Interacting Dark Sectors in Cosmology

New Physics from Galaxy Clustering, GGI

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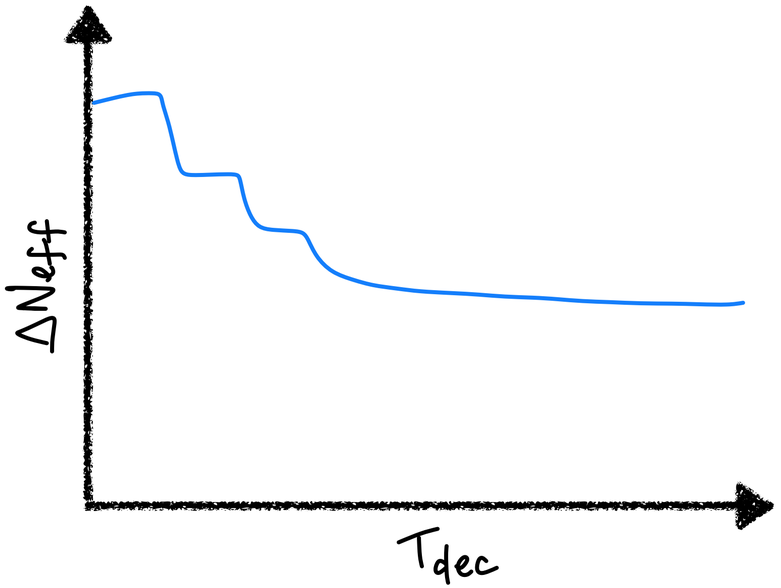
Motivations for Interacting DM-DR

- What new physics might we expect?
  - $N_{\rm eff}$ - generic feature of new dofs at high energy
  - DM interactions - for freeze-out models of DM production, we might expect DM-DR interactions as a result

  - Tensions in data
  - Hubble
  - LSS - S_8, Lyα

Light Relics (N_{eff})



Minimal Extensions

ΔNeff ~ 0.027 Scalar

0.047 Fermion

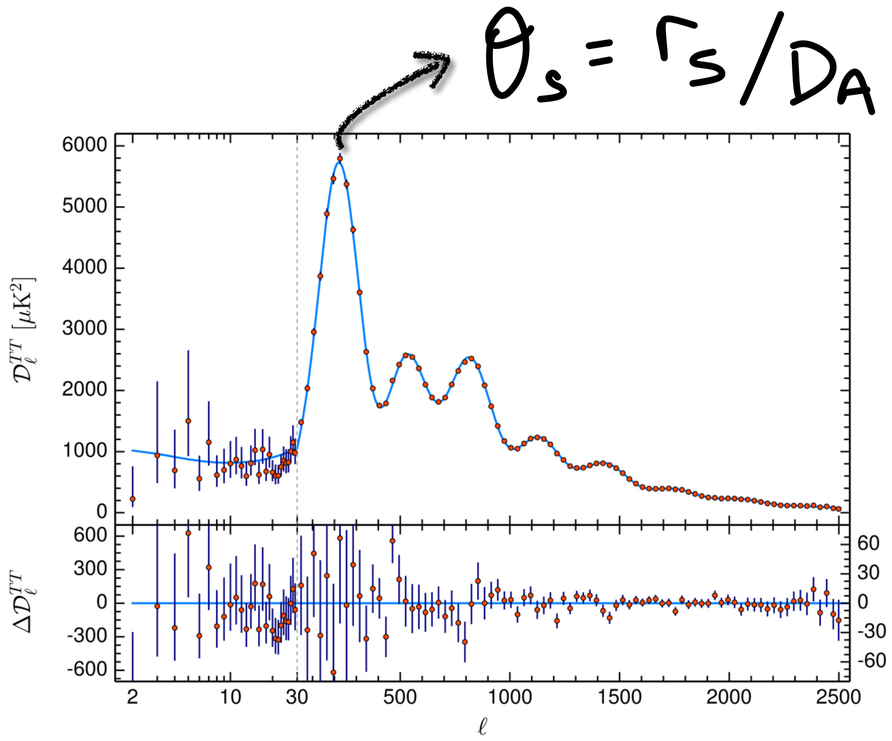
0.057 Gauge Boson

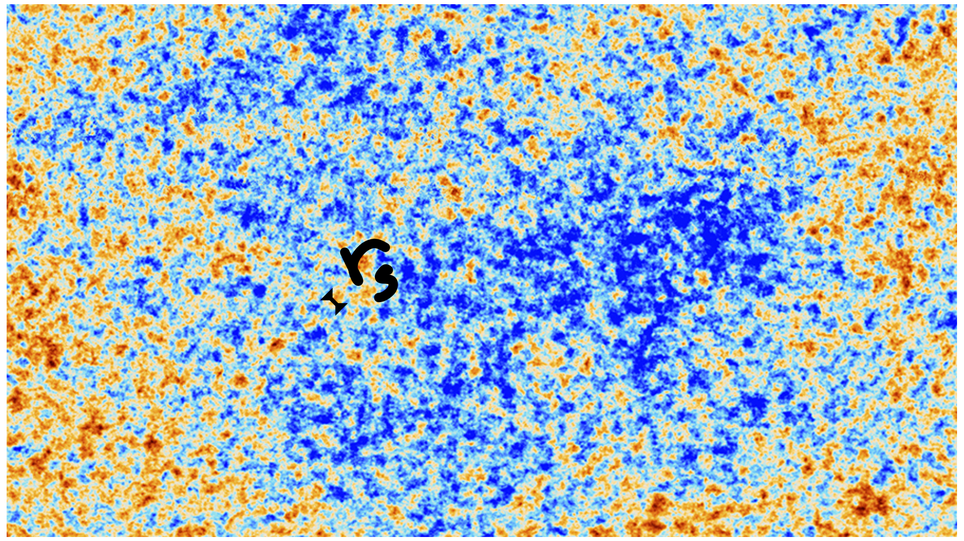
Forecasts for future sensitivity:

Simons SO: 0.05

Already seeing constraints from ACT DR6

Hubble Tension

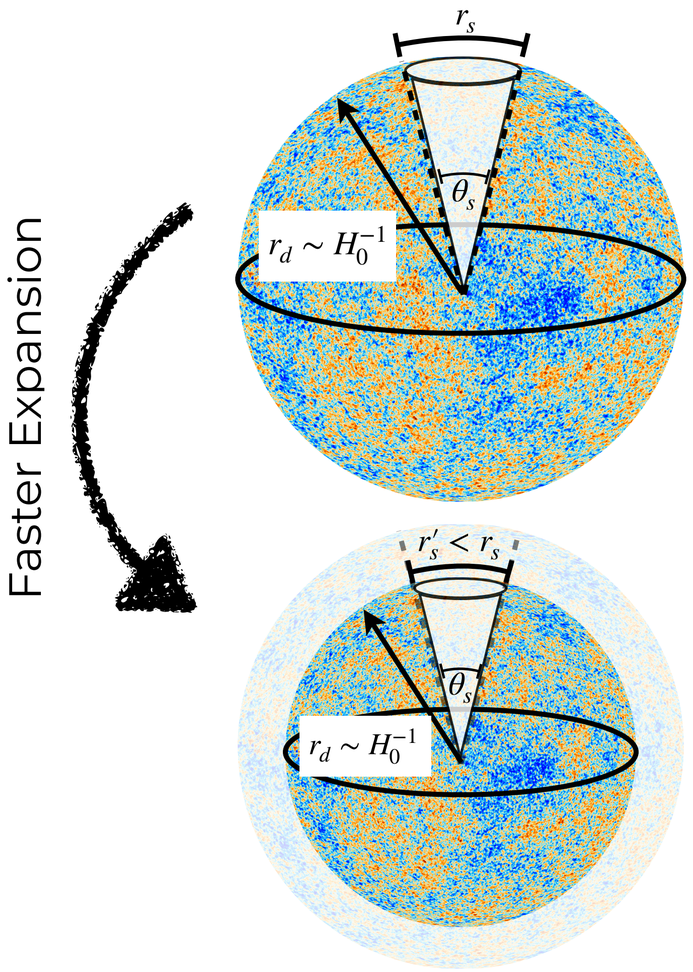




Hubble Tension

$$r_s = \int_{z_{rec}}^{\infty} dz \frac{c_s}{H(z)} \qquad D_{\mathrm{CMB}} \propto 1/H_0$$

