Constraining Atomic Dark Matter with Cosmological Observables

Jared Barron

Based on work in progress with Saurabh Bansal, David Curtin, Yuhsin Tsai

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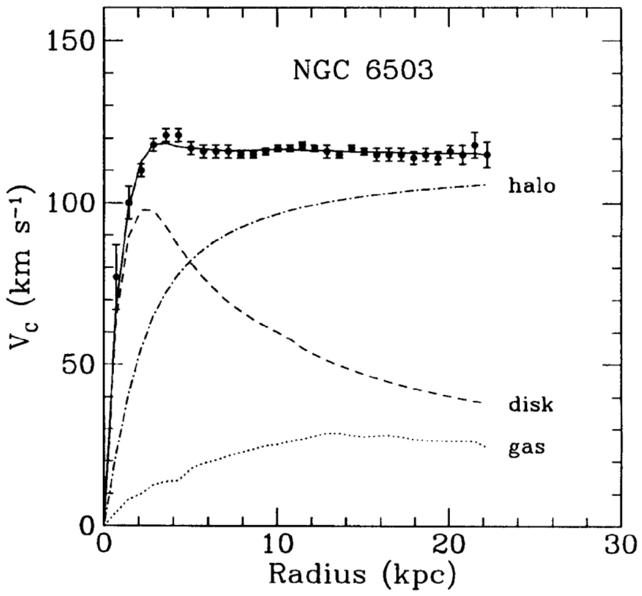
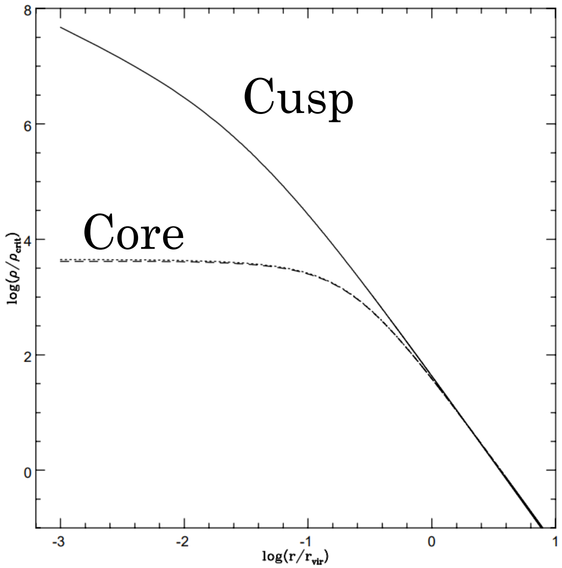
Dark Matter: CDM or something more?

- 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.
  - Missing satellites.
  - Hubble tension.
- Could a component of dark matter have non-trivial interactions in the dark sector?



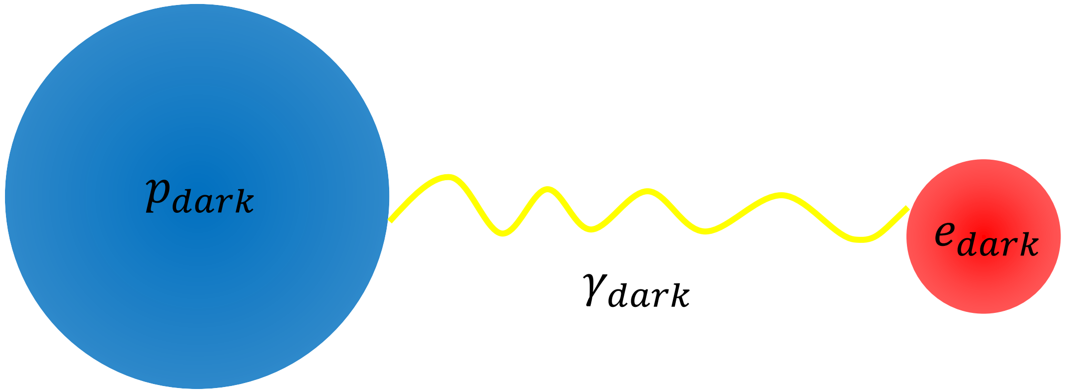
Freese, 2008



Popolo, 2009

Atomic Dark Matter

- Assume some fraction $\hat{r} \equiv \frac{\Omega_{ADM}}{\Omega_{DM}}$ of the dark matter is coupled to dark radiation in the early universe.
- This dark matter cannot contribute to growth of density perturbations in the early universe until the dark matter and dark radiation decouple.
- Such a dark sector can also exhibit dissipative behaviour, affecting structure growth on galactic scales.
- Introduce a dark sector with fermions p_{dark} and e_{dark} with masses $m_p{}'$, $m_e{}'$, neutral under the SM gauge group but oppositely charged under a dark $U(1)$ gauge force with dark fine structure constant α_D.
- Assume $m_p' \gg m_e'$.
- Bound state is dark 'hydrogen'.
- No assumption about coupling to SM.



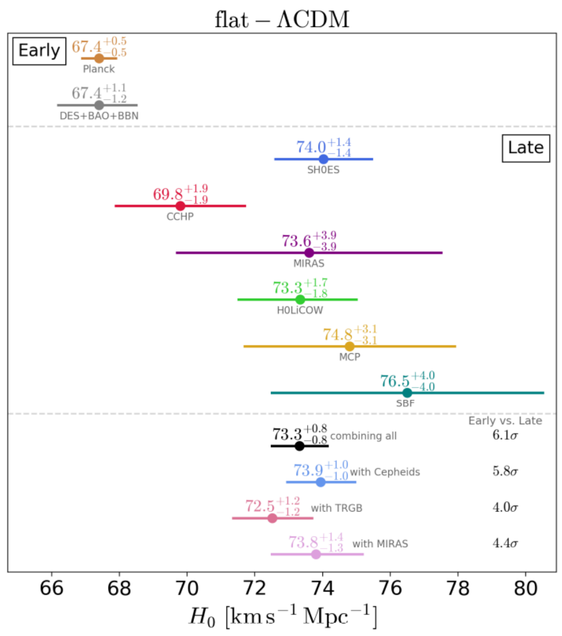
Why Atomic Dark Matter?

Theory

- Approximately $\mathbb{Z}_2$-symmetric mirror sectors can address the little hierarchy problem.
- e.g. Mirror Twin Higgs.
- The visible sector has atoms – why shouldn't the dark matter?

Experiment

- Atomic dark matter interactions can address the core-cusp problem.
- Additional dark radiation can ameliorate the Hubble tension.



