Queen's UNIVERSITY ARTS AND SCIENCE

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

Loop-mediated
Dark Matter – neutrino interactions

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MSc Candidate, Queen's University

TeVPA 2022. Kingston, ON. August 11th, 2022

The Standard Model is incomplete

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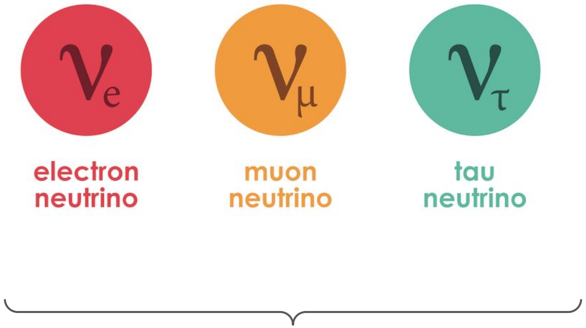
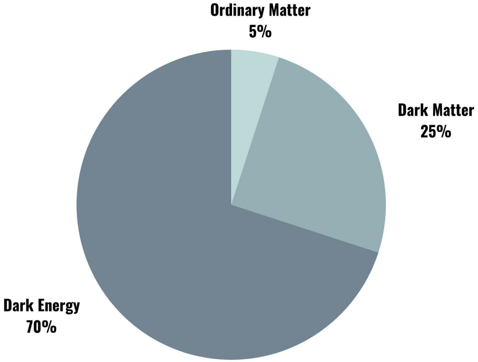
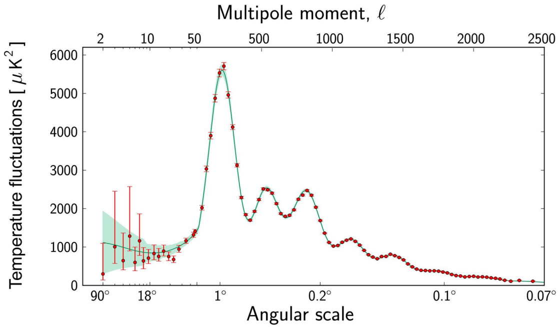


Neutrino mass mechanism

The Standard Model is incomplete



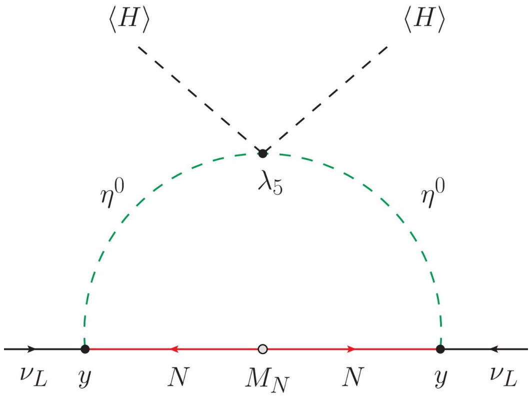


Neutrino mass mechanism

Astrophysical and cosmological evidence of dark matter

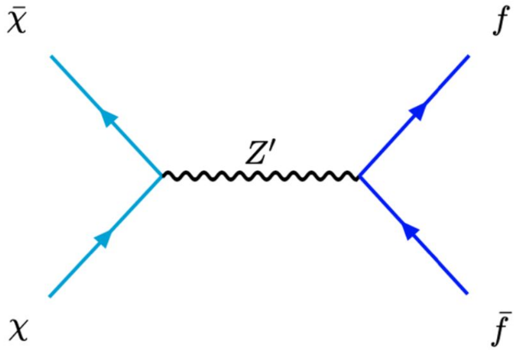
Theoretical Framework

Dark matter interactions with the standard model through the neutrino sector



Scotogenic model

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



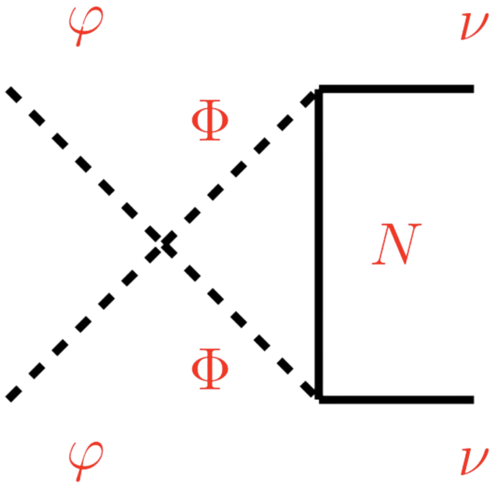
LR/U(1)' models

L, B−L symmetries

Senjanovic, G., & Mohapatra, R. N. (1975). PRD, 12(5), 1502.
Mohapatra, R. N., & Pati, J. C. (1975). PRD, 11(9), 2558.
G.B. Gelmini and M. Roncadelli, Phys. Lett. 99B (1981) 411
+many more

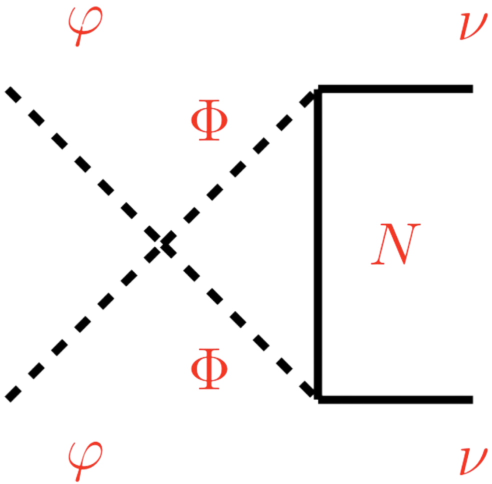
Research Question

Can dark matter interact with neutrinos via a 1-loop diagram, reproduce the observed relic abundance and still be consistent with current constraints?



Chao, W. (2020). arXiv: 2009.12002

Dark matter annihilation into neutrinos



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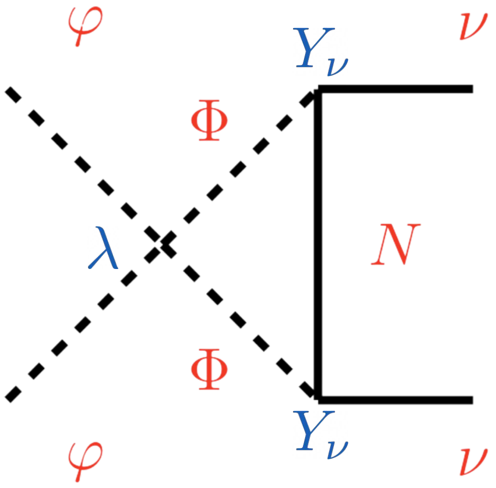
Real scalar DM	φ
Complex scalar mediator	Φ
Heavy neutrino mediator	N

Dark matter annihilation into neutrinos



Chao, W. (2020). arXiv: 2009.12002

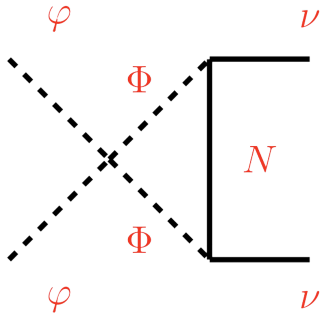
Real scalar DM φ

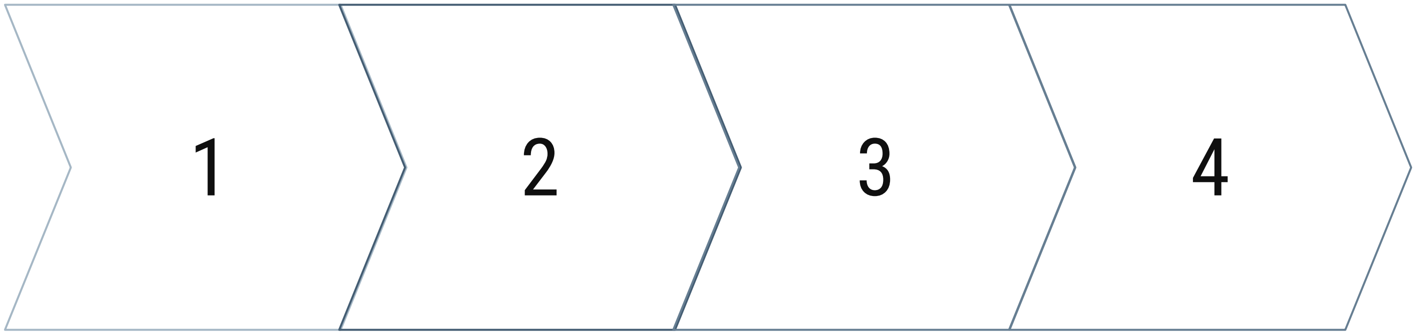
Complex scalar mediator Φ

Heavy neutrino mediator N

Couplings $\lambda, \ Y_\nu$

The Dark Matter Escape Room





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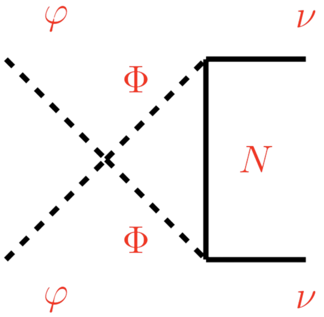
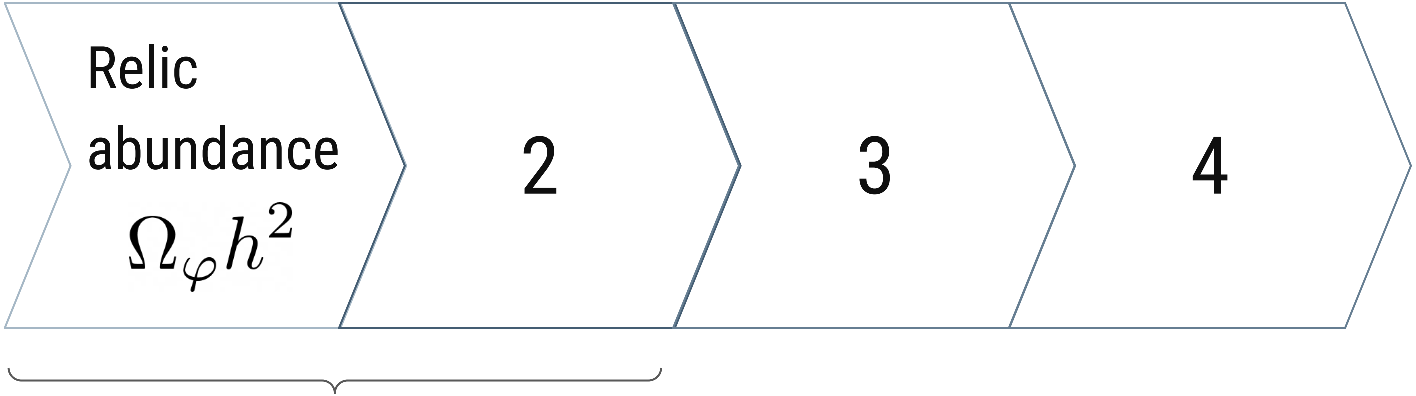




Relic abundance

$\Omega_\varphi h^2$

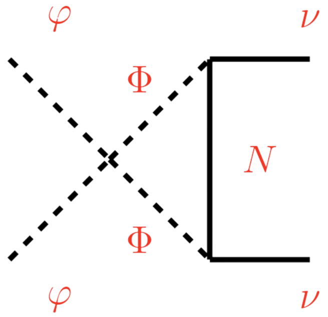
2

3

4

Early universe DM-neutrino interactions

The Dark Matter Escape Room



Relic abundance $\Omega_\varphi h^2$

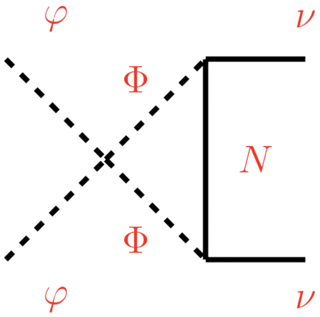
Annihilation & scattering N_{eff}, u

3

4

Early universe DM-neutrino interactions

The Dark Matter Escape Room



Relic abundance $\Omega_\varphi h^2$

Annihilation & scattering N_{eff}, u

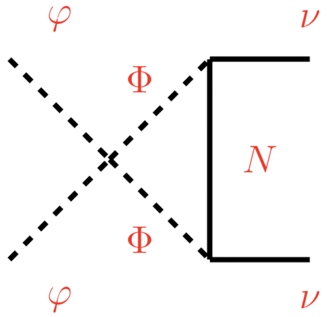
Extragalactic annihilation $\langle \sigma v \rangle$

4

Early universe DM-neutrino interactions

Supernova Relic Neutrinos (DSNB)

The Dark Matter Escape Room



Relic abundance $\Omega_\varphi h^2$

Annihilation & scattering $N_{\rm eff}, u$

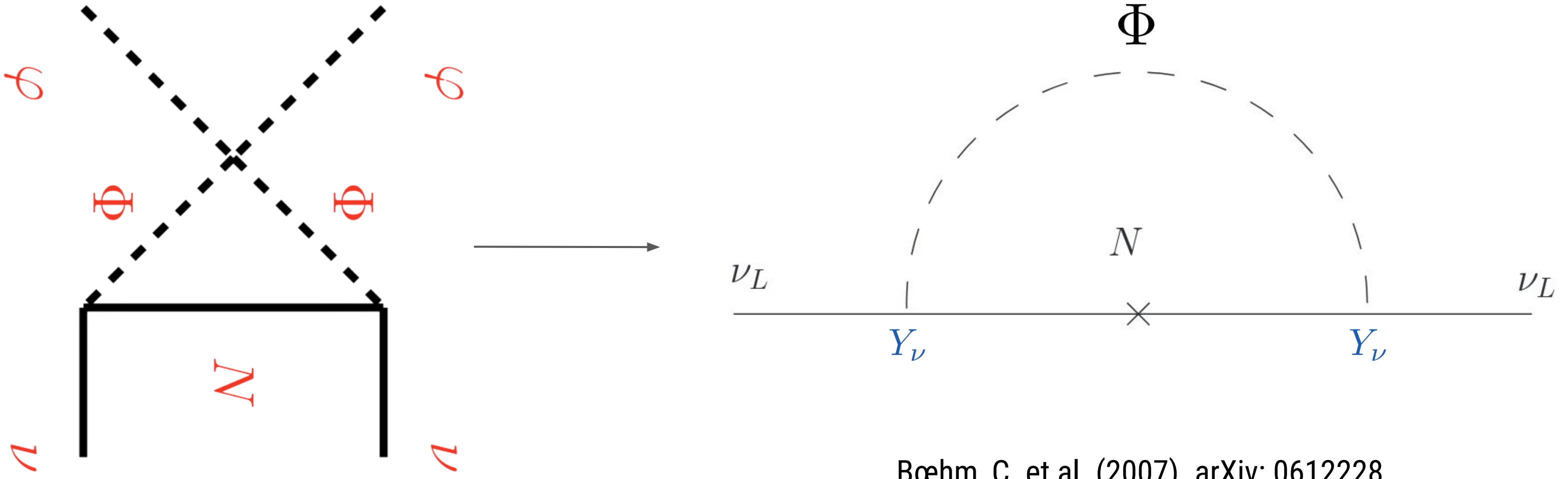
Extragalactic annihilation $\langle \sigma v \rangle$

Lightest ν mass m_{ν_0}

Early universe DM-neutrino interactions

Supernova Relic Neutrinos (DSNB)

Neutrino mass mechanism



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

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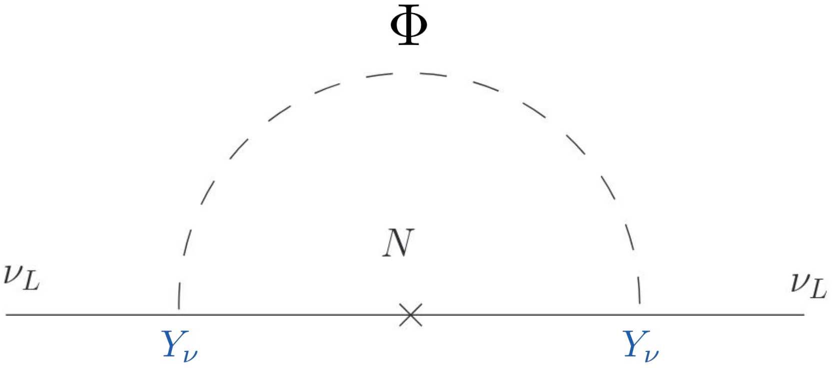


