



A global analysis of loop-mediated Dark Matter–neutrino interactions

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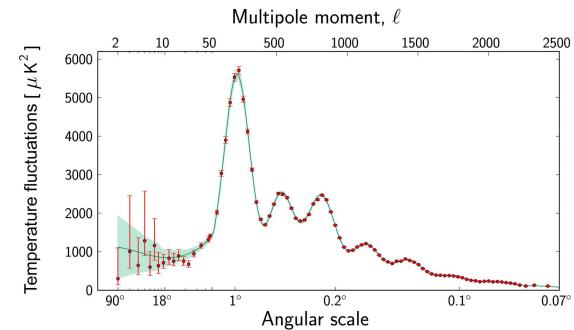
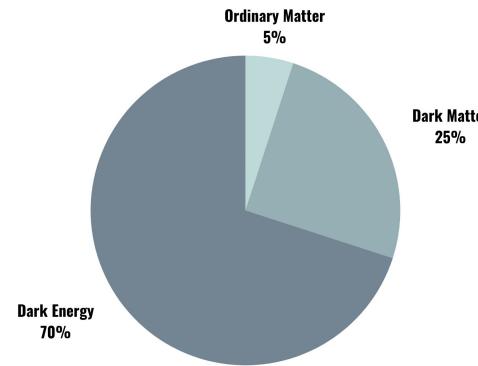
The Standard Model is incomplete

The Standard Model is incomplete



Neutrino mass
mechanism

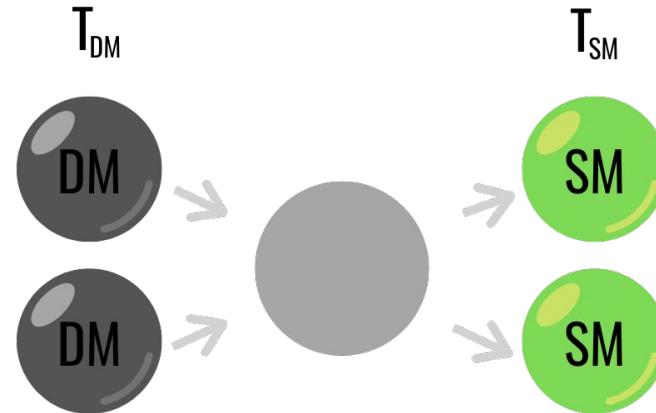
The Standard Model is incomplete



Neutrino mass mechanism

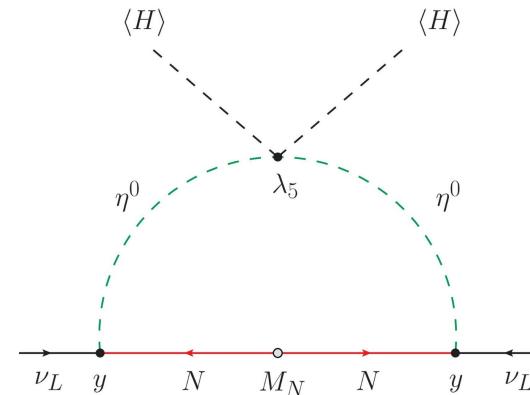
Astrophysical and cosmological evidence of dark matter

Weakly Interacting Massive Particles (WIMPs)



Theoretical Framework

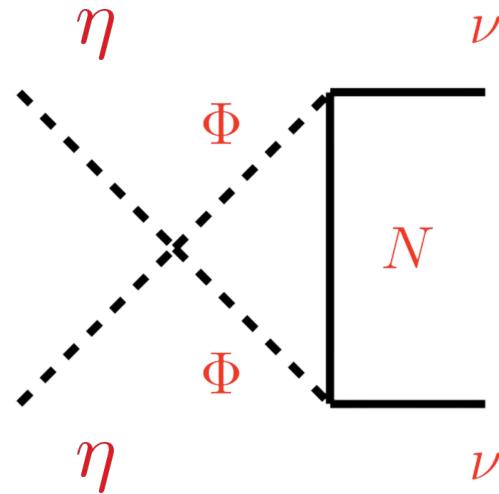
Dark matter
interactions with the
standard model
through the neutrino
sector



Scotogenic model

Ma, E. (2006).
+many more extensions

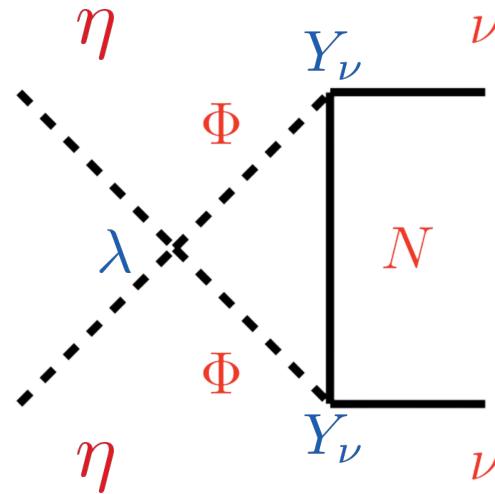
The Dark Matter Model



Real scalar DM η
Complex scalar mediator Φ
Neutral singlet mediator N

Chao, W. (2020). arXiv: 2009.12002

The Dark Matter Model



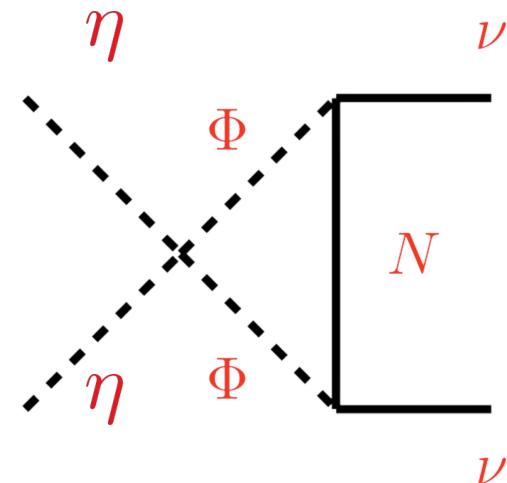
Real scalar DM η
Complex scalar mediator Φ
Neutral singlet mediator N

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Couplings λ, Y_ν

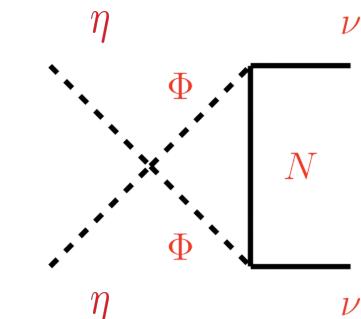
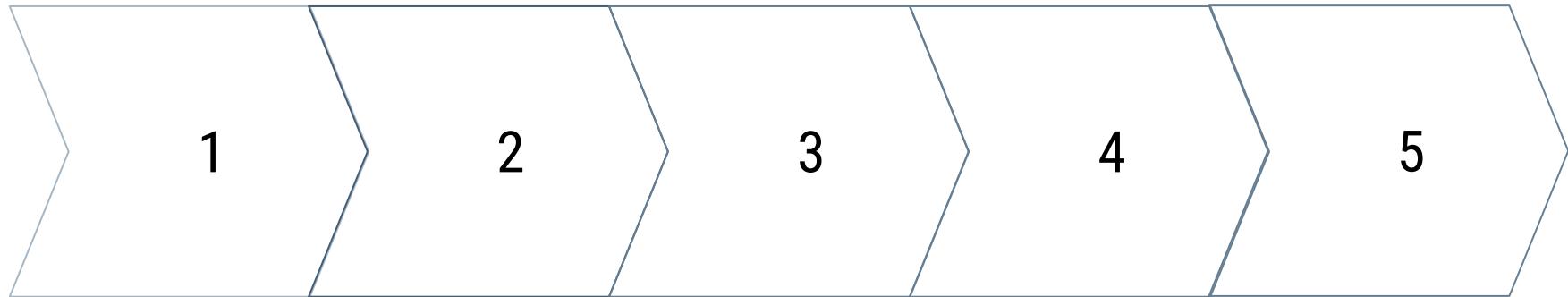
Research Question

Can loop-mediated
DM-neutrino interactions
reproduce the total or part of
the observed relic abundance
and be consistent with
current constraints?