Verde, Treu, Riess, 2019

Cosmology of Atomic Dark Matter

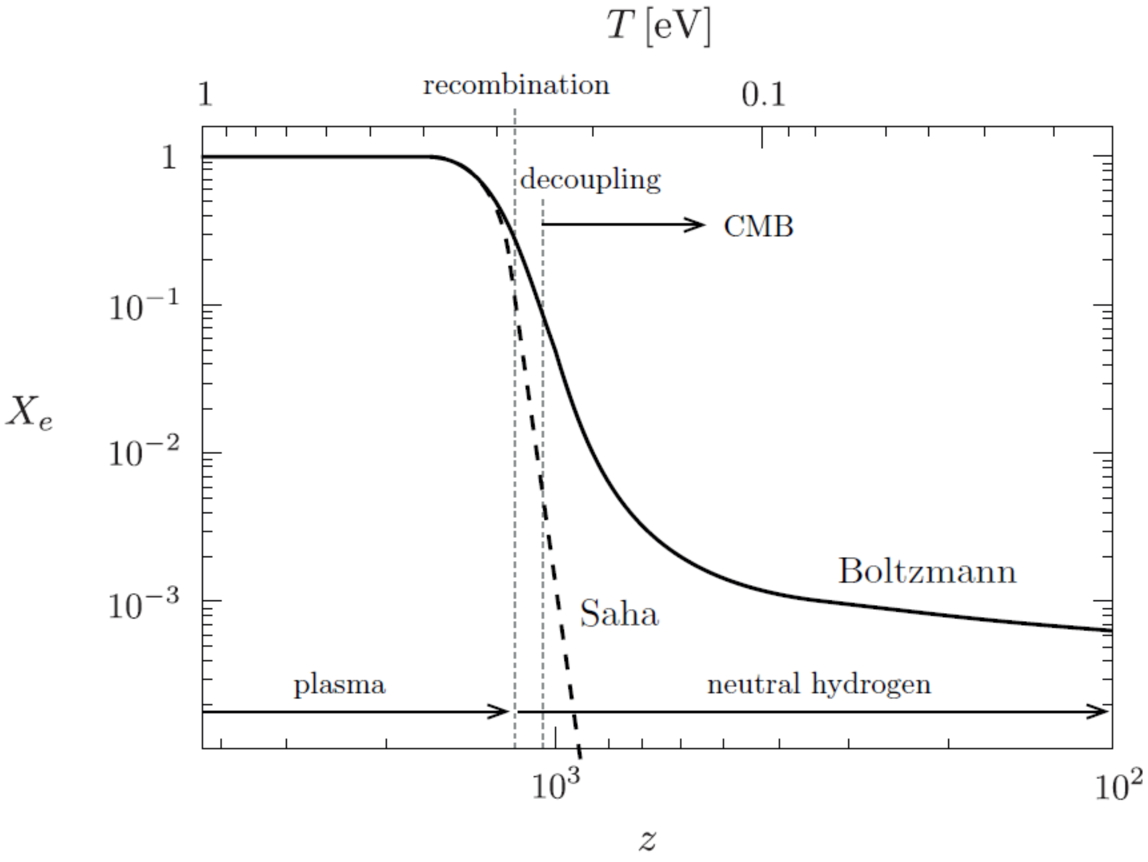
- Unlike CDM, atomic dark matter can undergo **dark recombination** and **dark acoustic oscillations**.
- To comply with bounds on $\Delta N_{\mathrm{eff}} < 0.3$, the dark sector must be cold.

$$\xi \equiv \left(\frac{T_D}{T_{SM}}\right) = \left(\frac{7}{8}\frac{4}{11}\Delta N_{\mathrm{eff}}\right)^{\frac{1}{4}} < 0.5$$

- Even accounting for the altered expansion history due to extra relativistic degrees of freedom, ADM produces unique signatures in the matter power spectrum and CMB.
- Cosmology of ADM first systematically reviewed by Cyr-Racine and Sigurdson in *Phys.Rev.D* 87 (2013) 10, and constraints placed in *Phys.Rev.D* 89 (2014) 6.
- We will update constraints with higher precision cosmological observations, and cover the full three-dimensional ADM parameter space.

(Dark) recombination and decoupling

- Dark recombination occurs after T_D falls below $B_D = \frac{\alpha_D^2 m_e'}{2}$.
- As free dark electron density drops, dark photons stop efficiently exchanging energy and momentum with the dark electrons.
- Dominant energy exchange mechanism is Thomson scattering, with cross-section $\sigma_T' = \frac{8\pi}{3}\left(\frac{\alpha_D}{m_e'}\right)^2$.
- When scattering rate $\Gamma_T \approx n_e' \sigma_T' < H$, the dark photons decouple from the dark electrons and baryons.



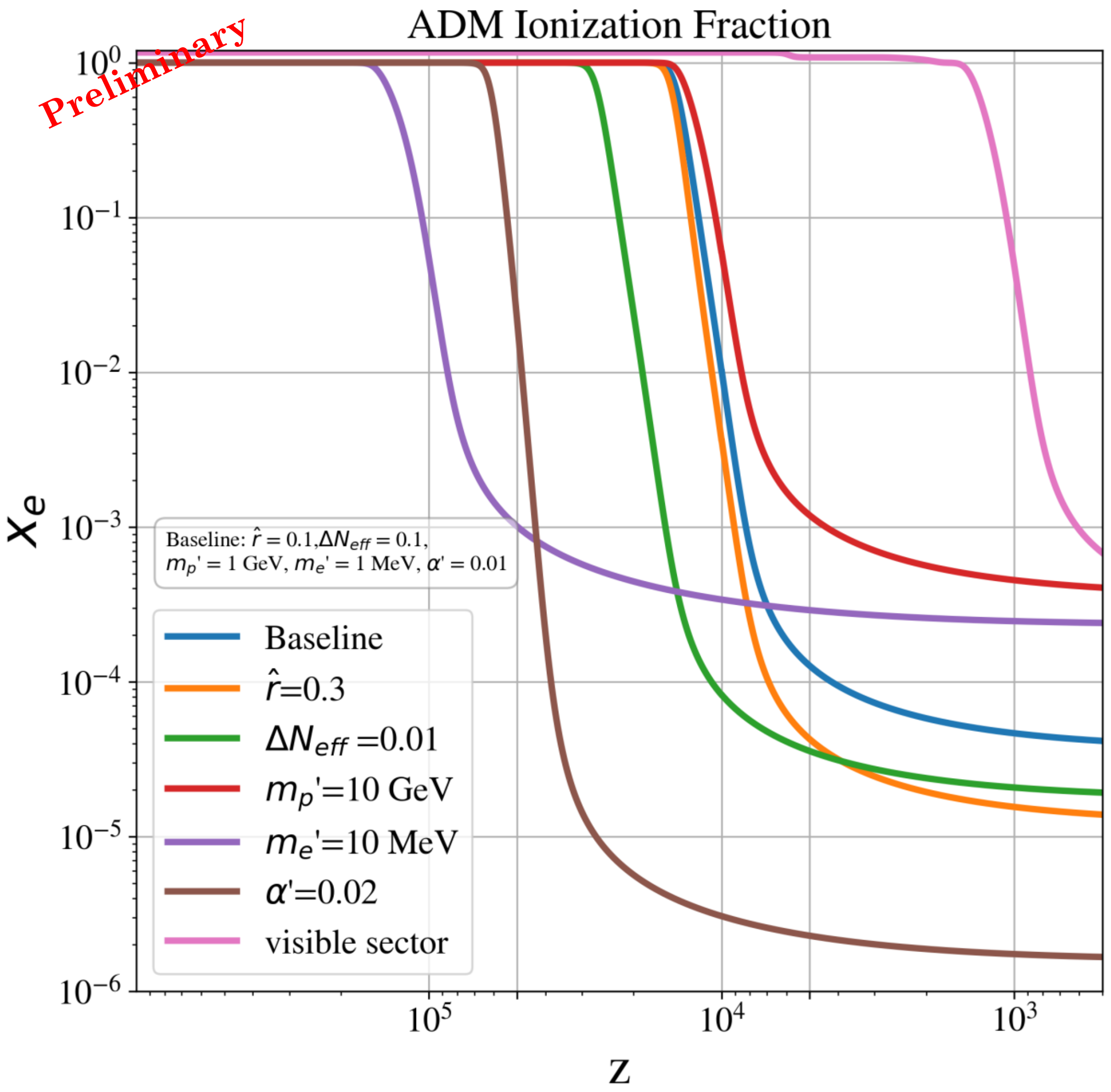
SM evolution of electron ionization fraction during recombination.

