Thermal effects in νDM production

Invisibles’23 Workshop, Göttingen

Salvador Rosauro-Alcaraz

In collaboration with A. Abada, G. Arcadi, M. Lucente & G. Piazza,
based on arXiv:2308.01341

This project has received funding /support from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska -Curie grant agreement No 860881-HIDDeN

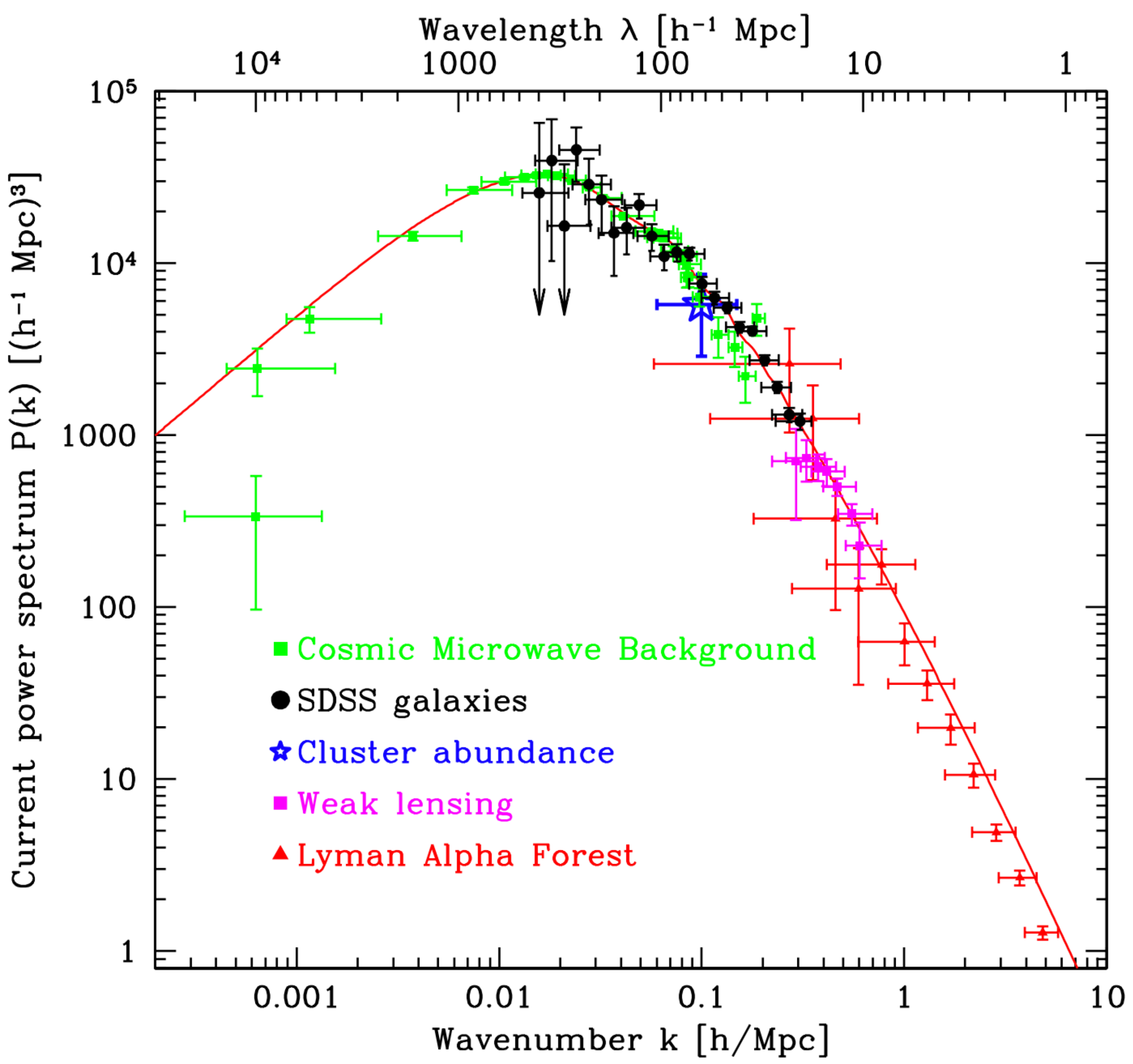
Introduction

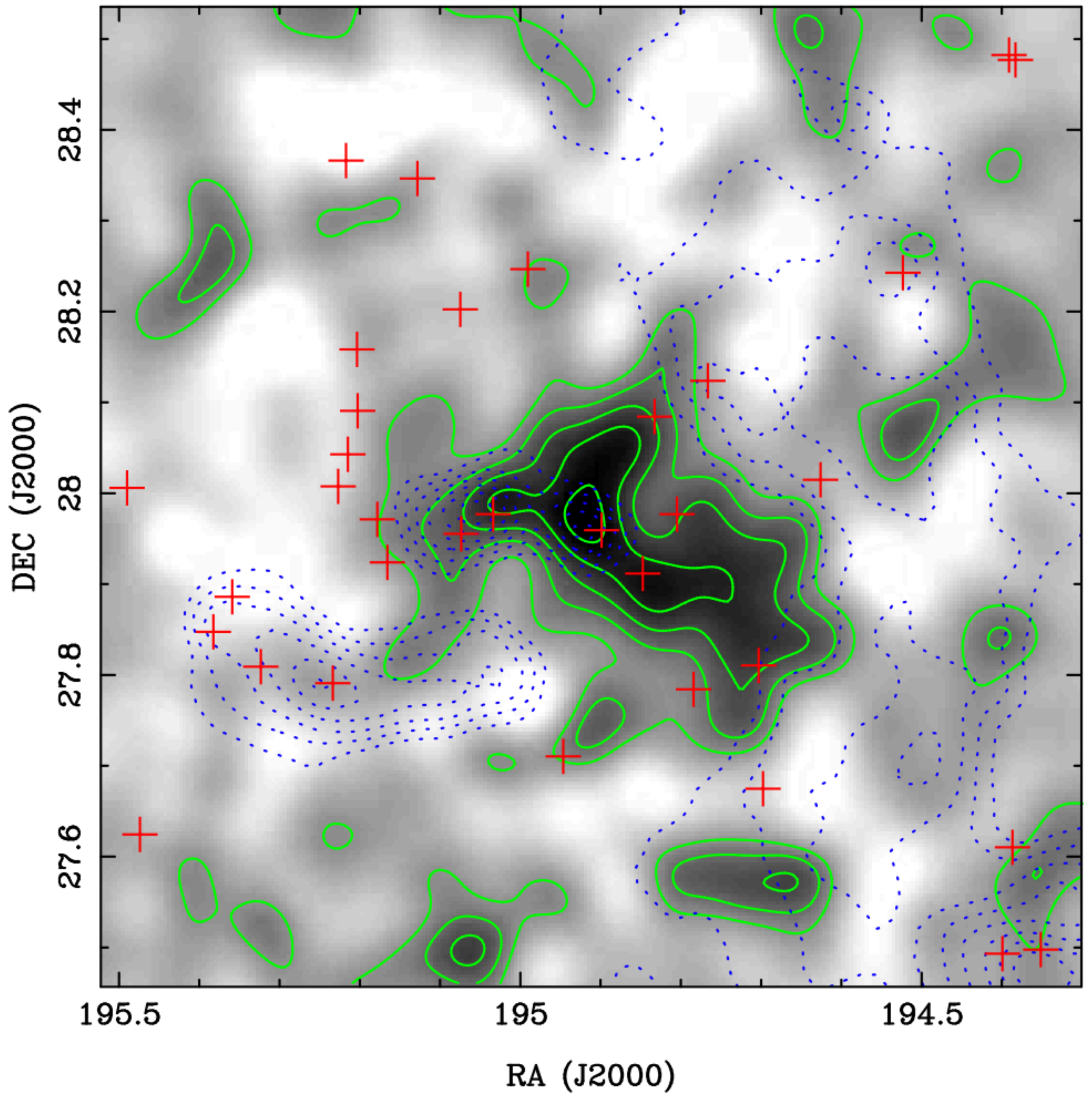
Dark matter

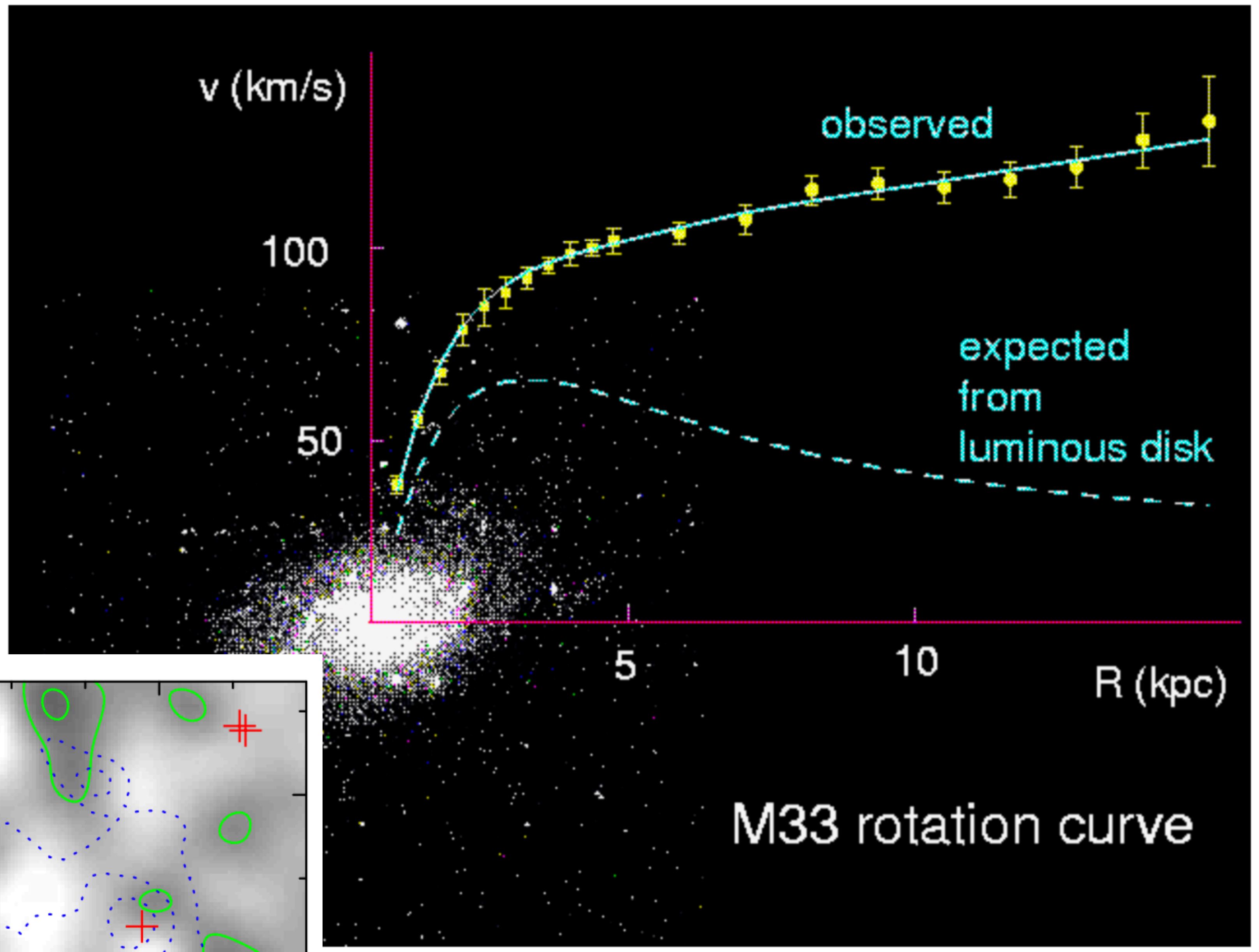
Planck Collaboration, arXiv:1807.06209

$$\Omega_{DM}^{obs} h^2 = 0.1193 \pm 0.0009$$

D. P. Roy, arXiv:physics/0007025



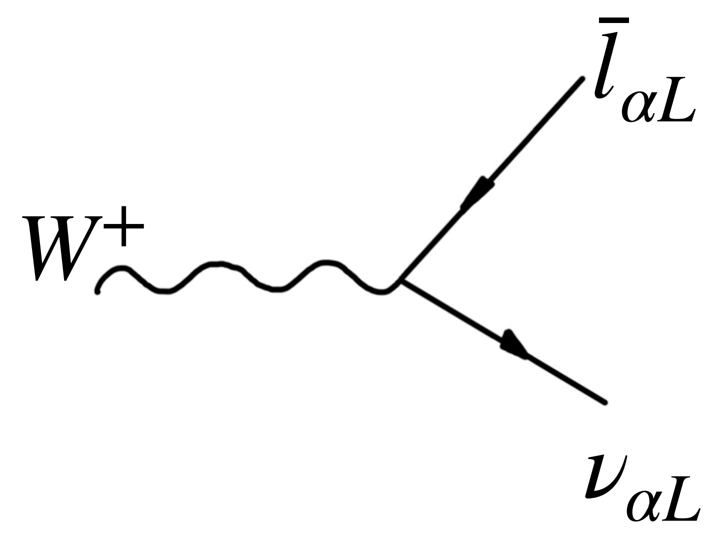




Introduction

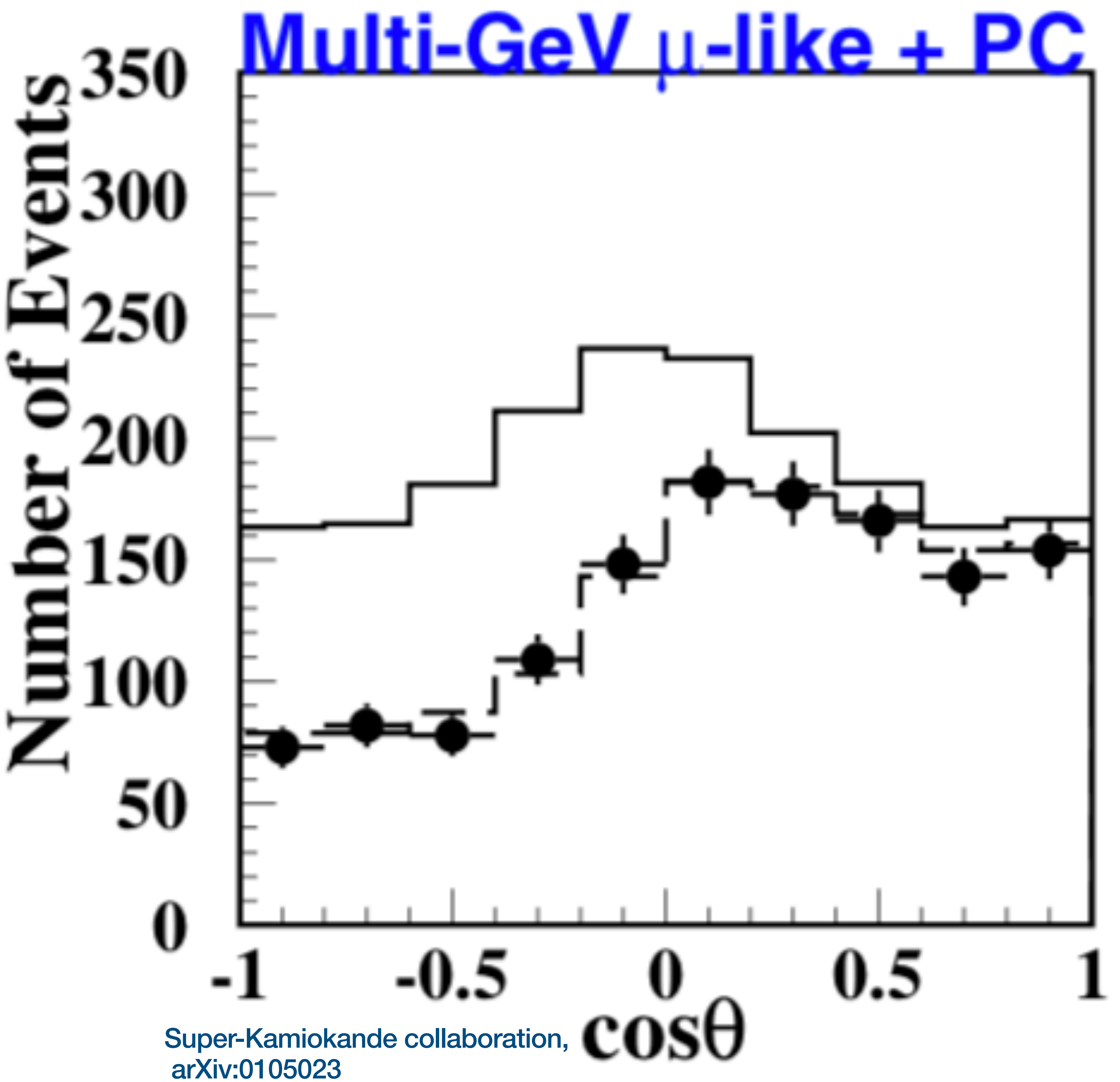
Origin of neutrino masses

$$\nu_L = U_{PMNS} P_L \nu_l$$



Propagation states

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences



Super-Kamiokande collaboration, arXiv:0105023

Introduction

Origin of neutrino masses

Include singlet fermions N_R

$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$

P. Minkowski, Phys. Lett. B (1977)
R. N. Mohapatra & G. Senjanovic, Phys. Rev. Lett (1980)
T. Yanagida, Conf. Proc C7902131 (1979)
M. Gell-Mann *et al. Conf. Proc C790927 (1979)*

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After SSB, Dirac mass term $m_D = v_H Y_\nu$

$$m_{\nu_l} \sim m_D M^{-1} m_D^T$$

$$\Theta = m_D M^{-1}$$

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"PMNS" mixing matrix

$$\begin{pmatrix}\nu_L \\ N_R^c\end{pmatrix} = \underbrace{\begin{pmatrix}N & \Theta \\ R & S\end{pmatrix}}_{\mathcal{U}} P_L \begin{pmatrix}\nu_l \\ n_h\end{pmatrix}$$

