Light Dark Sector @ Neutrino Experiments

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SFG, Ian Shoemaker [in finalization]

SFG, Manfred Lindner, Werner Rodejohann, PLB 2017 [arXiv:1702.02617]

Thermal Relic DM

- **Symmetric**

- **Relic density fully determined by annihilation cross section**

$$\rho_\chi \propto \frac{1}{\langle \sigma v \rangle}$$

$\Rightarrow \langle \sigma v \rangle \sim 1$ pb, the typical size of cross sections at LHC

- **Characteristic scale of EW**

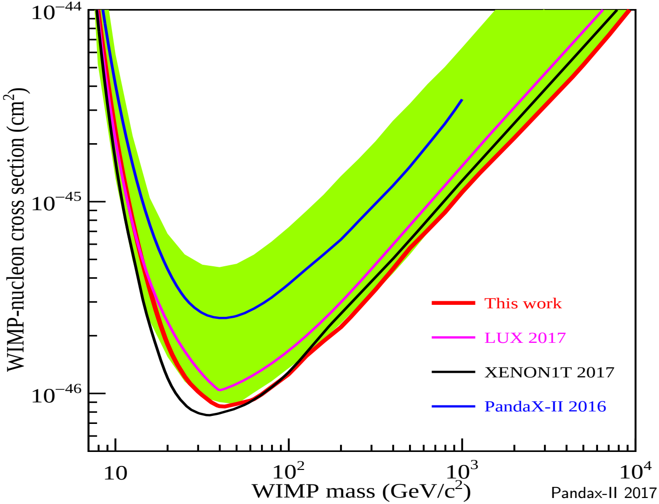
$$\langle \sigma v \rangle \propto \frac{g_\chi^4}{m_\chi^2}$$

corresponding to $m \sim 100$ GeV for EW coupling.

- **Alternatives**: axion, fuzzy DM, light DM, asymmetric DM

Current Status of DM Search

- DM can be light if its coupling is small: $\langle \sigma v \rangle \propto g_\chi^4 / m_\chi^2$



Pandax-II 2017 [arXiv:1708.06917]

Light DM

- WIMPless DM - $m_\chi \propto g_\chi^2$
- DM has no SM gauge coupling
- Renormalizable portables – limited

$$\mathcal{L}_{\rm portal} = \begin{cases} \epsilon F_{\mu\nu} F_h'^{\mu\nu} & \text{(photon portal)} \\ h|H^2||H_h^2| & \text{(Higgs portal)} \\ y(LH)N & \text{(neutrino portal)} \end{cases}$$

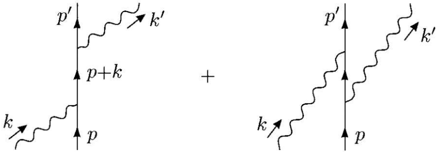
where $F'_{\mu\nu}$, H_h, and N are hidden sector fields.

- Full Lagrangian

$$i\bar{\chi}\not{D}\chi - m_\chi \bar{\chi}\chi - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m^2_{V'} V'^{\mu} V'_{\mu} - \epsilon F_{\mu\nu} F'^{\mu\nu}$$

Reactor Compton-like Production of DM

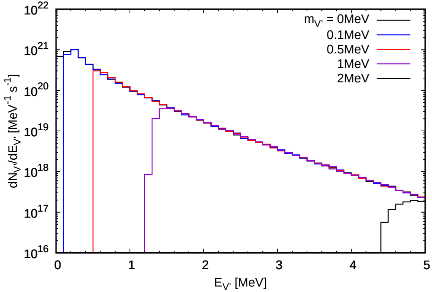
- $\gamma e^- \to V' e^-$ with prompt γ-rays from nuclear fissions



$$\frac{dN_\gamma}{dE_\gamma} = 0.58 \times 10^{21} \left(\frac{P}{\mathrm{GW}}\right) \exp\left(-\frac{E_\gamma}{0.91\mathrm{MeV}}\right)$$

$$\frac{dN_{V'}}{dE_{V'}} = \int \frac{1}{\sigma_{tot}} \frac{d\sigma_{\gamma\to V'}}{dE_{V'}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma$$

