Minimal FIMP models during reheating and inflationary constraints

Emanuele Copello
Johannes-Gutenberg Universität Mainz

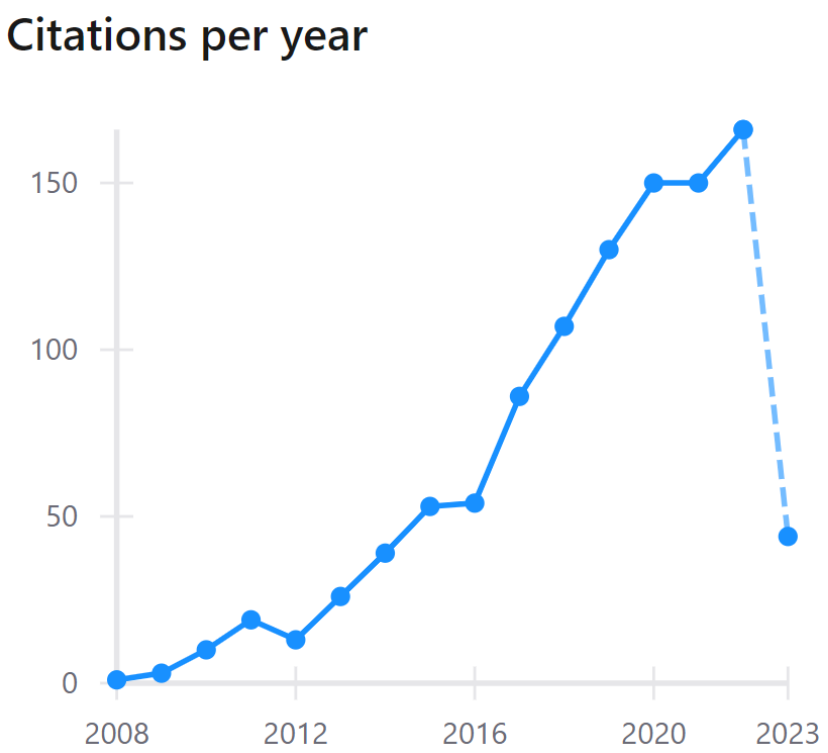
Based on an upcoming work (2306.xxxx) with
Mathias Becker (JGU), Julia Harz (JGU), Jonas Lang (TUM) and Yong Xu (JGU)

17th Kosmologietag 2023
ZiF Bielefeld, June 1, 2023

Warm-up: FIMPs and Dark Matter

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

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



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

…many more…

Incoming mitp 2024 workshop!
(More at the end of the talk…)

Warm-up: RD or "non-standard" expansions?

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

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

Arias et al. (2019): *Reconstructing Non-standard Cosmologies with Dark Matter* (arXiv:1906.04183)

Allahverdi et al. (2020): *The First Three Seconds: a Review of Possible Expansion Histories of the Early Universe* (arXiv:2006.16182)

What if ***REHEATING*** after *inflation* was a prolonged phase?

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

Chung et al. (1999), arXiv:hep-ph/9809453
Giudice et al. (2001), arXiv:hep-ph/0005123
Co et al. (2010), arXiv:1506.07532
Drees&Hajkarim (2018), arXiv:1711.05004
…many others…

Calibbi et al. (2021)
arXiv:2102.06221

1) Minimal renormalizable FIMP models
2) Generic non-adiabatic MD reheating
3) LLP searches: much shorter lifetimes!

Our work adds:
+ specific inflation and reheating models
+ constraints on $T_{\rm rh}$ from CMB

Talk outline

1) DM production in minimal FIMP models
2) Inflationary reheating scenarios
3) DM production with low reheating temperatures
4) Phenomenology: predictions for LLP lifetime
5) Phenomenology: constraints on inflation (CMB)
6) Conclusions

DM production in minimal FIMP models

Hall et al. (2010), arXiv:0911.1120

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = \mathcal{C}_{\rm DM}$$

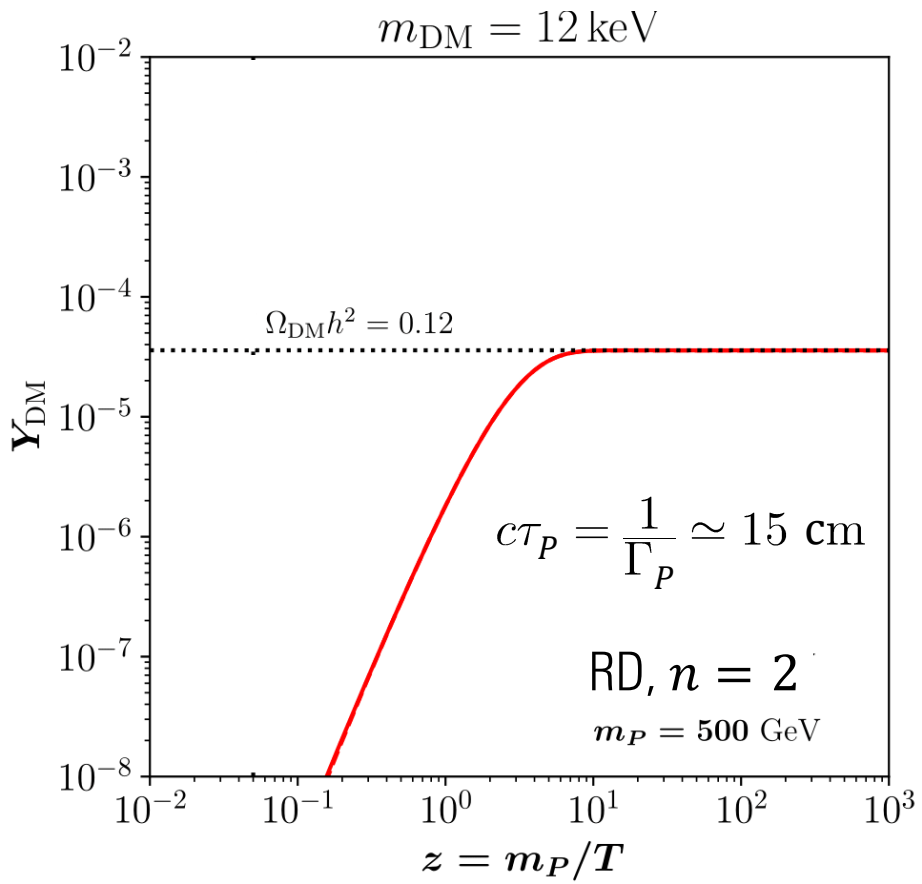
$$H = \frac{\sqrt{\rho}}{\sqrt{3}M_{\rm Pl}} \simeq \frac{T_*^2}{\sqrt{3}M_{\rm Pl}} \left(\frac{T}{T_*}\right)^n$$

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

$$\Gamma_P \simeq \frac{y_{DM}^2 m_P}{16\pi}$$

Trilinear interaction:

$$\mathcal{L}_{\rm int} \supset y_{\rm DM}\ P\ \chi_{DM}\ f_{\rm SM}$$

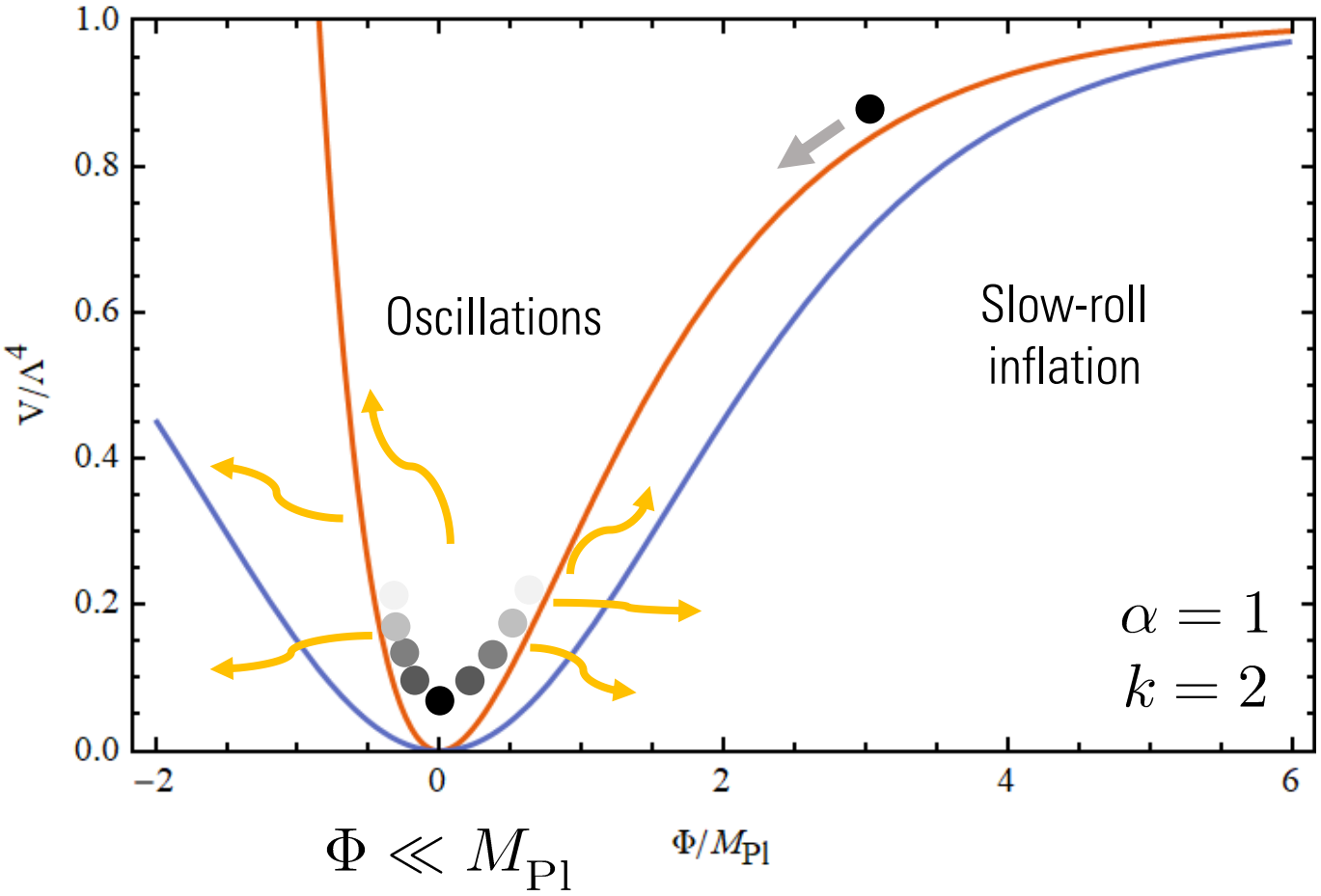


How does this change if not in RD?

Inflation and reheating

Starobinsky (1980)
Kallosh & Linde (2013), arXiv:1306.5220
Kallosh & Linde (2013), arXiv:1307.7938
Kallosh & Linde (2021), arXiv:2110.10902

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



$\Phi \ll M_{\rm Pl}$

α-attractor E-models

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

α-attractor T-models

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

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

Reheating potential!

Friedmann-Boltzmann equations for Reheating

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

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

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

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

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

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

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

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

BOSONIC reheating (**BR**) $\Phi \to bb$

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

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

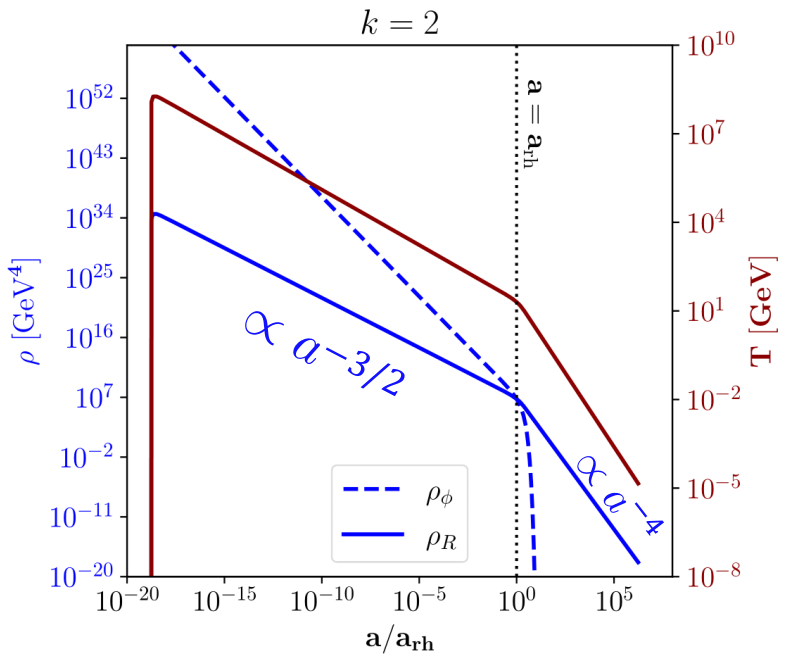
FERMIONIC reheating (**FR**) $\Phi \to ff$

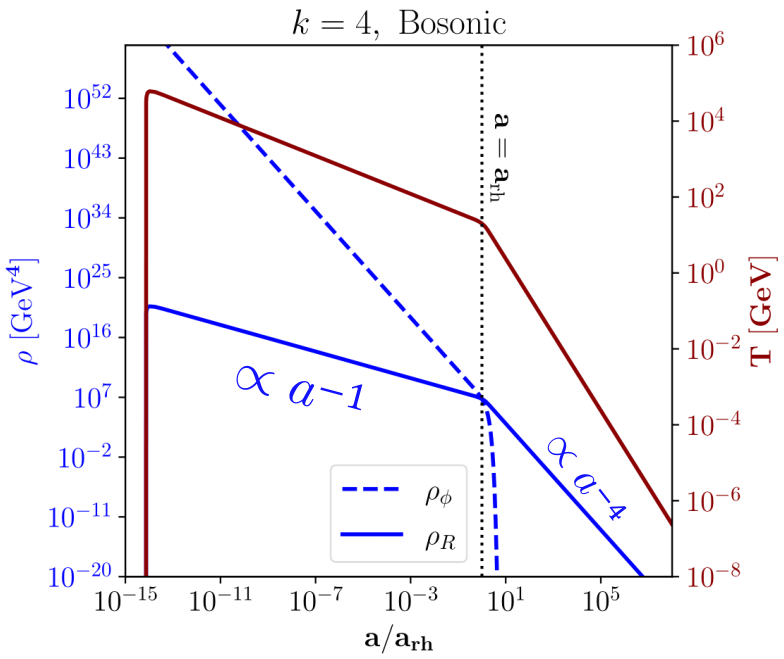
$$\Gamma_\Phi^{\rm FR} = \frac{y^2}{8\pi} m_\Phi(t)$$

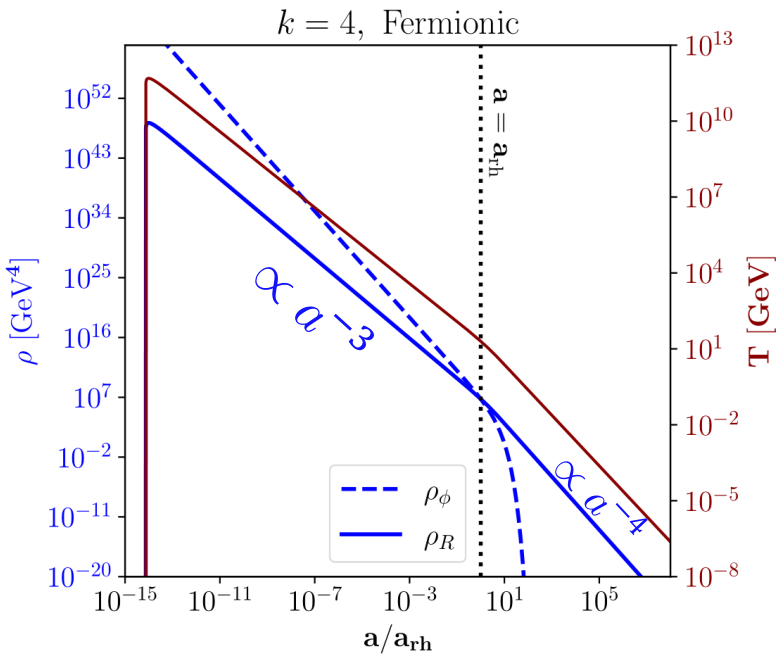
$$\simeq k(k-1)\lambda^{\frac{2}{k}} M_{\rm Pl}^{\frac{2(4-k)}{k}} \rho_\Phi^{\frac{k-2}{k}}(t)$$

