NUFACT - Uppsala - September 2017

Probing light dark sectors with coherent neutrino-nucleus scattering

Adam Ritz

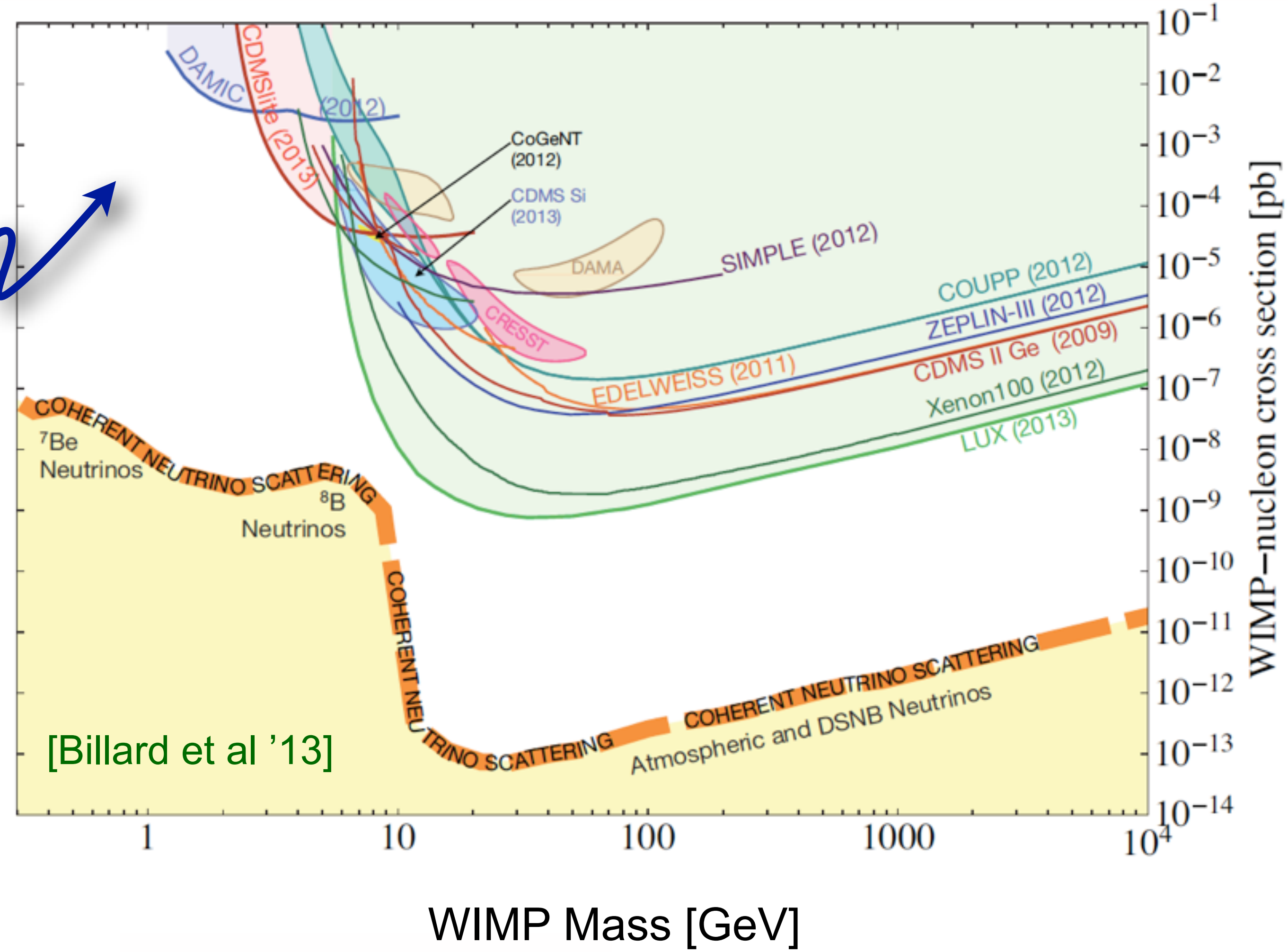
University of Victoria

P. deNiverville, M. Pospelov & AR, 2015

[related work with B. Batell, C.-Y. Chen, P. deNiverville, D. McKeen, M. Pospelov & members of MiniBooNE, T2K & SHiP]

WIMP-like (thermal relic) DM & neutrinos

For sub-GeV DM: $m_e < m_{DM} < m_{had}$, a (high intensity) relativistic beam is advantageous, as direct detection sensitivity drops due to recoil thresholds given $v_{DM\ halo} \sim 10^{-3}$.



Convergence of direct detection sensitivity to DM and neutrinos (and broad model-space for DM) motivates exploration of the accelerator neutrino program for use in (light) DM searches

WIMP-like (thermal relic) DM & neutrinos

- maybe dark matter is more like the CvB...
  - neutrinos are a (small) component of dark matter
  - very abundant ~ O(100/cm^3)
  - very hard to see via direct detection, since KE~10^{-4} eV

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany

(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10—10 [illegible] eV), however. We examine a

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1—10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1—10^2 GeV; or strongly interacting particles of masses 1—10^{13} G

WIP-like (thermal relic) DM & neutrinos

- maybe dark matter is more like the CvB...
  - neutrinos are a (small) component of dark matter
  - very abundant ~ $O(100/cm^3)$
  - very hard to see via direct detection, since KE~10^{-4} eV

- BUT muon neutrinos were discovered (and still studied) via hadronic production in meson decays (large rate!), and observing the (weak) scattering of the relativistic neutrino beam

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

Light (thermal relic) DM

The Lee-Weinberg bound (WIMP mass ≥ few GeV) applies if annihilation in the early universe is via SM forces.

$$\sigma_{\rm ann} \propto \frac{m_{\rm DM}^2}{M_{\rm mediator}^4}$$

⇒ viable thermal relic density for a sub-GeV WIMP requires new annihilation channels through light states, i.e. light DM as part of a hidden sector.

[Boehm et al ’03, Fayet ’04,’06; Pospelov, AR, Voloshin ’07; Hooper & Zurek ’08]

DM Annihilation

Standard Model $\xleftarrow{\hspace{2em}}$ *Light mediators* $\xrightarrow{\hspace{2em}}$ **Hidden Sector**

DM Production!

➪ by inversion, light mediators allow direct production of DM at ***low energy!***

(particularly if $m_{\rm mediator} > 2\, m_{\rm DM}$)

$\mathrm{Br}(\mathrm{mediator} \to \mathrm{DM}) \sim 1$

EFT for a (neutral) hidden sector

Standard Model $\xleftrightarrow{\text{mediators}}$ **Hidden Sector**

$$\mathcal{L} = \sum_{n=k+l-4} \frac{\mathcal{O}_k^{(SM)} \mathcal{O}_l^{(med)}}{\Lambda^n} \sim \mathcal{O}_{portals} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Generic interactions are irrelevant (dimension > 4), but there are three UV-complete relevant or marginal "portals" to a neutral hidden sector

- Vector portal: $\mathcal{L} = -\frac{\epsilon}{2} B^{\mu\nu} F'_{\mu\nu}$ [Okun; Holdom; Foot et al]
- Higgs portal: $\mathcal{L} = -H^\dagger H (AS + \lambda S^2)$ [Patt & Wilczek]
- Neutrino portal: $\mathcal{L} = -Y_N^{ij} \bar{L}_i H N_j$

Many more UV-sensitive interactions at dim ≥ 5 (e.g. axions)

(Minimal) Vector portal DM model

mediators

Standard Model $\longleftrightarrow$ **Hidden Sector**

$$\mathcal{L} = -\frac{1}{4}F'^{\,2}_{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{\,2}_{\mu} + |D_\mu\chi|^2 - m^2_{\rm DM}|\chi|^2 + \cdots$$

$\Downarrow$

$$\mathcal{L}_{\rm int} = -\epsilon A'_\mu J^\mu_{\rm em}$$

A' - couples to the SM via the EM current

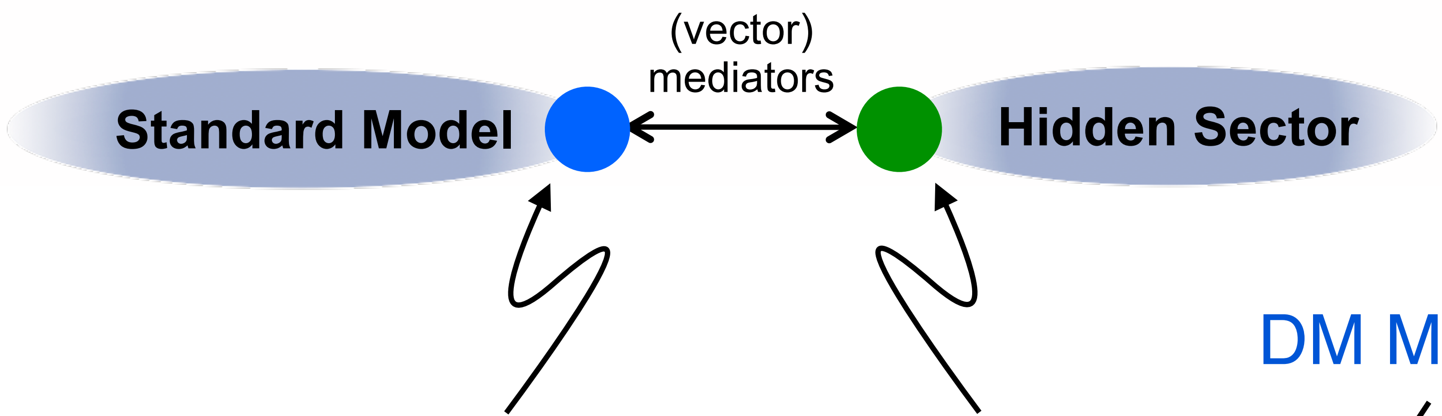
(scalar or pseudo-Dirac, to avoid CMB limits)

$\Downarrow$

DM candidate, coupled through U(1)', with "fine structure constant" α'

