# WHAT DOES COSMOLOGY TELL US ABOUT THE MASS OF THERMAL–RELIC DARK MATTER ?

Rui An

University of Southern California

PPC 2022

ArXiv: 2202.03515, with Vera Gluscevic, Erminia Calabrese and J. Colin Hill

# OUTLINE

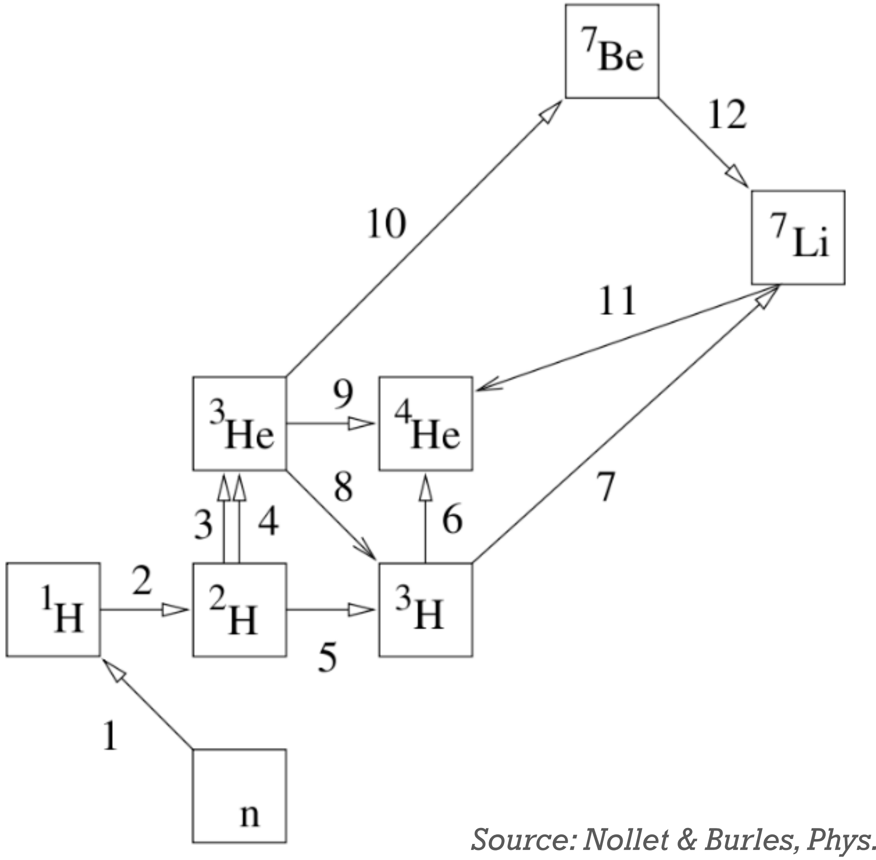
- Effects of the thermal-relic DM on primordial abundances
- Effects of the thermal-relic DM on CMB
- Data, analysis method, and constraints
- Summary

