Neutrino portal to FIMP dark matter with an early matter era

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New Techniques for Dark Matter Discovery
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based on C. Cosme, **M. Dutra**, T. Ma, Y. Wu and L. Yang, 2020 [arXiv:2003.01723]

Carleton UNIVERSITY

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

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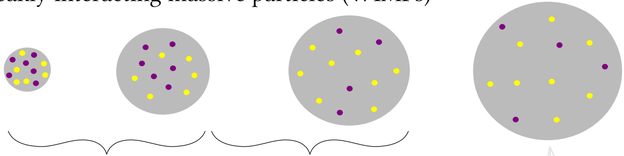
Introduction

The freeze-in production in the early universe

time (t), scale factor (a) → ● visible particles (SM) ● dark matter particles (DM)

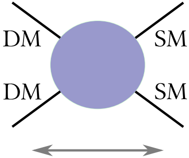
Weakly interacting massive particles (WIMPs):



thermal equilibrium

freeze-out

27% of the cosmic energy today



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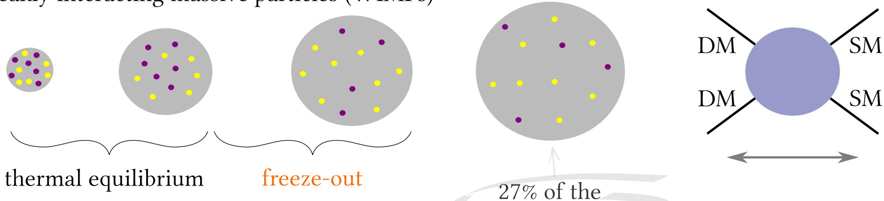
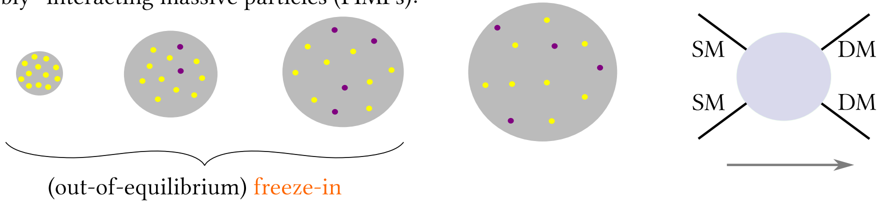


27% of the cosmic energy today

Feebly* interacting massive particles (FIMPs):



* Weaker than "weak"!

Is the freeze-in scenario testable? Well... yes!

Direct detection

US Cosmic Visions 2017
arXiv: 1707.04591

T. Hambye, M.H.G. Tytgat,
J. Vandecasteele, L. Vanderheyden
arXiv: 1807.05022

Indirect detection

V. Brdar, J. Kopp, J. Liu, X. Wang
arXiv: 1710.02146

A. Biswas, S. Ganguly, S. Roy
arXiv: 1907.07973

Self-interaction

N. Bernal, C. Cosme, T. Tenkanen
arXiv: 1803.08064

Accelerators

S. Heeba, F. Kahlhoefer
arXiV: 1908.09834

Colliders

G. Bélanger, N. Desai, A. Goudelis, J. Harz,
A. Lessa, J.M. No, A. Pukhov, S. Sekmen,
D. Sengupta, B. Zaldivar, J. Zurita
arXiv: 1811.05478

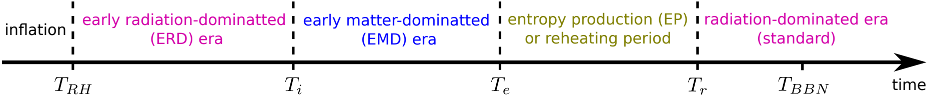
L. Calibbi, L. Lopez-Honorez, S. Lowette, A. Mariotti
arXiv: 1805.04423

