BBN Constraints on Ultralight Scalar Dark Matter

Tien-Tien Yu (University of Oregon)

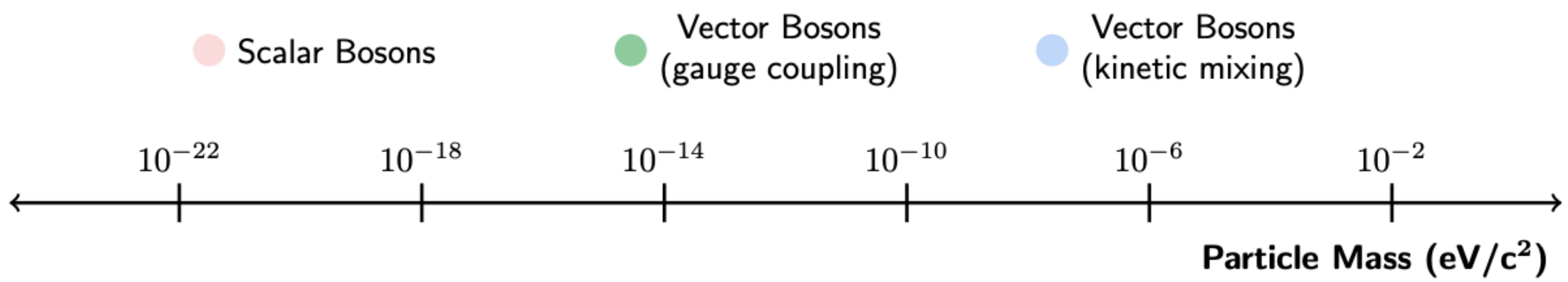
UNIVERSITY OF OREGON

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]

BSM in Particle Physics and Cosmology, 50 years later
January 11, 2024

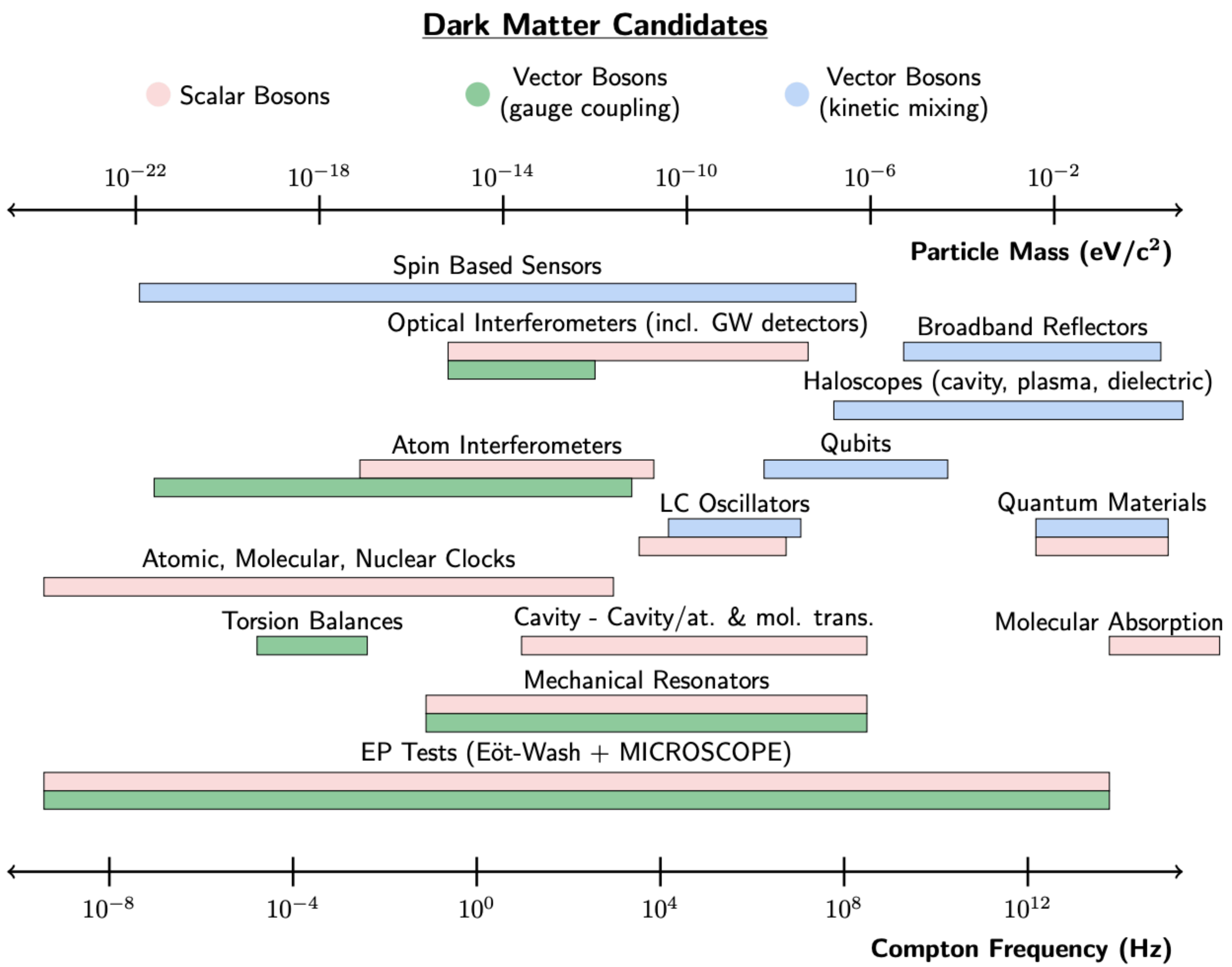
ICISE, Quy Nhon, Vietnam

Dark Matter Candidates



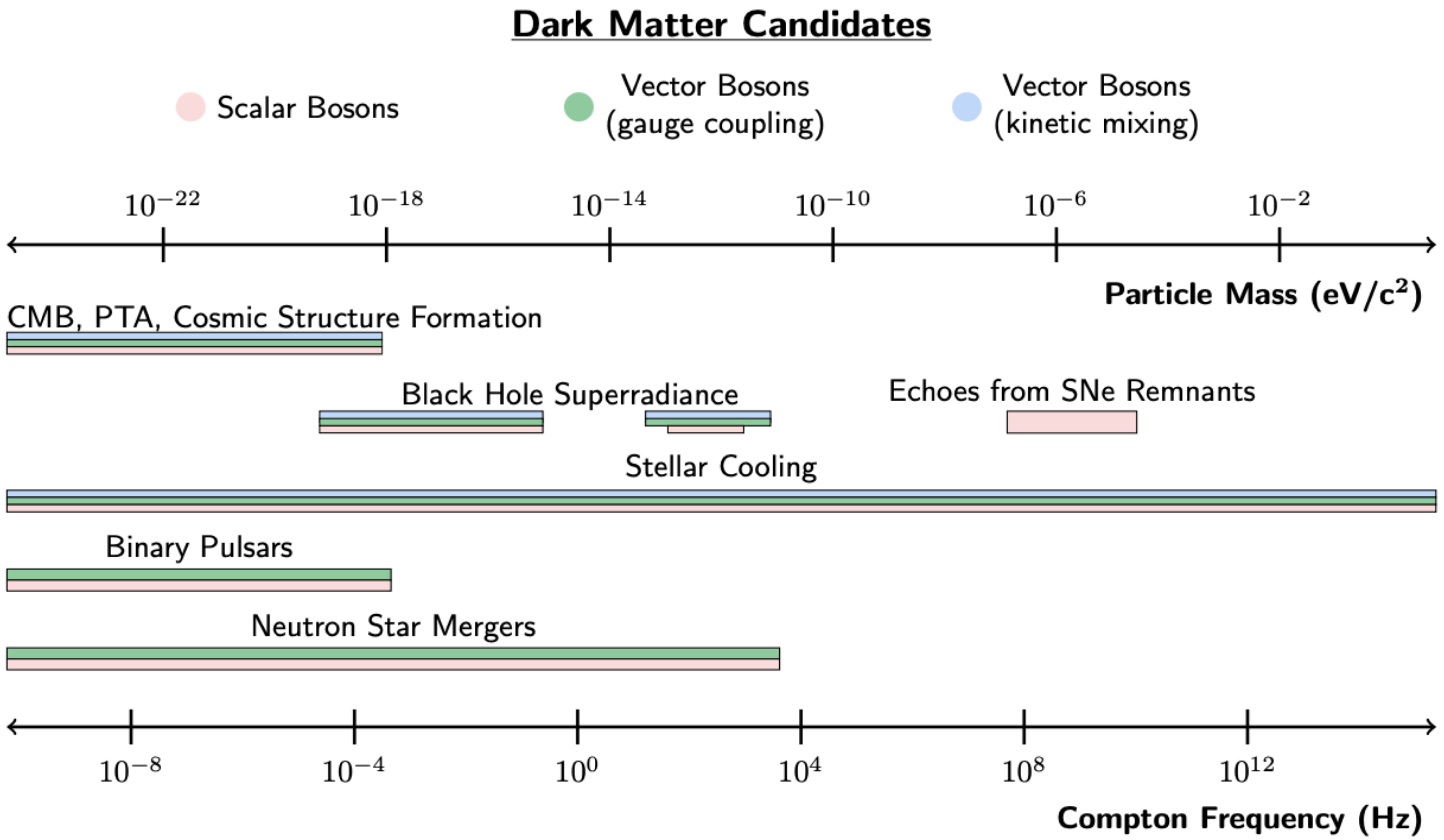
[arXiv:2203.14915]

Direct Detection



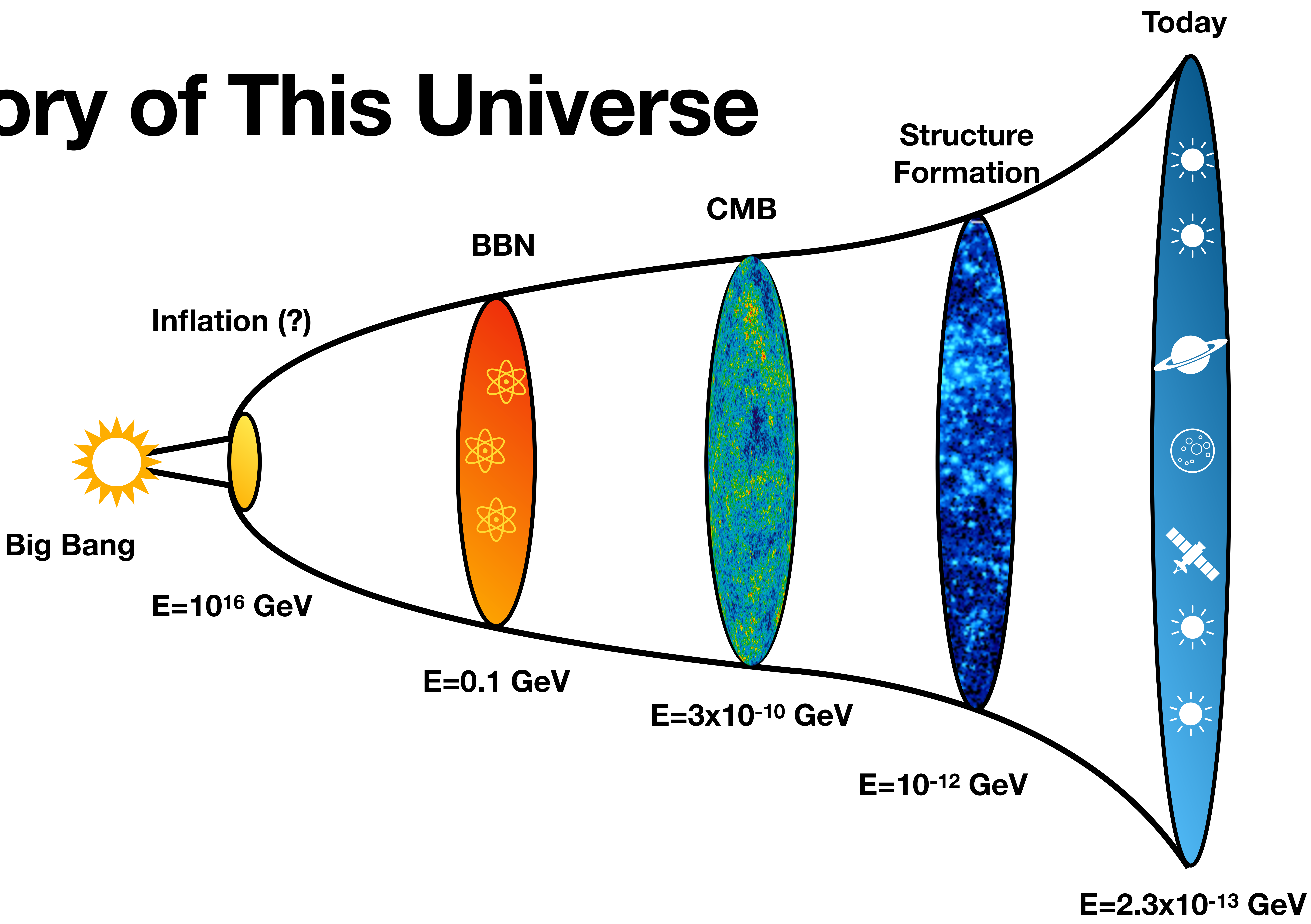
[arXiv:2203.14915]

