UNIVERSITY OF OREGON

Imprints of Ultralight Scalars across Cosmological History

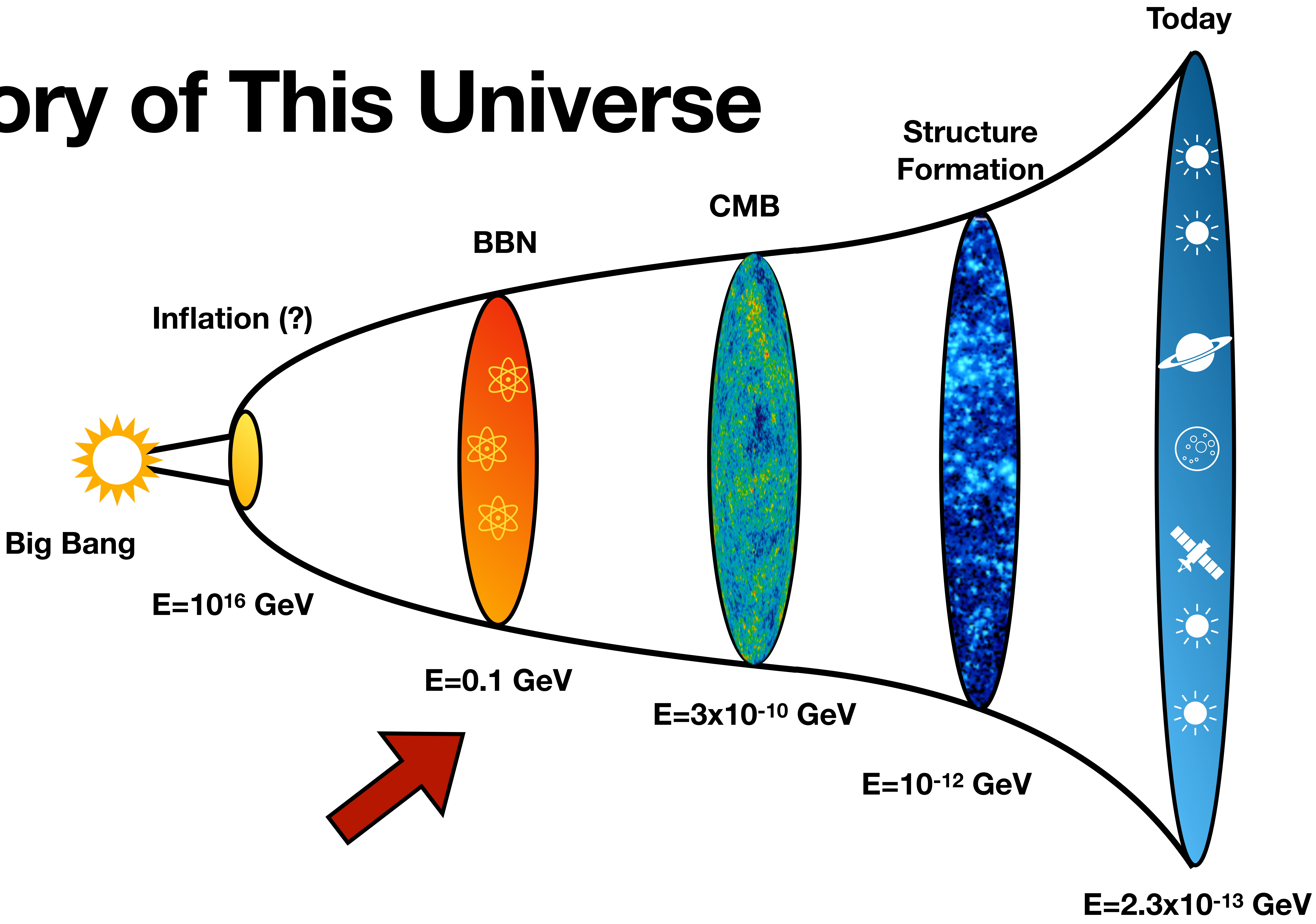
Tien-Tien Yu (University of Oregon)

based on S. Sibiryakov, P. Sørensen, TTY *JHEP 20 (2020) 075* [arXiv: 2006.04820]
T. Bouley, P. Sørensen, TTY *JHEP 03 (2023)* 104 [arXiv: 2211.09826]
S. Ghosh, K. Boddy, TTY [arXiv: 2511.tonight]

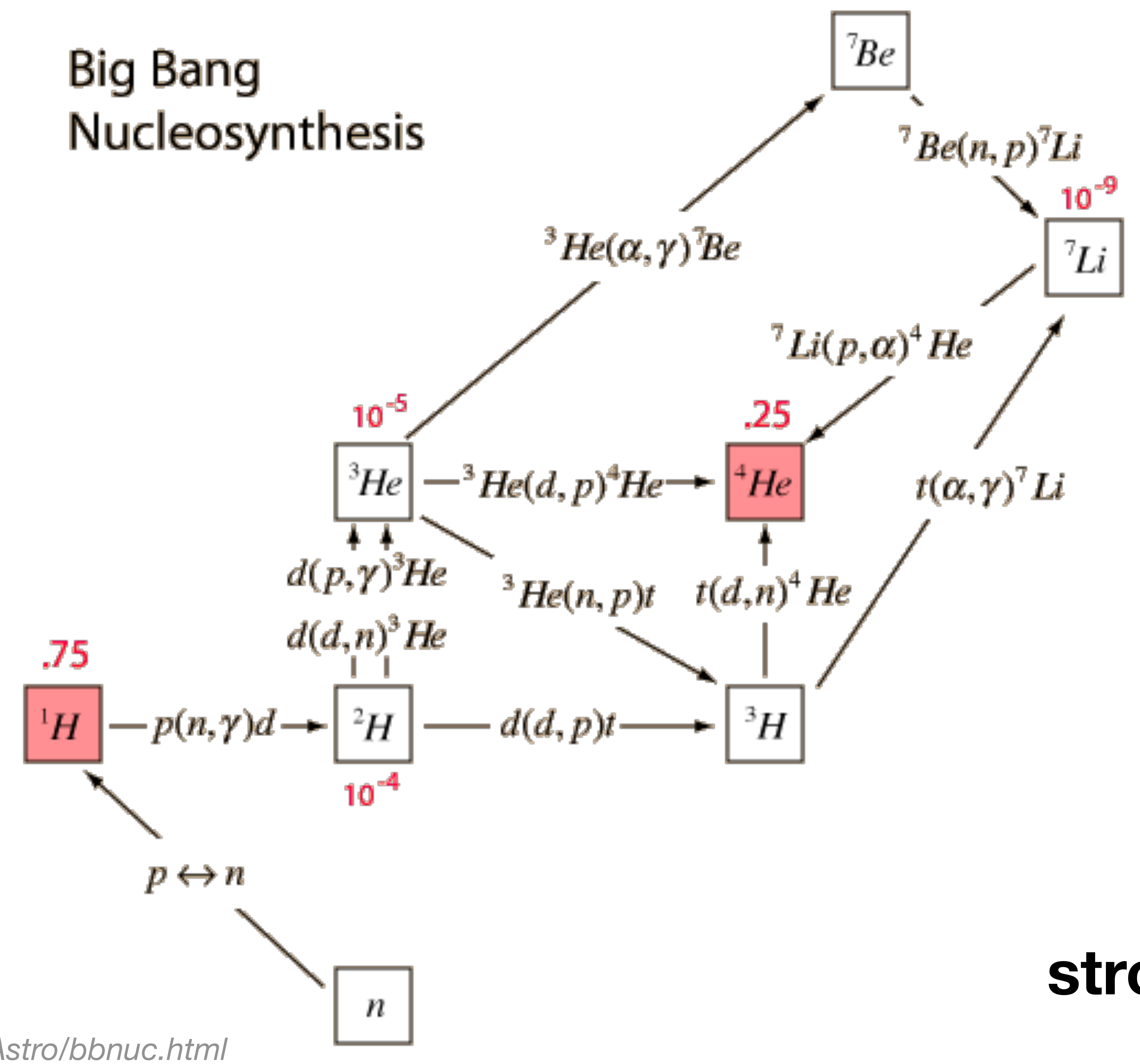
N3AS Seminar

November 18, 2025

History of This Universe



nuclear pathways



http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/bbnuc.html

Depends on:

- number of neutrino families
- neutron lifetime
- baryonic density
- well-understood sequence of events

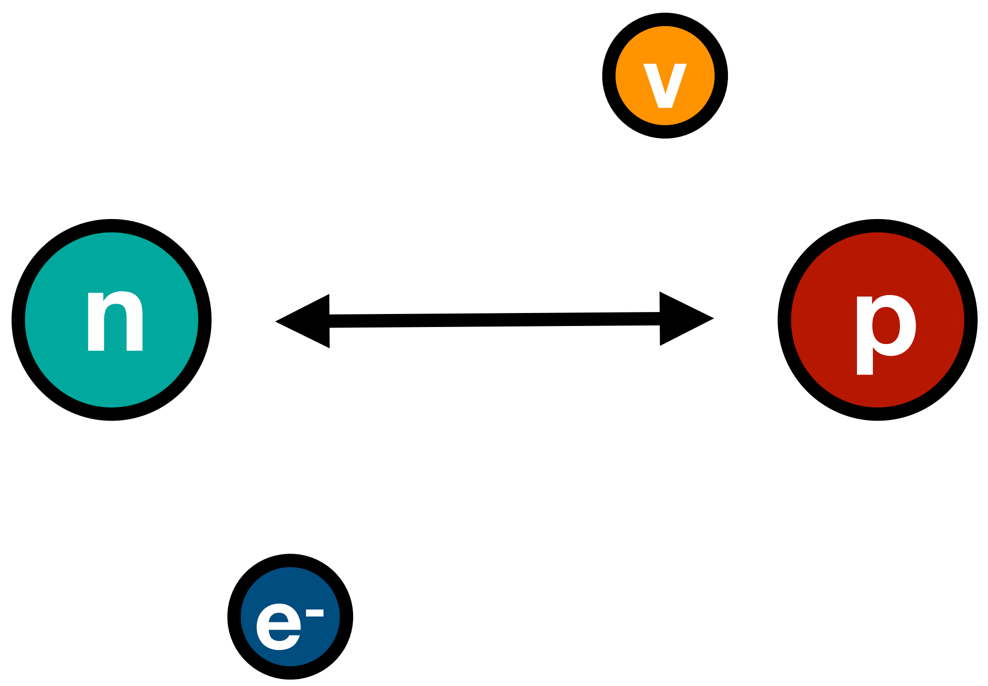
Consistency of predictions*

strong constraints on BSM physics

big bang nucleosynthesis

T>1 MeV

weak interactions keep neutrons and protons in thermal equilibrium



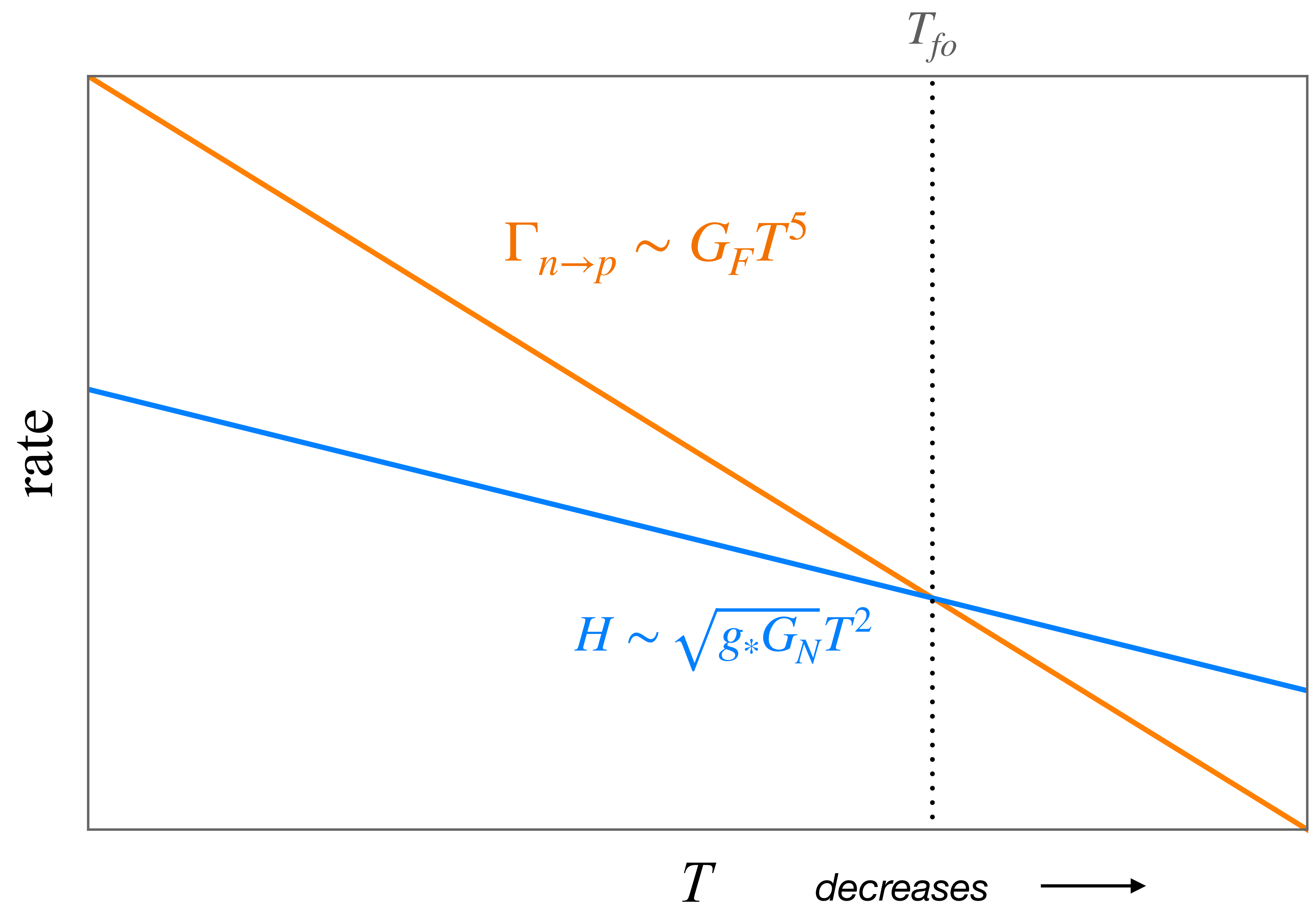
$$n \leftrightarrow p + e^- + \bar{\nu}$$

