Minimal FIMP models during reheating and inflationary constraints

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Based on arXiv:2306.17238 in collaboration with

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SUSY2023

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

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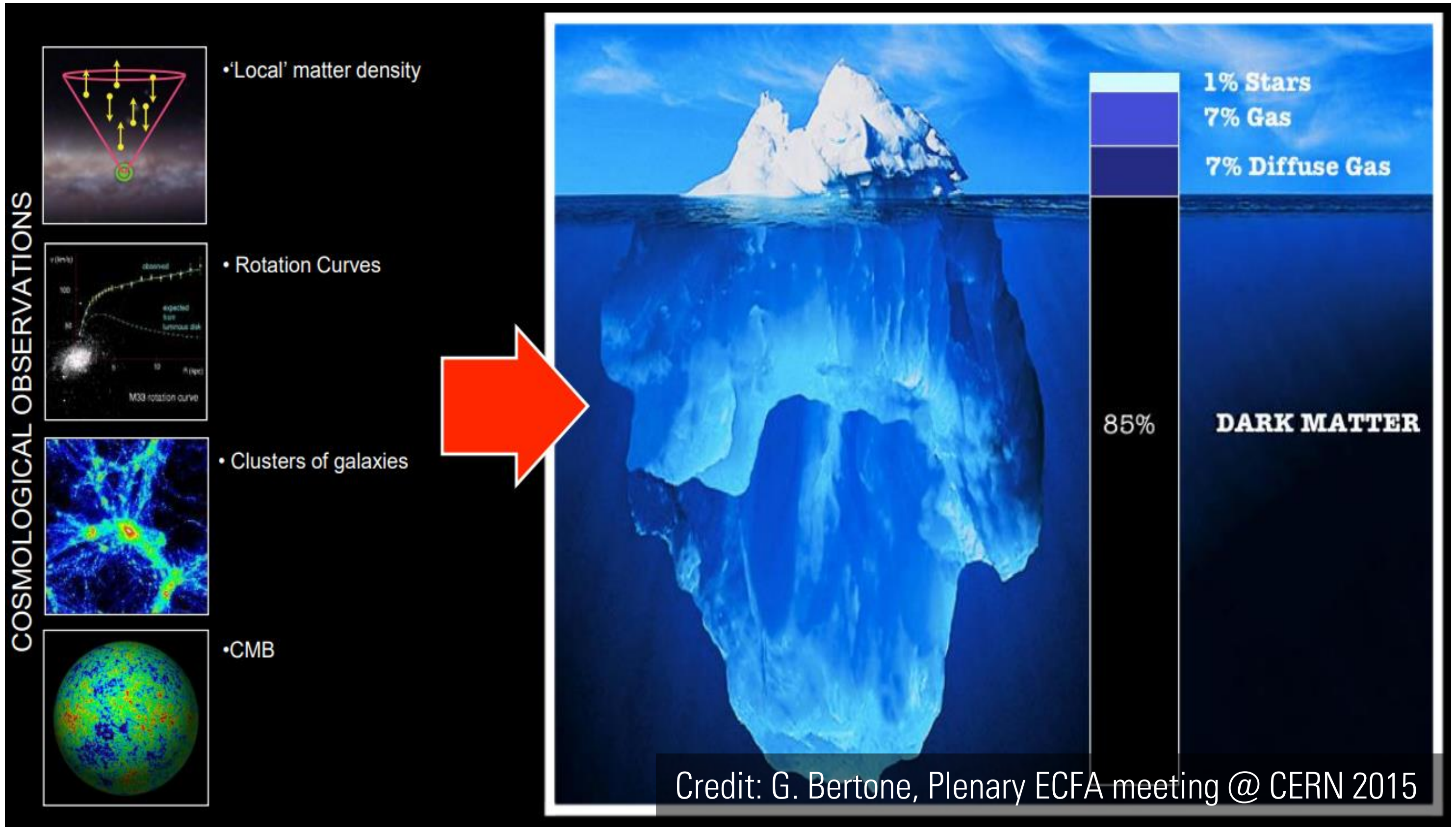
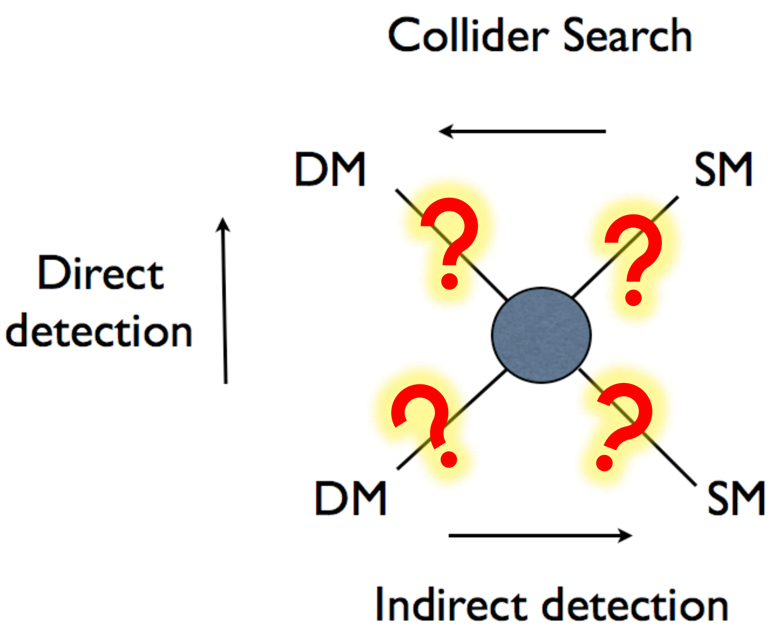
The Dark Matter puzzle

See plenary talks by, e.g.:
Leszek Roszkowski
Manfred Lindner



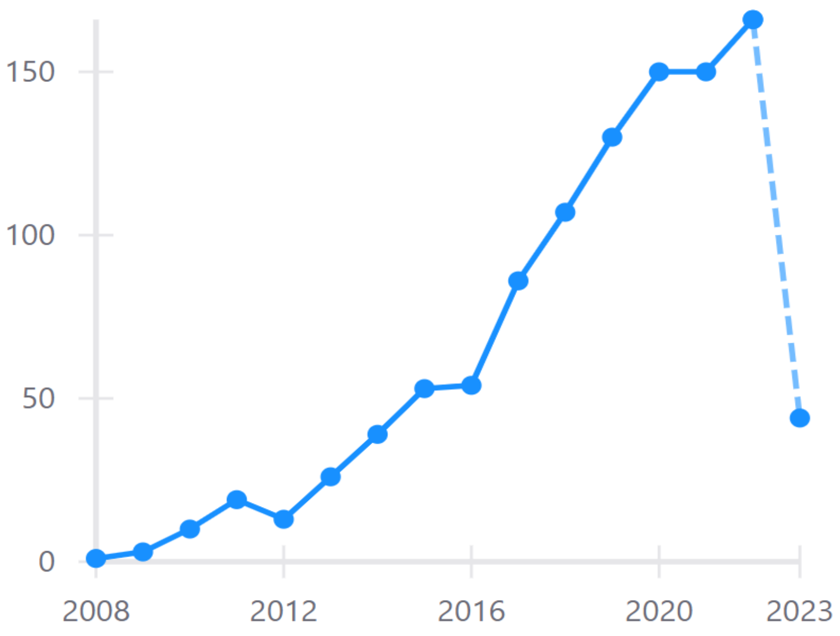


What if DM is a FIMP?

What if DM interacts very feebly with the other particles?

