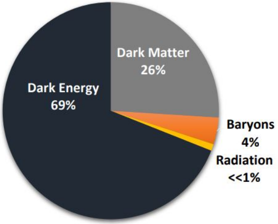
Strongly and weakly interacting dark matter candidates

Marco Nikolic
Supervisor (Research): Josef Pradler
Supervisor (University): Massimiliano Procura

supported by FWF Research Group grant FG1

May 24, 2022

Overview



Dark sector

$\boxed{\text{SIMPs}}$

-) strongly interacting dark matter candidates
-) self-interacting dark matter
-) rather new theory

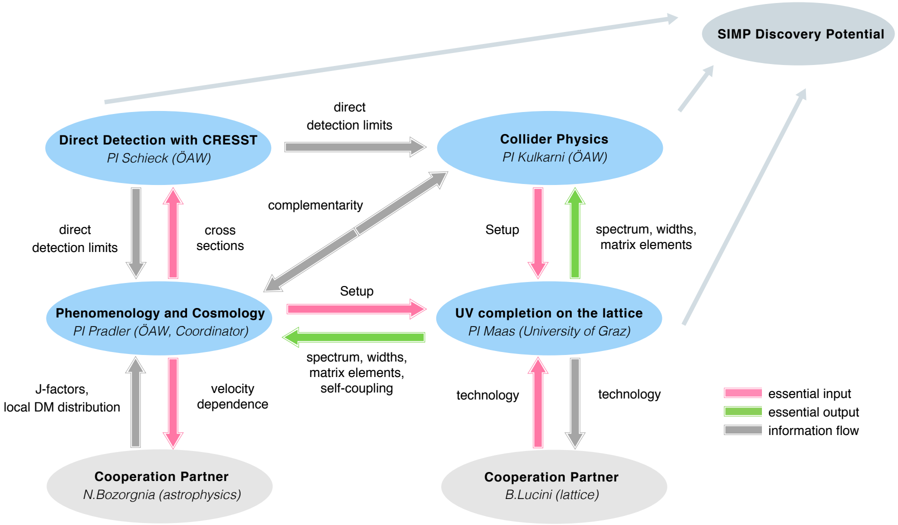
$\boxed{\text{Dark radiation}}$

-) indirect searches of dark matter
-) dark radiation from dark matter decays
-) max. sensitivity in direct detection experiments and PTOLEMY

Strongly interacting massive particles (SIMPs)

Low-energy effective description of dark $Sp(4)$ theories
(arXiv:2202.05191)

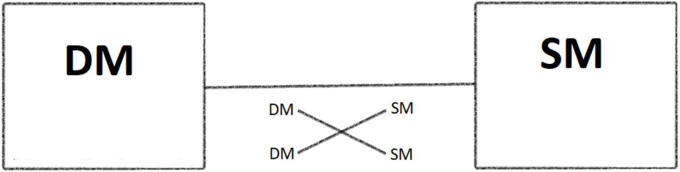
Project and Groups



FWF research group STRONG-DM

Freeze out and thermal relic dark matter

WIMP paradigm



WIMP dark matter

- DM in thermal equilibrium with SM particle via annihilations
  DM DM $\to$ SM SM
- decoupled from thermal equilibrium, when universe cooled down $\to$ freeze out
- DM relic abundance $\Omega_{dm} \sim 0.26$
- cold dark matter (non-relativistic) with mass $m_{\text{WIMP}} \sim O(\text{GeV} - \text{TeV})$
- searched for ~ 35 yr, WIMPs have not been observed

Is dark matter a WIMP?

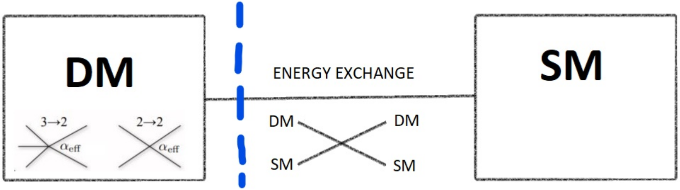
- The WIMP paradigm is being challenged (e.g. neutrino floor in direct detection experiments)
- Are there different signatures from another thermal DM?
- Is there an alternative DM candidate we can search for?

IF YES:

- What would happen if dark matter was secluded from the SM sector?
- What would its mass be?
- What interactions would appear?
- How would it interact with SM?

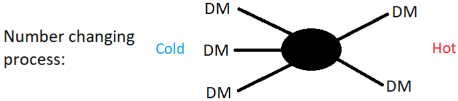
Production of SIMPs in the early stages of the universe

SIMP paradigm



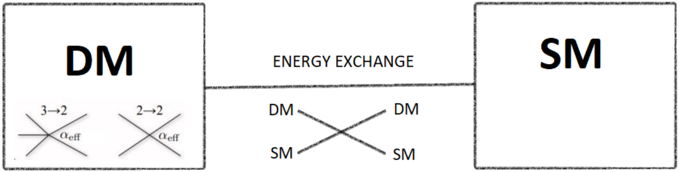
Strongly interacting massive particles (SIMPs) as DM

- $3 \to 2$ annihilation implies heating of DM sector
- DM must be coupled to SM $\Rightarrow$ opens door to phenomenology, $m_{\mathrm{SIMP}} \sim O(MeV)$
- DM abundance regulated by number changing process in DM sector only



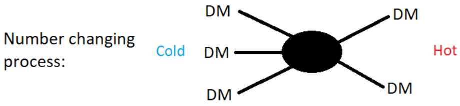
Production of SIMPs in the early stages of the universe

SIMP paradigm



Strongly interacting massive particles (SIMPs) as DM

- $3 \to 2$ annihilation implies heating of DM sector
- DM must be coupled to SM $\Rightarrow$ opens door to phenomenology, $m_{\text{SIMP}} \sim O(MeV)$
- DM abundance regulated by number changing process in DM sector only



Project goal

- build a model for SIMPs
- use QCD-like physics
- chiral symmetry breaking $\Rightarrow$ Goldstone bosons = DM composite states
- what interactions and masses would appear?
- want to introduce small mass splitting in SIMP masses
- what interactions and masses would appear in the non-degenerate case?
- relevant for future DM physics

- We consider $N_f = 2$ fermions in pseudo-real representation with gauge group $\mathrm{Sp}(4)_c$
- All fundamental representations of $Sp(2N)$ are pseudo-real
- UV Lagrangian (massless fermions):

$$\mathcal{L}_{\mathrm{UV}} = \sum_{q=u,d} \bar{q} i \gamma^\mu \partial_\mu q \quad \rightarrow \quad \mathcal{L}_{\mathrm{UV}} = \Psi^\dagger \mathrm{i} \bar{\sigma}^\mu \partial_\mu \Psi \qquad \text{with } \Psi = \begin{pmatrix} u_L \\ d_L \\ -S\sigma^2 \bar{u}_R^T \\ -S\sigma^2 \bar{d}_R^T \end{pmatrix} \tag{1}$$

$S \ldots$ antisymmetric matrix in color space
$\sigma^2 \ldots$ Pauli matrix in flavor space