Implementation of ADM in CLASS

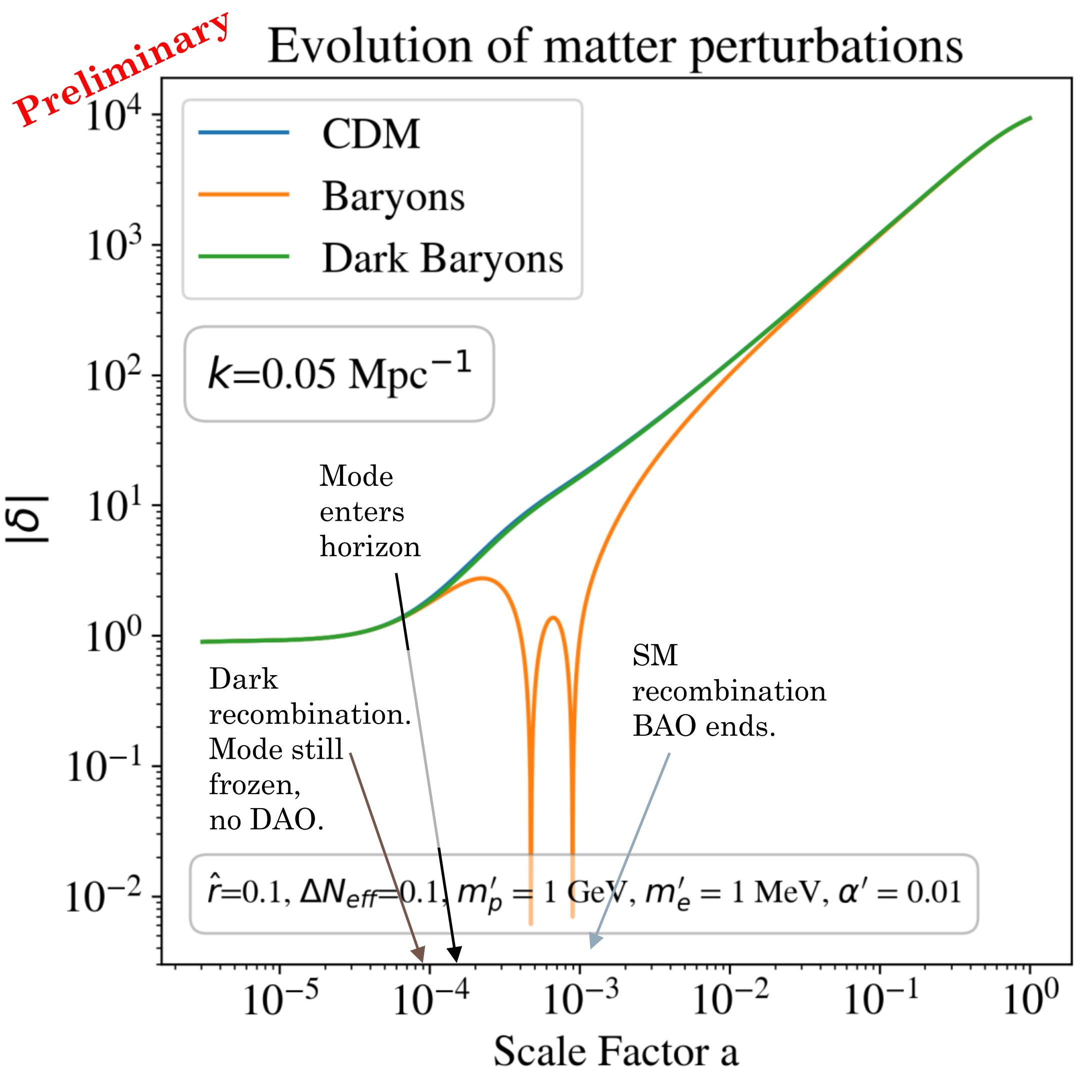
- The Cosmological Linear Anisotropy Solving System (CLASS) is a numerical code that produces CMB and LSS spectra given cosmological parameter inputs.
- Modified to include the dark radiation and dark hydrogen, and solve for the dark recombination.
  - Built on top of modifications by Bansal et al. for MTH. (hep-ph:2110.04317)
- After dark recombination, the dark sector perturbation evolutions are handled by the Effective Theory of Structure (ETHOS) framework in CLASS.

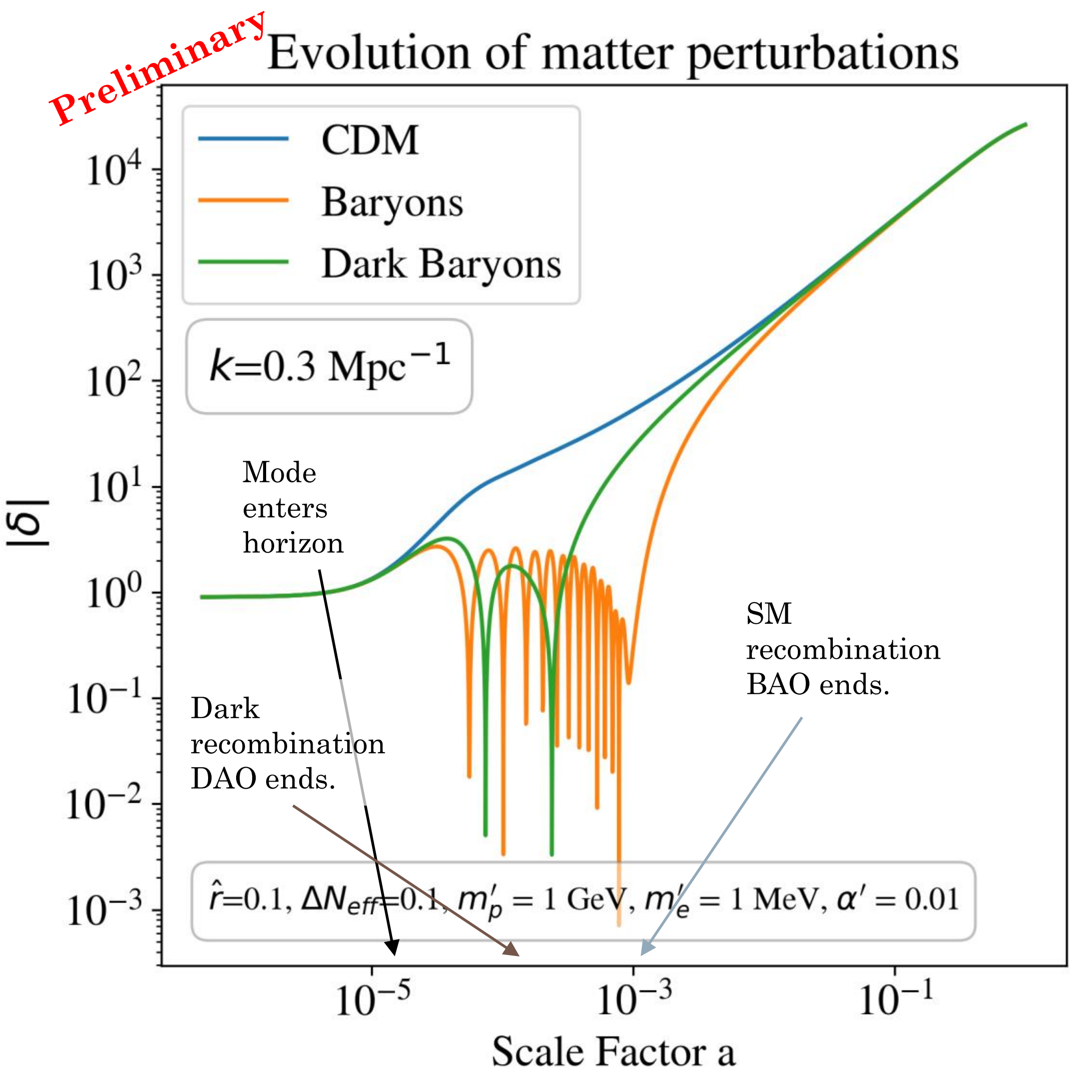
Dark Recombination

- Higher $\hat{r} \rightarrow$ lower x_e'.
  - Why: Higher e_{dark} abundance.
- Lower $\Delta N_{\text{eff}} \rightarrow$ earlier recombination.
  - Why: Higher T_{SM} for same T_D.
- Higher $m_p' \rightarrow$ higher $x_e{}'$.
  - Why: Lower e_{dark} abundance.
- Higher $m_e{}' \rightarrow$ earlier recombination and higher $x_e{}'$.
  - Why: Higher B_D and lower σ_T.
- Higher $\alpha' \rightarrow$ earlier recombination and lower $x_e{}'$.
  - Why: Higher B_D and higher σ_T.



