KeV fermion from a simple 3-portal model

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This talk will cover (in mixed order):

- Motivation
- Model
- some phenomenology (mostly neutrino related)
- conclusions

- Hidden sectors are called for due to mounting evidences for
  - Dark Matter
  - neutrino masses
- No way to do physics if no communication between the visible and “hidden” sectors.
- Basic requirements to write down the QFT lagrangian
  - Lorentz inv.
  - gauge inv.
  - renormalizability

- In SM, there are three gauge invariant, dim < 4 operators: (1) $Y^{\mu\nu}$ (2) $\bar{L}\tilde{H}$ (3) $H^{\dagger}H$.
  (The quantum numbers: $L(1, 2, -1/2), H(1, 2, 1/2)$)
- They are allowed to couple to any
  - dim-2 antisymmetric gauge invarinat tensors
  - dim-3/2 gauge singlet fermions
  - dim-1 or dim-2 scalars

  in an UV theory.

- Three possible portals between the visible and hidden sectors
  - Kinematic mixing: $Y^{\mu\nu} X_{\mu\nu}$, X any $U(1)$.
  - Higgs: $|\phi|^2 |H|^2$, ϕ, any complex scalar.
    For real scalar, $\phi |H|^2$ is also possible.
  - neutrino $\bar{L}\tilde{H}\chi$, χ any singlet fermion.
- So the hidden sector is not totally hidden, it just stands in the shadow.

- In 2006, we studied a simple model with hidden sector SM +gauge $U(1)_s$. [WFC, J Ng, J Wu, PRD74]

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} - \frac{\epsilon}{2}B^{\mu\nu}X_{\mu\nu} + \left|\left(\partial_\mu - \frac{1}{2}g_s X_\mu\right)\phi_s\right|^2 - V(\phi_s, \Phi),$$

$$\begin{pmatrix} X \\ B \end{pmatrix} = \begin{pmatrix} c_\epsilon & 0 \\ -s_\epsilon & 1 \end{pmatrix} \begin{pmatrix} X' \\ B' \end{pmatrix},$$

$$s_\epsilon = \frac{\epsilon}{\sqrt{1-\epsilon^2}}, \quad c_\epsilon = \frac{1}{\sqrt{1-\epsilon^2}}.$$

- The SSB of $U(1)_s$ is done by ϕ_s (SM singlet)
- Massive vector boson in SSB Gauged symmetry (not massless Goldstone)

$$\begin{pmatrix} B' \\ A_3 \\ X' \end{pmatrix} = \begin{pmatrix} c_W & -s_W & 0 \\ s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\eta & -s_\eta \\ 0 & s_\eta & c_\eta \end{pmatrix} \begin{pmatrix} \gamma \\ Z \\ Z_s \end{pmatrix}$$

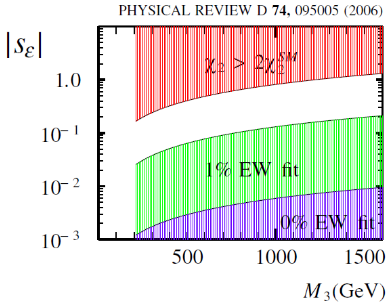
$$\tan_{2\eta} = \frac{2 s_W s_\epsilon}{c_W^2 (M_3/M_W)^2 + s_W^2 s_\epsilon^2 - 1}$$

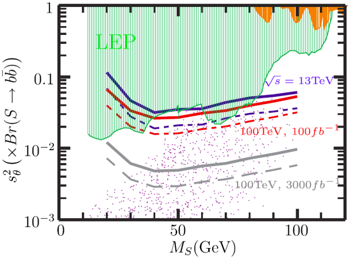
$$\begin{aligned} M_Z^2 &= M_Z^{2\rm SM}\left\{c_\eta^2 - s_{2\eta} s_W s_\epsilon + s_\eta^2 s_W^2 s_\epsilon^2\right\} + s_\eta^2 M_3^2 \\ M_{Z_s}^2 &= M_Z^{2\rm SM}\left\{s_\eta^2 + s_{2\eta} s_W s_\epsilon + c_\eta^2 s_W^2 s_W^2 s_\epsilon^2\right\} + c_\eta^2 M_3^2 \end{aligned}$$

- Moreover, two portals (kinematic and Higgs) provide more handles for experimental studies.
- The kinematic mixing allows the SM fields couple weakly to the new gauge boson.