- Global flavor symmetry is enlarged to $SU(4)$
- 2 flavor QCD: fermions in complex representation with global flavor symmetry $SU(2)_L \times SU(2)_R \subset SU(4)$
- Global flavor symmetry spontaneously broken

$$\mathrm{SU}\,(4) \xrightarrow{SSB} \mathrm{Sp}\,(4)$$

Breaking patterns - explicit symmetry breaking

symmetry explicitly broken by mass term

$$\mathcal{L}_{\rm UV} = \bar{q} i \gamma^\mu \partial_\mu q + \bar{q} M q \quad \rightarrow \quad \mathcal{L} = \Psi^\dagger \mathrm{i} \bar{\sigma}^\mu D_\mu \Psi - \frac{1}{2} \Psi^T \sigma^2 S M \Psi + \mathrm{h.c.} \tag{2}$$

- degenerate mass matrix: $M = m\, E$

$$E = \begin{pmatrix} 0 & \mathbb{I}_{2\times 2} \\ -\mathbb{I}_{2\times 2} & 0 \end{pmatrix}. \tag{3}$$

$\mathrm{SU}(4) \overset{explicit}{\rightarrow} \mathrm{Sp}(4)$

- non-degenerate mass Matrix

$$m_u \neq m_d \Rightarrow M = M_{\rm deg} + \Delta M = \begin{pmatrix} 0 & 0 & m_u & 0 \\ 0 & 0 & 0 & m_d \\ -m_u & 0 & 0 & 0 \\ 0 & -m_d & 0 & 0 \end{pmatrix} \tag{4}$$

$\mathrm{SU}(4) \overset{explicit}{\rightarrow} Sp(2)_u \times Sp(2)_d$

Breaking patterns

COMPLEX

$U(2) \times U(2)$

↓ axial anomaly | $m_u = m_d = 0$

$SU(2) \times SU(2) \times U(1)$

↓ chiral symmetry breaking | $m_u = m_d = 0$
and/or explicit breaking | $m_u = m_d \neq 0$

$SU(2) \times U(1)$

↓ strong isospin breaking | $m_u \neq m_d$

$U(1) \times U(1)$

PSEUDOREAL

$U(4)$

↓ $m_u = m_d = 0$ | axial anomaly

$SU(4)$

↓ $m_u = m_d = 0$ | chiral symmetry breaking
$m_u = m_d \neq 0$ | *and/or* explicit breaking

$Sp(4)$

↓ $m_u \neq m_d$ | strong isospin breaking

$SU(2) \times SU(2)$

UV-theory to effective theory - existence of pseudo-Goldstone bosons

- Whenever a continuous global symmetry is broken, the Goldstone theorem guarantees the existence of low-energy Goldstone bosons
- $\mathrm{SU}(4) \xrightarrow{SSB} \mathrm{Sp}(4)$ leads to existence of massless Goldstone bosons
- Number of Goldstone bosons is determined by the dimension of the coset space $SU(4)/Sp(4)$
- Counting:

$$\left.\begin{array}{c} SU(4) \text{ has 15 generators} \\ Sp(4) \text{ has 10 generators} \end{array}\right\} \Rightarrow 5 \text{ massles Goldstone bosons } \pi \in SU(4)/Sp(4)$$

- Goldstone bosons determined by broken generators T^A, $A = 1, \ldots, 5$
- Additional symmetry breaking due to mass term (explicit breaking)
- symmetry is not exact $\Rightarrow$ Goldstone gain non-zero mass (pseudo-Goldstone bosons)

$$m_\pi \neq 0$$

UV-Lagrangian to effective Lagrangian for fermions (dark quarks) with degenerate masses

UV-theory to effective theory - kinetic term

- UV-Lagrangian

$$\mathcal{L}_{\mathrm{UV}} = \Psi^\dagger \mathrm{i}\gamma^\mu \partial_\mu \Psi \qquad \text{with } \Psi = \begin{pmatrix} \psi_L \\ -S\sigma^2 \bar{\psi}_R^T \end{pmatrix} \tag{5}$$

- inputs to build chiral Lagragian:
  - parameterization of the chiral field (degenerate vacuua)

$$\Sigma = V \Sigma_0 V^T, \quad \text{where } V = \exp\left(i \frac{\pi_n(x) T^n}{f_\pi} \right) \tag{6}$$

  - respecting symmetries:
    -) Lorentz invariance (only even number of derivatives possible)
    -) chiral symmetry invariance (only combination of Σ and $\Sigma^\dagger$)
    -) P,C invariance
  - low energy $\Rightarrow$ smallest possible number of derivatives

- effective Lagrangian:

$$L_2 = \frac{f_\pi^2}{4} \mathrm{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger \right] \tag{7}$$

From UV Lagrangian to effective Lagrangian - degenerate mass term

- UV-Lagrangian

$$\mathcal{L}_{\text{UV}} = \bar{q} i \gamma^\mu \partial_\mu q + \bar{q} M q \quad \rightarrow \quad \mathcal{L}_{\text{UV}} = \Psi^\dagger \mathrm{i} \bar{\sigma}^\mu D_\mu \Psi - \frac{1}{2} \Psi^T \sigma^2 S M \Psi + \text{h.c.} \tag{8}$$

- How to obtain mass term in the effective Lagrangian?
  - take symmetry transformation, $\Psi \rightarrow U\Psi$, $U \in \mathrm{SU}(4)$
  - treat M as a spurion field
  - chiral invariance $\Rightarrow M \rightarrow U^\star M U^\dagger$

$$\left.\begin{array}{l} \Sigma \overset{SU(4)}{\rightarrow} U \Sigma U^T \\ M \overset{SU(4)}{\rightarrow} U^\star M U^\dagger \end{array}\right\} \Rightarrow \mathrm{Tr}\left[\Sigma M\right] + \mathrm{Tr}\left[M^\dagger \Sigma^\dagger\right] \tag{9}$$

- total effective Lagrangian:

$$L_2 = \frac{f_\pi^2}{4} \mathrm{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger\right] + 2\mu^3 \left(\mathrm{Tr}\left[M\Sigma\right] + \mathrm{Tr}\left[\Sigma^\dagger M^\dagger\right]\right) \tag{10}$$

From UV Lagrangian to effective Lagrangian - Goldstone mass

- effective Lagrangian in terms of Goldstone fields π (degenerate fermion masses)

$$\begin{aligned} \mathcal{L}_\pi = \mathrm{Tr}\, \partial_\mu \pi \partial^\mu \pi - m_\pi^2 \,\mathrm{Tr}\, \pi^2 + \frac{m_\pi^2}{3 f_\pi^2} \mathrm{Tr}\, \pi^4 \\ - \frac{2}{3 f_\pi^2} \mathrm{Tr} \left(\pi^2 \partial^\mu \pi \partial_\mu \pi - \pi \partial^\mu \pi \pi \partial_\mu \pi \right) \end{aligned} \tag{11}$$

- Goldstone matrix

$$\pi \equiv \sum_{n=1}^{5} \pi_n T^n = \frac{1}{2\sqrt{2}} \begin{pmatrix} \pi_3 & \pi_1 - i\pi_2 & 0 & \pi_5 - i\pi_4 \\ \pi_1 + i\pi_2 & -\pi_3 & -\pi_5 + i\pi_4 & 0 \\ 0 & -\pi_5 - i\pi_4 & \pi_3 & \pi_1 + i\pi_2 \\ \pi_5 + i\pi_4 & 0 & \pi_1 - i\pi_2 & -\pi_3 \end{pmatrix} \tag{12}$$

- masses of Goldstone fields

$$m_\pi = \frac{8\mu^3 m}{f_\pi^2} \tag{13}$$

- kinetic term implies 4-point interaction $\Rightarrow$ 2 to 2 scattering for free
- Semi-annihilation and 5-point interaction are absent, because $\mathrm{Tr}\,[\pi^n] = 0$ for n odd
- How to include 3 to 2 interaction?

