Title: Light dark matter at long baseline (and coherent scattering) neutrino experiments

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Abstract:

Perimeter Institute - July 2017

Light dark matter and neutrino beams

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University of Victoria

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

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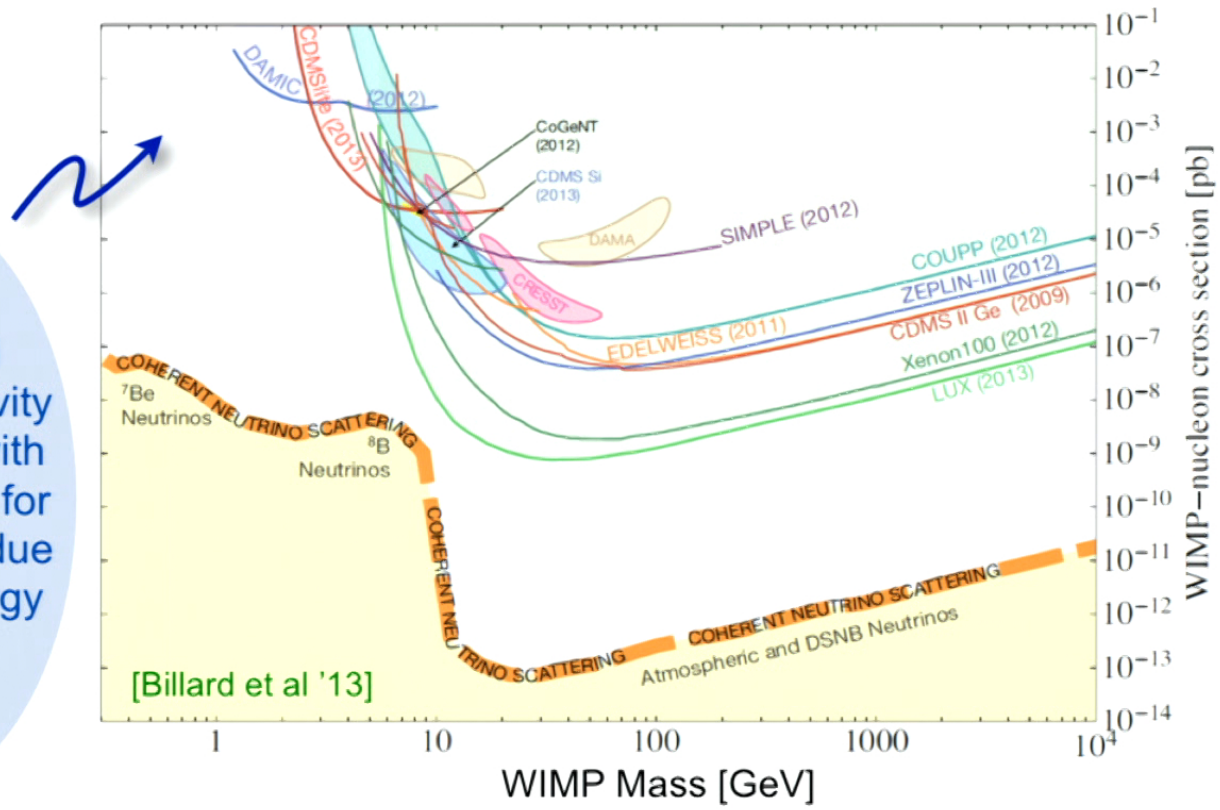
WIMP (thermal relic) DM

Conventional direct sensitivity to halo DM with $v \sim 10^{-3}$ drops for $m < O(\text{GeV})$, due to recoil energy thresholds.



For sub-GeV DM: $m_e < m_{DM} < m_{had}$, a (high intensity) relativistic beam can be used to detect scattering.

Philosophy - Neutrinos and Dark Matter…

- 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

HYSICAL 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

HYSICAL 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 [illegible] masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ [illegible]

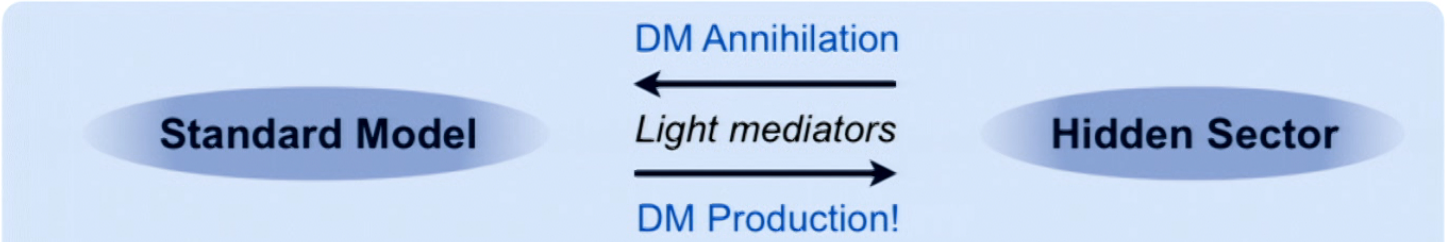
Light (thermal relic) DM

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]

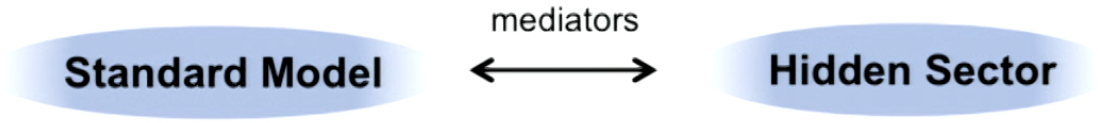


➪ by inversion, light mediators allow direct production of DM at ***low energy!***

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

Br(mediator → DM) ~ 1

EFT for a (neutral) 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: $\mathcal{L} = -\frac{\kappa}{2} B^{\mu\nu} V_{\mu\nu}$ [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 ⟷ **Hidden Sector**

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu^2 + |D_\mu\chi|^2 - m_{\rm DM}^2|\chi|^2 + \cdots$$

$$\Downarrow$$

$$\mathcal{L}_{\rm int} = -\kappa e V_\mu J^\mu_{\rm em}$$

A' - couples to the SM via the EM current

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

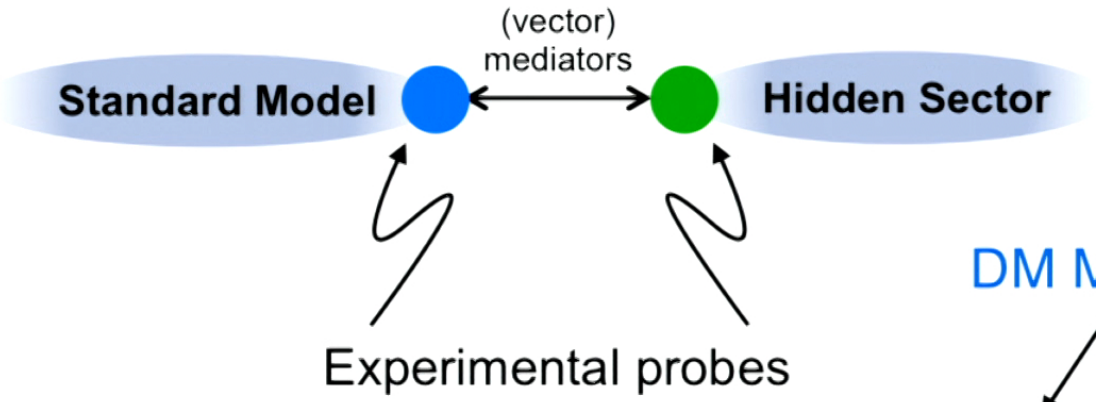
$$\Downarrow$$

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 $\{\kappa, \alpha', m_V, m_{DM}\}$

