Natural Dark Energy from Lorentz Breaking

Diego Blas

CERN

w/ B. Audren, M. Ivanov, J. Lesgourgues, S. Sibiryakov

JCAP 1107 (2011) 026 [arXiv:1104.3579]
arXiv:1302.xxxx

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(a variation on LB and cosmology)

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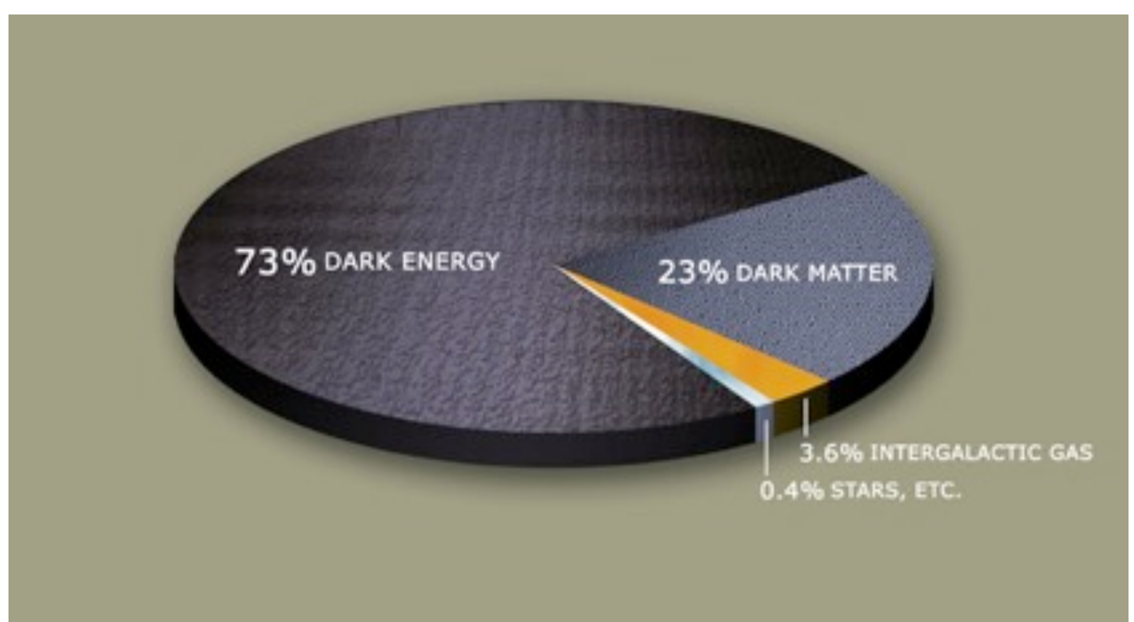
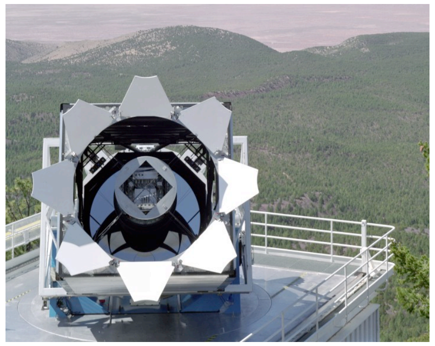
Aspects of LB theories of gravity

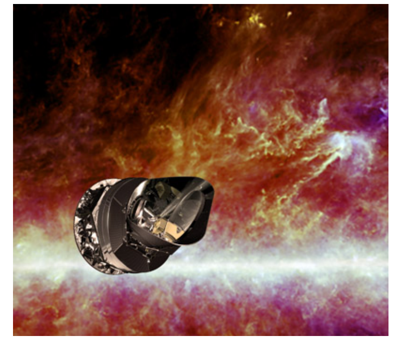
- Better UV properties than GR
- New ideas for black hole physics
- Potentially useful for AdS/CFT (condensed matter)

- Models of modified gravity at low energies
- Any new ideas for cosmology? Late time, inflation,...

