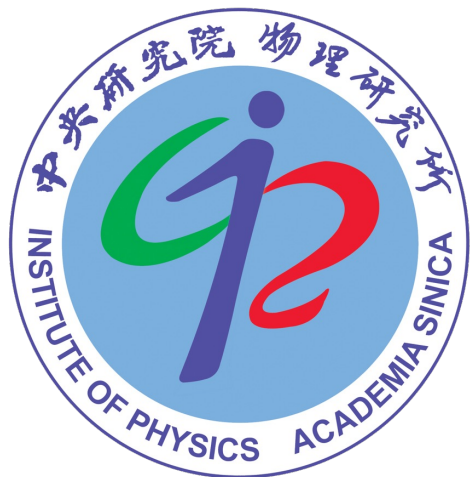




TeV-scale unification of light dark matter & neutrino mass

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(Academia Sinica)

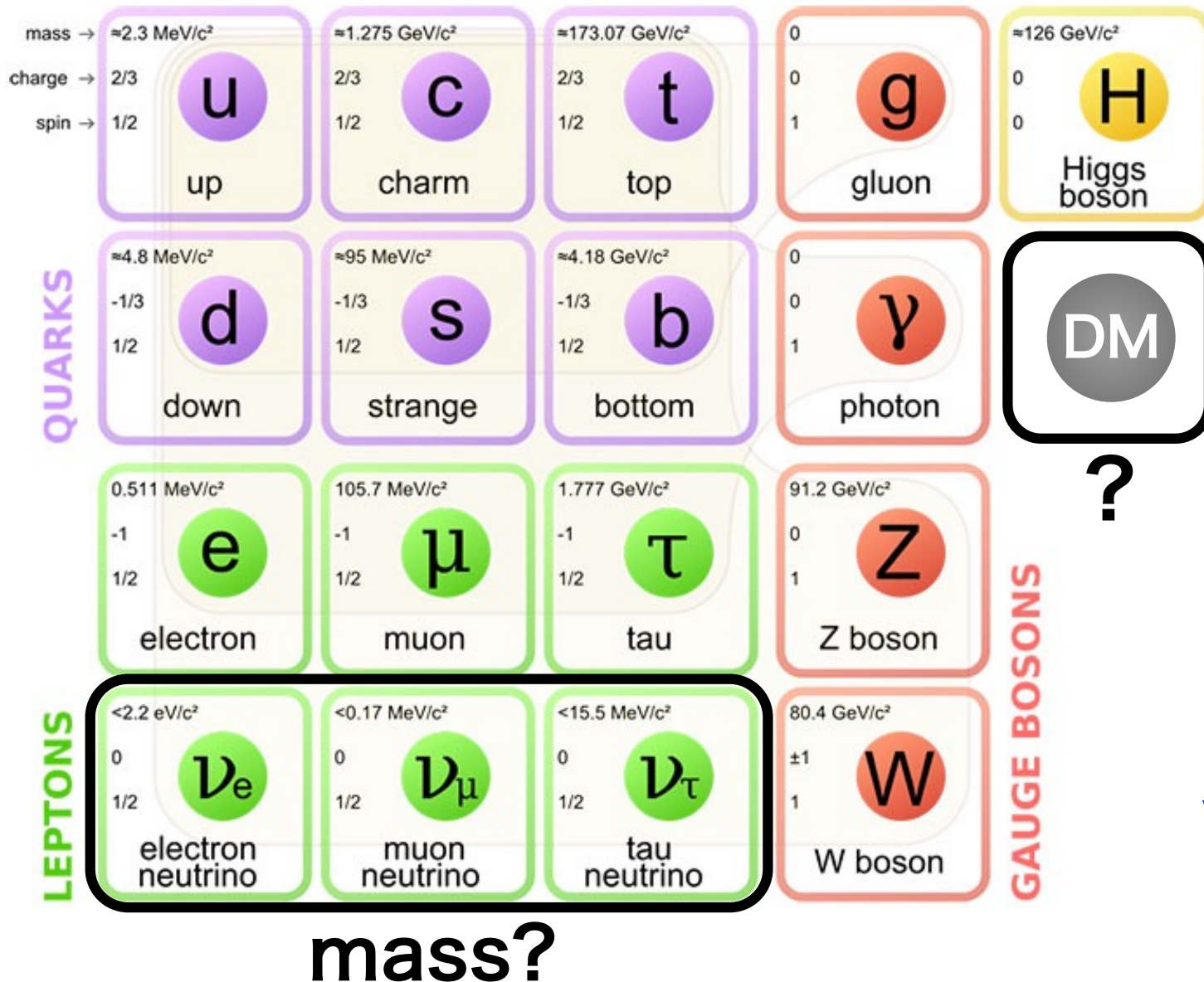
arXiv : 2603.05200

In collaboration with C.W. Chiang (NTU) & V.Q. Tran (NCTS)

