Searches for Exotic Particles in Next-Generation Neutrino Experiments: Inelastic/Elastic BDM, Low-Mass DM, and ALP

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Snowmass2021 NF03 Kick-off Meeting

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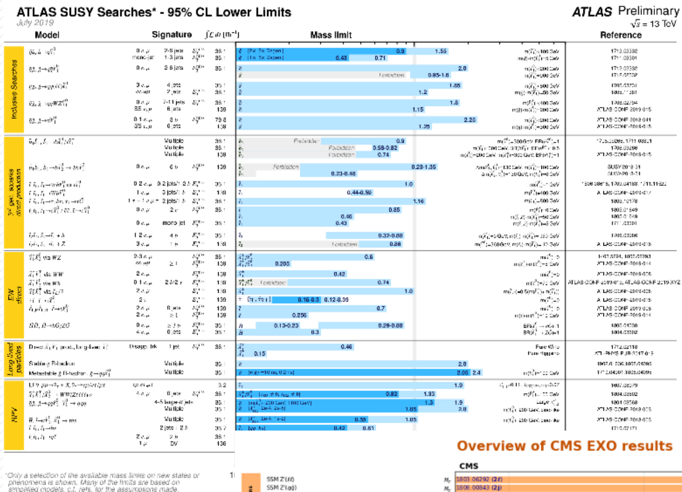
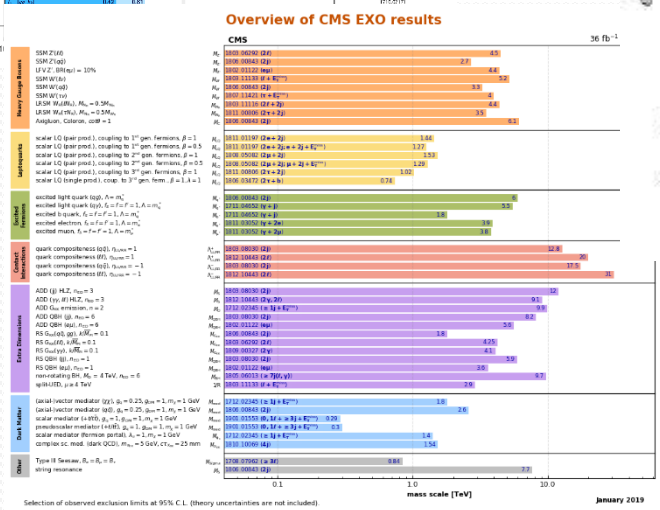
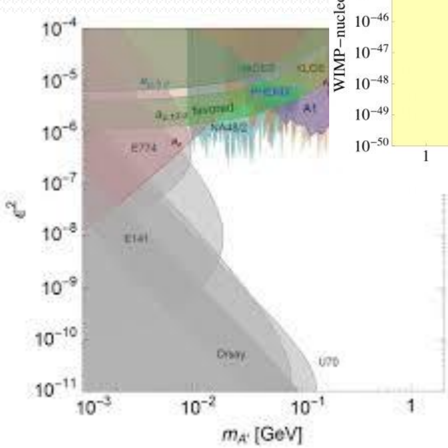
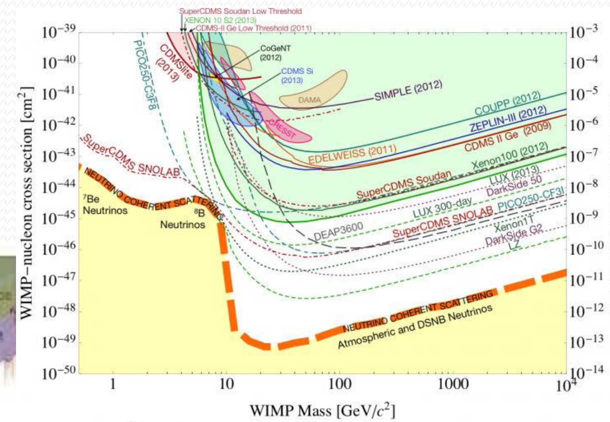
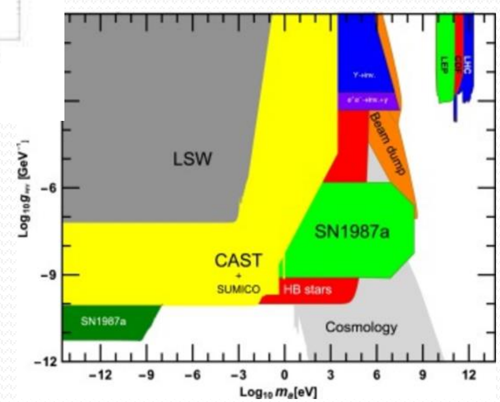
Hunt for New Physics: Current Status





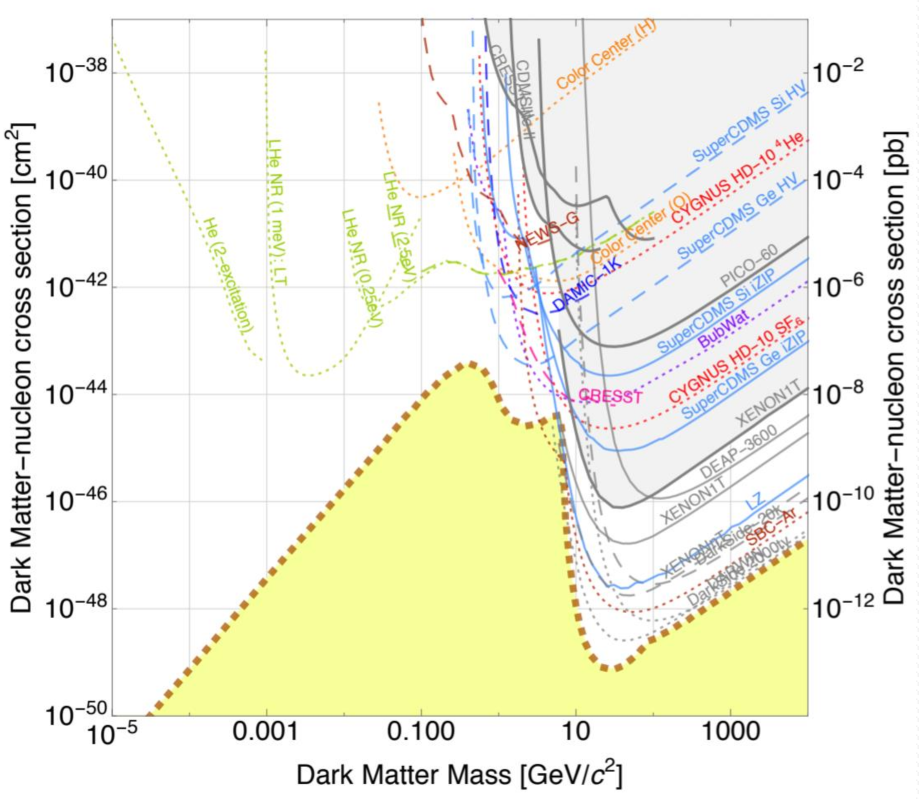






Current Status of Dark Matter Searches

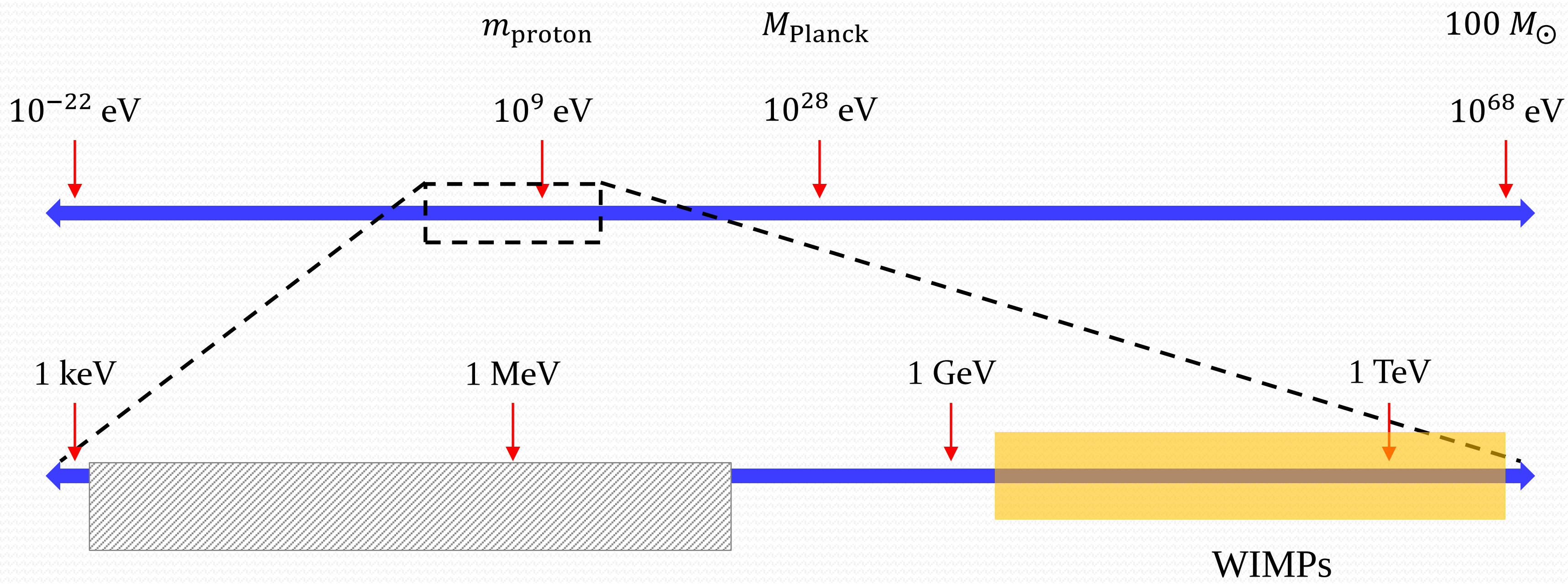
- No observation of DM signatures via non-gravitational interactions while many searches/interpretations designed/performed under nonrelativistic WIMP/WIMP-like scenarios
  - ⇒ Excluding more parameter space in dark matter models



[US Cosmic Visions, Battaglieri et al (2017)]

Ideas of beyond-the-WIMP are timely and well motivated!

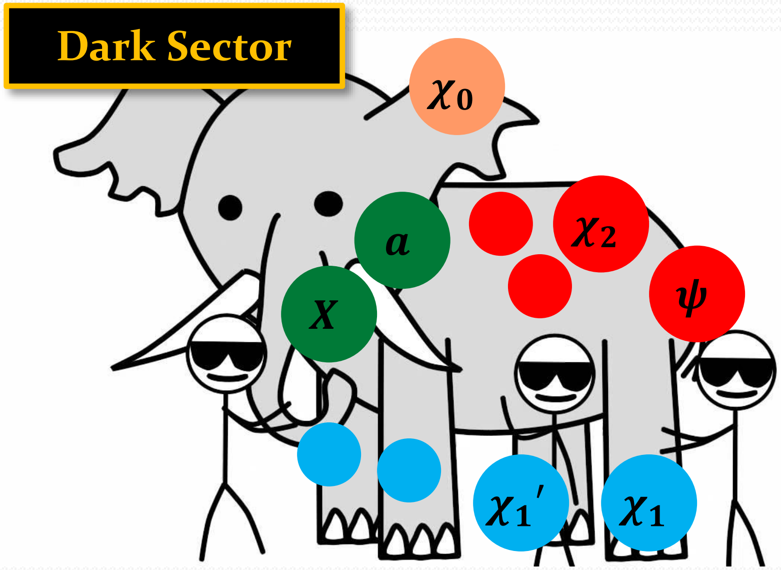
The Dark Matter Landscape



- ✓ Less constrained by current searches
- ✓ Probing dark sectors: **(Light) dark matter + (light) new mediators** (e.g., ALP, dark photon)

Non-Conventional Dark Sector Scenarios

- SM sector contains several stable particles, many unstable particles, and force mediators.