Bœhm, C. et al. (2007). arXiv: 0612228

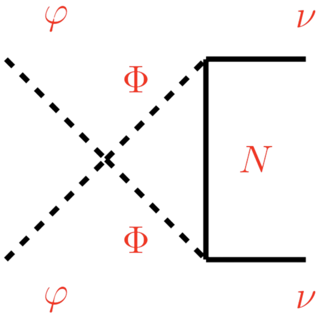
Neutrino mass m_ν

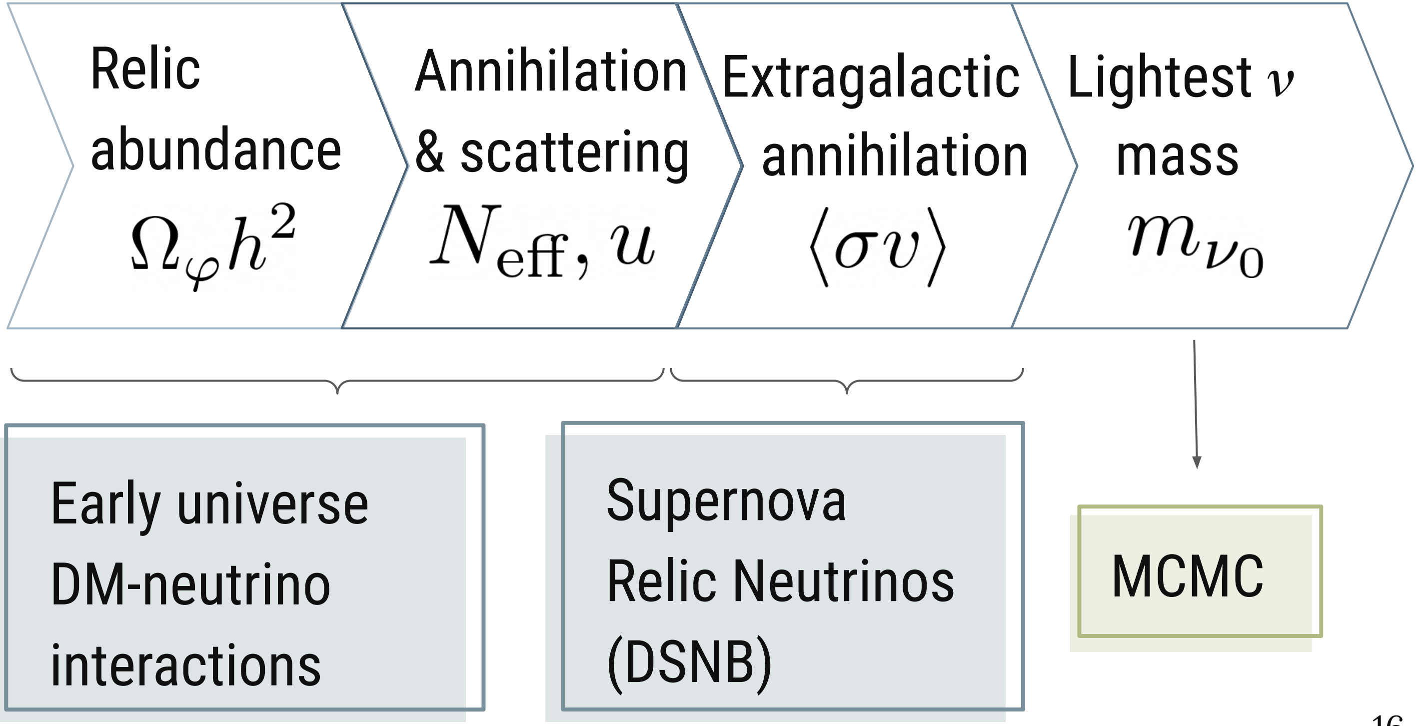
Complex scalar mediator $\Phi = \dfrac{\phi_1 + i\phi_2}{\sqrt{2}}$

Heavy neutrino mediator N

Couplings Y_ν

The Dark Matter Escape Room





Relic abundance $\Omega_\varphi h^2$

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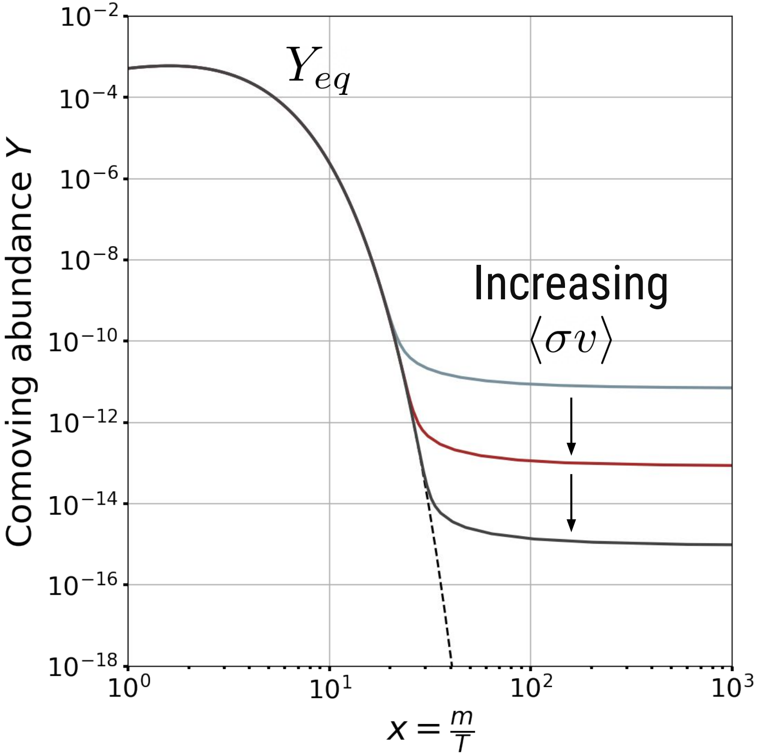
Early universe DM-neutrino interactions

Supernova Relic Neutrinos (DSNB)

MCMC

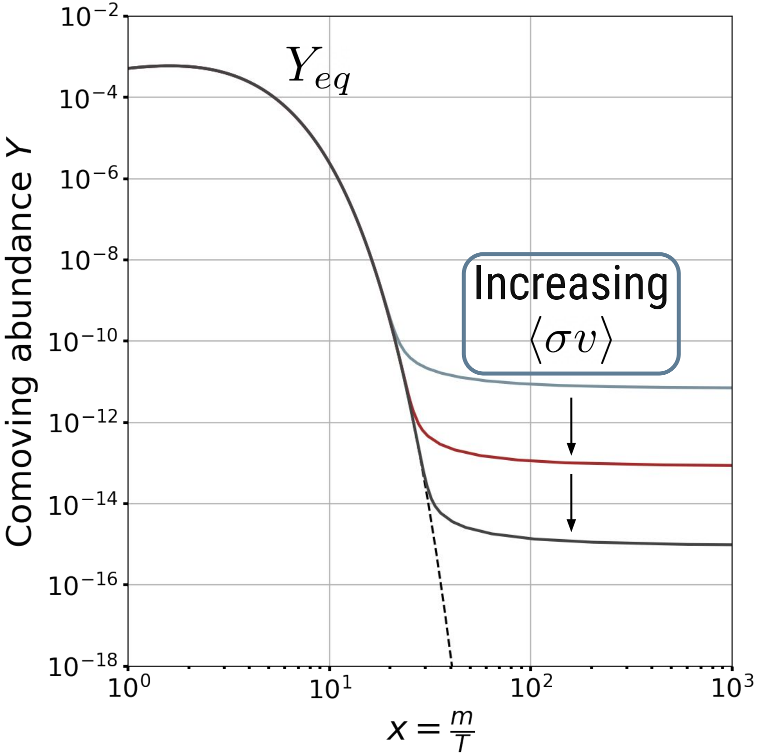
First Test: Dark Matter Relic Abundance



Boltzmann equation

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

First Test: Dark Matter Relic Abundance



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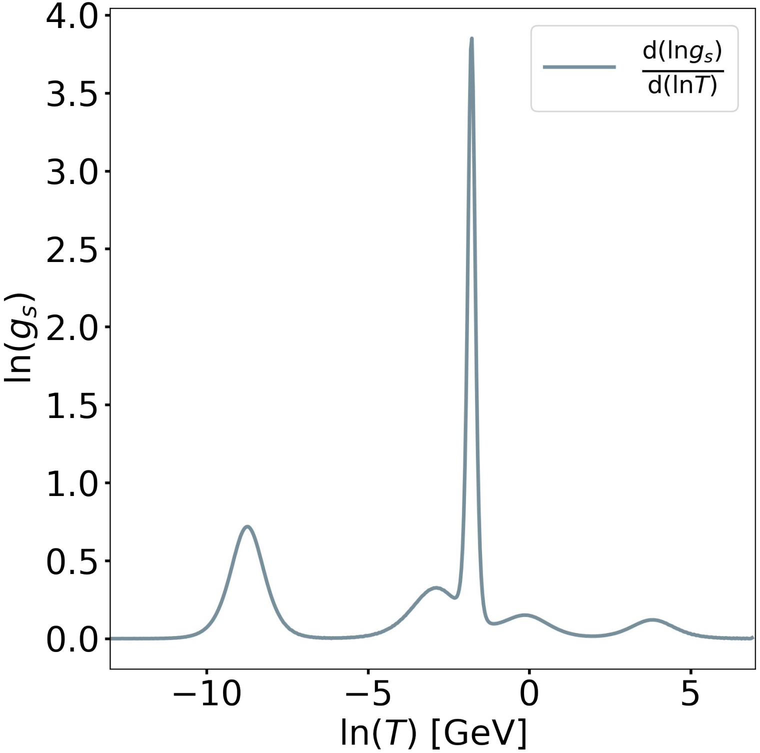

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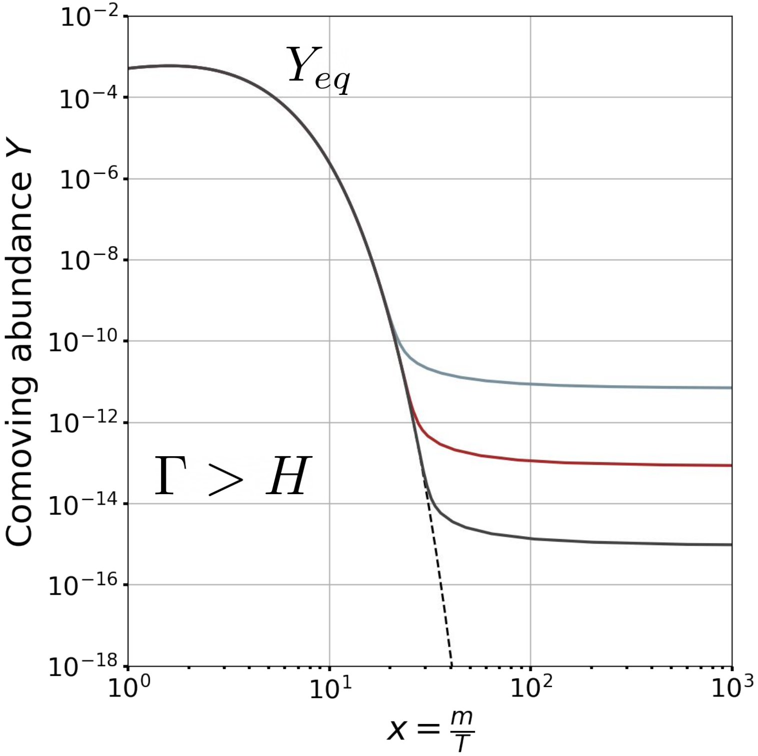

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$\Gamma > H$ Follows equilibrium abundance

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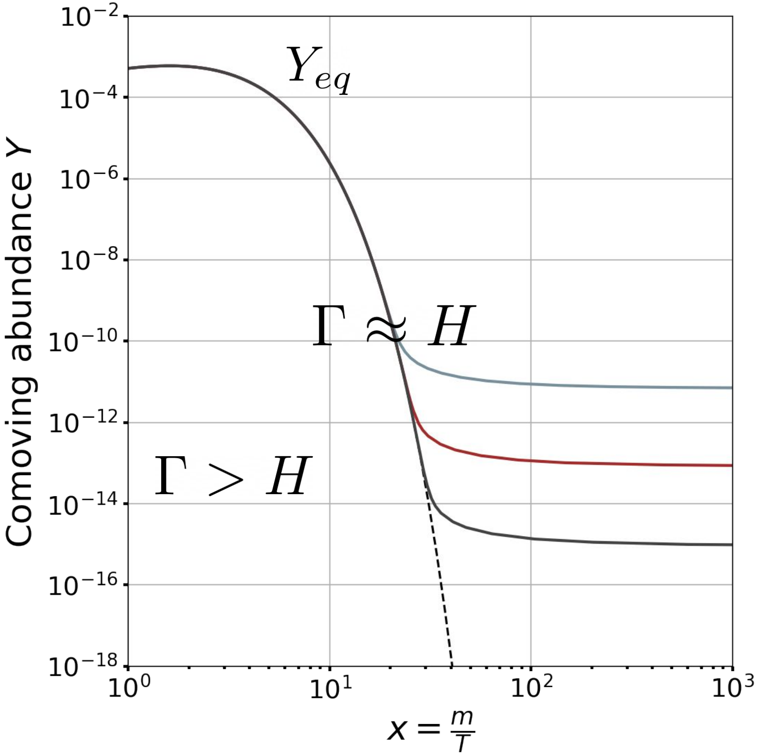

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$\Gamma \approx H$ Freeze-out

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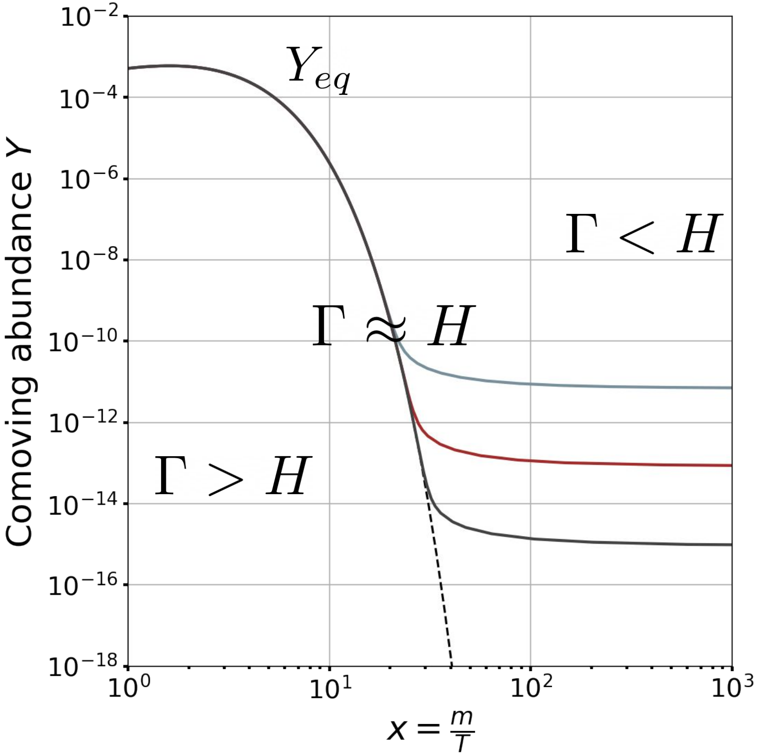

Boltzmann equation

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$\Gamma > H$ Follows equilibrium abundance

$\Gamma \approx H$ Freeze-out

$\Gamma < H$ Away from equilibrium, sets **relic abundance**

First Test: Dark Matter Relic Abundance

Interaction Lagrangian

$$-\mathcal{L}_{\text{int}} = \frac{1}{2}m_{\varphi}^2\varphi^2 + \frac{1}{2}\lambda\Phi^2\varphi^2 + Y_\nu\overline{\nu_L}\Phi N_R + \text{ h.c.}$$

