Queen's University ARTS AND SCIENCE

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

Dark Matter – neutrino interactions

through a 1-loop diagram

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MSc Candidate, Queen's University

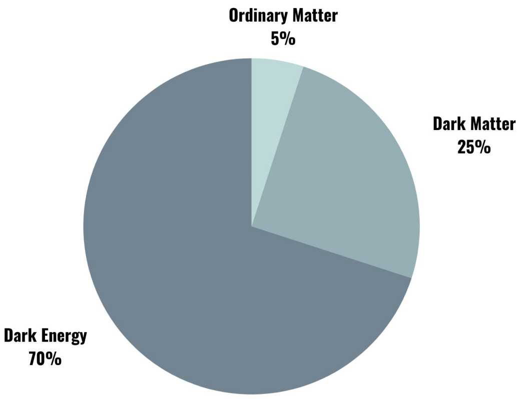
2022 CAP Congress. Hamilton, ON. June 8th, 2022

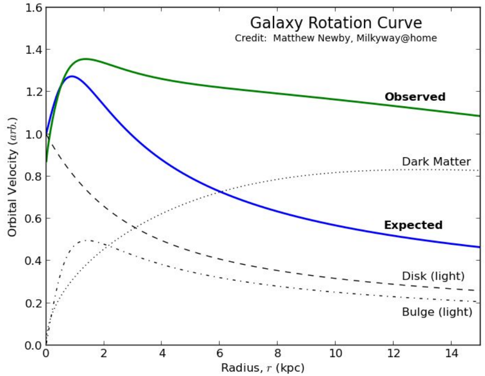
The Standard Model is incomplete

The Standard Model is incomplete

Neutrino mass mechanism

The Standard Model is incomplete



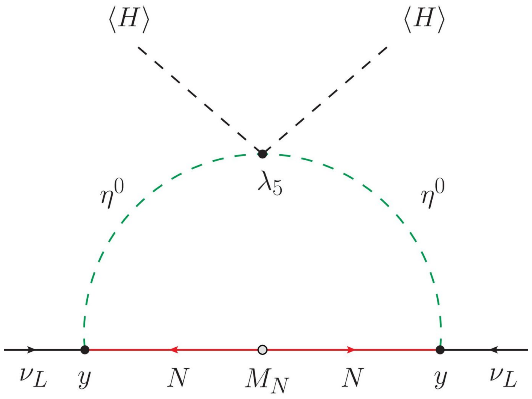


Neutrino mass mechanism

Astrophysical and cosmological evidence of dark matter

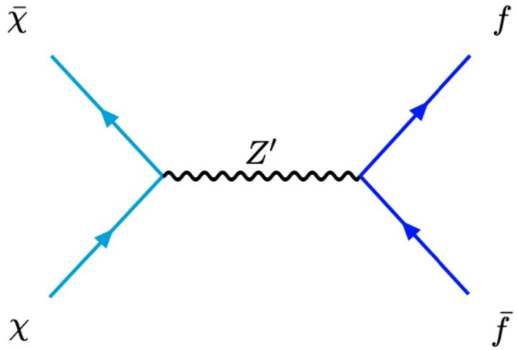
Theoretical Framework

Dark matter interactions with the standard model through the neutrino sector



Scotogenic model

Ma, E. (2006).

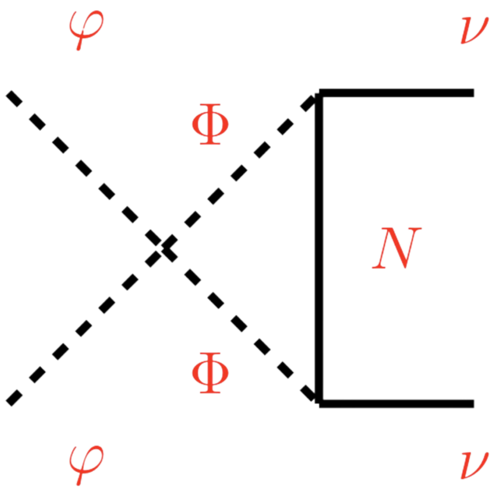


U(1)' models

L, B−L symmetries

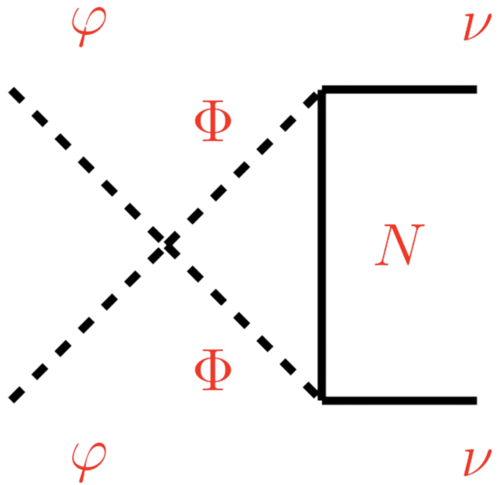
Research Question

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



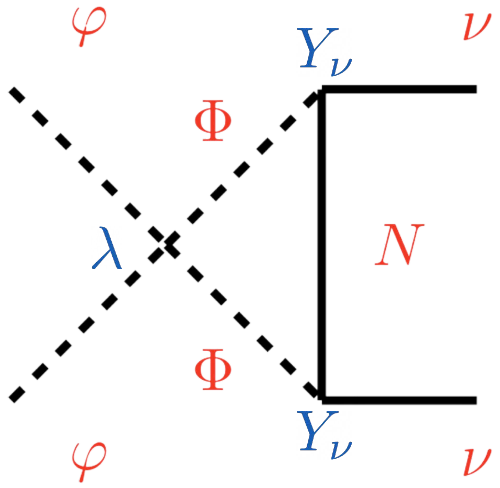
Chao, W. (2020). arXiv: 2009.12002

Real scalar DM φ

Complex scalar mediator Φ

Heavy neutrino mediator N

Dark matter annihilation into neutrinos

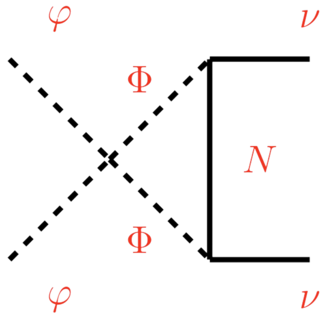


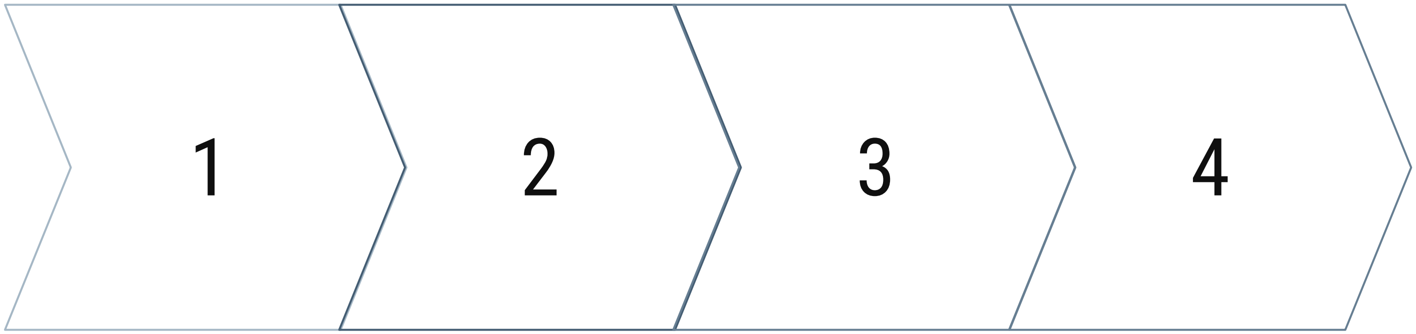
Chao, W. (2020). arXiv: 2009.12002

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

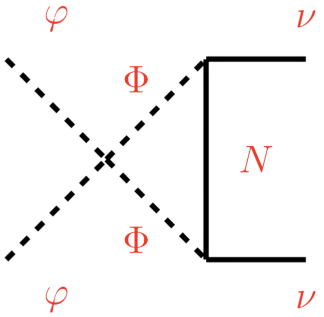
Couplings $\lambda,\ Y_\nu$

The Dark Matter Escape Room





The Dark Matter Escape Room



Relic abundance $\Omega_\varphi h^2$

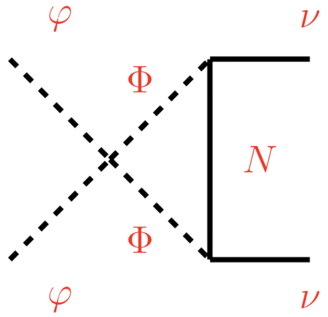
2

3

4

Early universe DM-neutrino interactions

The Dark Matter Escape Room



Relic abundance $\Omega_\varphi h^2$

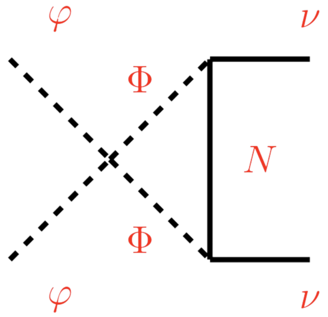
Annihilation & scattering N_{eff}, u

3

4

Early universe DM-neutrino interactions

The Dark Matter Escape Room



Relic abundance
$\Omega_\varphi h^2$

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

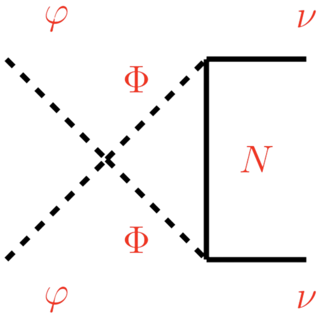
Extragalactic annihilation
$\langle \sigma v \rangle$

