Thermal effects in νDM production

Salvador Rosauro-Alcaraz, Pôle Théorie IJCLab

In collaboration with A. Abada, G. Arcadi, M. Lucente and G. Piazza

57^{th} Rencontres de Moriond, March 2023

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

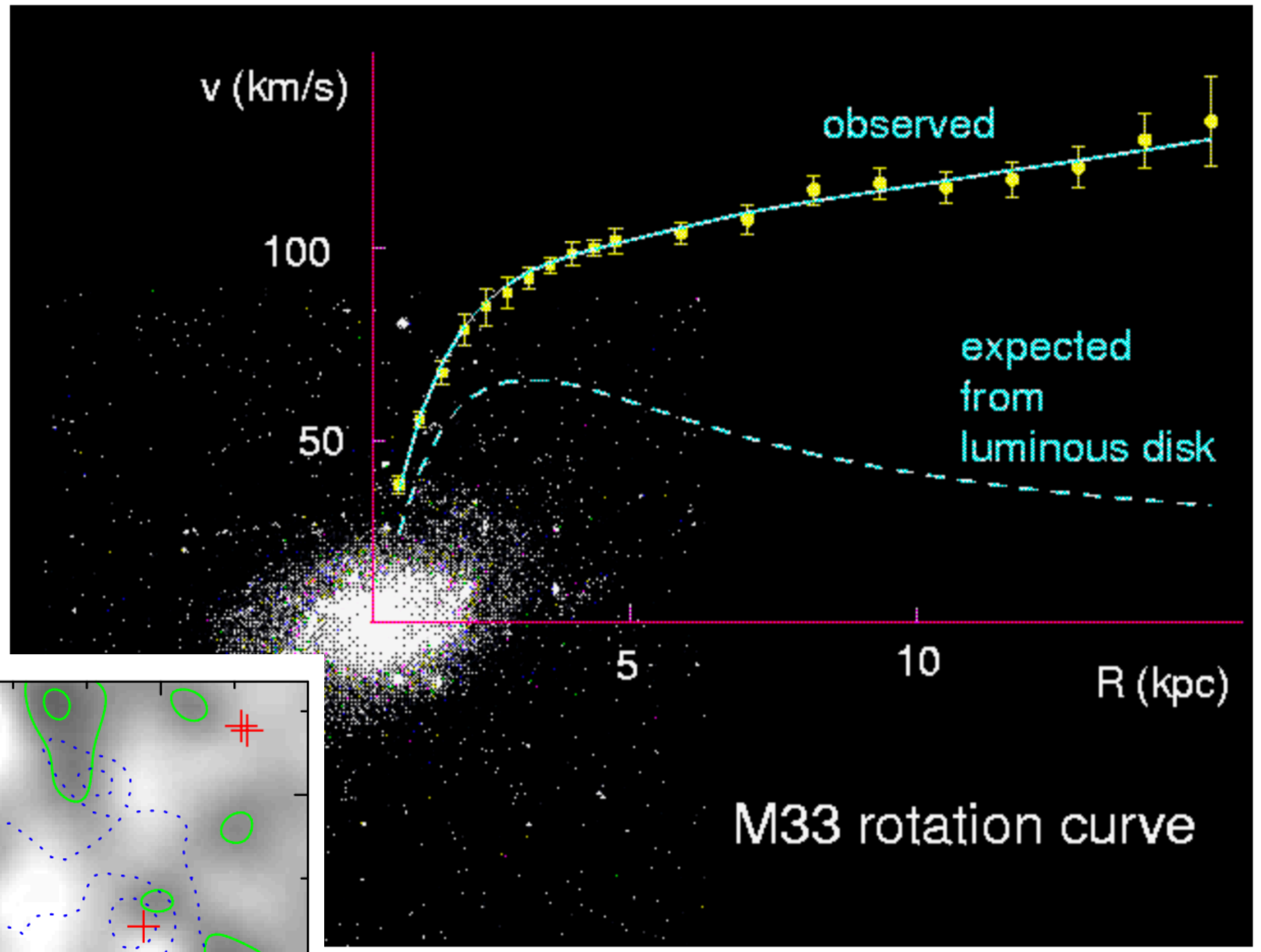
Introduction

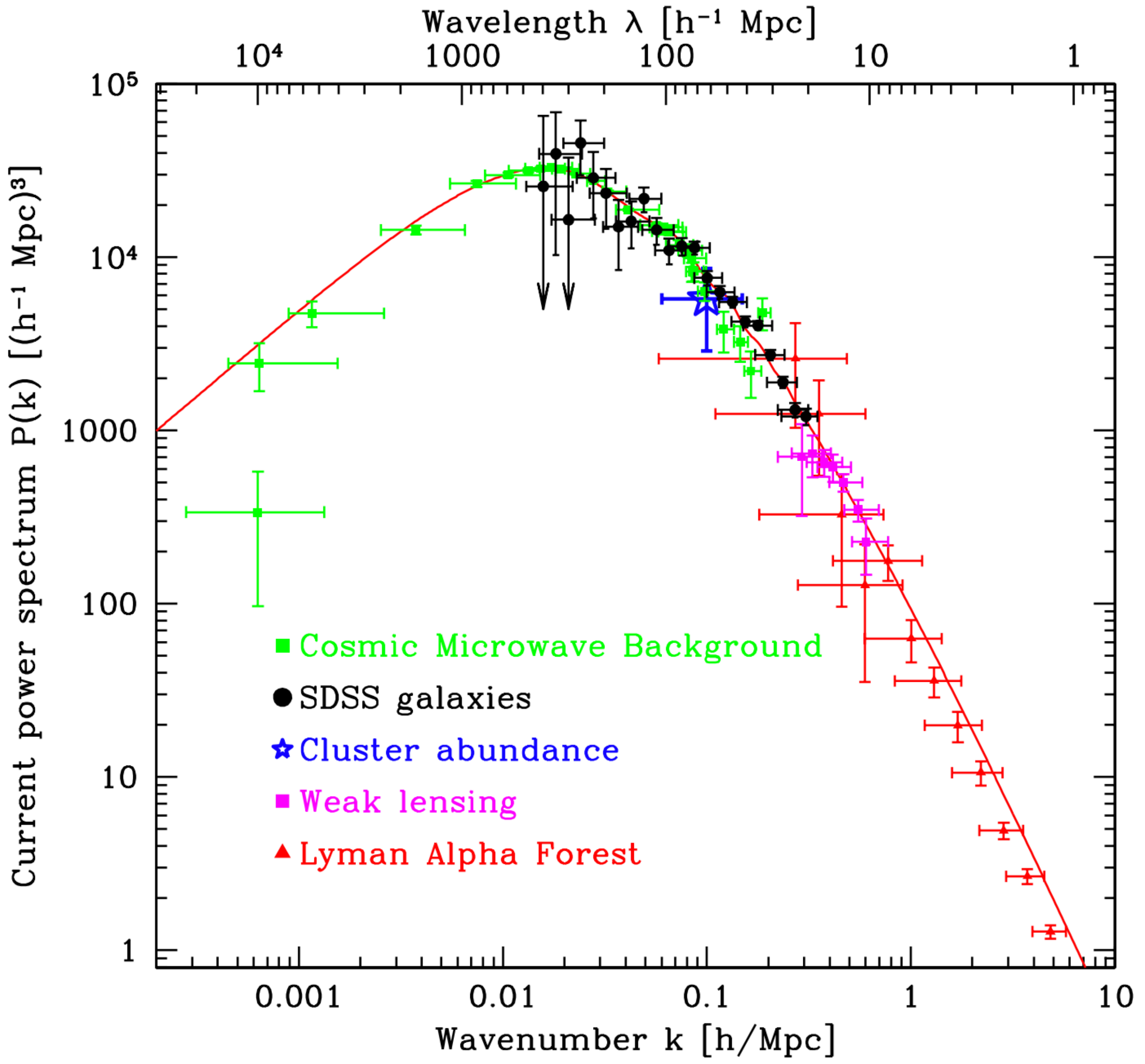
Dark matter

Planck Collaboration, arXiv:1807.06209

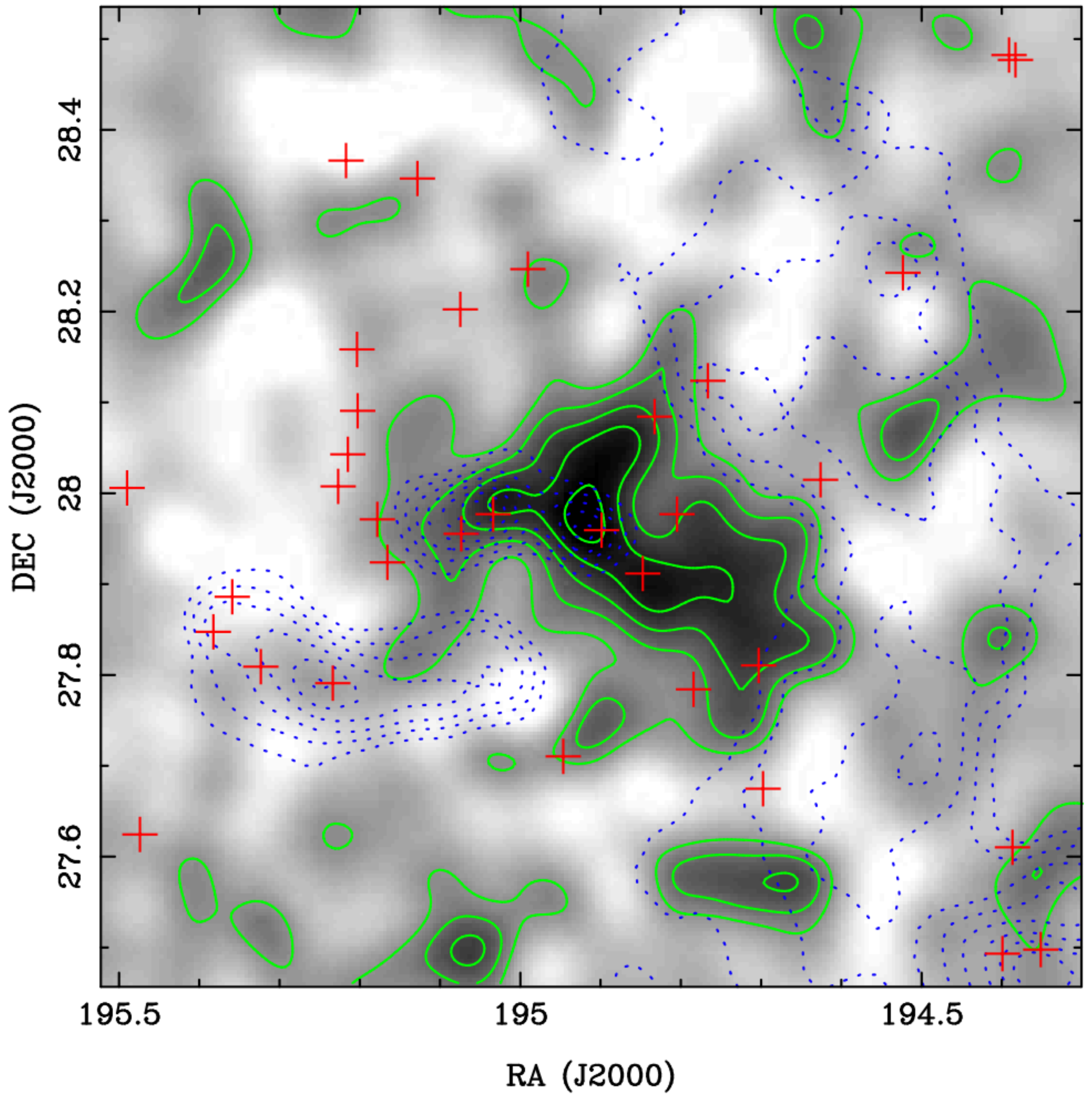
$$\Omega_{DM}h^2 = 0.1193 \pm 0.0009$$

Roy, arXiv:physics/0007025





Tegmark *et al.*
arXiv:0310725

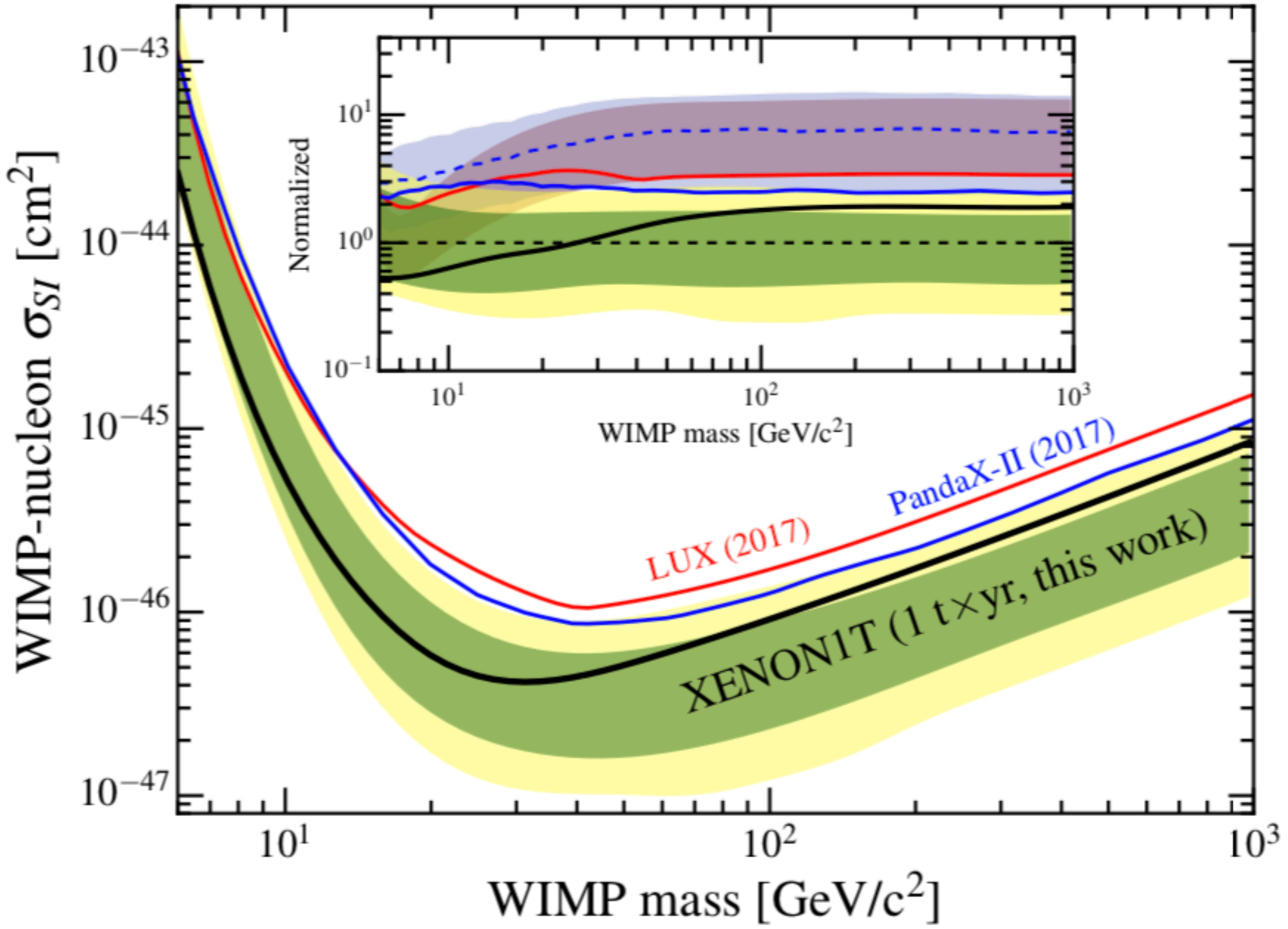


Gavazzi *et al.*
arXiv:astro-ph/0904.0220

Introduction

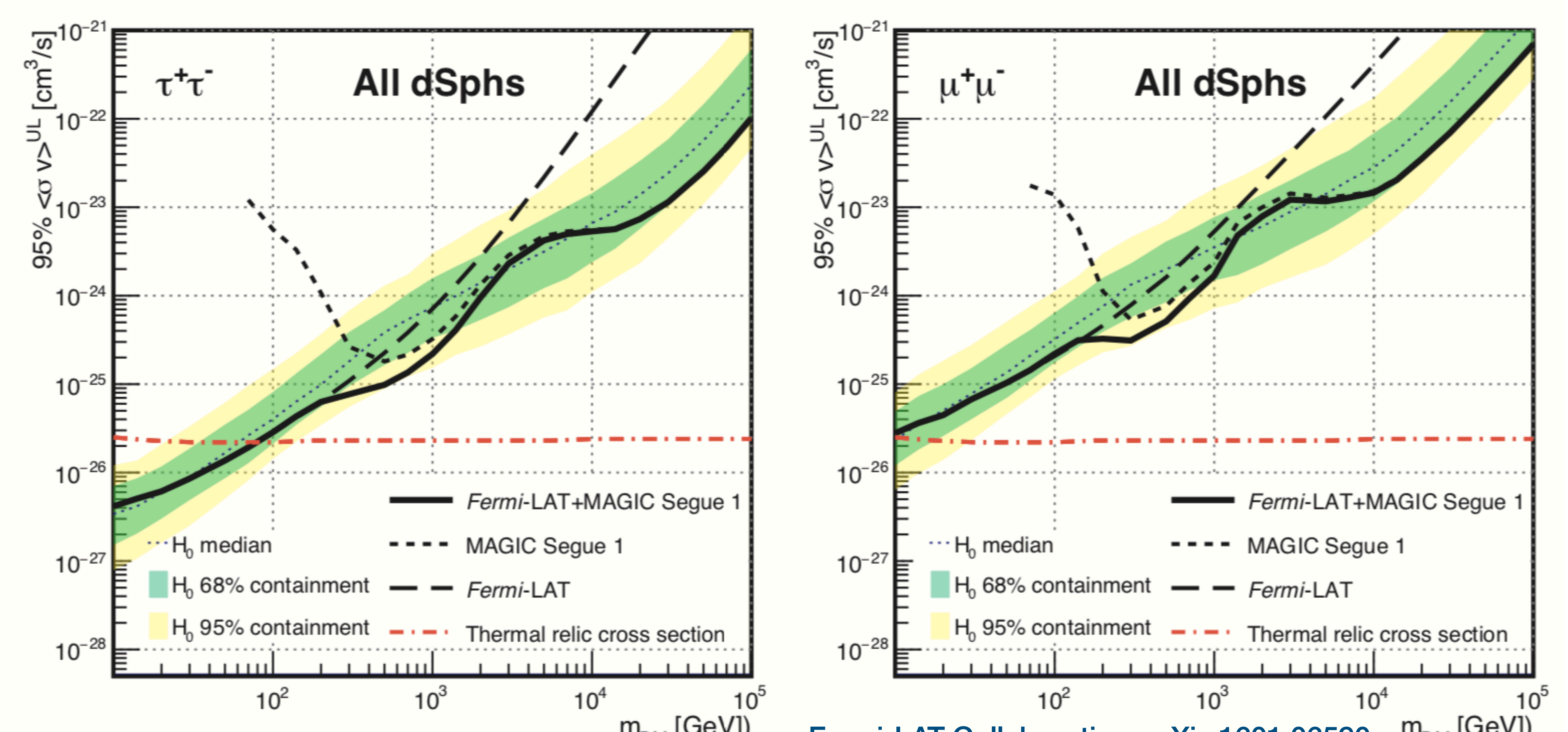
Dark matter

XENON Collaboration, arXiv:1805.12562



Direct detection

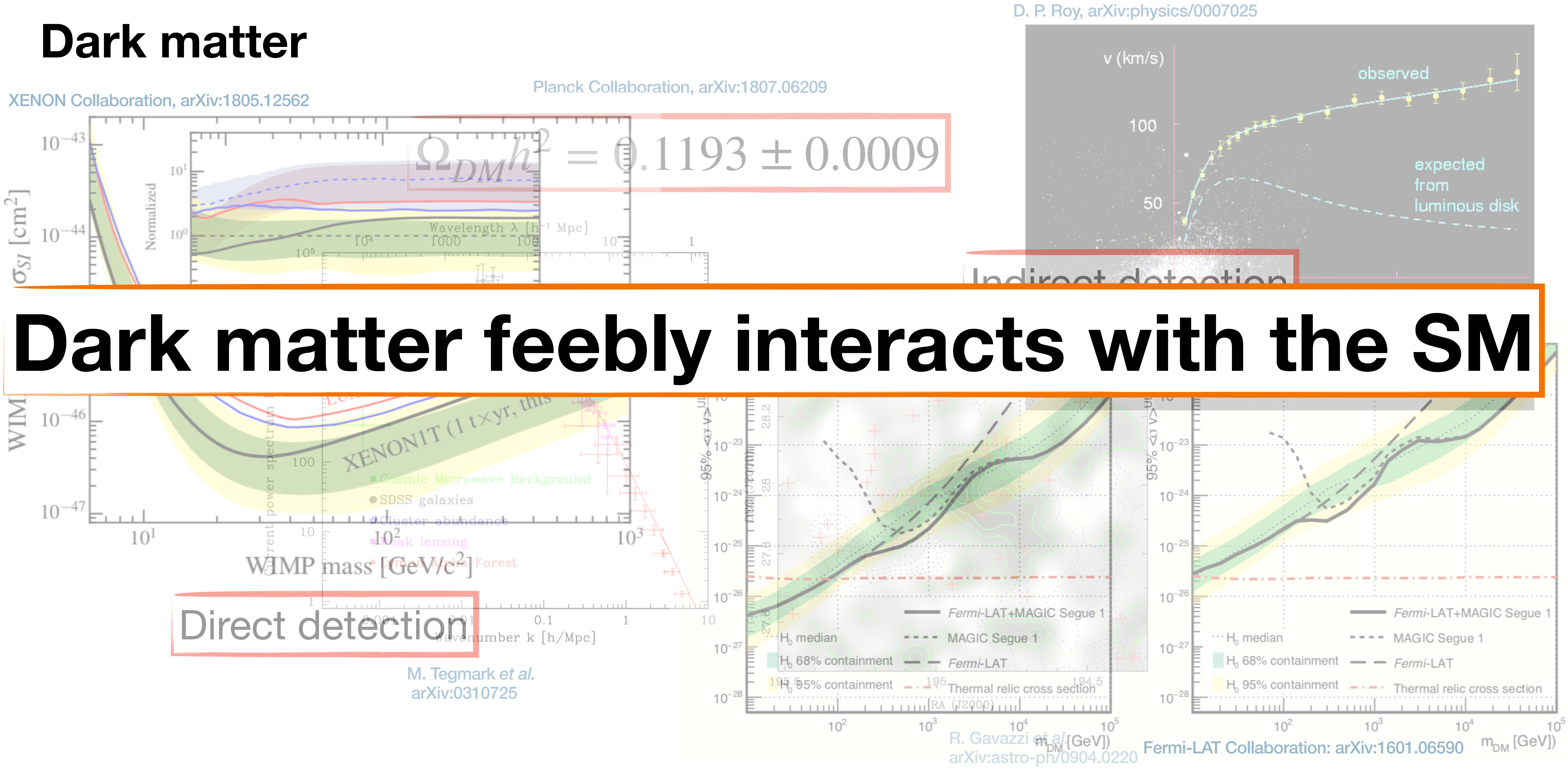
Indirect detection



Fermi-LAT Collaboration: arXiv:1601.06590

Introduction

Dark matter



Origin of neutrino masses

Inverse Seesaw

In order to have large Yukawa couplings

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

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

Source of LNV

Approximate L-symmetry

If $\mu \ll M \rightarrow m_\nu \sim v^2 Y_\nu^T M^{-1} \mu M^{-1} Y_\nu$

Neutrino mixing can be large$\rightarrow$ $\theta \sim v Y_\nu M^{-1}$