Astro + Cosmo

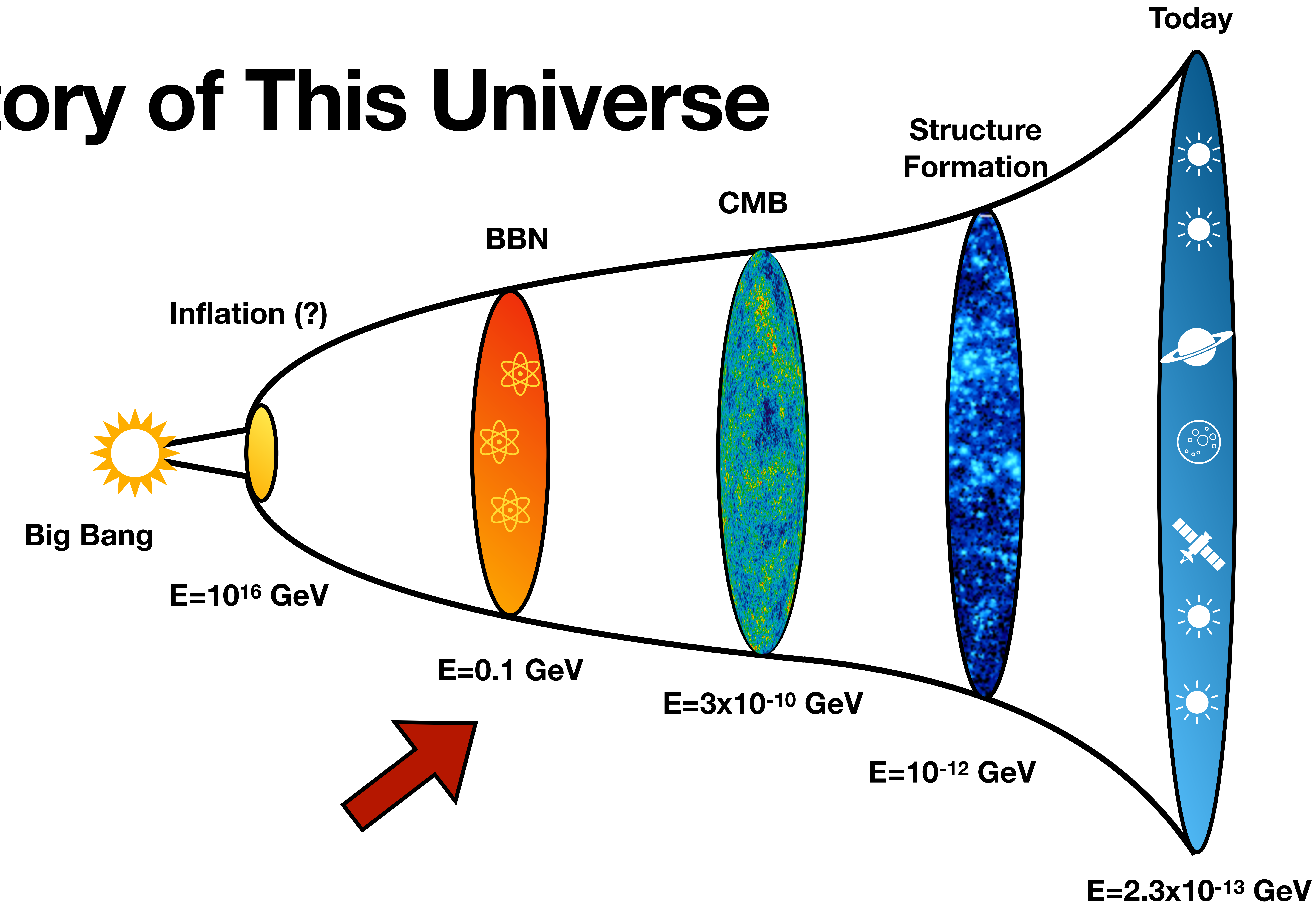


[arXiv:2203.14915]

History of This Universe

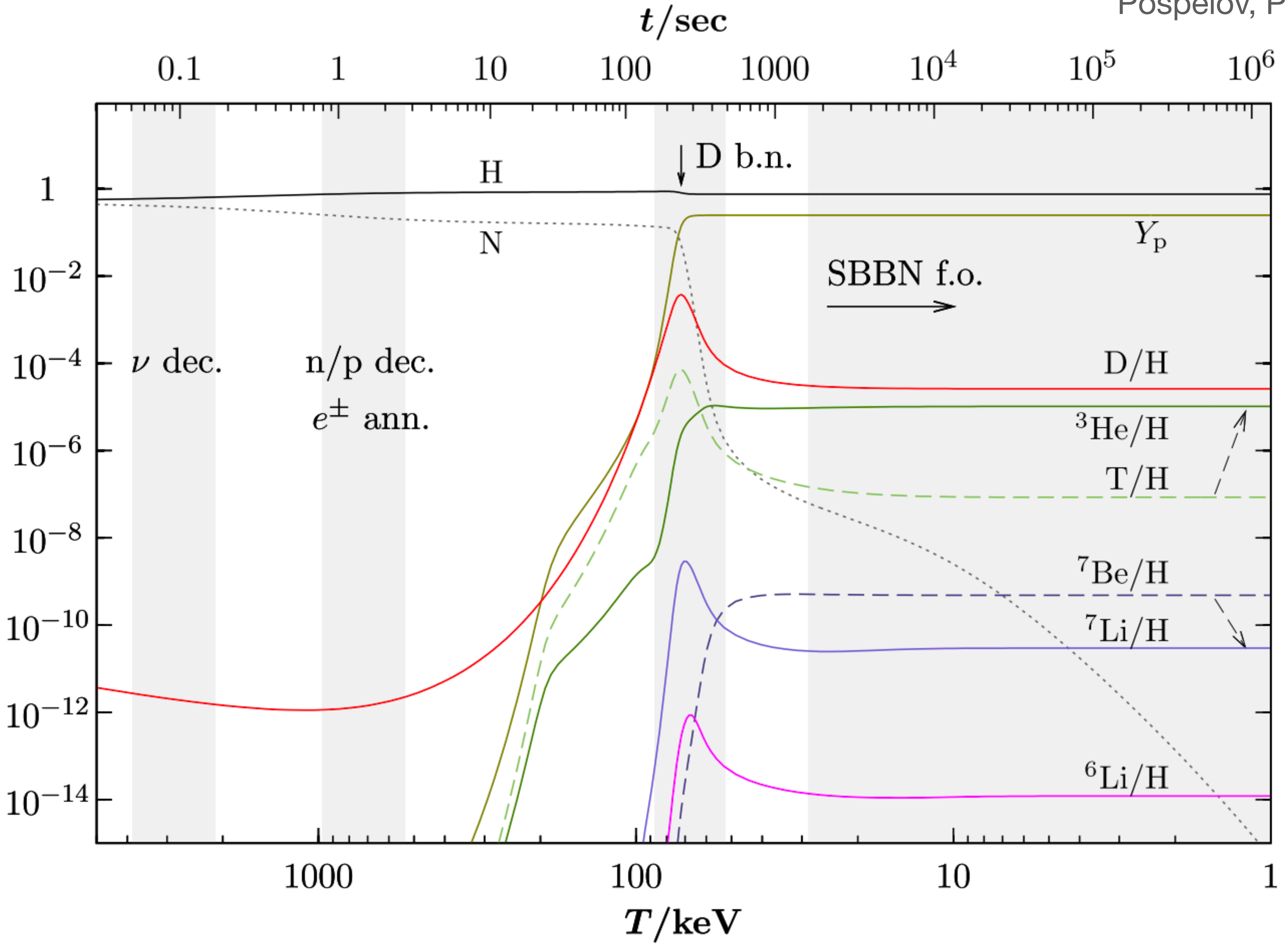


History of This Universe



standard BBN picture

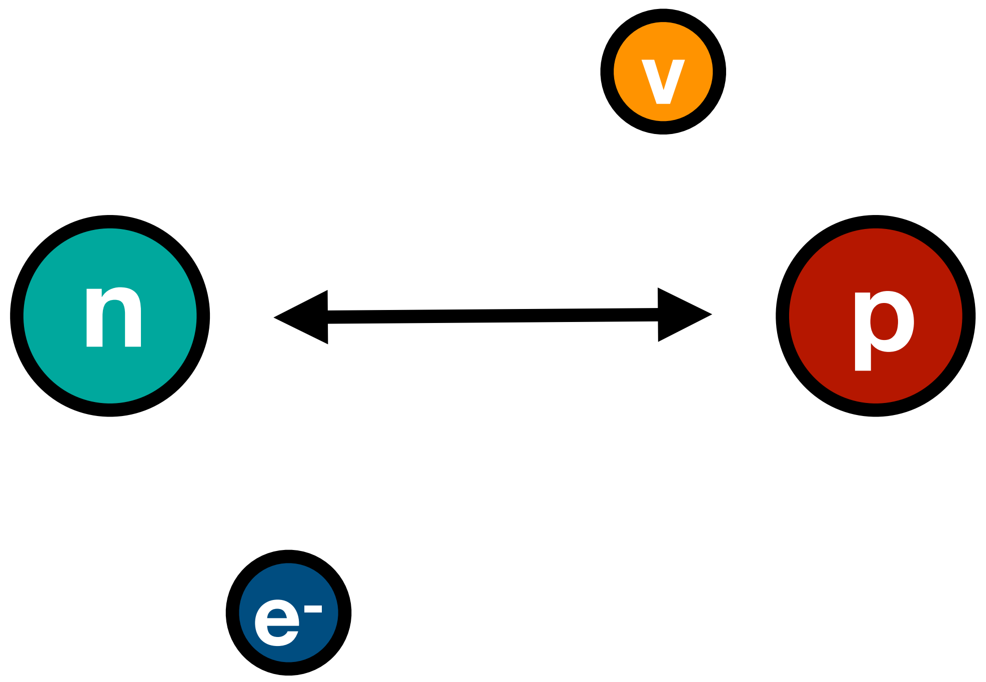
Pospelov, Pradler [arXiv:1011.1054]