θ_s fixed $\Rightarrow$ $r_s \downarrow$ & $H_0 \uparrow$



Credit: H. Bagherian

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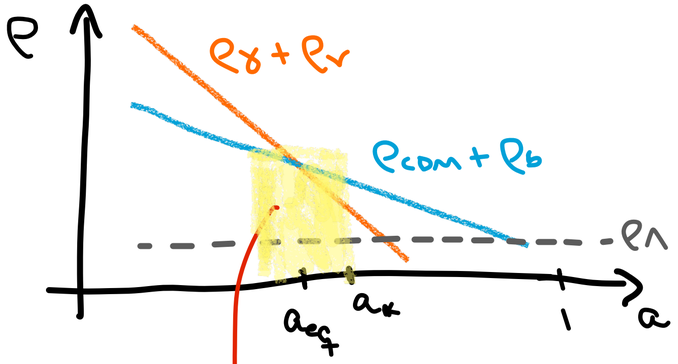
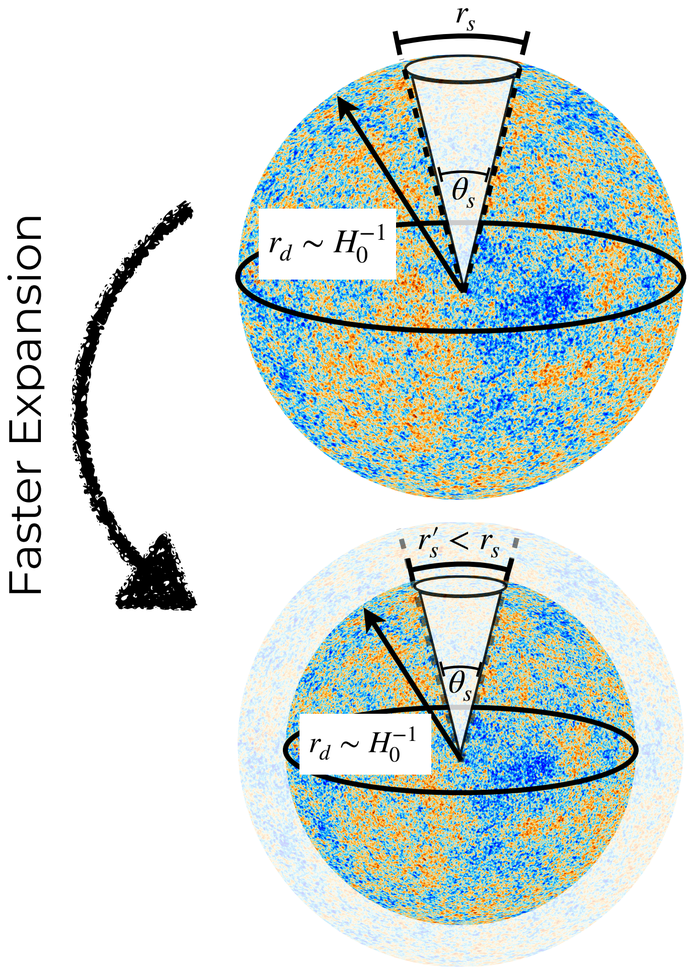


add extra energy near recombination

(ρ_{new} ~ few % of ρ_{rad})



Credit: H. Bagherian

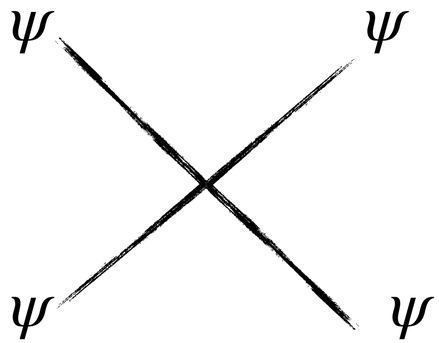
Outline

- Interacting DM-DR models
  - Interacting DM-DR with mass threshold
  - New Atomic Dark Matter (nuADaM)
- Cosmological Signatures
- Constraints from ACT DR6 on $N_{\rm eff}$
- Updated Constraints from ACT (Preliminary)

Interacting Radiation w/ a massive mediator

$$\mathscr{L}_{DS} \propto \lambda\phi\psi^2 + \lambda^2(\phi^*\phi)^2$$
$$+m_\phi^2\phi^*\phi + \lambda_{DM}\phi\chi^2$$

$$m_\phi \sim \text{eV}$$



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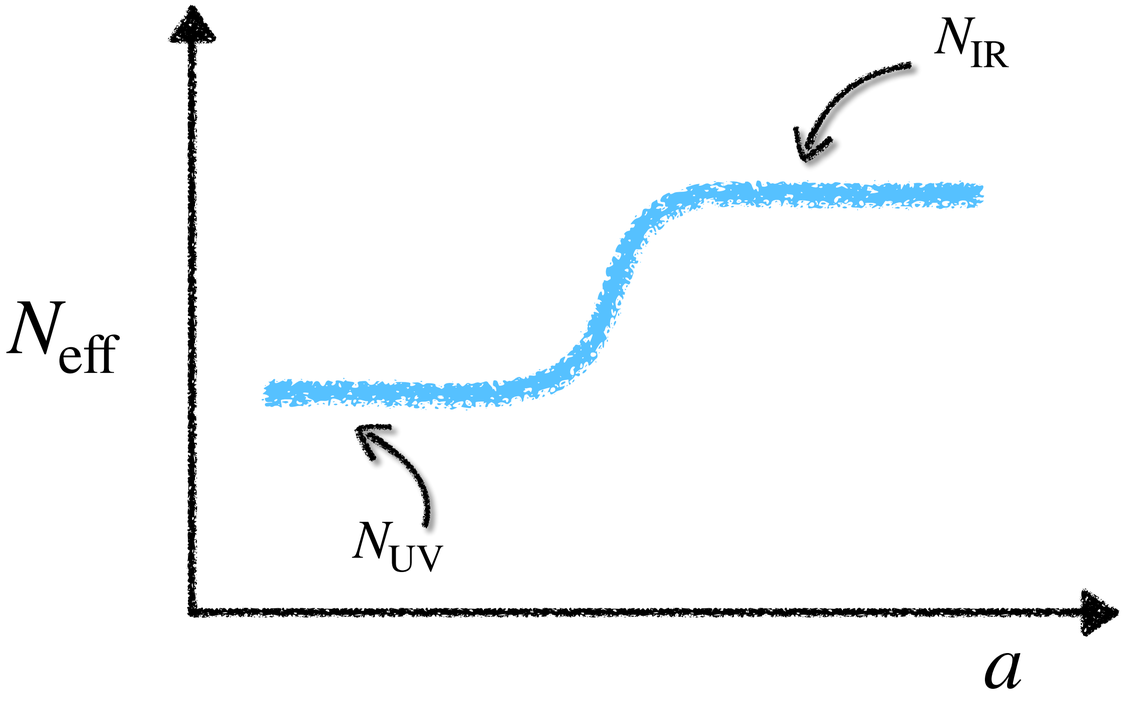

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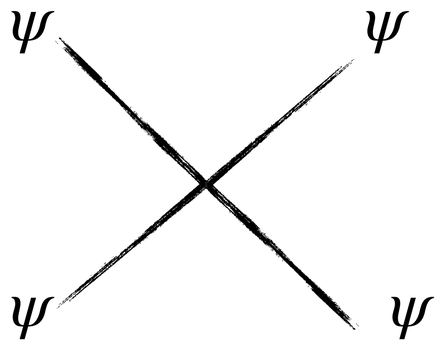
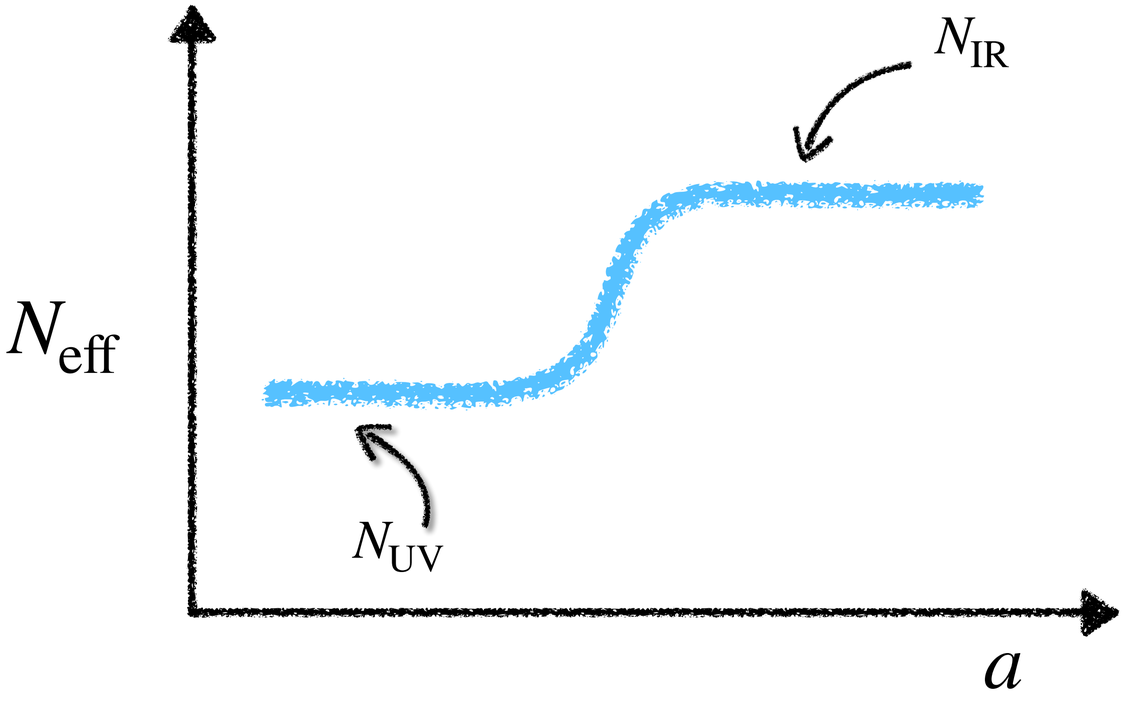