R. T. Co, F. D'Eramo, L. J. Hall, D. Pappadopulo
arXiv: 1506.07532

MATHUSLA theory white paper
arXiv: 1806.07396

J. M. No, P. Tunney, B. Zaldivar
arXiv: 1908.11387

Early matter-dominated era (EMDE)



inflation

early radiation-dominatted (ERD) era

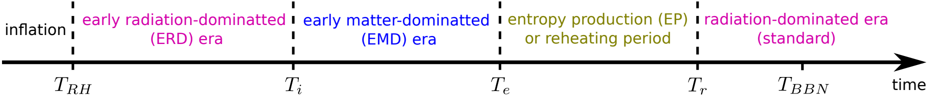
early matter-dominatted (EMD) era

entropy production (EP) or reheating period

radiation-dominated era (standard)

T_{RH} T_i T_e T_r T_{BBN} time

Early matter-dominated era (EMDE)



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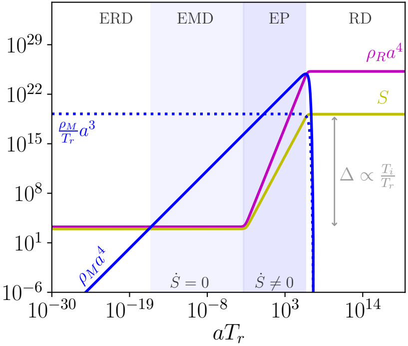
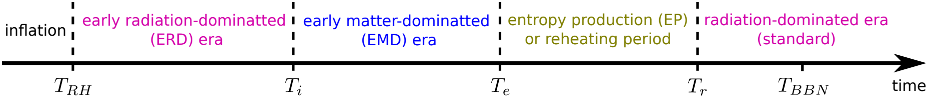


Early matter-dominated era (EMDE)



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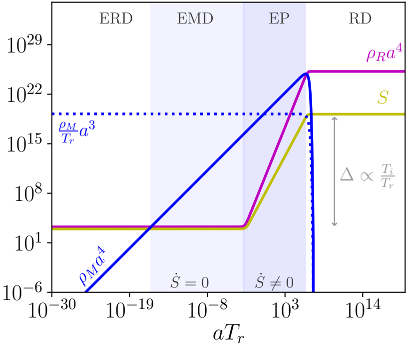

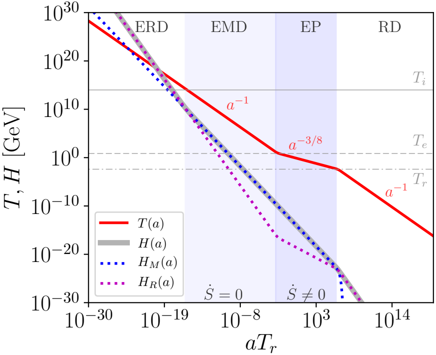

$H_{\text{RD}} \propto T^2$ $\quad H_{\text{EMDE}} \propto T^{3/2}$ $\quad H_{\text{EP}} \propto T^4$ $\quad \Delta \sim \frac{3}{4}\frac{T_i}{T_r} \sim \frac{3}{4}\frac{T_e^5}{T_r^5}$

EMDE & cosmic relics

$$Y_{\mathsf{DM}} \equiv \frac{N_{\mathsf{DM}}}{S} = \frac{n_{\mathsf{DM}}}{s} \Rightarrow Y_{\mathsf{DM}}^{\mathsf{after}} = \frac{N_{\mathsf{DM}}}{S^{\mathsf{after}}} = \frac{N_{\mathsf{DM}}}{S^{\mathsf{before}}} \frac{S^{\mathsf{before}}}{S^{\mathsf{after}}} = \frac{Y_{\mathsf{DM}}^{\mathsf{before}}}{\Delta}$$

