LDM with proton beam-dumps and SHiP

Oliver Lantwin *on behalf of the SHiP collaboration, and* Rex Tayloe [oliver.lantwin@cern.ch]

LDMA 2019, Venice

November 21, 2019

Search for light dark matter in neutrino beams

- A Search for sub-GeV dark matter via: Portal particles mediating SM and dark matter interactions
- Model consistent with thermal freeze out with low-mass dark matter (Phys.Rev. D95 (2017) no.3, 035006)

Vector portal: $\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\kappa}{2}V^{\mu\nu}F_{\mu\nu}$

Baryonic portal: $\mathcal{L}_B = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}^B V_{\mu\nu}^B + \frac{1}{2}m_B^2 V_\mu^B V_\mu^B + \sum_{N=n,p} i\bar{N}\not{D}N$

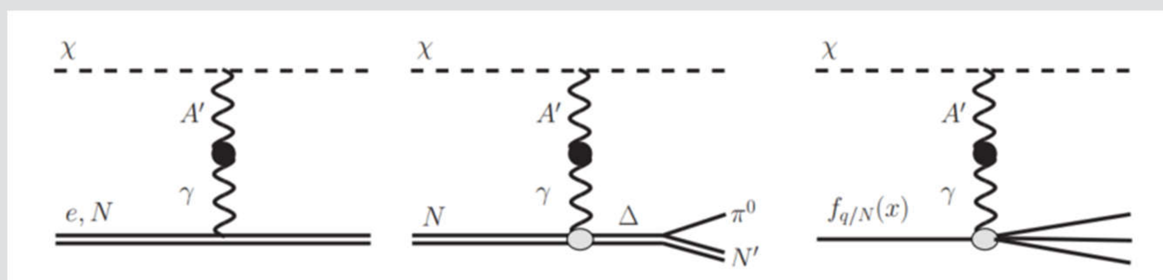
Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP

Patrick deNiverville,[1] Chien-Yi Chen,[1,2] Maxim Pospelov,[1,2] and Adam Ritz[1]
[1]*Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
[2]*Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*
(Dated: September 2016)

LSND, MiniBooNE, COHERENT, CCM search for this dark matter assuming:

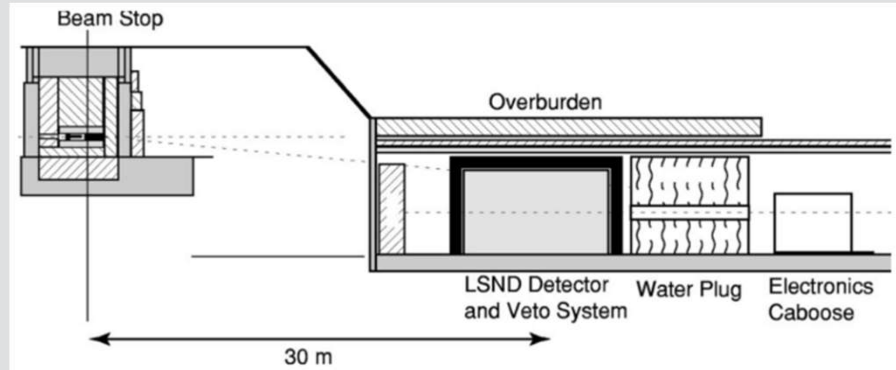
$$p \to \text{beam dump} \to \pi^0/\eta$$
$$\pi^0/\eta \to \gamma + V \to \gamma + \chi^\dagger + \chi$$

And then search for χ interactions in large neutrino detectors via various reaction channels, eg:



LSND experiment at Los Alamos

- Liquid Scintillator Neutrino Detector at Los Alamos Natl Lab in 1994-1999
- 800 MeV protons on beam dump
- 170 ton scintillation/Cherenkov detector 30m from beam stop



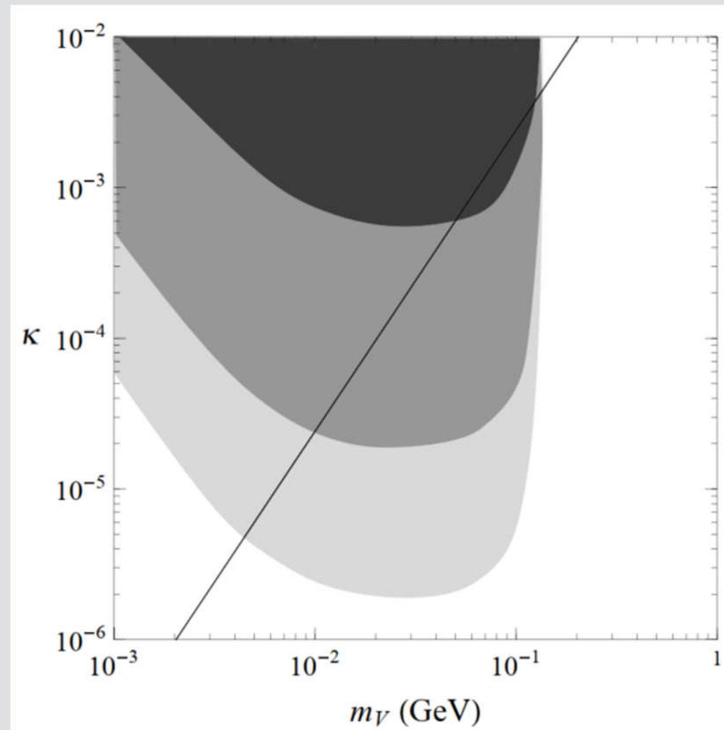
Analysis:

- search for dark matter via:

$$p \to \text{beam dump} \to \pi^0$$
$$\pi^0 \to \gamma + V \to \gamma + \chi^\dagger + \chi$$
$$\chi + e \to \chi + e$$

Results:

- expected sensitivities (10^1, 10^3, 10^6 events)
- and appearing as “LSND” in later plots
- from: Phys.Rev. D80 (2009) 095024

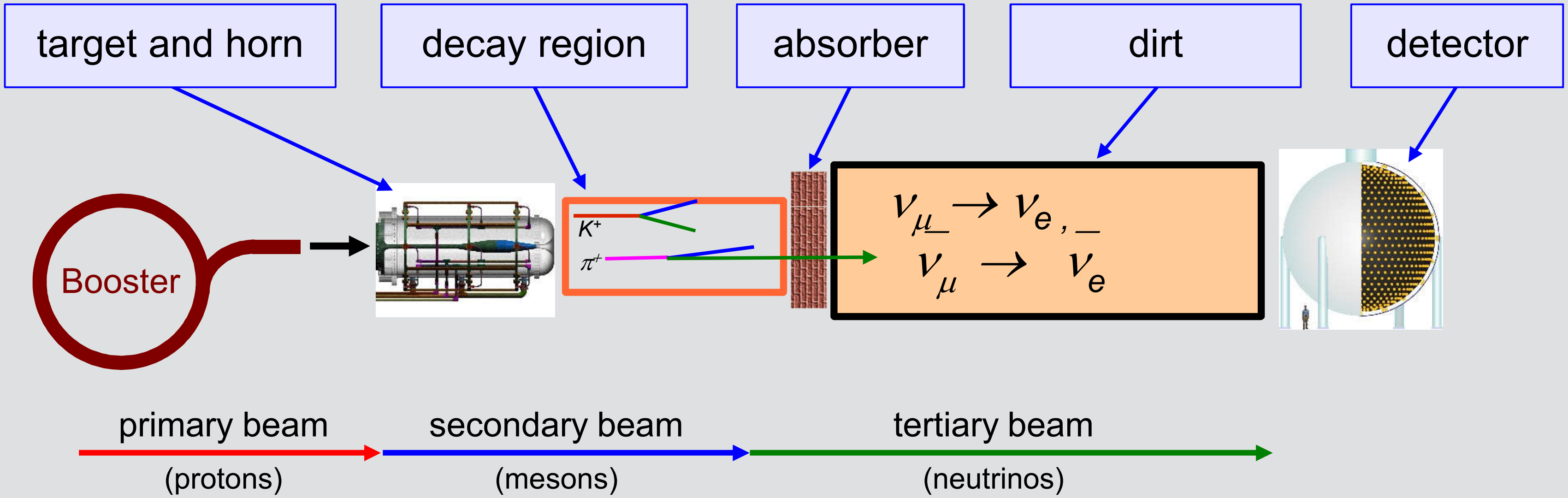


Exploring portals to a hidden sector through fixed targets

Brian Batell, Maxim Pospelov, and Adam Ritz
Phys. Rev. D **80**, 095024 – Published 24 November 2009