Bosonic and fermionic reheating

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







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

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

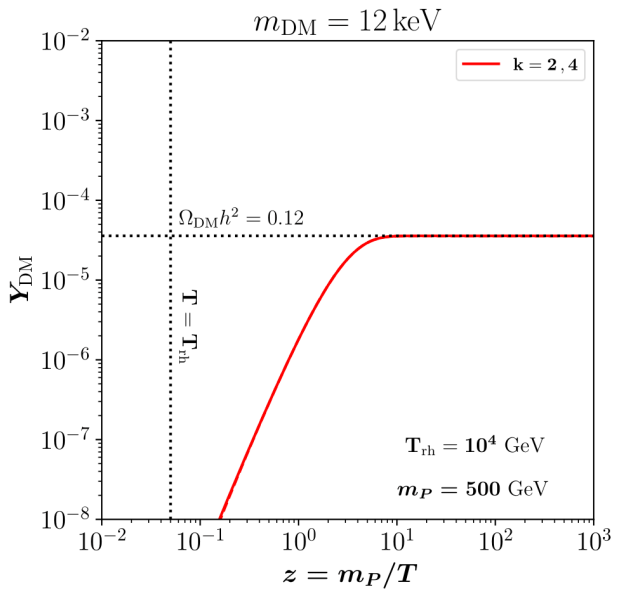
$$H(T) \simeq \frac{\sqrt{\rho_\Phi(T_{\rm rh})}}{\sqrt{3}M_{\rm Pl}} \left(\frac{T}{T_{\rm rh}}\right)^{2k}$$

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

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

DM production during BR and FR

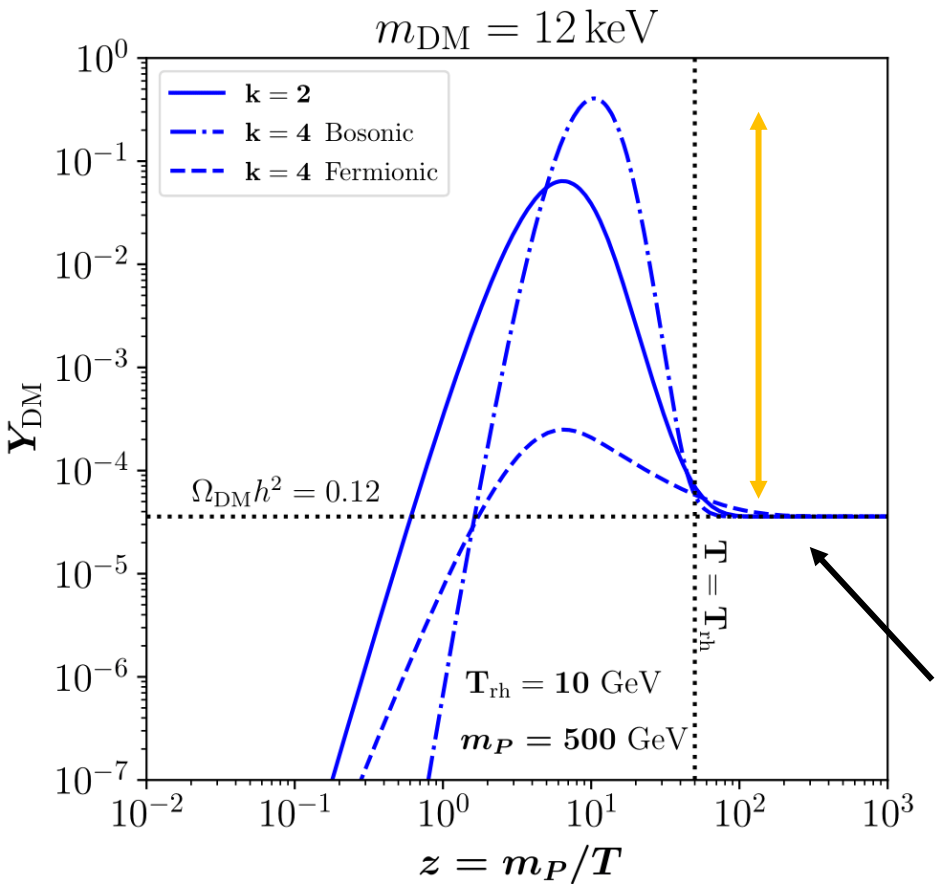
$T_{rh} \gg m_P$



$$Y^{\rm pr.}_{\rm DM}(T) \sim \frac{\langle \Gamma(T) \rangle_T}{H(T)} \sim \Gamma_P \frac{m_P\, M_{\rm Pl}}{T^3}$$

$$c\tau \simeq 0.15 \text{ m}$$

$T_{rh} \ll m_P$



$$Y_{\rm DM}(T) \sim Y^{\rm pr.}_{\rm DM} D(T)$$

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

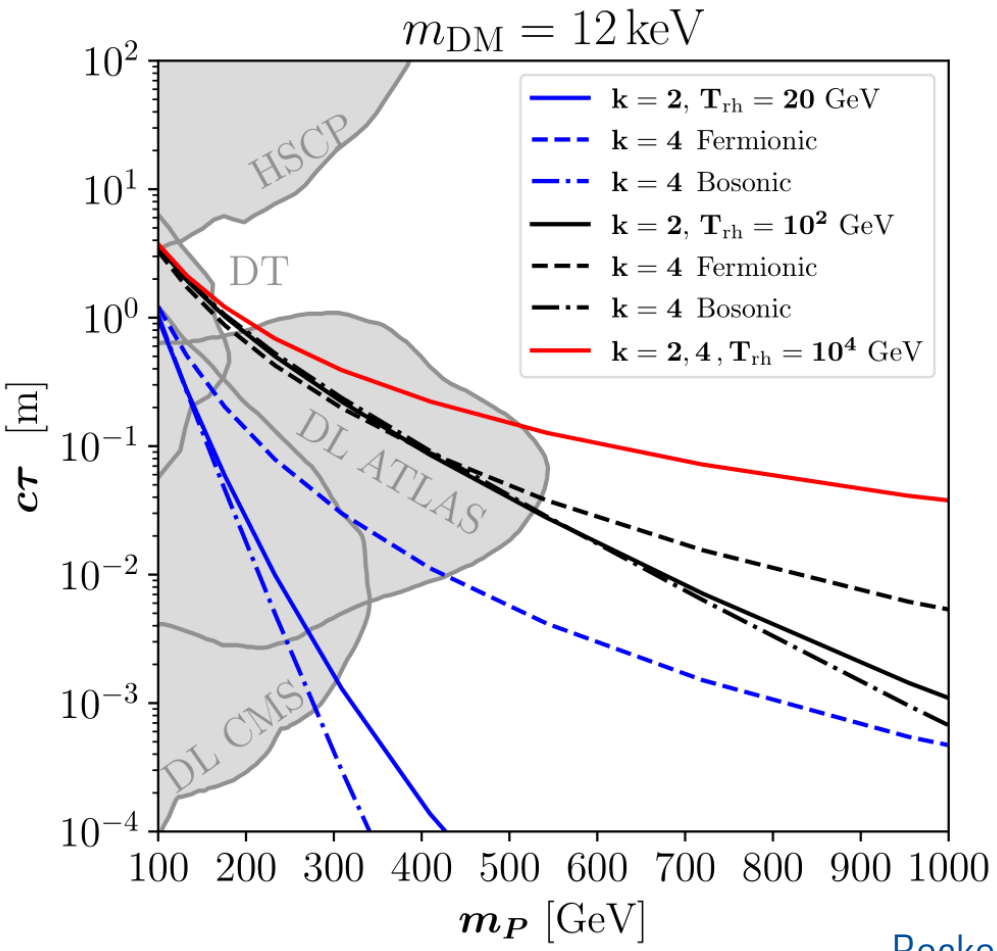
Type	$T_{\rm rh}$ [GeV]	$c\tau$ [m]
$k = 2$	10	2.23×10^{-7}
$k = 4$ BR	10	2.17×10^{-11}
$k = 4$ FR	10	2.01×10^{-3}

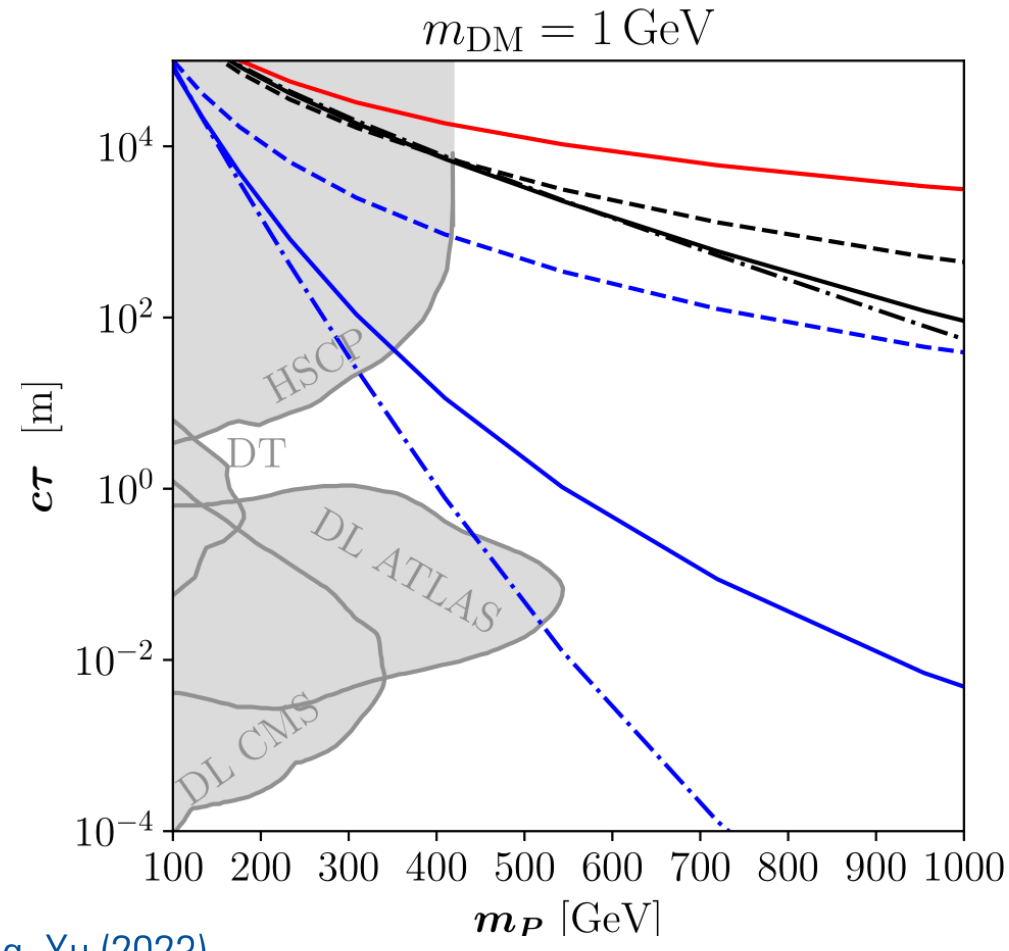
Becker, **EC**, Harz, Lang, Xu (2023)

Lifetime of parent particle

Leptophilic Majorana DM with charged scalar

LLP limits from Calibbi et al. (2021)

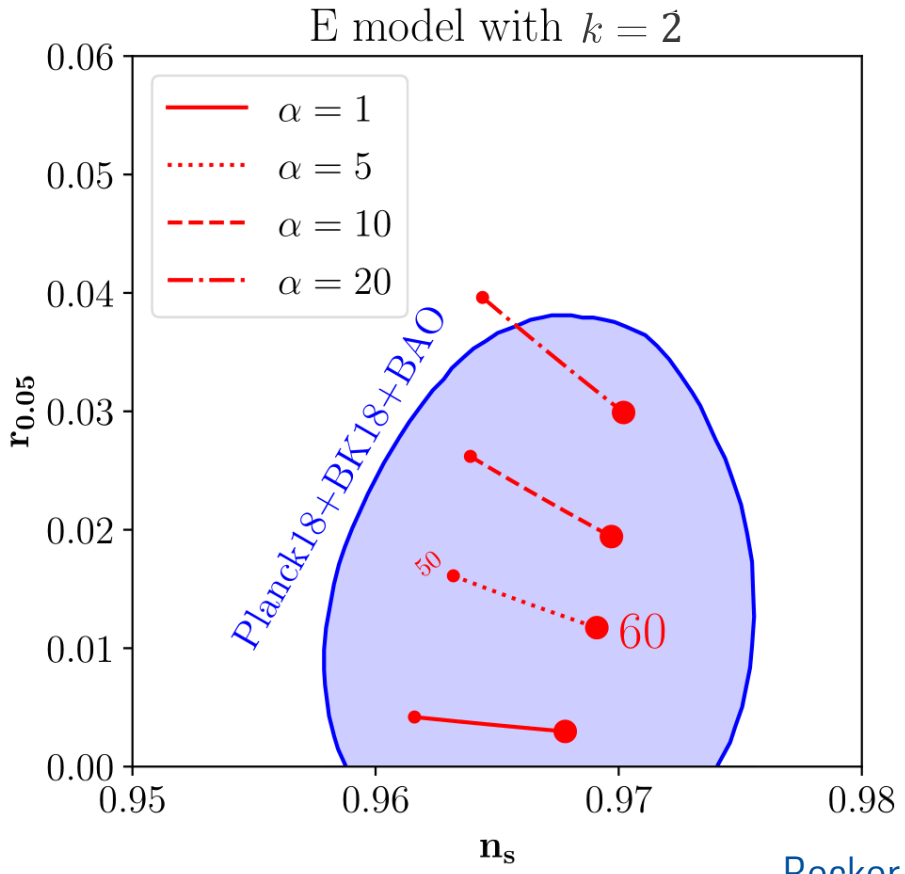


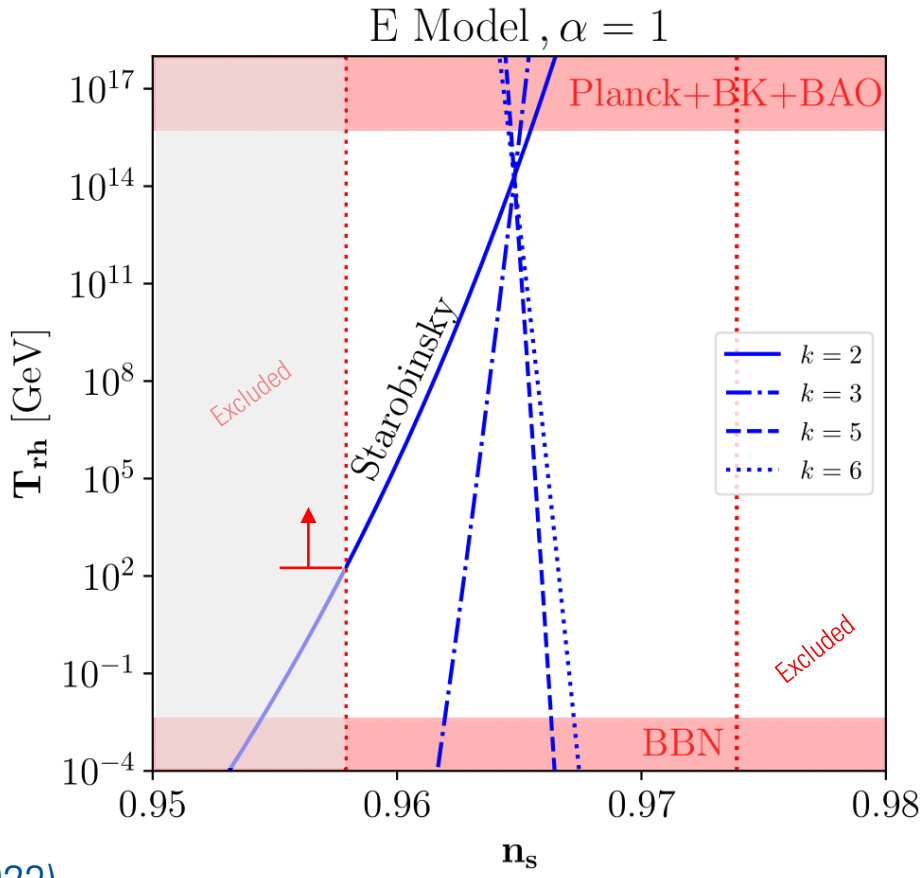


Becker, EC, Harz, Lang, Xu (2023)

