# Searching for Low-Mass Dark Matter at Neutrino Experiments

TEXAS A&M UNIVERSITY
Physics & Astronomy

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In collaboration with B. Dutta, S. Liao, J.-C. Park, S. Shin, L. Strigari, and A. Thompson [PRL 124 (2020) 12, 121802; arXiv:2006.09386]
V. Brdar, B. Dutta, W. Jang, I. Shoemaker, Z. Tabrizi, A. Thompson, and J. Yu, in progress

# Contents

## Part I: Review on Dark Matter

- ✓ Motivation for dark matter, known properties of dark matter, WIMP dark matter candidate, dark matter searches, …

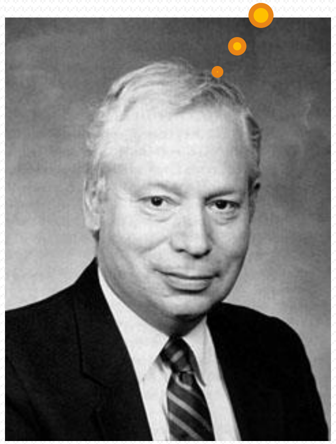
## Part II: Low-Mass Dark Matter Searches at Neutrino Facilities

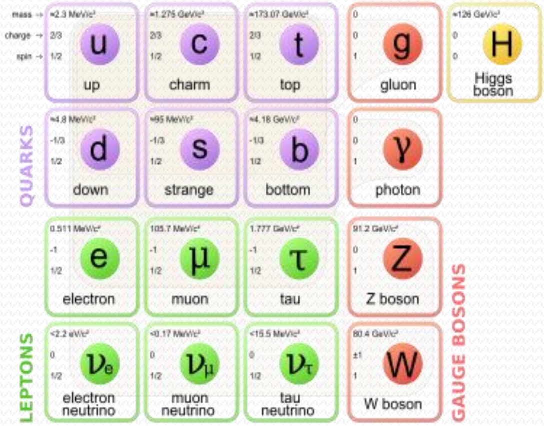
- ✓ Motivation for light dark matter, COHERENT and DUNE experiments, production of LDM, search strategy (timing information), backgrounds, sensitivity reaches, …

# Eternal Question

What is the Universe made of?

Standard Model!



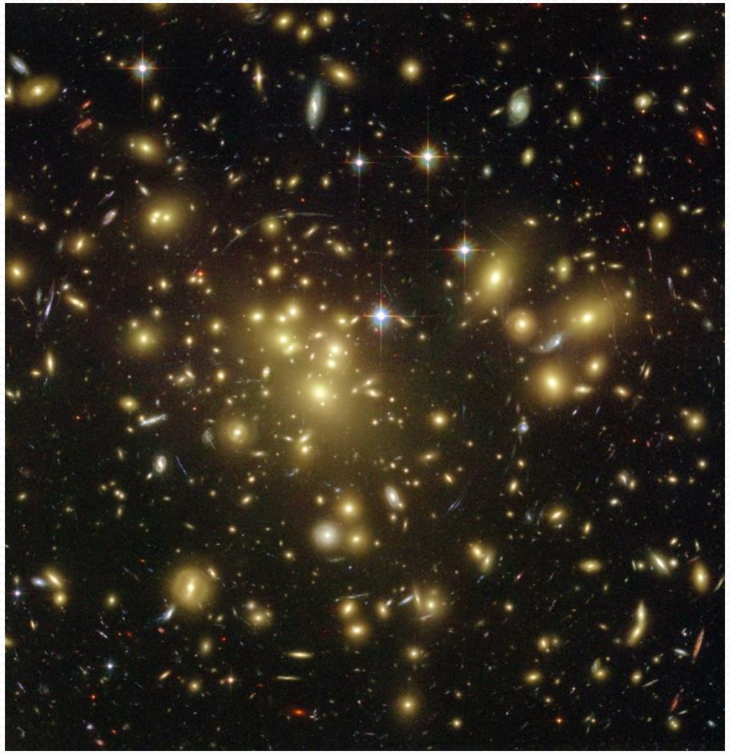



- ❑ Particle Physics: the branch of physics that deals with the properties, relationships, and interactions of subatomic particles.

Not the end of story ⇒ **more to explore** including **Dark Matter!!**

# Motivation for Dark Matter

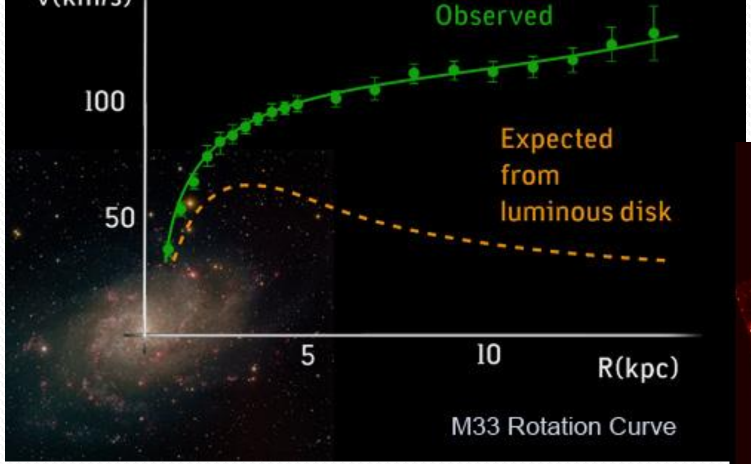
- The modern problem of DM: conceptually very similar to the old problem of unseen planets (e.g., discovery of Neptune)
  - ✓ Observing large scale of astrophysical systems from galactic to astrophysical scales
  - ✓ Some "**anomalies**" observed
  - ✓ Explaining them by assuming the existence of unseen objects $\Rightarrow$ **Dark Matter**



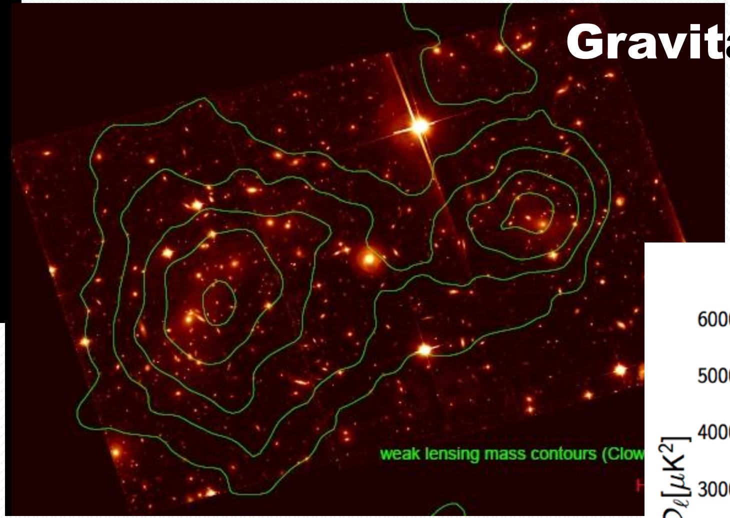
[Abell 1689 by Hubble Space Telescope]

# Evidence

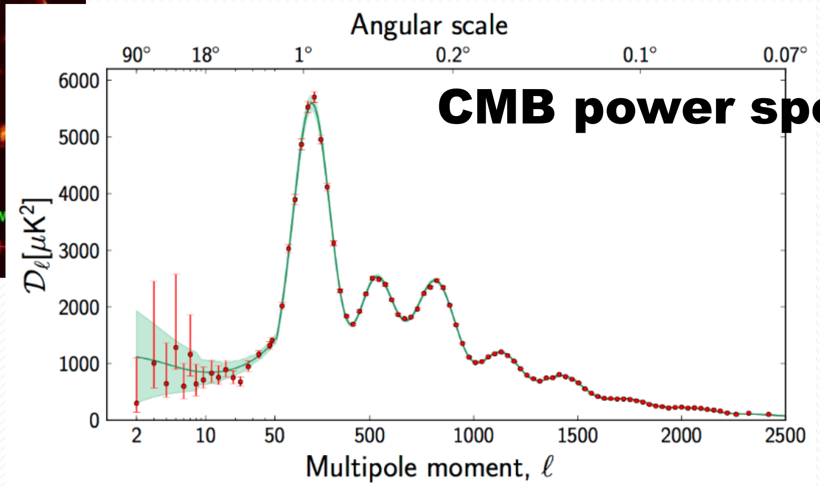
**Rotation curves**




**Gravitational lensing**

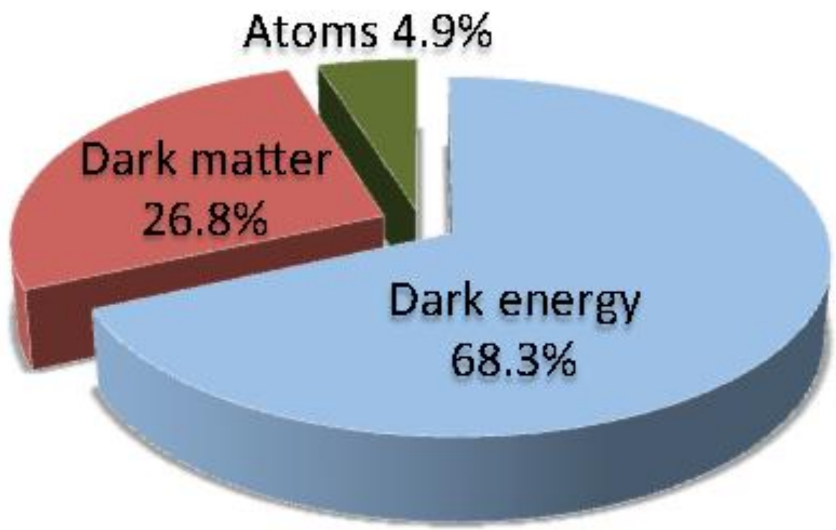



**CMB power spectrum**



# Energy Budget

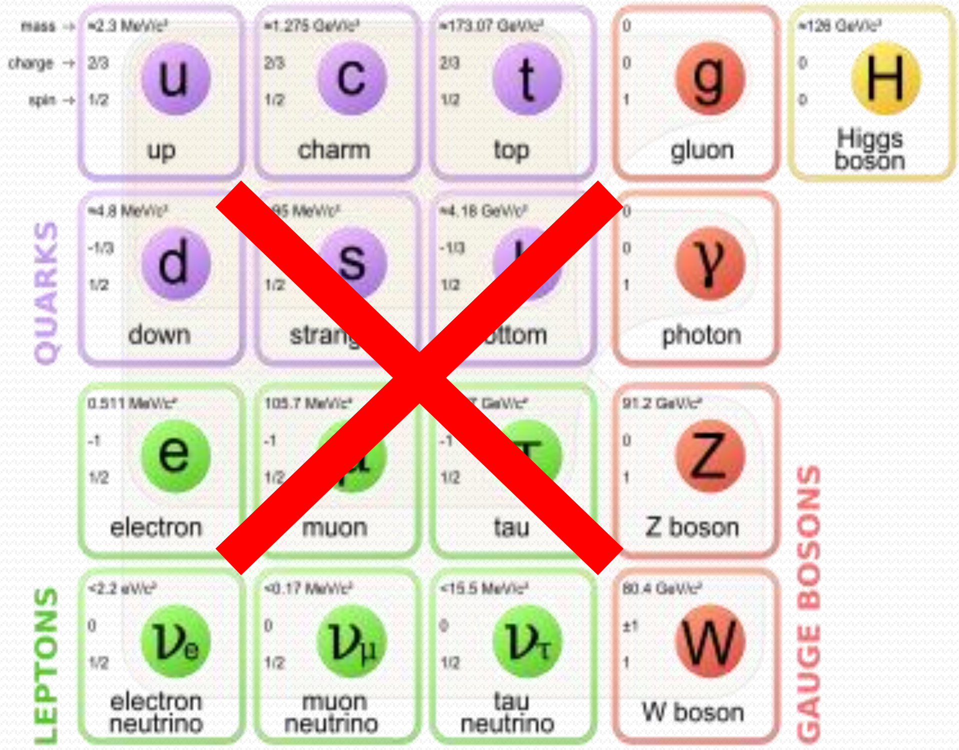
- ~5 % : Baryonic matter (stars, luminous gas, radiation, intergalactic gas, neutrinos, super massive black holes, etc.)
- ~27 %: Dark matter (not identified yet)
- ~68 %: Dark energy (not identified yet)