- Allows viable sub-GeV thermal relic DM candidates [Boehm et al '03, Fayet '04,'06; Pospelov, AR, Voloshin '07; Hooper & Zurek '08].
- For $m_{DM} < m_V$, the correct relic density fixes a specific relation between $\{\varepsilon, \alpha', m_V, m_{DM}\}$

Probing the vector portal



DM Models

Experimental probes

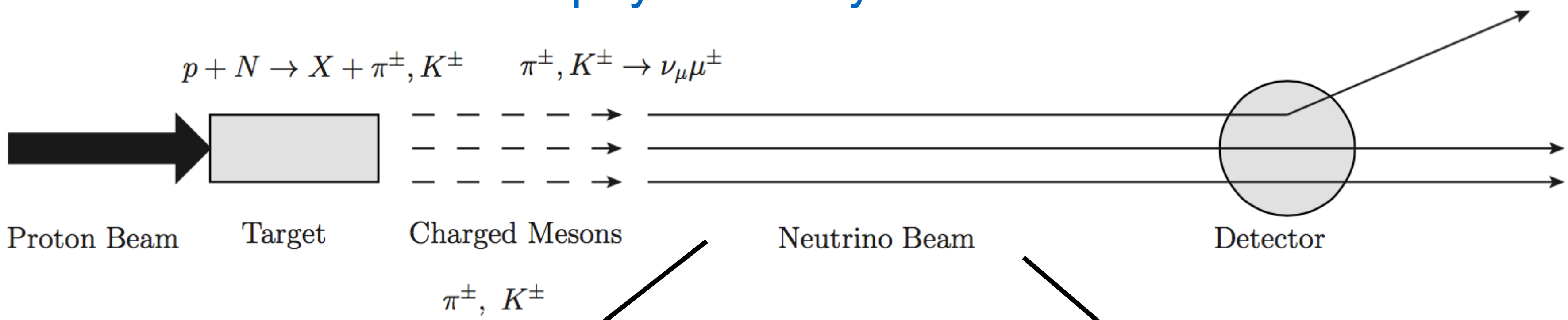
- Precision corrections
  - e.g. lepton g-2, EDMs
- rare (visible) decays
  - e.g. collider/fixed target production plus e.g. leptonic A' decays, $O(\varepsilon^2)$ x Br(SM)

- rare (invisible) decays/missing E
  - e.g. collider production plus missing energy in decays and scattering, $O(\varepsilon^2)$ x Br(Hid)
- anomalous NC-like scattering
  - e.g. fixed target production plus anomalous NC-like scattering, $O(\varepsilon \times \varepsilon^2 \alpha')$

(also astrophysics & cosmology)

Fixed target probes - Neutrino Beams

Probes of new physics - beyond “neutrino NSI”



New ν-SM interactions (NSI)
- heavy mediators
- light mediators

New light states
- sterile ν
- hidden sectors
  e.g. light DM

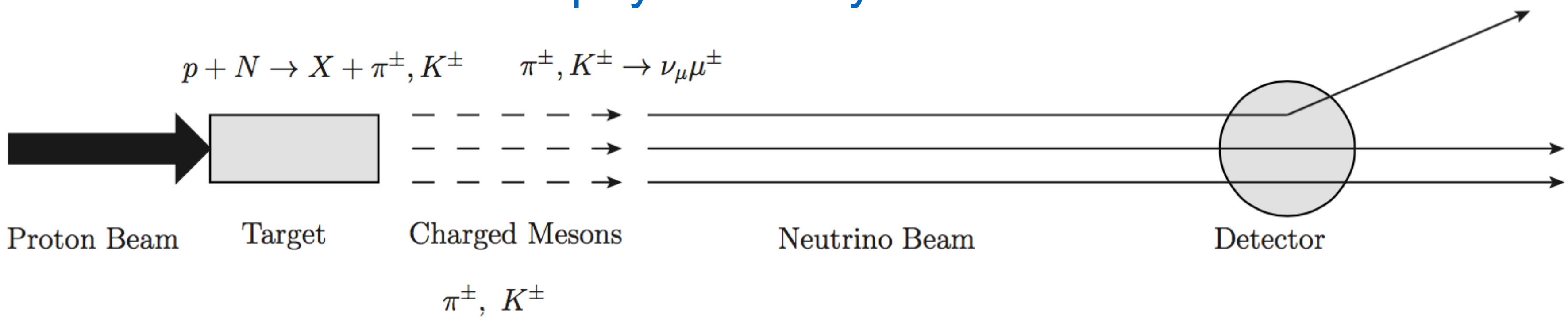
[see talk by J. Liao]

[also Dent et al ’16]

Focus of this talk

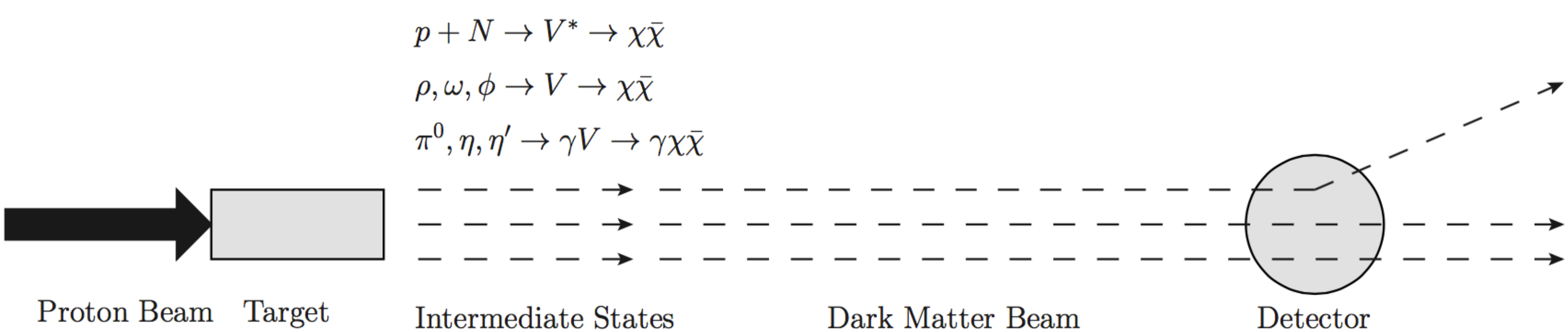
Fixed target probes - Neutrino Beams

Probes of new physics - beyond “neutrino NSI”



Basic idea: use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam.

[Batell et al ’09, ’14, deNiverville et al ’11, ’12, ’16]



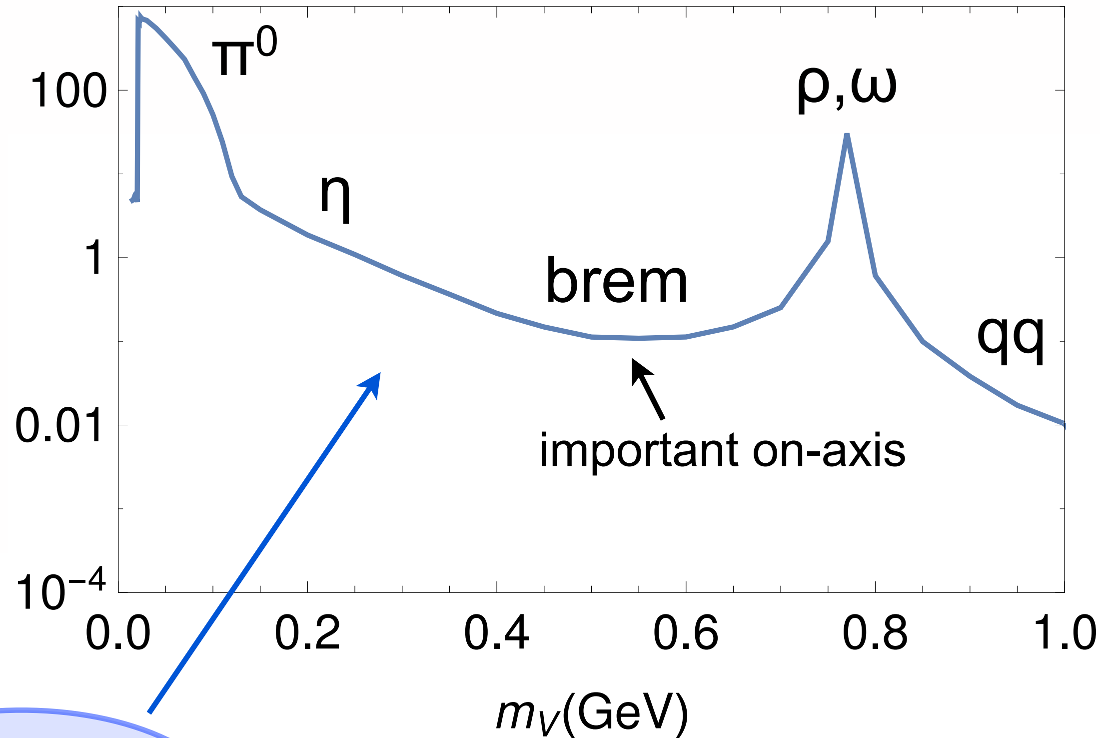
[see also Dobrescu et al ’15, Izaguirre et al ’17]

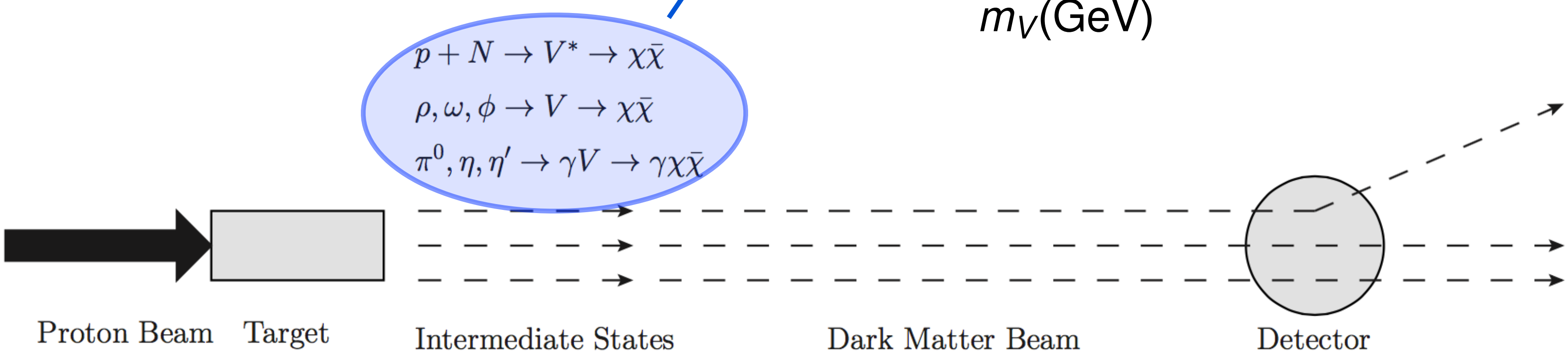
Fixed target - DM production

[deNiverville et al ’16]

