Precision Cosmological Constraints on Atomic Dark Matter

Jared Barron

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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.

Some Motivations for Atomic Dark Matter

Experiment

- Hubble tension.
- S_8 tension.
- Small scale behaviour of DM (e.g. core-cusp).

Theory

- Approximately $\mathbb{Z}_2$-symmetric mirror sectors can address naturalness issues.
- e.g. Mirror Twin Higgs
- Twin/mirror sectors have their own gauge forces, and can have dark matter – dark radiation interactions.
- The SM sector has rich particle content and forces. Why shouldn't the dark matter?

Questions

- How much do current cosmological observations constrain the atomic dark matter (aDM) parameter space?

- To what extent can aDM alleviate the Hubble and S_8 tensions?

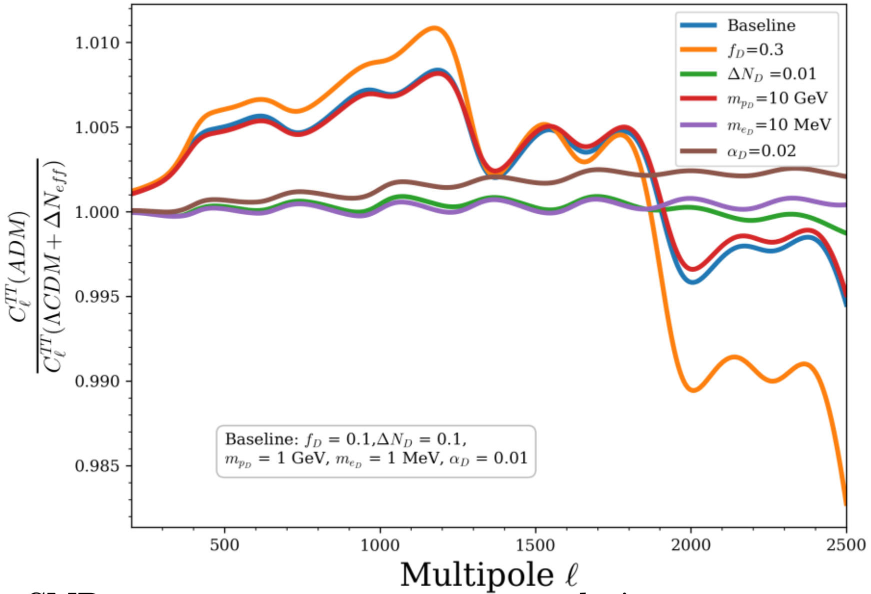
Cosmology of Atomic Dark Matter

- Early universe: dark plasma.
- Dark acoustic oscillations (DAOs) due to dark photon pressure support.
- Dark recombination at temperatures below dark hydrogen binding energy.
- Dark photons decouple from atomic dark matter.
- 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.

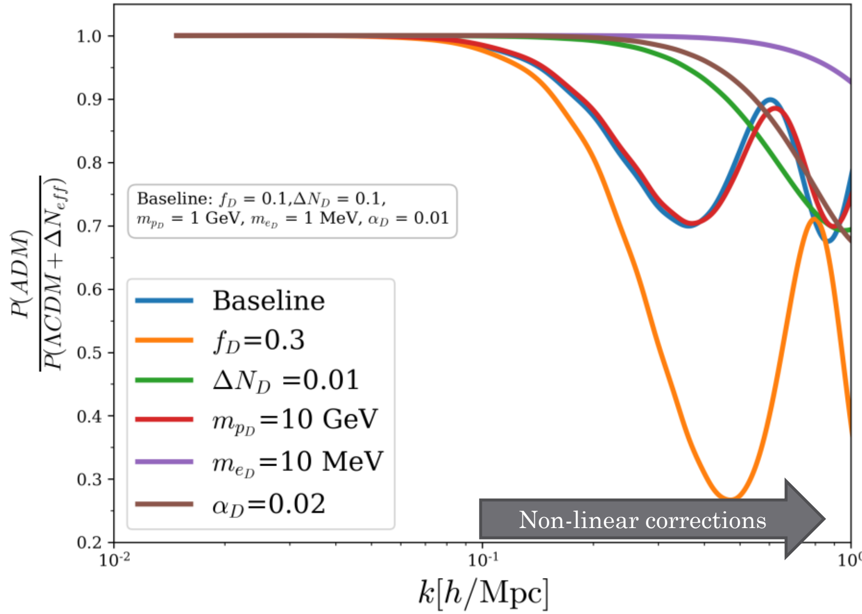
CMB and Matter Power Spectrum

- Complex effect on CMB power spectrum. Percent-level deviations from ΛCDM.
- Matter power spectrum: Suppression and oscillations for *k* that enter horizon before dark decoupling.
- Lower ΔN_D, higher binding energy $\mathrm{B_D}$ → suppression starts at higher *k*.
- Non-linear evolution smears out oscillations at low redshifts. [2101.12229]

Spectra computed with CLASS_aDM, at https://github.com/jp-barron/class_adm-3.1.git



CMB temperature power spectrum relative to $\Lambda\mathrm{CDM} + \Delta N_\mathrm{eff}$