From UV Lagrangian to effective Lagrangian - Wess-Zumino-Witten term

- effective Lagrangian:

$$L_2 = \frac{f_\pi^2}{4} \mathrm{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger\right] + 2\mu^3 \left(\mathrm{Tr}\left[M\Sigma\right] + \mathrm{Tr}\left[\Sigma^\dagger M^\dagger\right]\right) \tag{14}$$

- 3 to 2 process $\Rightarrow$ need 5 point interaction term
- 5-point interaction out of Goldstones $\Rightarrow$ Wess-Zumino-Witten interaction

$$L_{WZW} = \frac{-iN_c}{240\pi^2} \int \mathrm{Tr}\left[(\Sigma^\dagger d\Sigma)^5\right] \tag{15}$$

- WZW in terms of Goldstone fields (degenerate masses $N_f = 2$)

$$L_{\mathrm{WZW}} = \frac{8N_c}{15\pi^2 f_\pi^5} \epsilon^{\mu\nu\rho\sigma}\, \mathrm{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right] + \mathcal{O}\left(\pi^6\right) \tag{16}$$

- WZW term allows only interactions with Goldstones of different generation

$$\epsilon^{\mu\nu\rho\sigma}\pi_1\partial_\mu\pi_2\partial_\nu\pi_3\partial_\rho\pi_4\partial_\sigma\pi_5 \tag{17}$$

UV-Lagrangian to effective Lagrangian for fermions (dark quarks) with non-degenerate masses

Reminder - UV-theory for non-degenerate quark masses

symmetry explicitly broken by mass term

$$\mathcal{L} = \Psi^\dagger \mathrm{i}\bar{\sigma}^\mu D_\mu \Psi - \frac{1}{2}\Psi^T \sigma^2 S M \Psi + \text{h.c.} \tag{18}$$

- degenerate mass matrix: $M = m\, E$

$$E = \begin{pmatrix} 0 & \mathbb{I}_{2\times 2} \\ -\mathbb{I}_{2\times 2} & 0 \end{pmatrix}. \tag{19}$$

$\mathrm{SU}(4) \overset{explicit}{\rightarrow} \mathrm{Sp}(4)$

- non-degenerate mass Matrix

$$m_u \neq m_d \Rightarrow M = M_{\text{deg}} + \Delta M = \begin{pmatrix} 0 & 0 & m_u & 0 \\ 0 & 0 & 0 & m_d \\ -m_u & 0 & 0 & 0 \\ 0 & -m_d & 0 & 0 \end{pmatrix} \tag{20}$$

$\mathrm{SU}(4) \overset{explicit}{\rightarrow} Sp(2)_u \times Sp(2)_d$

UV-theory for non-degenerate quark masses

- splitting of decay constants and vacuum condensates

$$f_\pi \xrightarrow{m_u \neq m_d} \begin{cases} f_\pi & \text{for } \pi_{1,2,4,5} \\ f_{\pi_3} & \text{for } \pi_3 \end{cases}, \quad \mu^3 \xrightarrow{m_u \neq m_d} \begin{cases} \mu_u^3 = \frac{1}{2}\langle u^T \sigma_2 S E_2 u\rangle \\ \mu_d^3 = \frac{1}{2}\langle d^T \sigma_2 S E_2 d\rangle \end{cases}, \tag{21}$$

- chiral Lagrangian

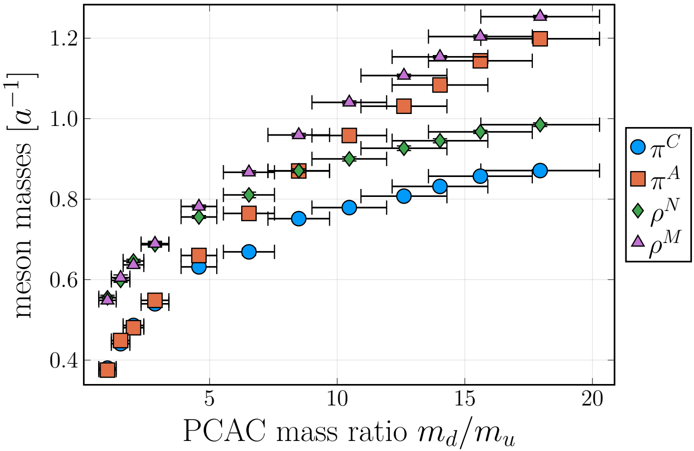
$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{mass}} + \mathcal{L}_{\text{WZW}} \\ &= \frac{4\mu_u^6}{\left(\mu_u^3 + \mu_d^3\right)^2} \left(\frac{f_\pi^2}{4} \text{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger\right] - \frac{1}{2}\mu_u^3 \left(\text{Tr}\left[M\Sigma\right] + \text{h.c.}\right)\right) \\ &+ \frac{\mu_d^6 \sqrt{\mu_u^6 + \mu_d^6}\left(\mu_u^3 + \mu_d^3\right)^5}{32\sqrt{2}\mu_u^{24}} \mathcal{L}_{\text{WZW}}^{\text{deg.}} \end{aligned} \tag{22}$$

- Goldstone masses

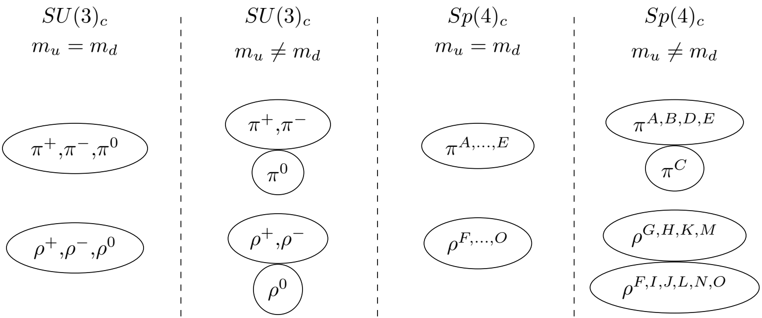
$$m_\pi^2 \equiv m_{\pi_{1,2,4,5}}^2 = \frac{2\mu_u^6 (m_u + m_d)}{f_\pi^2(\mu_u^3 + \mu_d^3)}, \quad m_{\pi_3}^2 = \frac{2\mu_u^6(m_u\mu_u^3 + m_d\mu_d^3)}{f_\pi^2(\mu_u^6 + \mu_d^6)}. \tag{23}$$

- results supported by lattice simulations

$$\beta{=}6.9 \qquad \left(\frac{m(\rho)}{m(\pi)}\right)_{deg} = 1.46(4)$$



Multiplet structure



- under "naive" parity $P : \psi(\mathbf{x}, t) \to \gamma_0 \psi(-\mathbf{x}, t)$
  $$5 \text{ Goldstones} = \begin{cases} 3 \text{ Pseudoscalars } \pi^A, \pi^B, \pi^C \\ 2 \text{ Scalars, } \pi^D, \pi^E \end{cases}$$
- under parity $D : \psi(\mathbf{x}, t) \to \pm i\gamma_0 \psi(-x, t)$
  5 Goldstones are Pseudoscalars

