Searching for Light Dark Matter at Neutrino Factories

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INFO 2013

Based on:

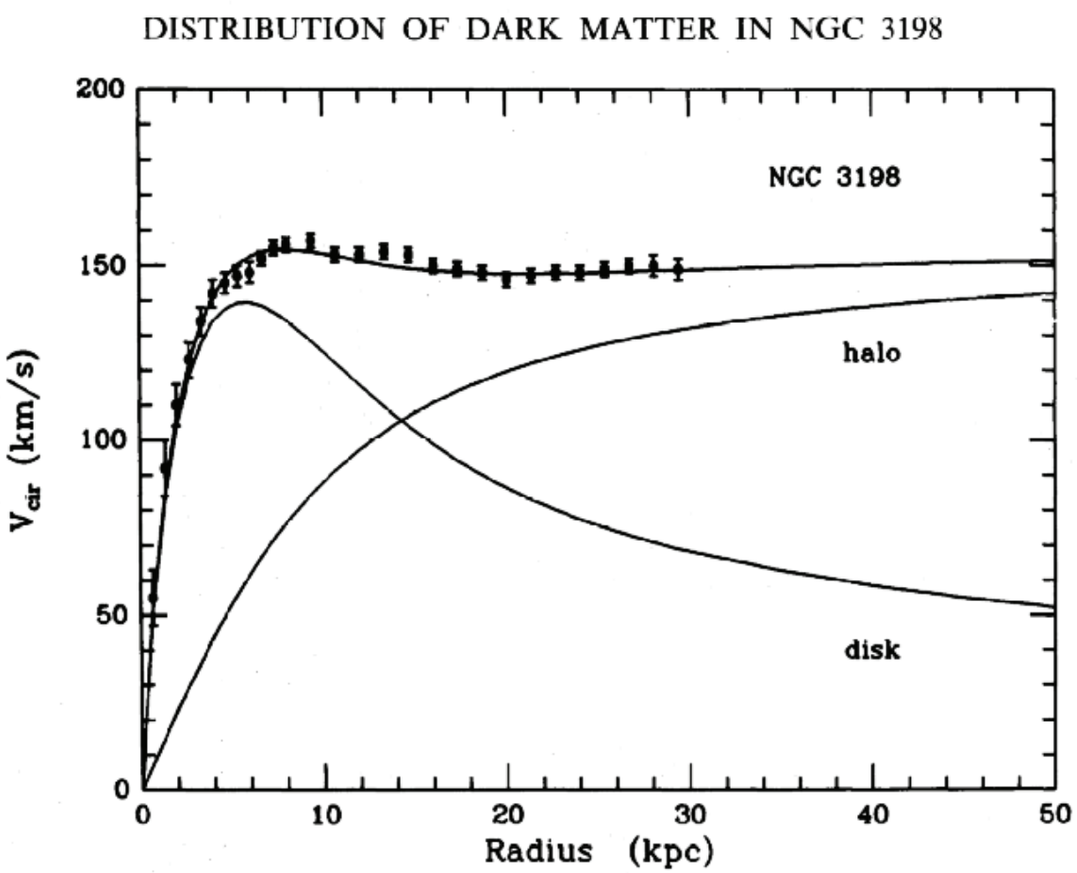
BB, Pospelov Ritz; arXiv:0906.5614

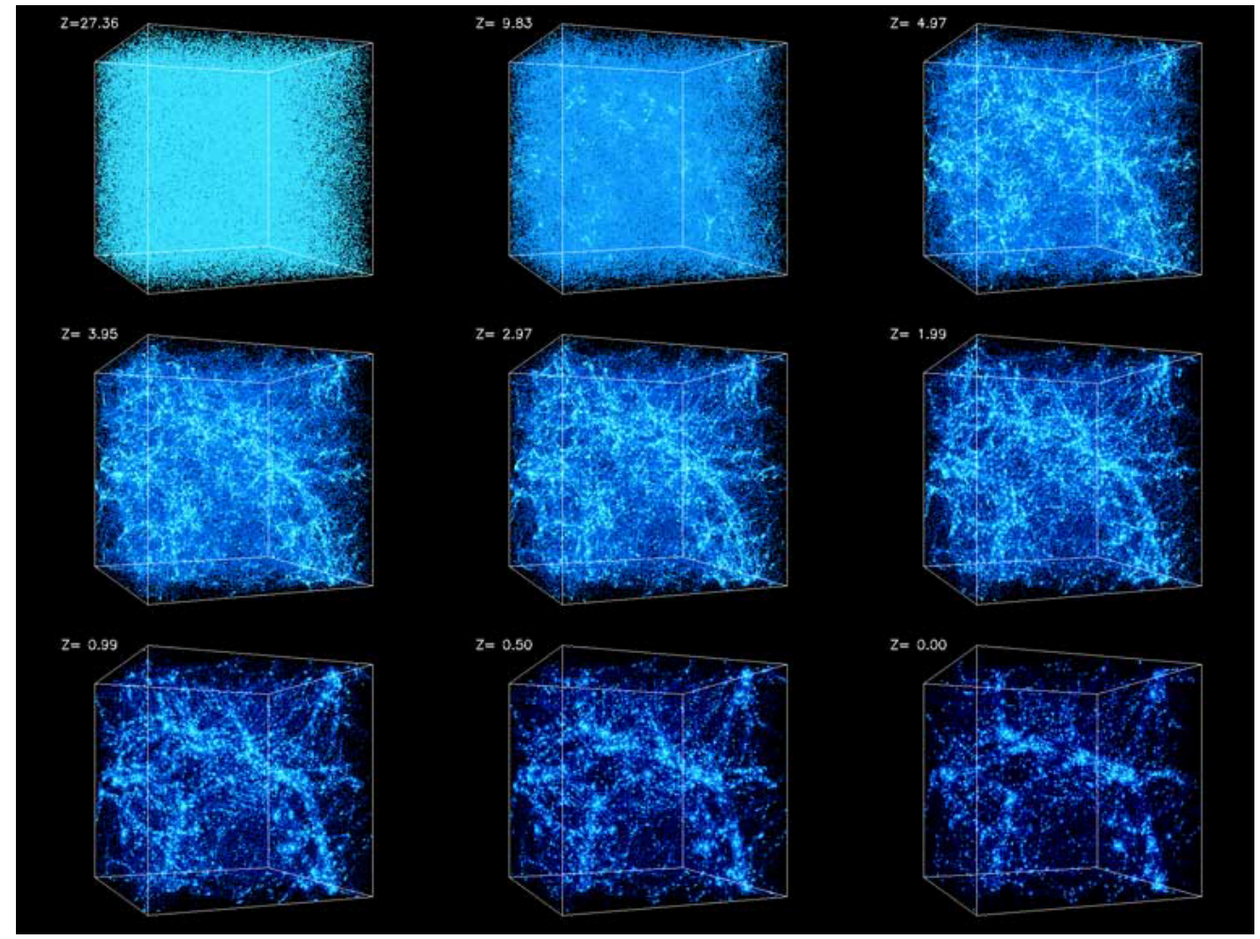
deNiverville, Pospelov, Ritz; arXiv:1107.4580