**Large majority unidentified!**

# Properties of Dark Matter

- Some of the DM properties known (albeit few):
  - Gravitationally interacting (although strength is tiny)
  - Not short-lived (i.e., stable to survive for a long time)
  - Not hot (i.e., non-relativistic)
  - Not baryonic (not made of ordinary matter)
  - Not electrically charged (otherwise, already detected)

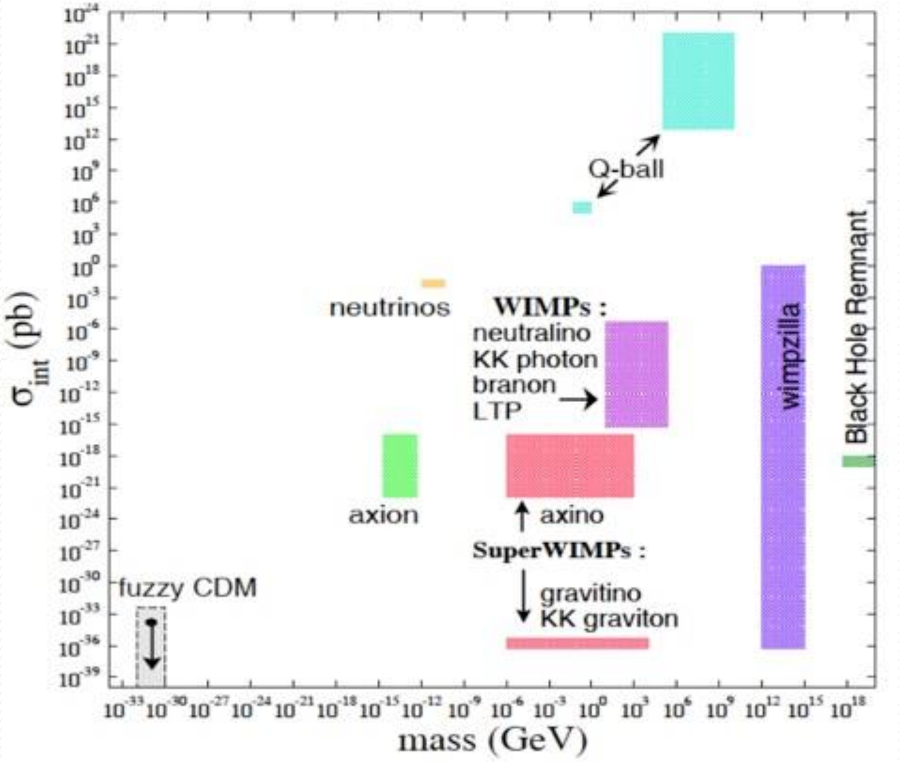



⇒ Need for **new physics/particles**

# Dark Matter Zoo

❑ There are many DM candidates depending on models/scenarios.

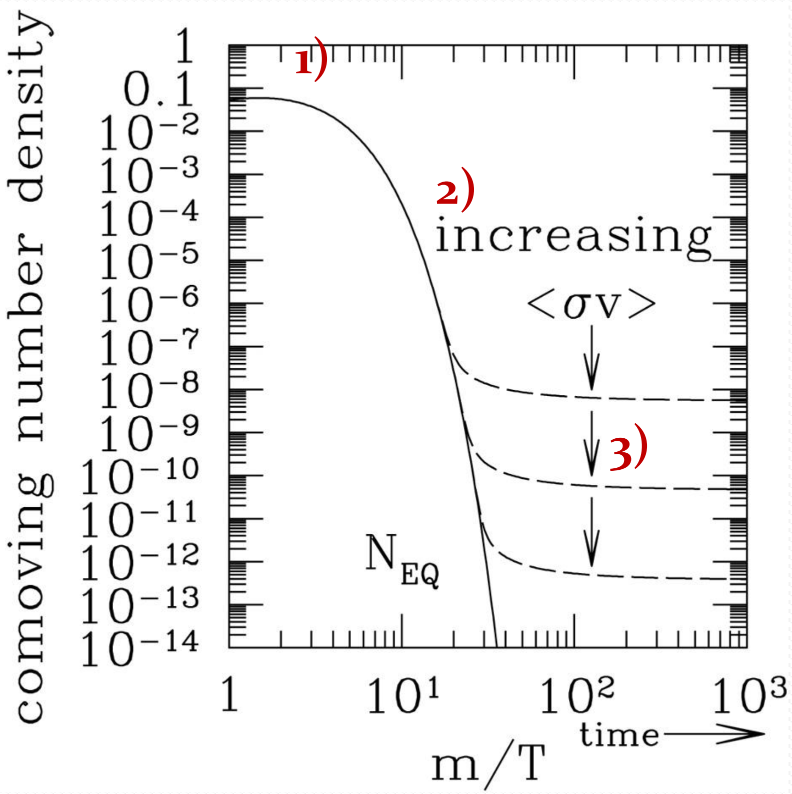
- Sterile neutrinos
- Axion
- WIMPs
- WIMPzillas
- Q-balls
- Gravitinos
- etc.




HEPAP/AAAC DMSAG Subpanel (2007)

In particular, ***Weakly Interacting Massive Particles (WIMPs)*** are well-motivated.

# WIMP Freeze-Out




1) Early universe: creation and annihilation processes in thermal equilibrium

   DM DM ↔ SM SM

2) When temperature drops below the DM mass, DM exponentially depleted because

   DM DM → SM SM (still allowed)

   SM SM → DM DM (kinematically forbidden)

3) When density becoming too sparse → hard to find other DM to get annihilated with

   → **Thermal Freeze-out!!**

# WIMP Miracle

- More technical calculation

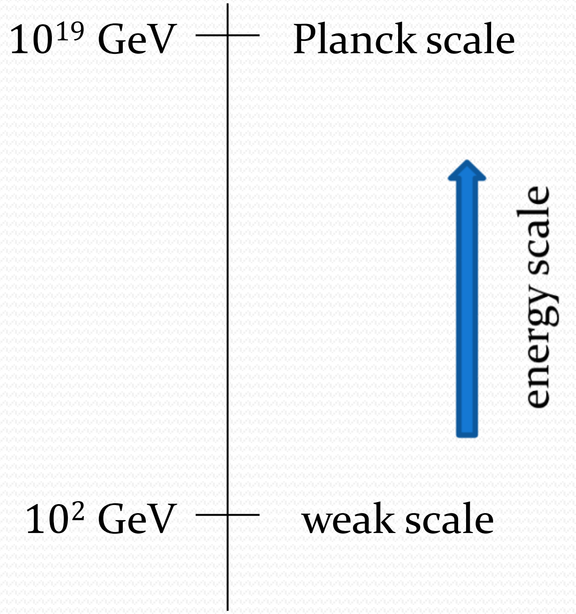
$$\Omega_{DM} \propto \frac{1}{<\sigma v>} \sim \frac{m_{DM}^2}{g^4}$$

$m_{DM}$: dark matter mass

$g$: the relevant coupling strength

- Surprisingly, $m_{DM} \sim 100$ GeV, i.e., weak scale

  → natural need for new physics at the weak → **WIMP Miracle!!**




- Particle physics motivating new physics at the weak scale by different/independent reasons (e.g., gauge hierarchy problem)

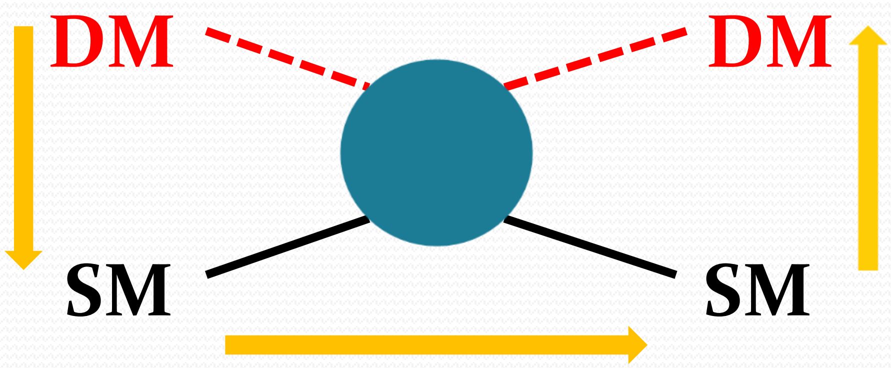
# Detecting Dark Matter

❑ Assuming that DM interacts non-gravitationally with known particles (Standard Model)

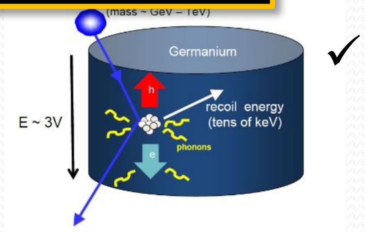
**DM indirect search**

✓ (Non-relativistic) DM annihilation/decay to $\gamma, e^+, \bar{p}$, etc.

✓ $\langle \sigma v \rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$




**DM direct search**




✓ (Non-relativistic) DM scattering off target nuclei

✓ $E_{\mathrm{recoil}} \sim 1 - 100\ \mathrm{keV}^{\dagger}$

**DM production**

✓ Active DM production at colliders

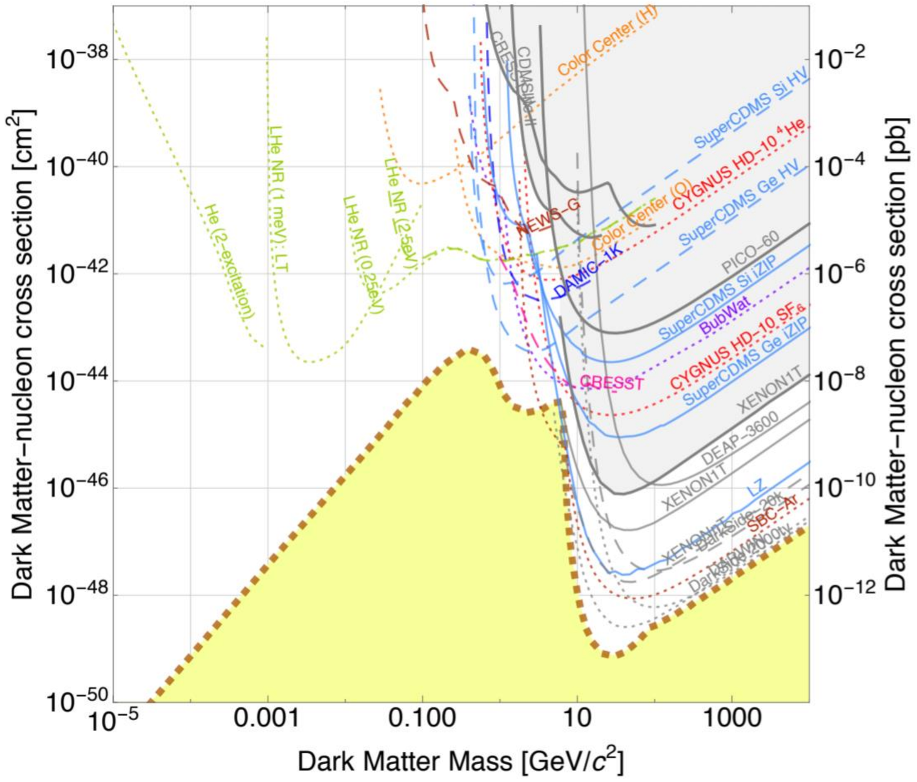
✓ Mono-X searches

✓ Expected rate inferred from/related to $\langle \sigma v \rangle \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