DM couple to SM

DM coupled to SM

- introduce a new Abelian dark gauge group $U(1)'$ with (massive) gauge field V^μ
- V^μ kinetically mix with SM hypercharge

$$\mathcal{L}_{\text{int}} = \frac{\varepsilon}{2\cos\theta_W} B_{\mu\nu} V^{\mu\nu}, \tag{24}$$

  where $B_{\mu\nu}$ and $V^{\mu\nu}$ are the $U(1)_D$ and $U(1)_Y$ field strengths
- covariant derivative:

$$\partial_\mu \Psi^{ia} \to D_\mu \Psi^{ia} = \partial_\mu \Psi^{ia} + i e_D V_\mu \mathcal{Q}_{ij} \Psi^{ja}. \tag{25}$$

DM coupled to SM

- Gauging the theory under $U(1)'$ may provide a source of explicit global symmetry breaking
- study how the gauge interaction term in the Lagrangian,

$$\mathcal{L} \supset -e_D V_\mu \left(\left(\Psi^i \right)^\dagger_a \overline{\sigma}^\mu \mathcal{Q}_{ij} \Psi^{ja} \right) \tag{26}$$

transforms under the remaining flavor symmetry Sp(4) as

$$\Psi^{ia} \to V_{ij} \Psi^{ja} = \left(1 + i\theta^N T^N_{ij} + \dots \right) \Psi^{ja}, \tag{27}$$

- variation in the Lagrangian density

$$\delta\mathcal{L} = ie_D V_\mu \left((\Psi)^\dagger \overline{\sigma}_\mu \theta^N \left[\mathcal{Q}, T^N \right] \Psi \right), \tag{28}$$

- remaining flavour symmetry is spanned by those generators T^N of $Sp(4)$ that commute with $\mathcal{Q}$.

DM coupled to SM

Charge Assignment $\mathcal{Q}$	Breaking Pattern	Multiplet Structure
$(+a,-a,-a,+a)$	$Sp(4)\to SU(2)\times U(1)$	$\begin{pmatrix}\pi^C\\ \pi^D\\ \pi^E\end{pmatrix},\ \begin{pmatrix}\pi^A\\ \pi^B\end{pmatrix}$
$(+a,+a,-a,-a)$	$Sp(4)\to SU(2)\times U(1)$	$\begin{pmatrix}\pi^C\\ \pi^A\\ \pi^B\end{pmatrix},\ \begin{pmatrix}\pi^D\\ \pi^E\end{pmatrix}$
$(+a,+b,-a,-b)$, $a\neq b$	$Sp(4)\to U(1)\times U(1)$	$(\pi^C),\ \begin{pmatrix}\pi^A\\ \pi^B\end{pmatrix},\ \begin{pmatrix}\pi^D\\ \pi^E\end{pmatrix}$
$\begin{pmatrix}0&0&a&0\\0&0&0&\pm a\\a&0&0&0\\0&\pm a&0&0\end{pmatrix}$	$Sp(4)\to SU(2)\times U(1)$	$\begin{pmatrix}\pi^C\\ \pi^{A,B}\\ \pi^{E,D}\end{pmatrix},\ \begin{pmatrix}\pi^{D,E}\\ \pi^{B,A}\end{pmatrix}$
other off-diagonal assignments	$Sp(4)\to U(1)\times U(1)$	$(\pi^C),\ \begin{pmatrix}\pi^A\\ \pi^E\end{pmatrix},\ \begin{pmatrix}\pi^B\\ \pi^D\end{pmatrix}$ or sim

- if π^C is singlet, it decays away, because it is not protected by flavor symmetry

$U(1)'$ interactions with mesons

- interaction with gauge field V_μ with dark sector in the effective theory through covariant derivative
$$D_\mu \Sigma = \partial_\mu \Sigma + i e_D V_\mu (\mathcal{Q}\Sigma + \Sigma\mathcal{Q}) \tag{29}$$
- e_D is the $U(1)'$ gauge coupling
- interaction depends on charge assignment Q
- for a charge assignment $(+1, -1, -1, +1)$
$$\mathcal{L}_{V-\pi} = -2ie_D V^\mu \left(\pi^A \partial_\mu \pi^B - \pi^B \partial_\mu \pi^A\right) + e_D^2 V_\mu V^\mu \pi^A \pi^B \tag{30}$$
- for $(+1, +1, -1, -1)$ V_μ couples only to π^D, π^E
- one pair of Golstones carry $U(1)'$ charge

$U(1)'$ interactions with mesons

- decays of Goldstone bosons occur through processes mediated by pairs of dark photons
- $\pi - V - V$ vertex is sourced by the gauged WZW action

$$\mathcal{L}_{\text{int}} \supset \frac{40iCe_D^2}{f_\pi^2}\varepsilon_{\mu\nu\alpha\beta}V^\mu\partial^\nu V^\alpha \operatorname{Tr}\left(\mathcal{Q}^2\partial^\beta\pi\right) \tag{31}$$

- since all generators of $SU(4)/Sp(4)$ are traceless $\Rightarrow$ anomaly cancellation $\mathcal{L}_{\text{int}} = 0$ for $\mathcal{Q}^2 \propto \mathbb{I}$

Conclusions

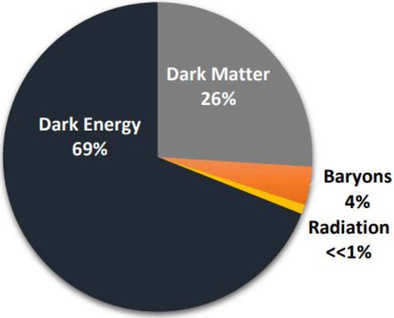
- SIMPs are composite states created through chiral symmetry breaking
- dynamics of SIMPs are described by effective (chiral) Lagrangian
- 2 to 2 scattering for free, 3 to 2 interaction given by WZW term
- $\mathrm{SU}\,(4) \xrightarrow{SSB} \mathrm{Sp}\,(4)$
- degenerate case: $\mathrm{SU}(4) \overset{explicit}{\rightarrow} Sp(4)$
- non-degenerate case: $\mathrm{SU}(4) \overset{explicit}{\rightarrow} Sp(2)_u \times Sp(2)_d$
- non-degenerate case: π^C lightest DM state
- multiplet structure given by symmetry $Sp(2)_u \times Sp(2)_d$
- DM couple to SM through dark $U(1)'$ gauge field (kinetic mixing)
- breaking patterns depend on charge assignments
- can achieve stability of SIMPs

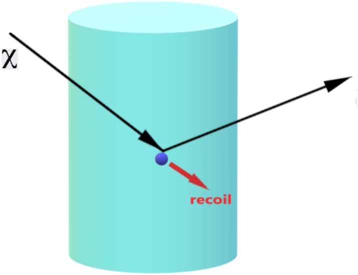
Dark radiation - indirect dark matter searches

Sensitivity of direct detection experiments to neutrino dark radiation from dark matter decay and a modified neutrino-floor (arXiv:2008.13557)

Probing sub-eV Dark Matter decays with PTOLEMY (arXiv:2012.09704)