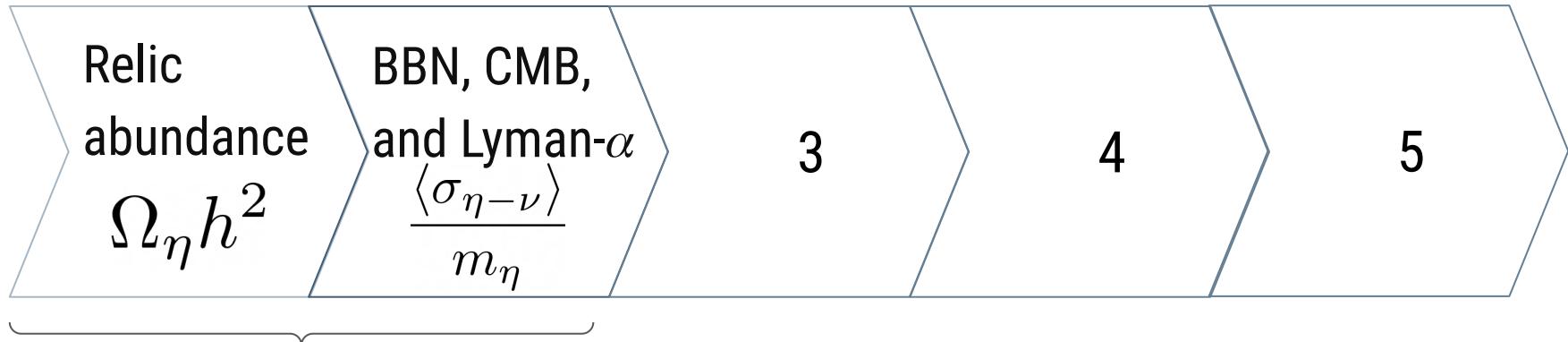


Chao, W. (2020). arXiv: 2009.12002

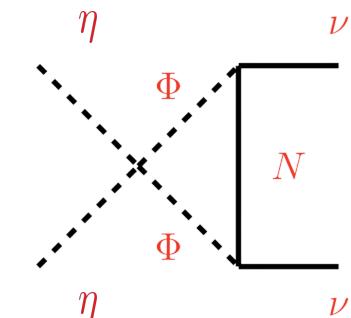
The Dark Matter Escape Room



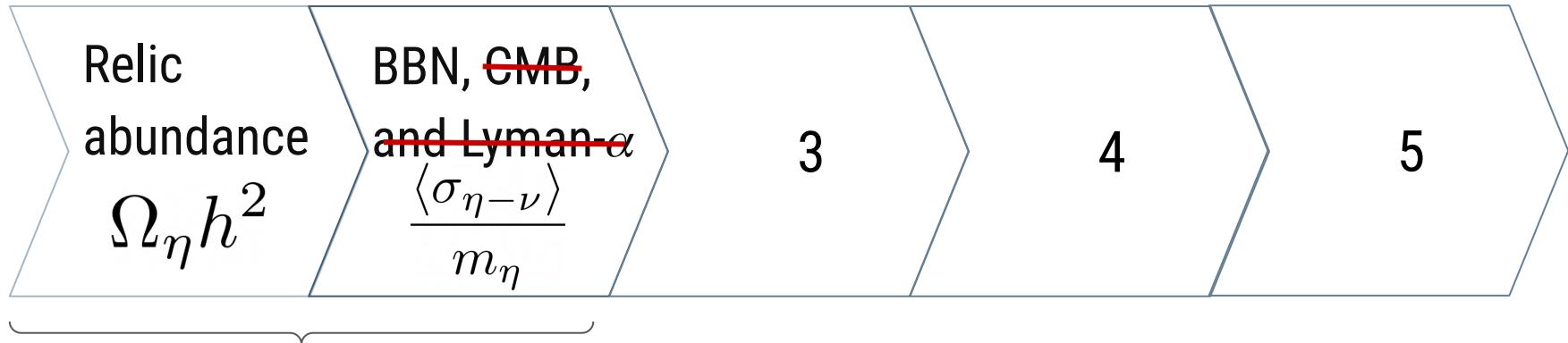
The Dark Matter Escape Room



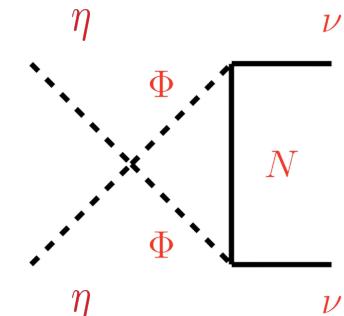
Early universe
DM-neutrino
interactions



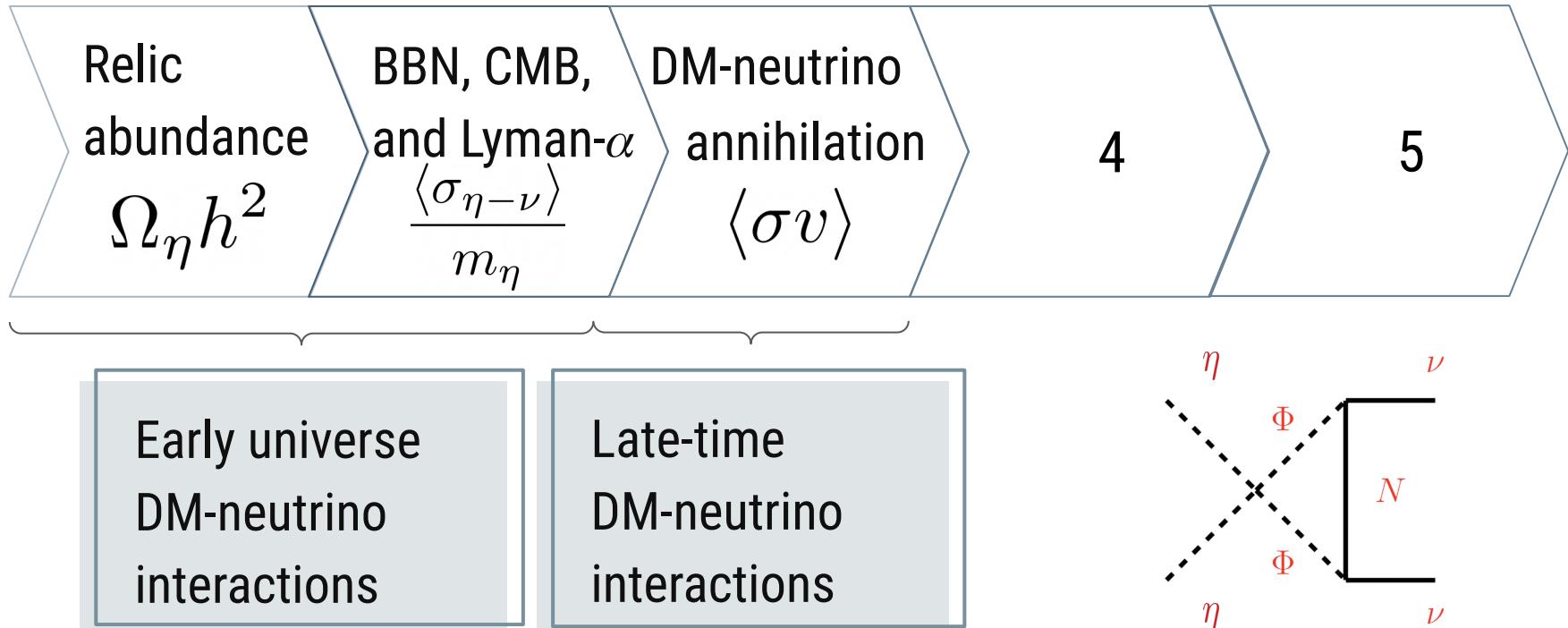
The Dark Matter Escape Room



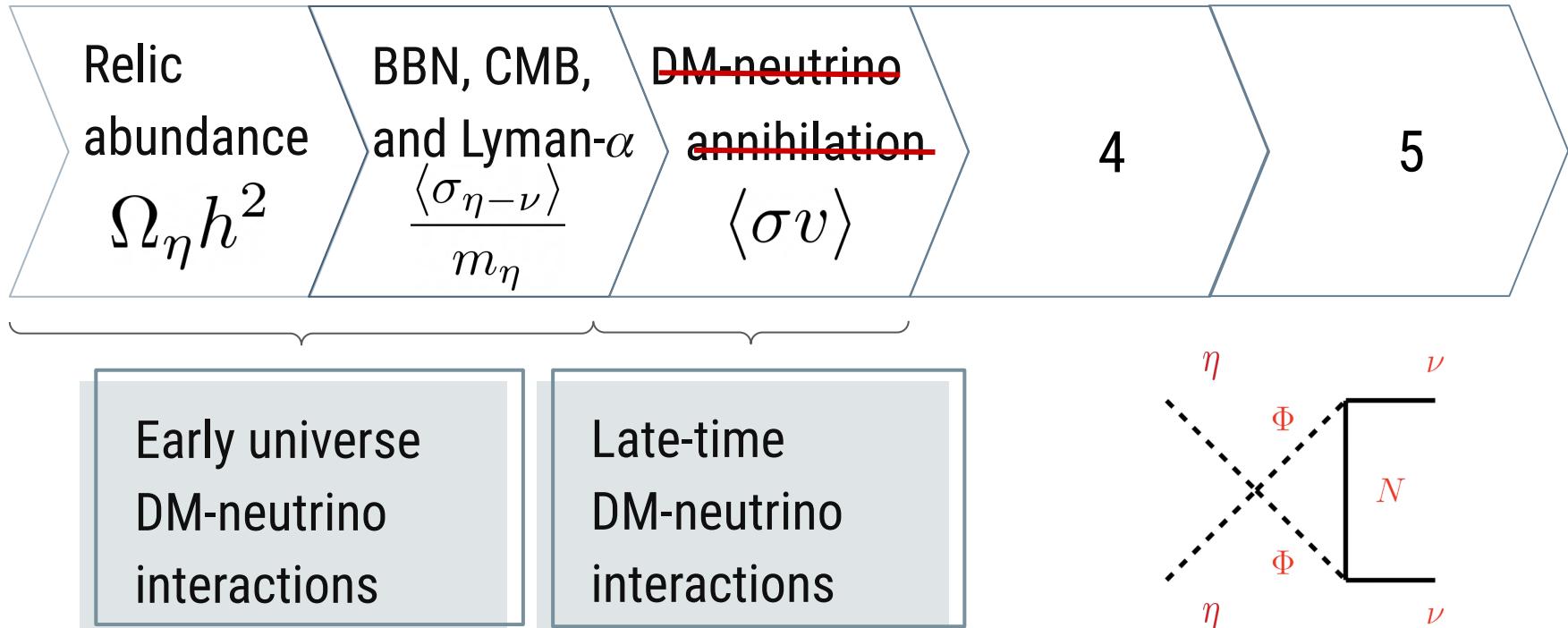
Early universe
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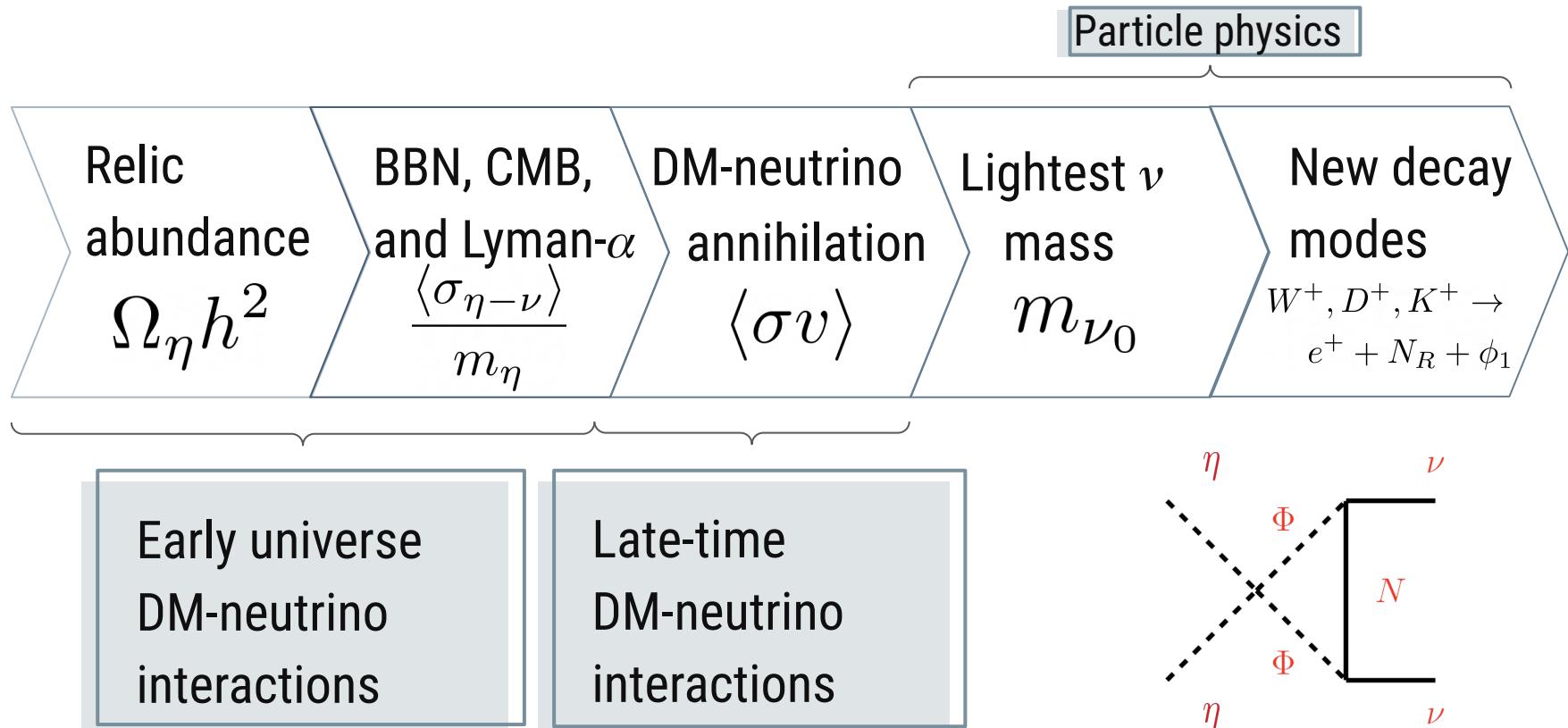
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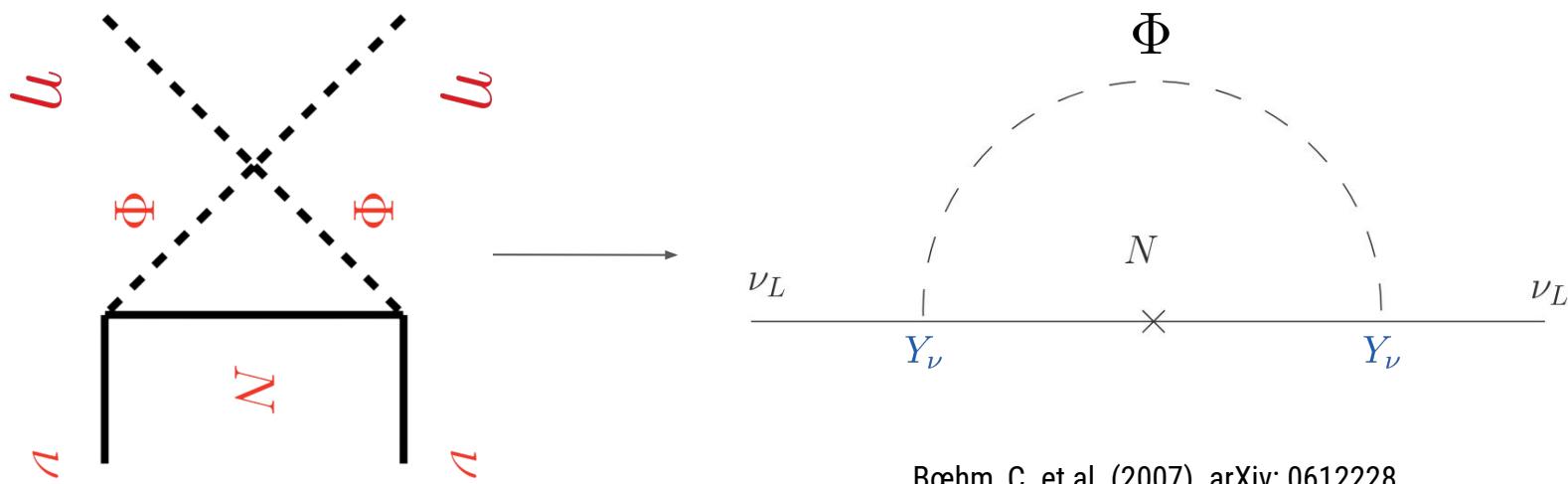
The Dark Matter Escape Room



The Dark Matter Escape Room



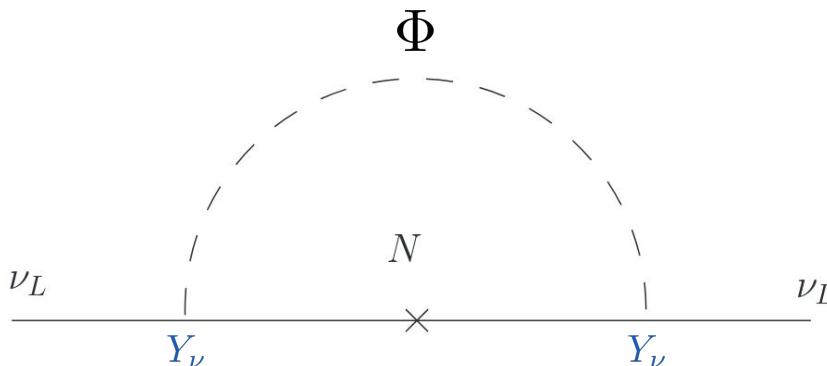
Neutrino mass mechanism



Böhm, C. et al. (2007). arXiv: 0612228

Neutrino mass mechanism

$$\Phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$$



Neutrino mass m_ν

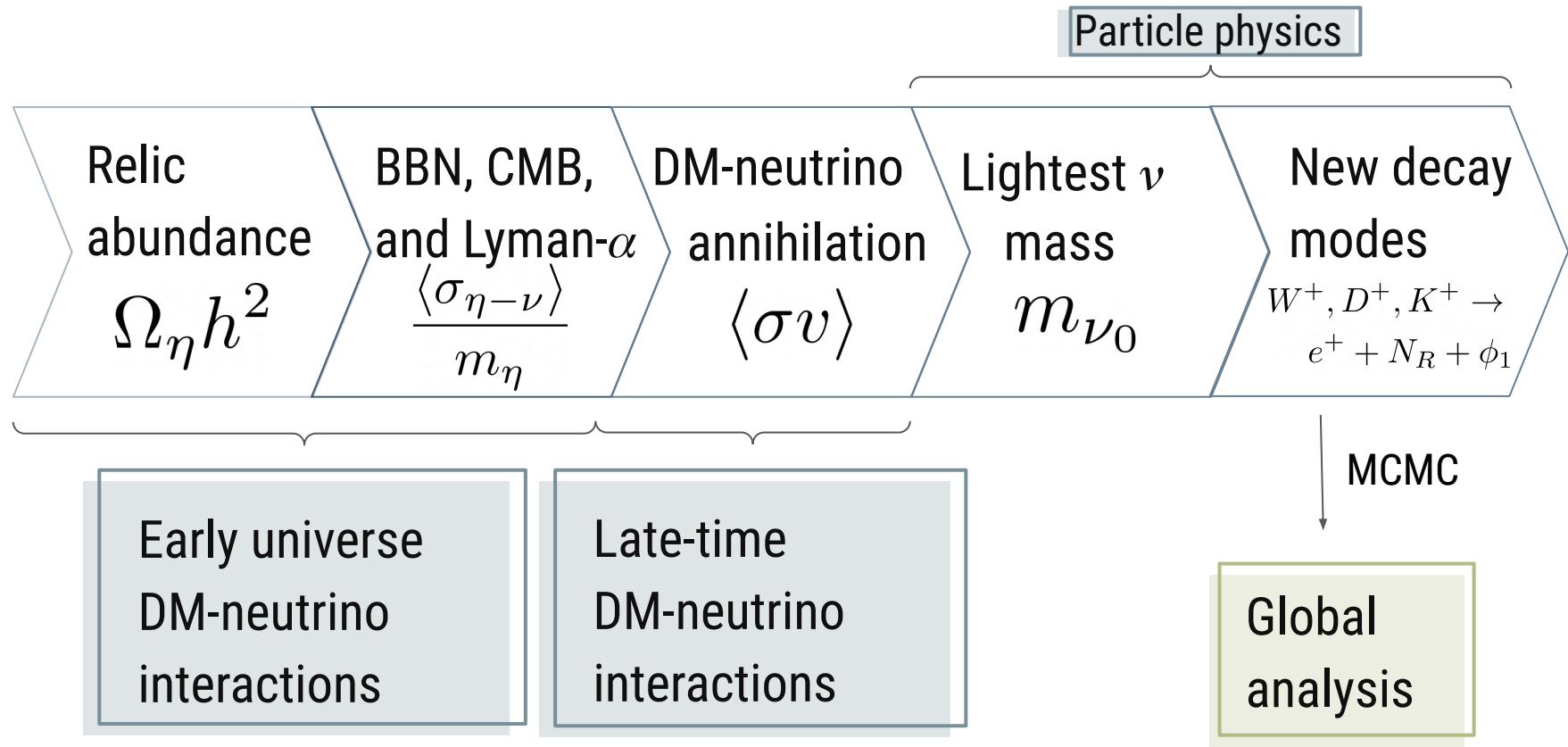
Scalar mediators mass splitting $\delta m_\phi = 1 - \frac{m_{\phi_2}}{m_{\phi_1}}$

Neutral singlet mediator N

Böhm, C. et al. (2007). arXiv: 0612228

Couplings Y_ν

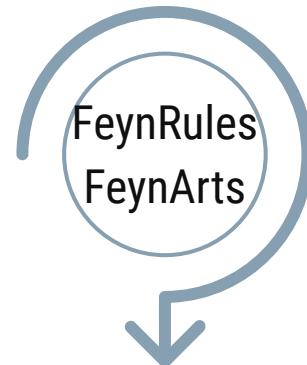
The Dark Matter Escape Room



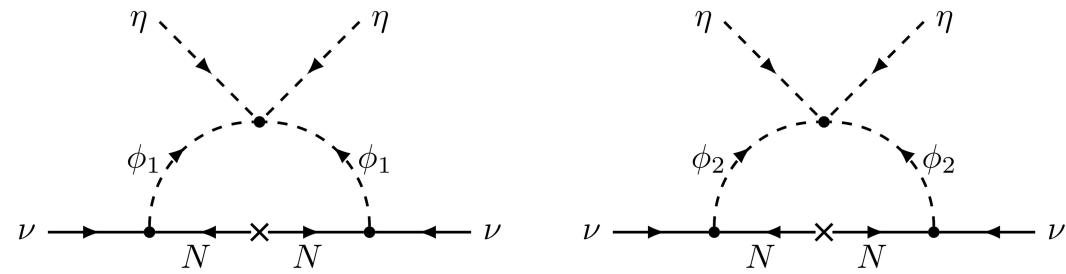
First Test: Dark Matter Relic Abundance

Interaction Lagrangian

$$-\mathcal{L}_{\text{int}} = \left[\frac{Y_\nu}{\sqrt{2}} \bar{\nu}(\phi_1 + i\phi_2) N_R + h.c. \right] + \frac{\lambda}{4} \eta^2 (\phi_1^2 - \phi_2^2) + \frac{1}{2} m_{\phi_1}^2 \phi_1^2 + \frac{1}{2} m_{\phi_2}^2 \phi_2^2$$



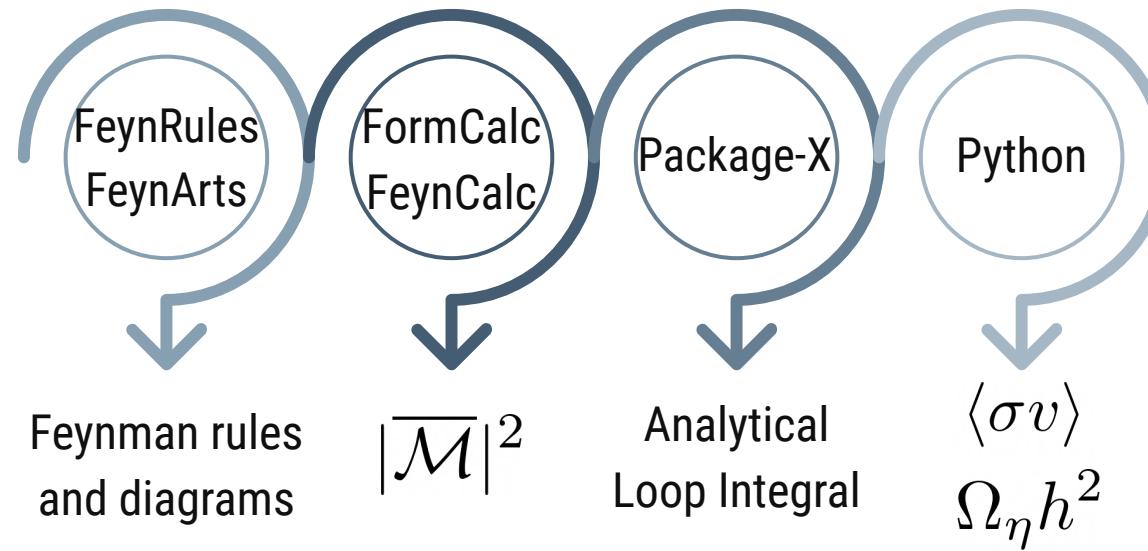
Feynman rules
and diagrams



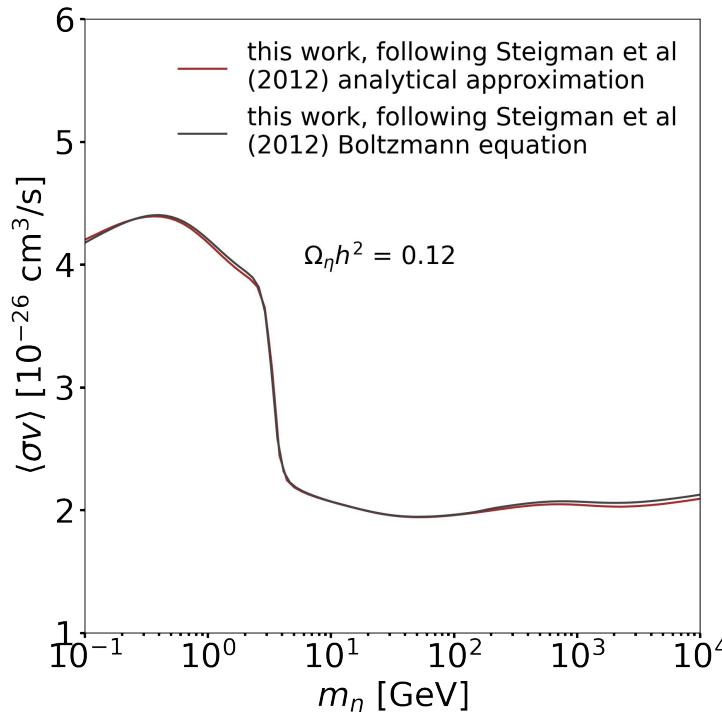
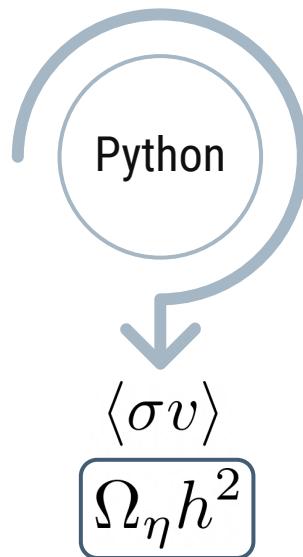
First Test: Dark Matter Relic Abundance