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

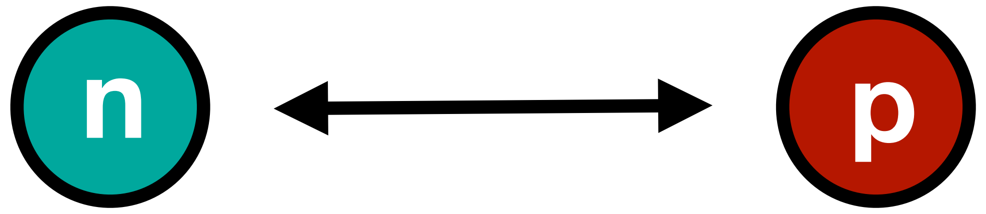
$$e^+ + n \leftrightarrow p + \bar{\nu}$$

$$\boxed{\frac{n}{p} = e^{-(m_n - m_p)/T}}$$

big bang nucleosynthesis

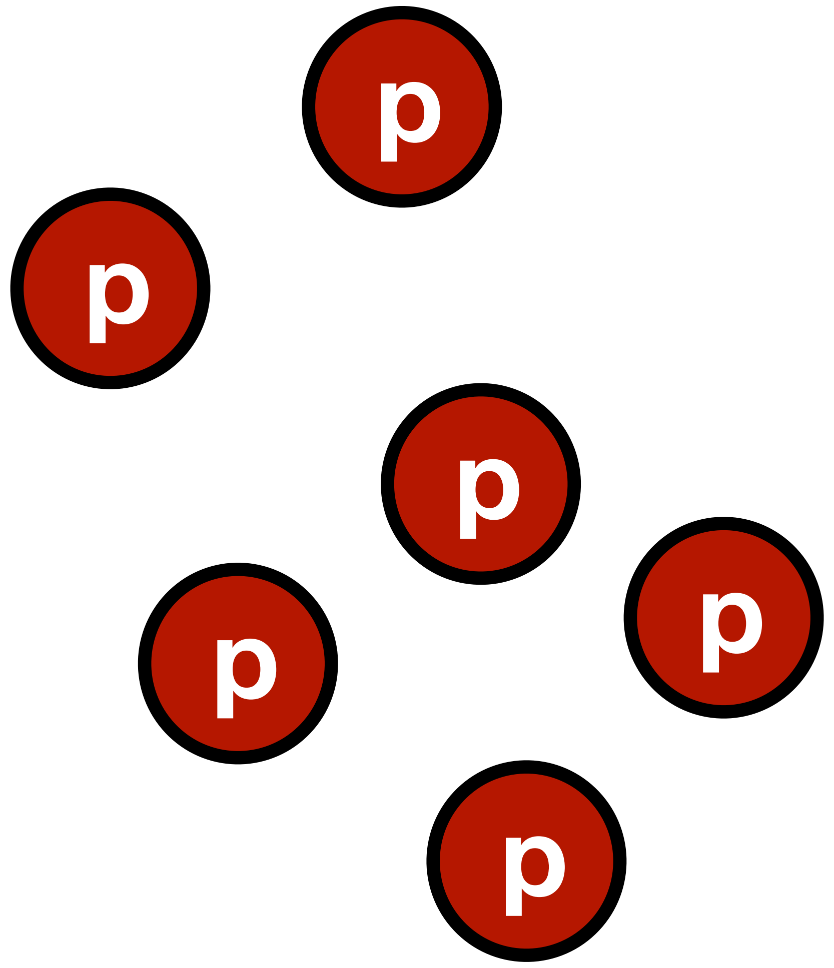


$\Gamma_{n\to p} \sim G_F T^5$

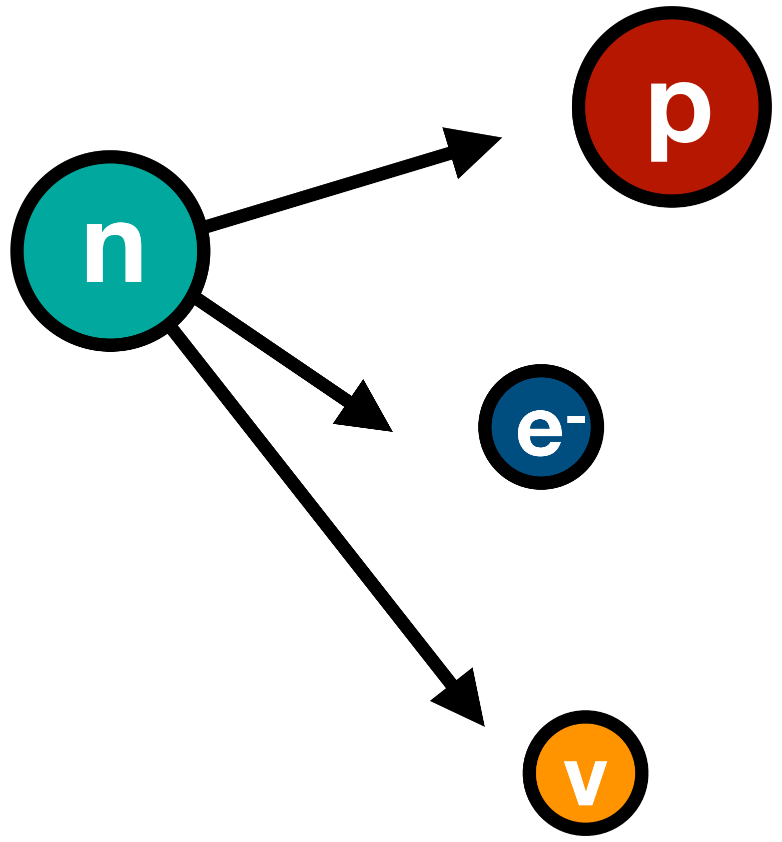


$$T_{fo} \sim \left(\frac{g_* G_N}{G_F^4}\right)^{1/6} \simeq 1 \text{ MeV}$$

$$\left.\frac{n}{p}\right|_{fo} = e^{-(m_n - m_p)/T_{fo}} \simeq \frac{1}{6}$$

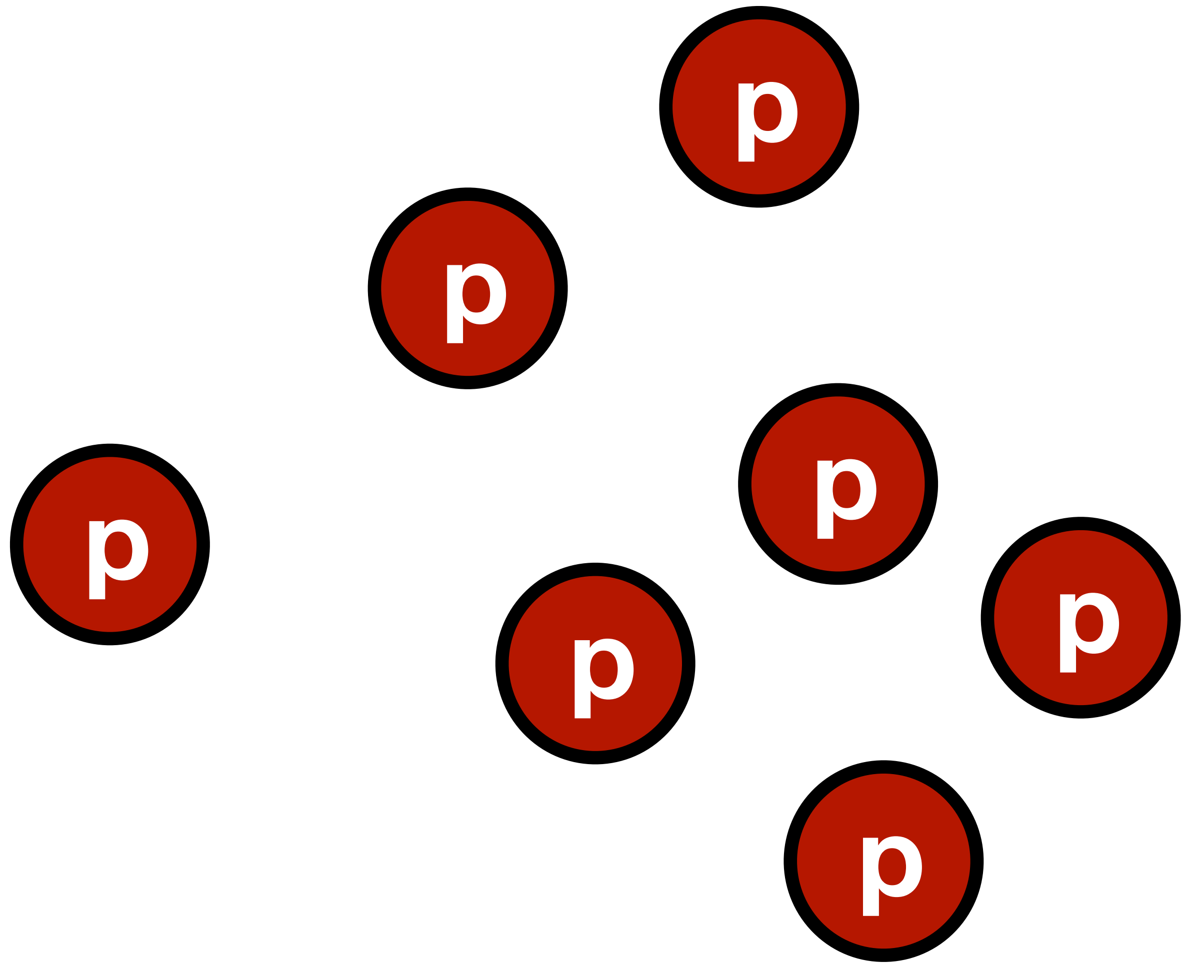


big bang nucleosynthesis

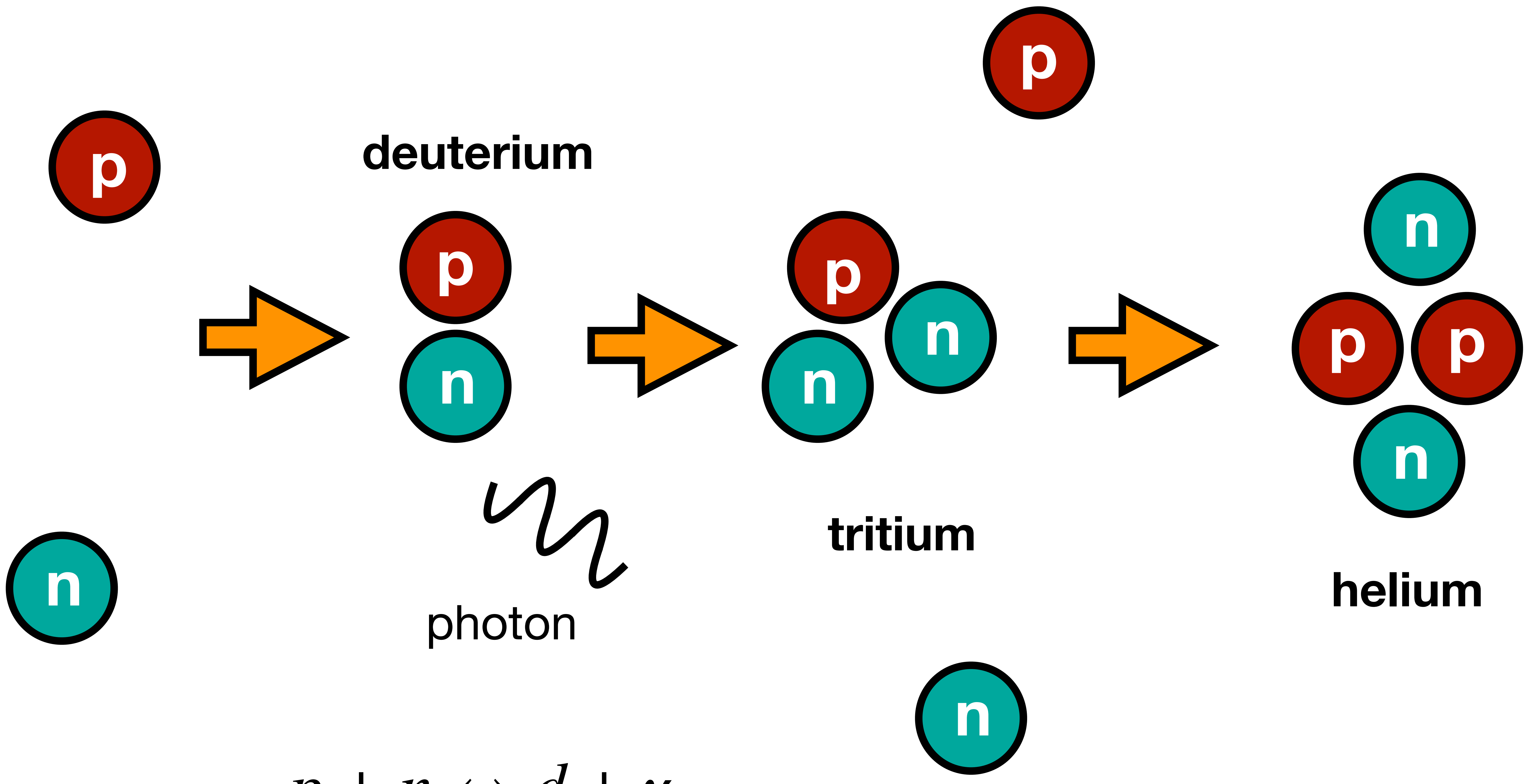


$$n \rightarrow p + e^- + \bar{\nu}_e$$ **neutron decay**

$$\left.\frac{n}{p}\right|_{fo} = e^{-(m_n - m_p)/T_{fo}} \simeq \frac{1}{6} \rightarrow \frac{1}{7}$$