Energy budget of the universe

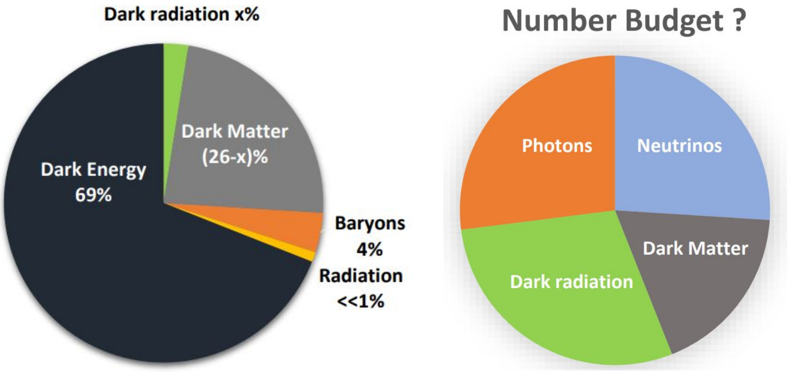




Dark matter

- many efforts to find DM in the laboratory to understand its particle nature
- direct detection experiments designed to search for nuclear recoils induced by DM
- DM has not been directly observed in laboratories ⇒ look for other possible signals

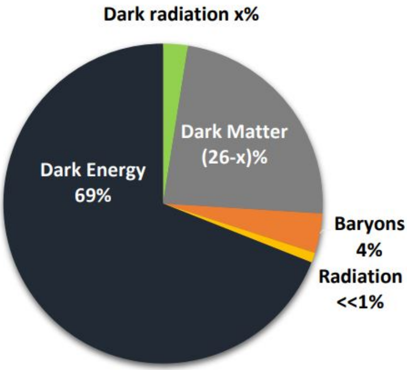
Energy budget of the universe

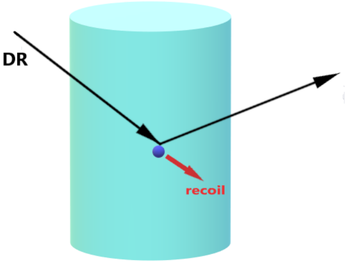


Dark radiation

- new form of relativistic particles produced by unstable dark matter (few % of total DM abundance) → dark radiation (DR)
- number budget unknown → large DR flux possible
- DR may leave a detectable signal in direct detection experiments

Energy budget of the universe





Dark radiation

- new form of relativistic particles produced by unstable dark matter (few % of total DM abundance) → dark radiation (DR)
- number budget unknown → large DR flux possible
- DR may leave a detectable signal in direct detection experiments

“What is the maximum sensitivity to DR that we can reach in direct detection experiments?”

- irreducible backgrounds from STANDARD NEUTRINO SOURCES (solar,atmospheric, supernova ν) in direct detection experiments
- backgrounds may mimic DR
- find region in parameter space of DR where DR and backgrounds are distinguishable

DARK RADIATION

DR in form of SM neutrinos

2-body decay

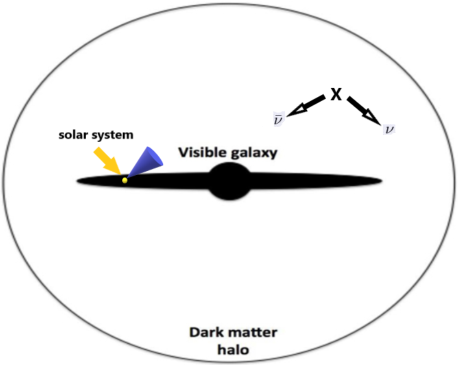
$$X \to \nu\nu \tag{32}$$

parameter space of DR: $\tau_X, m_X, f_X \quad (f_X = 0.1)$
benefit of scenario: interactions of neutrinos are known

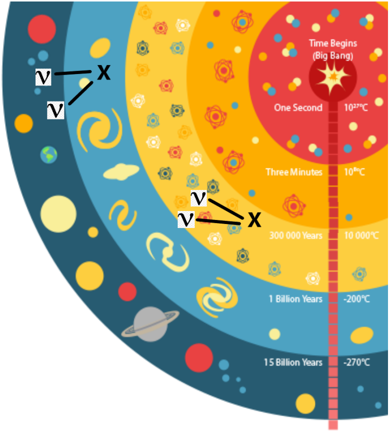
Dark Radiation as SM neutrinos

$$\frac{d\Phi_{X2\nu}(\tau_X, m_X)}{dE_\nu} = \frac{d\Phi_{\nu,\text{gal.}}}{dE_\nu} + \frac{d\Phi_{\nu,\text{e.g.}}}{dE_\nu}$$

galactic flux



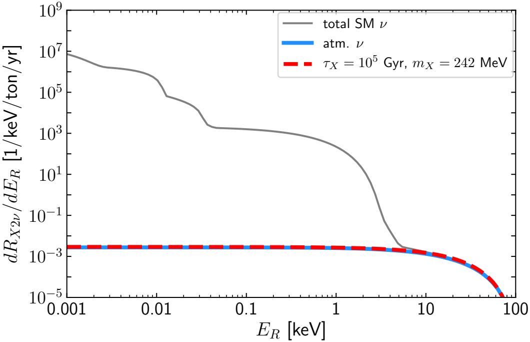
extragalactic flux



DARK RADIATION vs. STANDARD NEUTRINO SOURCES

DARK RADIATION vs. STANDARD NEUTRINO SOURCES

Backgrounds vs. DR



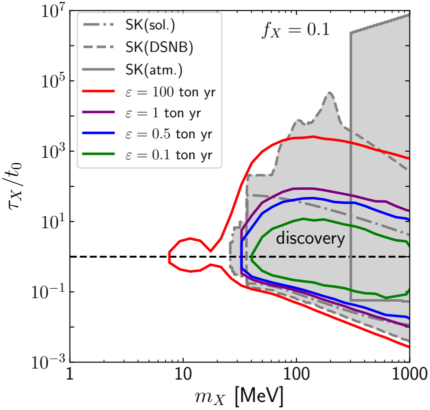
- DR-induced recoil events may be misinterpreted as standard neutrino sources
- experiments lose sensitivity to DR at certain combinations of progenitor lifetime τ_X and mass m_X

How we can properly discriminate DR from standard neutrino sources?

use hypothesis testing based on likelihood statistics

Discovery potential - DR discovery with 3σ significance

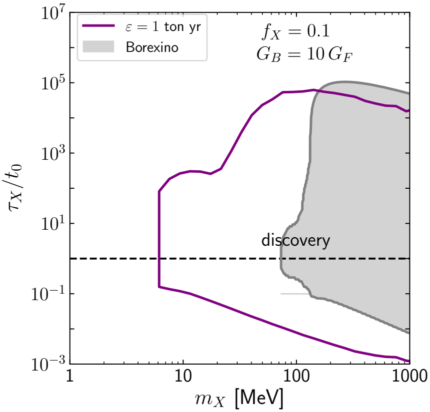
- find DR signals in the presence of standard neutrino sources (sol,atm,supernova)
- establish the minimum lifetime corresponding to the smallest DR flux, where DR and backgrounds are still distinguishable
- test DR+standard neutrino background hypothesis against standard neutrino only-background hypothesis
- generate mock data by Monte Carlo simulations, which represent recoil energies of DR and background rates
- general tool: likelihood function



