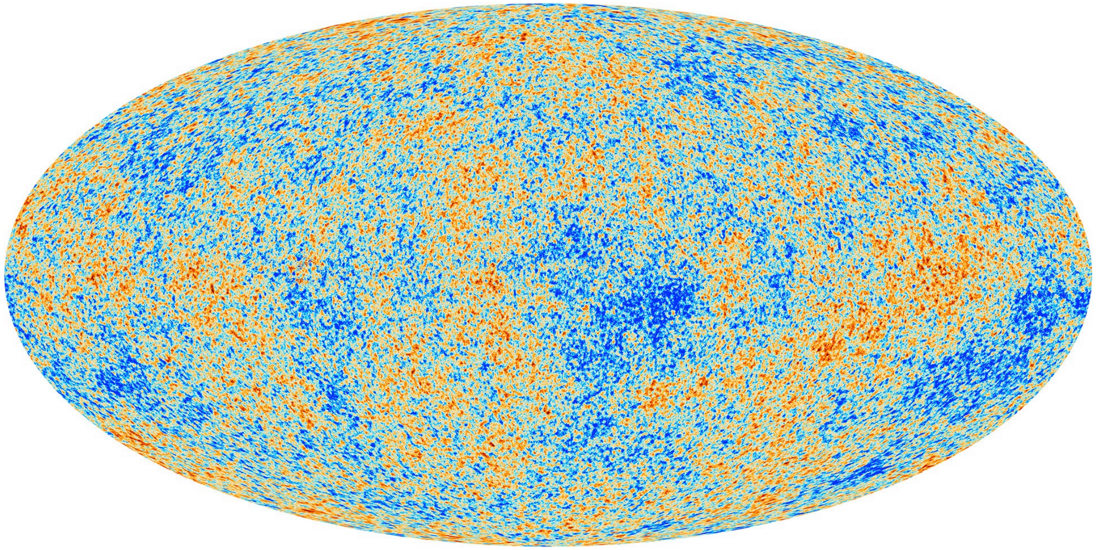
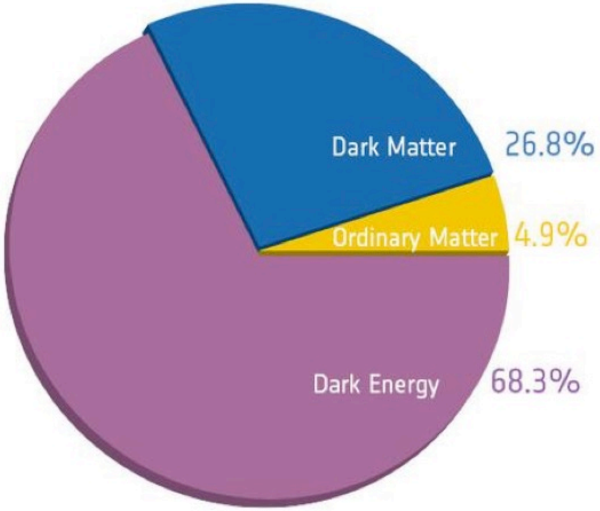
Cold dark matter:
Theoretical convenience or observational fact?

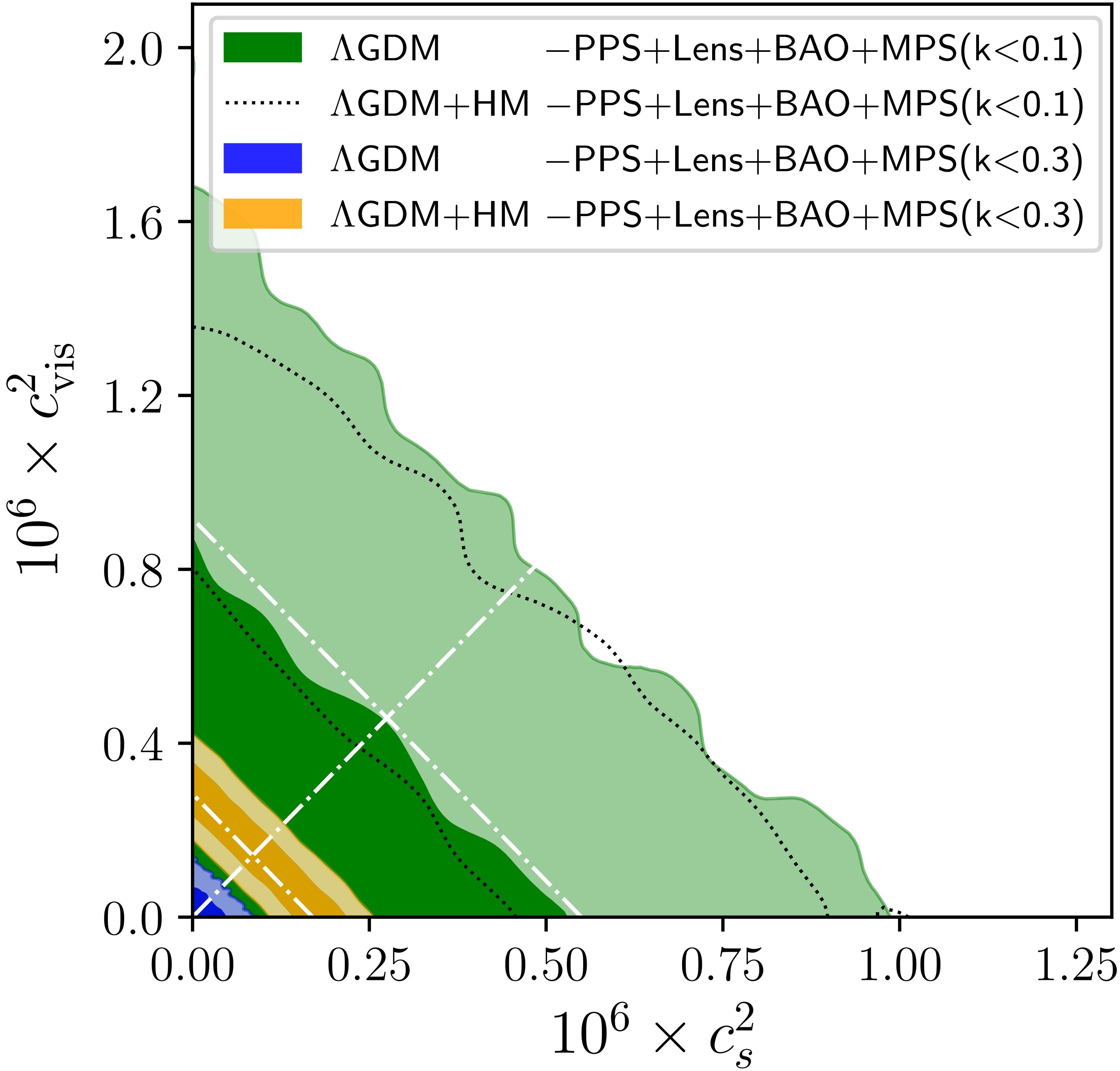




Dan Thomas

With Michael Kopp, Costas Skordis, Stephane Ilic

1601.05097 Initial constraints
1605.00649 Theoretical exploration
1802.09541 Time dependent equation of state
1905.02739 WiggleZ and halo-model



