Future Directions in Dark Sector Searches

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Washington University in St. Louis

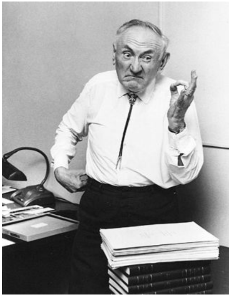
[from my own (somewhat biased) point of view]

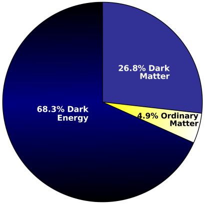
Path to Dark Sector Discoveries at Neutrino Experiments

Colorado State University, Fort Collins

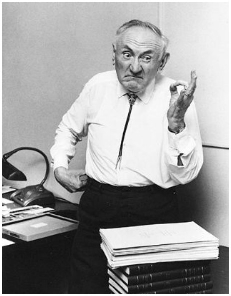
06/06/2023

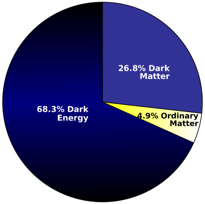
Dark Matter: a 90 years old puzzle

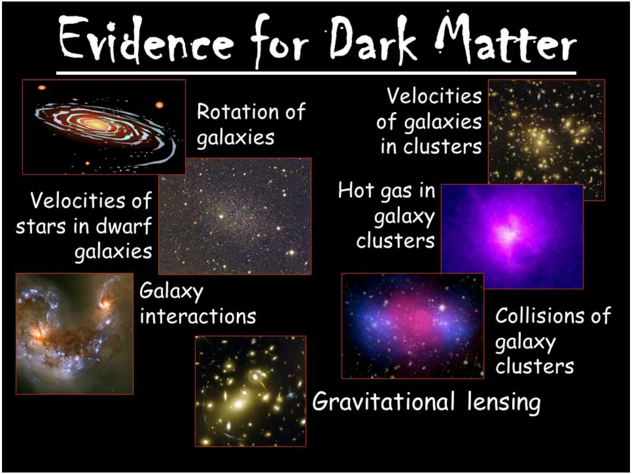




Dark Matter: a 90 years old puzzle



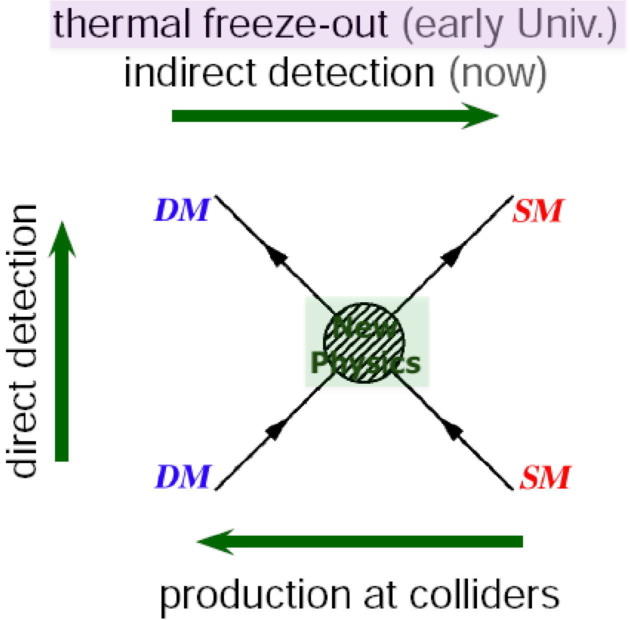




But no evidence of non-gravitational interactions of DM.

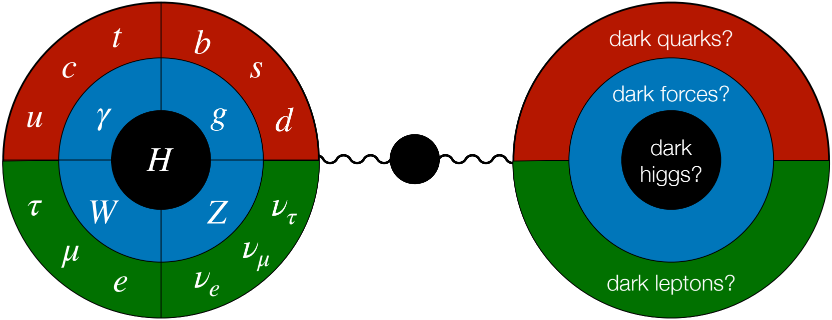
Many models, but which is the right one?

[G. Bertone and T. Tait, *Nature* **562**, 51 (2018)]

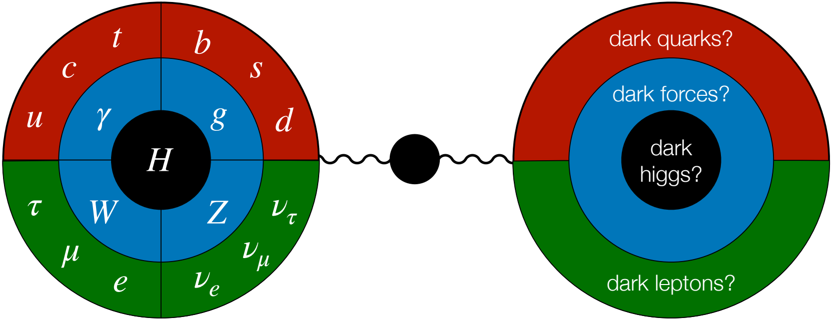

thermal freeze-out (early Univ.)
indirect detection (now)
direct detection
DM
DM
SM
SM
New Physics
production at colliders

But what if the dark matter experiences new forces?