28/Jul/2026

The standard model of particle physics 1/18

The Standard Model (SM) is GOOD, but



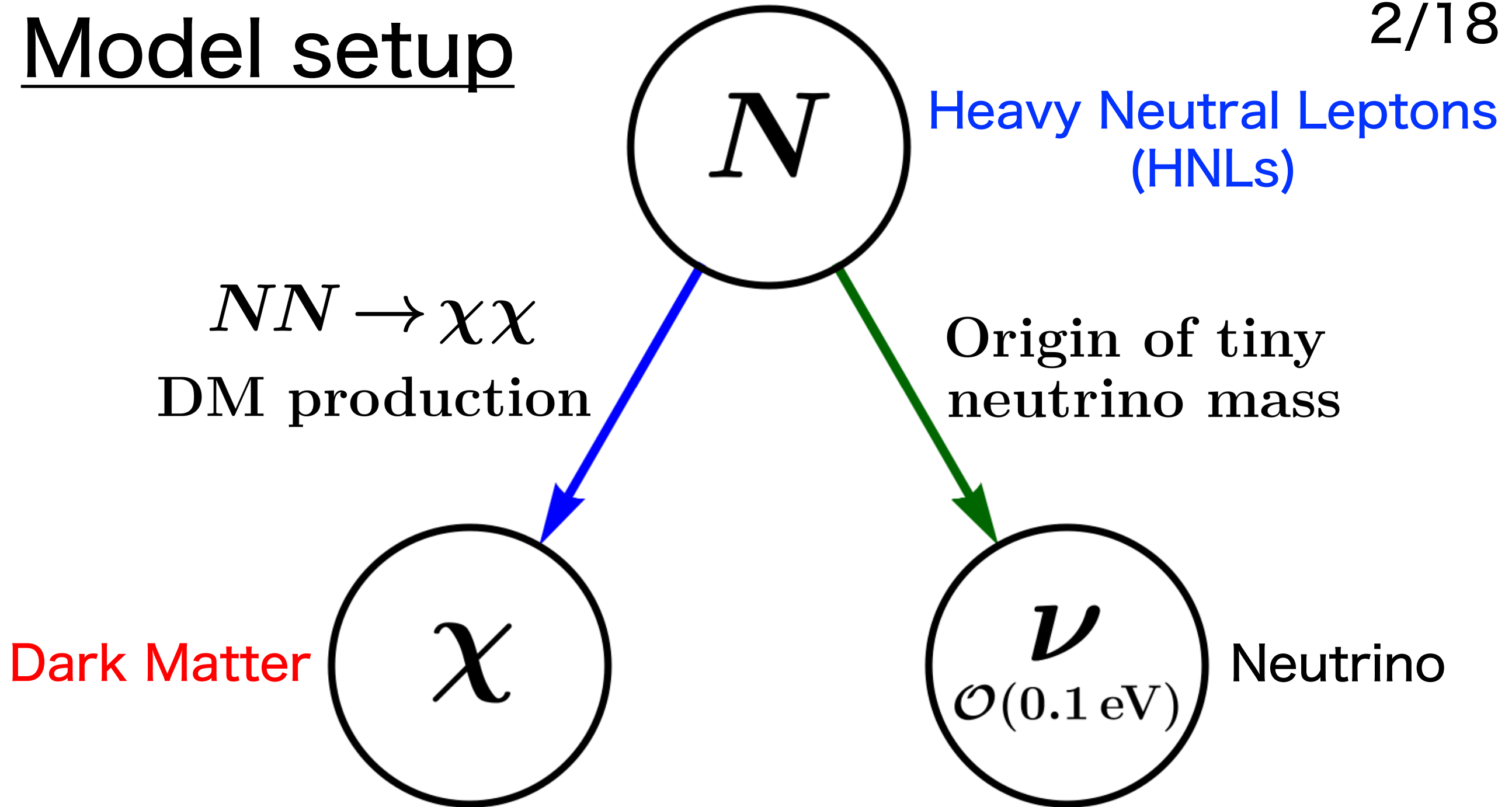
Unsolved problems

- Dark matter (DM)
- Neutrino mass
- Baryon asymmetry
- Strong CP problem
- Dark energy
-

We need new physics beyond the SM !!!

Model setup

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Particle content

global lepton # symmetry		e_{Rj}	E_{Lj}	H		N_{Rj}	S_{Lj}	ϕ
	$SU(2)_L$	1	2	2		1	1	1
	$U(1)_Y$	-1	$-1/2$	$1/2$		0	0	0
	$U(1)_L$	1	1	0		1	2	1
	spin	$1/2$	$1/2$	0		$1/2$	$1/2$	0

Yukawa sector

$$\begin{aligned} \mathcal{L}_Y = & - \left(Y_D\right)_{jk} \overline{E_{Lj}} \tilde{H} N_{Rk} - \left(Y_N\right)_{jk} \overline{S_{Lj}} N_{Rk} \phi \\ & - \frac{1}{2} \left(\mu_S\right)_{jk} \overline{S_{Lj}} S^c_{Lk} + \text{h.c.} \end{aligned}$$

U(1)_L explicit breaking term

Scalar potential

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$$\mathcal{V} = -\frac{1}{2}\mu_h^2|H|^2 - \frac{1}{2}\mu_\phi^2|\phi|^2 + \frac{1}{2}\lambda_h|H|^4 \\ + \frac{1}{2}\lambda_\phi|\phi|^4 + \lambda_{h\phi}|H|^2|\phi|^2 - \frac{1}{\sqrt{2}}\kappa_\phi^3\text{Re}(\phi)$$

U(1)_L explicit breaking term

Scalar mass spectrum $\lambda_{h\phi} \rightarrow 0$ (enhanced Poincaré symmetry)

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_h + h) \end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}(v_\phi + \rho + i\chi)$$

$$m_\rho^2 = \lambda_\phi v_\phi^2 + m_\chi^2, \quad m_\chi^2 = \frac{\kappa_\phi^3}{2v_\phi}$$

pseudo Nambu-Goldstone Boson DM (pNGB DM)

Scalar interactions

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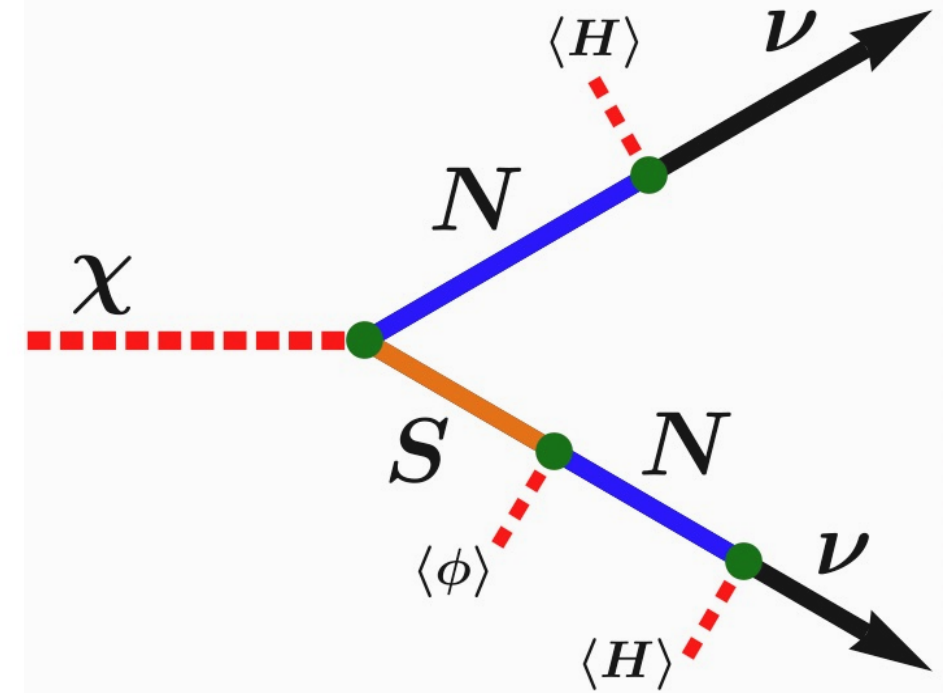
$$\mathcal{V} \supset \frac{1}{2} \lambda_\phi v_\phi \rho^3 + \frac{1}{2} \lambda_\phi v_\phi \rho \chi^2 + \frac{1}{4} \lambda_\phi \rho^2 \chi^2$$

- accidental Z_2 symmetry : $\rho \rightarrow \rho$, $\chi \rightarrow -\chi$
(C-symmetry : $\phi \rightarrow \phi^*$)

Decaying pNGB DM

- $\mathcal{L}_Y \supset -Y_N \overline{S}_L N_R \phi$
breaks C-symmetry.

- $\Gamma_{\chi \rightarrow \nu\nu} \propto \left(\frac{m_\nu}{v_\phi} \right)^2$ (long-lived DM)



Neutrino mass (inverse seesaw mechanism)

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$$\mathcal{L}_Y \supset -m_D \overline{\nu}_L N_R - m_N \overline{S}_L N_R - \frac{1}{2} \mu_S \overline{S}_L S_L^c = -\frac{1}{2} \overline{\Psi}_f^c \mathcal{M}_f \Psi_f$$

- fermion mass mixing matrix (one generation)

$$\mathcal{M}_f = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & m_N \\ 0 & m_N & \mu_S \end{pmatrix} \quad m_D = \frac{1}{\sqrt{2}} Y_D v_h, \quad m_N = \frac{1}{\sqrt{2}} Y_N v_\phi$$

- unitary mixing matrix

$$\mathcal{U} \simeq \begin{pmatrix} 1 - \xi^2/2 & i\xi/\sqrt{2} & \xi/\sqrt{2} \\ \xi\omega & -i/\sqrt{2} & 1/\sqrt{2} \\ -\xi & i/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \quad \xi \equiv \frac{m_D}{m_N} \quad \omega \equiv \frac{\mu_S}{m_N}$$

flavor basis

$$\begin{pmatrix} \nu_1 \\ N_1 \\ N_2 \end{pmatrix} = \mathcal{U} \begin{pmatrix} \nu_L \\ N_R^c \\ S_L \end{pmatrix}$$

mass eigenstates

Neutrino mass (inverse seesaw mechanism)