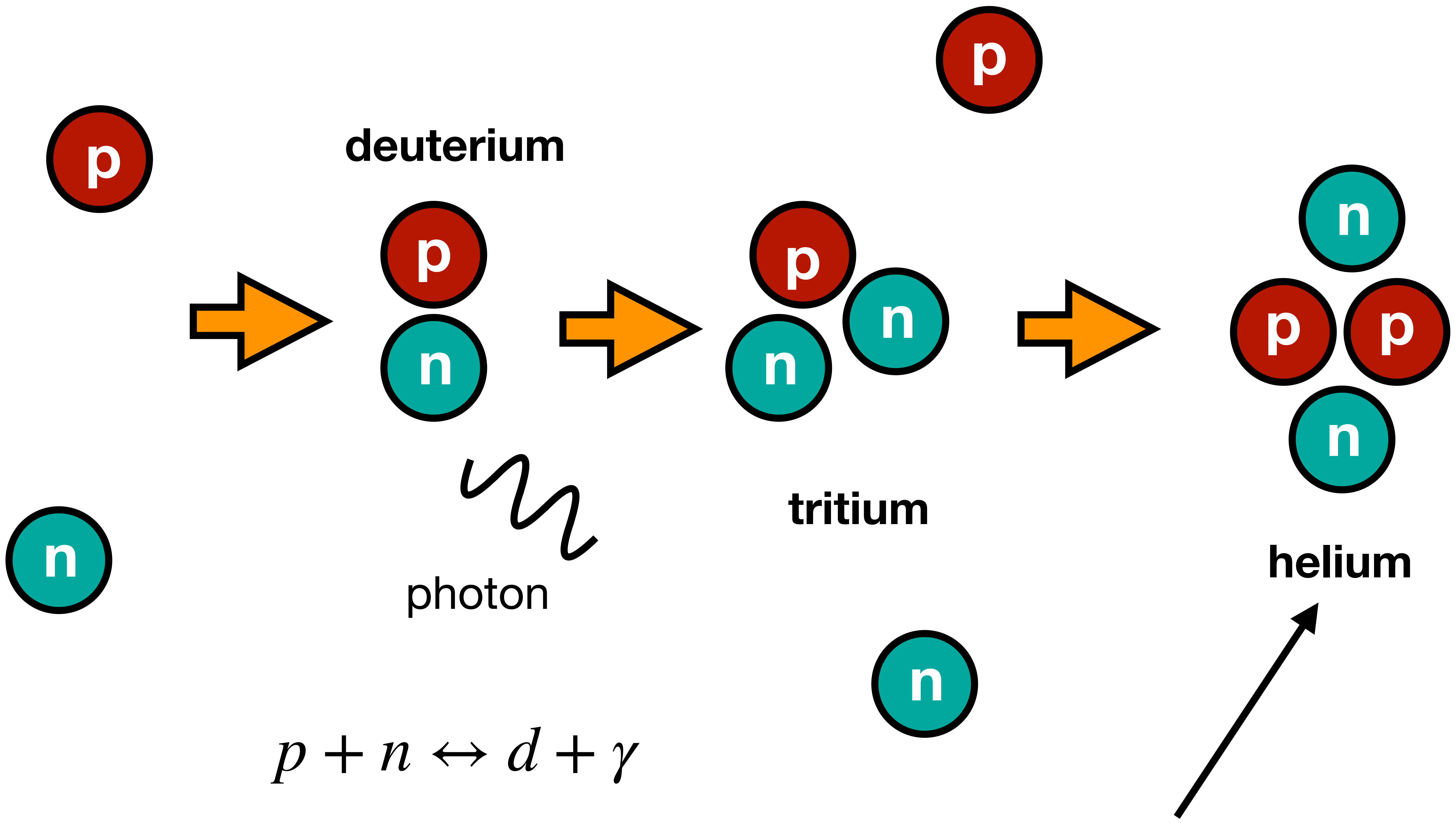


Helium-4 formation



$$p + n \leftrightarrow d + \gamma$$

Helium-4 formation

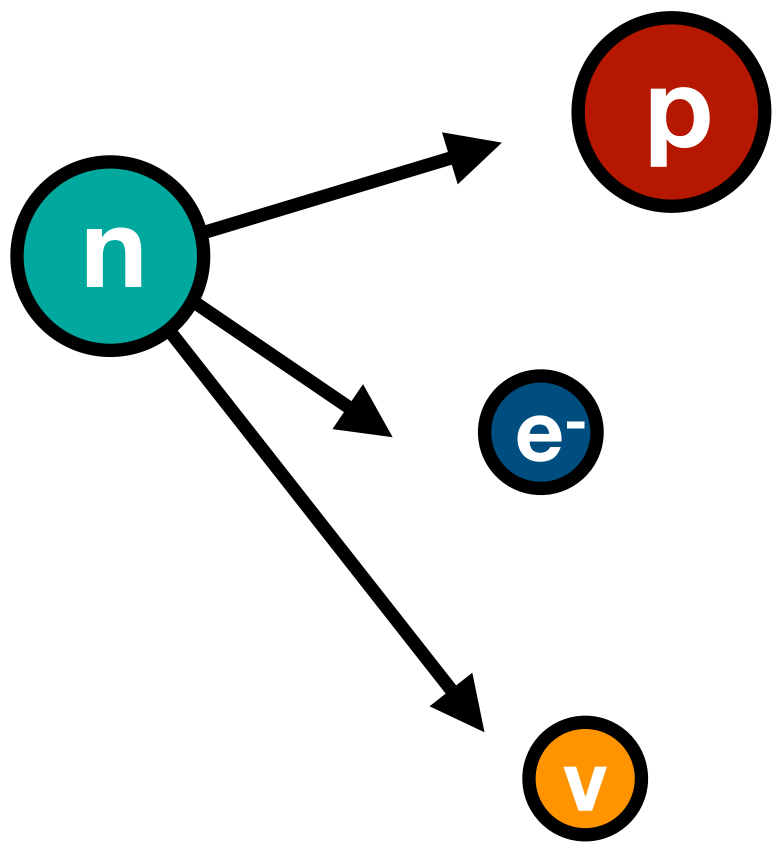


$$p + n \leftrightarrow d + \gamma$$

very stable!

all free neutrons end up here

Helium-4 formation



$$n \to p + e^- + \bar{\nu}_e$$ **neutron decay**

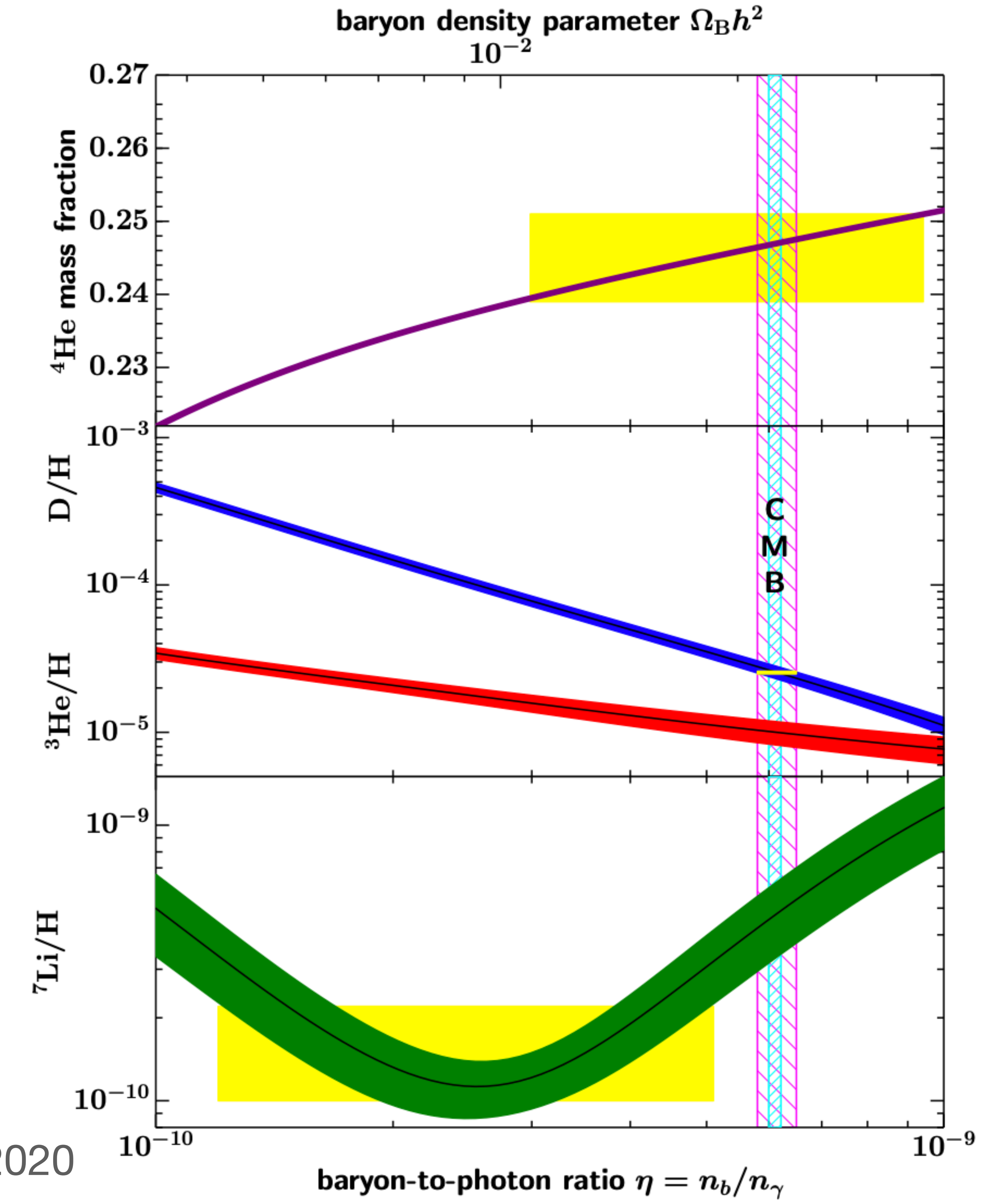
new physics can change this!

$$\left.\frac{n}{p}\right|_{fo} = e^{-(m_n - m_p)}/T_{fo} \simeq \frac{1}{6} \to \frac{1}{7}$$

determines 4He abundance

$$\boxed{{}^4\mathrm{He} \to Y_p = \frac{2(n/p)}{1+n/p} \simeq 0.25}$$

primordial abundances



PDG 2020

Helium-4

$$Y_{\mathrm{th}} = 0.24709 \pm 0.00025 \qquad Y_{\mathrm{exp}} = 0.245 \pm 0.003$$

$$\frac{\Delta Y_p}{Y_p} = \frac{Y_{\mathrm{exp}} - Y_{\mathrm{th}}}{Y_{\mathrm{th}}} = -0.008458 \pm 0.012183$$

$$\boxed{\frac{\Delta Y_{\mathrm{p}}}{Y_{\mathrm{p}}} \simeq \frac{\Delta X_{n,\mathrm{W}}}{X_{n,\mathrm{W}}} - \Delta\left(\int_{a_{\mathrm{W}}}^{a_{\mathrm{BBN}}} \frac{da}{aH(a)}\Gamma_n(a)\right)}$$

neutron abundance

neutron decay

neutron abundance at BBN

$$X_{n,BBN} = X_{n,W} \exp\left(- \int_{a_W}^{a_{BBN}} \frac{da}{aH} \Gamma_n \right)$$

$$\frac{\Delta X_{n,BBN}}{X_{n,BBN}} = \frac{\Delta X_{n,W}}{X_{n,W}} - \left(\int_{a_W}^{a_{BBN}} \frac{da}{aH} \Delta\Gamma_n \right) - \frac{\Gamma_n}{H} \frac{\Delta a}{a} \Bigg|_{a_W}^{a_{BBN}}$$

$$\approx \boxed{\frac{\Delta X_{n,W}}{X_{n,W}}} - \left(\int_{a_W}^{a_{BBN}} \frac{da}{aH} \boxed{\Delta\Gamma_n} \right) + \frac{\Gamma_n}{H} \Bigg|_{a_{BBN}} \boxed{\frac{\Delta T_{BBN}}{T_{BBN}}}$$

$$\frac{\Delta T_{BBN}}{T_{BBN}} \simeq \boxed{\frac{\Delta B_D}{B_D}}$$

Need to know these

neutron abundance at freeze-out

Instantaneous approximation: $$X_{n,W} \simeq e^{-m_{np}/T_W}$$

approximate weak freeze-out temperature

$$\frac{\Delta X_{n,W}}{X_{n,W}} = -\frac{m_{np}}{T_W}\left(\frac{\Delta m_{np}}{m_{np}} - \frac{\Delta T_W}{T_W}\right)$$

however, we need to go beyond instantaneous approximation…

neutron abundance at freeze-out

neutron abundance
$$\frac{n_n}{n_b} = \frac{1}{1+e^{m_{np}/T}} \equiv X_n^{\text{eq}}$$

kinetic equation
$$\frac{dX_n}{dt} = -\lambda_{n\to p}\left(1+e^{-m_{np}/T}\right)\left(X_n - X_n^{\text{eq}}\right)$$

neutron-proton conversion

phase-space integral
$$\lambda_{n\to p} = \frac{1+3g_A^2}{\pi^3}\, G_F^2\, T^5 J\left(m_{np}/T\right)$$

