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Dark Photon / Dark Matter Measurements with CEνNS Detectors

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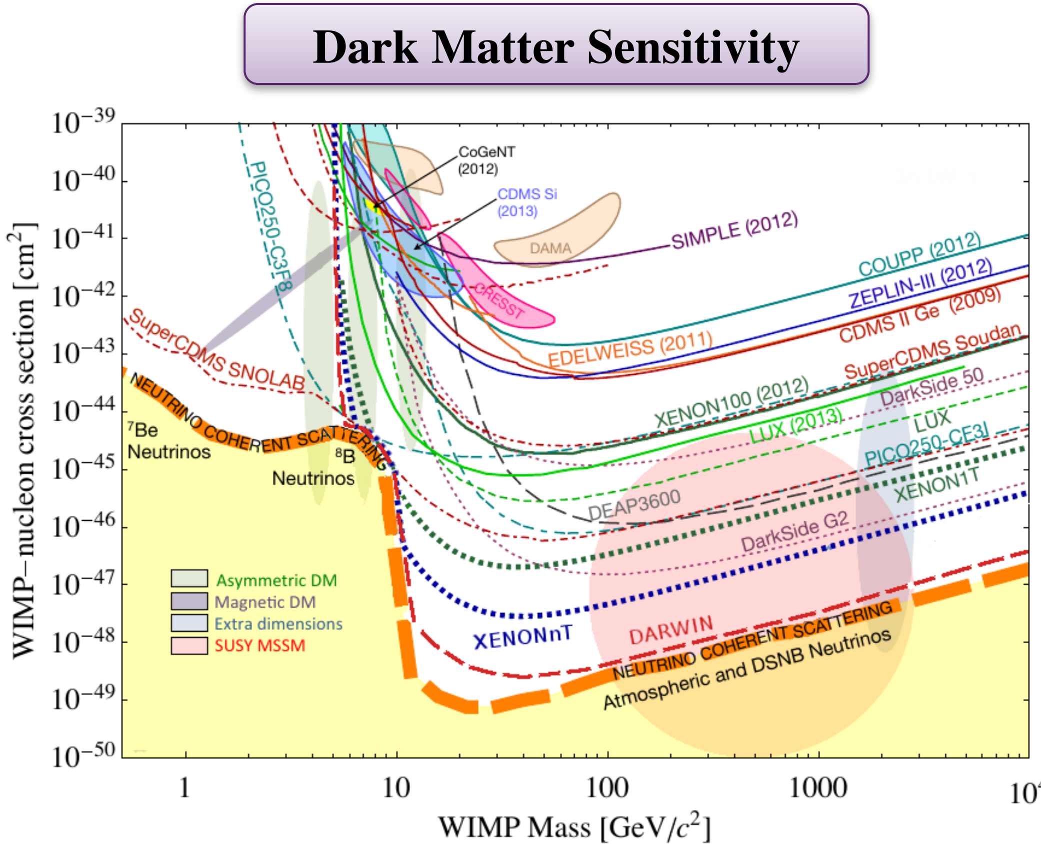
Where Are We With Direct Searches?

<u>"WIMP Miracle"</u>

- Electroweak scale masses (~100 GeV) and cross sections (10^{-38} cm^2) give correct relic abundances
- Conflicting claims, mostly ruled out phase space
- A rich dark sector easily bypasses "miracle"



G.L. Baudis, *Phys. Dark Univ.* **4** (2014) 50. arXiv:1408.4371 [astro-ph].

Where Are We With Direct Searches?

"WIMP Miracle"

What about here

- sections (10-
correct relic a

- Conflicting cl
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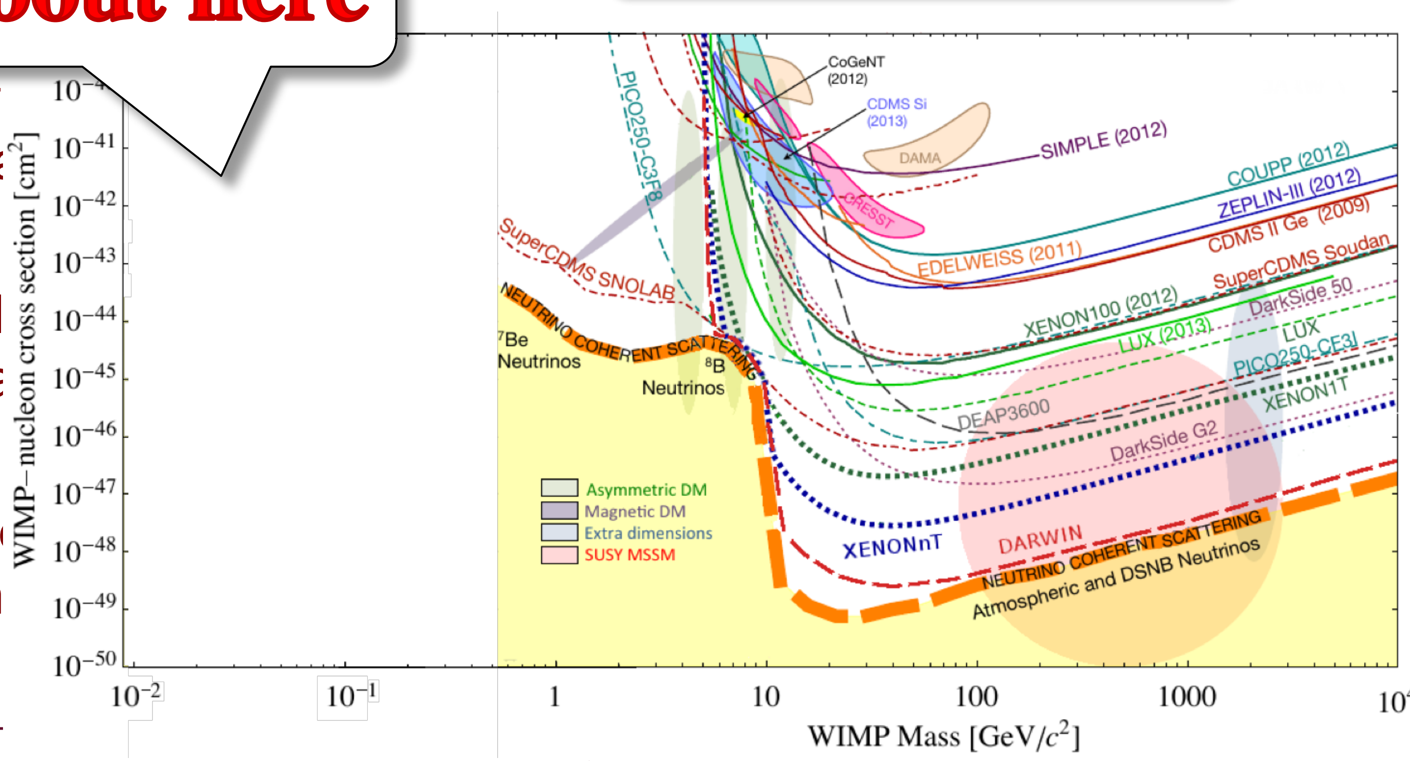
- A rich dark s
bypasses "m

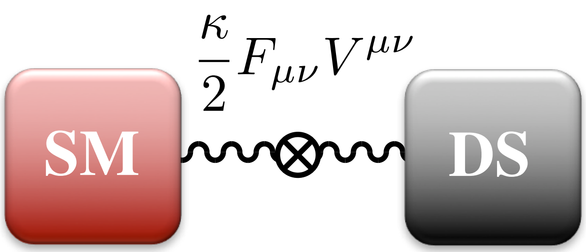
Dark Matter Sensitivity

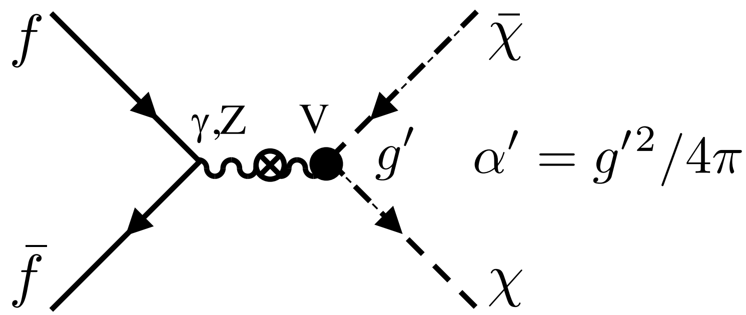


G.L. Baudis, *Phys. Dark Univ.* **4** (2014) 50. arXiv:1408.4371 [astro-ph].

