Dark Tridents
@ Off-Axis Liquid Argon Neutrino Detectors

Yue Zhang
(Northwestern & Fermilab & COFI fellow)

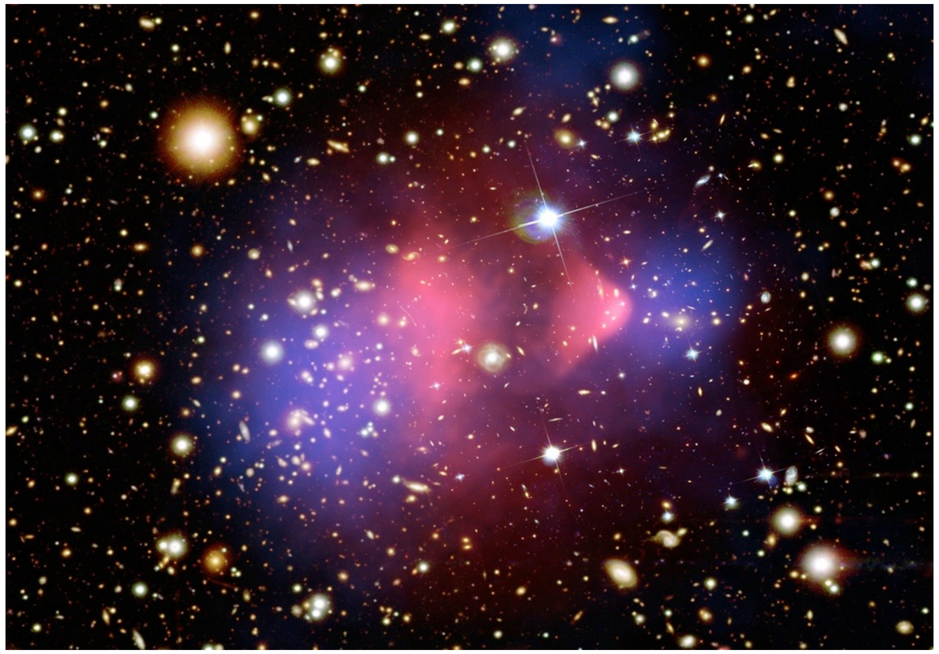
COFI Seminar, September 19, 2018

Andre de Gouvêa, Patrick J. Fox, Roni Harnik, Kevin J. Kelly, **YZ**
(arXiv:1809.06388)

What Is The Nature of Dark Matter?

Overwhelming evidence. All are gravitational effects.

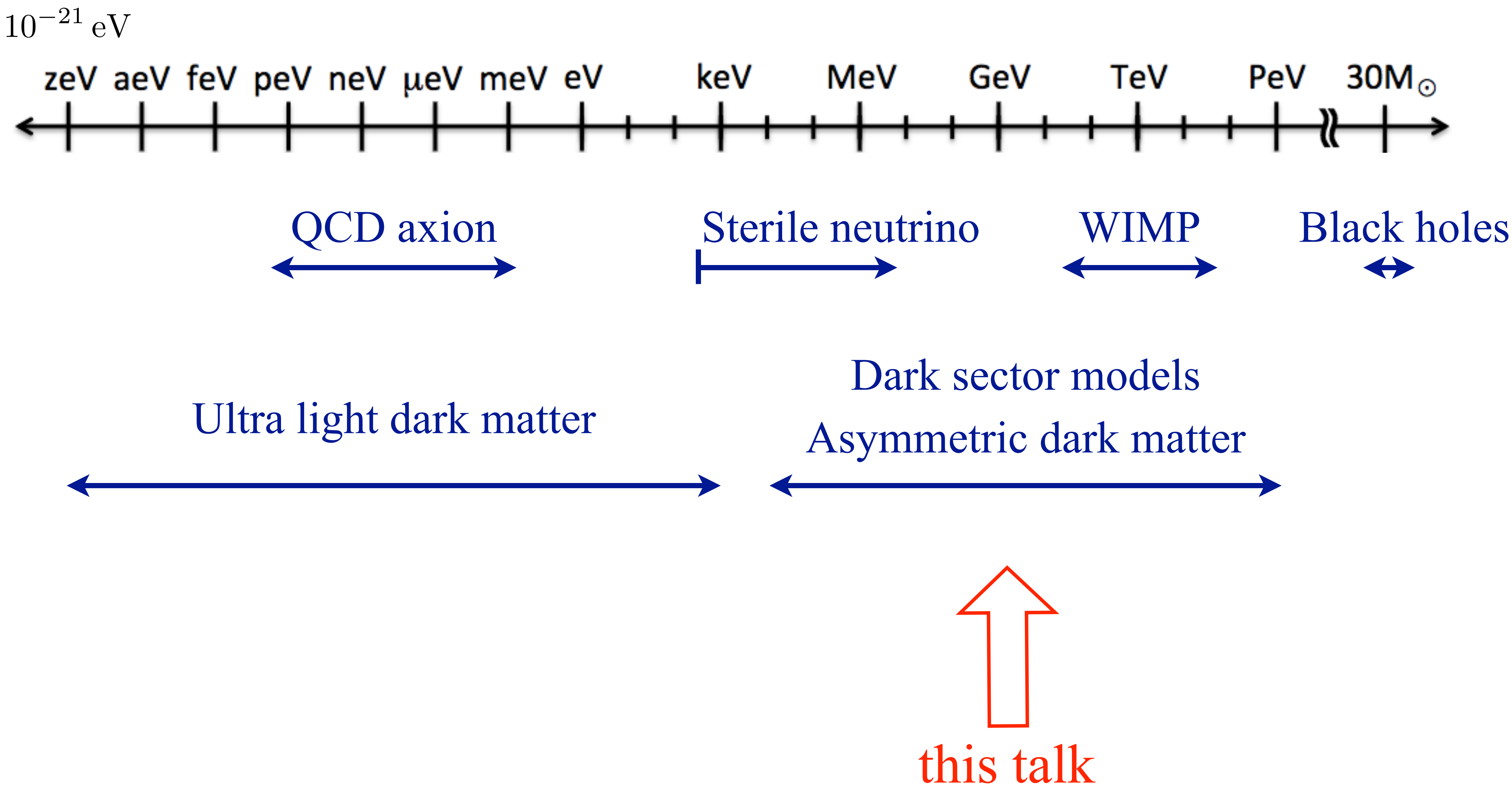
- Galactic rotational curves
- Bullet cluster
- Gravitational lensing
- Large scale structure & CMB



- $\Omega_{DM} \sim 0.26$
- Cosmologically long-lived
- Not relativistic
- Not too strongly interacting with us

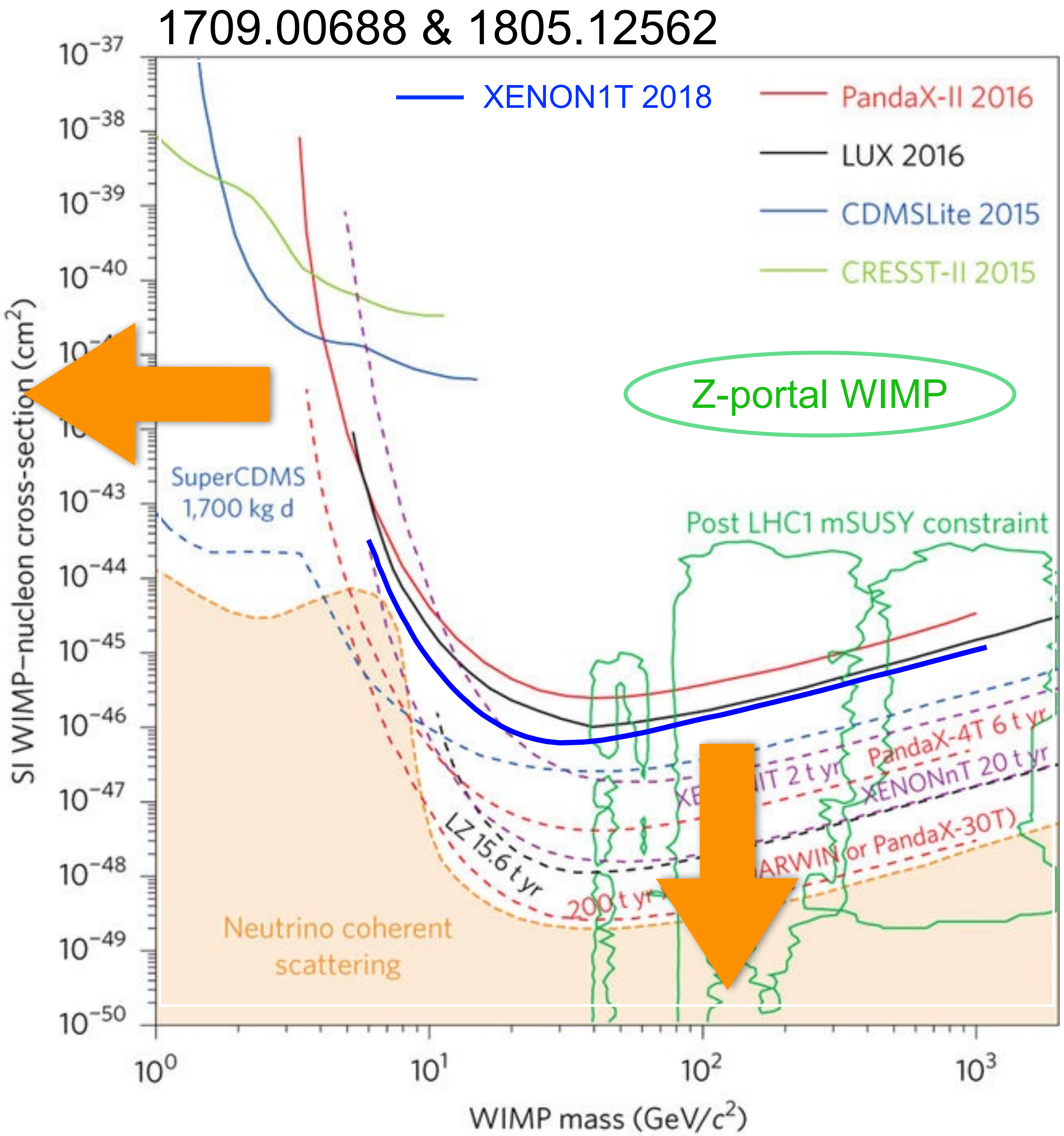
Is dark matter a particle? How can we detect it in labs?

