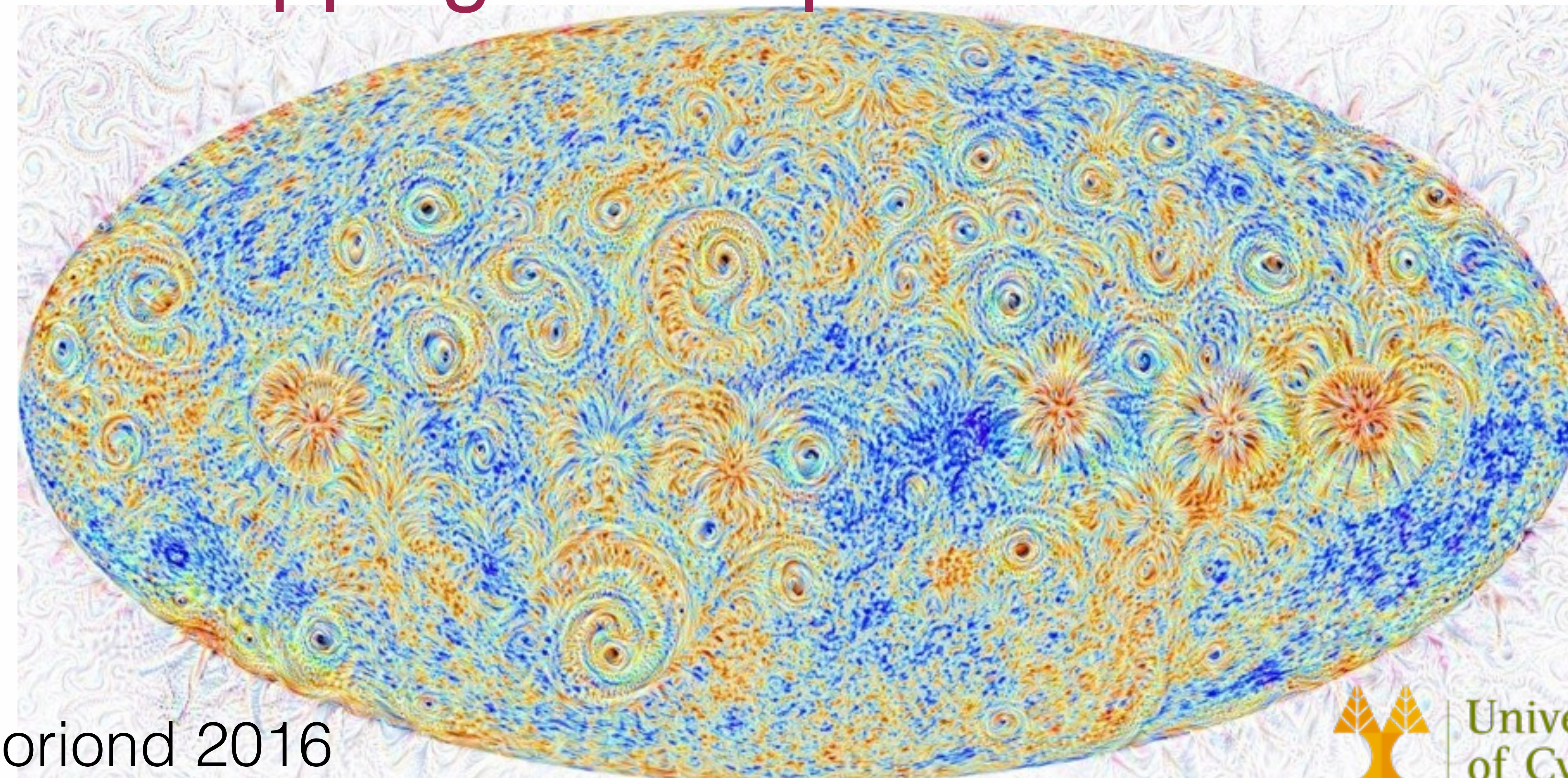
Generalised Dark Matter: Imprints on the CMB and mapping to non-perturbative models



Moriond 2016

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Thomas et al, **1601.05097** Kopp et al, 1604.xxxxx

Outline

- Generalised dark matter (GDM), 3 new parameters
- CMB with Λ-GDM and constraints from Planck
- Connection to warm dark matter, EFTofLSS, and mapping to non-equilibrium thermodynamics and EFT of fluids.

