Confronting Dark Matter Freeze-In during Reheating with Constraints from Inflation

Work with M. Becker, E. Copello, J. Lang, Y. Xu, *arXiv:2306.17238*

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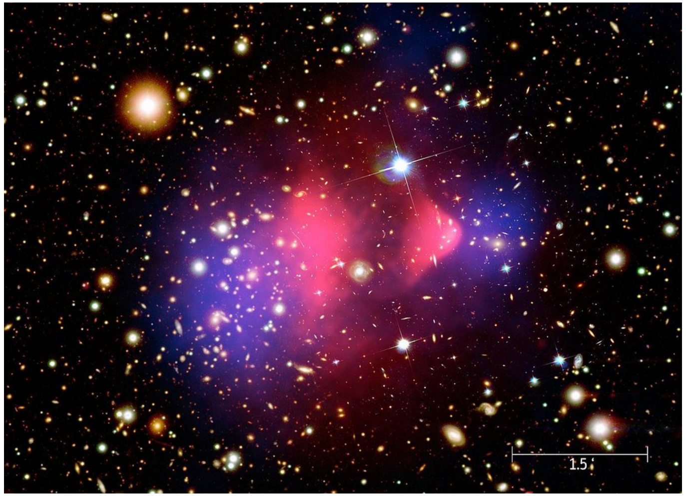
Long-lived Particles Bethe Forum Bonn

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Motivation.

Why dark matter?

Rotation Curves of Spiral Galaxies



Bullet Cluster

Different qualitative and quantitative evidence for the existence of Dark Matter!

$$\Omega_{\rm CDM} h^2 = 0.120 \pm 0.001$$

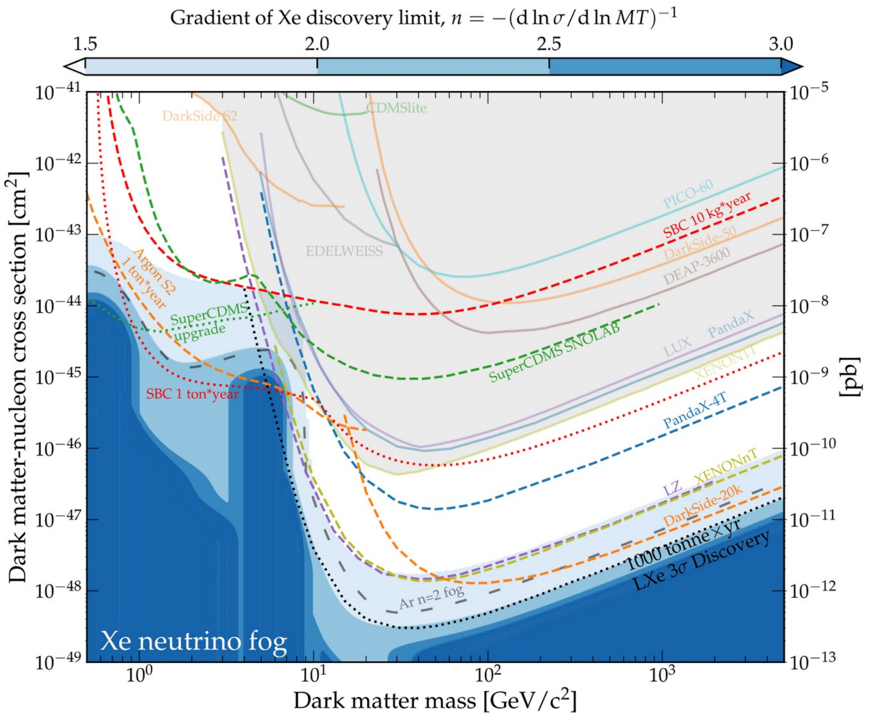
PLANCK 2018

What is dark matter?

WIMP miracle?

$$\Omega h^2 \sim \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle\sigma v\rangle} \sim 0.1$$

$$\langle\sigma v\rangle \sim \frac{g^4}{m_\chi^2} \sim 10^{-9}\mathrm{GeV}^{-2}$$



- *Minimal* WIMP models are currently under tension due to no observations at the LHC, direct or indirect detection

- Many possible reasons such as

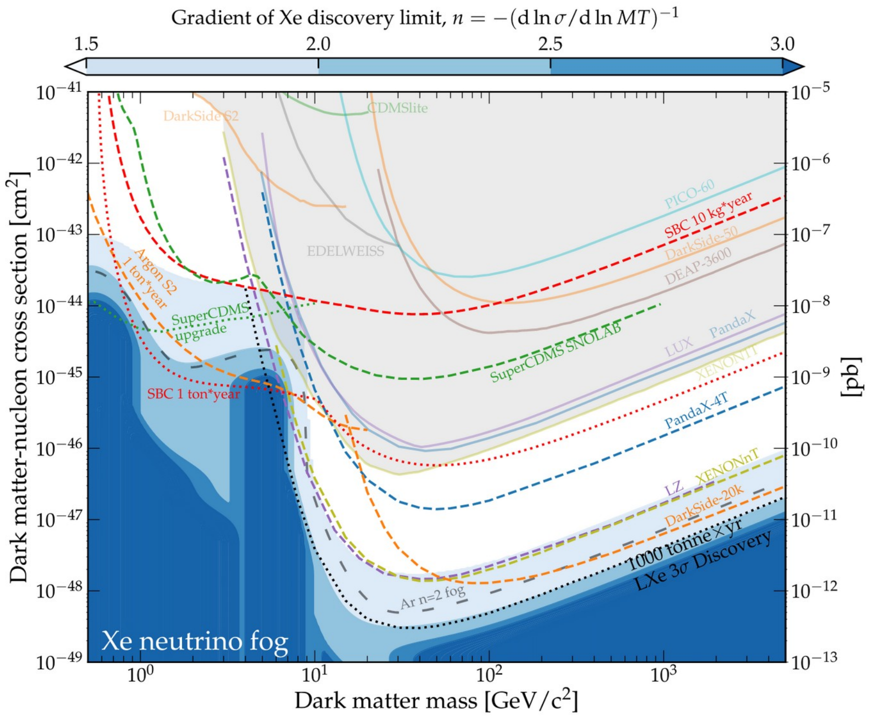
  (a) a more complex WIMP model that can evade bounds
  (b) "exception" or effect that have been overlooked (co-scattering, early kinetic decoupling, bound states, etc.)
  (c) freeze-in instead of freeze-out
  (d) completely different DM candidate (PBHs, wavy DM etc.)

What is dark matter?

WIMP miracle?

$$\Omega h^2 \sim \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \sim 0.1$$

$$\Rightarrow \quad \langle \sigma v \rangle \sim \frac{g^4}{m_\chi^2} \sim 10^{-9}\mathrm{GeV}^{-2}$$



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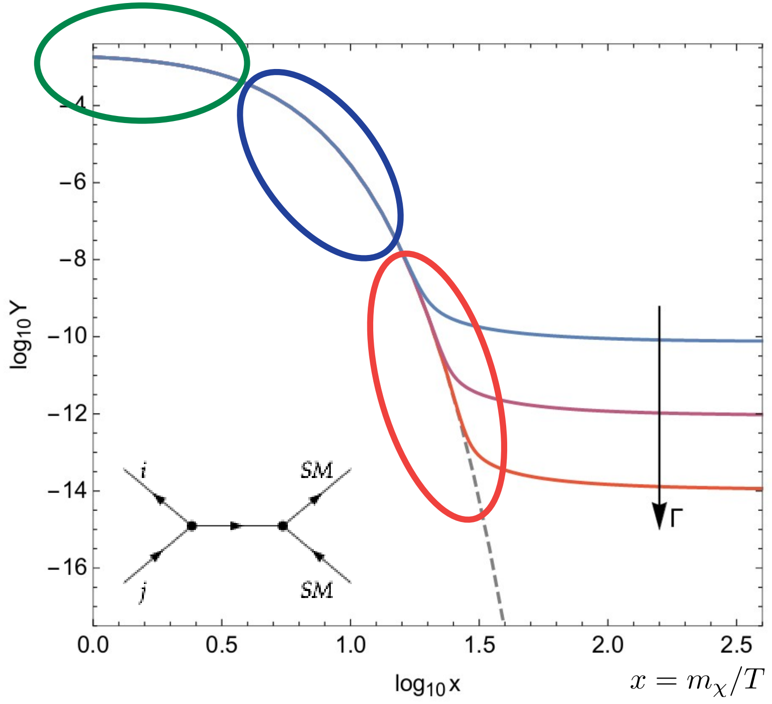
Freeze-in vs Freeze-out



cooling down →

(1) Thermal equilibrium regime (T >> m)

annihilation and production of DM in thermal equilibrium $Y \approx \text{const.}$

(2) Annihilation regime (T ~ m/10)

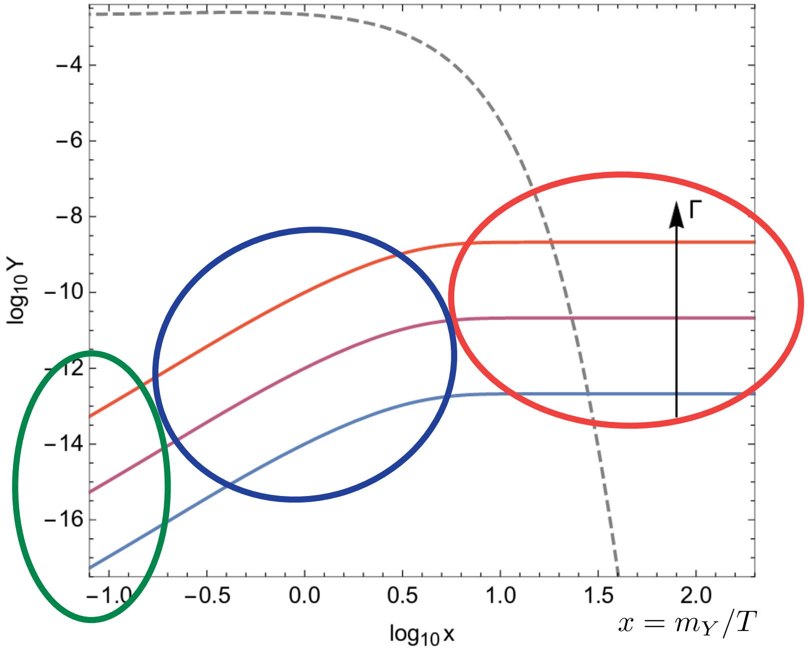
SM particles not energetic enough to create DM particles $Y \approx \exp(-m_{DM}/T)$

(3) Freeze-out (T ~ m/30)

Annihilation rate falls behind expansion rate → DM abundance

$$\Omega_\chi h^2 = \frac{n_\chi m_\chi}{\rho_{\text{crit}}} \propto \frac{1}{<\sigma_{\text{eff}} v>}$$

Freeze-in vs Freeze-out



cooling down →

(1) DM *not* in thermal equilibrium with SM bath

DM is feebly interacting with the SM bath; $\lambda \sim \mathcal{O}(10^{-7})$
abundance negligible

(2) DM production

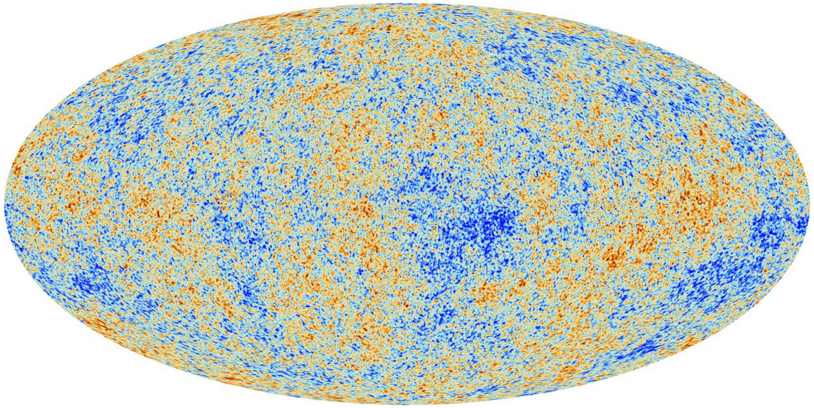
DM gets produced via decay of a heavier particle Y that is in equilibrium with the SM bath $Y \to \mathrm{SM}\ \chi$

(3) Freeze-in

when T falls below mass of parent particle Y, production gets Boltzmann suppressed $n_Y \approx \exp(-m_Y/T)$

$$\Omega_\chi h^2 \sim 4.48 \times 10^8 \frac{g_Y}{g_*^S \sqrt{g_*}} \frac{m_\chi}{\mathrm{GeV}} \frac{M_{\mathrm{Pl}} \Gamma_Y}{m_Y^2}$$

Why Inflation?



- **Horizon problem:**

  At recombination photons could have had causal contact only up to θ ~ 3.5°

  → why so homogeneous?

- **Flatness problem:**

$$\frac{d}{dt}(\Omega_k) = -2\frac{\ddot{a}}{\dot{a}}\Omega_k$$

for radiation or matter domination $\ddot{a} < 0$
→ unstable fixed point

→ why is the Universe so flat? Extreme fine-tuning would have been required!