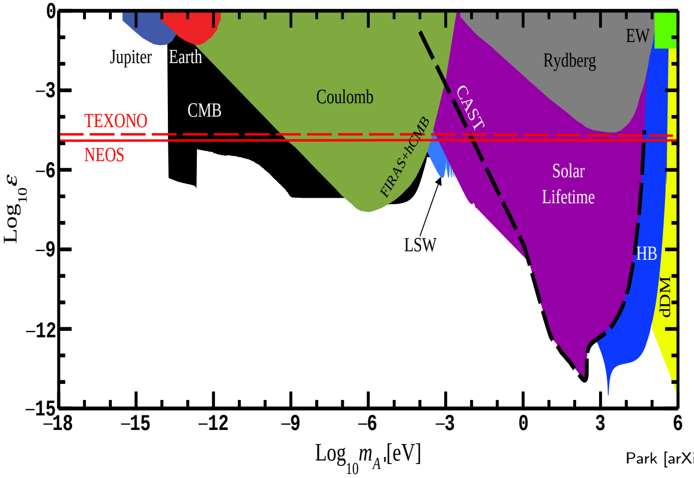
$$\frac{d\sigma_{\gamma\to V'}}{dE_{V'}} = \frac{\epsilon^2 \alpha m_e}{(s - m_e^2)^2} \left[\frac{3m_e^4 - m_e^2(t - 3m_{V'}^2) + s(2m_e^2 - u)}{(s - m_e^2)^2} + \frac{3m_e^4 - m_e^2(t - 3m_{V'}^2) + u(2m_e^2 - s)}{(u - m_e^2)^2} + 2\frac{m_e^2(4m_e^2 + m_{V'}^2) - (m_e^2 + m_{V'}^2)t}{(s - m_e^2)(u - m_e^2)} \right]$$



typical power reactor is $P \sim \mathcal{O}(GW)$

Constraint on Meta-Stable Dark Photon V'

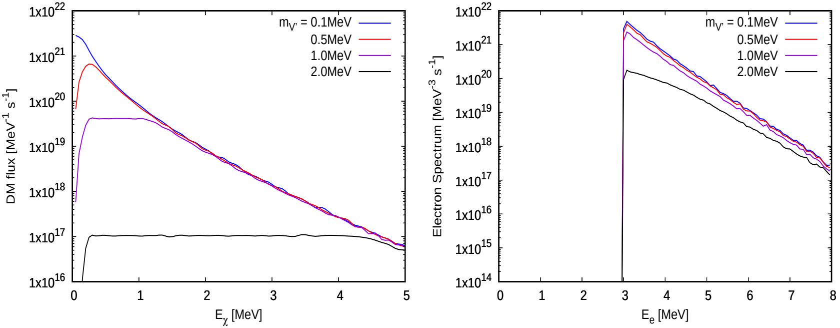
- $m_{V'} < 2m_\chi \Rightarrow$ Meta-Stable V'
- Inverse Compton-like Process $\sigma(V'e^- \to \gamma e^-) \propto \epsilon^2$.



Park [arXiv:1705.02470]

Constraint on Unstable V'

- $m_{V'} > 2m_\chi \Rightarrow$ Prompt decay $V' \to \chi\bar{\chi}$ with Br ≈ 1
- Elastic Scattering: $\sigma(\chi e^- \to V'^* \to \chi e^-) \propto \epsilon^2 g_\chi^2$

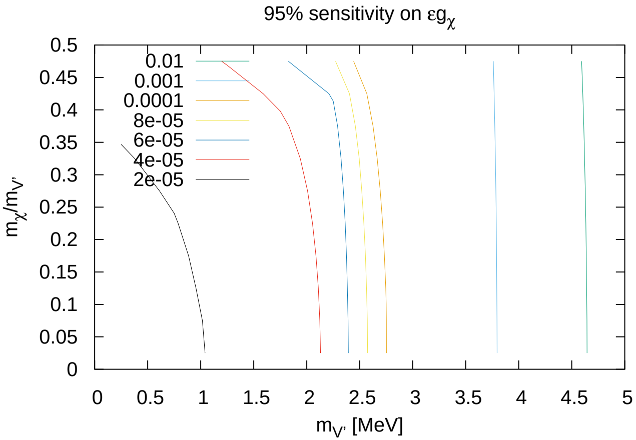


- Energy threshold $E_e > 3\,\text{MeV}$ @ TEXONO
- Mainly sensitive to $m_{V'} \lesssim 1\,\text{MeV}$