deNiverville, McKeen, Ritz; arXiv:12005.3499

Proposal to search for light DM with MiniBooNE

Aguilar-Arevalo et al.; arXiv:1211.2258


DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)
0
50
100
150
200
0
10
20
30
40
50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Z= 4.97
Z= 3.95
Z= 2.97
Z= 1.99
Z= 0.99
Z= 0.50
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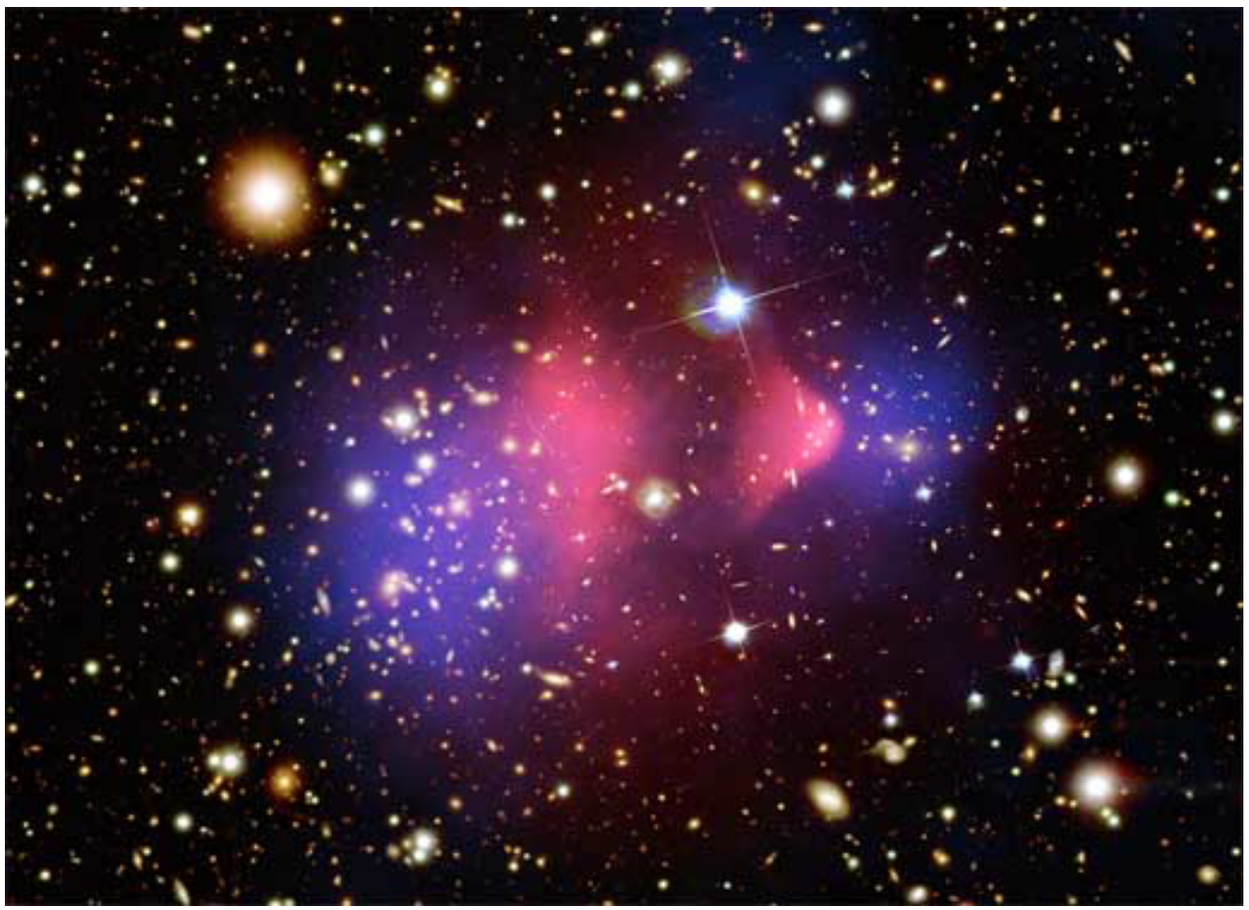
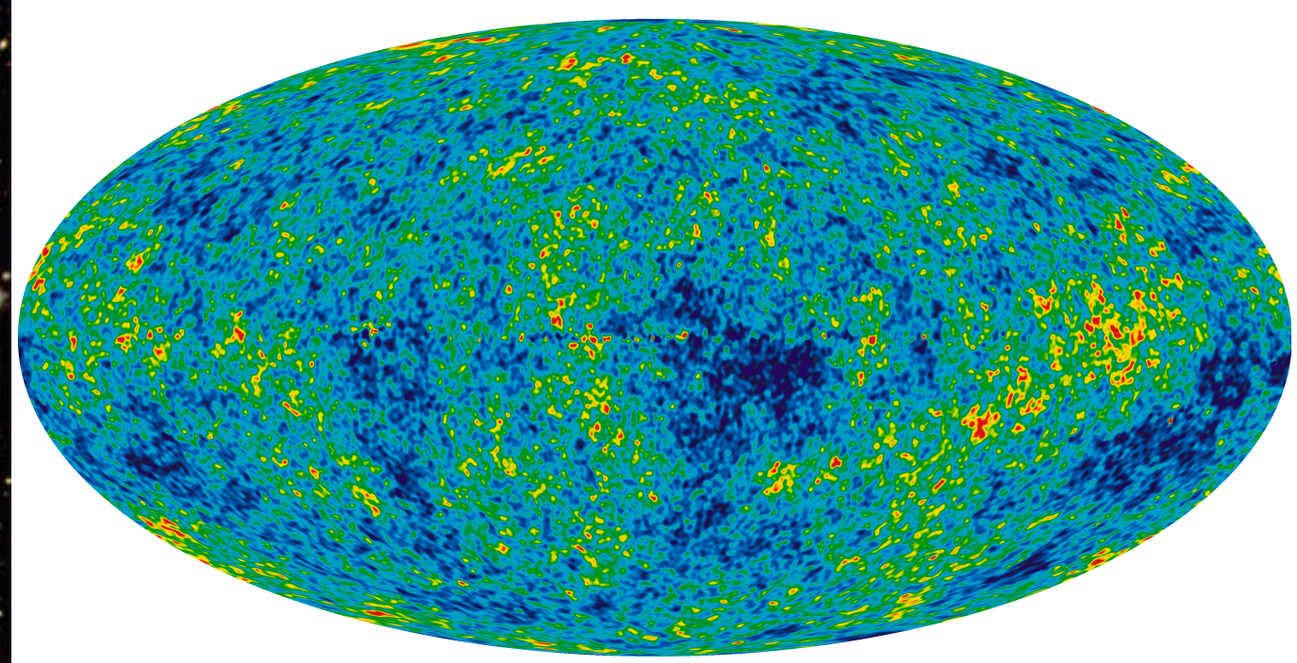
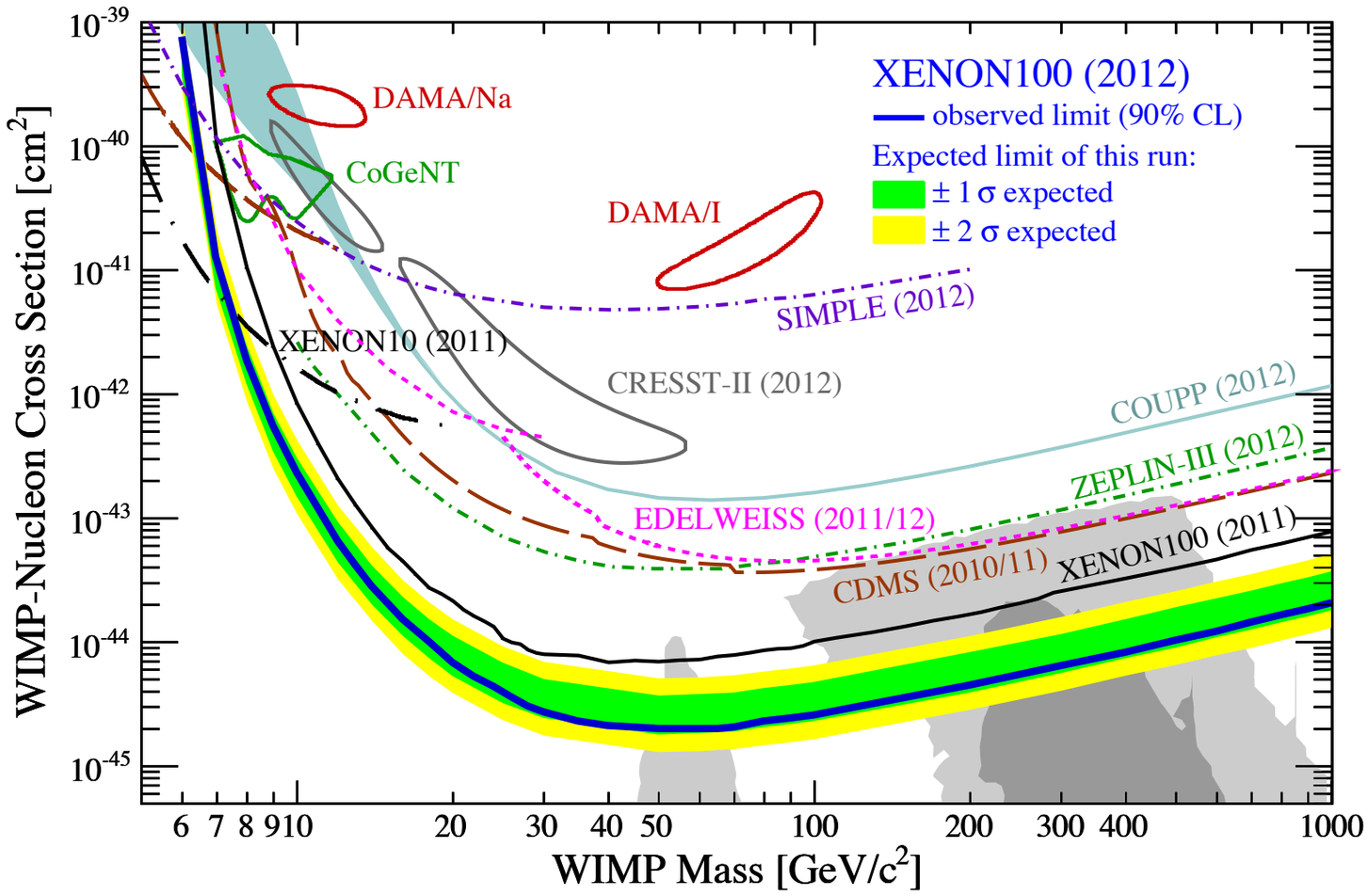
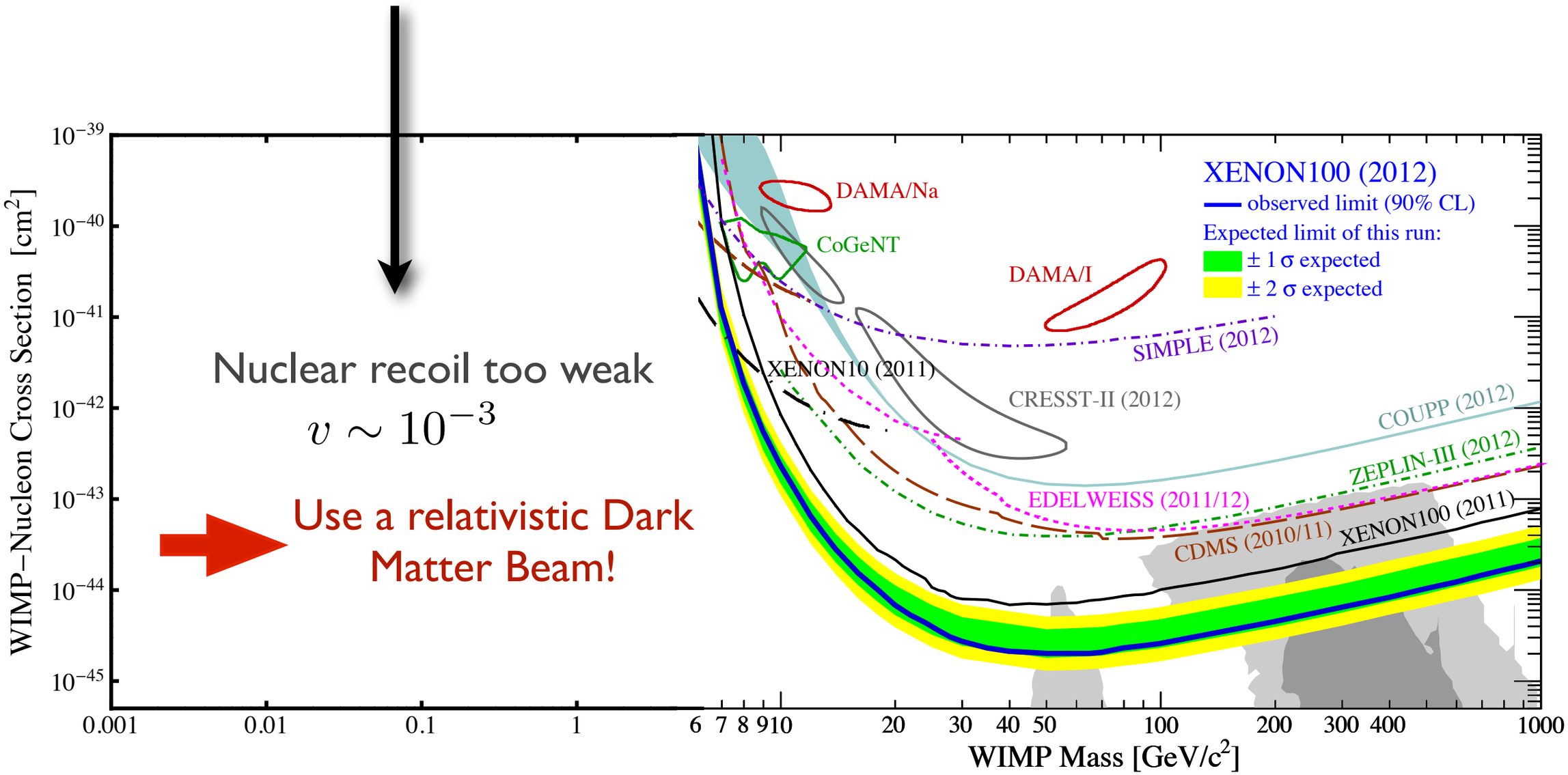




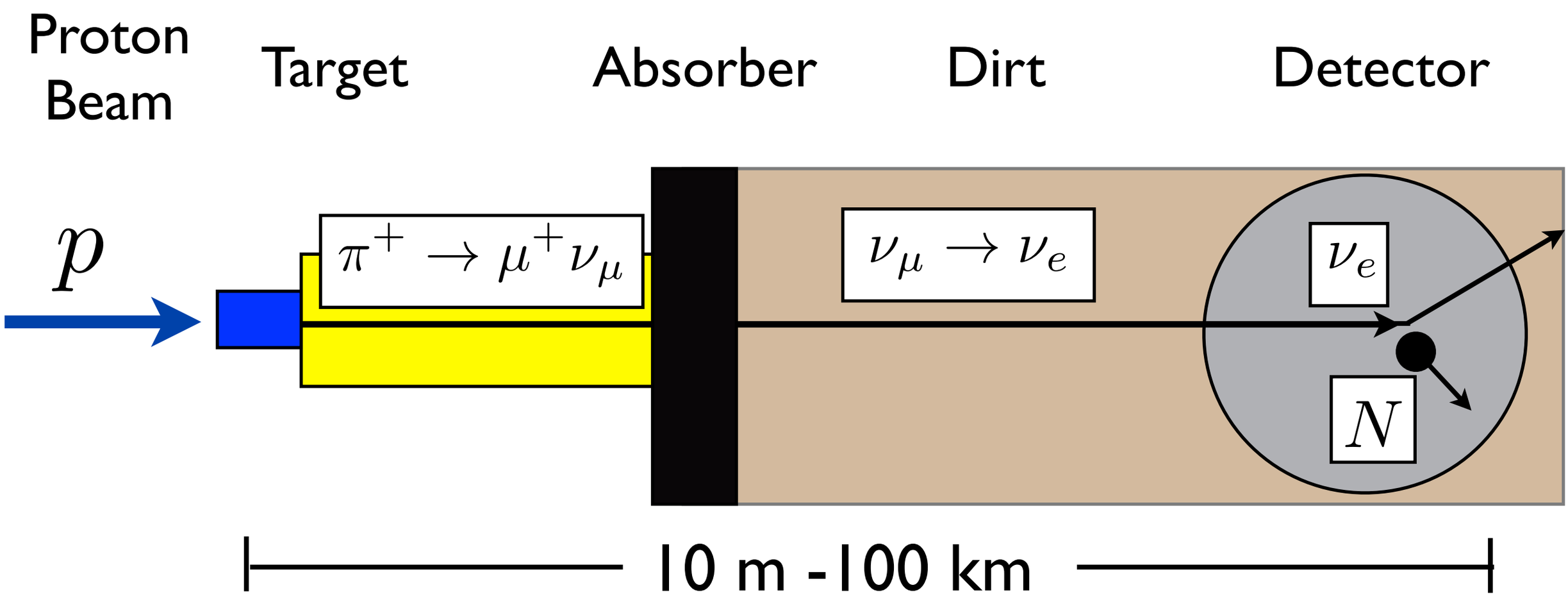
Direct Detection



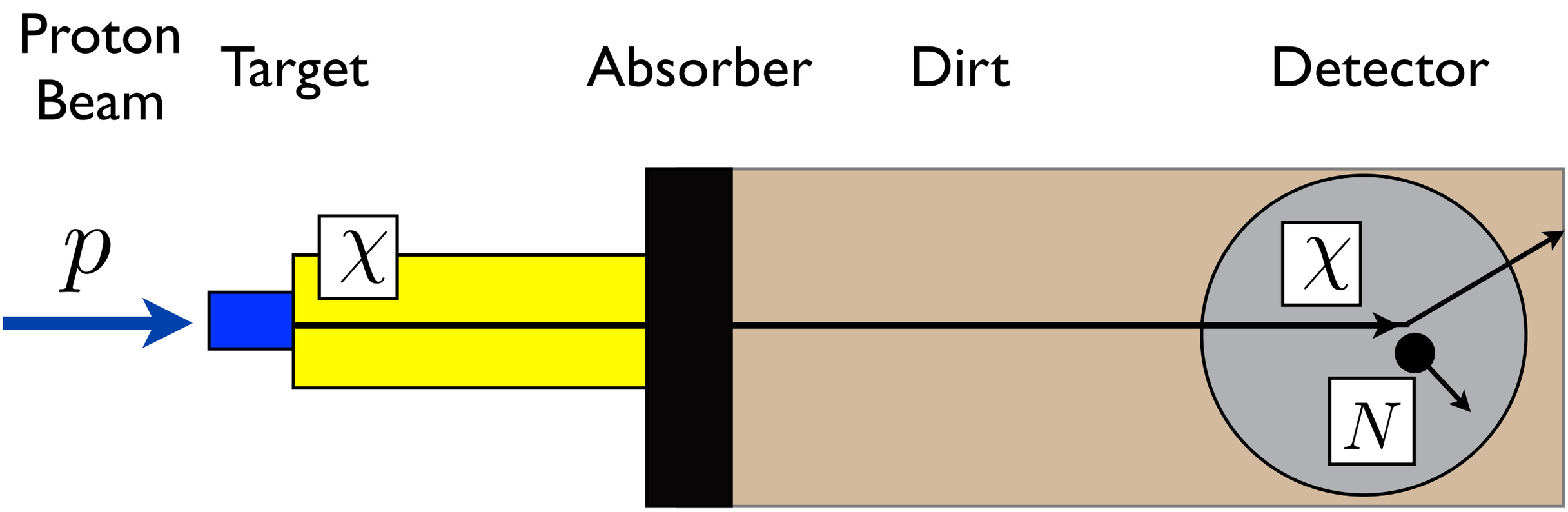
What about here?



