Probing low-reheating scenarios with minimal freeze-in DM *(at the volcano Cumbal)*

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Based on 241X.XXXXX, in collaboration with: N. Bernal & C.S. Fong

Outline

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2. Setups:
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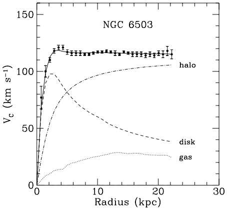
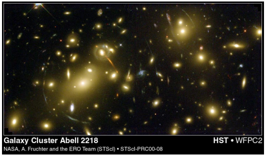
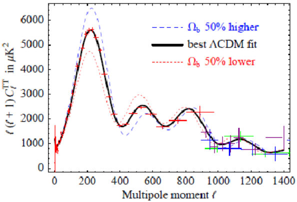
3. Minimal freeze-in during reheating:
   - ☞ Radiation domination
   - ☞ Kination domination
4. Conclusions

Evidence for dark matter is abundant and compelling







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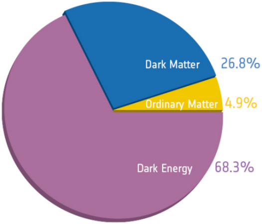
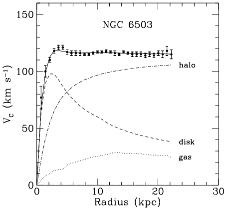
- Cluster and supernova data
- Bullet cluster
- Weak lensing
- CMB anisotropies
- Big bang nucleosynthesis

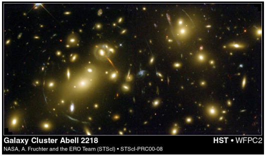


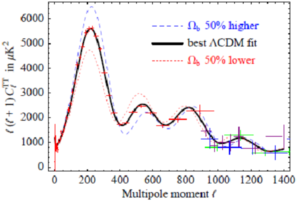
DM: massive, neutral, stable.

Despite of this evidence the nature of DM is still unknown.

Evidence for dark matter is abundant and compelling







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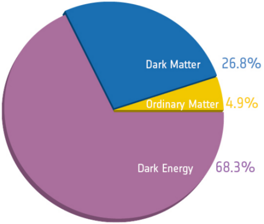

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WIMP mechanism

Weekly Interacting Massive Particles $\chi + \chi \Longleftrightarrow \mathrm{SM} + \mathrm{SM}$

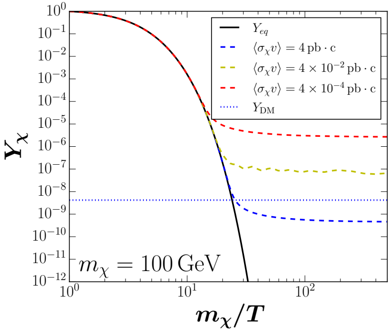
- ✔ Reach thermal equilibrium
- ✔ At $T \gg m_\chi$, same rates for production and annihilation of DM.
- ✔ $\Omega_\chi h^2 \sim \frac{3\times10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma_\chi v\rangle}$.
- ✔ For $\Omega_\chi h^2 \sim 0.1 \Rightarrow$ $\langle\sigma_\chi v\rangle \approx 3\times10^{-26}\mathrm{cm}^3/\mathrm{s} = 1\mathrm{pb}\cdot\mathrm{c}$.

The WIMP miracle

$$\sigma_\chi \sim \frac{g^2}{m_\chi^2} = 1\mathrm{pb},$$
$$m_\chi \sim \alpha_{\mathrm{an}}(T_{\mathrm{eq}}M_{\mathrm{P}})^{1/2} \sim 100\ \mathrm{GeV},$$
$$g_\chi \sim g_{weak} \sim 0.1.$$

- ✔ Self-interactions are too small to have relevant impacts on structure formation.

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_\chi v\rangle\left[n_\chi^2 - n_{\mathrm{SM,eq}}^2\right].$$



➢ The chemical frezee-out has also played a role in the abundance of light elements as well as the CMB radiation, both in stark agreement with current observations.