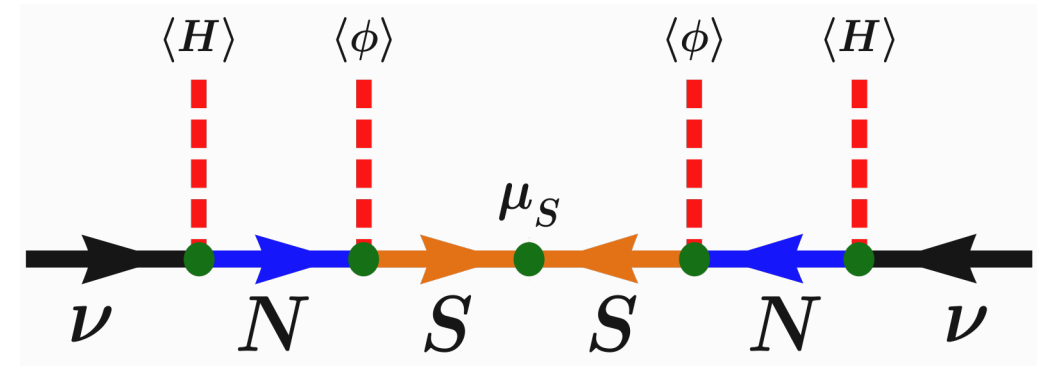
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$$\mathcal{L}_Y \supset -m_D \overline{\nu}_L N_R - m_N \overline{S}_L N_R - \frac{1}{2} \mu_S \overline{S}_L S_L^c = -\frac{1}{2} \overline{\Psi}_f^c \mathcal{M}_f \Psi_f$$

- neutrino mass eigenvalue (one generation)

$$m_\nu \simeq \mu_S \frac{m_D^2}{m_N^2} \quad (\mu_S \ll m_D \ll m_N)$$

$$\simeq 0.1 \text{ eV} \left(\frac{\mu_S}{1 \text{ keV}} \right) \left(\frac{m_D}{10 \text{ GeV}} \right)^2 \left(\frac{m_N}{1 \text{ TeV}} \right)^{-2}$$



- DM-HNL interactions

$$\mathcal{L}_Y \supset i \frac{m_\nu}{v_\phi} \overline{\nu}_M \gamma^5 \nu_M \chi - \frac{m_N}{2v_\phi} \sum_{k=1,2} \overline{N}_{kM} (\rho + i\gamma^5 \chi) N_{kM}$$

$$\text{Majorana fermion : } \nu_M = \nu + \nu^c \quad N_{kM} = N_k + N_k^c$$

Lifetime of dark matter

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- pNGB DM mainly decays into a pair of neutrinos $m_N \gg m_\chi$

$$\Gamma_\chi \simeq \Gamma_{\chi \rightarrow \nu_M \nu_M} = \frac{m_\nu^2}{4\pi v_\phi^2} m_\chi$$

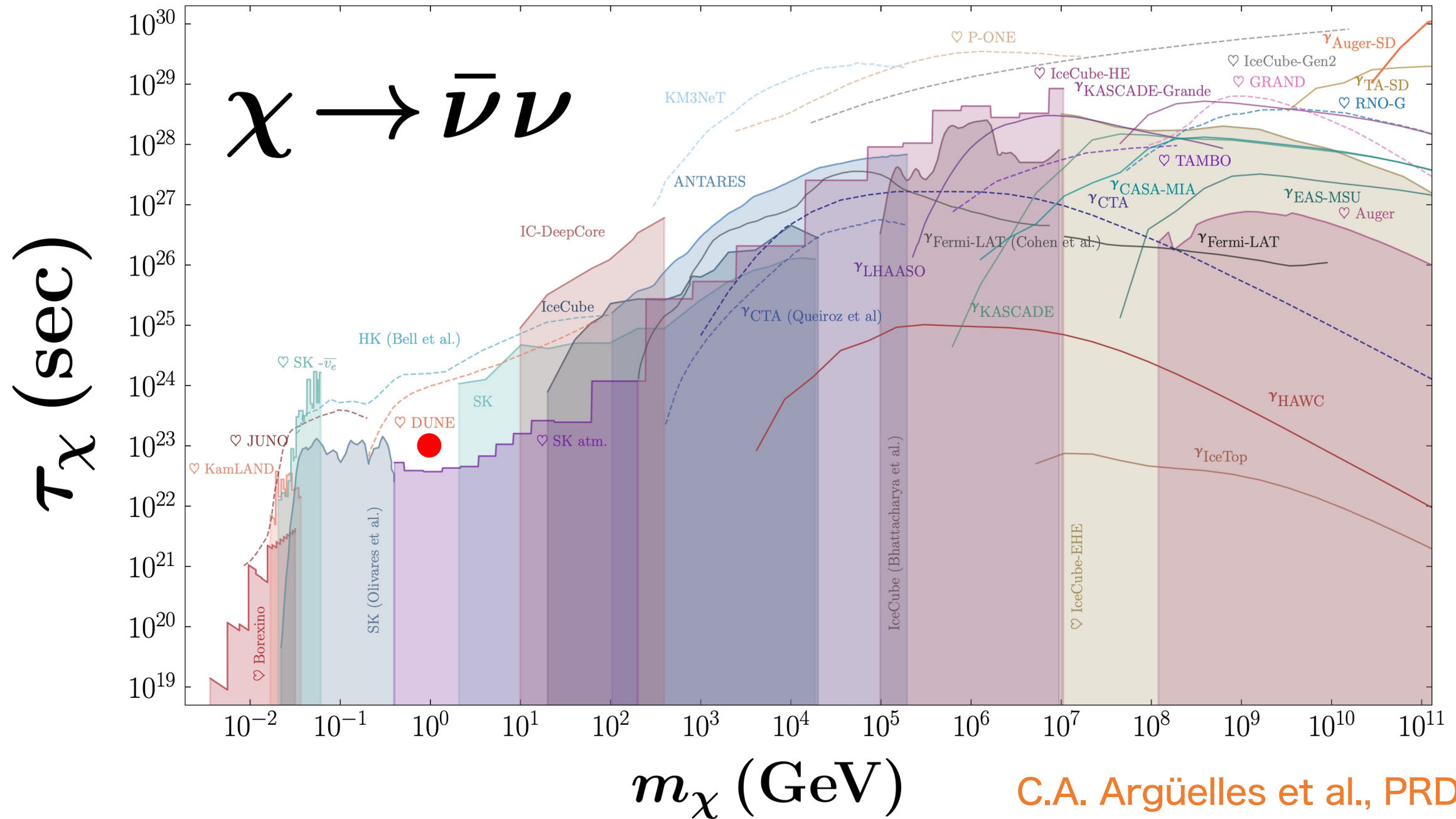
- This width is remarkably small due to the **tiny neutrino mass** and a **large symmetry-breaking scale**, e.g.,

