CEνNS: Inelastic Exploration

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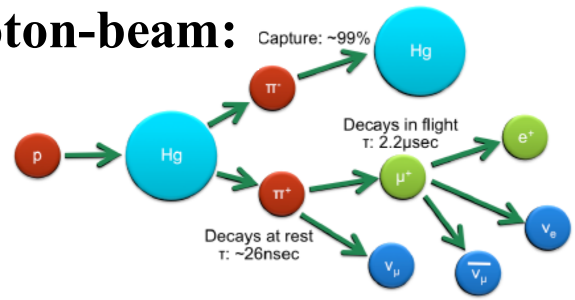
Talk at Magnificent CEνNS, Valencia, Spain

12^{th} June 2024

CEνNS ν signal

- **Proton-beam:**

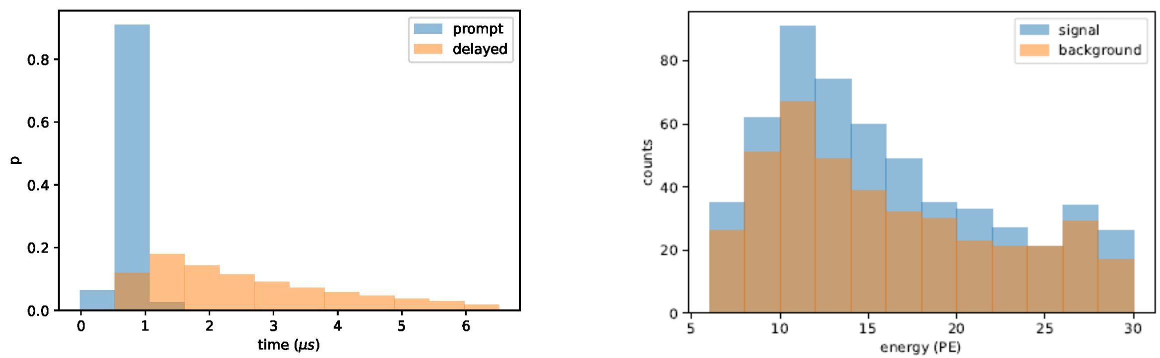


Prompt: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

Delayed: $\mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \nu_e$

COHERENT, CCM, JSNS^2

COHERENT: CsI data:2018



COHERENT (2017) **No CEνNS rejected at 6.7σ: CsI (2020): 11.6σ**

COHERENT (2020) **No CEνNS rejected at 3.8σ : LAr**

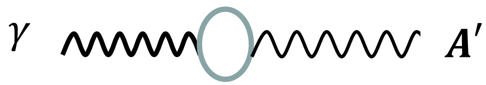
- **Reactor: CONUS. CONNIE, MINER…**
- The high-intensity proton beam and gamma flux provide a great opportunity to search for new physics at CEνNS, e.g., light DM, ALP etc. **COHERENT, CCM**

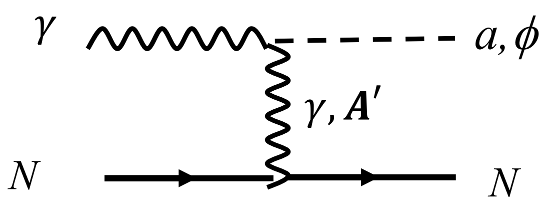
New physics at CEνNS

For example,

A': Vector
ϕ=scalar
a=pseudo-scalar

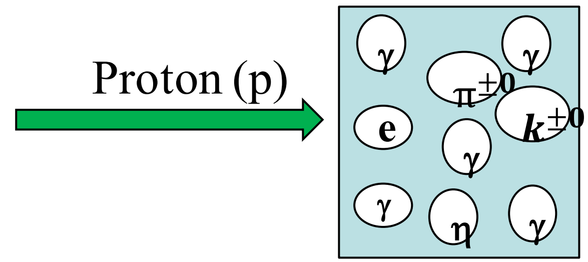
- From γ:

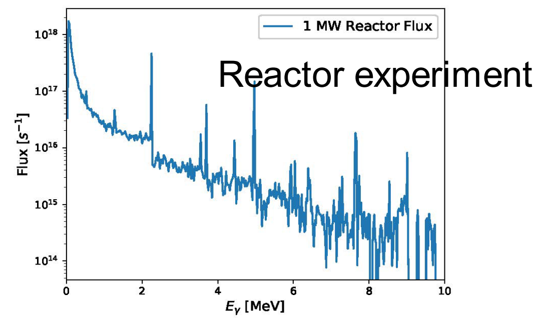




Primakoff

Proton beam based

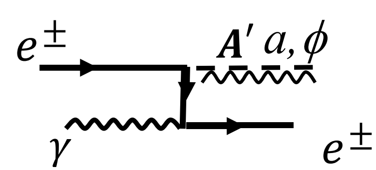


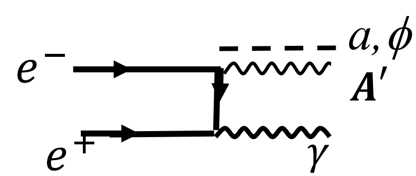


- *A', a, ϕ* : Nuclear deexcitations (nucleon coupling via q,g)

- From $e^{\pm}$:

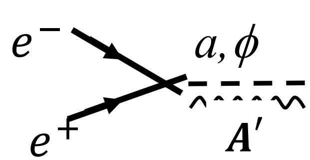
Compton

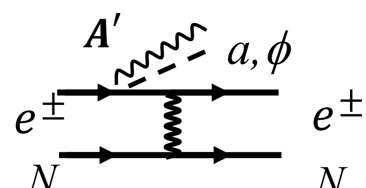




Associated

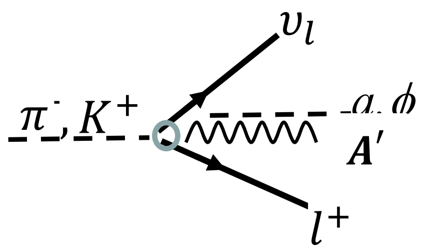
Resonance





Bremsstrahlung

New physics at CEνNS



PHYSICS REPORTS No. 3 (1962) 151-21)5.
Bandyopadhyay, Ghosh, Roy, PRD 105 (2022) 11, 115039.