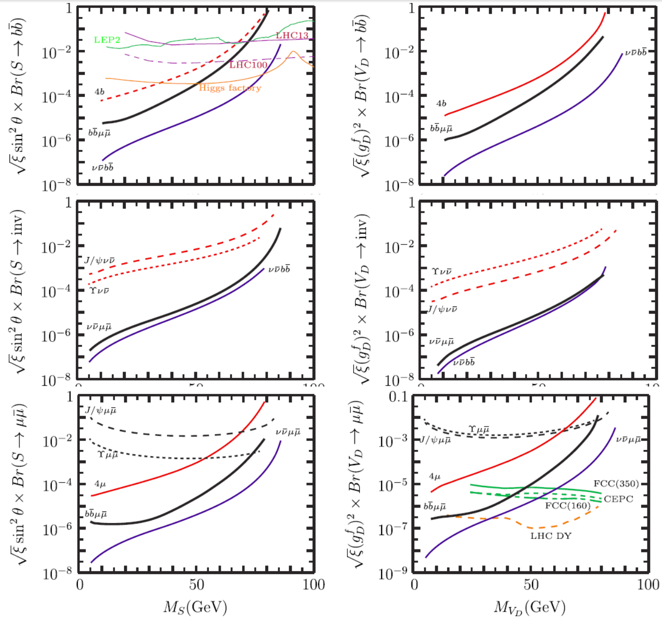
$$Z^\mu \bar{f} f \ : \ i\gamma^\mu \frac{g_2}{c_W}\Big[\left(c_\eta g_f^L - s_\eta s_W s_\epsilon Y_f^L\right)\hat{L} + \left(c_\eta g_f^R - s_\eta s_W s_\epsilon Y_f^R\right)\hat{R}\Big] \,,$$
$$Z_s^\mu \bar{f} f \ : \ i\gamma^\mu \frac{g_2}{c_W}\Big[\left(-s_\eta g_f^L - c_\eta s_W s_\epsilon Y_f^L\right)\hat{L} + \left(-s_\eta g_f^R - c_\eta s_W s_\epsilon Y_f^R\right)\hat{R}\Big] \,,$$

  Now is under intensive investigation.
- The Higgs portal opens another window in collider physics.
- However, there is no neutrino mass nor DM in it.





- All EW precision constraints [WFC, J Ng, J Wu, PRD74]
- We have recently explored the possibility to probe the light scalar ($<$ 80GeV) at the LHC ($pp \to t\bar{t}S(\to b\bar{b})$) and ILC ($e^+e^- \to Z \to f\bar{f}X$). This is relevant in this new study. [WFC, T Modak, J Ng, PRD97, WFC,J Ng, G White, PRD97]



[WFC,J Ng, G White, PRD97]

- A simple remedy is adding a pair of vector χ which is charged under $U(1)_s$ to our model. Note it is anomoly-free.
- After simple SSB of $U(1)_s$, no residual symmetry (with the more complicated arrangement, residual parity can be arranged)
- DM candidate requires a long lifetime which is comparable to the age of universe.
- χ mass is free. If around keV, it is possible to solve the small scale structure problem, the core-cusp problem in the cold WIMP scenario (or even the 3.5 keV gamma-ray line)

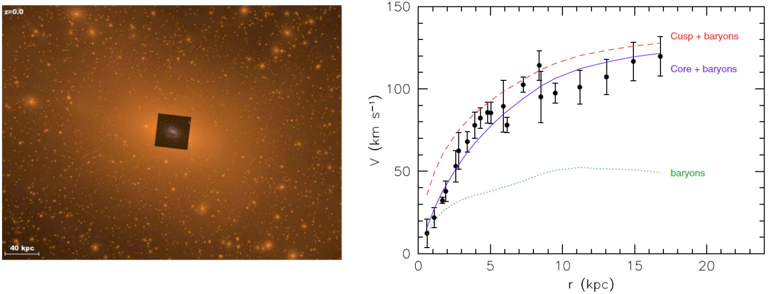


Fig. 1. Cusp-core problem. (*Left*) Optical image of the galaxy F568-3 (*Inset*, from the Sloan Digital Sky Survey) is superposed on the dark matter distribution from the "Via Lactea" cosmological simulation of a Milky Way-mass CDM halo (12). In the simulation image, intensity encodes the square of the dark matter density, which is proportional to the annihilation rate and highlights the low-mass substructure. (*Right*) Measured rotation curve of F568-3 (points) compared with model fits assuming a cored dark matter halo (blue solid curve) or a cuspy dark matter halo with a Navarro–Frenk–White (NFW; 8) profile (red dashed curve, concentration $c = 9.2$, $V_{200} = 110\ \mathrm{km \cdot s^{-1}}$). The dotted green curve shows the contribution of baryons (stars + gas) to the rotation curve, which is included in both model fits. An NFW halo profile overpredicts the rotation speed in the inner few kpc. Note that the rotation curve is measured over roughly the scale of the 40-kiloparsec (kpc) image (*Inset*, *Left*).