MiniBooNE experiment at Fermilab

- Designed and built to search for electron-appearance oscillations ($\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and to study ν interactions
- On the Fermilab Booster Neutrino Beamline (BNB)
- 8 GeV protons, ~6E20/yr
- Running recently complete: 2002-2019!
- 800 ton mineral oil Cherenkov detector

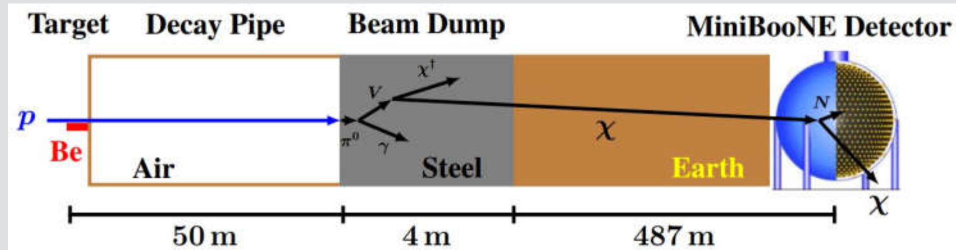


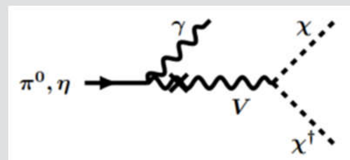
Dark Matter search with MiniBooNE: experiment

- dedicated dark matter run in 2014, with beam steered off neutrino target to reduce neutrino backgrounds by ~x50
- $2\text{x}10^{20}$ protons delivered
- search for portal dark matter via:

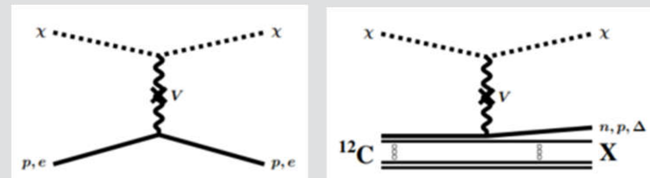
$$p \rightarrow \text{beam dump} \rightarrow \pi^0/\eta$$
$$\pi^0/\eta \rightarrow \gamma + V \rightarrow \gamma + \chi^\dagger + \chi$$
$$1)\ \chi + N \rightarrow \chi + N$$
$$2)\ \chi + N \rightarrow \chi + N^*$$
$$3)\ \chi + e \rightarrow \chi + e$$