Interaction Lagrangian

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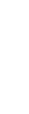


First Test: Dark Matter Relic Abundance



Boltzmann equation - Stiff ODE

$$\frac{dY}{dx} = \frac{s\langle\sigma v\rangle}{Hx} \left[1 + \frac{1}{3} \frac{d(\ln g_s)}{d(\ln T)} \right] (Y_{eq}^2 - Y^2)$$

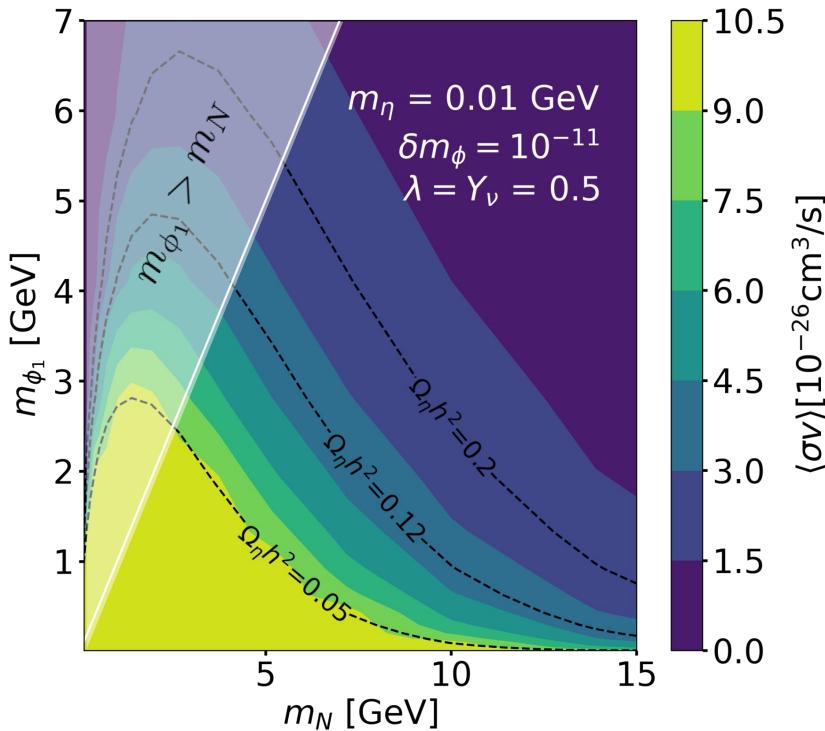


Asymptotic solutions to freeze-out



Analytical approximation

First Test: Dark Matter Relic Abundance



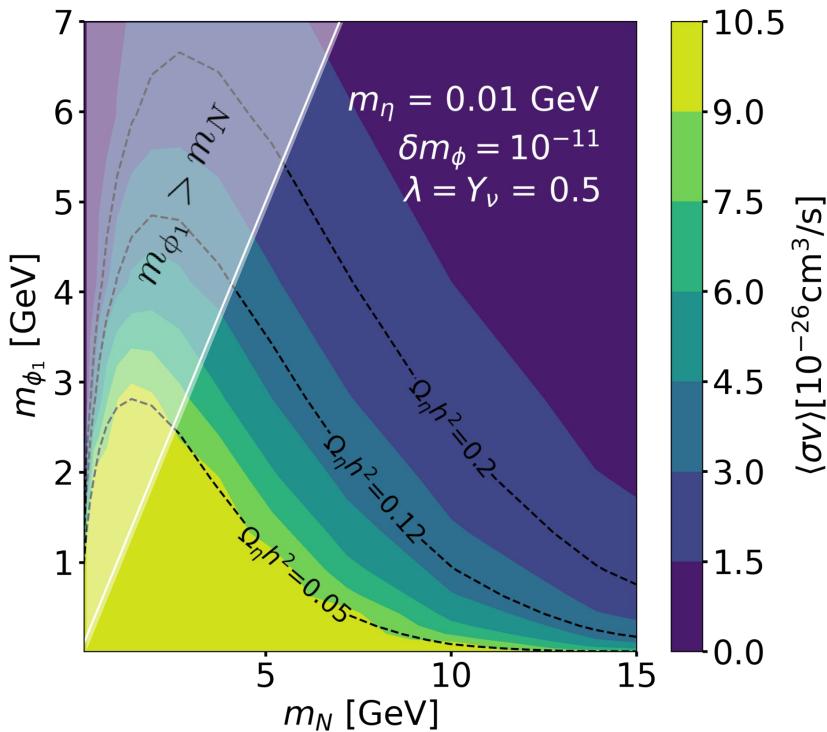
Imposing that

$$m_N > m_{\phi_1} > m_\eta$$

Parameters of the model

$$\theta = \{m_\eta, m_{\phi_1}, \delta m_\phi, m_N, \lambda, Y_\nu\}$$

First Test: Dark Matter Relic Abundance



Imposing that

$$m_N > m_{\phi_1} > m_\eta$$

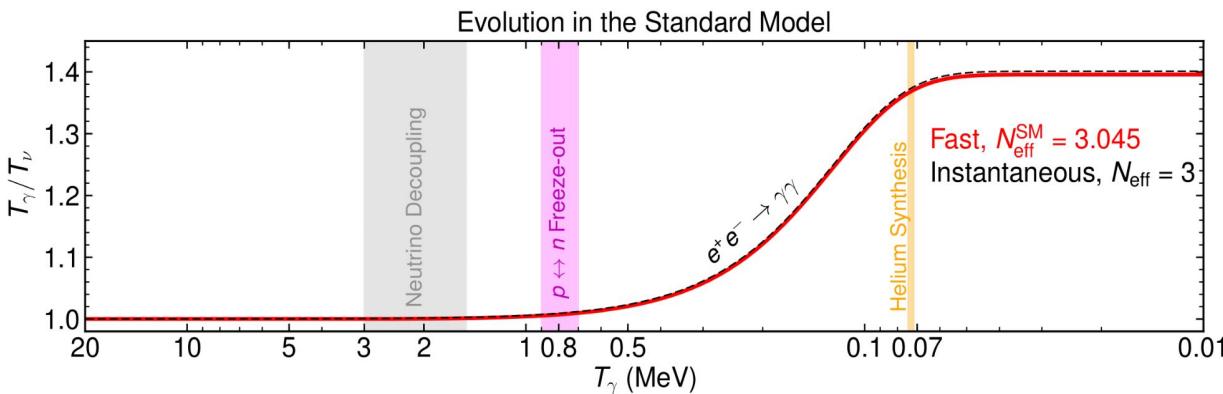
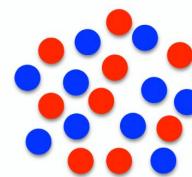
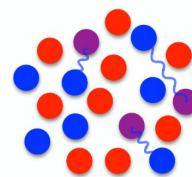
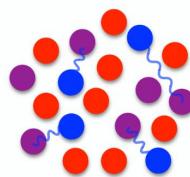
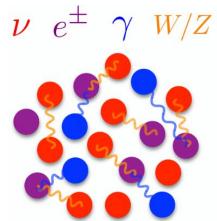
Constraint from Planck 2018

$$\Omega_c h^2 = 0.1200 \pm 0.0012$$

(68%, Planck TT,TE,EE + lowE + lensing)

Second Test: Primordial abundances and N_{eff}

Big Bang Nucleosynthesis (BBN)

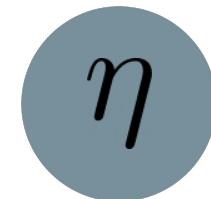
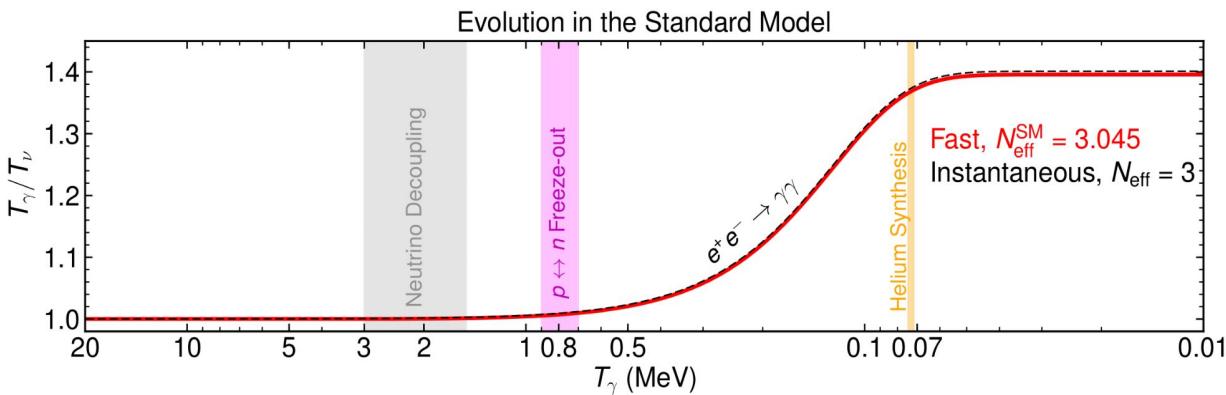
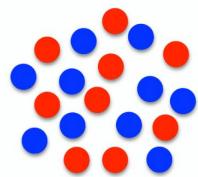
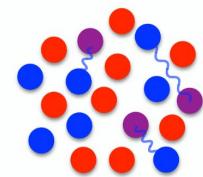
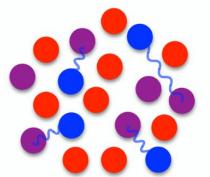
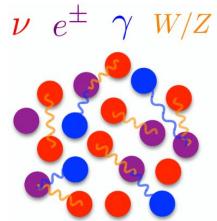


$$T_\gamma/T_\nu = (11/4)^{1/3}$$

$$\rho_{\text{rad}} = \rho_\gamma \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{\frac{4}{3}} N_{\text{eff}} \right]$$

Second Test: Primordial abundances and N_{eff}

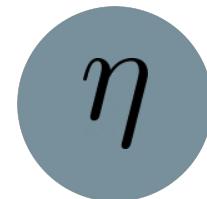
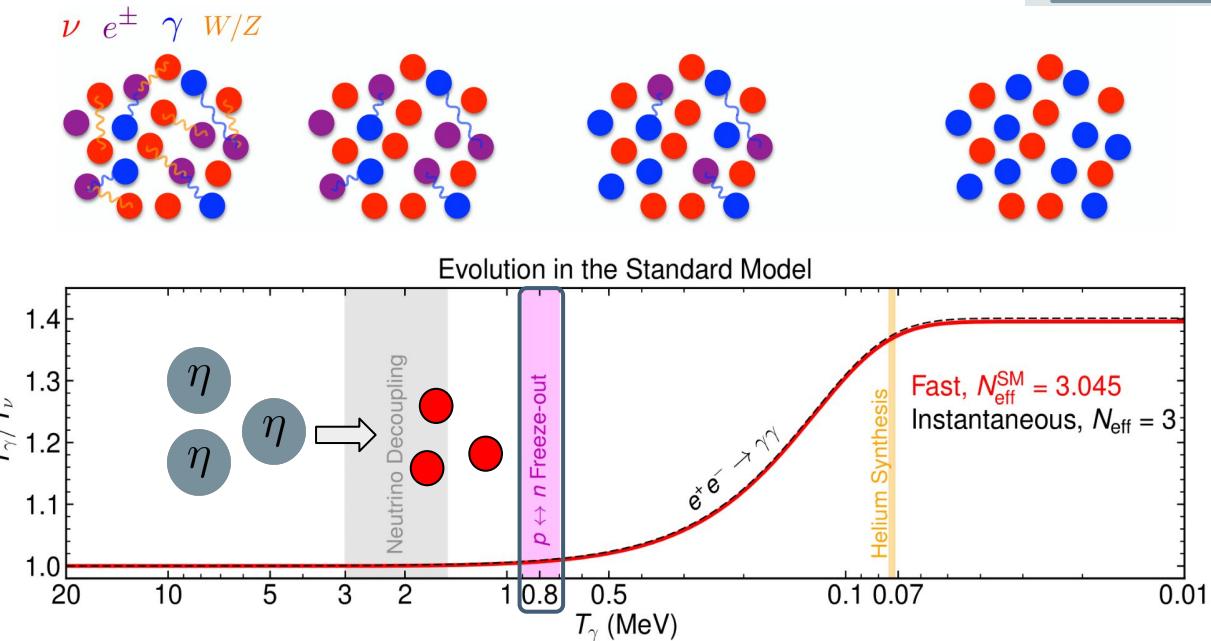
BBN and light dark matter



$$m_\eta \leq 20 \text{ MeV}$$

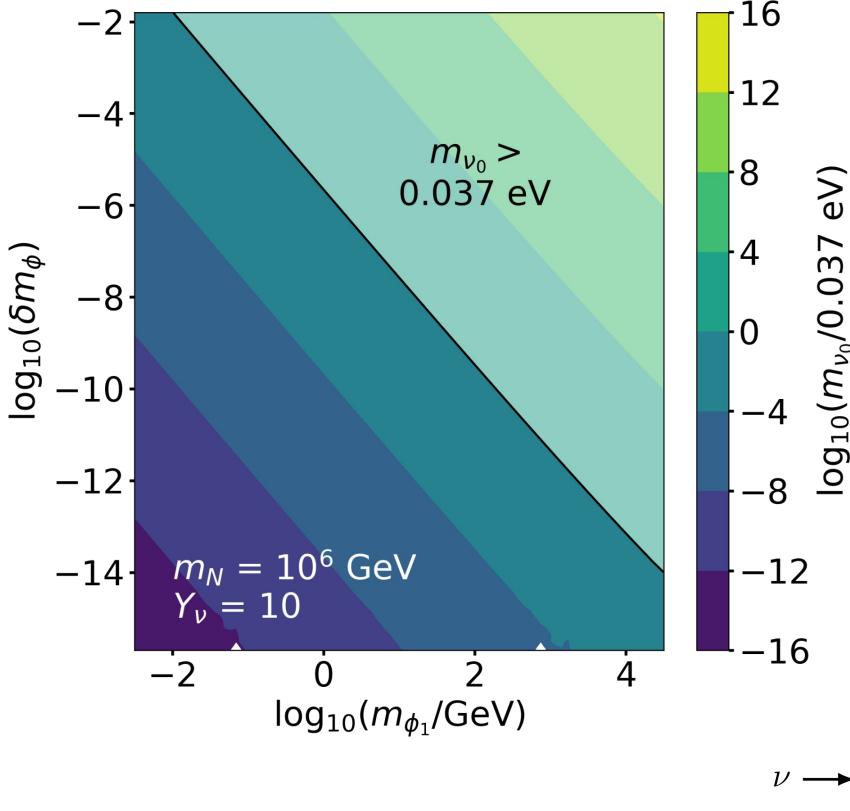
Second Test: Primordial abundances and N_{eff}