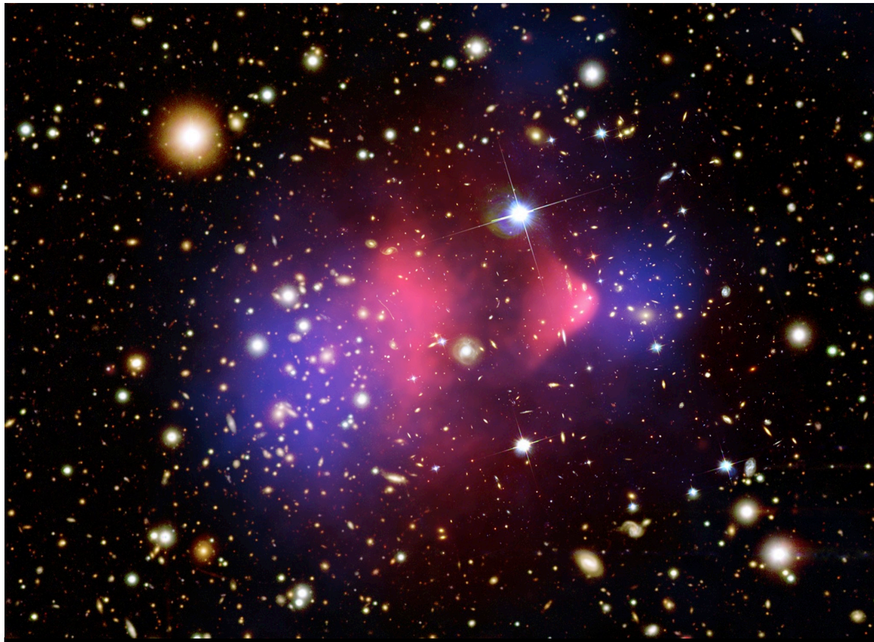
ΛGDM −PPS+Lens+BAO+MPS(k<0.1)
ΛGDM+HM −PPS+Lens+BAO+MPS(k<0.1)
ΛGDM −PPS+Lens+BAO+MPS(k<0.3)
ΛGDM+HM −PPS+Lens+BAO+MPS(k<0.3)
$10^6 \times c_{\rm vis}^2$
$10^6 \times c_s^2$
0.0
0.4
0.8
1.2
1.6
2.0
0.00
0.25
0.50
0.75
1.00
1.25

Why Cold DM?

Why DM?

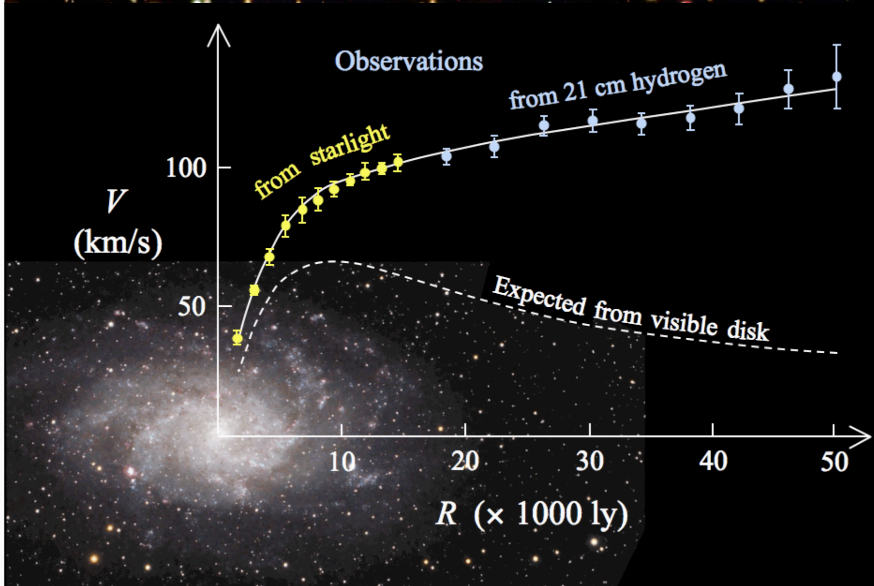
- Many observations (varied scales):
  CMB
  expansion history
  lensing
  bullet cluster
  rotation curves…
- No good alternative

(hard to do all of the above at once)



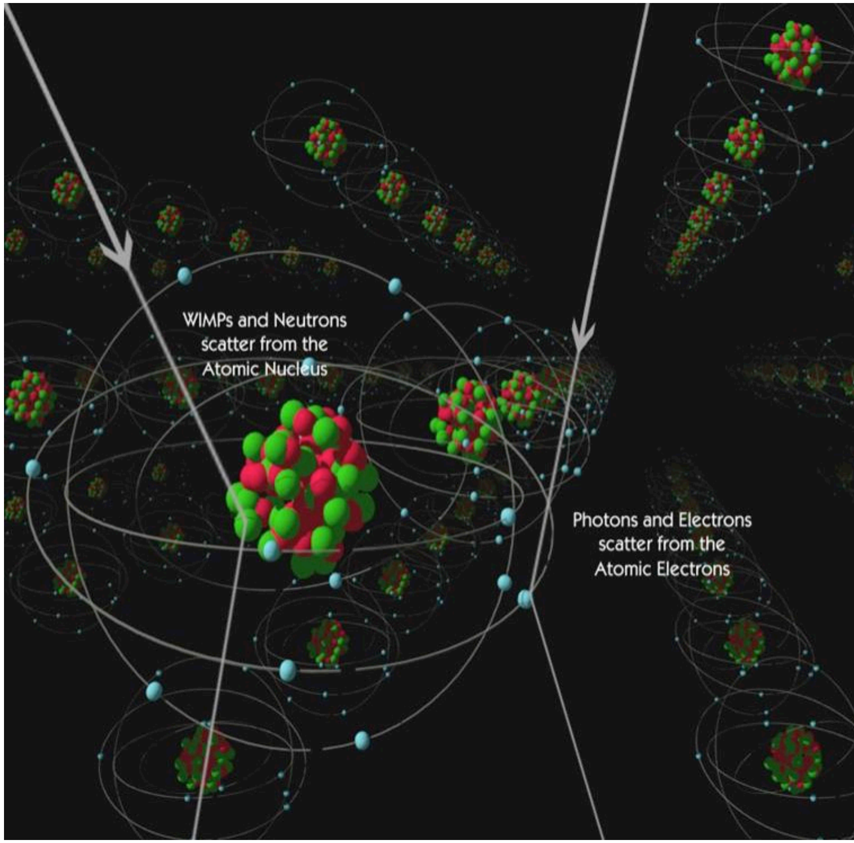
Why CDM?

- Seems to fit most observations
- WIMPs are CDM



Why *not* Cold DM?

- Gravitational evidence only
- Particle not found:
  Is there a preferred candidate?
- Small scale problems
- There are well motivated non-CDM: WDM, FDM, EFTofLSS[1]
- Null test/being agnostic:
  what do the data say?
- Do all observations require same DM properties?