(*Symmetry* Magazine)



[Snowmass reports: 2207.06898, 2207.06905, 2209.04671]



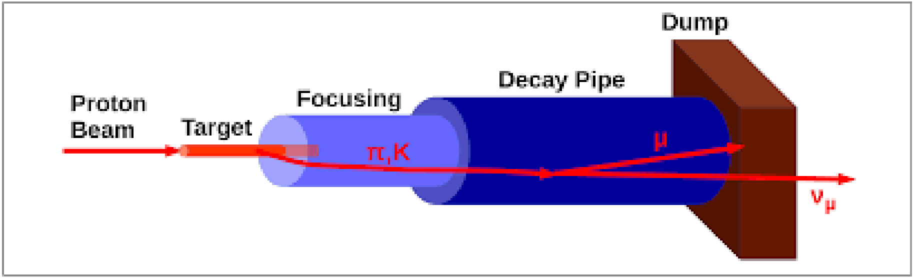
[Snowmass reports: 2207.06898, 2207.06905, 2209.04671]

Examples:

Vector portal	$\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu}$	[Bilmis *et al.* (PRD '15); Berryman *et al.* (JHEP '20)]
Higgs portal	$(\mu S + \lambda S^2) H^\dagger H$	[Batell, Berger, Ismail (PRD '19); MicroBooNE (PRL '21)]
Neutrino portal	$y \bar{L} H N$	[Kelly, Machado (PRD '21); MicroBooNE (PRD '22)]
Axion portal	$\frac{1}{f_a} a F^{\mu\nu} \tilde{F}_{\mu\nu}$	[Kelly, Kumar, Liu (PRD '21); ArgoNeuT (PRL '23)]

[see also talks by Batell, Tabrizi, Kelly, Kalra]

Why in neutrino experiments?



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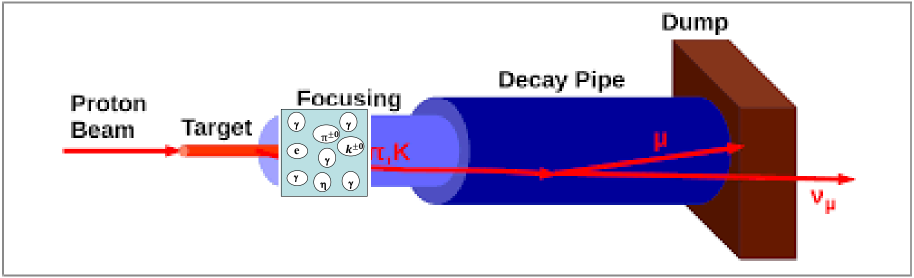
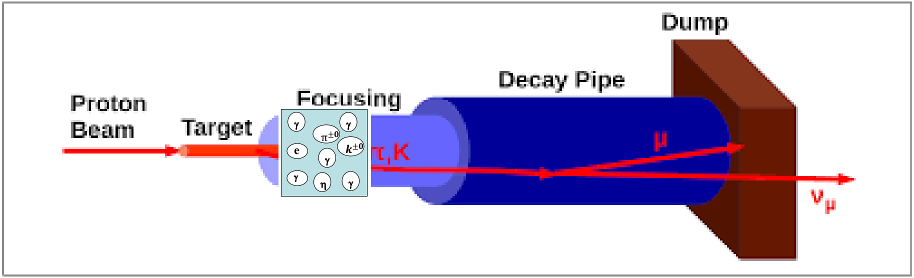
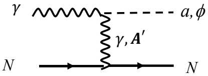




Various Production Modes:



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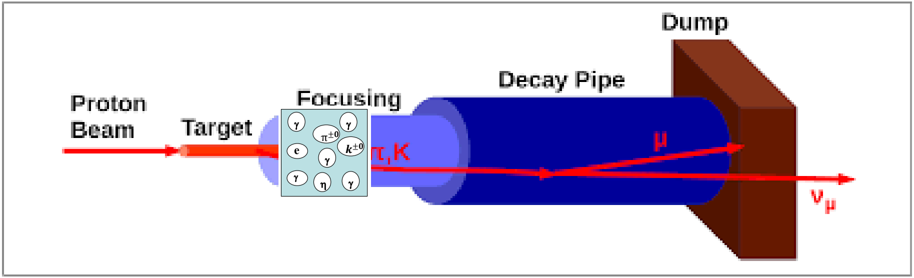

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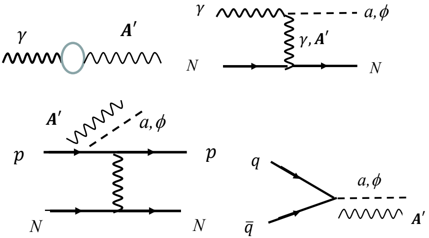
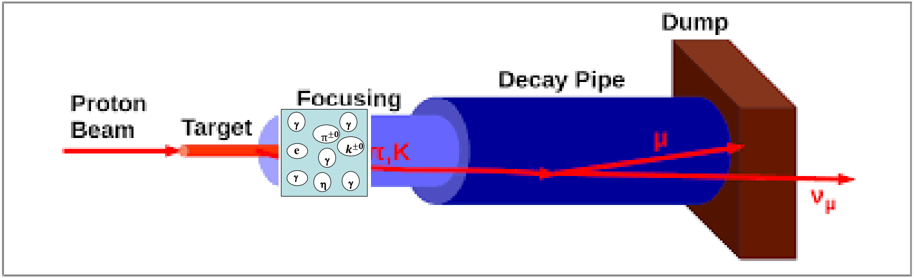


Why in neutrino experiments?



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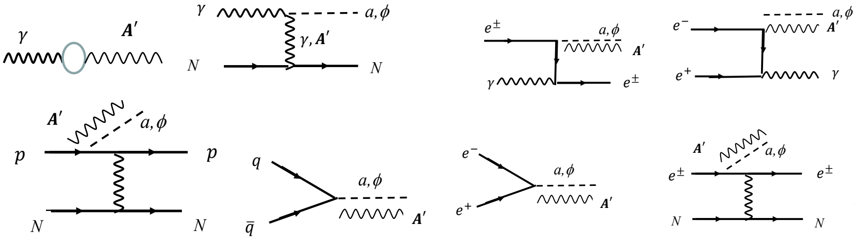
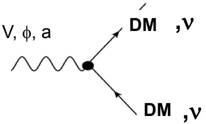
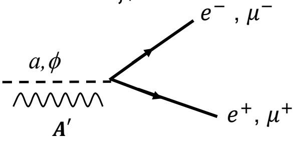


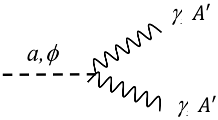
Detection methods

Short-lived mediators:

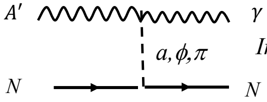


Longer-lived mediators: *Decays*

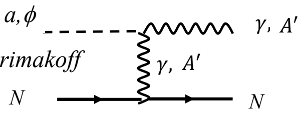


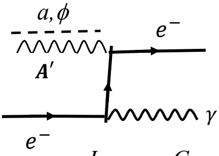


Scattering

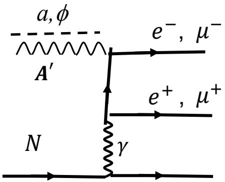


Inverse -Primakoff





Inverse -Compton



Bethe-Heitler pair production

[slide from Bhaskar Dutta]

Example 1:
Axion-like Particles (ALPs)

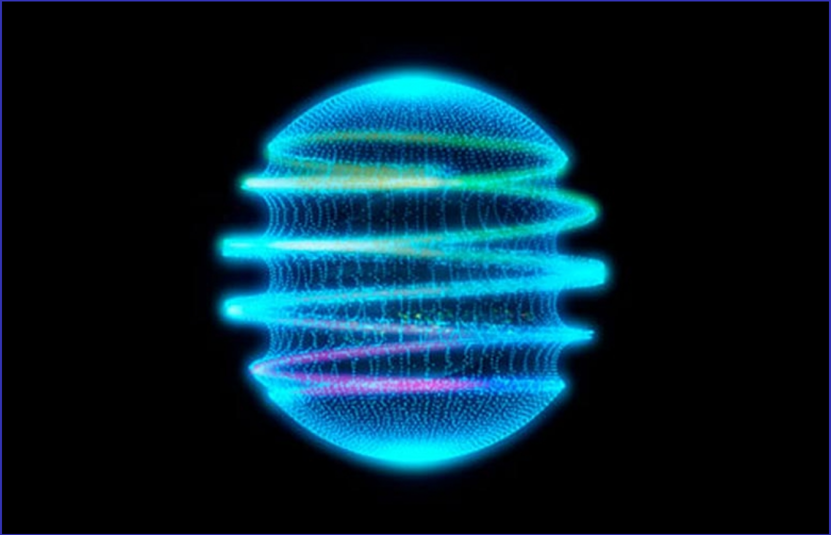
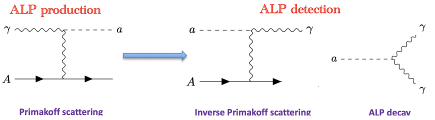
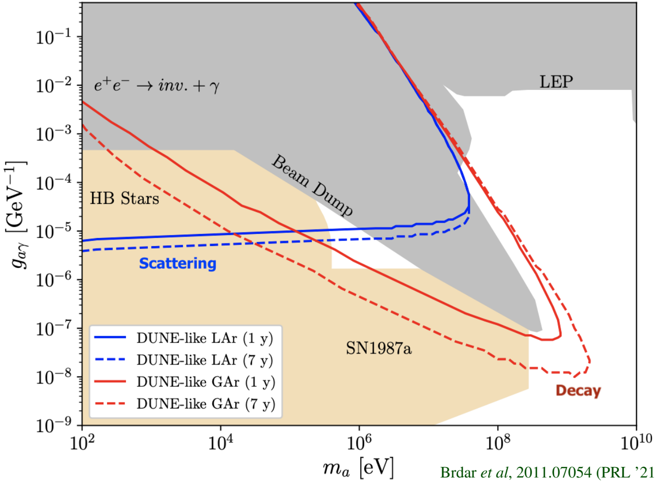


figure from CERN EP Newsletter

ALP at DUNE

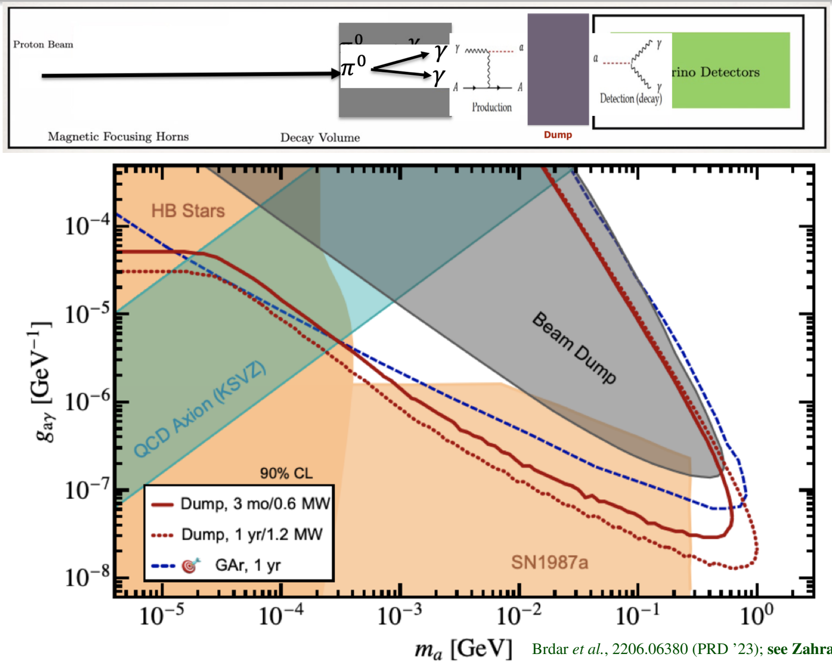
$$\mathcal{L}_{a\gamma\gamma} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$





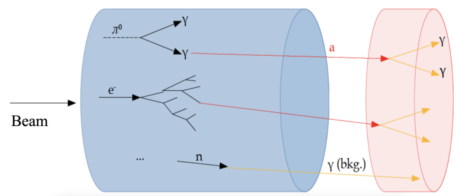
Brdar *et al*, 2011.07054 (PRL '21); **see Zahra's talk**