Challenges on the WIMP paradigm

It is not free of challenges, both at th. and exp. levels

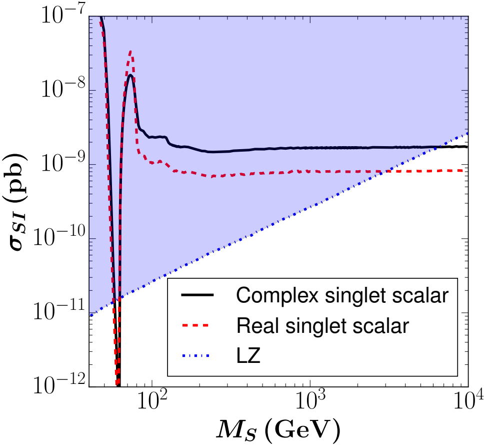
⋆ May need some degree of fine tuning.
⋆ The null results have lead to more and more constraints.

✘ Direct searches have already excluded simplified WIMP models where the SM gauge portal is the unique channel.

✘ DD substantially constrains the DM mass region to lie around the Higgs resonance or above the TeV scale.

$$\mathcal{V} \supset \frac{1}{2} M_S S^2 + \frac{1}{2}\lambda_{Sh} S^2 H^\dagger H.$$

$$\text{LZ} \Rightarrow \quad M_S \gtrsim 3\,(6)\ \text{TeV}, \quad \lambda_{Sh} \gtrsim 0.4\,(3).$$



Freeze-in mechanism (Hall+ 2011)

☞ FIMPs: χ never reache thermal equilibrium with SM.

✔ Ω_χ is set by:

$$\mathrm{SM} + \mathrm{SM} \to \chi,$$

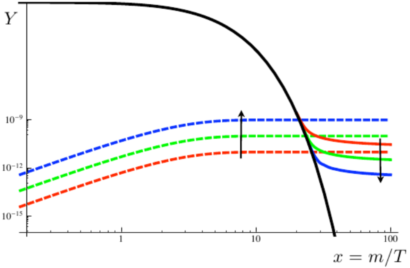
$$\mathrm{SM} + \mathrm{SM} \to \chi + \chi.$$

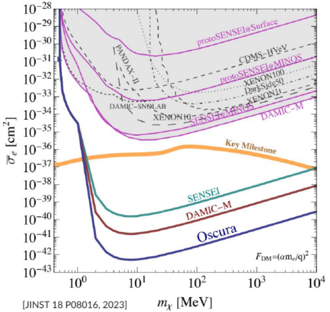
✔ m_χ ranges over several orders of magnitude.

✘ Testing the through direct detection or collider experiments might be highly challenging.

☞ BUT recent developments have shown this to be increasingly feasible.

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_\chi v\rangle_{2\to2}\left[\cancel{n_\chi^2} - n_{\chi,\mathrm{eq}}^2\right].$$





[JINST 18 P08016, 2023]

Minimal freeze-in model (Hall+ 2011, Chu/Hambye 2011)

① A $U(1)'$ gauge extension with very light gauge boson $\hat{X}_\mu$.

② A Dirac fermion χ with a $U(1)'$ charge e' and no SM charges; the SM does not transform under $U(1)'$.

③ The hidden and visible sectors are connected through the kinetic mixing term with the SM hypercharge gauge boson $\hat{A}_\mu$.

$$\mathcal{L}_D = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{1}{2}m_{\gamma'}^2\hat{X}_\mu\hat{X}^\mu + \frac{\epsilon_Y}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - e'\hat{X}_\mu\bar{\chi}\gamma^\mu\chi\,.$$

After the EWSB, the mass basis becomes (with $\epsilon \equiv \epsilon_Y \cos\theta_W$)

$$\hat{A}_\mu = A_\mu + \epsilon A'_\mu\,,\;\; \hat{X}_\mu = A'_\mu - \epsilon\,\tan\theta_W\,Z_\mu\,,\;\; \hat{Z}_\mu = Z_\mu\,,$$

