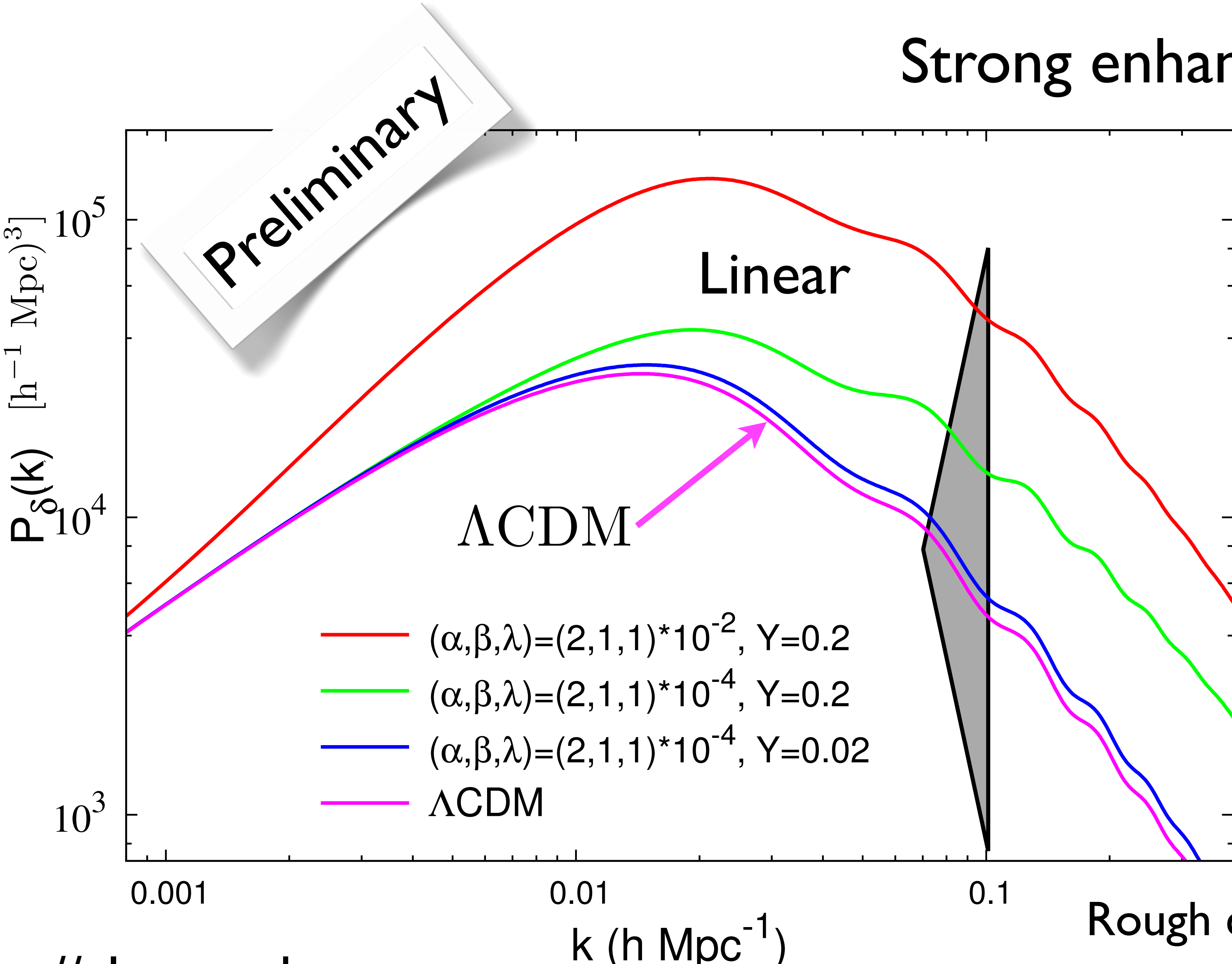


$$k_Y^2 \equiv \frac{3H_0^2\Omega_{dm}Y}{(\beta+\lambda)(1-Y)}$$

$$k_2 = k_Y\sqrt{\frac{\Omega_{dm}+\Omega_b}{\Omega_\gamma}}$$

Matter power spectrum: numerical

Strong enhancement !