BBN and light dark matter



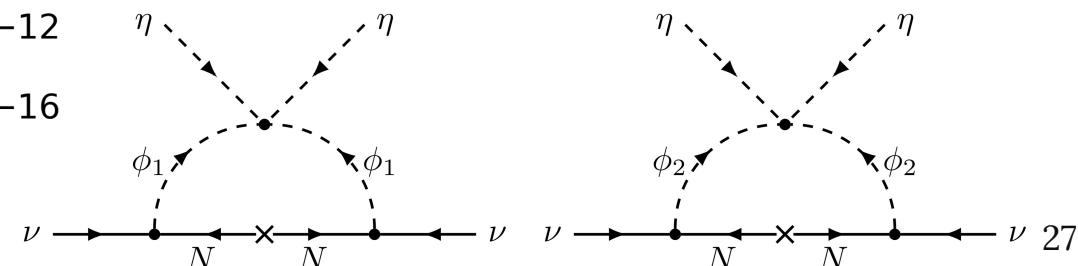
$$\begin{aligned} m_\eta &\leq 20 \text{ MeV} \\ Y_P & \quad Y_D \quad N_{\text{eff}} \end{aligned}$$

Fourth test: Adding neutrino masses

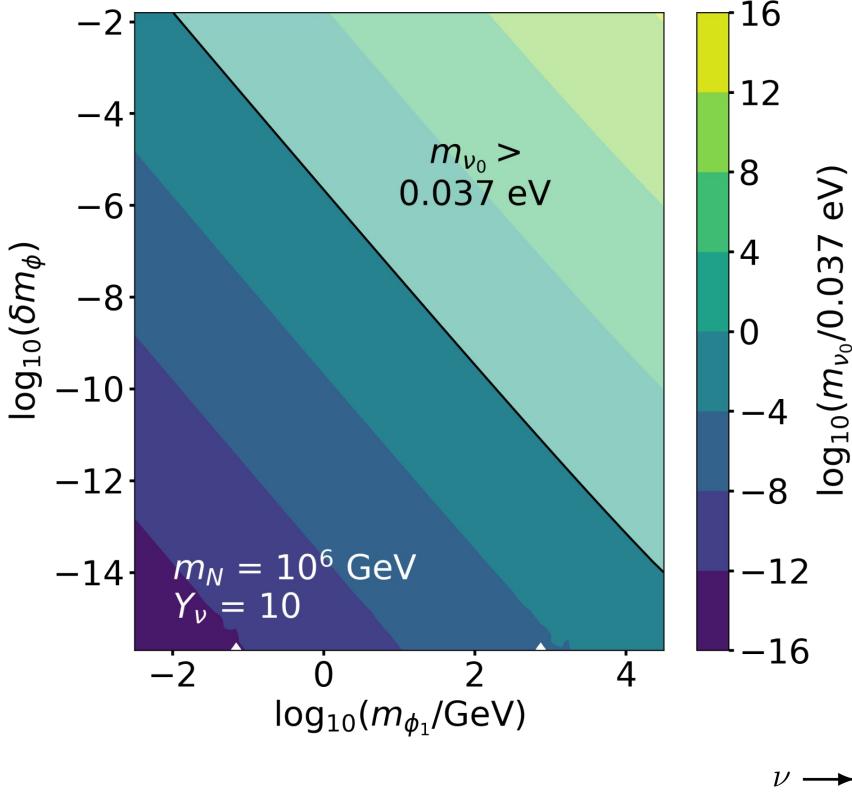


$$m_\nu = \frac{Y_\nu^2}{32\pi^2} m_N \left[\frac{m_{\phi_1}^2}{(m_N^2 - m_{\phi_1}^2)} \ln \left(\frac{m_N^2}{m_{\phi_1}^2} \right) - \frac{m_{\phi_2}^2}{(m_N^2 - m_{\phi_2}^2)} \ln \left(\frac{m_N^2}{m_{\phi_2}^2} \right) \right]$$

Böhm, C. et al. (2007). arXiv: 0612228



Fourth test: Adding neutrino masses

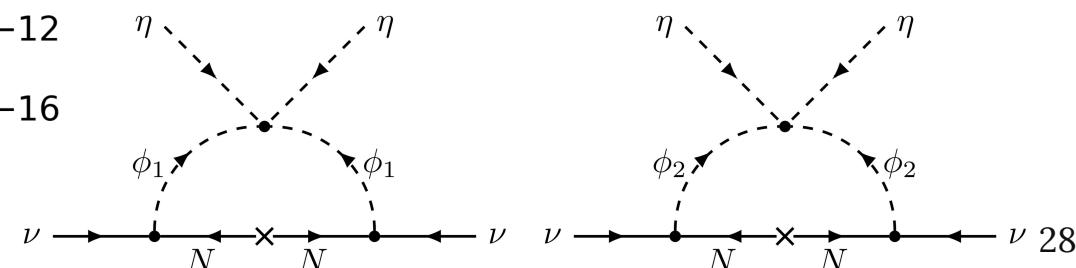


$$m_\nu = \frac{Y_\nu^2}{32\pi^2} m_N \left[\frac{m_{\phi_1}^2}{(m_N^2 - m_{\phi_1}^2)} \ln \left(\frac{m_N^2}{m_{\phi_1}^2} \right) - \frac{m_{\phi_2}^2}{(m_N^2 - m_{\phi_2}^2)} \ln \left(\frac{m_N^2}{m_{\phi_2}^2} \right) \right]$$

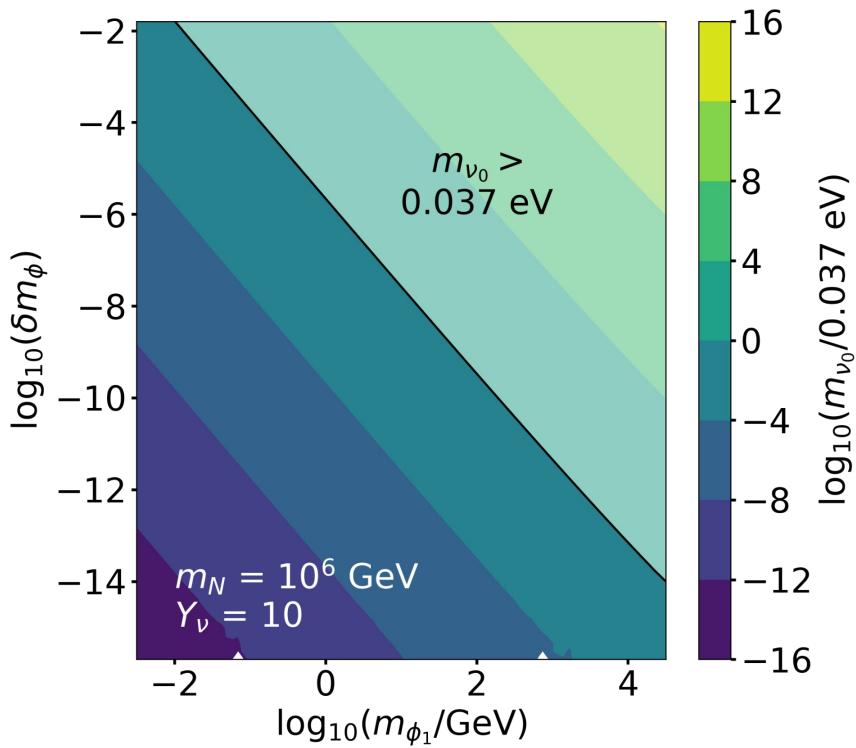
$$m_\nu \approx m_{\phi_1}^2 - m_{\phi_2}^2$$

$$\delta m_\phi = 1 - \frac{m_{\phi_2}}{m_{\phi_1}}$$

Böhm, C. et al. (2007). arXiv: 0612228



Fourth test: Adding neutrino masses

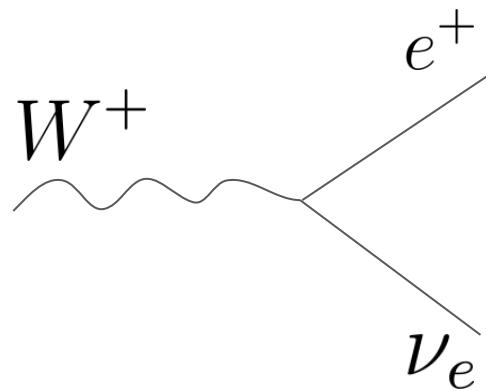


Mass of the lightest neutrino

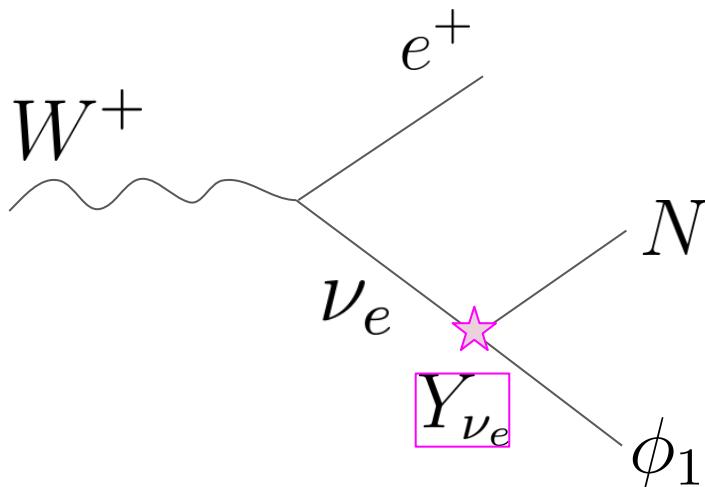
$$m_{\nu_0} < 0.037 \text{ eV}$$

95% C.L., Normal Ordering. The GAMBIT Cosmology Workgroup. (2021). arXiv: 2009.03287

Fifth test: New decay modes



Fifth test: New decay modes



W boson, D meson and Kaon decays

$$\Gamma_{W \rightarrow e, N, \phi_1} < 0.042 \rightarrow Y_{\nu_e} \lesssim 4$$

$$m_K < m_{\phi_1} + m_N < m_D \rightarrow Y_{\nu_e} \lesssim 0.4$$

$$m_{\phi_1} + m_N < m_K \rightarrow Y_{\nu_e} \lesssim 3 \times 10^{-3}$$

Fairbairn, M. and Alvey, J.B.G. (2019) arXiv: 1902.01450

Charged mesons \rightarrow KLOE, NA62 data

DSNB anti-neutrino SK search

SK – $\bar{\nu}_e$, $\langle \sigma v \rangle$

$$27 < m_\chi < 30 \text{ MeV}$$

Argüelles, C.A. et al. (2021). arXiv: 1912.09486

CMB & Matter Power Spectrum

$$\sigma_{\text{DM}-\nu,0} \lesssim 10^{-45} (m_{\text{DM}}/\text{GeV}) \text{ cm}^2$$

$$\sigma_{\text{DM}-\nu} \propto T^2$$

Wilkinson, R.J. et al. (2014). arXiv: 1401.7597

BBN primordial abundances

$$N_{\text{eff}}, m_\eta \leq 20 \text{ MeV}$$

Obtained using AlterBBN

New decay modes

Fairbairn, M., Alvey, J.
arXiv: 1902.01450

$$\Gamma_{W \rightarrow e, N, \phi_1} < 0.042 \rightarrow Y_{\nu_e} \lesssim 4$$

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Relic abundance

$$\Omega_c h^2 = 0.1200 \pm 0.0012$$

(68%, Planck TT,TE,EE + lowE + lensing)

Mass of the lightest neutrino

$$m_{\nu_0} < 0.037 \text{ eV}$$

95% C.L., Normal ordering. The GAMBIT Cosmology Workgroup. (2021). arXiv: 2009.03287

DSNB anti-neutrino SK search

$$-2 \ln \mathcal{L}_{\text{ann}} = \left(\frac{-\langle \sigma v \rangle}{\langle \sigma v \rangle_{\text{data}}} \right)^2$$

Argüelles, C.A. et al. (2021). arXiv: 1912.09486

CMB & Matter Power Spectrum

$$-2 \ln \mathcal{L}_{\text{sc}} = \left(\frac{-\langle \sigma_{\eta-\nu} \rangle / m_\eta}{10^{-45} \text{cm}^2 / \text{GeV}} \right)^2$$

Wilkinson, R.J. et al. (2014). arXiv: 1401.7597

BBN primordial abundances

$$-2 \ln \mathcal{L}_{N_{\text{eff}}} = \chi^2$$

Obtained using AlterBBN

Relic abundance

$$-2 \ln \mathcal{L}_{\text{RA}} = \left(\frac{\Omega_{\text{DM}} h^2 - \Omega_\eta h^2}{0.0012} \right)^2$$

(68%, Planck TT,TE,EE + lowE + lensing)

New decay modes

$$-2 \ln \mathcal{L}_{\text{decays}} = \left(\frac{-Y_\nu}{3 \times 10^{-3}} \right)^2 + \left(\frac{-Y_\nu}{0.4} \right)^2 + \left(\frac{-\Gamma_W}{0.042} \right)^2$$

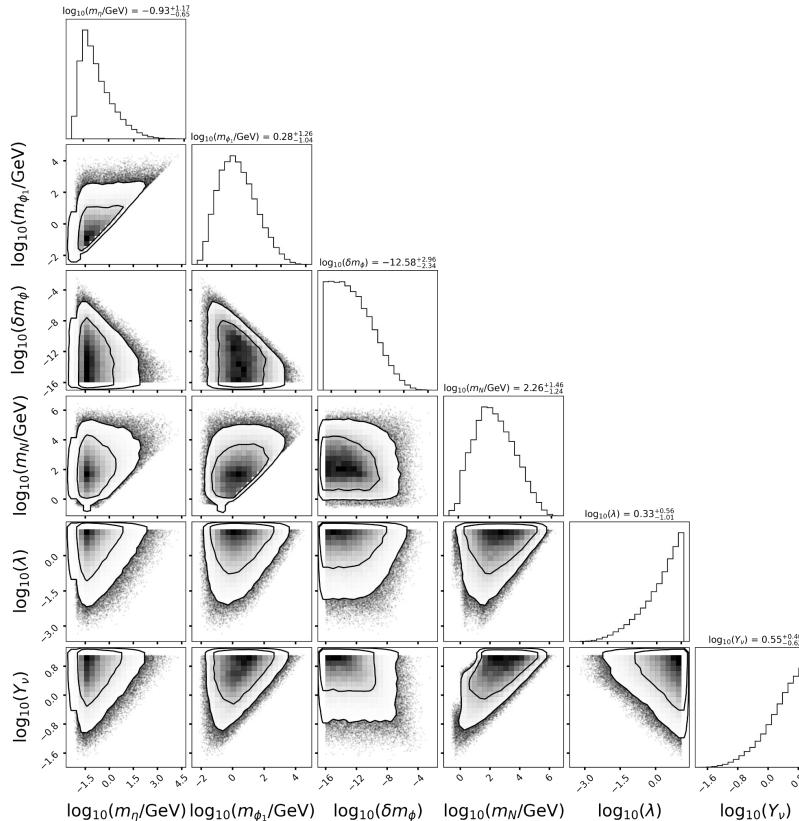
Fairbairn, M. and Alvey, J.B.G. (2019) arXiv: 1902.01450

Mass of the lightest neutrino

$$-2 \ln \mathcal{L}_{m_{\nu_0}} = \left(\frac{-m_{\nu_0}}{0.037 \text{ eV}} \right)^2$$

95% C.L., Normal ordering. The GAMBIT Cosmology Workgroup. (2021). arXiv: 2009.03287

Final Test: Global Analysis



Posterior distribution

Using emcee in the Frontenac cluster

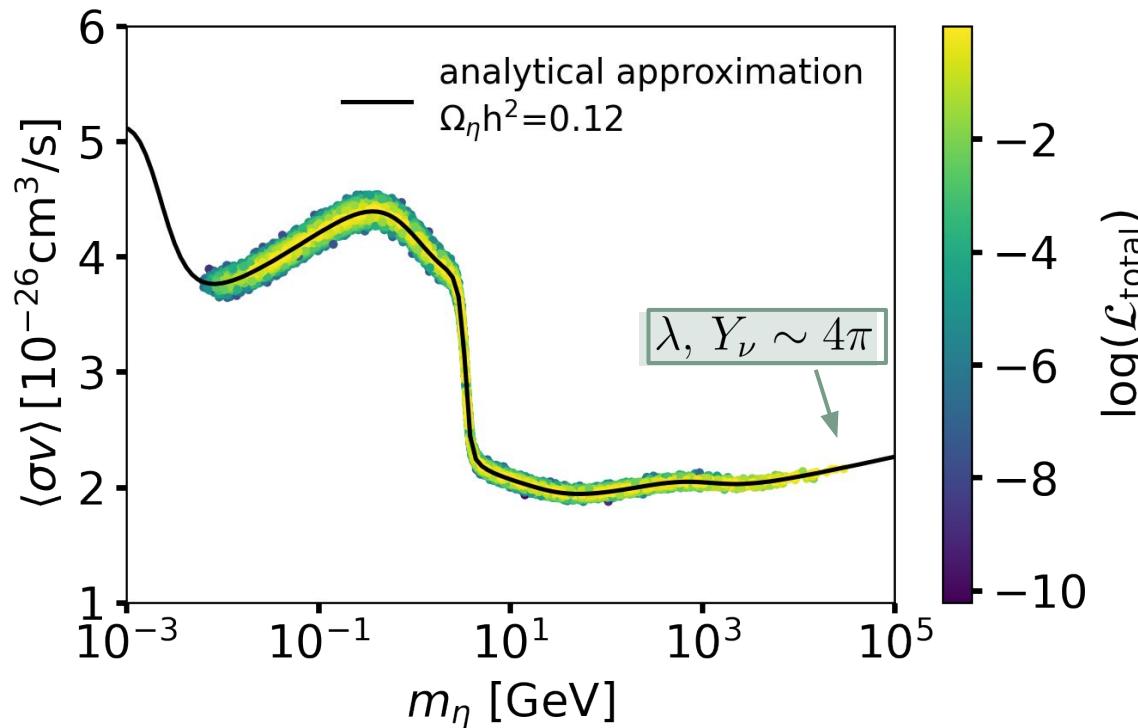
Prior $m_N > m_{\phi_1} > m_\eta$

68.27% and 95.45% C.R.