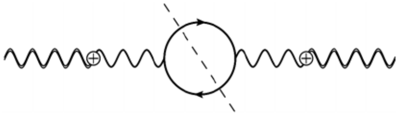
which in turn leads to

$$\mathcal{L}_D \supset \frac{1}{2}m_{\gamma'}^2 A'_\mu A'^\mu - \epsilon\, e\, A'_\mu J^\mu_{\rm EM} - e'\left(A'_\mu - \epsilon\tan\theta_W\,Z_\mu\right)\bar{\chi}\gamma^\mu\chi\,.$$

with canonical kinetic terms for both SM and dark photons.

In-medium (plasma) effects

☞ SM photons gain a thermal mass $m_\gamma \sim e\,T$.



☞ Dark photons gain a thermal mass $m'_\gamma \sim \sqrt{\epsilon}\, m_\gamma$.

$$\mathcal{L}_D^{\rm IM} \supset \frac{1}{2}\, m_{\gamma'}^2\, \tilde{A}'_\mu\, \tilde{A}'^\mu + \frac{1}{2}\, m_\gamma^2\, \tilde{A}_\mu\, \tilde{A}^\mu + e \left(\tilde{A}_\mu + \frac{\epsilon\, m_{\gamma'}^2}{m_{\gamma'}^2 - m_\gamma^2}\, \tilde{A}'_\mu \right) J^\mu_{\rm EM}$$

$$+\, e' \left(\tilde{A}'_\mu - \frac{\epsilon\, m_\gamma^2}{m_{\gamma'}^2 - m_\gamma^2}\, \tilde{A}_\mu - \epsilon\, \tan\theta_W\, Z_\mu \right) \overline{\chi}\, \gamma^\mu\, \chi\,.$$

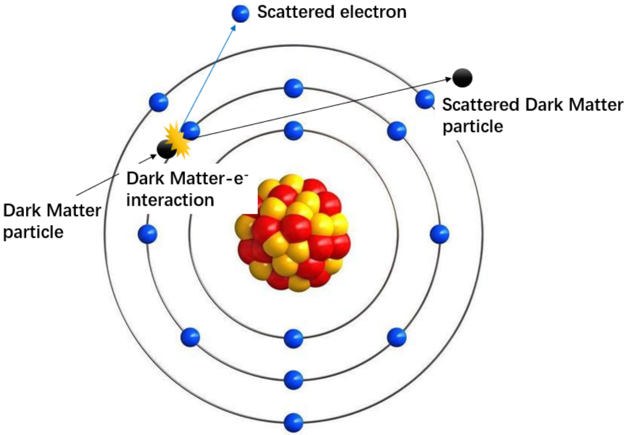
☞ For $m_{\gamma'} \lesssim 10^{-21}$ MeV and $m_\gamma \sim 0.1\,T$, $m_\gamma \gg m_{\gamma'}$ in the early universe or in stellar environments, resulting in a suppressed coupling of $J^\mu_{\rm EM}$ to the DP by $\epsilon\,(m_{\gamma'}/m_\gamma)^2$.

☞ the DP production in the early universe is negligible and the stellar constraints are also correspondingly relaxed.

Probing the minimal freeze-in model

For the case of scattering with electrons:

$$\bar{\sigma}_e = \frac{16\pi\, \mu_{\chi e}^2\, \alpha^2\, \kappa^2}{(\alpha\, m_e)^4}\,, \quad \kappa \equiv \frac{e'\epsilon}{e}.$$



Dark matter abundance via freeze-in

A $\chi, \bar{\chi}$ relic population is generated through:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \langle \sigma_\chi v \rangle_{\bar{f}f \to \chi\chi} n_{f,\text{eq}}^2 + \langle \Gamma_{Z \to \chi\chi} \rangle \, n_{Z,\text{eq}} + \langle \Gamma_{\gamma * \to \chi\chi} \rangle \, n_{\gamma *,\text{eq}}.$$