To explain oscillation data $\rightarrow$ $2N_R + 2S$$\rightarrow$(2,2)-ISS

Abada & Lucente, arXiv:1401.1507

Origin of neutrino masses

(2,3)-Inverse Seesaw

Add 2 N_R and 3 S Abada & Lucente, arXiv:1401.1507

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

3 light neutrinos → $m_{light} \sim \theta^2 \mu$

1 light sterile state → $m \sim \mu$

2 pseudo-Dirac pairs → $m_{N_\pm} \sim \sqrt{m_D^2 + M^2} \pm \frac{1}{2}\mu$

Heavy states around the EW scale

Could a neutrino be the DM?

(2,3)-Inverse Seesaw

$\mu \sim keV$ to explain m_{light}

3 light neutrinos → $m_{light} \sim \theta^2 \mu, \quad \theta \equiv m_D M^{-1}$

1 light sterile state → $m \sim \mu$

2 pseudo-Dirac pairs → $m_{N_\pm} \sim \sqrt{m_D^2 + M^2} \pm \frac{1}{2}\mu$

Heavy states around the EW scale

Could such a sterile neutrino be the DM?

(2,3)-Inverse Seesaw

$\mu \sim keV$ to explain m_{light}

Good DM candidate, which automatically has interactions suppressed by μ

3 light neutrinos → $m_{light} \sim \theta^2 \mu, \quad \theta \equiv m_D M^{-1}$

1 light sterile state → $m \sim \mu$

2 pseudo-Dirac pairs → $m_{N_\pm} \sim \sqrt{m_D^2 + M^2} \pm \frac{1}{2}\mu$

Heavy states around the EW scale

Could such a sterile neutrino be the DM?