Interacting Radiation w/ a massive mediator

C



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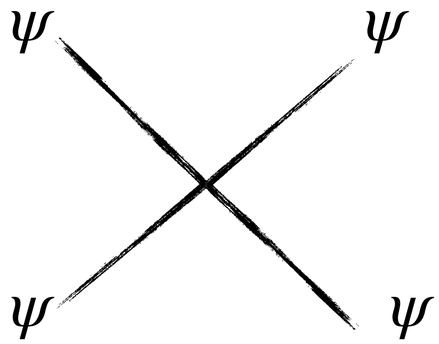
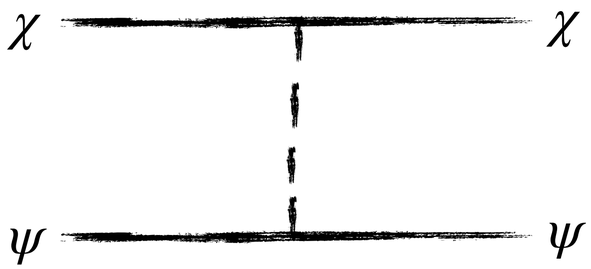
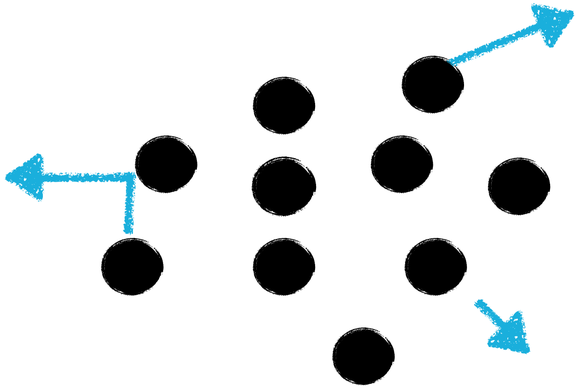
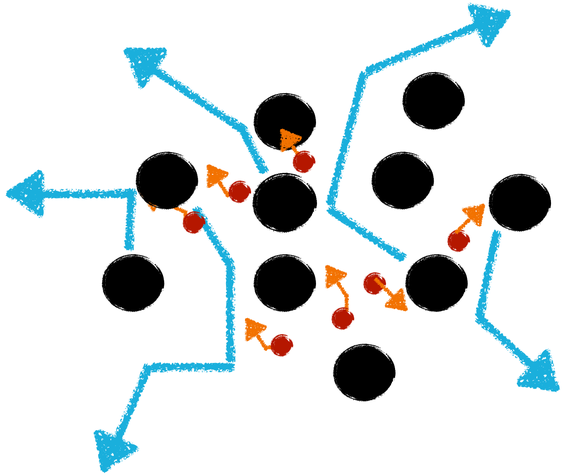


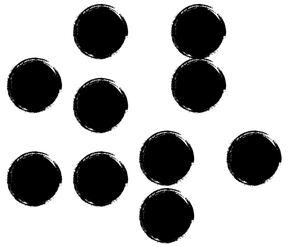


DM-DR Interactions w/ a massive mediator



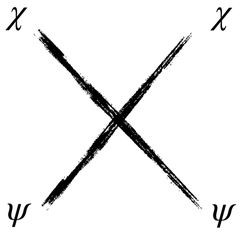


vs

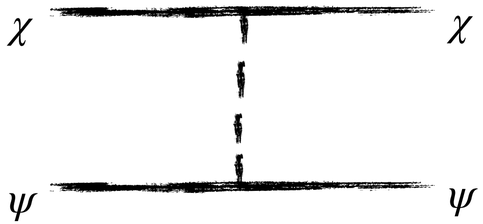


Standard CDM

$$\Gamma \propto \frac{T_d^2}{M_\chi}\left(\frac{T_d}{m_\phi}\right)^4$$



$$T \sim m_\phi$$



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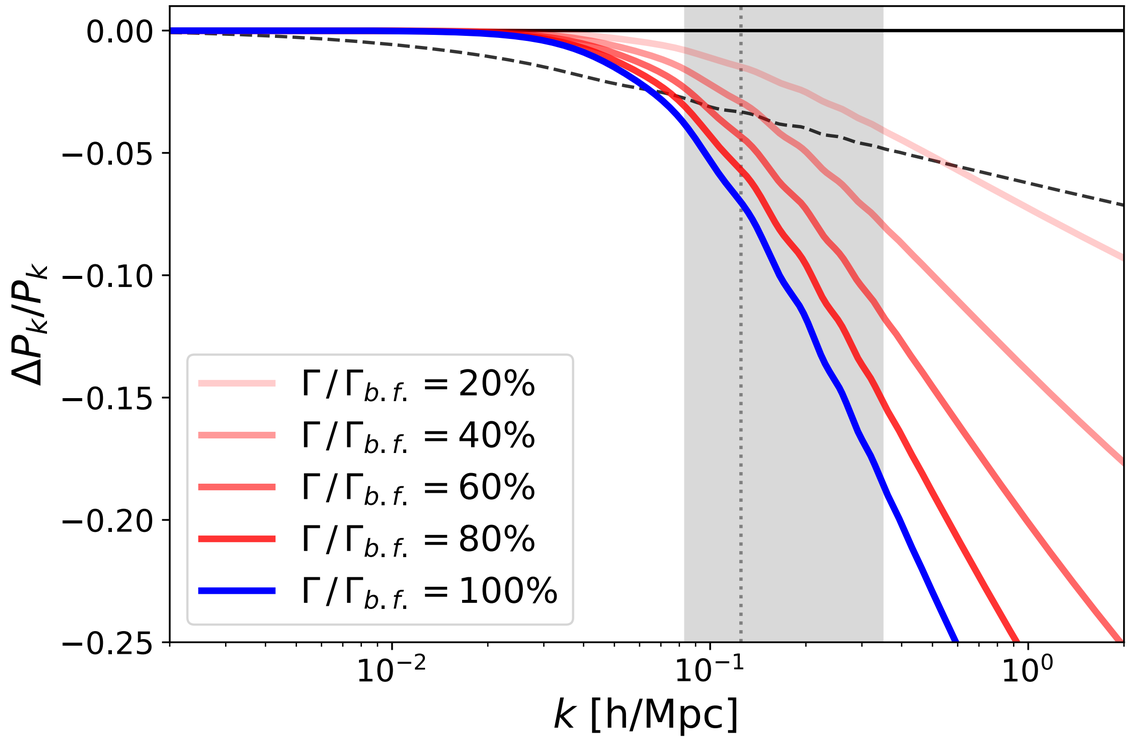
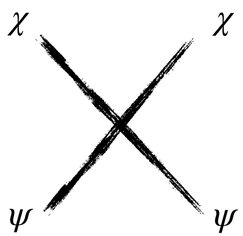


$$\frac{P_{\text{interacting}}}{P_{\text{not-interacting}}} \simeq \begin{cases} 1 & k \ll k_{s.o.} \\ 1 - \sqrt{2}\,\frac{\Gamma}{H} \times \log k/k_{s.o.} & k \gg k_{s.o.} \end{cases}$$