# EFFECTS OF THE THERMAL-RELIC DM ON PRIMORDIAL ABUNDANCES

The nuclear network of the dominate reactions taking place during BBN

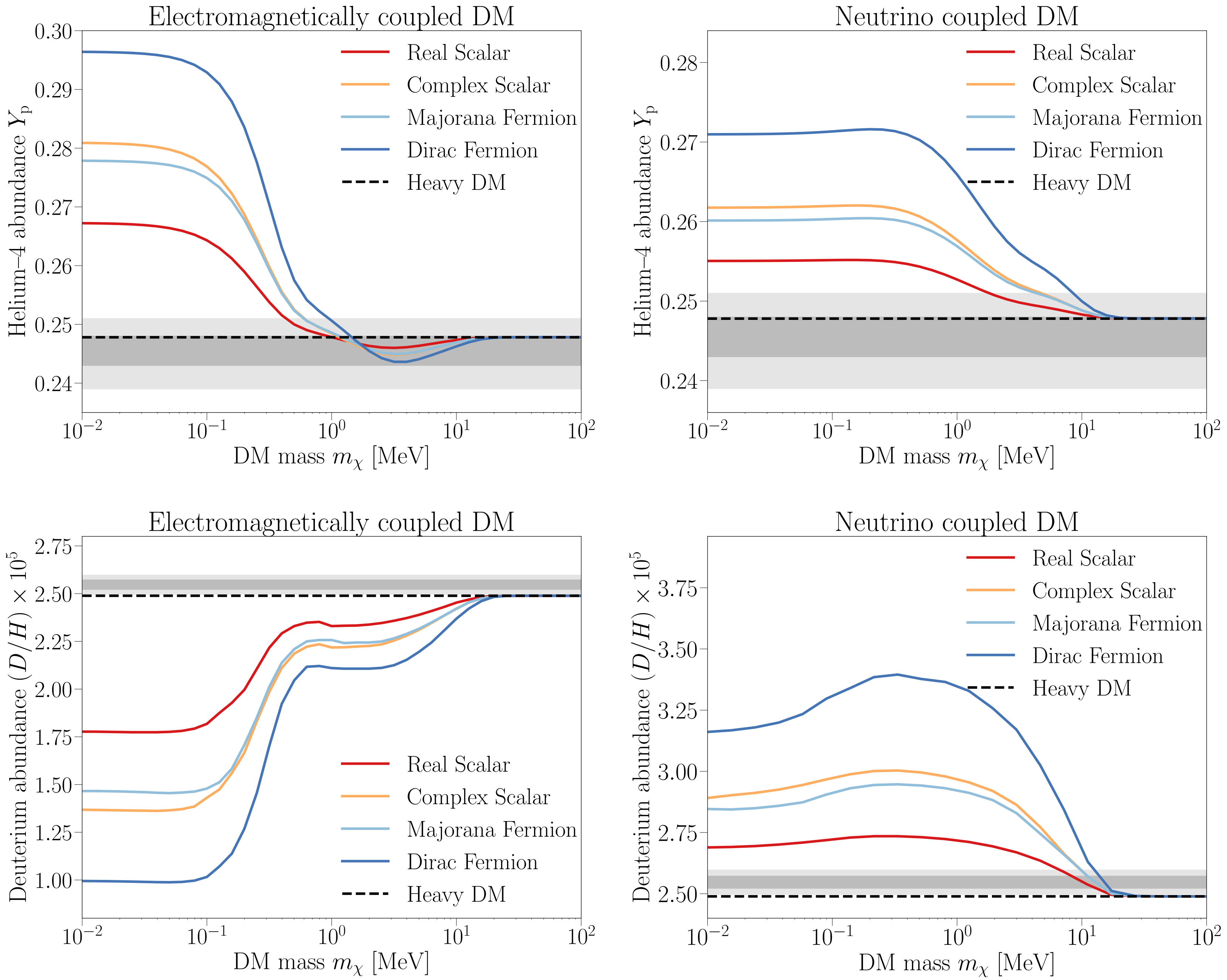
He-4 Ababundance:

$$Y_p = \frac{2(n/p)}{1+(n/p)} \xrightarrow{n/p \sim 1/7} \approx 0.25$$




1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3\mathrm{He}$
4. $d(d,n)^3\mathrm{He}$
5. $d(d,p)t$
6. $t(d,n)^4\mathrm{He}$
7. $t(\alpha,\gamma)^7\mathrm{Li}$
8. $^3\mathrm{He}(n,p)t$
9. $^3\mathrm{He}(d,p)^4\mathrm{He}$
10. $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
11. $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

