Minimal FIMP models during reheating and inflationary constraints

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Based on arXiv:2306.17238 in collaboration with

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Motivation: freeze-in sensitivity

$$\mathcal{L}_{\rm int} \supset y\, \bar{f}_{\rm SM}\, \chi\, P + h.c.$$

simplified *t*-channel DM model

If $\quad y \ll 1, \quad n_\chi^i \simeq 0$

$$P \to \chi f_{\rm SM}$$

Freeze-In production peaks at $T_{\rm f.i.} \sim m_P/4$

Long-lived particle (LLP) signatures

Motivation: freeze-in sensitivity

$T_{\mathrm{RH}} \gg T_{\mathrm{f.i.}}$ ➡ DM mainly produced during radiation domination

$T_{\mathrm{RH}} \ll T_{\mathrm{f.i.}}$ ➡ DM mainly produced during reheating

No evidence to assume RD before BBN!

We could ask ourselves:

a) What is the impact of **low reheating temperature** scenarios on **LLPs**?

b) Can we gain information about **inflationary models** from **colliders**?

Inflation and reheating

α-attractor E-models and T-models

$$\boxed{V_{\rm E}(\Phi) = \Lambda^4 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\Phi}{M_{\rm Pl}}}\right)^k \qquad V_{\rm T}(\Phi) = \Lambda^4 \left[\tanh\left(\frac{\Phi}{\sqrt{6\alpha}M_{\rm Pl}}\right)\right]^k}$$

same reheating potential $(\Phi/M_{\rm Pl} \ll 1)$

$$\boxed{V(\Phi) = \lambda \frac{\Phi^k}{M_{\rm Pl}^{k-4}}}$$

Starobinsky (1980)
Ellis et al. (2013), arXiv:1307.3537
Kallosh & Linde (2013), arXiv:1306.5220
Kallosh & Linde (2013), arXiv:1307.7938
Ellis et al. (2020), arXiv:2009.01709
Kallosh & Linde (2021), arXiv:2110.10902
...

Dynamics of reheating

Garcia et al. (2020), arXiv:2004.08404
Garcia et al. (2020), arXiv:2012.10756
Bernal and Xu (2022), arXiv:2209.07546

$$\dot{\rho}_\Phi + \frac{6k}{k+2} H \rho_\Phi = -\frac{2k}{k+2} \Gamma_\Phi \rho_\Phi$$

$$\dot{\rho}_R + 4H\rho_R = \frac{2k}{k+2} \Gamma_\Phi \rho_\Phi$$

$$H^2 = \frac{\rho_\Phi + \rho_R}{3M_{\mathrm{Pl}}^2}$$

$$\rho_\Phi(a) \simeq \rho_\Phi(a_{\mathrm{rh}}) \left(\frac{a_{\mathrm{rh}}}{a}\right)^{\frac{6k}{k+2}}$$

$$\rho_R(a) \simeq \frac{2\sqrt{3}k}{k+2} \frac{M_{\mathrm{Pl}}}{a^4} \int_{a_{\mathrm{end}}}^{a} \mathrm{d}a' \boxed{\Gamma_\Phi(a')} \rho_\Phi^{1/2}(a')(a')^3$$

BOSONIC reheating (BR) $\quad \Gamma^{\mathrm{BR}}_{\Phi\to bb} \propto \mu^2 m_\Phi^{-1}(t) \quad m_\Phi(t) \propto \rho_\Phi^{\frac{k-2}{2k}}(t)$

FERMIONIC reheating (FR) $\quad \Gamma^{\mathrm{FR}}_{\Phi\to ff} \propto y^2 m_\Phi(t) \quad \frac{\mu}{M_{\mathrm{Pl}}}, y \ll 1$

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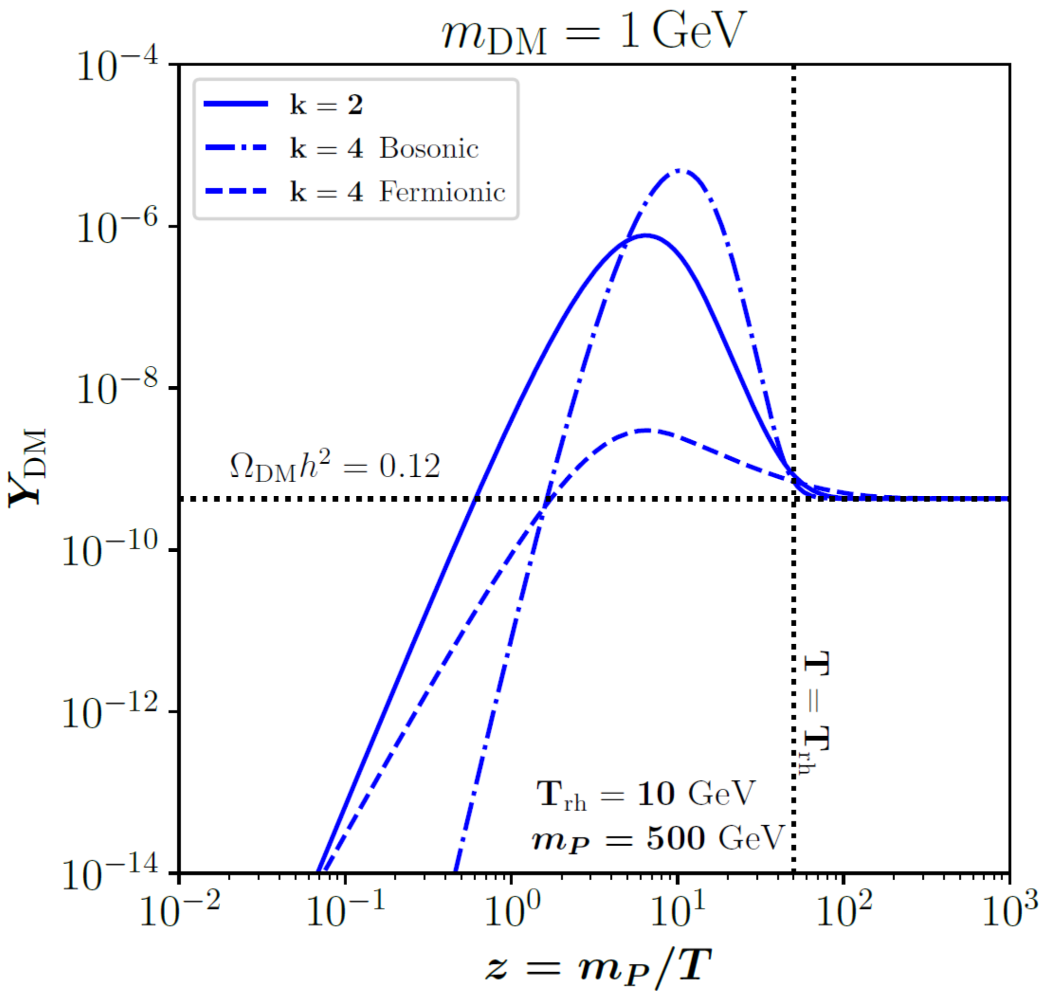
DM production during BR and FR



$$Y_{\mathrm{DM}}(T) \sim \frac{\Gamma_P}{H} \frac{S(T)}{S(T_{\mathrm{rh}})} \sim \begin{cases} \left(\dfrac{z_{\mathrm{fi}} T_{\mathrm{rh}}}{m_P}\right)^{4k-1} \\ \left(\dfrac{z_{\mathrm{fi}} T_{\mathrm{rh}}}{m_P}\right)^{\frac{9-k}{k-1}} \end{cases}$$