Smooth suppression in log k due to weak coupling



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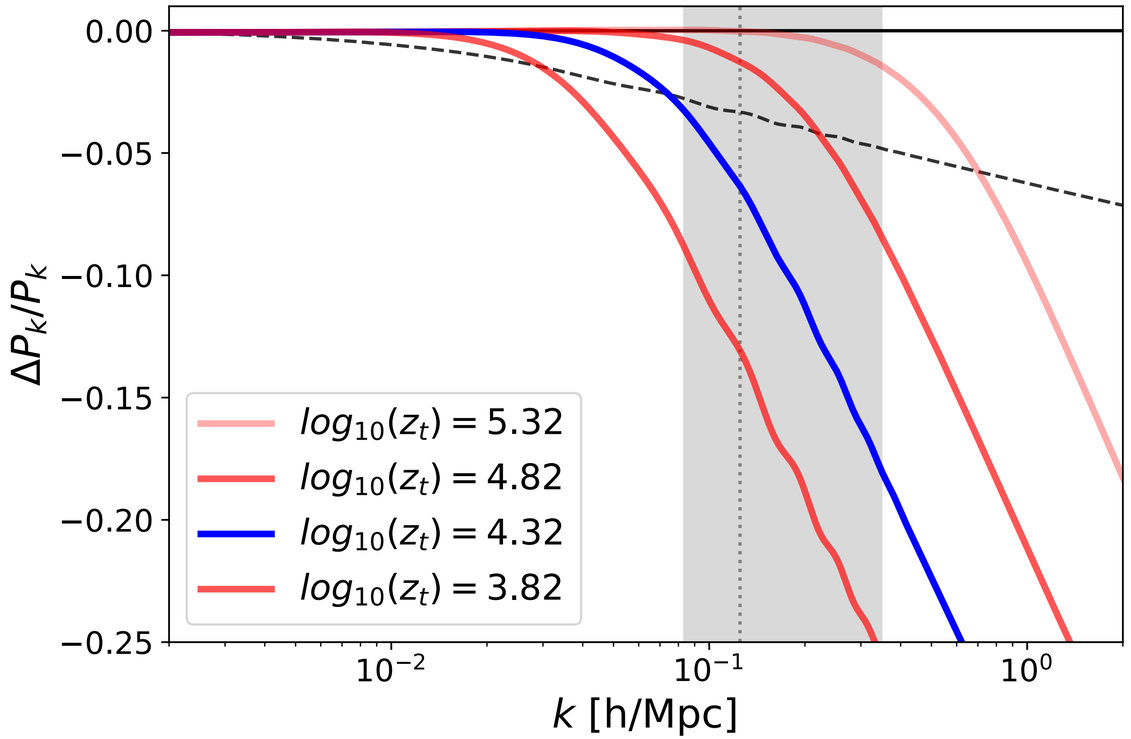

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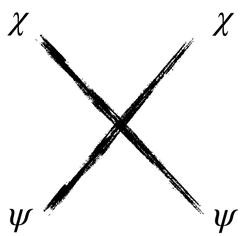
Shut-off when T ~ m



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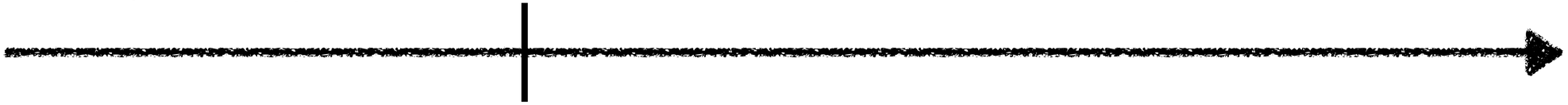
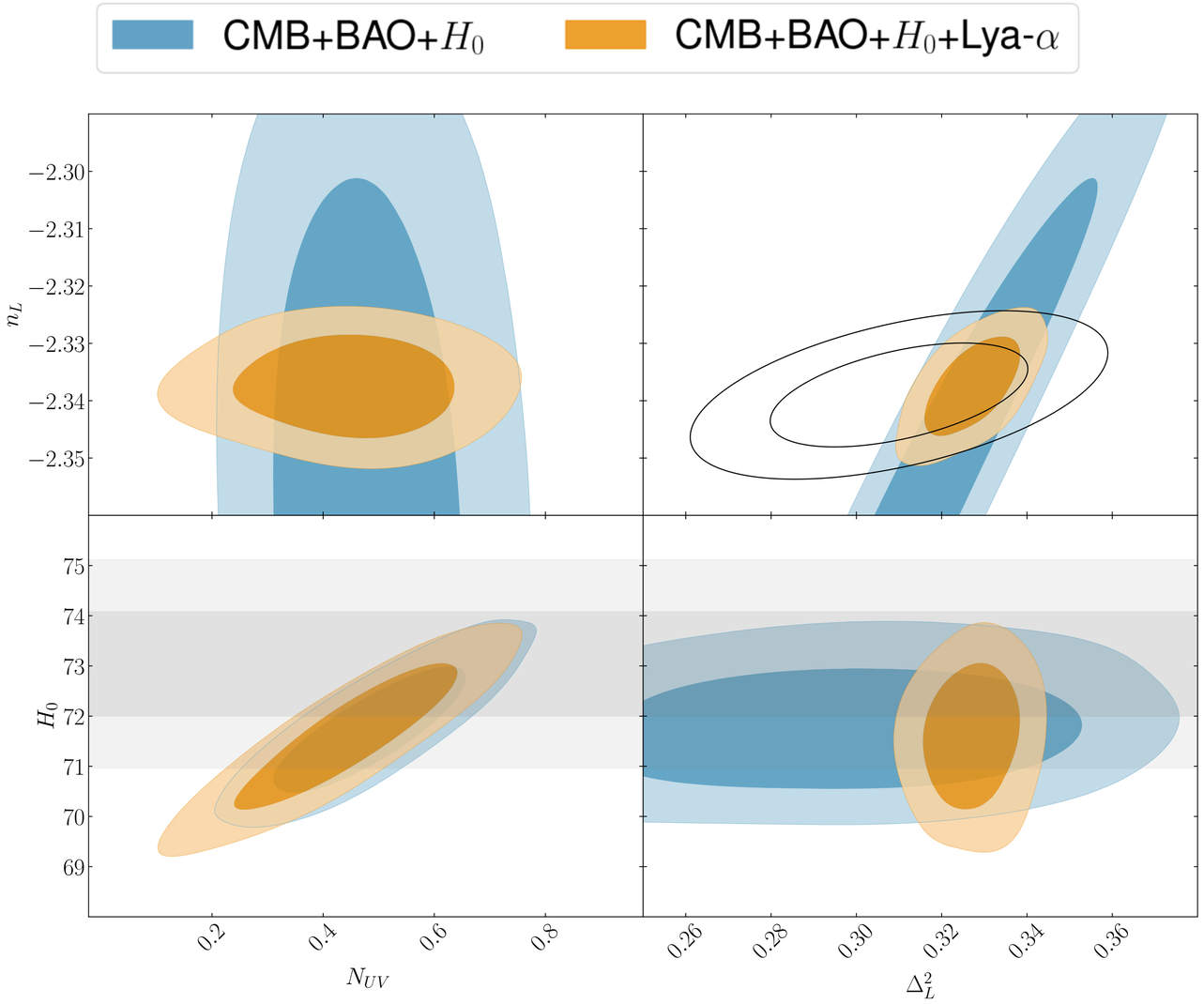


