Neutrino Portal to FIMP Dark Matter with an Early Matter Era

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in collaboration with
M. Dutra, T. Ma, Y. Wu, and L. Yang

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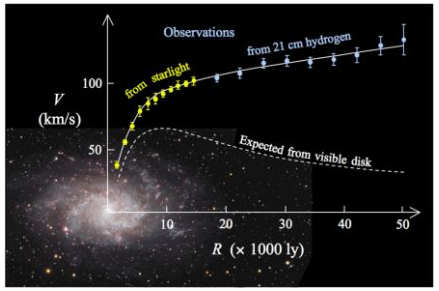
TeVPA 2023

FCT Fundação para a Ciência e a Tecnologia

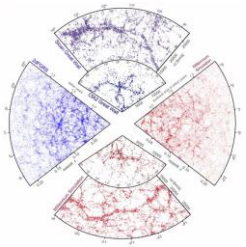
Introduction - Dark Matter (DM)

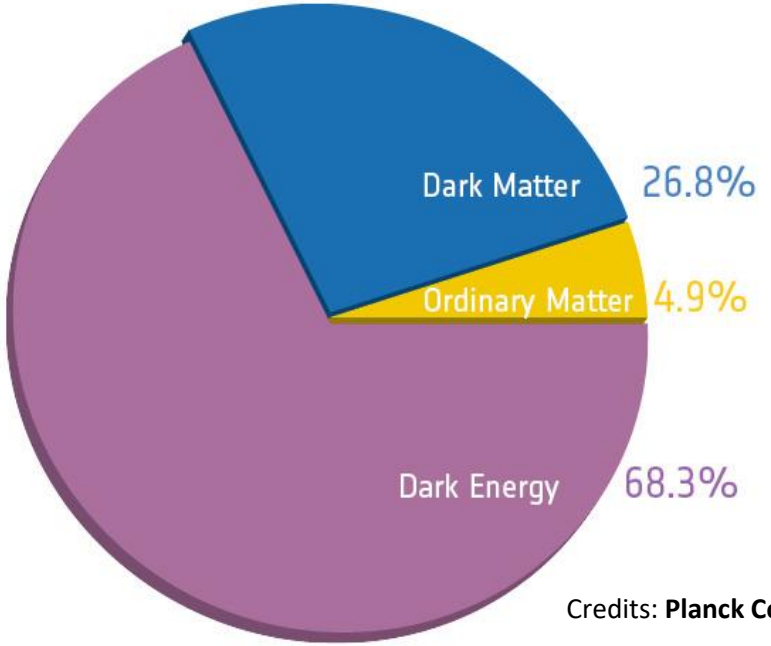
Galaxy Rotation Curves



Merging clusters (Bullet Cluster)

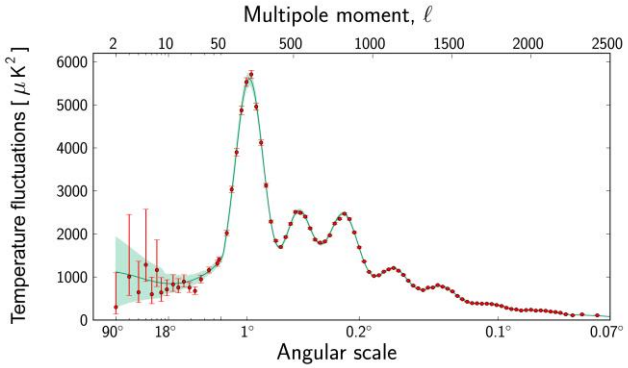
Structure formation



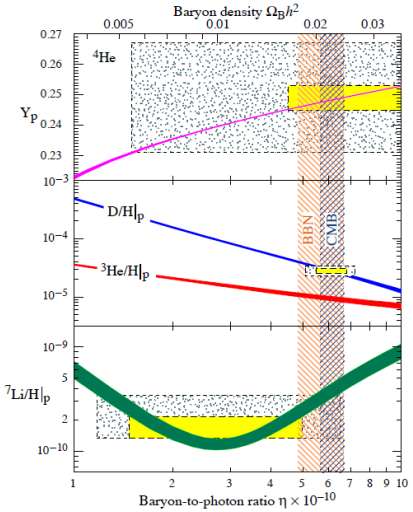


Credits: **Planck Collab.**

Cosmic Microwave Background (CMB)



Big Bang Nucleosynthesis (BBN)



Properties of a DM candidate

- Stable or very long-lived (lifetime ≥ age of the Universe);
- Cold (non-relativistic);
- Very small interaction with the electromagnetic field;
- It must have the observed abundance.

Introduction - Dark Matter production mechanisms

Freeze-out

$$X\overline{X} \leftrightarrow SM$$

- Interactions **freeze-out** when: $\Gamma_X = n_X \langle \sigma v \rangle \lesssim H$;
- **WIMPs** – Weakly Interacting Massive Particles;
- $\Omega_{X,0} h^2 \sim \frac{1}{\lambda}$;
- But:
  - **no detection** so far;
  - Large parameter space **very constrained by experiments.** [Arcadi et al. **arXiv:1703.07364**]

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vs

FIMP

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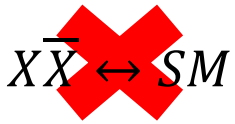

Introduction - Dark Matter production mechanisms

Freeze-out vs Freeze-in

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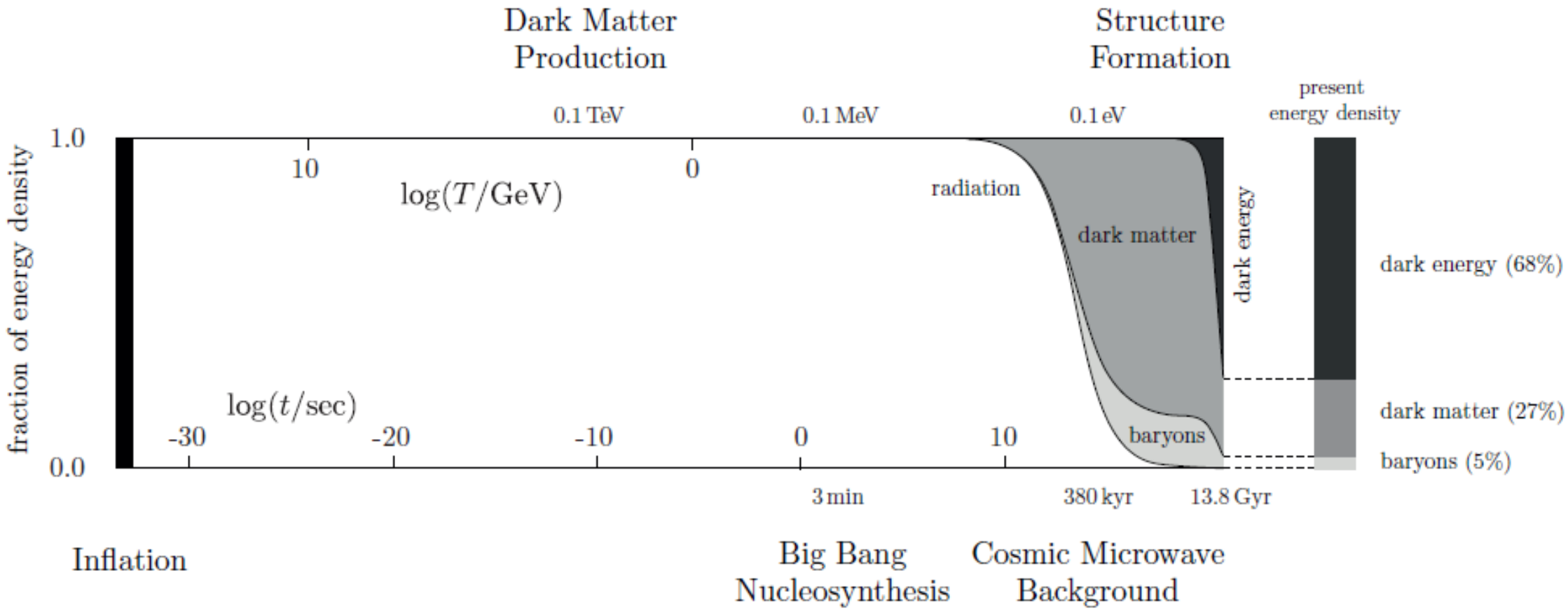
vs

Freeze-in

- $\Gamma_X < H$ **always**;
- **FIMPs** – Feebly Interacting Massive Particles;
- $\Omega_{X,0}h^2 \sim \lambda$;
- **Small couplings** to attain the **observed relic abundance**;
- Can evade stringent observational constraints;
- But: **hard** to **probe**.

Introduction – An early matter-dominated period



Credits: **Daniel Baumann, *Cosmology, Part III Math Tripos***

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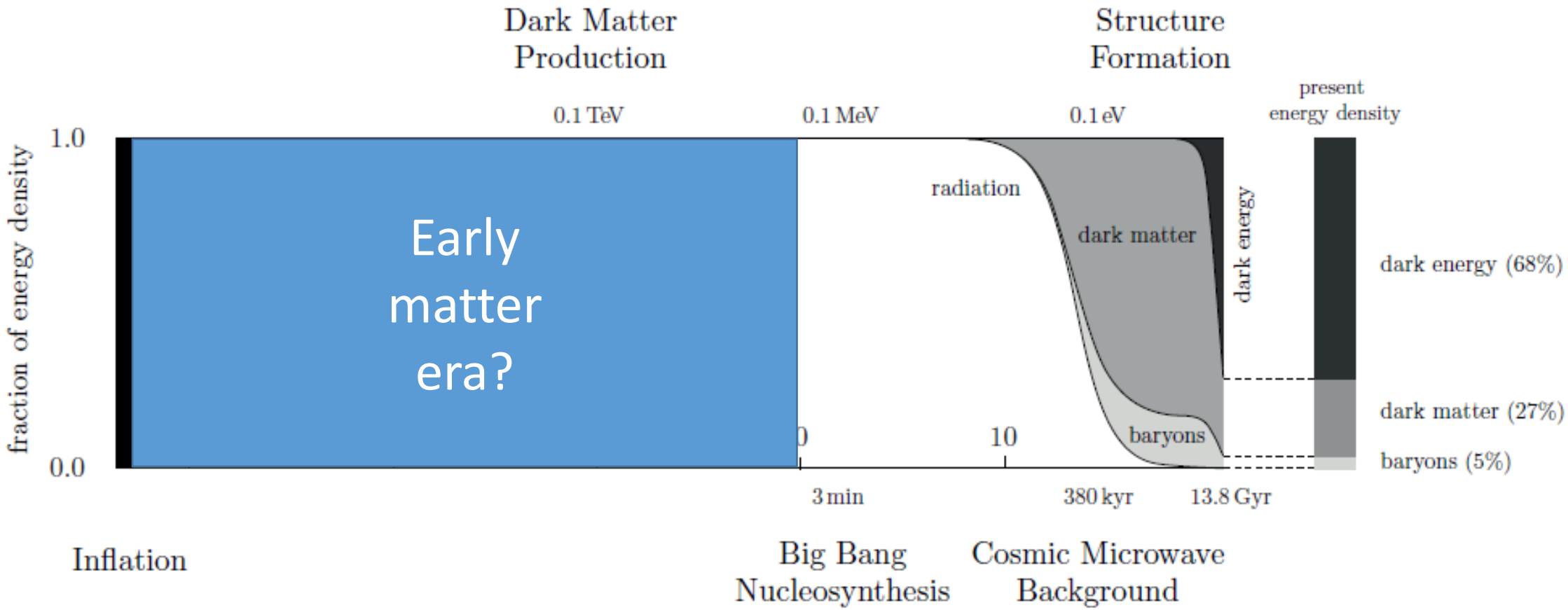


Introduction – An early matter-dominated period

Matter era: scalar field (inflaton candidates, meta-stable candidates, moduli fields…)

End of matter dominated period: **matter** component **decays** into Standard Model (SM) particles

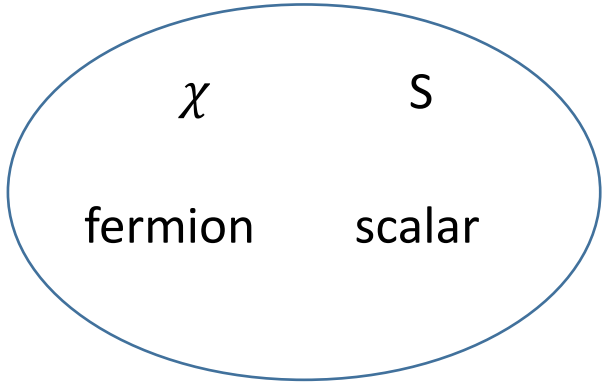
Dilution of **DM** number density

Freeze-in: Couplings to the visible sector **need to be larger** than usual freeze-in

DM production during a **non-standard expansion** may result to important **experimental and observational** ramifications.