(NB: notation κ = ε on some slides)

Probing the vector portal



DM Models

- Precision corrections
  - e.g. lepton g-2, EDMs
- rare (visible) decays
  - e.g. collider/fixed target production plus e.g. leptonic A' decays, $O(\kappa^2)$ x Br(SM)
- rare (invisible) decays/missing E
  - e.g. collider production plus missing energy in decays and scattering, $O(\kappa^2)$ x Br(Hid)
- anomalous NC-like scattering
  - e.g. fixed target production plus anomalous NC-like scattering, $O(\kappa^2 \times \kappa^2\alpha')$

(also astrophysics & cosmology)

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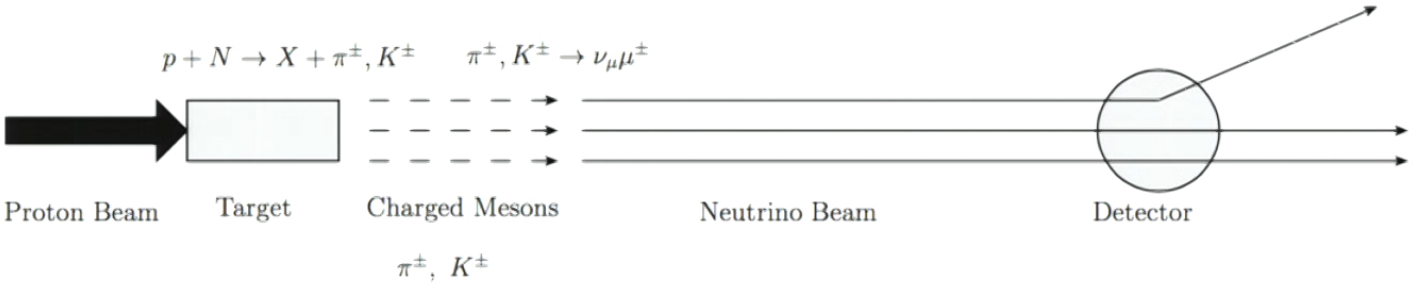
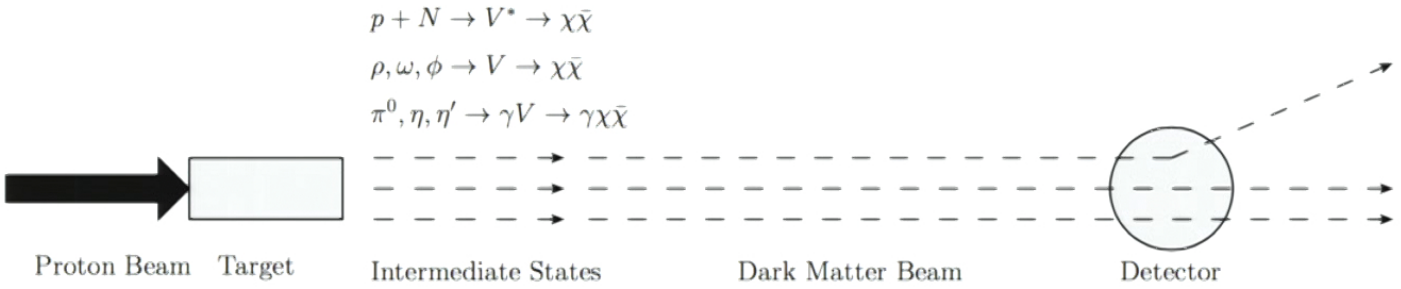
Fixed target probes - Neutrino Beams



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



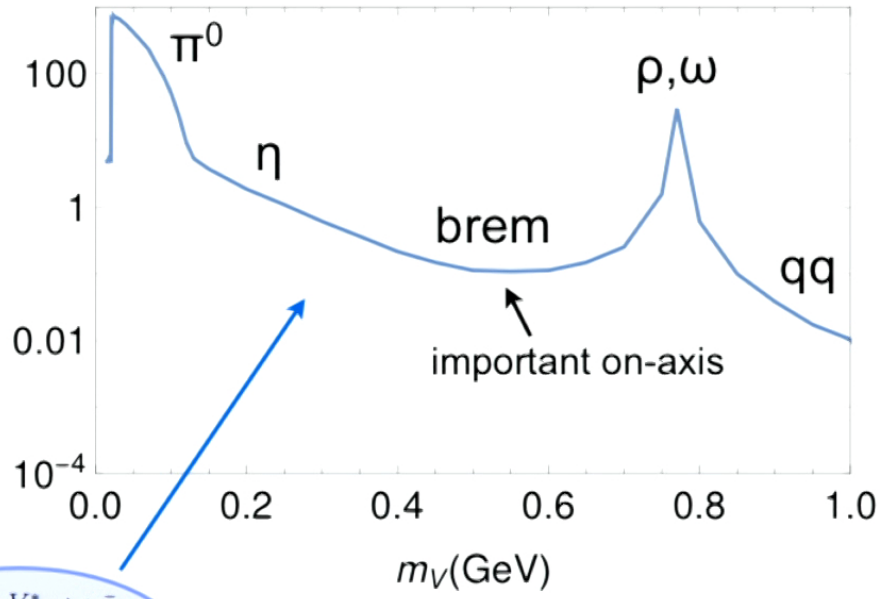
[Batell et al '09, deNiverville et al '11]

Fixed target - DM production

[deNiverville et al '16]

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

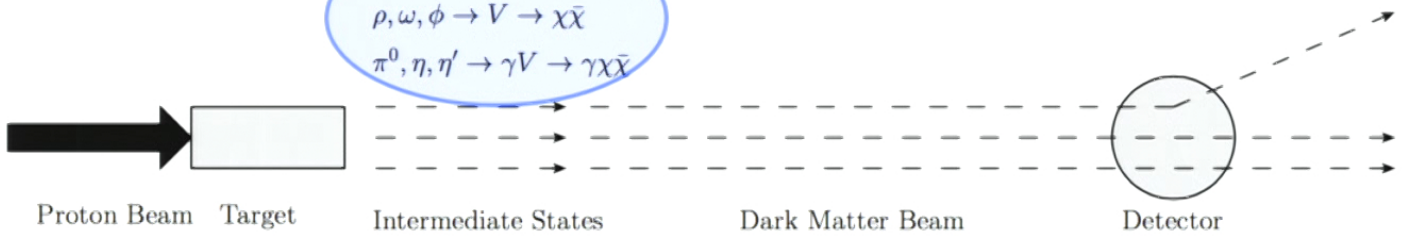
- NB: some components of production model can be validated with data, but not all...



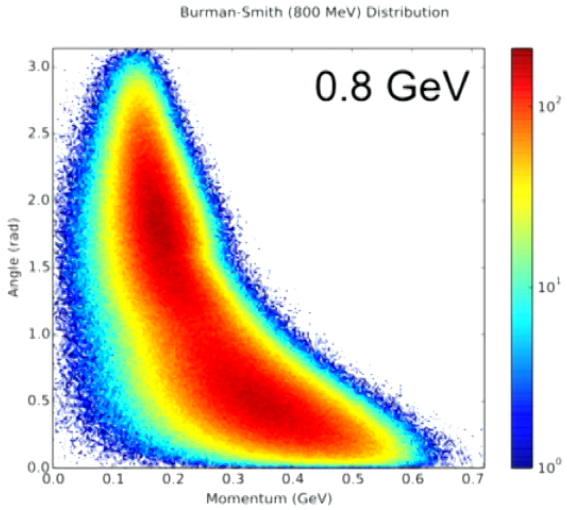
$p + N \to V^* \to \chi\bar{\chi}$

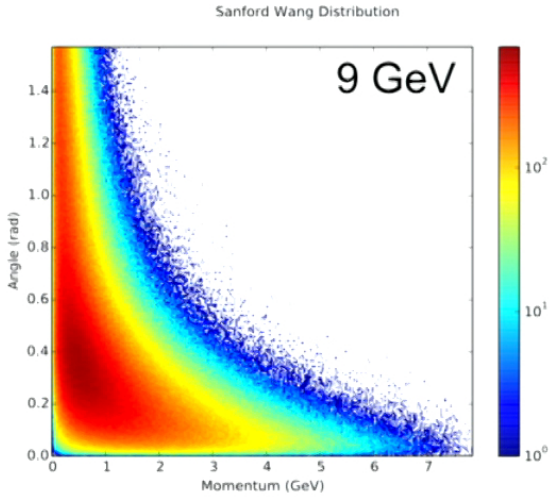
$\rho, \omega, \phi \to V \to \chi\bar{\chi}$