SFG & Ian Shoemaker [in finalization]

TEXONO Constraint

- 187kg CsI(TI) @ 28m from the core of a 2.9GW reactor



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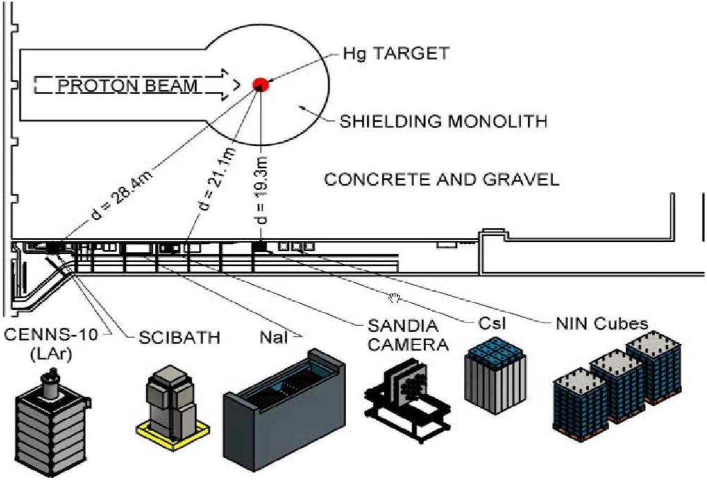
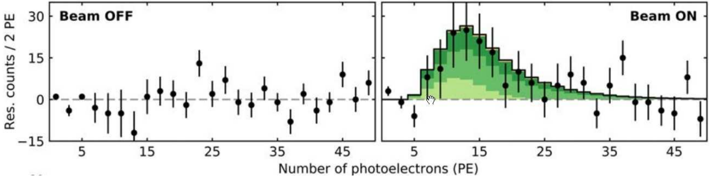
Fixed Target Experiment - COHERENT

- Much higher energy $\sim \mathcal{O}(100\,\text{MeV})$ with $800\,\text{MeV}$ proton beam



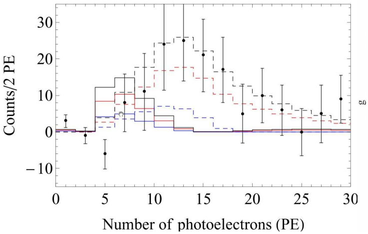
COHERENT data

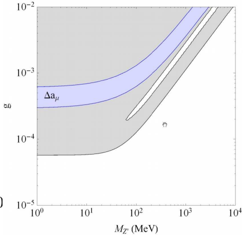
- 308.1 live-days (Beam ON) with 7.48 GWhr ($\sim 1.76 \times 10^{23}$POT)



COHERENT [arXiv:1708.01294]

- Constraint on NSI





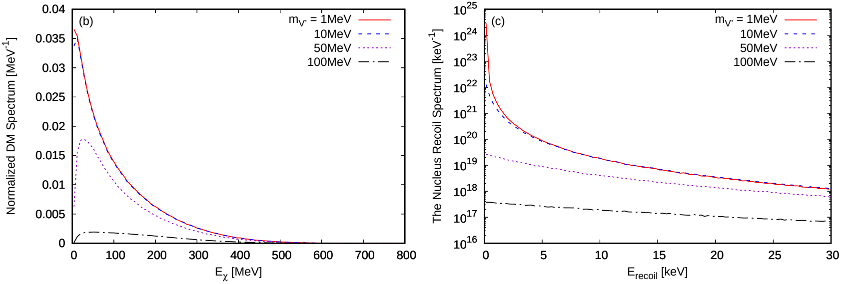
Liao & Marfatia [arXiv:1708.04255]