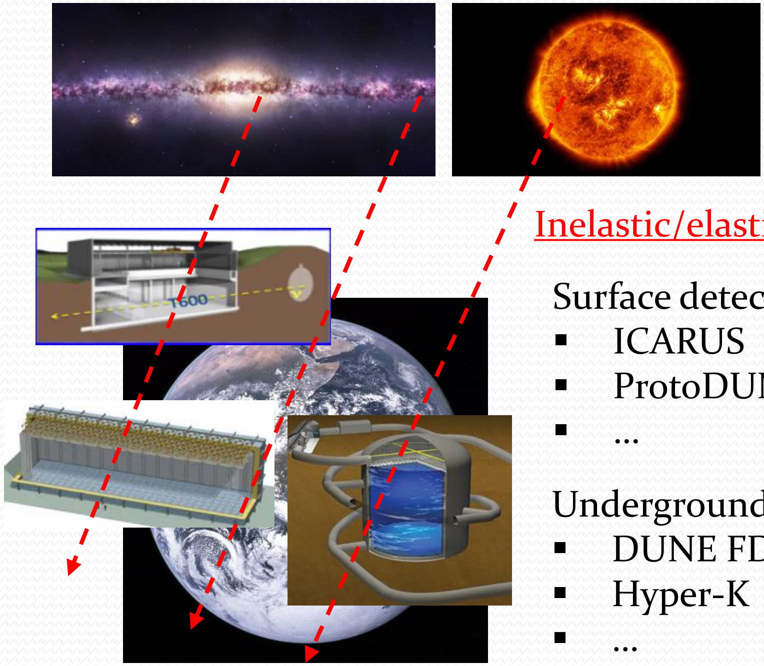


- χ_0: **dominant relic** (as in the minimal setup)
- More members in the dark sector
  - ✓ **More dark matter species**, say χ_1, …
  - ✓ **Unstable members**, say χ_2, ψ, …
  - ✓ **Mediators** of mediating interactions between SM particles and dark-sector particles, say dark photon (X), ALP (a), …
- E.g., models of inelastic boosted dark matter (iBDM) ∋ heavier (dominant) relic dark matter + lighter (boosted) dark matter + dark photon [**DK**, Park, Shin, PRL 119 (2017) 16, 161801]

Searches for Exotic Particles at Next-Generation ν Exp.

- Such exotic particles are usually (very) weakly interacting with SM particles and/or often coming from astrophysical sources. ⇒ High-intensity facilities and/or large-volume detectors are better motivated.
  ⇒ Next-generation ν experiments (either ongoing or near-future) are good places to perform searches!

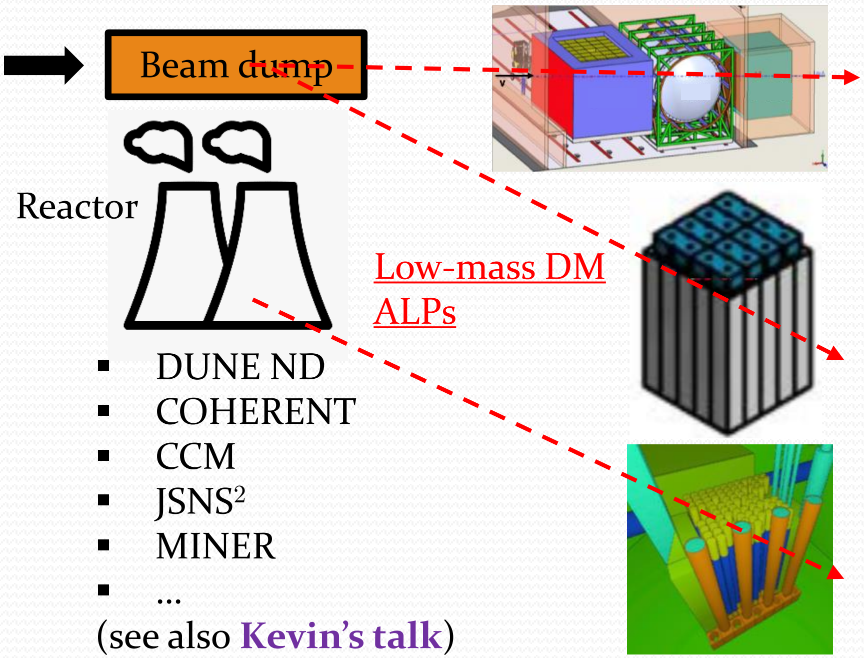
Part I: Cosmogenic signal



Surface detector
- ICARUS
- ProtoDUNE
- …

Underground detector
- DUNE FD
- Hyper-K
- …

Part II: Lab-produced signal



- DUNE ND
- COHERENT
- CCM
- JSNS^2
- MINER
- …

(see also **Kevin's talk**)

Part I: Cosmogenic Signal

Snowmass2021 - Letter of Interest

[Link to this LOI]

Physics Opportunities with Inelastic Boosted Dark Matter in the Next-Generation Large-Mass Neutrino and Dark Matter Experiments

NF Topical Groups:

■ (NF3) Beyond the Standard Model

Authors: Haider Alhazmi, Joshua Berger, Hector Carranza, Animesh Chatterjee, Albert De Roeck, Gian Giudice, Chang Hyon Ha, Lucien Heurtier, Wooyoung Jang, Doojin Kim, Kyoungchul Kong, Hyun Su Lee, Pedro A. N. Machado, Zahra Gh. Moghaddam, Gopolang Mohlabeng, Jong-Chul Park, Seodong Shin, Leigh H. Whitehead, and Jaehoon Yu

Snowmass2021 - Letter of Interest

[Link to this LOI]

Searches for Boosted Dark Matter at Surface Experiments

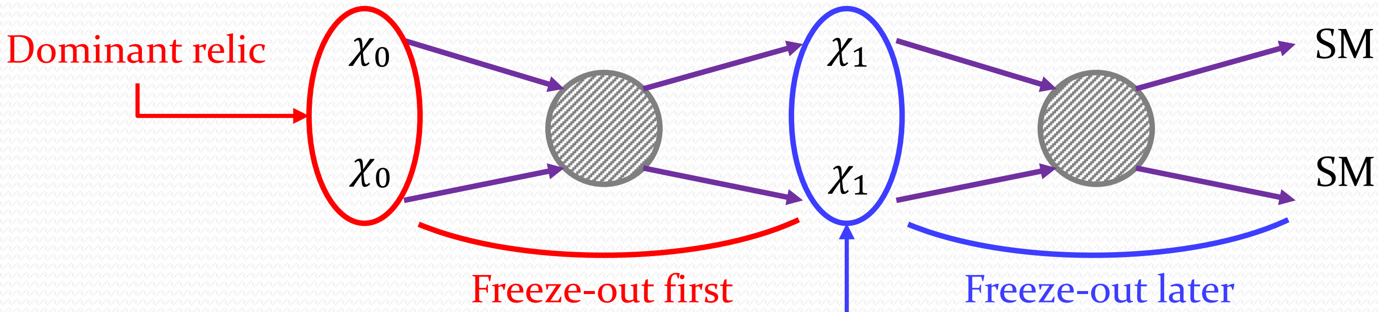
NF Topical Groups:

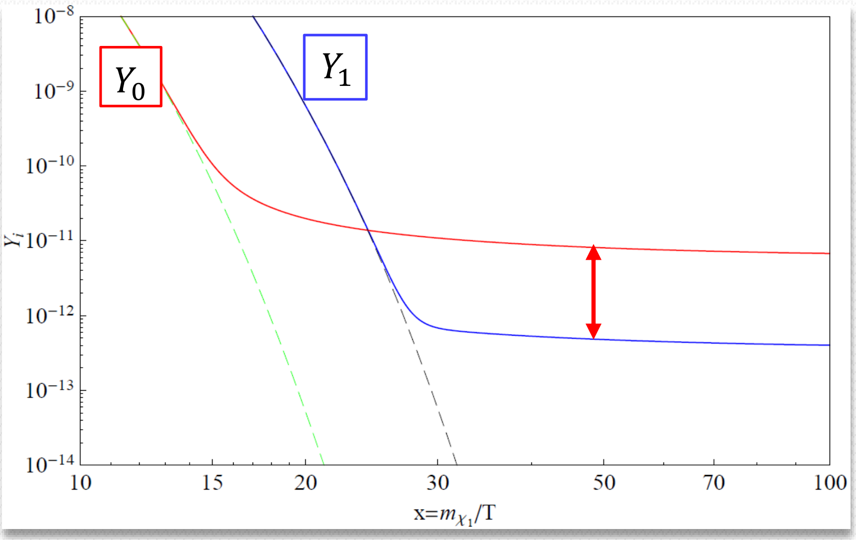
■ (NF3) Beyond the Standard Model

Authors: Hector Carranza (University of Texas at Arlinton), Albert De Roeck (CERN), Wooyoung Jang (University of Texas at Arlinton), Doojin Kim (Texas A&M University), Kyoungchul Kong (University of Kansas), Jong-Chul Park (Chungnam National University), Seodong Shin (Jeonbuk National University), and Jaehoon Yu (University of Texas at Arlinton)

Two-component Boosted DM Scenario

- A possible relativistic source: BDM scenario (cosmogenic), stability of the two DM species ensured by separate symmetries, e.g., $Z_2 \otimes Z_2'$, $U(1) \otimes U(1)'$, etc.

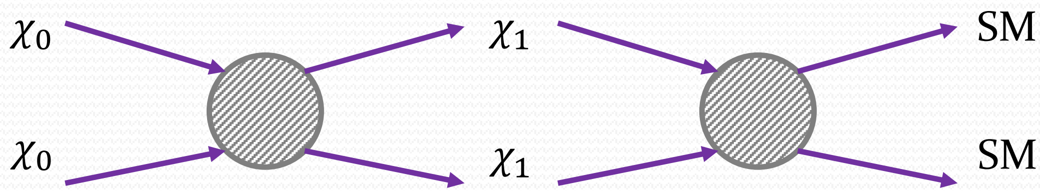




"Assisted" freeze-out mechanism

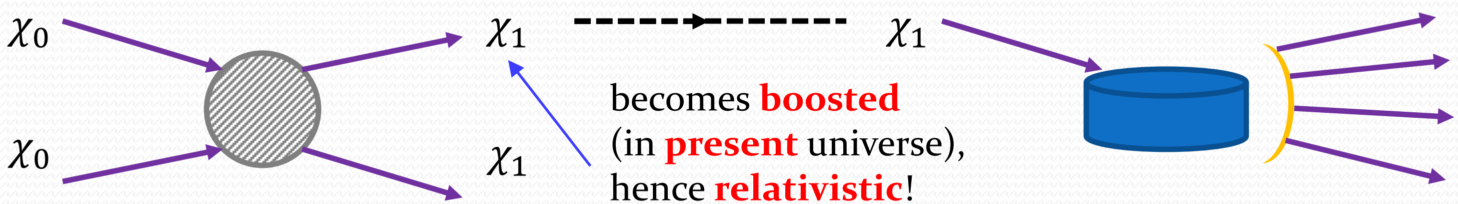
[Belanger, Park (2011)]

Motivation for BDM



✓ Heavier relic χ_0: hard to detect it due to tiny/negligible coupling to SM

✓ Lighter relic χ_1: hard to detect it due to small amount

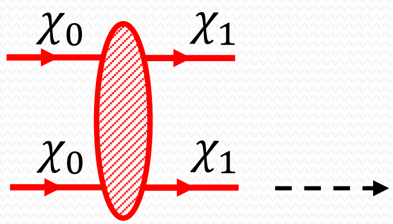


becomes **boosted** (in **present** universe), hence **relativistic**! ($\gamma_1 = m_0/m_1$)

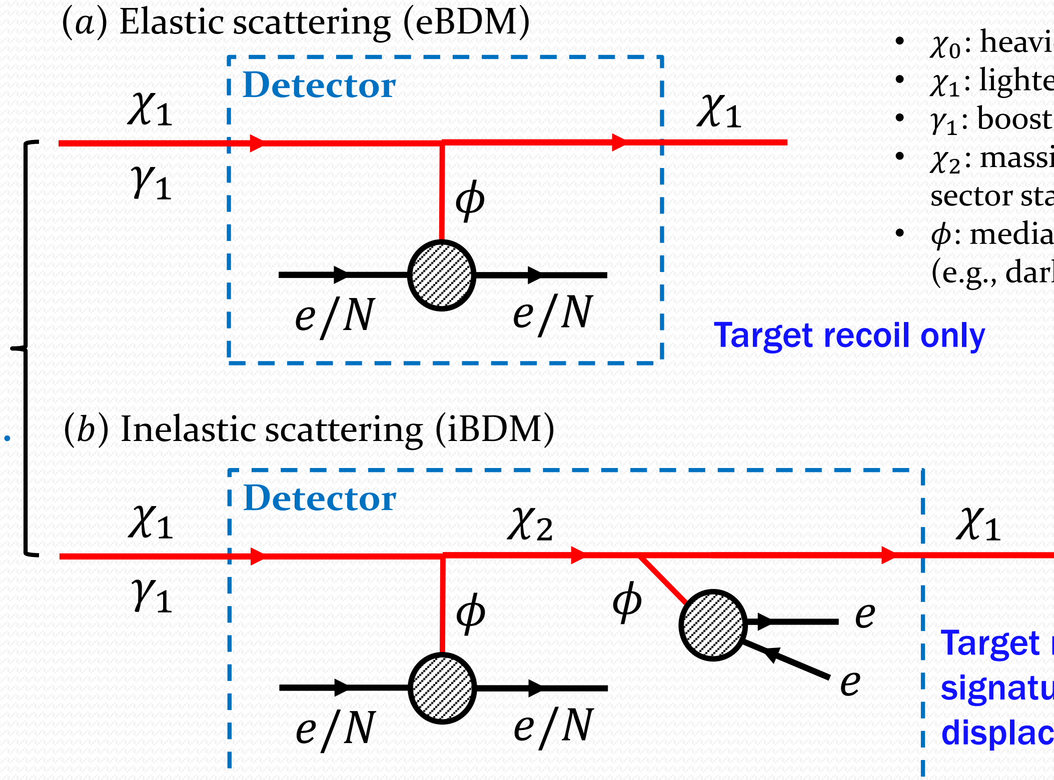
- Galactic Center (GC)
- Sun (see **Yun-Tse's talk**)
- Dwarf galaxies

(Laboratory)

Boosted Dark Matter Signals



GC, Sun, dwarf galaxies ..



- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle (e.g., dark photon)

Target recoil only

Target recoil + secondary signatures (could be displaced)

BDM mechanisms:
- Pair-annihilation
- Decay
- Semi-annihilation
- Induced nucleon decay
- Cosmic-ray-induced
- …

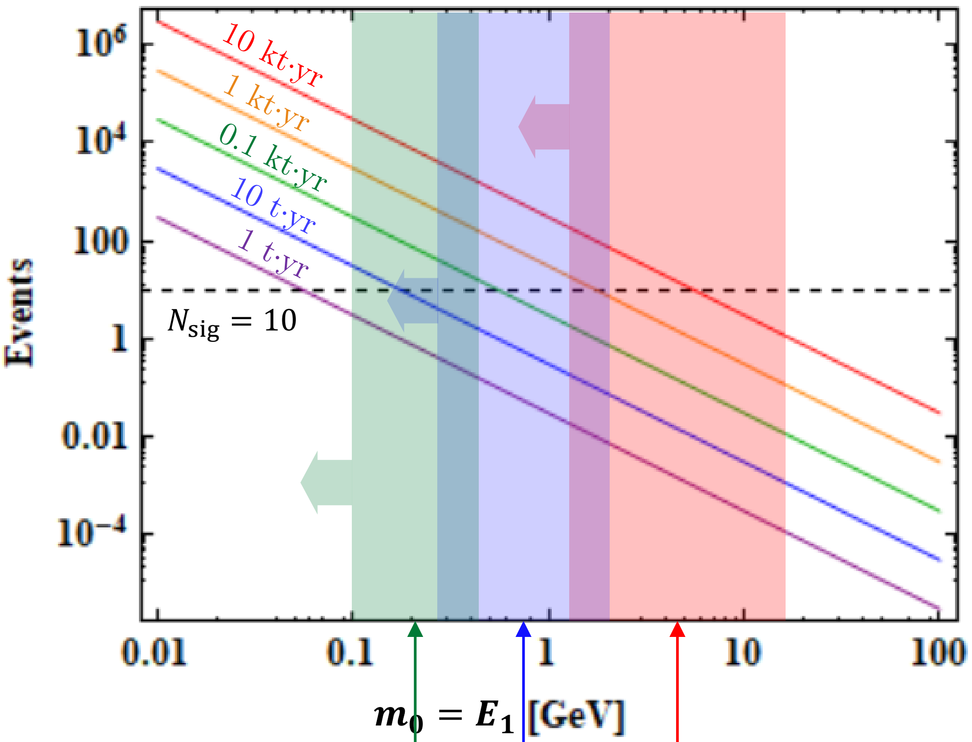
Numerous related studies: Agashe et al, 1405.7370; Belanger et al, 1112.4491; Berger et al, 1410.2246; Kong et al, 1411.6632; Bhattacharya et al, 1407.3280; Kopp et al, 1503.02669; Necib et al, 1610.03486; Alhazmi et al, 1611.09866; Berger et al, 1912.05558; Kim et al, 1612.06867; Kachulis et al, 1711.05278; Cherry et al, 1501.03166; Giudice et al, 1712.07126; McKeen et al, 1812.05102; Ha et al, 1811.09344; Arguelles et al, 1907.08311; Chatterjee et al, 1803.03264; Kim et al, 1804.07302; Aoki et al, 1806.09154; D'Eramo et al, 1003.5912; Huang et al, 1312.0011; Heurtier et al, 1905.13223; Bringmann et al, 1810.10543; Ema et al, 1811.00520; Kim et al, 2003.07369;De Roeck et al, 2005.08979; Fornal et al, 2006.11264; Cao et al, 2006.12767; Alhazmi et al, 2006.16252; many more

Rough Estimate of the BDM Events

- BDM flux (in the case of annihilating BDM from GC)

$$\mathcal{F}_1 = 1.6 \times 10^{-8}\text{cm}^{-2}\text{s}^{-1}\left(\frac{\langle\sigma v\rangle_{0\to1}}{5\times10^{-26}\text{cm}^3\text{s}^{-1}}\right)\left(\frac{100\text{ GeV}}{m_0}\right)^2$$

- Cross section of BDM with target electron/nucleon is assumed to be $\sigma_\chi \sim 10^{-35}\text{cm}^2$ (which would be obtained with $\epsilon \sim 10^{-4}$ and $m_X = 30$ MeV in the dark photon case)
- No acceptance, no background considerations.

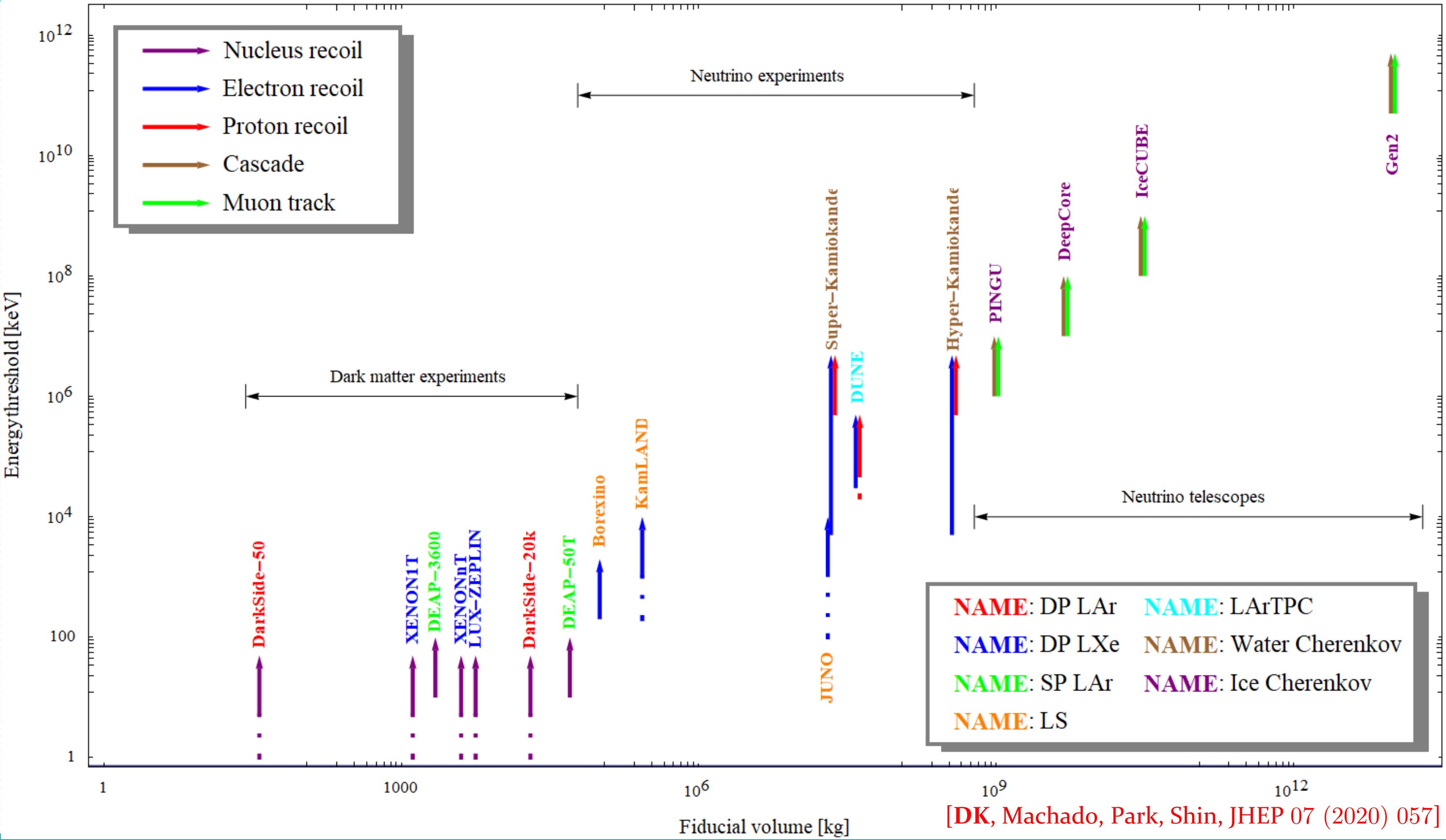


t-scale DM detectors (e.g., Xenon1T) can access.

Sub-kt-scale ν detectors (e.g., Borexino, ICARUS) are motivated

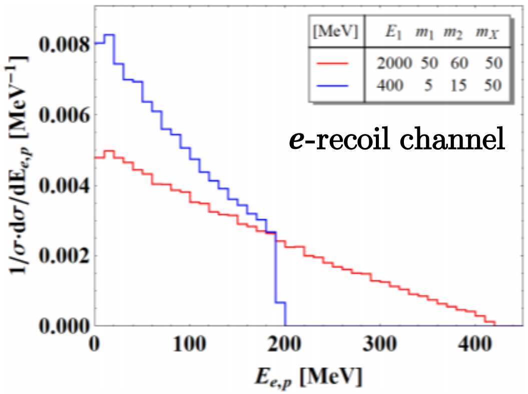
kt-scale ν detectors (e.g., DUNE, HK) are motivated

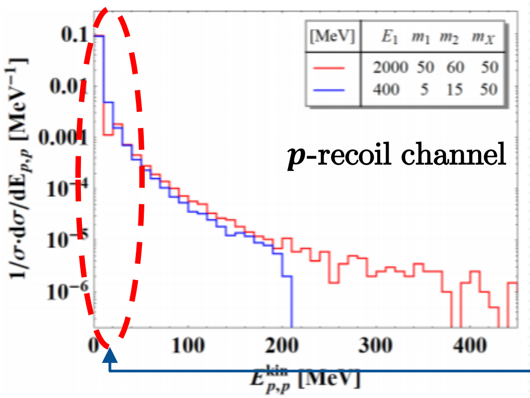
Complementarity among Neutrino (& t-scale DM) Exp.

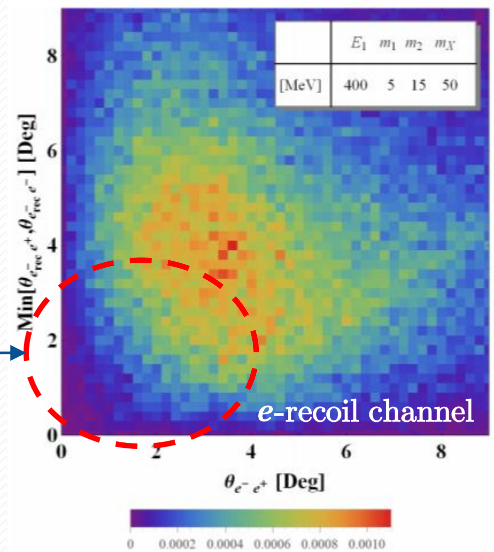


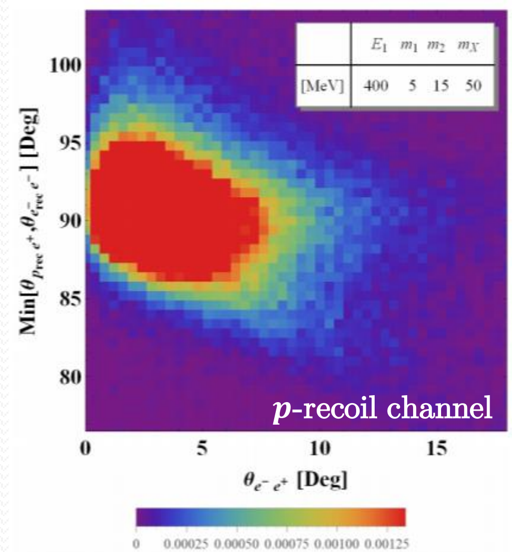
[DK, Machado, Park, Shin, JHEP 07 (2020) 057]

iBDM Searches at Underground Experiments









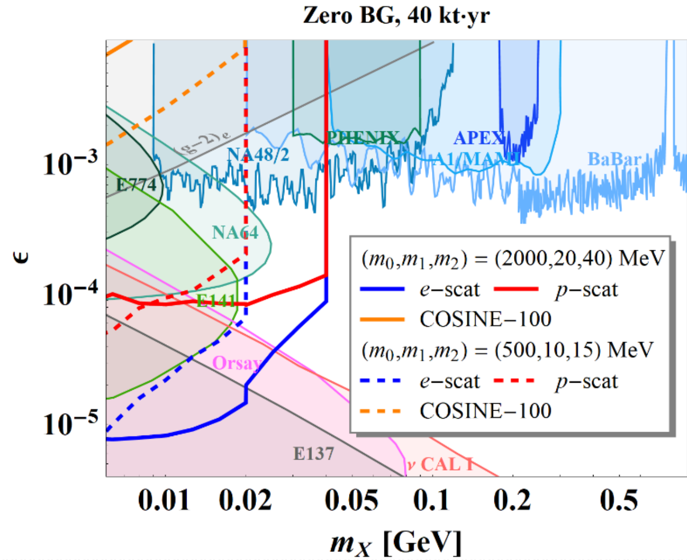
e-recoil channel: particles rather collimated, good angular resolution motivated (cf. dE/dx analysis)