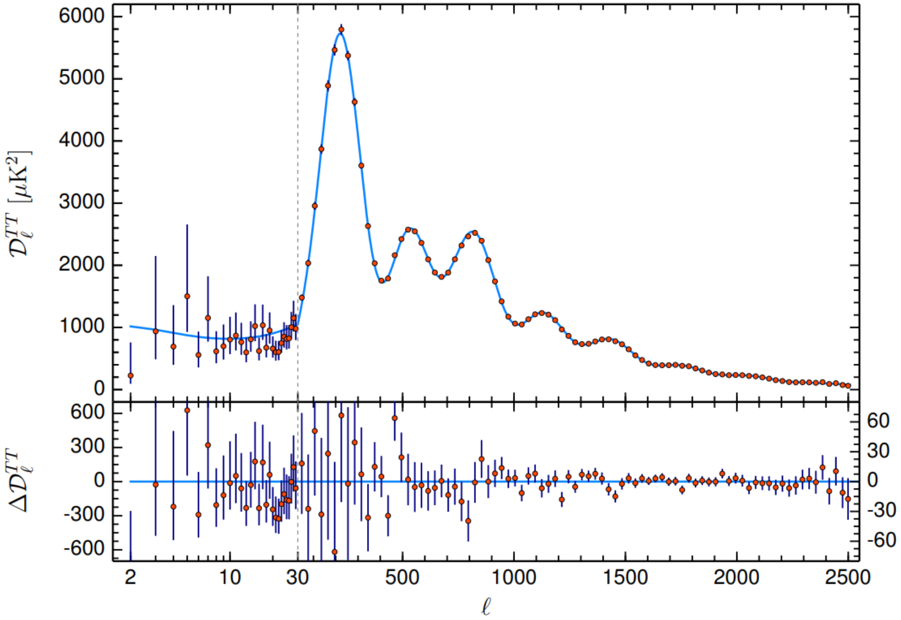


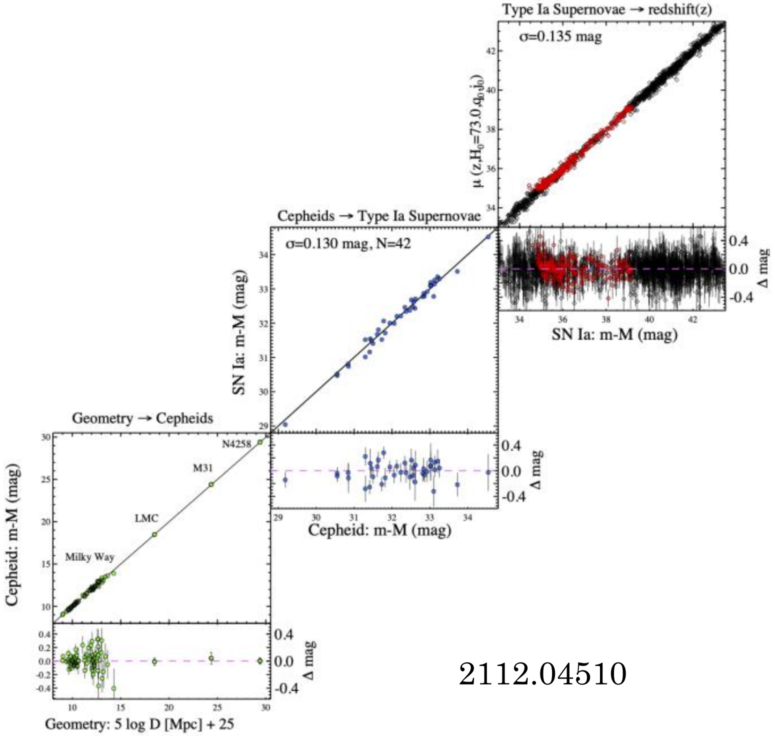
Matter power spectrum relative to $\Lambda\mathrm{CDM} + \Delta N_\mathrm{eff}$

Datasets: CMB, BAO, H_0, S_8

- 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]
- Pantheon supernova dataset. [1710.00845]
- SH0ES measurement of H_0 using Cepheid variables and Type Ia supernovae. [2112.04510]
- Planck SZ 2013 measurement of S_8. [1303.5080]