in three different detection channels



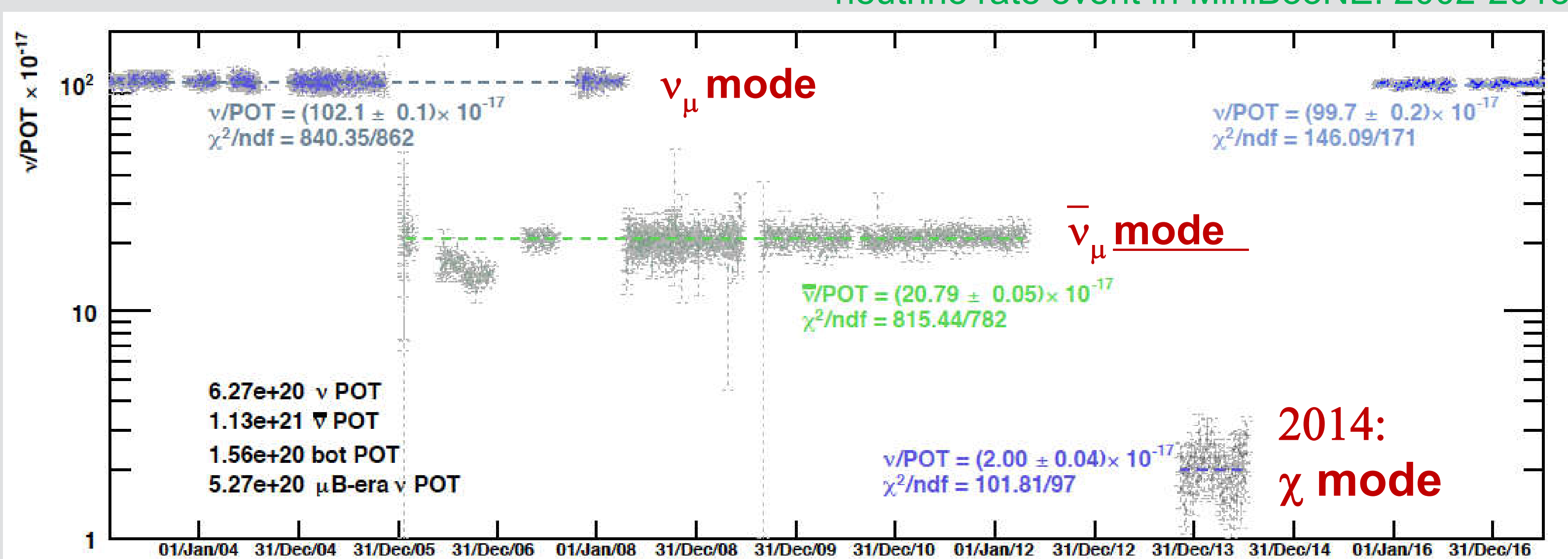


production



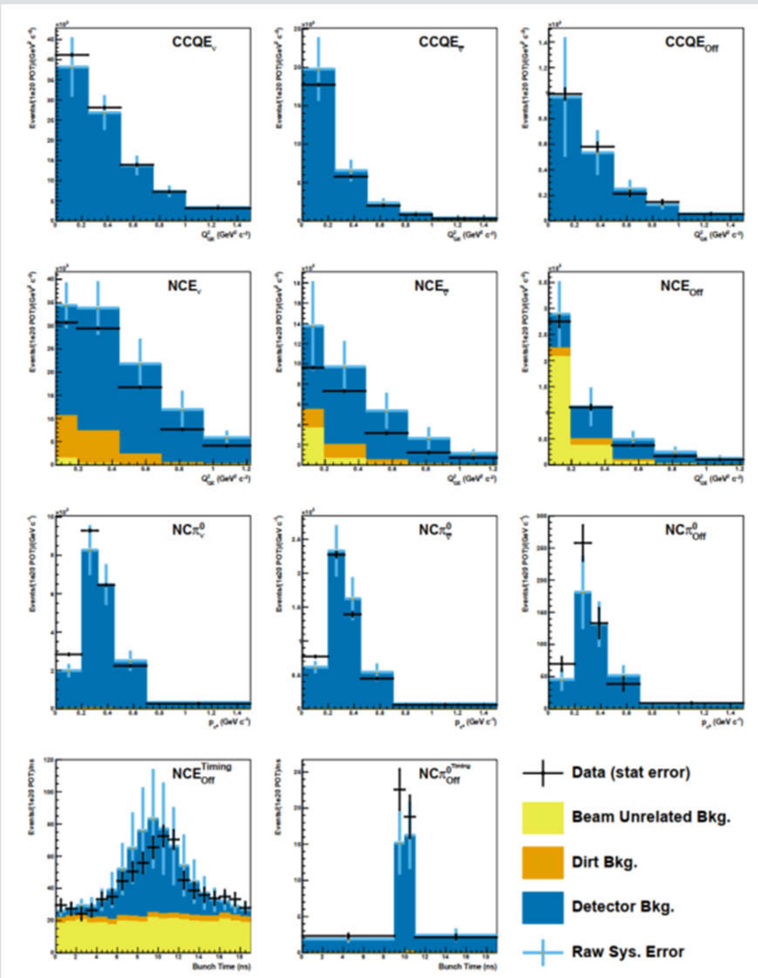
detection

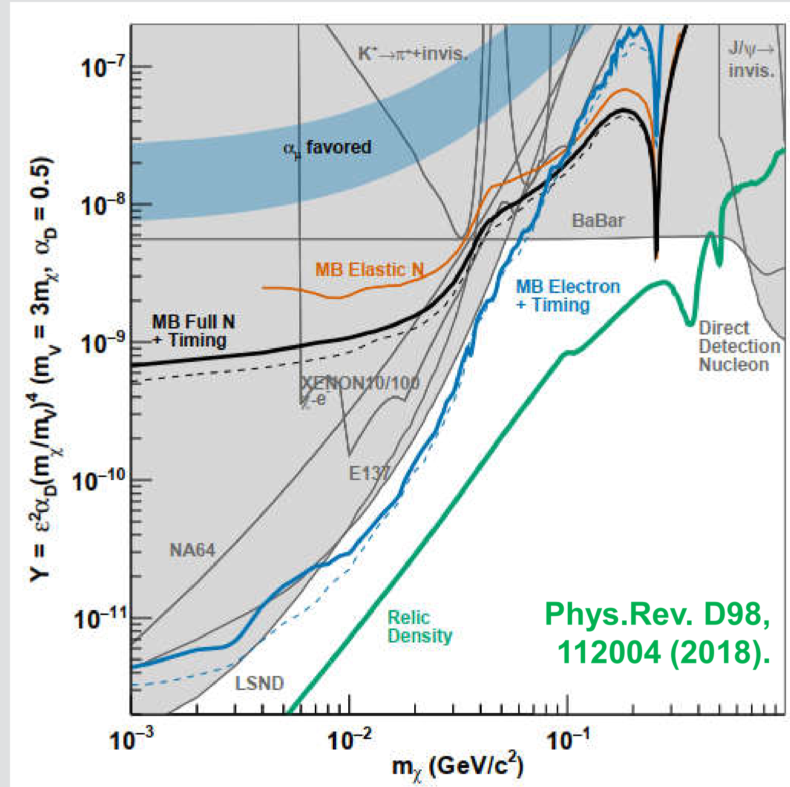
neutrino rate event in MiniBooNE: 2002-2018



Dark Matter search with MiniBooNE: analysis/results

- search for nucleon, electron, π^0 final states
- global on/off target analysis to constrain neutrino flux/backgrounds

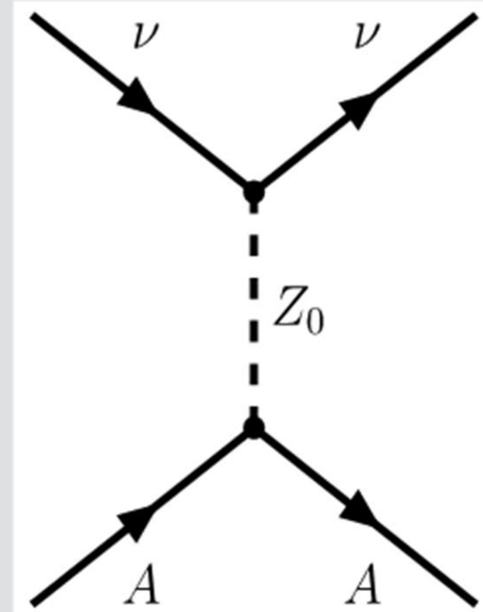




Results:

- χ - nucleon elastic channel
  - extends dark matter limits to smaller m_χ
  - excludes a vector mediator solution to g-2 anomaly
  - **Phys. Rev. Lett. 118, 221803 (2017).**
- χ-nucleon inelastic, χ-e channels:
  - further extends dark matter limits closer to thermal solution
  - **Phys.Rev. D98, 112004 (2018).**

Coherent Elastic ν-Nucleus Scattering:

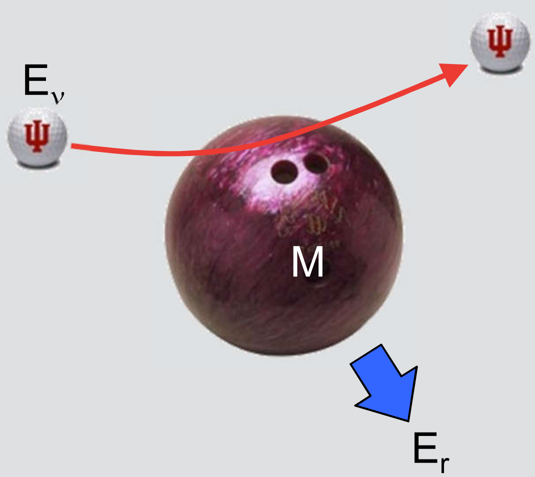


"CEvNS":

Coherent Elastic ν-Nucleus Scattering: νA→νA

Neutrino scatters with low momentum transfer coherently, elastically from entire nucleus (eg Cs, I, Ar) . For a large nucleus, R_N~few fm, and:

$$E_\nu \lesssim \frac{hc}{R_N} \cong 50 \text{ MeV}$$

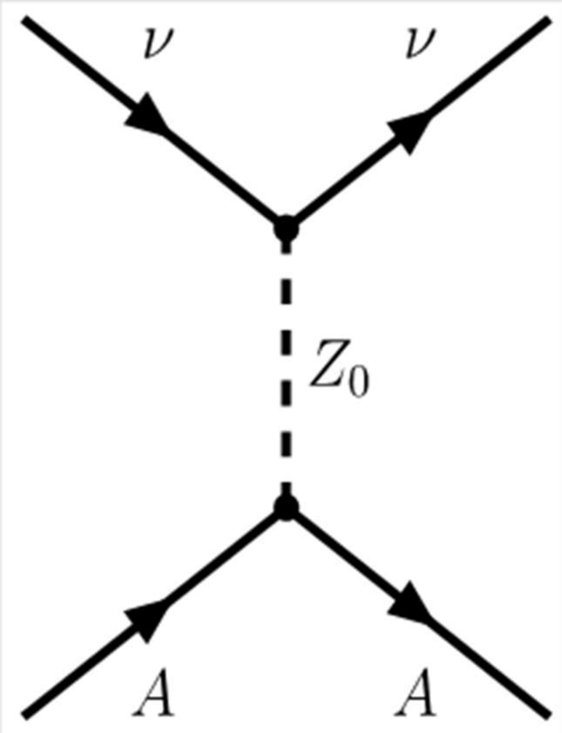


Recently discovered (in CsI), 40 years after its prediction...

Coherent Elastic ν-Nucleus Scattering:

Physics of CEvNS:

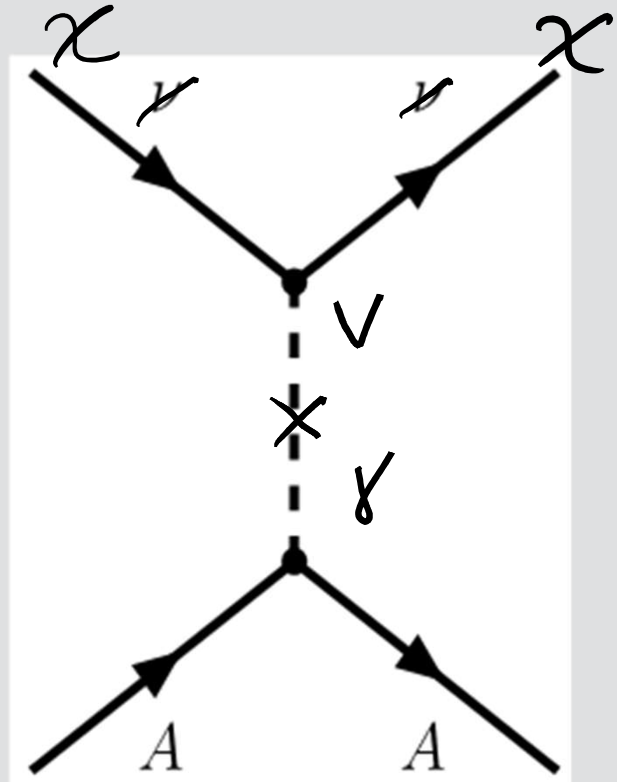
- Supernovae: Expected to be important in core-collapse SN and possible SN detection channel.
- Nuclear Physics: nuclear form factors
- ν oscillations: A possible ν_s detection channel
- Standard Model tests, eg: $\sin^2 \theta_w$
- Dark Matter: Important background for 10-ton searches



Coherent Elastic χ-Nucleus Scattering:

Physics of CEvNS:

- Supernovae: Expected to be important in core-collapse SN and possible SN detection channel.
- Nuclear Physics: nuclear form factors
- ν oscillations: A possible ν_s detection channel
- Standard Model tests, eg: $\sin^2 \theta_w$
- Dark Matter: Important background for 10-ton searches
- Search for accelerator-produced DM …



Coherent Elastic χ-Nucleus Scattering:

Vector portal: $\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\kappa}{2}V^{\mu\nu}F_{\mu\nu}$