Dark Acoustic Oscillations





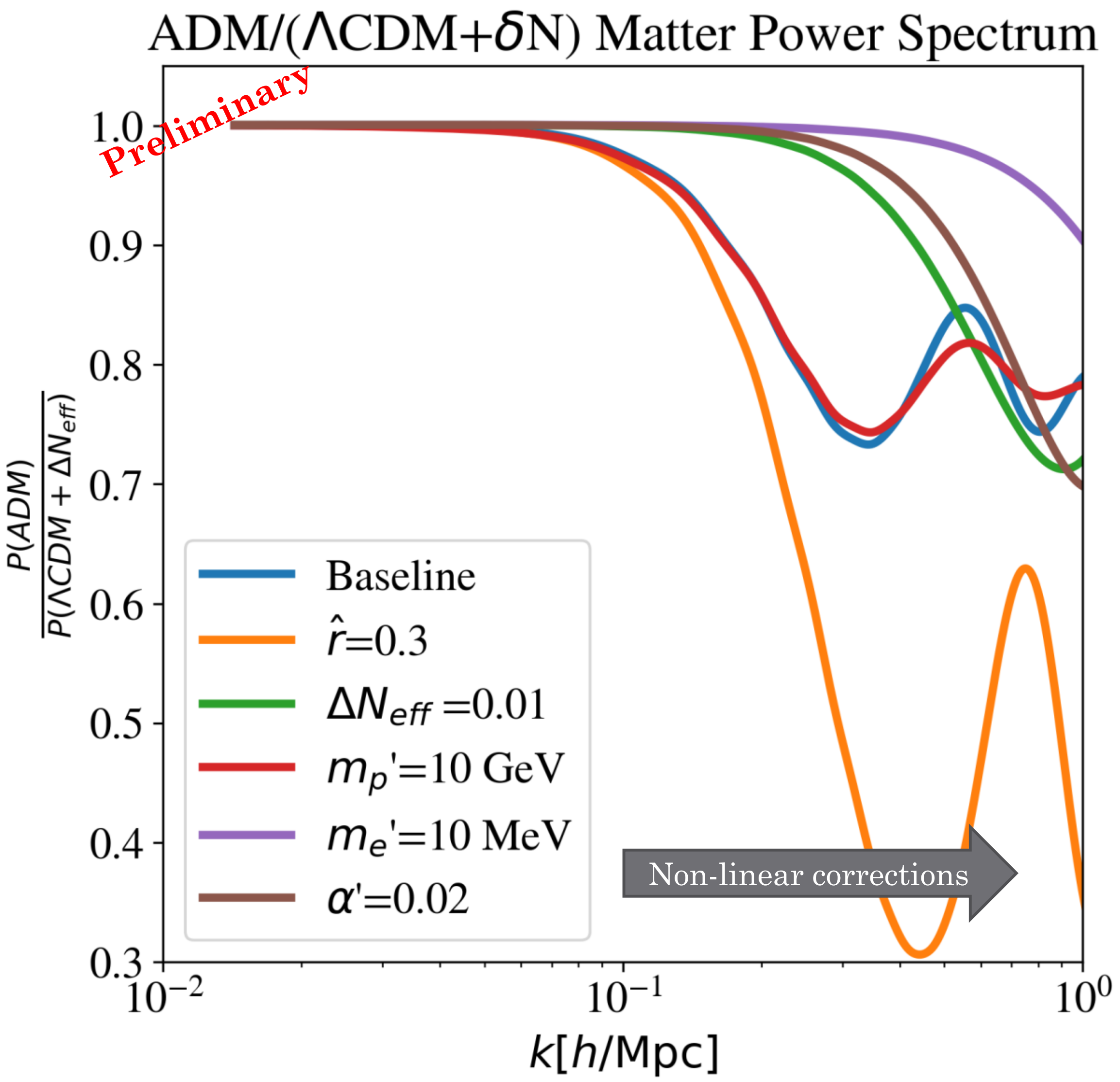
Modification of Matter Power Spectrum

- Suppression and oscillations for k that enter horizon before dark decoupling.

- Higher $\hat{r} \to$ more suppression.
- Why: Higher fraction of DM undergoes DAO.

- Lower ΔN_{eff}, higher m_e', higher $\alpha' \to$ suppression turns on at higher k.
- Why: Low-k modes enter after recombination, not suppressed.

- Cannot trust linear power spectrum above $k = 0.1\ h\ \text{Mpc}^{-1}$.



Baseline: $\hat{r} = 0.1, \Delta N_{eff} = 0.1, m_p' = 1\ \text{GeV}, m_e' = 1\ \text{MeV}, \alpha' = 0.01.$

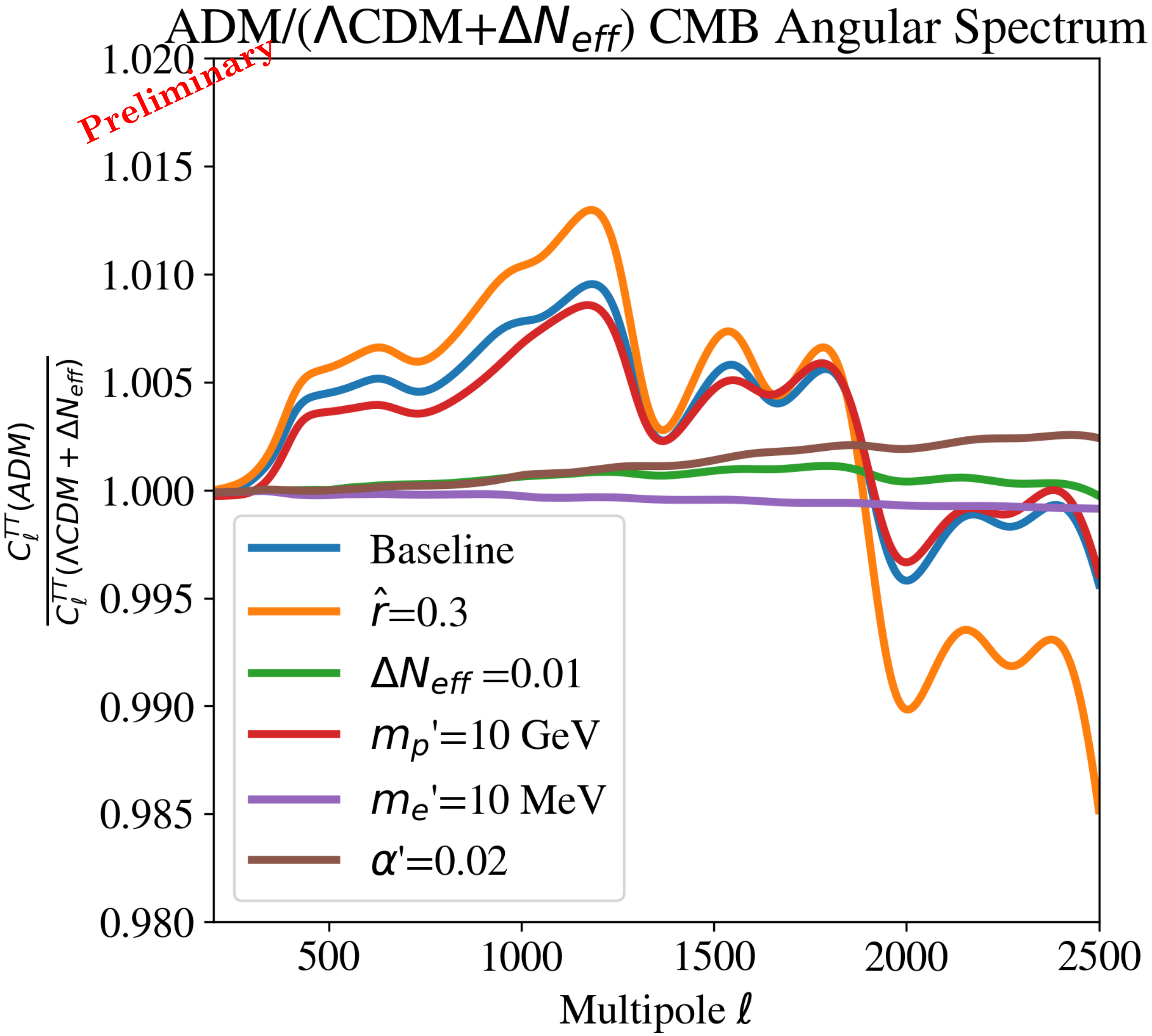
Modification of CMB

- Complex pattern of modifications to spectrum.