COHERENT Constraint on Light DM

- $\pi^0 \to \gamma V'$ with $f_{\pi^0} \approx f_{\pi^\pm}$

$$\mathrm{Br}_{\pi^0 \to \gamma V'} \approx 2\epsilon^2 \left(1 - \frac{m_{V'}^2}{m_{\pi^0}^2}\right)^3$$

- $V' \to \chi\bar{\chi}$ & $\chi N \to \chi N$ via V' mediation



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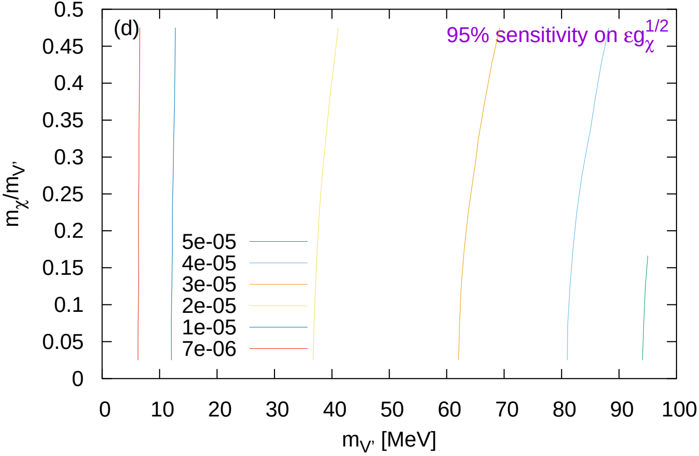
COHERENT Sensitivity on Light DM



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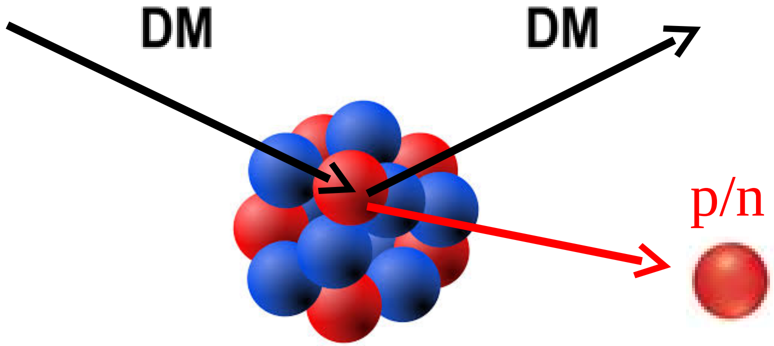
Boosted DM detection strategies:

Boosted DM detection:

⇨ DM particle is energetic enough to knock a nucleon out!