Hall et al. *(2010),* arXiv:0911.1120
"Freeze-In Production of FIMP Dark Matter"

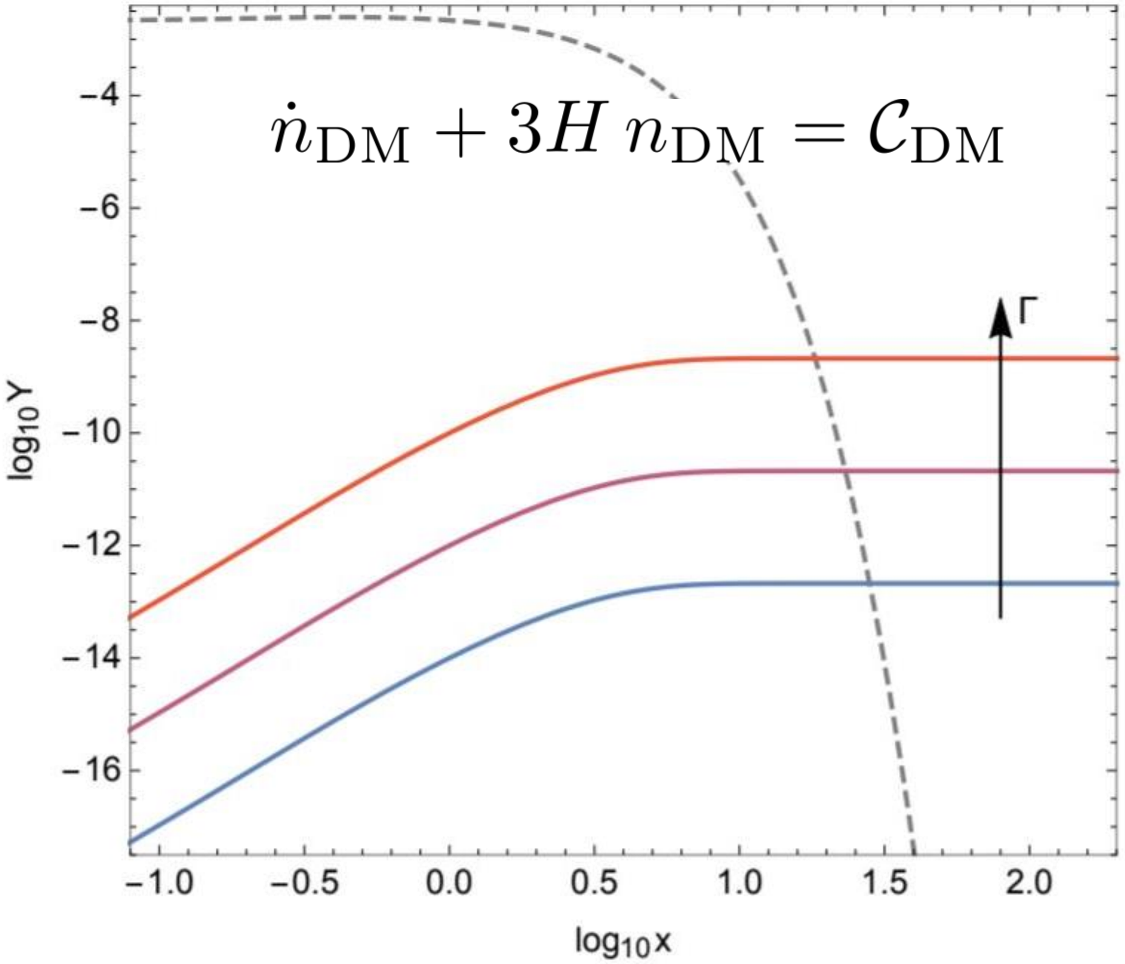
Citations per year



Feebly Interacting (Massive) Particles (**FIMPs**)
have gained increasing interest in the last decade

(non-exhaustive list)
Curtin et al. *(2019),* arXiv:1806.07396
Bélanger et al. *(2019),* arXiv:1811.05478
LLP@LHC White Paper (2020), arXiv:1903.04497
FIPs 2022 @CERN, Antel et al. (2023), arXiv:2305.01715
https://longlivedparticles.web.cern.ch/
...many more...

DM production in minimal FIMP models



Credit: Bernal et al. *Int.J.Mod.Phys.A (2017)*

$$\mathcal{L}_{\mathrm{int}} \supset y\, P \chi B_{\mathrm{SM}} \qquad P \to \chi + B_{\mathrm{SM}}$$

$$\mathcal{C}_{\mathrm{DM}} = \frac{g_P}{2\pi^2} \Gamma_P\, m_P^2\, T\, K_1\left(\frac{m_P}{T}\right)$$

$$H = \frac{\sqrt{\rho}}{\sqrt{3} M_{\mathrm{Pl}}} \simeq \frac{T^2}{\sqrt{3} M_{\mathrm{Pl}}}$$ (radiation domination)

Tiny coupling $\Longrightarrow$ long-lived parent particle!

How does this change if not in Radiation Domination?

Warm-up: RD or “non-standard” expansions?

No evidences to assume a radiation-dominated Universe prior to Big Bang Nucleosynthesis (BBN)

$$T > T_{\rm BBN} \simeq 4\,{\rm MeV}\,?$$

Arias et al. (2019), arXiv:1906.04183
Allahverdi et al. (2020), arXiv:2006.16182

What if reheating after inflation was a (very) prolonged phase?

What if FIMPs were produced in this “non-standard” scenario?

What is the impact on the LLP predictions and on inflationary models?

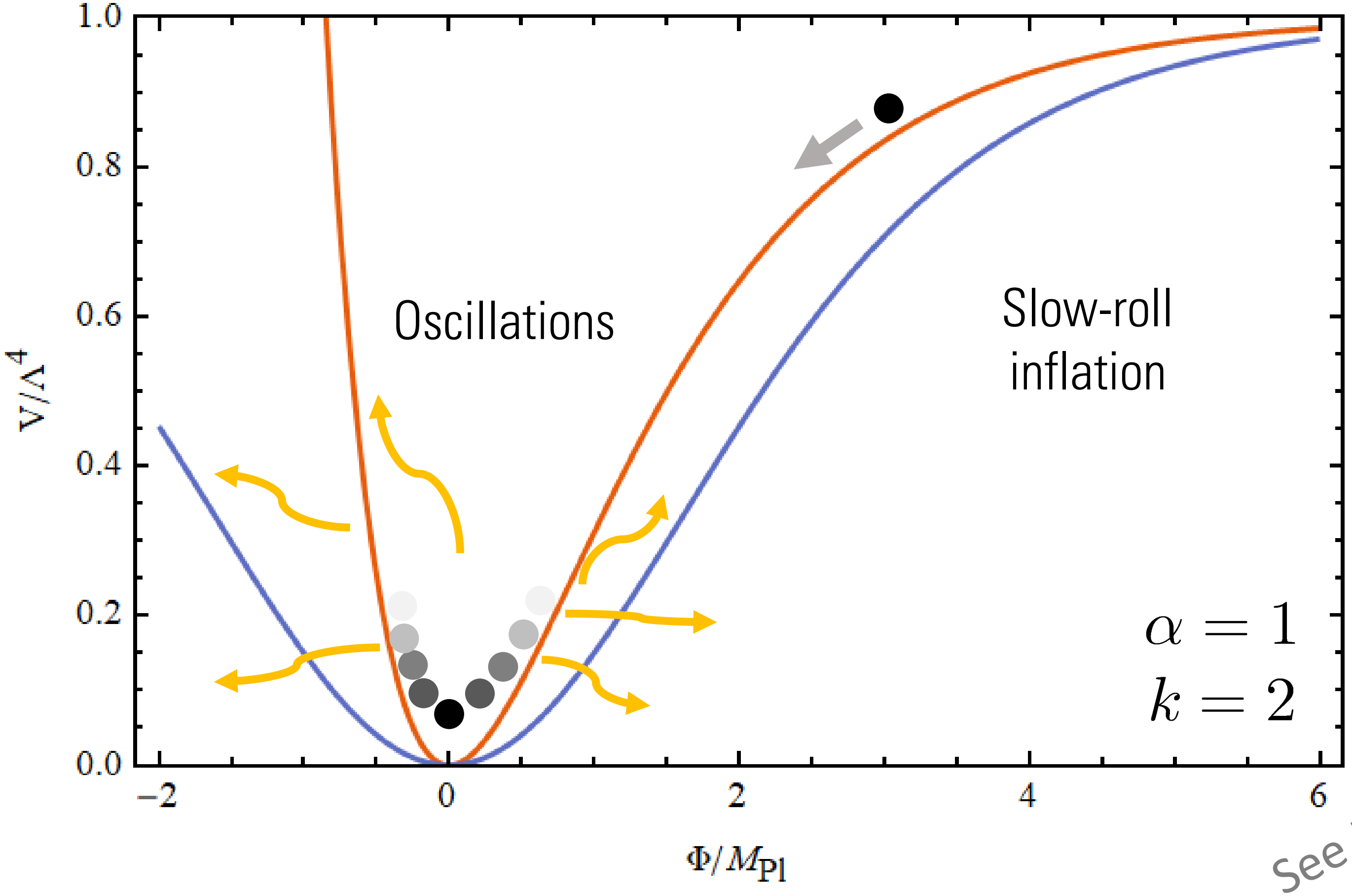
Chung et al. (1999), arXiv:hep-ph/9809453
Giudice et al. (2001), arXiv:hep-ph/0005123
Co et al. (2015), arXiv:1506.07532
Drees&Hajkarim (2018), arXiv:1711.05004
Calibbi et al. (2021), arXiv:2102.06221
Bernal and Xu (2022), arXiv:2209.07546
Bhattiprolu et al. (2022), arXiv:2210.15653
Cosme et al. (2023), arXiv:2306.13061
Silva-Malpartida et al. (2023), arXiv:2306.14943

That’s what I’m going to talk about today!