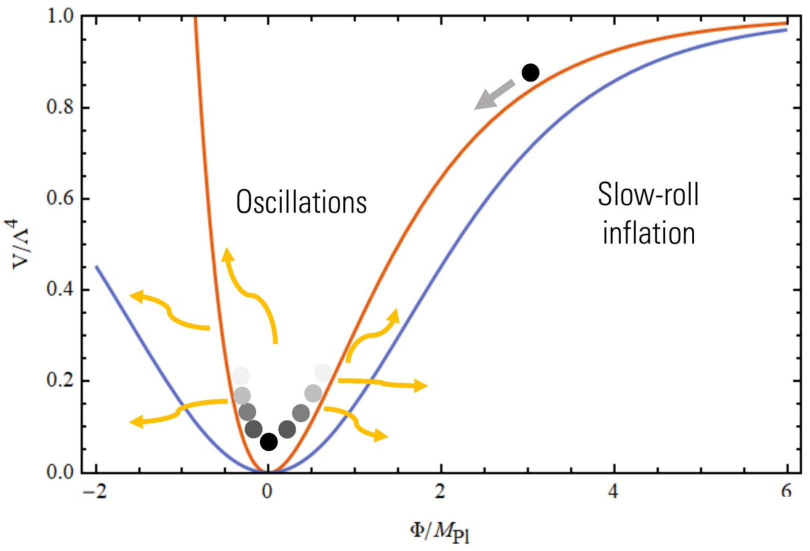
Introduce accelerated expansion $\ddot{a} > 0$ before radiation domination

Inflation and reheating

Introduce scalar inflaton field

$$\frac{1}{2}\dot{\Phi}^2 + V(\Phi) = 3H^2$$

with $\rho_\Phi = \frac{1}{2}\dot{\Phi}^2 + V(\Phi)$ $\quad p_\Phi = \frac{1}{2}\dot{\Phi}^2 - V(\Phi)$ $\quad \omega = \frac{p_\Phi}{\rho_\Phi}$

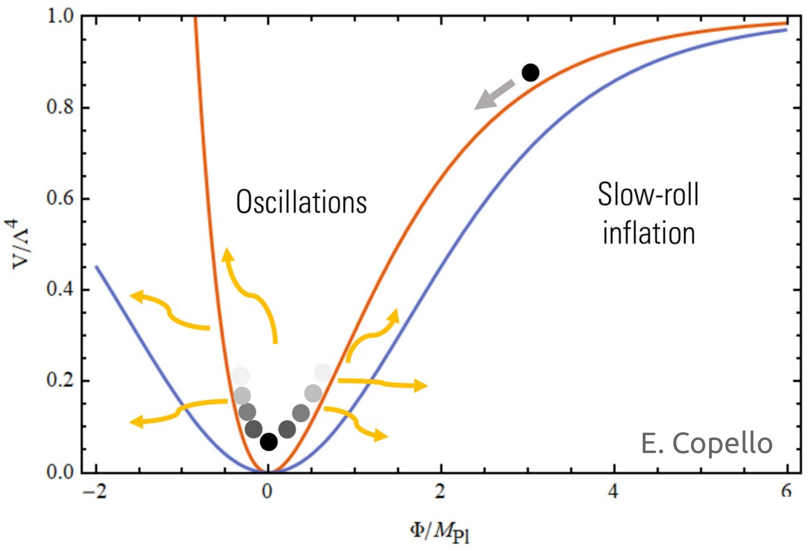


Such that the flatness and horizon problem is solved:

$$H^2 + \dot{H} = \frac{\ddot{a}}{a} = -\frac{1}{6}(\rho + 3p) > 0$$

If potential energy dominates over kinetic energy $V(\Phi) \gg \dot{\Phi}$ **, the field is slowly rolling down the potential.**

Inflation and reheating



Slow-roll parameters define the end of inflation:

$$\epsilon_V \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 < 1 \qquad \eta_V \equiv M_{\rm Pl}^2\left(\frac{V''}{V}\right) < 1$$

Length of inflation measured by numbers of efolds:

$$N(\Phi) = \int_{t_i}^{t_{\rm end}} H dt$$

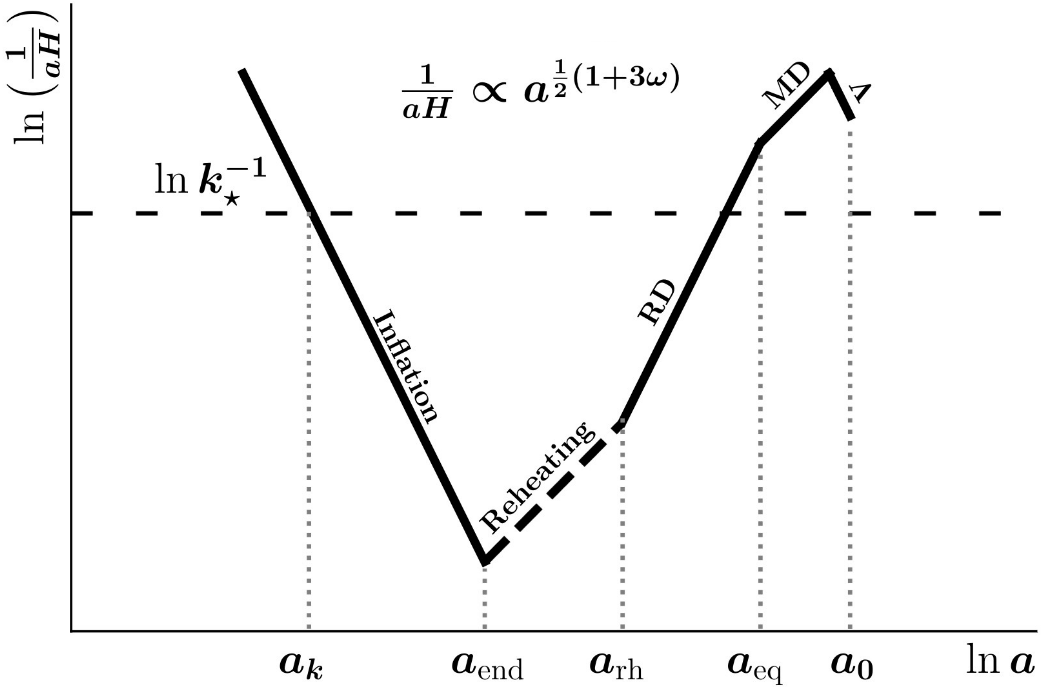
At end of inflation, inflaton oscillates and transmits energy to SM particles = reheating

$$\langle \dot{\rho}_\Phi \rangle + 3H \langle \rho_\Phi \rangle = -\Gamma_\Phi \langle \rho_\Phi \rangle$$

$$\Gamma_{\Phi \to F\bar{F}} = \frac{y^2}{8\pi} m_\Phi \qquad \Gamma_{\Phi \to XX^\dagger} = \frac{g^2}{8\pi m_\Phi}$$

The reheating temperature T_{rh} is defined as $\rho_\Phi(a_{\rm rh}) = \rho_R(a_{\rm rh})$

Evolution of the Universe



Dark Matter production during reheating.

The model set-up

Heavier parent particle P carries SM gauge charges, with DM (SM) odd (even) under Z_2 symmetry

$y_{\rm DM}\, P\, \chi\, f_{\rm SM}$

	Majorana DM model	Scalar Singlet DM model
Interaction	$y_{\rm DM} X \overline{\chi} f_R$	$y_s s \overline{F} f_R$
Spin DM χ	$1/2$	0
Spin parent P	0	$1/2$

Relevant for reheating

$\mathcal{L}_{\Phi X} \supset -\mu_X \Phi |X|^2$ $\qquad$ $\mathcal{L}_{\Phi F} = -y_F \Phi \bar{F} F$

For this work, we neglect non-thermal production of DM via the inflaton

$\mathcal{L}_{\rm Yuk.} \supset -y_\chi \Phi \bar{\chi}\chi$ $\qquad$ $\mathcal{L}_{\Phi s} = -\mu_s s \Phi^2 - \frac{\sigma_s}{2} s^2 \Phi^2$

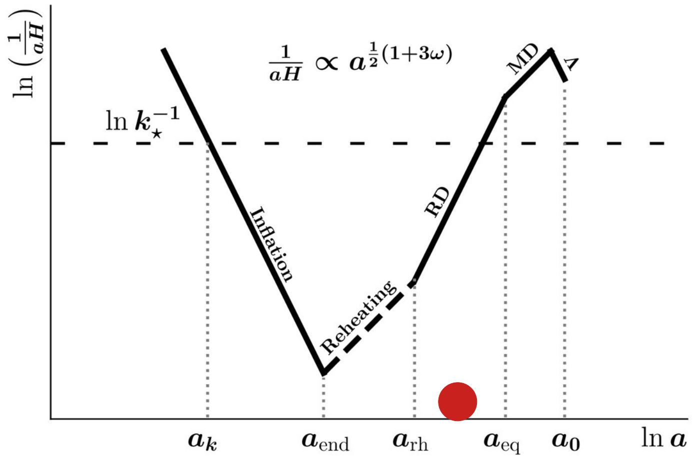
And neglect Higgs interactions (→ flatness inflaton potential, stability of EW vacuum)

Upcoming work includes a systematic study of all possibilities!

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

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

Freeze-in Dark Matter Production



$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = \frac{g_P}{2\pi^2}\Gamma_P m_P^2\, T K_1\left(\frac{m_P}{T}\right)$$

Standard case, $T_{rh} > T_{fi}$

$$Y_{\rm DM}^{\rm RD}(T) \sim \frac{\Gamma(T)}{H(T)} \sim \Gamma_P \frac{m_P\, M_{\rm Pl}}{T^3}$$

$$Y_{\rm DM}^{\rm RD}(z_{\rm fi}) \sim z_{\rm fi}^3 \frac{\Gamma_P\, M_{\rm Pl}}{m_P^2}$$

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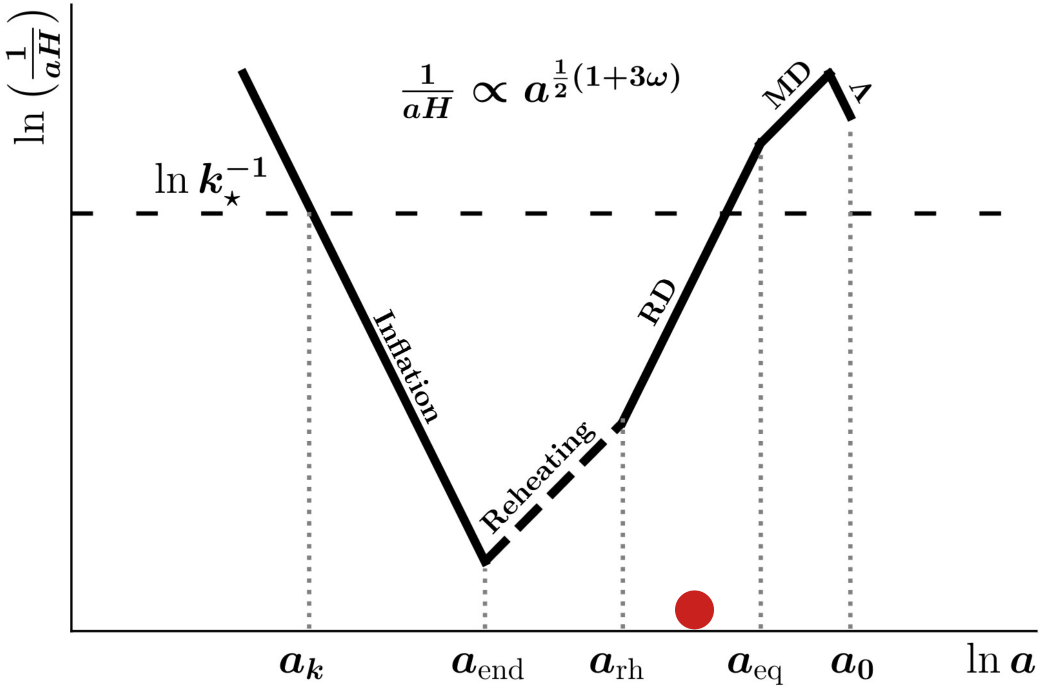
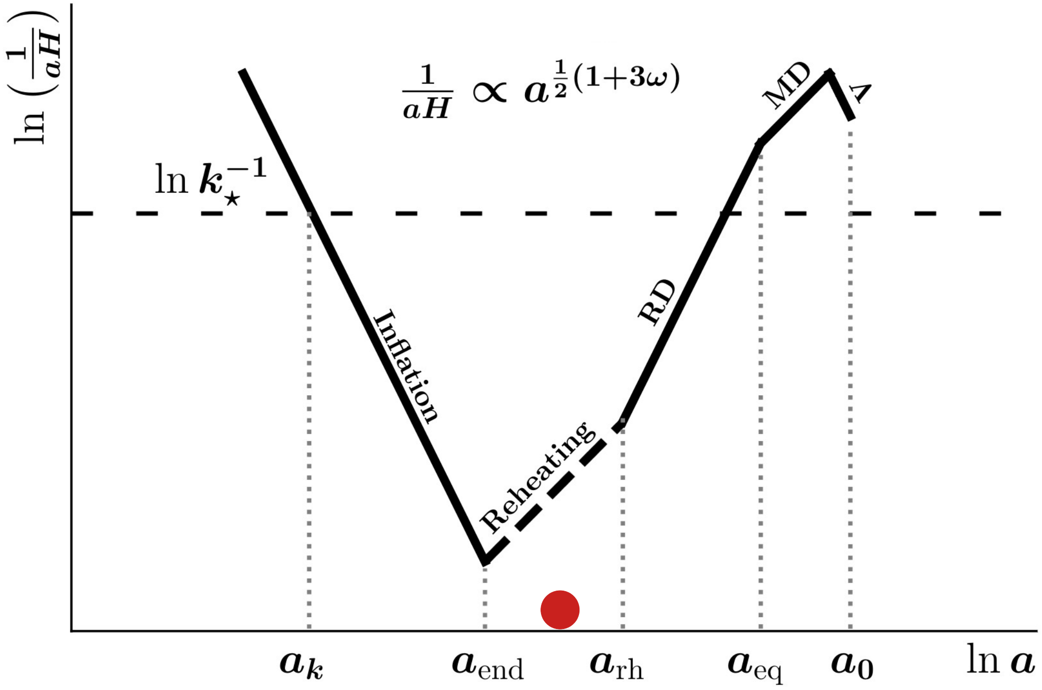


$T_{rh} > m_P$

Evolution of the Universe



$m_P > T_{rh}$

Pre-thermalization effects

Requiring fast thermalization, we find the following condition for k=2:

$$z_{\rm th} \equiv \frac{m_P}{T_{\rm th}} = 3 \times 10^{-3} \left(\frac{g_s(T_{\rm rh})}{106.75}\right)^{\frac{1}{20}} \left(\frac{m_P}{1\ {\rm TeV}}\right)^{\frac{1}{5}} \left(\frac{m_P}{T_{\rm rh}}\right)^{\frac{4}{5}} \left(\frac{\lambda}{10^{-12}}\right)^{\frac{1}{10}} \left(\frac{\alpha_g}{10^{-2}}\right)^{-\frac{4}{5}} \ll 1$$

such that

$$\frac{m_p}{T_{\rm rh}} \lesssim 10^3 \left(\frac{1\ {\rm TeV}}{m_P}\right)^{1/5}$$

We assume that gauge charged parent particle P thermalizes rapidly and is in equilibrium with SM bath, as long as m_P/T_{rh} not to huge.