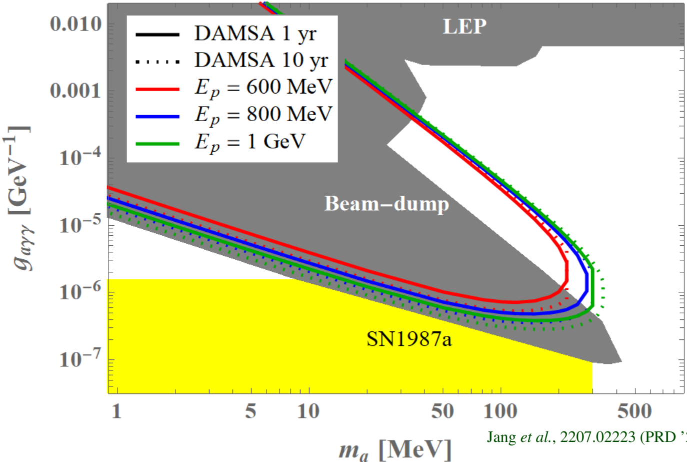
ALP at Targetless DUNE



Brdar *et al.*, 2206.06380 (PRD '23); **see Zahra's talk**

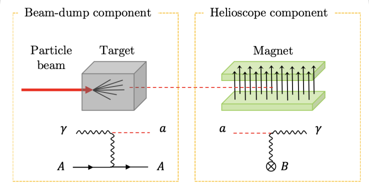
ALP at DAMSA



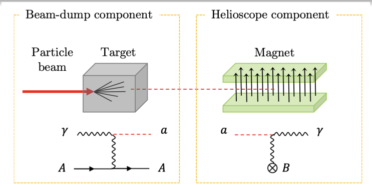


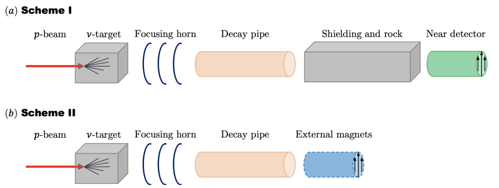
Jang *et al.*, 2207.02223 (PRD '23); **see Jae's talk**

ALP at PASSAT

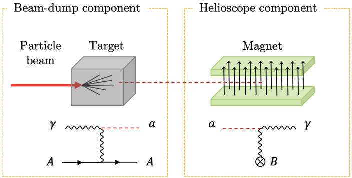


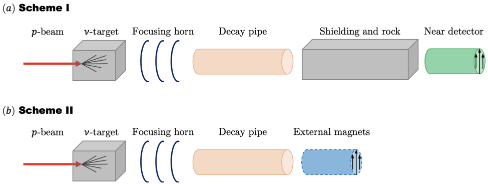
ALP at PASSAT

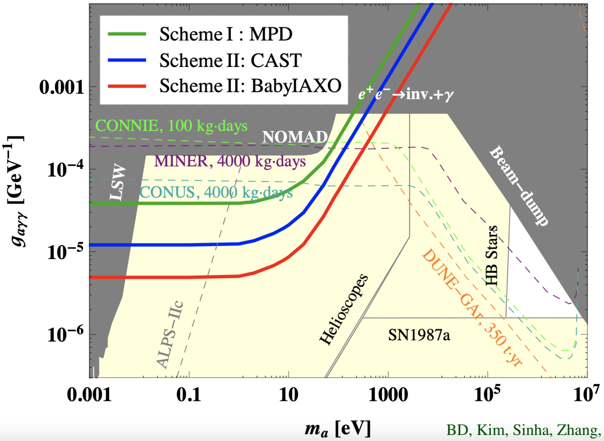




ALP at PASSAT

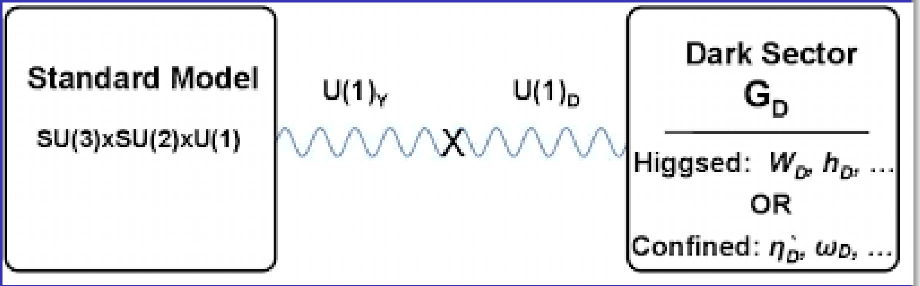




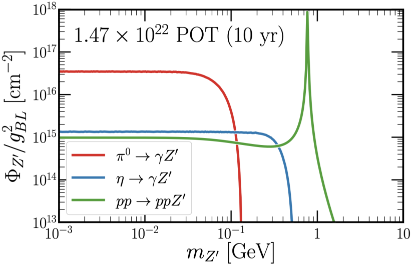


BD, Kim, Sinha, Zhang, 2101.08781 (PRD ’21)

Example 2: Light Vector Bosons (Z')

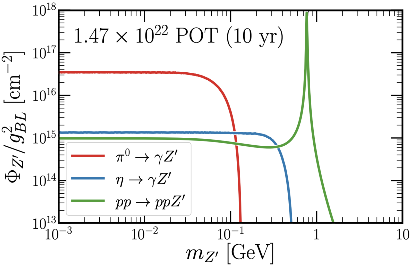


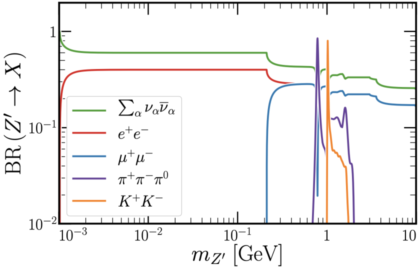
$U(1)_{B-L}$ at DUNE



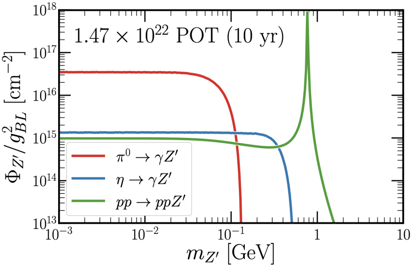
1.47×10^{22} POT (10 yr)
$\pi^0 \to \gamma Z'$
$\eta \to \gamma Z'$
$pp \to ppZ'$
$\Phi_{Z'}/g_{BL}^2$ [cm^{-2}]
$m_{Z'}$ [GeV]
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{-3}
10^{-2}
10^{-1}
1
10