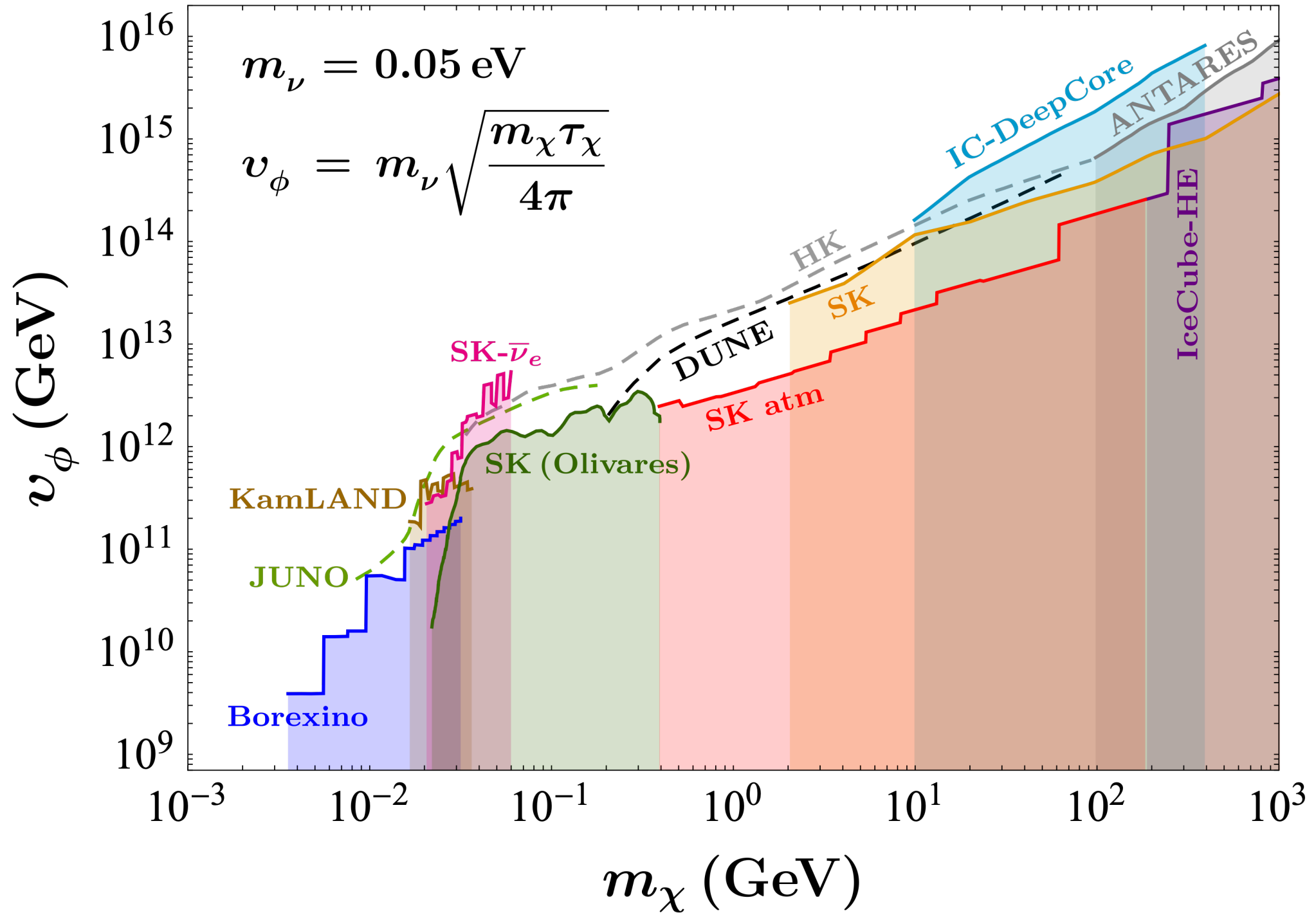
$$\tau_\chi \simeq 10^{23} \text{ sec} \left(\frac{m_\nu}{0.1 \text{ eV}} \right)^2 \left(\frac{m_\chi}{1 \text{ GeV}} \right) \left(\frac{v_\phi}{10^{13} \text{ GeV}} \right)^{-2}$$

which satisfies the experimental lower bound on DM lifetime from Super-Kamiokande.

Lower bound on DM lifetime

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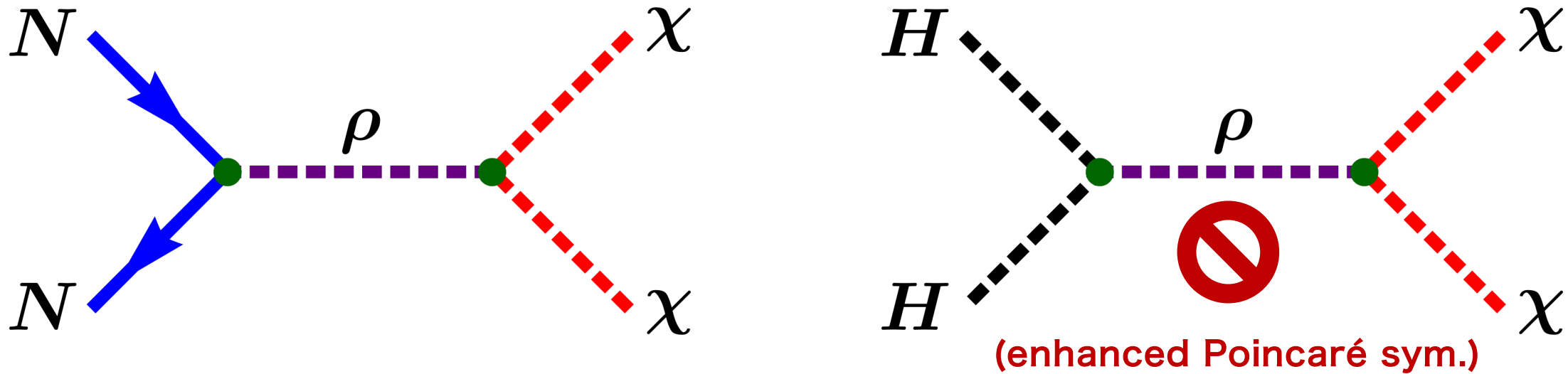




Freeze-in production of pNGB DM

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- DM can be produced **non-thermally** from the Higgs boson and HNLs via the **freeze-in mechanism**.
- HNLs can reach thermal equilibrium with the SM plasma through a sizable Y_D and $T_R \gg m_N$ (IR freeze-in).



$$\mathcal{L}_{\text{ann}} = -\lambda_{h\phi} v_{\phi} (H^{\dagger} H) \rho - \frac{m_N}{2v_{\phi}} \bar{N} N \rho - \frac{1}{2} \lambda_{\phi} v_{\phi} \rho \chi^2$$

Boltzmann equation

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- We assume $\lambda_{h\phi} \rightarrow 0$ and $m_\rho \gg m_N \gg m_\chi$

Bessel function

$$\frac{\partial n_\chi}{\partial t} + 3\mathcal{H}n_\chi = \mathcal{R}_{NN \rightarrow \chi\chi} = \frac{\lambda_\phi^2 m_N^2 T^2}{128\pi^5} \int_{2x_N}^{\infty} dz \frac{Z_N^3 Z_\chi K_1(z)}{(z^2 - x_\rho^2)^2 + x_\rho^2 \gamma_\rho^2}$$

reaction rate

$$Z_a = (z^2 - 4x_a^2)^{1/2} \quad x_a = m_a/T \quad \gamma_\rho = \Gamma_\rho/T$$

