Searching for Light Dark Matter with Proton Beam Dumps

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Dark Interactions: Perspectives from Theory and Experiment
Brookhaven National Laboratory
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Based on:

BB, Pospelov Ritz; arXiv:0906.5614

deNiverville, Pospelov, Ritz; arXiv:1107.4580

deNiverville, McKeen, Ritz; arXiv:1205.3499

BB, deNiverville, McKeen, Pospelov, Ritz; arXiv:1405.1049

BB, Essig, Surujon; arXiv:??? (to appear tonight)

MiniBooNE Proposals

Dharmapalan et al. ,[MiniBooNE Collaboration], arXiv:1211.2258

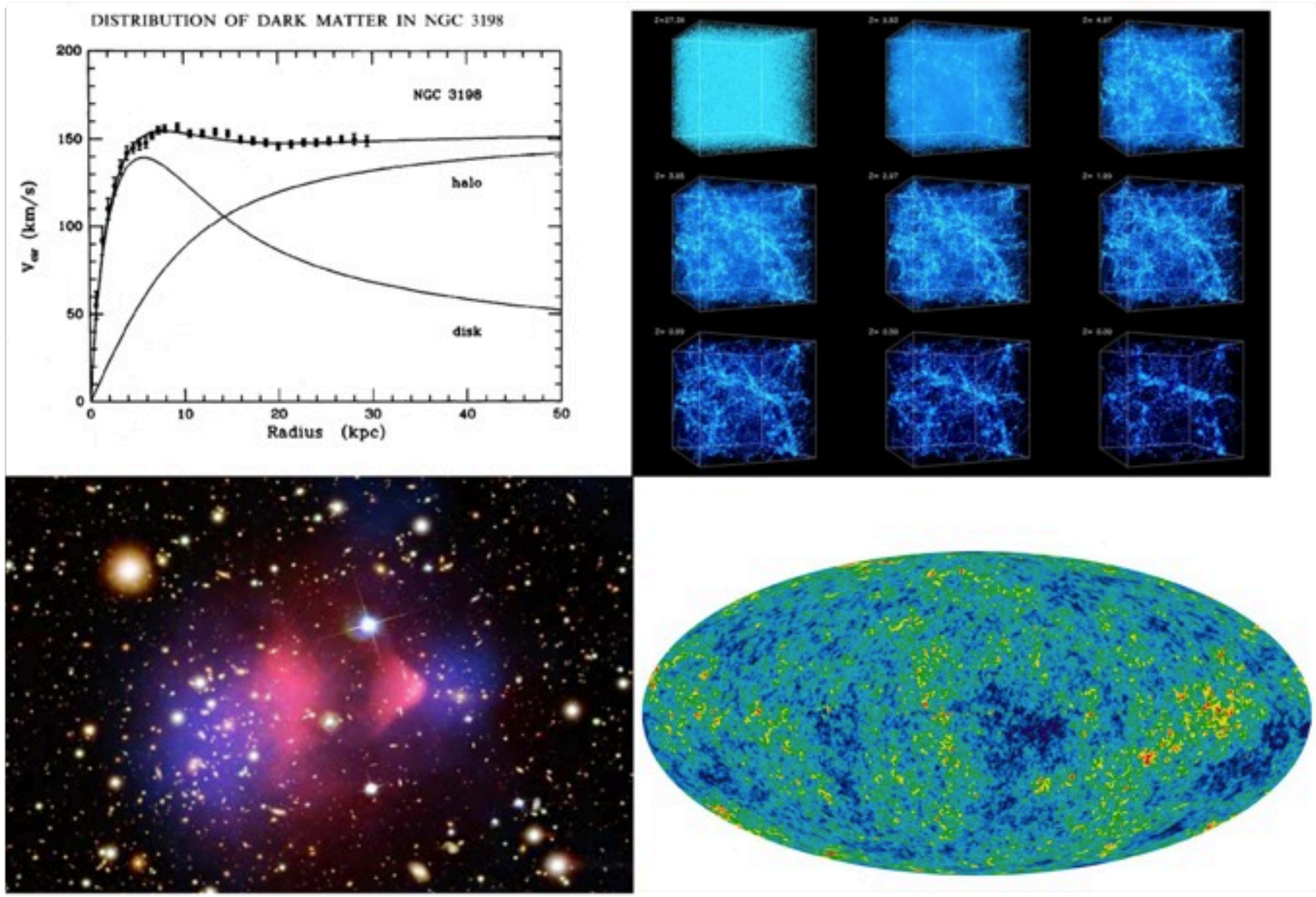
http://www.fnal.gov/directorate/program_planning/Jan2014PACPublic/PAC_Agenda_Draft_Jan_2014.htm

[See also: Morrissey, Spray; arXiv:1402.4817 for related work on proton beams]

Outline

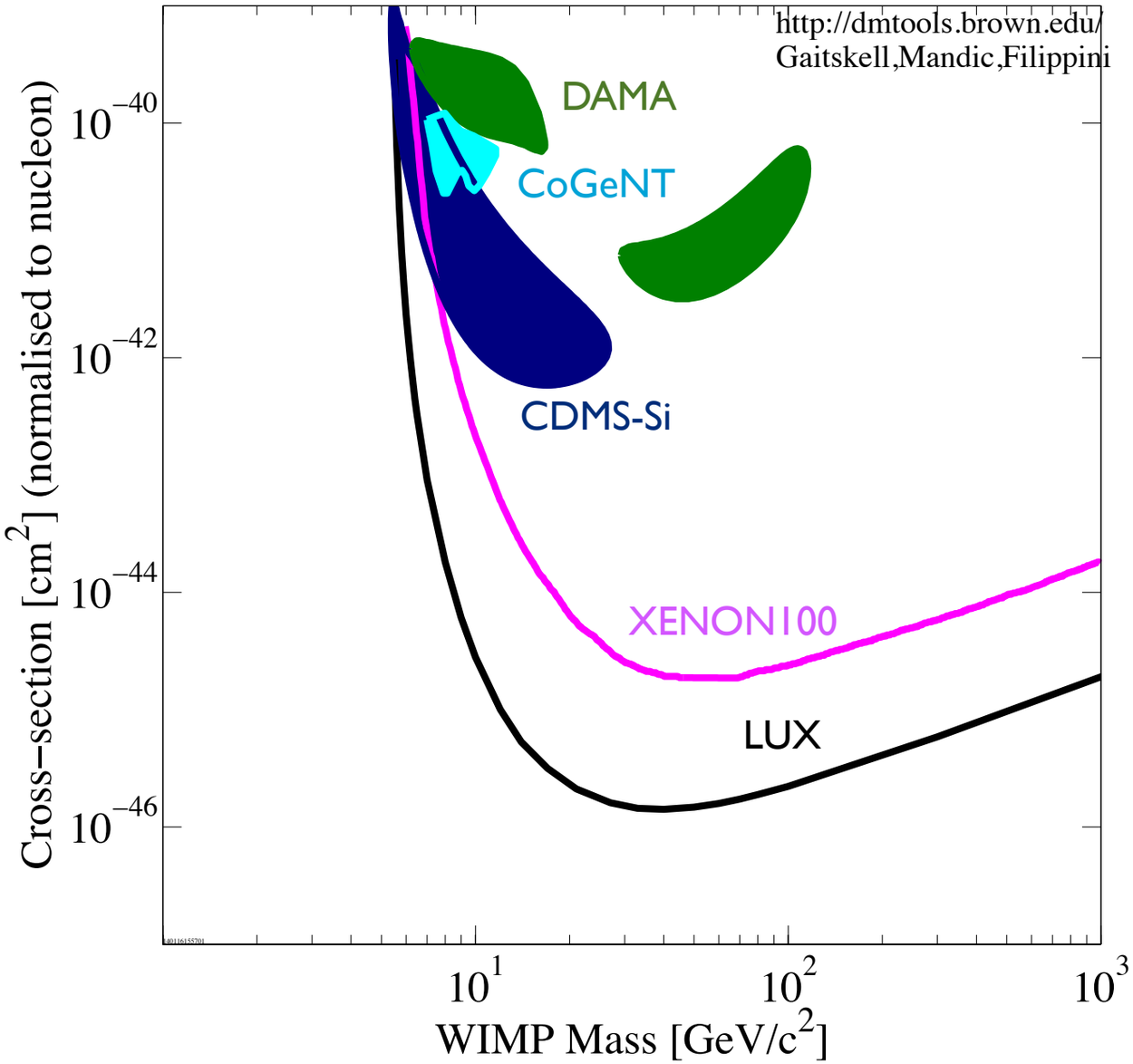
- Motivation and basic experimental principle
- Theories of light dark matter
  - Vector portal ("dark force") - new constraints from SLAC E137
  - Leptophobic DM
- The MiniBooNE beam-dump dedicated run
- Outlook

