Freeze-In Dark Matter through Neutrino Portal with an Early Matter Era

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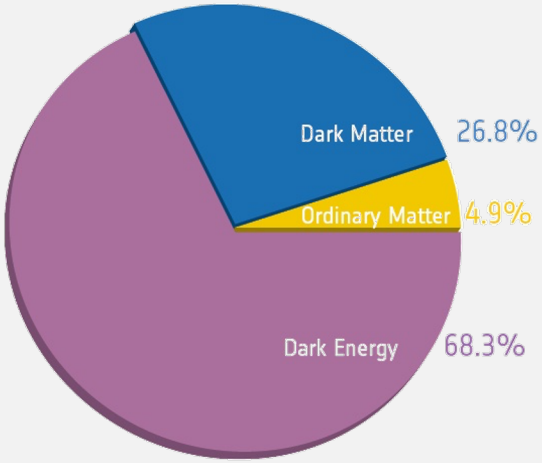
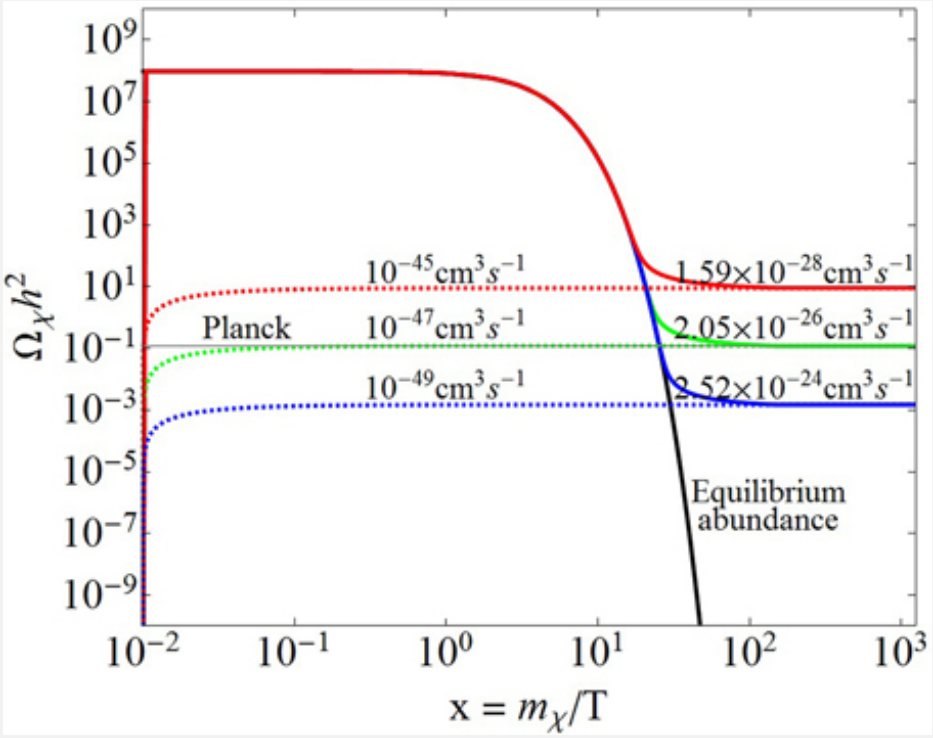
In collaboration with C. Cosme, M. Dutra, T. Ma, L. Yang; arXiv: 2003.01723

Outline

- Introduction
  - Freeze-In DM
  - Early Matter Era
- Neutrino Portal
- Phenomenology
  - Direct Detection
  - Indirect Detection
- Summary

Freeze-Out & Freeze-In





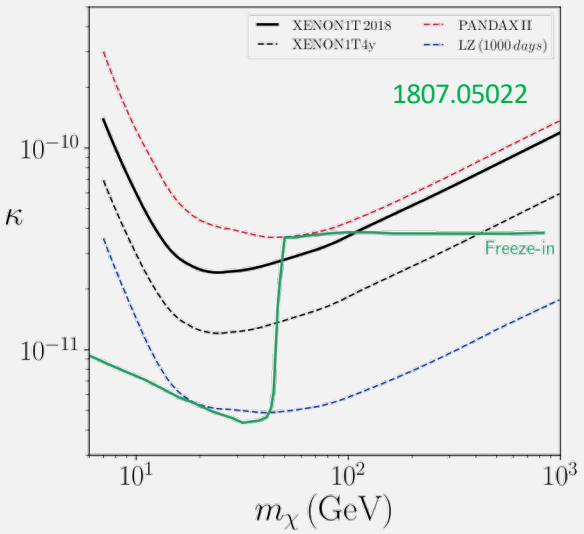
Freeze-out

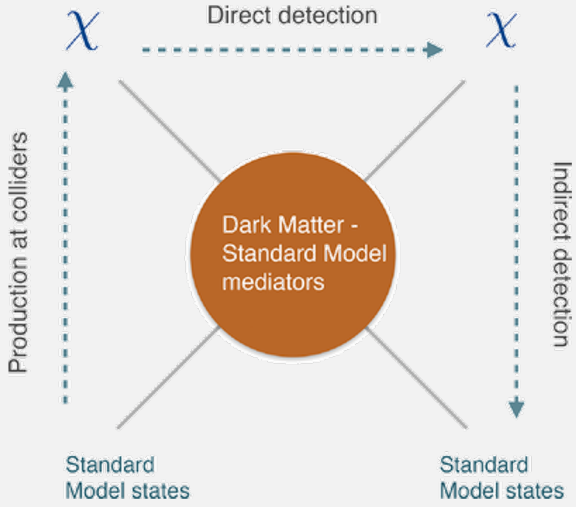
- In **thermal equilibrium** with SM at early time
- **Larger** coupling (cross section), **Less** relic