- In terms of comoving number density $Y_\chi = n_\chi/s$

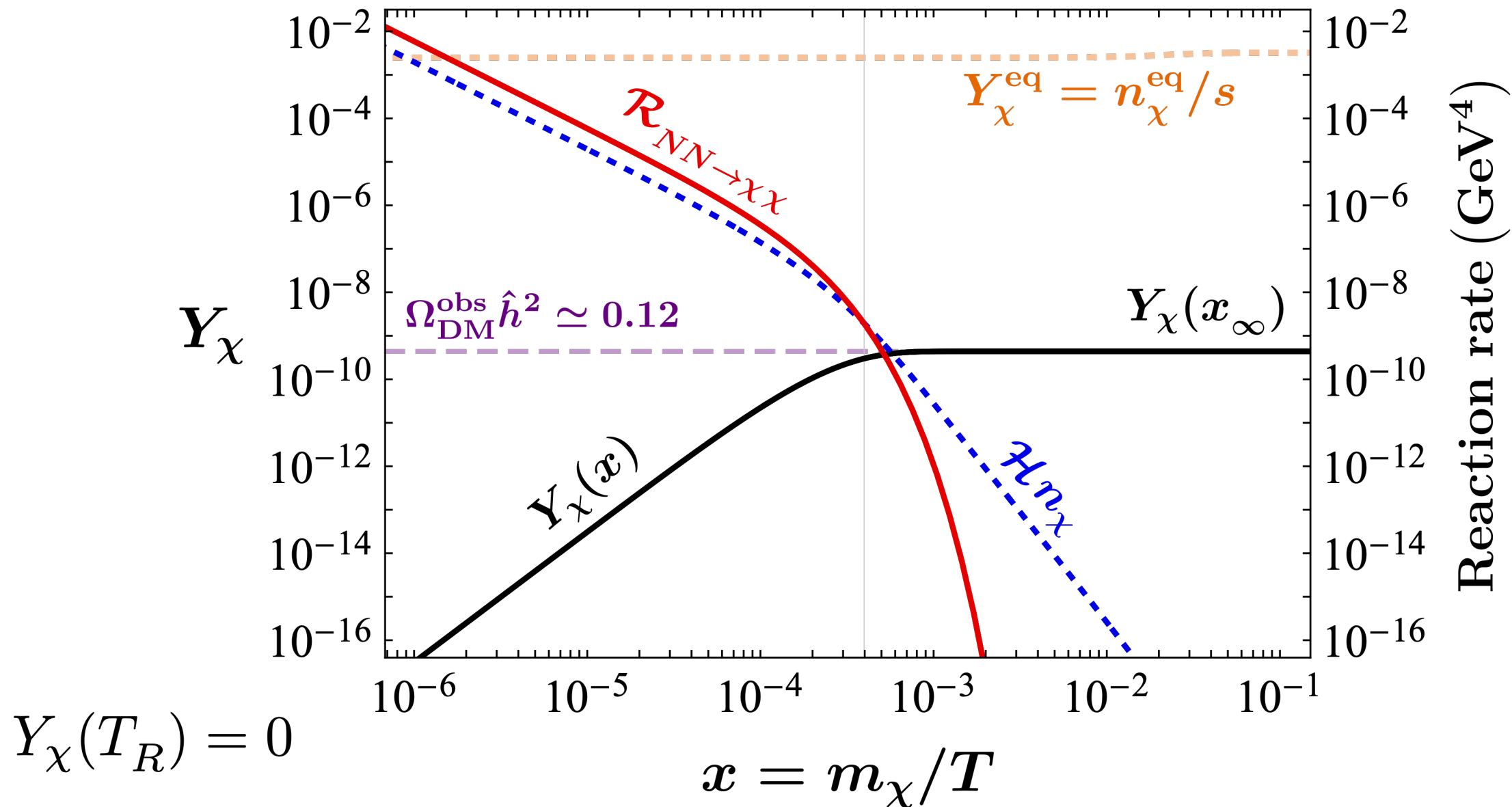
$$\frac{\partial Y_\chi}{\partial x} = \frac{135\sqrt{10} m_{\text{Pl}} x^4 \mathcal{R}_{NN \rightarrow \chi\chi}(x)}{2\pi^3 g_{*s}(x) \sqrt{g_*(x)} m_\chi^5}$$

$$x = m_\chi/T \quad \mathcal{H} = \sqrt{\pi^2 g_*(T)/90} (T^2/m_{\text{Pl}}) \quad s = 2\pi^2 g_{*s}(T) T^3/45$$

Evolution of DM number density

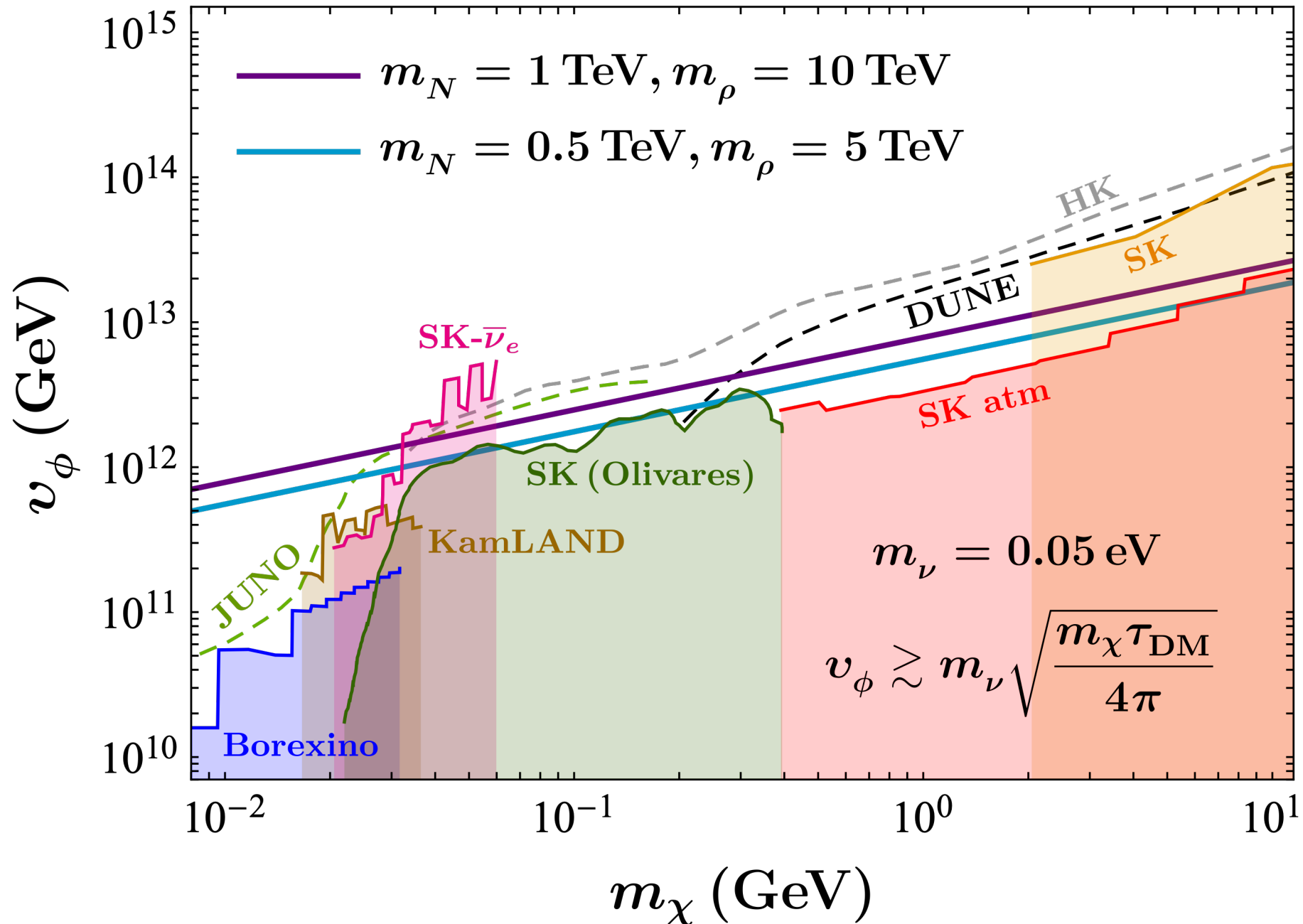
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$$(m_\chi, m_N, m_\rho, v_\phi) = (1, 10^3, 10^4, 8 \times 10^{12}) \text{ GeV}$$