- *Charged meson decay: quarks and lepton couplings*
  - Not helicity suppressed ➔ both electron and muon final states contribute
  - Needs to include all the internal bremsstrahlung diagrams IB_i (i=1,23)
  - Satisfy the experimental constraint from **PIENU** (pions) and **NA62**(Kaons)

$$\eta^0, \pi^0 \rightarrow \gamma A'_\mu$$

- *Neutral meson decays*

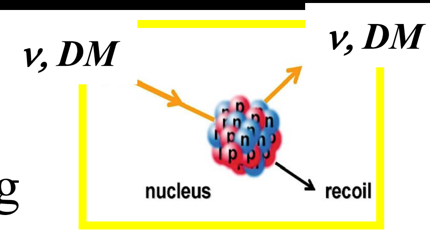
- There can be more production processes, e.g., $\nu + N \rightarrow \nu_s + N$ (coherently enhanced) using $\bar{\nu}_s \sigma_{\mu\nu} F^{\mu\nu} \nu$

- Neutrons can be used (from reactor and beam-based)

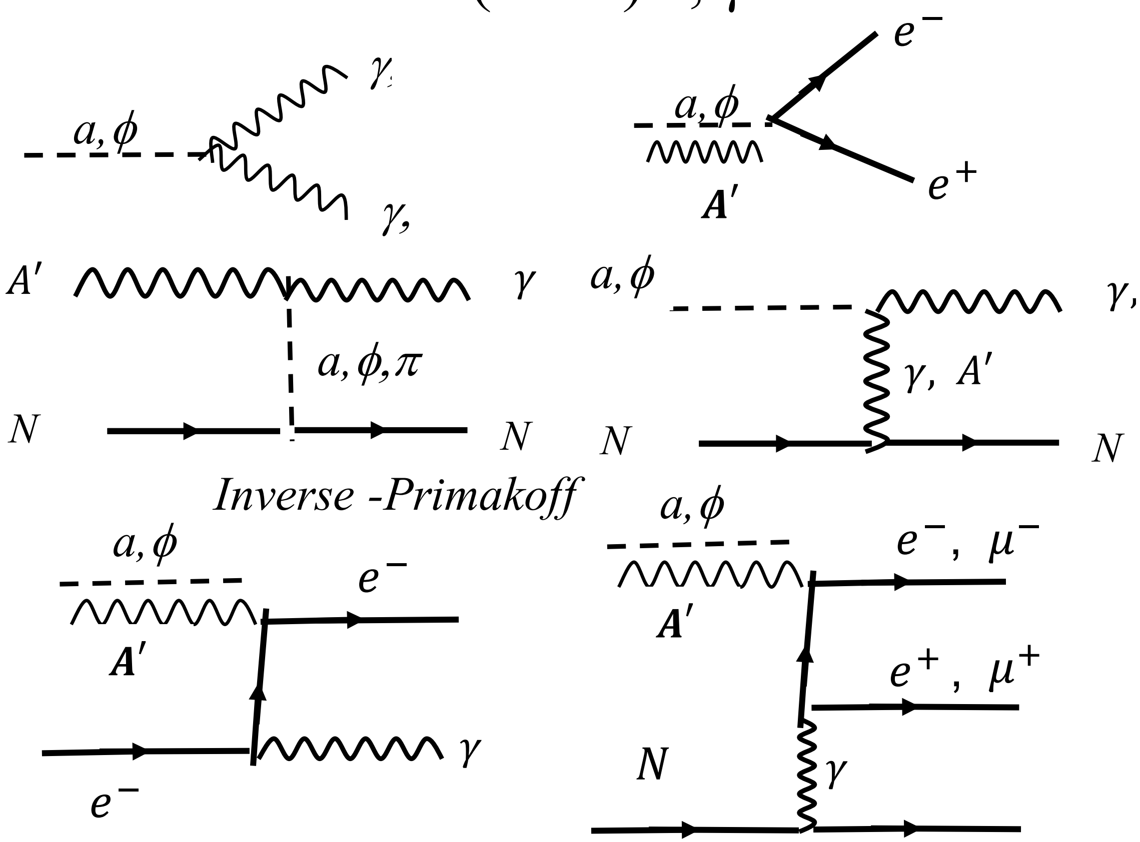
CEνNS: Dark Sector Signal

CEνNS signal at the detector: O(10) KeV and less nuclear recoil

Similar nuclear recoil for dark matter coherent nucleus scattering



- In this talk: O(MeV) e, γ

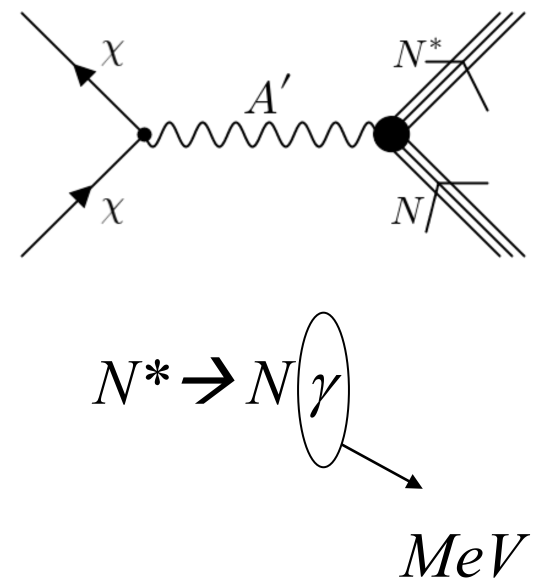


Inverse -Primakoff

Inverse -Compton

Bethe-Heitler pair production

Inelastic nucleus Scattering



Absorption also produces similar signal

New Physics via Inelastic processes

- ❑ Light dark matter at CEνNS experiment
- ❑ ALP at reactor
- ❑ ATOMKI anomaly at CEνNS experiment
- ❑ Results for light DM at large neutrino facilities

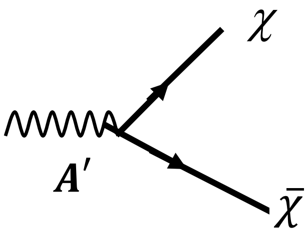
All these examples will involve O(MeV) line signals

Light DM at CEνNS via elastic channels: **Deniverville, Pospelov, Ritz, PRD, 2015; Dutta, Kim, Liao, Park, Shin, Strigari, PRL, 2020; COHERENT, PRD 2019, PRD 2021; CCM, PRD 2022**

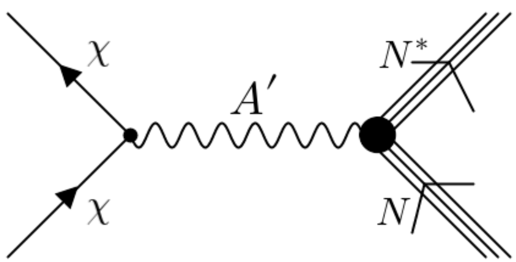
ALP at reactor: Production via line, Primakoff, Compton and detection inverse Primakoff/Compton and decay:
Dent, Dutta, Kim, Liao, Mahapatra, Sinha, Thompson, PRL, 2020;
D. Aristizabal Sierra, V. De Romeri, L. Flores, D. Papoulias, JHEP, 2021/ TEXONO, PRD 2007

1. MeV Signal – Light DM

$$
\begin{aligned}
\pi^- + p &\rightarrow n + A' \\
\pi^0 &\rightarrow \gamma + A' \\
\eta^0 &\rightarrow \gamma + A' \\
e^{\pm *} &\rightarrow e^{\pm} + A'
\end{aligned}
$$



DM (χ) can be scalar/fermion



$N^* \rightarrow N\gamma$

MeV

We use Bigstick: Shell Model code for this calculation

- This calculation estimates the cross-section measured for coherent scattering with KeV nuclear recoil
- Also provides a line signal estimate for the MeV range