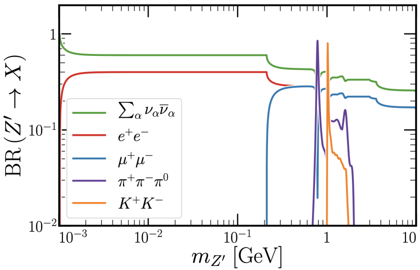
$U(1)_{B-L}$ at DUNE

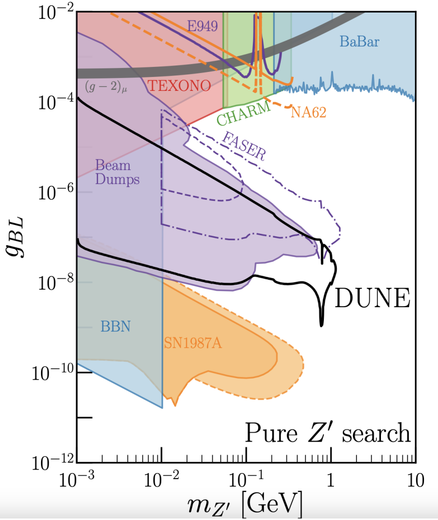

1.47 × 10^22 POT (10 yr)
$\Phi_{Z'}/g_{BL}^2$ [cm^{-2}]
$\pi^0 \to \gamma Z'$
$\eta \to \gamma Z'$
$pp \to ppZ'$
$m_{Z'}$ [GeV]


BR $(Z' \to X)$
$\sum_\alpha \nu_\alpha \bar{\nu}_\alpha$
e^+e^-
$\mu^+\mu^-$
$\pi^+\pi^-\pi^0$
K^+K^-
$m_{Z'}$ [GeV]

$U(1)_{B-L}$ at DUNE

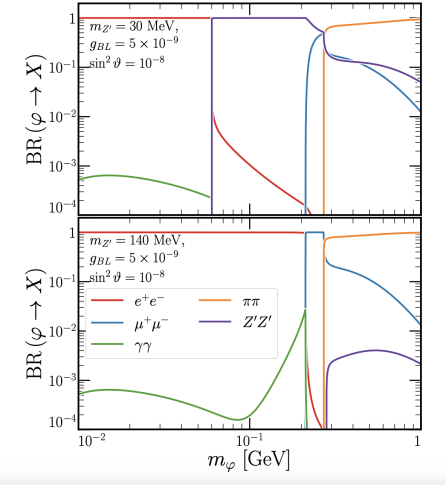




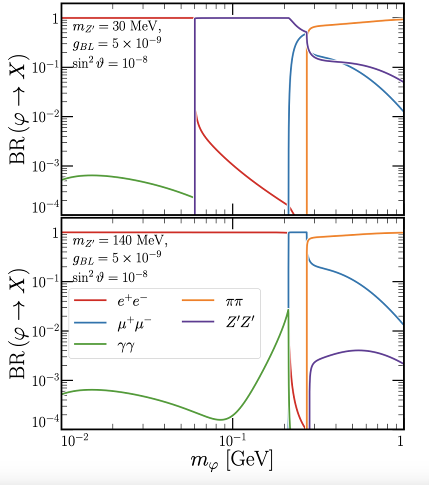


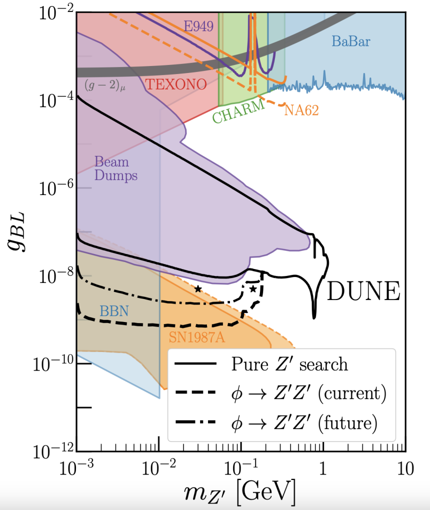
BD, Dutta, Kelly, Mohapatra, Zhang, 2104.07681 (JHEP '21)

Z' with a Scalar



Z' with a Scalar

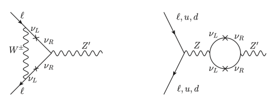




BD, Dutta, Kelly, Mohapatra, Zhang, 2104.07681 (JHEP '21)

Neutrinophilic Z'

$$\mathcal{L} \supset g' Z'_\mu \sum_{i=1}^{n} \nu^\dagger_{R,i} \overline{\sigma}^\mu Q_{R,i} \nu_{R,i}$$



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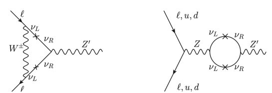
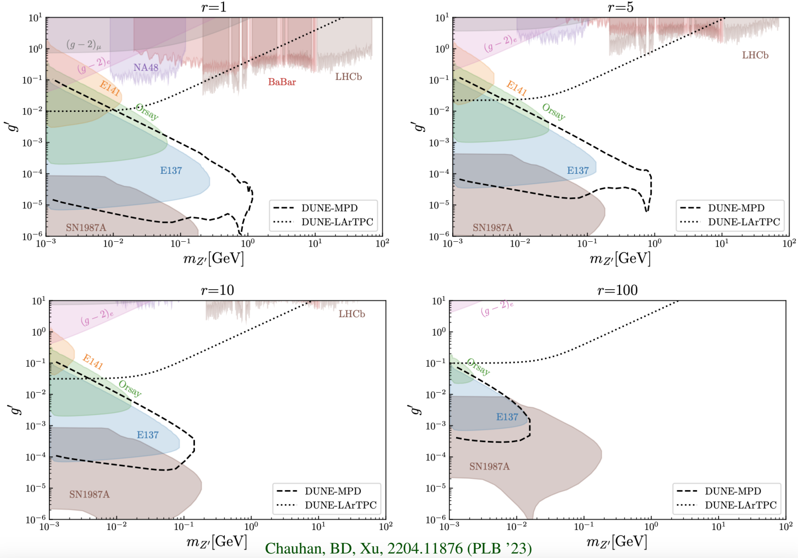
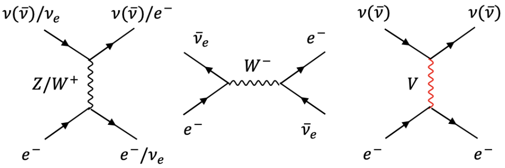




Chauhan, BD, Xu, 2204.11876 (PLB ’23)