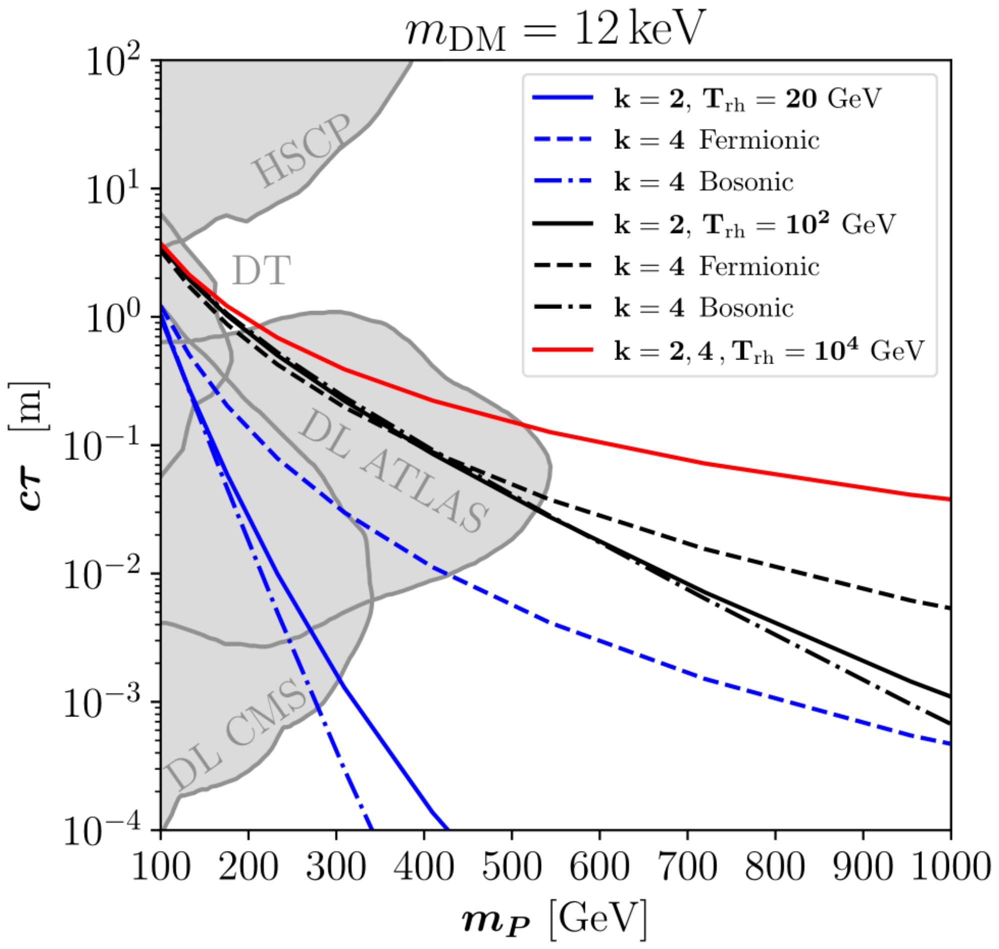
Type	T_{rh} [GeV]	$c\tau$ [m]
$k = 2$	10	1.8×10^{-2}
$k = 4$ BR	10	1.8×10^{-6}
$k = 4$ FR	10	1.7×10^{2}
$k = 2,\ 4$	10^4	1.3×10^{4}

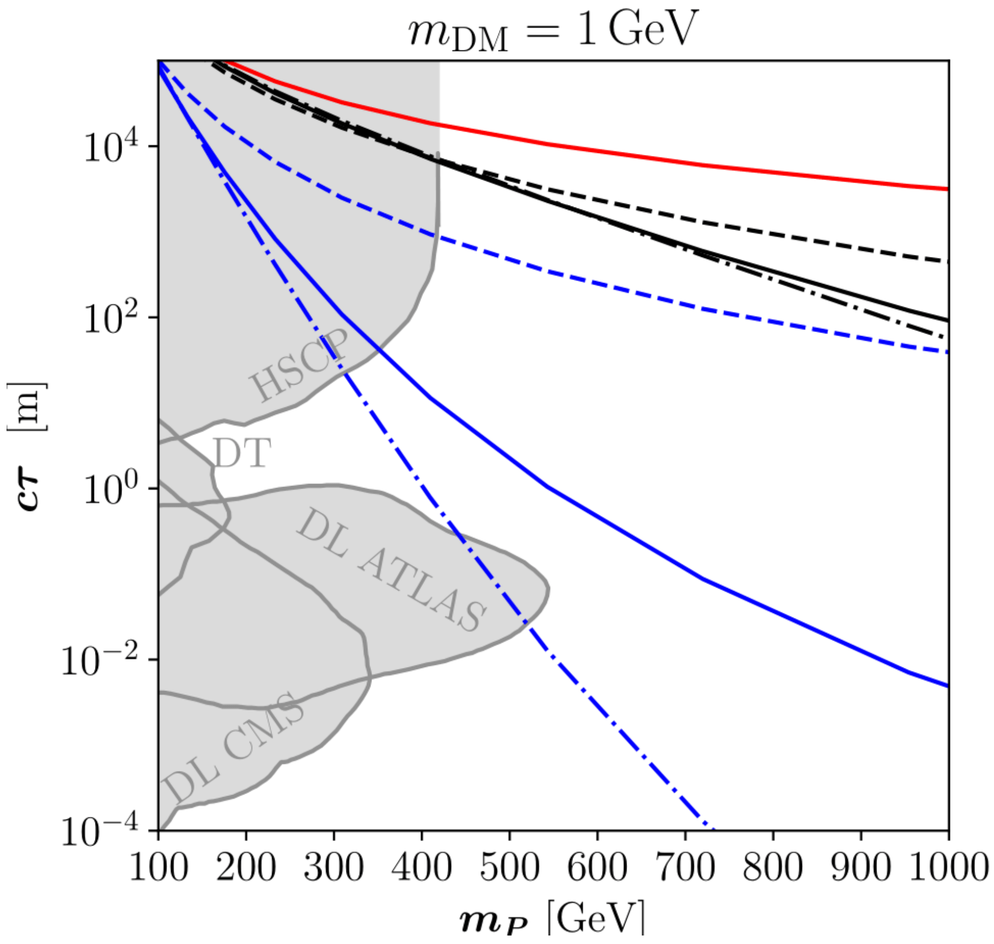
Becker, **EC**, Harz, Lang, Xu (2023)