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$$\begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix} = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix} P_L \begin{pmatrix} \nu_l \\ n_h \end{pmatrix}$$

Interactions between n_h and SM through active-heavy mixing

$$\mathscr{L} \supset \frac{g}{\sqrt{2}} W_\mu \bar{\ell} \gamma^\mu P_L \left(N\nu_l + \Theta n_h\right) + h.c.$$

At least need 2 heavy ν to explain oscillations

P. Minkowski, Phys. Lett. B (1977)
R. N. Mohapatra & G. Senjanovic, Phys. Rev. Lett (1980)
T. Yanagida, Conf. Proc C7902131 (1979)
M. Gell-Mann *et al. Conf. Proc C790927 (1979)*

A. Donini *et al.*, arXiv:1106.0064
A. Abada & M. Lucente, arXiv:1401.1507

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Neutrino as dark matter

$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$

One could have a singlet fermion with $M = m_{DM} \sim \mathrm{keV}$

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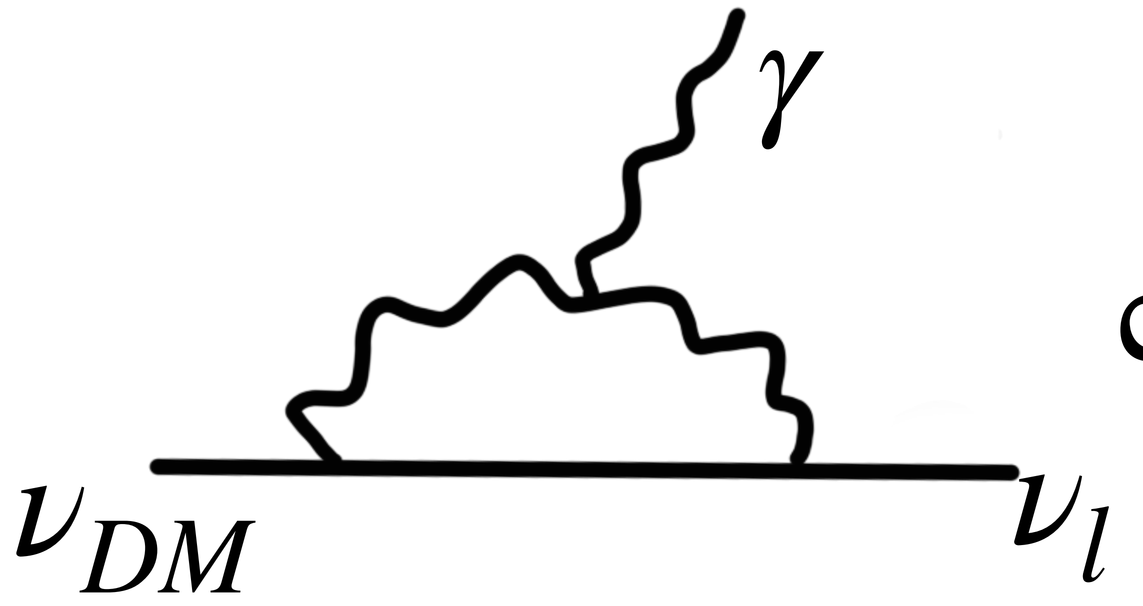
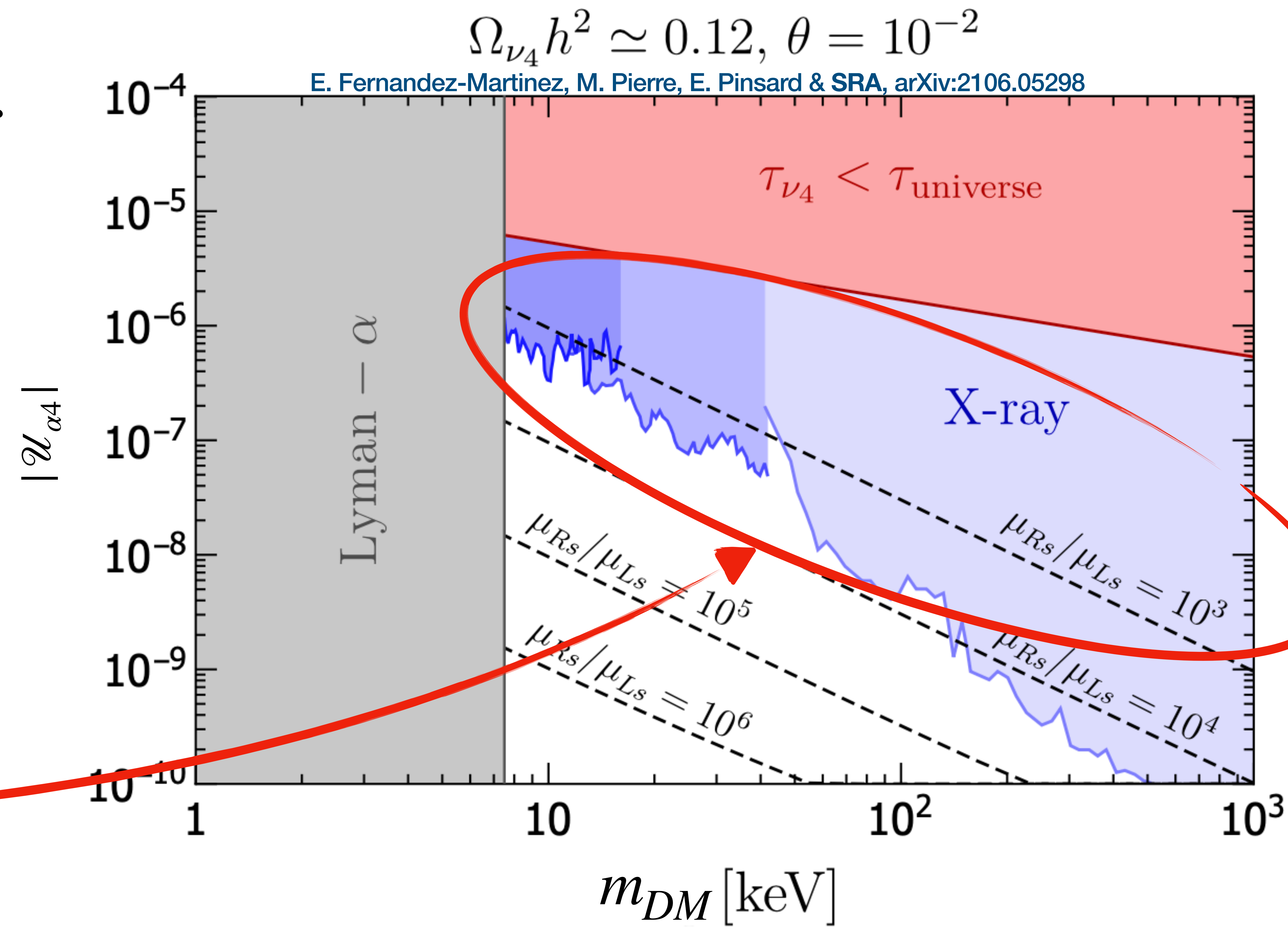


$\propto |\mathcal{U}_{\alpha 4}|^2$

Monochromatic X-ray signal



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Neutrino dark matter production

For $T \leq 1\,\mathrm{GeV}$

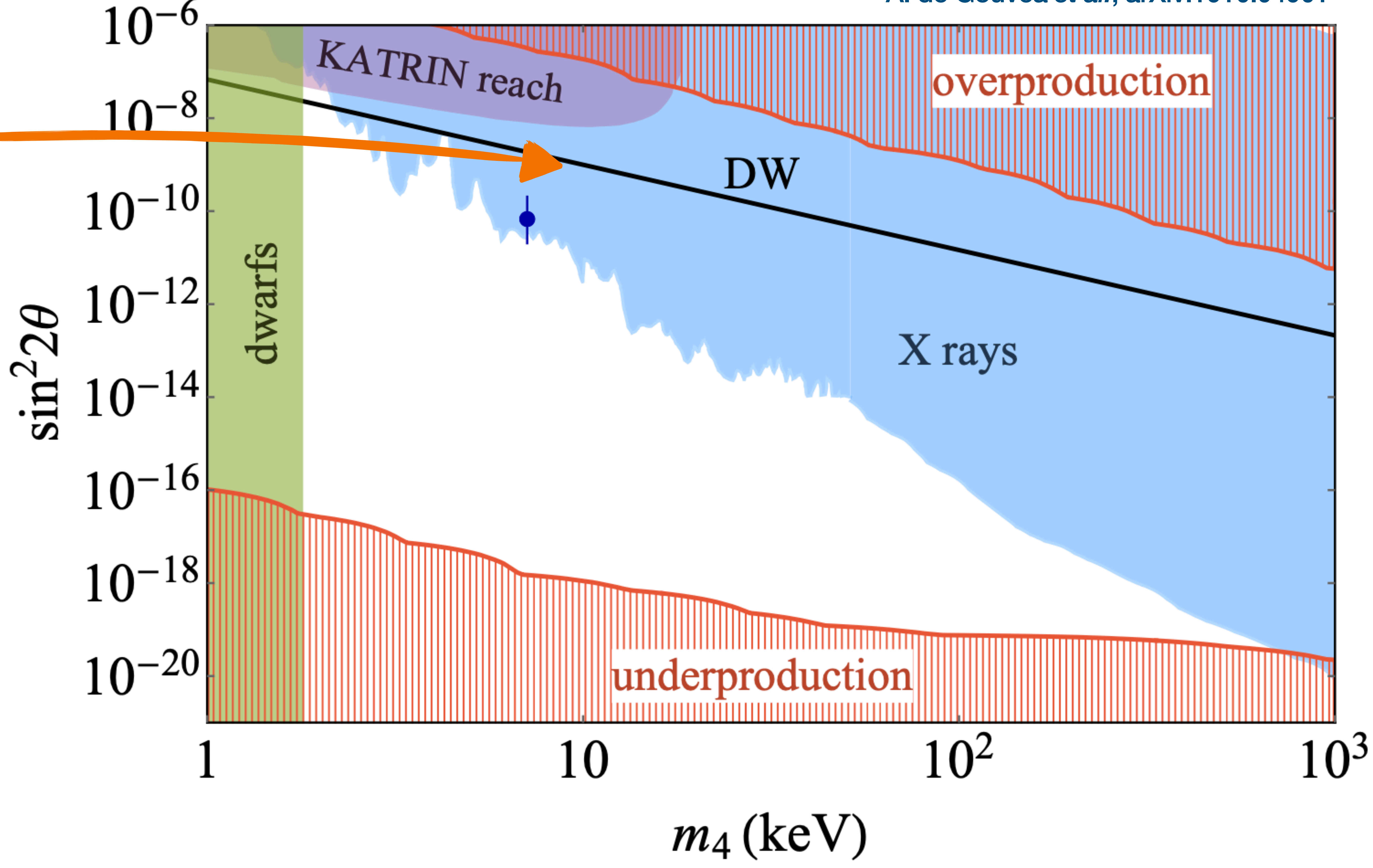
- Dodelson-Widrow mechanism

S. Dodelson & L. Widrow, arXiv:hep-ph/9303287

DM abundance from ν oscillations and collisions in the plasma

Irreducible contribution

A. de Gouvêa *et al.*, arXiv:1910.04901



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- Shi-Fuller mechanism
  X. Shi & G. Fuller, arXiv:astro-ph/9810076

- Add ν self-interactions with a scalar mediator
  A. de Gouvêa *et al.*, arXiv:1910.04901

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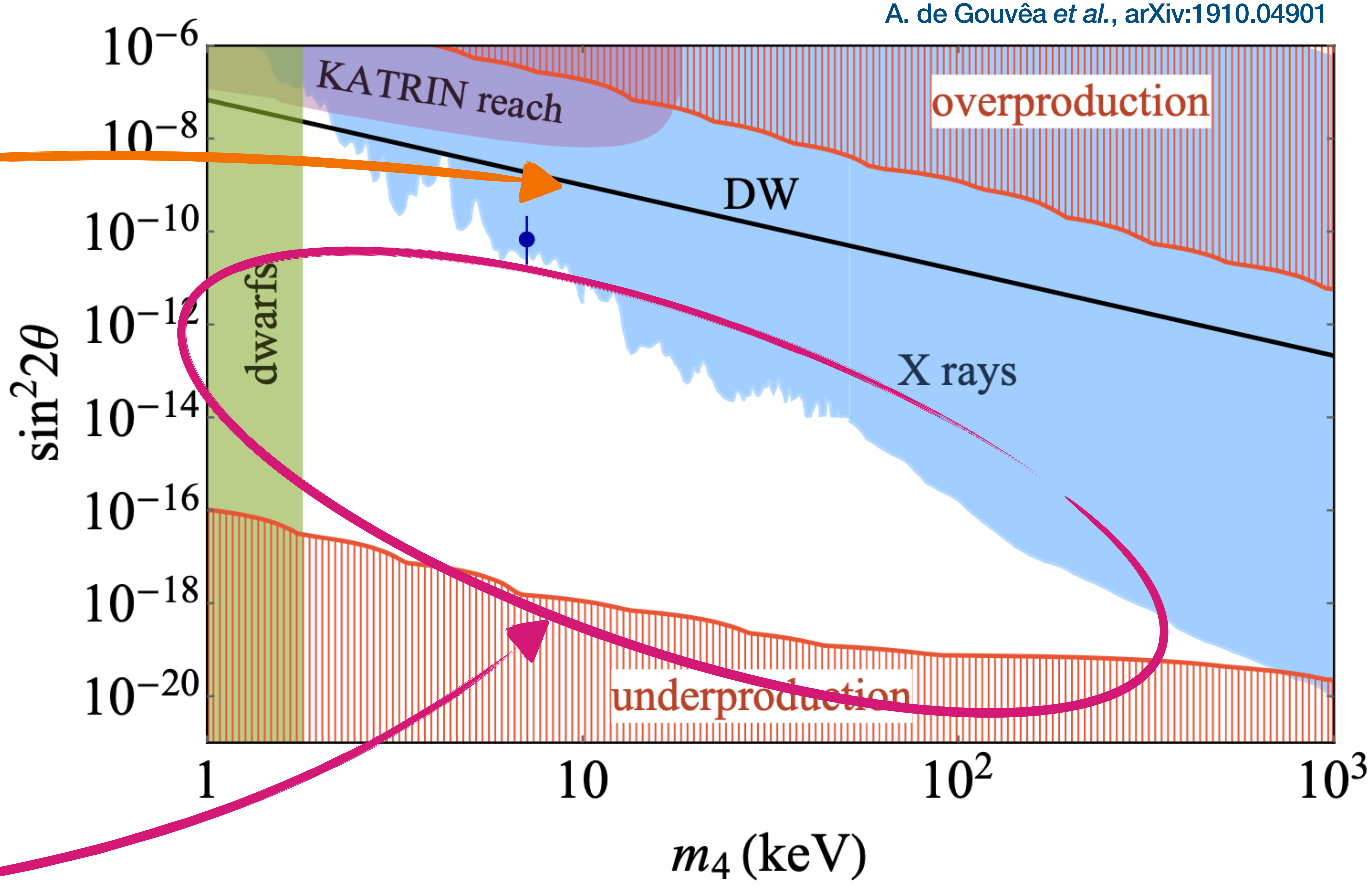

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For $T \sim 100\,\mathrm{GeV}$

Colder spectrum than with DW

Freeze-in production through decay of heavier particles→DM

$$\Gamma_s(T) \ll H(T)$$

$$\frac{df_{DM}}{dt} = \Gamma_s(p,t)\left[f_{DM}^{\mathrm{eq}}(p,t) - f_{DM}(p,t)\right]$$

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$$\Omega_{DM}h^2 \propto \frac{m_{DM}\Gamma_s(A \to B + DM)}{m_A^2}$$

$m_A \sim 150\,\text{GeV}$

$m_{DM} \sim 10\,\text{keV}$

$\Gamma_s \sim 10^{-16}\,\text{GeV}$

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- SM bosons & heavy ν decays to DM

A. Abada *et al.*, arXiv:1406.6556
D. Boyanovsky & L. Lello, arXiv:1508.04077
M. Lucente, arXiv:2103.03253
A. Datta *et al.*, arXiv:2104.02030
A. Abada, G. Arcadi, G. Piazza, M. Lucente & **SRA**, arXiv:2308.01341

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- Scalar coupled to singlet neutrinos

A. Merle *et al.*, arXiv:1306.3996
M. Drewes & J. U. Kand, arXiv:1510.05646
V. De Romeri *et al.*, arXiv:2003.12606
E. Fernandez-Martinez, M. Pierre, E. Pinsard & **SRA**, arXiv:2106.05298

Talk by T. Tong!