[1]: breakdown of CDM paradigm on its own terms

Introducing Generalised DM

Hu 1998

Simple, model-independent, covers lots of alternatives

$$T_{\mu\nu}^{\mathrm{CDM}} = \rho u_\mu u_\nu$$

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

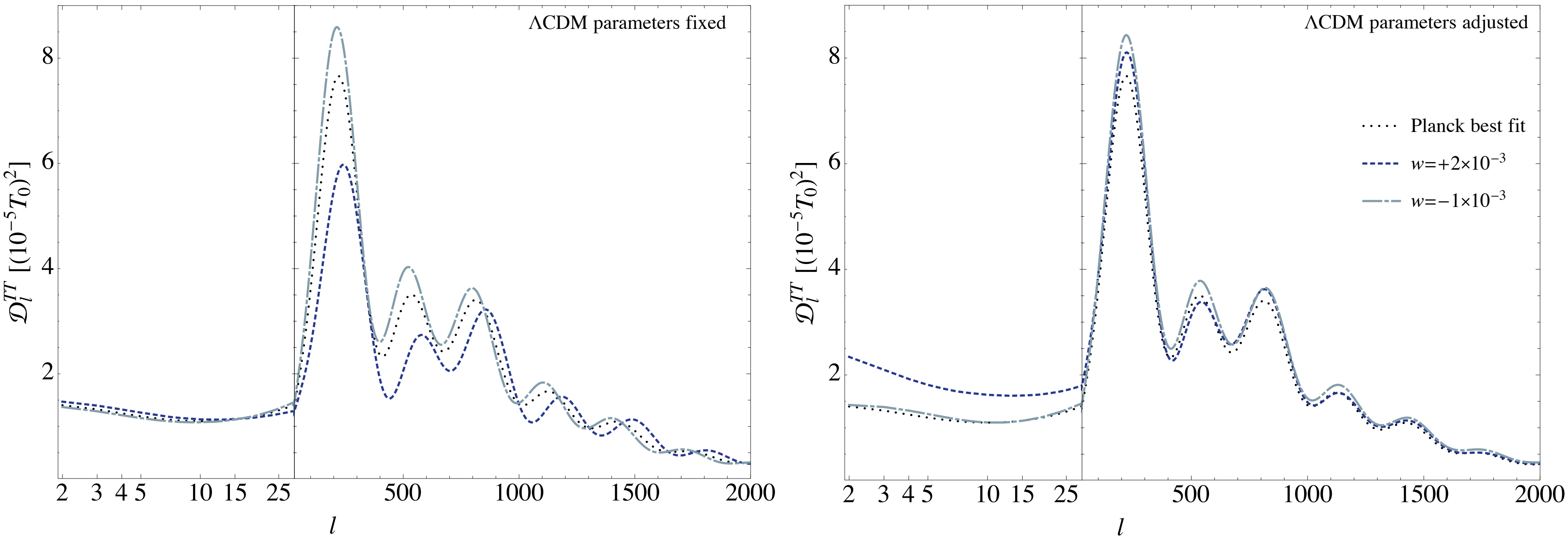
- Background: density, pressure
- Perturbations: density, velocity, pressure, shear
- Closure equations needed for $\bar{P}$ δP Σ
- Introduce 3 new parameters w c_s^2 c_{vis}^2

  CDM recovered when all 3 are zero
- Captures WDM, FDM, EFTofLSS… and many others

Phenomenology of w

Changes evolution of background DM density

- Distance to last-scattering->peak location; degeneracy with H_0
- Matter-radiation equality-> peak heights; degeneracy with $\Omega_{\rm DM}$



Left: standard parameters not varied

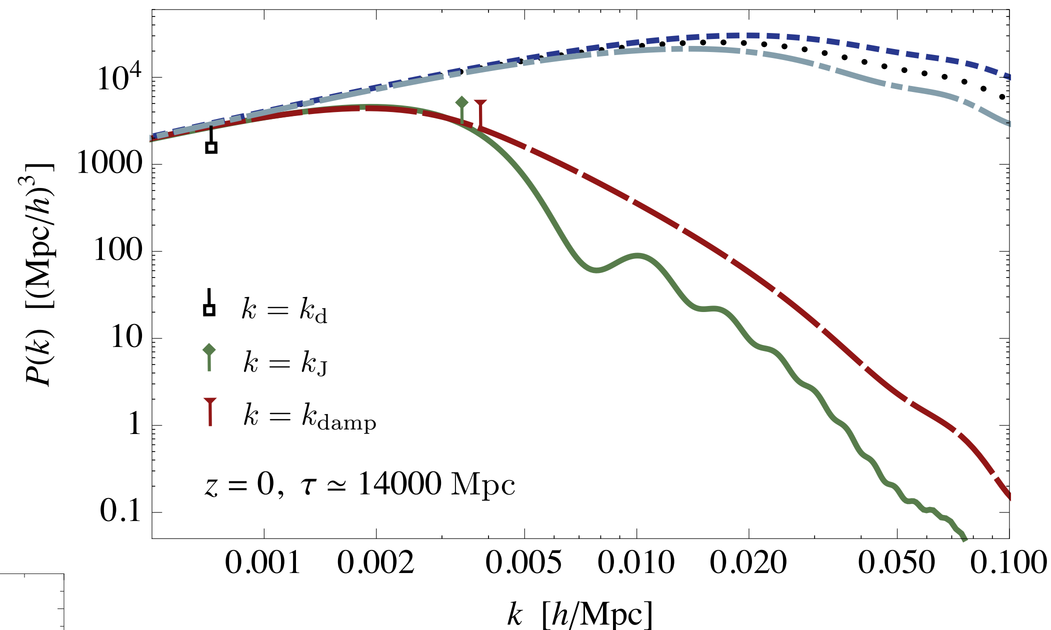
Right: standard parameters varied to compensate w

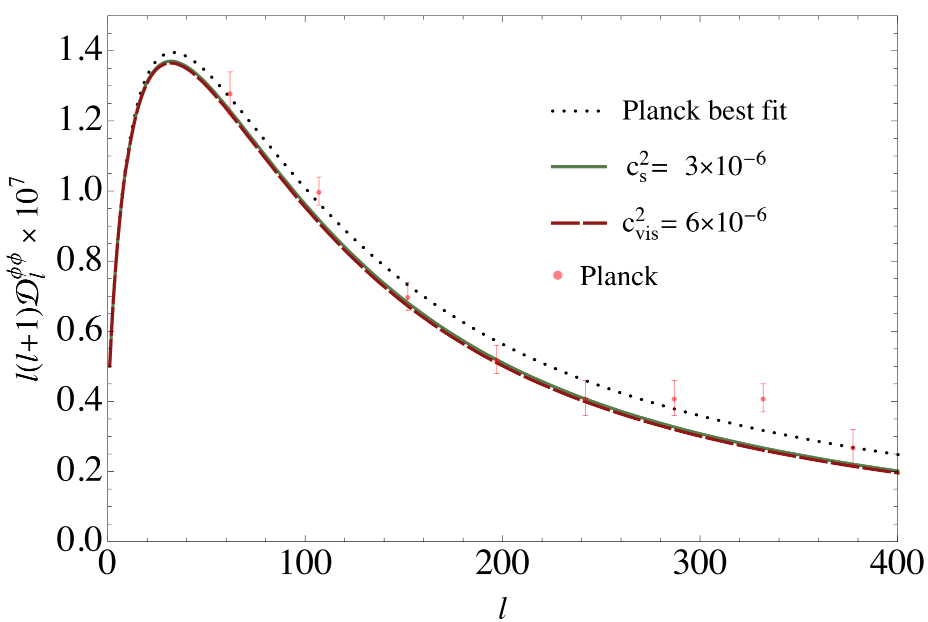
Phenomenology of c_s^2 $c_{\rm vis}^2$

Evolution of density perturbations modified

This affects gravitational potentials

→ Affects CMB lensing





Both parameters reduce perturbations below $k_{\rm dec}^{-1} = \tau\sqrt{c_s^2 + \frac{8}{15}c_{\rm vis}^2}$