Neutrino Factories

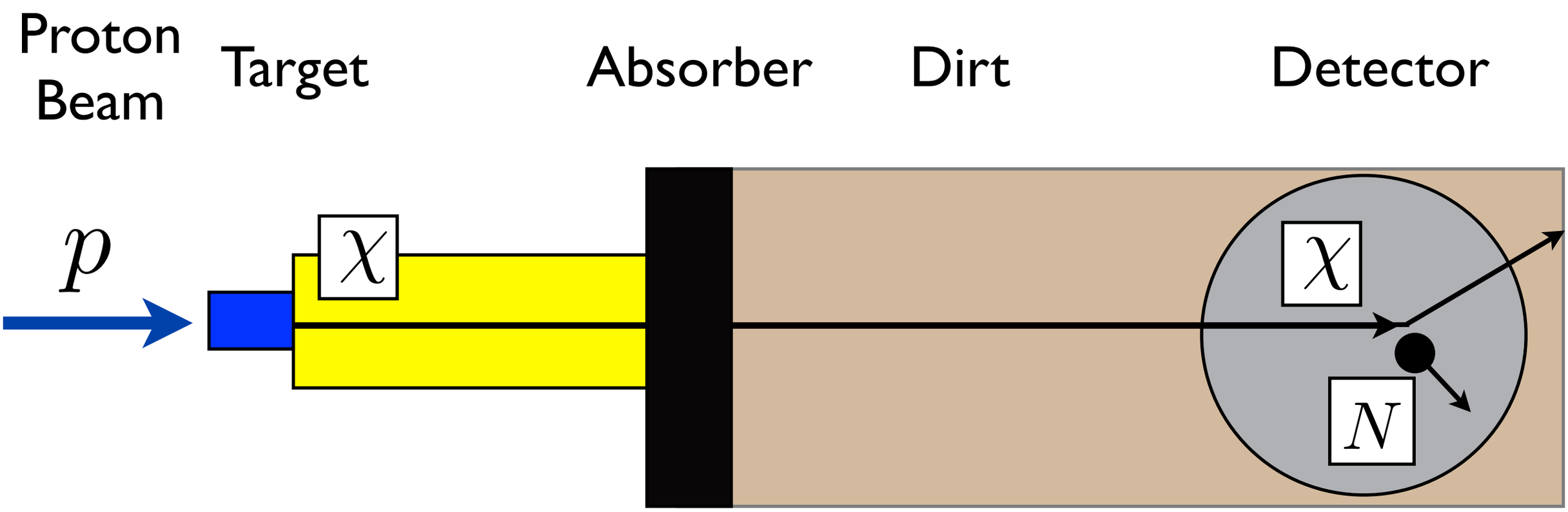


A Dark Matter Beam!



[BB, Pospelov, Ritz '09]
[deNiverville, Pospelov, Ritz '11]
[deNiverville, McKeen, Ritz '12]

A Dark Matter Beam!



MiniBooNE, MINOS, MicroBooNE, NOvA, T2K, LBNE, Project X, ...

Experiment	proton beam energy ($\sqrt{s}$)	Near detector distance	POT
Booster/ MiniBooNE	8.9 GeV (4.2 GeV)	540 m	1.8×10^{21}
NuMi/MINOS	120 GeV (15.5 GeV)	970 m	1.6×10^{21}
J-PARC Main Ring/T2K	30 GeV (7.7 GeV)	280 m	3.0×10^{20}
CNGS/OPERA, ICARUS	400 GeV (28 GeV)	No near detector	1.7×10^{20}

Can probe DM (in principle!) up to masses O(10 GeV)

Why Light Dark Matter?

Dark Matter provides one of the few *empirical* hints for new dynamics

But, absolutely no empirical suggestion for the mass of the DM

A great deal of attention has been given to the WIMP

"WIMP miracle" - particle with weak scale mass, weak interactions yields the observed dark matter relic abundance

In tandem with the hierarchy problem, WIMP is a compelling picture for DM

Huge experimental effort to discover WIMP DM (e.g. Direct Detection)

But so far, no new physics at LHC - perhaps DM is not at the weak scale

We must search everywhere we can for Dark Matter,
both high mass and low mass!

Light Dark Matter

Lee-Weinberg bound: $m_\chi \gtrsim \mathcal{O}(\mathrm{GeV})$

(Assumes DM annihilates via Standard Model interactions)

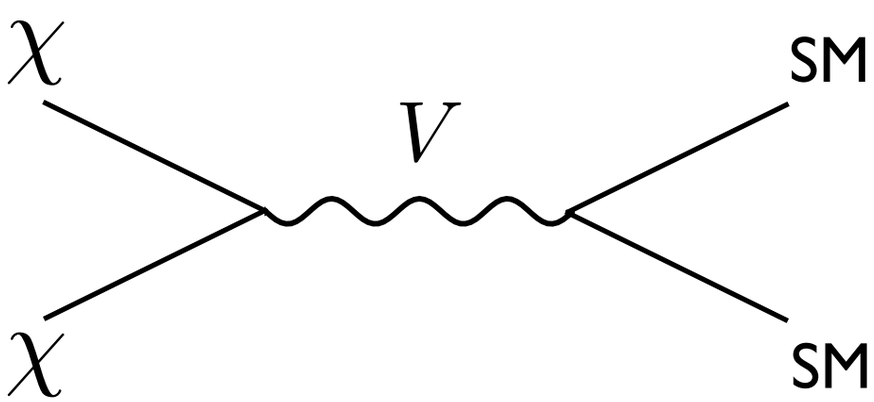
New forces ⇒ viable light thermal relic dark matter!

[Boehm, Fayet '03]

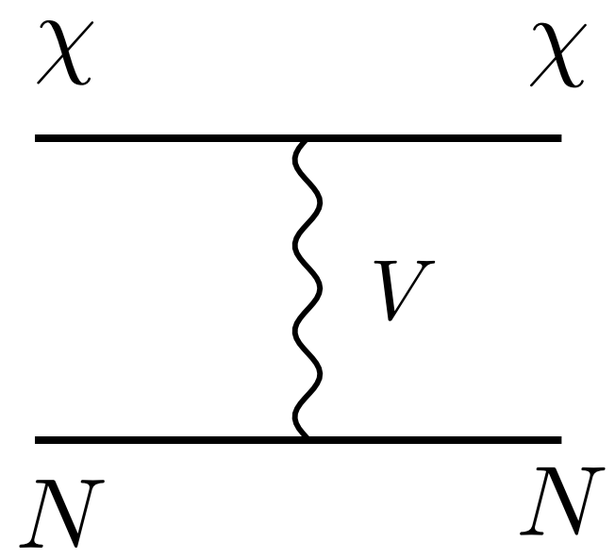
Force carriers serve dual purpose:

1. Open new annihilation channels

2. Mediate interactions with the SM

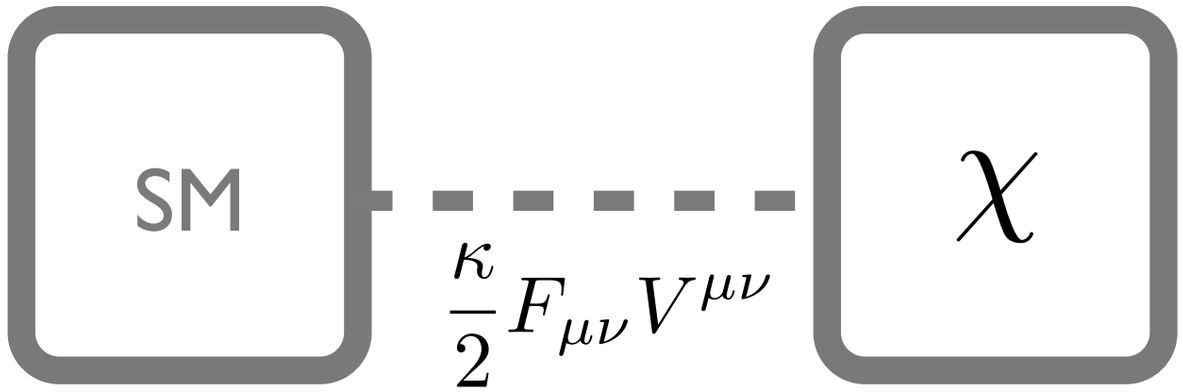


Annihilation



Scattering

A minimal vector portal model

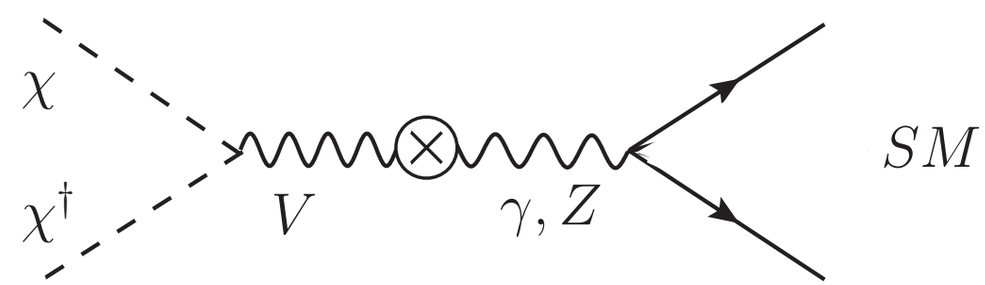


[Holdom]
[Pospelov, Ritz, Voloshin]

Dark photon mediates interaction between DM and SM

4 new parameters: $m_\chi, m_V, \kappa, \alpha'$

Can obtain correct relic abundance

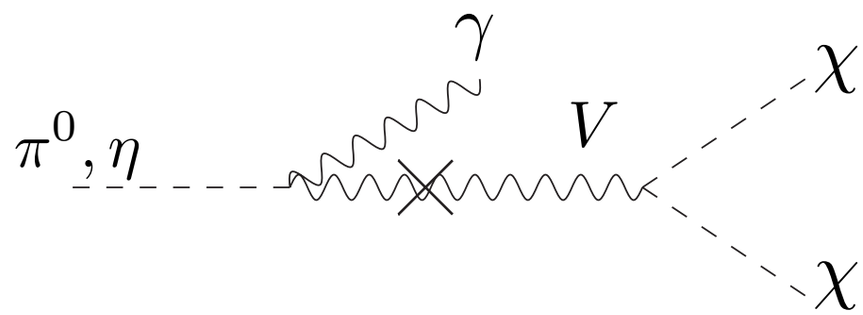


Scalar DM: p-wave annihilation, CMB ok [deNiverville, Pospelov, Ritz]

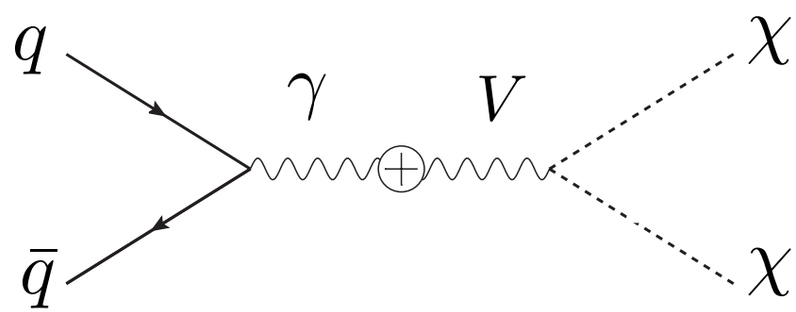
Dark photon can address g-2 anomaly [Pospelov]

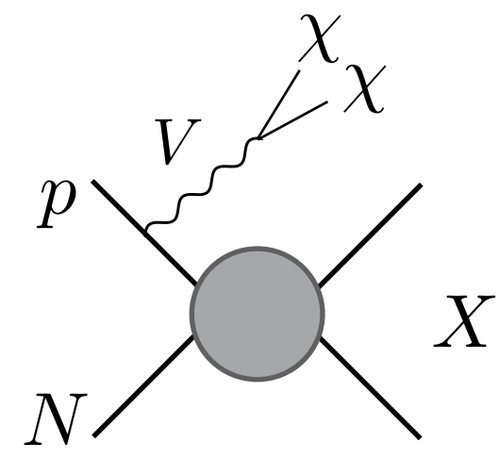
Production of the Dark Matter beam

Decays of mesons:

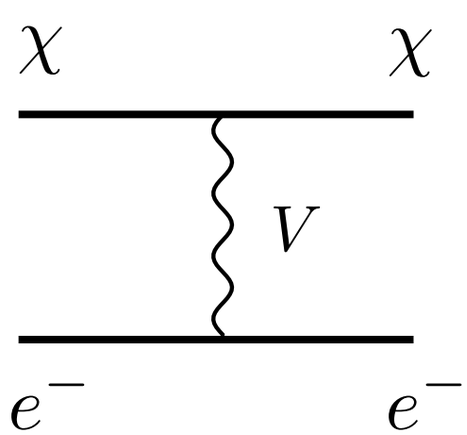


Direct production

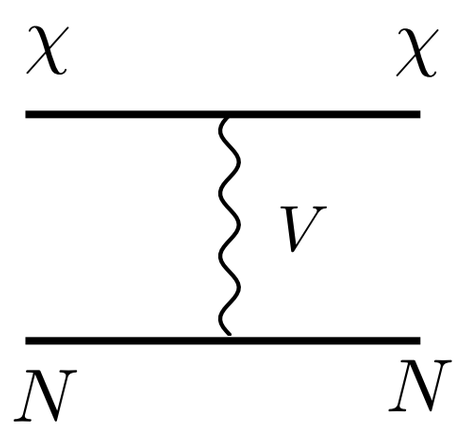




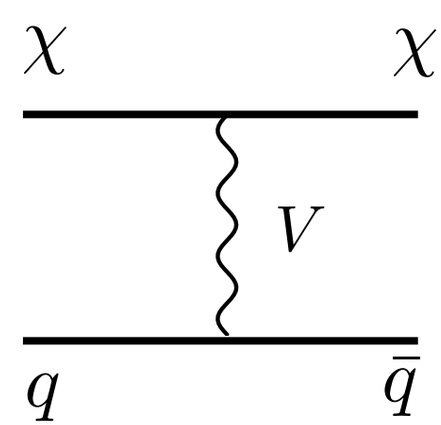
Detection via scattering



$\chi - e^-$ elastic



$\chi -$ nucleon elastic



deep inelastic

Low Mass WIMP Searches with a Neutrino Experiment: A Proposal for Further MiniBooNE Running

Presented to the FNAL PAC Oct 15, 2012

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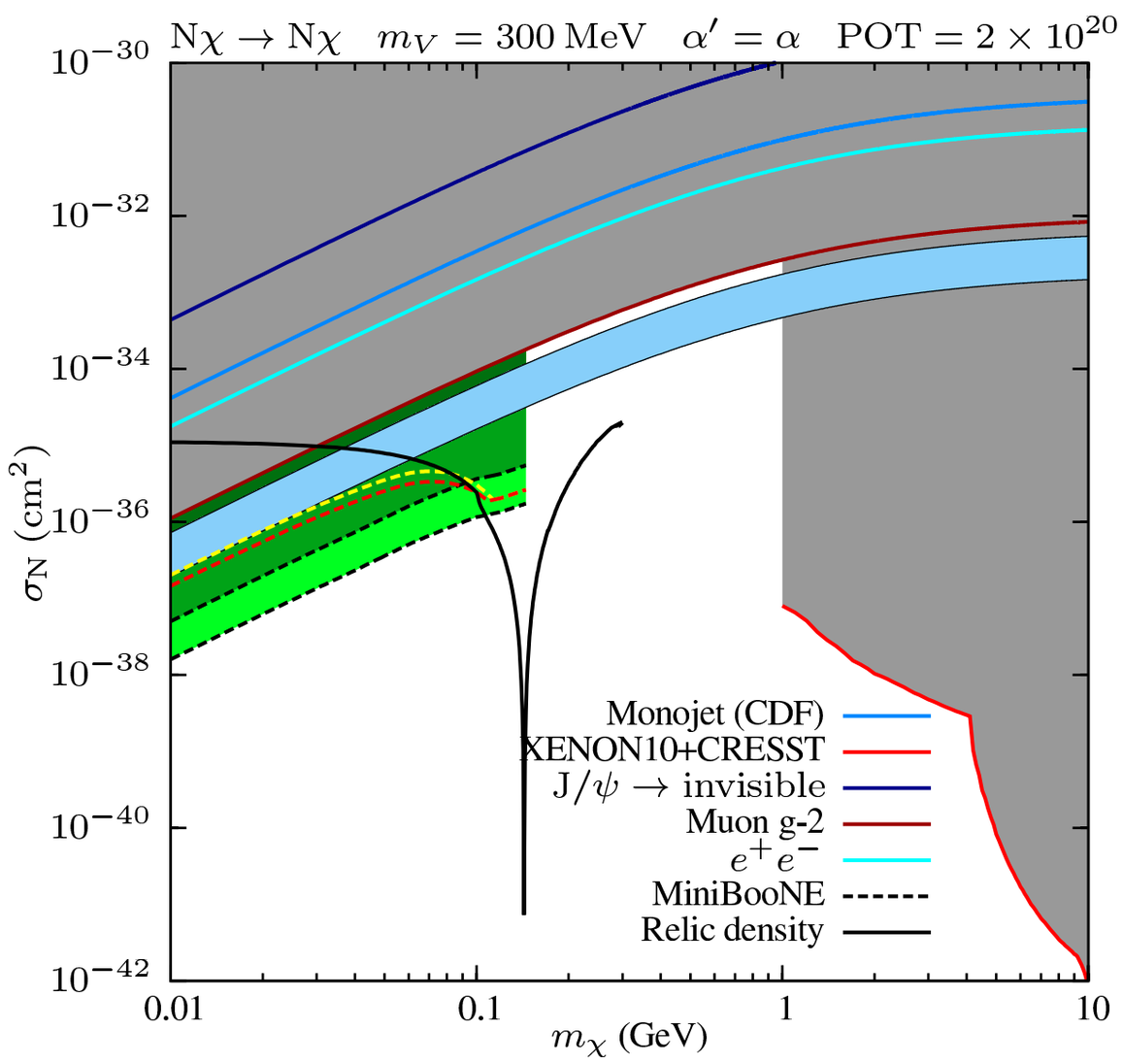
University of Victoria, Victoria, BC, V8P 5C2

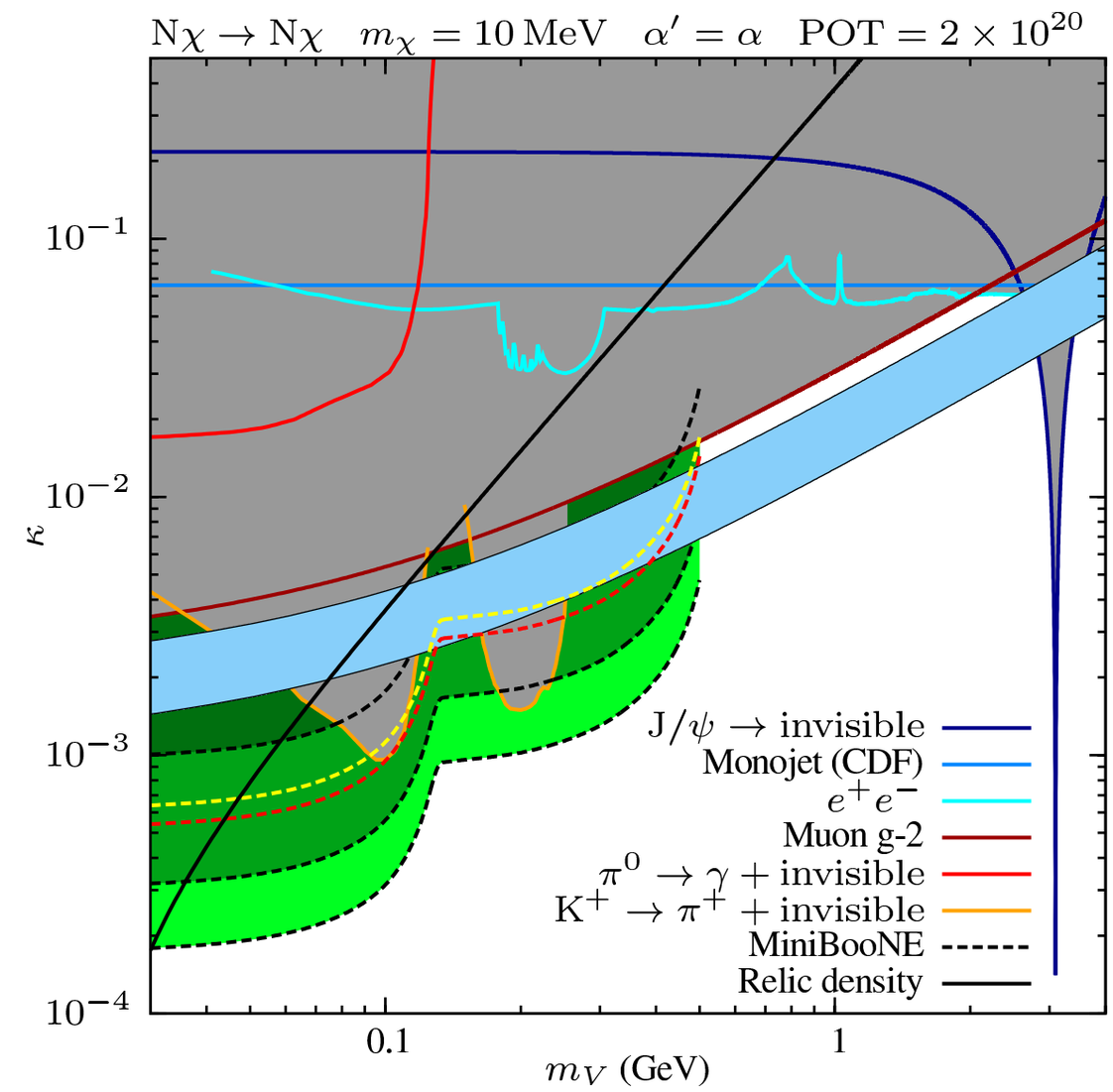
arXiv:1211.2258v1 [hep-ex] 9 Nov 2012

arXiv:1211.2258

MiniBooNE Sensitivity

[Aguilar-Arevalo et al., arXiv:1211.2258]