The model – Neutrino portal to FIMP Dark Matter with an early matter era

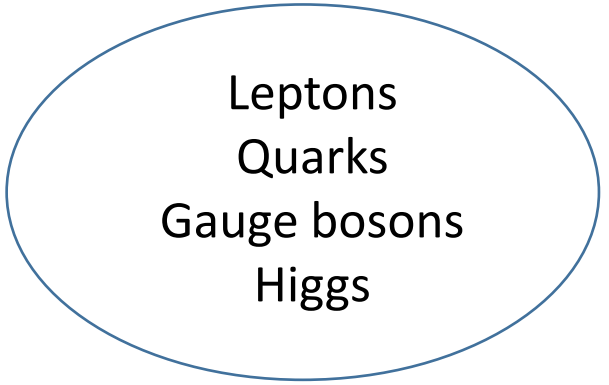
Hidden sector



3 Heavy neutrinos

N_R

Standard Model/visible sector



+ extra scalar for the early matter era

- SM neutrinos mass: **Type-I seesaw** mechanism;

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{hidden}} + \mathcal{L}_{\mathrm{seesaw}} + \mathcal{L}_{\mathrm{portal}}$$

$$\mathcal{L}_{\mathrm{hidden}} = \overline{\chi}(i\partial\!\!\!/ - m_\chi)\chi + |\partial_\mu S|^2 - m_S^2|S|^2 + V(S)$$

$$\mathcal{L}_{portal} = -\left(\lambda_\chi^i S\overline{\chi}\left(N_\ell^i\right)_R + h.c\right)$$

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

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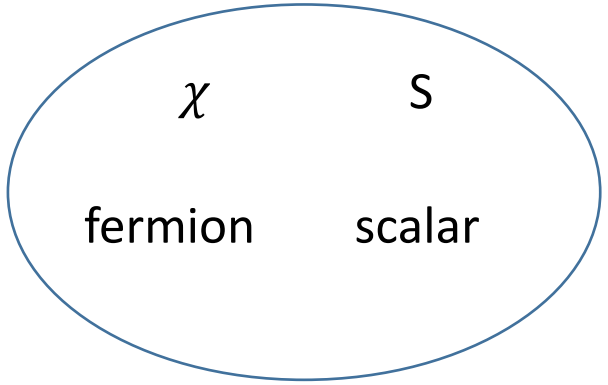

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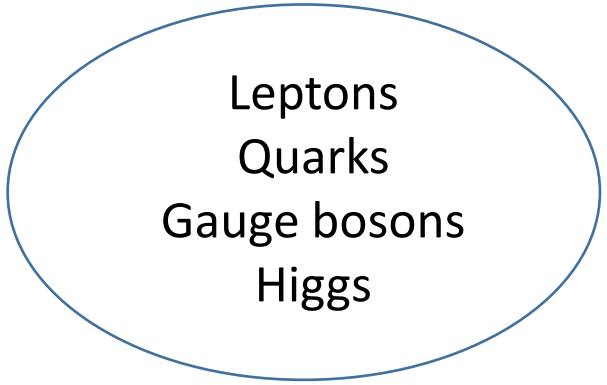

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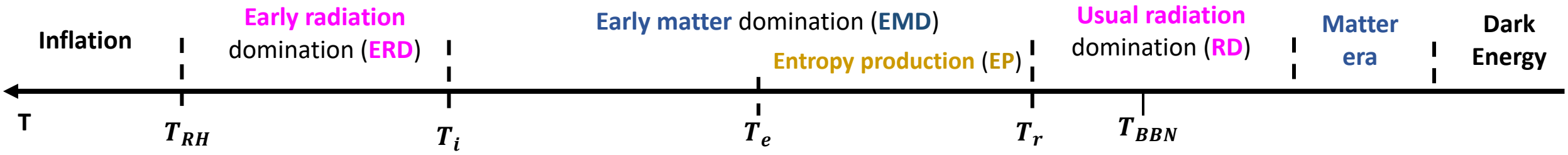
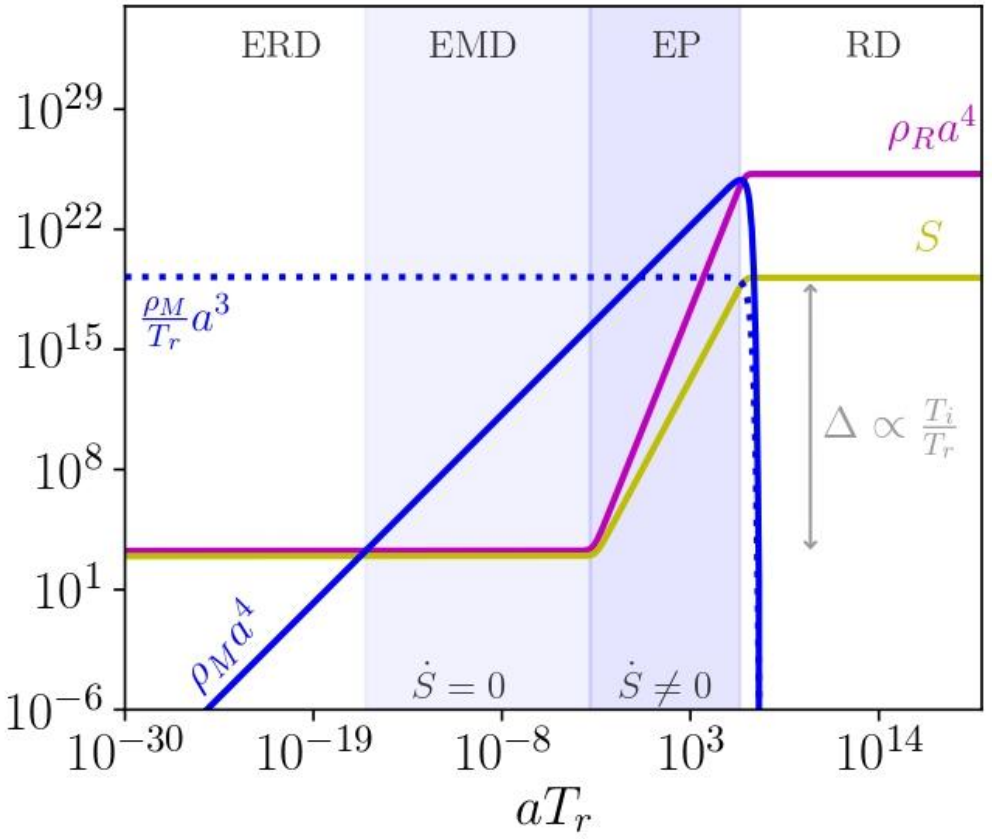
Evolution of the Universe



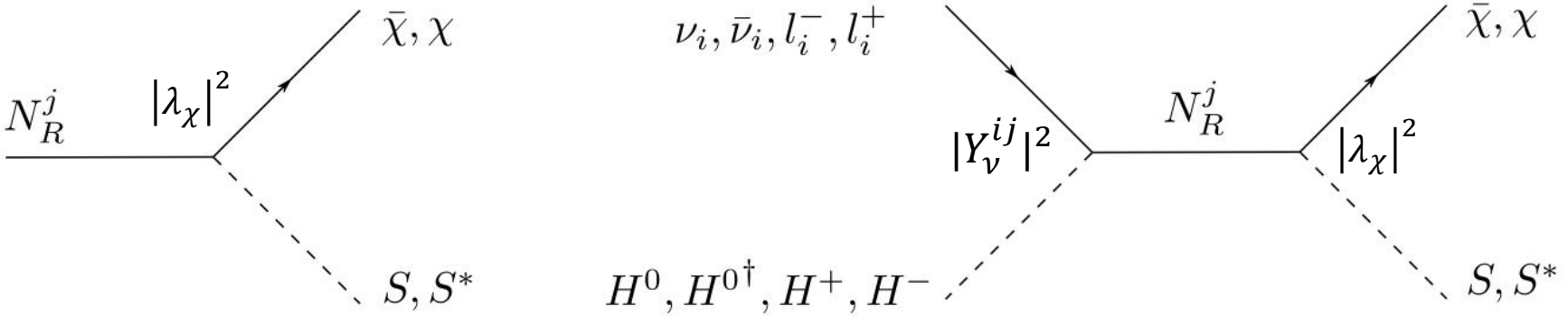
- $\boldsymbol{\rho_M} \gg \rho_R, \rho_{DM}$ for some initial temperature T_i;
- $H_{RD} = \frac{\pi}{\sqrt{90}}\sqrt{g_*}\frac{T^2}{M_{Pl}}$;
- $H_{EMD}(T) = H_{RD}(T_r)\sqrt{\Delta\frac{4g_s(T)}{3g_e(T_r)}}\left(\frac{T}{T_r}\right)^{\frac{3}{2}}$

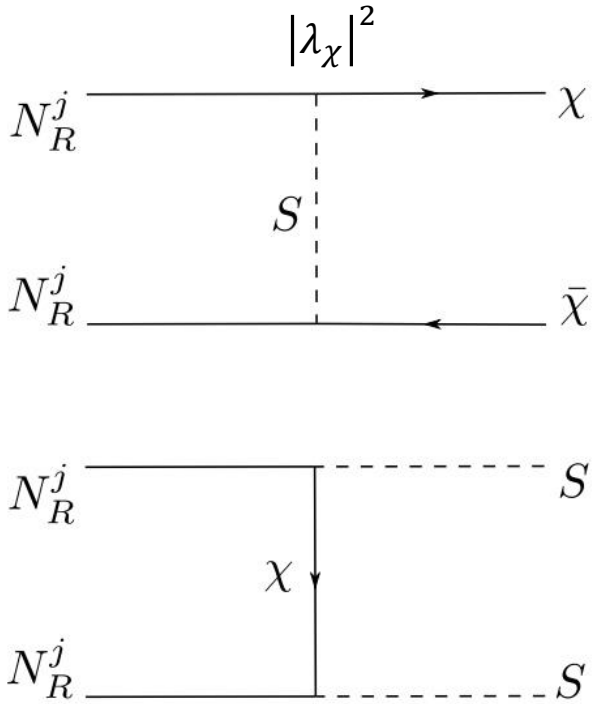
  $\Delta \equiv$ Amount of **entropy production** during EMD; related with the duration of the EMD $\Rightarrow$ **larger** Δ, **longer** EMD;
- $H_{EP}(T) = H_{RD}(T_r)\frac{g_e(T)}{g_e(T_r)}\left(\frac{T}{T_r}\right)^4$;



Dark matter production – Processes contributing to DM

Processes contributing to the Freeze-in production:





Dark matter production – Relic abundance

DM relic abundance

- DM production ⇒ $\frac{n_{DM}}{s} \equiv Y_{DM}$ becomes constant;
- **DM relic abundance**:

$$\Omega_{DM,0} \equiv \frac{\rho_{DM,0}}{\rho_{c,0}} = \frac{m_{DM}}{3H_0^2 M_{Pl}^2} n_{DM} = \frac{m_{DM}}{3H_0^2 M_{Pl}^2} Y_{DM,0}\, s_0 \simeq 0.26$$

$$Y_{DM,0} = Y_{ERD} + Y_{EMD} + Y_{EP} + Y_{RD}$$

- The yield Y_{DM} for some period is given by:

$$Y_{DM}(T_f) - Y_{DM}(T_i) = \int_{T_i}^{T_f} dT\; g_{*s} \frac{R_{DM}}{H T\, s}$$

Has to take into account all the processes contributing to DM (depends on λ_χ, Y_ν^{ij})

Depends on the epoch

$$R_2^{1\to 23} \approx n_1 \Gamma_{1\to 23}$$

$$R_3^{12\to 34} \equiv n_1^{eq} n_2^{eq} \langle \sigma v \rangle_{12\to 34}$$

Phenomenology – Indirect detection prospects

- **Indirect detection experiments**: Look for the product of the decay or annihilation of DM particles;
- In the case $\boldsymbol{m_{DM} > m_N}$ ⟹ **DM annihilates** to **N** ⟹ **N decays** into SM particles;
- Experiments like INTEGRAL/SPI, Fermi-LAT and H.E.S.S. place **stringent constraints** on the **dark matter annihilation cross-section** into **heavy neutrinos**.

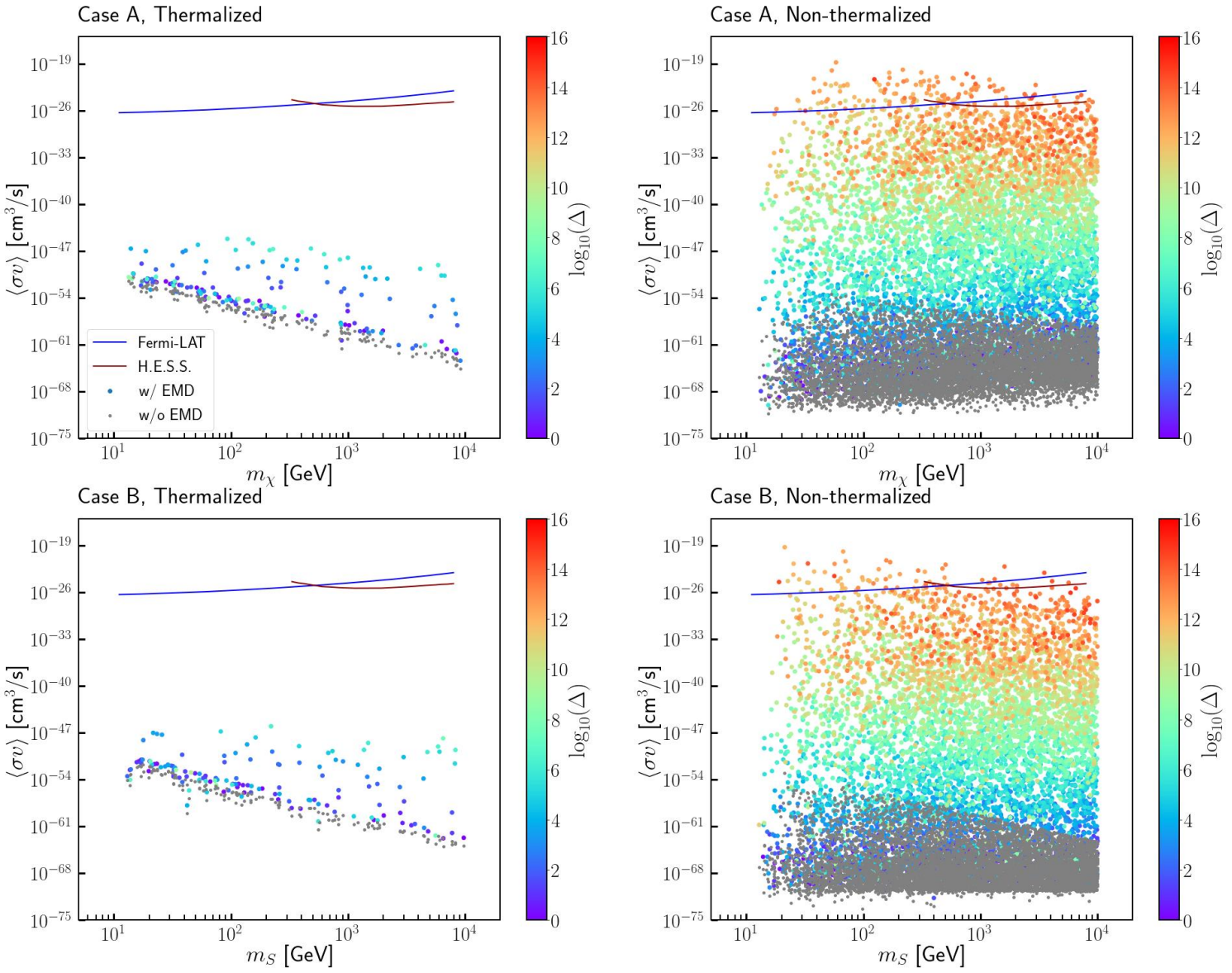
Phenomenology – Indirect detection prospects

$$m_{DM} > m_N$$

Case A: χ is DM

Case B: S is DM

Parameters	Case A	Case B
m_χ	$[1\,\mathrm{GeV}, 10^4\,\mathrm{GeV}]$	$[m_S, 10^6\,\mathrm{GeV}]$
m_S	$[m_\chi, 10^6\,\mathrm{GeV}]$	$[1\,\mathrm{GeV}, 10^4\,\mathrm{GeV}]$
m_N	$[10\,\mathrm{GeV}, 10^6\,\mathrm{GeV}]$	
T_i	$[10^2\,\mathrm{GeV}, 5\times10^{14}\,\mathrm{GeV}]$	
T_r	$[4\,\mathrm{MeV}, T_i]$	



$\langle\sigma v\rangle_{DMDM\to NN}$ bounds from [Campos et al. arXiv:1702.06145]

Conclusions

- We have studied the **DM neutrino portal via freeze-in in an early matter-era**;
- Discussed the **dynamics** of the Universe and DM throughout the **modified cosmic history**;
- Evaluated the **relevant constraints** of the model;
- If the **freeze-in** happens **during** an **early-matter** dominated epoch ⇒ **larger couplings** to SM;
- **Indirect detection**: **early-matter** era **enhances cross sections** relevant for indirect detection, can be **tested** with **current** experiments.