$m_A \sim 150\,\text{GeV}$

$m_{DM} \sim 10\,\text{keV}$

$\Gamma_s \sim 10^{-16}\,\text{GeV}$

Production through SM + heavy ν decays

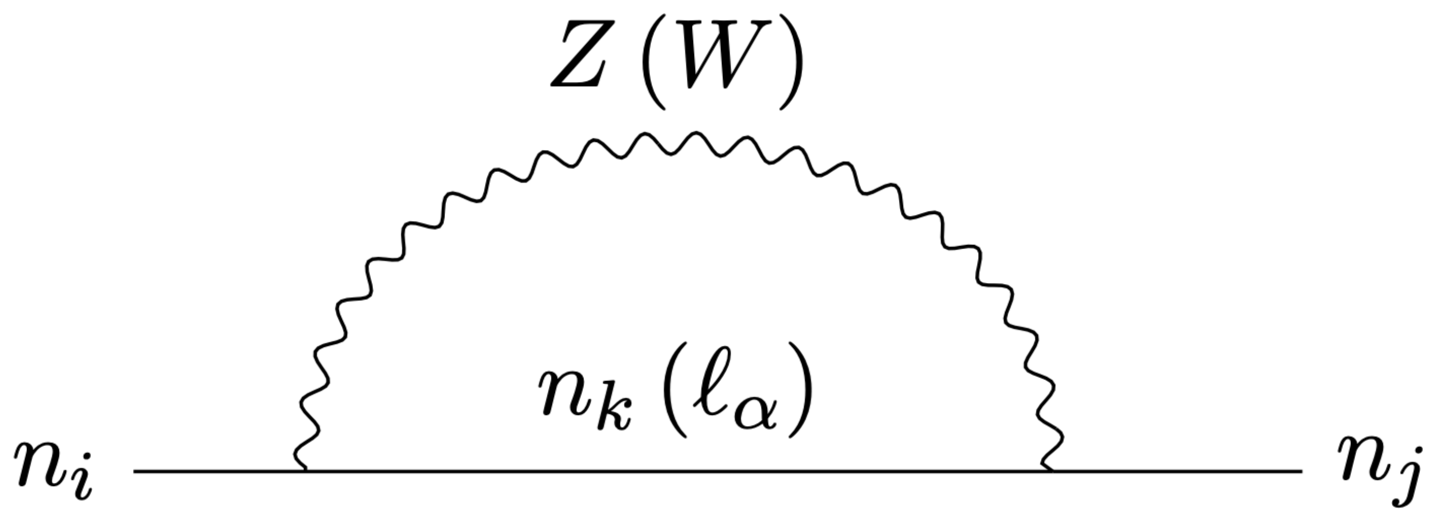
Propagating states in the early Universe

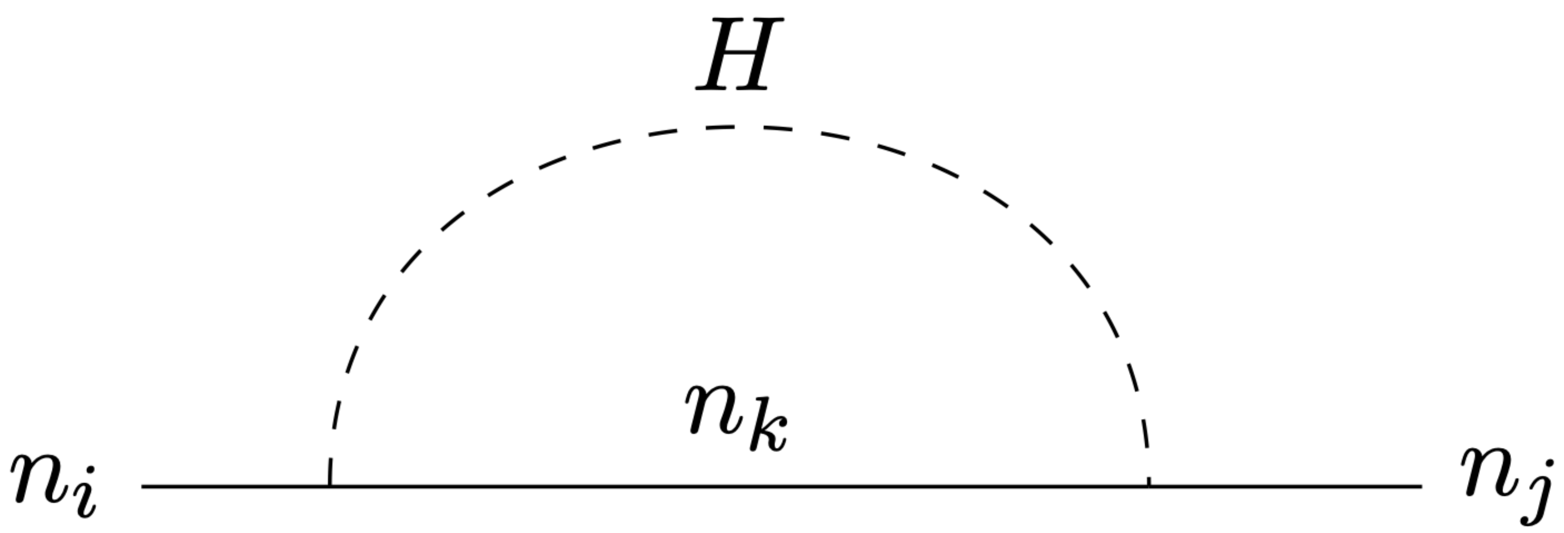
One should not use the $T = 0$ ν-states to compute the production rate

D. Boyanovsky *et al.*, arXiv:1609.07647
A. Abada, G. Arcadi, G. Piazza, M. Lucente & **SRA**, *arXiv:2308.01341*

Just like matter effects in ν oscillations, the mixing changes with T

Le Bellac, Thermal Field Theory (1996)

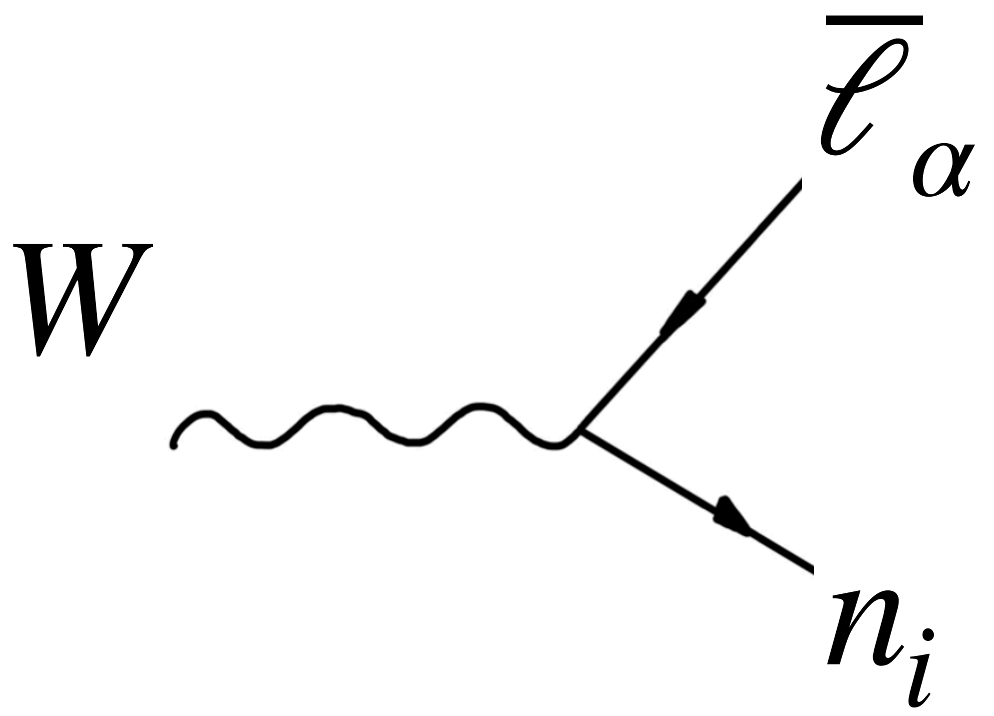




Optical theorem in TFT

M. Le Bellac, Thermal Field Theory (1996)
H. Weldon, Phys. Rev. D (1983)

Example



How does the n_i distribution evolve with time?

$$\frac{\partial f_{n_i}}{\partial t} = -\Gamma_{\rm dec} f_{n_i} + \Gamma_{\rm inv}(1 - f_{n_i})$$

$\Gamma_{\rm dec}$ represents the decay through $n_i \overline{\ell}_\alpha \to W$, while $\Gamma_{\rm inv}$ the inverse process

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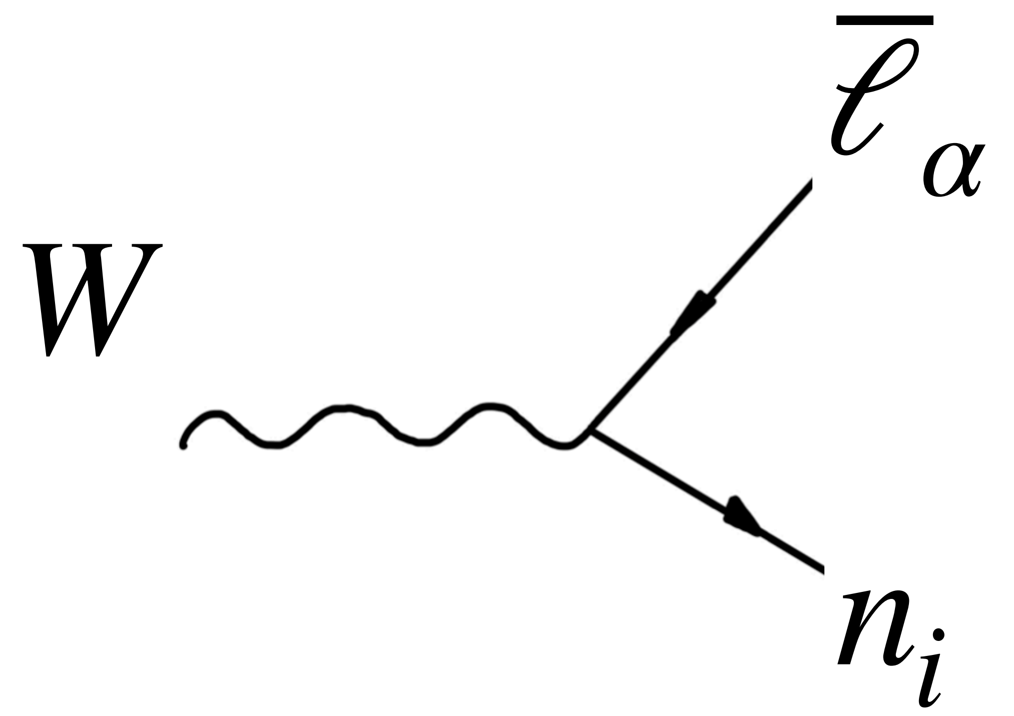

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$$\Gamma \equiv \Gamma_{\rm dec} + \Gamma_{\rm inv} \propto \int \frac{d^3q}{(2\pi)^3} \frac{|\mathcal{M}|^2}{2E_\ell 2E_W} \left[f_F(1+f_B) + (1-f_F)f_B\right] \delta(p_0 + E_\ell - E_W)$$

$$\frac{\partial f_{n_i}}{\partial t} = \Gamma \left[f_{n_i}^{\rm eq} - f_{n_i}\right]$$

Γ is the rate at which n_i approaches equilibrium

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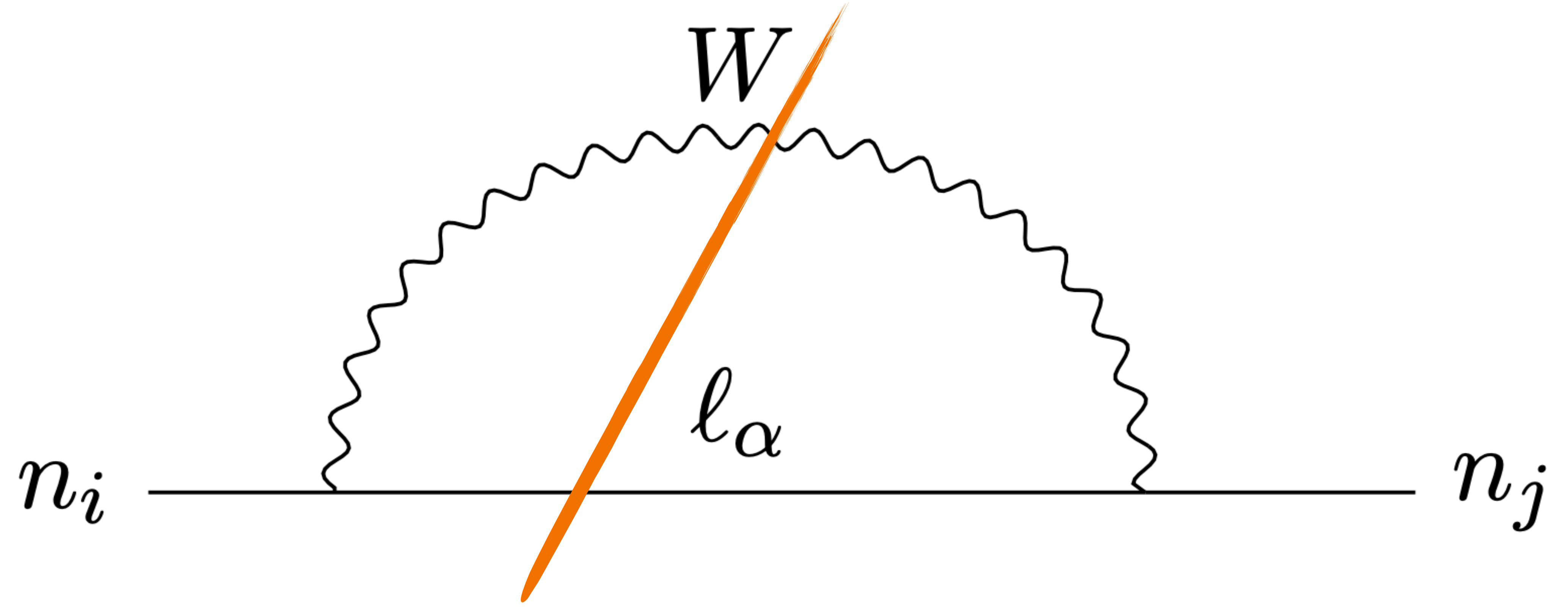

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$$\frac{\partial f_{n_i}}{\partial t} = \Gamma \left[f_{n_i}^{\rm eq} - f_{n_i} \right]$$

$$\mathrm{Im}\Sigma_{ii} \propto \int \frac{d^3q}{(2\pi)^3} \frac{|\mathcal{M}|^2}{2E_\ell 2E_W} \left[f_B(E_W) + f_F(E_\ell) \right] \delta(p_0 + E_\ell - E_W)$$

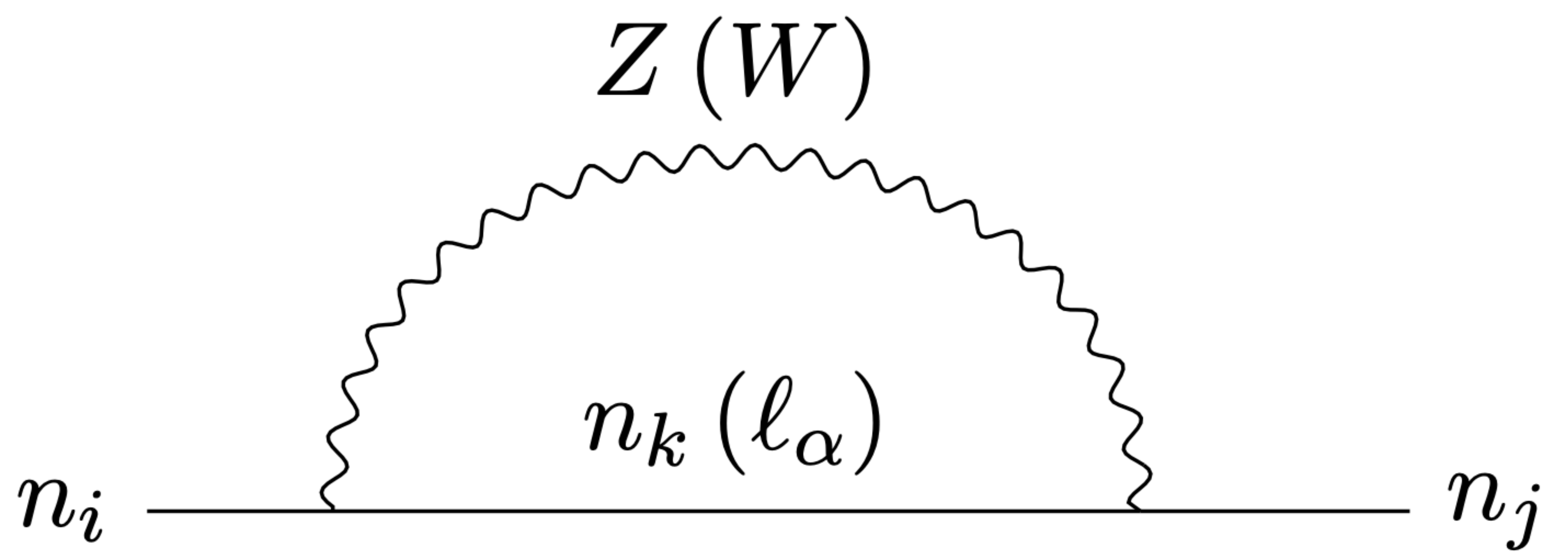
$$\Gamma \propto \int \frac{d^3q}{(2\pi)^3} \frac{|\mathcal{M}|^2}{2E_\ell 2E_W} \left[f_F + f_B \right] \delta(p_0 + E_\ell - E_W)$$

DM production without heavy ν

Gauge boson contributions

Consider just a light ν species and the keV DM candidate

D. Boyanovsky *et al.*, arXiv:1609.07647
A. Abada, G. Arcadi, G. Piazza, M. Lucente & **SRA**, *arXiv:2308.01341*



$$\Sigma^W_{ij}(p_0, p, T) = \sum_\alpha \mathcal{U}^\dagger_{i\alpha}\mathcal{U}_{\alpha j}\sigma\left(p_0, p, T\right)$$