New interference effects in $\nu(\bar{\nu}) - e$ scattering

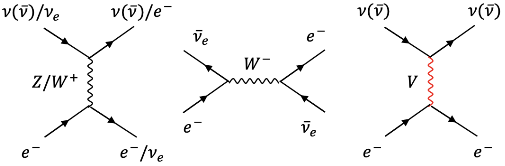


$$\mathcal{L} \supset g_V Q_\ell V_\mu \bar{\ell}\gamma^\mu \ell + g_V Q_{\nu_\ell} V_\mu \bar{\nu}_\ell \gamma^\mu \nu_\ell \,,$$

$$\left(\frac{d\sigma_{\rm int}}{dE_e}\right)_{\nu_\mu} \propto -Q_{\nu_\mu} Q_e (2E_{\nu_\mu} - E_e)\,,$$

$$\left(\frac{d\sigma_{\rm int}}{dE_e}\right)_{\bar{\nu}_\mu} \propto Q_{\nu_\mu} Q_e (2E_{\nu_\mu} - E_e)\,,$$

New interference effects in $\nu(\bar{\nu}) - e$ scattering



$$\mathcal{L} \supset g_V Q_\ell V_\mu \bar{\ell}\gamma^\mu \ell + g_V Q_{\nu_\ell} V_\mu \bar{\nu}_\ell \gamma^\mu \nu_\ell \,,$$

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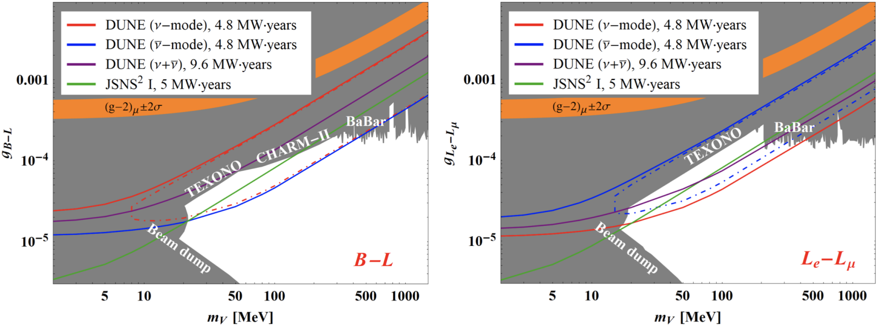
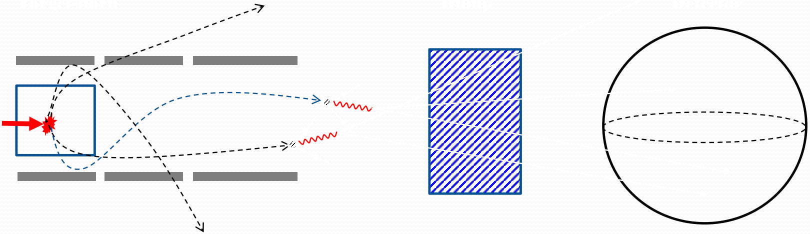


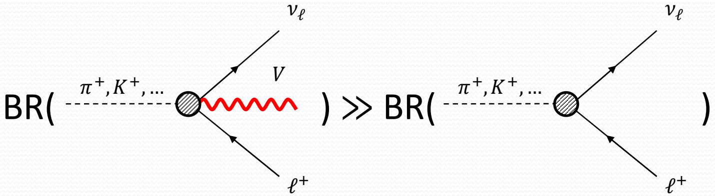
BD, Kim, Sinha, Zhang, 2105.09309 (PRD '21)

Production from Charged Meson Decays

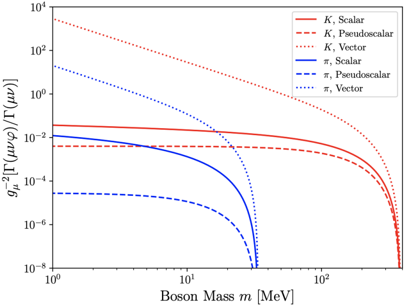


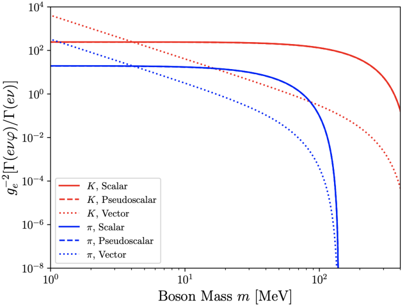
Why this is important?

1. Large BR enhancement for 3-body decays.



(assuming an $\mathcal{O}(1)$ dark-sector coupling for purposes of comparison)

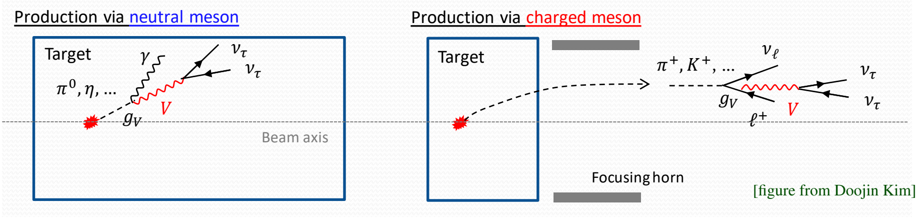




Dutta *et al.*, 2110.11944 (PRL '22)

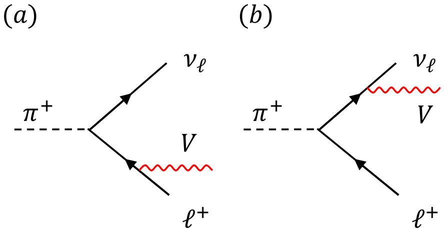
Why this is important?

2. Focusing of charged mesons.



[figure from Doojin Kim]

3. Dominant production channel for leptophilic dark-sector particles.



Case Study: Anomalous Tau Appearance at Near Detector

Why tau neutrinos?