Thank you for your attention! / Grazie per l'attenzione!

Backup slides

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]	

Table 1. The scan ranges for each input parameter in all cases. Note that Y_ν^{ij} is fully determined by m_N and $R = \mathbb{I}$, and λ_χ is chosen to give the observed dark matter relic density and is required to be less than 4π.

Parameter Space

in the interaction matrix Y_ν^{ij}, which is parameterized in the Casas-Ibarra scheme [64]:

$$Y_\nu = \frac{i\sqrt{2}}{v} U_{\rm PMNS}\, m_\nu^{1/2}\, R\, m_N^{1/2}, \tag{2.6}$$

where $U_{\rm PMNS}$ is the PMNS matrix containing three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$ and three phases $(\delta_{\rm CP}, \alpha_1, \alpha_2)$ and is parametrized as

$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \mathscr{P} \tag{2.7}$$

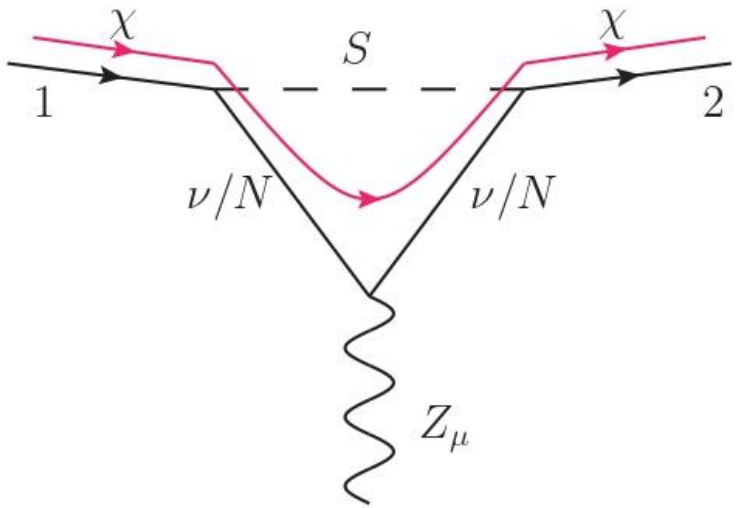
where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$, and $\mathscr{P} = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$. The value of these angles and phases are taken from the recent global fitting results [65] [1]. $m_{\nu/N}^{1/2}$ represent the diagonal matrices with square root of the eigen-masses $(\sqrt{m_{\nu/N}^i})$ in the diagonal entries and R is an extra complex orthogonal matrix $(R^T R = \mathbb{I})$ parameterized by three complex angles.

Phenomenology – Direct detection prospects

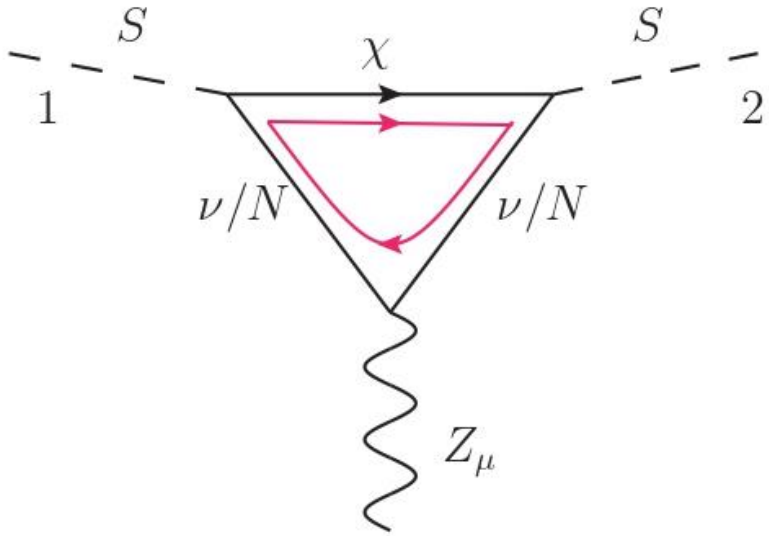
- **Direct detection experiments**: Scattering of DM with atomic nuclei in detectors; identify the deposited energies;

- Direct detection relevant vertices:

Case A: χ is DM



Case B: S is DM



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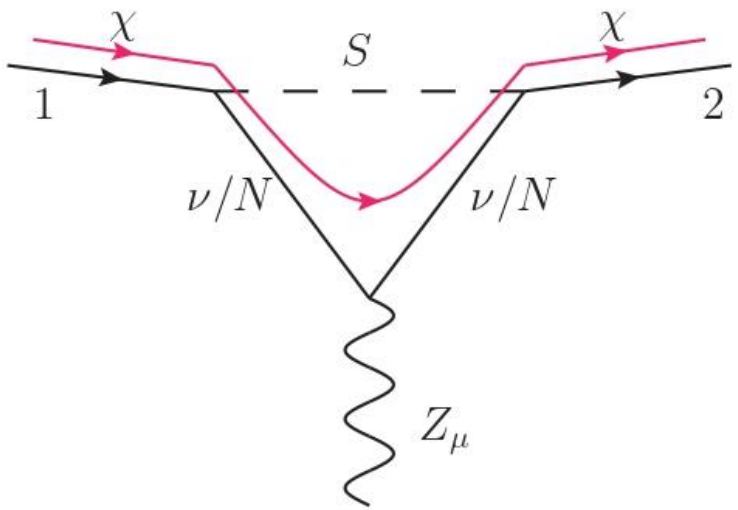

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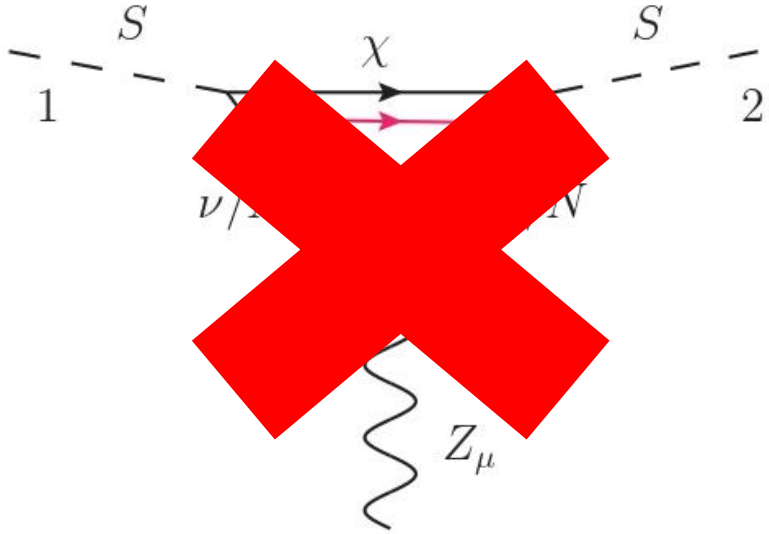

Very suppressed – not consider this case for direct detection

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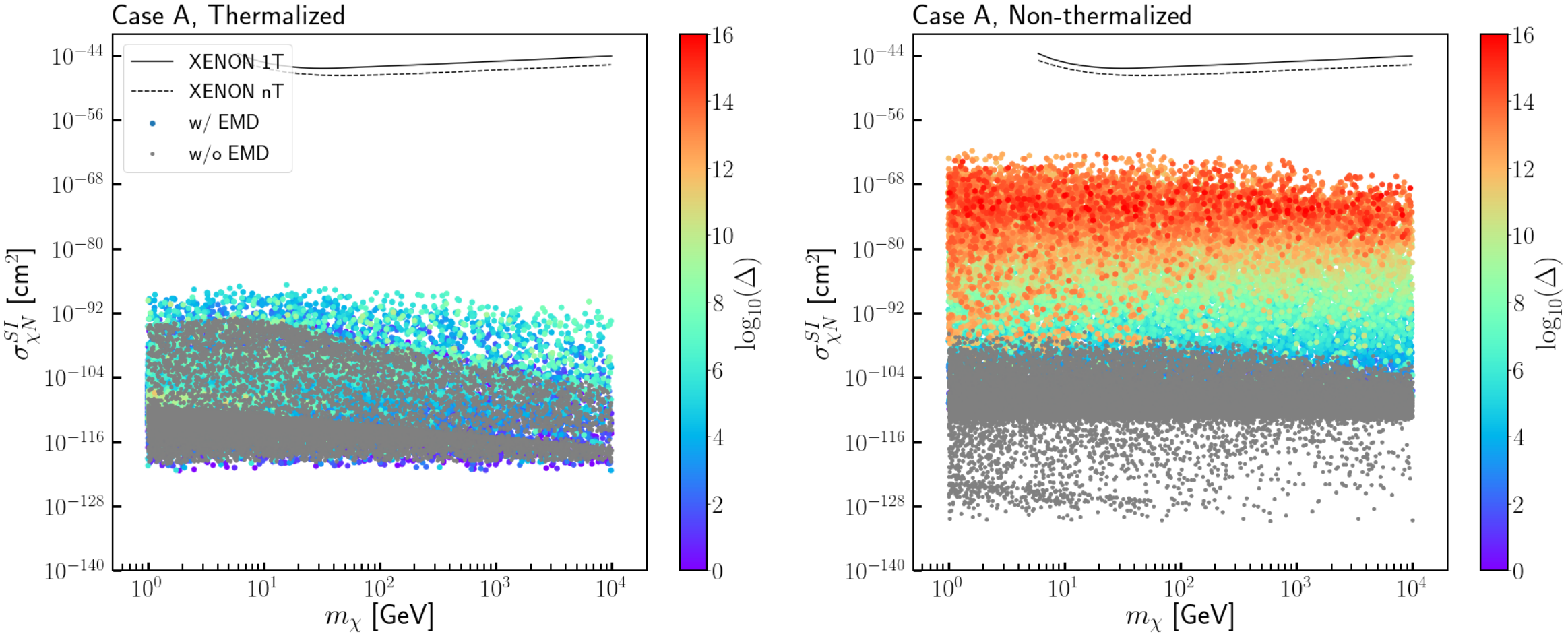

$\sigma^{SI}_{\chi N}$ - Spin Independent DM-nucleon scattering cross section

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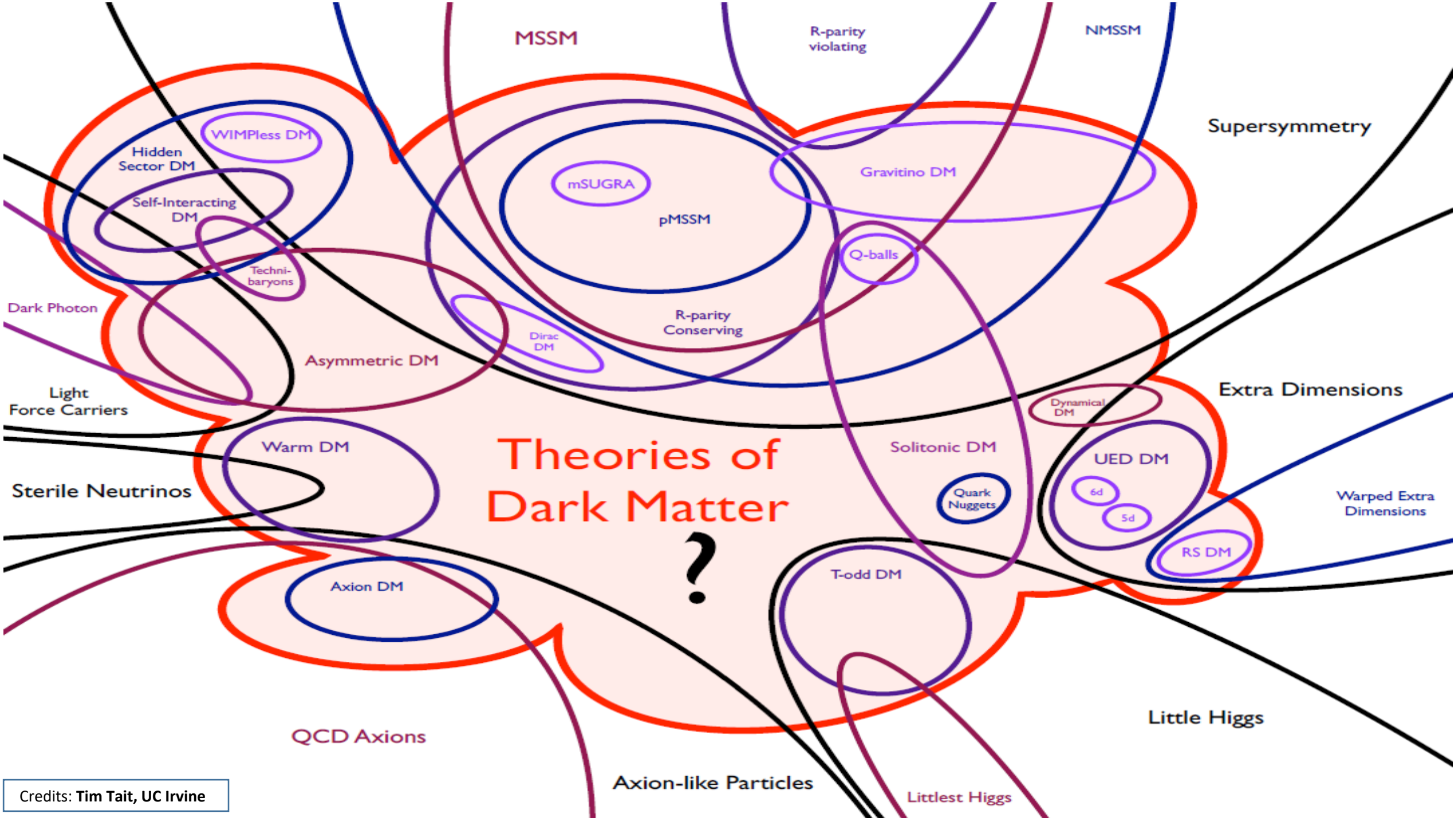
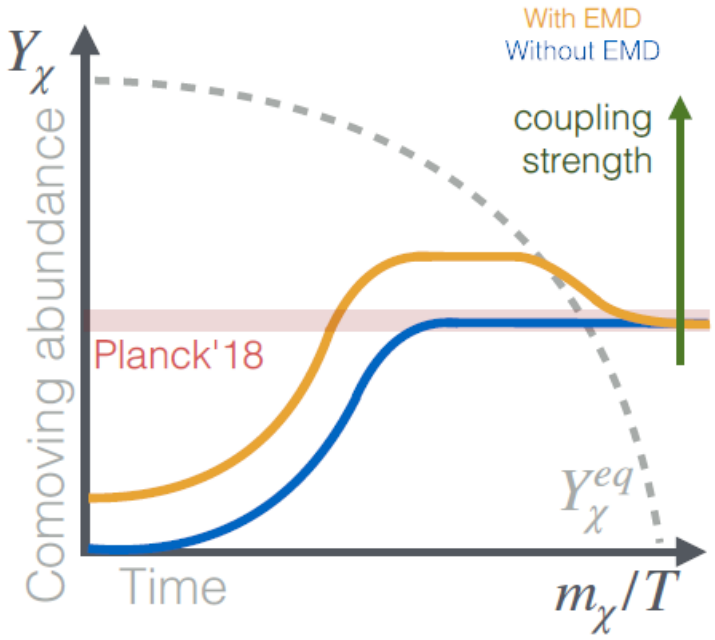