→ degeneracy

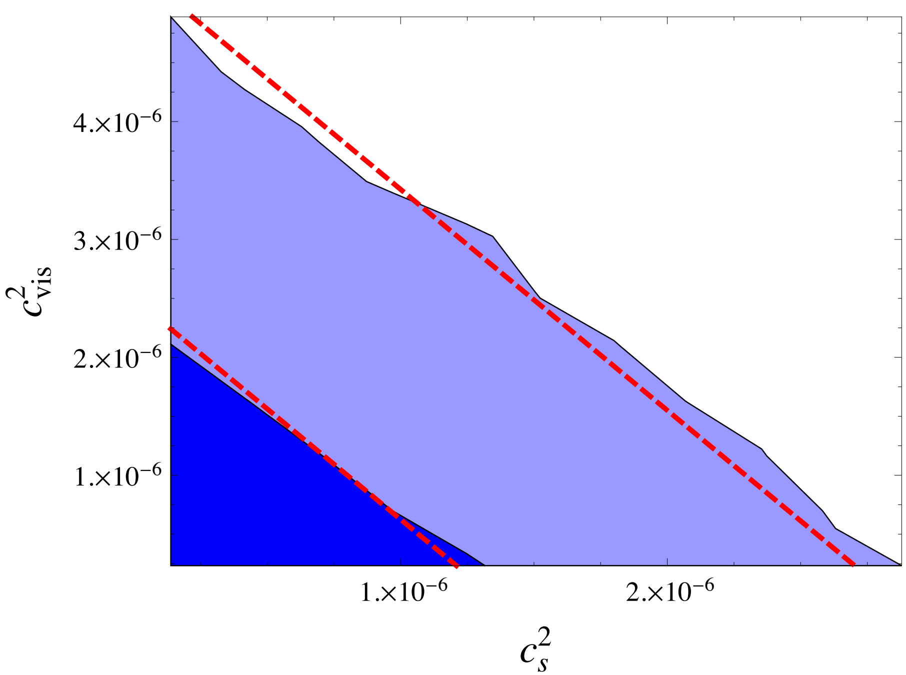
c_s^2 causes oscillations below Jeans scale k_J

MANCHESTER 1824
The University of Manchester

Planck T+P+lens, BAO, HST, MPS

w

- Upper bound on $|w|$ $\mathcal{O}\left(10^{-3}\right)$
- Expansion history (BAO, HST) important
- Degeneracies with ω_m H_0
- Constraints 50% worse if neutrino mass varied
- Robust to non-linear modeling



c_s^2 & $c_{\rm vis}^2$

- Upper bound $\mathcal{O}\left(10^{-6}\right)$
- CMB lensing important
- Expected $k_{\rm dec}$ degeneracy
- Robust to non-linear modelling & neutrino mass
- WiggleZ conservative cut: 3x improvement

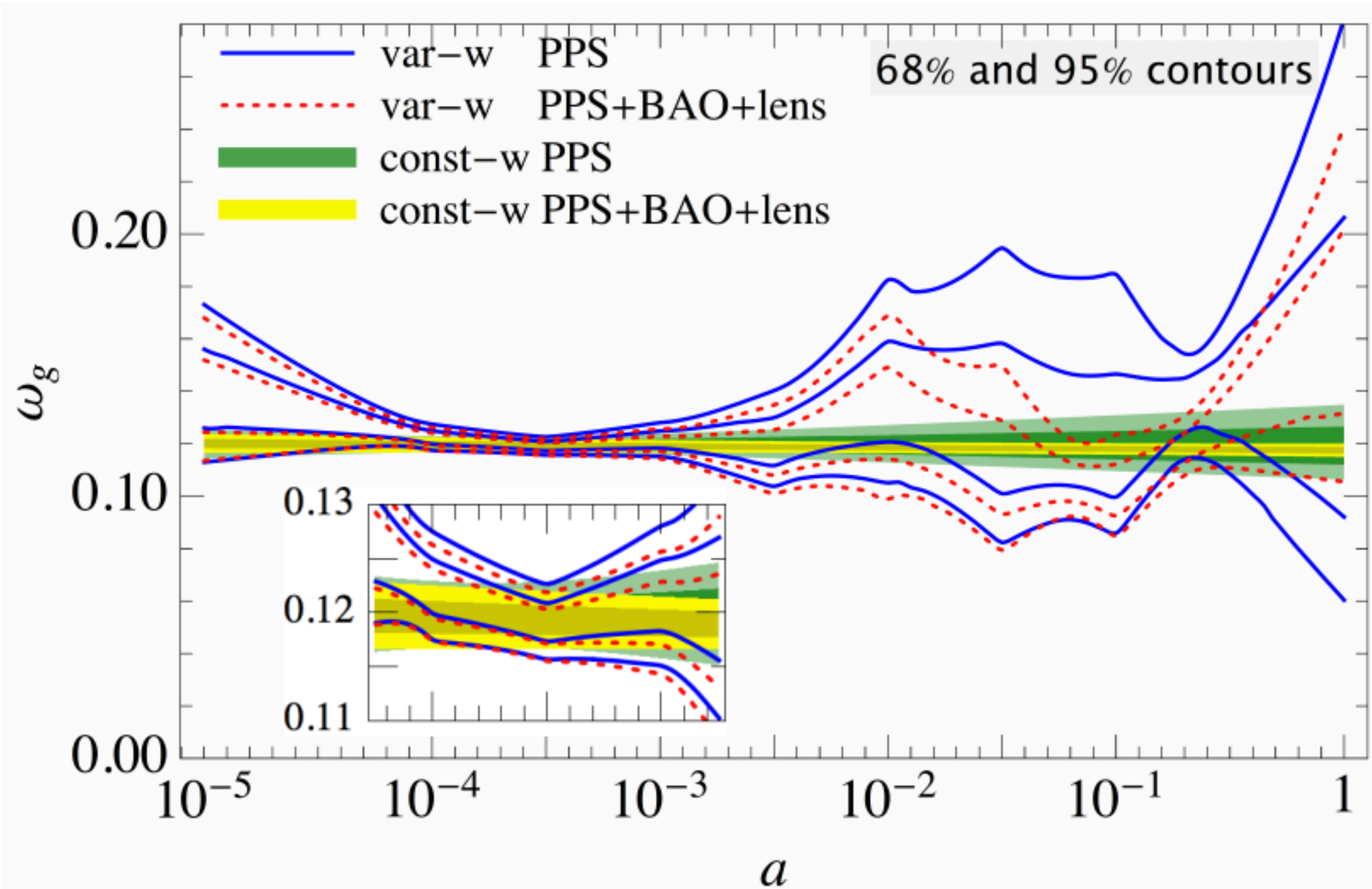
Constraints

Likelihood (PPS+...)	Model (Λ-GDM+...)	$10^2 w$ 95.5%	$10^2 w$ 99.7%	$10^6 c_s^2$ (upper bound) 95.5%	$10^6 c_s^2$ (upper bound) 99.7%	$10^6 c_{vis}^2$ (upper bound) 95.5%	$10^6 c_{vis}^2$ (upper bound) 99.7%
		$-0.040^{+0.473}_{-0.468}$	$-0.040^{+0.700}_{-0.701}$	3.31	6.31	5.70	11.3
+ Lens		$0.066^{+0.434}_{-0.427}$	$0.066^{+0.654}_{-0.642}$	1.92	3.44	3.27	5.99
+ Lens + BAO		$0.074^{+0.111}_{-0.110}$	$0.074^{+0.164}_{-0.163}$	1.91	3.21	3.30	6.06
	+ HM	$-0.029^{+0.477}_{-0.481}$	$-0.029^{+0.716}_{-0.690}$	3.11	5.39	5.62	11.1
+ Lens	+ HM	$-0.087^{+0.448}_{-0.461}$	$-0.087^{+0.668}_{-0.649}$	1.92	3.83	3.13	5.79
+ Lens + BAO	$+ m_\nu$	$0.101^{+0.159}_{-0.143}$	$0.101^{+0.248}_{-0.201}$	1.90	3.54	2.86	4.82
+ Lens + BAO + MPS ($k < 0.1h\text{Mpc}^{-1}$)		$0.040^{+0.109}_{-0.108}$	$0.040^{+0.164}_{-0.157}$	0.667	1.21	1.10	1.91
+ Lens + BAO + MPS ($k < 0.1h\text{Mpc}^{-1}$)	+ HM	$0.045^{+0.106}_{-0.109}$	$0.045^{+0.161}_{-0.161}$	0.633	1.11	0.953	1.83
+ Lens + BAO + MPS ($k < 0.3h\text{Mpc}^{-1}$)		$0.035^{+0.112}_{-0.112}$	$0.035^{+0.175}_{-0.168}$	0.0616	0.103	0.0958	0.16
+ Lens + BAO + MPS ($k < 0.3h\text{Mpc}^{-1}$)	+ HM	$0.046^{+0.113}_{-0.111}$	$0.046^{+0.169}_{-0.163}$	0.201	0.254	0.333	0.428