[Weinberg et al. PNAS Oct 2015]

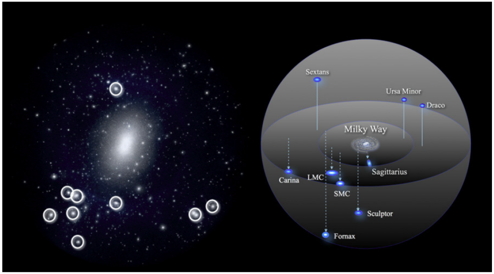
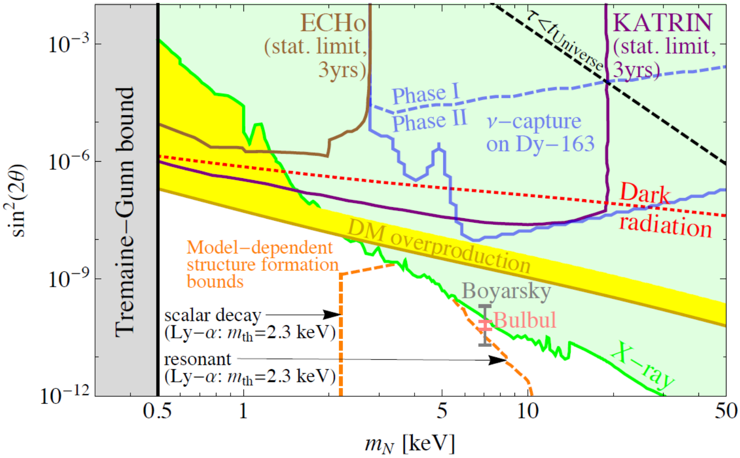


Fig. 2. Missing satellite and too big to fail problems. (*Left*) Projected dark matter distribution (600 kpc on a side) of a simulated, $10^{12} M_{\odot}$ CDM halo (18). As in Fig. 1, the numerous small subhalos far exceed the number of known Milky Way satellites. Circles mark the nine most massive subhalos. (*Right*) Spatial distribution of the classical satellites of the Milky Way. The central densities of the subhalos (*Left*) are too high to host the dwarf satellites (*Right*), predicting stellar velocity dispersions higher than observed. (*Right*) Diameter of the outer sphere is 300 kpc; relative to the simulation prediction (and to the Andromeda galaxy), the Milky Way's satellite system is unusually centrally concentrated (19).

12250 | www.pnas.org/cgi/doi/10.1073/pnas.1308716112 Weinberg et al.

[Weinberg et al. PNAS Oct 2015]

- The RH neutrinos as warm DM have been intensively studied before. (eg. minimal νSM: 2 heavy N_R, 1 light N_R.)
- The constraint is summarized in the plot



[R. Adhikari et al JCAP01(2017)025]

The Tremaine-Gunn bound is from the Fermi-Dirac. The ballpark is following:

- To not escape from the gravitational potential, U,

$$|U|m \gtrsim \frac{p_F^2}{2m}\,,\; m \gtrsim p_F/\sqrt{|U|}$$

(m: DM mass, p_F: Fermi momentum)

- Total number of DM ($n\lambda = L, \vec{p} = 2\pi\hbar\vec{n}/L$)

$$n_F^3 \sim (Lp_F/2\pi\hbar)^3 \sim (L/2\pi\hbar)^3 m^3 U^{3/2}$$

- Then the DM mass density ($=$ total $\# \times m/L^3$)

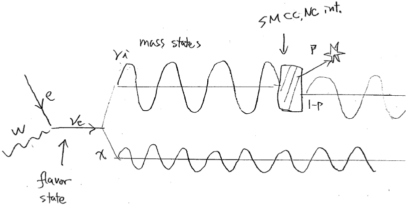
$$\rho_{DM} \sim m^4/(2\pi\hbar)^3 (G\rho_{DM} L^3/L)^{3/2}$$

- Thus

$$m \gtrsim [(2\pi\hbar)^3/\sqrt{\rho_{DM}} L^3 G^3/2]^{1/4} \sim 200eV$$

if $\rho_{DM} \sim 1m_p/m^3$, $L \sim 100kps$.

