Testing Lorentz Invariance of the Universe

Université libre Bruxelles

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in collaboration with Benjamin Audren, Diego Blas, Julien Lesgougues, Sergey Sibiryakov

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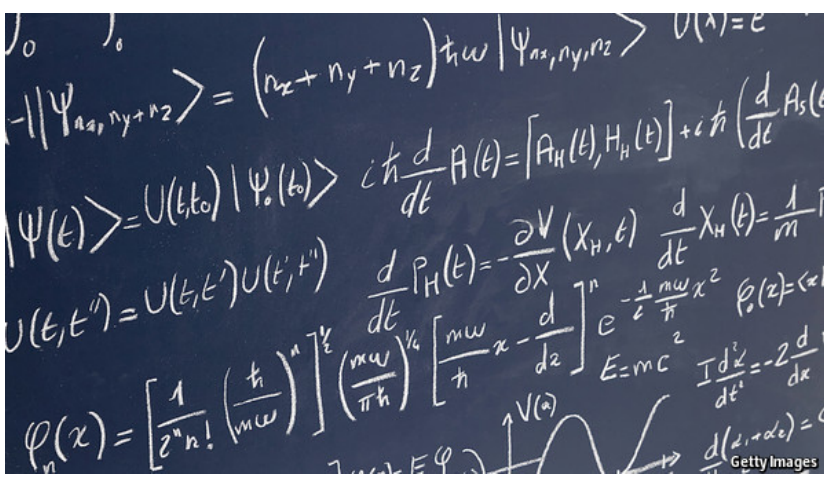
arXiv:1409.xxxx

Problems in theoretical physics

Field theory in UV:

1) Quantum gravity
2) GUT
3) SUSY/strings
4) …



More theorists!

Particle physics:

1) Neutrino masses
2) Hierarchy problem
3) BSM
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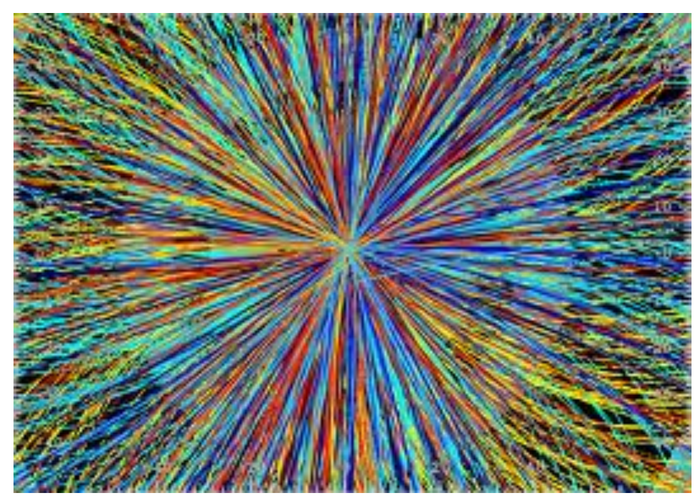
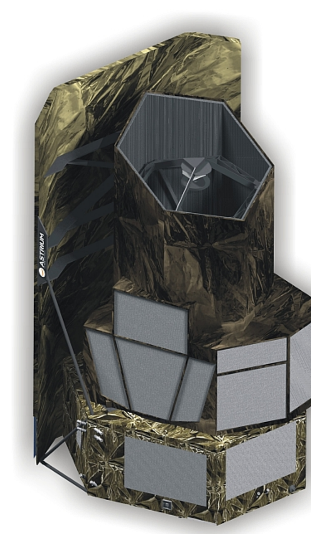


LHC new runs
other experiments

Cosmology:

1) Dark Matter
2) Dark Energy
3) Inflation
4) Baryon asymmetry



Euclid, LiteBird…

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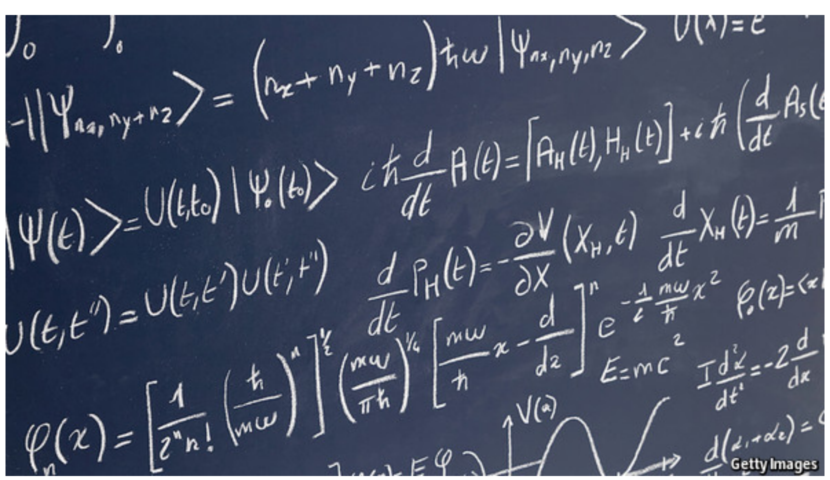

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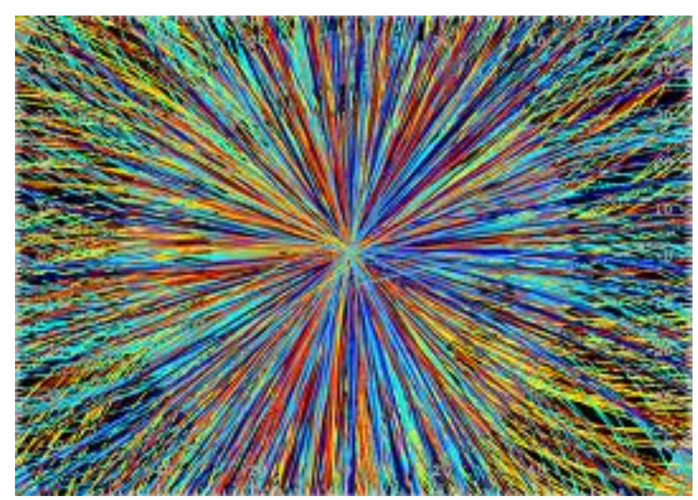

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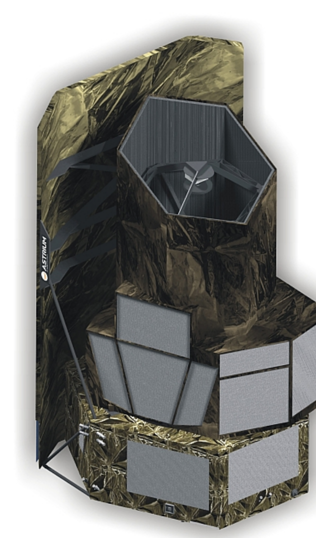

Euclid, LiteBird…

Why Lorentz Invariance?

All current data are compatible with
the ΛCDM model
(assumes Lorentz Invariance as a fundamental property
of Nature)

GR is a unique LI theory of gravity with EOM
of the second order

Very precise tests and tight bounds
on LI in the SM sector

$$< 10^{-20}$$

Why not Lorentz Invariance?

For other sectors
bounds are milder or even don't exist!

Gravity	Dark Matter	Dark Energy
$< 10^{-7}$	$???$	$< 10^{-2}?$

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Abandoning LI =>
good for UV behaviour in gravity
(Horava' 09)

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Addressing dark energy and inflation:
massive gravity, ghost condensate,…

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Given the key role played by LI in modelling Nature,
it is essential to test it to the best possible accuracy in all the sectors

Outline of my talk:

Lorentz-violating gravity: from UV to IR

LV in dark matter

Physical effects of LV on cosmological observables

Current constraints on LV in gravity and dark matter

Anisotropic scaling: idea

Lifshitz, 1941

$$S = \int dt d^3x \left(\dot{\varphi}^2 - \varphi(-\Delta)^z \varphi - V(\varphi)\right)$$

$$\mathbf{x} \mapsto b^{-1}\mathbf{x}\ , \quad t \mapsto b^{-z} t\ , \quad \varphi \mapsto b^{(3-z)/2}\varphi$$

$z = 3$ ➡ φ is dimensionless

The most general renormalizable action:

$$S = \int dt d^3x \Big[\dot{\varphi}^2 + \left(A_1(\varphi)\Delta^3\varphi + A_2(\varphi)(\partial\varphi)^6 + \ldots\right) + \left(B_1(\varphi)\Delta^2\varphi + B_2(\varphi)(\partial\varphi)^4 + \ldots\right) + C^2(\varphi)\varphi\Delta\varphi - V_0(\varphi)\Big]$$

$$G \sim \frac{1}{|\vec{k}|^6}$$

Second order in time derivatives ➡ no ghosts

$C^2(0) = c^2$ ➡ linear dispersion relation $\omega^2 = c^2 p^2$ in IR

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Nice UV-properties $G \sim \frac{1}{|\vec{k}|^6}$

Second order in time derivatives → no ghosts

$C^2(0) = c^2$ → linear dispersion relation $\omega^2 = c^2p^2$ in IR

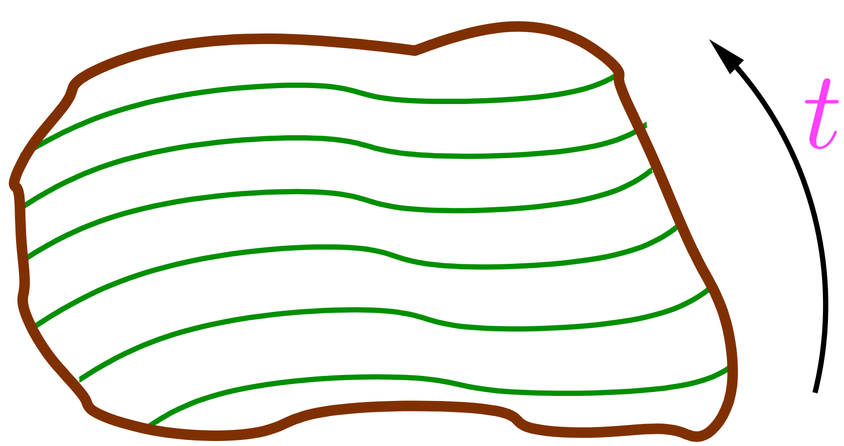
Gravity with anisotropic scaling

Let's do something similar for gravity

I) Lorentz group is a gauge group, thus its breaking gives

→ new degree of freedom

II) Geometrically, preferred time amounts to splitting coordinates in space and time, in other words, equipping space-time manifold with space-like foliations



Excitation of the foliation = new scalar dof.

ADM decomposition of the metric (in GR -- a gauge choice)

$$ds^2 = (N^2 - N_i N^i)dt^2 - 2N_i dt dx^i - \gamma_{ij} dx^i dx^j$$

Horava gravity

+ Blas, Pujolas, Sibiryakov'09

$$S = \frac{M_P^2}{2}\int d^3x dt \sqrt{\gamma} N \Big(K_{ij}K^{ij} - \zeta K^2 - \mathcal{V} \Big)$$

$$K_{ij} = \frac{\dot{\gamma}_{ij} - \nabla_i N_j - \nabla_j N_i}{2N}$$

difference from GR

projectable model

$$\mathcal{V}_I = -\xi R \quad + \quad M_*^{-2}\big(A_1 \Delta R + A_2 R_{ij} R^{ij} + \dots\big)$$
$$+ \quad M_*^{-4}\big(B_1 \Delta^2 R + B_2 R_{ij} R^{jk} R_k^i + \dots\big)$$

non projectable

$$\mathcal{V}_{II} = \mathcal{V}_I - \alpha a_i a^i$$
$$+ M_*^{-2}\big(C_1 a_i \Delta a^i + C_2 (a_i a^i)^2 + C_3 a_i a_j R^{ij} + \dots\big)$$
$$+ M_*^{-4}\big(D_1 a_i \Delta^2 a^1 + D_2 (a_i a^i)^3 + D_3 a_i a^i a_j a_k R^{jk} + \dots\big)$$

R_{ij} -- 3d Ricci tensor

$a_i \equiv N^{-1}\partial_i N$

ADM decomposition

$$ds^2 = (N^2 - N_i N^i)dt^2 - 2N_i dt dx^i - \gamma_{ij} dx^i dx^j$$

Think of the splitting as physical

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$$K_{ij} = \frac{\dot{\gamma}_{ij} - \nabla_i N_j \ldots}{\ldots}$$

Gradient inst.
Strong coupling

$$\mathcal{V}_I = \ldots R + A_2 R_{ij}R^{ij} + \ldots)$$

$$\ldots M_*^{-4}(B_1 \Delta^2 R + B_2 R_{ij}R^{jk}R^i_k + \ldots)$$

$$\mathcal{V}_{II} = \mathcal{V}_I - \alpha a_i a^i$$

$$+ M_*^{-2}(C_1 a_i \Delta a^i + C_2 (a_i a^i)^2 + C_3 a_i a_j R^{ij} + \ldots)$$