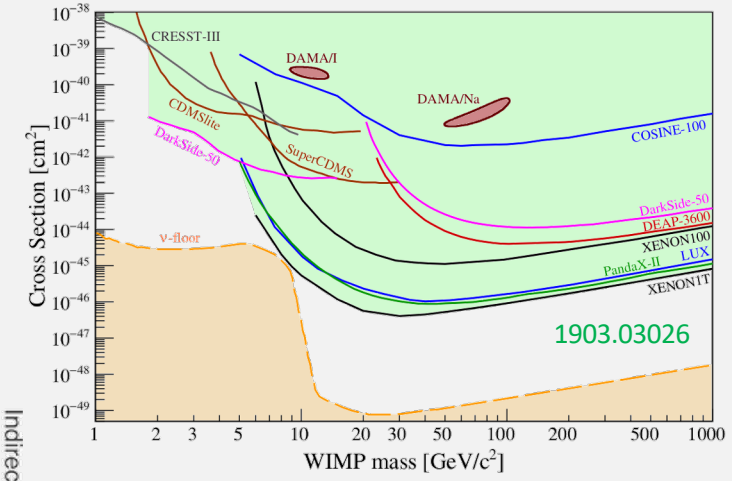
Freeze-In

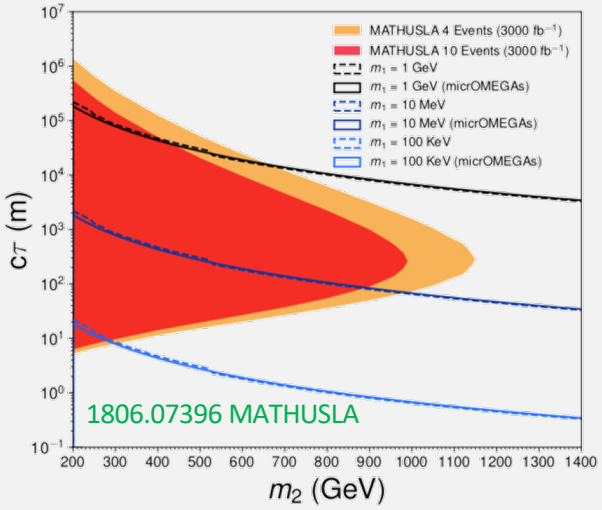
- **Out of thermal equilibrium** with SM
- **Larger** coupling (cross section), **More** relic

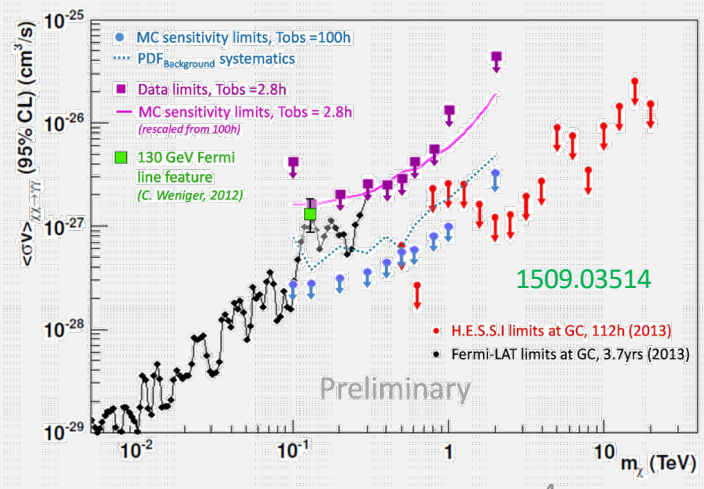
DM Searches


XENON1T 2018
XENON1T4y
PANDAX II
LZ (1000 days)
1807.05022
Freeze-in
κ
m_χ (GeV)

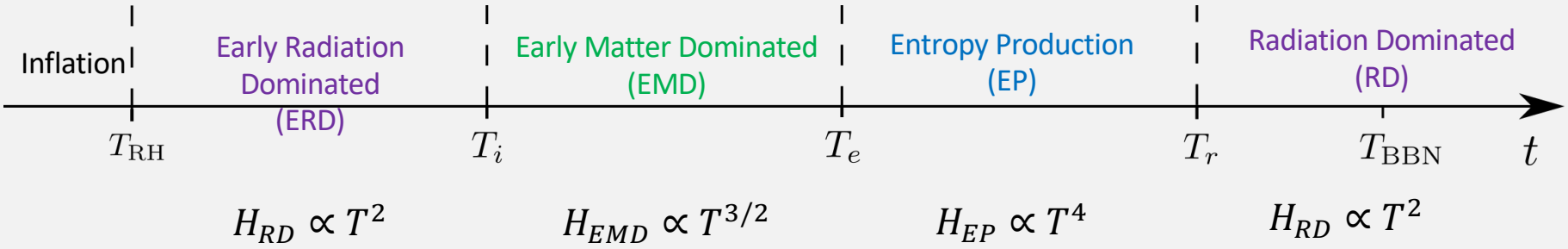

χ
Direct detection
χ
Production at colliders
Indirect detection
Dark Matter - Standard Model mediators
Standard Model states
Standard Model states

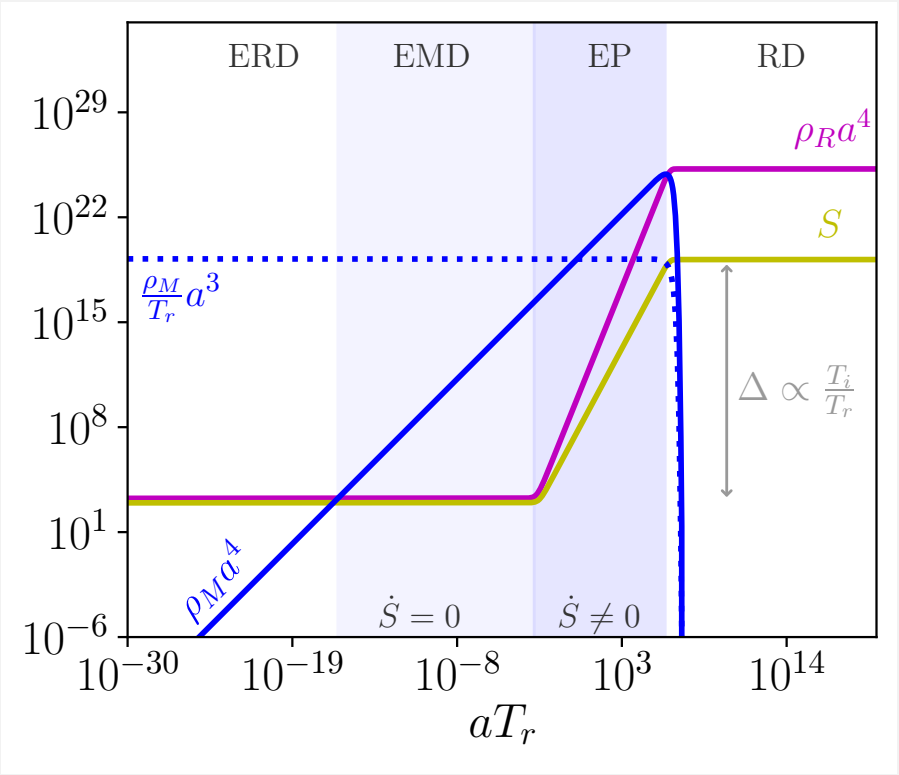

CRESST-III
DAMA/I
DAMA/Na
CDMSlite
DarkSide-50
SuperCDMS
COSINE-100
DarkSide-50
DEAP-3600
XENON100
LUX
PandaX-II
XENON1T
ν-floor
1903.03026
Cross Section [cm^2]
WIMP mass [GeV/c^2]