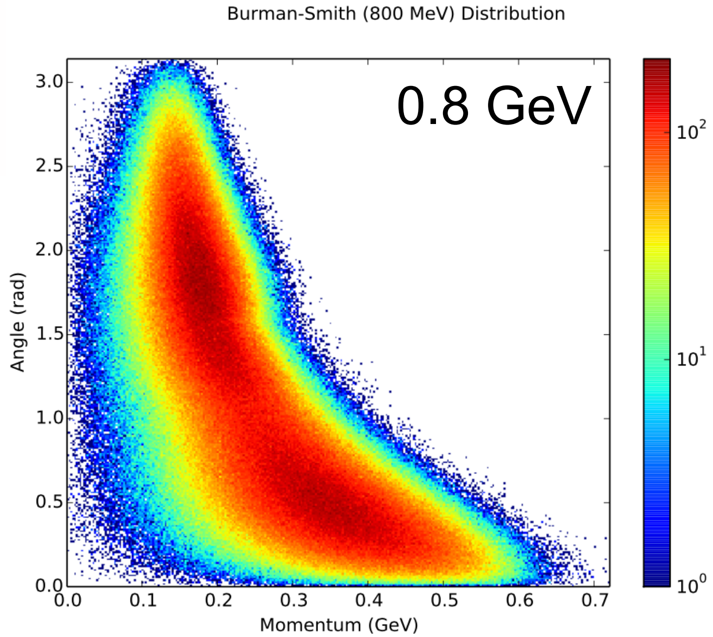
Unnormalized production rate at e.g. MiniBooNE (vector mediator)

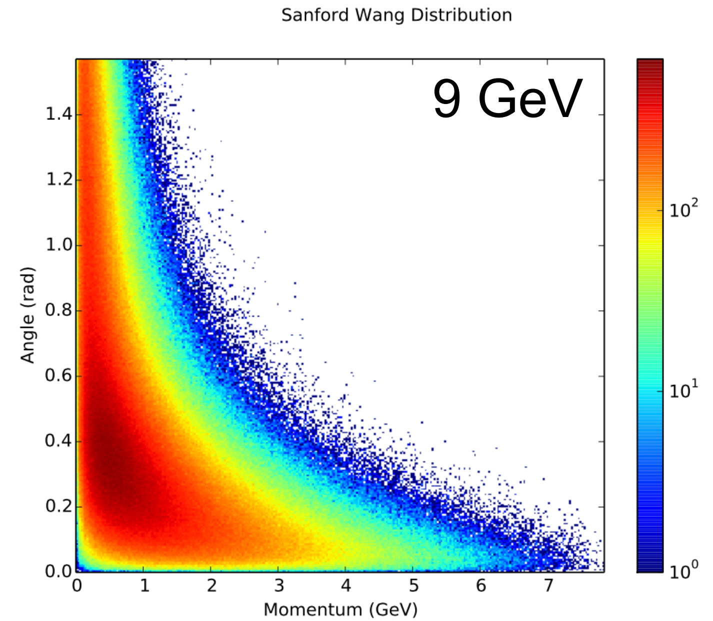
- NB: some components of production model can be validated with data, but not all...

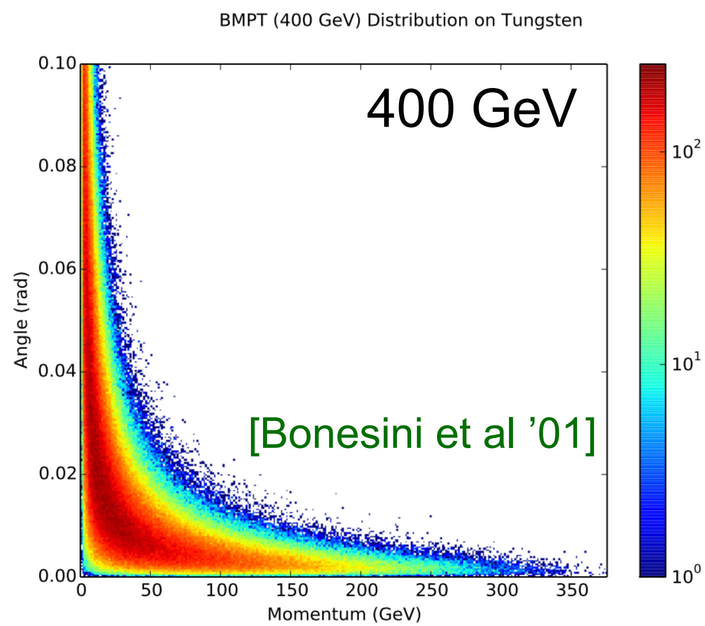




DM Production - π, η model distributions





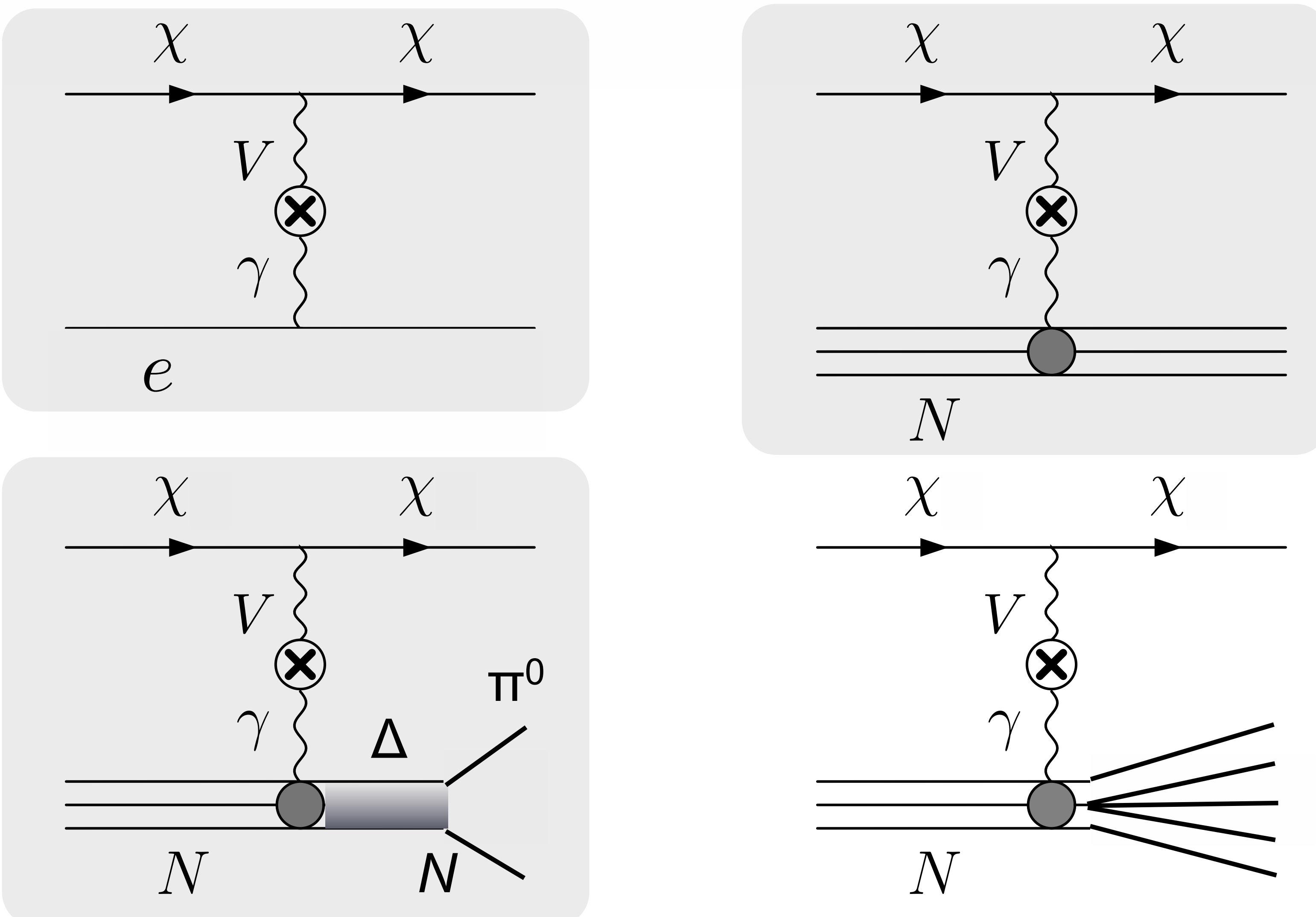


- Rate for π^0,η given by averaging rates for π^+, π^-
- calibrated for thin targets, so will broaden for an absorber
- *charged mesons are magnetically focused, and neutrino energy spectrum has a lower peak*

[deNiverville et al '12, '16]

Signatures

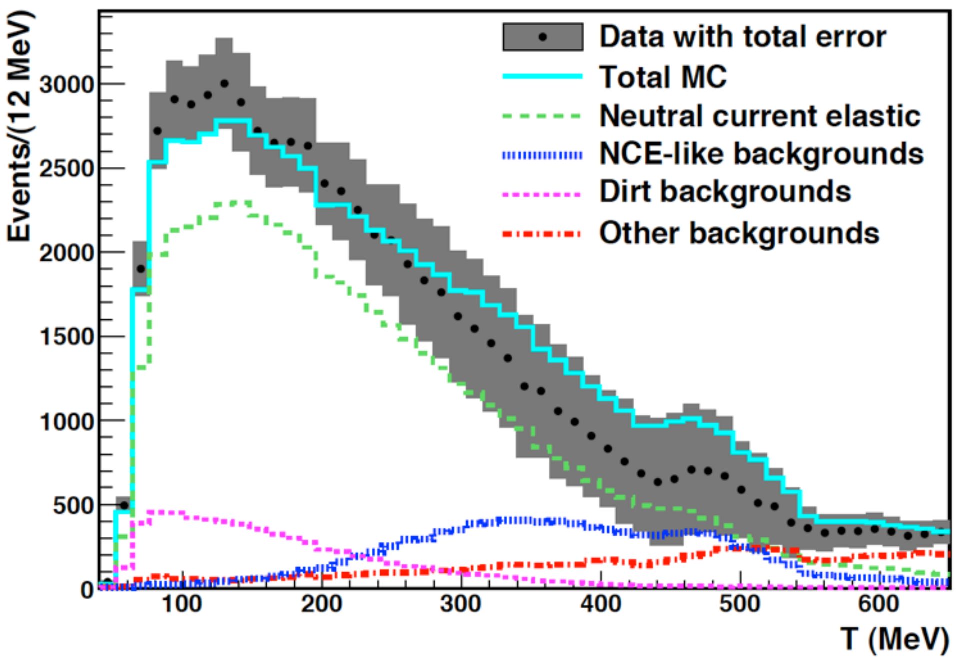
Characteristic DM (in)elastic scattering signatures



Mimics scattering of neutrinos, which provide dominant background

Neutrino backgrounds...