First Test: Dark Matter Relic Abundance

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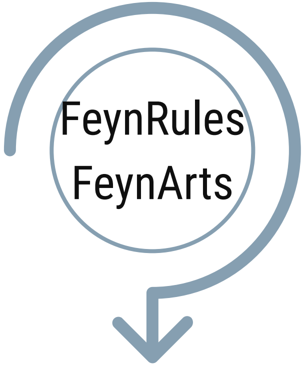

FeynRules
FeynArts

Feynman rules
and diagrams

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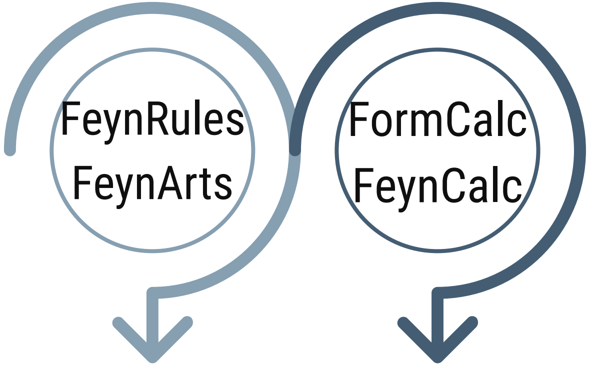

FeynRules
FeynArts

FormCalc
FeynCalc

Feynman rules and diagrams

$$|\overline{\mathcal{M}}|^2$$

First Test: Dark Matter Relic Abundance

Interaction Lagrangian

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Feynman rules
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FormCalc
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$$|\overline{\mathcal{M}}|^{2}$$

Package-X

Analytical
Loop Integral

First Test: Dark Matter Relic Abundance

Interaction Lagrangian

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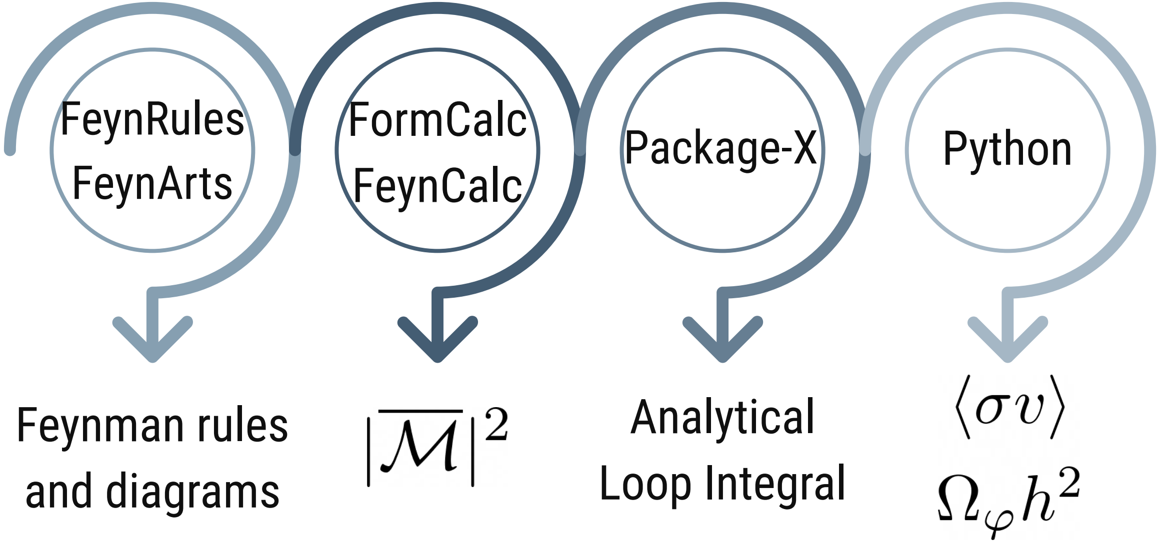

FeynRules
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Feynman rules
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FormCalc
FeynCalc

$|\overline{\mathcal{M}}|^2$

Package-X

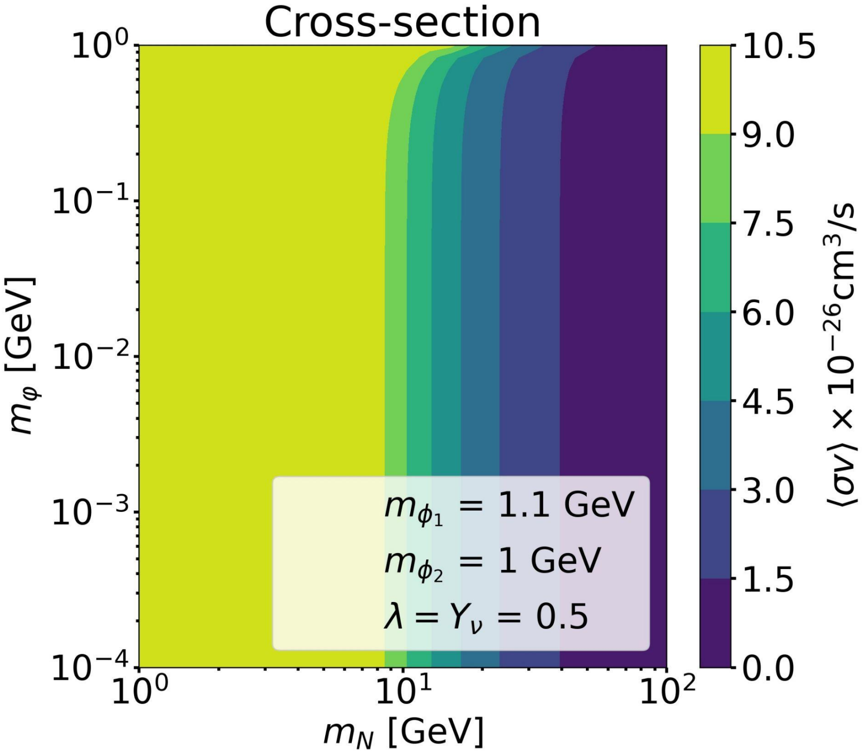
Analytical
Loop Integral

Python

$\langle\sigma v\rangle$

$\Omega_\varphi h^2$

First Test: Dark Matter Relic Abundance



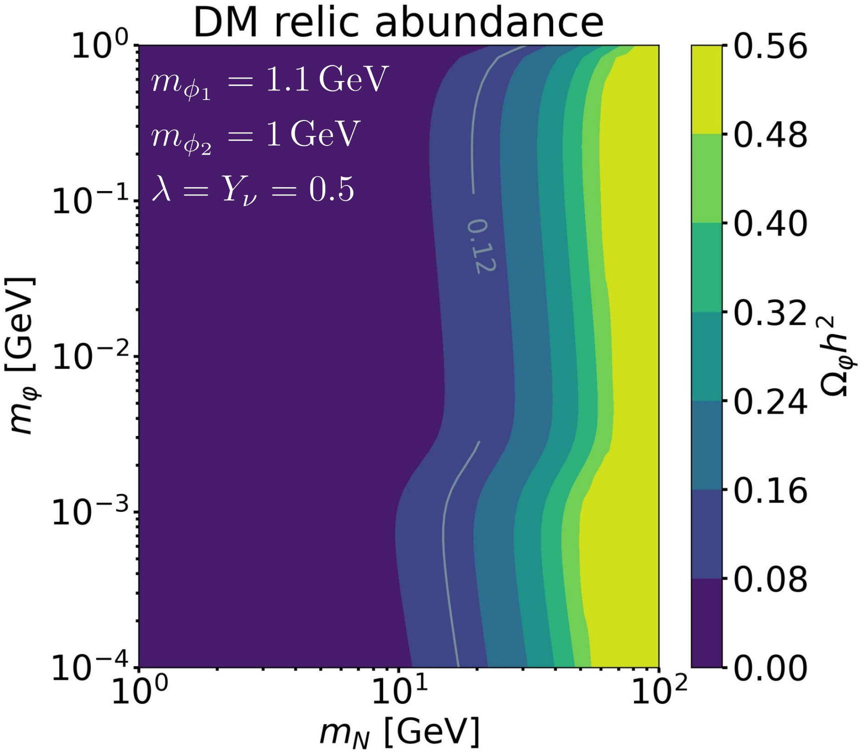
Stability constraint

$$\boxed{m_N > m_\phi > m_\varphi}$$

Nearly independent of

$$m_\varphi \leq 100\,\mathrm{MeV}$$

First Test: Dark Matter Relic Abundance



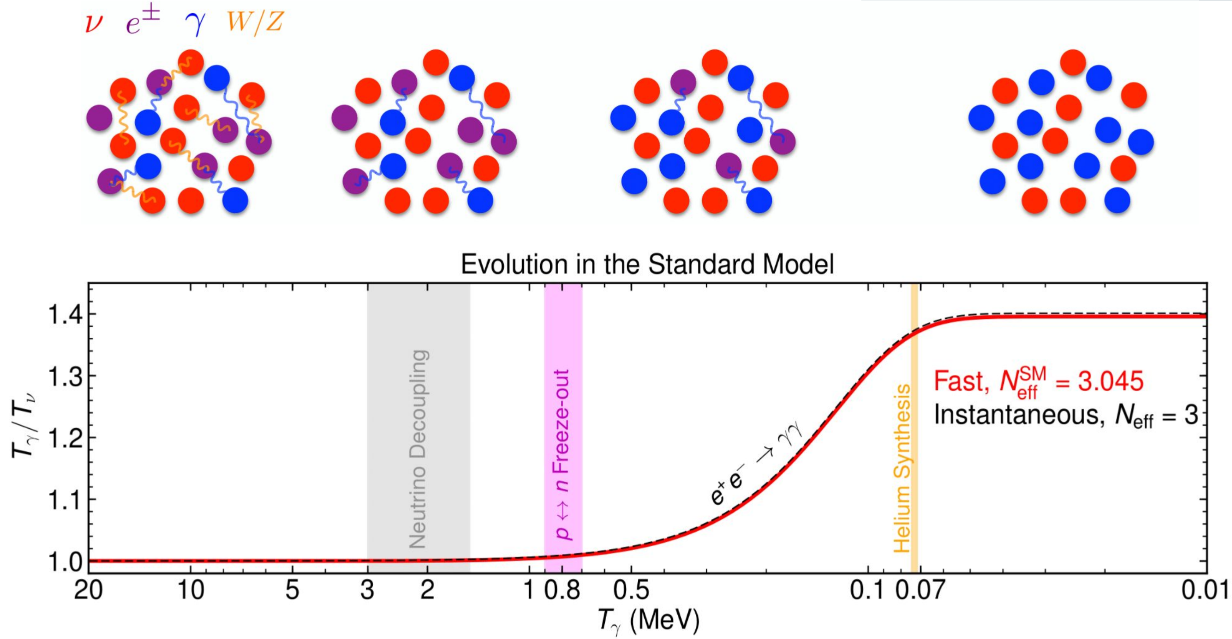
Constraint from Planck 2018

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

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

Second Test: Primordial abundances and N_{eff}

Big Bang Nucleosynthesis (BBN)



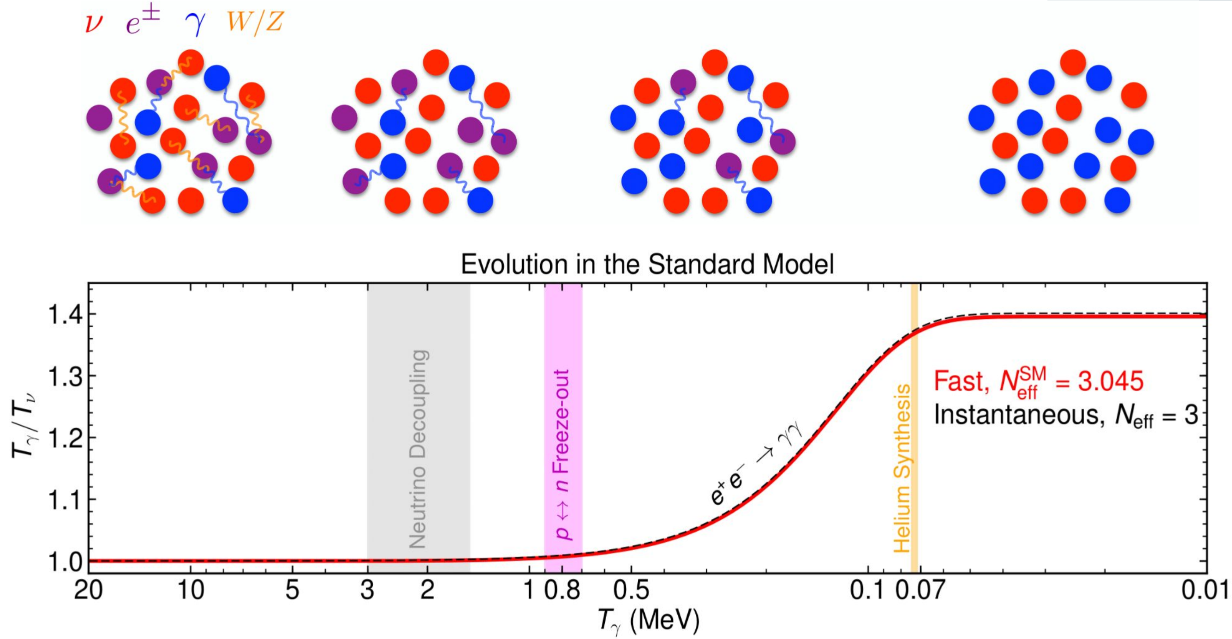
$$T_\gamma/T_\nu = (11/4)^{1/3}$$

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

Escudero, M. (2020). arXiv: 2001.04466

Second Test: Primordial abundances and N_{eff}

BBN and light dark matter



φ

$$m_\varphi \leq 20\,\mathrm{MeV}$$

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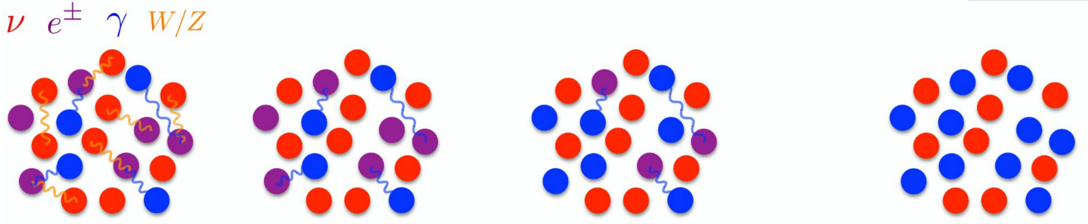
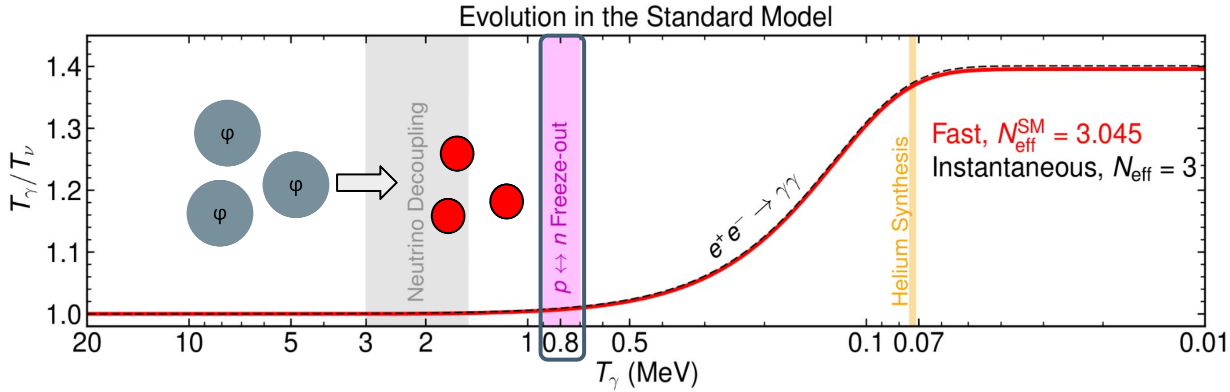
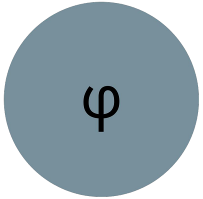
Second Test: Primordial abundances and N_{eff}

