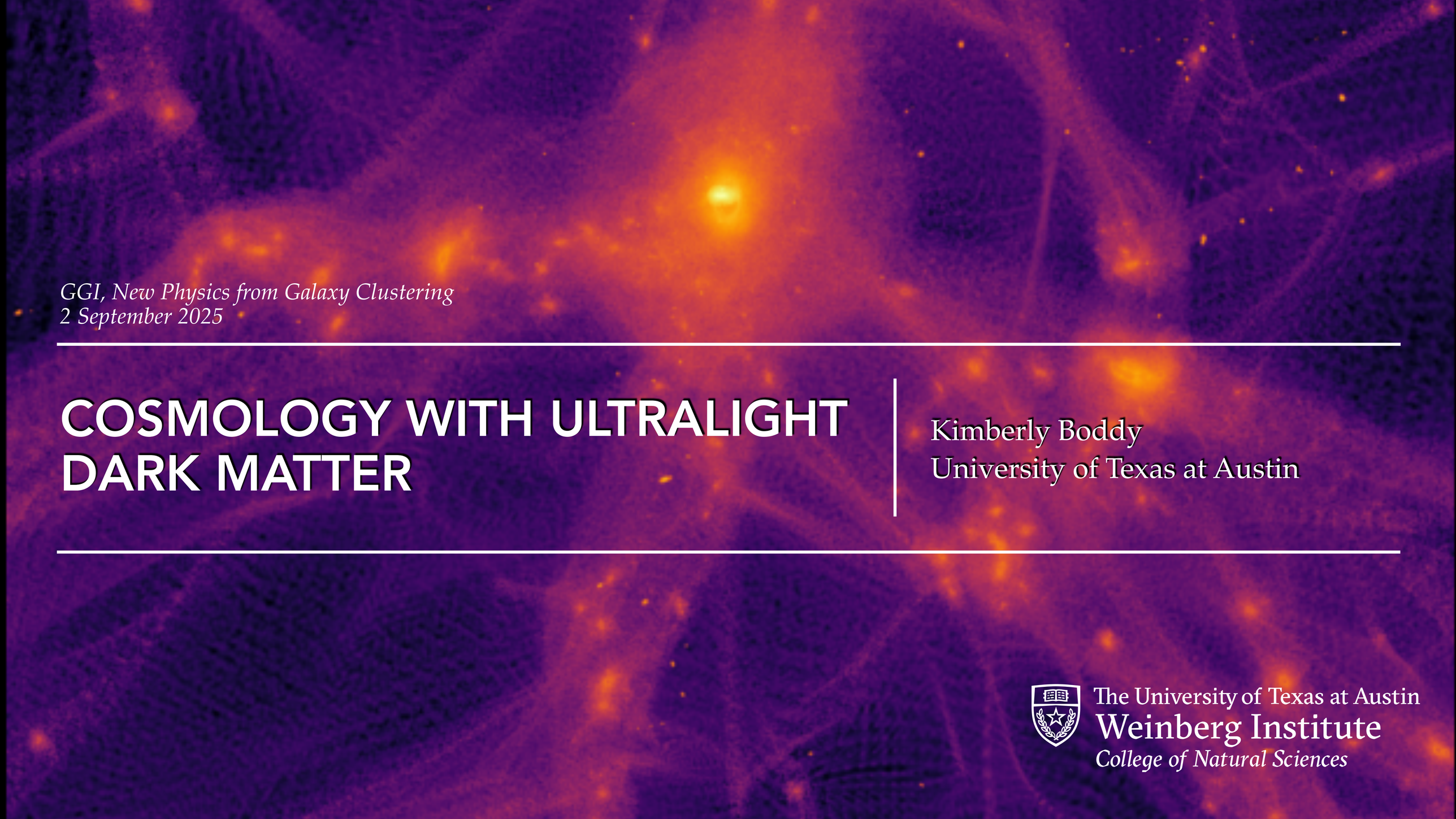


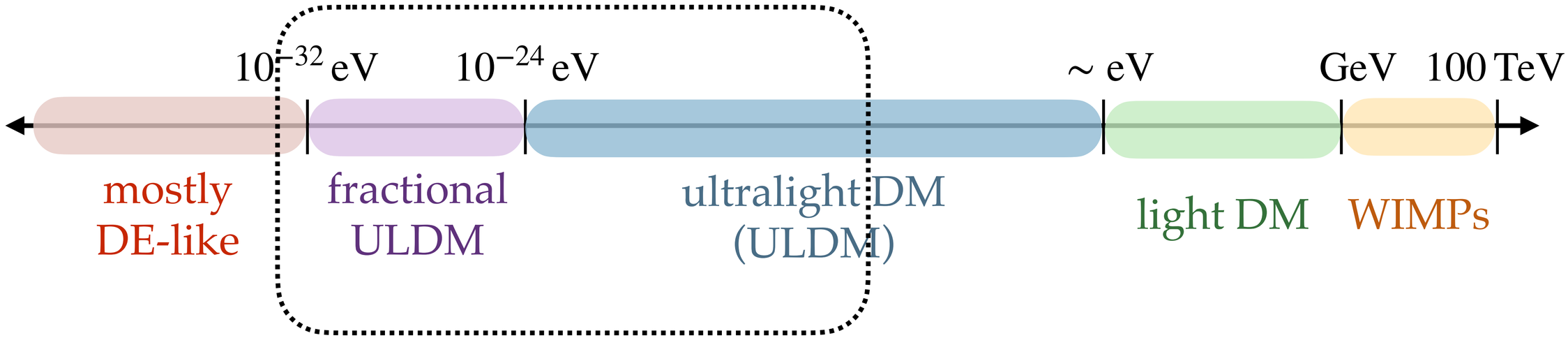
GGI, New Physics from Galaxy Clustering
2 September 2025

COSMOLOGY WITH ULTRALIGHT DARK MATTER

Kimberly Boddy
University of Texas at Austin

The University of Texas at Austin
Weinberg Institute
College of Natural Sciences

Dark Matter Mass Range



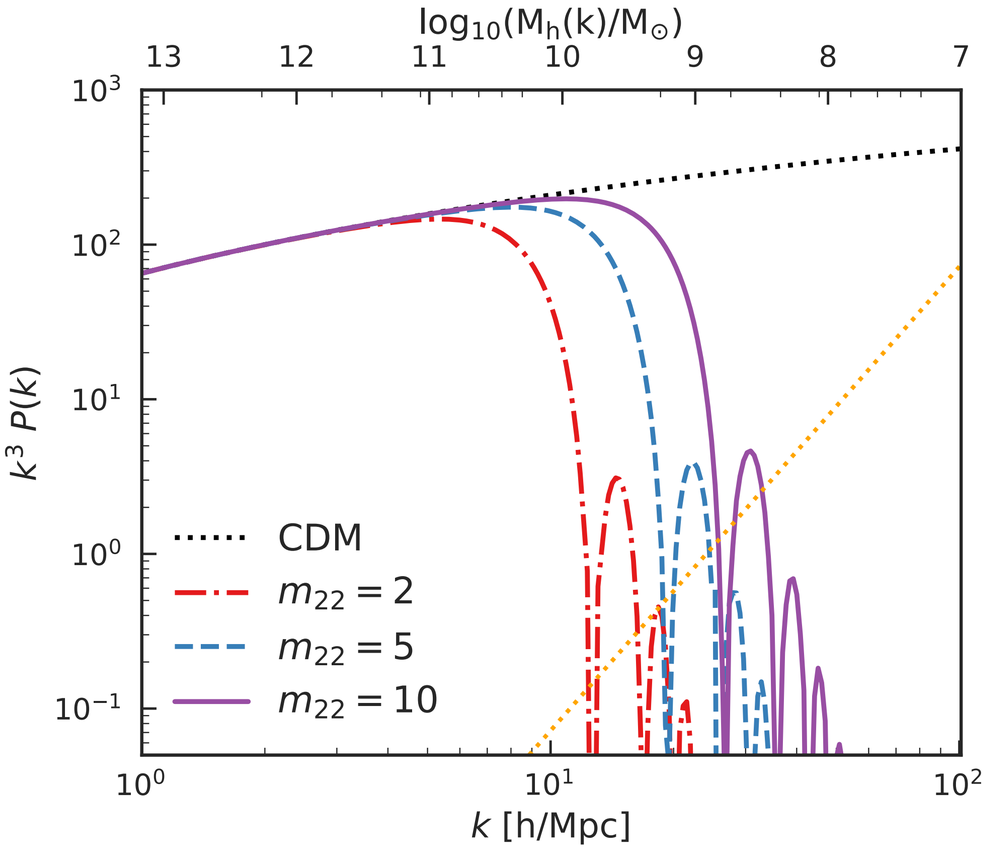
wave-like dark matter regime:
high occupation number
classical oscillating wave