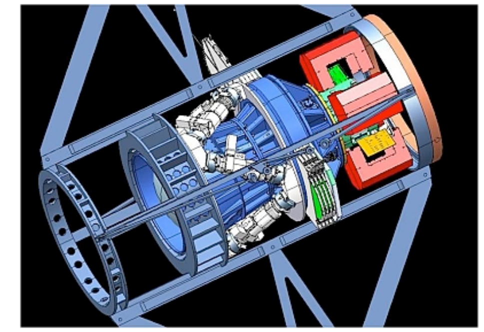




SDSS

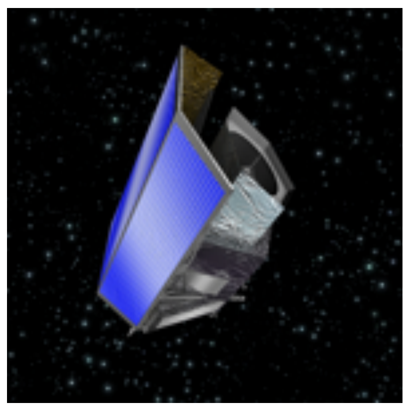


Planck



DES

EUCLID

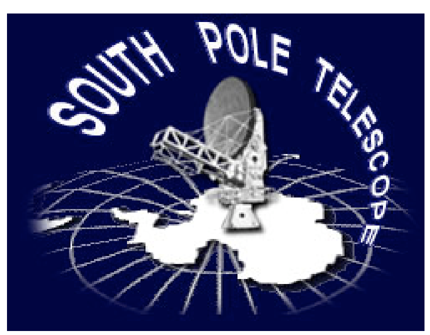


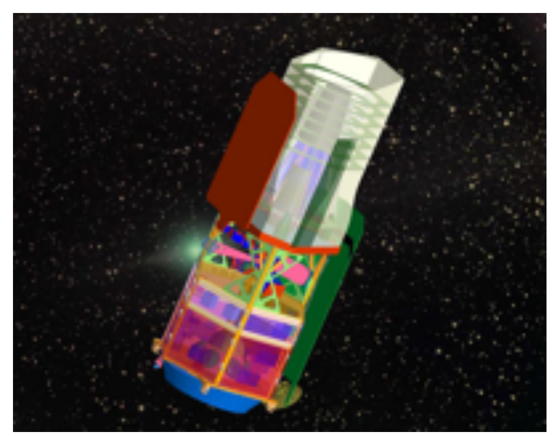
LSST

Large Synoptic Survey Telescope

HETDEX

SPT





WFIRST

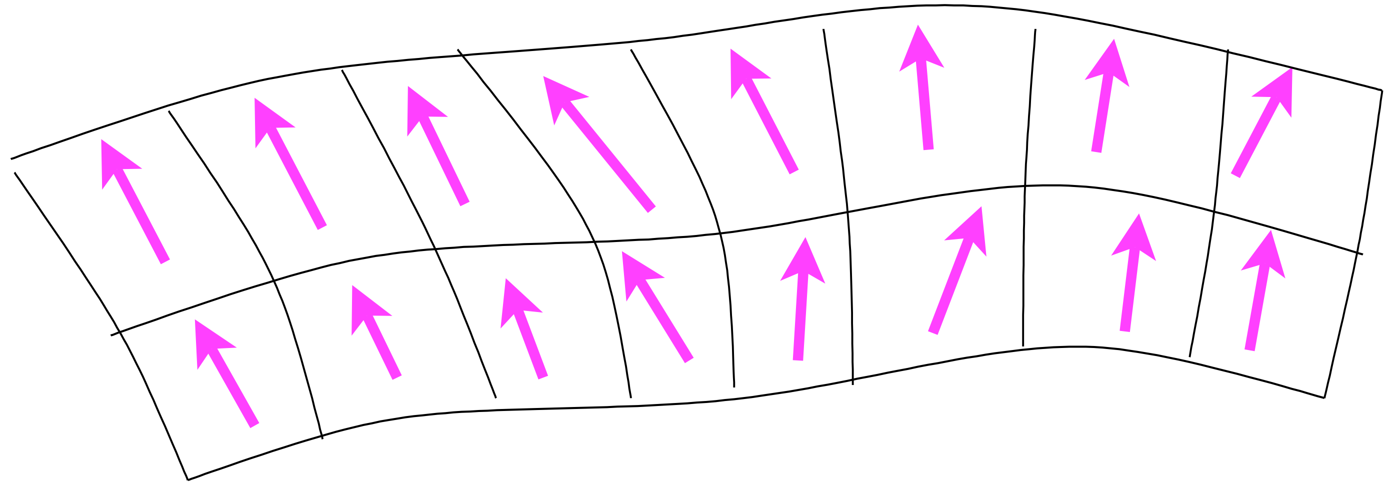
...

Big effort to understand gravity at large distances!

Breaking Lorentz Invariance

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

Associated to a time-like unit vector u_μ



Generic:
Einstein-aether

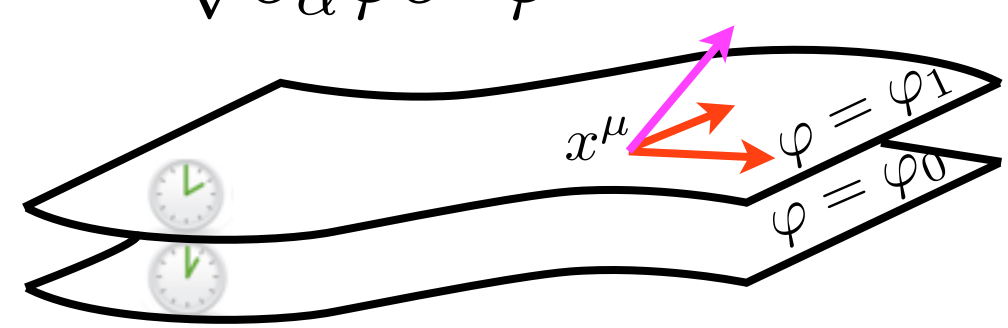
$$u_\mu u^\mu = 1$$

Scalar-vector

Hypersurface orthogonal:
Khronometric

$$u_\mu \equiv \frac{\partial_\mu \varphi}{\sqrt{\partial_\alpha \varphi \partial^\alpha \varphi}}$$

Khronon



Gravitational Lagrangian (low energies)

Ingredients: u_μ , $g_{\mu\nu}$

Khronometric:

$$\mathcal{L}_{\chi GR} = \mathcal{L}_{EH} + \sqrt{-g}\left(\lambda\left(\nabla^\mu u_\mu\right)^2 + \alpha\left(u^\nu \nabla_\nu u_\mu\right)^2 + \beta \nabla_\mu u_\nu \nabla^\nu u^\mu\right)$$

low energy Lagrangian of Hořava gravity $\Lambda_{IR} \sim \sqrt{\alpha}\, M_P$

Solar system + GW: $\alpha = 2\beta$, $\alpha \sim \lambda \lesssim 10^{-2}$

Einstein-Aether:

$$\ldots + \; c_1 \sqrt{-g} \nabla_\mu u^\nu \nabla^\mu u^\nu$$

Expressed as ↑ if $u_\mu \equiv \frac{\partial_\mu \varphi}{\sqrt{\partial_\alpha \varphi \partial^\alpha \varphi}}$

E.g. scalar pert. around FRW

$c_1 = 0$

Solar system + GW: $\alpha = -(3\lambda + \beta)$, $\alpha \sim \lambda \lesssim 10^{-2}$

Matter Lagrangian (low energies)

Matter part: +SM Fields + DM + DE

$$\mathcal{L}_m = \mathcal{L}_{LI}(\mathrm{SM}, \mathrm{DM}, \mathrm{DE}, g_{\mu\nu}) + \kappa_{SM}\ \mathcal{L}_{LB}(\mathrm{SM}, g_{\mu\nu}, u_\mu)$$
$$+\kappa_{DM}\ \mathcal{L}_{LB}(\mathrm{DM}, g_{\mu\nu}, u_\mu) + \kappa_{DE}\ \mathcal{L}_{LB}(\mathrm{DE}, g_{\mu\nu}, u_\mu)$$

Particle physics $\kappa_{SM} \lesssim 10^{-20}$

$$\kappa_{DM}, \kappa_{DE}?$$

In the following $\kappa_{SM} = 0$ $\kappa_{DM} = 0$

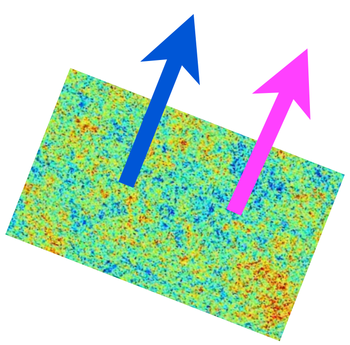
LB and Dark Energy

$$\kappa_{DE}$$

Homogeneous Cosmology

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

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!

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

From BBN (${}^4\mathrm{He}$ abundance)

$$G_c = G_N + O(.01)$$

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

Quintessence model: ΘCDM

Assuming that LI is broken (**EAther** or **Khronon**):

Add a field with an **exact** shift symmetry

$$\Theta \mapsto \Theta + C$$

Derivatively coupled! Very simple Lagrangian

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

Stable under radiative corrections:
breaks $\Theta \mapsto -\Theta$

It is technically natural to assume a small μ !

ΘCDM: Homogeneous cosmology

Friedman equation

$$H^2 = \frac{8\pi G_c}{3}\left(\frac{\dot{\Theta}^2}{2} + \rho_m\right) = \frac{8\pi G_c}{3}\left(\frac{\mu^4}{2} + \rho_m\right)$$

Scalar equation

Naturally small!

$$\frac{d}{dt}\left(a^3\dot{\Theta} + \mu^2 a^3\right) = 0 \quad \Rightarrow \quad \dot{\Theta} = -\mu^2 + \frac{C}{a(t)^3} \quad \Rightarrow \quad \boxed{\begin{array}{l} \rho_\Theta = \mu^4/2 \\ \omega = -1 \end{array}}$$

Stiff matter at BBN $C \approx 0$

NB: If $\rho_{mat} = 0$ Minkowski is a solution!