Reheating phase

Starting from a generic reheating potential at the end of inflation

$$V(\Phi) = \lambda \frac{|\Phi|^k}{M^{k-4}}$$

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

One can derive the evolution of the energy density of the inflaton and radiation

$$\langle \rho_\Phi \rangle = \left(\frac{k}{2} + 1\right) \lambda \frac{\langle \Phi^k \rangle}{M_{\rm Pl}^{k-4}}\,,$$

$$\langle P_\Phi \rangle = \left(\frac{k}{2} - 1\right) \lambda \frac{\langle \Phi^k \rangle}{M_{\rm Pl}^{k-4}}\,,$$

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

$\rightarrow$

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

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

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

And identify the reheating temperature by $\rho_\Phi(a_{\rm rh}) = \rho_R(a_{\rm rh})$

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

→

approximated:

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

(for intuition, we solved it numerically)

And identify the reheating temperature by $\rho_\Phi(a_{\rm rh}) = \rho_R(a_{\rm rh})$

Bosonic and Fermionic Reheating

$$\mu_X \Phi |X|^2$$

Bosonic reheating

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

$$y \Phi \bar{F} F$$

Fermionic reheating

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

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

Bosonic:

$$\rho_R(a) \propto a^{-\frac{6}{2+k}}$$

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

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

	k=2	k=4
ρ_R	$a^{-3/2}$	a^{-1}
T	$a^{-3/8}$	$a^{-1/4}$

Fermionic:

$$\rho_R(a) \propto a^{-\frac{6(k-1)}{2+k}}$$

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

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

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Bosonic and Fermionic Reheating

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

$$T_{\text{max},b}^4 = \frac{15}{4\pi^3 g_s} \frac{k}{\sqrt{3k(k-1)}} \frac{M_P^{\frac{2k-4}{k}}}{\lambda^{\frac{1}{k}}} \mu_{\text{eff}}^2 \rho_{\text{end}}^{\frac{1}{k}} \left(\frac{3}{2k+4}\right)^{\frac{2k+4}{2k+1}}$$

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

$y \Phi \bar{F} F$

Fermionic reheating

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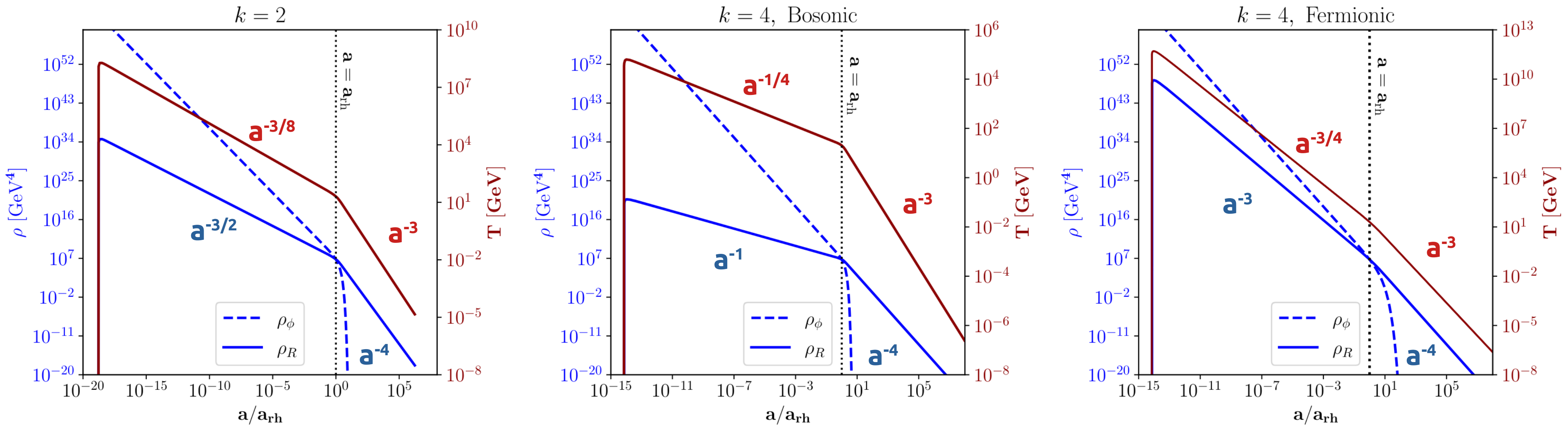
$$T_{\text{rh},f}^4 = \frac{30}{\pi^2 g_s} \left[\frac{k\sqrt{3k(k-1)}}{7-k} \lambda^{\frac{1}{k}} \frac{y_{\text{eff}}^2}{8\pi}\right]^{k} M_{\text{Pl}}^4$$

Evolution of energy densities and temperature



Freeze-in Dark Matter Production

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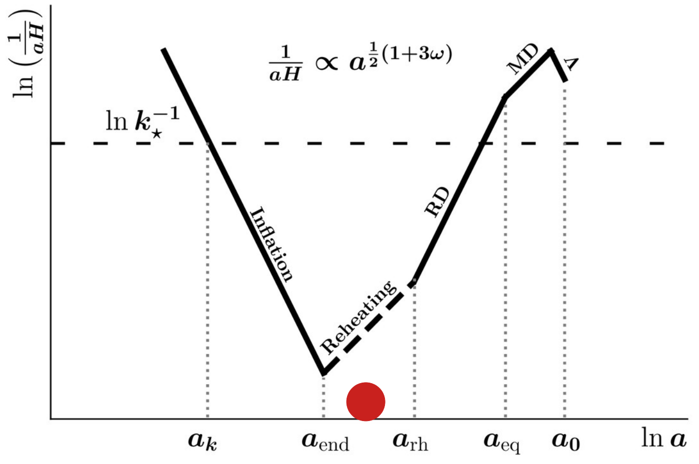

Non-standard case, $T_{\rm fi} > T_{\rm rh}$

- Production of entropy during reheating
- Altered expansion rate

$$D(T) \simeq \frac{S(T)}{S(T_{\rm rh})} = \frac{s(T)a(T)^3}{s(T_{\rm rh})a(T_{\rm rh})^3} \simeq \begin{cases} \left(\frac{T_{\rm rh}}{T}\right)^{1+2k} & \text{BR} \\ \left(\frac{T_{\rm rh}}{T}\right)^{\frac{7-k}{k-1}} & \text{FR} \end{cases}$$

$$Y_{\rm DM}^{\rm RH}(T) \sim \frac{\Gamma(T)}{H(T)} D(T)$$

$$Y_{\rm DM}^{\rm RH}\left(\frac{m_P}{z_{\rm fi}}\right) \sim z_{\rm fi}^3 \frac{\Gamma_P M_{\rm Pl}}{m_P^2} \times \begin{cases} \left(\frac{z_{\rm fi} T_{\rm rh}}{m_P}\right)^{4k-1} & \text{BR} \\ \left(\frac{z_{\rm fi} T_{\rm rh}}{m_P}\right)^{\frac{9-k}{k-1}} & \text{FR} \end{cases}$$

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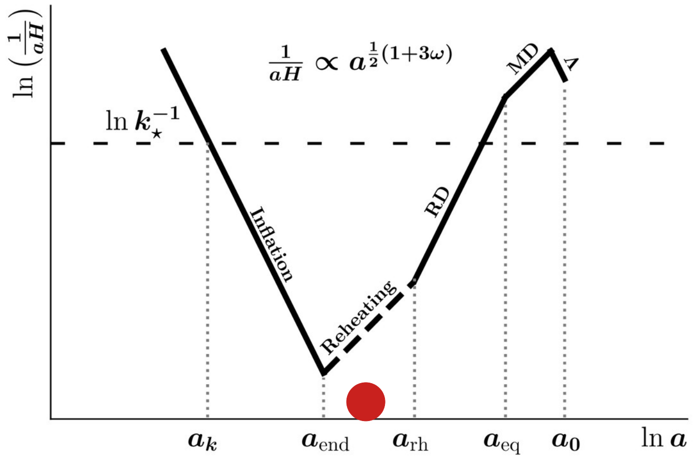

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$$H(a) = \frac{\sqrt{\rho_\Phi(a) + \rho_R(a)}}{\sqrt{3}\, M_{\rm Pl}}$$

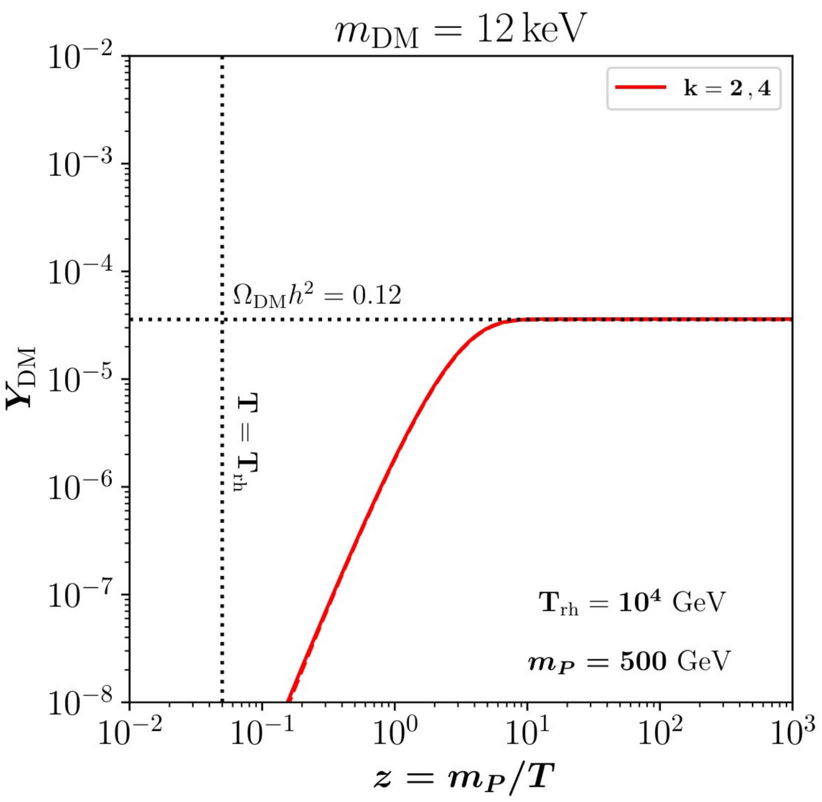
$$\frac{\Omega_{\rm DM}h^2}{0.12} \simeq \left(\frac{1.5\,{\rm m}}{c\tau}\right)\left(\frac{106.75}{g_s}\right)^{3/2}\left(\frac{m_{\rm DM}}{100\,{\rm keV}}\right)\left(\frac{200\,{\rm GeV}}{m_P}\right)^2 \times \begin{cases} \frac{2k+4}{3}\left(\frac{T_{\rm rh}}{m_P}\right)^{4k-1}\mathcal{I}_{\rm rh,b} + \mathcal{I}^0_{\rm RD} & \text{in BR} \\ \frac{2k+4}{3k-3}\left(\frac{T_{\rm rh}}{m_P}\right)^{\frac{9-k}{k-1}}\mathcal{I}_{\rm rh,f} + \mathcal{I}^0_{\rm RD} & \text{in FR} \end{cases},$$

$$\mathcal{I}_{\rm rh,b} = \int_{z_{\rm end}}^{z_{\rm rh}} z'\, z'^{2+4k} K_1(z')\,,$$

$$\mathcal{I}_{\rm rh,f} = \int_{z_{\rm end}}^{z_{\rm rh}} z'\, z'^{\frac{2k+6}{k-1}} K_1(z')\,,$$