Neutrino elastic scattering provides a large background at all ν-beam facilities with a decay volume after the target, e.g. at MiniBooNE



~10^5 -10^6 scattering events, with neutral current cross-sections measured to O(18%) [MiniBooNE '10]

➠ Counting experiments are not enough…

Neutrino backgrounds...

Ways to enhance S/B...

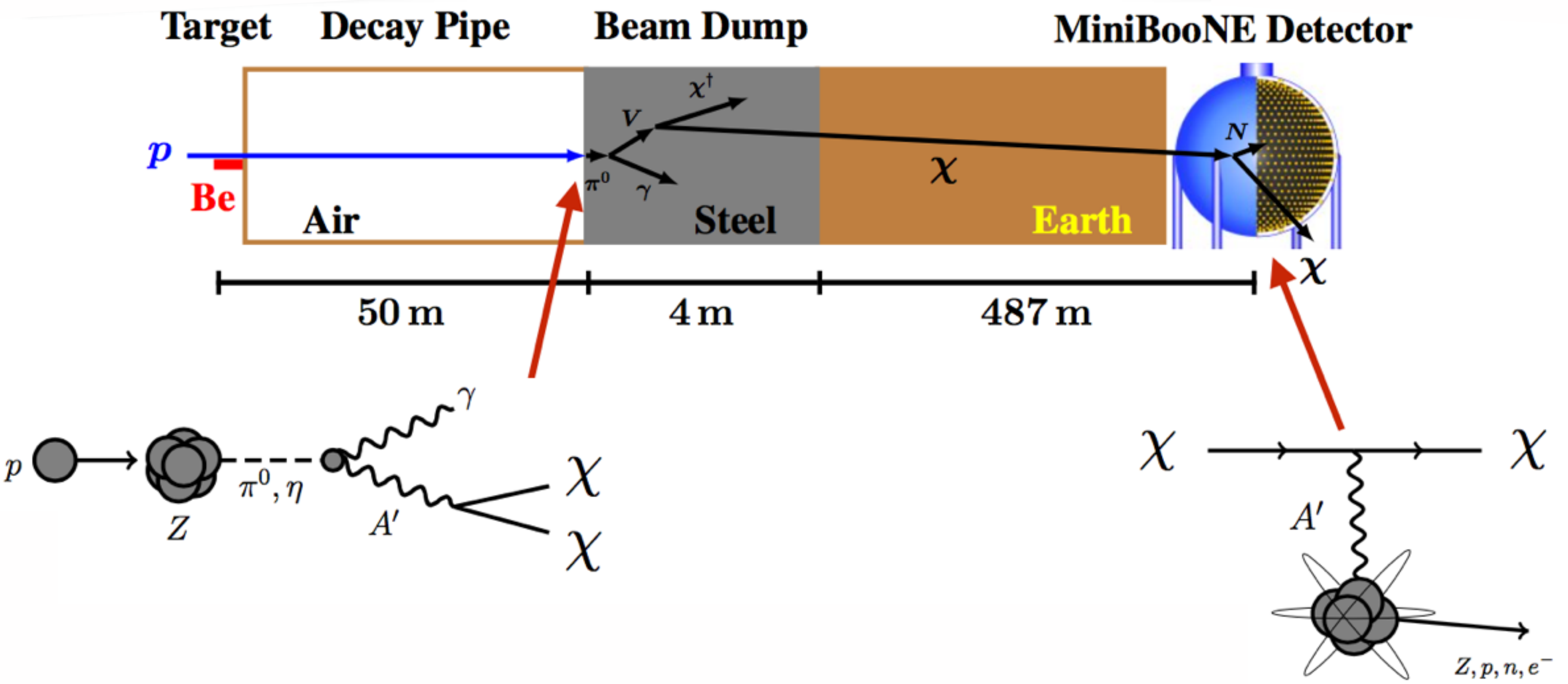
- Run as a "beam dump"
  - steer beam past target and into absorber. This removes decay volume, cuts down neutrino background by a large factor, ~50 at MiniBooNE (but cannot run parasitically, unless well off axis)
- Timing
  - time delay (Υ=10) = O(10ns), effective for higher mass
  - possible at MiniBooNE, also very effective at a far detector (e.g. T2K $\rightarrow$ SuperK)
- Energy cuts (especially if detector is off-axis)
  - neutrino beam peaks at lower energy
  - different scattering kinematics
- Scattering angle cuts
  - forward angle cut ($\cos\theta > 0.99$) very effective for e-scattering

Multiple techniques are being tested in the current MiniBooNE analyses

MiniBooNE beam dump

Optimized use of neutrino facility in beam dump mode, steering beam off-target to minimize the neutrino background

~2x10^{20} POT at FNAL Booster

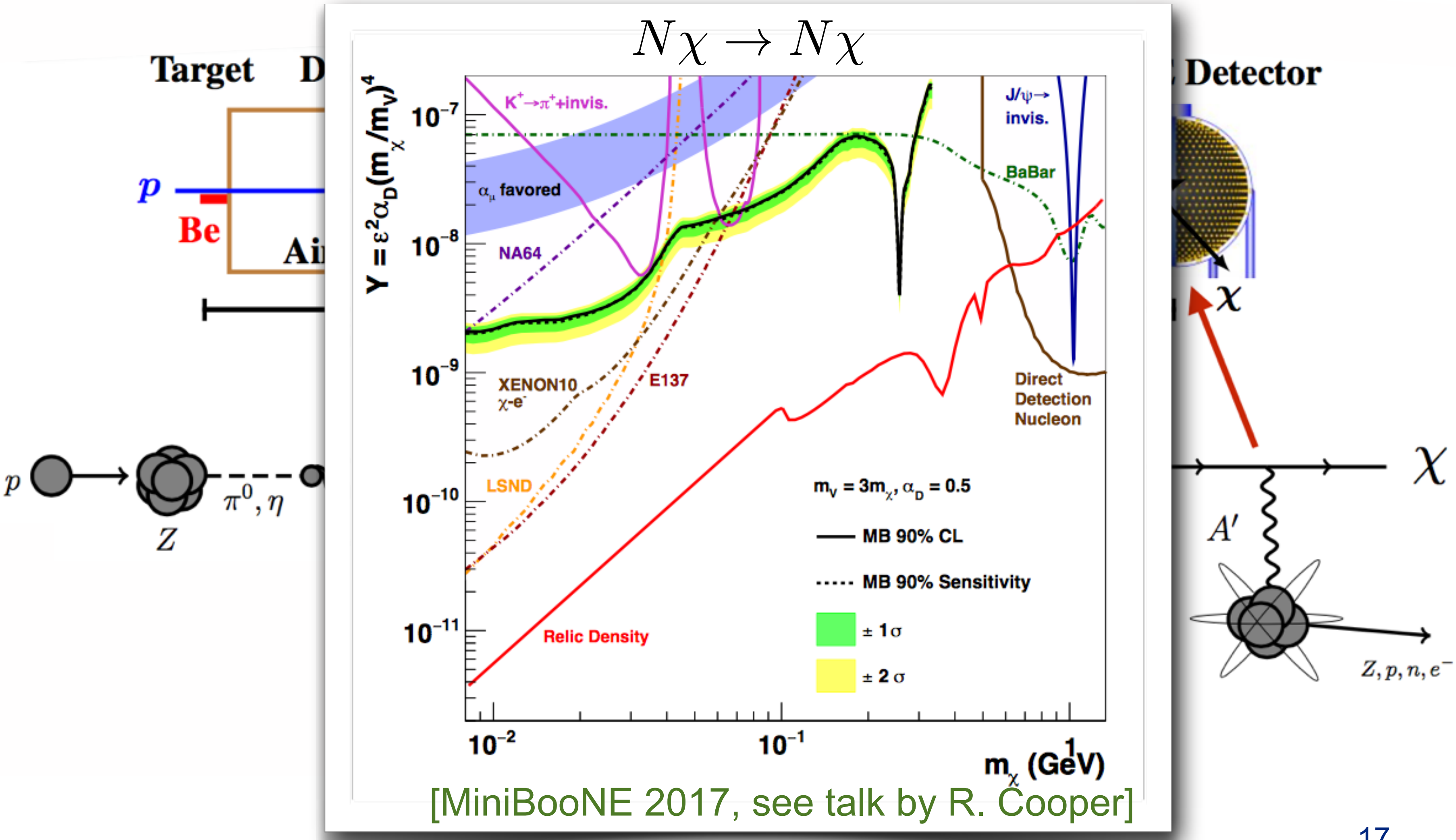


[proposals - Batell et al '09, '14, deNiverville et al '11, '12, '16, + MiniBooNE '12]