BBN and light dark matter







$$m_\varphi \leq 20\,\mathrm{MeV}$$

$$Y_P \quad Y_D \quad N_{\text{eff}}$$

Escudero, M. (2020). arXiv: 2001.04466

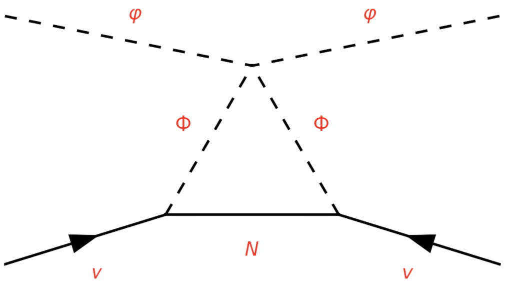
Second Test: DM-neutrino scattering

Thermally averaged scattering cross-section

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

Fermi-Dirac distribution

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



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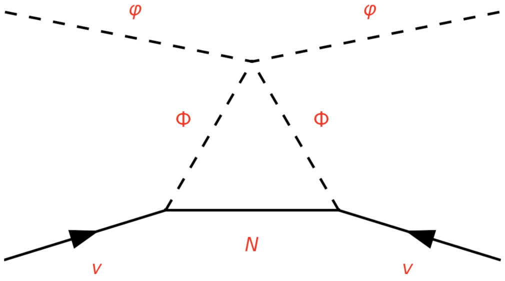


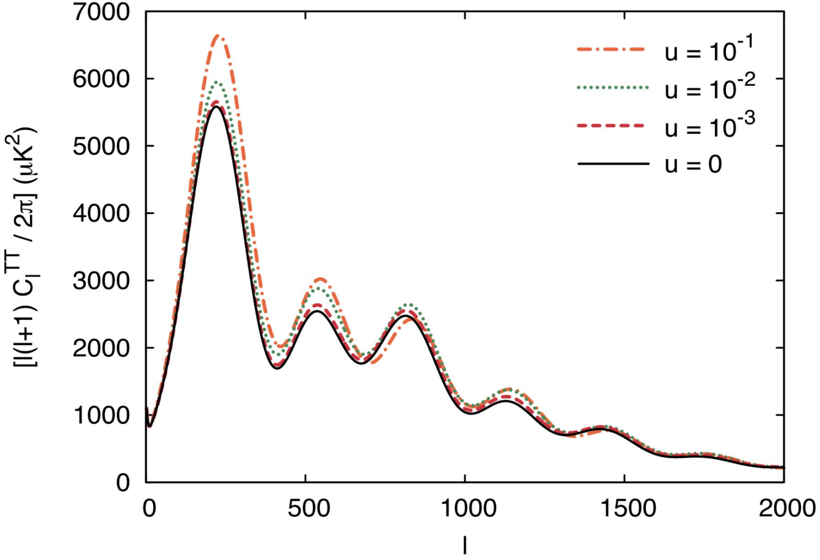
Fermi-Dirac distribution $f_\nu(k) = \frac{1}{e^{-k/T_\nu} + 1}$

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

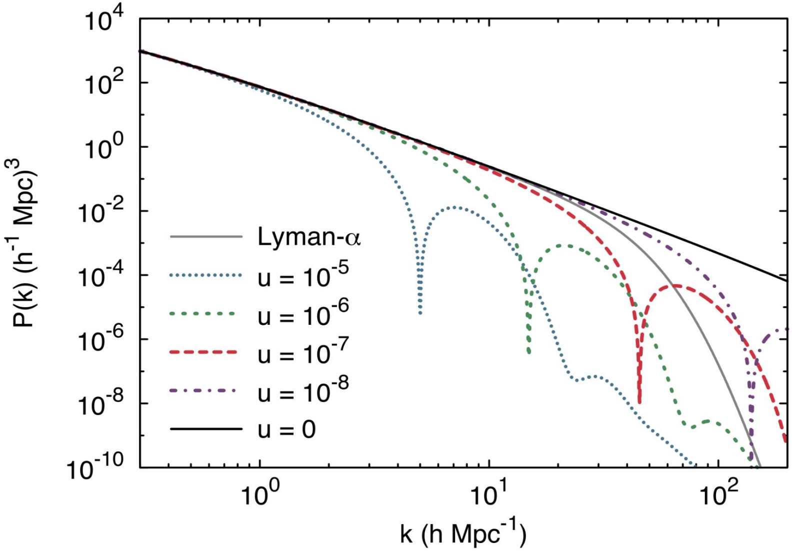
Wilkinson, R.J. et al. (2014). arXiv: 1401.7597

Second Test: DM-neutrino scattering

CMB Power Spectrum



Matter Power Spectrum



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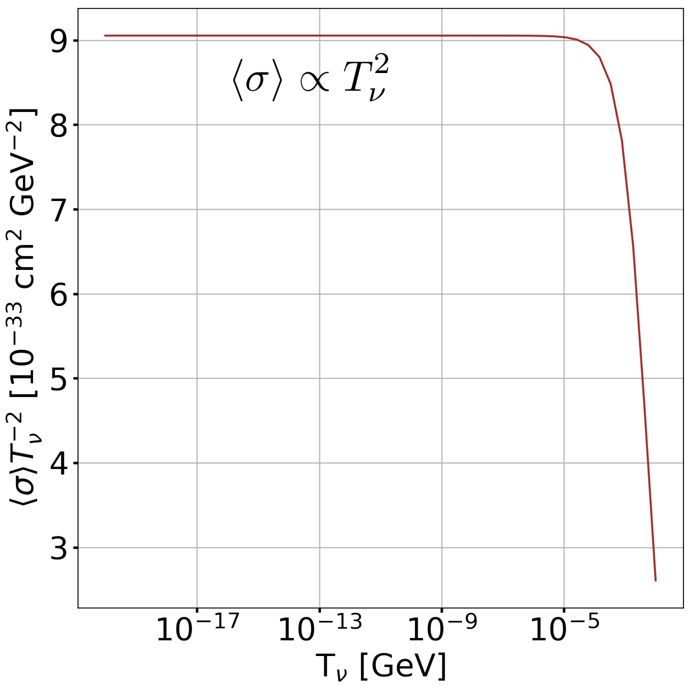
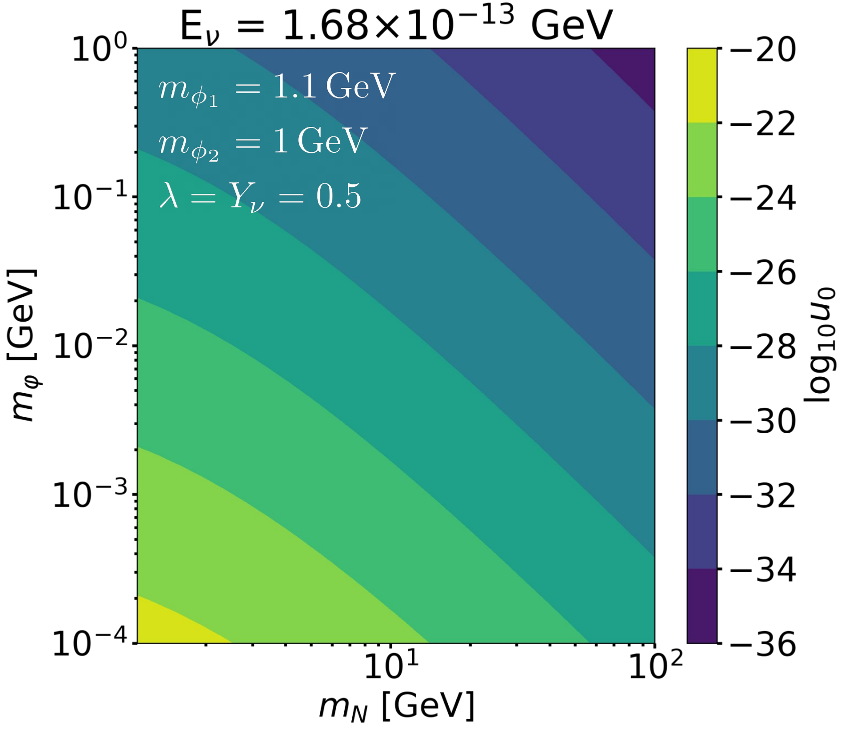
Second Test: DM-neutrino scattering





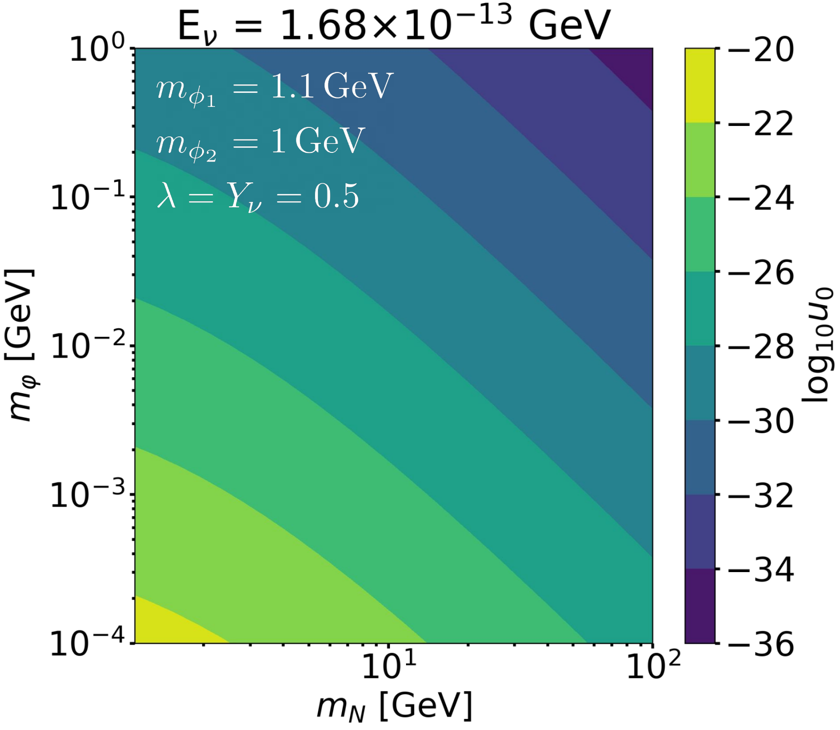
Second Test: DM-neutrino scattering

CMB & Matter Power Spectrum

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

$$\sigma_{\mathrm{DM}-\nu} \propto T^2,\; 10^{+13}u_0 < 2.56$$

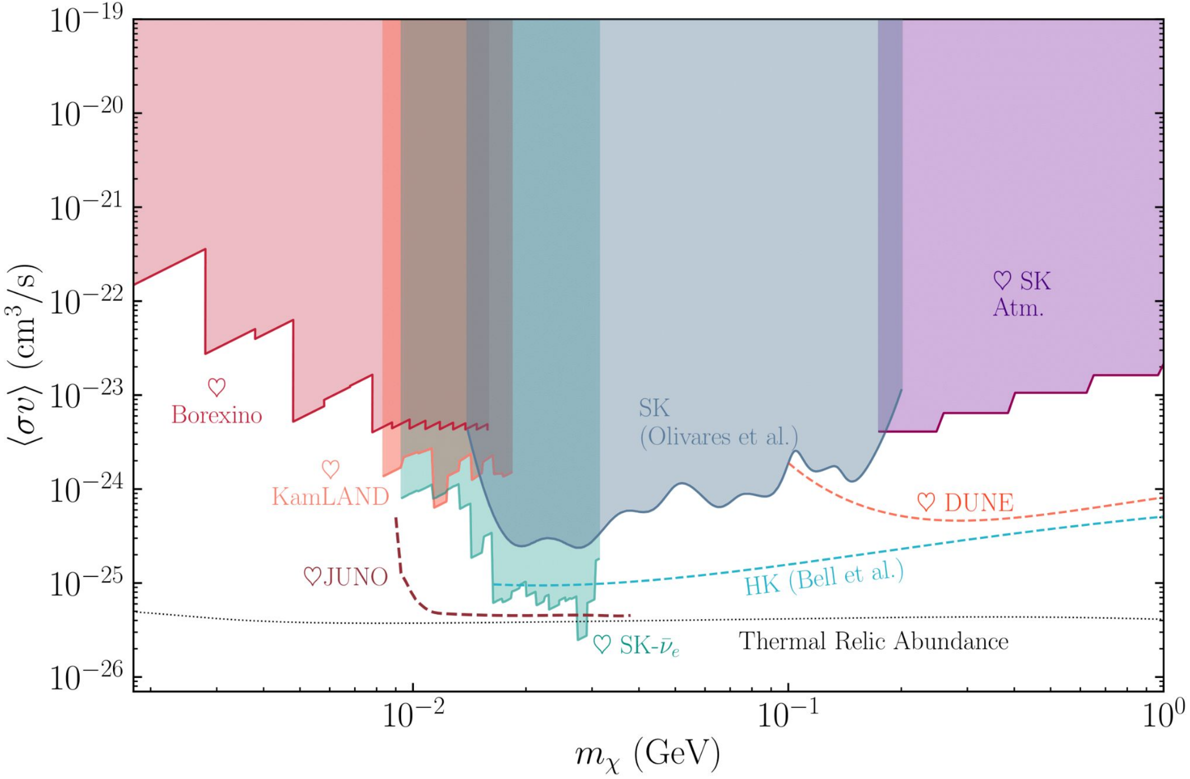
Wilkinson, R.J. et al. (2014). arXiv: 1401.7597



Third Test: Extragalactic DM Annihilation

Strongest constraint comes from the relic supernova electron antineutrino flux detected by Super-Kamiokande

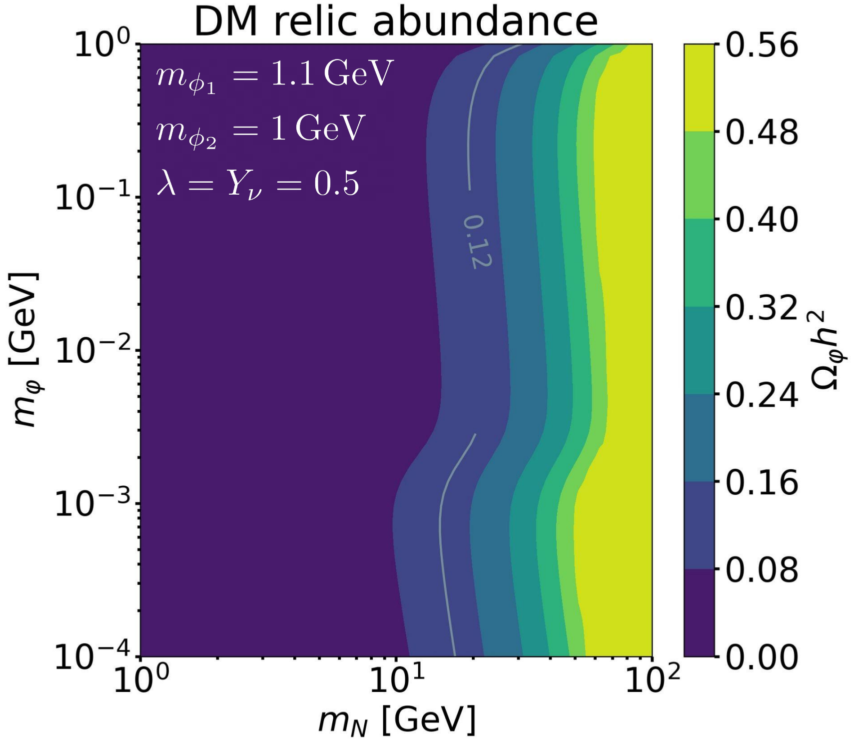
$$27 < m_\chi < 30\,\mathrm{MeV}$$



Linyan, W. (2018). Ph.D. thesis.