4

Early universe DM-neutrino interactions

Supernova Relic Neutrinos (DSNB)

The Dark Matter Escape Room



Relic abundance $\Omega_\varphi h^2$

Annihilation & scattering N_{eff}, u

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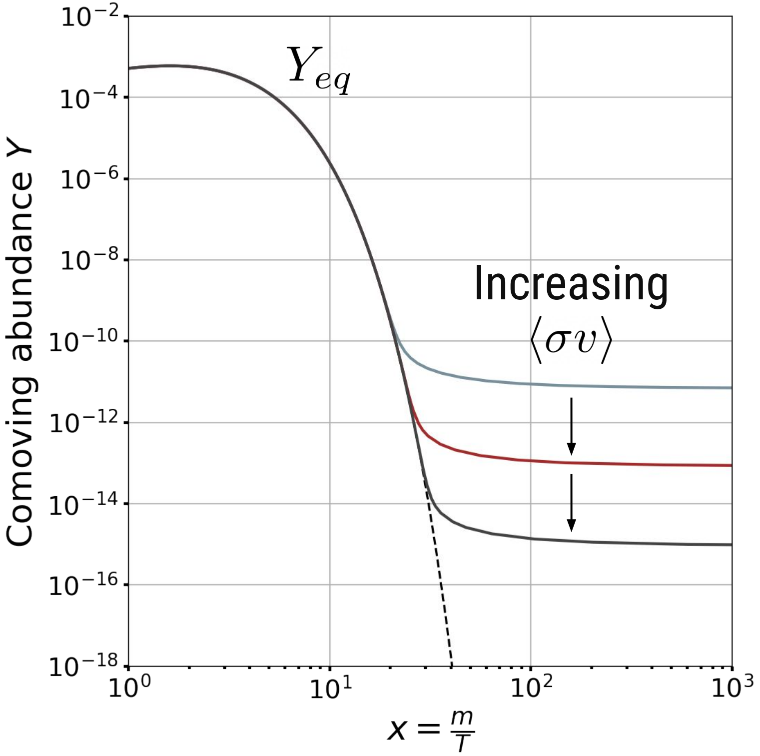
MCMC

Early universe DM-neutrino interactions

Supernova Relic Neutrinos (DSNB)

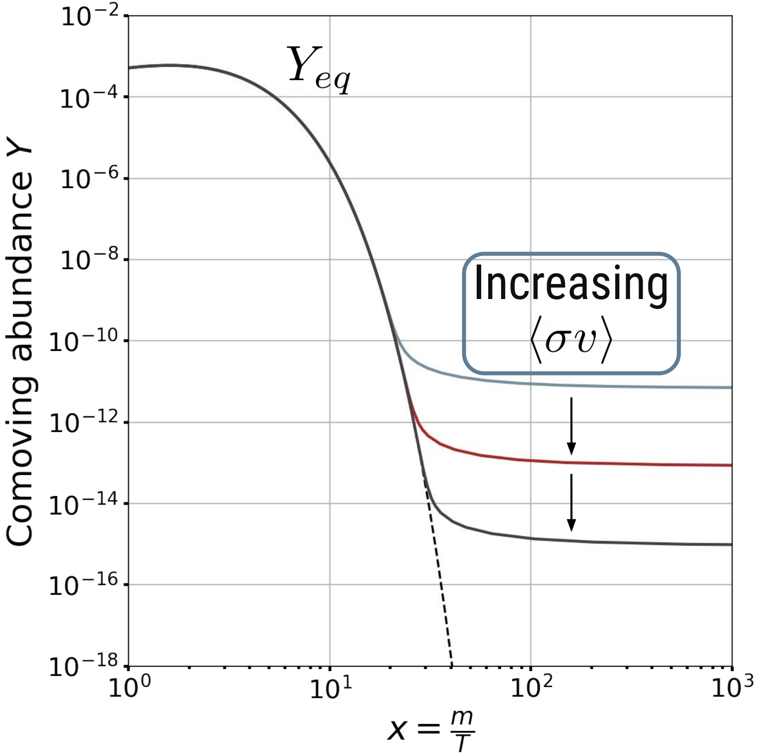
First Test: Dark Matter Relic Abundance



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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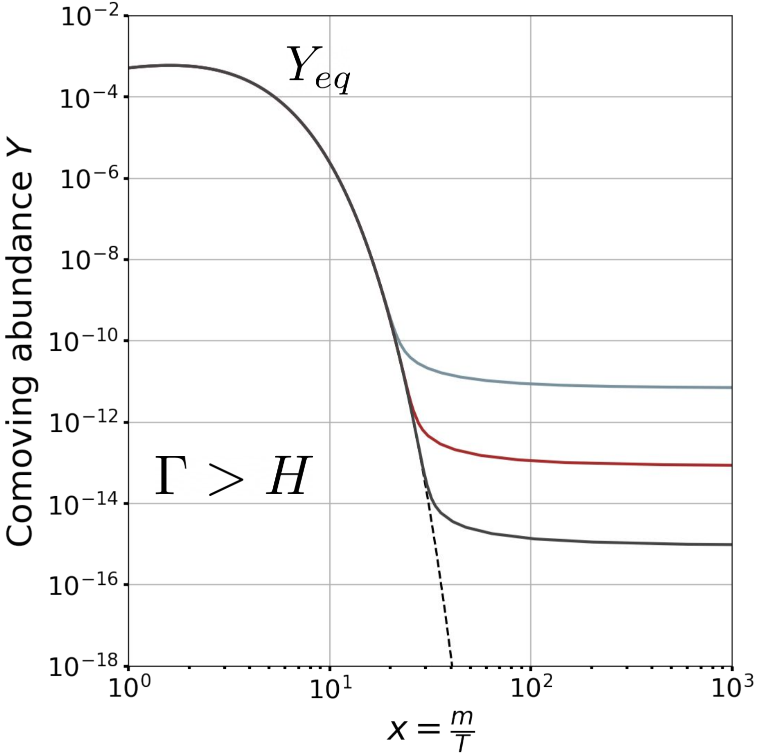

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$\Gamma > H$ Follows equilibrium abundance

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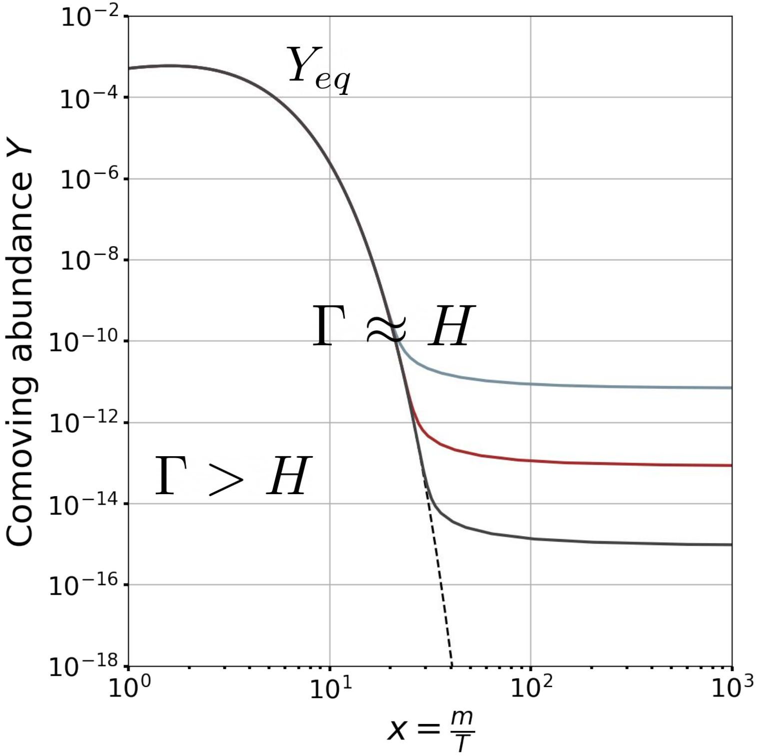

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$\Gamma > H$ Follows equilibrium abundance

$\Gamma \approx H$ Freeze-out

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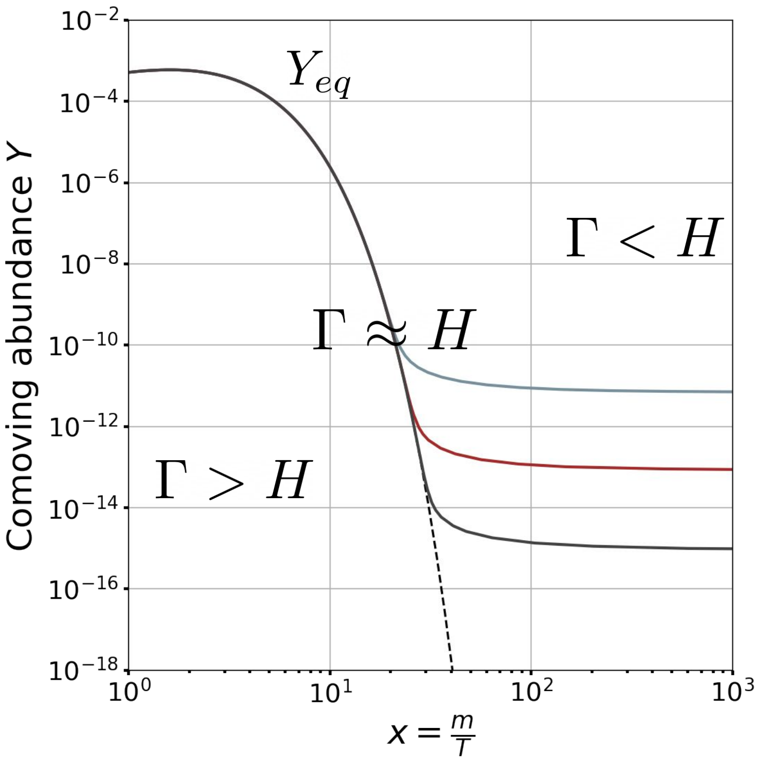

