11TH WORKSHOP
FLASY
ROME 2025
Flavor Symmetries and Consequences in Accelerators and Cosmology

Sterile ν DM production

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INFN, Sezione di Bologna

In collaboration with A. Abada, G. Arcadi, M. Lucente & G. Piazza, based on arXiv:2308.01341 & arXiv:2503.20017

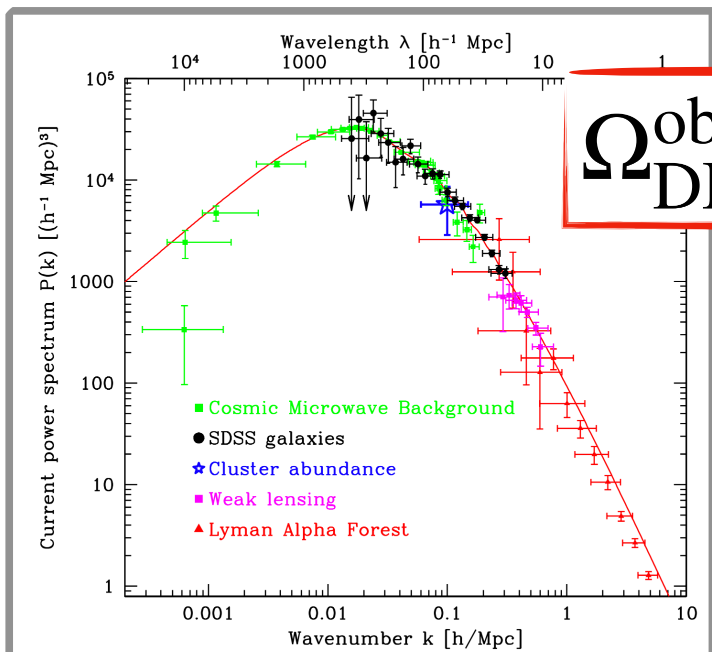
FLASY 2025, Roma Tre University

INFN BOLOGNA

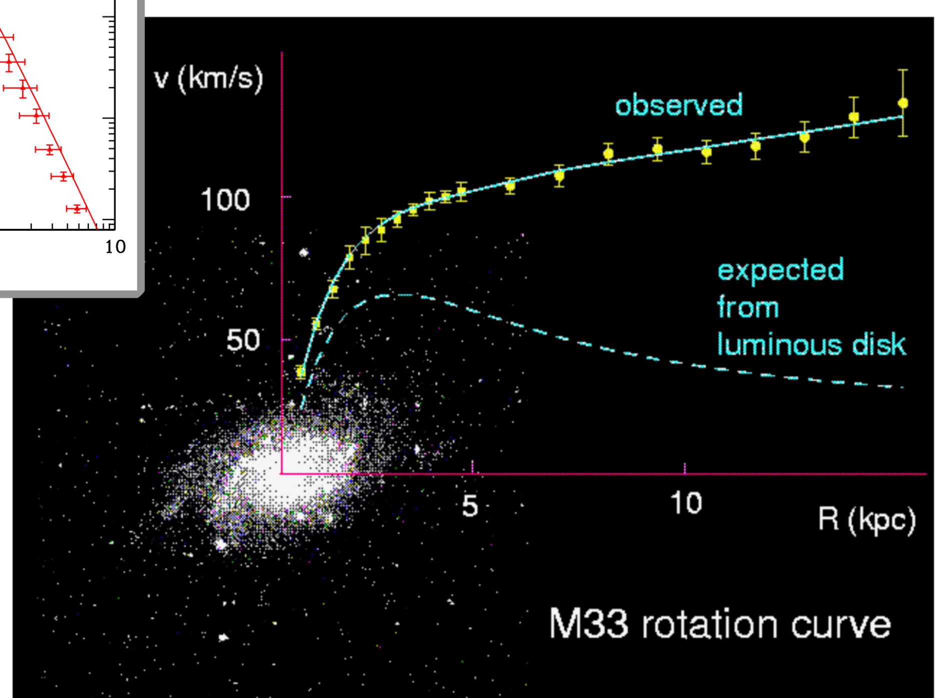
Introduction

Dark matter

Only gravitational probes



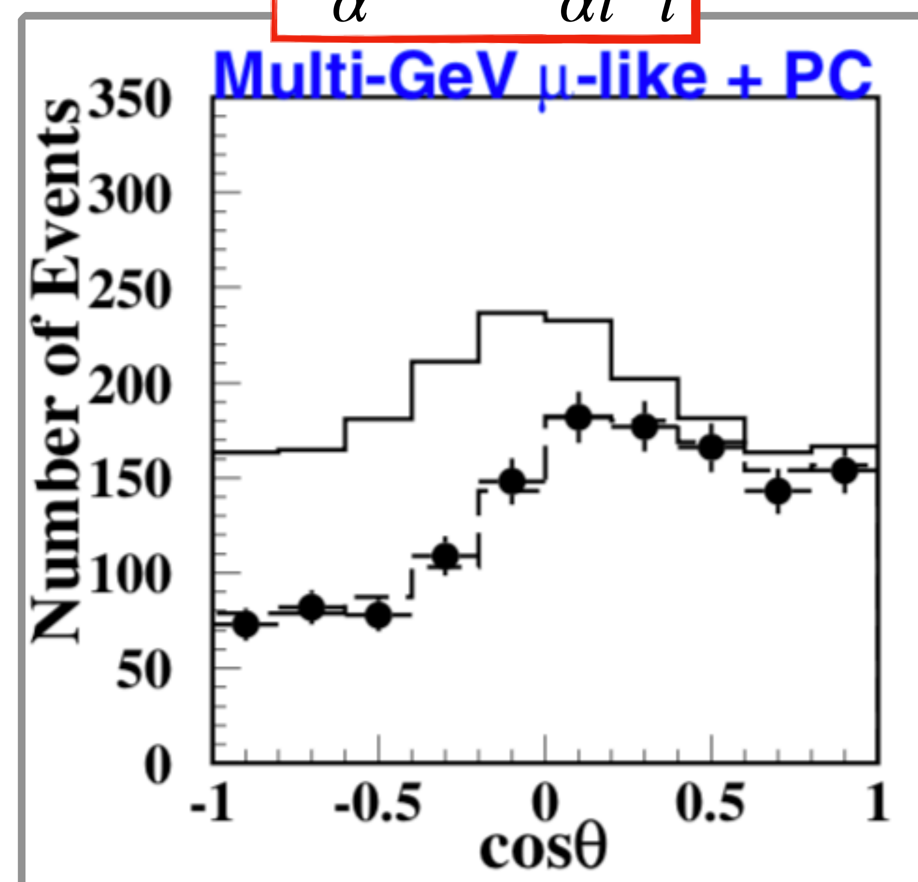
$$\Omega_{\rm DM}^{\rm obs} h^2 \simeq 0.12$$



See Talk by F. Calore

Massive neutrinos

$$\nu_\alpha = \tilde{U}_{\alpha i} \nu_i$$



Super-Kamiokande Collaboration, arXiv: hep-ex/0105023

Massive neutrinos

Type-I seesaw

In the **SM** we only have **left-handed** ν

Add the right-handed counterpart → N_R

Complete SM singlet

Massive neutrinos

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Complete SM singlet

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

New scale not related to EW symmetry breaking!

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)*

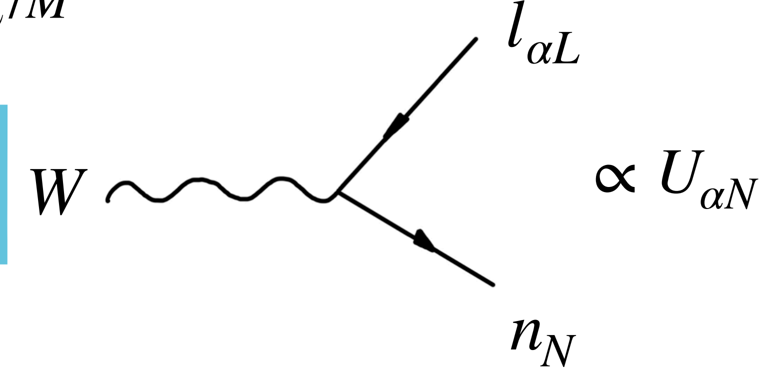
Massive neutrinos

Type-I seesaw

$U_{\alpha N} \sim v_H Y_\nu / M$

Relation between **flavor** and **mass basis**

$$\nu_{\alpha L} = \tilde{U}_{\alpha i} P_L \nu_i + U_{\alpha N} P_L n_N$$



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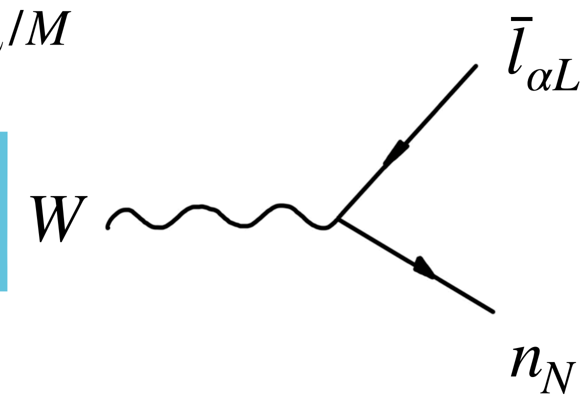


$\propto U_{\alpha N}$

Need at least **2** N_R to explain **oscillation data**

A. Ibarra & G. Ross, arXiv:hep-ph/0312138

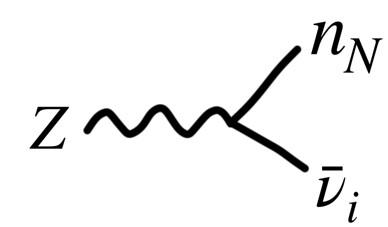
Massive neutrinos

Type-I seesaw: constraints

Relation between **flavor** and **mass basis**

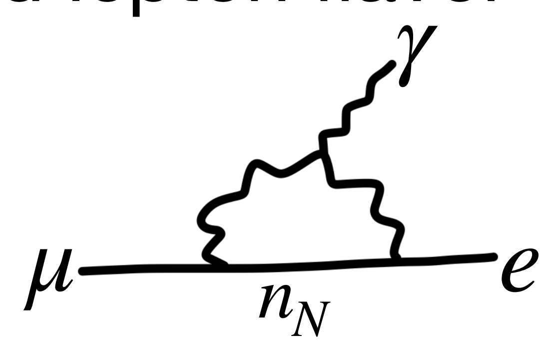
$$\nu_{\alpha L} = \tilde{U}_{\alpha i} P_L \nu_i + U_{\alpha N} P_L n_N$$

Z-boson invisible width



$$\Gamma^Z_{\text{inv}} \sim \Gamma^Z_{\text{SM}} \left[1 - \frac{1}{3}(|U_{ei}|^2 + |U_{\mu i}|^2 + 4|U_{\tau i}|^2) \right]$$

Charged lepton flavor violation



$$\mathcal{B}\left(\mu \to e\gamma\right) \propto |U_{ei} U^*_{\mu i}|^2$$

Massive neutrinos

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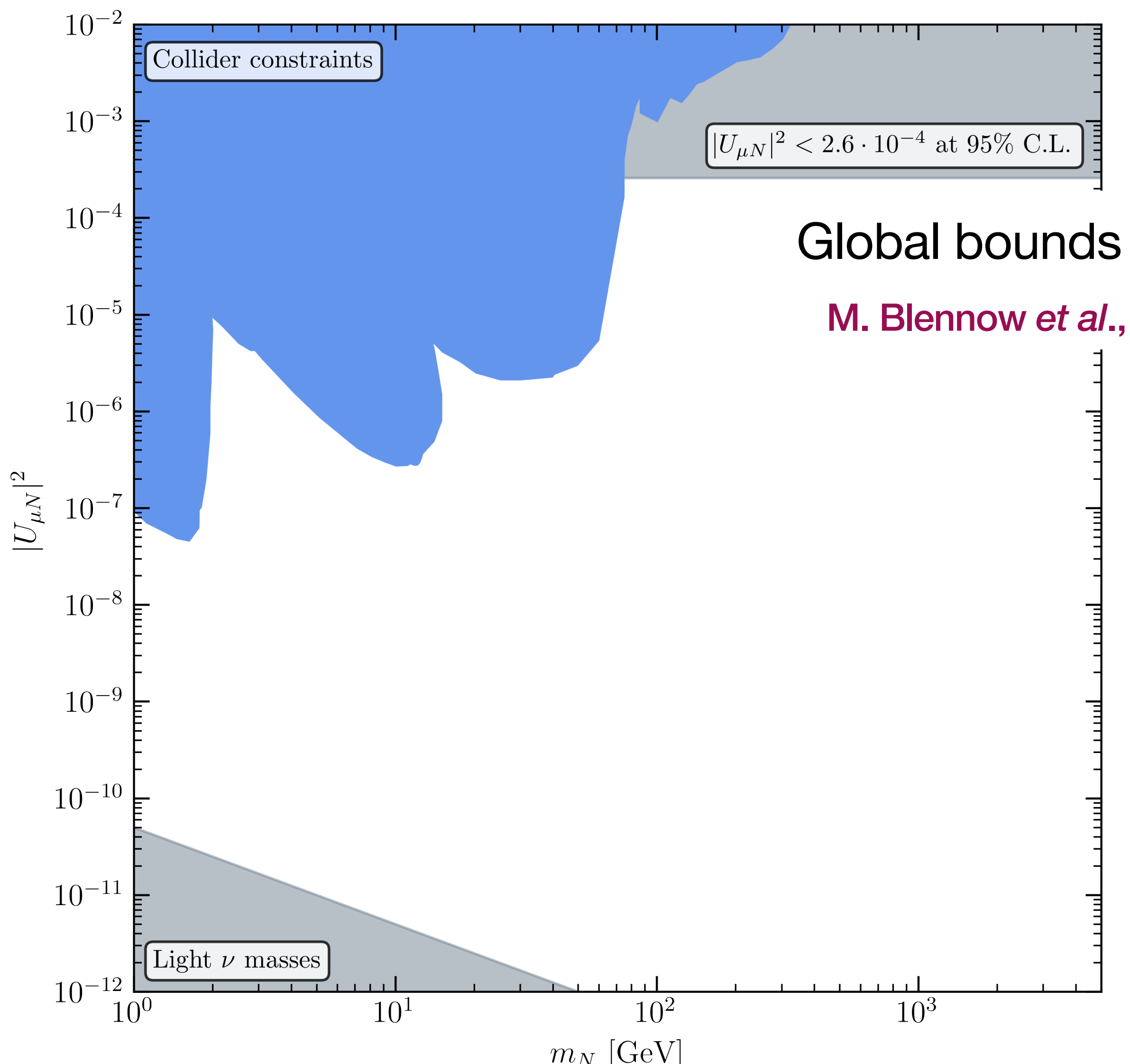
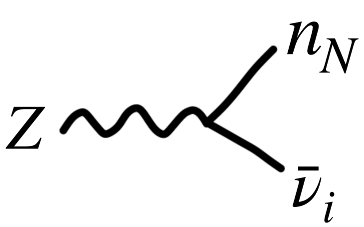


Global bounds for $m_N \gtrsim M_Z$

M. Blennow *et al*., arXiv:2306.01040

Heavy-Neutrino-Limits by
E. Fernandez-Martinez *et al*., arXiv:2304.06772

Z-boson invisible width



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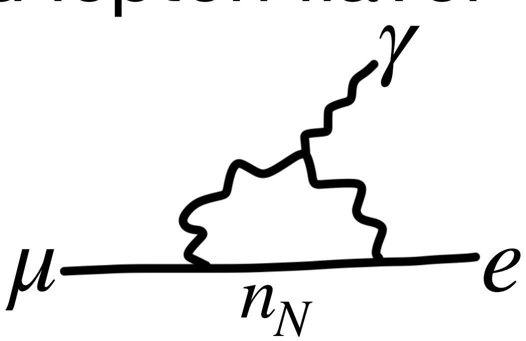

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Massive neutrinos

Neutrino dark matter

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

New scale not related to EW symmetry breaking!

