Neutrino Portal to FIMP Dark Matter with an Early Matter Era

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in collaboration with
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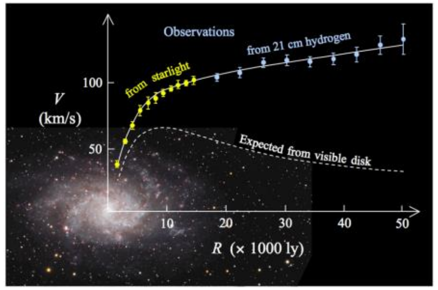
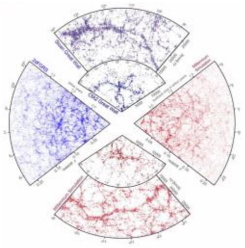
Introduction – Evidence for Dark Matter (DM)

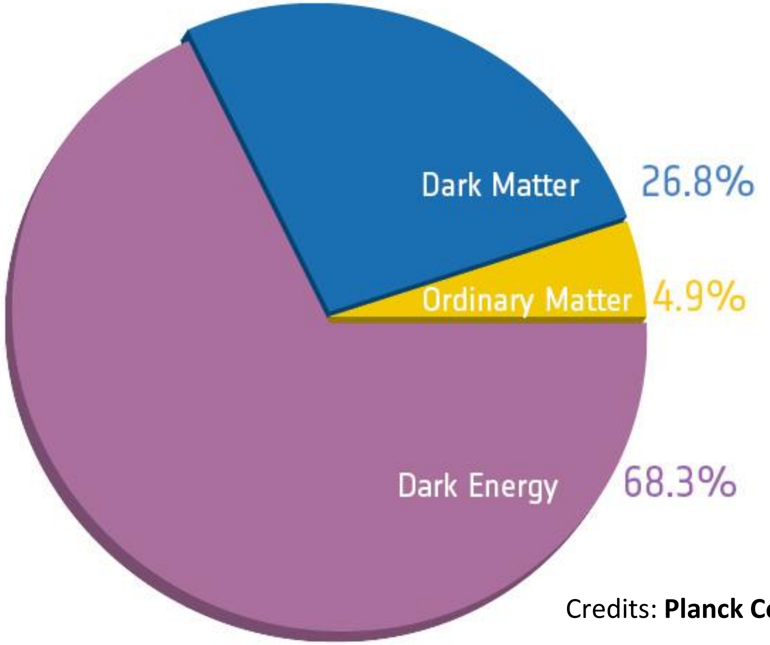
Galaxy Rotation Curves



Merging clusters (Bullet Cluster)

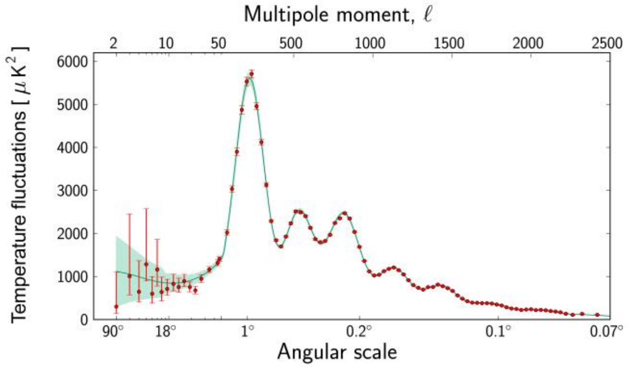
Structure formation



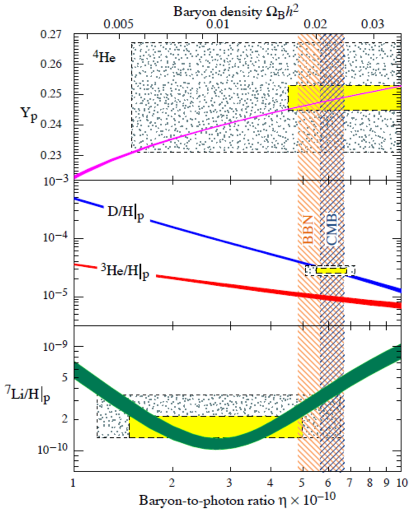


Credits: **Planck Collab.**

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 **ruled out by experiments.** [Arcadi et al. **arXiv:1703.07364**]

Introduction - Dark Matter production mechanisms

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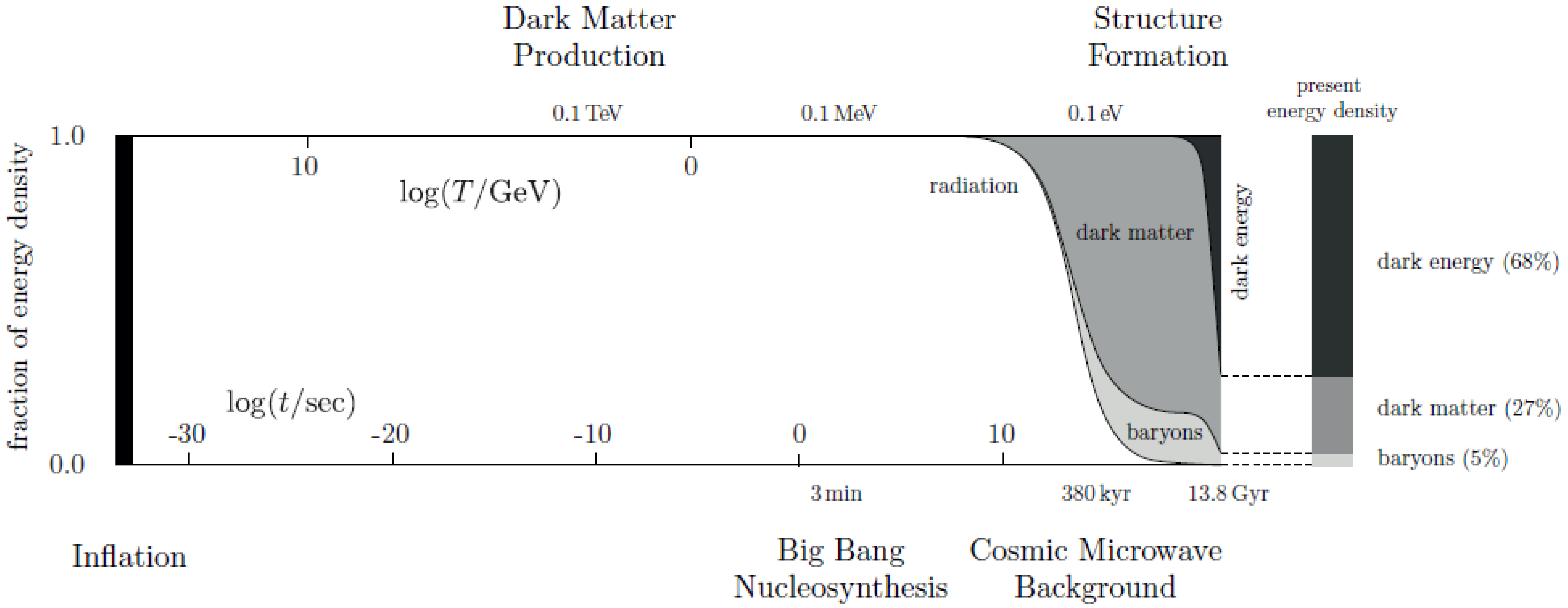
vs

Freeze-in

$$\underset{\longleftarrow}{\cancel{X\overline{X} \leftrightarrow SM}}$$

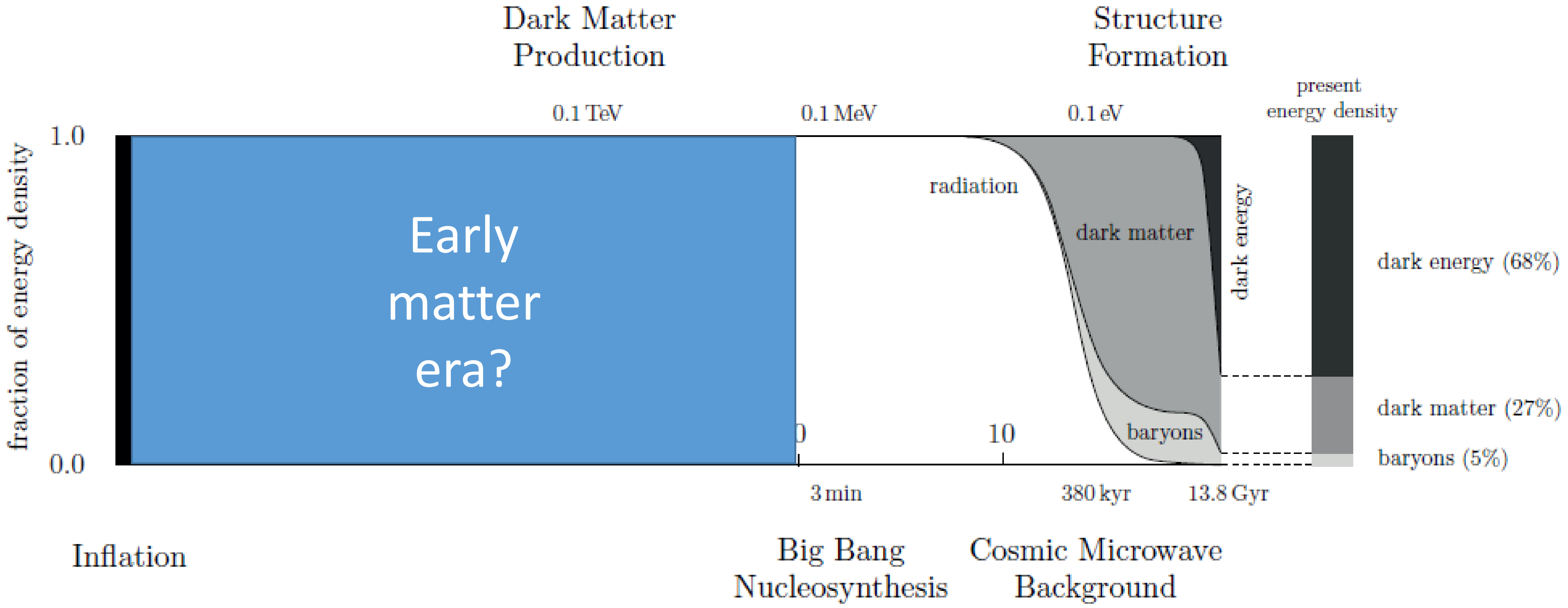
- $\Gamma_X < H$ **always**;
- **FIMPs** – Feebly Interacting Massive Particles;
- $\Omega_{X,0}h^2 \sim \lambda$;
- **Small couplings** to attain the **observed relic abundance**;
- Can evade stringent observational constraints;
- But: **hard** to **probe**.