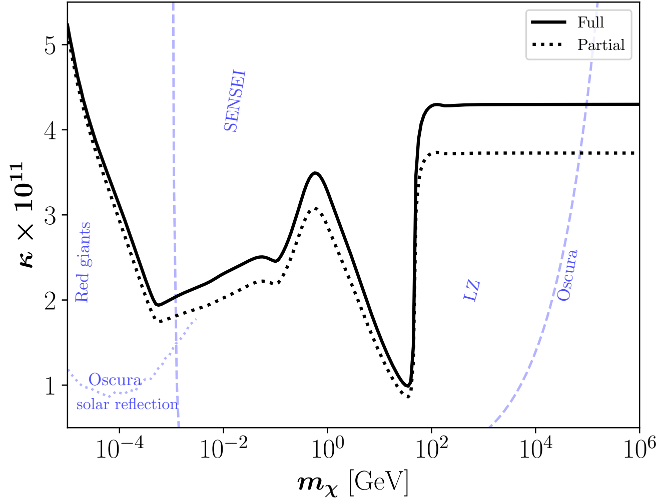
① SM fermion annihilations and Z-boson decays for $m_\chi \gtrsim m_e$.

② Plasmon decays are the unique source of DM for $m_\chi < m_e$.

Since $m_{\gamma'} < 10^{-21}$ GeV,

the freeze-in production is identical to the massless dark photon scenario and hence $m_{\gamma'}$ will not play a role in our analysis; the phenomenological relevant parameters are therefore m_χ and κ.

Dark matter abundance via freeze-in



Quantum statistical corrections amount to $\sim 10\%$ effects for $m_\chi \gtrsim 1$ MeV, while for $m_\chi \lesssim 1$ MeV when plasmon decays dominate, the effects decrease to around 2% for $m_\chi \sim 10^{-2}$ MeV.

Reheating

It is generally assumed that the reheating period is preceded by a cosmic inflationary epoch in which the inflaton ϕ slowly rolls along a plateau on its way to the minimum of the scalar potential.

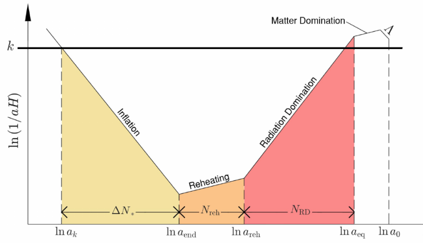
- The cosmic reheating period (coherent oscillations around the minimum) can be approximated by different inflaton potentials $V(\phi)$.

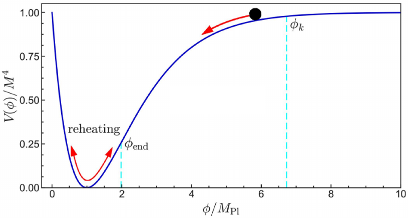
- Monomial potentials ϕ^n for the inflaton during reheating.

- Such potentials can naturally arise from, for example, the α-attractor T-model

$$V(\phi) = \lambda M_P^4 \left[\tanh\left(\frac{\phi}{\sqrt{6\,\alpha}\,M_P}\right)\right]^n$$

$$\simeq \lambda M_P^4 \times \begin{cases} 1, & \phi \gg M_P, \\ \left(\frac{\phi}{\sqrt{6\,\alpha}\,M_P}\right)^n, & \phi \ll M_P\,. \end{cases}$$





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Reheating dynamics: evolution of ρ_ϕ

Post-inflationary oscillations of the inflaton ϕ at the bottom of $V(\phi)$,

$$V(\phi) = \lambda \, \frac{\phi^n}{\Lambda^{n-4}} \,.$$

Since $\rho_\phi \equiv \frac{1}{2}\,\dot{\phi}^2 + V(\phi)$ and $p_\phi \equiv \frac{1}{2}\,\dot{\phi}^2 - V(\phi)$,

$$w \equiv p_\phi/\rho_\phi = (n-2)/(n+2).$$

EoM for the oscillating inflaton field

$$\ddot{\phi} + (3\,H + \Gamma_\phi)\,\dot{\phi} + V'(\phi) = 0 \Rightarrow \frac{d\rho_\phi}{dt} + \frac{6\,n}{2+n}\,H\,\rho_\phi = -\frac{2\,n}{2+n}\,\Gamma_\phi\,\rho_\phi \,.$$

