Multi-interacting dark matter in the Boltzmann code CLASS

Deanna C. Hooper

*Loosely based on Becker, **DCH**, Kahlhoefer, Lesgourgues, Schöneberg (2010.04074)*

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What is CLASS?

- Code designed to simulate the evolution of linear perturbations in the universe
- End goal: compute cosmological observables (CMB and matter power spectra) for a given model
- Modular, modern, easy to use and modify, fast
- Written in C with an object-oriented style, and with a python wrapper to interface with MontePython
- Features many different cosmological models

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- Code designed to simulate the evolution of linear perturbations in the universe
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- Features many different cosmological models

Want to play about with CLASS? Check out the tutorial!

Why interacting DM?

- The standard cosmological paradigm has several issues: small scale crisis, H_0 and S_8 tensions, EDGES anomaly
- Many alternatives to cold dark matter have been proposed to solve these, such as interacting dark matter
- Each type of interaction can provide different benefits
- We want to see if we can combine these effects
- We have implemented dark matter with multiple possible interaction channels in `CLASS`

DM - baryon interactions

- We have implemented DM - baryon interactions with a power-law dependence on the relative bulk velocity *(Dvorkin et al. 1311.2937, Muñoz et al. 1509.00029, Slatyer et al. 1803.09734)*

- DM and baryons are assumed to be non-relativistic ($m_{\rm DM} \geq 1$ MeV), and following a Maxwell velocity distribution

- We consider a momentum transfer cross section of the form

$$\sigma = \sigma_{\rm DM-b} v^{n_b}$$

- We consider $n_b = \{-4,4\}$. Well-motivated cases include $n_b = 0$ (contact interactions) and $n_b = -4$ (milicharged, may explain EDGES)

DM - photon interactions

- We consider DM - photon interactions similar to the standard Thomson scattering *(Wilkinson et al. 1309.7588, Stadler et al. 1803.10229)*

- We assume the interactions are independent of temperature

- We parametrise the scattering cross section relative to the Thompson cross section as

$$u_{\mathrm{DM}-\gamma} = \frac{\sigma_{\mathrm{DM}-\gamma}}{\sigma_{\mathrm{Th}}} \left(\frac{m_{\mathrm{DM}}}{100\mathrm{GeV}} \right)^{-1}$$