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difference from GR

projectable model

non projectable

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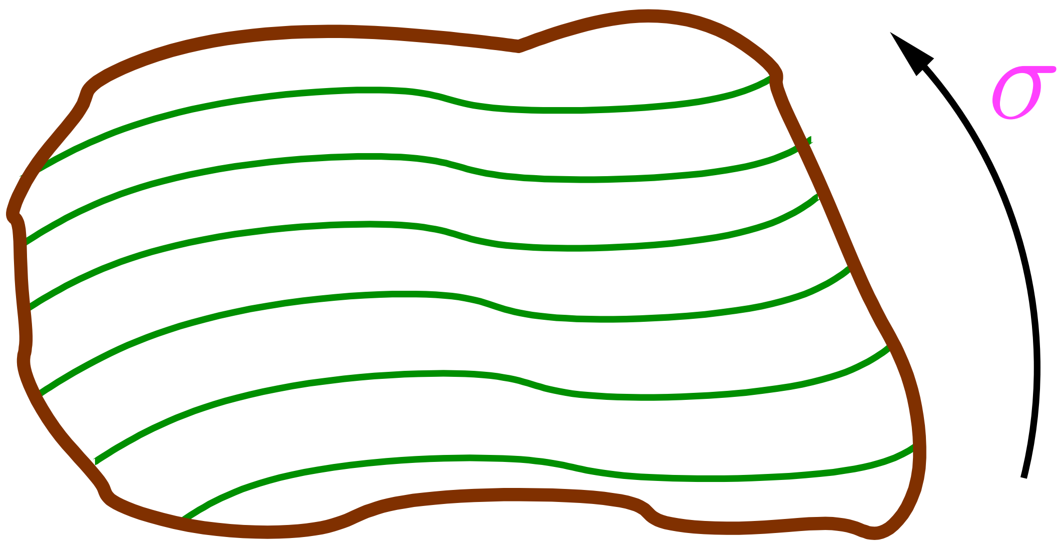
Think of the splitting as physical

Stuckelberg description

Convenient to compare with GR at low energies (where deviations are weak)

Inconvenient to analyse the UV structure (where deviations from GR are strong)



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

ADM formulation = the gauge $t = \sigma$

σ sets global time

Khronon !

Low-energy action

Invariant object -- unit normal to the foliation surfaces:

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

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

$$+\lambda\left(\nabla_\mu u^\mu\right)^2 + \alpha u^\mu u^\nu \nabla_\mu u_\rho \nabla_\nu u^\rho\Big]$$

cf. with Einstein-aether theory (Jacobson and Mattingly'01): an EFT for unit time-like LV vector

$$+\, c_1 \sqrt{-g}\nabla_\mu u^\nu \nabla^\mu u_\nu \qquad + l(u_\mu^2 - 1)$$

Both theories have the same scalar and tensor sectors!
(completely characterised by α, β, λ)

Degrees of freedom

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

$$+\lambda\left(\nabla_\mu u^\mu\right)^2 + \alpha u^\mu u^\nu \nabla_\mu u_\rho \nabla_\nu u^\rho\Big]$$

- ★ Massless Spin 2 graviton $\omega^2 = c_t^2\,\mathrm{k}^2$
- ★ $\varphi = t + \chi$ massless scalar (new force!)

Khronon (→ χ)

$$\omega^2 = c_\chi^2\,\mathrm{k}^2$$

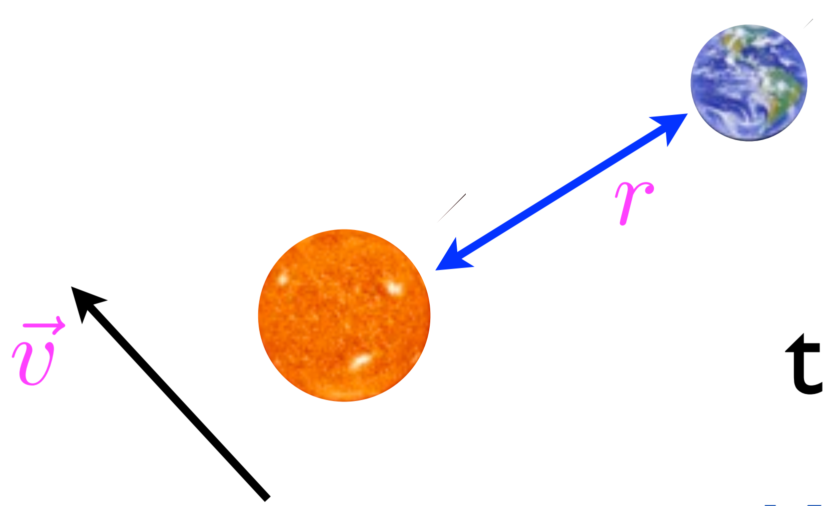
$$c_t^2 = \frac{1}{1-\beta}$$

$$c_\chi^2 = \frac{\beta+\lambda}{\alpha}$$

EA-case: extra vector polarisations

not relevant for CMB-TT and LSS

Constraints from the visible sector



PPN bounds $|\alpha, \beta, \lambda| < 10^{-7}$

can be avoided for
the special choice of parameters:

Khronometric: $\alpha = 2\beta$

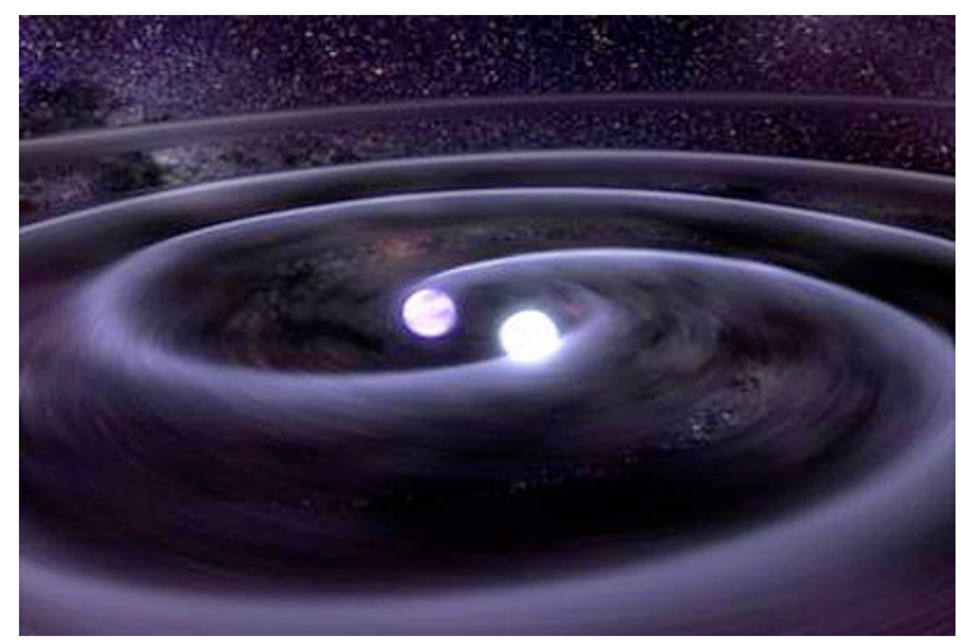
Einstein-aether: $\alpha = -(\beta + 3\lambda)$

Constrains from GW emission in binary systems, cosmology (Einstein -aether only)

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

Yagi, Blas, Yunes, Barouse'14

Zuntz, Ferreira ,Zlosnik'08



Dark matter

Is non-relativistic (small velocities).
Is it possible to test its Lorentz invariance?

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Yes!

number density

DM-aether interaction:

$$S_{[\mathrm{DMu}]} = -m \int \mathrm{d}^4 x \sqrt{-g}\, n\, F(u_\mu v^\mu)$$

(assume DM - perfect pressureless fluid)

D.Blas, MI, S.Sibiryakov' 12

aether

DM 4-velocity

LV effects related to DM are summarised in

$$Y \equiv F'(1)$$

Relativistic cosmology - ΛLVDM model

$$G_{\mu\nu} = \frac{1}{M_P^2} T_{\mu\nu}^{SM} + \frac{1}{M_P^2} T_{\mu\nu}^{dm,LV} + \frac{1}{M_P^2} T_{\mu\nu}^{aether} + \Lambda g_{\mu\nu}$$

$$T_{\mu\nu}^{dm,LV} = T_{\mu\nu}^{dm} + Y \cdot \rho_{[dm]} O(u_\mu v_\nu^{[dm]})$$

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Blas, Sibiryakov' 11

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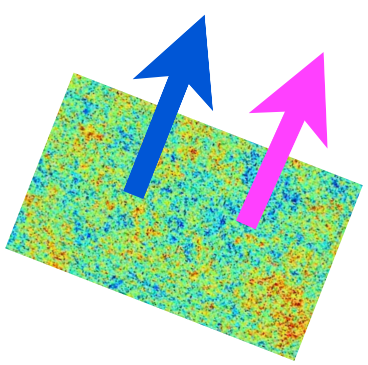
Background: Homogeneous and isotropic (preferred foliation aligned with CMB frame)



$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = \mathrm{d}t^2 - a(t)^2 \mathrm{d}x^i \mathrm{d}x^i$$

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

Friedmann equations almost not modified!

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_c}{3}\rho_m$$

$$G_c = \frac{1}{8\pi M_P^2[1 + 3\lambda/2 + \beta/2]}$$

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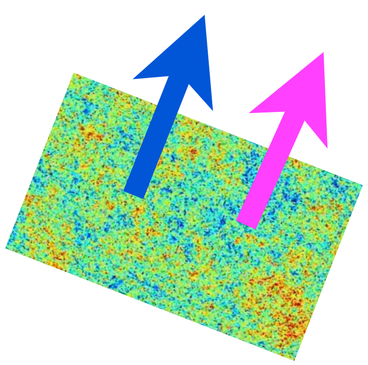


$$ds^2 = g_{\mu\nu} dx$$

$$u_\mu = (u_0(t),$$

Friedmann eq

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_c}{3} \rho_m$$

differs from Newtonian limit

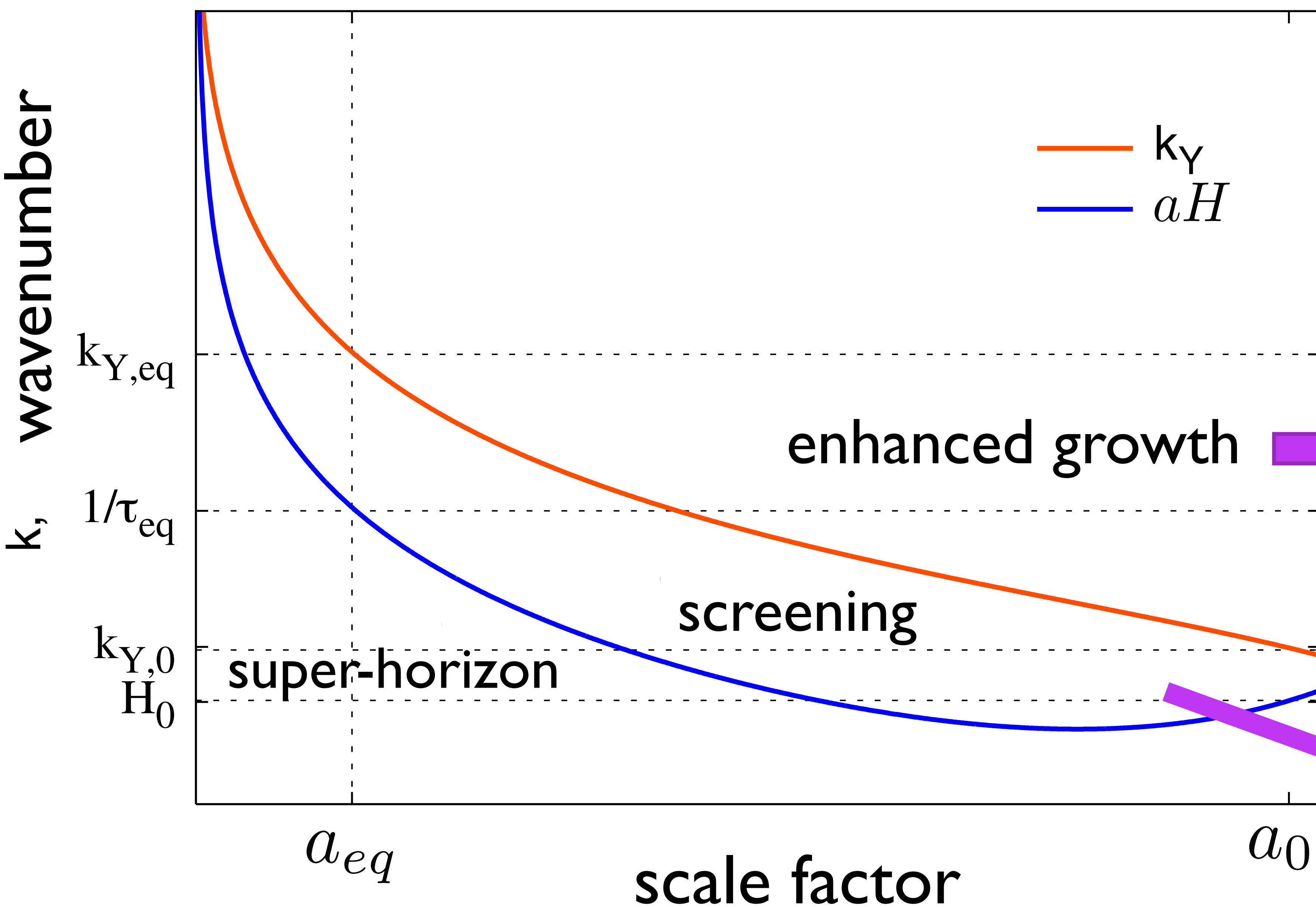
$$G_N = \frac{1}{8\pi M_P^2 (1 - \alpha/2)}$$