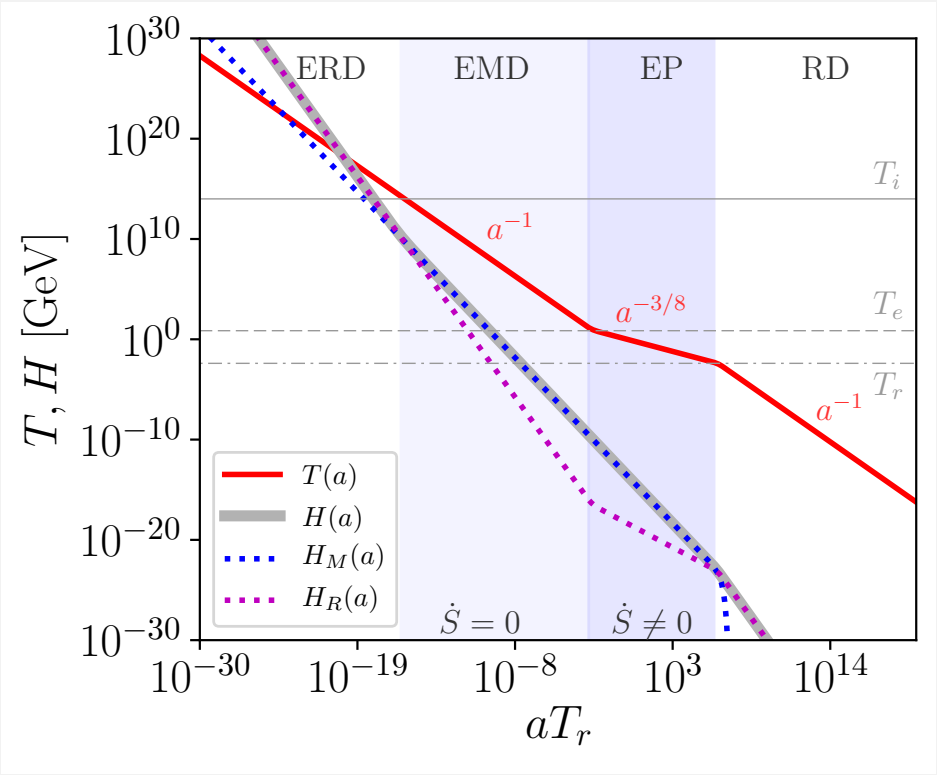

MATHUSLA 4 Events (3000 fb^{-1})
MATHUSLA 10 Events (3000 fb^{-1})
m_1 = 1 GeV
m_1 = 1 GeV (micrOMEGAs)
m_1 = 10 MeV
m_1 = 10 MeV (micrOMEGAs)
m_1 = 100 KeV
m_1 = 100 KeV (micrOMEGAs)
1806.07396 MATHUSLA
$c\tau$ (m)
m_2 (GeV)


MC sensitivity limits, Tobs =100h
PDF$_{Background}$ systematics
Data limits, Tobs =2.8h
MC sensitivity limits, Tobs = 2.8h
(rescaled from 100h)
130 GeV Fermi line feature
(C. Weniger, 2012)
1509.03514
H.E.S.S.I limits at GC, 112h (2013)
Fermi-LAT limits at GC, 3.7yrs (2013)
Preliminary
$\langle\sigma v\rangle_{\chi\bar{\chi}\to\gamma\gamma}$ (95% CL) (cm^3/s)
m_χ (TeV)

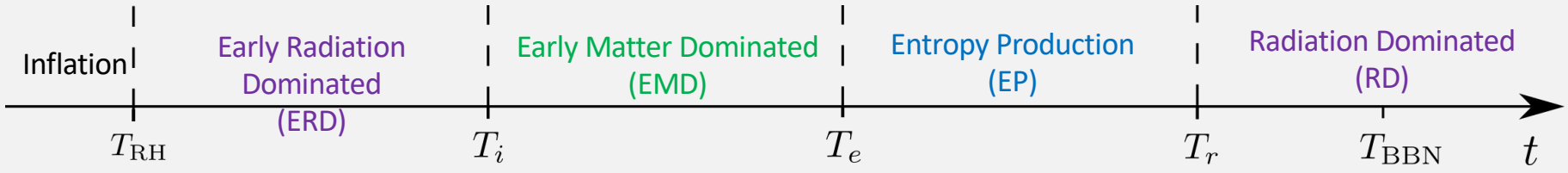
Early Matter Dominated Era (EMDE)

