TeV-scale unification of light dark matter & neutrino mass

Shu-Yu HO
(Academia Sinica)

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

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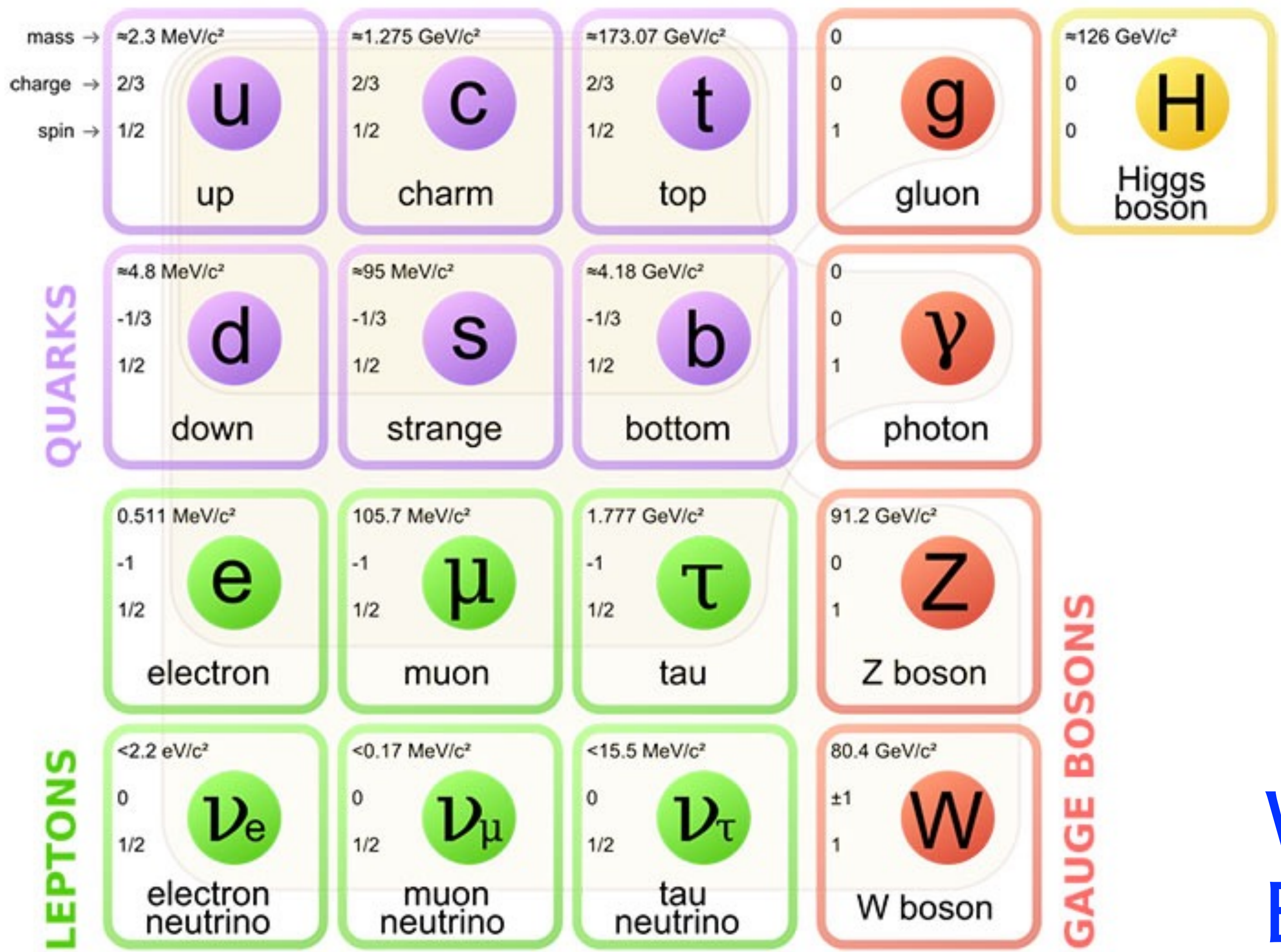
The 16th Particle Physics Phenomenology Workshop @ NTHU

The standard model of particle physics

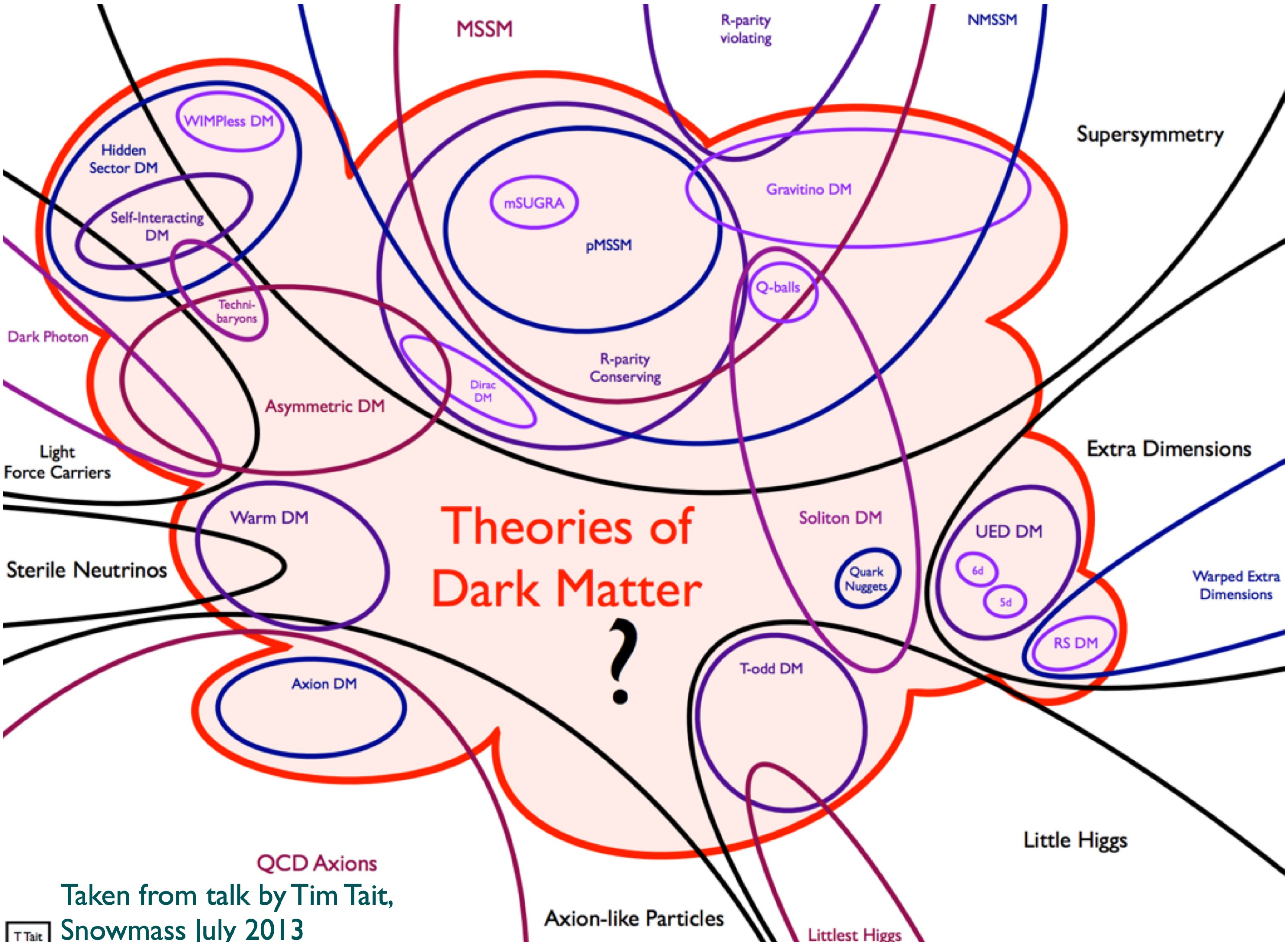
The Standard Model (SM) is GOOD, but ……



Unsolved problems

- Dark matter
- Neutrino mass
- Baryon asymmetry
- Dark energy
- Quantum gravity
- ………