Credits: **Tim Tait, UC Irvine**

Introduction – An early matter-dominated period

Matter era: scalar field (inflaton candidates, meta-stable candidates, moduli fields…)



End of matter dominated period: **matter** component **decays** into Standard Model (SM) particles;

↓

Dilution of **DM** number density

↓

Freeze-in: Couplings to the visible sector **need to be larger** than usual freeze-in

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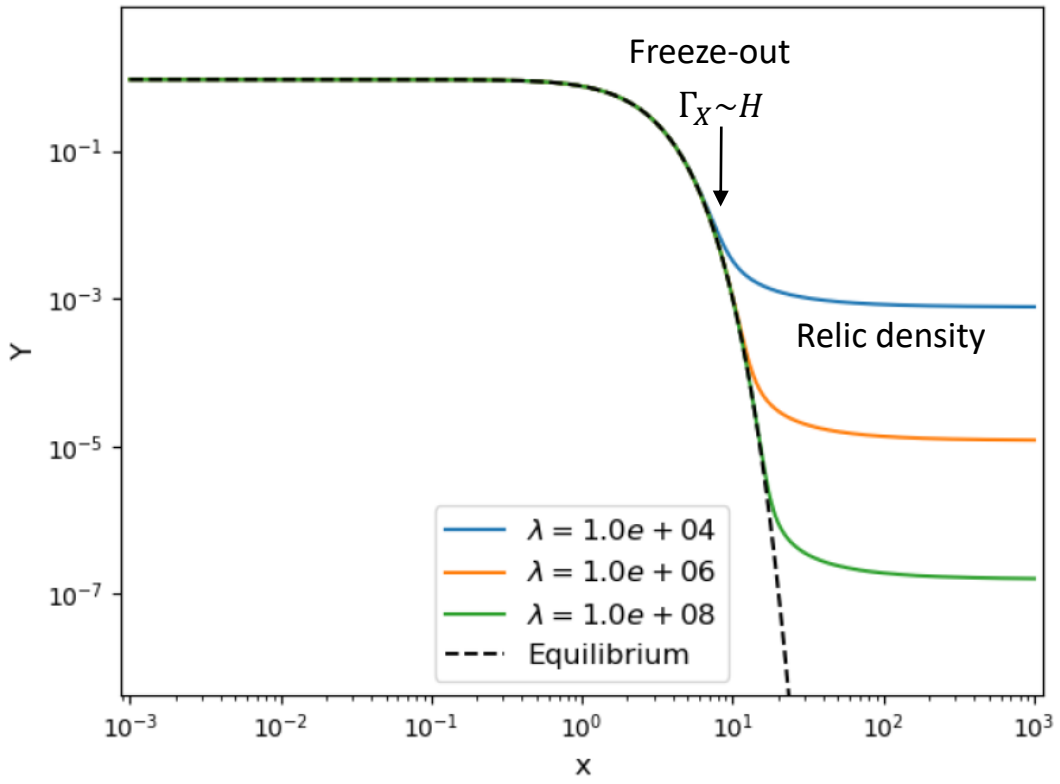
Introduction - Dark Matter production mechanisms

Freeze-out mechanism (Weakly Interacting Massive Particles – WIMPs)



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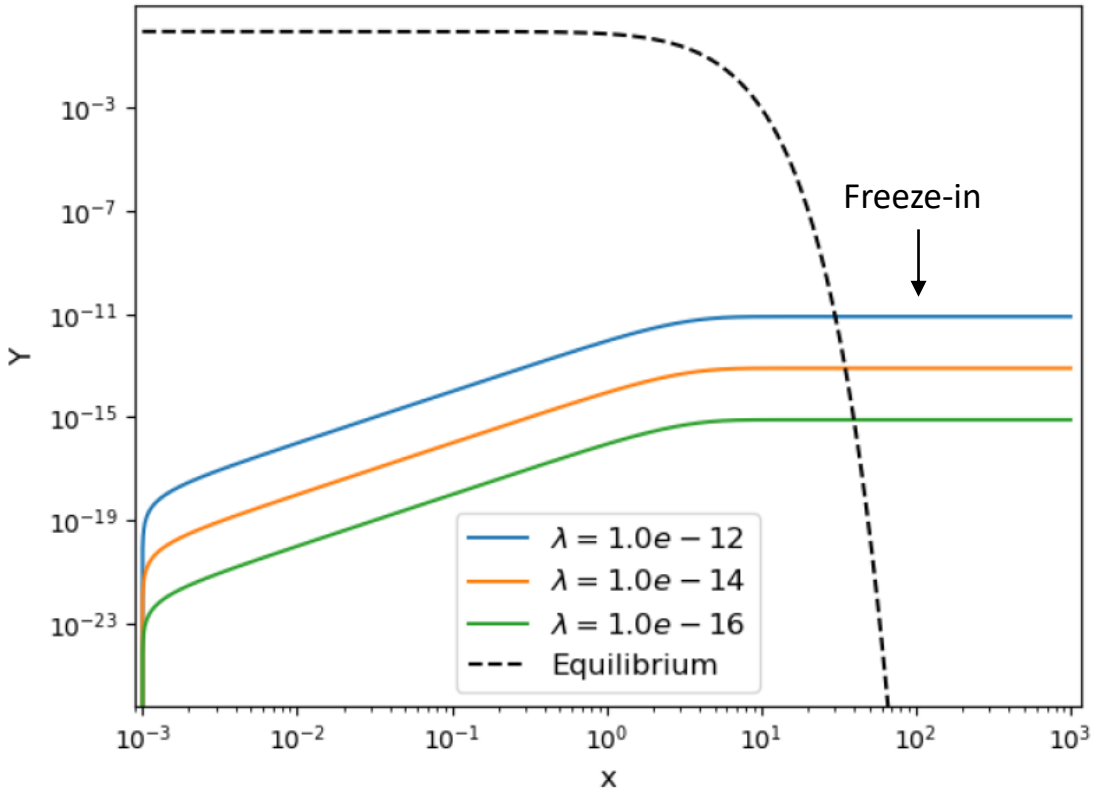

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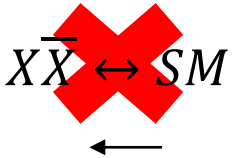

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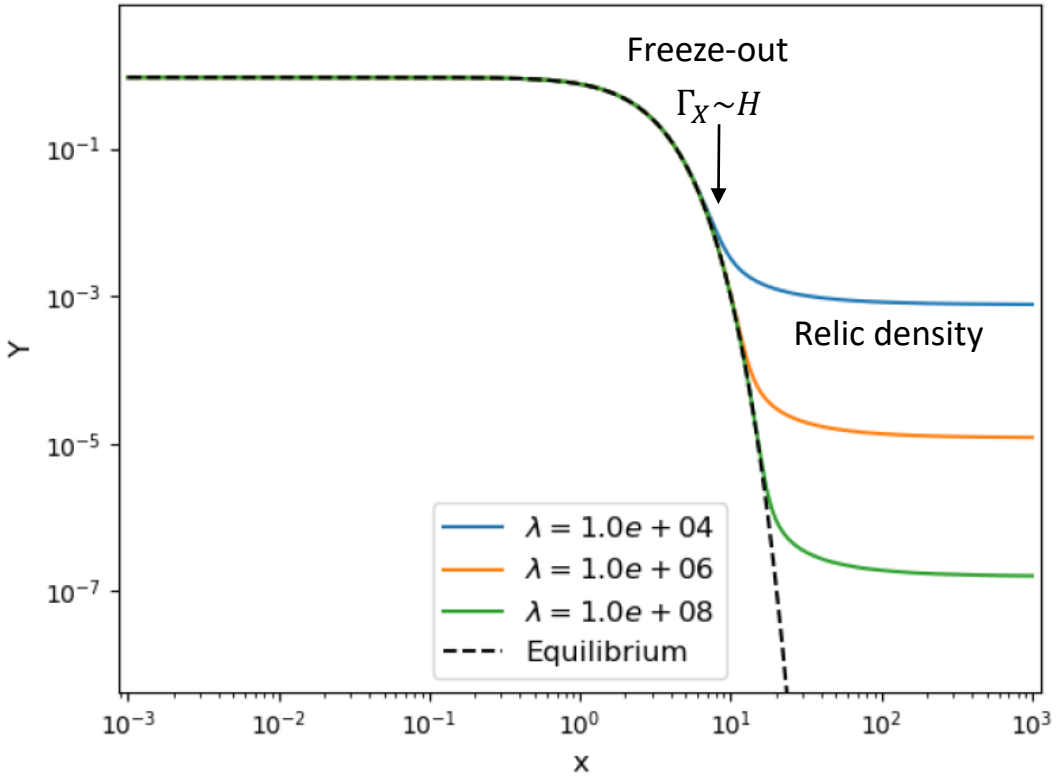
Freeze-out mechanism (Weakly Interacting Massive Particles – WIMPs)



Credits: **Taylor Gray, Carleton U.**

$$Y \equiv \frac{n_X}{s}, \quad x \equiv \frac{m}{T}$$

$$X\overline{X} \leftrightarrow SM$$

Dark Matter (DM) **evolution**:

$$\frac{dn_X}{dt} + 3Hn_X = -\langle\sigma v\rangle\left(n_X^2 - \left(n_X^{eq}\right)^2\right)$$

Interactions **freeze-out** when:

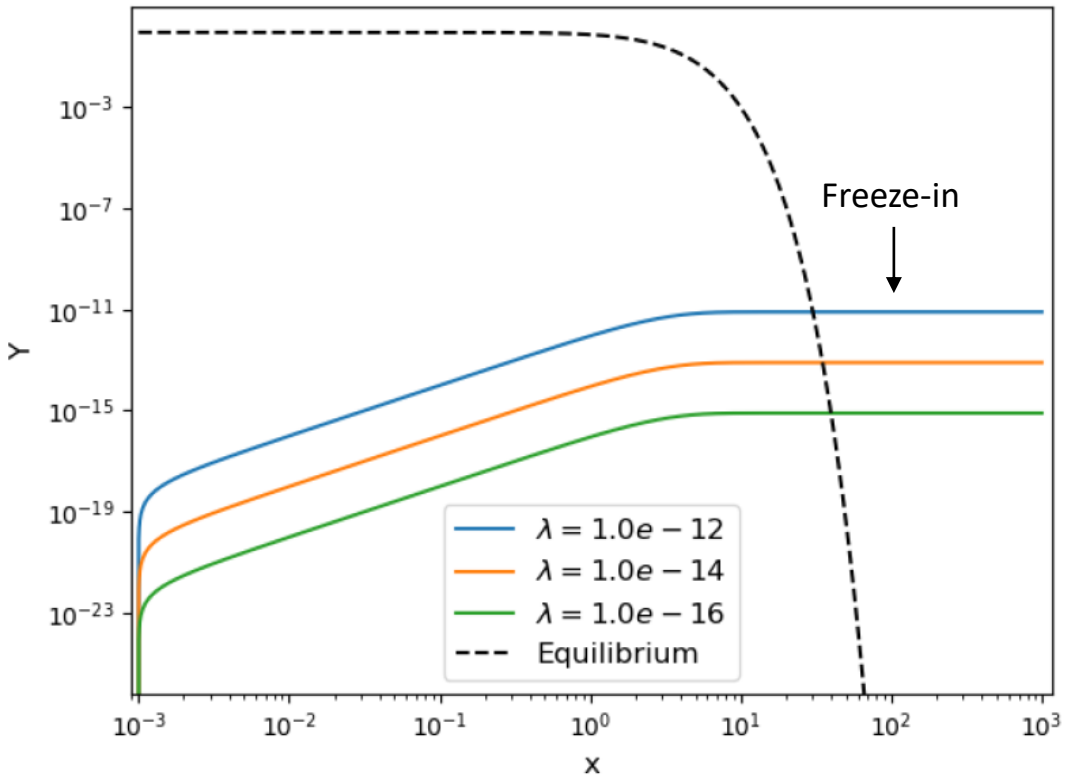
$$\Gamma_X = n_X\langle\sigma v\rangle \lesssim H$$

Present DM **abundance**:

$$\Omega_{X,0}h^2 \equiv \frac{\rho_{X,0}}{\rho_{c,0}/h^2} \sim \frac{1}{\langle\sigma v\rangle} \sim \frac{1}{\lambda}$$

Introduction - Dark Matter production mechanisms

Freeze-in mechanism - Feebly Interacting Massive Particles (FIMPs)