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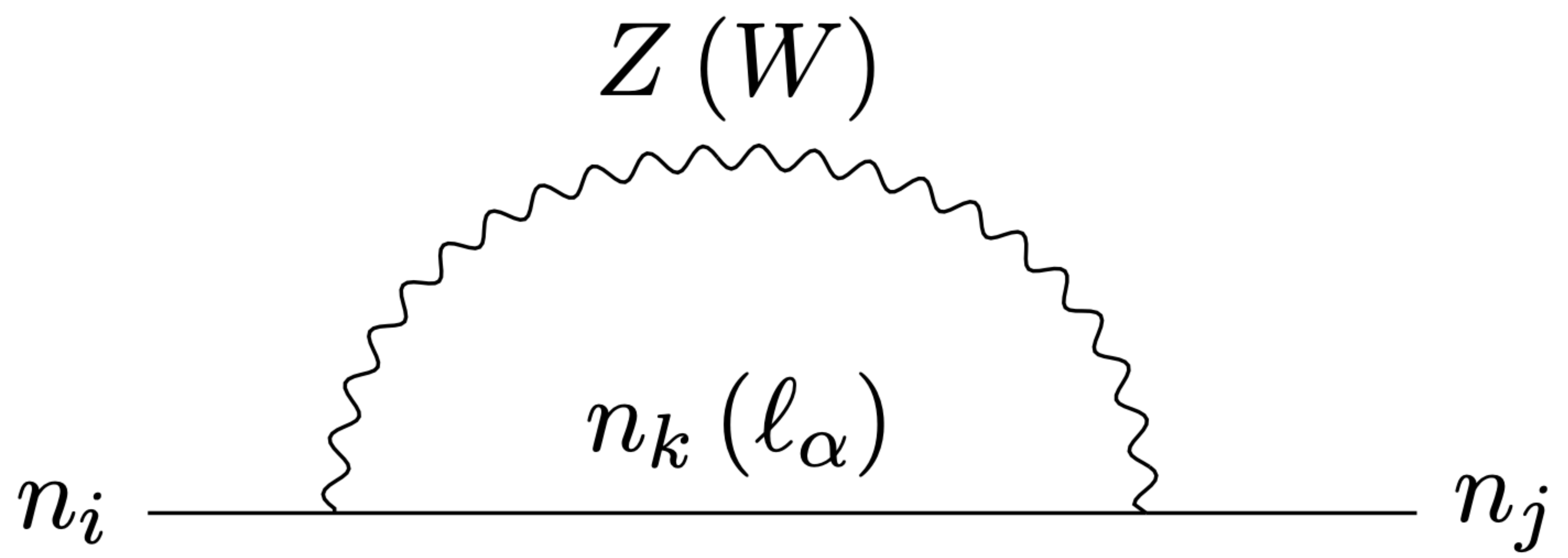

$$\Sigma^W_{ij}(p_0, p, T) = \sum_\alpha \mathcal{U}^\dagger_{i\alpha}\mathcal{U}_{\alpha j}\sigma\left(p_0, p, T\right)$$

Self-energy corrections

The new dispersion relations are given by

$$\mathcal{U}_{\alpha 4} \sim \sin 2\theta$$

$$(p_0^2 - p^2)\mathbb{I}_{2\times 2} + \begin{pmatrix} \Omega^h(T) - \frac{m^2_{DM}}{4}\tan^2 2\theta & -\frac{m^2_{DM}}{2}\tan 2\theta \\ -\frac{m^2_{DM}}{2}\tan 2\theta & -m^2_{DM}\left[1 + \frac{1}{4\alpha^h}\tan^2 2\theta\right] \end{pmatrix} = 0$$

DM production without heavy ν

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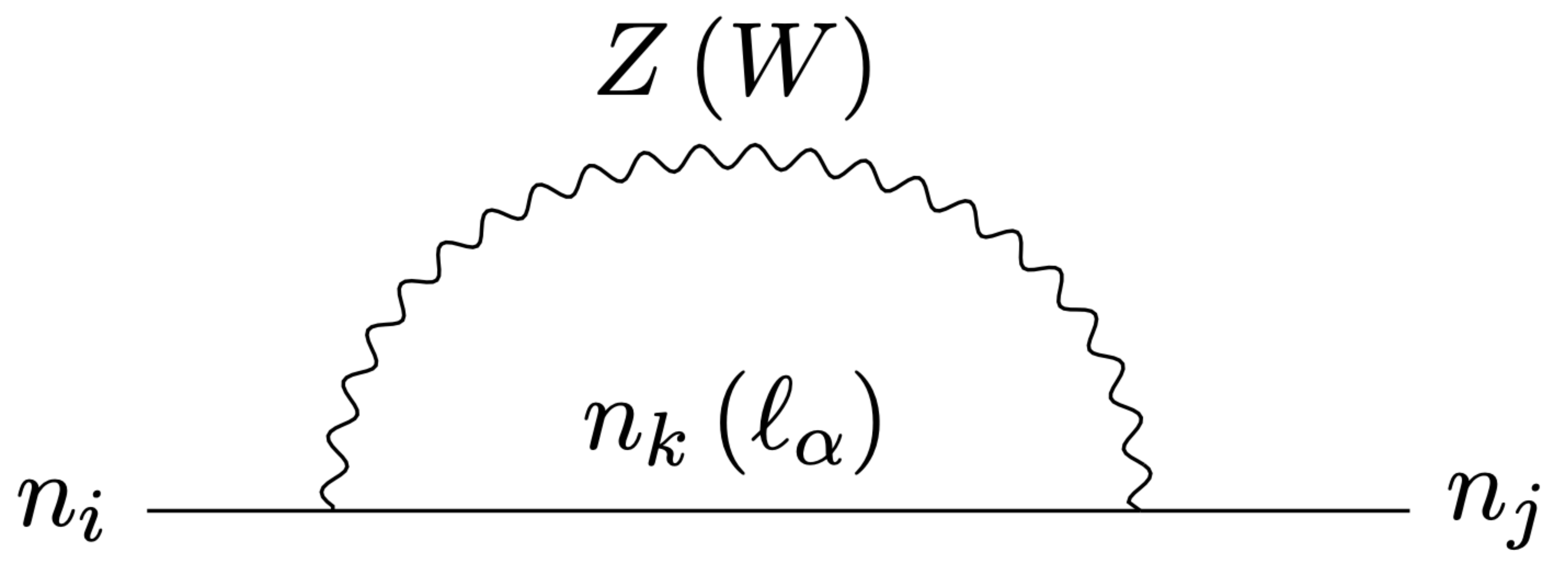
$$\Gamma_s^h \sim \theta^2 \left[\frac{\mathrm{Im}\Omega^h}{|\Omega^h|^2} + \frac{\mathrm{Im}\alpha^h}{|\alpha^h|^2} \right]$$

Only for Majorana ν



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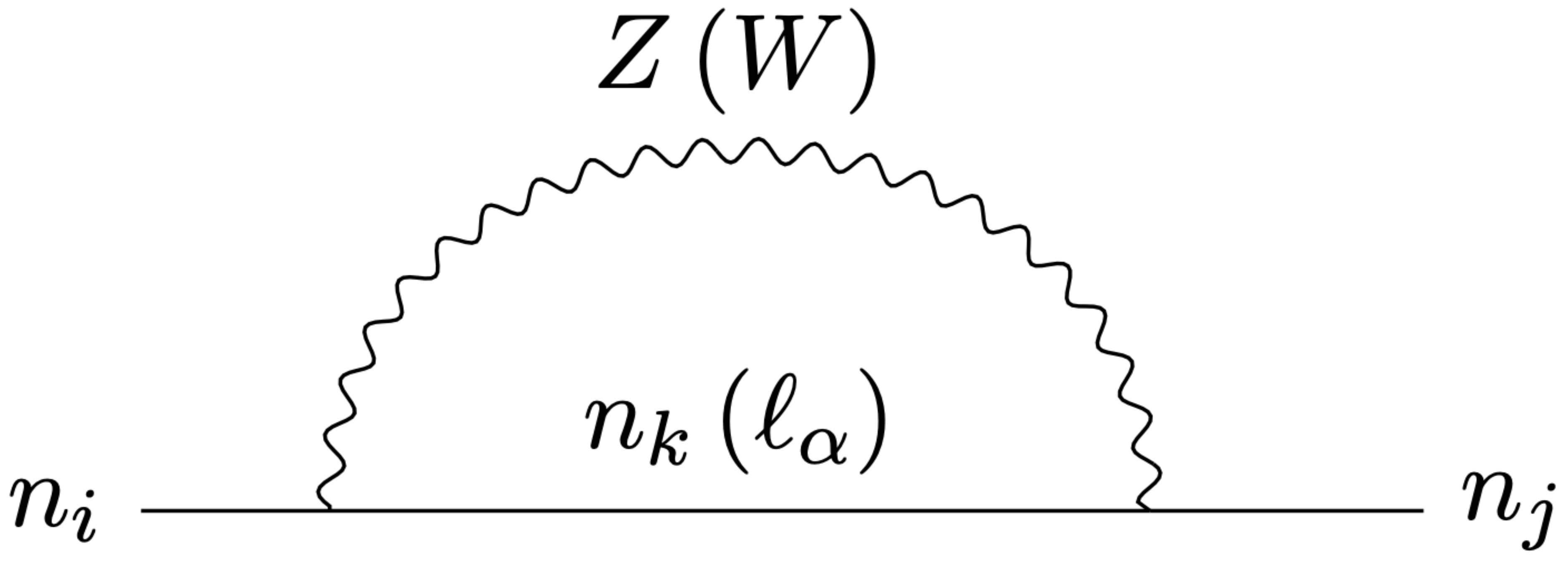
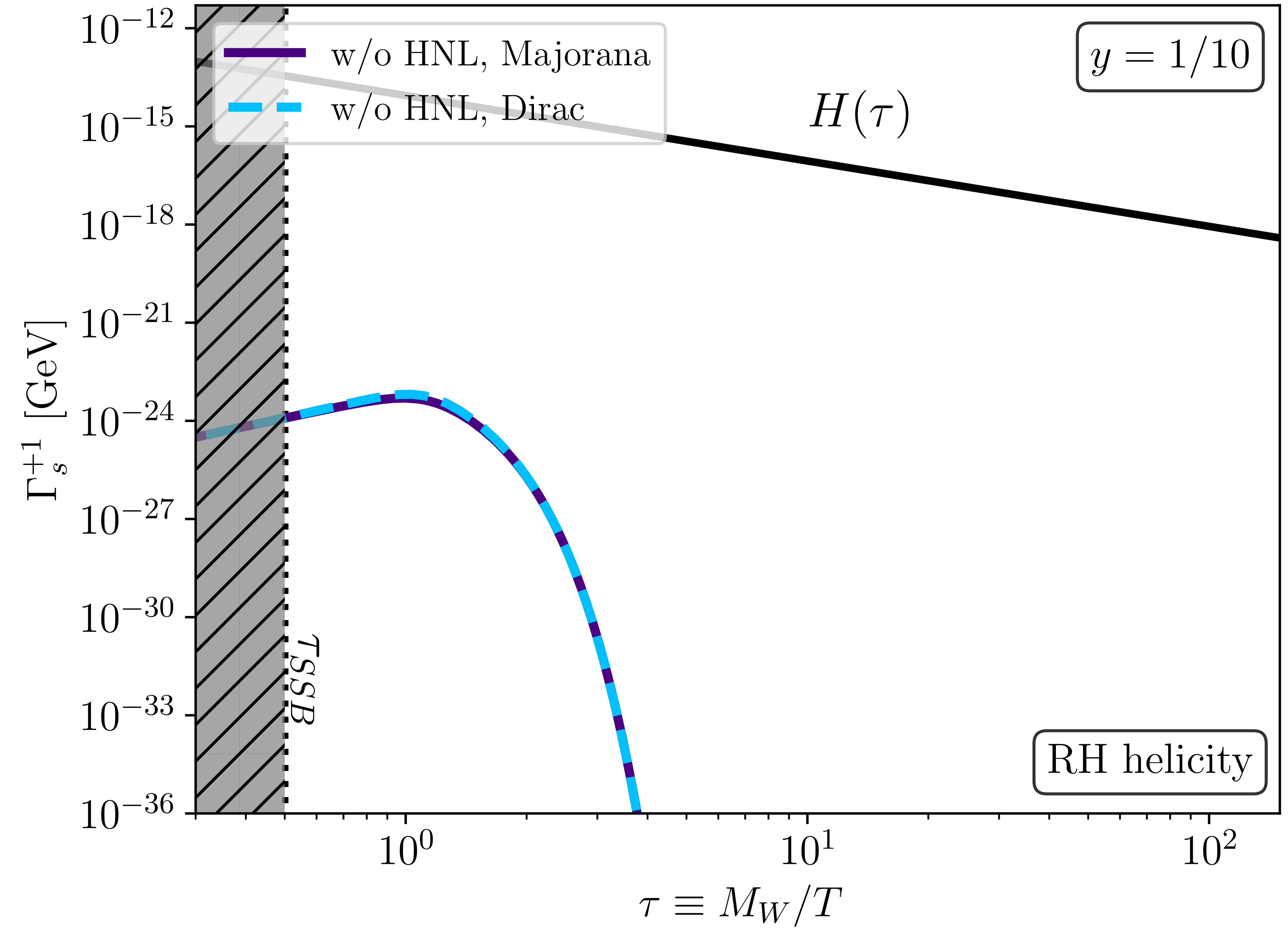
$$\Gamma_s^h \sim \theta^2 \left[\frac{\mathrm{Im}\Omega^h}{|\Omega^h|^2} + \frac{\mathrm{Im}\alpha^h}{|\alpha^h|^2} \right]$$