$$G_c = \frac{1}{8\pi M_P^2 [1 + 3\lambda/2 + \beta/2]}$$

Effects on perturbations: LV in DM

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

Screening horizon



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

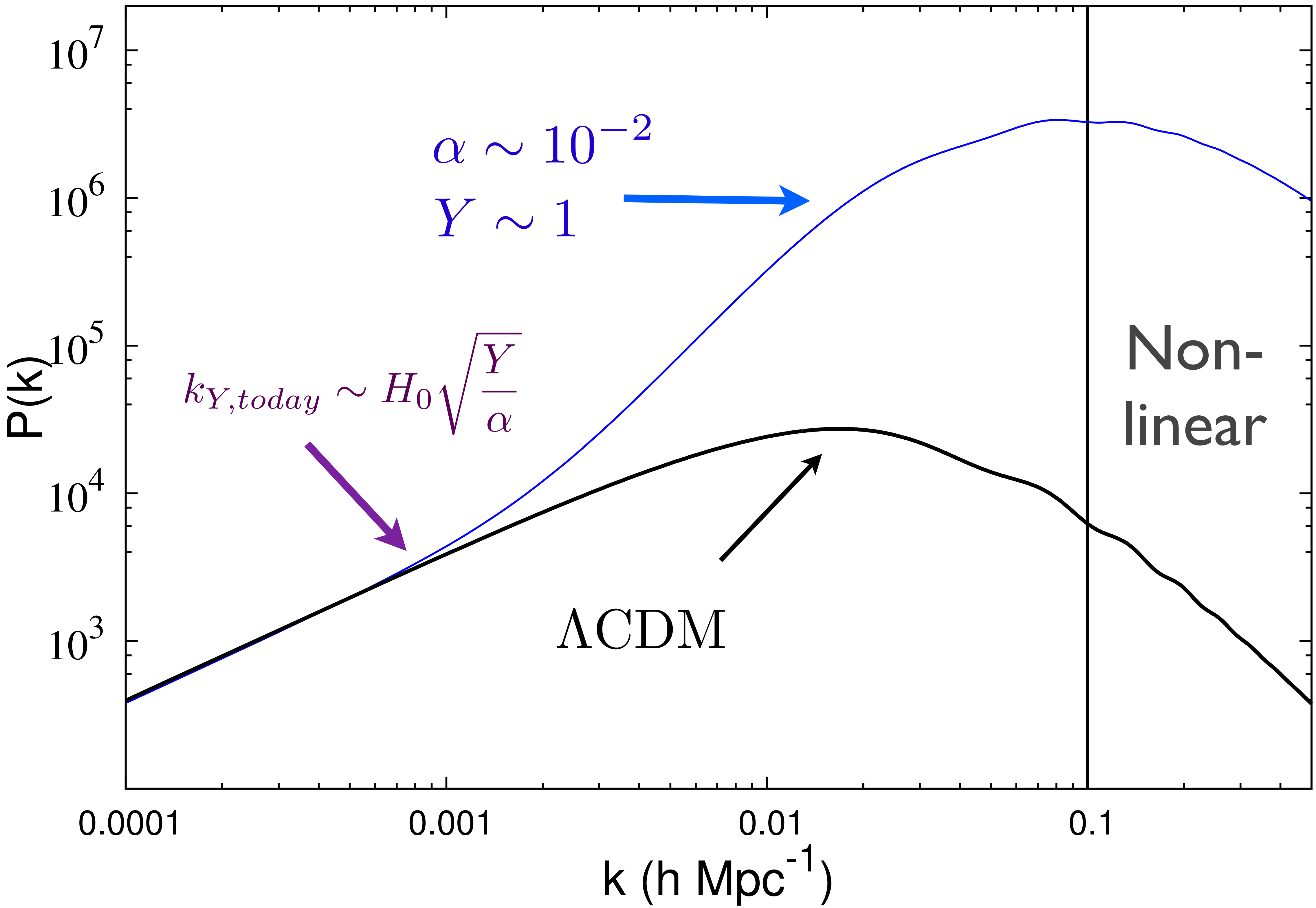
$$\delta \sim a^{1+\frac{\kappa}{2}}$$

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

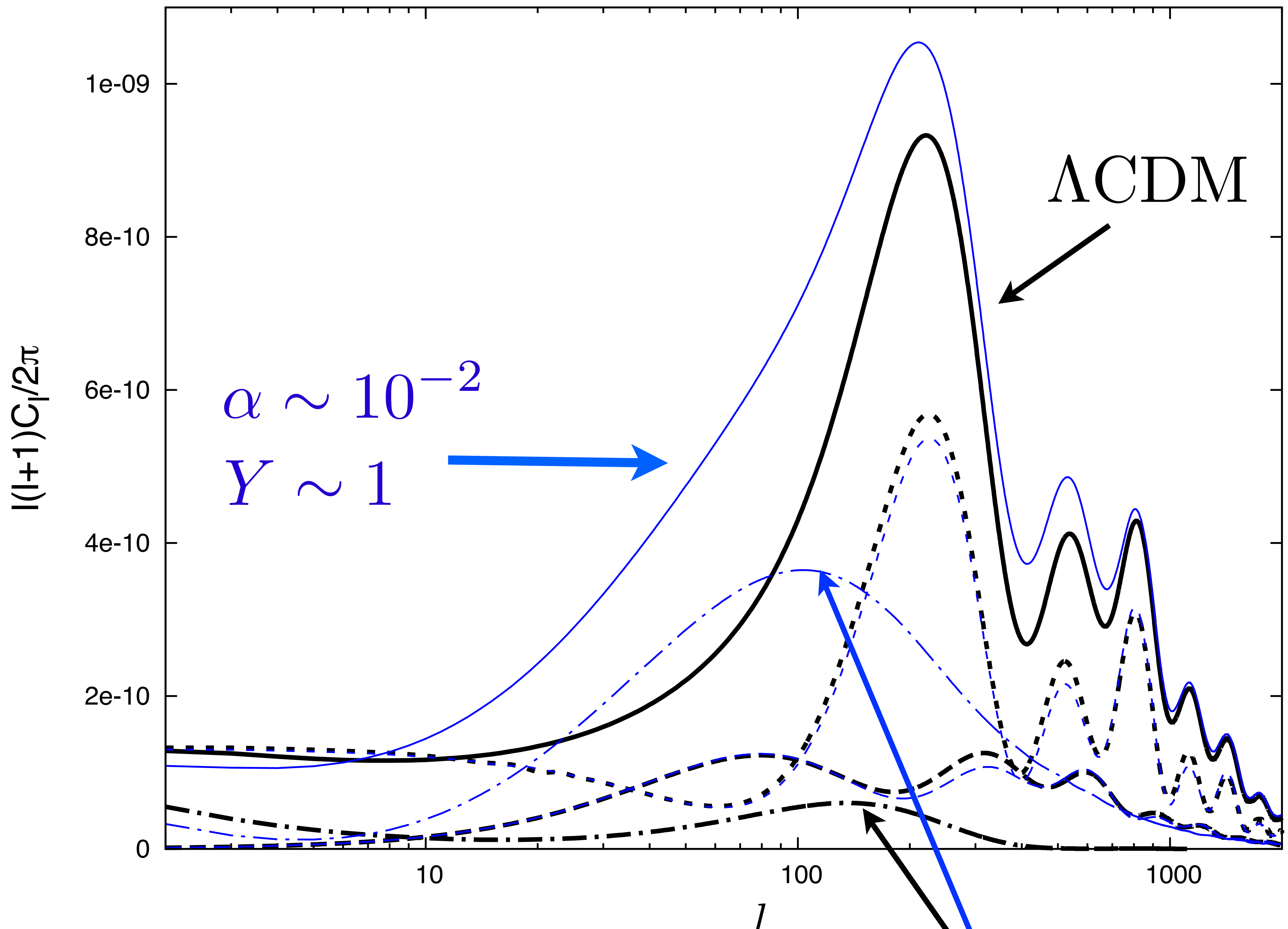
$$\delta \sim a$$

LV in DM: Matter power spectrum

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



LV in DM: Cosmic microwave background



$$\frac{\delta T}{T} = \phi + \delta_\gamma/4 + \vec{v}_\gamma \cdot \vec{n} + 2\int_{t_{rec}}^{t_0} dt\dot{\phi}$$

Sachs-Wolfe Doppler Integrated Sachs-Wolfe

LV in gravity: effects on perturbations

1) Modified Poisson equation:

$$H^2 = 8\pi G_c \rho/3$$

$$G_c = \frac{G_0}{1+\beta/2+3\lambda/2}$$

$$k^2\phi = -4\pi G_N a^2[\Sigma\rho_i\delta_i + \delta\rho_{aether}]$$

$$G_N = G_0/(1-\alpha/2)$$

$$\frac{G_N}{G_c} - 1 = \frac{\alpha+\beta+3\lambda}{2} + O(2)$$

DM, baryons
matter domination

$$\delta \sim \tau^{(-1+\sqrt{1+24\frac{G_N}{G_c}})/2}$$

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matter domination

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+ Solar system constraints

Khronometric ($\alpha = 2\beta$)

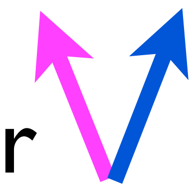
$$\frac{G_N}{G_c} - 1 = \frac{3(\beta+\lambda)}{2} + O(2) > 0$$

Einstein-Aether:

$$\frac{G_N}{G_c} - 1 = O(2)$$

LV in gravity: effects on perturbations

II) Anisotropic stress:



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

$$\phi - \psi = O(\beta)$$

Free-streaming below the scale imposed by

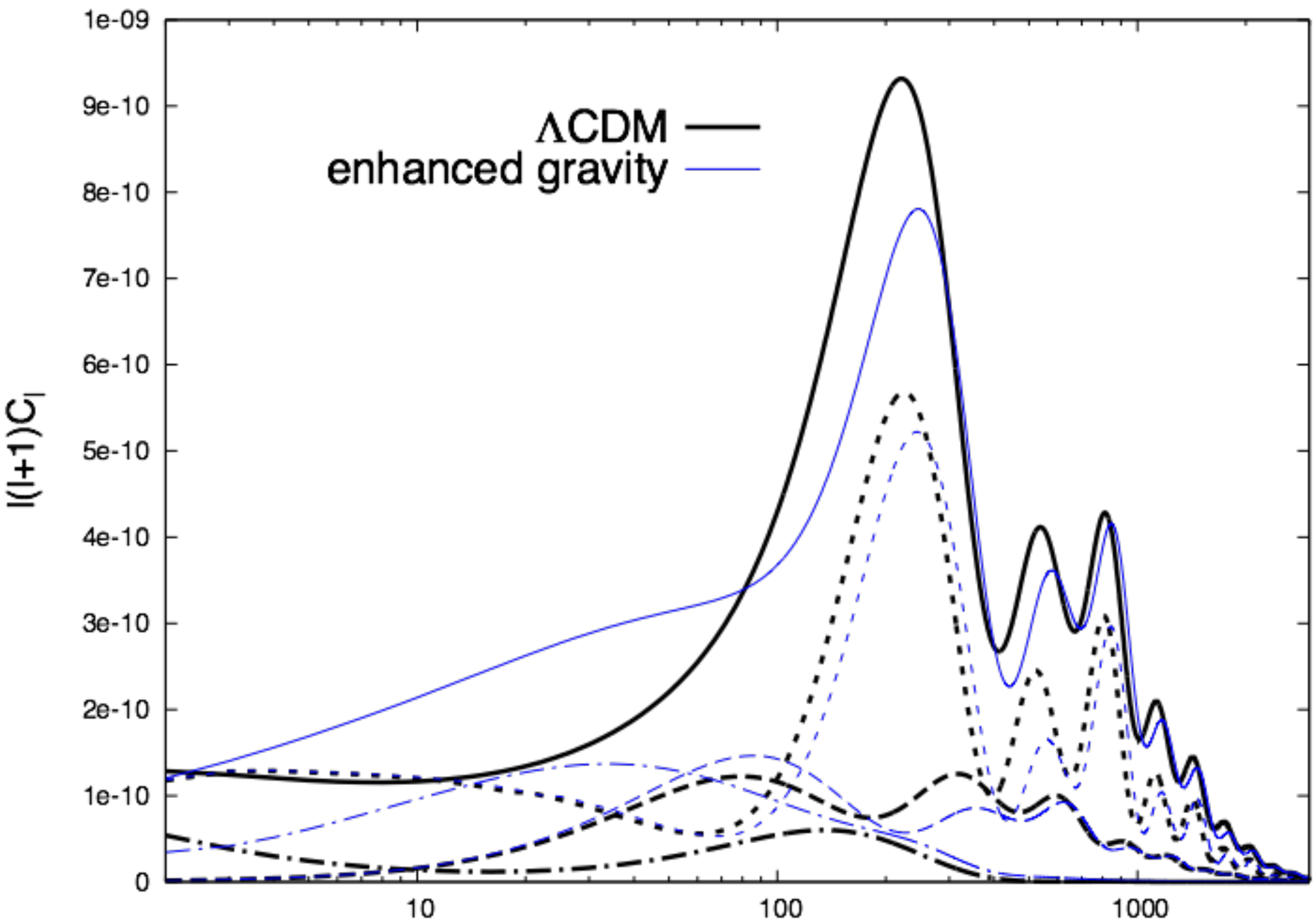
c_χ - aether speed of sound

Enhanced gravity: effects on CMB

$$\frac{G_N}{G_c} - 1 \sim 1$$

$$\beta = 0$$

$$Y = 0$$



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Sachs-Wolfe   Doppler   Integrated Sachs-Wolfe