- L is too small for a beam of ν_μ to oscillate into ν_τ at ND.
- Production rate of D mesons is too small to detect enough ν_τ events at DUNE energies.
- Therefore, appearance of tau events at ND are anomalous and a 'smoking gun' signature of new physics (modulo bkg issues).
- A popular mechanism: sterile neutrinos. [Alex Sousa's group]
- An alternative mechanism based on charged-meson-decays. [BD, Dutta, Han, Kim, 2304.02031]

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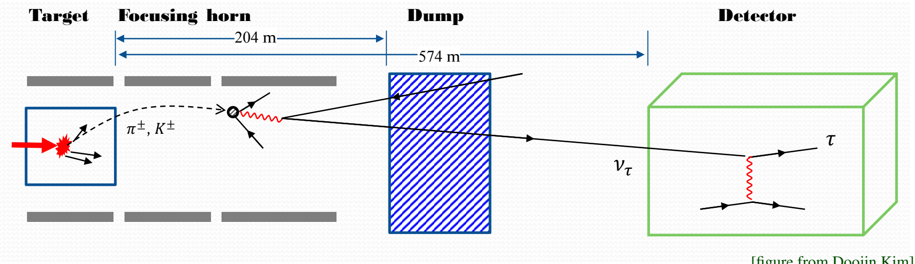
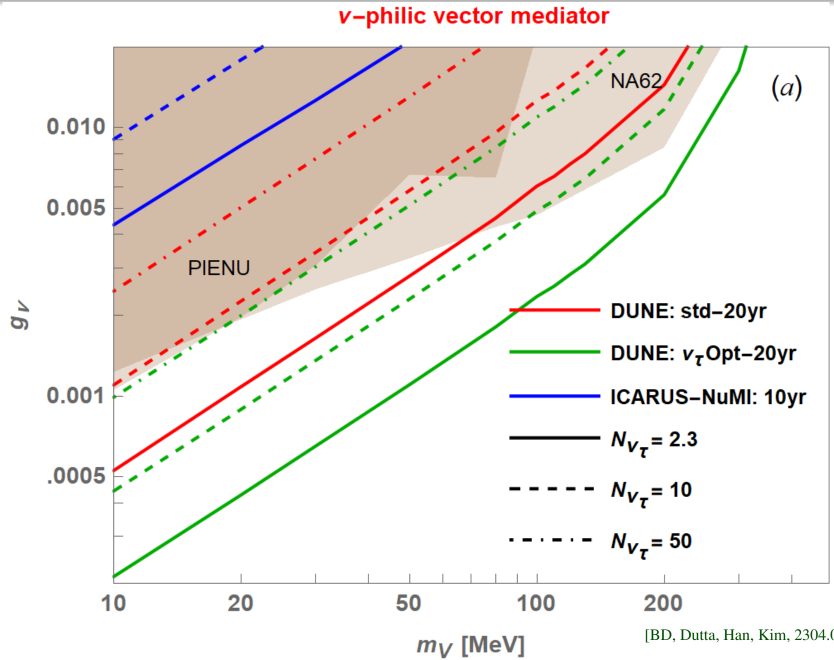


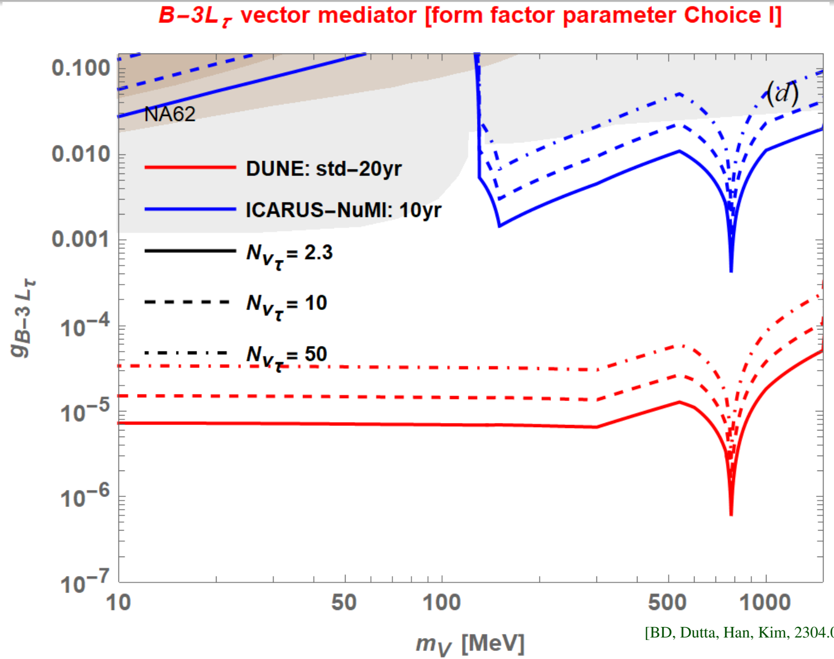
[figure from Doojin Kim]

Neutrinophilic Case



[BD, Dutta, Han, Kim, 2304.02031]

$B - 3L_\tau$ Case



[BD, Dutta, Han, Kim, 2304.02031]

Other Dark Matter Signals at Neutrino Detectors

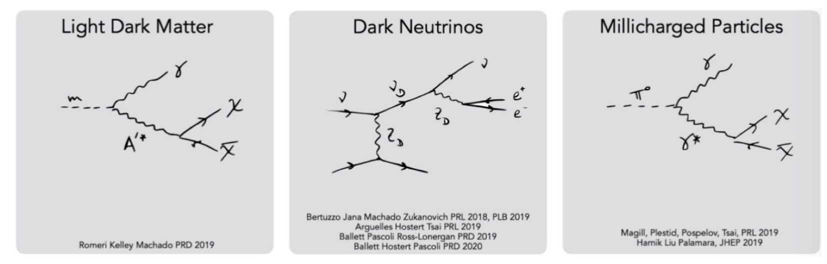
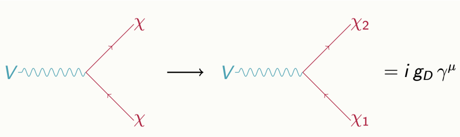
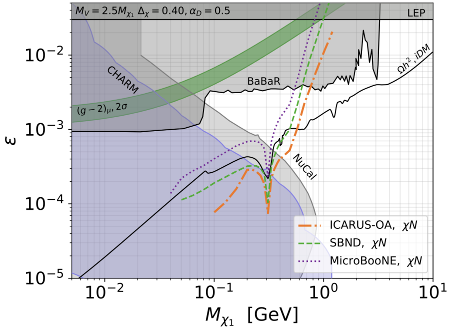
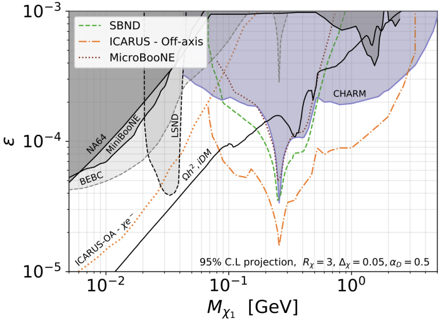