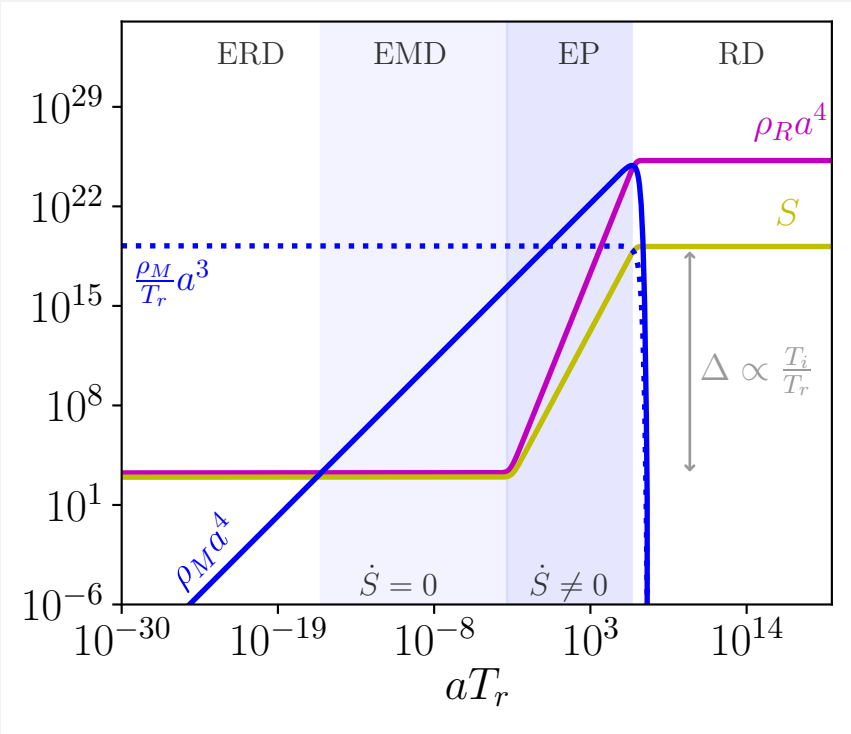


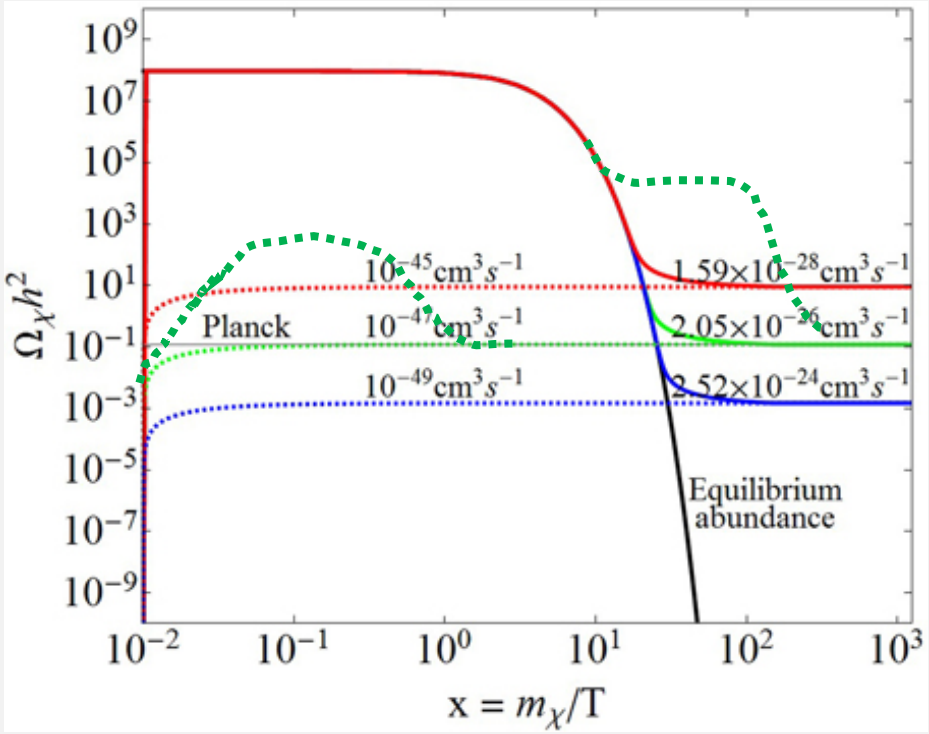




EMDE and Relic Density

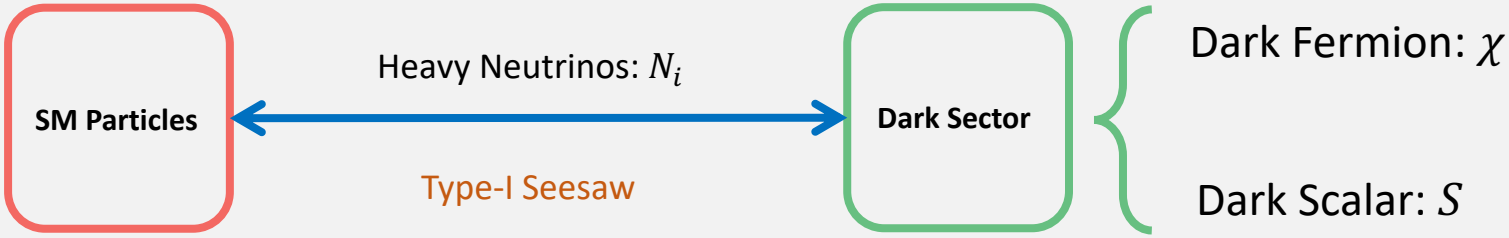






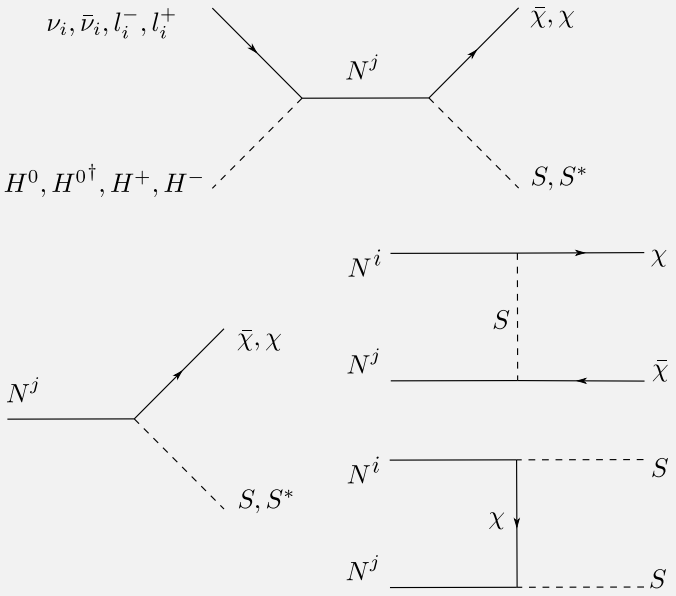
$$\Delta \sim \frac{T_i}{T_r} \qquad Y_{DM} \equiv \frac{n_{DM}}{s} \quad \Longrightarrow \quad Y_{DM}^{after} = \frac{n_{DM}}{s^{before}} \frac{s^{before}}{s^{after}} = \frac{Y_{DM}^{before}}{\Delta}$$

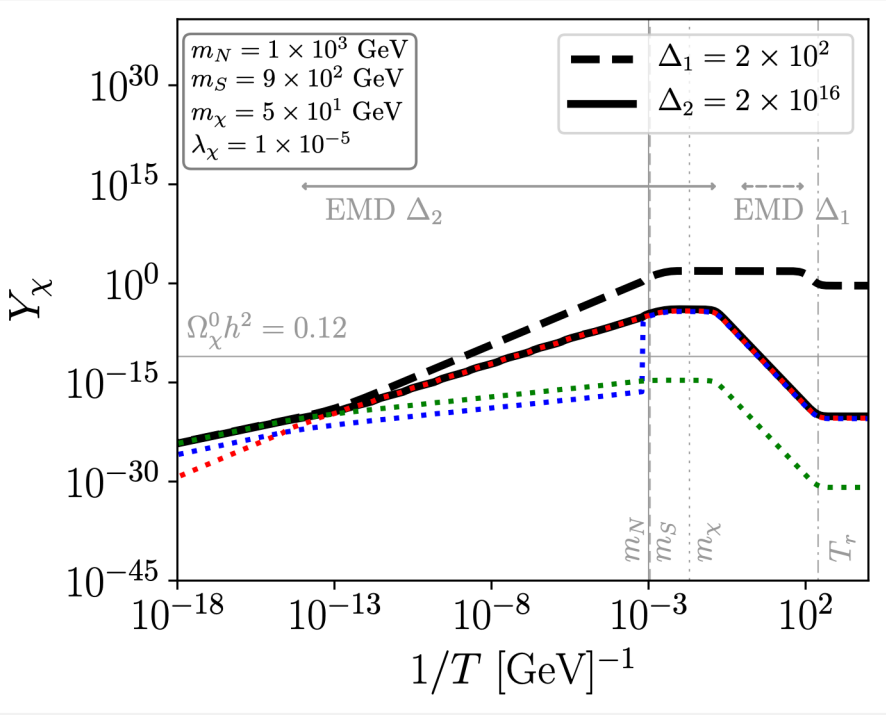
Neutrino Portal



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

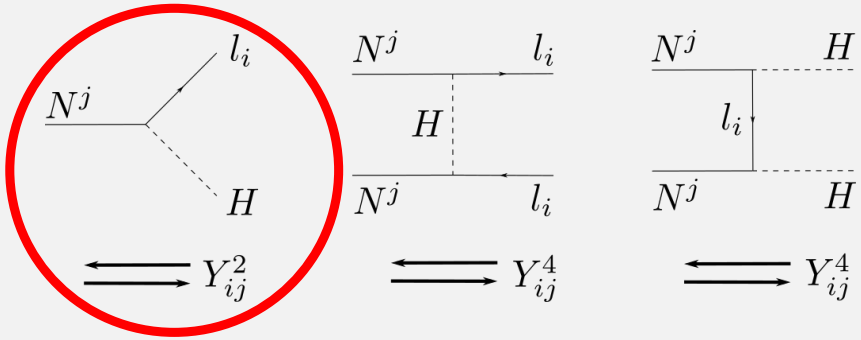
Processes relevant to DM production:



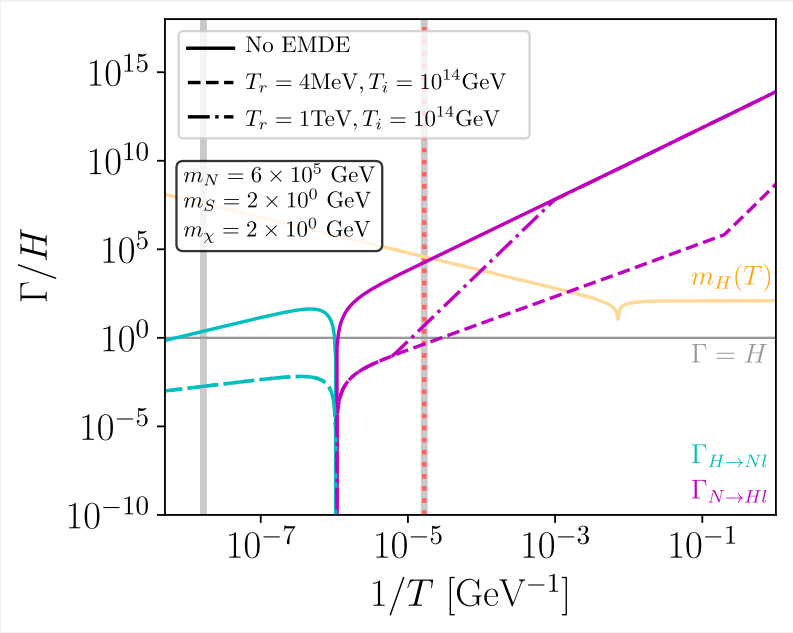


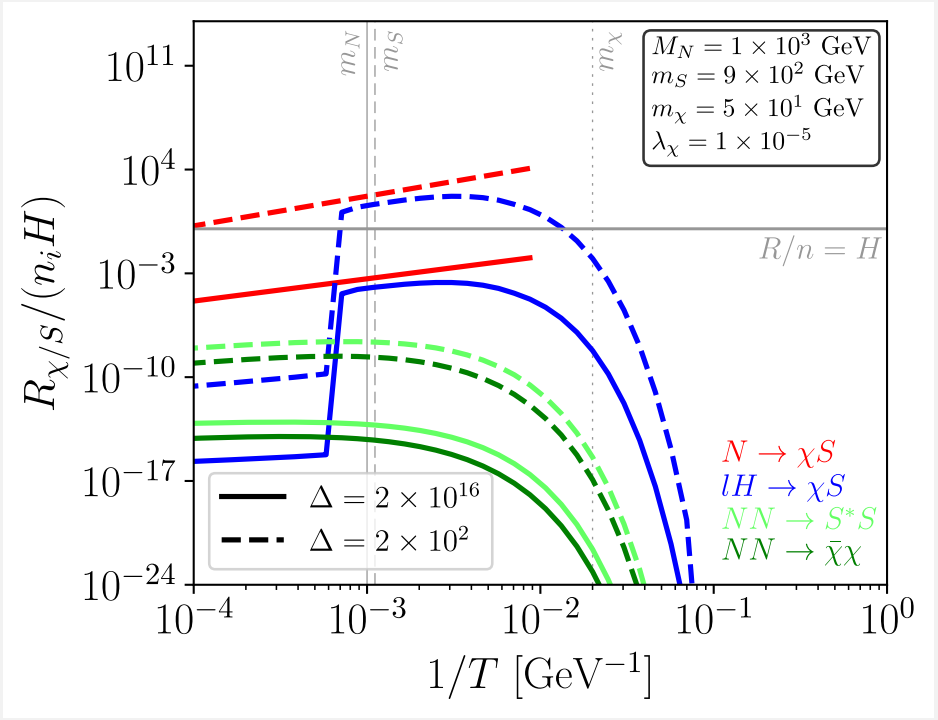
Thermalization of N

Freeze-In Condition



Processes relevant for DM production should satisfy:
$\Gamma_i(T) < H(T)$, during freeze-in period





N thermalized: All channels should be included

N not thermalized: Only s-channel should be included

Phenomenology

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

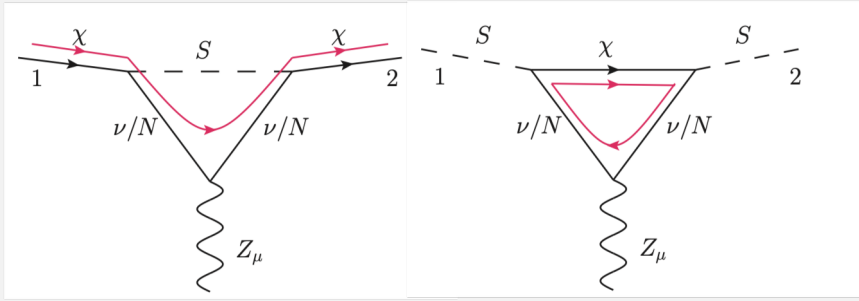
- Y_ν^{ij}: Determined from Type-I seesaw mechanism.
- λ_χ: Providing the observed relic density
- Thermalization of N
- Freeze-in condition satisfied