Neutron abundance at Weak freeze-out

$$\boxed{X_{n,\text{W}} = -\int_0^\infty da \frac{dX_n^{\text{eq}}}{da} \exp\left[-\int_a^\infty \frac{da_1}{a_1}\frac{\lambda_{n\to p}}{H(a_1)}\left(1+e^{-\frac{m_{np}}{T}}\right)\right]}$$

neutron abundance at freeze-out

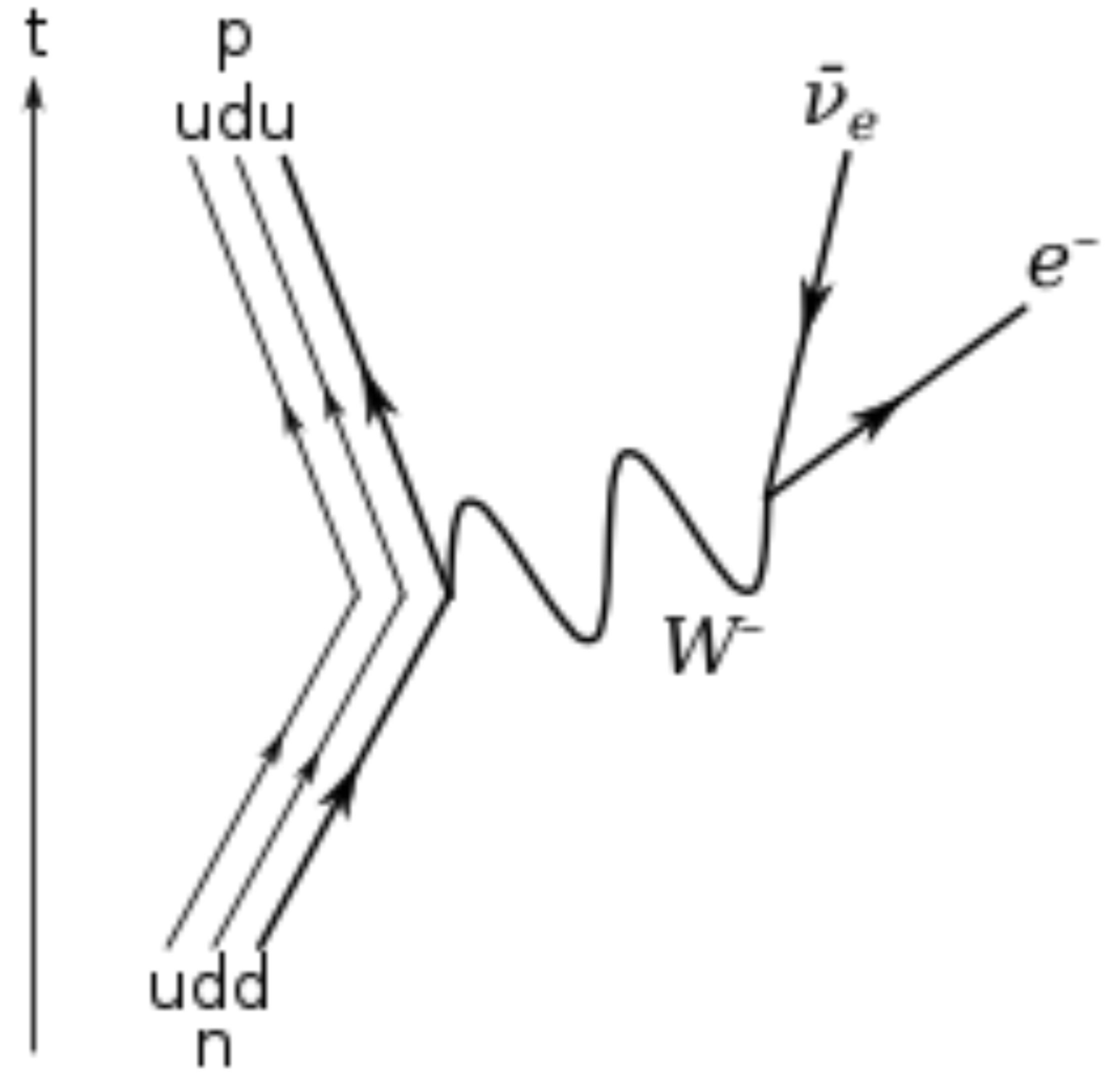
need to go beyond instantaneous approximation…

$$\frac{\Delta X_{n,W}}{X_{n,W}} = -\frac{m_{np}}{T_W}\left(\frac{\Delta m_{np}}{m_{np}} - \frac{\Delta T_W}{T_W}\right)$$

instead,

$$\boxed{\begin{aligned}\Delta X_{n,W} = \int_0^\infty \frac{da}{a}\frac{m_{np}}{2T(1+\cosh(m_{np}/T))}\exp\left[-\int_a^\infty \frac{da'}{a'}\tilde{\lambda}_{n\to p}\right] \times \Bigg\{ -\tilde{\lambda}_{n\to p}\frac{\Delta m_{np}}{m_{np}} + \\ \int_a^\infty \frac{da'}{a'}\tilde{\lambda}_{n\to p}\left[\frac{m_{np}X_n^{eq}}{T}\frac{\Delta m_{np}}{m_{np}} - \frac{6{g_A}_n^2}{1+3{g_A}_n^2}\frac{\Delta {g_A}_n}{{g_A}_n} - 2\frac{\Delta G_F}{G_F} - \frac{m_{np}J'}{TJ}\frac{\Delta m_{np}}{m_{np}} \right. \\ \left. + \frac{3\zeta(3)}{2J}\frac{m_e^2}{T^2}\left(\frac{\Delta m_e}{m_e} - \frac{\Delta m_{np}}{m_{np}}\right)\right]\Bigg\}.\end{aligned}}$$

neutron decay



phase space factor

$$\Gamma_n = \frac{1+3{g_{A}}_n^2}{2\pi^3} G_F^2 m_e^5 P\left(\frac{m_{np}}{m_e}\right)$$

$$\boxed{\frac{\Delta\Gamma_n}{\Gamma_n} = \frac{6{g_{A}}_n^2}{1+3g_{A_n}}\frac{\Delta g_{A_n}}{g_{A_n}} + 2\frac{\Delta G_F}{G_F} + 5\frac{\Delta m_e}{m_e} + \frac{m_{np}P'}{m_e P}\left(\frac{\Delta m_{np}}{m_{np}} - \frac{\Delta m_e}{m_e}\right)}$$

4He analytic constraint

neutron abundance@weak freezeout

deuterium binding energy

axial coupling

$$\frac{\Delta Y_p}{Y_p} = \frac{\Delta X_{n,W}}{X_{n,W}} + \frac{\Gamma_n}{H}\frac{\Delta B_D}{B_D}\bigg|_{a_{BBN}} - \int_{a_W}^{a_{BBN}} \frac{da}{a}\frac{\Gamma_n}{H}\left(\frac{6{g_A}_n^2}{1+3g_{A_n}}\frac{\Delta g_{A_n}}{g_{A_n}} + 2\frac{\Delta G_F}{G_F} + 5\frac{\Delta m_e}{m_e} + \frac{m_{np}P'}{m_e P}\left(\frac{\Delta m_{np}}{m_{np}} - \frac{\Delta m_e}{m_e}\right)\right)$$

Fermi constant

electron mass

neutron-proton mass difference

$$\frac{\Delta Y_{\mathrm{p}}}{Y_{\mathrm{p}}} = \frac{Y_{\mathrm{p}}^{\mathrm{exp}} - Y_{\mathrm{p}}^{\mathrm{th}}}{Y_{\mathrm{p}}^{\mathrm{th}}} = -0.008 \pm 0.012$$

Scalar with non-universal coupling

$$\mathcal{L} \supset 2\pi \frac{\phi^2}{M_{\rm pl}^2} \left[\frac{d_e^{(2)}}{4e^2} F_{\mu\nu}F^{\mu\nu} - \frac{d_g^{(2)}\beta_3}{2g_3} G^A_{\mu\nu}G^{A\mu\nu} - d_{m_e}^{(2)} m_e \bar{e}e - \sum_{i=u,d} \left(d_{m_i}^{(2)} + \gamma_{m_i} d_g^{(2)} \right) m_i \bar{\psi}_i \psi_i \right]$$

$$d_{\hat{m}} \equiv \frac{d_{m_d} m_d + d_{m_u} m_u}{m_d + m_u} \qquad \text{symmetric}$$

$$d_{\delta m} \equiv \frac{d_{m_d} m_d - d_{m_u} m_u}{m_d - m_u} \qquad \text{anti-symmetric}$$

Scalar with non-universal coupling

$$\mathcal{L} \supset 2\pi \frac{\phi^2}{M_{\rm pl}^2}\left[\frac{d_e^{(2)}}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g^{(2)}\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - d_{m_e}^{(2)} m_e \bar{e}e - \sum_{i=u,d}\left(d_{m_i}^{(2)} + \gamma_{m_i} d_g^{(2)}\right) m_i \bar{\psi}_i \psi_i\right]$$

$$\frac{\Delta\alpha}{\alpha} = d_e^{(2)}\frac{\varphi^2}{2}\,,$$

$$\frac{\Delta\Lambda_{\rm QCD}}{\Lambda_{\rm QCD}} = d_g^{(2)}\frac{\varphi^2}{2}\,,$$

$$\frac{\Delta m_f}{m_f} = d_{m_f}^{(2)}\frac{\varphi^2}{2} \quad \text{for } f = e, u, d$$

$$\frac{\Delta m_{np}}{m_{np}} = \frac{b\alpha\Lambda_{\rm QCD}}{m_{np}}\left(d_e^{(2)}\frac{\varphi^2}{2} + d_g^{(2)}\frac{\varphi^2}{2}\right) + \frac{m_d - m_u}{m_{np}}\left((d_{\delta m}^{(2)} + \gamma d_g^{(2)})\frac{\varphi^2}{2}\right)$$

$$\frac{\Delta B_D}{B_D} = 18 d_g^{(2)}\frac{\varphi^2}{2}$$

$$\frac{\Delta G_F}{G_F} = d_e^{(2)}\frac{\varphi^2}{2}$$

$$\varphi = \sqrt{4\pi}\phi/M_{\rm Pl}$$

induces mass terms for scalar!

know: scalar is all of DM now $\quad \phi_0 = \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi}$

need to know: value of scalar field at BBN $\quad \phi_{\rm BBN}$

scalar evolution

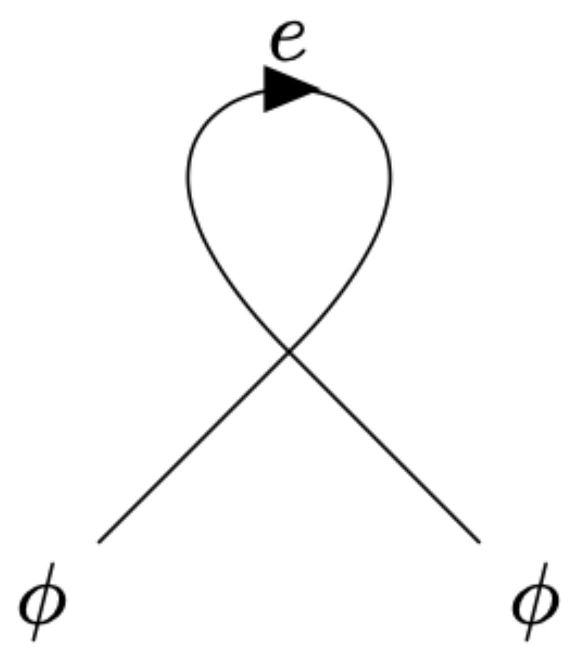
$$\ddot{\phi} + \boxed{3H\dot{\phi}} + \boxed{(m_\phi^2} + \boxed{m_{\text{induced}}^2})\phi = 0$$

$\rho_{\text{DM}} \propto$ constant $\qquad \rho_{\text{DM}} \propto a^{-3}(t) \qquad ???$

electron coupling

$$\ddot{\phi} + 3H\dot{\phi} + \left(m_\phi^2 + \boxed{m^2_{\text{induced}}}\right)\phi = 0$$

$m_{\text{induced}} =$

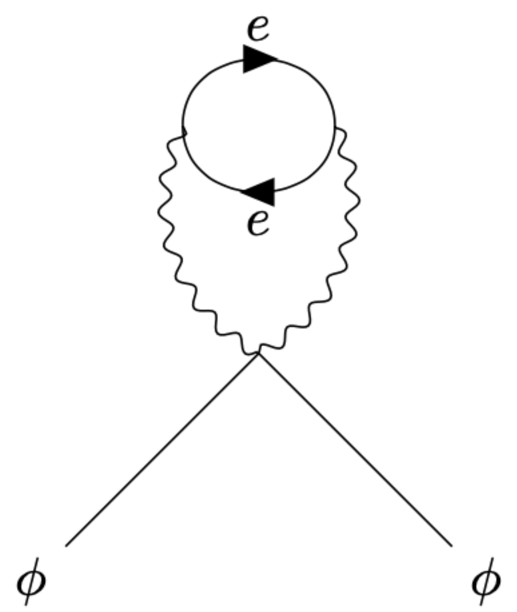


$$m^2_{\text{eff}} = m_\phi^2 + \frac{4\pi d^{(2)}_{m_e}}{M^2_{\text{pl}}}\Theta_e = m_\phi^2 + \boxed{\frac{4\pi d^{(2)}_{m_e}}{M^2_{\text{pl}}}(\rho_e - 3P_e)}$$

photon coupling

$$\ddot{\phi} + 3H\dot{\phi} + (m_\phi^2 + \boxed{m_{\text{induced}}^2})\phi = 0$$

$$m_{\text{induced}} =$$



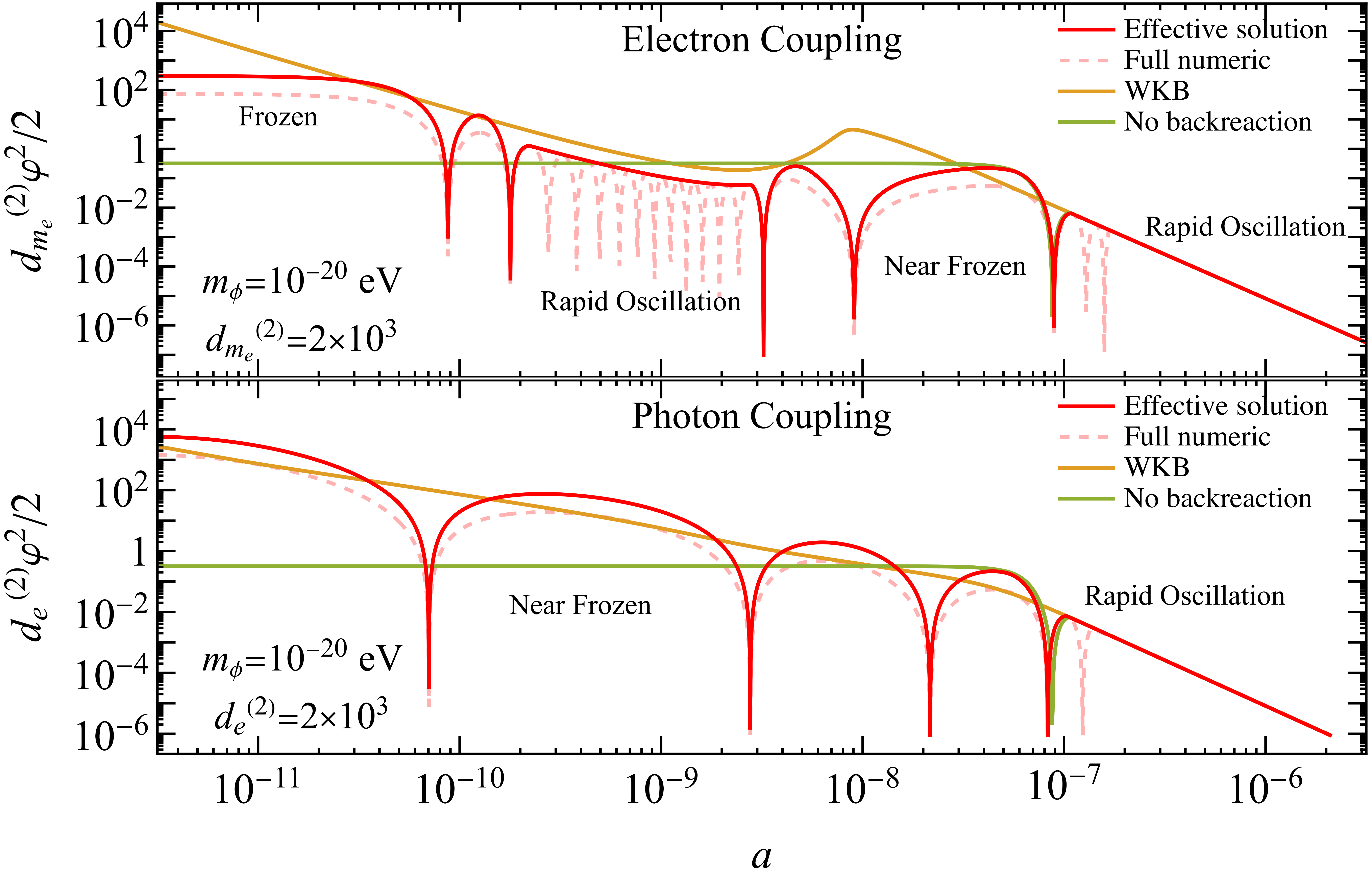
tough to calculate…

in high-temperature limit: $$\Pi_2 = \boxed{\frac{2\pi d_e^{(2)}}{M_{\text{pl}}^2}\frac{\alpha}{4\pi}\frac{\pi^2}{3}T^4}.$$

in low-temperature limit: $$m_{\text{eff}} \simeq m_\phi$$

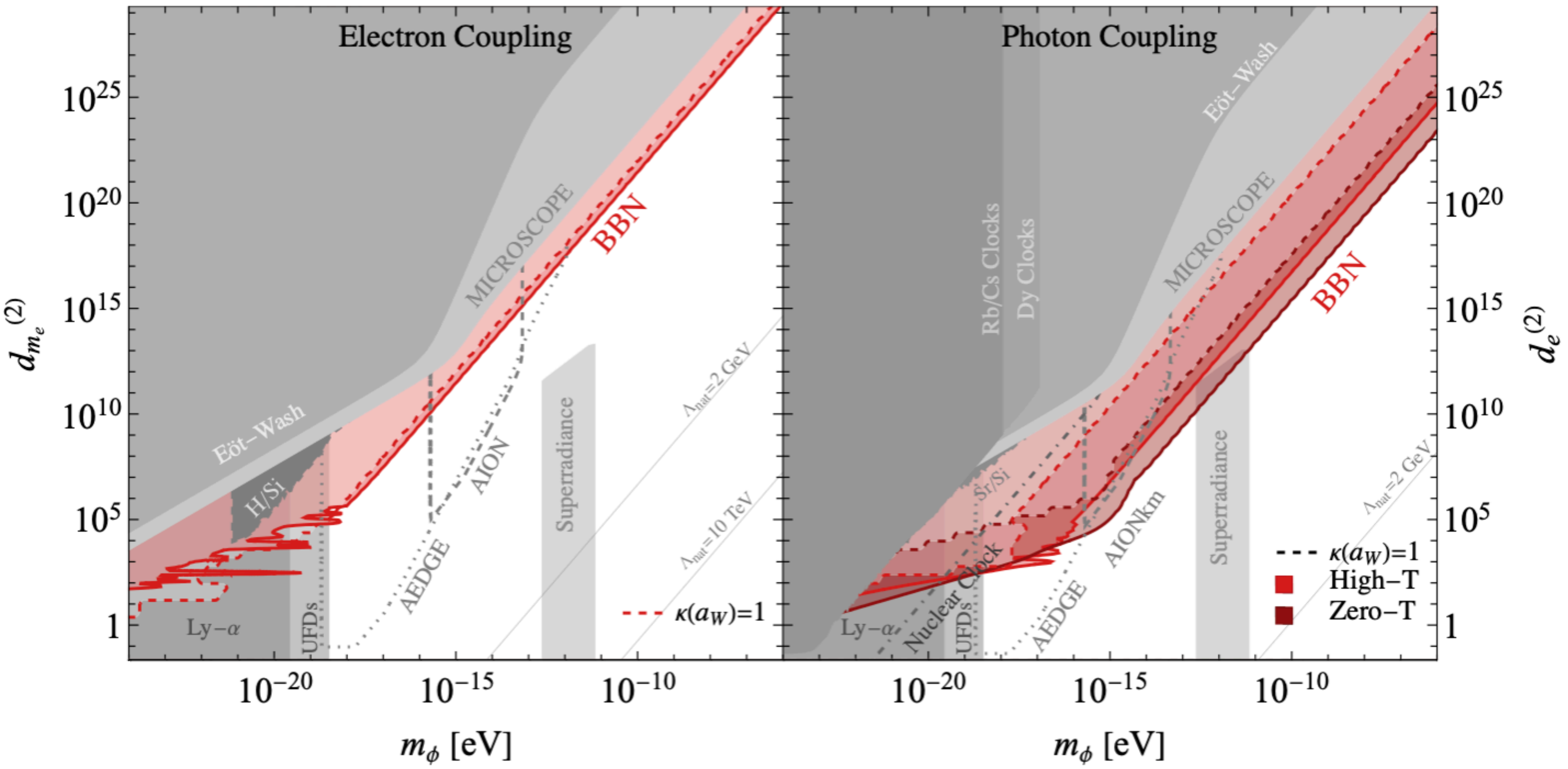
scalar evolution

T. Bouley, P. Sørensen, TTY *JHEP 03 (2023)* 104 [arXiv: 2211.09826]

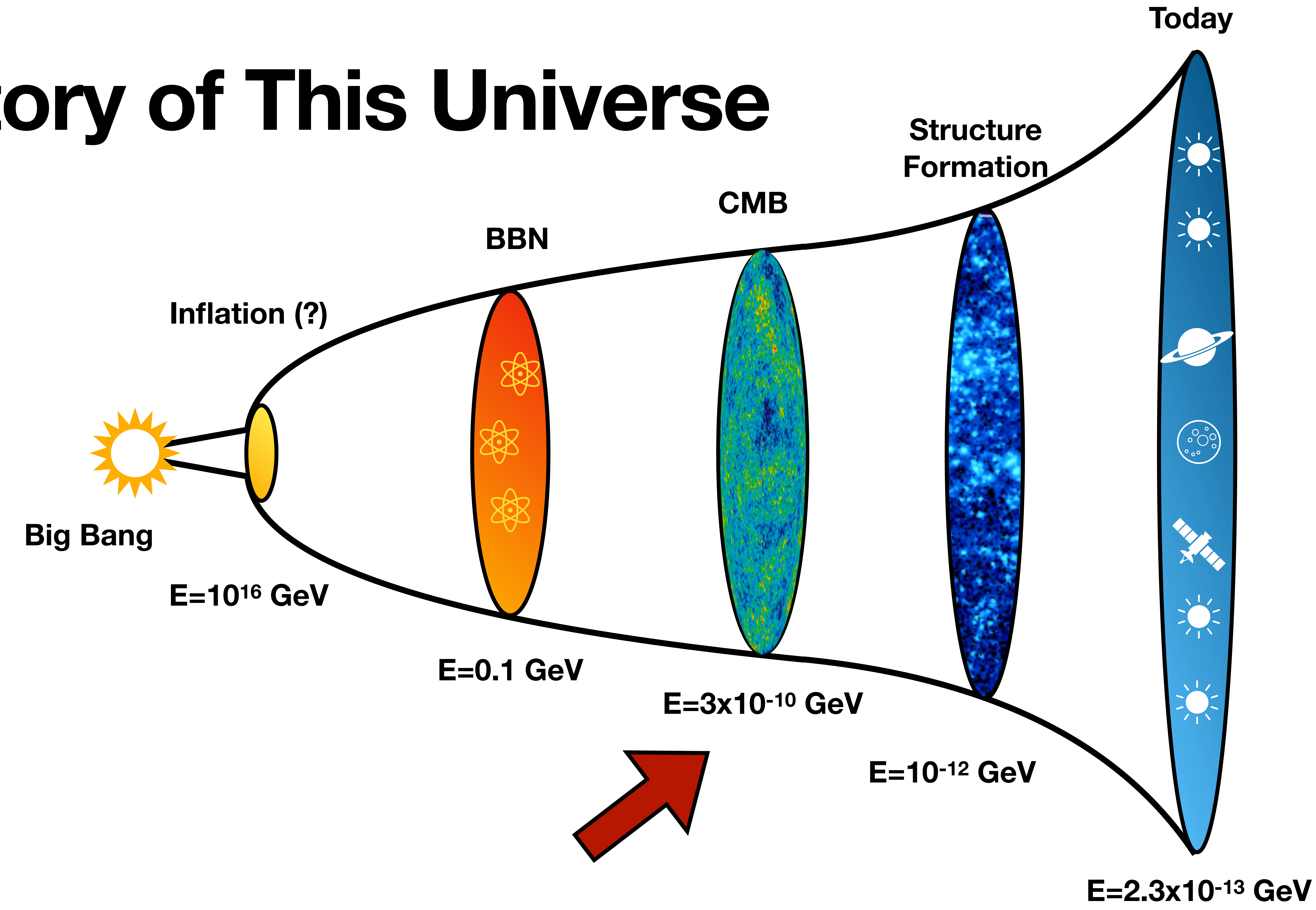


Non-Universally coupled scalar(s)

T. Bouley, P. Sørensen, TTY *JHEP 03 (2023)* 104 [arXiv: 2211.09826]



History of This Universe

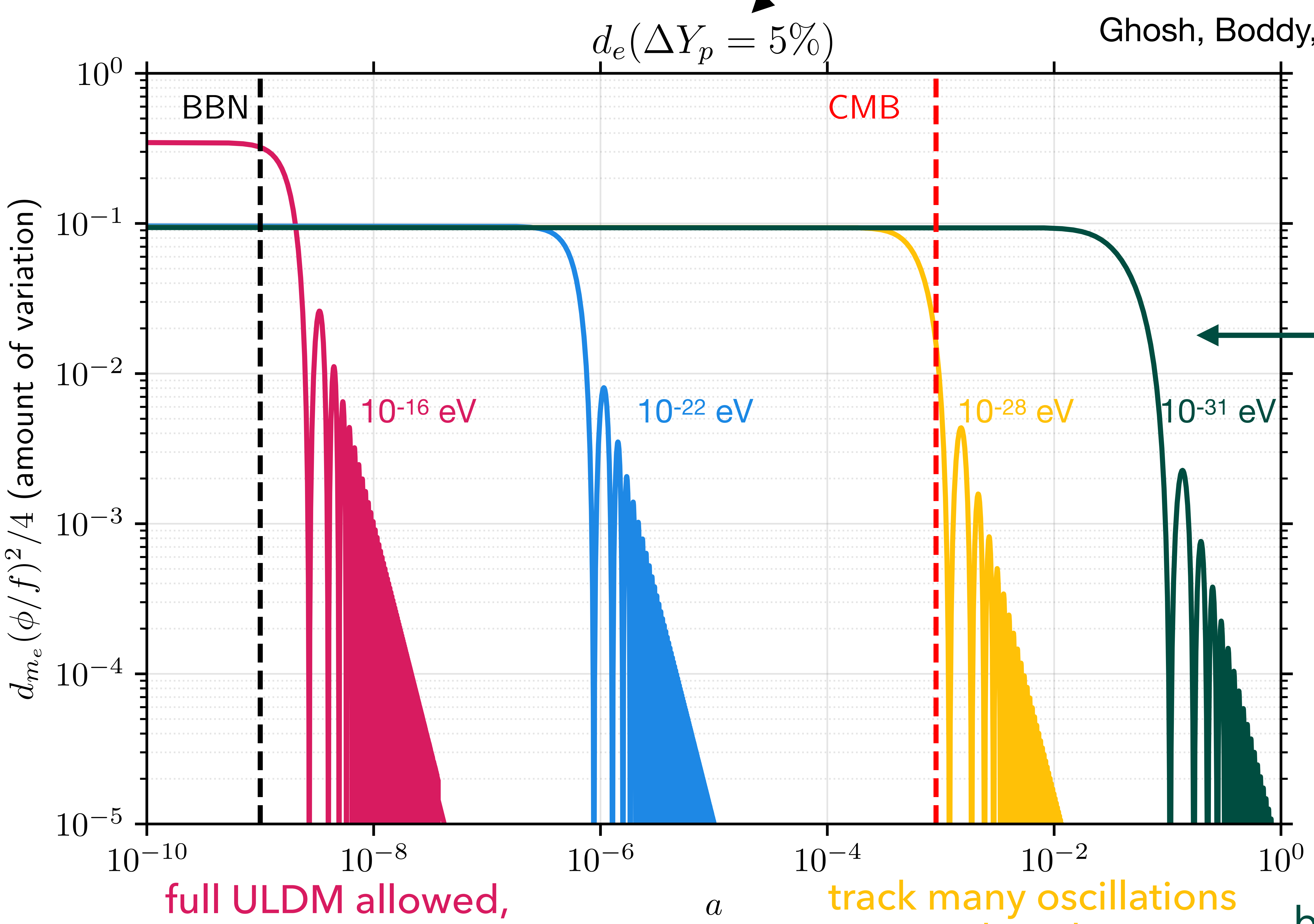


redshift dependence of variations

need to modify helium abundance as input for CMB calculations

$$\frac{\Delta\alpha(z)}{\alpha} = 2\pi d_e^{(2)} \frac{\phi^2(z)}{M_{\rm pl}^2}$$

Ghosh, Boddy, TTY (in prep)



see also Baryakhtar, et al. arXiv.2405.10358, arXiv.2502.04432

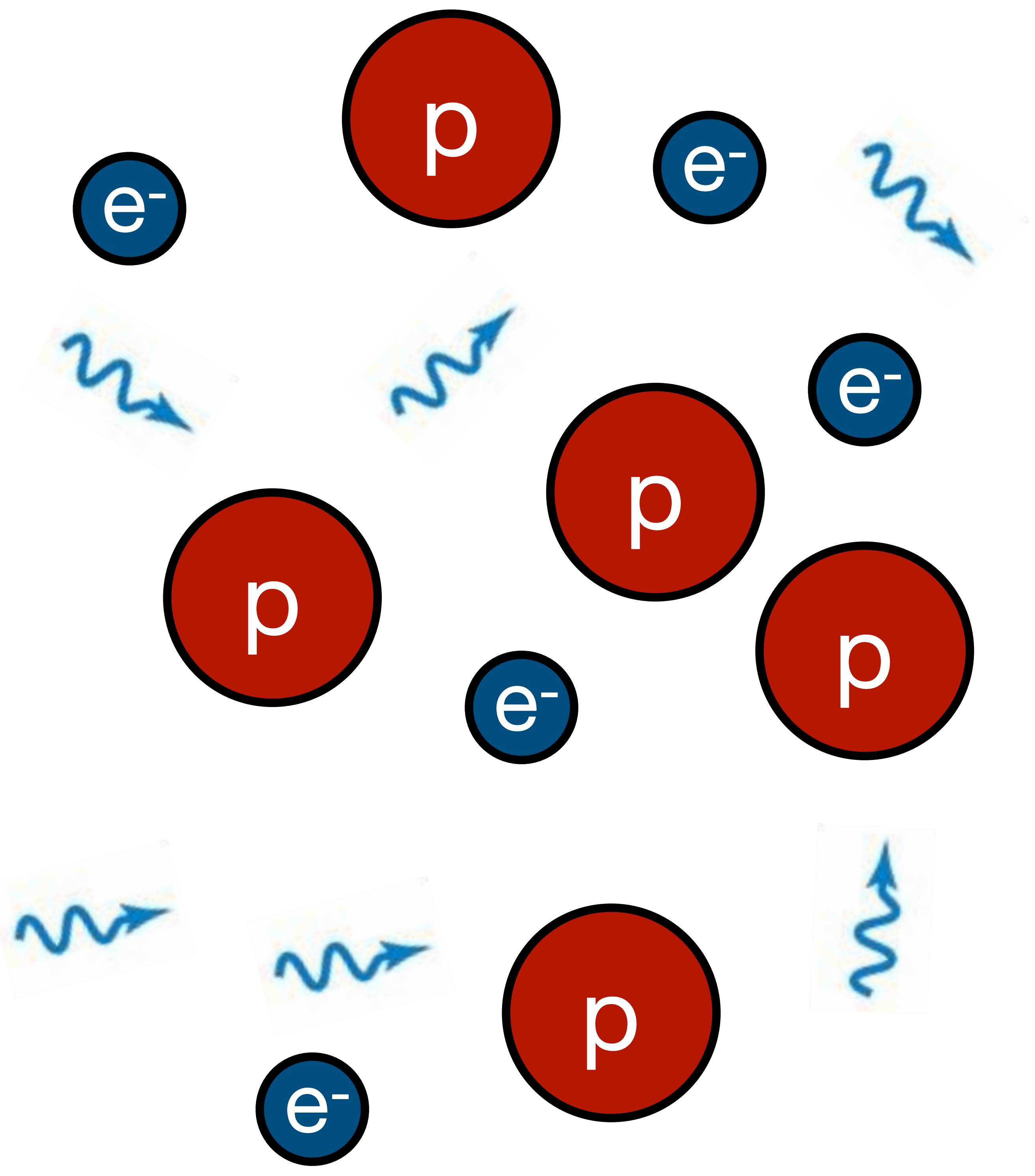
full ULDM allowed, shifts Y_p

fractional ULDM

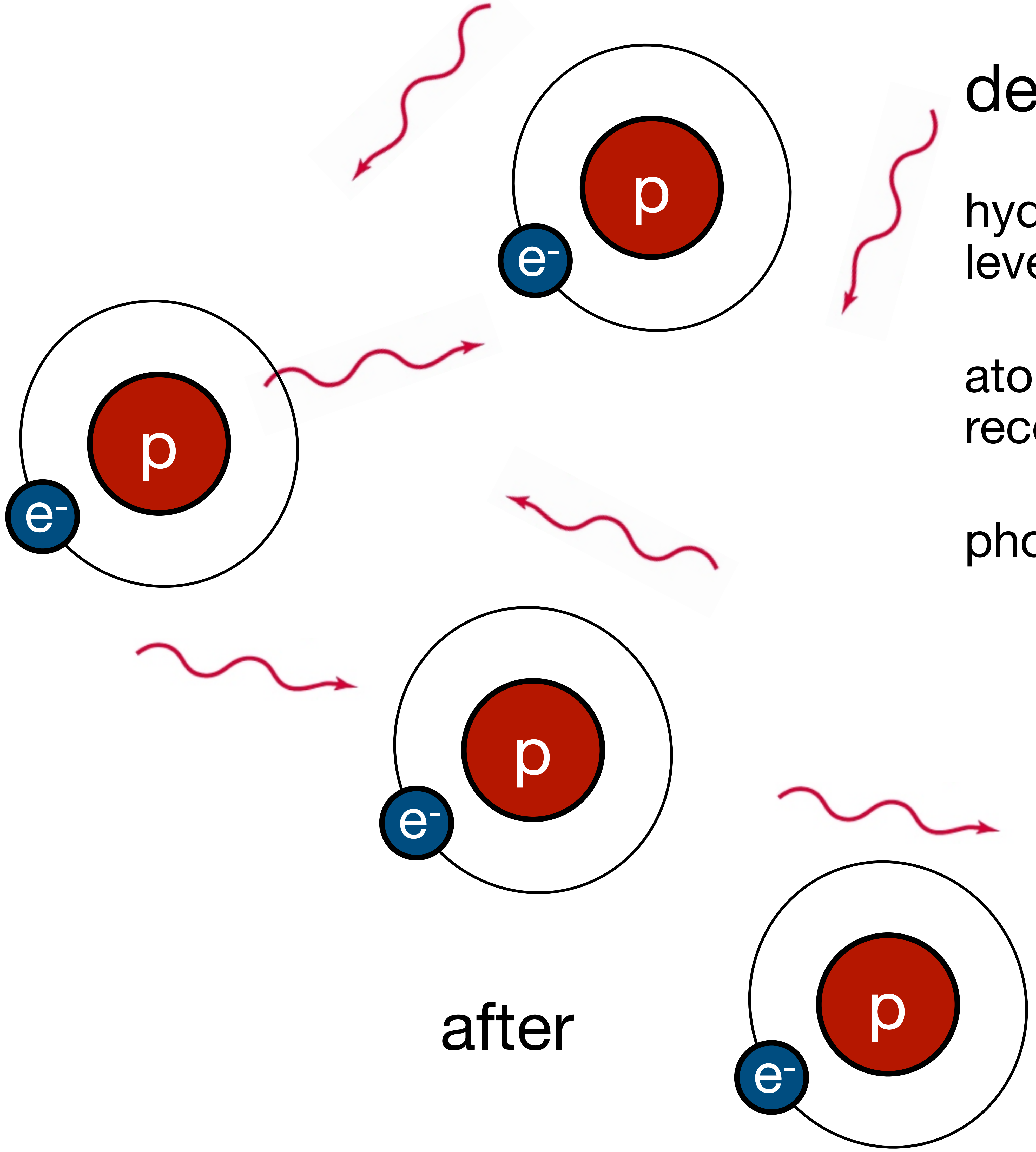
track many oscillations to avoid washing out impact of ϕ

constant VFC, but need to account for shift in Y_p

recombination



before



after

depends on:

hydrogen and helium energy levels

atomic transitions and recombination rates

photon-electron interactions

α_{EM} and m_e in recombination

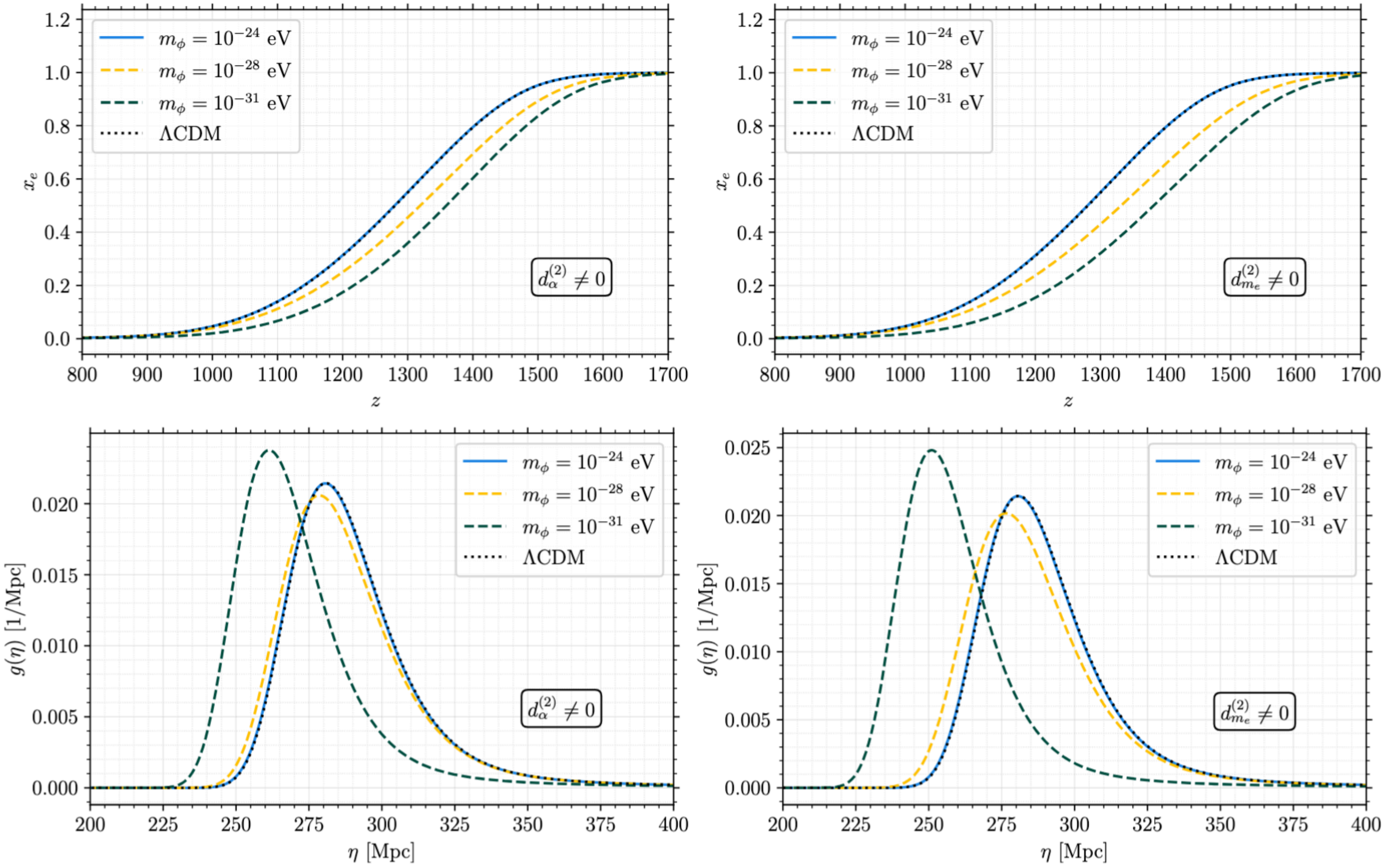
free-electron fraction

sensitive to energy

levels of H $\propto \alpha^2 m_e$

visibility function:

sensitive to $\sigma_T \propto \alpha^2/m_e^2$



gravitational effects of ULDM

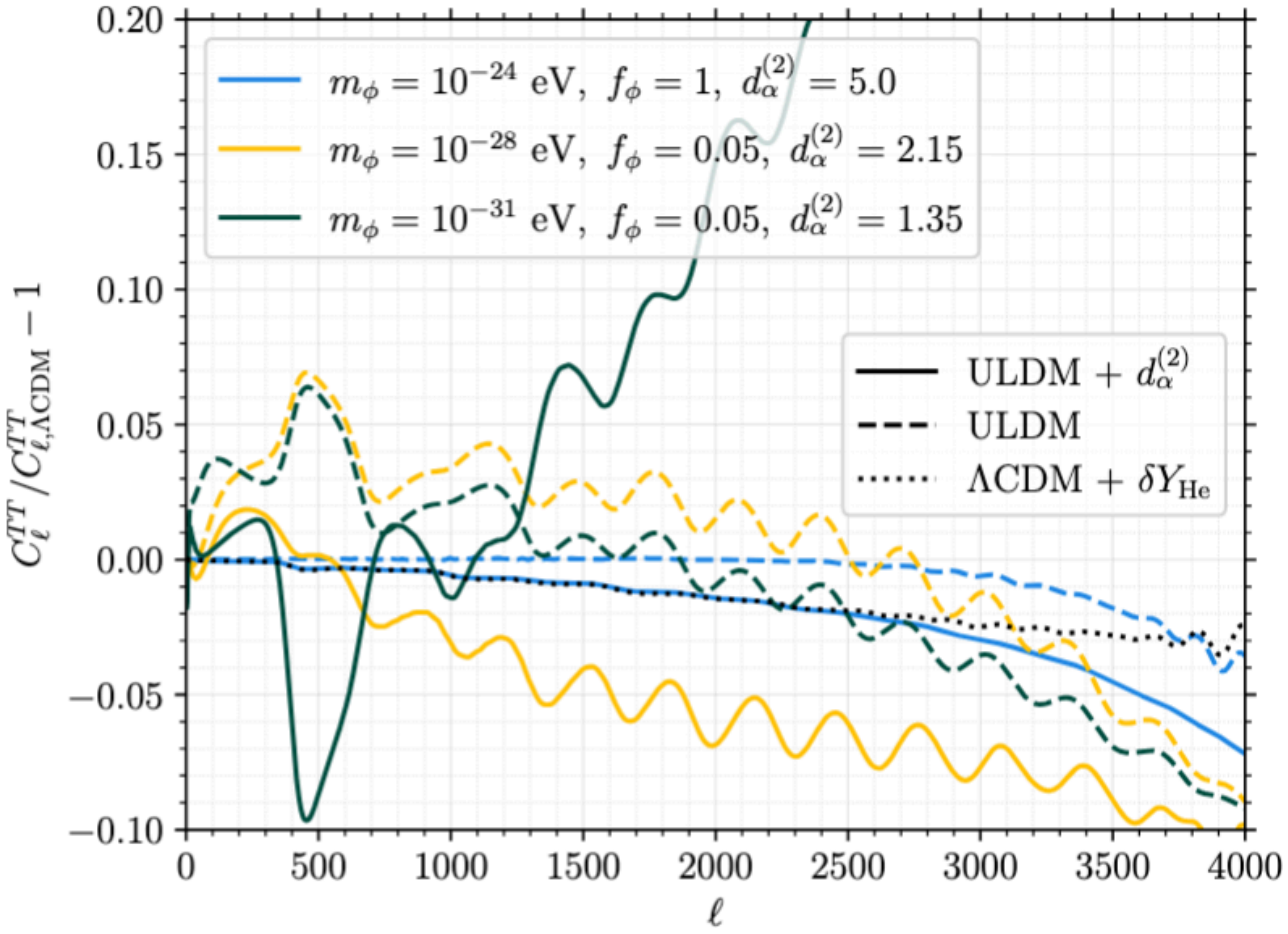
a coherently oscillating field leads to a new Jeans scale $k_J \sim \sqrt{m_\phi H}$

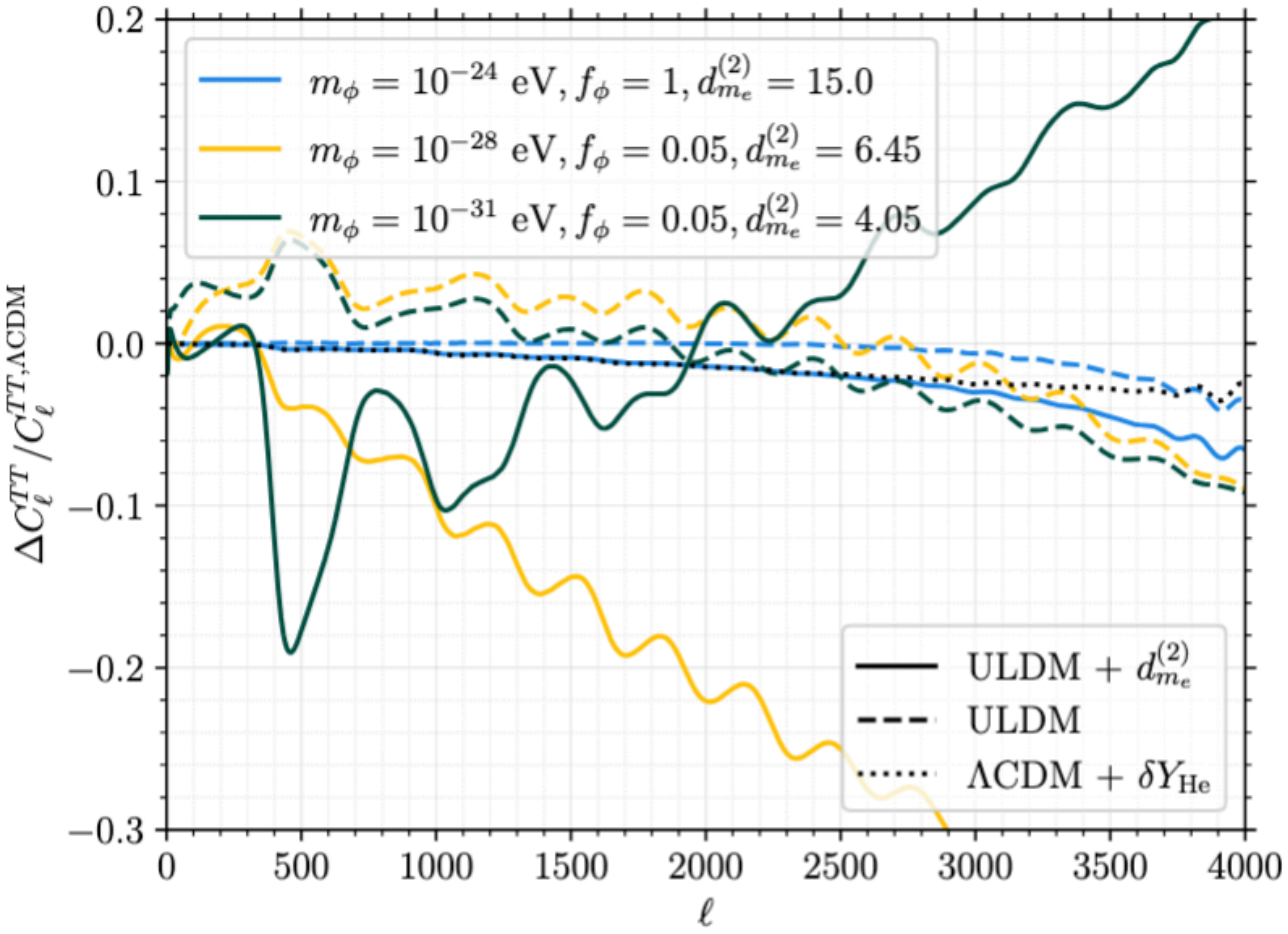
ULDM suppresses structure for $k < k_J$

sufficiently low-mass ULDM modifies CMB power spectra

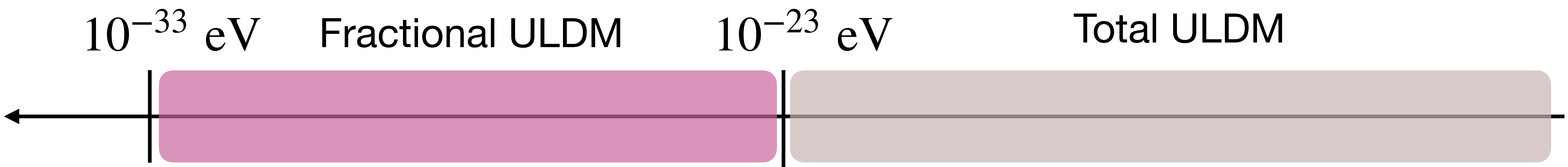
ULDM constrained to be a fraction of total DM energy density

combined effects





Parameter space exploration



$\boxed{\text{Low Mass (LM)}}$

$$m_\phi, f_\phi(=\frac{\omega_\phi}{\omega_\phi + \omega_{\text{CDM}}}), d_e, d_{m_e}$$

MCMC analysis

(With all parameters)

$\boxed{\text{High Mass (HM)}}$

$$m_\phi, f_\phi(=1), d_e, d_{m_e}$$

Only effect on CMB is ΔY_p

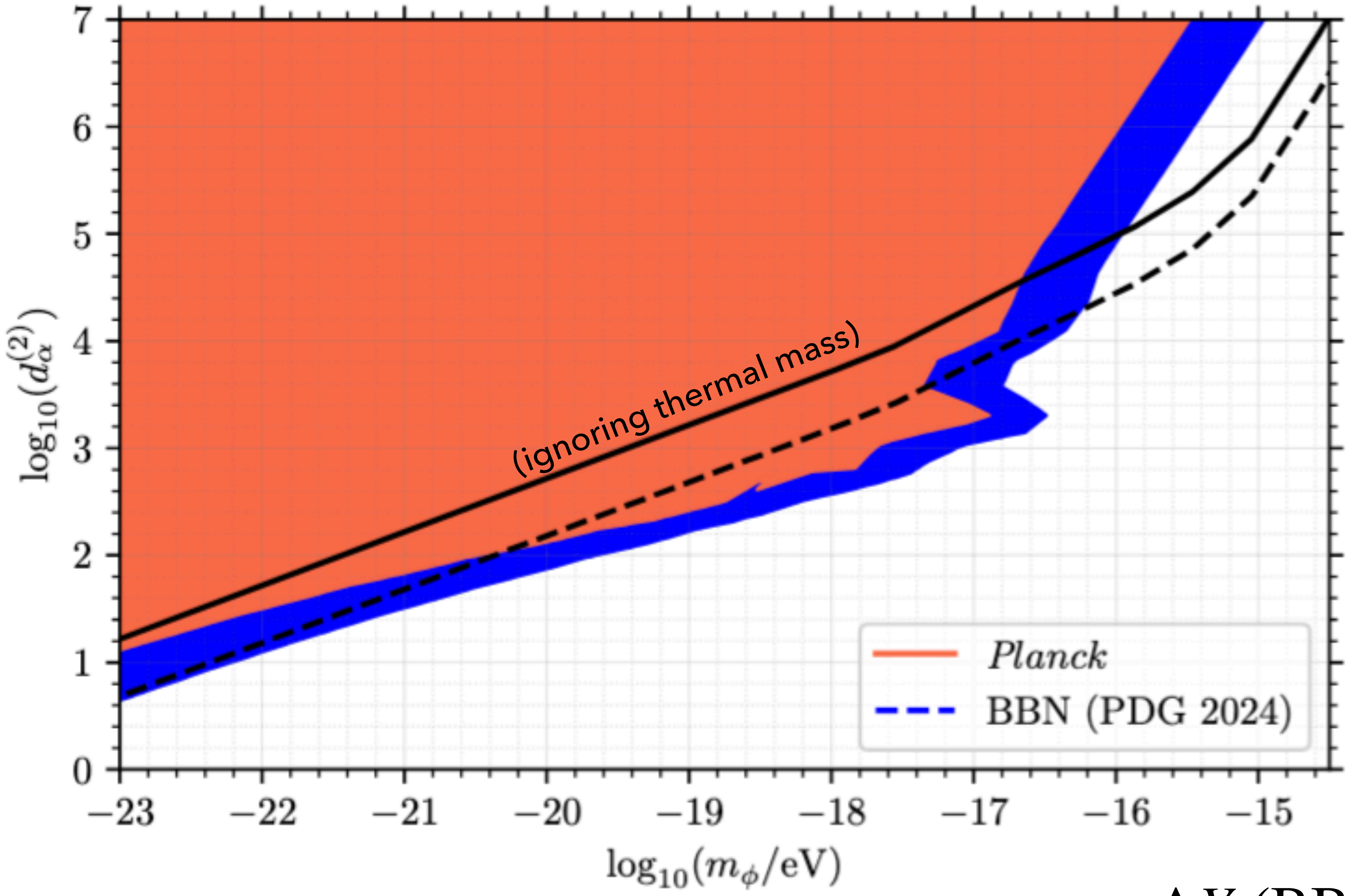
(Variation at recombination is very small)