Believing in dark matter

- Extensions of the standard model of particle physics (SM)

> Axions, Wimps, Sterile ν } natural extensions of SM

- Cold dark matter (CDM) gives concordant picture within General Relativity (GR)

> Internal galaxy and cluster dynamics
> Expansion history
> Large scale structure
> Lensing CMB BBN

- Modified gravity?:
  - ✦ GR's success for a century
  - ✦ Lack of working alternatives

> no modified gravity theory yet to explain all those phenomena

Dark matter fluid

$$T_{\mu\nu} = \rho u_\mu u_\nu \; + P(g_{\mu\nu} + u_\mu u_\nu) \; + \Sigma_{\mu\nu}$$

- Cold and Collisionless particles in the continuum limit are described before shell crossing as pressureless perfect fluid (=CDM in **camb** and **class**)

Planck 2015 XX, 1502.02114 $\beta_{c,\mathrm{iso}} < 0.038$
Planck 2015 XIII, 1502.01589 $\omega_c = 0.12 \pm 0.0027$

- A general fluid can have pressure P=P(ρ,S,$\nabla_\mu u^\mu$,...). We allow for non-adiabatic, but exclude bulk viscosity

- Shear $\Sigma_{\mu\nu}$(ρ,$\nabla_\mu u_\nu$, $g_{\mu\nu}$,...), spatial and traceless

No heat flux. u_μ is wlog defined as Landau-Lifshitz frame: $u_\mu T^\mu{}_\nu = -\rho u_\nu$

$$T^\mu{}_\nu = T_g{}^\mu{}_\nu + T_\Lambda{}^\mu{}_\nu + T_{\mathrm{SM}}{}^\mu{}_\nu \;\; = (8\pi G_\mathrm{N})^{-1} G^\mu{}_\nu$$

↖g for GDM

Generalised Dark Matter

Linear scalar perturbation

- Perturbed stress-energy-momentum tensor

$$T_{\mu\nu} = \rho u_\mu u_\nu + P(g_{\mu\nu} + u_\mu u_\nu) + \Sigma_{\mu\nu}$$

g for GDM

$$\delta_g = \delta\rho_g/\bar{\rho}_g \qquad w = \bar{P}_g/\bar{\rho}_g \qquad \Sigma^i_{g\,j} = \bar{\rho}_g(1+w)(\partial_i\partial_j\Sigma_g)^{\text{tracefree}}$$

$$u_{g\,i} = -a\,\partial_i\theta_g \qquad \Pi_g = \delta P_g/\bar{\rho}_g$$

- Perturbed conservation equation $\nabla_\mu T_g{}^\mu{}_\nu = 0$

- GDM closure relations

derived for neutrinos: Blas et al 2011 JCAP 7

$$\Pi_g = c_a^2\delta_g + (c_s^2 - c_a^2)\hat{\Delta}_g$$

rest frame

non-adiabatic pressure Π_{nad} vanishes if P=P(ρ)

$$\dot{\Sigma}_g = -3\mathcal{H}\Sigma_g + \frac{4}{(1+w)}c_{\text{vis}}^2\hat{\Theta}_g$$

Newtonian

made-up by W. Hu 1998 ApJ 506

- GDM parameters $w(\tau)$ 'equation of state', $c_s^2(k,\tau)$ 'sound speed', $c_{\text{vis}}^2(k,\tau)$ 'viscosity'

$$c_a^2 = \frac{\dot{\bar{P}}_g}{\dot{\bar{\rho}}_g} = w - \frac{\dot{w}}{3\mathcal{H}(1+w)}$$

'adiabatic sound speed'