No time and space dependence here: single values of the parameters

Time dependence

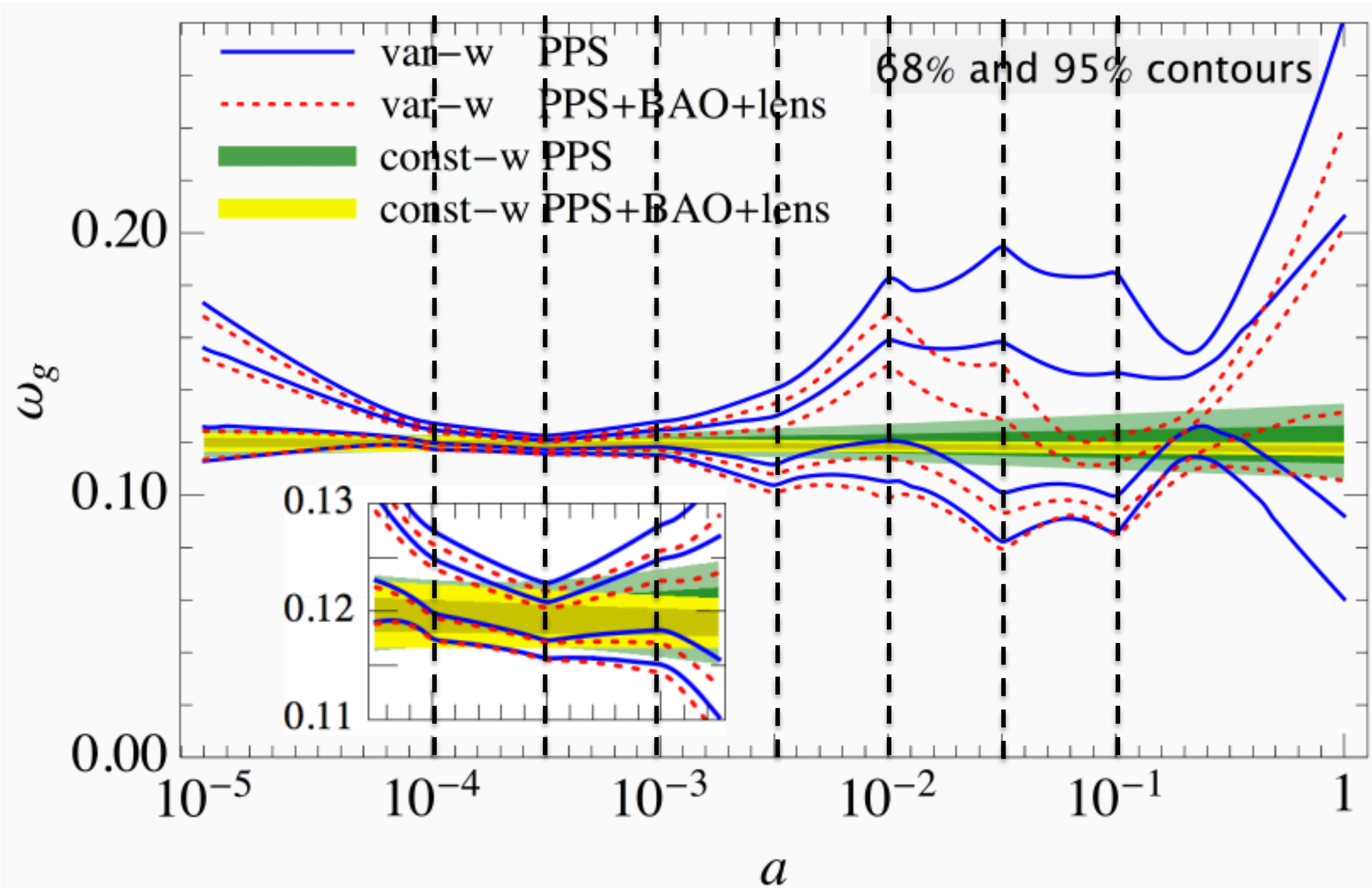
Treat varying w as test of DM density scaling: $\omega_g = a^3 h^2 \rho(a)/\rho_{\rm crit}$



MANCHESTER 1824
The University of Manchester

Time dependence

Treat varying w as test of DM density scaling: $\omega_g = a^3 h^2 \rho(a)/\rho_{\rm crit}$



MANCHESTER 1824
The University of Manchester

Constraints

Likelihood (PPS+...)	Model (Λ-GDM+...)	$10^2 w$ 95.5%	$10^2 w$ 99.7%	$10^6 c_s^2$ (upper bound) 95.5%	$10^6 c_s^2$ (upper bound) 99.7%	$10^6 c_{\rm vis}^2$ (upper bound) 95.5%	$10^6 c_{\rm vis}^2$ (upper bound) 99.7%
		$-0.040^{+0.473}_{-0.468}$	$-0.040^{+0.700}_{-0.701}$	3.31	6.31	5.70	11.3
+ Lens		$0.066^{+0.434}_{-0.427}$	$0.066^{+0.654}_{-0.642}$	1.92	3.44	3.27	5.99
+ Lens + BAO		$0.074^{+0.111}_{-0.110}$	$0.074^{+0.164}_{-0.163}$	1.91	3.21	3.30	6.06
	+ HM	$-0.029^{+0.477}_{-0.481}$	$-0.029^{+0.716}_{-0.690}$	3.11	5.39	5.62	11.1
+ Lens	+ HM	$-0.087^{+0.448}_{-0.461}$	$-0.087^{+0.668}_{-0.649}$	1.92	3.83	3.13	5.79
+ Lens + BAO	$+ m_\nu$	$0.101^{+0.159}_{-0.143}$	$0.101^{+0.248}_{-0.201}$	1.90	3.54	2.86	4.82
+ Lens + BAO + MPS ($k < 0.1h\mathrm{Mpc}^{-1}$)		$0.040^{+0.109}_{-0.108}$	$0.040^{+0.164}_{-0.157}$	0.667	1.21	1.10	1.91
+ Lens + BAO + MPS ($k < 0.1h\mathrm{Mpc}^{-1}$)	+ HM	$0.045^{+0.106}_{-0.109}$	$0.045^{+0.161}_{-0.161}$	0.633	1.11	0.953	1.83
+ Lens + BAO + MPS ($k < 0.3h\mathrm{Mpc}^{-1}$)		$0.035^{+0.112}_{-0.112}$	$0.035^{+0.175}_{-0.168}$	0.0616	0.103	0.0958	0.16
+ Lens + BAO + MPS ($k < 0.3h\mathrm{Mpc}^{-1}$)	+ HM	$0.046^{+0.113}_{-0.111}$	$0.046^{+0.169}_{-0.163}$	0.201	0.254	0.333	0.428