Sub-GeV Dark Matter: Vector Portal

- Lee-Weinberg bound: $M_\chi > O(1\text{ GeV})$ presumes weak annihilation rate $\sim M_\chi^2 / M_Z^4$ which is too low
- New forces and force carriers → viable light thermal relic
  1. Mediate SM interactions to a dark sector
  2. Open up annihilation channels – circumventing L-W bound
- U(1) kinematic mixing with 4 parameters: m_χ, m_V, k, g'

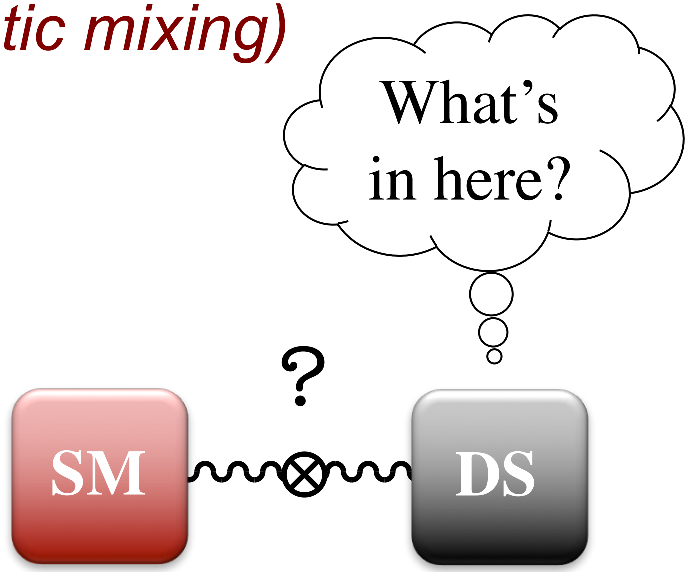




C. Boehm & P. Fayet, *Nucl. Phys.* **B683** (2004) 219. arXiv:hep-ph/0305261 [hep-ph].
C. Boehm et al., *Phys. Rev. Lett.* **92** (2004) 101301. arXiv:astro-ph/0309686 [astro-ph].

Sub-GeV Theories in General

- Vector portal is just one particular model
- Other linkages between Standard Model and potential rich Dark Sector possible
  - *Hypercharge portal (U(1) kinematic mixing)*
  - Higgs portal
  - Neutrino portal
- Field is summarized in SLAC Dark Sectors 2016 and US Cosmic Visions 2017 (required reading!)

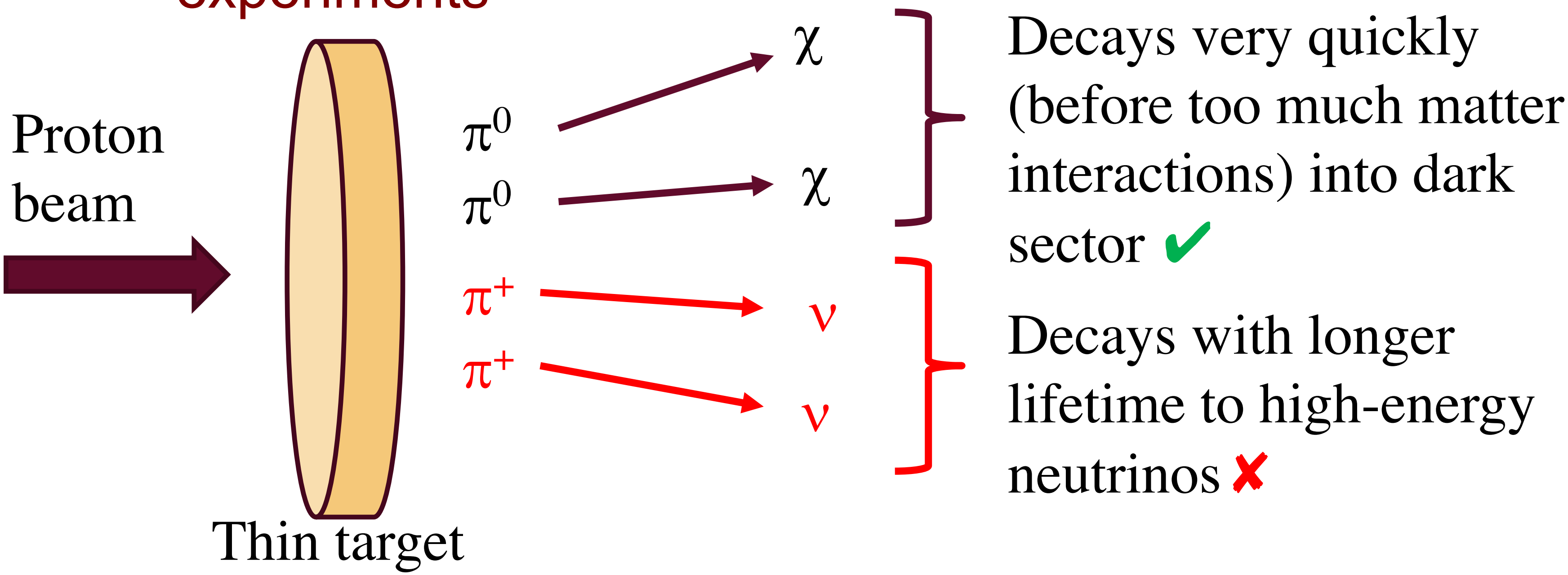


Dark Sectors 2016 Workshop: arXiv:1608.08632 [hep-ph].
US Cosmic Visions: New Ideas in Dark Matter: Community Report, arXiv:1707.04591 [hep-ph].

Why a Beam Dump Experiment?

- Neutrinos scatters are a background to the DM search

→ This is true in high-energy or low-energy neutrino experiments



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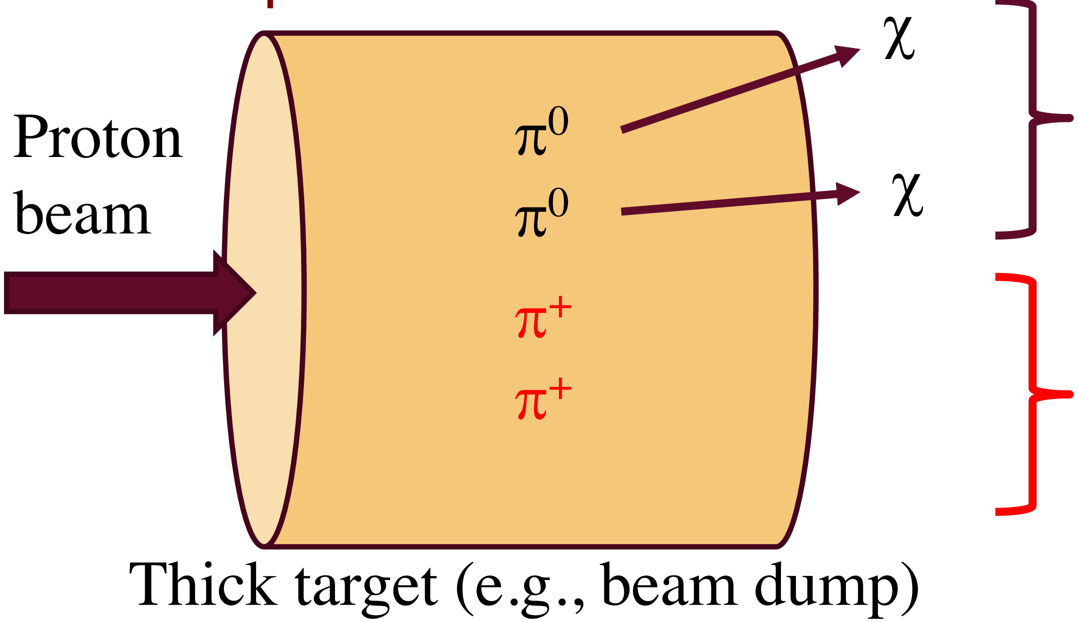


Decays very quickly (before too much matter interactions) into dark sector ✔

Absorbed or decay at rest low-energy neutrinos ✔

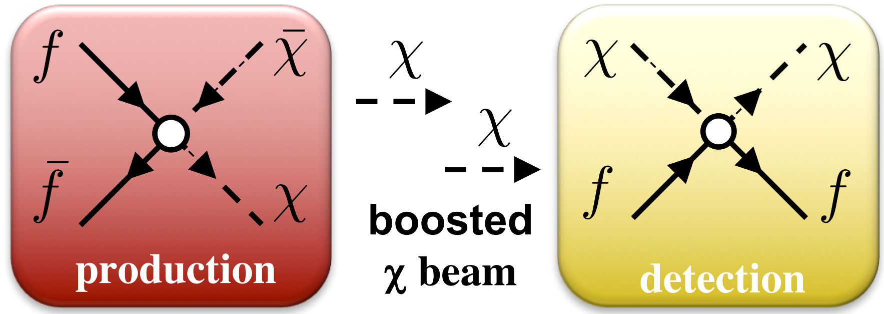
Previous Beam Dump / Fixed Target Experiments – Proton Beams

Experiment	Location	approx. Date	Amount of Beam (10^{20} POT)	Beam Energy (GeV)	Target Mat.	Ref.
CHARM	CERN	1983	0.024	400	Cu	[16]
PS191	CERN	1984	0.086	19.2	Be	[17, 18]
E605	Fermilab	1986	4×10^{-7}	800	Cu	[19]
SINDRUM	SIN,PSI					
ν-Cal I	IHEP Serpukhov	1989	0.0171	70	Fe	[20–22]
LSND	LANSCE	1994-1995 1996-1998	813 882	0.798	H20, Cu W,Cu	[23]
NOMAD	CERN	1996-1998	0.41	450	Be	[18, 24]
WASA	COSY	2010		0.550	LH2	[25]
HADES	GSI	2011	0.32 pA*t	3.5	LH2,No,Ar+KCl	[26]
MiniBooNE	**Fermilab**	**2003-2008** **2005-2012** **2013-2014**	**6.27** **11.3** **1.86**	**8.9**	**Be** **Be** **Steel**	**[27]** **[28]** **[29]**