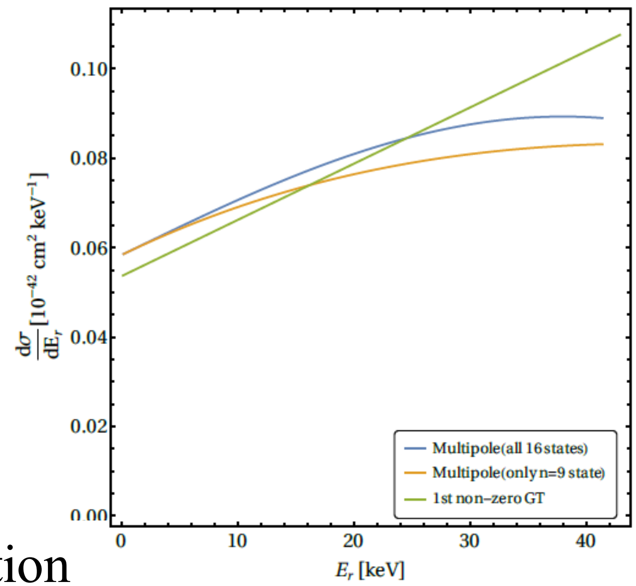
B. Dutta, W. Huang, J. Newstead, V. Pandey, PRD 2022

MeV Signal - DM

$$\frac{d\sigma_{\text{inel}}^{DM}}{dE_r} = \frac{2e^2\epsilon^2 g_D^2 E'^2_\chi}{p_\chi p'_\chi (2m_N E_r + m_{A'}^2)^2} \frac{m_N}{2\pi} \frac{4\pi}{2J+1} \left\{ \sum_{J\geqslant 1, spin} \left[\frac{1}{2}(\vec{l}\cdot\vec{l}^* - l_3 l_3^*) \left(|\langle J_f || \hat{\mathcal{T}}_J^{mag} || J_i \rangle|^2 + |\langle J_f || \hat{\mathcal{T}}_J^{el} || J_i \rangle|^2 \right) \right] \right.$$

$$\left. + \sum_{J\geqslant 0, spin} \left[l_0 l_0^* \, |\langle J_f || \hat{\mathcal{M}}_J || J_i \rangle|^2 + l_3 l_3^* \, |\langle J_f || \hat{\mathcal{L}}_J || J_i \rangle|^2 - 2\, l_3 l_0^* Re \left(\langle J_f || \hat{\mathcal{L}}_J || J_i \rangle \langle J_f || \hat{\mathcal{M}}_J || J_i \rangle^* \right) \right] \right\}$$

$$\begin{aligned}\frac{d\sigma_{DM}^{GT}}{dE_r} &= \frac{2e^2\epsilon^2 g_D^2 E'^2_\chi}{p_\chi p'_\chi (2m_N E_r + m_{A'}^2)^2} \frac{m_N}{2\pi} \frac{4\pi}{2J+1} \\ &\times \left[\frac{(\vec{l}\cdot\vec{l}^* - l_3 l_3^*)}{2} |\langle J_f || \hat{\mathcal{T}}_J^{el5} || J_i \rangle|^2 \right. \\ &\left. + l_3 l_3^* \, |\langle J_f || \hat{\mathcal{L}}_J || J_i \rangle|^2 \right]. \\ &= \frac{2e^2\epsilon^2 g_D^2 E'^2_\chi}{p_\chi p'_\chi (2m_N E_r + m_{A'}^2)^2} \frac{m_N}{2\pi} \frac{4\pi}{2J+1} \\ &\times \frac{\vec{l}\cdot\vec{l}^*}{2} \frac{g_A^2}{6\pi} |\langle J_f || \sum_{i=1}^{A} \frac{1}{2} \hat{\sigma}_i \hat{\tau}_0 || J_i \rangle|^2. \end{aligned}$$

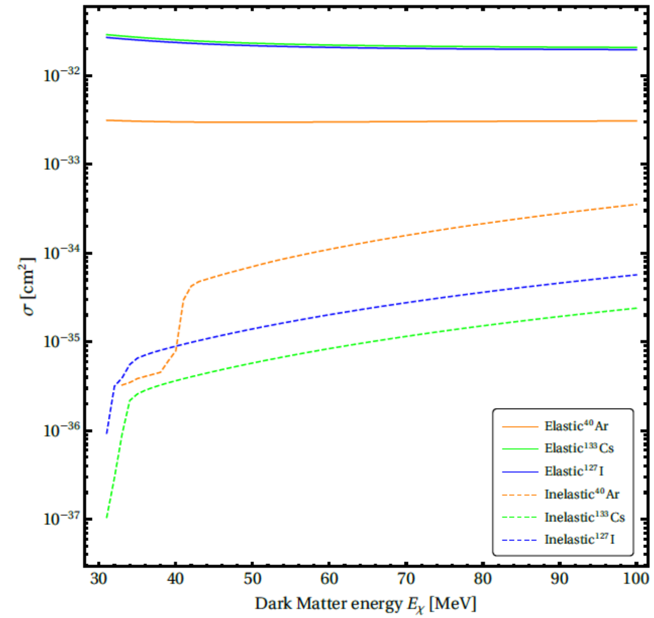


For ν-DM scattering with E_ν=30 MeV

- GT: dominates the cross-section
- Cross-section can be calculated:
  Using shell model code, e.g., BIGSTICKand
  Experimental measurements

MeV Signal - DM

We use BIGSTICK: SDPF-NR interaction for Ar



For elastic scattering:

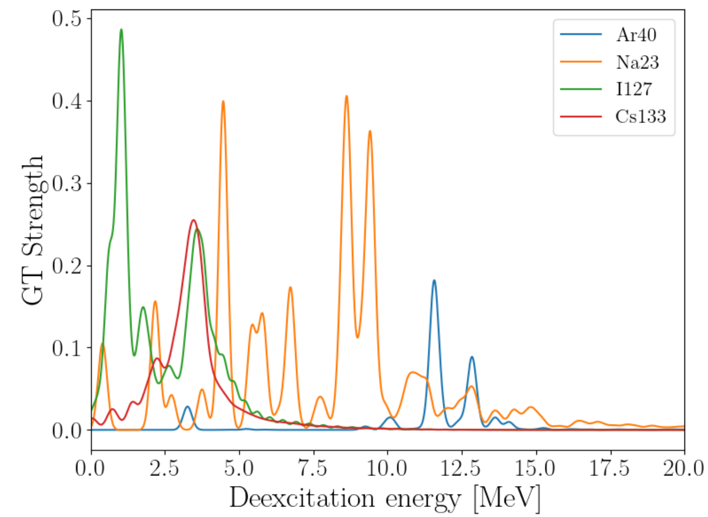
$$\frac{d\sigma_{\rm el}^{DM}}{dE_r} = \frac{e^2\epsilon^2 g_D^2 Z^2}{4\pi(E_\chi^2 - m_\chi^2)(2m_N E_r + m_{A'}^2)^2} F^2(q^2) \times \left[2E_\chi^2 m_N\left(1 - \frac{E_r}{E_\chi} - \frac{m_N E_r}{2E_\chi^2}\right) + E_r^2 m_N\right]$$

- Inelastic to elastic Cross-section ratio ~ 10^{-1}-10^{-3}
- The signal is now in the Mev Region (not KeV), neutrino background is easy to overcome
- The signal is a line signal
- Impact of threshold is different

Scattering	Experiment	Elastic	Inelastic	Ratio
ν-^{40}Ar	COHERENT	2.27×10^2	3.15	7.21×10
ν-^{40}Ar	CCM	1.91×10^4	2.65×10^2	7.21×10
ν-^{133}Cs	COHERENT	1.16×10^3	1.52×10^{-2}	7.65×10^3
ν-^{127}I	COHERENT	1.06×10^3	3.75×10^{-1}	2.81×10^3
χ-^{40}Ar	COHERENT	1.18	1.13×10^{-1}	1.04×10
χ-^{40}Ar	CCM	9.92×10	9.52	1.04×10
χ-^{133}Cs	COHERENT	4.11	4.91×10^{-3}	8.38×10^2
χ-^{127}I	COHERENT	3.87	1.16×10^{-2}	3.33×10^2

MeV signal-Light DM

- The cross-section for the line signal is smaller compared to the elastic signal



- The background is small

- threshold requirement is ~ 0.5-10 MeV

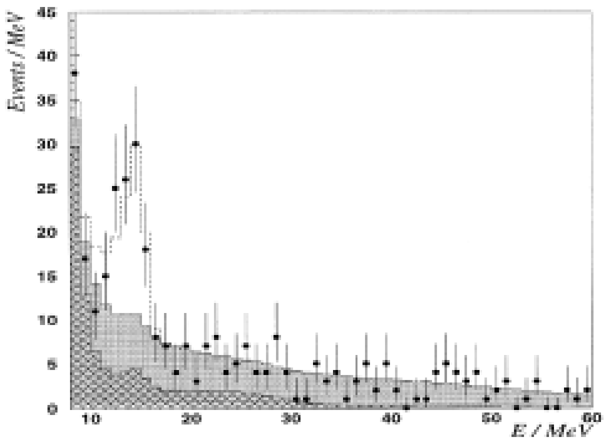
➔ Better sensitivity of the parameter space

Experiment	E_{beam} [GeV]	POT [yr^{-1}]	Target	Detector: material	mass	distance	angle	runtime	E_r^{th}
KARMEN	0.8	1.16×10^{22}	Ta	CH_2	56 t	17.7 m	100°	4 years	10 MeV
COHERENT†	1	6.0×10^{23}	Hg	NaI[Tl]	3.5 t	22 m	120°	3 year	$\sim$few keV
CCM†	0.8	7.5×10^{21}	W	Ar	7 t	20 m	90°	3 years	25 keV
PIP2-BD†	2	9.9×10^{22}	C	Ar	100 t	15 m	N/A	5 years	20 keV

- For Carbon, we use the measurement (KARMEN) of the 15.1 MeV line (in the neutral current data),
- We use the BIGSTICK calculations

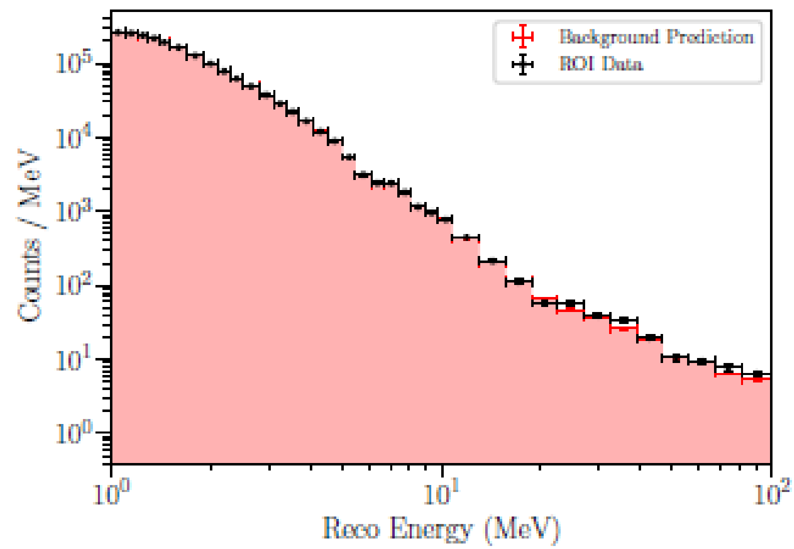
MeV signal-Light DM

KARMEN:



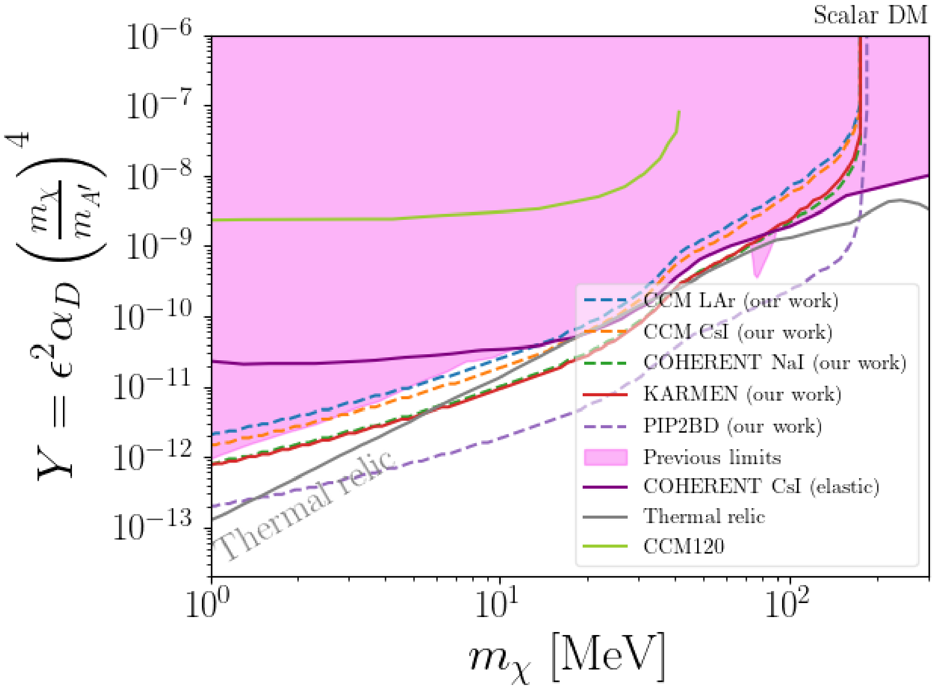
$$^{12}C(\nu_\mu \nu_\mu')\,^{12}C^*(1^+,1;15.1\ \mathrm{MeV})$$