- One theoretical problem is the generation of the RH neutrino.
- N_R can only be produced via Yukawa with SM lepton which is too small.
- Mixing with SM neutrino and the de-coherent scattering can generate the N_R by oscillation in the plasma (Doldelson-Widrow), or with MSW-like resonance (Shi-Fuller)



- Narrow window $\sim 0.5 - 2$ keV for N_R DM.

- A keV RH neutrino within the type-I see-saw requires certain fine turning or complicated model building (eg extra-dim).
- For simplicity, we still employ the high-scale type-I see-saw for neutrino masses.
- Instead of RH neutrinos, the χ plays the role of DM.
- χ is charged under $U(1)_s$, so it cannot play the role as the RH neutrino directly. $\bar{L}\tilde{H}\chi$ is forbidden by the $U(1)_S$ symmetry.

- This simple model consists of
  (1) a shadow gauged $U(1)_s$
  (2) ϕ_s (for SSB)
  (3) N_R (for type-I)
  (4) vector χ (for DM)

Field	ℓ_L	H	N_R	χ_L	χ_R	ϕ
$SU(2)_L$	2	2	1	1	1	1
$U(1)_Y$	$-\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
$U(1)_s$	0	0	0	1	1	1

- neutrino masses, keV DM, many experimental handles,
- The questions will be
  (1) whether this minimal setup allows a consistent solution to accommodate the warm dark matter?
  (2) Are there detectable experimental signals?

The model

- The complete Lagrangian

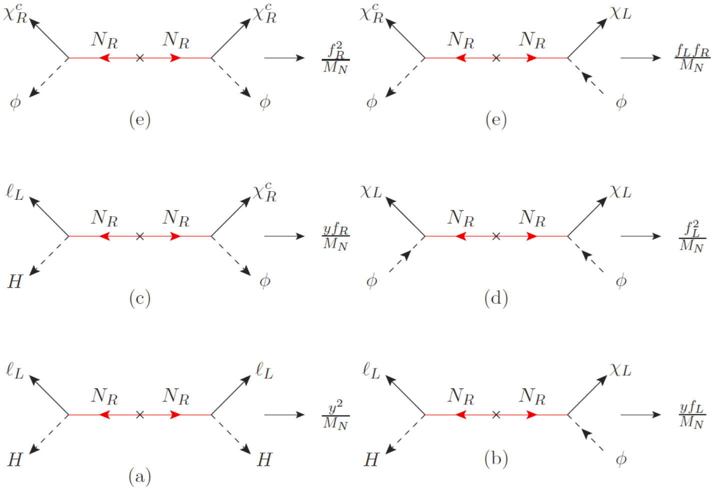
$$\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\text{SMI}} + \mathcal{L}_{\text{sh}} + \mathcal{L}_{N\chi} \\
\mathcal{L}_{\text{SMI}} &= \mathcal{L}_{\text{SM}} + \overline{N_R} i\partial\!\!\!/ N_R - \left(y \bar{\ell}_L N_R \tilde{H} + \frac{1}{2} M_N \overline{N_R^c} N_R + h.c. \right) \\
\mathcal{L}_{\text{sh}} &= -\frac{1}{4} X^{\mu\nu} X_{\mu\nu} - \frac{\epsilon}{2} B^{\mu\nu} X_{\mu\nu} + \left| \left(\partial_\mu - i g_s X_\mu \right) \phi \right|^2 + \bar{\chi}(i\partial\!\!\!/ - g_s X\!\!\!/)\chi - M_\chi \bar{\chi}\chi - V \\
\mathcal{L}_{N\chi} &= -f_L \overline{\chi_L} N_R \phi - f_R \overline{\chi_R^c} N_R \phi^* + h.c. \\
V(H, \phi) &= -\mu_s^2 \phi^* \phi + \lambda_s (\phi^* \phi)^2 + \kappa (H^\dagger H)(\phi^* \phi) - \mu^2 H^\dagger H + \lambda (H^\dagger H)^2
\end{aligned}$$

g_s: gauge coupling, M_χ: Dirac mass

- The portal terms are in red
- Global Lepton number is broken by M_N.
- In SM, $v = \sqrt{\mu^2/\lambda}$, $m_H = \sqrt{2}\mu$. (μ sets the mass, λ sets the cubic and quartic couplings. 2 independent free parameters.)
- Next, we implement type-I, at least 2 N_R for realistic m_ν

The model

- Integrating out N_R



- both dim-4 and dim-5 effective operators will be generated

Neutral Fermion mass

- Expect the hierarchy $M_N \gg v_s \gtrsim v$.
- Decouple the N_R's, all contributions are lumped together.