During reheating $a_I \ll a \ll a_{\rm rh}$

$$\rho_\phi(a) \simeq \rho_\phi(a_{\rm rh}) \left(\frac{a_{\rm rh}}{a}\right)^{\frac{6\,n}{2+n}} = \rho_\phi(a_{\rm rh}) \left(\frac{a_{\rm rh}}{a}\right)^{3(1+\omega)} \,.$$

$$H(a) \simeq H(a_{\rm rh}) \times \begin{cases} \left(\frac{a_{\rm rh}}{a}\right)^{\frac{3}{2}(1+\omega)} & \text{for } a \leq a_{\rm rh}\,, \\ \left(\frac{a_{\rm rh}}{a}\right)^{2} & \text{for } a_{\rm rh} \leq a\,. \end{cases}$$

At the end of the reheating, the energy densities of the inflaton and radiation are equal, $\rho_R(a_{\rm rh}) = \rho_\phi(a_{\rm rh}) = 3\,M_P^2\,H(a_{\rm rh})^2$.

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Reheating dynamics: evolution of ρ_R

The evolution of ρ_R is governed by the Boltzmann equation

$$\frac{d\rho_R}{dt} + 4\,H\,\rho_R = +\frac{2\,n}{2+n}\,\Gamma_\phi\,\rho_\phi\,.$$

$\Rightarrow$ During reheating ρ_ϕ is transferred to the $\rho_R \sim T^4$.

During cosmic reheating, the behavior of the background is uncertain.

$$T(a) = T_{\rm rh} \times \begin{cases} \left(\dfrac{a_{\rm rh}}{a}\right)^{\alpha} & \text{for } a_I \le a \le a_{\rm rh}\,, \\ \left(\dfrac{g_{\star s}(T_{\rm rh})}{g_{\star s}(T)}\right)^{\frac{1}{3}} \dfrac{a_{\rm rh}}{a} & \text{for } a_{\rm rh} \le a\,, \end{cases}$$

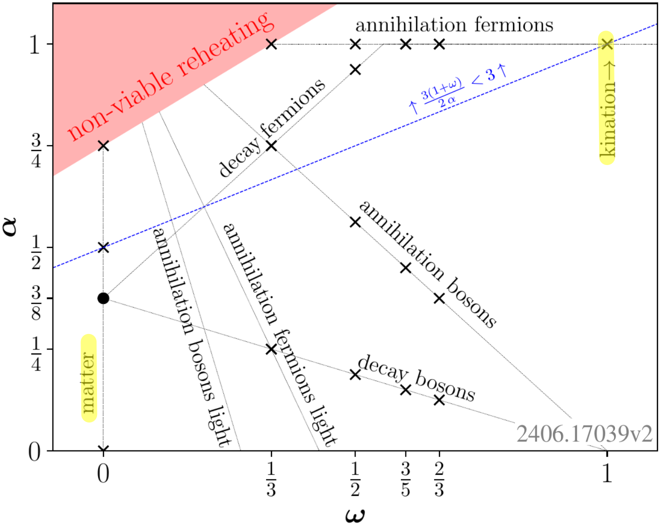
☞ $T_{\rm rh}$ denotes the SM temperature $a = a_{\rm rh}$ (reheating temperature).

☞ For $T < T_{\rm rh}$ the Universe begins to be dominated by SM radiation. It must satisfy $T_{\rm rh} > T_{\rm BBN} \simeq 4$ MeV.

☞ For $\alpha > 0$, at the beginning of reheating, the thermal plasma reaches a temperature $T_{\rm max} \equiv T(a_I) > T_{\rm rh}$.

☞ After reheating (when $a > a_{\rm rh}$), $T(a) \propto 1/a$ as expected in an era where the SM entropy is conserved.