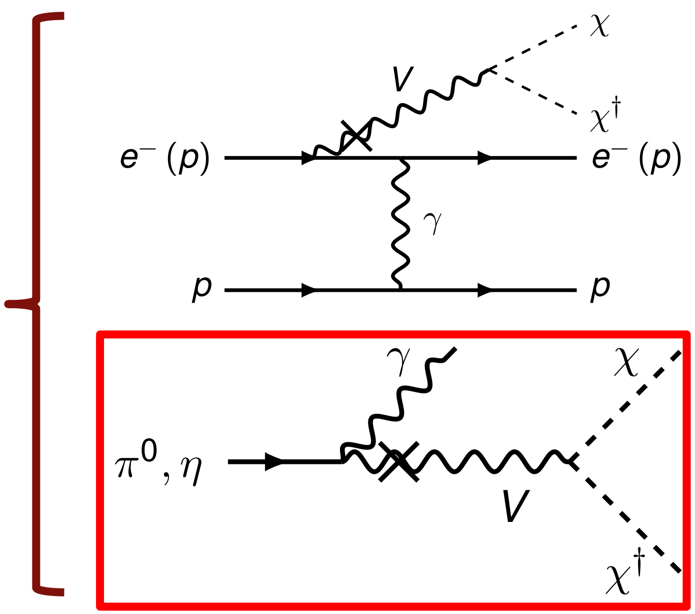
Table by R.T. Thornton, Indiana University Nuclear Physics Seminar, Nov. 21, 2014

Dark Matter Beam and Detection

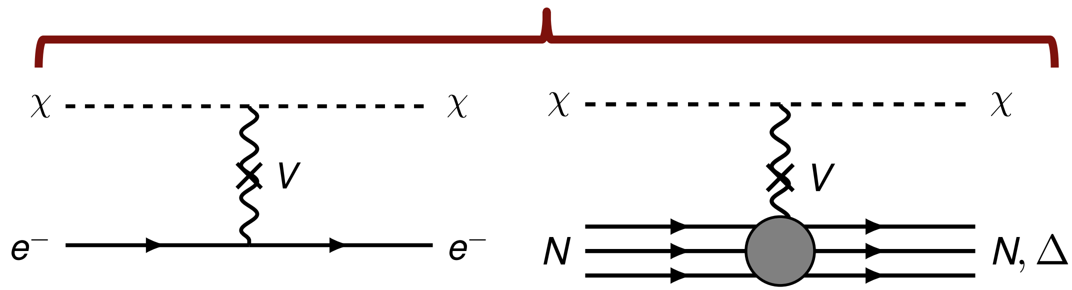
- High-energy production and scattering detection



Production



Detection



B. Batell et al., *Phys. Rev. Lett.* **113** (2014) 171802. arXiv:1406.2698 [hep-ph].
P. deNiverville et al., *Phys. Rev.* **D84** (2011) 075020. arXiv:1107.4580 [hep-ph].

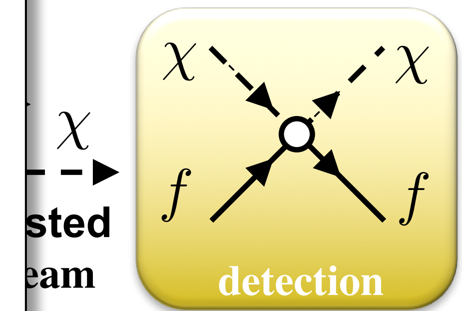
Dark M… tion

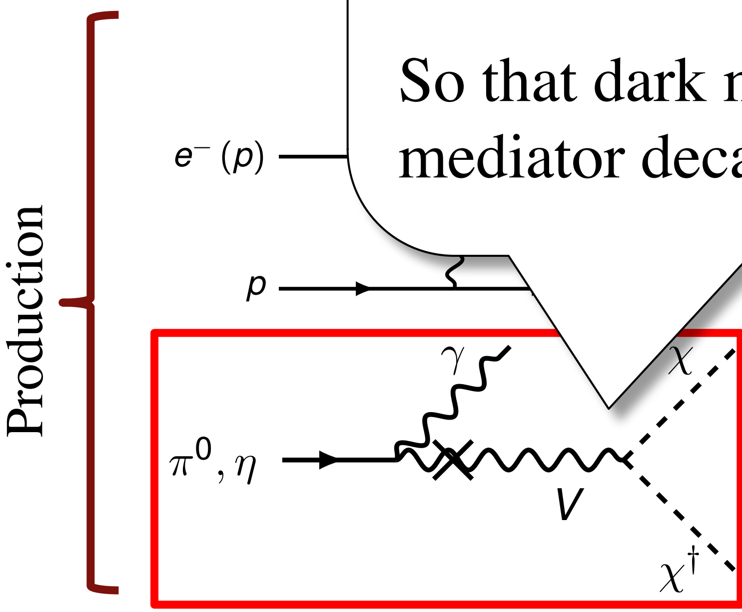
- High-ene…
  scatterin…

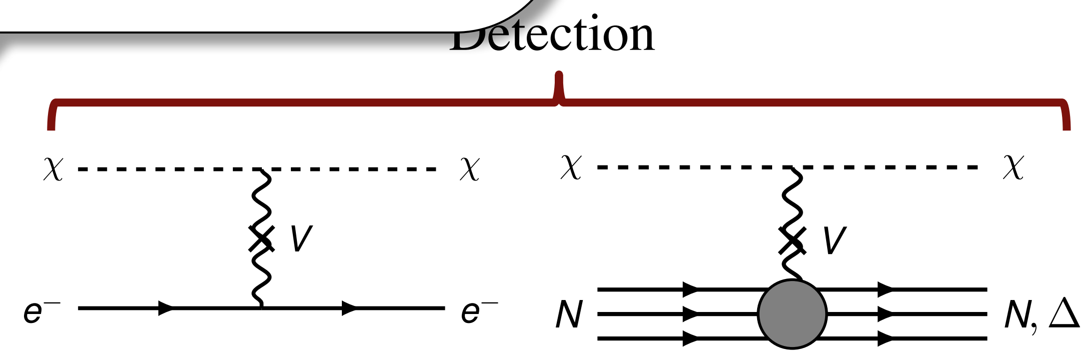
Assumes the “invisible” decay modes

$$m_V > 2\, m_\chi$$

So that dark matter is preferred in mediator decays.







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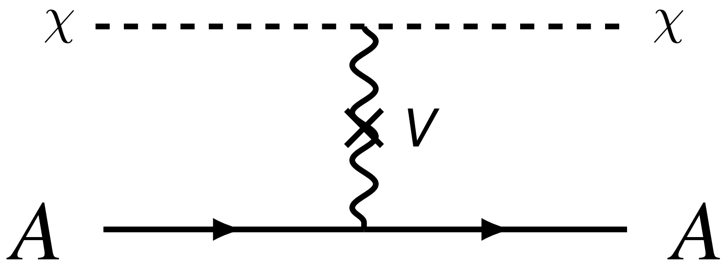
Dark M

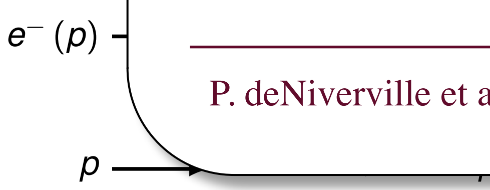
- High-e
scatter

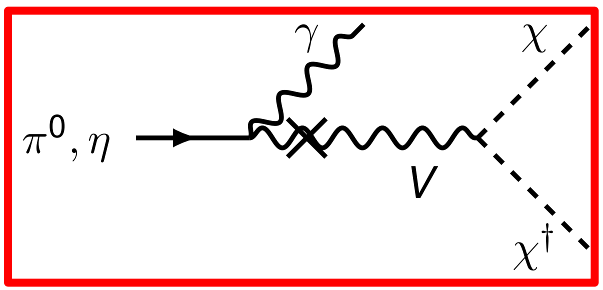
But wait, there's more!

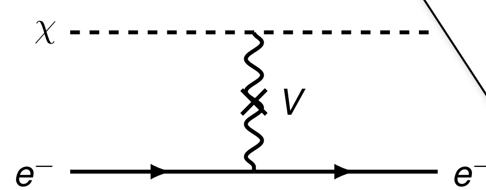


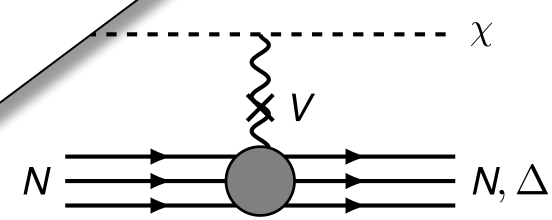
P. deNiverville et al., *Phys. Rev.* **D92** (2015) 095005. arXiv:1505.07805 [hep-ph].