Strongest constraints

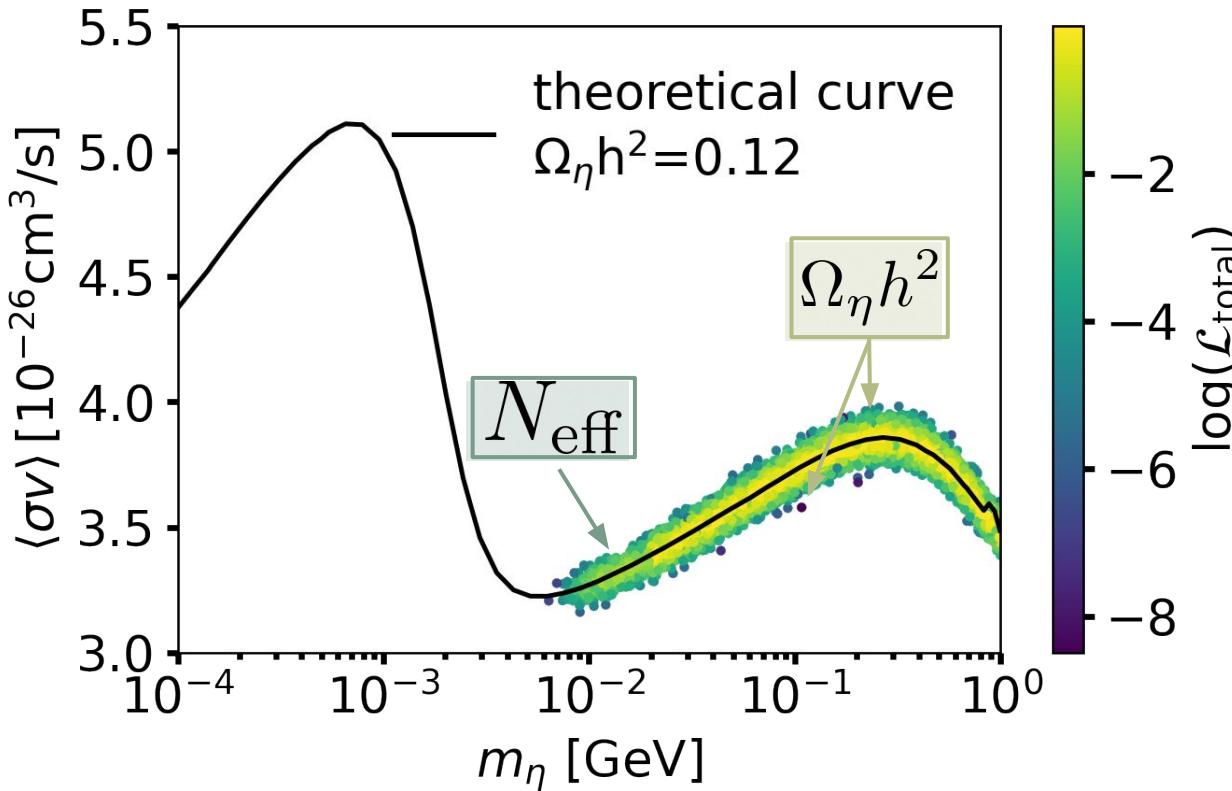
$N_{\text{eff}} + m_{\nu_0} + \Omega_\eta h^2$
+new decays

Total likelihood over model prediction

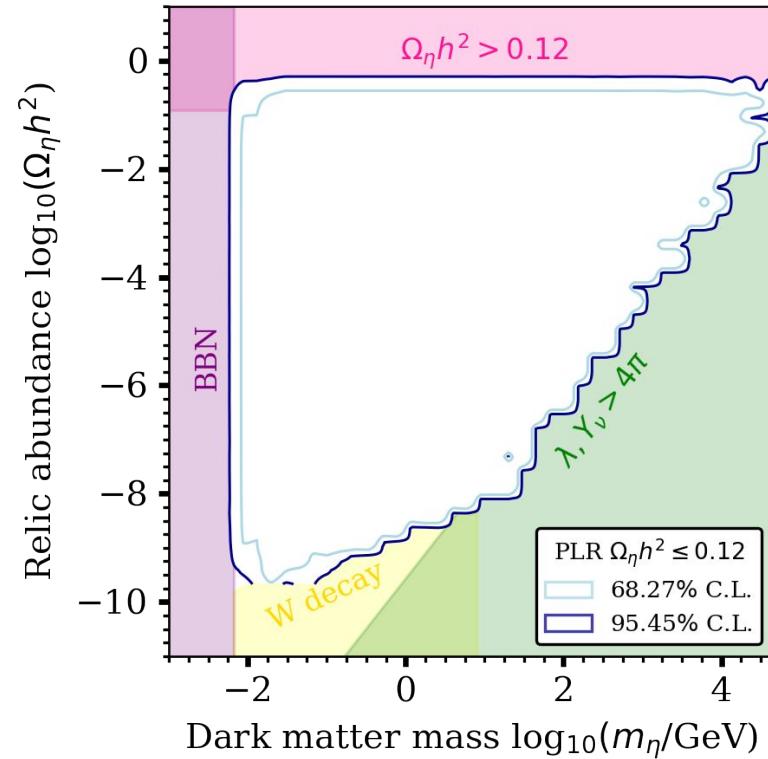
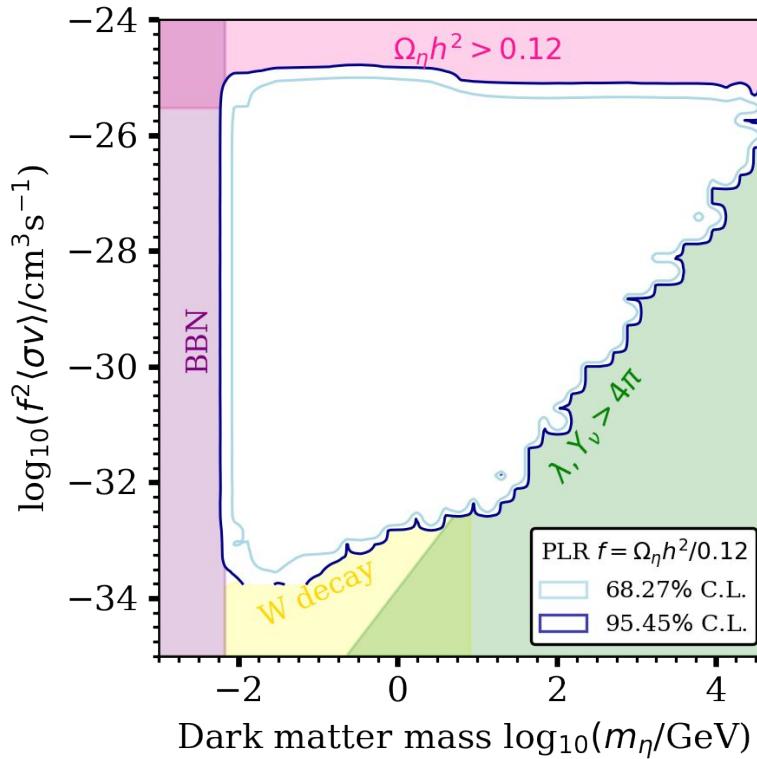


Total likelihood over model prediction

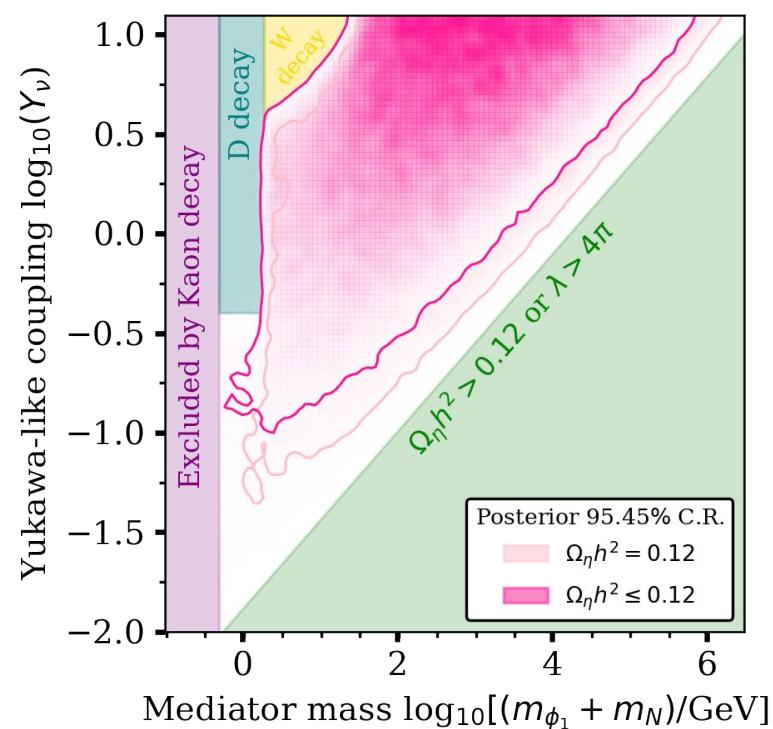
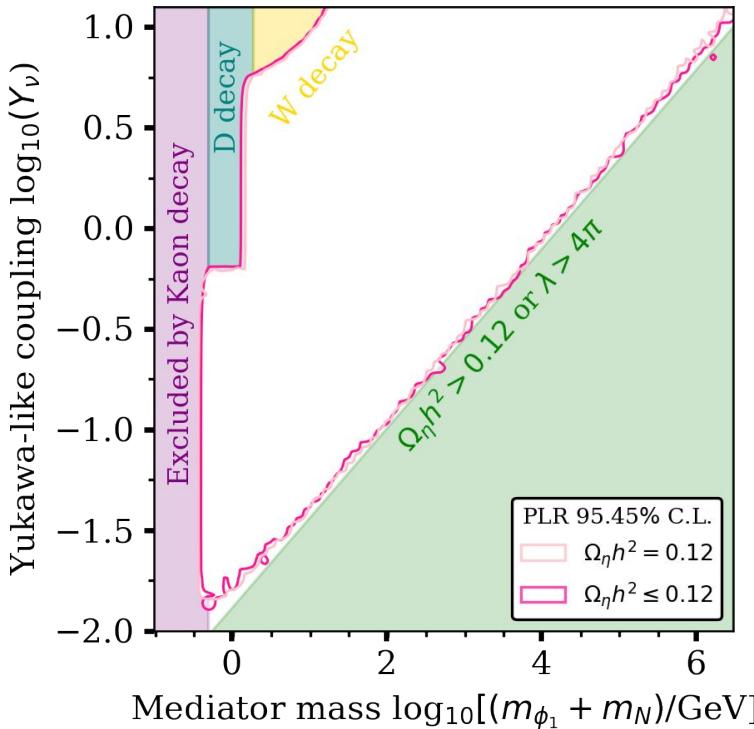
sub-GeV zoom



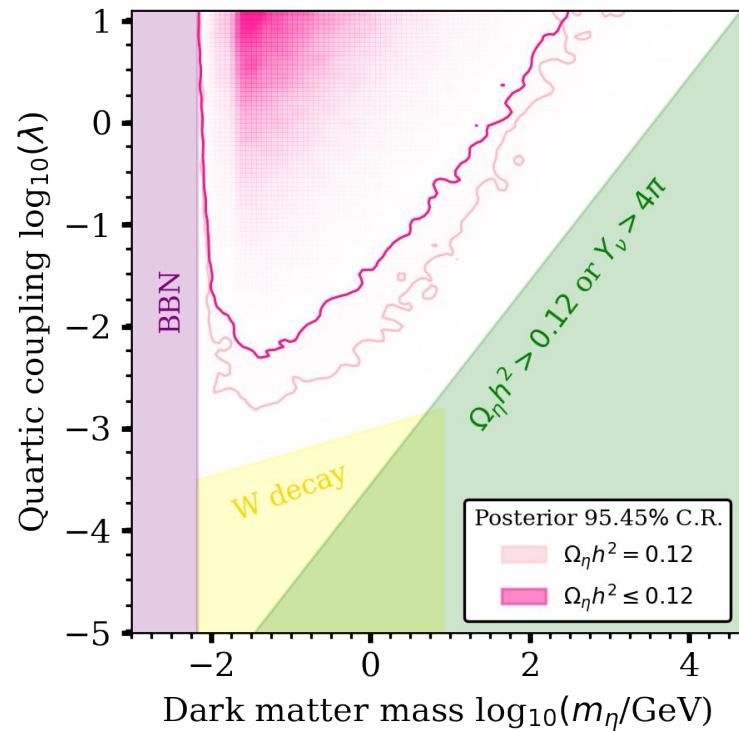
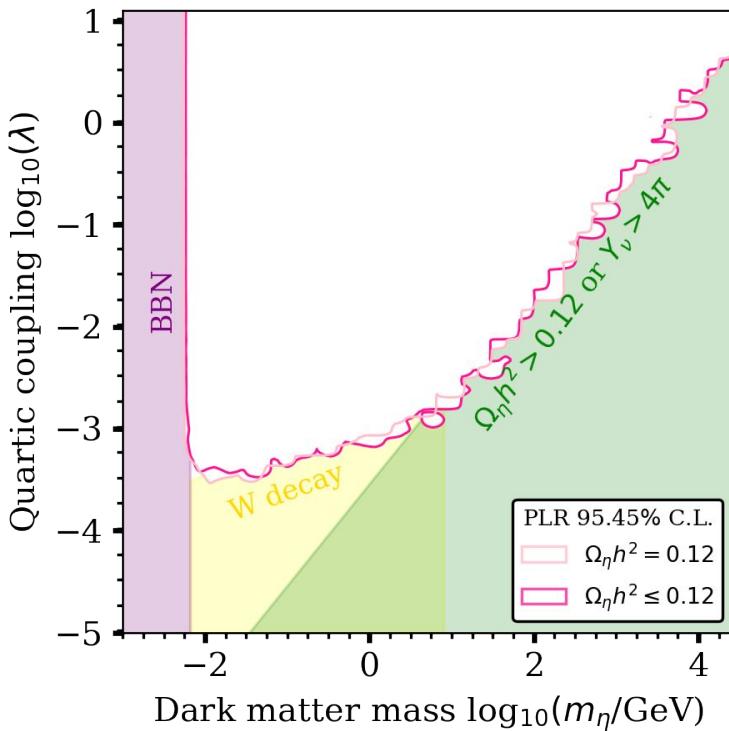
Final Test: Global Analysis