Credits: **Taylor Gray, Carleton U.**

$$Y \equiv \frac{n_X}{s}, \quad x \equiv \frac{m}{T}$$

$$X\bar{X} \not\leftrightarrow SM$$

DM **evolution**:

$$\frac{dn_X}{dt} + 3Hn_X = 2\Gamma_{\sigma \to XX} \frac{K_1(m_\sigma/T)}{K_2(m_\sigma/T)} n_\sigma^{eq}$$

Interactions rate:

$$\Gamma_X < H \quad \textbf{always}$$

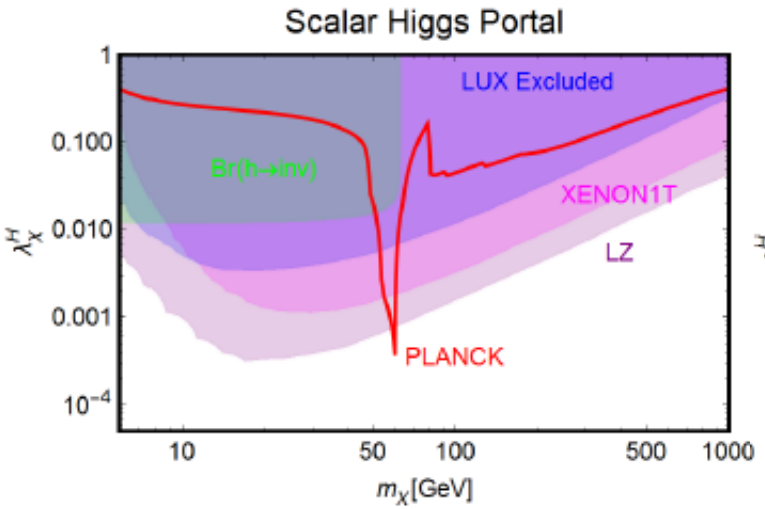
Present DM **abundance**:

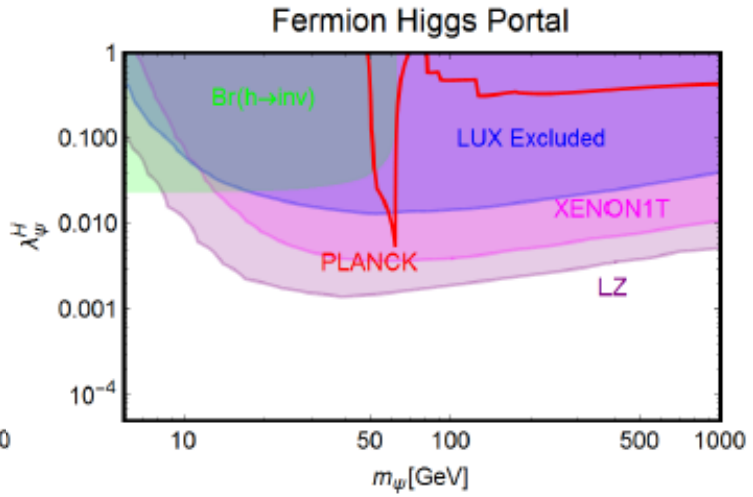
$$\Omega_X h^2 \sim \Gamma_{\sigma \to XX} \sim \lambda$$

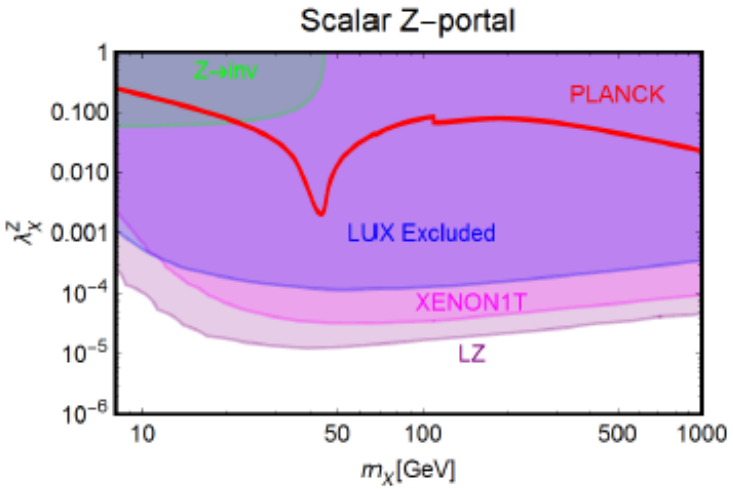
Introduction - Dark Matter production mechanisms

Freeze-out mechanism

- **WIMPs –** no detection so far; very constrained by experiments.





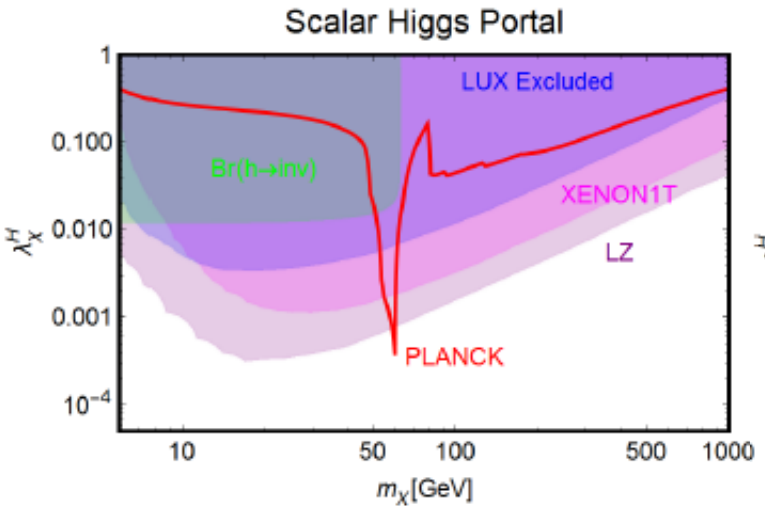


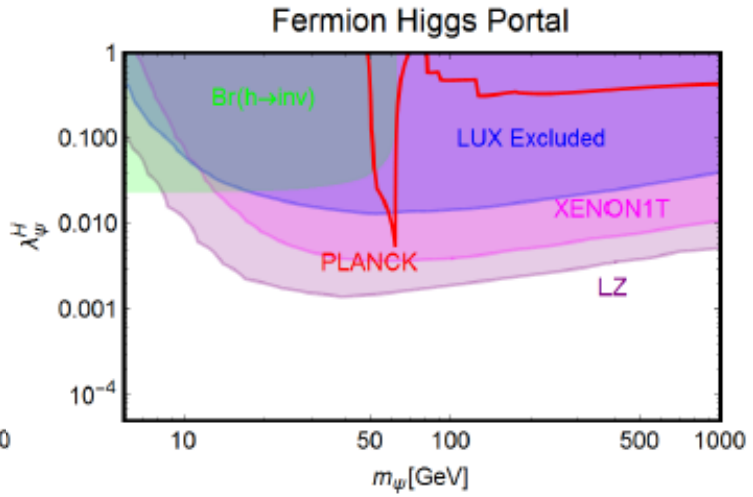
Credits: **Arcadi et. al, arXiv:1703.07364**

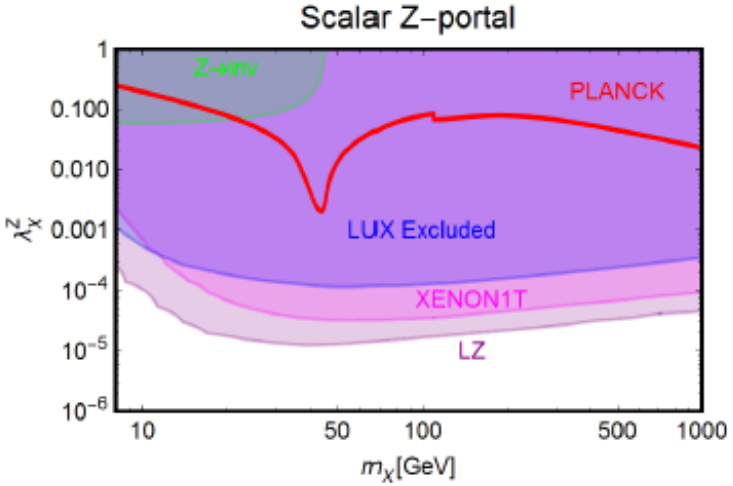
Introduction - Dark Matter production mechanisms

Freeze-out mechanism

- **WIMPs –** no detection so far; very constrained by experiments.







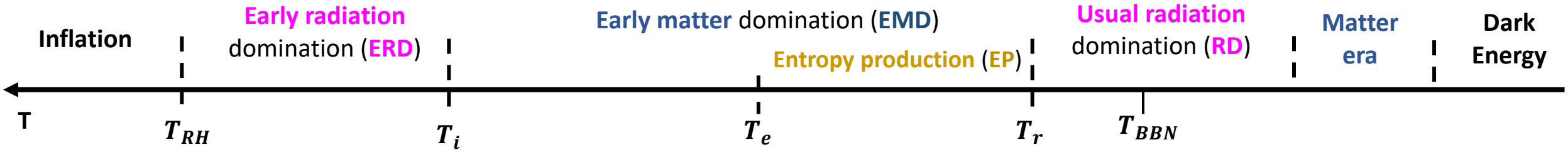
Credits: **Arcadi et. al, arXiv:1703.07364**

“The waning of the WIMP?”

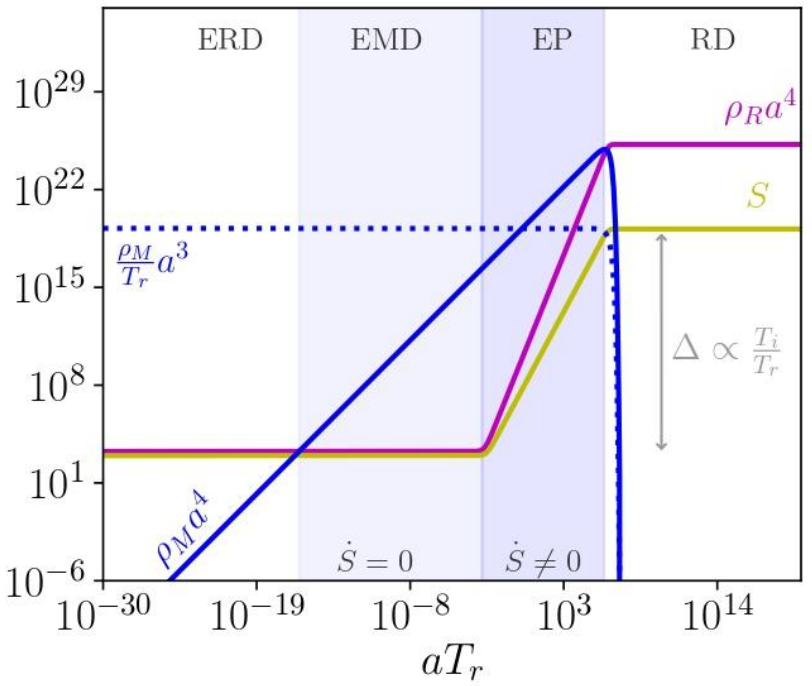
The model – Neutrino portal to FIMP Dark Matter with an early matter era

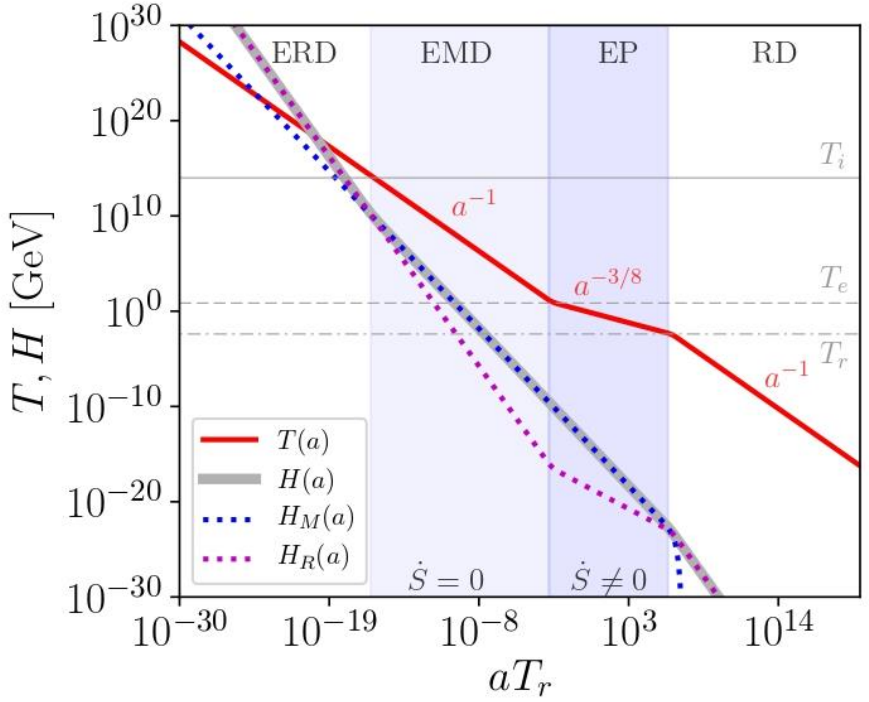
- **Why** neutrino portal? Neutrinos are another intriguing piece of the cosmic puzzle;
- **Freeze-in** + **Non-standard cosmologies** + **Higgs portal**: Bernal, **CC**, Tenkanen arXiv: 1803.08064; Bernal, **CC**, Tenkanen, Vaskonen arXiv: 1806.11122; Hardy arXiv: 1804.06783;
- **Freeze-out** + **Neutrino portal**: Blennow et al, arXiv: 1903.00006;
- **Freeze-out** + **Non-standard cosmologies** (including **early-matter era**): Drees, F. Hajkarim arXiv:1711.05007; D'Eramo, Fernandez, and Profumo arXiv: 1703.04793; Hamdan and Unwin arXiv: 1710.03758;
- **Freeze-in** + **Neutrino portal**: Becker arXiv: 1806.08579; Chianese, King arXiv: 1806.10606; Chianese, Fu, King arXiv: 1910.12916;
- **Freeze-in** + **Early-matter era** + **Neutrino portal**: this work.