- Higher $\hat{r} \rightarrow$ Larger deviations.
  - Why: Higher fraction of DM undergoes DAO.

- Lower ΔN_{eff}, higher $m_e{}'$, higher $\alpha' \rightarrow$ smaller deviations.
  - Why: Dark photons began free-streaming earlier. Gravitational potential altered less.

- Polarization spectrum and lensing also altered.



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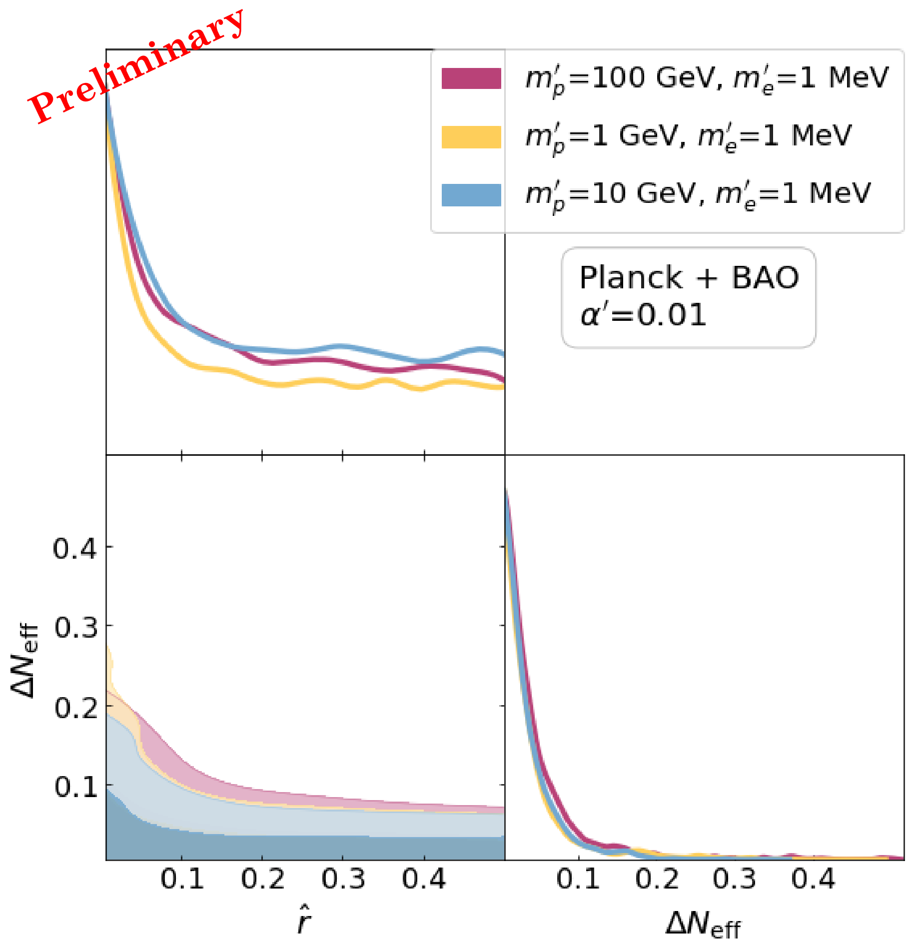
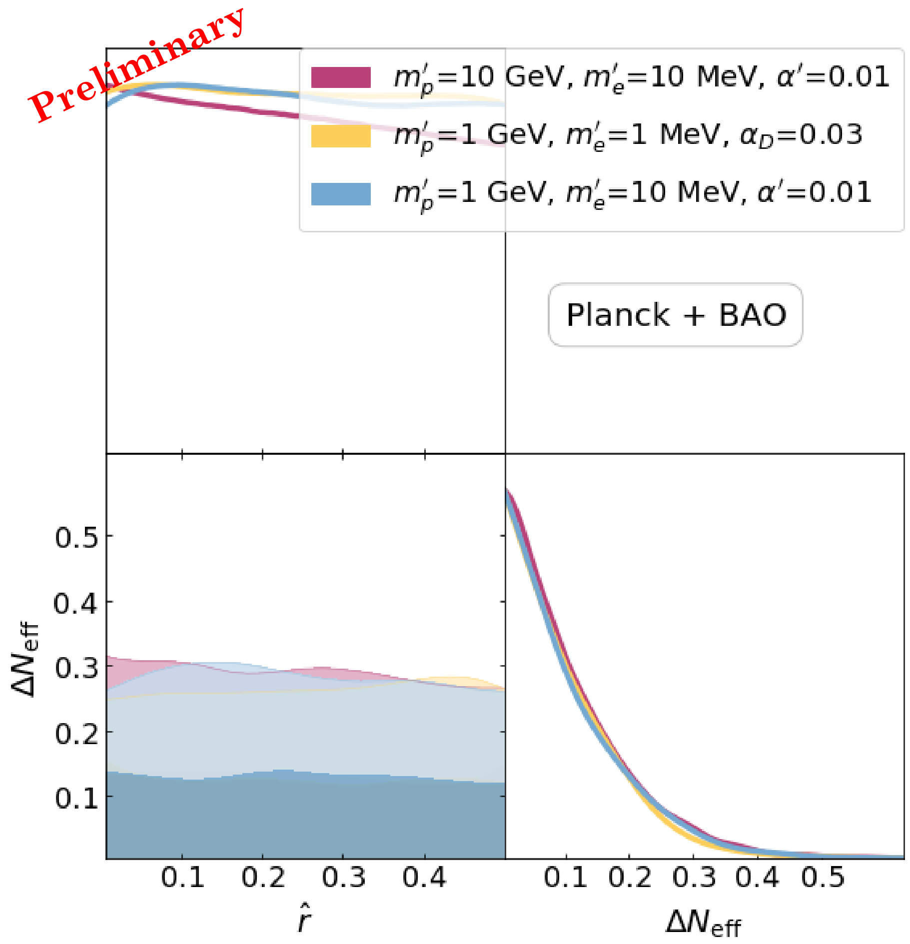
Constraining the ADM parameter space

- Using Planck 2018 high- and low-l, lensing, and BOSS DR12 BAO datasets.
  - Plan to add: KV450 measurements of LSS, SH0ES measurement of H_0.
- Scan parameter space with Markov Chain Monte Carlo (MCMC). (MontePython)
- Compute 95% C.L. constraints keeping the dark masses and coupling fixed.
- As $\hat{r} \to 0$, recover ΛCDM, so limit on ΔN_{eff} should go to ΛCDM limit.