big bang nucleosynthesis

T>1 MeV

weak interactions keep neutrons and protons in thermal equilibrium



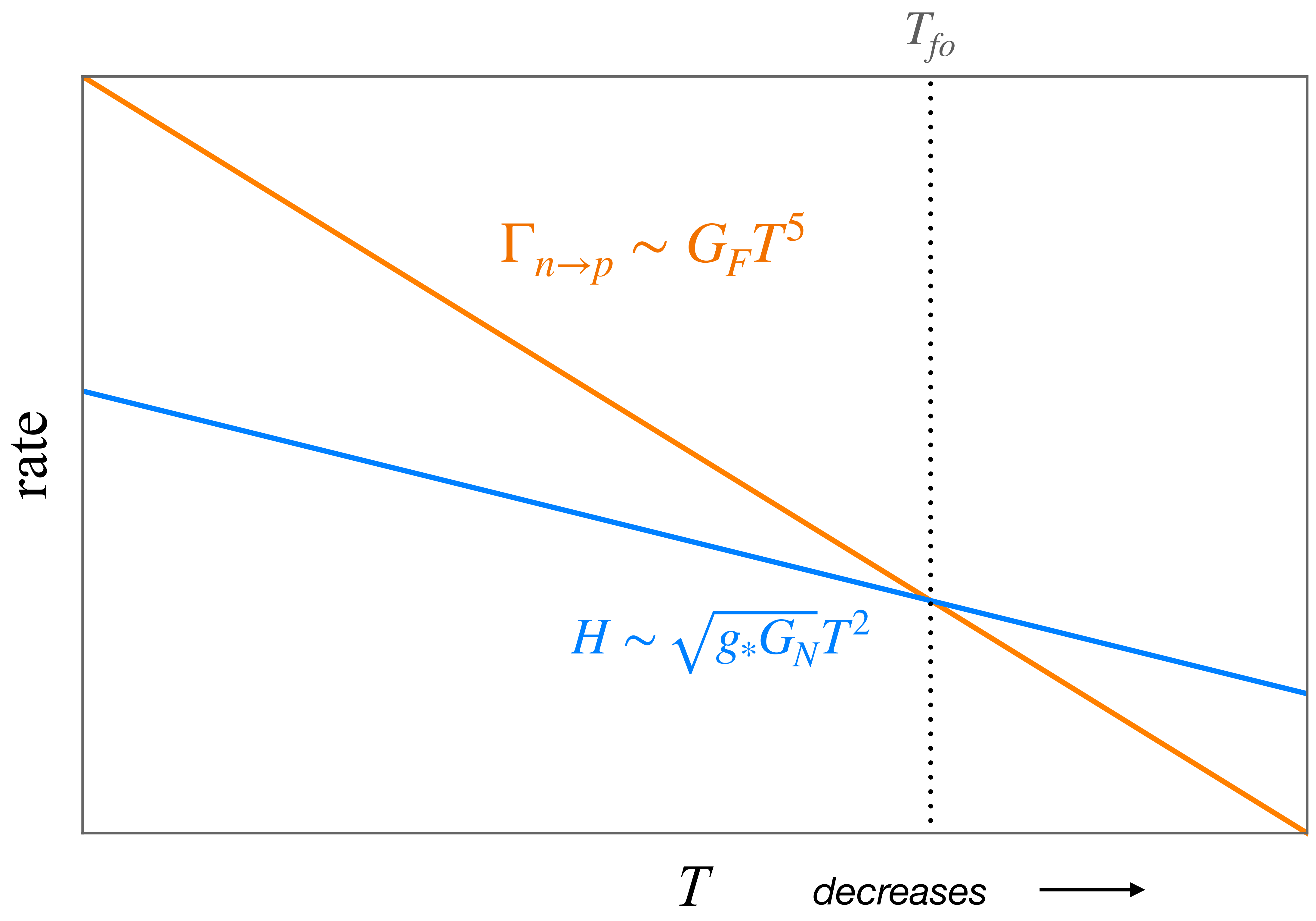
$$n \leftrightarrow p + e^- + \bar{\nu}$$

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

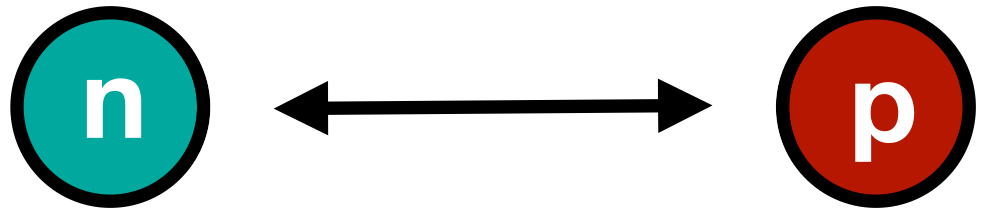
$$e^+ + n \leftrightarrow p + \bar{\nu}$$