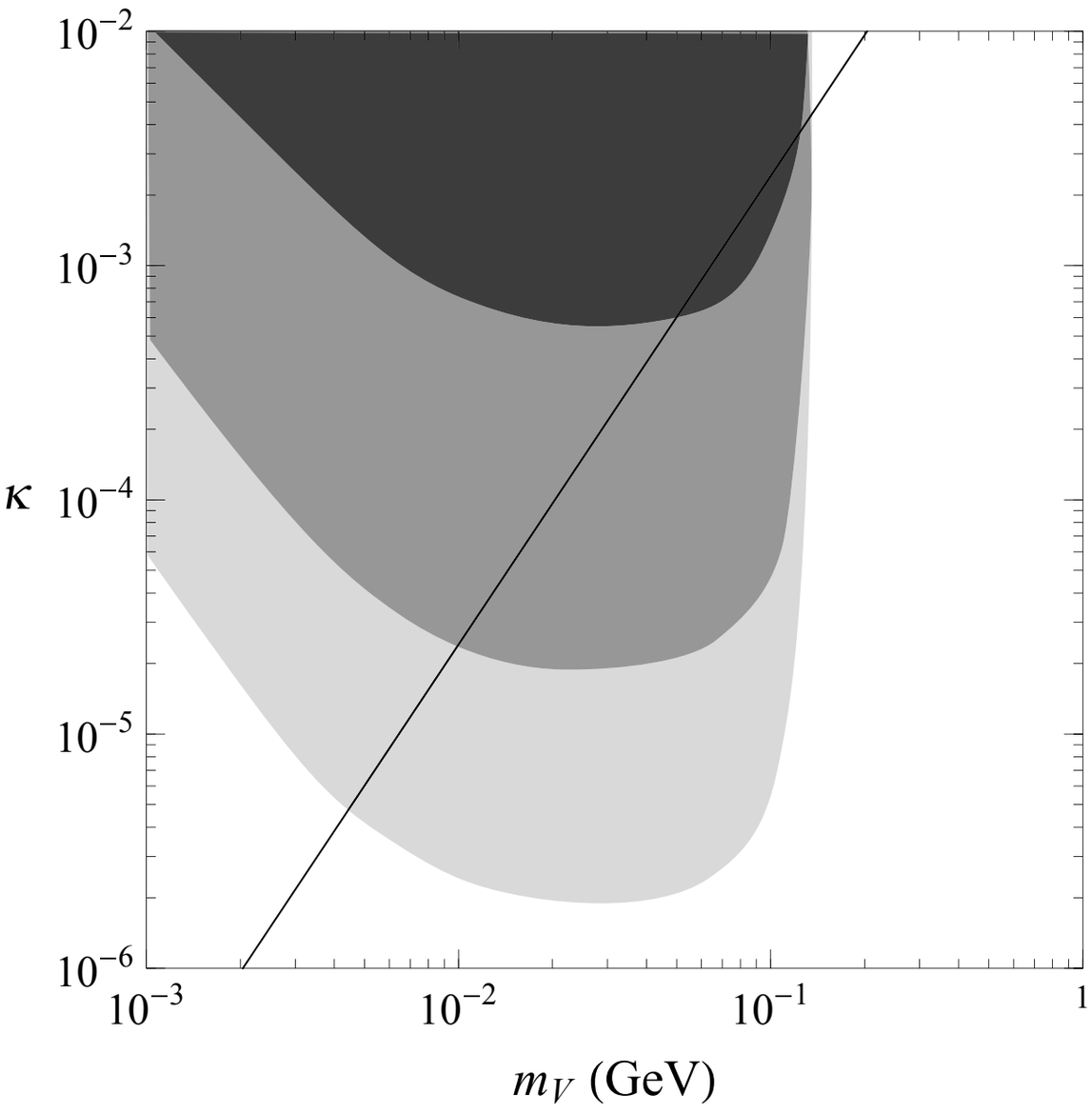
See next talk by R. Van de Water

LSND

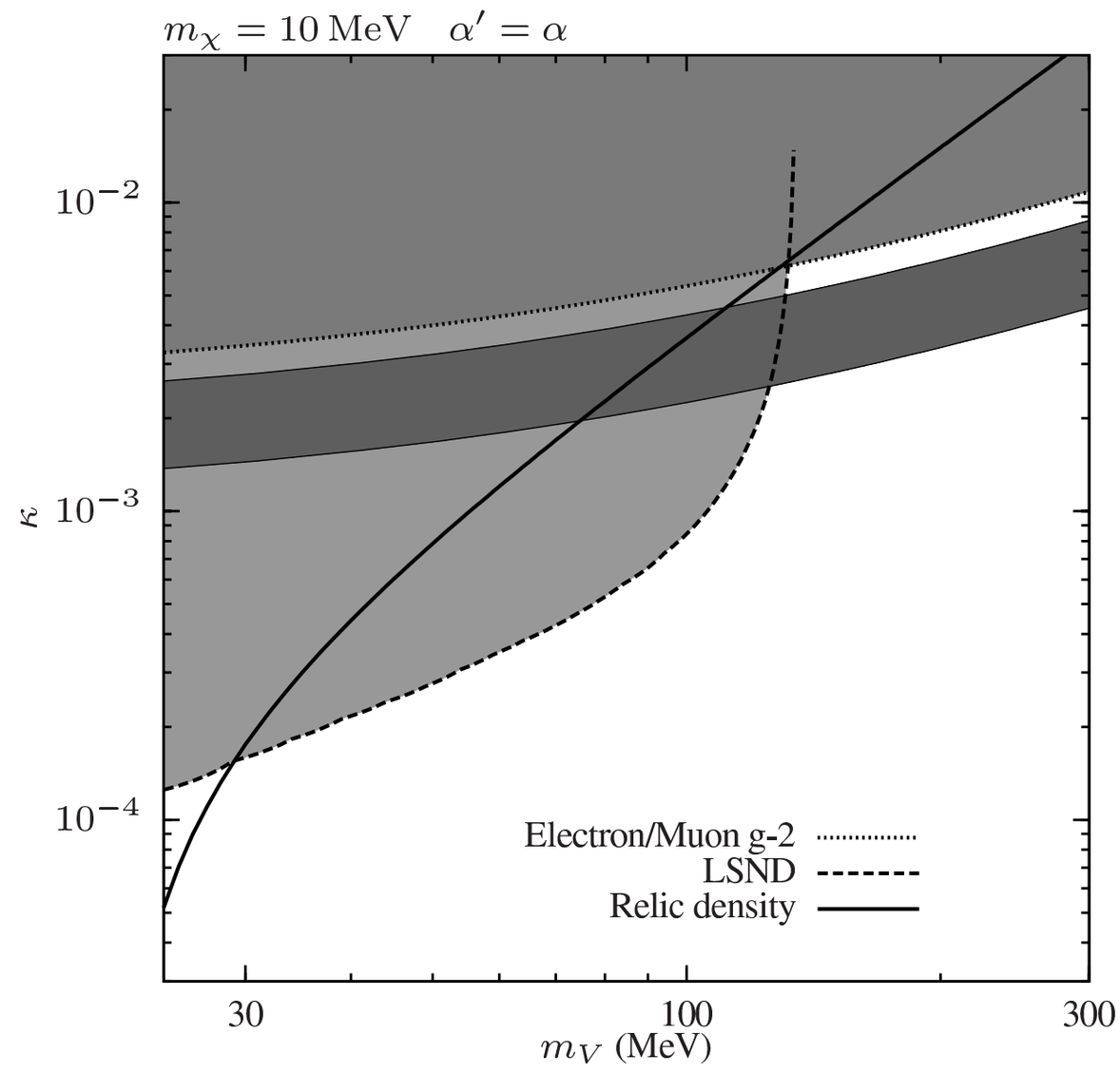
Production: $\pi^0 \to \gamma V \to \gamma \chi \bar{\chi}$

Sensitivity to $\chi e \to \chi e$

- LAMPF, 800 MeV protons, ~ 10^{23} POT
- water / high Z target
- detector: 30m off axis from target, cylindrical, 170 tons mineral oil

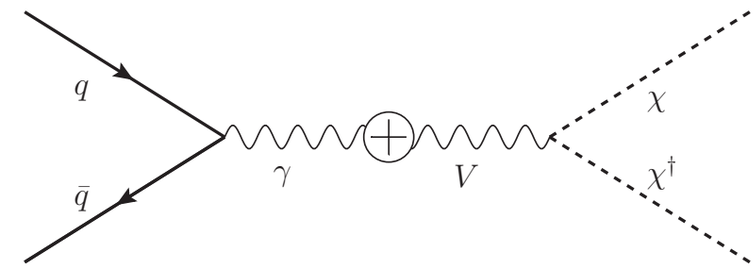


[BB, Pospelov, Ritz '09]



[deNiverville, Pospelov, Ritz '11]

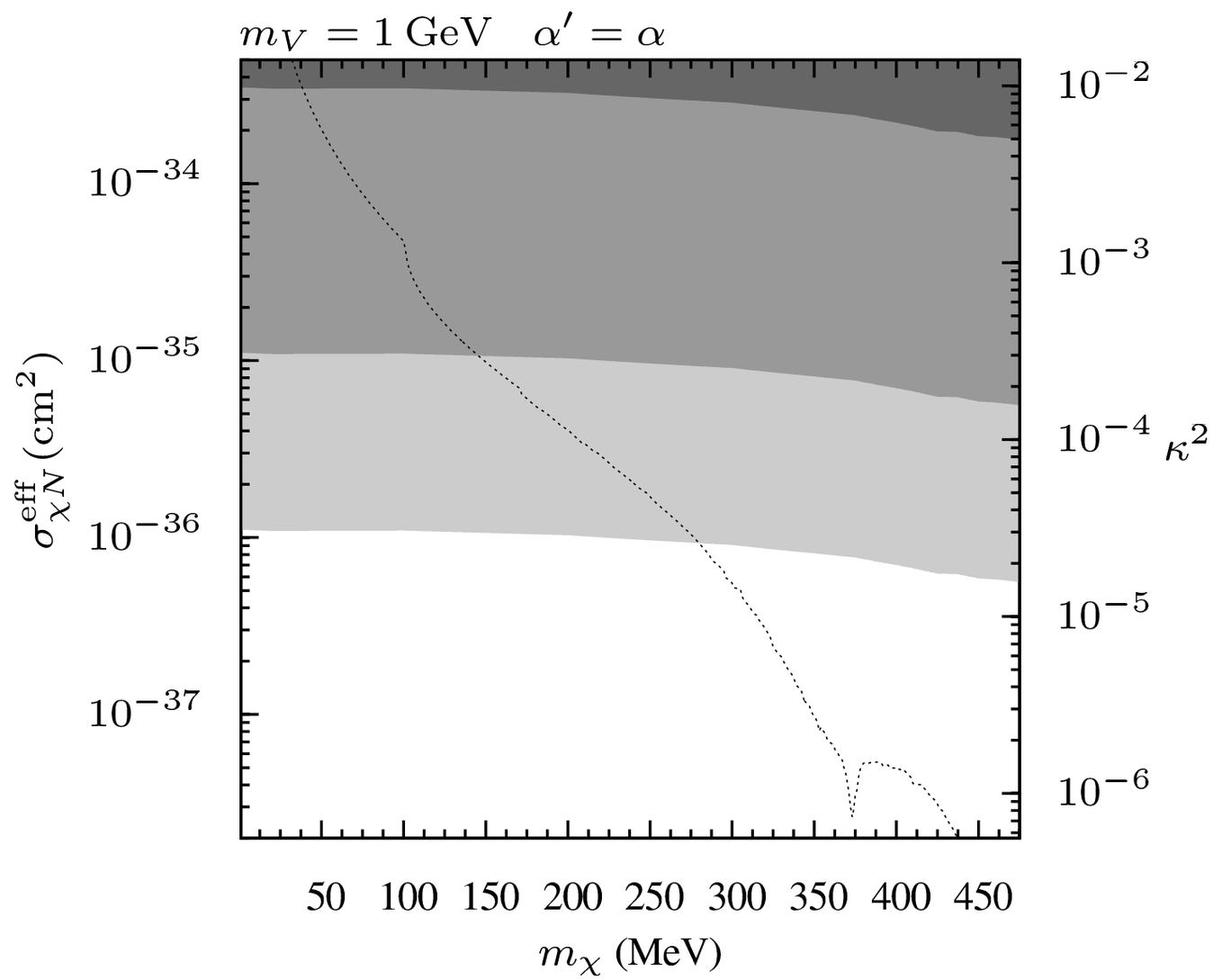
T2K



- JParc Main Ring, 30 GeV protons, ~10^{21} POT
- ND280 near detector: P0D, Tracker, ECAL

280 m from target, 2.5° off axis

Yield for $\chi N \to \chi N$ elastic scattering



[deNiverville, McKeen Ritz, '11]

There is a large signal!

- New ideas needed to overcome large neutrino background
- Studies of NC electron, π^0, inelastic processes needed

NOvA

- Fermilab Main Injector, 120 GeV protons
- ~ (6-10) x 10^{20} POT/yr
- Near Detector: Off-Axis 14.6 mrad, liquid scintillator cells

2.8m x 4.1 m x 14.3 m, ~1km from target, $\theta_{\rm det} \sim 0.2^{\rm o}$

LBNE

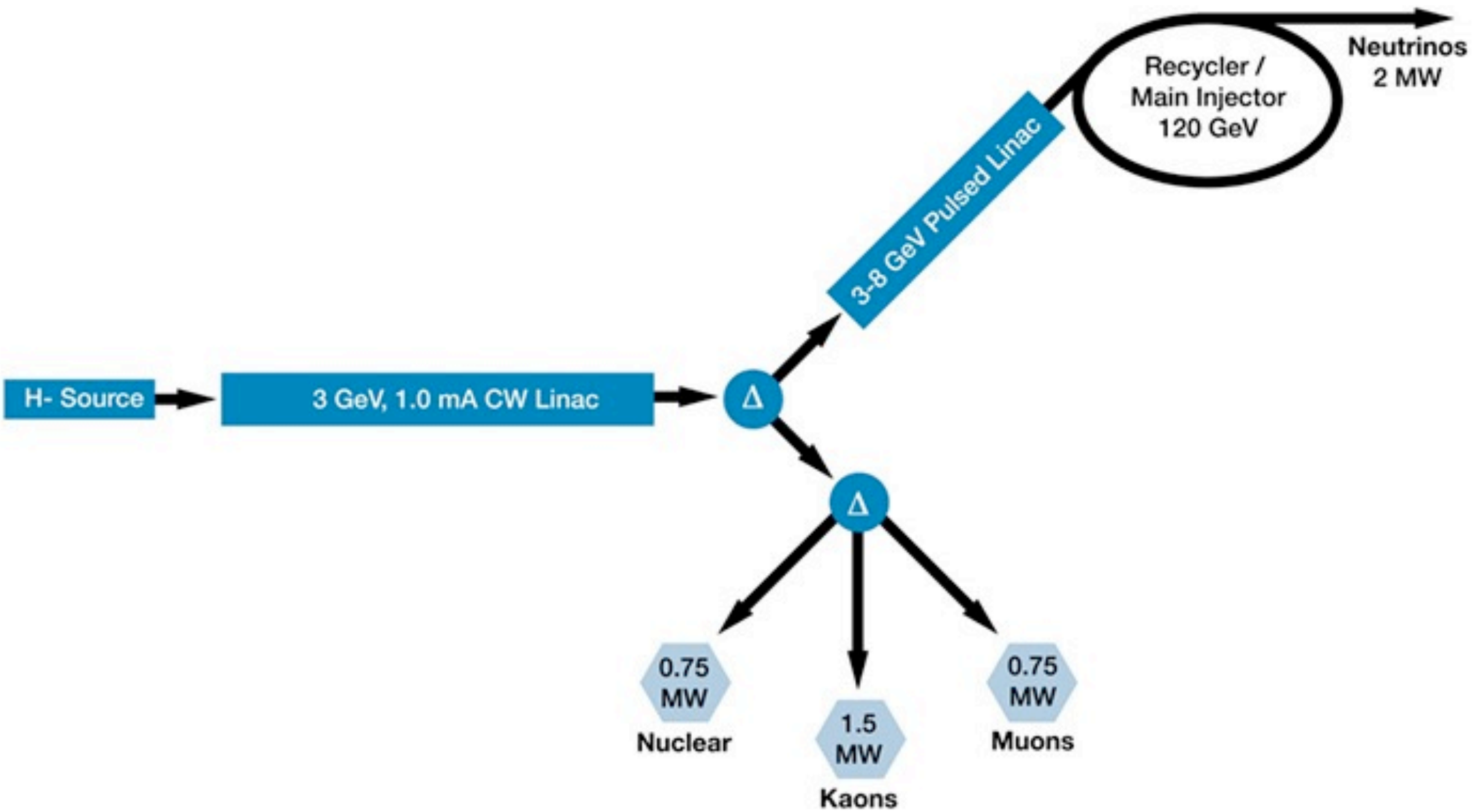
- Fermilab Main Injector, 120 GeV protons
- ~ 5 x 10^{20} POT/yr
- Near Detector: Straw Tube tracker + ECAL

3.5m x 3.5 m x 7.5 m, 500m from target, $\theta_{\rm det} \sim 0.4^{\rm o}$

Dedicated studies needed!