Introduction - An early matter-dominated period



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

Introduction - An early matter-dominated period



Introduction - An early matter-dominated period

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

↓

Dilution of **DM** number density

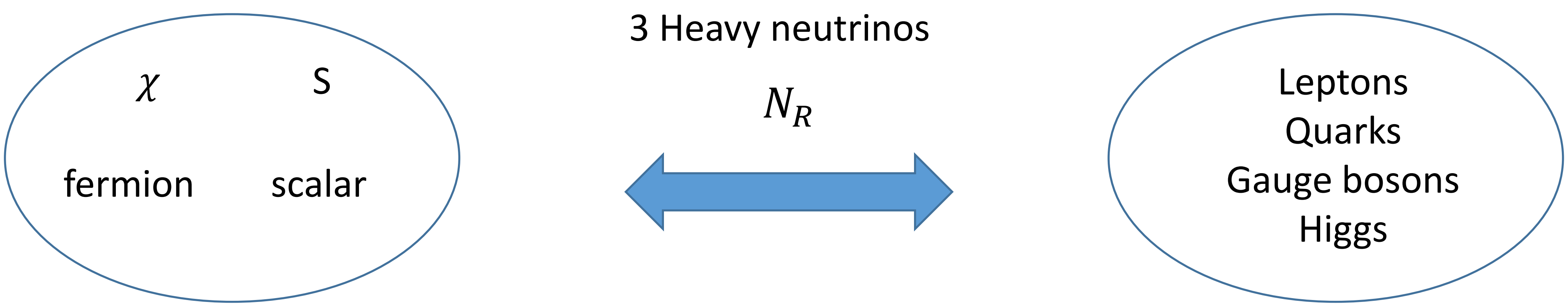
↓

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 **Standard Model/visible sector**



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

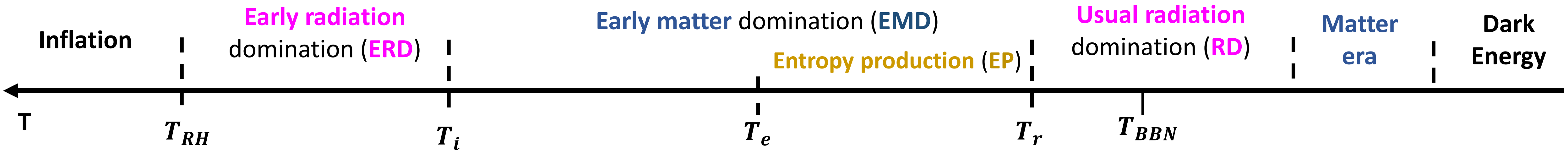
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{hidden}} + \mathcal{L}_{\mathrm{seesaw}} + \mathcal{L}_{\mathrm{portal}}$$

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

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

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

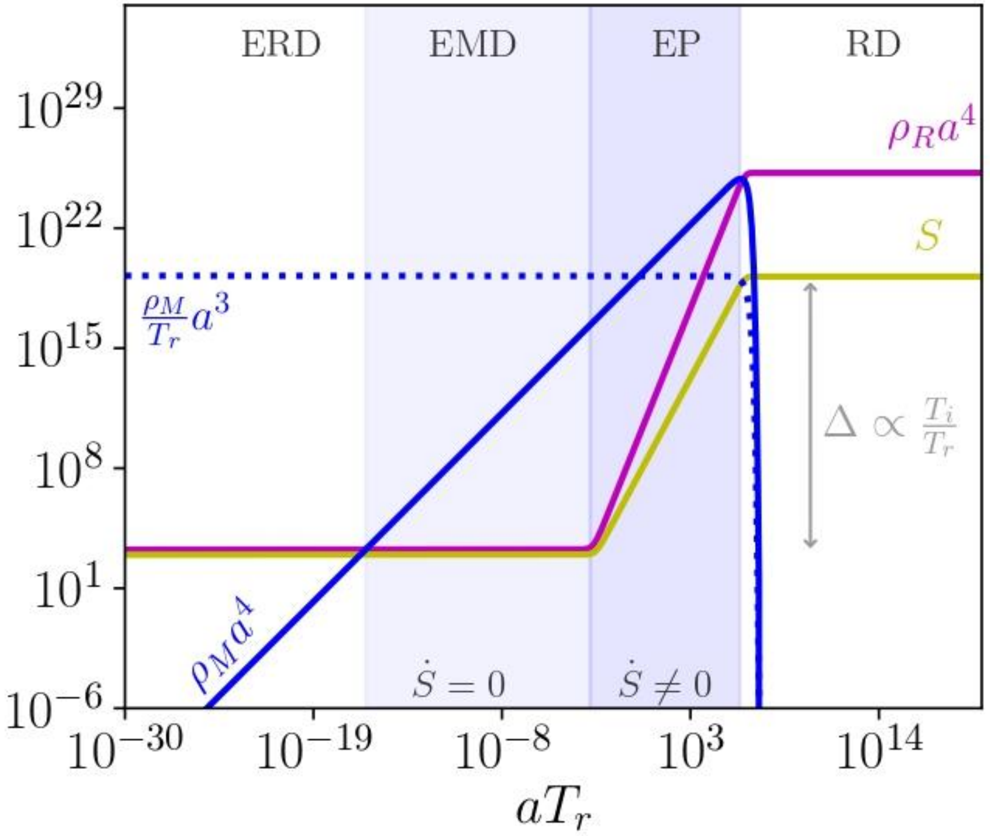
Evolution of the Universe



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

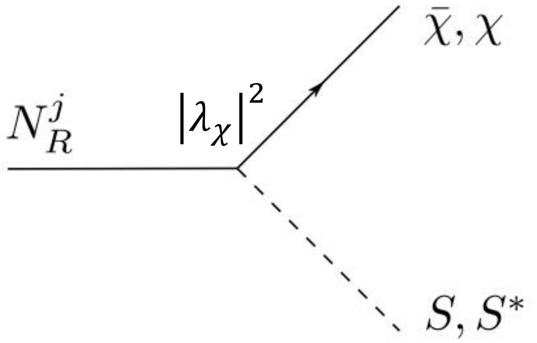
  $\Delta \equiv$ Amount of **entropy production** during EMD; related with the duration of the EMD $\Rightarrow$ **larger** Δ, **longer** EMD;

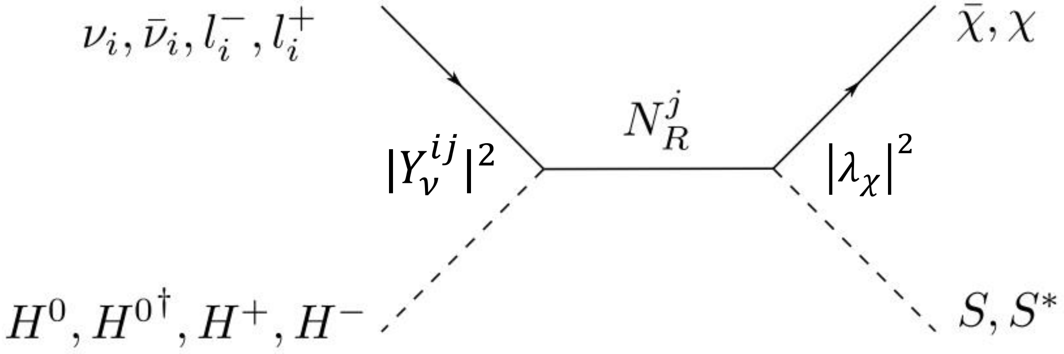
- $H_{EP}(T) = H_{RD}(T_r) \frac{g_e(T)}{g_e(T_r)} \left(\frac{T}{T_r}\right)^4$;

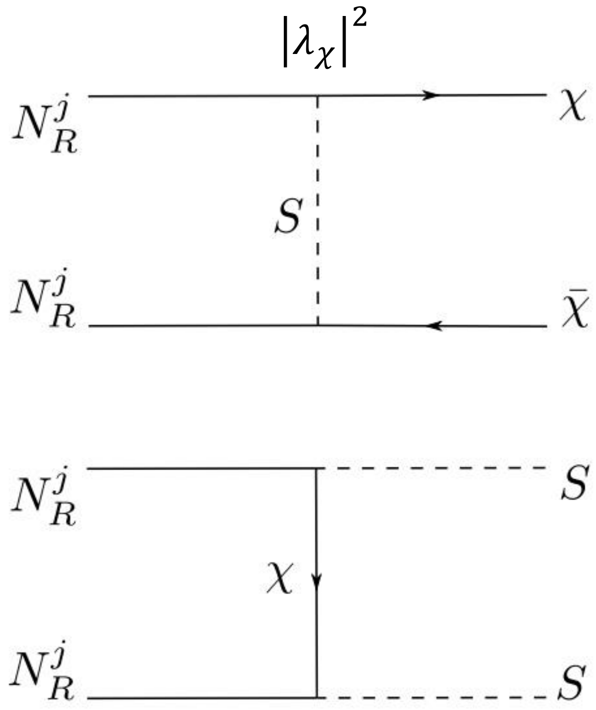


Dark matter production – Processes contributing to DM

Processes contributing to the Freeze-in production:







Dark matter production – Relic abundance

DM relic abundance

- DM production $\Rightarrow$ $\frac{n_{DM}}{s} \equiv Y_{DM}$ becomes constant;

- **DM relic abundance**:

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

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

- 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

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

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

Important remarks

- **Freeze-in** + **early matter** era:

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

- **Heavy neutrinos thermalization:**

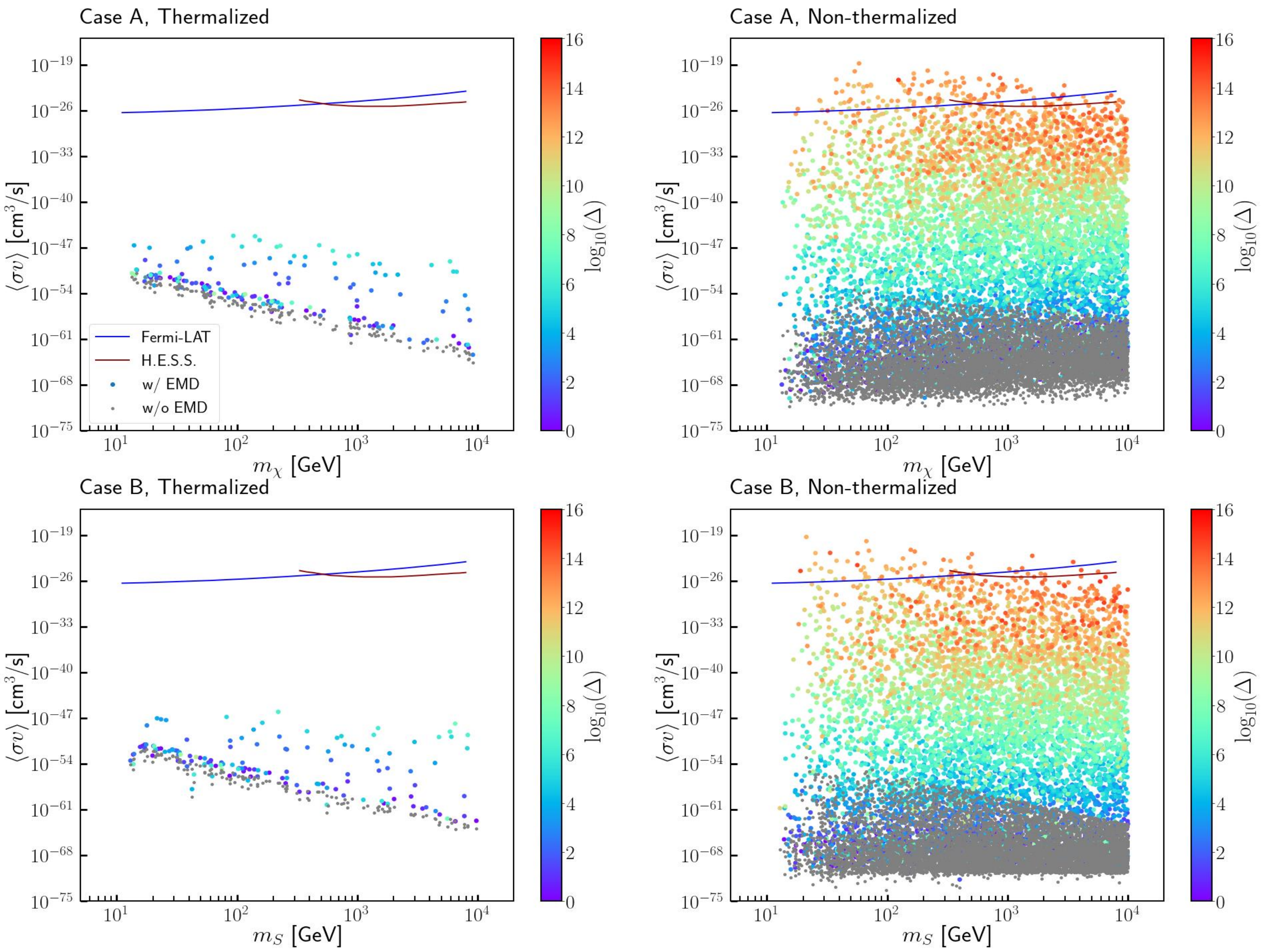
Thermalized heavy neutrinos: **all processes** (s-channels, t-channels, decays) are relevant for **DM production**

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

Case B:
S is DM



$m_{DM} > m_N$

DM annihilates into **N**

N decays into SM particles

$\langle \sigma v \rangle_{DMDM \to NN}$ 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 $\Rightarrow$ **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! / Muito obrigada pela vossa atenção!

Backup slides

Parameter Space

Parameters	Case A	Case B
m_χ	[1 GeV, 10^4 GeV]	[m_S, 10^6 GeV]
m_S	[m_χ, 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]:

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

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

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

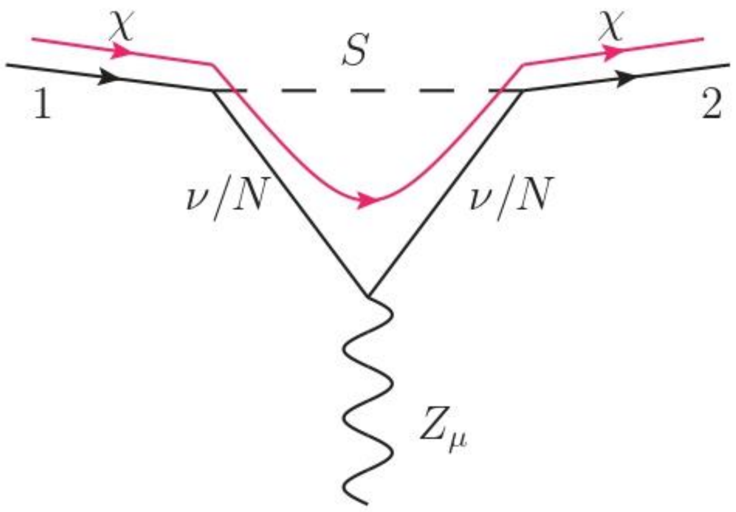
where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$, and $\mathscr{P} = \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$. The value of these angles and phases are taken from the recent global fitting results [65] [1]. $m_{\nu/N}^{1/2}$ represent the diagonal matrices with square root 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

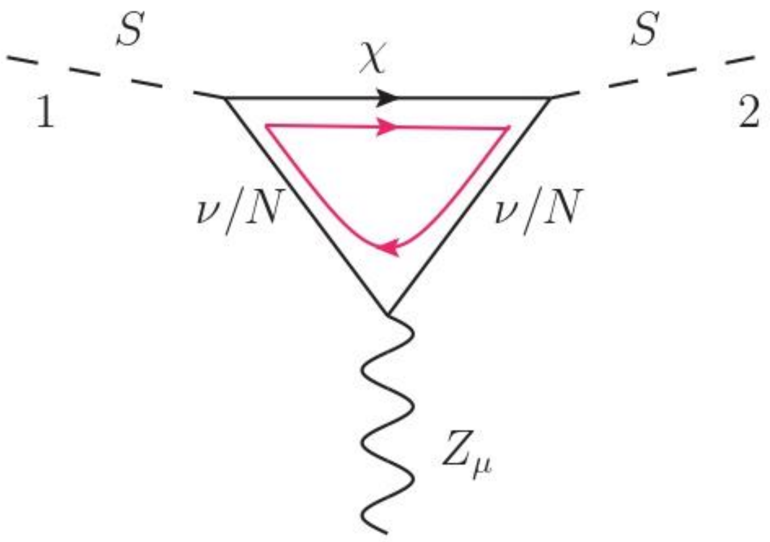
- **Direct detection experiments**: Scattering of DM with atomic nuclei in detectors; identify the deposited energies;

- Direct detection relevant vertices:

Case A: χ is DM



Case B: S is DM



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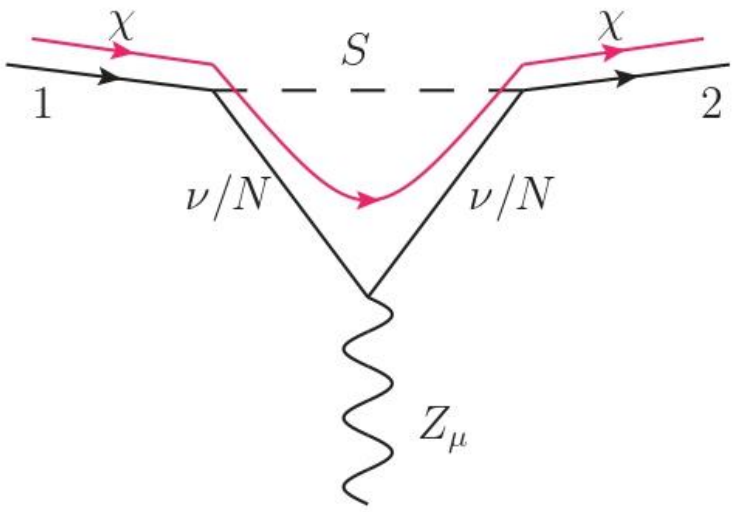
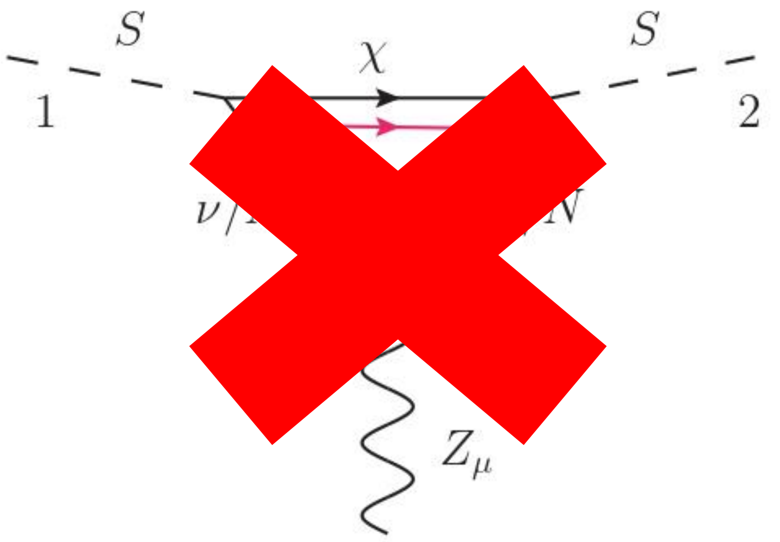