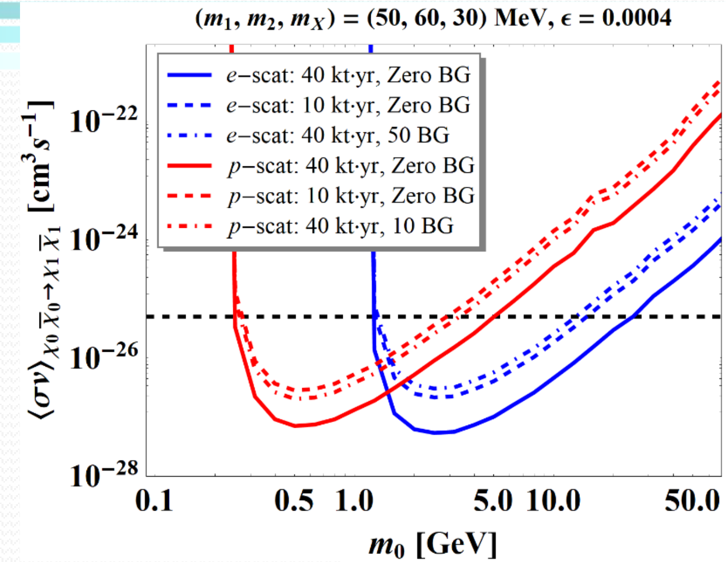
p-recoil channel: a majority of proton recoils populated in the lower energy regime, small threshold motivated

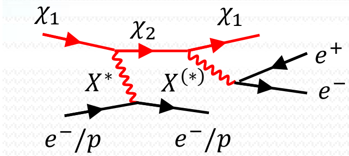
High-capability detectors (available in next-generation ν experiments) better motivated

(cf. See **Yun-Tse's talk** for BDM-induced DIS.)

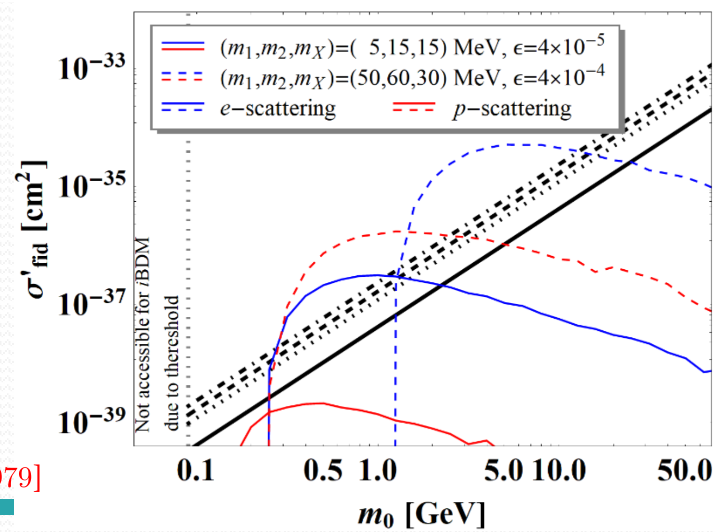
iBDM Searches at DUNE







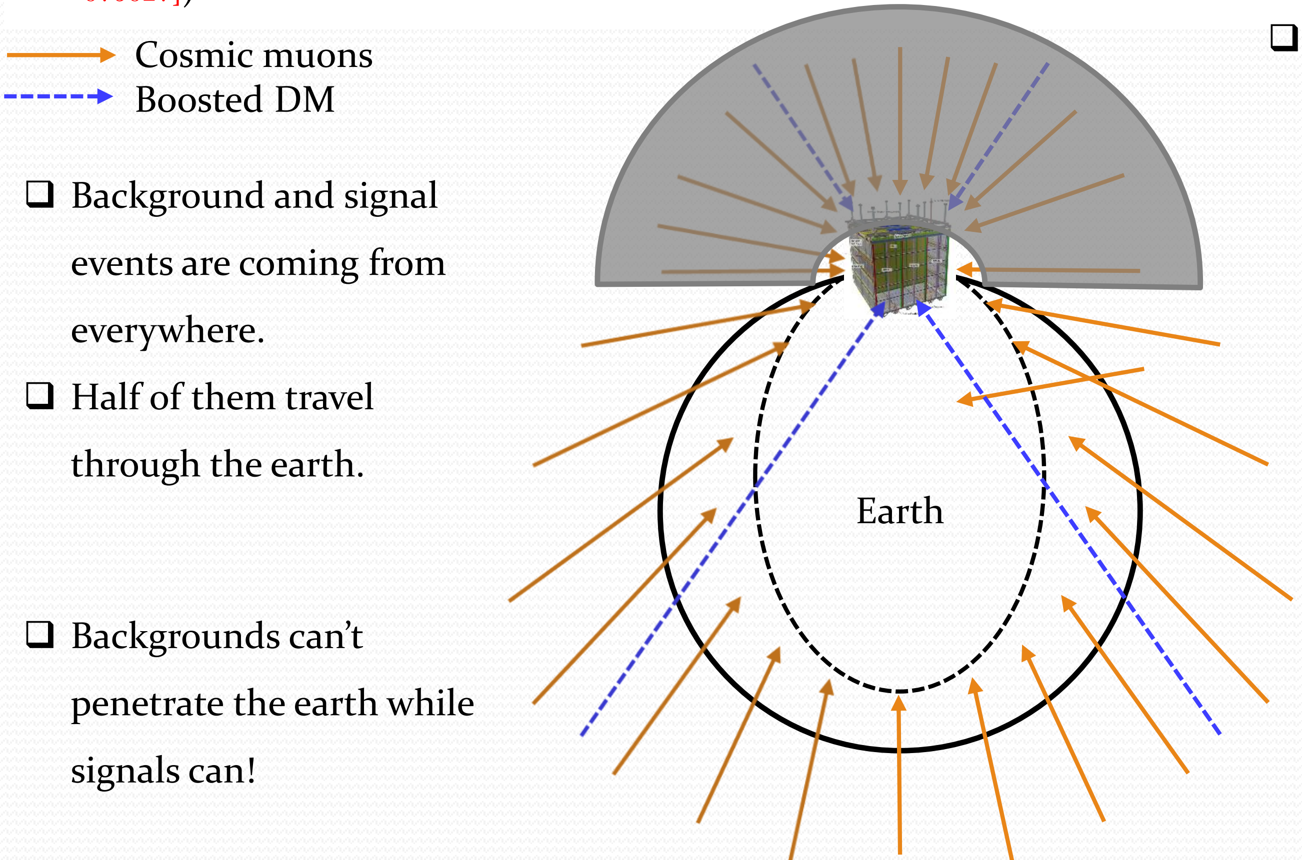
- ❑ Backgrounds and parameterized detector effects were considered.
- ❑ Various model-independent and model-dependent sensitivities were investigated.
- ❑ DUNE(-like) detectors can probe a wide range of unexplored parameter space.



[De Roeck, **DK**, Moghaddam, Park, Shin, Whitehead, JHEP accepted, arXiv:2005.08979]

eBDM Searches at "Surface" Experiments: Earth Shielding

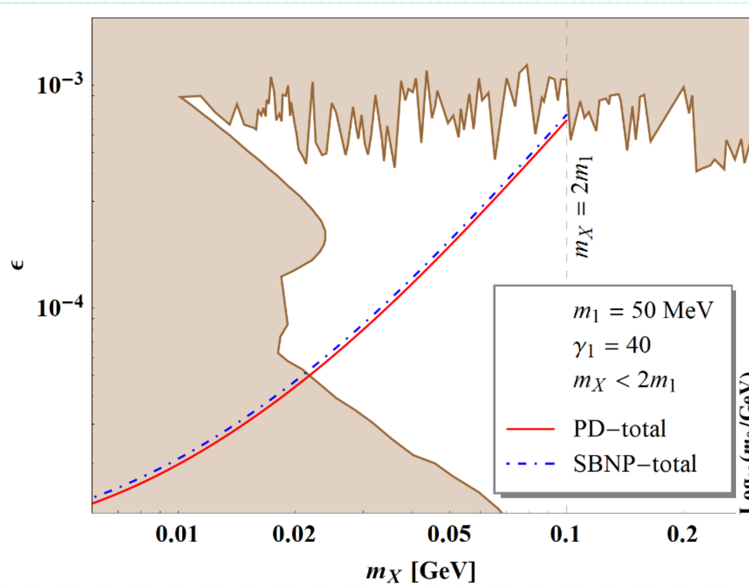
- eBDM search (recoil only) at surface detectors are challenging because of enormous comic-origin BGs. (cf. iBDM search at ProtoDUNE [Chatterjee, De Roeck, **DK**, Moghaddam, Park, Shin, Whitehead, Yu, PRD98 (2018) 7, 075027])



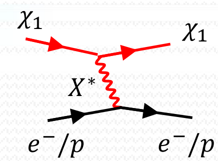
- Background and signal events are coming from everywhere.
- Half of them travel through the earth.
- Backgrounds can't penetrate the earth while signals can!

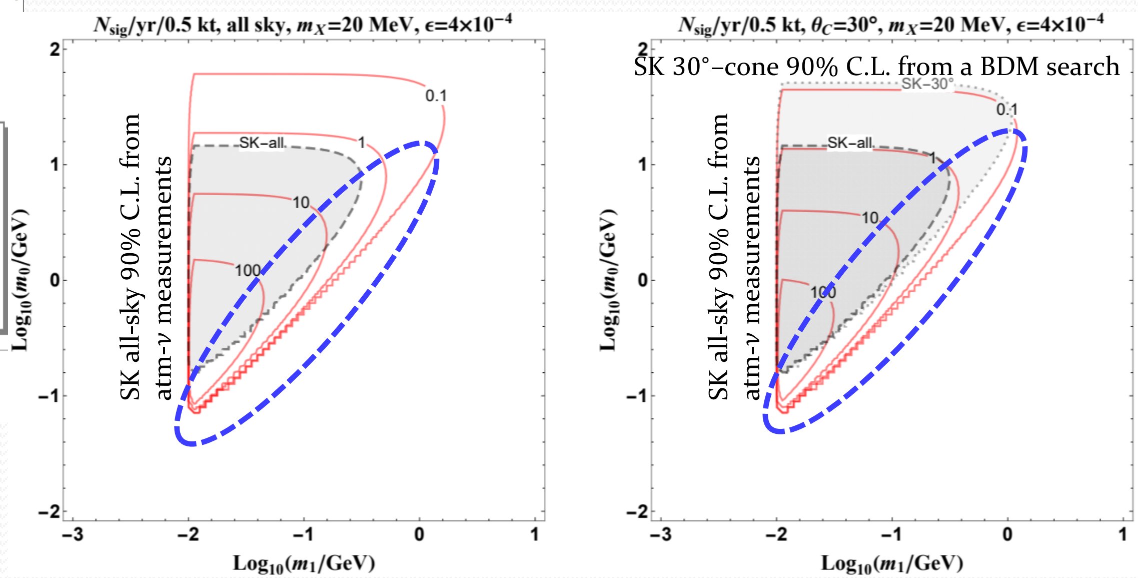
- Accept only **events traveling through the earth** (i.e., coming out of the bottom surface) at the price of half statistics; direction inferred from recoil track ⇒ Essentially **no cosmic-origin BGs** except atmospheric neutrino background (cf. observation of upward-μs induced by ν_μ created by DM annihilation [NOvA Collaboration])

Elastic BDM Searches at Surface Detectors



PD=ProtoDUNE
SBNP=MicroBooNE+ICARUS+SBND combined

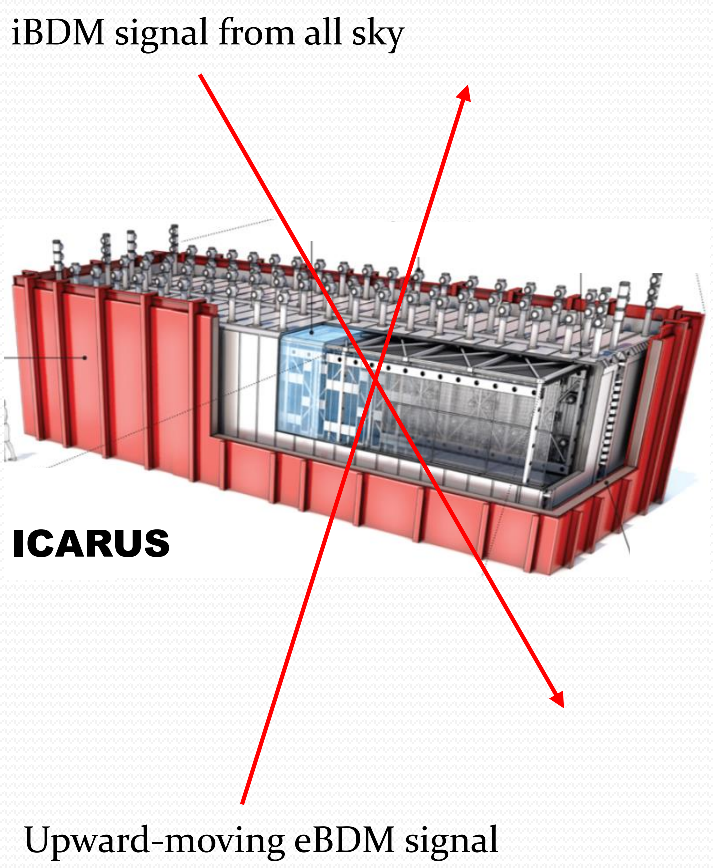




[**DK**, Kong, Park, Shin, JHEP 08 (2018) 155]

- A wide range of unexplored parameter space can be probed even at surface-based detectors in the elastic scattering channel of BDM.
- Full ProtoDUNE/SBN can cover the parameter space (blue circles) uncovered by Super-K! (especially the region where the relevant recoil energy is lower than 100 MeV.)