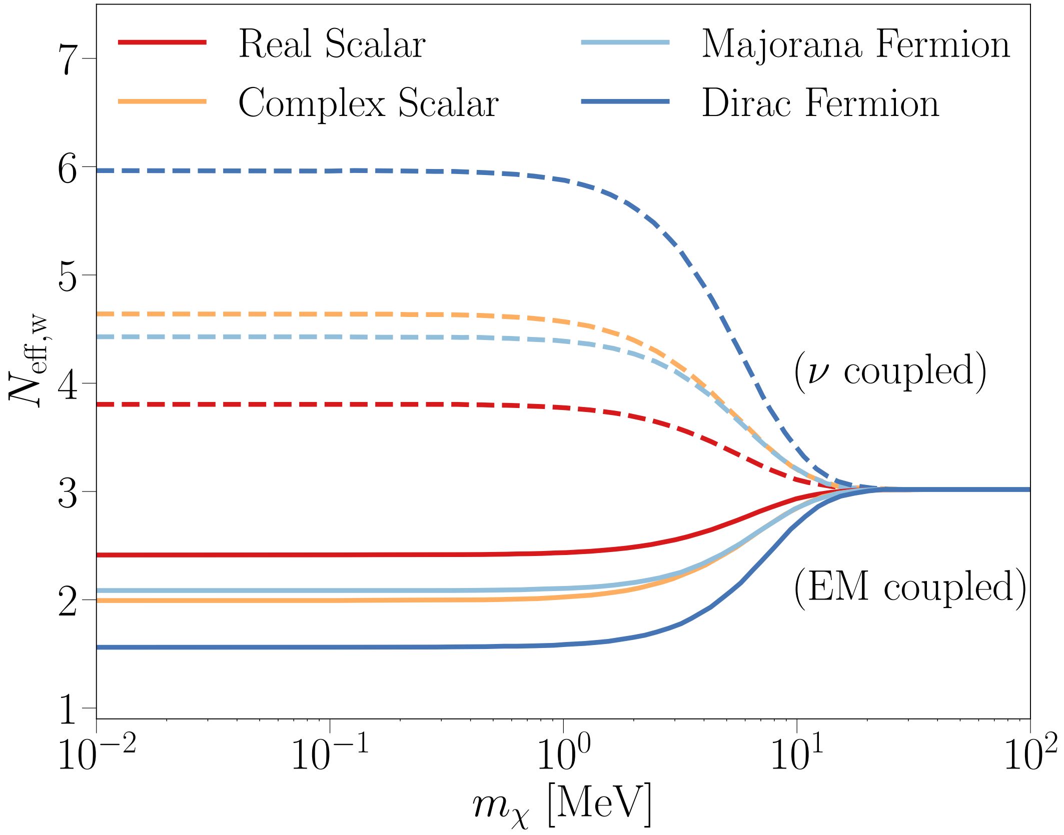
*Source: Nollet & Burles, Phys. Rev. D 61, 123505 (2000)*




## Primordial abundance of helium-4 and deuterium, as a function of DM mass

*Note that we assume only the standard neutrino species* ($\Delta N_\upsilon = 0$) *and use* $\Omega_b h^2 = 0.0224$ *here*

# EFFECTS OF THE THERMAL-RELIC DM ON CMB: $Y_p$ AND $N_{eff}$




$$N_{\mathrm{eff,w}}(m_\chi) = 3\left[\frac{11}{4}\left(\frac{T_\upsilon}{T_\gamma}\right)_0^3\right]^{\frac{4}{3}}$$

$$N_{\mathrm{eff}}(m_\chi, \Delta N_\upsilon) = N_{\mathrm{eff,w}}\left(1 + \frac{\Delta N_\upsilon}{3}\right)$$

$N_{\mathrm{eff,w}}$ includes the contribution from the Standard–Model neutrinos, as well as contribution from light DM

$\Delta N_\upsilon$ includes the contribution from any other new relativistic species