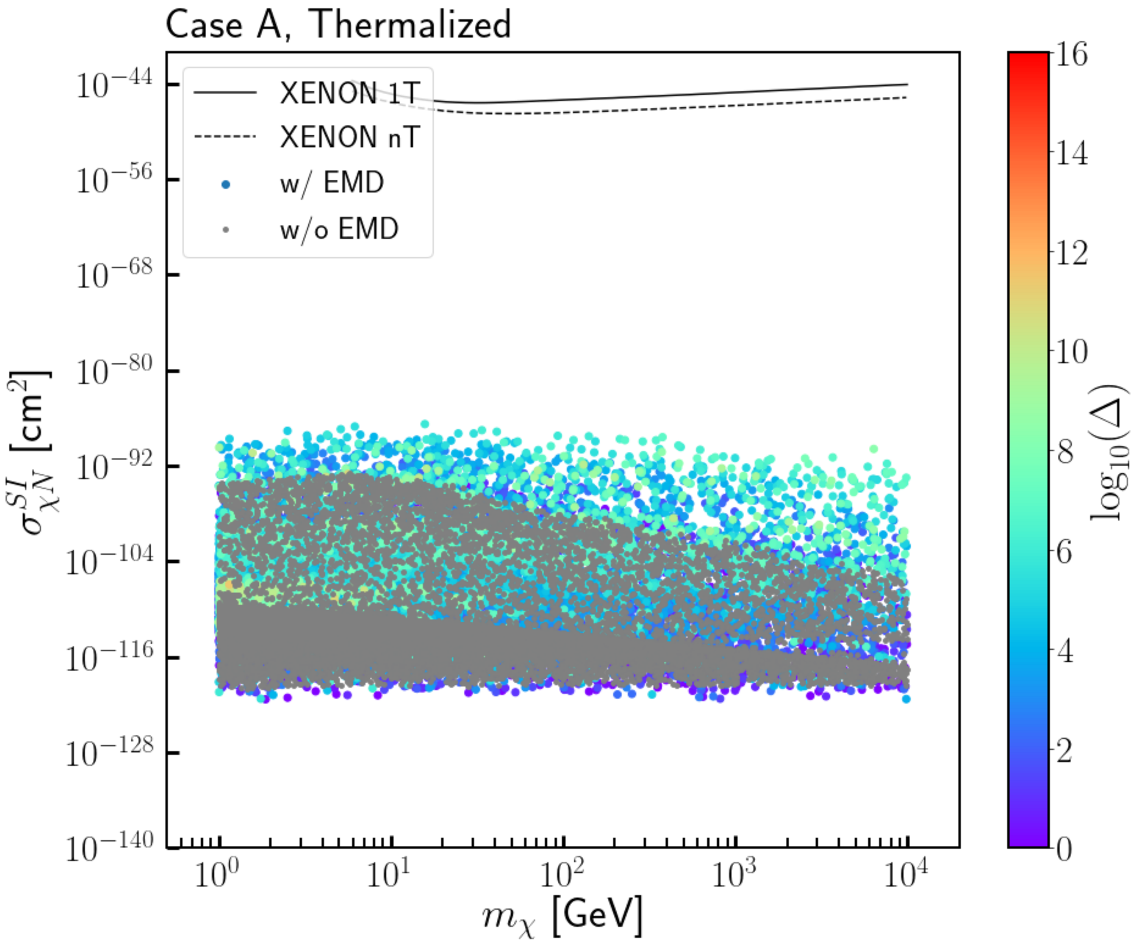
Case B: S is DM

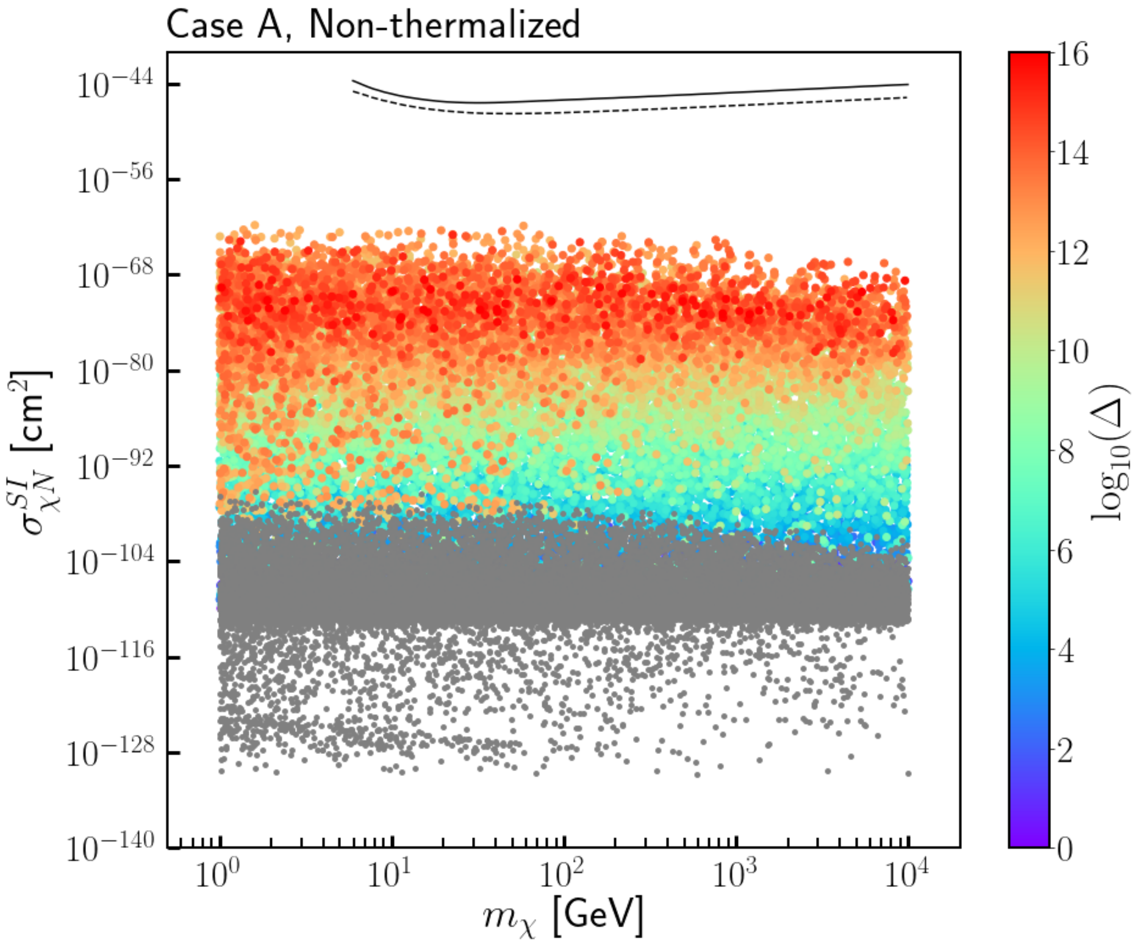


Very suppressed – not consider this case for direct detection

Phenomenology – Direct detection prospects

Direct detection experiments: Scattering of DM with atomic nuclei in detectors;





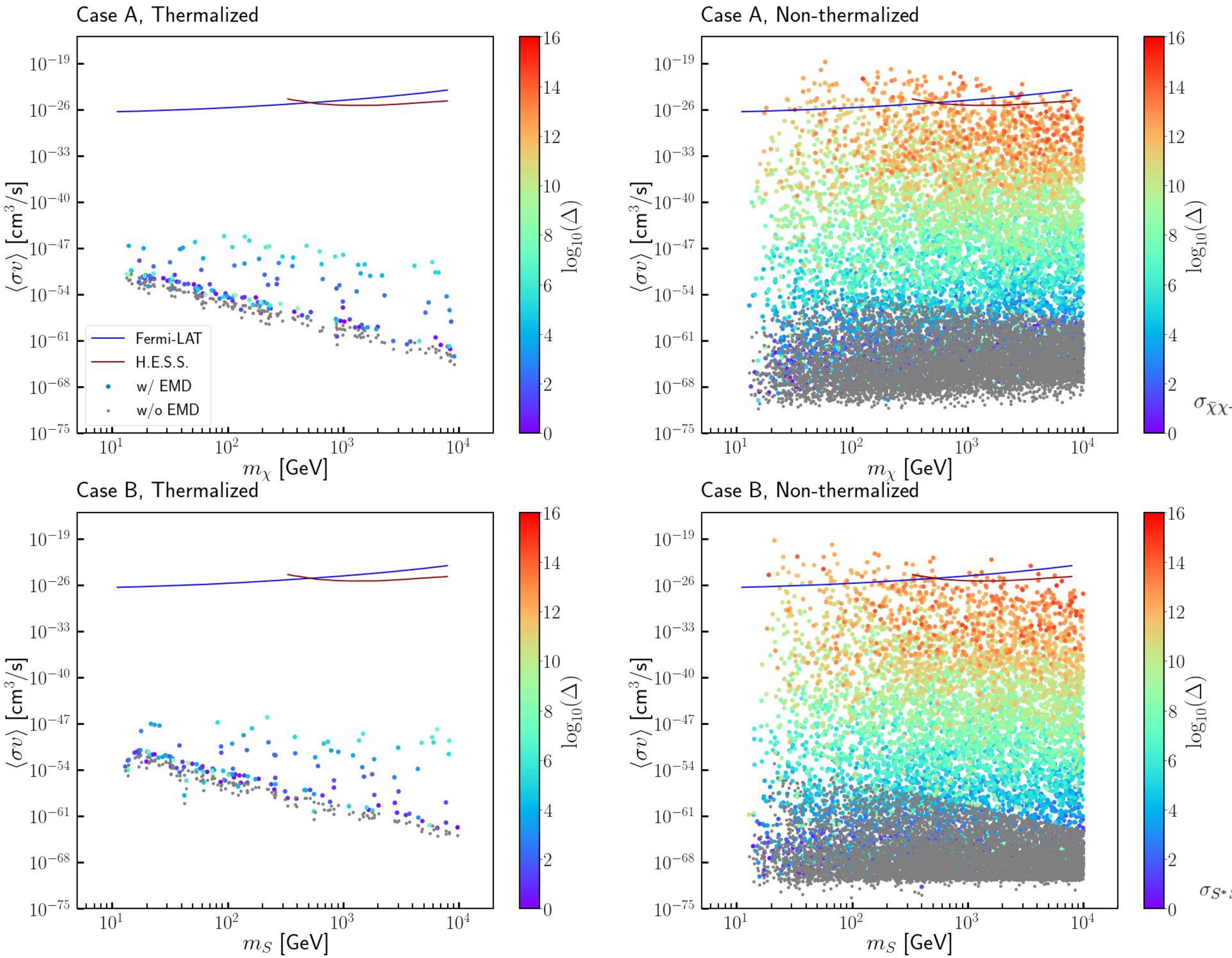
$\boldsymbol{\sigma_{\chi N}^{SI}}$ - Spin Independent DM-nucleon scattering cross section

Case A: χ is DM

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**]

Phenomenology – Indirect detection prospects

- **Indirect detection experiments**: Look for the product of the decay or annihilation of DM particles;

- In the case $m_{DM} > m_N$ $\Longrightarrow$ **DM annihilates** to **N** $\Longrightarrow$ **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**.