- discovery region is superseded by SK constraints (grey) $\Rightarrow$ direct detection experiments with $\varepsilon \lesssim O(1)$ ton yr cannot measure this form of DR

Discovery potential - DR discovery with 3σ significance

- find DR signals in the presence of standard neutrino sources (sol,atm,supernova)
- establish the minimum lifetime corresponding to the smallest DR flux, where DR and backgrounds are still distinguishable
- test DR+standard neutrino background hypothesis against standard neutrino only-background hypothesis
- generate mock data by Monte Carlo simulations, which represent recoil energies of DR and background rates
- general tool: likelihood function



- discovery region for new dark states (semi sterile neutrinos) $\Rightarrow$ larger discovery region by new interaction

Detectability of DR in the future neutrino experiment PTOLEMY (on going)

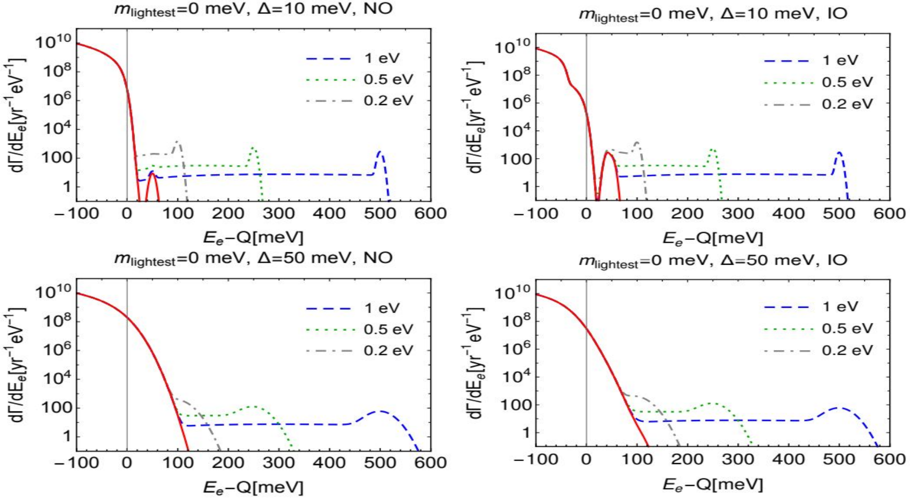
- proposal to measure CνB (relic neutrinos)
- if CνB measured, accurate measurement of m_ν
- detection via β-decaying nuclei (neutrino capture):

$$(A, Z) + \nu_e \rightarrow (A, Z+1) + e^- \quad (33)$$

- target material: 100 g tritium

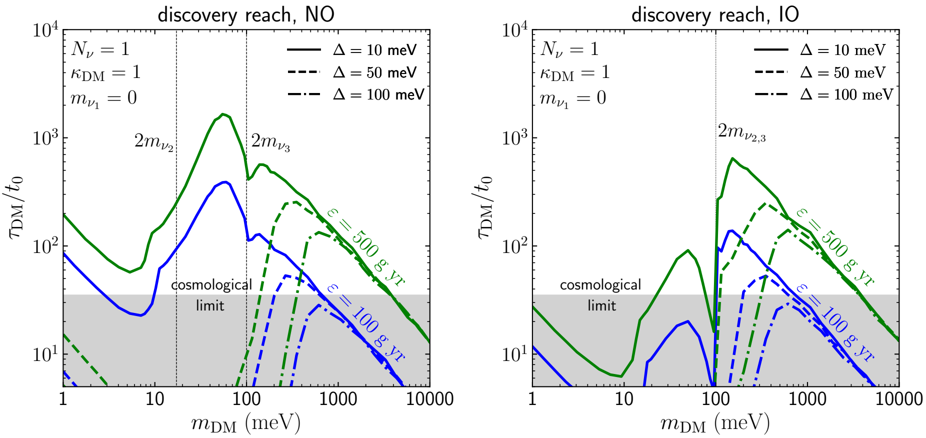
DR in PTOLEMY

- another possibility: search for DR signals in PTOLEMY
- massive neutrinos: $X \to \nu\bar{\nu}$
- backgrounds: CνB + β-decay from tritium



Discovery potential

- background-only H_0 : CνB + β against signal+background H_1 : DR + CνB + β



Conclusions

- DR in form of SM neutrinos almost completely excluded $\Rightarrow$ increase exposure
- DR in form of baryonic neutrinos still detectable
- search for DR in PTOLEMY

Thank you for your attention!

Backup slides

Breaking patterns - SSB

- Global flavor symmetry spontaneously broken, because vacuum condensate is not invarinat under $SU(4)$
- Under an infinitesimal transformation under the group $SU(4)$, the fermion field transforms as

$$\Psi \to \left(1 + i\sum_{a=1}^{15} \theta^a T^a\right)\Psi, \tag{34}$$

  where T^a are generators of $SU(4)$
- chiral condensate becomes

$$\langle qq \rangle \to \langle qq \rangle - \frac{i}{2}\theta^a \Psi^T \sigma_2 S \left(ET^a + \left(T^a\right)^T E\right)\Psi + \text{ h.c.} \tag{35}$$

- vacuum condensate is invariant if $ET^a + \left(T^a\right)^T E = 0 \Rightarrow$ invariant under Sp(4)

Multiplet structure

$$
\begin{array}{ll|ll|ll}
 & & & & J^P & J^D \\
\pi_1 = & \frac{1}{\sqrt{2}}\left(\bar{u}\gamma_5 d + \bar{d}\gamma_5 u\right) & \pi^A = & \bar{u}\gamma_5 d & 0^- & 0^- \\
\pi_2 = & \frac{i}{\sqrt{2}}\left(\bar{d}\gamma_5 u - \bar{u}\gamma_5 d\right) & \pi^B = & \bar{d}\gamma_5 u & 0^- & 0^- \\
\pi_3 = & \frac{1}{\sqrt{2}}\left(\bar{u}\gamma_5 u - \bar{d}\gamma_5 d\right) & \pi^C = & \frac{1}{\sqrt{2}}\left(\bar{u}\gamma_5 u - \bar{d}\gamma_5 d\right) & 0^- & 0^- \\
\pi_4 = & \frac{i}{\sqrt{2}}\left(\bar{d}\gamma_5 SC\bar{u}^T - d^T SC\gamma_5 u\right) & \pi^D = & \bar{d}\gamma_5 SC\bar{u}^T & 0^+ & 0^- \\
\pi_5 = & \frac{1}{\sqrt{2}}\left(\bar{d}\gamma_5 SC\bar{u}^T + d^T SC\gamma_5 u\right) & \pi^E = & d^T SC\gamma_5 u & 0^+ & 0^-
\end{array}
$$

- under “naive” parity $P : \psi(\mathbf{x}, t) \to \gamma_0\psi(-\mathbf{x}, t)$
  $$5 \text{ Goldstones} = \begin{cases} 3 \text{ Pseudoscalars } \pi^A, \pi^B, \pi^C \\ 2 \text{ Scalars, } \pi^D, \pi^E \end{cases}$$
- under parity $D : \psi(\mathbf{x}, t) \to \pm i\gamma_0\psi(-x, t)$
  5 Goldstones are Pseudoscalars