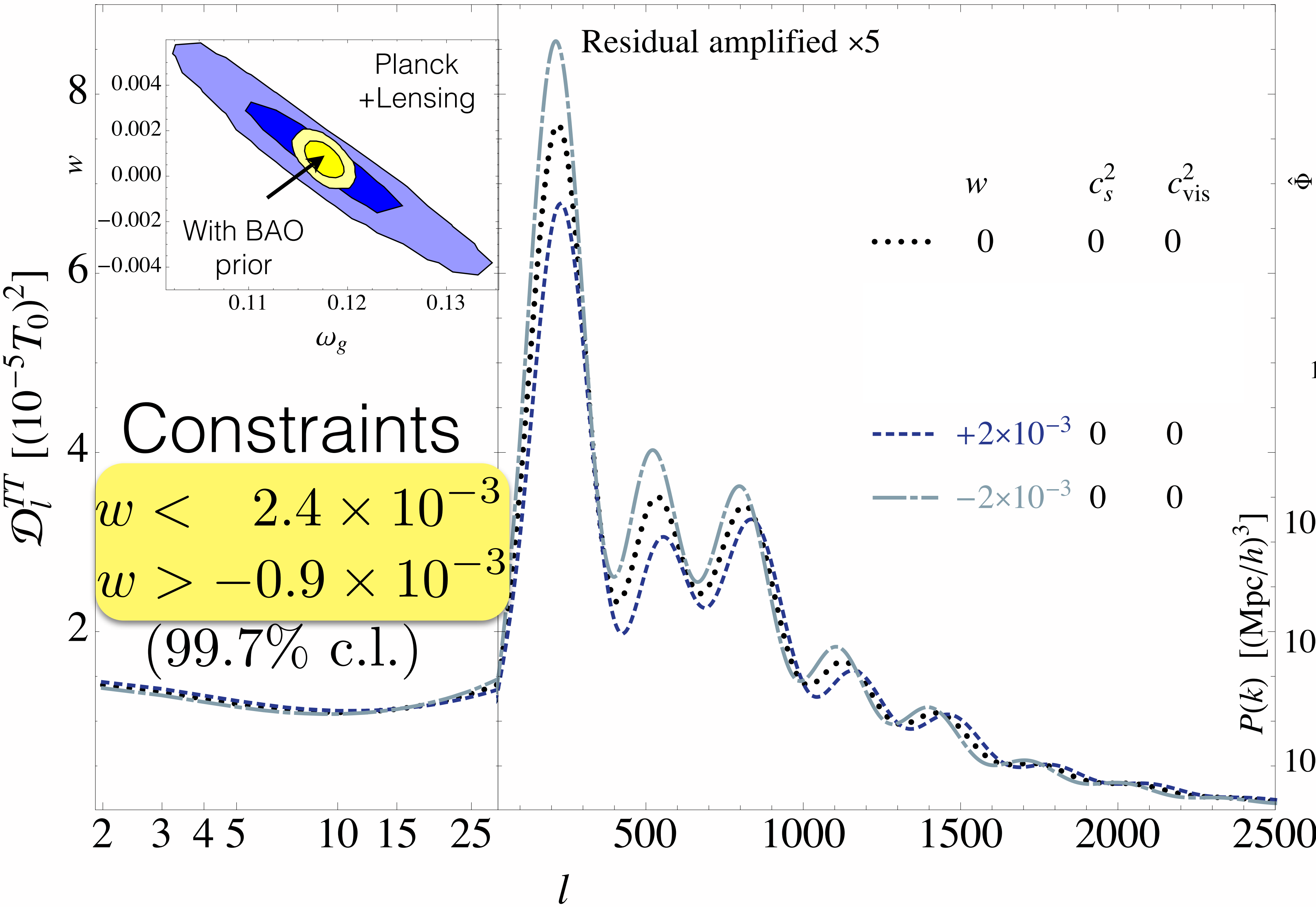
Extending ΛCDM into Λ-GDM: imprints on the CMB and constraints from Planck

$$a^3 \rho_g \propto \omega_g (1 + 3w \ln(1+z))$$

$$k_{\rm decay}^{-1} \mathcal{H} \simeq \sqrt{c_s^2 + 0.5\, c_{\rm vis}^2}$$

CMB and constraints

Based on a modified `class` code Lesgourgues 2011 , MCMC 6+3 params with `montepython`

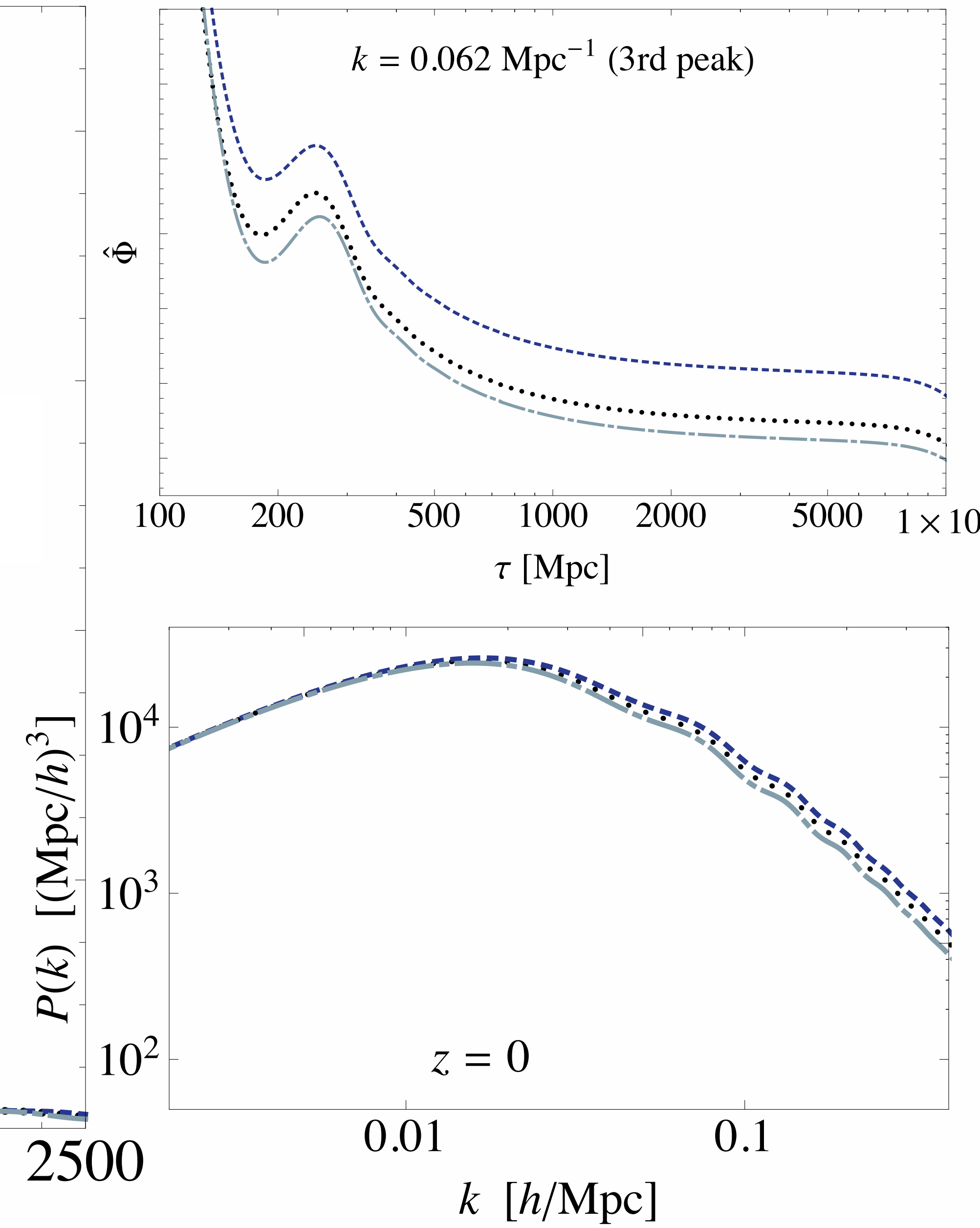


Constraints

$w < 2.4 \times 10^{-3}$

$w > -0.9 \times 10^{-3}$

(99.7% c.l.)