Constraints on inflation from CMB

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

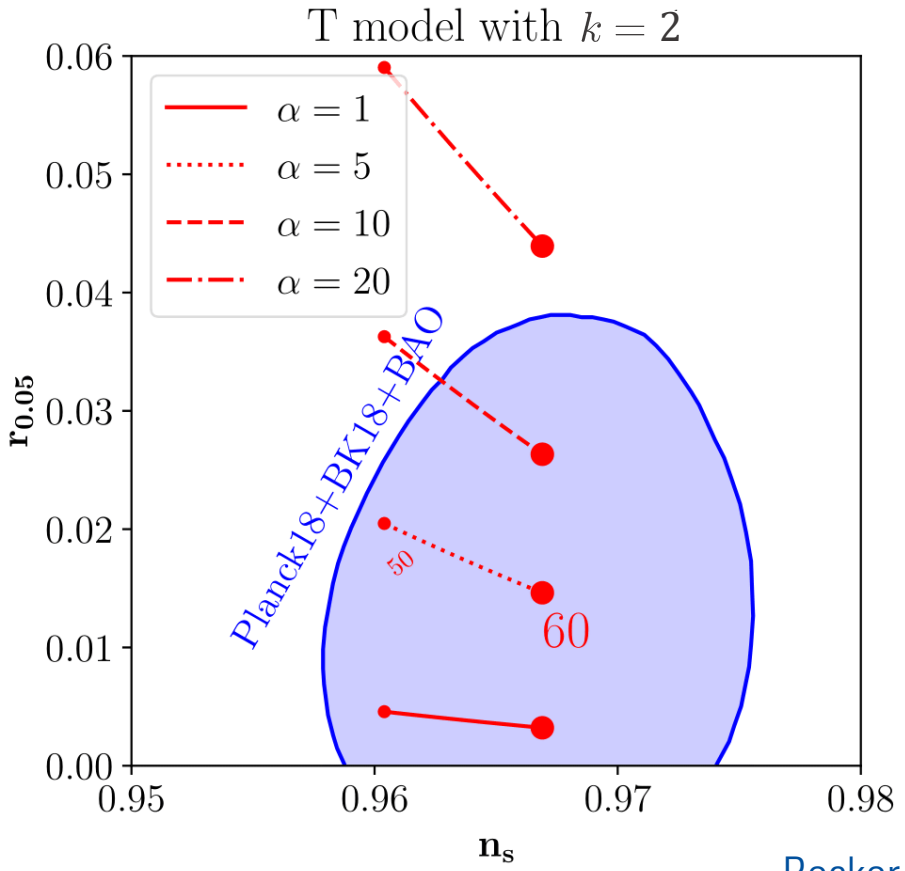


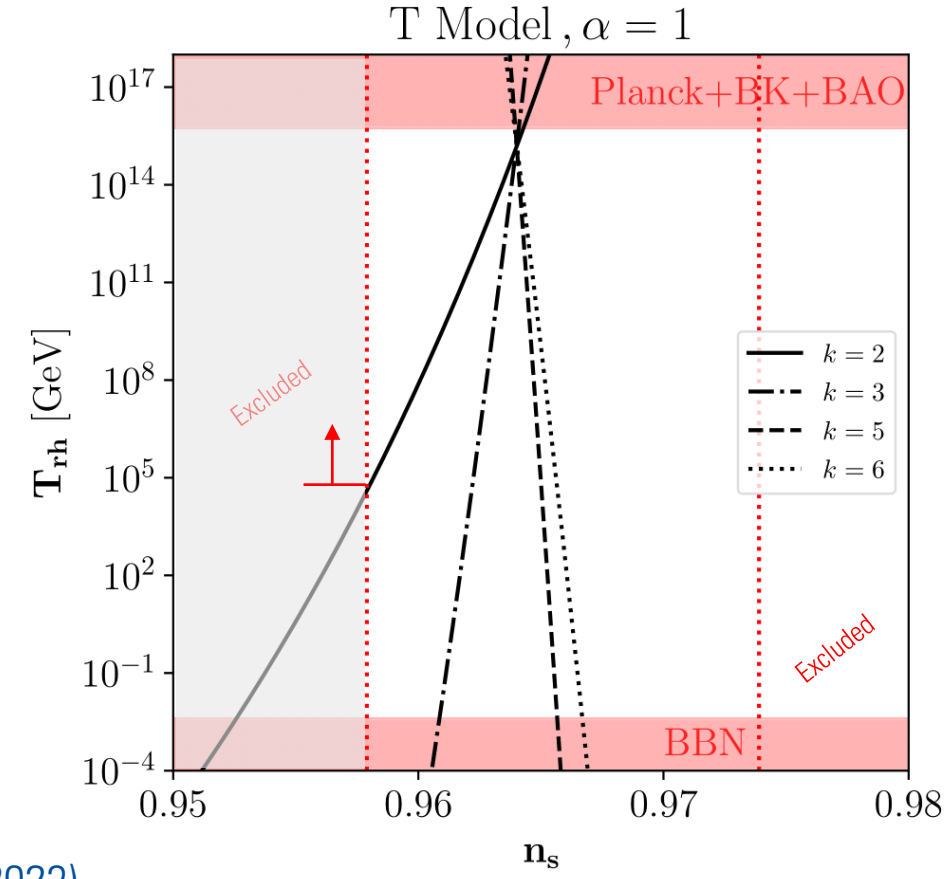


Becker, **EC**, Harz, Lang, Xu (2023)

Constraints on inflation from CMB

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

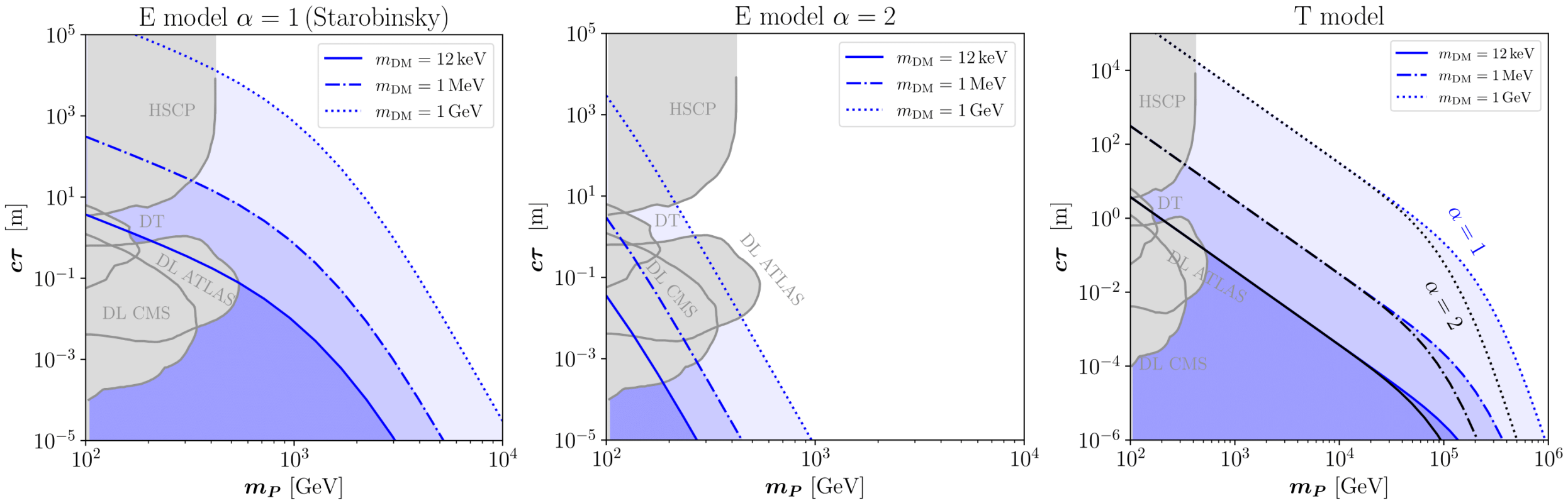




Becker, **EC**, Harz, Lang, Xu (2023)