(tachyonic instability)

PseudoGoldstones & DE

✦ Small mass protected by shift symmetry

$$\phi \mapsto \phi + C$$

$$\mathcal{L} = \partial_\mu \phi \partial^\mu \phi + \Lambda^4 \left(1 + \cos(\phi/f)\right)$$

Non-perturbative potential

$$\Lambda^4 \sim H_0^2 M_P^2 \quad \Rightarrow \quad f \gtrsim M_P$$

Non-perturbative gravitational effects break the invariance: appearance of operators $\frac{\phi^2}{M_P^2} R$

- Phenomenology very similar to ΛCDM

ΘCDM: Perturbations

$$\varphi = t + \chi \,, \; \Theta = \bar{\Theta} + \xi$$

- Spectrum $k \gg k_c \equiv \mu^2/(M_P\sqrt{\alpha}) \sim H_0/\sqrt{\alpha}$

$$\omega_\chi^2 = c_\chi^2 k^2, \quad \omega_\xi^2 = k^2,$$

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

- Spectrum $k \ll k_c \equiv \mu^2/(M_P\sqrt{\alpha}) \sim H_0/\sqrt{\alpha}$

$$\omega_+^2 = k_c^2 + (c_\chi^2 + 1)k^2$$

gapped mode

$$\omega_-^2 = \frac{c_\chi^2\, k^4}{k_c^2}$$

slow mode (clusters)

$c_- \sim k/k_c \ll 1$

⇒ expected enhancement of structure formation at large scales

ΘCDM: Perturbations II

- LB enhancement structure: DM dom, subhorizon

$$\delta'' + 2H\delta' = -\frac{k^2\phi}{a^2}$$

$$\frac{k^2\phi}{a^2} = \frac{3H^2(1+\beta/2+3\lambda/2)}{2(1-\alpha/2)}\,\delta = \frac{3G_N}{2G_c}H^2\delta$$

$$\boxed{\delta \sim \tau^{-1+\sqrt{1+24\frac{G_N}{G_c}}}} \qquad \frac{G_N}{G_c} - 1 = \frac{\alpha+\beta+3\lambda}{2} + O(2)$$

+ Solar system constraints

Khronometric

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

Einstein-Aether:

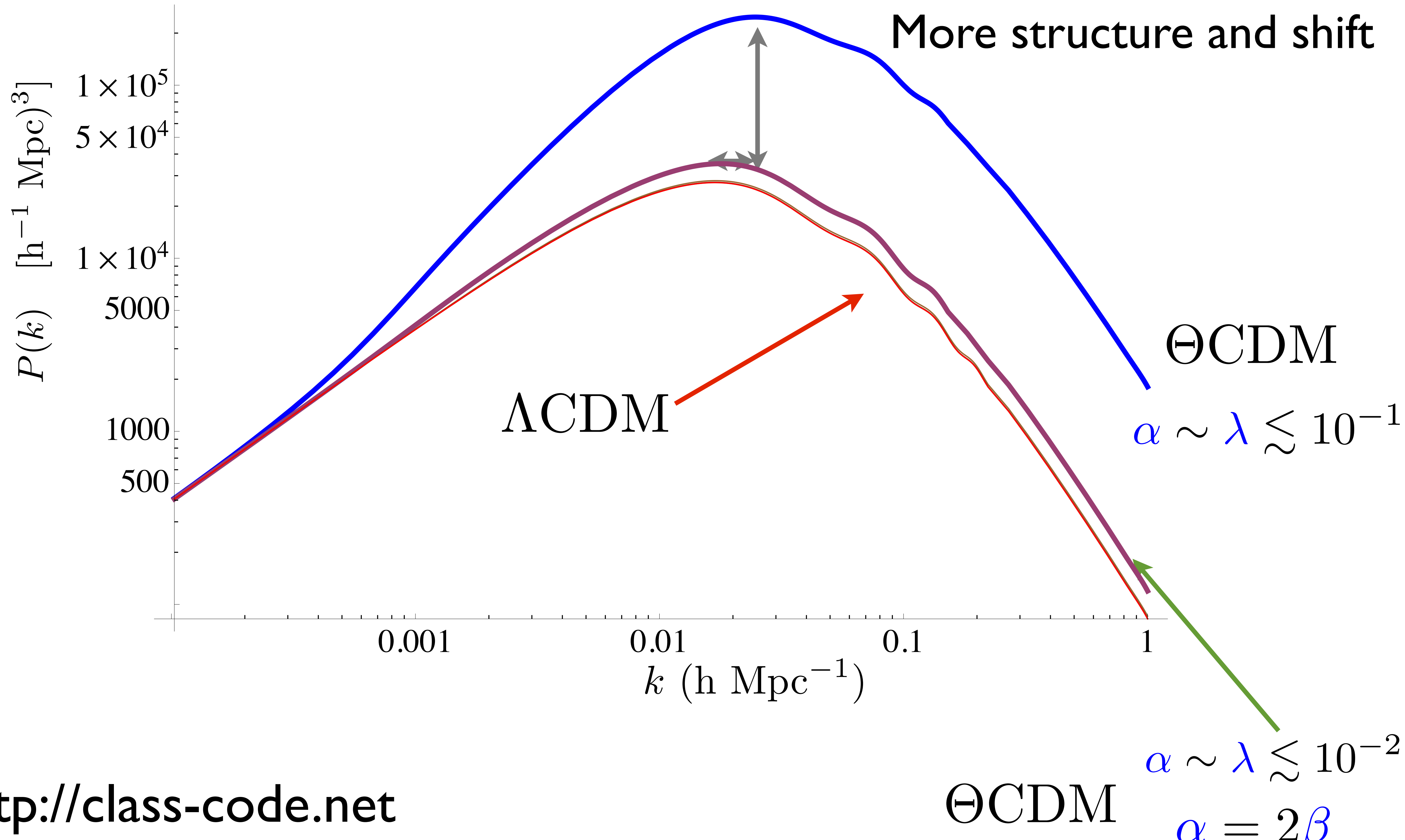
$$\frac{G_N}{G_c} - 1 = O(2)$$

- Anisotropic stress $\mathrm{d}s^2 = a(t)^2\left[(1+2\phi)\mathrm{d}t^2 - \delta_{ij}(1-2\psi)\mathrm{d}x^i\mathrm{d}x^j\right]$

$$\boxed{\phi - \psi = O(\beta)}$$

Cosmological perturbations

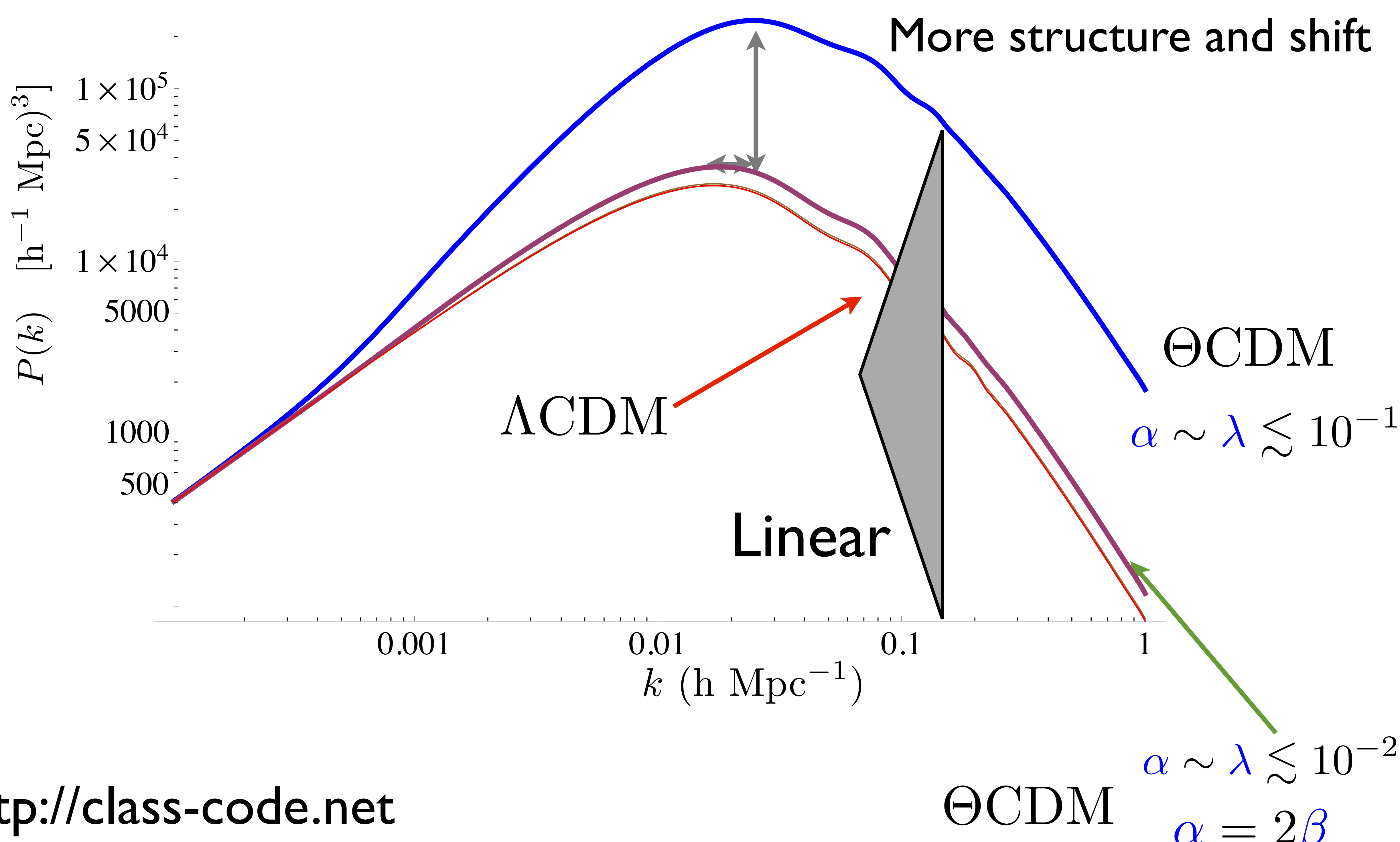
$$\langle \delta(k)\delta(k')\rangle \equiv \delta^{(3)}(k+k')P(k)k^3$$