Exploits ~10 years prior work to characterize flux, detector response and backgrounds

MiniBooNE beam dump

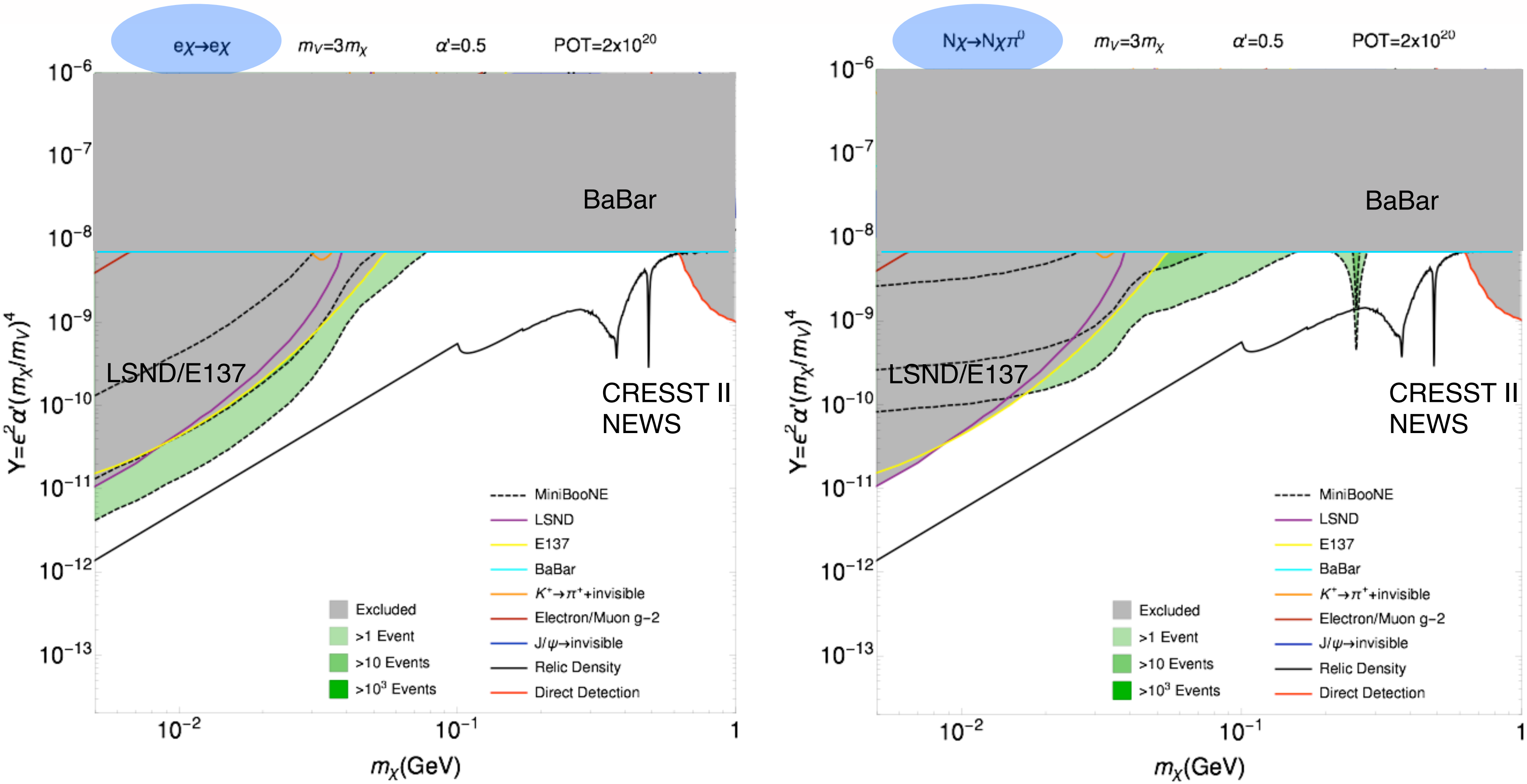
Optimized use of neutrino facility in beam dump mode, steering beam off-target to minimize the neutrino background



[MiniBooNE 2017, see talk by R. Cooper]

MiniBooNE - further scattering channels

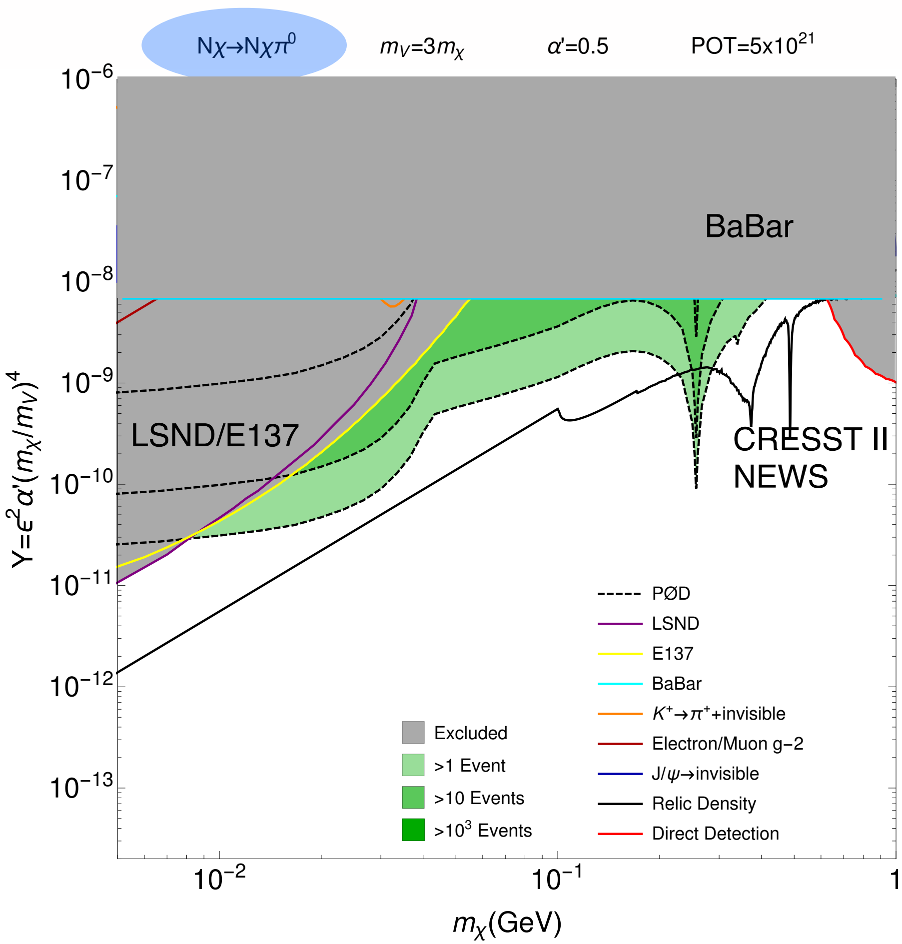
[deNiverville et al ’11, ’12, ’16]



Green contours show 1, 10, 1000 events

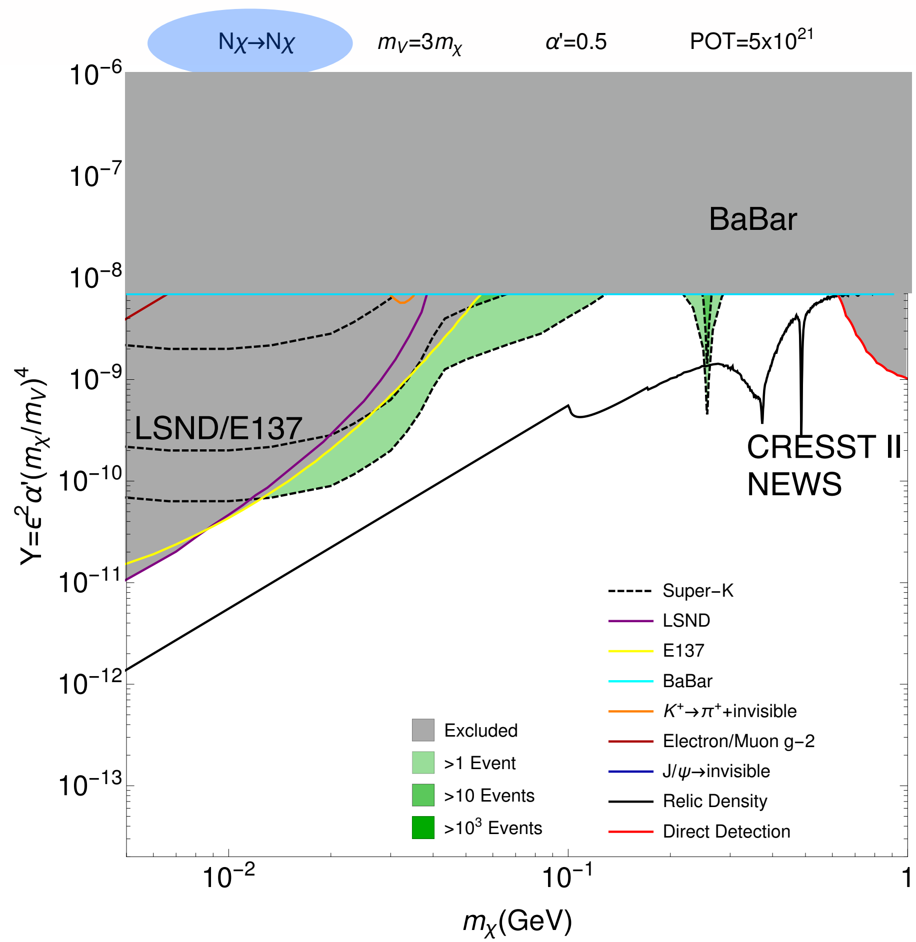
Further sensitivity at high mass... (T2K)

[deNiverville et al ’12, ’16, discussions with A. Konaka, H. Tanaka]



ND280 - P0D

(significant neutrino backgrounds...)