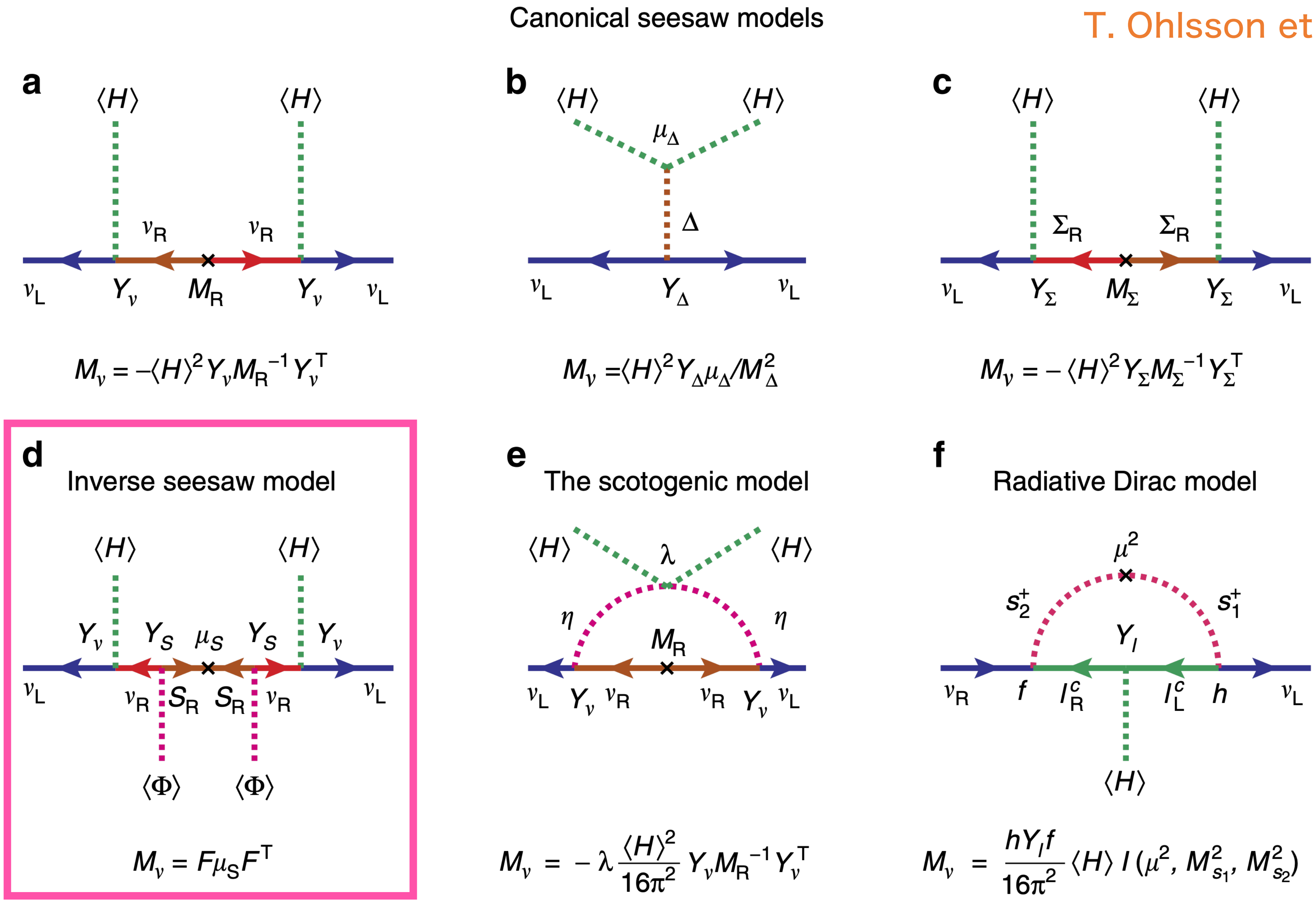
We need new physics
Beyond the SM !!!



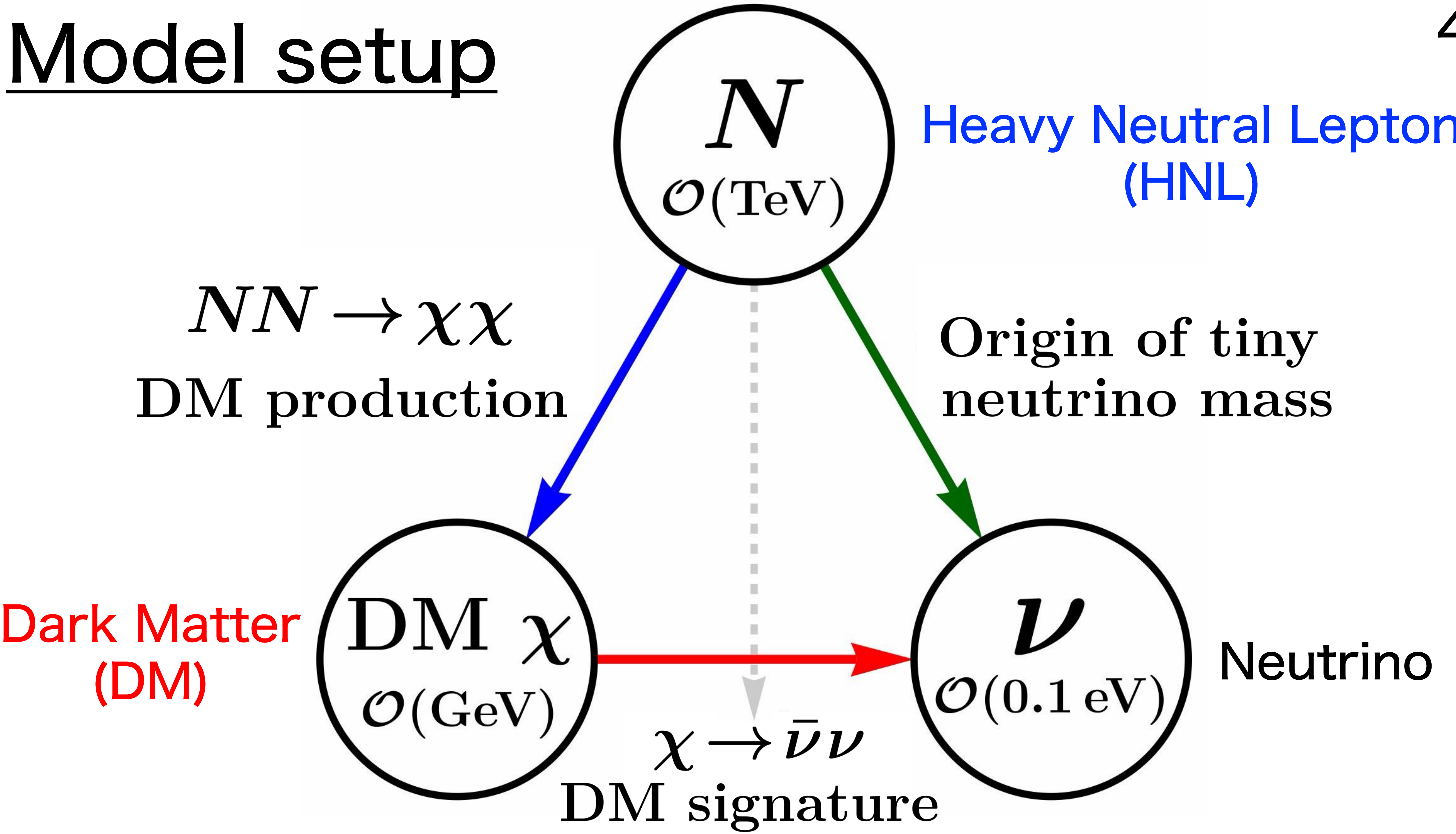
Taken from talk by Tim Tait,
Snowmass July 2013