http://class-code.net

Cosmological perturbations

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



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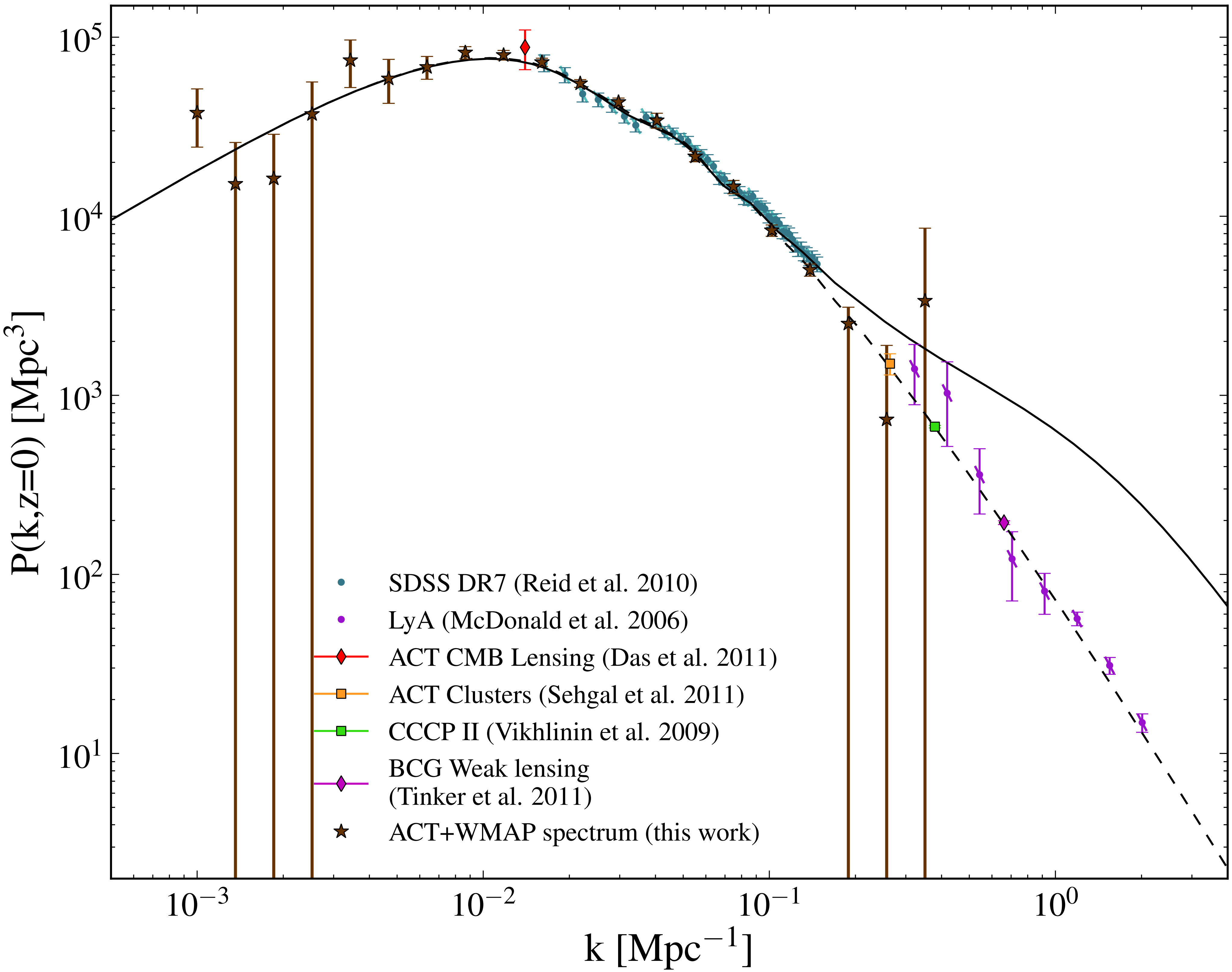
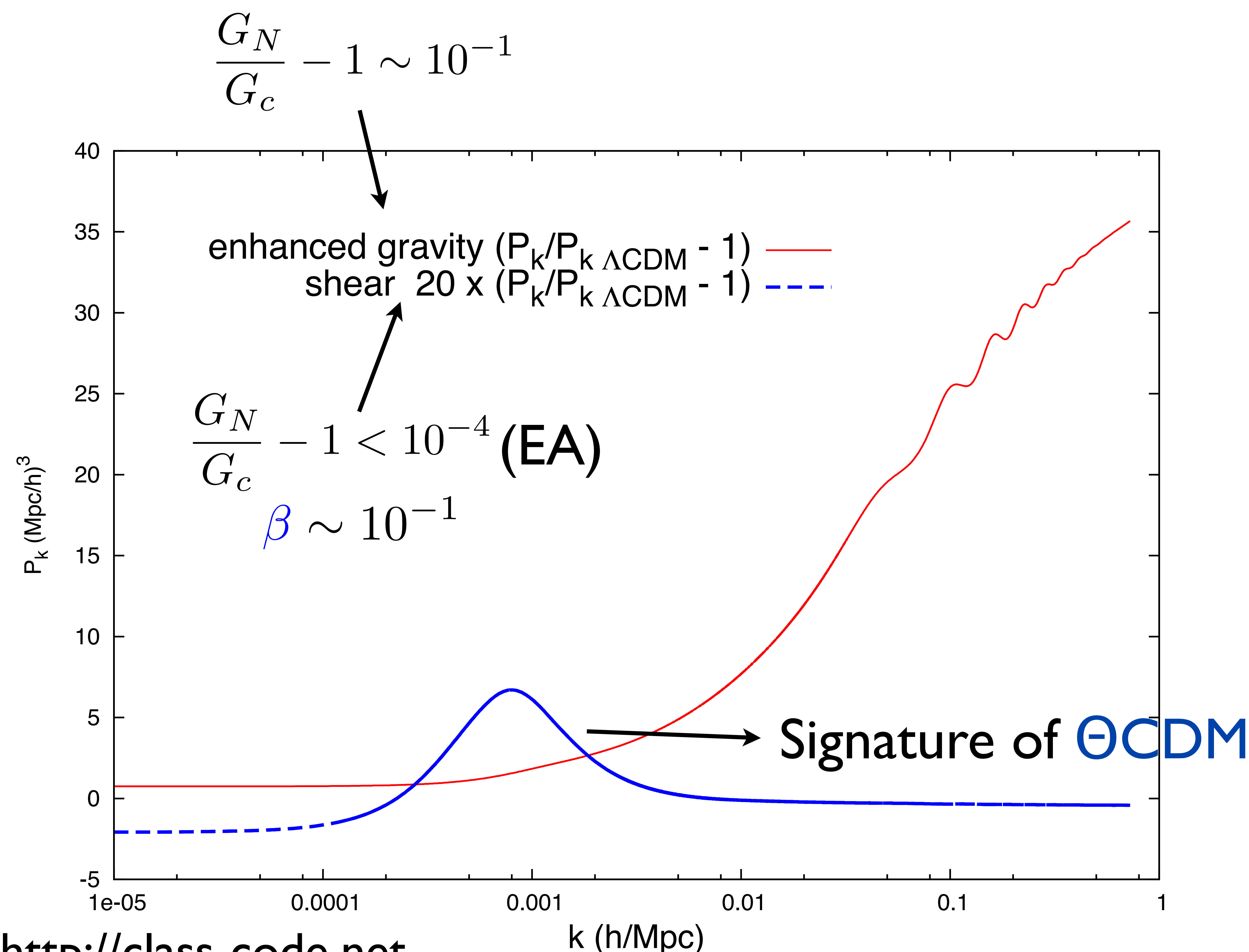
Hlozek et alt., 11