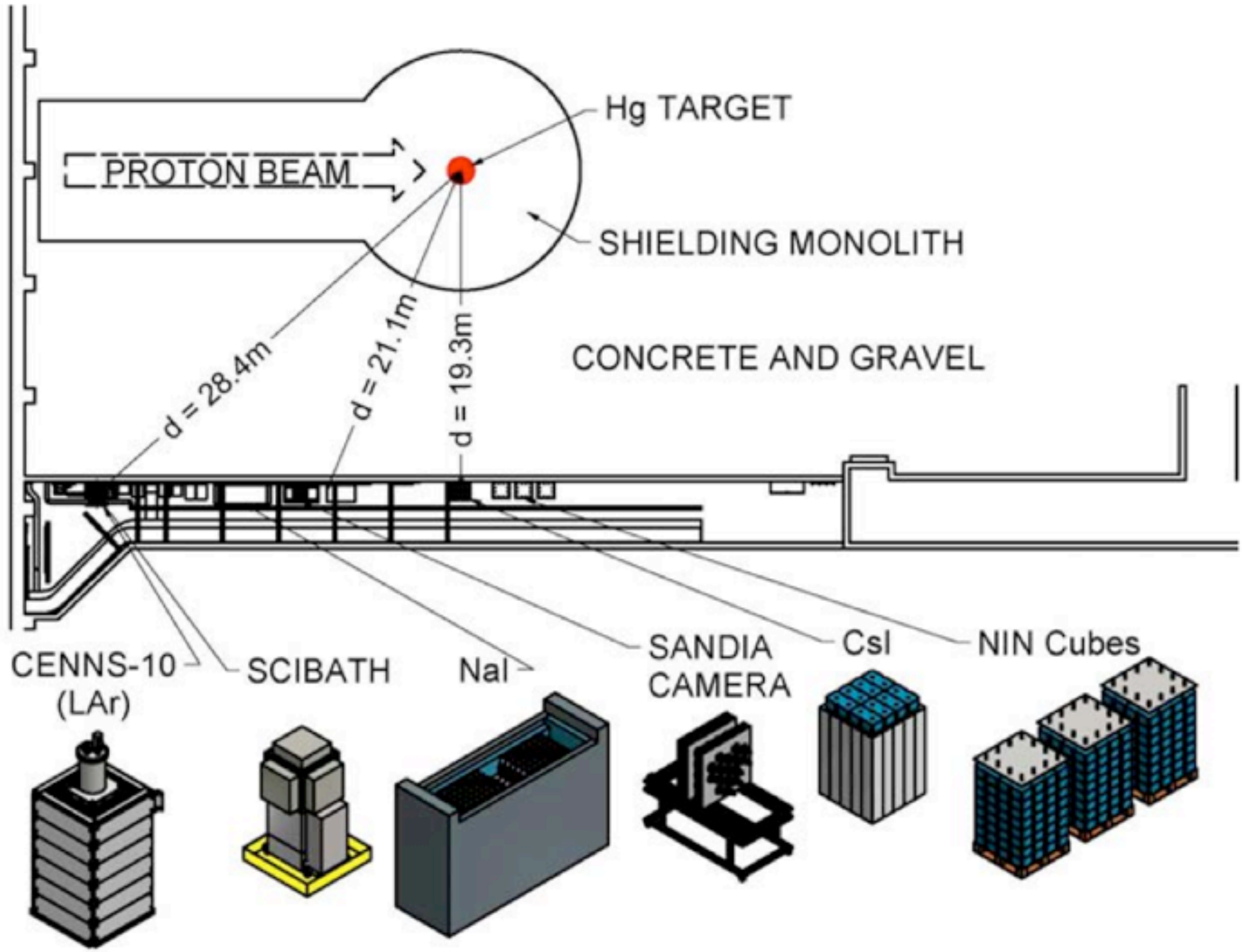


SuperK

(very low background with timing cut)

Further sensitivity at low mass... (COHERENT)

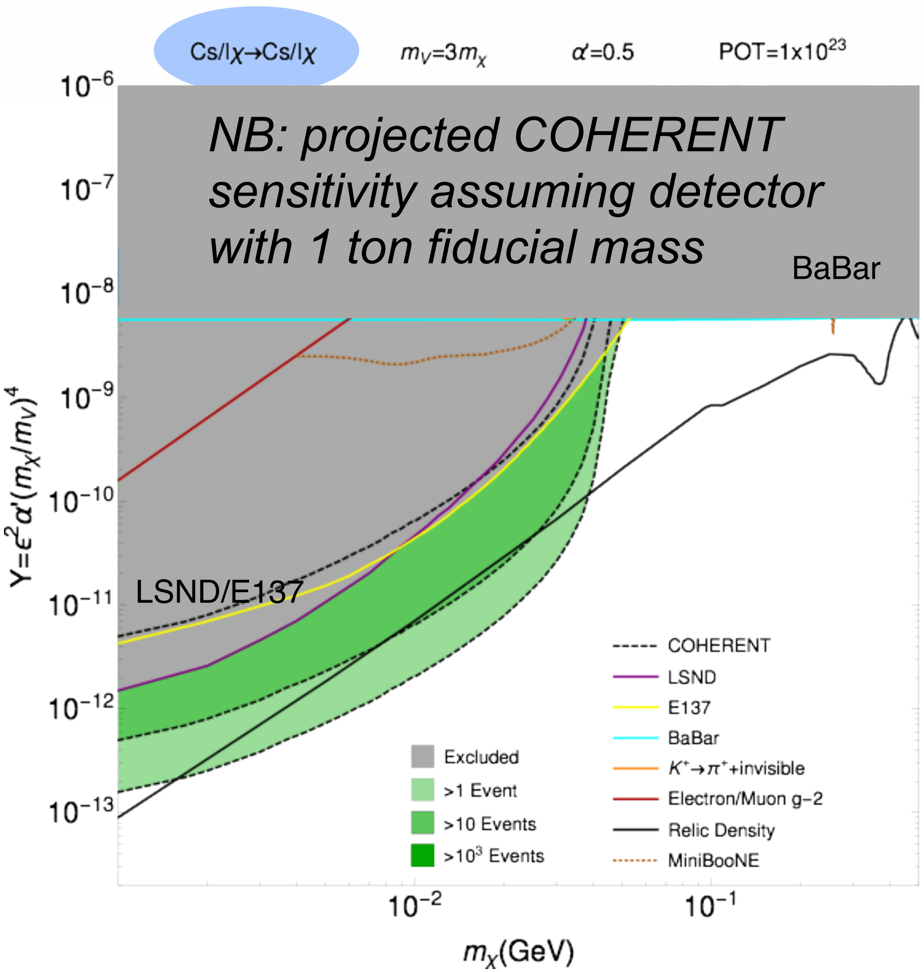
Can improve low mass sensitivity (beyond LSND) via nuclear scattering, using the intense SNS source, and low threshold detectors



[COHERENT '17, see talk by K. Scholberg]

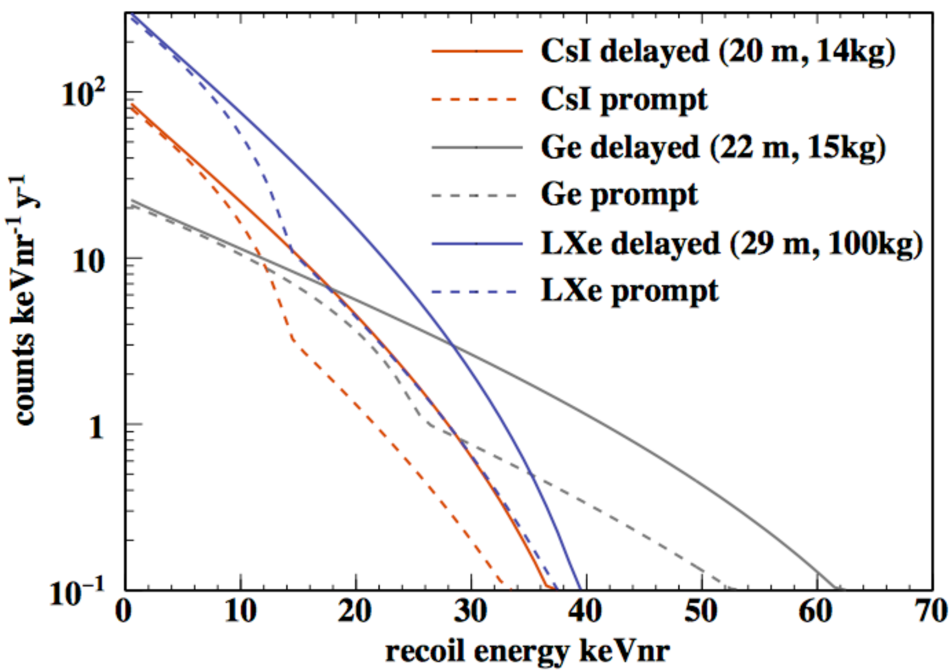
COHERENT (SNS)

[deNiverville et al ’15]



updated with $E_R > 5\,\mathrm{keV}$

[COHERENT ’16]

