Precision Cosmology of Atomic Dark Matter

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Based on arxiv:2212.02487 w/ Saurabh Bansal, David Curtin, Yuhsin Tsai

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Some Motivations

Experiment

- Hubble tension: Additional dark radiation allows for a higher H_0 value from CMB measurements by reducing the sound horizon at recombination.
- S_8 tension: Interactions between dark matter and dark radiation can suppress the growth of structure, yielding a lower S_8.

Theory

- Approximately $\mathbb{Z}_2$-symmetric mirror sectors can address naturalness issues.
- e.g. Mirror Twin Higgs (see Yuhsin's talk).
- Twin/mirror sectors have their own gauge forces, and can have dark matter – dark radiation interactions.
- What happens if we also allow the dark photon coupling to vary from the SM value?

Atomic Dark Matter

- Dark sector fermions p_D and e_D with masses $\boldsymbol{m_{p_D}}, \boldsymbol{m_{e_D}}$, oppositely charged under a dark $U(1)$ gauge force mediated by a massless dark photon with dark fine structure constant $\boldsymbol{\alpha_D}$.

$$\mathcal{L}_{aDM} = A_{\mu\nu}A^{\mu\nu} + i\bar{p}_D(\not{D} - m_{p_D})p_D + i\bar{e}_D(\not{D} - m_{e_D})e_D$$

- Asymmetric, overall neutral abundance that accounts for a fraction $\mathbf{f_D} \equiv \frac{\Omega_{aDM}}{\Omega_{DM}} \leq 1$ of the dark matter.

- Temperature ratio of the dark photons to SM photons today $\boldsymbol{\xi} \equiv T_D/T_{SM}$. Equivalently, $\boldsymbol{\Delta N_D} \equiv \left(\frac{8}{7}\right)\left(\frac{11}{4}\right)^{\frac{4}{3}} \xi^4$, effective number of additional neutrinos at CMB.

- First studied by Kaplan et al. in 0909.0753.

Cosmology of Atomic Dark Matter: Quick Review

- In the early universe, the dark photons, dark protons, and dark electrons form a tightly coupled plasma.
- The competition between gravity and the pressure support of the dark photons leads to **dark acoustic oscillations** (DAO) in the dark plasma.
- After T_D falls below $B_D = \frac{\alpha_D^2 \mu_D}{2}$, the dark protons and electrons 'recombine' into **dark hydrogen**, H_D.
- When the dark photons no longer efficiently exchange energy with the atomic dark matter, they begin free-streaming.
- The DAOs and additional radiation in the early universe leave distinctive imprints on the CMB and large-scale structure (LSS) of the universe.
- First studied by Cyr-Racine et al. in 1209.5752, 1310.3278.

Computing Cosmological Evolution of aDM

- The Cosmological Linear Anisotropy Solving System (CLASS) is a numerical code that produces CMB and matter power spectra given cosmological parameter inputs.
- Modified CLASS to include the atomic dark matter sector, and solve for the dark recombination. https://github.com/jp-barron/class_adm-3.1.git
  - Built on top of modifications by Bansal et al. for MTH. [2110.04317]
- After dark recombination, the dark sector perturbation evolution is handled by the Effective Theory of Structure (ETHOS) framework in CLASS. [1512.05344]

ETHOS	DR	χ	$\dot{\kappa}_{DR-DM}$	$\dot{\kappa}_{\chi}$	c_{χ}^2	$\alpha_{\ell=2}$	$\alpha_{\ell\geq 2}$	$\dot{\kappa}_{DR-DR}$	β_{ℓ}
aDM	γ_D	H_D	$-\frac{1}{\tau_D}$	$-\frac{4\rho_{\gamma D}}{3\rho_D}\tau_D^{-1}$	c_D^2	9/10	1	0	0

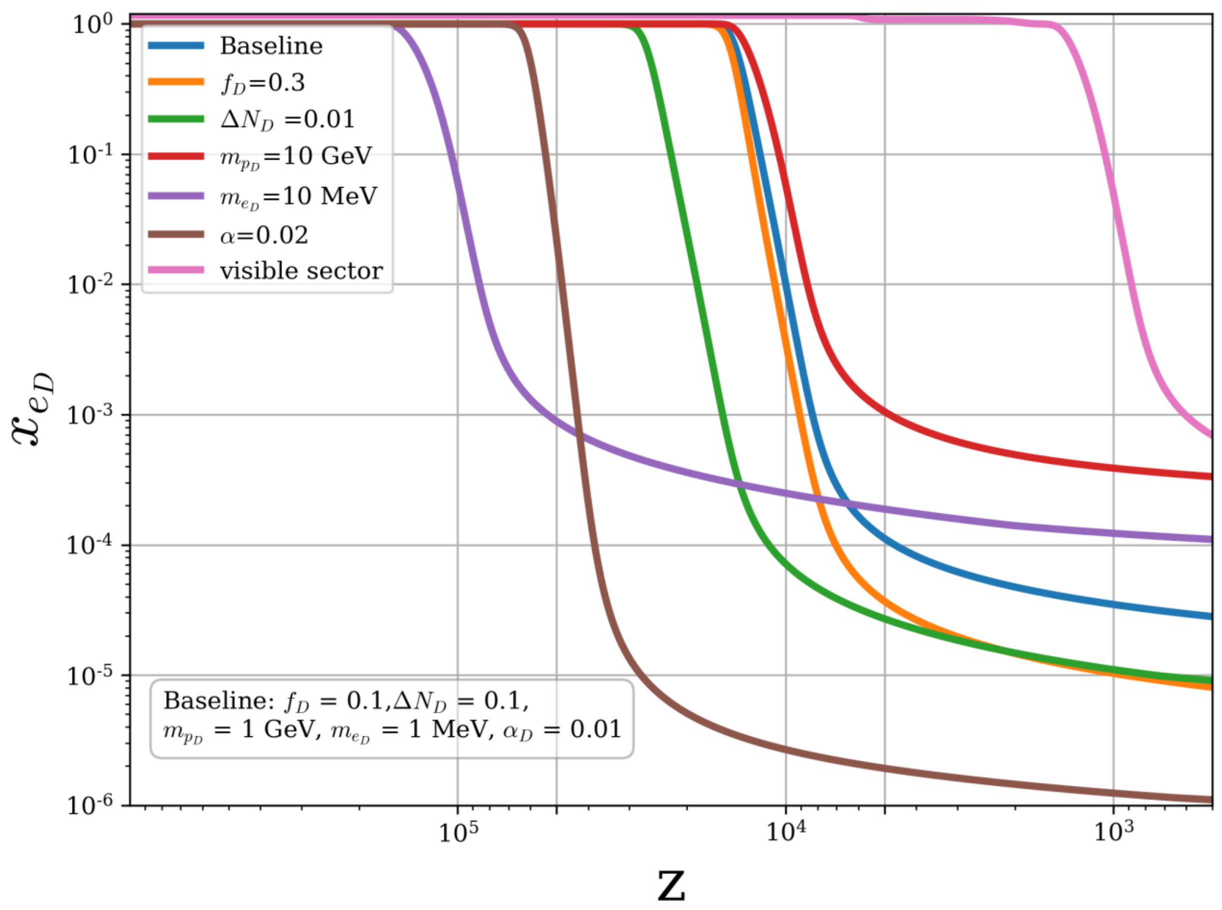
Mapping of aDM parameters to ETHOS parameters

Dark recombination

- Dark recombination occurs after T_D falls below $B_D = \frac{\alpha_D^2 \mu_D}{2}$.
- Redshift of dark recombination controlled by B_D and ΔN_D.
- In CLASS: Use Saha equation for ionization fraction x_D above 0.999.

$$\frac{x_D^2}{1-x_D} = \frac{1}{n_D}\left(\frac{T_{DM} m_{e_D}}{2\pi}\right)^{3/2} e^{-B_D/T_{DM}}$$

- Then, solve for $\frac{dx_D}{dt}$ with effective multi-level atom formalism using HYREC-2. [Lee and Ali-Haïmoud, 2007.14114]
  - Neglects some sub-dominant radiative transfer effects that are only modelled for parameters near SM values.



Dark decoupling

- When energy transfer rate between dark photons and dark electrons/protons drops below Hubble, they decouple.
- Dominant energy exchange mechanism is usually Thomson scattering, with cross-section

$$\sigma_{T_D} = \frac{8\pi}{3}\left(\frac{\alpha_D}{m_{e_D}}\right)^2.$$

- Other processes can dominate over Thomson scattering and delay decoupling
  - For high α_D and m_{e_D}/m_{H_D}, Rayleigh scattering.
  - For low α_D and ξ, bremsstrahlung, photo-recombination/ionization*.
- Opacity of dark plasma set by Thomson, Rayleigh, photo-ionization rates.