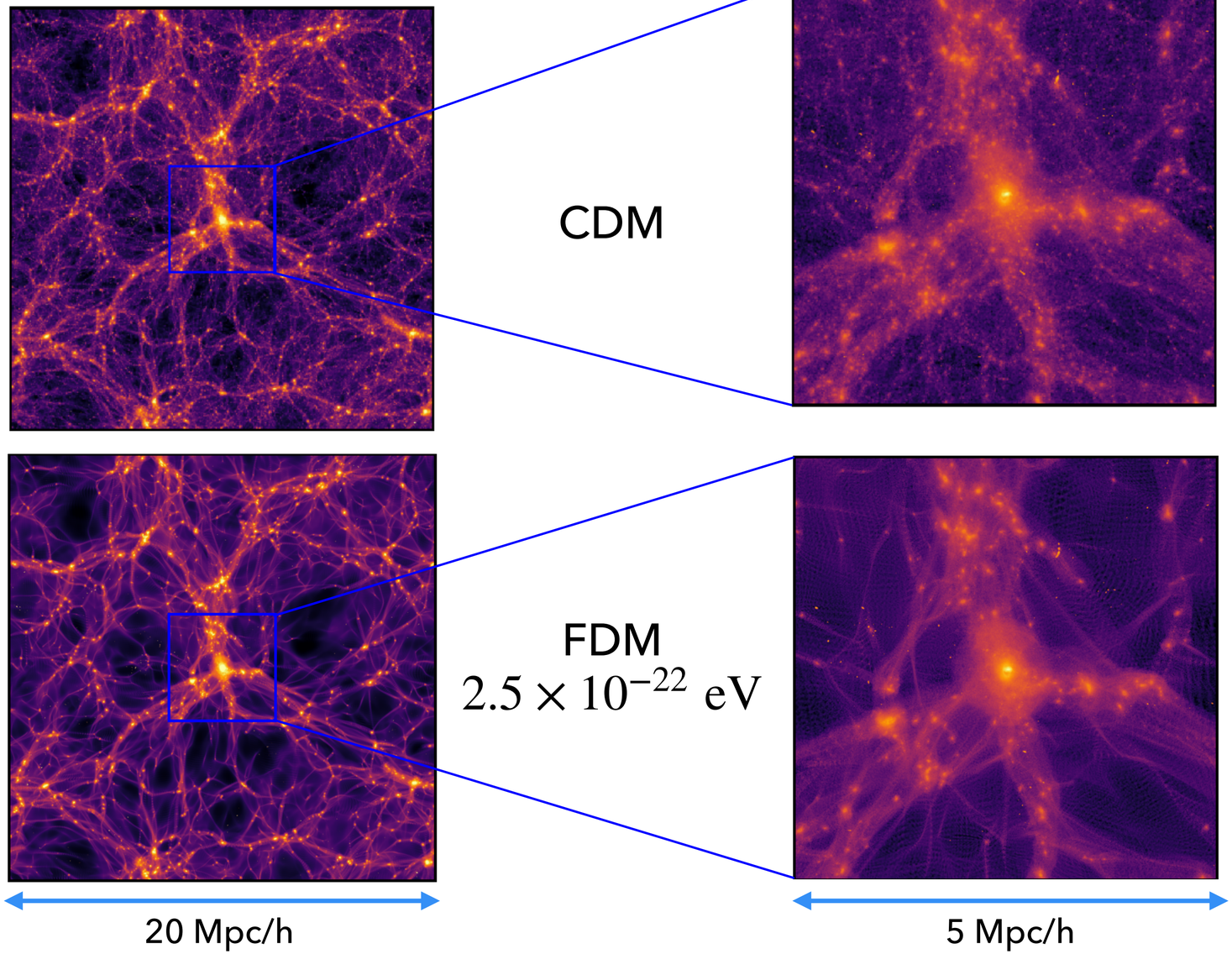
Subhajit Ghosh

$$\mathscr{L}_\phi = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 + \mathscr{L}_{\rm int}$$

figure inspired by Lin (PoS 2019)

Structure Formation with Fuzzy Dark Matter





Ni, Wang, Feng, Di Matteo (MNRAS 2019)

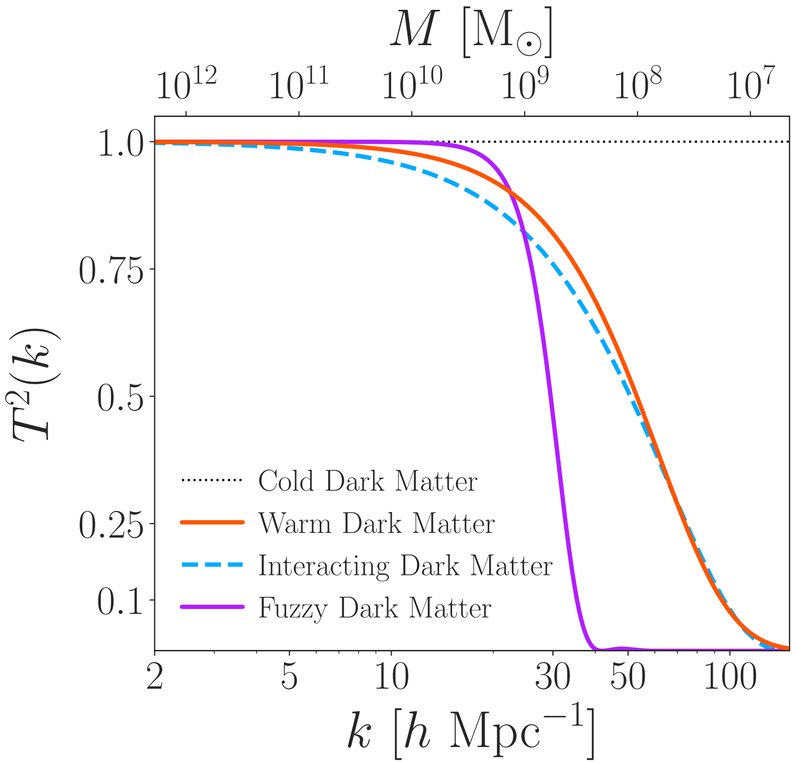
Sipp, LaChance, Croft, Ni, Di Matteo (MNRAS 2023)

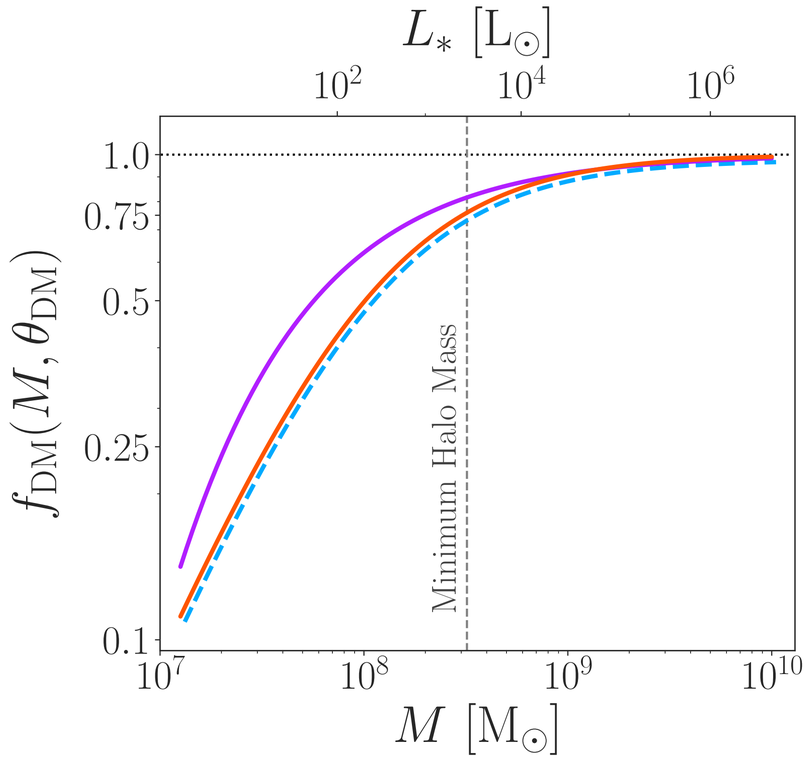
Constraints from Small Scale Structure Formation