Lifetime of the parent particle

Leptophilic Majorana DM with charged scalar

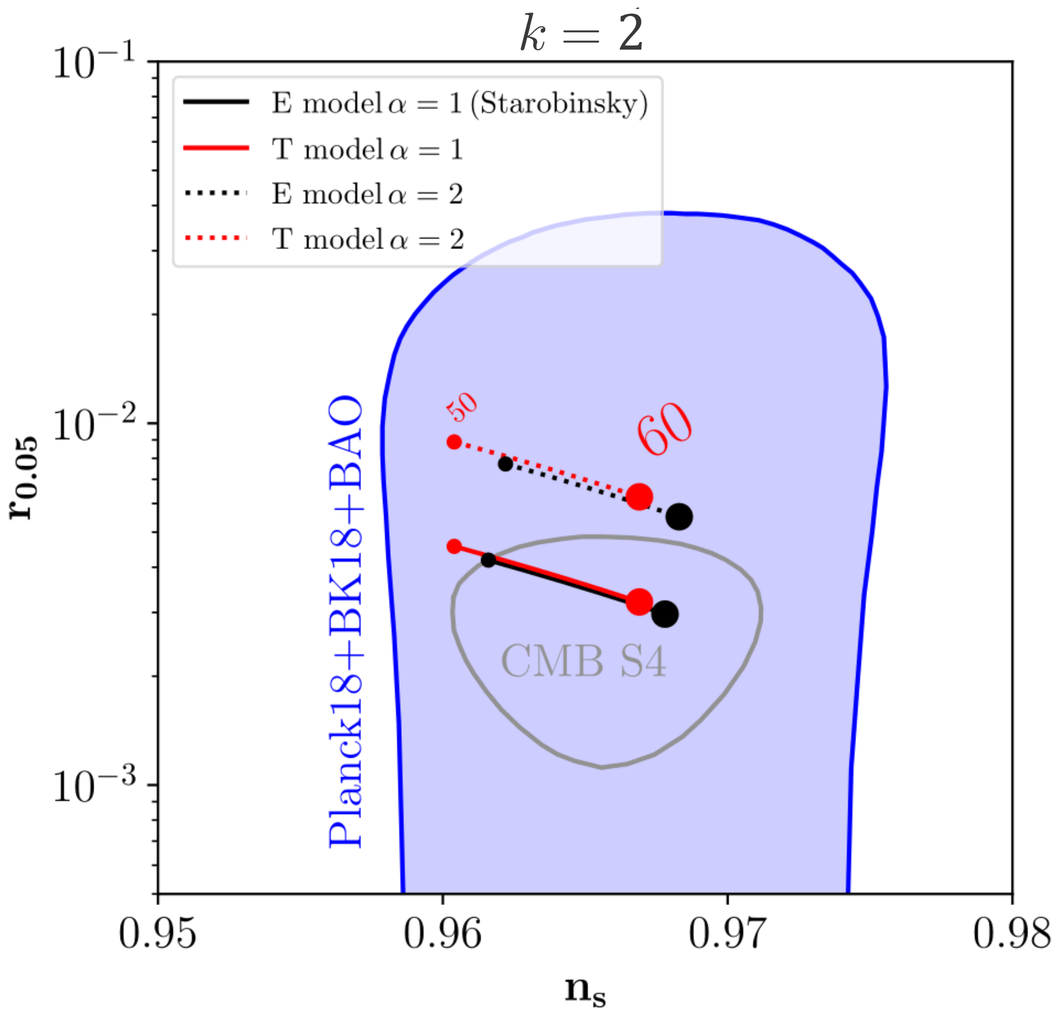
Becker, **EC**, Harz, Lang, Xu (2023)

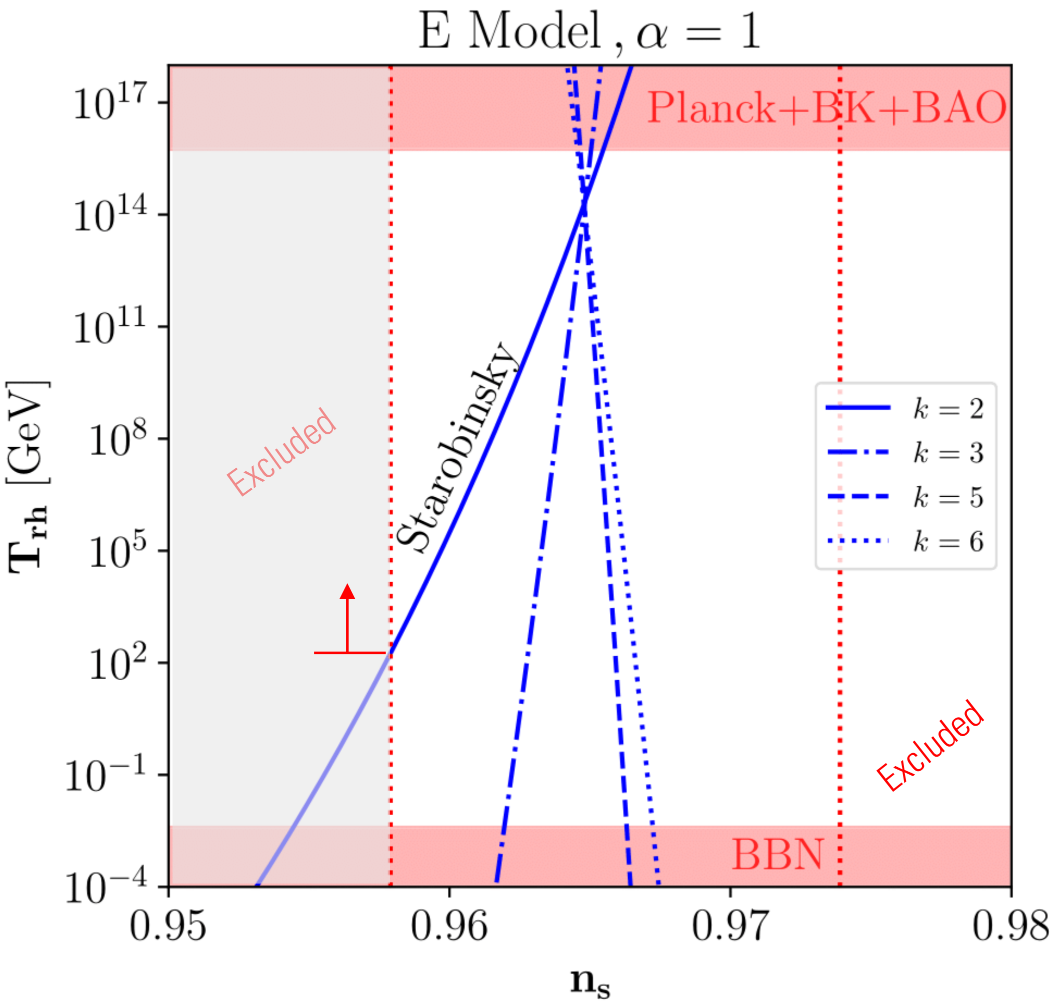




LLP limits from Calibbi et al. (2021)