Inflation and reheating

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
…

$$\ddot{\Phi} + (3H + \Gamma_\Phi)\,\dot{\Phi} + V'(\Phi) = 0$$



α-attractor E-models

$$\boxed{V(\Phi) = \Lambda^4 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\Phi}{M_{\rm Pl}}}\right)^k}$$

α-attractor T-models

$$\boxed{V(\Phi) = \Lambda^4 \left[\tanh\left(\frac{\Phi}{\sqrt{6\alpha}M_{\rm Pl}}\right)\right]^k}$$

See Keith Olive's plenary talk!

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

Reheating potential!

Dynamics of reheating

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

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

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

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

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

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

$$\langle w_\Phi \rangle = \frac{\langle \rho_\Phi \rangle}{\langle P_\phi \rangle} = \frac{k-2}{k+2}$$

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

BOSONIC reheating (BR) $\quad \Phi \to bb \quad \Gamma_\Phi^{\rm BR} = \frac{\mu^2}{8\pi\, m_\Phi(t)}$

FERMIONIC reheating (FR) $\quad \Phi \to ff \quad \Gamma_\Phi^{\rm FR} = \frac{y^2}{8\pi} m_\Phi(t)$

$$m_\Phi^2(t) = \partial_\Phi^2 V(\Phi) = k(k-1)\lambda \frac{\Phi^{k-2}(t)}{M_{\rm Pl}^{k-4}} \simeq k(k-1)\lambda^{\frac{2}{k}} M_{\rm Pl}^{\frac{2(4-k)}{k}} \rho_\Phi^{\frac{k-2}{k}}(t)$$

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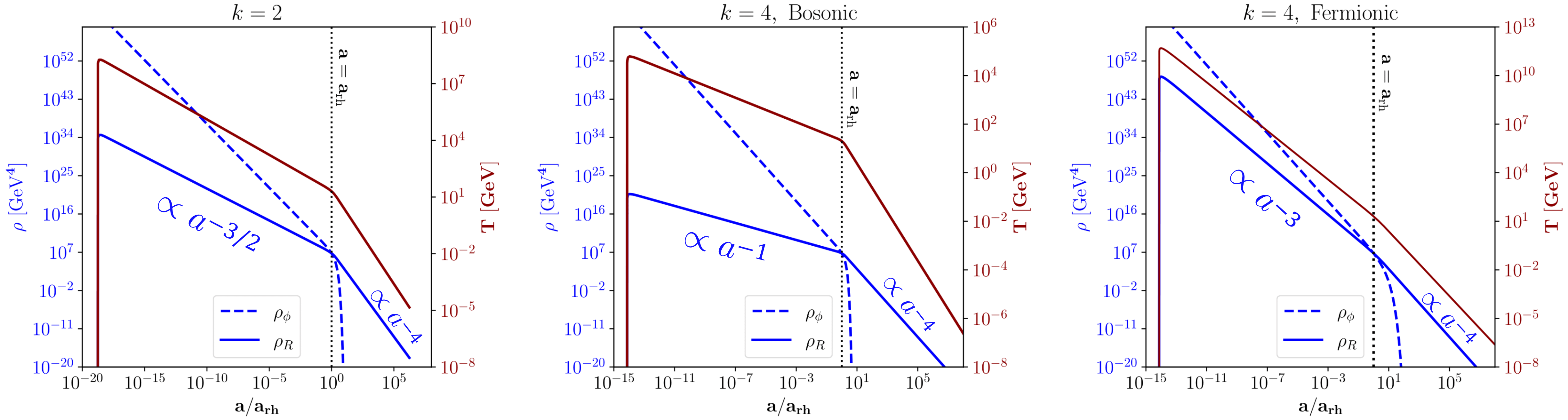
Bosonic and fermionic reheating

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



Reheating defined by:

$$\rho_\Phi(a_{\rm rh}) = \rho_R(a_{\rm rh})$$

$$T(a) \simeq T_{\rm rh}\left(\frac{a_{\rm rh}}{a}\right)^{\frac{3}{4+2k}}$$

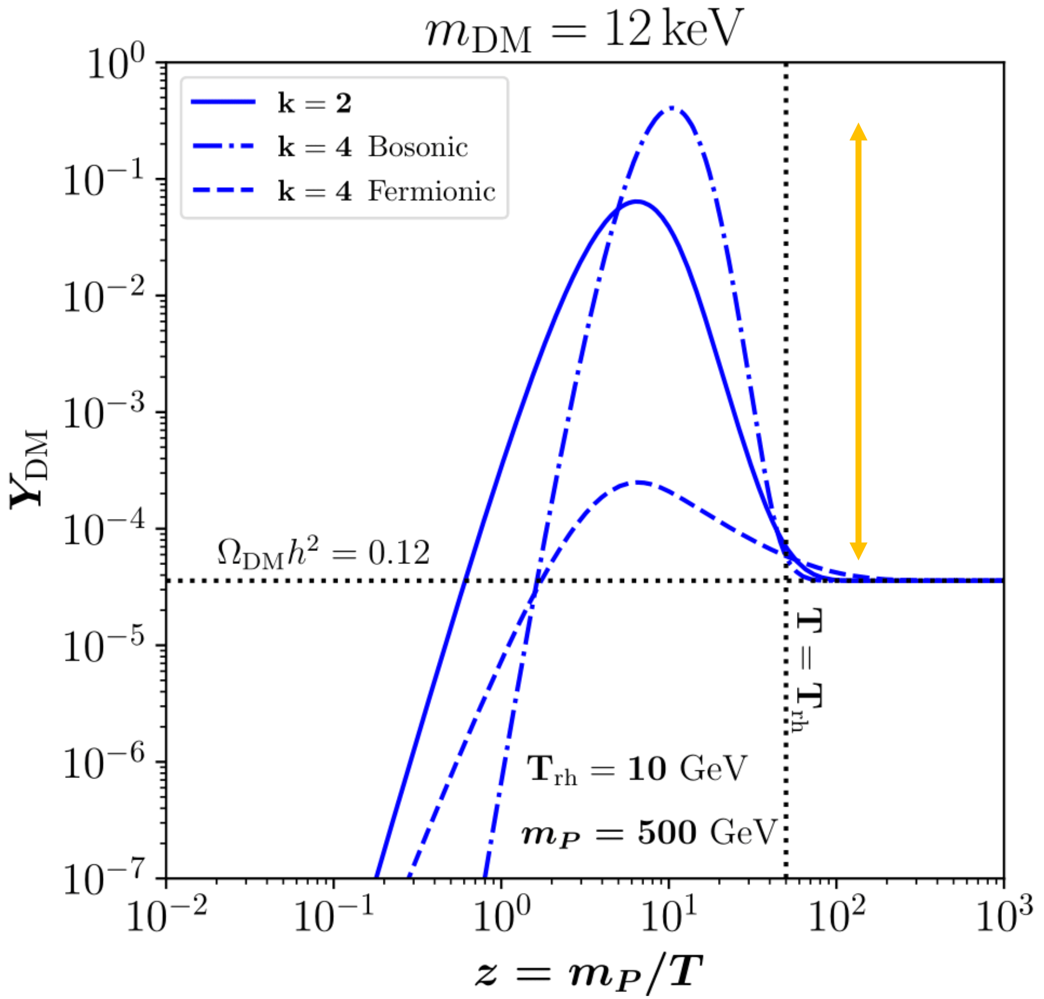
$$T(a) \simeq T_{\rm rh}\left(\frac{a_{\rm rh}}{a}\right)^{\frac{3k-3}{4+2k}}$$

$$H(T) \simeq \frac{\sqrt{\rho_\Phi(T_{\rm rh})}}{\sqrt{3}M_{\rm Pl}}\left(\frac{T}{T_{\rm rh}}\right)^{2k}$$

$$H(T) \simeq \frac{\sqrt{\rho_\Phi(T_{\rm rh})}}{\sqrt{3}M_{\rm Pl}}\left(\frac{T}{T_{\rm rh}}\right)^{\frac{2k}{k-1}}$$