Including spin-1 states - ρ-mesons

- 5 axial-vector and 10 vector mesonic states under parity D: $\rho_\mu = \sum_{a=1}^{15} \rho_\mu^a T^a$.
- add kinetic and mass terms for the spin-1 states to chiral Lagrangian $\mathcal{L}_\pi$

$$\mathcal{L}_\rho = -\frac{1}{2}\operatorname{Tr}\left(\rho_{\mu\nu}\rho^{\mu\nu}\right) + \frac{1}{2}m_\rho^2 \operatorname{Tr}\left(\rho_\mu \rho^\mu\right) \tag{36}$$

- interactions between Goldstone bosons and spin-1 states

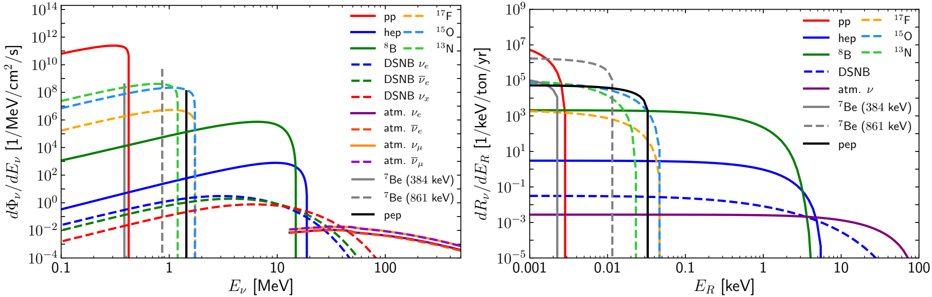
$$D_\mu \Sigma = \partial_\mu \Sigma + i g_{\rho\pi\pi}\left[\rho_\mu \Sigma + \Sigma \rho_\mu^T\right], \tag{37}$$

- axial-vectors heavier than vectors

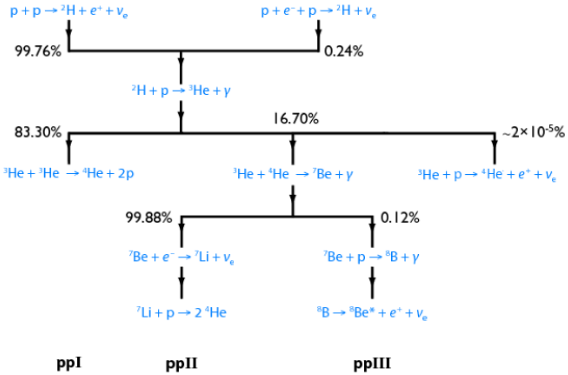
$$m_a^2 = m_\rho^2 / Z^2. \tag{38}$$

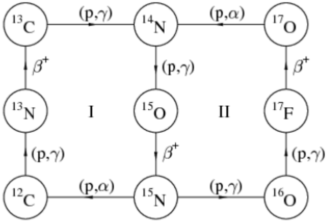
- axial-vectors not important for DM physics

Neutrino fluxes



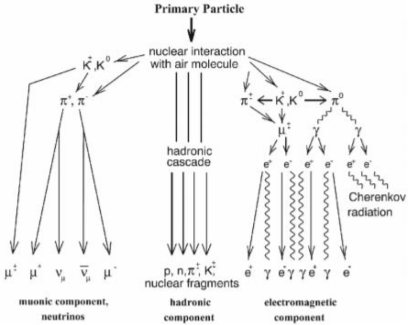
Neutrino sources





- Solar neutrinos produced in the Sun by fusion processes

Neutrino sources



atmospheric neutrinos

- Cosmic rays collide with nuclei in the atmosphere
- hadronic showers: pions, kaons, neutrons, protons
- muon decay: $\mu^- \to e^- + \bar{\nu}_\mu + \nu_e, \qquad \mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$
- electromagnetic showers: production of photons and electrons

Irreducible neutrino background

coherent scattering

$$\nu + N \to \nu + N \tag{39}$$

- spin-independent neutrino-nucleus cross section

$$\frac{d\sigma_{N\nu}(E_\nu, E_R)}{dE_R} = \frac{Q_W^2 G_F^2 m_N F(\vec{q})^2}{4\pi}\left[1 - \frac{E_R m_N}{2E_\nu^2}\right], \tag{40}$$

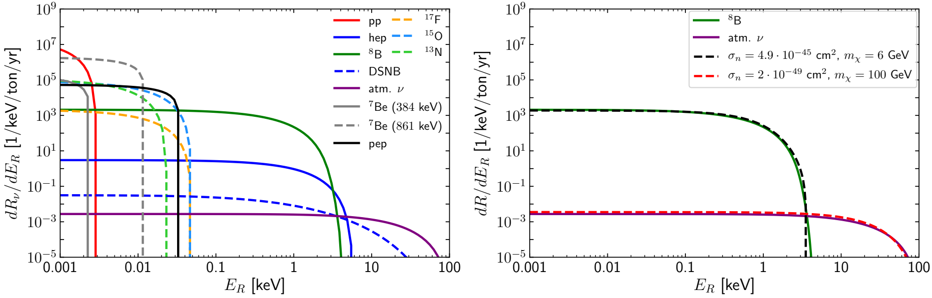
  Fermi constant $G_F = 1.1663787(6) \cdot 10^{-5}\ \mathrm{GeV}^{-2}$
  weak charge $Q_W = (4\sin^2\theta_W - 1)Z + N$, Weinberg angle θ

- Helm form factor

$$F(\vec{q}) = \frac{3j_1(\vec{q}R)}{\vec{q}R} e^{-\vec{q}^2 s^2/2} \tag{41}$$

- Coherence lost, when momentum transfer too large

WIMP event mimicked by neutrino backgrounds



- Large number of neutrino-induced nuclear recoils at $E_R \sim$ few keV
- Relevant neutrino backgrounds: solar, atmospheric and supernova neutrinos
- ^{8}B-ν mimic WIMP with $\sigma_n = 4.9 \cdot 10^{-45}$ cm^2, $m_\chi = 6$ GeV
  atm. ν mimic WIMP with $\sigma_n = 2 \cdot 10^{-49}$ cm^2, $m_\chi = 100$ GeV

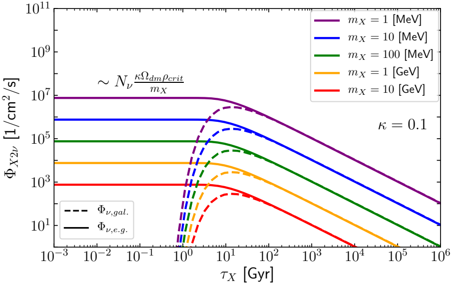
Dark radiation from an anomalous neutrino source

Two-body decay into neutrino pair (monochromatic injection)

$$X \to \nu\nu, \quad \frac{dN}{dE_\nu} = N_\nu \delta(E_\nu - E_{\rm in}), \quad N_\nu = 2 \tag{42}$$

$$\frac{d\Phi_{\nu,\rm gal.}}{dE_\nu} = N_\nu \frac{\kappa e^{-\frac{t_0}{\tau_X}}}{m_X \tau_X} r_\odot \rho_\odot \langle J_{\rm dec}(\theta)\rangle \delta(E_\nu - E_{\rm in}), \quad E_{\rm in} = \frac{m_X}{2} \tag{43}$$

$$\frac{d\Phi_{\nu,\rm e.g.}}{dE_\lambda} = N_\nu \frac{\kappa \Omega_{\rm dm}\rho_{\rm crit}}{H_0 m_X} \frac{1}{E_\nu} \frac{\frac{1}{\tau_X} e^{-\frac{t(\alpha-1)}{\tau_X}}}{\sqrt{\alpha^3 \Omega_M + \Omega_\Lambda}} \theta(\alpha - 1), \quad \alpha = E_{\rm in}/E_\nu \tag{44}$$