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;

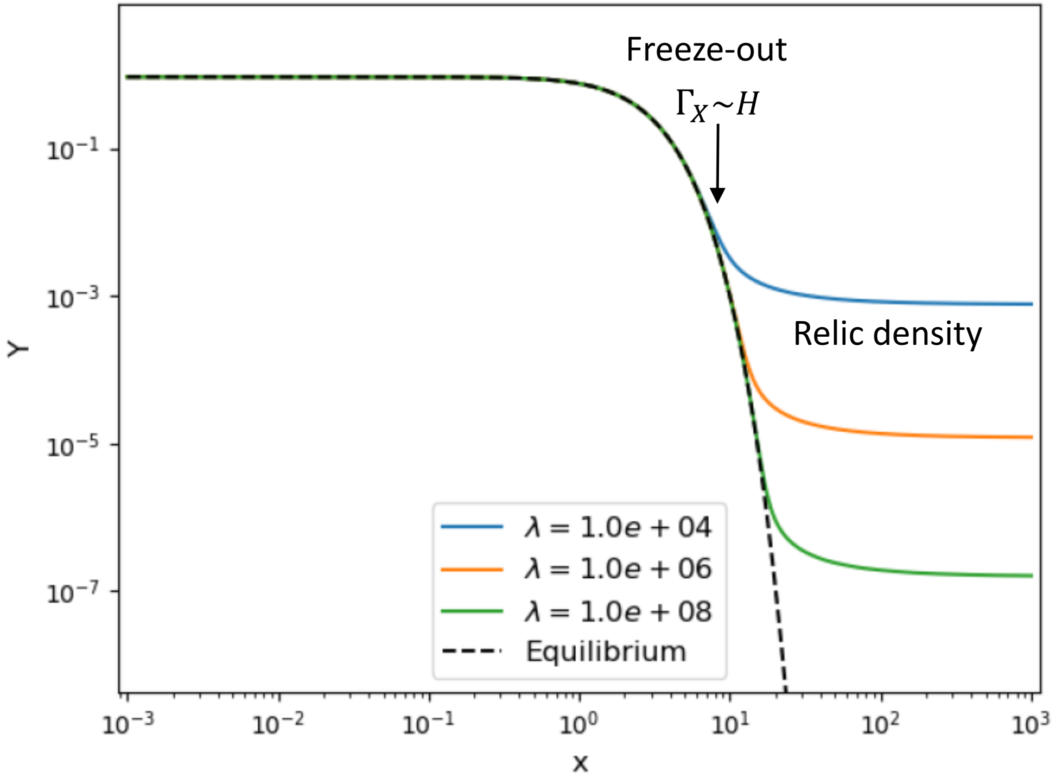
- **Freeze-out** + **Non-standard cosmologies** (including **early-matter era**): Drees, F. Hajkarim arXiv:1711.05007; D'Eramo, Fernandez, and Profumo arXiv: 1703.04793; Hamdan and Unwin arXiv: 1710.03758;

- **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.

Introduction - Dark Matter production mechanisms

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



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

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

$$X\bar{X} \leftrightarrow SM$$

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:

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

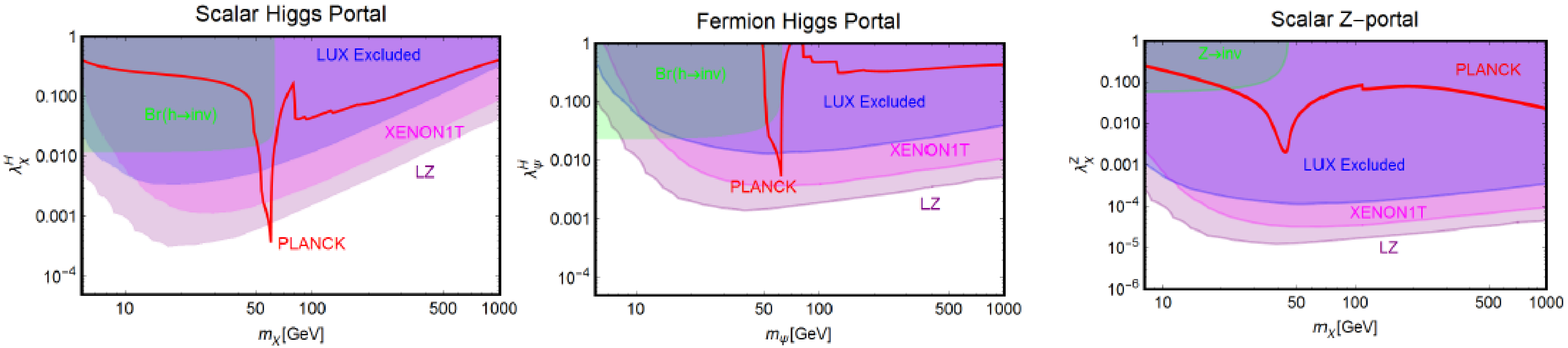
Present DM **abundance**:

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

But: no detection so far; very constrained by experiments. [Arcadi et al. **arXiv:1703.07364**]

Freeze-out mechanism

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

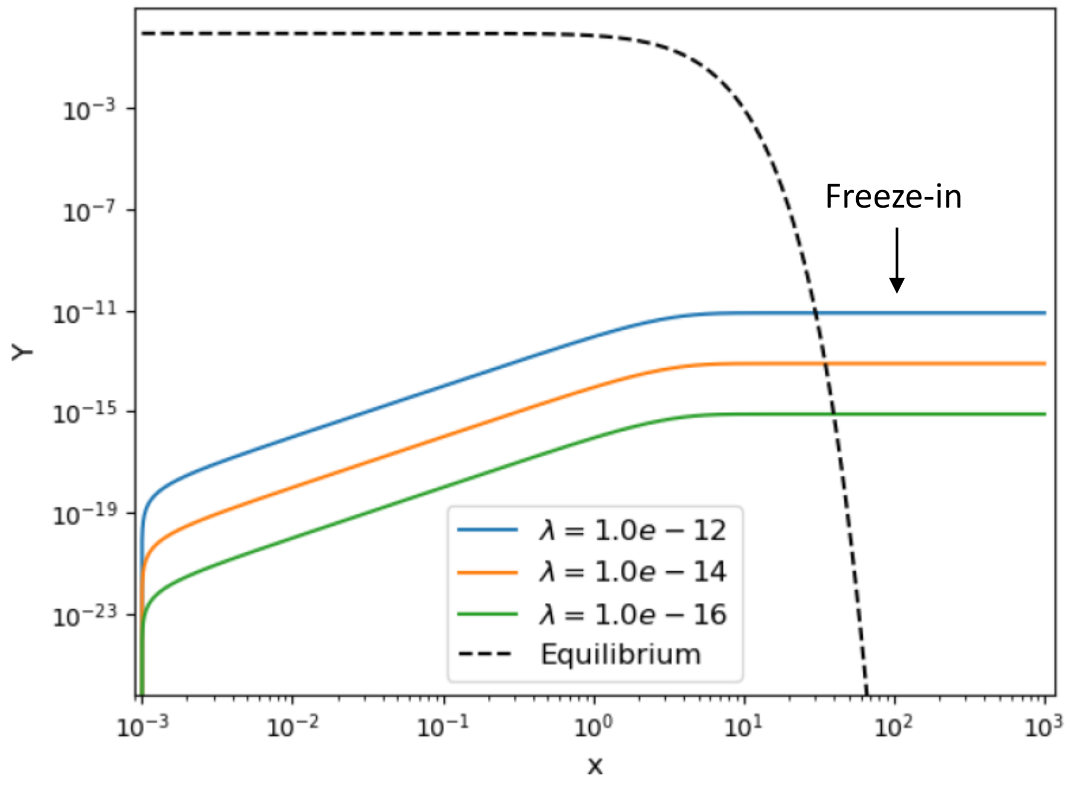


Credits: **Arcadi et. al, arXiv:1703.07364**

“The waning of the WIMP?”

Introduction - Dark Matter production mechanisms

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



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

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

$$\cancel{X\bar{X} \leftrightarrow SM}$$
$$\longleftarrow$$

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:

$\Gamma_X < H$ **always**

Present DM **abundance**:

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

Introduction – An early matter-dominated period

- **End** of matter dominated period: **matter** component **decays** into Standard Model (SM) particles ⇒ **Dilution** of **DM** number density;

Consequences:

- **Freeze-out:** Earlier freeze-out ⇒ **Smaller couplings** than in the standard case to match **DM abundance**;

- **Freeze-in: Couplings** to the visible sector are **larger** than usual freeze-in;

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

Evolution of the Universe

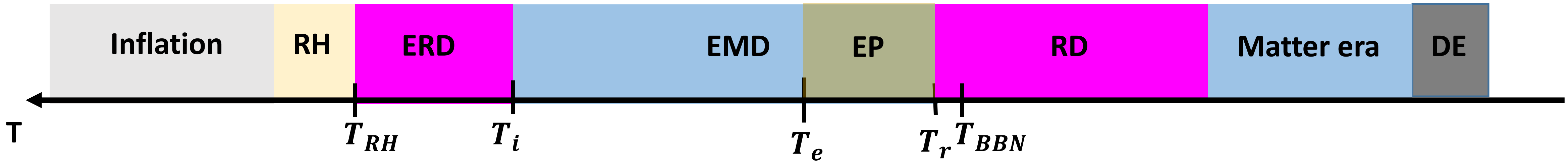
$\boldsymbol{\rho_M} \gg \rho_R, \rho_{DM}$ for some initial temperature T_i