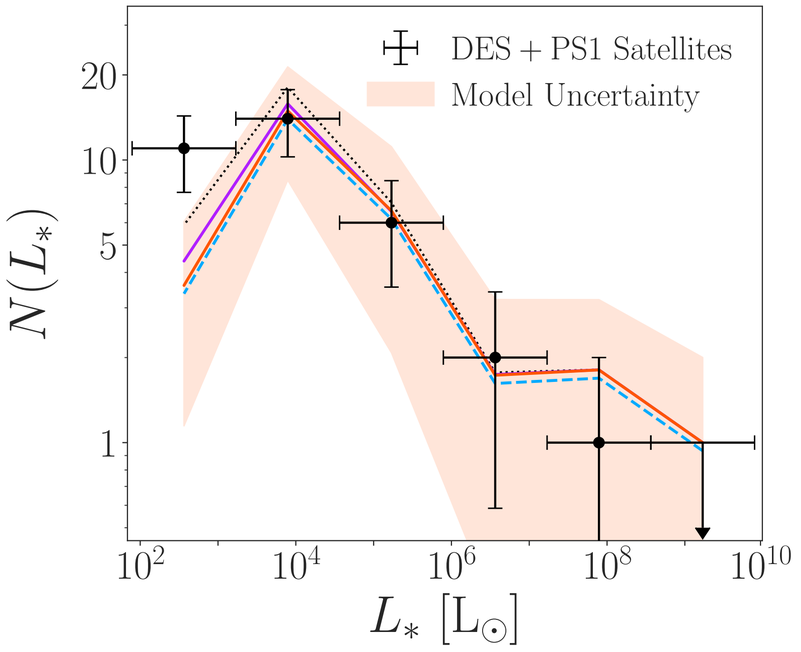
e.g., abundance of Milky Way satellites

$$m_\phi > 2.9 \times 10^{-21}\ \text{eV}$$

$$\lambda_{\text{dB}} \lesssim 0.5\ \text{kpc}$$

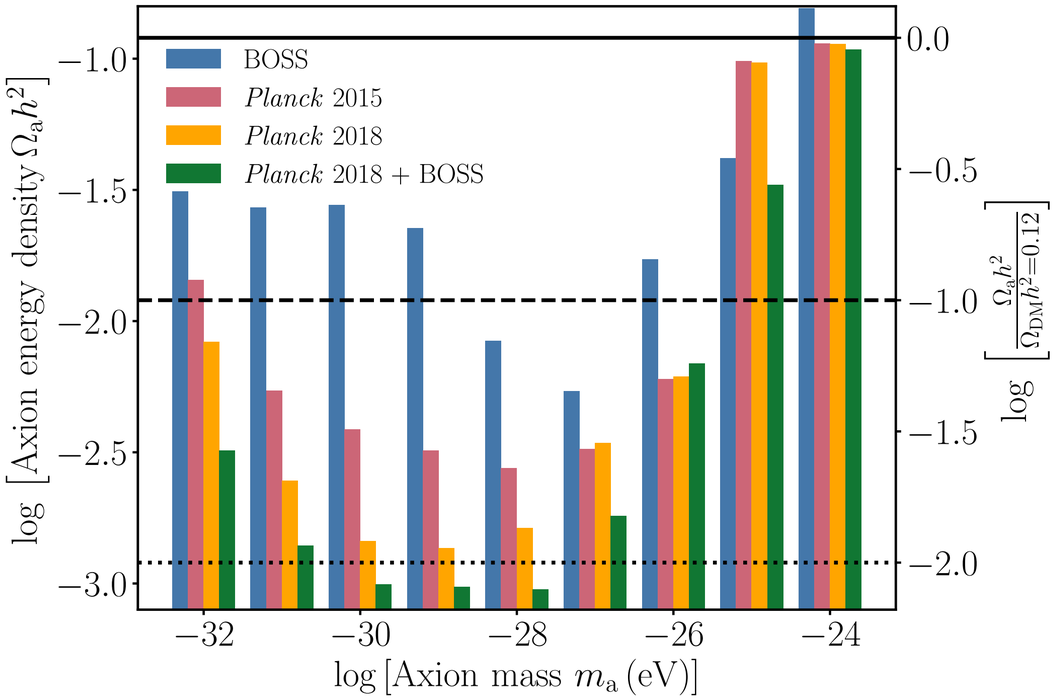


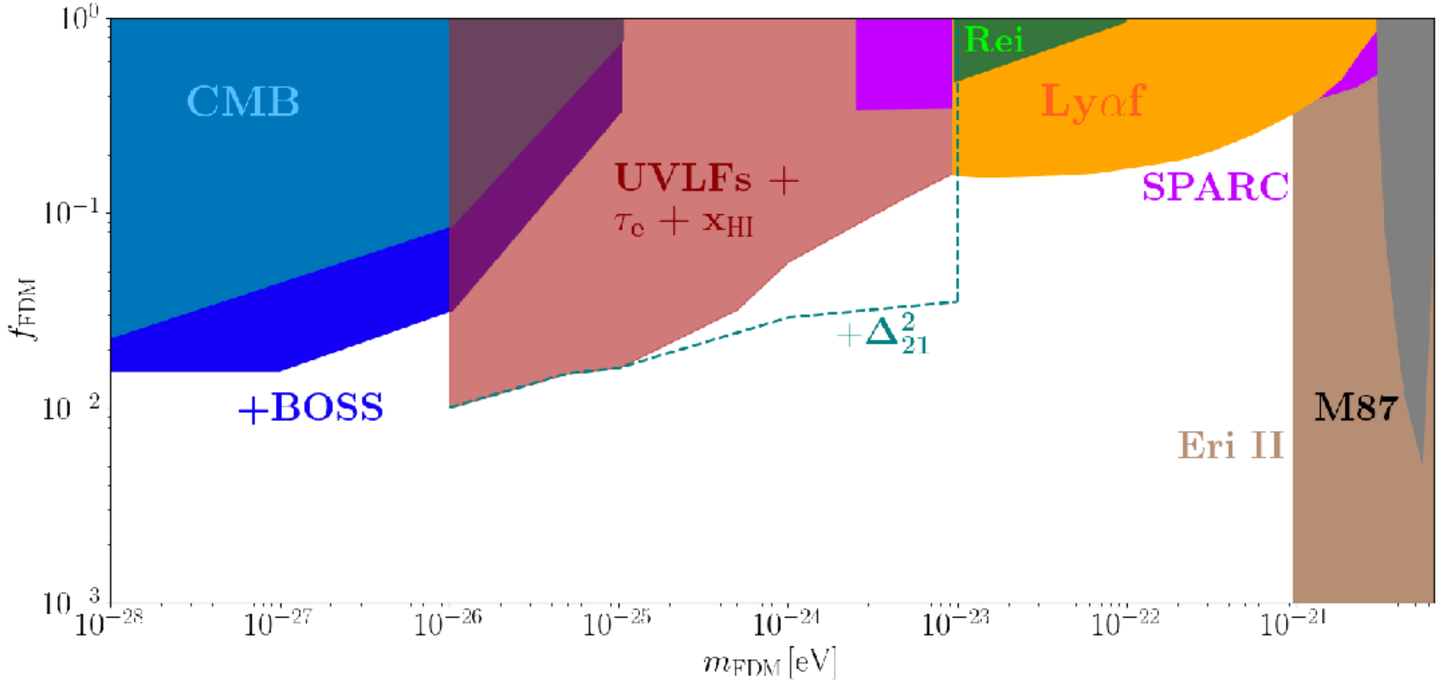




DES Collaboration, Nadler+ incl. KB (PRL 2021)

Constraints on Fractional ULDM



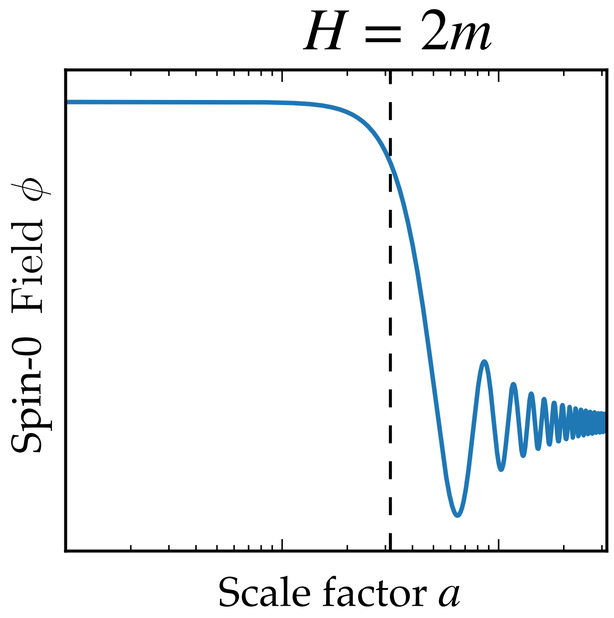


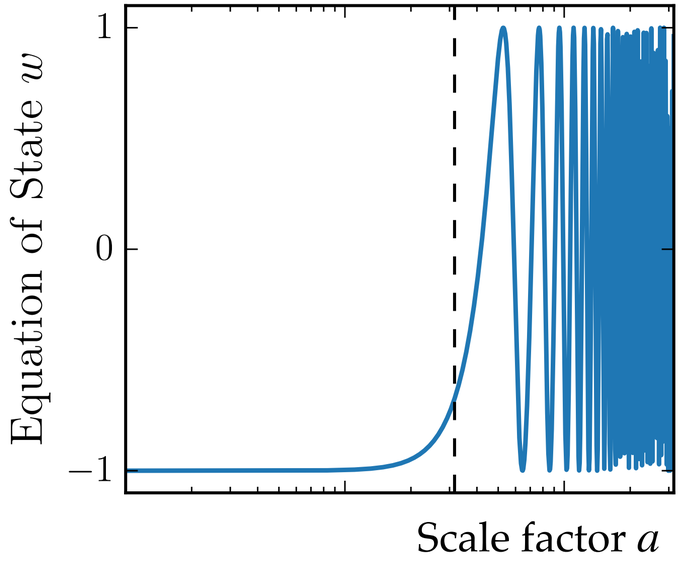
Rogers+ (JCAP 2023)

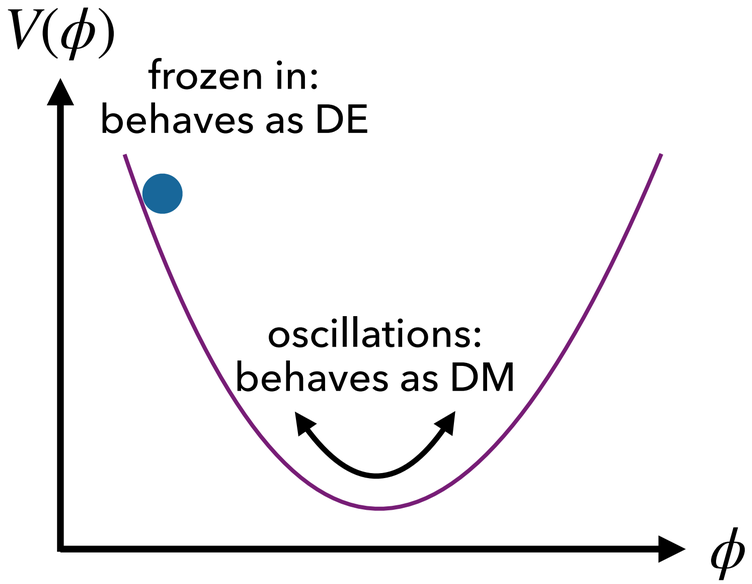
Lazare, Flitter, Kovetz (PRD 2024)

Cosmic Evolution of ULDM

- Background field evolution in FRW universe:
  $\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$
- Early times: $H \gg m \quad \rightarrow \quad \phi(t) = \phi(t_0)$ and $w = -1$
- Late times: $H \ll m \quad \rightarrow \quad \phi(t) \sim e^{imt}$ and $w = 0$

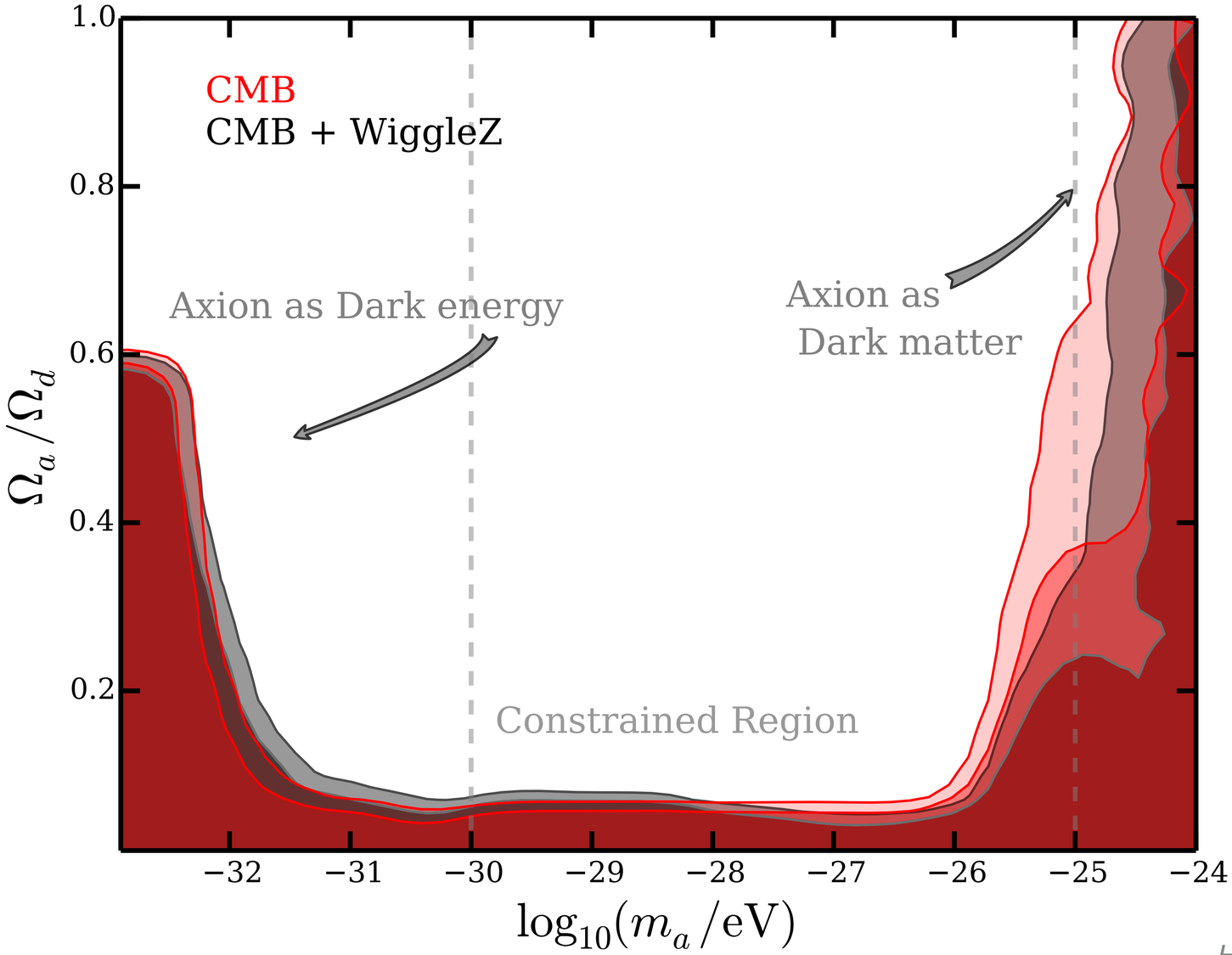






Marsh (Phys. Rept. 2016)