Likelihood statistics

- Likelihood function:

$$\mathcal{L}\left(\tau_X, \vec{\phi}_\nu\right) = \frac{\left(\mu_{\rm DR}\left(\tau_X\right) + \sum_{j=1}^{n_\nu} \mu_\nu\left(\phi_\nu^j\right)\right)^{N_{\rm obs}} e^{-\left(\mu_{\rm DR}\left(\tau_X\right) + \sum_{j=1}^{n_\nu} \mu_\nu\left(\phi_\nu^j\right)\right)}}{N_{\rm obs}\,!} \times \prod_{i=1}^{\mu_{\rm obs}} \frac{f\left(E_{R_i}, \tau_X, \vec{\phi}_\nu\right)}{\mu_{\rm DR}\left(\tau_X\right) + \sum_{j=1}^{n_\nu} \mu_\nu\left(\phi_\nu^j\right)} \times \prod_{j=1}^{n_\nu} L_j\left(\phi_\nu^j\right) \tag{45}$$

- measure of discrepancy is obtained by the test statistics (likelihood ratio)

$$q_0 = -2\ln\lambda(0) = \begin{cases} -2\ln \dfrac{L(\Gamma_X = 0, \tilde{\vec{\phi}}_\nu; m_X\,|E_R)}{L(\hat{\Gamma}_X, \hat{\vec{\phi}}_\nu; m_X\,|E_R)} & \text{for } \hat{\Gamma}_X > 0 \\ 0 & \text{for } \hat{\Gamma}_X \le 0, \end{cases}$$

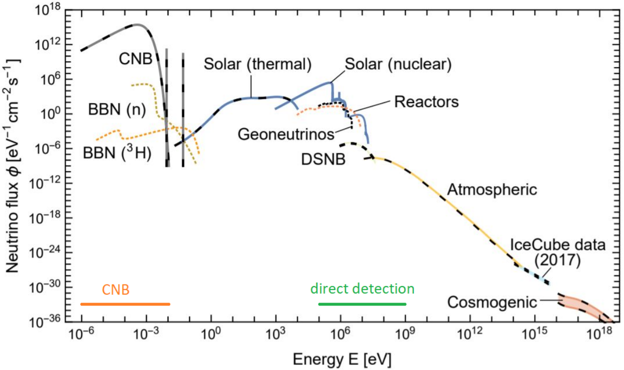
Improve sensitivity

- reducing uncertainty of neutrino fluxes
- measure direction of recoil energies when hitting solar neutrino background
- using different detector materials for additional information

other DR sources

- new particle with different strength
- DR from multi-body decays
- evaporating primordial back holes or emerging from supernova explosions

Neutrino flux - CνB



- CνB neutrino flux at $E_\nu \sim 10^{-4}$ eV $\Rightarrow$ nuclear recoils of $E_R \lesssim 10^{-15}$ eV in direct detection $\rightarrow$ impossible to measure, large thresholds
- detection via β-decaying nuclei (neutrino capture): $(A, Z) + \nu_e \rightarrow (A, Z+1) + e^-$
- CνB rate: $\Gamma_{\mathrm{CNB}} \approx (4 \text{ or } 8)\ \mathrm{yr}^{-1} \left(\dfrac{M_{\mathrm{T}}}{100\ \mathrm{g}}\right)$

Detection of CνB

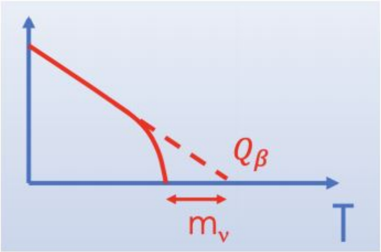
- Consider unstable nucleus (A, Z), that decays through β -decay,

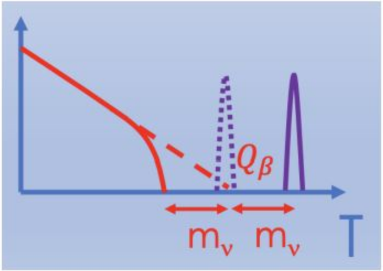
$$(A, Z) \rightarrow (A, Z+1) + e^{-} + \bar{\nu}_e$$

  releasing energy Q_β
- There exists a threshold-less reaction of neutrino capture

$$(A, Z) + \nu_e \rightarrow (A, Z+1) + e^{-}$$

- β -decays create a background for neutrino capture, but we can distinguish them using different kinematics
- PTOLEMY will measure neutrino mass m_ν
- CνB rate:
  $\Gamma_{\rm CNB} \approx (4 \text{ or } 8)\ {\rm yr}^{-1} \left(\frac{M_{\rm T}}{100\ {\rm g}}\right)$





Suppression factor (Pauli-blocking) and accumulating neutrinos

- galactic rate is affected by Pauli-blocking issues
- galactic rate suppressed by Pauli-blocking
- Non-escaping neutrinos: galactic neutrinos from DM decay are injected at non-relativistic speeds with $v_\nu \ll v_{\rm esc} \sim 10^{-3}c$
- happens when $\dfrac{m_{\rm DM} - 2m_\nu}{m_{\rm DM}} \lesssim 10^{-6}$

References

Yonit Hochberg, Eric Kuflik, Hitoshi Murayama, Tomer Volansky, and Jay G. Wacker. Model for Thermal Relic Dark Matter of Strongly Interacting Massive Particles. Phys. Rev. Lett., 115(2):021301, 2015. doi: 10.1103/PhysRevLett.115.021301, arXiv:1411.3727.

Yonit Hochberg, Eric Kuflik, Tomer Volansky, and Jay G. Wacker. Mechanism for Thermal Relic Dark Matter of Strongly Interacting Massive Particles. Phys. Rev. Lett., 113:171301, 2014. doi: 10.1103/PhysRevLett.113.171301, arXiv:1402.5143.

Hyun Min Lee and Min-Seok Seo. Communication with SIMP dark mesons via Z' -portal. Phys. Lett., B748:316–322, 2015. doi: 10.1016/j.physletb.2015.07.013, arXiv:1504.00745.

Nicolas Bernal, Camilo Garcia-Cely, and Rogerio Rosenfeld. WIMP and SIMP Dark Matter from the Spontaneous Breaking of a Global Group. JCAP, 1504(04):012, 2015. doi: 10.1088/1475-7516/2015/04/012, arXiv:1501.01973.

Yonit Hochberg, Eric Kuflik, and Hitoshi Murayama. SIMP Spectroscopy. JHEP, 05:090, 2016. doi: 10.1007/JHEP05(2016)090, arXiv:1512.07917.

Martin Hansen, Kasper LangÃ¦ble, and Francesco Sannino. SIMP model at NNLO in chiral perturbation theory. Phys. Rev., D92(7):075036, 2015. doi: