Physics Opportunities in the CEvNS Experiments

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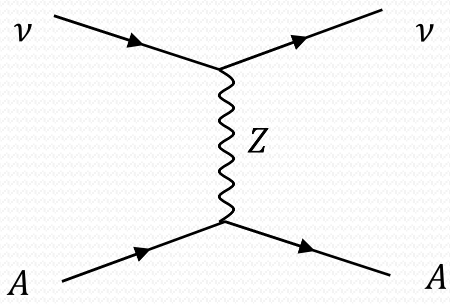
Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

- Coherent elastic neutrino nucleus scattering (CEvNS): A neutrino hits a nucleus via an exchange of a SM Z gauge boson, and the nucleus recoils as a whole, being coherent when $QR \ll 1$ with Q, R being momentum transfer and nucleus radius, respectively (up to $E_\nu \sim 50$ MeV) [Freedman, Schramm, Tubbs (1977)].

$$\nu + A_N^Z \to \nu + A_N^Z$$

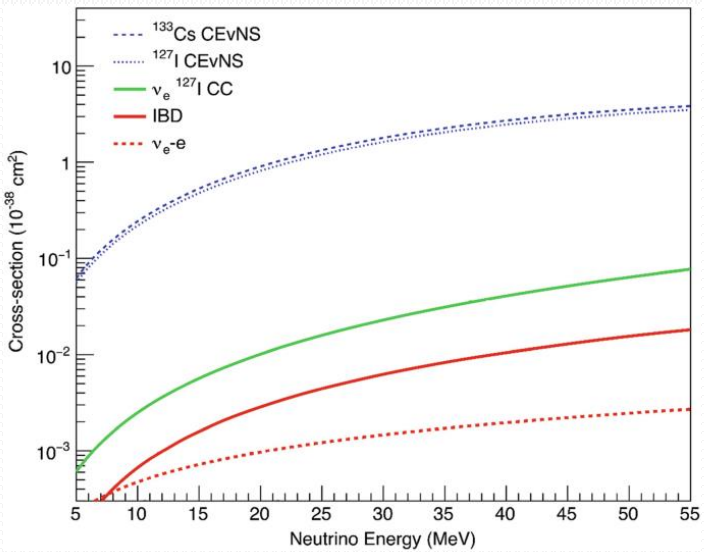


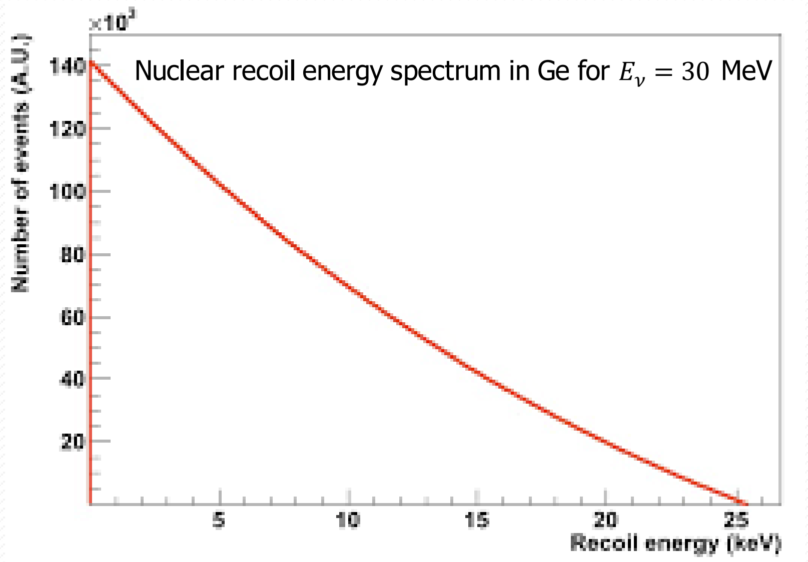
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(Q^2)^2$$

$$\propto N^2$$

T: recoil kinetic energy
E_ν: neutrino energy
M_A: target mass ($M_A = AM_{\text{nucleon}}$)
$F(Q^2)$: nucleon form factor
$Q_W = N - Z(1 - 4\sin^2\theta_W)$

CEvNS Experiments



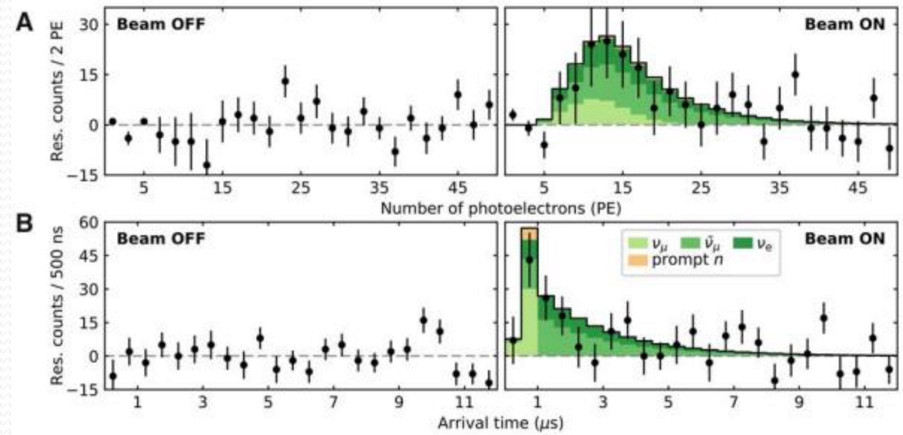


Large cross section (by neutrino standards), but tiny nuclear recoil energy

- Various experiments to check CEvNS
  - ✓ Proton beam: COHERENT, CCM
  - ✓ Reactors: MINER, CONNIE, CONUS, SoLid, NEON, ν-cleus, Ricochet, SBC-CEvNS, vIOLETA, νGeN, RED-100, …

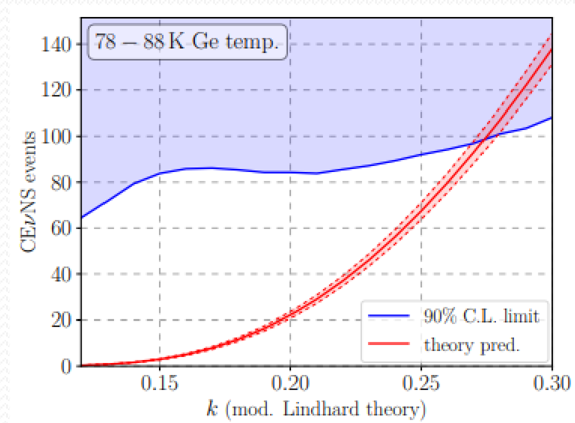
Measurements of CEvNS Events

- COHERENT [COHERENT Collaboration, arXiv:1708.01294]:
  No CEvNS rejected at 6.7σ – CsI detector



- COHERENT [COHERENT Collaboration, arXiv:2003.10630]:
  No CEvNS rejected at more than 3σ – LAr detector

- No significant CEvNS event observations yet in reactor neutrino experiments
  - ✓ CONUS [CONUS Collaboration, arXiv:2011.00210]: Ge detector
  - ✓ CONNIE [CONNIE Collaboration, arXiv:2110.13033]: Skipper-CCD



CEνNS experiments are **NEW** physics machines

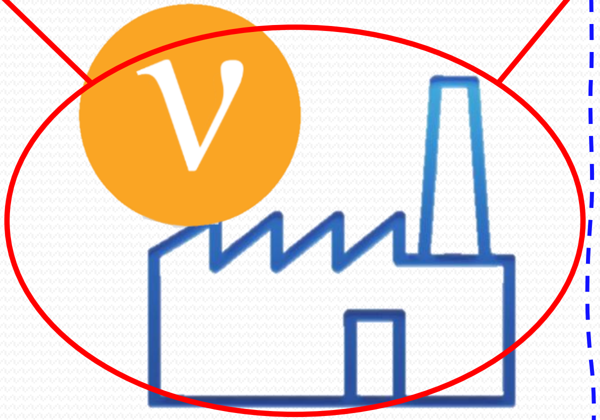
as well as **NEU**trino factories.

… much more BSM potentials than expected

BSM Physics in CEvNS Experiments

Neutrino-sector BSM

- Beyond 3 neutrino flavors (e.g., sterile neutrinos)
- Non-standard interactions of neutrinos
- …



Non-neutrino-sector BSM

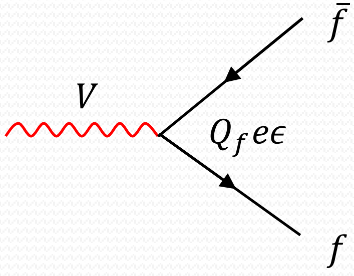
- (Light) dark matter search
- (Light) mediators or portal scenarios [e.g., dark photon, axion-like particles (ALP)]
- …

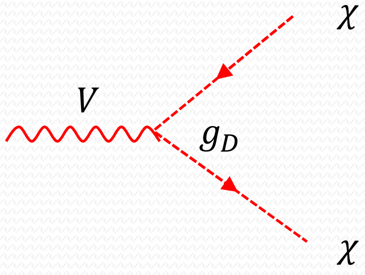
This talk

Light Dark Matter in Stopped Pion Neutrino Experiments

Vector portal (scalar) dark-matter scenario

$$\mathcal{L} \supset e\epsilon V^\mu J_\mu^{\mathrm{EM}} + g_D V^\mu J_\mu^D$$

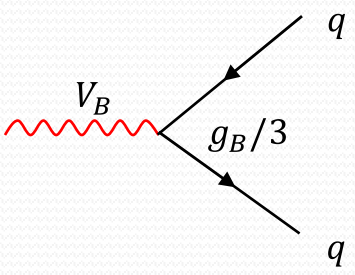


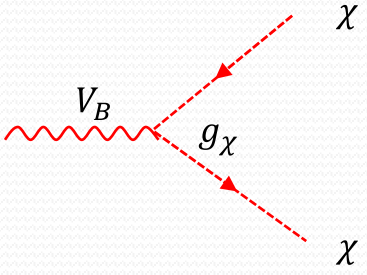


Leptophobic (scalar) dark-matter scenario

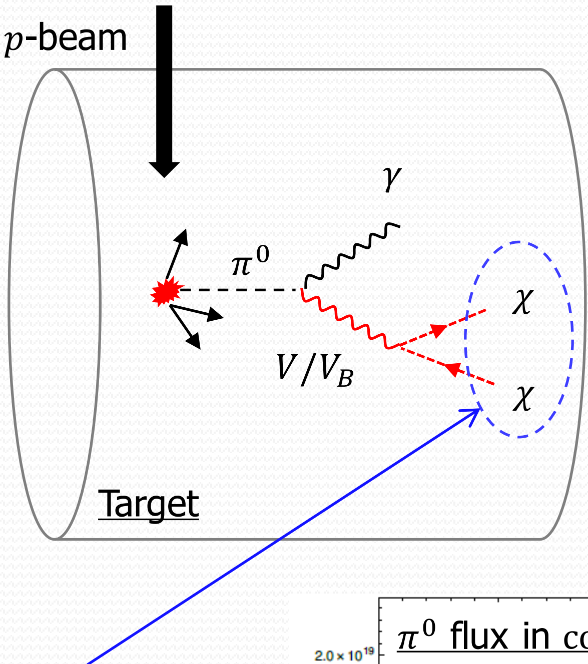
$$\mathcal{L} \supset g_B V^\mu J_\mu^{\mathrm{B}} + g_\chi V^\mu J_\mu^D$$

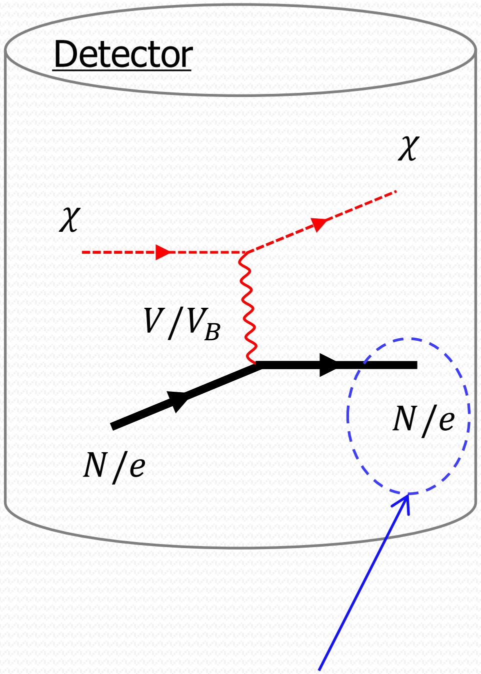
$$J_\mu^{\mathrm{B}} = \frac{1}{3}\sum_i \bar{q}_i \gamma_\mu q_i$$





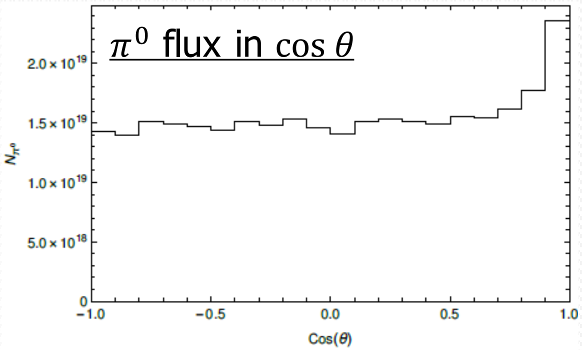
Production and Detection of Dark Matter





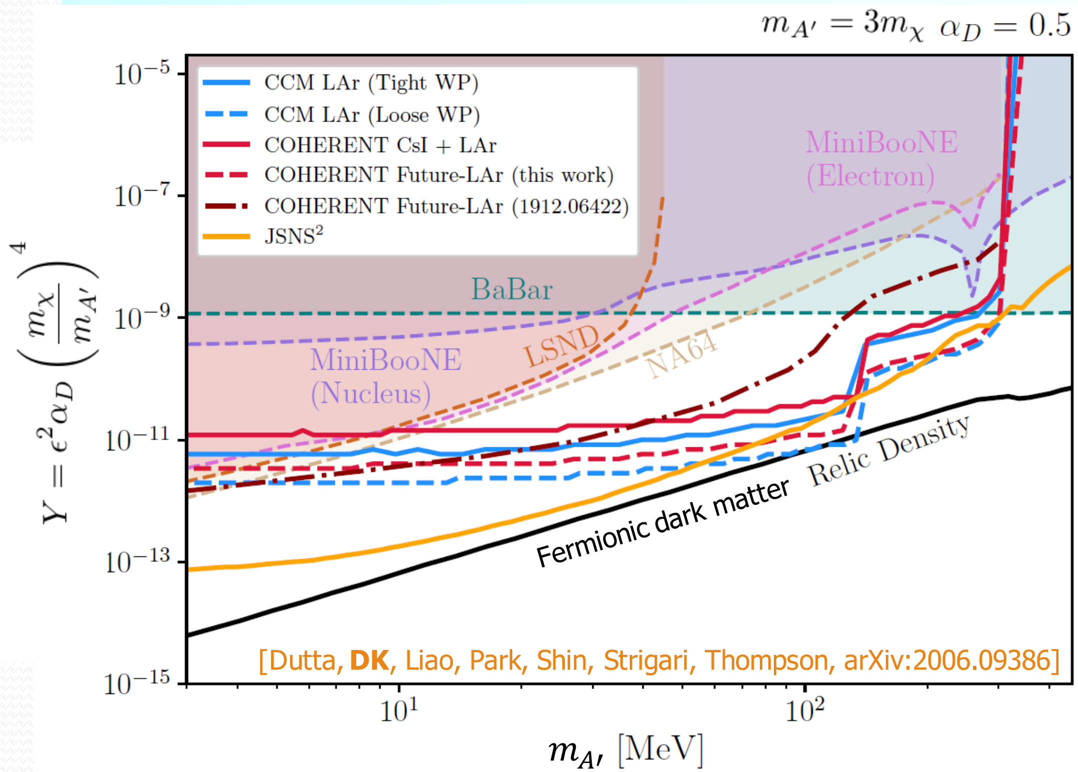
π^0-induced DM flux widespread in angle

$N_{\pi^0} = \sim 0.1$/POT

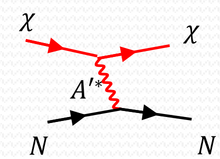


Observing a scattering off a nucleus/electron

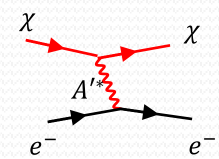
Dark Matter Search Prospects



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



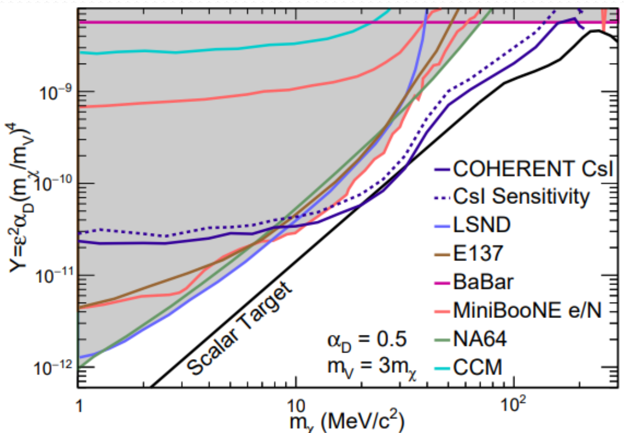
For COHERENT & CCM

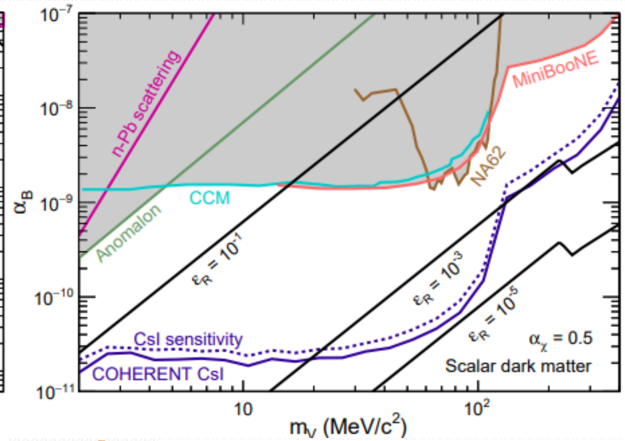


For JSNS^2

- Prompt (i.e., π-induced ν) and delayed (i.e., μ-induced ν) neutrino-induced backgrounds can be suppressed by energy and timing cuts, respectively [Dutta, **DK**, Liao, Park, Shin, Strigari, arXiv:1906.10745]
- Analyses done with energy $\oplus$ timing cuts

Experimental Results at COHERENT and CCM





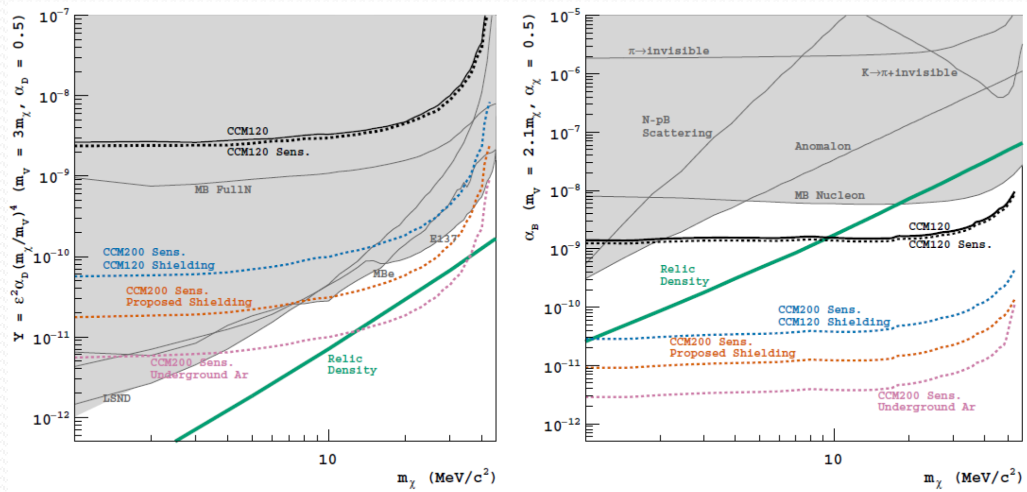
[COHERENT Collaboration, arXiv:2110.11453& 2205.12414]

COHERENT

- ❑ CsI detector with 3.2×10^{23} POTs
- ❑ Side-band analysis with a timing cut

CCM

- ❑ CCM120 sensitivity reaches at 90% C.L. with 1.8×10^{21} POTs in the engineering run.
- ❑ Prospective limits are based on 2.25×10^{22} POTs (3 year run).
- ❑ Analyses done with energy ⊕ timing cuts

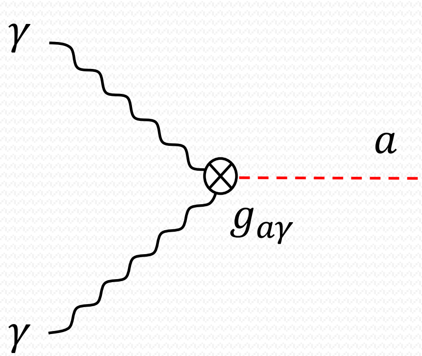


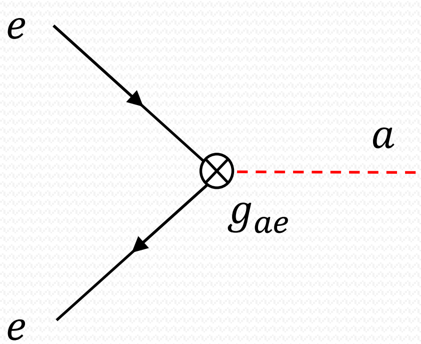
(a) vector portal (b) leptophobic

[CCM Collaboration, arXiv:2105.14020 & 2109.14146]

ALP in Reactor and Stopped-π ν Experiments

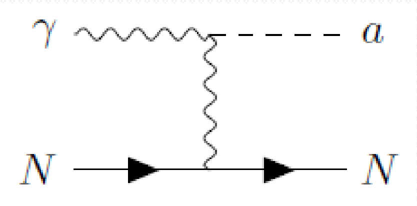
$$\mathcal{L}_{\rm ALP} \supset -\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - g_{ae}\, a\, \bar{e}\, i\gamma_5\, e$$





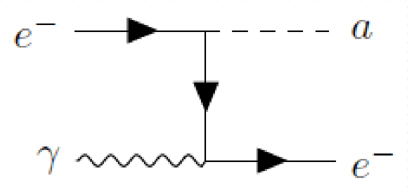
Production of ALP

Scenarios of ALP coupling to photon

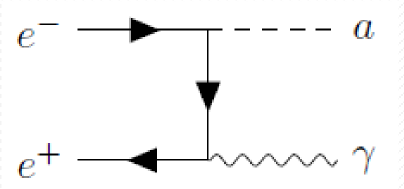


Primakoff

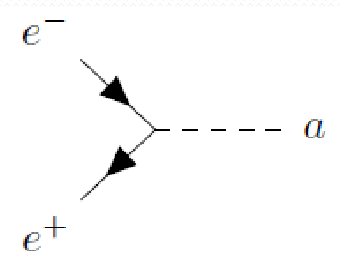
Scenarios of ALP coupling to electron



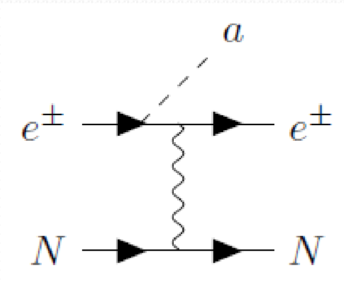
Compton



Associated production



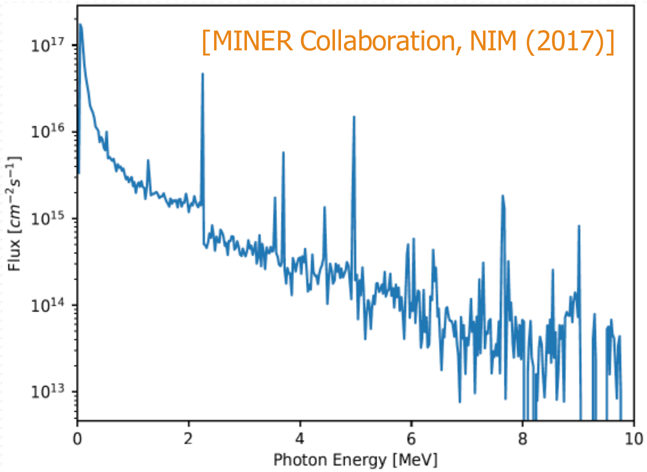
Resonant production



ALP-bremsstrahlung

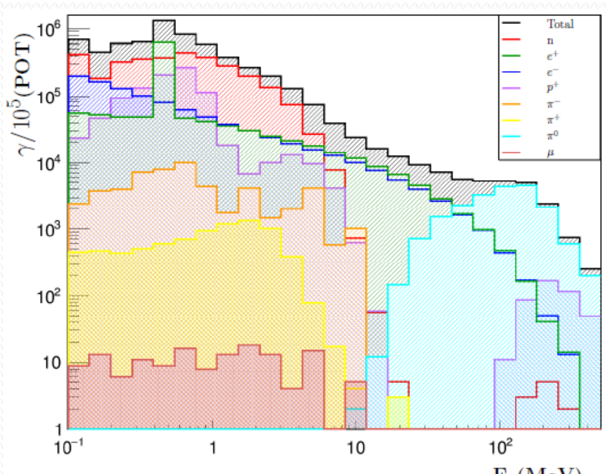
⇒ **γ and e** are the major sources of ALPs.

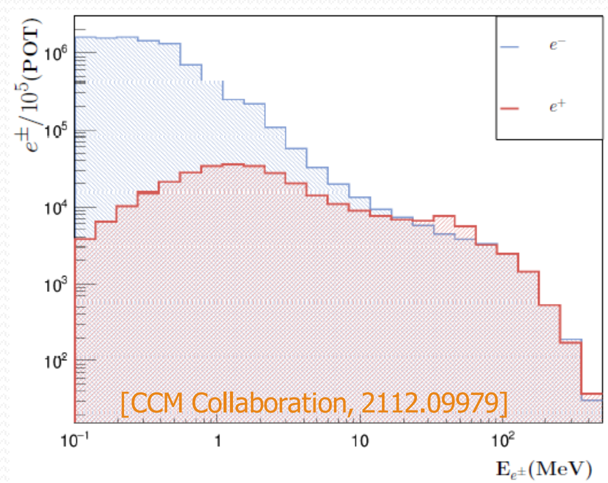
Photon and e± Fluxes



- ❑ Expected photon flux based on a GEANT simulation for a MW MINER-like reactor: **$\sim 10^{19}$ photons/s**.
- ❑ Cascade photons, photons from isotope decays etc included.

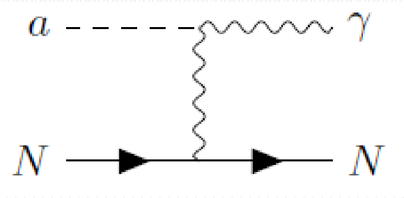
- ❑ GEANT4 10.5 simulation using the QGSP_BIC_HP library
- ❑ Flux estimates based on 10^5 POTs.



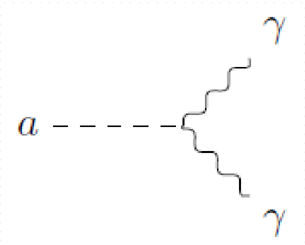


Detection of ALP

Scenarios of ALP coupling to photon

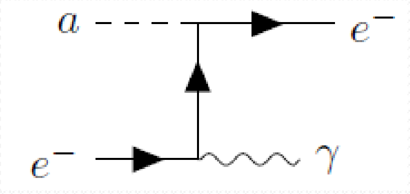


Inverse Primakoff

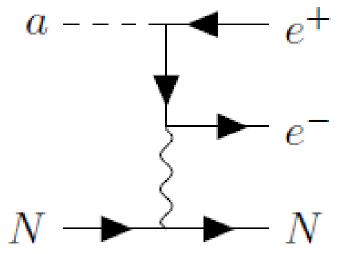


Diphoton decay

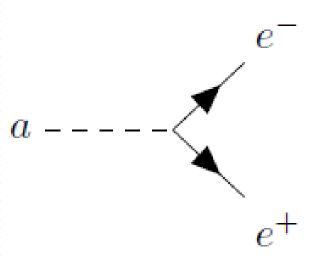
Scenarios of ALP coupling to electron



Inverse Compton

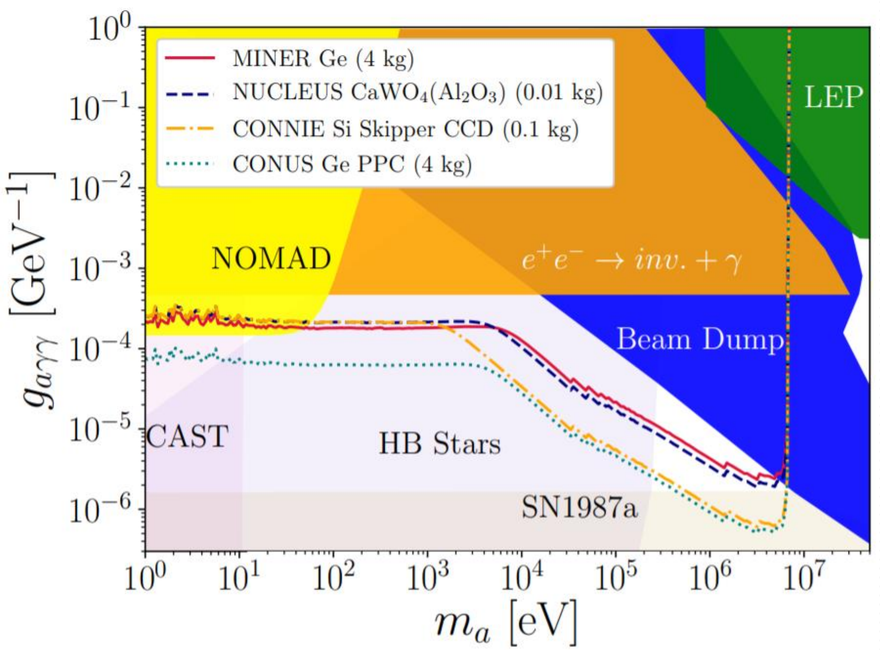


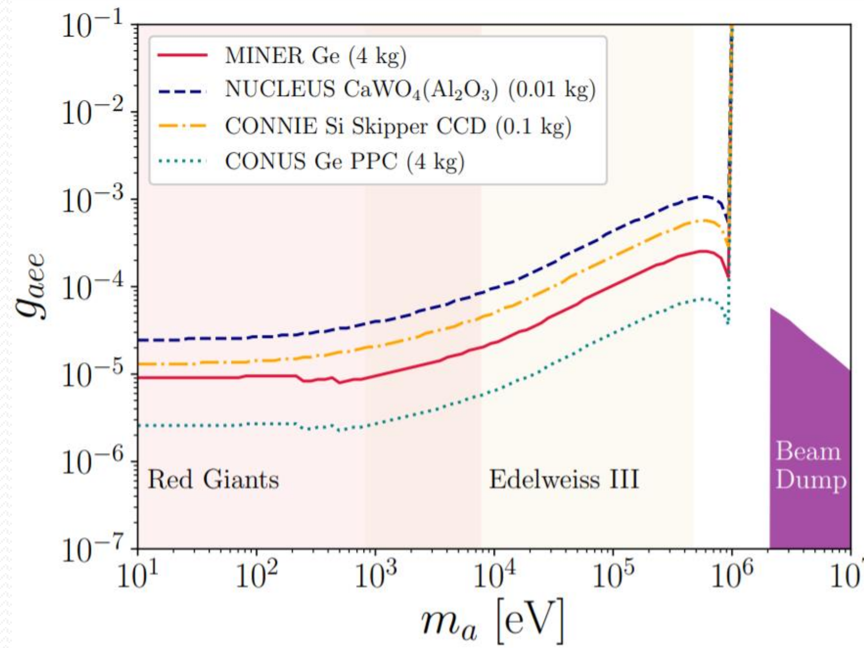
External pair conversion



Di-lepton decay

ALP Search Prospects: Reactors

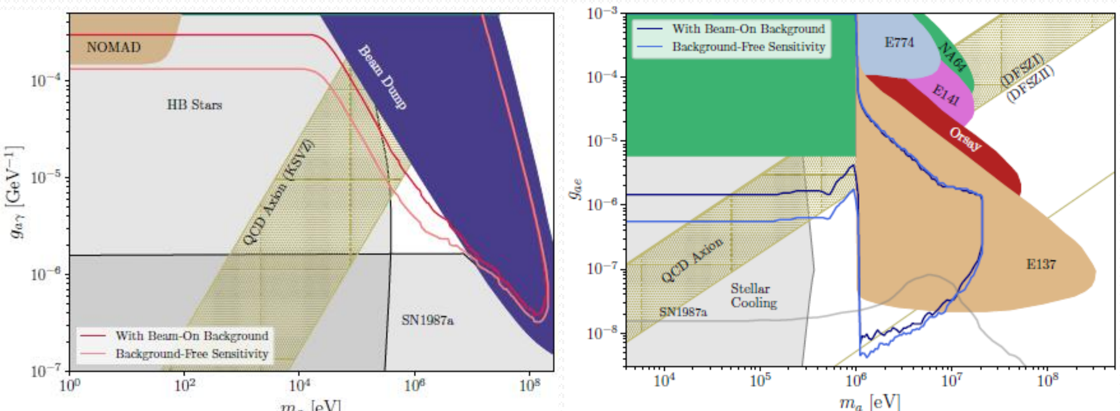




Experiment	Core Thermal Power	Core Proximity (m)	Bkg Rate in ROI (DRU)	Exposure (kg·days)
MINER (Ge)	1 MW	2.25	100	4000
ν-cleus ($CaWO_4$)	4 GW	40	100	10
CONNIE (Si CCD)	4 GW	30	700	100
CONUS (Ge PPC)	4 GW	17	100	4000

[Dent, Dutta, **DK**, Liao, Mahapatra, Sinha, Thompson, arXiv:1912.05733]
See also [Aristozabal-Sierra, De Romeri, Flores, Papoulias, arXiv:2010.15712]

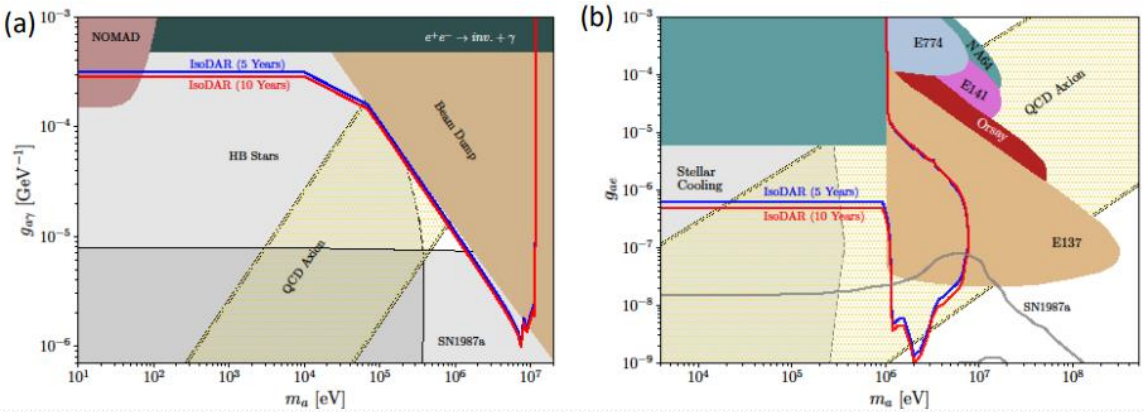
ALP Search Prospects: CCM, IsoDAR, and DAMSA



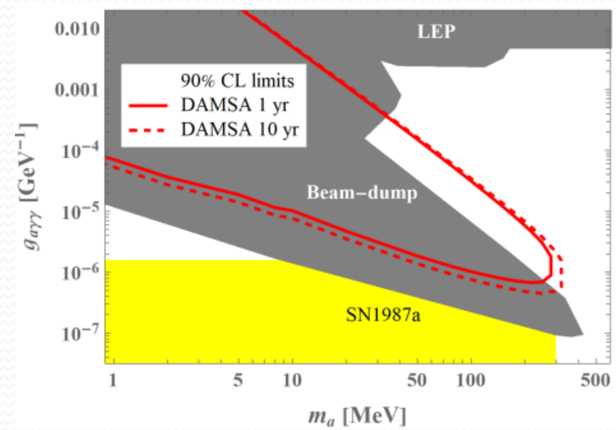
[CCM Collaboration, arXiv:2112.09979]

CCM

- ❑ 90% C.L. with a total exposure of 2.25×10^{22} POT (3 year run)
- ❑ Only one coupling is turned on, and the other is assumed negligible/suppressed.



[IsoDAR Collaboration, arXiv:2207.13659]

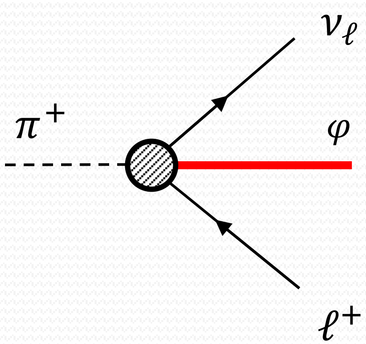


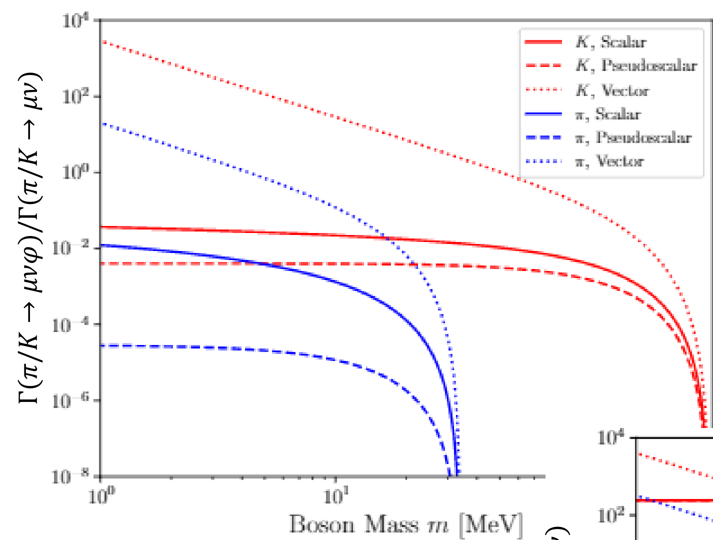
[Jang, **DK** et al, arXiv:2207.02223]

IsoDAR: LSC detector (Yemilab) with 7.9×10^{24} 60 MeV protons

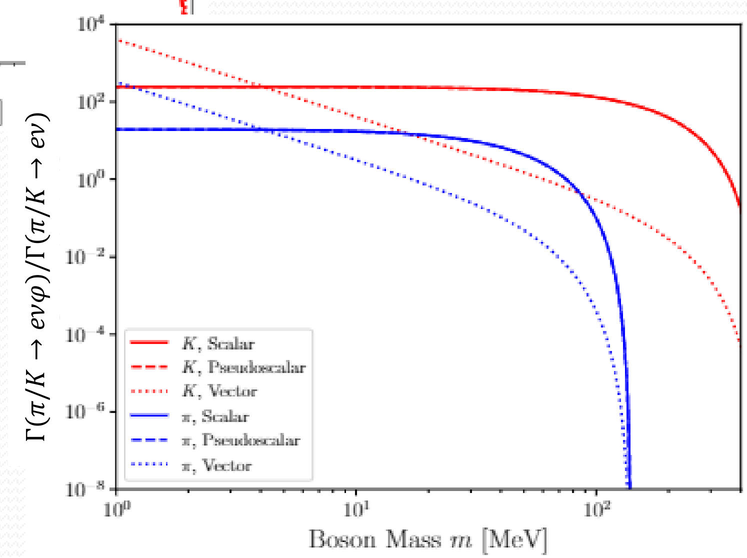
DAMSA: RAON with 1.4×10^{23} 600 MeV protons

Dark-Sector Signals from Charged Mesons





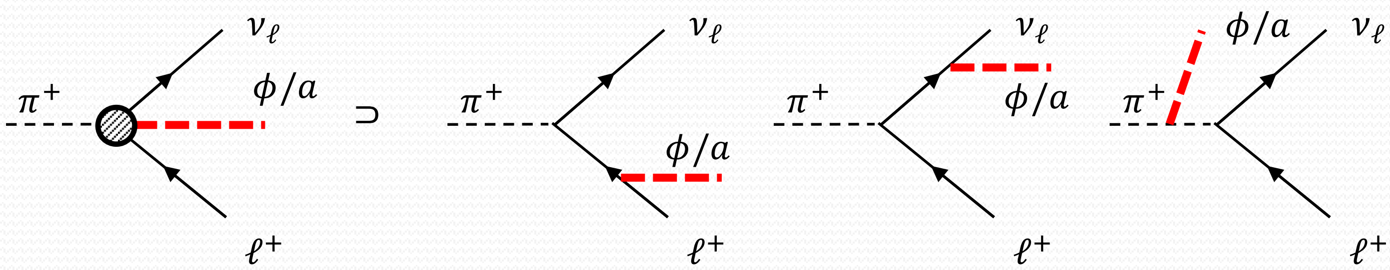
- φ is assumed to couple to the charged lepton only and the associated couplings are set to be unity for comparison.



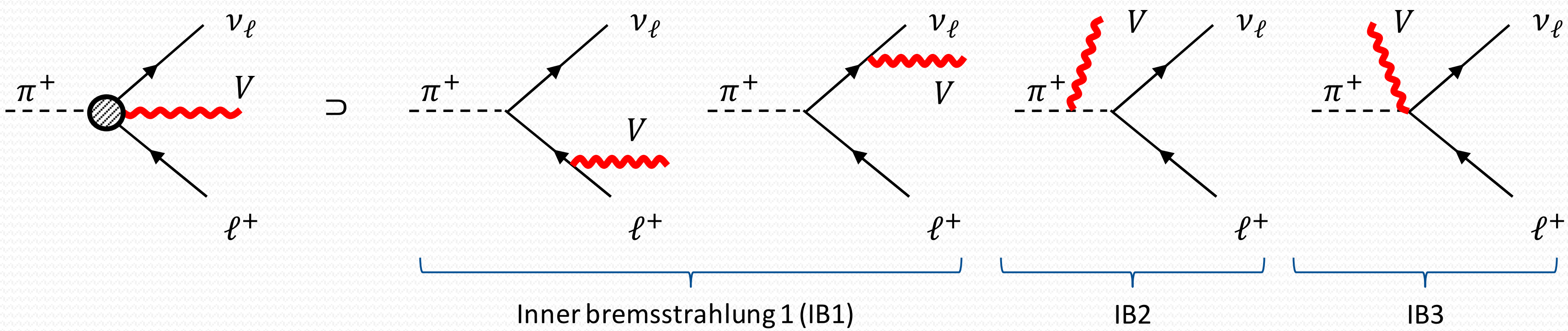
By adding the third particle φ (e.g., scalar, pseudoscalar, vector, etc), the helicity suppression (present in the corresponding two-body decays) can be evaded, i.e., 3-body decays can be **hugely enhanced**. The decay to a massive vector is even more enhanced due to the longitudinal polarization. [e.g., Carlson, Rislow, arXiv:1206.3587]

Various Dynamics in the Three-Body Decay

(Pseudo)scalar case



Vector case

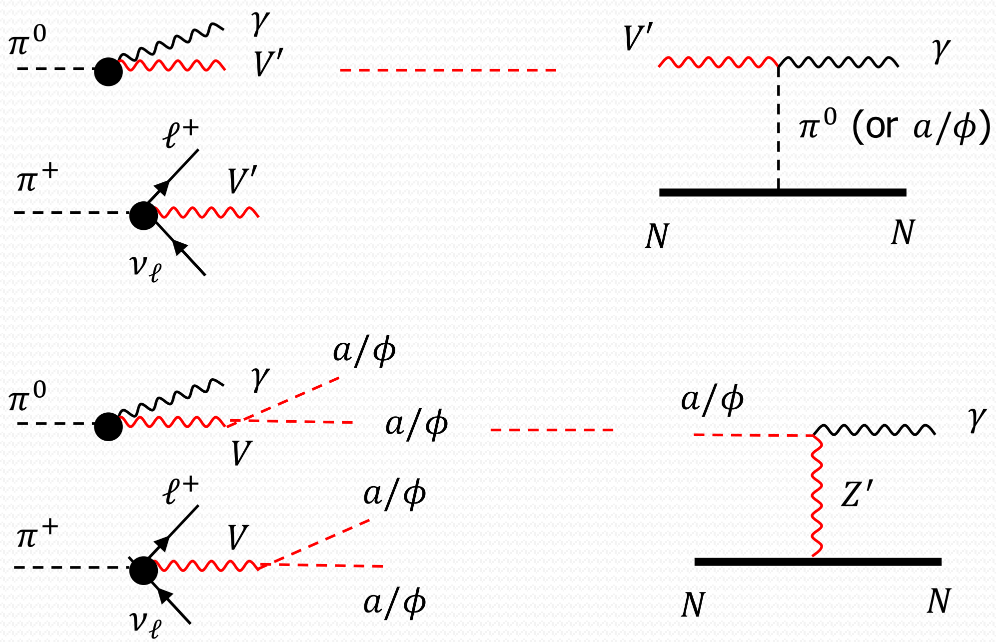


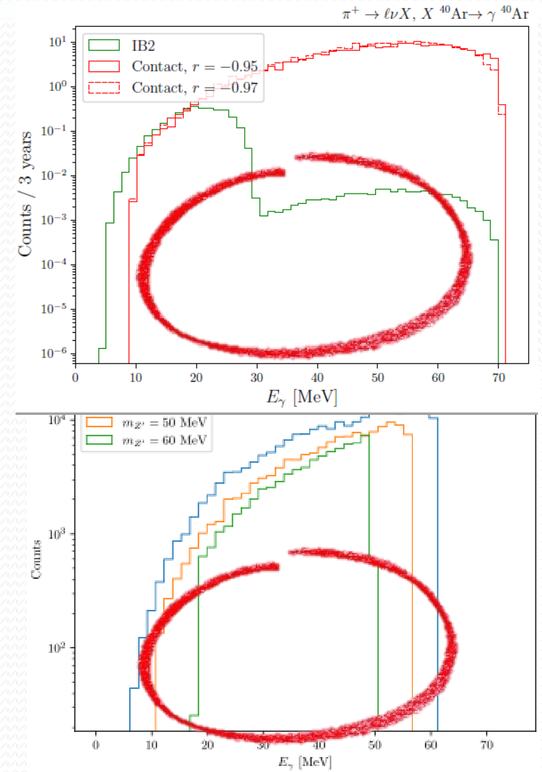
- Typically, IB3 contributions ≫ IB2 ≈ IB1

Cf. For models having couplings to the quark contents inside the meson, (QCD-origin) structure-dependent (SD) terms may arise.
See also [Khodjamirian, Wyler, arXiv:hep-ph/0111249] for more details.

Various Testable Scenarios/Predictions at CCM

Production Detection





High-energy deposits!

- These scenarios predict electromagnetic signals depositing more than MeV ($\gg$ hadronic recoil energy).

Take-Home Messages

- ❑ CEvNS events have been recently discovered, and CEvNS experiments are excellent **NEW** physics testers as well as **NEU**trino factories.
- ❑ CEvNS experiments are sensitive to Dark-Sector physics signals including
  - ✓ light dark matter signals
  - ✓ axion-like particles signals
- ❑ Charged mesons are overlooked but efficient sources of new physics particles especially in the stopped-pion neutrino experiments.

Thank you!