Baryonic portal: $\mathcal{L}_B = \mathcal{L}_\chi - \frac{1}{4}V^B_{\mu\nu}V^B_{\mu\nu} + \frac{1}{2}m_B^2 V^B_\mu V^B_\mu + \sum_{N=n,p} i\bar{N}\not{D}N$

A Search for sub-GeV dark matter via:

- Portal particles mediating SM and dark matter interactions
- Model consistent with thermal freeze out with low-mass dark matter

Light new physics in coherent neutrino-nucleus scattering experiments

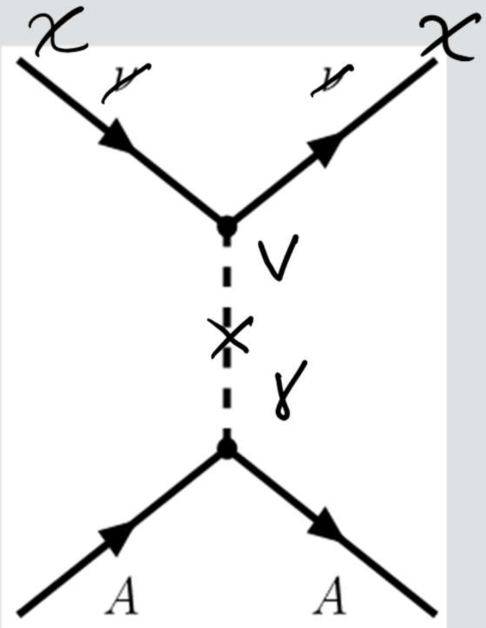
Patrick deNiverville,[1] Maxim Pospelov,[1,2] and Adam Ritz[1]

[1] *Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*
(Dated: May 2015)

DOI: 10.1103/PhysRevD.92.095005
e-Print: : arXiv:1505.07805 [hep-ph]

Then, at an intense proton source:

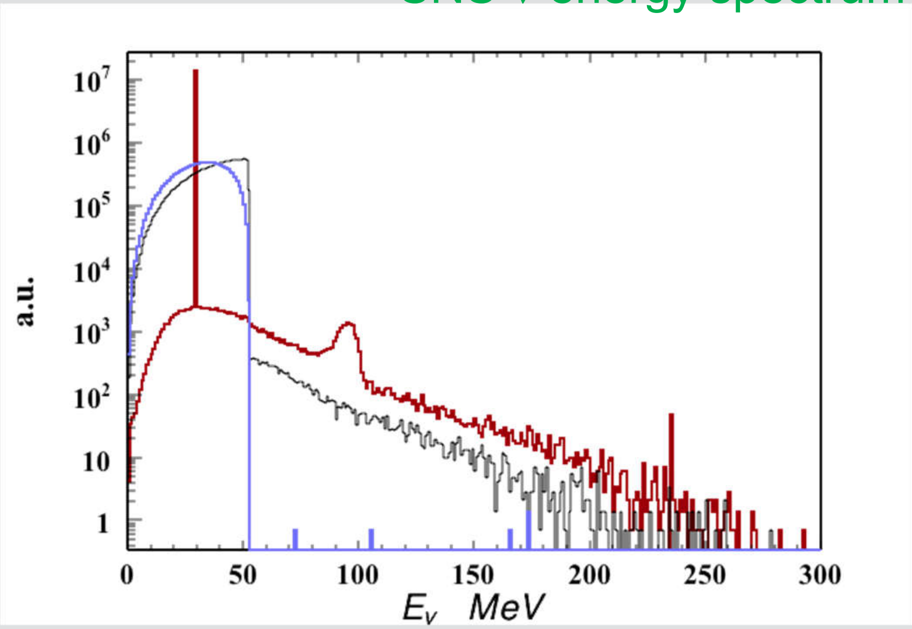
$$p \to \text{target} \to \pi^{0,\pm},$$
$$\pi^0 \to \gamma + V \to \gamma + \chi^\dagger + \chi,$$
$$\chi + N \to \chi + N$$



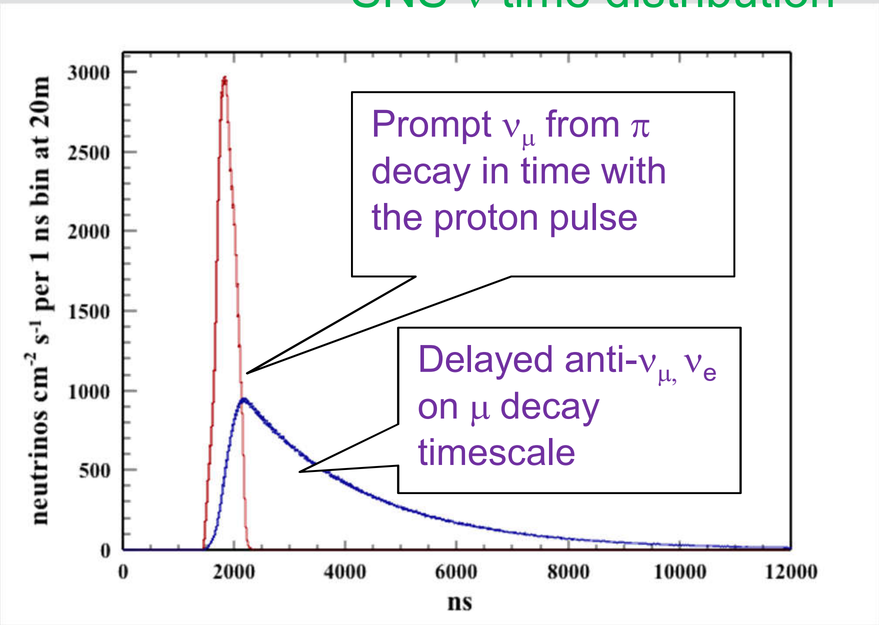
COHERENT experiment at ORNL/SNS

- Located in low-background area ("ν-alley"), >20m shielding
- near (20-28 m) SNS target with
- 1.4MW, 5000MW/yr, 1.5E23POT/yr,
- pulsed 1GeV proton beam

SNS ν energy spectrum

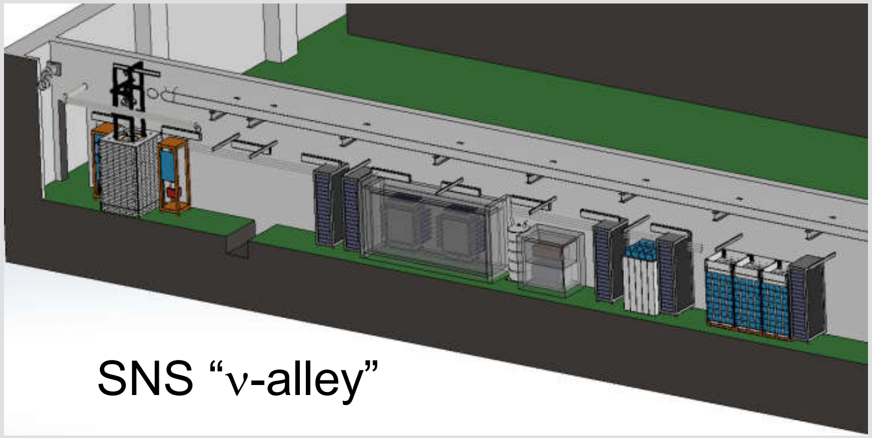


SNS ν time distribution

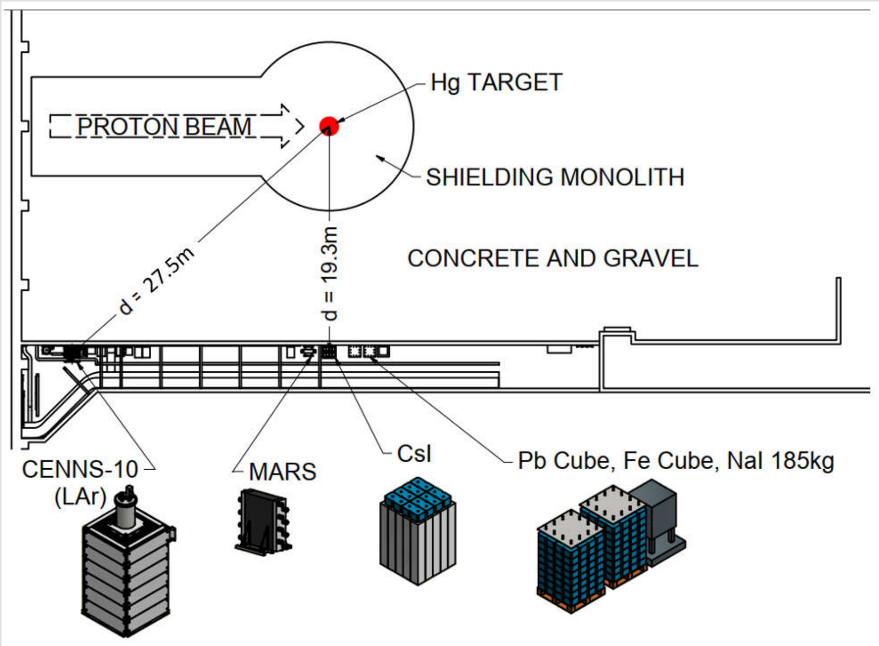


COHERENT experiment at ORNL/SNS

- multiple detectors have/will run to observe CEvNS process:
  - CsI: discovery
  - LAr: currently running, engineering run published, physics results imminent
  - Ge, NaI: coming soon



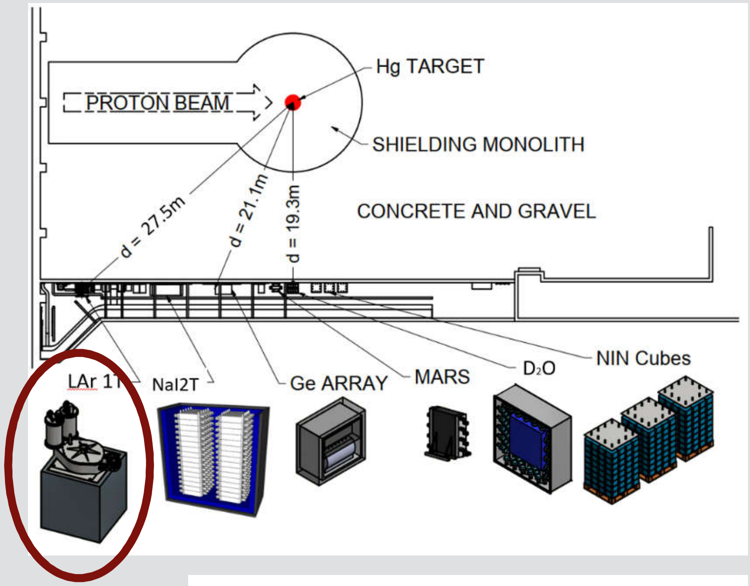
- scalability and demonstrated low background have focused our efforts on LAr
  - see first limits from engineering run of 27~kg (CENNS-10) detector at: arXiv:1909.05913 [hep-ex]
  - results from current data sample (~140 SM CEvNS events) imminent



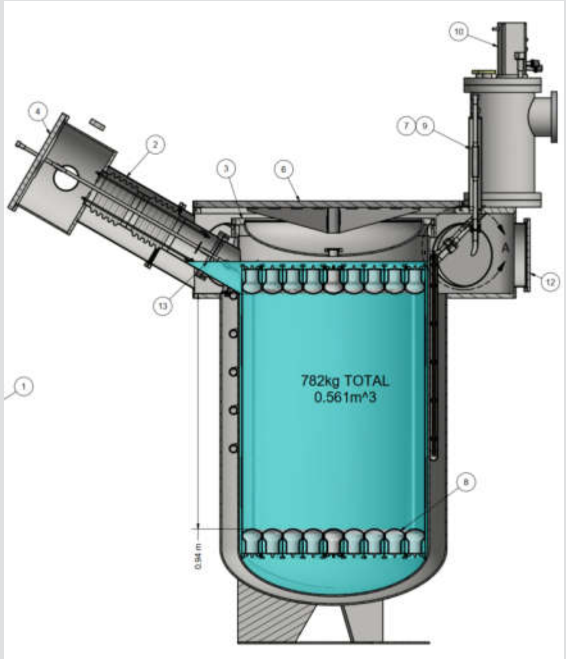
- Ton-scale LAr experiment proposed

COHERENT experiment at ORNL/SNS

- multiple detectors have/will run to observe CEvNS process:
  - CsI: discovery
  - LAr: currently running, engineering run published, physics results imminent
  - Ge, NaI: coming soon



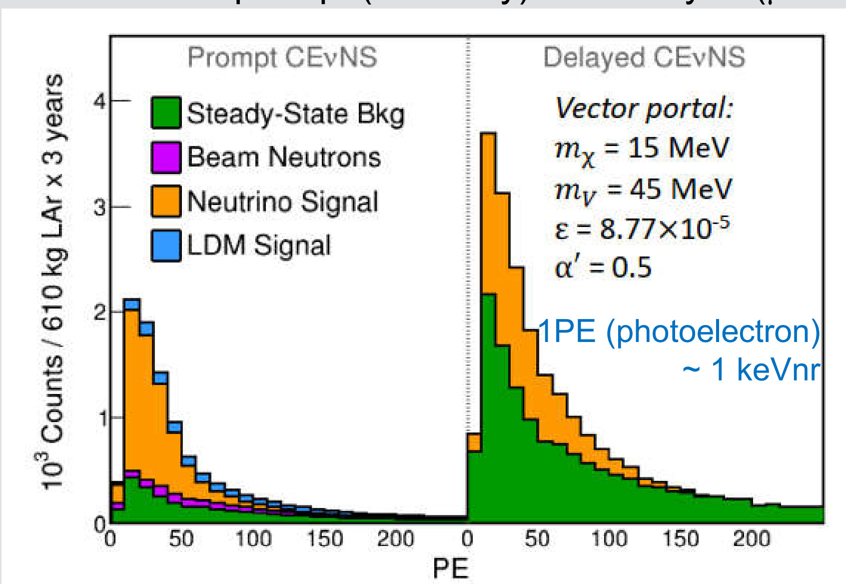
- scalability and demonstrated low background have focused our efforts on LAr
  - see first limits from engineering run of 27~kg detector at: arXiv:1909.05913 [hep-ex]
  - results from current data sample (~140 SM CEvNS events) imminent



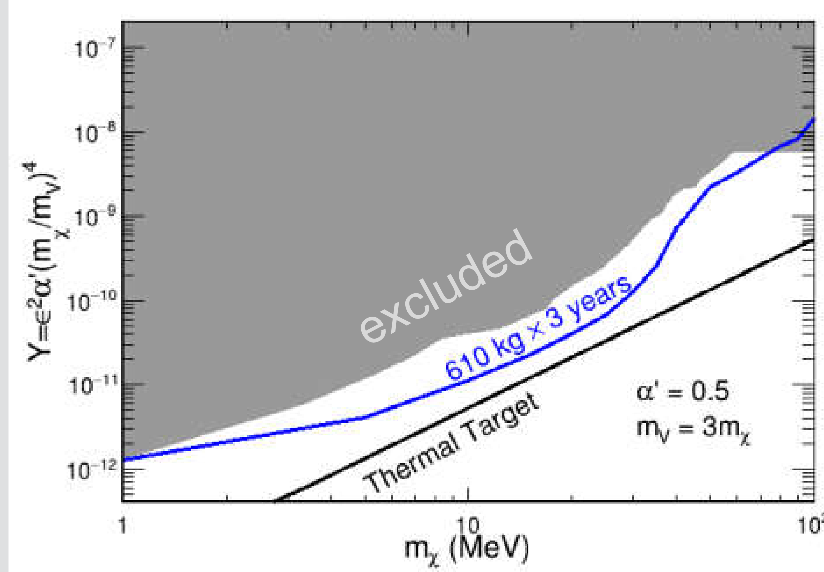
- Ton-scale LAr experiment, scintillation detector, proposed. Sensitivity studies: arXiv:1911.06422 [hep-ex]
  Some plots on next pages...

COHERENT LAr search for dark matter

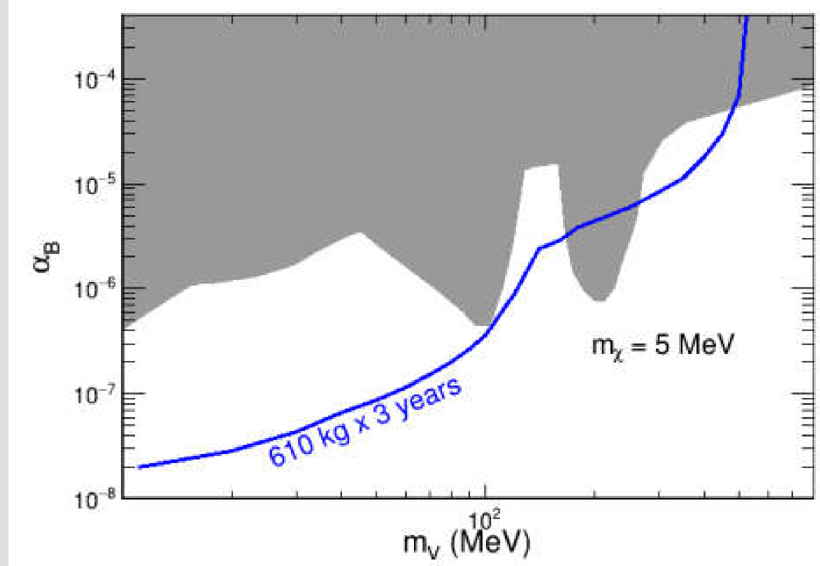
- 750 kg (610 kg fiducial) LAr detector
- 3 yrs at SNS, data driven (CENNS-10) simulations
- CEvNS is largest background but well-constrained with time/energy structure. dark matter all prompt, neutrinos prompt (π^0-decay) and delayed (μ-decay)



- vector portal: improved constraints for m_χ<80MeV, reaches thermal target for α'<0.1
- baryonic portal: significant improvement for
- m_χ<500MeV

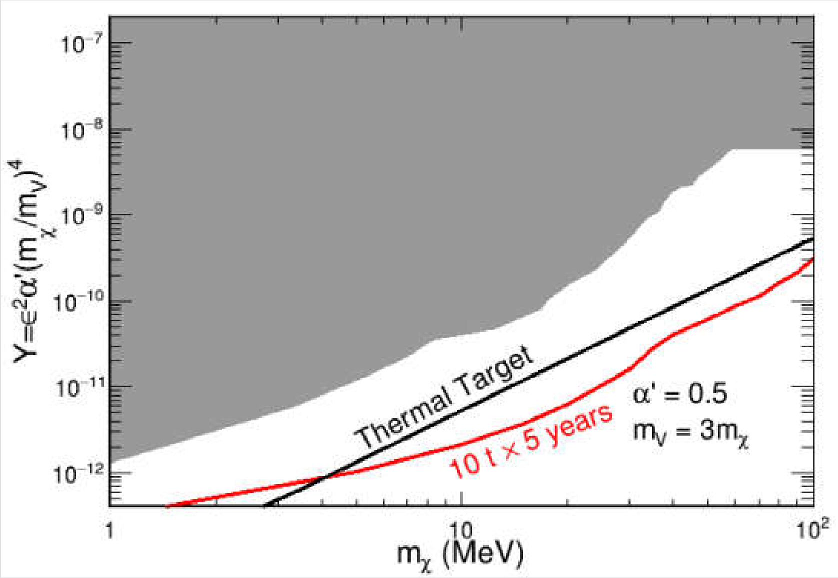


arXiv:1911.06422 [hep-ex]

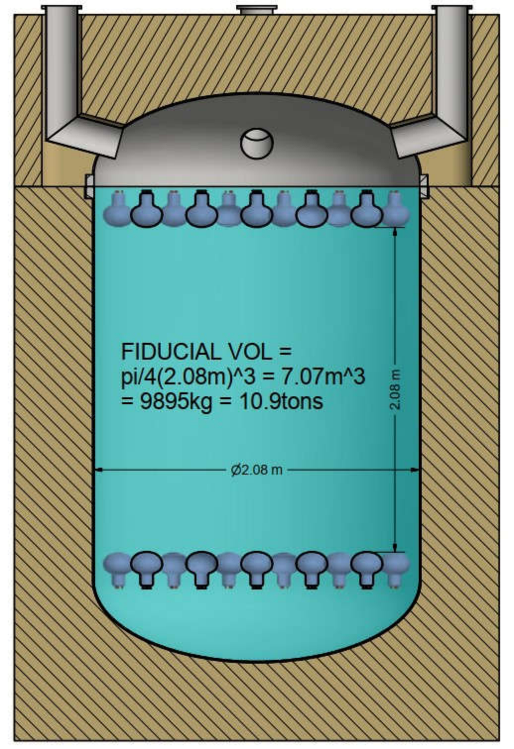


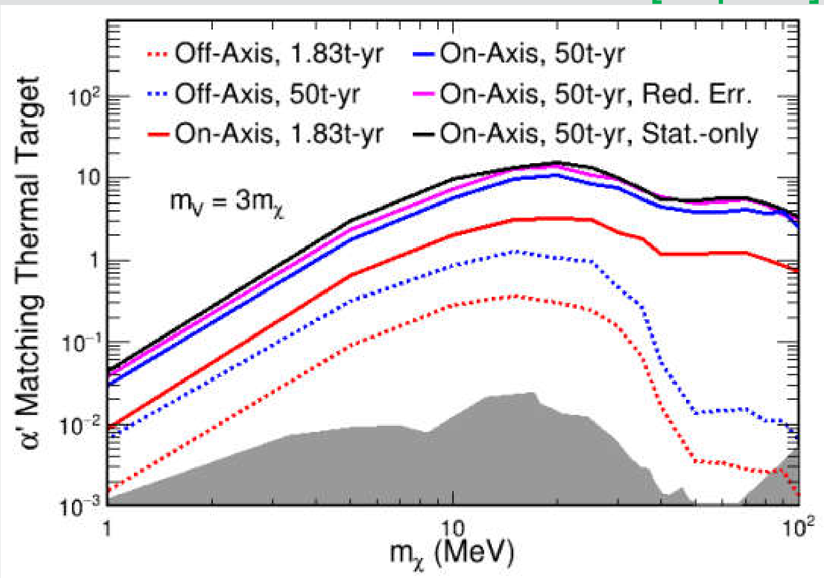
COHERENT LAr search for dark matter

- longer term at SNS after beam/detector upgrades.
- on beam axis for highest sensitivity
- scalar DM excluded for all $\alpha' < 1$ for $5 < m_\chi < 100$ MeV



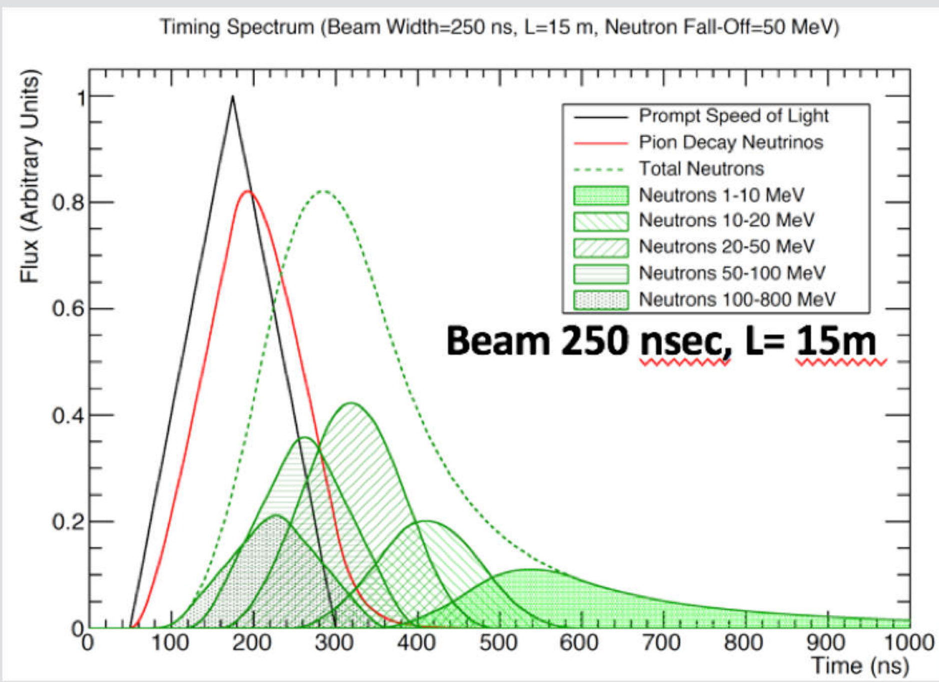
arXiv:1911.06422 [hep-ex]