Neutrino mass model

T. Ohlsson et al. (2013)



Model setup


N
$\mathcal{O}(\mathrm{TeV})$
Heavy Neutral Lepton
(HNL)
$NN \to \chi\chi$
DM production
Origin of tiny
neutrino mass
Dark Matter
(DM)
DM χ
$\mathcal{O}(\mathrm{GeV})$
ν
$\mathcal{O}(0.1\,\mathrm{eV})$
Neutrino
$\chi \to \bar{\nu}\nu$
DM signature

Particle content

HNL

	e_{Rj}	E_{Lj}	H	N_{Rj}	S_{Lj}	ϕ
$\mathrm{SU}(2)_L$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U}(1)_\mathrm{Y}$	-1	$-1/2$	$1/2$	0	0	0
$\mathrm{U}(1)_\mathrm{L}$	1	1	0	1	2	1
spin	$1/2$	$1/2$	0	$1/2$	$1/2$	0

global lepton # symmetry

Yukawa sector

$$\mathcal{L}_Y = -(Y_D)_{jk}\overline{E_{Lj}}\widetilde{H}N_{Rk} - (Y_N)_{jk}\overline{S_{Lj}}N_{Rk}\phi - \frac{1}{2}(\mu_S)_{jk}\overline{S_{Lj}}S^c_{Lk} + \mathrm{h.c.}$$

U(1)_L soft breaking term

Scalar potential

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

U(1)_L soft breaking term

Scalar mass spectrum $\lambda_{h\phi} \to 0$ (enhanced Poincaré sym.)

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

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

pseudo Nambu-Goldstone Boson (pNGB)

Scalar interactions

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

- accidental Z_2 symmetry : $\rho \to \rho \ , \ \chi \to -\chi$

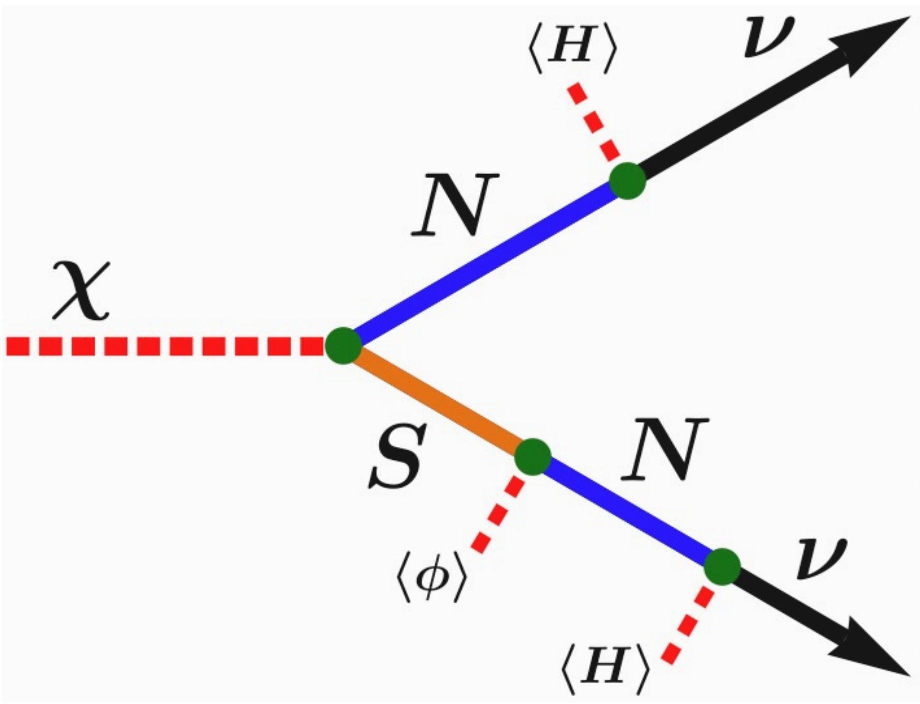
  (C–symmetry : $\phi \to \phi^*$)

Decaying pNGB DM

- $\mathcal{L}_Y \supset -Y_N \overline{S_L} N_R \phi$

  breaks C-symmetry

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



Neutrino mass (inverse seesaw)

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

- fermion mass mixing matrix

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

- unitary mixing matrix

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

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

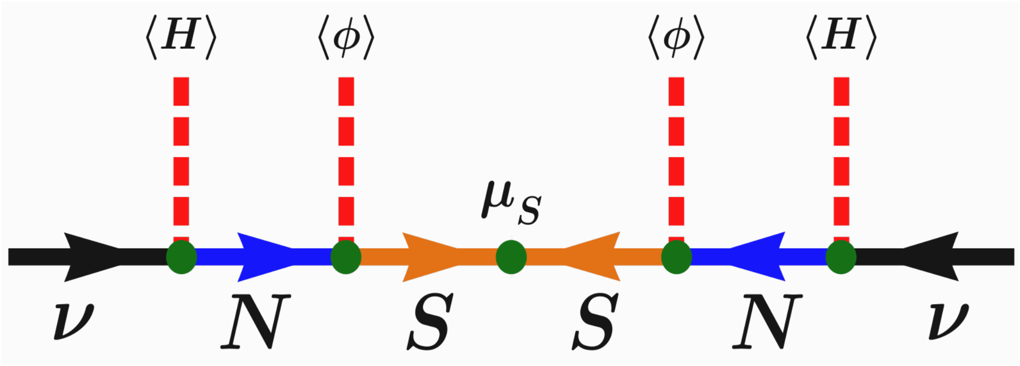
Neutrino mass (inverse seesaw)

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

- neutrino mass eigenvalue

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

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



- DM-HNL interactions

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

Majorana fermion : $\nu_\mathrm{M} = \nu + \nu^c \quad N_{k\mathrm{M}} = N_k + N_k^c$

Lifetime of dark matter

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

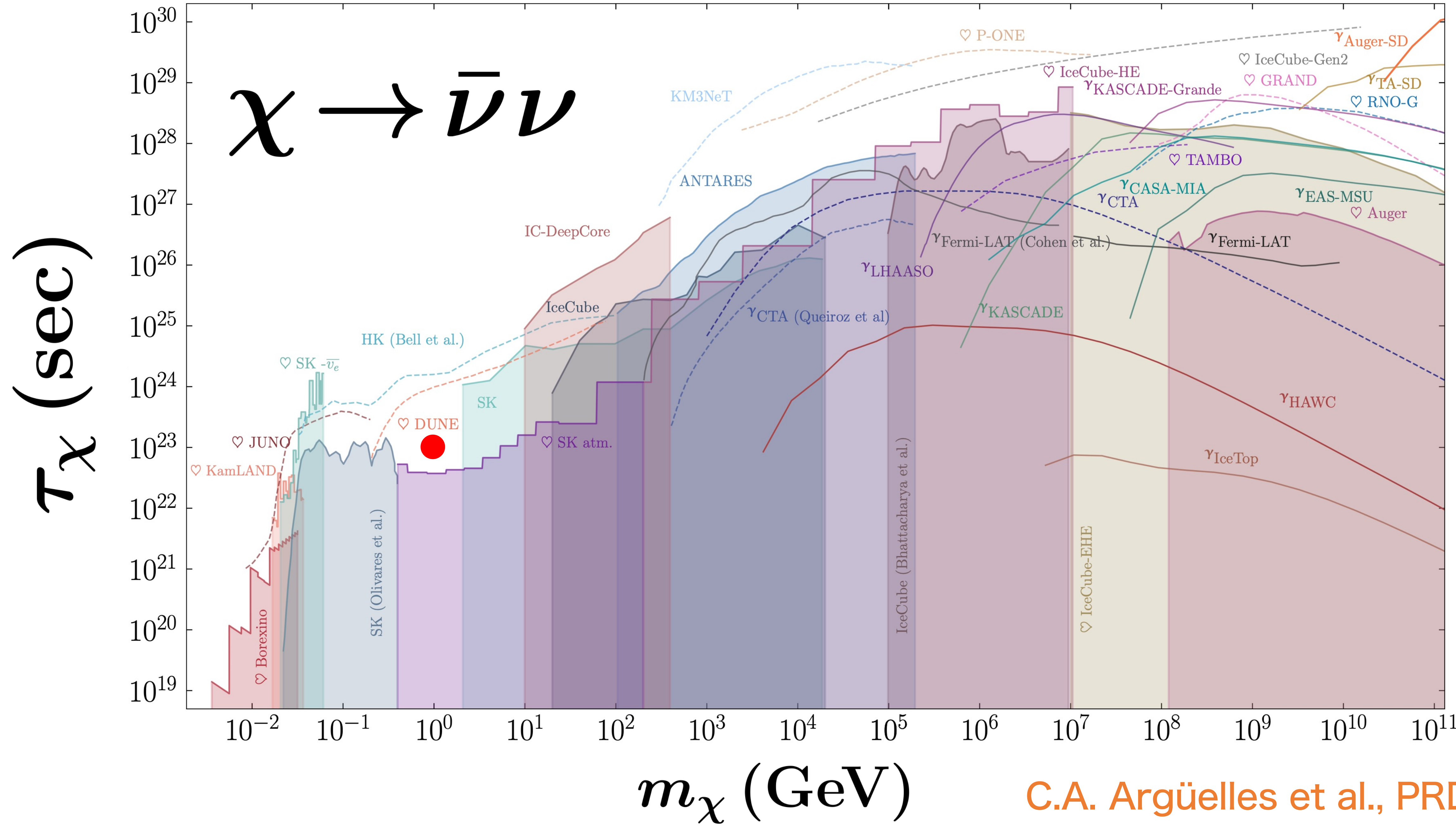
$$\Gamma_\chi \simeq \Gamma_{\chi \to \nu_{\mathrm{M}} \nu_{\mathrm{M}}} = \frac{m_\nu^2}{4\pi v_\phi^2} m_\chi$$