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

big bang nucleosynthesis

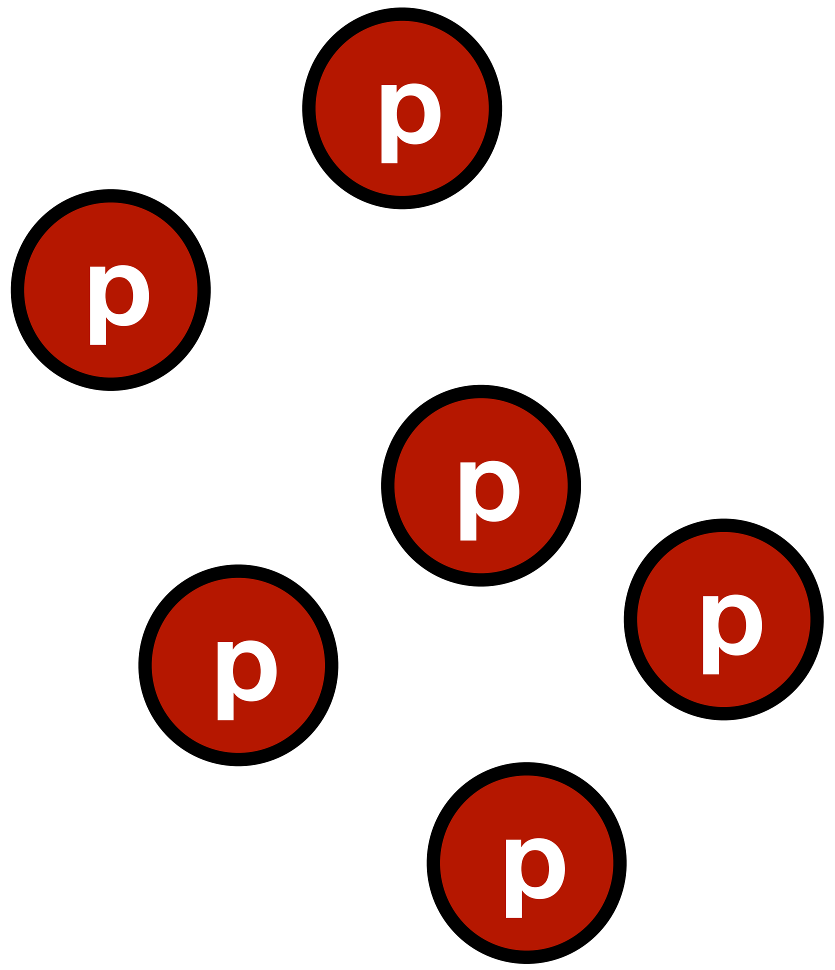


$\Gamma_{n\to p} \sim G_F T^5$

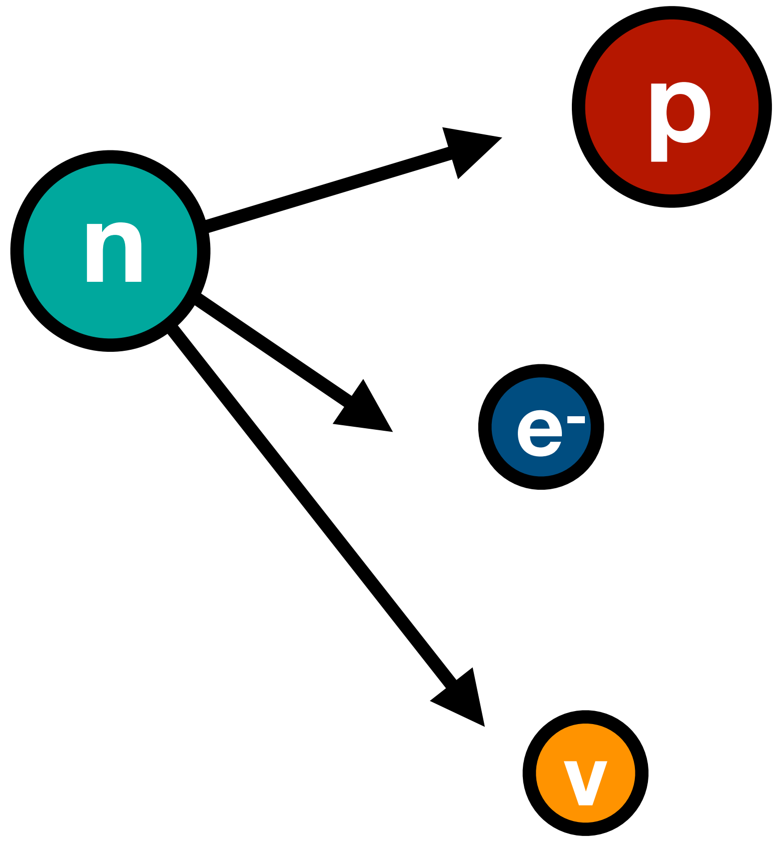


$$T_{fo} \sim \left(\frac{g_* G_N}{G_F^4}\right)^{1/6} \simeq 1 \text{ MeV}$$

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

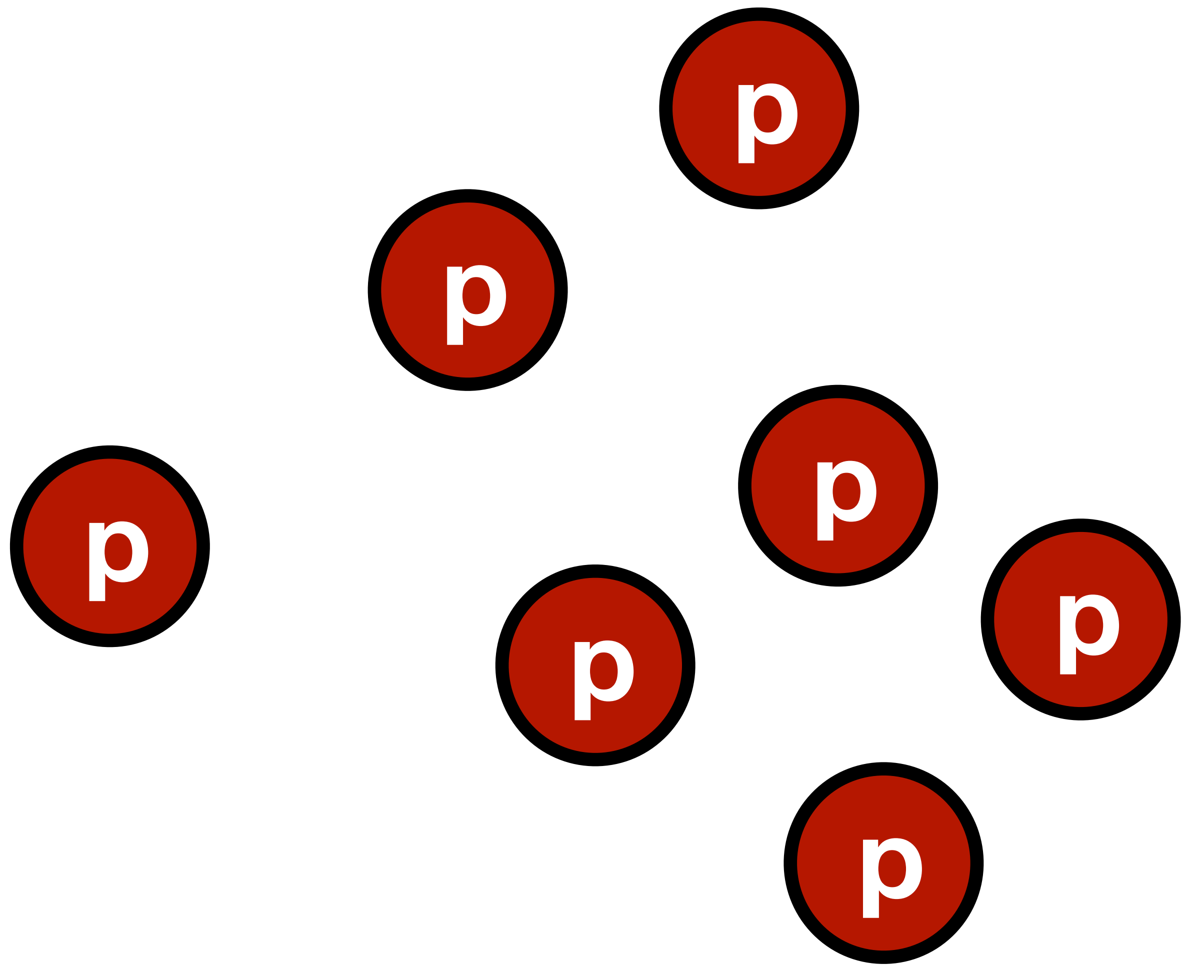


big bang nucleosynthesis

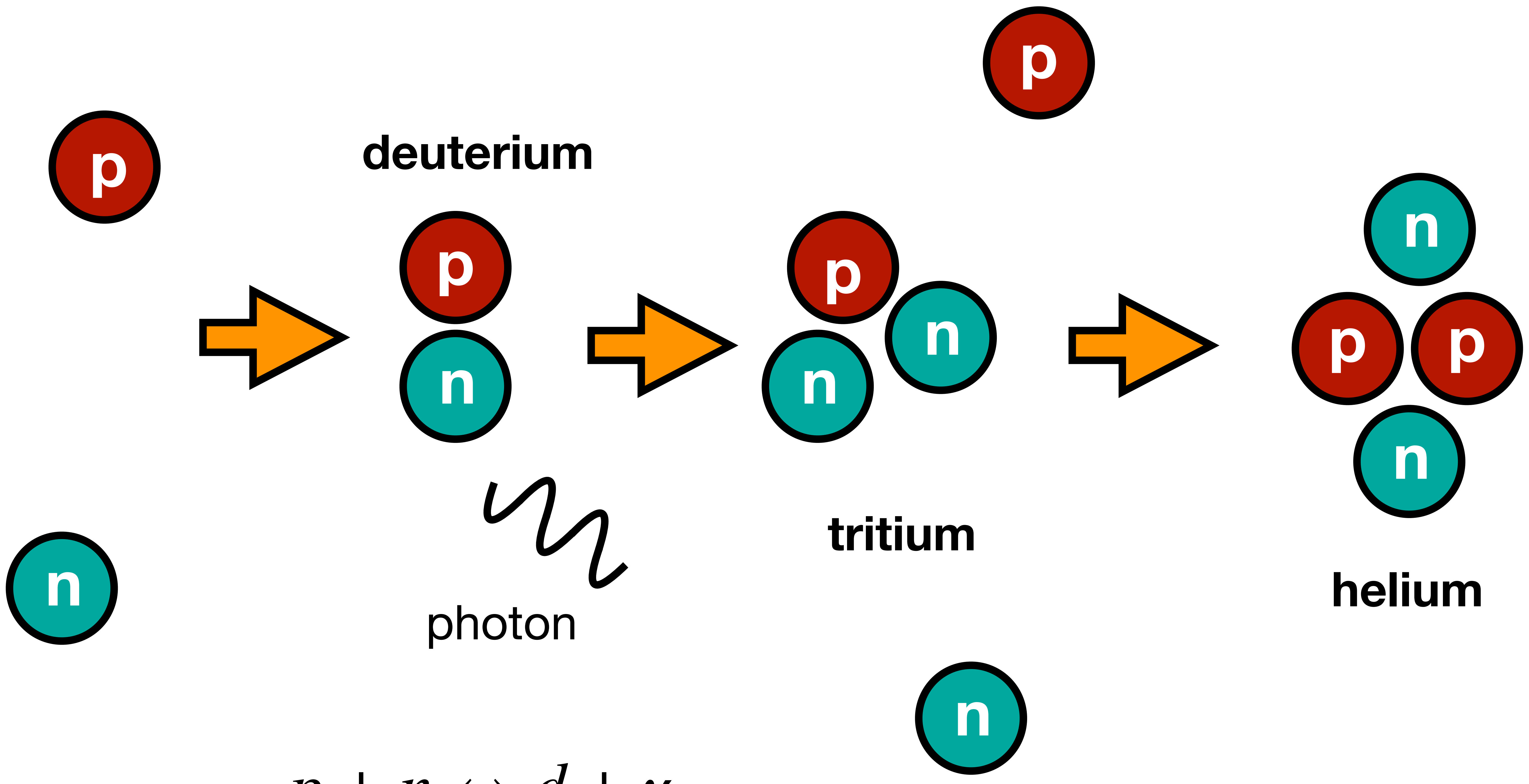


$$n \to p + e^- + \bar{\nu}_e$$ **neutron decay**

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

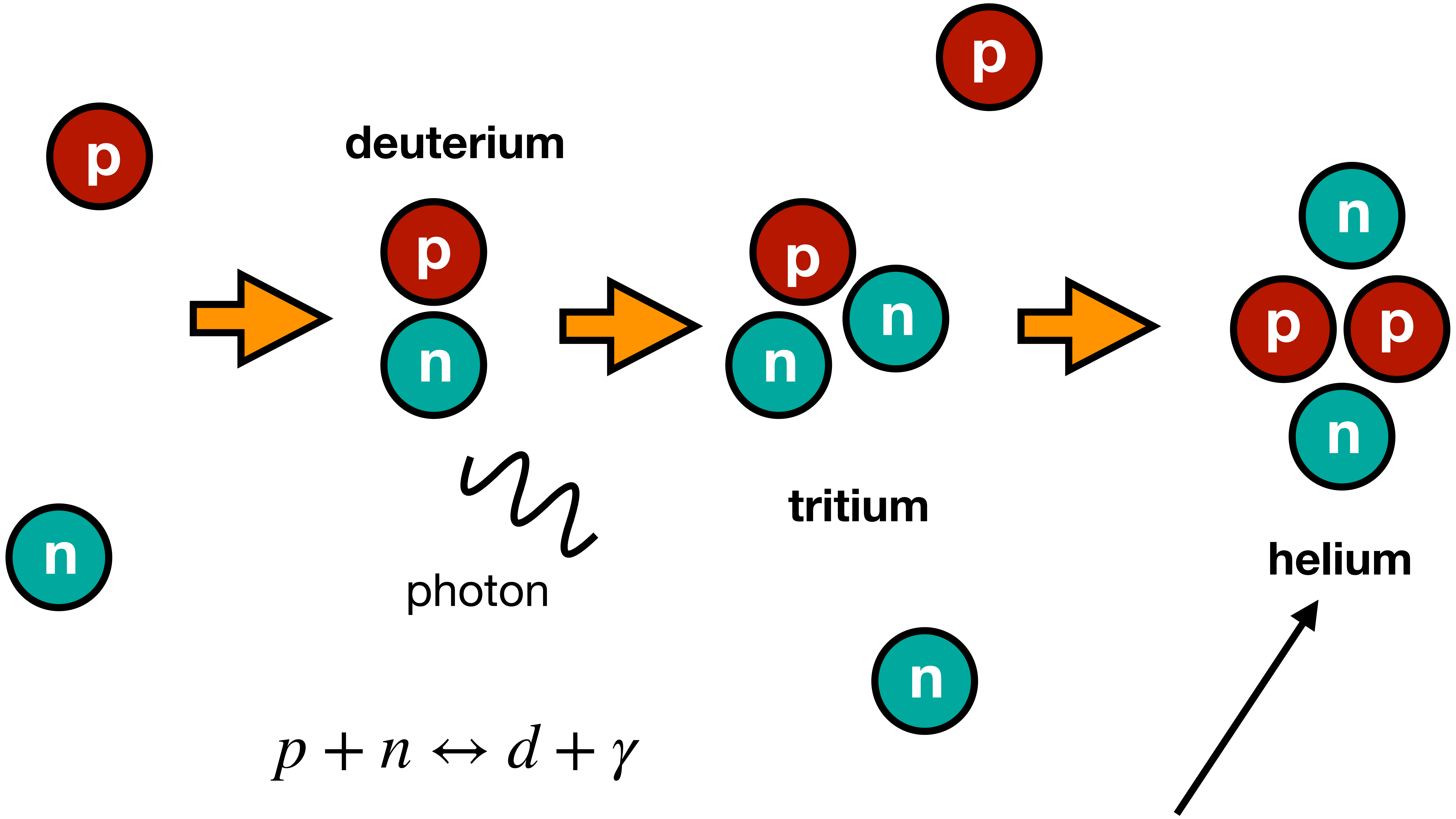


Helium-4 formation



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

Helium-4 formation

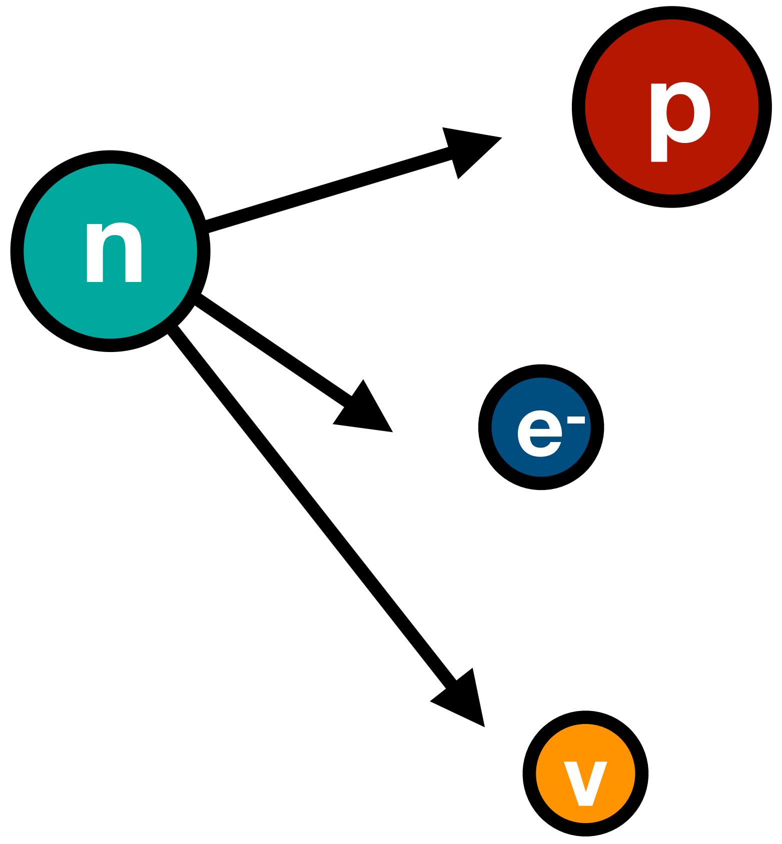


$$p + n \leftrightarrow d + \gamma$$

very stable!

all free neutrons end up here

Helium-4 formation



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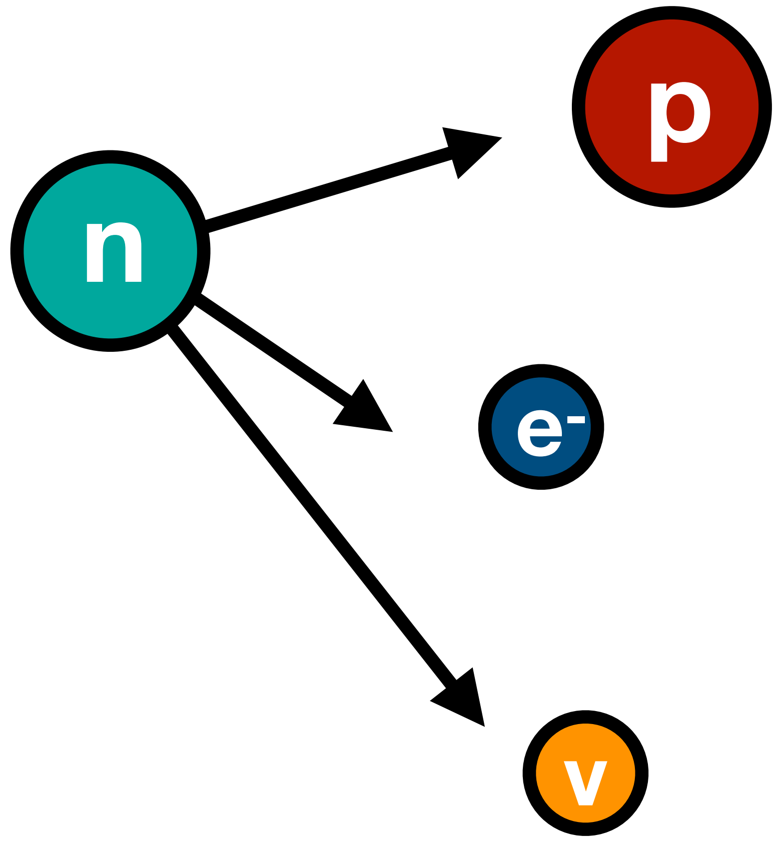
$$\left.\frac{n}{p}\right|_{fo} = e^{-(m_n - m_p)/T_{fo}} \simeq \frac{1}{6} \to \frac{1}{7}$$

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

Helium-4 formation



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

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

determines 4He abundance

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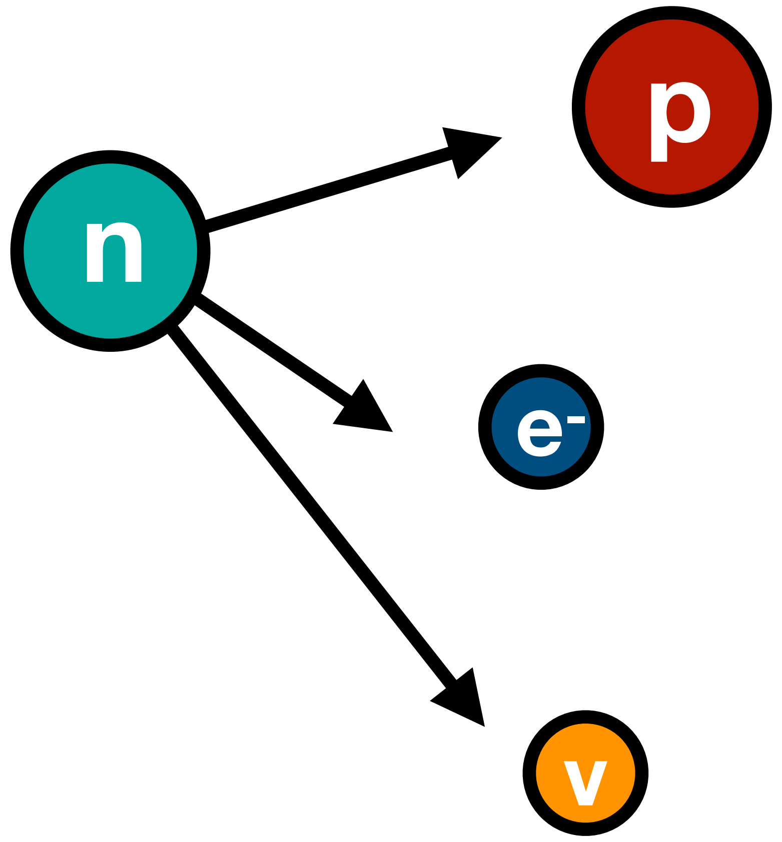
Helium-4 formation