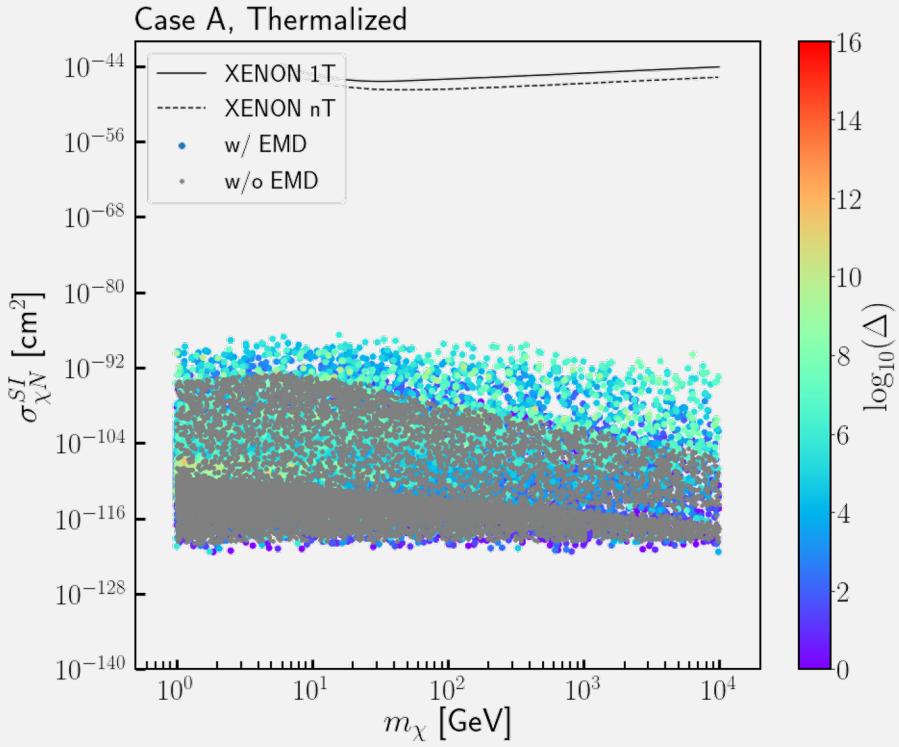
Direct Detection

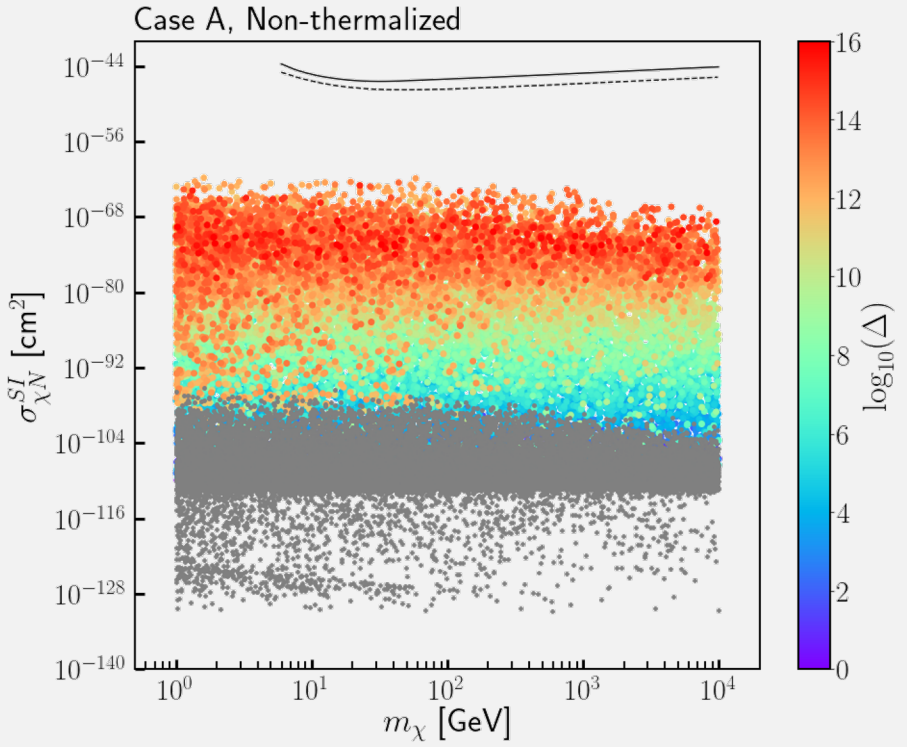
Spin Independent

$$\sigma_0^{SI} = \frac{\mu_{\chi N}^2 |g_{Z\chi\chi}|^2}{4\pi m_Z^4} \left[Z(g_d^V + 2g_u^V) + (A - Z)(g_u^V + 2g_d^V) \right]^2$$

$$= \frac{\mu_{\chi N}^2}{\mu_{\chi p}^2} A^2 \sigma_{\chi N}^{SI},$$



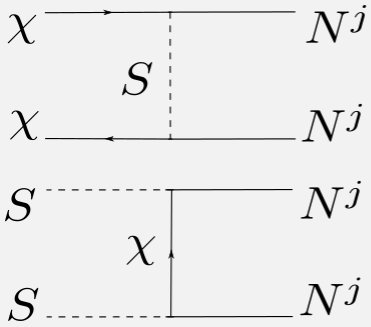


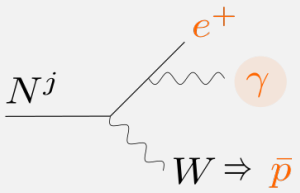


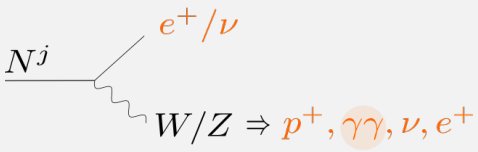
Indirect Detection

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

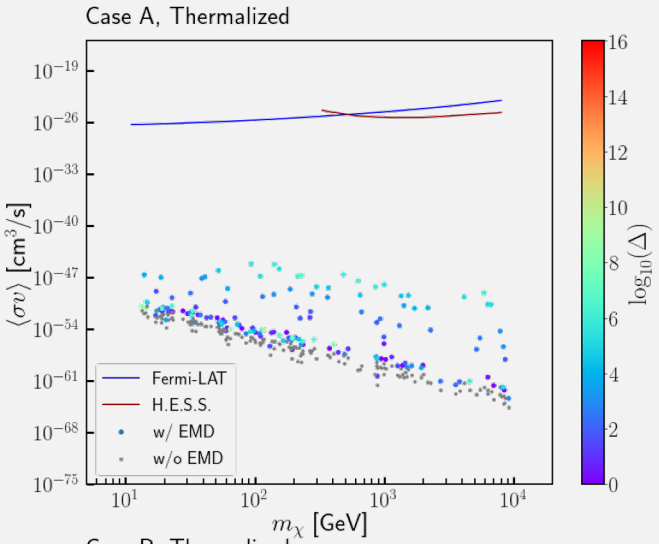
$$\sigma_{S^*S\to NN}v\Big|_{v\approx 0} = \frac{|\lambda_\chi|^4}{8\pi}\left(1-\frac{m_N^2}{m_S^2}\right)^{3/2}\frac{m_N^2}{(m_\chi^2+m_S^2-m_N^2)^2}.$$