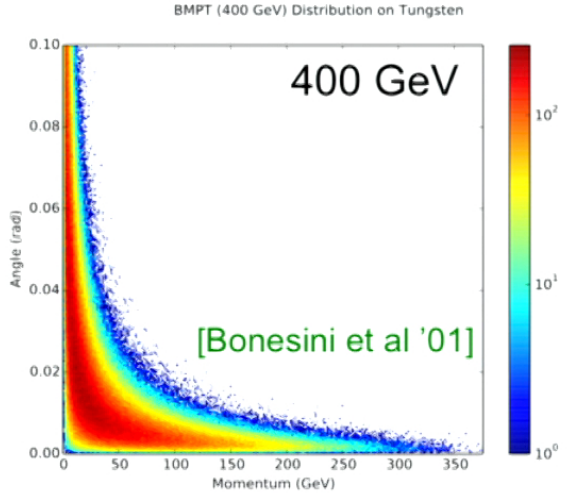
$\pi^0, \eta, \eta' \to \gamma V \to \gamma\chi\bar{\chi}$



DM Production - π, η distributions

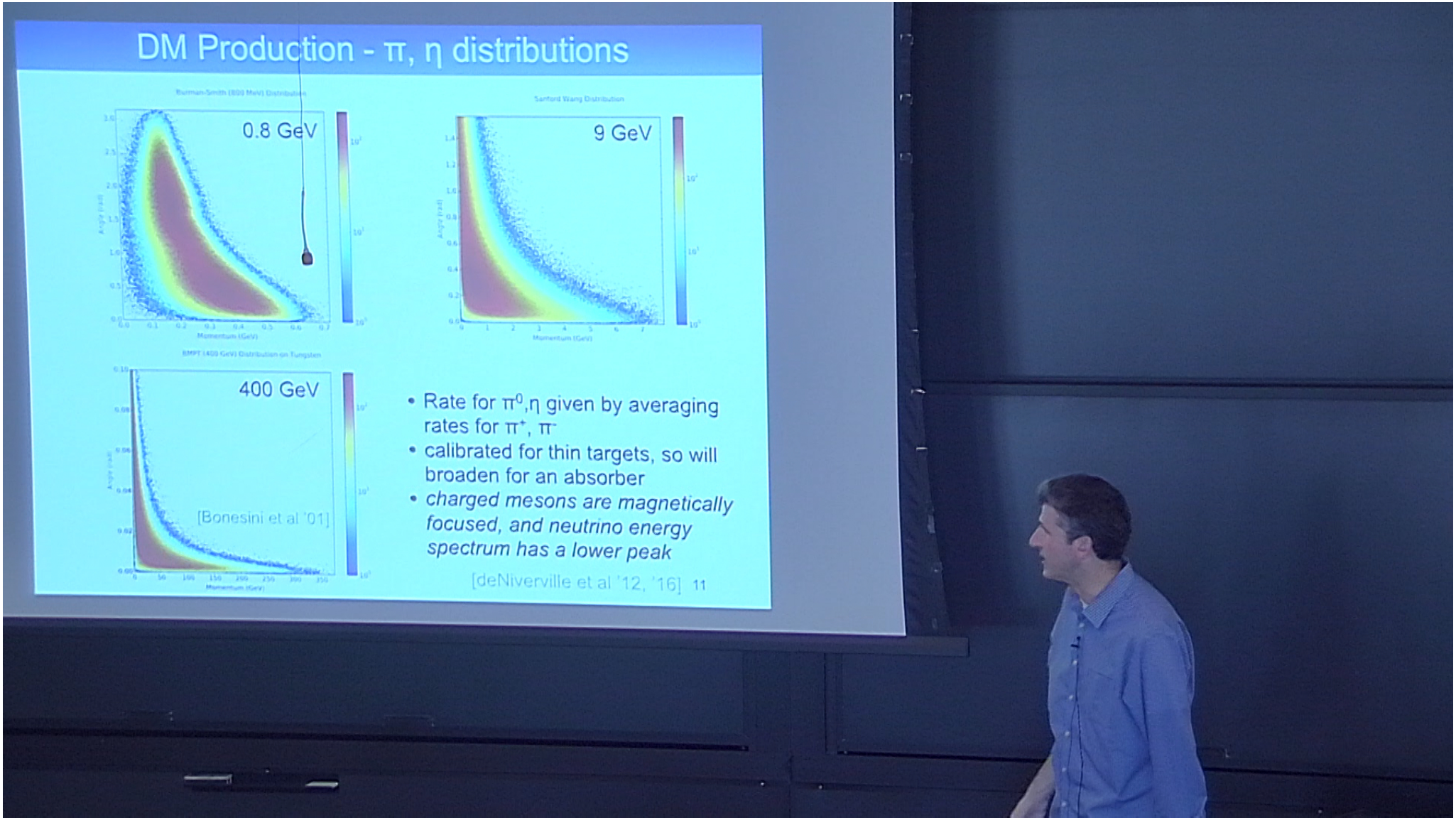






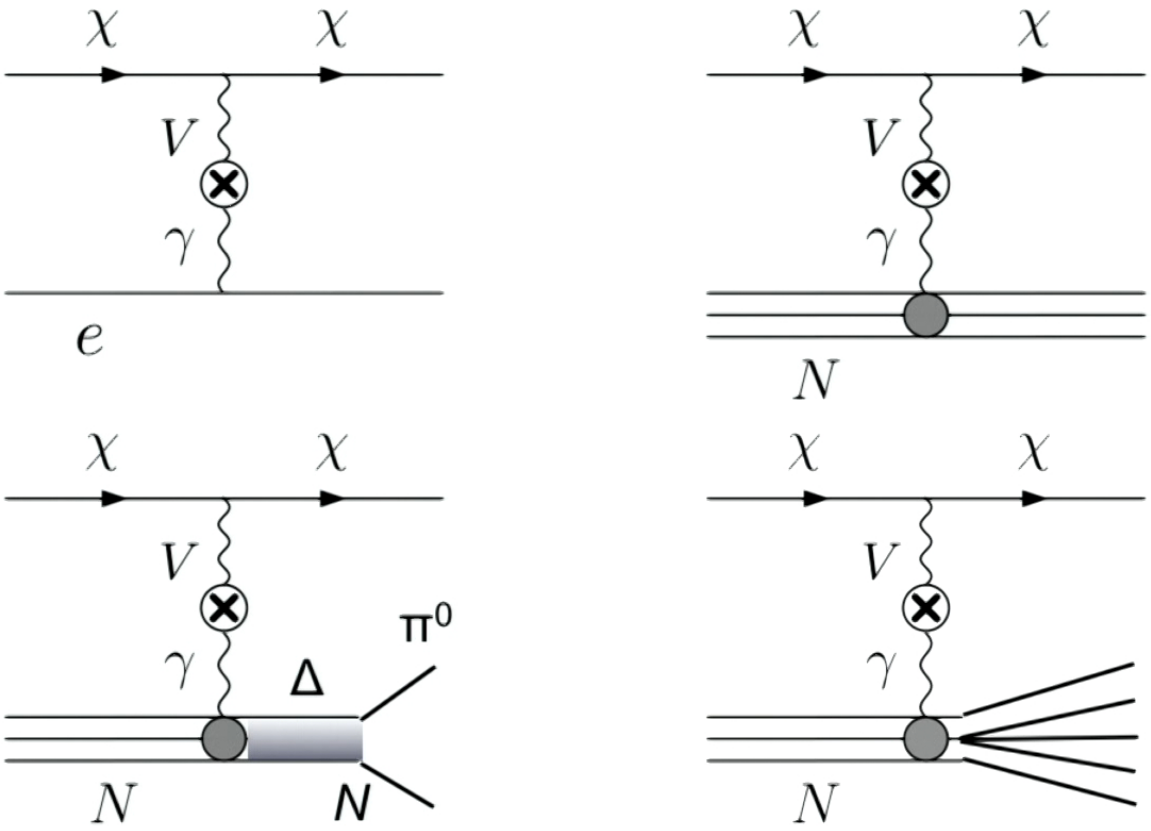
- Rate for π^0,η given by averaging rates for π^+, π^-
- calibrated for thin targets, so will broaden for an absorber
- *charged mesons are magnetically focused, and neutrino energy spectrum has a lower peak*