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

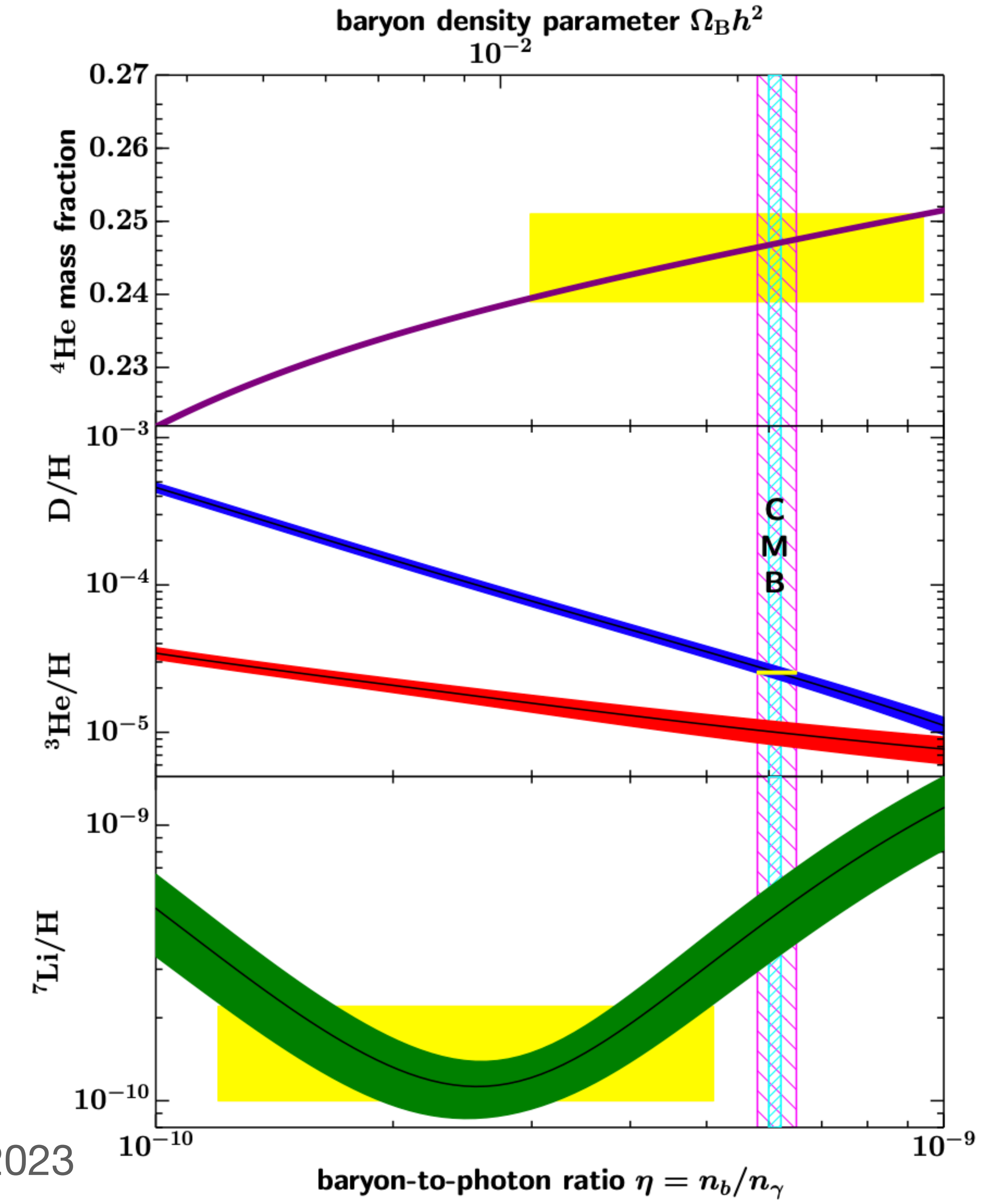
new physics can change this!