Dark Matter



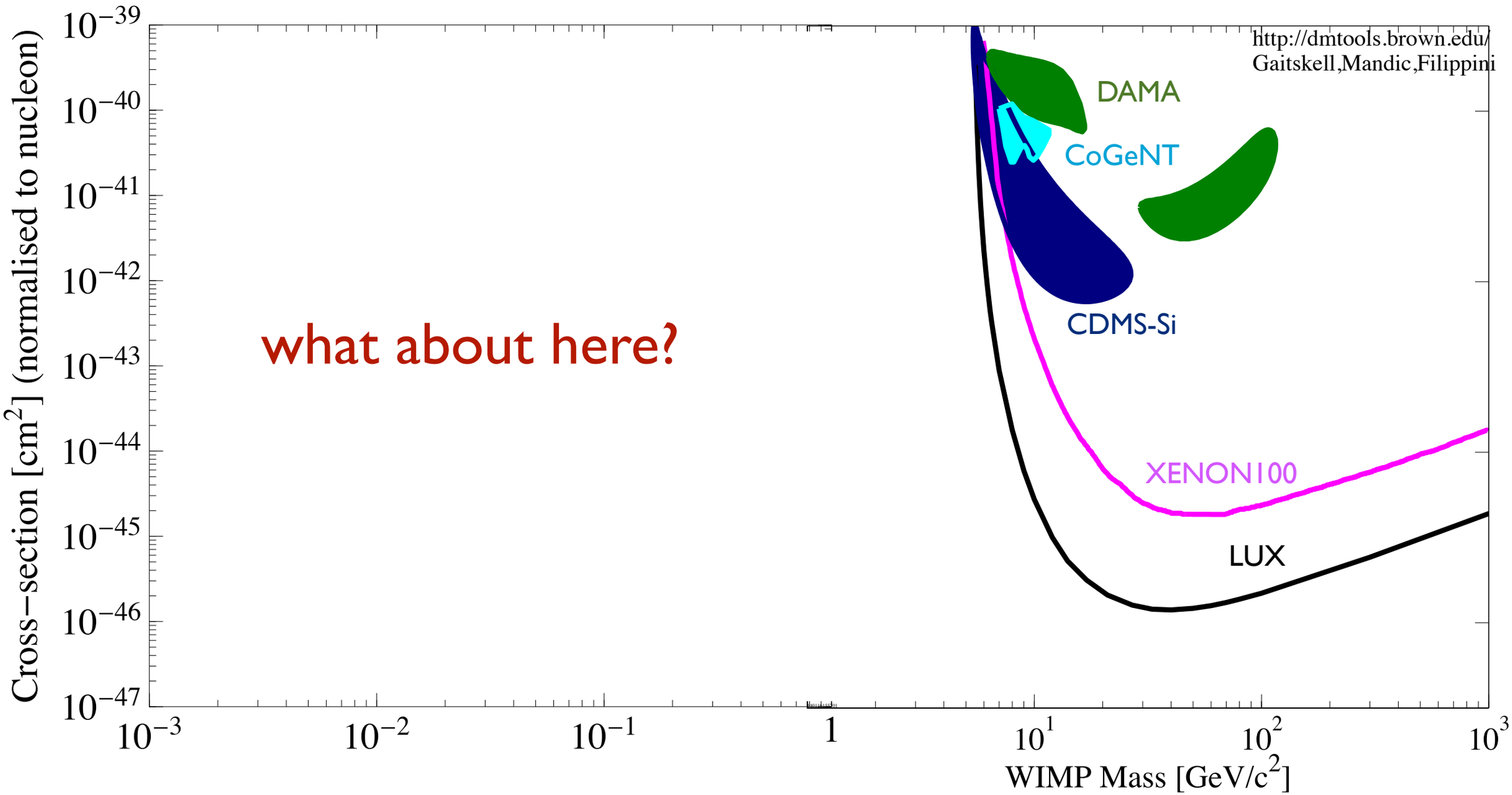
- One of the few empirical hints of new physics
- Detecting non-gravitational interactions of DM is a top-priority

Direct Detection



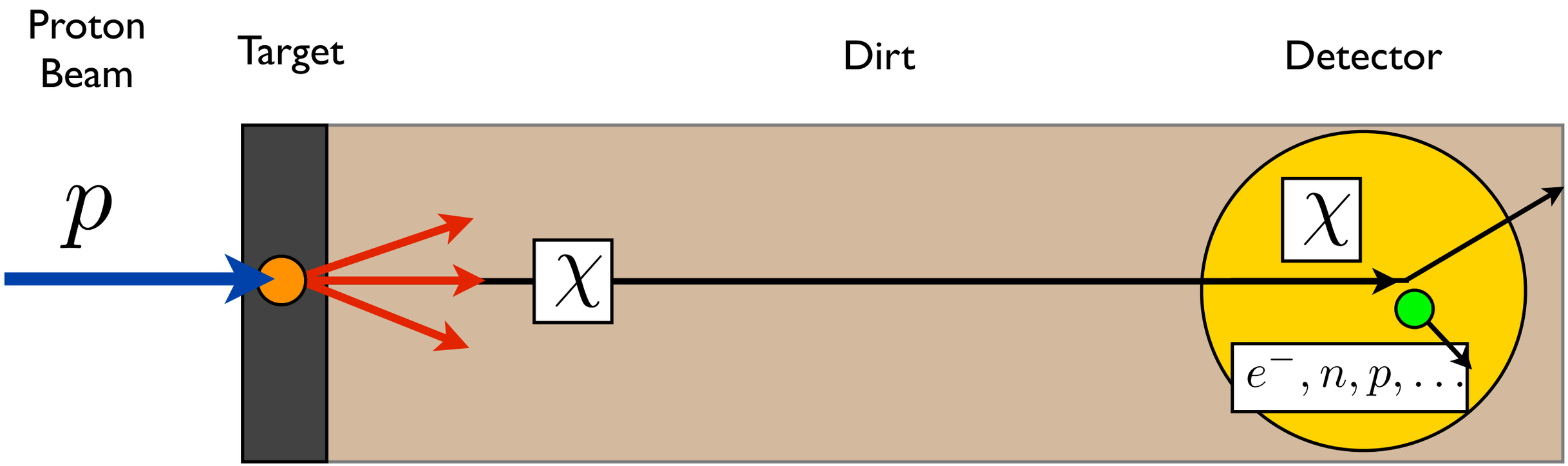
- Enormous progress over past 2 decades
- Probe DM masses above ~ GeV

Direct Detection



- Nuclear recoil too weak - $v_{\rm DM} \sim 10^{-3}$
- Can we find a relativistic source of Dark Matter?

Relativistic Dark Matter Beam!



[BB, Pospelov Ritz, '09]

- Superior sensitivity for many models with light DM + light mediator
- Can be done with neutrino experiments (e.g. MiniBooNE, MINOS, NOvA, MicroBooNE, T2K, LBNE, ...)
- Provides a strong motivation for intense proton sources (e.g. FNAL)
- Can be done with electron beams (see next talk by P. Schuster)

[Izaguirre, Krnjaic, Schuster, Toro, '13&'14]

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? Why not!

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!

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

Dark sector may be complicated - multi-component, several mass scales

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

Light Dark Matter and Light Mediators

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

(Assumes DM annihilates via Standard Model interactions)

New forces ⇒

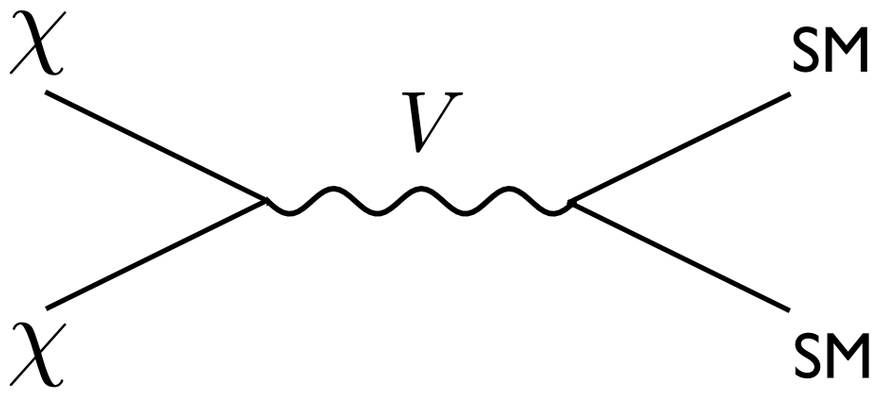
Viable light thermal relic dark matter!

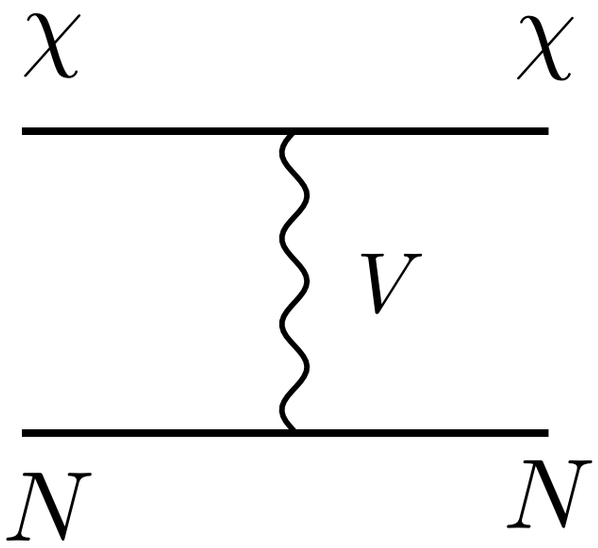
[Boehm, Fayet '03]

Efficient annihilation of symmetric DM component in Asymmetric DM

Force carriers may serve dual purpose:

1. Open new annihilation channels
2. Mediate interactions with the SM





Probing Light Dark Matter and Light Mediators

- CMB [Padmanabhan, Finkbeiner]
- BBN [Serpico,Raffelt], [Pospelov,Pradler],
- Supernova, stellar cooling [Dreiner, Fortin, Hanhart, Ubaldi]
- DM self-interactions [Tulin, Yu, Zurek]
- X-, Gamma-rays [Essig, Kuflik, McDermott, Volansky, Zurek]
- Monojet searches $pp \to \chi\bar{\chi} + j$
- Rare meson decays, e.g. $K^+ \to \pi^+ + \text{inv}$ [E949 '07] , $J/\psi \to \text{inv}$ [BES-II '07]
- Precision QED, (e.g. anomalous magnetic moments) [Fayet, Pospelov]
- B-factories, monophoton search [Izaguirre et al., Essig et al.]
- Direct Detection (via electron scattering) [Essig, Mardon, Volansky]

1. Vector portal DM ("dark force")

[Holdom]
[Pospelov, Ritz, Voloshin],
[Hooper, Zurek]
[Arkani-Hamed, Finkbeiner, Slatyer, Weiner]
...