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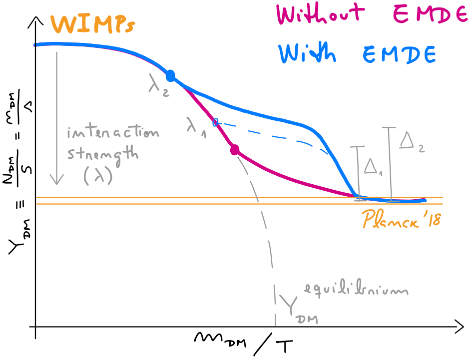

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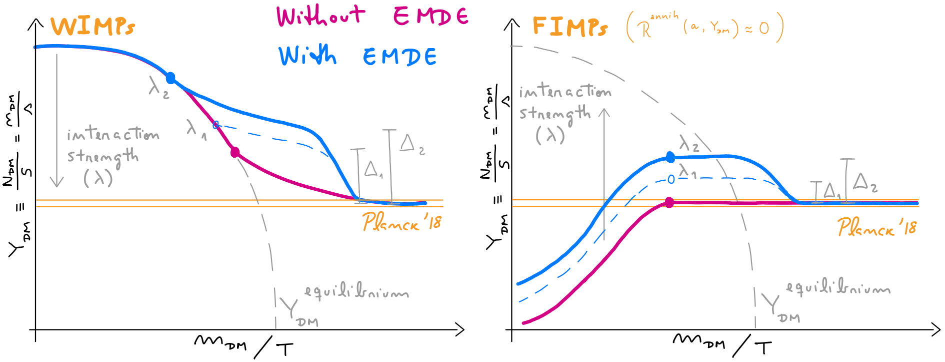


Neutrino portal to FIMPs

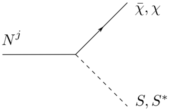
The model

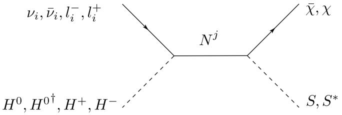
Beyond the standard model sector [arXiv:2003.01723]

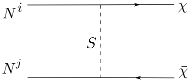
- three heavy neutrinos (N^j) interacting with SM leptons and Higgs and generating neutrino masses via seesaw Type-I
- dark fermion (χ) and dark scalar (S) as FIMP candidates, having Yukawa couplings to the heavy neutrinos

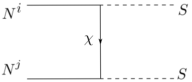
$$\mathcal{L} \supset -\left(\overline{L_L^i} Y_\nu^{ij} \tilde{H} (N_\ell^j)_R + h.c.\right) - \left(\lambda_\chi^i S \overline{\chi} (N_\ell^i)_R + h.c.\right)$$

Processes contributing to the freeze-in production of χ and S:







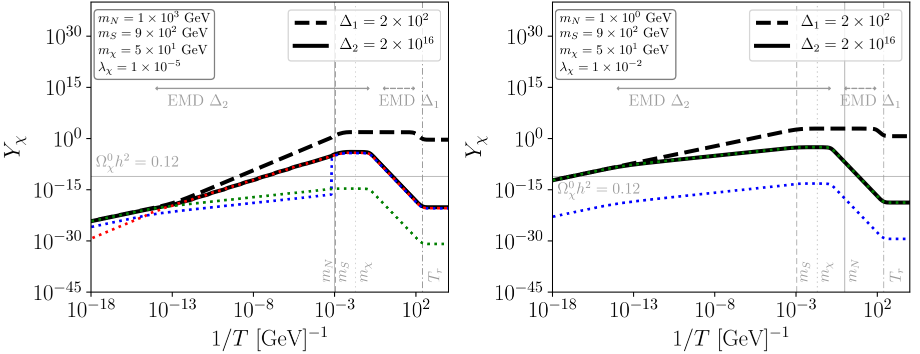


Relic density evolution

– – – EMDE from $T_i = 1\,\mathrm{GeV}$ to $T_e = 12$ MeV, with $T_r = 4\,\mathrm{MeV}$