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

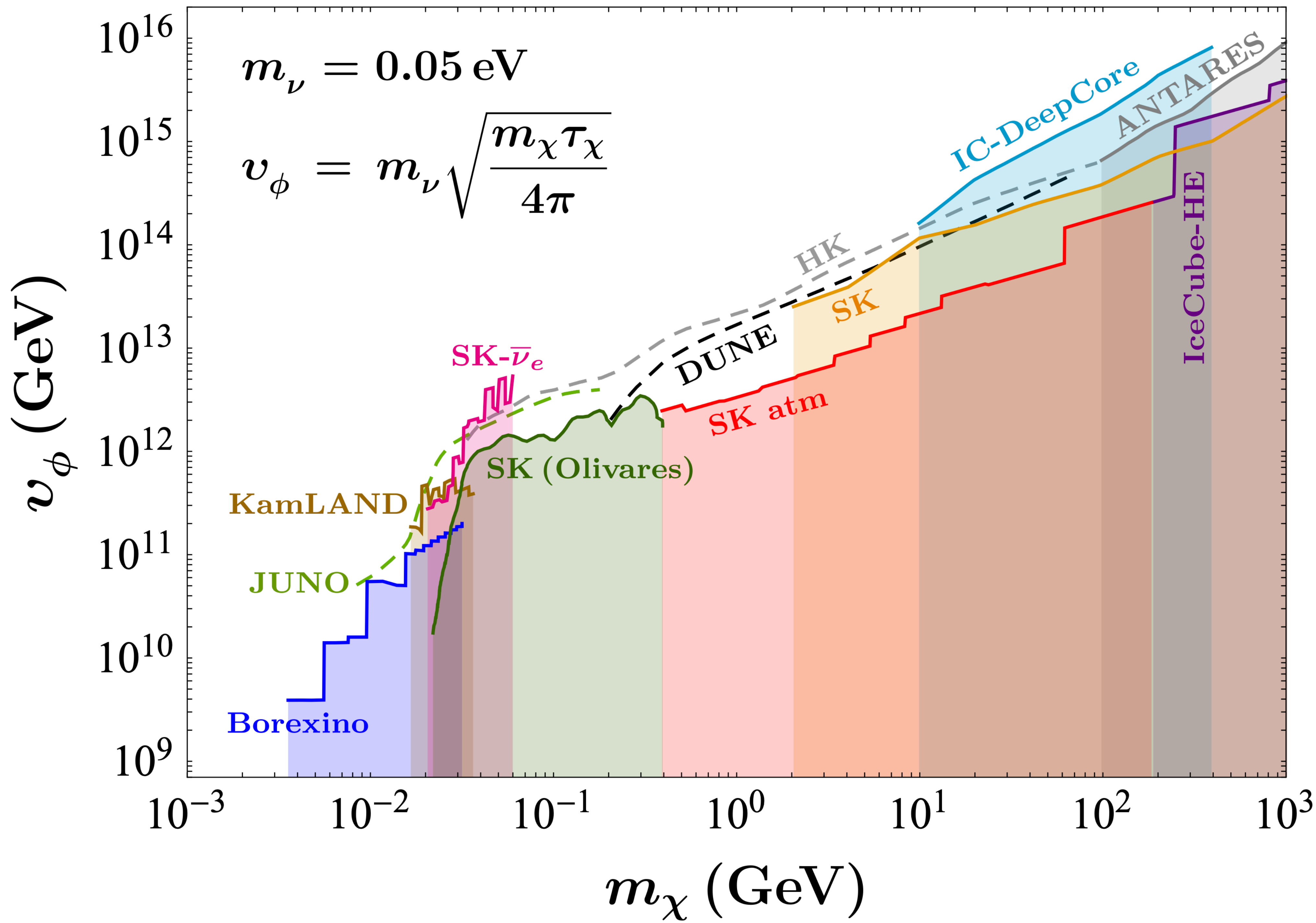
$$\tau_\chi \simeq 10^{23}\,\mathrm{sec} \left(\frac{m_\nu}{0.1\,\mathrm{eV}} \right)^2 \left(\frac{m_\chi}{1\,\mathrm{GeV}} \right) \left(\frac{v_\phi}{10^{13}\,\mathrm{GeV}} \right)^{-2}$$

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

Lower bound on DM lifetime

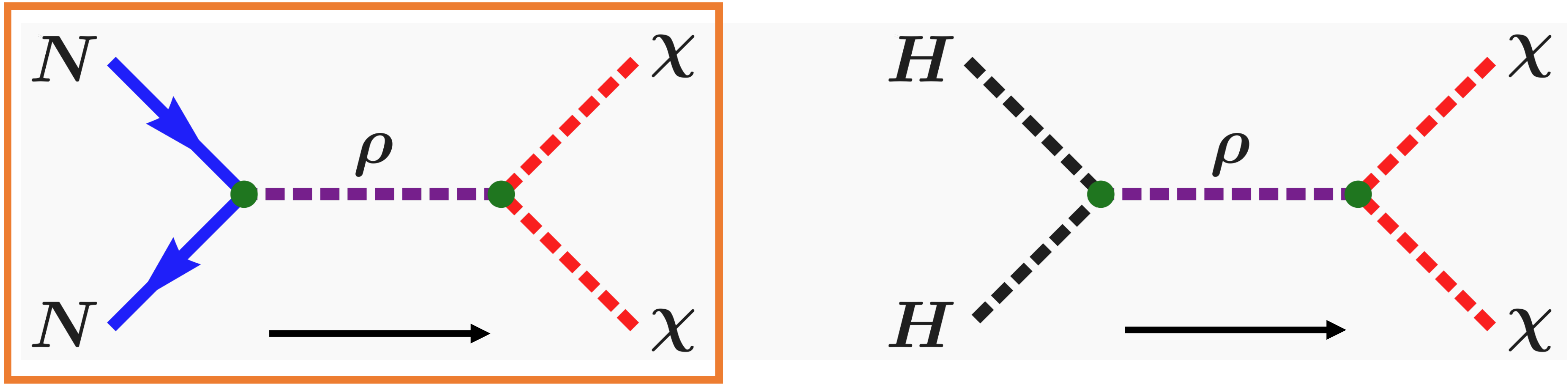


C.A. Argüelles et al., PRD 2023


$m_\nu = 0.05\,\mathrm{eV}$
$v_\phi = m_\nu \sqrt{\frac{m_\chi \tau_\chi}{4\pi}}$
IC-DeepCore
ANTARES
IceCube-HE
HK
SK
DUNE
SK atm
SK-$\overline{\nu}_e$
SK (Olivares)
KamLAND
JUNO
Borexino
v_ϕ (GeV)
m_χ (GeV)
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Freeze-in production of DM

- 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).