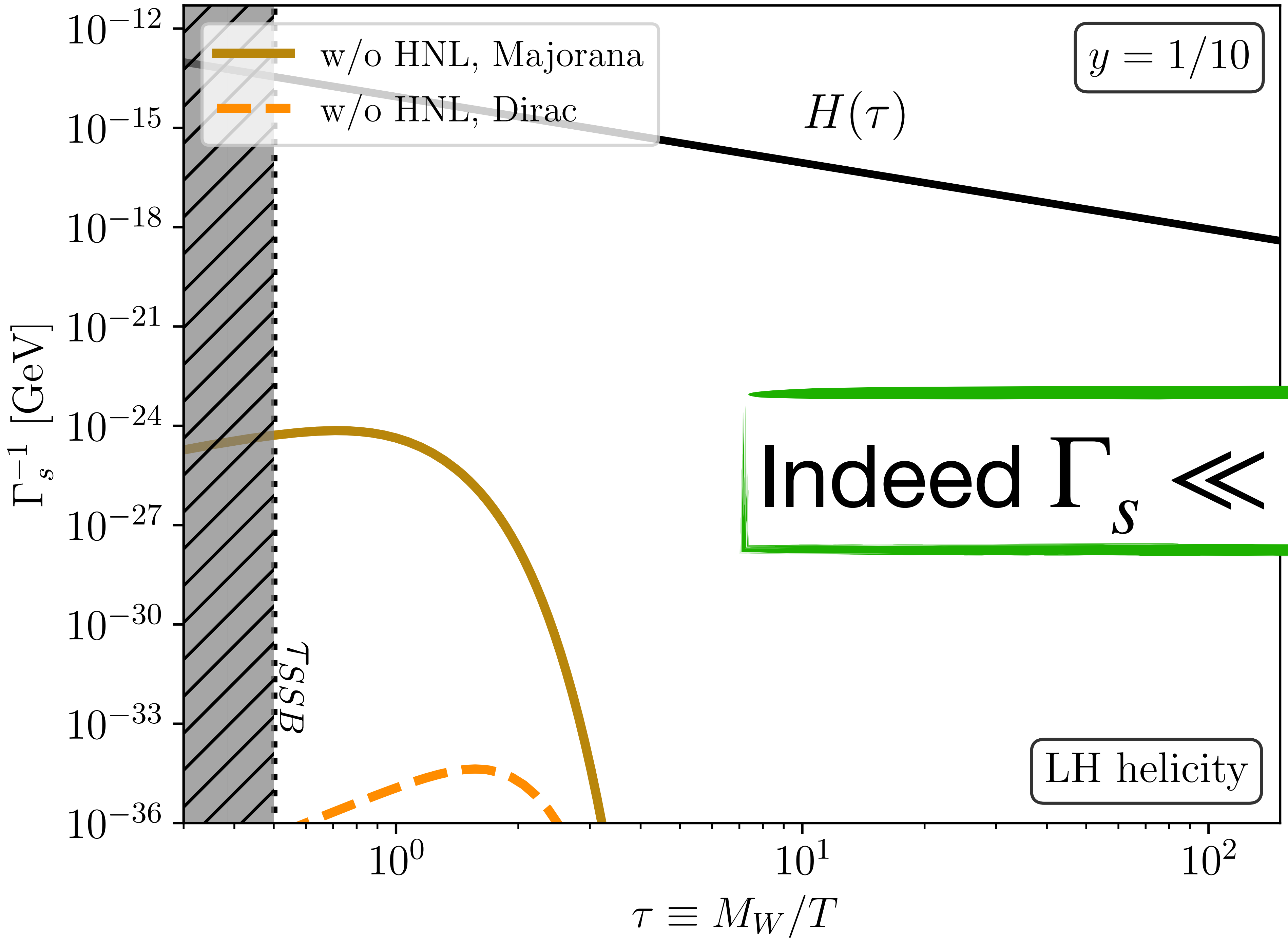
$m_{DM} \sim 10$ keV

$|\mathcal{U}_{\alpha 4}| \sim 10^{-6}$



$y \equiv p/T$





Indeed $\Gamma_s \ll H$

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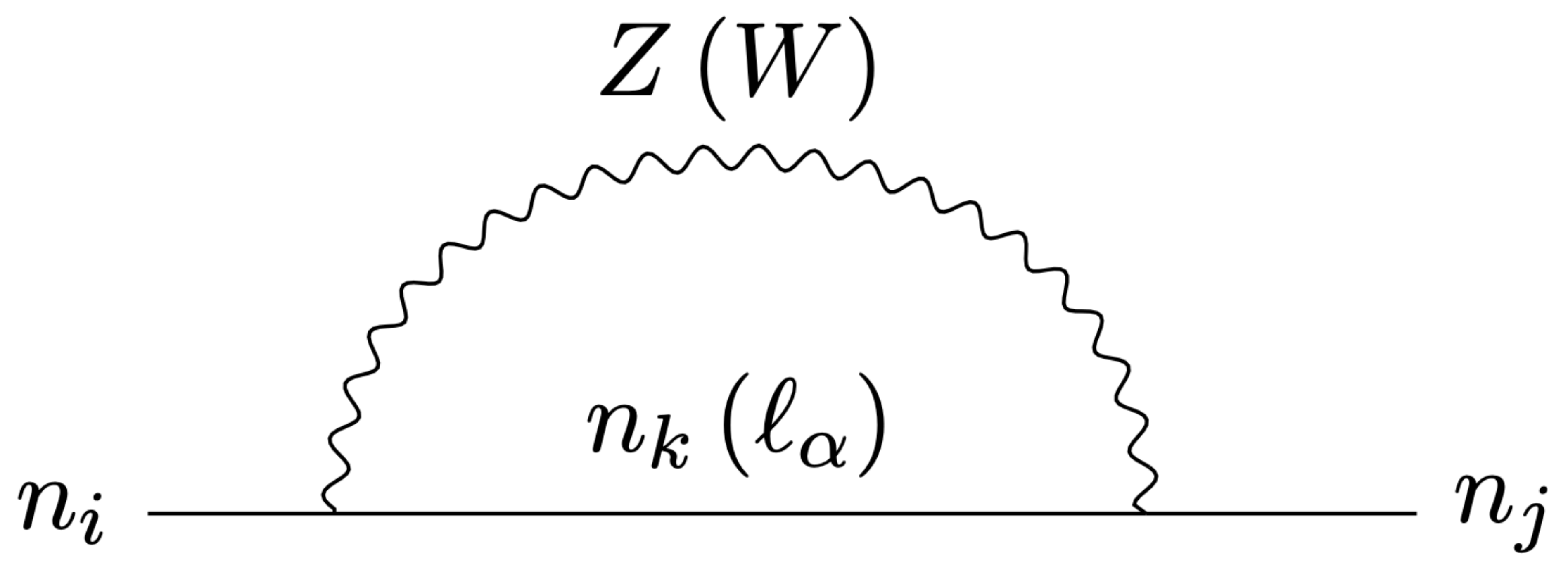
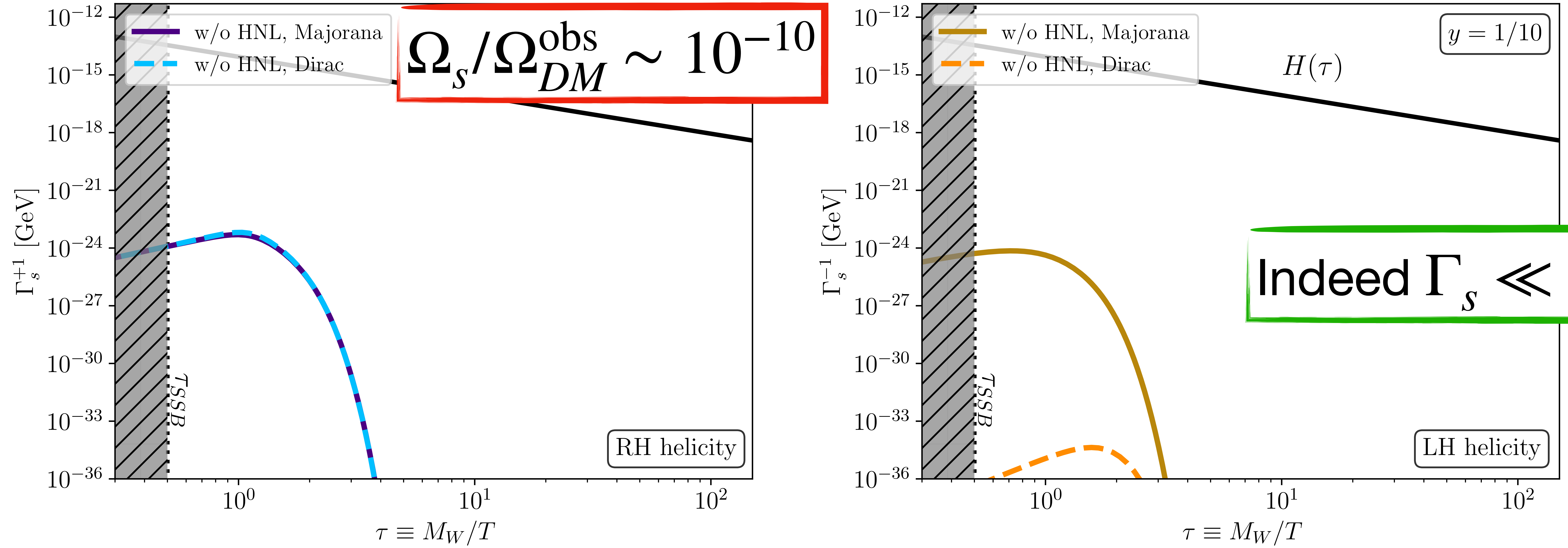


$y \equiv p/T$

$\Omega_s/\Omega_{DM}^{obs} \sim 10^{-10}$

Indeed $\Gamma_s \ll H$



DM production including heavy ν

Higgs contribution

A. Abada, G. Arcadi, G. Piazza, M. Lucente & **SRA**, *arXiv:2308.01341*

$$\mathscr{L}_H \supset -\frac{H}{2v_H}\sum_{i,j}\bar{n}_i\left[C_{ij}\left(m_iP_L + m_jP_R\right) + C_{ij}^*\left(m_iP_R + m_jP_L\right)\right]n_j$$

$$\sum_{\alpha=e,\mu,\tau}\mathscr{U}_{\alpha i}^*\mathscr{U}_{\alpha j}$$

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$$C_{ij} = \sum_{\alpha=e,\mu,\tau}\mathscr{U}^*_{\alpha i}\mathscr{U}_{\alpha j}$$

- Both helicities couple to the Higgs
- Heavy ν can give large contributions (mixing angles not affected)
- Fermion decays (n_h) to scalars tend to be larger with T

T. Lundberg & R. Pasechnik, arXiv:2007.01224

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A. Abada, G. Arcadi, G. Piazza, M. Lucente & **SRA**, *arXiv:2308.01341*

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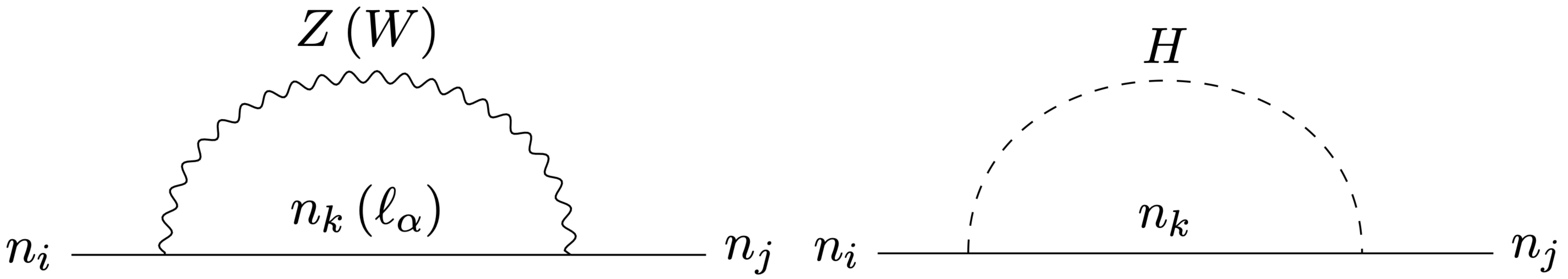


Take into account **all contributions**, which will describe all possible **2-body decays involving any ν, SM boson and DM**

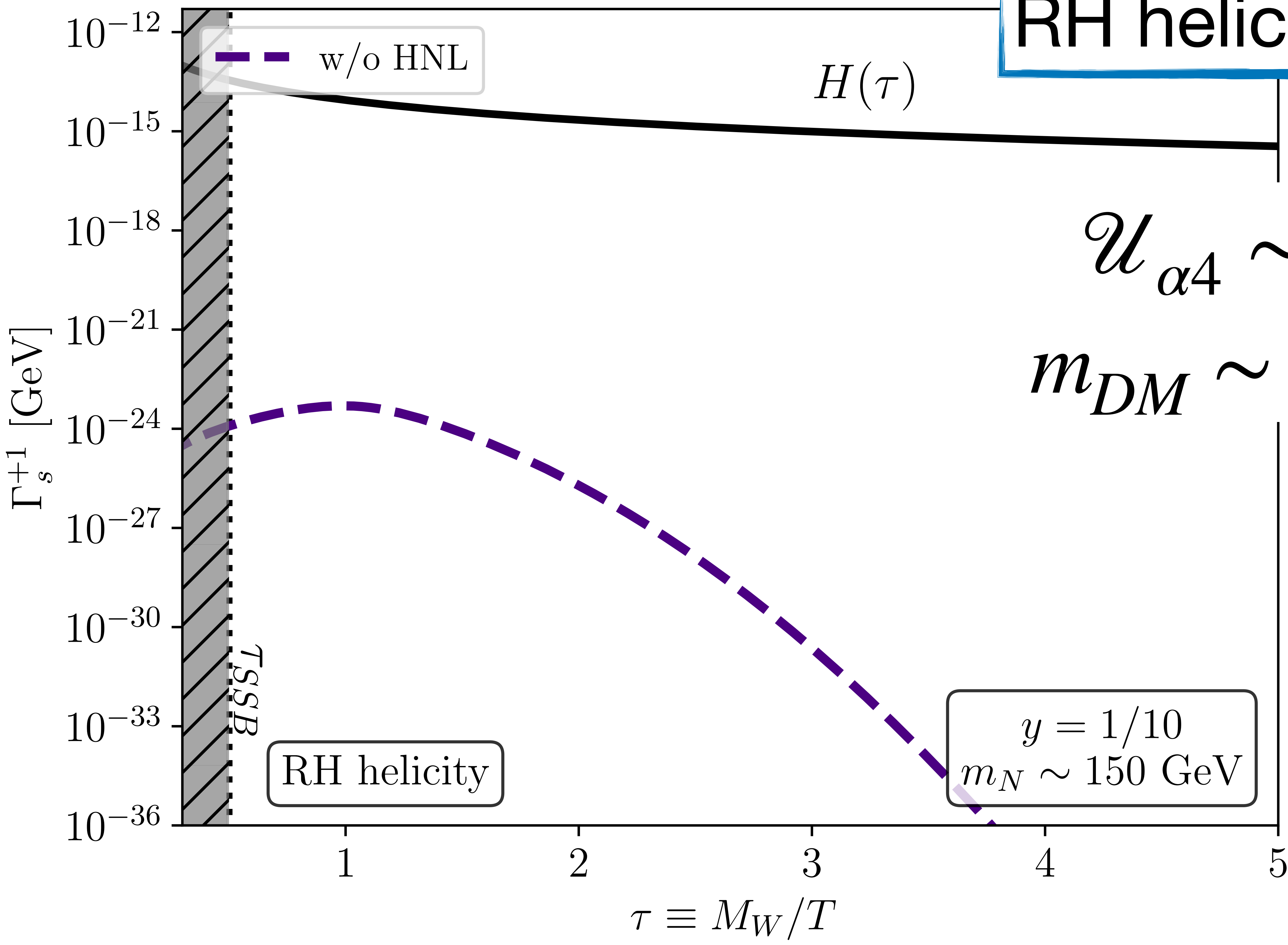
Results

Production rates for fixed momenta

$$\Gamma_s^h(\tau, p) \ll H(\tau)$$

$$y \equiv p/T$$

RH helicity



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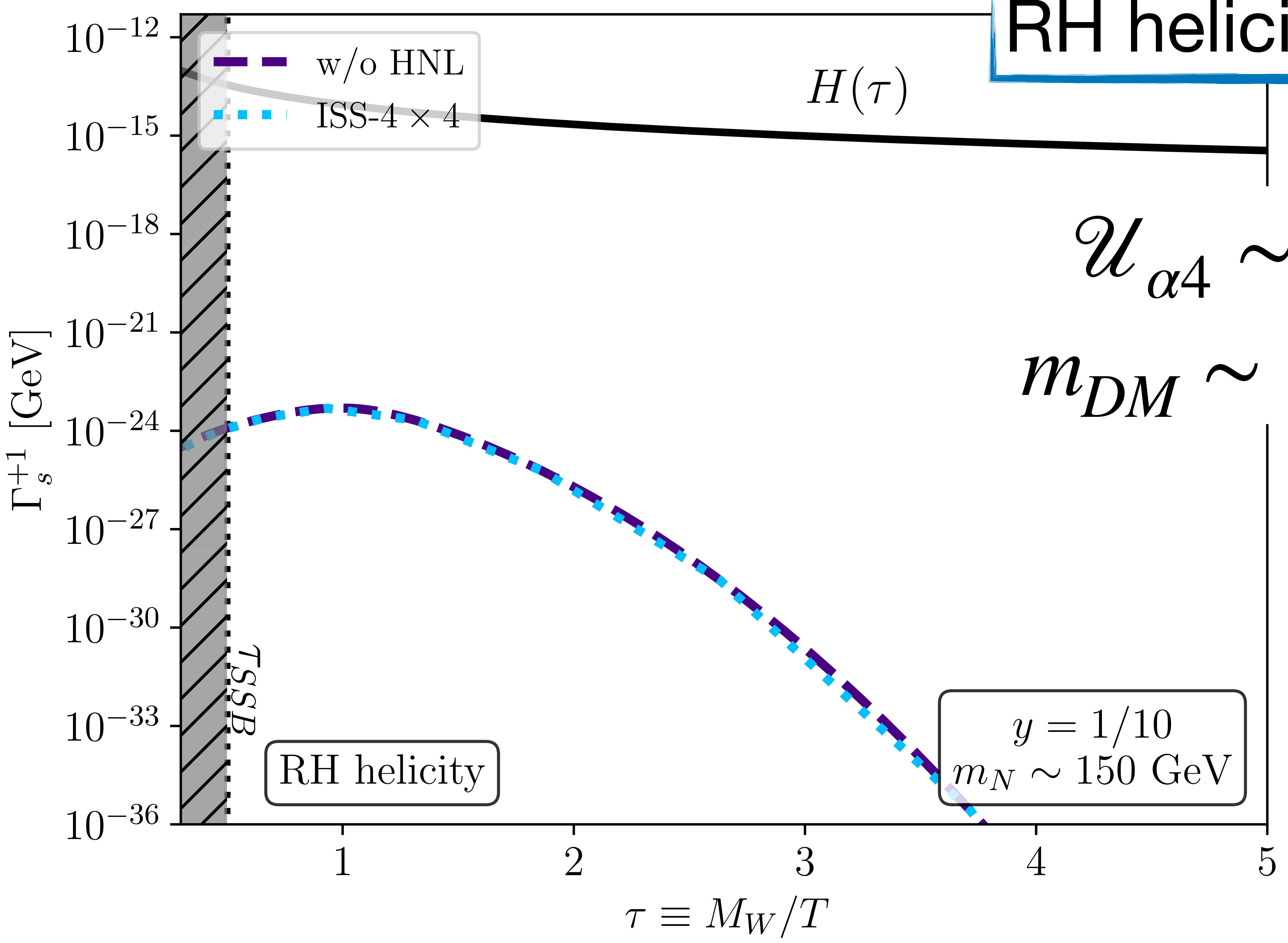

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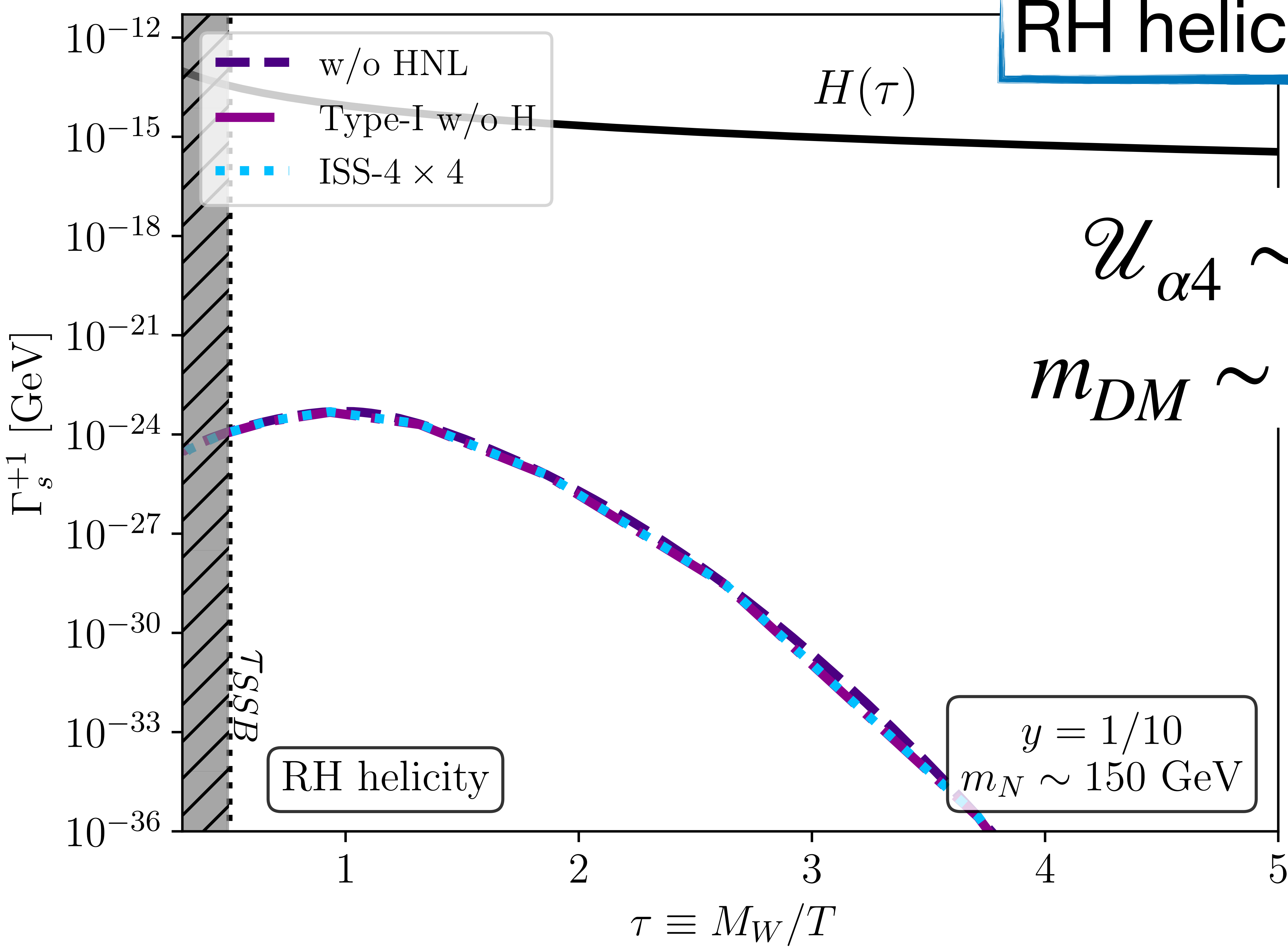