# Current Status of Dark Matter Searches

❑**No observation** of DM signatures via non-gravitational interactions while many searches/interpretations designed/performed under nonrelativistic WIMP/WIMP-like scenarios

$\Rightarrow$ merely excluding more parameter space in dark matter models




[US Cosmic Visions, Battaglieri et al (2017)]

***Time to pause, rethink and redesign our approach/search strategies!***

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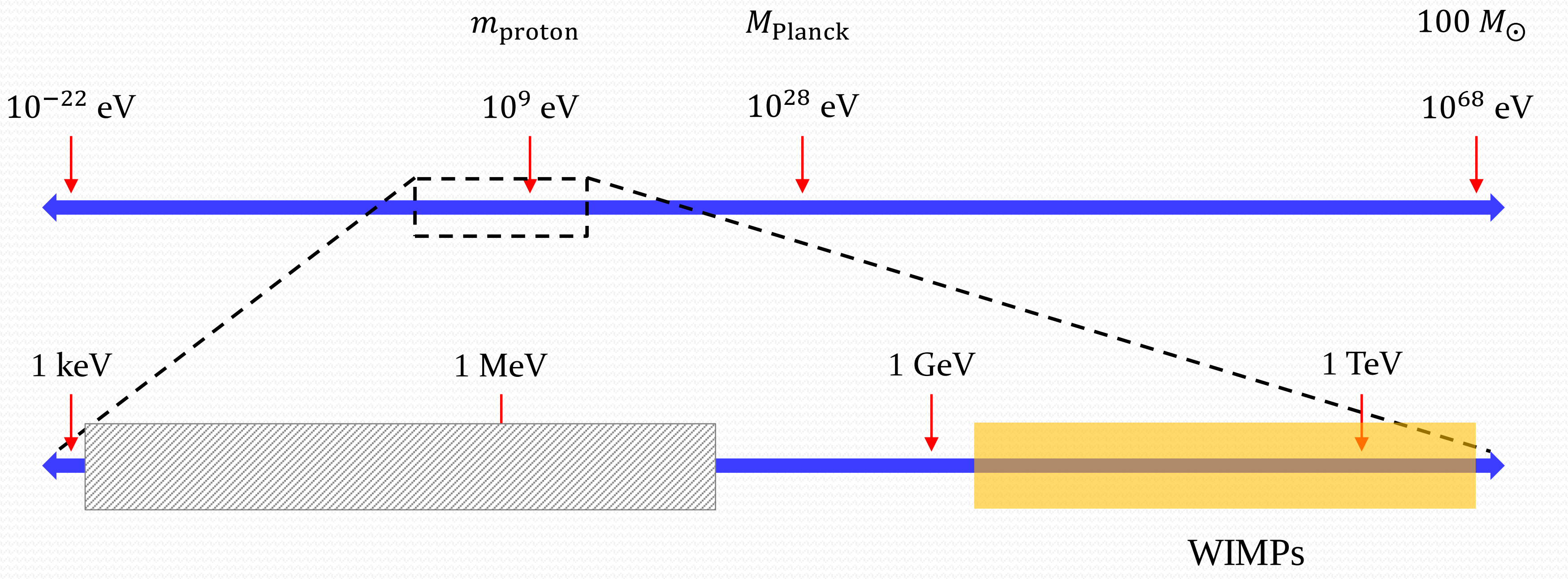
# The Dark Matter Landscape




- ✓ Probing dark sectors: **(Light) dark matter + new mediators**
- ✓ Can be a thermal dark matter candidate
- ✓ Less constrained by current searches ⇒ Complementary search at neutrino experiment!

# Light Dark-Sector Particle Models/Searches: Mediator

- Various light mediator scenarios have been proposed.
  - ✓ Dark matter scenarios based on hidden sectors: e.g., models of asymmetric dark matter, Sommerfeld enhancements motivated by SIMP, etc (see the review [Essig et al (2013)])
  - ✓ $g-2$ of electron: $2.4\sigma$ discrepancy [Davoudiasl, Marciano (2018)]
  - ✓ Neutrino sector physics: new neutrino interactions to satisfy the MiniBooNE excess [Bertuzzo, Jana, Machado, Funchal (2018)]
  - ✓ Solutions of Yukawa coupling hierarchy problem [Dutta, Ghosh, Kumar (2019)]
  - ✓ See also US cosmic vision [Battaglieri et al (2017)]
- Light mediator searches at existing/future experiments, e.g., NA64, Belle I/II, Babar, SHiP, FASER, MATHSULA, SeaQuest

# Light Dark-Sector Particle Models/Searches: Dark Matter

- Various light dark matter-involving pheno has been studied.
  - ✓ Boosted dark matter scenarios [Agashe, Cui, Necib, Thaler (2014); Berger, Cui, Zhao (2014); Kong, Mohlabeng, Park (2014); **DK**, Park, Shin (2016)]
  - ✓ Fast-moving DM via induced nucleon decays [Huang, Zhao (2013)]
  - ✓ MeV-range DM indirect detection at gamma-ray telescopes [Boddy, Kumar (2015)]
  - ✓ Energetic cosmic-ray-induced (semi-)relativistic dark matter scenarios [Yin (2018); Bringmann, Pospelov (2018); Ema, Sala, Sato (2018); Dent, Dutta, Newstead, Shoemaker (2019)]
  - ✓ Ultra high energy cosmic ray phenomena [Bhattacharya, Gandhi, Gupta (2014); Heutier, **DK**, Park, Shin (2019)]

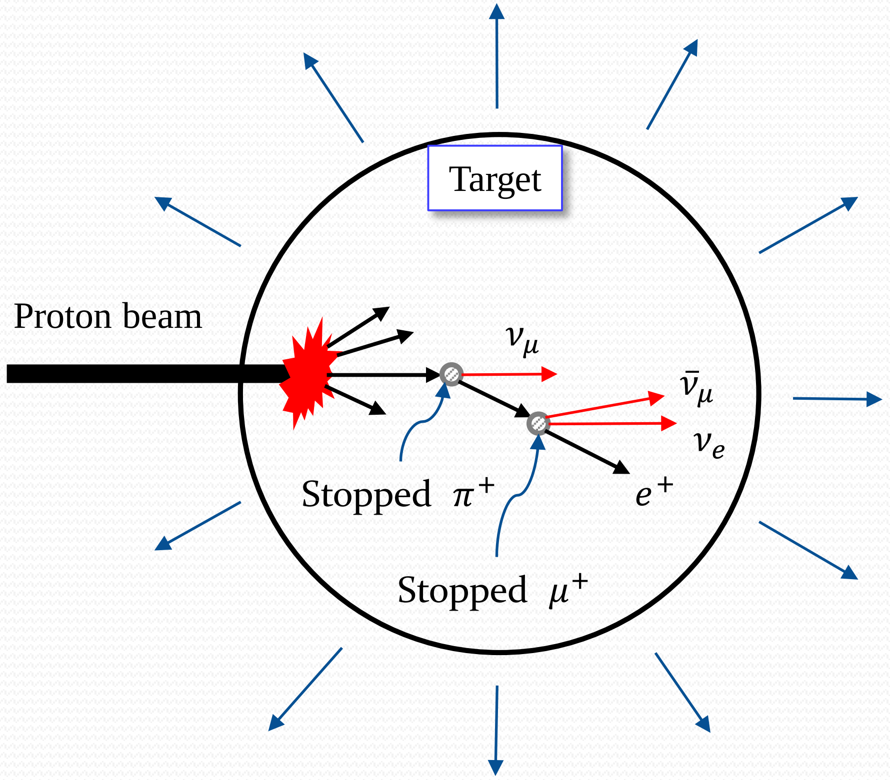
- Cosmogenic light dark matter searches at existing/future experiments, e.g., SK/HK, COSINE-100, ProtoDUNE, DUNE
- Beam-produced light dark matter searches at existing/future experiments, e.g., BDX, MicroBooNE, SeaQuest, LDMX, T2HKK, DUNE, SHiP, and proposals [Bjorken, Essig, Schuster, Toro (2009); Batell, Pospelov, Ritz (2009); deNiverville, Pospelov, Ritz (2011); Izaguirre, Krnjaic, Schuster, Toro (2014); Berlin, Gori, Schuster, Toro (2018), and many more]

# Why Neutrino Experiments?

- ✓ **High Intensity**: The number of photons, which may create dark matter and mediators, are enormous.
- ✓ **"Bonus" Physics Case**: The same experimental setup is used for studying not only neutrino physics (CEνNS, ν oscillations, etc) but dark matter/mediator-induced events.
- ✓ **Complementarity**: The searches can provide complementary information in exploring relevant parameter space.

# Low-Energy ν-Beam Experiments (Stopped Pion Experiments)

# Production of Neutrinos




Isotropic neutrino flux

Beam-related neutron backgrounds

# Benchmark Stopped-Pion Experiments

| Experiment | $E_{\text{beam}}$ [GeV] | POT [$\text{yr}^{-1}$] | Target | Detector: mass, distance, angle, $E_r^{\text{th}}$ |
|---|---|---|---|---|
| COHERENT [15, 17, 18] | 1 | $1.5 \times 10^{23}$ | Hg | CsI[Na]: 14.6 kg, 19.3 m, 90°, 6.5 keV<br>LAr: 24 kg (0.61 ton), 28.4 m, 137°, 20 keV |
| JSNS$^2$ [19–21] | 3 | $3.8 \times 10^{22}$ | Hg | Gd-LS: 17 ton, 24 m, 29°, 2.6 MeV |
| CCM [22–24] | 0.8 | $1.0 \times 10^{22}$ | W | LAr: 7 ton, 20 m, 90°, 25 keV |

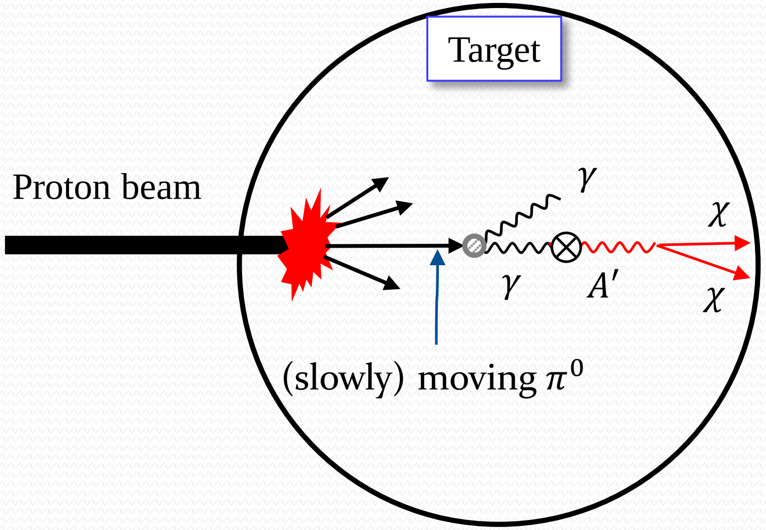
**Table 2.** Key specifications of benchmark experiments and detectors under consideration. All three experiments use a proton beam, and the POT values are expected spills for 5,000 hours operation per year. The mass of the liquid argon detector in parentheses in COHERENT is for a future upgrade.