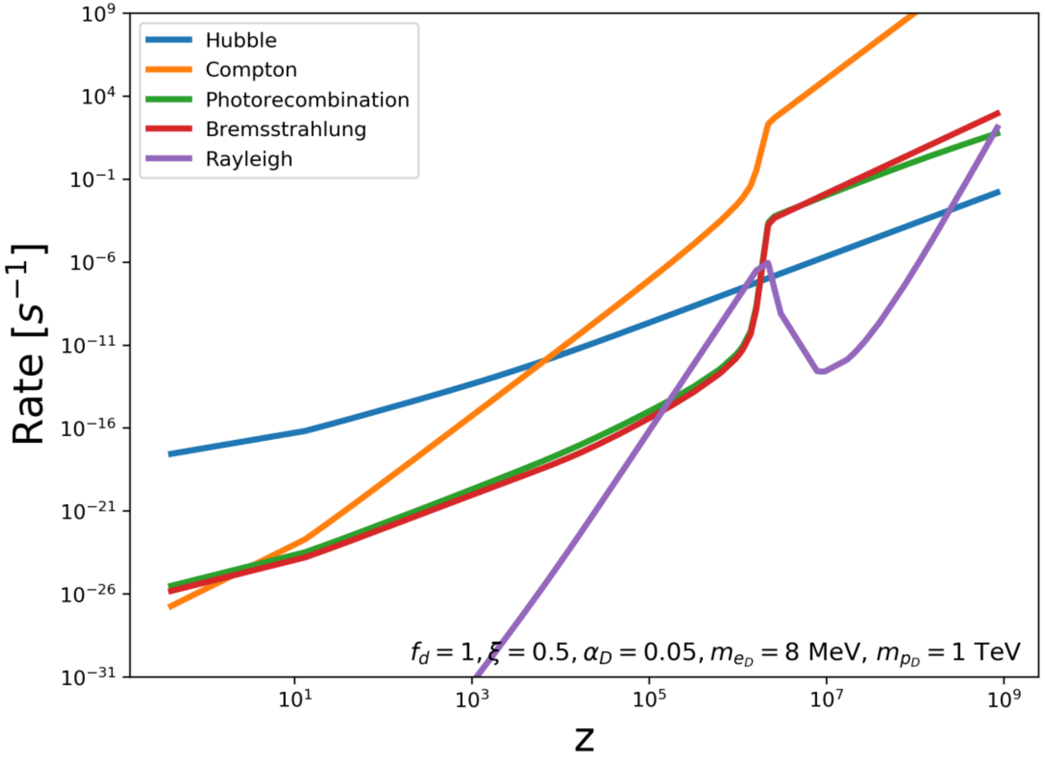
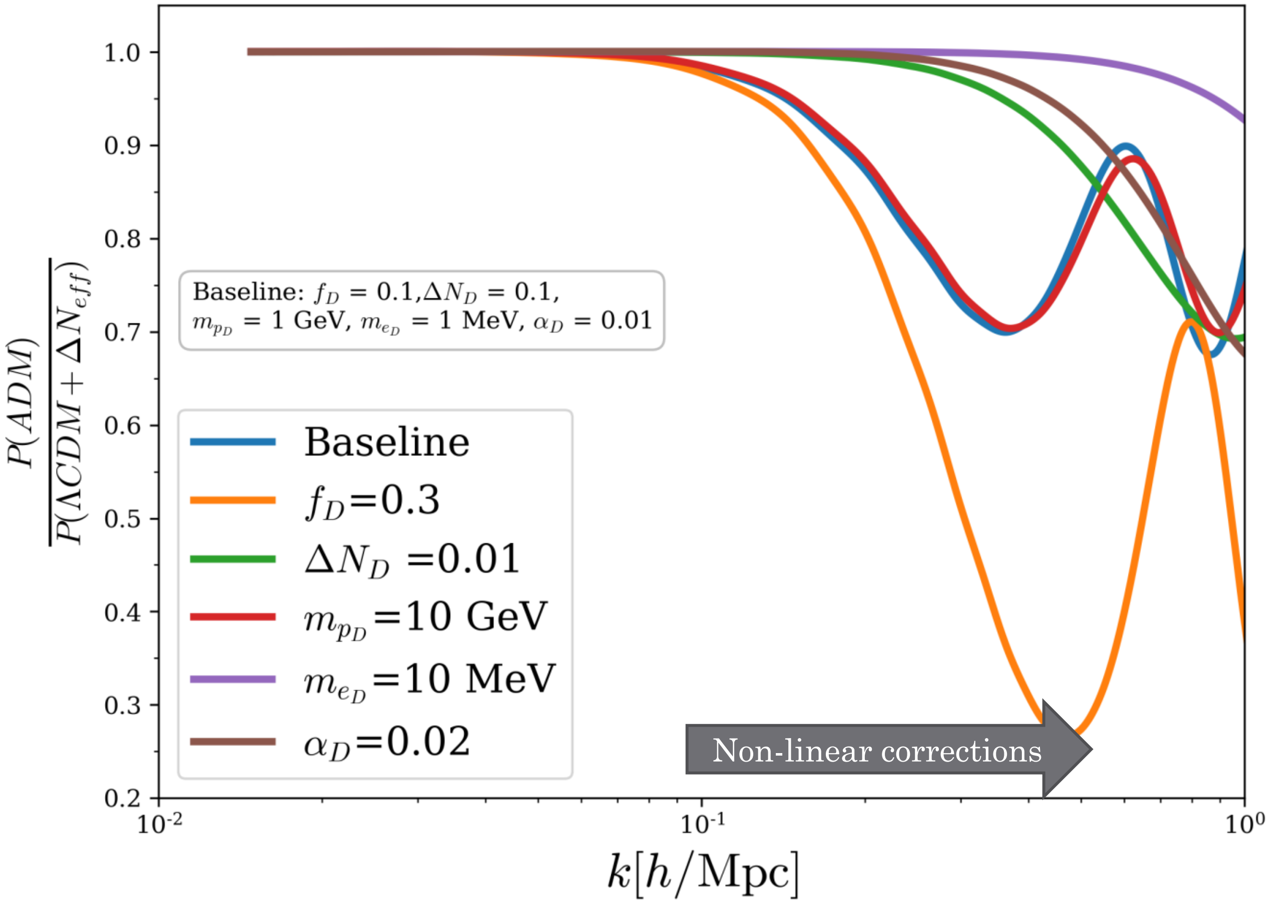


*Photo-heating/cooling processes not yet included in CLASS-aDM due to numerical instabilities – to be added soon. Similar rate to bremsstrahlung.