Constraints on $\Delta N_{\rm eff}$ and $\hat{r}$





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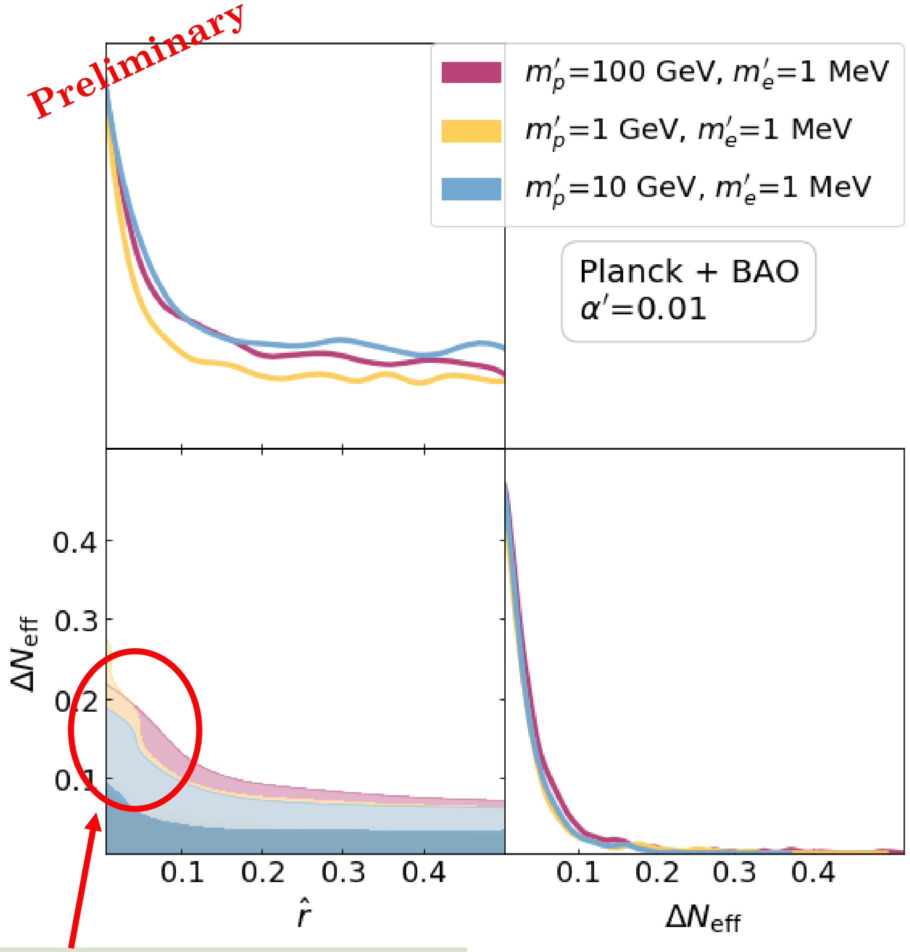
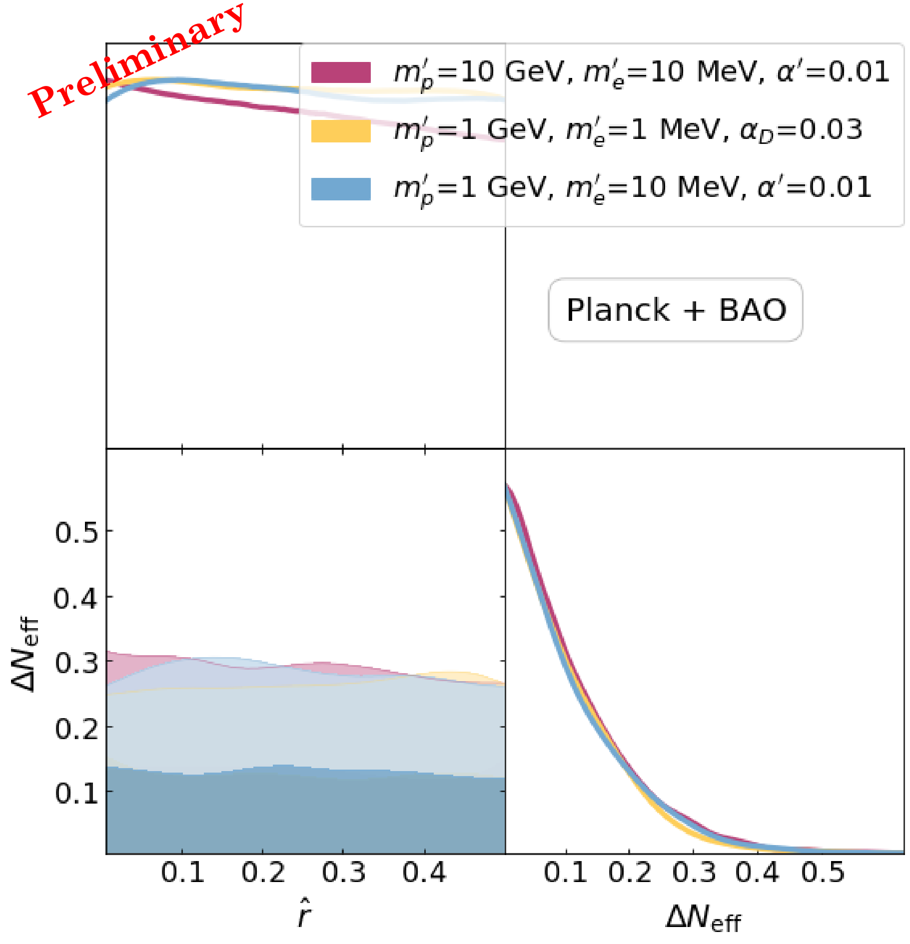
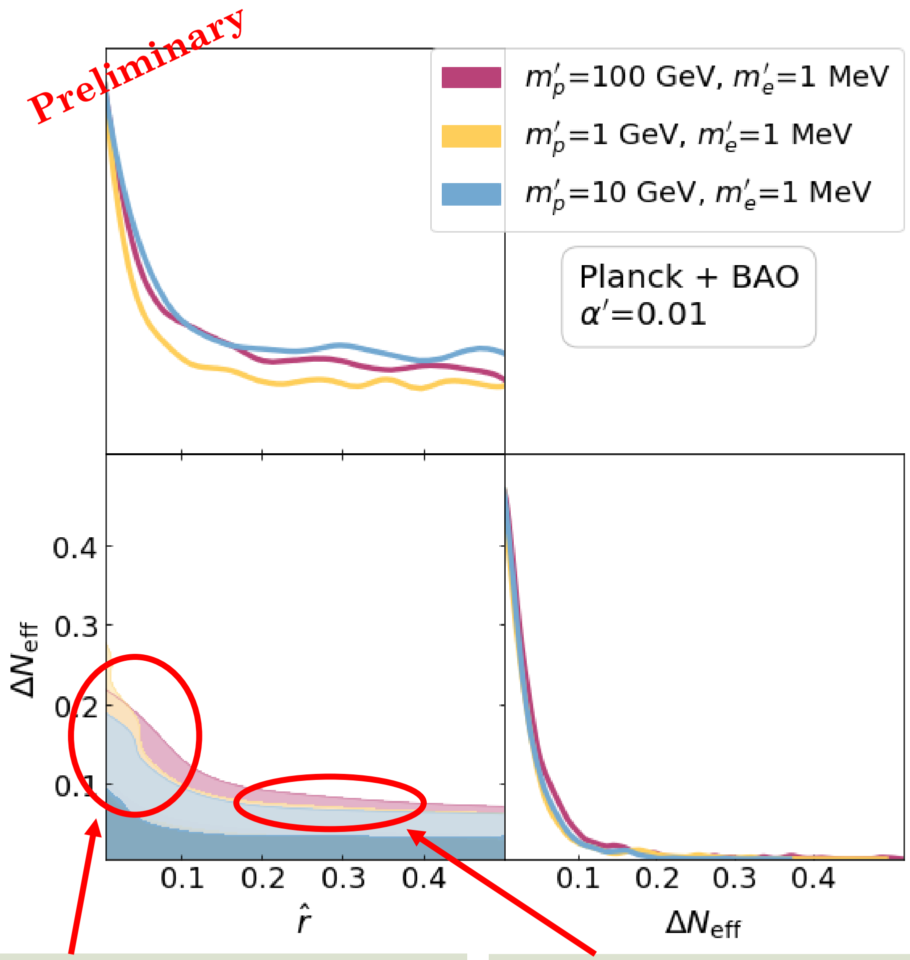