[deNiverville et al '12, '16] 11


DM Production - π, η distributions
0.8 GeV
9 GeV
400 GeV
[Bonesini et al '01]
• Rate for π⁰,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] 11

Signatures

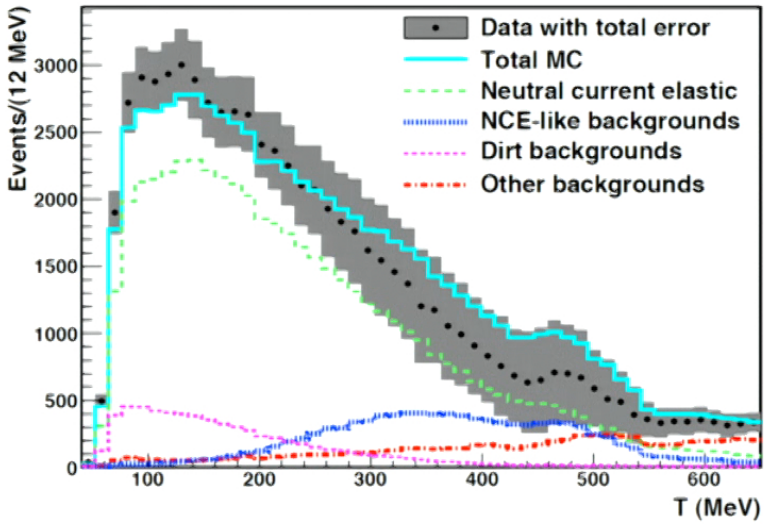
Characteristic DM (in)elastic scattering signatures



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…

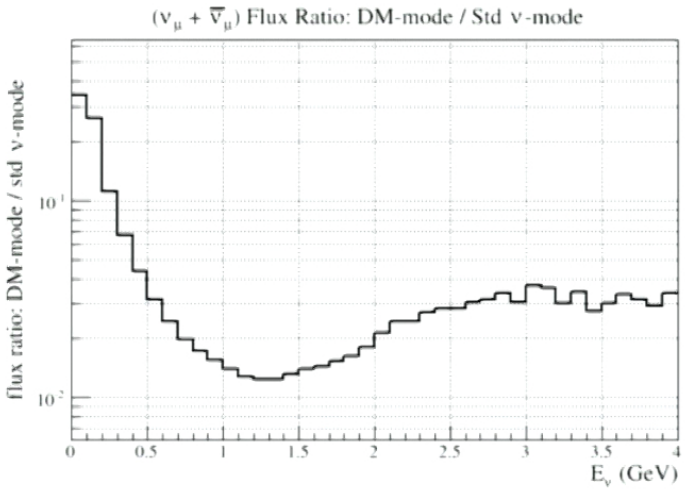
Neutrino backgrounds...

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 (but cannot run in “parasitic” mode, unless well off axis)
- Timing
  - time delay (Y=10) = O(10ns), effective for higher mass
  - possible at MiniBooNE, also very effective at a far detector (e.g. T2K → 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

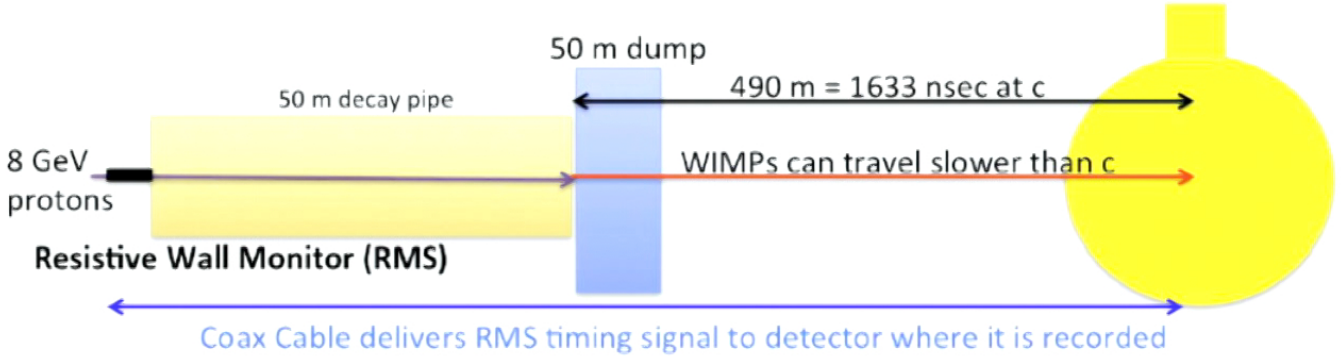
Multiple techniques are being tested in the current MiniBooNE analysis

MiniBooNE beam dump



- removal of decay volume for charged mesons reduces neutrino background by factor of ~50

WIMP Time of Flight



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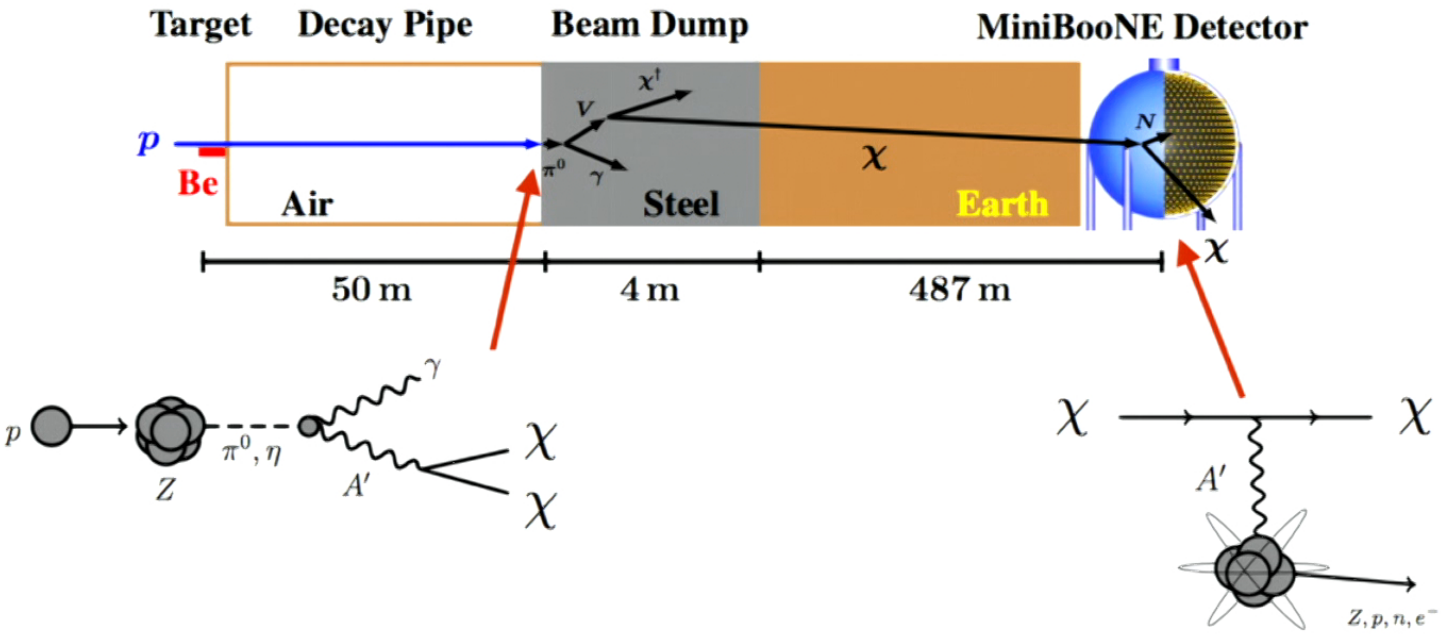
MiniBooNE beam dump

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

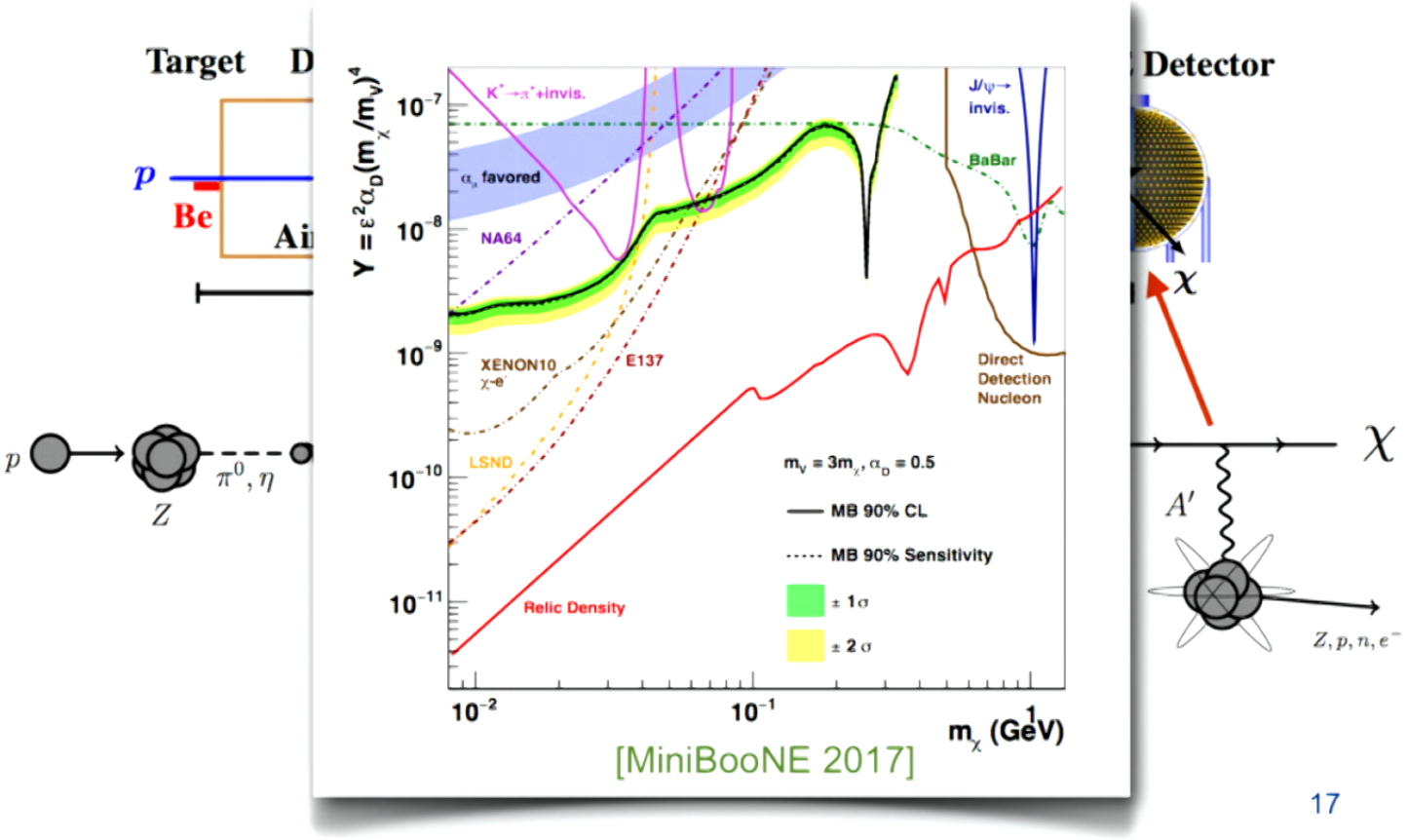
~2x10^{20} POT approved at FNAL Booster



[Batell et al '09, '14, deNiverville et al '11, '12 '16, + MiniBooNE '12]
[see also Dobrescu et al '15, Izaguirre et al '17]

MiniBooNE beam dump

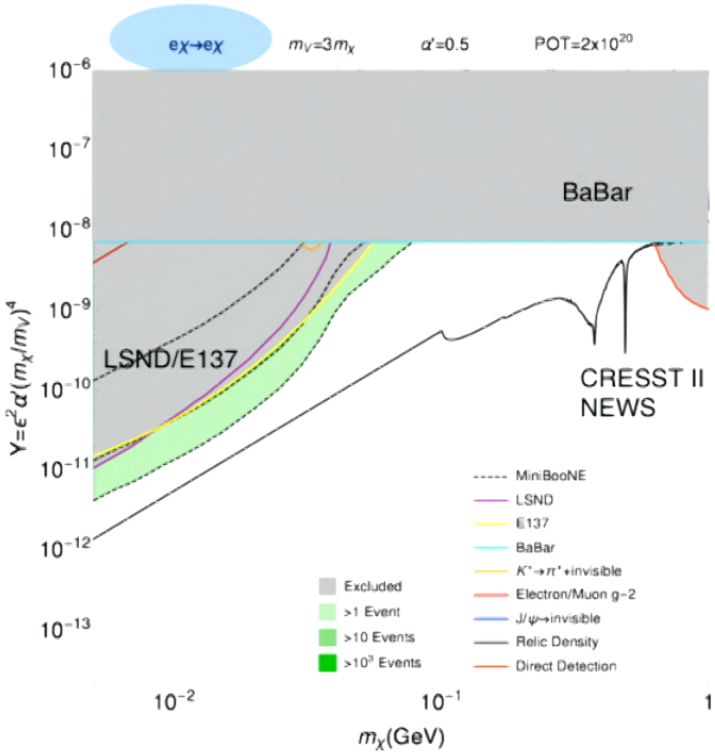
Optimized use of neutrino facility in beam dump mode, aligning beam off-target to minimize the neutrino background

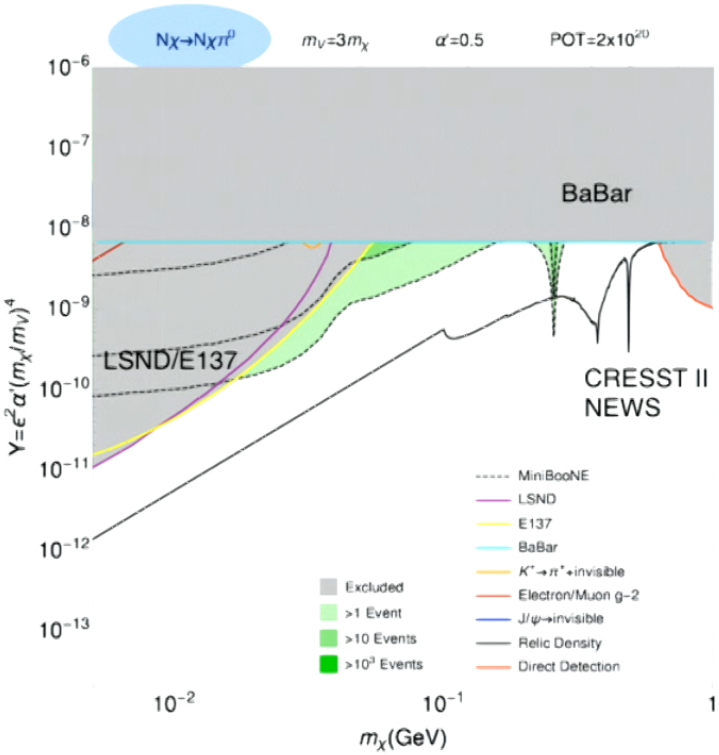


[MiniBooNE 2017]

MiniBooNE - further scattering channels

[deNiverville et al '11, '12, '16]

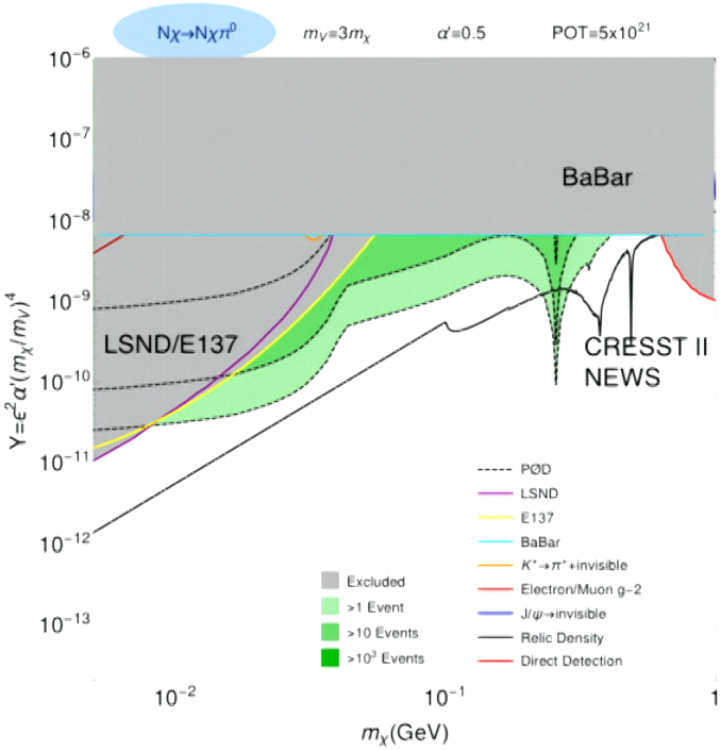




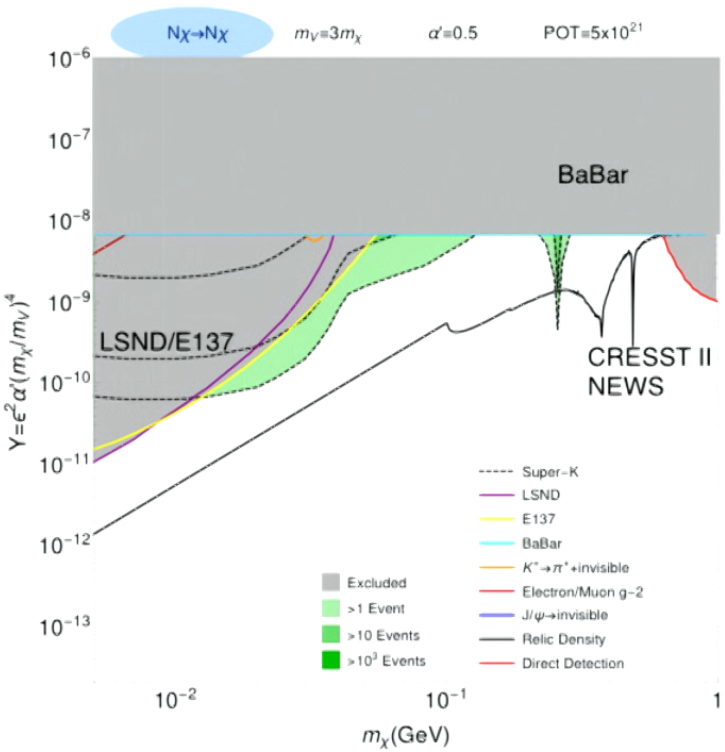
Green contours show 1, 10, 1000 events

Sample event rates - T2K

[deNiverville et al '12, '16]



ND280 - P0D

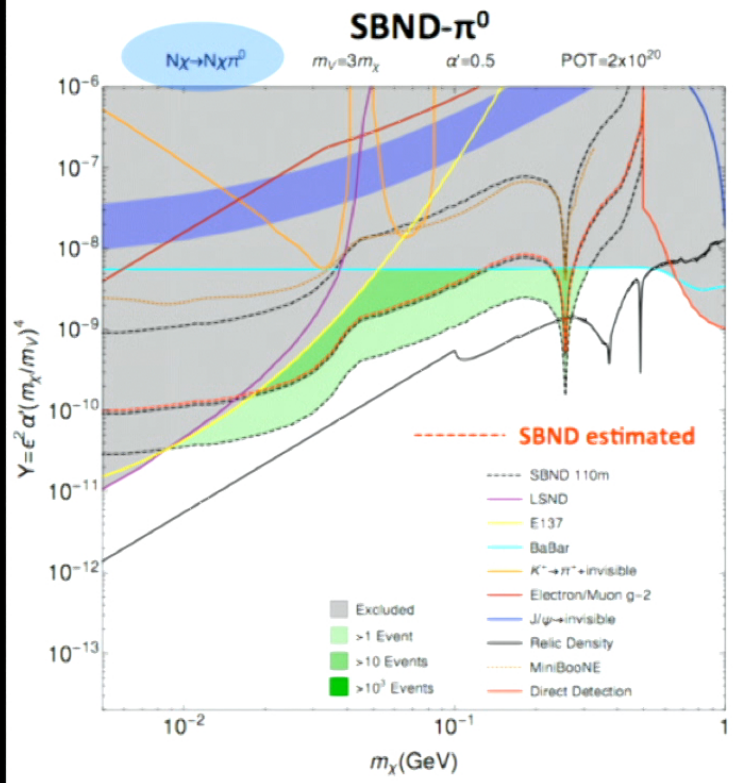


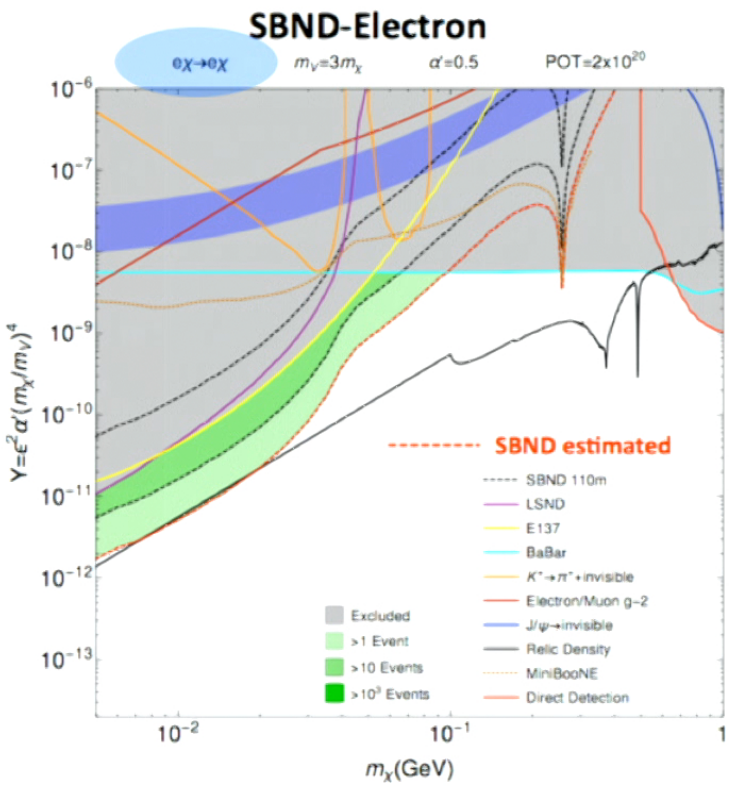
SuperK

(very low background with timing cut)

Future facilities

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





An optimized setup with a 110 ton LArTPC at ~100m from the absorber on the Booster beamline

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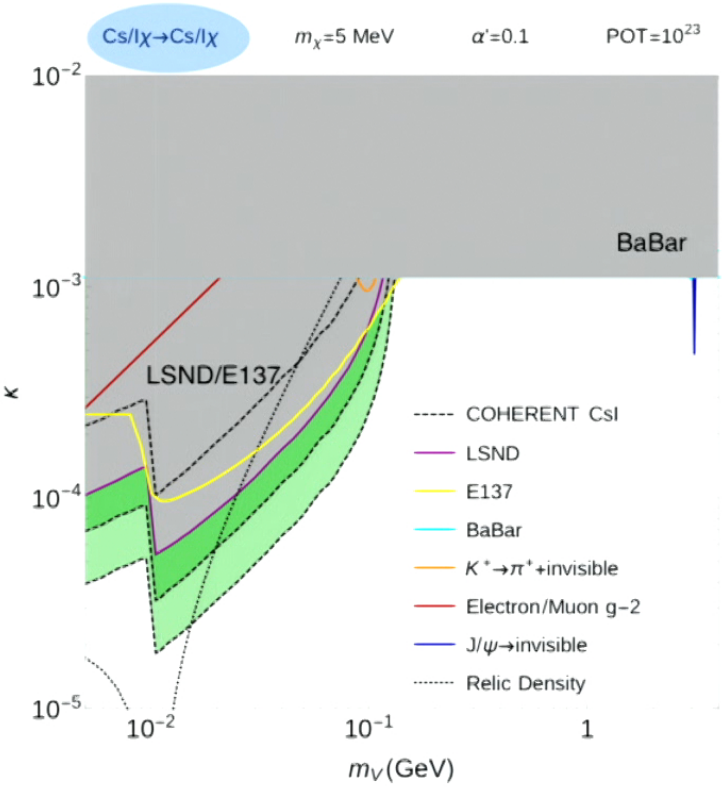
Future facilities

COHERENT (SNS)

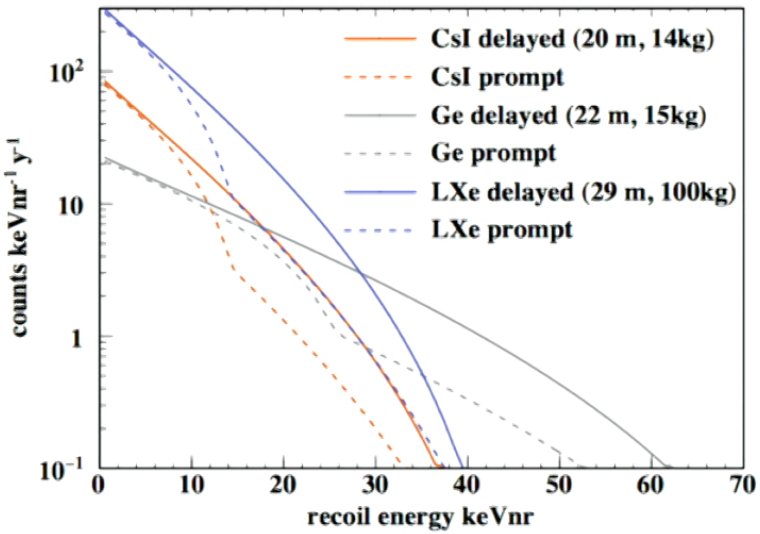
[see also talk by L. Strigari]



Includes V-production via pion capture: $\pi^- + p \rightarrow n + V$

[deNiverville et al '15]

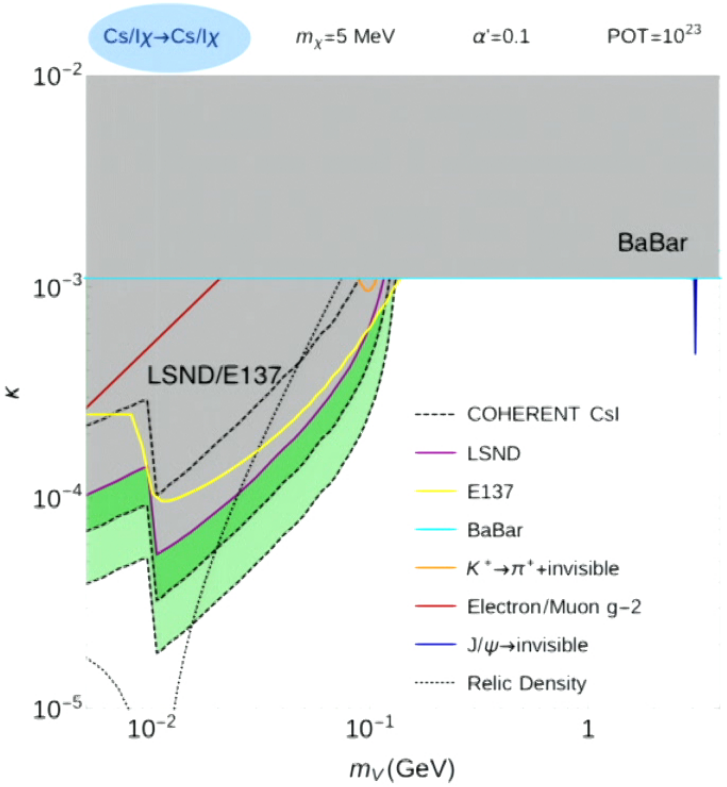
[COHERENT '16]



Recoil energy cut limits neutrino background

Future facilities

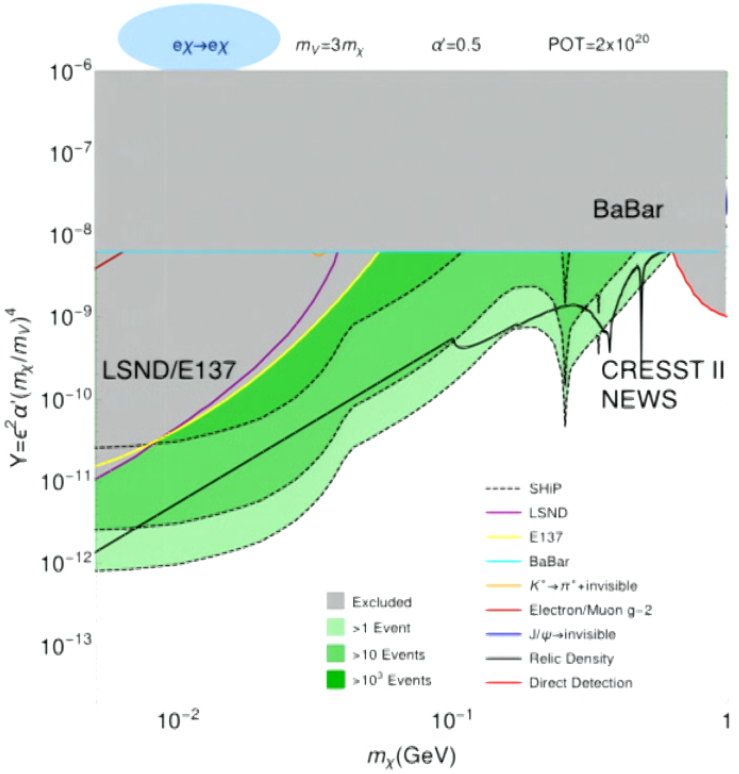
COHERENT (SNS)