Future Plan I



- We are planning to investigate iBDM sensitivities and upward-moving eBDM sensitivities at the ICARUS detector.
- Why ICARUS
  - ✓ Just commissioned
  - ✓ Sub-kt-scale detector mass (0.476 kt active volume)
  - ✓ High-capability detector technology adopted (liquid argon time projection chamber)
  - ✓ Can be a good testbed before DUNE

(cf. see **Animesh's talk** for the low-mass DM search at ICARUS using the NuMI beam)

Part II: Lab-Produced Signal

Snowmass2021 - Letter of Interest

Dark Matter Searches at the Next-Generation CEνNS and Neutrino Facilities: from Photon to Dark Photon

NF Topical Groups:

■ (NF3) Beyond the Standard Model

Authors: Bhaskar Dutta (Texas A&M University), Wooyoung Jang (University of Texas at Arlington), Doojin Kim (Texas A&M University), Jong-Chul Park (Chungnam National University), Seodong Shin (Jeonbuk National University), Louis Strigari (Texas A&M University), Adrian Thompson (Texas A&M University), and Jaehoon Yu (University of Texas at Arlington)

Link to this LOI

Snowmass2021 - Letter of Interest

Search for Axion-Like Particles at the Next Generation Neutrino Experiments

Vedran Brdar[a], Albert De Roeck[b], Bhaskar Dutta[c], Patrick Huber[d], Wooyoung Jang[e], Doojin Kim[c], Ian M. Shoemaker[d], Zahra Tabrizi[d], Adrian Thompson[c], and Jaehoon Yu[e]

[a]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
[b]CERN, Geneva, Switzerland
[c]Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, College Station, TX 77845, USA
[d]Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, VA 24061, USA
[e]University of Texas at Arlington, Arlington, TX 76019, USA

Link to this LOI

Snowmass2021 - Letter of Interest

Search for Axion-Like Particles at the Reactor Neutrino Facilities

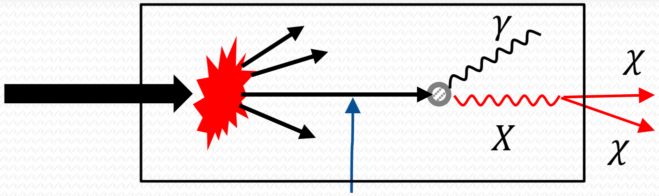
James B. Dent[a], Albert De Roeck[b], Bhaskar Dutta[c], Doojin Kim[c], Rupak Mahapatra[c], Kuver Sinha[d], and Adrian Thompson[c]

[a]Department of Physics, Sam Houston State University, Huntsville, TX 77341, USA
[b]CERN, Geneva, Switzerland
[c]Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, College Station, TX 77845, USA
[d]Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA

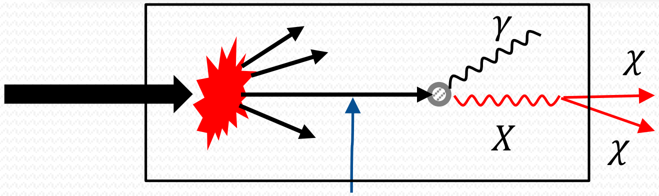
Link to this LOI

Low-mass Dark Matter (LDM) Production

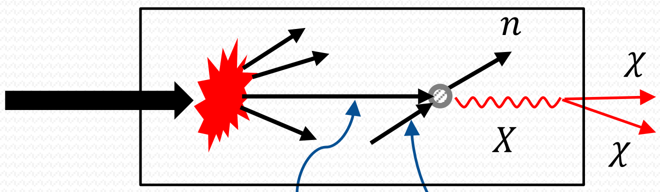
Low-energy beam (e.g., COHERENT, CCM, JSNS[2]) vs High-energy beam (e.g., DUNE, SBN)



(slowly) moving π^0



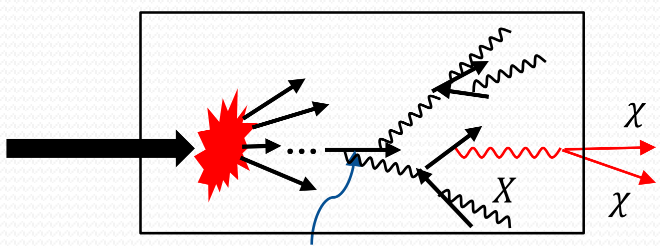
relativistic π^0, η, …



Stopped π^- $\quad$ p in target

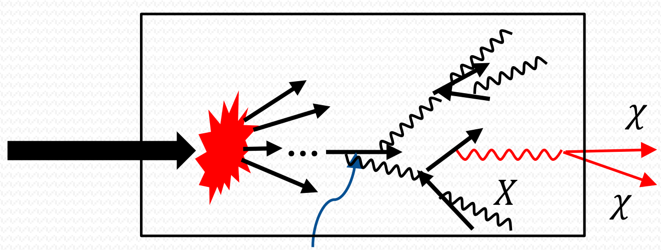
$\pi^- + p \to n + X$ [deNivervill, Pospelov, Ritz (2015)]

$\pi^\pm$ usually decay in flight



secondary $e^\pm$

+ Brem. contributions

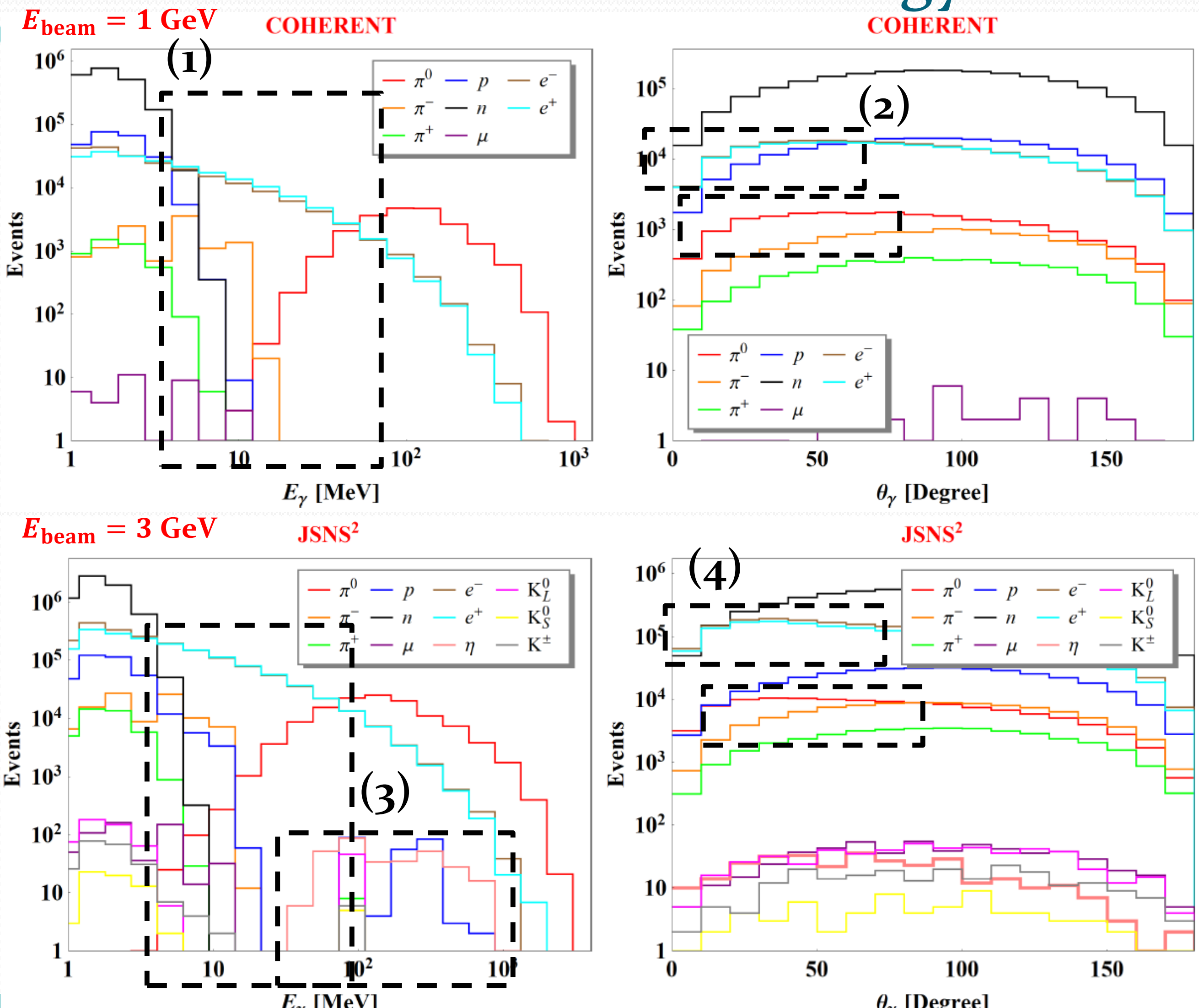


secondary $e^\pm$

+ Brem. contributions

Dedicated simulation using e.g., GEANT is needed!

Photon Flux at Low-Energy Beam Experiments



- Simulation done with GEANT4+FTFP BERT [Dutta, **DK**, Liao, Park, Shin, Strigari, Thompson, arXiv:2006.09386]

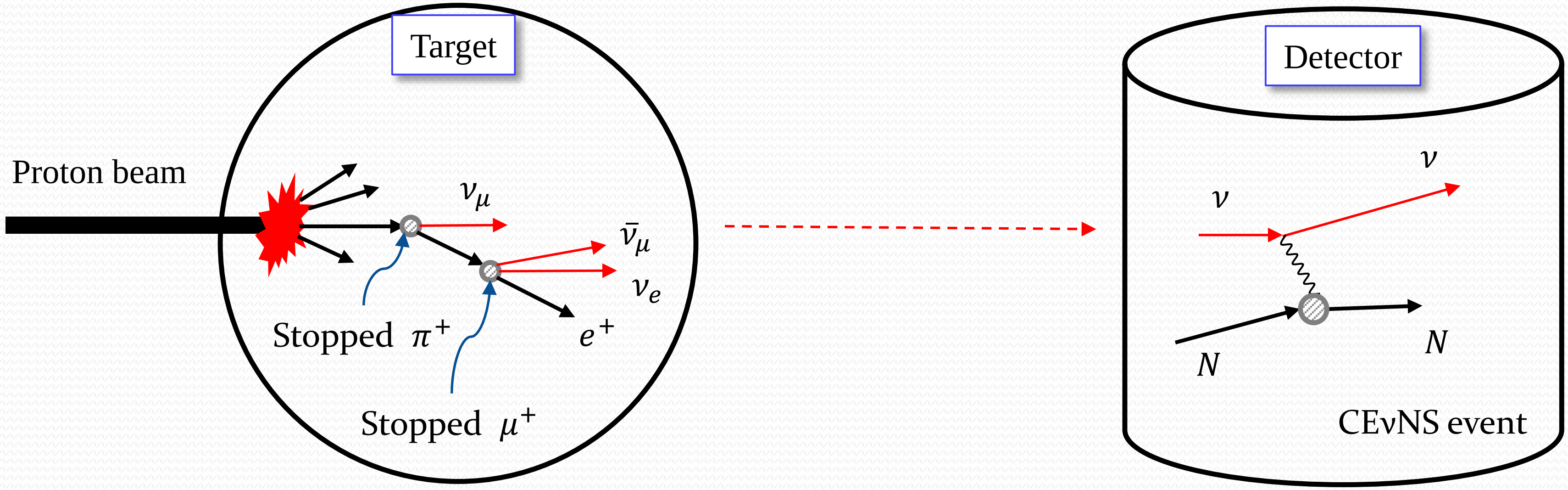
(1) Significant $e^\pm$-induced cascade photons