- Suppress the matter power spectrum, may solve the S_8 tension

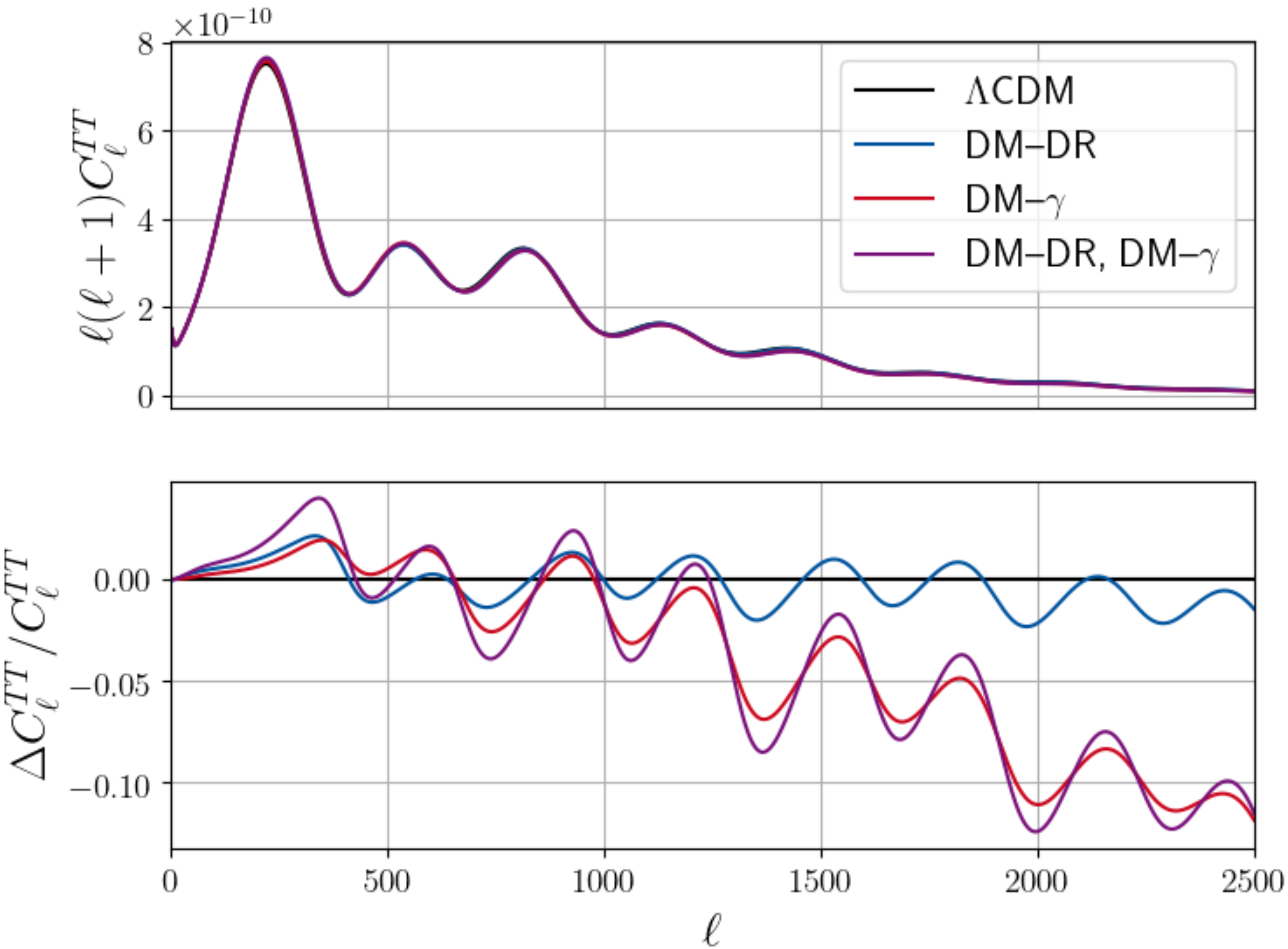
DM - dark radiation interactions

- DM - DR interactions were implemented in CLASS v2.9 *(Archidiacono, **DCH**, et al. 1907.01496)*
- For general interactions, implementation based on the ETHOS formalism *(Cyr-Racine et al. 1512.05344)*
- DR is assumed to be massless and not interacting with SM particles. Can be either free-streaming or fluid-like
- Parameters: current momentum exchange rate $\Gamma^0_{\mathrm{DM-DR}}$, amount of dark radiation N_{DR}, temperature dependence of scattering rate n_{DR}
- Case of $n_{\mathrm{DR}} = 0$ may solve H_0 and S_8 tensions *(Buen-Abad et al. 1505.03542)*