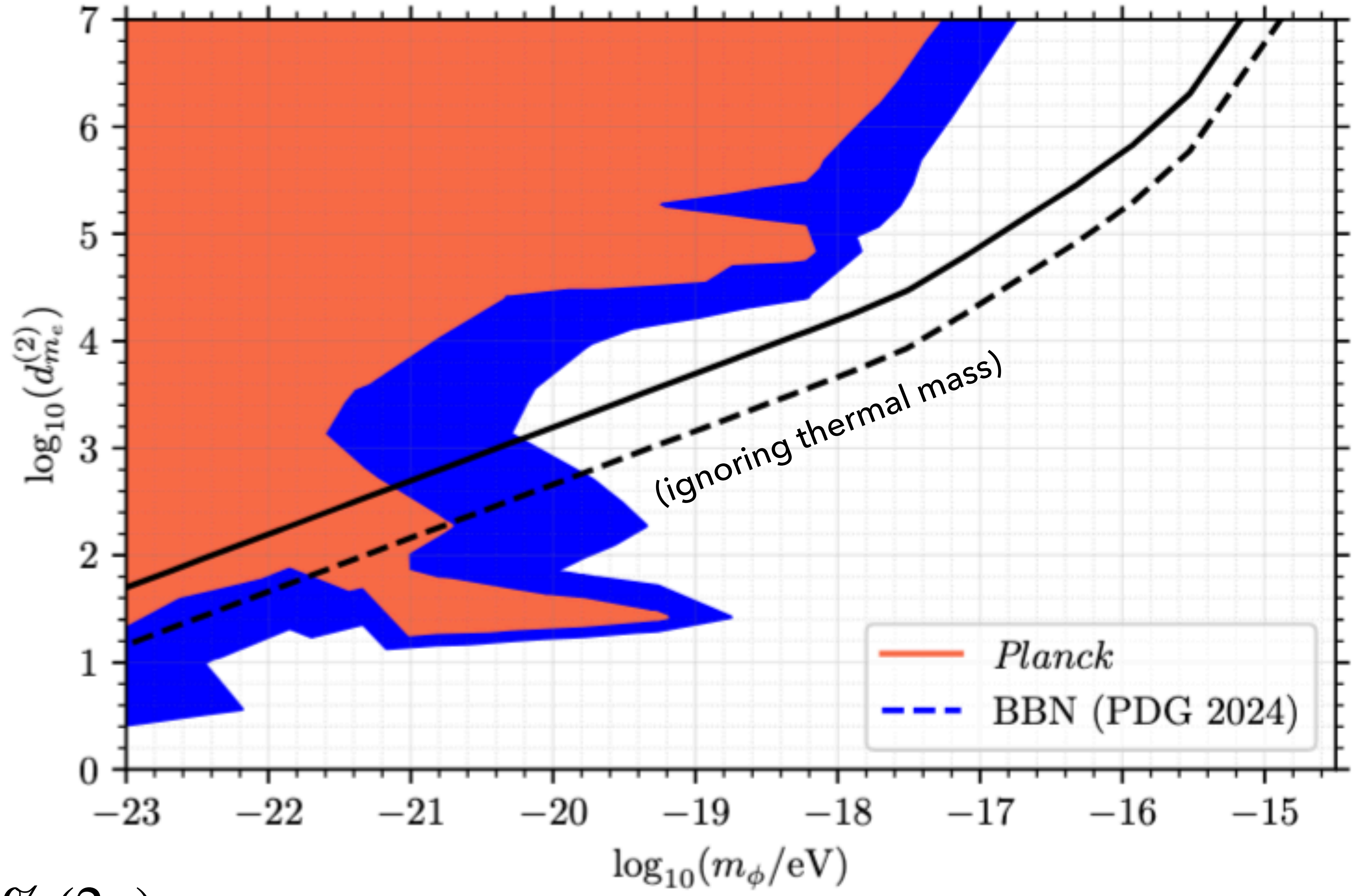
MCMC analysis

$$Y_p = Y_{p,\text{BBN}^{(0)}}(1 + \Delta Y_p)$$

CMB constraints: “high”-mass regime

Ghosh, Boddy, TTY (in prep)



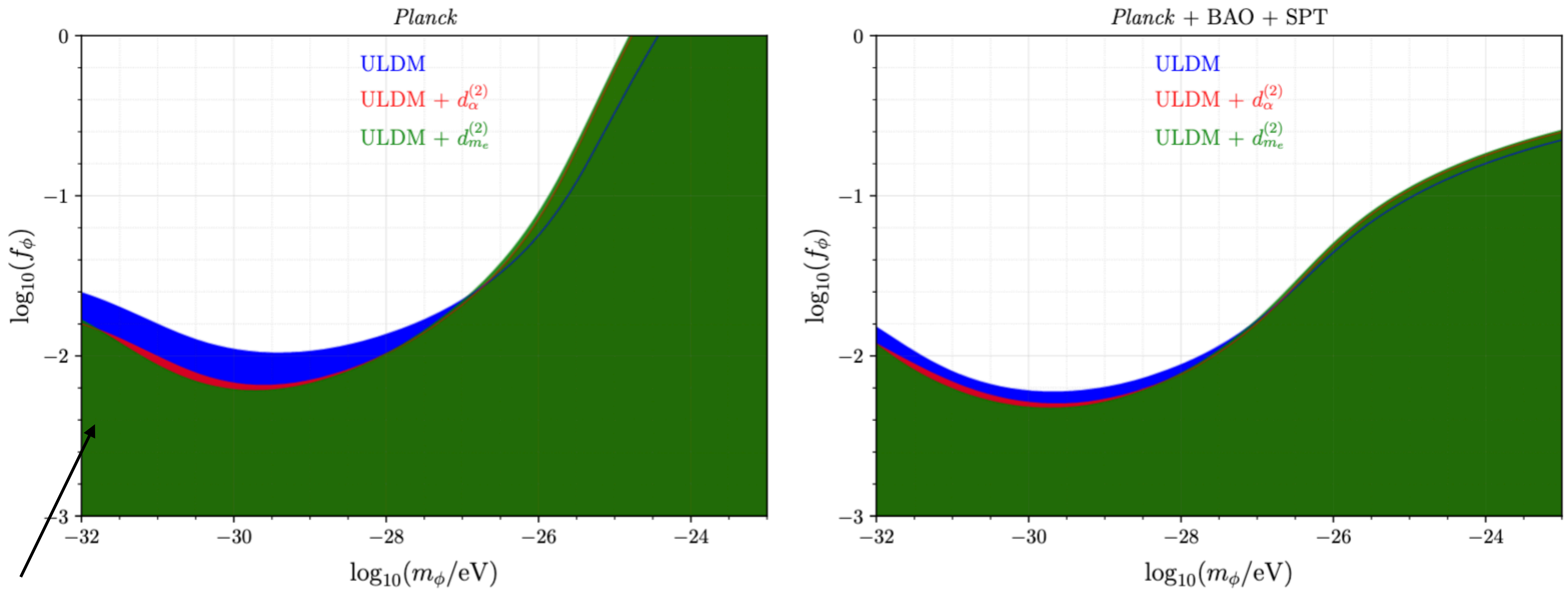


$$\Delta Y_\mathrm{p}(\mathrm{BBN}) = 2.4\,\%\,(2\sigma)$$

$$\Delta Y_\mathrm{p}(\mathrm{Planck\ 2018}) = 8.4\,\%\,(2\sigma)$$

CMB constraints: fractional ULDM

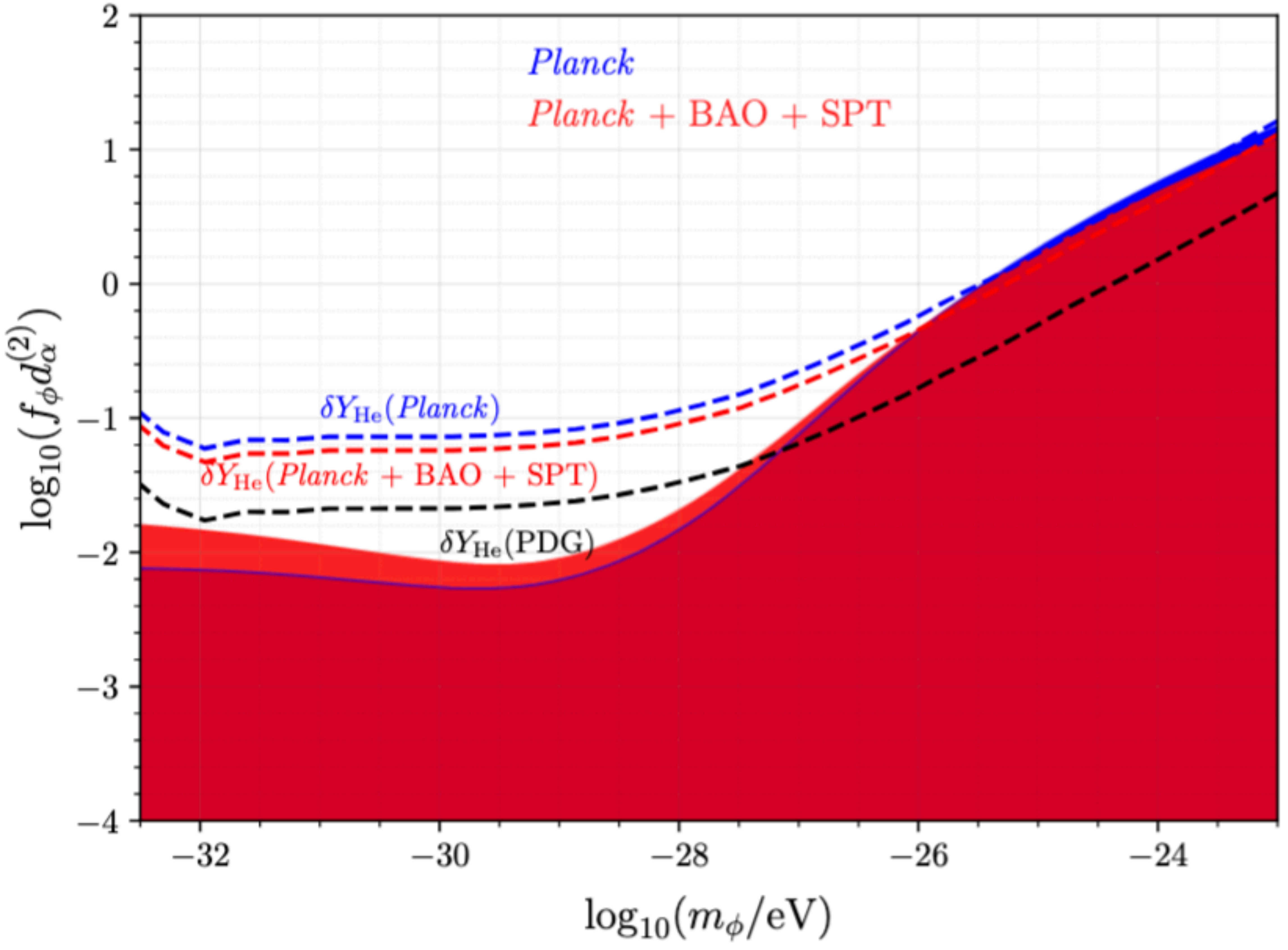
Ghosh, Boddy, TTY (in prep)

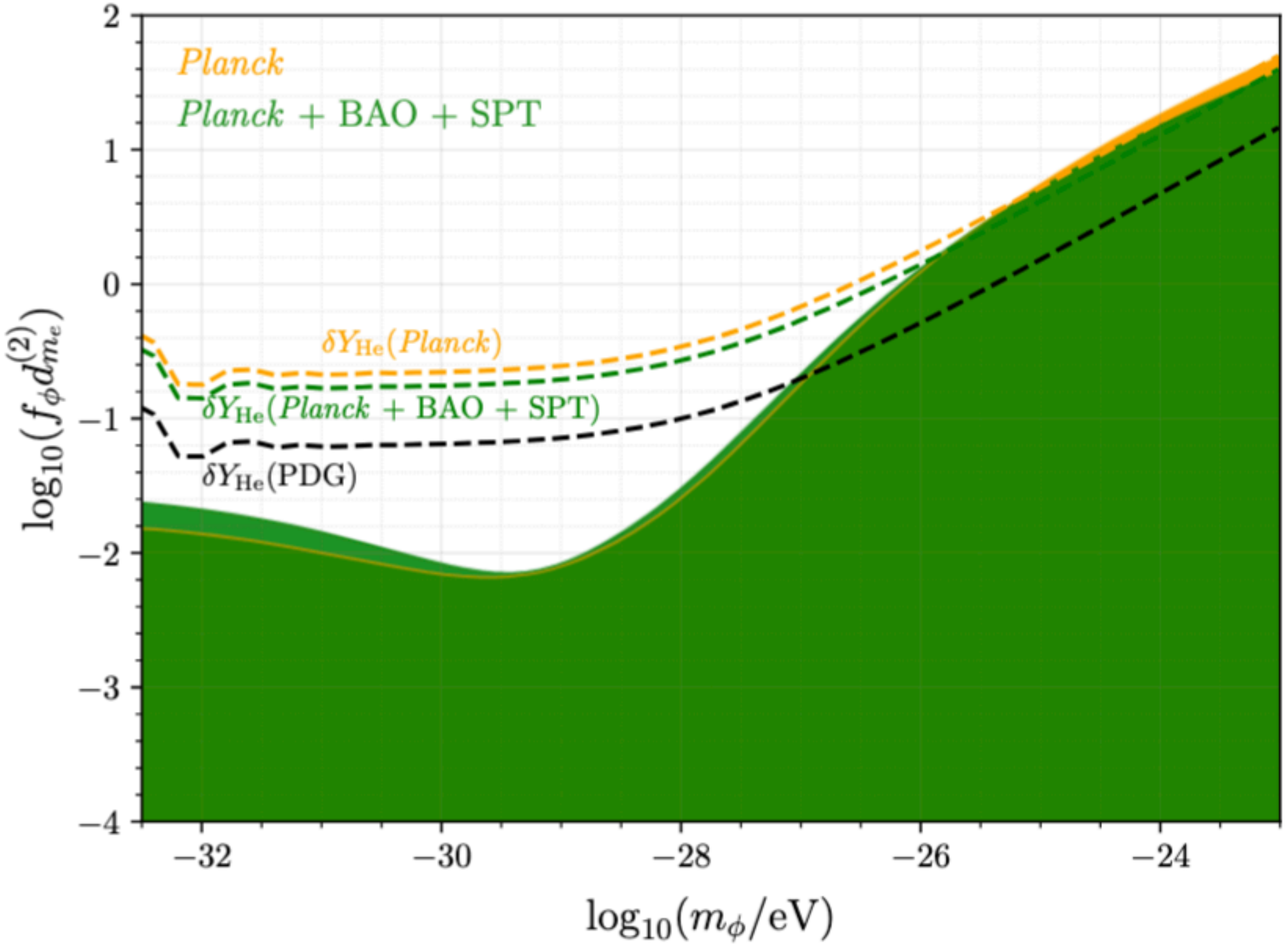


improvement due to fixed variation (and impact on Y_p)

CMB constraints: comparison with BBN

Ghosh, Boddy, TTY (in prep)





Conclusions

- quadratically-coupled scalar DM provides a framework for varying fundamental constants and can leave significant impacts on measurements across cosmological history, from BBN to CMB to today
- induced mass through coupling to matter is key and leads to interesting effects
- BBN constraints arise from changing the He4 abundance
- including both effects of changing m_e and α on the He4 abundance and recombination can improve on CMB constraints