(Gd-LS = gadolinium-doped liquid scintillator)

**JSNS$^2$:**

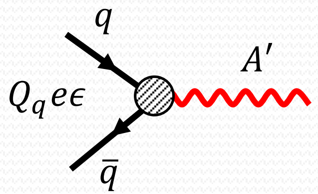
1) Higher energy threshold → ideal for electron scattering signal (vs. nucleus scattering signal at COHERENT and CCM)
2) Forward-directed detector location → potentially exposed to more beam-related backgrounds

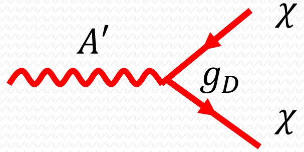
# Dark Matter Production I



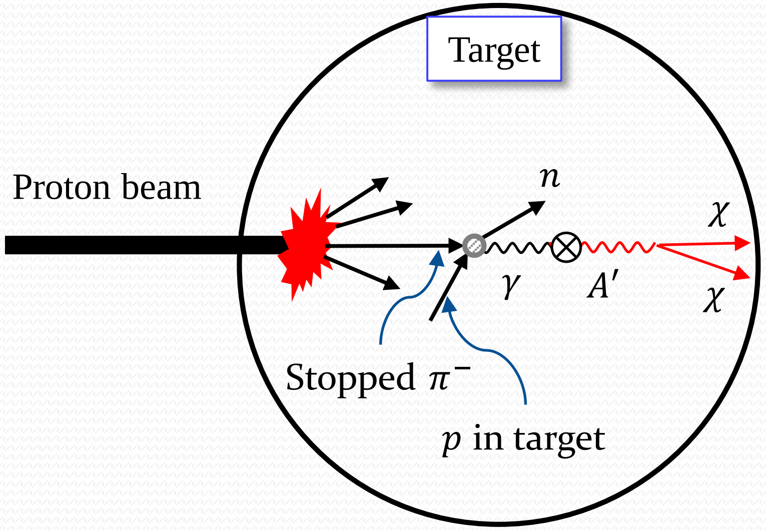

$\pi^0 \to \gamma + A'$

$A' \to \chi + \chi$



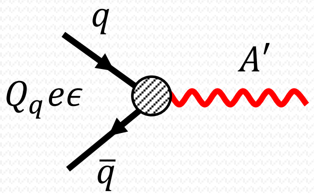
# Dark Matter Production II

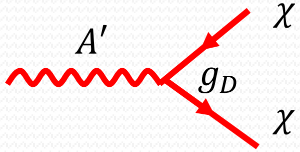



$\pi^- + p \to n + A'$

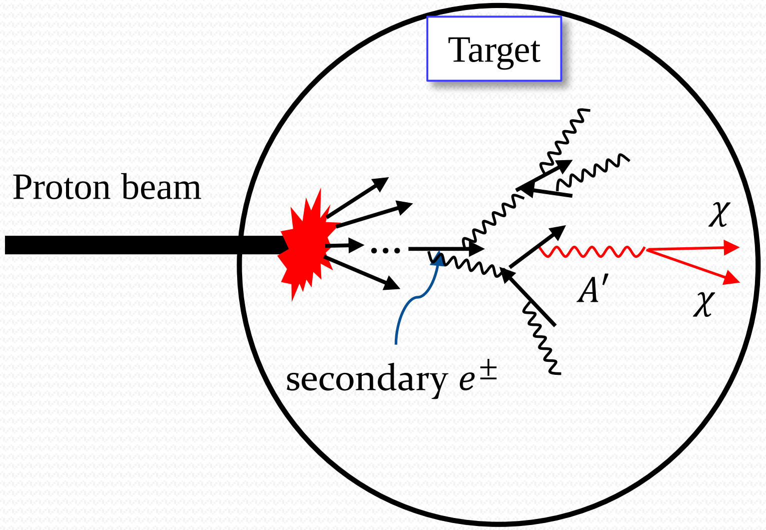
[deNivervill, Pospelov, Ritz (2015)]

$A' \to \chi + \chi$



# Dark Matter Production III




$e^{\pm *} \to e^{\pm} + A'$ $\qquad$ $A' \to \chi + \chi$


Cf.) Another (subdominant) process: charge exchange, $\pi^{-/+} + p/n \to \pi^0 + n/p$, $\pi^0 \to \gamma + A'$ [JSNS² TDR]

**Dedicated simulation using e.g., GEANT is needed!**

# GEANT Simulation

| Experiment | COHERENT | | JSNS$^2$ | | CCM | |
|---|---|---|---|---|---|---|
| | $\pi^+$ | $\pi^-$ | $\pi^+$ | $\pi^-$ | $\pi^+$ | $\pi^-$ |
| $N_{\pi^\pm}$ | 0.1098 | 0.0470 | 0.5260 | 0.4962 | 0.0665 | 0.0259 |
| Decay ($\pi \to \mu + \nu$) | 0.0803 | 0.0001 | 0.2603 | 0.0019 | 0.0520 | 0.00004 |
| Inelastic (w. $\pi^0$) | 0.0016 | 0.0004 | 0.0214 | 0.0124 | 0.0006 | 0.0002 |
| Inelastic (w.o. $\pi^0$) | 0.0239 | 0.0113 | 0.2081 | 0.2071 | 0.0112 | 0.0053 |
| Capture at rest (w. $\pi^0$) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Capture at rest (w.o. $\pi^0$) | 0.0 | 0.0333 | 0.0 | 0.2443 | 0.0 | 0.0192 |
| Transportation | 0.0037 | 0.0017 | 0.0351 | 0.0296 | 0.0022 | 0.0009 |
| $N_{\pi^0}$ | 0.1048 | | 0.6142 | | 0.0633 | |
| $N_\eta$ | 0.0 | | 0.0015 | | 0.0 | |
| $N_{K^+}$ | 0.0 | | 0.0061 | | 0.0 | |
| $N_{K^-}$ | 0.0 | | 0.0001 | | 0.0 | |

Charge exchange process

Panofsky process

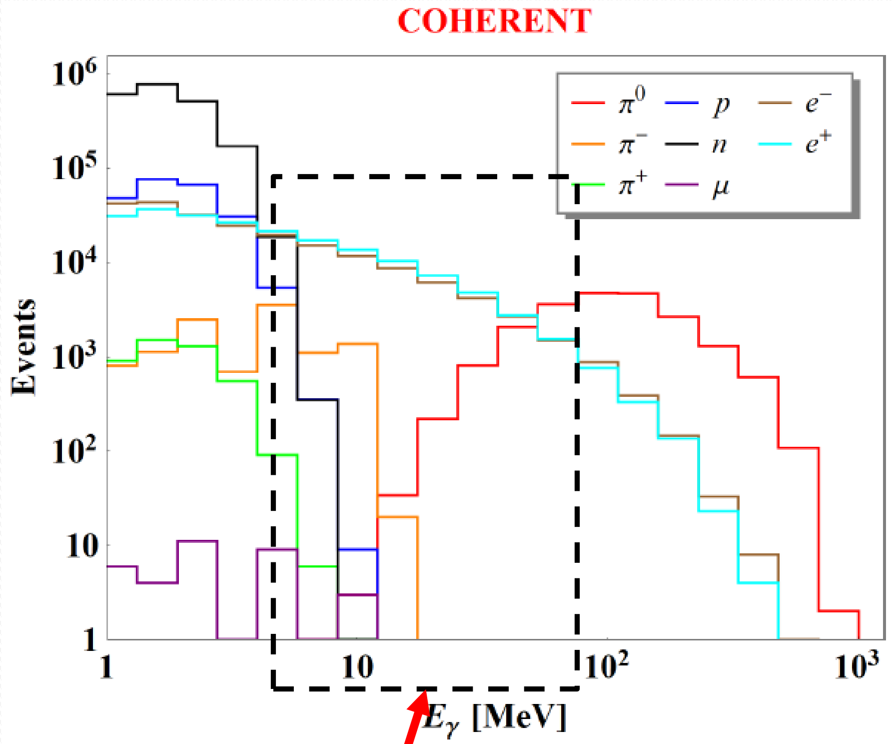
Primary $\pi^0$ production

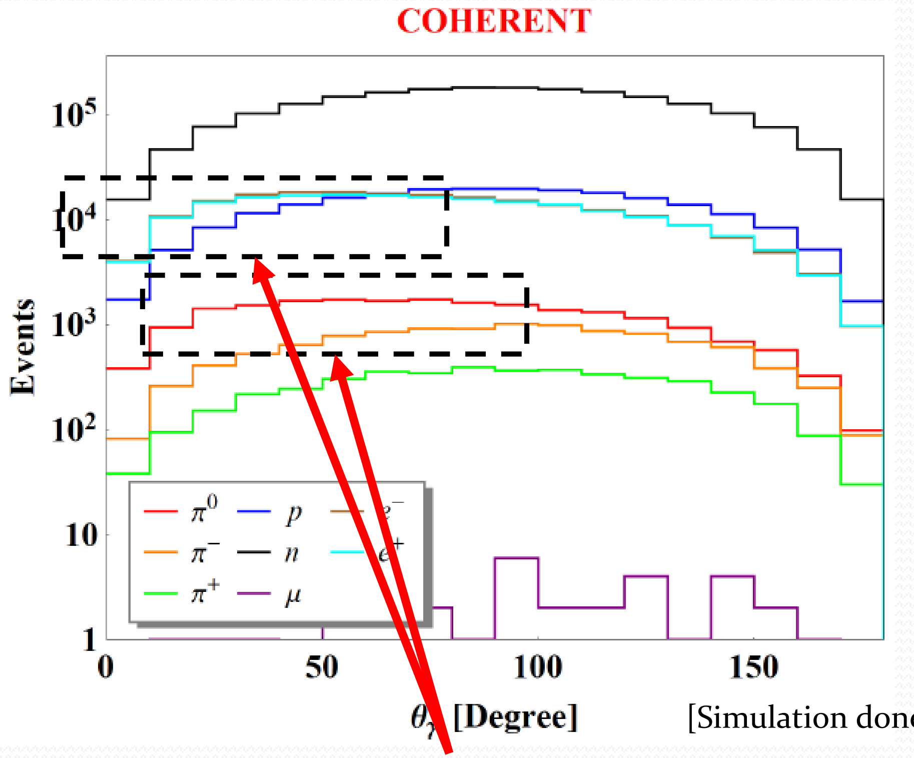
Heavier meson production

**Table 3**. A summary of our GEANT4 10.5 (FTFP_BERT) simulation results with $10^5$ protons struck on the target of each benchmark experiment. $N_i$ denotes the fractional number of particles of species $i$ per POT. The 4th through 9th rows describe further processes that produced charged pions undergo. See the text for details.

(Caveat: production rates depend on the physics listing used.)