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

Boltzmann equation

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

Bessel function

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

reaction rate

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

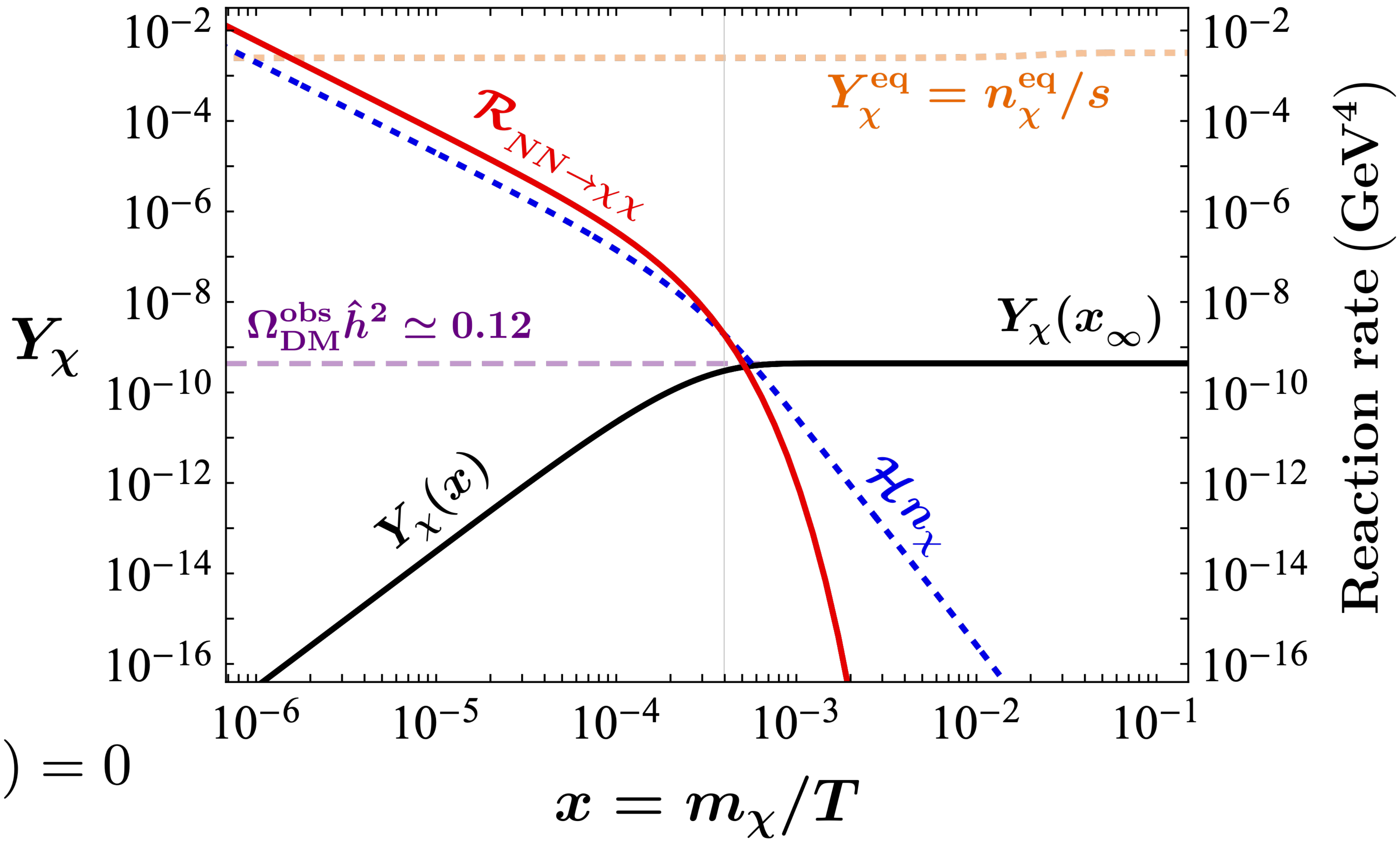
- In terms of comoving number density $Y_\chi = n_\chi/s$

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

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

Time evolution of DM number density

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



$Y_\chi(T_R) = 0$

Analytical solution for Boltzmann equation

- Using the narrow width approximation

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

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

- Integrating the Boltzmann eq. from x = 0 to x = ∞

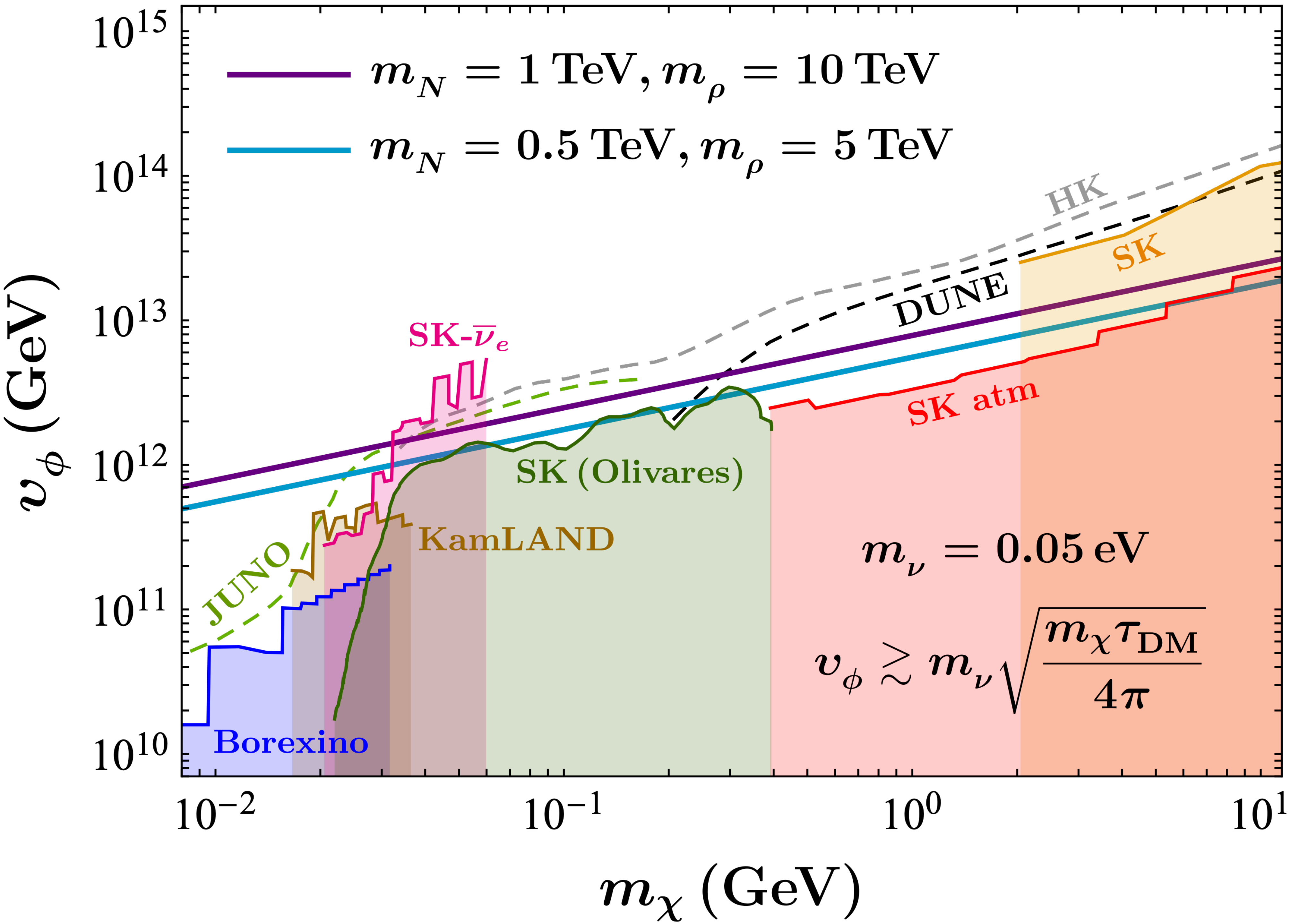
$$Y_\chi(x_\infty) \simeq \frac{405\sqrt{10}}{2(2\pi)^5} \frac{m_N^2 m_{\rm Pl}}{g_{*s}\sqrt{g_*}\,\upsilon_\phi^2 m_\rho}$$