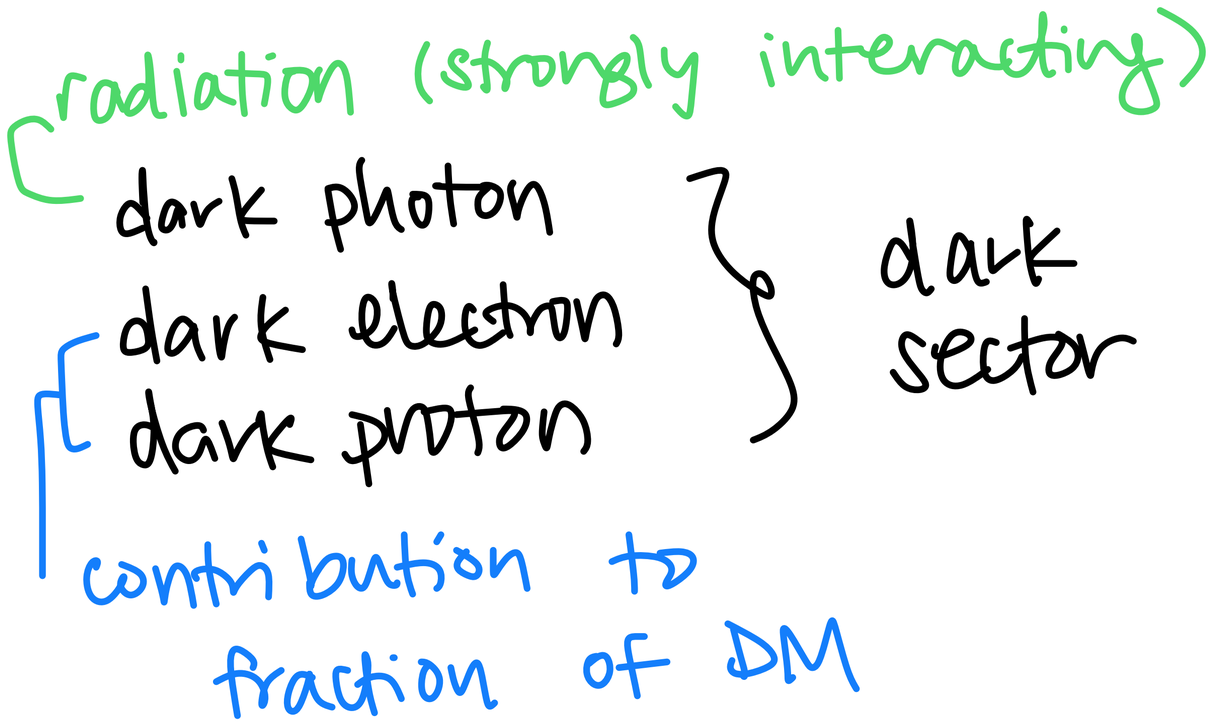


Compressed likelihood on amplitude $\left(k^3\frac{\mathrm{P}(k)}{2\pi^2}\right)$ and slope $\left(\frac{\mathrm{dlnP(k)}}{d\mathrm{ln}k}\right)$ of MPS at z = 3

$k = 0.009$ s/km

New Atomic Dark Matter (NuADM)

Buen-Abad et al, arXiV: 2411.08097



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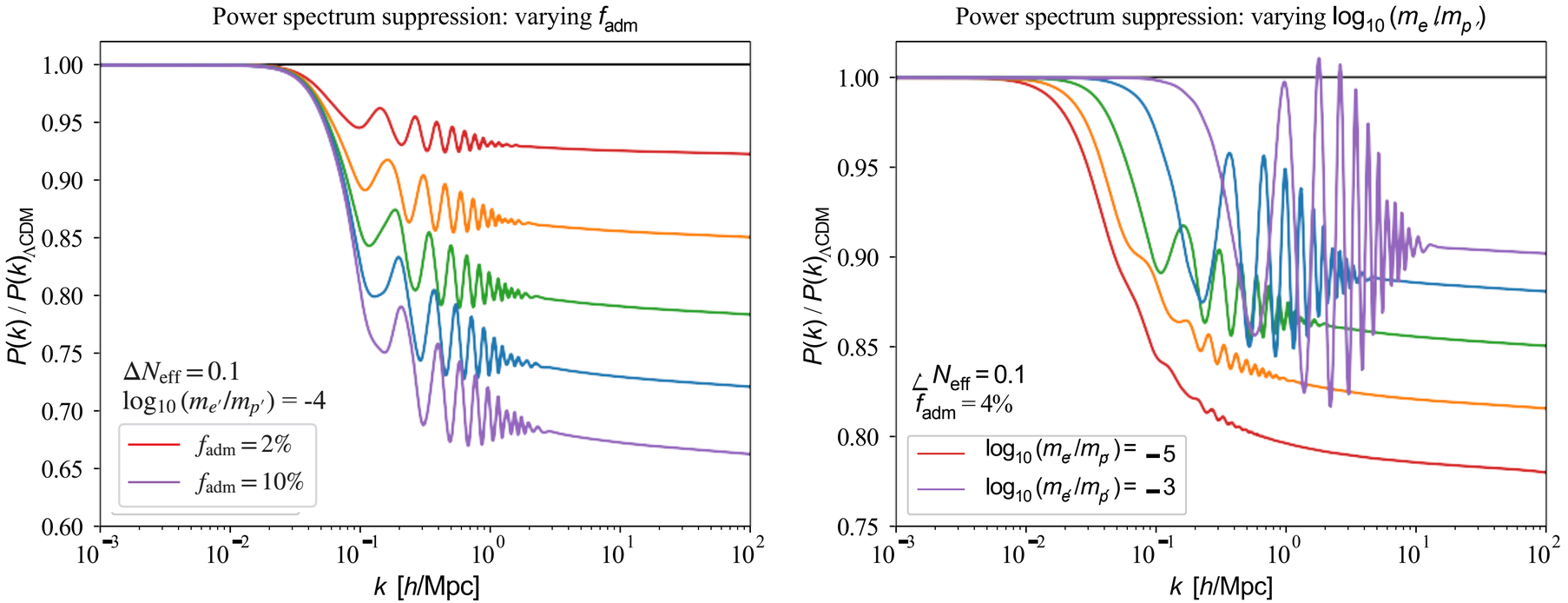

- Suppression of matter power spectrum at the scale of dark recombination
- Dark acoustic oscillations near decoupling redshift
- Fraction of interacting dark matter determines the amount of suppression