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

determines 4He abundance

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

primordial abundances

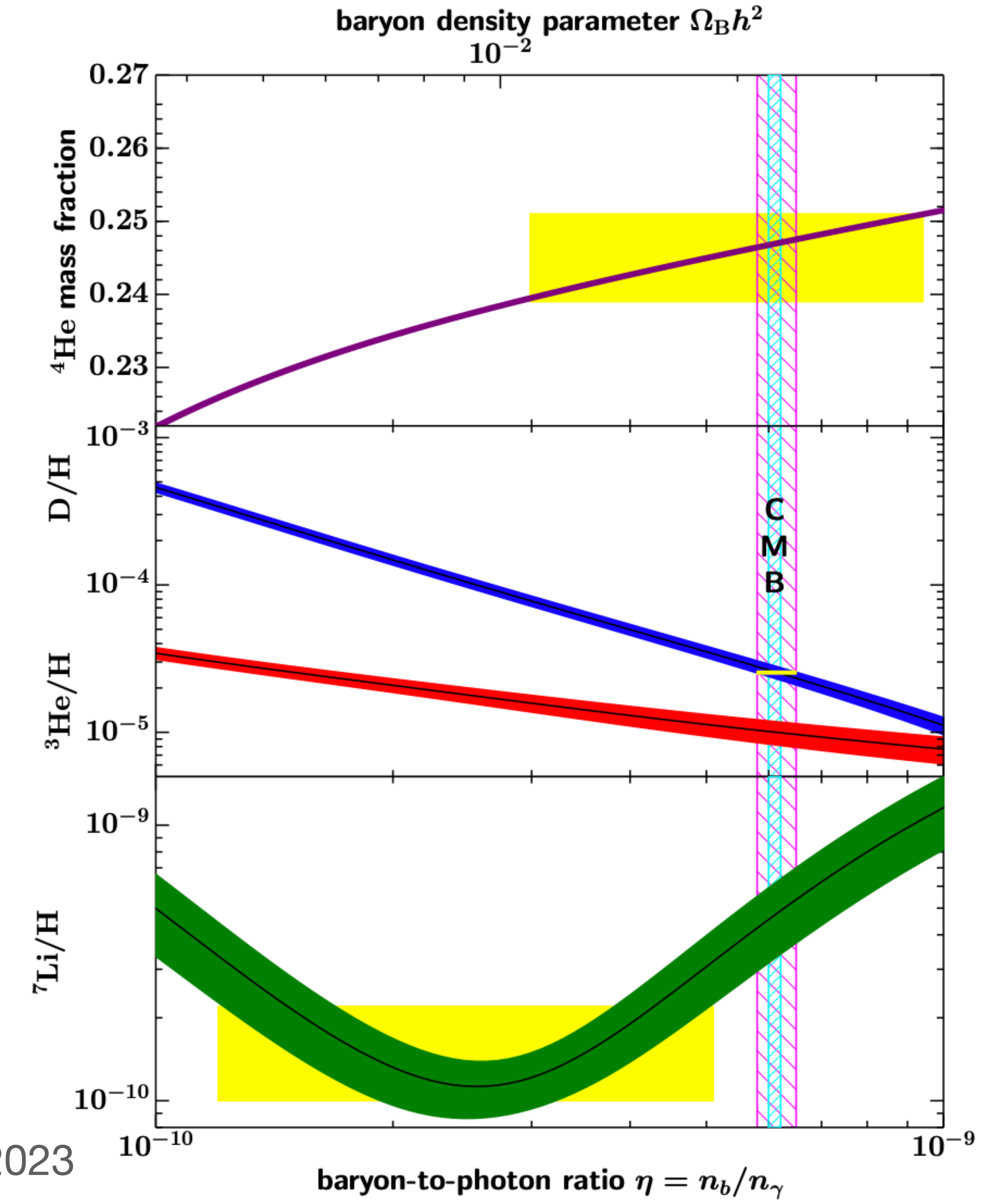


PDG 2023

Helium-4

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

primordial abundances



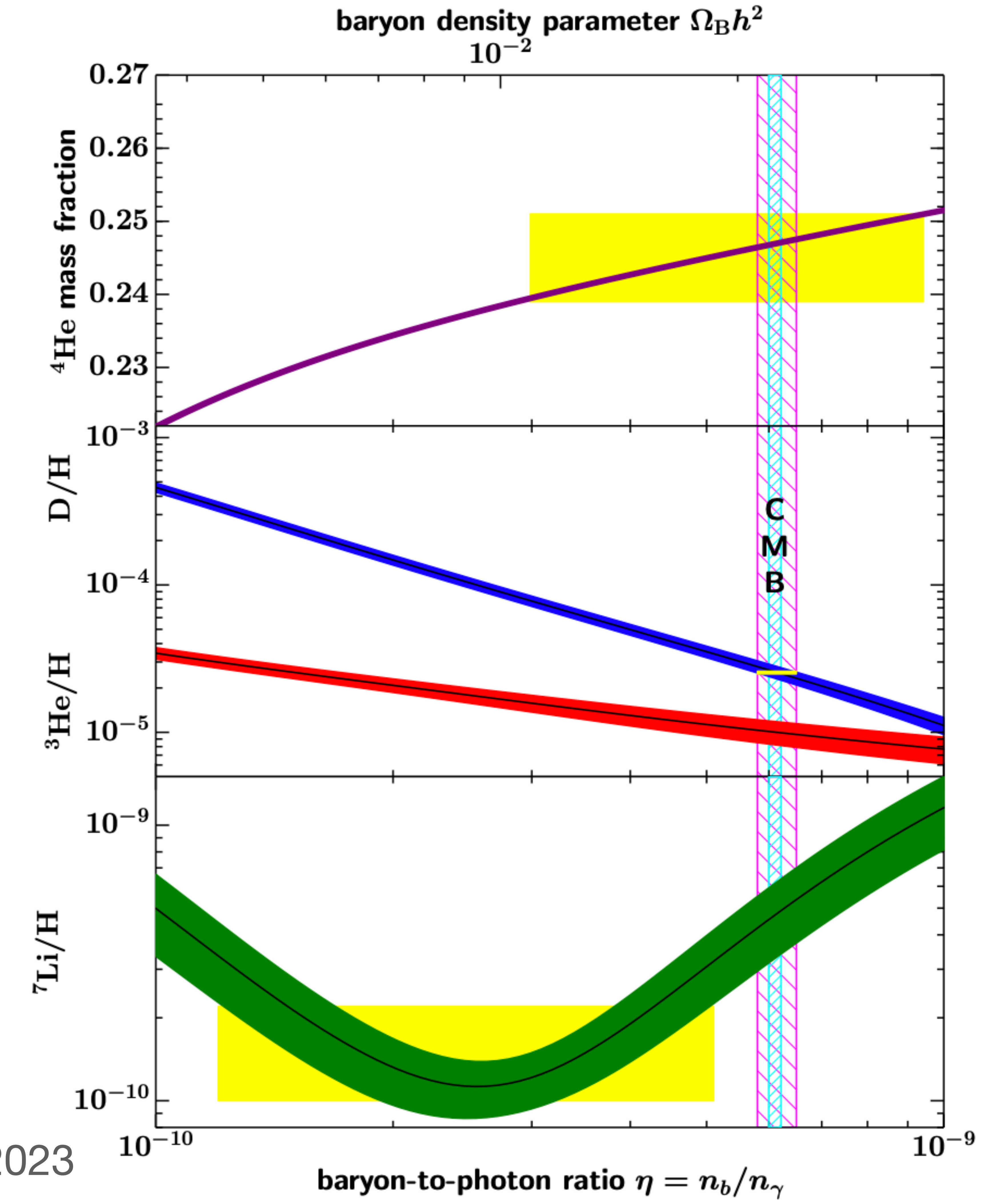
PDG 2023

Helium-4

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

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

primordial abundances



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

neutron abundance

neutron decay

neutron abundance at BBN

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

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

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

neutron abundance at BBN

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

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

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neutron abundance at BBN

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

neutron abundance at BBN

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

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

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

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

however, we need to go beyond instantaneous approximation…

neutron abundance at freeze-out

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

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

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

phase-space integral

Neutron abundance at Weak freeze-out

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

neutron abundance at freeze-out

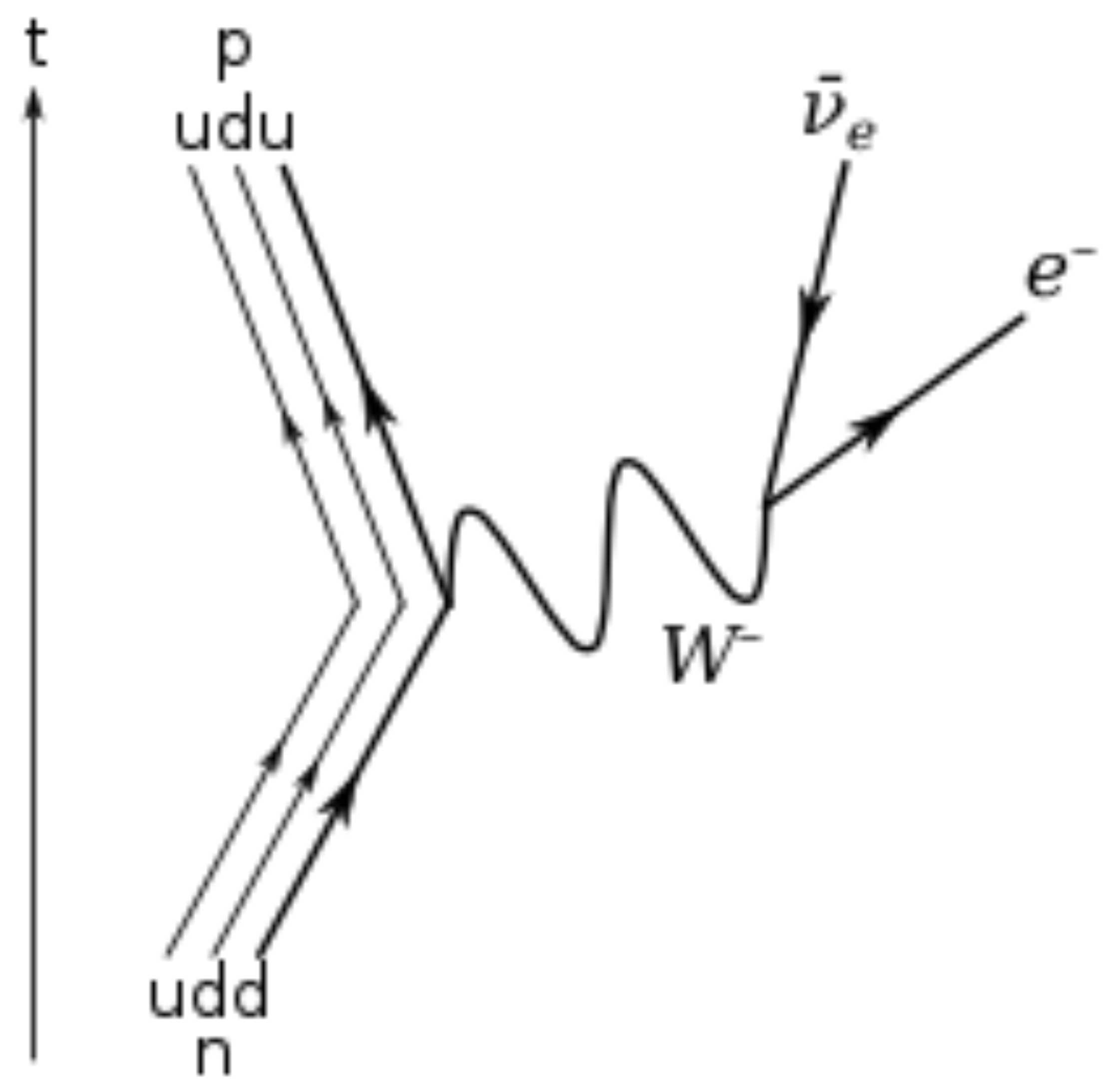
need to go beyond instantaneous approximation…

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

instead,

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

neutron decay



phase space factor

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

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

4He analytic constraint

neutron abundance@BBN

deuterium binding energy

axial coupling

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

Fermi constant

electron mass

neutron-proton mass difference

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

Scalar with universal coupling

Scalar field

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2$$

universal coupling

$$g_{\mu\nu} \to g_{\mu\nu}(1 + 2\kappa)$$

$$\frac{\phi^2}{\Lambda^2}$$

additional contributions to SM particle masses!

$$\mathcal{L}_{\rm SM} \to \mathcal{L}_{\rm SM} \pm \frac{\phi^2}{\Lambda^2} m_f \bar{f} f \pm \frac{\phi^2}{\Lambda^2} m_V^2 V^2$$

Scalar with universal coupling

Scalar field

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

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

scalar evolution

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 \quad \Rightarrow \quad V(\phi) = \frac{1}{2} m_{\mathrm{eff}}^2 \phi^2$$

$$\boxed{\ddot{\phi} + 3H\dot{\phi} + m_{\mathrm{eff}}^2 \phi = 0}$$

scalar evolution

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

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

$H \qquad B$

effective mass

$$m_{f,V}^2 \to m_{f,V}^2 \left(1 \pm \frac{\phi^2}{\Lambda^2}\right)$$

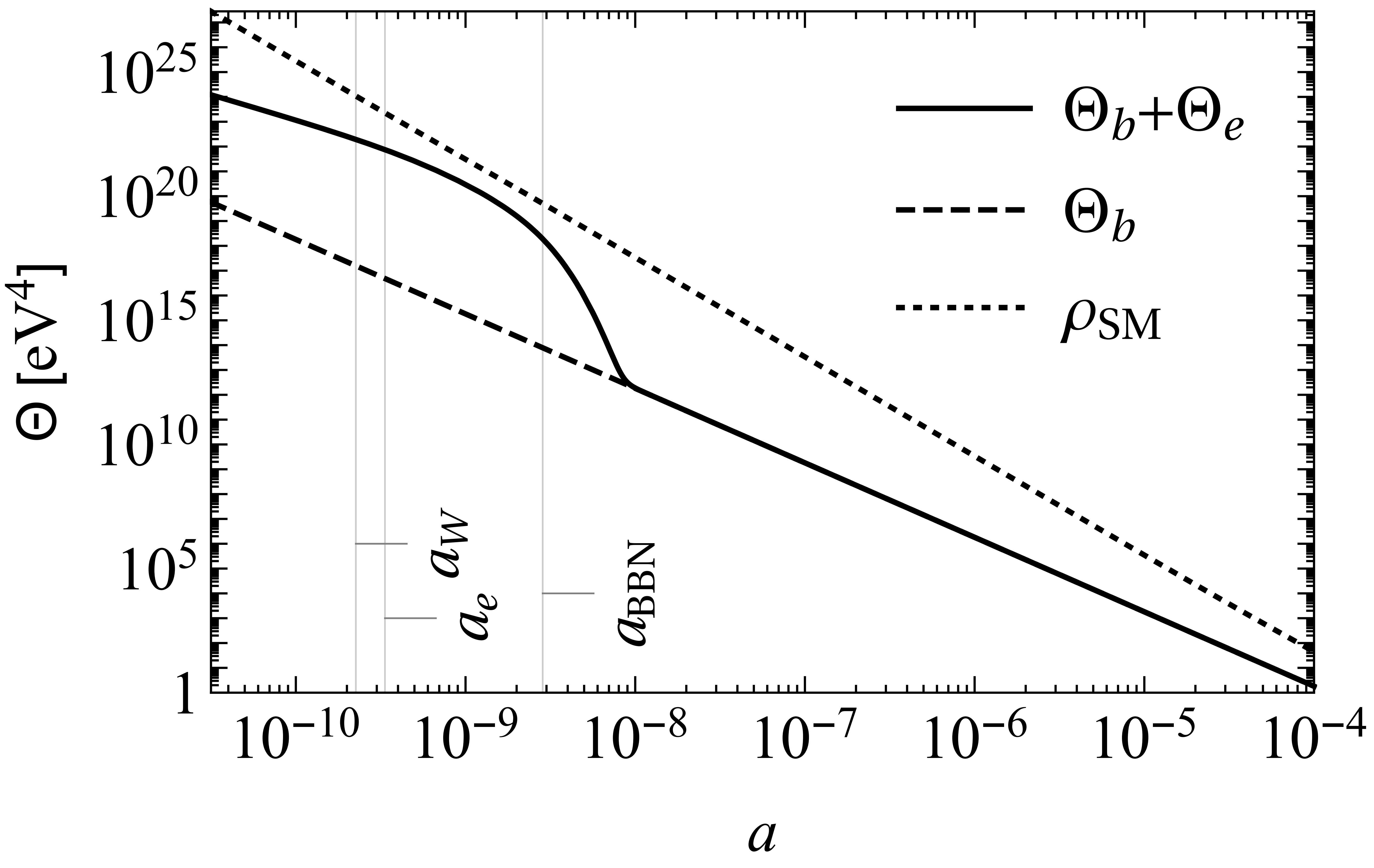
$$m_\phi^2 \to m_{\phi,\mathrm{eff}}^2 \equiv m_\phi^2 \pm \frac{2}{\Lambda^2}\Theta_{\mathrm{SM}}$$

$$\Theta_{\mathrm{SM}} = \rho_{\mathrm{SM}} - 3p_{\mathrm{SM}}$$

trace of SM energy-momentum tensor

SM Energy-Momentum Tensor

S. Sibiryakov, P. Sørensen, TTY *JHEP 20 (2020) 075* [arXiv: 2006.04820]



scalar evolution

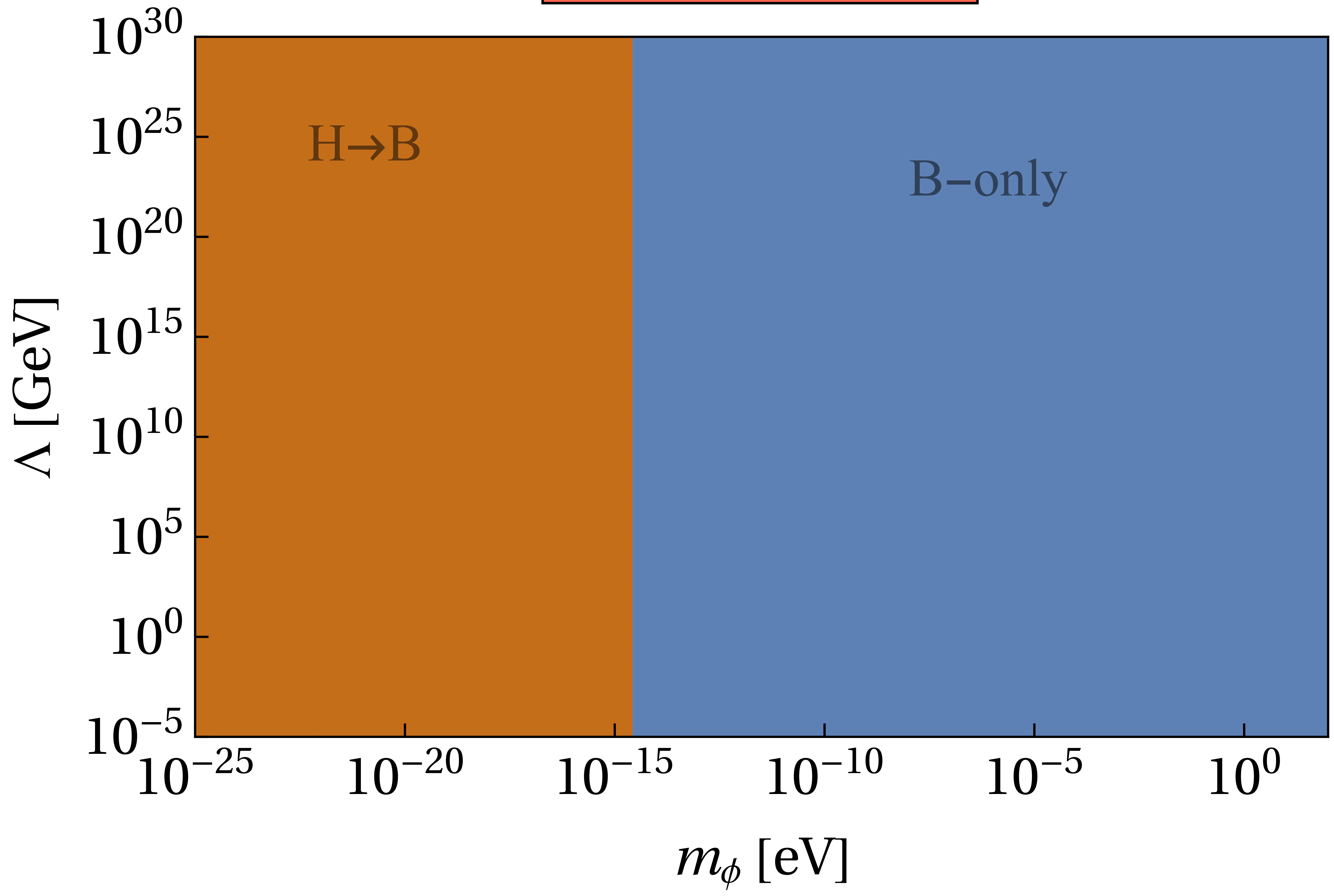
$$\ddot{\phi} + \boxed{3H\dot{\phi}} + \boxed{(m_\phi^2} + \boxed{m_{\rm induced}^2})\phi = 0$$