DM production during BR and FR

$$\mathcal{L}_{\rm int} \supset y\, P \chi f_{\rm SM}$$



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

$$Y_{\rm DM}(T) \sim Y^{\rm RD}_{\rm DM}(T) D(T) \sim \frac{\Gamma(T)}{H(T)} \frac{S(T)}{S(T_{\rm rh})}$$

$$D(T) = \frac{S(T)}{S(T_{\rm rh})} \simeq \begin{cases} \left(\frac{T_{\rm rh}}{T}\right)^{1+2k} & \text{BR} \\ \left(\frac{T_{\rm rh}}{T}\right)^{\frac{7-k}{k-1}} & \text{FR} \end{cases}$$

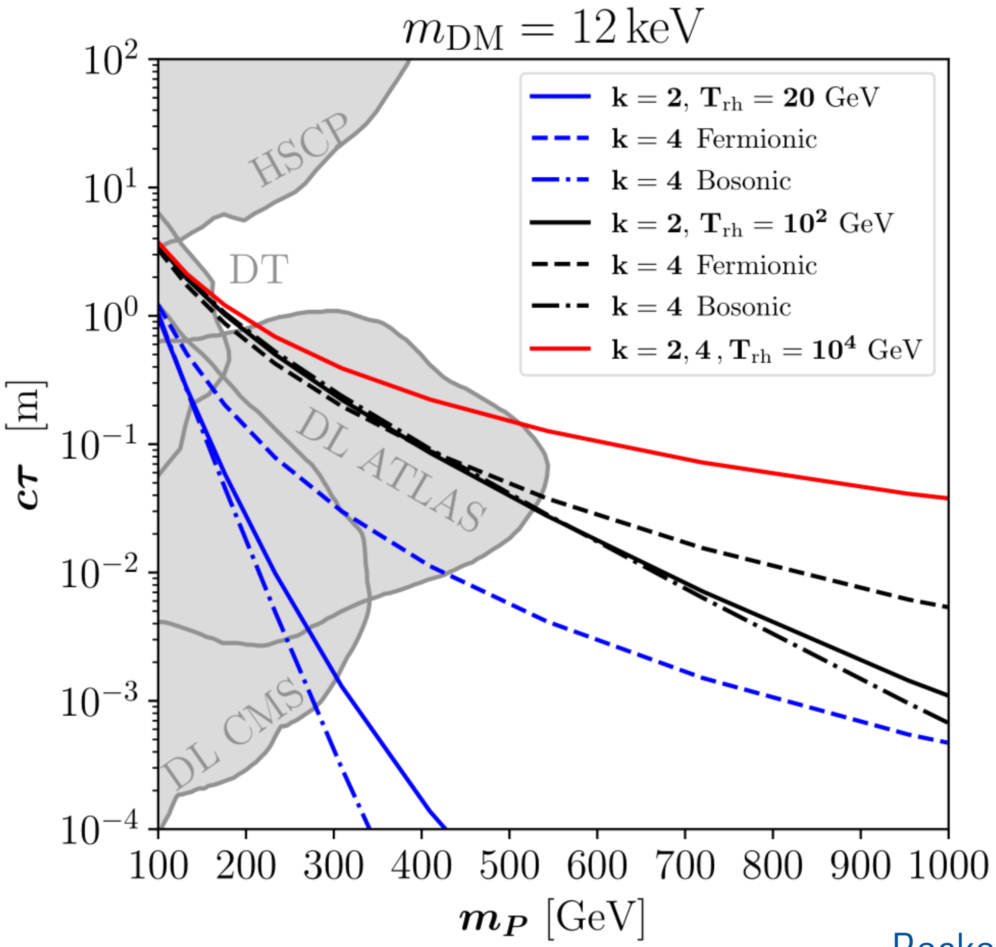
Type	$T_{\rm rh}$ [GeV]	$c\tau$ [m]
$k = 2$	10	2.23×10^{-7}
$k = 4$ BR	10	2.17×10^{-11}
$k = 4$ FR	10	2.01×10^{-3}

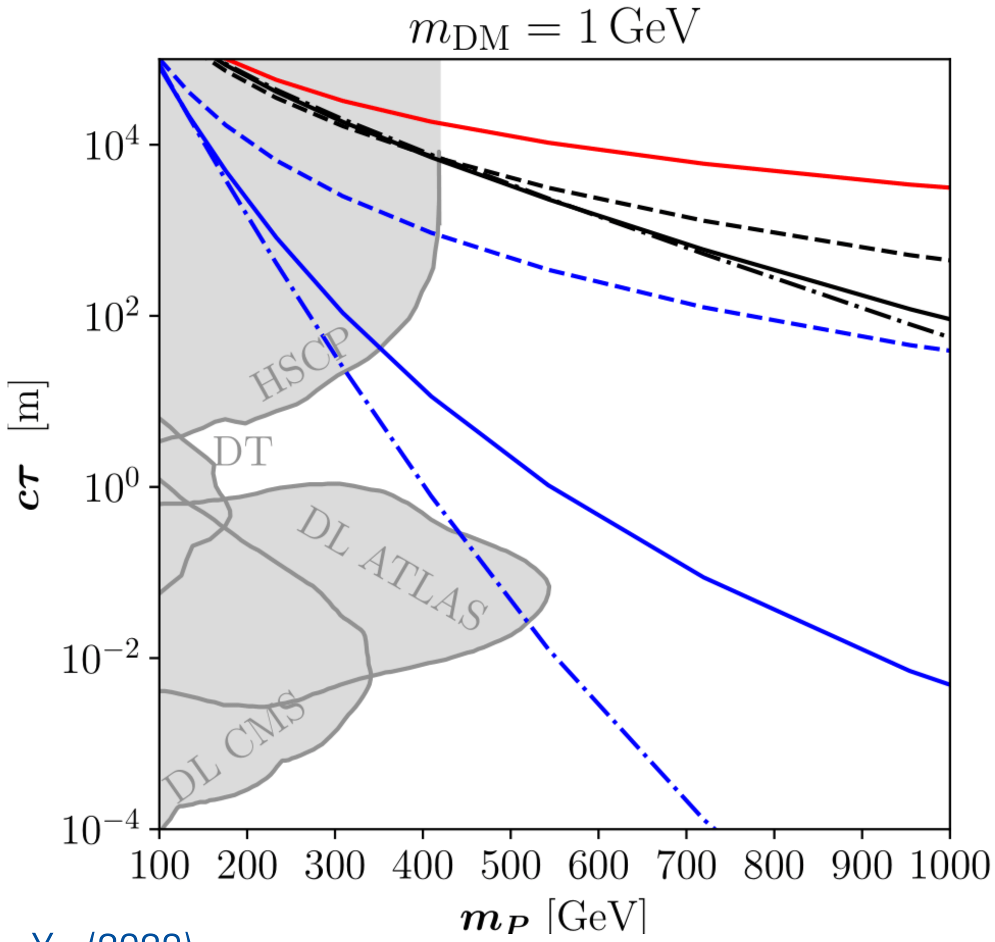
$T_{\rm rh} \gg m_P$ $\qquad c\tau \simeq 0.15\,{\rm m}$

Lifetime of parent particle

Leptophilic Majorana DM with charged scalar

LLP limits from Calibbi et al. (2021)