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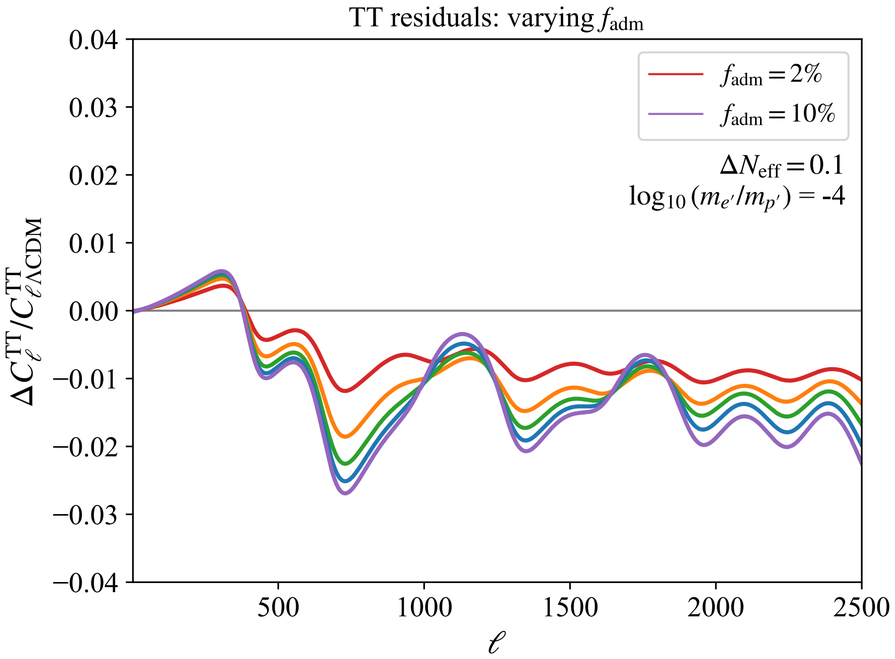
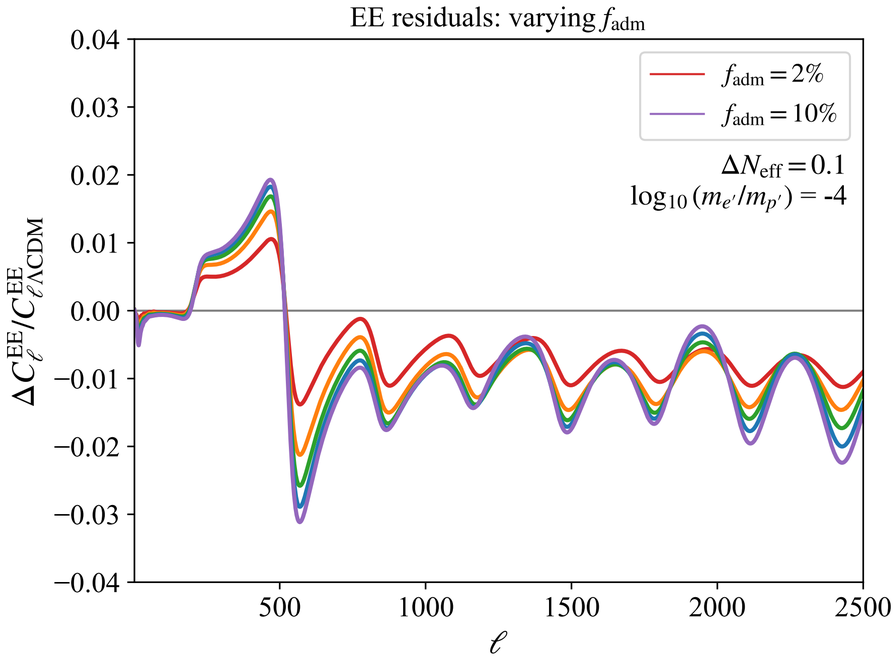
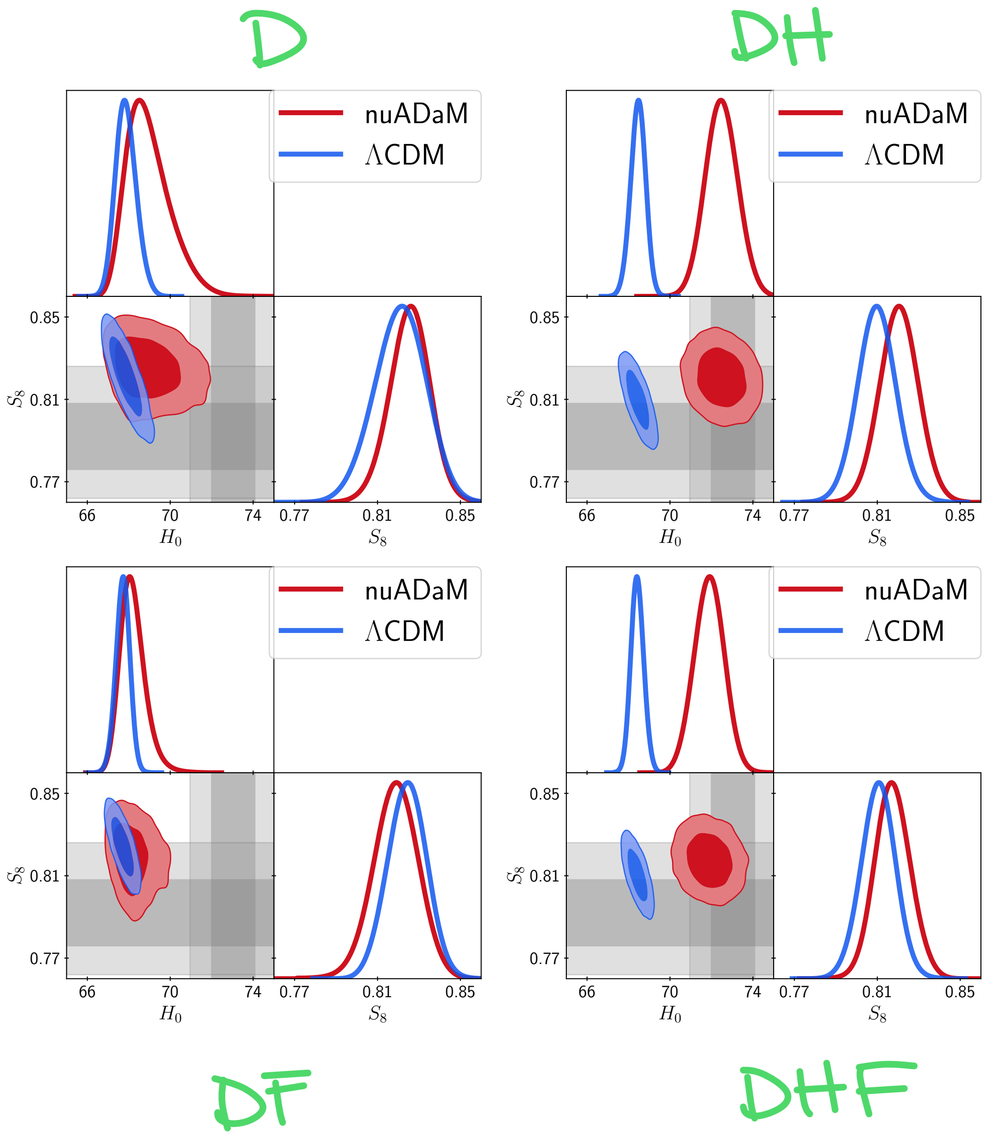




- Constant suppression of high-l tail given by fraction of interacting dark matter
- Different l-dependence to the damping of the tail

New Atomic Dark Matter (NuADM)

Buen-Abad et al, arXiV: 2411.08097



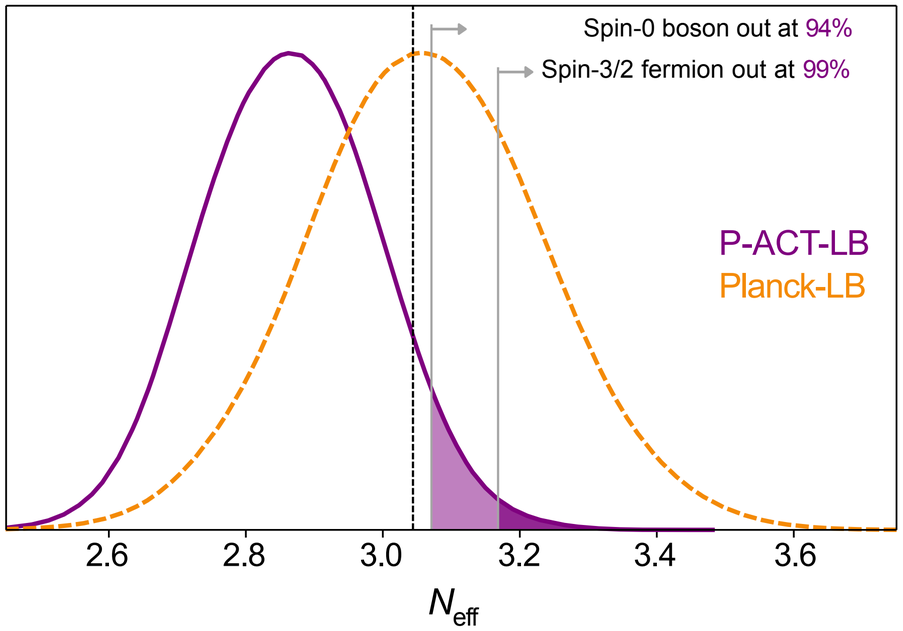
Cosmological Signatures

- CMB
  - Silk damping
  - Phase shift
- LSS
  - DM interactions - suppression of structure formation at small scales
  - DAO

> dynamics in DR can alter these effects

ACT DR6 Constraints

Free-streaming



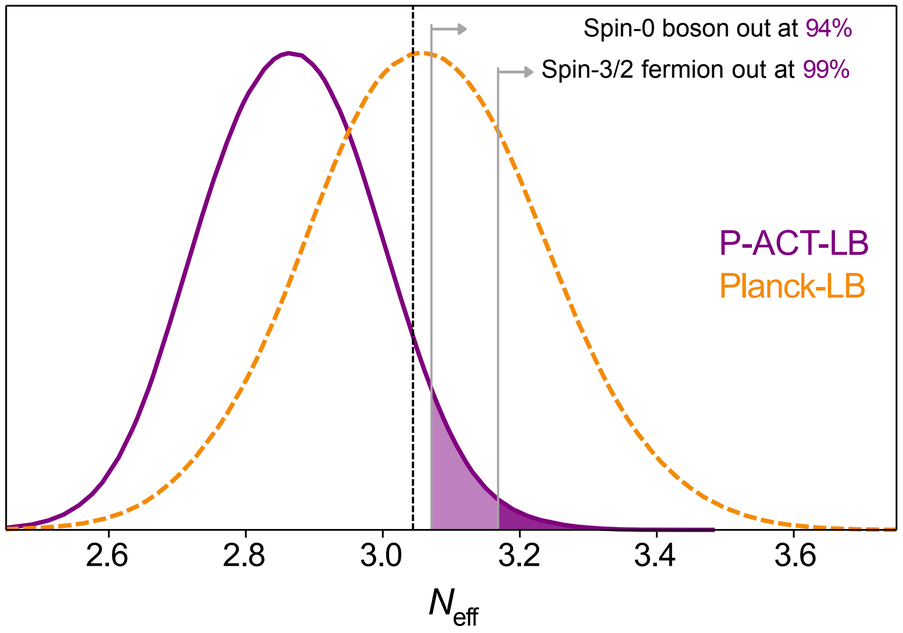
$$N_{\rm eff} = 2.73 \pm 0.14 \quad (68\%, \text{P-ACT}),$$
$$= 2.86 \pm 0.13 \quad (68\%, \text{P-ACT-LB}),$$