Use wider range of WiggleZ data…

→ 10x improvement of constraints

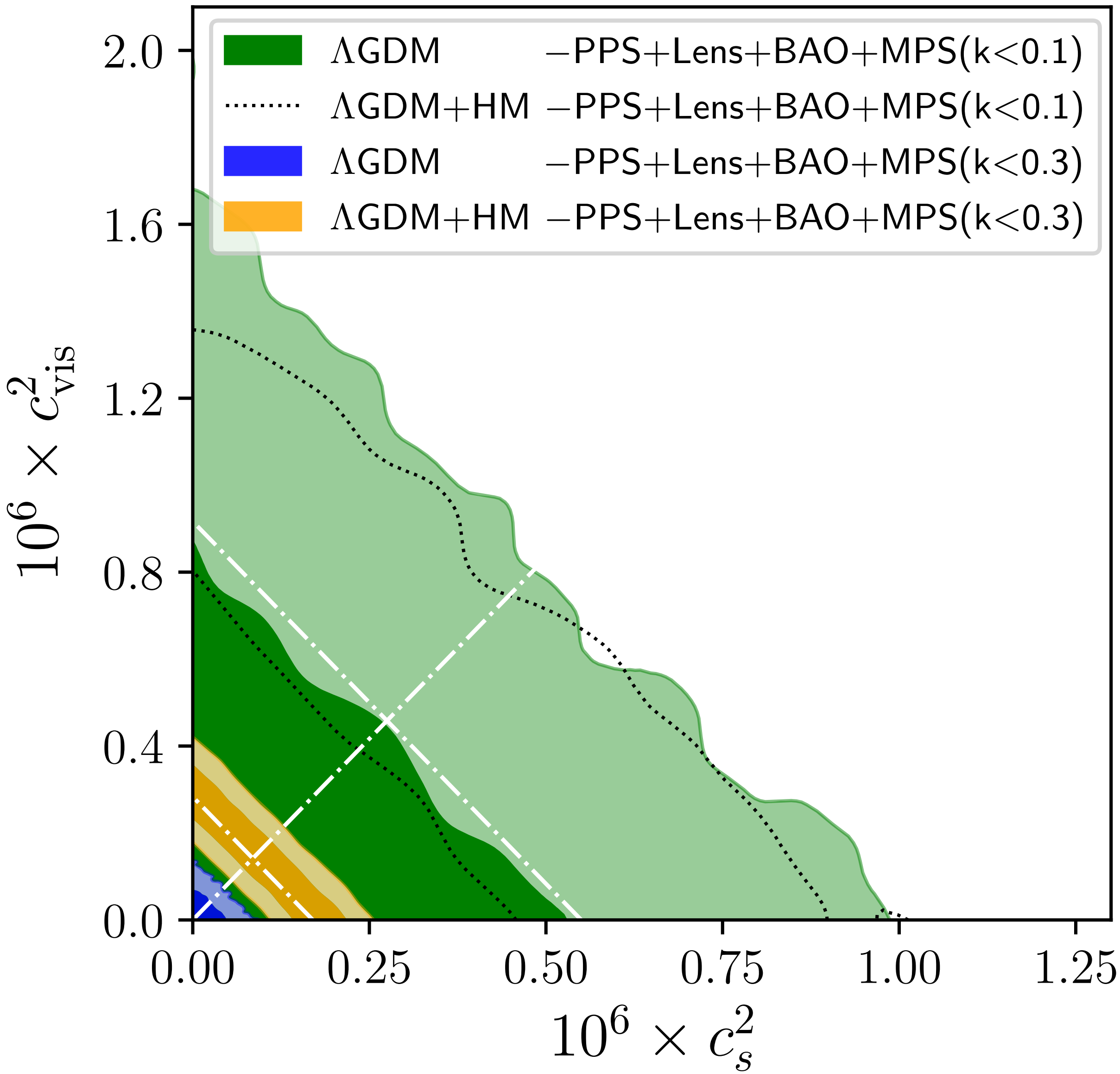
Unconservative WiggleZ

Conservative $k < 0.1$ constraints robust to non-linear modeling

Unconservative $k < 0.3$ not robust

Current data able to constrain interesting values of parameters ~ $\mathcal{O}\left(10^{-7}\right)$

…but non-linear modelling needs to be rigorous



Summary

- GDM extends CDM with 3 new parameters: $w \quad c_s^2 \quad c_{\rm vis}^2$
- Captures phenomenology of many popular alternatives
- *Data-driven* null test/confirmation of standard model

- Robust constant GDM parameter constraints:

$w \quad \mathcal{O}\left(10^{-3}\right)$ (Expansion history important; degeneracies)

c_s^2 & $c_{\rm vis}^2 \quad \mathcal{O}\left(10^{-6}\right)$ (CMB lensing and LSS important)

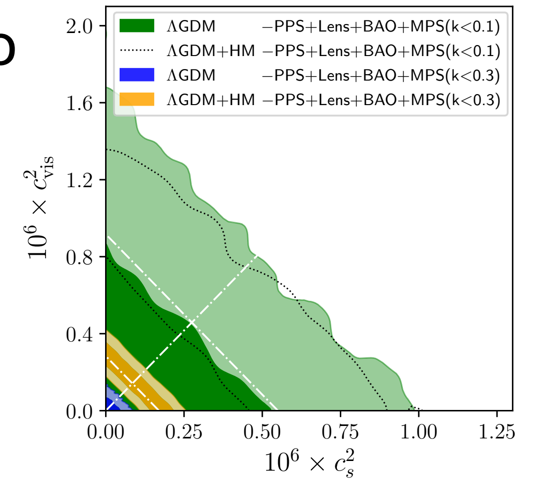
- Time dependent constraints on w

  → constrains dark matter density over cosmic time

- Hints…

Hints… and the future

- Rigorously modelling non-linear scales crucial to determining the nature of the dark matter



- Possible detection:

  halomodel needs to be verified in detail

- Currently close to a detection of EFTofLSS level parameters:

  Simons Observatory CMB lensing might deliver this?

- Work in progress on full scale and time dependence… tentative 2σ detections… BUT lots of interesting nuances that are currently under investigation…

Watch this space…

The University of Manchester

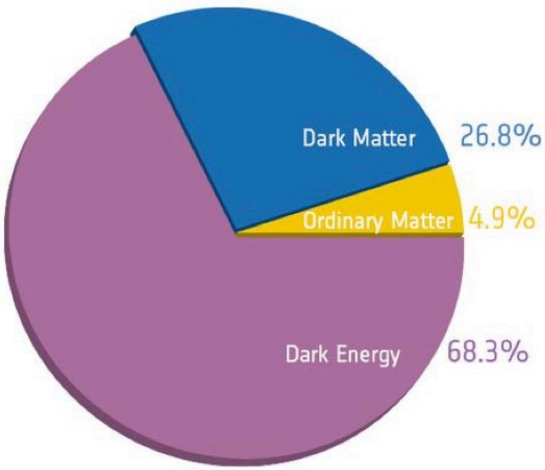
Auxiliary Slides

Cosmological *Cold* DM Paradigm

MANCHESTER 1824
The University of Manchester

Collisionless, initially cold, dark matter particle:

1. Decouples when non-relativistic
2. Collisionless for all cosmological purposes
3. Negligible velocity dispersion



Calculationally:

- Cosmological perturbation theory (linear scales only)
  → Pressureless perfect fluid
- N-body simulations (all scales)
  → Vlasov equation; cold initial conditions; not a fluid;
  shell crossing → velocity dispersion becomes non-zero

Relating GDM to models

- WDM: parameters scale as a^{-2}
- FDM/axions: $c_s^2 = (k/2am)^2 \quad w = c_{\mathrm{vis}}^2 = 0$
- Self interacting DM, e.g. coupled "dark atoms" and "dark photons"
- EFTofLSS: nonlinearities on small scales have an effect on linear scales, so even CDM isn't pressureless perfect fluid.