# Photon Spectra at COHERENT



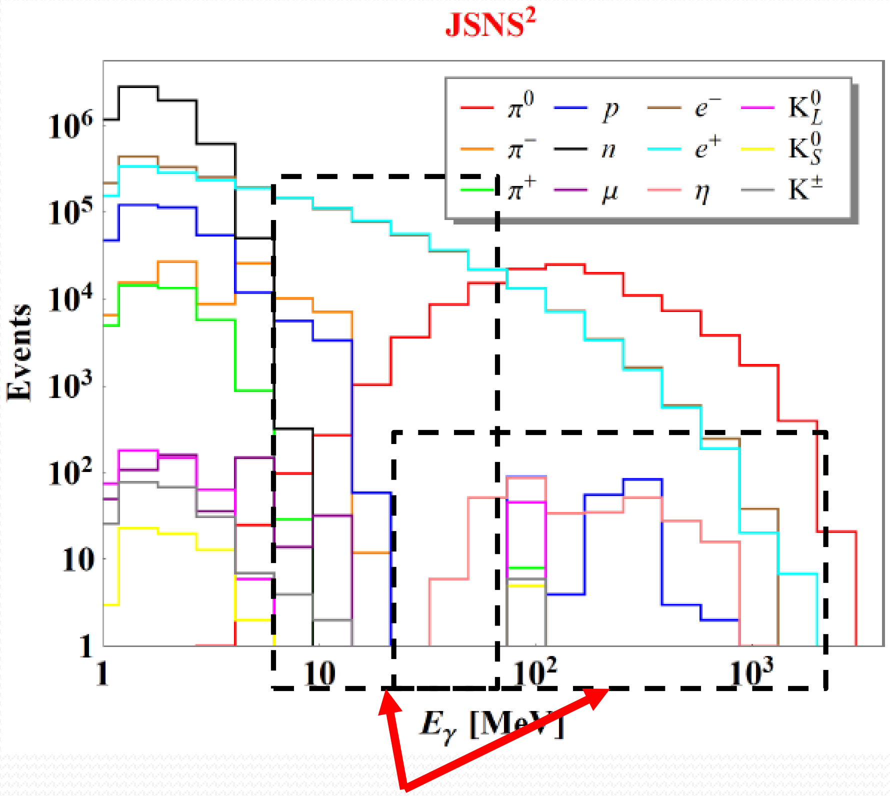



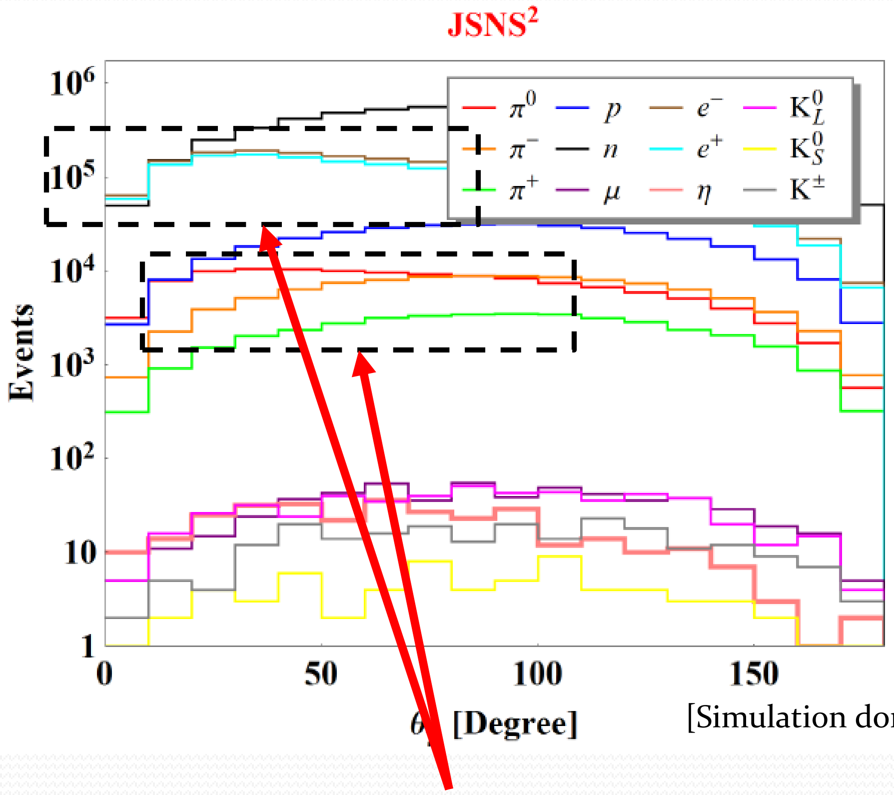

[Simulation done with $10^5$ protons]

- ✓ Significant $e^{\pm}$-induced cascade photons → more contribution to production of low-mass dark photon, hence low-mass DM.
- ✓ $\pi^0, e^{\pm}$-induced photons are slightly more forward-directed than the charged pion-induced.

(Similar behaviors/expectations at CCM)

# Photon Spectra at JSNS$^2$




[Simulation done with $10^5$ protons]

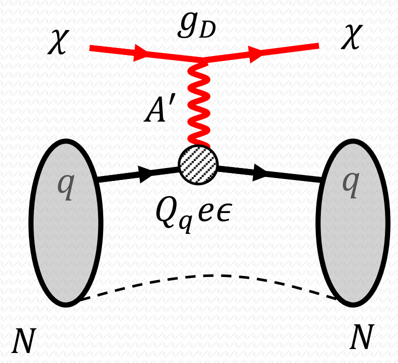
- ✓ More cascade photons and contributions by heavier mesons due to higher beam energy
- ✓ Slightly more forward-directed than the case of COHERENT again due to higher beam energy

# Dark Matter Signal: Target Recoil

❑ Nucleus scattering channel at COHERENT and CCM:

$$\frac{d\sigma}{dE_{r,N}} = \frac{e^2\epsilon^2 g_D^2 Z^2 \cdot |F|^2}{4\pi p_\chi^2 (2m_N E_{r,N} + m_{A'}^2)^2} \left\{ 2E_\chi^2 m_N \left(1 - \frac{E_{r,N}}{E_\chi} - \frac{m_N E_{r,N}}{2E_\chi^2}\right) + m_N E_{r,N}^2 \right\}$$

$Z$: atomic number, $F$: form factor
$E_\chi$: energy of incoming dark matter,
$E_{r,N}$: recoil kinetic energy of target nucleus
$m_N$: mass of target nucleus, $m_{A'}$: mass of dark photon

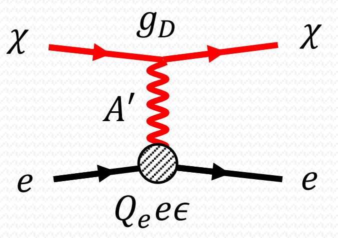



Typical recoil energy is much smaller than MeV.

❑ Electron scattering channel at JSNS$^2$ because a nucleus recoil doesn't overcome the detector threshold.

$$\frac{d\sigma}{dE_{r,e}} = \frac{e^2\epsilon^2 g_D^2 Z \cdot m_e^2}{\pi\lambda(s, m_e^2, m_\chi^2)\left\{2m_e(m_e - E_{r,e}) - m_{A'}^2\right\}^2} \times \left[m_e\left\{E_\chi^2 + (m_e + E_\chi - E_{r,e})^2\right\} + (m_e^2 + m_\chi^2)(m_e - E_{r,e})\right]$$

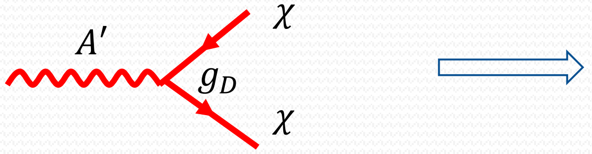
$E_{r,e}$: recoil kinetic energy of target electron
$m_e$: mass of target electron, $s = E_\chi^2 + 2E_\chi m_e + m_\chi^2$, $\lambda(x,y,z) = (x-y-z)^2 - 4yz$



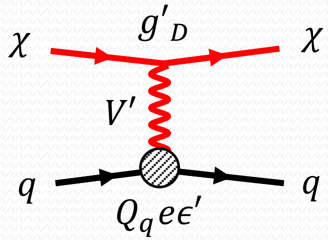
# Parameter Space: Dark Matter

- In general, the scattering process could be mediated by a different particle (e.g., Baryon number gauged dark gauge boson [deNiverville, Pospelov, Ritz (2015)])

  : $A' \rightarrow V'$, $m_{A'} \rightarrow m_{V'}$, $Q_q e\epsilon \rightarrow Q_B e\epsilon'$, $g_D = e\epsilon_D \rightarrow g'_D = e\epsilon'_D$




Production via $A'$



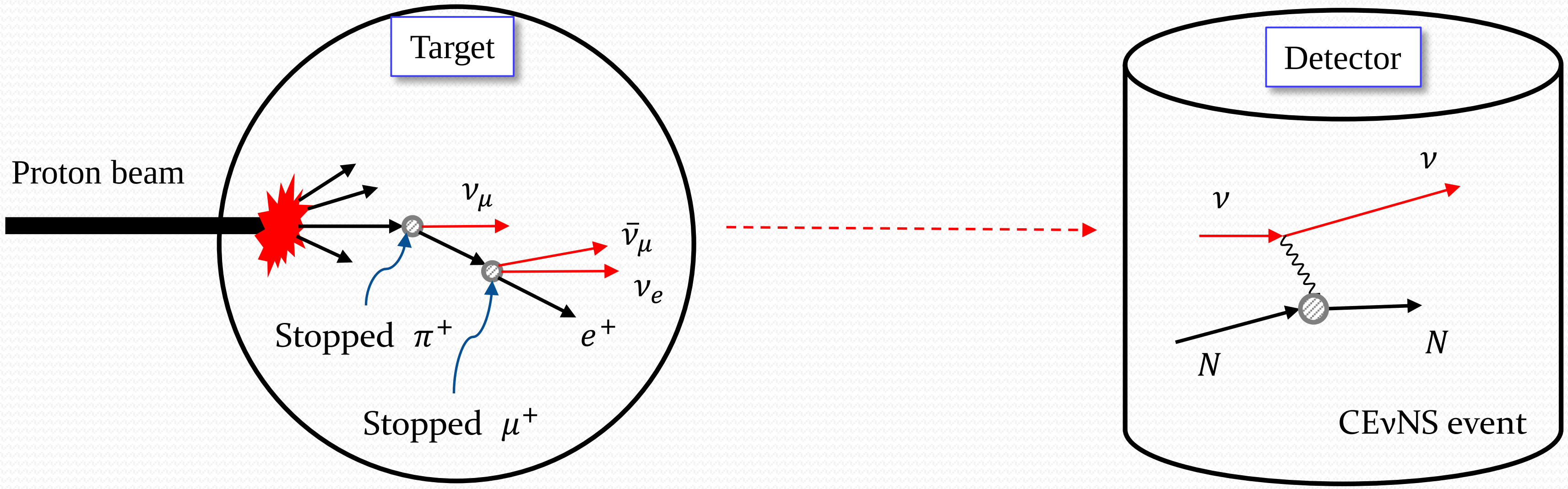

Detection via $V'$

- Dark photon $A'$ production to dark matter scattering can be described by two variables,

$$\epsilon_{\rm eff} \equiv \epsilon\epsilon'\epsilon'_D\sqrt{\mathrm{BR}_{A'\rightarrow\chi\chi}} \text{ and } m_{V'}$$

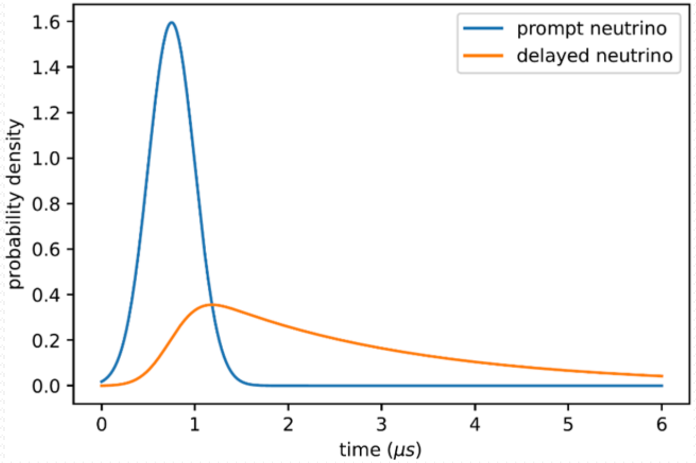
  but I will focus on the single mediator scenario throughout the talk for simplicity.