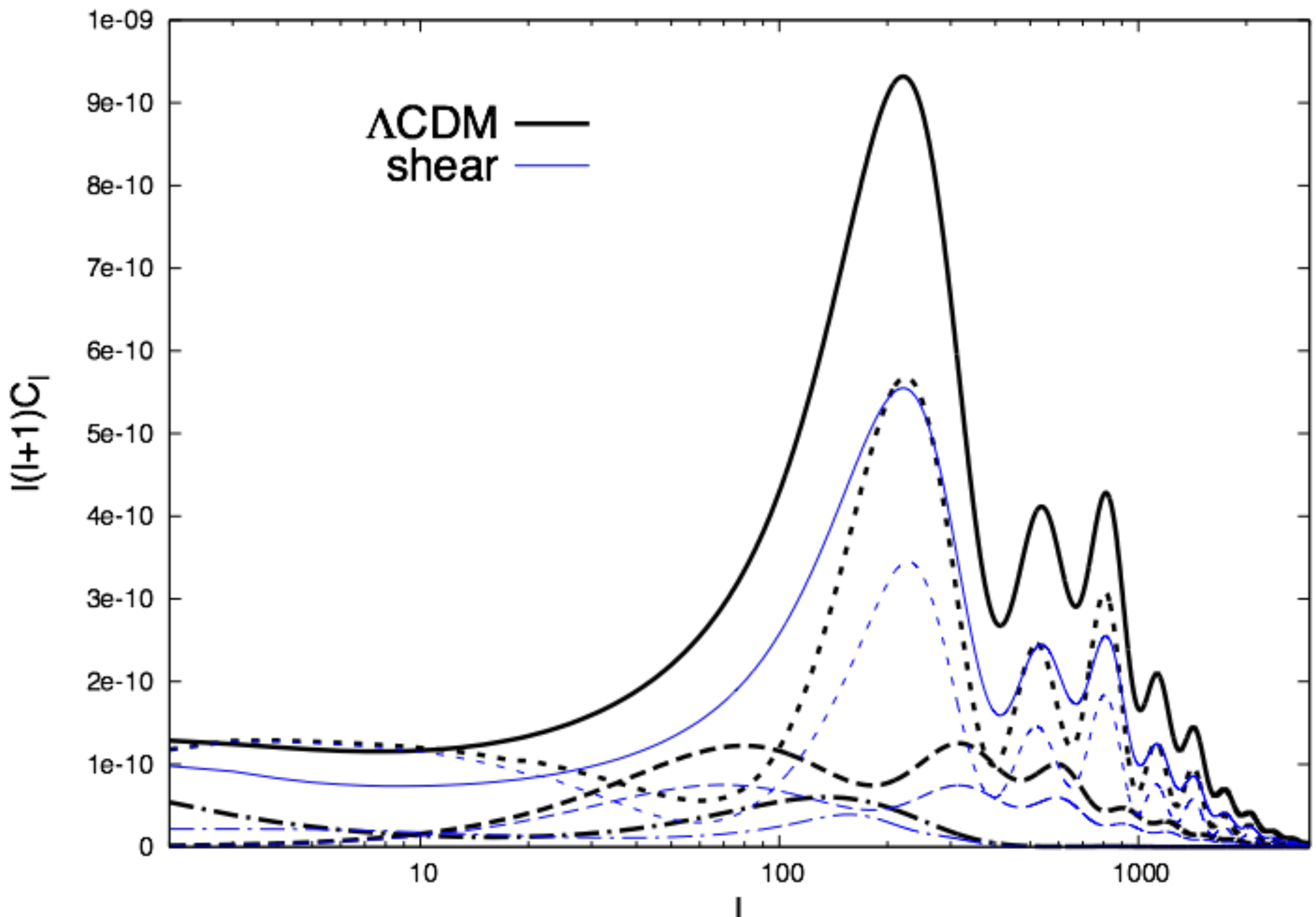
B.Audren, D.Blas, J.Lesgourgues, S.Sibiryakov 13'

Shear: effects on CMB

$\beta \sim 1$

$\frac{G_N}{G_c} - 1 = 0$

$Y = 0$



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LV in gravity: effects on MPS

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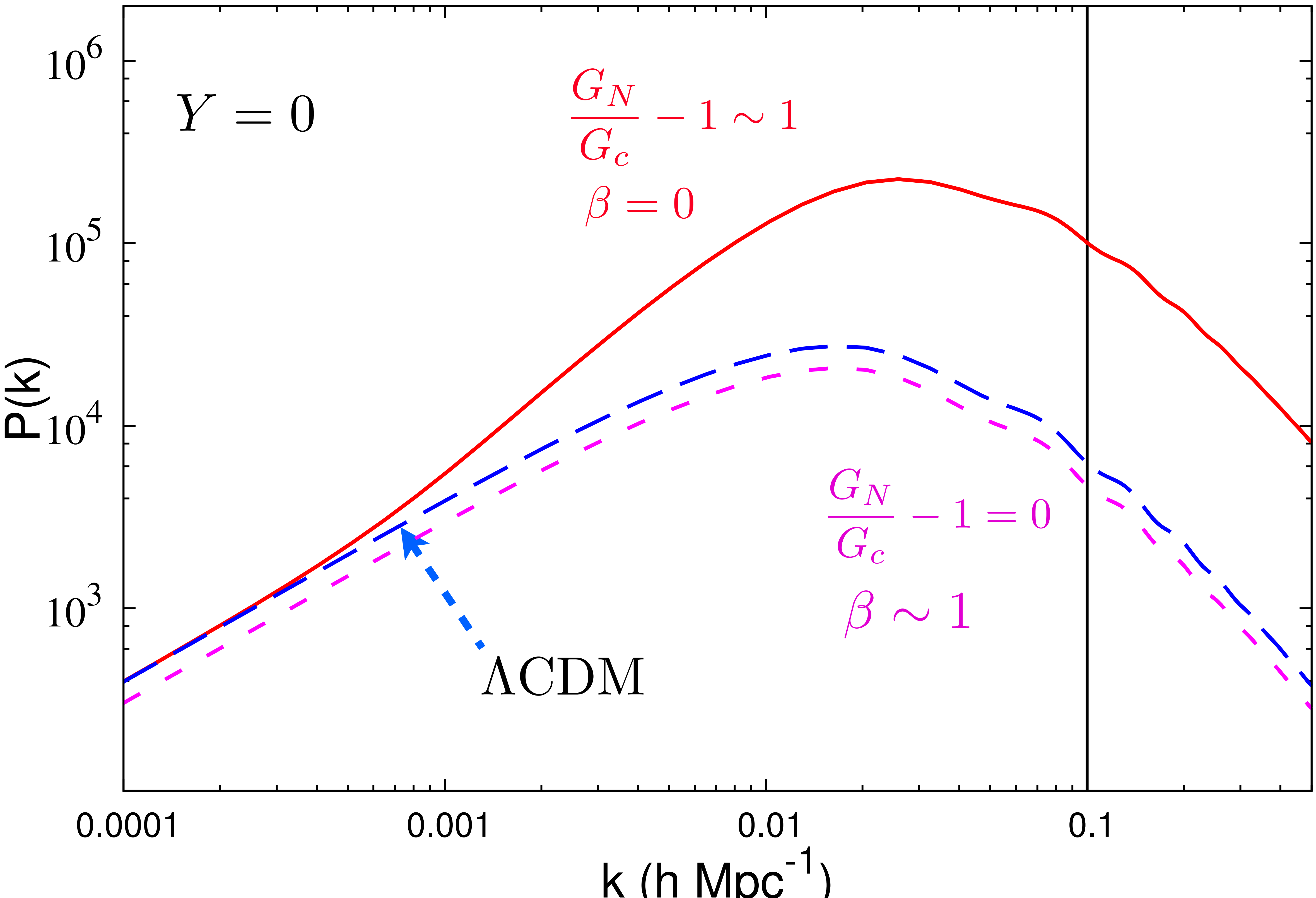
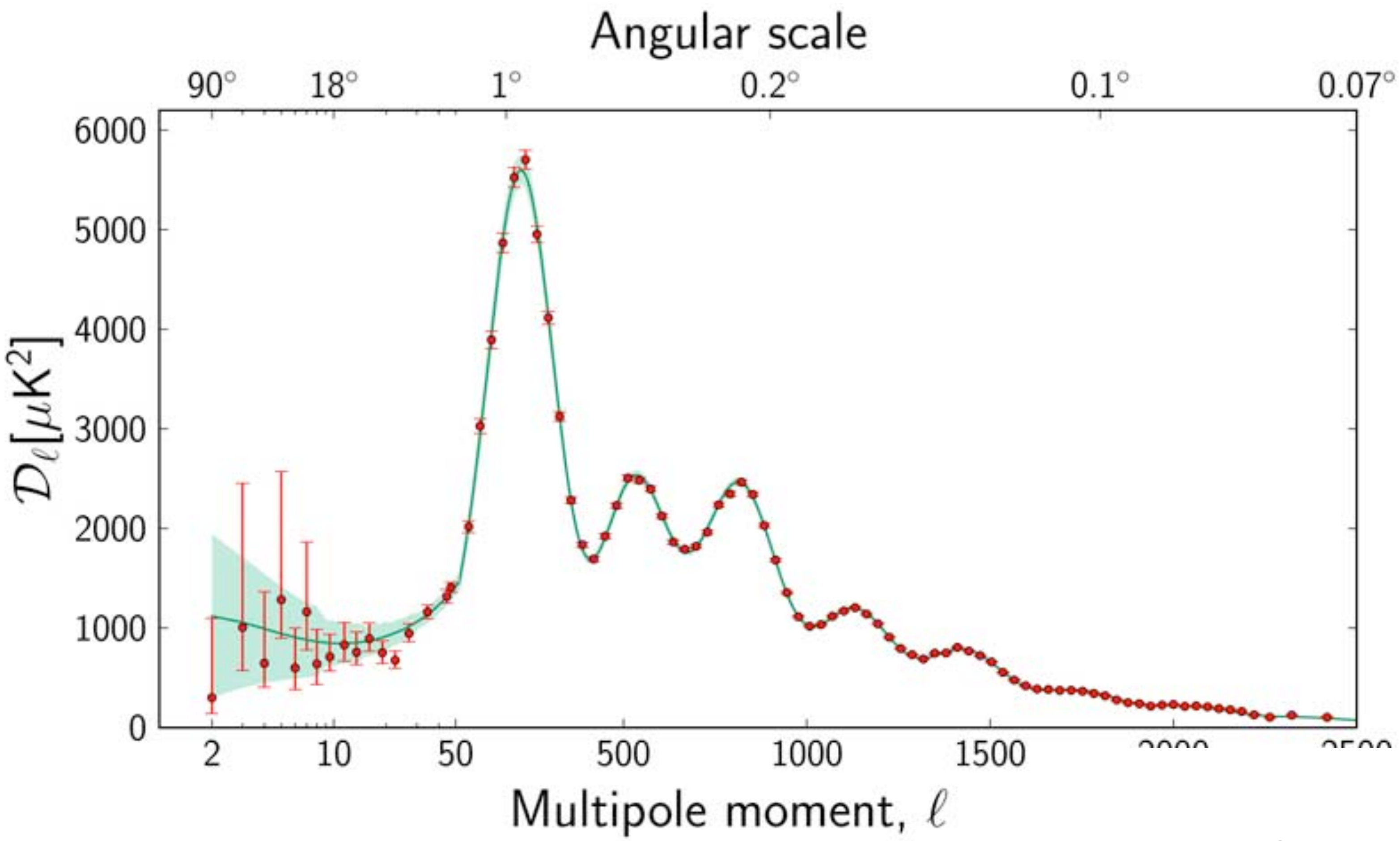
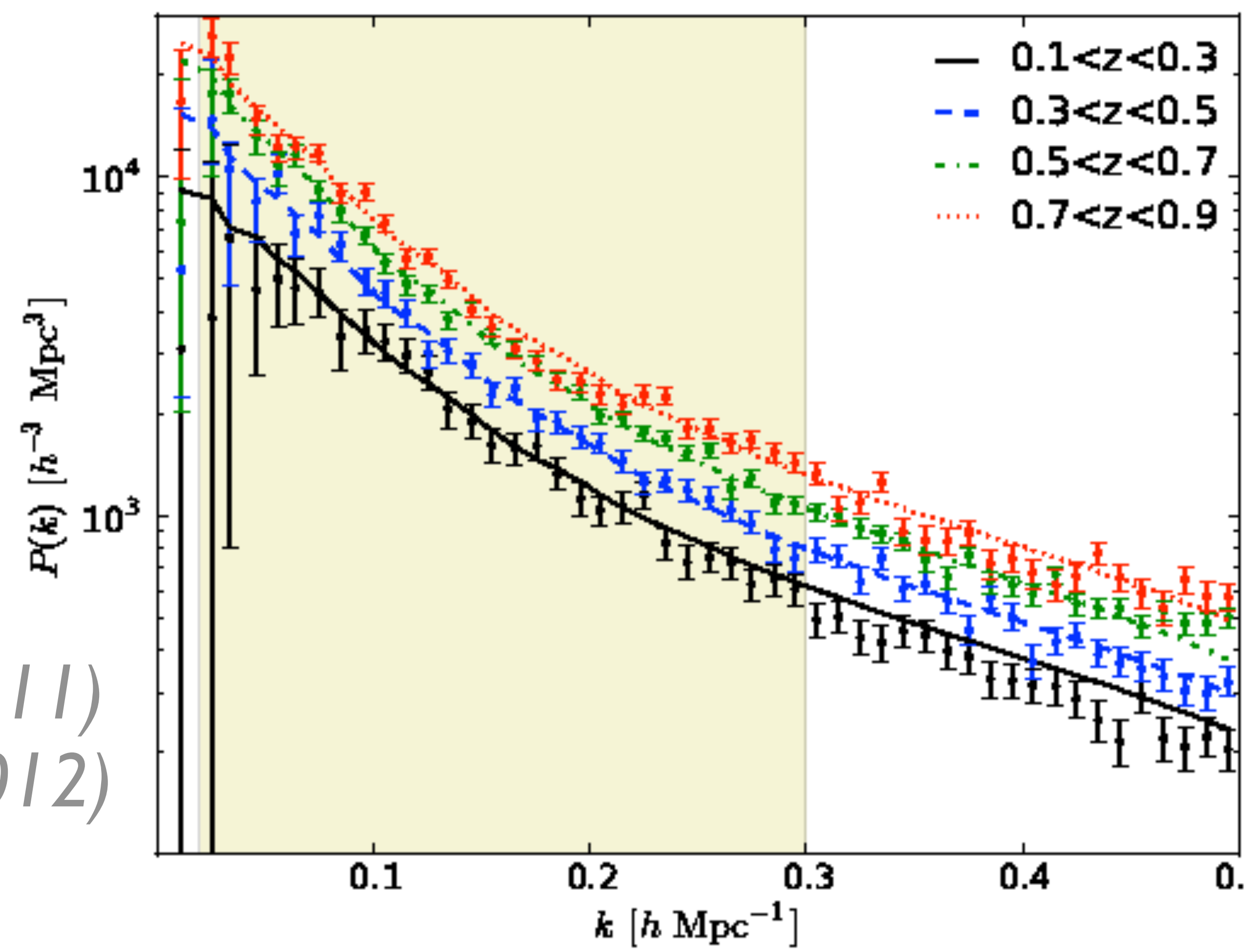