  Parameters $\mathcal{O}\left(10^{-6}\right)$ with approximate time dependence $(Df\mathcal{H})^2$
- Other ways to generalise perfect fluids or multiple coupled perfect fluids
- Note: WIMPs have non-zero GDM parameters, $\mathcal{O}\left(10^{-20}\right)$

Closure Equations

MANCHESTER 1824
The University of Manchester

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

- Can be approx derived from Boltzmann hierarchy
- Higher moments comprise the Hubble friction term
- Similar to coupled photon-baryon fluid

$$\Pi_{\text{nad}} \left(\equiv \frac{\delta P}{\bar{\rho}} - c_a^2(w)\delta \right) = \left(c_s^2 - c_a^2 \right) \hat{\Delta}^2 \qquad c_a^2 = w - \frac{\dot{w}}{3\mathcal{H}(1+w)}$$

$$\rightarrow \frac{\delta P}{\bar{\rho}} = c_s^2 \delta + 3\mathcal{H}(1+w)\left(c_s^2 - c_a^2 \right)\theta$$

- Choice of gauge invariant density: fluid rest frame is natural choice
- Separates equation of state and sound speed phenomenology:

Adiabatic part has no effect deep in horizon

$\rightarrow$ c_s^2 causes oscillations and is the sound speed

$c_s^2 = c_a^2$ reduces to adiabatic case

The University of Manchester

Closure equations

Many gory details… see 1605.00649

- Natural (not mandatory) to associate pressure with density and shear with velocity
- Eqn of state creates adiabatic sound speed

  (pressure that is in sync with density pert)
- Non-adiabatic pressure controlled by sound speed parameter
- Aim to separate phenomenology:

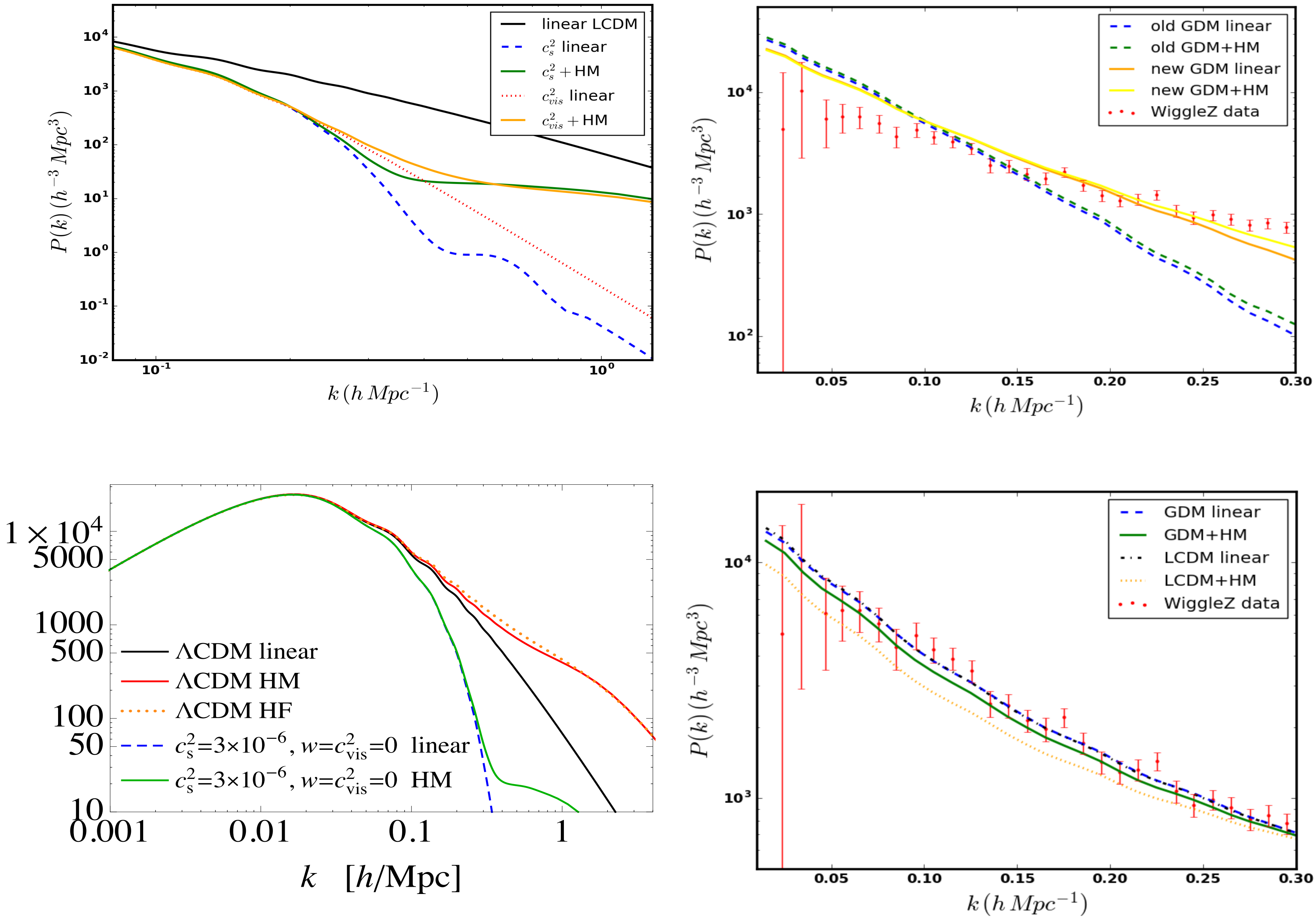
Shear damps &diff between potentials; pressure causes oscillations

Viscosity is thickness of fluid; resistance to shearing flows

GDM agnostic about cause of pressure (vel disp, interactions); these are differentiated through shear.

More than choice can be motivated.