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

- DM Relic abundance

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

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

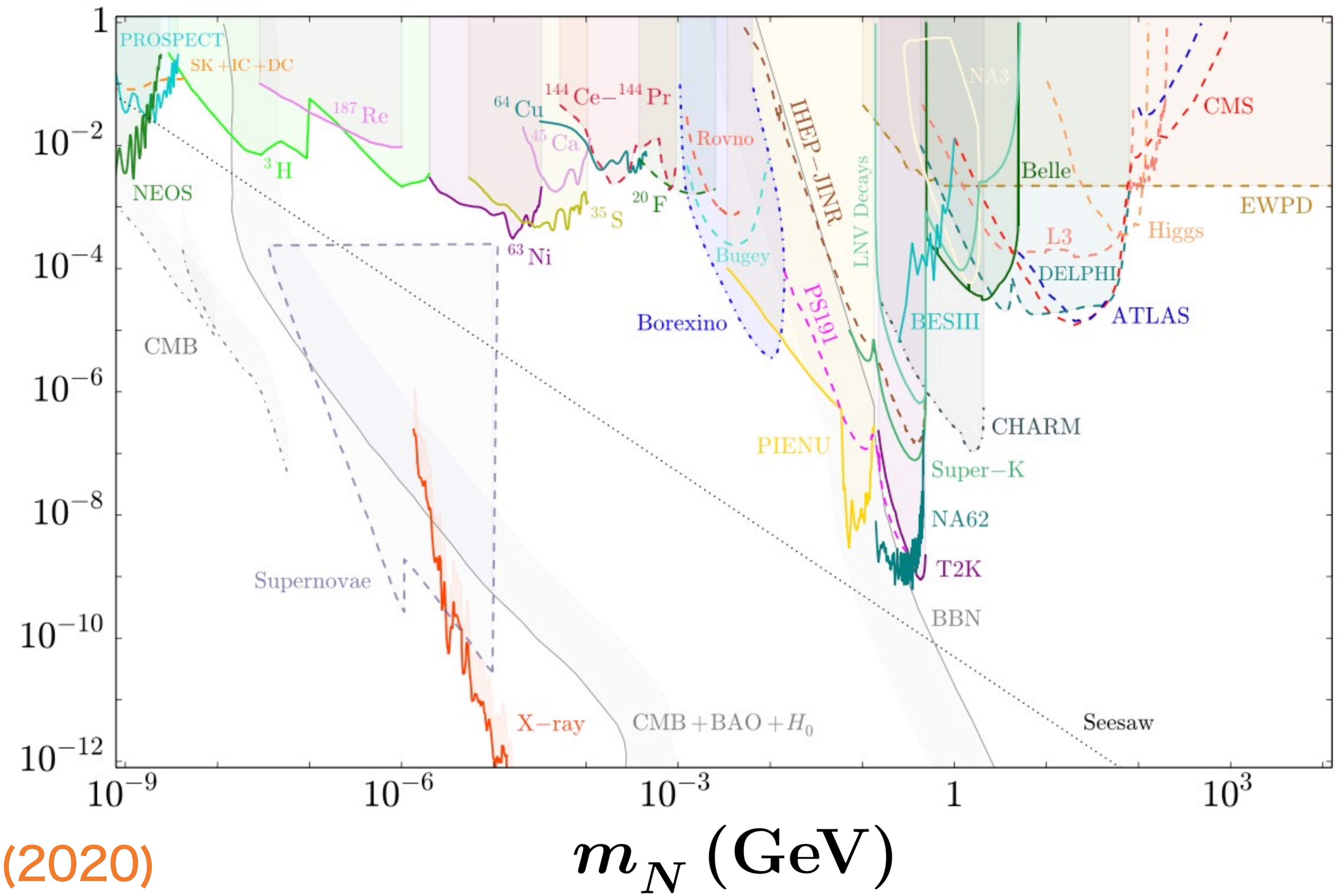


$m_N = 1$ TeV, $m_\rho = 10$ TeV
$m_N = 0.5$ TeV, $m_\rho = 5$ TeV
HK
SK
DUNE
SK-$\overline{\nu}_e$
SK atm
SK (Olivares)
KamLAND
JUNO
Borexino
$m_\nu = 0.05\,\mathrm{eV}$
$v_\phi \gtrsim m_\nu \sqrt{\frac{m_\chi \tau_{\mathrm{DM}}}{4\pi}}$
v_ϕ (GeV)
m_χ (GeV)