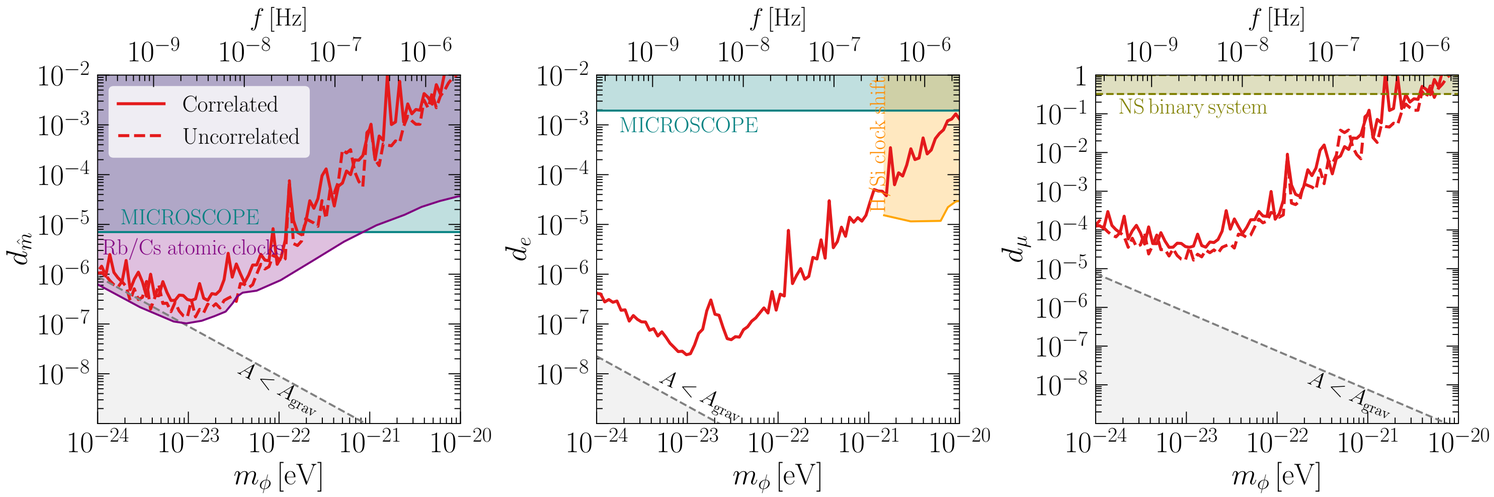
Impact on CMB

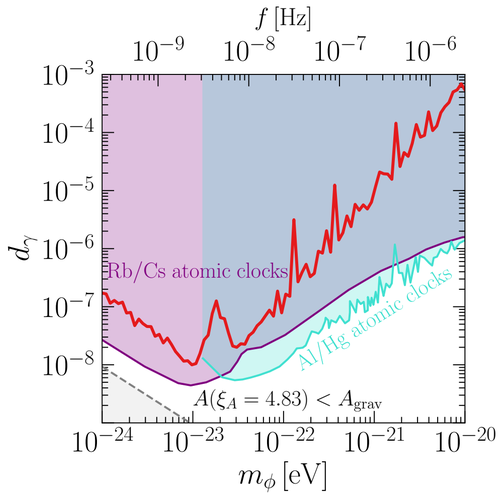


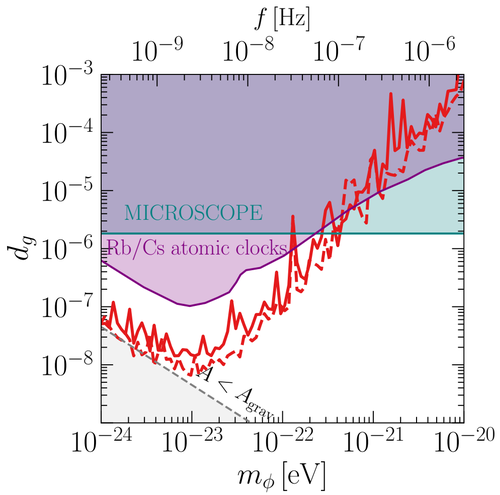
Hlozek, Grin, Marsh, Ferreira (PRD 2015)

Introduce Interactions with Standard Model

$$\mathscr{L} \supset \frac{\phi}{\Lambda}\left[\frac{d_\alpha}{4e^2}F_{\mu\nu}F^{\mu\nu} + \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G_A^{\mu\nu} - \sum_{f=e,\mu} d_f m_f \bar{f}f - \sum_{q=u,d}(d_q + \gamma_q d_g) m_q \bar{q}q\right]$$







See also constraints with quasar absorption lines

Baryakhtar, Simon, Weiner (PRD 2024, 2025)

$$\Lambda = M_{\rm pl}/\sqrt{2\pi}$$

NANOGrav (2306.16219)

Quadratic Couplings

- Introduce quadratic interactions (focus on two couplings)

$$\mathscr{L}_{\rm int} = \left(\frac{\phi}{\Lambda}\right)^2 \left[\frac{d_\alpha}{4e^2} F_{\mu\nu}F^{\mu\nu} - d_e m_e \bar{e}e\right]$$

- ϕ-dependent shift to fundamental constants

$$\frac{\Delta\alpha}{\alpha} = d_\alpha \left(\frac{\phi}{\Lambda}\right)^2 \quad \text{and} \quad \frac{\Delta m_e}{m_e} = d_e \left(\frac{\phi}{\Lambda}\right)^2$$

- Backreaction due to thermal mass induced by SM bath: $m_{\rm eff}^2 = m_\phi^2 + m_{\rm ind}^2$

Bouley, Sørensen, Yu (JHEP 2023)

- Field evolution: $\ddot{\phi} + 3H\dot{\phi} + m_{\rm eff}^2\phi = 0$

Impact of VFC on BBN: Helium-4 Abundance

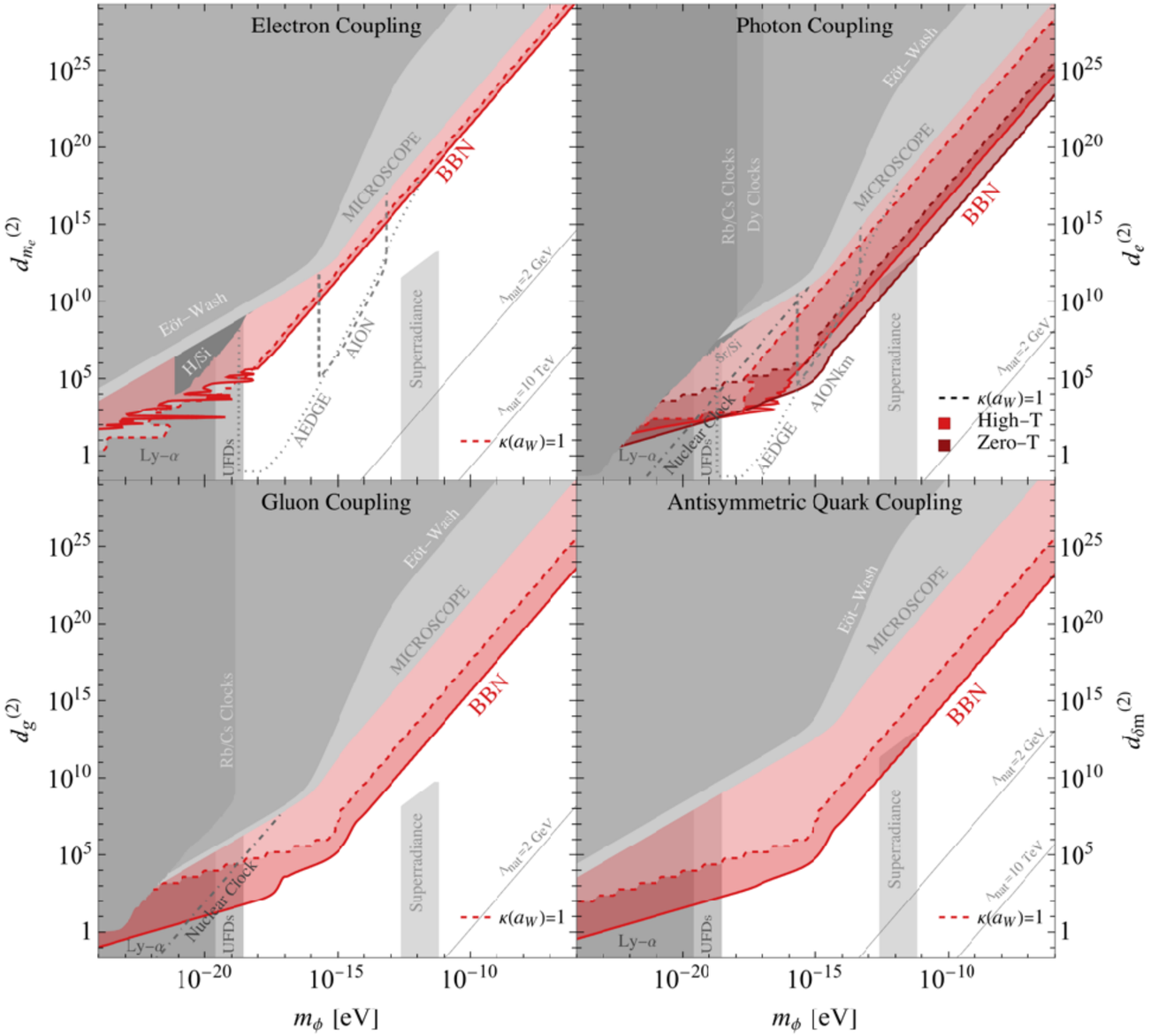
- He-4 abundance depends on
  - Weak freeze-out of

    $n + \nu_e \leftrightarrow p + e^-$

    $n + e^+ \leftrightarrow p + \bar{\nu}_e$
  - Neutron lifetime
- VFC changes abundance