(2,3)-Inverse Seesaw

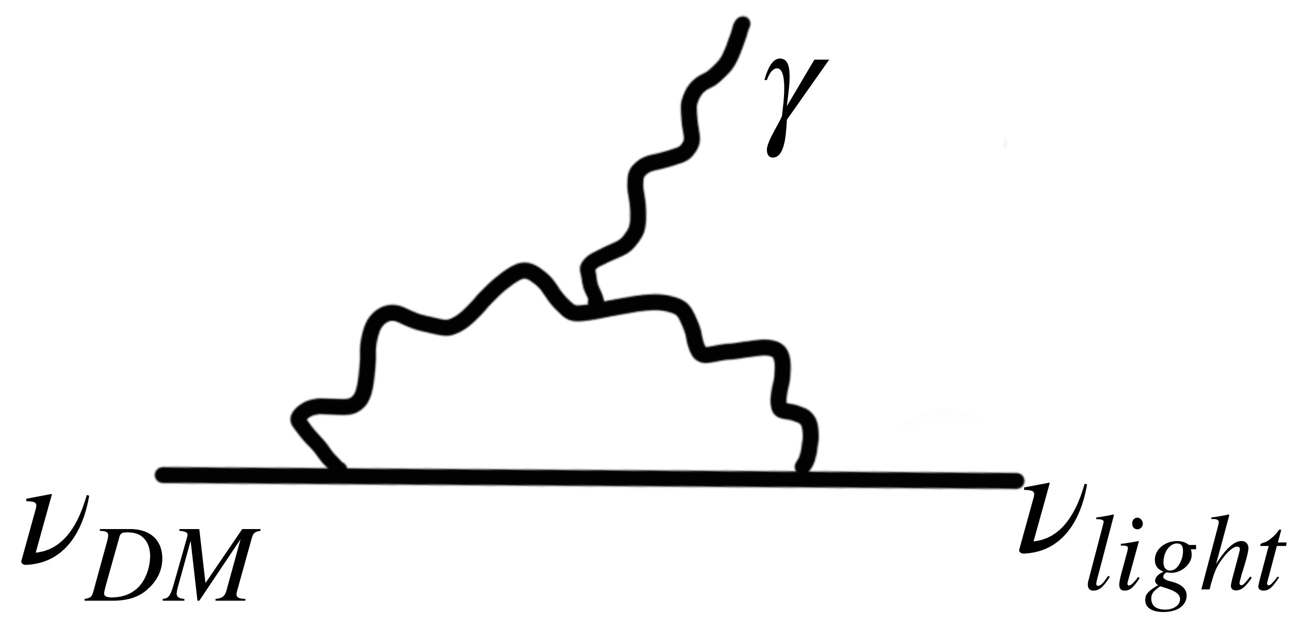
$\mu \sim keV$ to explain m_{light}

Good DM candidate, which automatically has interactions suppressed by μ

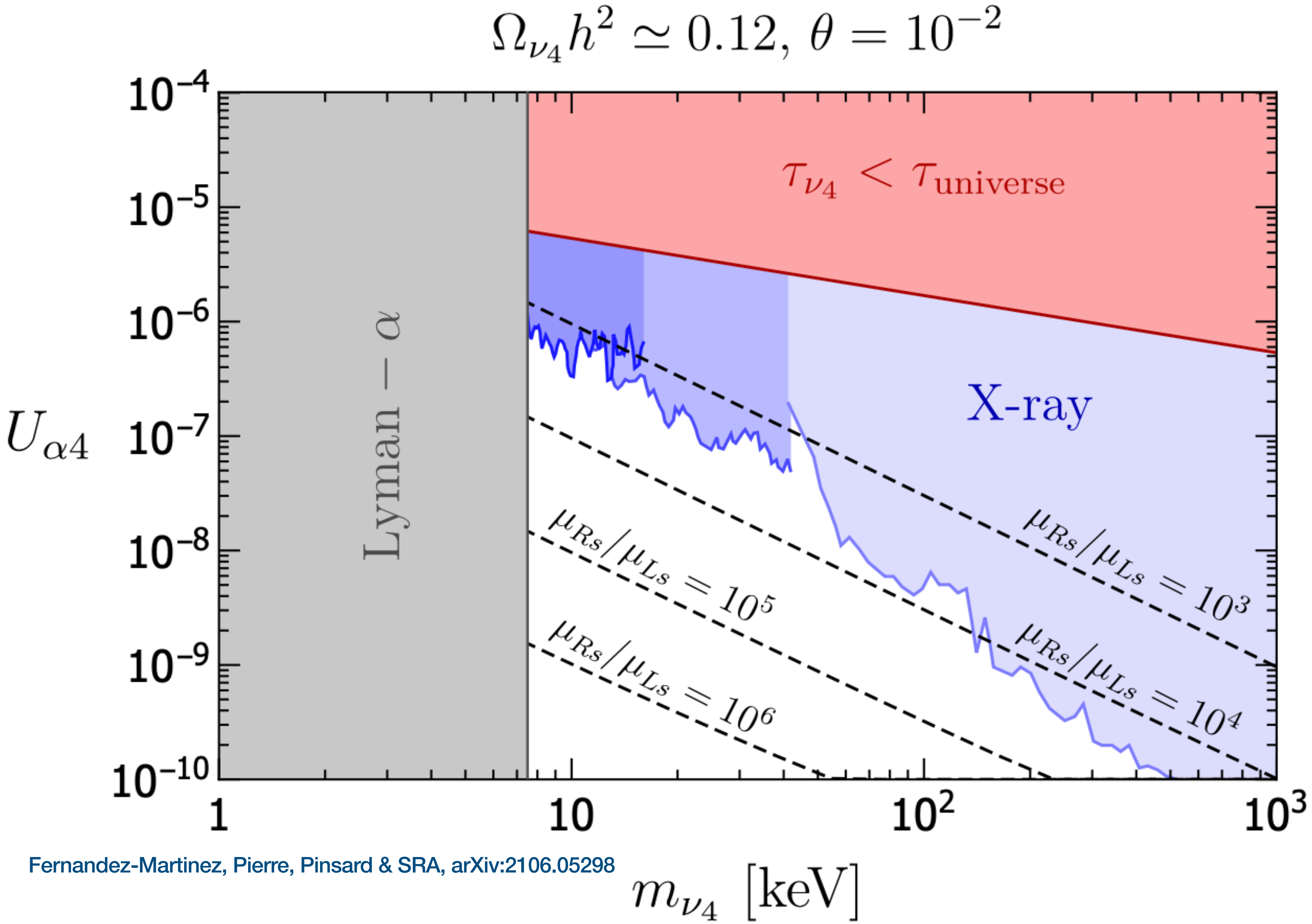
Smoking gun signal

X-ray signal from $\nu_{DM} \rightarrow \nu_{light}\gamma$

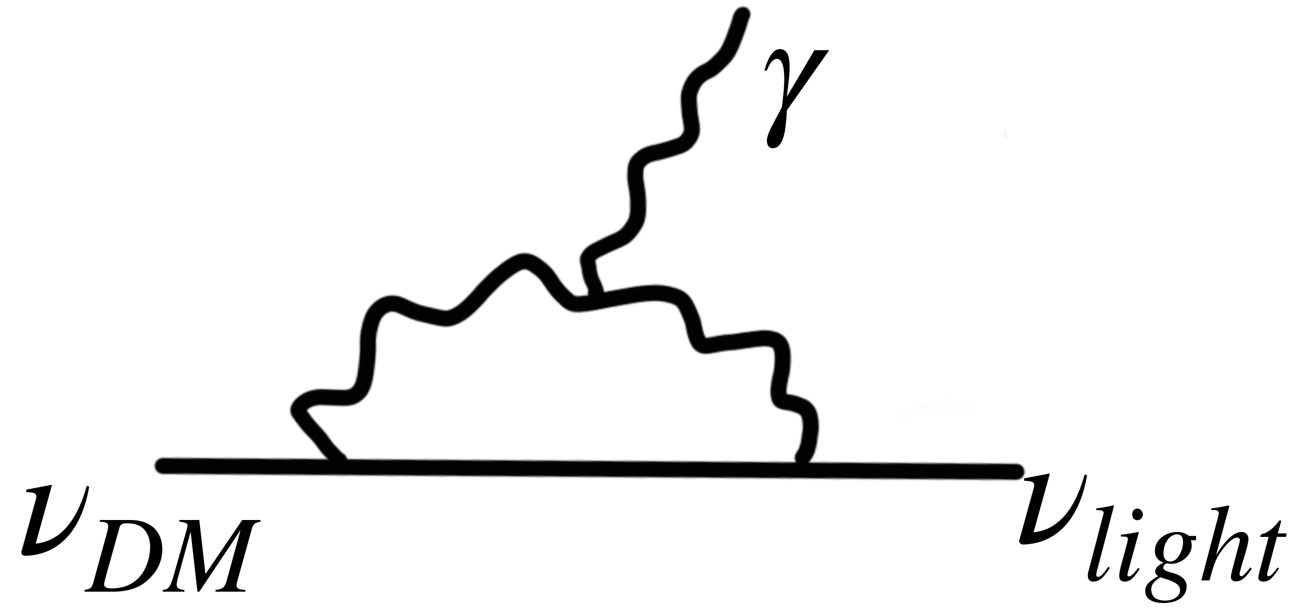
Pal & Wolfenstein, Phys. Rev. D (1982)



Could such a sterile neutrino be the DM?



ndidate, which automatically
ons suppressed by μ



Severely constrained

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

Fernandez-Martinez, Pierre, Pinsard & SRA, arXiv:2106.05298

Neutrino DM through freeze-in

$$\Gamma_{DM}(T) \ll H(T) \to n_{DM}(T) \ll n_{DM}^{eq}(T)$$

DM never reaches equilibrium

$$N_{N_\pm} \to \nu_{DM} + B$$

B → H and Z

$$B' \to \nu_{DM} + \bar{\nu}_{light}(l^+)$$

B' → H, Z and W

Abada, Arcadi & Lucente, arXiv:1406.6556
Merle & Schneider, arXiv:1409.6311
Roland, Shakya & Wells, arXiv:1412.4791
Boyanovsky, Lello & Pisarski, arXiv: 1609.07647
Abada, Arcadi, Domcke & Lucente, arXiv:1709.00415
Becker, arXiv:1806.08579
De Romeri, Karamitros, Lebedev & Toma: arXiv:2003.12606
Lucente, arXiv: 2103.03253

Neutrino DM through freeze-in