$$\mathcal{I}^0_{\rm RD} = \int_{z_{\rm rh}}^{z_0} z'\, z'^3 K_1(z')\,.$$

Time evolution of DM Yield

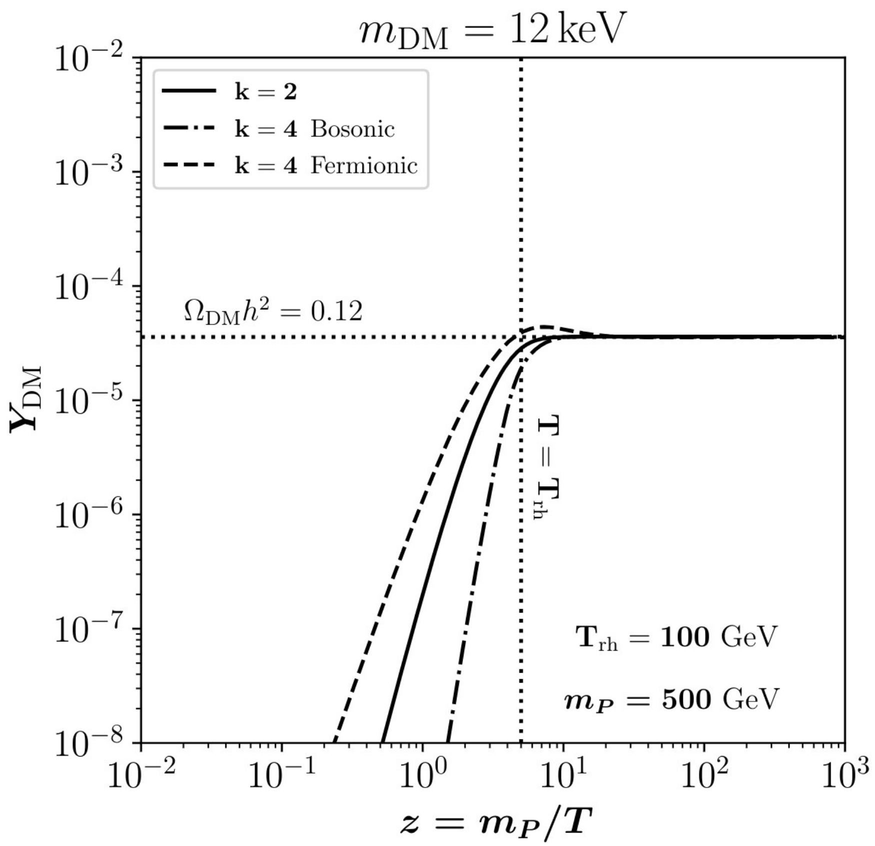


$T_{rh} > m_P$

→ recovery of classical freeze-in during RD

→ no impact of reheating phase

Time evolution of DM Yield



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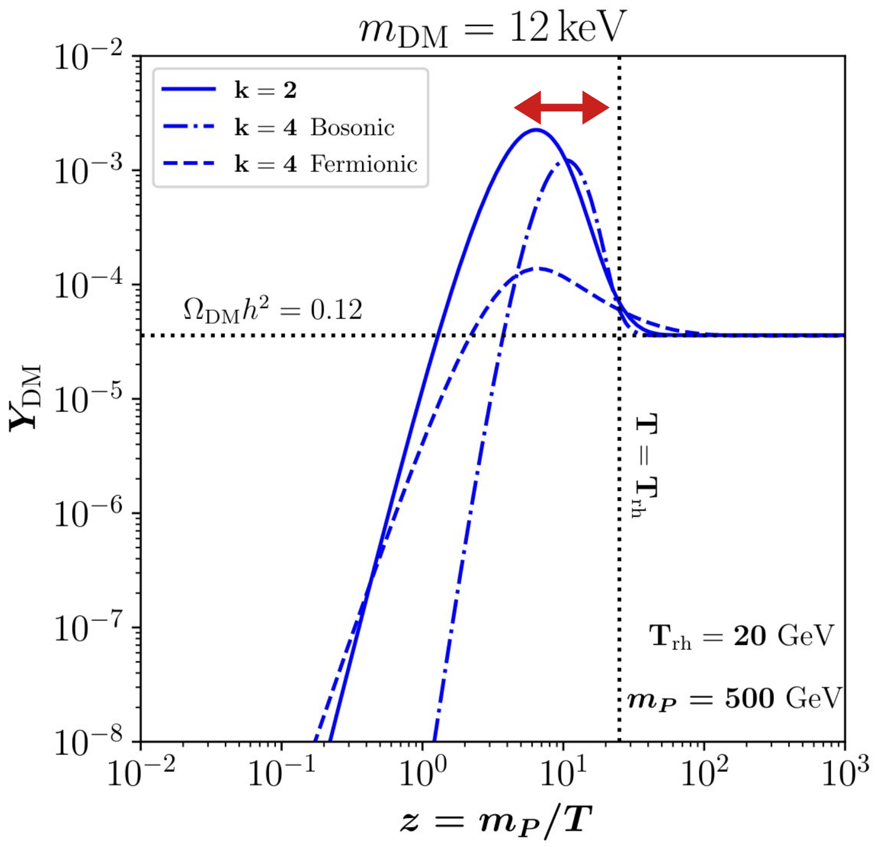

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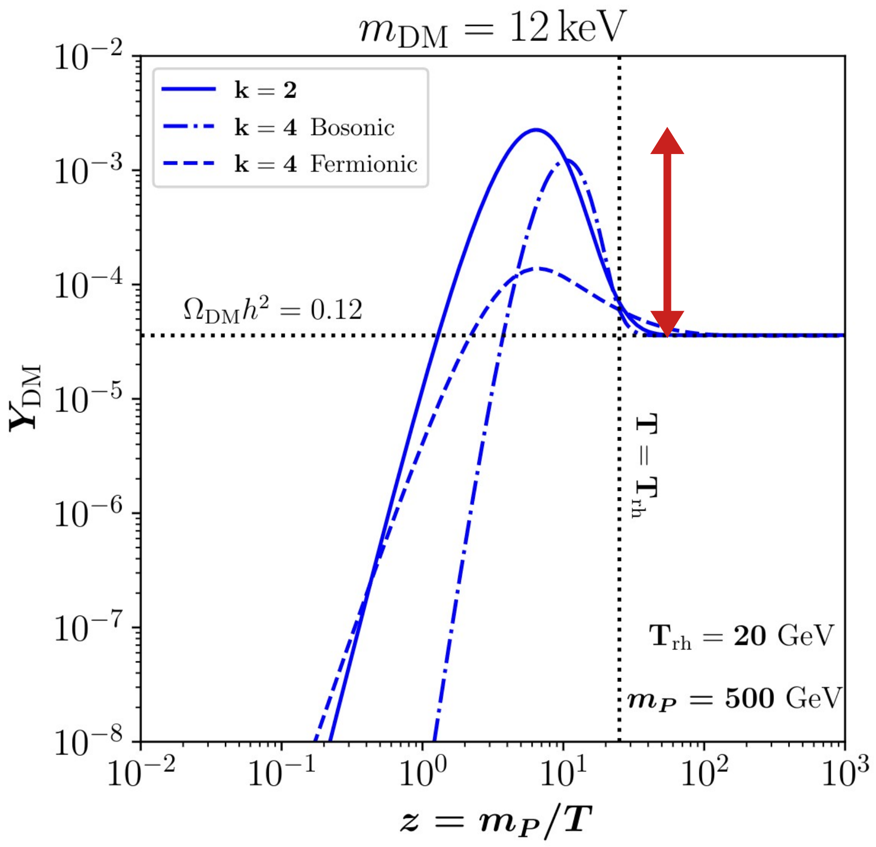
→ DM production peaks at later times for bosonic reheating

$$(z_{\rm fi})_{{\rm BR},\,k=4} \;>\; (z_{\rm fi})_{k=2} \;\gtrsim\; (z_{\rm fi})_{{\rm FR},\,k=4}$$

Time evolution of DM Yield



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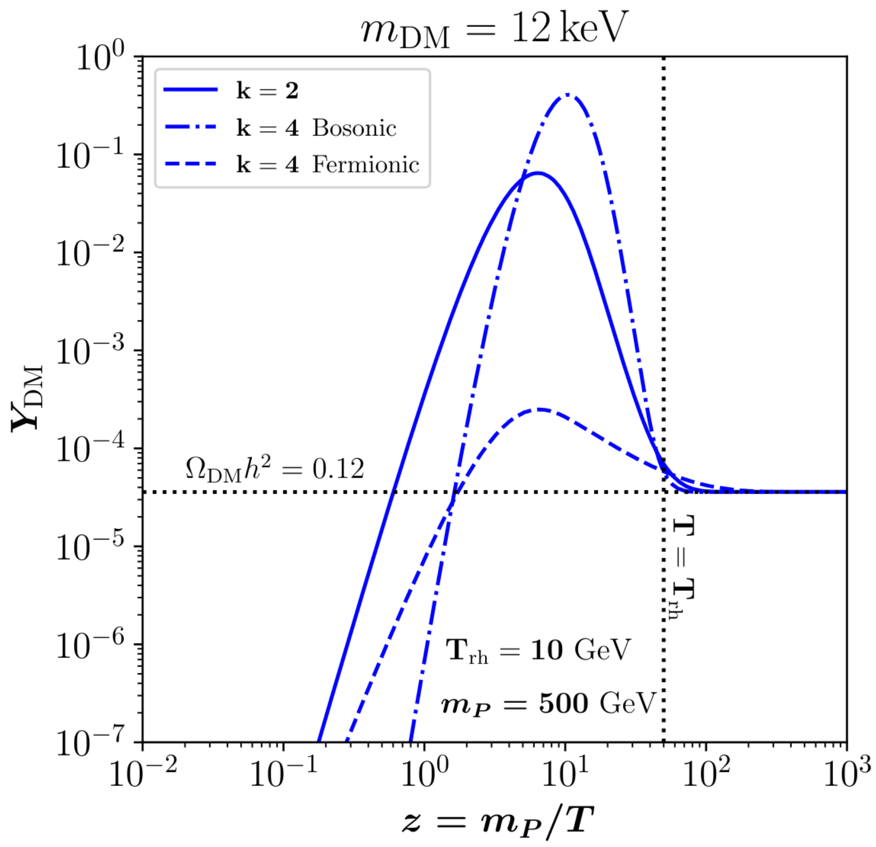
$$(z_{\rm fi})_{{\rm BR},\,k=4} > (z_{\rm fi})_{k=2} \gtrsim (z_{\rm fi})_{{\rm FR},\,k=4}$$

→ dilution factor decreases for

$$D^{{\rm BR},k=4}\,(T_{\rm fi}) > D^{{\rm k=2;\ FR,k=4}}\,(T_{\rm fi})$$

Time evolution of DM Yield



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$$D^{{\rm BR},k=4}(T_{\rm fi}) > D^{{\rm k=2;\ FR,k=4}}(T_{\rm fi})$$

Constraints on decay length from relic abundance

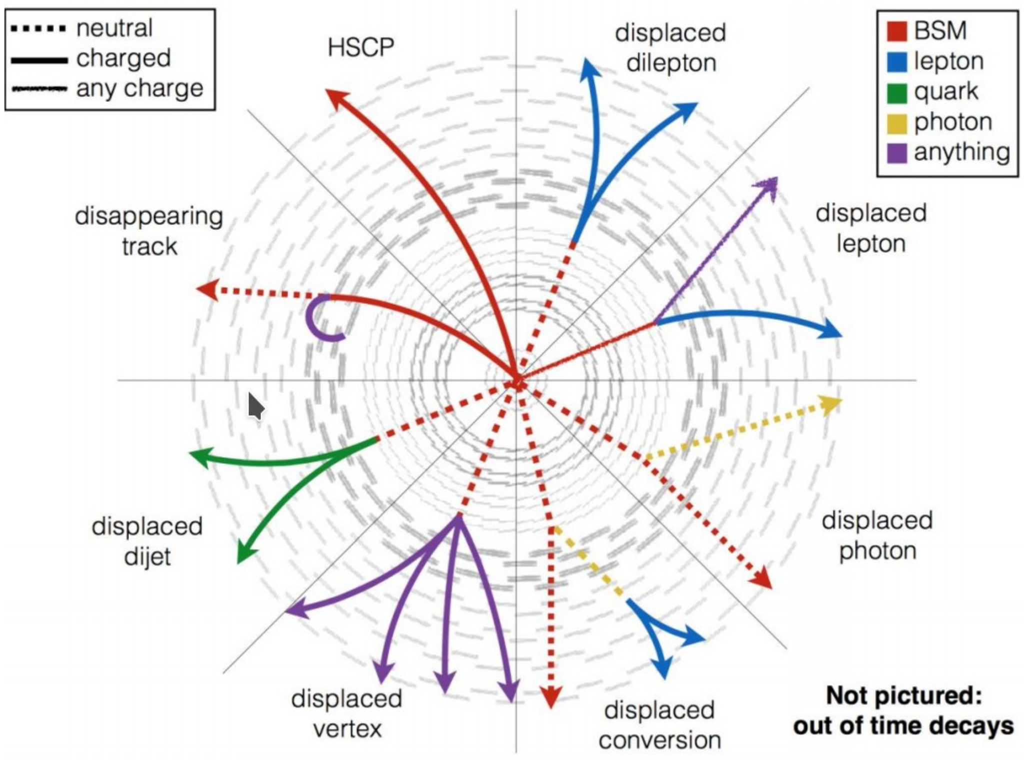
$$\frac{\Omega_{\rm DM}h^2}{0.12} \simeq \left(\frac{1.5\,\mathrm{m}}{c\tau}\right)\left(\frac{106.75}{g_s}\right)^{3/2}\left(\frac{m_{\rm DM}}{100\,\mathrm{keV}}\right)\left(\frac{200\,\mathrm{GeV}}{m_P}\right)^2 \times \begin{cases} \frac{2k+4}{3}\left(\frac{T_{\rm rh}}{m_P}\right)^{4k-1} \mathcal{I}_{\rm rh,b} + \mathcal{I}^0_{\rm RD} & \text{in BR} \\ \frac{2k+4}{3k-3}\left(\frac{T_{\rm rh}}{m_P}\right)^{\frac{9-k}{k-1}} \mathcal{I}_{\rm rh,f} + \mathcal{I}^0_{\rm RD} & \text{in FR} \end{cases},$$

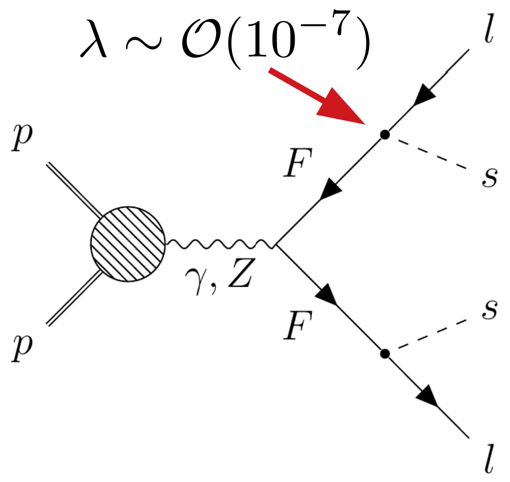
Type	$T_{\rm rh}$ [GeV]	$c\tau$ [m]
$k=2$	10	2.2×10^{-7}
$k=4$ BR	10	2.2×10^{-11}
$k=4$ FR	10	2.0×10^{-3}
$k=2$	20	2.6×10^{-5}
$k=4$ BR	20	4.3×10^{-7}
$k=4$ FR	20	5.6×10^{-3}
$k=2$	100	3.9×10^{-2}
$k=4$ BR	100	4.1×10^{-2}
$k=4$ FR	100	4.9×10^{-2}
$k=2$	10^4	0.15
$k=4$ BR	10^4	0.15
$k=4$ FR	10^4	0.15

m_{DM} = 12keV, m_P= 500 GeV

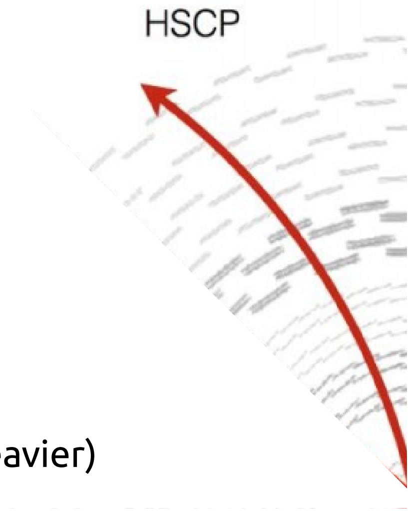
Collider Constraints.