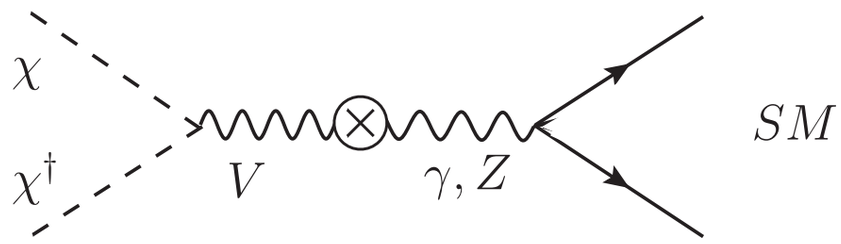
$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(V_{\mu\nu})^2 + + \frac{1}{2} m_V^2 (V_\mu)^2 - \frac{\kappa}{2} V_{\mu\nu} F^{\mu\nu} + \dots$$

$$D_\mu = \partial_\mu - i g_D V_\mu$$

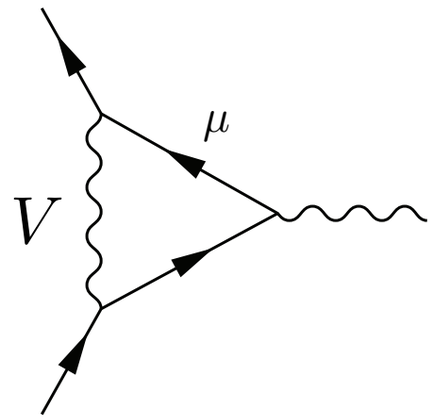
(see talk by D. Morrissey)

- Dark photon mediates interaction between DM and SM
- 4 new parameters: $m_\chi, m_V, \kappa, \alpha'$ $\quad (V = A',\ \kappa = \epsilon,\ \alpha' = \alpha_D)$
- Scalar DM annihilation is p-wave, CMB ok

[deNiverville, Pospelov, Ritz]



- Dark photon can address g-2 anomaly [Fayet, Pospelov]