Combined LLP+CMB constraints

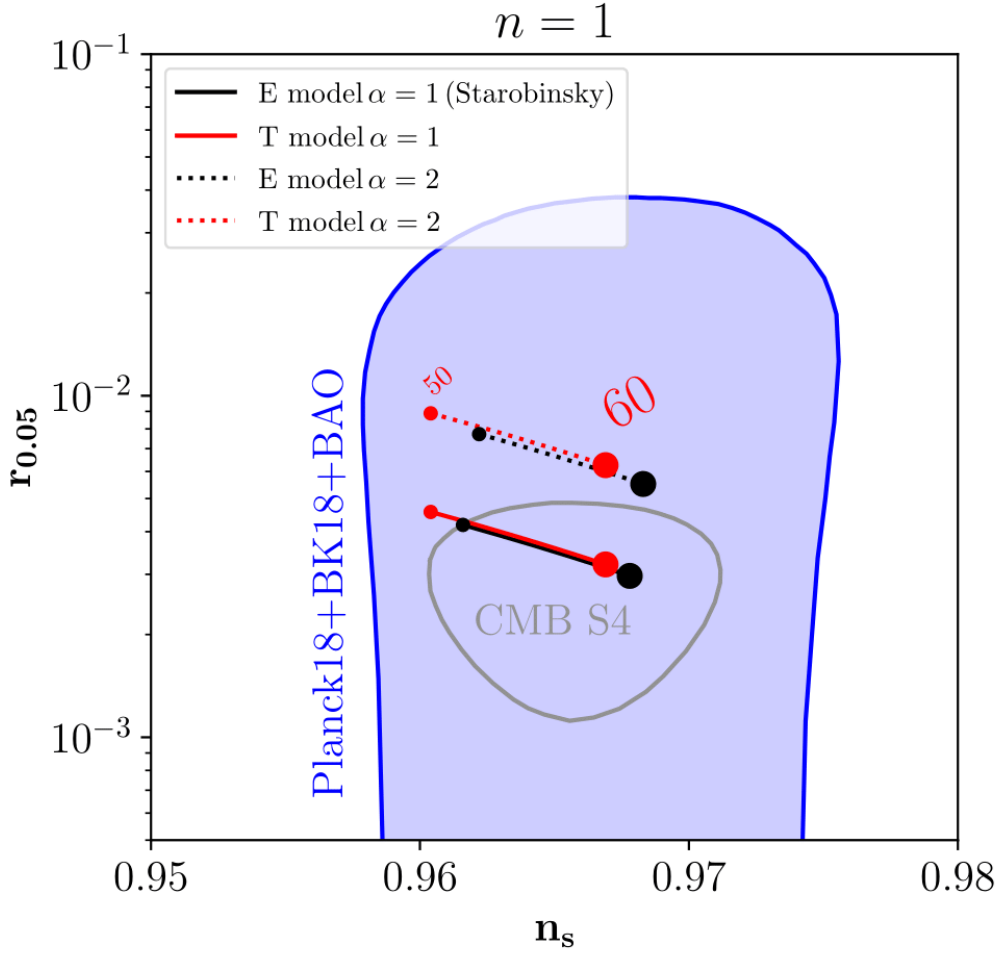
$k = 2$

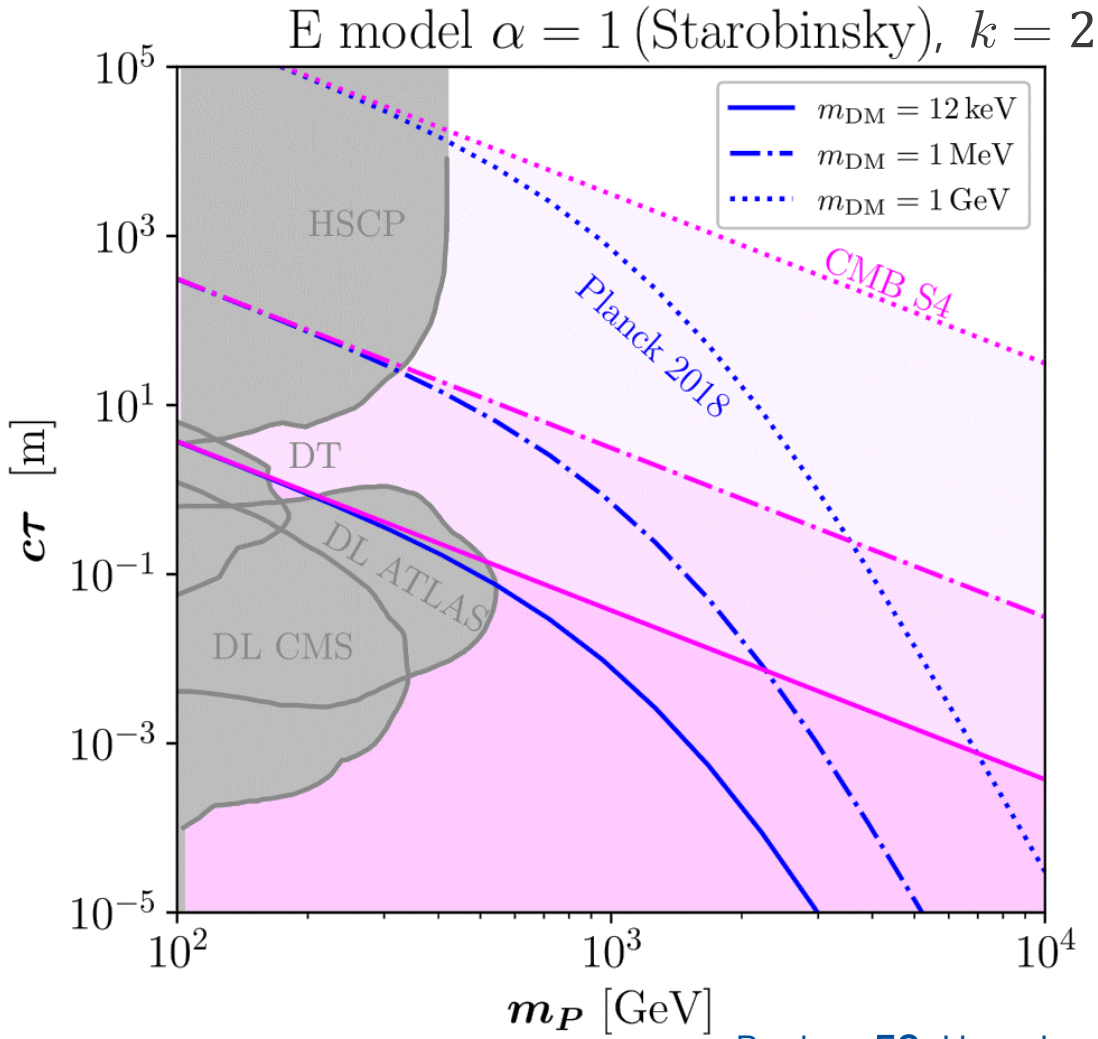


Becker, **EC**, Harz, Lang, Xu (2023)

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.

Advertisement!

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Mainz Institute for Theoretical Physics

The Dark Matter Landscape: From Feeble to Strong Interactions

26 August 2024 to 13 September 2024
Mainz Institute for Theoretical Physics, Johannes Gutenberg University

Enter your search term

Organized by Matthias Becker (JGU Mainz, Diversity coordinator), Laura Lopez Honorez (Univ. Libre de Bruxelles), Tracy Slater (Massachusetts Institute of Technology), Juri Smirnov (Univ. of Liverpool), and Julia Harz (JGU Mainz).

MITP supports equal opportunities in science.

Thank you for your attention!

Stay tuned and check soon the arXiv!