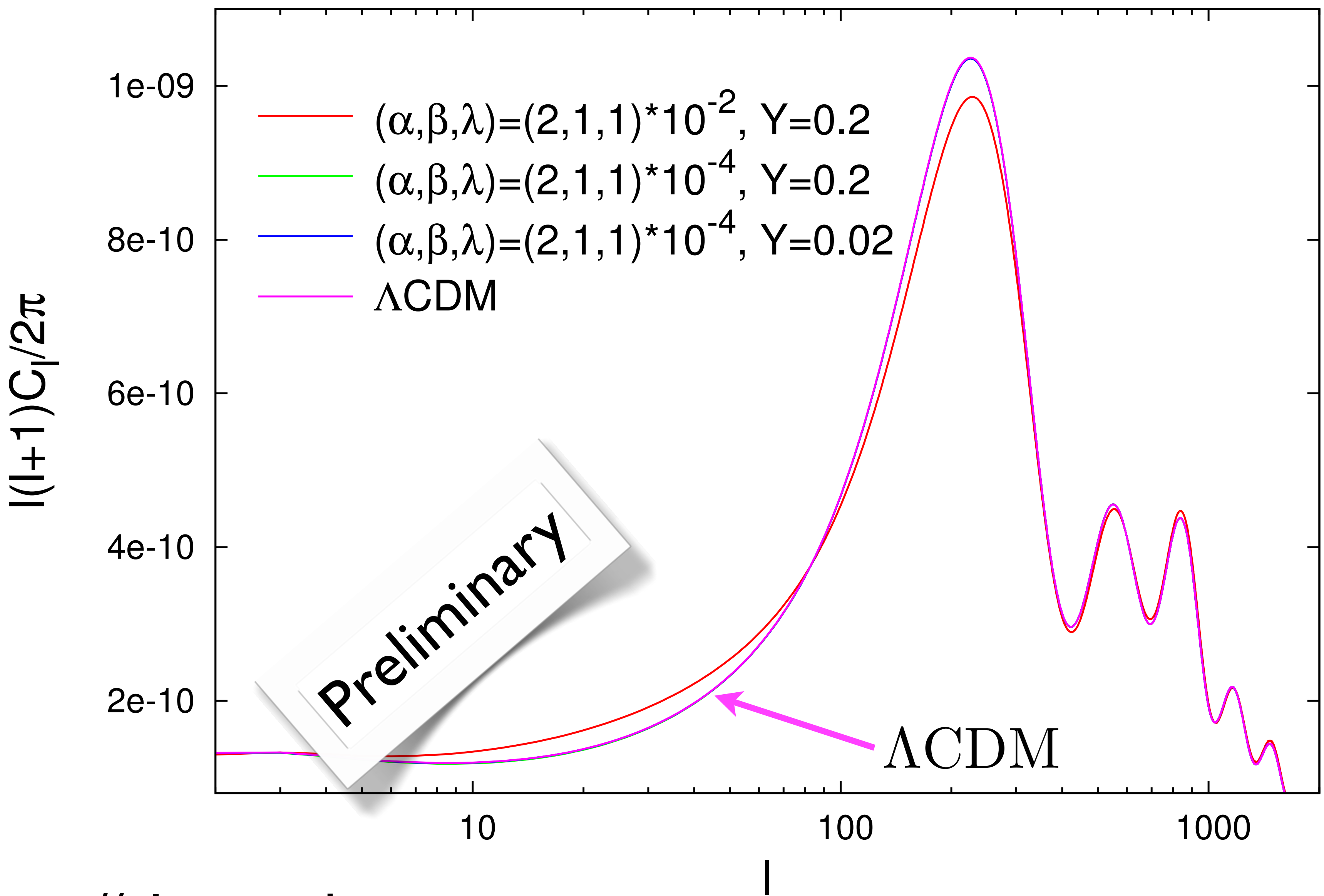


Rough constraint

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

http://class-code.net

Cosmic microwave background

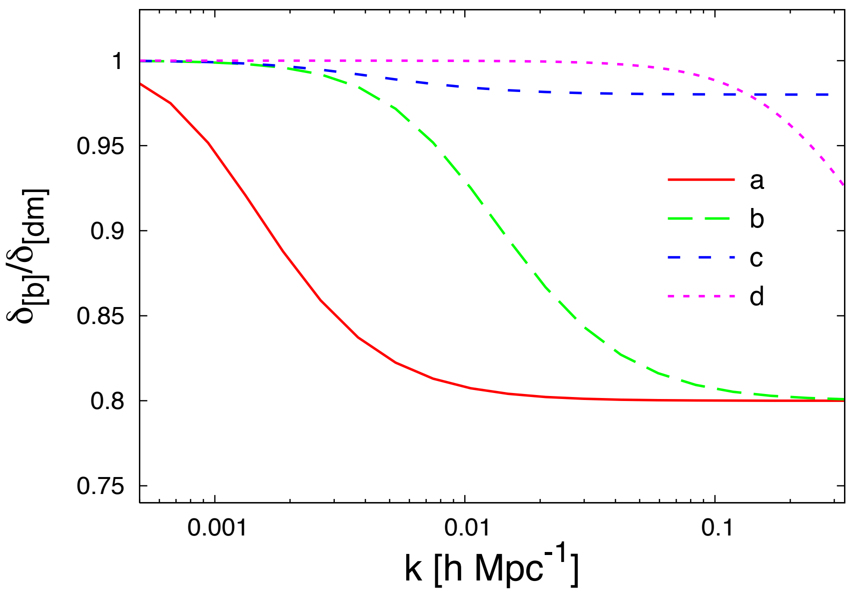


http://class-code.net

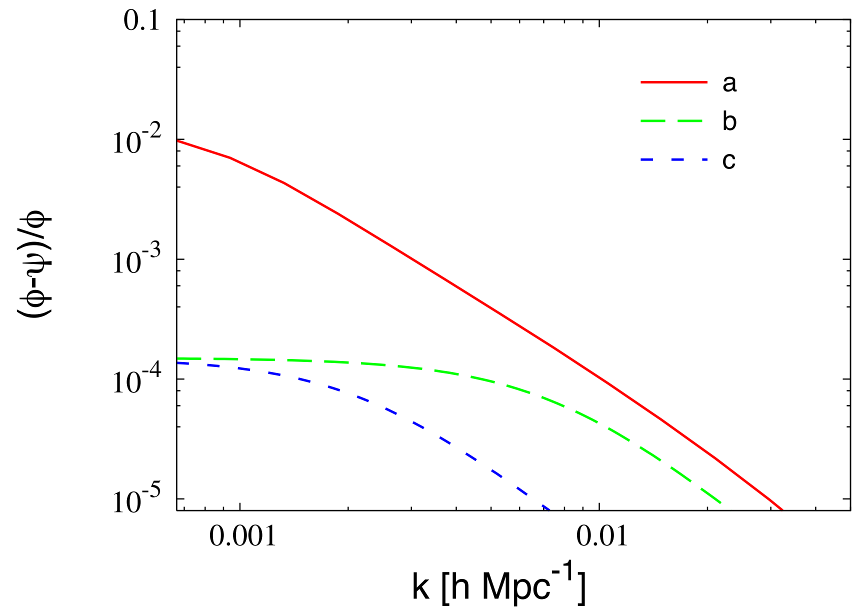
$Y < 10^{-2}$

Other effects

Baryons bias



Anisotropic stress



	α	β	λ	Y	$k_{Y,0}$ (h Mpc^{-1})	$k_{Y,eq}$ (h Mpc^{-1})
a	$2 \cdot 10^{-2}$	10^{-2}	10^{-2}	0.2	$9.2 \cdot 10^{-4}$	$6.5 \cdot 10^{-2}$
b	$2 \cdot 10^{-4}$	10^{-4}	10^{-4}	0.2	$9.1 \cdot 10^{-3}$	0.65
c	$2 \cdot 10^{-4}$	10^{-4}	10^{-4}	0.02	$2.6 \cdot 10^{-3}$	0.18
d	10^{-7}	0	10^{-7}	0.2	0.41	29

Rough constraint on LV in dark matter:

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

Summary

- Developing theoretical frameworks for deviations from LI is important to better understand our Universe
- Effects of LV in **dark matter** on cosmology: same background evolution, but distinct signals for (linear) perturbations.
- Cosmological observations allow to constrain deviations from LI in **dark matter** at the level 10^{-2} or better

OUTLOOK

* Study of the parameter space, comparison with data, effects at non-linear scales