- 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



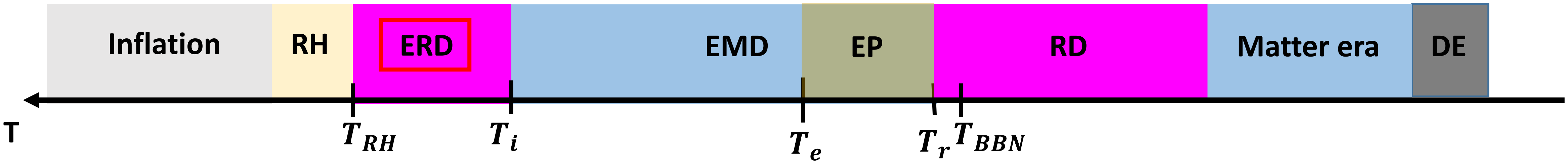
T_{RH} - Inflationary reheating temperature;

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; $T_r \gtrsim T_{BBN} \sim 4\ \text{MeV}$

Evolution of the Universe



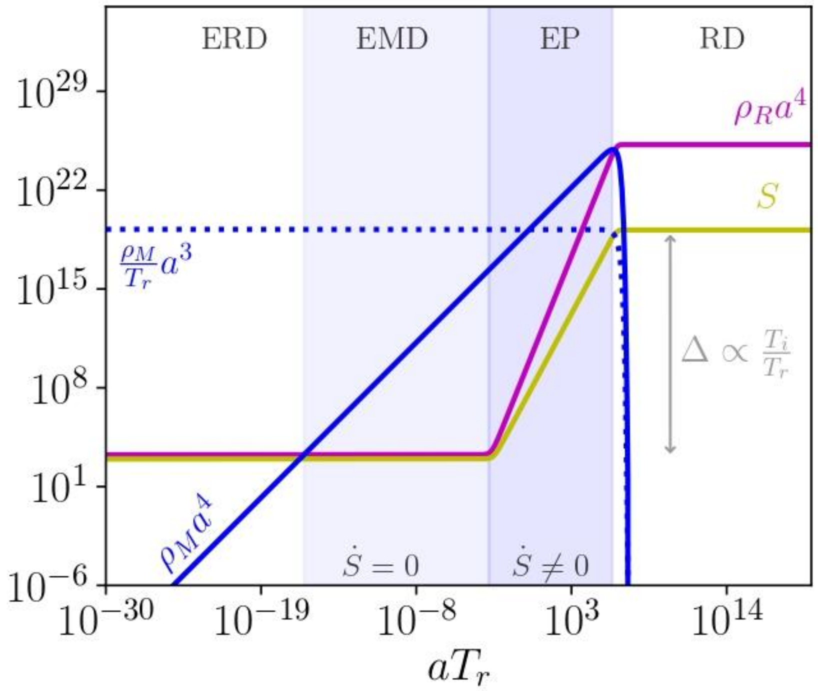
ERD:

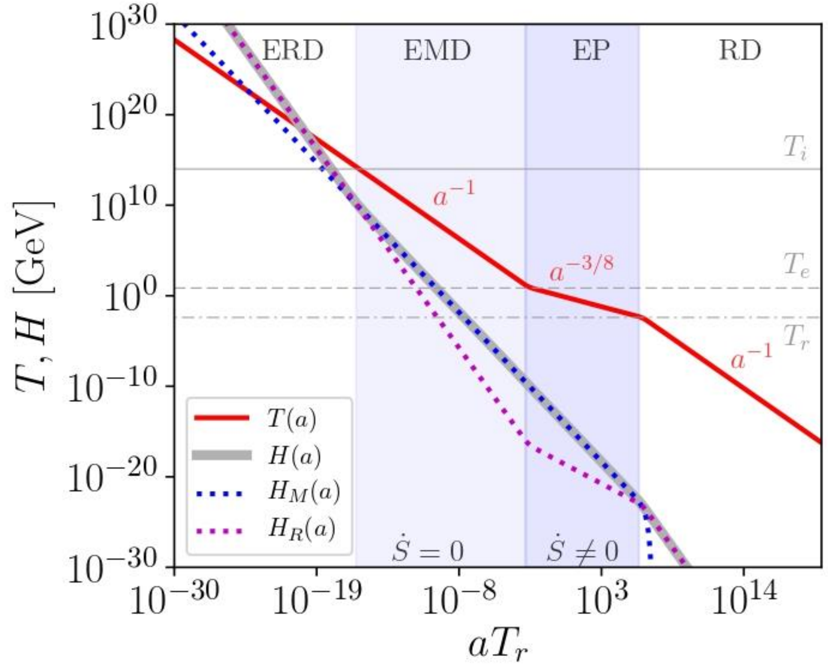
- **M** is **not dominant** yet;

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

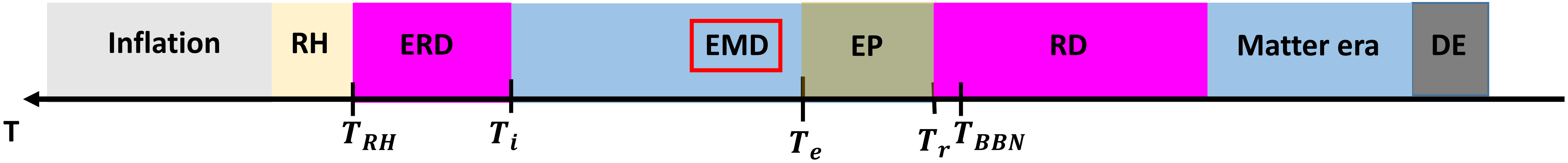
- **Continuity** of $H(T)$:

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





Evolution of the Universe

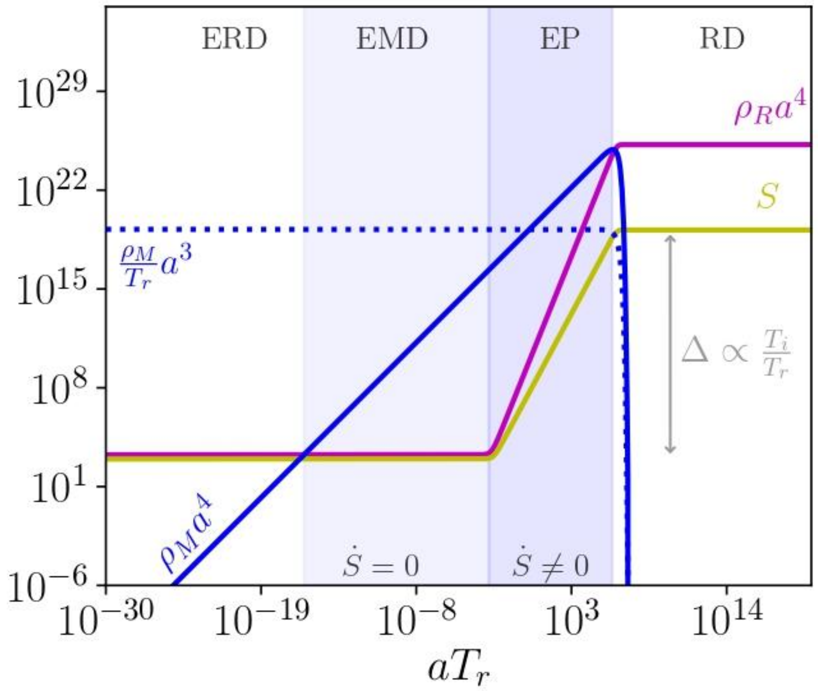


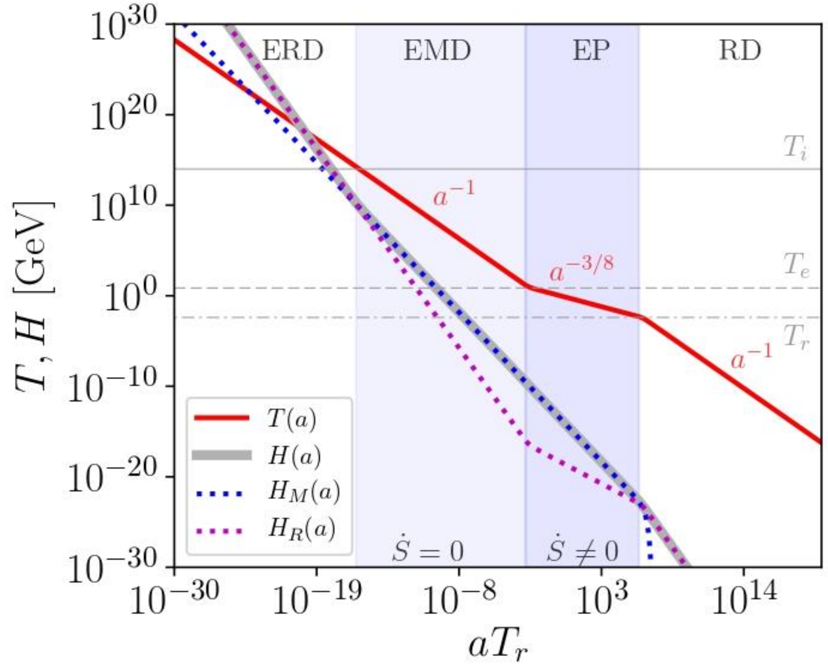
EMD:

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

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

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





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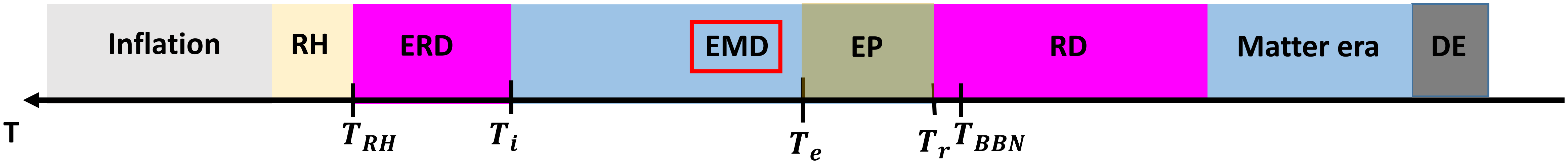
Evolution of the Universe