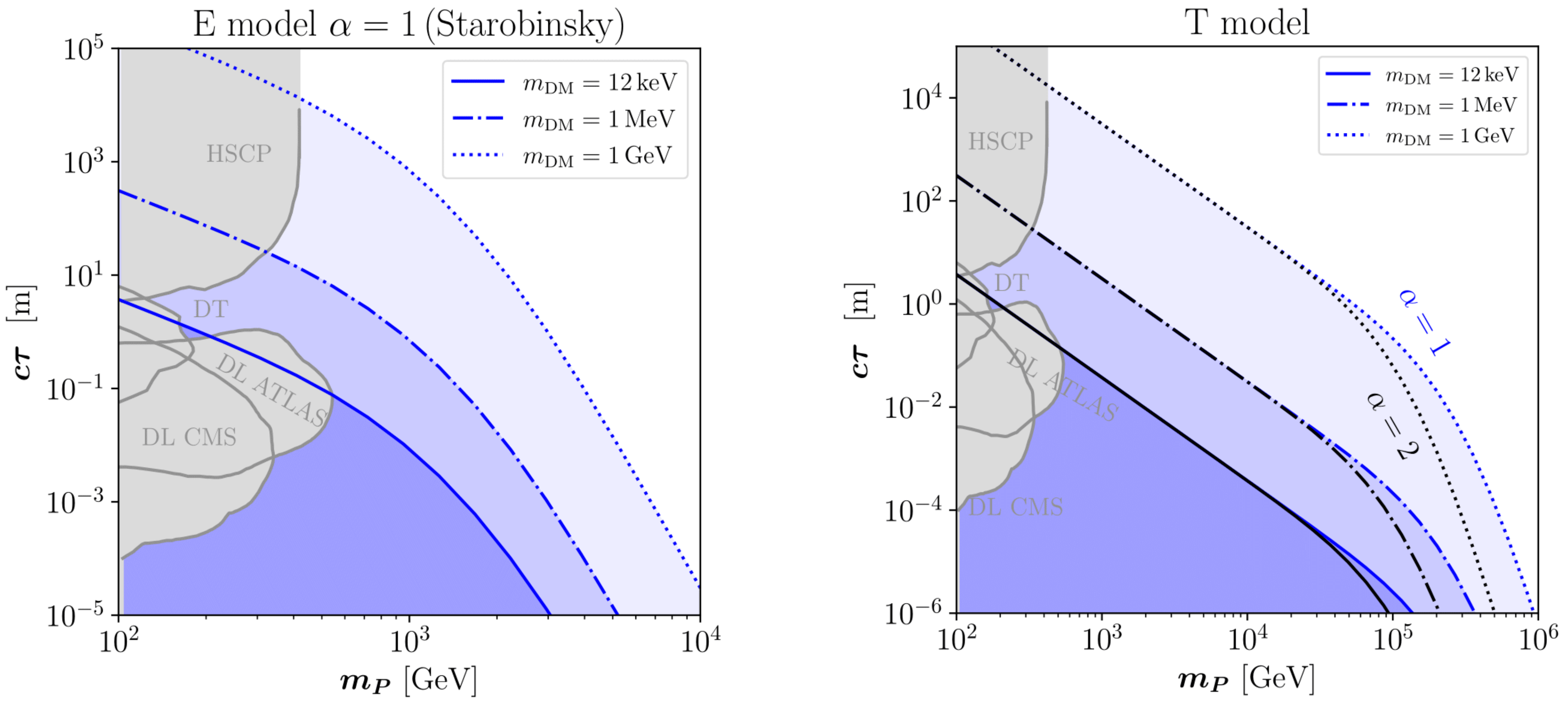
Constraints on inflation from CMB





Becker, **EC**, Harz, Lang, Xu (2023)

Combined LLP+CMB constraints



Becker, **EC**, Harz, Lang, Xu (2023)

Conclusions

- ✓ DM production + interpretation of collider limits in FIMP models depend on: *i)* the reheating temperature, *ii)* the nature of the inflaton-matter coupling, *iii)* the form of the inflaton and reheating potentials.

- ✓ Inflationary constraints measure how strongly DM production can be altered during reheating.

- ✓ A positive LLP signal has the potential to distinguish between inflation models.

Thank you for your attention!

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Backup slides

Lifetime of parent particle: two observations

Bélanger et al. (2019), arXiv:1811.05478 (see their Eq. 3.2)

$$\Omega_{\rm DM}h^2 \propto \cancel{\int_{\ln a_{\rm end}}^{\ln a_{\rm rh}} \mathrm{d}\ln a' \left(\frac{a'}{a_{\rm end}}\right)^3 \frac{\mathcal{C}_{\rm rh}}{H_{\rm rh}}} + \int_{\ln a_{\rm rh}}^{\ln a} \mathrm{d}\ln a' \left(\frac{a'}{a_{\rm end}}\right)^3 \frac{\mathcal{C}_{\rm RD}}{H_{\rm RD}}$$

Ok only when $T_{\rm rh} \gg m_P$, otherwise DM abundance and parent particle lifetime underestimated

Lifetime of parent particle: two observations

Calibbi et al. (2021), arXiv:2102.06221 (see their Eqs. A.10, B.20)

Matter-dominated reheating

$$H(T_{rh}) = \Gamma_\Phi \quad \Longrightarrow \quad \Gamma_\Phi = \sqrt{\frac{\pi^2 g_\star}{90}}\frac{T_{\rm rh}^2}{M_{\rm Pl}}$$

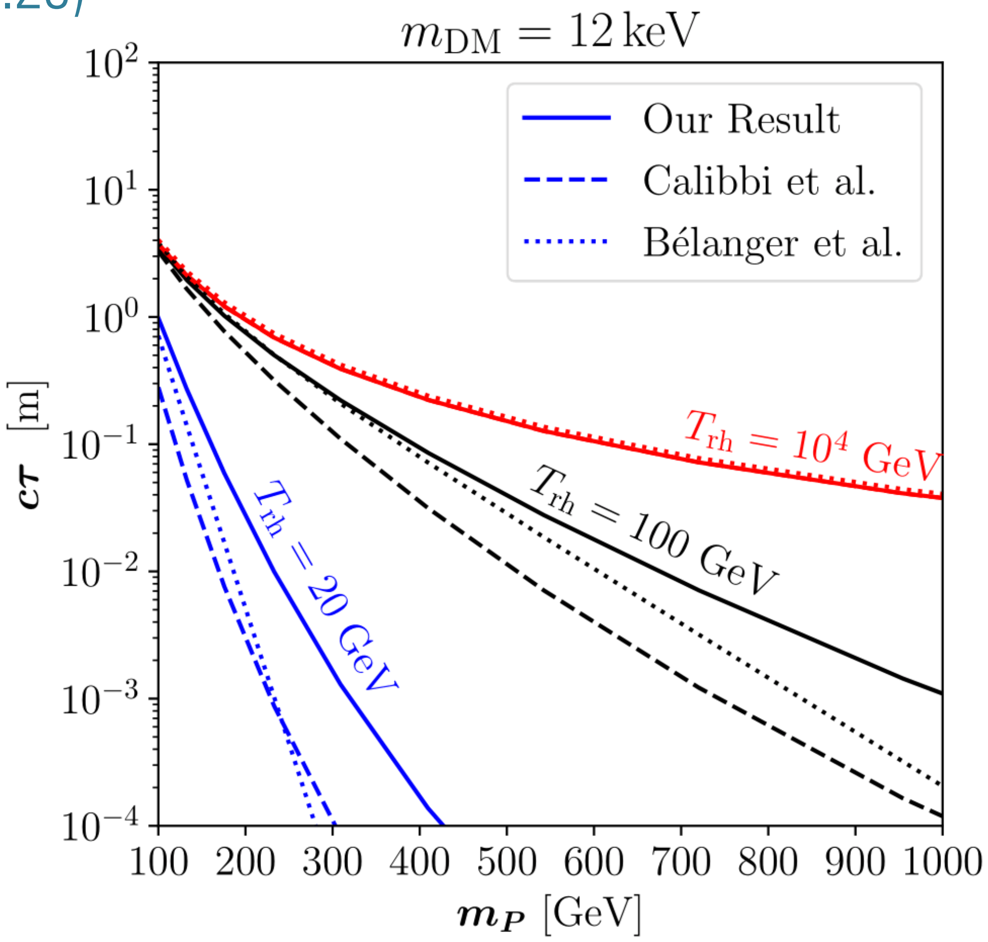
Our method:

$$\rho_\Phi(a_{\rm rh}) = \rho_R(a_{\rm rh}) \ \text{with} \ \Gamma_\Phi = \Gamma_\Phi^{\rm BR,\,FR} \qquad (\star)$$

Calibbi et al. predicts *larger* dilution effects, hence *smaller* lifetimes wrt. our definition.

$(\star)$ is more sensible, especially for potentials with $k > 2$.

[See also Garcia et al. (2020), arXiv:2004.08404]

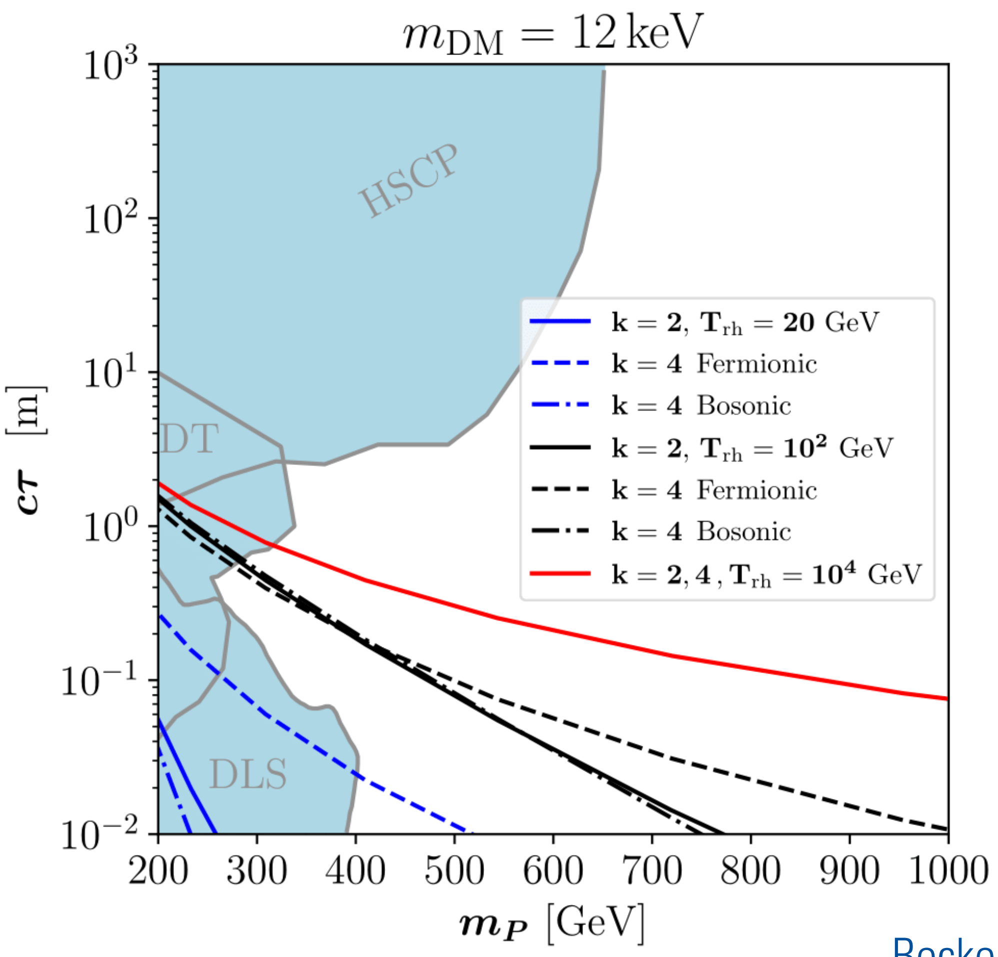


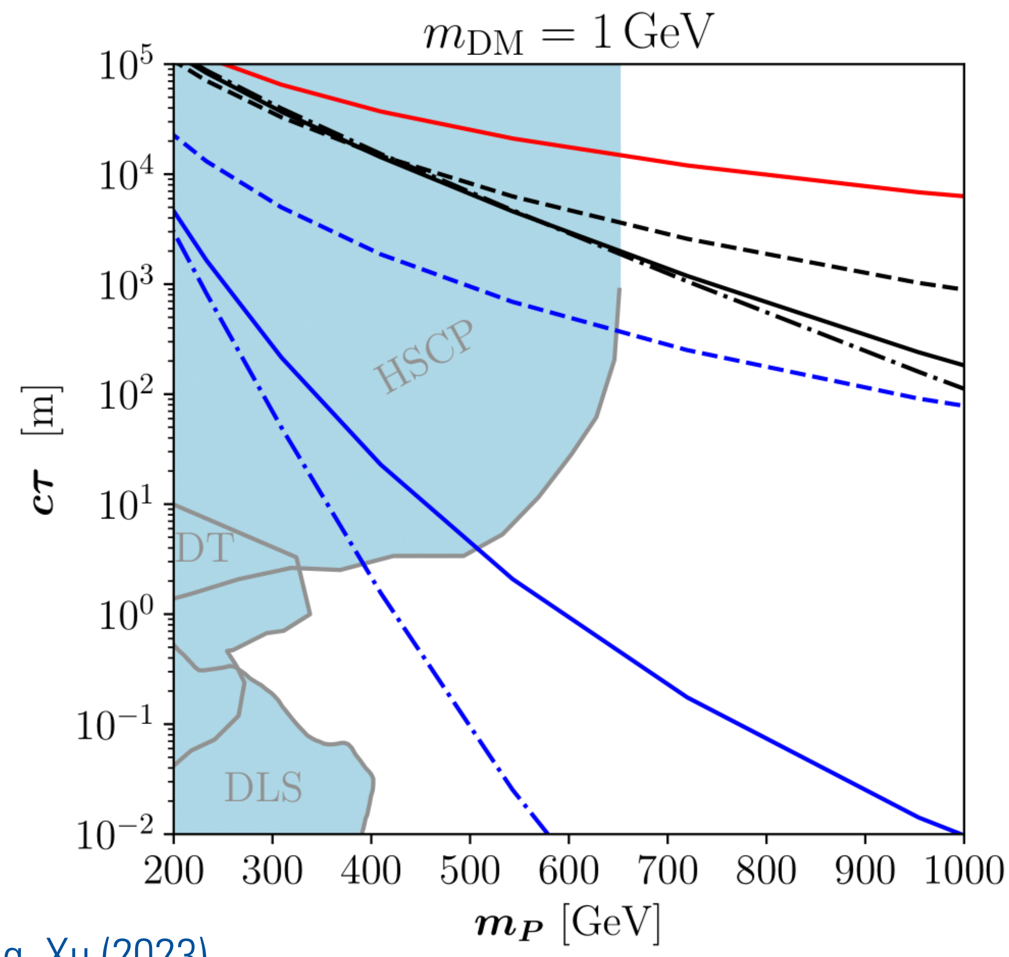
Becker, **EC**, Harz, Lang, Xu (2023)