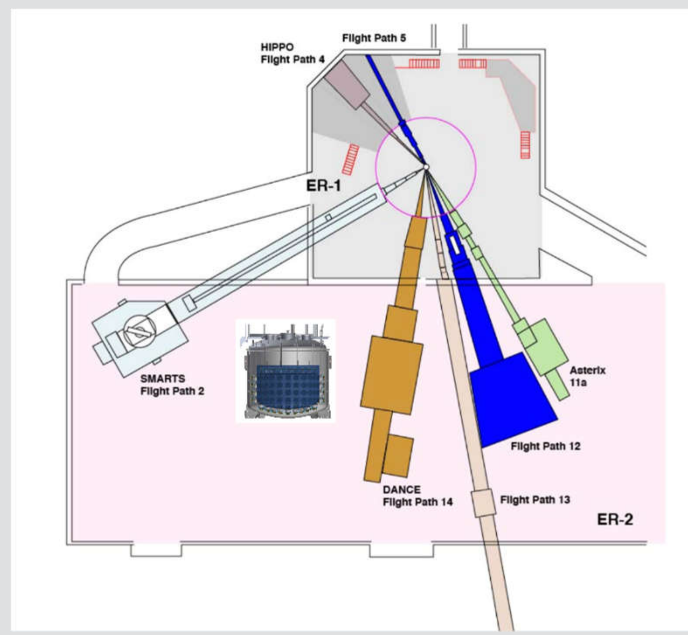




Coherent Captain-Mills (CCM) experiment at LANL

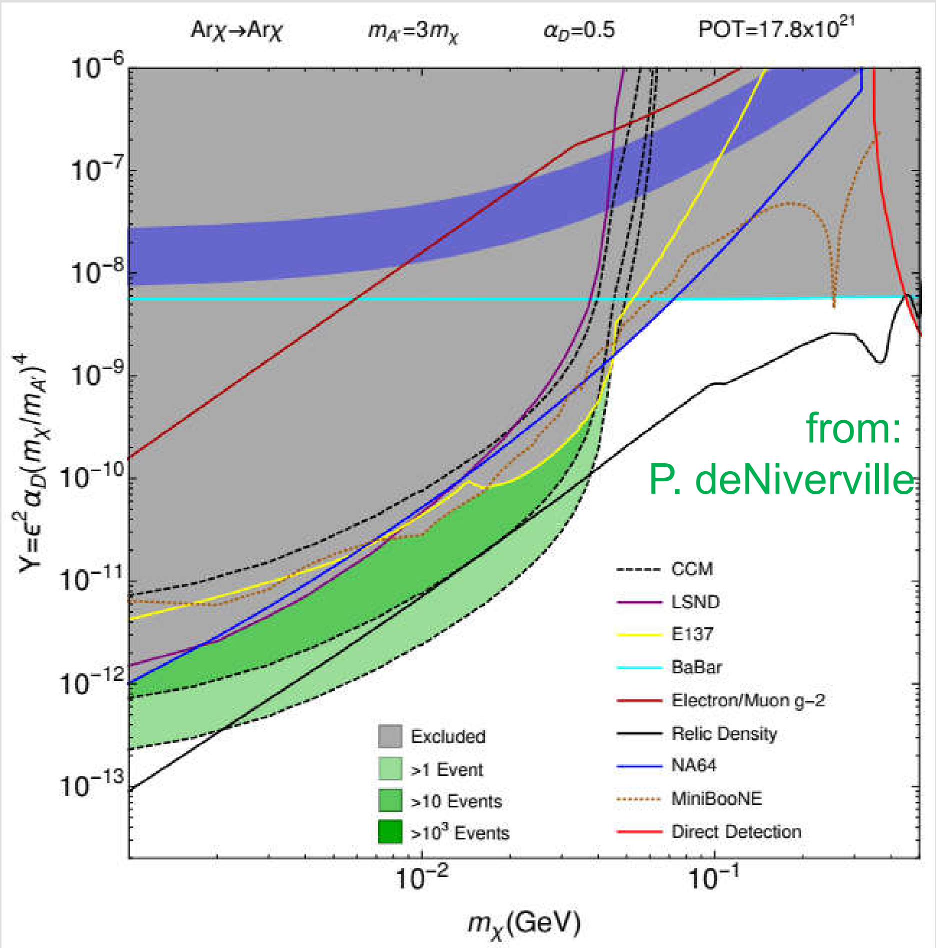
- Located at LANSCE-Lujan (neutron) facility at Los Alamos Natl Lab
- near (20-40 m) neutron target with
- 80kW pulsed 800 MeV proton beam
- 7 ton (fiducial), existing detector
- shielding under construction
- will exploit prompt signal (before neutrons)

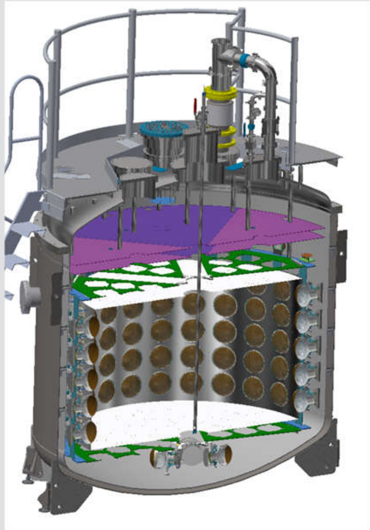


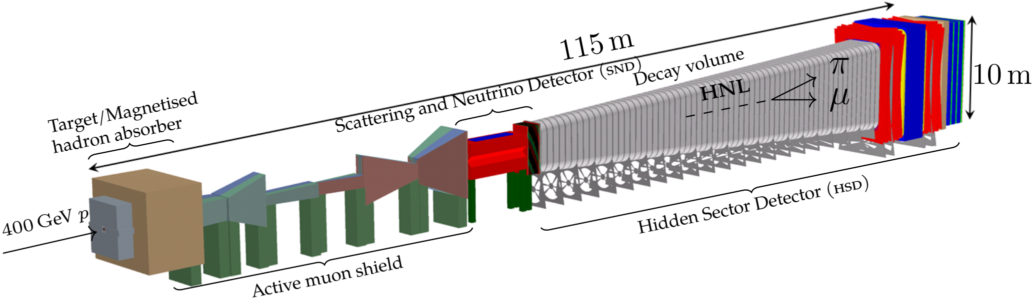


Coherent Captain-Mills (CCM) experiment at LANL

- backgrounds not yet measured
- CCM event sensitivity, 3 years:



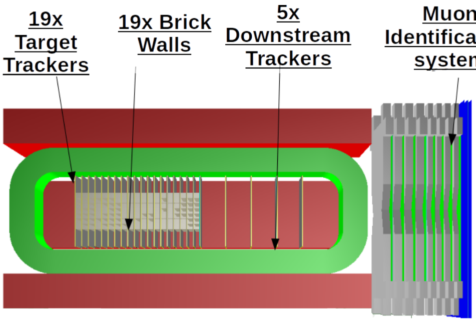




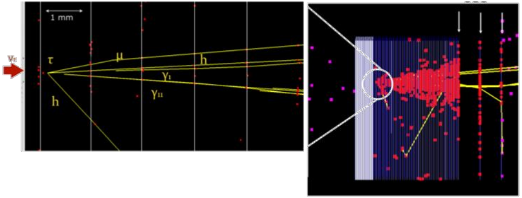
Two detectors for two complementary signatures:

- Scattering (light dark matter & neutrinos)
- Decay (visible decays of hidden sector particles)

Focus on the **scattering and neutrino detector (SND)** *today*



- 10 t detector 38 m from the target
- Combination of nuclear emulsions and SciFi trackers
  - Similar to OPERA
  - Reoptimised for SHiP
- Look for electron recoil signature
  → electron shower

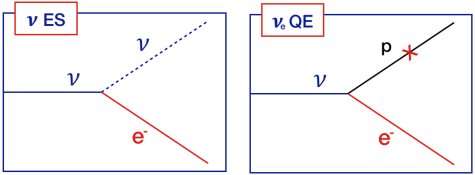


Essentially: ECAL with micrometric tracking!