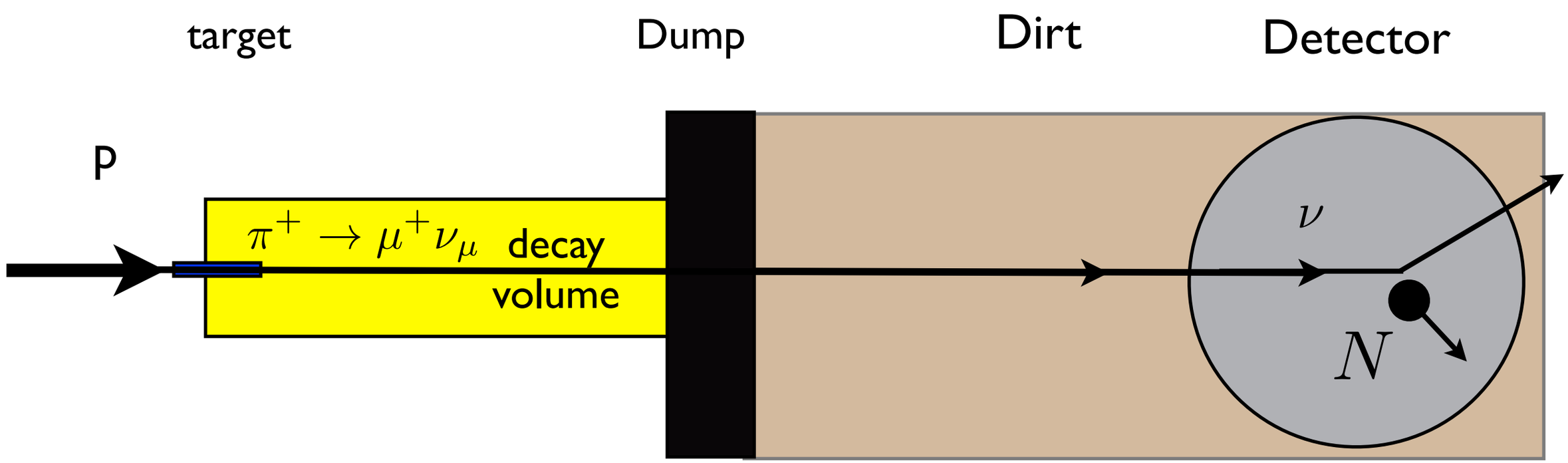
Project X: New high-intensity proton source

3 MW at 3 GeV ⇒ potential for $\sim 10^{23}\,\frac{\mathrm{POT}}{\mathrm{yr}}$

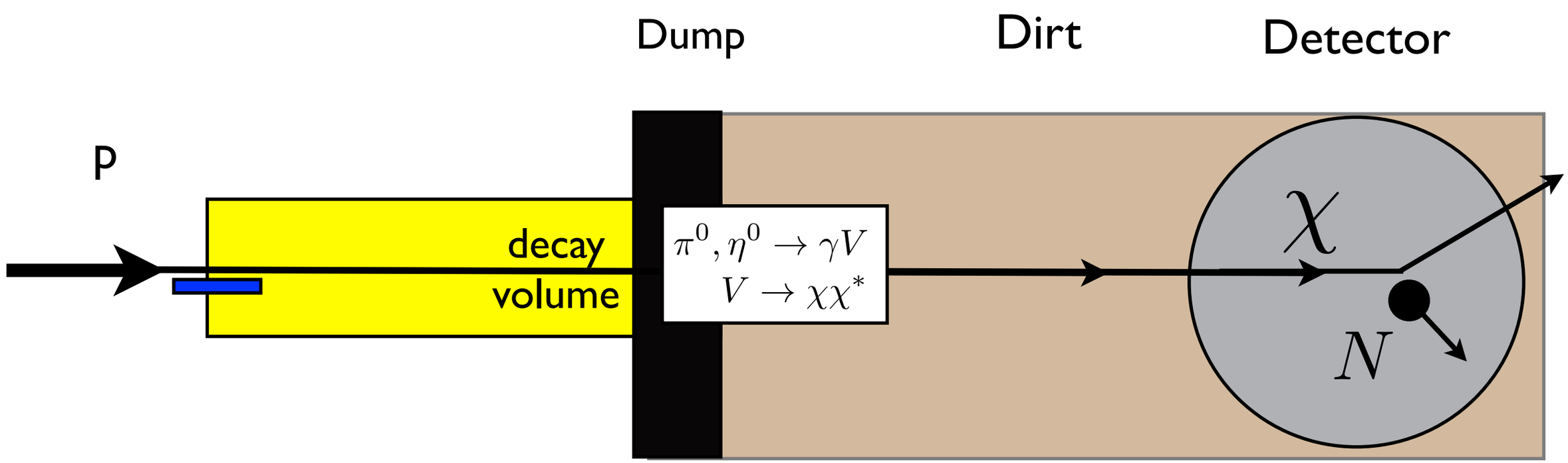


Overcoming the neutrino background

- Neutrinos produced from meson decays in the decay pipe

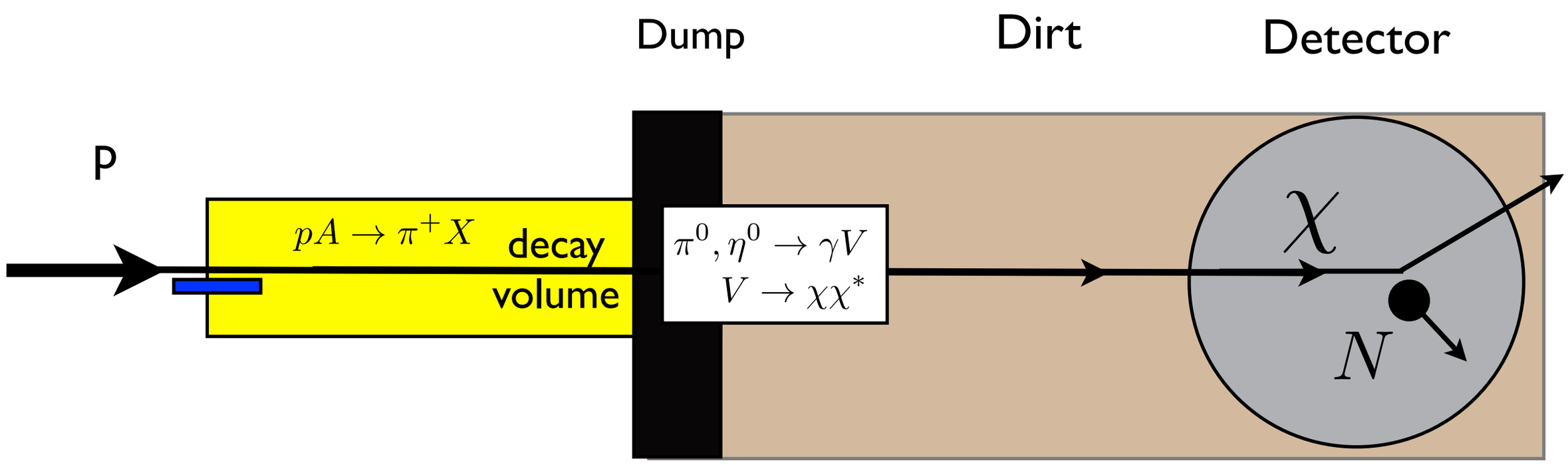


MiniBooNE proposal: run protons into the dump

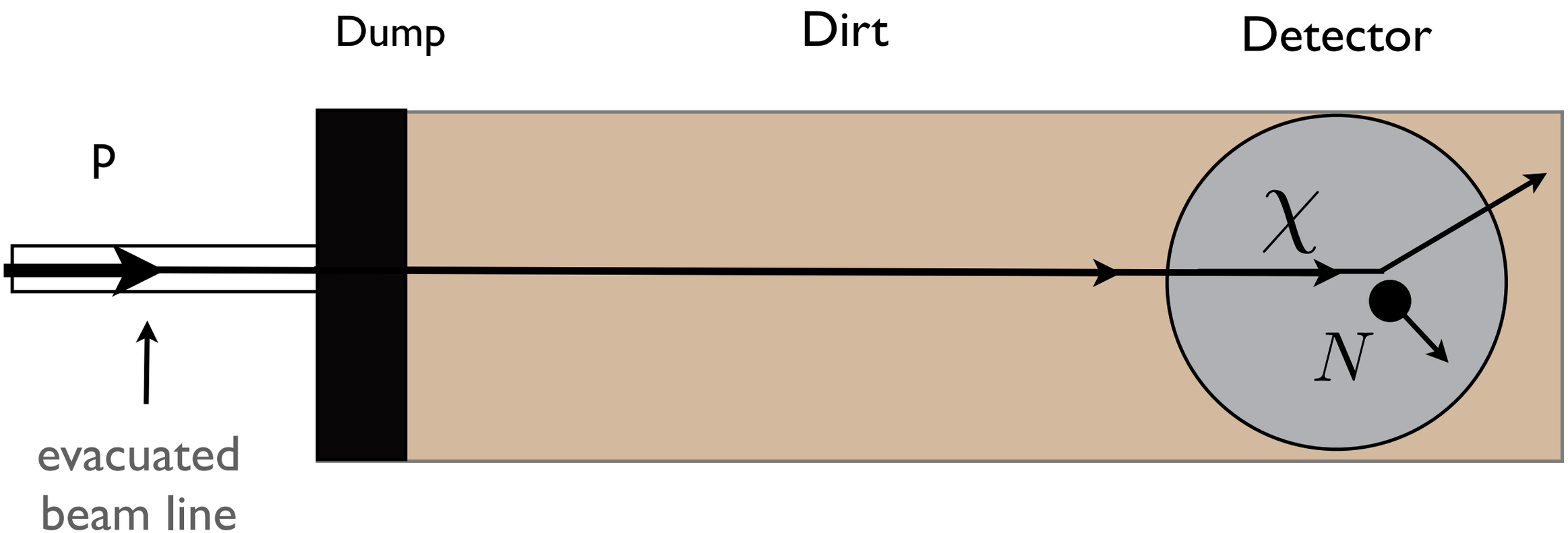


Neutrino background reduced by factor of ~ 50

Still, neutrinos produced through proton - air reactions in decay pipe



Optimally, dump should be positioned immediately following beam line

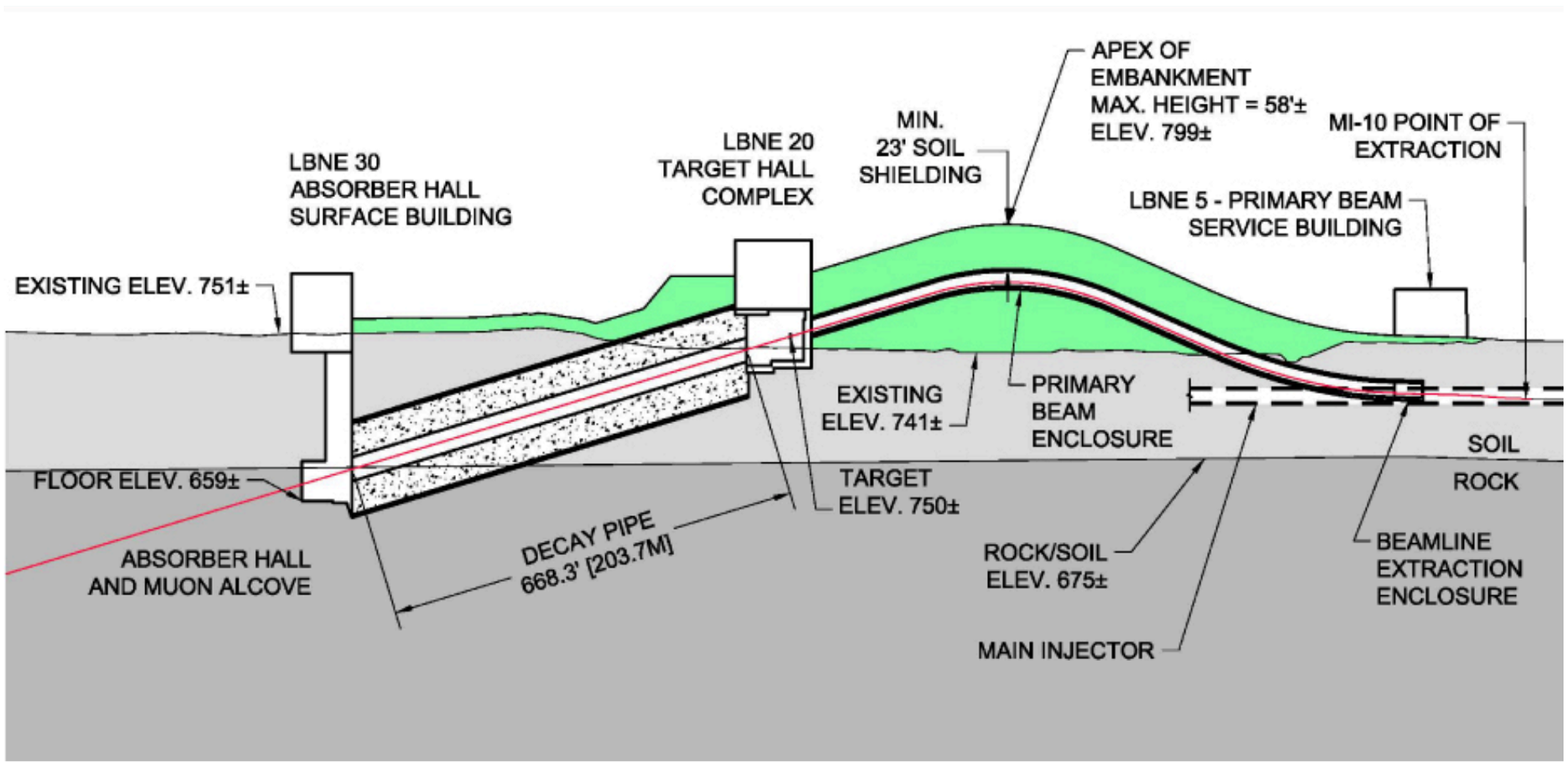


Neutrino background potentially reduced by factor of ~ 2-3 orders of magnitude!