For standard model $N_{\mathrm{eff}} = 3.046$

# DATA, ANALYSIS METHOD, AND CONSTRAINTS

CMB: Planck 2018, ACT DR4, SPT-3G

Primordial abundances (PA): Helium–4, Deuterium

**Method :**

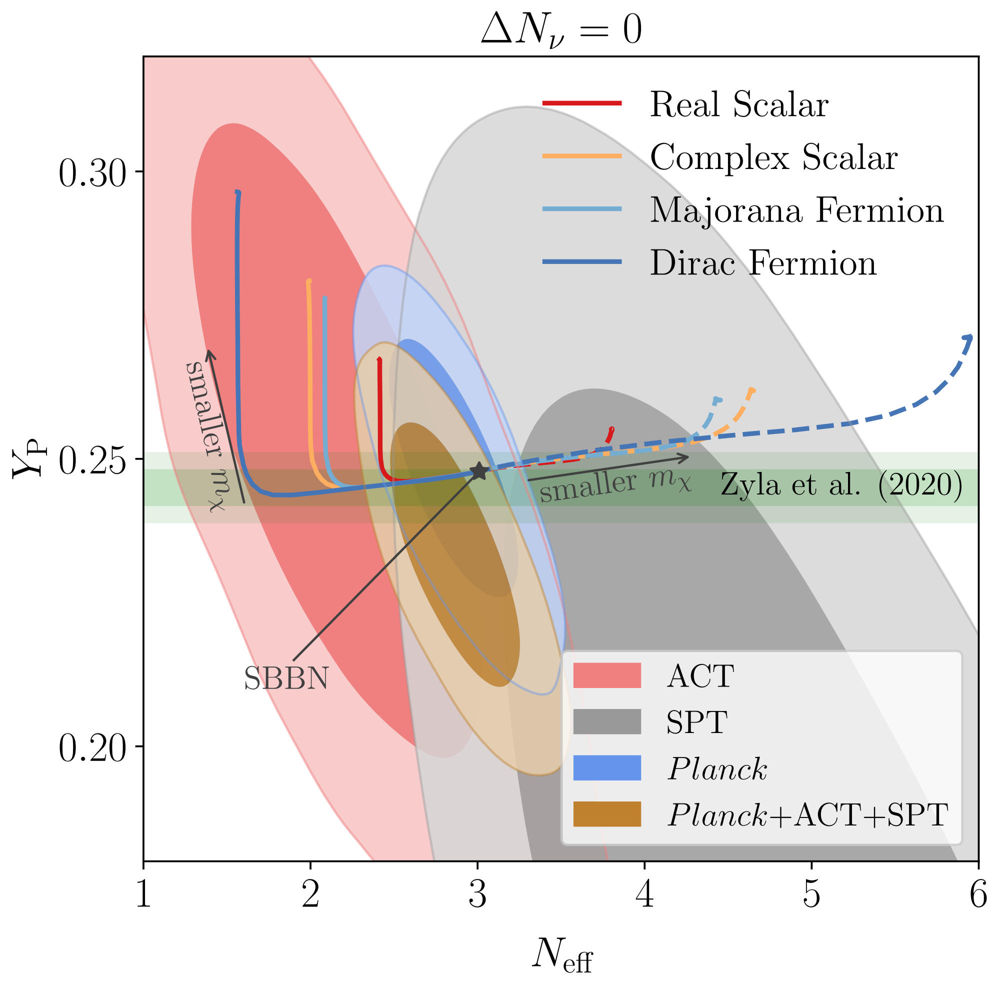
***Step 1***. *run mcmc to sample the posterior distributions of the six standard cosmological parameters with the addition of $N_{eff}$ and $Y_p$*
***Step 2***. *convert the resulting probability distribution on the relevant cosmological parameters $\Omega_b h^2$, $N_{eff}$ and $Y_p$ to the distribution on $m_\chi$ and $\Delta N_\upsilon$:*