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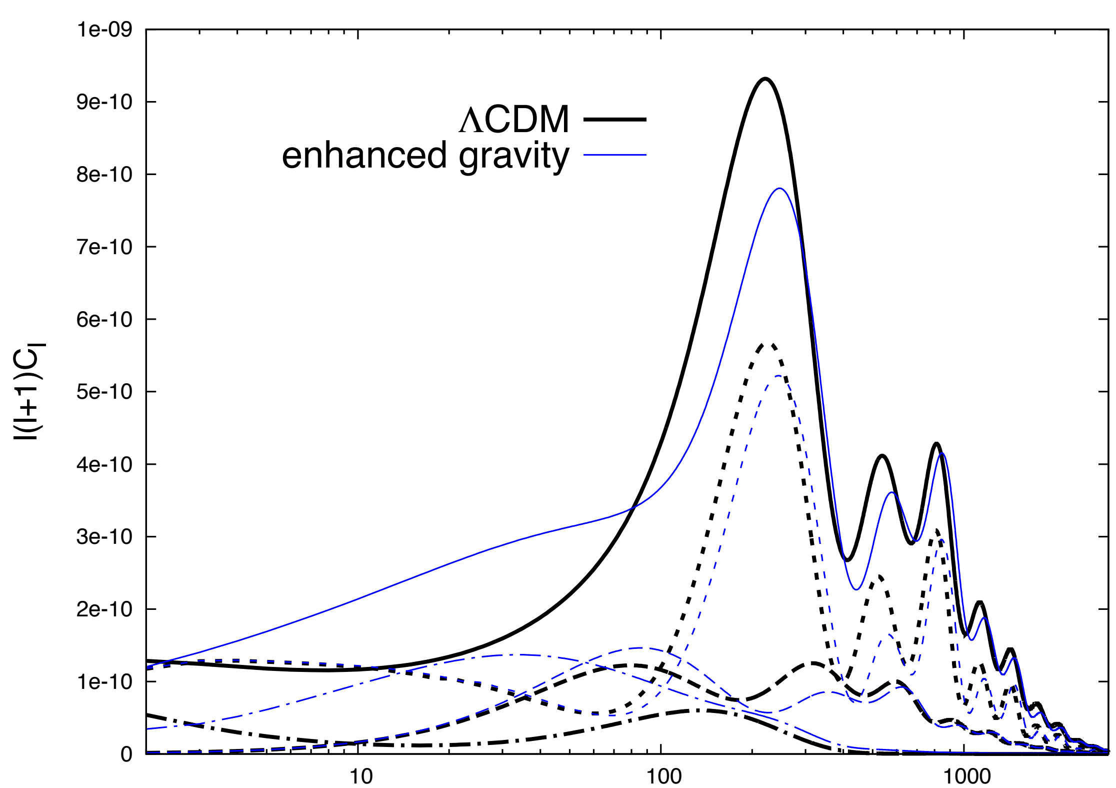
Cosmic Microwave Background

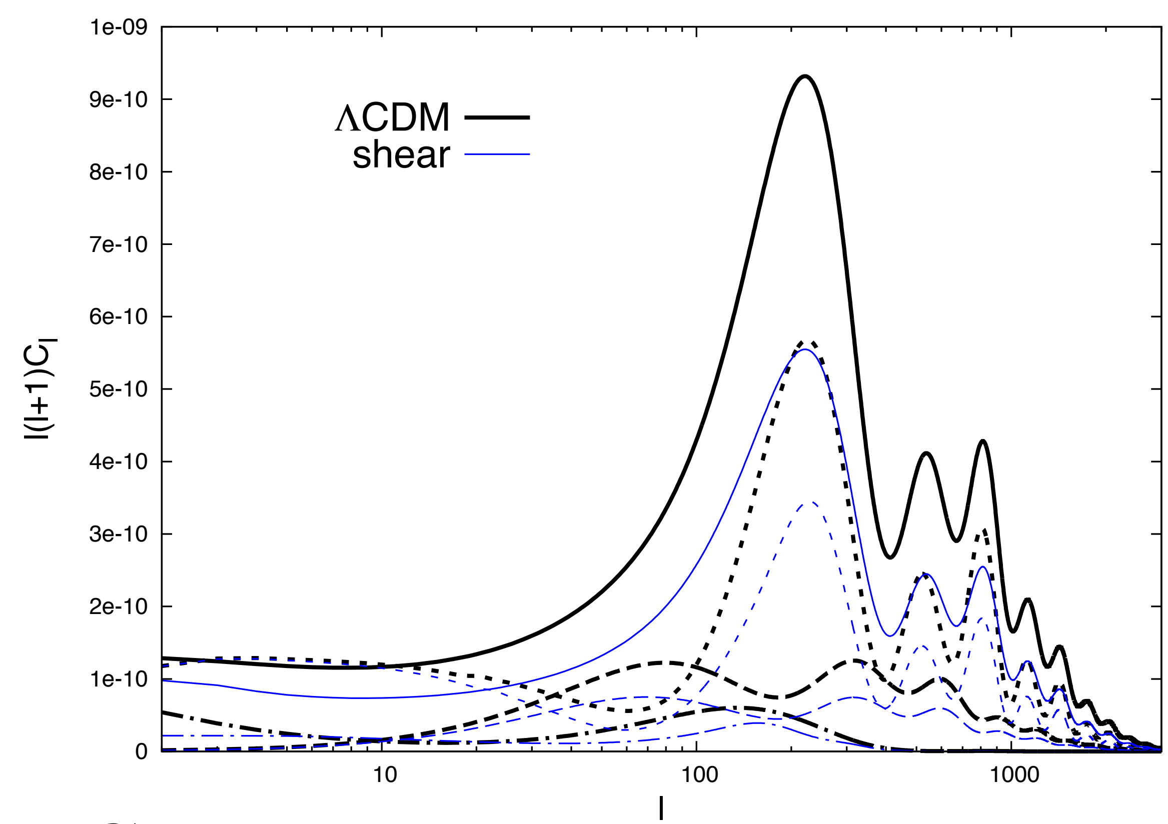
$$\ddot{\delta}_\gamma + k^2 c_s^2 \delta_\gamma \supset -\left(\frac{4k^2}{3}\psi\right) \qquad k^2\psi \sim \frac{G_N}{G_c}\delta_\gamma \quad \Rightarrow \quad c_s^{eff}$$