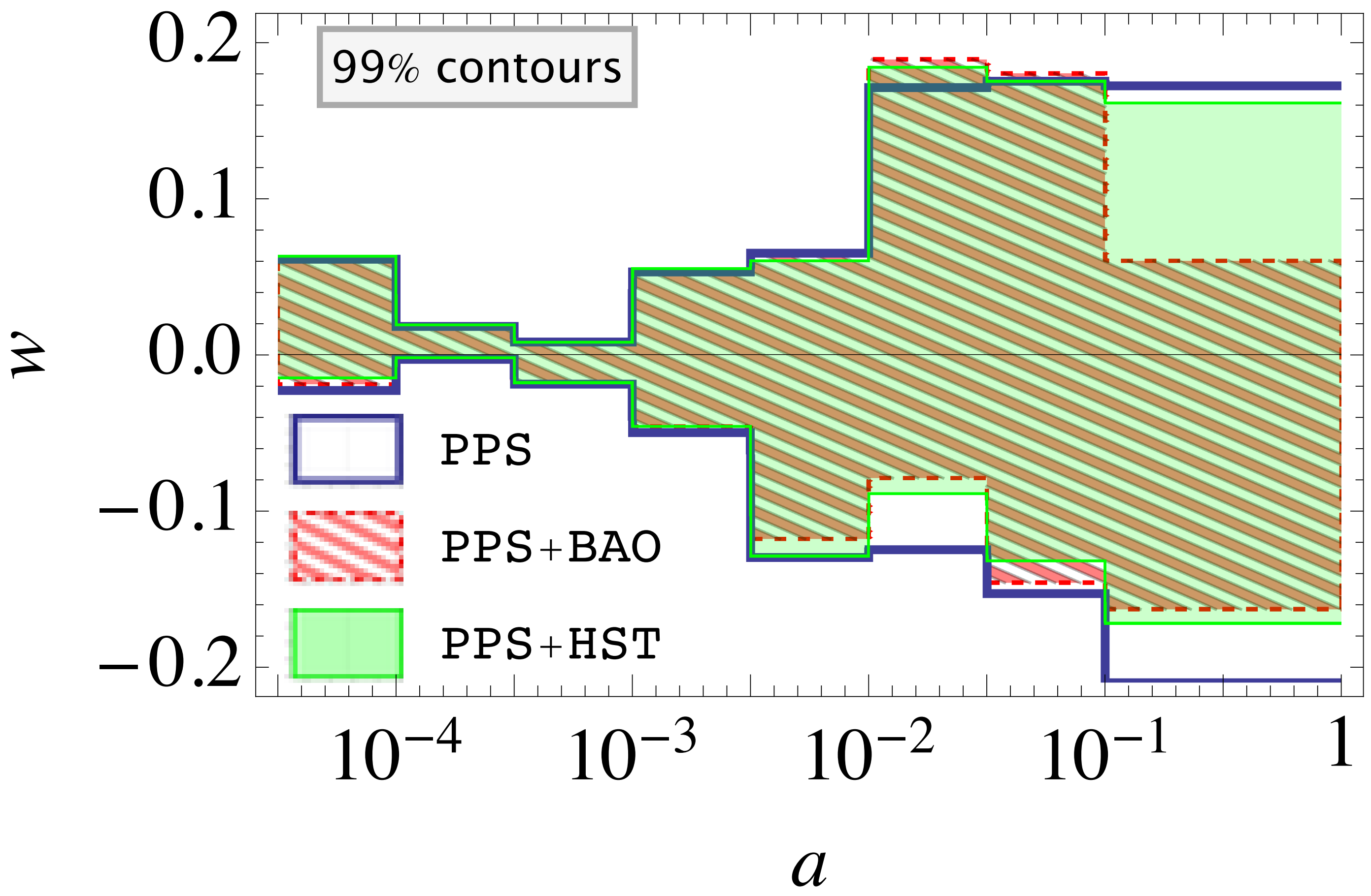
Justification is which existing model phenomenology is captured.



linear LCDM
c_s^2 linear
c_s^2 + HM
c_{vis}^2 linear
c_{vis}^2 + HM
$P(k)\,(h^{-3}\,Mpc^3)$
$k\,(h\,Mpc^{-1})$
old GDM linear
old GDM+HM
new GDM linear
new GDM+HM
WiggleZ data
$P(k)\,(h^{-3}\,Mpc^3)$
$k\,(h\,Mpc^{-1})$
ΛCDM linear
ΛCDM HM
ΛCDM HF
$c_s^2=3\times10^{-6}$, $w=c_{vis}^2=0$ linear
$c_s^2=3\times10^{-6}$, $w=c_{vis}^2=0$ HM
k [h/Mpc]
GDM linear
GDM+HM
LCDM linear
LCDM+HM
WiggleZ data
$P(k)\,(h^{-3}\,Mpc^3)$
$k\,(h\,Mpc^{-1})$

MANCHESTER 1824

The University of Manchester



Phenomenology of GDM

w changes time evolution of background dark matter density

$\Rightarrow$ affects expansion history, matter radiation equality

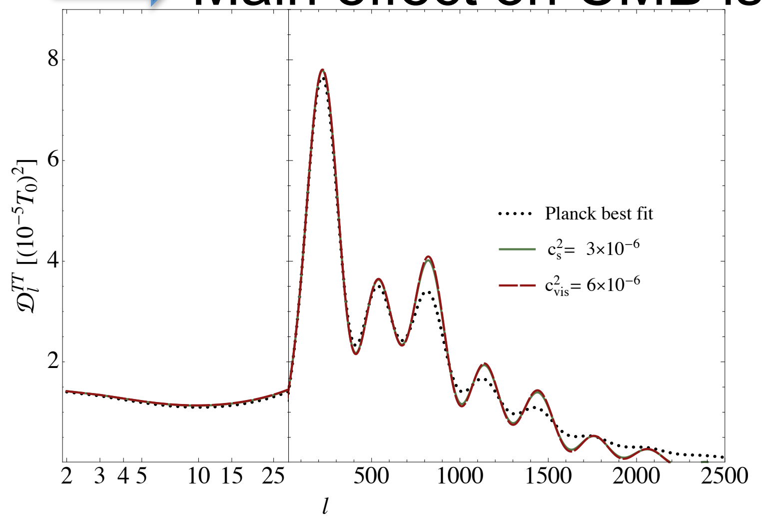
c_s^2 and $c_{\rm vis}^2$ affect DM density perturbations, through 3 scales:

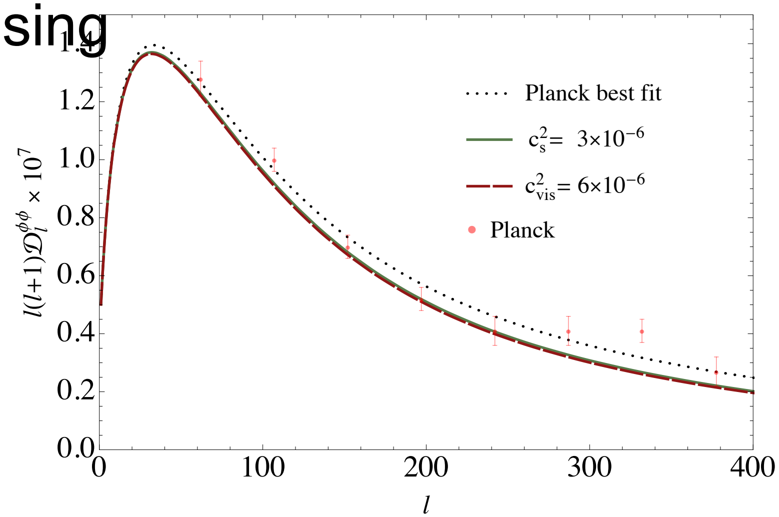
- Decay scale, $k_{\rm dec}^{-1} = \tau\sqrt{c_s^2 + \frac{8}{15}c_{\rm vis}^2}$:
  scale on which density perturbations start to decay
- Jeans scale, $k_J^{-1} \approx 0.2 c_{\rm eff}^2 \tau$; $\qquad c_{\rm eff}^2 = c_s^2 - 0.4 c_{\rm vis}^2$
  scale below which perturbations undergo acoustic oscillations
- Damping scale, $k_{\rm damp}^{-1} \approx \frac{0.18\tau}{\sqrt{1+\frac{15c_s^2}{8c_{\rm vis}^2}}} c_{\rm vis}$
  scale below which acoustic oscillations cease
  For $c_{\rm vis}^2 \gtrsim 0.57 c_s^2$, there are no oscillations at all

GDM CMB phenomenology: c_s^2 $c_{\rm vis}^2$

Evolution of density perturbations affects gravitational potentials

➡ Main effect on CMB is lensing





Left: TT C_ls. The residuals of the $c_s^2, c_{\rm vis}^2 \neq 0$ curves with respect to the best-fit C_ls have been multiplied by a factor of 100 to make them more visible.

Right: Lensing potential power spectrum.