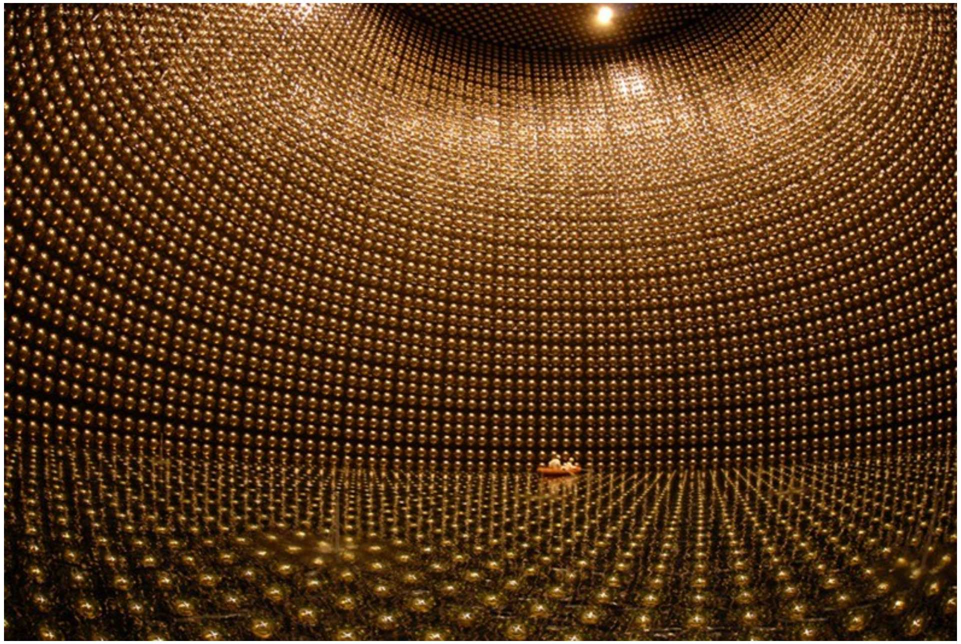
→ v ~ O(1) c



Looking for proton/neutron
knocked out of a nucleus.
Similar to neutrino neutral current interaction!

$$\sigma_{\nu p \to \nu p}(E) \simeq 6 \times 10^{-46} \mathrm{cm}^2 \left(\frac{E_\nu}{\mathrm{MeV}} \right)^2$$

DM-nucleon scattering cross section
can be less constrained!



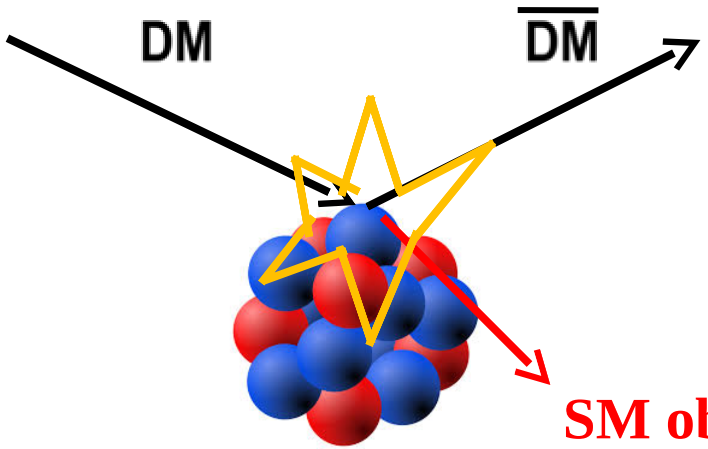
Large Volume Neutrino Experiments
Super-K ~ 50K ton! DUNE ~ 68K ton!

DM IND detection strategies:

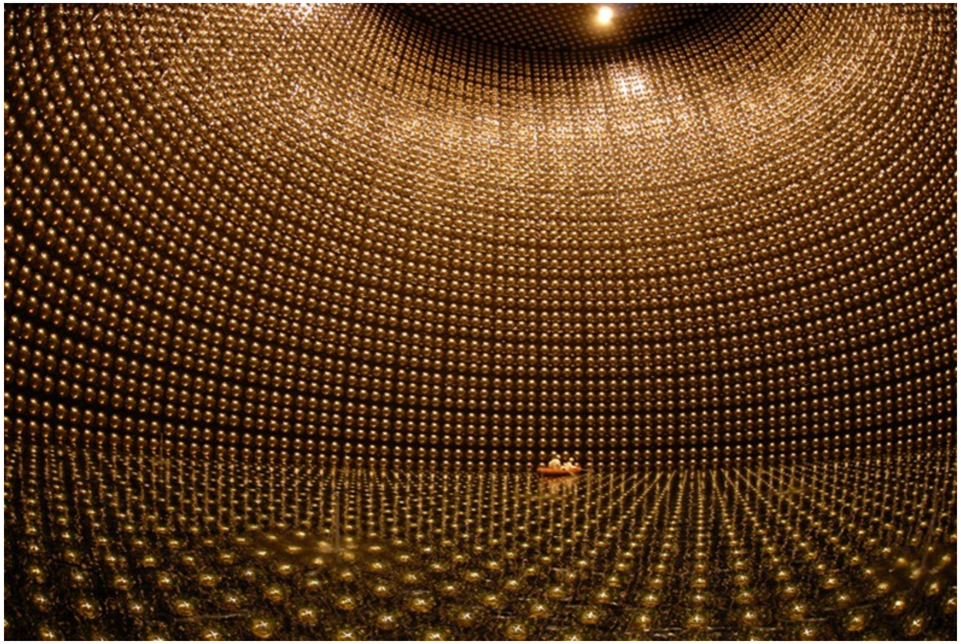
DM Induced Nucleon Decay:

DM as initial state is invisible in nucleon decay experiments.