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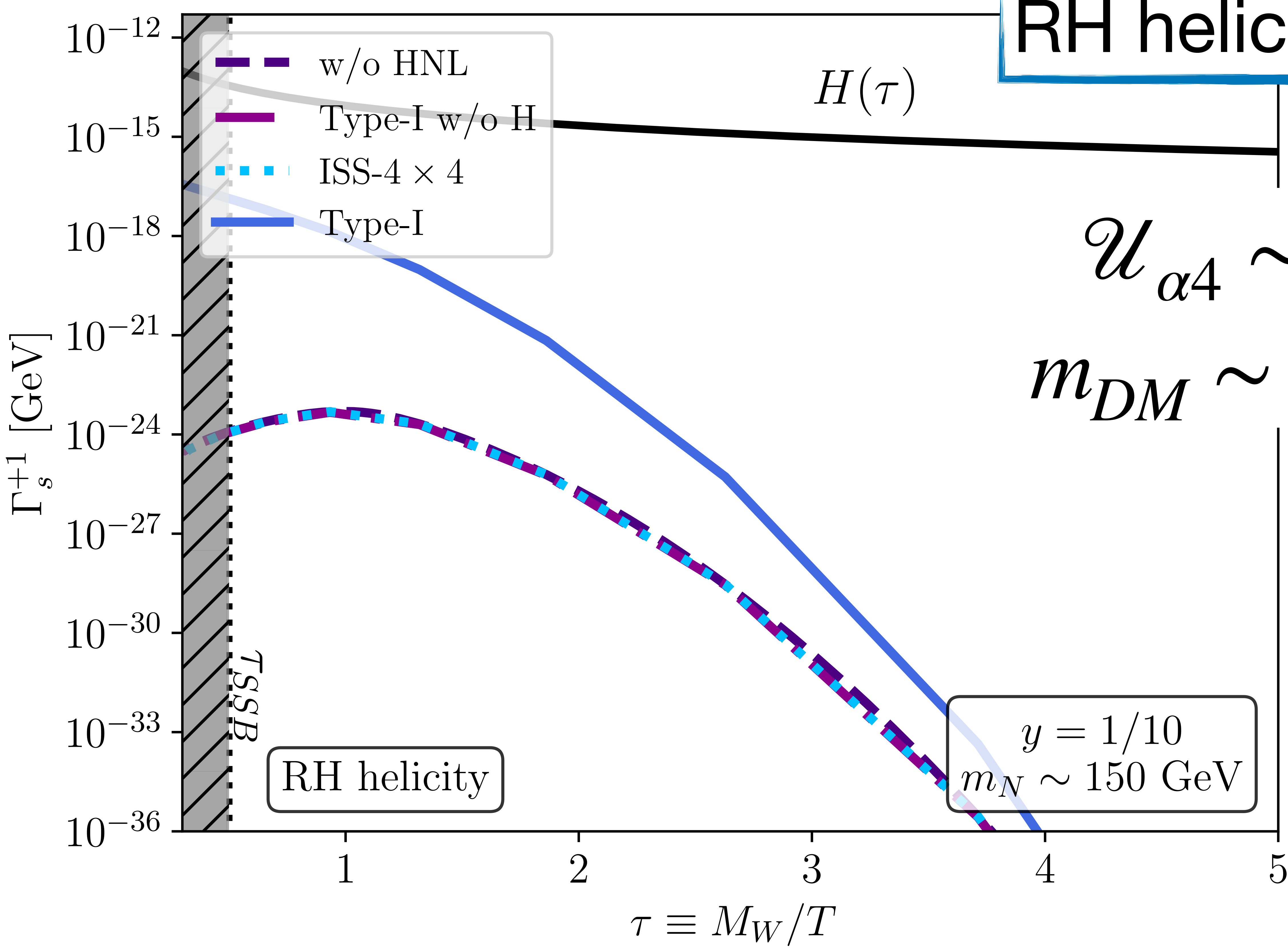

Results

Production rates for fixed momenta

$\Gamma_s^h(\tau, p) \ll H(\tau)$

$y \equiv p/T$

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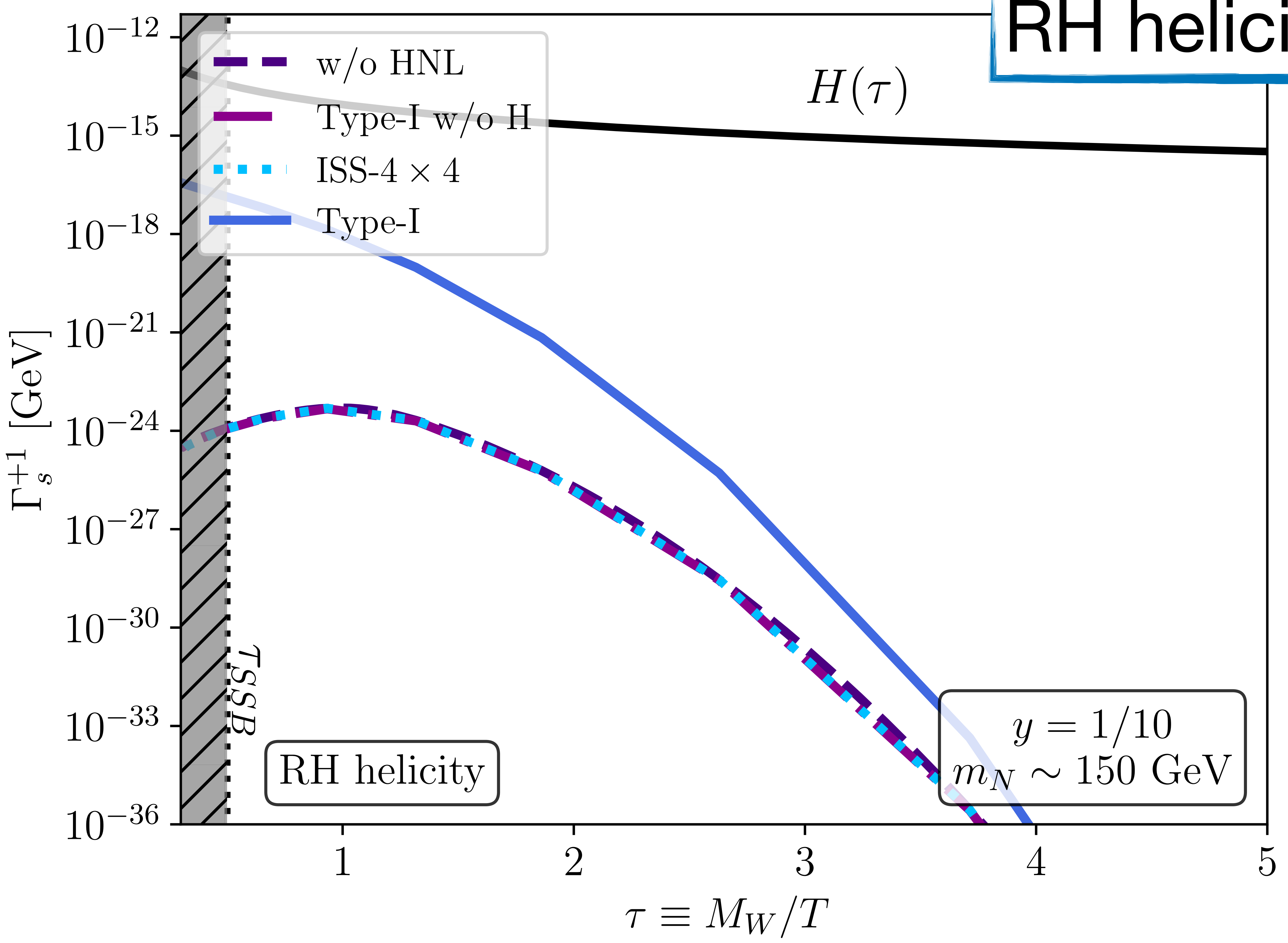
RH helicity



Inclusion of heavy ν and Higgs contribution improves greatly the production

$$f_{DM} = \Omega_s/\Omega_{DM}^{obs} \gtrsim 0.05$$

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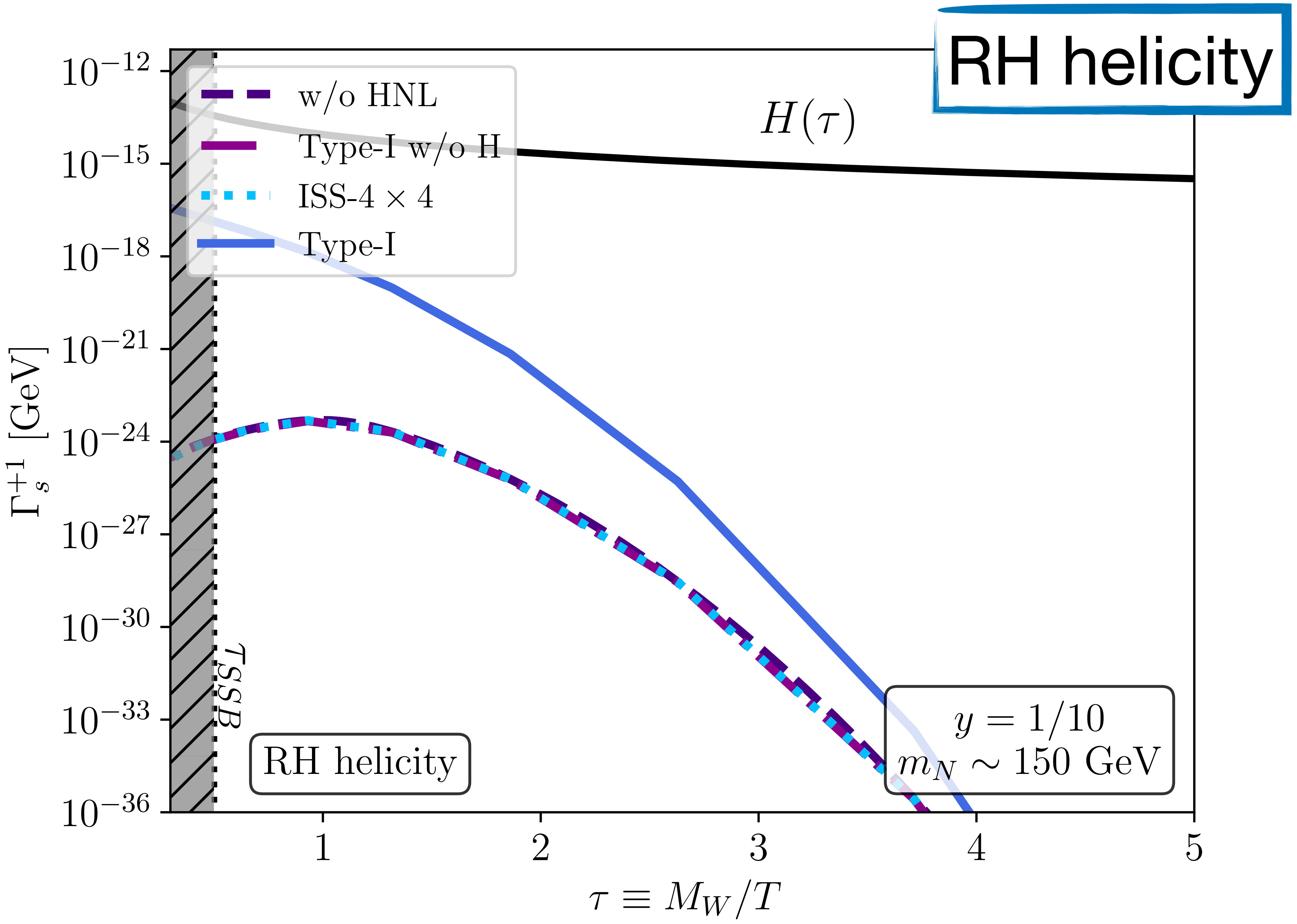

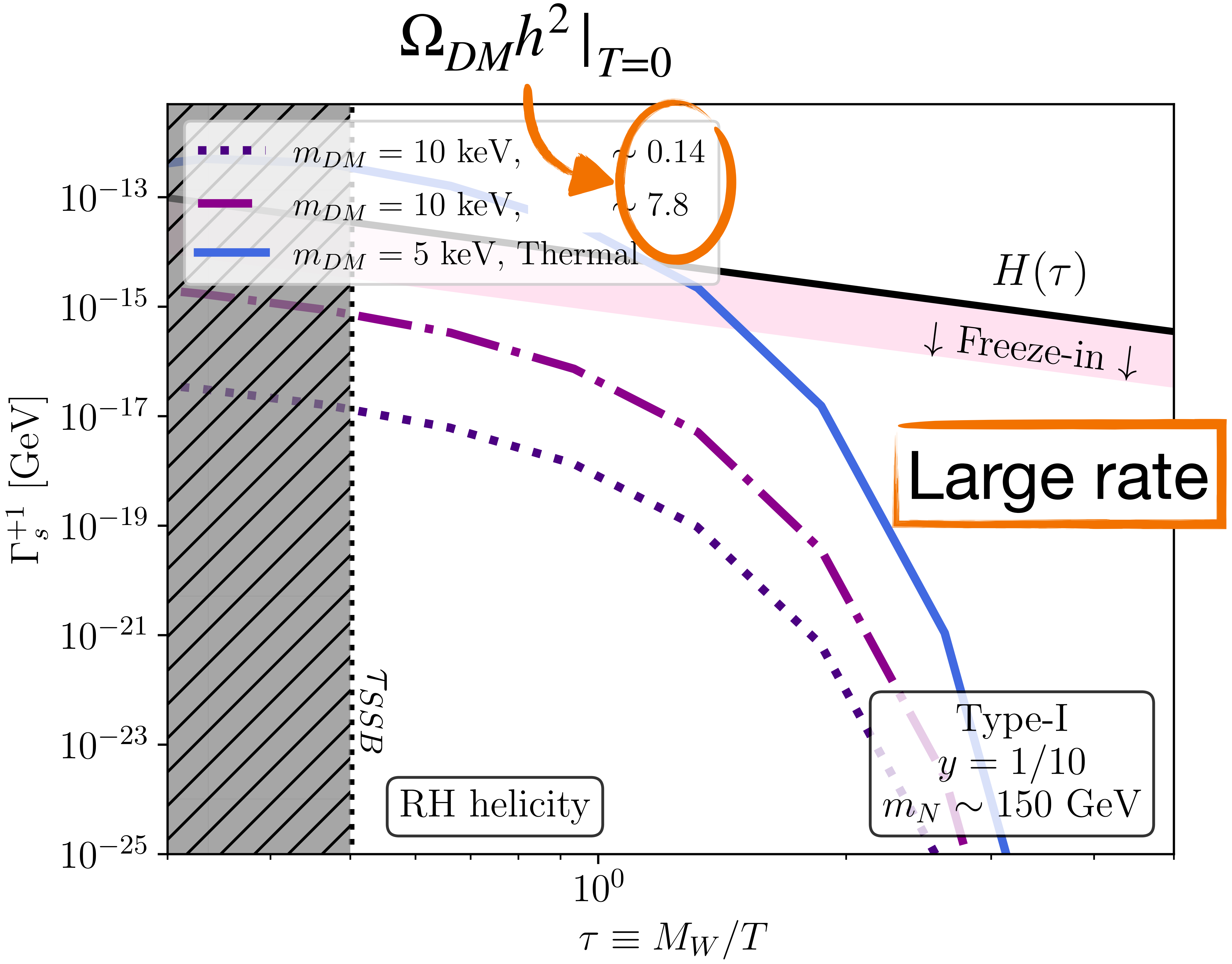

Conclusions

- keV **neutrino DM** is still an interesting candidate
- Among the many possible production mechanisms, **freeze-in** comes up naturally within **neutrino mass models** necessary to explain oscillation data
- However **thermal effects** play a **fundamental role** in the production, dramatically changing the picture from the rates in vacuum

Conclusions

- We find that **weak gauge bosons do not contribute** to the production beyond the DW mechanism $\Omega_s/\Omega_{DM}^{\rm obs} \sim 10^{-10}$

- However production through **heavier ν decays to the Higgs and DM** completely changes this picture, opening the possibility to **freeze-in ν DM**

$$\Omega_s/\Omega_{DM}^{\rm obs} > 0.05$$

- A **scan of parameter space** is necessary to check whether the whole DM abundance can be explained or not within this mechanism

This project has received funding /support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska -Curie grant agreement No 860881-HIDDeN

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Back up

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Neutrino as dark matter

Type-I seesaw

$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N_R - \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$

$$\mathscr{U}_{\alpha 4} \sim \frac{v_H (Y_\nu)_{\alpha 4}}{m_{DM}}$$

Small Yukawa coupling

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M. C. Gonzalez-Garcia & J. Valle (1992)
M. Malinsky *et al.*, arXiv:0506296

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$$\mathscr{L} \supset -\bar{L}_L Y'_\nu \tilde{\Phi} N_R - \overline{N}'^c_R \Lambda N_R - \frac{1}{2}\overline{N}'^c_R \mu N'_R + h.c.$$

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Active-heavy mixing $\mathcal{O}(1)$ thanks to approximate L-number symmetry $\mu \ll m_D, \Lambda$

$$m_\nu \sim (m_D/\Lambda)^2 \mu$$

Λ can be at the EW scale, while $\mu \sim \mathrm{keV}$

A. Abada & M. Lucente, arXiv:1401.1507

Need at least a pair of N_R and N'_R for oscillations

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(2,3)-ISS

Add 2 N_R and 3 N'_R → One N'_R has mass $\mu = m_{DM} \sim \mathrm{keV}$

A. Abada & M. Lucente, arXiv:1401.1507
A. Abada *et al.*, arXiv:1406.6556

Need at least a pair of N_R and N'_R for oscillations

$$\mathcal{U}_{\alpha 4} \sim \left(\frac{v_H Y'_\nu}{\Lambda}\right) \frac{\mu_{ss'}}{m_{DM}}$$