Need at least **2** N_R to explain **oscillation data**

A. Ibarra & G. Ross, arXiv:hep-ph/0312138

Add a third N_R with $M \sim \mathcal{O}(\mathrm{keV})$

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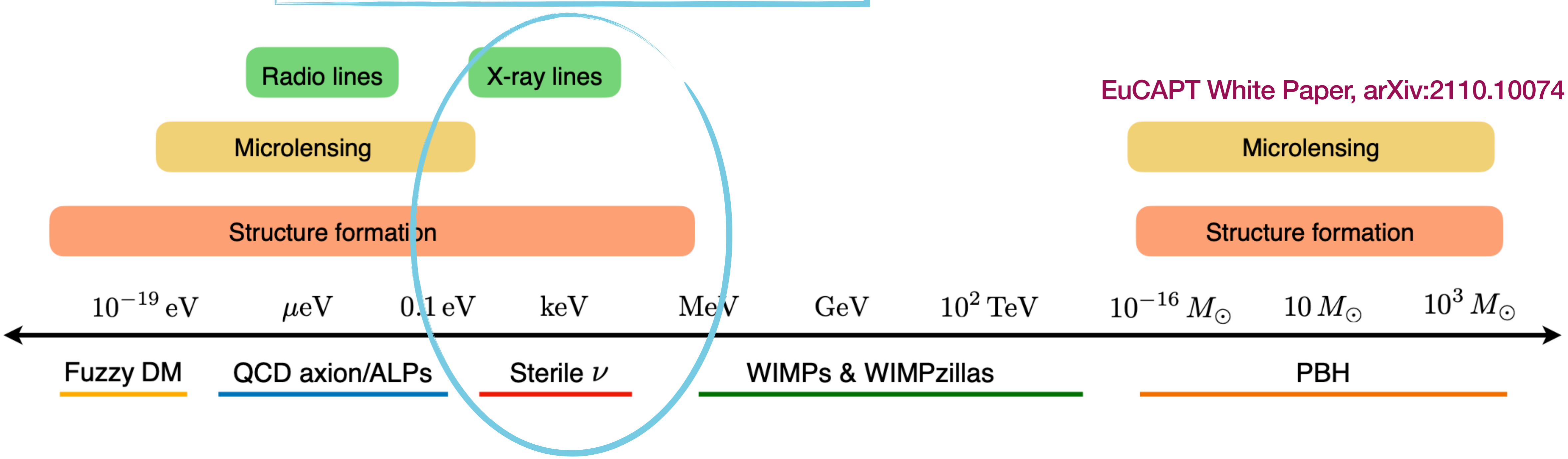
Add a third N_R with $M \sim \mathcal{O}\left(\mathrm{keV}\right)$

How do we search this DM?

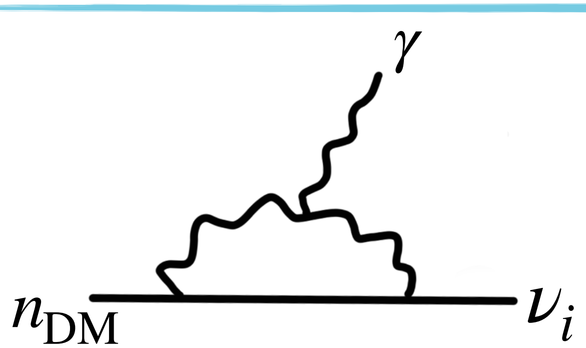


Massive neutrinos

Neutrino dark matter

Unstable DM candidate: $\tau_{\rm DM} > \tau_{\rm Universe}$

Monochromatic X-ray signal as smoking gun

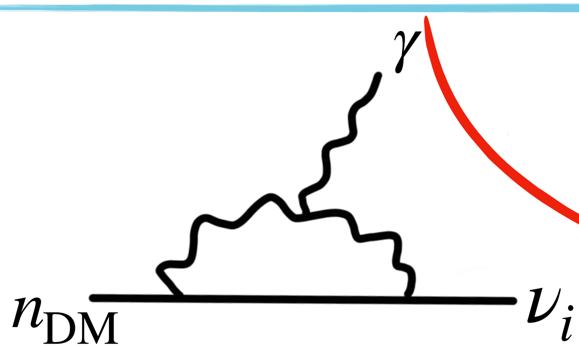


$$\propto G_F^2 \left|\theta_{\alpha \rm DM}\right|^2 m_{\rm DM}^5$$

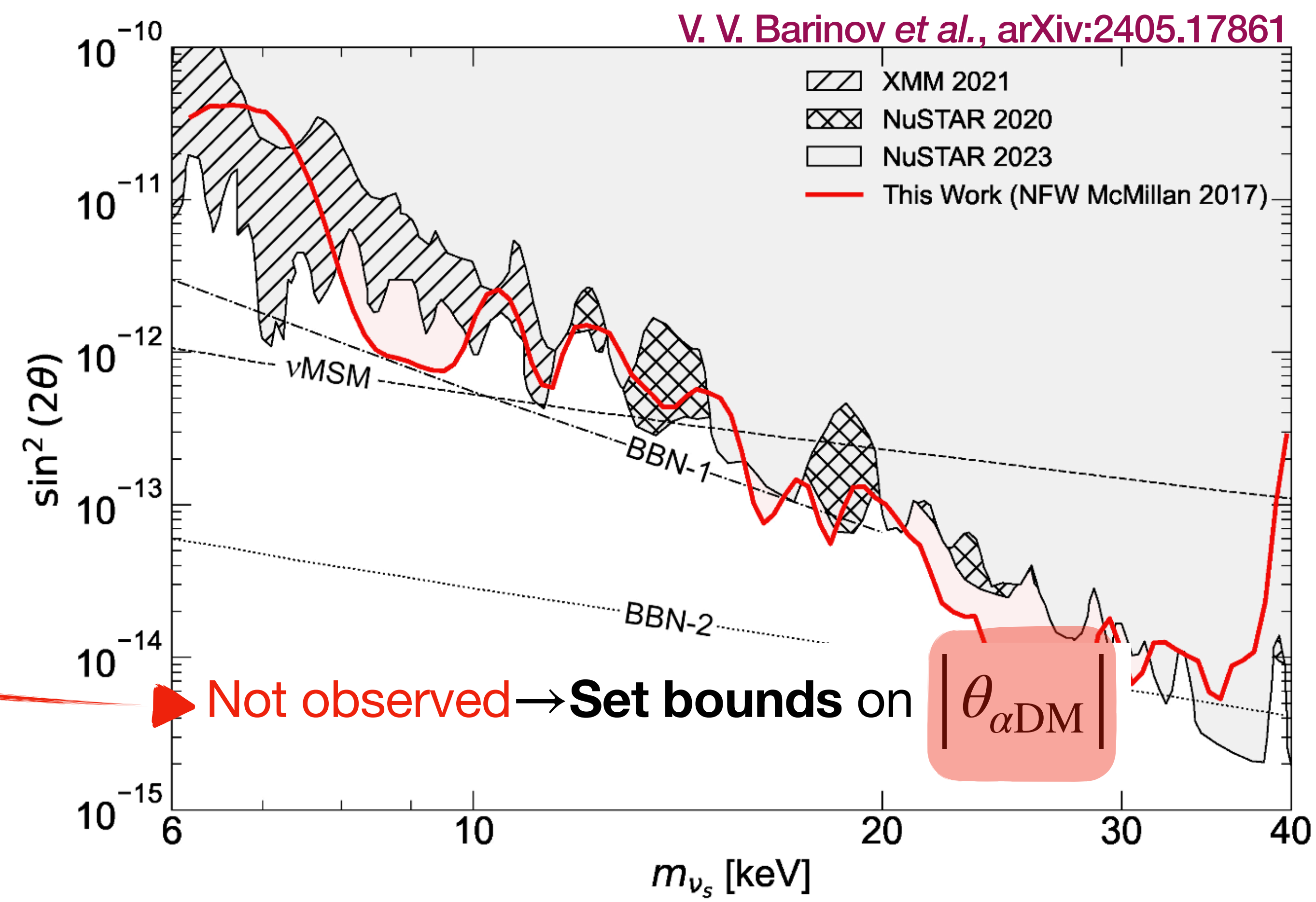
Massive neutrinos

Neutrino dark matter

Monochromatic X-ray signal as smoking gun



$\propto G_F^2 \left|\theta_{\alpha\mathrm{DM}}\right|^2 m_{\mathrm{DM}}^5$



Not observed → **Set bounds on** $\left|\theta_{\alpha\mathrm{DM}}\right|$

Neutrino dark matter

Production mechanism

Temperatures $T \lesssim 1\,\mathrm{GeV}$

Dodelson-Widrow mechanism

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

DM abundance from ν **oscillations** and **collisions** in the plasma

$$\Omega_{\mathrm{DM}} h^2 \propto \left|\theta_{\alpha \mathrm{DM}}\right|^2 m_{\mathrm{DM}}$$

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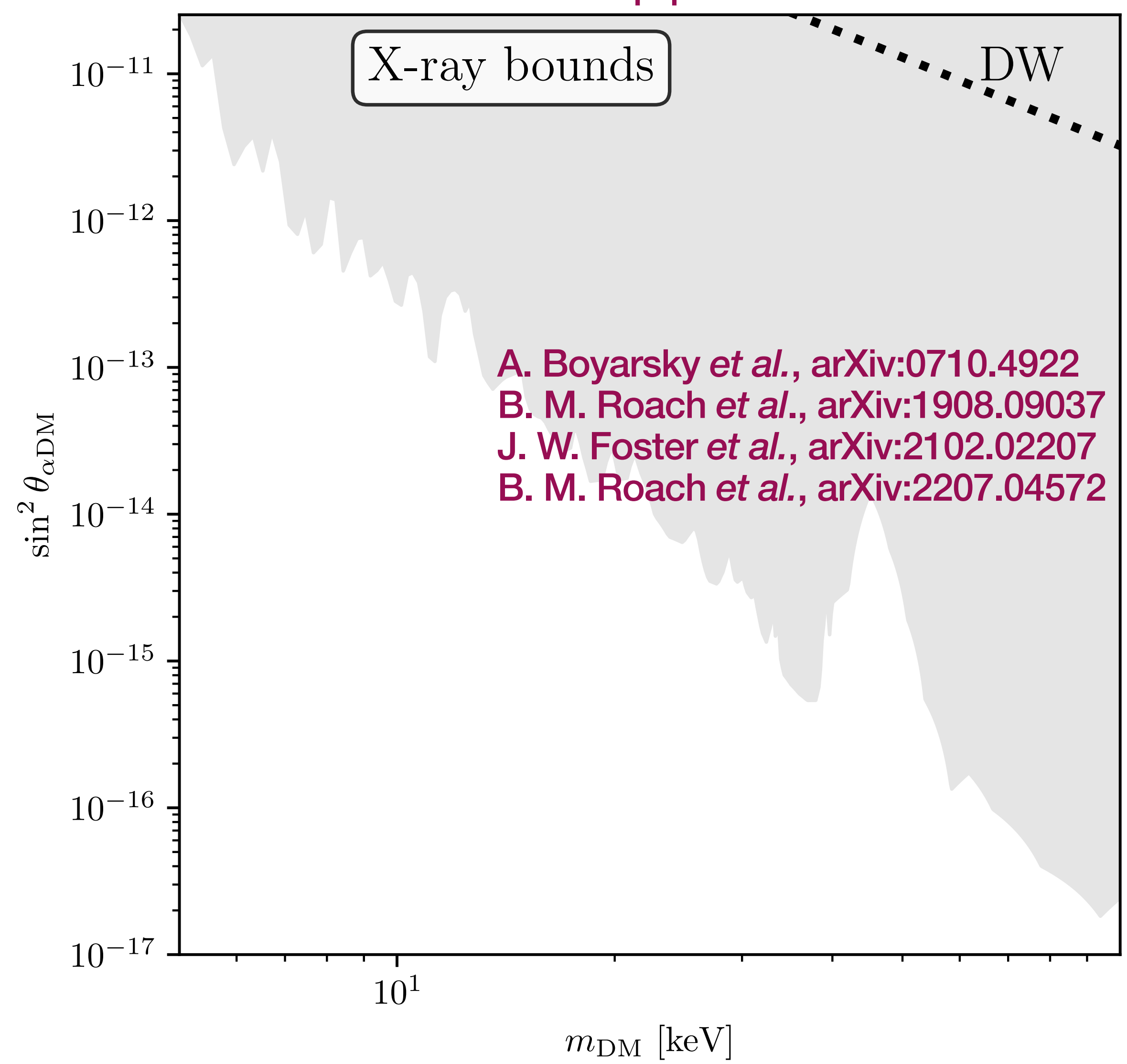
T. Asaka, M. Laine & M. Shaposhnikov, arXiv:hep-ph/0612182



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DM abundance from ν **oscillations** and **collisions** in the plasma

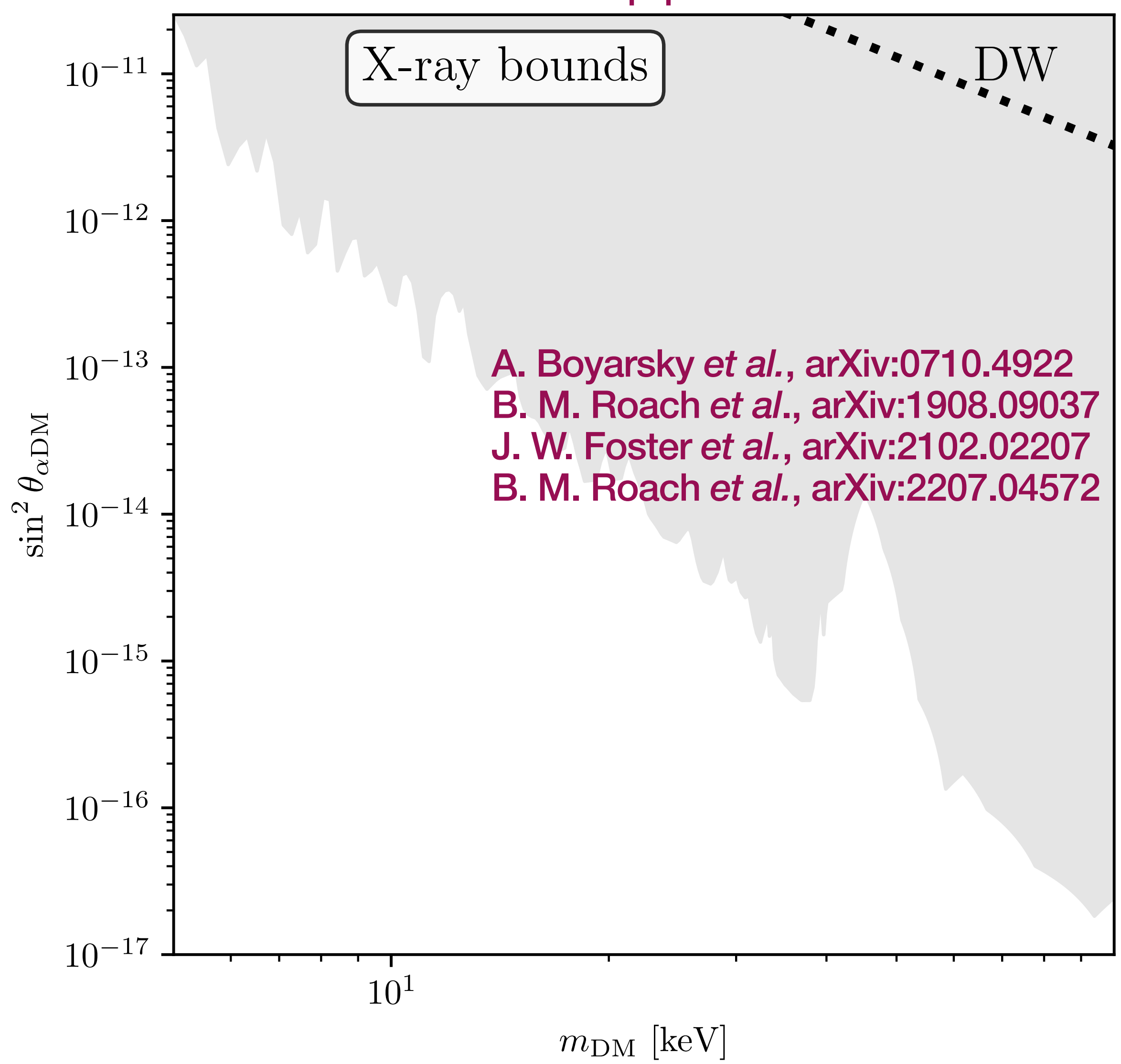
$$\Omega_{\rm DM}h^2 \propto \left|\theta_{\alpha \rm DM}\right|^2 m_{\rm DM}$$

A. Merle, A. Schneider & M. Totzauer, arXiv:1512.05369

At most it can produce $\mathscr{F}_{\rm DM} = \dfrac{\Omega_{\rm DM}h^2}{\Omega_{\rm DM}^{\rm obs}h^2} \simeq 0.1$

Irreducible contribution

T. Asaka, M. Laine & M. Shaposhnikov, arXiv:hep-ph/0612182



A. Boyarsky *et al.*, arXiv:0710.4922
B. M. Roach *et al.*, arXiv:1908.09037
J. W. Foster *et al.*, arXiv:2102.02207
B. M. Roach *et al.*, arXiv:2207.04572

Neutrino dark matter

Production mechanism

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

Freeze-in via 2-body decays

Neutrino dark matter

Production mechanism

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

Freeze-in via 2-body decays

$$\left.\begin{aligned} &Z\,(h) \leftrightarrow \nu_i + n_{\mathrm{DM}} \\ &W \leftrightarrow \ell_\alpha + n_{\mathrm{DM}} \\ &n_N \leftrightarrow h\,(Z) + n_{\mathrm{DM}} \end{aligned}\right\}$$

$$\Gamma_s \propto \left|\theta_{\alpha \mathrm{DM}}\right|^2 \ll H$$

DM never reaches equilibrium

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

Neutrino dark matter

Production mechanism

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Irreducible contribution*

*In the Type-I seesaw

Neutrino dark matter

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Irreducible contribution

How much DM is produced?