Wide Range of Possibilities



US Cosmic Visions Community Report (1707.04591)

WIMP Seems Hard To Find



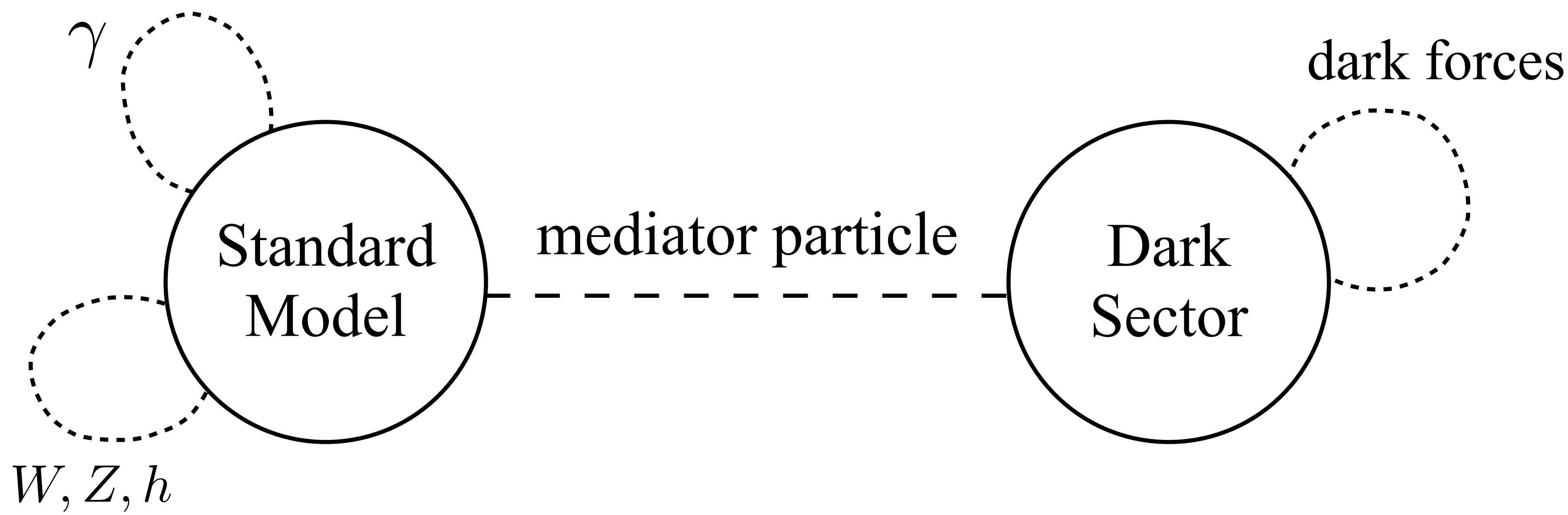
Useful to think broadly various possibilities of dark matter and where to look for it.

- WIMP: be patient.
- Other theories.

New DM signals?

Dark Matter From Dark Sector

Dark sector particles are all SM singlets. SM particles are also singlets under possible dark gauge interactions.



Mediator = dark photon, dark scalar, right-handed neutrino, etc.

Dark Sector: Motivations and a Lesson

Historically, dark sectors have been considered for many reasons: explore phenomena that cannot be accommodated by the WIMP

- Sommerfeld enhanced DM annihilation inspired by PAMELA, AMS-02.
- Light DM inspired by DAMA, CoGeNT, etc.
- Asymmetric DM for relic density observations.
- Strong self-interaction inspired by small scale structure puzzles.
- Dark forces make dark matter bound states (from onium to nuggets).

Wise, **YZ** (1407.4121, 1411.1772)

A new territory to imagine & explore new experimental signals

New Dark Matter Signals

Traditional methods (direct/indirect detection, colliders), have been envisioned from WIMP. Dark sector theories has the freedom to accommodate brand new dark matter signals.

Broaden the missions of the ongoing & near future experiments built for other reasons — they may be the correct DM detector.

In this talk, I will discuss exploring

new dark matter signals

in neutrino detectors.

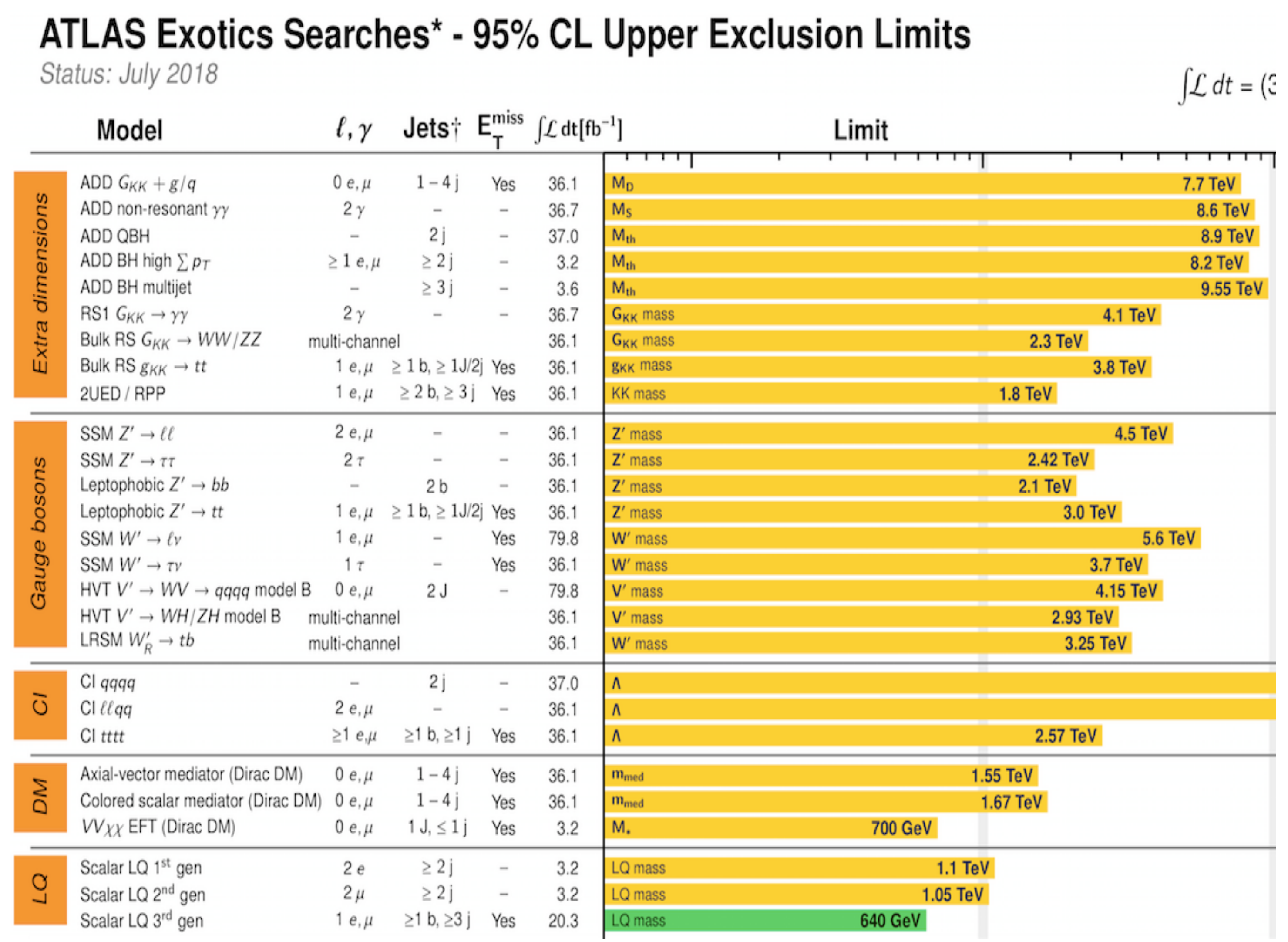
Neutrino Detectors

Large volume: MicroBooNE: 89 ton Borexino: 278 ton
DUNE: 40 kilo-ton Super-K: 220 kilo-ton

Let them also be dark matter detectors!

Analog of ATLAS and CMS detectors for the LHC.

It will be useful to also make neutrino detectors multi-purpose.



Challenges

Neutrino detectors typically have larger energy thresholds compared to dark matter detectors.

$E^{\rm th}_{\nu-\rm detector} \sim$ MeV — often too high to detect WIMP particles.

Available recoil energy in WIMP detection:

$$E = \mu v^2 = 10^{-6}\mu \lesssim \text{a few hundred keV} < E^{\rm th}_{\nu-\rm detector}$$

Exception: $E^{\rm th}_{\rm Borexino} \sim$ 200 keV, at the edge of kinematic limit, could amplify the annual modulation effect & sensitive to inelastic dark matter (Higgsino DM).