Observational data



Planck

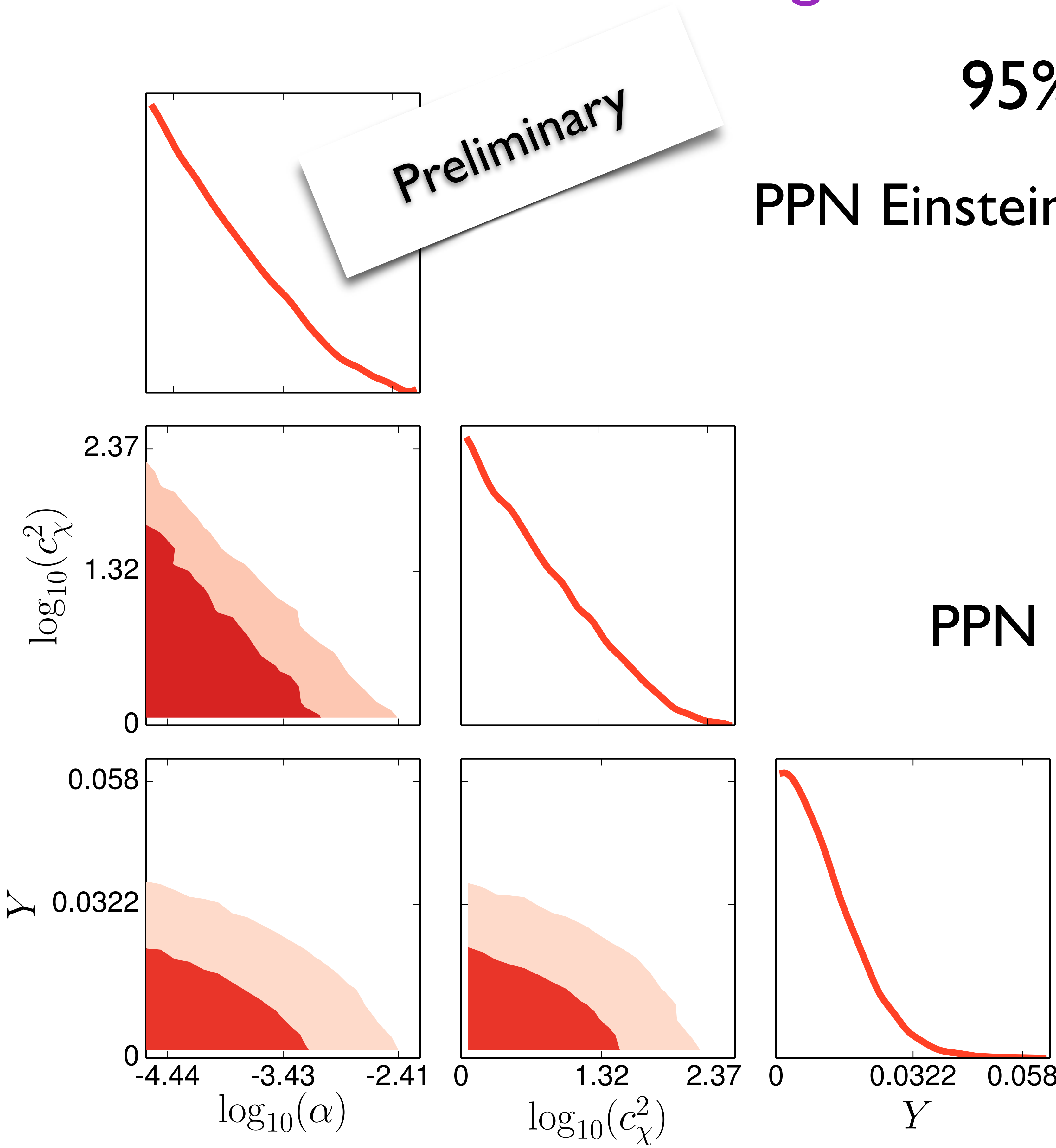
WiggleZ survey



use CLASS *Blas, Lesgourgues, Tram (2011)*

and MONTE PYTHON *Audren et. al. (2012)*

Cosmological bounds



95% CL upper limits

PPN Einstein-aether $3\lambda = -(\alpha + \beta)$

$$\alpha < 5.0 \cdot 10^{-3}$$
$$c_\chi^2 < 240$$
$$Y < 0.028$$

PPN Khronometric $\alpha = 2\beta$

$$\alpha < 1.1 \cdot 10^{-3}$$
$$c_\chi^2 < 54$$
$$Y < 0.029$$

Conclusions:

- Lorentz violation is a consistent framework to test deviations from $\Lambda\mathrm{CDM}$ motivated by quantum gravity

- Consequences of LV in cosmology:
  enhanced growth of structures at small scales (i)
  accelerated growth of structures (ii)
  additional cosmic shear (iii)

- Bounds at the level few $\times 10^{-3}$ on LV in gravity and 0.03 on LV in Dark Matter

Outlook:

* Nonlinear structure formation, 'DM problems'

Other directions:

Technically natural dark energy with LV
- resolves Cosm. Const. Problem

Blas, Sibiryakov' 11 Audren, Blas, Lesgourges, Sibiryakov' 13

Inflation with LV
- curious phenomenology for NG

MI, Sibiryakov' 13

Rigorous treatment of renormalisability in extended Horava's gravity

.....

Thank you for your attention!

Conclusions:

Lorentz violation is a consistent framework to test deviations from $\Lambda\mathrm{CDM}$

Consequences of LV in cosmology:
accelerated growth of structures
+

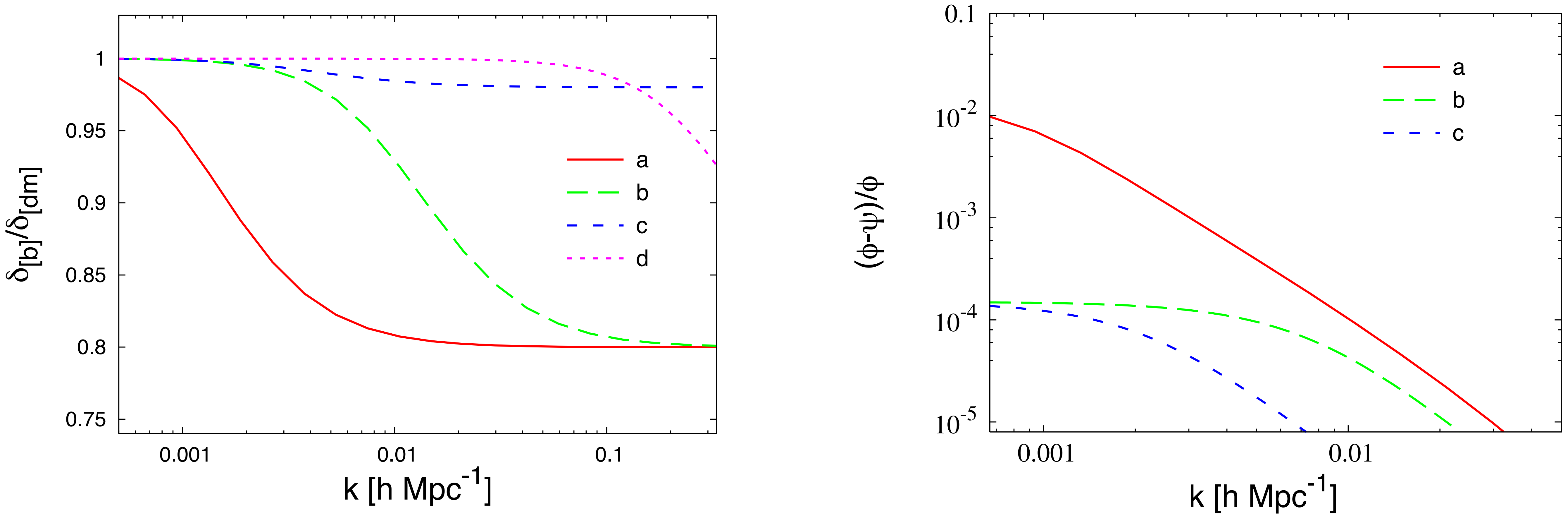
Thank you for your attention!