Collider-accessible TeV-scale HNLs

- Current searches

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

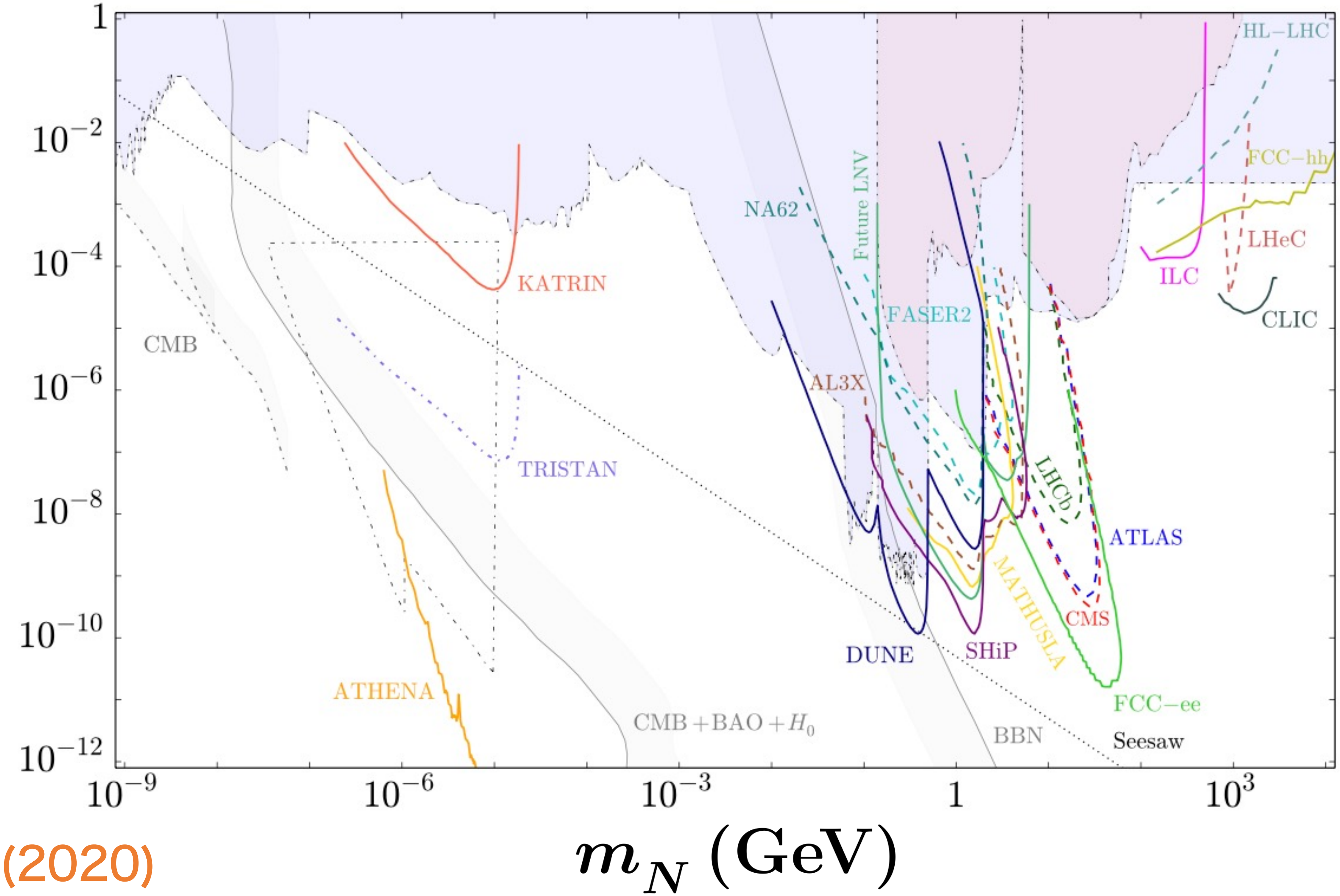


C. Bolton et al. (2020)

Collider-accessible TeV-scale HNLs

- Future searches

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

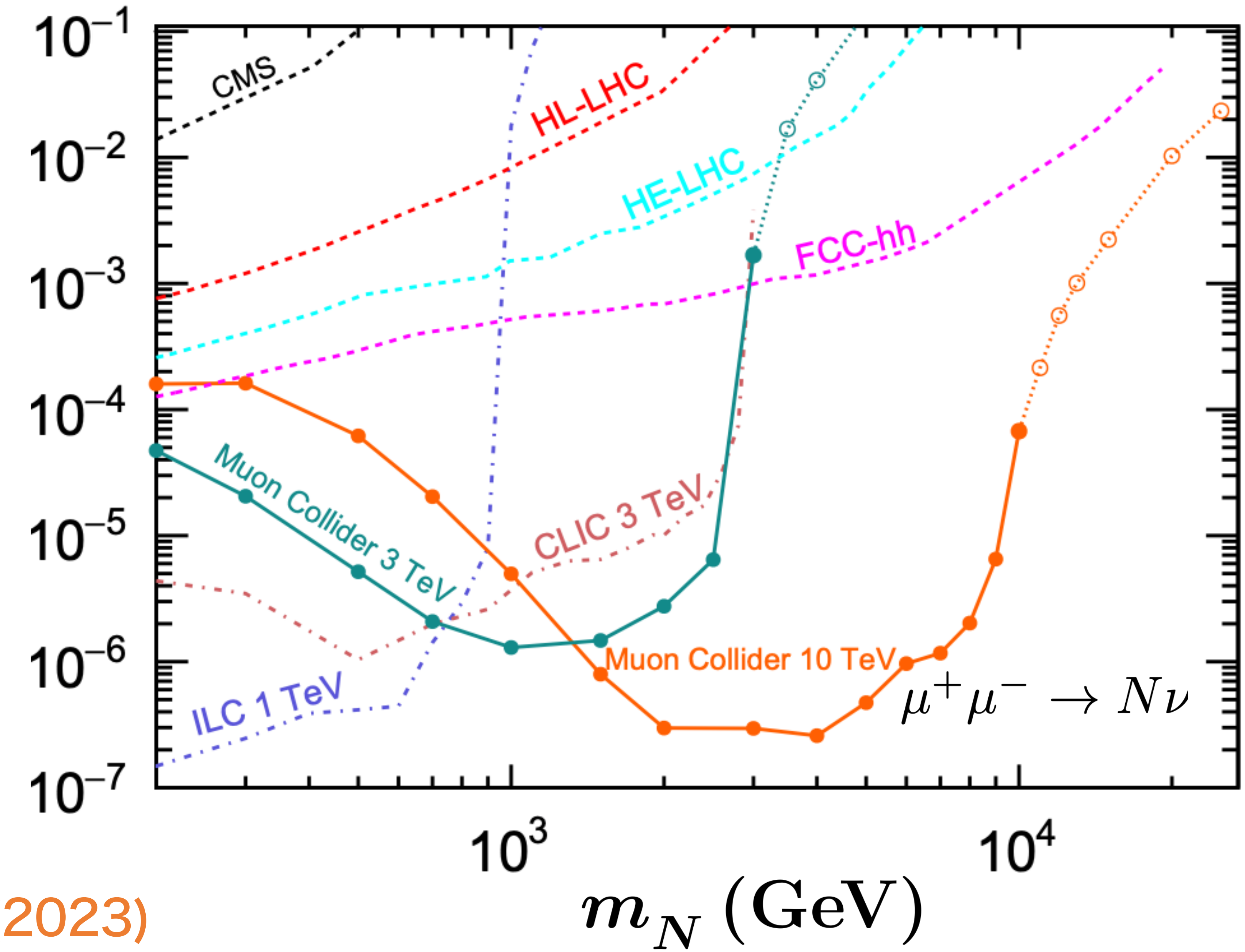


C. Bolton et al. (2020)

Collider-accessible TeV-scale HNLs

- Future searches

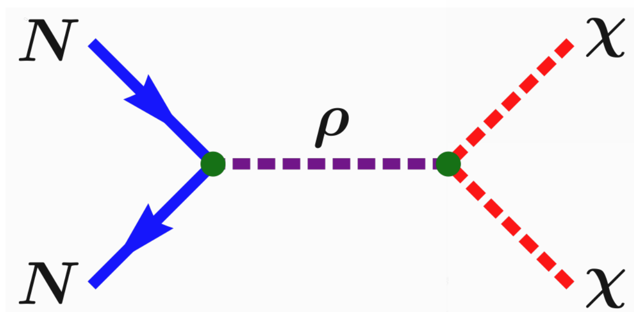
$$\xi^2 = \left(\frac{m_D}{m_N}\right)^2$$



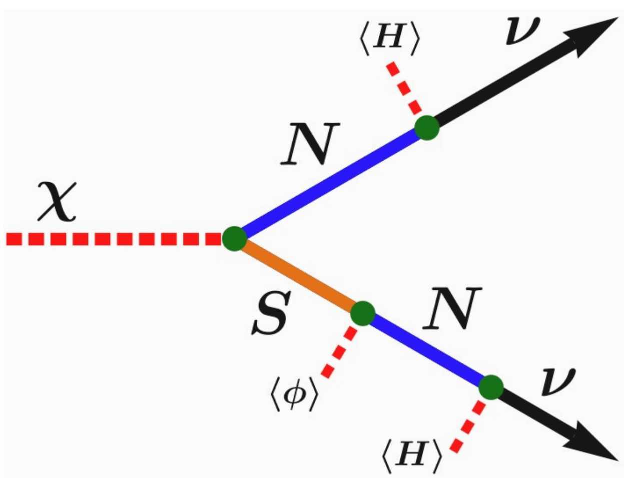
K. Mękała et al. (2023)