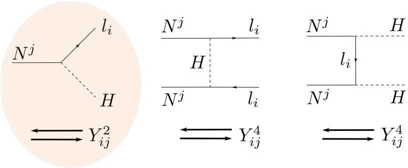
—— EMDE from $T_i = 10^{14}\,\mathrm{GeV}$ to $T_e = 7.6\,\mathrm{GeV}$, with $T_r = 4\,\mathrm{MeV}$

🟥···· decay contribution 🟦···· s-channel contribution 🟩···· t-channel contribution



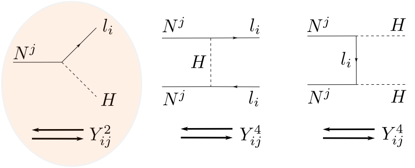
$$\frac{dY_\chi}{da} = \frac{R^{\text{decays}}(a) + R^{\text{s-channels}}(a) + R^{\text{t-channels}}(a)}{a s(a) H(a)} - \frac{Y_\chi}{S}\frac{dS}{da}$$

Thermalization of N



$$\Gamma_{int}(T) > H(T) \Rightarrow n_N \sim n_{\text{thermal bath}}$$

Thermalization of N



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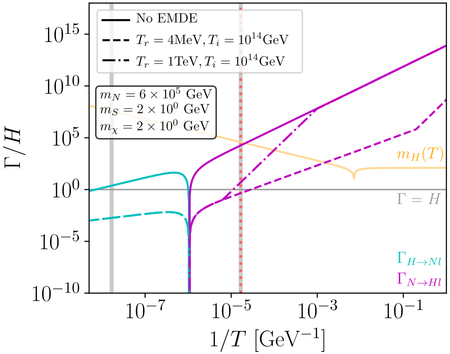

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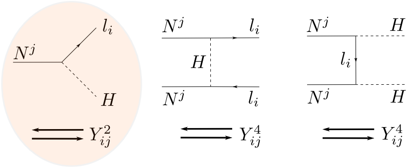

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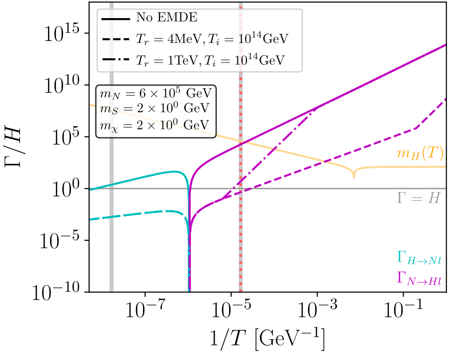
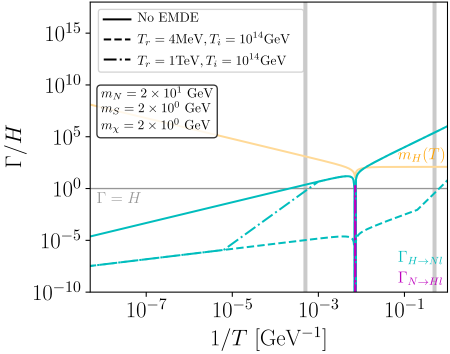
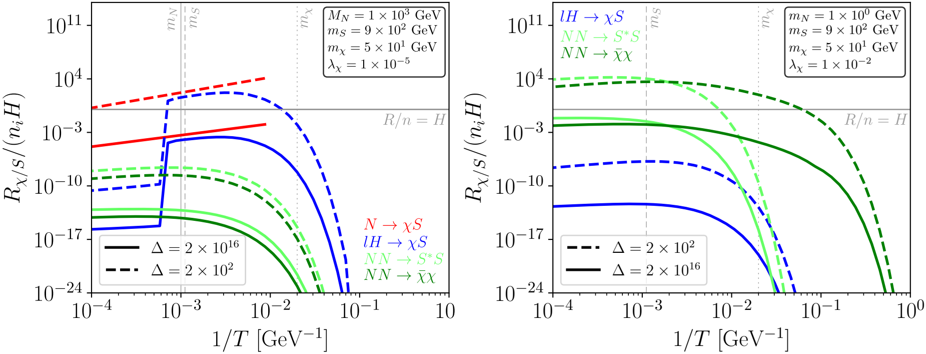