Lots of previous work on BBN,
including detailed analyses for specific models

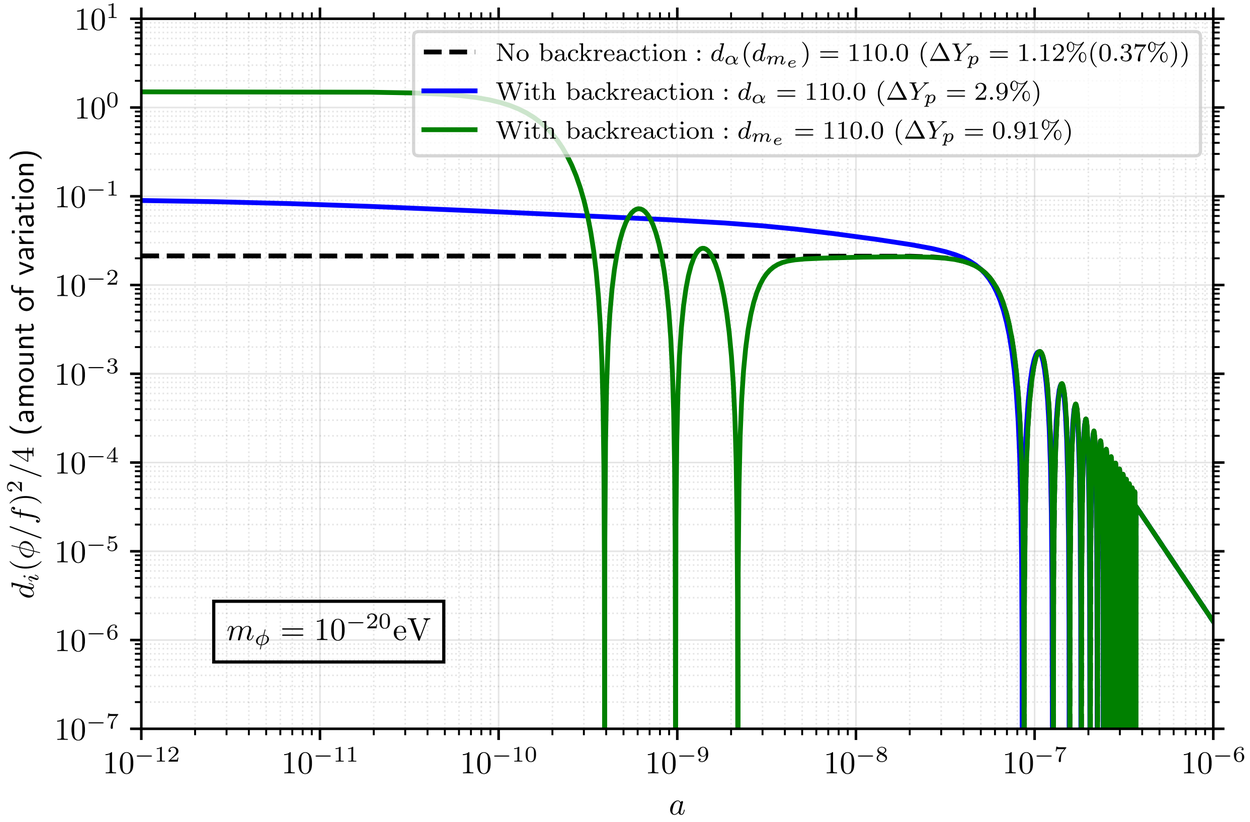
Work on CMB/post-CMB
typically uses simple parameterizations for VFC
that are active only during CMB era



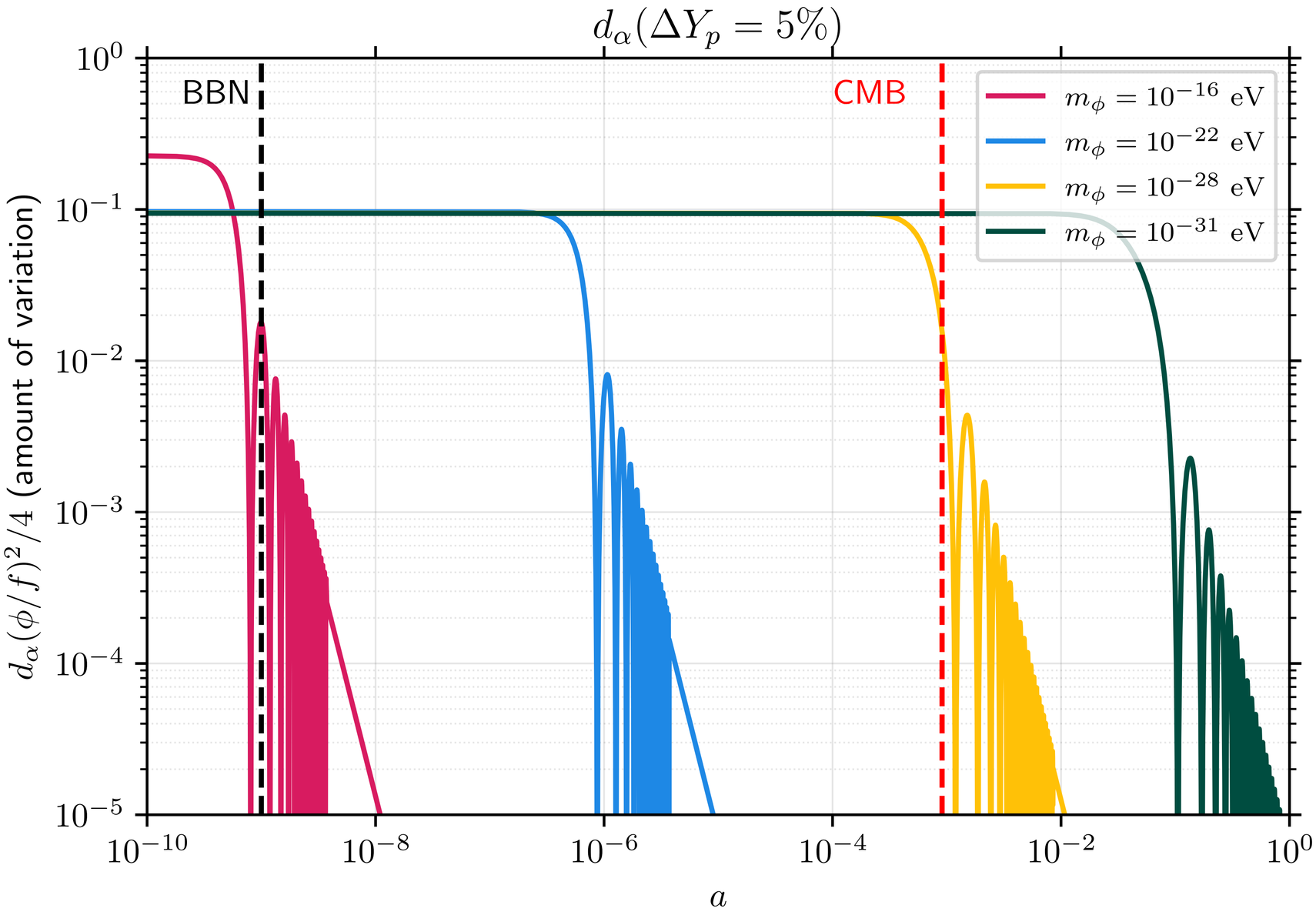
Bouley, Sørensen, Yu (JHEP 2023)

VFC During CMB Era

- Incorporate evolving VFC (model dependent) for EM couplings (for now…)
- Study impact on CMB under complete model with “scalarCLASS”, based on modifications to AxiCLASS (Poulin, Smith, Karwal+)



Oscillations during BBN and CMB Eras



full ULDM allowed, but VFC shifts Y_p

fractional ULDM

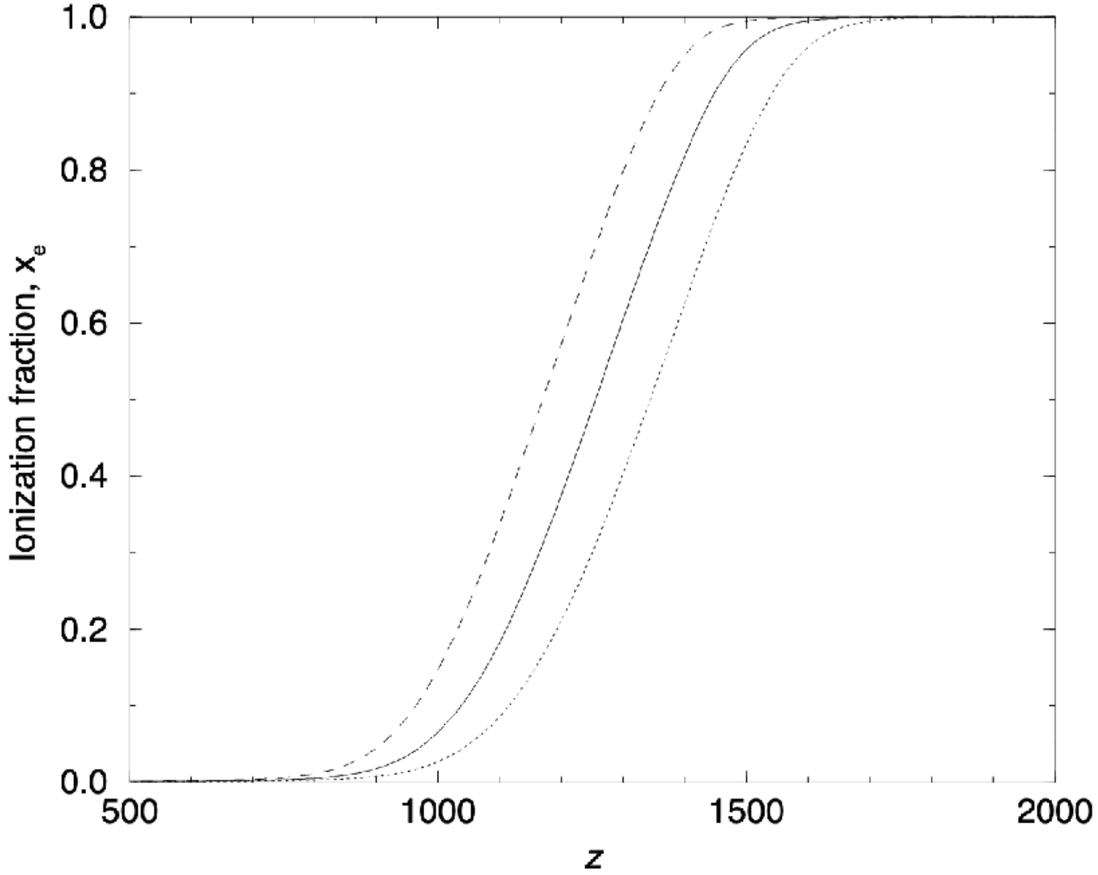
track many oscillations to avoid washing out impact of ϕ