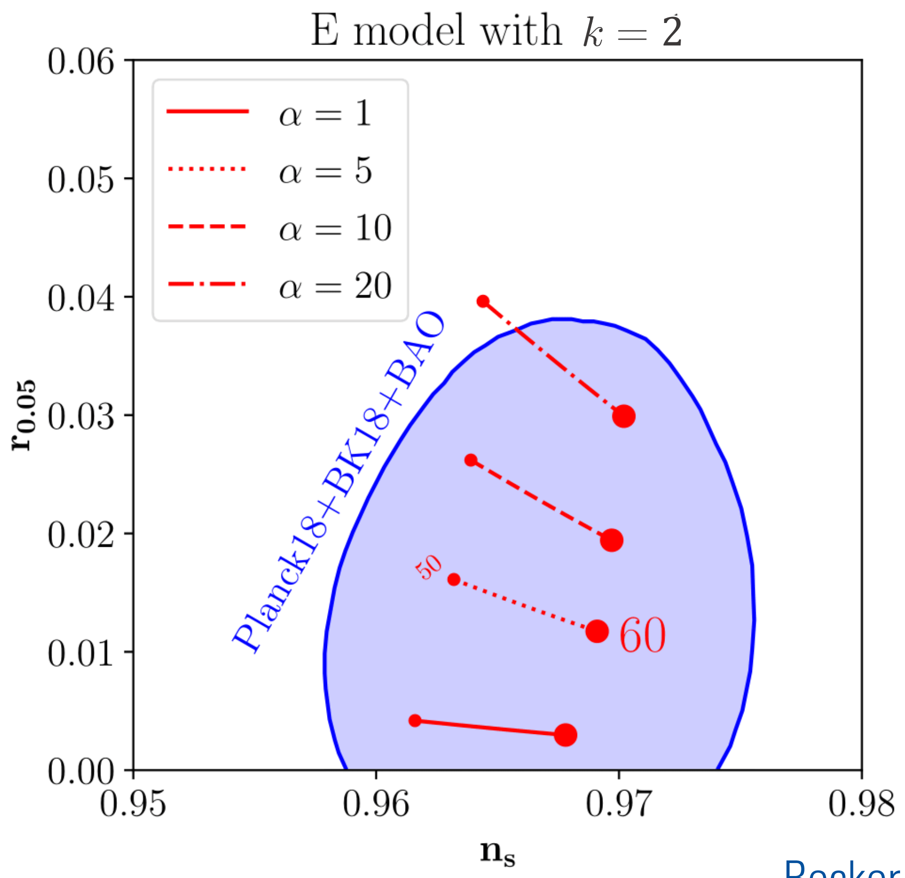


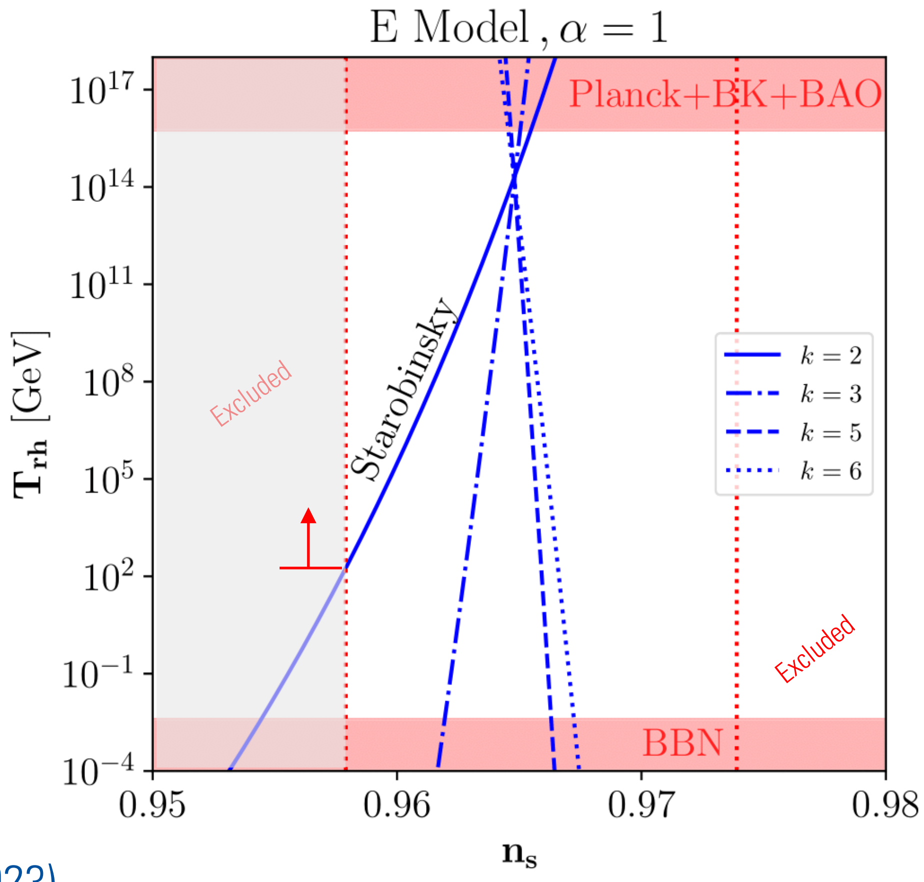


Becker, **EC**, Harz, Lang, Xu (2023)

Constraints on inflation from CMB

E models $$V(\Phi) = \Lambda^4 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\Phi}{M_{\rm Pl}}}\right)^k$$