(2) $\pi^0, e^\pm$-induced photons slightly more forward-directed

(3) More cascade photons and contributions by heavier mesons

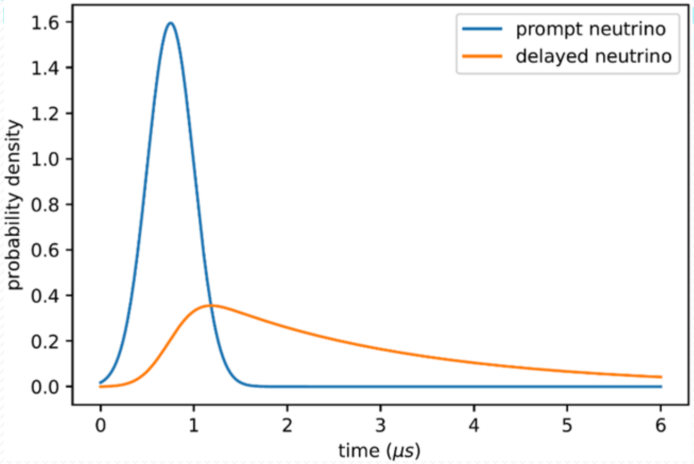
(4) Slightly more forward-directed than the case of COHERENT/ CCM

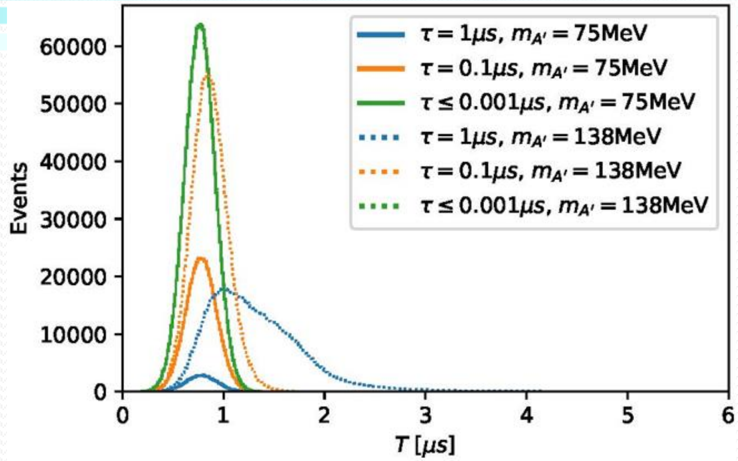
Who is Background?

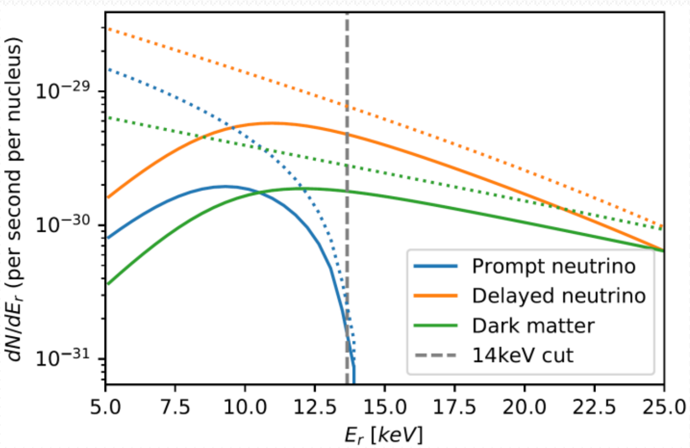


1) "Prompt" neutrinos from the decay of stopped (positively)-charged pions.
   - ✓ Mean life time of $\pi^+ = 2.6 \times 10^{-8}$s.
   - ✓ Neutrino energy is single-valued, hence deposit energy is upper-bounded. $\Rightarrow$ Energy cut
2) "Delayed" neutrinos from the decay of stopped muons.
   - ✓ Neutrinos are more energetic than prompt neutrinos.
   - ✓ Mean life time of $\mu^+ = 2.2 \times 10^{-6}$s. $\Rightarrow$ Timing cut with μs-scale timing resolution

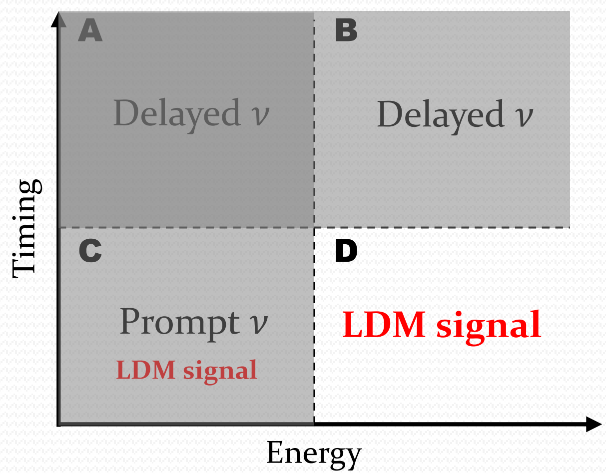
Bkdg Rejection Using Timing Spectra for Low-E Beam Exp.





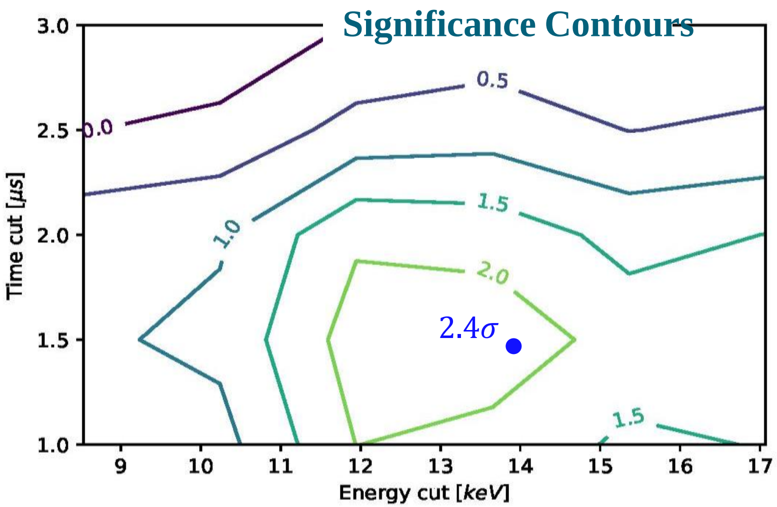


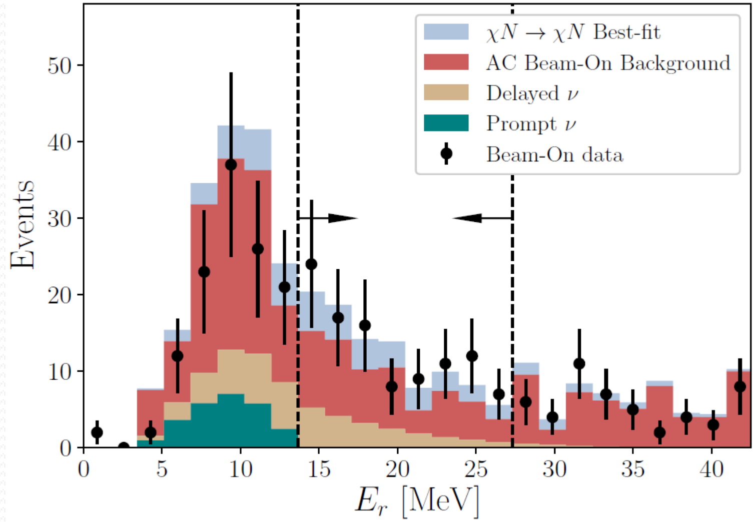
(Example distributions in COHERENT)



- ❑ A combination of energy and timing cuts can remove SM/NSI ν backgrounds [Dutta, **DK**, Liao, Park, Shin, Strigari, PRL124 (2020) 12, 121801]
- ❑ Similar strategies are applied for CCM and JSNS^2.

Excess in COHERENT Data?



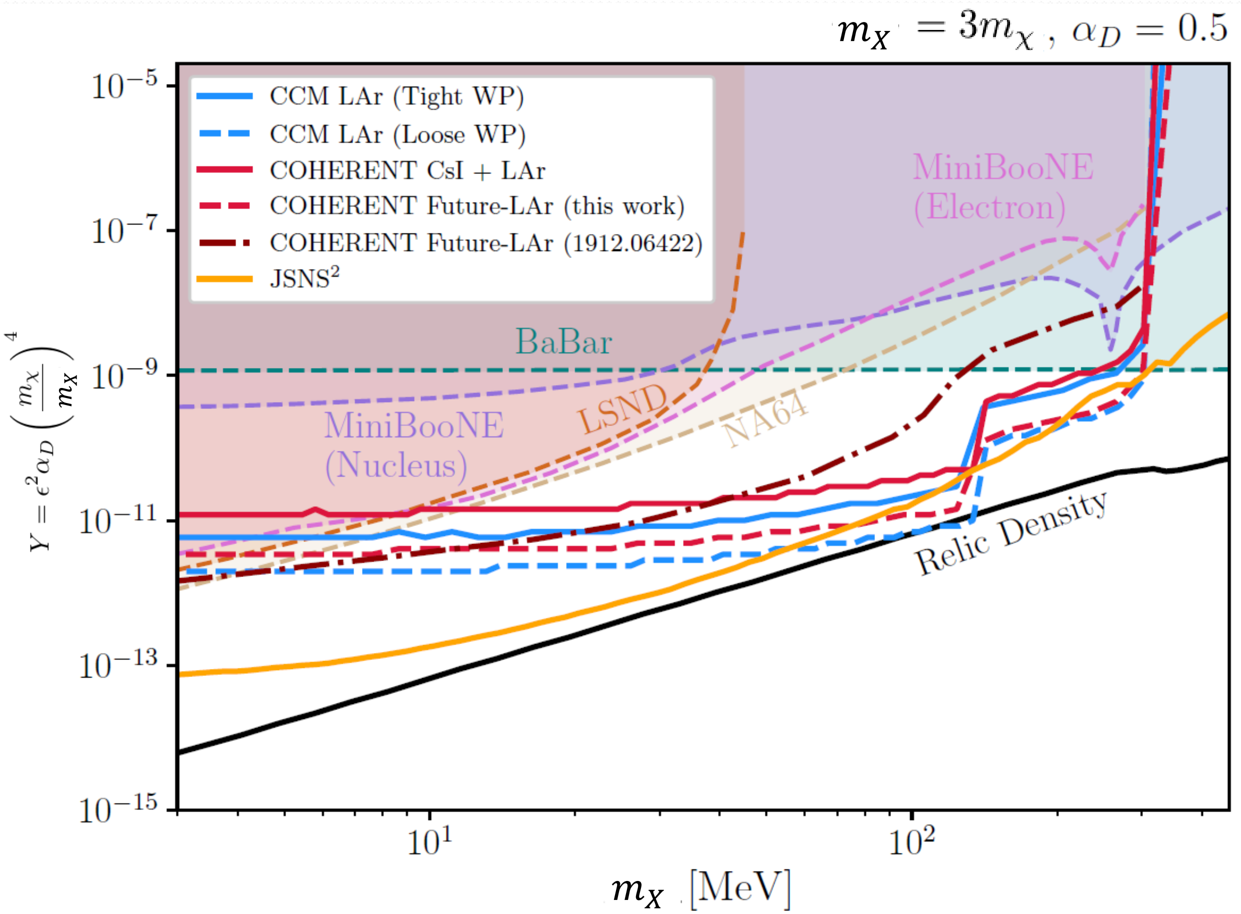


- A mild excess in COHERENT CsI 2018 data with 14 keV $< E_r <$ 26 keV, $T < 1.5$ μs, $R_n = 4.7$ fm [Dutta, **DK**, Liao, Park, Shin, Strigari, PRL124 (2020) 12, 121801]
- The excess can be explained by DM not by NSI (since the cuts remove the prompt and delayed neutrinos).

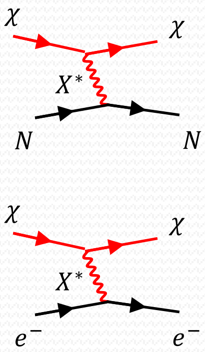
One can search for DM signals in upcoming (near-future) stopped pion neutrino experiments!