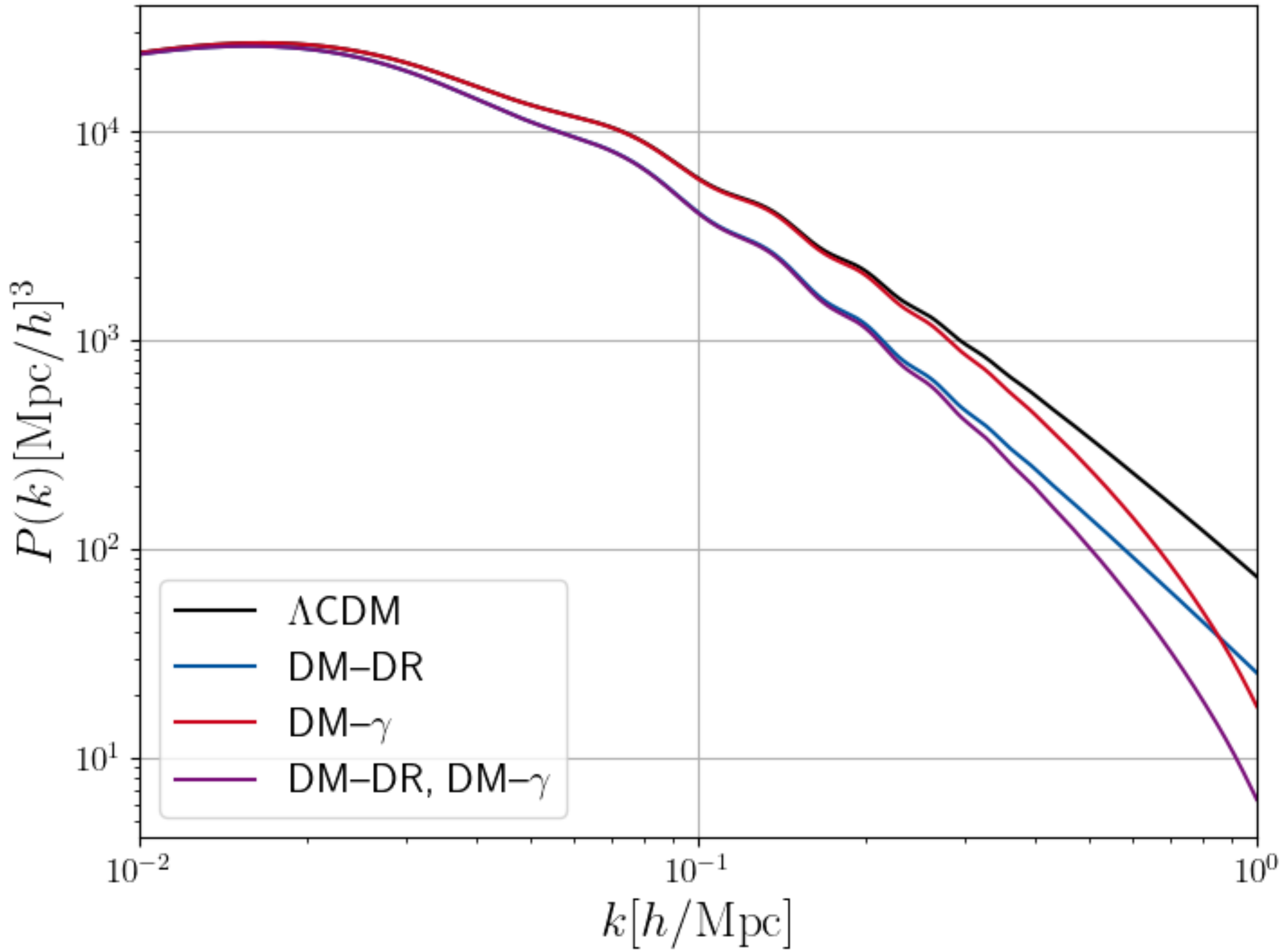
Multi-interacting DM in CLASS

- We consider one dark matter species with multiple possible interaction channels
- CLASS now integrates the dark matter temperature together with normal matter temperature
- An analytic calculation of the decoupling redshifts ensures an early enough start without wasting computing time
- Special treatment for different tight coupling regimes
- This implementation allows us to study the imprint of multi-interacting dark matter on cosmological observables

Effects on the observables



Effects on the observables



Code efficiency

Case	Runtime [s]	% Slowdown
ΛCDM	0.936	0.0
DM–b ($n_b = -4$)	0.959	2.4
DM–b ($n_b = -2$)	0.949	1.4
DM–b ($n_b = 0$)	0.950	1.5
DM–γ	0.940	0.4
DM–DR, $n_{\rm DR} = 0$, fluid DR	1.307	39.6
DM–DR, $n_{\rm DR} = 0$, free-streaming DR	2.181	132.9
DM–DR, $n_{\rm DR} = 4$, fluid DR	1.622	73.3
DM–DR, $n_{\rm DR} = 4$, free-streaming DR	4.082	336.0
DM–b ($n_b = -4$)+DM–γ	0.994	6.1
DM–b ($n_b = -2$)+DM–γ	0.982	4.9
DM–b ($n_b = 0$)+DM–γ	0.983	4.9
DM–b ($n_b = -4$)+DM–DR, $n_{\rm DR} = 0$, fluid DR	1.360	45.3
DM–b ($n_b = -2$)+DM–DR, $n_{\rm DR} = 0$, fluid DR	1.374	46.7
DM–b ($n_b = 0$)+DM–DR, $n_{\rm DR} = 0$, fluid DR	1.340	43.1
DM–γ+DM–DR	1.356	44.8
DM–b ($n_b = -4$)+DM–γ+DM–DR, $n_{\rm DR} = 0$, fluid DR	1.590	69.8
DM–b ($n_b = -2$)+DM–γ+DM–DR, $n_{\rm DR} = 0$, fluid DR	1.378	47.2
DM–b ($n_b = 0$)+DM–γ+DM–DR, $n_{\rm DR} = 0$, fluid DR	1.396	49.1