1807.06209

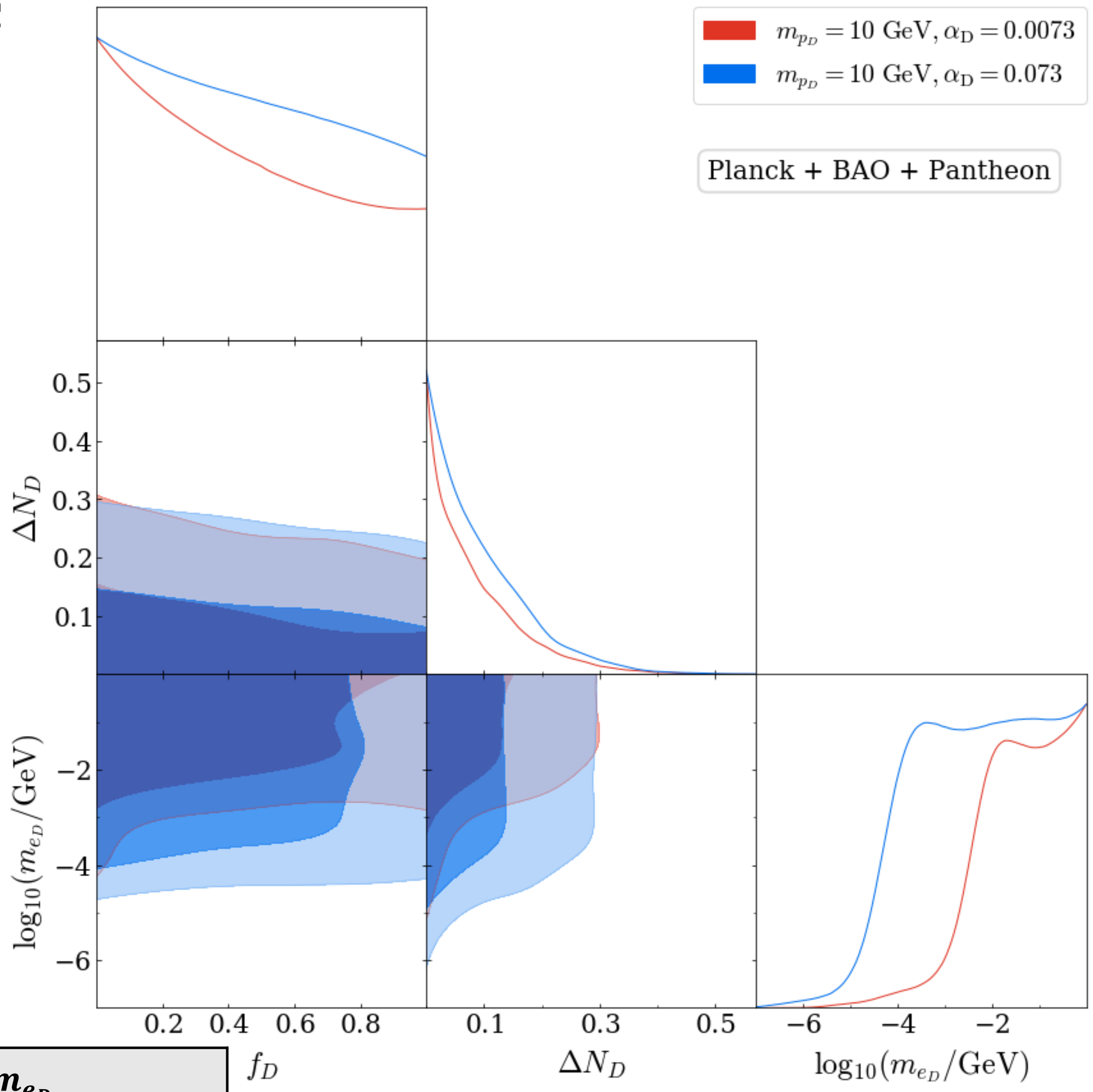




2112.04510

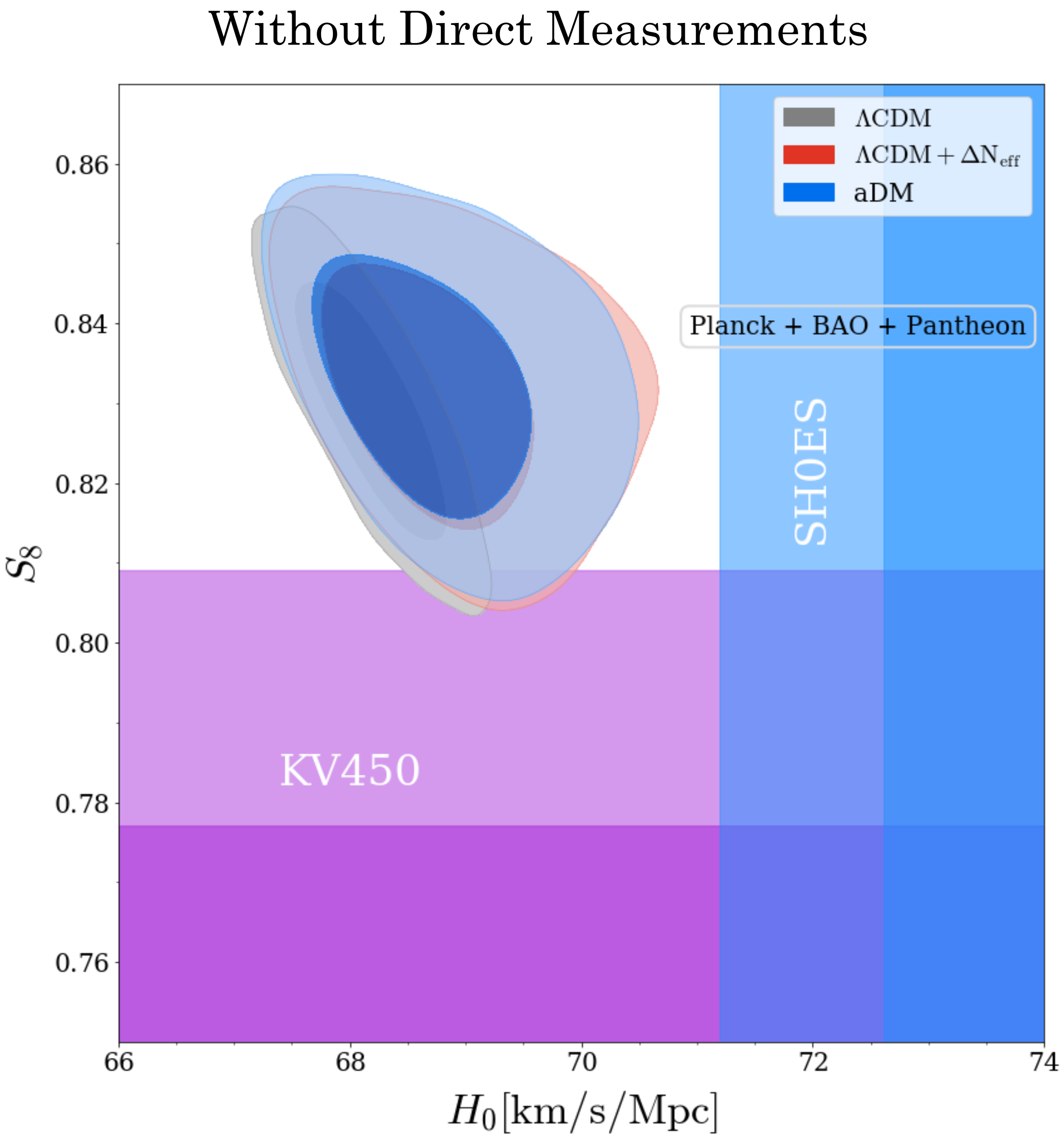
3D scans: constraining ΔN_D, f_D, and m_{e_D}