Currently, none of the existing or proposed experiments can run in such a mode

Either

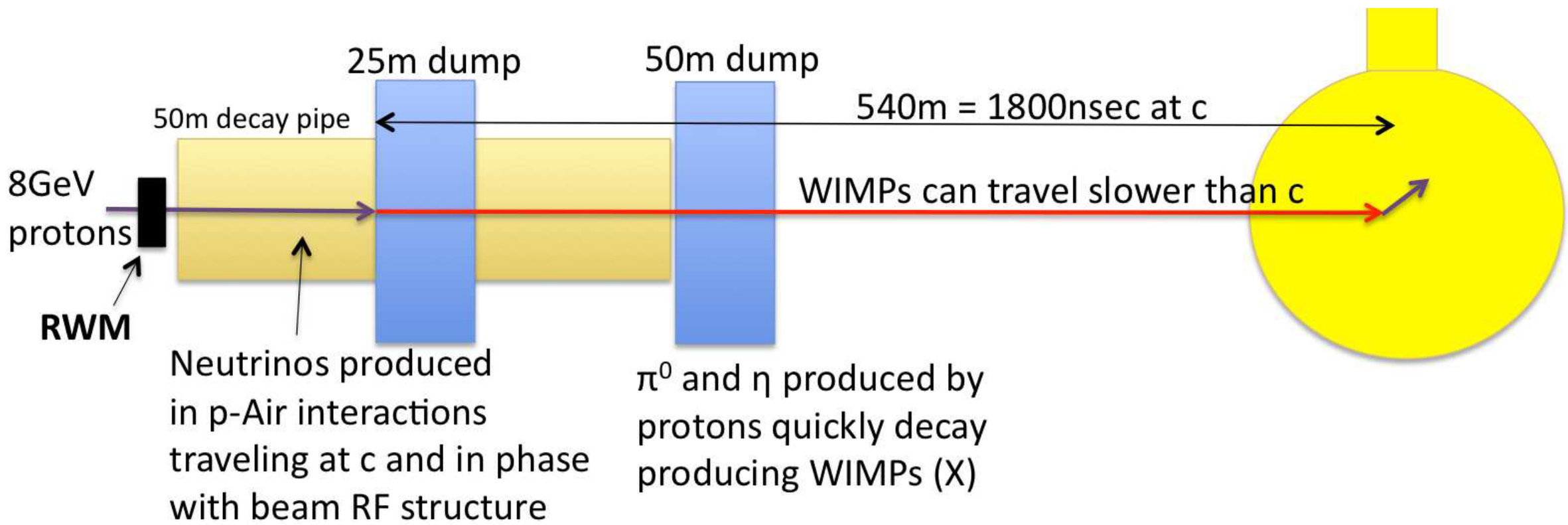
- Design a dedicated beam line/dump experiment (requires new detector)
- Adapt existing proposals, e.g. add spur line to LBNE:



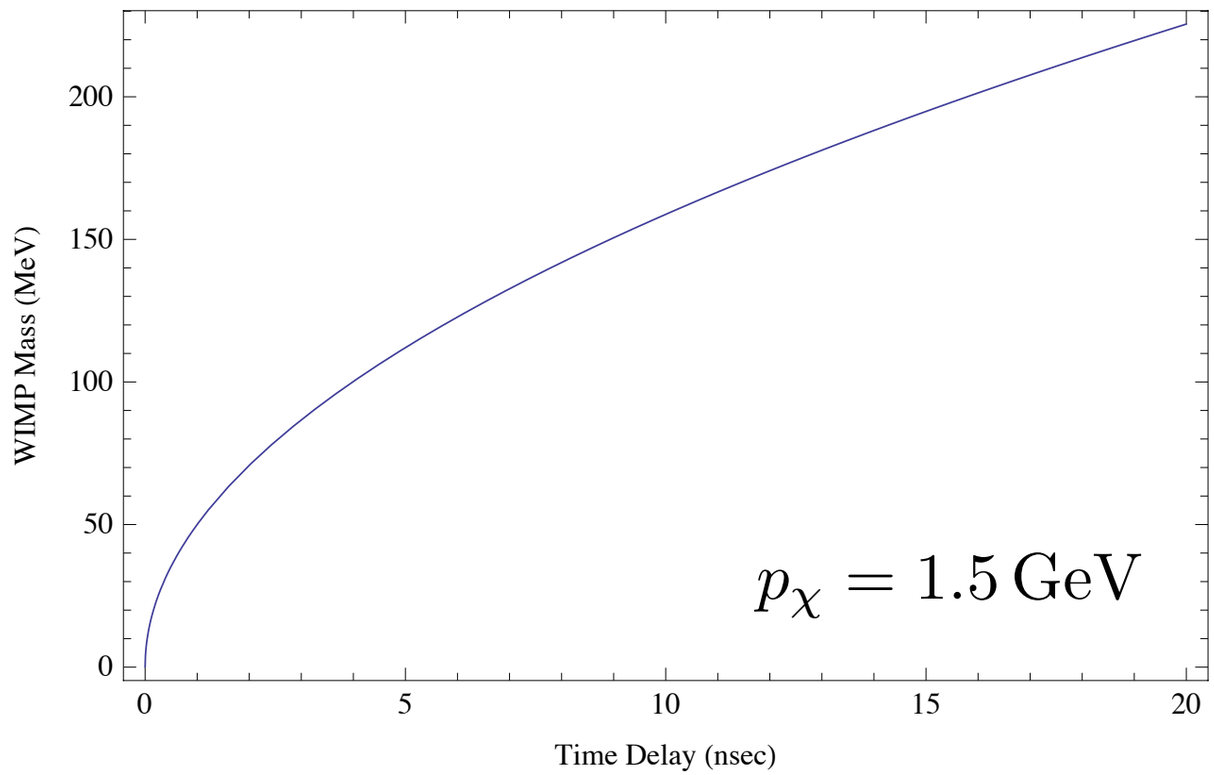
Timing

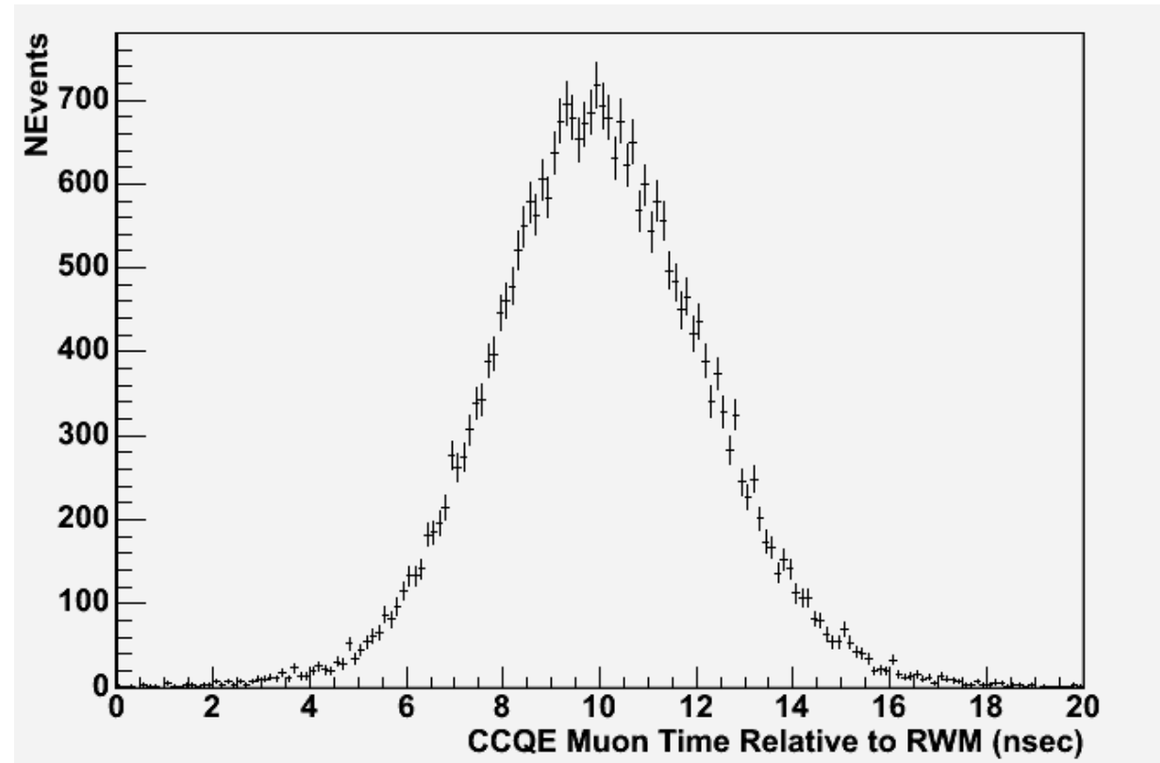
Dark matter is heavier than neutrinos - arrives at the detector later!

e.g. at MiniBooNE



Timing

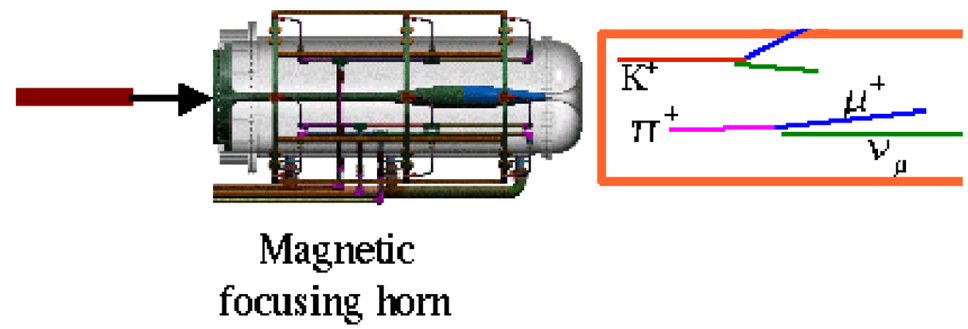




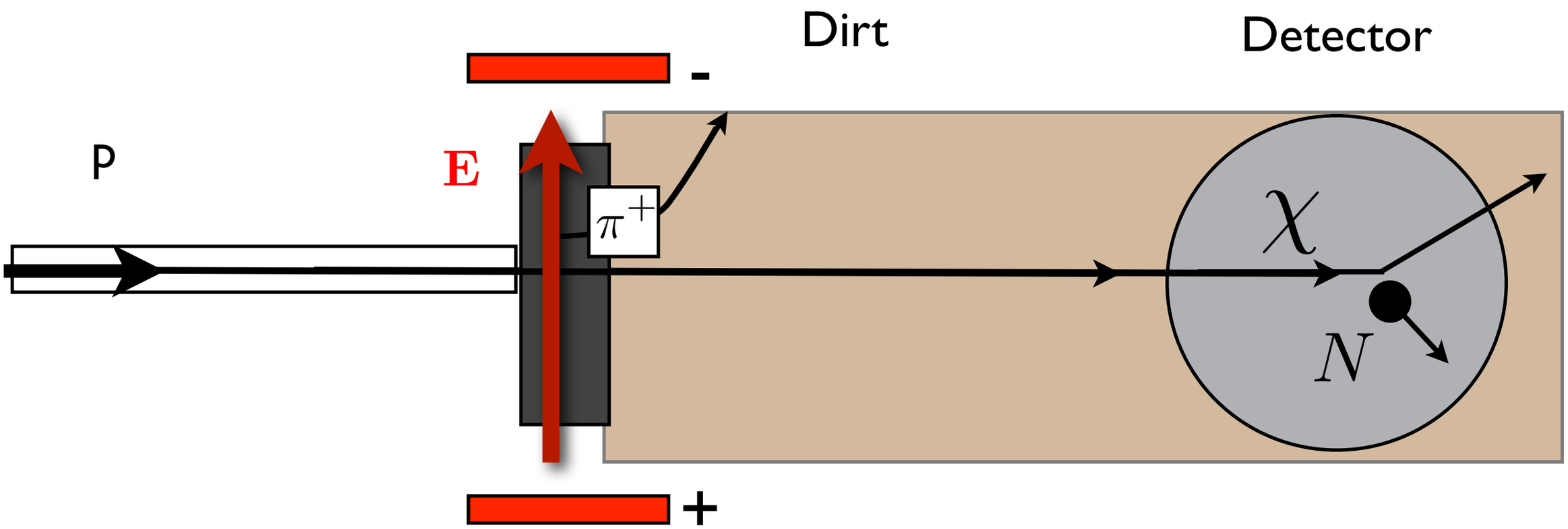
Timing cut (nsec)	Background Reduction (%)	WIMP Velocity β	WIMP Mass (MeV)
3.0	90	0.9984	85
4.6	99	0.9974	108
5.9	99.9	0.9967	122