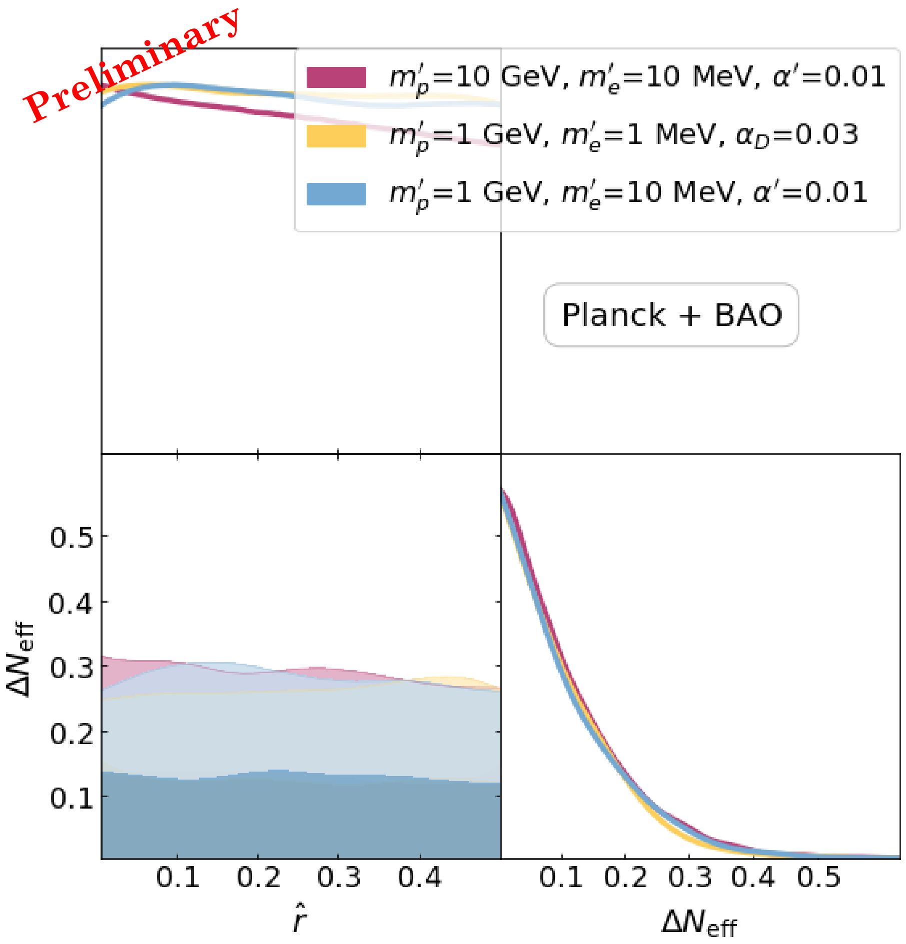
Constraint on $\Delta N_{\rm eff}$ weakens for small ADM fraction.

Constraints on $\Delta N_{\rm eff}$ and $\hat{r}$

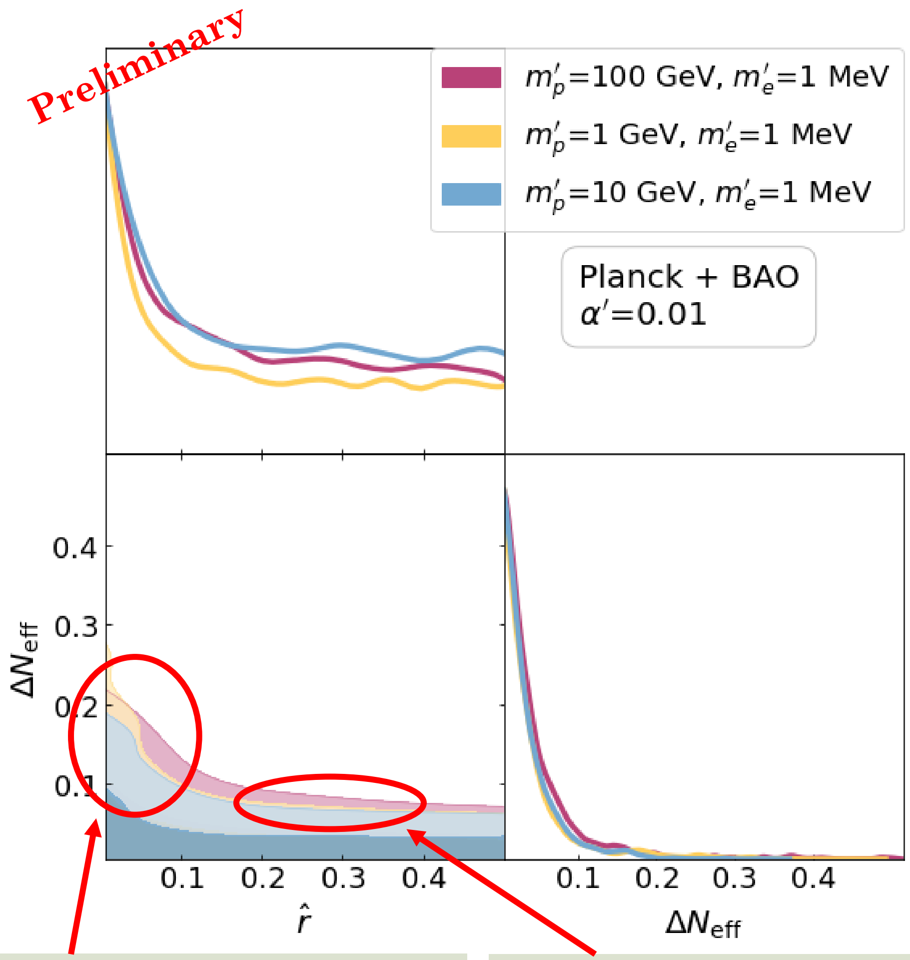


Constraint on $\Delta N_{\rm eff}$ weakens for small ADM fraction.

Constraint is mostly insensitive to m_p'.