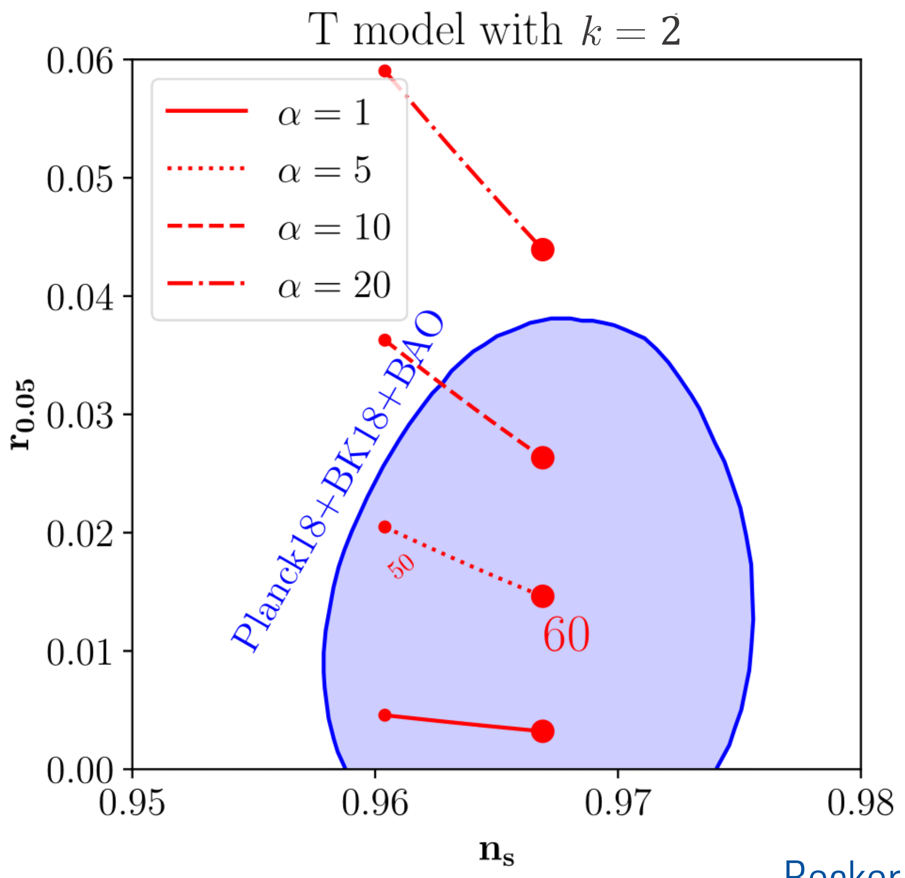


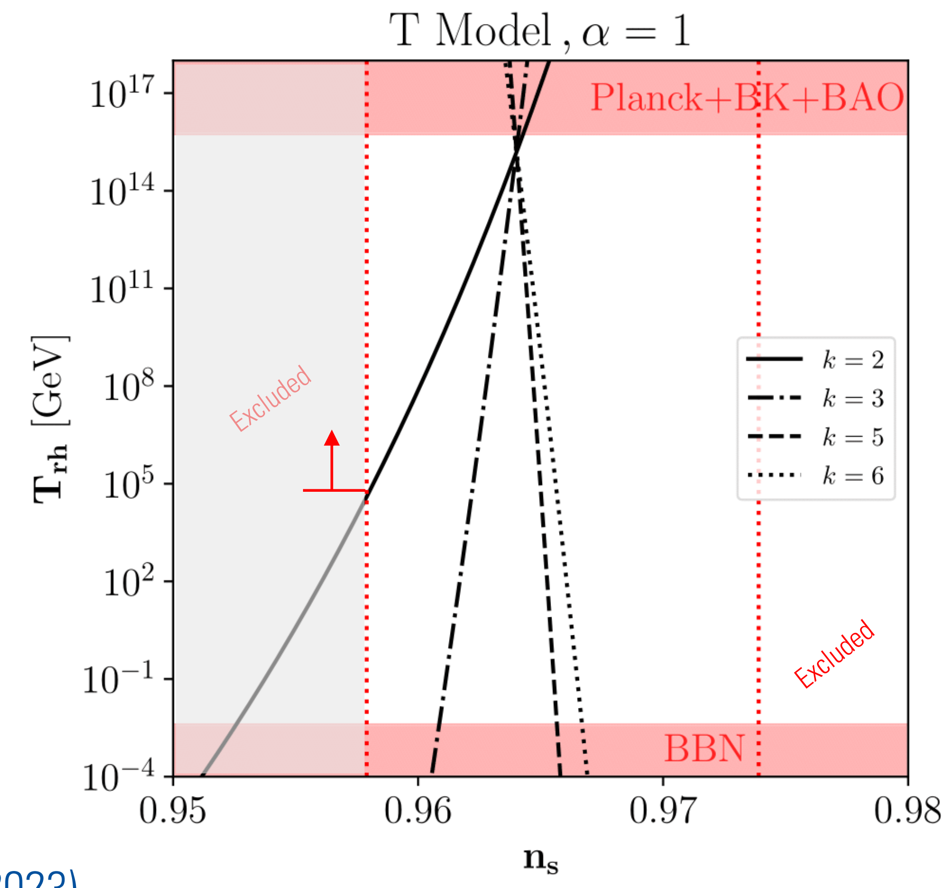


Becker, **EC**, Harz, Lang, Xu (2023)

Constraints on inflation from CMB

T models $$V(\Phi) = \Lambda^4 \left[\tanh\left(\frac{\Phi}{\sqrt{6\alpha}M_{\mathrm{Pl}}}\right)\right]^k$$

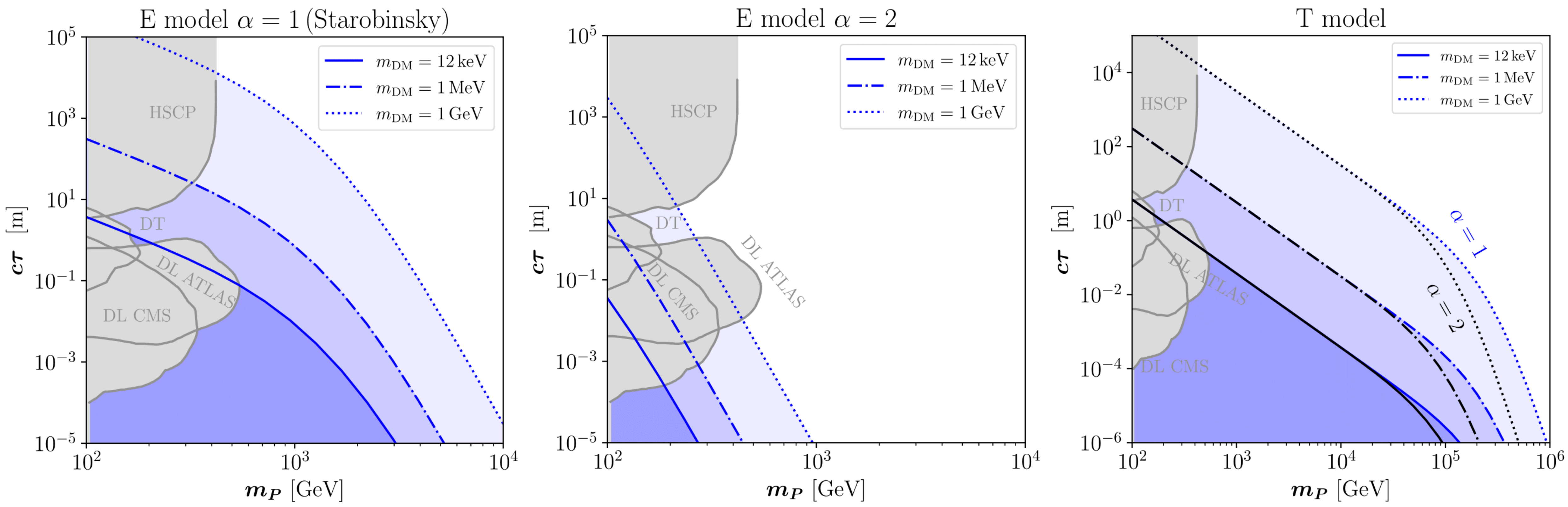




Becker, **EC**, Harz, Lang, Xu (2023)