Shift of the peaks, change of zero point of oscillation and amplitude

http://class-code.net



$$\frac{G_N}{G_c} - 1 \sim 10^{-1}$$



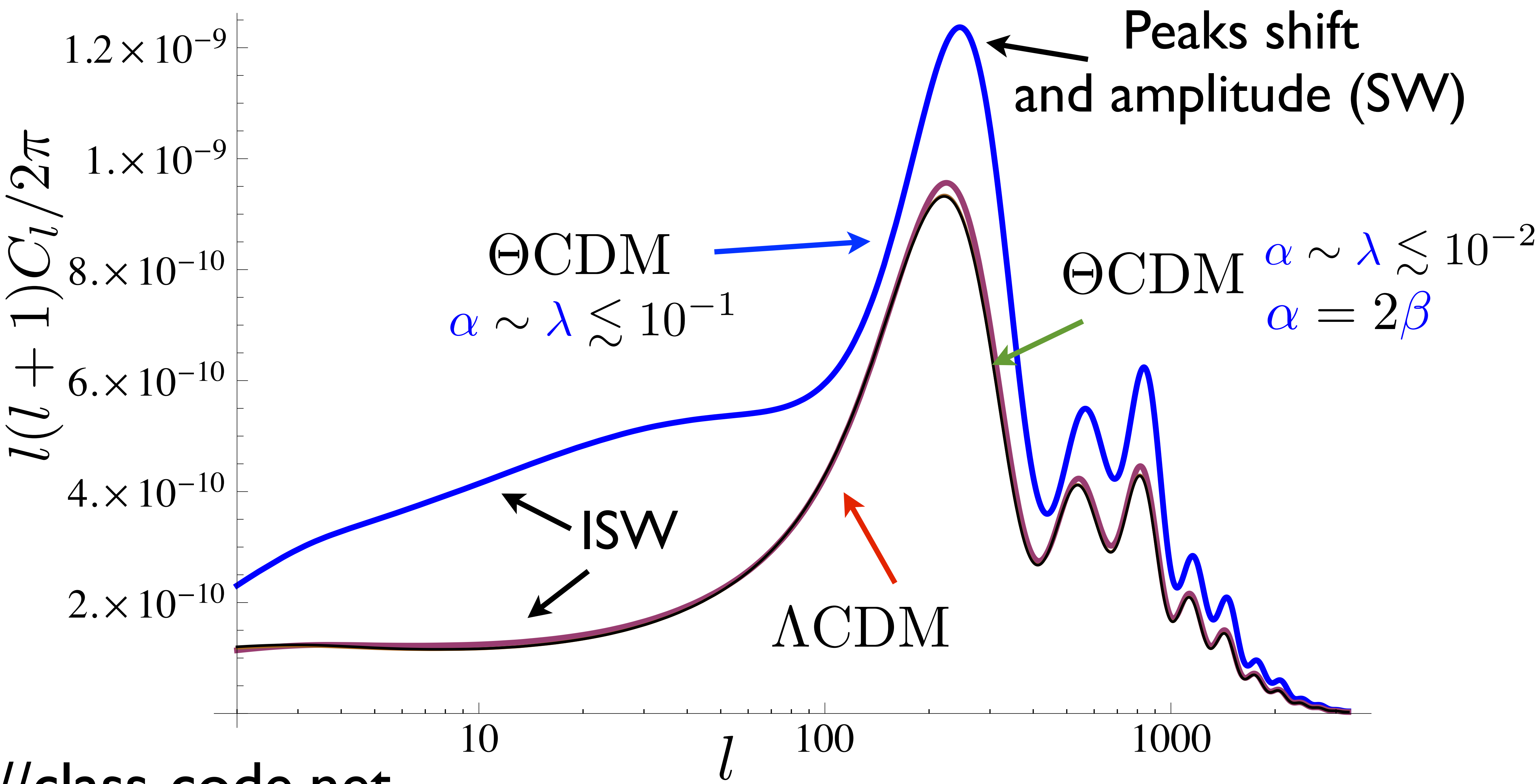
$$\frac{G_N}{G_c} - 1 < 10^{-4}\text{(EA)} \qquad \beta \sim 1$$

$$\Theta_\gamma \equiv \delta_\gamma/4$$

$$\Theta_l(k,\eta_0) \sim [\Theta_0(k,\eta_*) + \psi(k,\eta_*)] j_l[k(\eta_0-\eta_*)] \quad \text{SW}$$

$$+3\Theta_1(k,\eta_*)\left(j_{l-1}[k(\eta_0-\eta_*)] - \frac{(l+1)j_l[k(\eta_0-\eta_*)]}{k(\eta_0-\eta_*)}\right) \quad \text{Doppler}$$

$$+\int_0^{\eta_0} d\eta\, e^{-\tau}\left[\dot\psi(k,\eta) - \dot\phi(k,\eta)\right] j_l[k(\eta_0-\eta)] \quad \text{ISW}$$