(depending on LV in gravity)

Outlook:

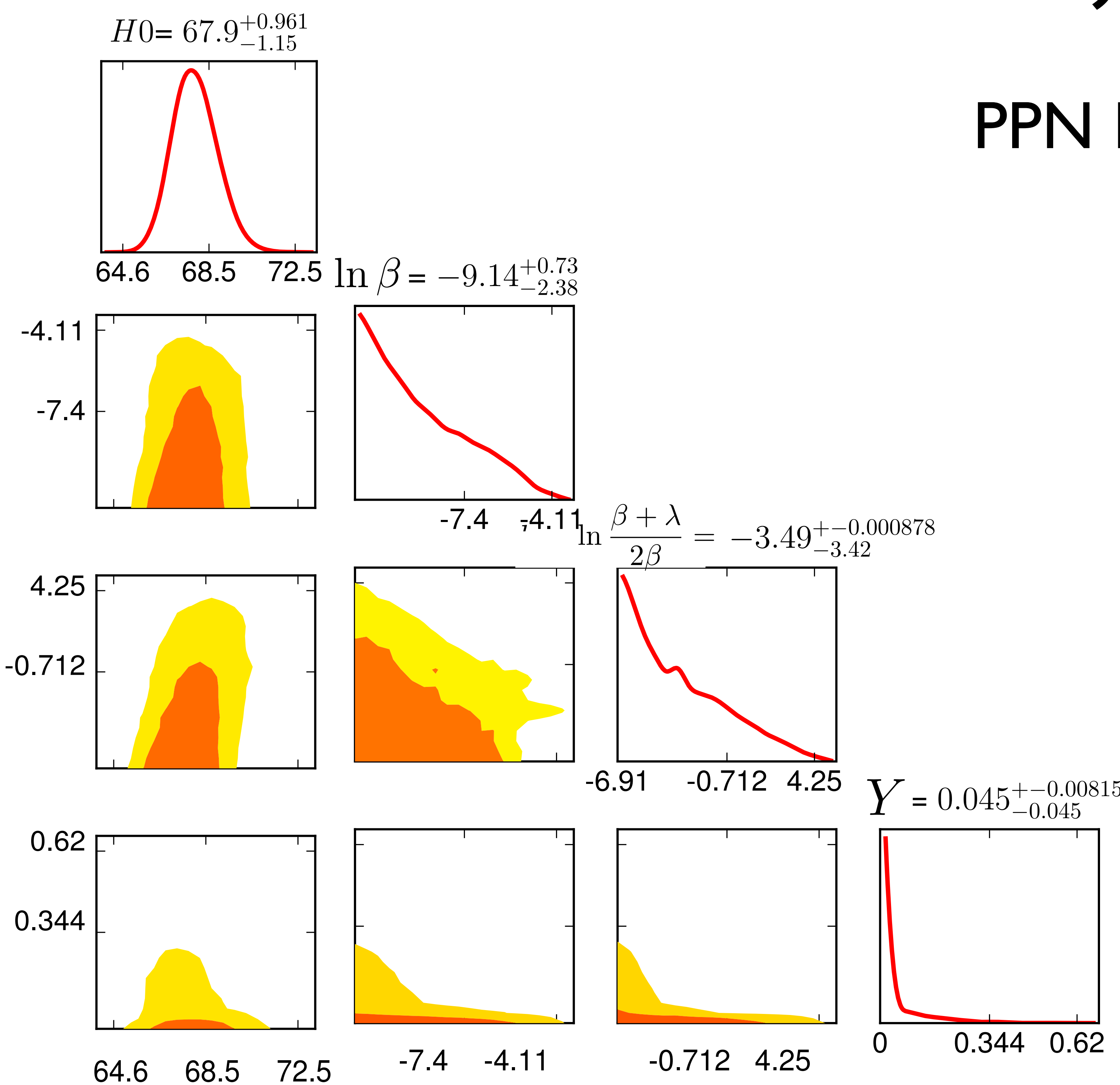
* Nonlinear structure formation, ‘DM problems’

Baryonic bias and 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

Cosmological bounds



95% CL upper limits

PPN Khronometric $\alpha = 2\beta$

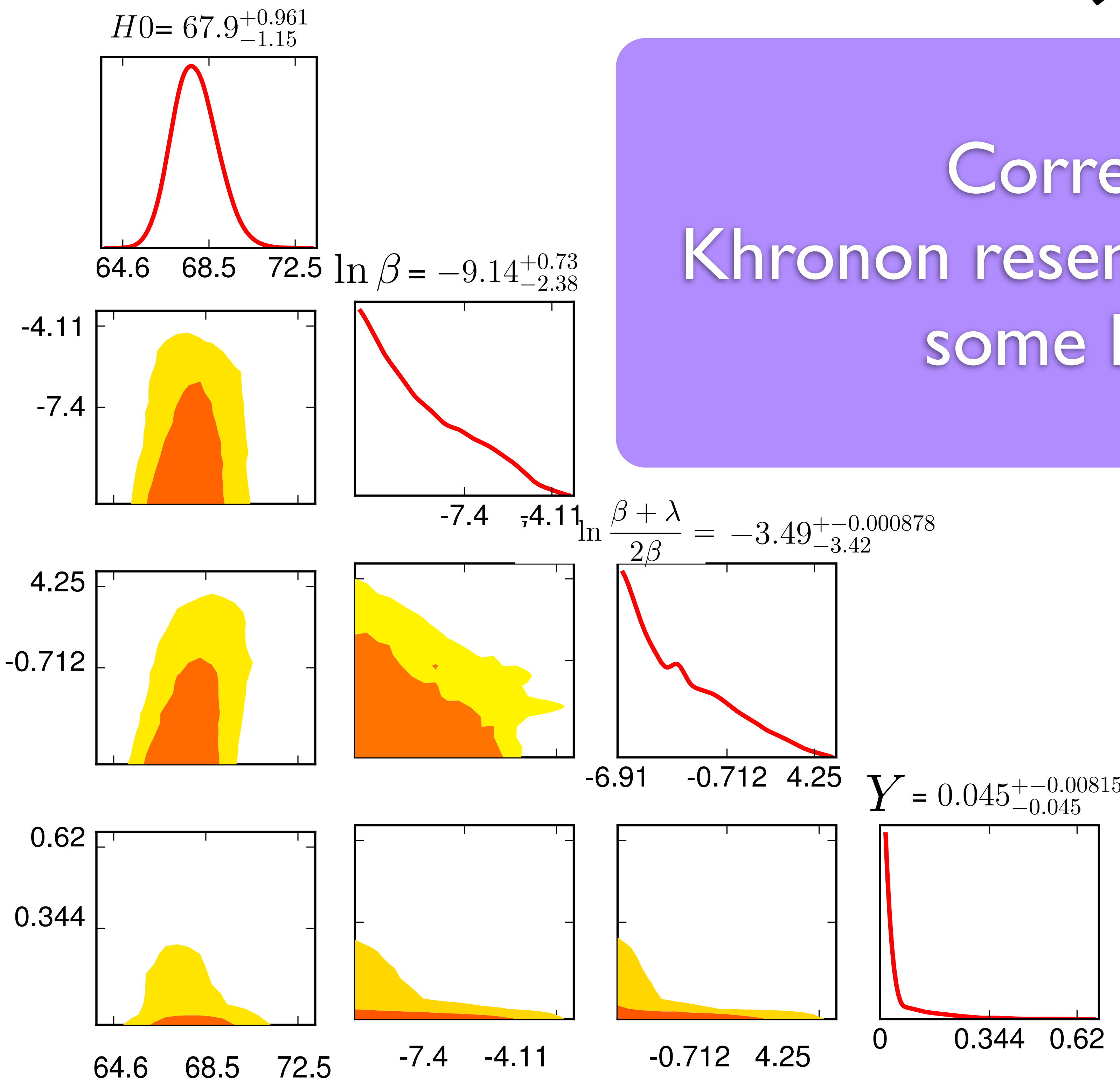
$$\beta < 0.004$$
$$\beta + \lambda < 2 \cdot 10^{-4}$$
$$Y < 0.2$$

PPN Einstein-aether

$$3\lambda = -(\alpha + \beta)$$

$$\alpha < 0.004$$
$$\beta < 0.003$$
$$Y < 0.6$$

Cosmological bounds



95% CL upper limits

Correlation with H0
Khronon resembles dark radiation for some LV parameters !

PPN Einstein-aether

$$3\lambda = -(\alpha+\beta)$$

$$\alpha < 0.004$$

$$\beta < 0.003$$

$$Y < 0.6$$

LV in gravity: effects on perturbations

1) Modified Poisson equation:

$$H^2 = 8\pi G_c \rho/3$$

$$k^2\phi = -4\pi G_N a^2 [\Sigma \rho_i \delta_i + \delta\rho_{aether}]$$

different from G_c , $\frac{G_N}{G_c} - 1 = \frac{\alpha + \beta + 3\lambda}{2} + O(2)$

DM, baryons
matter domination

$$\delta \sim \tau^{\left(-1+\sqrt{1+24\frac{G_N}{G_c}}\right)/2}$$

+ Solar system constraints

Khronometric ($\alpha = 2\beta$ **)**

$$\frac{G_N}{G_c} - 1 = \frac{3(\beta + \lambda)}{2} + O(2) > 0$$

Einstein-Aether:

$$\frac{G_N}{G_c} - 1 = O(2)$$

Gravity action: $g_{\mu\nu}\,, u^{\mu}$

Einstein-aether:

$$S_{æ} \equiv -\frac{M_0^2}{2}\int \mathrm{d}^4x\sqrt{-g}\Big[R + K^{\mu\nu}{}_{\sigma\rho}\nabla_\mu u^\sigma \nabla_\nu u^\rho + l(u_\mu u^\mu - 1)\Big]$$

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

Khronometric:

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

$$\lambda \equiv c_2$$
$$\beta \equiv c_1 + c_3$$
$$\alpha \equiv c_1 + c_4$$

c_i are not independent!

Both theories have the same scalar and tensor sectors!

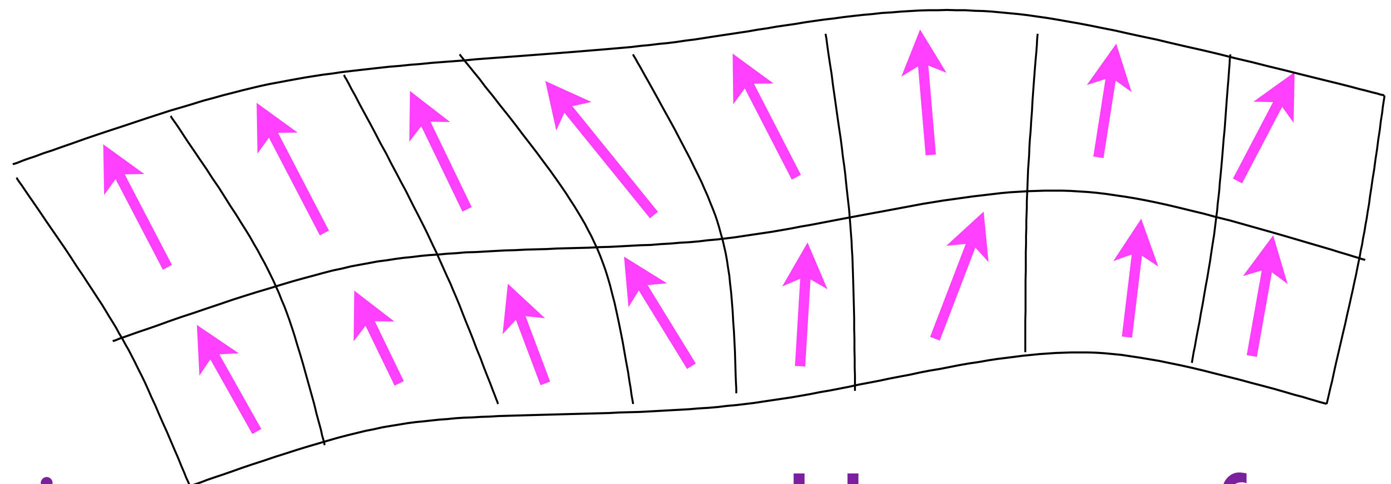
(completely characterized by α, β, λ)

Vectors not relevant for CMB-TT and LSS

Breaking Lorentz Invariance

Space-time filled by a preferred **time** direction

Associated to a time-like unit vector u_μ



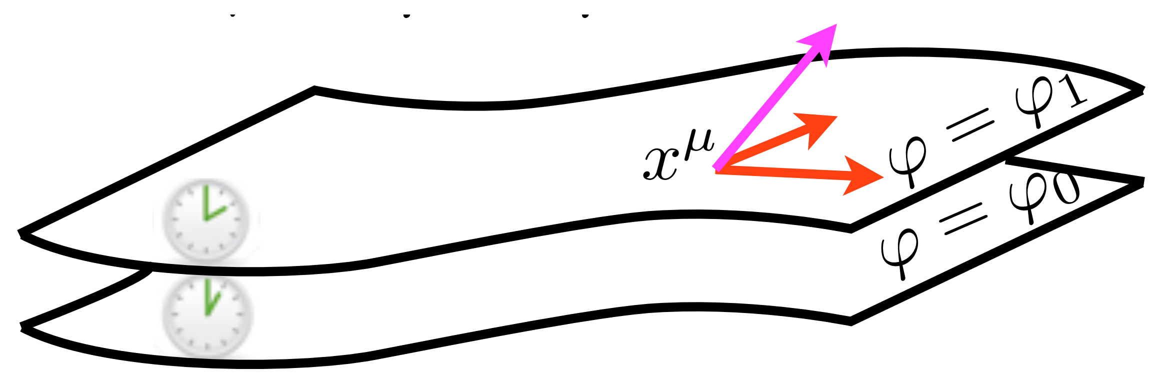
Generic:
Einstein-aether theory

$$u^\mu u_\mu = 1$$

Jacobson, Mattingly' 01

Hypersurface orthogonal:
Khronon

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



Gravity Lagrangian:

Einstein-aether: $\mathcal{L}_{GR} + \mathcal{L}_u$

$$\mathcal{L}_u \sim c_1, c_2, c_3, c_4 \; M_P^2 (\nabla u_\mu)^2$$

Khronometric: $u_\mu = \dfrac{\partial_\mu \varphi}{\sqrt{(\partial\varphi)^2}}$ →

$$\lambda \equiv c_2$$
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c_i are not independent!