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

Fourth test: Adding neutrino masses



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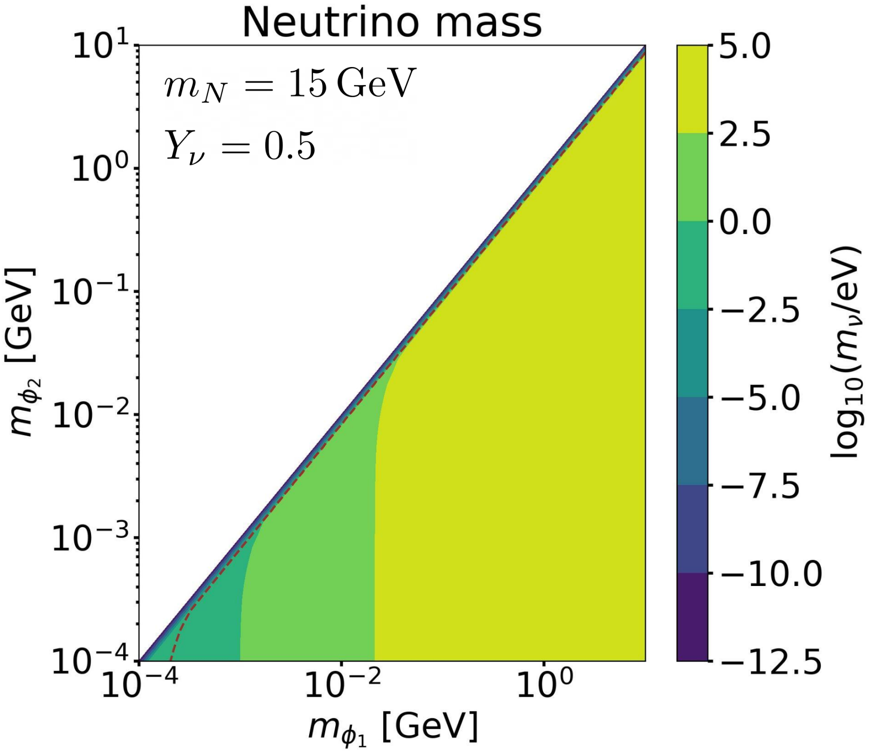

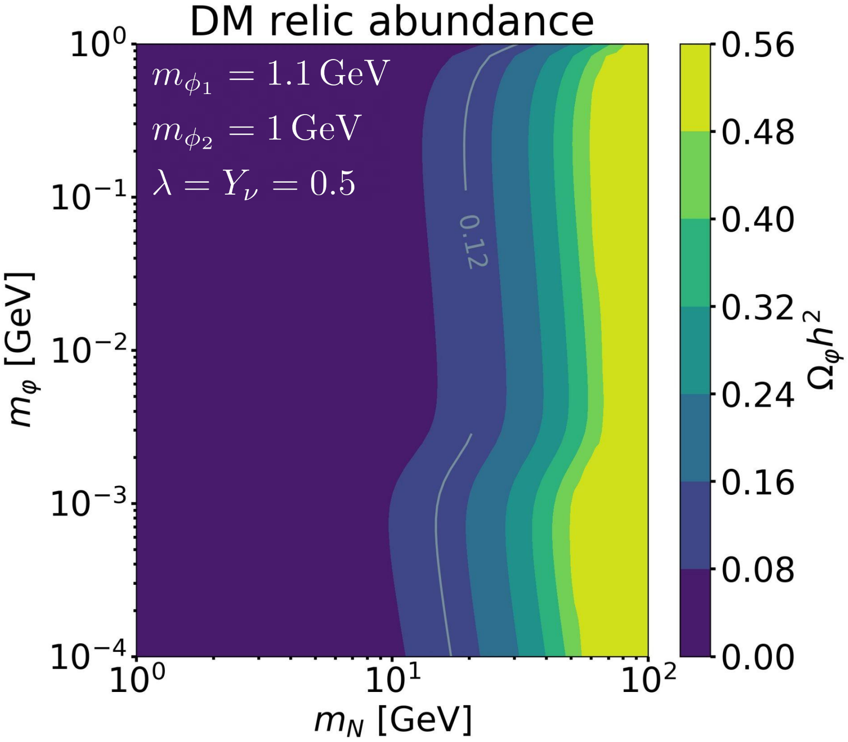

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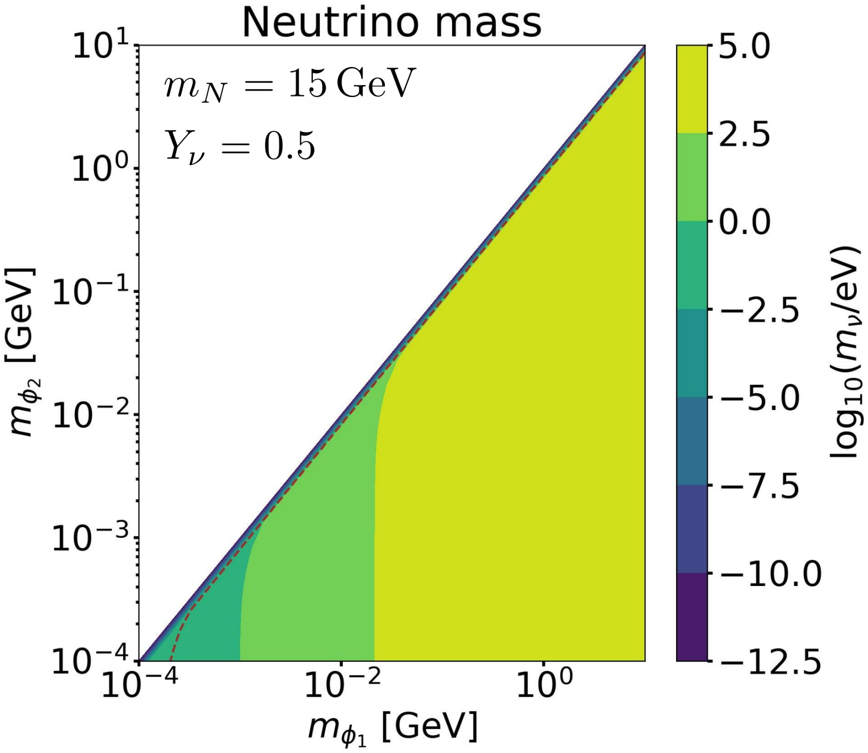
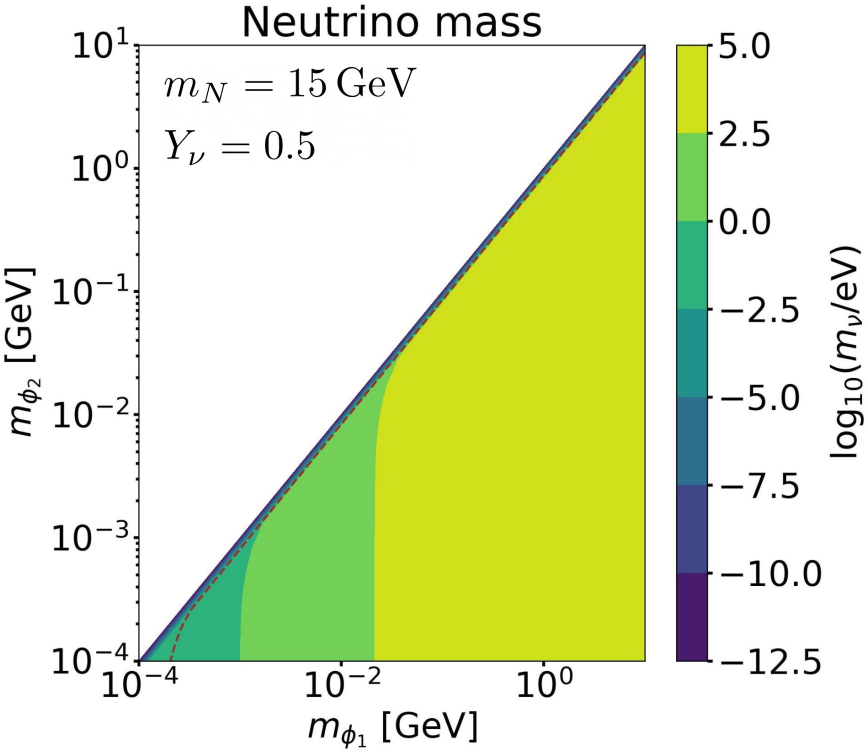


Mass of the lightest neutrino

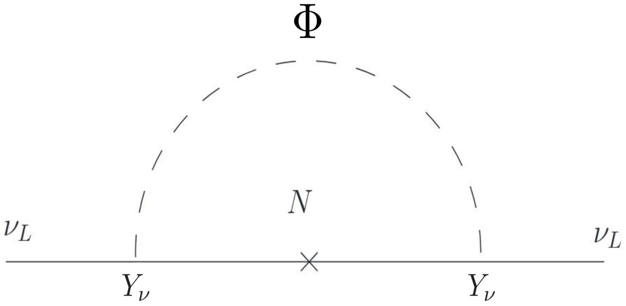
$$m_{\nu_0} < 0.037\,\mathrm{eV}$$

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

Fourth test: Adding neutrino masses

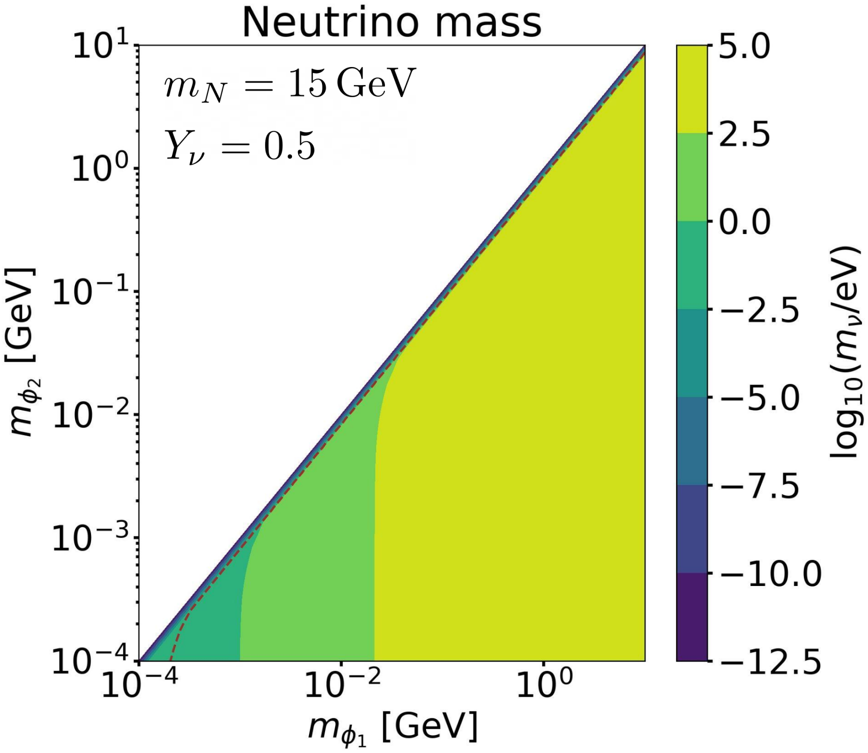


$$m_\nu = \frac{Y_\nu^2}{32\pi^2} m_N \left[\frac{m_{\phi_1}^2}{\left(m_N^2 - m_{\phi_1}^2\right)} \ln\left(\frac{m_N^2}{m_{\phi_1}^2}\right) - \frac{m_{\phi_2}^2}{\left(m_N^2 - m_{\phi_2}^2\right)} \ln\left(\frac{m_N^2}{m_{\phi_2}^2}\right) \right]$$



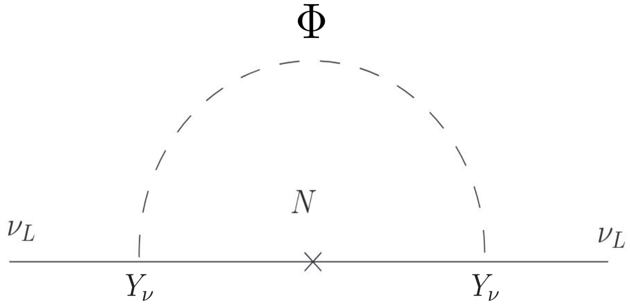
Bœhm, C. et al. (2007). arXiv: 0612228

Fourth test: Adding neutrino masses



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

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



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

Final Test: Combining All Constraints

Supernova relic neutrino flux

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

$$27 < m_\varphi < 30\,\mathrm{MeV}$$

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

BBN primordial abundances

$$N_{\mathrm{eff}},\ m_\varphi \leq 20\,\mathrm{MeV}$$

Obtained using AlterBBN

CMB & Matter Power Spectrum

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

$$\sigma_{\mathrm{DM}-\nu} \propto T^2,\ 10^{+13}u_0 < 2.56$$

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

Relic abundance

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

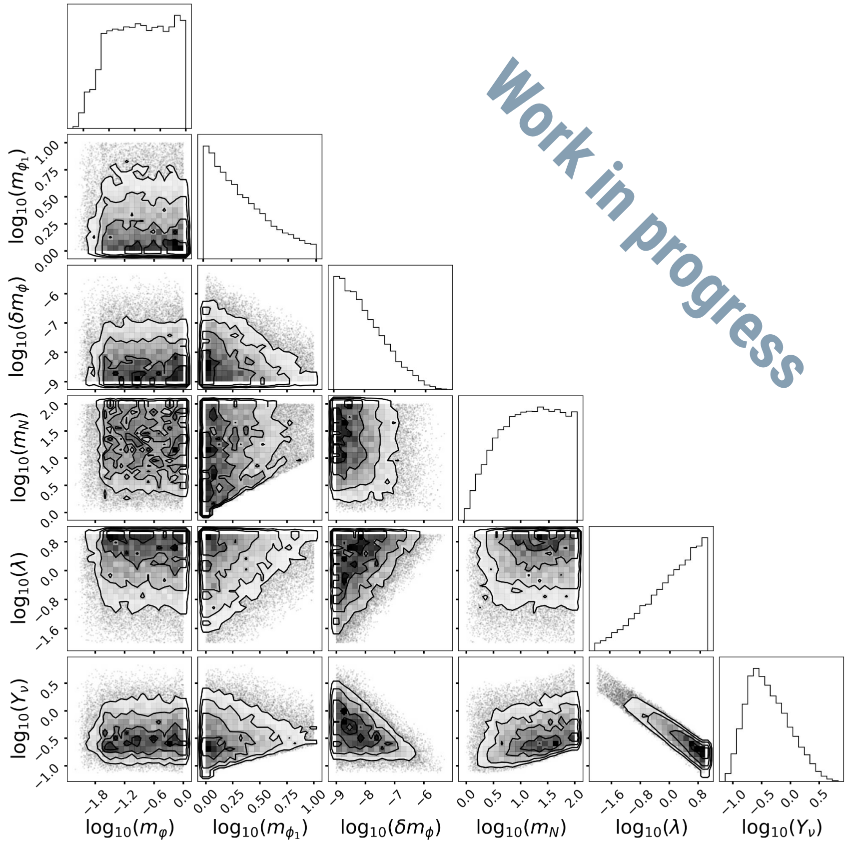
$(68\%,\ \text{Planck TT,TE,EE} +\ \text{lowE} +\ \text{lensing})$

Mass of the lightest neutrino

$$m_{\nu_0} < 0.037\,\mathrm{eV}$$

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

Final Test: Combining All Constraints



Work in progress

Preliminary MCMC

emcee run in the Frontenac cluster

Prior $m_N > m_\phi > m_\varphi$

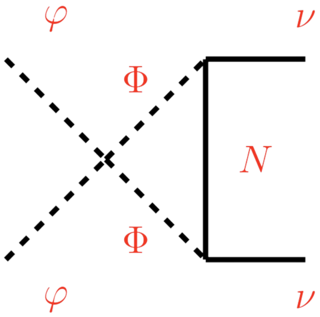
$$\delta m_\phi = 1 - \frac{m_{\phi_2}}{m_{\phi_1}}$$

Strongest constraints

$$N_{\mathrm{eff}} + m_{\nu_0} + \Omega_\varphi h^2$$

More tests to be done!

Did this DM model escape the room?



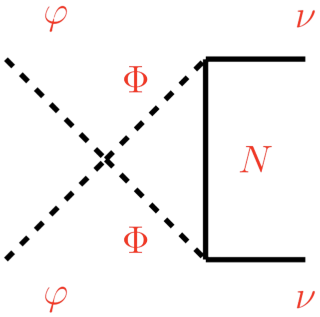
Relic abundance $\Omega_\varphi h^2$

Annihilation & scattering N_{eff}, u

Extragalactic annihilation $\langle \sigma v \rangle$

Lightest ν mass m_{ν_0}

Did this DM model escape the room?



Relic abundance $\Omega_\varphi h^2$

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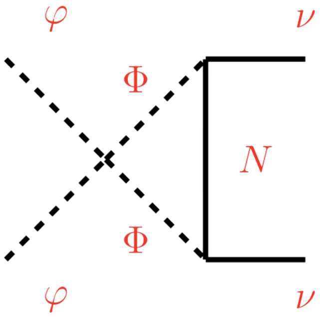
✅

Did this DM model escape the room?