- $m_{e_D}, \alpha_D \sim T_{dec}$.
- Large f_D not ruled out for sufficiently large m_{e_D}.
- Constraint on ΔN_D sharply transitions from < 0.3 to much tighter as m_{e_D} is lowered.

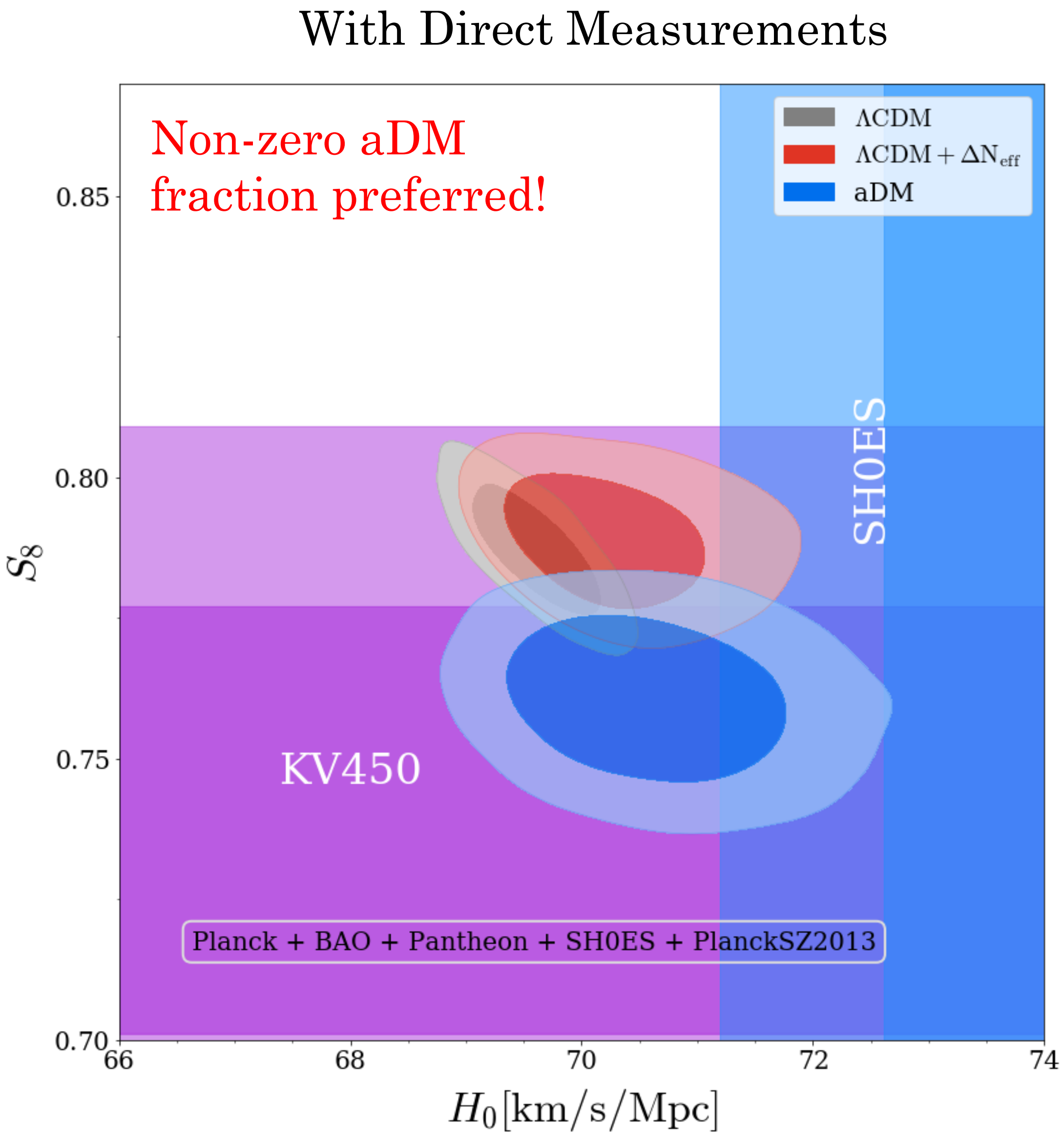


Parameter	f_D	ΔN_D	m_{e_D}
Prior	$0 < f_D < 1$	$0 < \Delta N_D < 1$	$-7 < \log_{10}(\frac{m_{e_D}}{\mathrm{GeV}}) < 0$