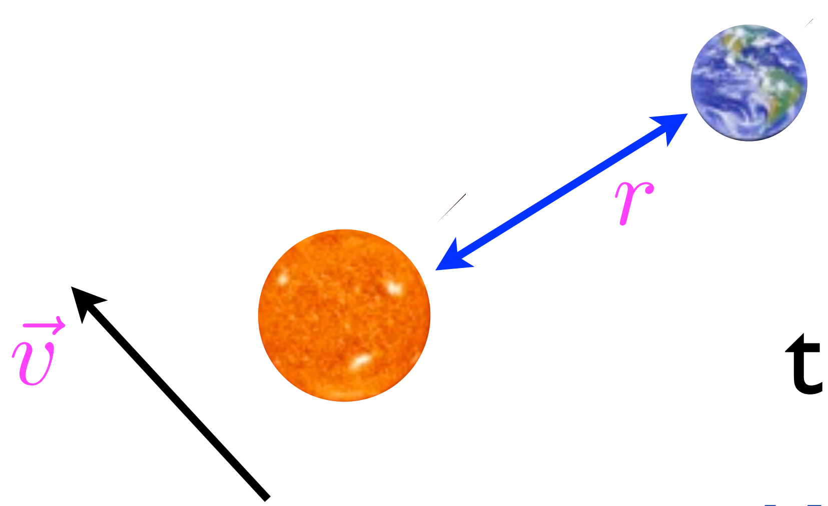
Bot … sectors!

…ss

Low-energy limit of Horava-Lifshitz gravity

$$\Lambda_{IR} \sim \sqrt{\alpha} M_P$$

Constraints from the visible sector



PPN bounds $|\alpha, \beta, \lambda| < 10^{-7}$

can be avoided for
the special choice of parameters:

Khron ... 2β

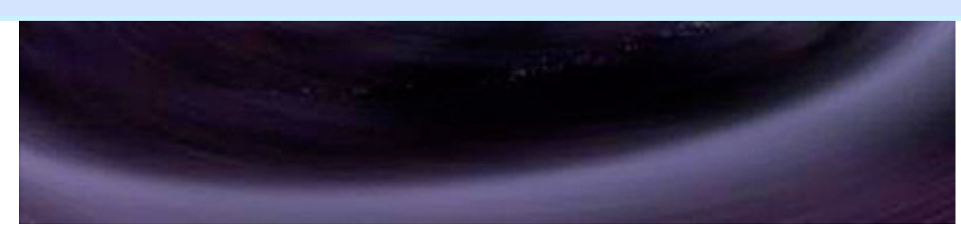
Einste ... $\lambda)$

Can be improved with new cosmological data !

Constrains from GW emissio
binary systems, cosmology
(Einstein -aether only)

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

Zuntz, Ferreira ,Zlosnik'08



All current data are compatible with the ΛCDM model (assumes Lorentz Invariance as a fundamental property of Nature)

Reasons to question this:

Recent successes of Lorentz-violating theory of quantum gravity (Horava' 09)

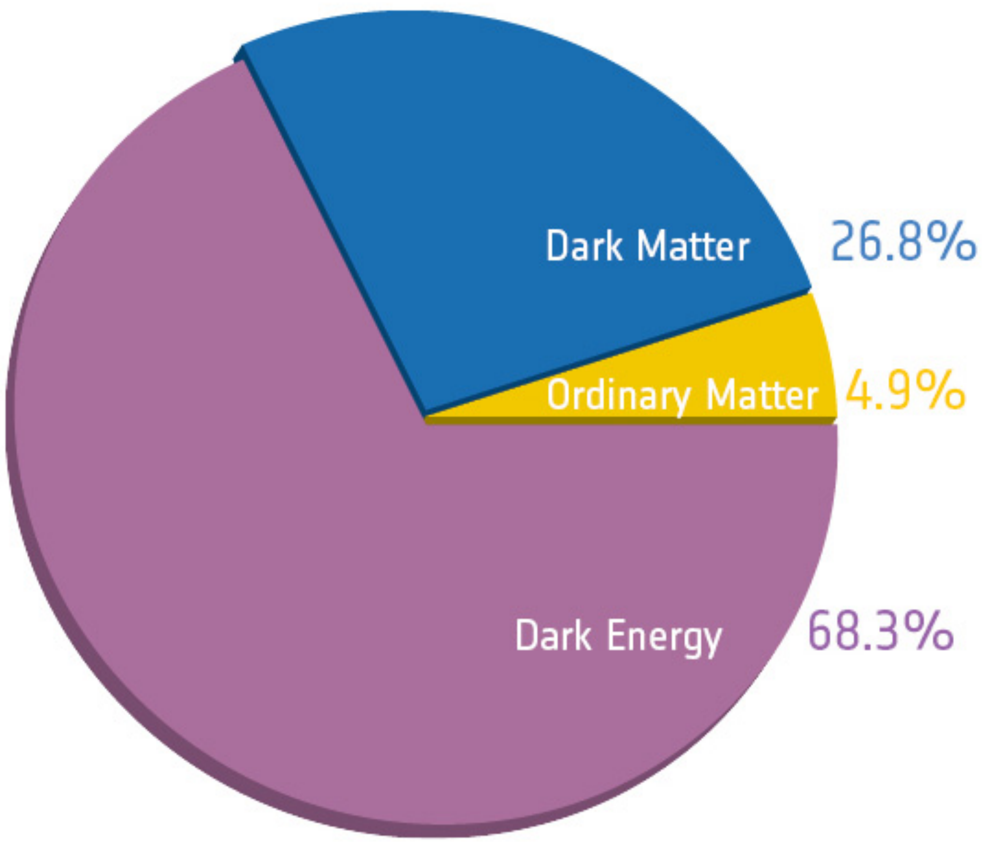
Lorentz invariance has been tightly constrained only in the sector of Standard Model particles

$< 10^{-20}$

What about other sectors?

For other sectors bounds are milder or even don't exist!

Gravity	Dark Matter	Dark Energy
$< 10^{-7}$	???	$< 10^{-2}$?



Given the key role played by LI in modeling Nature, it is essential to test it to the best possible accuracy in all the sectors

Dark matter

Is non-relativistic (small velocities).
Is it possible to test its Lorentz invariance?

Yes!

Generalized point particle action

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

aether

DM velocity

Generalized point particle action

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

aether

DM velocity

Newtonian limit: u^i, v^i - small

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

DM density

$f'(1)$

Generalized point particle action

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aether → u_μ; DM velocity → v^μ

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DM density → ρ; $f'(1)$ → Y

- all effects are encoded in one parameter Y

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- modified inertial mass (coefficient in front of $(v^i)^2$)

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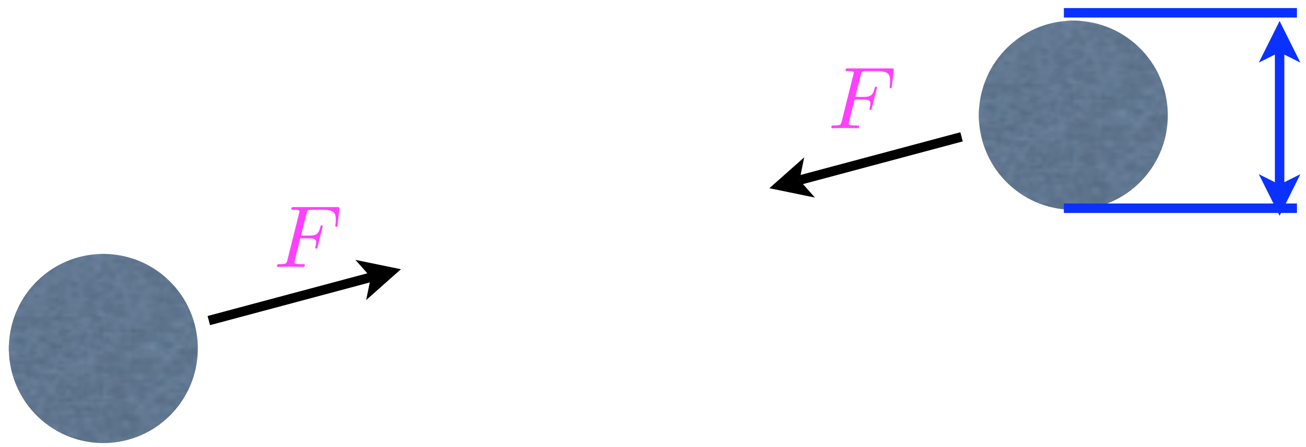
DM density → ρ; $f'(1)$ → Y

- all effects are encoded in one parameter Y
- modified inertial mass (coefficient in front of $(v^i)^2$)
- effective potential for aether in matter $m_{eff} = \frac{Y \rho}{\alpha M_P^2}$



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

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

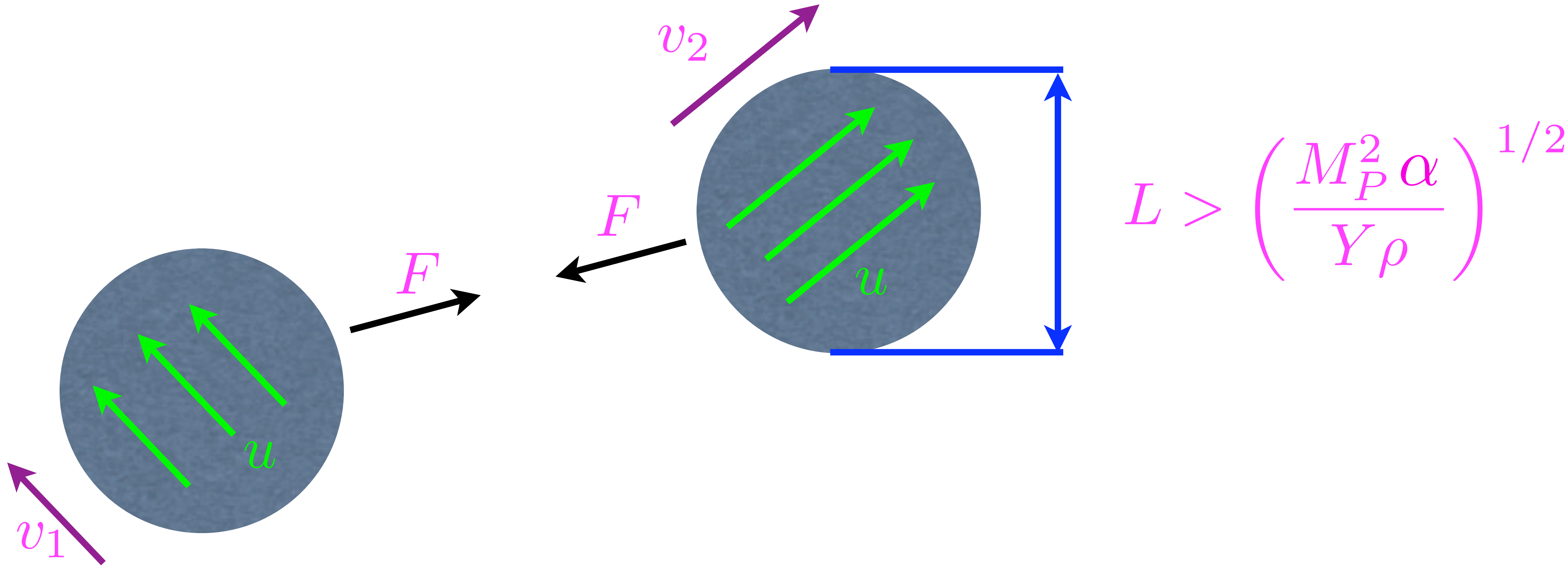
$$m_{\text{inert}} = m_{\text{grav}}(1-Y)$$

Accelerated Jeans instability !