$$
\begin{aligned}
-M_N \mathcal{L}_5 =& y^2 \overline{\ell_L^c} \ell_L H H + y f_L \overline{\chi_L^c} \phi^* \ell_L H + y f_R \overline{\chi_R} \ell_L \phi H \\
&+ f_L^2 \overline{\chi_L^c} \chi_L \phi^* \phi^* + f_R^2 \overline{\chi_R^c} \chi_R \phi^* \phi^* + f_L f_R \overline{\chi_L} \chi_R \phi \phi^* + h.c.
\end{aligned}
$$

- For 1 generation, in (ν, χ_L, χ_R^c) basis

$$
M_\nu \sim \begin{pmatrix} y^2 \frac{v^2}{M_N} & y f_L \frac{v v_s}{2M_N} & y f_R \frac{v v_s}{2M_N} \\ y f_L \frac{v v_s}{2M_N} & f_L^2 \frac{v_s^2}{M_N} & \frac{1}{2}(M_\chi + f_L f_R \frac{v_s^2}{M_N}) \\ y f_R \frac{v v_s}{2M_N} & \frac{1}{2}(M_\chi + f_L f_R \frac{v_s^2}{M_N}) & f_R^2 \frac{v_s^2}{M_N} \end{pmatrix}
$$

- $y^2/M_N \sim 10^{-14}(GeV)^{-1}$ for sub-eV m_ν.
- Take $f_L = f_R \simeq 0.1$, $M_N = 10^{10}$GeV $(y = 0.01)$, $v_s = 1$TeV, $f^2 v_s^2/M_N \ll 10$keV. M_χ takes control

mass splitting

- The previous example has a splitting $\sim keV$ for $M_\chi \sim 10\text{keV}$.
- Again $y^2/M_N \simeq 10^{-14}(GeV)^{-1}$, $f_L = f_R = f$, $v_s = 1\text{TeV}$
- $M_N = 10^{10}\text{GeV}$ $(y = 0.01)$, $f \simeq 1$, $M_\chi \simeq 80$ keV

$$\Rightarrow \simeq 10\text{keV}, \simeq 100\text{keV}$$

- $M_N = 10^{8}\text{GeV}$ $(y = 10^{-3})$, $f \simeq 0.3$, $M_\chi \sim$ MeV

$$\Rightarrow \simeq 10\text{keV}, \simeq 1\text{MeV}$$

- Larger splitting $\rightarrow$ lower $\not{L}$ scale, or higher v_s, M_χ.

SM interactions

- mixing angle $\sim yfvv_s/2M_\chi M_N \lesssim 10^{-4}$.
- Extend to 3 generations, 5 by 5 matrix, M_ν.
- $3(=(n-1)(n-2)/2)$ Dirac phases, 4 Majorana phases.
- $M_\nu^{diag} = U^\dagger M_\nu U$, $\nu_\alpha = U_{\alpha i}\nu_i$, α: flavor, i: mass
- In the mass basis, the SM CC is

$$\frac{ig}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{5} U_{i\alpha} \overline{e}_\alpha \gamma_{\mu L} \nu_i W^{\mu,-} + h.c.$$

- NC interaction (by Unitarity of U)

$$\frac{ig}{2\cos\theta_w}\left[\sum_{i=1}^{5} \bar{\nu}_i \gamma_{\mu L} \nu_i - \left(\sum_{i,j=1}^{5} (U^\dagger)_{j\chi_L} U_{\chi_L i} \bar{\nu}_j \gamma_{\mu L} \nu_i + \sum_{i,j=1}^{5} (U^\dagger)_{j\chi_R^c} U_{\chi_R^c i} \bar{\nu}_j \gamma_{\mu L} \nu_i\right)\right] Z^\mu$$

decay

- If $M_\chi \sim \mathcal{O}(10keV)$, only 2 decay modes
- $\chi_\pm \to 3\nu$ through Z-mediated

$$\Gamma(\chi_\pm \to 3\nu) = \frac{G_F^2 M_\chi^5}{96\pi^3} \sum_{i=1}^{3} |U_{\chi i}|^2$$

- $\chi \to \gamma\nu$ through 1-loop

$$\Gamma(\chi_\pm \to \gamma\nu) = \frac{9\alpha G_F^2}{256\pi^4} M_\chi^5 \sum_{\alpha=e,\mu,\tau} \sum_{i=1,2,3} |U_{4\alpha}|^2 |U_{\alpha i}|^2$$