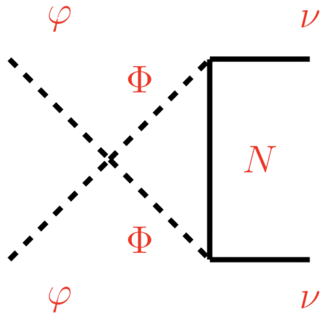
Relic abundance
$\Omega_\varphi h^2$
✓

Annihilation & scattering
N_{eff}, u
✓

Extragalactic annihilation
$\langle \sigma v \rangle$
✓

Lightest ν mass
m_{ν_0}
✓

Did this DM model escape the room?



Relic abundance $\Omega_\varphi h^2$ ✓

Annihilation & scattering N_{eff}, u ✓

Extragalactic annihilation $\langle \sigma v \rangle$ ✓

Lightest ν mass m_{ν_0} ✓

Future work:

- MCMC for + masses, constraints & errors
- Allow for DM underabundance
- Statistical analysis: profile likelihood ratios & p-values

Thank you!

Questions?

Collaborators: Aaron Vincent (Queen's) and Gopolang Mohlabeng (UCI)

E-mail: karen.maciascardenas@queensu.ca

BACKUP SLIDES

Squared Amplitude

FeynRules

$$-\mathcal{L}_{\text{int}} = \frac{1}{2} m_{\varphi}^2 \varphi^2 + \frac{1}{2} \lambda \Phi^2 \varphi^2 + Y_\nu \overline{\nu_L} \Phi N_R + \text{ h.c.}$$

Squared amplitude with FormCalc / FeynCalc

$$|\overline{\mathcal{M}}|^2 = \frac{\lambda^2 m_N^2 s Y_\nu^4 C_0\left(0,0,s,m_\Phi^2,m_N^2,m_\Phi^2\right)^2}{64\pi^4}$$

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

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

Cross-section and relic abundance approximations

s-wave cross-section

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

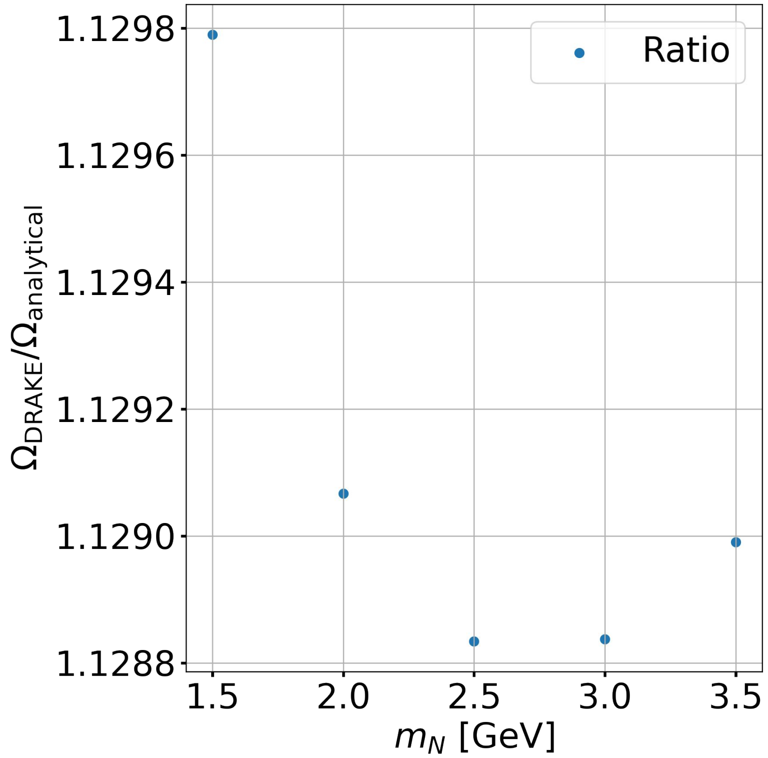
$$\langle \sigma v \rangle \approx \frac{\lambda^2 Y_\nu^4 m_N^2}{512\pi^5} |C_0\left(0, 0, 4m_\varphi^2, m_\Phi^2, m_N^2, m_\Phi^2\right)|^2$$

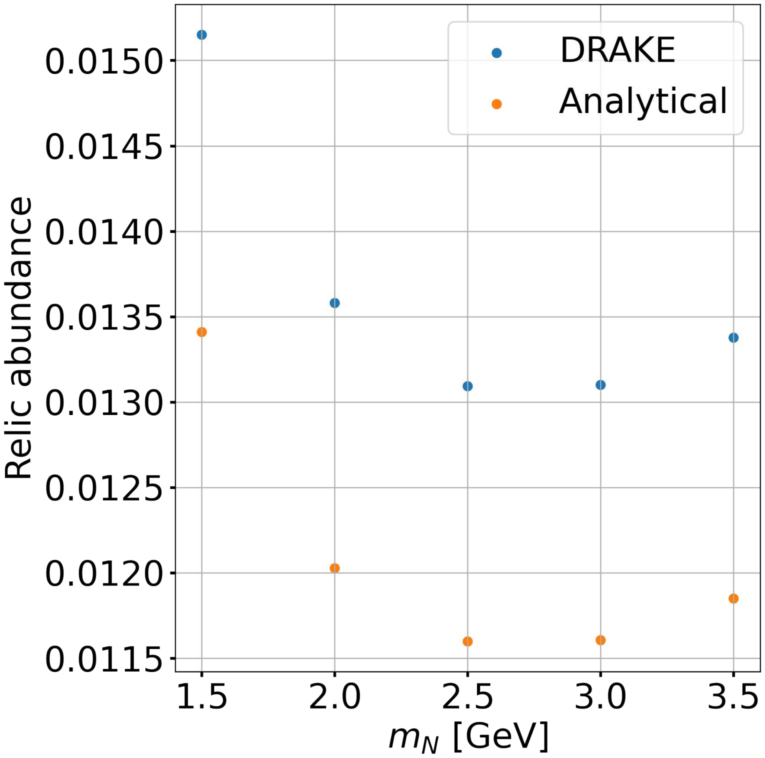
DM relic abundance approximation

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

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

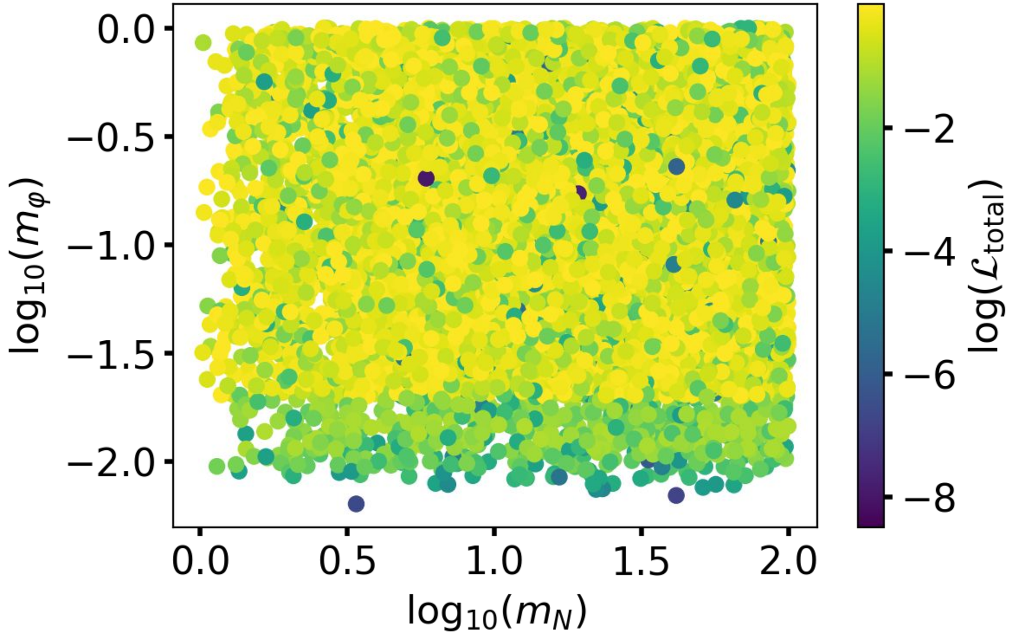
Comparison to the Boltzmann code DRAKE

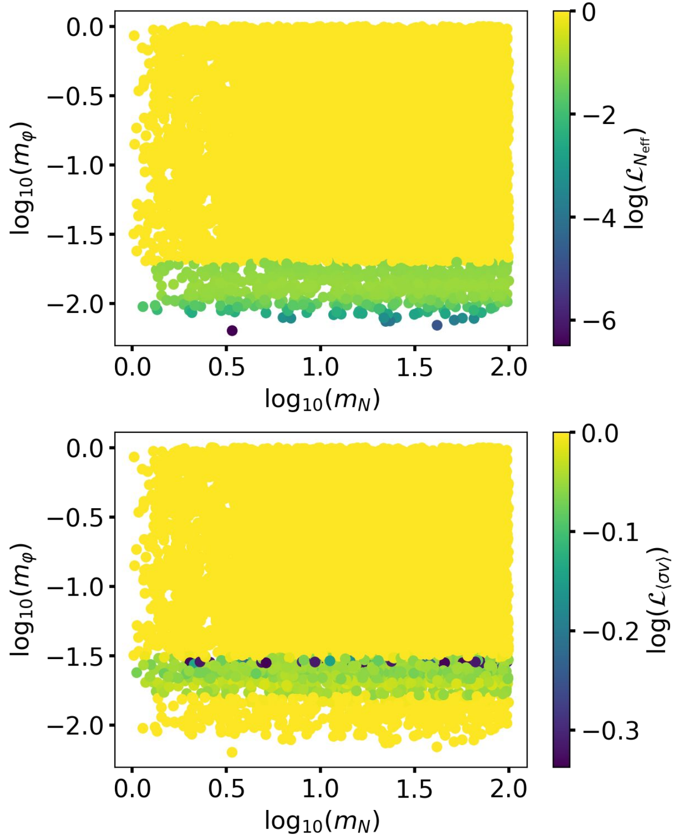




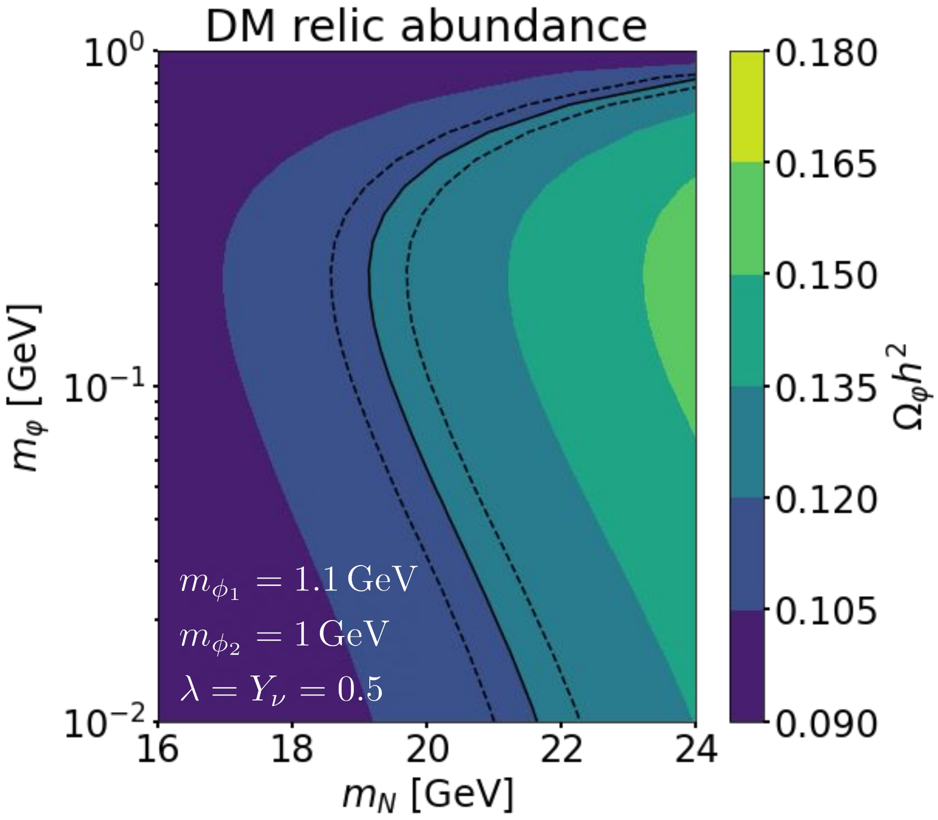
Binder, Tobias, et al. "Dark matter relic abundance beyond kinetic equilibrium." The European Physical Journal C 81.7 (2021): 1-21.

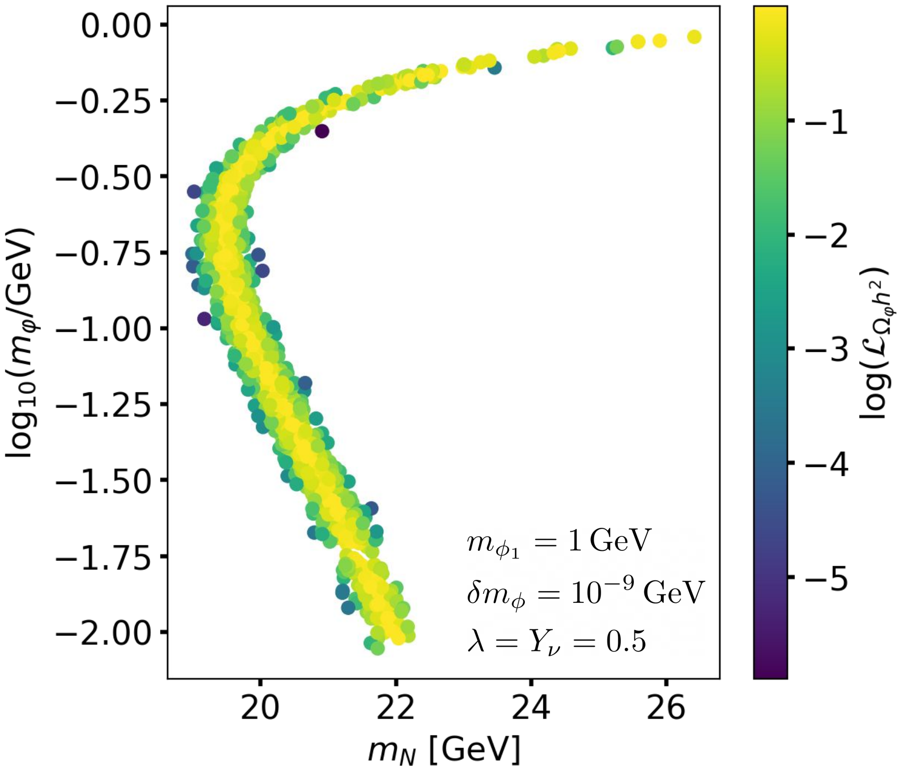
DM mass vs heavy neutrino mass likelihoods