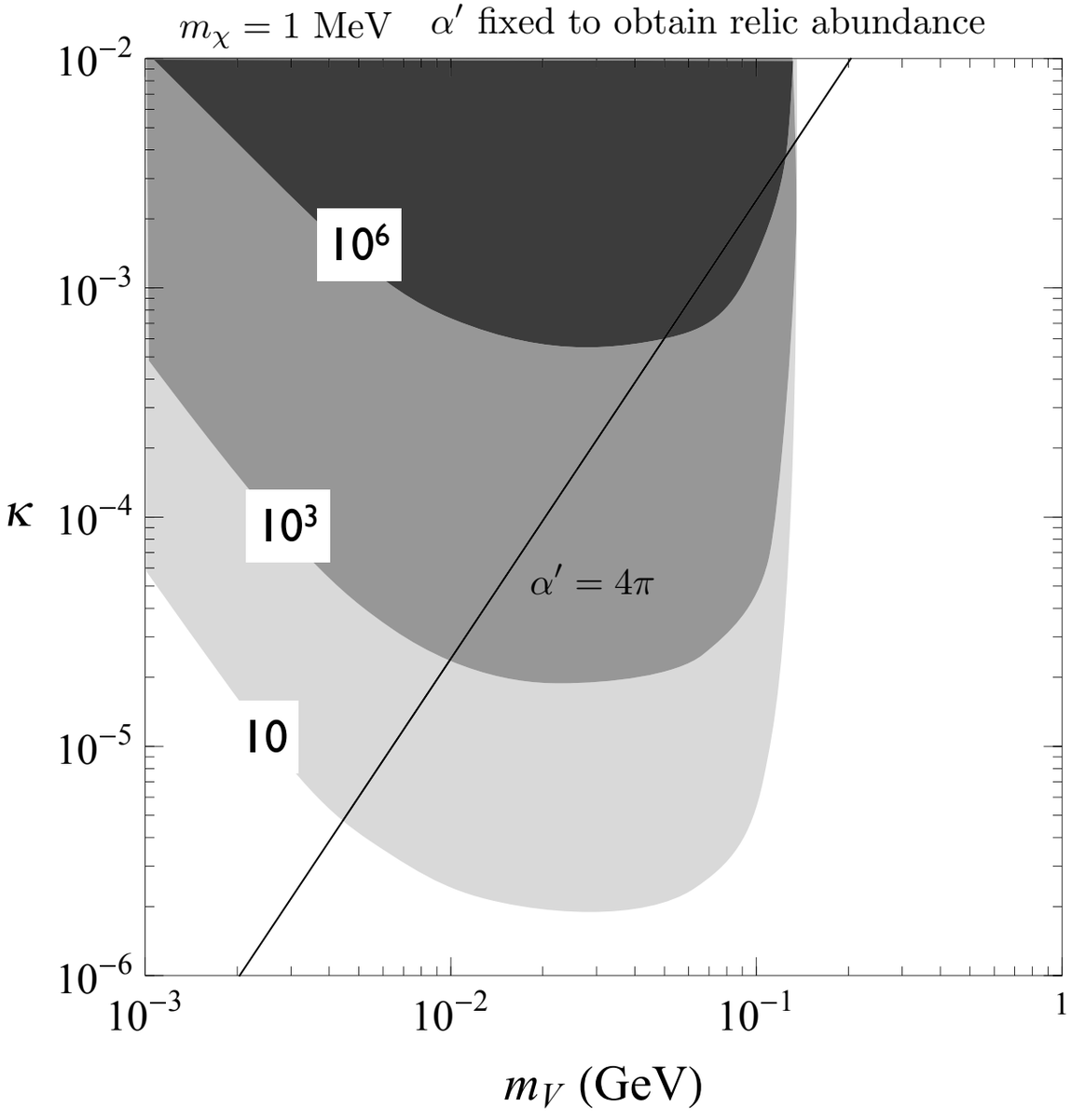
LSND

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

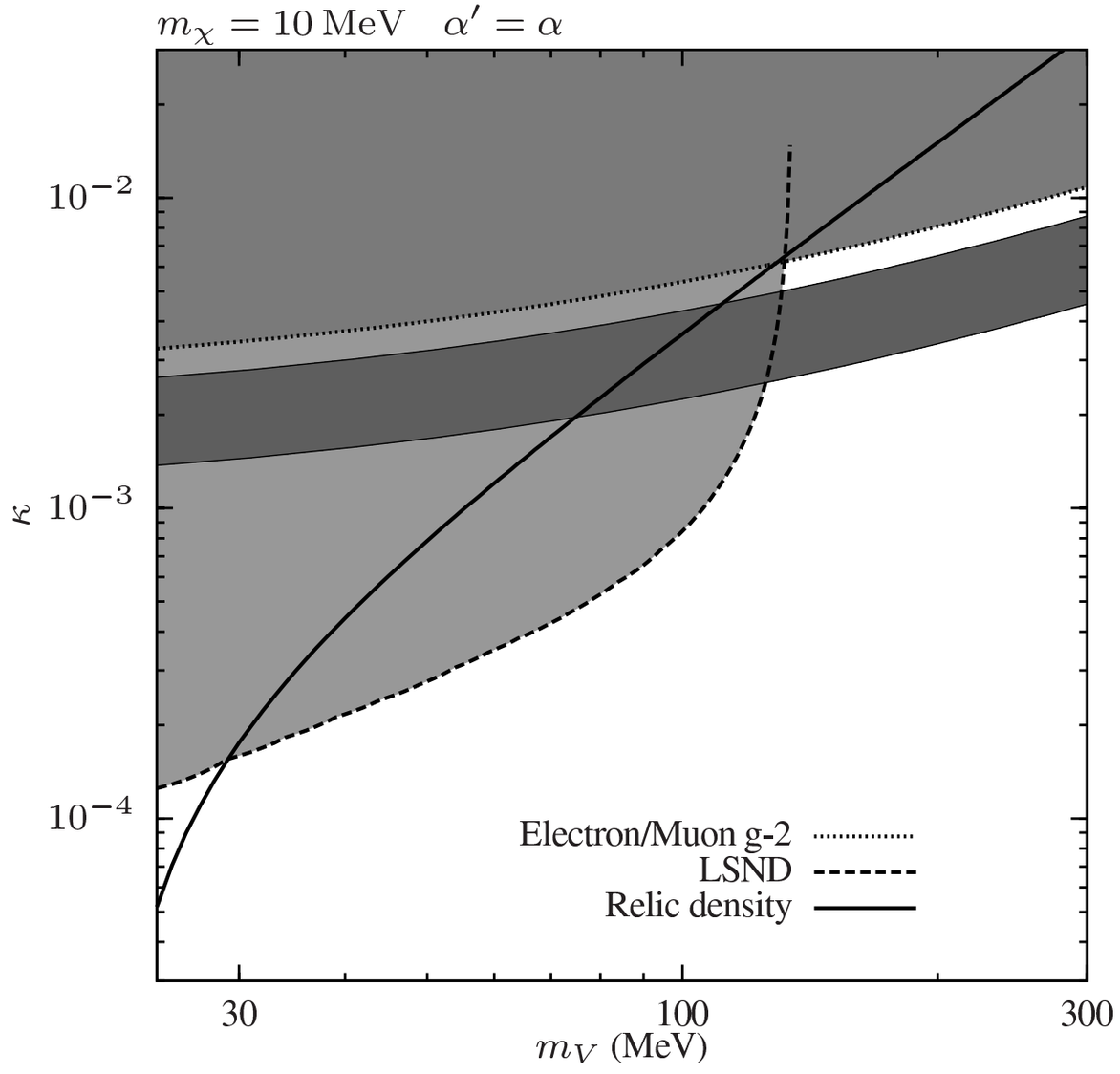
Sensitivity to $\chi e \to \chi e$

[Auerbach et al. (LSND Collaboration), '01]

- 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]



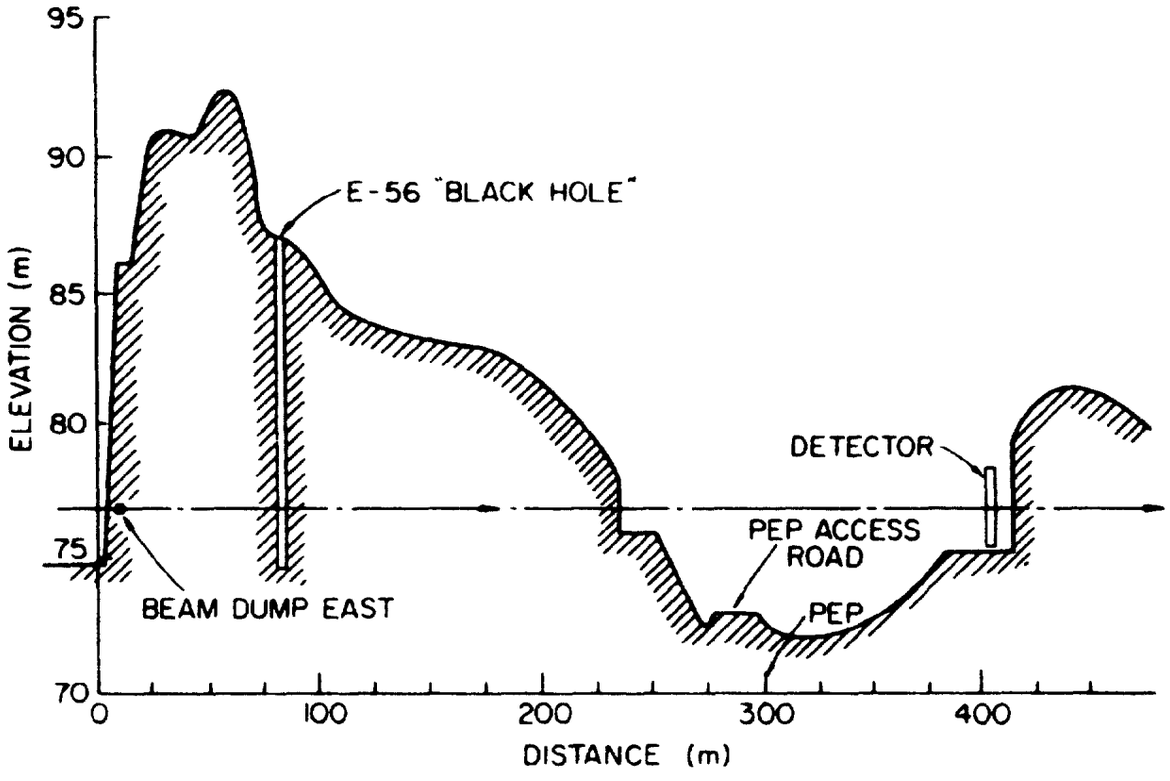
[deNiverville, Pospelov, Ritz '11]

New limits from SLAC E137

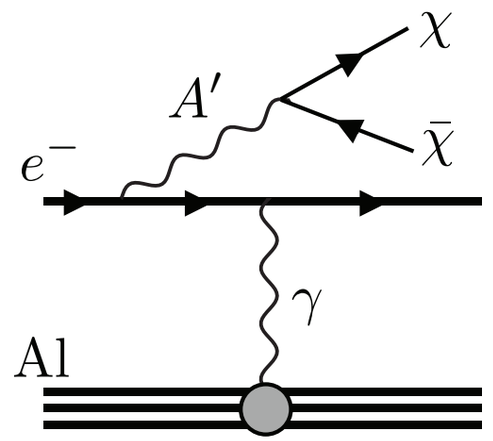
[BB, Essig, Surujon '14]

[Bjorken et al., (E137 Collaboration) '88]

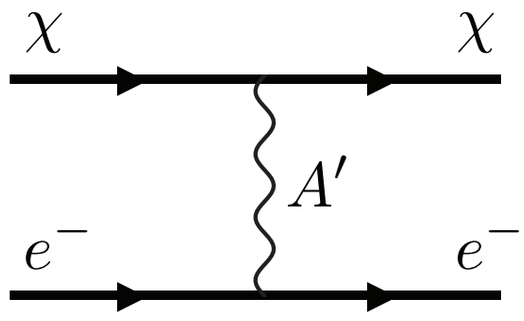
- 20 GeV electron beam; 30 C dumped;
- Aluminum target
- Shower calorimeter detector, 400m from dump



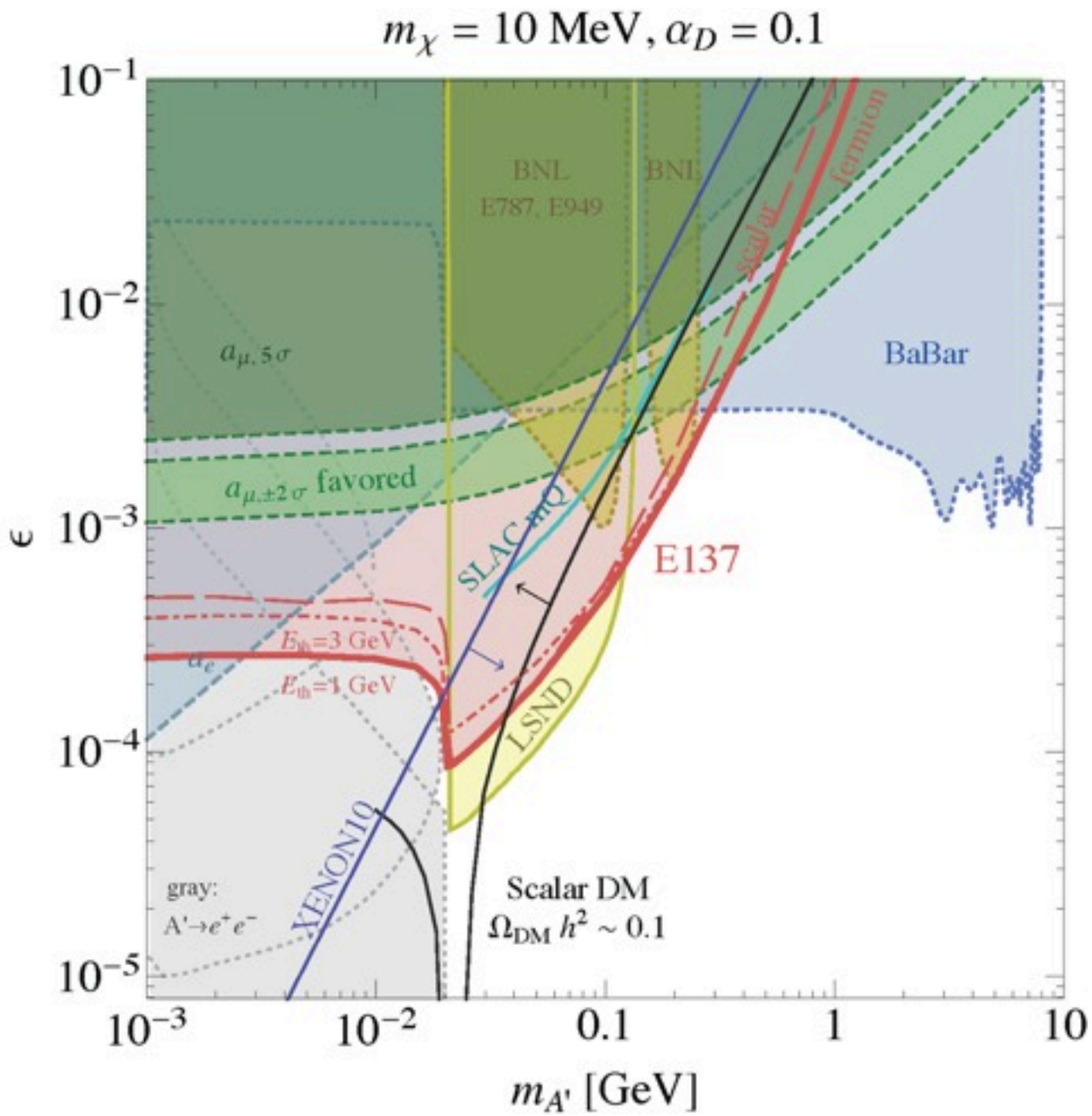
Production

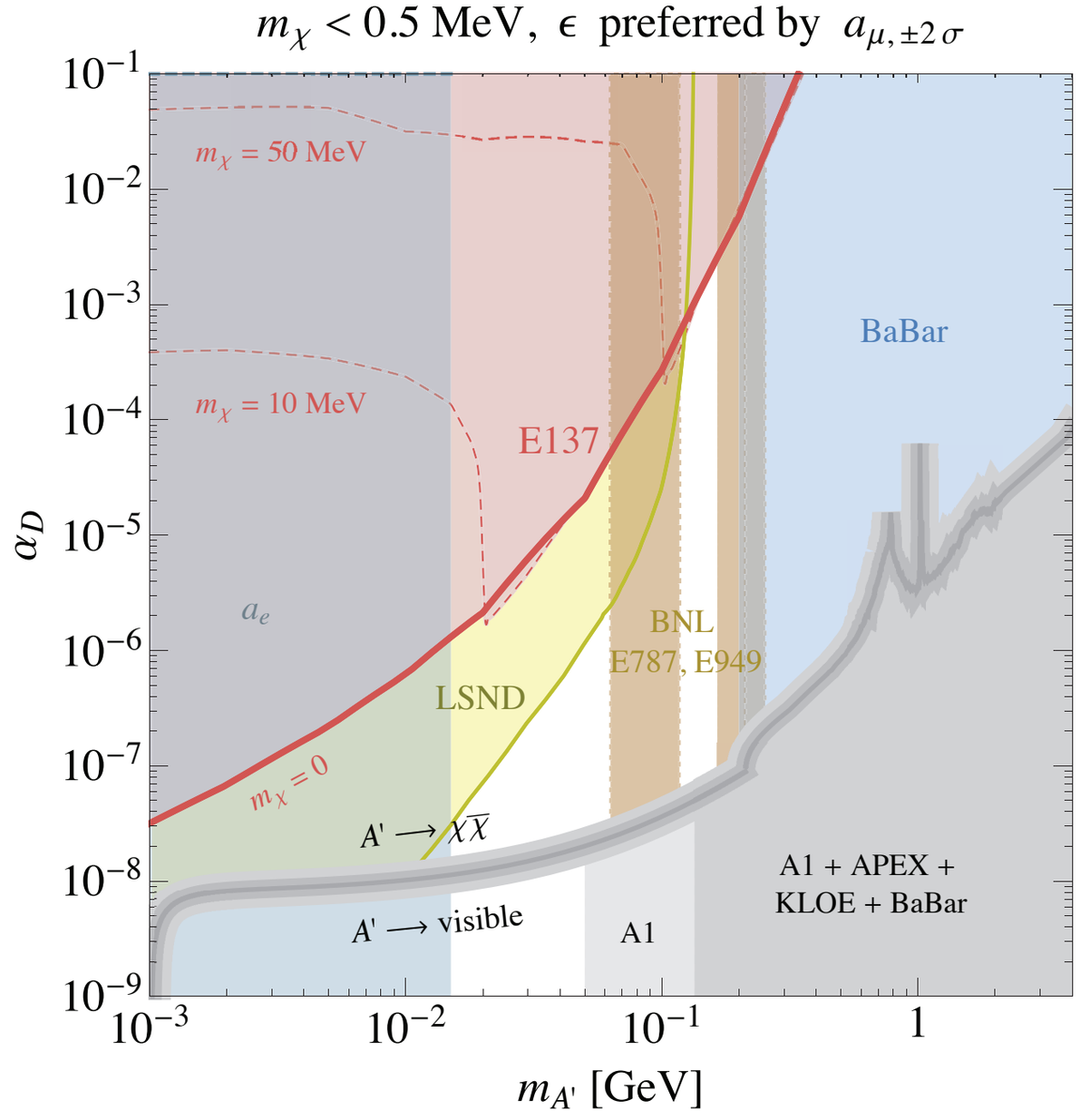


Scattering



Current constraints on vector portal DM





[BB, Essig, Surujon '14]

2. Leptophobic DM

[BB, deNiverville, McKeen, Pospelov, Ritz '14]

- Dark matter couples dominantly to quarks

- Focus on model based on local $U(1)_B$ baryon number symmetry

$$\mathcal{L} = i\bar{\chi}\gamma^\mu D_\mu \chi - m_\chi \bar{\chi}\chi - \frac{1}{4}(V_B^{\mu\nu})^2 + \frac{1}{2}m_V^2 (V_B^\mu)^2 + \frac{g_B}{3} V_B^\mu \sum_i \bar{q}_i \gamma_\mu q_i + \dots$$

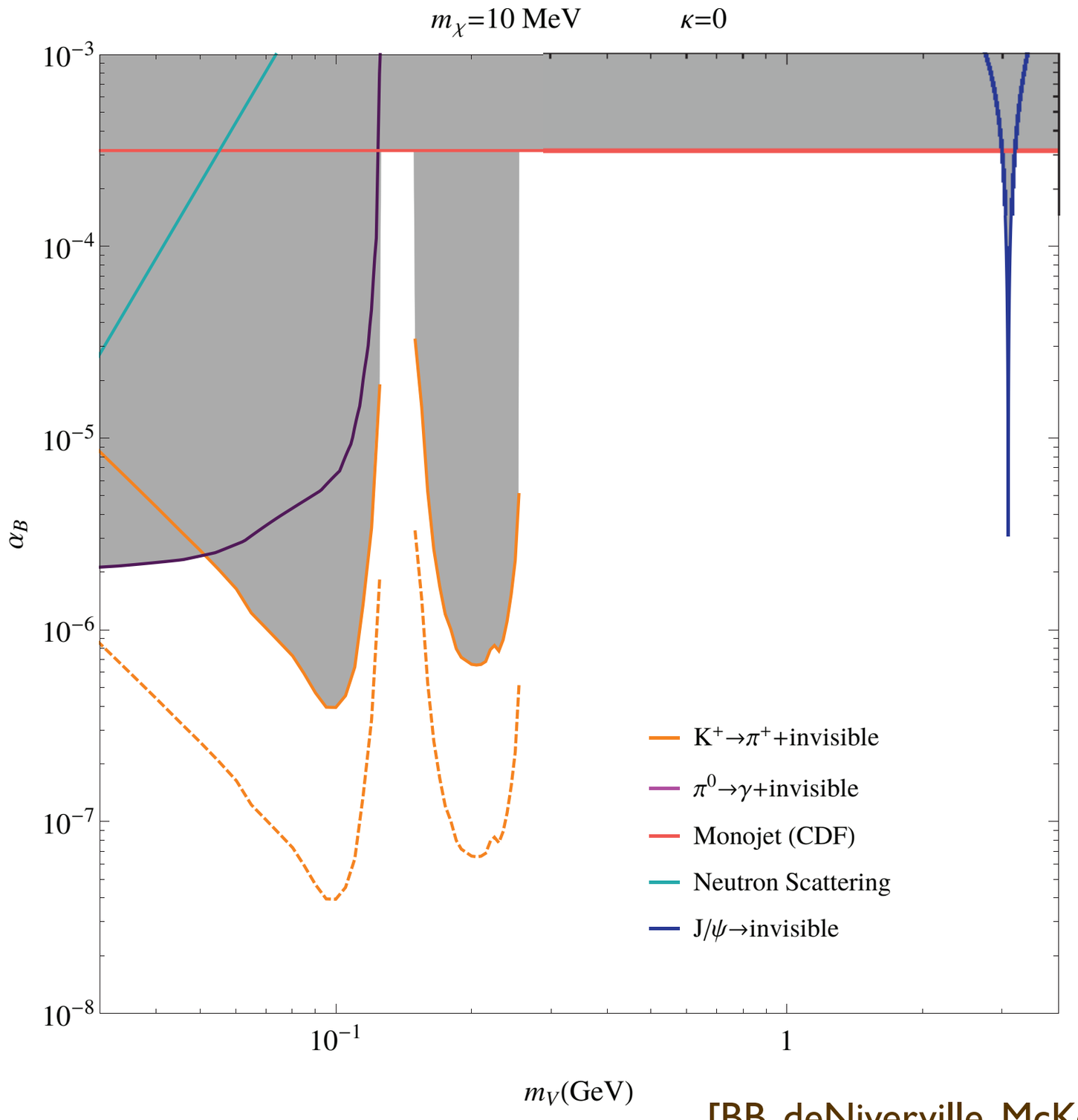
$$D^\mu = \partial^\mu - i g_B q_B V_B^\mu$$

- 4 new parameters: $m_\chi, m_V, \alpha_B, q_B$

- $U(1)_B$ is "safe" - preserves approximate symmetries of SM (CP, P, flavor)

- Gauge anomalies can be cancelled by new states at the weak scale

Current constraints on leptophobic DM



[BB, deNiverville, McKeen, Pospelov, Ritz '14]

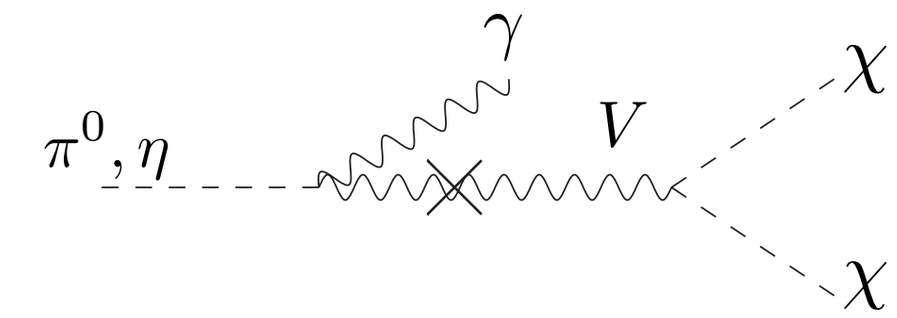
MiniBooNE dedicated beam dump run

[Dharmapalan et al. ,(MiniBooNE Collaboration), arXiv:1211.2258]

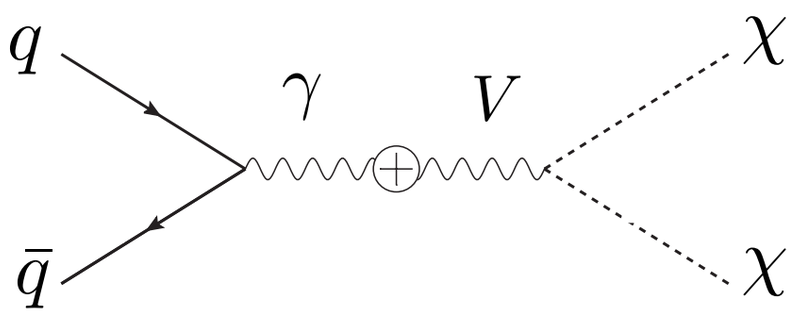
- Basic idea: direct protons onto beam dump to reduce neutrino flux
- 2 proposals to the FNAL PAC
- Test run approved fall 2013
- Been running in beam-dump mode since November 2013
- We've collected ~ 1.5 E 20 POT to date
- Plan to run until ~ September & collect ~ 2 E 20 POT

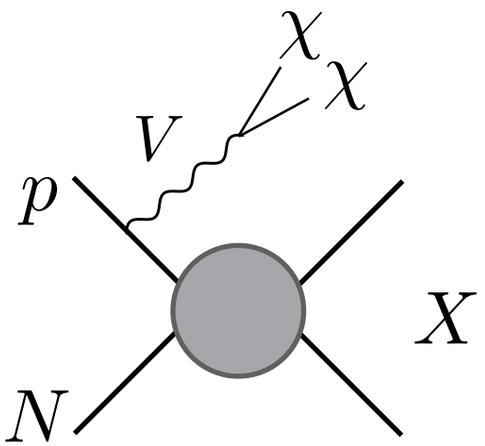
Production of the Dark Matter beam

Meson decays, mixing

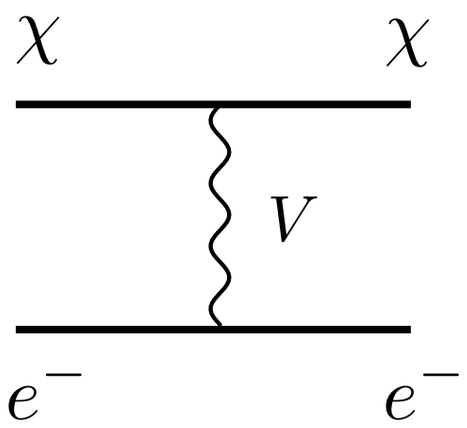


Direct production

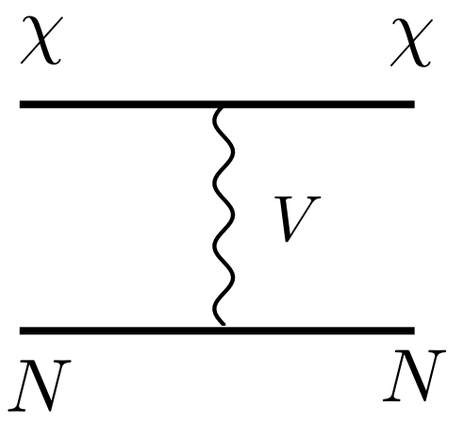




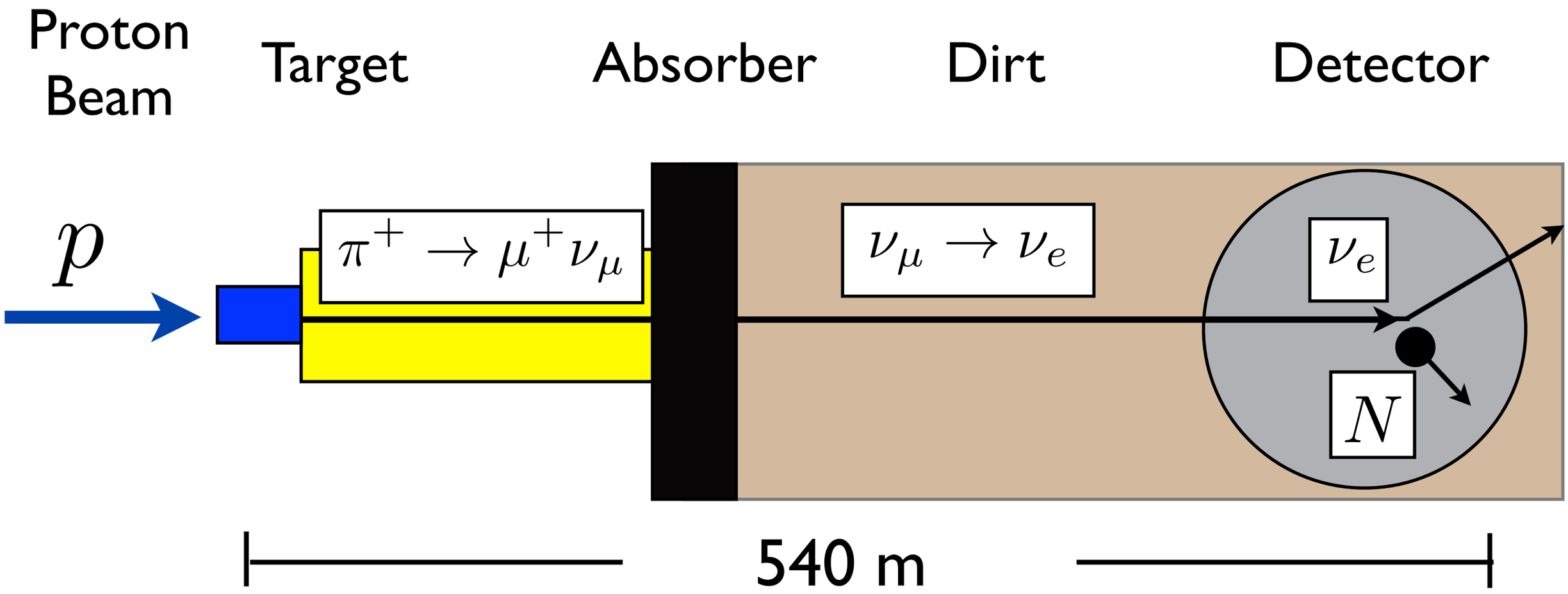
Detection via scattering



$\chi - e^-$ elastic



$\chi -$ nucleon elastic

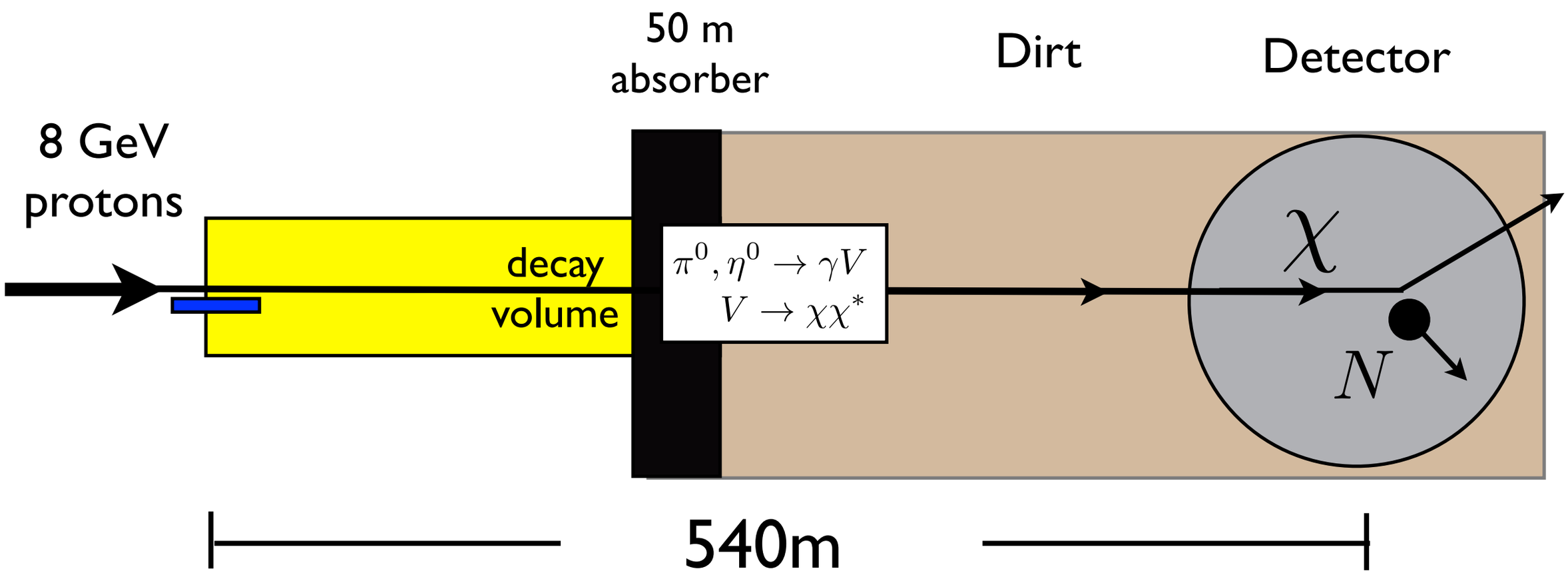

Proton Beam
Target
Absorber
Dirt
Detector
p
$\pi^+ \to \mu^+ \nu_\mu$
$\nu_\mu \to \nu_e$
ν_e
N
540 m

Beating down the neutrino background

The signature of dark matter is a neutral current scattering event

Very similar to neutrino induced neutral current event!

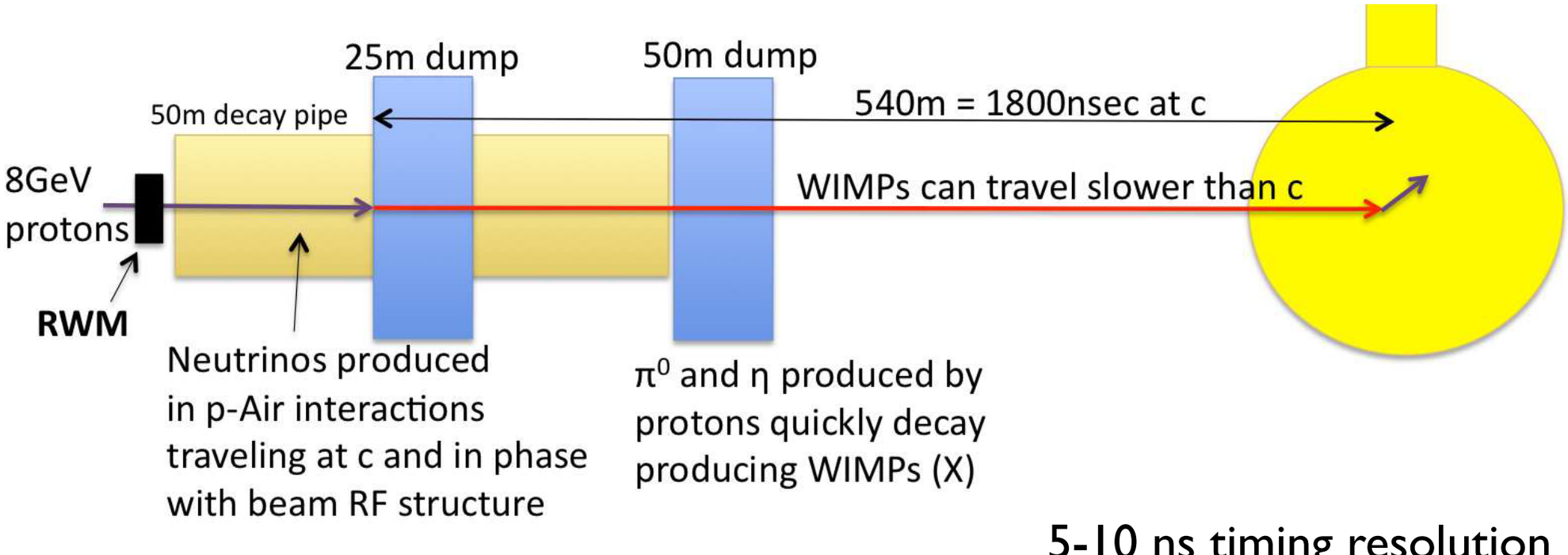
Focus protons onto the beam dump - charged pions absorbed or stopped!

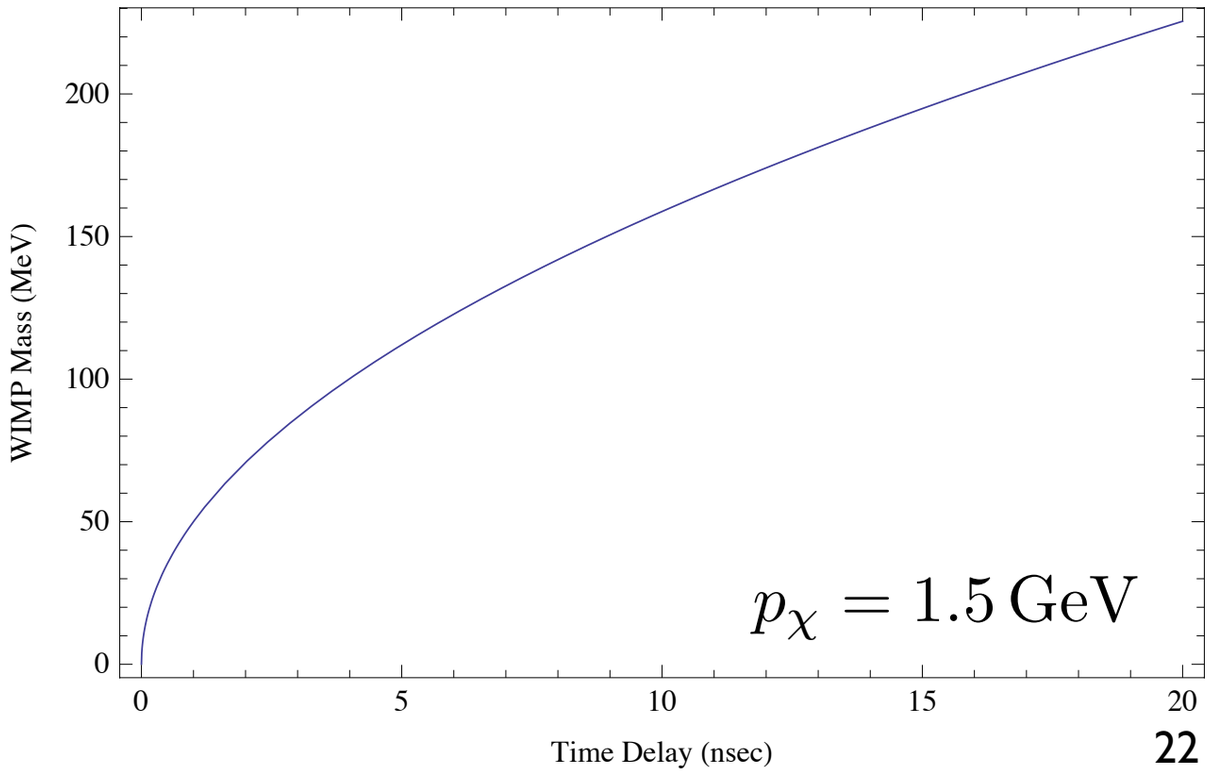


Neutrino background reduced by factor of ~ 50!

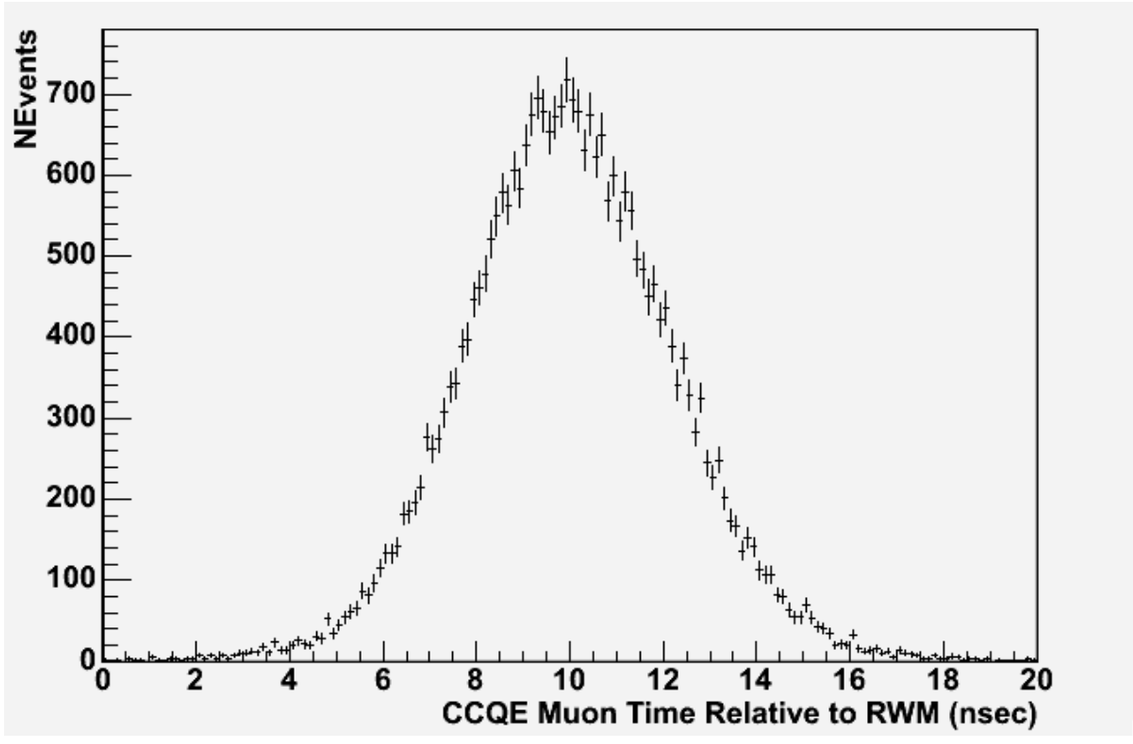
Timing

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

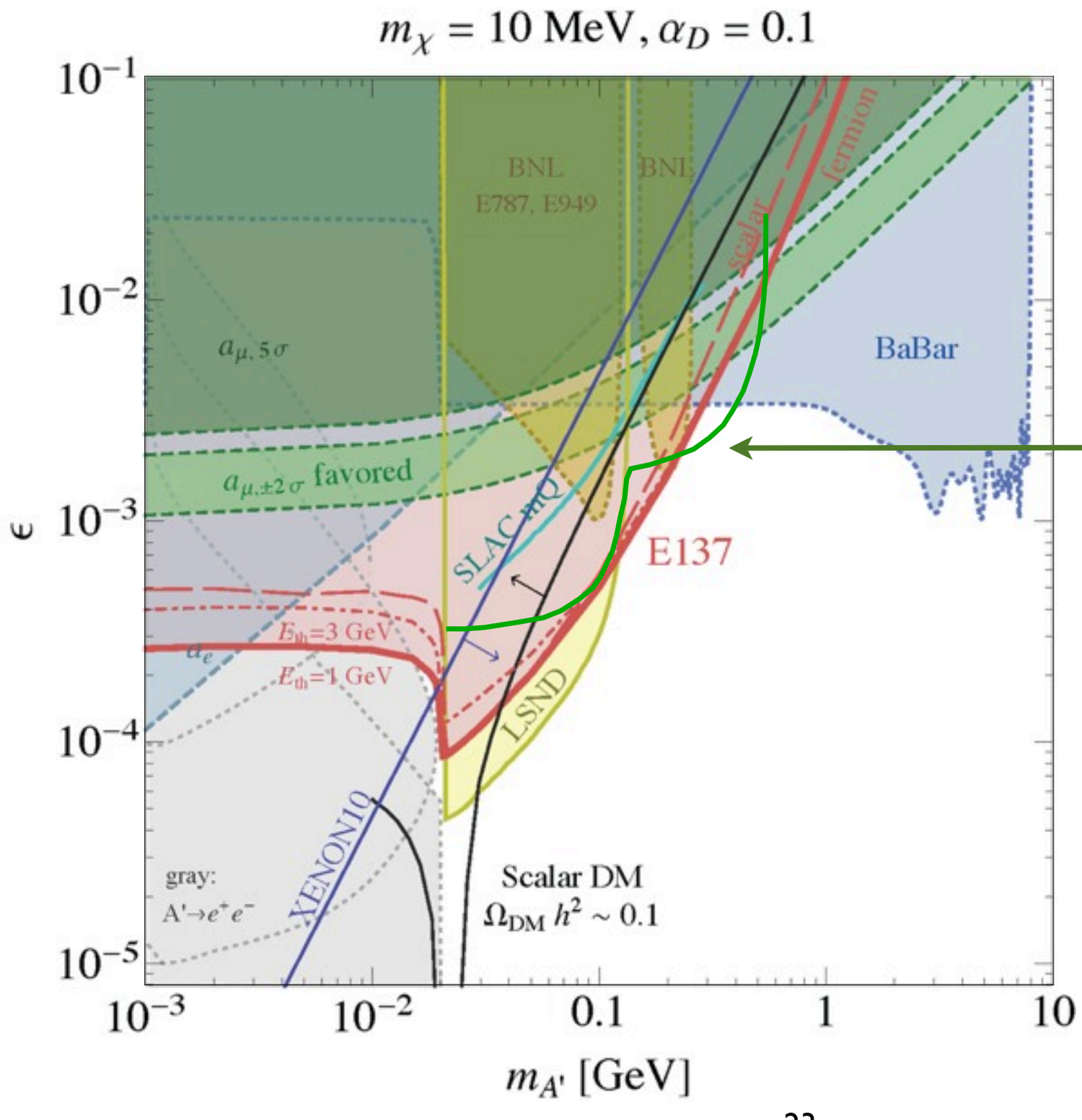




5-10 ns timing resolution

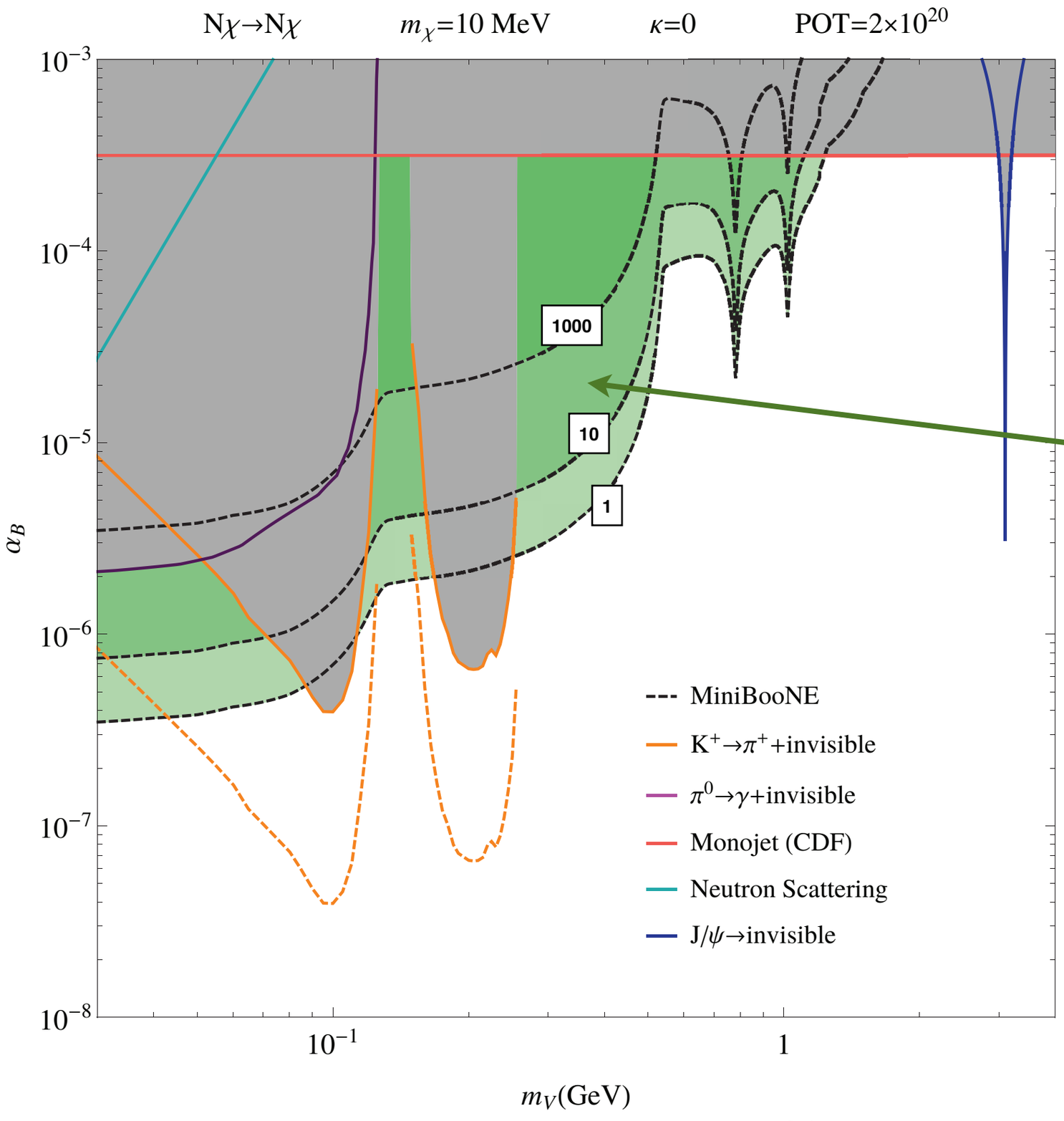


MiniBooNE sensitivity to vector portal DM



MiniBooNE
90% C.L.
[arXiv:1211.2258]

MiniBooNE sensitivity to leptophobic DM



MiniBooNE signal

Unique sensitivity over much of the parameter space!

Outlook

- 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 dedicate run is underway at MiniBooNE ... results soon!
- Main obstacle for proton beams is neutrino neutral current background
  - Dump, Timing, Defocusing... new ideas needed!
- Efforts are underway to study the potential of other experiments!
- Provides a strong motivation for intense proton beam facillities