Long lived particle searches at the LHC





Heavy Stable Charged Particles (HSCP)



Recast for Majorana DM model (Calibbi, Lopez Honorez et al. 2021)

Recast for scalar singlet DM model (Belanger, JH et al. 2019)

- parent particle **is sufficiently long lived** such that it **decays outside the detector** → ionizing tracks
- **higher ionization energy loss / larger time-of-flight (TOF)** than SM particles (as heavier)

- decay outside the tracker → *tracker-only analysis*
- decay outside the muon chamber → *tracker + TOF analysis ($c\tau$ > 10m)*

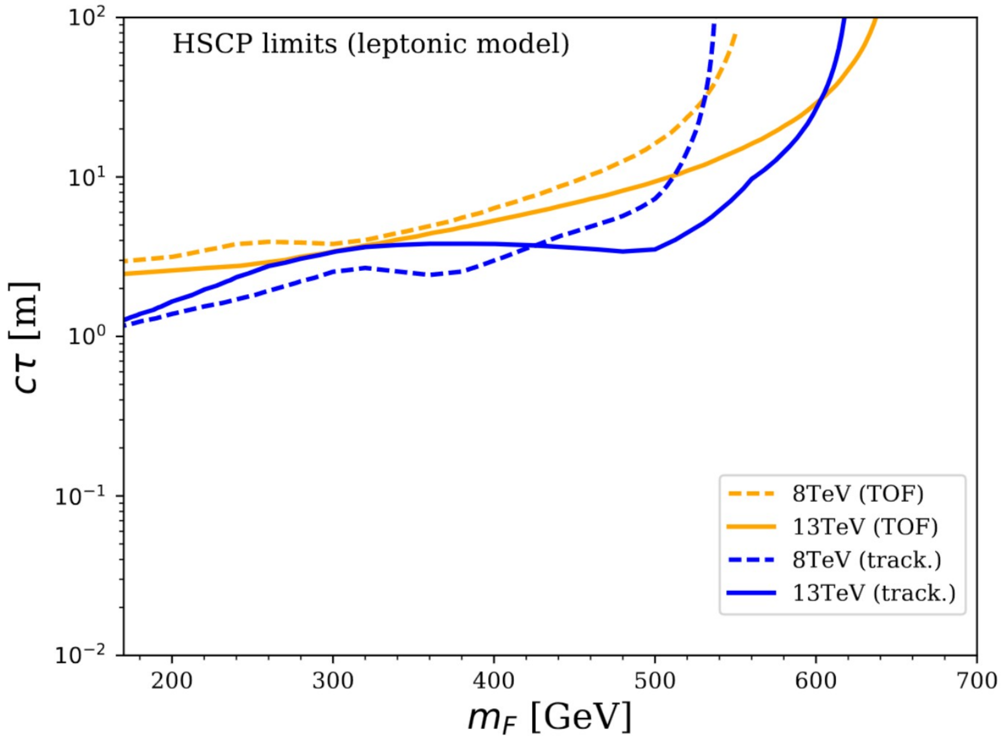
- comparison with upper limits obtained by production of **staus** in a gauge mediated SUSY breaking model

- F has smallish life time → **re-scale the efficiency** of particles that surpasse the tracker (L = 3m) / detector (L = 11 m)

$$\sigma_{eff} = \sigma \times f_{LLP}(L, \tau)$$

CMS Coll., Searches for long-lived charged particles in pp collisions at √s=7 and 8 TeV, JHEP 07 (2013) 122
CMS Coll., Search for heavy stable charged particles with 12.9 fb−1 of 2016 data, CMS-PAS-EXO-16-036 (2016).

Heavy Stable Charged Particles (HSCP)



CMS Coll., Searches for long-lived charged particles in pp collisions at √s=7 and 8 TeV, JHEP 07 (2013) 122
CMS Coll., Search for heavy stable charged particles with 12.9 fb−1 of 2016 data, CMS-PAS-EXO-16-036 (2016).

Displaced Leptons (DL)

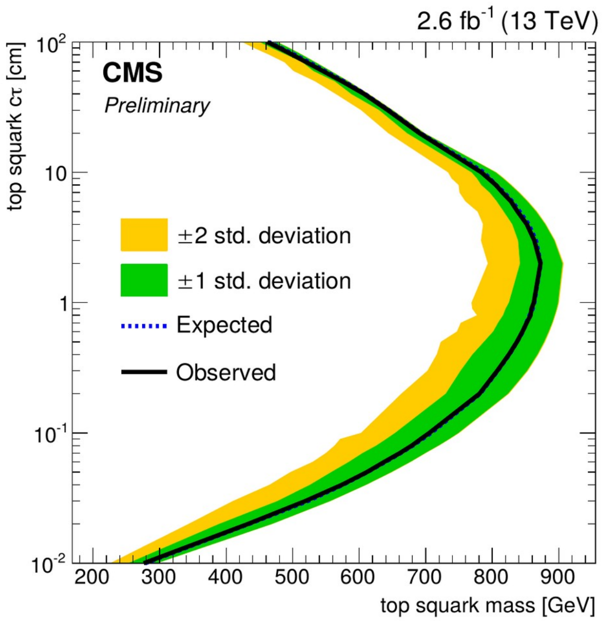
Recast for Majorana DM model (Calibbi, Lopez Honorez et al. 2021)

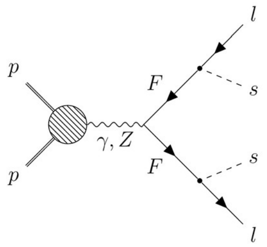
Recast for scalar singlet DM model (Belanger, JH et al. 2019)

- F can decay into **both muon and electron**
- CMS search for **non-prompt RPV violating SUSY decays** into **e/μ** final state

$$\tilde{t}_1 \to b\ell$$

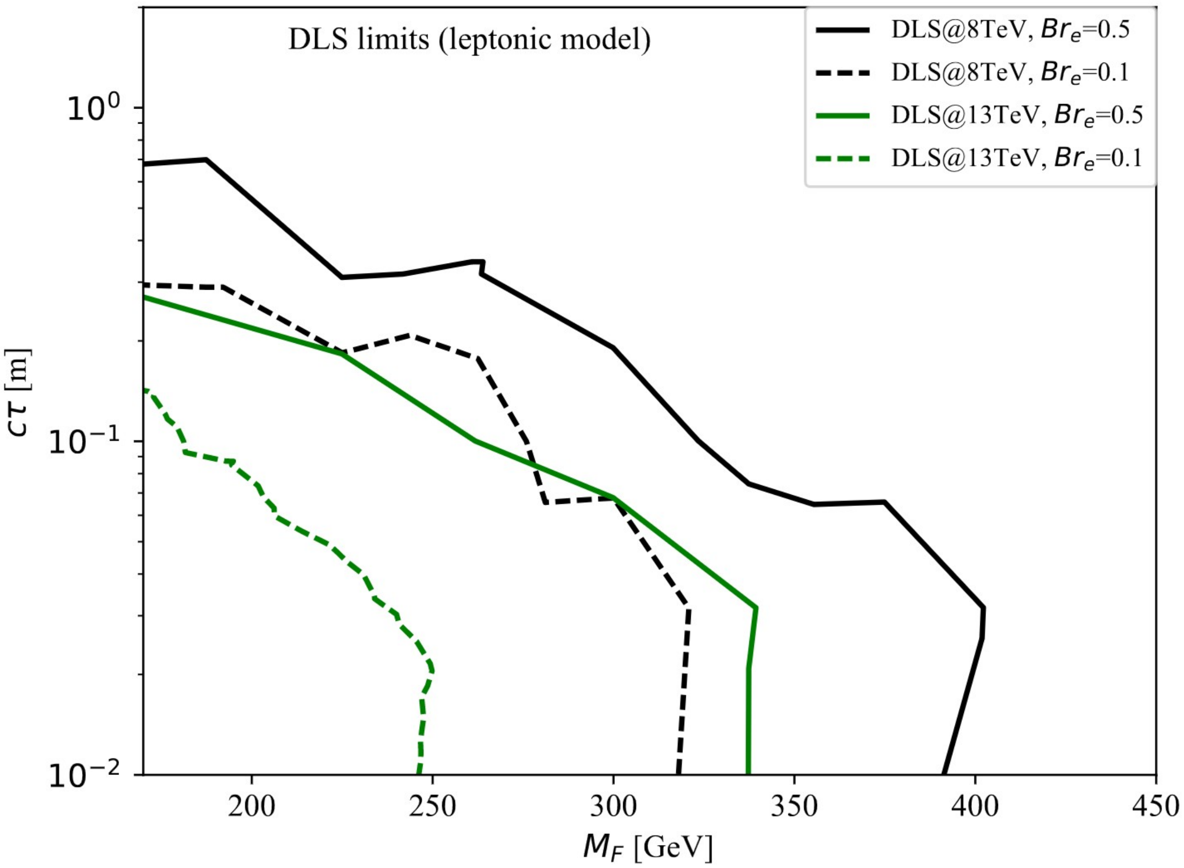
- search optimized for lifetimes **longer** than prompt searches, but **shorter** than long-lived BSM signatures



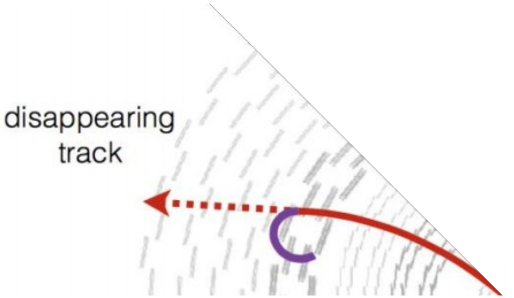


CMS Coll., Search for Displaced Supersymmetry in events with an electron and a muon with large impact parameters, Phys. Rev. 1240 Lett. 114 (2015), no. 6 061801
CMS Coll., Search for displaced leptons in the e-mu channel, CMS-PAS-EXO-16-022 (2016).

Displaced Leptons (DL)

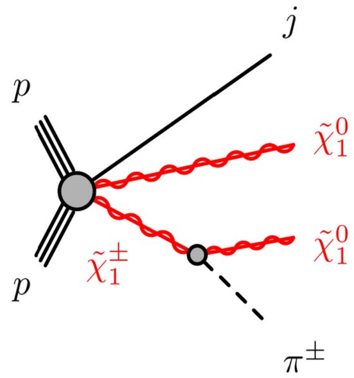


Disappearing Tracks (DT)



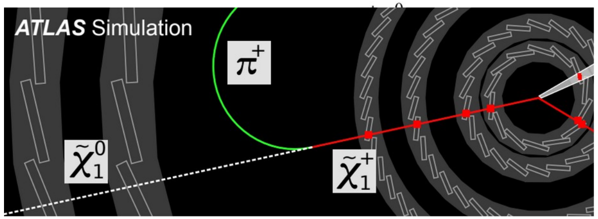
Recast for Majorana DM model (Calibbi, Lopez Honorez et al. 2021)

Recast for scalar singlet DM model (Belanger, JH et al. 2019)