figure from Pedro Machado



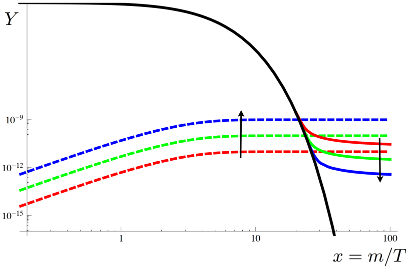


large splitting



small splitting

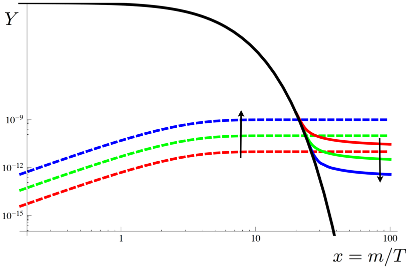
[Batell, Berger, Darmé, Frugiuele, 2106.04584 (PRD '21)]



[Hall, Jedamzik, March-Russell, West (JHEP '10)]

- Feeble couplings make it hard to probe directly.
- Use portal couplings.

Freeze-in Dark Matter via HNL Portal



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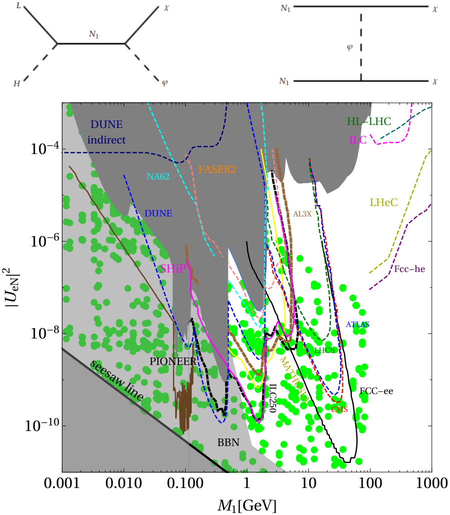
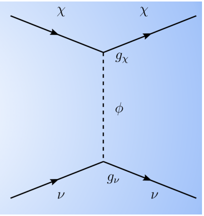
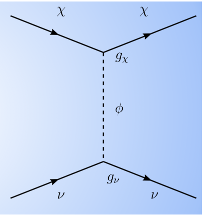


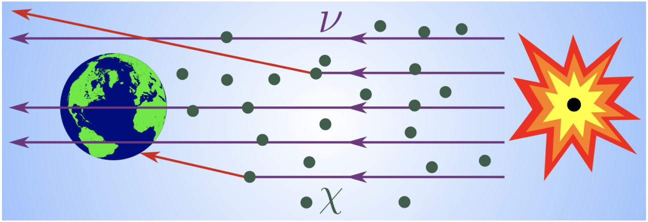
[Barman, BD, Ghoshal, 2210.07739]

Dark Matter-Neutrino Interactions

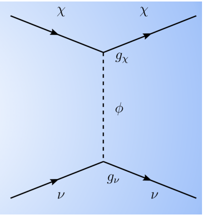


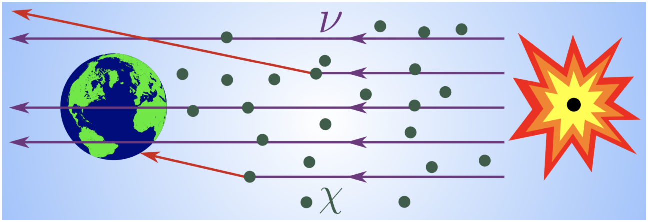
Dark Matter-Neutrino Interactions

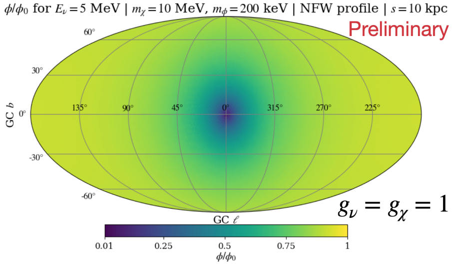




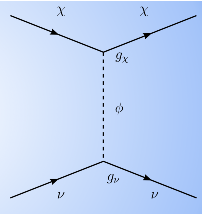
Dark Matter-Neutrino Interactions

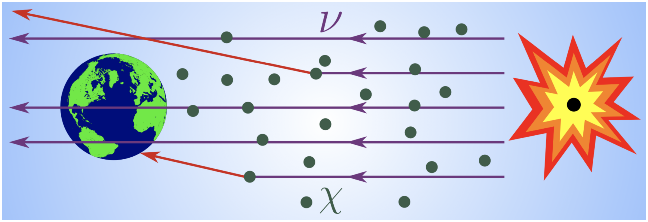


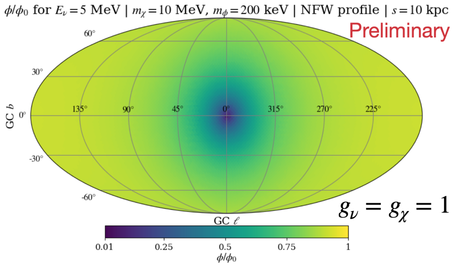


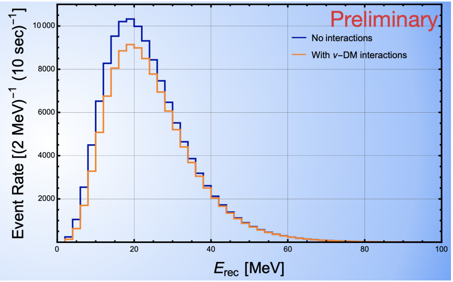


Dark Matter-Neutrino Interactions









[BD, Kim, Sathyan, Sinha, Zhang (in preparation)]

- Neutrinos down-scatter to lower energies.
- If the energy threshold for supernova neutrinos could be lowered ...

Conclusion

- Neutrino experiments can be versatile.
- Beam-based neutrino experiments are sensitive to a diverse set of dark sector models.
- Can provide competitive/best limits (or discover dark sector physics).
- The future of dark (sector physics) is bright.