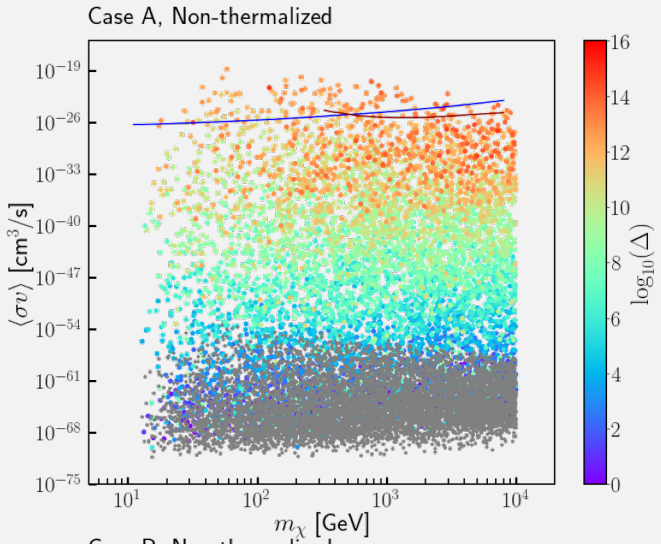


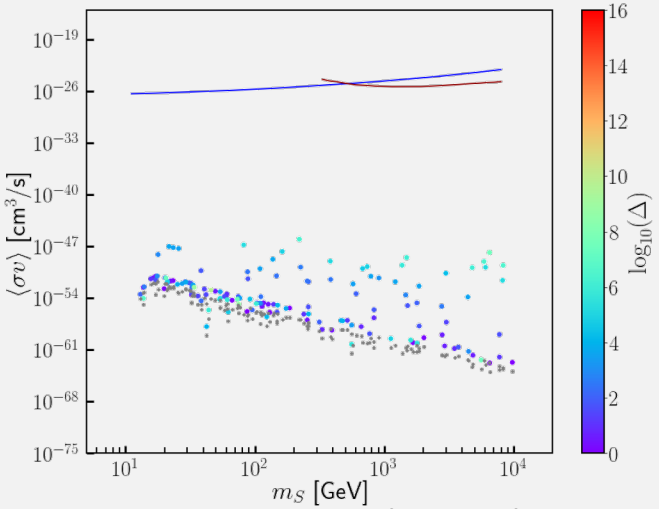


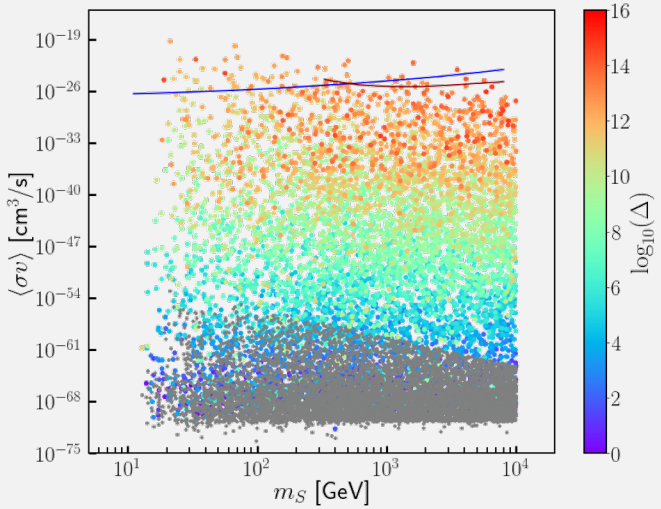


Upper Bounds on $\langle\sigma v\rangle_{DM\,DM\to N\,N}$ from Campos et al. 1702.06145









Summary

- Explored the neutrino portal Freeze-In DM model with Early Matter-dominated Era (EMDE)
- EMDE should be compensated by larger couplings in order to obtain observed relic density for Freeze-In
- The enhanced cross section in indirect detection is within the reach of current indirect detection experiments

Thanks for Attention!

Backup Slides

Hubble Parameter

$$\text{ERD}: \quad H_{\text{ERD}}(T) = \frac{\pi\sqrt{g_e(T)}}{3\sqrt{10}}\frac{T^2}{M_P}$$

$$\text{EMDE}: \quad H_{\text{EMDE}}(T) = H_{\text{RD}}(T_r)\sqrt{\frac{4}{3}\Delta\frac{g_{\mathfrak{s}}(T)}{g_e(T_r)}}\left(\frac{T}{T_r}\right)^{3/2}$$

$$\text{EP}: \quad H_{\text{EP}}(T) = H_{\text{RD}}(T_r)\frac{g_e(T)}{g_e(T_r)}\left(\frac{T}{T_r}\right)^4$$

$$\text{RD}: \quad H_{\text{RD}}(T) = \frac{\pi\sqrt{g_e(T)}}{3\sqrt{10}}\frac{T^2}{M_P}$$

Dark Matter Yield

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

$$y_{\rm RD} \equiv \frac{135\sqrt{5}}{\pi^3\sqrt{2}} M_P \int_{T_0}^{T_r} dT \frac{g^*_s(T)}{g_s(T)\sqrt{g_e(T)}} \frac{R_{\rm DM}(T)}{T^6}$$

$$y_{\rm EMDE} \equiv \frac{135\sqrt{15}}{2\pi^3\sqrt{2}} \frac{1}{\sqrt{\Delta T_r}} M_P \int_{T_e}^{T_i} dT \frac{g^*_{\mathfrak{s}}(T)}{g^{3/2}_{\mathfrak{s}}(T)} \frac{R_{\rm DM}(T)}{T^{11/2}}$$

$$y_{\rm EP} \equiv \frac{240\sqrt{10}}{\pi^3} g^{3/2}_e(T_r) M_P T^7_r \int_{T_r}^{T_e} dT \frac{g^*_e(T)}{g^3_e(T)} \frac{R_{\rm DM}(T)}{T^{13}}$$

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

Type-I Seesaw

$$\mathcal{L}_{\rm seesaw} = \frac{1}{2}\overline{N}^i_\ell (i\partial\!\!\!/\delta^{ij} - m_N^{ij}) N^j_\ell - \left(\overline{L^i_L} Y_\nu^{ij} \tilde{H} (N^j_\ell)_R + h.c.\right),$$

Casas-Ibarra scheme hep-ph/0103065

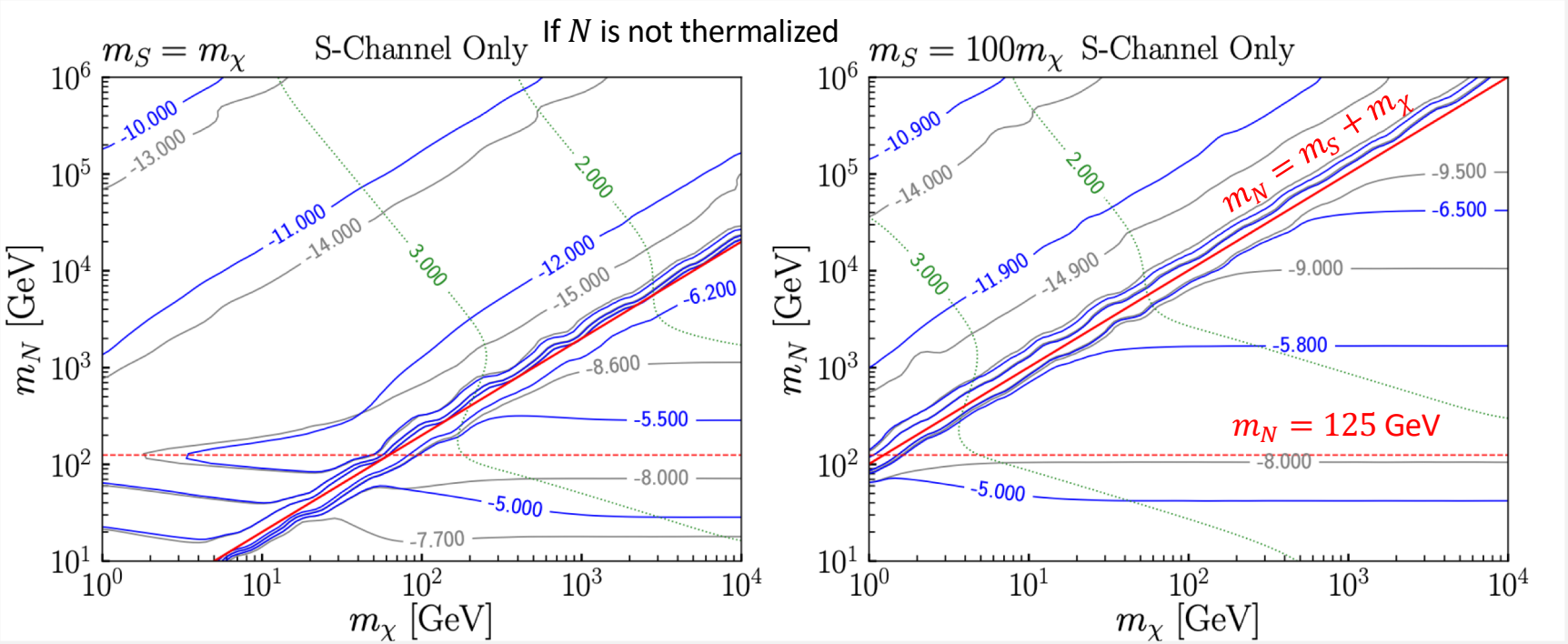
$$Y_\nu = \frac{i\sqrt{2}}{v} U_{\rm PMNS}\, m_\nu^{1/2}\, R\, m_N^{1/2},$$