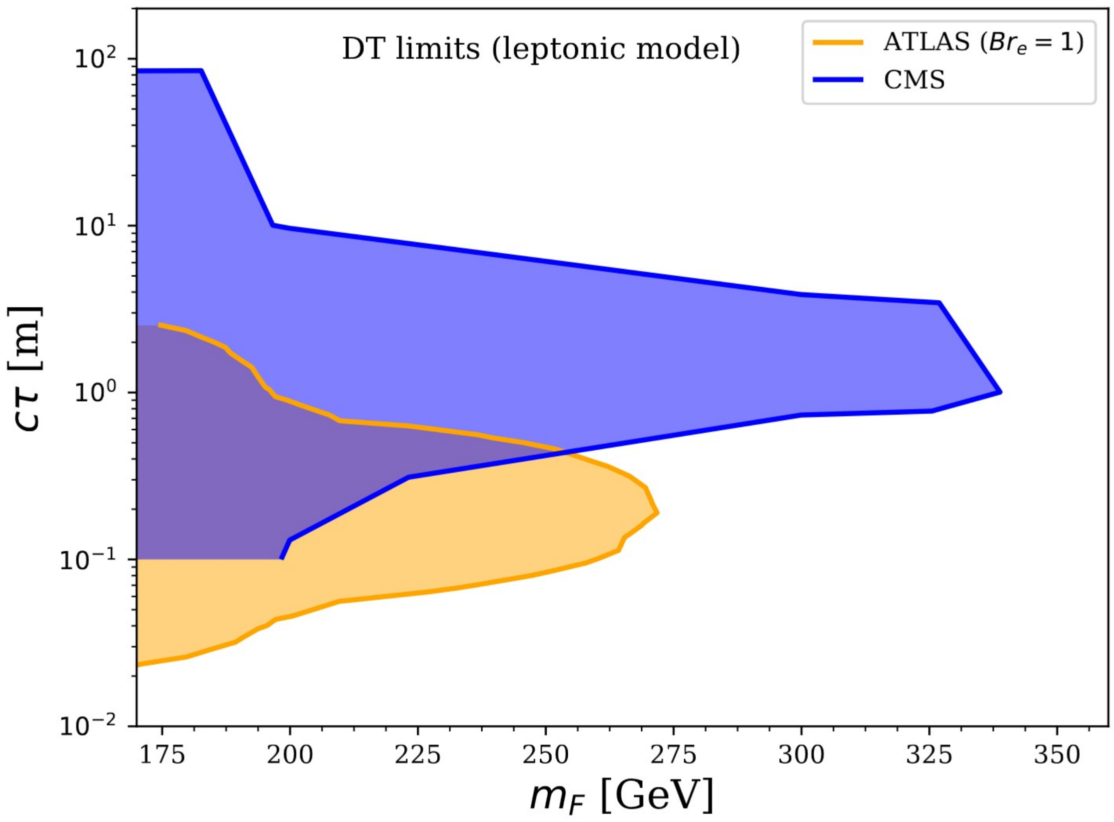
- **isolated track** reconstructed in the pixel and strip detectors without any hit in the outer tracker (CMS) or a track with only pixel hits (ATLAS)
- ATLAS can reconstruct tracks down to 12 cm, CMS 25-30 cm
- CMS has better coverage for longer life times cτ > 1m
- **AMSB** motivated scenario with mass **degenerate lightest chargino** and **neutralino**
- **Recasting** of two analyses of ATLAS and CMS

$$\mathcal{N} = \sigma_{\mathrm{pp}\to\mathrm{F}\bar{\mathrm{F}}} \times \varepsilon(m, \tau) \times \mathcal{L}$$



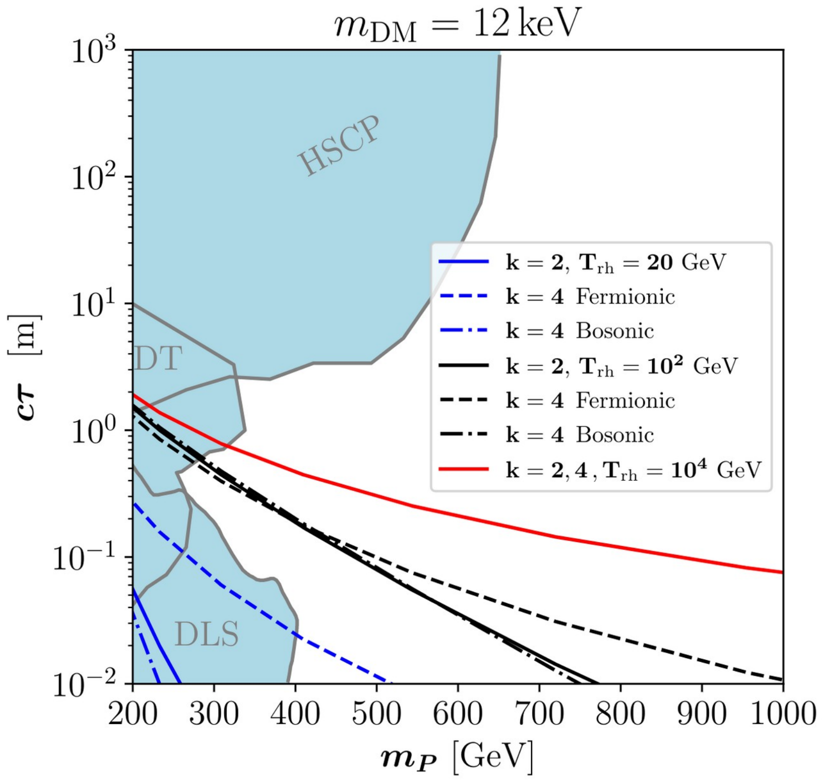
ATLAS Coll., Search for long-lived charginos based on a disappearing-track signature in pp collisions at √s= 13TeV with the ATLAS detector, JHEP06 (2018) 022
CMS Coll., Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at √s=13 TeV, arXiv:1804.07321

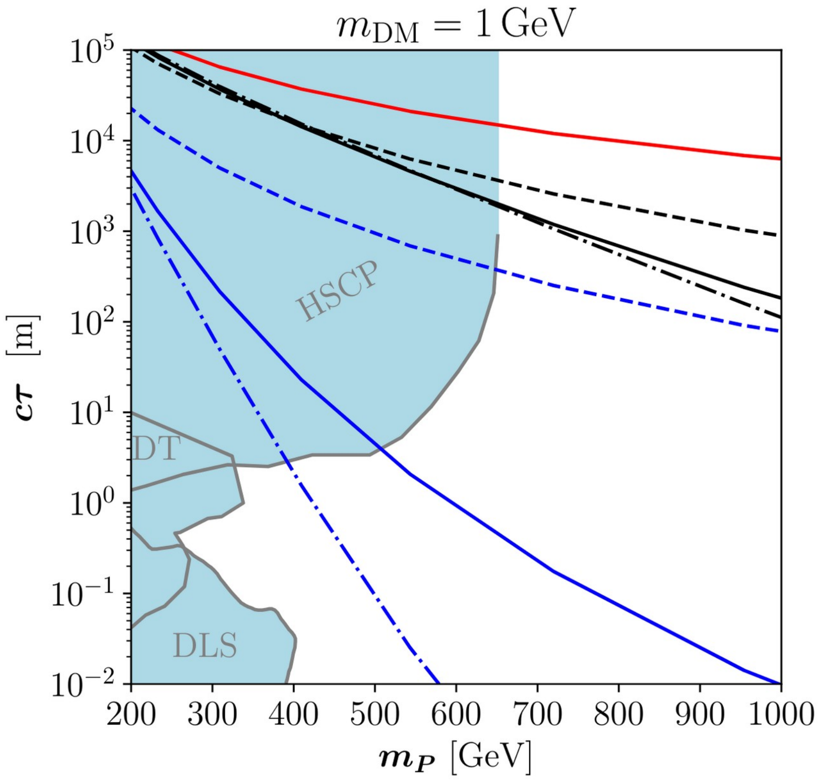
Disappearing Tracks (DT)



Constraints from LLP searches at the LHC

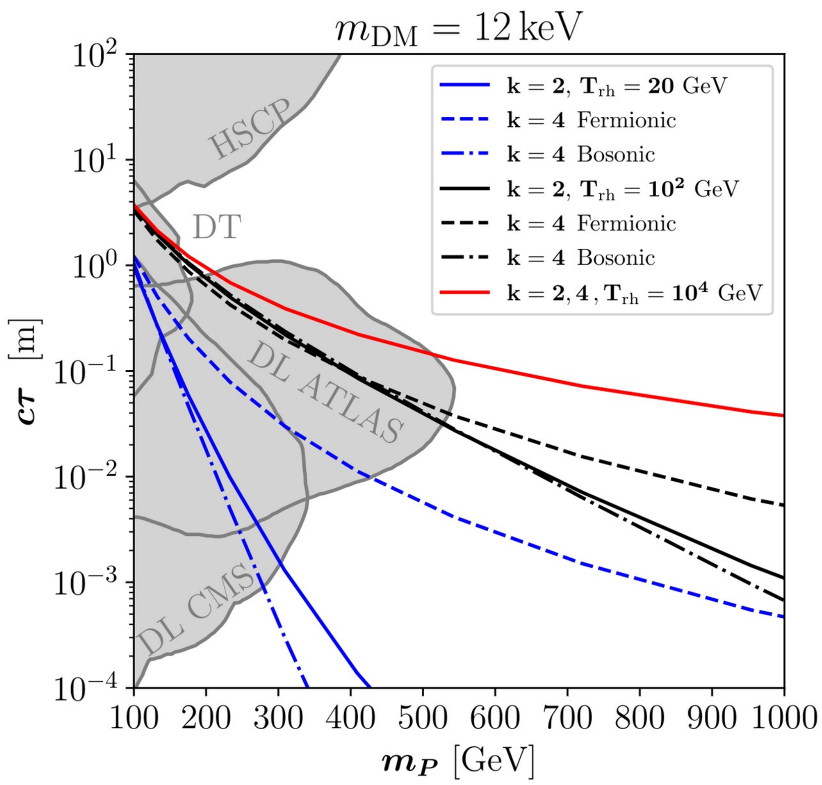
Leptophilic scalar singlet DM model

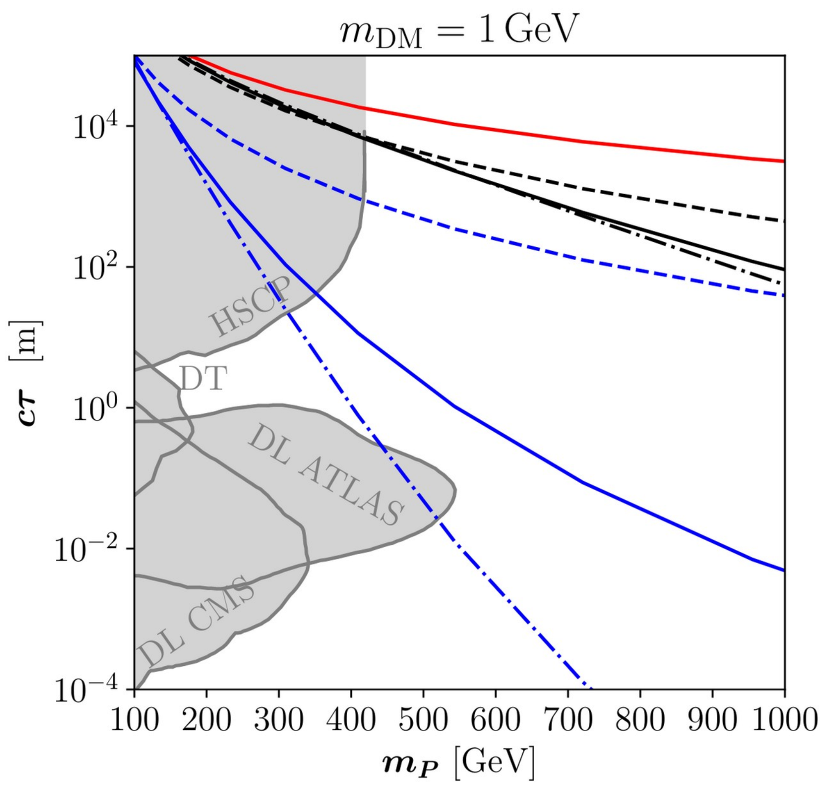




Constraints from LLP searches at the LHC

Muonphilic Majorana DM model

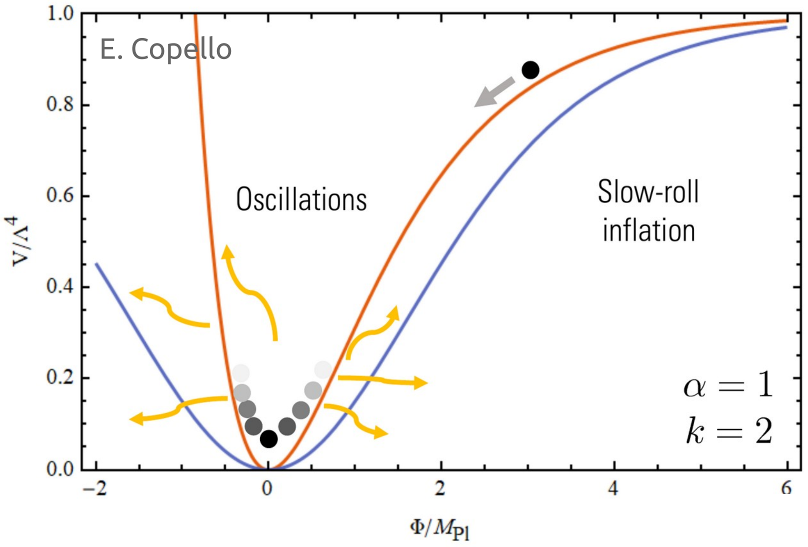




Constraints from Inflation.

Linking to inflationary models

$$V(\Phi) = \lambda \frac{|\Phi|^k}{M^{k-4}}$$



Reheating potential can be obtained (Φ<M_{Pl}), e.g. from

E-model:

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

$$V(\Phi) \simeq \Lambda^4 \left(\frac{2}{3\alpha}\right)^n \left(\frac{\Phi}{M_{\rm Pl}}\right)^{2n} \equiv \frac{\lambda}{M_{\rm Pl}^{k-4}}\Phi^k$$

T-model:

$$V(\Phi) = \Lambda^4 \left[\tanh\left(\frac{\Phi}{\sqrt{6\alpha}M_{\rm Pl}}\right)\right]^{2n}$$

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

$$k = 2n$$

$$\lambda = \left(\frac{\Lambda}{M_{\rm Pl}}\right)^4 \left(\frac{1}{6\alpha}\right)^n$$

Linking to inflationary models

End of inflation if slow roll conditions are fulfilled:

$$\epsilon_V \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 < 1 \qquad \eta_V \equiv M_{\rm Pl}^2\left(\frac{V''}{V}\right) < 1$$

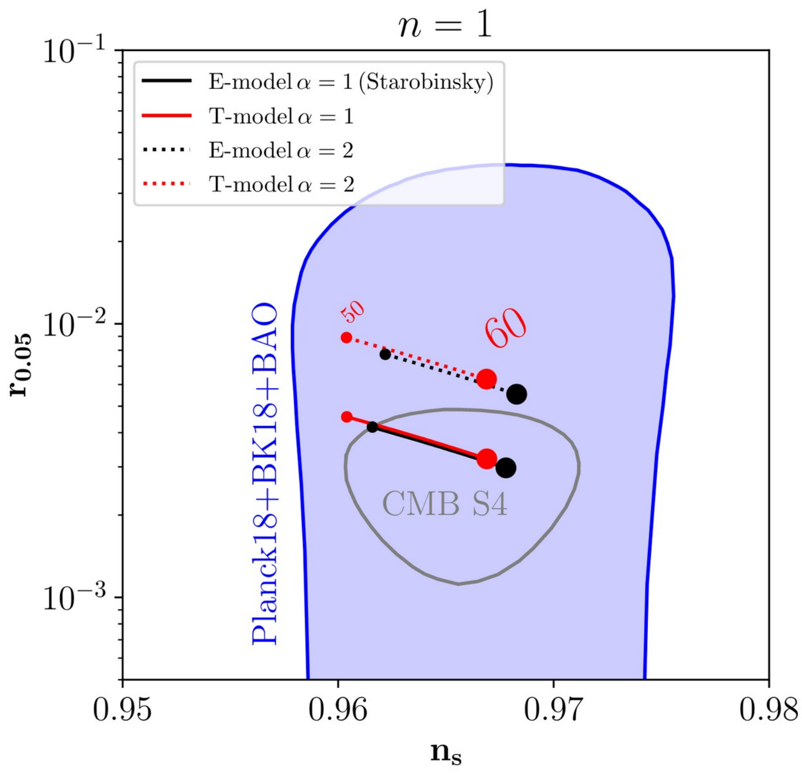
Experimental constraints can be evaluated by

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

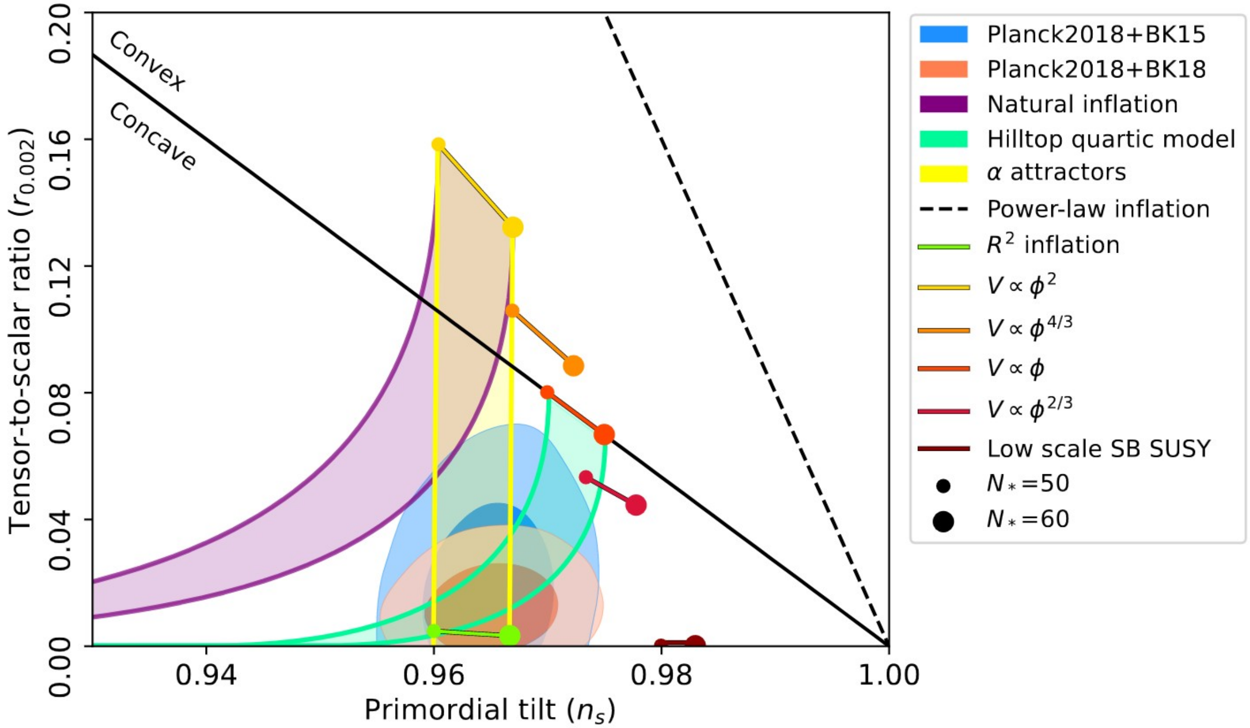
$$A_{s,\star} = \frac{V}{24\pi^2 \epsilon_V M_{\rm Pl}^4}$$

and compared with

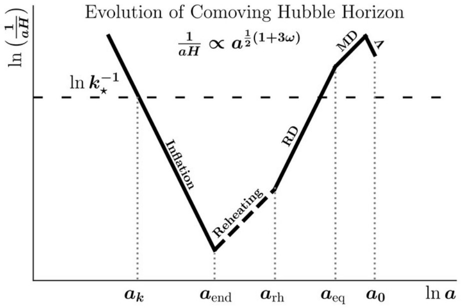
$$A_{s,\star} = (2.1 \pm 0.1) \times 10^{-9} \qquad n_s = 0.9659 \pm 0.0040 \qquad r_{0.05} < 0.035, \qquad 95\%\ \text{C.L.}$$



Experimental status: PLANCK+BICEP/Keck Array



Reheating temperature from inflation



From slow roll conditions, field value at the end of inflation can be evaluated

$$\rho_{\Phi,\rm end} = \frac{3}{2} V(\Phi_{\rm end})$$

Derive expression for T_{rh} by relating different epochs and cross-link to observables

$$\frac{k_\star}{a_0 H_0} = \frac{a_\star}{a_{\rm end}} \frac{a_{\rm end}}{a_{\rm rh}} \frac{a_{\rm rh}}{a_{\rm eq}} \frac{a_{\rm eq}}{a_0} \frac{H_\star}{H_0}$$

$$k_\star = a_\star H_\star$$

$$N_\star \equiv \frac{a_\star}{a_{\rm end}} = \int_{\Phi_{\rm end}}^{\Phi_\star} \frac{1}{\sqrt{2\epsilon_V}} \frac{d\phi}{M_{\rm Pl}}$$

$$N_{\rm rh} \equiv \ln\left(\frac{a_{\rm rh}}{a_{\rm end}}\right) = \frac{1}{3(1+w_{\rm rh})} \ln\left(\frac{\rho_{\rm end}}{\rho_{\rm rh}}\right)$$

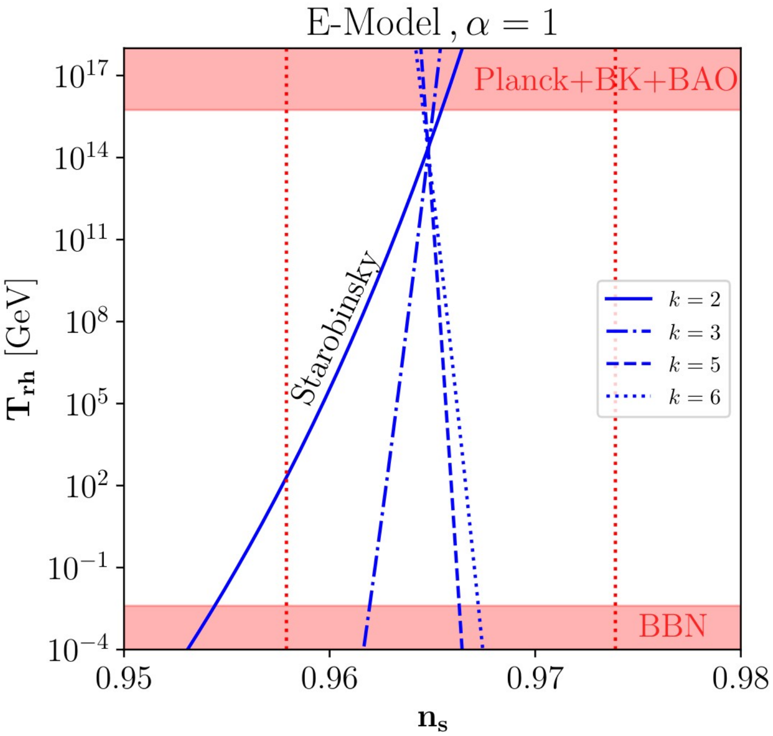
$$H_\star = \pi M_P \sqrt{\frac{r A_{s,\star}}{2}}$$

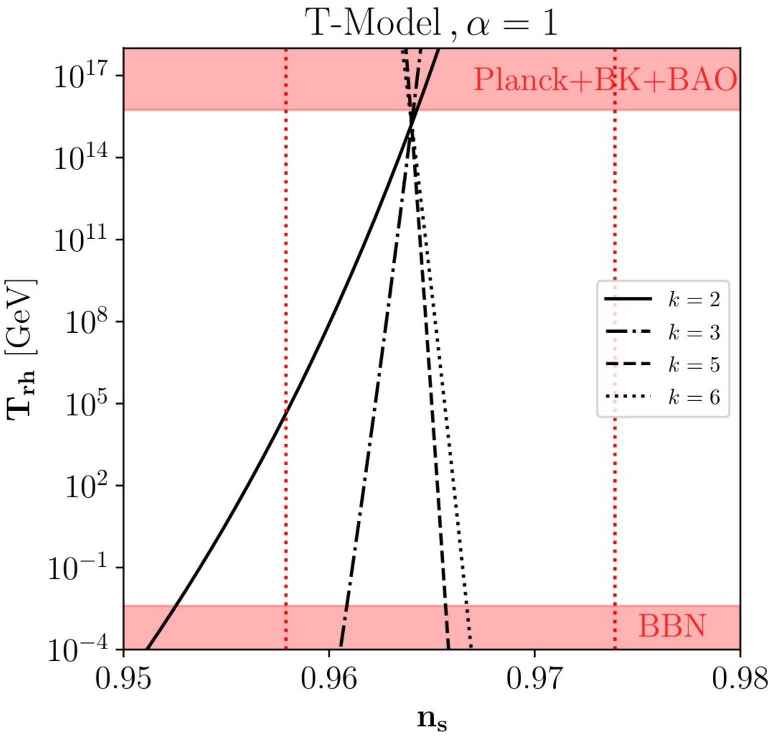
$$N_{\rm rh} = \frac{4}{3(1+w_{\rm rh})}\left[\frac{1}{4}\ln\left(\frac{45}{\pi^2 g_{*,\rm rh}}\right) + \ln\left(\frac{V_{\rm end}^{1/4}}{H_\star}\right) \frac{1}{3}\ln\left(\frac{11\, g_{*s,\rm rh}}{43}\right) + \ln\frac{k_\star}{a_0 T_0} + N_\star + N_{\rm rh}\right]$$

For ω_{rh}=1/3, k=4, not defined.

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

Constraints on reheating temperature from inflation

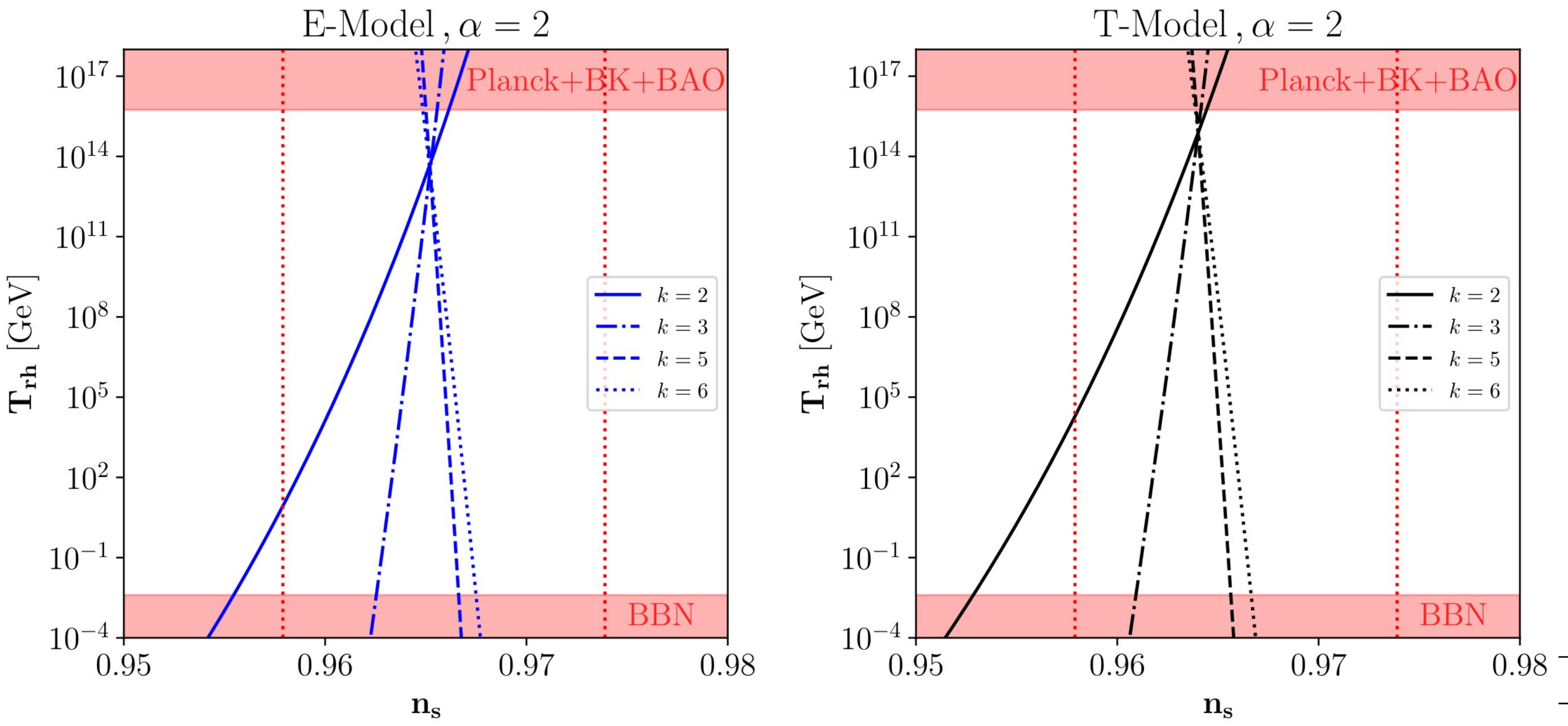




Type	α	$T_{\rm rh}$ [GeV]
E-model	1	$1.8 \cdot 10^2$
E-model	2	7.8
T-model	1	$4.0 \cdot 10^4$
T-model	2	$1.8 \cdot 10^4$