We can run MCMCs for IDM with `MontePython`

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See talk by Brinckmann

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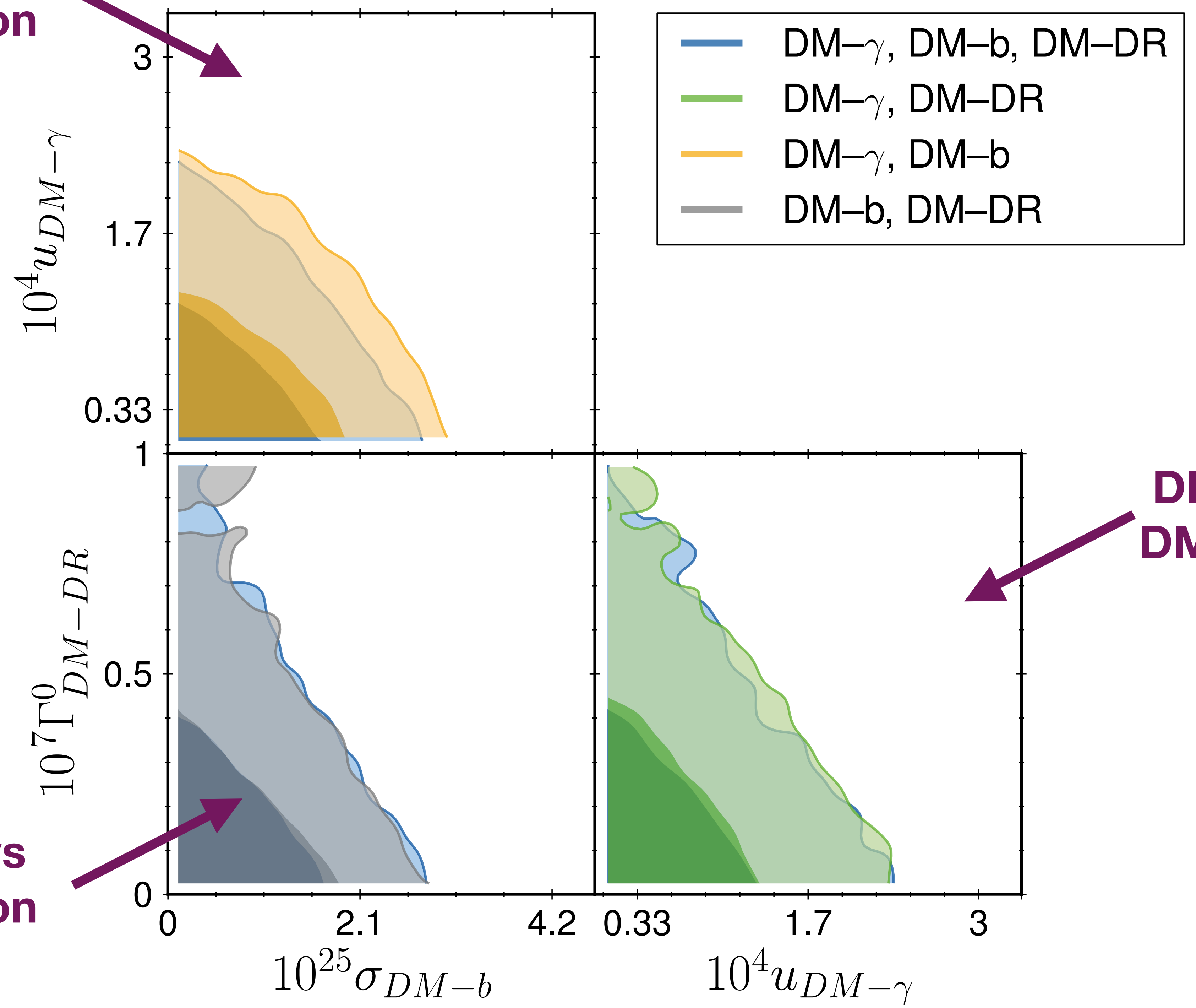
IDM cross sections

Becker, **DCH**, et al. 2010.04074

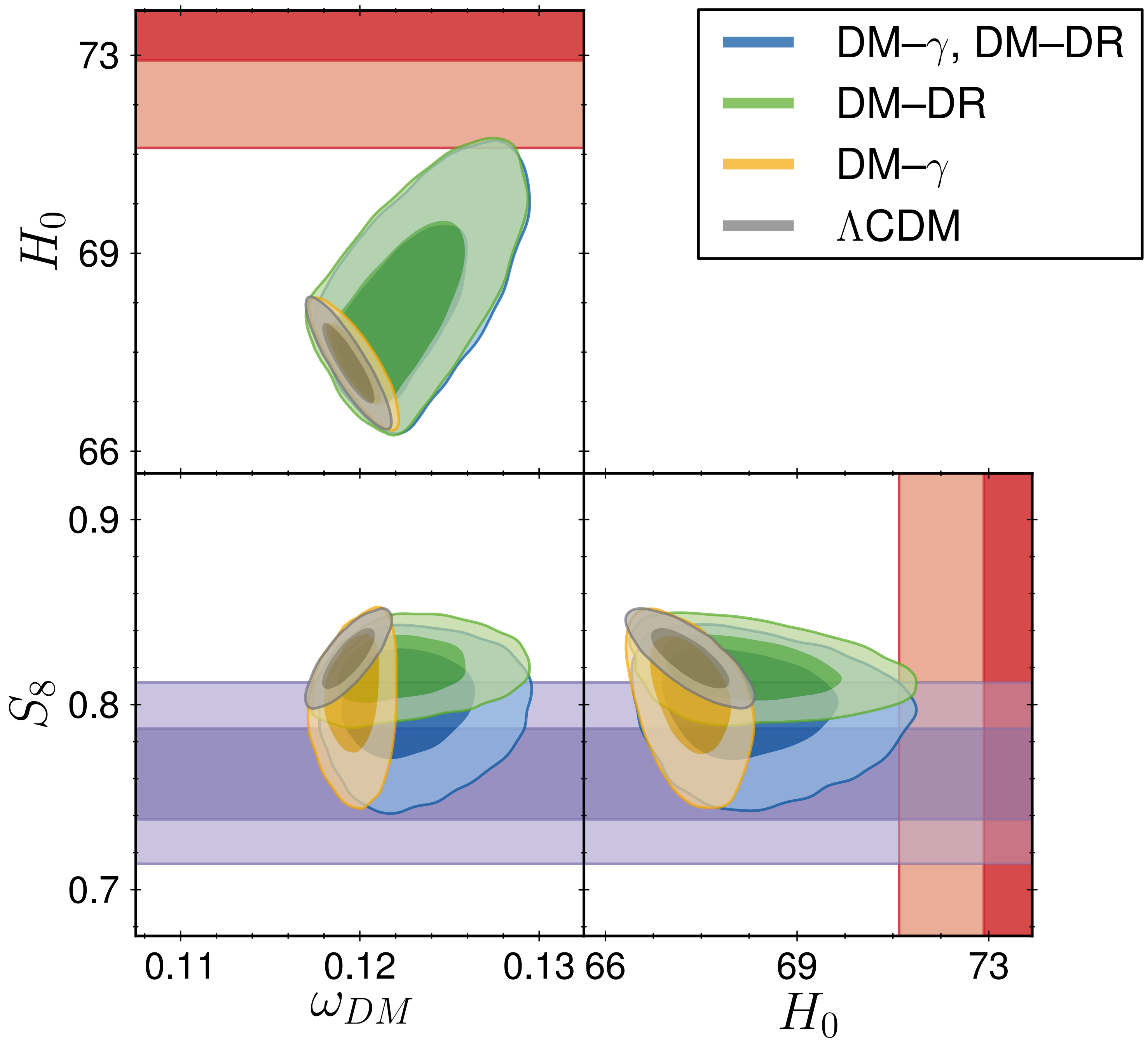
DM - photon vs DM - baryon



DM - DR vs DM - photon

DM - DR vs DM - baryon

Cosmological tensions



*Becker, **DCH**, et al. 2010.04074*

- DM - photon interactions push to a lower S_8 than ΛCDM
- DM - DR interactions push to higher H_0 than ΛCDM
- Together they allow for both higher H_0 and lower S_8 values
- Comes at the expense of three new parameters

Summary

- CLASS is a flexible, fast, and user-friendly Boltzmann code designed to compute the cosmological observables for different models
- Many models already implemented, including dark matter decay, annihilation, and now multiple interaction channels
- We have used this to show that the effects of different interactions on the cosmological observables are additive
- Such interacting models can solve both the H_0 and S_8 tensions, but at the expense of adding three new parameters
- The public release of our code as CLASS v3.1 paves the way for the study of various rich dark sectors

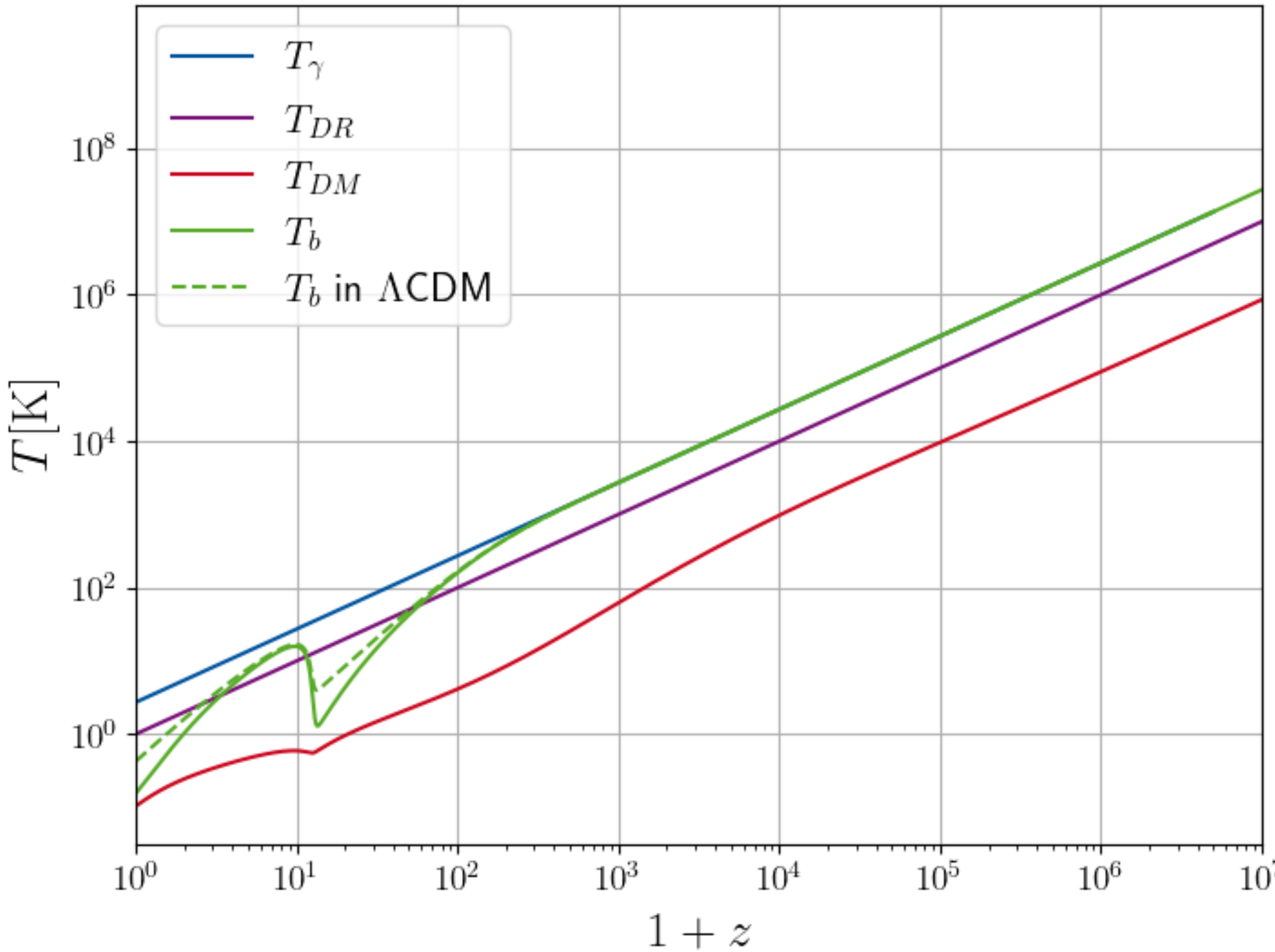
Thank you for your attention

CLASS structure

1. input.c: parse/make sense of input parameters (advanced logic)
2. background.c: calculate homogeneous cosmology
3. thermodynamics.c: ionisation history, scattering rates, temperatures
4. perturbations.c: linear Fourier perturbations
5. primordial.c: primordial spectrum, inflation
6. nonlinear.c: recipes for non-linear corrections to 2-point statistics
7. transfer.c: from Fourier to multipole space
8. spectra.c: 2-point statistics (power spectra)
9. lensing.c: CMB lensing
10. output.c: print out (not used from python)

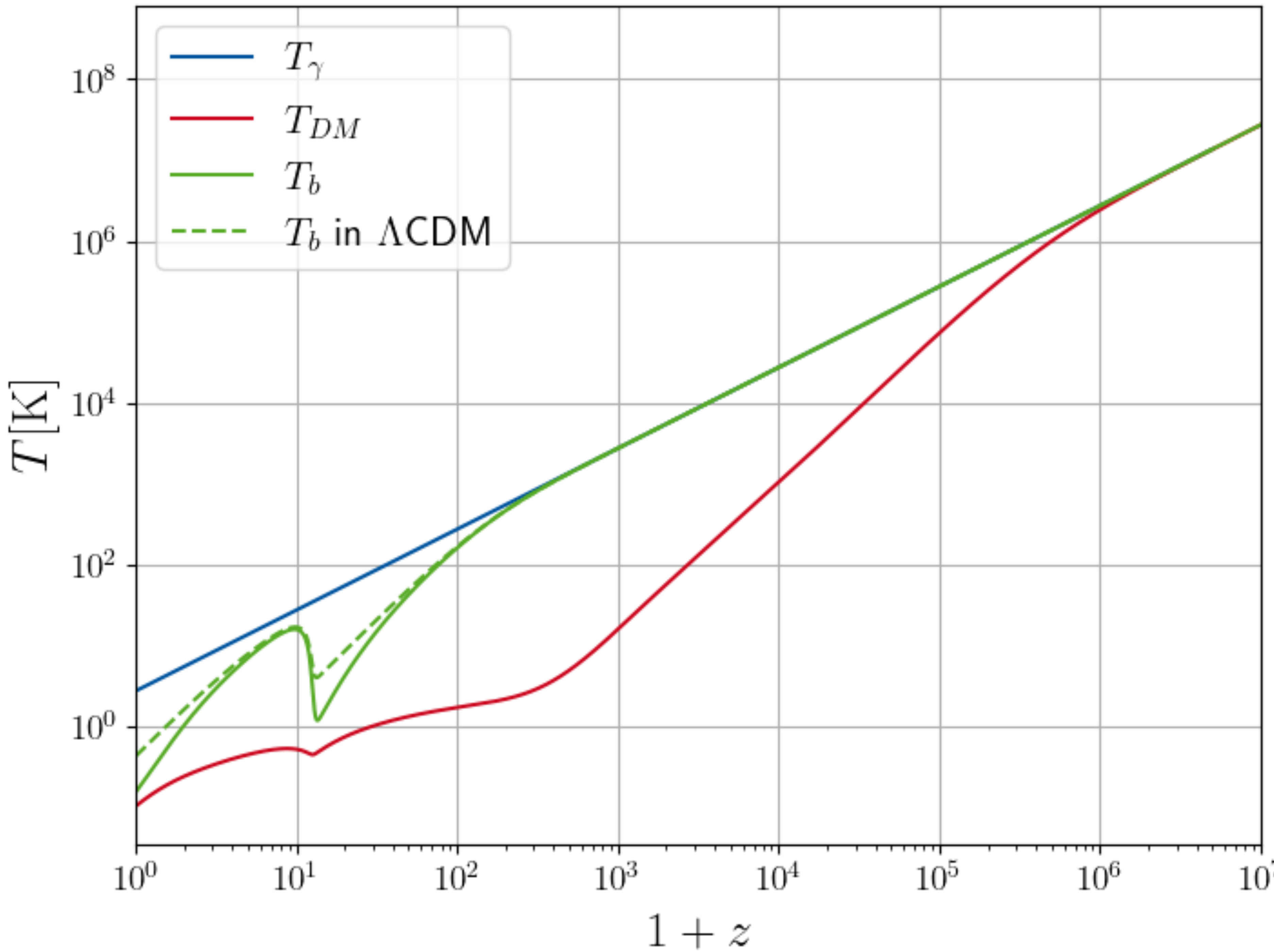
IDM temperature evolution

DM – DR and DM – baryon interactions



IDM temperature evolution

DM – photon and DM – baryon interactions



IDM cross sections

*Becker, **DCH**, et al. 2010.04074*

Case	DM–b	DM–b	DM–b	DM–γ	DM–DR
Index	$n_b = -4$	$n_b = -2$	$n_b = 0$	-	$n_{\rm DR} = 0$
Parameter	$\sigma_{{\rm DM}-b}$	$\sigma_{{\rm DM}-b}$	$\sigma_{{\rm DM}-b}$	$u_{{\rm DM}-\gamma}$	$\Gamma^0_{\rm DM-DR}$
Units	$[10^{-41}{\rm cm}^2]$	$[10^{-33}{\rm cm}^2]$	$[10^{-25}{\rm cm}^2]$	$[10^{-4}]$	$[10^{-8}]$
DM–b ($n_b = -4$)	2.7	-	-	-	-
DM–b ($n_b = -2$)	-	3.6	-	-	-
DM–b ($n_b = 0$)	-	-	2.2	-	-
DM–γ	-	-	-	1.8	-
DM–DR	-	-	-	-	6.2
DM–b ($n_b = -4$)+DM–γ	2.7	-	-	1.9	-
DM–b ($n_b = -2$)+DM–γ	-	3.7	-	1.8	-
DM–b ($n_b = 0$)+DM–γ	-	-	2.3	1.7	-
DM–b ($n_b = -4$)+DM–DR	2.4	-	-	-	5.6
DM–b ($n_b = -2$)+DM–DR	-	3.1	-	-	6.0
DM–b ($n_b = 0$)+DM–DR	-	-	1.9	-	6.7
DM–γ + DM–DR	-	-	-	1.6	5.5
DM–b ($n_b = -4$)+DM–γ+DM–DR	2.5	-	-	1.7	5.4
DM–b ($n_b = -2$)+DM–γ+DM–DR	-	3.4	-	1.7	6.0
DM–b ($n_b = 0$)+DM–γ+DM–DR	-	-	1.9	1.5	6.1

Solving S_8 and H_0 tensions?

- Case of $n = 0$ may solve both tensions (e.g. Buen-Abad et al. 1505.03542)
- DR acts like extra N_{eff} $\rightarrow$ H_0 increases to maintain $z_{\rm eq}$
- Unlike with massive neutrinos, DR is always relativistic $\rightarrow$ late time background history unaffected (relative to ΛCDM + N_{eff})
- DM-DR behaves as coupled fluid at early times, enhances peaks on small scales, compensates damping introduced by new relativistic particle
- Collisional damping with DR suppresses DM growth, leading to a small scale matter power suppression $\rightarrow$ lower S_8
- Matter power spectrum like ΛCDM up to some suppression feature in *k,* no effect on lensing