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

PRISMA+

JG|U

Backup slides

Lifetime of parent particle: two observations

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

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

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

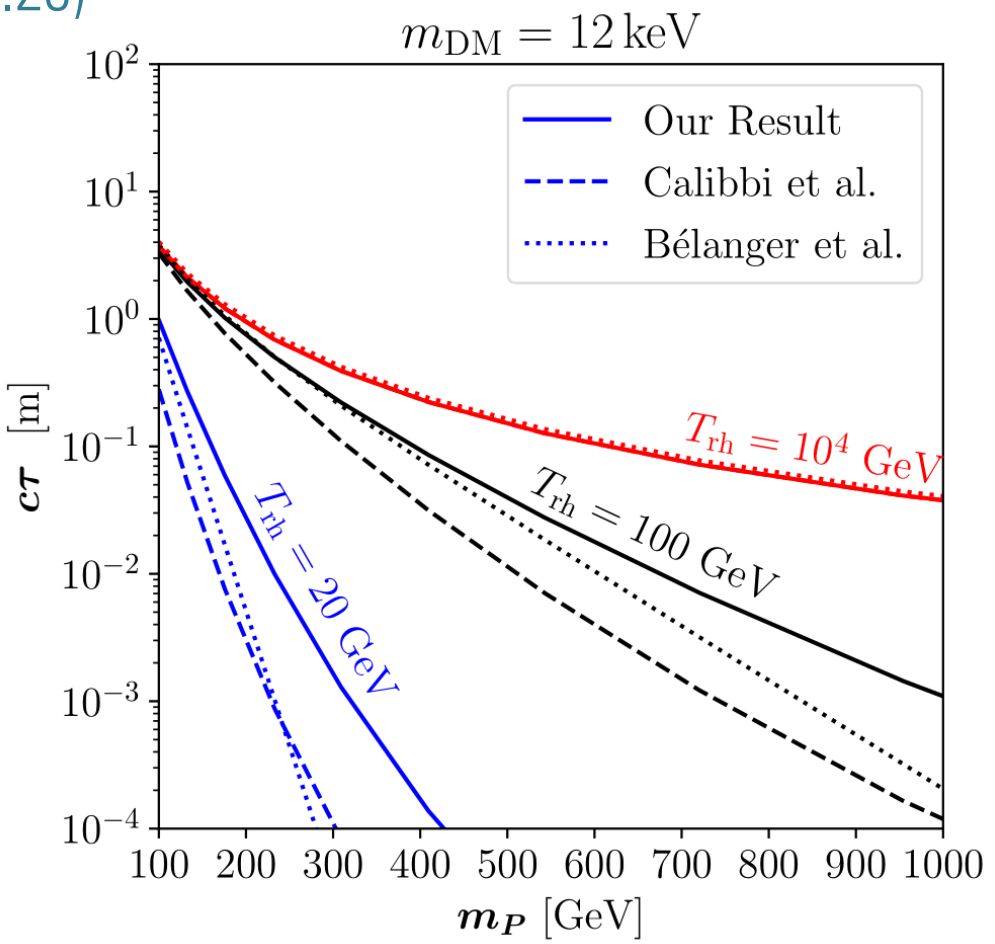
$$H(T_{rh}) = \Gamma_\Phi \quad \Rightarrow \quad \Gamma_\Phi = \sqrt{\frac{\pi^2 g_\star}{90}} \frac{T_{\rm rh}^2}{M_{\rm Pl}}$$

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 $k > 2$.



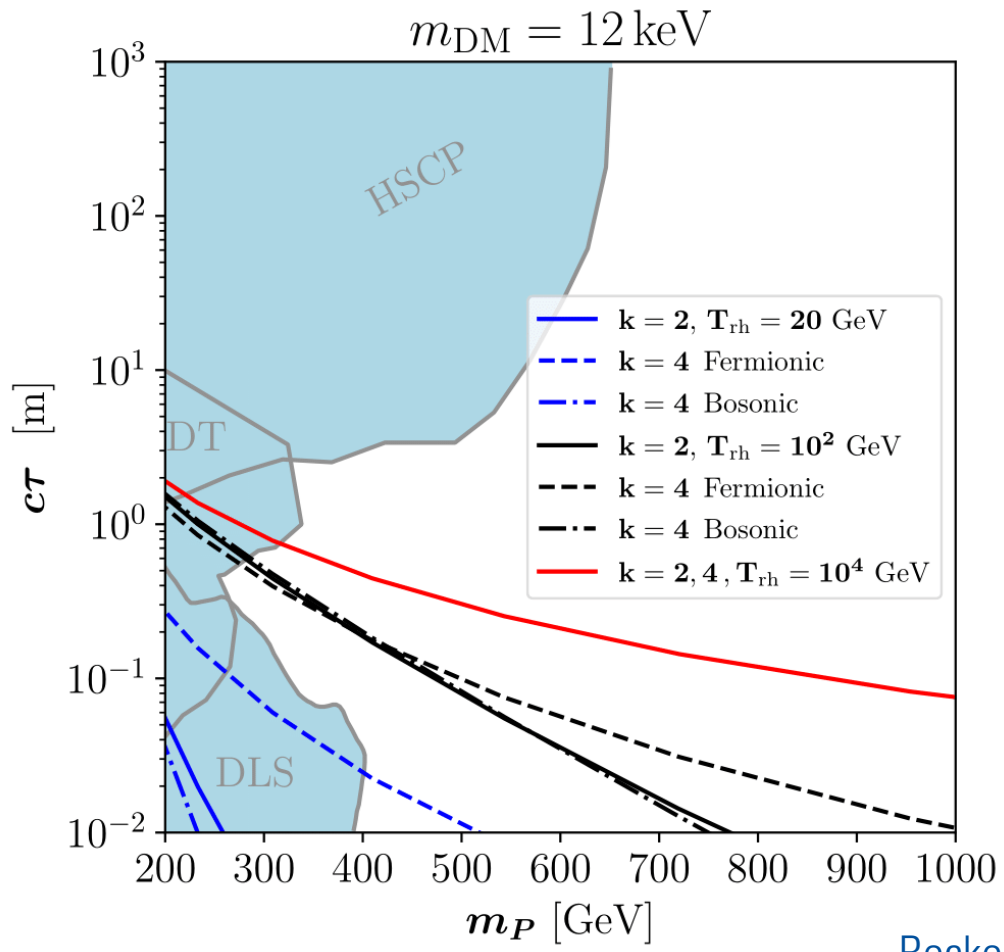
[See also Garcia et al. (2020), arXiv:2004.08404]

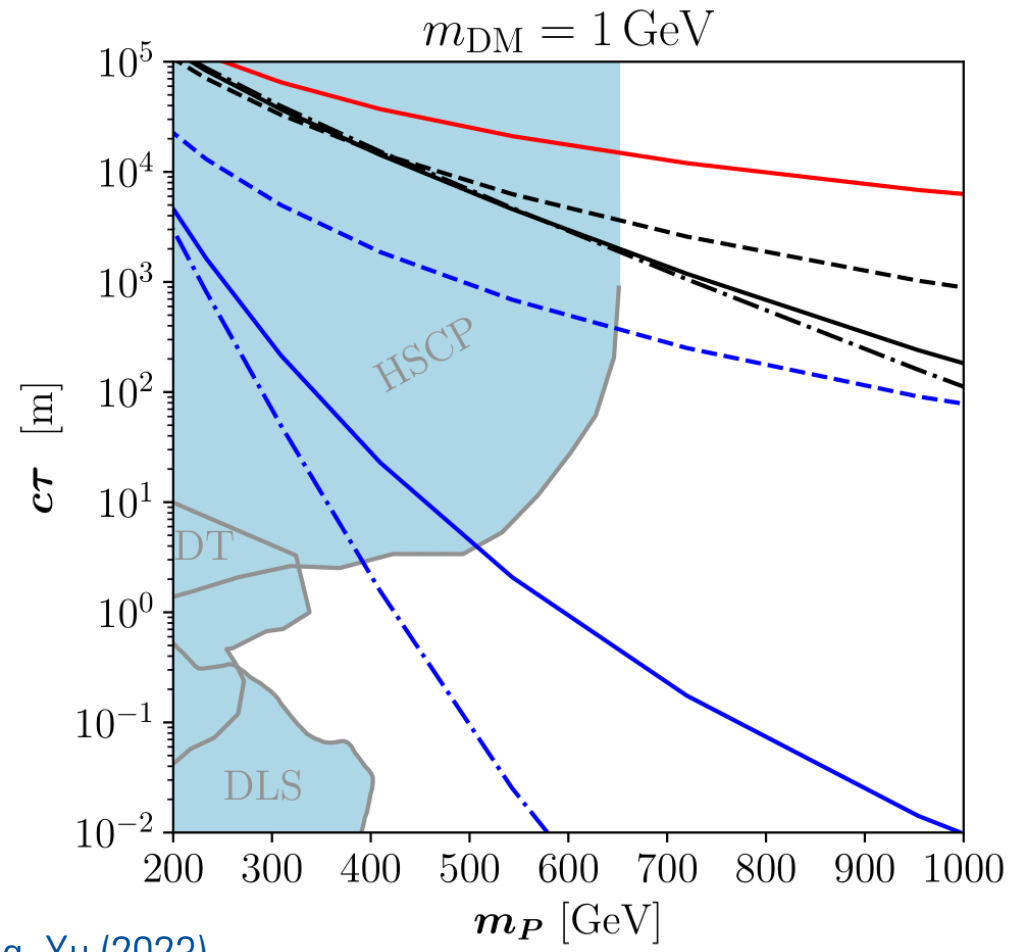
Becker, **EC**, Harz, Lang, Xu (2023)