Production









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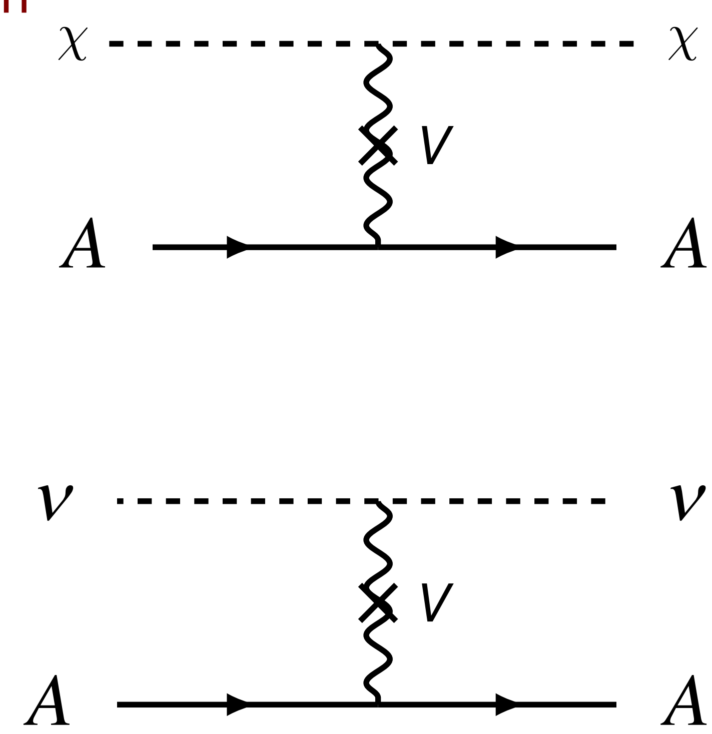
CEνNS Process and Dark Matter

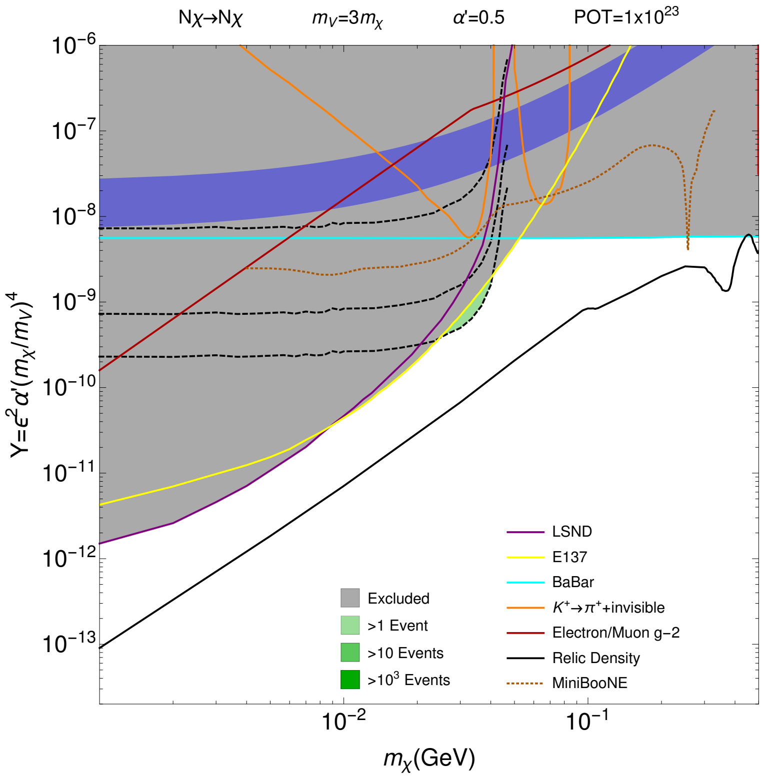
- Like neutrinos, expect large cross section enhancements
- "More" nuclear model independent than quasi-elastic or inelastic scattering
- CEνNS process is "well-known" from robust Standard Model prediction (N^2)
- Dark matter also enhanced ~A^2, and CEνNS backgrounds from prediction