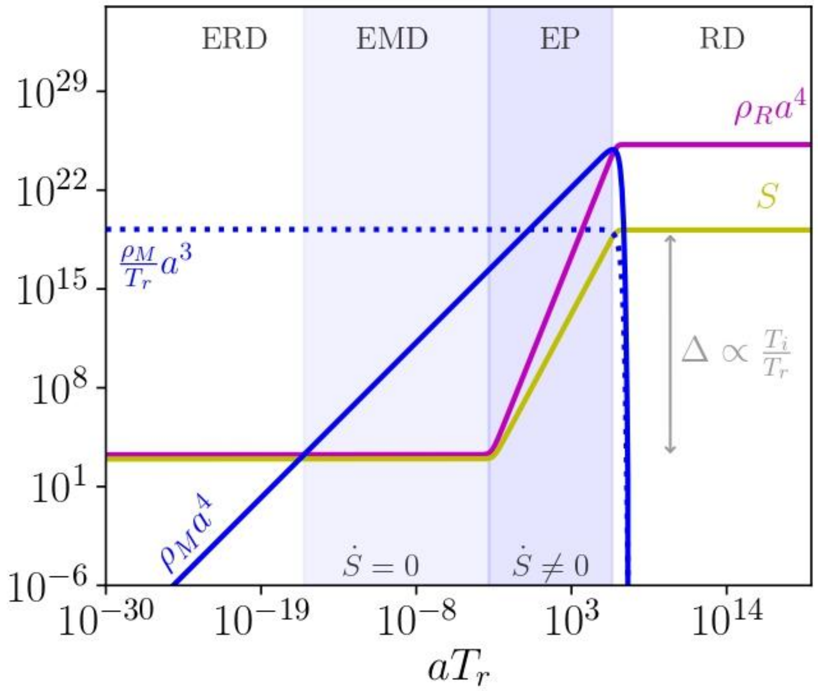


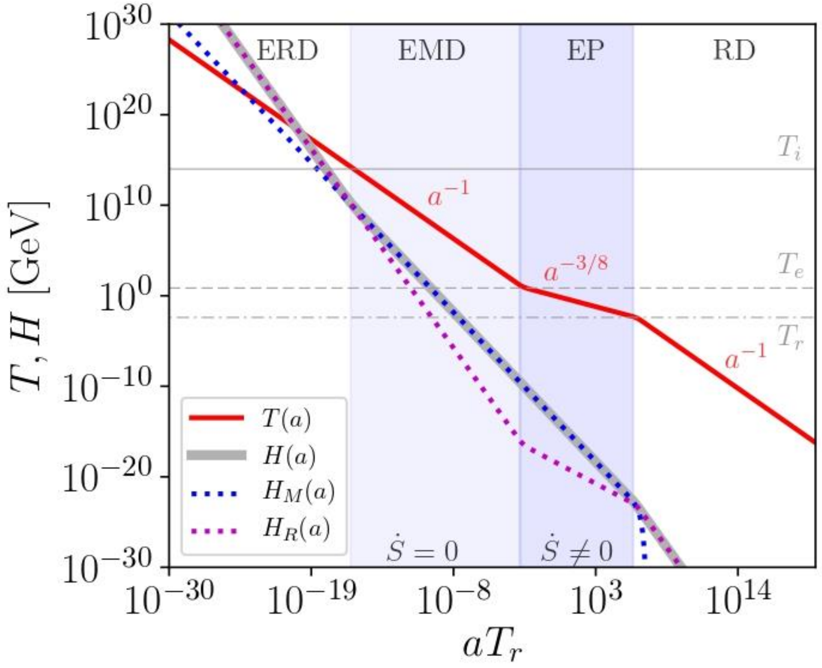
EMD:

$$\Delta = \frac{3}{4}\frac{g_e(T_i)}{g_{\mathfrak{s}}(T_i)}\frac{T_i}{T_r}$$

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

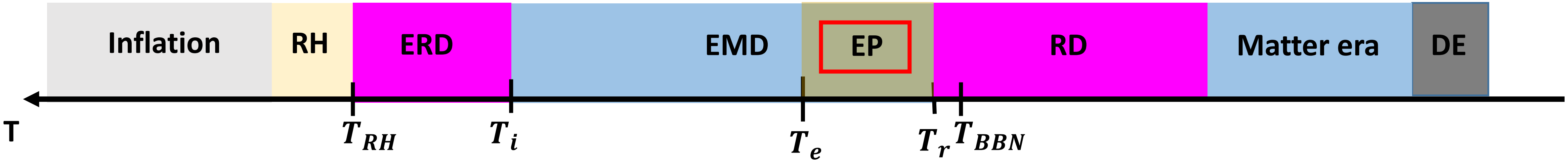
- $\boldsymbol{T_e}$ is fixed by $\boldsymbol{T_i}$ and $\boldsymbol{T_r}$;





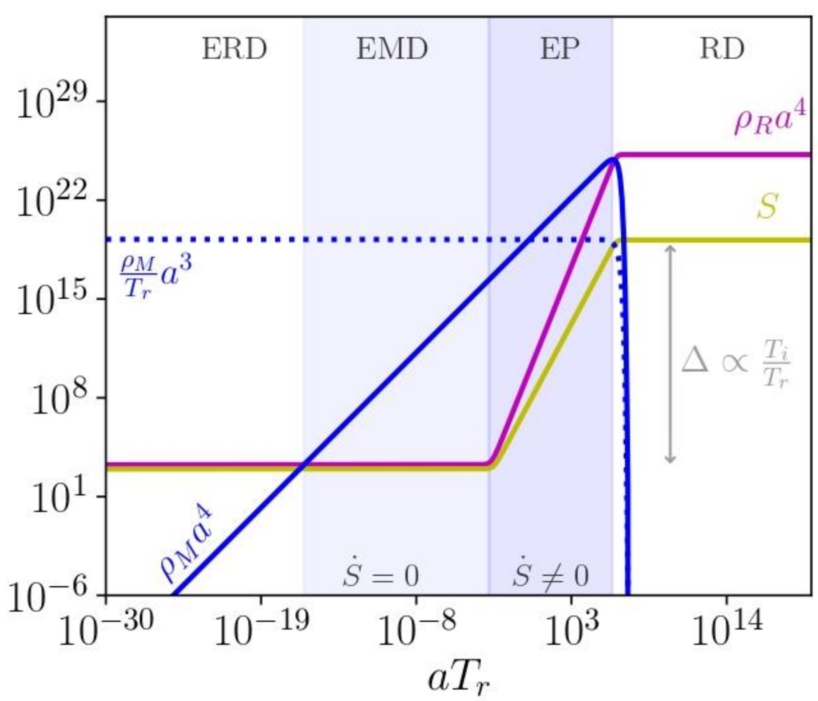
- $\boldsymbol{T_i}$ and $\boldsymbol{T_r}$ **parametrize** the early matter era.

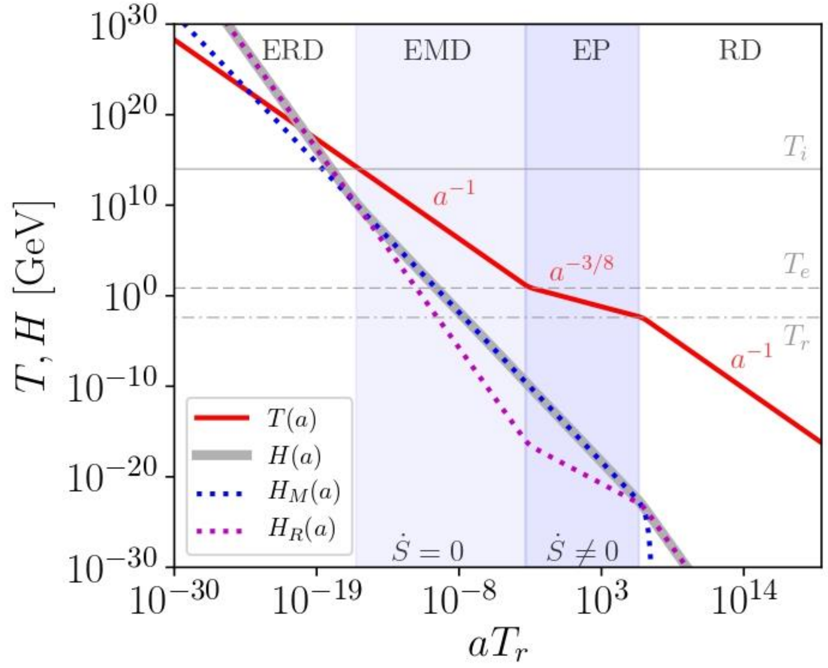
Evolution of the Universe



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 – Relic abundance

- To compute the **DM relic abundance**, we need to know how its **number density** evolves:

$$\frac{dN_{DM}}{dt} = (\dot{n}_{DM} + 3H(t)n_{DM})a^3 = R_{DM}(t)a^3$$

$$N_{DM} = n_{DM}a^3$$

Reaction rate density

- **Reaction rate** densities:

$1 \rightarrow 23$ process: $R_2^{1\rightarrow 23} \approx n_1 \Gamma_{1\rightarrow 23}$

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

Dark matter production – Relic abundance

- Total yield: $Y_{DM,0} = Y_{ERD} + Y_{EMD} + Y_{EP} + Y_{RD}$
- **DM relic abundance**:

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

When does the **DM Freeze-in production happen**?

- $1 \rightarrow 2$ or resonant $2 \rightarrow 2$ processes: $T_{FI} \sim m_{decaying/mediator}$;
- Otherwise: T_{FI} above the Boltzmann suppression of the heaviest particle involved.

Dark matter production - Constraints

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

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

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

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

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

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** 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 $\Rightarrow$ **s-channel annihilations** contribute for **DM production.**

Phenomenology – Indirect detection prospects

- **Indirect detection experiments**: Look for the product of the decay or annihilation of DM particles;
- In the case $m_{DM} > m_N$ ⟶ **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**.

