TRIUMF - November 2012

Light dark matter and neutrino beams

Adam Ritz

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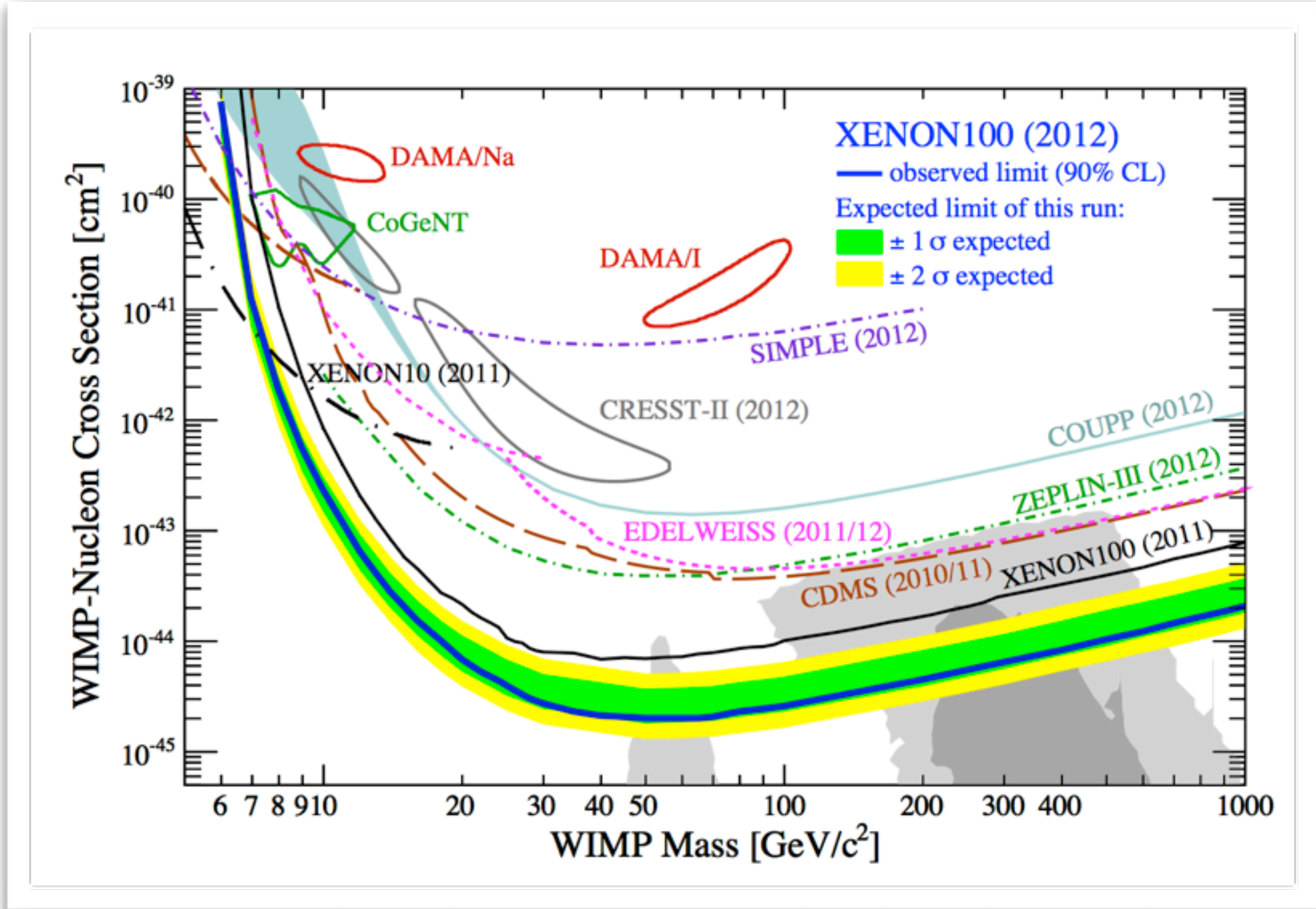
MiniBooNE + B. Batell, P. deNiverville, D. McKeen,

M. Pospelov & AR - 1211.2258

P. deNiverville, D. McKeen & AR - 1205.349

P. deNiverville, M. Pospelov & AR - 1107.4580

Overview - Direct probes of light dark matter?



[XENON100 ’12]

Impressive direct detection sensitivity to thermal relic (WIMP) dark matter in the halo with O(GeV - TeV) mass.

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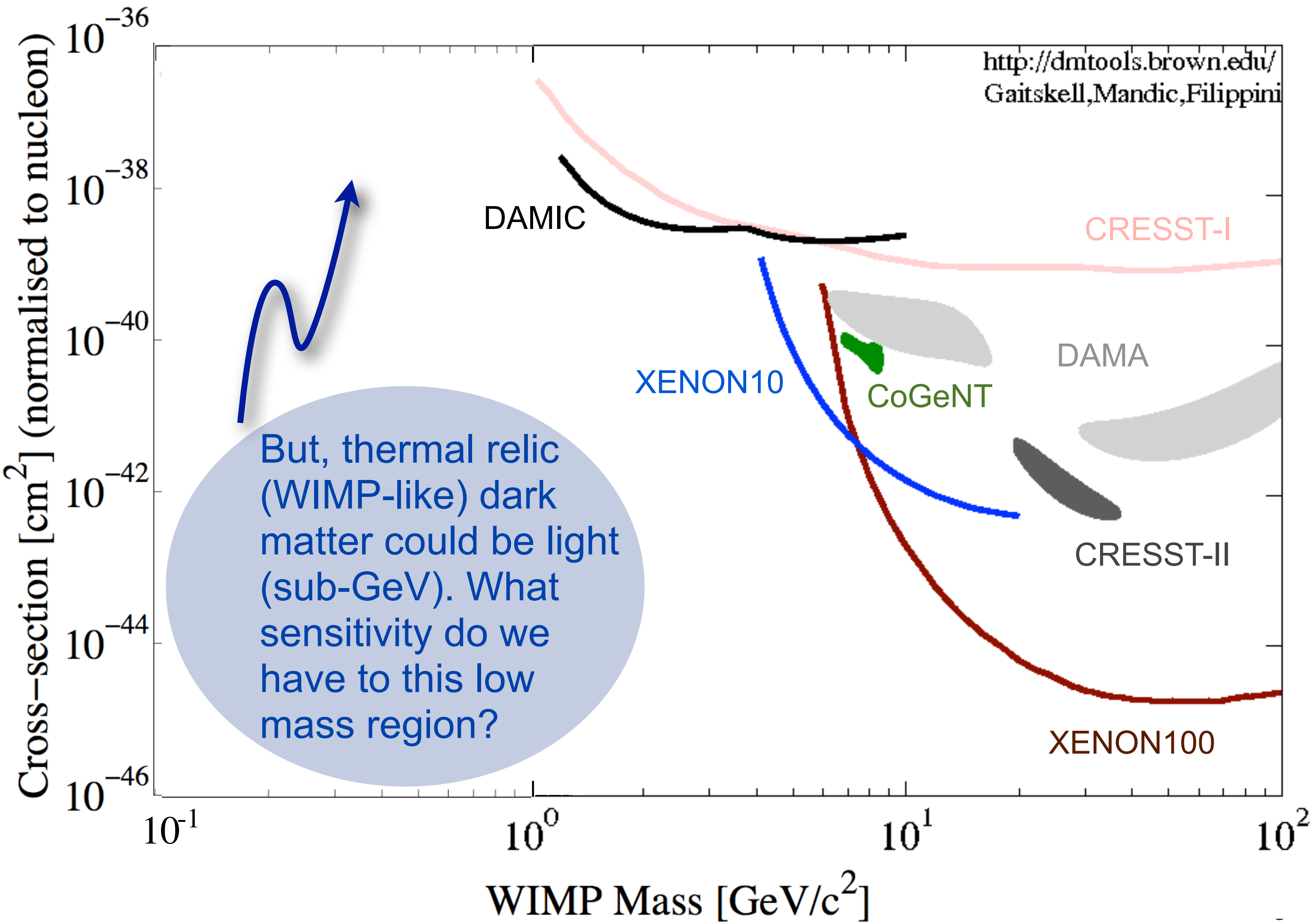

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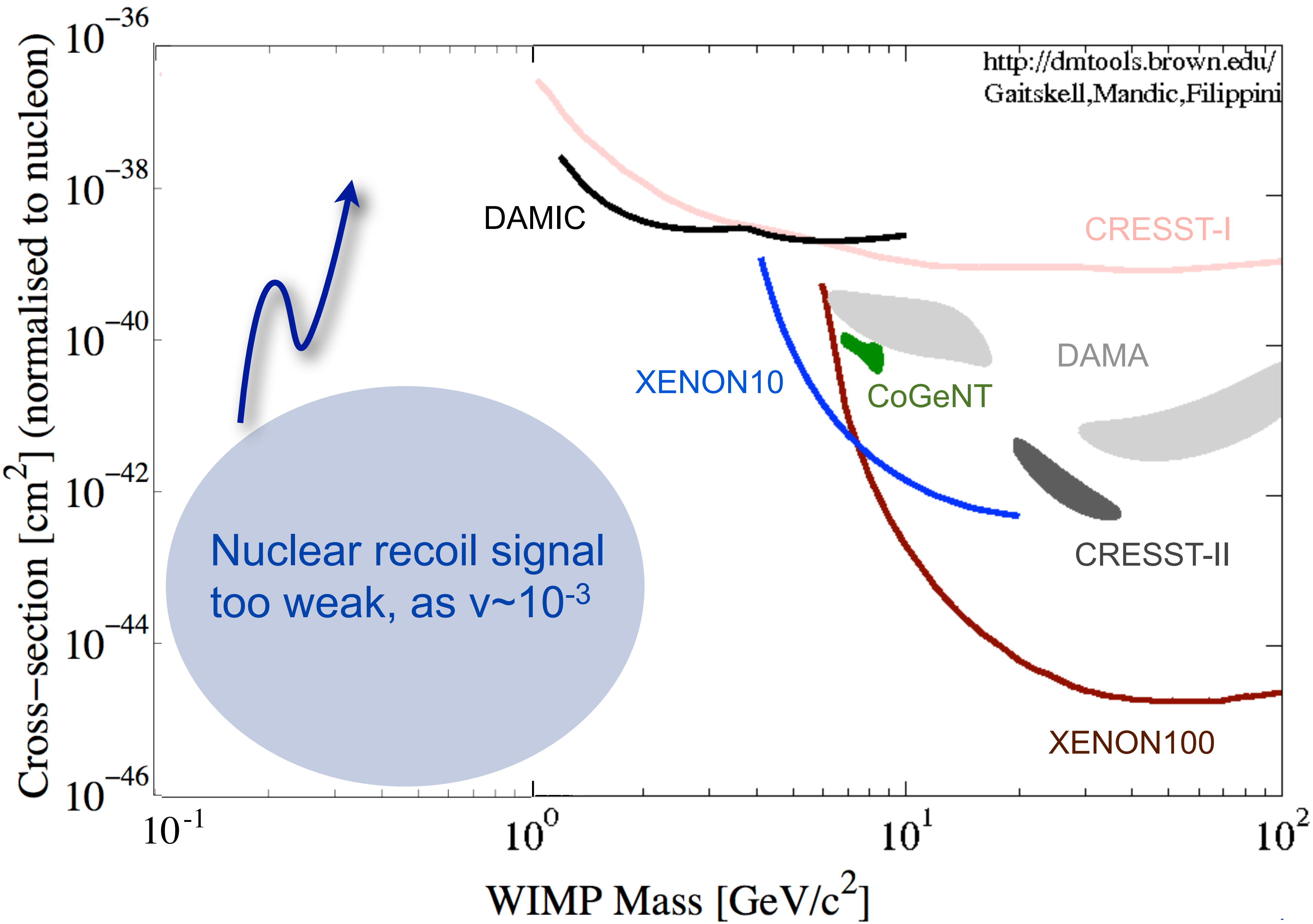

Neutrinos and Dark Matter

➠ 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

➠ BUT muon neutrinos were discovered by producing them in meson decays (large rate!), and observing the (weak) scattering of the relativistic 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)

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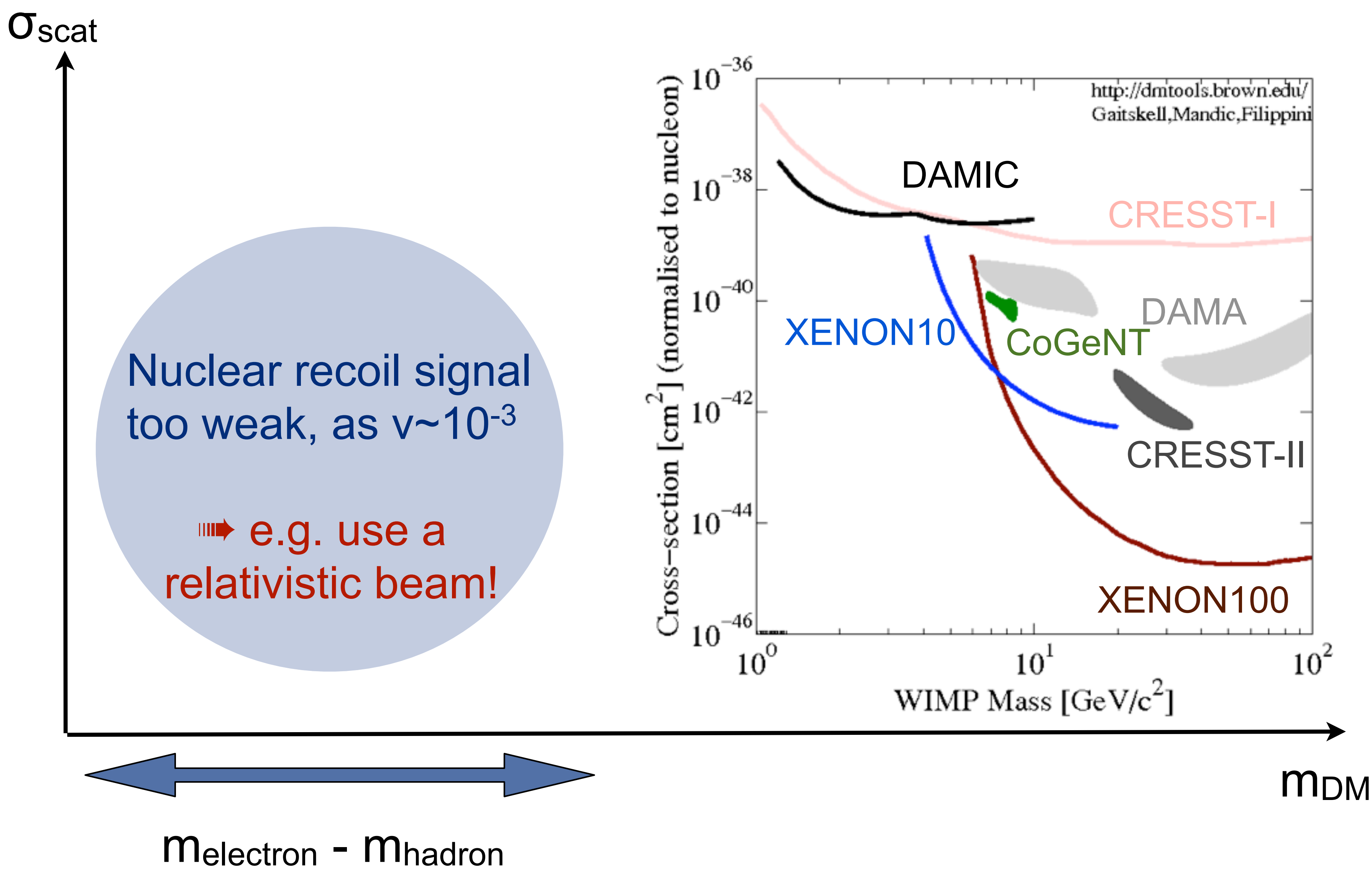
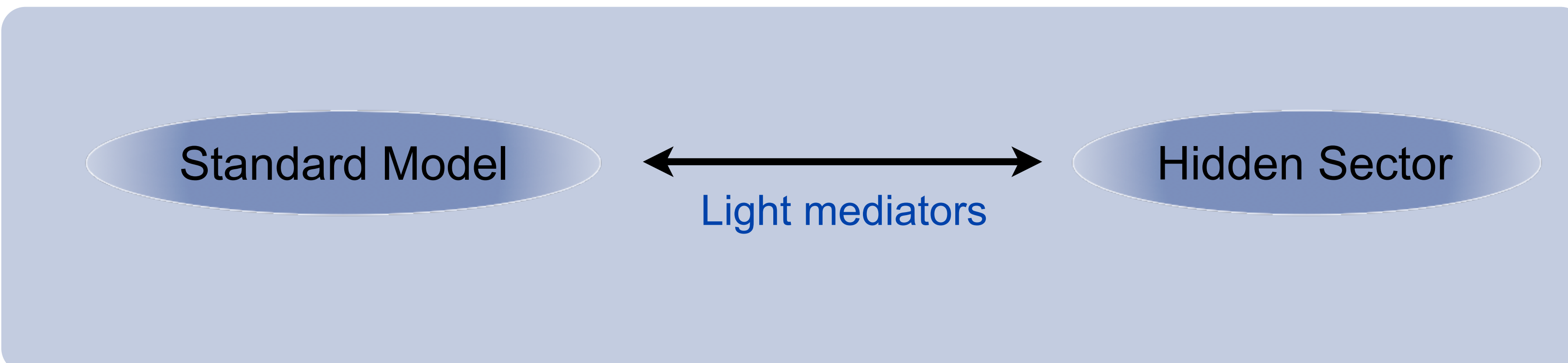


Light (thermal relic) DM

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

⇒ 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 & Fayet '03]



Also motivated by anomalies of course - e.g. MeV-scale models motivated by an (earlier!) ϒ-ray line anomaly (at 511keV) [Boehm, Fayet, Hooper, Silk, ...]

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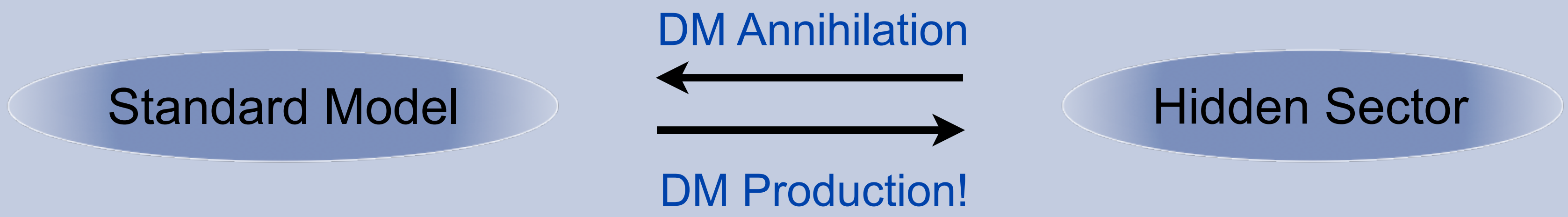


➪ by inversion, light mediators allow direct production of DM at ***low energy!***

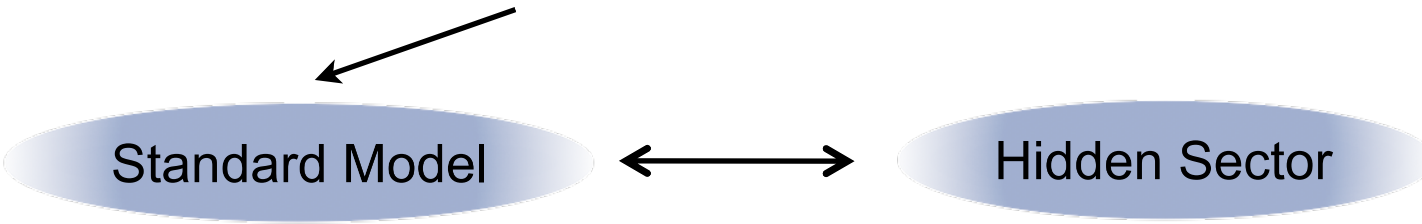
(particularly if $m_{mediator} > 2\ m_{DM}$)

$Br(med \to DM) \sim 1$

New forces - Portals

- Parametrize the interactions of a *neutral* hidden sector via the EFT expansion

$$\mathcal{L} = \Lambda^4 \mathcal{O}_0 + \mu^2 \mathcal{O}_2 + c\mathcal{O}_4 + \frac{1}{\Lambda_5}\mathcal{O}_5 + \frac{1}{\Lambda_6^2}\mathcal{O}_6 + \cdots$$



- To form low dimension (marginal or relevant) operators, only a limited new (light) dofs are allowed
  1. a new U(1) vector (V) kinetically mixed with hypercharge
  2. a scalar sector (e.g. singlet S) coupled to the Higgs
  3. a set of RH neutrino-like Majorana fermions (N)

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- Vector portal (V): $\mathcal{O}_4 = -\frac{\kappa}{2} V^{\mu\nu} B_{\mu\nu}$ [Okun ’82, Holdom ’86]
- Higgs portal (S): $\mathcal{O}_3 = ASH^\dagger H \quad \mathcal{O}_4 = \lambda_S S^2 H^\dagger H$
- Neutrino portal (N): $\mathcal{O}_4 = Y_N^{ij} \bar{L}_L^i H N^j$
- Axion portal (a): $\mathcal{O}_5 = \frac{a}{8\pi f_a}(\alpha_3 G\tilde{G} + C_\gamma \alpha F\tilde{F})$
- (many more at dim ≥ 5)

relevant or marginal (the first three portals)

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- Vector portal: ➠ V = superWIMP DM $\mathcal{O}_4 = -\frac{\kappa}{2} V^{\mu\nu} B_{\mu\nu}$
- Higgs portal: ➠ S = singlet scalar DM $\mathcal{O}_4 = \lambda_S S^2 H^\dagger H$
- Neutrino portal: ➠ N = sterile neutrino DM $\mathcal{O}_4 = Y_N^{ij} \bar{L}_L^i H N^j$
- Axion portal: ➠ a = axion DM $\mathcal{O}_5 = \frac{a}{8\pi f_a}(\alpha_3 G\tilde{G} + C_\gamma \alpha F\tilde{F})$
- (many more at dim ≥ 5)

These interactions automatically lead to a number of light DM candidates...

New forces - Portals

- Parametrize the interactions of a neutral hidden sector via the EFT expansion

$$\mathcal{L} = \Lambda^4 \mathcal{O}_0 + \mu^2 \mathcal{O}_2 + c\mathcal{O}_4 + \frac{1}{\Lambda_5}\mathcal{O}_5 + \frac{1}{\Lambda_6^2}\mathcal{O}_6 + \cdots$$

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- (many more at dim ≥ 5)

More generally, these "bilinear" portals mediate interactions with new (and simple) light dark matter scenarios

Constraints on sub-GeV thermal relic DM

Classes of sub-GeV (thermal relic) DM models

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm m}} \sim \frac{1 \text{ pb}}{\langle \sigma v \rangle_{\rm fo}}$$

[Boehm et al ’03; Fayet ‘04,’06; Pospelov, AR, Voloshin ’07;...]

- U(1) mediator

  - fermionic DM: s-wave annihilation, so is constrained by CMB distortion to be a subdominant component of DM.
  [Padmanabhan & Finkbeiner et al ’05; Slatyer et al ’08]

  - scalar DM: p-wave annihilation, and is viable for sufficiently small mixing κ.

- Scalar mediator

  - fermionic DM: p-wave annihilation, so can be viable with large mixing, but this leads to tension with limits from B → K + $E_{\rm miss}$.
  [Bird, Kowalewski & Pospelov ’06]

  - scalar DM: s-wave annihilation, and also needs large mixing, so constrained by CMB limits and rare B-decays.

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  - scalar DM: s-wave annihilation, and also needs large mixing, so constrained by CMB limits and rare B-decays.

Vector portal model

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

$\Downarrow$

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

V - production through mixing with EM current: O(κ^2)

$\Downarrow$

DM candidate, coupled through U(1)'

- Allows viable sub-GeV thermal relic DM candidates [Boehm et al '03, Fayet '04,'06; Pospelov, AR, Voloshin '07; Hooper & Zurek '08]. [NB: Weak-scale candidates of interest due to enhanced low-v annihilation [Finkbeiner & Weiner, '07; Pospelov, AR, Voloshin '07; Arkani-Hamed et al '08; Pospelov, AR '08].]
- For $m_{DM} < m_V$, the correct relic density fixes a specific relation between $\{\alpha', m_V, m_{DM}, \kappa\}$ [Pospelov, AR & Voloshin '07] and we also require perturbativity of the U(1) coupling α' (e.g. $\alpha' \sim \alpha$).

(Some) Experimental Sensitivity

Astrophysics/Cosmology

- BBN - minimal for m > 1-2 MeV

  [Serpico & Raffelt '04, Jedamzik & Pospelov '09]

- SN - minimal even for MeV mass, due to thermalization in the core
- CMB (and galaxy) - minimal, as annihilation is p-wave [Padmanabhan & Finkbeiner et al '05; Slatyer et al '08]

Particle Physics Sensitivity [when $m_V > 2m_\chi$]

[several pioneering early studies by Fayet: 1980-90]

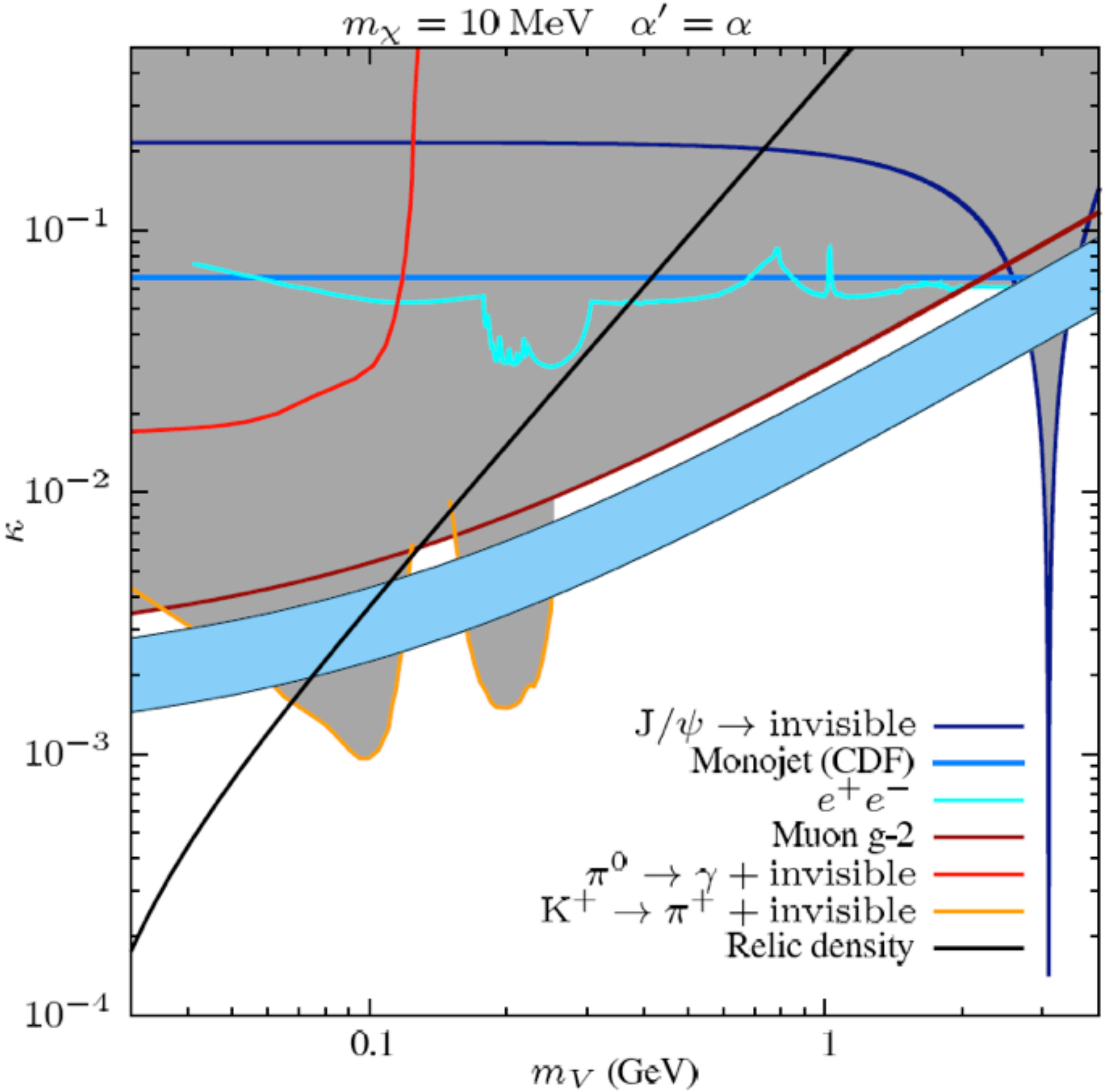
- Correction to g-2 - limited for higher mass [Fayet; Pospelov '08]
- Dark Force Searches, $V \rightarrow l^+l^-$ - limited as Br($V \rightarrow$DM)~1

  [Bjorken et al. '09; Batell et al '09; Reece & Wang '09; MAMI '11, APEX '11, BaBar'12, ...]

$$\Rightarrow \left(\frac{\alpha}{\alpha'}\right)\kappa^4 < 10^{-6}$$

- E_{miss} in rare decays
  - low mass (e.g. π, K) [E949,...]
  - higher mass (e.g. J/ψ, ϒ(1S)) [BESII'08, BaBar'09, Fayet'09]

Parameter space



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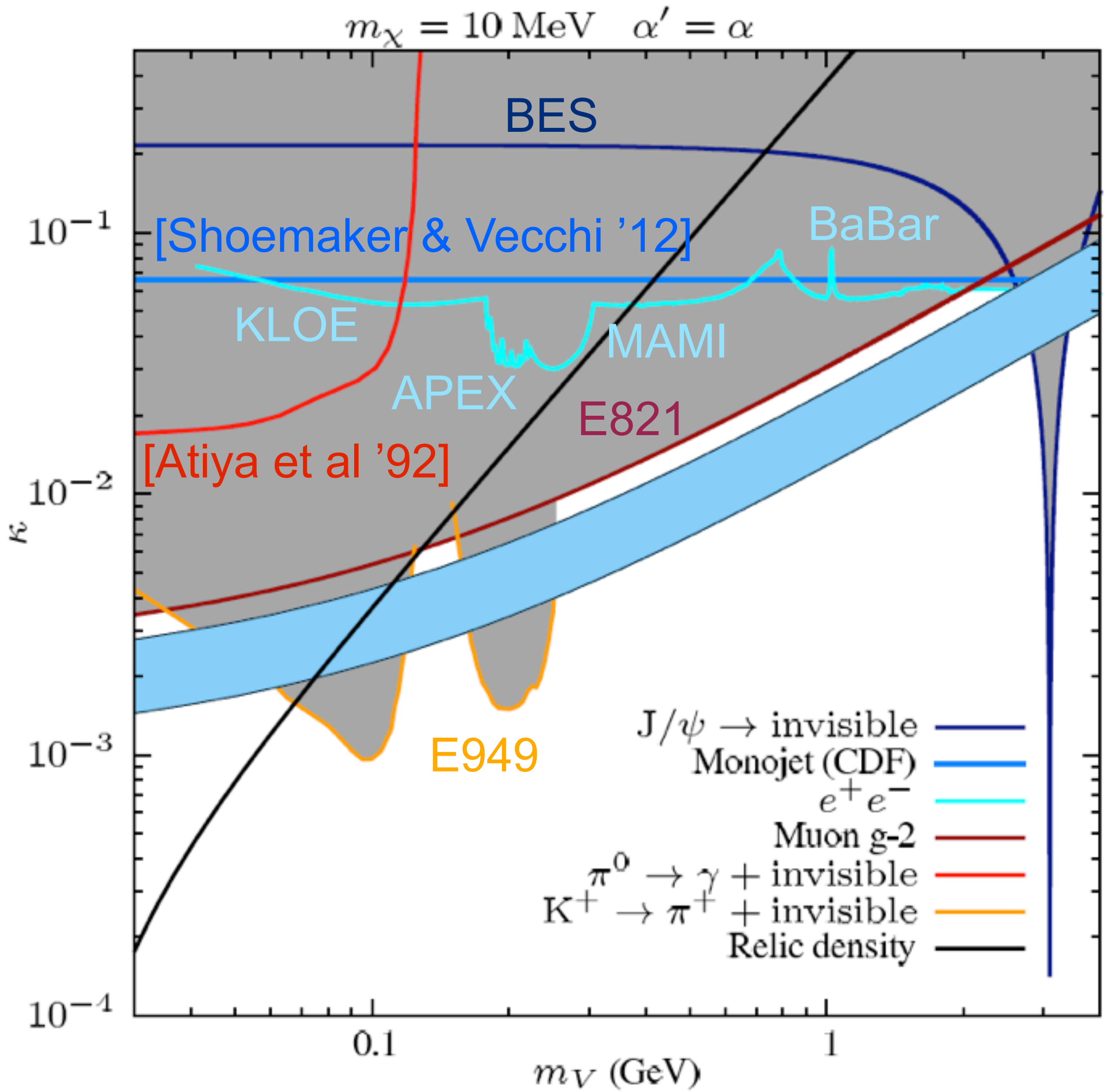
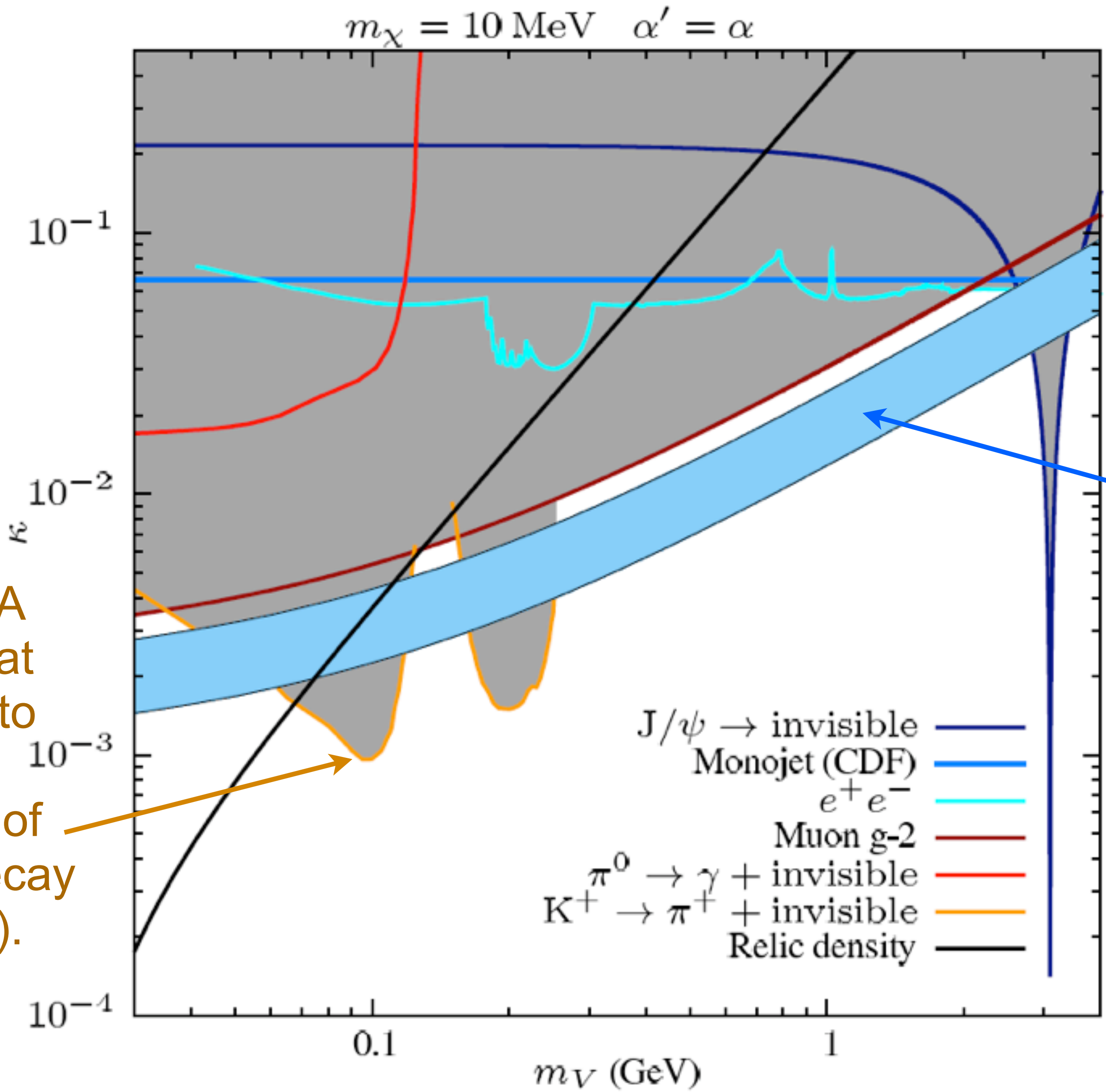


also some inferred limits at lower mass from LSND, CHARM, NOMAD, ...

[Batell et al. '09; Essig et al. '10; deNiverville et al. '11, '12]

Parameter space

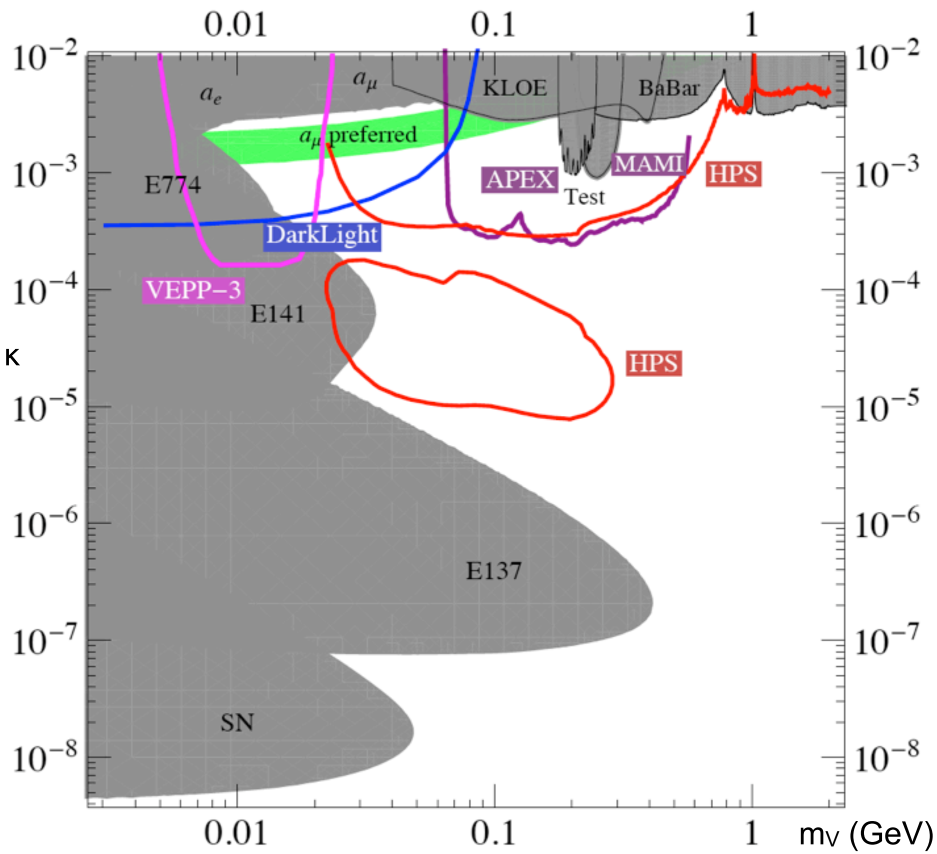


NB: ORKA proposal at Fermilab to improve precision of this K^+ decay by O(100).

V-loop shift helps resolve muon g-2 discrepancy

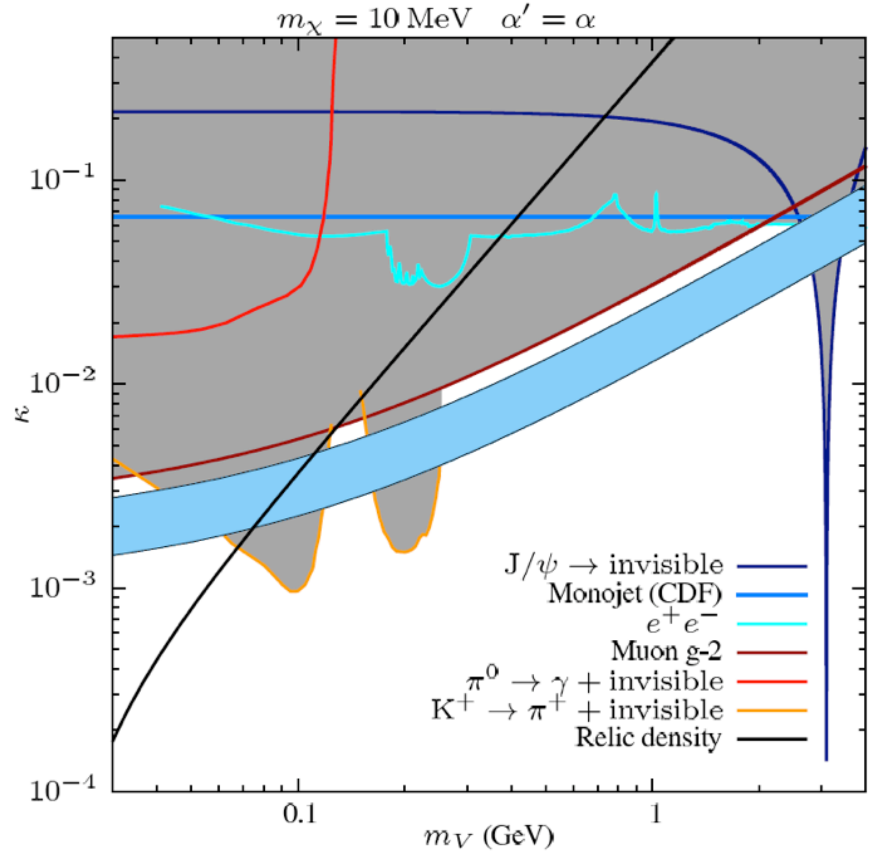
[Pospelov '08]

Another dark force regime



$m_V < 2m_\chi$

[Intensity Frontier Worskhop, Hewett, Weerts et al '12]

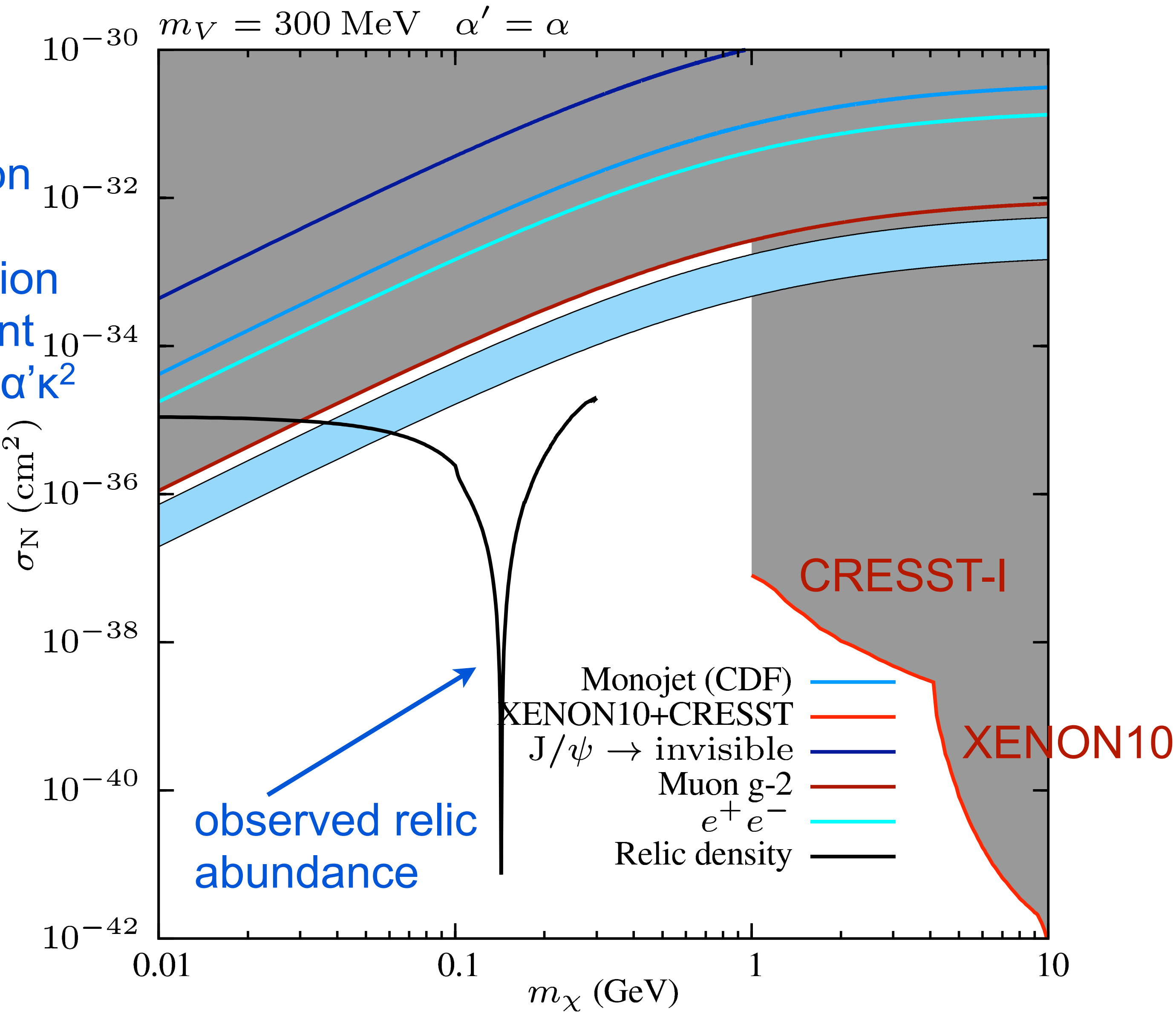


$m_V > 2m_\chi$

Some limits removed due to short V-lifetime, others weakened by $Br(V \to 2l) \sim \alpha\kappa^2/\alpha'$

Direct detection plane

per nucleon scattering cross section (in coherent regime) ~ $\alpha' \kappa^2$



(Some) Experimental Sensitivity

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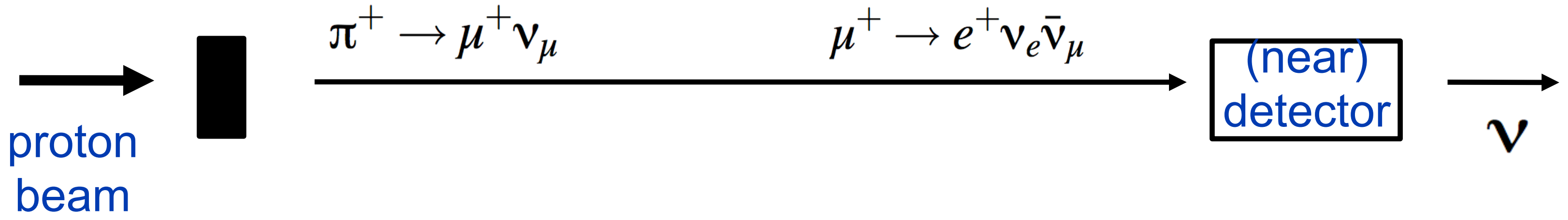
- Fixed targets/neutrino detectors - this talk!

Fixed target probes - Neutrino Beams



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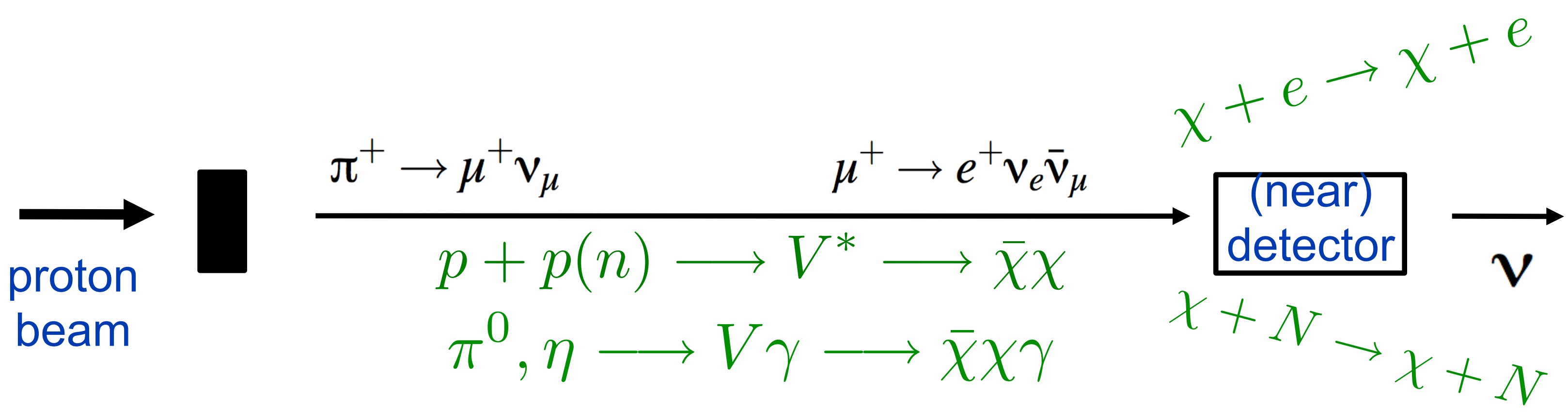
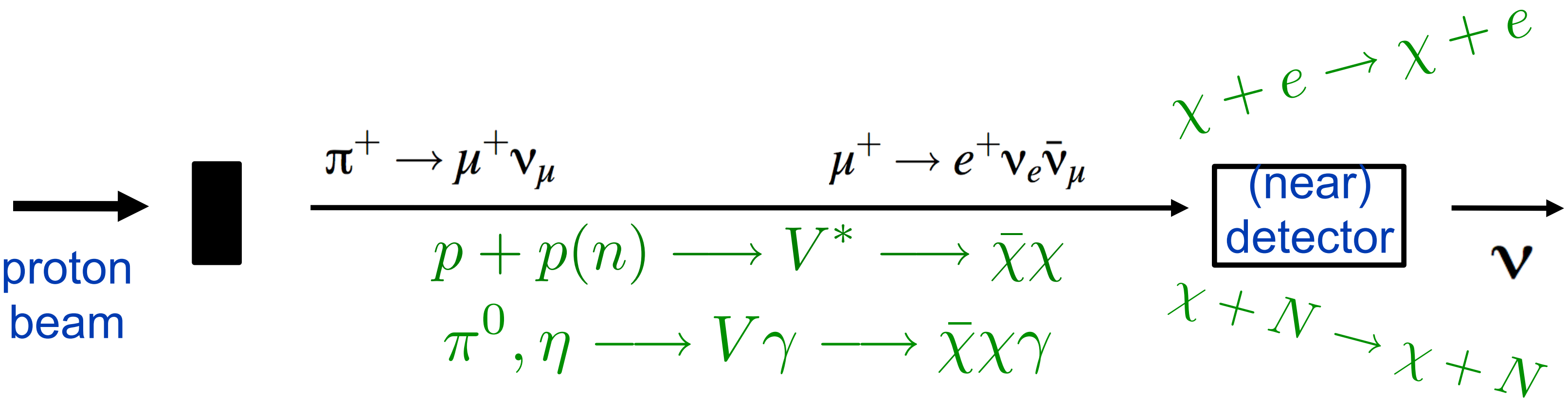


We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam.

Fixed target probes - Neutrino Beams



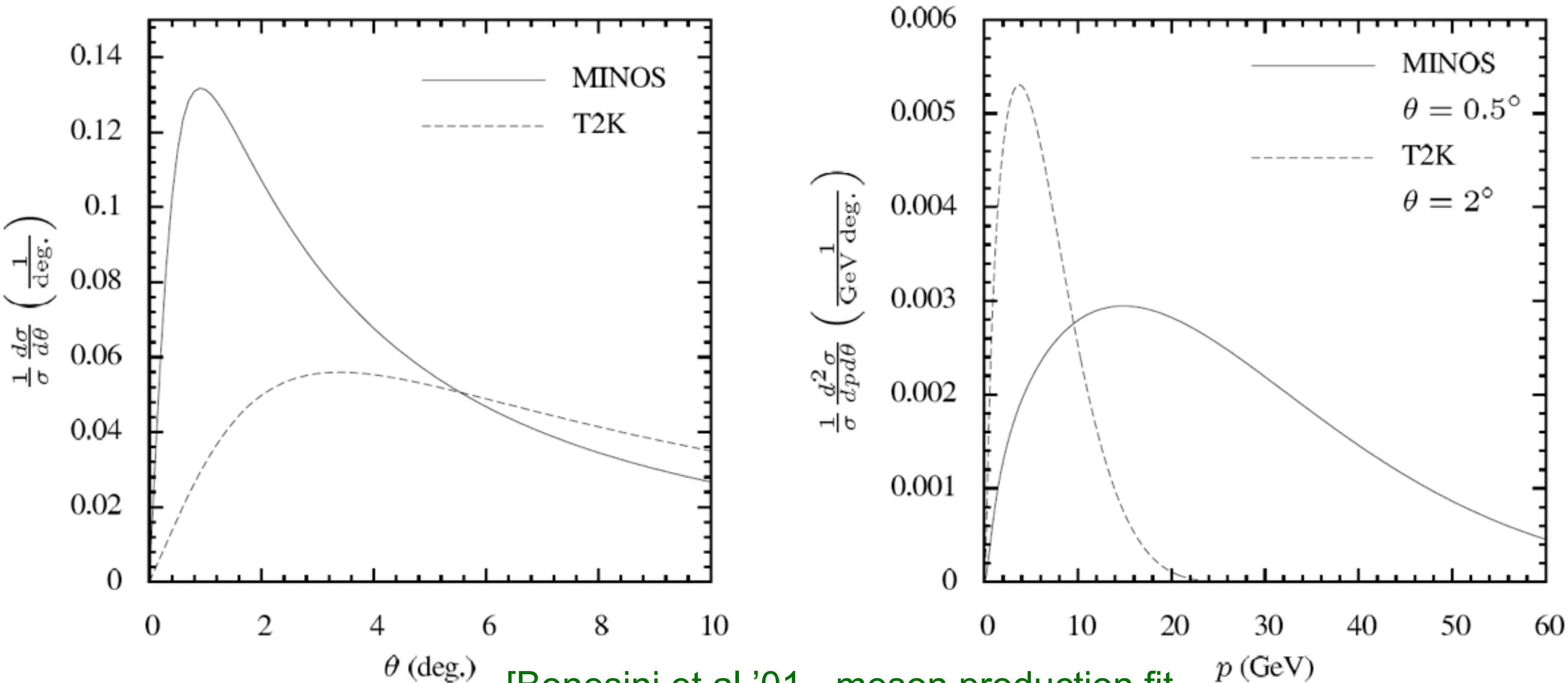
We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

T2K
30 GeV protons
(➠ ~5x10^{21} POT)
280m to on- and off-axis detectors

MINOS
120 GeV protons
10^{21} POT
1km to (~27ton) segmented detector

MiniBooNE
8.9 GeV protons
10^{21} POT
540m to (~650ton) mineral oil detector

DM production (meson decay)

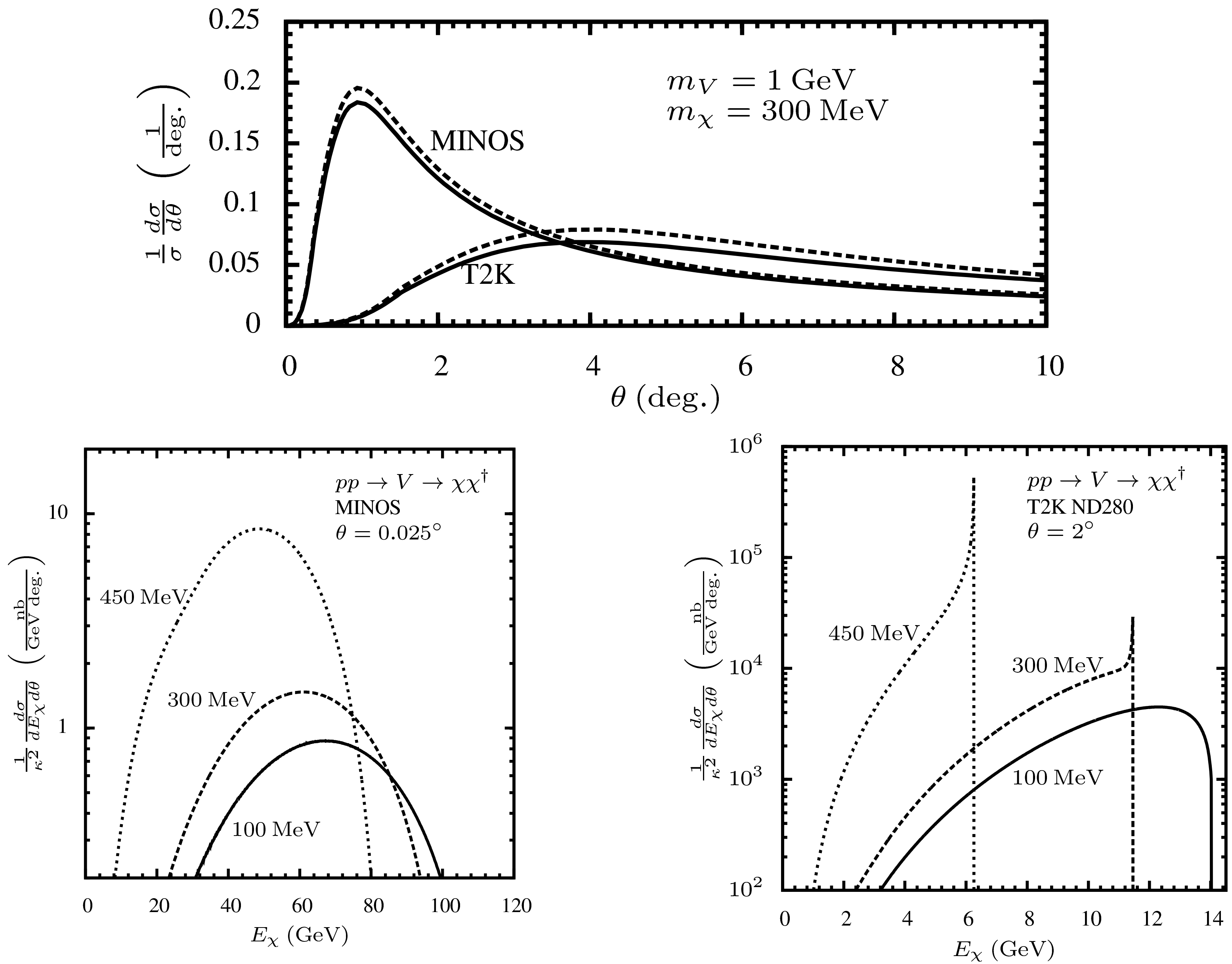


[Bonesini et al '01 - meson production fit, also data from NA61 (for T2K) and HARP (for MiniBooNE)]

NB: Neutrino energy spectrum has a lower peak

T2K (2^o) ~ 0.7 GeV
MINOS ~ 3 GeV

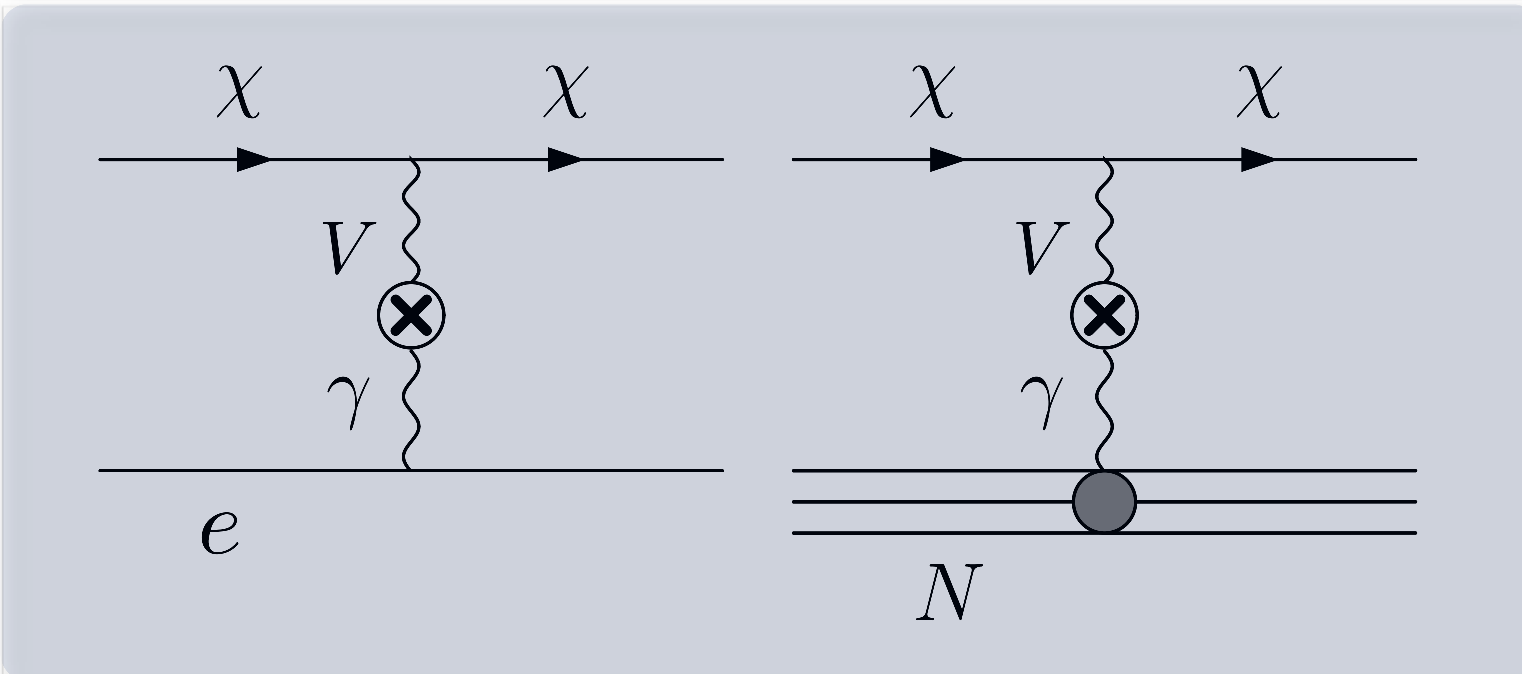
DM production (parton level)



[using narrow width approximation with on-shell V]

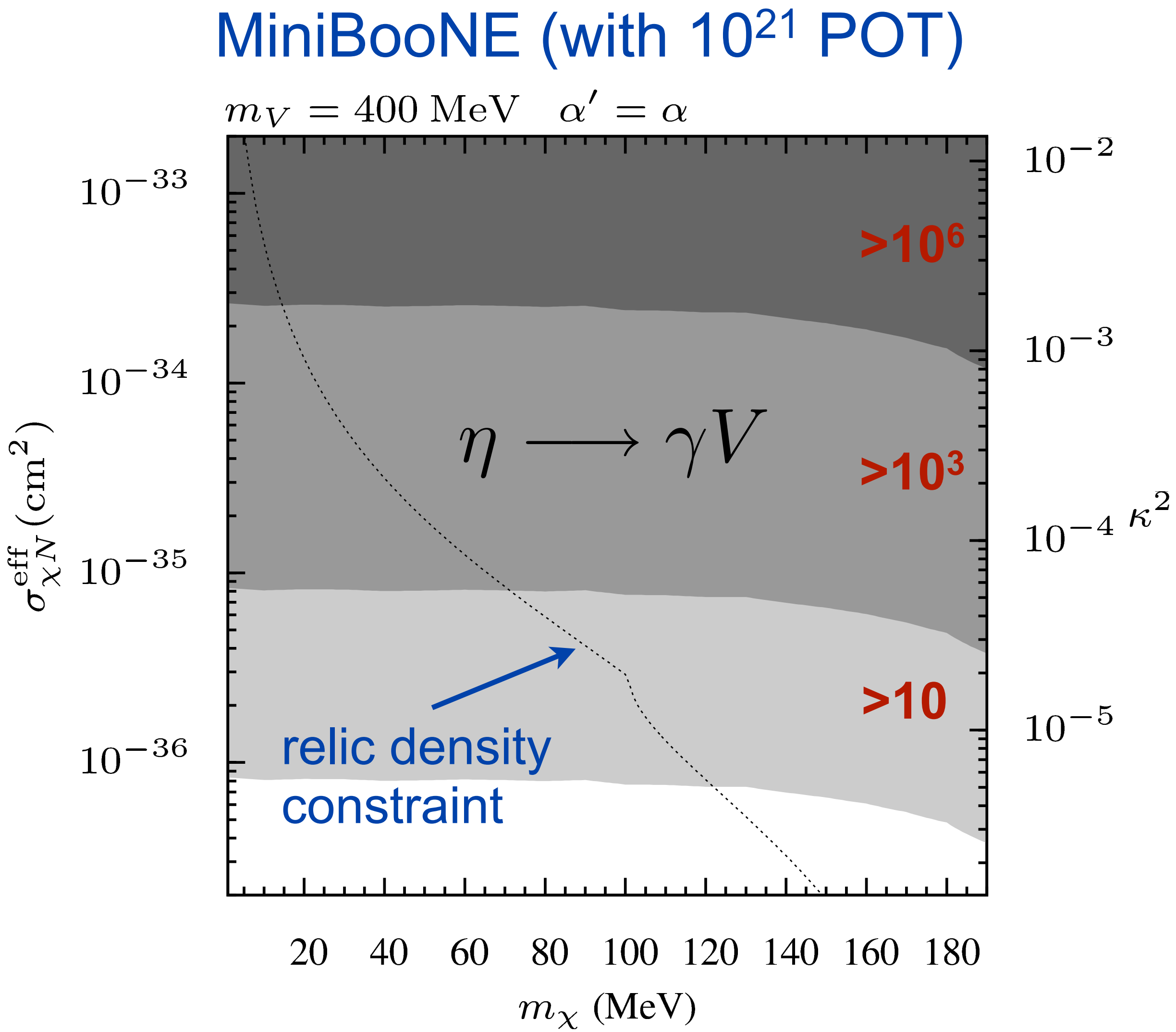
Signatures

Characteristic DM elastic scattering signatures



These processes mimic neutral current elastic scattering of neutrinos, and can lead to an observable excess.

Results - lower mass (MiniBooNE)



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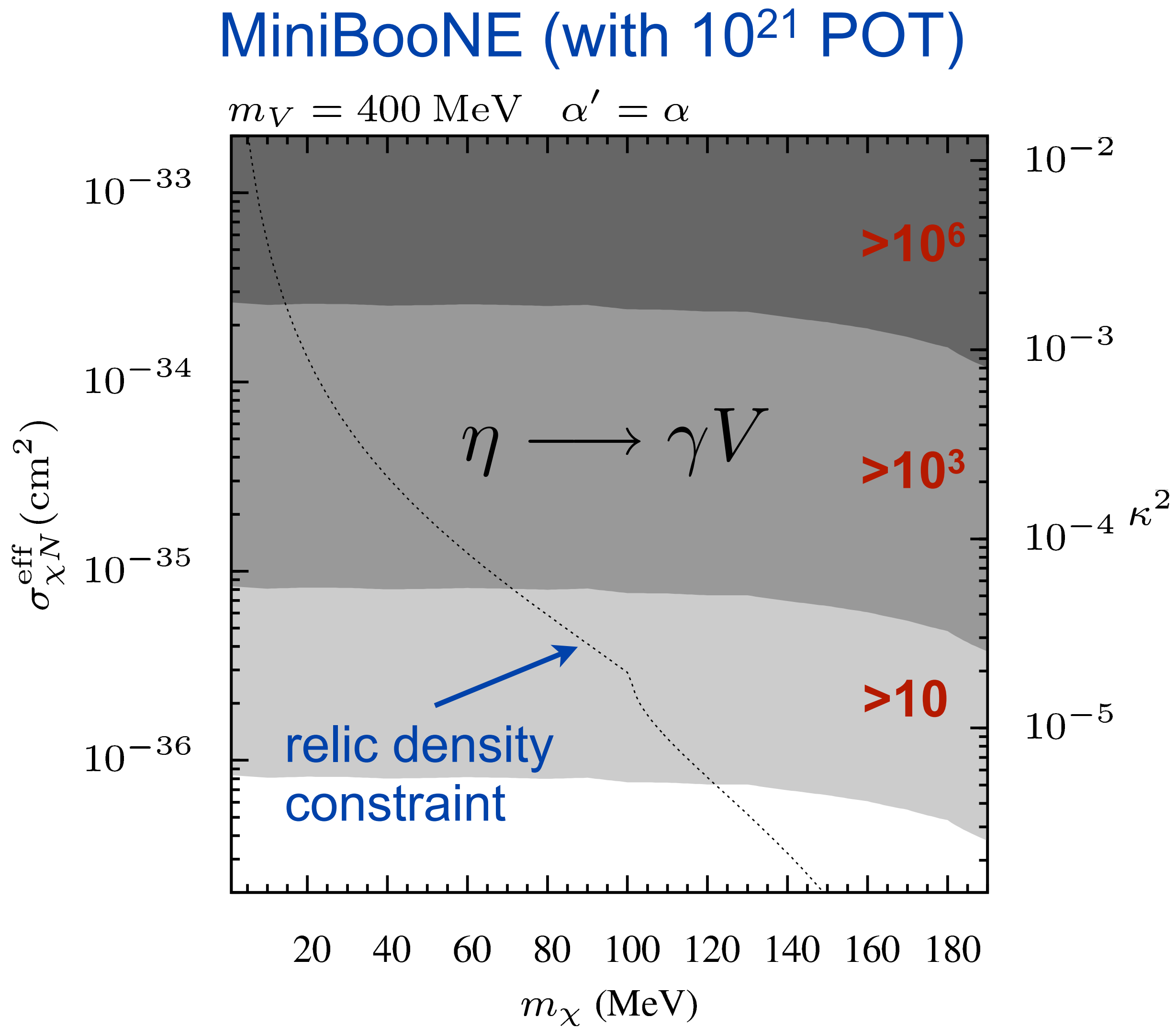
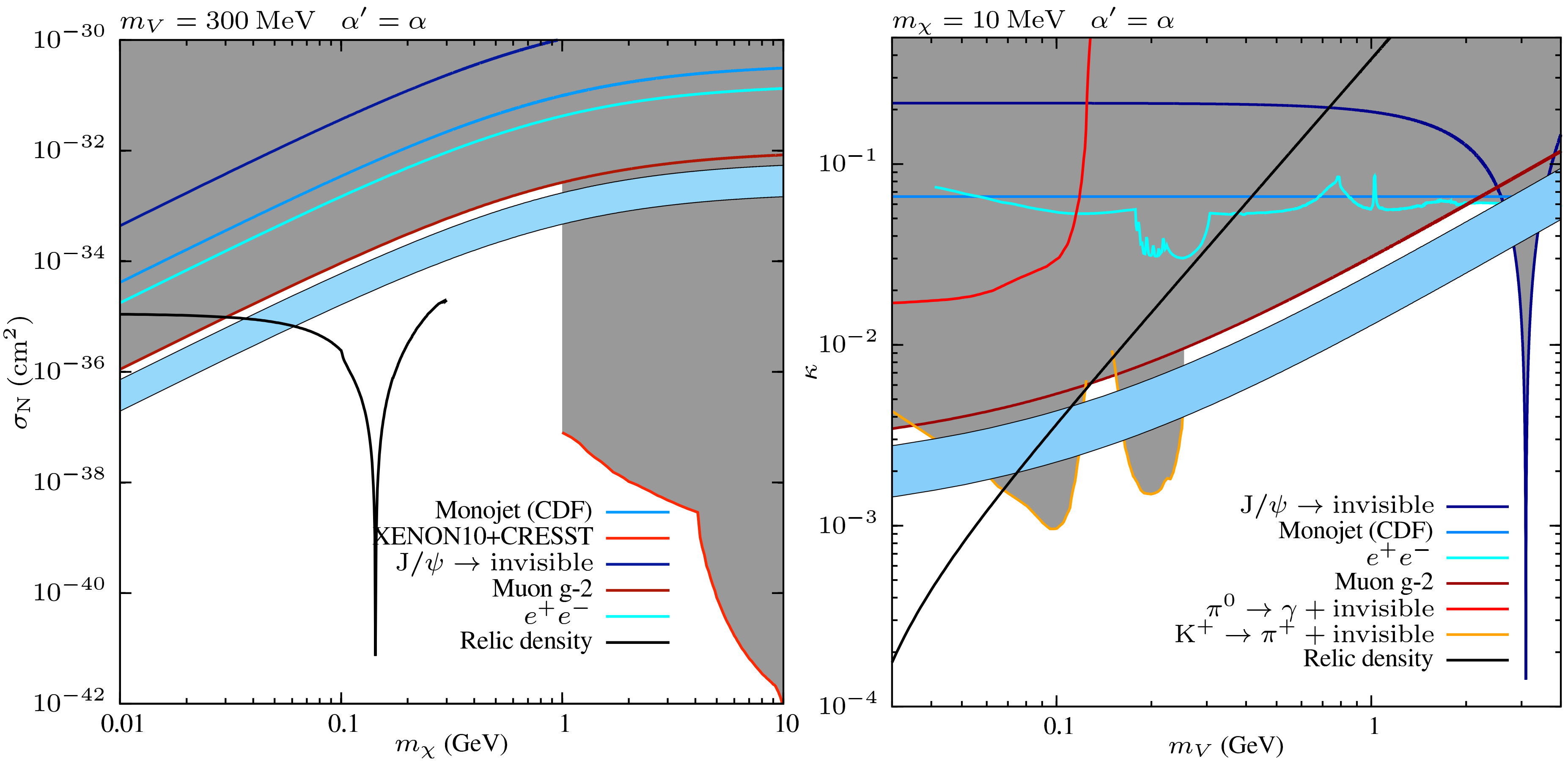


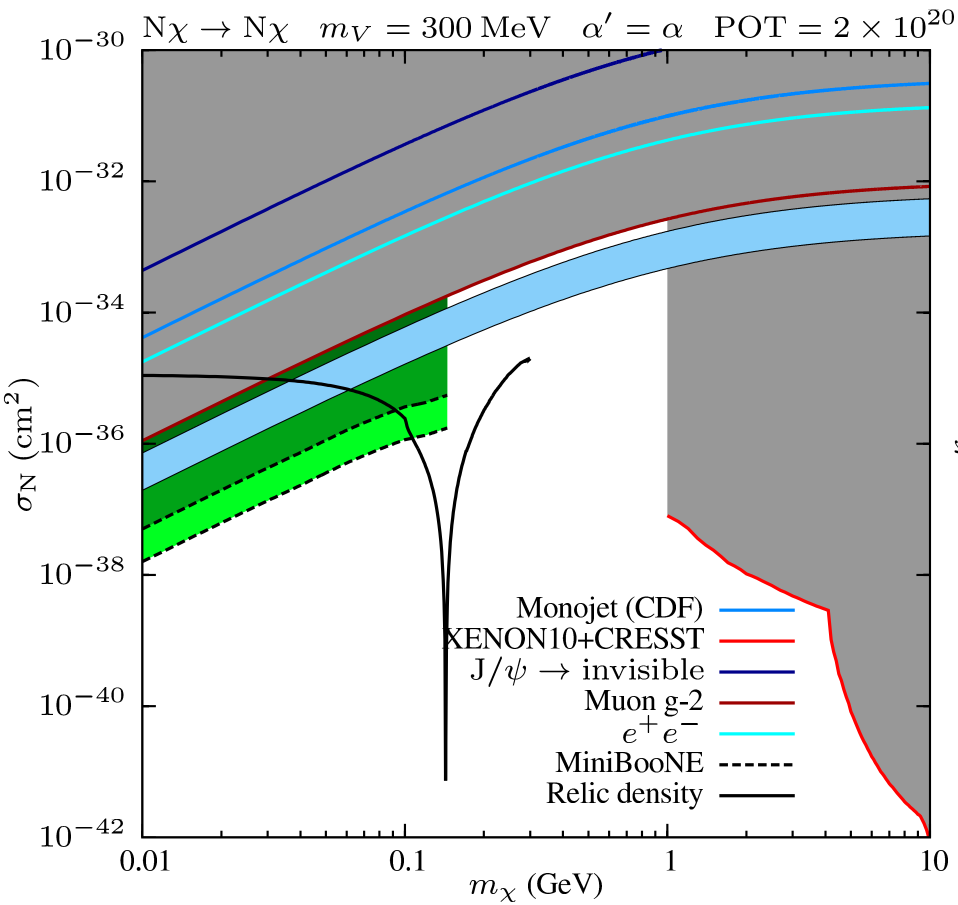
Constraints on MeV DM: Existing neutral current analyses at LSND and MiniBooNE strongly constrain O(1 MeV) *thermal relic* DM

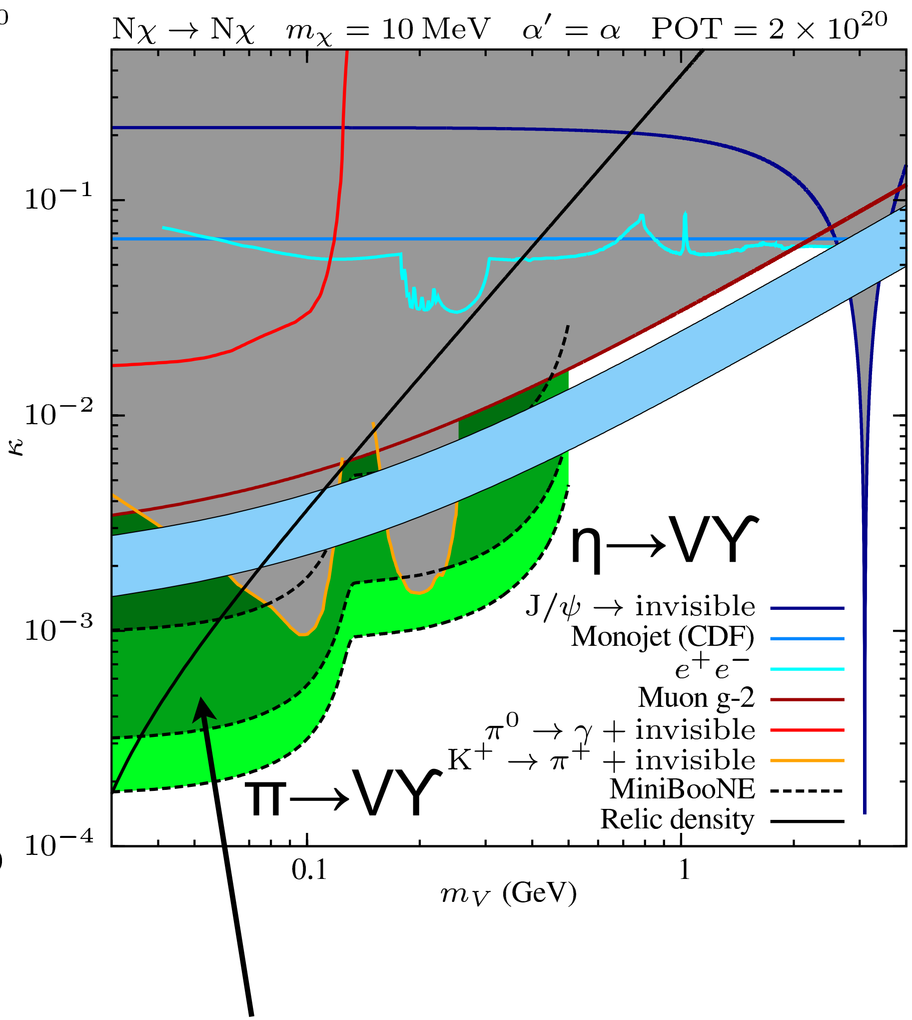
[deNiverville, Pospelov, AR '11]

Summary of existing limits



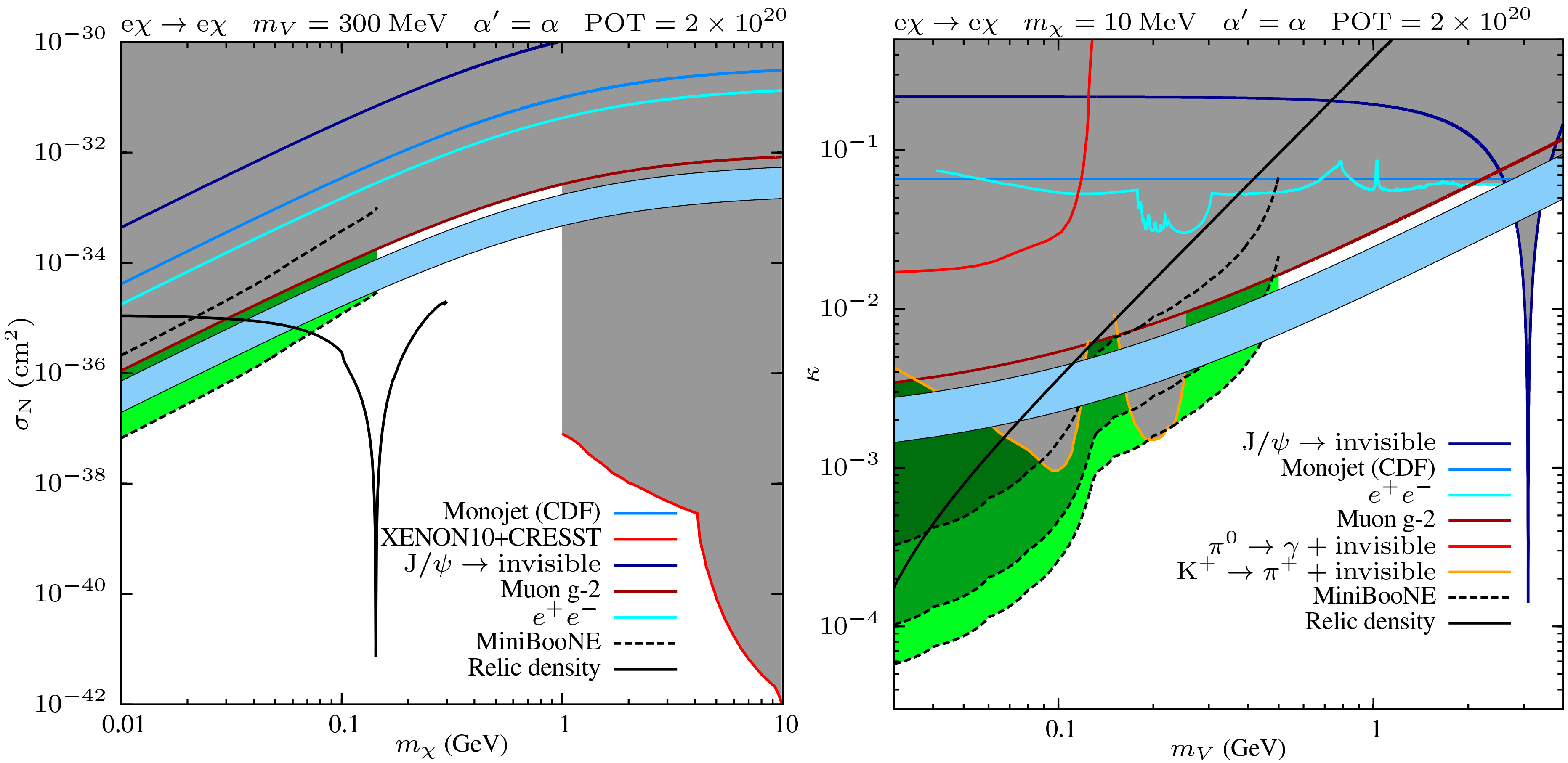
MiniBooNE sensitivity (Nχ→Nχ)





1-10, 10-10^3, >10^3 events

MiniBooNE sensitivity (eχ→eχ)



Better sensitivity at lower V masses, as momeuntum transfer doesn't saturate at low V mass

Neutrino backgrounds...

Neutrino elastic scattering provides a large background, but several features allow S/B to be enhanced

- Timing (3ns resolution at MiniBooNE, along with pulsed beams)
  - time delay (γ=10) = O(10ns)
- Energy cuts
  - neutrino beam peaks at lower energy
  - different scattering kinematics

MiniBooNE proposal to FNAL PAC

FAC presentation
Oct 15, 2012

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

Presented to the FNAL PAC Oct 15, 2012

The MiniBooNE Collaboration

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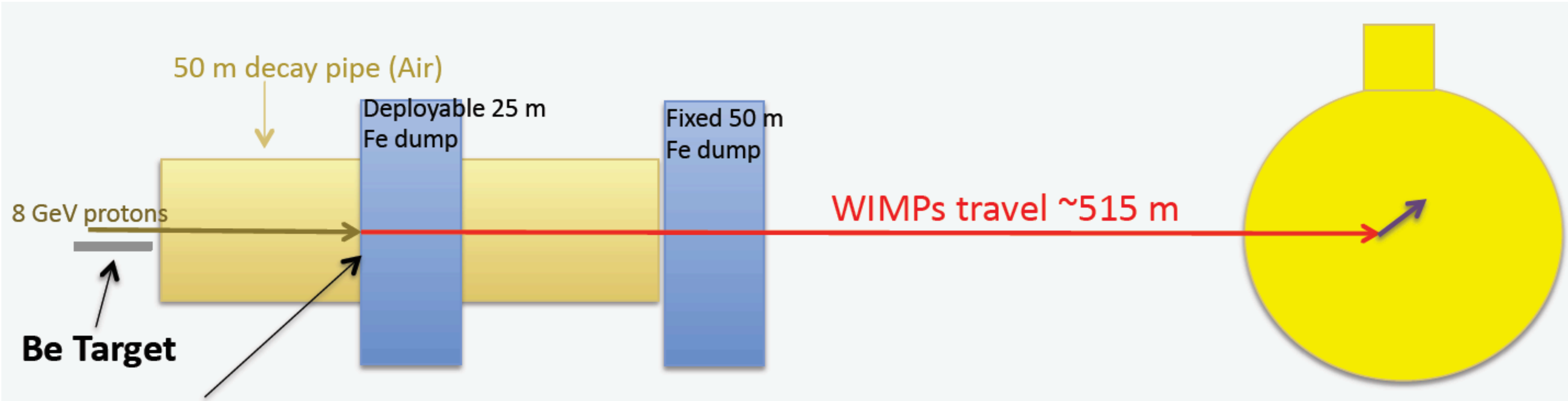
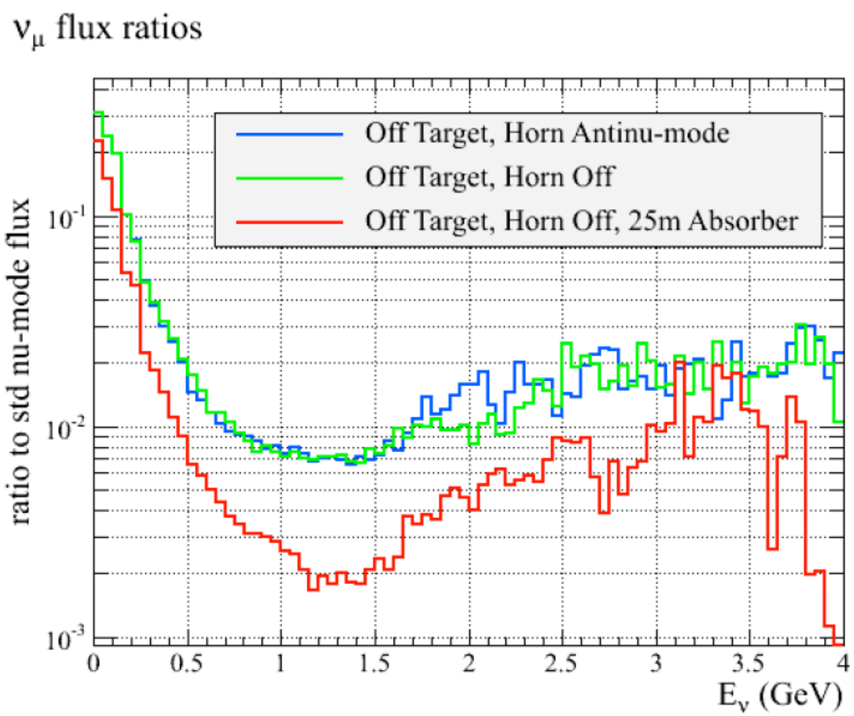
Request: $2x10^{20}$ POT in 2013/14 to run with beam off target

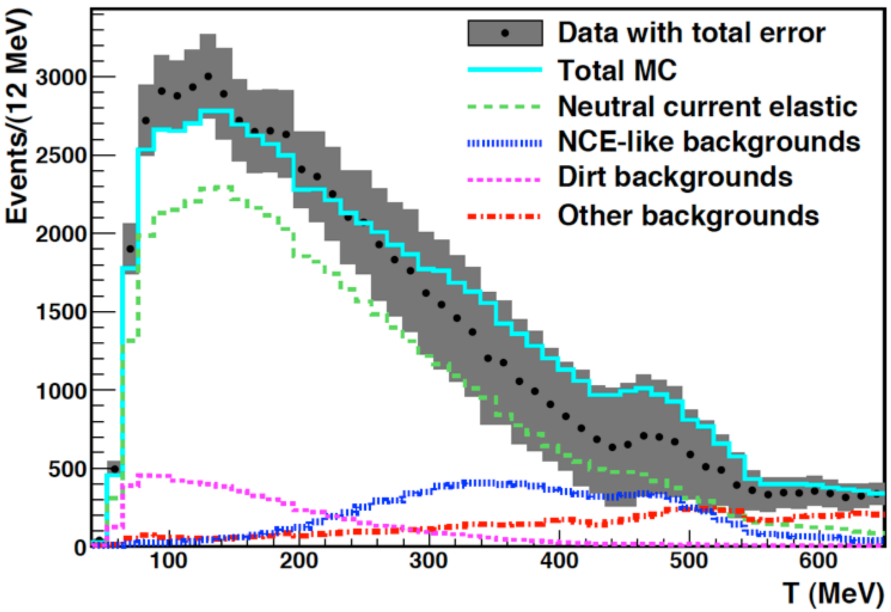
MiniBooNE beam dump





- removal of decay volume for charged mesons reduces neutrino background by factor of ~40 (70) with 50m (25m) absorber

MiniBooNE beam dump - Nχ scattering

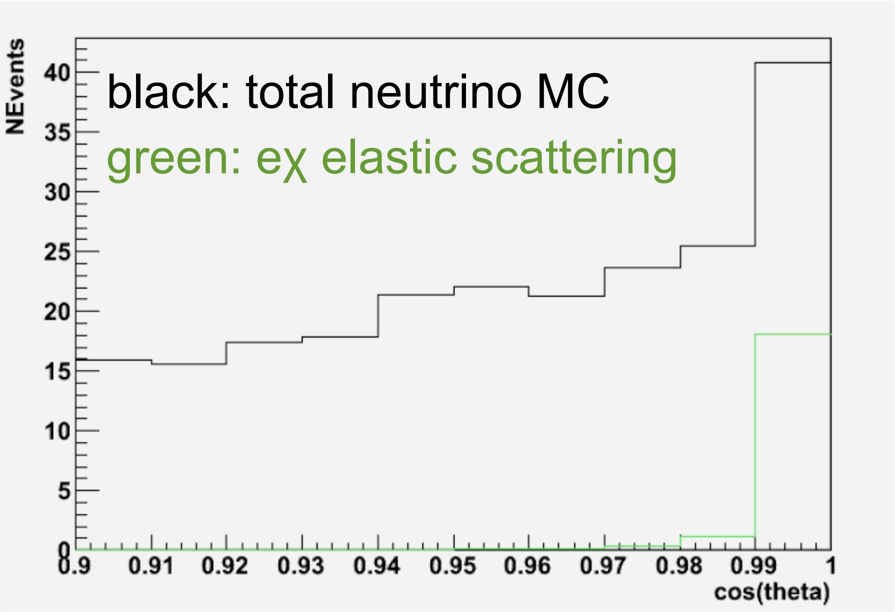


- neutral current cross-sections measured to O(18%) [MiniBooNE '10]

estimated neutrino backgrounds and 90% CL upper limits

POT ($\times 10^{20}$)	Beam Configuration	25m Absorber ν-Background	25m Absorber 90% U.L.	50m Absorber ν-Background	50m Absorber 90% U.L.
10.1	$\bar{\nu}$ beam on target			60605	16294
6.5	ν beam on target			95531	22136
6.5	beam off target	1137	267	2275	531
4.0	beam off target	700	166	1400	328
2.0	beam off target	350	85	700	166
1.0	beam off target	175	44	350	85

MiniBooNE beam dump - eχ scattering

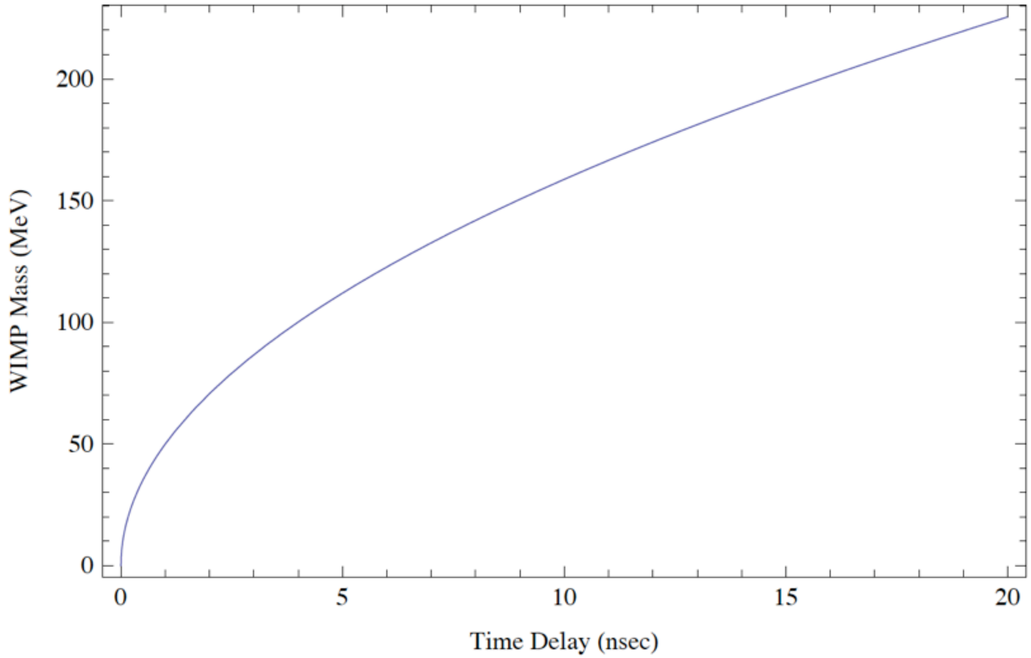


- neutrino background can be significantly reduced (98%) with a forward angle cut

estimated neutrino backgrounds and 90% CL upper limits

POT ($\times 10^{20}$)	Beam Configuration	25m Absorber ν-Background	25m Absorber 90% U.L.	50m Absorber ν-Background	50m Absorber 90% U.L.
10.1	$\bar{\nu}$ beam on target			31	8.6
6.5	ν beam on target			41	10.3
6.5	beam off target	0.45	2.75	0.90	3.20
4.0	beam off target	0.30	2.60	0.60	2.90
2.0	beam off target	0.15	2.45	0.30	2.60
1.0	beam off target	0.08	2.38	0.15	2.45

MiniBooNE beam dump - timing

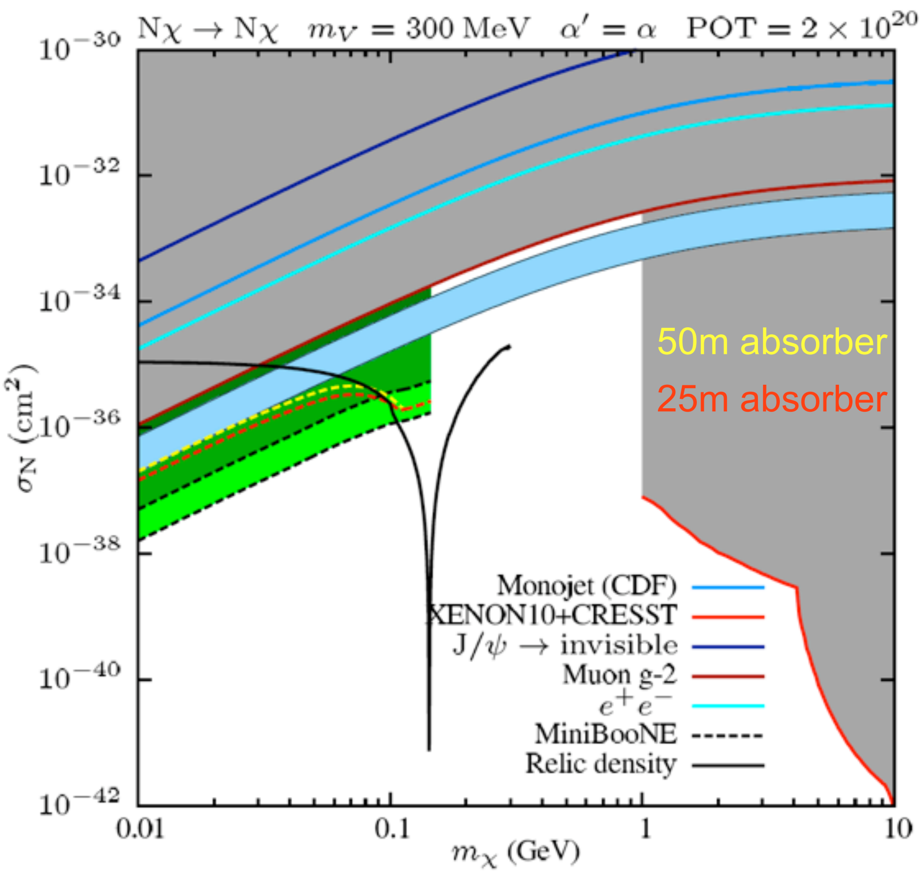


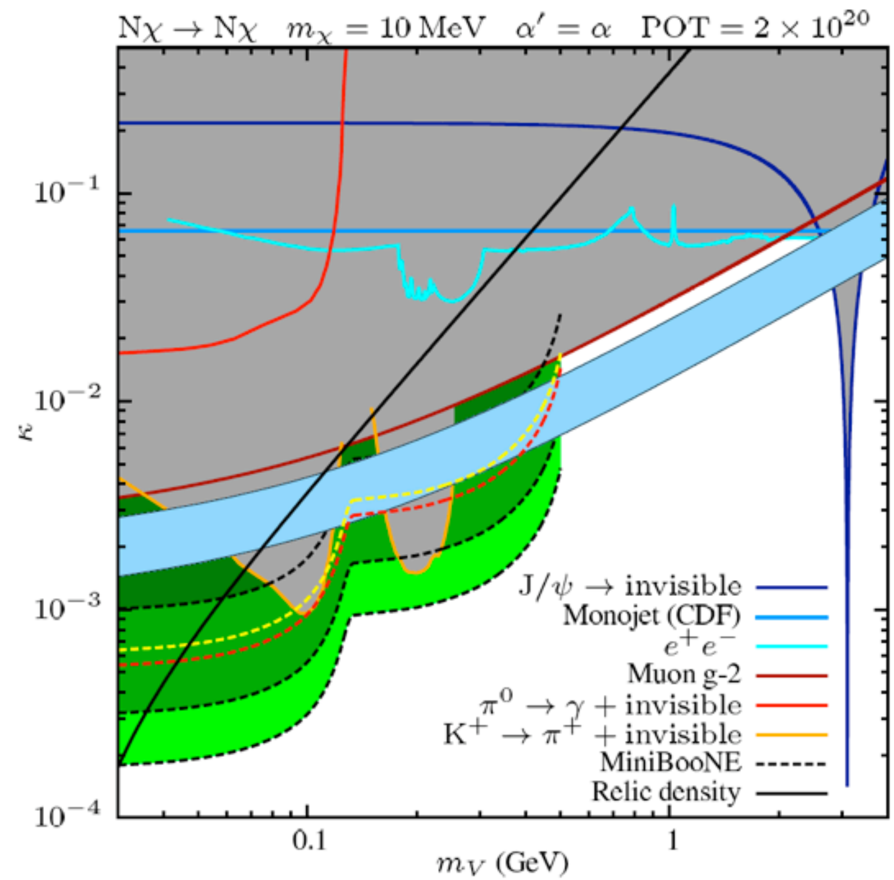
- Travel time from 25m absorber to detector is 1716ns at v=c.
- Absolute beam-detector event timing known to ~ 1.8ns
- For higher mass WIMPs, with v<c, a timing cut can be used to further reduce the neutrino background

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

MiniBooNE beam dump

Nucleon scattering sensitivity - estimated 90% CL limits for $2\text{x}10^{20}$ POT

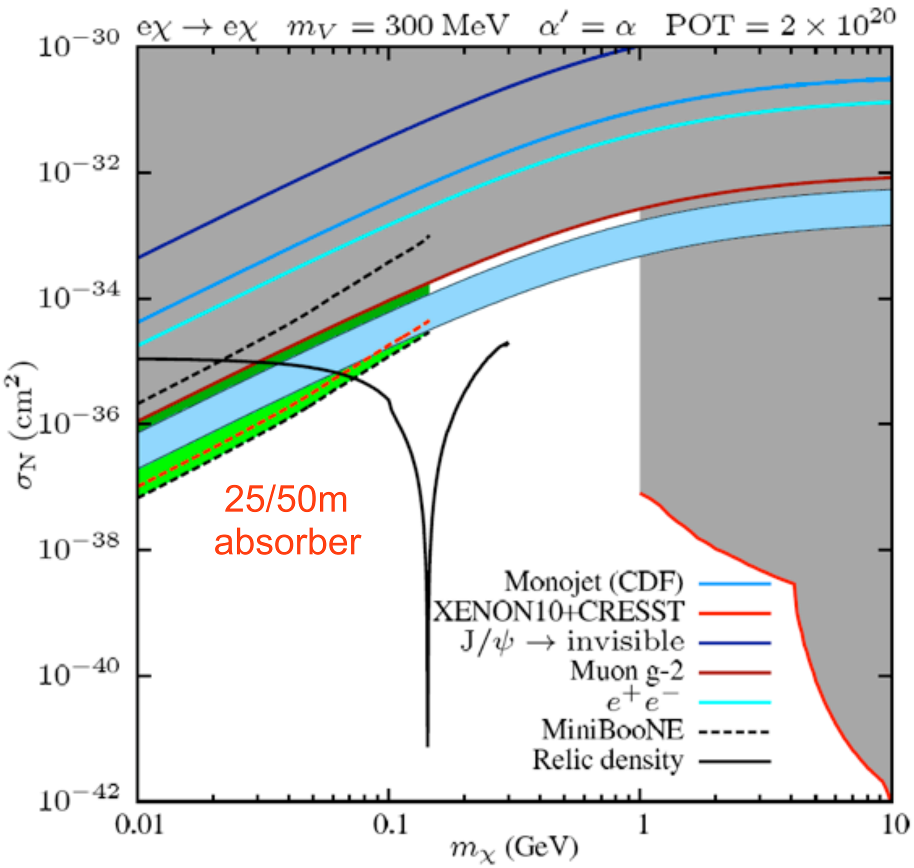


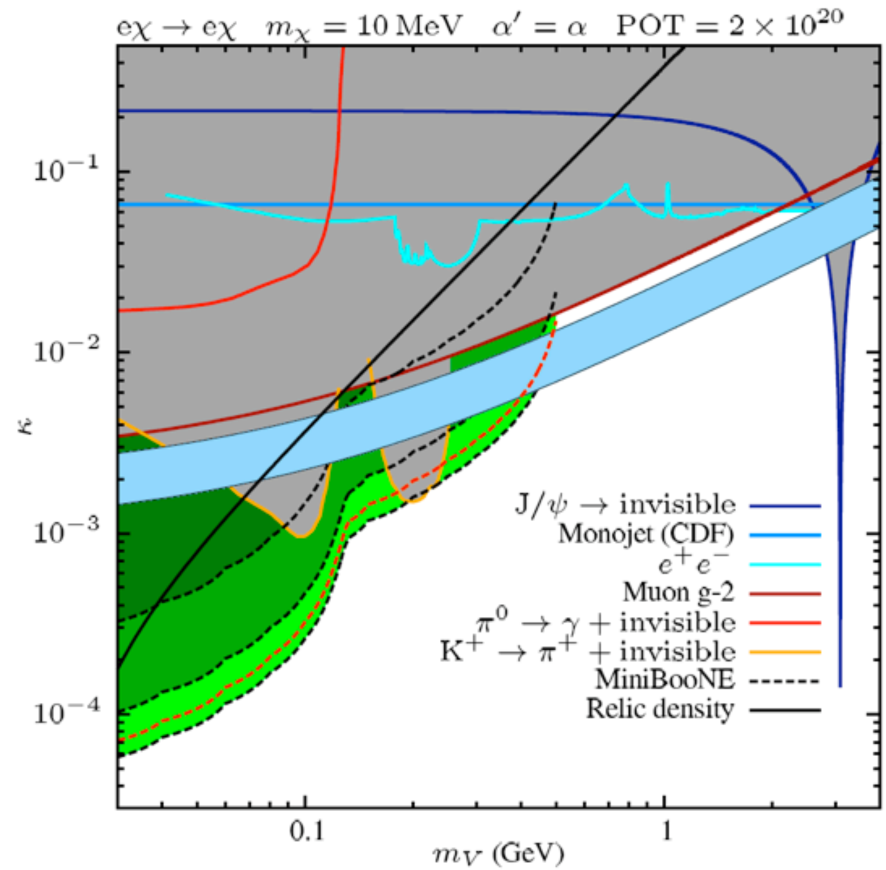


NB: For these parameters, able to cover the range in which V-loops can resolve the g-2 discrepancy

MiniBooNE beam dump

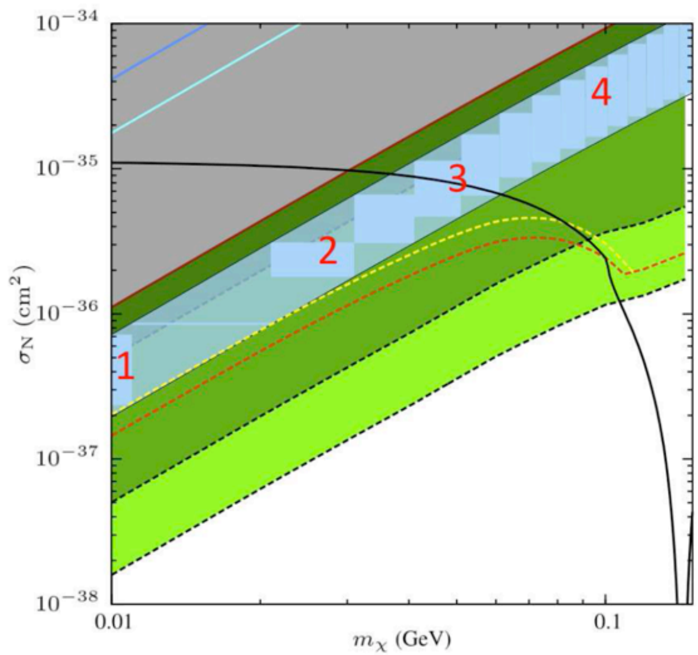
Electron scattering sensitivity - estimated 90% CL limits for 2×10^{20} POT

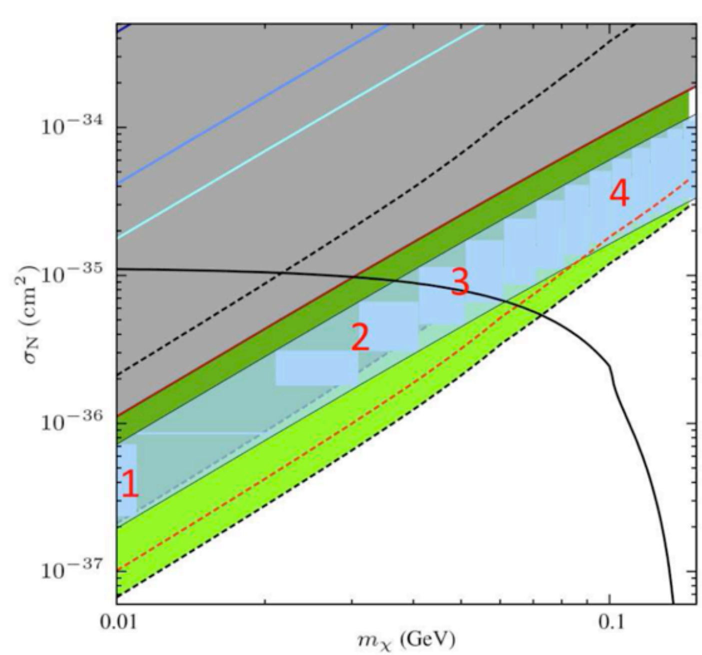




NB: For these parameters, able to cover the range in which V-loops can resolve the g-2 discrepancy

MiniBooNE beam dump - signal significance

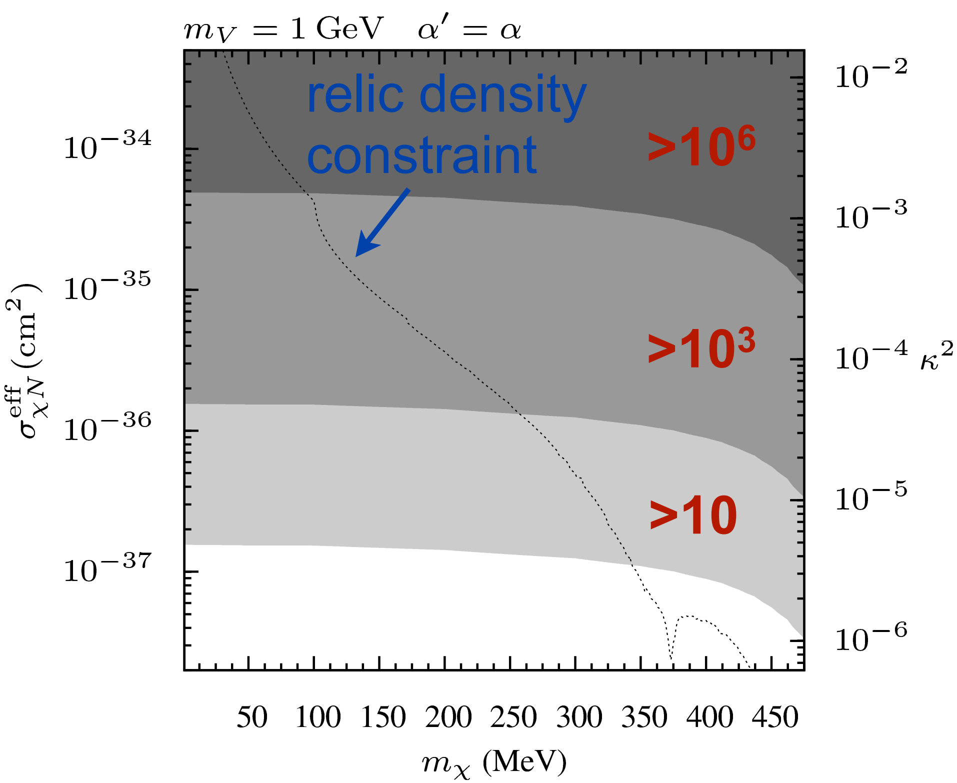


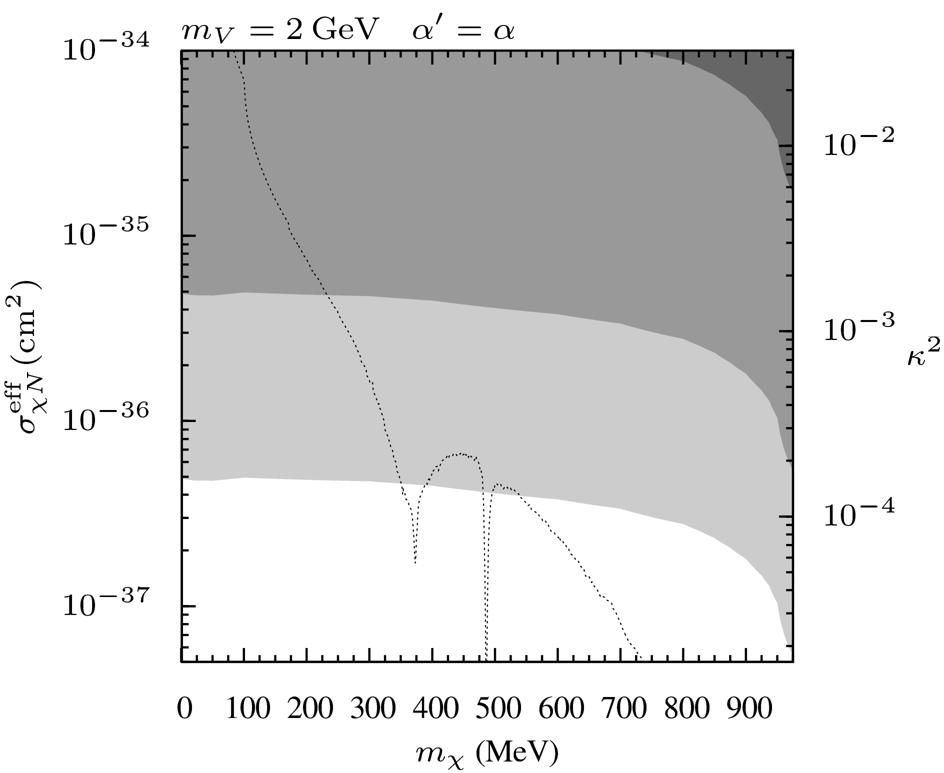


	Scattering Channel	Beam Mode (2.0×10^{20} POT)	WIMP mass (MeV)/ cross section (cm^2)	Signal	Background and Errors	Probability
1	Nucleon	25m	$10/4 \times 10^{-37}$	1859	350±66	$< 10^{-10}$
2	Nucleon	25m	$30/3 \times 10^{-36}$	1453	350±66	$< 10^{-10}$
3	Nucleon	25m	$50/8 \times 10^{-36}$	1326	203±40	$< 10^{-10}$
4	Nucleon	25m	$100/3 \times 10^{-35}$	1186	9.2±3.4	$< 10^{-10}$
1	Electron	25m	$10/4 \times 10^{-37}$	13.2	0.15	$< 10^{-10}$
2	Electron	25m	$30/3 \times 10^{-36}$	7.7	0.15	$\sim 10^{-9}$
3	Electron	25m	$50/8 \times 10^{-36}$	4.8	0.09	$\sim 10^{-6}$
4	Electron	25m	$100/3 \times 10^{-35}$	1.4	0.004	$\sim 10^{-3}$

Results - higher mass (T2K, MINOS)

[deNiverville, McKeen, AR '12]

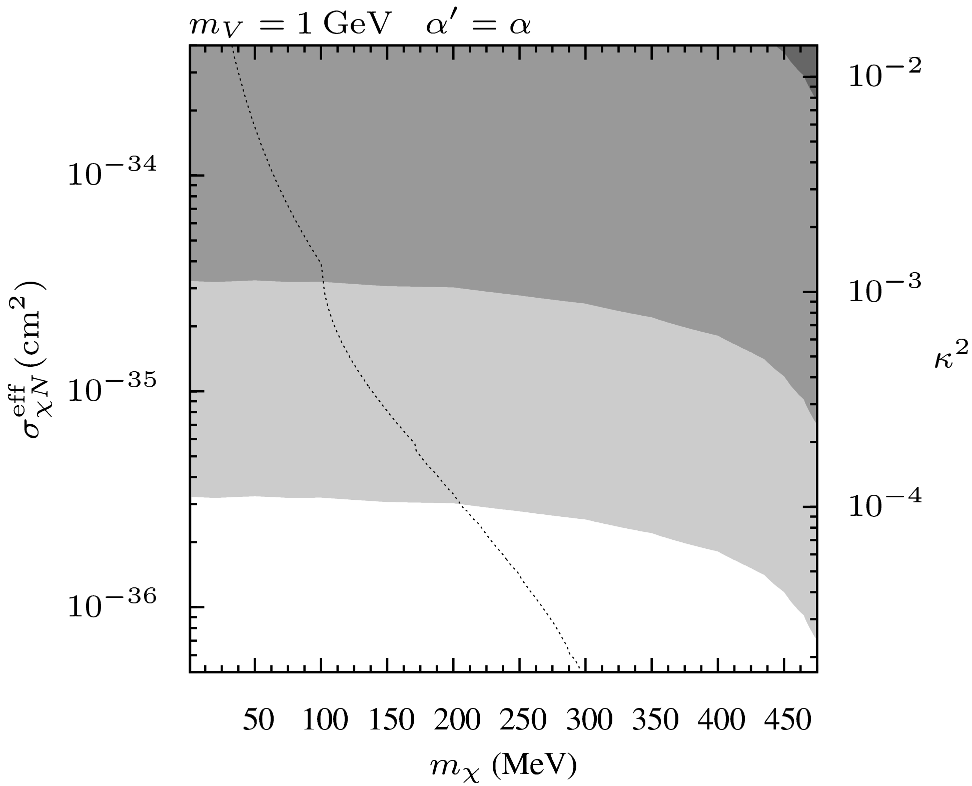




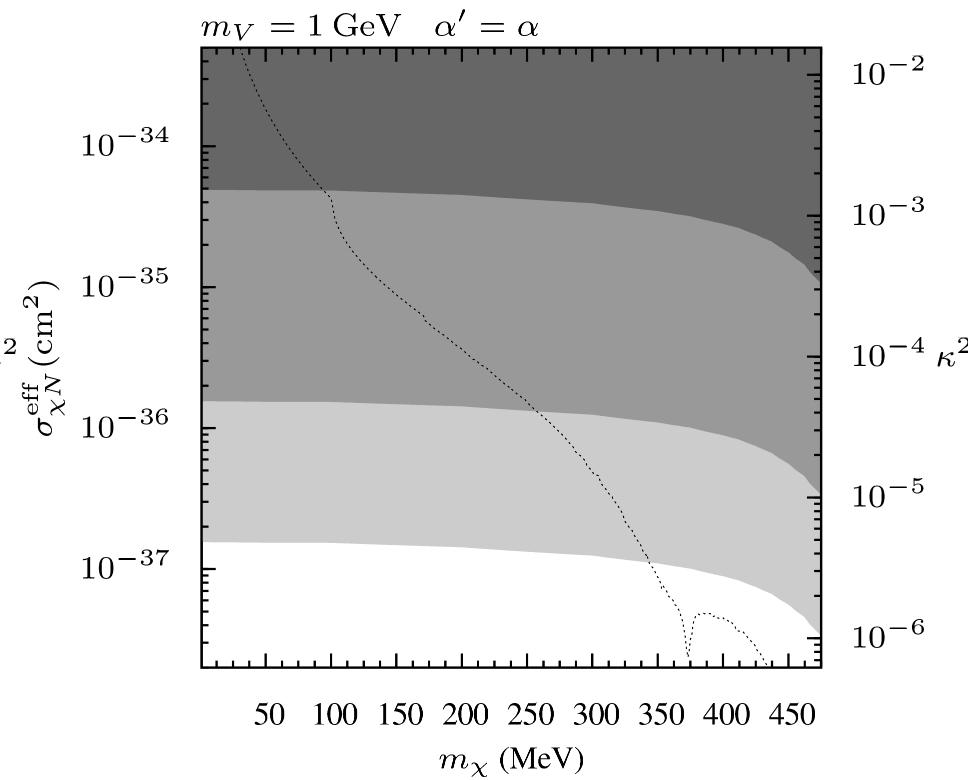
T2K - INGRID on-axis detector (with 5×10^{21} POT)

Results - higher mass (T2K, MINOS)

[deNiverville, McKeen, AR '12]



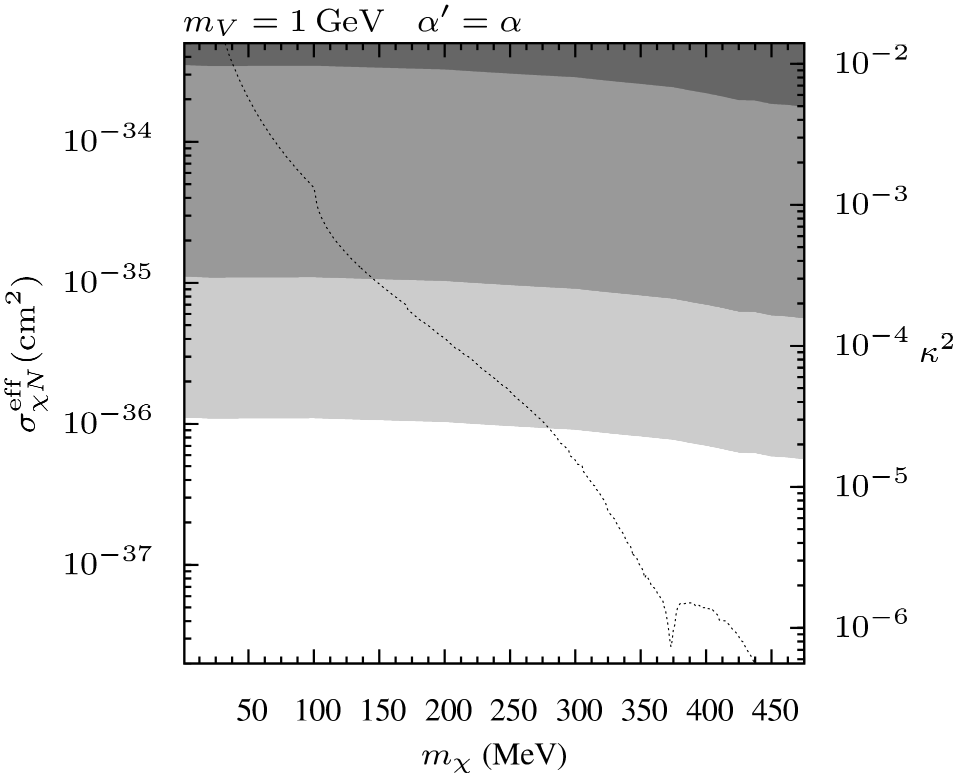
MINOS



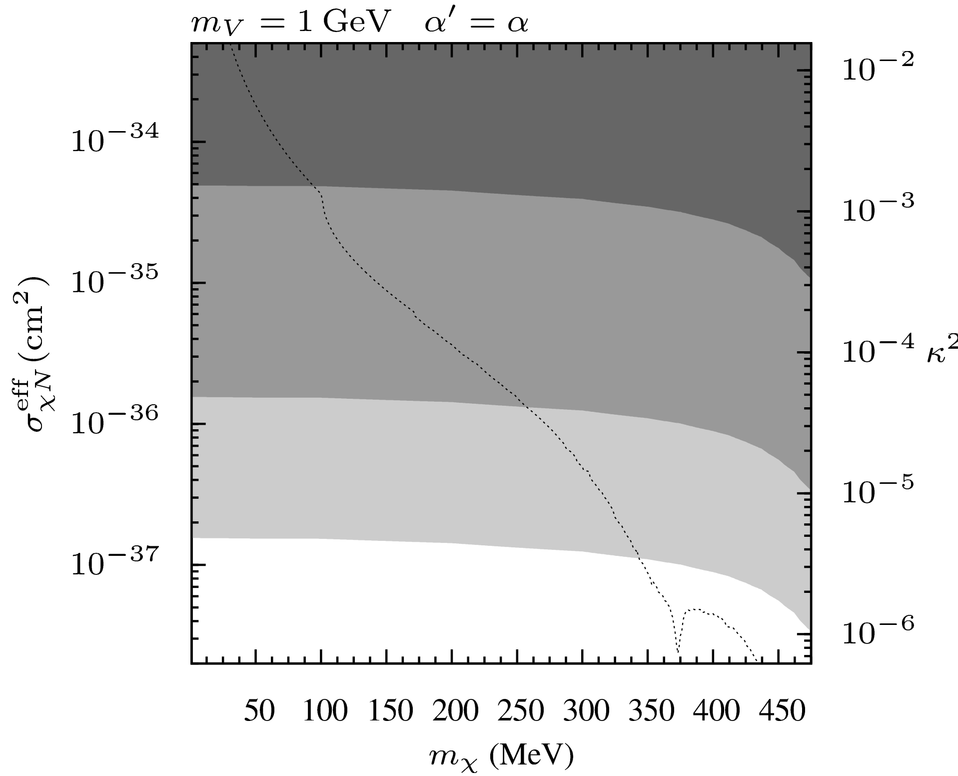
T2K - INGRID (on-axis)

Results - higher mass (T2K, MINOS)

[deNiverville, McKeen, AR ’12]



T2K - ND280
(2$^{\rm o}$ off-axis)



T2K - INGRID
(on-axis)

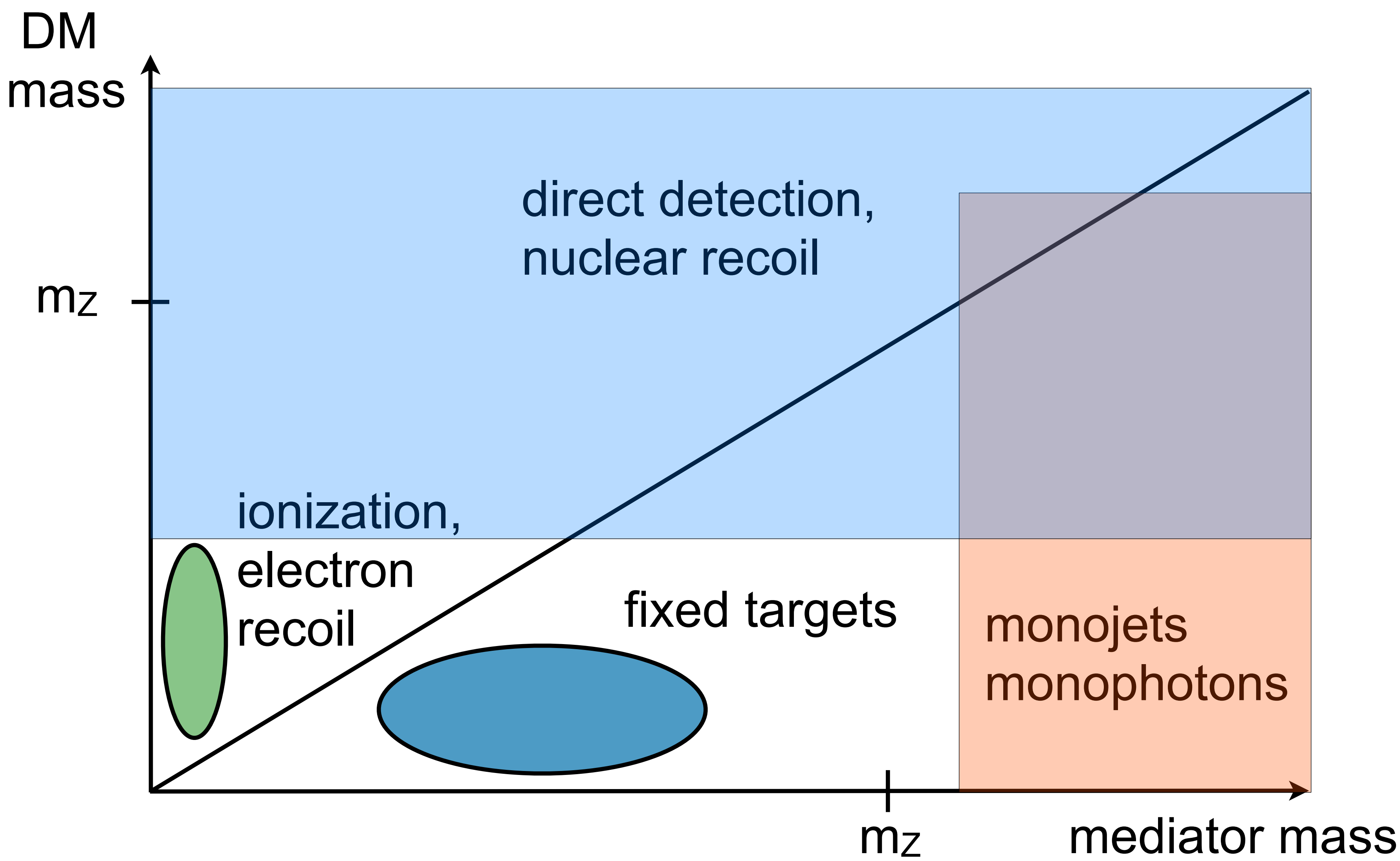
Concluding Remarks

Light DM at the Luminosity frontier

- WIMP (i.e. thermal relic) DM in the MeV-GeV range is viable, but difficult to probe using conventional direct detection.
- Models coupled via the vector portal (and possibly others) can be tested using fixed-target neutrino facilities.
- Existing NC analyses from LSND and MiniBooNE rule out a class of MeV-scale models motivated by the galactic 511 keV line
- Higher mass sensitivity to σ_{scat} = 1-10pb for O(10^3-10^4) events,
  - reducible background with timing, E_{min} cuts, etc
  - MiniBooNE proposal for off-target (beam dump) run
  - could be extended to O(1GeV) at MINOS, T2K,...

  [related work by Spannowsky, Tait, Wallace]

Complementary (direct) probes of dark matter



Concluding Remarks

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Alternative (complementary) probes of light DM

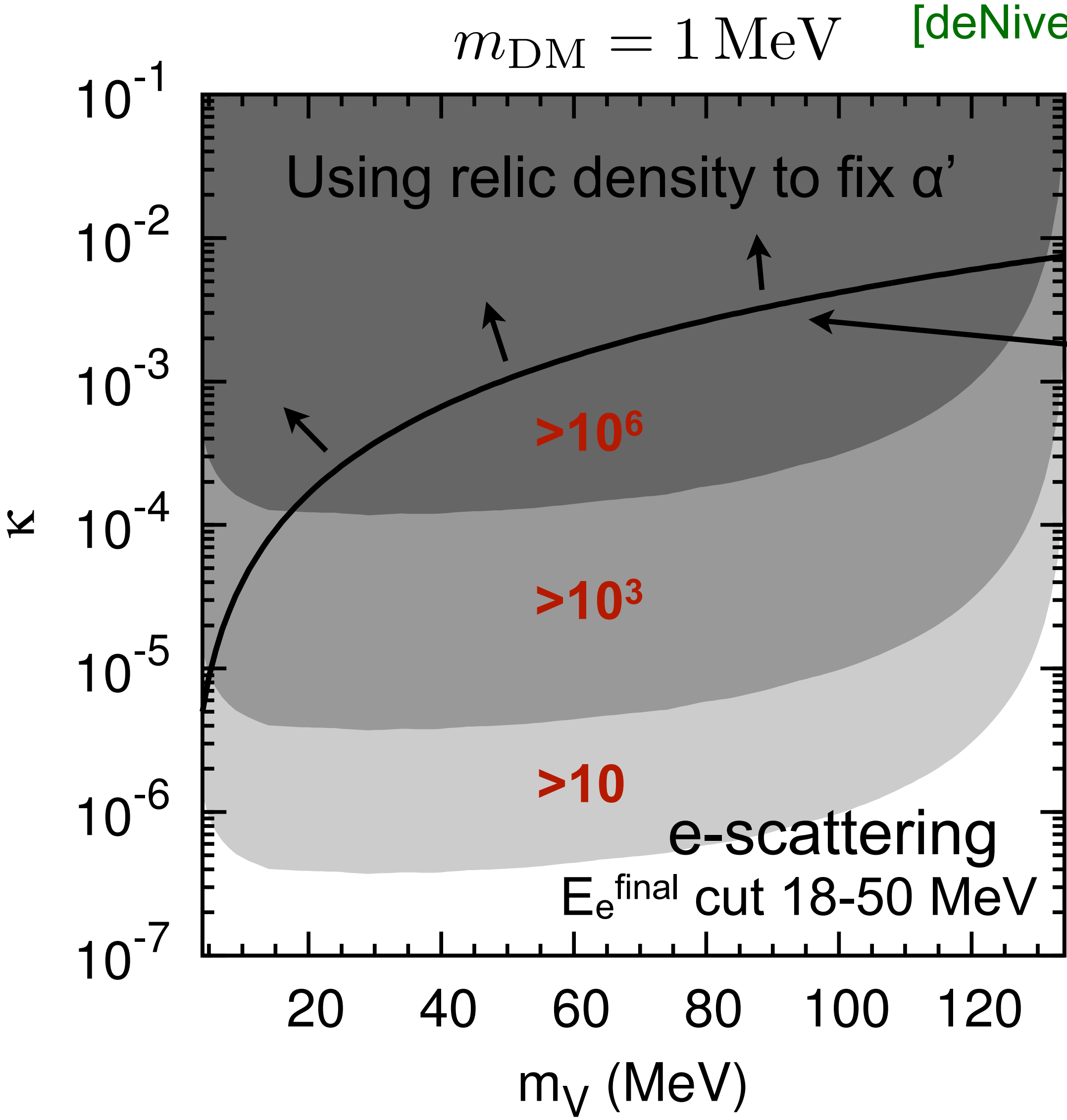
- Direct detection via electron scattering (complementary, as more sensitive in the light mediator regime, e.g. with $m_V < m_\chi$).
  [Essig & Volansky '11; Graham et al '12; Essig et al '12 (Xenon10 data)]
- Collider searches (1-jet, 1-photon, but limited for light mediators).
  [Goodman et al '10; Fox et al '11; Shoemaker & Vecchi '11] + lepton jets etc.
- Rare decays (e.g. $\Phi \rightarrow E_{miss}$, Kaons)

Extra slides

Constraints on MeV-scale DM

[deNiverville, Pospelov, AR '11]

via $\pi^0 \to \gamma V$

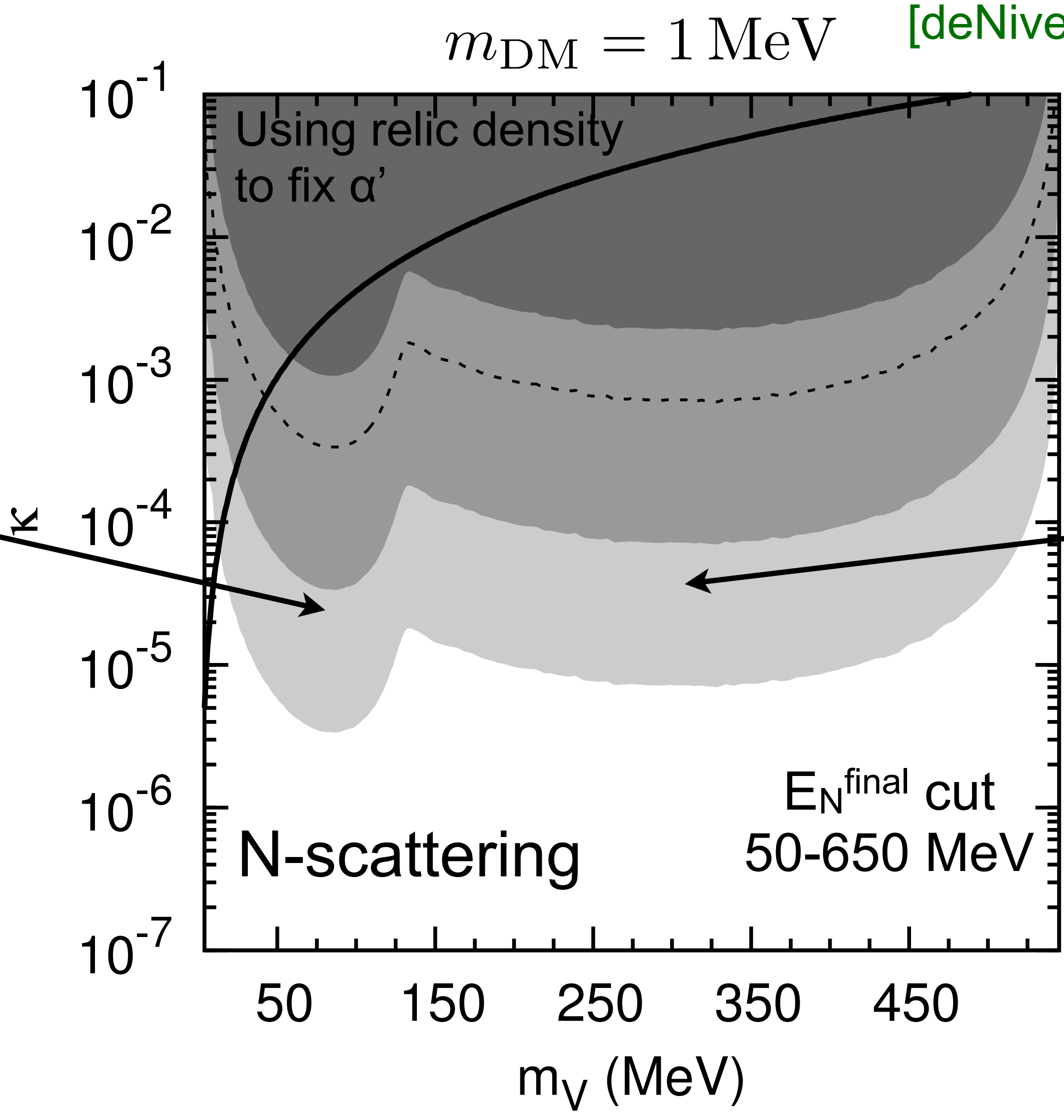


perturbativity constraint required for relic density & an explanation of 511 keV line (shifts lower for higher m_{DM})

Background at LSND is ~300 Elastic Scattering events [LSND '01]

Constraints on MeV-scale DM

[deNiverville, Pospelov, AR '11]



from π^0's

from η's

(Naive) background is ~ 6×10^4 NC neutrino events

[MiniBooNE '10]