- Monochromatic x-ray line for each χ.
- If $M_\chi = 10keV, \tau_\chi > \tau_{Univ}$

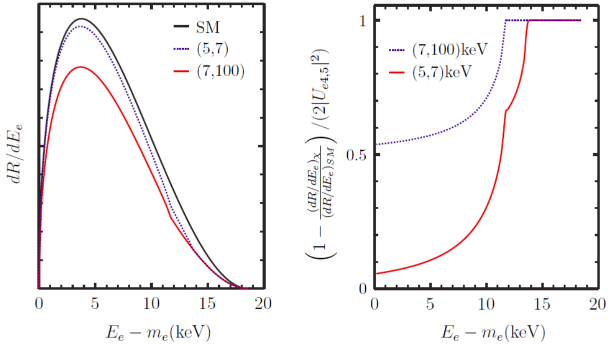
$$\sum_i |U_{\chi i}|^2 < 1.8 \times 10^{-2}$$

- The Kurie plot is a kinematic prob of neutrino masses.
- For nuclear β-decay, with $M \gg Q, E_e, m_\nu$, the differential decay rate is

$$\frac{dR}{dE_e} = K_\beta E_e (Q + m_e - E_e)(E_e^2 - m_e^2)^{\frac{1}{2}}$$
$$\left\{ |U_{e5}|^2 \left[(Q + m_e - E_e)^2 - M_2^2\right]^{\frac{1}{2}} + |U_{e4}|^2 \left[(Q + m_e - E_e)^2 - M_1^2\right]^{\frac{1}{2}} + \sum_{i=1}^{3} |U_{ei}|^2 \left[(Q + m_e - E_e)^2 - m_i^2\right]^{\frac{1}{2}} \right\}.$$

- $Q = 18.59$keV for tritium
- cutoff at $E = Q + m_e - M_{1,2}$, gives kinks

$\frac{dR}{dE_e}$ and $1 - XS_\chi / XS_{SM}$



$(M_1, M_2) = (5, 7)$keV, $U_{e4,5} = 0.4(L), 0.01(R)$.

$0\nu\beta\beta$ decay

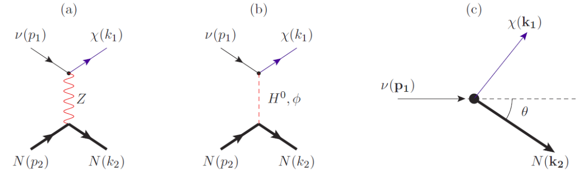
- The effective m_{ee}

$$m_{ee} = \left| U_{e1}^2 m_1 + U_{e2}^2 e^{2i\alpha_2} m_2 + U_{e3}^2 e^{2i\alpha_3} m_3 + U_{e4}^2 e^{2i\alpha_4} M_1 + U_{e5}^2 e^{2i\alpha_5} M_2 \right|$$

- one expects the active neutrinos to contribute $10^{-2} - 10^{-3}$ eV to m_{ee}.
- for $M_{1,2} \sim 10 keV$, they contribute $10^{-4} - 10^{-2}$ eV, depending on the Yukawa.
- Will significantly change the expectations of $0\nu\beta\beta$ decays.

Coherent scattering

- $\nu + N \rightarrow \chi + N$



- The bound of recoil energy

$$T_{\pm} = \frac{ME_\nu^2 - \frac{1}{2}m_\chi^2(M+E_\nu) \pm E_\nu \left[M^2E_\nu^2 - m_\chi^2 M(M+E_\nu) + \frac{1}{4}m_\chi^4\right]^{\frac{1}{2}}}{M(M+2E_\nu)}.$$

- Z-mediated

$$\frac{d\sigma^{(Z)}}{dT} = \frac{G_F^2 Q_W^2 |U_{\alpha 4}|^2}{4\pi} M \left[1 - \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu} + \frac{T^2}{2E_\nu^2} - \frac{m_\chi^2}{4E_\nu^2}\left(\frac{2E_\nu}{M} - \frac{T}{M} + 1\right)\right] F_Z^2(q^2)$$

- From the new dim-4 Yukawa

$$\frac{d\sigma^{(H)}}{dT} = \frac{y_\chi^2 g_{HNN}^2}{4\pi} M \cos^2\alpha \left(\frac{1}{M_H^2} + \frac{v}{v_s}\frac{\tan\alpha}{M_\phi^2}\right)^2 \left(1 + \frac{T}{2M}\right)\left(\frac{MT}{E_\nu^2} + \frac{m_\chi^2}{2E_\nu^2}\right) F_H^2(q^2)$$