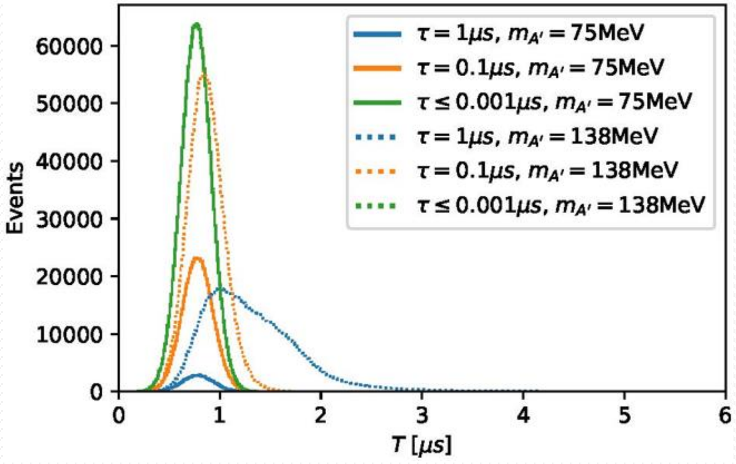
# Backgrounds?

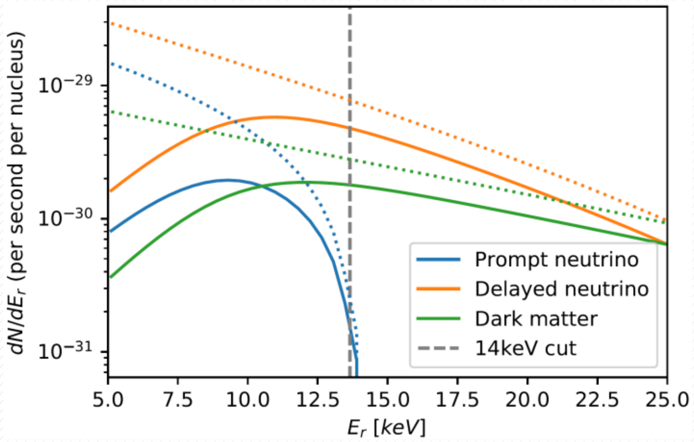



1) "Prompt" neutrinos from the decay of stopped (positively)-charged pions.
   - ✓ Mean life time of $\pi^+ = 2.6 \times 10^{-8}$s.
   - ✓ Neutrino energy is single-valued ($E_\nu = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}$), hence deposit energy is upper-bounded. ⇒ Energy cut
2) "Delayed" neutrinos from the decay of stopped muons.
   - ✓ Neutrinos are more energetic than prompt neutrinos. ($E_\nu^{\max} = \frac{m_\mu^2 - m_e^2}{2m_\mu}$)
   - ✓ Mean life time of $\mu^+ = 2.2 \times 10^{-6}$s. ⇒ Timing cut with $\mu$s-scale timing resolution

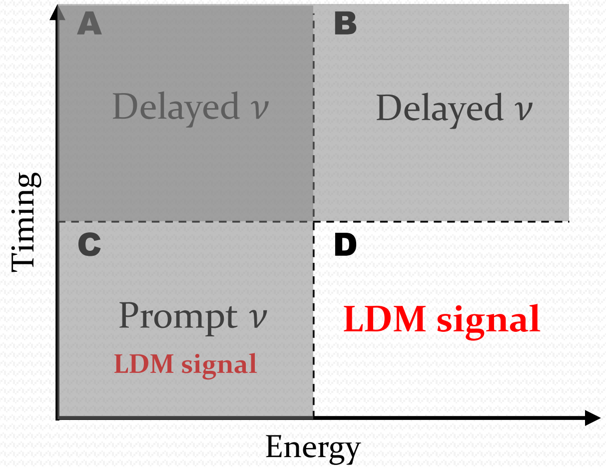
# Background Rejection Using Timing Spectra



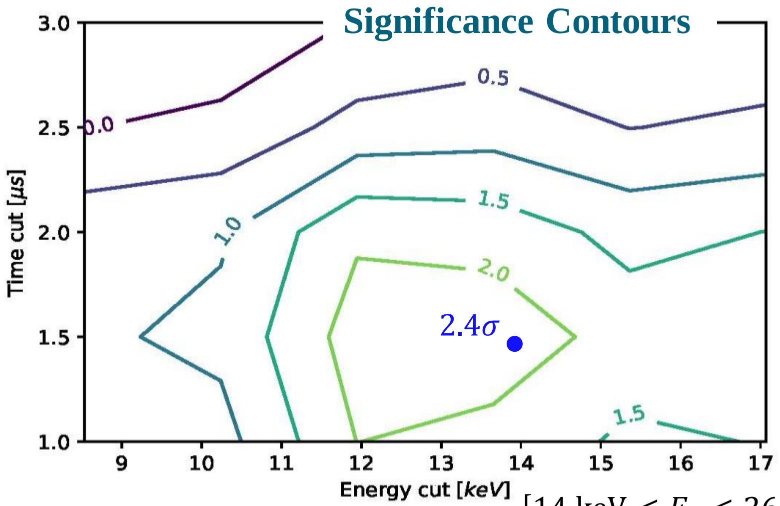




(Example distributions in COHERENT)

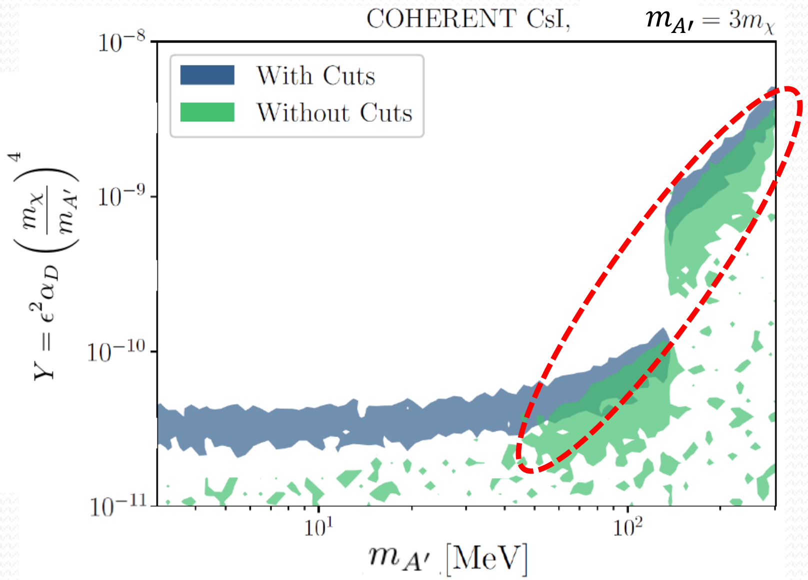



- A combination of energy and timing cuts can remove SM/NSI $\nu$ backgrounds [Dutta, **DK**, Liao, Park, Shin, Strigari, PRL124 (2020) 12, 121801]
- Similar strategies are applied for CCM and JSNS$^2$.

# Application to CsI Data of COHERENT




[14 keV < $E_r$ < 26 keV, $T$ < 1.5 $\mu$s, $R_n$ = 4.7 fm]




- ❑ A mild excess(?): Can be explained by DM not by NSI of neutrinos (since the cuts remove the prompt and delayed ν's).
- ❑ Fit to the excess after the cuts needs to fit the full data set (before the cuts), and the figure (r.h.s) holds for
  - ✓ $\tau \leq 4$ ns, $m_{A'} < 138$ MeV
  - ✓ $\tau \leq 30$ ns, $m_{A'} \cong 138$ MeV (non-relativistic dark photon case)
  - ✓ Any $m_\chi < m_{A'}/2$

[Dutta, **DK**, Liao, Park, Shin, Strigari, Thompson, arXiv:2006.09386]

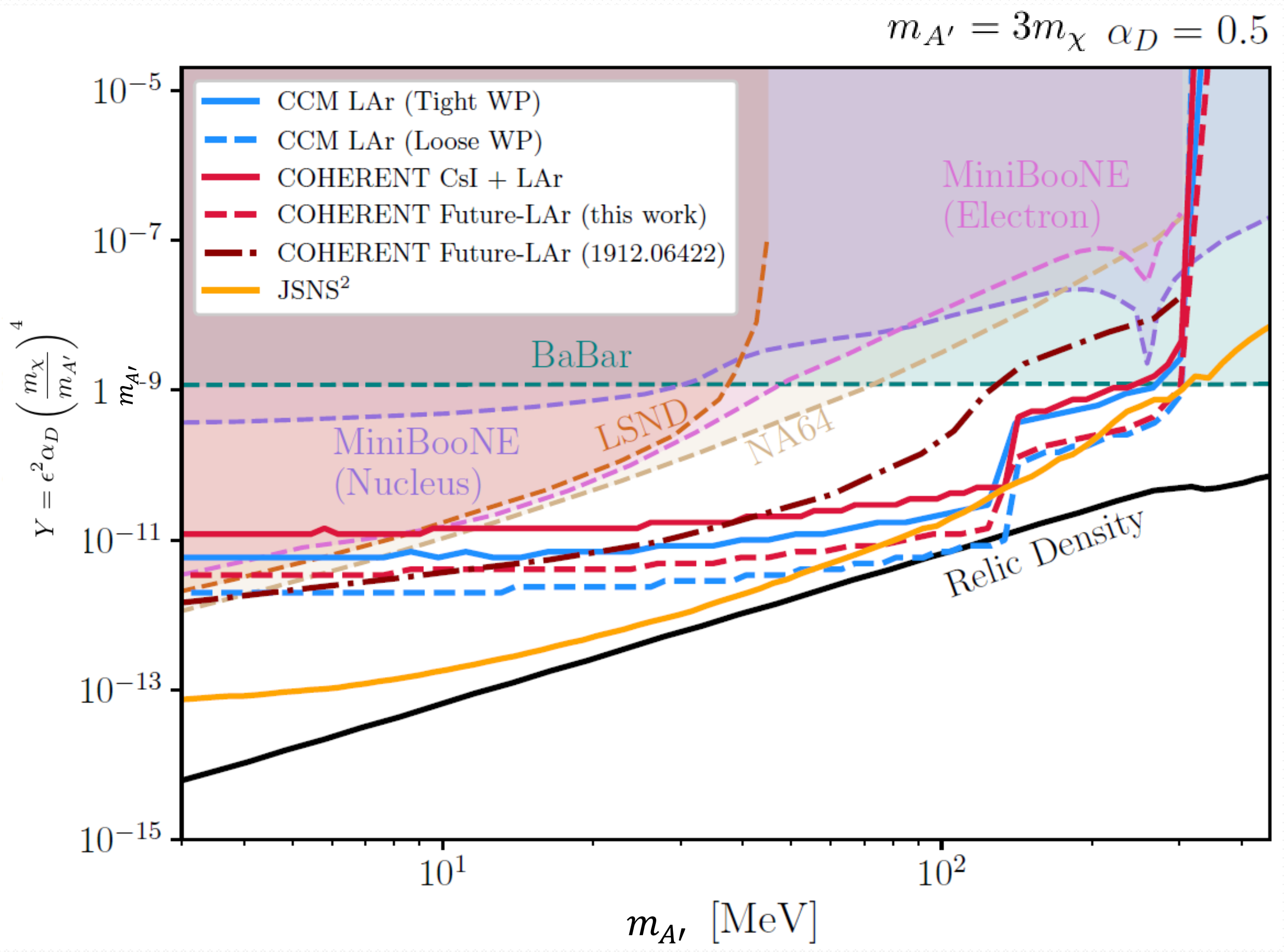
# No Excess – Constraining Parameter Space

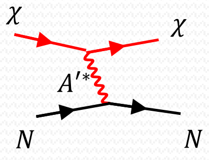
- We apply similar strategies for CCM and JSNS$^2$.

| | Channel | $E_r$ cut | $t$ cut |
|---|---|---|---|
| COHERENT-CsI | Nucleus scattering | 14 keV$< E_r <$26 keV | $t < 1.5\ \mu$s |
| COHERENT-LAr | Nucleus scattering | $E_r > 21$ keV | $t < 1.5\ \mu$s |
| CCM | Nucleus scattering | $E_r > 50$ keV | $t < 0.1\ \mu$s (Tight WP)<br>$t < 0.4\ \mu$s (Loose WP) |
| JSNS$^2$ | Electron scattering | $E_r > 30$ MeV | $t < 0.25\ \mu$s |

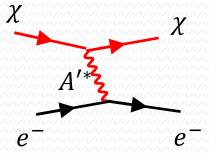
**Table 5.** A summary of the recoil energy and timing cuts that we use for our data analysis.