Sub-GeV DM

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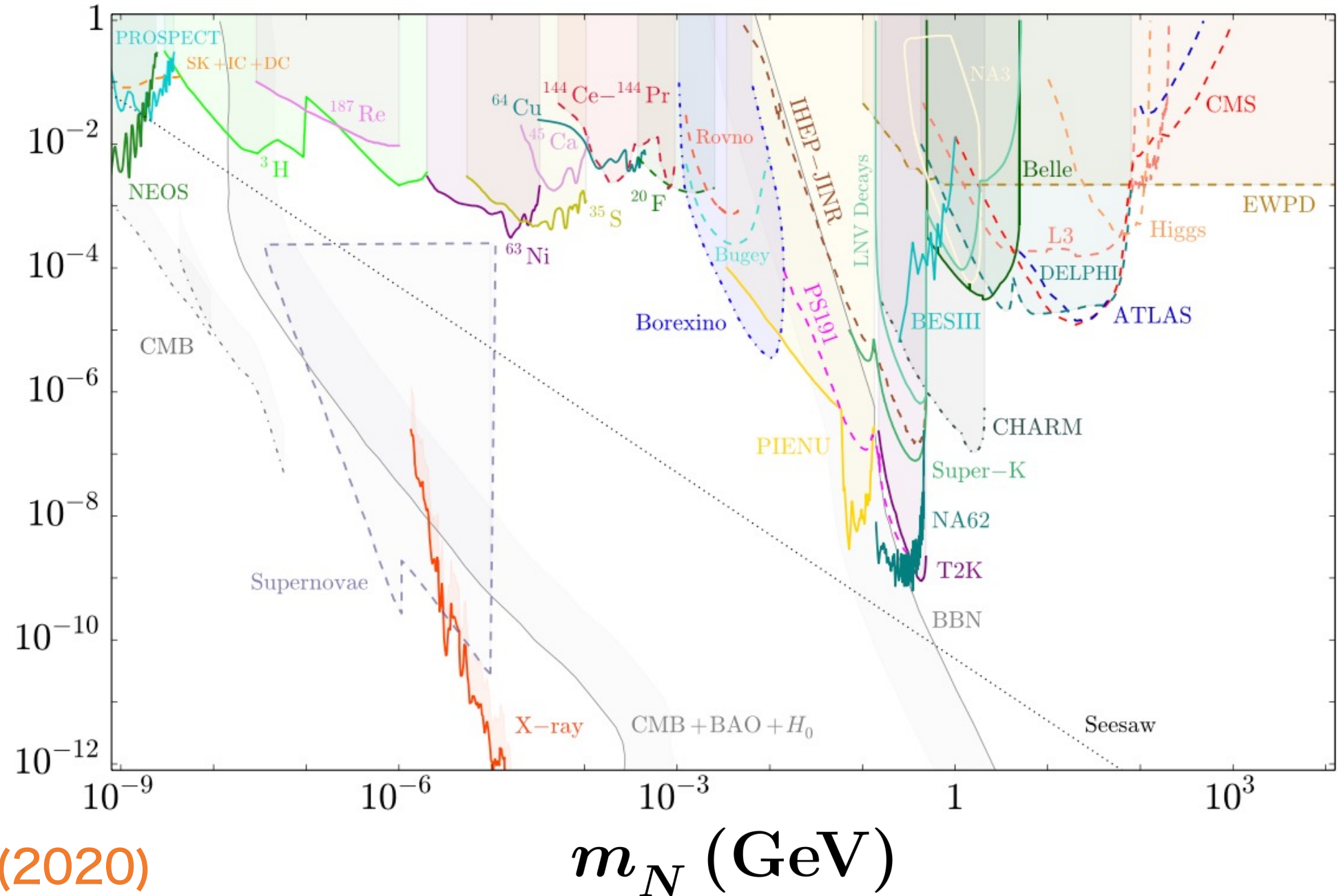


Collider-accessible TeV-scale HNLs

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- Current searches

$$\xi^2 = |V_{eN}|^2 = \left(\frac{m_D}{m_N} \right)^2$$



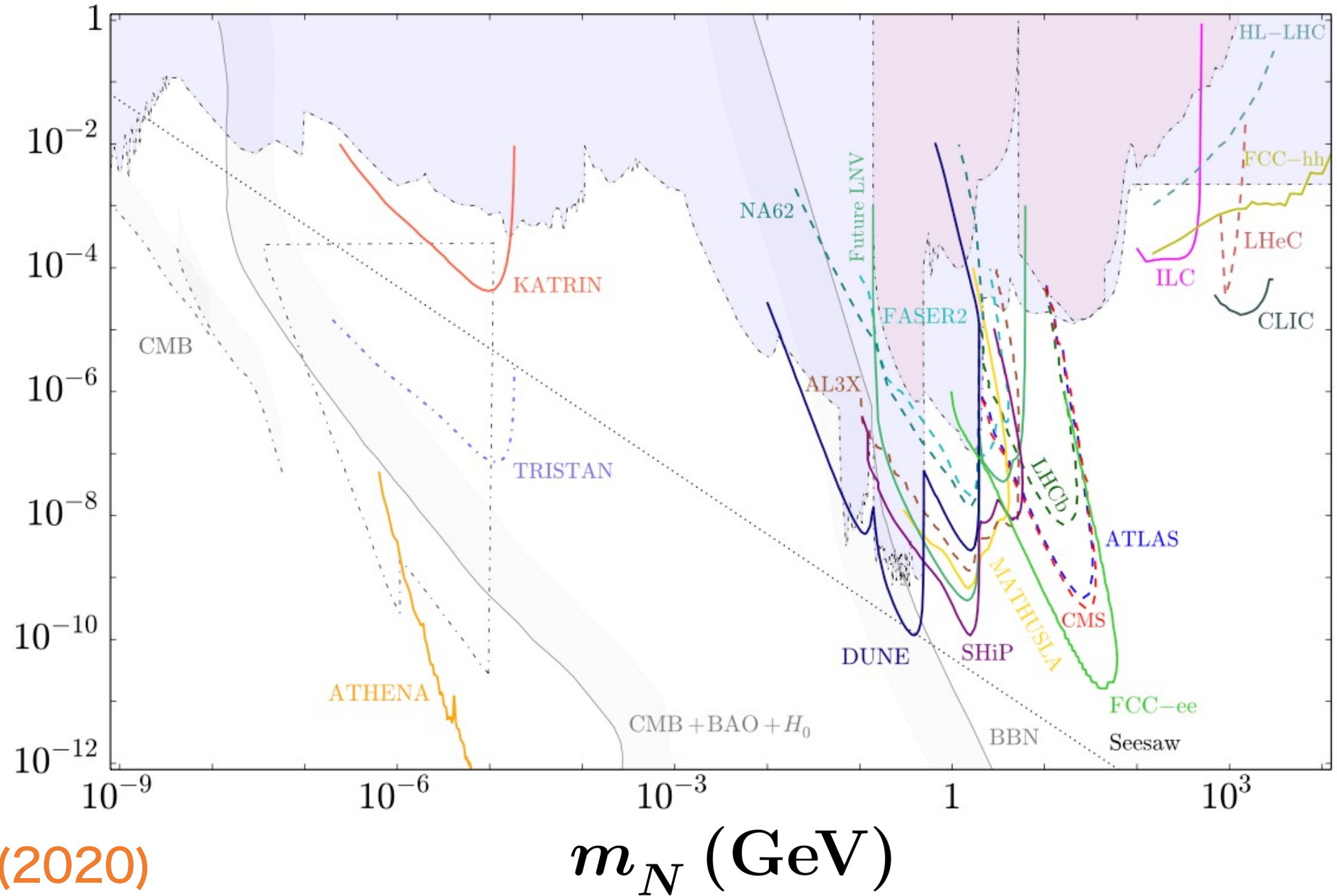
C. Bolton et al. (2020)