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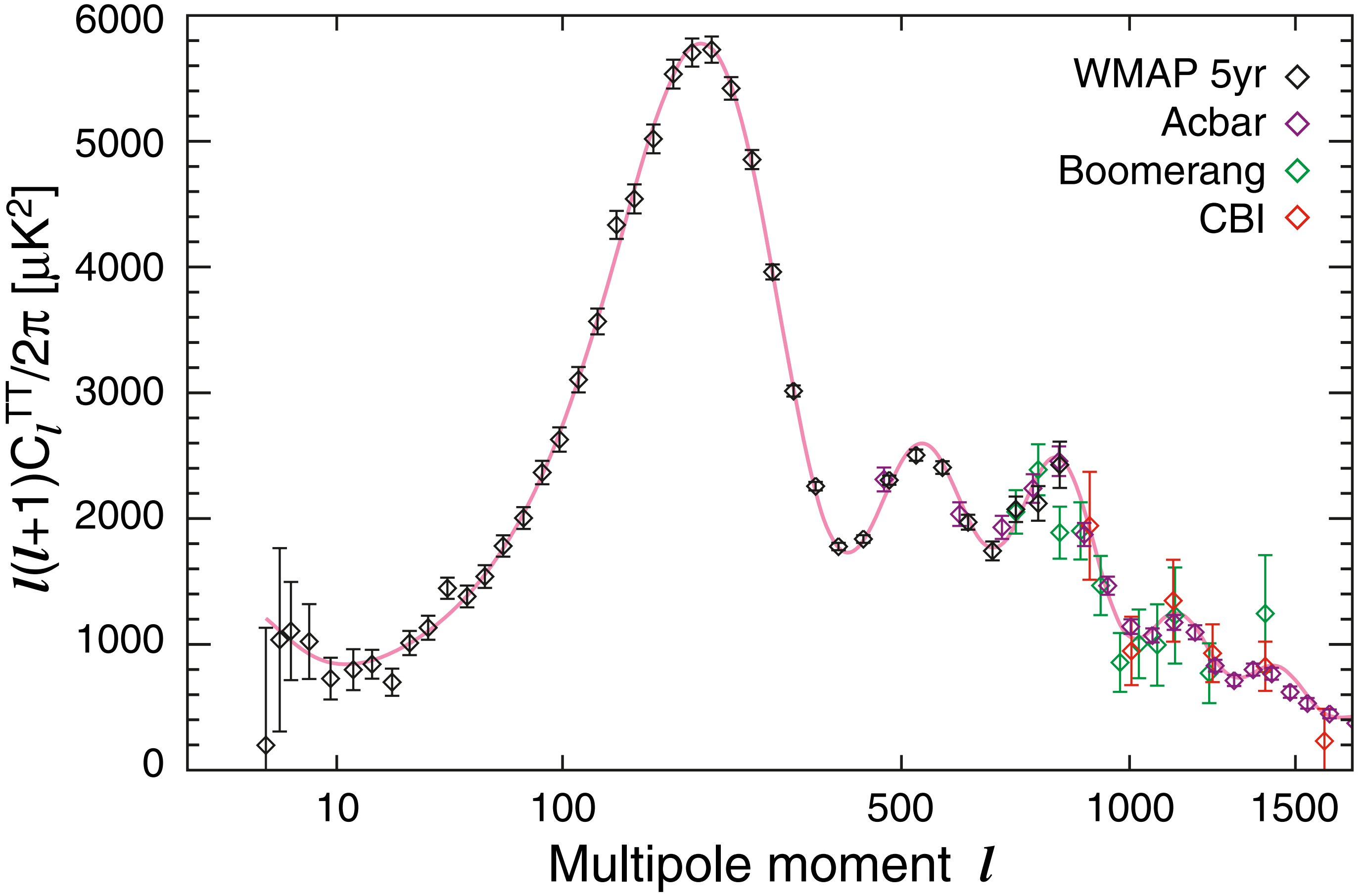
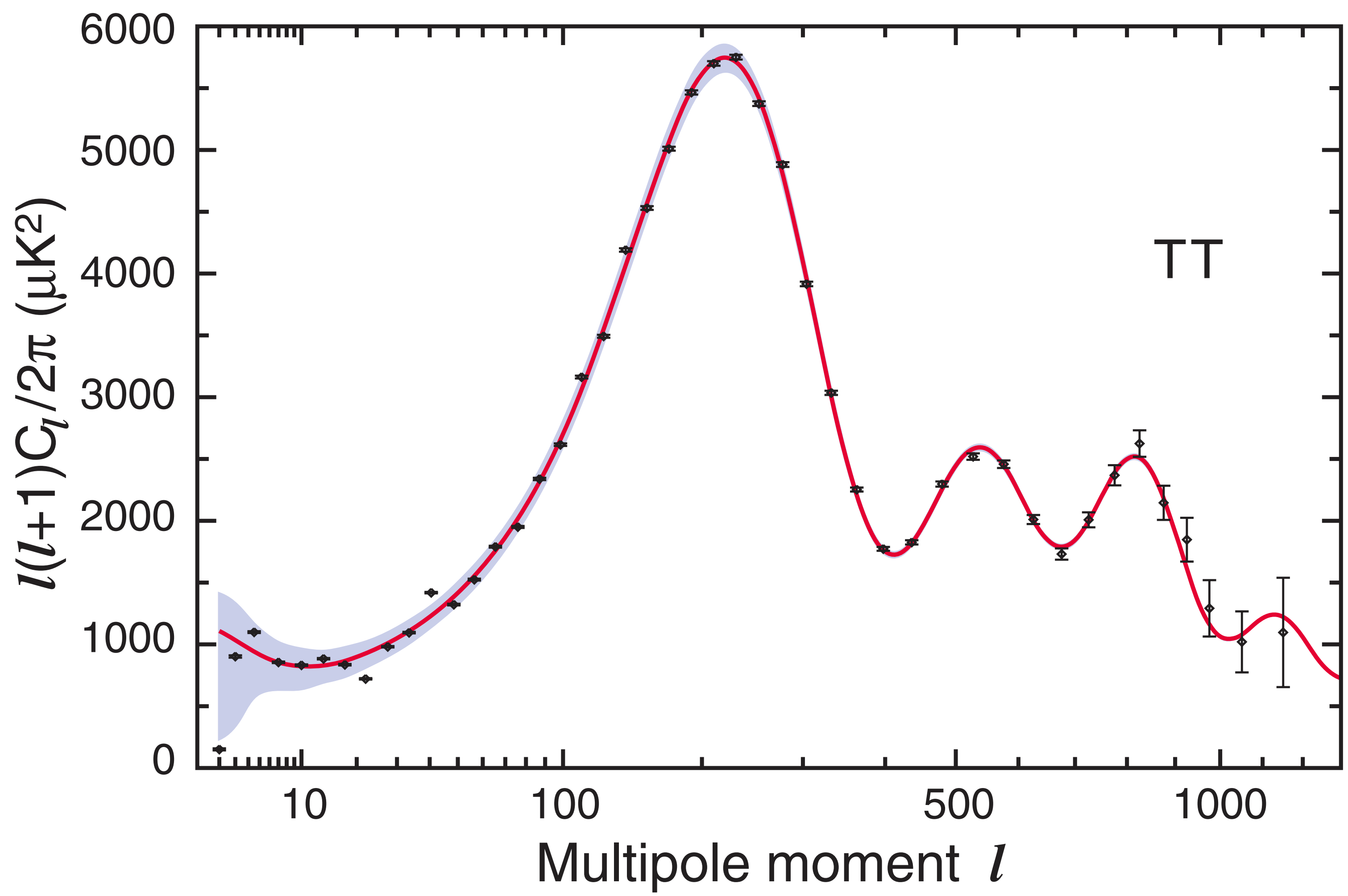

6000
5000
4000
3000
2000
1000
0
WMAP 5yr
Acbar
Boomerang
CBI
10
100
500
1000
1500
Multipole moment l
$l(l+1)C_l^{TT}/2\pi$ [μK^2]

WMAP9

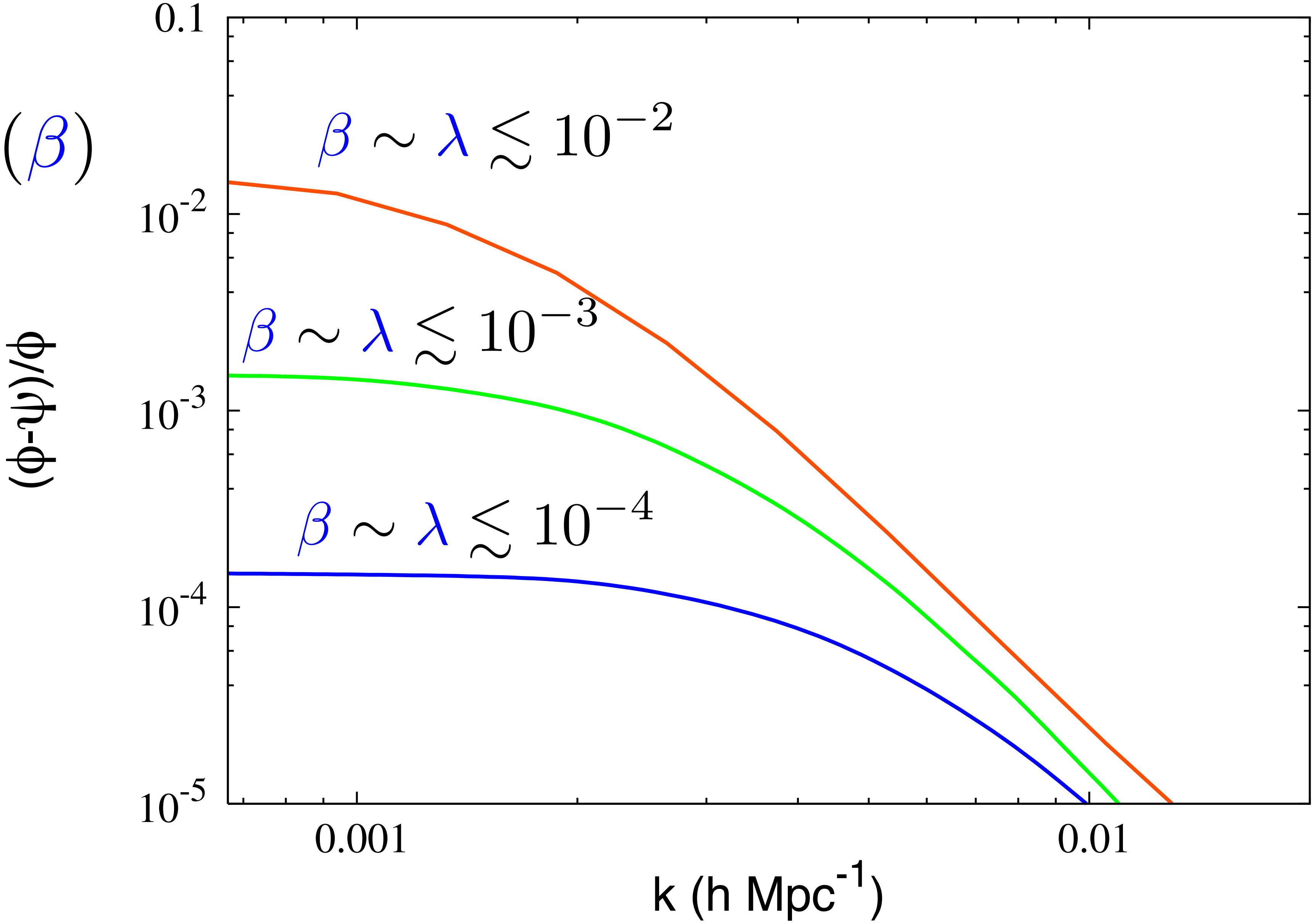

6000
5000
4000
3000
2000
1000
0
TT
10
100
500
1000
Multipole moment l
$l(l+1)C_l/2\pi$ (μK^2)

Other effects

Anisotropic stress

$$\phi - \psi - \beta(\dot{\chi} + 2\mathcal{H}\chi)$$

$O(\beta)$



Bounds

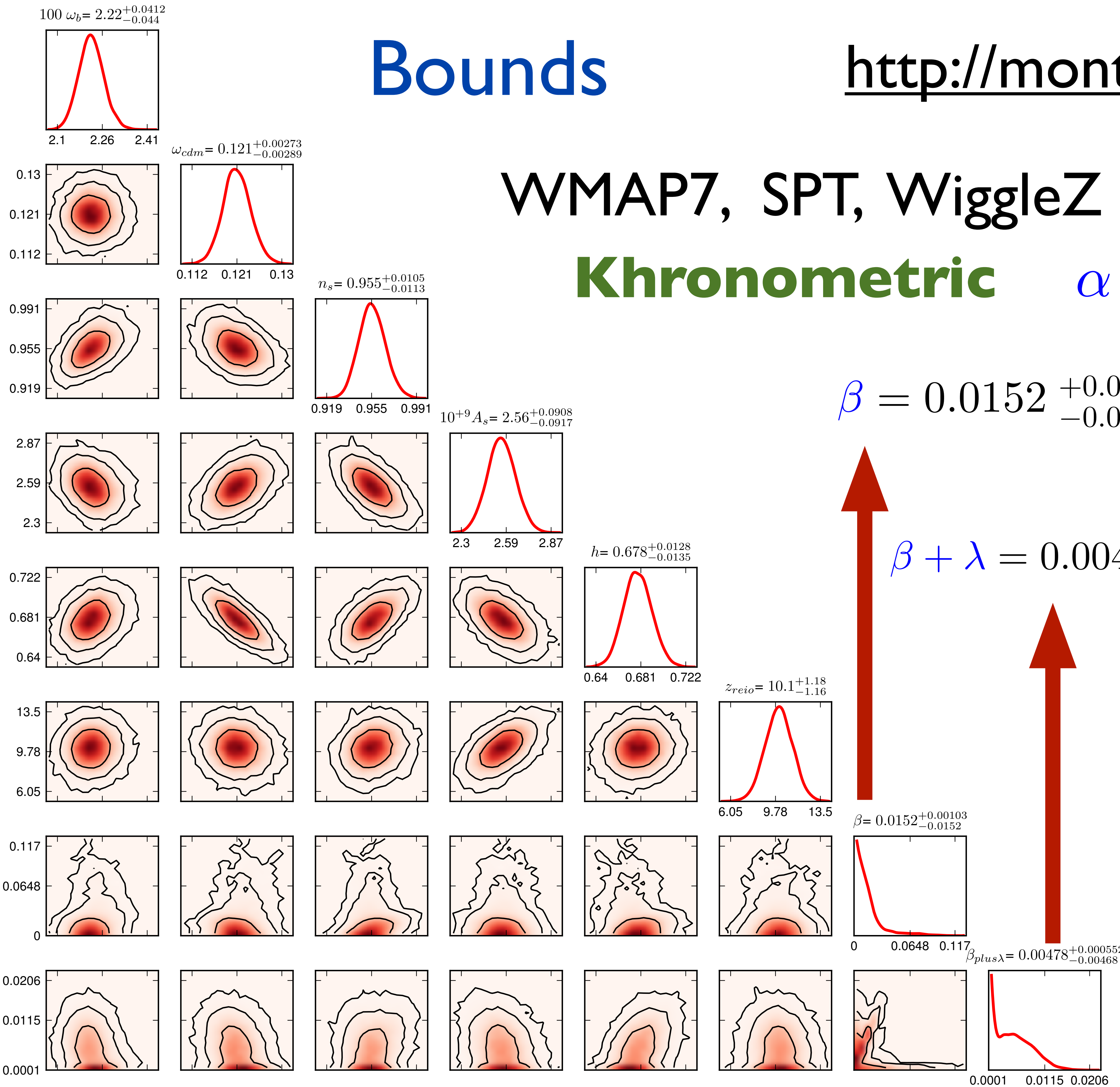
http://montepython.net/

WMAP7, SPT, WiggleZ

Khronometric $\alpha = 2\beta$

$$\beta = 0.0152\ ^{+0.001}_{-0.0152}$$

$$\beta + \lambda = 0.00478\ ^{+0.00055}_{-0.00468}$$



Conclusions

- Breaking Lorentz invariance in the dark sector as an **alternative to GR/ΛCDM** with better UV properties.

- ΘCDM model for **dark energy** $w = -1$

  $\rho_\Theta = \mu^4/2$ UV insensitive

- Same background evolution. Different perturbations.

  growth of structure enhanced

  anisotropic stress at linear scales:

  effects on the **CMB** and **matter power spectrum**

  - Comparison with data (LB bounds at percent level!)
  - Other bounds: weak lensing, polarization (EA)?...