Lifetime of parent particle

Leptophilic real scalar DM (vectorlike fermion P)

LLP limits from Bélanger et al. (2019)





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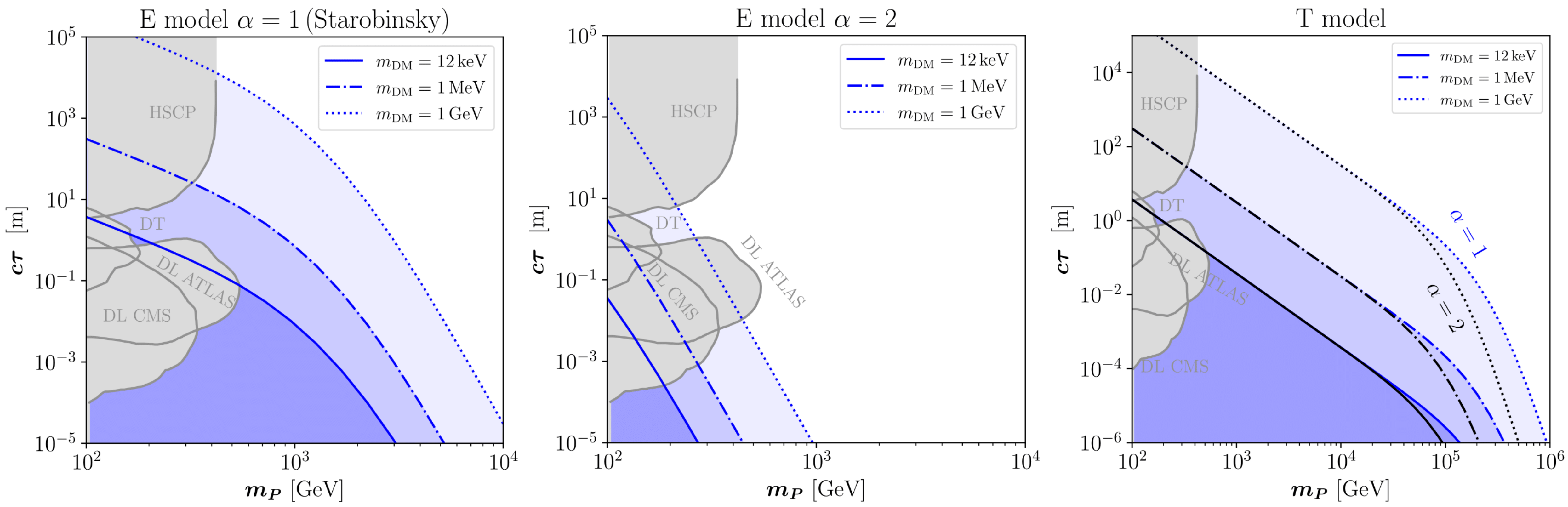
Combined LLP+CMB constraints



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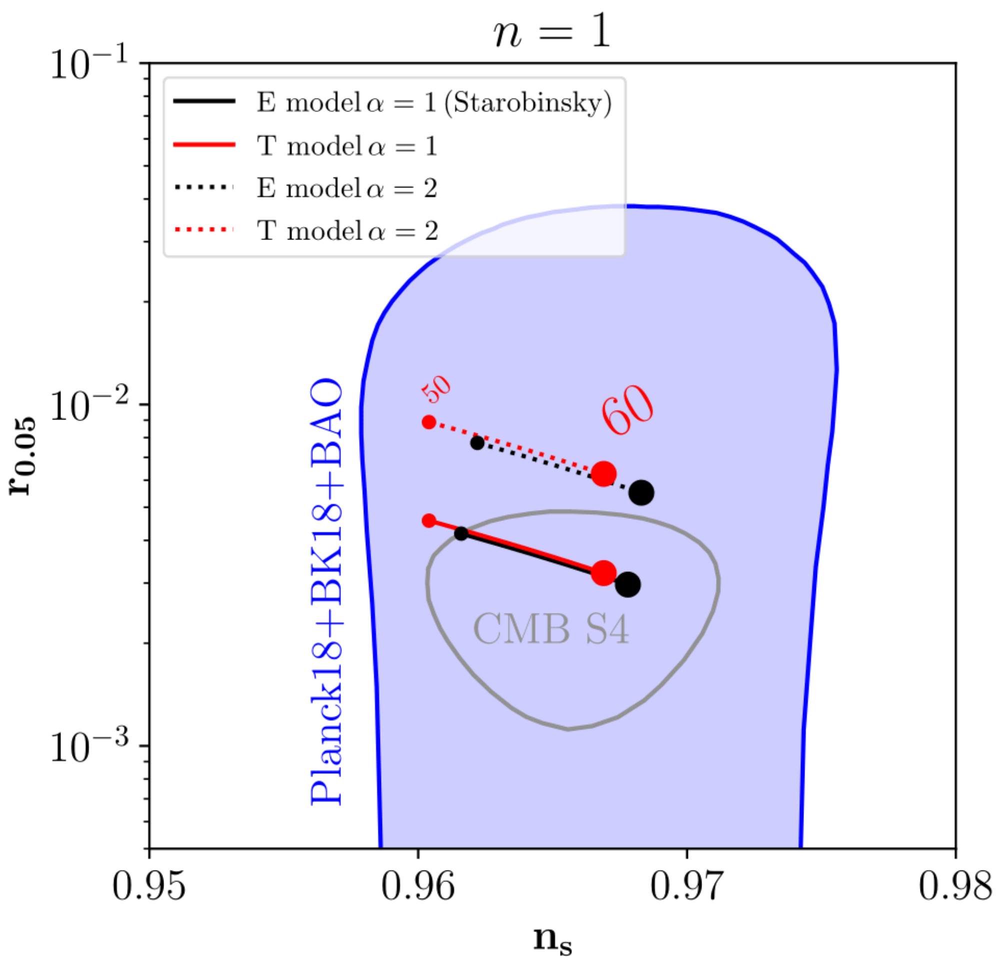
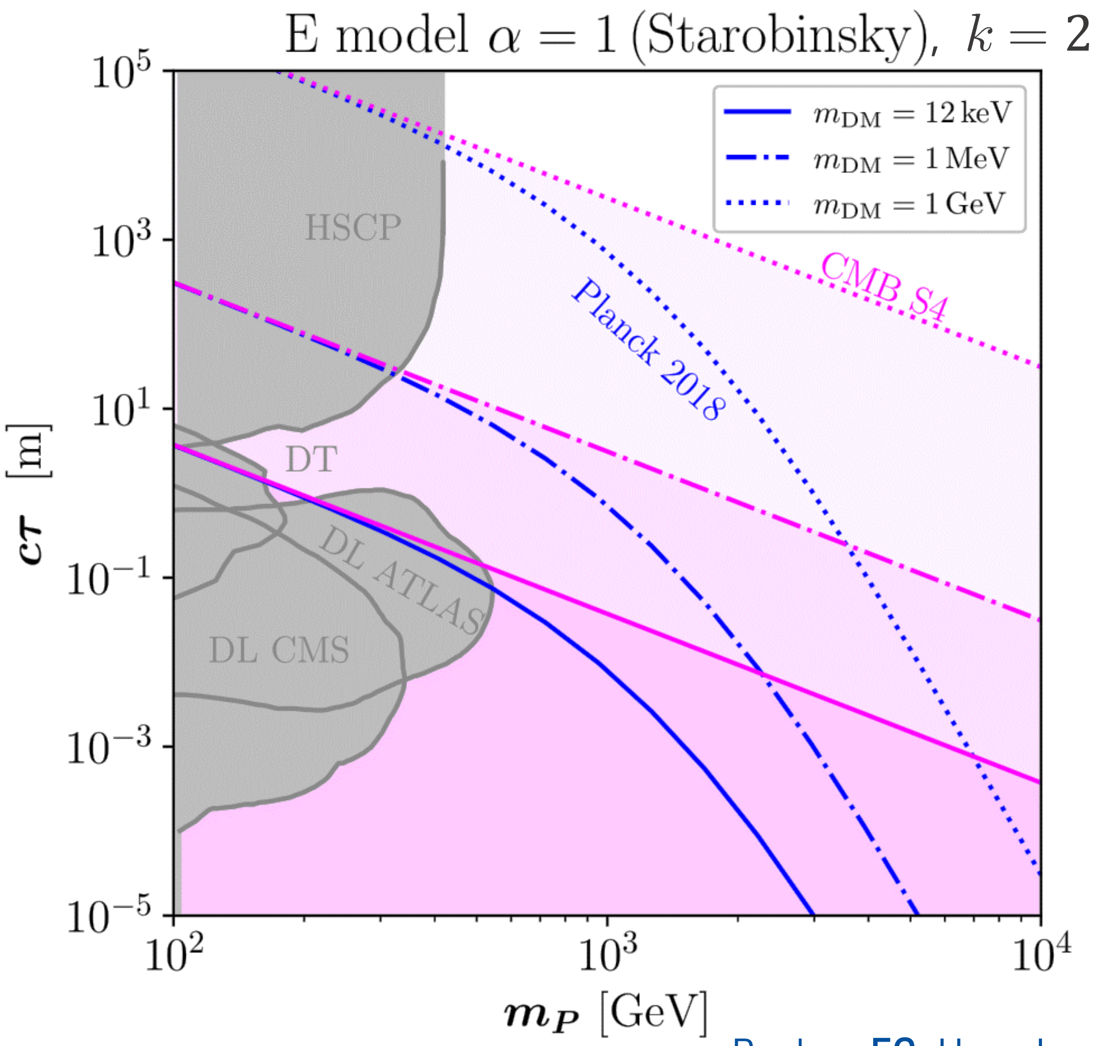
Combined LLP+CMB constraints