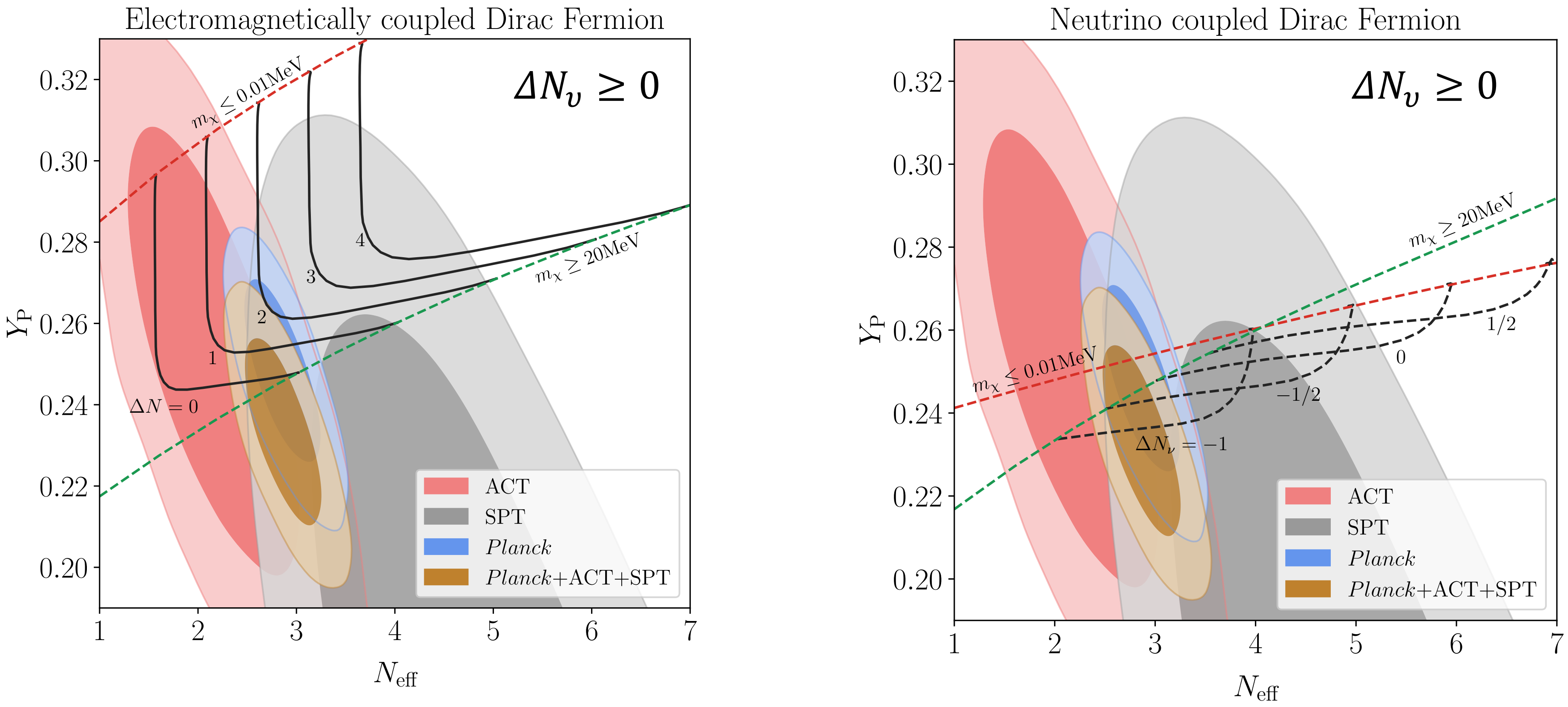
$$\chi^2_{\rm CMB} = (\mathbf{X} - \mathbf{X}_{\rm obs})\, \mathbf{Cov}^{-1} (\mathbf{X} - \mathbf{X}_{\rm obs})^T$$

$$\chi^2_{\rm PA} = \frac{\left[Y_{\rm p} - Y_{\rm p}^{\rm obs}\right]^2}{{\sigma_{Y_{\rm p}^{\rm th}}}^2 + {\sigma_{Y_{\rm p}^{\rm obs}}}^2} + \frac{\left[Y_{\rm D} - Y_{\rm D}^{\rm obs}\right]^2}{{\sigma_{Y_{\rm D}^{\rm th}}}^2 + {\sigma_{Y_{\rm D}^{\rm obs}}}^2}$$