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$\Gamma > H$ Follows equilibrium abundance

$\Gamma \approx H$ 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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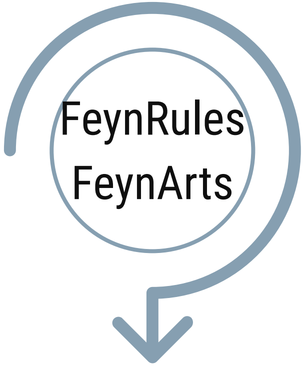
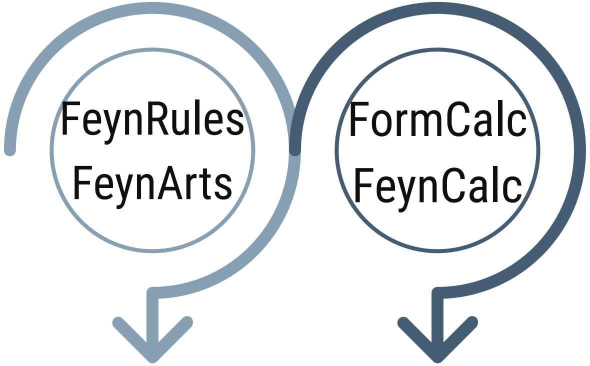


Feynman rules
and diagrams

First Test: Dark Matter Relic Abundance

Interaction Lagrangian

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



Feynman rules and diagrams

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

First Test: Dark Matter Relic Abundance

Interaction Lagrangian

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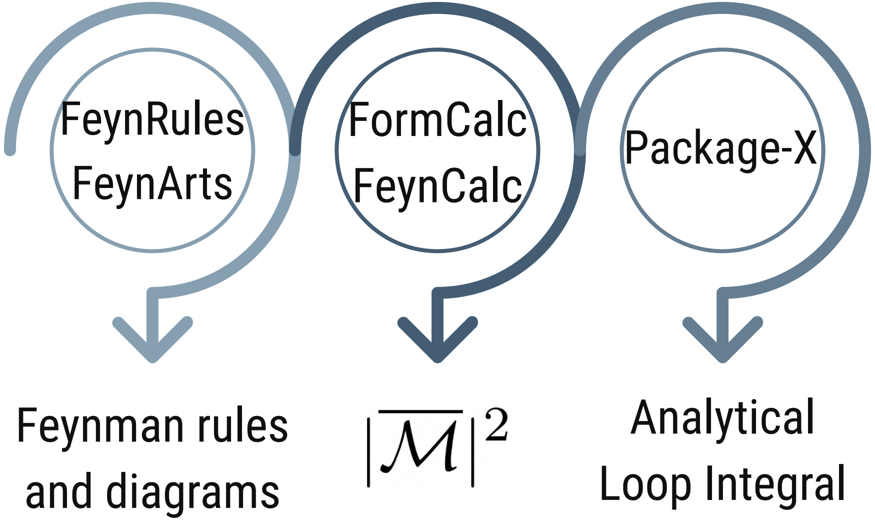

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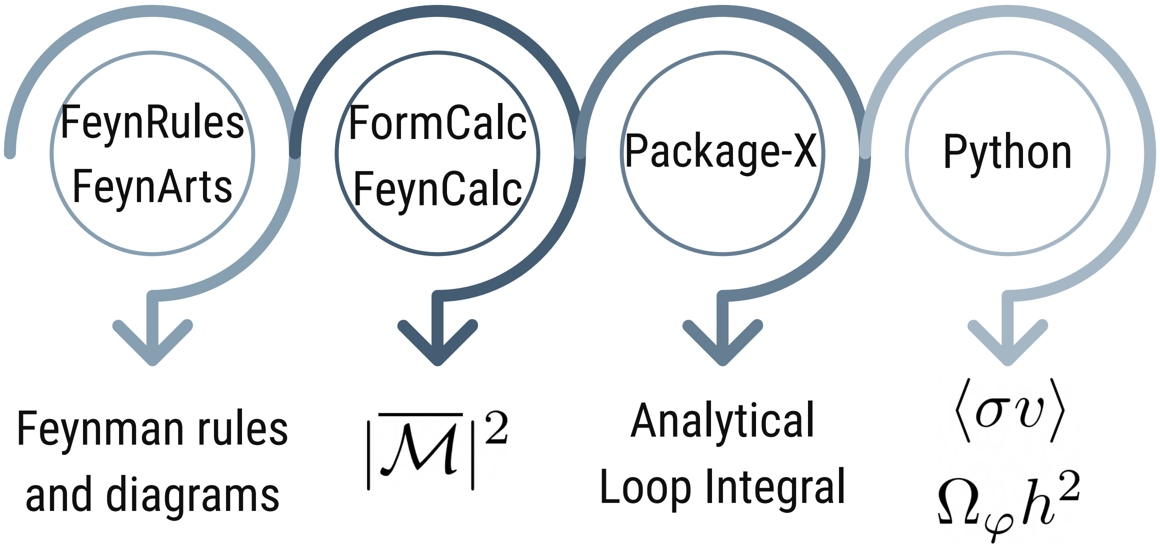

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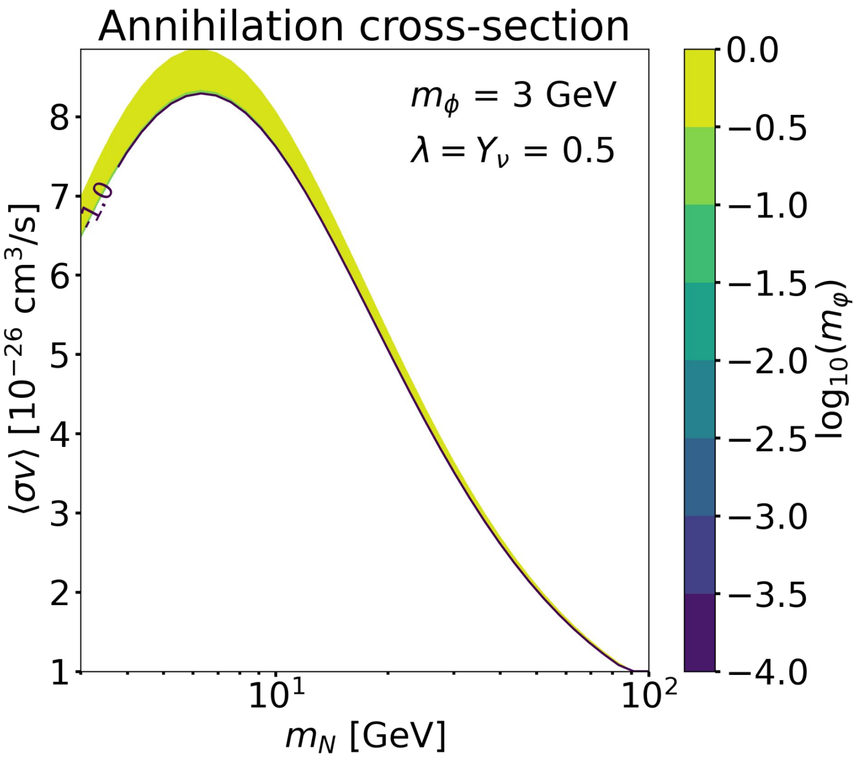
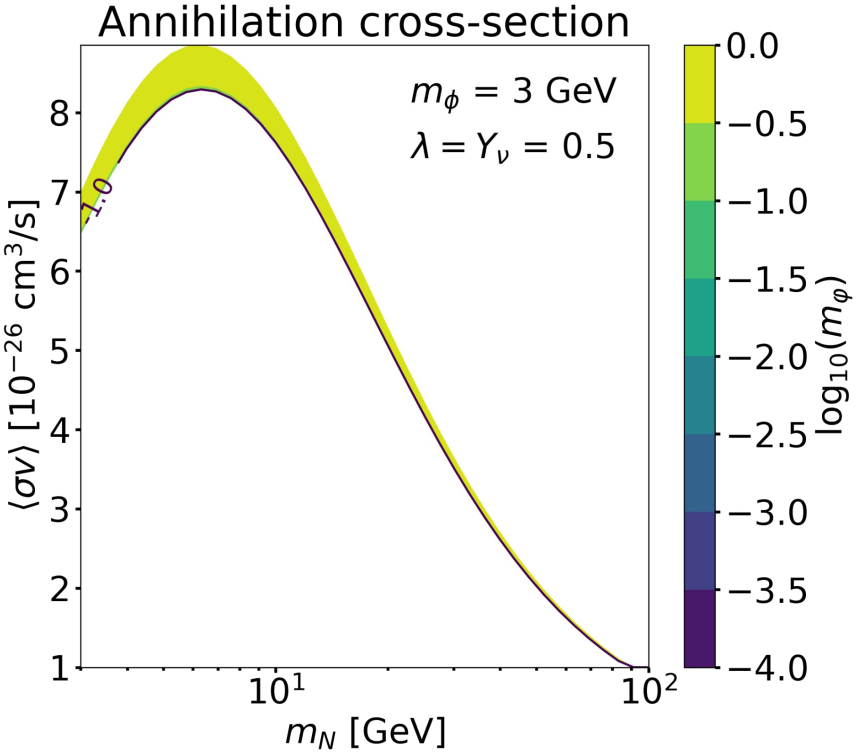


Stability constraint

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

First Test: Dark Matter Relic Abundance



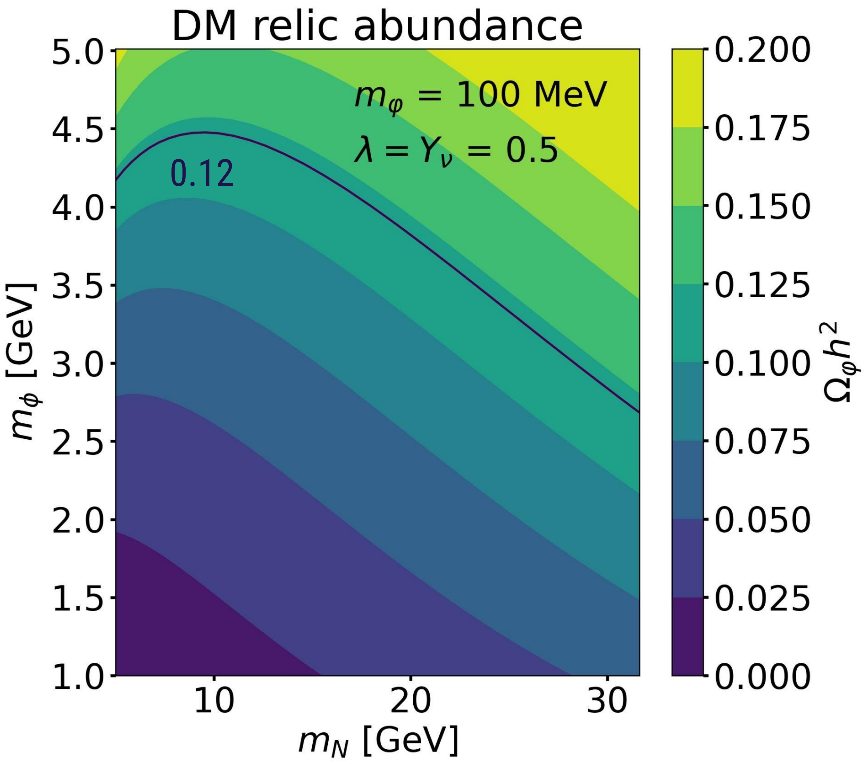
Stability constraint

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

Nearly independent of

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

First Test: Dark Matter Relic Abundance



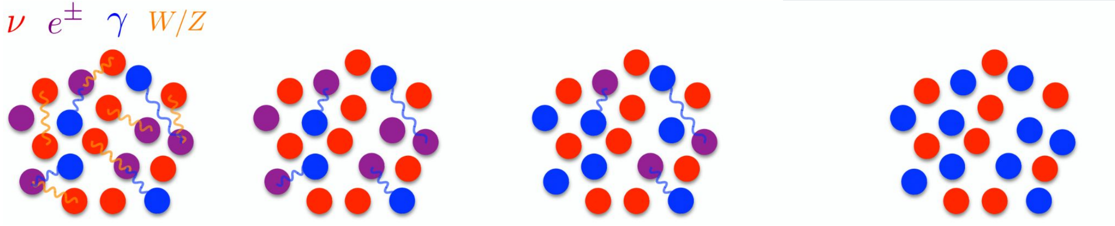
Constraint from Planck 2018

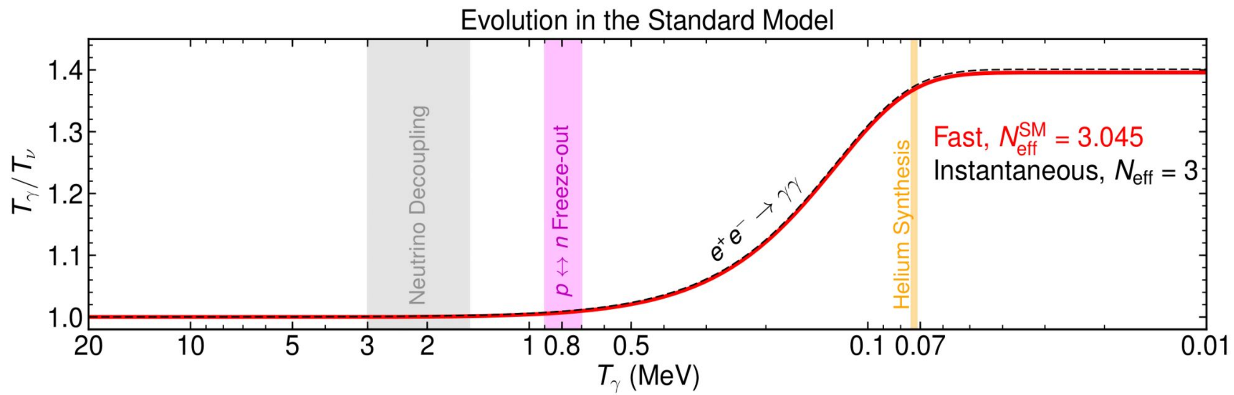
$$\Omega_c h^2 = 0.1200 \pm 0.0012$$

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

Second Test: Primordial abundances and N_{eff}

Big Bang Nucleosynthesis (BBN)





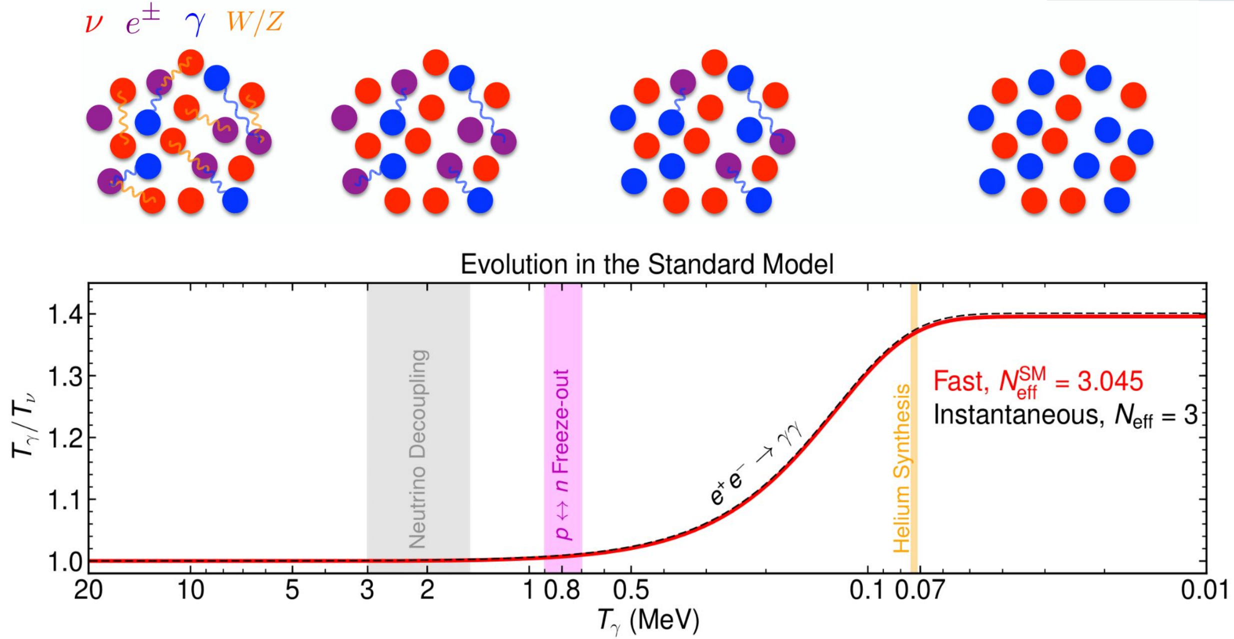
$$T_\gamma/T_\nu = (11/4)^{1/3}$$

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

Escudero, M. (2020). arXiv: 2001.04466

Second Test: Primordial abundances and N_{eff}

BBN and light dark matter



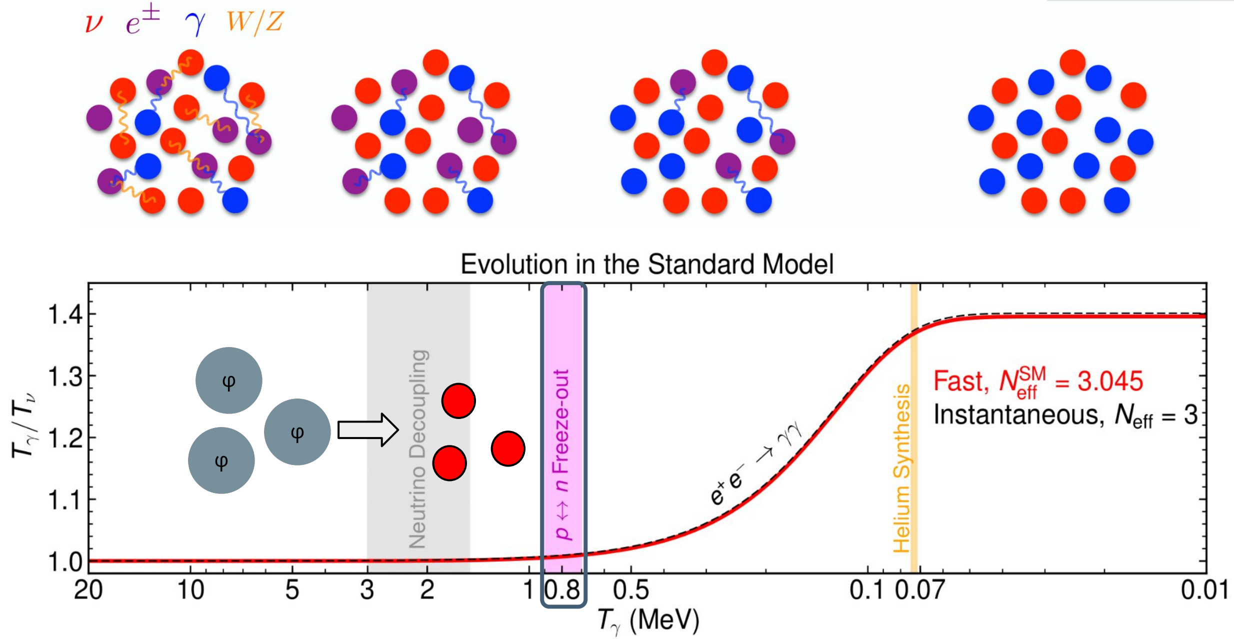
φ

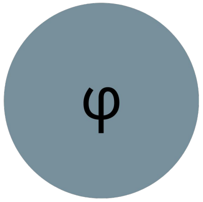
$$m_\varphi \leq 20\,\mathrm{MeV}$$

Escudero, M. (2020). arXiv: 2001.04466

Second Test: Primordial abundances and N_{eff}

BBN and light dark matter





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

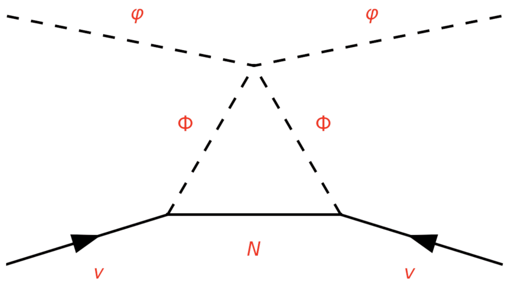
$$Y_P \quad Y_D \quad N_{\rm eff}$$

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

Second Test: DM-neutrino scattering

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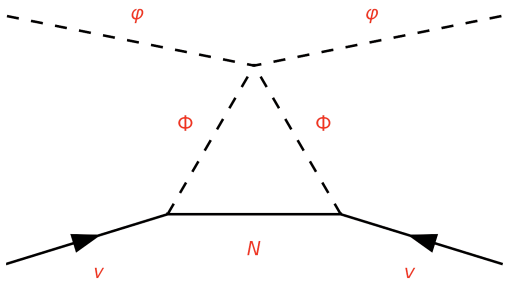


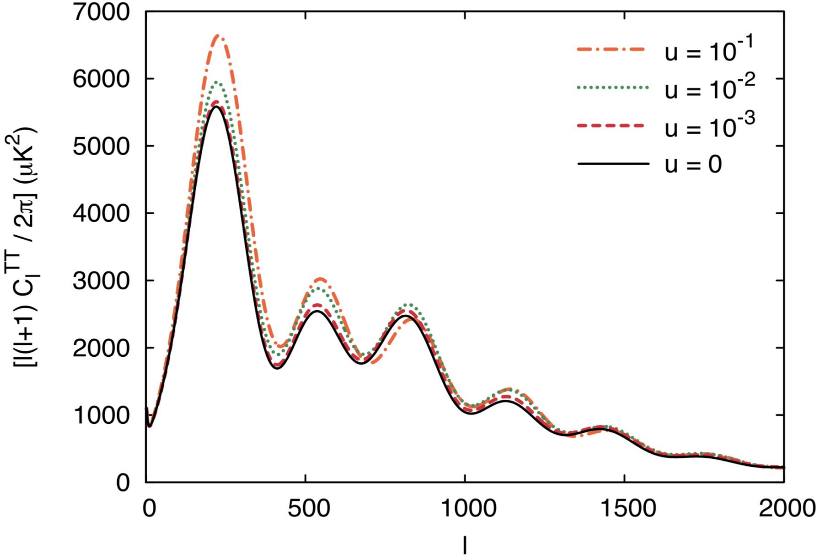
Fermi-Dirac distribution $f_\nu(k) = \frac{1}{e^{-k/T_\nu} + 1}$

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

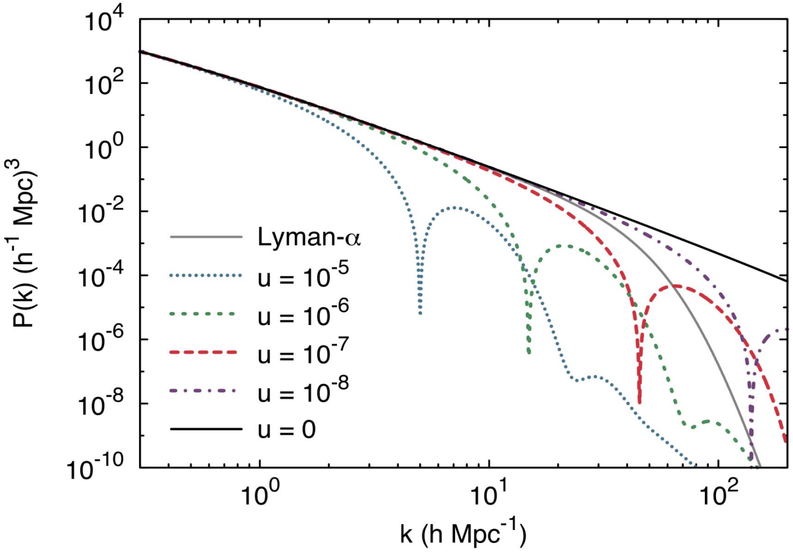
Wilkinson, R.J. et al. (2014). arXiv: 1401.7597

Second Test: DM-neutrino scattering

CMB Power Spectrum

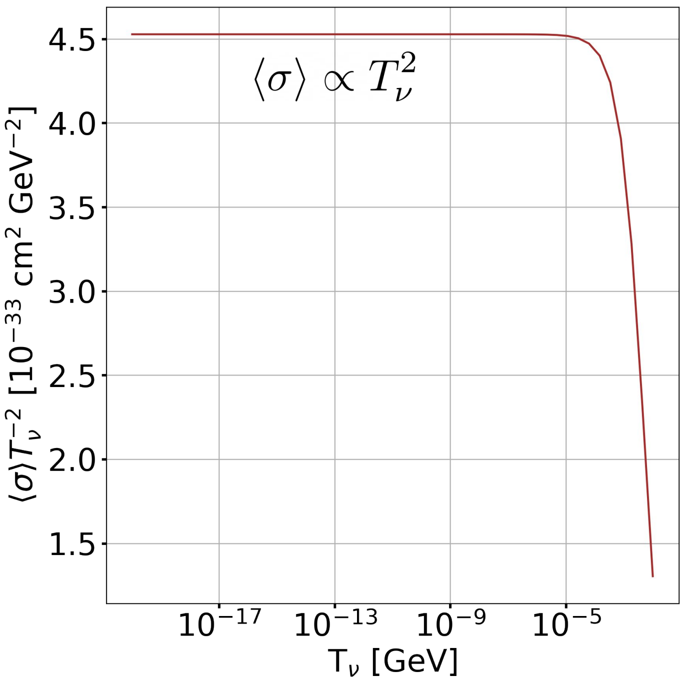


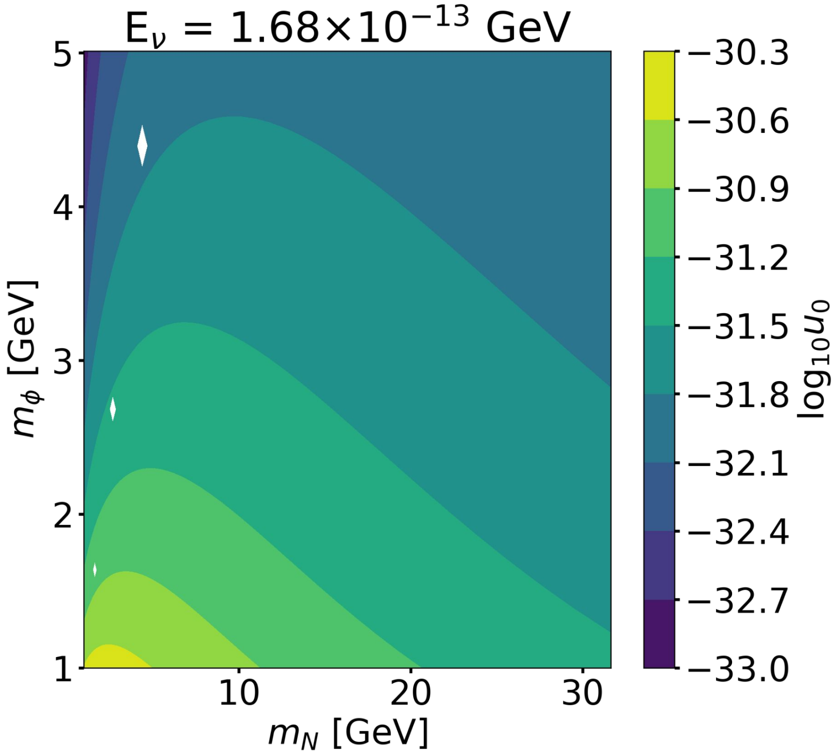
Matter Power Spectrum



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

Second Test: DM-neutrino scattering

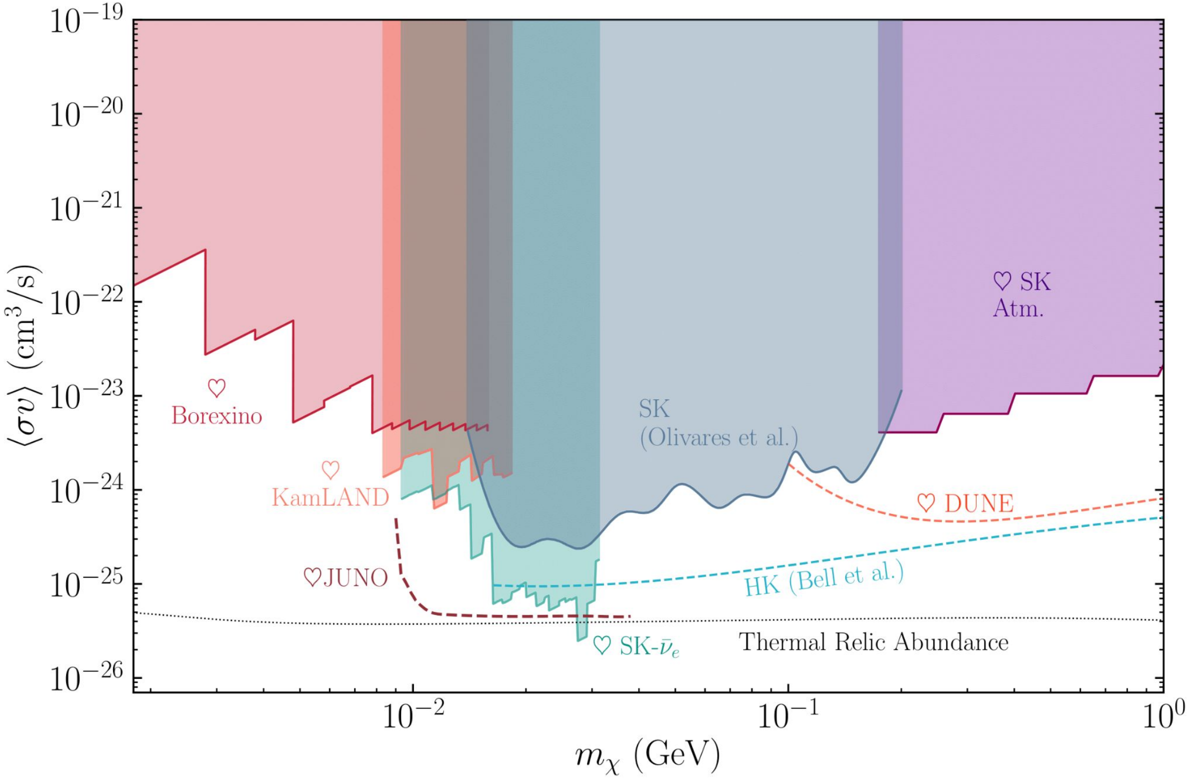




Third Test: Extragalactic DM Annihilation

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: Combining All Constraints

Fourth 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

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

BBN primordial abundances

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

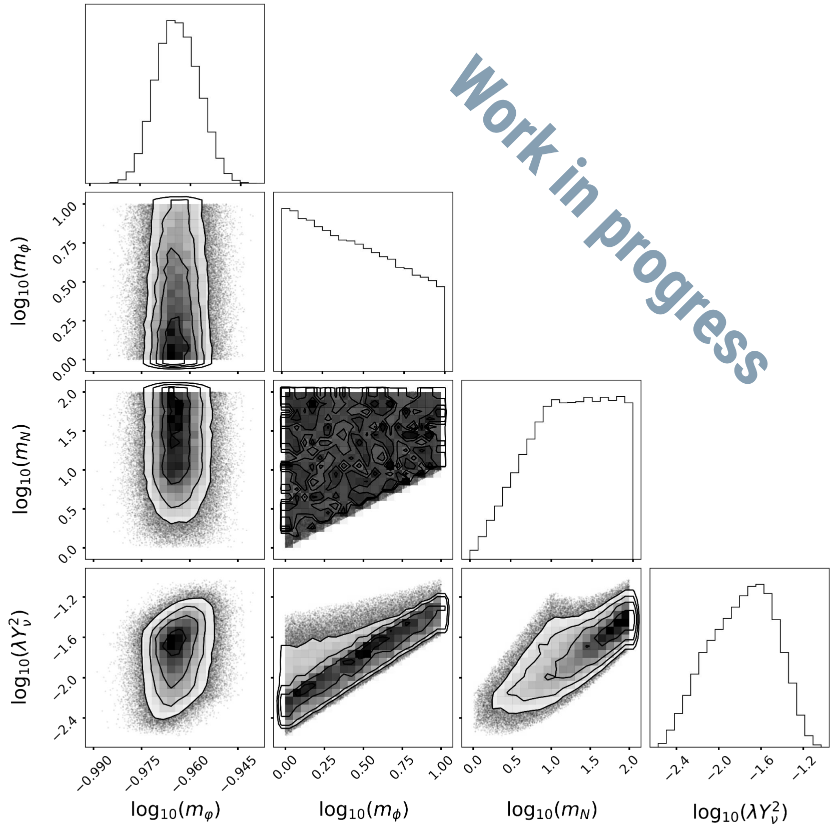
Obtained using AlterBBN

Relic abundance

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

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

Fourth Test: Combining All Constraints



Preliminary MCMC

using emcee

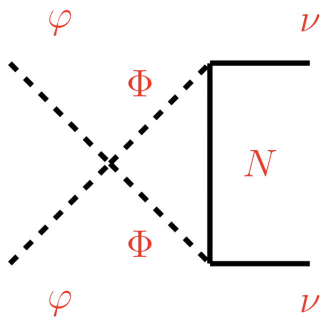
Prior $m_N > m_\phi > m_\varphi$

Strongest constraint

$\Omega_\varphi h^2 + \langle\sigma\rangle_{\mathrm{DM}-\nu}$

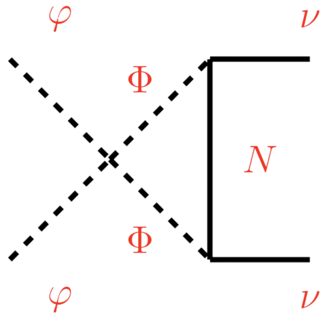
More tests to be done!

Summary



Relic abundance $\Omega_\varphi h^2$ → Annihilation & scattering $N_{\rm eff}, u$ → Extragalactic annihilation $\langle \sigma v \rangle$ → MCMC

Summary



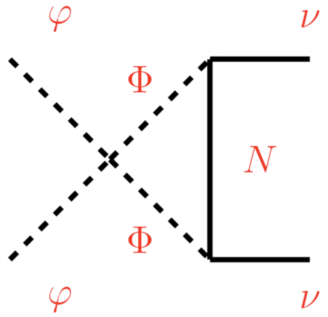
Relic abundance $\Omega_\varphi h^2$ ✅

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

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

MCMC

Summary



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

Annihilation & scattering N_{eff}, u ✅

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

MCMC ❓

Future work:

- Running the MCMC at different points - Profile likelihood ratios
- Neutrino mass generation mechanism

Queen's University ARTS AND SCIENCE

Arthur B. McDonald Canadian Astroparticle Physics Research Institute

Thank you!

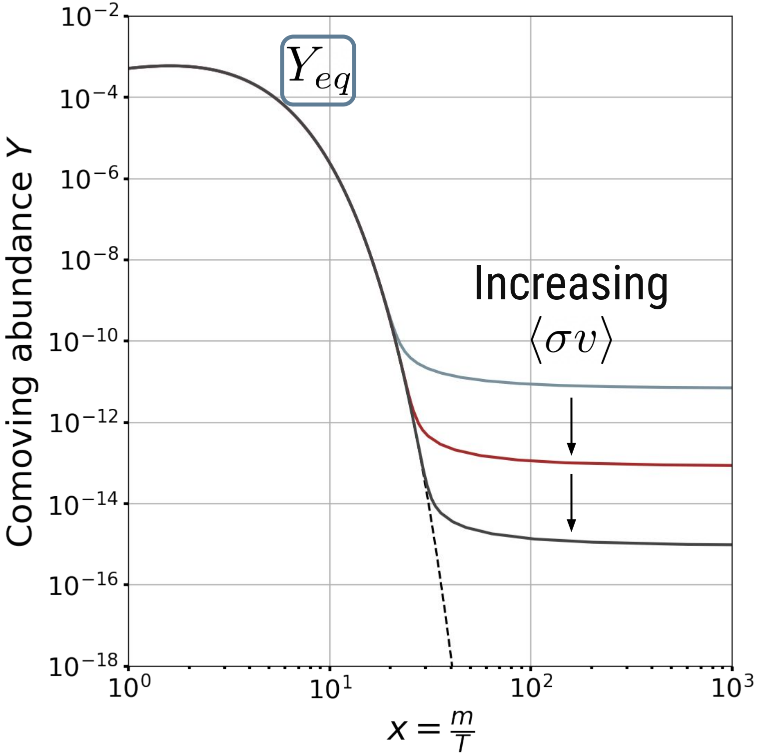
Questions?

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

E-mail: karen.maciascardenas@queensu.ca

BACKUP SLIDES

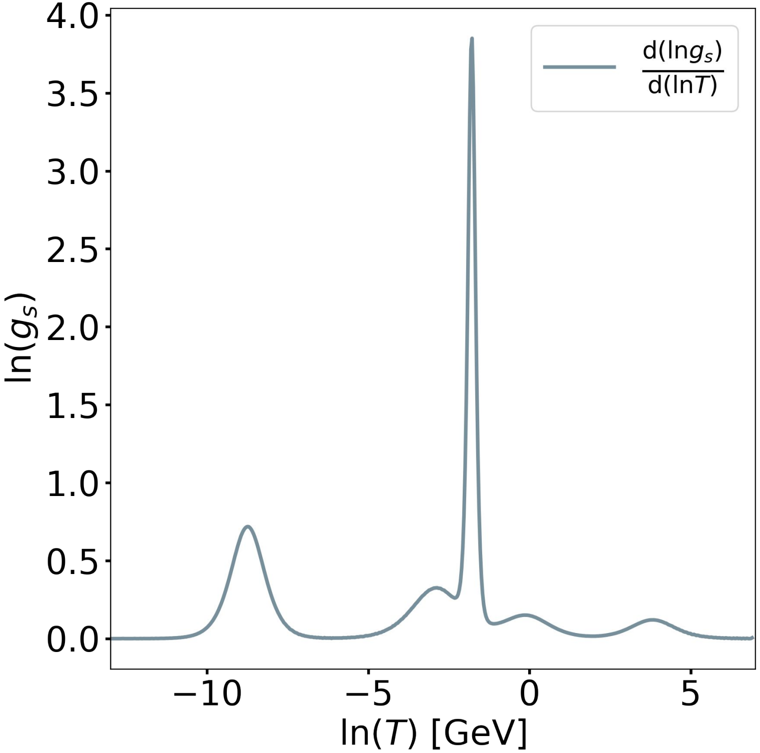
First Test: Dark Matter Relic Abundance



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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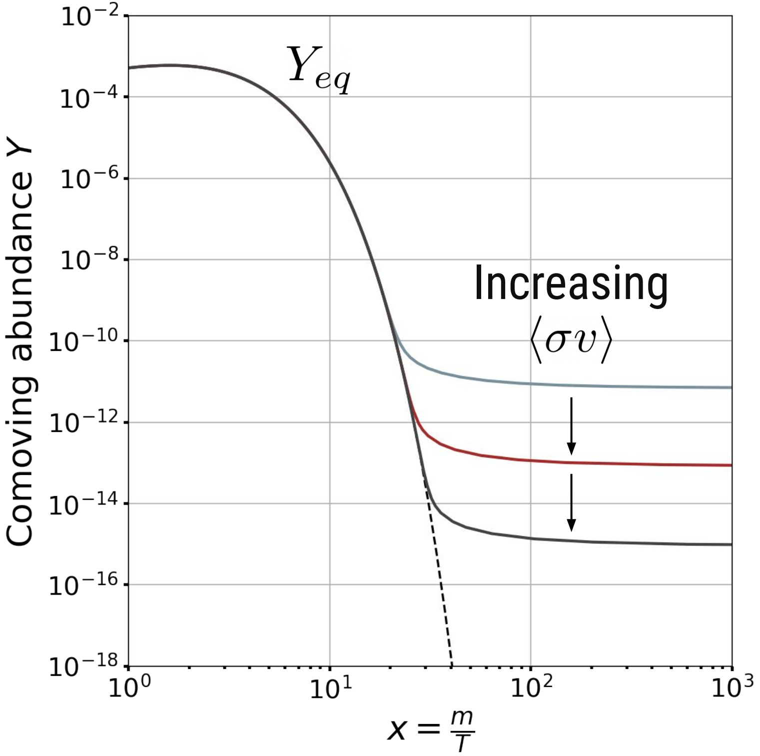

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$$\varphi + \varphi \longleftrightarrow \nu + \nu$$

DM annihilation rate $\Gamma \sim Y \langle \sigma v \rangle$

First Test: Dark Matter Relic Abundance

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

$$C_0 \left(0, 0, s, m_\Phi^2, m_N^2, m_\Phi^2\right) =$$

$$\frac{\text{DiLog}\left(\frac{2\left(m_N{}^2 - m_\phi{}^2\right)}{2m_N{}^2 - \sqrt{s(s-4m_\phi{}^2)} - 2m_\phi{}^2 + s}, s\right)}{s} + \frac{\text{DiLog}\left(\frac{2\left(m_N{}^2 - m_\phi{}^2\right)}{2m_N{}^2 + \sqrt{s(s-4m_\phi{}^2)} - 2m_\phi{}^2 + s}, s\right)}{s}$$

$$- \frac{\text{DiLog}\left(\frac{2\left(m_N{}^2 - m_\phi{}^2 + s\right)}{2m_N{}^2 - \sqrt{s(s-4m_\phi{}^2)} - 2m_\phi{}^2 + s}, s\right)}{s} - \frac{\text{Li}_2\left(\frac{2\left(m_N{}^2 - m_\phi{}^2 + s\right)}{2m_N{}^2 - 2m_\phi{}^2 + s + \sqrt{s(s-4m_\phi{}^2)}}\right)}{s}$$

$$+ \frac{\text{Li}_2\left(\frac{\left(m_N{}^2 - m_\phi{}^2\right)\left(m_N{}^2 - m_\phi{}^2 + s\right)}{m_N{}^4 - 2m_\phi{}^2 m_N{}^2 + s m_N{}^2 + m_\phi{}^4}\right)}{s} - \frac{\text{Li}_2\left(\frac{\left(m_N{}^2 - m_\phi{}^2\right)^2}{m_N{}^4 - 2m_\phi{}^2 m_N{}^2 + s m_N{}^2 + m_\phi{}^4}\right)}{s}$$

First Test: Dark Matter Relic Abundance

s-wave cross-section

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

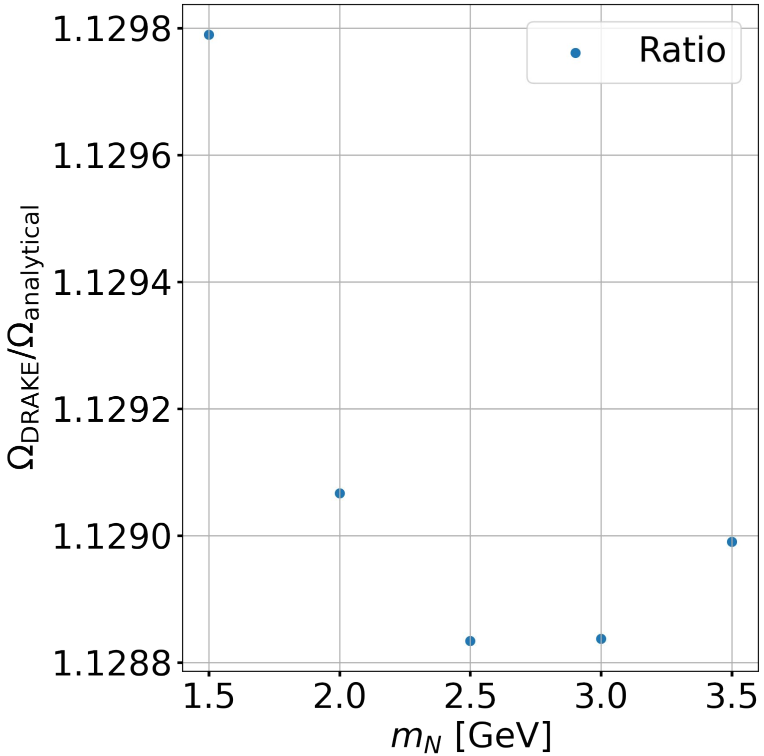
$$\langle \sigma v \rangle \approx \frac{\lambda^2 Y_\nu^4 m_N^2}{512\pi^5} |C_0\left(0, 0, 4m_\varphi^2, m_\Phi^2, m_N^2, m_\Phi^2\right)|^2$$

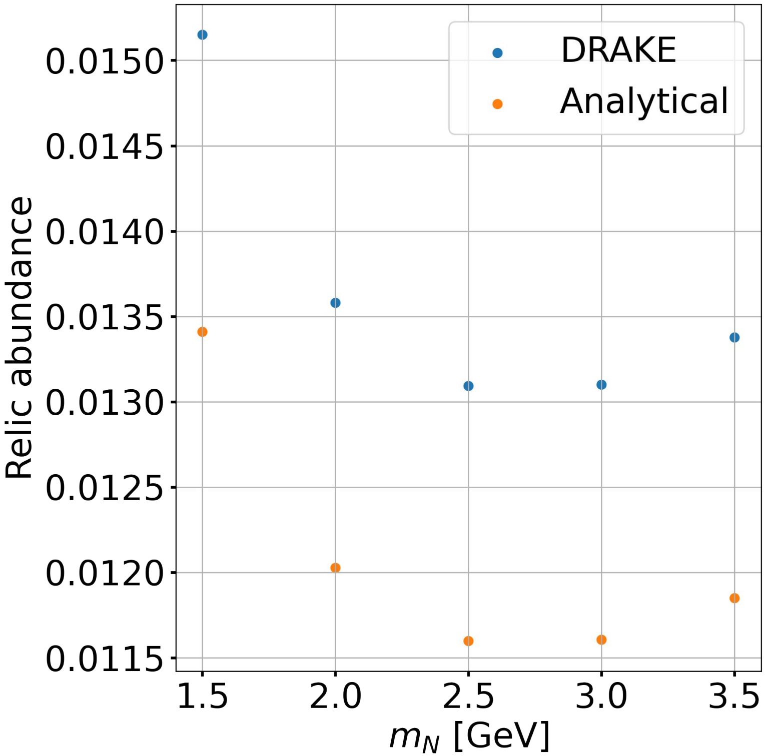
DM relic abundance approximation

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

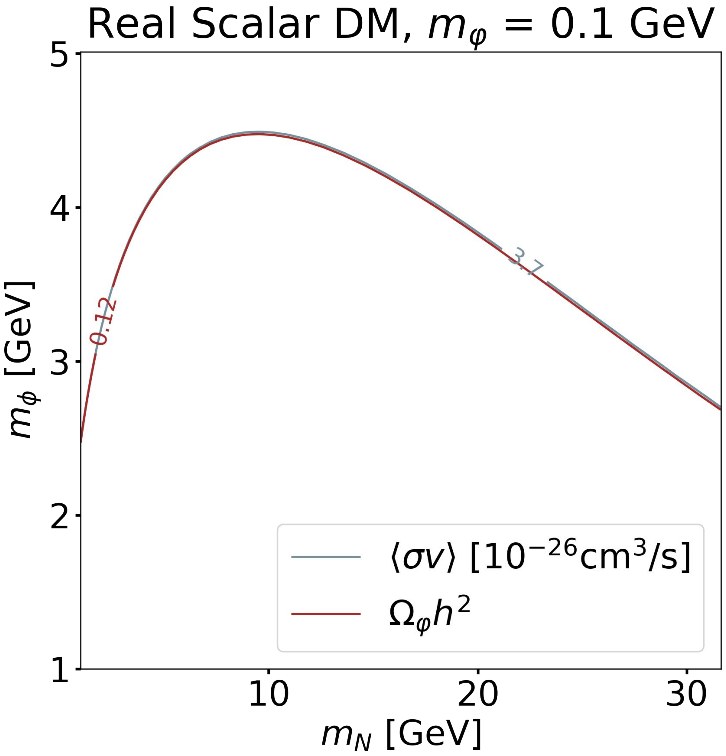
$$\Omega_c h^2 = \frac{9.92 \times 10^{-28}}{\langle \sigma v \rangle} \left(\frac{x_*}{g_*^{1/2}} \right) \left(\frac{(\Gamma/H)_*}{1 + \alpha_* (\Gamma/H)_*} \right)$$

Comparison to the Boltzmann code DRAKE

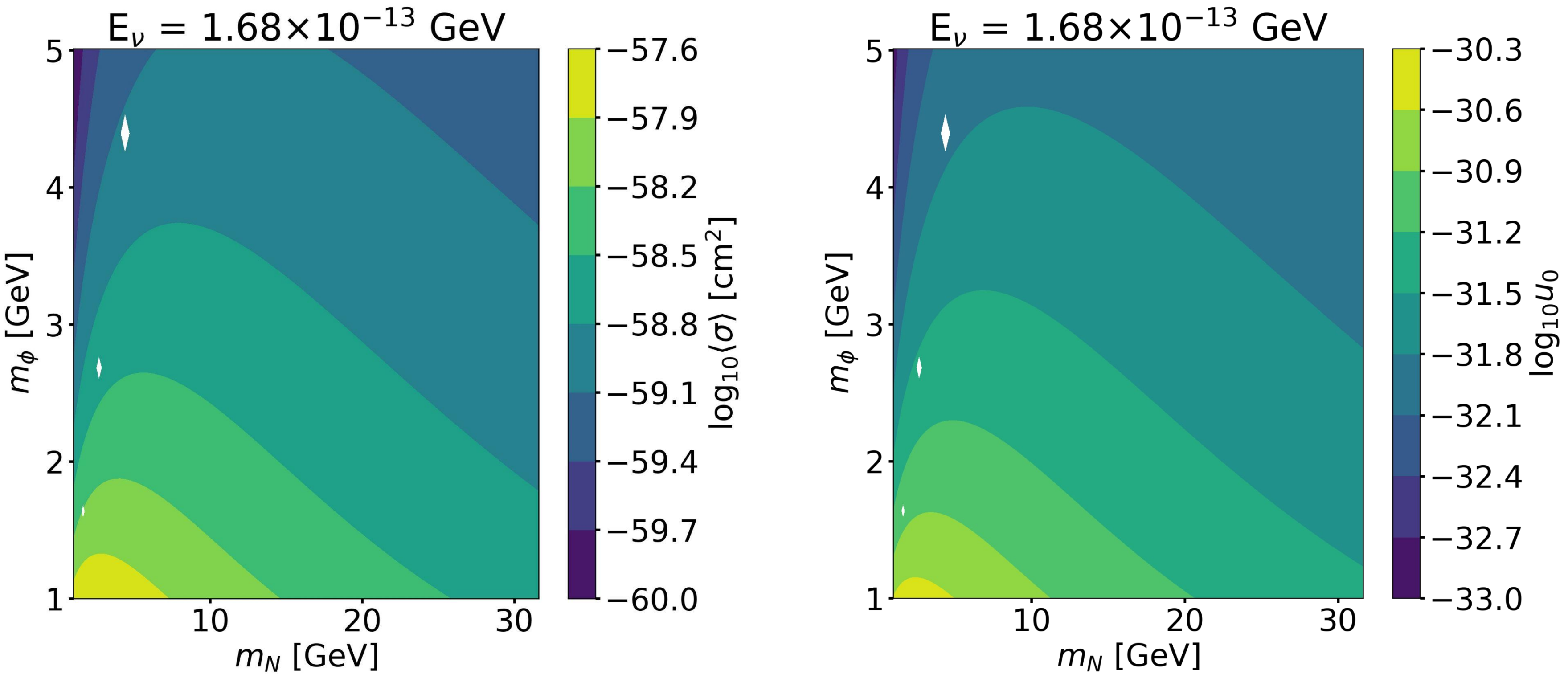




First Test: Dark Matter Relic Abundance



Second Test: DM-neutrino scattering



Structure formation

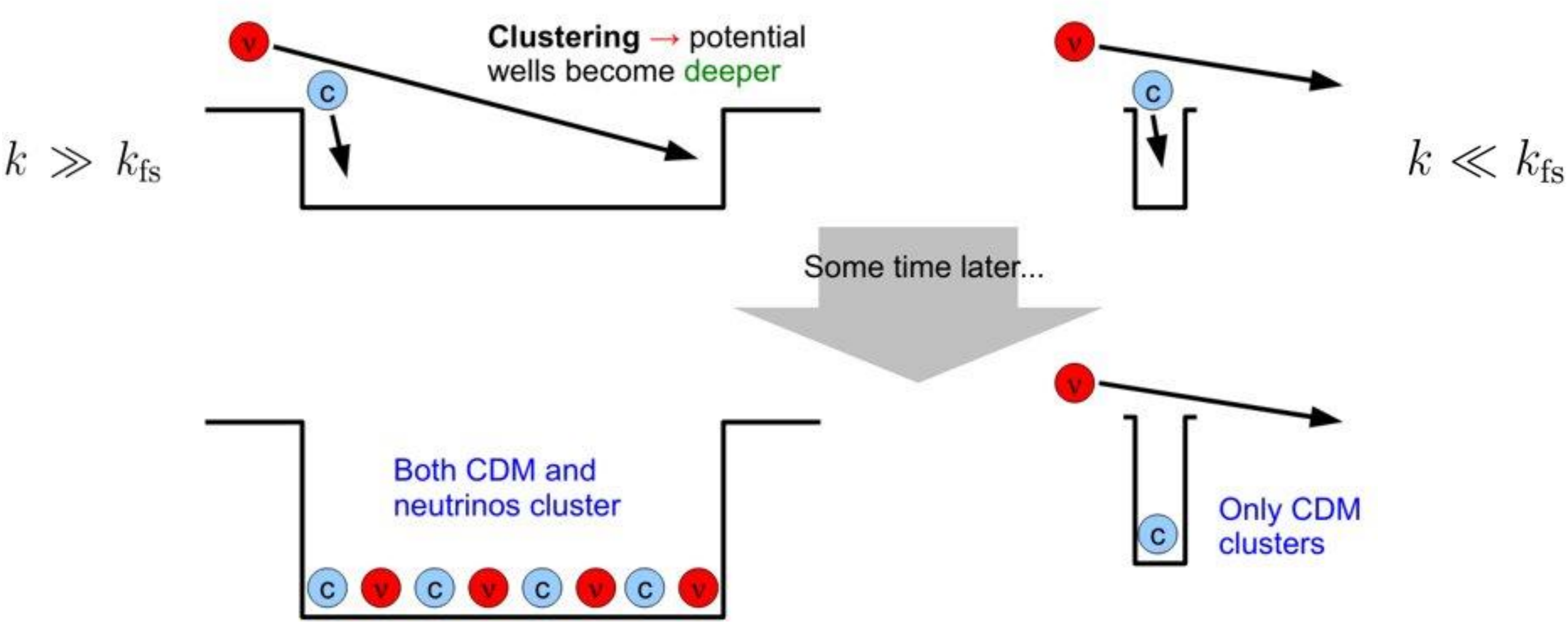


Diagram by Yvone Y. Y. Wong