Evolution of the Universe



- $\rho_M \gg \rho_R, \rho_{DM}$ for some initial temperature T_i;
- $H_{RD} = \frac{\pi}{\sqrt{90}}\sqrt{g_*}\frac{T^2}{M_{Pl}}$;
- $H_{EMD}(T) = H_{RD}(T_r)\sqrt{\Delta\frac{4g_s(T)}{3g_e(T_r)}}\left(\frac{T}{T_r}\right)^{\frac{3}{2}}$
- $H_{EP}(T) = H_{RD}(T_r)\frac{g_e(T)}{g_e(T_r)}\left(\frac{T}{T_r}\right)^4$;





$\Delta \sim \frac{T_i}{T_r} \equiv$ Amount of **entropy production** during EMD; related with the **duration of the EMD** ⇒ **larger** Δ, **longer** EMD

Evolution of the Universe

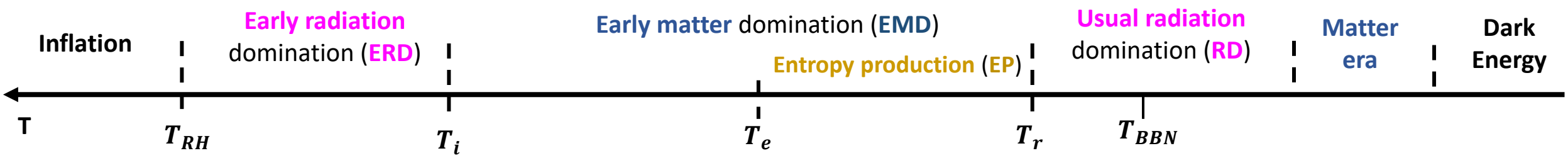
$\boldsymbol{\rho_M} \gg \rho_R, \rho_{DM}$ for some initial temperature T_i

- Hubble parameter: $H(t) = \sqrt{\rho_{tot}}/(\sqrt{3}M_P)$, with $\rho_{tot}(t) = \rho_R(t) + \rho_M(t)$;
- Solve:

$$\begin{cases} \dot{\rho}_M + 3H(t)\rho_M = -\rho_M \Gamma_M \\ \dot{\rho}_R + 4H(t)\rho_R = B_R \rho_M \Gamma_M \end{cases}$$

- The thermal history of the Universe has **4** important **periods**:
  - **Early radiation** domination (ERD);
  - **Early matter** domination (EMD);
  - **Entropy production** (EP);
  - **Usual radiation** domination (RD);

Evolution of the Universe



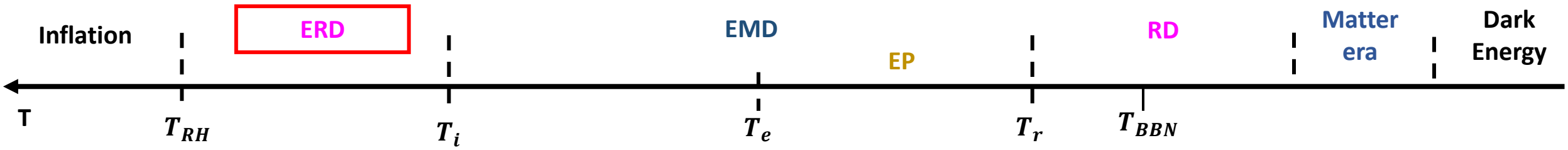
T_{RH} - Inflationary reheating temperature;

T_i - Beginning of the early matter-era;

T_e - End of the isentropic early matter-era ⇒ entropy production starts;

T_r - Decay of the matter component; usual radiation takes place; $T_r \gtrsim T_{BBN} \sim 4$ MeV

Evolution of the Universe



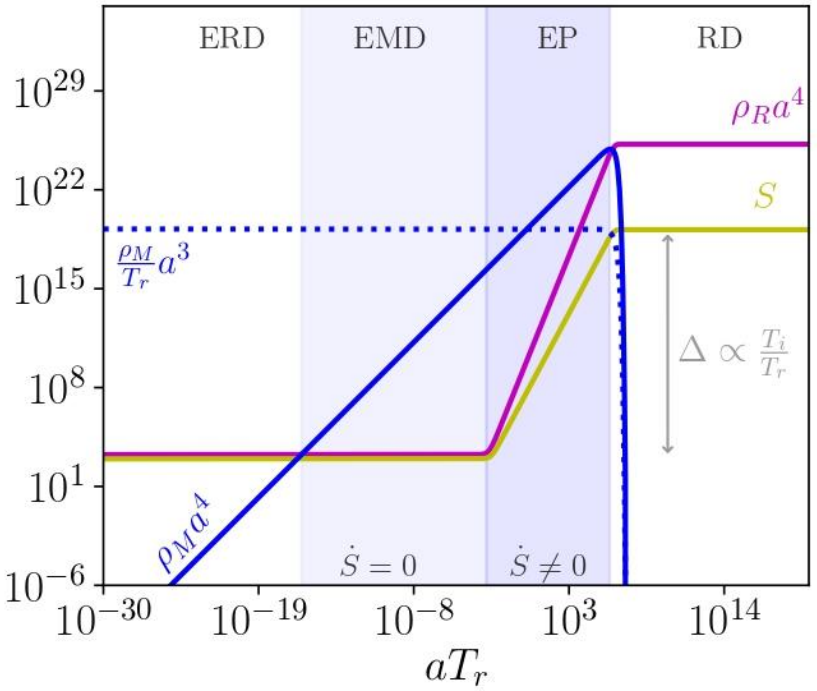
ERD:

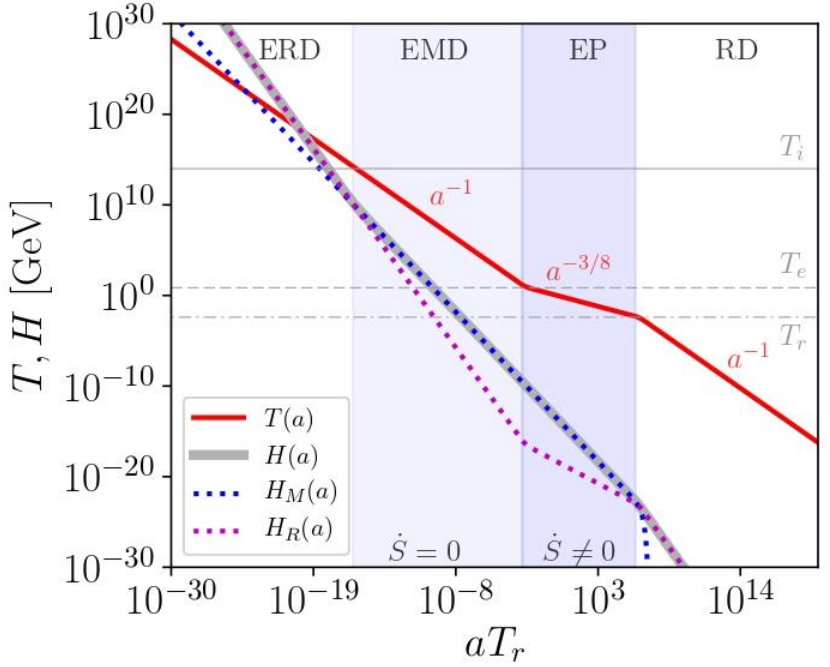
- **M** is **not dominant** yet;

$$H_{RD} = \frac{\pi}{\sqrt{90}}\sqrt{g_*}\frac{T^2}{M_{Pl}}$$

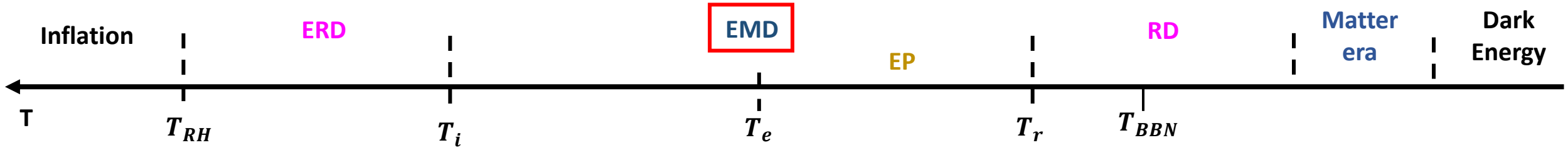
- **Continuity** of $H(T)$:

$$H_{RD}(T_i) = H_{EMD}(T_i)$$





Evolution of the Universe

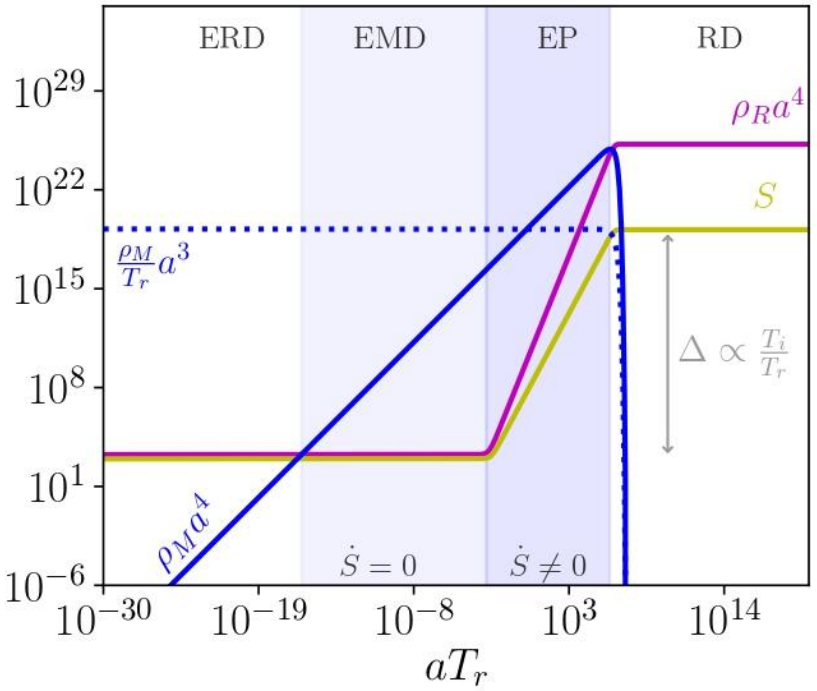


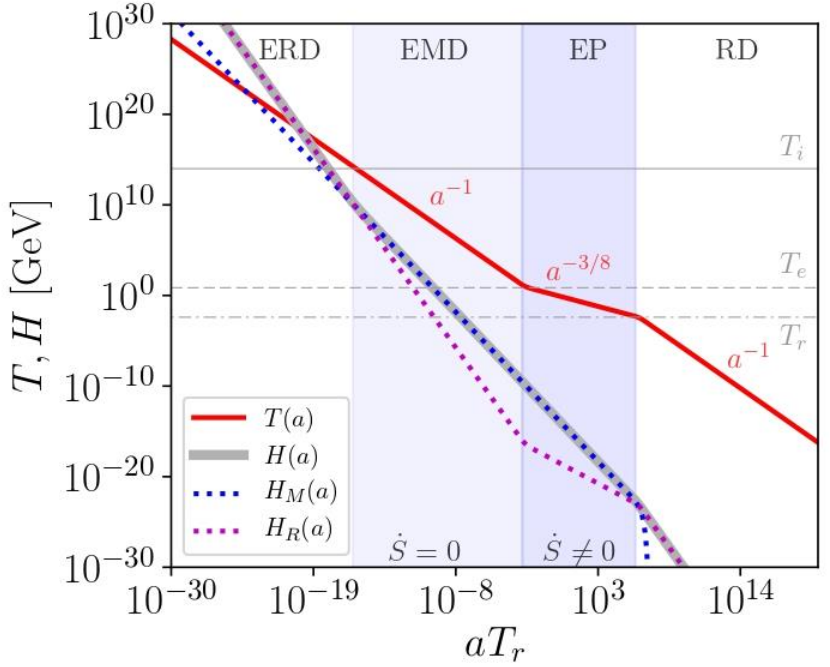
EMD:

- Until T_e, entropy **s** is **constant**.

$$H_{EMD}(T) = H_{RD}(T_r)\sqrt{\Delta\frac{4g_s(T)}{3g_e(T_r)}}\left(\frac{T}{T_r}\right)^{\frac{3}{2}}$$

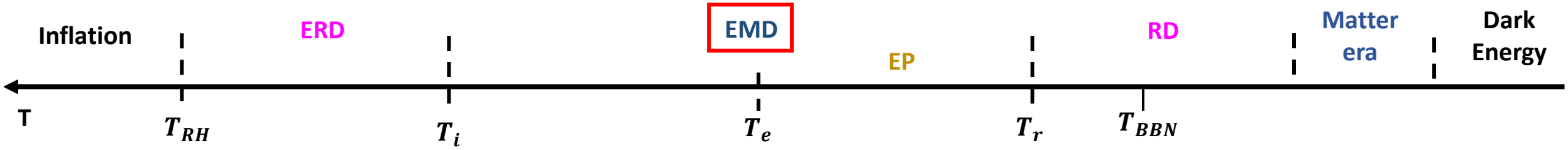
- $T > T_r$: $H_{EMD}(T) > H_{RD}(T)$ ⇒ **Faster** expansion of the Universe.