[New COHERENT LAr 2020 data, work in progress]

No Excess – Constraining Parameter Space



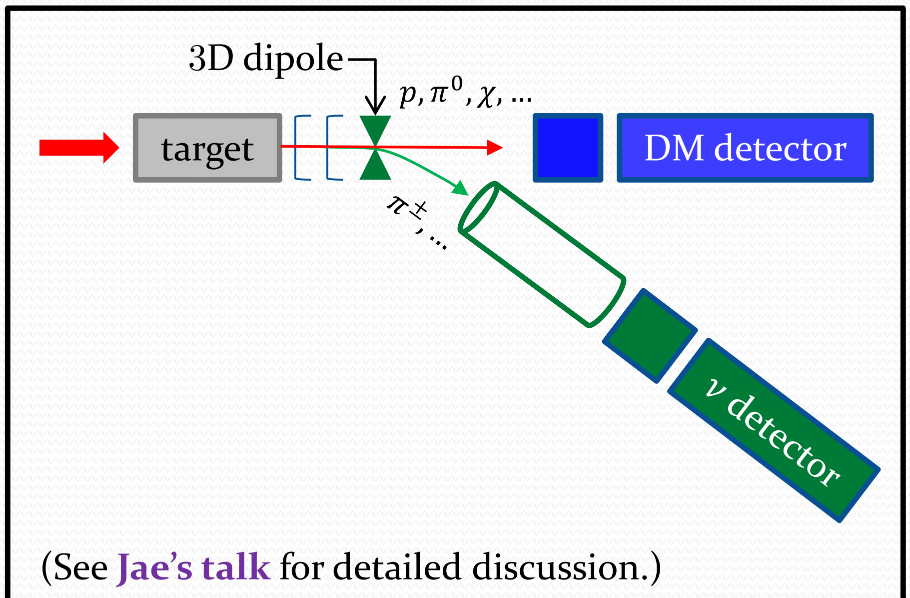
[Dutta, **DK**, Liao, Park, Shin, Strigari, Thompson, arXiv:2006.09386]



- COHERENT, CCM, and JSNS^2 possess competitive sensitivities to LDM signals especially toward the lower mass regime. (see **Dan's talk** for an alternative approach of COHERENT.)

Future Plan II

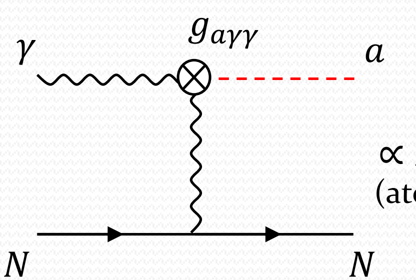
- Low-mass DM searches at neutrino experiments using a higher energy beam such as DUNE [De Romeri, Kelly, Machado (2019); Celentano, Darme, Marsicano, Nardi (2020)], SBN [de Gouvea, Fox, Harnik, Kelly, Zhang (2018)], MiniBooNE/ NOvA [Celentano, Darme, Marsicano, Nardi (2020)].
- Our plan is to improve LDM sensitivities (significantly) using full photon spectra and (if realized) a novel way/concept of separating LDM signal and neutrino events (cf. no delayed neutrinos).



From Photon-to-ALP Production to ALP Detection

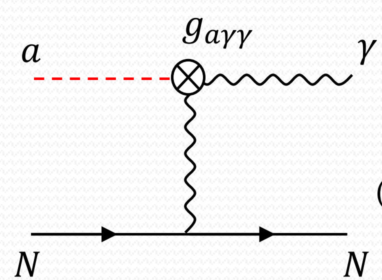
- We use the photon flux to probe ALPs.

$$\mathcal{L}_{int} \supset -\frac{g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}}{4} - g_{aee} a \bar{\psi}_e \gamma_5 \psi_e$$



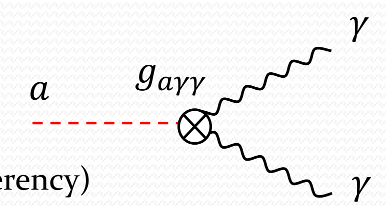
$\propto Z^2$
(atomic coherency)

Primakoff

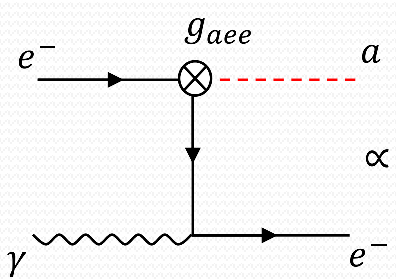


$\propto Z^2$
(atomic coherency)

Inverse Primakoff

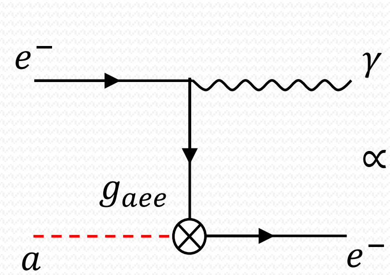


Decay to photons



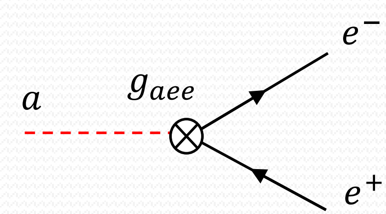
$\propto Z$

Compton-like



$\propto Z$

Compton-like



Decay to e^-e^+

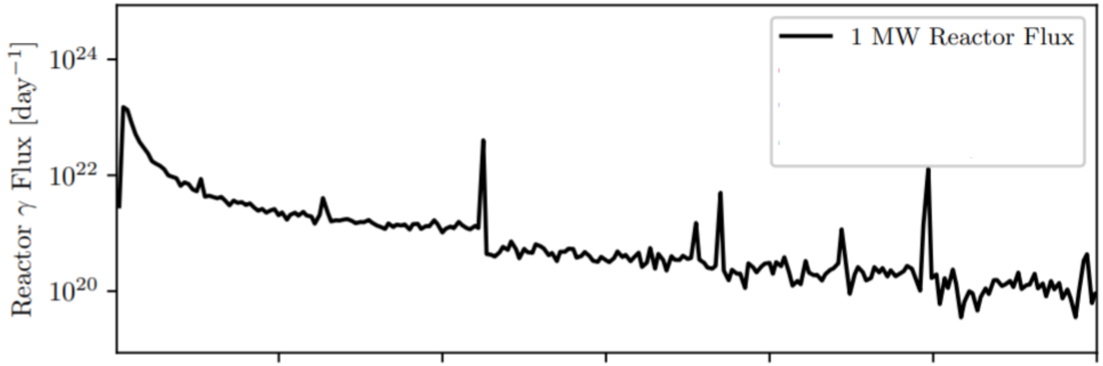
<u>ALP production at target</u>

<u>ALP detection at detector</u>

(cf. Nucleon-ALP coupling can be used. [TEXONO Collaboration, hep-ex/0609001])

Advantages of ALP Searches at Reactors

✓ Reactors are generally featured by a huge size of photon flux!



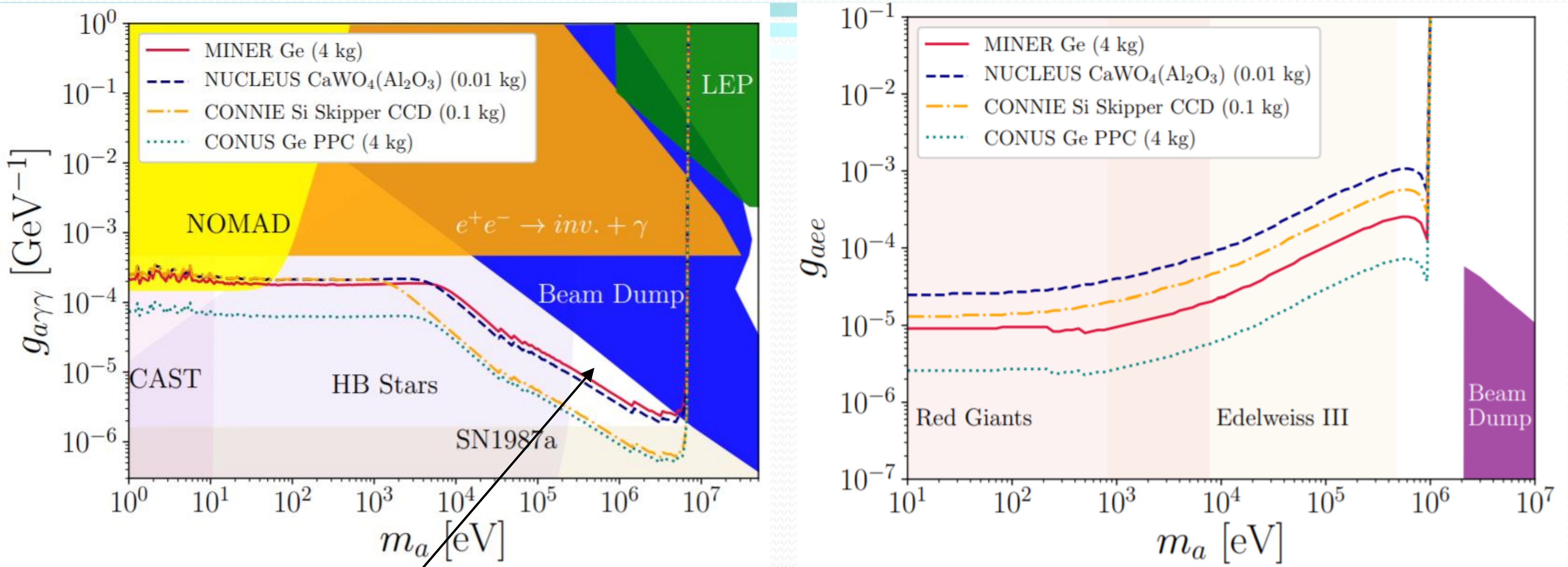
1-MW MINER photon flux at the reactor core

Experiment	Core Thermal Power	Core Proximity (m)	Bkg Rate in ROI (DRU)	Exposure (kg·days)
MINER (Ge)	1 MW	2.25	100	4000
ν-cleus ($CaWO_4$)	4 GW	40	100	10
CONNIE (Si CCD)	4 GW	30	700	100
CONUS (Ge PPC)	4 GW	17	100	4000

✓ There are many ongoing/near-future high-power reactor neutrino experiments.

✓ Detectors are very close to the reactor core so that a large fraction of signal can reach the detectors.

Expected Signal Sensitivities

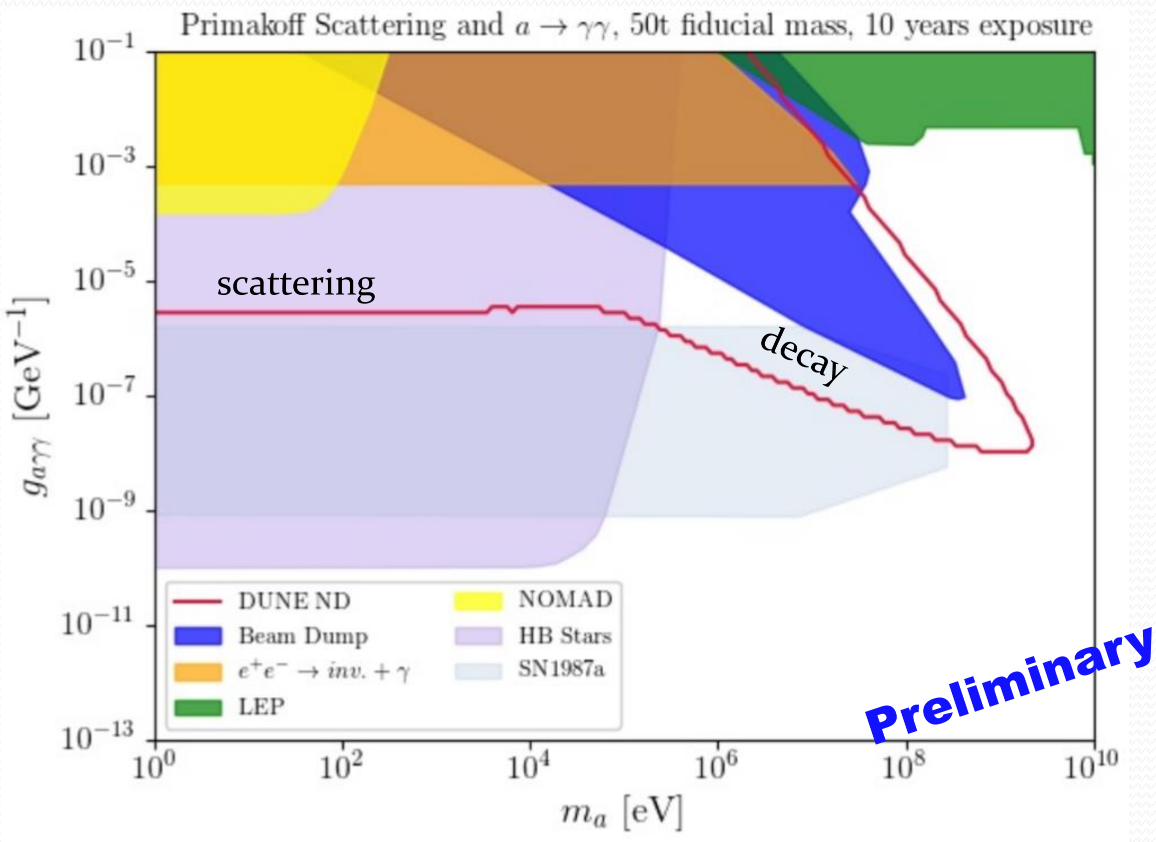


[Dent, Dutta, **DK**, Liao, Mahapatra, Sinha, Thompson, PRL124 (2020) 21, 211804]

- Part of "Cosmological Triangle" (allowed by all data [Carenza, Straniero, Dobrich, Giannotti, Lucente, Mirizzi (2020)]) can be probed in reactor neutrino experiments.
- Astrophysical constraints (CAST, HB Stars, Supernova) are model-dependent, hence lab-based ALP searches can provide more conservative constraints.