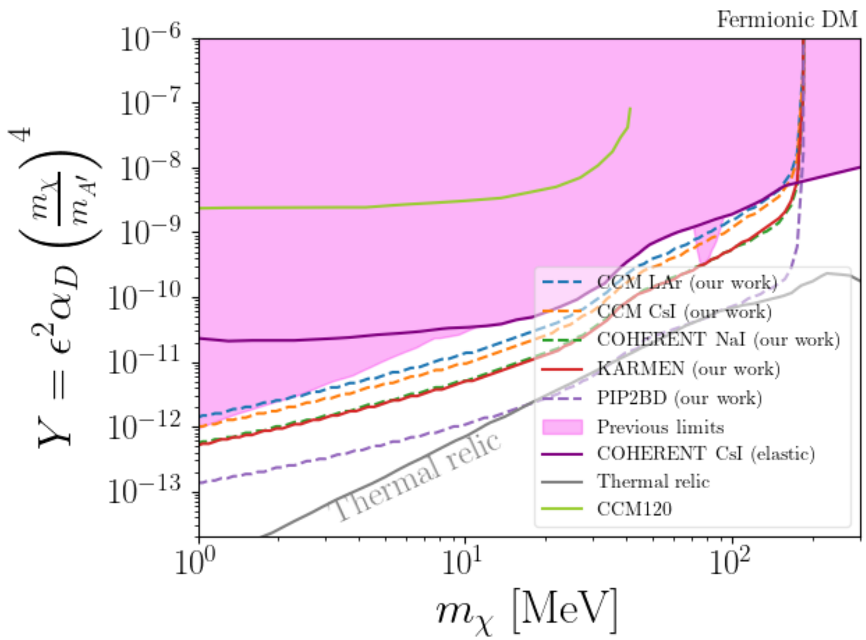
CCM 120



The background will be reduced
by 1/100 in CCM200 for the same POT

MeV signal – DM: COHERENT & CCM



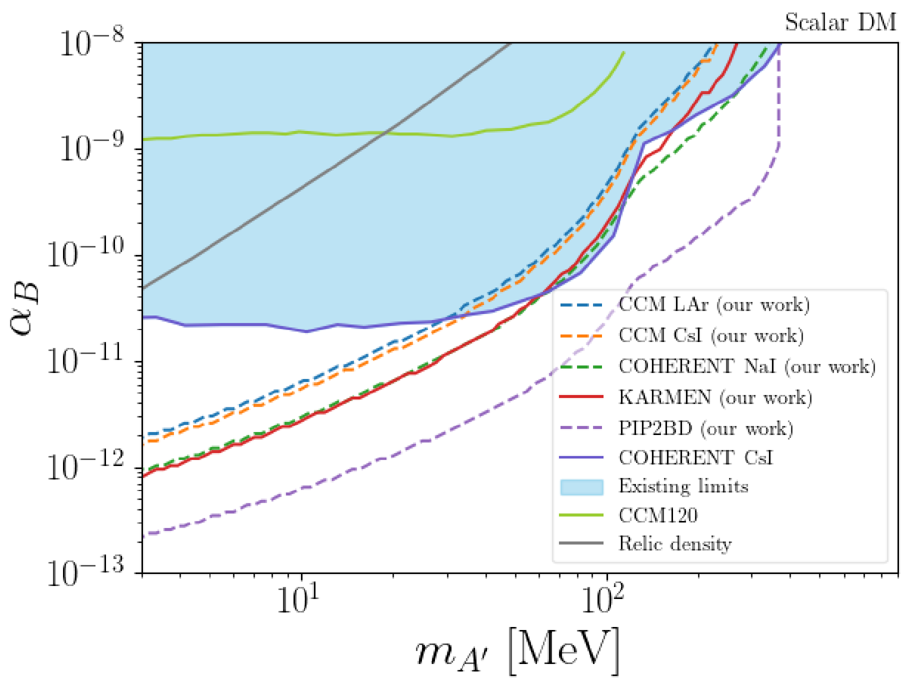


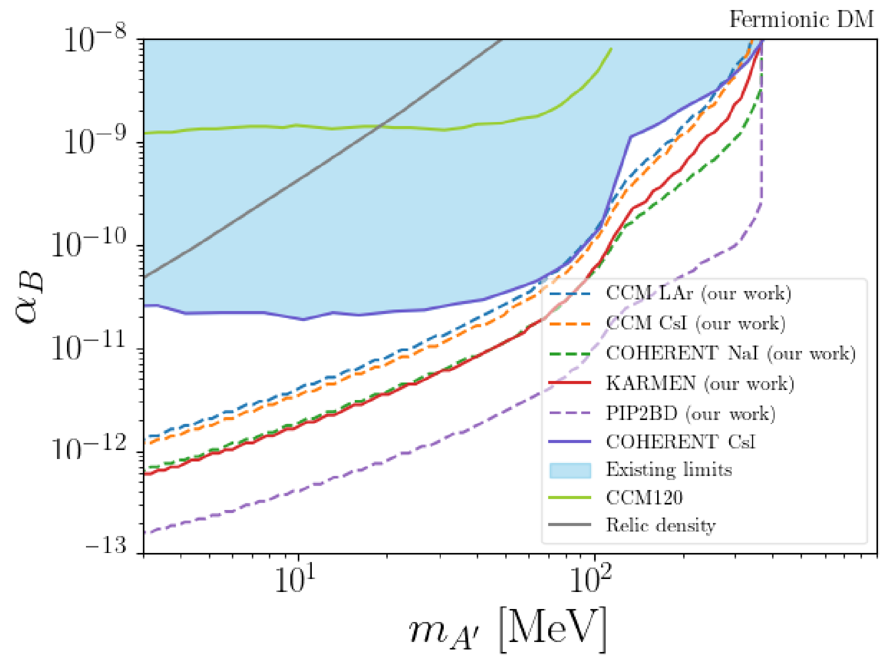
$g_D = \sqrt{2\pi}$, $\quad \frac{M_{A'}}{M_\chi} = 3$

- We use CCM 120 background measurements and projections for CCM 200 (for MeV region)
- t < 200 ns, prompt window reduces the neutrino background down to O(1) events
- Rescale the shell model prediction to be consistent with the experiment, **W. Tornow et al., 2210.14316**
- A lower threshold detector will help to improve the sensitivity in the elastic channel

B. Dutta, W. Huang, J. Newstead, PRL 2023

MeV signal – Light DM: COEHERNT & CCM





$U(1)_B$ Model

$$m_{A'}/m_\chi \approx 2$$

- Karmen seems to be providing the best limit with the observation
  Is the neutron background correctly estimated?
- CCM 200 is measuring the MeV scale electromagnetic signal

2. Axion Absorption

- Axions/ALPs interaction with the nucleon: $\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu\gamma^5 N, \quad g_{ann} = \frac{1}{f_a}$

- ALPs can be produced from the deexcitation

Channel	E_γ (keV)	Transitions	Φ_γ (fission^{-1})	(GCi)
$p(n,\gamma)d$	2230	Isovector M1	0.25	0.61
$^{10}B(n,\alpha)^7Li^*$	478	M1 $(\frac{1}{2}^-) \to (\frac{3}{2}^-)$	0.28	0.68

TEXONO,
Phys.Rev.D 75 (2007) 052004

ALPs can be absorbed at the detector and produce line signals:

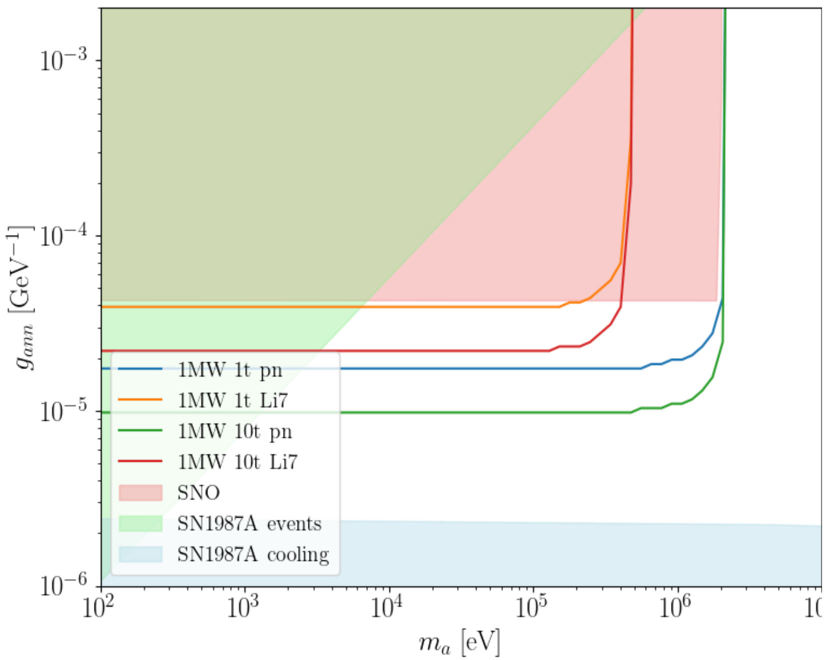
$$\sigma_{\rm abs}(E_a, \Delta_2) = \frac{g_A^2 \pi}{6(2J+1)} g_{ann}^2 \delta(E_a - E_r - \Delta_2)\, p_a\, |\langle J_f || \sum_{i=1}^{A} \frac{1}{2} \hat{\sigma}_i \hat{\tau}_0 || J_i \rangle|^2$$

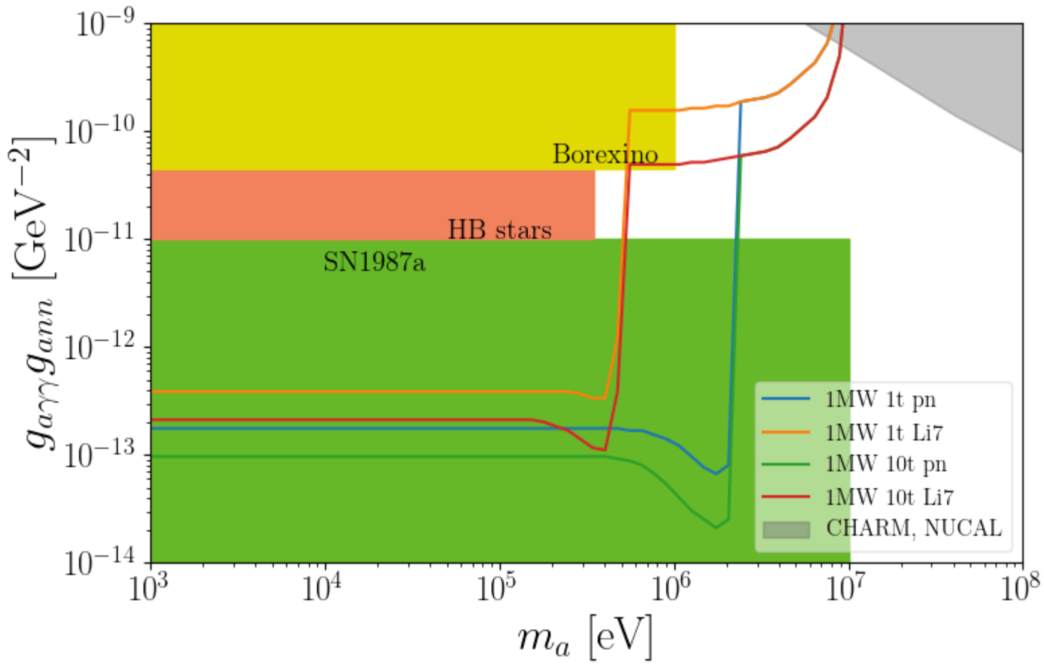
$a + N \rightarrow N^*$

- We can probe g_{ann} : Target and detector excitation;
  $g_{ann}\, g_{a\gamma\gamma}$: Primakoff production (detection) and deexcitation detection (production);
  $g_{ann}\, g_{aee}$: Compton production (detection) and deexcitation detection (production)

2. Axion Absorption

CsI detector: 1, 10ton, 1 MW reactor, detector is 1 m away from the core





- The production is via pn/Li and the detection uses the deexcitation photons at CsI (left)

- The production is via Primakoff, deexcitation and the detection is via decay, dexcitation and inverse Primakoff (right)
- The parameter space constraints are from: **Lella et al, 2306.01048**

B. Dutta, W. Huang, J. Newstead, To appear

3. ATOMKI Anomaly

- Neutrons in these experiments can be used ATOMKI anomaly (>5 σ) with Be8

$$p+A \rightarrow N^* \rightarrow N + e^+e^-$$

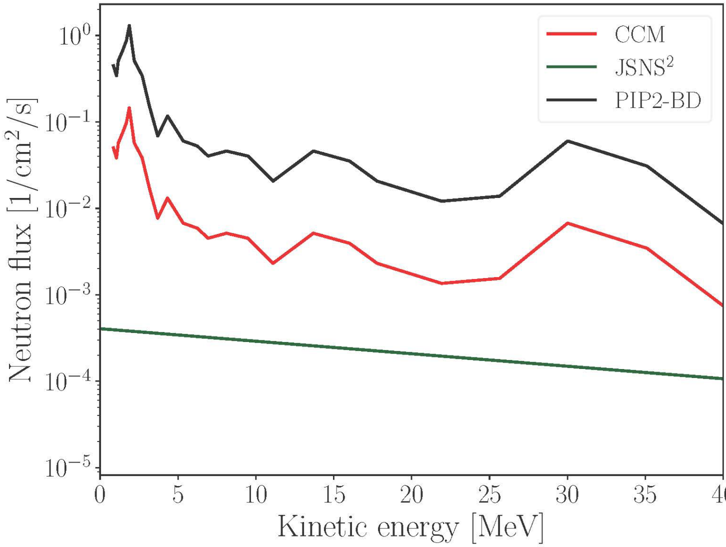
- Excess also has been observed with He4 and C12

Excess can be explained by X-boson prompt decays

➢ Neutron flux at CCM/JSNS^2 detectors to produce X boson at the detector which decays promptly

- CCM flux is at the detector using experimental results and MCNP
- JSNS^2 $\phi_n(E_n) = \frac{\alpha}{30}\exp(-E_n/30\text{MeV})$

α is fit to the data at the detector=387/beam spill



- CCM: neutrons excite the Oxygen of PMT glass
- JSNS2: neutrons excite Carbon, Oxygen of PMT glass

$\sigma_n \sim 10^{-2\text{-}3}$ *Barn*
Using GSM-CC

3. ATOMKI Anomaly

$$\mathcal{L} = \epsilon_p \bar{p}\gamma^\mu\gamma^5 p X_\mu + \epsilon_n \bar{n}\gamma^\mu\gamma^5 n X_\mu$$