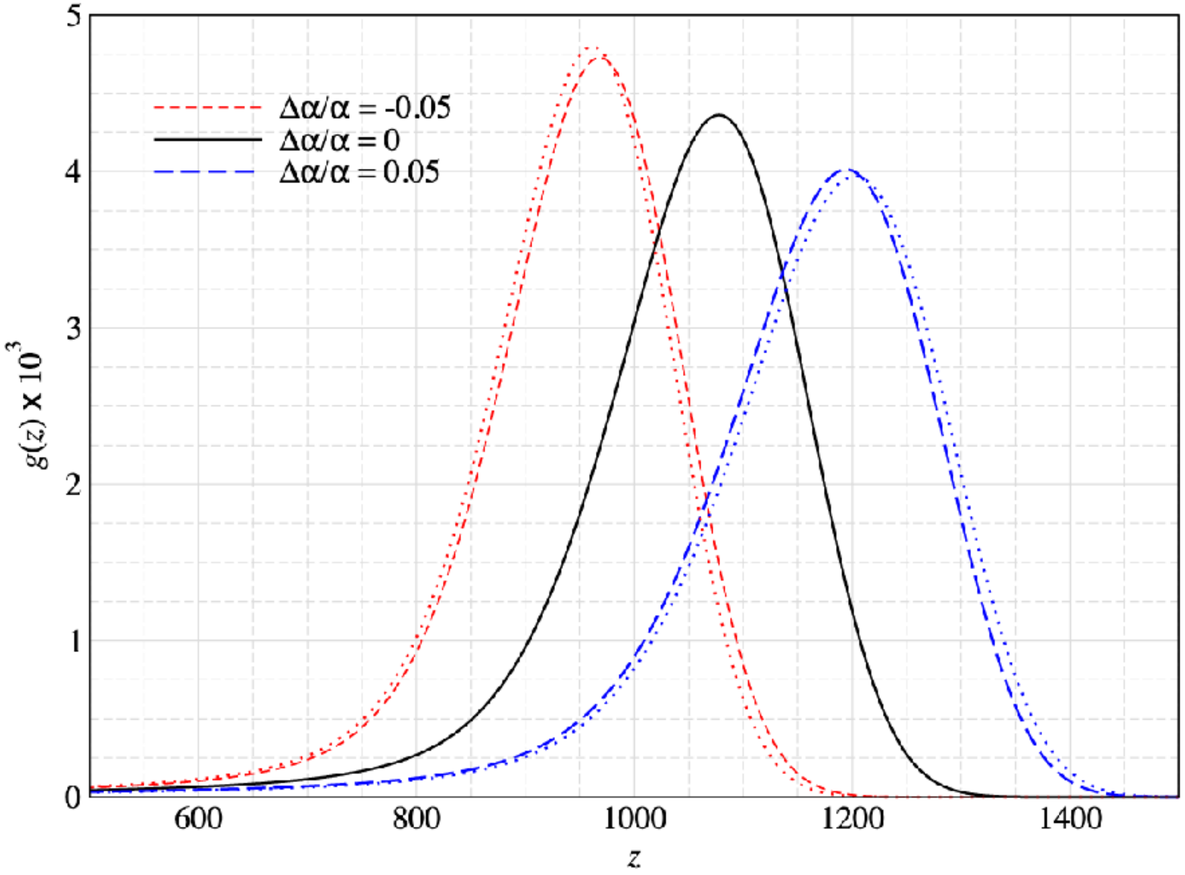
constant VFC, but need to account for shift in Y_p!!!

Ghosh, KB, Yu (in prep)

Impact of Constant VFC on Recombination

$$\sigma_{\rm T} \propto \alpha_{\rm EM}^2 m_{\rm e}^{-2} \qquad A_{2\gamma} \propto \alpha_{\rm EM}^8 m_{\rm e} \qquad P_{\rm S} A_{1\gamma} \propto \alpha_{\rm EM}^6 m_{\rm e}^3$$
$$\alpha_{\rm rec} \propto \alpha_{\rm EM}^2 m_{\rm e}^{-2} \qquad \beta_{\rm phot} \propto \alpha_{\rm EM}^5 m_{\rm e} \qquad T_{\rm eff} \propto \alpha_{\rm EM}^{-2} m_{\rm e}^{-1}.$$



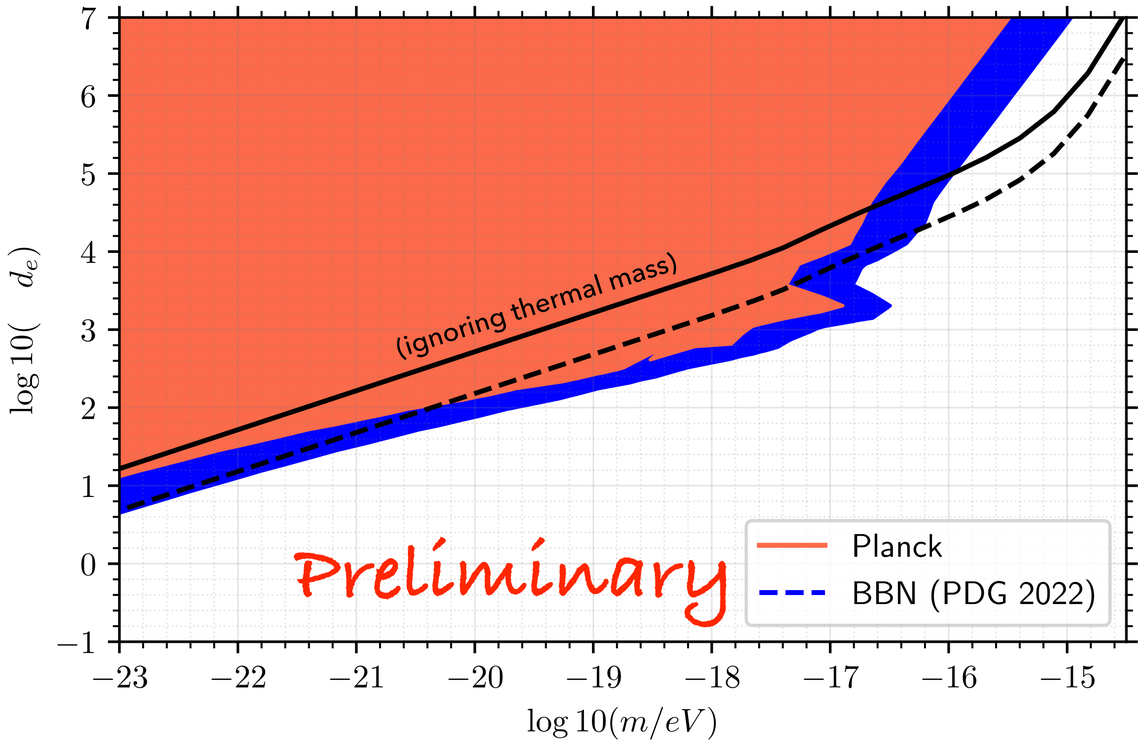


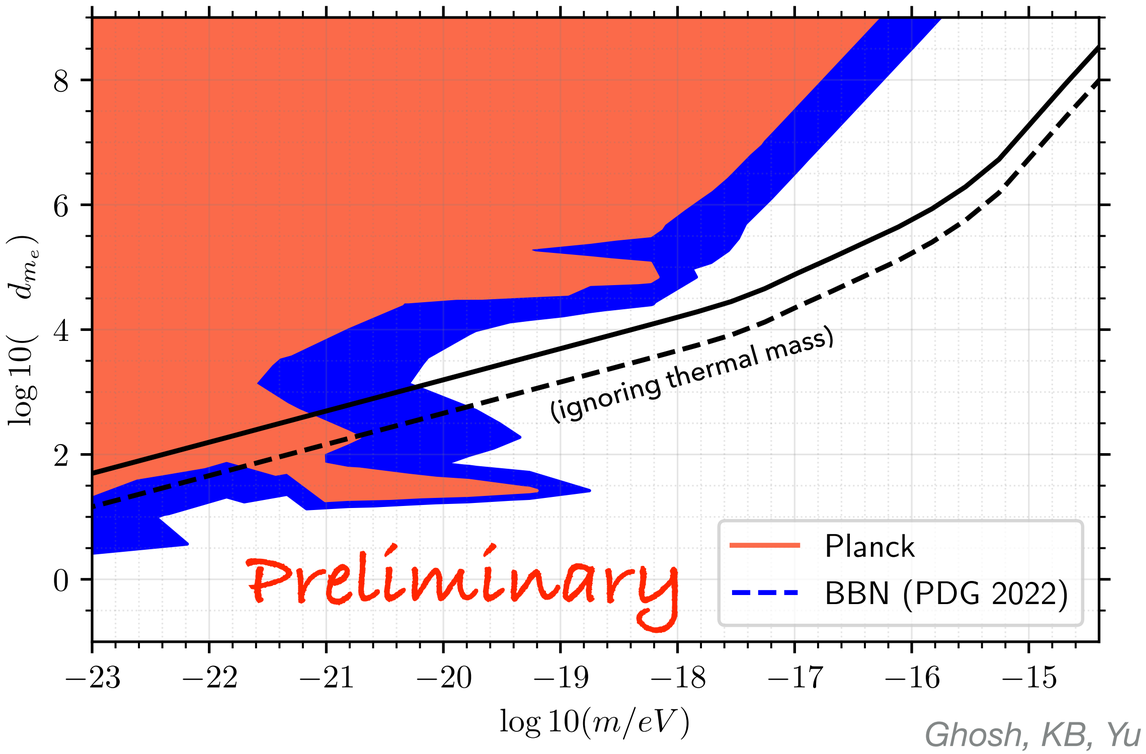
Kaplinghat, Scherrer, Turner (PRD 1999)

Hart, Chluba (MNRAS 2018)