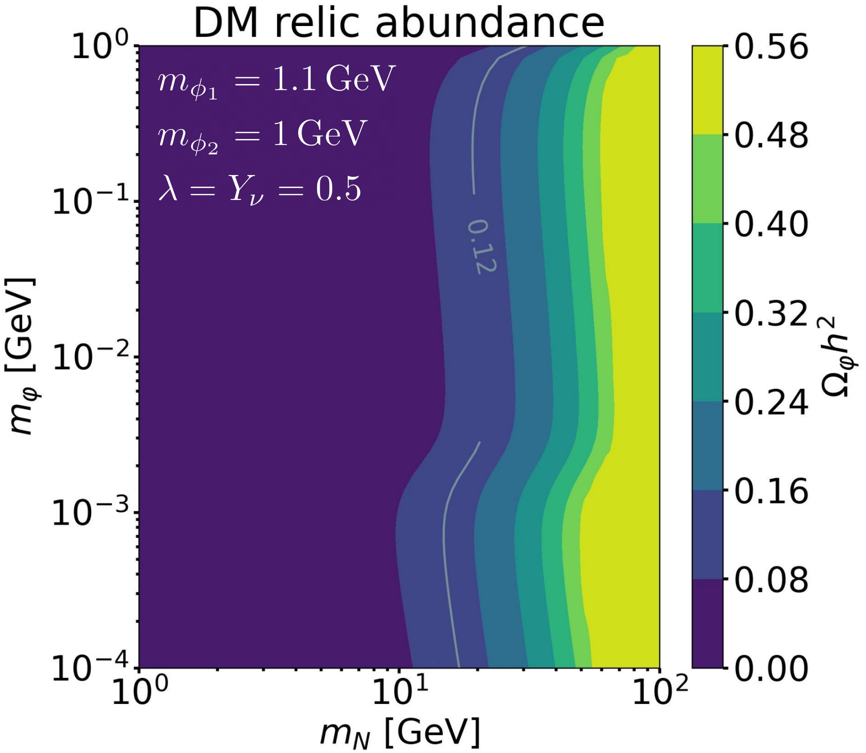


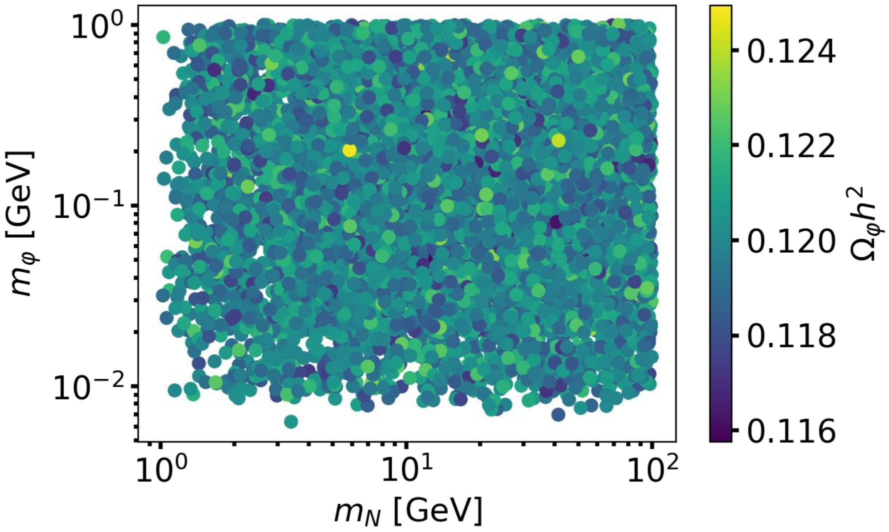
2D Relic Abundance Likelihood



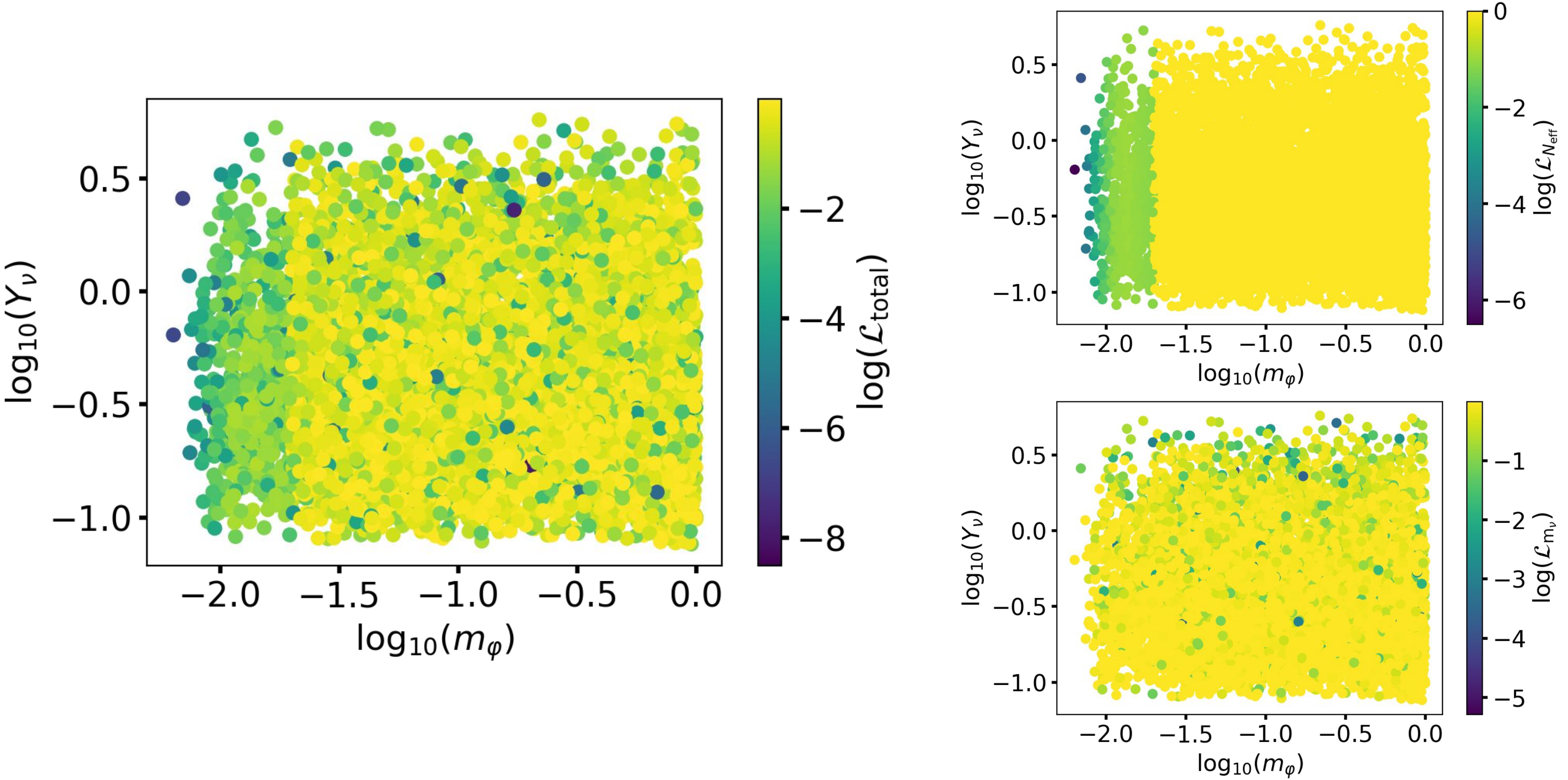


Relic abundance for fixed + varying parameters

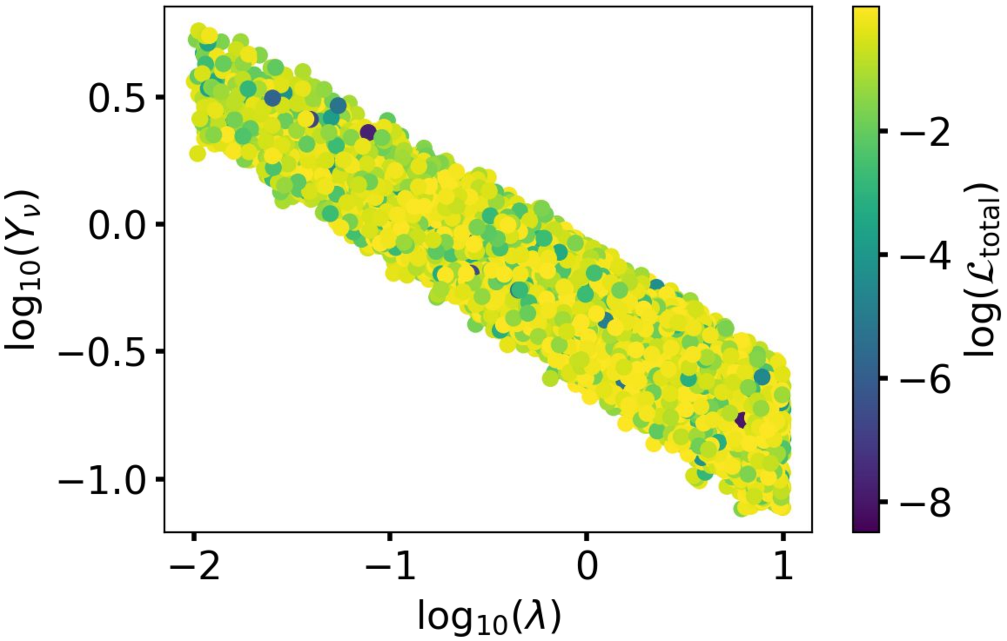


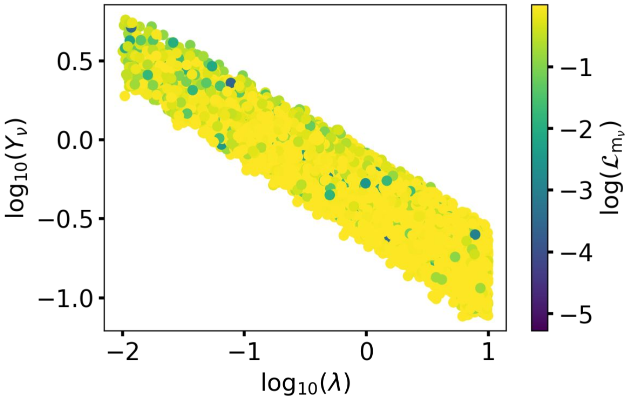


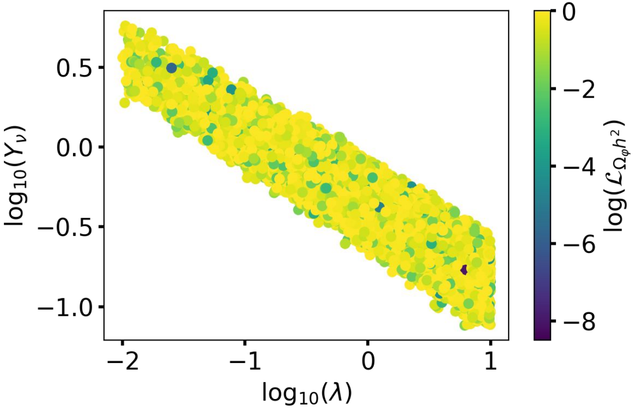
Yukawa coupling vs DM mass likelihoods



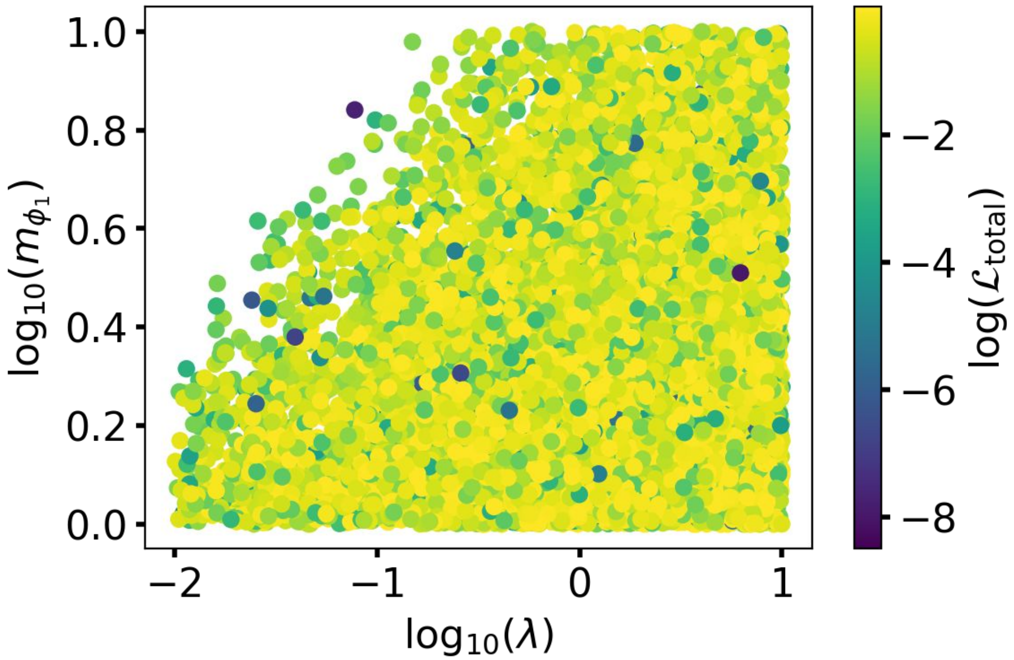
Yukawa coupling vs λ coupling likelihoods