→ **spectral index sets lower limit on T_{rh}**

Constraints on reheating temperature from inflation



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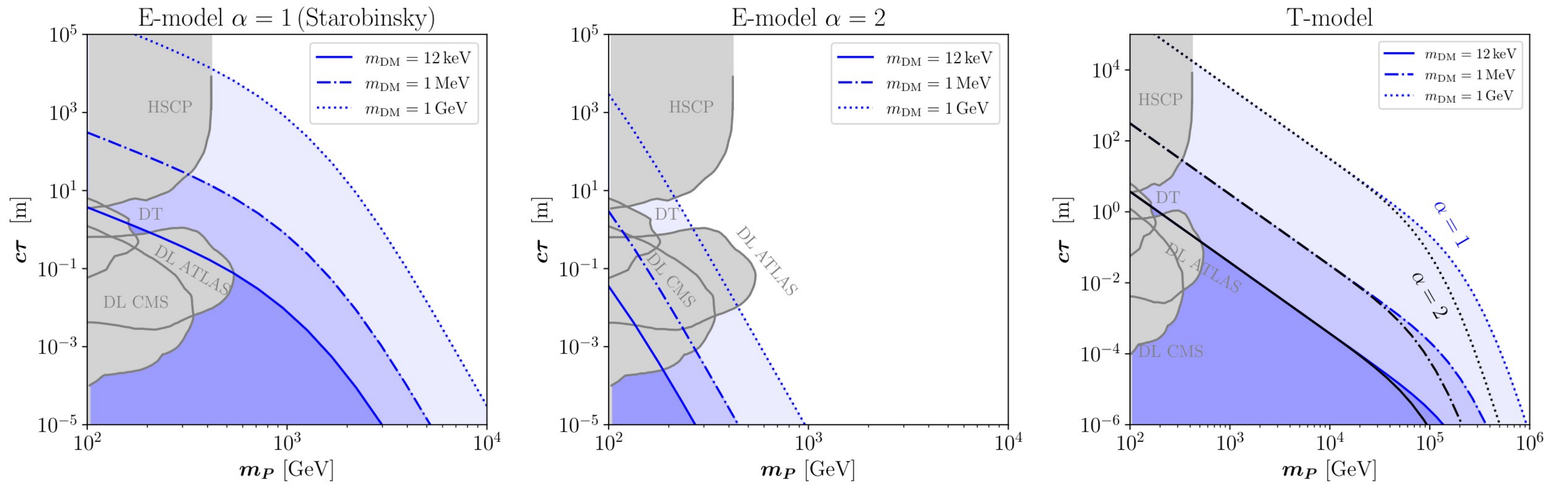
Combining results.

Combining results

Muonphilic Majorana DM model



→ **bound on spectral index**
→ **lower bound on T_{rh}**
→ **lower bound on cτ**

$$\Omega_{\rm DM} h^2 \sim m_{\rm DM}\,(c\tau)^{-1}$$

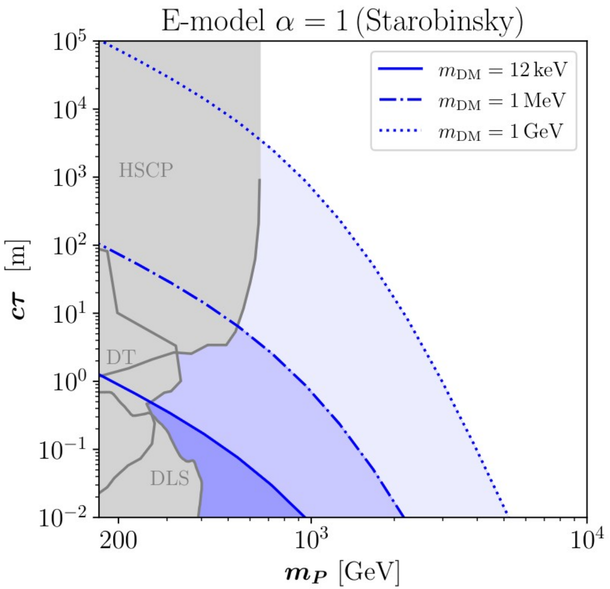
→ **higher m_{DM}**
→ **more stringent constraints**

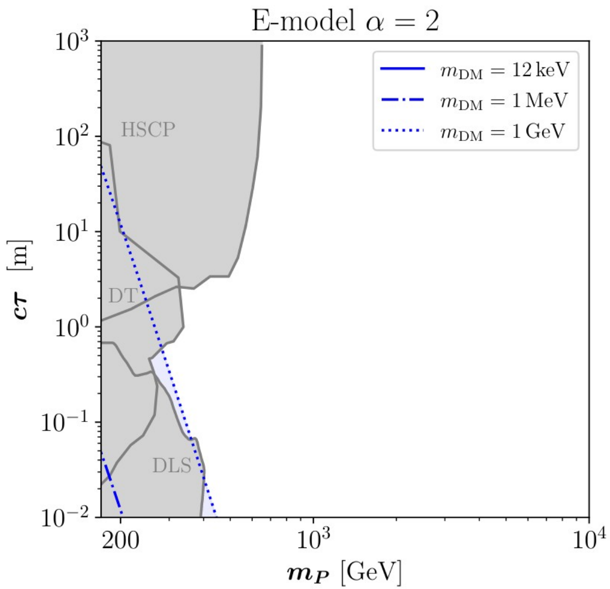
$T_{\rm rh} \gg m_P$ $\quad c\tau \sim m_P^{-2}$

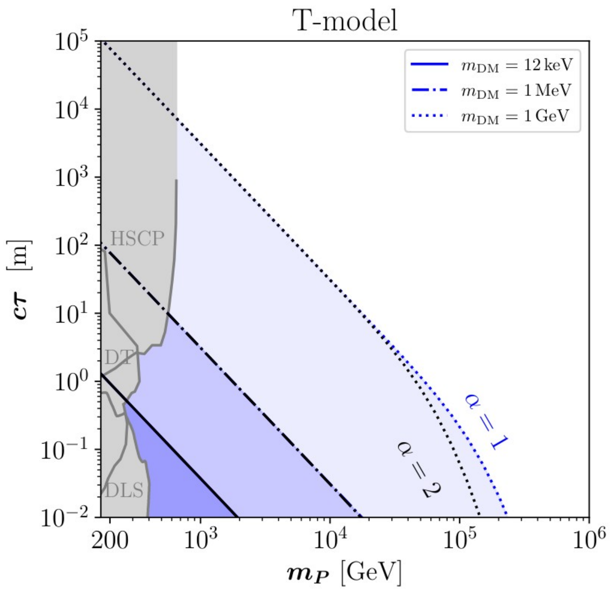
$T_{\rm rh} \ll m_P$ $\quad c\tau \sim m_P^{-9}$

Combining results

Leptophilic scalar singlet DM model







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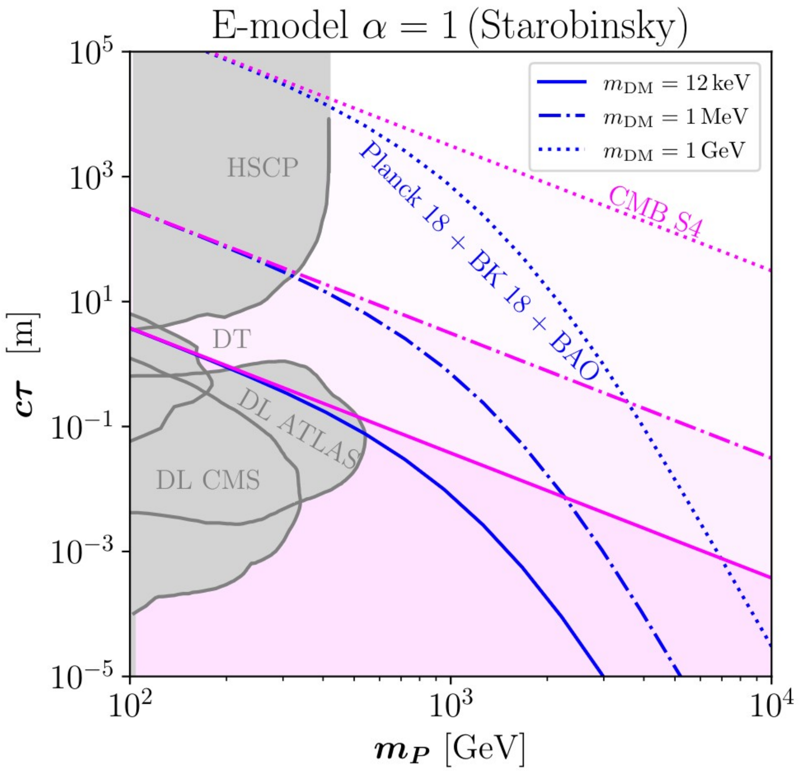
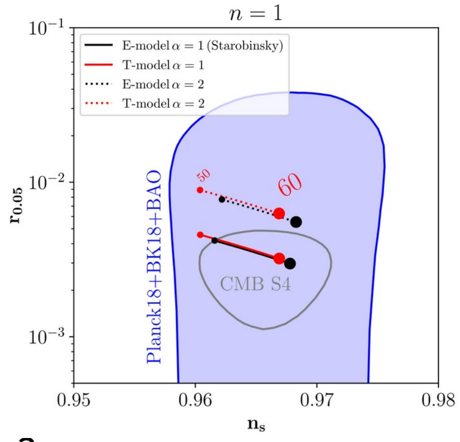
Future prospects.

Future prospects: CMB-S4





- CMB-S4 has potential to rule out α=2
- E- and T-model for α=1 give similar results
- Kink due to change in scaling moves to larger m_P
- Constraints from inflation reach high m_P

For m_P > T_{rh}

→ lower reheating temperatures imply smaller decay lengths

→ minimal decay length from Lyman-α moved to smaller values

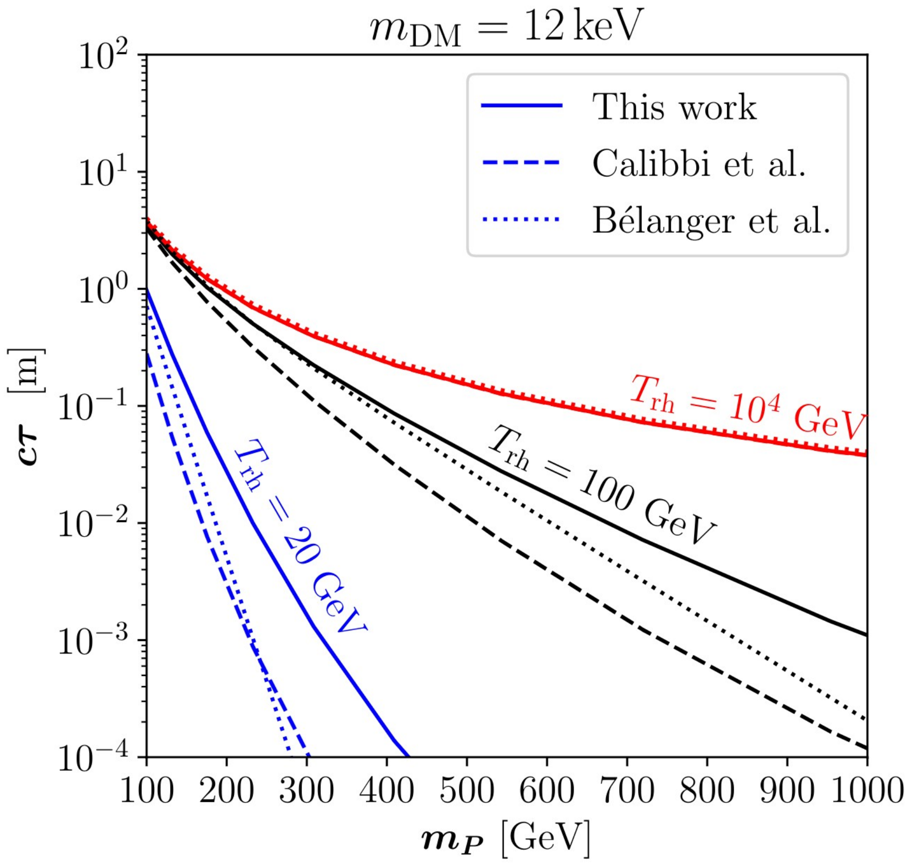
Conclusions

- Freeze-in during reheating leads to smaller parent particle decay lengths required for not overproducing DM
- Constraints from inflation in particular relevant for large parent particle masses
- reheating potential, nature of inflaton-matter coupling, as well as magnitude of reheating temperature can have significant impact on FIMP DM production and interpretation of collider limits
- Long-lived DM parent particle can shed light on reheating dynamics
- Too small T_{rh} could rule out many popular high-scale baryogenesis/leptogenesis models

→ Complementary insights from early Universe and laboratory experiments!

Thank you for your attention!

Comparison


$m_{\rm DM} = 12\,\rm keV$
This work
Calibbi et al.
Bélanger et al.
$T_{\rm rh} = 10^4$ GeV
$T_{\rm rh} = 100$ GeV
$T_{\rm rh} = 20$ GeV
$c\tau$ [m]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
100 200 300 400 500 600 700 800 900 1000
m_P [GeV]