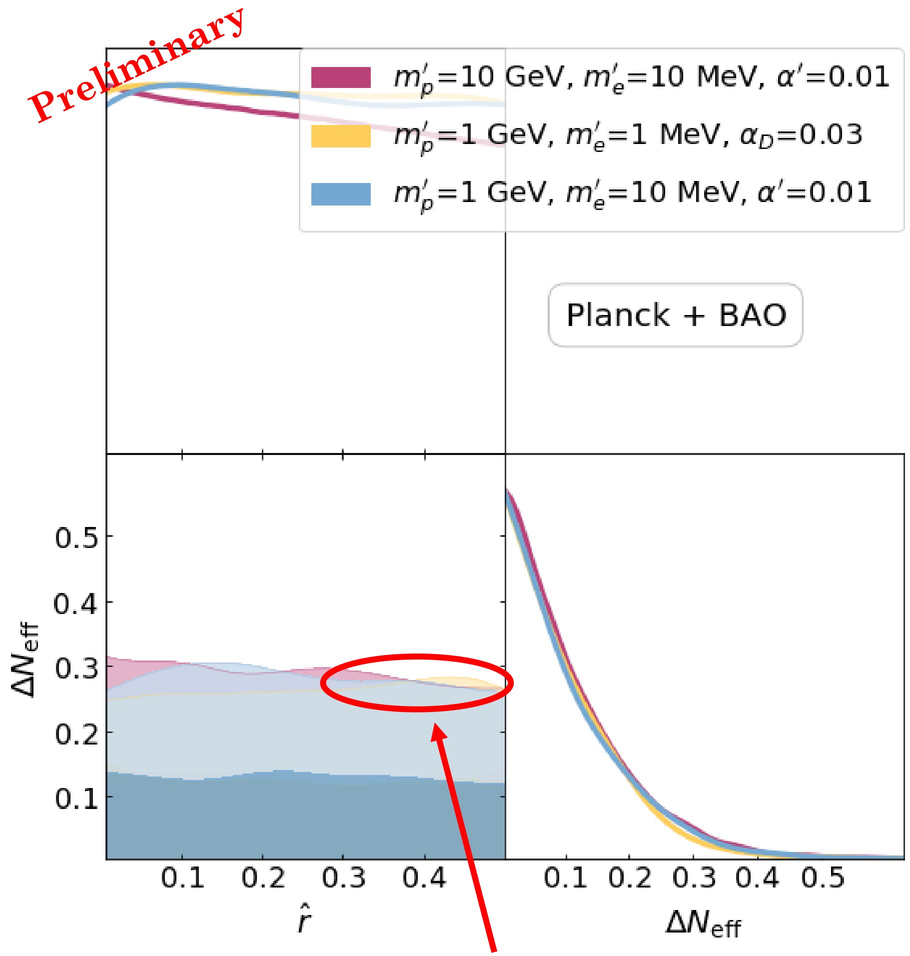


Constraints on ΔN_{eff} and $\hat{r}$



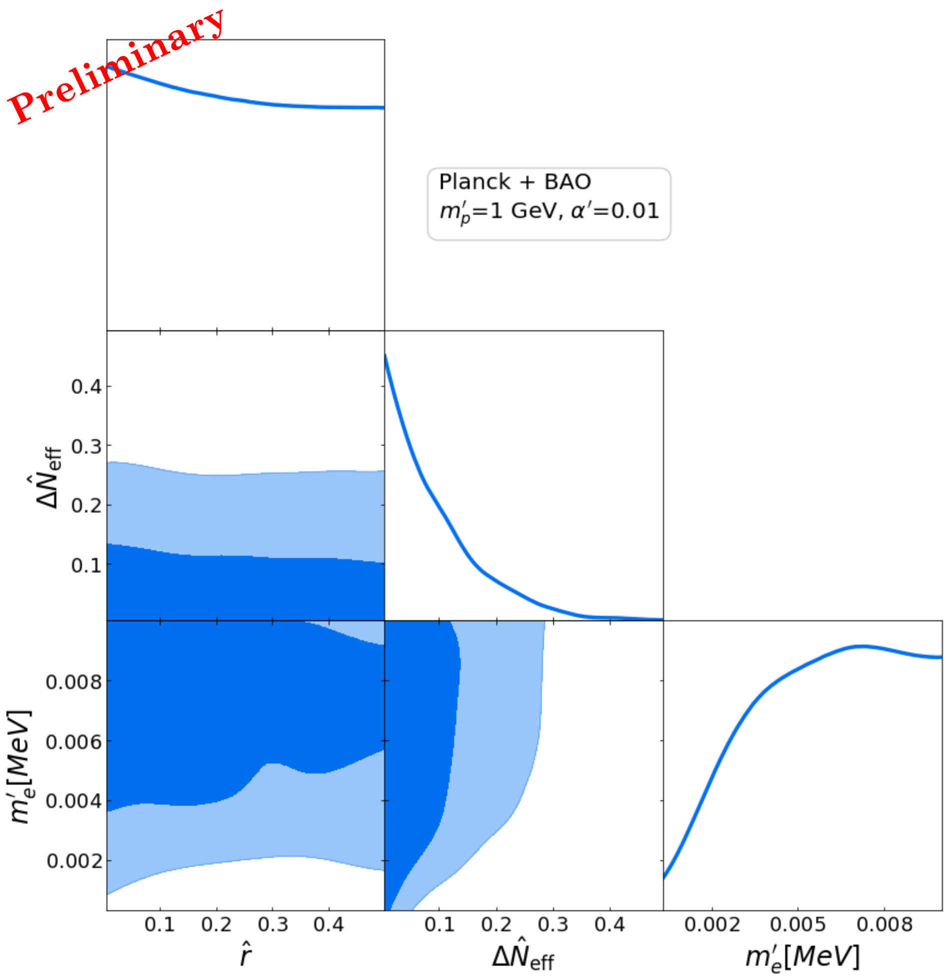
Constraint on ΔN_{eff} weakens for small ADM fraction.

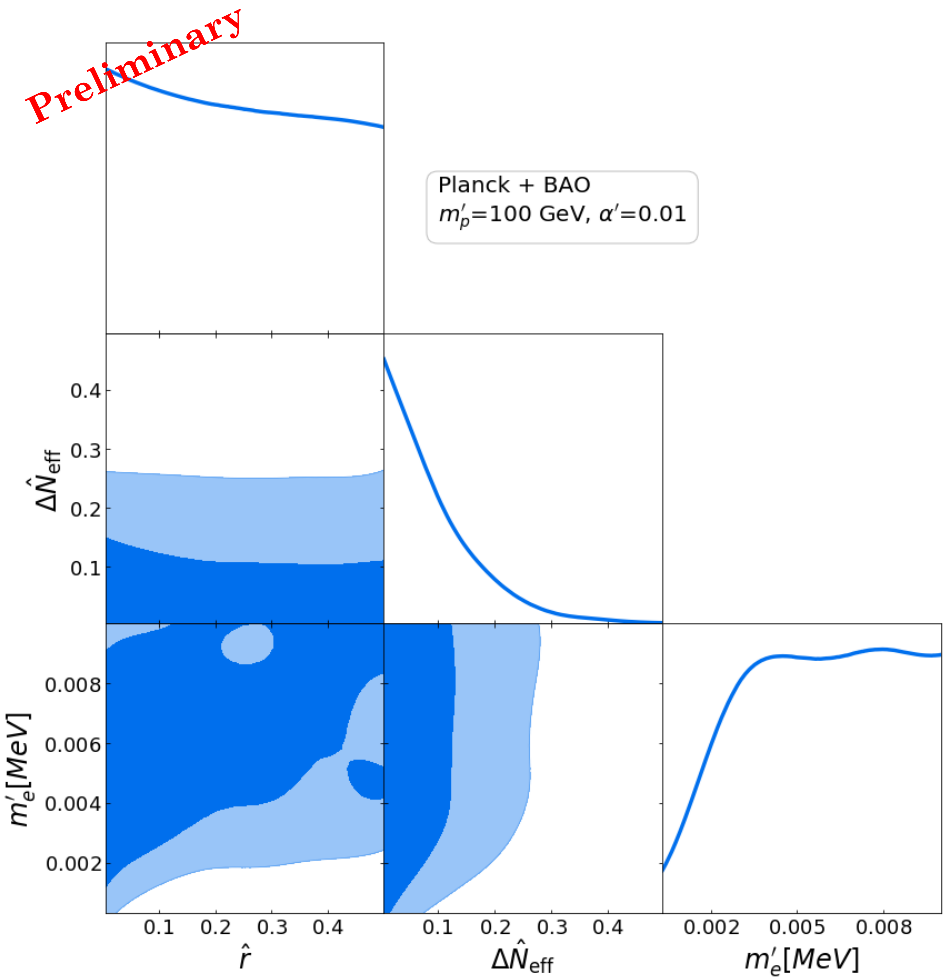
Constraint is mostly insensitive to m'_p.



For higher m'_e or α_D, large ADM fraction is allowed as long as ΔN_{eff} does not exceed ≈0.3.

Constraints on $\Delta N_{\rm eff}$, $\hat{r}$, and m_e'





- $\hat{r} > 10\%$ is ruled out at 95% confidence level for $m_e' < 2$ MeV, with m_p' from $1 - 100$ GeV and $\alpha' = 0.01$.
- For higher m_e', a large fraction of the DM could be atomic, with $\Delta N_{\rm eff}$ up to 0.3.

Conclusion

- Next steps:
  - Broaden range of parameter scans.
  - Include matter power spectrum and local Hubble constant measurements.
  - Expand ADM scenario to include dark helium.
- 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 can place new constraints on the atomic dark matter parameter space from precision observations.

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Thank you for your attention!

References

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