$$\Gamma_{DM}(T) \ll H(T) \rightarrow n_{DM}(T) \ll n^{eq}_{DM}(T)$$

DM never reaches equilibrium

$$N_{N_\pm} \rightarrow \nu_{DM} + B$$

B: H and Z

$$B' \rightarrow \nu_{DM} + \bar{\nu}_{light}(l^+)$$

B': H, Z and W

For a freeze-in particle, its final abundance can be estimated as

$$\Omega_{DM}h^2 \sim \frac{m_{DM}\Gamma_{DM}(N \rightarrow \nu_{DM} + H)}{m_N^2}$$

For $m_N \sim 150$ GeV
$\Gamma_{DM} \sim 10^{-16}$ GeV

Abada, Arcadi & Lucente, arXiv:1406.6556
Merle & Schneider, arXiv:1409.6311
Roland, Shakya & Wells, arXiv:1412.4791
Boyanovsky, Lello & Pisarski, arXiv: 1609.07647
Abada, Arcadi, Domcke & Lucente, arXiv:1709.00415
Becker, arXiv:1806.08579
De Romeri, Karamitros, Lebedev & Toma: arXiv:2003.12606
Lucente, arXiv: 2103.03253

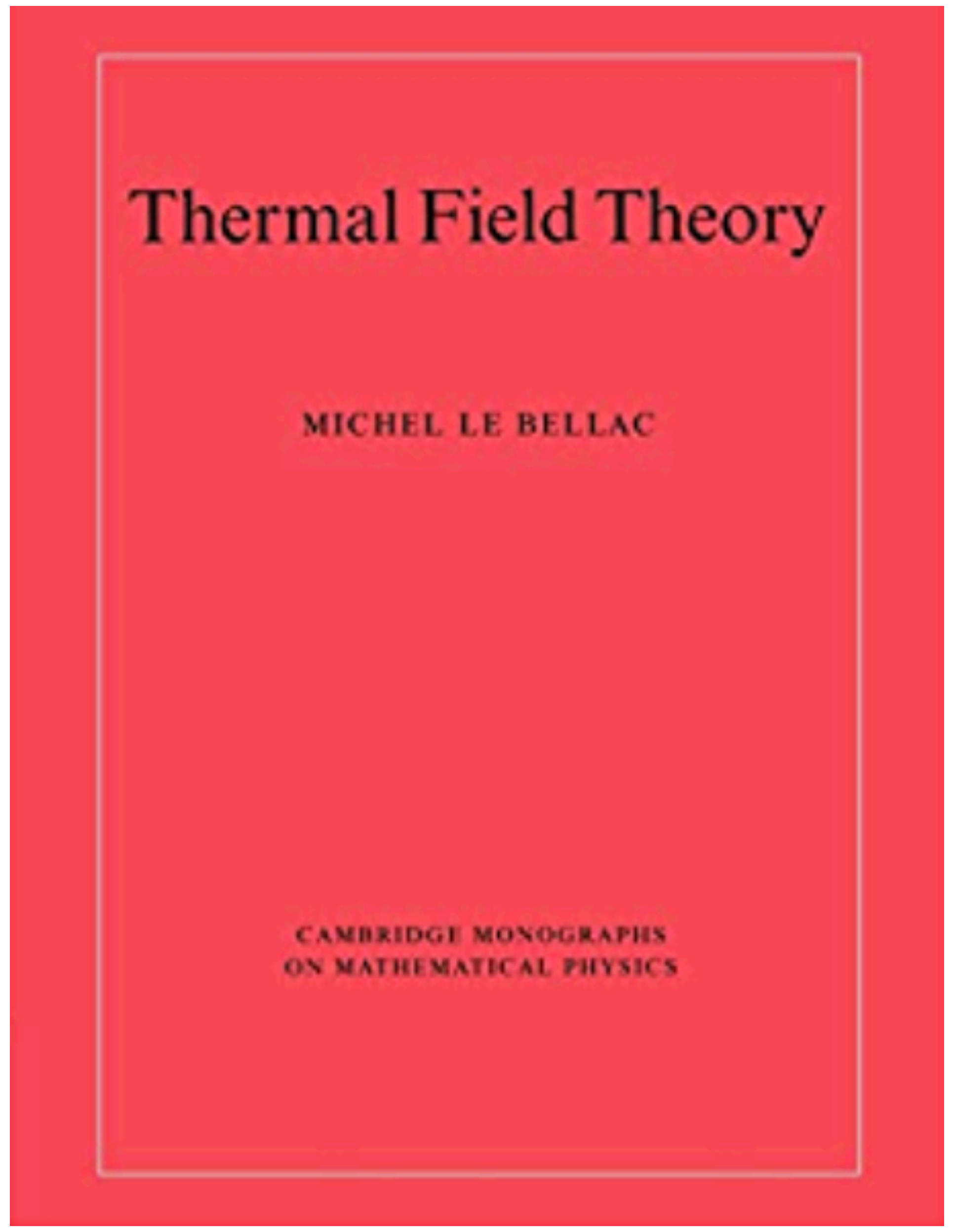
Neutrino DM through freeze-in

For a freeze-in particle, its final abundance can be estimated as

$$\Omega_{DM}h^2 \sim \frac{m_{DM}\Gamma_{DM}(N \to \nu_{DM} + X)}{m_N^2}$$

For $m_N \sim 150$ GeV
$\Gamma_{DM} \sim 10^{-16}$ GeV

Abada, Arcadi & Lucente, arXiv:1406.6556
Lucente, arXiv: 2103.03253

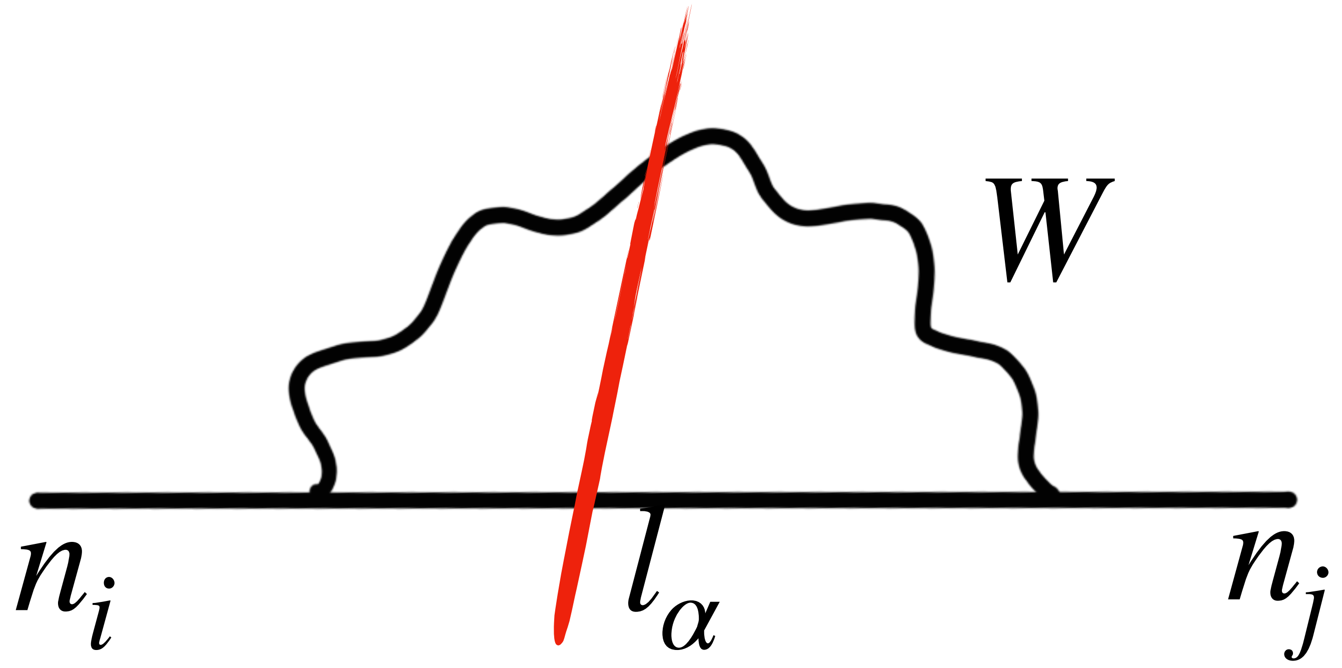


Le Bellac, Thermal Field Theory (1996)

How do we compute Γ_{DM} ?

Thermal QFT

Glimpse at Thermal-QFT



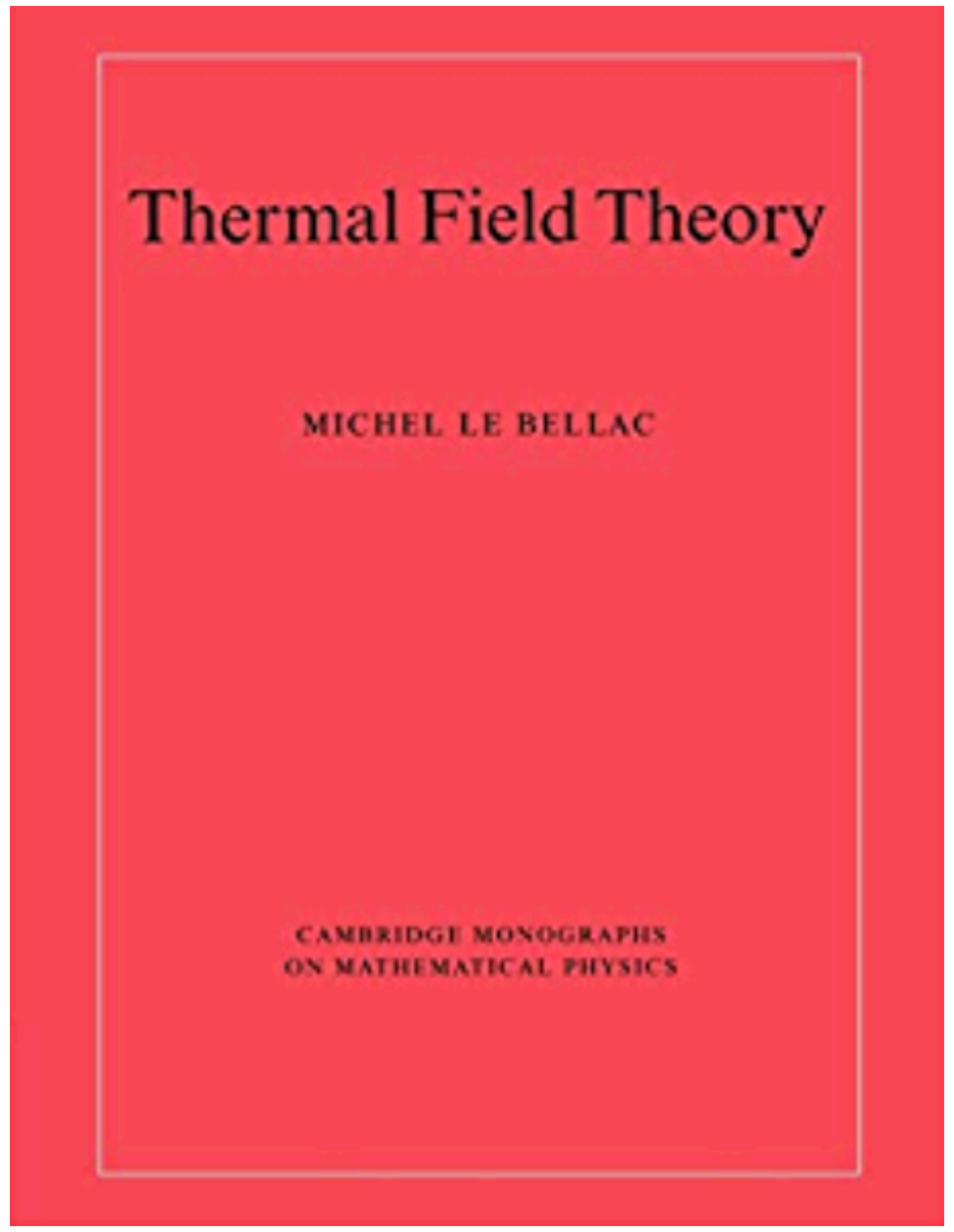
$$\sim \int (f_B + f_F)$$

$W \to \nu_{DM} l$ and its inverse process

Weldon, Phys. Rev. D (1983)

$$f_B(1 - f_F) + f_F(1 + f_B)$$

W and l distributions



Le Bellac, Thermal Field Theory (1996)

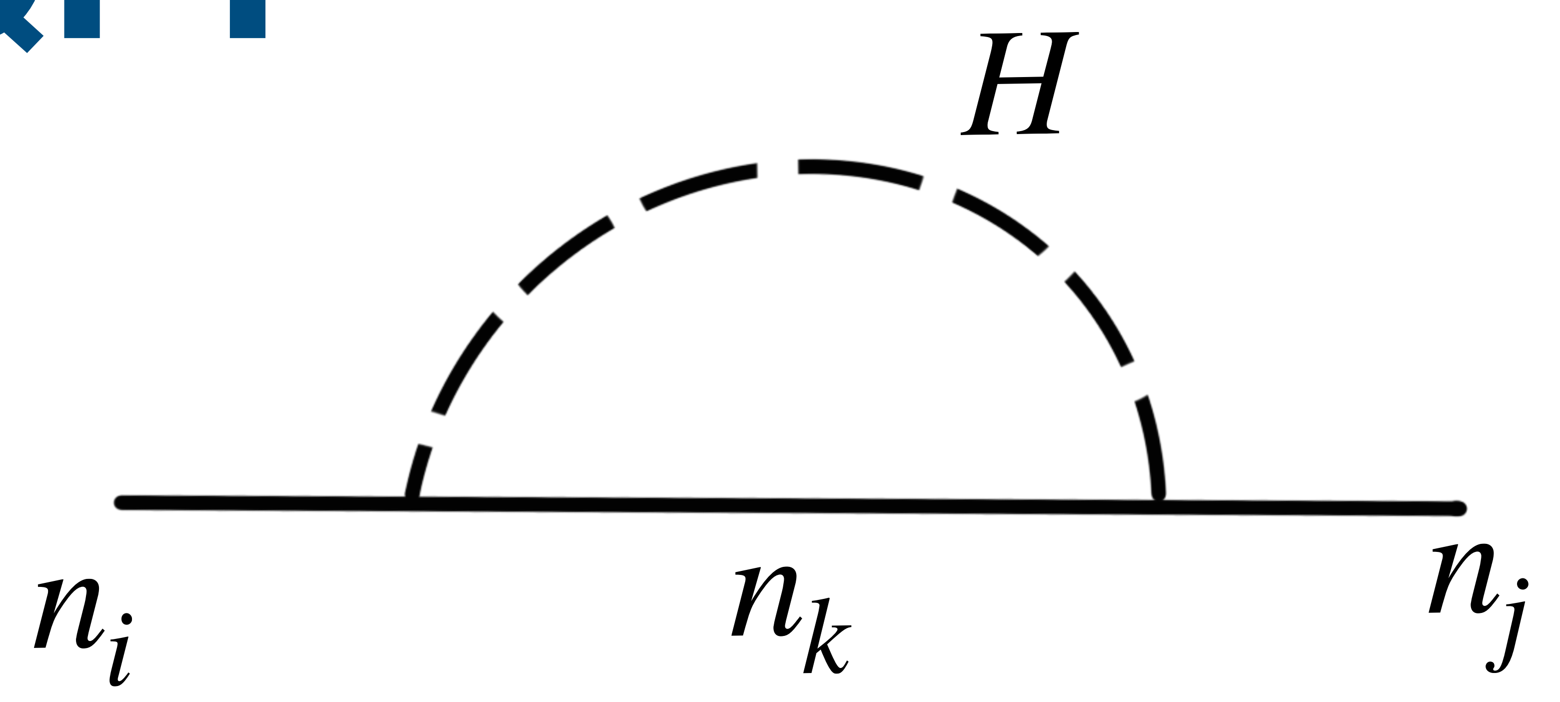
The one-loop self-energy is related to the rate at which a species enters equilibrium

Production rates in thermal QFT

$$\begin{pmatrix} \nu_{\alpha L} \\ N_R^c \\ S \end{pmatrix} = \sum_i \mathcal{U}_{\alpha i} P_L n_i$$

Mass basis

Flavour basis



Abada, Arcadi, Lucente, Piazza & SRA, in preparation

$$\Sigma_{ij}(p_0, p, T) = \sum_k C_{ik} C_{kj} \sigma(p_0, p, T, m_k)$$

Le Bellac, Thermal Field Theory (1996)
Boyanovsky, Lello & Pisarski, arXiv: 1609.07647

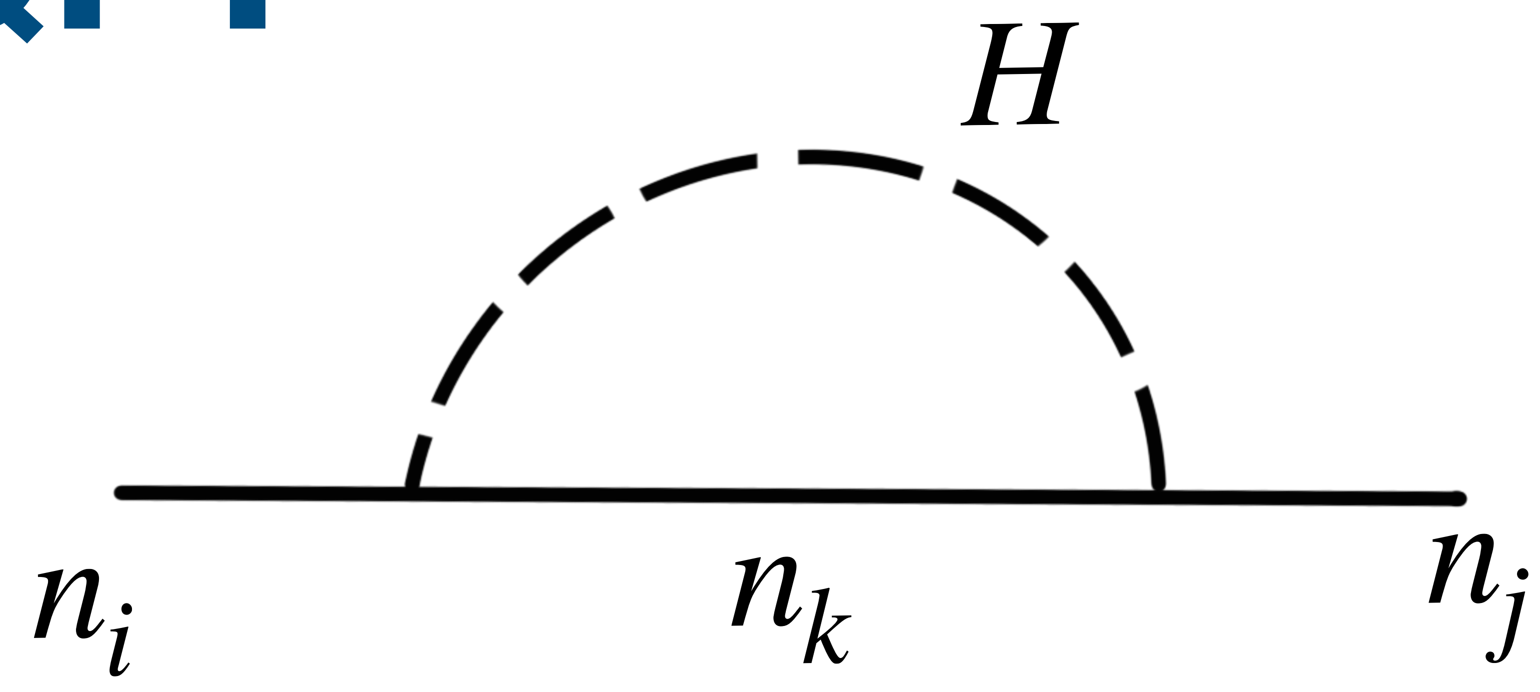
Production rates in thermal QFT

$$\begin{pmatrix} \nu_{\alpha L} \\ N_R^c \\ S \end{pmatrix} = \sum_i \mathcal{U}_{\alpha i} P_L n_i$$

Mass basis

Flavour basis

$$\Sigma_{ij}(p_0, p, T) = \sum_k C_{ik} C_{kj} \sigma(p_0, p, T, m_k)$$



Abada, Arcadi, Lucente, Piazza & SRA, in preparation

Modified dispersion relation

$$\left[\not{p} - \mathcal{M}_d + \Sigma(T)\right] n = 0$$

$$n_i = \sum_{j'} \mathcal{A}_{ij'}(T) \mathcal{N}_{j'}(T)$$

Propagating state in the medium

Le Bellac, Thermal Field Theory (1996)
Boyanovsky, Lello & Pisarski, arXiv: 1609.07647

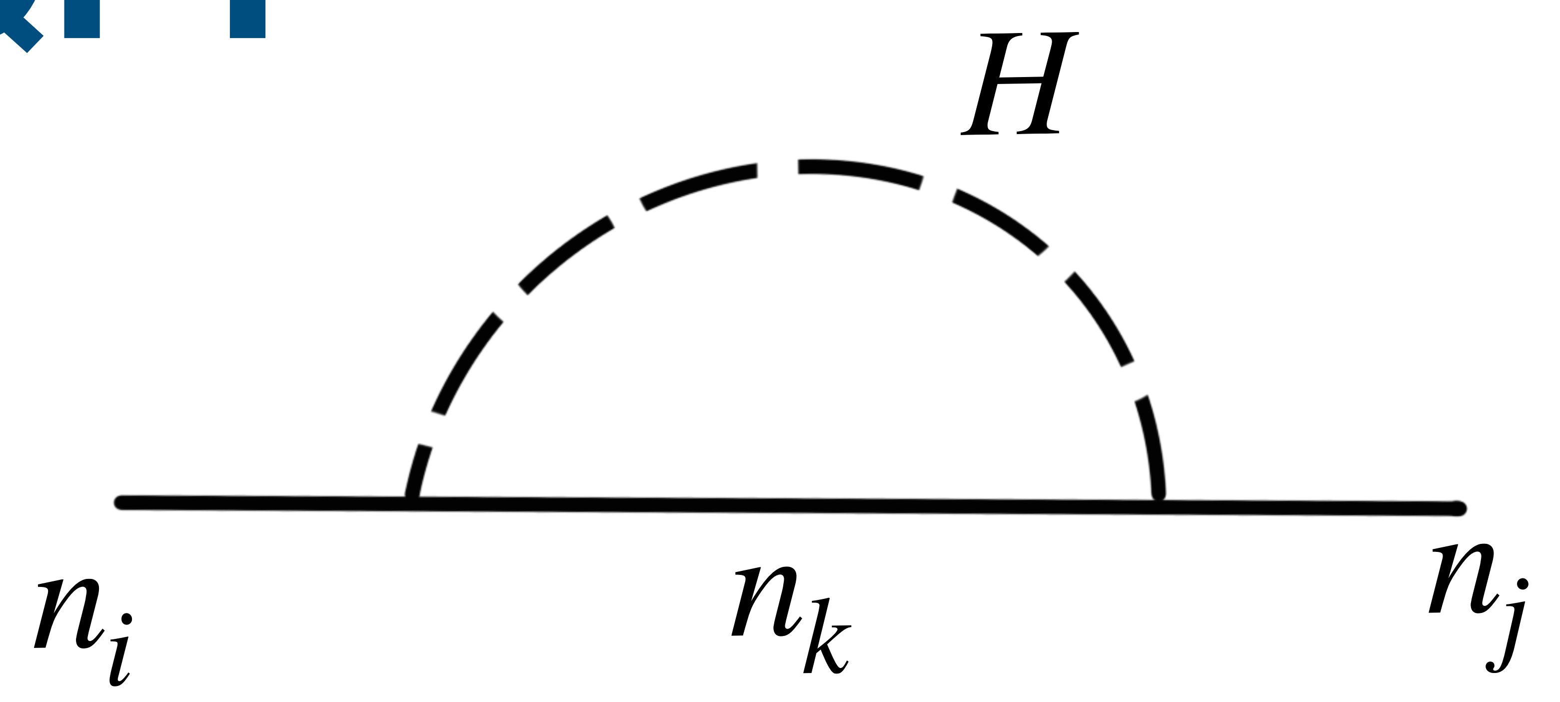
Production rates in thermal QFT

$$\begin{pmatrix} \nu_{\alpha L} \\ N_R^c \\ S \end{pmatrix} = \sum_i \mathcal{U}_{\alpha i} P_L n_i$$

Mass basis

Flavour basis

$$\Sigma_{ij}(p_0, p, T) = \sum_k C_{ik} C_{kj} \sigma(p_0, p, T, m_k)$$



Abada, Arcadi, Lucente, Piazza & SRA, in preparation

Modified dispersion relation

$$\left[\not{p} - \mathcal{M}_d + \Sigma(T)\right] n = 0$$

$$n_i = \sum_{j'} \mathcal{A}_{ij'}(T) \mathcal{N}_{j'}(T)$$

Propagating state in the medium

Mixing angle in the medium $\mathcal{U}(T) = \mathcal{U}\mathcal{A}(T)$

Le Bellac, Thermal Field Theory (1996)
Boyanovsky, Lello & Pisarski, arXiv: 1609.07647

Dumping of the production rate

Propagating modes and relaxation rate

$$\mathcal{S}^{-1} = p_0^2 - p^2 - \mathcal{M}_d + \Omega^h$$

Depends on helicity

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

Consider only 2 species (DM and a light ν)

$$\theta_{eff}(T) \equiv \frac{\mathcal{U}_{\alpha 4}}{\sqrt{\left(1 + Re\frac{\Omega^h(T)}{m_{DM}^2}\right)^2 + \left(\frac{Im\Omega^h(T)}{m_{DM}^2}\right)^2}}$$

$$\Gamma_{DM}^h \sim 2\theta_{eff}^2(T) Im\left[\Omega^h(T)\right]$$

Competition between the suppression of the mixing angle
and the bigger dumping rate at larger temperatures

Boyanovsky, Lello & Pisarski, arXiv: 1609.07647

Results

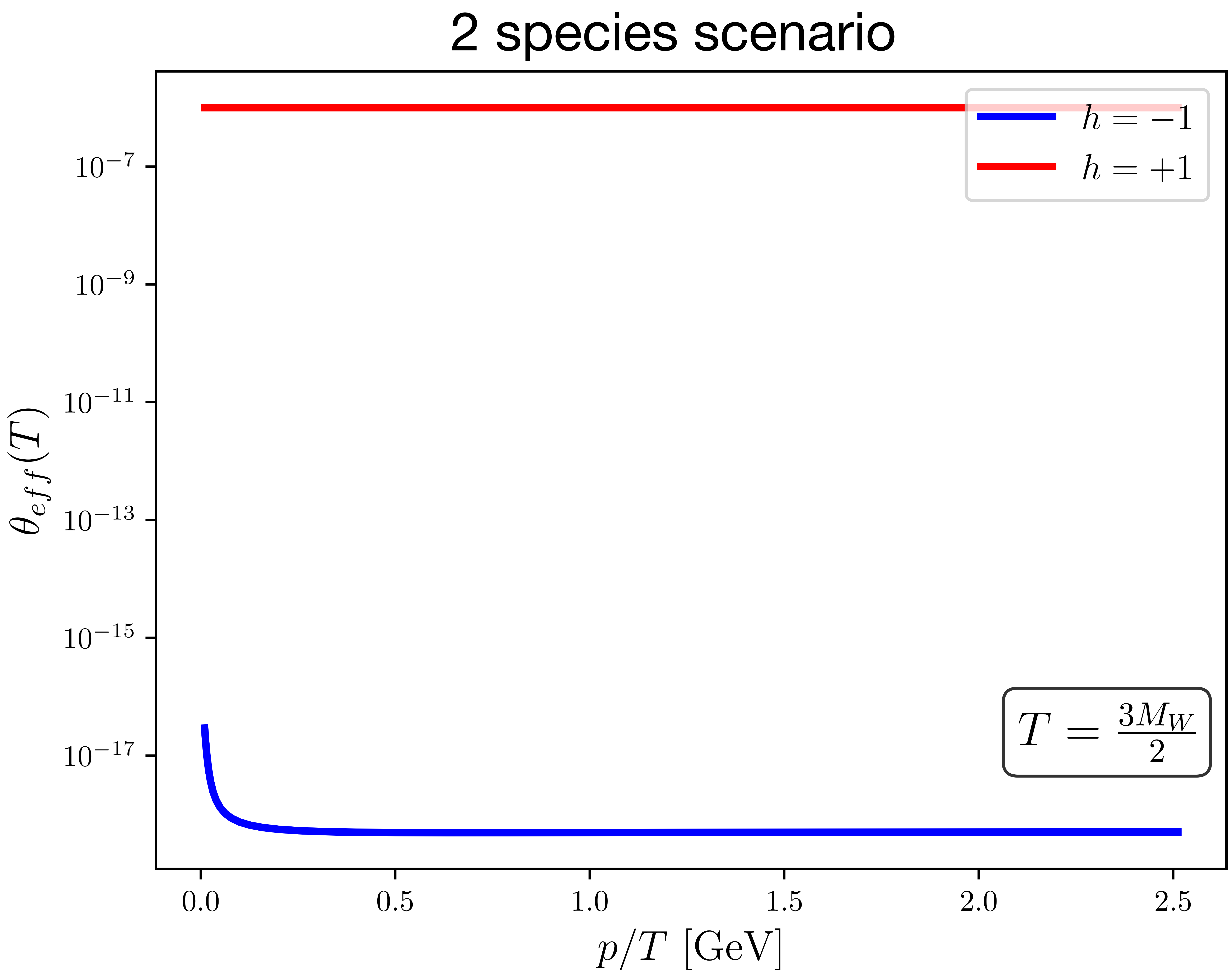
Effective mixing angle

- For negative helicity

  Large "thermal mass" for ν_α from W and Z

- For positive helicity

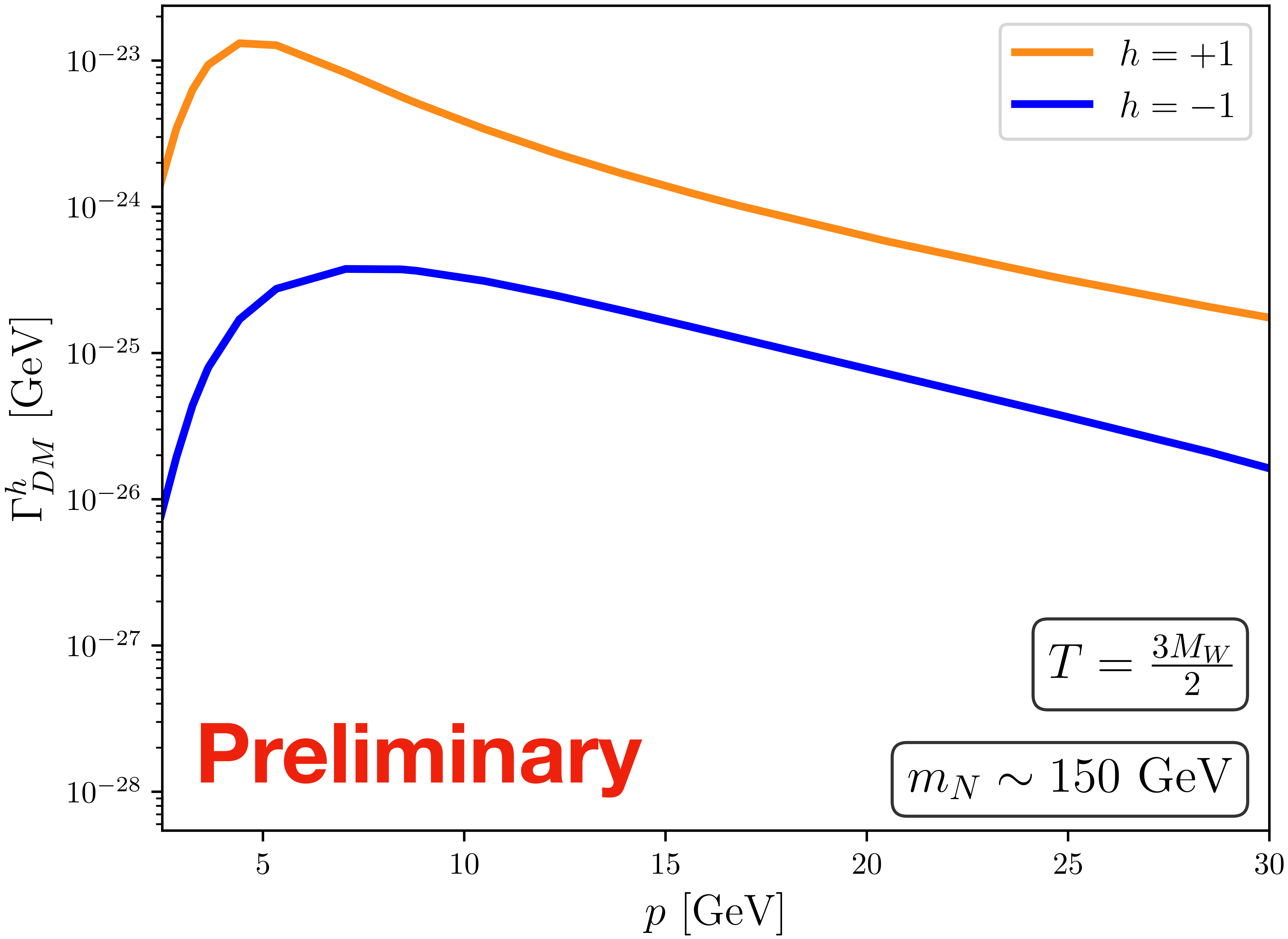
  Weak boson decays suppressed by $\frac{m_{DM}}{2p}$



Results

Production rates

Abada, Arcadi, Lucente, Piazza & SRA, in preparation



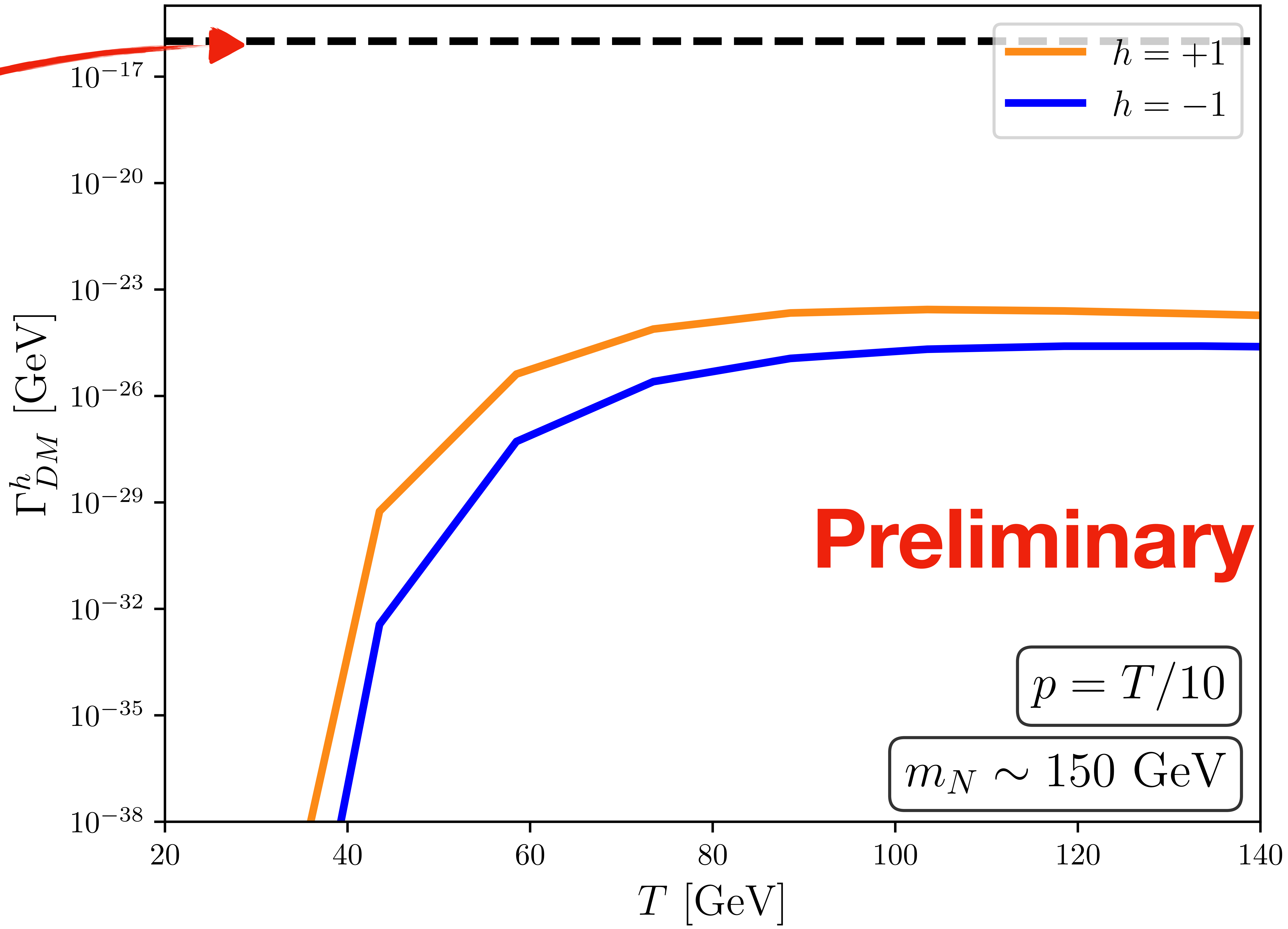
Results

Production rates

Abada, Arcadi, Lucente, Piazza & SRA, in preparation

Explains full DM abundance

$$\frac{dn^h_{DM}}{dt} = \Gamma^h_{DM}(t,p)\,n_{eq}(t)$$



Conclusions

keV ν are good DM candidate naturally arising in low-scale Seesaws

Interactions with the plasma translate into a suppression of the mixing angle for LH helicity neutrinos

Included heavy neutrinos necessary to explain ν masses, and contribute to the DM abundance through $N \to H\nu_{DM}$

Improvement with respect to considering just two light species, but not enough DM

Taking into account CPV might change the picture

Production possible in non-minimal scenarios not relying on mixing

Thank you!