Eby, Fox, Harnik, Kribs (in preparation, private communication)

More Energetic Dark Matter Sources

A few avenues considered so far, beyond WIMP:

- Light dark matter produced in fixed target collisions

Batell, Pospelov, Ritz (0906.5614)
Izaguirre, Krnjaic, Schuster, Toro (1307.6554)

- Boosted dark matter from galactic center or the Sun

Agashe, Cui, Thaler (1405.7370)
Berger, Cui, Zhao (1410.2246)

- Self-Destructing Dark Matter scenario.

Grossman, Harnik, Telem, **YZ** (1712.00455)

Outline

In this talk, I will mainly focus on the possibility of producing light dark matter particles (beam) at neutrino experiments.

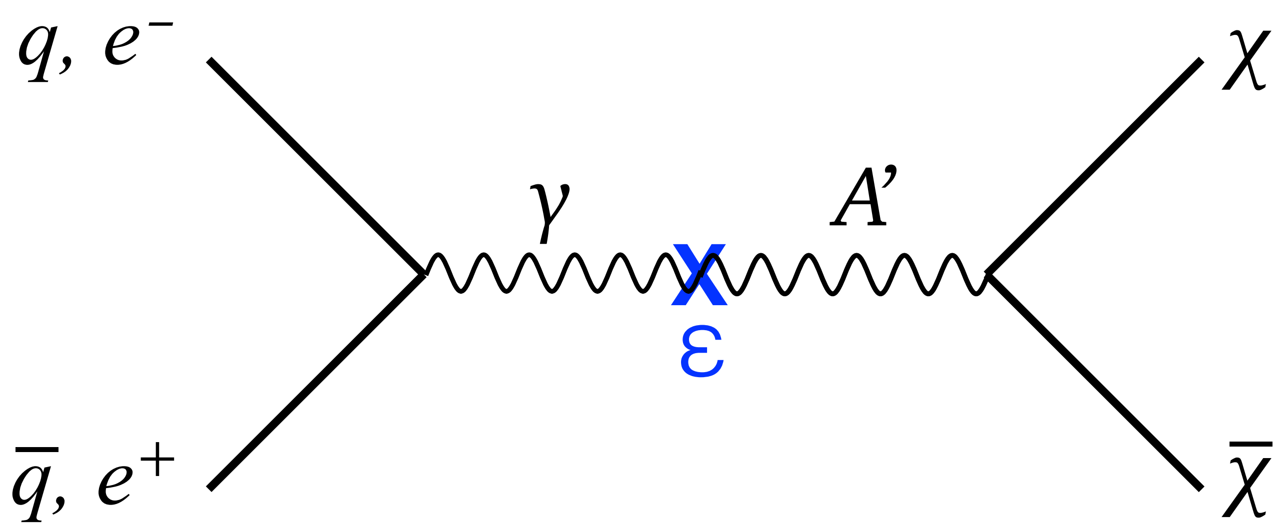
I will pay special attention to the experimental facilities (liquid argon detectors) on the Fermilab campus.

I will first review the existing works, and then point out and explore a class of new & exciting signals (the dark tridents).

The new signals are general and could be explored in similar experimental setups around the world.

Benchmark Model of Dark Sector

Counterpart of QED: dark photon *A'* portal to DM χ (fermion or scalar).



$$\mathcal{L}_{\rm int} = (\varepsilon e J^{\mu}_{\rm SM} + g_D \bar{\chi}\gamma^{\mu}\chi)\, A'_{\mu}$$

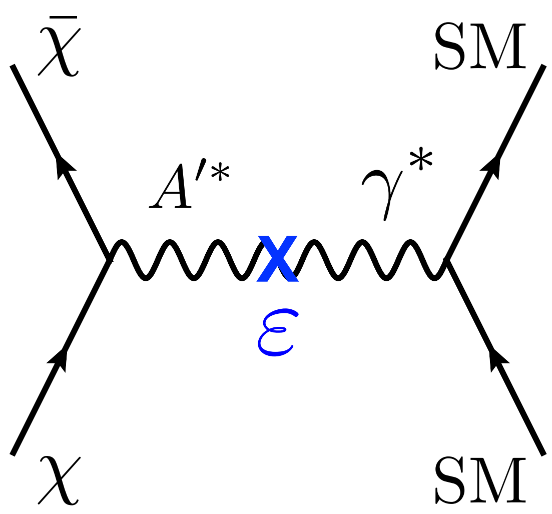
strong limits from dark photon searches

allowed to be sizable

To produce at neutrino experiments, require $M_\chi, M_{A'} < \mathrm{GeV}$

Early Universe Stories

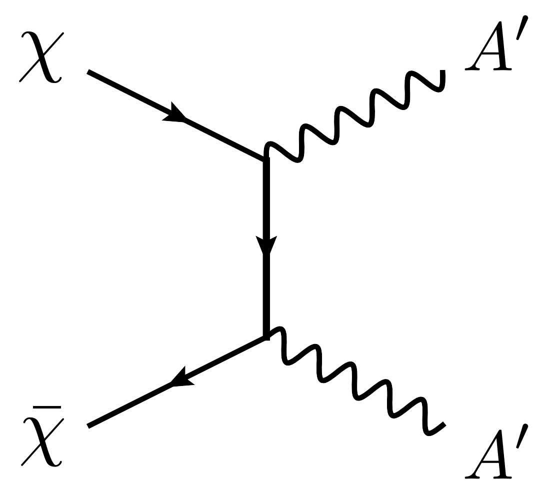
WIMP-like case: $m_\chi \ll m_{A'}$



$$\sigma_{\rm ann} v = \frac{6 g_D^2 M_\chi}{(4M_\chi^2 - M_{A'}^2)^2} \Gamma_{A'}(2M_\chi)$$

$$\propto \varepsilon^2$$

Secluded case: $m_\chi > m_{A'}$



$$\sigma_{\rm ann} v = \frac{g_D^4}{16\pi M_\chi^2} \frac{\left(1 - \frac{M_{A'}^2}{M_\chi^2}\right)^{3/2}}{\left(1 - \frac{M_{A'}^2}{2M_\chi^2}\right)^2}$$

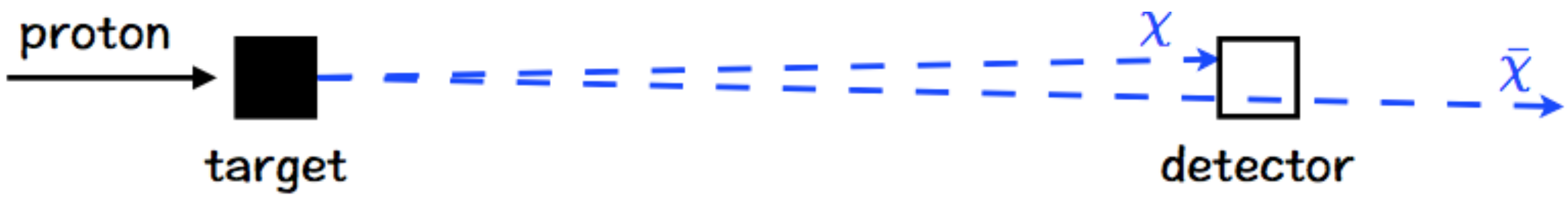
We will consider χ both as thermal relics and asymmetric dark matter.

Forbidden dark matter: $m_\chi \lesssim m_{A'}$.

Tito D'Agnolo, Ruderman (1505.07107)

Making and Detecting Dark Matter Beam

All studies in the literature assume a mass relation: $m_{A'} > 2m_\chi$



$$\pi^+ \to \mu^+ \nu_\mu \qquad\qquad \nu_\mu n \to \mu^- p,\ \nu_\mu n$$

$$\pi^0, \eta, \cdots \to \gamma A',\ A' \to \chi\bar{\chi} \qquad\qquad \chi p \to \chi p \quad (t\text{-channel } A')$$

Same signal as neutrino neutral-current interaction (background here).