- w ↗ means ρ_g ↗ and ρ_{rad}/ρ_{matter} ↘ during recombination
- w is anticorrelated with ω_g , correlated with H_0
- w is not correlated with c_s^2, c_{vis}^2

Xu, Chang, PRD 88, 2013
Calabrese et al, PRD 80 2009
Thomas et al, 1601.05097
Kopp et al, 1604.xxxxx

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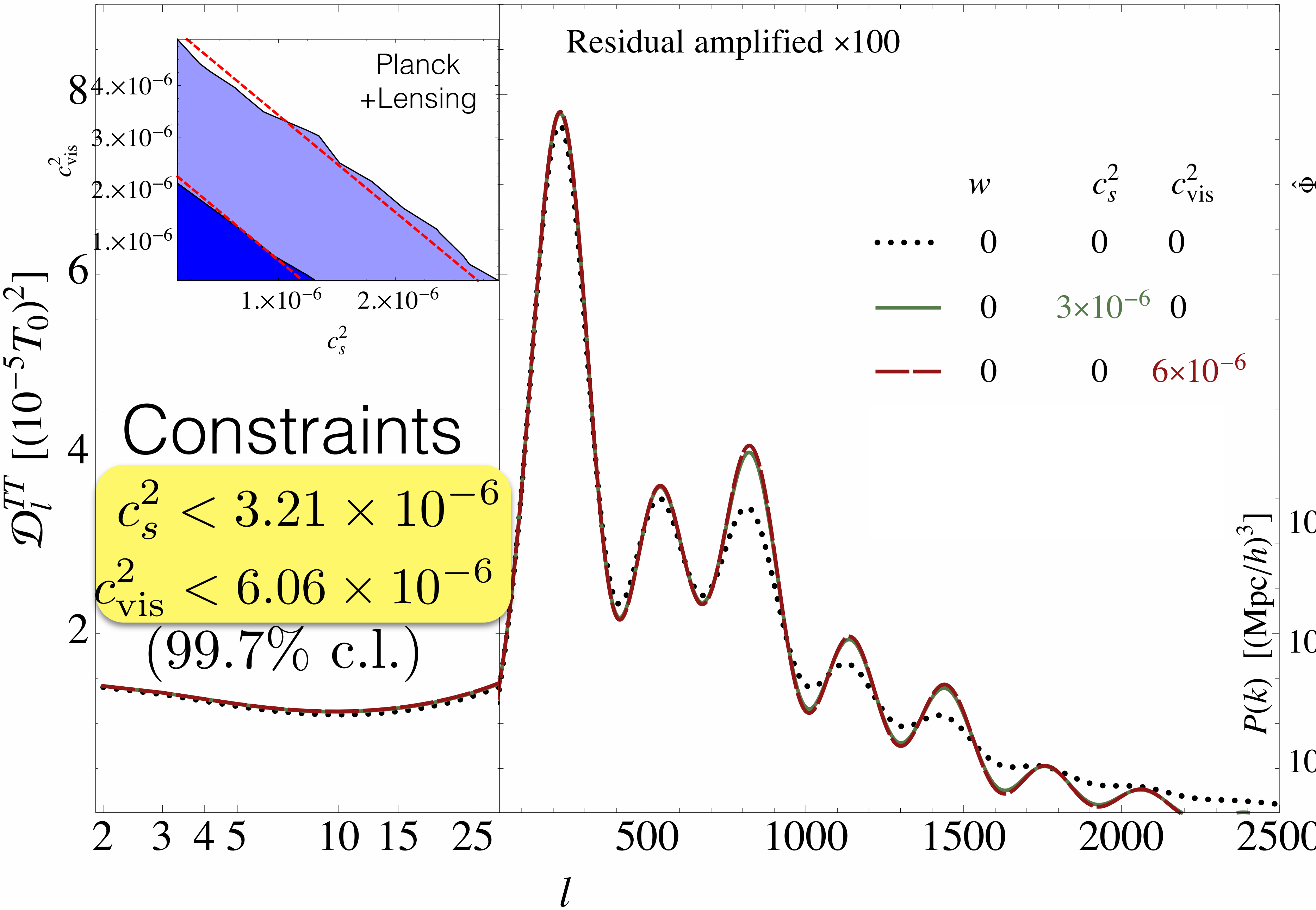
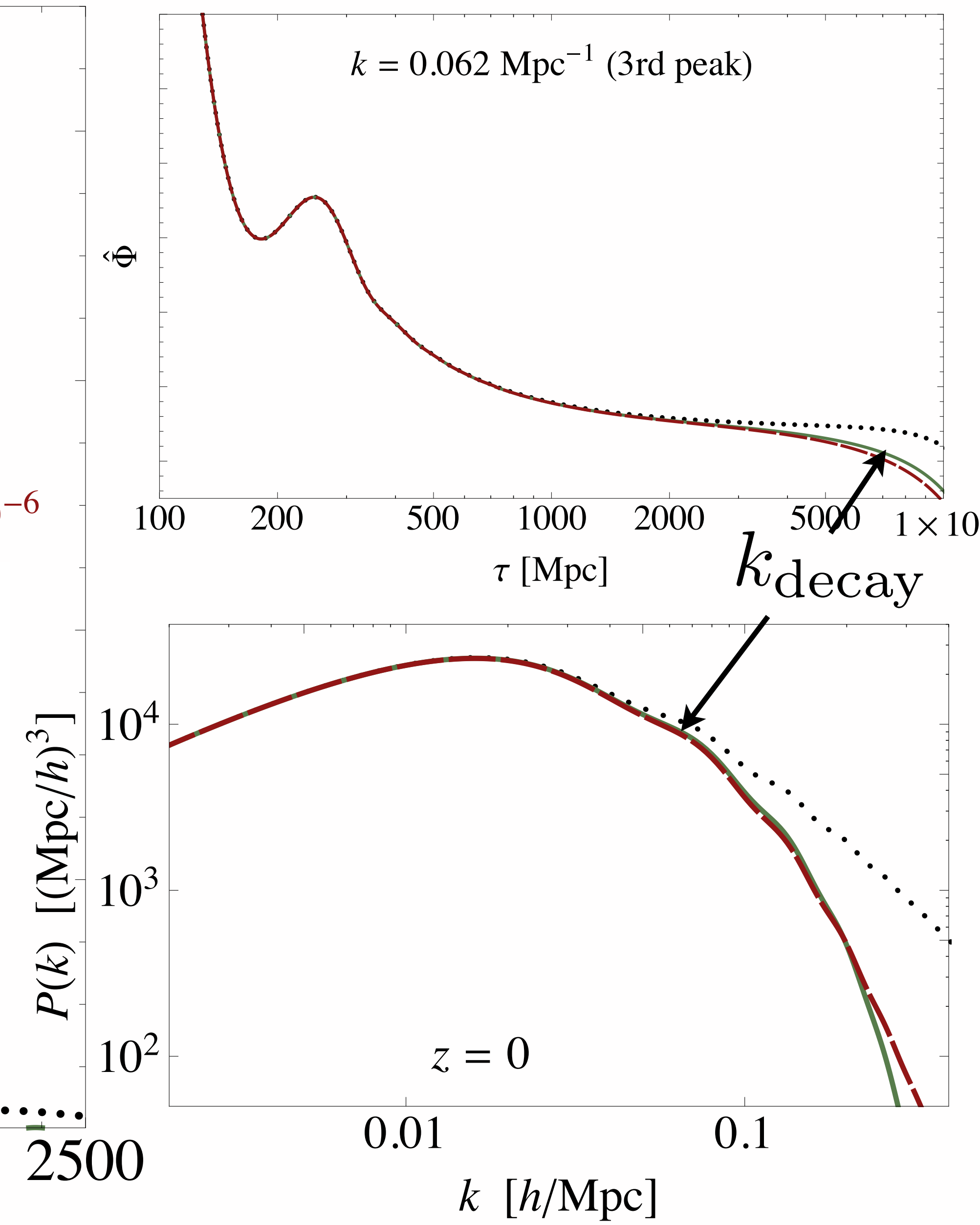