Collider-accessible TeV-scale HNLs

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- Future searches

$$\xi^2 = |V_{eN}|^2 = \left(\frac{m_D}{m_N}\right)^2$$



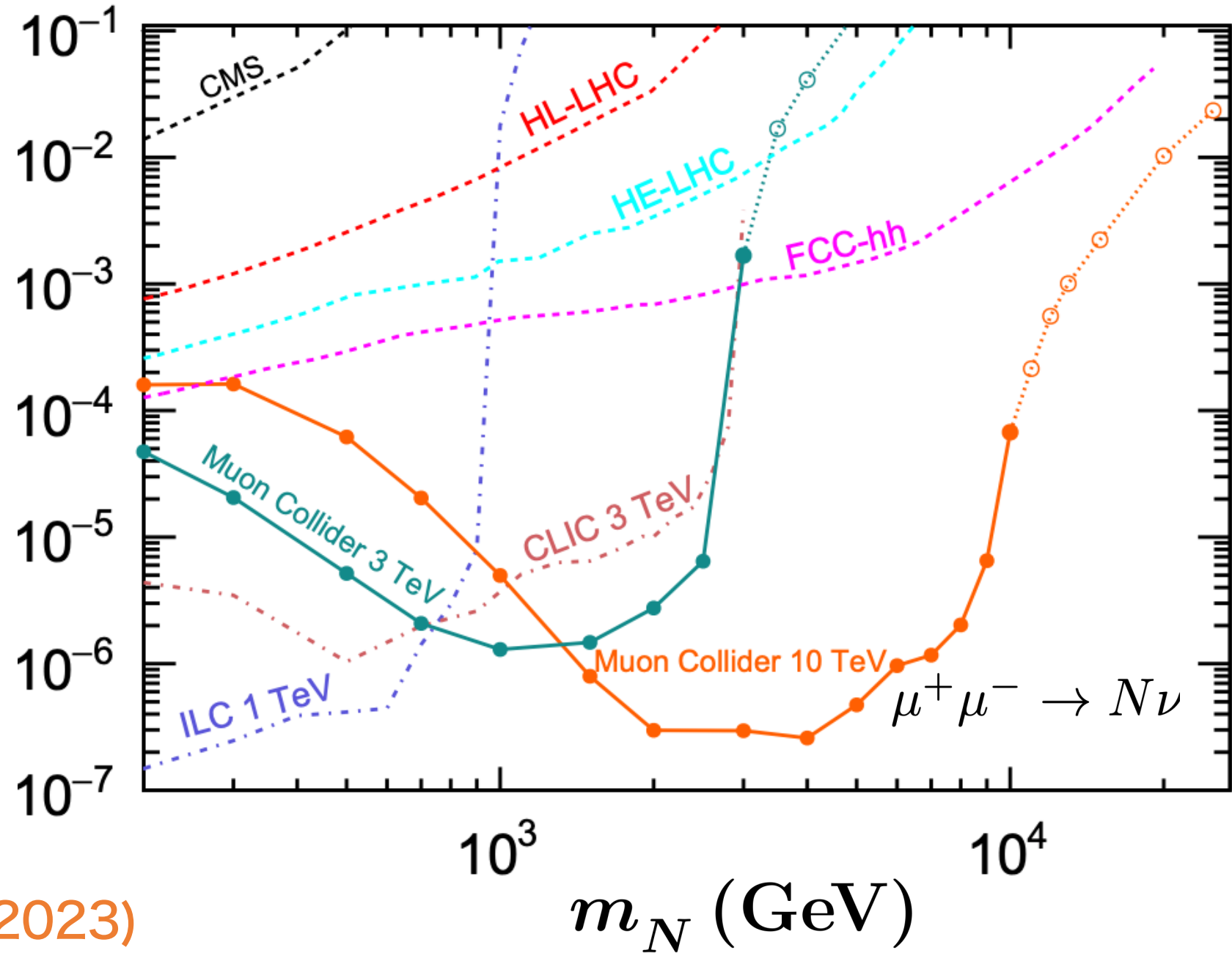
C. Bolton et al. (2020)

Collider-accessible TeV-scale HNLs

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- Future searches

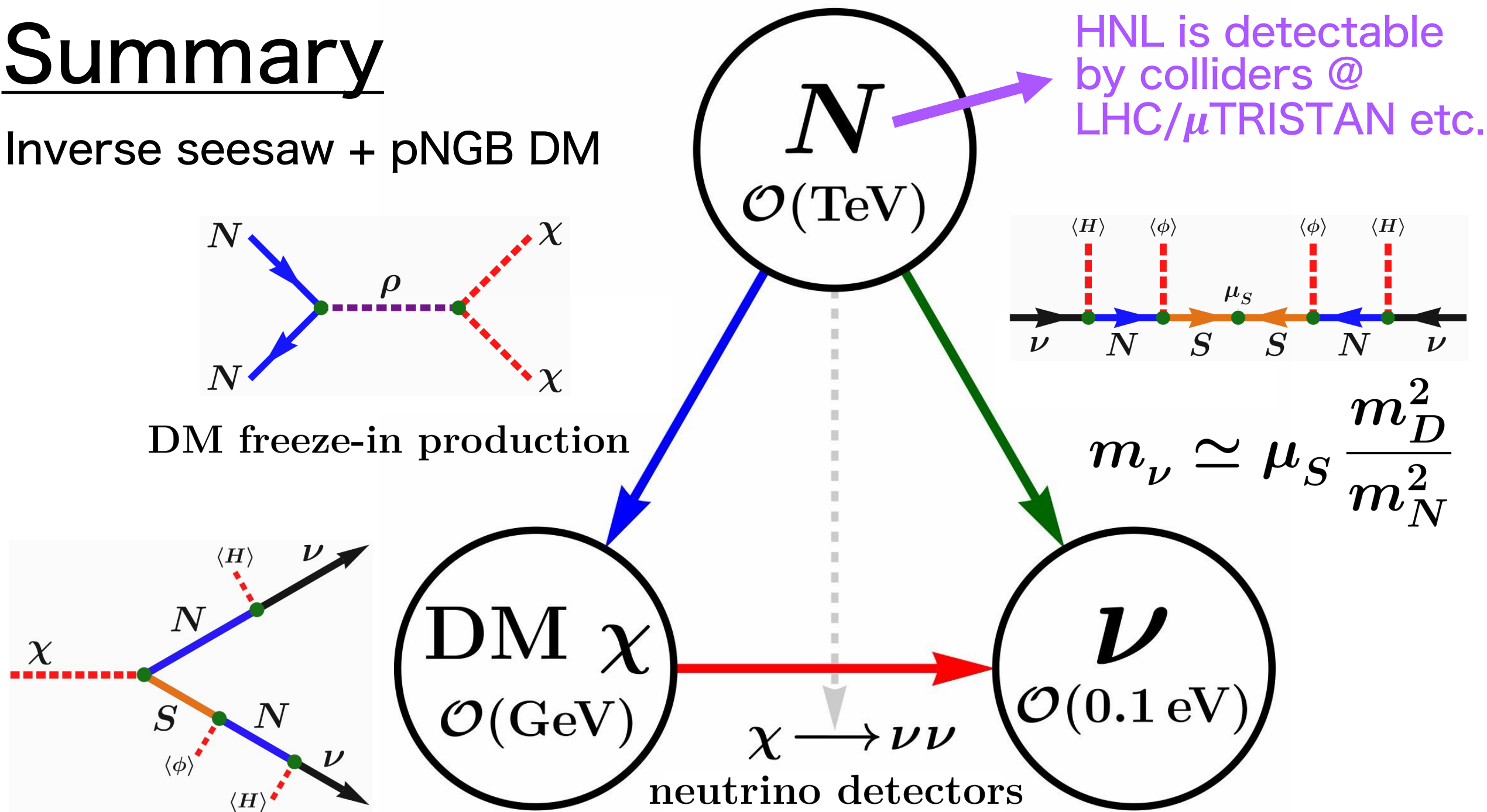
$$\xi^2 = |V_{eN}|^2 = \left(\frac{m_D}{m_N}\right)^2$$