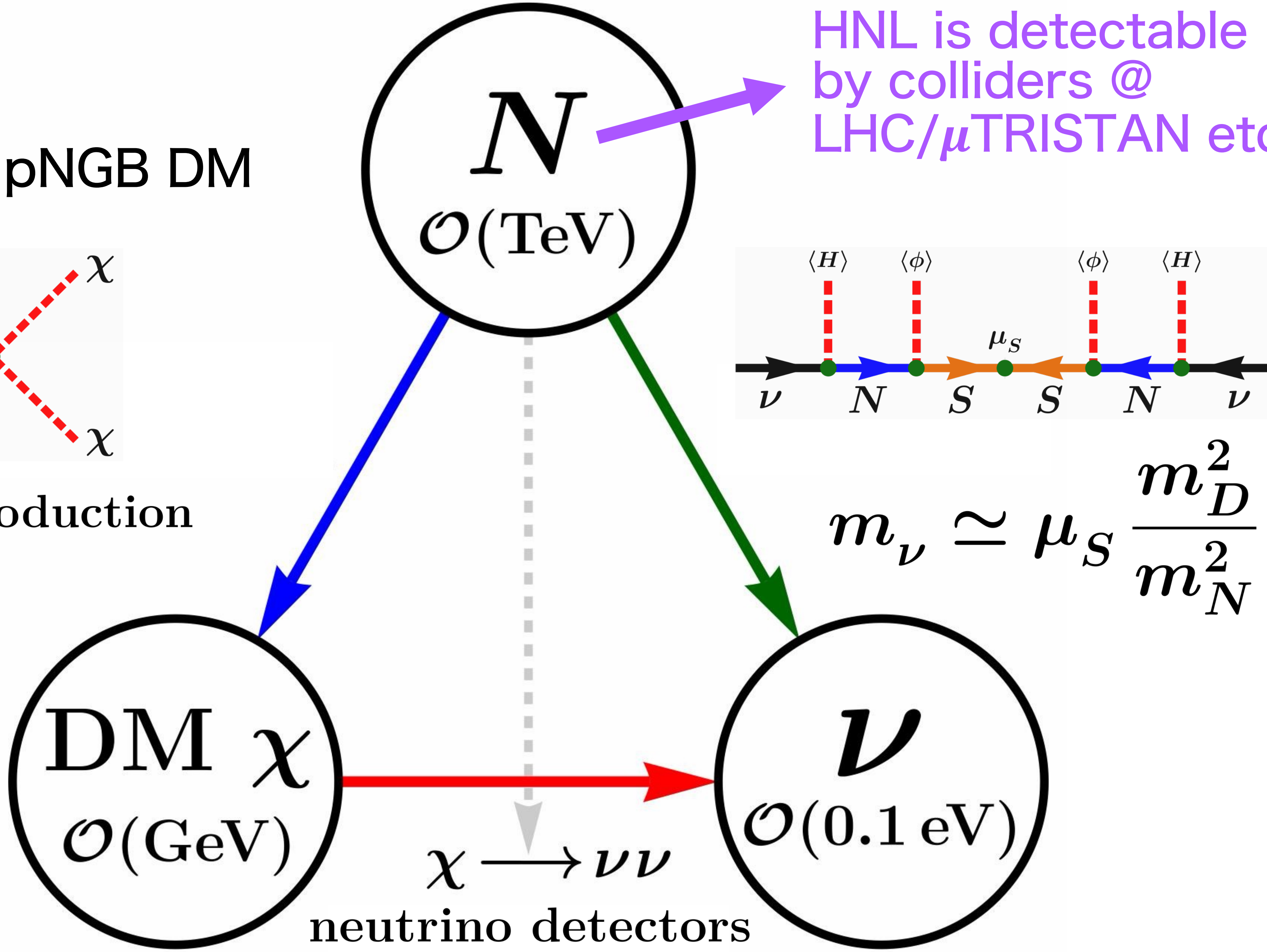
Summary

Inverse seesaw + pNGB DM



DM freeze-in production





HNL is detectable by colliders @ LHC/μTRISTAN etc.

$$m_\nu \simeq \mu_S \frac{m_D^2}{m_N^2}$$

Backup Slides

Enhanced Poincaré symmetry

R. Foot et al. (2014)

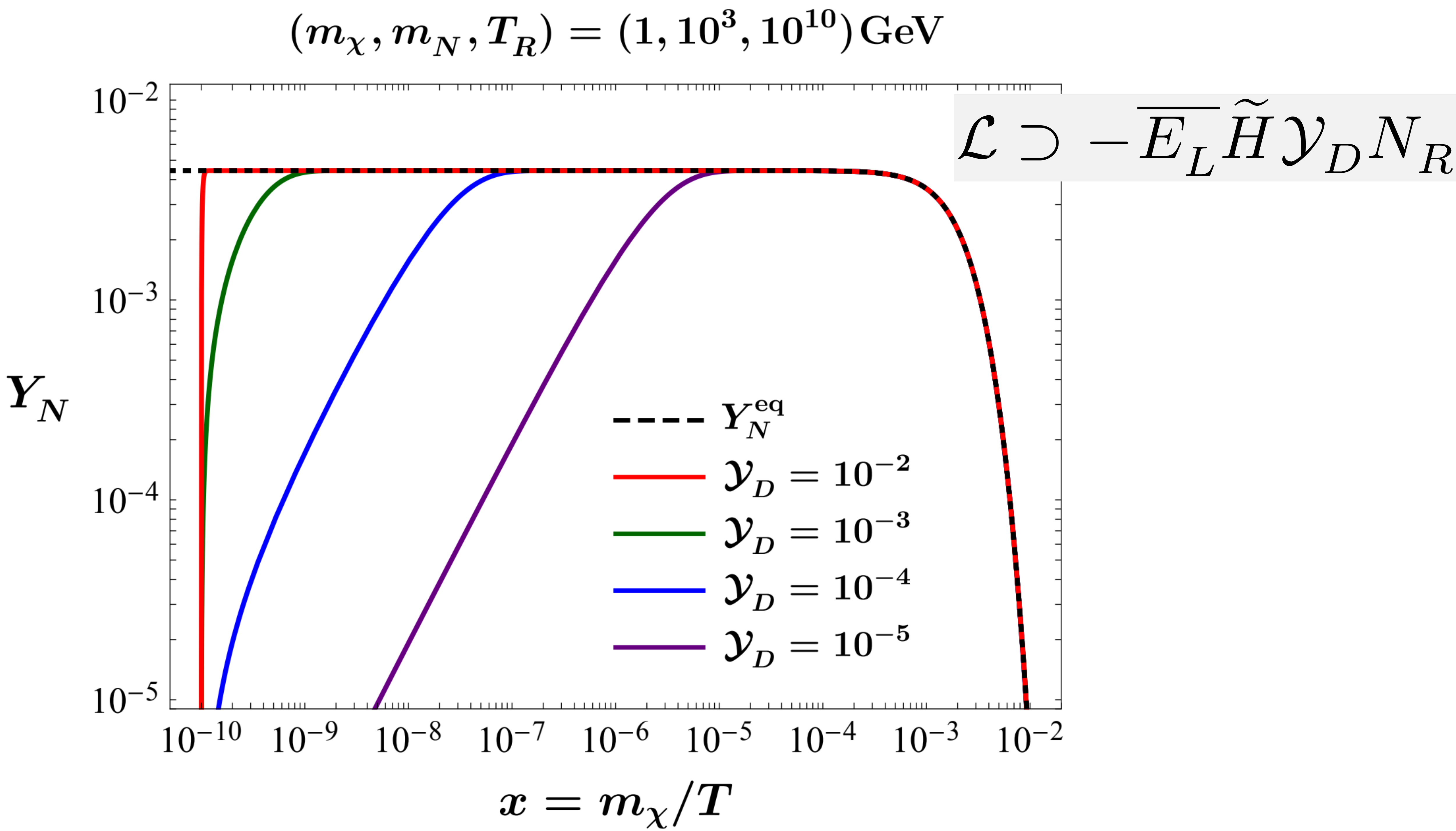
- In the $\lambda_{h\phi} \to 0$ limit, one can perform independent Poincaré transformation that leave the actions separately invariant.

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

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

- Poincaré sym. is enhanced : $\mathcal{G}_P^{H\phi} \xrightarrow{\lambda_{h\phi} \to 0} \mathcal{G}_P^H \otimes \mathcal{G}_P^\phi$

- Smallness of $\lambda_{h\phi}$ is technically natural due to this enhanced Poincaré symmetry ('t Hooft naturalness).


$(m_\chi, m_N, T_R) = (1, 10^3, 10^{10})\,\mathrm{GeV}$
$\mathcal{L} \supset -\overline{E_L}\widetilde{H}\mathcal{Y}_D N_R$
Y_N
$x = m_\chi/T$
$Y_N^{\rm eq}$
$\mathcal{Y}_D = 10^{-2}$
$\mathcal{Y}_D = 10^{-3}$
$\mathcal{Y}_D = 10^{-4}$
$\mathcal{Y}_D = 10^{-5}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}