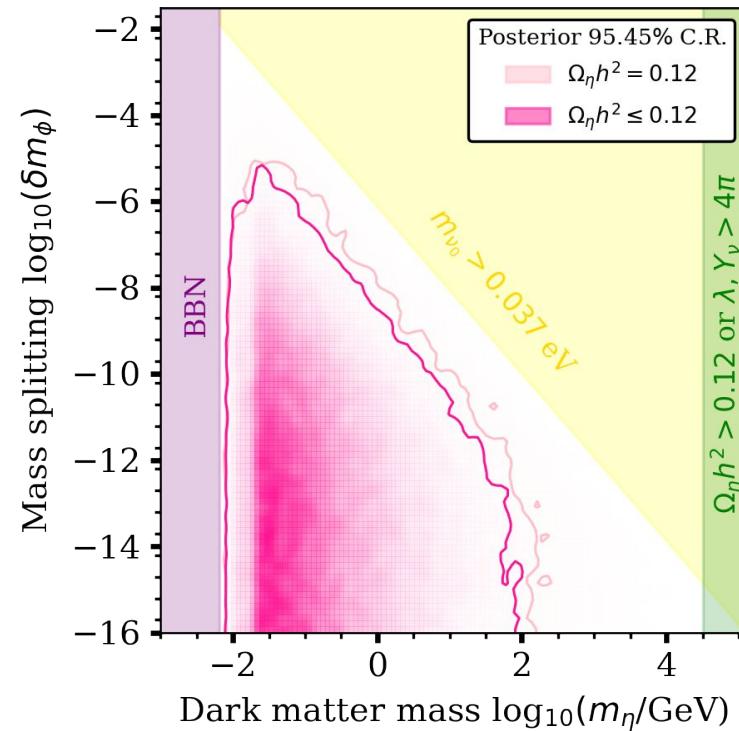
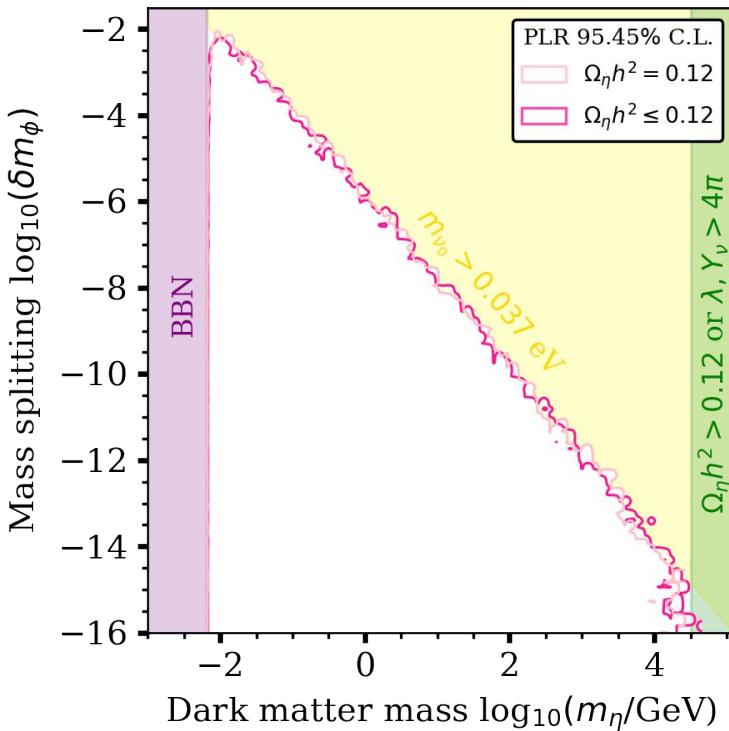
Final Test: Global Analysis



Final Test: Global Analysis



Final Test: Global Analysis

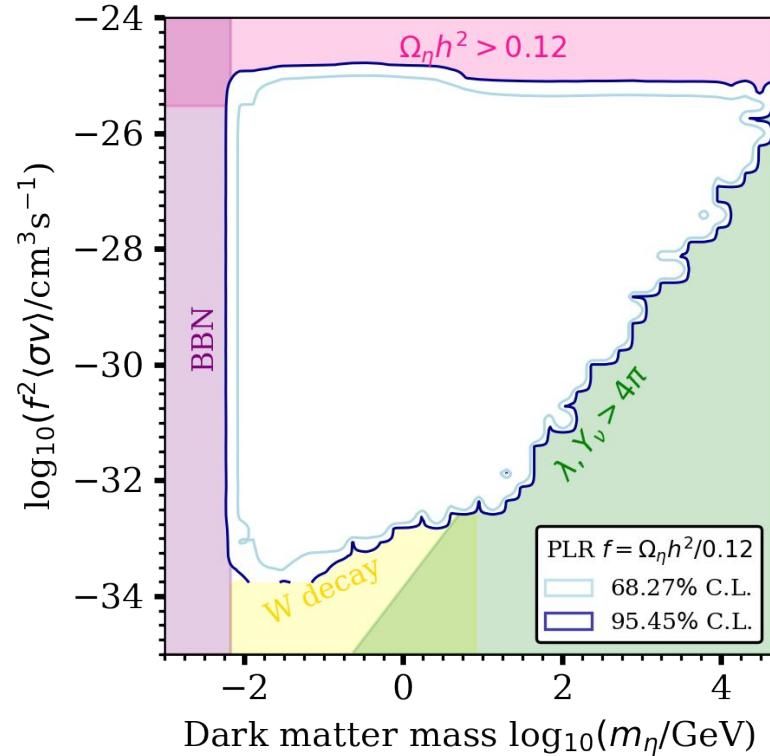


Summary of Results

$$\Omega_\eta h^2 \leq 0.12 \pm 0.0012$$

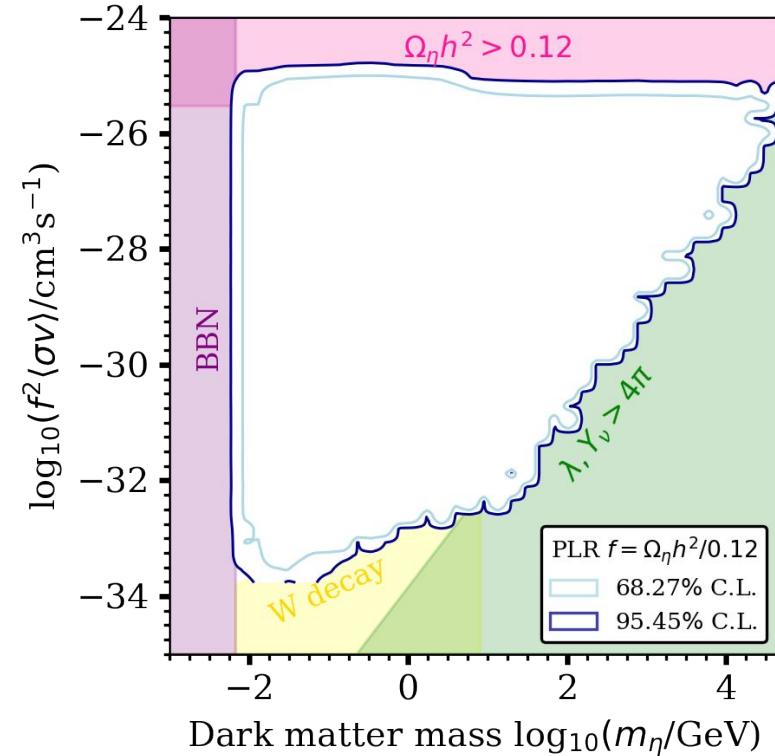
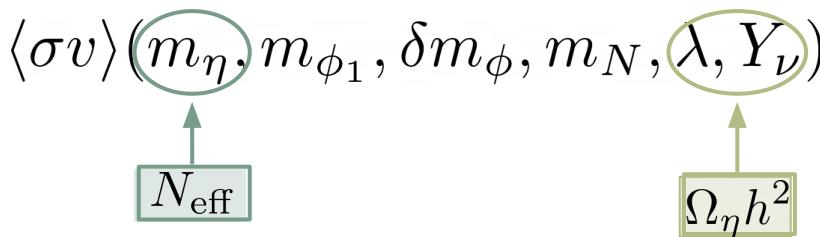
$$\langle\sigma v\rangle(m_\eta, m_{\phi_1}, \delta m_\phi, m_N, \lambda, Y_\nu)$$

N_{eff}



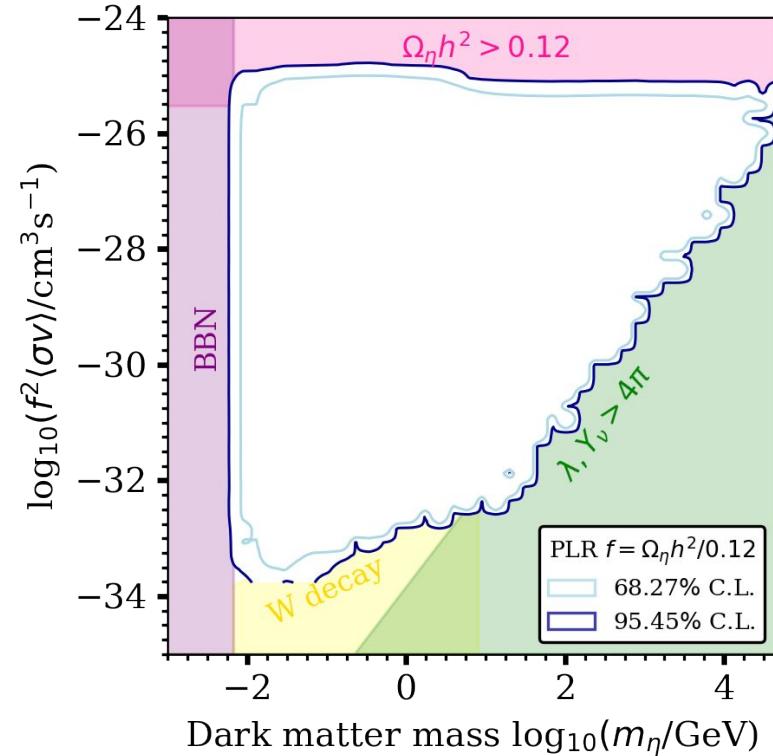
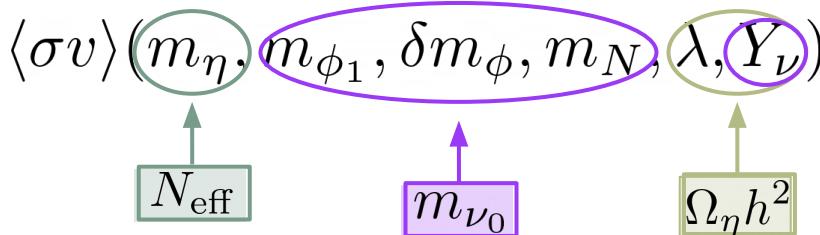
Summary of Results

$$\Omega_\eta h^2 \leq 0.12 \pm 0.0012$$



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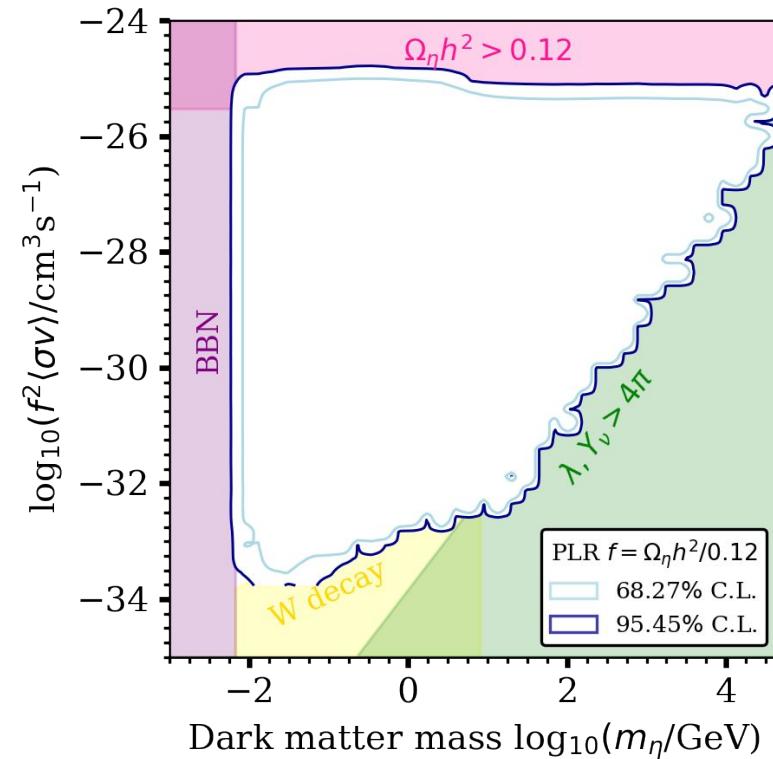
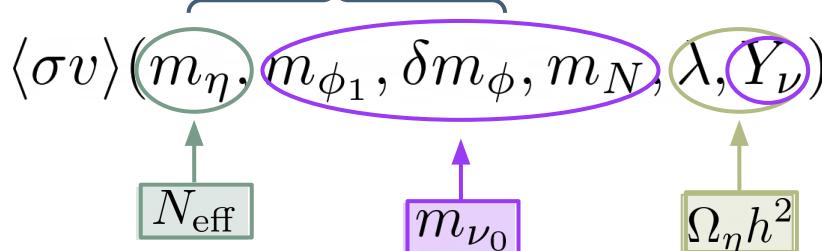
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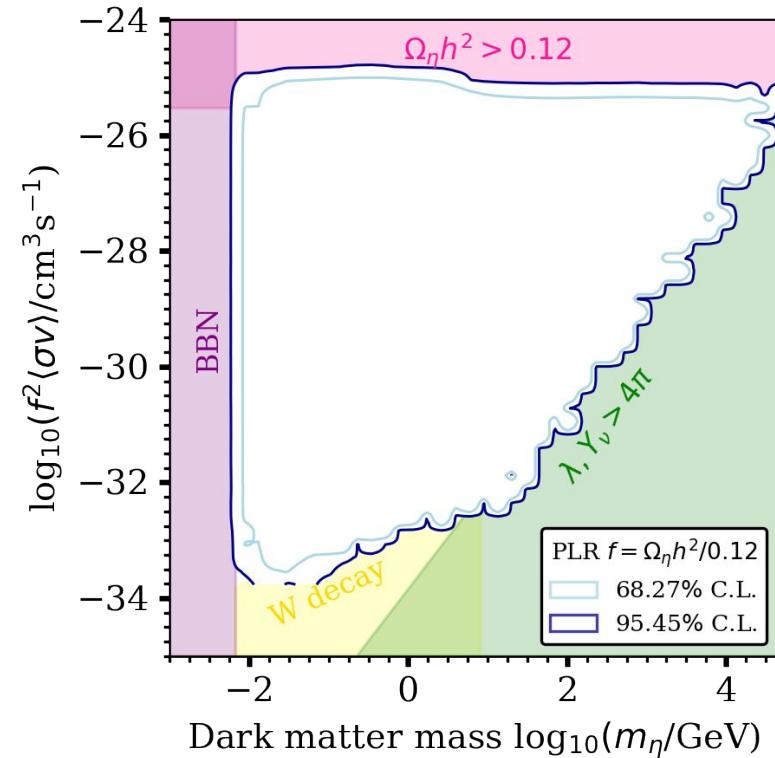
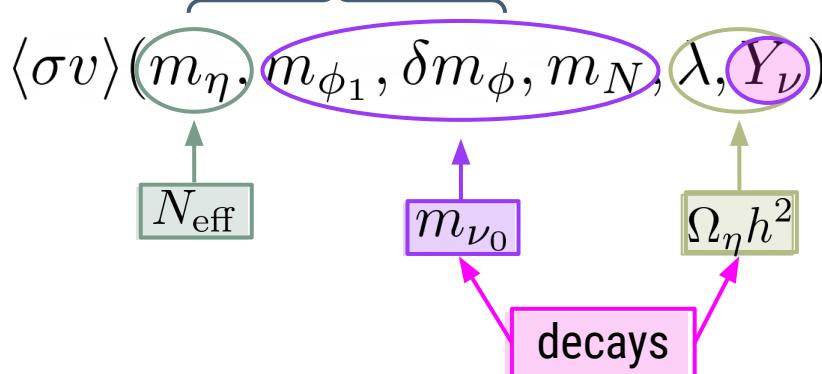
$$m_N > m_{\phi_1} > m_\eta$$



Summary of Results

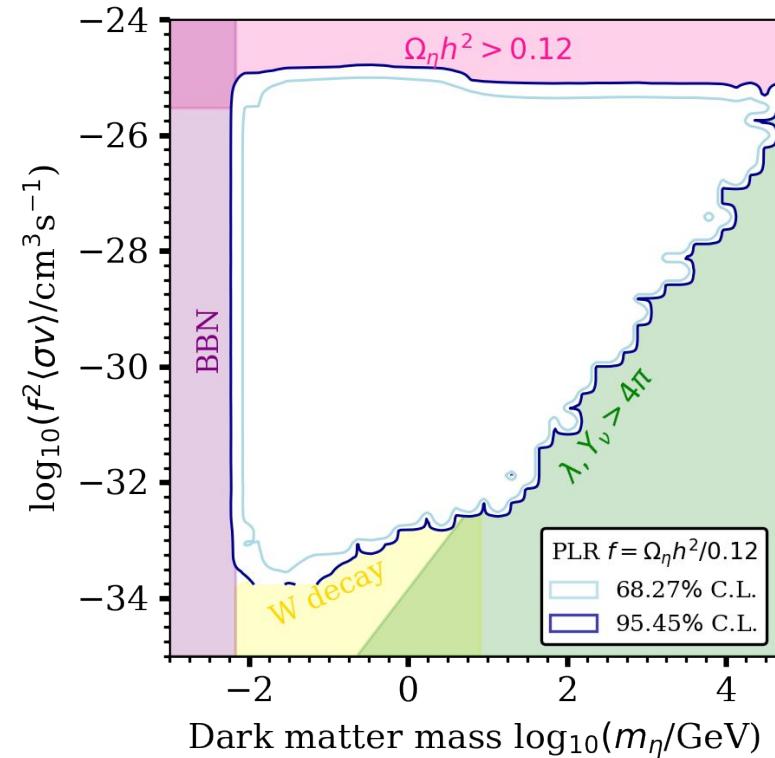
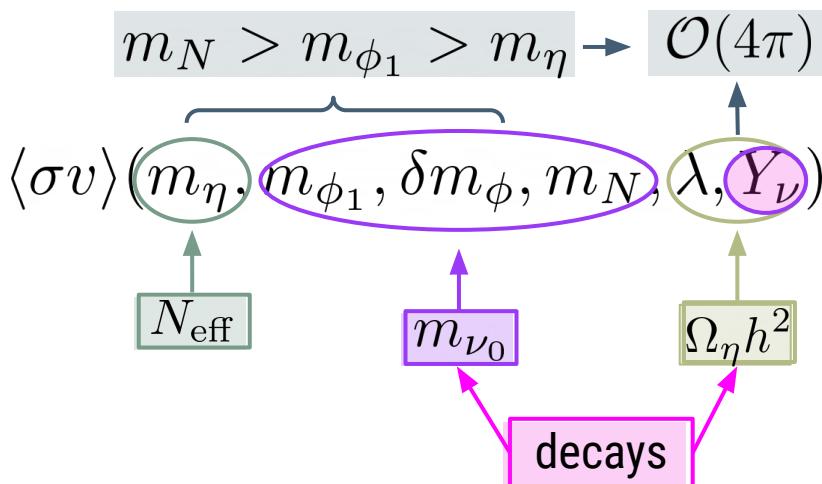
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Summary of Results

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Did this DM model escape the room?