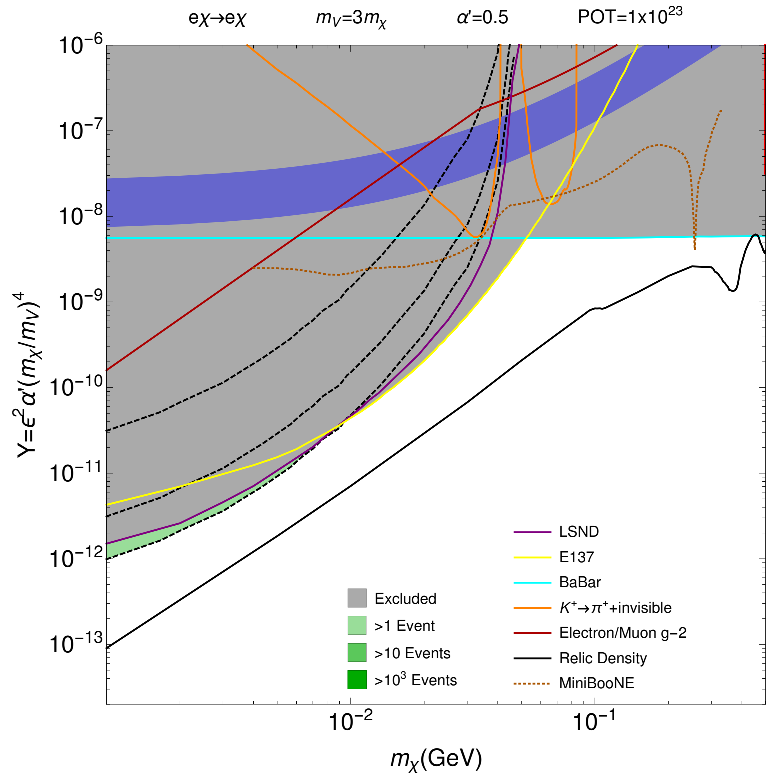


P. deNiverville et al., *Phys. Rev.* **D92** (2015) 095005. arXiv:1505.07805 [hep-ph].

CEνNS Enhances Dark Matter Searches

- Ton-scale argon; no CEνNS interaction

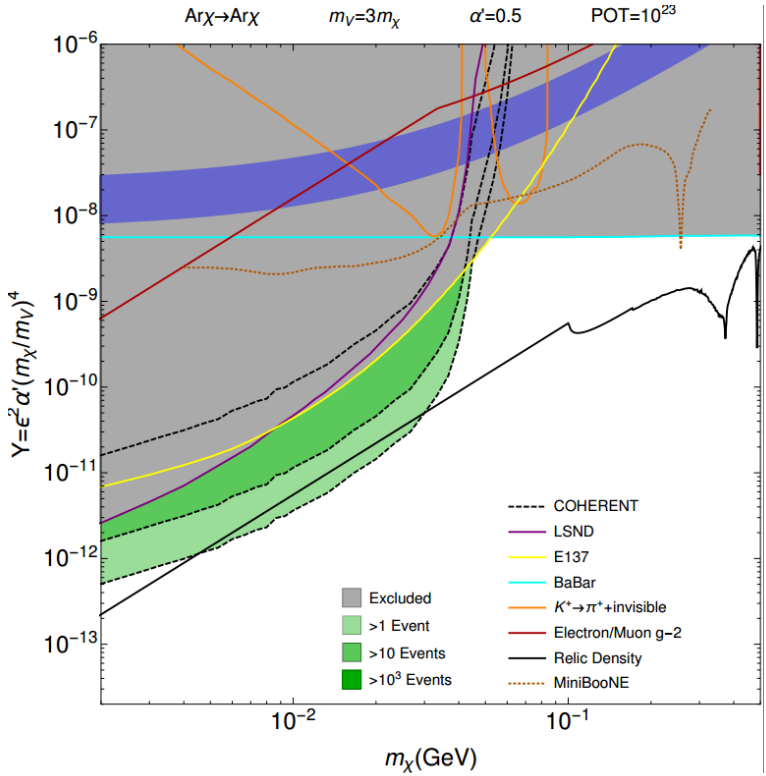


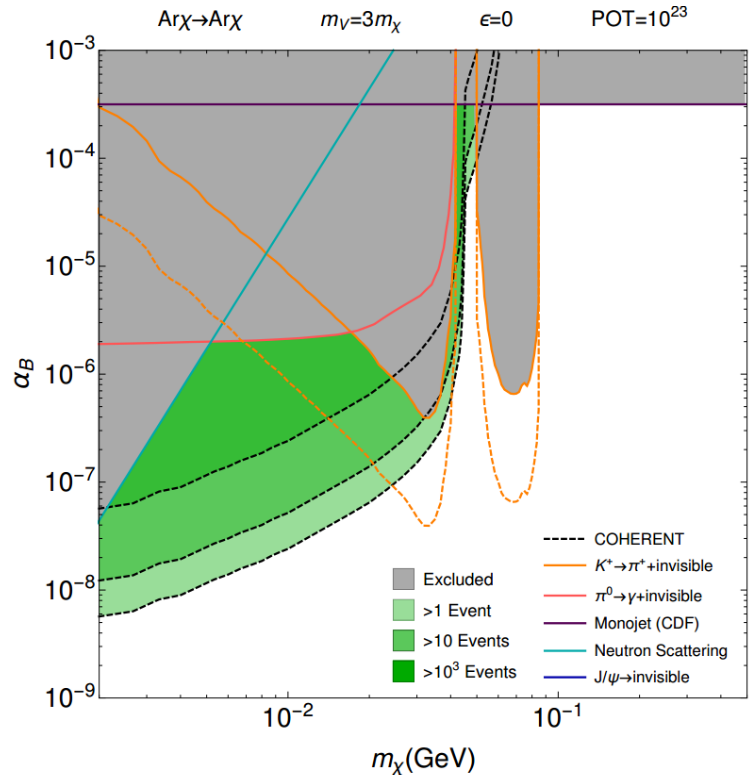


Acknowledgements to P. deNiverville for updated exclusion plots

CEνNS Enhances Dark Matter Searches

- Ton-scale argon; using CEνNS interaction

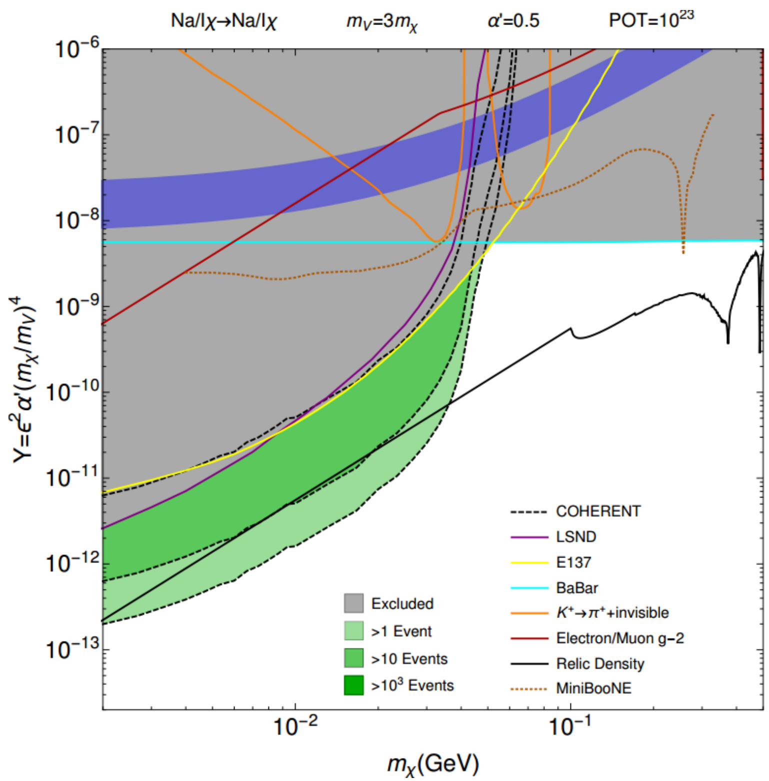


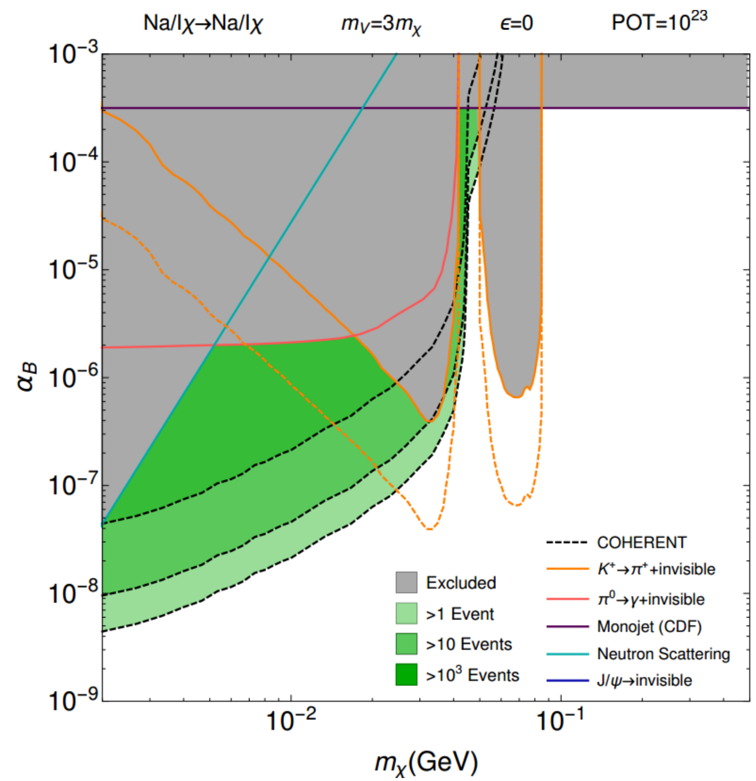


Acknowledgements to P. deNiverville for updated exclusion plots

CEνNS Enhances Dark Matter Searches

- 5-ton NaI; using CEνNS interaction





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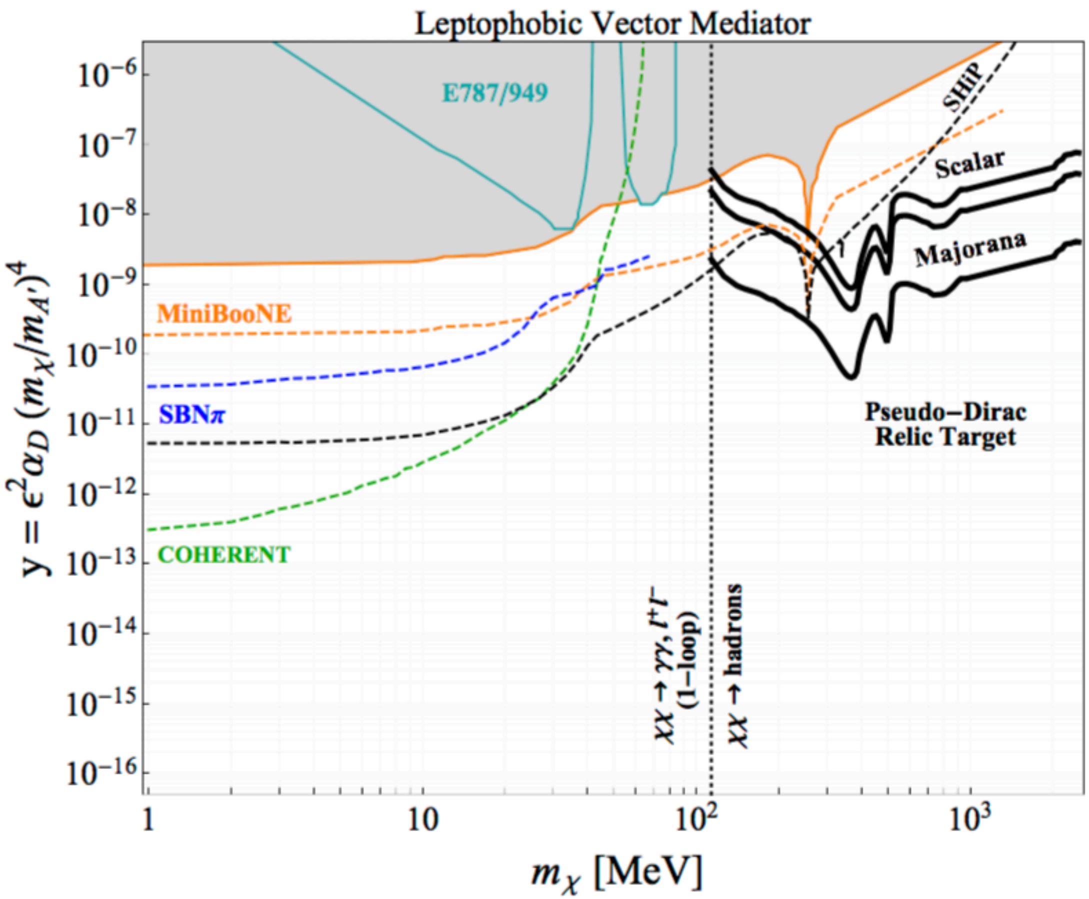
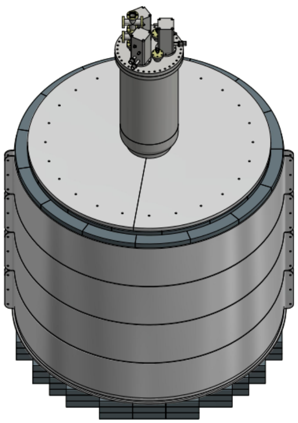
COHERENT and Leptophobic Dark Matter

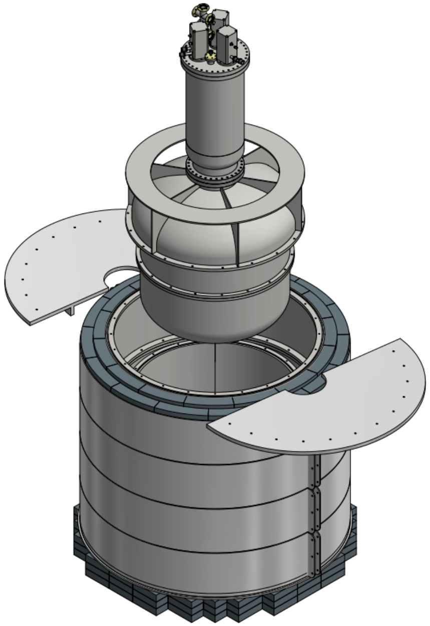


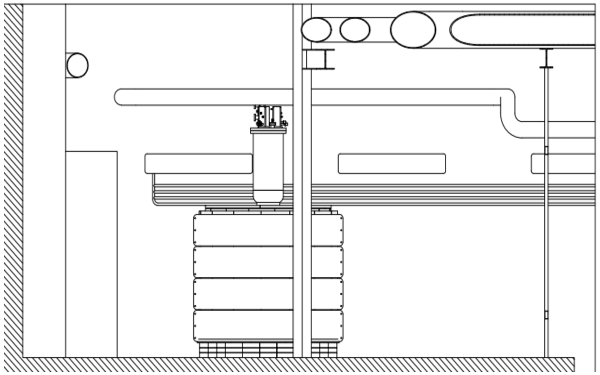
US Cosmic Visions: New Ideas in Dark Matter: Community Report, arXiv:1707.04591 [hep-ph].