$\Delta \equiv$ Amount of **entropy production** during EMD; related with the duration of the EMD ⇒ **larger** Δ, **longer** EMD;

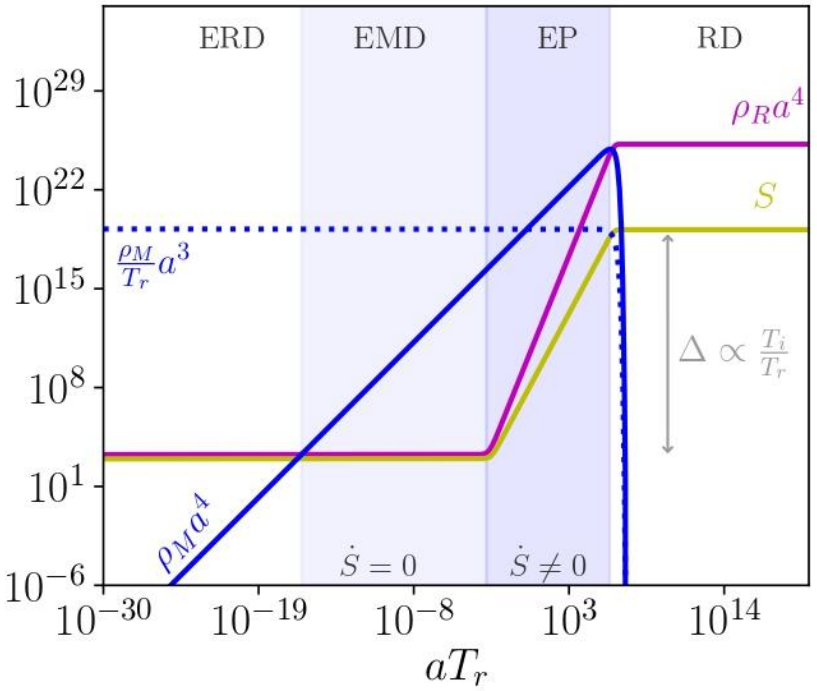
Evolution of the Universe

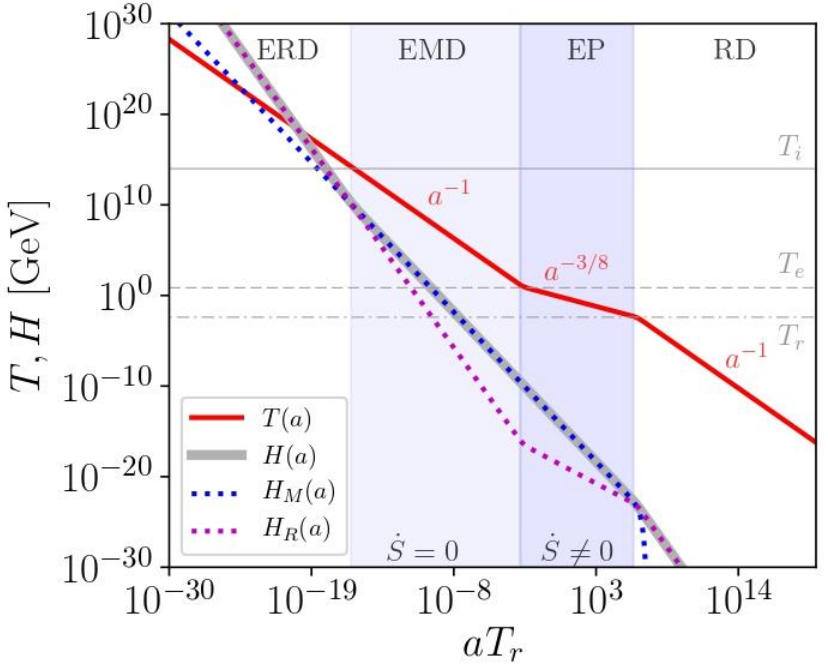


EMD:

$$\Delta = \frac{3}{4}\frac{g_e(T_i)}{g_s(T_i)}\frac{T_i}{T_r}$$

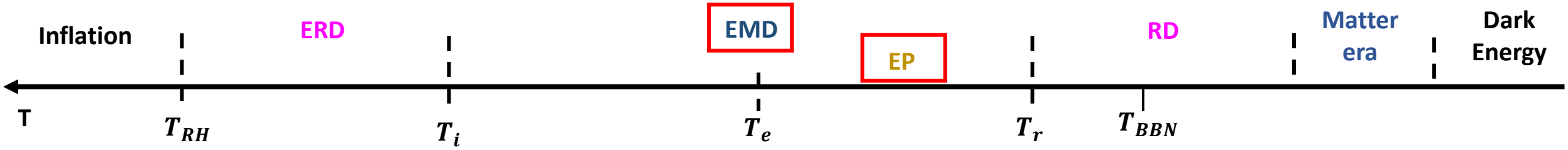
$$\frac{T_e}{T_r} = \left(\Delta \frac{4}{3}\frac{g_s(T_e)g_e(T_r)}{g_e^2(T_e)}\right)^{\frac{1}{5}}$$





- T_e is fixed by T_i and T_r;
- T_i and T_r **parametrize** the early matter era.

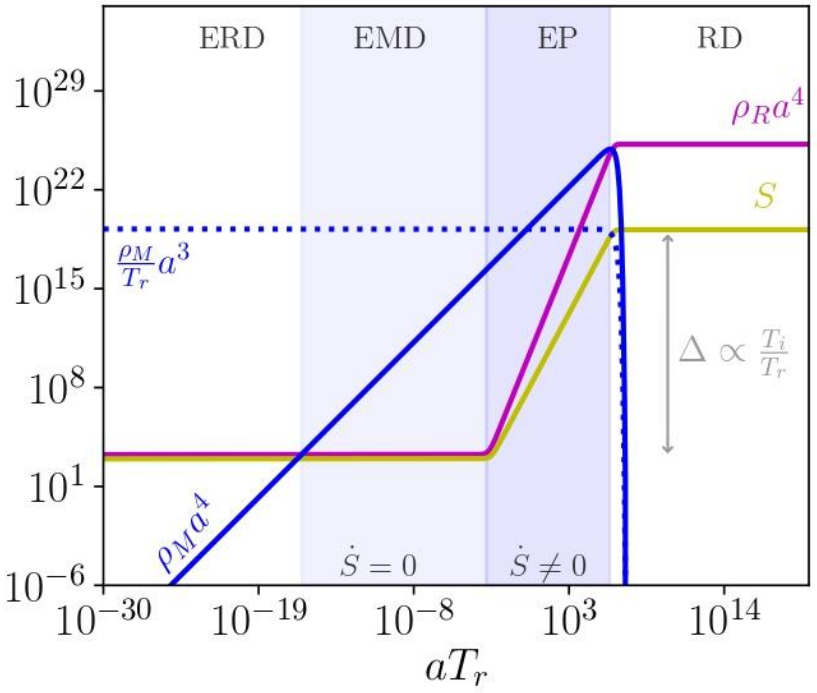
Evolution of the Universe

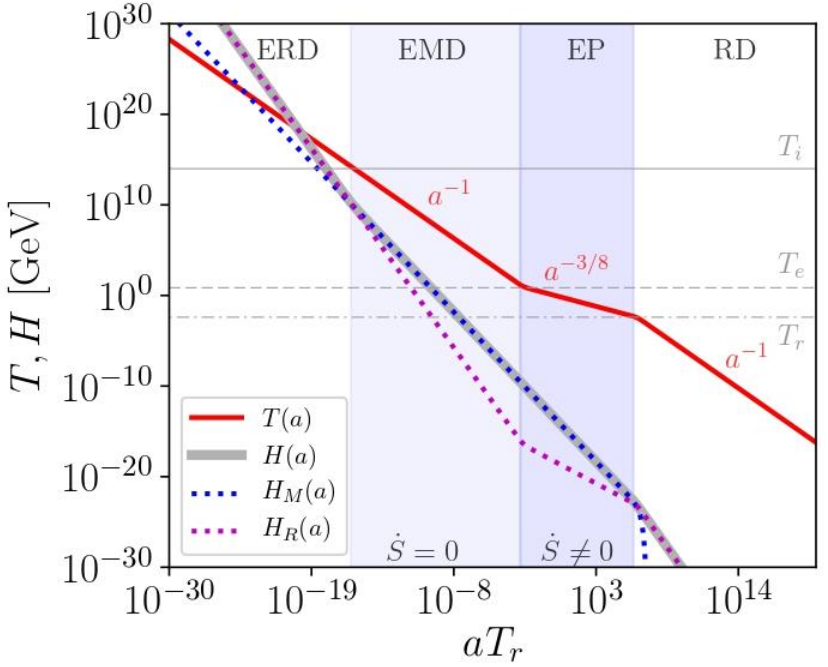


EP:

- **M decays** (not instantaneously) only into the visible sector ⇒ **DM dilution**;
- Entropy is not conserved: Entropy production ⇒ $T \sim a^{-3/8}$

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





Dark matter production - Constraints

Freeze-in conditions: $\Gamma_{decays}, \Gamma_{s-channels}, \Gamma_{t-channels} \ll H(T)$

Can we have the feeling of **how the early matter era is affecting our model?**

- Case: $\frac{\Gamma_{N_R \to \bar{\chi} S}}{H(T)} \ll 1$

Recall: $\Delta \sim \frac{T_i}{T_r}$

$$\lambda_\chi \ll \left(\frac{10^3 \mathrm{GeV}}{m_N}\right)^{\frac{1}{2}} \left(\frac{g_e(100\mathrm{GeV})}{103.5}\right)^{\frac{1}{4}} \frac{0.01}{(1-\epsilon^2)} \times \begin{cases} 2.5 \times 10^{-8} \dfrac{T}{100\mathrm{GeV}}, & \text{for } \Delta = 1 \\ 1.5 \times 10^{-4} \left(\dfrac{T}{100\mathrm{GeV}}\right)^{\frac{3}{4}} \left(\dfrac{T_r}{4MeV}\right)^{\frac{1}{4}} \left(\dfrac{\Delta}{2 \times 10^{16}}\right)^{\frac{1}{4}}, & \text{for } \Delta = 2 \times 10^{16} \end{cases}$$

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Longer EMD allows out-of-equilibrium processes with **larger couplings**

Heavy neutrinos thermalization

- Chemical equilibrium between **N** and **SM** driven by decays and inverse decays: $N \leftrightarrow Hl$ or $H \leftrightarrow Nl$;

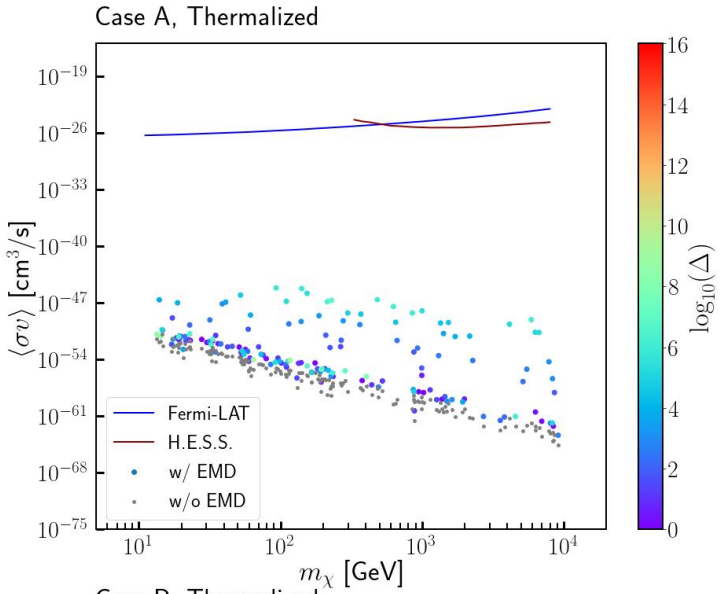
- Heavy neutrinos **thermalized** with the SM when $\boldsymbol{\Gamma_{decays} > H}$;

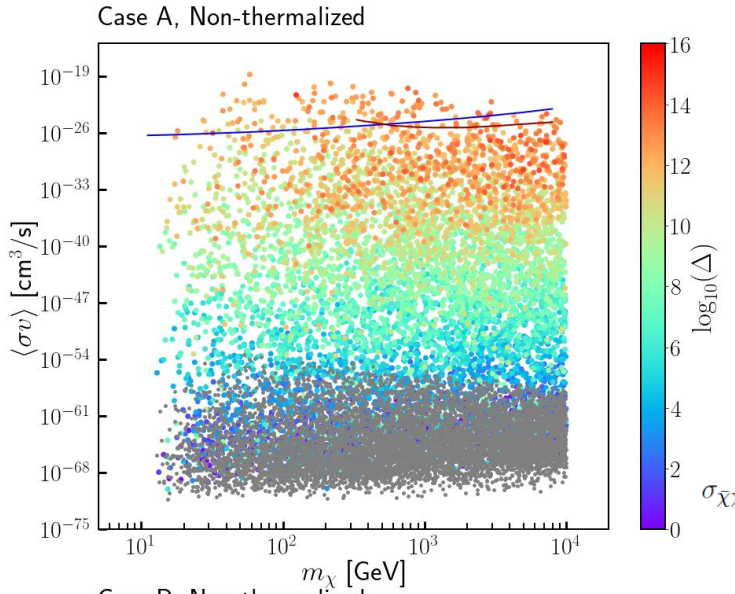
Thermalized heavy neutrinos: **all processes** (s-channels, t-channels, decays) are relevant for **DM production**

Non-thermalized heavy neutrinos: neutrinos not abundant enough to decay and annihilate via t-channel into FIMPs ⇒ only **s-channel** contributes for **DM production.**

Phenomenology – Indirect detection prospects

Case A: χ is DM

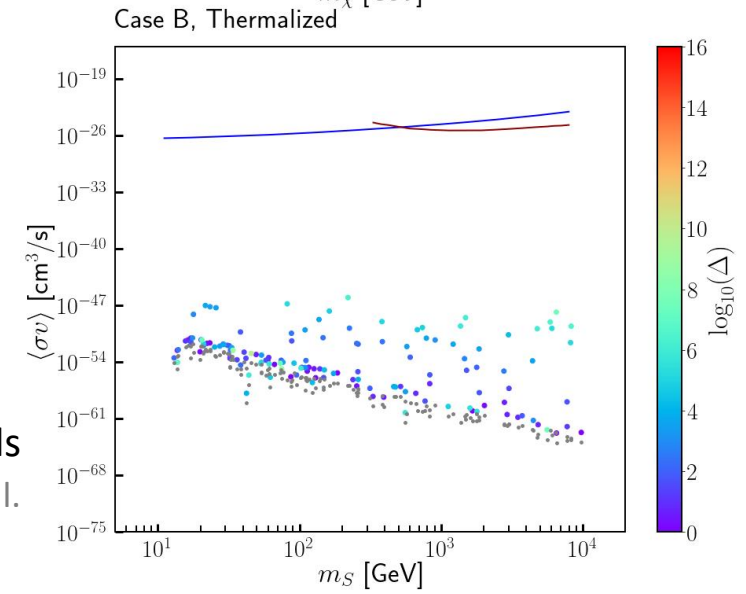


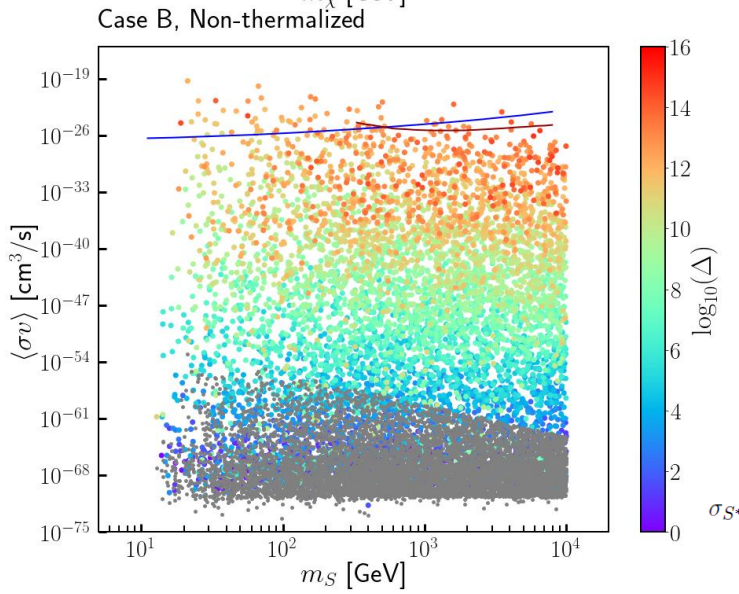


$$m_{DM} > m_N$$

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

Case B: S is DM





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

$\langle\sigma v\rangle_{DMDM\to NN}$ bounds from [Campos et al. **arXiv:1702.06145**]