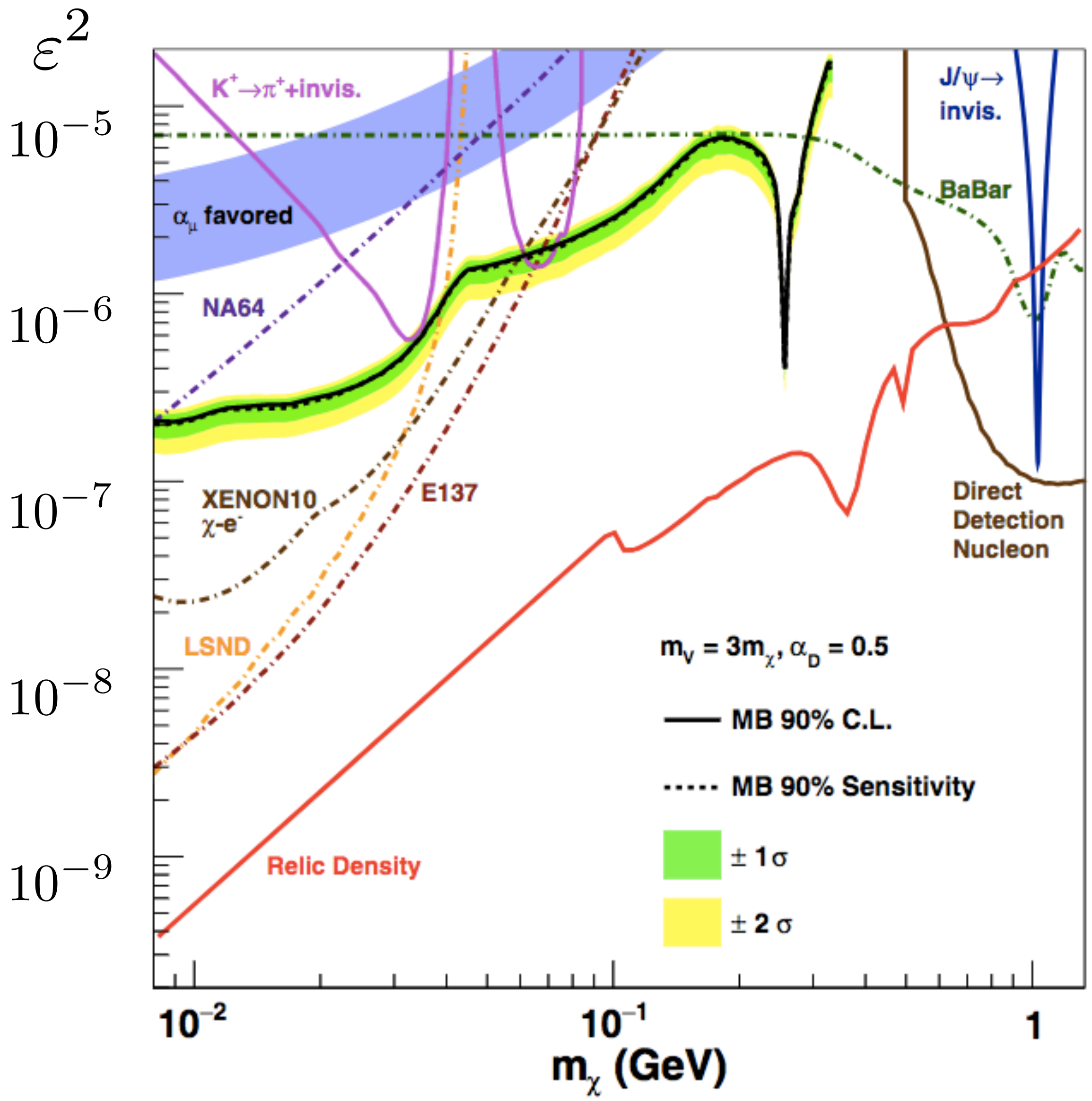
Flux ratio: $\dfrac{\Phi_\chi}{\Phi_\nu} \sim \varepsilon^2$

Scattering cross section ratio: $\dfrac{\sigma_{\chi p}}{\sigma_{\nu p}} \sim \dfrac{\varepsilon^2 e^2 g_D^2 / M_{A'}^4}{g^4/M_W^4}$

New physics important if $\varepsilon \gtrsim \dfrac{M_{A'}}{\sqrt{g_D} M_W} \sim 10^{-3} \left(\dfrac{1}{g_D}\right)^{1/2} \left(\dfrac{M_{A'}}{100\,\mathrm{MeV}}\right)$

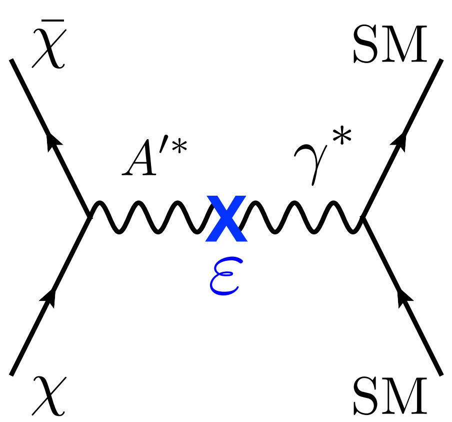
Batell, Pospelov, Ritz (0906.5614)

A Result From MiniBooNE



$\alpha_D = 0.5$

$M_{A'} = 3M_\chi > 2M_\chi$



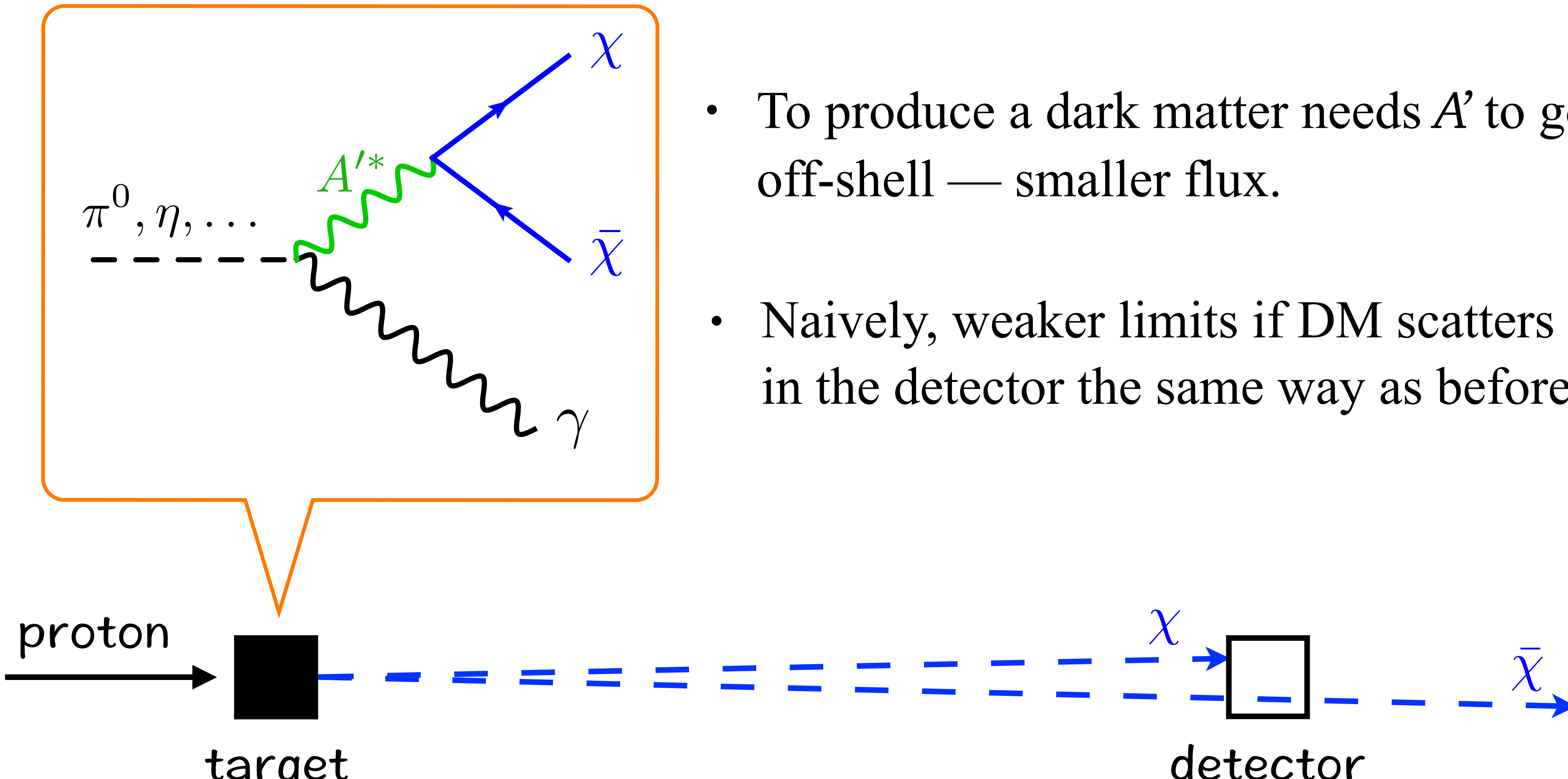
thermal freeze out channel

Beam dump mode run in 2012-13. Look for nuclear (electron) recoils.

MiniBooNE-DM Collaboration (1702.02688 & 1807.06137)

The Complimentary Region

I will next focus on: $m_{A'} < 2m_\chi$ — unexplored region in the literature. *A’* is kinematically forbidden to decay into dark matter.



- To produce a dark matter needs *A’* to go off-shell — smaller flux.
- Naively, weaker limits if DM scatters in the detector the same way as before.