Hierarchy in the elements of μ

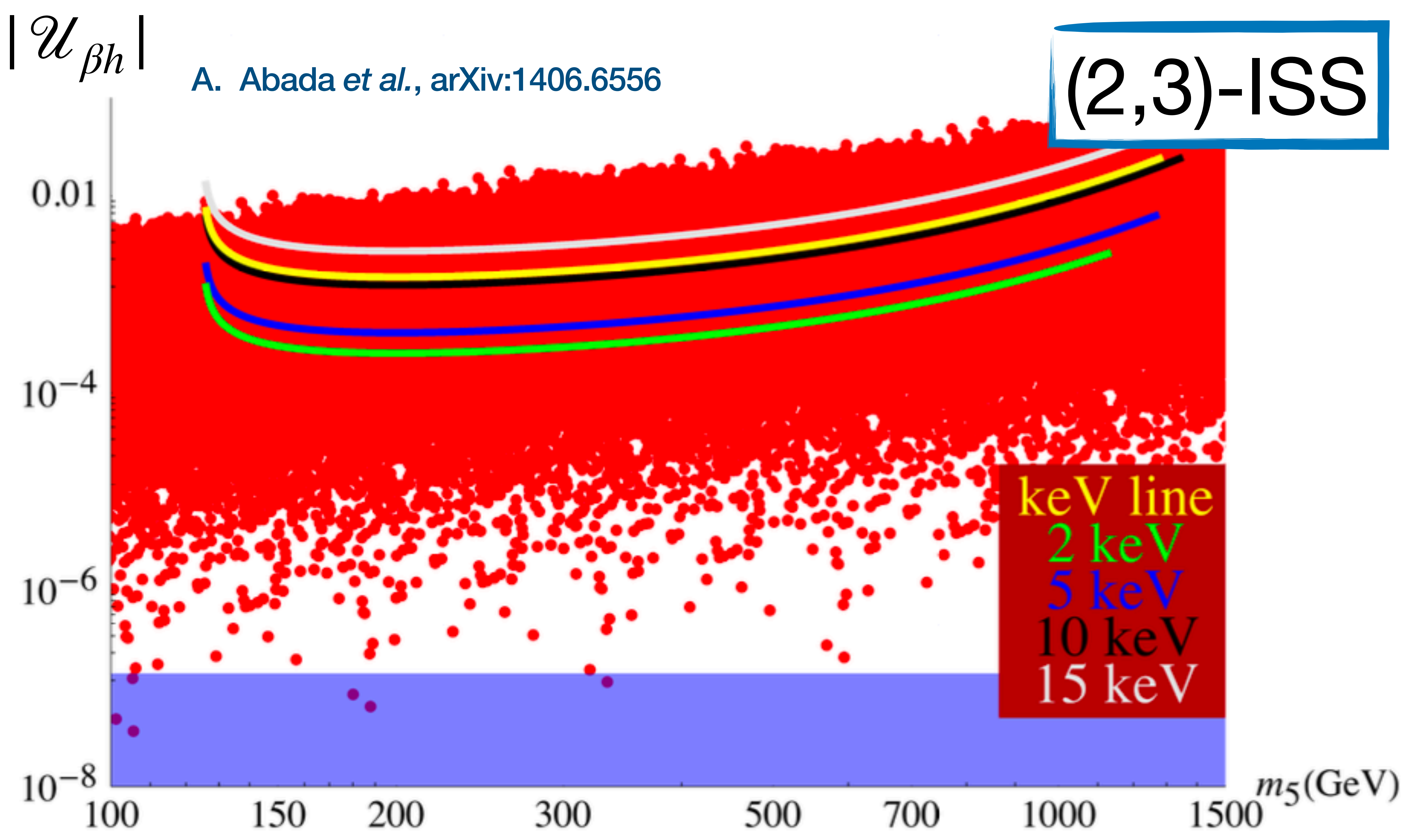
Production through SM + heavy ν decays

Rates using states at $T = 0$

$$n_h \to H + \nu_{DM}$$

A. Abada *et al.*, arXiv:1406.6556
M. Lucente, arXiv:2103.03253

$$\Gamma_s \sim m_{n_h} \left(1 - \frac{M_H^2}{m_{n_h}^2} \right) \sum_{\alpha,\beta} |\mathcal{U}_{\alpha 4}|^2 |\mathcal{U}_{\beta h}|^2$$



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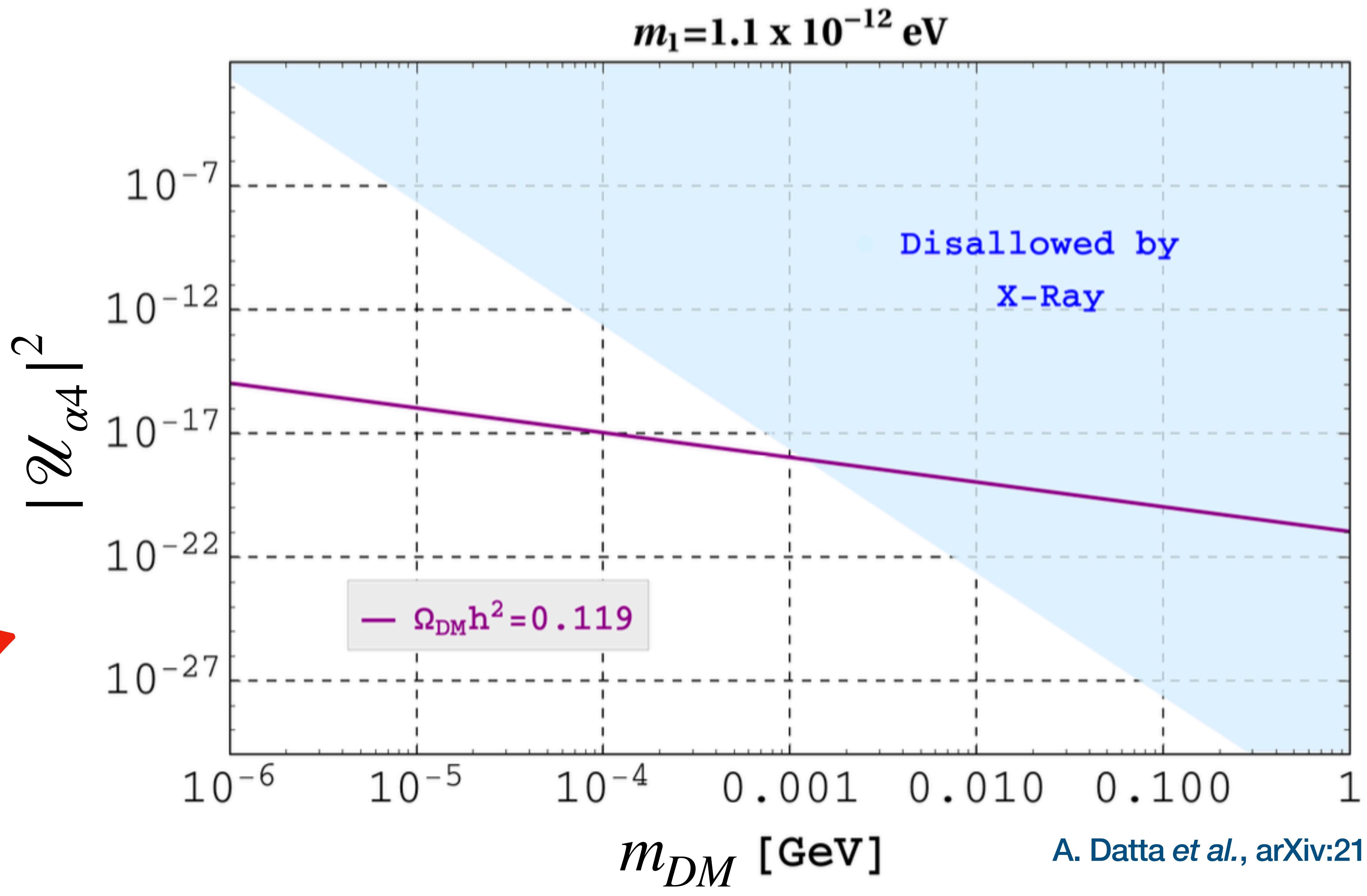

A. Datta *et al.*, arXiv:2104.02030

$$\Gamma_s \sim G_F M^3_{Z(W)} \sum_{\alpha=e,\mu,\tau} |\mathcal{U}_{\alpha 4}|^2$$

$$Z(W) \to \nu_l(\ell_\alpha) + \nu_{DM}$$

Self-energy decomposition

Projections

$$\not{\Sigma} = \gamma_0 \Sigma^{(0)} - \vec{\gamma} \cdot \hat{p} \Sigma^{(1)} + \Sigma^{(2)} \mathbb{1}$$

$$\Sigma^{(0)} = \frac{1}{4} \mathrm{Tr}\left[\gamma^0 \not{\Sigma}\right]$$

$$\Sigma^{(1)} = \frac{1}{4} \mathrm{Tr}\left[\vec{\gamma} \cdot \hat{p} \not{\Sigma}\right]$$

$$\Sigma^{(2)} = \frac{1}{4} \mathrm{Tr}\left[\not{\Sigma}\right]$$

$$\not{\Sigma}^{W}_{ij}(p_0, p, T) = \sum_{\alpha} \mathcal{U}^{\dagger}_{i\alpha} \mathcal{U}_{\alpha j} \sigma\left(p_0, p, T\right)$$

σ is the **self-energy contribution** in the **flavor basis** when ν masses can be neglected with respect to the other scales

Self-energy decomposition

Dispersion relation in the toy 2x2 case

$$(p_0^2 - p^2)\mathbb{I}_{2\times 2} + \begin{pmatrix} \Omega^h(T) - \frac{m_{DM}^2}{4}\tan^2 2\theta & -\frac{m_{DM}^2}{2}\tan 2\theta \\ -\frac{m_{DM}^2}{2}\tan 2\theta & -m_{DM}^2\left[1 + \frac{1}{4\alpha^h}\tan^2 2\theta\right] \end{pmatrix} = 0$$

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$$\Omega^h(T) = (p_0 - hp)(\sigma_L^{(0)} + h\sigma_L^{(1)})$$

LH helicity $h = -1$

$$\Omega^{-1} = 2p(\sigma_L^{(0)} - \sigma_L^{(1)})$$

RH helicity $h = +1$

$$\Omega^{+1} = \frac{m_{DM}^2}{2p}(\sigma_L^{(0)} + \sigma_L^{(1)})$$

DM production without heavy ν

Gauge boson contributions

D. Boyanovsky *et al.*, arXiv:1609.07647
A. Abada, G. Arcadi, G. Piazza, M. Lucente & **SRA**, *arXiv:2308.01341*

$$\Omega^h(T) \equiv 2p\left(\Delta_L + i\gamma_L\right) = \begin{cases} 2p(\sigma^{(0)} - \sigma^{(1)}) \\ \frac{m_{DM}^2}{2p}(\sigma^{(0)} + \sigma^{(1)}), \end{cases}$$

LH ν receive large thermal corrections ($h = -1$)

Self-energy corrections chirality suppressed for RH ν ($h = +1$)

The equilibration rate is related to $\Gamma_s^h = -2\mathrm{Im}\left(p_0\right)$

$$(p_0^2 - p^2)\mathbb{I}_{2\times 2} + \begin{pmatrix} \Omega^h(T) - \frac{m_{DM}^2}{4}\tan^2 2\theta & -\frac{m_{DM}^2}{2}\tan 2\theta \\ -\frac{m_{DM}^2}{2}\tan 2\theta & -m_{DM}^2\left[1 + \frac{1}{4\alpha^h}\tan^2 2\theta\right] \end{pmatrix} = 0$$

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$$\Omega^h(T) = (p_0 - hp)(\sigma_L^{(0)} + h\sigma_L^{(1)})$$

$$p_0^2 - p^2 + \Omega^h - \frac{\theta^2 m_{DM}^2}{1 + m_{DM}^2/\Omega^h} = 0 \text{ for light } \nu$$

$$p_0^2 - p^2 - m_{DM}^2 - \theta^2 m_{DM}^2\left(\frac{1}{\alpha^h} + \frac{1}{1 + \Omega^h/m_{DM}^2}\right) = 0 \text{ for DM}$$

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For Dirac ν

$$\Gamma_s^h = \frac{2\theta^2\gamma_L}{\left(1 + 2p\Delta_L/m_{DM}^2\right)^2 + 4p^2\gamma_L^2/m_{DM}^4} \equiv 2\left(\theta_{eff}^h\right)^2\gamma_L$$

D. Boyanovsky *et al.*, arXiv:1609.07647
A. Abada, G. Arcadi, G. Piazza, M. Lucente & **SRA**, *arXiv:2308.01341*

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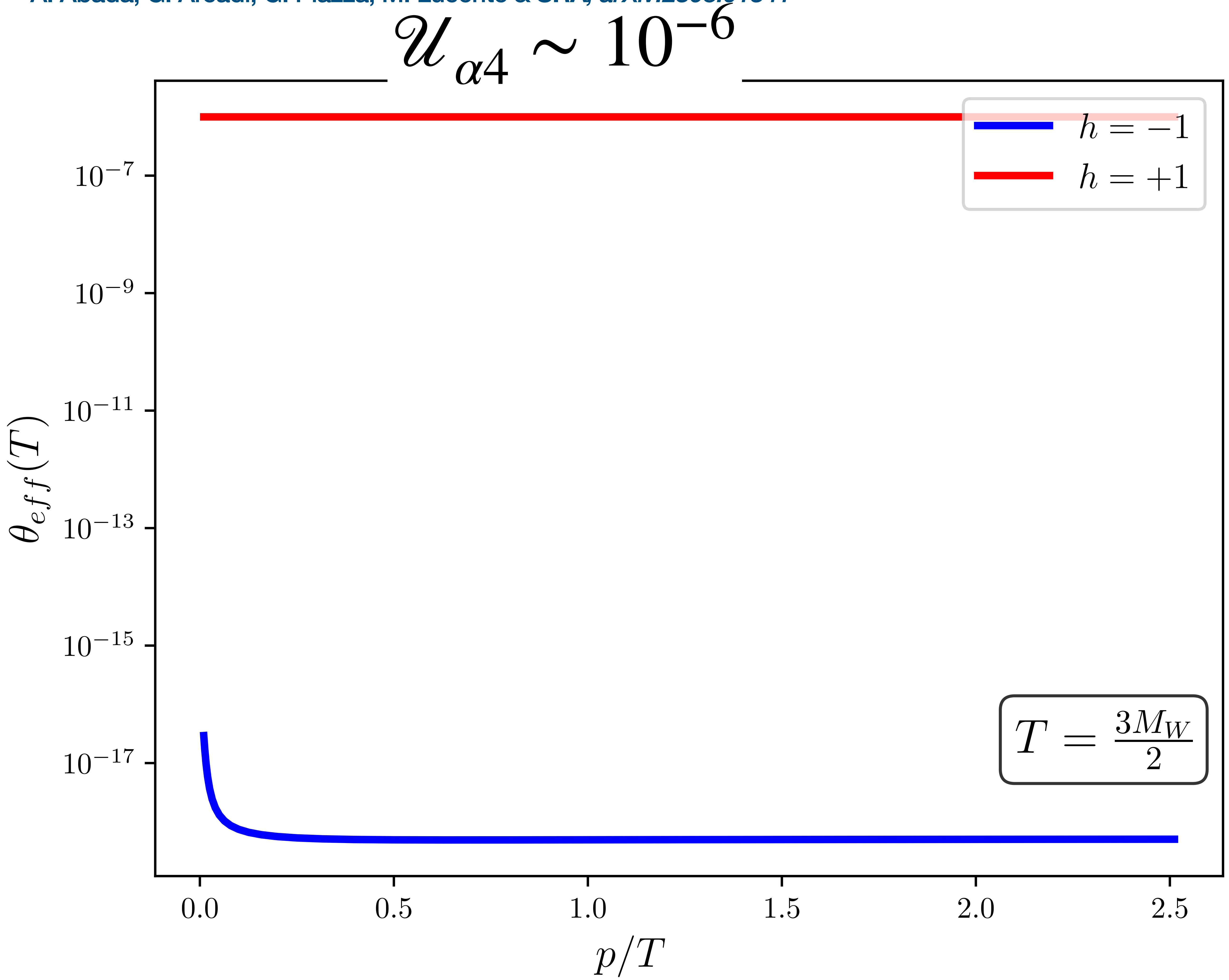