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

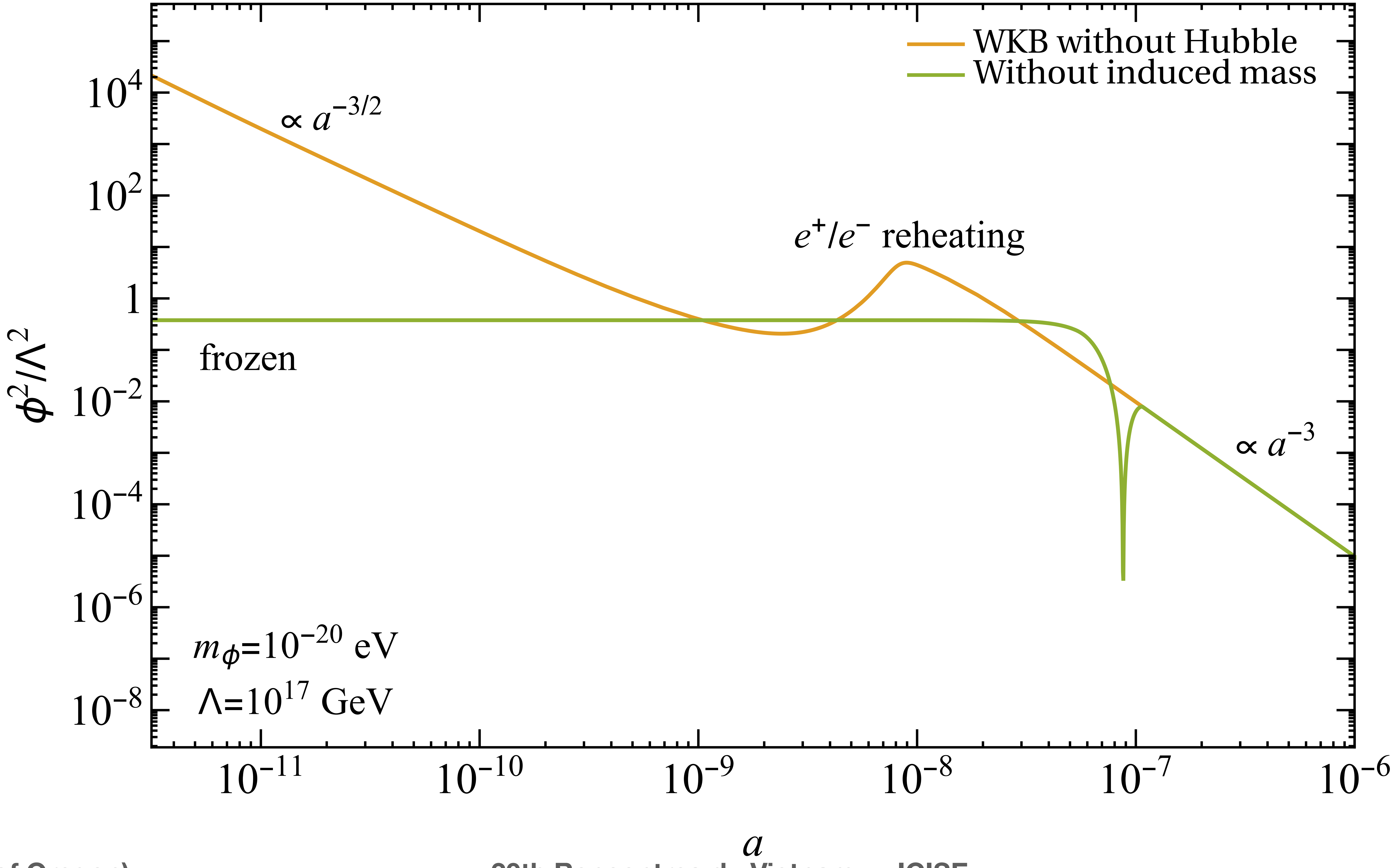
$H \quad B \quad I$

scalar evolution

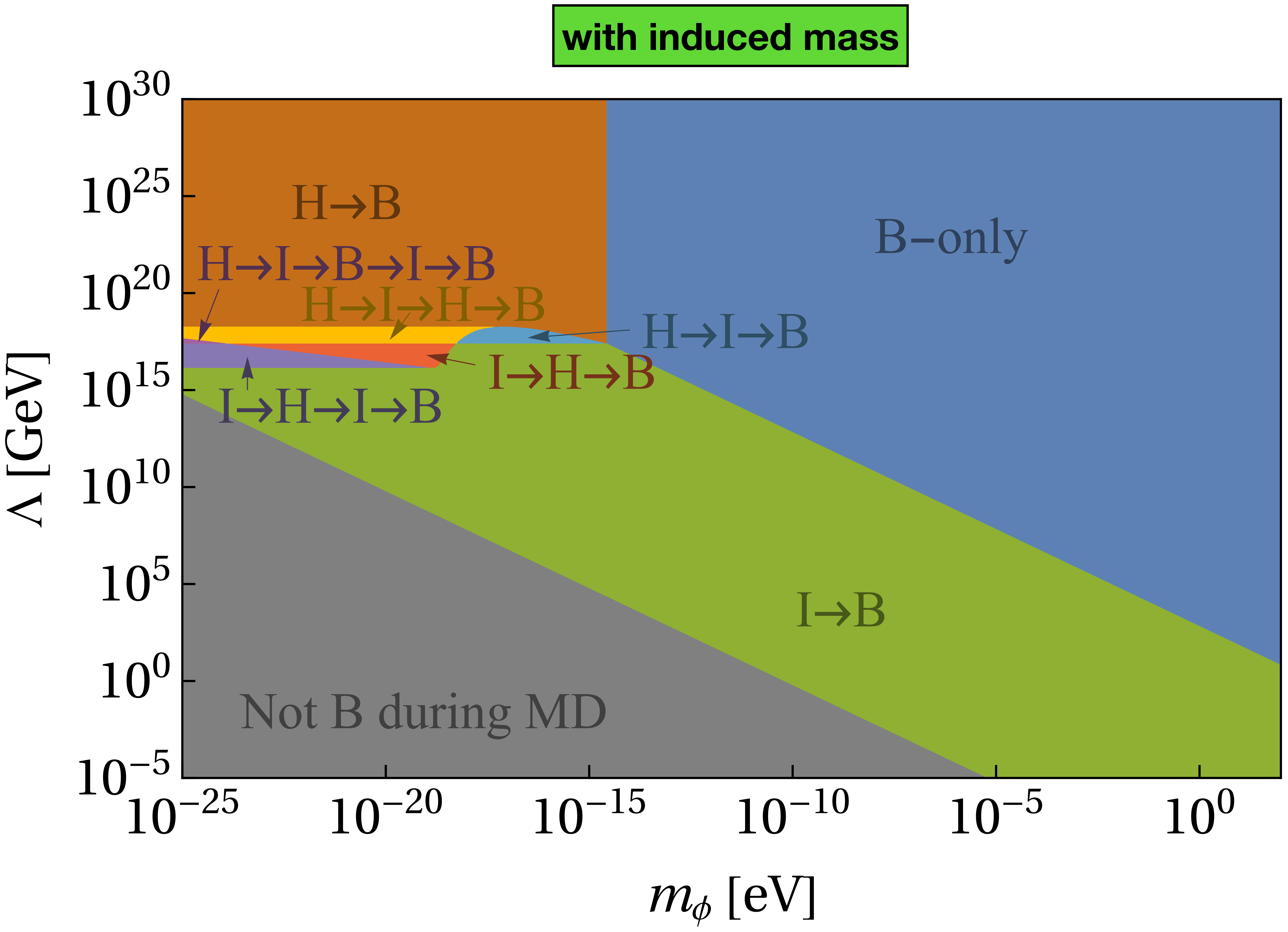
without induced mass



scalar evolution



scalar evolution



scalar evolution

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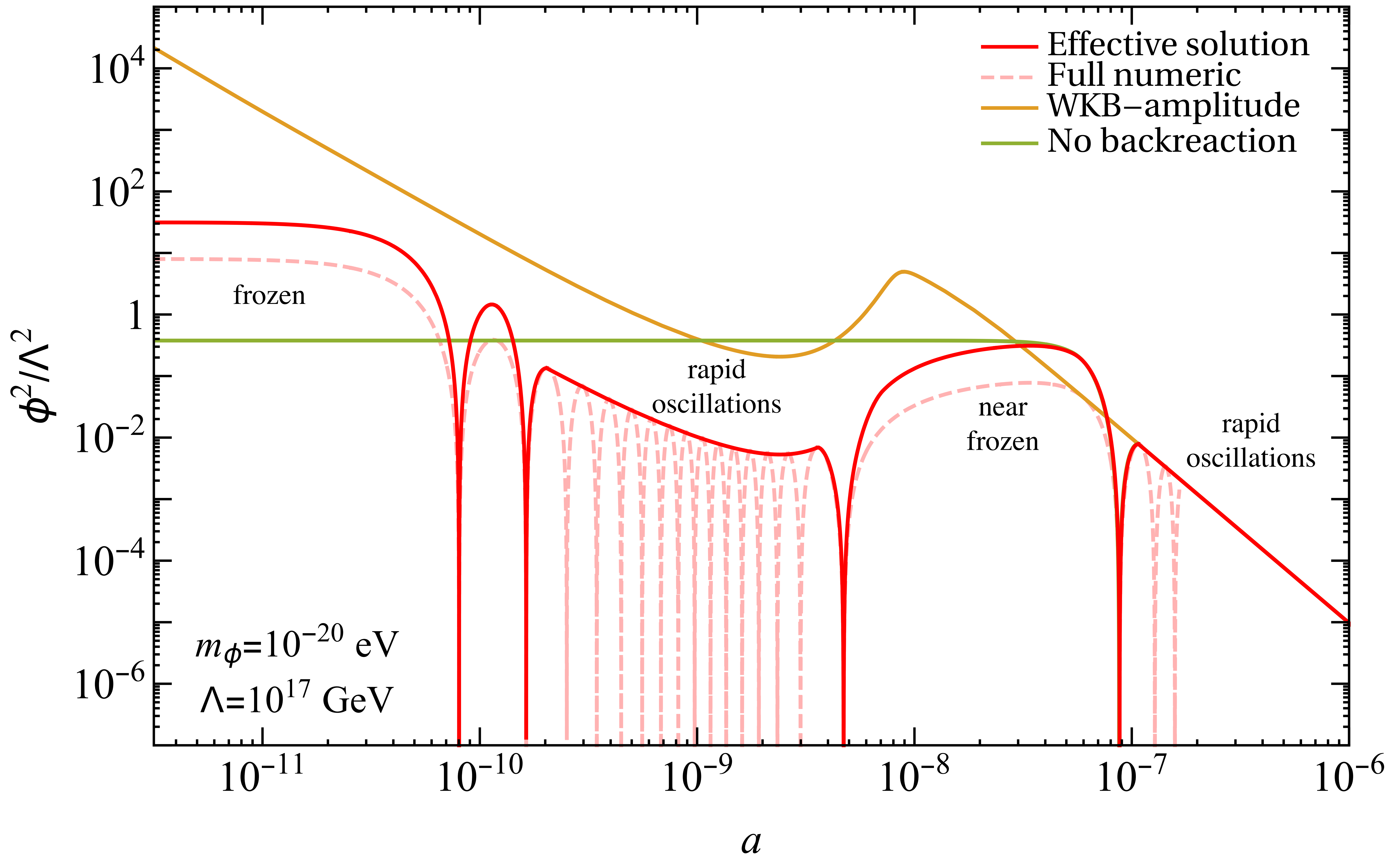
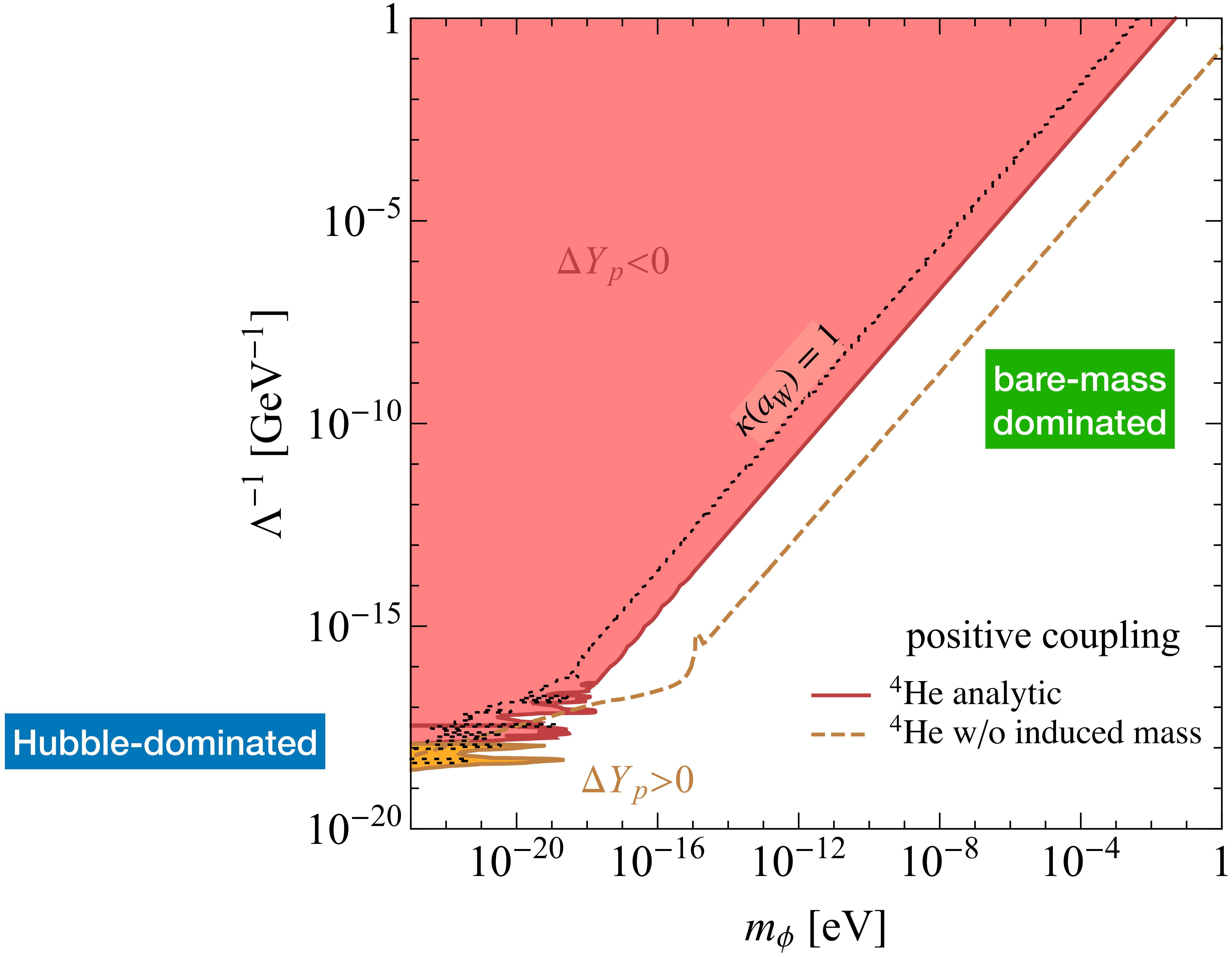