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

[deNiverville et al '15]

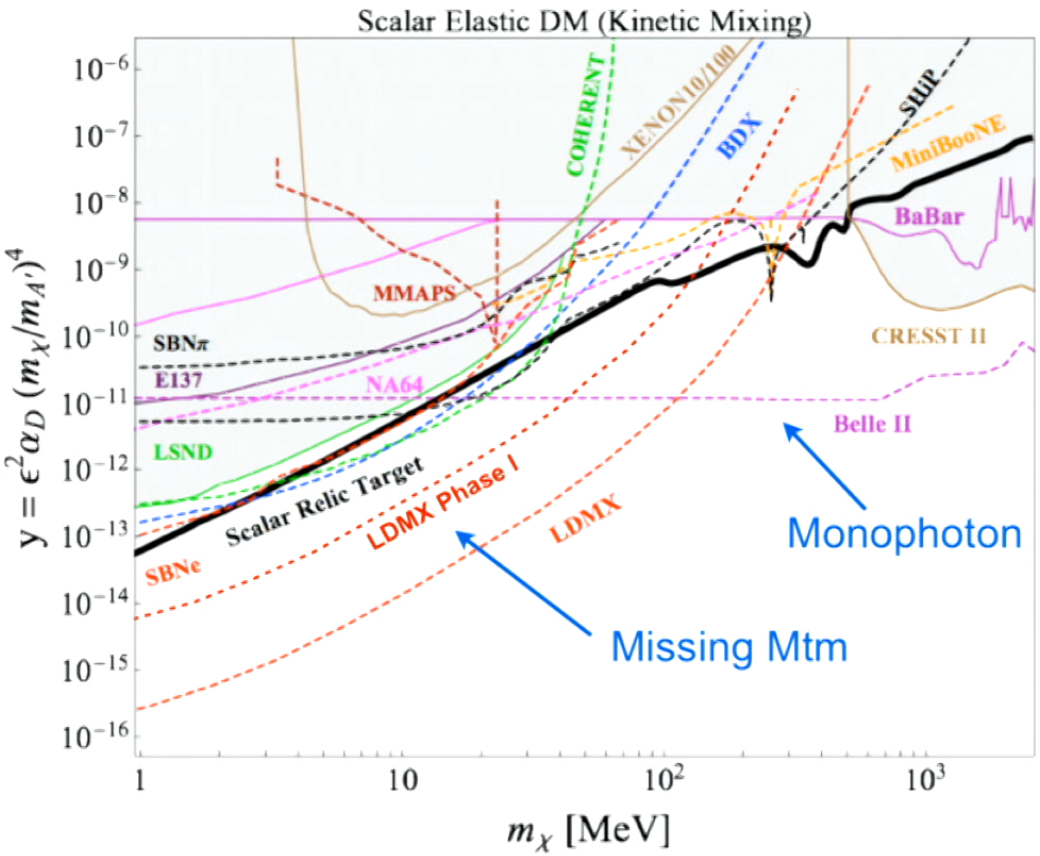
SHiP (LArTPC at 100m)



[deNiverville et al '16]

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

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

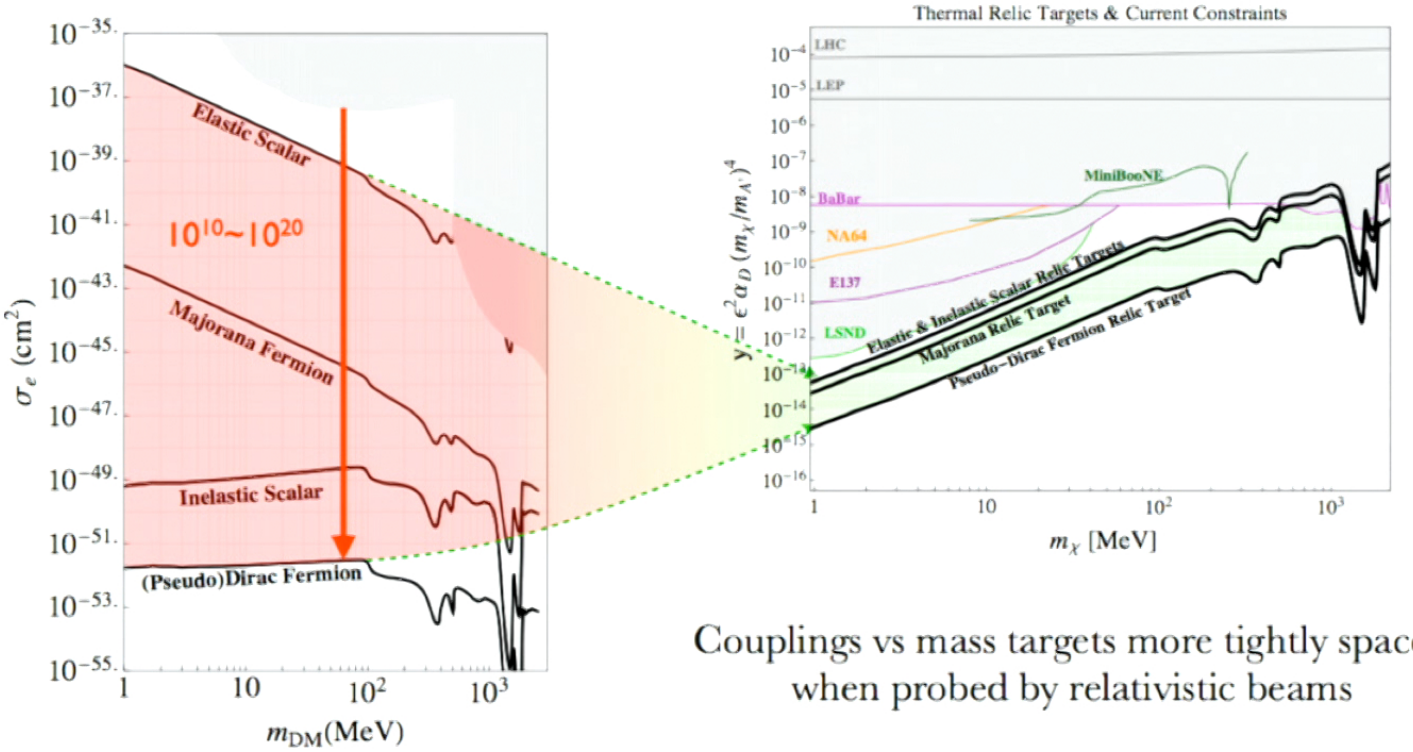


Event rate ~ ε^2 for missing E/mtm vs ε^4 for scattering

[See also talk by E. Izaguirre]

Complementarity with direct detection

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



Couplings vs mass targets more tightly spaced when probed by relativistic beams

[from B. Echenard, E. Izaguirre, WG3 Summary, Cosmic Visions 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)

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

- 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 (removal of decay volume, kinematic cuts)*
  - *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)