H_0 and S_8



Without Direct Measurements
ΛCDM
ΛCDM + ΔN_eff
aDM
Planck + BAO + Pantheon
SH0ES
KV450
0.86
0.84
0.82
0.80
0.78
0.76
S_8
66
68
70
72
74
H_0[km/s/Mpc]



With Direct Measurements
Non-zero aDM
fraction preferred!
ΛCDM
ΛCDM + ΔN_eff
aDM
SH0ES
KV450
Planck + BAO + Pantheon + SH0ES + PlanckSZ2013
0.85
0.80
0.75
0.70
S_8
66
68
70
72
74
H_0[km/s/Mpc]

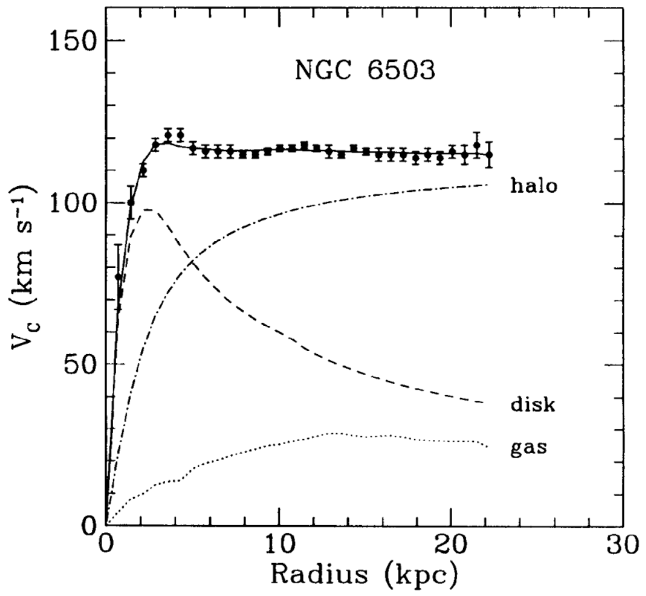
Conclusion

- CLASS_aDM code can compute CMB and linear matter power spectrum for a wide range of aDM parameter values.
- We computed the current constraints on the full aDM parameter space for the first time by comparing with precision cosmological 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, the Hubble and S_8 tensions can be eased but not eliminated. A significant fraction of aDM that recombines near $z = 2 \times 10^4$ is preferred, along with a non-zero amount of dark radiation, in order to accommodate the local measurements.

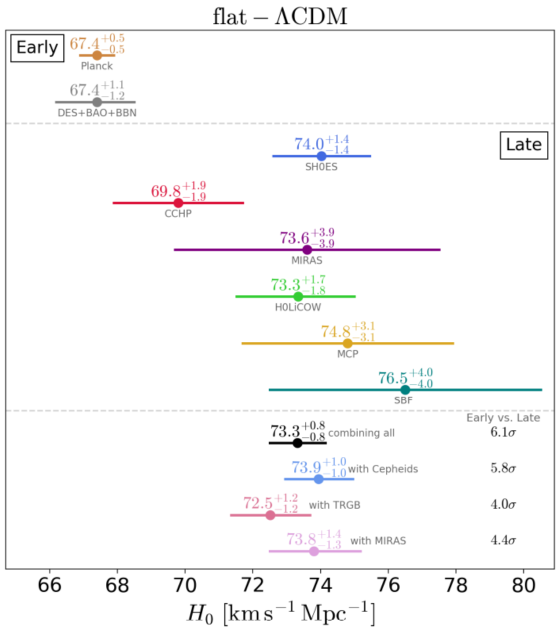
Backup Slides

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



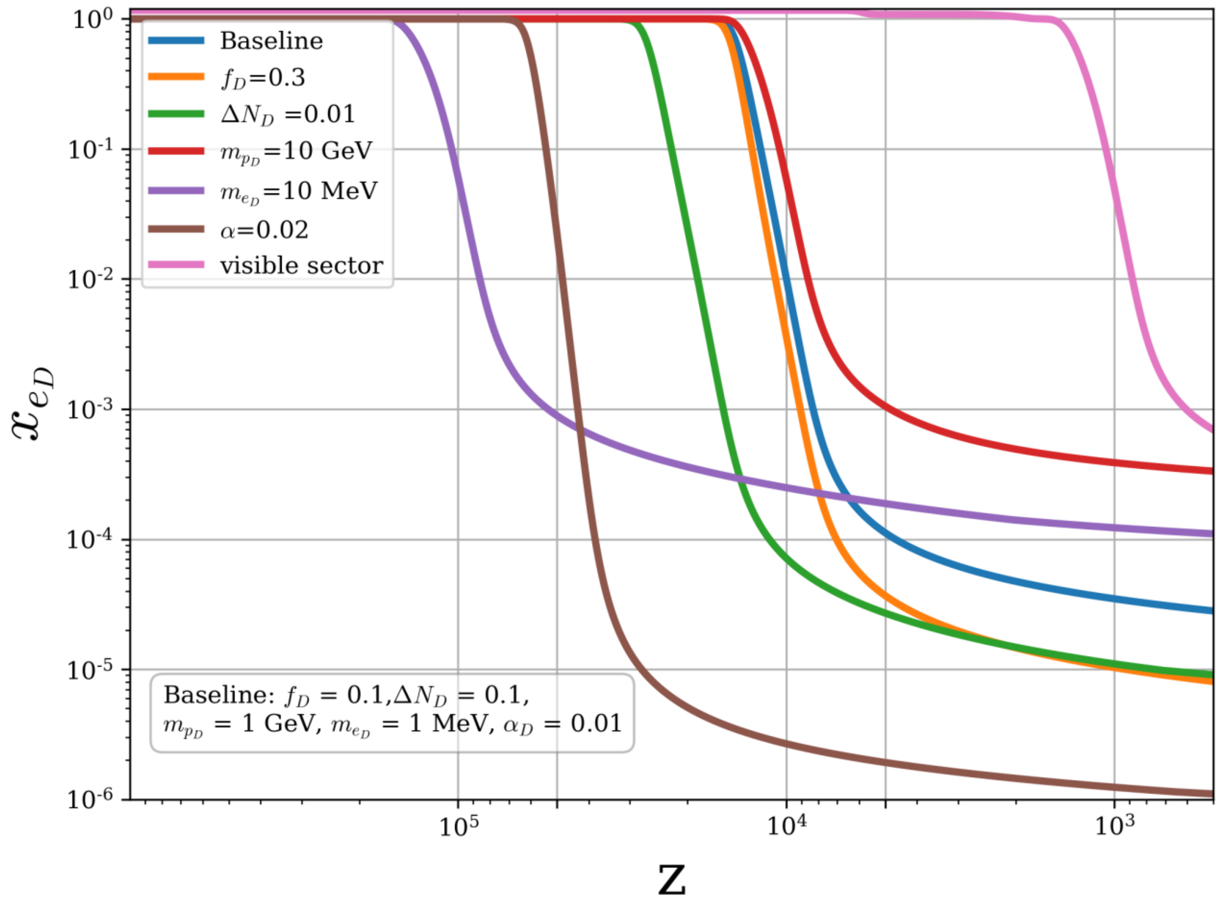
Verde, Treu, Riess, 2019

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.

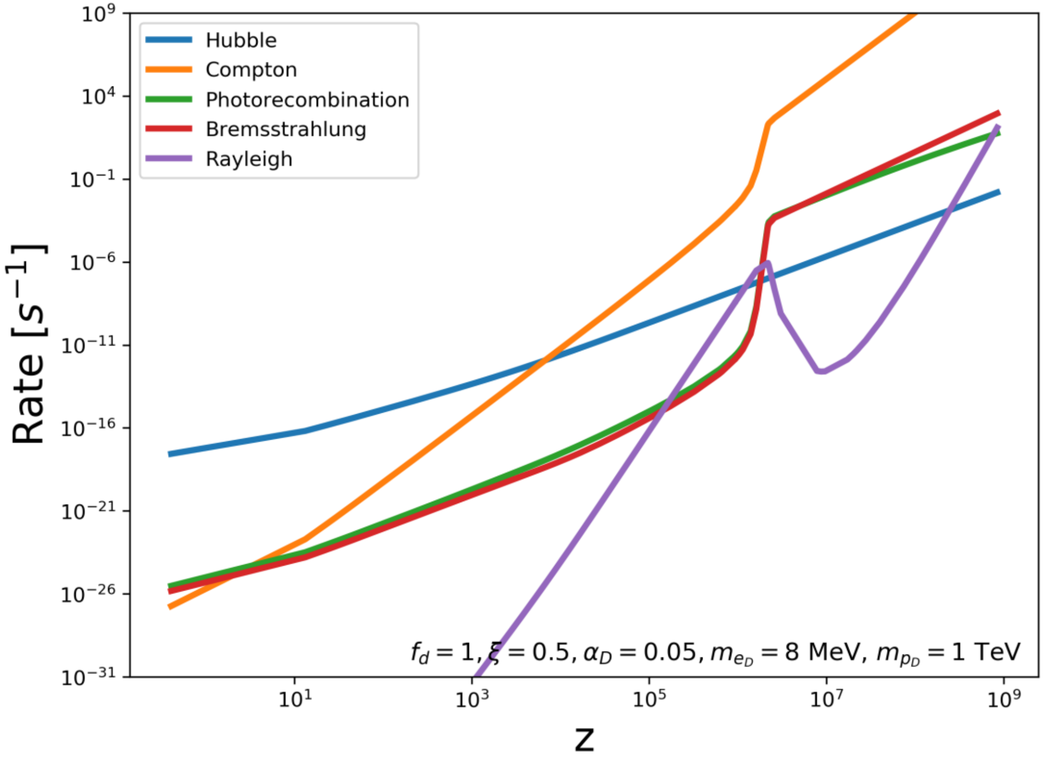
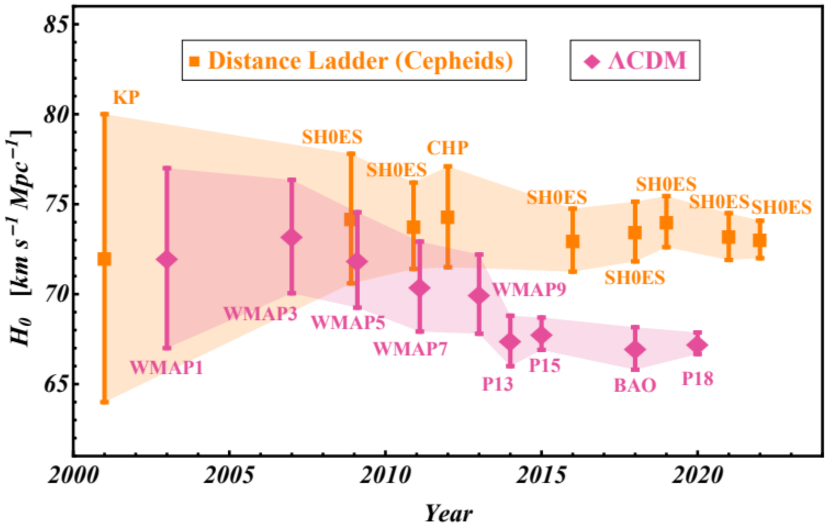
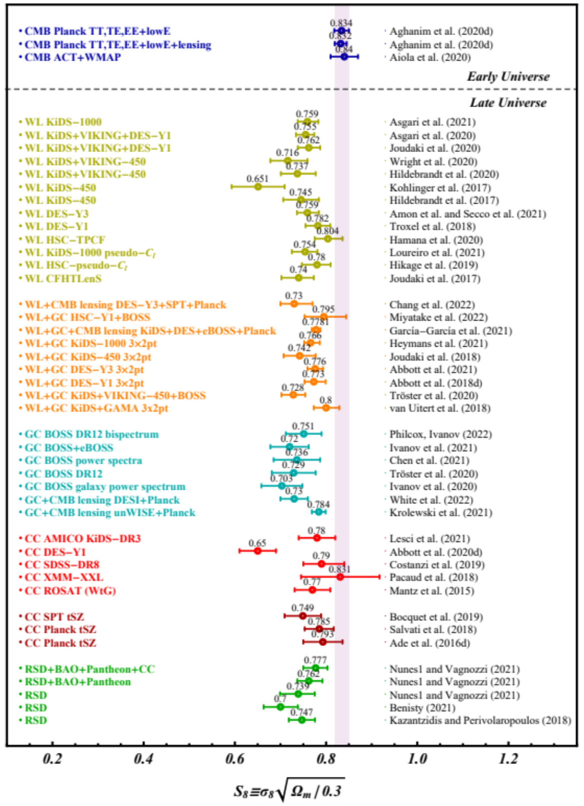


*Photo-heating/cooling processes not yet included in CLASS-aDM due to numerical instabilities – to be added soon. Similar rate to bremsstrahlung.

Hubble and S_8 tensions

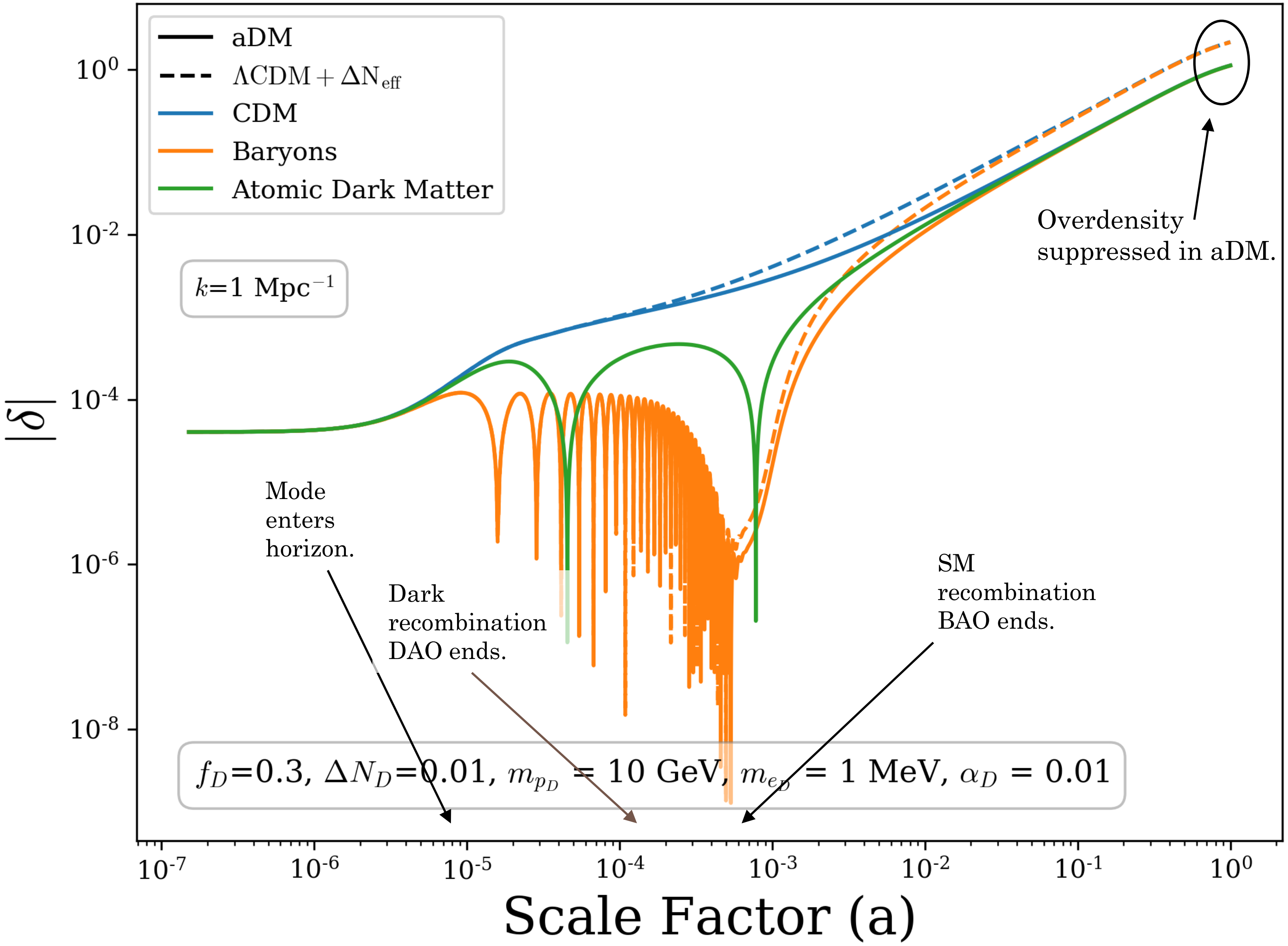
- H_0 measures the rate of expansion of the universe today.
  - Planck 2018 (CMB): $H_0 = 67.4 \pm 0.5$ km/s/Mpc
  - SH0ES (distance ladder): $H_0 = 73.04 \pm 1.04$ km/s/Mpc
- S_8 measures the size of fluctuations in the matter density at the scale $8\ h^{-1}$ Mpc.
  - Planck 2018 (CMB): $S_8 = 0.834 \pm 0.016$
  - KiDS-1000 (weak lensing): $S_8 = 0.754^{+0.027}_{-0.029}$