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: $\overline{L_L^i} Y_\nu^{ij} \widetilde{H} \left(N_\ell^j\right)_R$ $\Longrightarrow$ contributes to the SM neutrinos mass;
- m_N is not constrained by any gauge symmetry $\Longrightarrow$ 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

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & m_N \end{pmatrix} \xrightarrow{\text{Diagonalizing}} M_\nu = -M_D^T m_N^{-1} M_D$$

Yukawa coupling:

$$Y_\nu \sim \frac{\sqrt{m_\nu m_N}}{\mathrm{v}} \quad \Longrightarrow \quad \text{Completely defined if we fix } m_N$$

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

Type-I seesaw mechanism

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & m_N \end{pmatrix} \xrightarrow{\text{Diagonalizing}} M_\nu = -\,M_D^T m_N^{-1} M_D$$

Yukawa coupling:

$$Y_\nu \sim \frac{\sqrt{m_\nu m_N}}{\mathrm{v}} \longrightarrow \text{Completely defined if we fix } m_N$$

Also:

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

“Seesaw”

ν

$\boldsymbol{N}$

Heavy neutrinos thermalization

- Heavy neutrinos **thermalized** when $\boldsymbol{\Gamma > H}$;

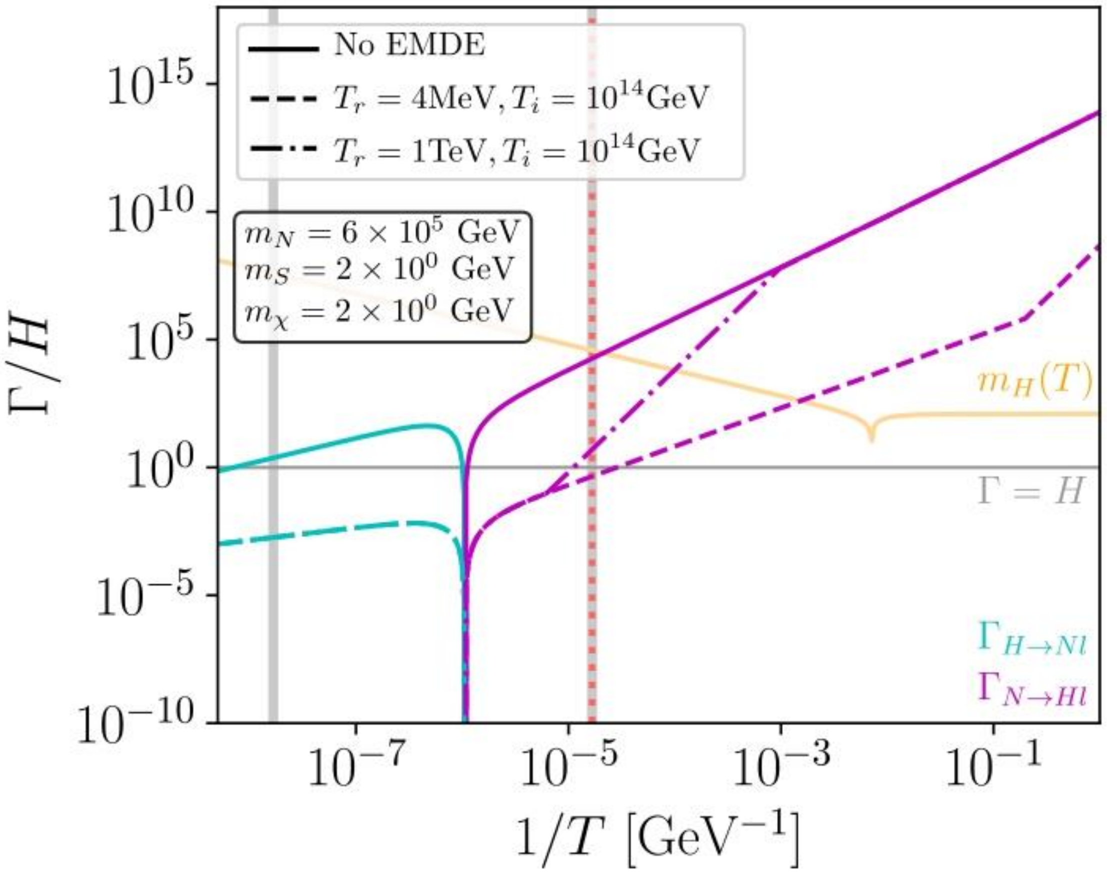
- **DM freeze-in** occurs between the **grey** vertical lines;

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.



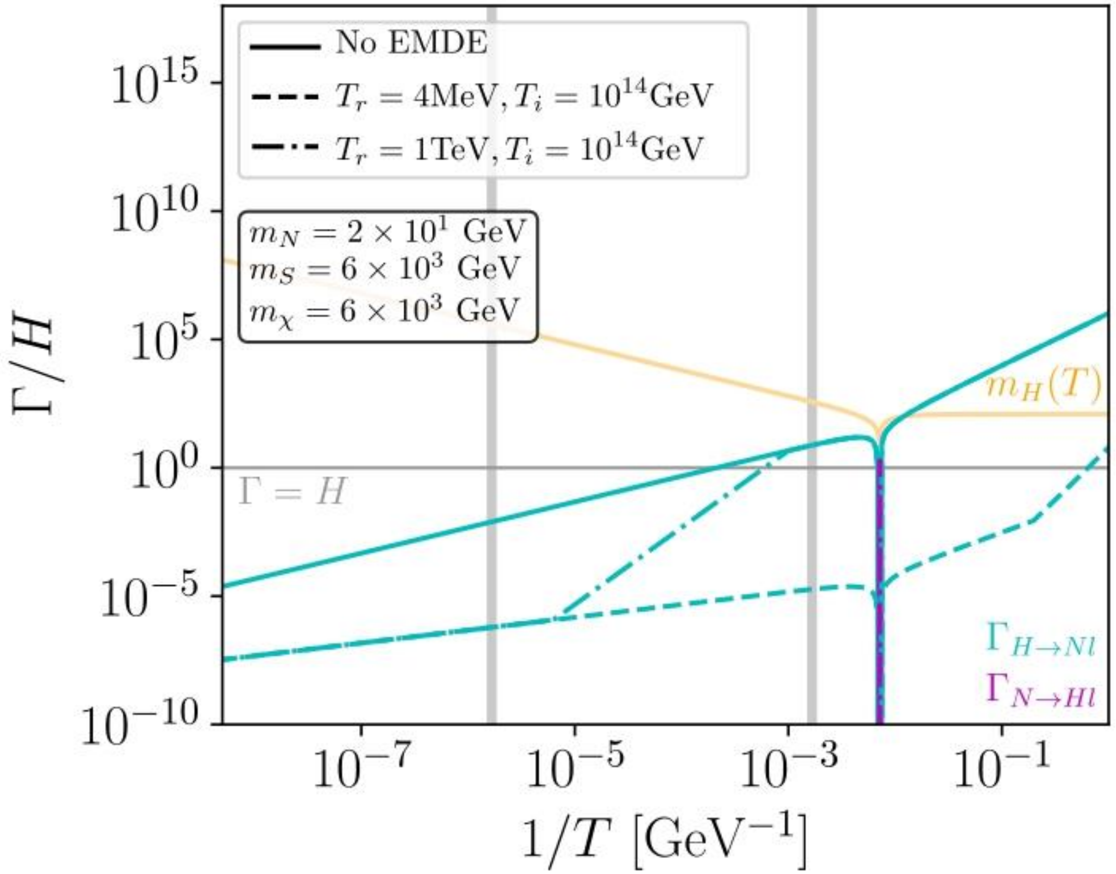
Heavy neutrinos thermalization

- 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**.

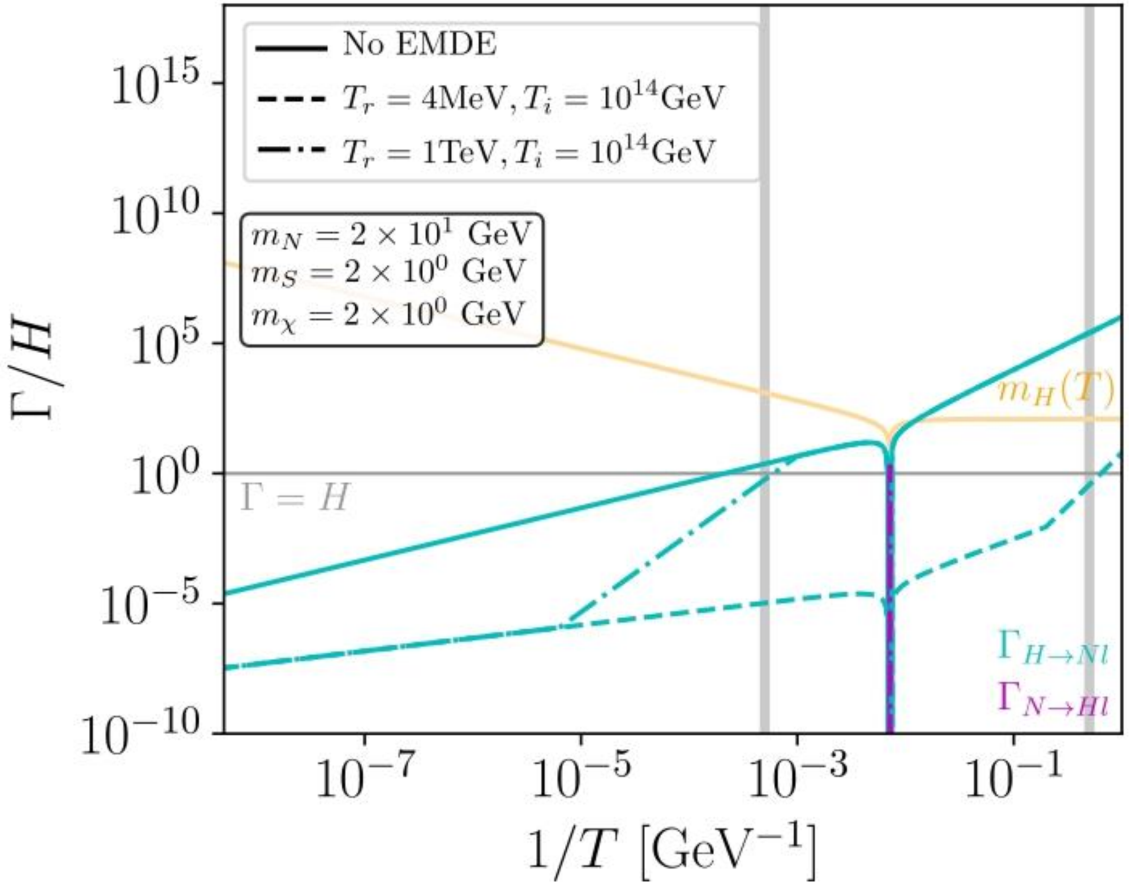


Heavy neutrinos thermalization

- 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**.