$$\begin{pmatrix} \widehat{(\nu^i_\ell)_L} \\ (N^i_\ell)_R \end{pmatrix} = \mathbb{N} \begin{pmatrix} \widehat{(\nu^i_m)_L} \\ (N^i_m)_R \end{pmatrix}, \qquad \mathbb{N} \equiv \begin{pmatrix} U & V \\ X & Y \end{pmatrix},$$

$$U \approx U_{\rm PMNS},$$
$$V \approx i\, U_{\rm PMNS}\, m_\nu^{1/2}\, R\, m_N^{-1/2},$$
$$X \approx i\, m_N^{-1/2}\, R^\dagger\, m_\nu^{1/2},$$
$$Y \approx \mathbb{I}_{3\times 3}.$$

Parameter spaces (S-channel Only)

If N is not thermalized



	Short/no EMDE	Long EMDE
Resonant Region	$\Omega h^2 \sim \lvert\lambda_\chi\rvert^2 \frac{m_\chi}{m_N}$	$\Omega h^2 \sim f(\lambda_\chi) m_\chi \sqrt{m_N}$
Non-Resonant Region	$\Omega h^2 \sim \lvert\lambda_\chi\rvert^2 m_N$	$\Omega h^2 \sim \lvert\lambda_\chi\rvert^2 m_N \sqrt{m_\chi}$

Resonant enhancement: Smaller couplings
Longer EMDE: Larger couplings

$T_r = 10$ MeV

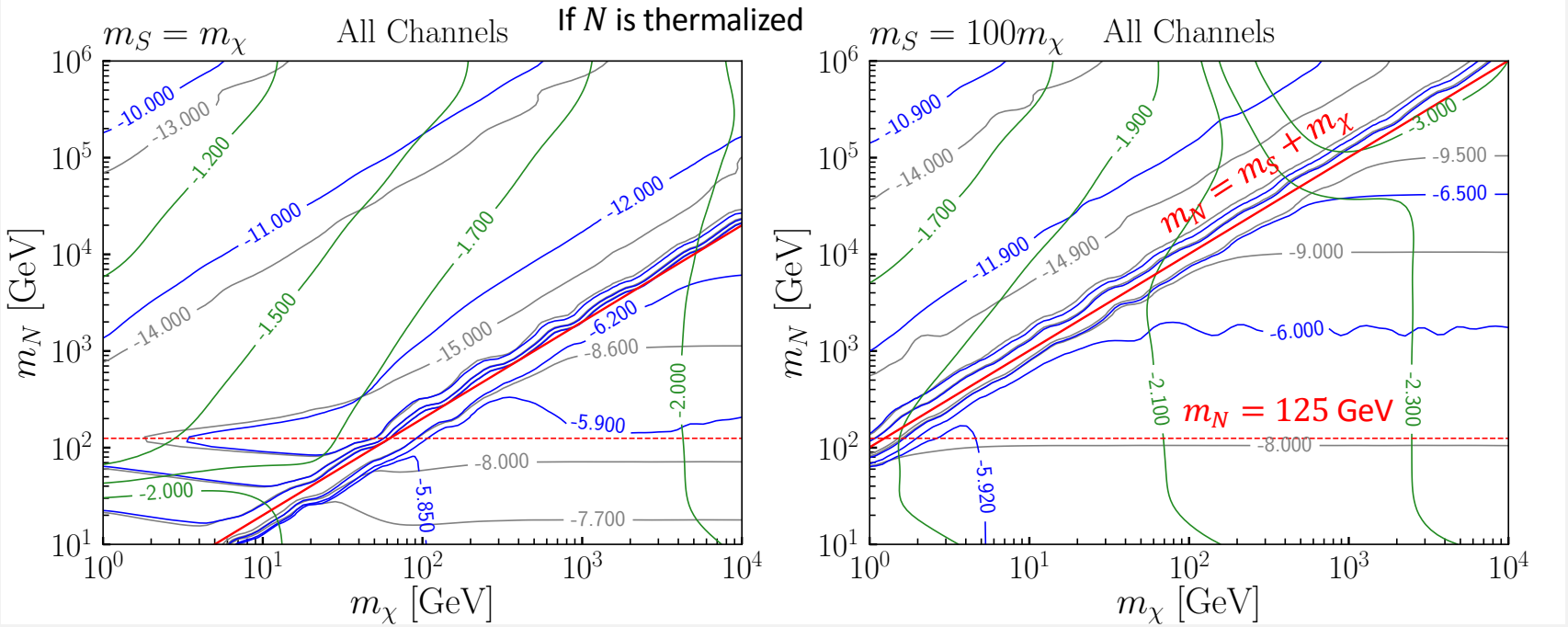
$T_i = 10$ MeV
No EMDE

$T_i = 10^3$ GeV
Short EMDE

$T_i = 10^{14}$ GeV
Long EMDE

Parameter spaces (All channels)

If N is thermalized



- S-channel: $\propto |\lambda_\chi|^2 |Y_\nu^{ij}|^2 \sim |\lambda_\chi|^2 m_N$
- Decay: $\propto |\lambda_\chi|^2$
- T-channel: $\propto |\lambda_\chi|^4$

S-channel Dominant: Large m_N and/or Short/No EMDE
T-channel Dominant: Small m_N and/or Long EMDE

$T_r = 10$ MeV

$T_i = 10$ MeV
No EMDE

$T_i = 10^3$ GeV
Short EMDE

$T_i = 10^{14}$ GeV
Long EMDE