- c^2 ↗ means **Φ** ↘ decays at late times: ***less lensing***
- c_s^2 is anticorrelated with c_{vis}^2 because $k_{decay}^{-1} = \tau\sqrt{c_s^2 + 0.5\, c_{vis}^2}$
- Not correlated with primary parameters but with Σm_ν

Mueller, PRD 71 2005
Calabrese et al, PRD 80 2009
Thomas et al, 1601.05097
Kopp et al, 1604.xxxxx

GDM: connection to specific DM models and mapping to non-equ.-thermodynamics and effective theory of fluids

Rough estimates

$$w \simeq c_s^2 \simeq c_{\rm vis}^2$$

GDM with constant parameters

Thomas et al, 1601.05097

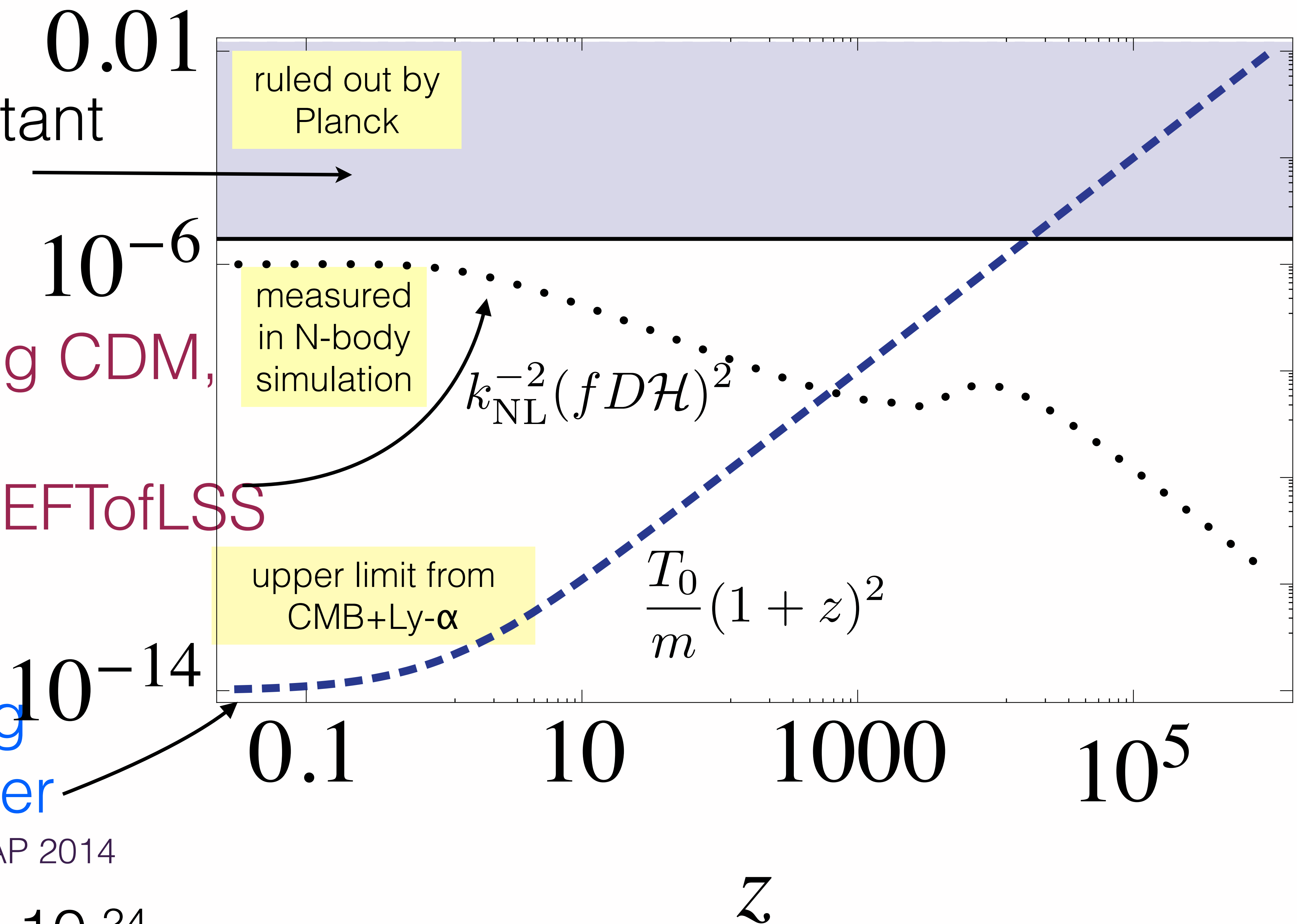
Freely streaming CDM, warmed-up by non-linearities, EFTofLSS