K. Mękała et al. (2023)

Summary

Inverse seesaw + pNGB DM



Backup Slides

Enhanced Poincaré symmetry

R. Foot et al. (2014)

- In the $\lambda_{h\phi} \rightarrow 0$ limit, one can perform independent Poincaré transformation that leave the actions separately invariant.

$$\mathcal{S} = \int d^4x \left[\mathcal{L}_H(x) + \mathcal{L}_\phi(x) + \mathcal{L}_{H\phi}(x) \right]$$

$$\xrightarrow{\lambda_{h\phi} \rightarrow 0} \mathcal{S} = \int d^4x \mathcal{L}_H(x) + \int d^4x' \mathcal{L}_\phi(x')$$

- Poincaré sym. is enhanced : $\mathcal{G}_P^{H\phi} \xrightarrow{\lambda_{h\phi} \rightarrow 0} \mathcal{G}_P^H \otimes \mathcal{G}_P^\phi$
- Smallness of $\lambda_{h\phi}$ is technically natural due to this enhanced Poincaré symmetry ('t Hooft naturalness).

Analytical solution for Boltzmann equation

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- Using the narrow width approximation

$$\lim_{\gamma \rightarrow 0, z > 0} \frac{x\gamma}{(z^2 - x^2)^2 + x^2\gamma^2} = \frac{\pi}{2x} \delta(z - x)$$

$$\mathcal{R}_{NN \rightarrow \chi\chi} \simeq \frac{m_\rho^3 m_N^2 T}{16\pi^3 v_\phi^2} K_1(x_\rho) \mathcal{B}_{\rho \rightarrow \chi\chi}$$

- Integrating the Boltzmann eq. from $x = 0$ to $x = \infty$

$$Y_\chi(x_\infty) \simeq \frac{405\sqrt{10}}{2(2\pi)^5} \frac{m_N^2 m_{Pl}}{g_{*s} \sqrt{g_*} v_\phi^2 m_\rho}$$

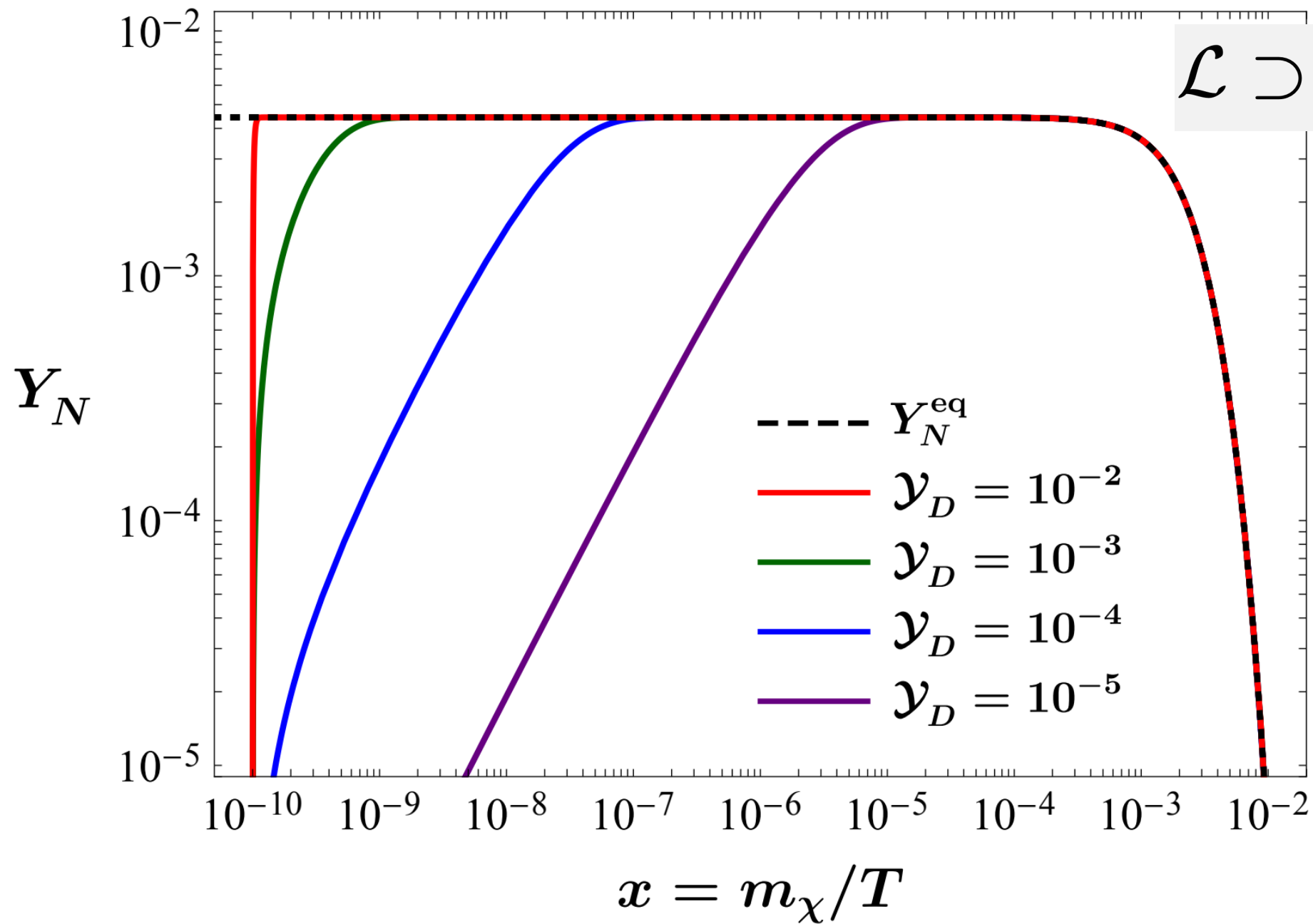
$$g_{*s} \simeq g_* \simeq 100$$

- DM Relic abundance

$$Y_{DM} \simeq 4.4 \times 10^{-10} \left(\frac{m_{DM}}{\text{GeV}} \right)^{-1} \left(\frac{\Omega_{DM} \hat{h}^2}{0.12} \right)$$

$$\Omega_\chi \hat{h}^2 \simeq 0.12 \left(\frac{m_\chi}{1 \text{ GeV}} \right) \left(\frac{m_N}{10^3 \text{ GeV}} \right)^2 \left(\frac{m_\rho}{10^4 \text{ GeV}} \right)^{-1} \left(\frac{v_\phi}{6 \times 10^{12} \text{ GeV}} \right)^{-2}$$

$$(m_\chi, m_N, T_R) = (1, 10^3, 10^{10}) \text{ GeV}$$



$$\mathcal{L} \supset -\overline{E}_L \tilde{H} \mathcal{Y}_D N_R$$