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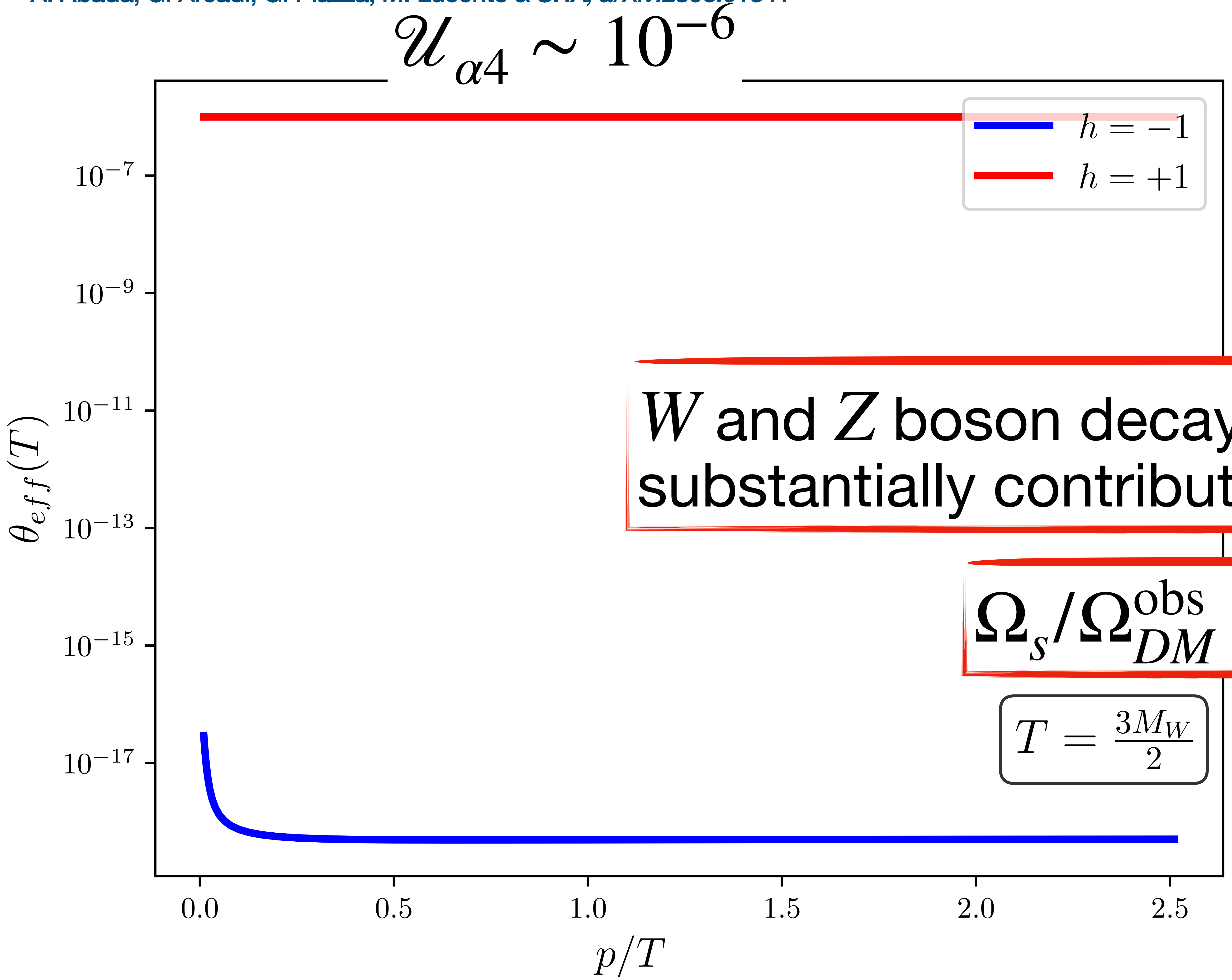

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Self-energy corrections chirality suppressed for RH ν ($h=+1$)

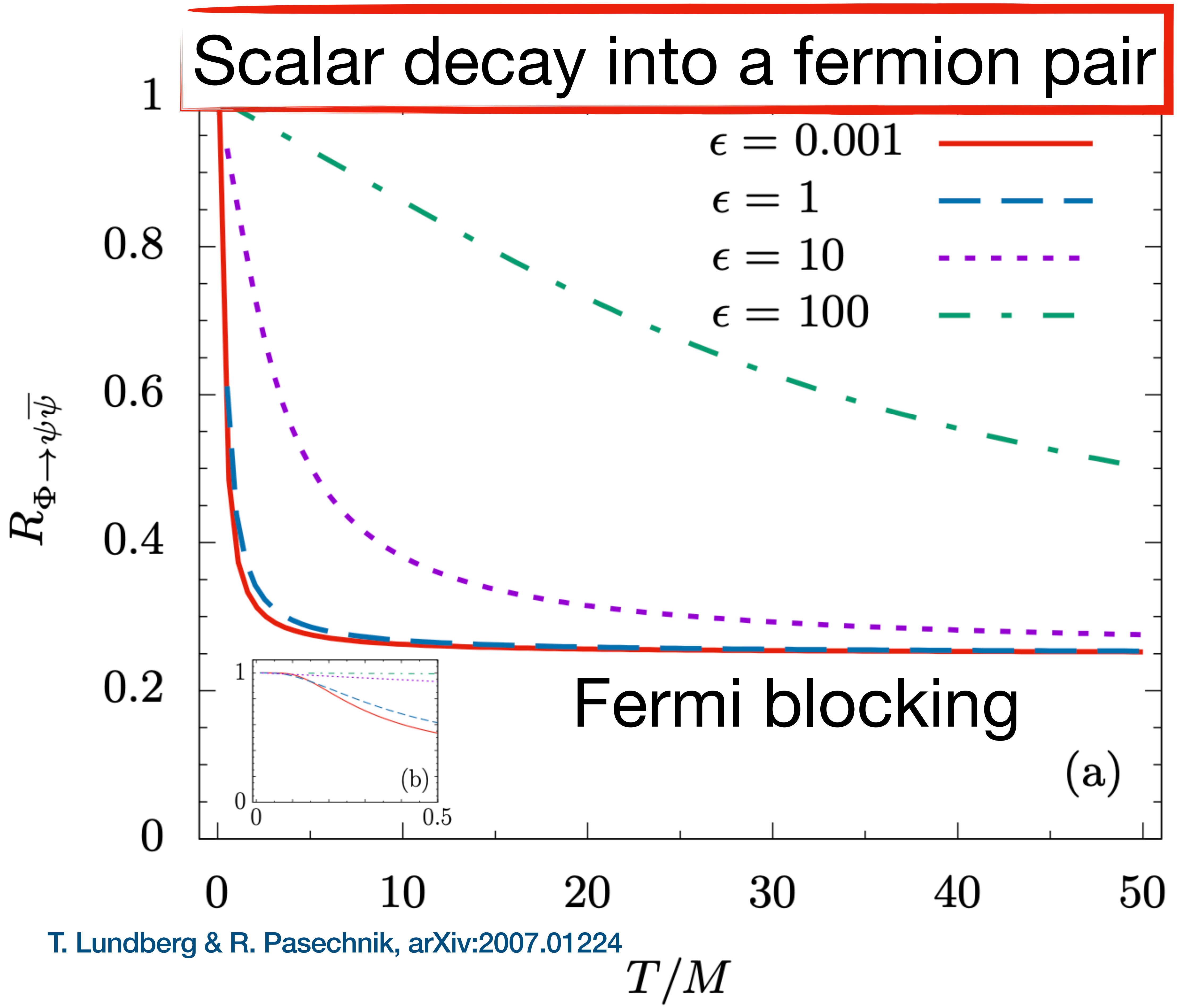
W and Z boson decays do not substantially contribute to DM production

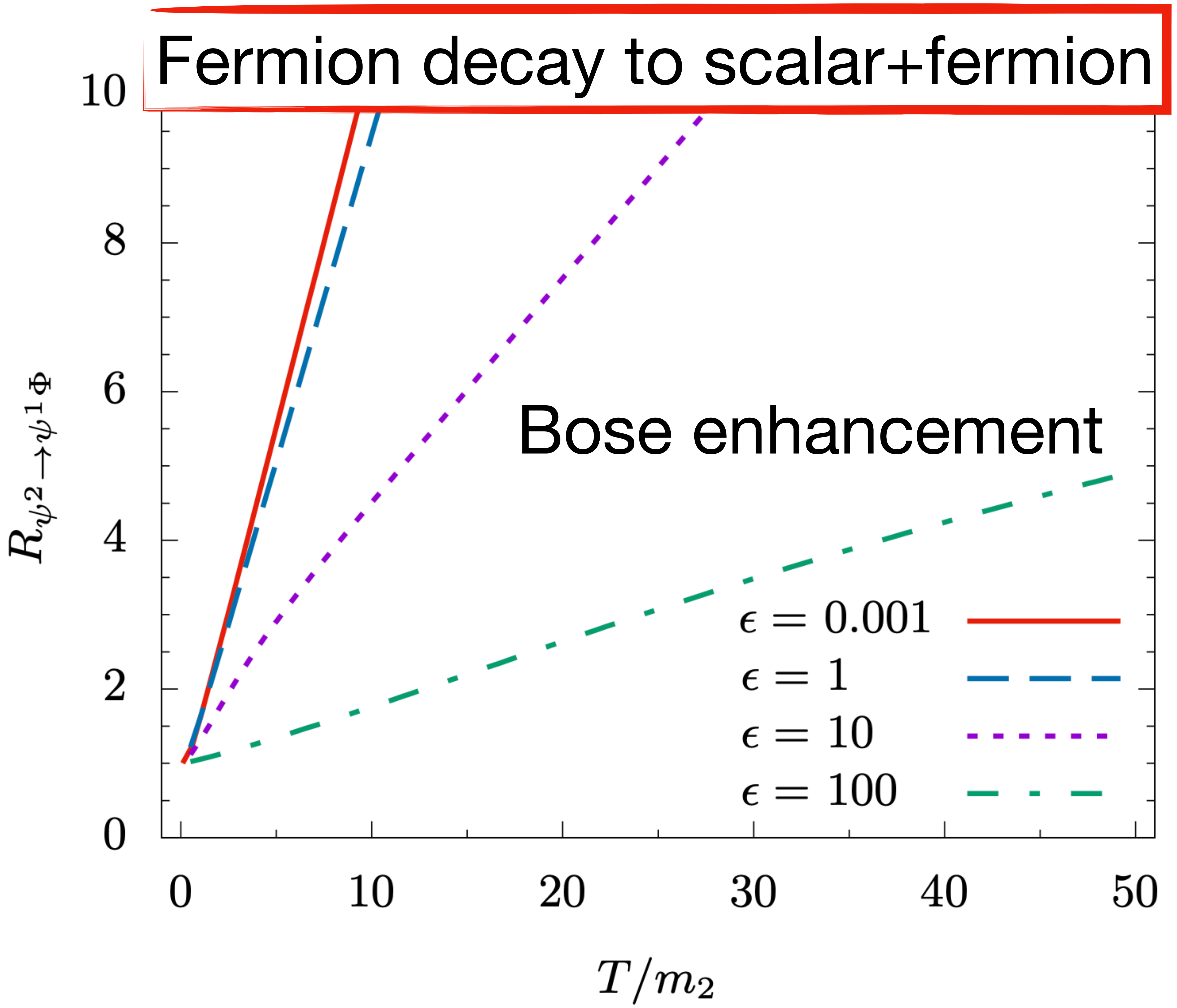
$\Omega_s/\Omega_{DM}^{\rm obs} \sim 10^{-10}$

$$\Gamma_s^h = 2\left(\theta_{eff}^h\right)^2 \gamma_L$$

DM production including heavy ν

Higgs contribution





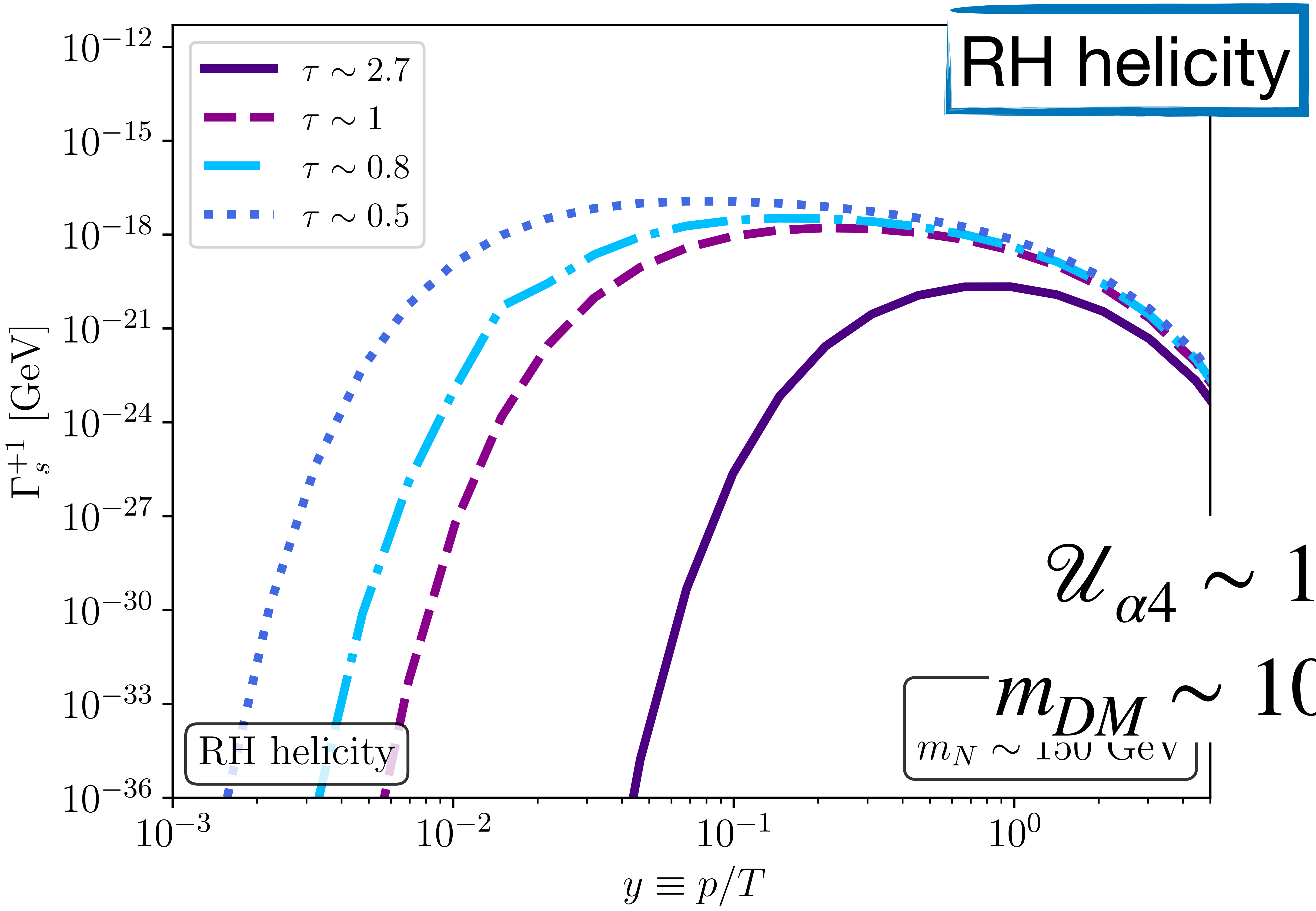
T. Lundberg & R. Pasechnik, arXiv:2007.01224

Results

Production rates for fixed temperature

$$\frac{df^h_{DM}}{d\tau} = \Gamma^h_s(\tau, y) \frac{f^{eq}_{DM}(\tau, y)}{\tau H(\tau)}$$

$$\tau \equiv M_W / T$$



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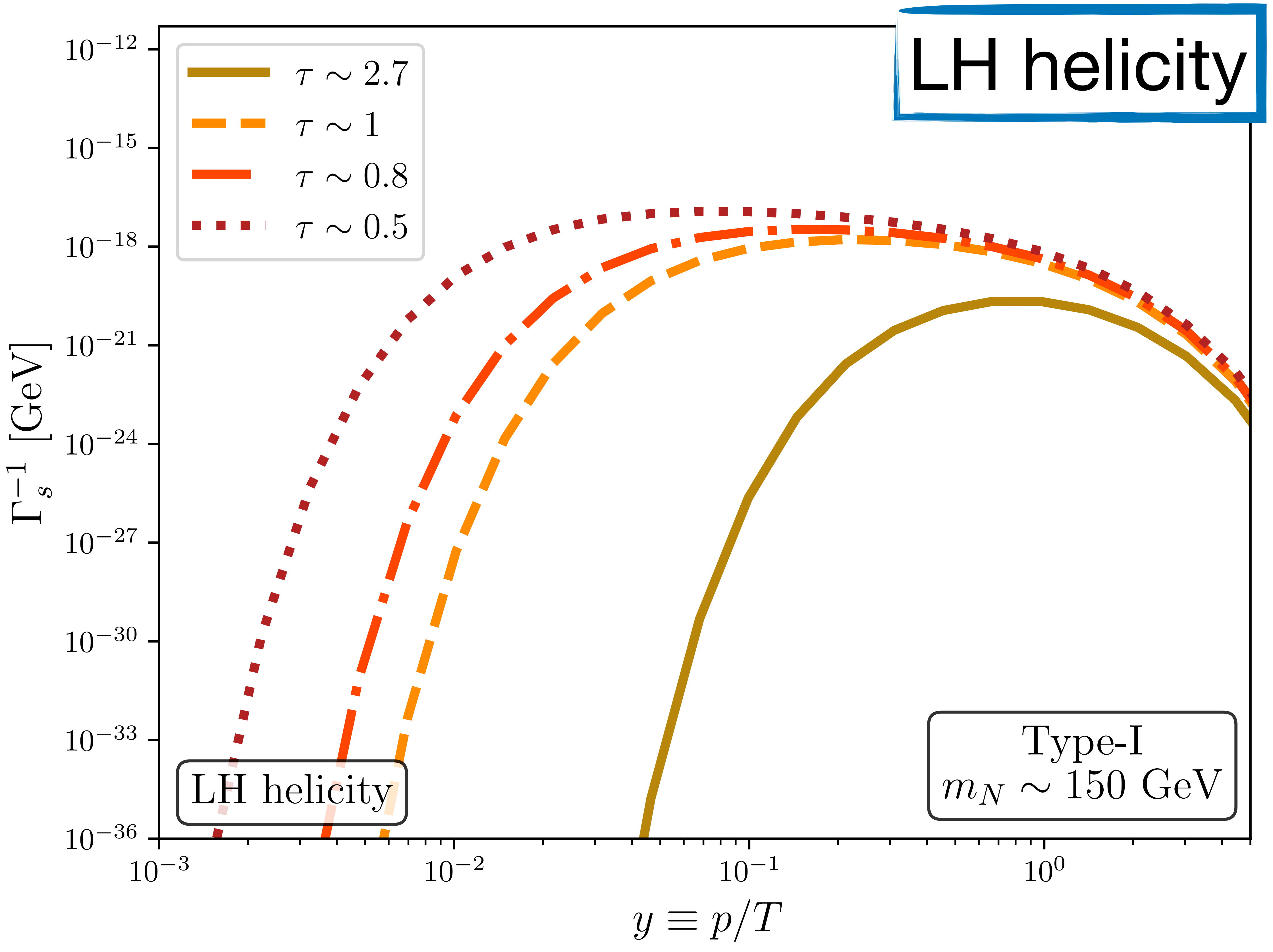

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