Relic
abundance

$$\Omega_\eta h^2$$

BBN, CMB,
and Lyman- α

$$\frac{\langle \sigma_{\eta-\nu} \rangle}{m_\eta}$$

DM-neutrino
annihilation

$$\langle \sigma v \rangle$$

Lightest ν
mass

$$m_{\nu_0}$$

New decay
modes

$$W^+, D^+, K^+ \rightarrow e^+ + N_R + \phi_1$$

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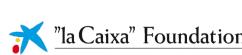
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Future work:

- Full flavour analysis
- Assisted freeze-out scenario



Thank you!



Relic
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 $\Omega_\eta h^2$

BBN, CMB,
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 $\frac{\langle \sigma_{\eta-\nu} \rangle}{m_\eta}$

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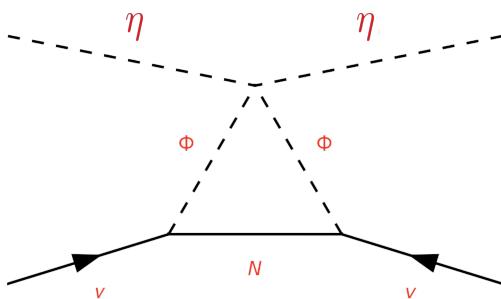
E-mail: karen.macias@csic.es

Co: Aaron Vincent, Gopolang Mohlabeng

BACKUP SLIDES

Second Test: DM-neutrino scattering

Thermally averaged
scattering cross-section



$$\langle\sigma\rangle_{\text{DM}-\nu} = \frac{\int d^3\mathbf{p}_\nu f_\nu \sigma}{\int d^3\mathbf{p}_\nu f_\nu}$$

Fermi-Dirac distribution

$$f_\nu(p_\nu) = \frac{1}{e^{p_\nu/T_\nu} + 1}$$

Strength parameter

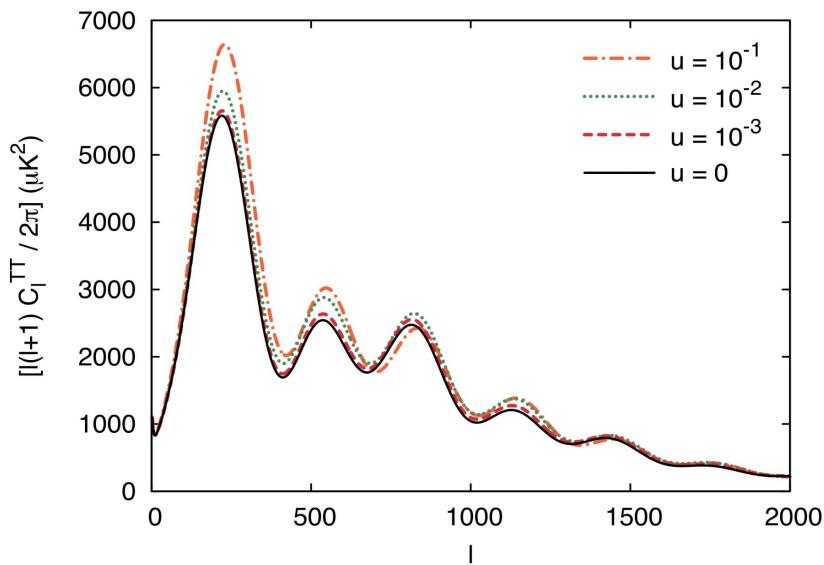
$$u \equiv \left[\frac{\langle\sigma\rangle_{\text{DM}-\nu}}{\sigma_{\text{Th}}} \right] \left[\frac{100 \text{ GeV}}{m_{\text{DM}}} \right]$$

Opacity parameter

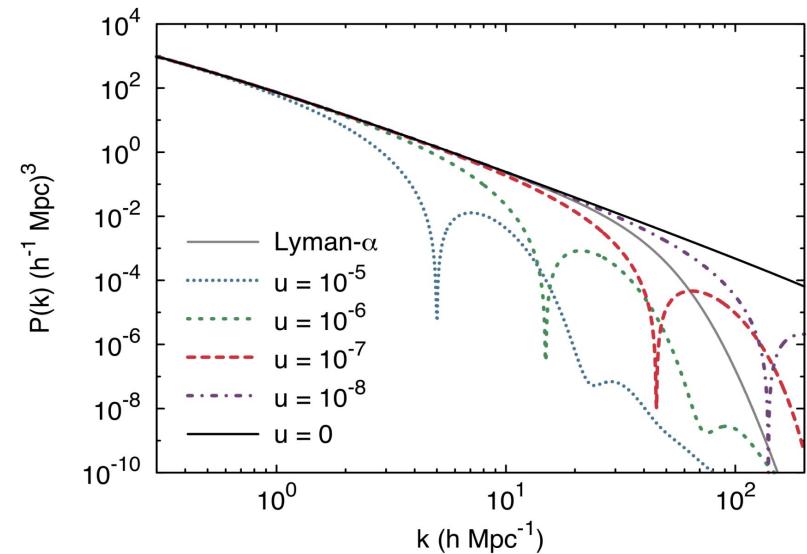
Wilkinson, R.J. et al. (2014). arXiv: 1401.7597

Second Test: DM-neutrino scattering

CMB Power Spectrum



Matter Power Spectrum



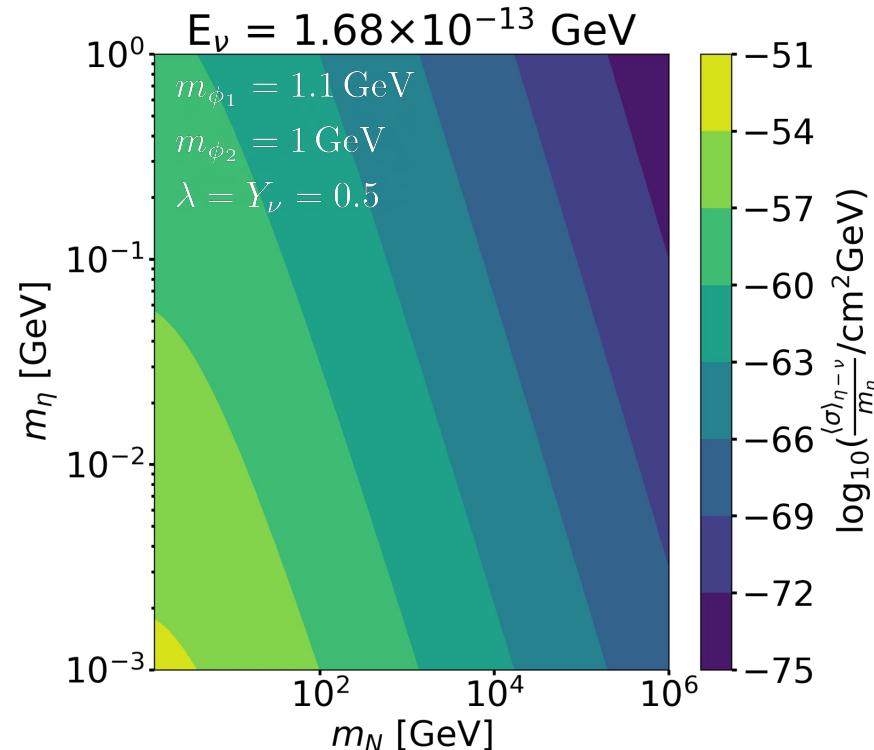
Second Test: DM-neutrino scattering

CMB & Matter Power Spectrum

$$\sigma_{\text{DM}-\nu,0} \lesssim 10^{-45} (m_{\text{DM}}/\text{GeV}) \text{ cm}^2$$

$$\sigma_{\text{DM}-\nu} \propto T^2$$

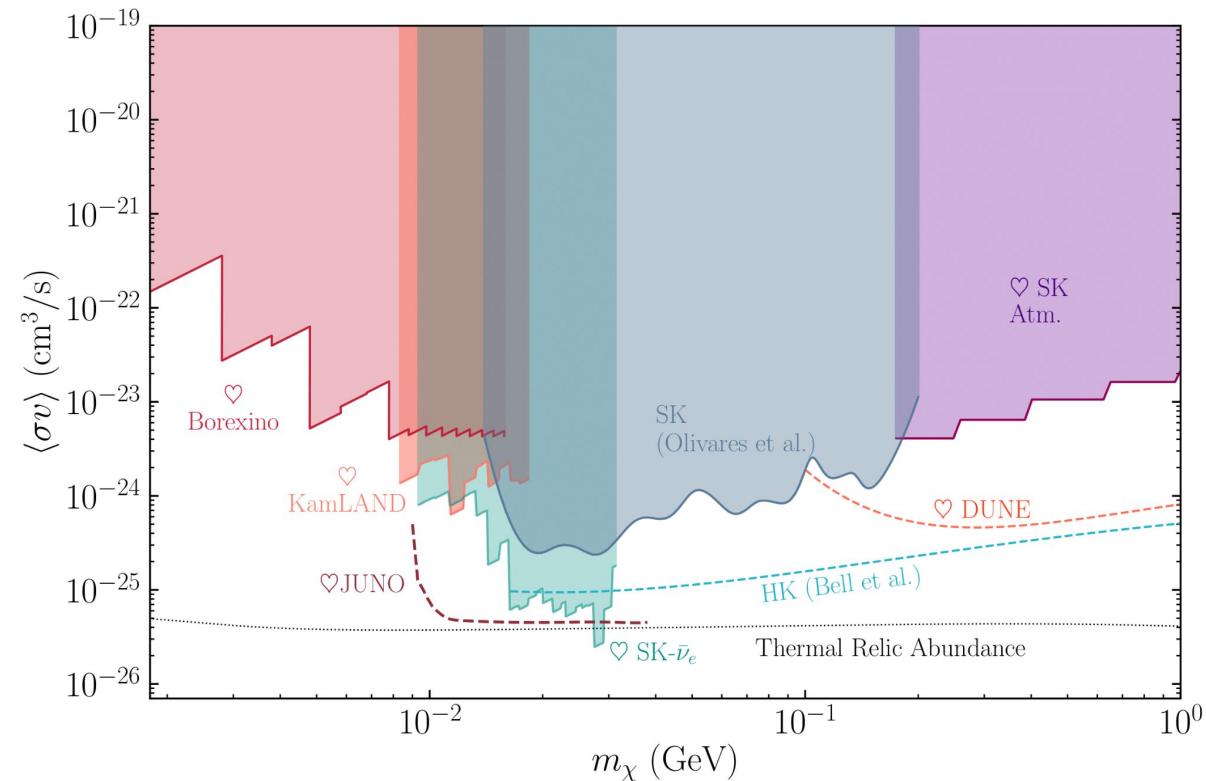
Wilkinson, R.J. et al. (2014). arXiv: 1401.7597



Third Test: Late-time DM annihilation

Strongest constraint
comes from the
electron antineutrino
DSNB search by
Super-Kamiokande

$27 < m_\chi < 30 \text{ MeV}$



Expressions in terms of Φ

FeynRules

Squared amplitude with
FormCalc / FeynCalc

$$-\mathcal{L}_{\text{int}} = (Y_\nu \bar{\nu} \Phi N_R + h.c.) + m_\Phi^2 |\Phi|^2 + \frac{1}{2} \mu^2 (\Phi^2 + (\Phi^\dagger)^2) + \frac{\lambda'}{2} \eta^2 |\Phi|^2 + \frac{\lambda}{2} \eta^2 \left(\frac{\Phi^2 + (\Phi^\dagger)^2}{2} \right).$$

$$|\mathcal{M}|_{\text{ann}}^2 = \frac{\lambda^2 Y_\nu^4 m_N^2 s}{128\pi^4} |C_0(0, s, 0, m_N^2, m_\Phi^2, m_\Phi^2)|^2$$

Analytical form of the
scalar Passarino-Veltman
integral with Package-X

$$\begin{aligned} C_0(0, 0, s, m_\Phi^2, m_N^2, m_\Phi^2) = & \\ & \frac{\text{DiLog}\left(\frac{2(m_N^2 - m_\phi^2)}{2m_N^2 - \sqrt{s(s-4m_\phi^2)} - 2m_\phi^2 + s}, s\right)}{s} + \frac{\text{DiLog}\left(\frac{2(m_N^2 - m_\phi^2)}{2m_N^2 + \sqrt{s(s-4m_\phi^2)} - 2m_\phi^2 + s}, s\right)}{s} \\ & - \frac{\text{DiLog}\left(\frac{2(m_N^2 - m_\phi^2 + s)}{2m_N^2 - \sqrt{s(s-4m_\phi^2)} - 2m_\phi^2 + s}, s\right)}{s} - \frac{\text{Li}_2\left(\frac{2(m_N^2 - m_\phi^2 + s)}{2m_N^2 - 2m_\phi^2 + s + \sqrt{s(s-4m_\phi^2)}}\right)}{s} \\ & + \frac{\text{Li}_2\left(\frac{(m_N^2 - m_\phi^2)(m_N^2 - m_\phi^2 + s)}{m_N^4 - 2m_\phi^2 m_N^2 + sm_N^2 + m_\phi^4}\right)}{s} - \frac{\text{Li}_2\left(\frac{(m_N^2 - m_\phi^2)^2}{m_N^4 - 2m_\phi^2 m_N^2 + sm_N^2 + m_\phi^4}\right)}{s} \end{aligned}$$

Expressions in terms of ϕ_1 and ϕ_2

FeynRules

Squared amplitude with
FormCalc / FeynCalc

$$-\mathcal{L}_{\text{int}} = (Y_\nu \bar{\nu} \Phi N_R + h.c.) + \frac{1}{2} m_{\phi_1}^2 \phi_1^2 + \frac{1}{2} m_{\phi_2}^2 \phi_2^2 + \frac{\lambda'}{4} \eta^2 (\phi_1^2 + \phi_2^2) + \frac{\lambda}{4} \eta^2 (\phi_1^2 - \phi_2^2)$$

$$|\overline{\mathcal{M}}|_{\text{ann}}^2 = \frac{\lambda^2 m_N^2 s Y_\nu^4}{512 \pi^4} (C_0(\phi_1) + C_0(\phi_2)) (C_0^*(\phi_1) + C_0^*(\phi_2))$$

Analytical form of the
scalar Passarino-Veltman
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$$\begin{aligned} C_0(0, 0, s, m_\Phi^2, m_N^2, m_\Phi^2) = & \\ & \frac{\text{DiLog}\left(\frac{2(m_N^2 - m_\phi^2)}{2m_N^2 - \sqrt{s(s-4m_\phi^2)} - 2m_\phi^2 + s}, s\right)}{s} + \frac{\text{DiLog}\left(\frac{2(m_N^2 - m_\phi^2)}{2m_N^2 + \sqrt{s(s-4m_\phi^2)} - 2m_\phi^2 + s}, s\right)}{s} \\ & - \frac{\text{DiLog}\left(\frac{2(m_N^2 - m_\phi^2 + s)}{2m_N^2 - \sqrt{s(s-4m_\phi^2)} - 2m_\phi^2 + s}, s\right)}{s} - \frac{\text{Li}_2\left(\frac{2(m_N^2 - m_\phi^2 + s)}{2m_N^2 - 2m_\phi^2 + s + \sqrt{s(s-4m_\phi^2)}}\right)}{s} \\ & + \frac{\text{Li}_2\left(\frac{(m_N^2 - m_\phi^2)(m_N^2 - m_\phi^2 + s)}{m_N^4 - 2m_\phi^2 m_N^2 + sm_N^2 + m_\phi^4}\right)}{s} - \frac{\text{Li}_2\left(\frac{(m_N^2 - m_\phi^2)^2}{m_N^4 - 2m_\phi^2 m_N^2 + sm_N^2 + m_\phi^4}\right)}{s} \end{aligned}$$

Cross-section and relic abundance approximations

S-wave cross-section

Wells, J.D. (1994). arXiv: 940219

$$\langle \sigma v \rangle \approx \frac{\lambda^2 Y_\nu^4 m_N^2}{1024\pi^5} |C_0(0, 0, 4m_\eta^2, m_\Phi^2, m_N^2, m_\Phi^2)|^2$$