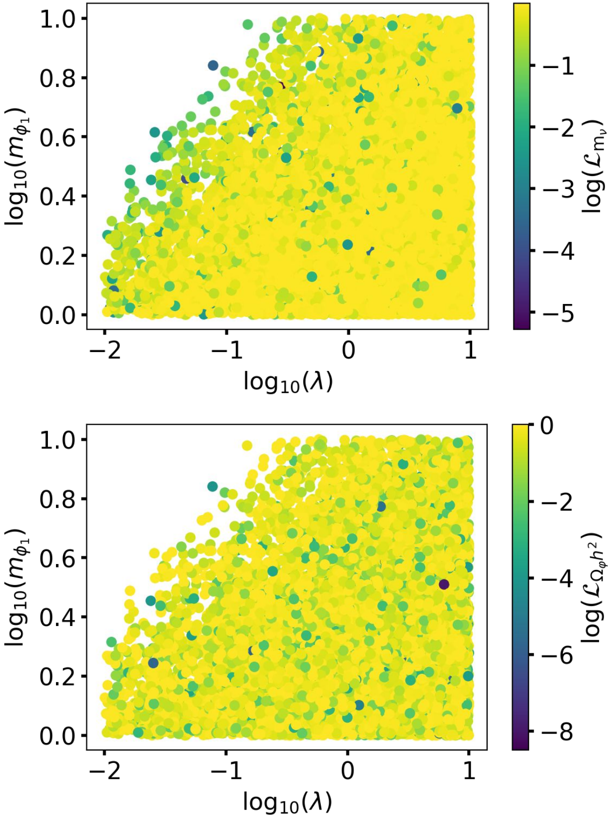




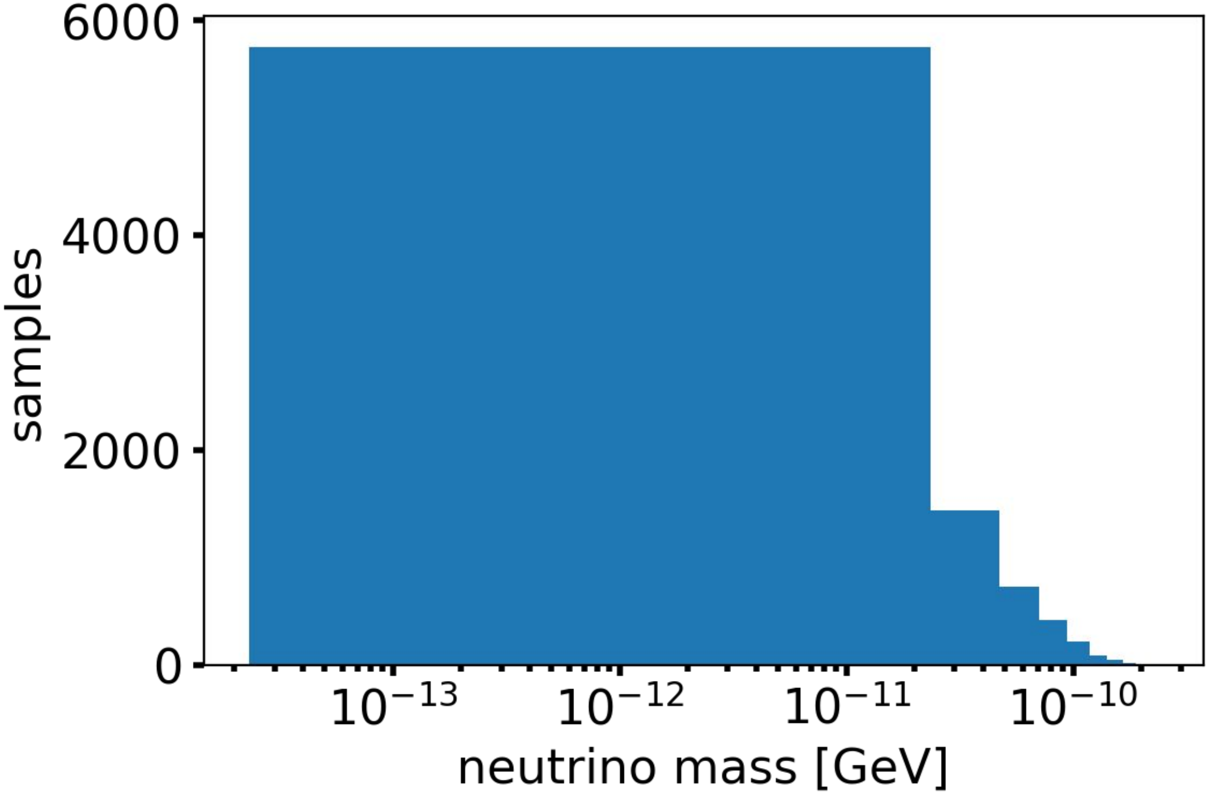


Scalar mediator mass vs λ coupling likelihoods

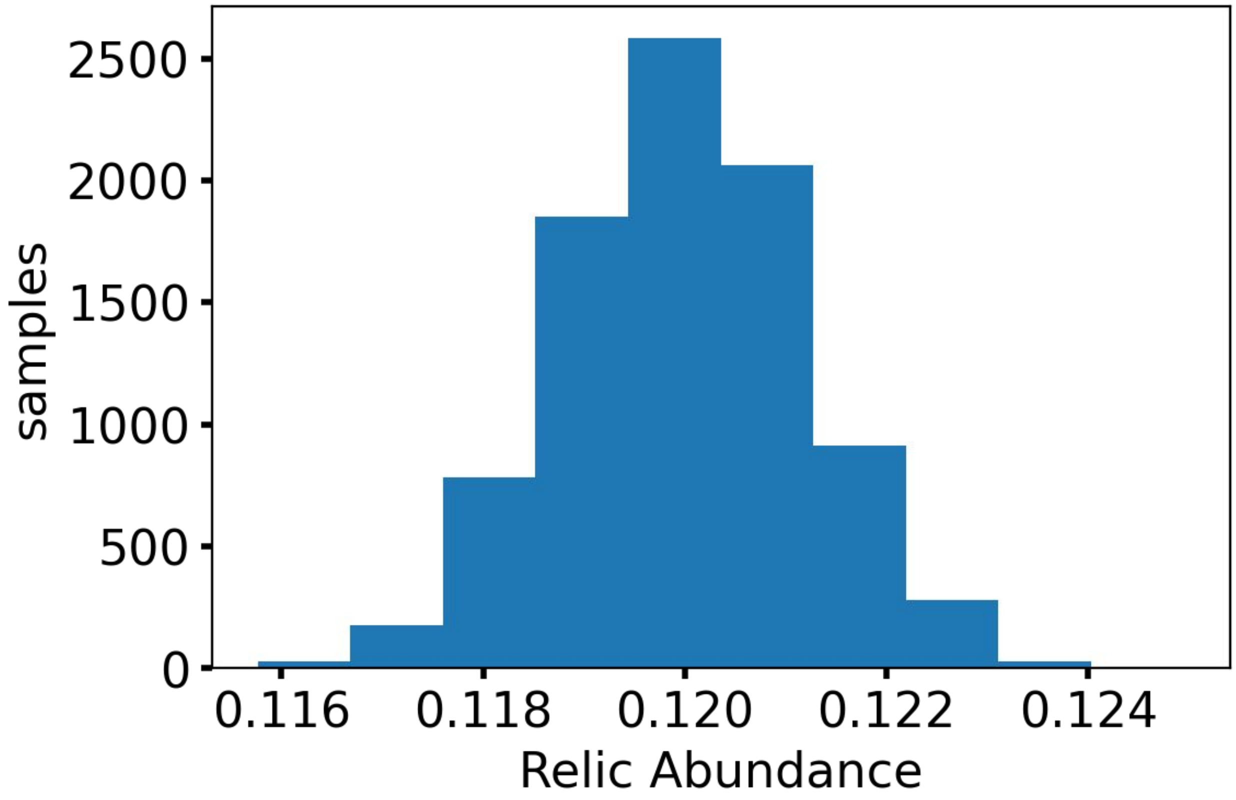




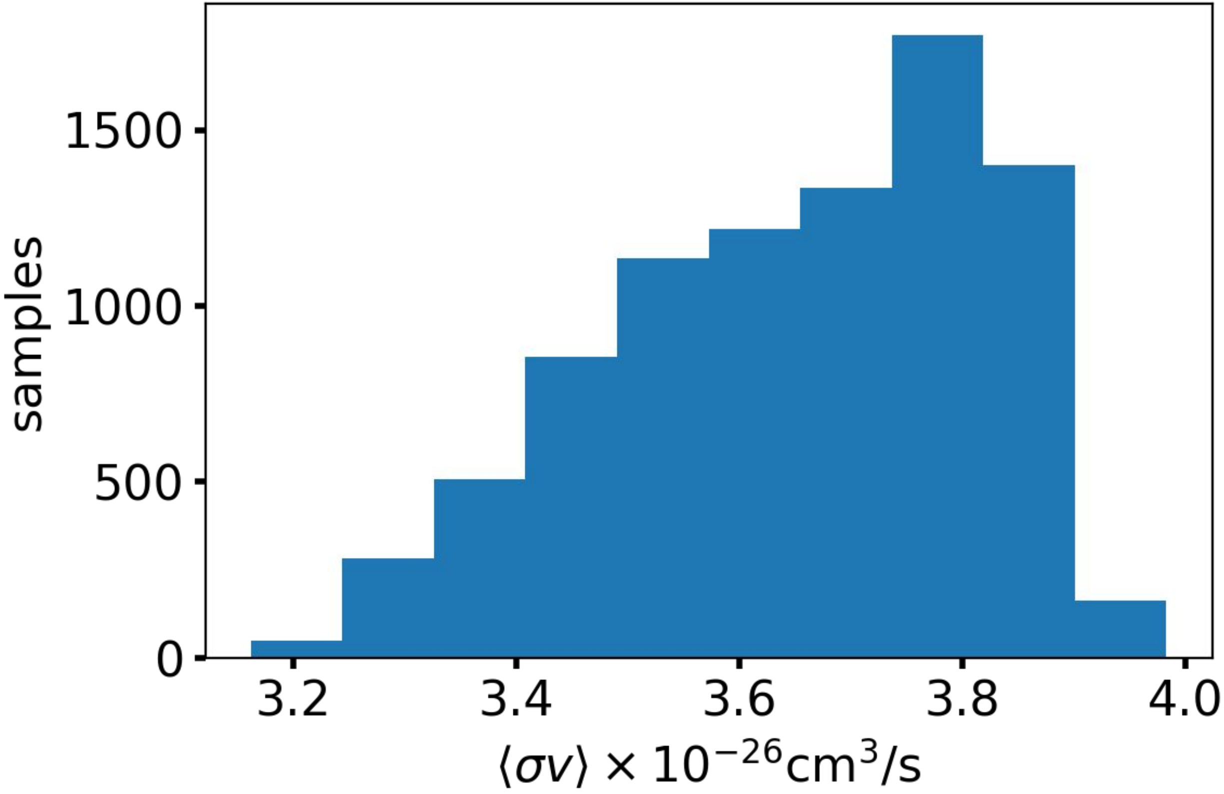
Neutrino mass sampling



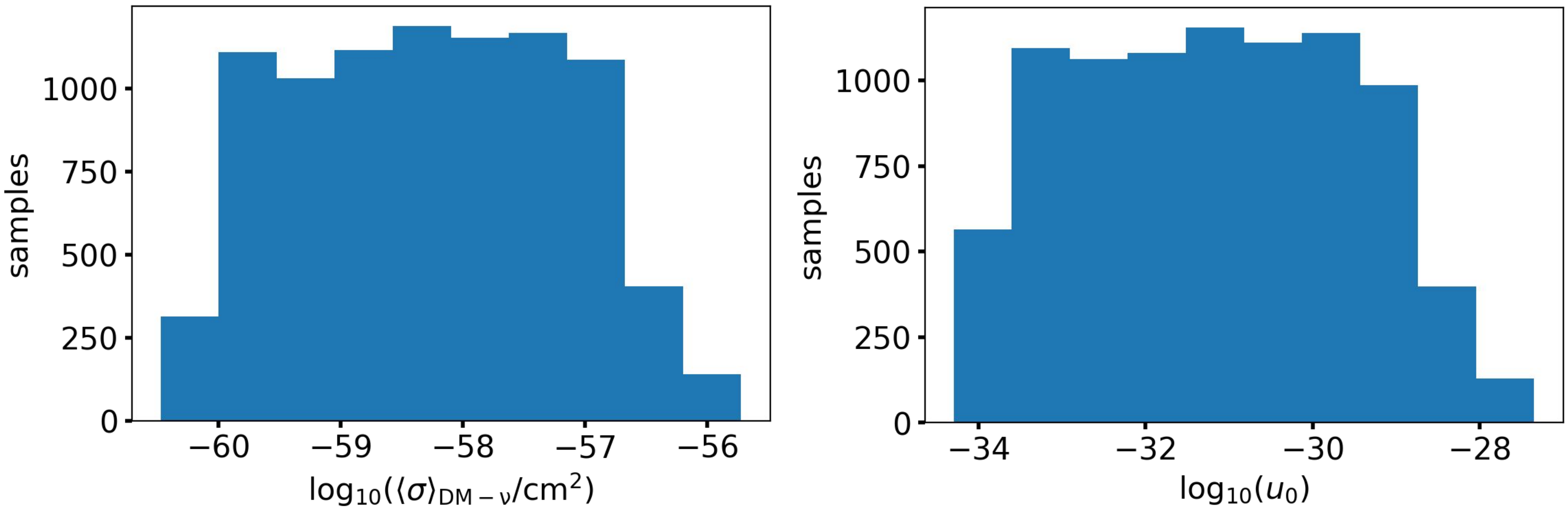
Relic abundance sampling



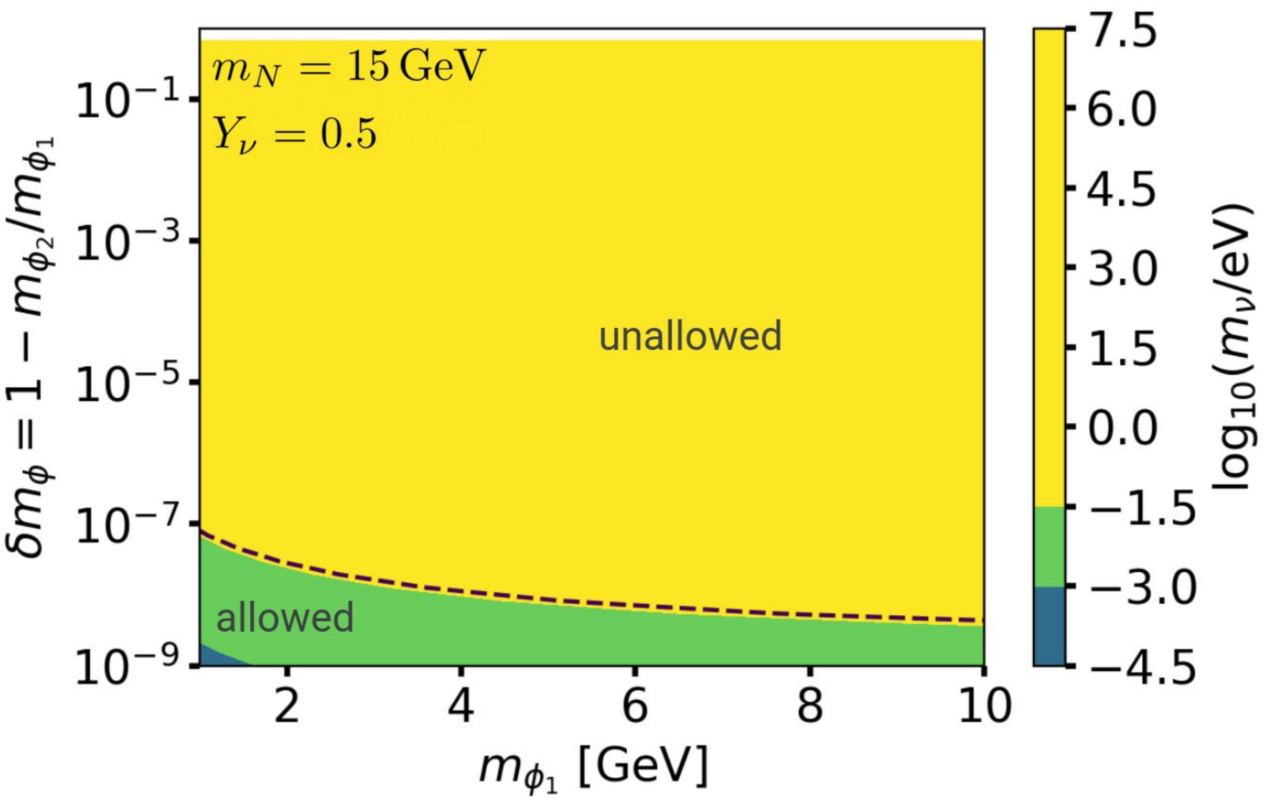
Annihilation cross-section sampling



Scattering cross-section sampling



Neutrino mass parameter space



Structure formation

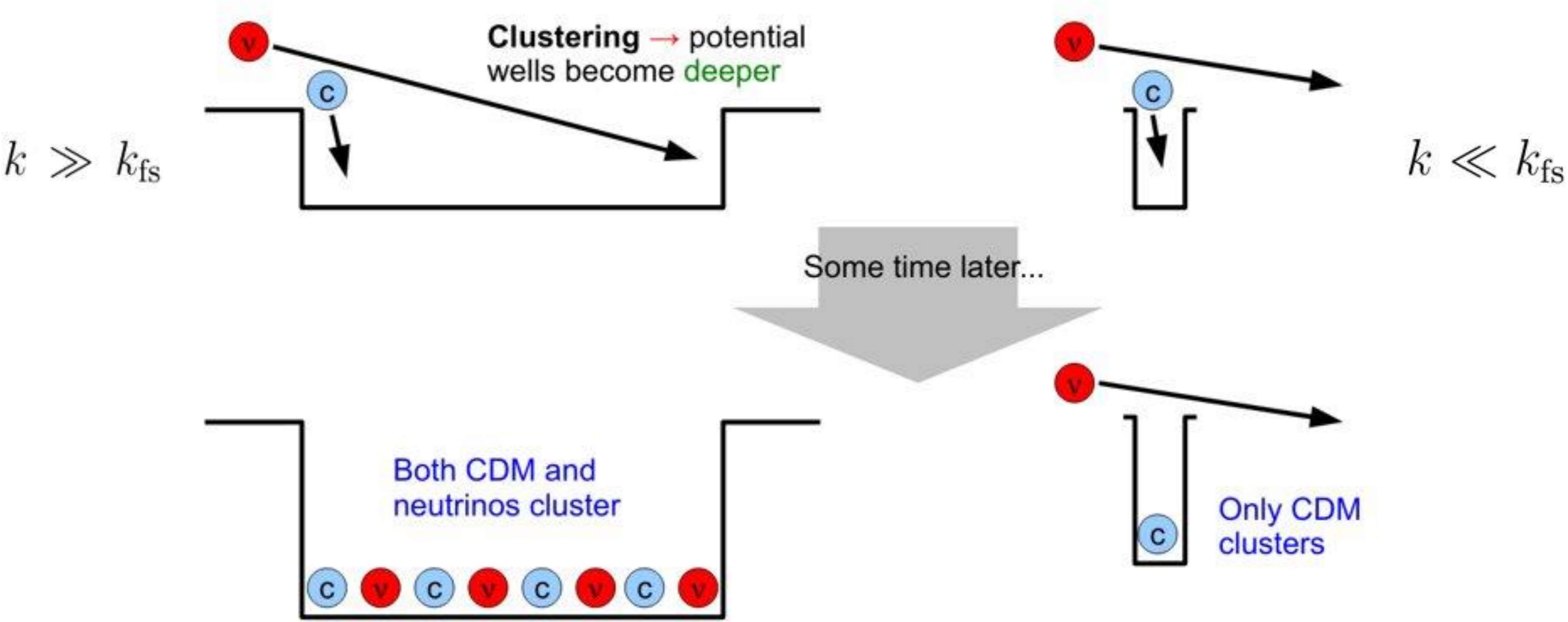


Diagram by Yvonne Y. Y. Wong