Images from 2105.05208

Dark Acoustic Oscillations

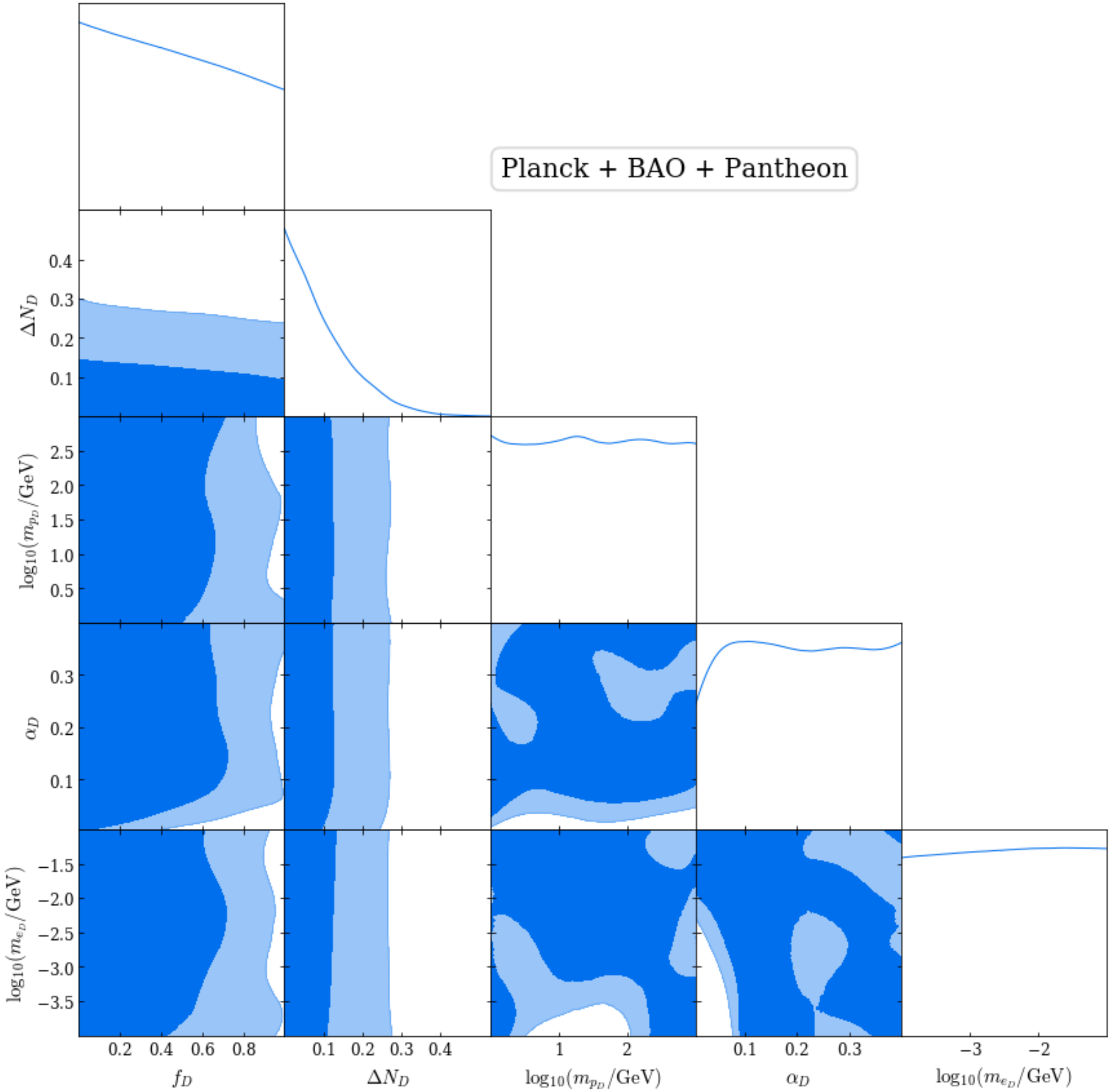


Constraining aDM parameter space

- 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: 5D scans

- 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 $\Delta N_{\rm eff} \lesssim 0.3$.
- No preference for non-zero f_D, but large fractions are possible.



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

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.

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 2×10^4.
- No preference for particular value of m_{p_D}.

$z_{\text{dark rec.}}$