CMB Constraints: "High"-Mass Regime

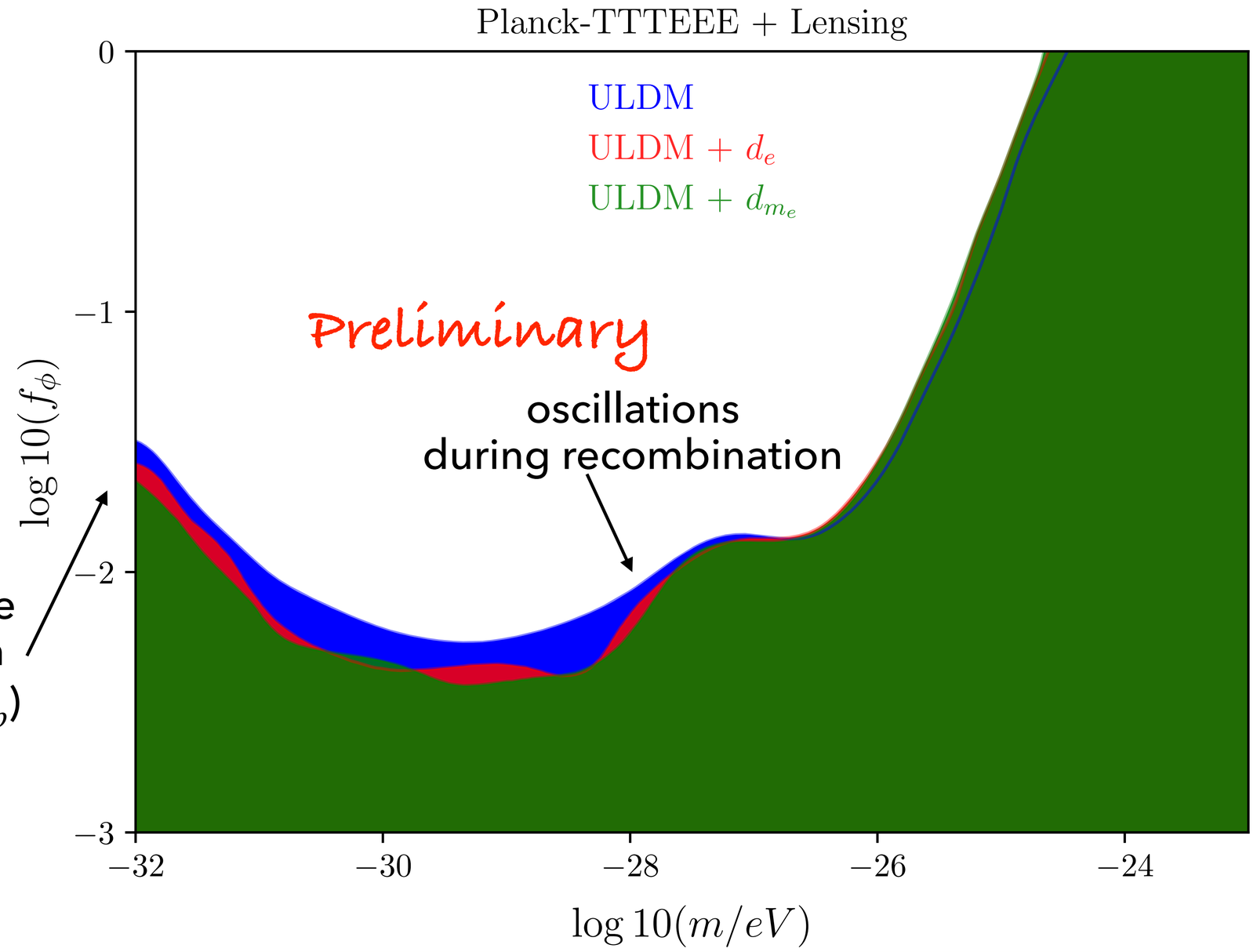
- Assume ULDM constitutes 100% of DM
- Only impact is on Y_p in this regime: adapt simple CMB analysis of LCDM+ΔY_p
  $\Delta Y_p/Y_p < 0.082$ at 95% CL
- From PDG 2022/24: $\Delta Y_p/Y_p < 0.024$ at 2σ





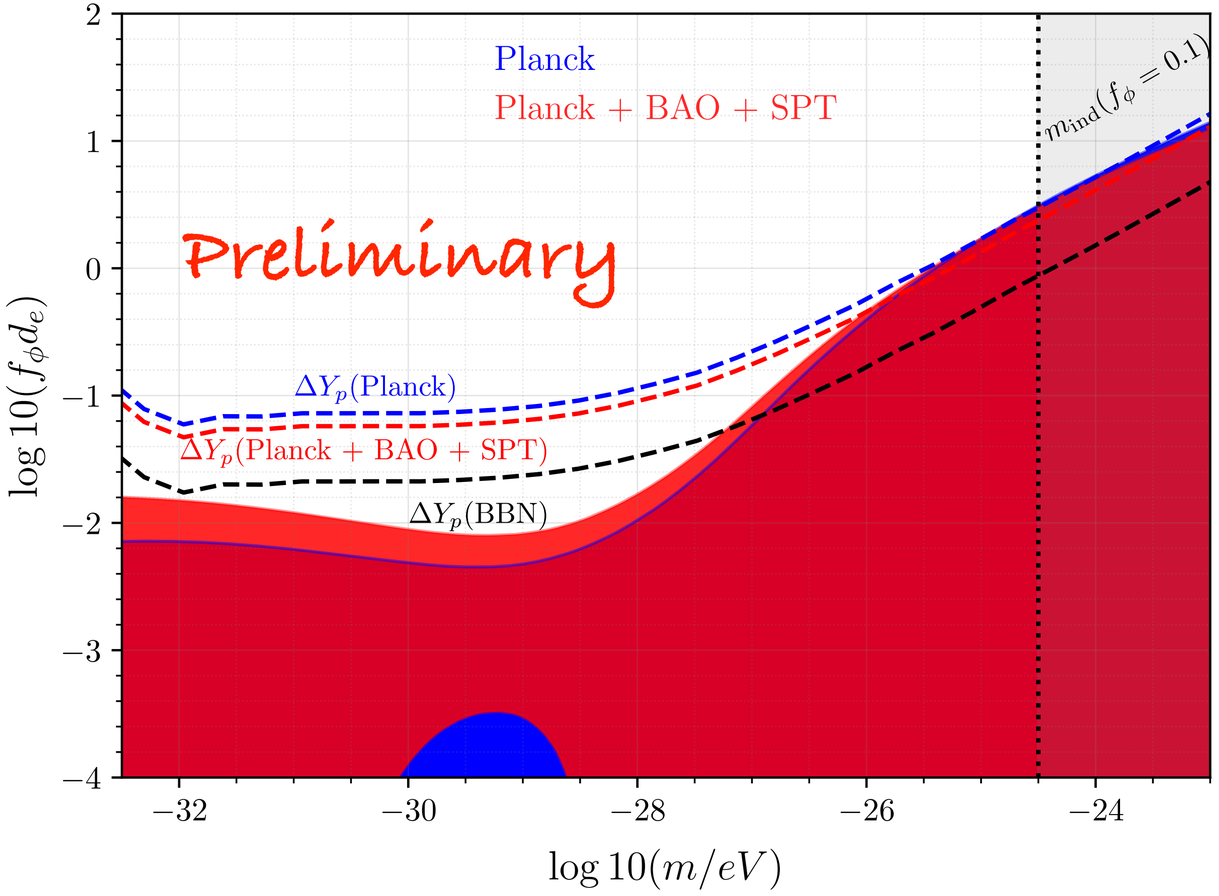
Ghosh, KB, Yu (in prep)

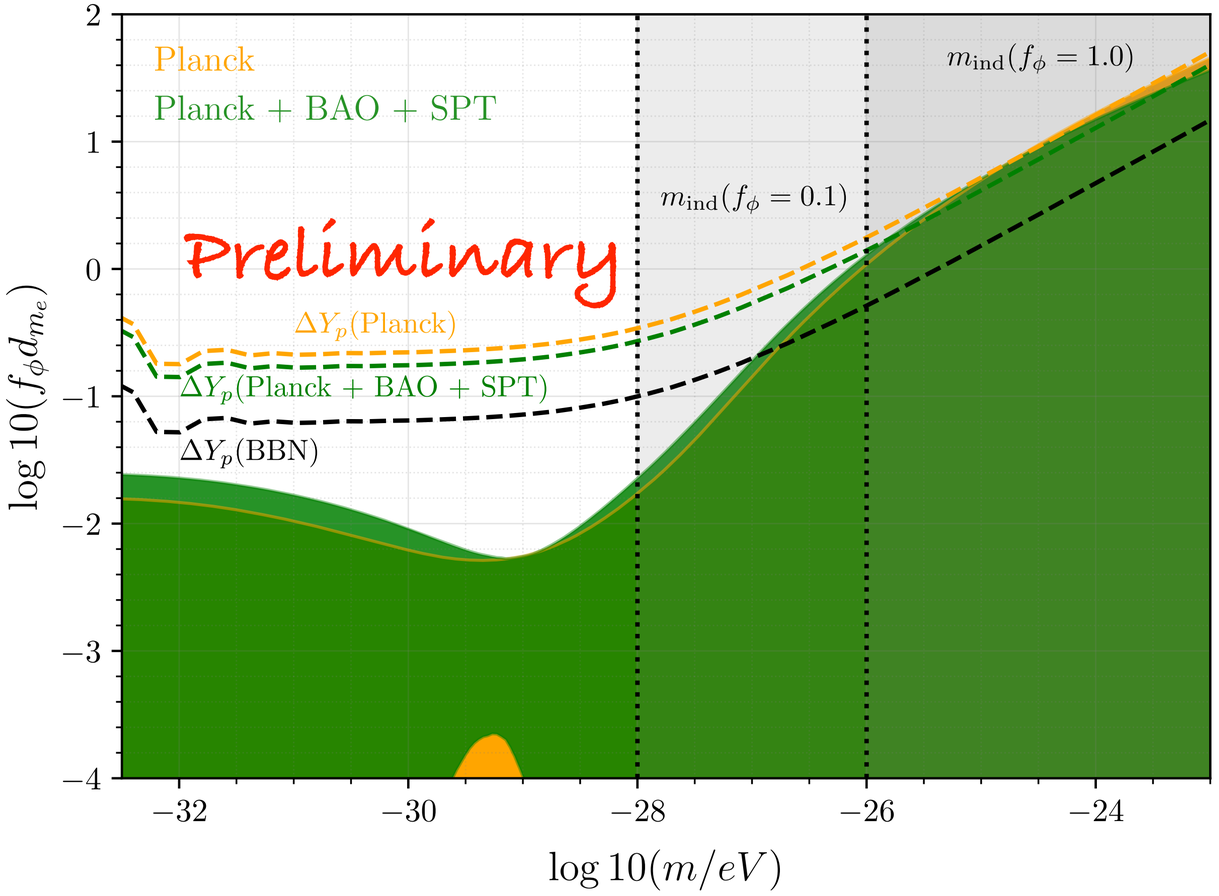
CMB Constraints: Fractional ULDM



Ghosh, KB, Yu (in prep)