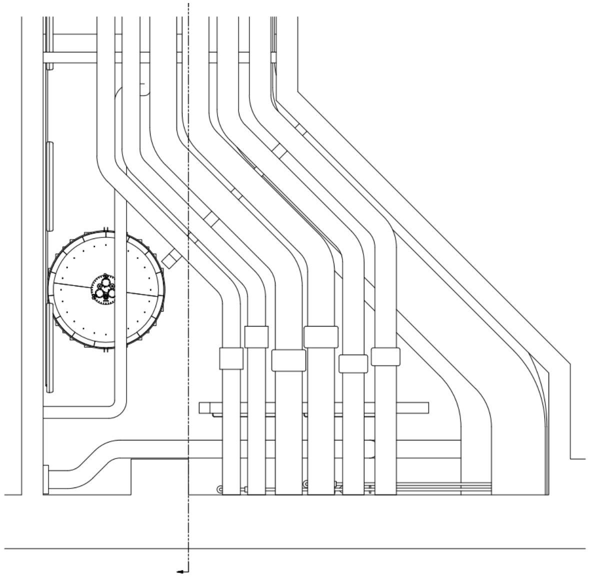
Ton-Scale Detectors for COHERENT

- 1-ton liquid argon option → modest $
- Scintillation-only in initial design
- Current design fits in “Neutrino Alley”



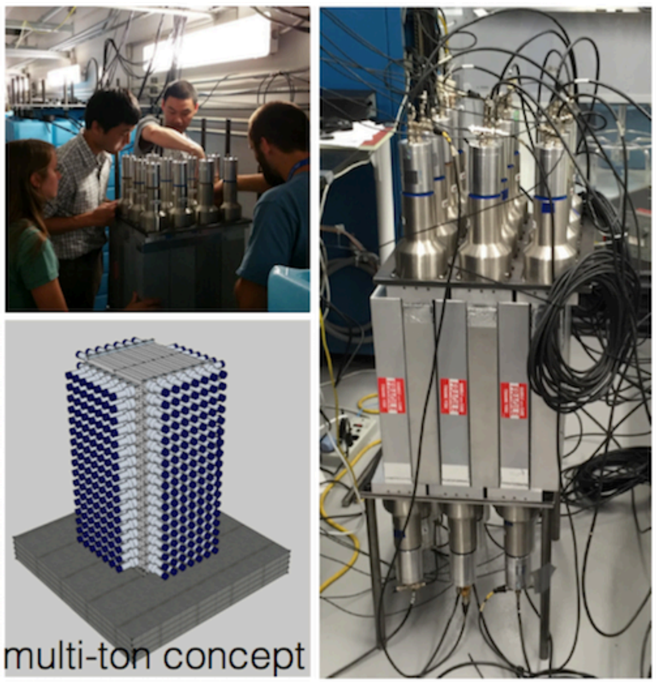






Ton-Scale Detectors for COHERENT

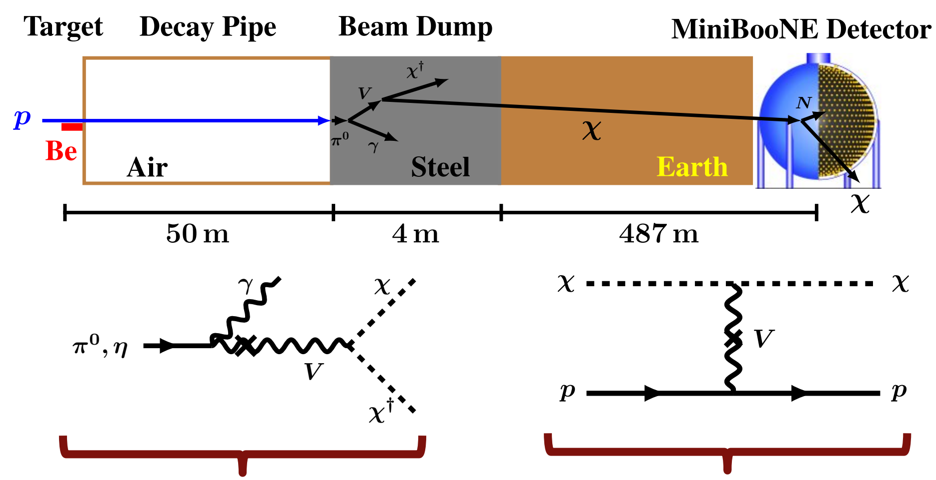
- Up to 9 tons of NaI crystals from discontinued DHS program
- 185 kg for initial deployment → 2 tons for next phase



LESSONS LEARNED ON MINIBOONE

(OR “SO YOU WANT TO SEARCH FOR SUB-GEV DARK MATTER”)

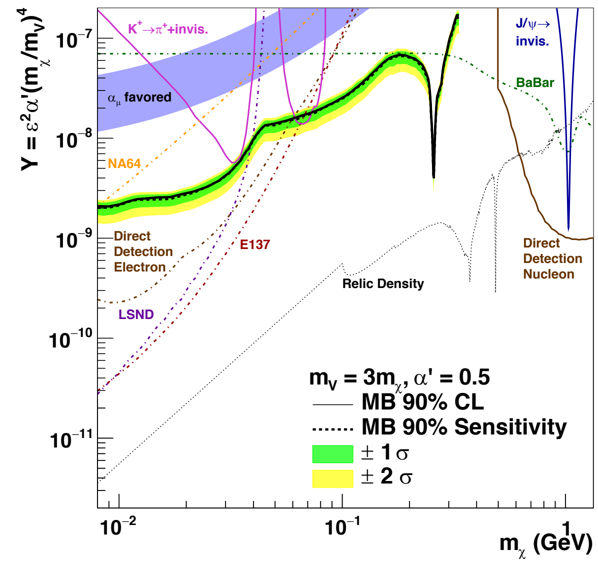
MiniBooNE-DM Summary



DM beam production via neutral mesons

Nucleon-DM elastic scattering detection

Confidence Limit Result



Dedicated Proton Beam Dump DM Search

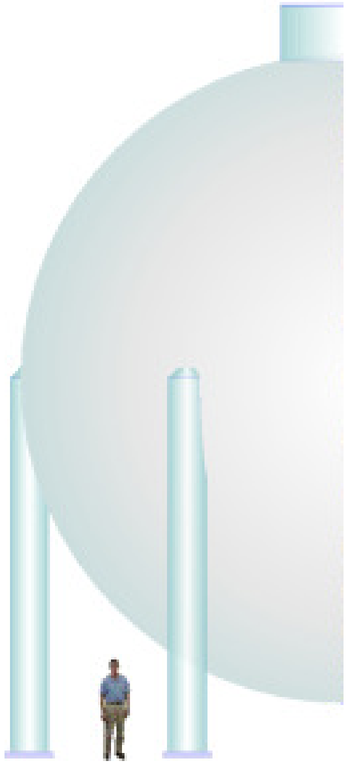
2014: beam off target run at Fermilab BNB, collected 1.86×10^{20} POT
2017: First results on DM search with nucleon-DM scattering (arXiv:1702.02688 [hep-ex])

Additional Analyses Ongoing

Beam timing to constrain heavier DM
Electron-DM elastic scattering and inelastic Δ production → π^0 final state in progress