Combined LLP+CMB constraints

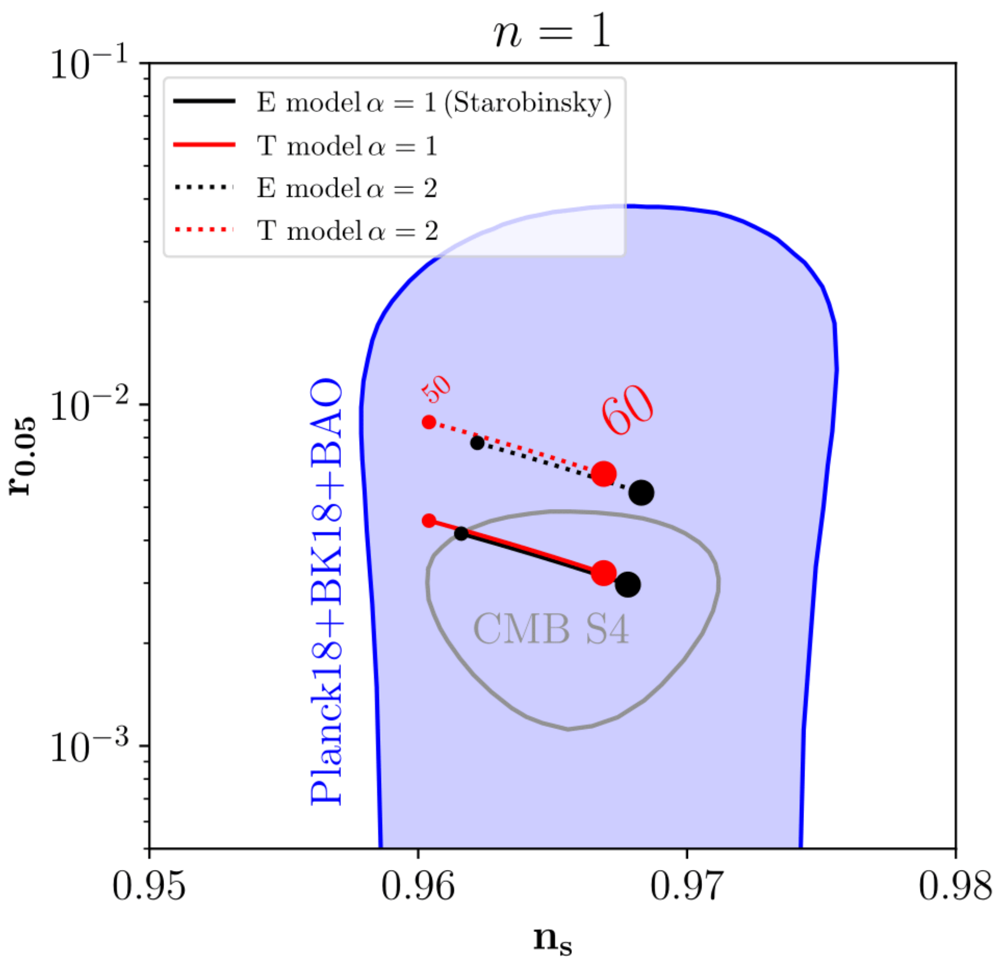
$k = 2$

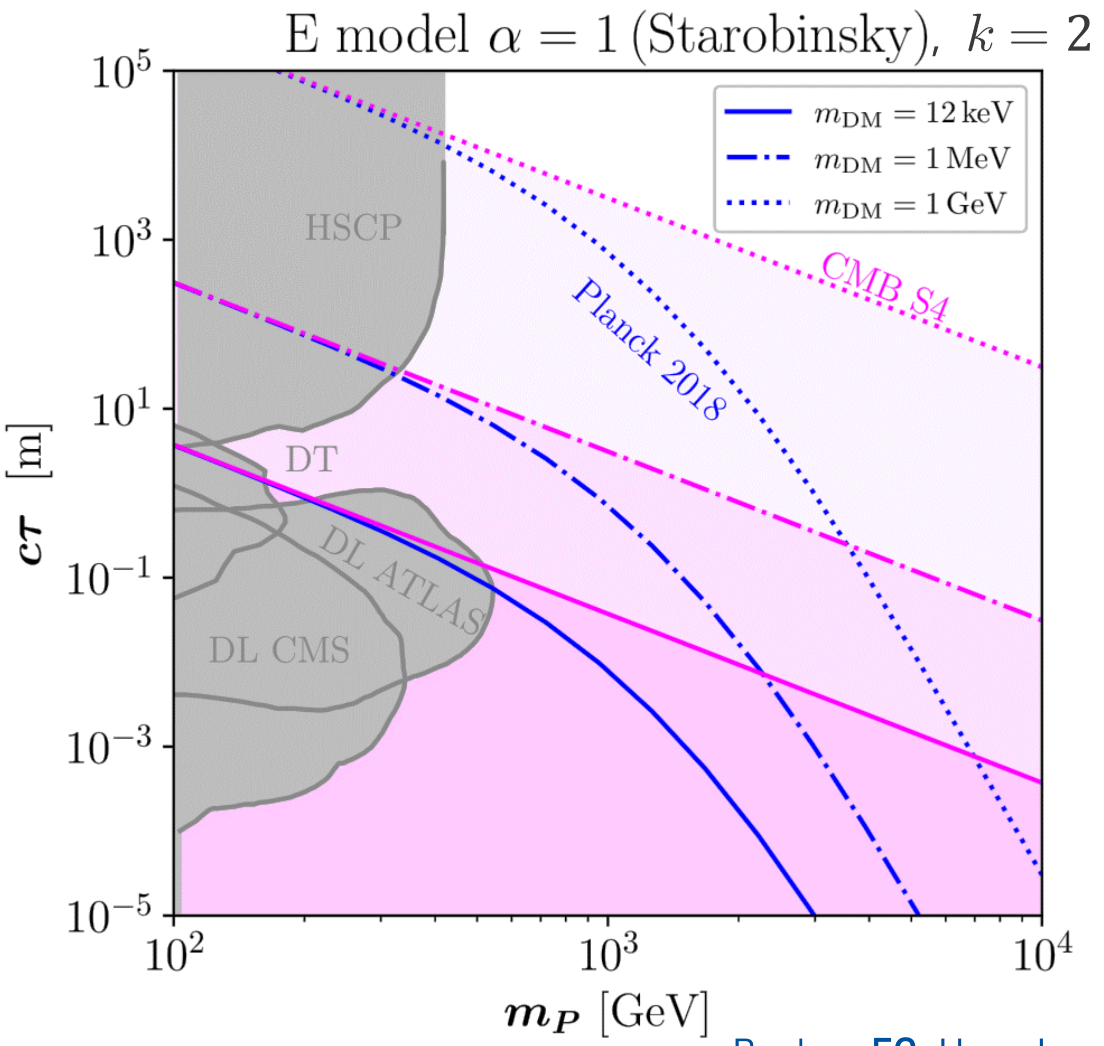


Becker, **EC**, Harz, Lang, Xu (2023)

Combined LLP+CMB constraints

CMB-S4 Science Book, arXiv:1610.02743





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

Conclusions

- DM production and the interpretation of collider limits in minimal FIMP models crucially depend on *i)* the reheating temperature, *ii)* the microscopic nature of the inflaton-matter coupling (BR vs. FR), *iii)* the form of the inflaton and reheating potentials.

- Inflationary constraints provide a measure for how strongly FIMP DM production can be altered during the reheating phase.

- A positive measurement of an LLP could have the potential to shed light on the dynamics taking place during the phase of inflationary reheating.

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

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

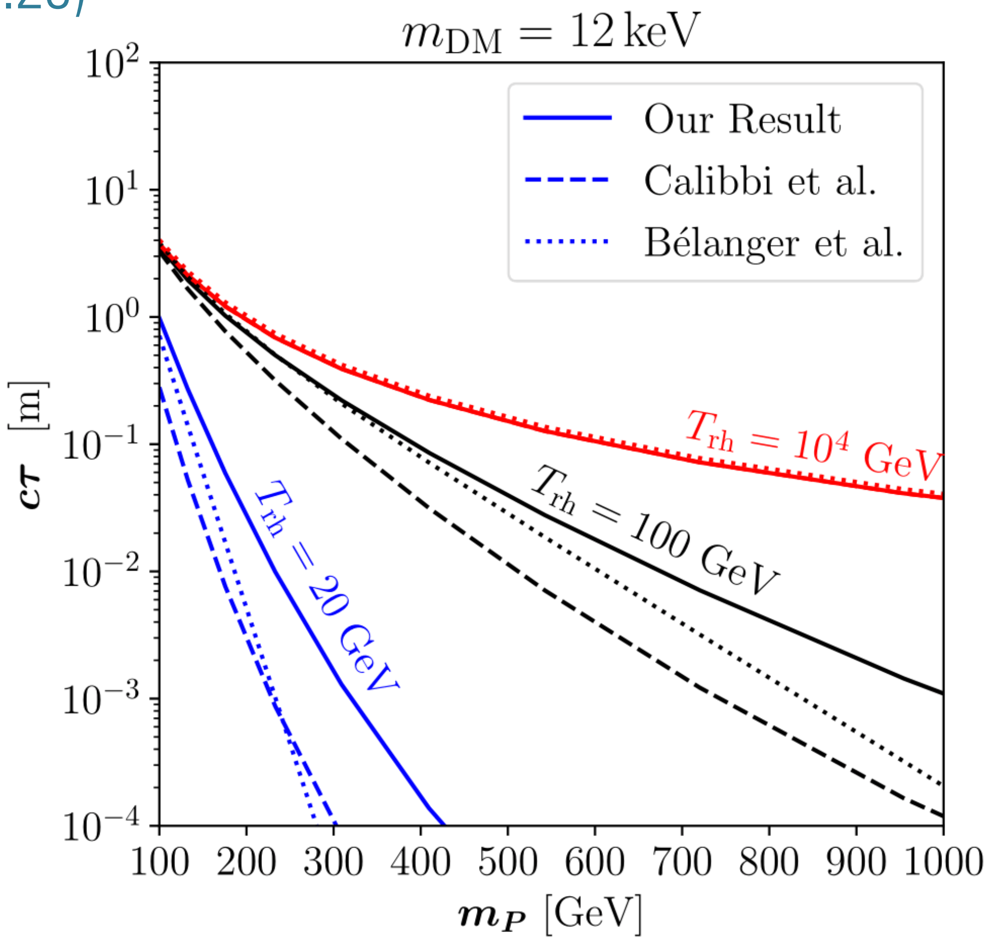
Our method:

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

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]