Freeze-in conditions

$$\Gamma_{decays},\, \Gamma_{s-channels},\, \Gamma_{t-channels} < H(T) \Rightarrow n_{\mathsf{DM}} \ll n_{\mathsf{bath}}$$

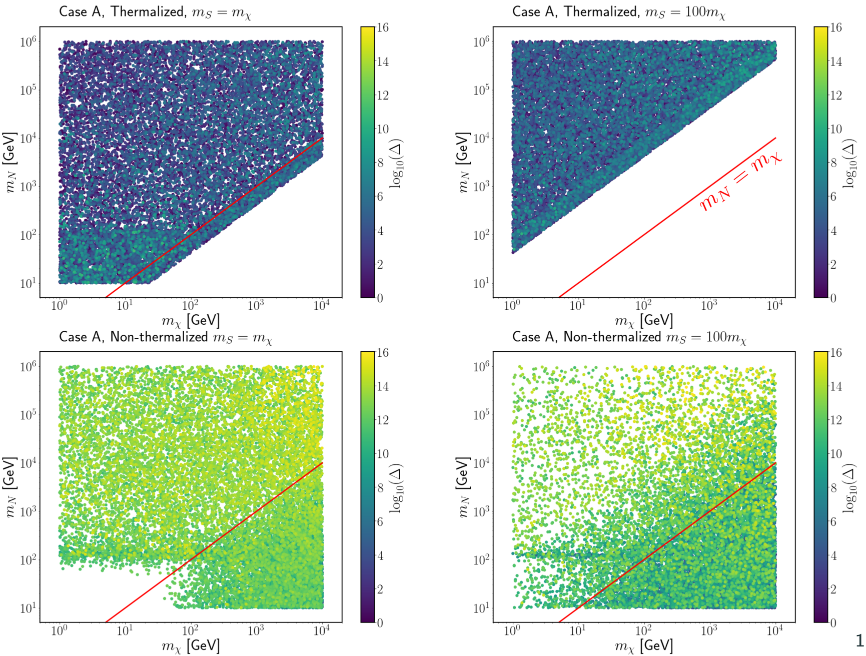


Viable parameter space

Scan of parameter space

Parameters	Case A	Case B
m_χ	$[1$ GeV, 10^4 GeV$]$	$[m_S$, 10^6 GeV$]$
m_S	$[m_\chi$, 10^6 GeV$]$	$[1$ GeV, 10^4 GeV$]$
m_N	$[10$ GeV, 10^6 GeV$]$	
T_i	$[10^2$ GeV, 5×10^{14} GeV$]$	
T_r	$[4$ MeV, $T_i]$	

- Y_{ij} determined from neutrino masses
- λ_χ determined from agreement with DM relic density
- all points in agreement with freeze-in conditions: $\Gamma_{decay}, \Gamma_{s-channels}, \Gamma_{t-channels} < H(T)$
- if N is thermalized before freeze-in: all channels contribute to freeze-in
- if N is not thermalized before freeze-in: only s-channels contribute to freeze-in