DM relic abundance approximation

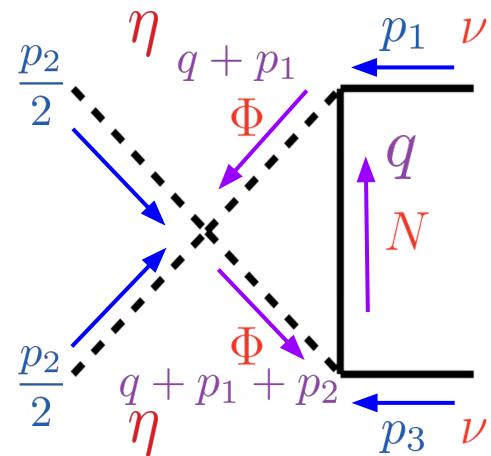
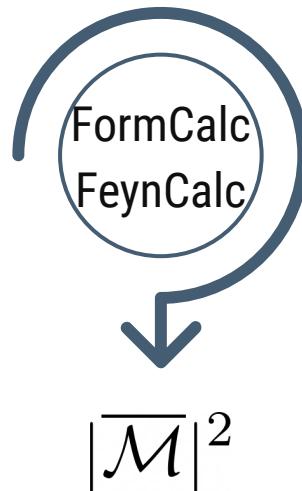
Steigman, G. et al. (2012). arXiv: 1204.3622

$$\Omega_c h^2 = \frac{9.92 \times 10^{-28}}{\langle \sigma v \rangle} \left(\frac{x_*}{g_*^{1/2}} \right) \left(\frac{(\Gamma/H)_*}{1 + \alpha_*(\Gamma/H)_*} \right)$$

First Test: Dark Matter Relic Abundance

Interaction Lagrangian

$$-\mathcal{L}_{\text{int}} = \left[\frac{Y_\nu}{\sqrt{2}} \bar{\nu}(\phi_1 + i\phi_2) N_R + h.c. \right] + \frac{\lambda}{4} \eta^2 (\phi_1^2 - \phi_2^2) + \frac{1}{2} m_{\phi_1}^2 \phi_1^2 + \frac{1}{2} m_{\phi_2}^2 \phi_2^2$$



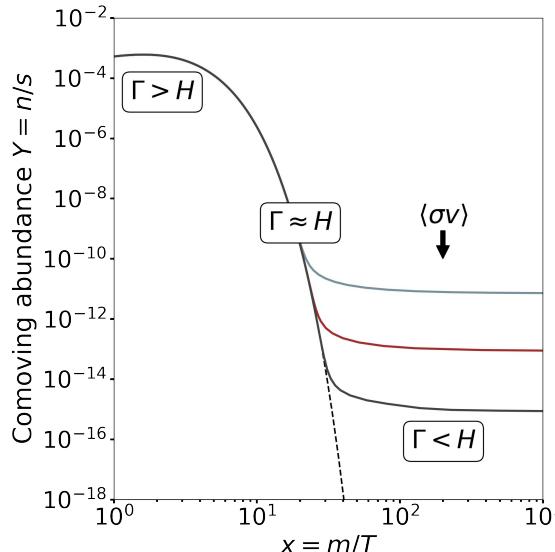
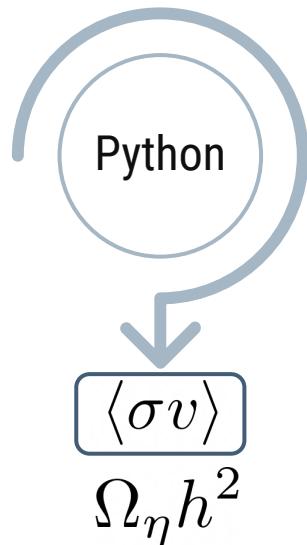
Passarino-Veltman reduction

$$C_0(p_1^2, p_2^2, (p_1 + p_2)^2, m_1^2, m_2^2, m_3^2)$$

$$= \frac{\mu^{4-D}}{i\pi^{D/2} r_\Gamma} \int \frac{(\text{numerator}) d^D q}{[q^2 - m_N^2] [(q + p_1)^2 - m_\Phi^2] [(q + p_1 + p_2)^2 - m_\Phi^2]}$$

$$|\overline{\mathcal{M}}|_{\text{ann}}^2 = \frac{\lambda^2 Y_\nu^4 m_N^2 s}{128\pi^4} |C_0(0, s, 0, m_N^2, m_\Phi^2, m_\Phi^2)|^2$$

First Test: Dark Matter Relic Abundance



Thermally-averaged annihilation cross-section

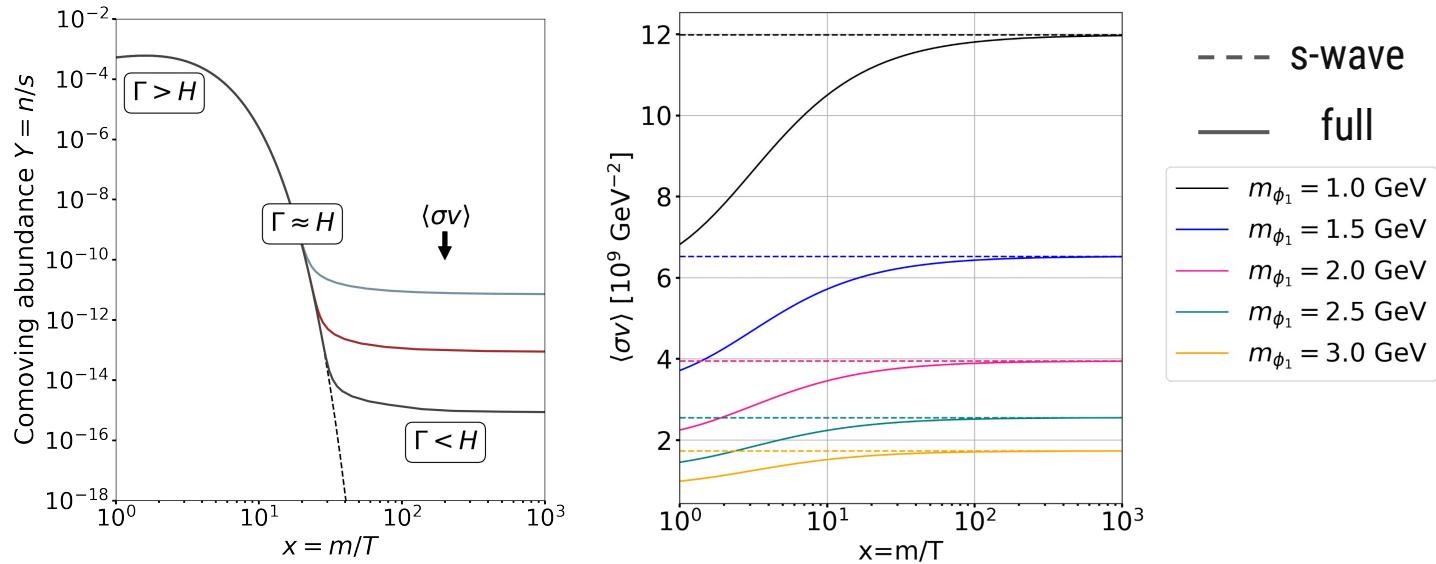
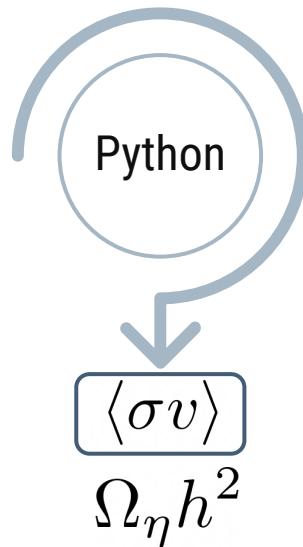
$$\langle \sigma v \rangle = \frac{1}{8m_\eta^4 T K_2^2(m_\eta/T)} \int_{4m_\eta^2}^{\infty} ds \sigma(s) (s - 4m_\eta^2) \sqrt{s} K_1\left(\frac{\sqrt{s}}{T}\right)$$

Non-relativistic limit

$$\langle \sigma v \rangle \simeq a_s + b_p \frac{6T}{m_\eta} + \dots$$

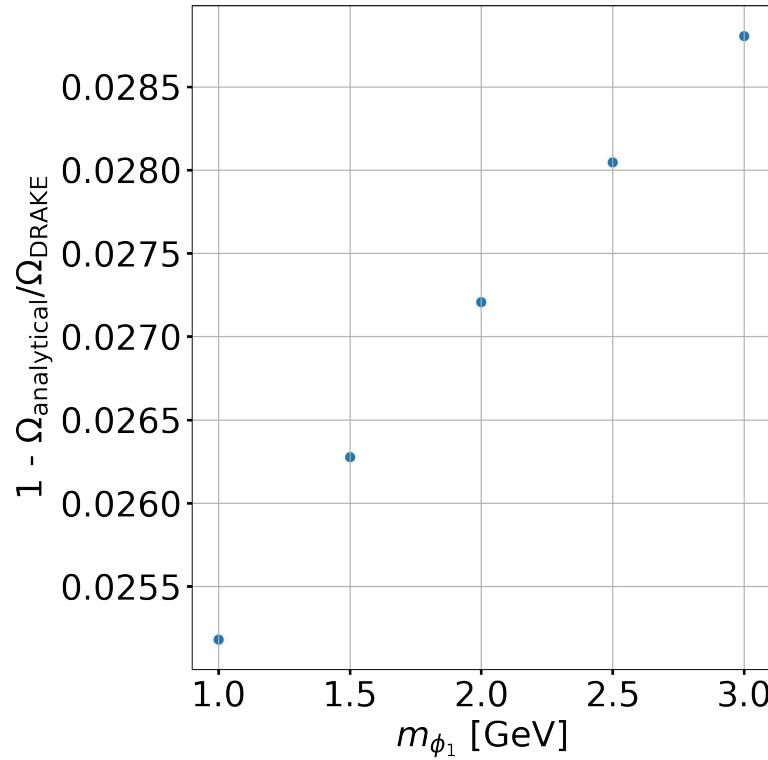
s-wave

First Test: Dark Matter Relic Abundance

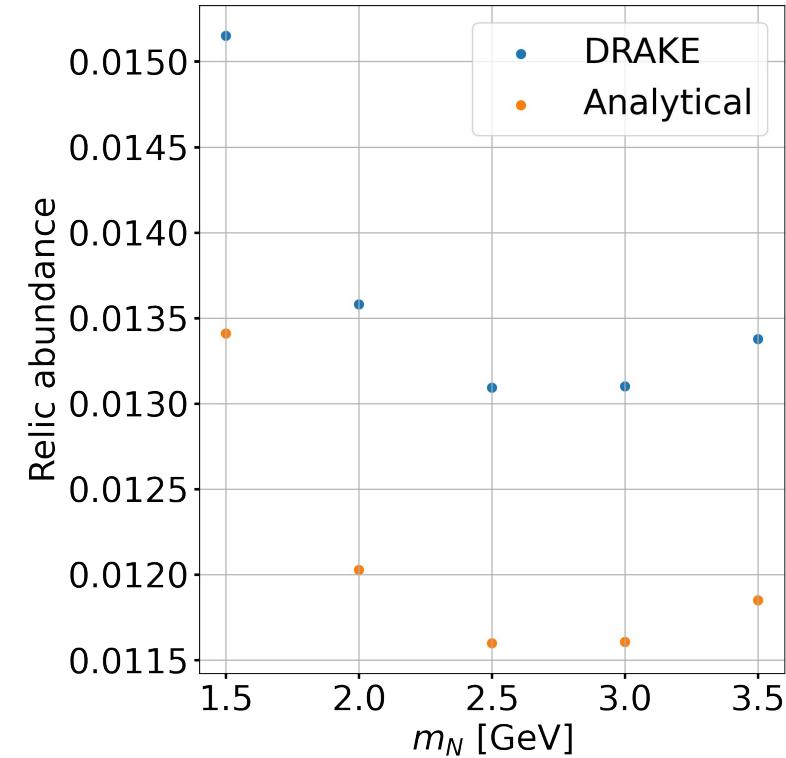
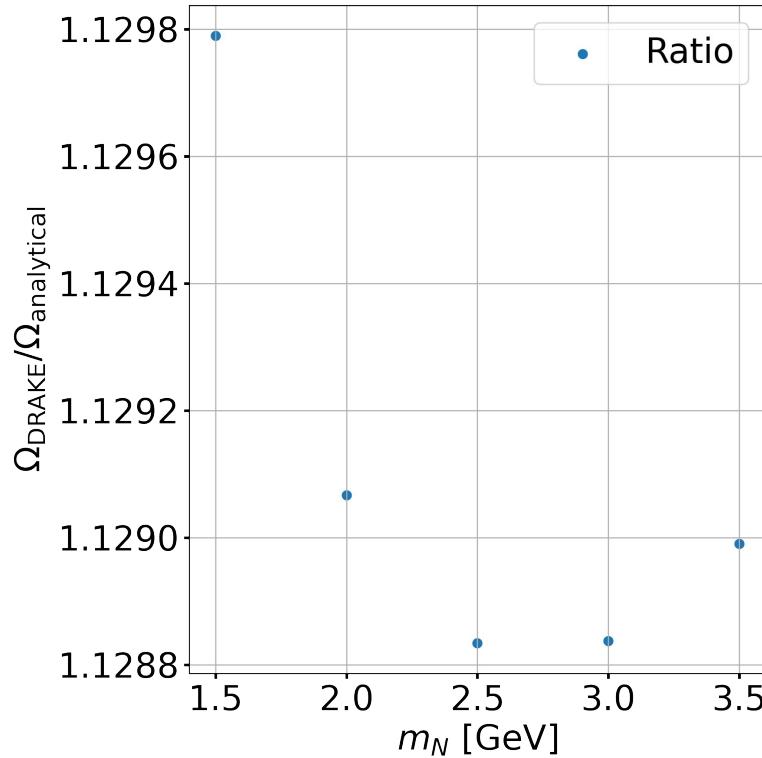


$$m_\eta = 10 \text{ MeV}, m_{\phi_2} = m_{\phi_1}, m_N = 5 \text{ GeV}, \text{ and } \lambda = Y_\nu = 0.5$$

Comparison to the Boltzmann code DRAKE



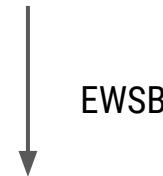
Comparison to the Boltzmann code DRAKE



Neutrino masses

Dirac

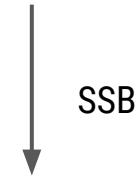
$$\mathcal{L}_{\text{lept}, \phi} \propto \lambda^{ij} \bar{\psi}^i \Phi \ell^j + \lambda_\nu^{ij} \bar{\psi}^i \Phi^c \nu_R^i$$



$$- \sum_i m_\nu^i (\bar{\nu}_R^i \nu_L^i + \bar{\nu}_L^i \nu_R^i)$$

Majorana

$$\Lambda^{-1} \phi^0 \phi^0 \nu_L^i \nu_L^j$$



$$- \frac{1}{2} \sum_i m_\nu^i (\bar{\nu}_L^{i,c} \nu_L^i + \bar{\nu}_L^i \nu_L^{i,c})$$

The role of Z_2 symmetry

- Unlike the Higgs, the new scalar does not develop a vev.
- It is stable and can be a DM candidate.
- Neutrino masses cannot be generated at tree-level.

$$\phi^0 \bar{N}_R^i \nu_L^\alpha$$

$$\begin{array}{c}
 \Lambda^{-1} \phi^0 \phi^0 \nu_L^i \nu_L^j \\
 \downarrow \text{SSB} \\
 -\frac{1}{2} \sum_i m_\nu^i (\bar{\nu}_L^{i,c} \nu_L^i + \bar{\nu}_L^i \nu_L^{i,c})
 \end{array}$$

Low-energy effective lagrangian

$$Y_\nu \bar{\nu} \Phi N_R$$

Majorana

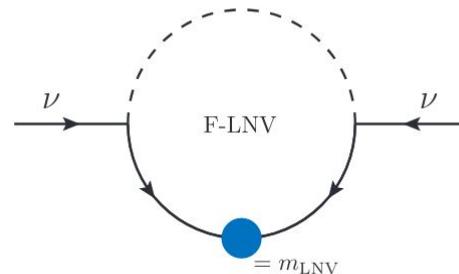
Valid up to a scale Λ

Trivial under $SU(2) \times U(1)$
→ N and Φ have no EW
interactions, but neutrinos do

Not gauge invariant

$$\begin{array}{c} \Lambda^{-1} \phi^0 \phi^0 \nu_L^i \nu_L^j \\ \downarrow \text{SSB} \\ -\frac{1}{2} \sum_i m_\nu^i (\bar{\nu}_L^{i,c} \nu_L^i + \bar{\nu}_L^i \nu_L^{i,c}) \end{array}$$

Radiative neutrino masses



arXiv: 1907.12478

Neutrino masses are obtained evaluating the diagram with vanishing external momenta → leading order term

External scalar lines can be removed in the context of computing the neutrino self-energy, as their effects will be absorbed into the masses of particles running in the loops