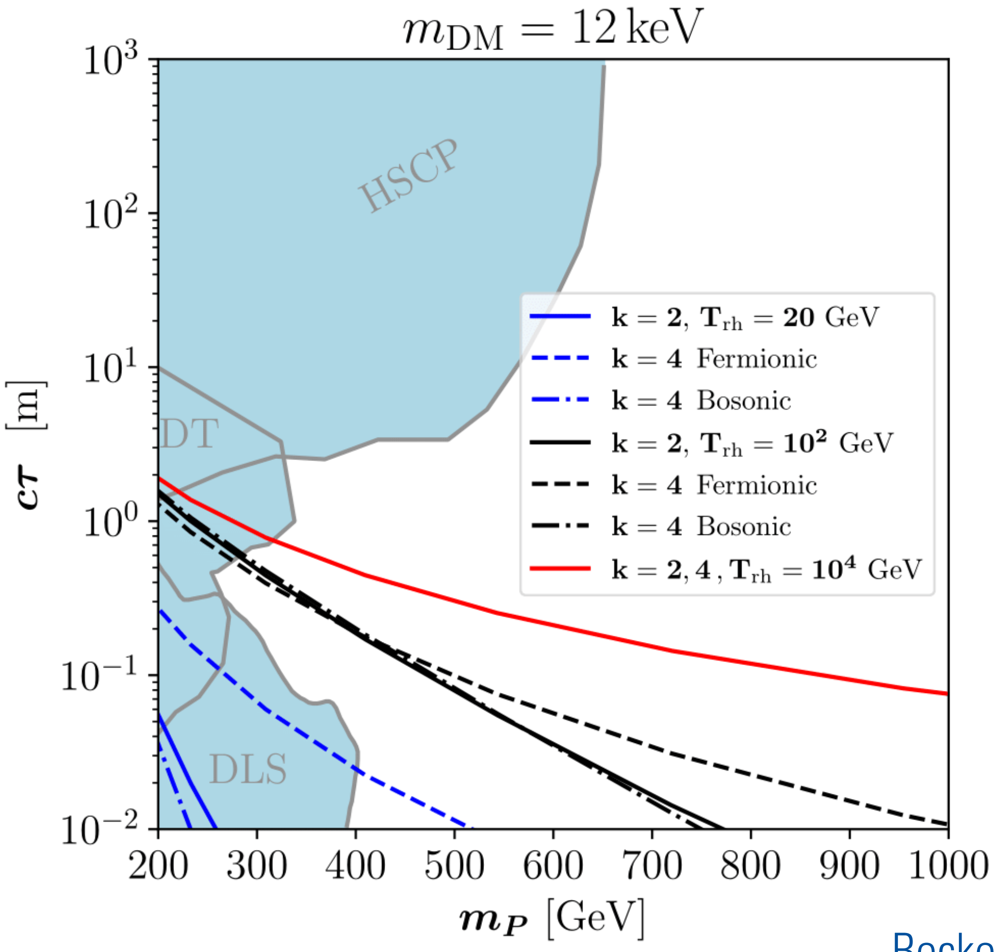


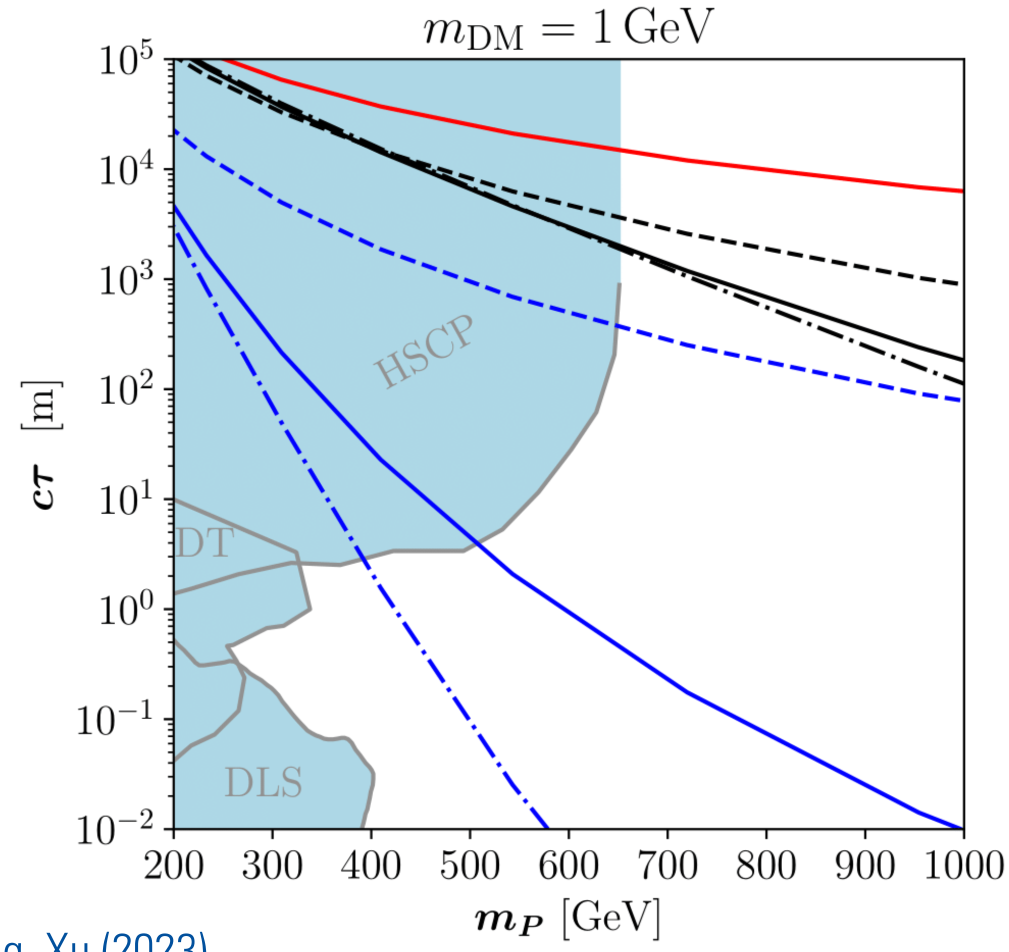
Becker, **EC**, Harz, Lang, Xu (2023)

Lifetime of parent particle

Leptophilic real scalar DM (vectorlike fermion P)

LLP limits from Bélanger et al. (2019)





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

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

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

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

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

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

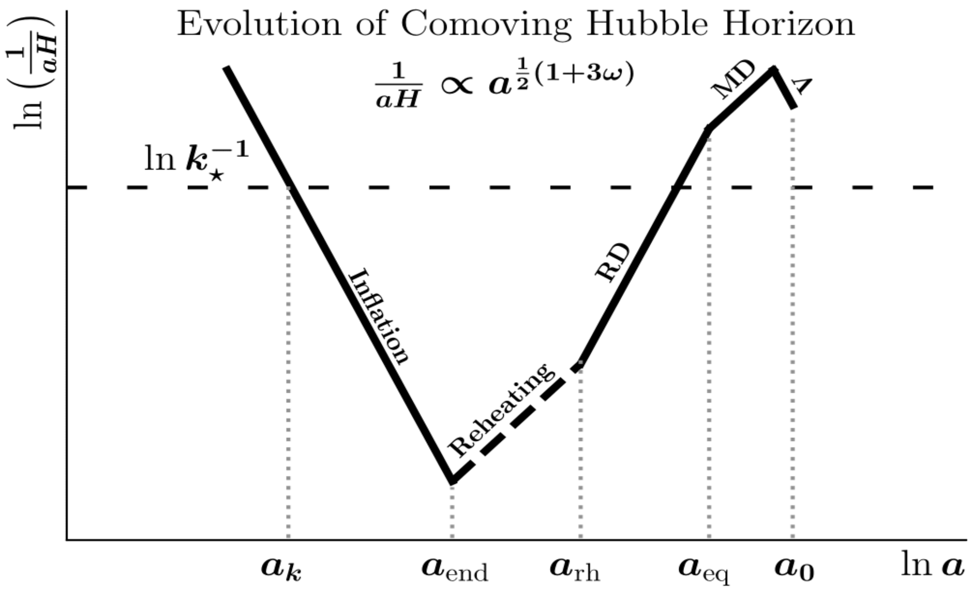
$$T^4_{{\rm rh},f} = \frac{30}{\pi^2 g_\star}\left[\frac{k\sqrt{3k(k-1)}}{7-k}\lambda^{\frac{1}{k}}\frac{y^2_{\rm eff}}{8\pi}\right]^k M^4_{\rm Pl}$$

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

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

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

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

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

FIMP models

Majorana DM / charged scalar parent model

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

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

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

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

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

Scalar singlet DM / vectorlike fermion parent model

$$\mathcal{L}_{\rm S} \supset \mathcal{L}_\Phi + \mathcal{L}_s + \mathcal{L}_{\Phi s} + \mathcal{L}_F + \mathcal{L}_{\Phi F} + \mathcal{L}_{\rm Yuk.}$$

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

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

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

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

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

More on E- and T- models