L - CMB lensing

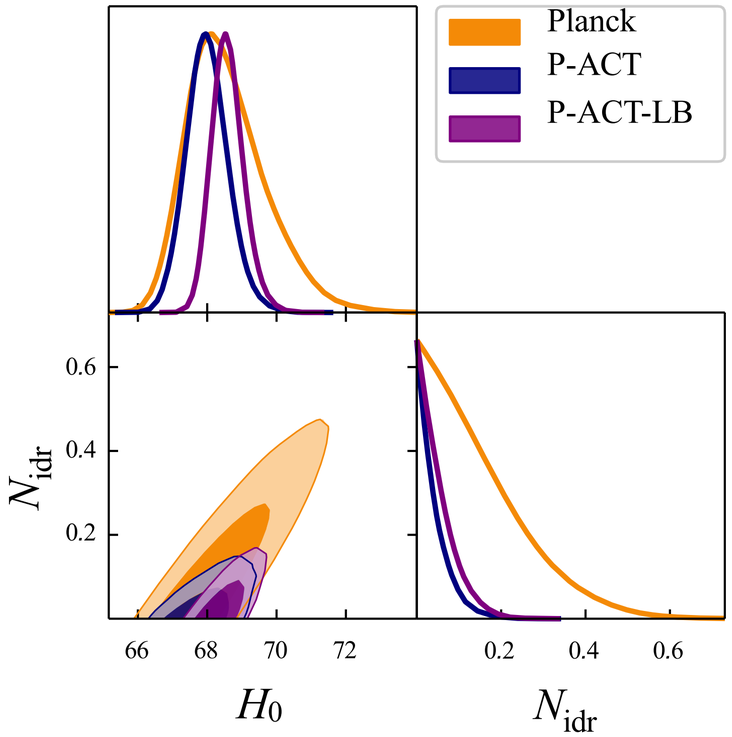
B - DESI DR1 BAO

ACT DR6 Constraints

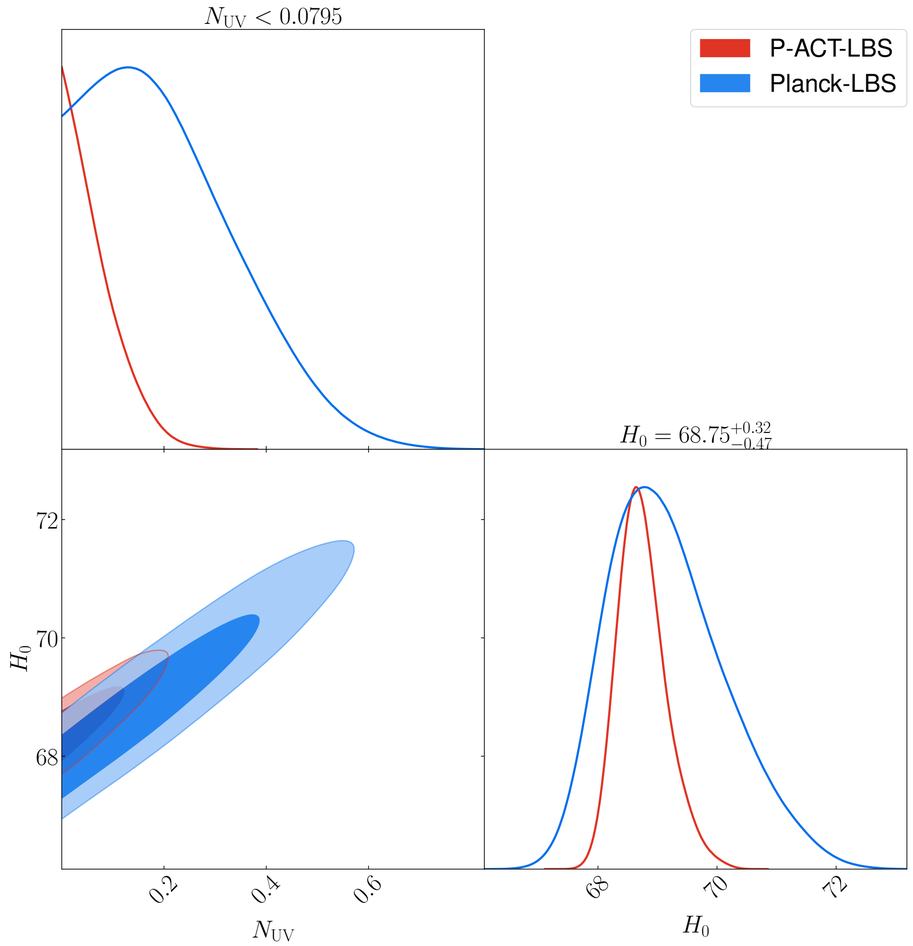
Free-streaming



Self-interacting

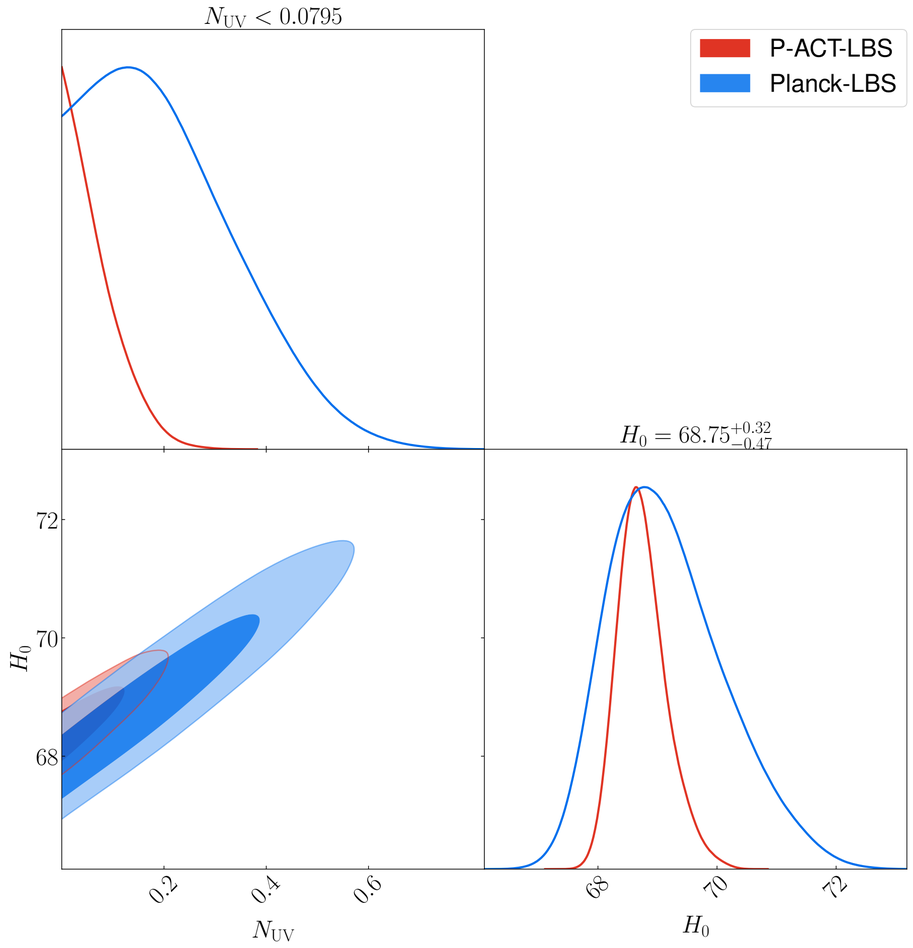


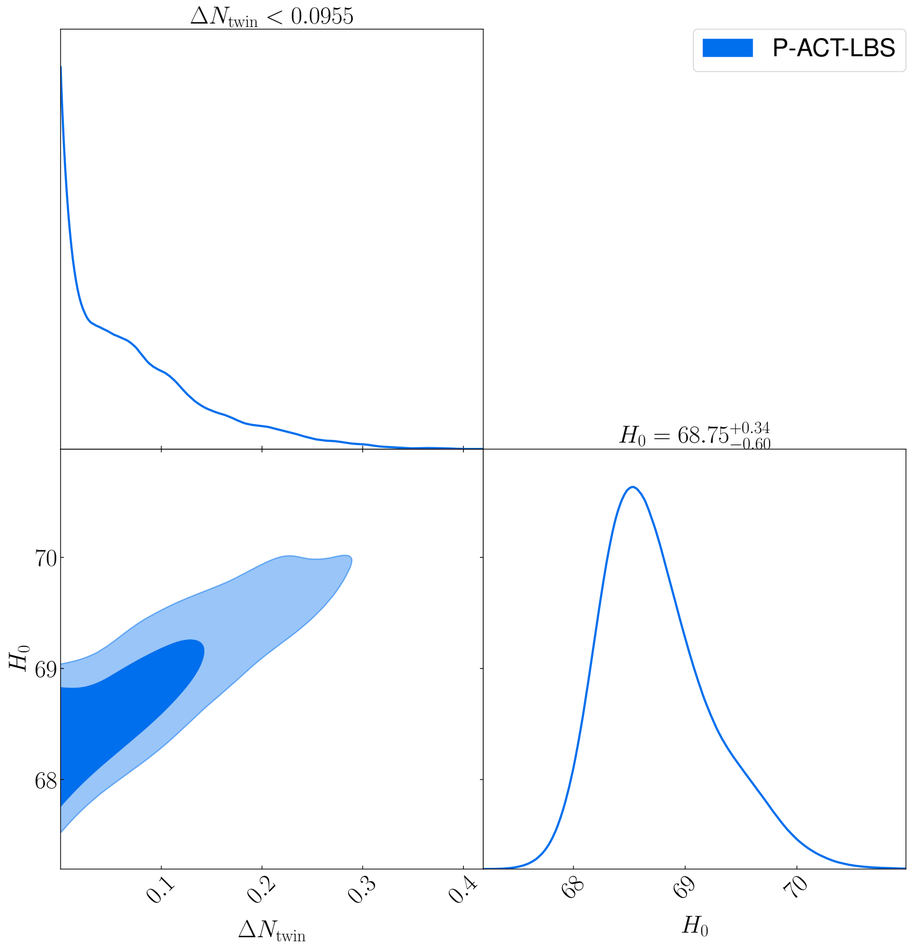
New Fits to ACT DR6 (Premlinary)



- ACT DR6 seems to disfavor most extra radiation models
- Likely due to Silk damping
  - DR6 shows enhanced power at small scales relative to ΛCDM in TT and EE
- CMB lensing takes over at smaller scales - modifications may be neccessary for modified DM models

New Fits to ACT DR6 (Premlinary)





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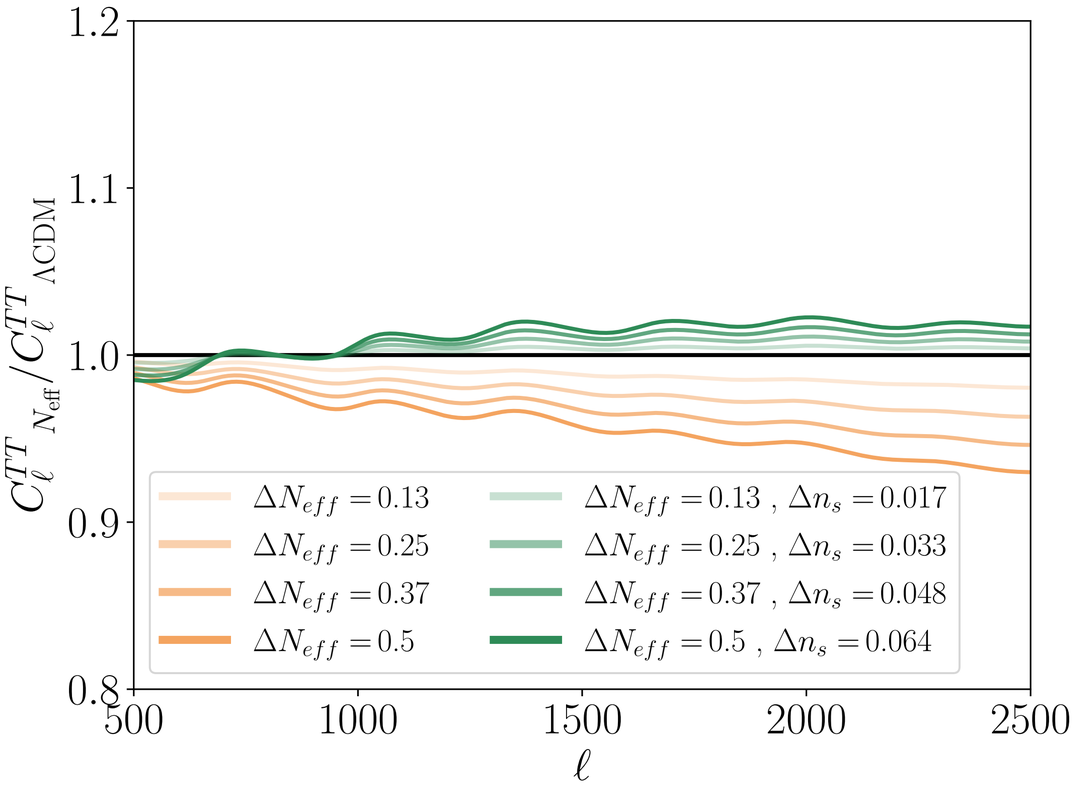


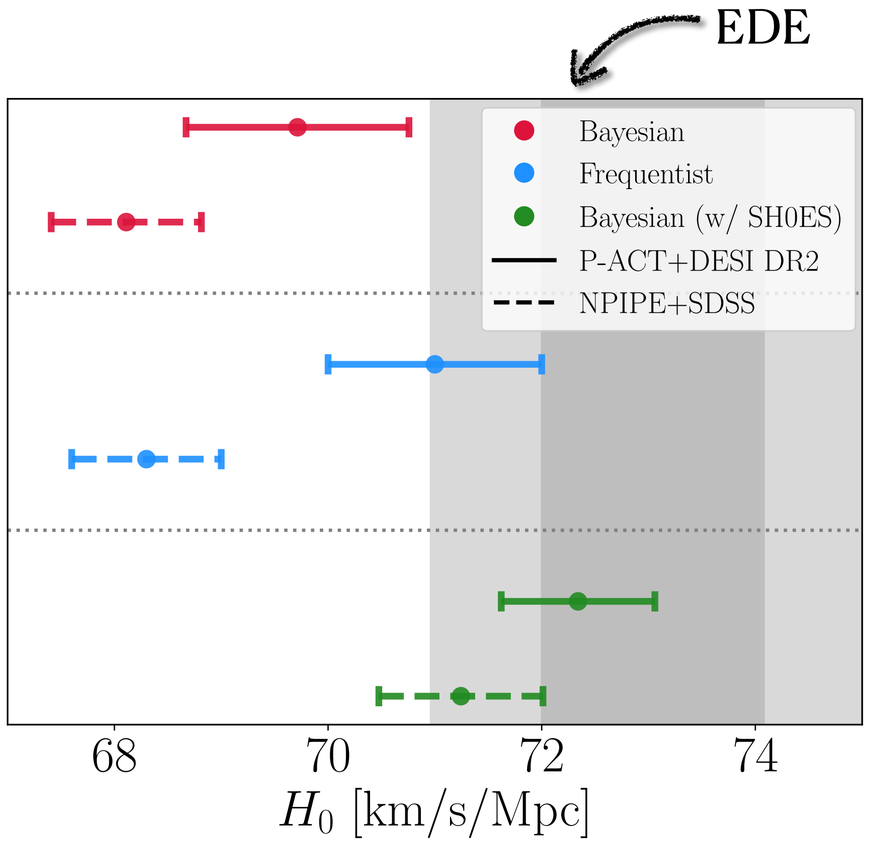
damping scale:

$$r_d^2 \approx \pi^2 \int_a^{a_*} \frac{da}{a^2} \frac{\lambda_{mfp}}{aH(a)}$$

$$\theta_d = \frac{r_d}{D_A} \propto \frac{r_d}{r_s} \propto \sqrt{H}$$

↑ n_s to compensate

Bayesian vs Frequentist Analysis



Poulin, Smith, Calderon, Simon: 2505.08051

- Models that are extensions of LCDM have issues with Bayesian analysis due to volume effects of priors
- 1D profile likelihoods can characterize results of Frequentist analysis
- Can be significant differences especially for non-Gaussian posteriors

Summary

- Extra radiation models disfavored by ACT DR6 data
  - Preliminary results show that this is also consistent for radiation models with dynamics

- DM-DR interactions with minimal energy density in radiation still have observable effects
  - Small fraction of DM interacting strongly - DAO
  - Weakly interacting DM-DR gives power-law suppression of MPS