# No Excess – Constraining Parameter Space




For COHERENT & CCM



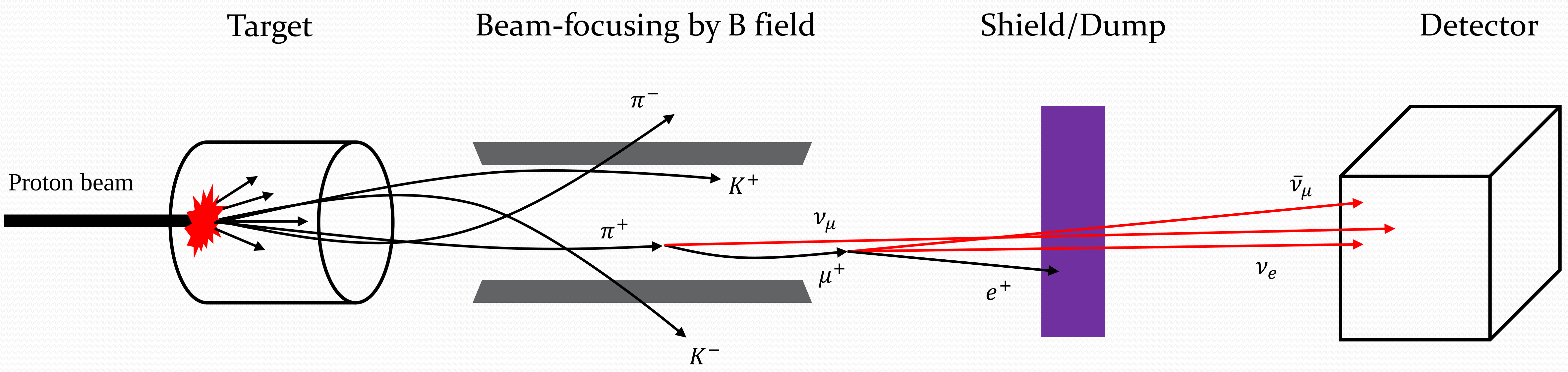

For JSNS$^2$

- ❑ COHERENT, CCM, and JSNS$^2$ possess competitive sensitivities to LDM signals especially toward the lower mass regime.
- ❑ Relic lines obtained by directly solving the Boltzmann equations and by using micrOMEGAs.

[Dutta, **DK**, Liao, Park, Shin, Strigari, Thompson, arXiv:2006.09386]

# High-Energy ν-Beam Experiments (Focused ν-Beam Experiments)

# Production of Neutrinos

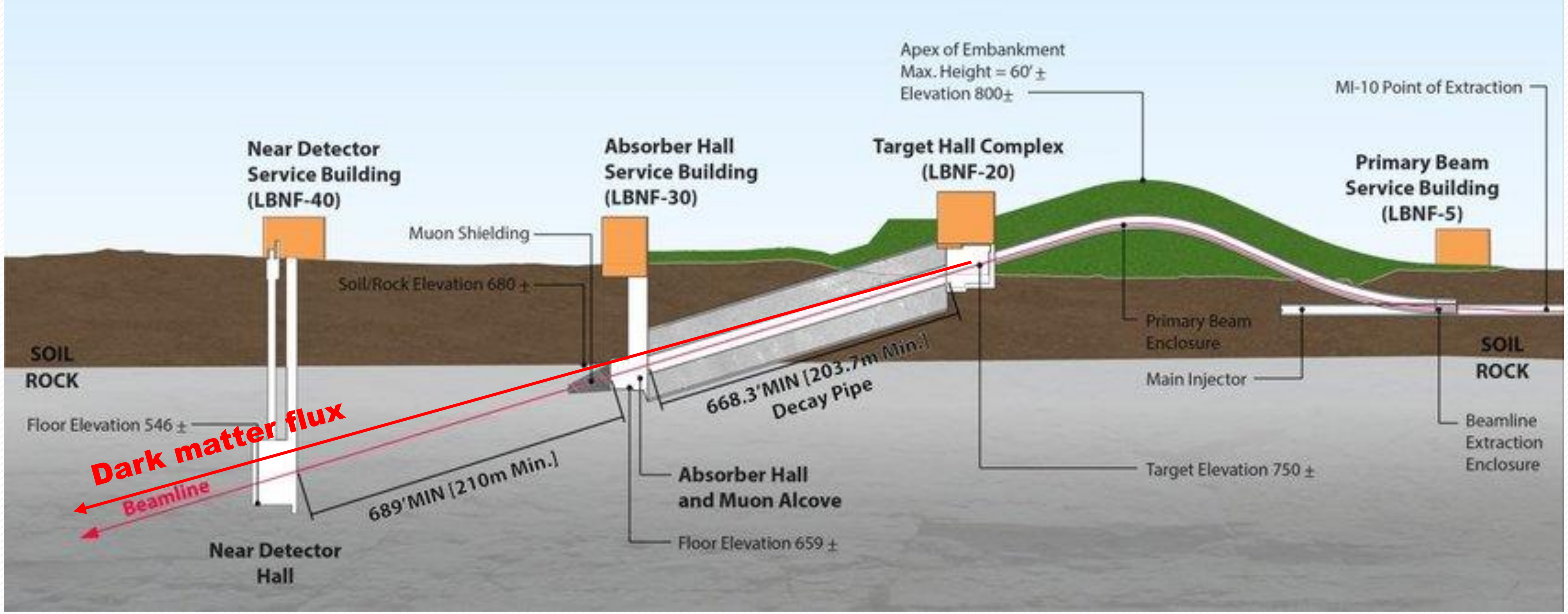


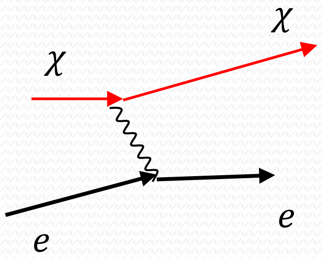

Focused neutrino flux

- Opposite behaviors are expected in the anti-neutrino mode.

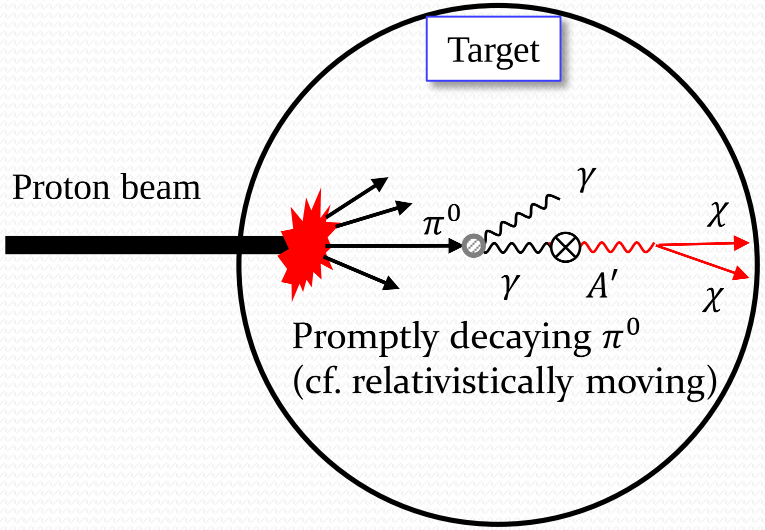
# Benchmark Experiment: DUNE

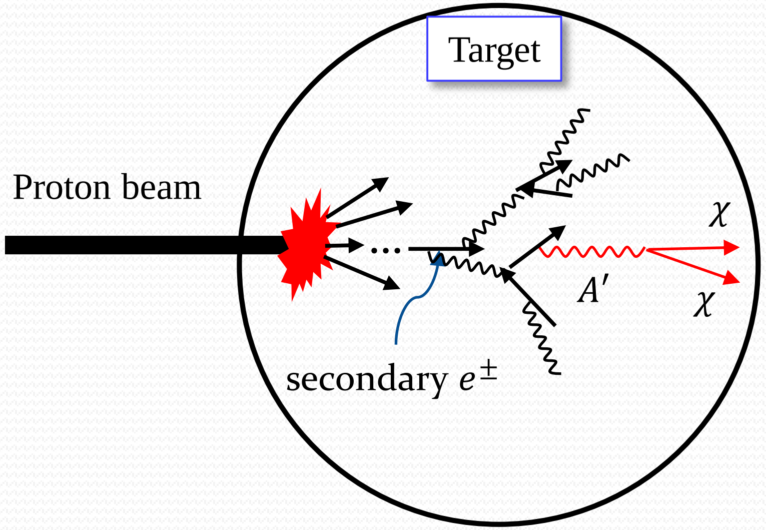
←Detector→←Shielding and rock→←Focusing→←Target→←120 GeV *p*-beam



# Dark Matter Production



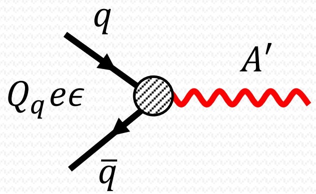



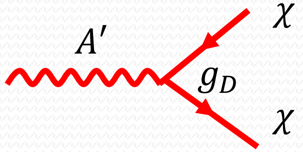

$\pi^0 \to \gamma + A'$

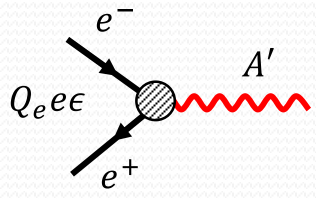
$A' \to \chi + \chi$

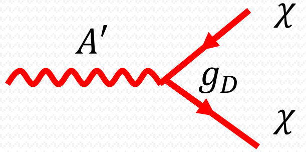
$e^{\pm *} \to e^\pm + A'$

$A' \to \chi + \chi$



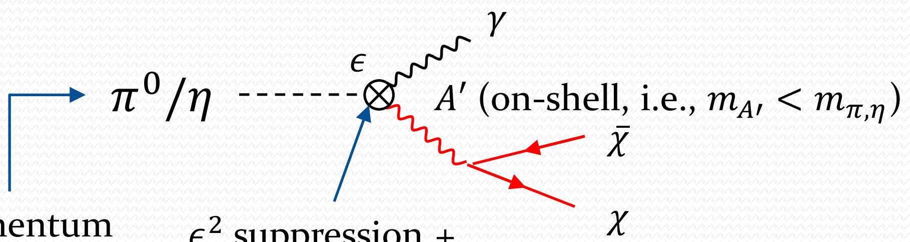




Full photon spectra at the target simulated with GEANT!