⇨ The signature can be very similar to a nucleon decay process



SM objects
e.g. mesons

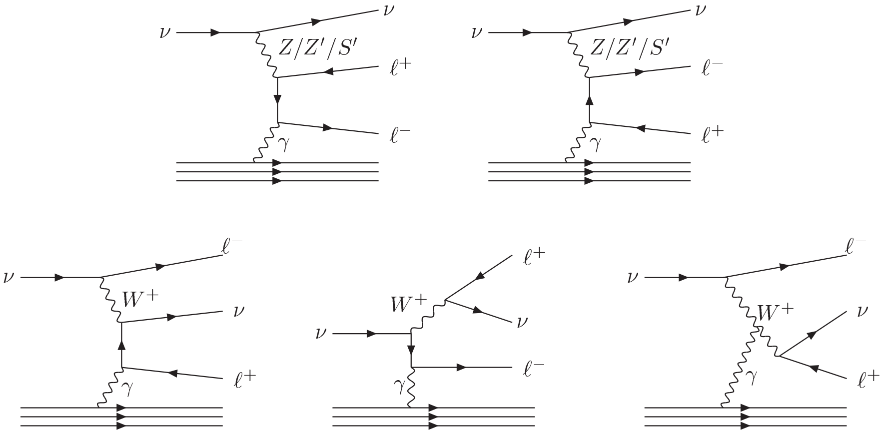


Looking for proton/neutron decay events.
But kinematics is very different!

Similar studies in
Darkogenesis model, J. Shelton, et. al. PRD (2010)
Hylogenesis model, H. Davoudiasl, et. al. PRL (2010)

Large Volume Nucleon Decay Experiments
Super-K ~ 50K ton! DUNE ~ 68K ton!

Neutrino Trident Production



- Produce particles (**Z/Z′/S′**) in *t* channel.

SFG, Manfred Lindner, Werner, Rodejohann PLB 2017 [arXiv:1702.02617]

Neutrino Trident Production

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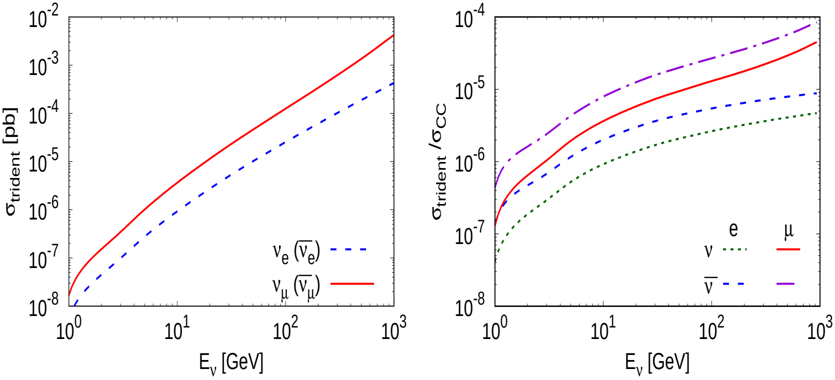
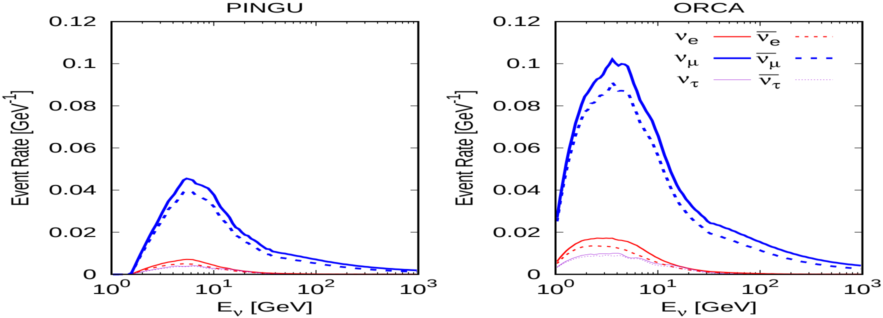


- Typically $\sigma_{\text{trident}} \sim (\mathbf{10^{-6} \sim 10^{-5}})\sigma_{\text{CC}}$.
- To collect a handful of events, at least $\mathbf{10^6}$ CC events.
- **IceCube/PINGU** & **ARCA/ORCA** are perfect candidates.