CMB-S4 Science Book, arXiv:1610.02743





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Details of the reheating phase

BOSONIC

$$\Gamma_{\Phi\to XX^\dagger}(t) = \frac{\mu^2_{\rm eff}(k)}{8\pi m_\Phi(t)}$$

$$\mu^2_{\rm eff}(k) = \mu^2\,\alpha_\mu(k,\mathcal{R})\,\frac{(k+2)(k-1)}{4}\sqrt{\frac{\pi\,k}{2(k-1)}}\,\frac{\Gamma(\frac{k+2}{2k})}{\Gamma(\frac{1}{k})}$$

$$\rho_R(a) \simeq \frac{\sqrt{3}}{8\pi}\,\frac{1}{1+2k}\sqrt{\frac{k}{k-1}}\,\frac{\mu^2_{\rm eff}}{\lambda^{\frac{1}{k}}}M_P^{\frac{2k-4}{k}} \times \rho_\Phi^{\frac{1}{k}}(a_{\rm rh})\left(\frac{a_{\rm rh}}{a}\right)^{\frac{6}{2+k}}\left[1-\left(\frac{a_{\rm end}}{a}\right)^{\frac{2(1+2k)}{2+k}}\right]$$

$$T^4_{{\rm max},b} = \frac{5}{4\pi^4 g_\star}\,\frac{k}{\sqrt{3k(k-1)}}\,\frac{M_P^{\frac{2k-4}{k}}}{\lambda^{\frac{1}{k}}}\mu^2_{\rm eff}\,\rho_{\rm end}^{\frac{1}{k}}\left(\frac{3}{2k+4}\right)^{\frac{2k+4}{2k-1}}$$

$$T^4_{{\rm rh},b} = \frac{30}{\pi^2 g_\star}\left[\frac{\sqrt{3}}{8\pi\,(1+2k)}\sqrt{\frac{k}{k-1}}\lambda^{-\frac{1}{k}}\frac{\mu^2_{\rm eff}}{M^2_{\rm Pl}}\right]^{\frac{k}{k-1}} M^4_{\rm Pl}$$

FERMIONIC

$$\Gamma_{\Phi\to F\bar{F}}(t) = \frac{y^2_{\rm eff}(k)}{8\pi}m_\Phi(t)$$

$$y^2_{\rm eff}(k) = y^2\alpha_y(k,\mathcal{R})\sqrt{\frac{\pi k}{2(k-1)}}\,\frac{\Gamma(\frac{k+2}{2k})}{\Gamma(\frac{1}{k})}$$

$$\rho_R(a) \simeq \frac{\sqrt{3}}{8\pi}\,\frac{k\sqrt{k(k-1)}}{7-k}y^2_{\rm eff}\lambda^{\frac{1}{k}}M_{\rm Pl}^{\frac{4}{k}} \times \rho_\Phi^{\frac{k-1}{k}}(a_{\rm rh})\left(\frac{a_{\rm rh}}{a}\right)^{\frac{6(k-1)}{2+k}}\left[1-\left(\frac{a_{\rm end}}{a}\right)^{\frac{2(7-k)}{2+k}}\right]$$

$$T^4_{{\rm max},f} = \frac{5}{6\pi^3 g_\star}\sqrt{3k(k-1)}\,\lambda^{\frac{1}{k}}M_{\rm Pl}^{\frac{4}{k}}y^2_{\rm eff}\,\rho_{\rm end}^{\frac{k-1}{k}}\left(\frac{3k-3}{2k+4}\right)^{\frac{2k+4}{7-k}}$$