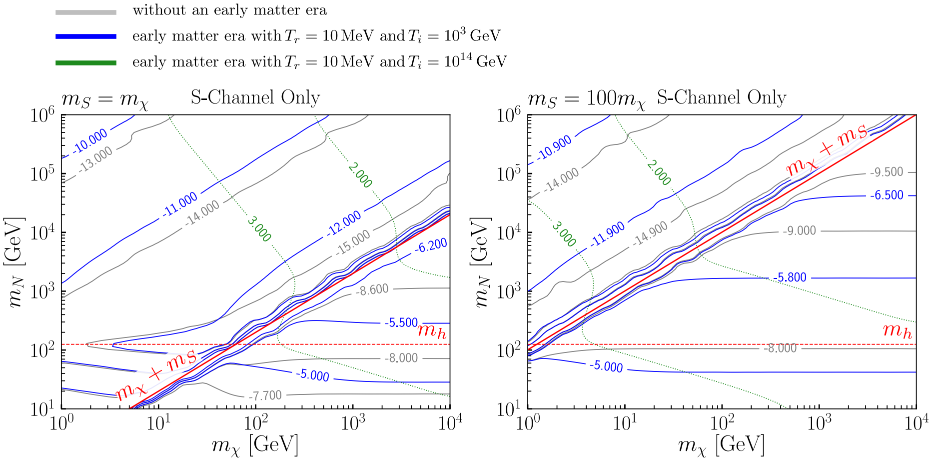


Case A, Thermalized, $m_S = m_\chi$

Case A, Thermalized, $m_S = 100 m_\chi$

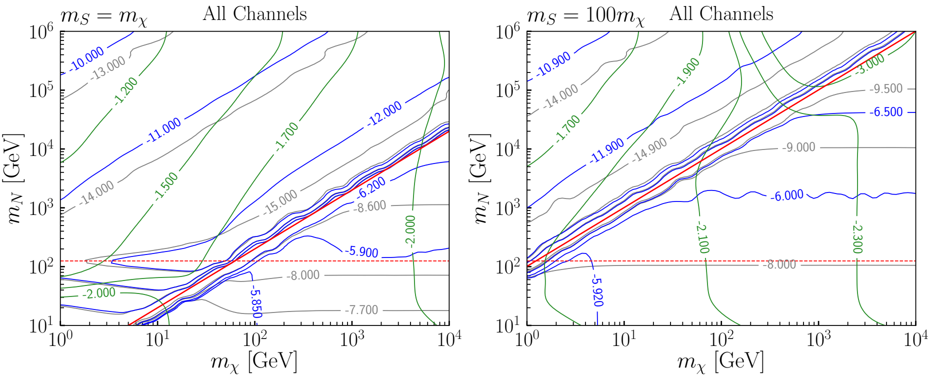
Case A, Non-thermalized $m_S = m_\chi$

Case A, Non-thermalized $m_S = 100 m_\chi$



- smaller λ_χ are needed to compensate the enhanced production of dark matter in the resonant region
- Increasing values of T_i (longer EMDE) brings the need for larger λ_χ to compensate dilution

- without an early matter era
- early matter era with $T_r = 10\,\mathrm{MeV}$ and $T_i = 10^3\,\mathrm{GeV}$
- early matter era with $T_r = 10\,\mathrm{MeV}$ and $T_i = 10^{14}\,\mathrm{GeV}$

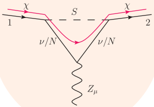


- s-channel dominance: always ($Y_{ij} \gg \lambda_\chi$), in resonant region ($Y_{ij} \gg \lambda_\chi$), never ($\lambda_\chi \gg Y_{ij}$ for large T_i)
- t-channel dominance: never, in non-resonant region ($Y_{ij} \sim \lambda_\chi$), always

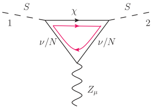
Phenomenology

Direct detection

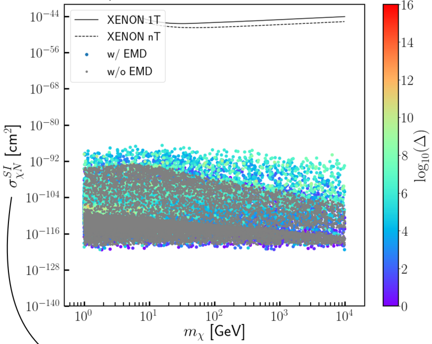
χ as FIMP:



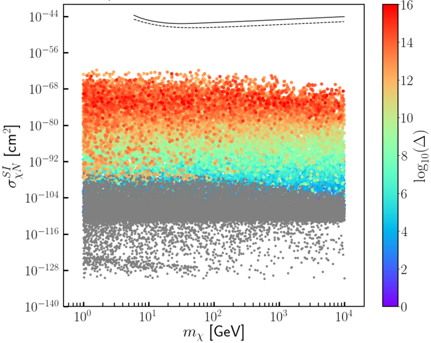
S as FIMP:



Case A, Thermalized

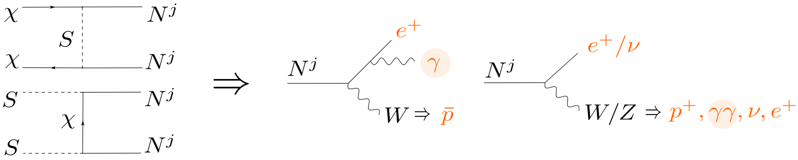


Case A, Non-thermalized



FIMP-nucleon scattering cross-section

Indirect detection

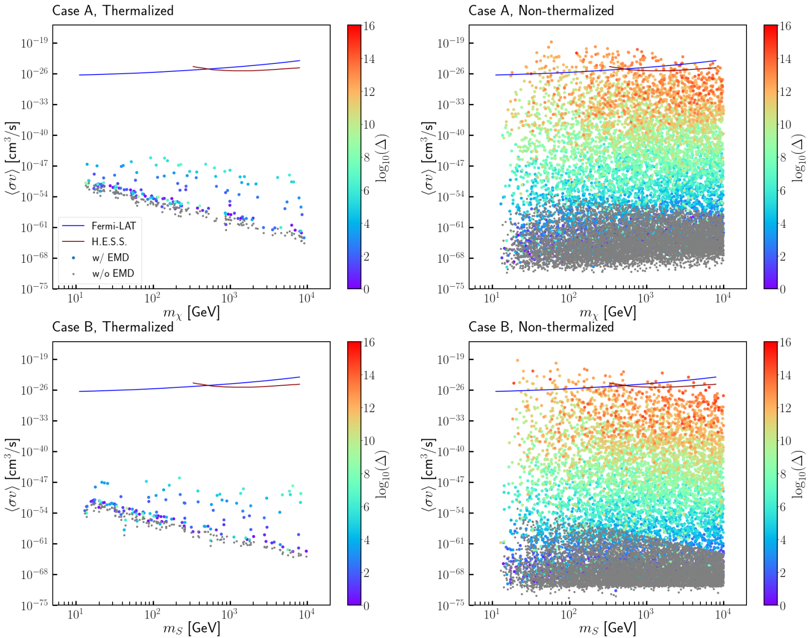


$$\sigma_{\bar{\chi}\chi\to NN} v\Big|_{v\approx 0} = \frac{|\lambda_\chi|^4}{16\pi}\sqrt{1-\frac{m_N^2}{m_\chi^2}}\,\frac{2m_\chi^2-m_N^2}{(m_\chi^2+m_S^2-m_N^2)^2}$$

$$\sigma_{S^*S\to NN} v\Big|_{v\approx 0} = \frac{|\lambda_\chi|^4}{8\pi}\left(1-\frac{m_N^2}{m_S^2}\right)^{3/2}\frac{m_N^2}{(m_\chi^2+m_S^2-m_N^2)^2}$$

- continuum gamma-ray emission
- EMDE-induced microhalos of dark matter (see for instance Yue Zhang 2015, arXiv:1502.06983): upper bounds on DM annihilation as low as $\langle\sigma v\rangle \sim 10^{-32}\text{cm}^3/s$ [Delos, Linden, Erickcek 2019, arXiv:1910.08553]

- bounds on $\langle\sigma v\rangle_{\mathbf{DMDM}\to NN}$ from Campos et al 2017 arXiv:1702.06145