Defocusing

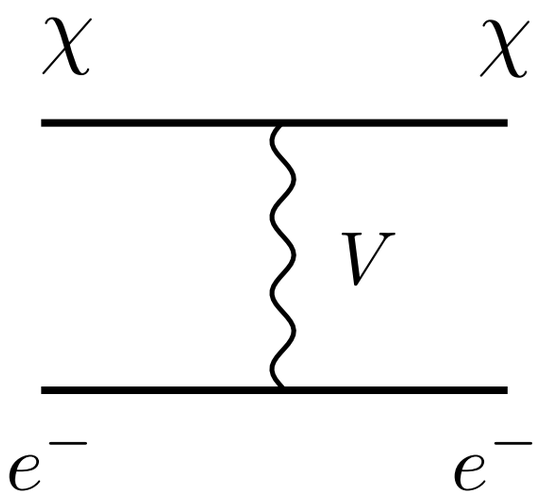
Typically, neutrinos are focused toward the target by a magnetic horn

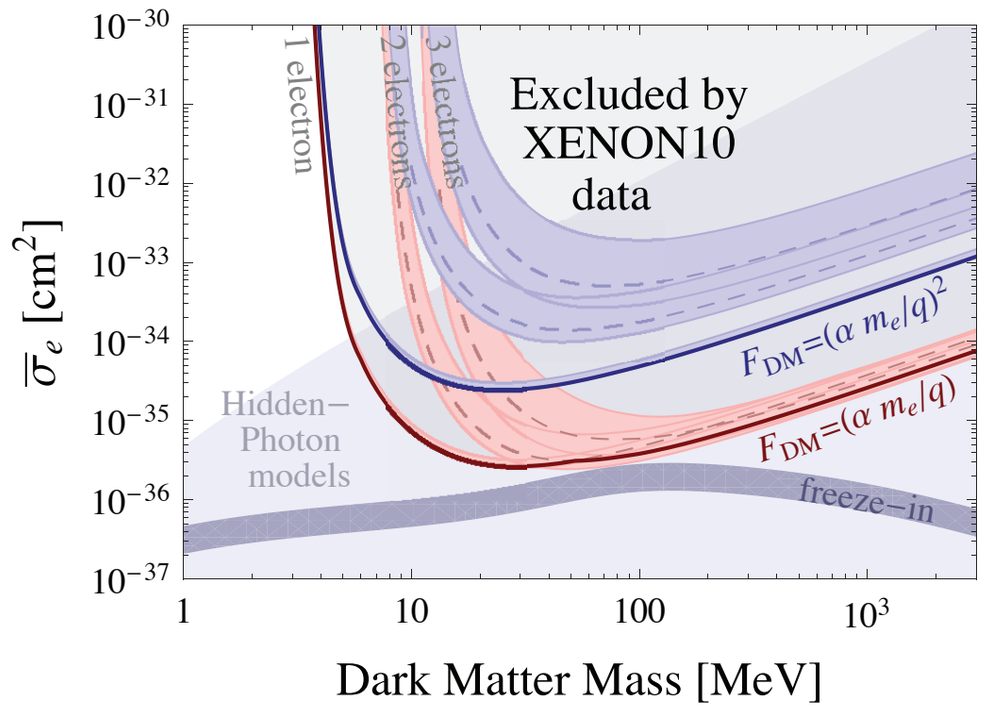


Instead, defocus charged particles, using E or B field

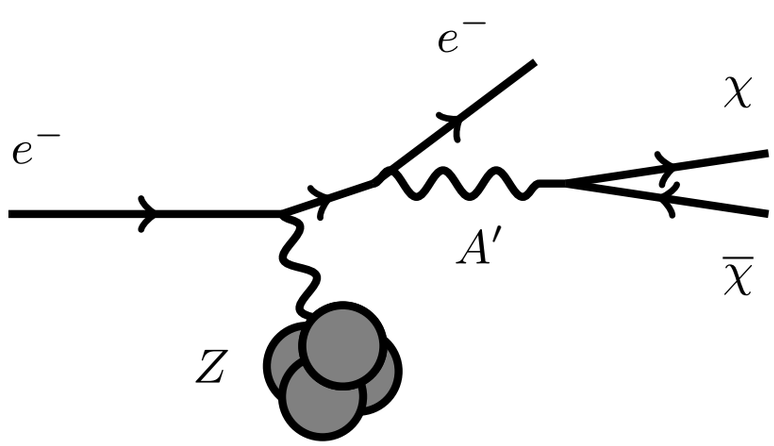


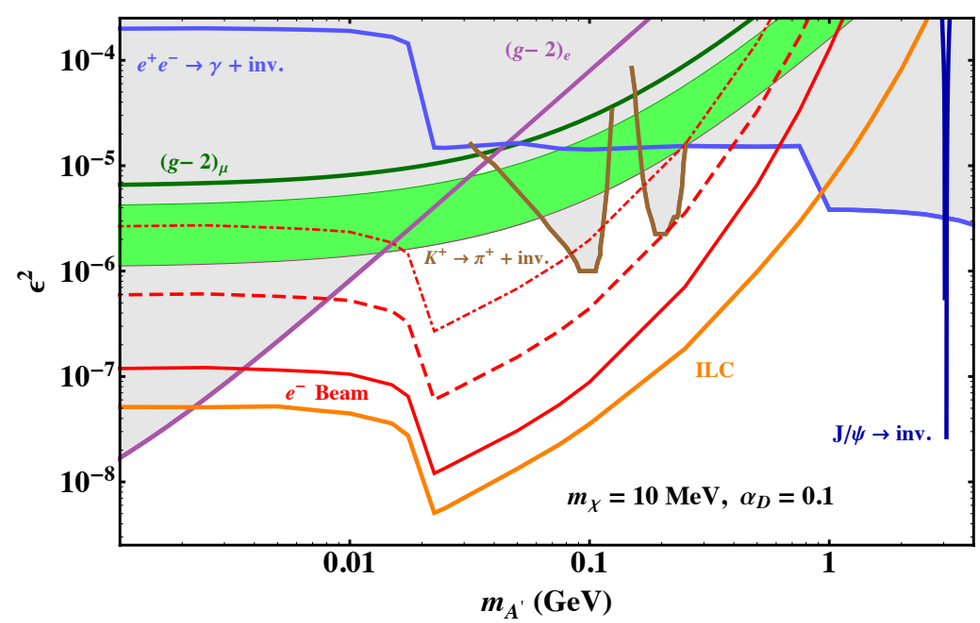
Direct Detection [Essig, Manalaysay, Mardon, Sorensen, Volansky `12]





Electron Beam Dumps [Izaguirre, Krnjaic, Schuster, Toro '13]





What are we looking for?

Experiments will put a limit (or see an excess!) on number of neutral current events ... can be interpreted in a variety of ways.

We should keep an open mind to how dark matter couples to the SM

If dark matter couples dominantly to quarks, proton beams (neutrino experiments) will have best sensitivity. If instead it couples dominantly to electrons, then electron beams will have unique sensitivity.

Given that we know absolutely nothing about how/if DM interacts with the SM, it is important to pursue both approaches!

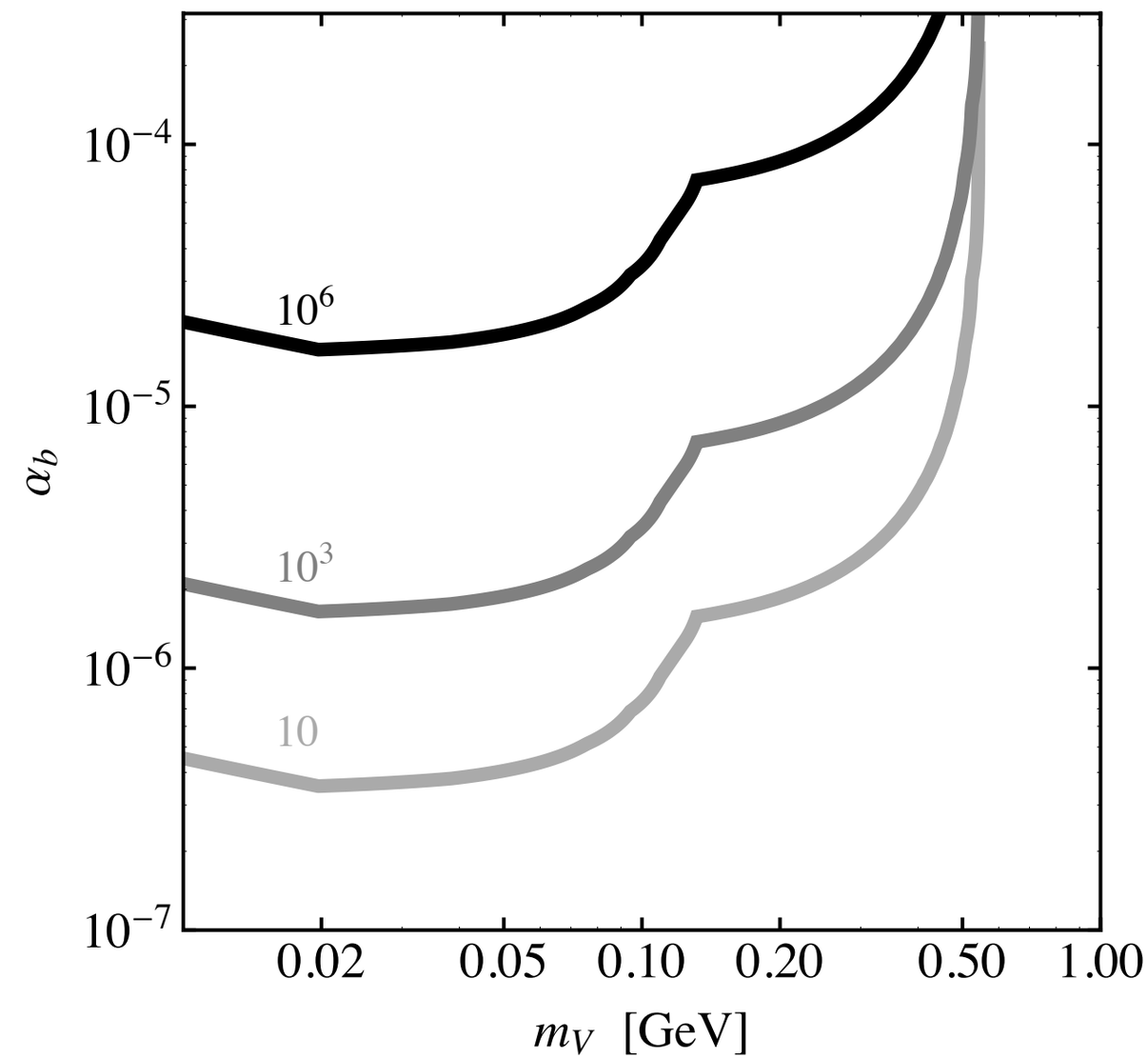
Much important work to be done on the theory/pheno side, in terms of model building (are there other viable ways to couple light DM to SM?), and "model independent" characterization of results

Example: Vector mediator coupled to baryon current

$$\mathcal{L} \supset -\frac{1}{4}V_{\mu\nu}^2 + |(\partial_\mu - ig_b Q_b V_\mu)\chi|^2 + \bar{q}i\gamma^\mu(\partial_\mu - ig_b \tfrac{1}{3}V_\mu)q$$

Constraints from precision QED, B-factories & electron fixed targets do not apply

Proton beams have unique sensitivity, e.g. MinBooNE:



[BB, deNiverville, McKeen, Pospelov, Ritz, to appear]

Outlook

- Proton fixed target/beam dump experiments (e.g. neutrino factories) offer a new way to search for dark matter
- Complementary to traditional probes (e.g. direct detection)
- First analysis is underway at MiniBooNE ... limits soon!
- Main obstacle is neutrino neutral current background
  - Dump, Timing, Defocusing... new ideas needed!
- Future neutrino experiments could run in a ``Dark matter mode", or can design dedicated experiments
- Early days! Studies needed for both theory and experiment

Dark matter provides an important new motivation for these experiments! We must take advantage of this opportunity!