4He analytic constraint

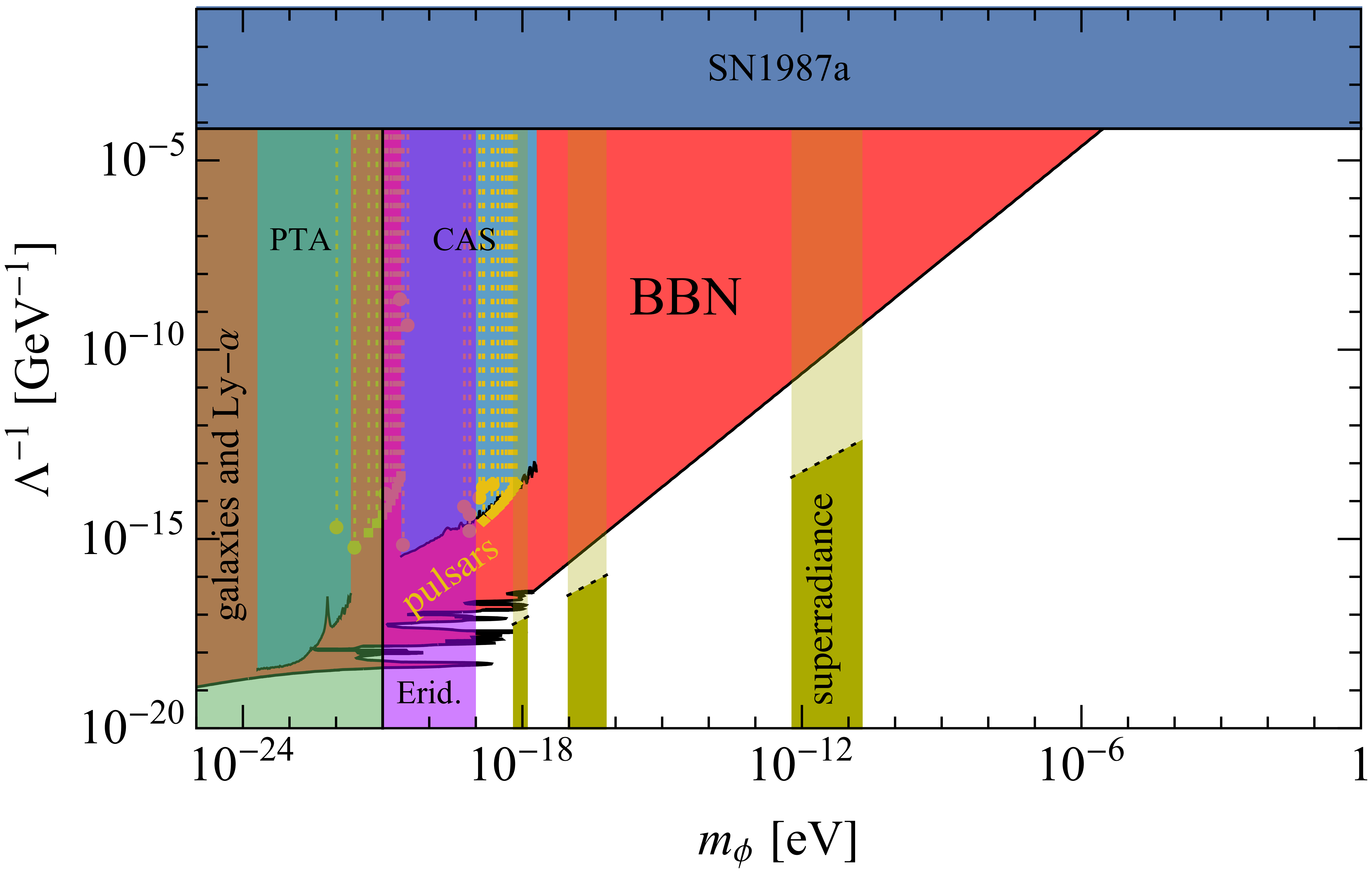
S. Sibiryakov, P. Sørensen, TTY *JHEP 20 (2020) 075* [arXiv: 2006.04820]

see also
Stadnik, Flambaum [1503.08540]



Universally-Coupled Scalar

S. Sibiryakov, P. Sørensen, TTY *JHEP 20 (2020) 075* [arXiv: 2006.04820]



Scalar with non-universal coupling

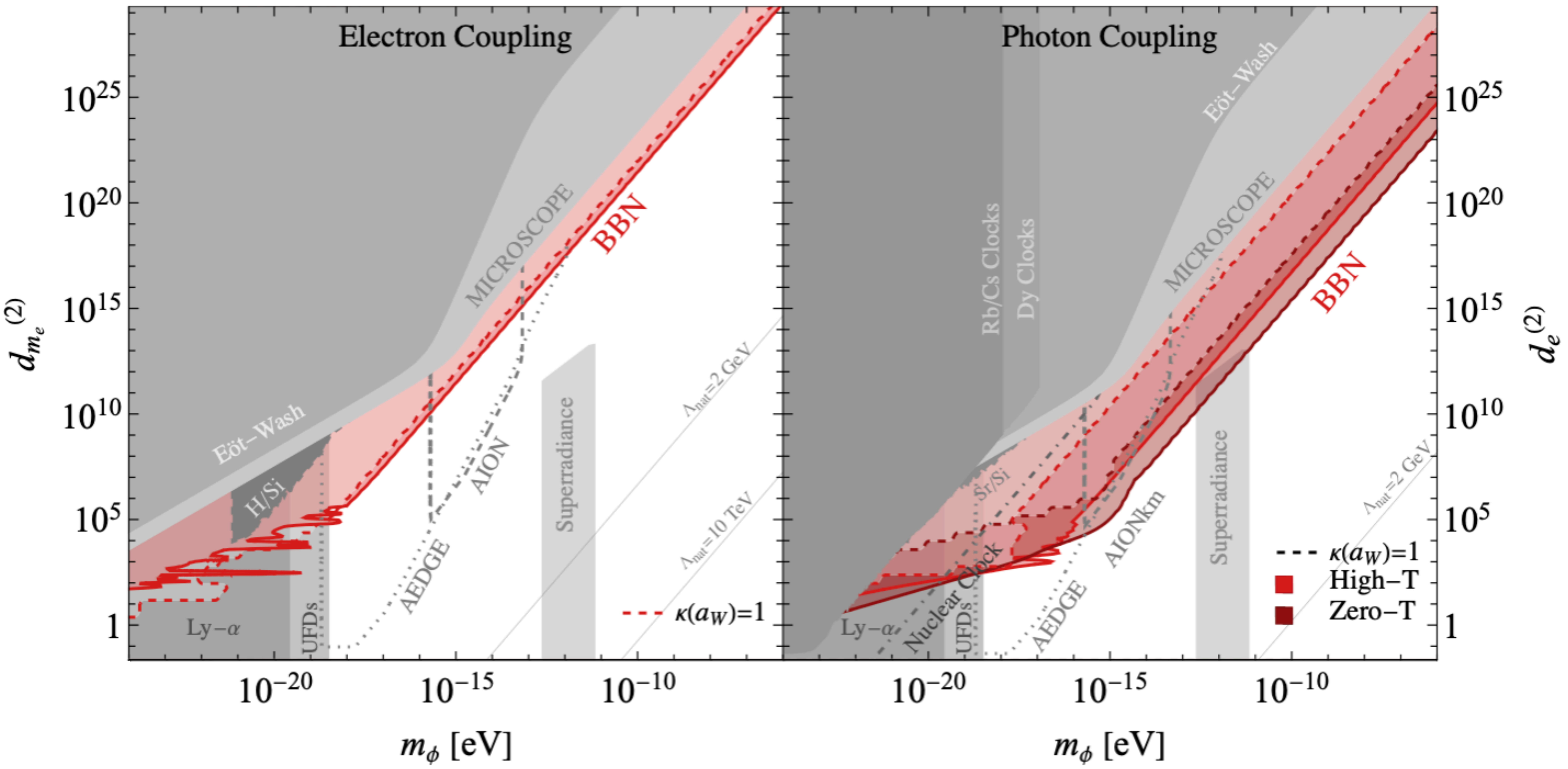
$$\mathcal{L} \supset 2\pi \frac{\phi^2}{M_{\rm pl}^2} \left[\frac{d_e^{(2)}}{4e^2} F_{\mu\nu}F^{\mu\nu} - \frac{d_g^{(2)}\beta_3}{2g_3} G^A_{\mu\nu}G^{A\mu\nu} - d_{m_e}^{(2)} m_e \bar{e}e - \sum_{i=u,d} \left(d_{m_i}^{(2)} + \gamma_{m_i} d_g^{(2)} \right) m_i \bar{\psi}_i \psi_i \right]$$

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

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

Non-Universally coupled scalar(s)

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



Conclusions

- BBN is well-explained by SM physics and therefore a powerful test of BSM physics
- ultralight scalar dark matter will modify the predictions of BBN
- the induced mass leads to non-trivial DM evolution
- instantaneous neutron freeze-out approximation is insufficient and leads to qualitatively different conclusions
- a large portion of ultralight scalar DM parameter space will have noticeable effects on BBN

cảm ơn!