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

Back up

Introduction

Neutrino masses

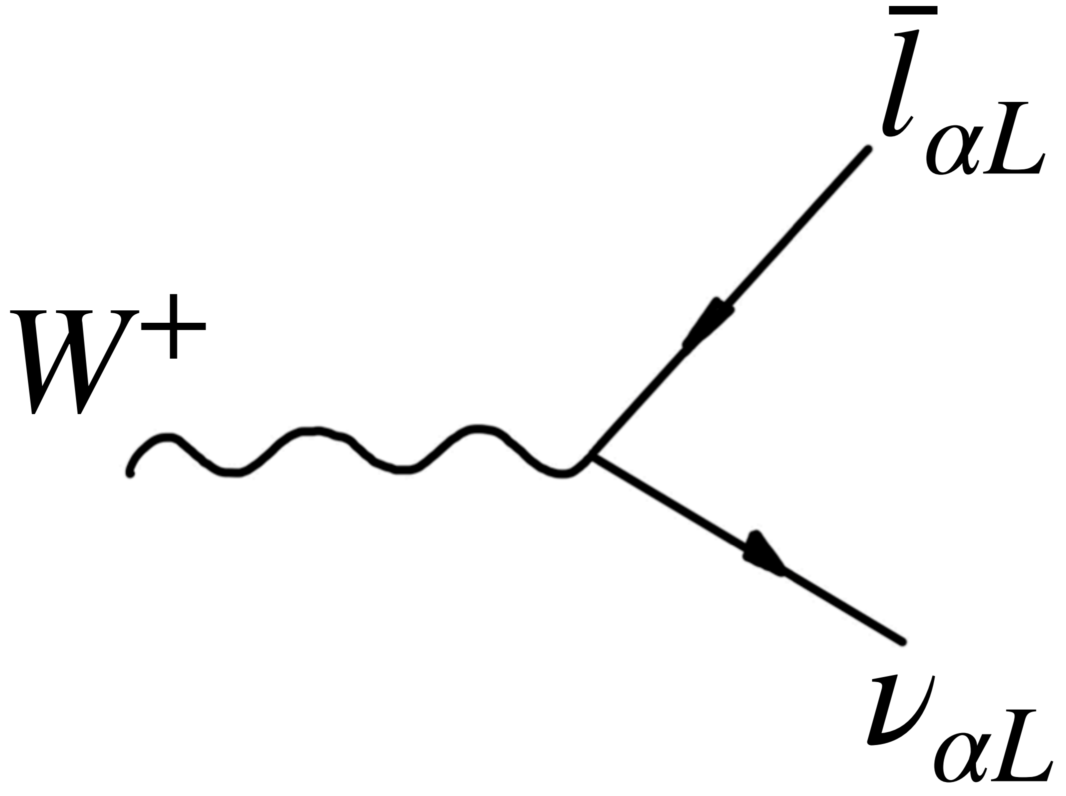
Oscillation driven by

$$|\Delta m^2_{atm}| \sim 2.5 \times 10^{-3}\ \text{eV}^2$$

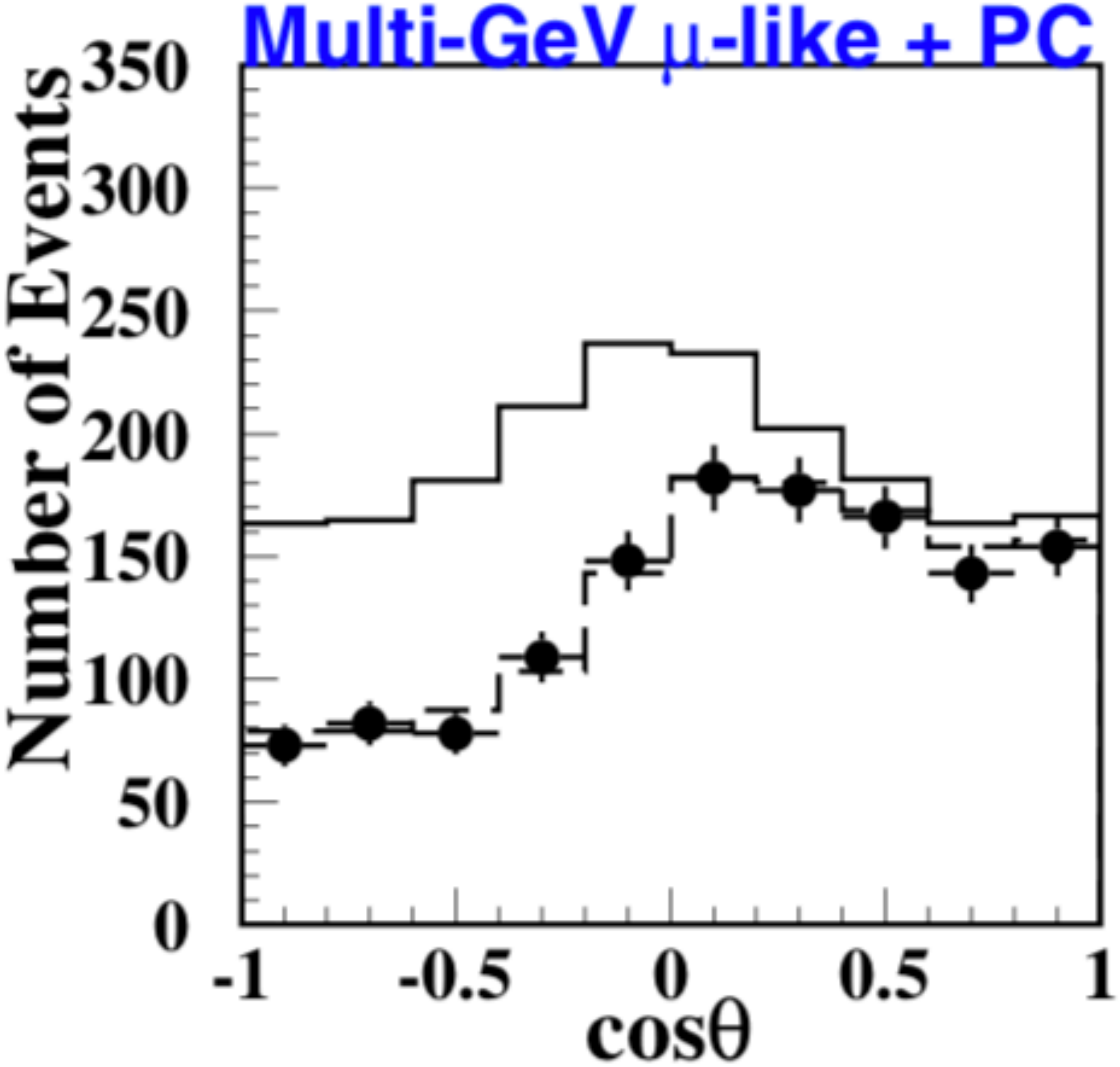
$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

Interaction states (ν_α)

Propagating states (ν_i)



$$\left[\not{p} - \mathscr{M}_d\right]_{ii} \nu_i = 0$$



Super-Kamiokande collaboration, arXiv:0105023

Origin of neutrino masses

Type-I Seesaw

Add a number of RH neutrinos (at least 2)

P. Minkowsky, Phys.Lett. **B67** (1977) 421
T. Yanagida, 1979
M. Gell-Mann, P. Ramon and R. Slansky, arXiv:1306.4669
S. L. Glashow, NATO Sci.Ser. B **61** (1980) 687
R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44** (1980) 912

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

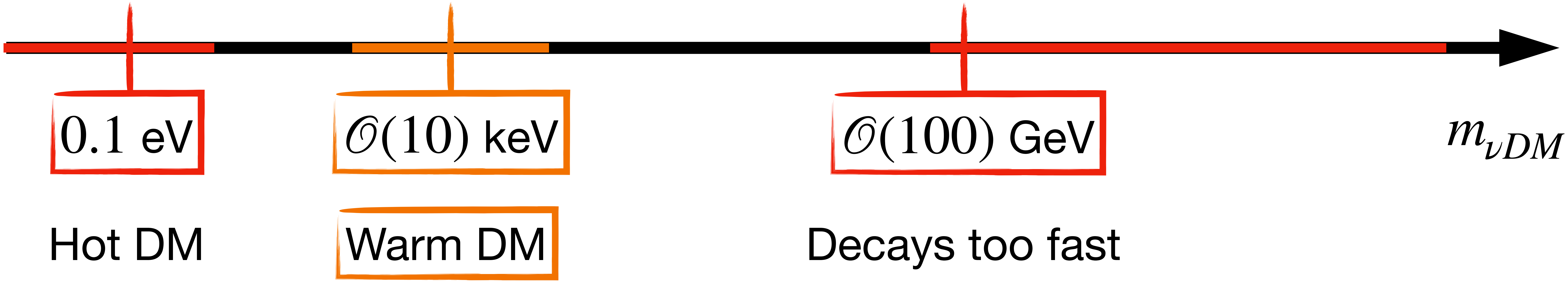
$\bar{N}_R^c M_M N_R$ → Allowed by gauge invariance

Seesaw limit $\quad M_M \gg vY_\nu \rightarrow m_\nu \sim v^2 Y_\nu^T M_M^{-1} Y_\nu$

Active-heavy mixing is suppressed $\rightarrow \theta \sim vY_\nu M_M^{-1}$

Could a neutrino be the DM?

Production through oscillations and collisions



Dodelson & Widrow, arXiv:hep-ph/9303287

Dodelson-Widrow mechanism effective at $T \sim 150$ MeV

Only depends on $m_{\nu DM}$ and its mixing with active neutrinos

Could a neutrino be the DM?

Production through oscillations and collisions

0.1 eV	$\mathcal{O}(10)$ keV	$\mathcal{O}(100)$ GeV	$m_{\nu DM}$
Hot DM	Warm DM	Decays too fast	

Dodelson & Widrow, arXiv:hep-ph/9303287

Dodelson-Widrow mechanism effective at $T \sim 150$ MeV

Only depends on $m_{\nu DM}$ and its mixing with active neutrinos

Smoking gun

X-ray signal from $\nu_{DM} \rightarrow \nu_{light}\gamma$

Pal & Wolfenstein, Phys. Rev. D (1982)

Severely constrained

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

Dumping of the production rate

Propagating modes and relaxation rate

$$\mathcal{S}^{-1} = p_0^2 - p^2 - \mathcal{M}_d + (p_0 - hp)(\Sigma_L^0 + h\Sigma_L^1)$$

Different helicity states interact differently with the thermal bath

$$\Omega^h \equiv (p_0 - hp)(\Sigma_L^0 + h\Sigma_L^1)$$

The production rate would be $\Gamma_{DM}^h = -2Im(p_0)$

Boyanovsky, Lello & Pisarski, arXiv: 1609.07647

Dumping of the production rate

Propagating modes and relaxation rate

$$\mathcal{S}^{-1} = p_0^2 - p^2 - \mathcal{M}_d + (p_0 - hp)(\Sigma_L^0 + h\Sigma_L^1)$$

Different helicity states interact differently with the thermal bath

$$\Omega^h \equiv (p_0 - hp)(\Sigma_L^0 + h\Sigma_L^1)$$

Ex: Toy 2x2 model $\mathcal{U} \simeq \begin{pmatrix} 1 & \theta \\ -\theta & 1 \end{pmatrix}$

$$p_0^2 \simeq p^2 + m_{DM}^2 + \frac{\theta^2 (m_{DM}^2)^2}{m_{DM}^2 + \Omega^h}$$

Boyanovsky, Lello & Pisarski, arXiv: 1609.07647

$$\theta_{eff}(T) \equiv \frac{\theta}{\sqrt{\left(1 + Re\frac{\Omega^h(T)}{m_{DM}^2}\right)^2 + \left(\frac{Im\Omega^h(T)}{m_{DM}^2}\right)^2}}$$

Inclusion of massive heavy neutrinos

Contributions to DM production

$W \leftrightarrow l\nu_{DM}$

$Z \leftrightarrow \nu_{light}\nu_{DM}$

$H \leftrightarrow \nu_{light}\nu_{DM}$

Chirality suppression for RH helicities

$\Gamma_{prod} \sim f_B(1 - f_F)$ Fermi blocking

$N \leftrightarrow H\nu_{DM}$

$N \leftrightarrow Z\nu_{DM}$

$\Gamma_{prod} \sim f_F(1 + f_B)$ Bose enhancement

More promising channels to produce DM

Example non-minimal scenario

$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{\Phi} N_R - \bar{S} M N_R - \frac{1}{2} \bar{S} \phi_2 Y_\mu S^c + h.c.$$

Merle & Totzauer, arXiv:1502.01011
Boulebnane, Heeck, Nguyễn & Teresi, arXiv:1709.07283
De Romeri, Karamitros, Lebedev & Toma, arXiv:2003.12606

$$\phi_2 \leftrightarrow \nu_{DM} N$$

$$N \leftrightarrow \phi_2 \nu_{DM}$$