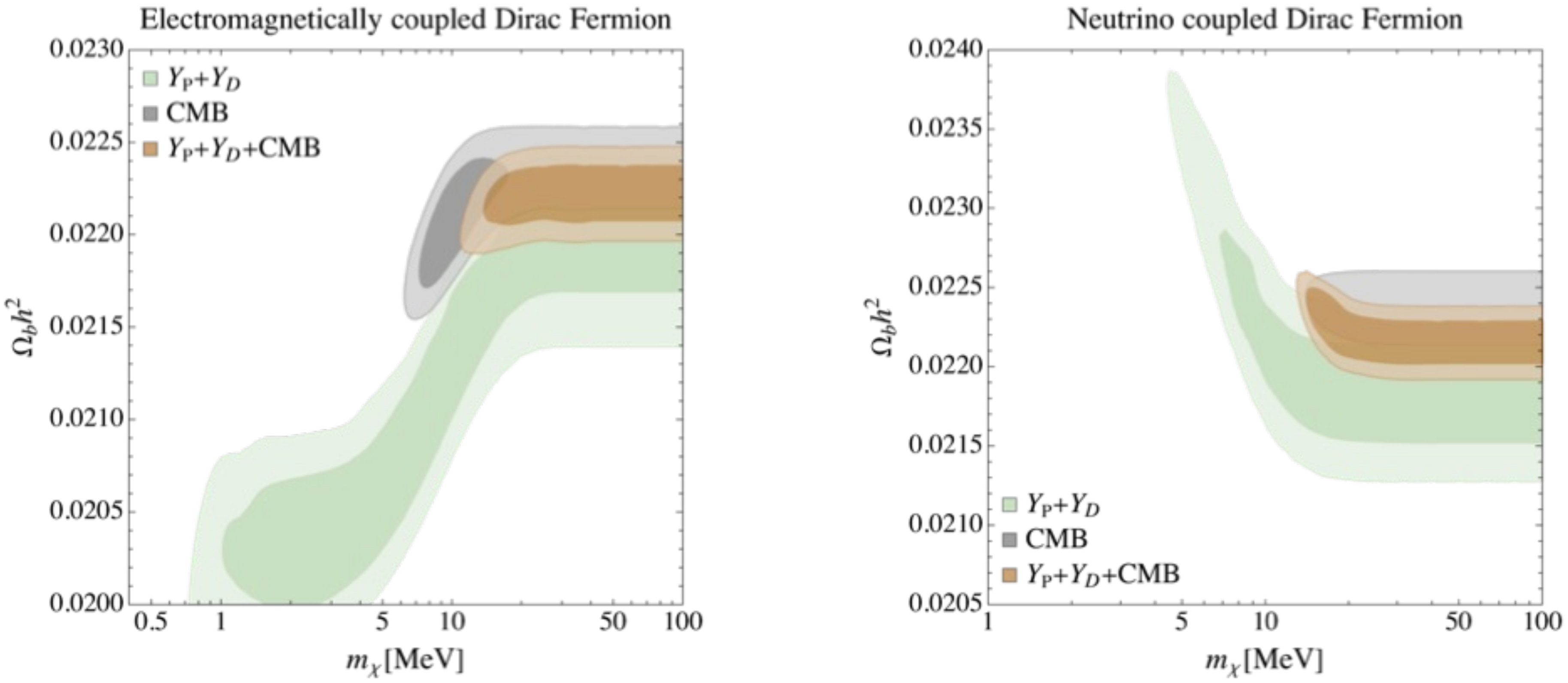
*where* $\mathbf{X} = \{\Omega_b h^2, N_{\rm eff}, Y_{\rm p}\}$

$N_{\rm eff}(m_\chi, \Delta N_\nu)$ and $Y_{\rm p}(m_\chi, \Delta N_\nu, \Omega_b h^2)$