Lifetime of parent particle

Leptophilic real scalar DM (vectorlike fermion P)

LLP limits from Bélanger et al. (2019)





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

Details of the reheating phase

BOSONIC

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

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

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

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

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

FERMIONIC

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

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

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

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

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

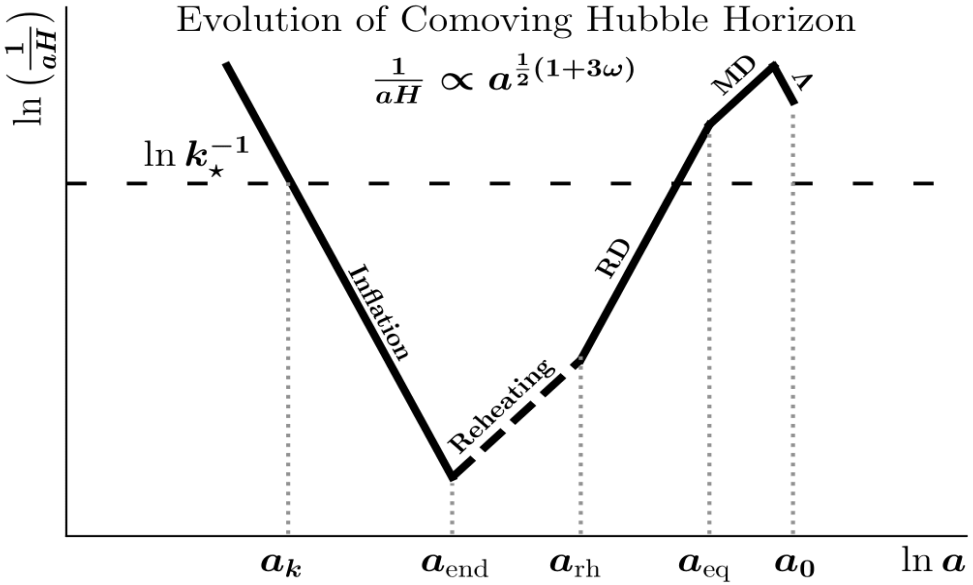
Formula for $T_{\rm rh}$ vs. n_s

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

Pivot scale
$k_* = a_* H_*$

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

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



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

After reheating, entropy conserved

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

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

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

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

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

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

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

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

Scalar singlet DM / vectorlike fermion parent model

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

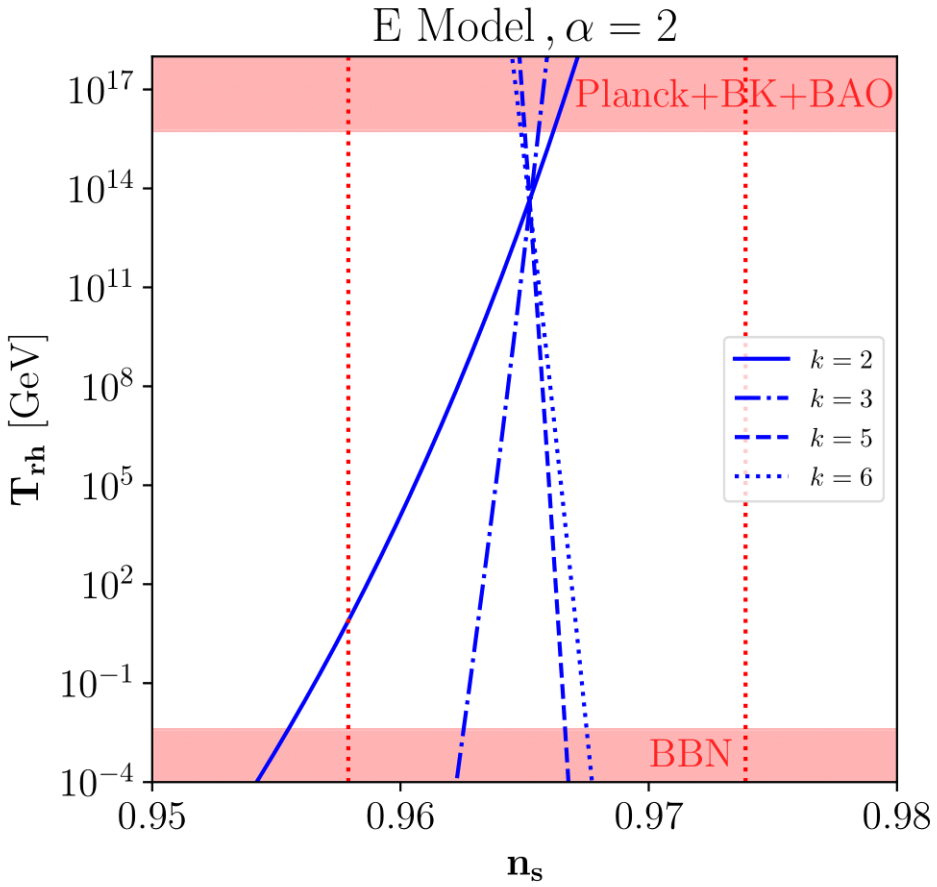
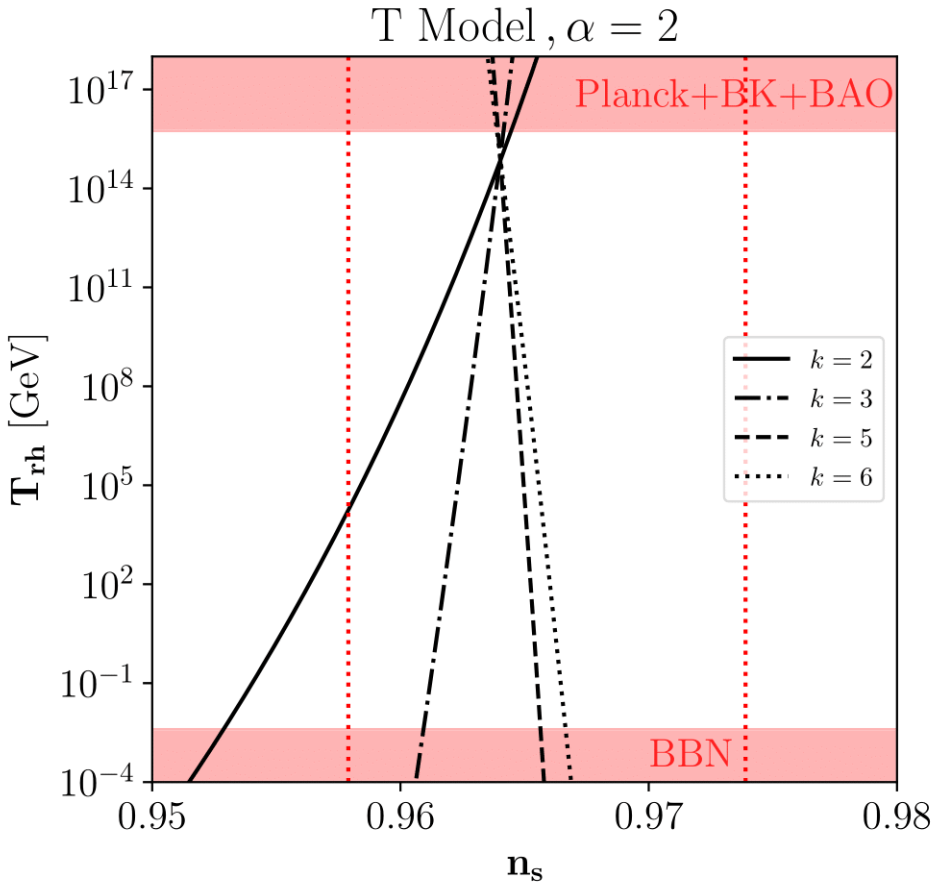
$$\mathcal{L}_s = \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 - \lambda_{sH} s^2 |H|^2$$

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

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

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

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

Emmy Noether-Programm DFG Deutsche Forschungsgemeinschaft
JG|U

More on E- and T- models