The model – Neutrino portal dark matter via Freeze-in in an early matter era

Type-I seesaw mechanism

- Explain the smallness of the neutrino masses;
- Introduce 3 heavy neutrinos (one for each generation), not predicted by SM.
- New Yukawa coupling: $\overline{L_L^i} Y_\nu^{ij} \tilde{H} \left(N_\ell^j \right)_R$ ⟹ contributes to the SM neutrinos mass;
- m_N is not constrained by any gauge symmetry ⟹ can be arbitrarily large (order of GUT scale);

The model – Neutrino portal dark matter via Freeze-in in an early matter era

Type-I seesaw mechanism

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & m_N \end{pmatrix}$$

Diagonalizing

$$M_\nu = -M_D^T m_N^{-1} M_D$$

Yukawa coupling:

$$Y_\nu \sim \frac{\sqrt{m_\nu m_N}}{\mathrm{v}}$$

Completely defined if we fix m_N

The model – Neutrino portal dark matter via Freeze-in in an early matter era

Type-I seesaw mechanism

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Yukawa coupling:

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Completely defined if we fix m_N

Also:

$$m_\nu \sim \frac{Y_\nu^2\ \mathrm{v}^2}{m_N}$$

"Seesaw"

Phenomenology – Direct detection prospects

Focusing on the spin-independent (SI) DM-nucleus scattering cross section, we have:

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

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

$$g_{Z\chi\chi} = -\frac{g\,\lambda_\chi^2}{32\pi c_W} \sum_{ij} \left(V^\dagger V\right)_{ij} \left(2m_N^2 C_0(m_\chi^2, 0^-, m_\chi^2, m_S^2, m_N^2, m_N^2)\right.$$
$$- m_N^2 C_0(m_\chi^2, 0^-, m_\chi^2, m_S^2, m_N^2, 0) + 4C_{00}(m_\chi^2, 0^-, m_\chi^2, m_S^2, m_N^2, 0)$$
$$\left. -2C_{00}(m_\chi^2, 0^-, m_\chi^2, m_S^2, m_N^2, m_N^2) - 2C_{00}(m_\chi^2, 0^-, m_\chi^2, m_S^2, 0, 0)\right),$$

where σ_0^{SI} is the SI DM-nucleus scattering cross section, $\sigma_{\chi N}^{SI}$ is the SI DM-nucleon scattering cross section, which is usually used to compare experimental results with different target isotopes, $\mu_{\chi N}$ is the reduced mass between DM and the nucleus (mass number A, charge number Z), $\mu_{\chi p}$ is the reduced mass between DM and the nucleon, i.e. $\mu_{\chi N} = \frac{m_\chi m_\mathcal{N}}{m_\chi + m_\mathcal{N}}$ and $\mu_{\chi p} = \frac{m_\chi m_p}{m_\chi + m_p}$ and g_q^V are the corresponding vector current couplings of the quarks with Z-boson:

$$g_u^V = \frac{g}{c_W}\left(\frac{1}{2} - \frac{4}{3}s_W^2\right), \quad g_d^V = \frac{g}{c_W}\left(-\frac{1}{2} + \frac{2}{3}s_W^2\right). \tag{6.3}$$

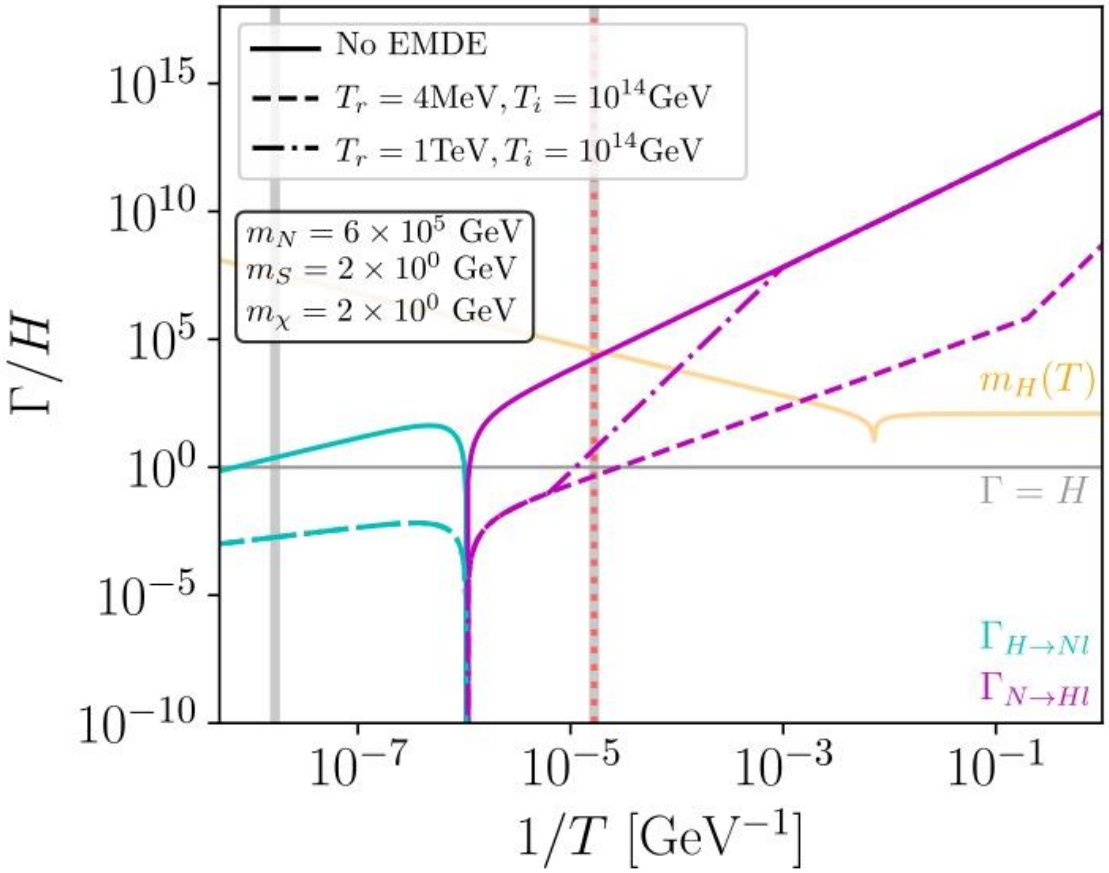
Heavy neutrinos thermalization

- Heavy neutrinos **thermalized** when $\boldsymbol{\Gamma > H}$;
- **DM freeze-in** occurs between the **grey** vertical lines;

Heavy N case (with $m_N \gg m_S, m_\chi$)

- **Large** Yukawa **coupling** ⇒ **N** easily thermalizes with the cosmic bath;

Long EMDE ⇒ no thermalization.

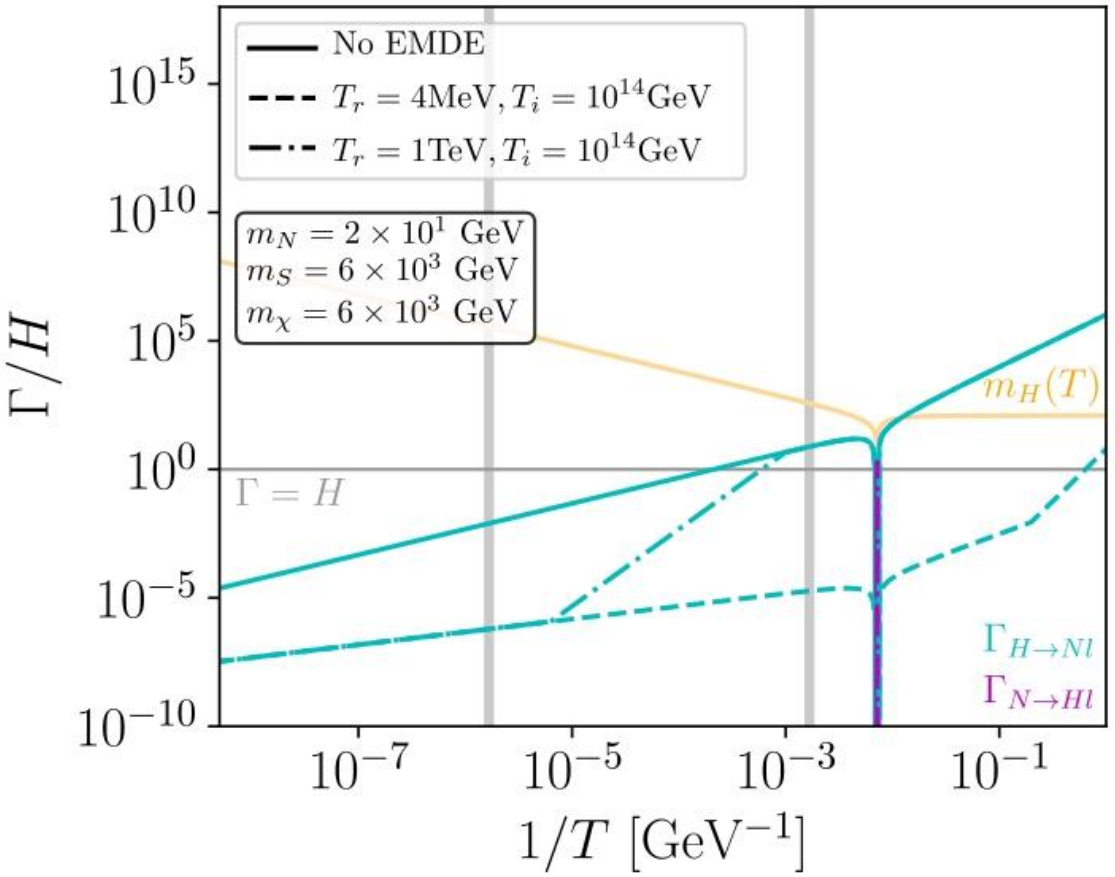


Heavy neutrinos thermalization

- Heavy neutrinos **thermalized** when $\boldsymbol{\Gamma > H}$;
- **DM freeze-in** occurs between the **grey** vertical lines;

Light N case (with $m_N < m_S, m_\chi$)

- **Freeze-in** occurs at $T \gg m_N$ $\Rightarrow$ decay widths suppressed by Yukawa couplings



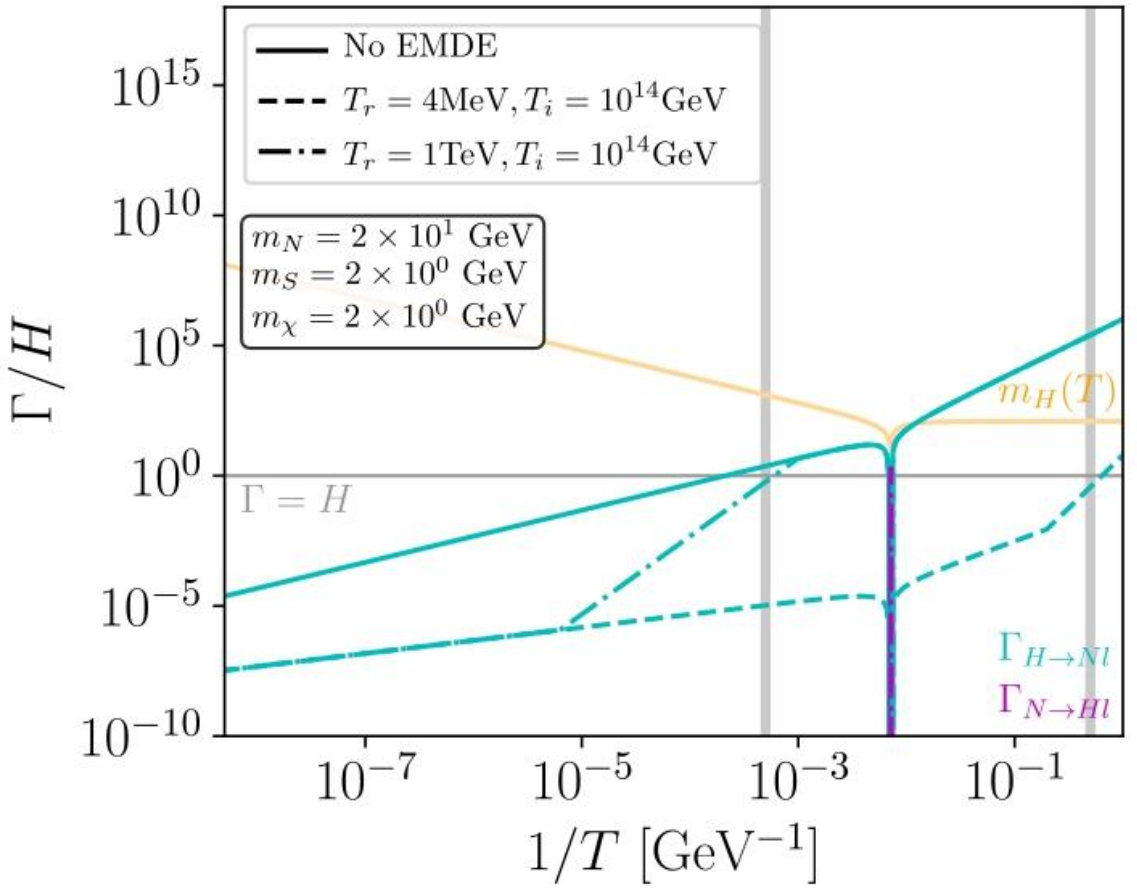
Heavy neutrino is **never thermalized**.

Heavy neutrinos thermalization

- Heavy neutrinos **thermalized** when $\boldsymbol{\Gamma > H}$;
- **DM freeze-in** occurs between the **grey** vertical lines;

Light N case (with $m_N > m_S, m_\chi$)

- **Long EMDE** difficults thermalization;



- Heavy neutrino is **thermalized** only for **short EMDE**.