Case A, Thermalized

Case A, Non-thermalized

Case B, Thermalized

Case B, Non-thermalized

Conclusions

Conclusions

- We have explored a model in which dark matter is produced in the early universe via the freeze-in mechanism, through a neutrino portal model that also provides neutrino masses
- If the freeze-in happens during or before an early matter-dominated era (EMDE), predicted by many BSM scenarios, larger SM-FIMP couplings are need from relic density constraints
- We have shown that an EMDE allows for enhanced cross-sections relevant for indirect detection, making the neutrino portal to FIMPs in the reach of current experiments

Backup slides

EMDE & FIMP relic density

In the presence of an early matter-dominated era (EMDE), the yield of a FIMP dark matter today has the following contributions:

$$Y^0_{\textsf{\textbf{DM}}} = y_{\textsf{\textbf{RD}}} + \frac{3}{4}\frac{g_e(T_r)}{g_{\mathfrak{s}}(T_r)} \left[y_{\textsf{\textbf{EP}}} + \frac{1}{\Delta}\left(y_{\textsf{\textbf{EMDE}}} + y_{\textsf{\textbf{ERD}}}\right) \right] ,$$

with

$$y_{\textsf{\textbf{RD}}} \equiv \frac{135\sqrt{5}}{\pi^3\sqrt{2}} M_P \int_{T_0}^{T_r} dT \, \frac{g_s^*(T)}{g_s(T)\sqrt{g_e(T)}} \frac{R^{\textsf{prod}}_{\textsf{\textbf{DM}}}(T)}{T^6}$$

$$y_{\textsf{\textbf{EP}}} \equiv \frac{240\sqrt{10}}{\pi^3} g_e^{3/2}(T_r) M_P T_r^7 \int_{T_r}^{T_e} dT \, \frac{g_e^*(T)}{g_e^3(T)} \frac{R^{\textsf{prod}}_{\textsf{\textbf{DM}}}(T)}{T^{13}}$$

$$y_{\textsf{\textbf{EMDE}}} \equiv \frac{135\sqrt{15}}{2\pi^3\sqrt{2}} \frac{1}{\sqrt{\Delta T_r}} M_P \int_{T_e}^{T_i} dT \, \frac{g_{\mathfrak{s}}^*(T)}{g_{\mathfrak{s}}^{3/2}(T)} \frac{R^{\textsf{prod}}_{\textsf{\textbf{DM}}}(T)}{T^{11/2}}$$

$$y_{\textsf{\textbf{ERD}}} \equiv \frac{135\sqrt{5}}{\pi^3\sqrt{2}} M_P \int_{T_i}^{T_{\textsf{\textbf{RH}}}} dT \, \frac{g_{\mathfrak{s}}^*(T)}{g_{\mathfrak{s}}(T)\sqrt{g_e(T)}} \frac{R^{\textsf{prod}}_{\textsf{\textbf{DM}}}(T)}{T^6} .$$

When do particles freeze-in?

The freeze-in can finish at the Boltzmann suppression of the heaviest of the particles involved ($\{m_i\}$). Also, it can be determined from approximate expressions of the dominant production rate, either in a resonant regime (NWA) or by $R_{\textsf{DM}} \propto T^n$:

$$T_{FI}\Big|^{X\text{ on-shell}} \sim m_X$$

$$T_{FI}\Big|^{\text{ERD/RD}} \sim \begin{cases} \max(T_{i/0}, \{m_i\}), & n < 5 \\ \max(T_{\textsf{RH}/r}, \{m_i\}), & n > 5 \end{cases}$$

$$T_{FI}\Big|^{\text{EMDE}} \sim \begin{cases} \max(T_e, \{m_i\}), & n < 4.5 \\ \max(T_i, \{m_i\}), & n > 4.5 \end{cases}$$

$$T_{FI}\Big|^{\text{EP}} \sim \begin{cases} \max(T_r, \{m_i\}), & n < 12 \\ \max(T_e, \{m_i\}), & n > 12\,. \end{cases}$$