Atmospheric Trident Production Event

SFG, Manfred Lindner, Werner, Rodejohann PLB 2017 [arXiv:1702.02617]

- $\nu + N \to \mu^+ \mu^- \nu' N^*$
- **Double muon tracks simultaneously produced at the same vertex!**



- **South Pole** (PINGU+DeepCore+IceCube) - **87** events
- **Mediterranean** (ORCA+ARCA) - **39** events

Backgrounds to Trident Production

- **Coincident Double CC muons**
  - Using only **time-window cut**
    - $N_{CC} \sim 10^5$ per year ($T = 3 \times 10^7 s$)
    - Rate of coincidence within time-window Δt

$$C^2_{N_{CC}} (\Delta t / T)^2 \lesssim 1 \quad \Rightarrow \quad \Delta t \approx \frac{\sqrt{2} T}{N_{CC}} \approx 500 s \, .$$

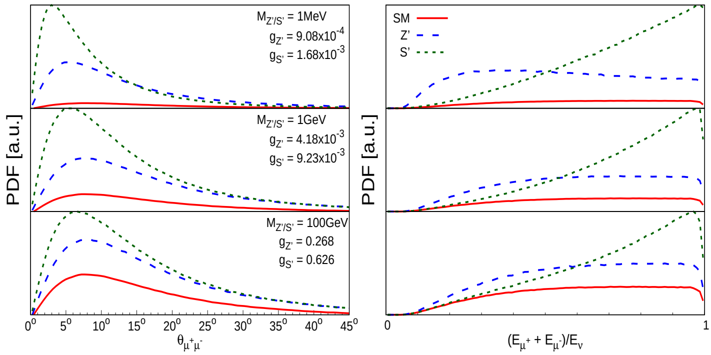
    - Large enough to cut off all coincident background!
  - **Vertex cut**

- **High-p_T pion**
  - $\nu + N \to \ell + \pi^\pm + X \to \ell + \mu^\pm + X'$
  - The muon from pion decay tends to be soft.
  - Momentum transfer with N is highly suppressed in trident production.
  - Much cleaner hadronic shower in trident event.

SFG, Manfred Lindner, Werner, Rodejohann PLB 2017 [arXiv:1702.02617]

Event Reconstruction

SFG, Manfred Lindner, Werner, Rodejohann PLB 2017 [arXiv:1702.02617]

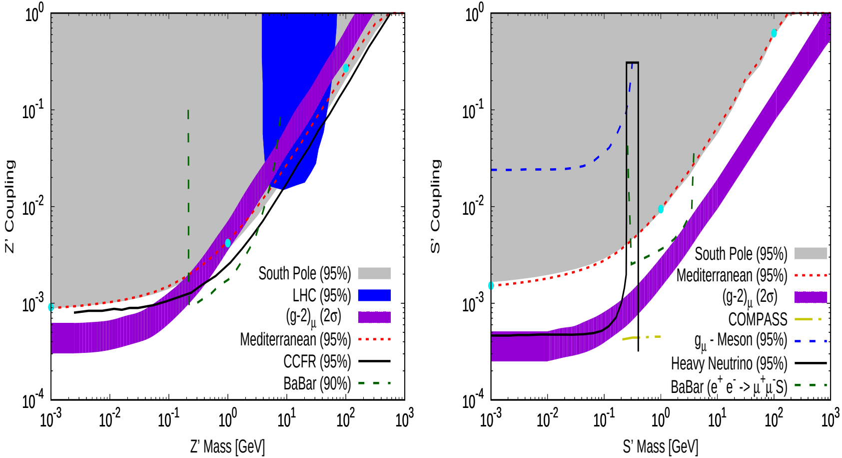


- **ORCA can do better than PINGU** in **angular resolution**.
- **Angular opening is not necessary** for recognizing double muon!
  - **Edepillim** can reconstruct energy from **radiation rate**
  - **Track length** can also tell the muon energy.
  - **Mismatch** between the two estimations for overlapping double muon.