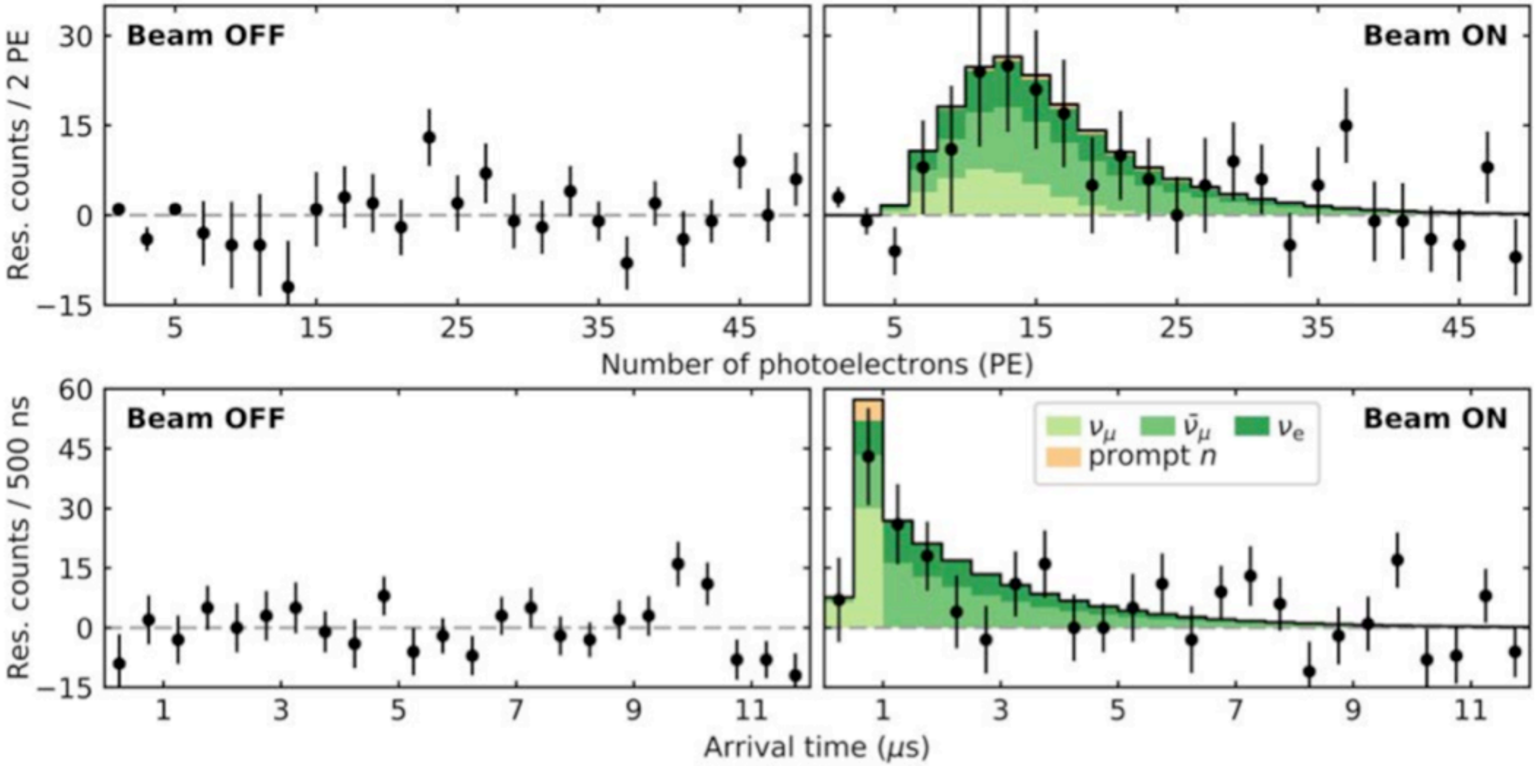


Recoil energy cut limits neutrino background (from DAR)

Includes A’-production via pion capture: $\pi^- + p \to n + V$

COHERENT (SNS)

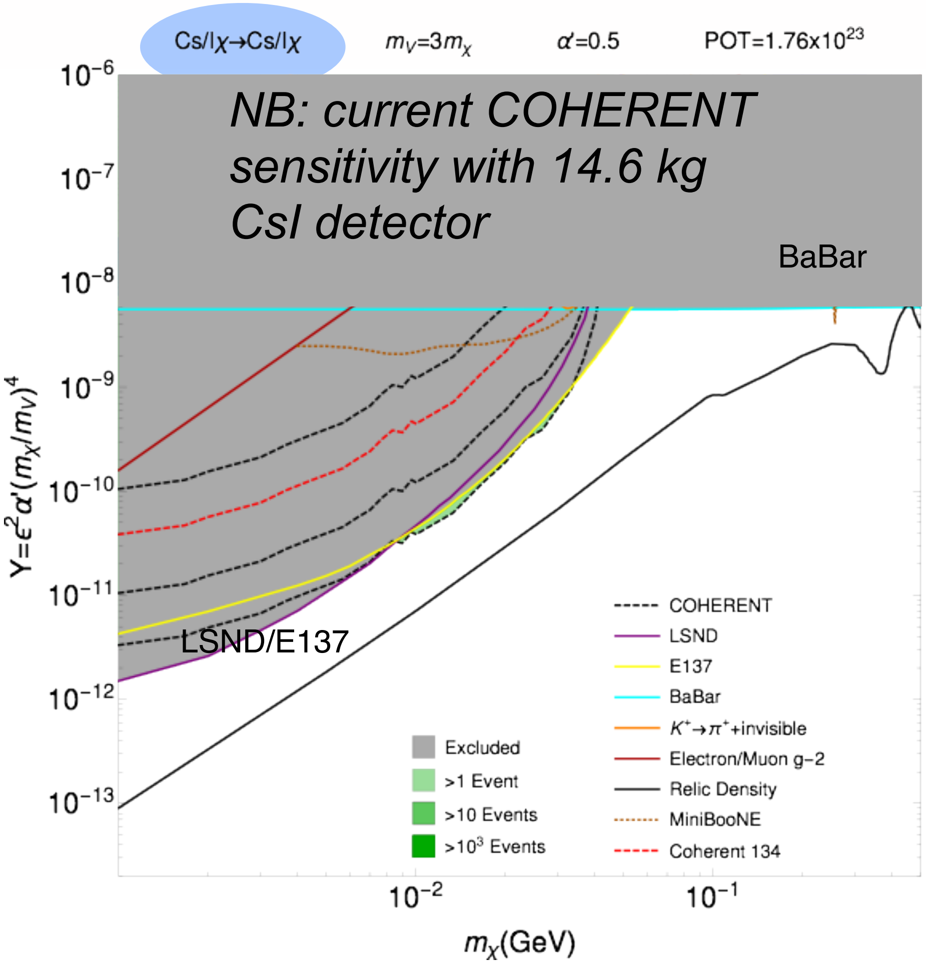
Recent detection of coherent ν scattering, consistent with the SM allows constraints to be set on any new contributions



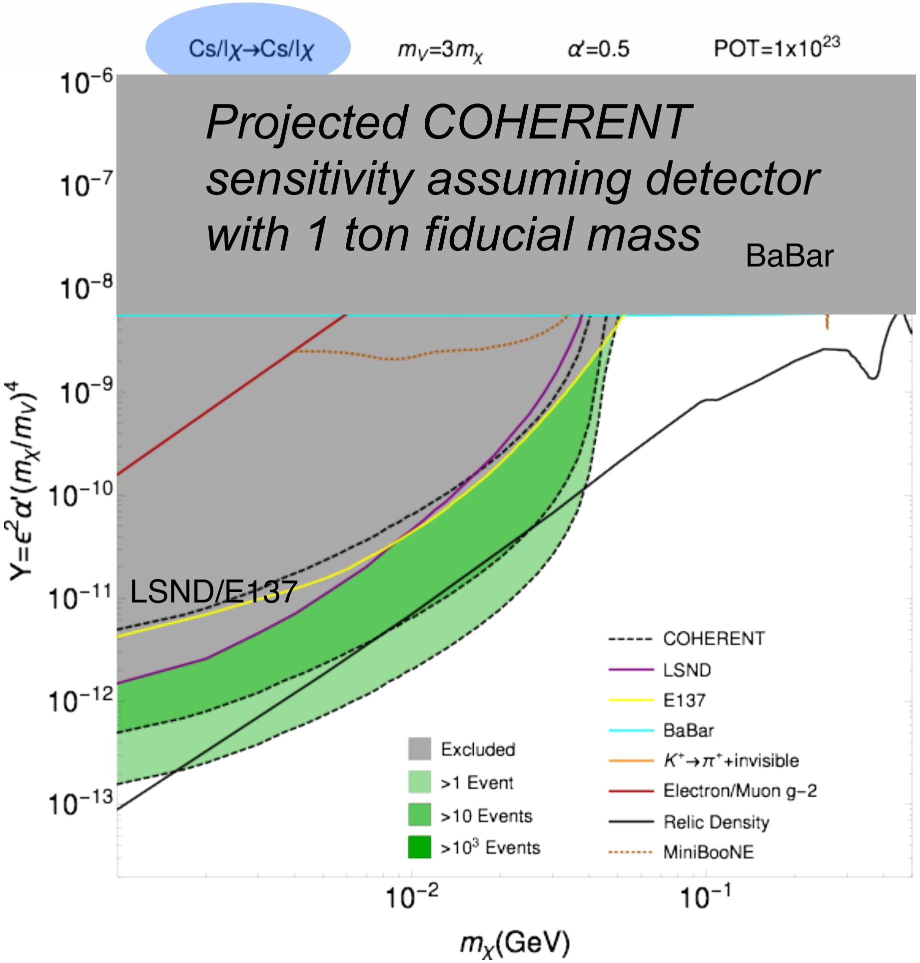
[COHERENT ’17, see talk by K. Scholberg]

COHERENT (SNS)

[deNiverville et al ’15; update courtesy P. deNiverville]



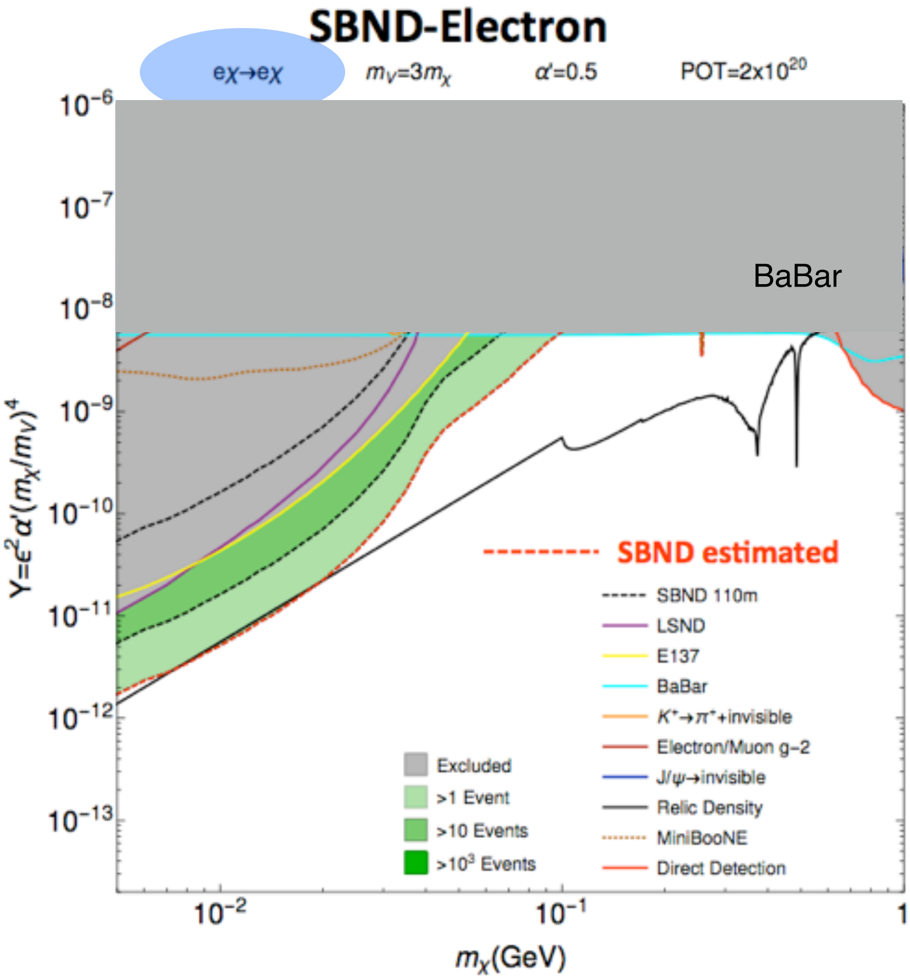
[deNiverville et al ’15]