COHERENT (Spallation neutron source at Oak Ridge)

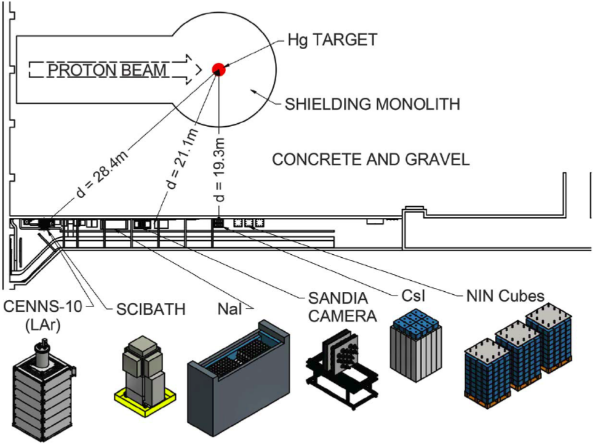
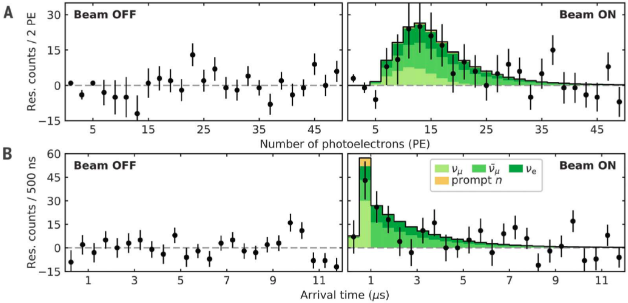


Fig. 2. COHERENT detectors populating the "neutrino alley" at the SNS. Locations in this basement corridor profit from more than 19 m of continuous shielding against beam-related neutrons and a modest 8 m.w.e. overburden able to reduce cosmic ray–induced backgrounds, while sustaining an instantaneous neutrino flux as high as 1.7×10^{11} ν_μ cm^{-2} s^{-1}.

[Akimov et al., Science 357, 1123V1126 (2017)]

[Akimov et al., Science 357, 1123V1126 (2017)]
Line spectrum, 29.79keV, from $\pi^+ \to \bar{\mu}\nu_\mu$. And continuous ones from $\mu^+ \to \bar{\nu}_\mu e^+ \nu_e$.

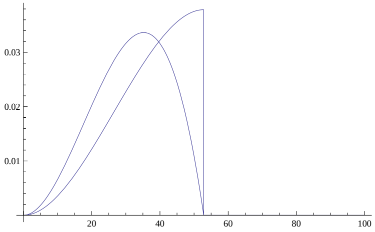


$$\phi_{\nu_\mu}(E_\nu) = \phi_0 \, \delta\left(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right),$$

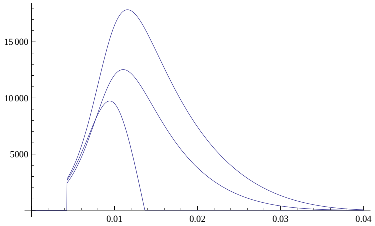
$$\phi_{\nu_e}(E_\nu) = \phi_0 \frac{192}{m_\mu}\left(\frac{E_\nu E_\mu}{m_\mu^2}\right)^2 \left[\frac{m_\mu}{2E_\mu} - \frac{E_\nu}{m_\mu}\left(1 + \frac{\mathbf{p}_\mu^2}{3E_\mu^2}\right)\right],$$

$$\phi_{\bar{\nu}_\mu}(E_\nu) = \phi_0 \frac{64}{m_\mu}\left(\frac{E_\nu^2}{m_\mu^2}\right)\left[\frac{3}{4} - \frac{E_\nu E_\mu}{m_\mu^2}\left(1 + \frac{\mathbf{p}_\mu^2}{3E_\mu^2}\right)\right],$$

- The neutrino spectrum from μ^+ decay($\bar{\nu}_\mu$: with cliff, ν_e: continuous)

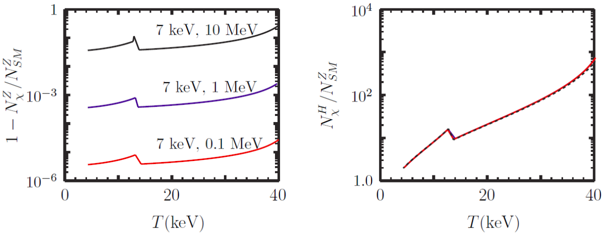


- and the SM coherent scattering cross sections (acceptance included)