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

$$\frac{\delta\rho}{\rho}$$

density contrast

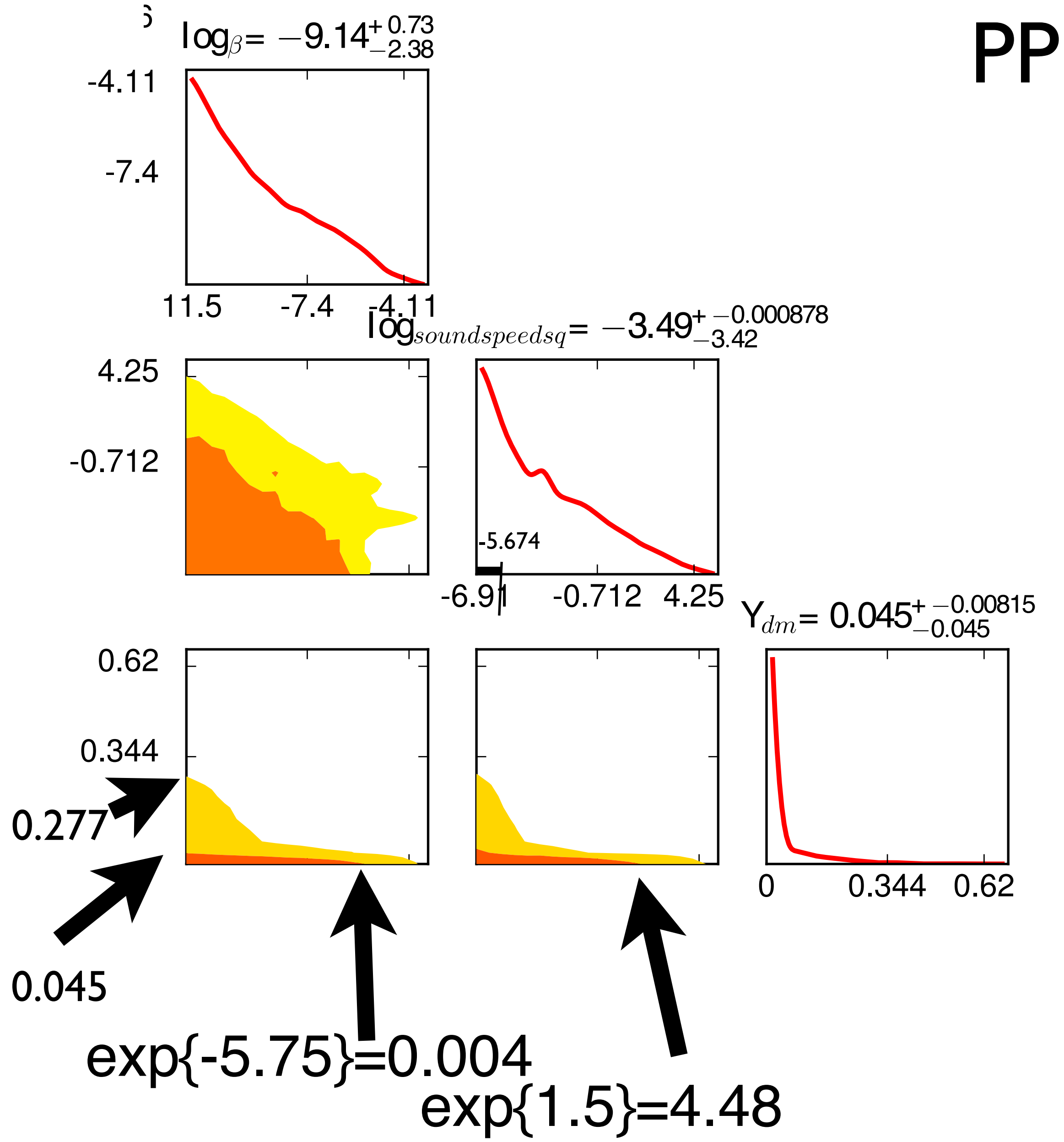


$F = F_N$

Screening regime

Standard growth of structures
chameleon-like mechanism

$$\delta \propto \tau^{2/3}$$



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$$H^2 = 8\pi G_c \rho/3$$

different from G_c , $\frac{G_N}{G_c} - 1 = \frac{\alpha+\beta+3\lambda}{2} + O(2)$

DM,

matter c

Aether - effective relativistic dof,
undergoes free-streaming

Kh

$\frac{G_N}{G_c} - 1 = \frac{\quad}{2} + O(2) > 0$

$\frac{\quad}{G_c} - 1 = O(2)$

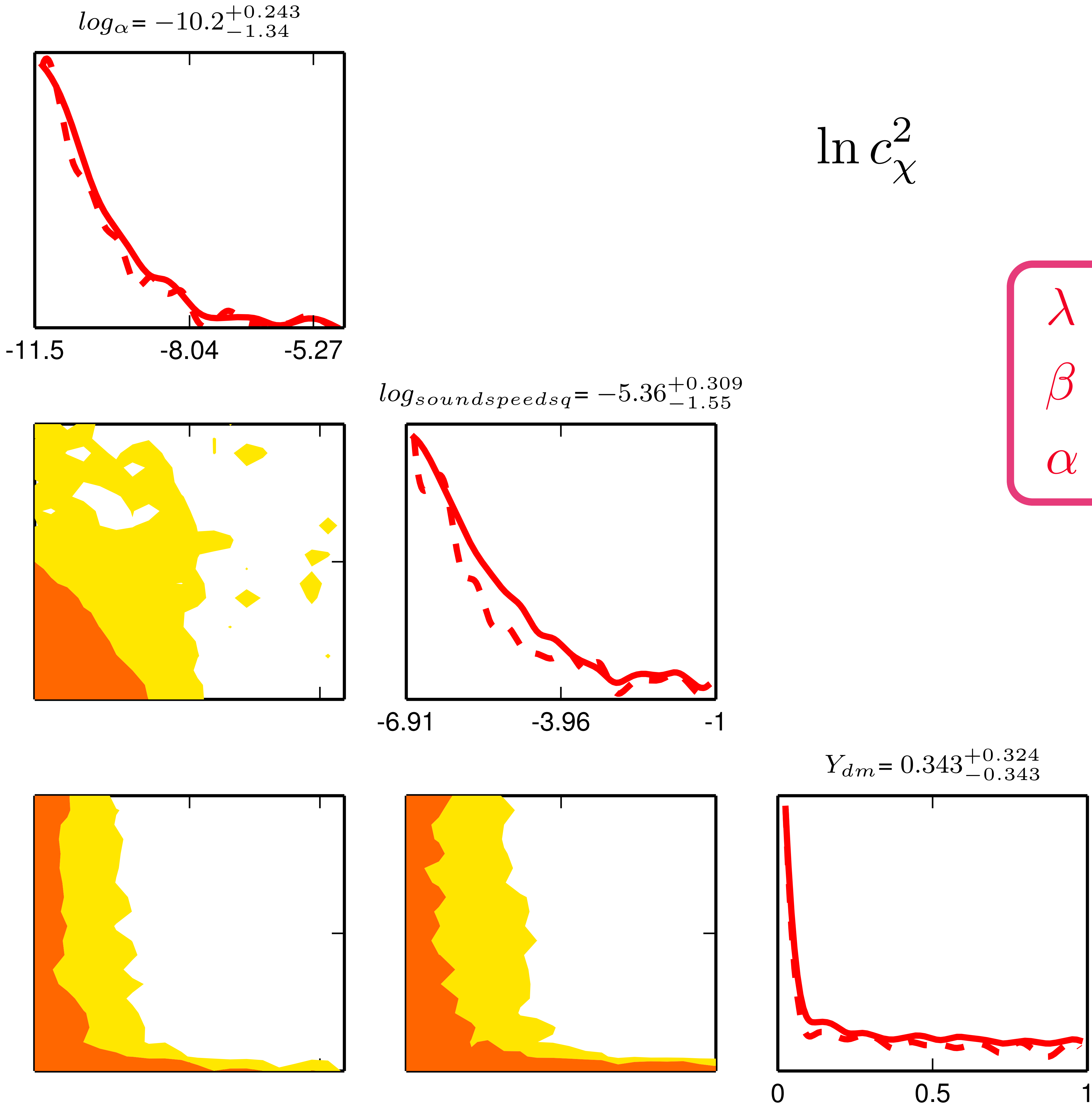
fluid

II) Anisotropic stress: aether

$$\phi - \psi = O(\beta)$$

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

$$\ln c_\chi^2$$



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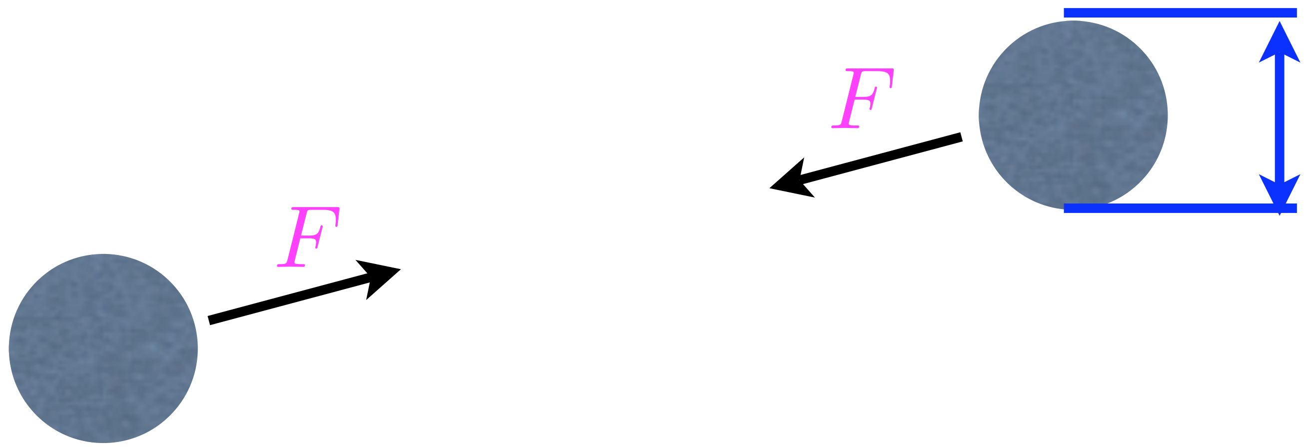
DM density

$f'(1)$

Big halos: $\dot{v}_i = -\partial_i \phi$

Small halos: $\dot{v}_i = -\dfrac{\partial_i \phi}{1 - Y}$



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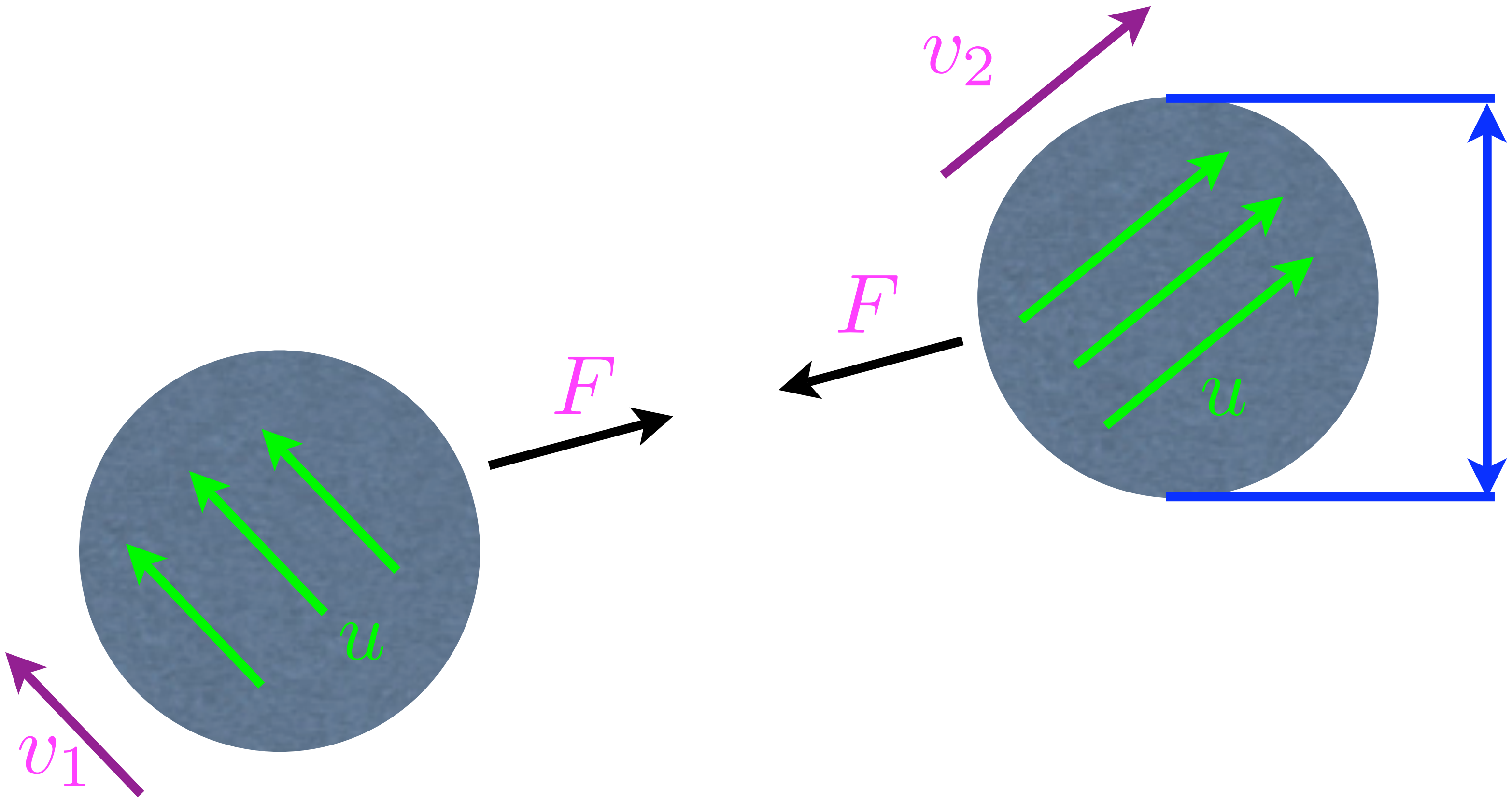

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