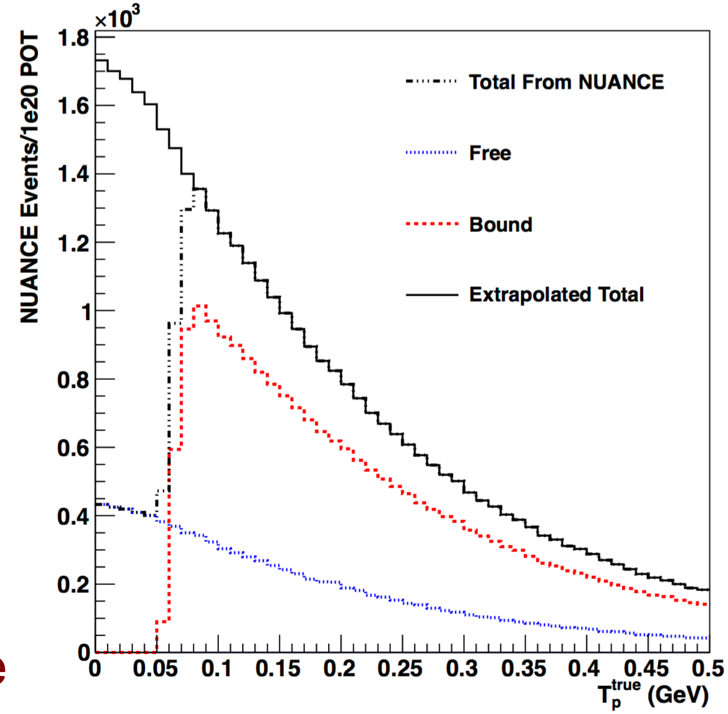
Beam-Related External Backgrounds

- MiniBooNE solved this by being huge!
- As already noted, neutron elastic scattering is indistinguishable from signal
- Neutrons largely (but not completely) suppressed by "Neutrino Alley" overburden and backfill
- Lesson learned: Be big, or handle your neutrons with auxiliary measurements



Nuclear Physics (and Now Quenching)

- Final sensitivity does not reach as far as initial predictions
- Inelastic nucleon interactions depend significantly upon nuclear model; e.g., binding, etc.
- CEνNS mostly removes this problem modulo form factors, but other experimental effects, e.g. quenching, arise

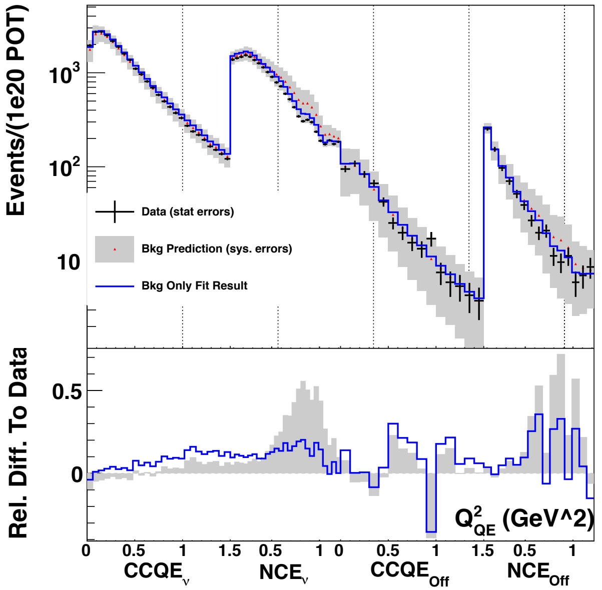


- <u>Lesson learned</u>: An honest sensitivity estimate must include a decent nuclear and quenching model → threshold effects

Correlated Errors and Sidebands

- Because MiniBooNE has been running for over a decade, there are numerous "sideband" analyses with similar systematic uncertainties

- Don't be afraid to get your hands dirty and deal with correlated errors
  → yes, they can be difficult



- <u>Lesson Learned</u>: Consider every possible sideband measurement to reduce the final correlated uncertainties

Conclusions

- MiniBooNE-DM successfully demonstrated using a neutrino detector to search for low-mass dark matter → many lesson learned
- CEνNS process greatly enhances sensitivity
- Next phase, ton-scale COHERENT detectors (LAr and NaI) are capable to constraining parts of relic density
- Unlike BNB searches, no modification of SNS target is required; DM search comes "for free"

The COHERENT collaboration

arXiv:1509.08702

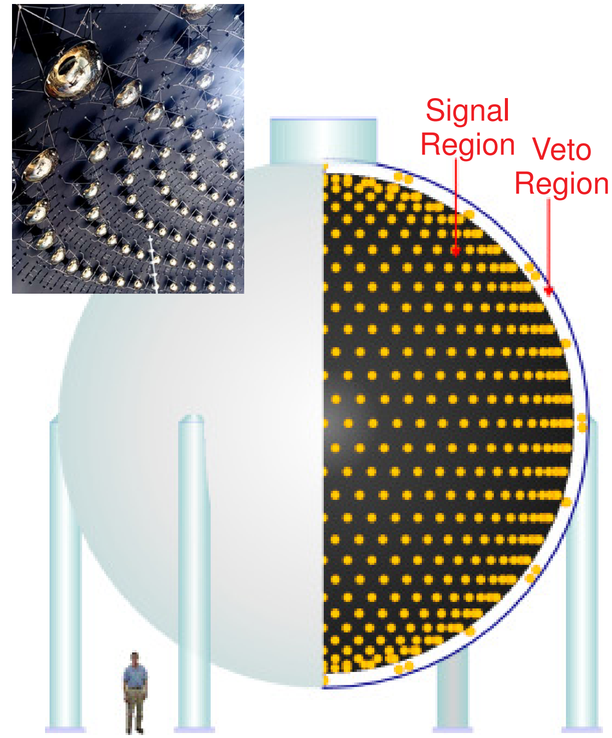
Institution	Board Member
University of California, Berkeley	Kai Vetter
University of Chicago	Juan Collar
Duke University	Kate Scholberg
University of Florida	Heather Ray
Indiana University	Rex Tayloe
Institute for Theoretical and Experimental Physics, Moscow	Dmitri Akimov
Lawrence Berkeley National Laboratory	Ren Cooper
Los Alamos National Laboratory	Steve Elliott
National Research Nuclear University MEPhI	Alex Bolozdynya
New Mexico State University	Robert Cooper
North Carolina Central University	Diane Markoff
North Carolina State University	Matt Green
Oak Ridge National Laboratory	Jason Newby
Sandia National Laboratories	David Reyna
University of Tennessee, Knoxville	Yuri Efremenko
Triangle Universities Nuclear Laboratory	Phil Barbeau
University of Washington	Jason Detwiler

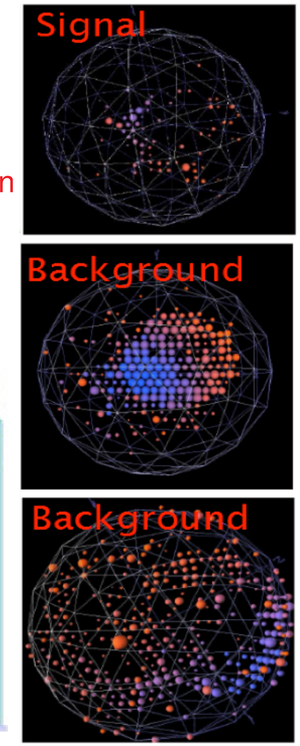
- Collaboration: ~65 members, 16 institutions (USA+ Russia)

BACKUPS

The MiniBooNE Detector

- 800 tons pure mineral oil (CH_2) Cherenkov tracker with some scintillation from trace fluors
- Inner region 1280 × 8” PMTs Outer veto region 240 × 8” PMTs (10% photocathode coverage)
- Excellent PID
- **Detector is very well characterized**