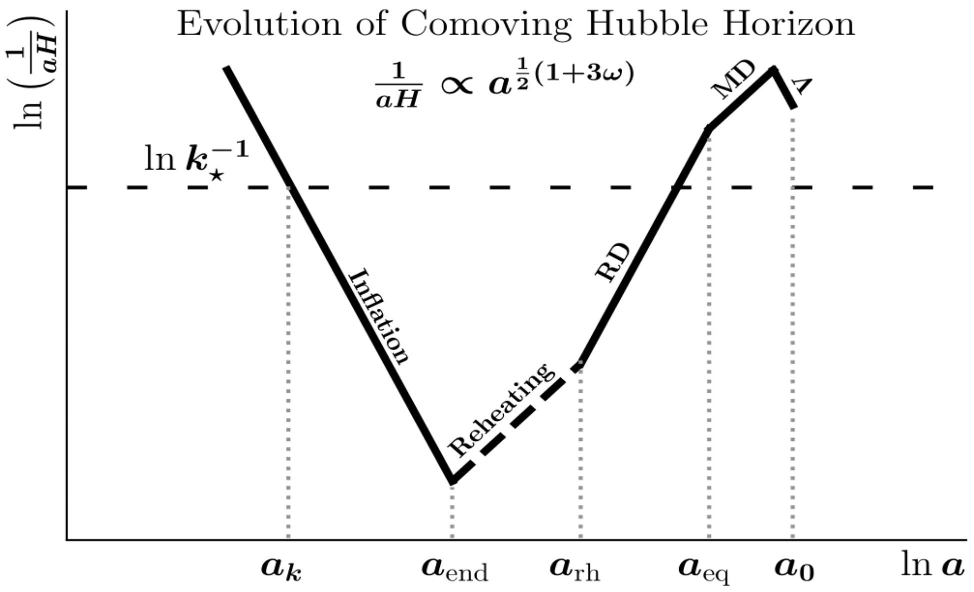
$$T^4_{{\rm rh},f} = \frac{30}{\pi^2 g_\star}\left[\frac{k\sqrt{3k(k-1)}}{7-k}\lambda^{\frac{1}{k}}\frac{y^2_{\rm eff}}{8\pi}\right]^k M^4_{\rm Pl}$$

Formula for T_{rh} vs. n_s

See, e.g., Cook et al. (2015), arXiv:1502.04673

Pivot scale
$k_* = a_* H_*$

$$\frac{a_0}{a_{\rm eq}} = \frac{a_*}{a_{\rm end}} \frac{a_{\rm end}}{a_{\rm rh}} \frac{a_{\rm rh}}{a_{\rm eq}} \frac{a_0 H_*}{k_*}$$



$$N_{\rm rh} = \frac{1}{3(1+w_{\rm rh})} \ln\left(\frac{\rho_{\rm end}}{\rho_{\rm rh}}\right) \qquad \rho_{\rm end} = \frac{3}{2} V_{\rm end} \qquad \rho_{\rm rh} = \frac{g_{*,\rm rh}\pi^2}{30} T_{\rm rh}^4$$

$$\Rightarrow \quad N_{\rm rh} = \frac{4}{1-3w_{\rm rh}}\left[-N_* - \ln\left(\frac{k_*}{a_0 T_0}\right) - \frac{1}{4}\ln\left(\frac{45}{g_{*\rm rh}\pi^2}\right) - \frac{1}{3}\ln\left(\frac{11 g_{*s,\rm rh}}{43}\right) + \ln\left(\frac{V_{\rm end}^{1/4}}{H_*}\right)\right]$$

After reheating, entropy conserved

$$g_{*s,\rm rh} T_{\rm rh}^3 = \left(\frac{a_0}{a_{\rm rh}}\right)^3 \left(2T_0^3 + 6\cdot\frac{7}{8} T_{\nu 0}^3\right) \quad \Rightarrow \quad \frac{T_{\rm rh}}{T_0} = \left(\frac{43}{11 g_{*s,\rm rh}}\right)^{1/3} \frac{a_0}{a_{\rm eq}} \frac{a_{\rm eq}}{a_{\rm rh}} \left(\frac{43}{11 g_{*s\rm rh}}\right)^{1/3} e^{-N_{\rm rh}} e^{-N_*} \frac{a_0 H_*}{k_*}$$

$$\Rightarrow \quad T_{\rm rh} = \left[\left(\frac{43}{11 g_{*s,\rm rh}}\right)^{\frac{1}{3}} \frac{a_0 T_0}{k_*} H_* e^{-N_*} \left(\frac{45 V_{\rm end}}{\pi^2 g_{*\rm rh}}\right)^{-\frac{1}{3(1+w_{\rm rh})}}\right]^{\frac{3(1+w_{\rm rh})}{3w_{\rm rh}-1}}$$

Inflationary parameters

$$\epsilon_V \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \; ; \quad \eta_V \equiv M_{\rm Pl}^2\left(\frac{V''}{V}\right)$$

$$N_* = \int_{\Phi_{\rm end}}^{\Phi_*} \frac{1}{\sqrt{2\epsilon_V}}\frac{d\phi}{M_{\rm Pl}} \qquad A_{s,*} = \frac{V}{24\pi^2\epsilon_V M_{\rm Pl}^4} = (2.1 \pm 0.1)\times 10^{-9}$$

$$r = 16\epsilon_V \; ; \quad n_s = 1 - 6\epsilon_V + 2\eta_V$$

$$r_{0.05} < 0.035, \quad 95\%\,\text{C.L.} \qquad n_s = 0.9659 \pm 0.0040$$

FIMP models

Majorana DM / charged scalar parent model

$$\mathcal{L}_{\mathrm{M}} \supset \mathcal{L}_{\Phi} + \mathcal{L}_{\chi} + \mathcal{L}_{X} + \mathcal{L}_{\Phi X} + \mathcal{L}_{\mathrm{Yuk.}}$$

$$\mathcal{L}_X = (D_\mu X)^\dagger (D^\mu X) - V(X)$$

$$\boxed{-\,\mu_X \Phi |X|^2} - \frac{\sigma_X}{2}\Phi^2 |X|^2$$

$$\mathcal{L}_{XH} = -\lambda_{XH} |H|^2 |X|^2$$

$$\mathcal{L}_{\mathrm{Yuk.}} = \boxed{-\left(y_{\mathrm{DM}}\, X \bar{\chi}\, f_R + h.c.\,\right)} - y_\chi \Phi \bar{\chi}\chi$$

Scalar singlet DM / vectorlike fermion parent model

$$\mathcal{L}_{\mathrm{S}} \supset \mathcal{L}_{\Phi} + \mathcal{L}_{s} + \mathcal{L}_{\Phi s} + \mathcal{L}_{F} + \mathcal{L}_{\Phi F} + \mathcal{L}_{\mathrm{Yuk.}}$$

$$\mathcal{L}_s = \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 - \lambda_{sH} s^2 |H|^2$$

$$\mathcal{L}_{\Phi s} = -\mu_s s \Phi^2\,,$$

$$\mathcal{L}_{\Phi F} = -\frac{\sigma_s}{2} s^2 \Phi^2 \boxed{-\, y_F \Phi \bar{F} F}$$

$$\mathcal{L}_{\mathrm{Yuk.}} \boxed{-\left(y_s\, s\, \bar{F} f_R + h.c.\,\right)}$$

$$\mathcal{L}_{\Phi H} = -\mu_H \Phi |H|^2 - \frac{\lambda_{\Phi H}}{2} \Phi^2 |H|^2$$

More on E- and T- models