Currently weaker than LSND and E137, but distinct as COHERENT does not rely on the electron coupling. Sensitivity will improve with more detector mass

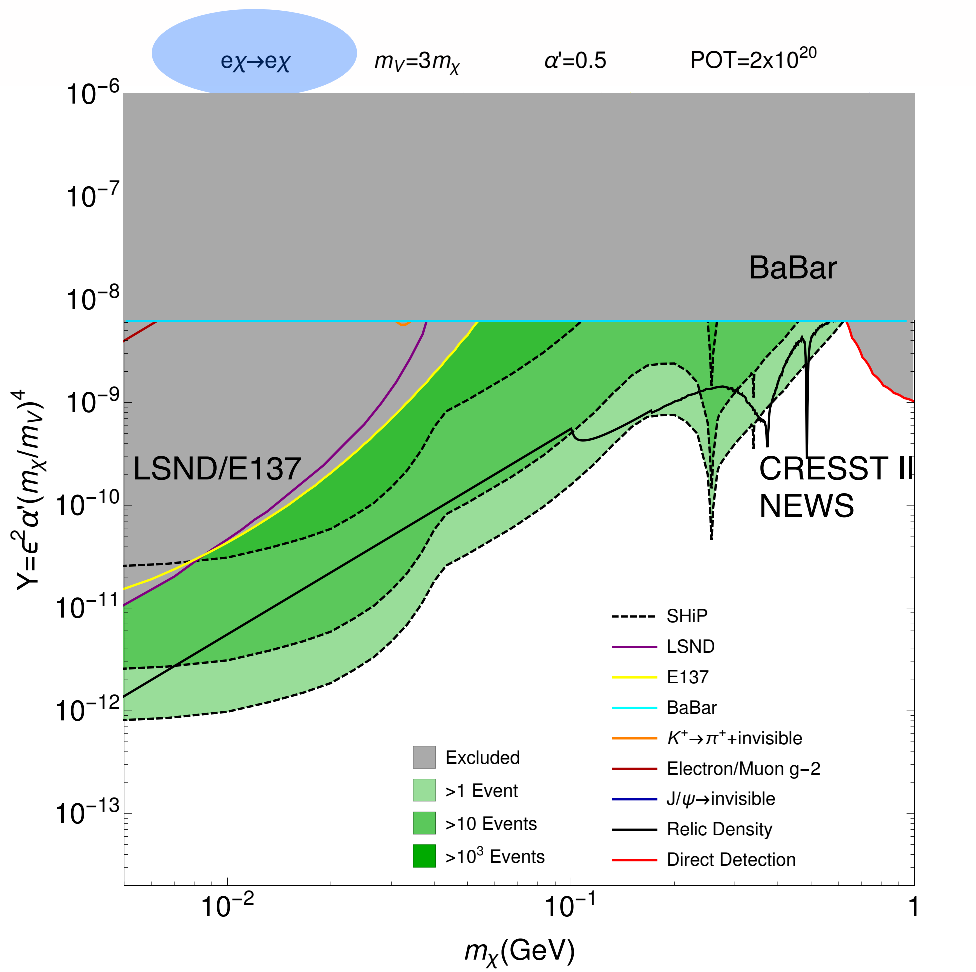
Future facilities...

SBND (112 ton LArTPC at ~100m)



[deNiverville et al '16; Van de Water, Cosmic Visions '17]

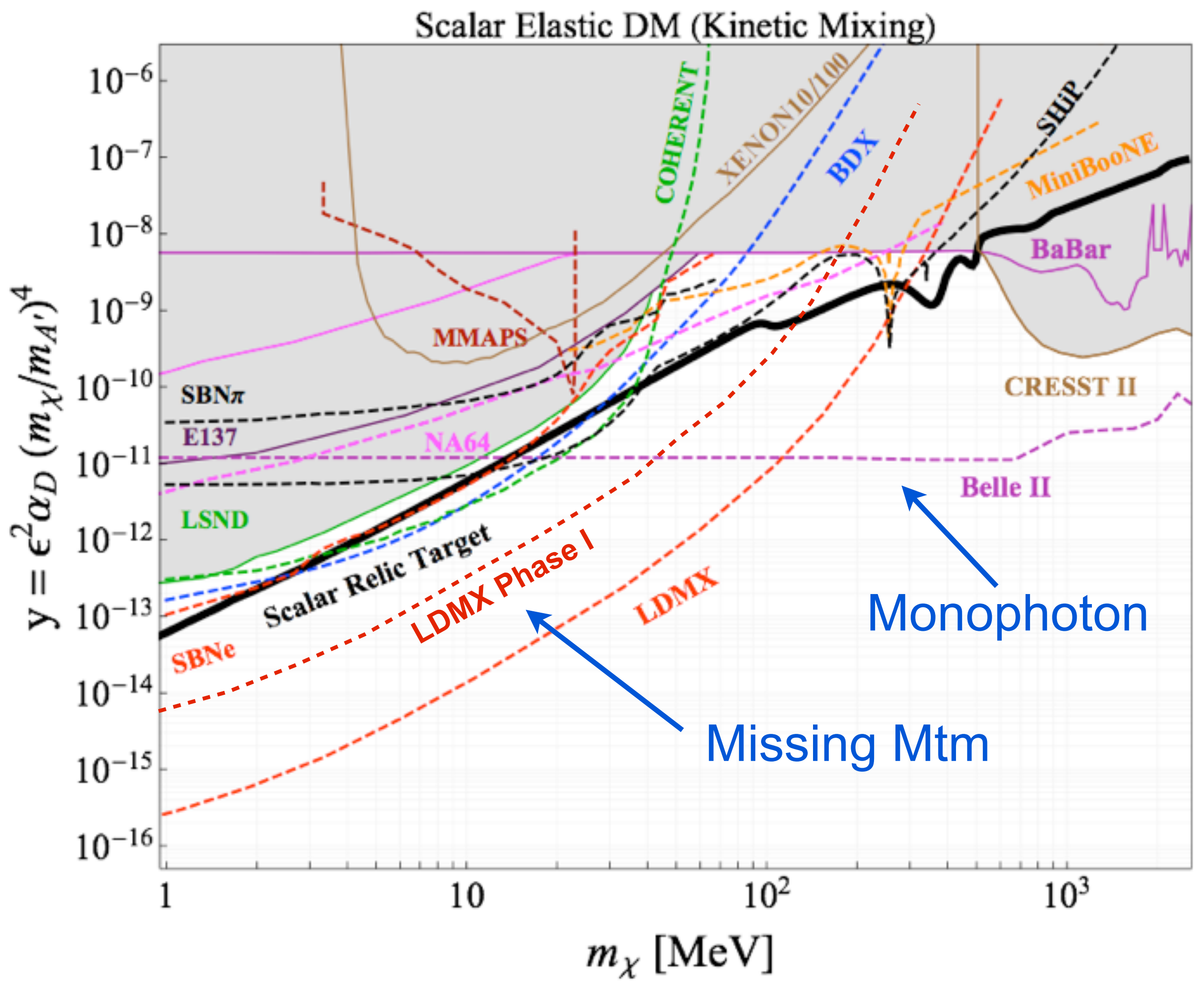
SHiP (LArTPC at 100m)



[deNiverville et al '16]
[see talk by P. Mermod]

Future reach in e/p channels (scattering + missing E/mtm...)

[Work of many, summarized in Battaglieri et al, Cosmic Visions Community Report '17]



Event rate ~ ε^2 for missing E/mtm vs ε^4 for scattering, but requires control of backgrounds

Also multiple complementary proposals to extend low-mass direct detection reach using nucleon and electron scattering [see e.g. Battaglieri et al, Cosmic Visions Community Report 2017]

Concluding Remarks

Light DM at the Luminosity frontier

- Light sub-GeV thermal relic DM is difficult to probe using conventional direct detection.
  - provides benchmark models to test within a broader exploration of the relevant/marginal “portal” operators (hidden sector)

$$B_{\mu\nu}V^{\mu\nu}, \quad (AS+\lambda S^2)H^\dagger H, \quad Y_N LHN, \quad \ldots$$

- Discussed a detection strategy by searching for deviations in NC (or NCQE) scattering at fixed-target neutrino facilities.
  - *MiniBooNE elastic scattering analysis complete, other channels in progress, utilizing various techniques to improve S/B*
  - *COHERENT has potential to improve low-mass sensitivity significantly, using MW source at the SNS, and low threshold detectors*
  - *public code: https://github.com/pgdeniverville/BdNMC/releases*

- More model-independently, these searches are for anomalous NC/CC ratios in scattering, distinct from NSI that impact oscillations.
  - *Discovery potential* (beyond setting limits) provides further motivation for improving calculational precision in production modes, and neutrino scattering (particularly if searches are carried out parasitically)