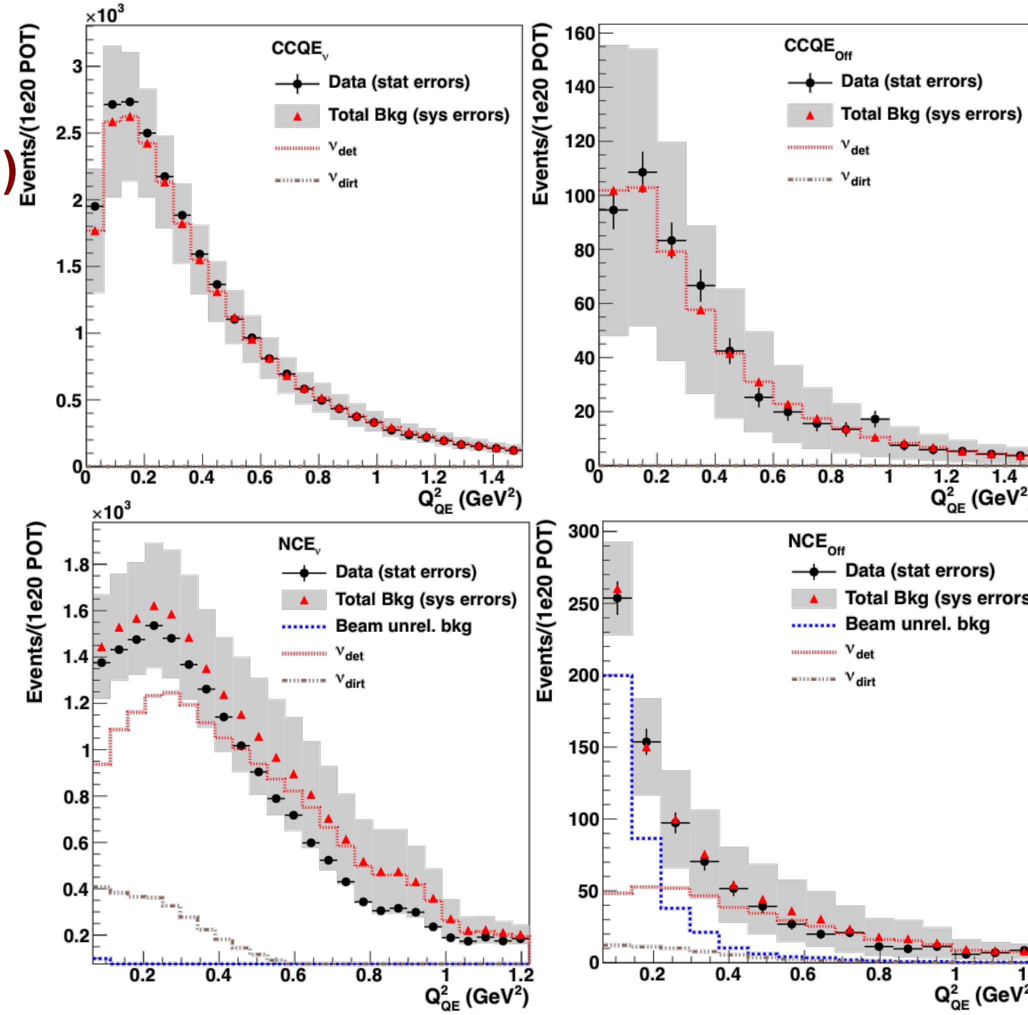




A.A. Aguilar-Arevalo et al., *Nucl. Instrum. Meth.* **A599** (2009) 28. arXiv:0806.4201 [hep-ex].

Simultaneous Fits

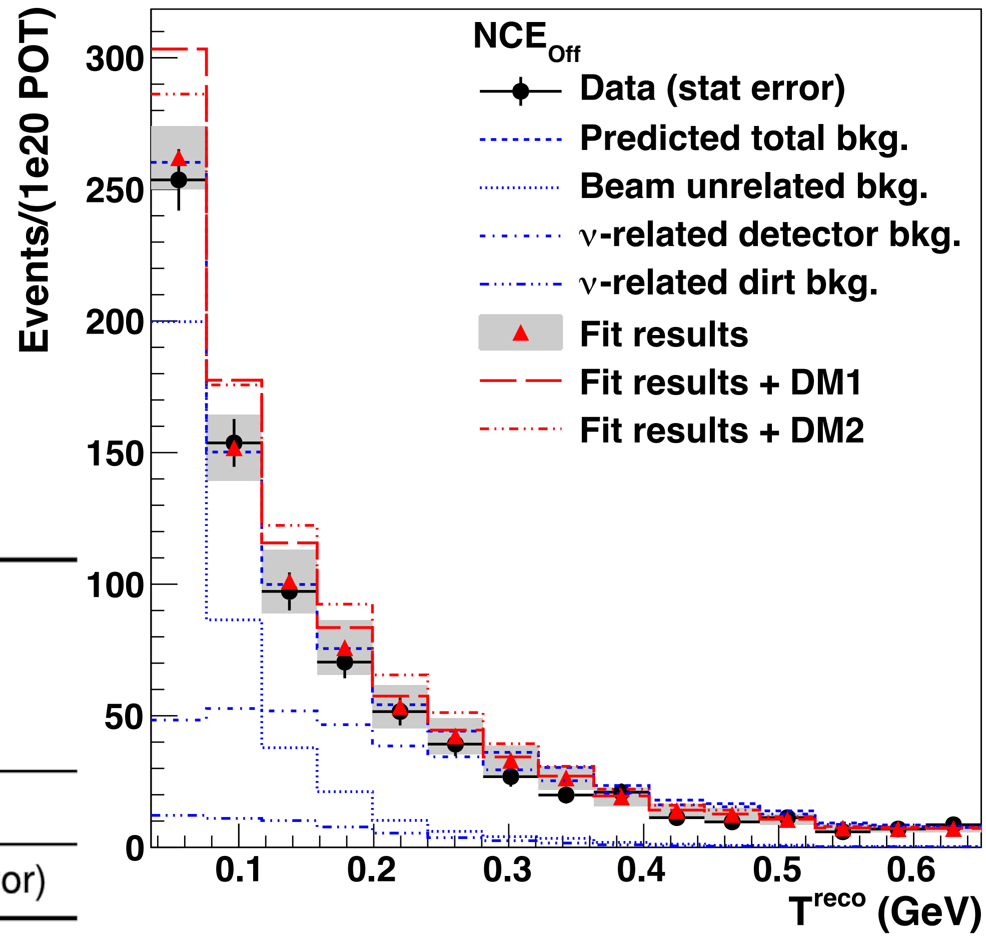
- 4 distributions
  - **NC beam off-target (signal)**
  - CC beam off-target
  - NC beam on-target
  - CC beam on-target
- CC ratios help reduce flux uncertainties
- NC ratios help reduce neutrino cross section uncertainties



Nucleon NC-Like Events

- A straightforward search yields no excess
- Uncertainties are quite large → improve!
- Use auxiliary channels with correlated errors

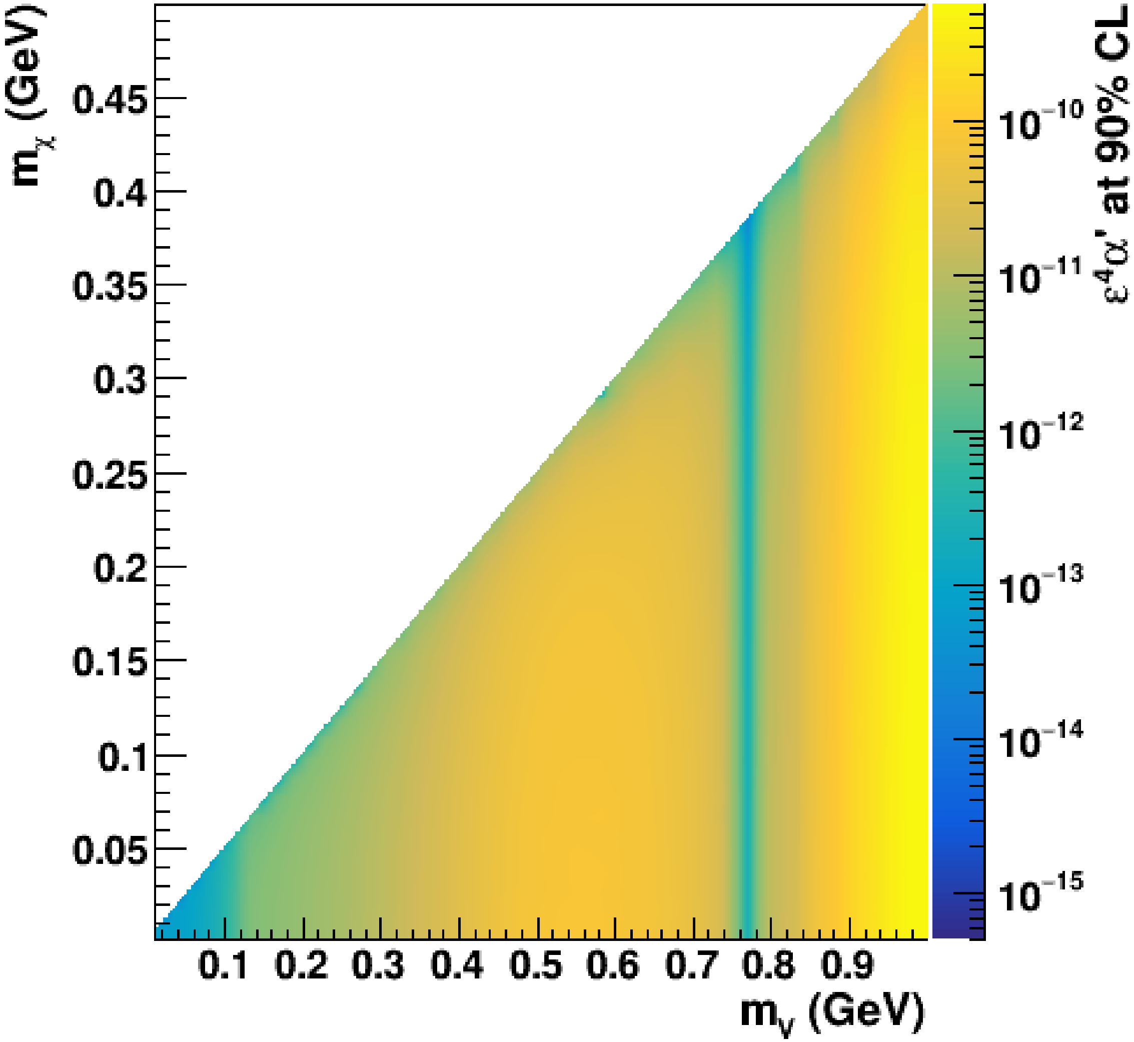
	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	33.5% (pred. sys.)
Data	1465	2.6% (stat.)
Fit Results	1548	12.8% (fit effective error)



Confidence Limit Results

- Treating invisible mode
  $m_V > 2\, m_\chi$

- Best sensitivity at m_V = 769 MeV, m_χ = 381 MeV due to ρ meson production



Confidence Limit Results

- Many ways to "slice" parameter space
- This parameter choice is rejected as solution for *g*-2 anomaly (Vector Portal)