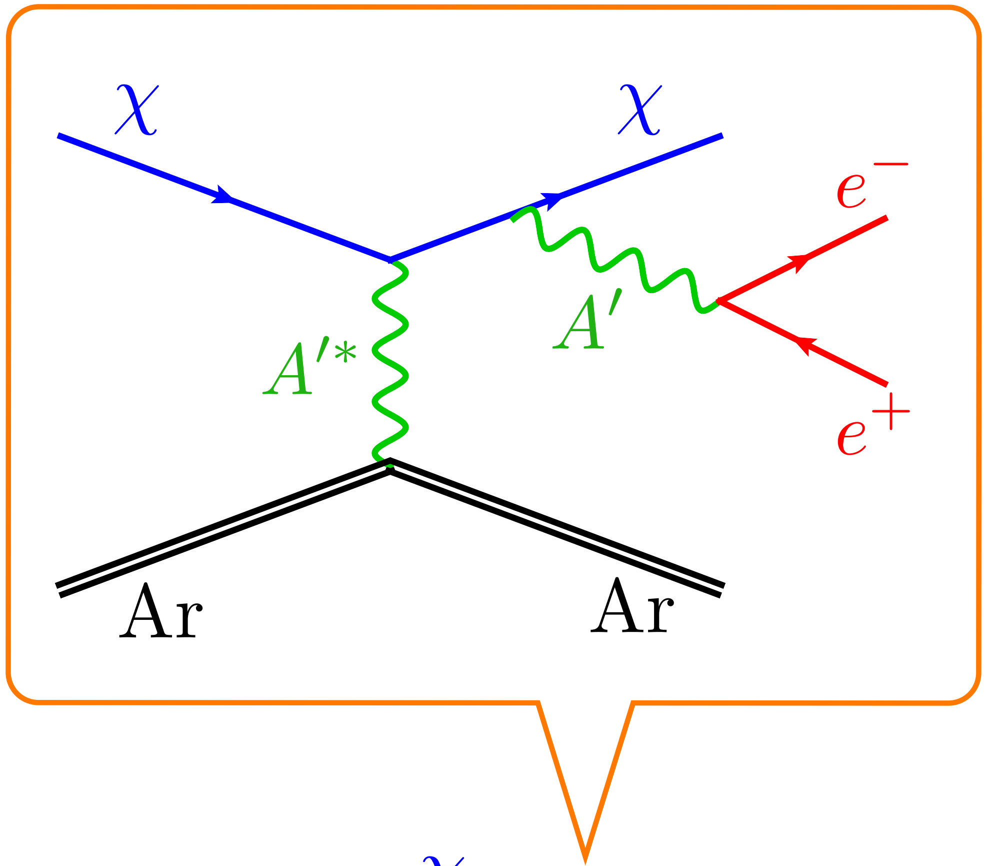
Dark Matter Trident Production

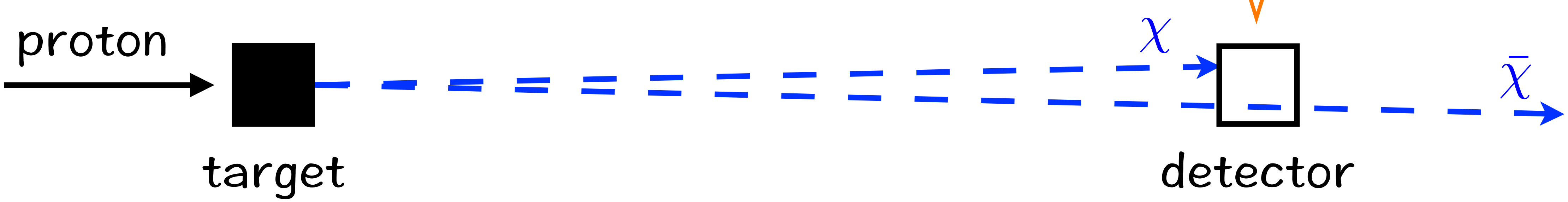
Beyond elastic scattering: consider *A'* radiations. *A'* has to decay back into SM. Take advantage of its visible decay feature.

Signal: charged-lepton pair creation.

$$\frac{\sigma_{\chi N \to \chi N + A'}}{\sigma_{\chi N \to \chi N}} \sim \frac{\alpha_D}{2\pi} \log \frac{Q^2}{M_{A'}^2}$$

Dark showers possible in the large α_D and large *log* limit.

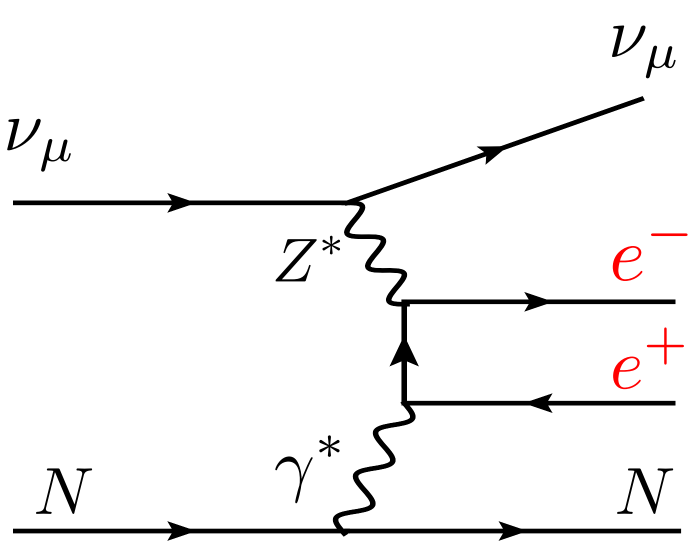




de Gouvêa, Fox, Harnik, Kelly, **YZ** (1809.06388)

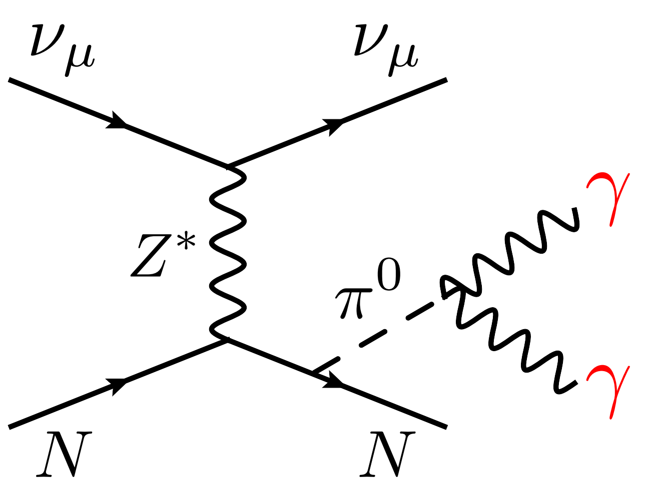
Background and Useful Cuts

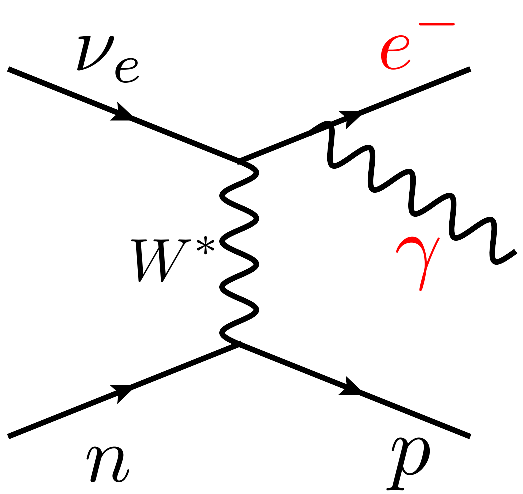
Neutrino trident production



$\sigma_{\nu\text{-trident}} \sim 10^{-5}\sigma_{\rm NC}$

Fake signals



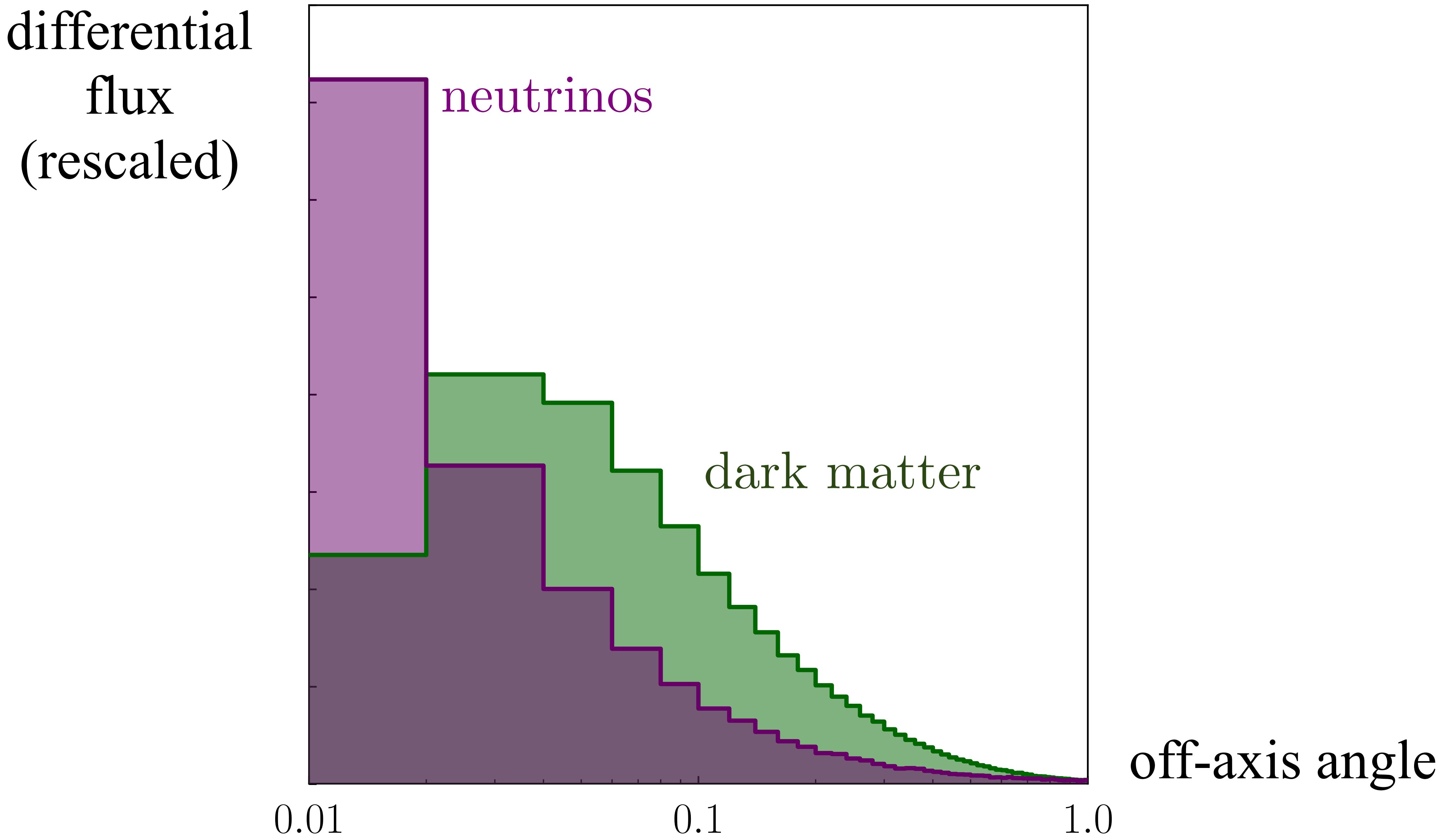


Require good particle ID (LArTPC)

Invariant mass: $m_{e^+e^-} = m_{A'}$ for dark matter trident signal.

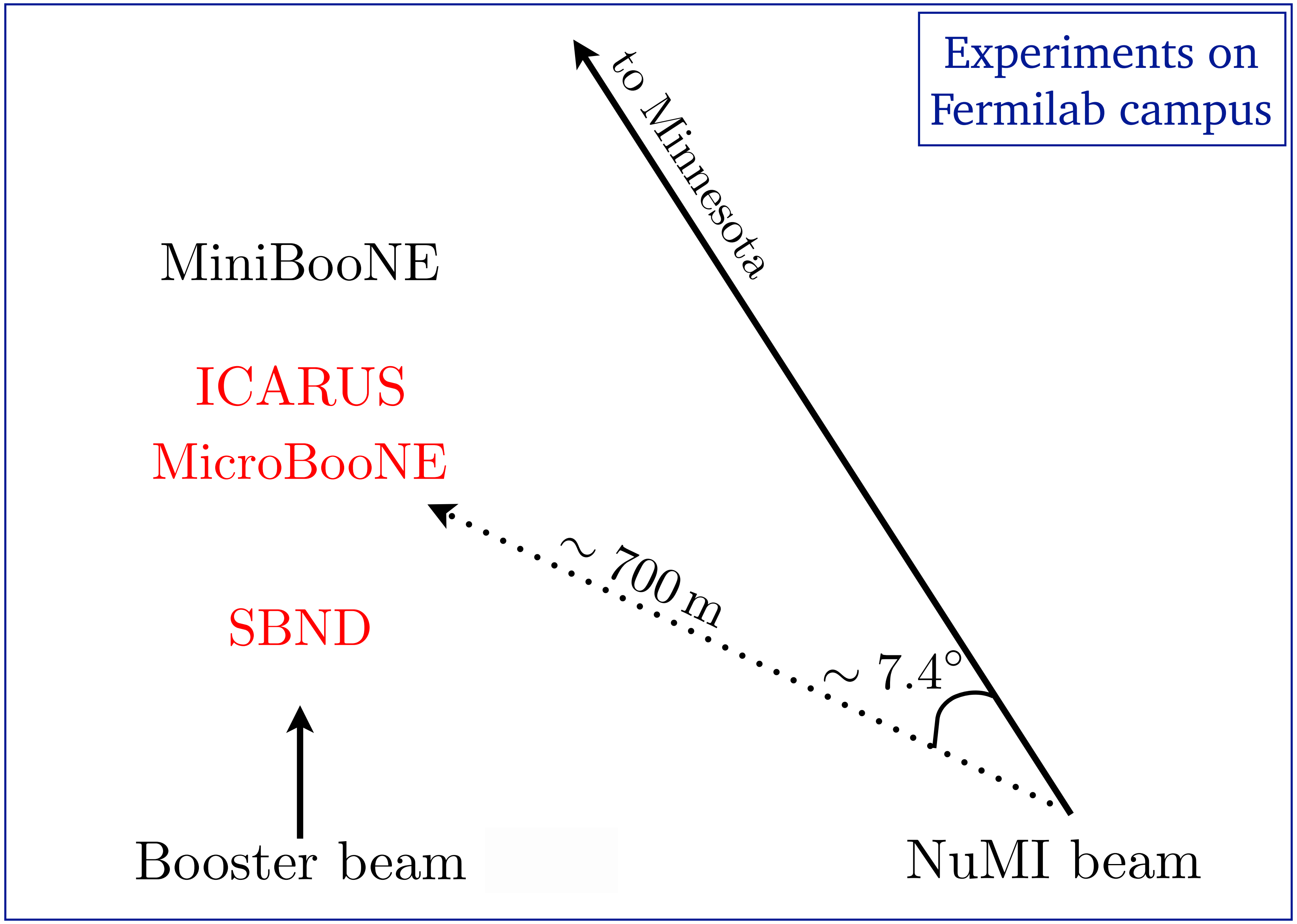
Off-axis detector with respect to neutrino beam direction can help suppress neutrino to DM flux ratio.

Dark Matter *vs.* Neutrino Fluxes



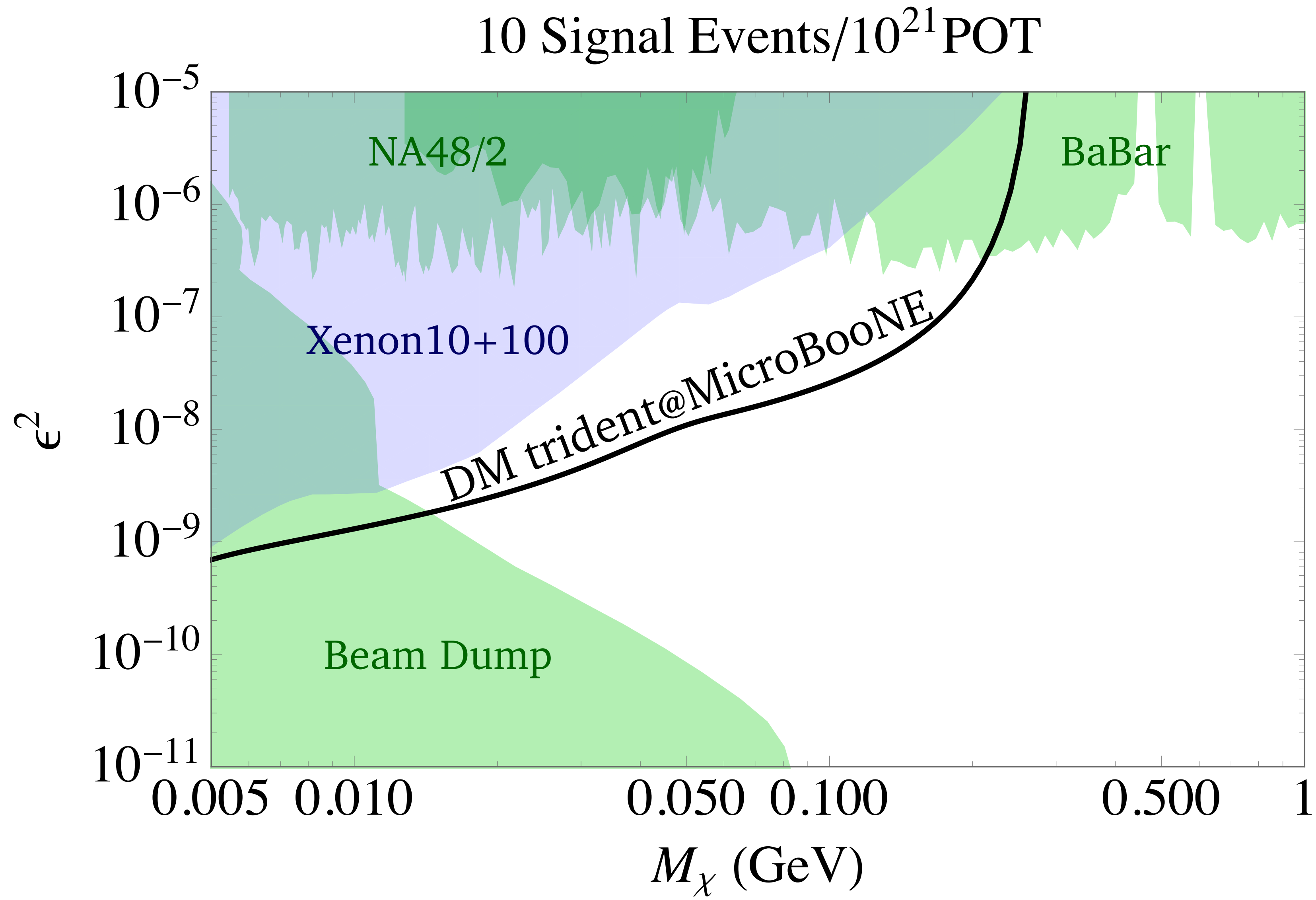
de Gouvêa, Fox, Harnik, Kelly, **YZ** (1809.06388)

A Useful Limit May Already Exist



Since MicroBooNE began taking data in 2015, NuMI has delivered $\sim 10^{21}$ POT. ν-related background events are estimated to be $\lesssim O(10)$.