Reheating scenarios



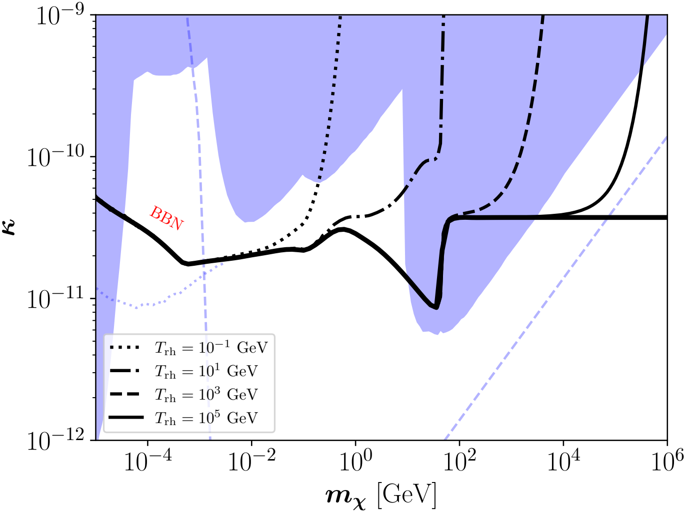
☞ ($\omega = 0, \alpha = 3/8$): massive inflaton ($\rho_\phi \sim a^{-3}$) decaying with a constant decay width into SM particles.

☞ $\alpha = 1$ (kination): ρ_ϕ is diluted faster than free radiation ($\omega > 1/3$)

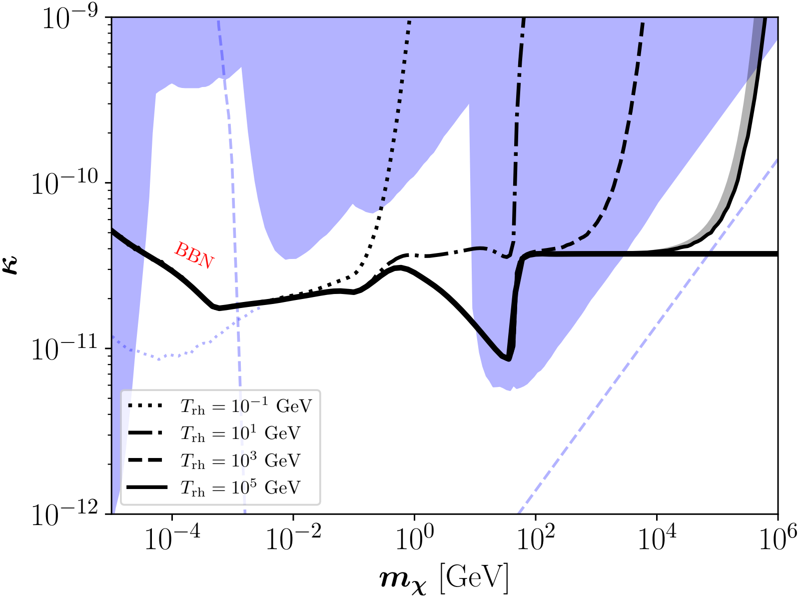
FIMP during instantaneous reheating

Assuming that DM is produced solely through the FIMP mechanism:

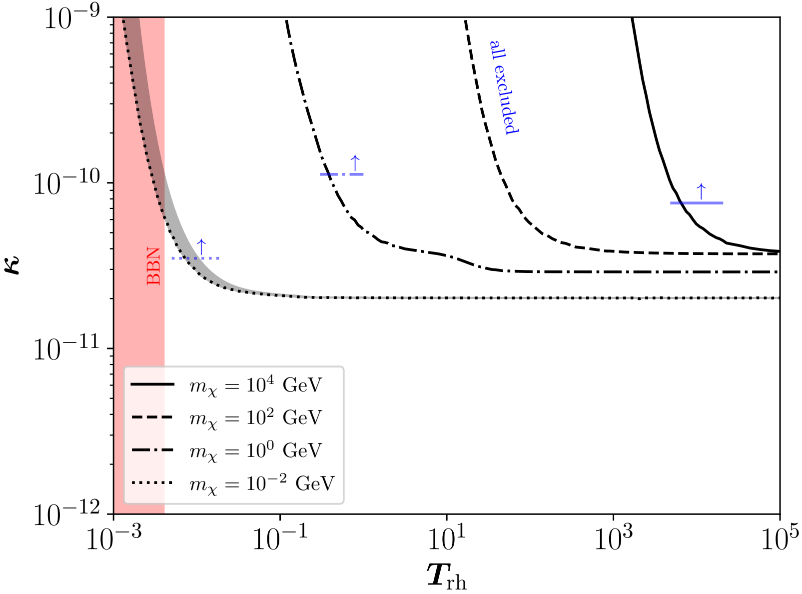
$$\frac{d\left(n\, a^3\right)}{da} = \frac{a^2}{H} \langle \sigma v \rangle\, n_{\rm eq}^2 \,.$$



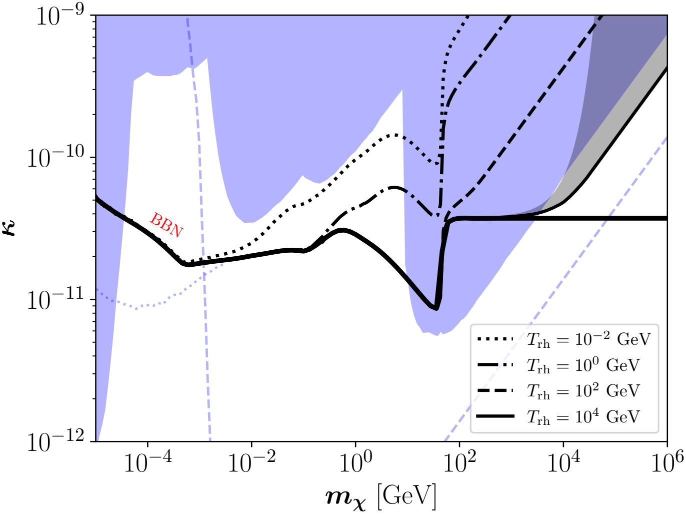
FIMP during non-instantaneous reheating



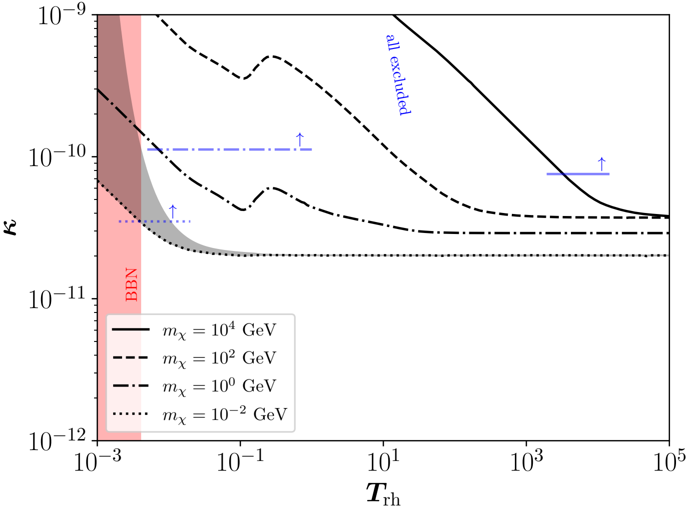
FIMP during non-instantaneous reheating



FIMP during kination



FIMP during kination



Summary

☞ We have explored the impact of a non-instantaneous reheating phase on the parameter space of the minimal freeze-in DM scenario.

☞ We considered cases where the inflaton energy density scales as non-relativistic matter or faster than radiation, as in kination.

☞ Our main finding is that low reheating scenarios with reheating temperatures $T_{\text{rh}} \lesssim 1$ TeV are already strongly constrained by current experiments and could be fully probed up to $T_{\text{rh}} \lesssim 10$ TeV by future and planned experiments.