CMB Constraints: Comparison with BBN

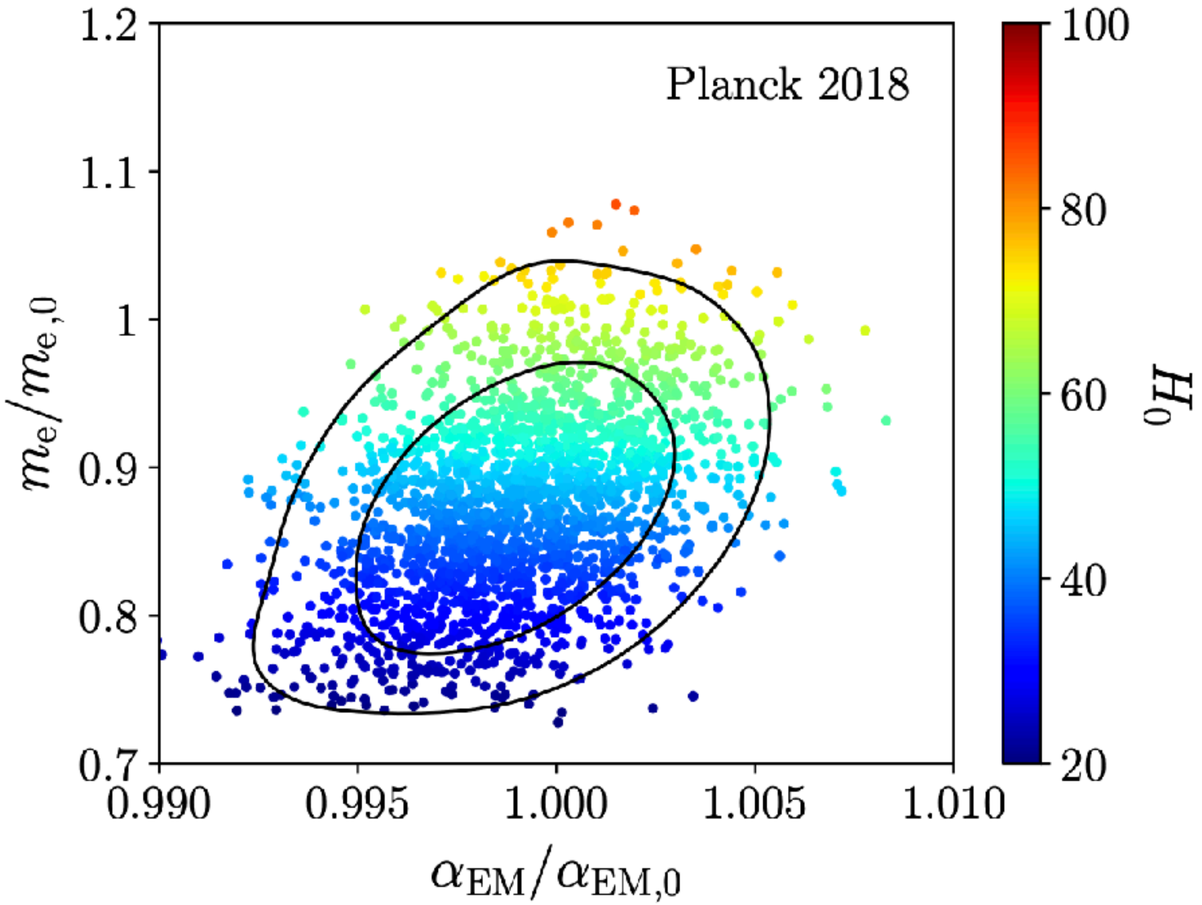


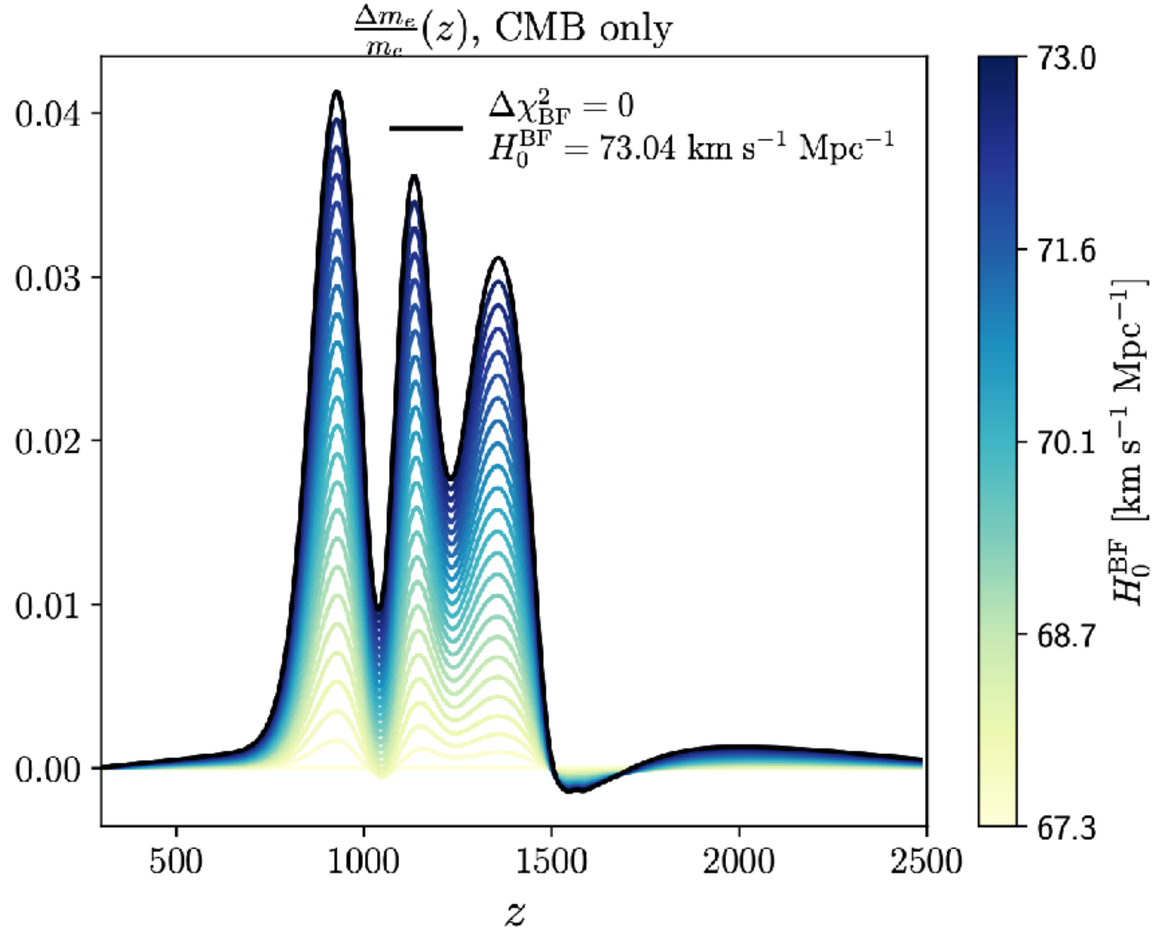


Ghosh, KB, Yu (in prep)

Implications for Hubble Tension

Fixed VFC

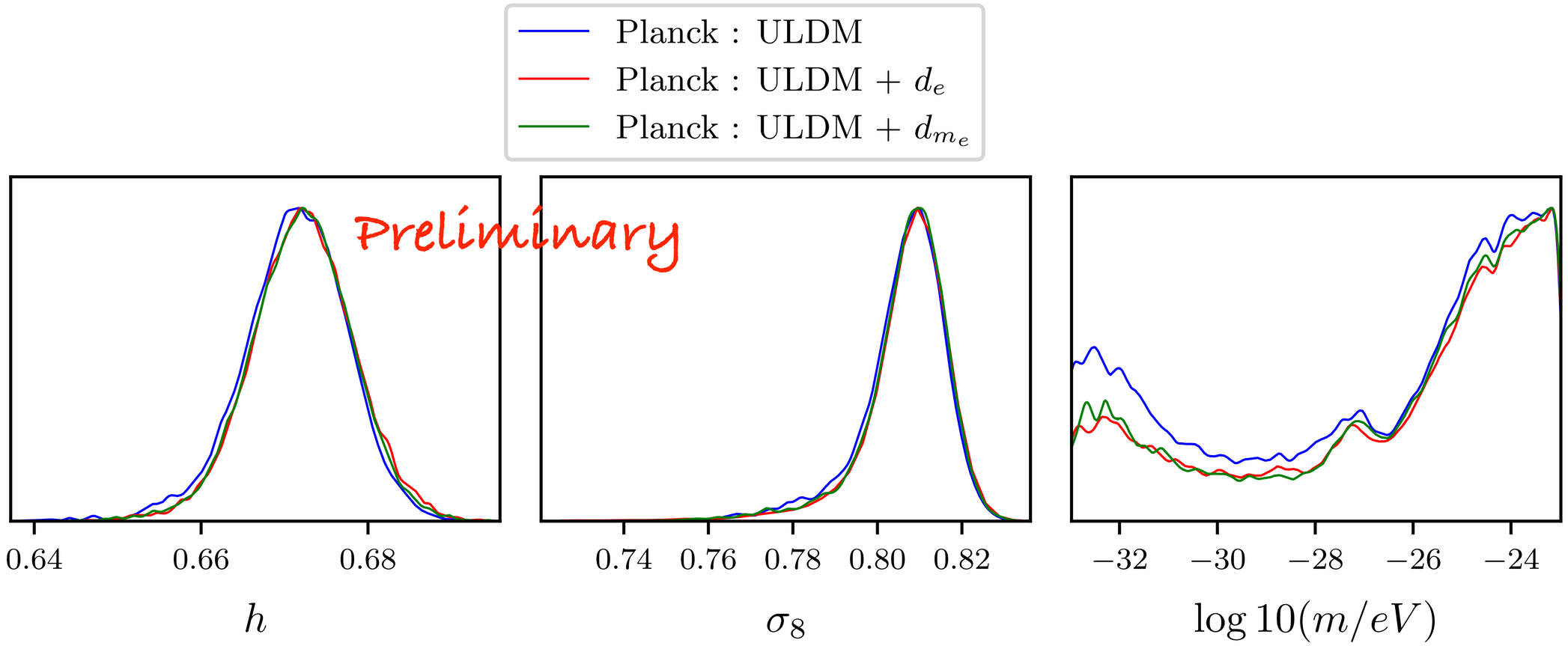




Hart, Chluba (MNRAS 2020)

Lee, Ali-Haïmoud, Schöneberg, Poulin (PRL 2023)

Alas...



Ghosh, KB, Yu (in prep)

Stay tuned…

See arXiv post soon!

Upcoming work

- Linear cosmology with ULDM-induced VFCs beyond α and m_e
- Constraints from CMB and LSS
  (Any EFT of LSS experts in the room?)
- BBN constraints on other element abundances