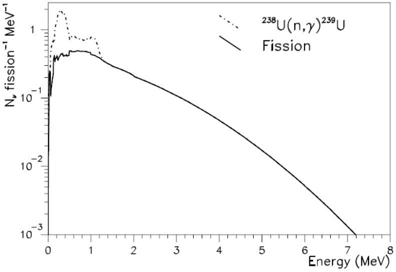
From top to down: $\bar{\nu}_\mu, \nu_e, \nu_\mu$

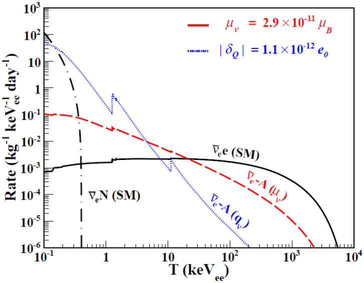
- XS deviation for 100keV and 1MeV fermion (Z-mediated).



- XS for scalar-mediated, insensitive to m_χ, no SM counter part
- Here $|U|^2 = 1$.

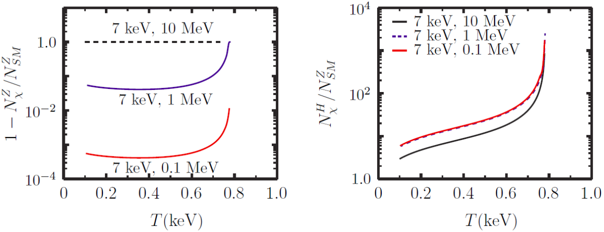
Nuclear Power plant is another place to look for the coherent scattering.





[PRD 75, 012001 (2007); Journal of Physics: Conf. Series 888 (2017) 012124]

- XS deviation for 100keV and 1MeV fermion (Z-mediated).



- XS for scalar-mediated, insensitive to m_χ, no SM counter part
- Here $|U|^2 = 1$.

EW precision tests

- T parameter: $M_3 > 2.29|s_\epsilon| TeV$
- Forward-backward asymmetries,atomic parity violation, Møller scattering: due to the interferences among photon, Z, and Z_s.
- Invisible Z decays: $= 499 \pm 1.5 MeV$

$$\Gamma(Z \to \chi\chi) = \frac{c_\epsilon^2 s_\eta^2 g_s^2}{12\pi} M_Z$$

or

$$s_\eta^2 \left[\frac{c_\epsilon^2 g_s^2}{3} - \frac{g_2^2}{8 c_W^2} \right] \leq 2.1 \times 10^{-4}.$$

Warm Dark matter

- Assume the SM and hidden sectors are coupled, χ is copiously produced after reheating.
- DM decouples from the plasma (freeze out), determined by $\sigma(\chi\chi \leftrightarrow ff)$, parameterized as

$$\sigma v \sim (\eta g_s/g_2)^2 G_F^2 T^2 \equiv A_\chi^2 G_F^2 T^2$$

- The decoupling temperature is determined by rate $\sim H$,

$$T_f \sim 40.6(g_*)^{1/6}(10^{-2}/A_\chi)^{2/3}\text{MeV}$$

which gives too much DM ($\Omega_{DM} = 0.228(39)$)

$$\Omega_\chi \sim \frac{250}{g_*(T_f)} \times \left(\frac{m_\chi}{keV}\right)$$

Warm Dark matter

- Use the entropy from ϕ decay (mostly into gluon pair, $\tau_\phi \sim 1\mathrm{sec}$) before BBN, to dilute the relic density.

$$D \sim 280.4 \times \frac{g_*(T_r)^{\frac{1}{4}}}{g_*(T_f)} \left(\frac{m_\phi}{1GeV}\right) \left(\frac{1\mathrm{sec}}{\tau_\phi}\right)^{1/2}$$

After dilution,

$$\Omega_\chi \sim \frac{0.89}{g_*(T_r)^{\frac{1}{4}}} \left(\frac{1GeV}{m_\phi}\right) \left(\frac{\tau_\phi}{1\mathrm{sec}}\right)^{1/2}$$

- That requires $m_\phi \simeq 2$ GeV.
- χ produced by DW washed away by ϕ?.
- Freeze-in?

Conclusion

- A simple 3-portal gauged $U(1)_s$ model is considered.
- A vector pair of new fermion introduced, the lighter can serve as a viable keV DM (better than ν_R)
- Viable parameter space available.
- The parameter space doesn't need excessive fine-tuning (both m_ϕ and M_χ are free parameters).
- In addition to the collider searches, many opportunities in low energy neutrino experiments.