A. Abada et al., arXiv:1406.6556
D. Boyanovsky & L. Lello, arXiv:1609.07647
M. Lucente, arXiv:2103.03253
A. Datta et al., arXiv:2104.02030
A. Abada, G. Arcadi, G. Piazza, M. Lucente & **SRA**, arXiv:2308.01341
A. Abada, G. Arcadi, M. Lucente & **SRA**, arXiv:2503.20017

Neutrino dark matter

Freeze-in production: $W\,(Z) \leftrightarrow \ell_\alpha\,(\nu_i) + n_{\rm DM}$

Consider the production through gauge boson decays

In vacuum

$$\Gamma_s \sim G_F M^3_{Z(W)} \left|\theta_{\alpha \rm DM}\right|^2$$

$$\Omega_{\rm DM} h^2 \sim m_{\rm DM} \Gamma_s / M^2_{Z(W)}$$

For $\theta_{\alpha \rm DM} \sim 10^{-6}$ it can be as large as $\Gamma_s \sim 10^{-12}\,\rm GeV$

Neutrino dark matter

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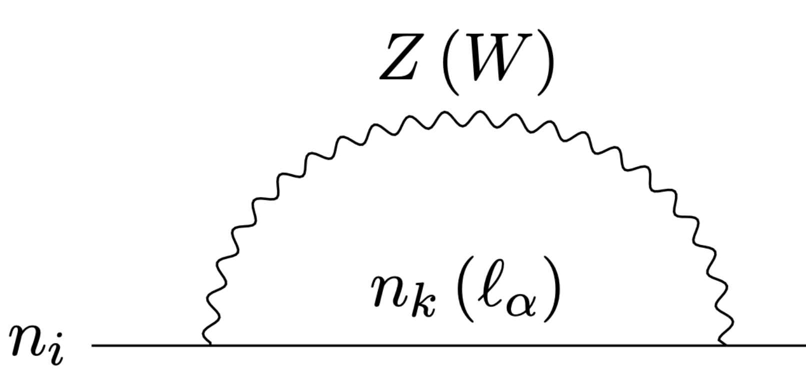
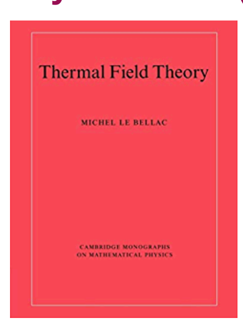
$$\Omega_{\rm DM} h^2 \sim m_{\rm DM}\Gamma_s / M^2_{Z(W)}$$

At $T \sim 100\,{\rm GeV}$ thermal effects
must be taken into account

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





Neutrino dark matter

Freeze-in production: $W\,(Z) \leftrightarrow \ell_\alpha\,(\nu_i) + n_{\rm DM}$

Consider the production
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$$\Gamma_s \sim G_F M^3_{Z(W)} \left|\theta_{\alpha\rm DM}\right|^2$$

$$\mathcal{M}^2 = \begin{pmatrix} \Omega^h(T) - \frac{m^2_{DM}}{4}\tan^2 2\theta_{\alpha\rm DM} & -\frac{m^2_{DM}}{2}\tan 2\theta_{\alpha\rm DM} \\ -\frac{m^2_{DM}}{2}\tan 2\theta_{\alpha\rm DM} & -m^2_{DM}\left[1 + \frac{1}{4\alpha^h}\tan^2 2\theta_{\alpha\rm DM}\right] \end{pmatrix}$$

$$\Omega^h(T) = (E - hp)\Sigma \sim g^2 T^2$$

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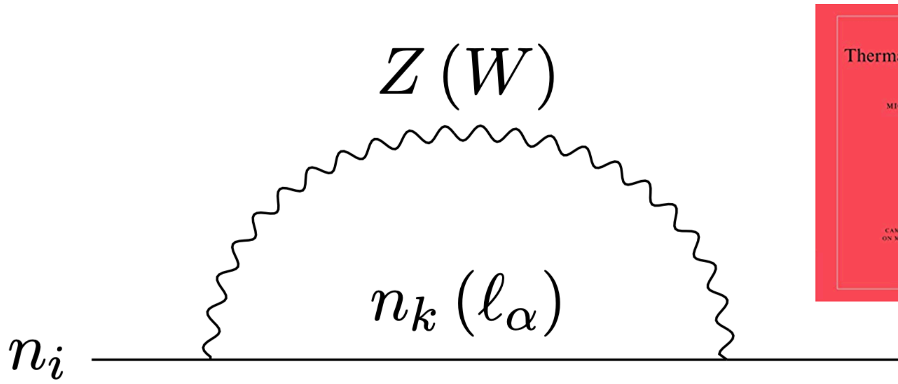

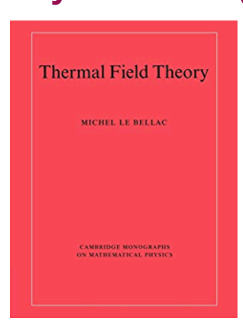

Neutrino dark matter

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$$\Omega^h(T) \sim g^2T^2$$

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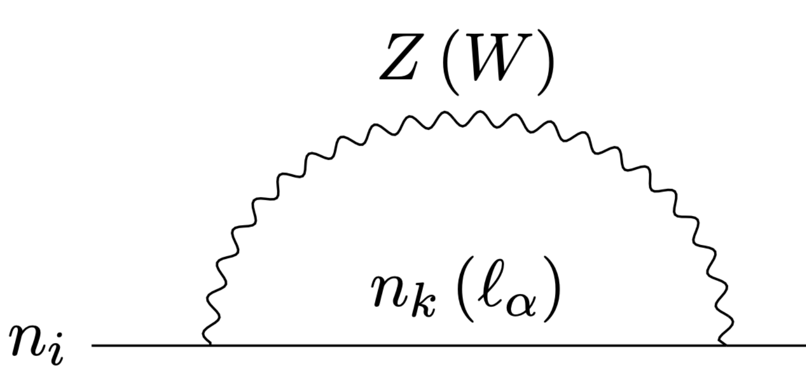

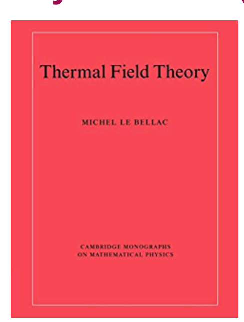

$$\sin 2\theta^{\rm eff}_{\alpha\rm DM} \sim \frac{m^2_{\rm DM}}{\Omega^h(T)}\sin 2\theta_{\alpha\rm DM}$$

Neutrino dark matter

Freeze-in production: $W(Z) \leftrightarrow \ell_\alpha(\nu_i) + n_{\rm DM}$

Consider the production
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In the plasma

$$\Gamma_s \sim G_F M^3_{Z(W)} \left|\theta_{eff}\right|^2$$

At $T \sim 100\,\mathrm{GeV}$ thermal effects
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Le Bellac, Thermal Field Theory (1996)
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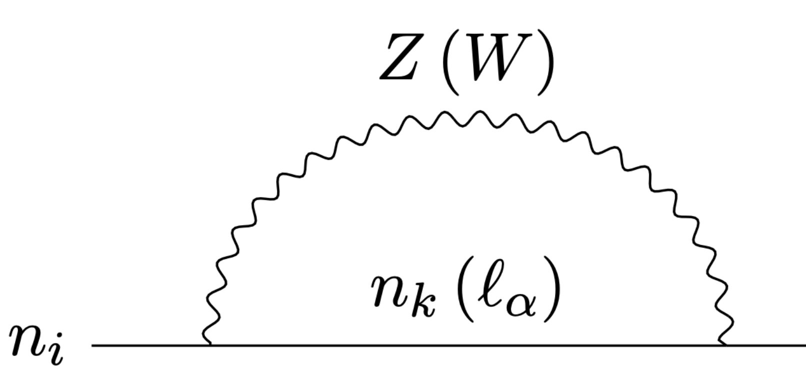
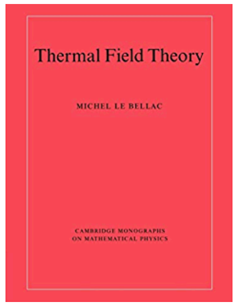
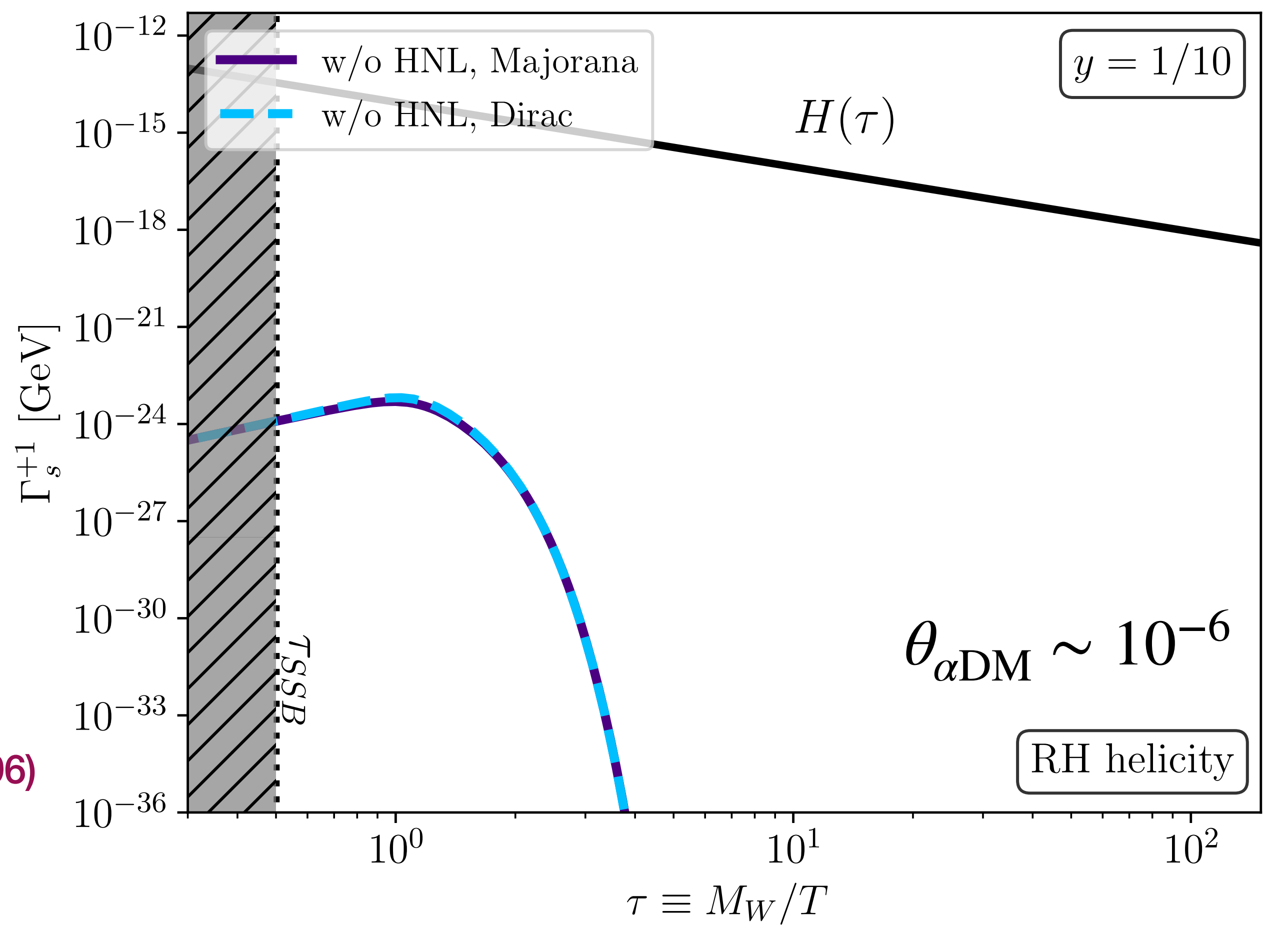






$\mathcal{F}_{\rm DM} \sim 0$ from $Z(W)$ decays

J. Ghiglieri and M. Laine, arXiv:1605.07720
D. Boyanovsky et al., arXiv:1609.07647
A. Abada, G. Arcadi, G. Piazza, M. Lucente & **SRA**, arXiv:2308.01341

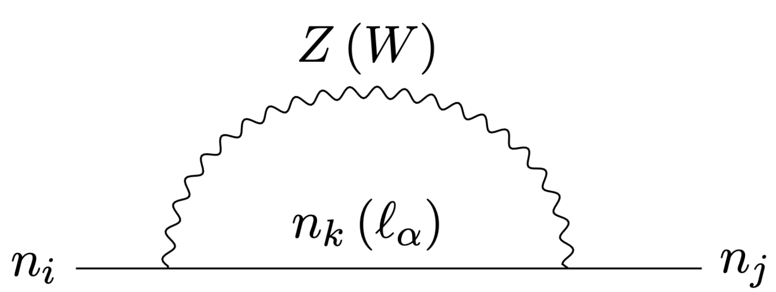
Neutrino dark matter

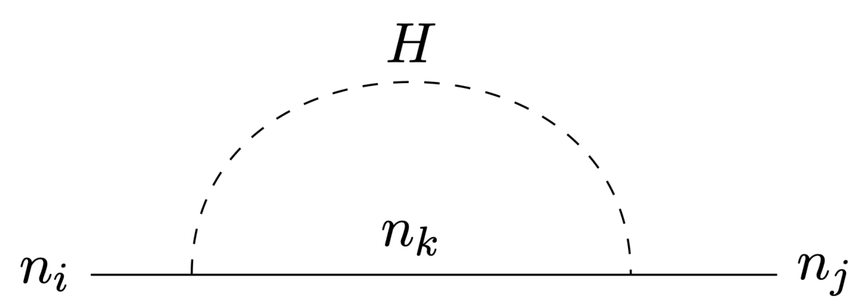
Freeze-in production: Heavy neutrino decay