Dark Trident: A Theorist's Limit

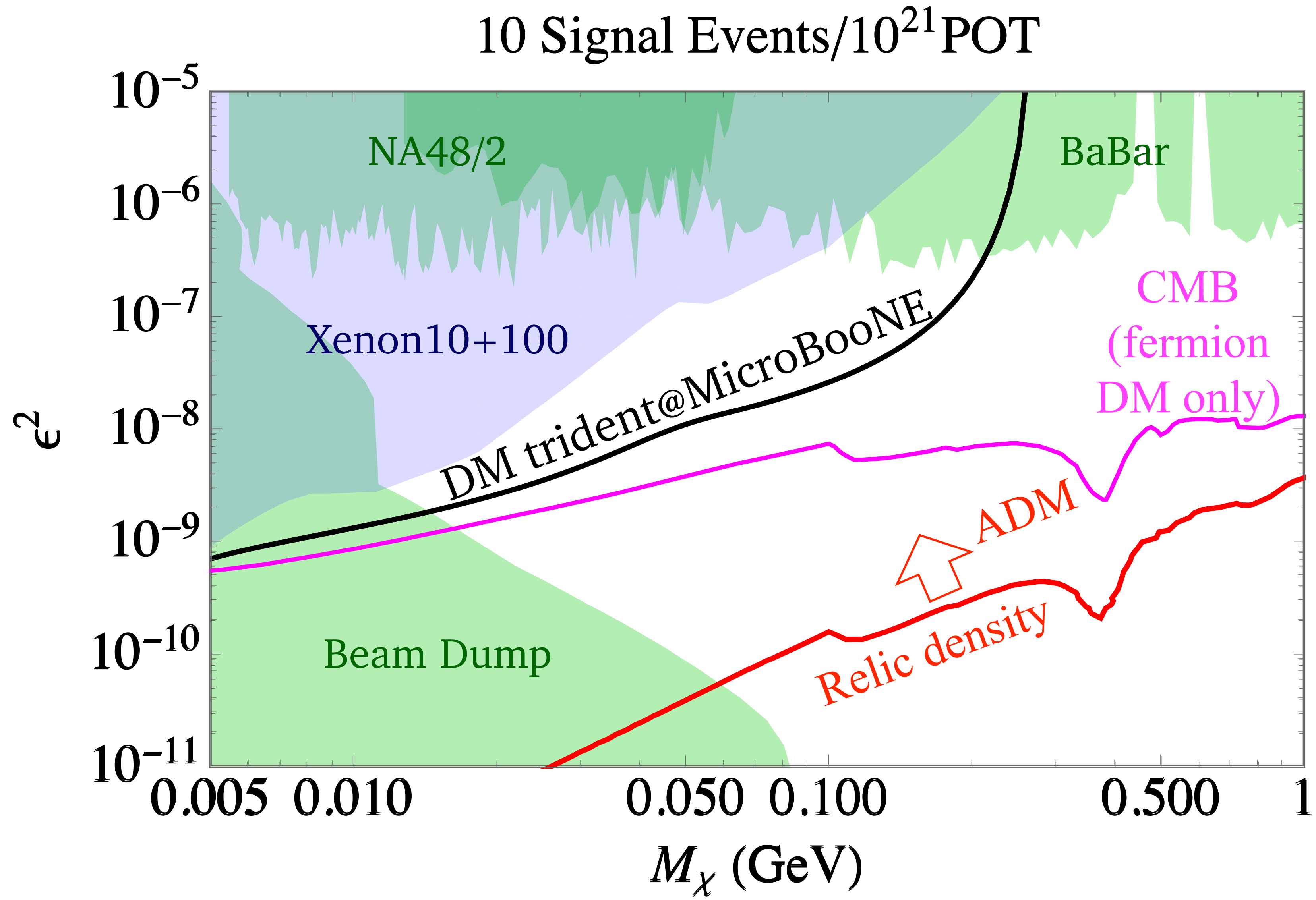


$\alpha_D = 0.5$

$M_{A'} = 3M_\chi/2 < 2M_\chi$

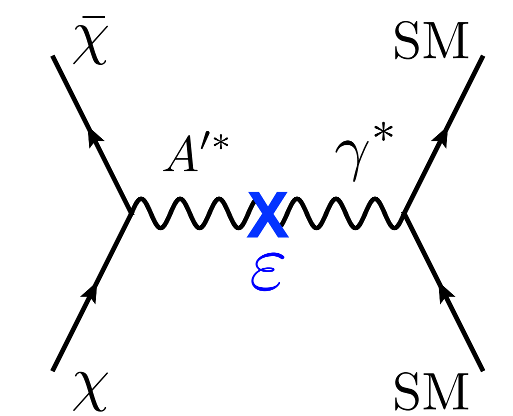
de Gouvêa, Fox, Harnik, Kelly, **YZ** (1809.06388)

Dark Trident: A Theorist's Limit



$\alpha_D = 0.5$

$M_{A'} = 3M_\chi/2 < 2M_\chi$

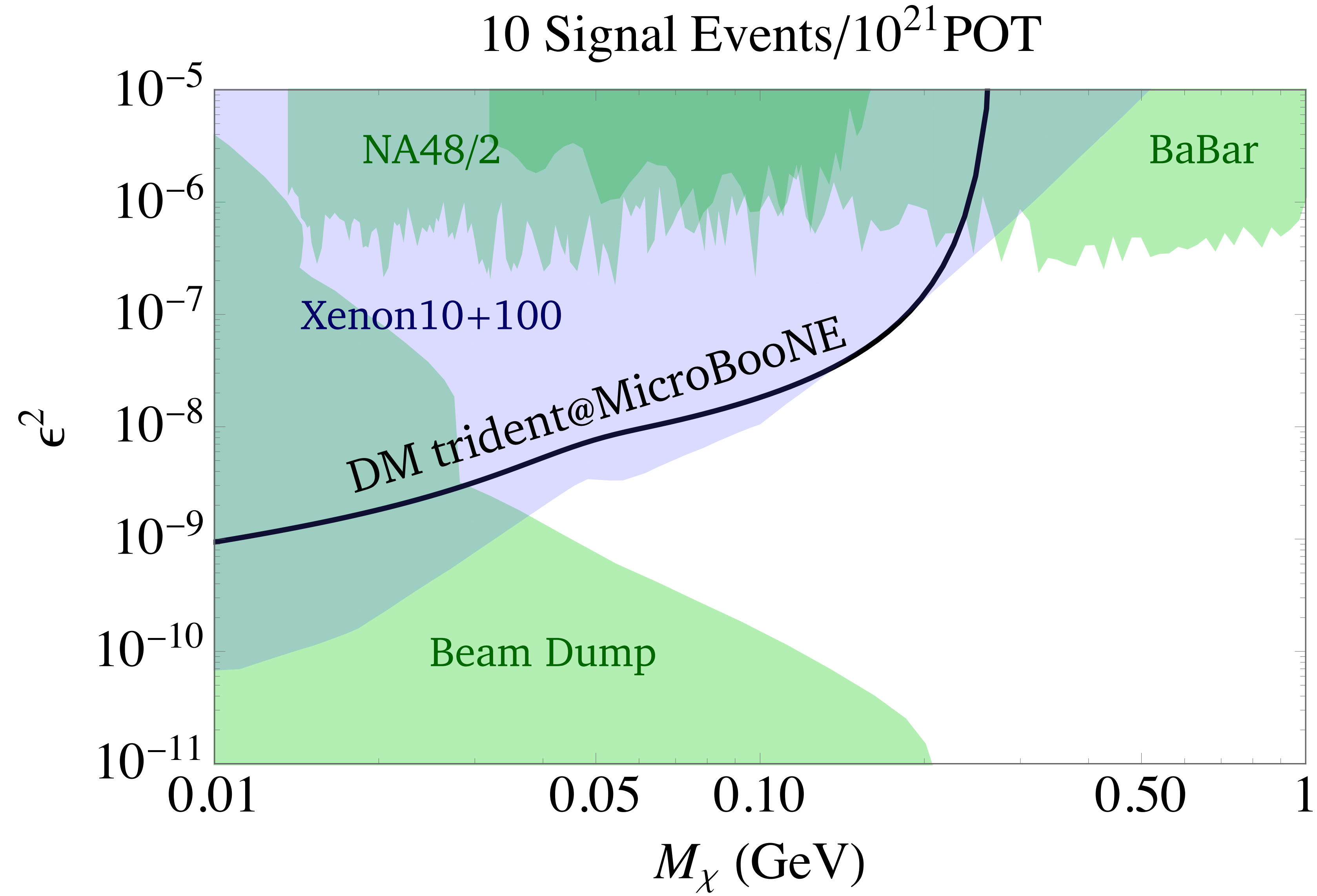


freeze out channel

- CMB constraint applies to Dirac fermion DM but not to complex scalar.
- Similar results also apply to asymmetric dark matter scenario.

de Gouvêa, Fox, Harnik, Kelly, **YZ** (1809.06388)

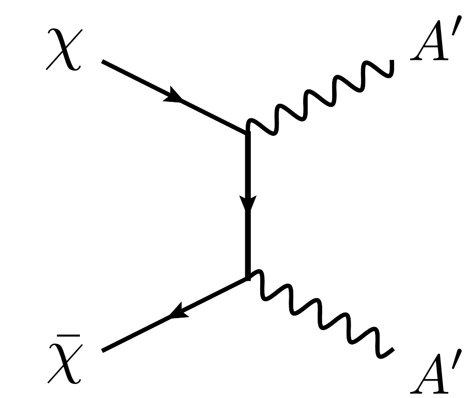
Dark Trident: A Theorist's Limit



Secluded scenario:

$\alpha_D = 0.5$

$M_{A'} = M_\chi/2$

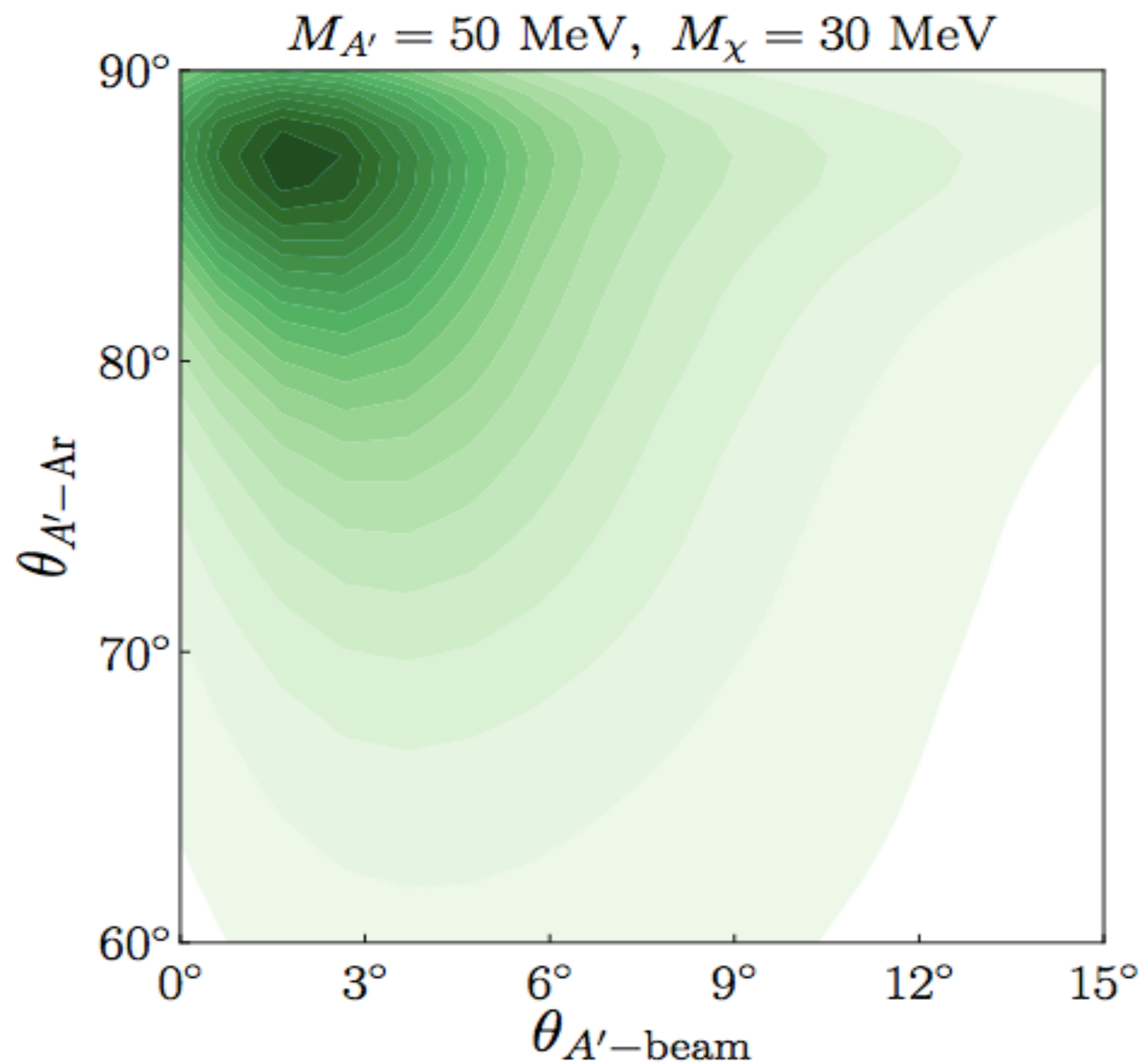


freeze out channel

Dominant annihilation: $\chi\bar{\chi} \to A'A'$. A positive discovery of ε away from the thermal targets could differentiate DM production mechanisms.

de Gouvêa, Fox, Harnik, Kelly, **YZ** (1809.06388)

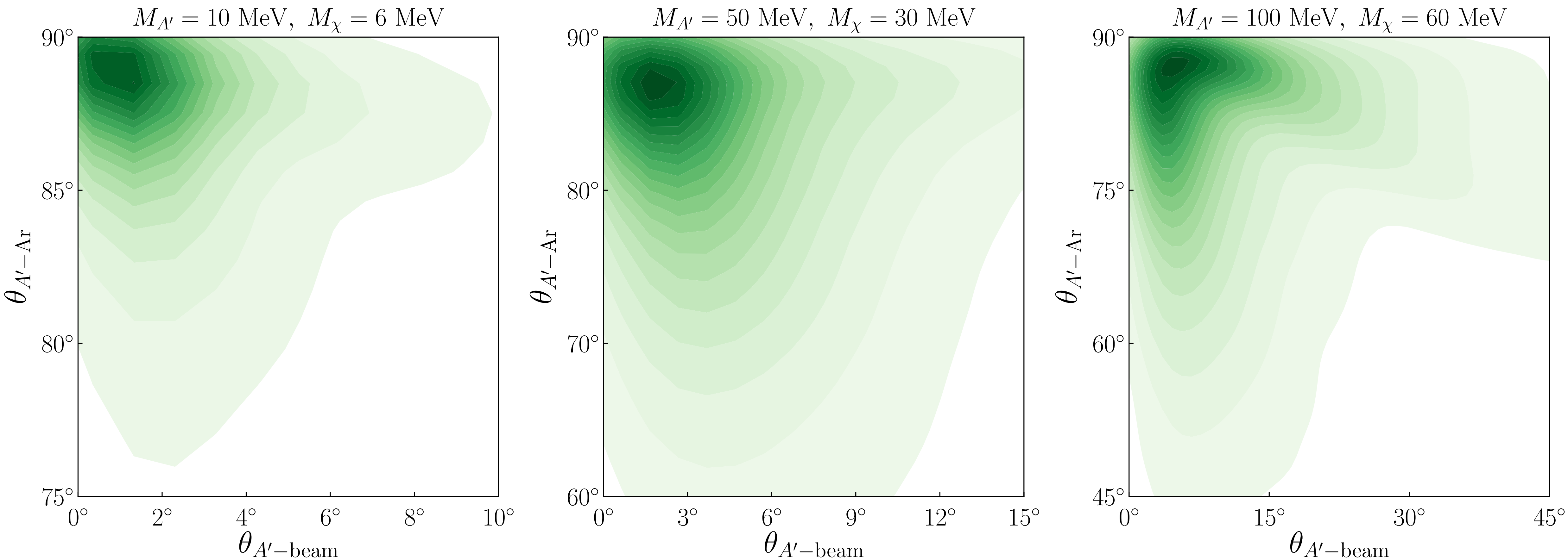
A Closer Look: angular distributions



Interestingly, outgoing *A'* most likely to travel along beam direction, with nuclear recoil perpendicular to beam direction.

de Gouvêa, Fox, Harnik, Kelly, **YZ** (1809.06388)

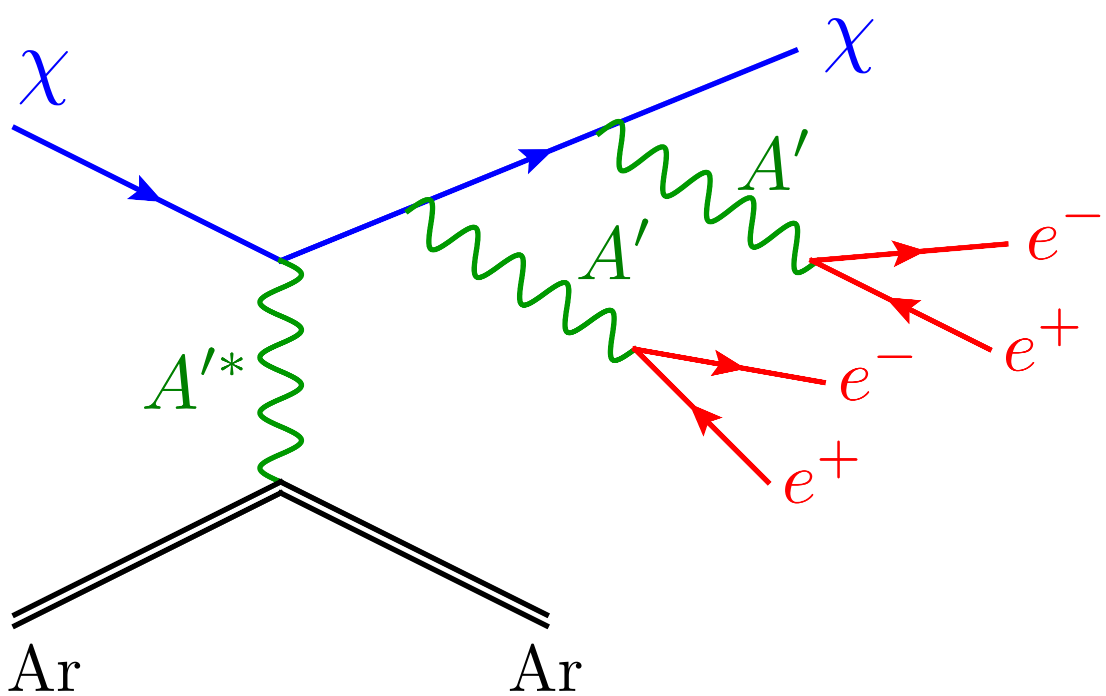
A Closer Look: angular distributions



This is a generic feature that applies to all mass ranges we explore.

de Gouvêa, Fox, Harnik, Kelly, **YZ** (1809.06388)

Beyond Trident: multiple *A'* emission



$M_{A'}$ (MeV)	M_χ (MeV)	$N_{n=2}/N_{n=1}$
100	60	$0.06\,\alpha_D$
50	30	$0.14\,\alpha_D$
10	6	$0.38\,\alpha_D$

- Large decay angles: observe multiple charged-lepton pairs.
- Collimated decays: liquid argon detectors capable of better measuring *dE/dx*, observe exotic tracks.

de Gouvêa, Fox, Harnik, Kelly, **YZ** (1809.06388)

Conclusion and Outlook

Although dark matter exists, it has not been rediscovered in laboratories, strongly suggests beyond existing approaches.

Cast a wide net: I have argued for broaden the missions of ongoing and near-future neutrino experiments.

I discussed new DM signals inside neutrino near detectors. Dark Tridents: charged-lepton pair(s) creation.

SBN program has promising opportunity of probing dark tridents.

Exciting discoveries are awaiting us.

thanks!