Parameter space to explain ATOMKI anomaly, Hostert, Pospelov, **PRD, 2023**

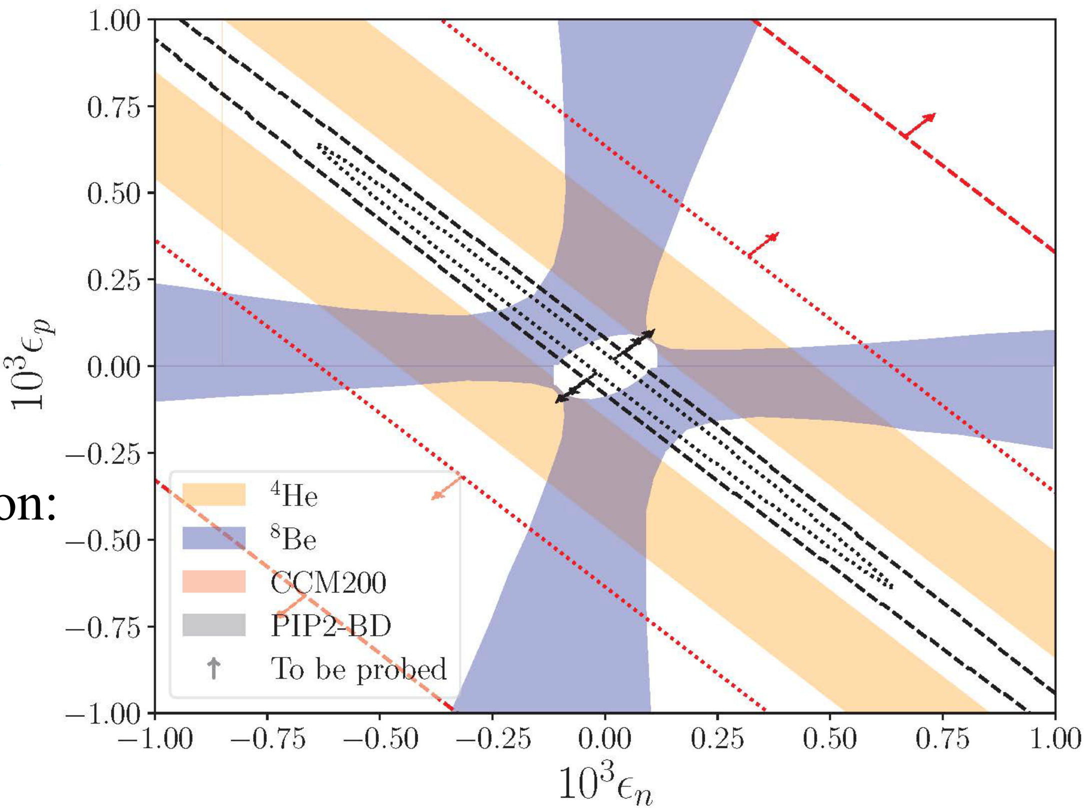
$$\phi_\gamma = nw\frac{N_A}{M_s}\frac{\Gamma_\gamma}{\Gamma_{\text{tot}}}\int \sigma_n(E_n)\frac{d\phi_n}{dE_n}dE_n$$

$$\Gamma_X^{J=1^+} = \frac{p_X}{18\pi}\left(2+\frac{E_X^2}{m_X^2}\right)(\epsilon_p+\epsilon_n)^2|\langle\hat{\sigma}\rangle|^2$$

$$\Gamma_X^{J=1^-} = \frac{p_X^3}{144\pi}(\epsilon_p-\epsilon_n)^2|\langle\hat{D}_3^\sigma\rangle|^2$$

X particle flux from deexcitaion:

$$\phi_X = \phi_\gamma\frac{\Gamma_X}{\Gamma_\gamma}$$

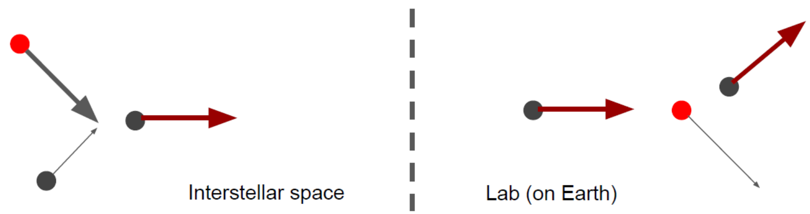


B. Dutta, B. Hu, W. Huang, R. Van de Water, To appear

Light DM at Large ν detectors

Various ways of probing Sub-GeV DM:

Cosmic ray scattered

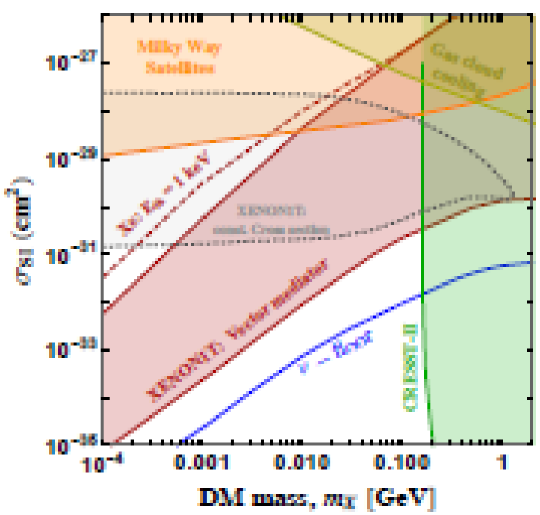


Bringmann, Pospelov, 2018

Ema, Sala, Sato, 2018

Dent, Dutta, Newstead, Shoemaker, 2019

Low mass DM (up to 10 GeV) becomes energetic ➔ detection becomes easier

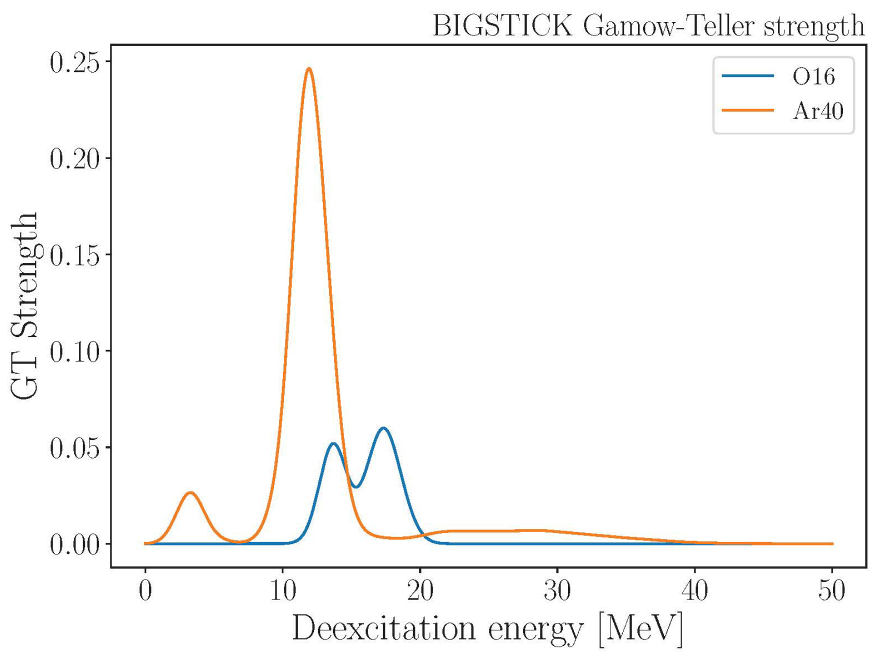


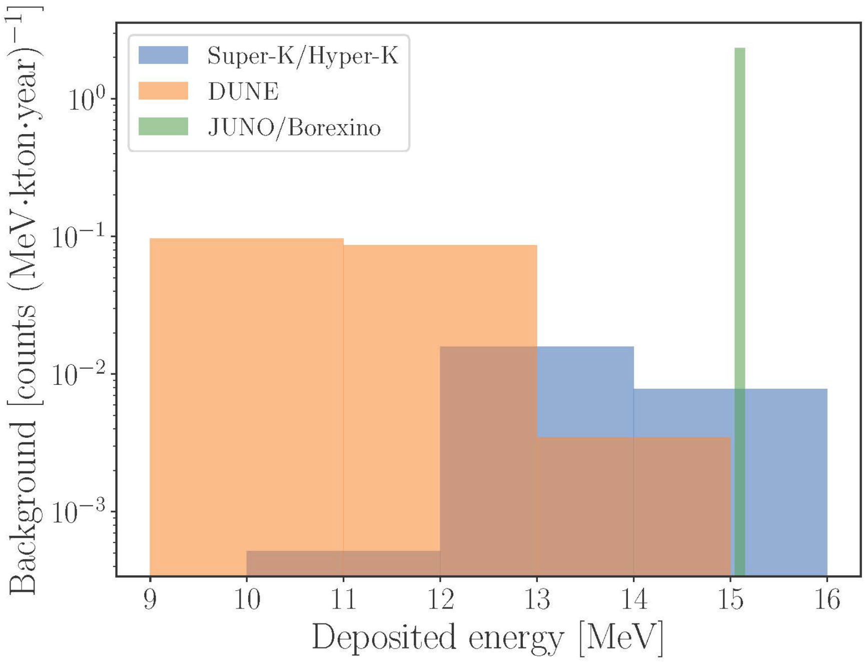
- Since light DM comes to the detector with higher energy, threshold does not matter

➔ Large scale neutrino detectors can be used

- We can use this boosted DM and inelastic nuclear scattering

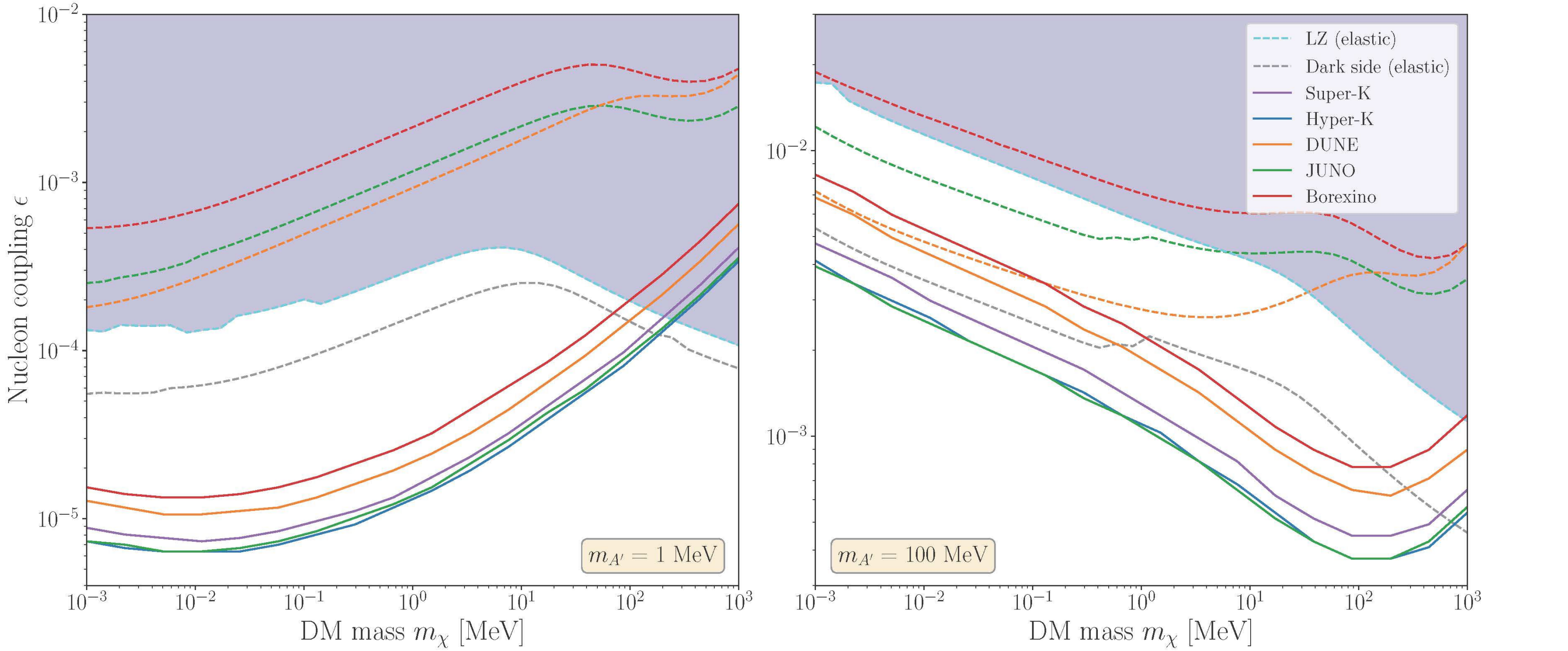
Direct Detection at Large ν detectors



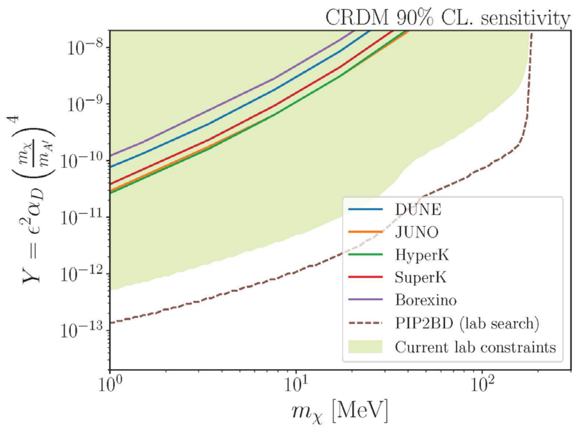


Deexcitation photons: Background events for various detectors

Large ν detectors : Light DM



- Solid lines denote the inelastic channel, while dashed lines are elastic channels.
- We use the hadronic interactions.



$$\frac{M_{A'}}{M_\chi} = 3$$

← Beam-dump-based DM limit

B. Dutta, W. Huang, D. Kim J. Newstead, J. Park, I. Shaukat Ali, 2402.04184

Outlook

- Beyond the SM physics can be probed at CEνNS
- New physics ideas can be probed efficiently at the inelastic nuclear scattering using deexcitation line signals
- Some regions of light DM parameter space show better sensitivity utilizing inelastic channel
- ALPs can be probed with g_{ann} couplings using absorption-based deexcitation.
- ATOMKI anomaly can be probed using the neutrons at the beam-dump based CEνNS experiments.
- Inelastic nuclear searches can provide a very good ability to probe light DM in large-scale neutrino detectors.