Consider the production through $n_N \to h\,(Z) + n_{\mathrm{DM}}$

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

A. Abada, G. Arcadi, M. Lucente & **SRA**, arXiv:2503.20017





Consider simultaneously 3 active ν + DM + 2 heavy N

Approximate lepton number symmetry→Large $U_{\alpha N}$

Neutrino dark matter

Freeze-in production: Heavy neutrino decay

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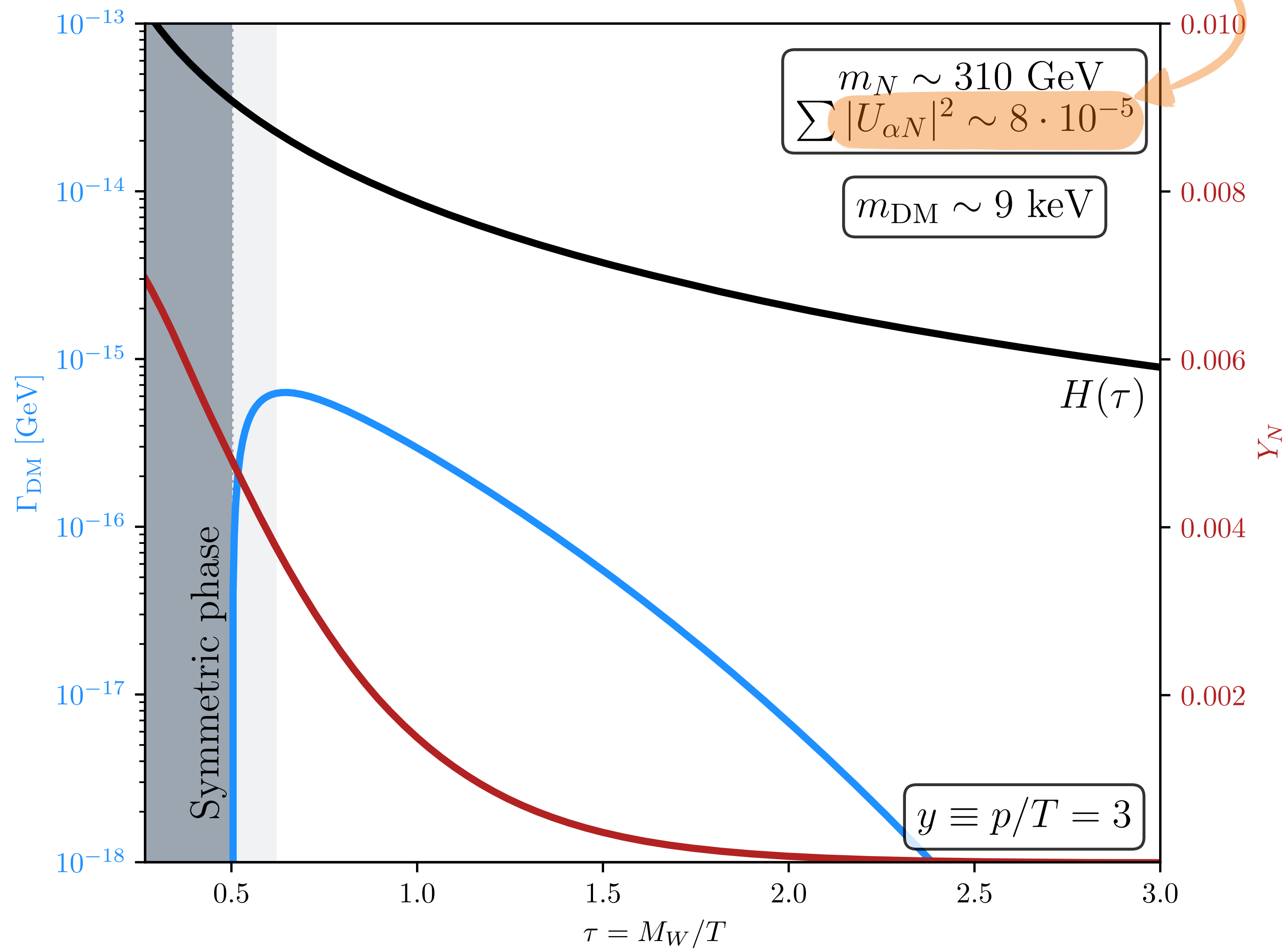
A. Abada, G. Arcadi, M. Lucente & **SRA**, arXiv:2503.20017

Active-heavy neutrino mixing



Neutrino dark matter

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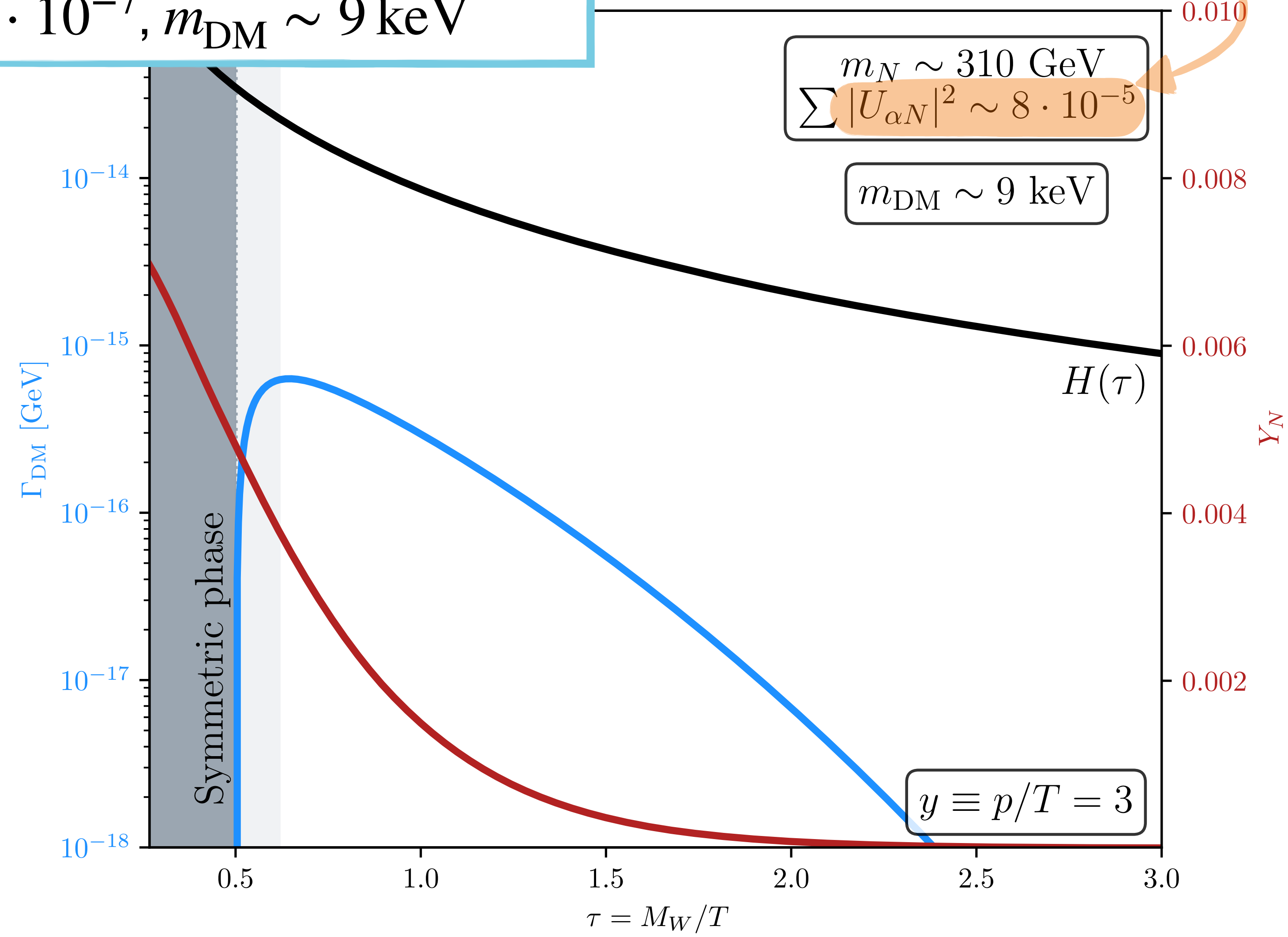
A. Abada, G. Arcadi, M. Lucente & **SRA**, arXiv:2503.20017

Active-heavy neutrino mixing

Benchmark point $\theta_{\alpha{\rm DM}} \sim 5 \cdot 10^{-7}, m_{\rm DM} \sim 9\,{\rm keV}$

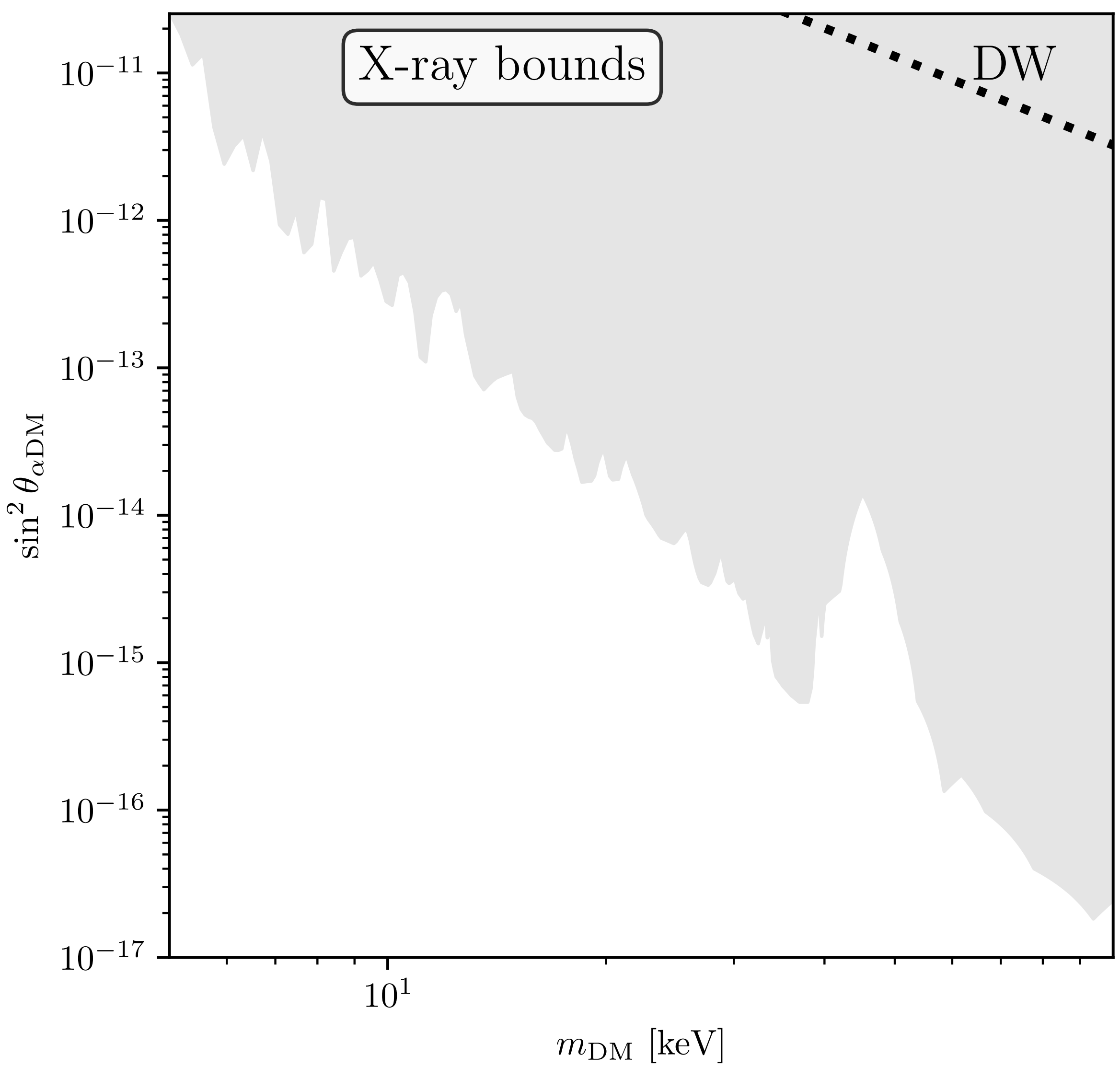
$$\mathscr{F}_{\rm DM} = \Omega_{n_{\rm DM}}/\Omega^{\rm obs}_{\rm DM} \sim 5$$

Using production rates in vacuum one finds $f^{T=0}_{\rm DM} \sim 100 f_{\rm DM}$



Neutrino dark matter

DM phenomenology



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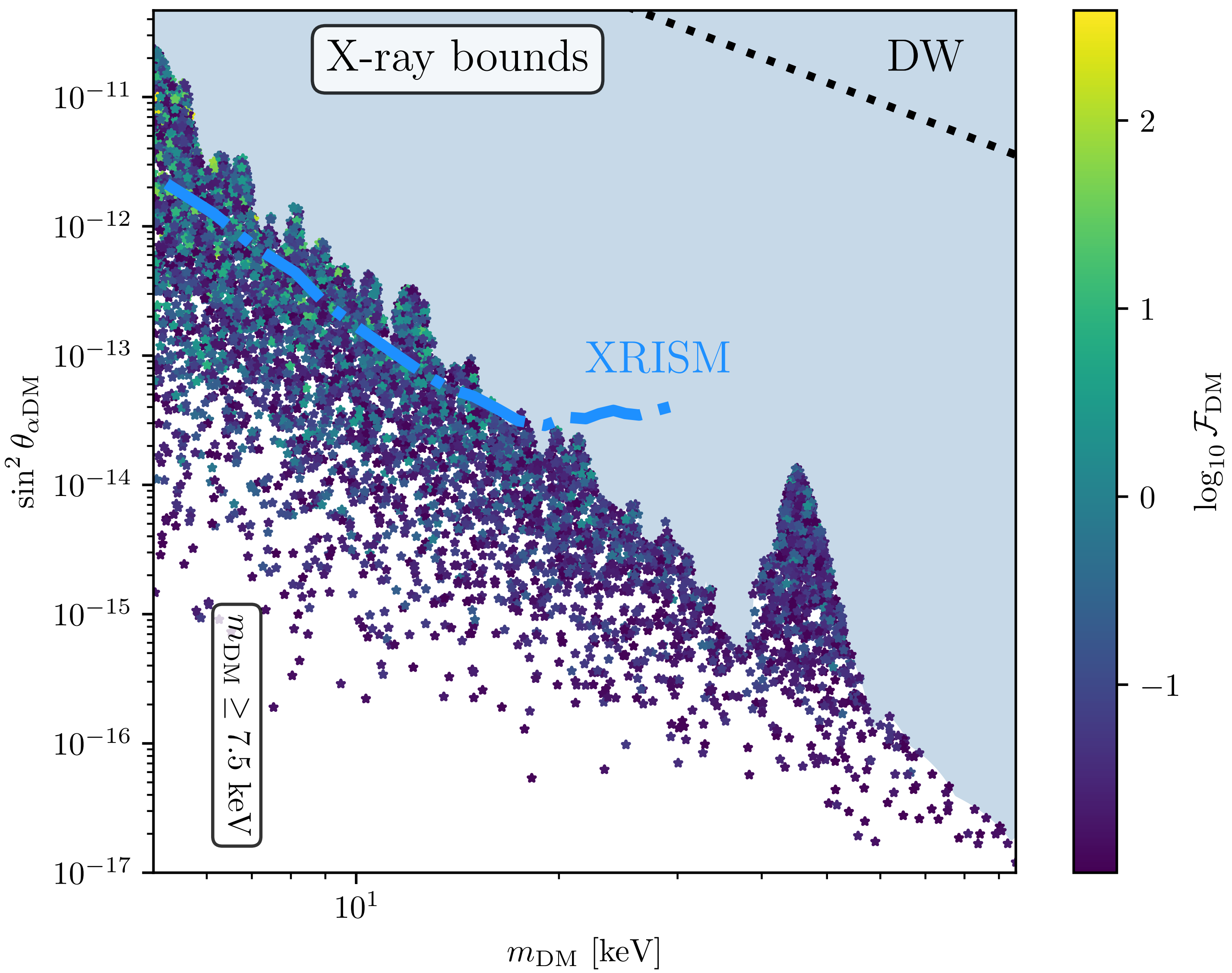


Constraints from Ly-α

G. Ballesteros, M. A. Garcia & M. Pierre, arXiv:2011.13458

$$m_{\rm DM} \gtrsim \left(\frac{m_{WDM}}{3\,\rm keV}\right)^{4/3} 7.5\,\rm keV$$

$$m_{WDM} \gtrsim 1.9 - 5.3\,\rm keV$$

M. Viel *et al.*, arXiv:1306.2314

$$m_{\rm DM} \gtrsim 4 - 16\,\rm keV$$

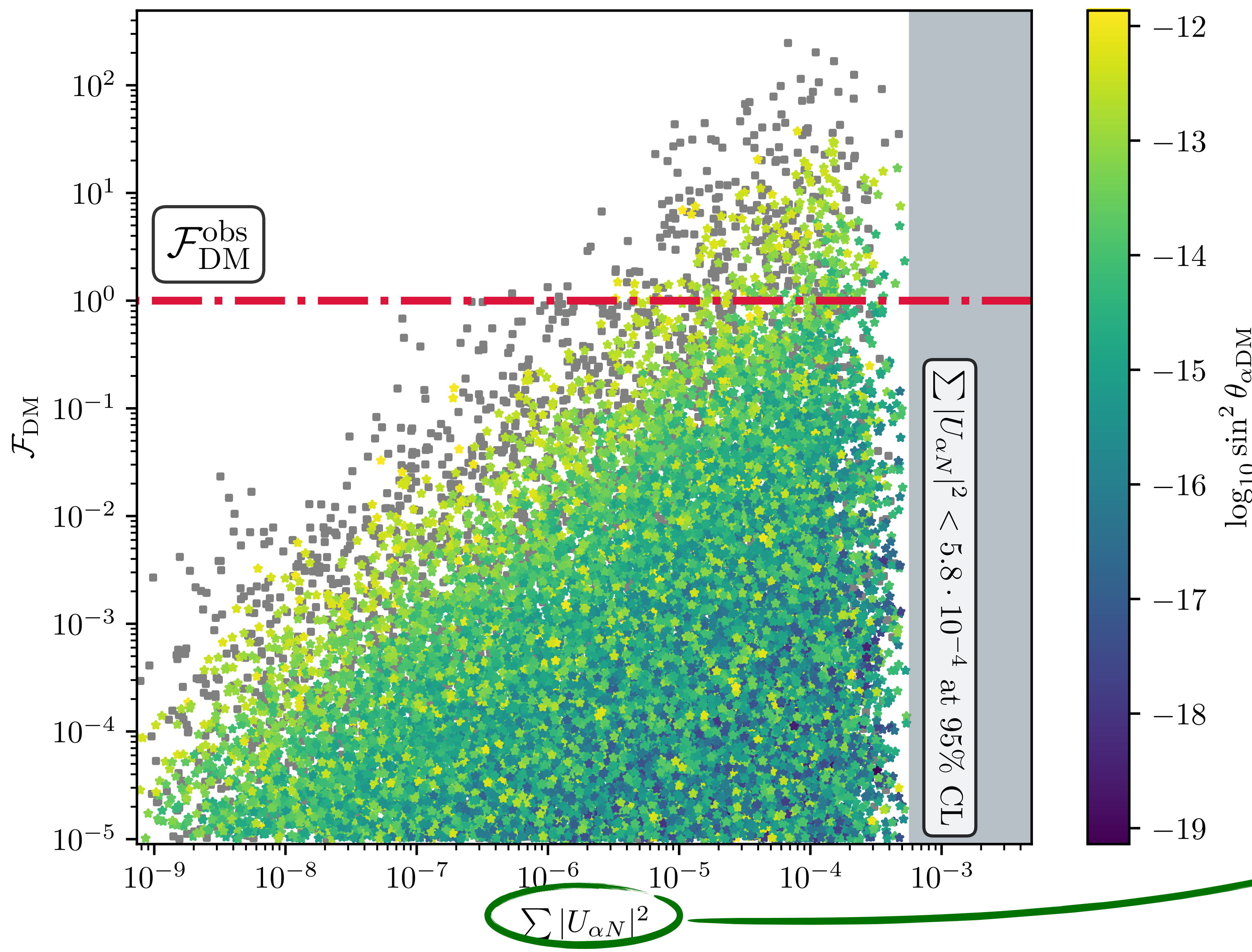
XRISM prospects

C. Dessert *et al.*, arXiv:2305.17160

Neutrino dark matter

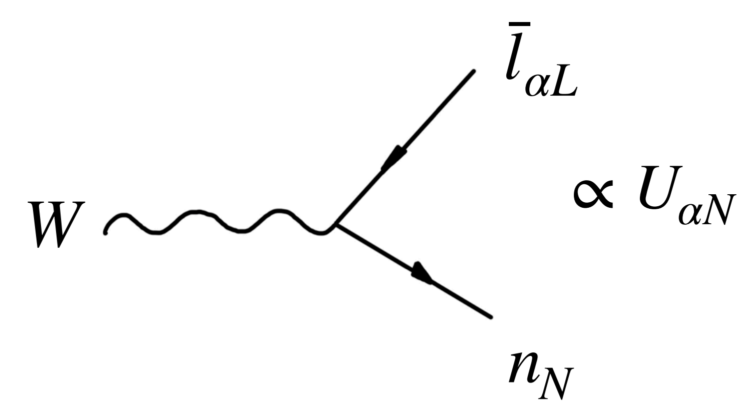
HNL related phenomenology

A. Abada, G. Arcadi, M. Lucente & **SRA**, arXiv:2503.20017



Bounds on $\sum |U_{\alpha N}|^2 \lesssim 5.8 \cdot 10^{-4}$

M. Blennow *et al.*, arXiv:2306.01040



Active-heavy mixing

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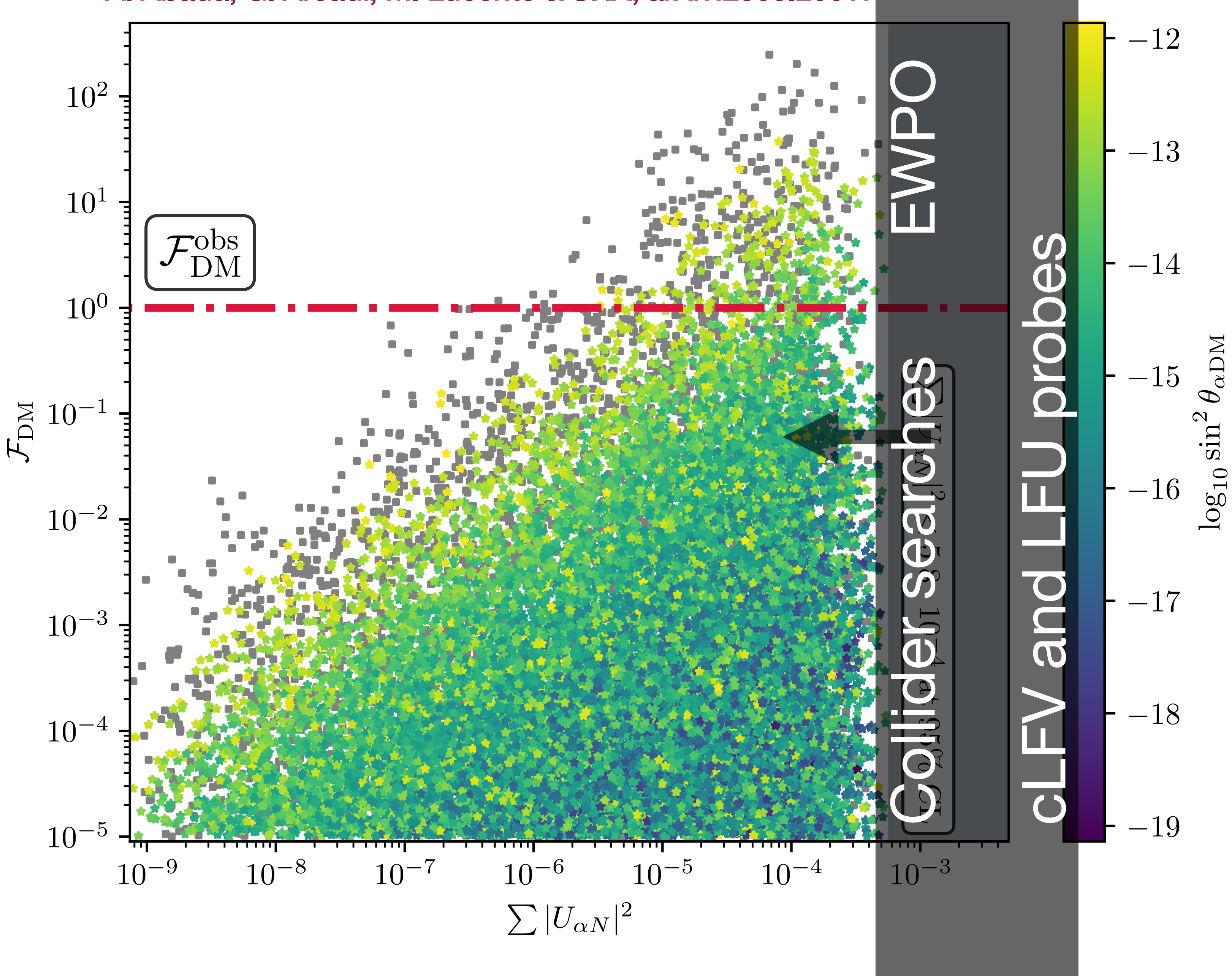
HNL related phenomenology

A. Abada, G. Arcadi, M. Lucente & **SRA**, arXiv:2503.20017



Neutrino dark matter

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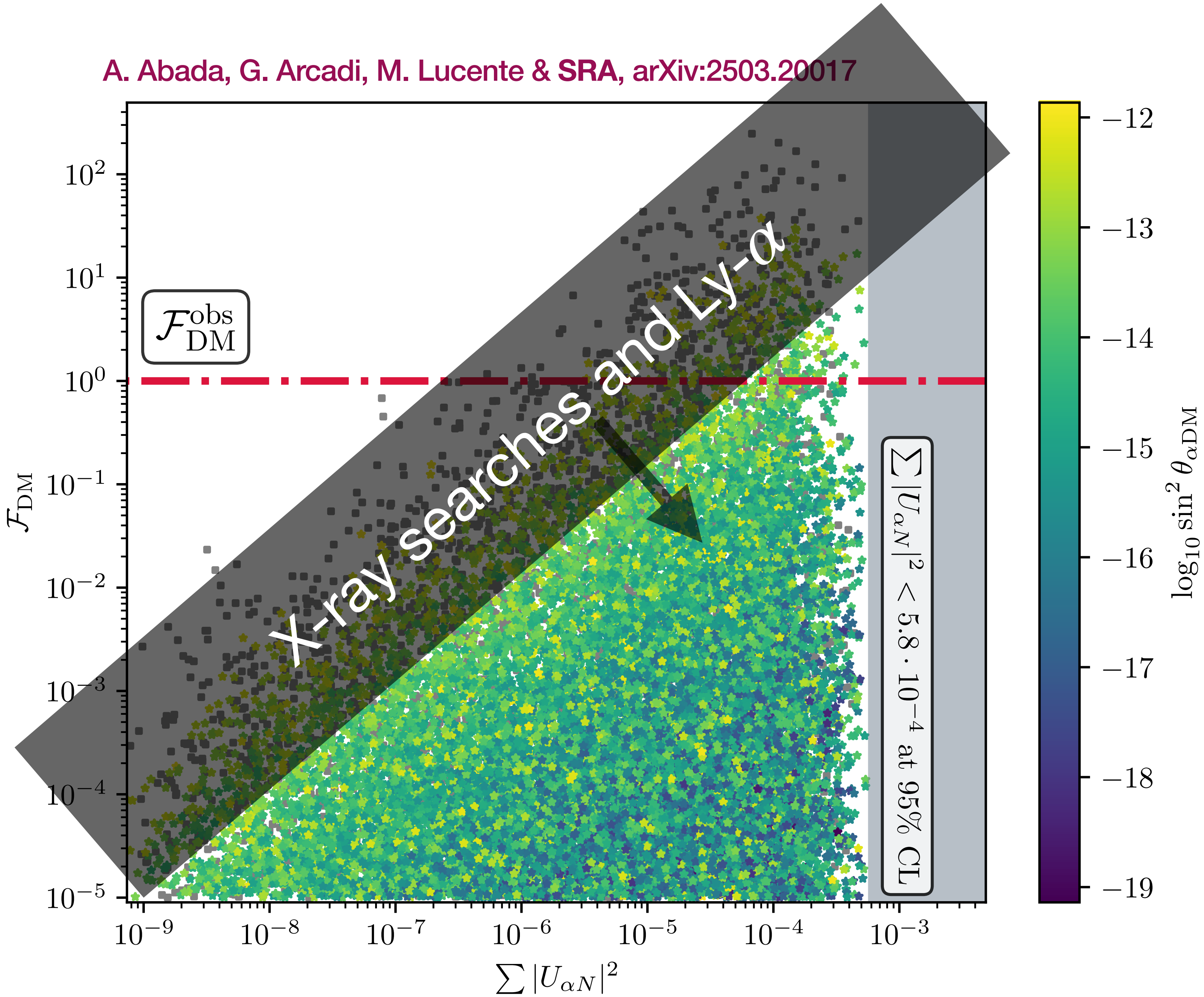

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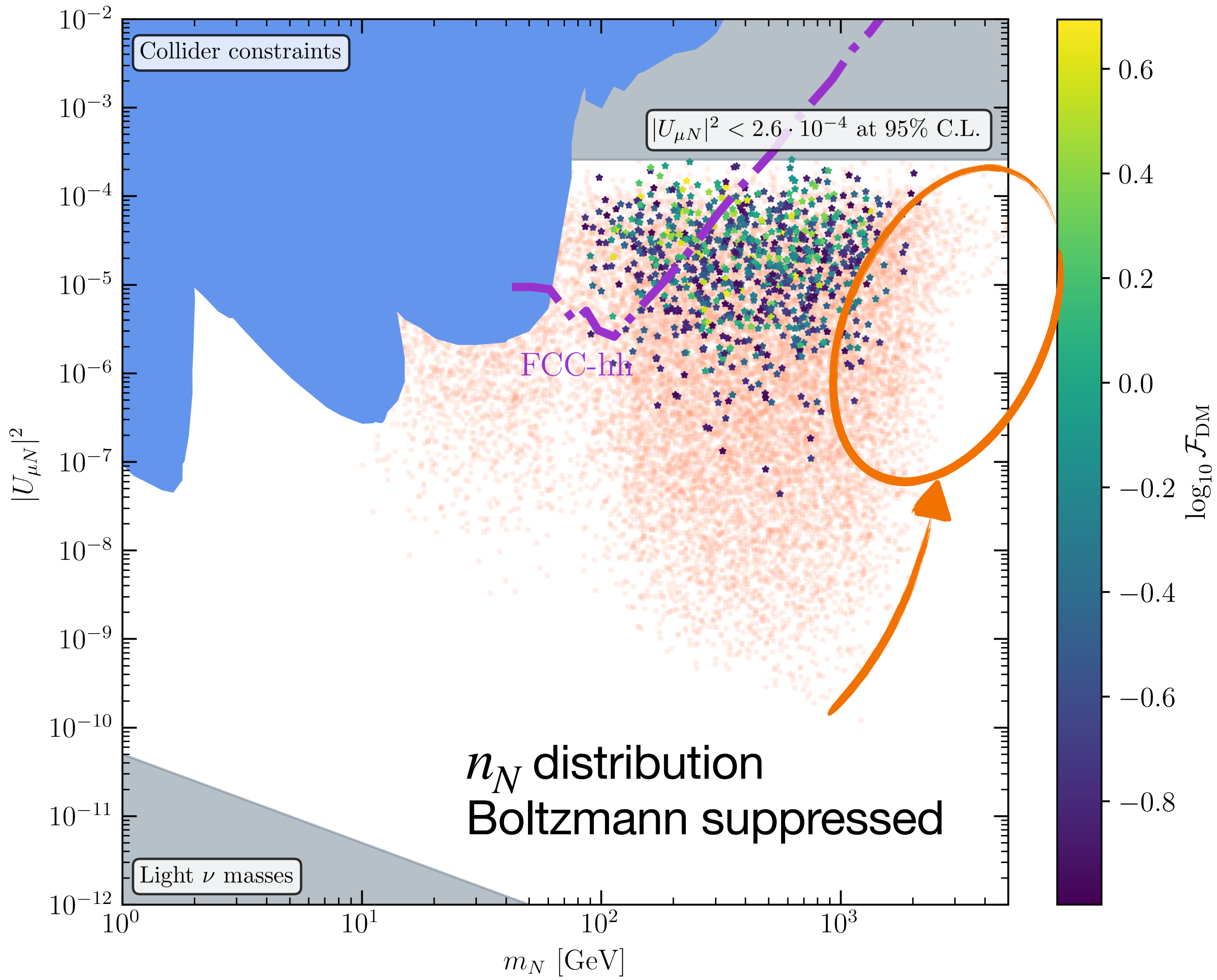

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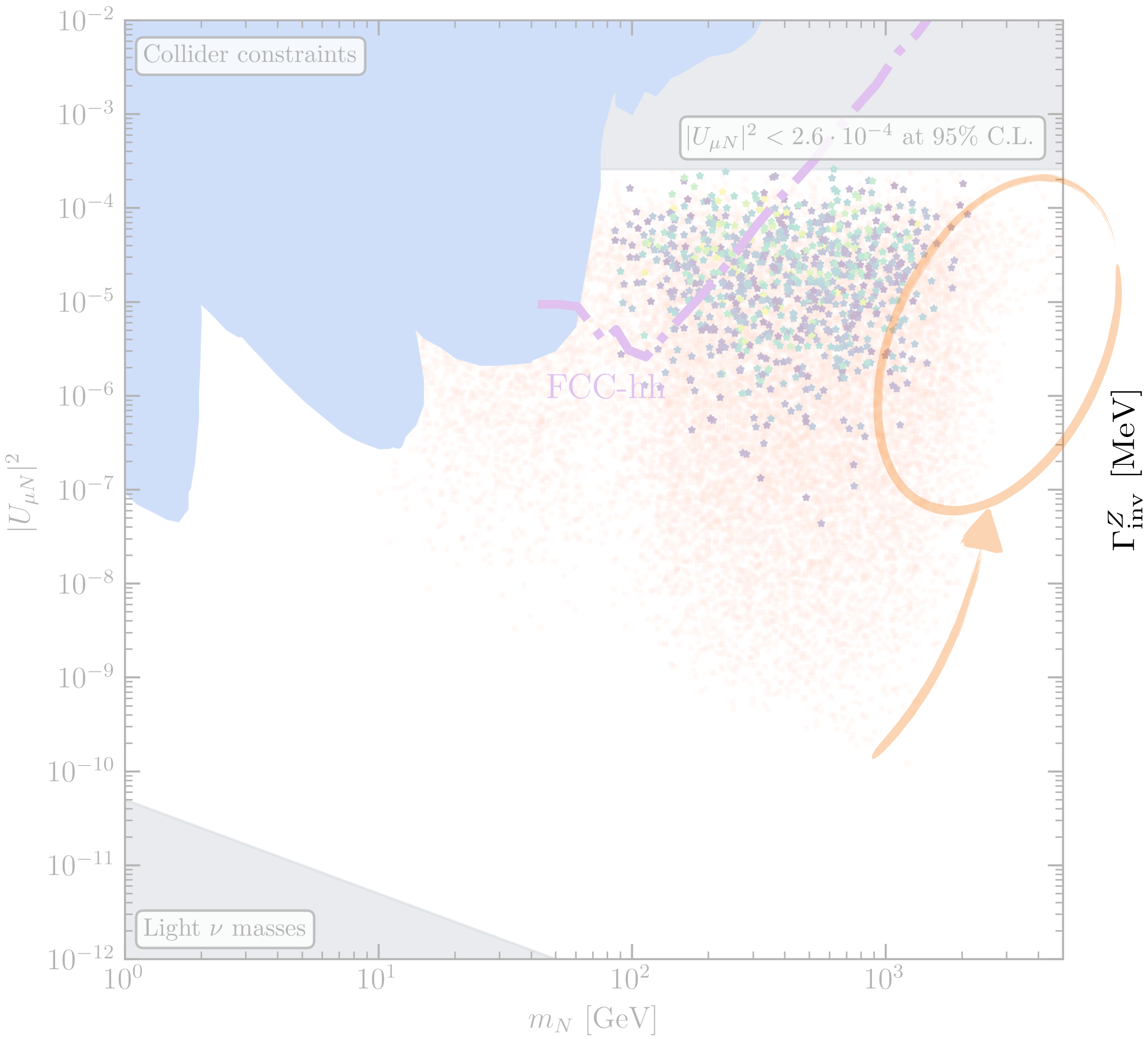
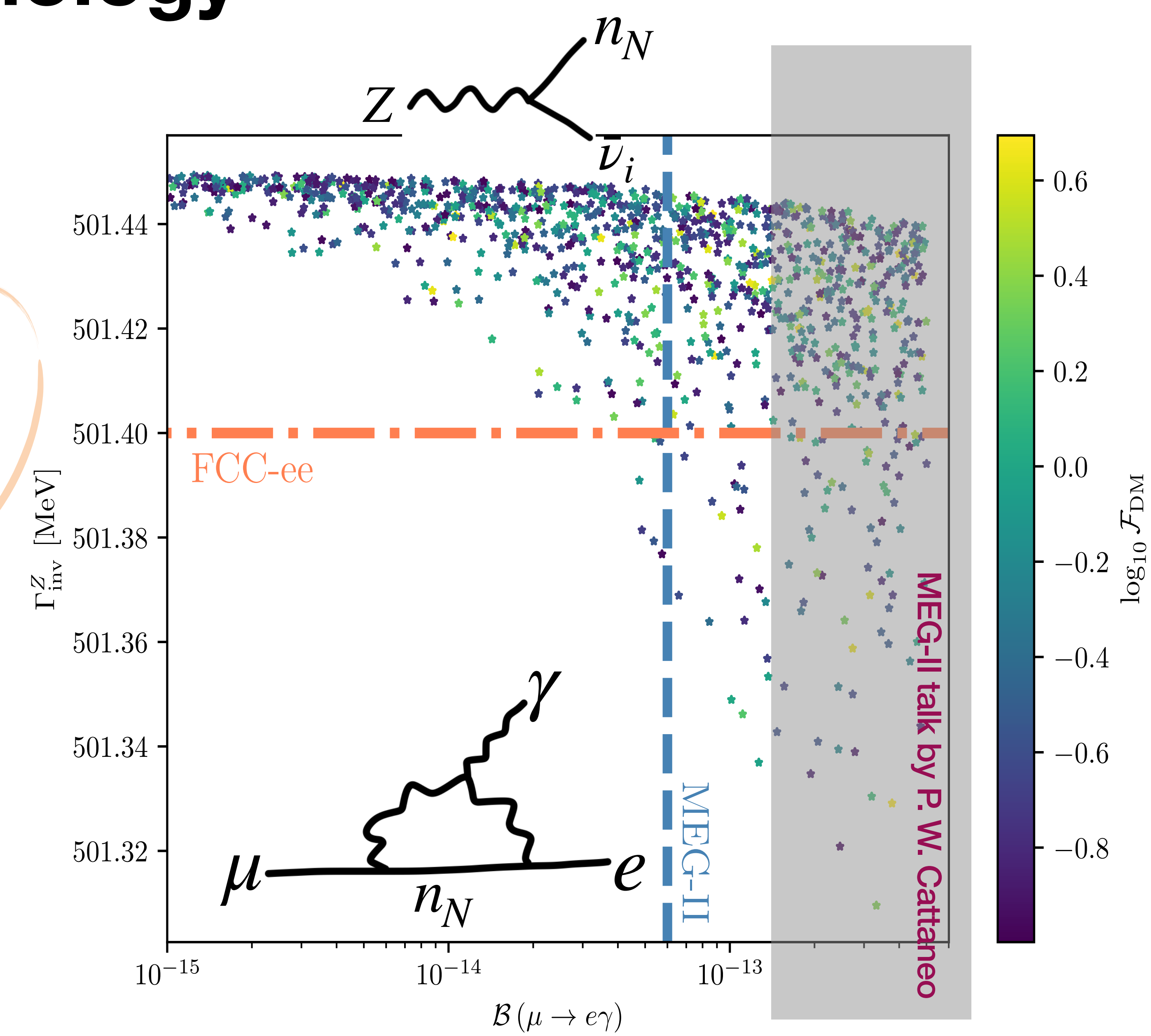




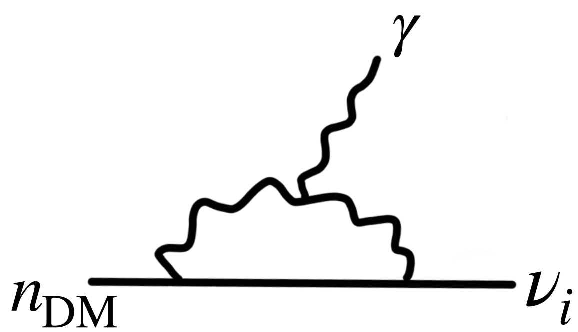
Flavor & EWPO best probes

Conclusions

Origin of ν masses

Type-I seesaw-mechanism

Sterile ν DM



We look for it through its mixing with SM neutrinos

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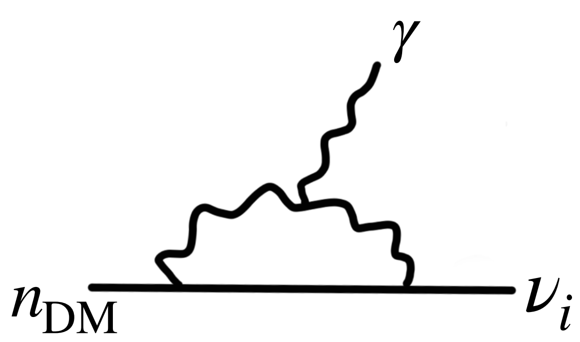

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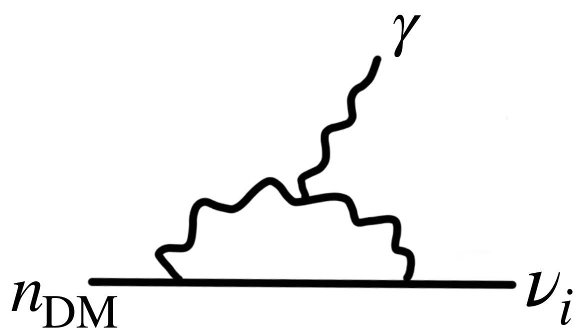

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DW mechanism

$T < 1\,\mathrm{GeV}$

Can only produce $\mathscr{F}_{\rm DM} \ll 1$

Conclusions

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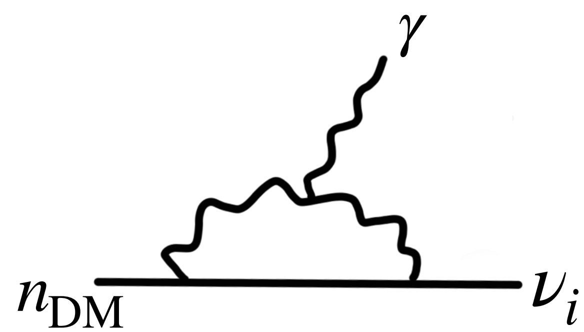

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Freeze-in production

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

Decays of $Z\,(W)$ do not produce DM

Conclusions

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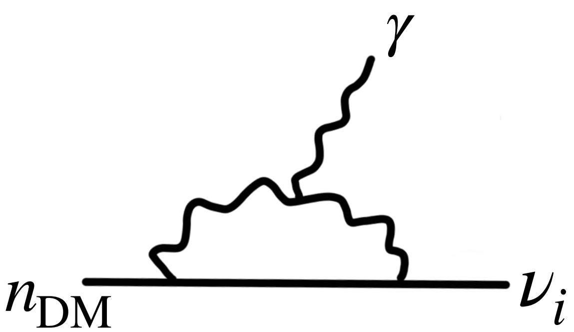


We look for it through its mixing with SM neutrinos

Can we produce enough DM only relying on neutrino mixing?

Freeze-in production

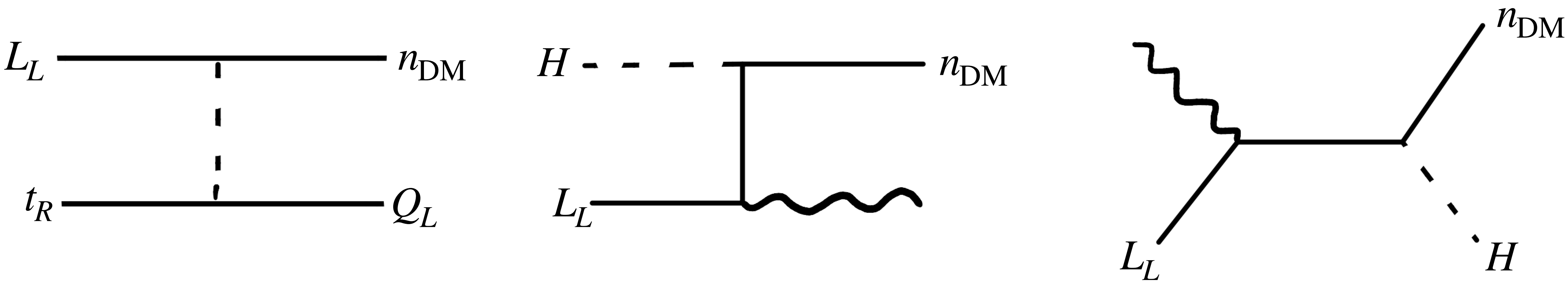
$T \sim 100\,\mathrm{GeV}$

Decays of $Z\,(W)$ do not produce DM

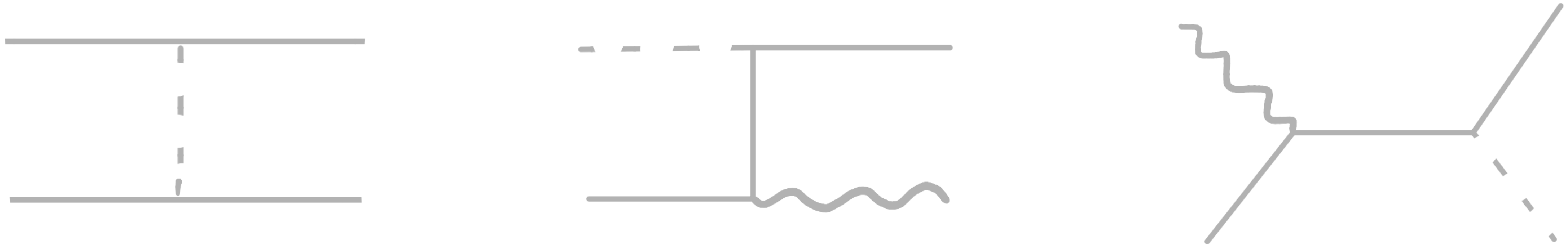
n_N decays are a promising production channel!

Outlook

- Account for production at $T > 160\,\mathrm{GeV}$: $2 \to 2$ processes, LPM

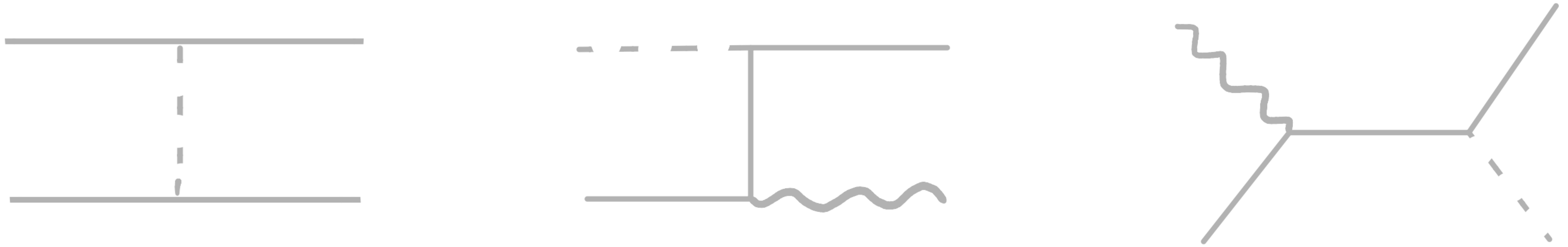


Outlook



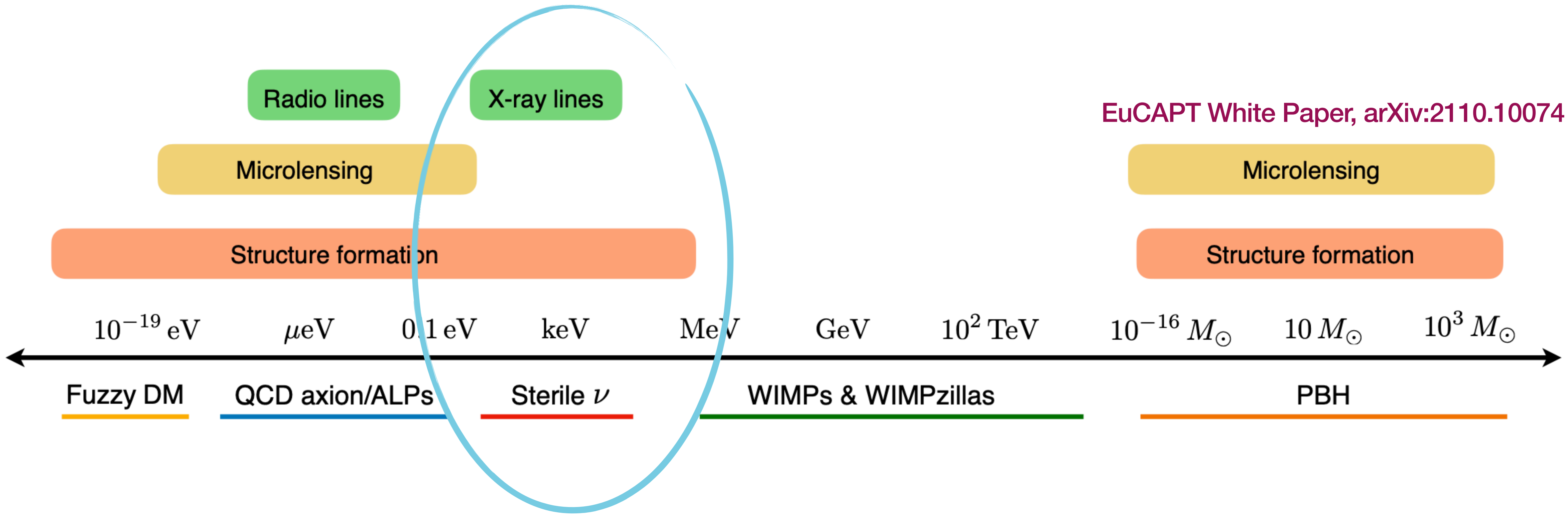
- Baryogenesis?

Outlook



- **Phenomenology**: strong correlations between DM searches and cLFV and EWPO probes

Outlook



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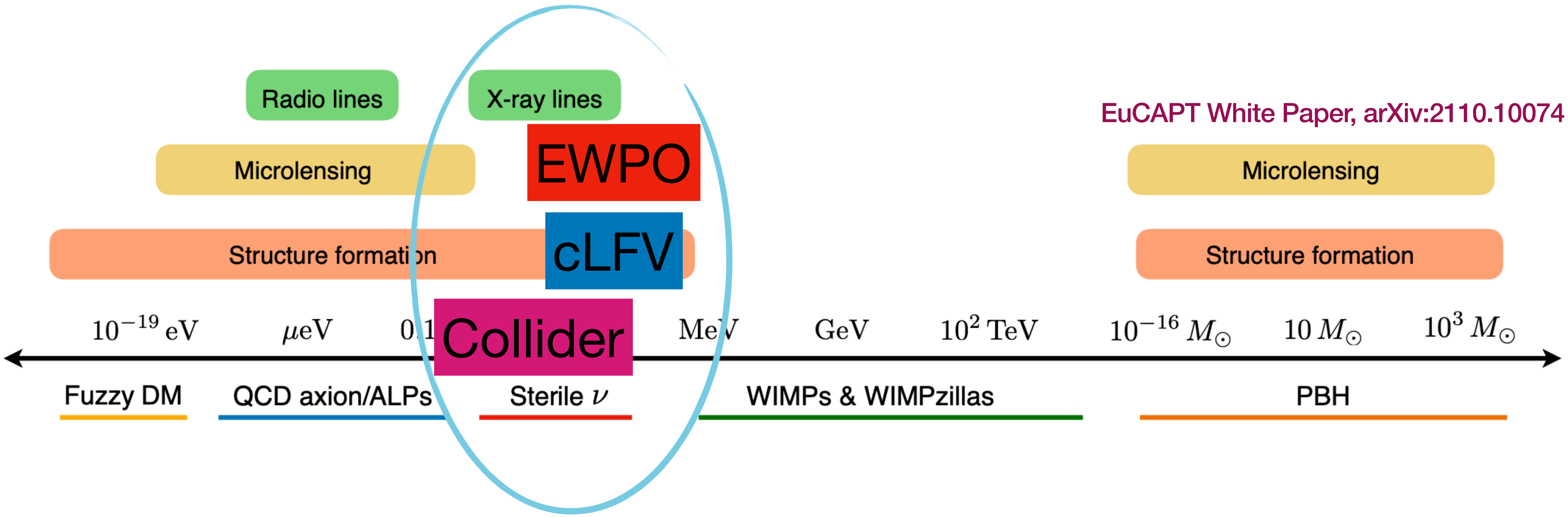

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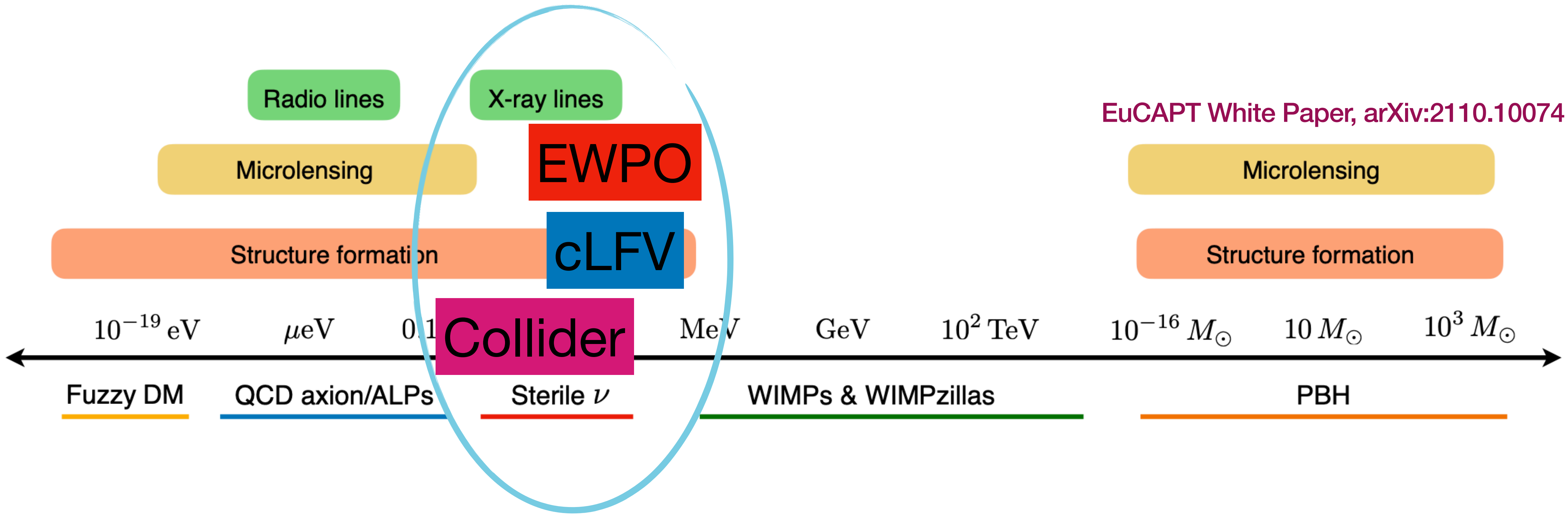


- **Phenomenology**: strong correlations between DM searches and cLFV and EWPO probes

Thank you!

Back up

Experimental probes

Z-pole

LFU

Observable
$M_W \simeq M_W^{\rm SM}\left(1+0.20\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$
$s_{\rm eff}^{2\ \rm Tev} \simeq s_{\rm eff}^{2\ \rm SM}\left(1-1.40\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$
$s_{\rm eff}^{2\ \rm LHC} \simeq s_{\rm eff}^{2\ \rm SM}\left(1-1.40\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$
$\Gamma_{\rm inv}^{\rm LHC} \simeq \Gamma_{\rm inv}^{\rm SM}\left(1-0.33\left(\eta_{ee}+\eta_{\mu\mu}\right)-1.33\eta_{\tau\tau}\right)$
$\Gamma_Z \simeq \Gamma_Z^{\rm SM}\left(1+1.08\left(\eta_{ee}+\eta_{\mu\mu}\right)-0.27\eta_{\tau\tau}\right)$
$\sigma_{\rm had}^0 \simeq \sigma_{\rm had}^{0\ \rm SM}\left(1+0.50\left(\eta_{ee}+\eta_{\mu\mu}\right)+0.53\eta_{\tau\tau}\right)$
$R_e \simeq R_e^{\rm SM}\left(1+0.27\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$
$R_\mu \simeq R_\mu^{\rm SM}\left(1+0.27\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$
$R_\tau \simeq R_\tau^{\rm SM}\left(1+0.27\left(\eta_{ee}+\eta_{\mu\mu}\right)\right)$
$R_{\mu e}^\pi \simeq \left(1-\left(\eta_{\mu\mu}-\eta_{ee}\right)\right)$
$R_{\tau\mu}^\pi \simeq \left(1-\left(\eta_{\tau\tau}-\eta_{\mu\mu}\right)\right)$
$R_{\mu e}^K \simeq \left(1-\left(\eta_{\mu\mu}-\eta_{ee}\right)\right)$
$R_{\mu e}^\tau \simeq \left(1-\left(\eta_{\mu\mu}-\eta_{ee}\right)\right)$
$R_{\tau\mu}^\tau \simeq \left(1-\left(\eta_{\tau\tau}-\eta_{\mu\mu}\right)\right)$

$\left\|V_{ud}^\beta\right\| \simeq \sqrt{1-\|V_{us}\|^2}\left(1+\eta_{\mu\mu}\right)$
$\left\|V_{us}^{\tau\to K\nu}\right\| \simeq \|V_{us}\|\left(1+\eta_{ee}+\eta_{\mu\mu}-\eta_{\tau\tau}\right)$
$\left\|V_{us}^{\tau\to K,\pi}\right\| \simeq \|V_{us}\|\left(1+\eta_{\mu\mu}\right)$
$\left\|V_{us}^{K_L\to\pi e\nu}\right\| \simeq \|V_{us}\|\left(1+\eta_{\mu\mu}\right)$
$\left\|V_{us}^{K_L\to\pi\mu\nu}\right\| \simeq \|V_{us}\|\left(1+\eta_{ee}\right)$
$\left\|V_{us}^{K_S\to\pi e\nu}\right\| \simeq \|V_{us}\|\left(1+\eta_{\mu\mu}\right)$
$\left\|V_{us}^{K_S\to\pi\mu\nu}\right\| \simeq \|V_{us}\|\left(1+\eta_{ee}\right)$
$\left\|V_{us}^{K^\pm\to\pi e\nu}\right\| \simeq \|V_{us}\|\left(1+\eta_{\mu\mu}\right)$
$\left\|V_{us}^{K^\pm\to\pi\mu\nu}\right\| \simeq \|V_{us}\|\left(1+\eta_{ee}\right)$
$\left\|\frac{V_{us}}{V_{ud}}\right\|^{K,\pi\to\mu\nu} \simeq \frac{\|V_{us}\|}{\sqrt{1-\|V_{us}\|^2}}$

M. Blennow *et al.*, arXiv:2306.01040

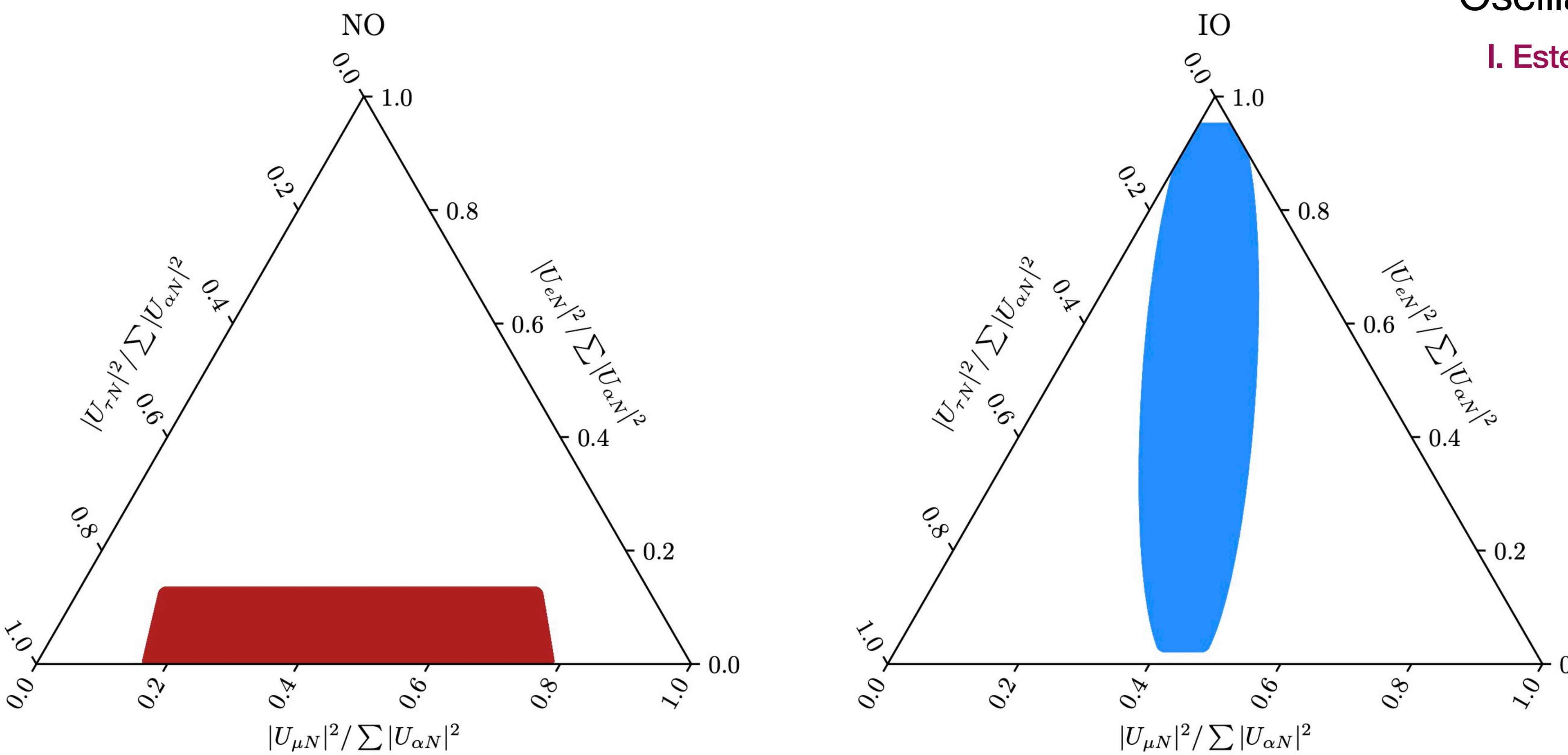
CKM-unitarity

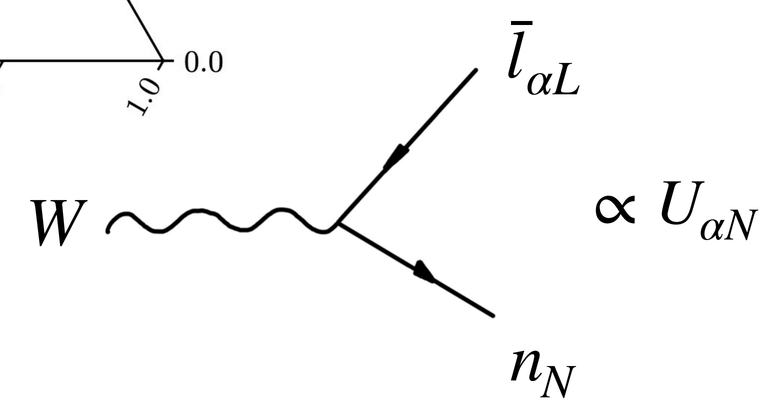
Massive neutrinos

Type-I seesaw

Oscillation data from NuFIT 6.0

I. Esteban *et al.*, arXiv:2410.05380





Need **at least 2** N_R to explain **oscillation data**

A. Ibarra & G. Ross, arXiv:hep-ph/0312138

Neutrino dark matter

Production mechanism

Temperatures $T \lesssim 1\,\mathrm{GeV}$

Dodelson-Widrow mechanism

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

DM abundance from ν **oscillations** and **collisions** in the plasma

$$\Omega_{\mathrm{DM}} h^2 \propto \left| \theta_{\alpha \mathrm{DM}} \right|^2 m_{\mathrm{DM}}$$

A. Merle, A. Schneider & M. Totzauer, arXiv:1512.05369

At most it can produce $\mathscr{F}_{\mathrm{DM}} = \dfrac{\Omega_{\mathrm{DM}} h^2}{\Omega_{\mathrm{DM}}^{\mathrm{obs}} h^2} \simeq 0.1$

Irreducible contribution

Possible solutions:

Resonant production in presence of L-asymmetry

X. Shi & G. M. Fuller, arXiv:astro-ph/9810076
M. Shaposhnikov, arXiv:0804.4542
J. Ghiglieri & M. Laine, arXiv:2004.10766

Introduction of ν-scalar interactions

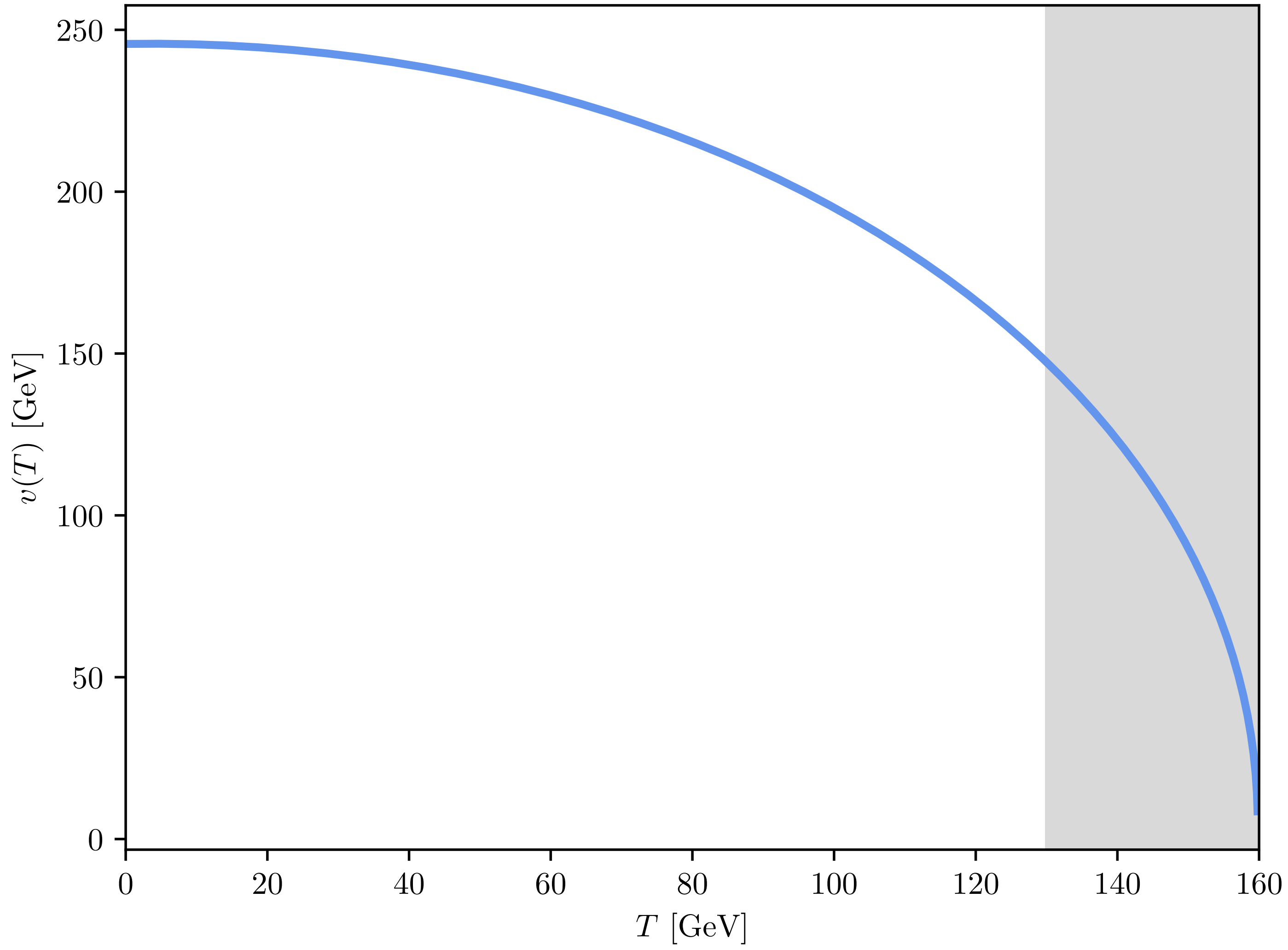
A. de Gouvêa *et al.*, arXiv:1910.04901
T. Bringmann *et al.*, arXiv:2206.10630

EW symmetry breaking

2-loop Higgs potential

M. Quiros, arXiv:hep-ph/9901313

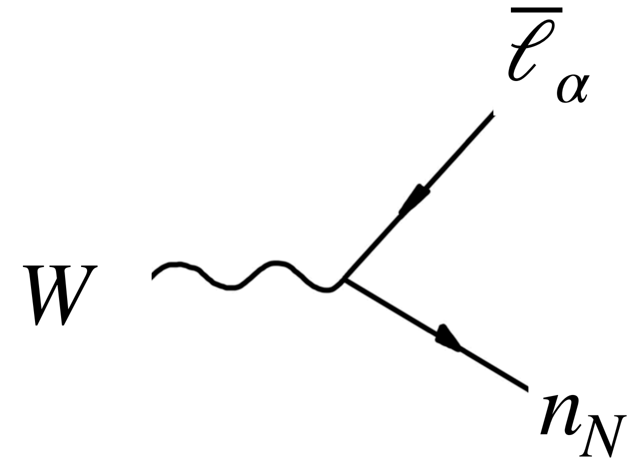
A. Abada, G. Arcadi, M. Lucente & **SRA**, arXiv:2503.20017



Optical Theorem in TFT

How does a species approach equilibrium?

Example



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

Γ represents the rate at which n_N approaches equilibrium

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

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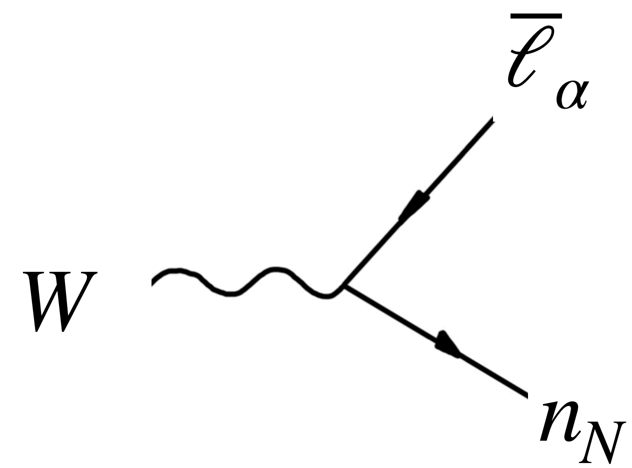

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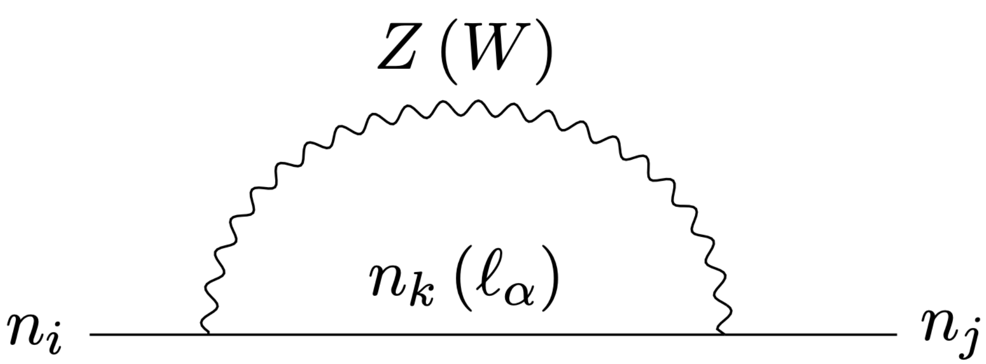
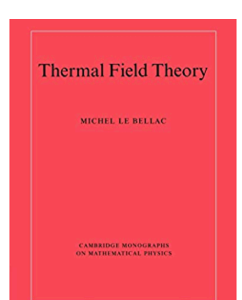


Le Bellac, Thermal Field Theory (1996)
H. Weldon, Phys. Rev. D (1983)



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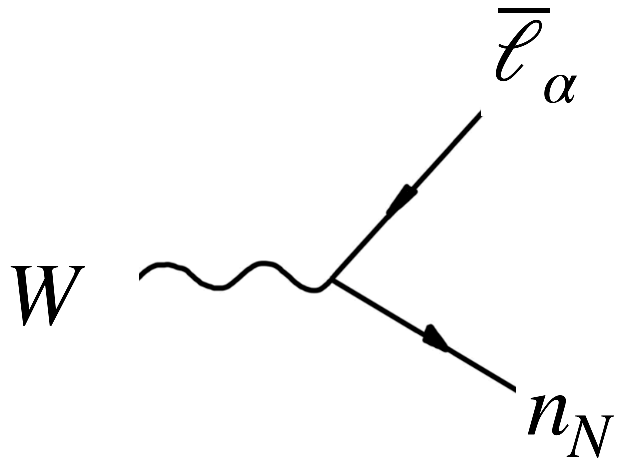

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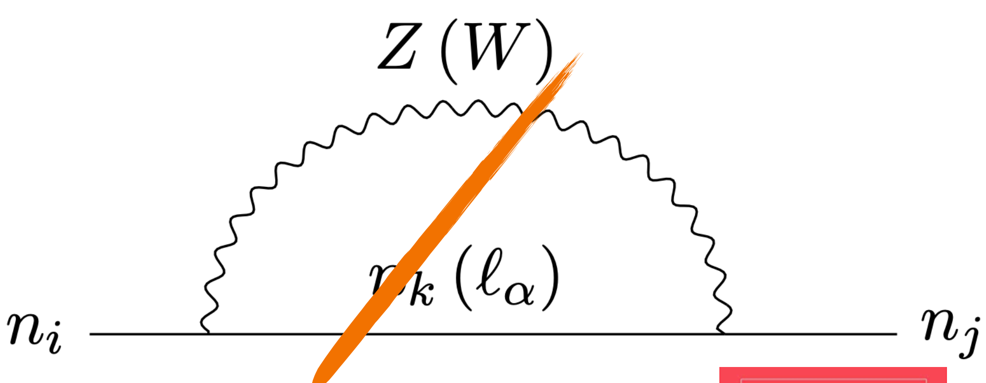

$$\mathrm{Im}\Sigma_{ii} \propto \int \frac{d^3q}{(2\pi)^3} \frac{|\mathcal{M}|^2}{2E_\ell 2E_W} \left[f_B(E_W) + f_F(E_\ell) \right] \delta(p_0 + E_\ell - E_W)$$

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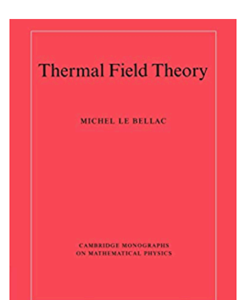

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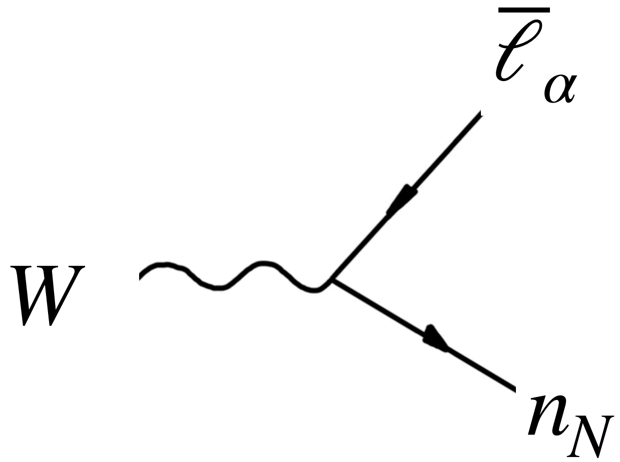

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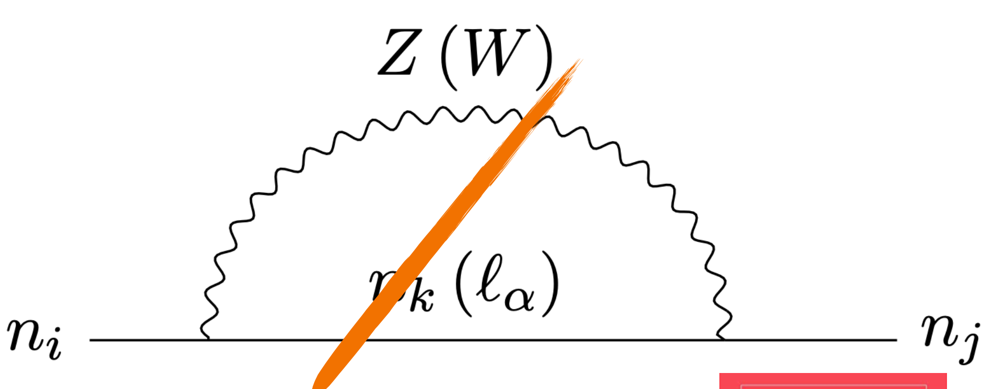

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ReΣ changes the dispersion relations

$$E^2 - p^2 - M^2 + (E - hp)\Sigma = 0$$

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