Future Plan III

- ALP searches at DUNE ND (LAr module + GAr module with B field, SAND) using the full photon spectrum.



[Brdar, Dutta, Jang, **DK**, Shoemaker, Tabrizi, Thompson, Yu, in progress]

Conclusions

- Null BSM signal observation at existing experiments motivates us to look into alternative new physics scenarios, especially non-minimal dark-sector scenarios.
- Models with **light mediators and light dark matter** are interesting and receiving rising attention.
- Ongoing/near-future **next-generation neutrino experiments are excellent places to search for cosmogenic and lab-produced signals induced by these particles** due to large detector volume and high intensity together with detector high-capability.
- Proposed searches and phenomenological studies will be **important aspects of the neutrino program** in the upcoming decade and beyond.

Thank you for your attention!

Bonus Slides

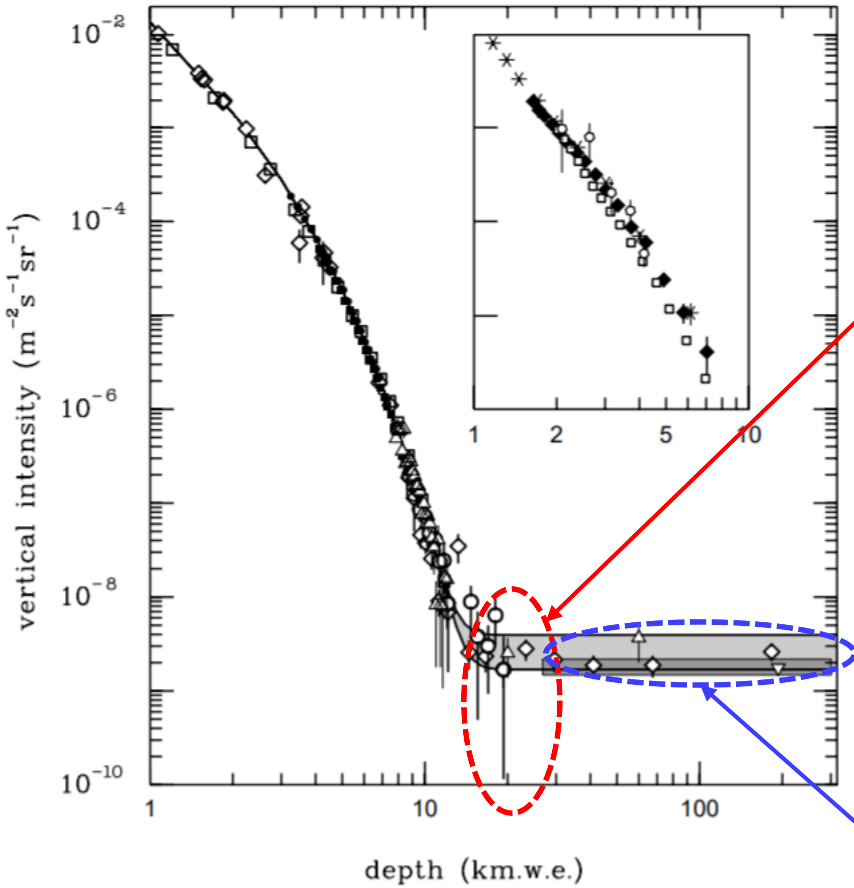
Event Selections

Target & detector technology		Liquid Argon & LArTPC
Depth [m.w.e.]		4,300
Dimension [m]	Active	Cubic (width × length × height) SP: $14.0 \times 58.2 \times 12.0$ (×2) DP: $12.0 \times 62.0 \times 12.0$ (×2)
	Fiducial†	$11.2 \times 57.2 \times 11.2$ (×4)
Mass [kt]	Active	SP: 13.7×2, DP: 12.1×2
	Fiducial	SP: 10.0×2, DP: 10.0×2
$E_{\rm th}$ [MeV]	electron	30
	proton	30-50
$E_{\rm res}$ [%]	electron	20 for $E < 0.4$ GeV 10 for $E < 1.0$ GeV $2 + \frac{8}{\sqrt{E/\rm GeV}}$ for $E \geq 1.0$ GeV
	proton	10 for $E < 1.0$ GeV $5 + \frac{5}{\sqrt{E/\rm GeV}}$ for $E \geq 1.0$ GeV
$\theta_{\rm res}$ [°]	electron	1
	proton	5
Vertex resolution $V_{\rm res}$ [cm]		1

Table 2. A summary of the characteristics of a far detector similar to the one proposed by the DUNE Collaboration [24–27]. The unit for depth, m.w.e., stands for meter-water-equivalent. The "†" symbol indicates the quoted dimensions of the fiducial volumes used in section 5 and detailed in the text.

[De Roeck, **DK**, Moghaddam, Park, Shin, Whitehead, arXiv:2005.08979]

Muon Flux inside Earth

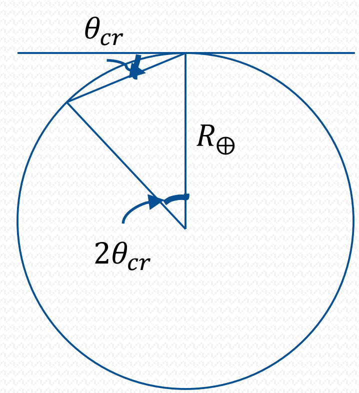


[Particle Data Group (2015)]

Flattened by neutrino-genic muons

- ❑ N_μ at sea level is $\sim 100\ \mathrm{m^{-2}s^{-1}sr^{-1}} = 3 \times 10^9\ \mathrm{m^{-2}yr^{-1}sr^{-1}}$. [Particle Data Group (2015)]
- ❑ N_μ at 20 km.w.e. $\approx$ 7 km below sea level is $\sim 10^{-9}\ \mathrm{m^{-2}s^{-1}sr^{-1}}$, i.e., suppressed by a factor of $\sim 10^{11}$. $\Rightarrow$ (Potential) muon-induced BG is negligible for muons incident at $\theta > \theta_{cr}$.

$$\theta_{cr} \approx \frac{7\ \mathrm{km}}{2R_\oplus} \approx 0.03^\circ$$



Key Specifications of Stopped Pion Experiments

(Gd-LS = gadolinium-doped liquid scintillator)

Experiment	E_{beam} [GeV]	POT [yr^{-1}]	Target	Detector: mass, distance, angle, E_r^{th}
COHERENT [15, 17, 18]	1	1.5×10^{23}	Hg	CsI[Na]: 14.6 kg, 19.3 m, 90°, 6.5 keV LAr: 24 kg (0.61 ton), 28.4 m, 137°, 20 keV
JSNS^2 [19–21]	3	3.8×10^{22}	Hg	Gd-LS: 17 ton, 24 m, 29°, 2.6 MeV
CCM [22–24]	0.8	1.0×10^{22}	W	LAr: 7 ton, 20 m, 90°, 25 keV

Table 2. Key specifications of benchmark experiments and detectors under consideration. All three experiments use a proton beam, and the POT values are expected spills for 5,000 hours operation per year. The mass of the liquid argon detector in parentheses in COHERENT is for a future upgrade.

JSNS^2:

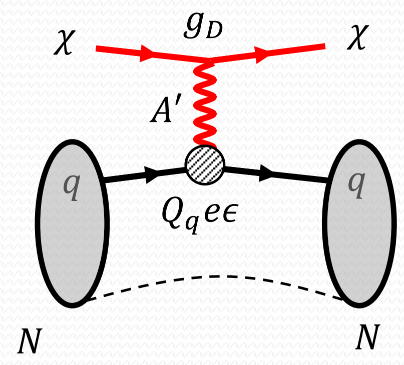
1) Higher energy threshold → ideal for electron scattering signal (vs. nucleus scattering signal at COHERENT and CCM)
2) Forward-directed detector location → potentially exposed to more beam-related backgrounds

Dark Matter Signal: Target Recoil

❑ Nucleus scattering channel at COHERENT and CCM:

$$\frac{d\sigma}{dE_{r,N}} = \frac{e^2\epsilon^2 g_D^2 Z^2 \cdot |F|^2}{4\pi p_\chi^2 (2m_N E_{r,N} + m_{A'}^2)^2} \left\{ 2E_\chi^2 m_N \left(1 - \frac{E_{r,N}}{E_\chi} - \frac{m_N E_{r,N}}{2E_\chi^2}\right) + m_N E_{r,N}^2 \right\}$$

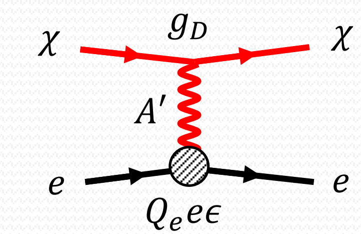
Z: atomic number, F: form factor
E_χ: energy of incoming dark matter,
$E_{r,N}$: recoil kinetic energy of target nucleus
m_N: mass of target nucleus, $m_{A'}$: mass of dark photon



Typical recoil energy is much smaller than MeV.

❑ Electron scattering channel at JSNS[2] because a nucleus recoil doesn't overcome the detector threshold.

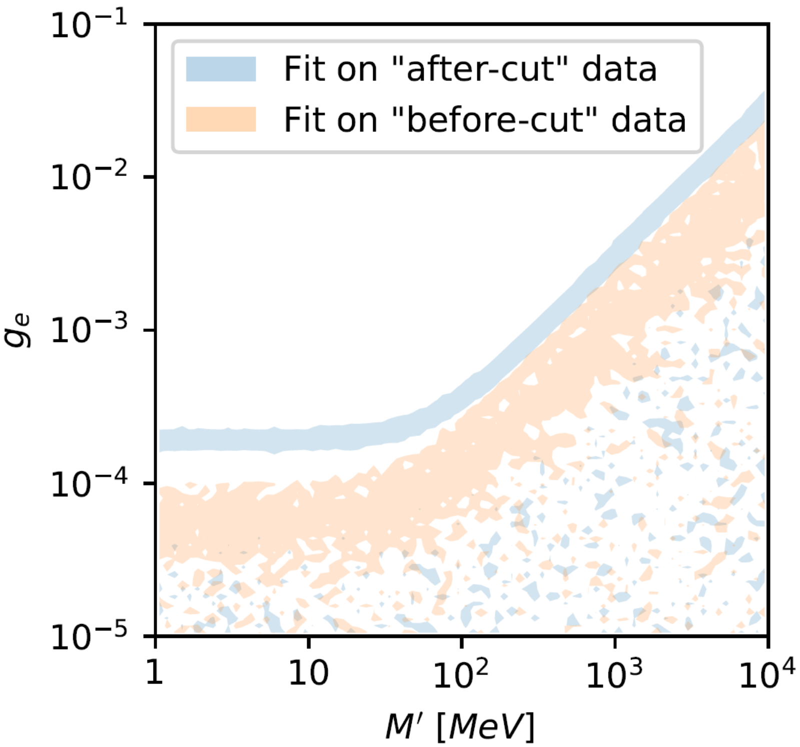
$$\frac{d\sigma}{dE_{r,e}} = \frac{e^2\epsilon^2 g_D^2 Z \cdot m_e^2}{\pi\lambda(s, m_e^2, m_\chi^2)\left\{2m_e(m_e - E_{r,e}) - m_{A'}^2\right\}^2} \times \left[m_e\left\{E_\chi^2 + (m_e + E_\chi - E_{r,e})^2\right\} + (m_e^2 + m_\chi^2)(m_e - E_{r,e})\right]$$



$E_{r,e}$: recoil kinetic energy of target electron
m_e: mass of target electron, $s = E_\chi^2 + 2E_\chi m_e + m_\chi^2$, $\lambda(x,y,z) = (x - y - z)^2 - 4yz$

If Mild Excess – Alternative Interpretation: NSI

- Example alternative new physics possibility, Non-Standard Interaction



- Benchmark case: non-zero coupling g_e, the NSI in the ν_e neutral-current interaction (along with a new mediator).
  - $\Rightarrow$ No overlapping regions, especially the prompt timing bin (i.e., $T < 1.5\ \mu s$) doesn't show a good fit. NSI affects the overall normalization of neutrino flux!
- The situation becomes even worse with $g_\mu \neq 0$, since it affects not only the delayed but the prompt spectrum.