Lorentz-violating dark energy: physical motivations and observational constraints

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New light on cosmology from CMB, ICTP, 1 August 2013

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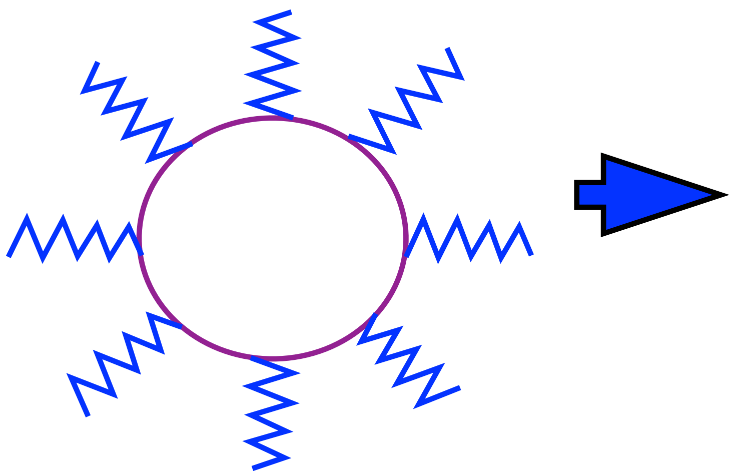
But we are unhappy with the CC:
small dimensionful parameter that must
be fine-tuned to the precision 10^{-120}

Fine-tuning problem

Cosmological constant

$\rho_{\Lambda,\, obs} \sim (10^{-3}\mathrm{eV})^4$

- loop corrections



$\rho_{\Lambda,\, theor} \sim (M_{Pl})^4 \sim (10^{28}\mathrm{eV})^4$

or $(M_{SUSY})^4 \sim (10^{12}\mathrm{eV})^4$

- phase transitions in the early Universe

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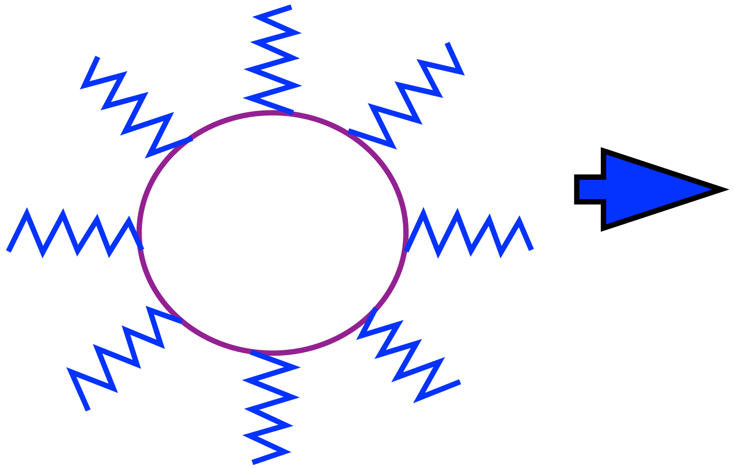

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Landscape + anthropic principle ???

Phenomenological perspective

Motivation to go beyond CC:

Alternative scenarios for late-time cosmology to test against the data

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- predictive power

Simplest dynamical DE:
standard quintessence (pseudo-Goldstone boson)

- small mass protected by (approximate) shift symmetry **+**

$$\phi \mapsto \phi + const$$

- weak predictive power **-**

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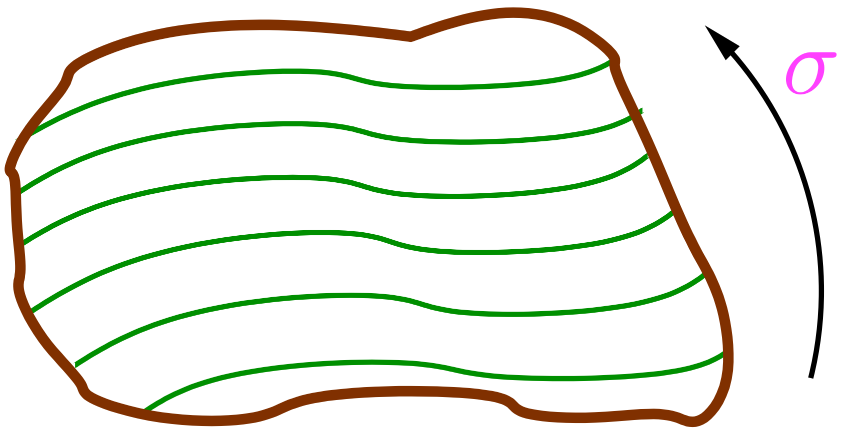
Next option: change the underlying symmetries

Allow for violation of Lorentz invariance

broken in cosmology anyway

Effective description of LV

preferred time = foliation of the manifold by space-like surfaces



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

choosing the gauge $t = \sigma$ → σ sets global time

KHRONON

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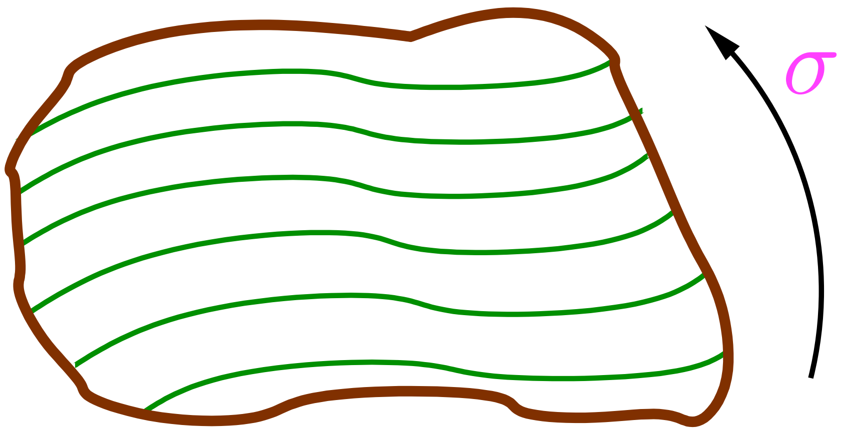

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NB. Foliation preserving transformations

⇒ symmetry $\sigma \mapsto \tilde{\sigma} = f(\sigma)$

Constructing KHRONO-METRIC action

- Invariant object -- unit normal to the foliation surfaces:

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

- low-energy EFT = Lagrangian with lowest number of derivatives

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

  cf. with Einstein-aether theory (*Jacobson & Mattingly, 2001*): a LV theory of a unit vector

- matter sector is Lorentz invariant at low energies

  ➡ direct coupling of the khronon to SM fields is forbidden

Natural DE

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 khronon:

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

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

Has high UV cutoff $M_\alpha \equiv M_{Pl}\sqrt{\alpha}$

Homogeneous cosmology

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

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

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

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

$$w = -1$$

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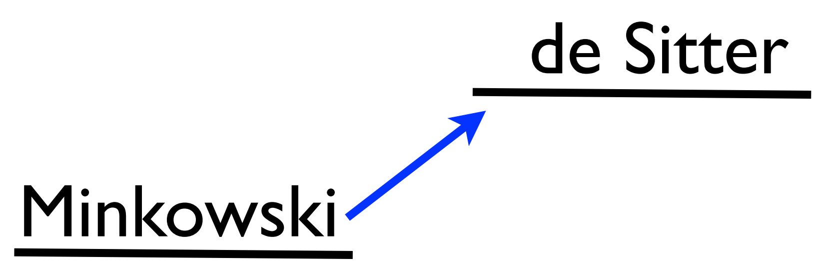
A new twist to CCP ? If and only if $\rho_{mat} = 0$ there is unstable Minkowski solution with $\dot{\Theta} = 0$



Perturbations in expanding Universe

$$\sigma(t,\mathbf{x}) = t + \chi(t,\mathbf{x})\,, \qquad \Theta(t,\mathbf{x}) = \bar{\Theta} + \xi(t,\mathbf{x})$$

$$k_c \equiv \mu^2/M_\alpha$$

$$\sim H_0/\sqrt{\alpha}$$

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$$\omega_+^2 = k_c^2 + O(k^2)$$ gapped mode

$$\omega_-^2 \propto k^4/k_c^2$$ slow mode

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

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DE clusters at large scales

NB. Can be thought of as UV completion of ghost condensation

Solar system constraints

Blas, Pujolas, S.S. (2011)

all PPN parameters the same as in GR

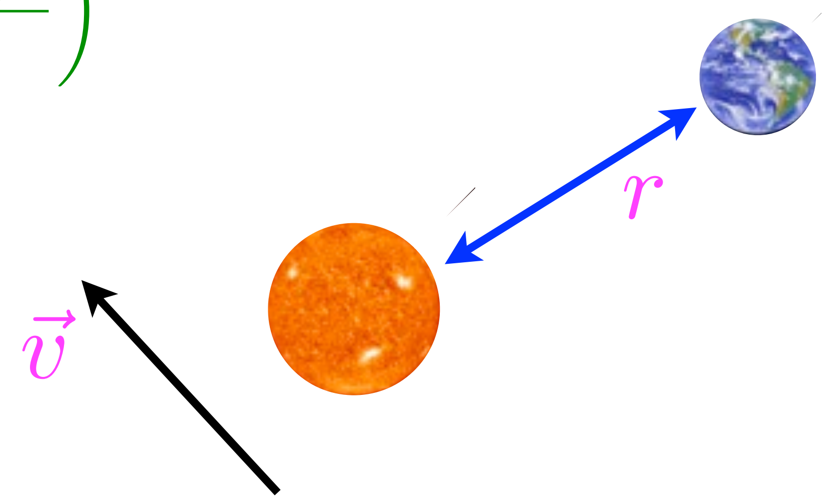
except $\underbrace{\alpha_1^{PPN}, \alpha_2^{PPN}}$

measure preferred
frame effects

Definition of $\alpha_{1,2}^{PPN}$

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

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



Experimental bounds:

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

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

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

- barring cancellations

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

- vanish if $\alpha = 2\beta$
  from gravity wave emission

Blas, Sanctuary (2011)
Yagi et al. (2013)

$$\alpha\ ,\ \beta\ ,\ \lambda' \lesssim 10^{-2}$$

interesting for cosmology

Cosmological signatures of ΘCDM

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

Poisson equation:

$$k^2\phi = -4\pi G_N a^2 \left[\sum \rho_n \delta_n + \delta\rho_\chi + \delta\rho_\xi \right]$$

shear equation:

$$k^2(\psi - \phi) = -12\pi G_0 a^2 \sum (\rho_n + p_n)\sigma_n + \beta k^2(\dot{\chi} + 2\mathcal{H}\chi)$$

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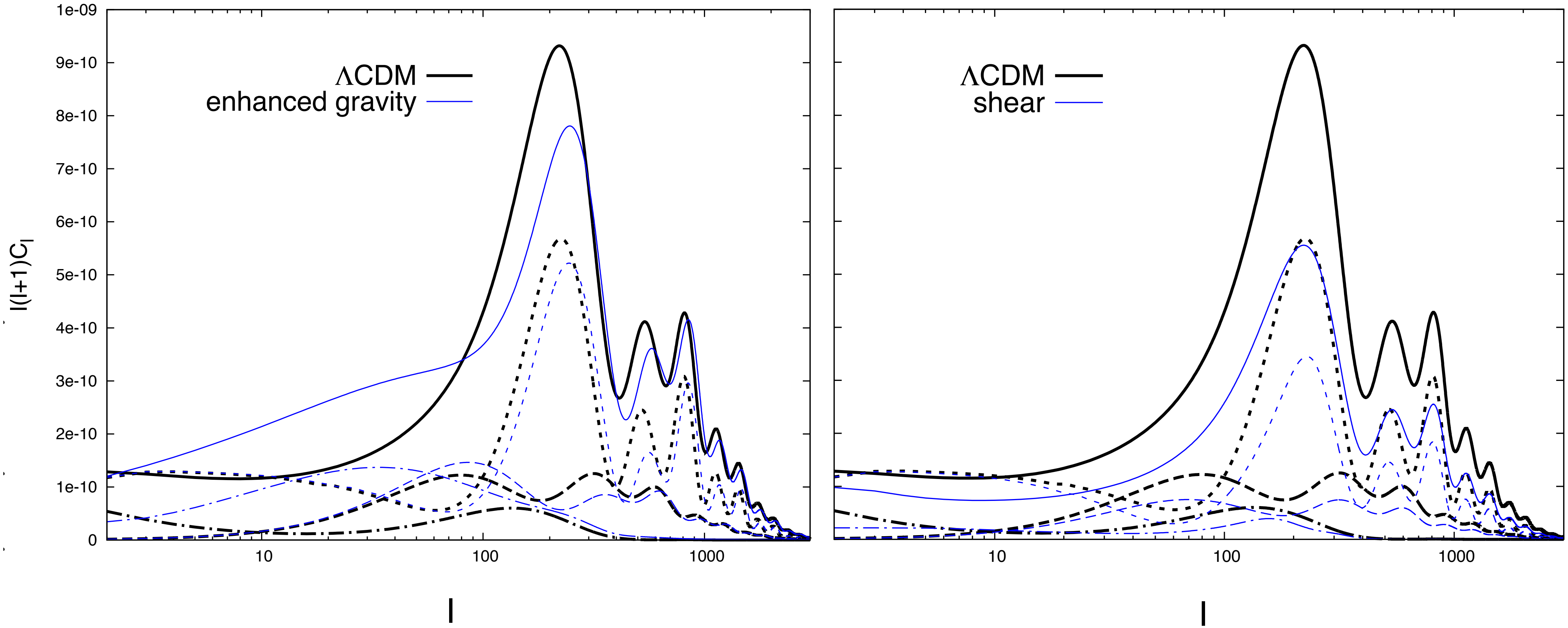
Two models for numerical studies

Model	α	β	λ	Σ
enhanced gravity	0.2	0	0.1	0.5
shear	0.05	0.25	−0.1	0

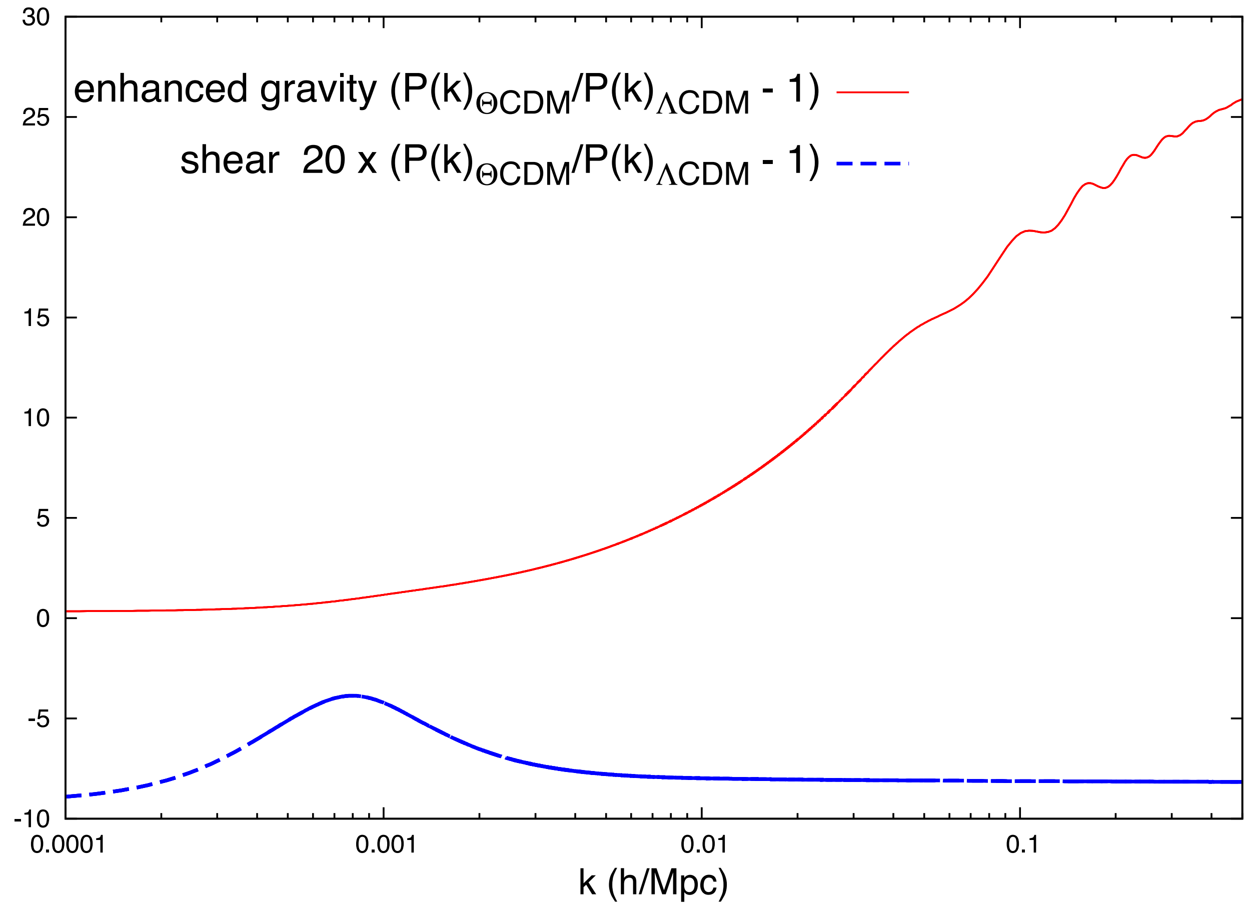
use CLASS *Blas, Lesgourgues, Tram (2011)*
and MONTE PYTHON *Audren et. al. (2012)*

CMB anisotropies

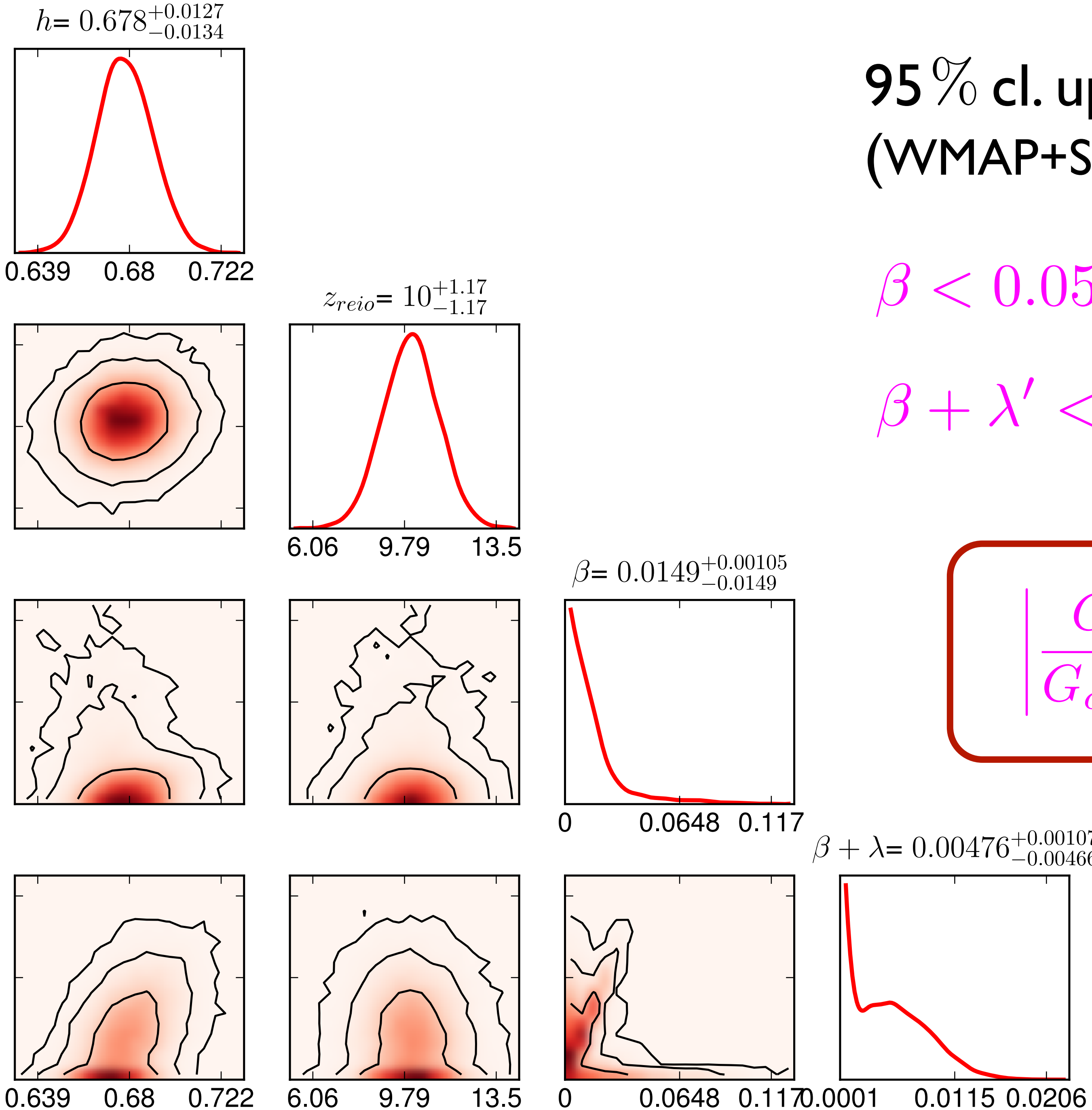


Temperature anisotropy spectrum (solid) and its decomposition in terms of Sachs-Wolfe (dotted), Doppler (dashed) and integrated Sachs-Wolfe (dot-dashed) contributions.

Matter power spectrum



Ratios of the matter power spectra in the two reference ΘCDM models and ΛCDM at redshift $z = 0$.



95 % cl. upper limits (WMAP+SPT+WiggleZ):

$$\beta < 0.05$$

$$\beta + \lambda' < 0.012$$

$$\left| \frac{G_N}{G_{cosm}} - 1 \right| < 0.018$$

OUTLOOK

- Lorentz violation is a consistent framework to test deviations from ΛCDM
- A simple, technically natural model for DE
- Signatures of ΘCDM: $w = -1$, enhanced structure formation, $G_N \neq G_{cosm}$, additional shear
- Bounds from WMAP+SPT+WiggleZ at the level several $\times 10^{-2}$. *Can be improved with Planck+BOSS.*
- Lorentz violation in dark matter
  $\approx$ fifth force in DM sector
  ➡ further enhancement of structure