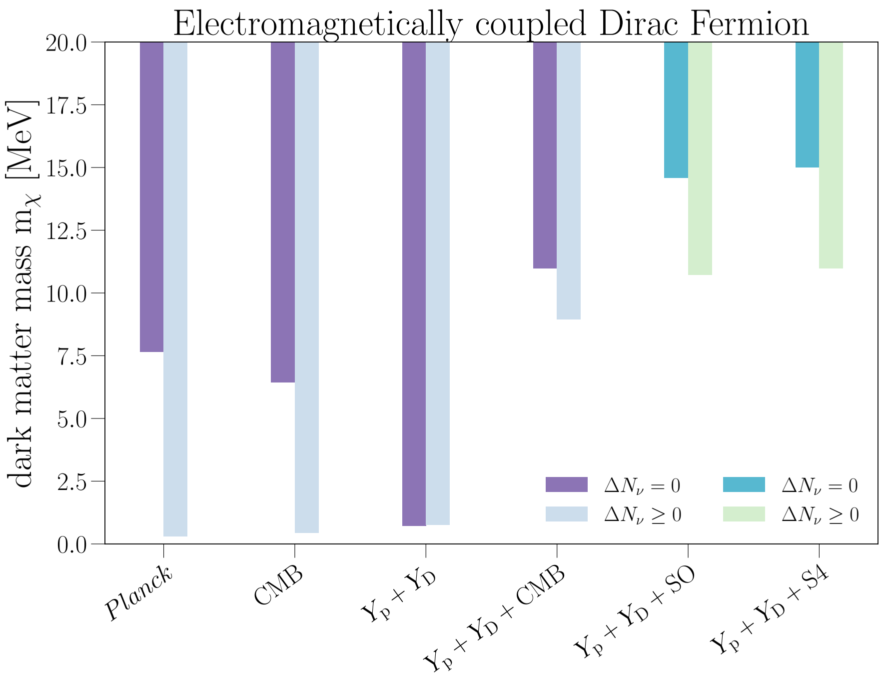


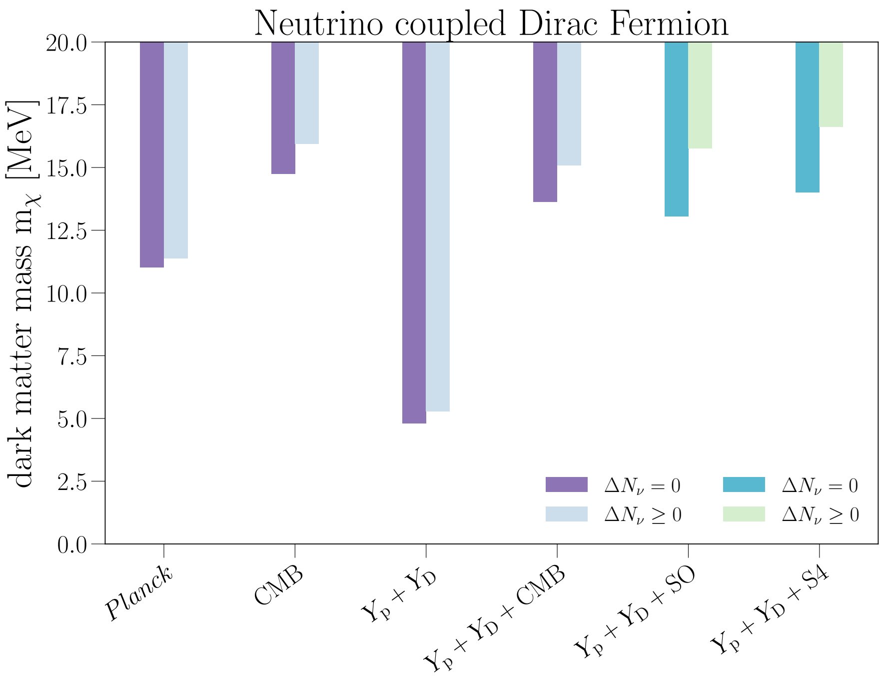

- Additional freedom can offset the reduction in the value of $N_{eff}$ caused by electromagnetically coupled DM, and weaken the mass bounds by up to an order of magnitude or more, from a few MeV to hundreds of keV
- For neutrino coupled models, the bounds are slightly improved.




- The combination of CMB data (=Planck+ACT+SPT) has a higher constraining power than the primordial abundance measurements alone
- There is a tension (at ~$1.8\sigma$ level) on $\Omega_b h^2$ between CMB and primordial abundances measurements, which mainly comes from $Y_D$.

# Current and Future constraints




- The combination of all CMB measurements and $Y_p + Y_D$ provides the lower mass limit of ~4 MeV at 95%CL, regardless of the model
- The forecasted mass bounds from Simons Observatory (SO)/CMB-S4 (S4) will improve by several MeV, as compared to Planck analyses

# SUMMARY

- Combining ACT and SPT with Planck improves the lower limit on $m_\chi$ by 40%–80% for neutrino coupled DM, and leads to a slightly weaker bound on electromagnetically coupled DM, due to a shift in the preferred values of $Y_p$ and $N_{eff}$.
- Allowing for new relativistic species can weaken the mass bounds for electromagnetically coupled DM by up to an order of magnitude or more, and slightly improve the bounds for neutrino coupled DM.
- The combination of CMB data has a higher constraining power than the primordial abundance measurements alone for most models.
- There is a tension between CMB and primordial abundance measurements (at ~$1.8\sigma$ level), which is derived by $Y_D$ measurement.
- Combining all CMB measurements with primordial abundance measurements, we rule out masses below ~4 MeV at 95% confidence for all models.
- The next generation of the CMB experiments will improve the bounds on DM mass by several MeV, as compared to current analyses