Z'/S' Sensitivities

$$\mathcal{L}_{Z'} \equiv g_{Z'} Q_{\alpha\beta} \left[\overline{L}_\alpha \gamma^\mu L_\beta + \overline{\ell}_{R\alpha} \gamma^\mu \ell_{R\beta} \right] \mathbf{Z'_\mu} + h.c.$$

$$\mathcal{L}_{S'} \equiv g_{S'} Q_{\alpha\beta} \left[\overline{\ell_{R\alpha}} \ell_{L\beta} + \overline{\nu^c_{L\alpha}} \nu_{L\beta} \right] \mathbf{S'} + h.c.$$



SFG, Manfred Lindner, Werner, Rodejohann PLB 2017 [arXiv:1702.02617]

Probing New Physics @ Neutrino Collider

- Trident event can produce **new particles** as **intermediate state**.
- This provides an opportunity to *directly* probe **new physics beyond the SM**.
- It essentially turns **neutrino oscillation experiment** to **neutrino collider**.
- **Neutrino oscillation experiments** reconstruct the intial state:
  - **Momentum**
  - **Flavor**
- **Neutrino collider** reconstructs NP with final-state particles.

Superlight Fuzzy DM

- The fuzzy DM can be naturally light

$$m_\phi \sim 10^{-22}\,\mathrm{eV}$$

- de Broglie wavelength $\lambda \sim$ galaxy size
- The local number of DM particles per de Broglie cubic λ^3

$$N_\phi \equiv \frac{\rho_{\rm DM}}{m_\phi^4 v^3} \sim \mathcal{O}(1) \left(\frac{m_\phi}{10\,\mathrm{eV}} \right)^{-4}$$

is large for $m_\phi \ll 1\,\mathrm{eV}$

- ϕ can be approximated as a non-relativistic plane wave solution

$$\phi(x) \simeq \frac{\sqrt{2\rho_{\rm DM}(x)}}{m_\phi} \cos\left[m_\phi(t - \vec{v} \cdot \vec{x})\right]$$

Fuzzy DM & Neutrinos

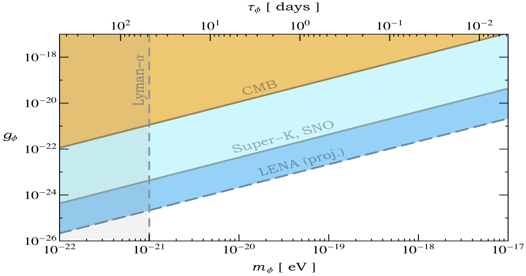
- Light scalar couples to a pair of SM ν

$$-\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} m_i \bar{\nu}_i \nu_i + g_\phi \phi \bar{\nu}_1 \nu_2 + \cdots$$

- Off-diagonal term in neutrino mass matrix

$$M_\nu = \begin{pmatrix} m_1 & g_\phi \langle \phi \rangle \\ g_\phi \langle \phi \rangle & m_2 \end{pmatrix}$$

- Extra mixing: $\sin\theta_{12}(t) \simeq \sin\theta_{12} + \frac{\cos\theta_{12}}{\Delta m_{12}} \frac{g_\phi \sqrt{2\rho_{\rm DM}}}{m_\phi} \cos(m_\phi t)$ [Solar]



Berlin [arXiv:1608.01307]

Summary

- Reactor prompt-γ with Compton-like and Inverse Compton-like processes
- Fixed-target experiment with coherent scattering
- Boosted DM at neutrino detectors & induced proton decay
- Neutrino trident produce @ Neutrino Collider
- Fuzzy DM with modified neutrino oscillation

Thank You!