Modification of Linear Matter Power Spectrum

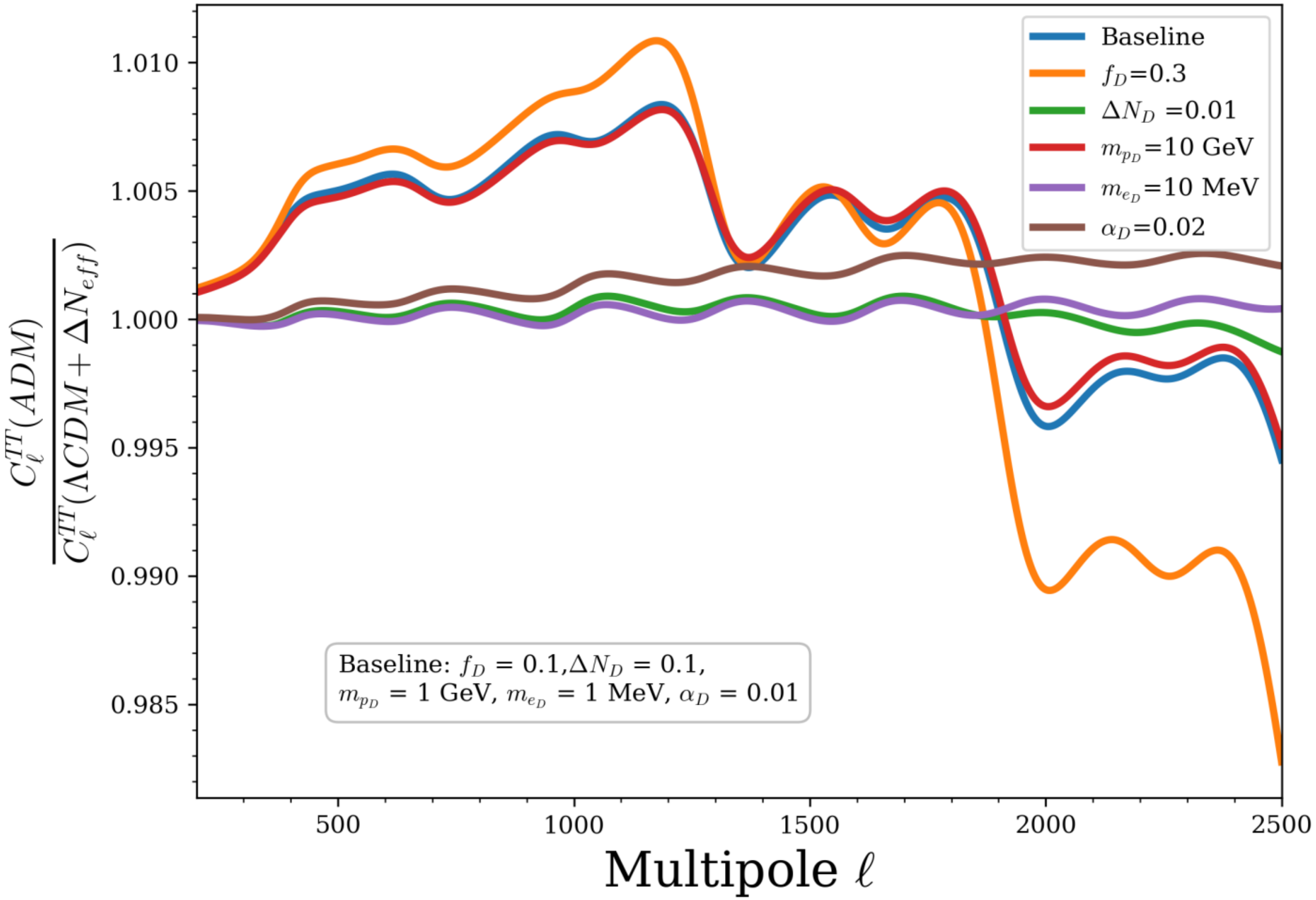
- Suppression and oscillations for k that enter horizon before dark decoupling.
- Higher f_D → more suppression.
- Lower ΔN_D, higher B_D → suppression starts at smaller scales.
- Cannot trust linear power spectrum above $k{\sim}0.1\ h\ \text{Mpc}^{-1}$.
- Non-linear evolution smears out oscillations at low redshifts. [2101.12229]



Matter power spectrum relative to ΛCDM + same amount of ΔN_{eff} as ΔN_D.

Modification of CMB Power Spectrum

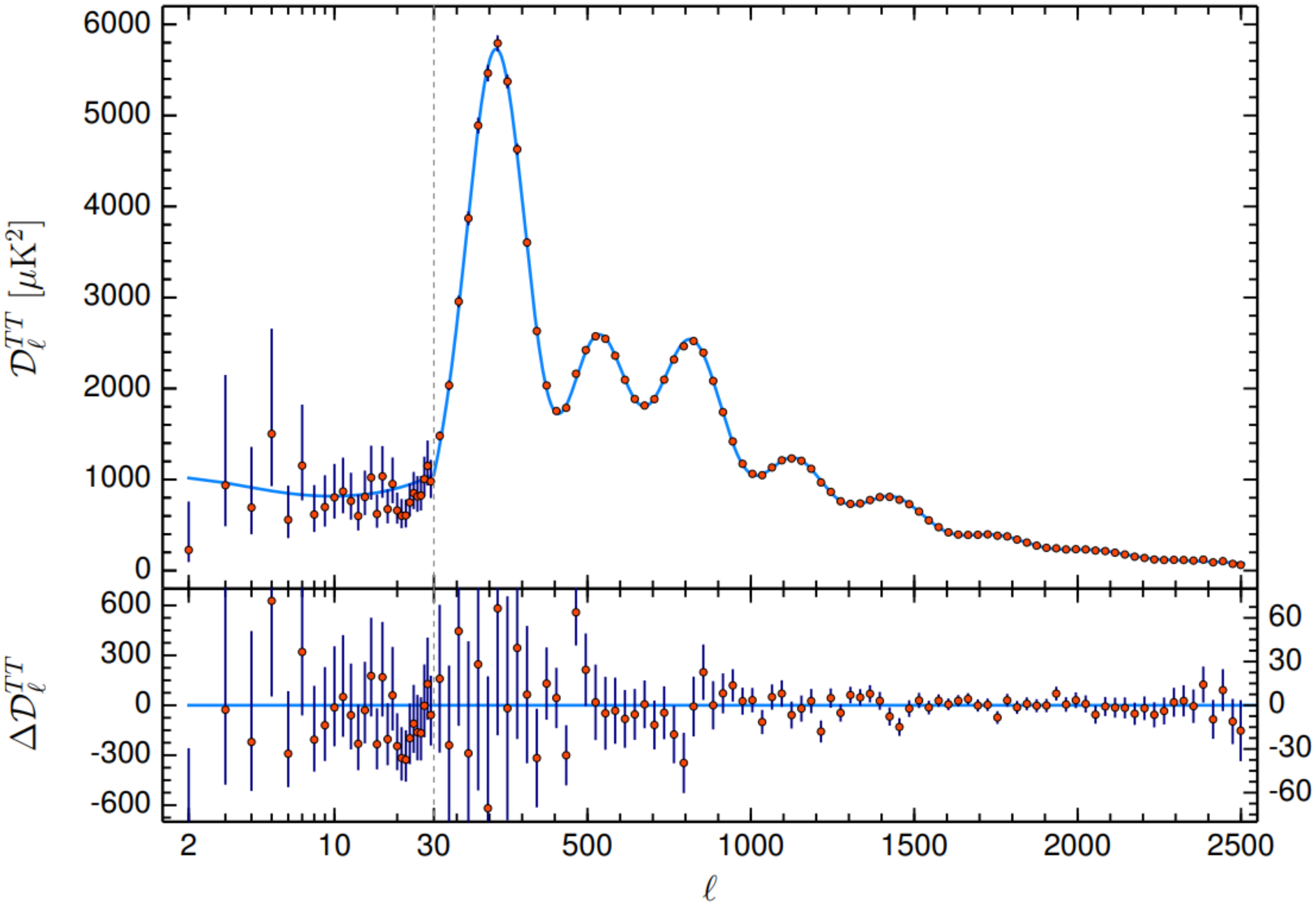
- Additional radiation damps the temperature power spectrum at high ℓ.
- aDM perturbations couple to gravitational potential, which couples to photon perturbations. Complex effect on power spectrum.
- Higher f_D → Larger deviations.
- Lower ΔN_{eff}, higher B_D → smaller deviations.
- Polarization spectrum and lensing also altered.



CMB temperature power spectrum relative to ΛCDM + same amount of ΔN_{eff} as ΔN_D.

Constraining aDM: CMB + BAO

- Planck 2018 TT, TE, EE, high- and low-l, lensing. [1907.12875]
- BAO: Measurements of D_V/r_S from 6dFGS, SDSS, BOSS. [1106.3366, 1409.3242, 1607.03155]



Planck 2018 temperature power spectrum

1807.06209

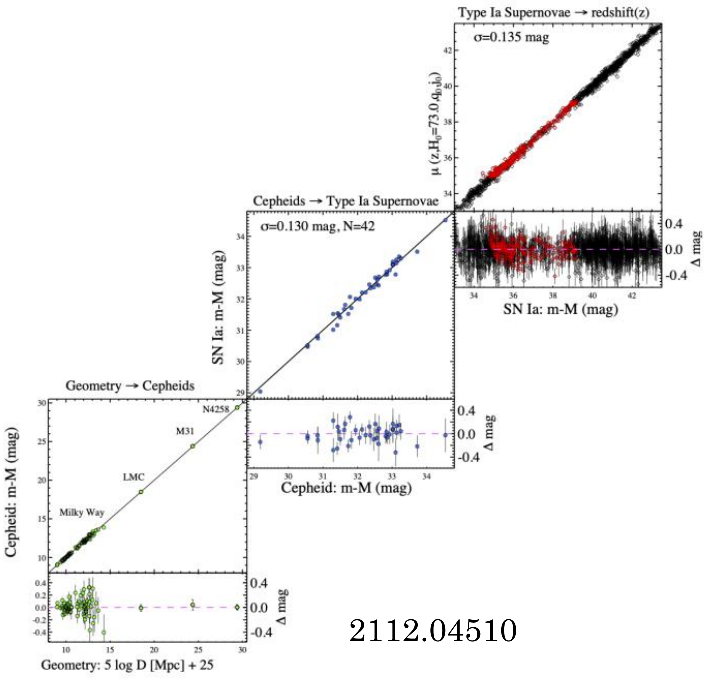
Constraining aDM: LSS, H_0, S_8

- KiDS+VIKING-450 cosmic shear dataset, with cutoff at $k = 0.3\ h\ \mathrm{Mpc}^{-1}$. [1812.06076]
- Pantheon supernova dataset. [1710.00845].
- SH0ES measurement of H_0 using Cepheid variables and Type Ia supernovae. [2112.04510]
- Planck Sunyaev-Zeldovich measurement of S_8.
  - Gives largest tension, to show how far aDM can pull S_8. [1303.5080]

Table 4. Fiducial result for the KV450 cosmic shear measurement.

Parameter	Symbol	Value
CDM density	$\Omega_{\rm CDM}h^2$	$0.118^{+0.038}_{-0.066}$
Scalar spectrum ampl.	$\ln 10^{10}A_s$	$3.158^{+1.154}_{-1.426}$
Baryon density	$\Omega_b h^2$	$0.022^{+0.003}_{-0.004}$
Scalar spectral index	n_s	$1.021^{+0.149}_{-0.141}$
Hubble parameter	h	$0.745^{+0.073}_{-0.043}$
IA amplitude	$A_{\rm IA}$	$0.981^{+0.694}_{-0.678}$
Baryon feedback ampl.	B	$2.484^{+0.189}_{-0.475}$
Constant *c*-term offset	δc	$0.000^{+0.0002}_{-0.0002}$
2D *c*-term amplitude	A_c	$1.022^{+0.129}_{-0.125}$
Redshift offset bin 1	δz_1	$-0.007^{+0.034}_{-0.034}$
Redshift offset bin 2	δz_2	$-0.010^{+0.019}_{-0.021}$
Redshift offset bin 3	δz_3	$0.013^{+0.020}_{-0.021}$
Redshift offset bin 4	δz_4	$0.001^{+0.012}_{-0.011}$
Redshift offset bin 5	δz_5	$-0.001^{+0.011}_{-0.011}$
Matter density	Ω_m	$0.256^{+0.064}_{-0.123}$
Power spectrum amplitude	σ_8	$0.836^{+0.132}_{-0.218}$
$\sigma_8\sqrt{\Omega_m/0.3}$	S_8	$0.737^{+0.040}_{-0.036}$

1812.06076



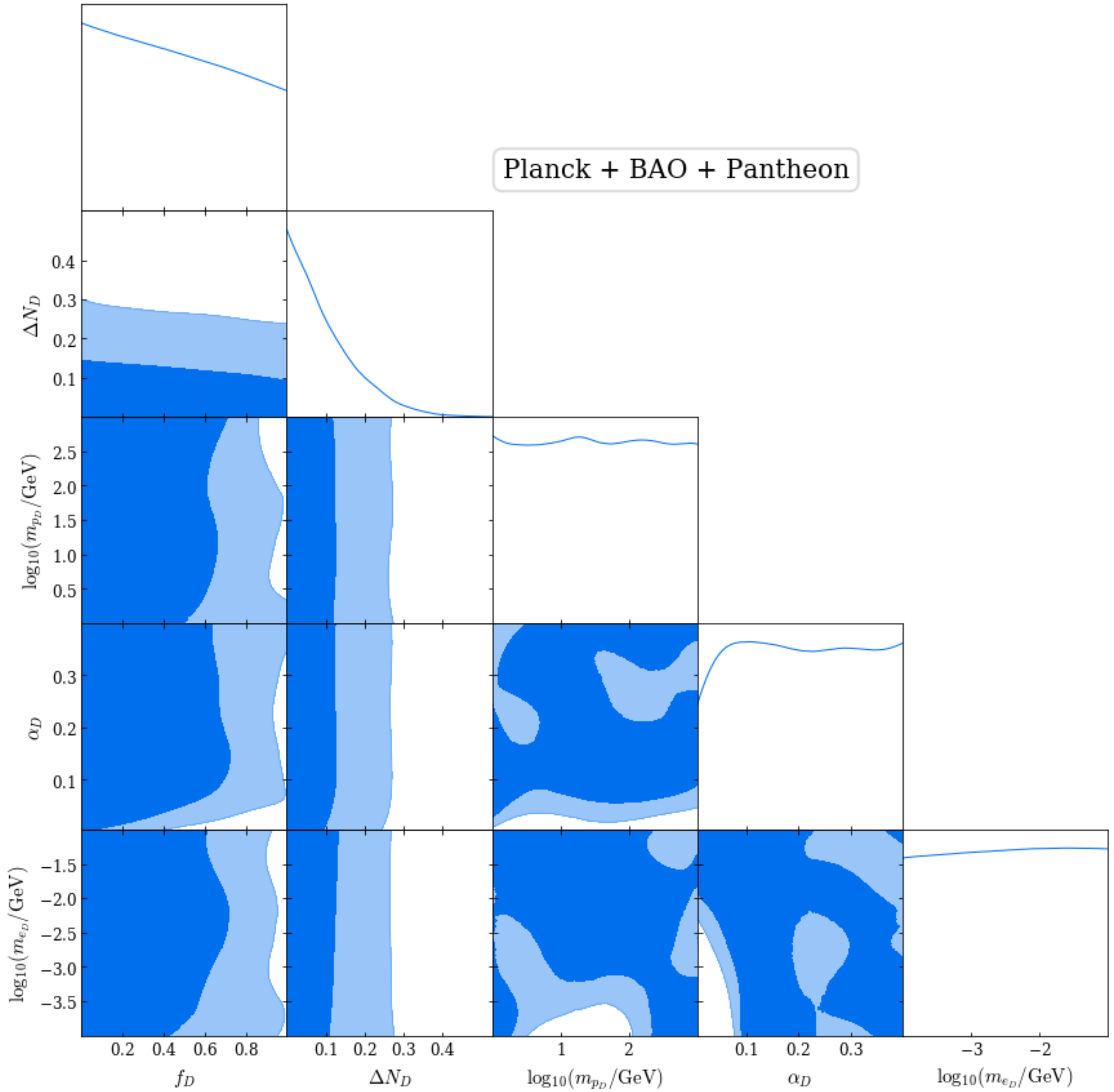
2112.04510

Constraining aDM parameter space

- Used Markov chain Monte Carlo package MontePython to sample posterior distribution of the model parameters, using publicly available likelihoods for the chosen datasets.
- Generated 95% confidence level contours from posterior.
- Ran ≥ 6 chains for each scan.
- Required Gelman-Rubin convergence $R - 1 < 0.02$ for each parameter.
- CDM parameters: $\{\omega_b, \omega_{cdm}, h, \ln 10^{10} A_S, n_s, \tau_{reio}\}$
  - h instead of θ_s because of a bug in CLASS 3.1 shooting procedure.
- Baseline dataset: Planck + BAO + Pantheon. Then add LSS, H_0, S_8 measurements.

Results

- Allow all five parameters $(f_D, \Delta N_D, m_{p_D}, m_{e_D}, \alpha_D)$ to vary.
- Only ΔN_D is robustly constrained.
- Recover Planck limit of $\Delta N_{\mathrm{eff}} \leq 0.3$.
- No preference for non-zero f_D.
- Ranges of priors limited by restriction that dark recombination not be at extreme redshifts $(> 10^8, \ll 100)$

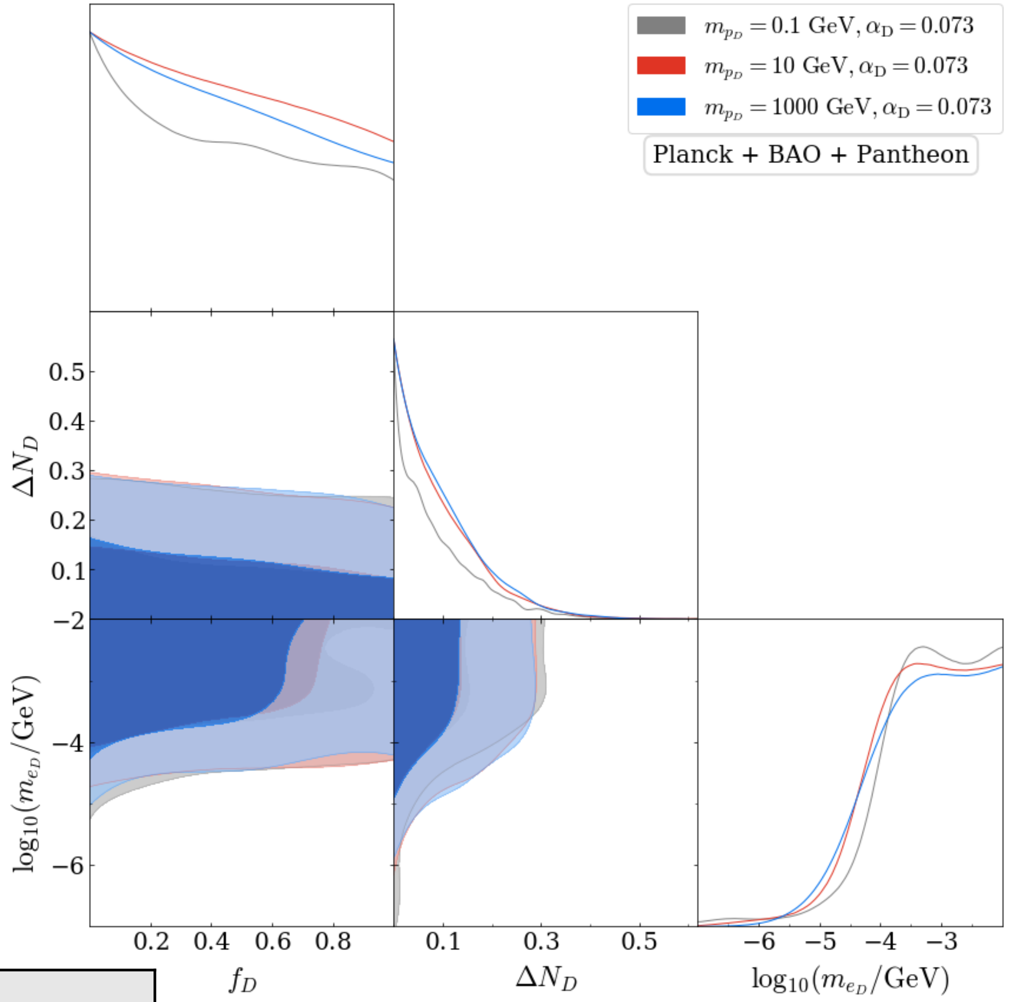


Parameter	$\boldsymbol{f_D}$	$\mathbf{\Delta N_D}$	$\boldsymbol{m_{p_D}}$	$\boldsymbol{m_{e_D}}$	$\boldsymbol{\alpha_D}$
Prior	$0 < f_D < 1$	$0 < \Delta N_D < 1$	$0 < \log_{10}(\frac{m_{p_D}}{\mathrm{GeV}}) < 3$	$-4 < \log_{10}(\frac{m_{e_D}}{\mathrm{GeV}}) < -2$	$0.005 < \alpha_D < 0.4$

3D scans: constraining ΔN_D, f_D, and m_{e_D}

- Varying m_{p_D} has little effect on constraints on other parameters.

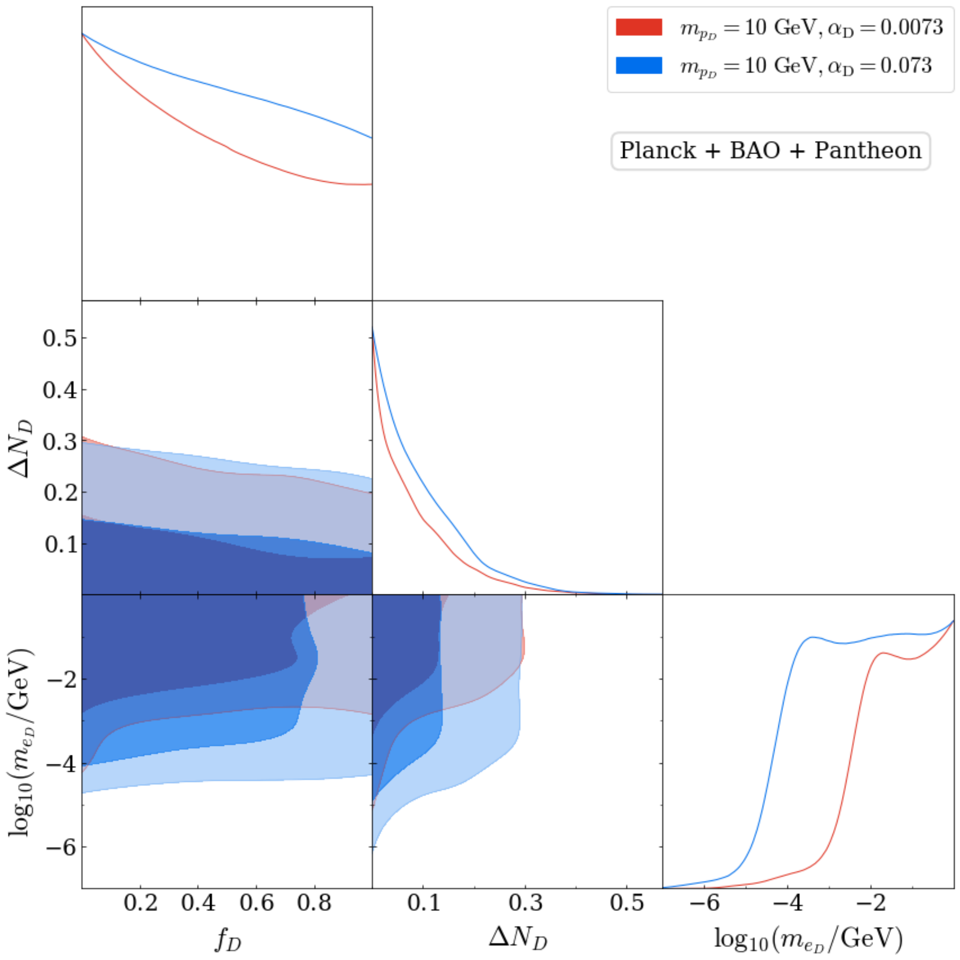
- Constraint on ΔN_D sharply transitions from < 0.3 to much tighter as m_{e_D} ($\sim B_D, z_{rec}^{dark}$) is lowered.



Parameter	f_D	ΔN_D	m_{e_D}
Prior	$0 < f_D < 1$	$0 < \Delta N_D < 1$	$-7 < \log_{10}(m_{e_D}/\mathrm{GeV}) < 0$

3D scans: constraining ΔN_D, f_D, and m_{e_D}

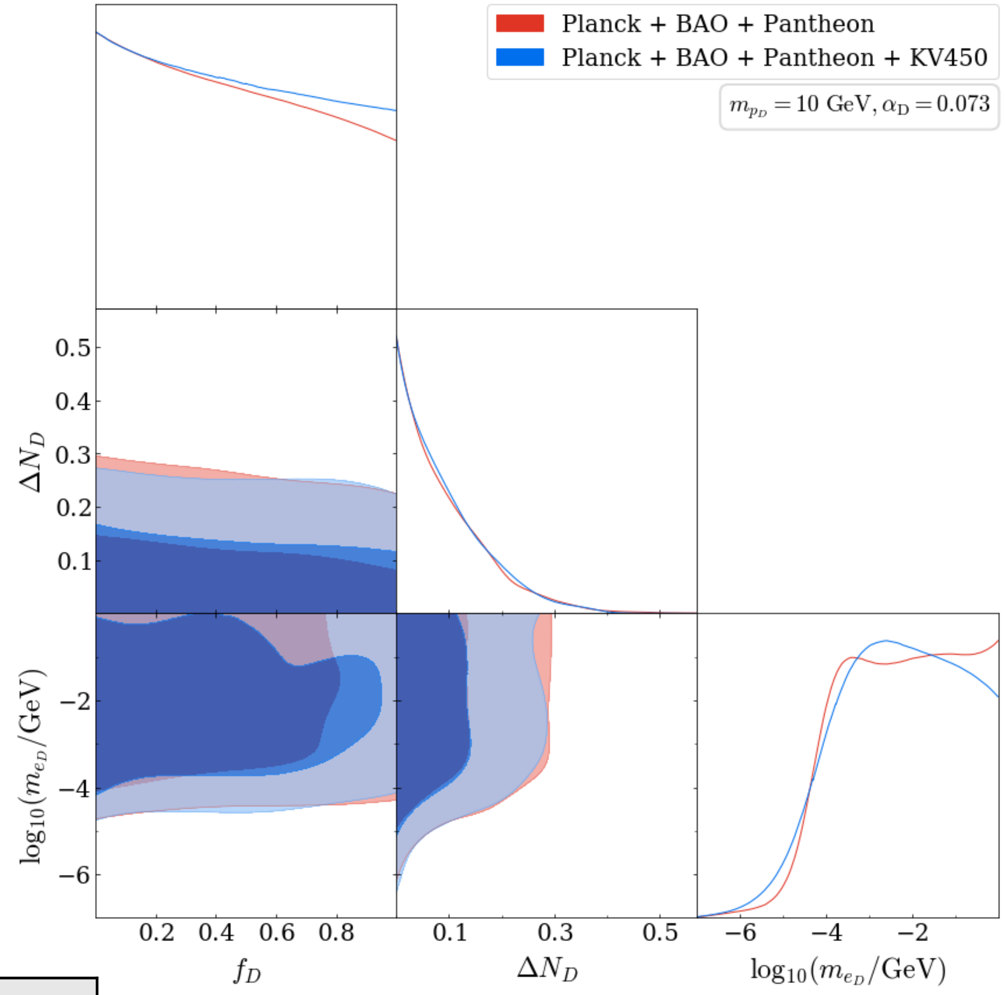
- For higher α_D, lower bound on m_{e_D} is lower.
- Large f_D not ruled out for a range of parameters.



Parameter	f_D	ΔN_D	m_{e_D}
Prior	$0 < f_D < 1$	$0 < \Delta N_D < 1$	$-7 < \log_{10}(\frac{m_{e_D}}{\mathrm{GeV}}) < 0$

Including KV450 dataset

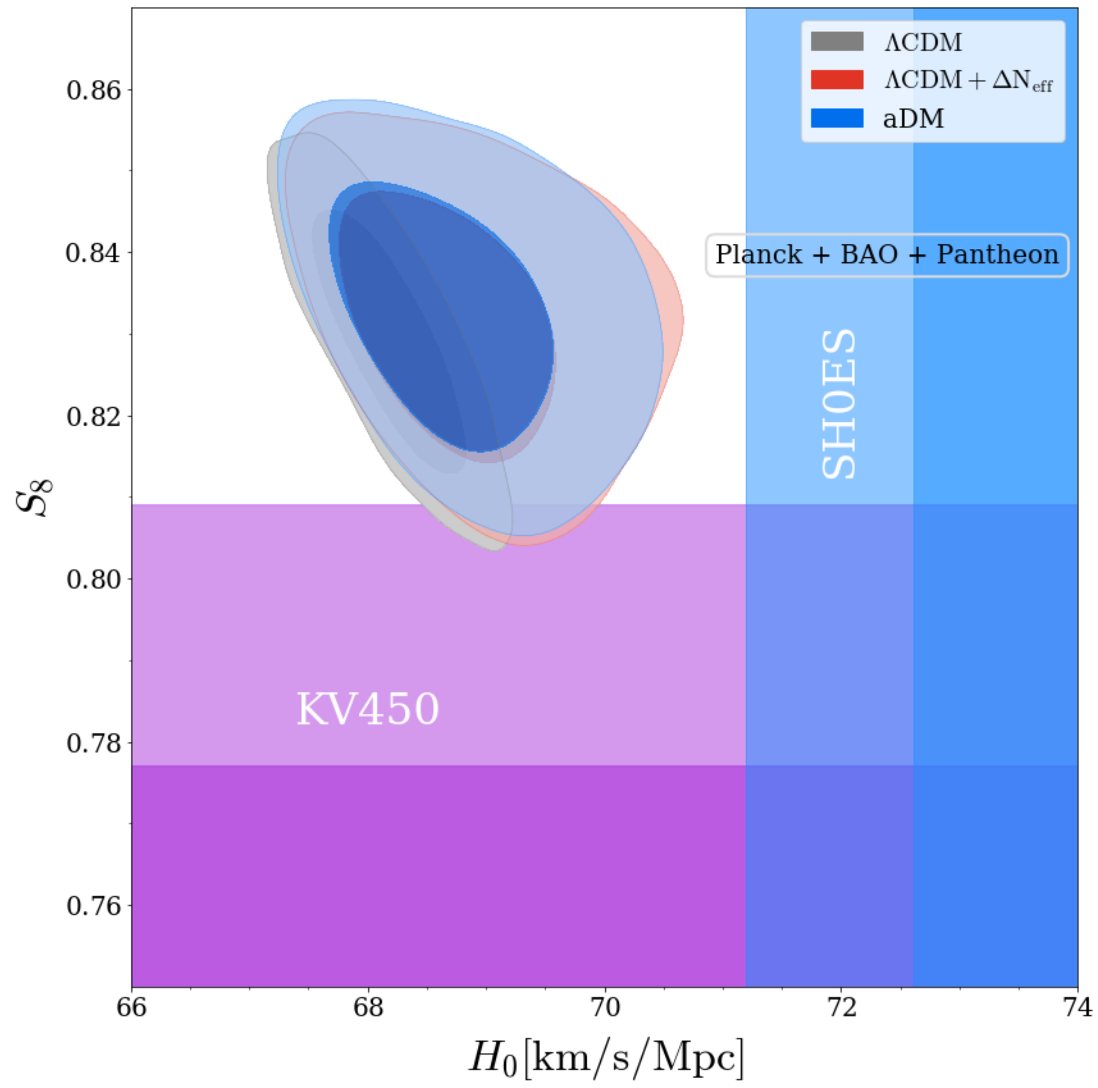
- Constraints almost identical to CMB+BAO.
- Very little constraining power with cut-off in k.
- Will not include KV450 cosmic shear dataset when comparing with/without local H_0 and S_8 measurements.



Parameter	f_D	ΔN_D	m_{e_D}
Prior	$0 < f_D < 1$	$0 < \Delta N_D < 1$	$-7 < \log_{10}(\frac{m_{e_D}}{\mathrm{GeV}}) < 0$

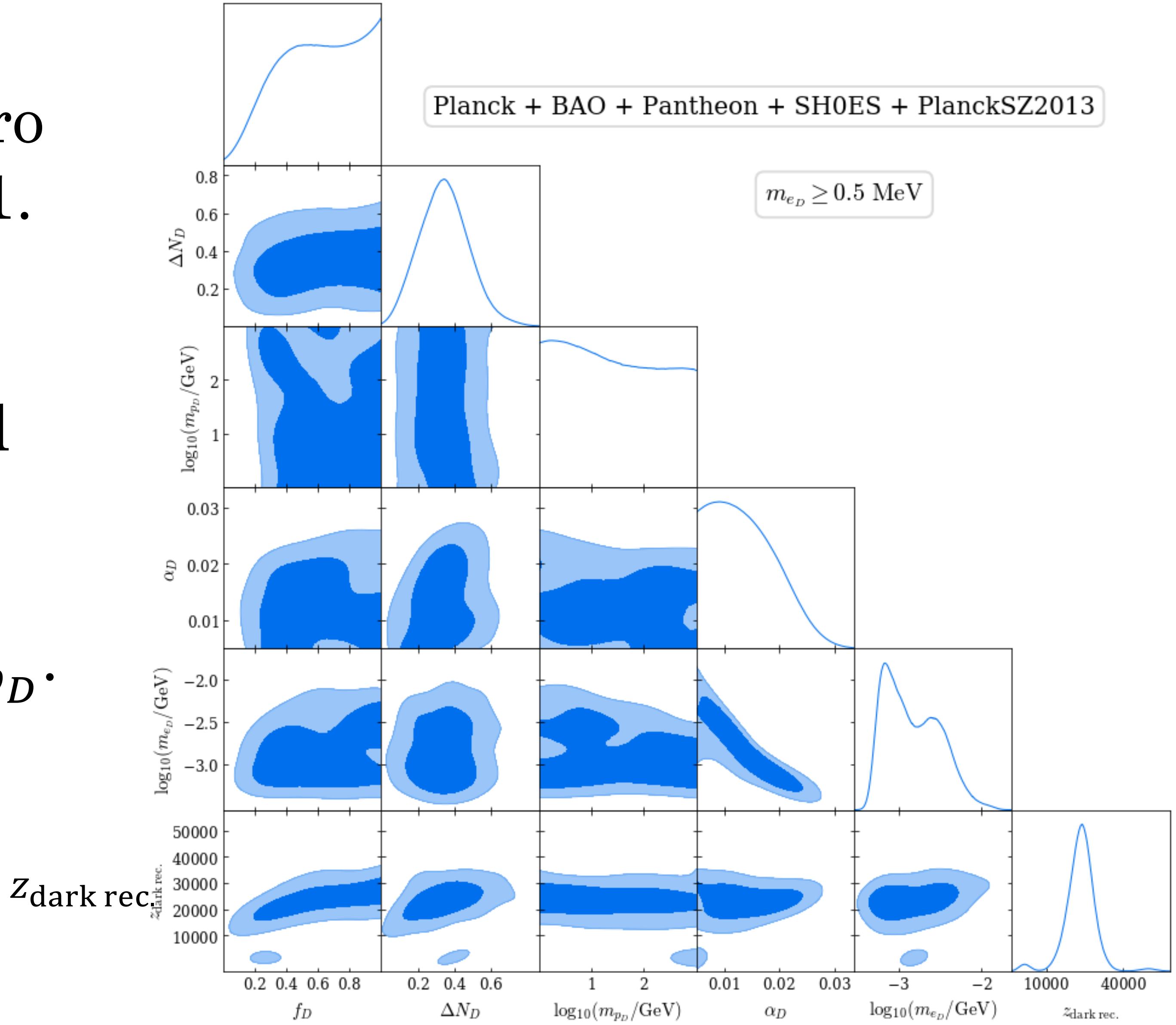
H_0 and S_8: Without direct measurements

- Best-fit region for H_0 extends to higher values than ΛCDM.
- No preference for lower S_8.
- Very similar contour to $\Lambda\text{CDM} + \Delta N_{\text{eff}}$.



Including local H_0 and S_8 measurements

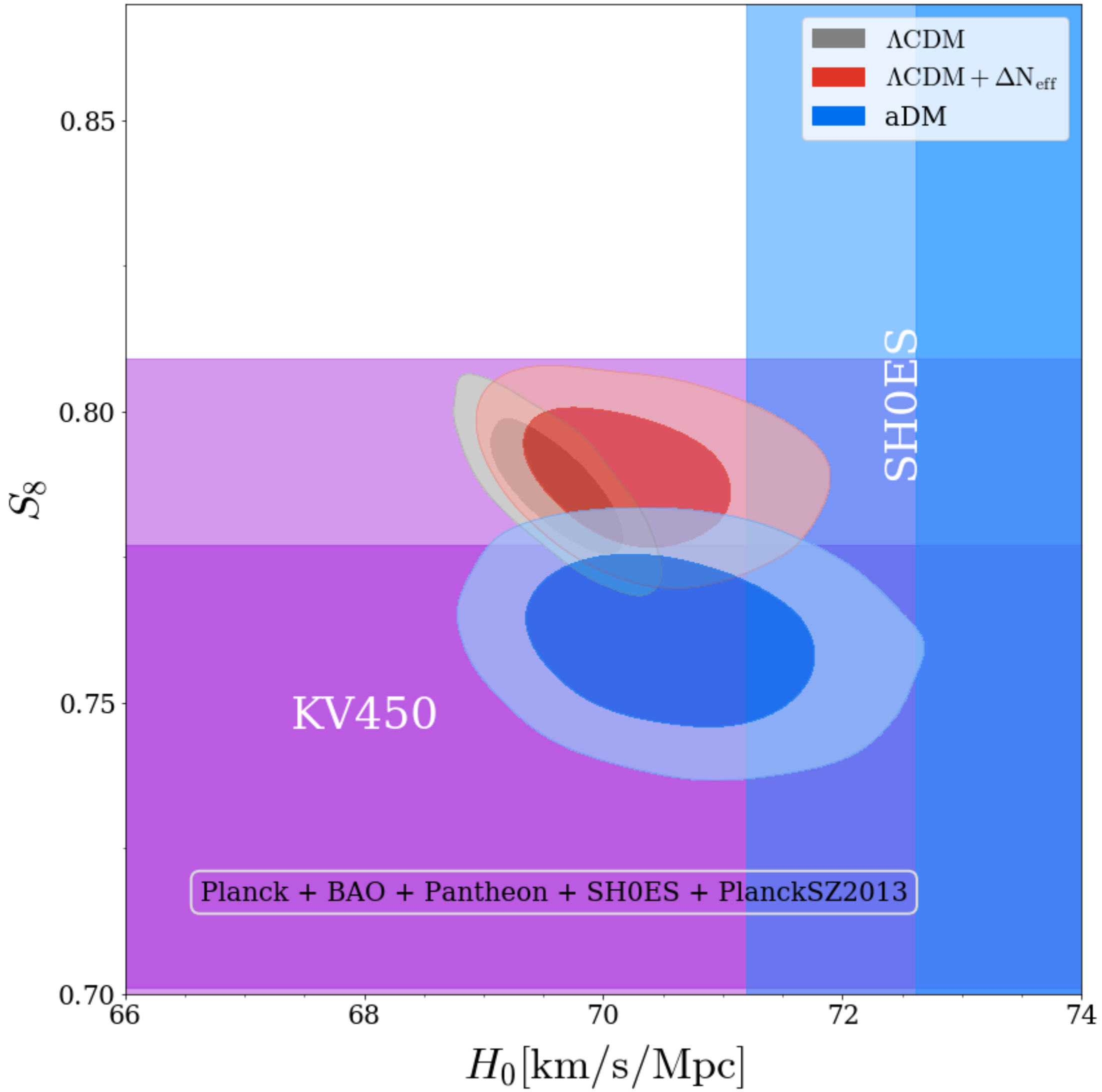
- Preference for non-zero $\Delta N_D \sim 0.3$ and $f_D > 0.1$.
- Strong preference for redshift of dark recombination around 2×10^3.
- No preference for particular value of m_{p_D}.



Lower bound of $m_{e_D} > 0.5$ MeV to avoid violating ΔN_{eff} constraints from BBN. Consistent calculation of Y_{He} for arbitrary m_{e_D} in the works now.

H_0 and S_8: With direct measurements

- Larger 95% confidence region.
- Best-fit aDM values pulled further than ΛCDM, with lower minimum χ^2.
- $\Lambda\text{CDM} + \Delta N_{\text{eff}}$ unable to accommodate lower S_8.
- DM-DR interactions necessary to allow lower S_8.



	ΛCDM		ΛCDM + $\Delta N_{\rm eff}$		aDM	
Param	best-fit	mean±σ	best-fit	mean±σ	best-fit	mean±σ
$100\ \Omega_b h^2$	2.264	$2.268^{+0.013}_{-0.012}$	2.261	$2.275^{+0.014}_{-0.014}$	2.278	$2.275^{+0.013}_{-0.015}$
$\Omega_{dm} h^2$	0.1165	$0.1163^{+0.00078}_{-0.00079}$	0.1171	$0.1182^{+0.0012}_{-0.0019}$	0.1252	$0.124^{+0.0025}_{-0.0026}$
h	0.6956	$0.696^{+0.0036}_{-0.0039}$	0.6958	$0.7027^{+0.0048}_{-0.0069}$	0.7085	$0.7062^{+0.0072}_{-0.009}$
$\ln(10^{10} A_s)$	3.033	$3.024^{+0.014}_{-0.013}$	3.031	$3.026^{+0.015}_{-0.013}$	3.054	$3.052^{+0.015}_{-0.014}$
n_s	0.9722	$0.9728^{+0.0037}_{-0.0037}$	0.9724	$0.9764^{+0.0042}_{-0.0047}$	0.973	$0.9721^{+0.004}_{-0.0047}$
τ_{reio}	0.05129	$0.04859^{+0.0071}_{-0.0069}$	0.04987	$0.0475^{+0.008}_{-0.0068}$	0.05609	$0.05634^{+0.0074}_{-0.0073}$
H_0	69.56	$69.6^{+0.36}_{-0.39}$	69.58	$70.27^{+0.48}_{-0.69}$	70.85	$70.62^{+0.72}_{-0.9}$
σ_8	0.8091	$0.8047^{+0.0052}_{-0.0047}$	0.8098	$0.809^{+0.0058}_{-0.0063}$	0.7629	$0.7679^{+0.0099}_{-0.011}$
S_8	0.7921	$0.7871^{+0.0073}_{-0.0078}$	0.7942	$0.7891^{+0.0079}_{-0.008}$	0.7563	$0.7606^{+0.01}_{-0.0098}$
f_D	-	-	-	-	0.3265	$\{0.17, 1\}$
ΔN_D	-	-	0.026	$0.115^{+0.027}_{-0.11}$	0.3934	$0.339^{+0.13}_{-0.14}$
$\log_{10}(m_{p_D}/\ \mathrm{GeV})$	-	-	-	-	2.987	$\{0.125, 3\}$
$\log_{10}(m_{e_D}/\ \mathrm{GeV})$	-	-	-	-	-3.819	$\{-4, -2.1\}$
α_D	-	-	-	-	0.04041	$\{.005, .05\}$
$z_{\text{dark rec.}}$	-	-	-	-	1.924×10^4	$22510^{+5.3\times10^3}_{-4.2\times10^3}$
$\chi^2_{\rm total}$	3853.12		3852.53		3829.62	
Planck	2777.98		2776.15		2783.61	
Pantheon	1026.24		1026.09		1025.94	
BAO	9.08		8.60		6.16	
SH0ES	10.60		11.038		4.43	
Lensing	10.55		11.19		9.46	
Planck SZ	18.07		19.45		0.017	

Best-fit $H_0 = 70.62^{+0.72}_{-0.9}$ km/s/Mpc is in $\sim 2\sigma$ tension with SH0ES measurement of $H_0 = 73.04 \pm 1.04$ km/s/Mpc.

$$\left(\chi^{\Lambda\mathrm{CDM}}_{min}\right)^2 - \left(\chi^{\mathrm{aDM}}_{min}\right)^2 = 23.5$$

Conclusion

- Atomic dark matter is a well-motivated, plausible interacting dark sector scenario.
- It can leave distinctive imprints on cosmological observables.
- By modifying CLASS to compute ADM cosmological evolution in generality, we place new constraints on the atomic dark matter parameter space from precision observations.
- There is no preference for atomic dark matter from CMB observations alone, but large aDM fractions can be allowed from large-scale measurements.
- When including low-redshift measurements of the Hubble constant and structure, a significant fraction of aDM that recombines near $z = 2 \times 10^3$ is preferred, along with a non-zero amount of dark radiation. The Hubble and S_8 tensions can be eased but not eliminated.

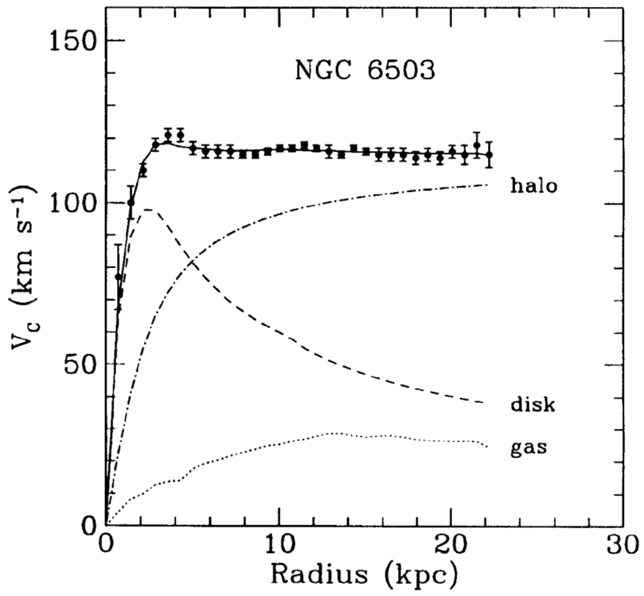
Future directions

- Adding dark helium to CLASS-aDM, with arbitrary Y_{He_D}.
- Reliable computation of non-linear matter power spectrum evolution for arbitrary aDM parameters would unlock many constraints at smaller scales. (Halofit for aDM?)
  - Cosmic shear for $k > 0.1\, h\, \mathrm{Mpc}^{-1}$.
  - Lyman-α forest.
  - 21 cm?
- Suggestions?

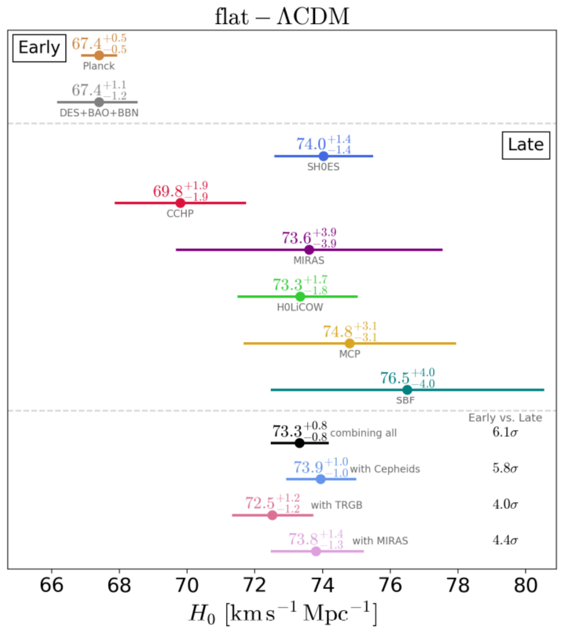
Backup Slides

Dark Matter: CDM or something more?

- The cold, collisionless dark matter paradigm explains many observations extremely well.
  - Galaxy rotation curves.
  - The Bullet cluster.
  - The cosmic microwave background spectrum.
  - Large scale structure in the universe.
- But it's not perfect.
  - Core vs cusp problem.
  - Hubble tension.
  - S_8 tension.
- Could a component of dark matter have non-trivial interactions in the dark sector?



Freese, 2008

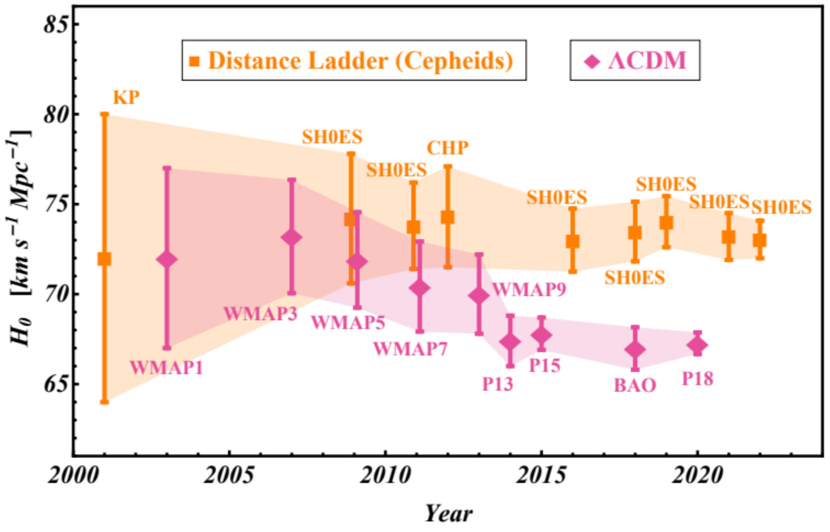


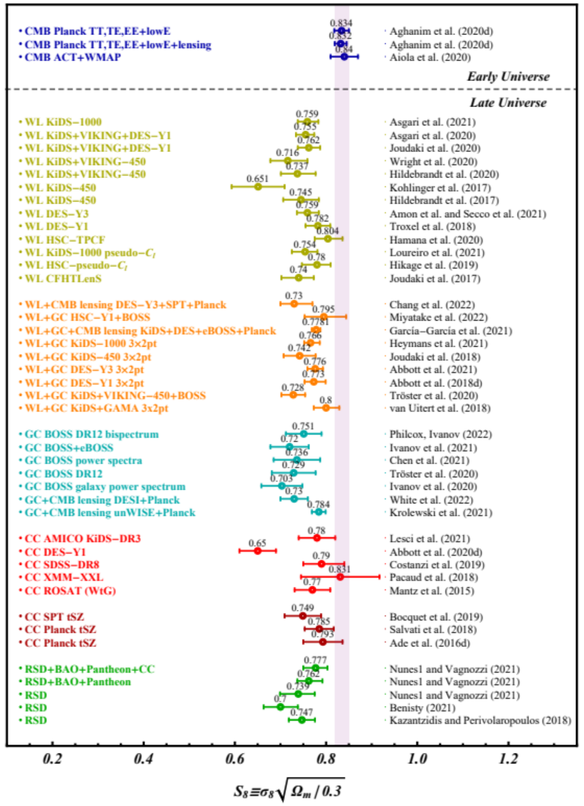
Verde, Treu, Riess, 2019

Hubble and S_8 tensions

- H_0 measures the rate of expansion of the universe today.
  - Planck 2018 (CMB): $H_0 = 67.4 \pm 0.5$ km/s/Mpc
  - SH0ES (distance ladder): $H_0 = 73.04 \pm 1.04$ km/s/Mpc

- S_8 measures the size of fluctuations in the matter density at the scale $8\ h^{-1}$ Mpc.
  - Planck 2018 (CMB): $S_8 = 0.834 \pm 0.016$
  - KiDS-1000 (weak lensing): $S_8 = 0.754^{+0.027}_{-0.029}$





Images from 2105.05208

Dark Acoustic Oscillations