Baumann et al, JCAP 2012

Freely streaming warm dark matter

Armendariz-Picon et al, JCAP 2014

CDM neutralino 10^{-24}



GDM from...

Particles (Boltzmann equation)

- Freely streaming warm dark matter

  Armendariz-Picon, Neelakanta, JCAP 2014

- Specific models, like self interacting massive neutrinos and dark atoms + dark photons

  Oldengott et al JCAP 2015

  Cyr-Racine, Sigurdson, PRD 2013

Fields (effective or fundamental)

- Axion condensates.

  Sikivie, Yang, PRL 2009

  Hlozek, et al, PRD 2015

- Effective theory of large scale structure (scales larger than the non-linear scale): Leads to Landau-Lifshitz type energy momentum tensor for CDM

  Baumann et al, JCAP 2012

- Mimetic dark matter and more general constrained-norm scalar field theories.

  Mirzagholi, Vikman, arXiv 2015

  Ballesteros, JCAP 2015

GDM mapping

Linear scalar perturbations

Non-equil. thermodynamics (Landau and Lifshitz, Vol.6 1987)		Effective theory of fluids (Ballesteros, JCAP 2015)
• Principle: thermodynamics		volume-preserving 3D-diffeos
4 free functions	$p, \zeta, \eta, \kappa\,(\rho, S)$	$F, m^2, \alpha, \gamma\,(b)$
• no bulk viscosity	$\zeta = 0$	$m^2 = 0$
• equation of state	$w = \frac{\bar{p}}{\bar{\rho}}$	$w = -1 + \frac{d\ln(-\bar{F})}{d\ln b}$
• non-adiabatic $\Pi_{\rm nad}$	κ	γ
algebraic function of	$\hat{\Delta}_g$	$\hat{\Delta}_g$
if ▸ $\kappa = 0$: $c_s^2 - c_a^2 = 0$; ▸ $\kappa \to \infty$: $c_s^2 - c_a^2 \propto \partial_S p\vert_\rho$		always: $c_s^2 - c_a^2 \propto (\bar{\gamma} - 1)k^2$ (Hu, et al, PRL 85, 2000: same for axions)
• shear Σ_g	$c_{\rm vis}^2 \propto \eta$	$c_{\rm vis}^2 \propto \bar{\alpha} - 1,\ \dot{\bar{\alpha}}$
algebraic function of	$\hat{\Theta}_g$ ✓	✗ $\hat{\Theta}_g, \hat{\Delta}_g, \hat{\Psi}$

Summary

- 'Generalized dark matter' GDM with 3 new parameters offers the possibility to **test dark matter properties** in a wide class of models: warm + free streaming, interacting, condensate, mimetic dark matter, EFTofLSS...

- GDM parameter estimation with **Planck** likelihood + BAO prior: strong constraints and **consistent with ΛCDM**.

- GDM mapping to thermodynamics and EFT of fluids defined **non-perturbatively**

Ongoing

- Extend GDM into nonlinear regime.

- Add large scale structures data: WiggleZ, CFHTlenS, Ly-α

- Constrain scale and time dependent GDM parameters, add bulk viscosity. Constrain isocurvature modes.

- Map specific models to GDM parameters