LDM background

Fully simulated background over 5 years (2×10^{20} protons on target):

Background	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic Scattering on e^-	81	45	56	35	217
Quasi-elastic Scattering	245	236			481
Resonant Scattering	8	77			85
Deep Inelastic Scattering		14			14
Total	334	372	56	35	797



› ν_τ, $\bar{\nu}_\tau$ background negligible

Irreducible:

› Elastic scattering

› $\bar{\nu}_e + p \rightarrow e^+ + n$

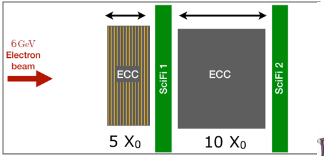
Reducible:

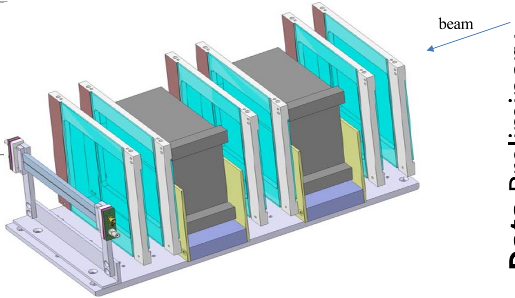
› Quasi-elastic: $\nu_e + n \rightarrow e^- + \not{p}$

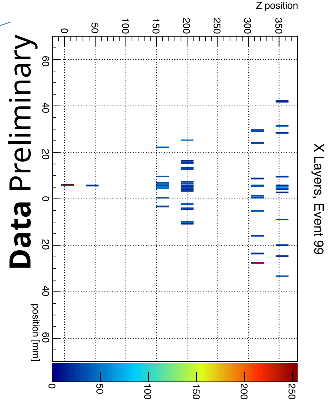
→ **proton energy threshold crucial!**

DESY test beam of Scattering and Neutrino Detector (SND) prototype

Test beam **last month** to test the **electromagnetic shower identification** and **energy measurement** with **emulsion cloud chambers** and **SciFi** → **SND prototype!**



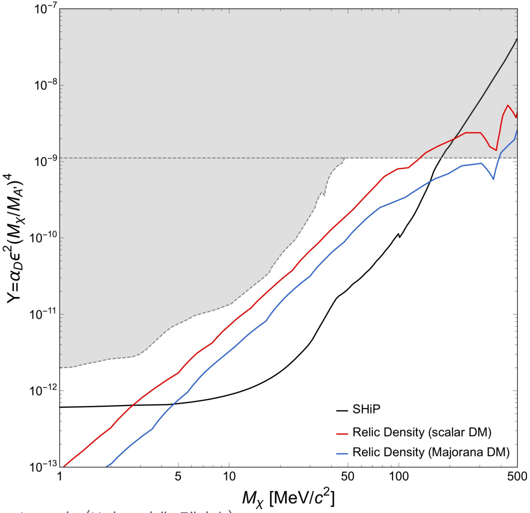




Institutes involved:

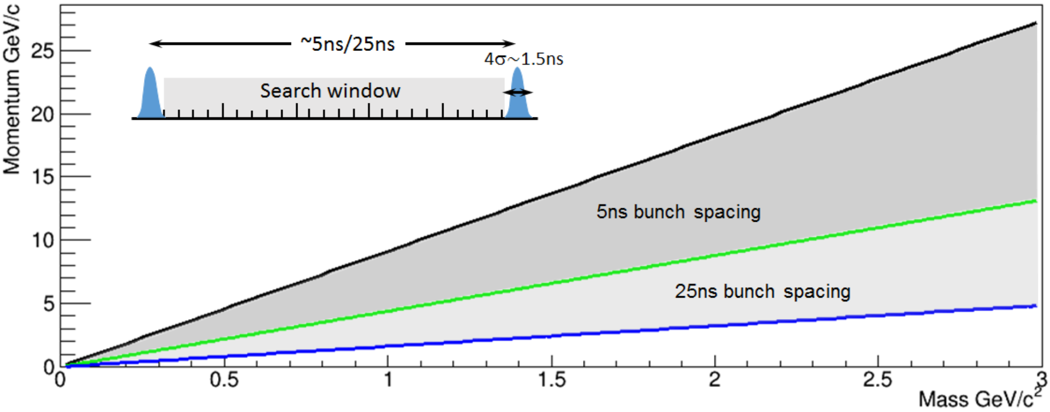
EPFL, Lebedev, MISiS, Moscow State University, Napoli, Zurich

$$M_{A'} = 3M_\chi, \alpha_D = 0.1$$



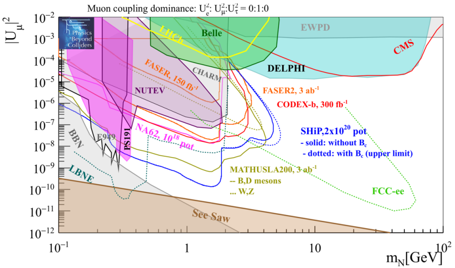
- Updated since PBC BSM report
- Signal simulated using **MadDump**
- Including A' production via
  - Meson decays (including cascade)
  - Prompt QCD
  - Drell-Yan
- Paper in internal review

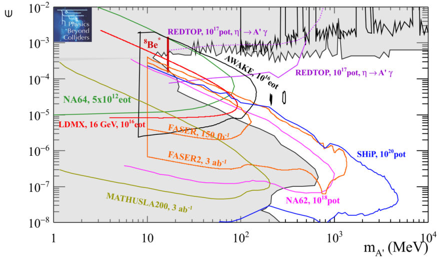
Confirming a signal with zero background

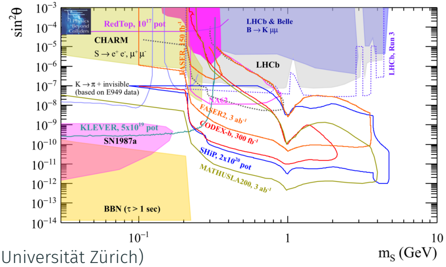


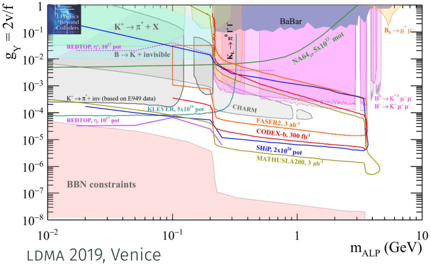
Use 100 ps time resolution to unambiguously distinguish massive LDM from ~massless ν

BSM sensitivities









Conclusion

- Proton beams give access to a variety of production mechanisms and high energies — complementary to electon beams and direct detection
- ϵ^2 vs. ϵ^4, but less model dependence
- Several results and new experiments over the next years!

For more on SHiP, see [SPSC-SR-248] and the forthcoming Comprehesive Design Study Report

Backup

Selection cuts:

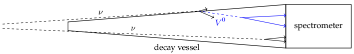
- $1 < E < 20$ GeV
- $10 < \vartheta_{\chi-e} < 20$ mrad

Visibility thresholds:

- protons: 170 MeV
- other charged particles: 100 MeV

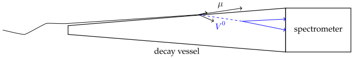
Conservative estimate from OPERA, could be improved by better reconstruction using machine learning techniques.

Neutrino background



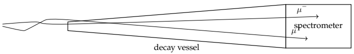
Selection cut	Expected Bkg
Basic selection	135
PID	12
Background tagger	0.05

Muon DIS



Selection cut	Expected Bkg
Reconstructed events	1.5×10^6
Selection cuts	566
Background tagger	$< 6 \times 10^{-4}$

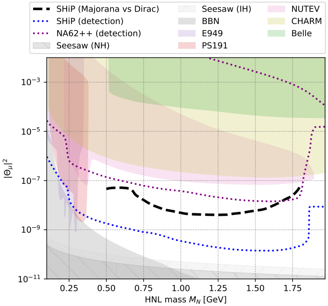
Muon combinatorial

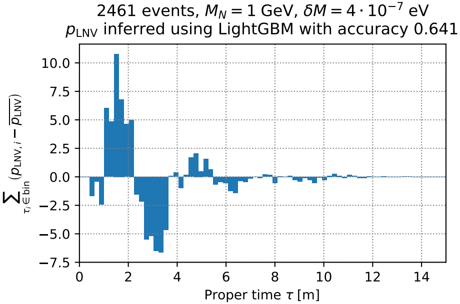


Selection cut	Expected Bkg
Acceptance	8.5×10^{15}
Selection cuts	10^9
Timing	10^{-2}

Less than 0.1 background events over 5 years — studied with full simulation

- SHiP could do more than just discover HNL:
  - Are neutrinos Majorana or Dirac?
  - What is their mass splitting? → HNL oscillations!





Details to be published soon: Tastet & Timiryasov [1911.XXXXX]!