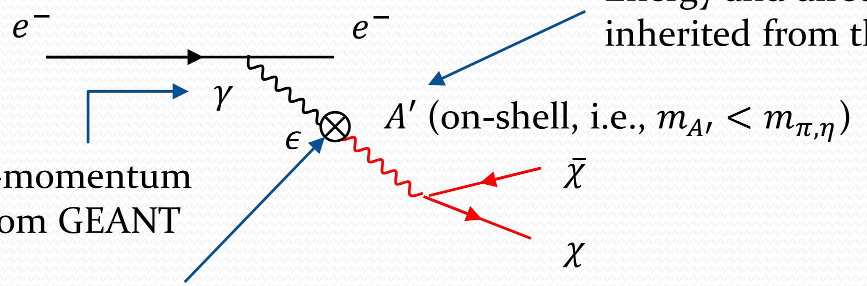
# Simulation of LDM Production




4-momentum from GEANT

$\epsilon^2$ suppression + phase-space suppression in BR

ROOT phase-space generator



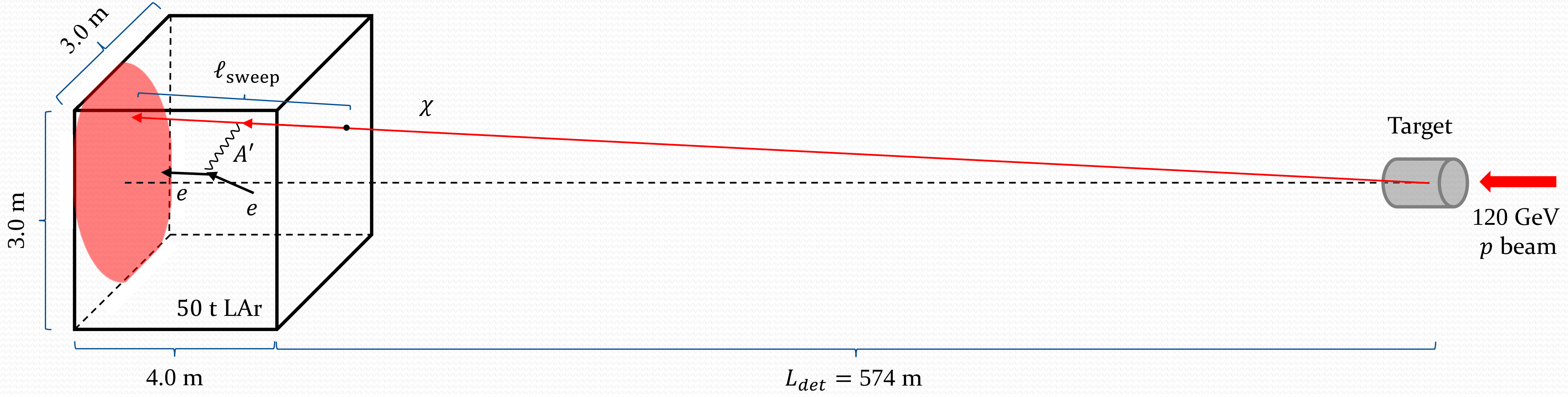

Energy and direction inherited from the photon

4-momentum from GEANT

$\epsilon^2$ suppression in BR + phase-space suppression in the massive vector radiation

ROOT phase-space generator

# Event Rate Calculation




- For a given set of dark matter particles getting through the detector

$$R = \sum_{\text{all accepted } \chi} n_T \, \sigma_\chi \, \ell_{\text{sweep}}$$

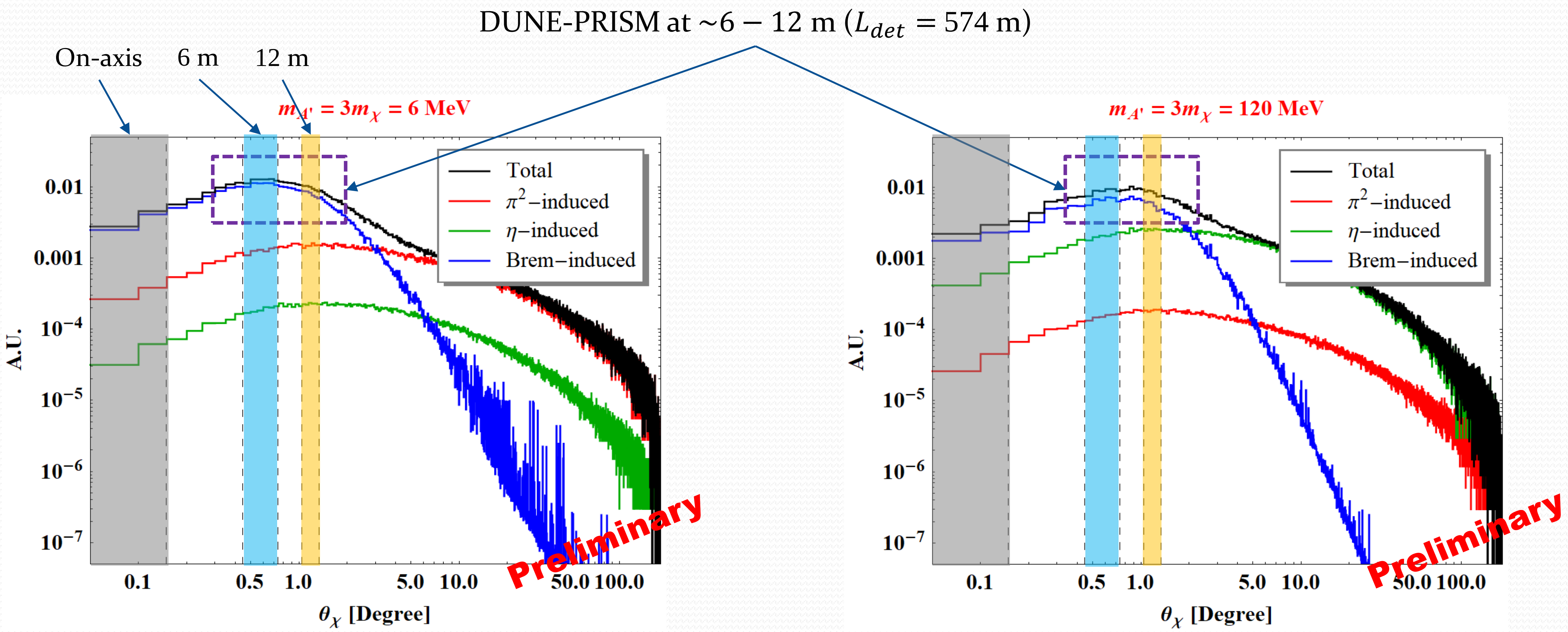
$\ell_{\text{sweep}}$ ~400 cm

$$\sigma_\chi = \int_{E_{r,e}^{th}}^{E_{r,N}^{\max}} dE_{r,e} \frac{(\epsilon e)^2 \alpha_D Z m_e^2}{\pi \lambda(s, m_e^2, m_\chi^2) \{2m_e(m_e - E_{r,e}) - m_V^2\}^2} \times \left[m_e \{E_\chi^2 + (m_e + E_\chi - E_{r,e})^2\} + (m_e^2 + m_\chi^2)(m_e - E_{r,e})\right]$$

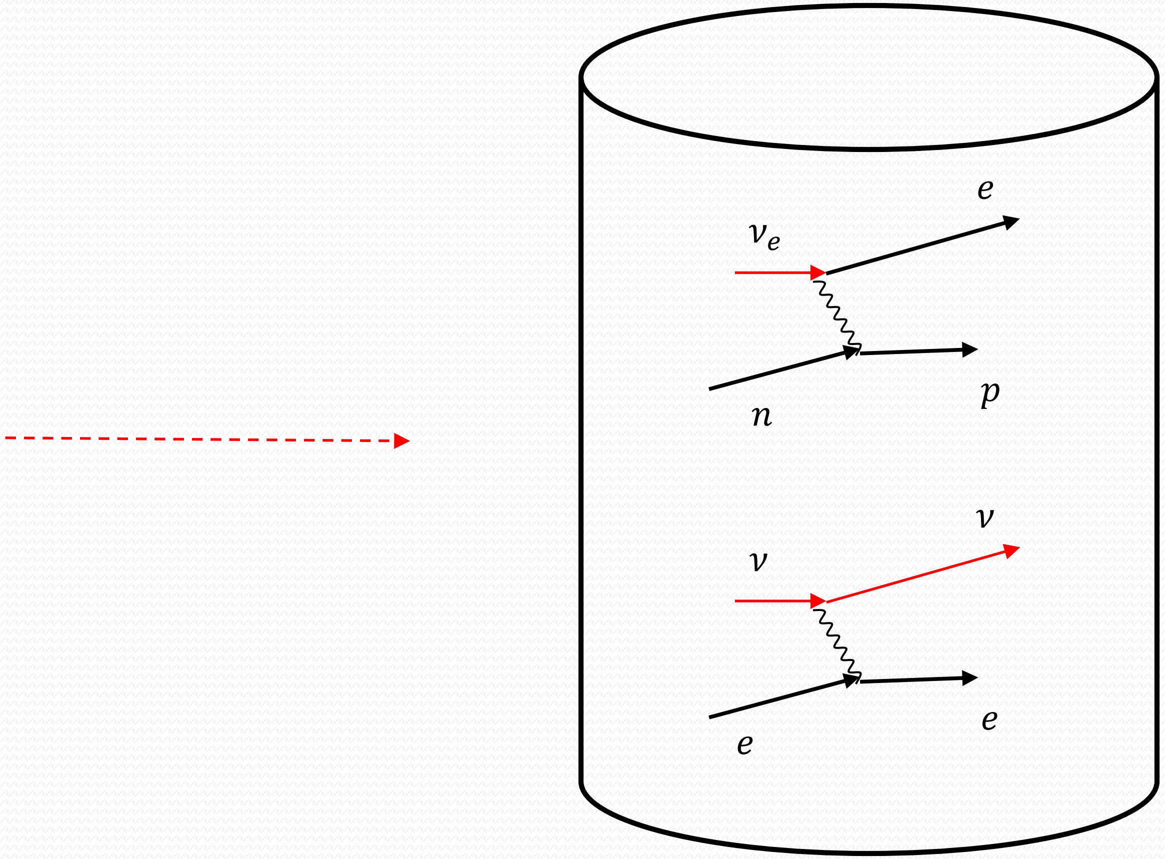
$Z$: # of electrons per atom

$E_{r,e}^{th} = 30$ MeV

# Angular Spectra of the LDM Flux from the Target



# Backgrounds?




**CCQE events**

with nucleons undetected/missed:

Reducible by an $E_e\theta_e^2$ cut

[deNivervill, Frugiuele (2018); De Romeri, Kelly, Machado (2019)]

***νe* scattering events**

Irreducible $\Rightarrow$ major background

# Background Estimates

## Neutrino-electron elastic scattering for flux determination at the DUNE oscillation experiment

[Marshall, McFarland, Wilkinson, arXiv:1910.10996]

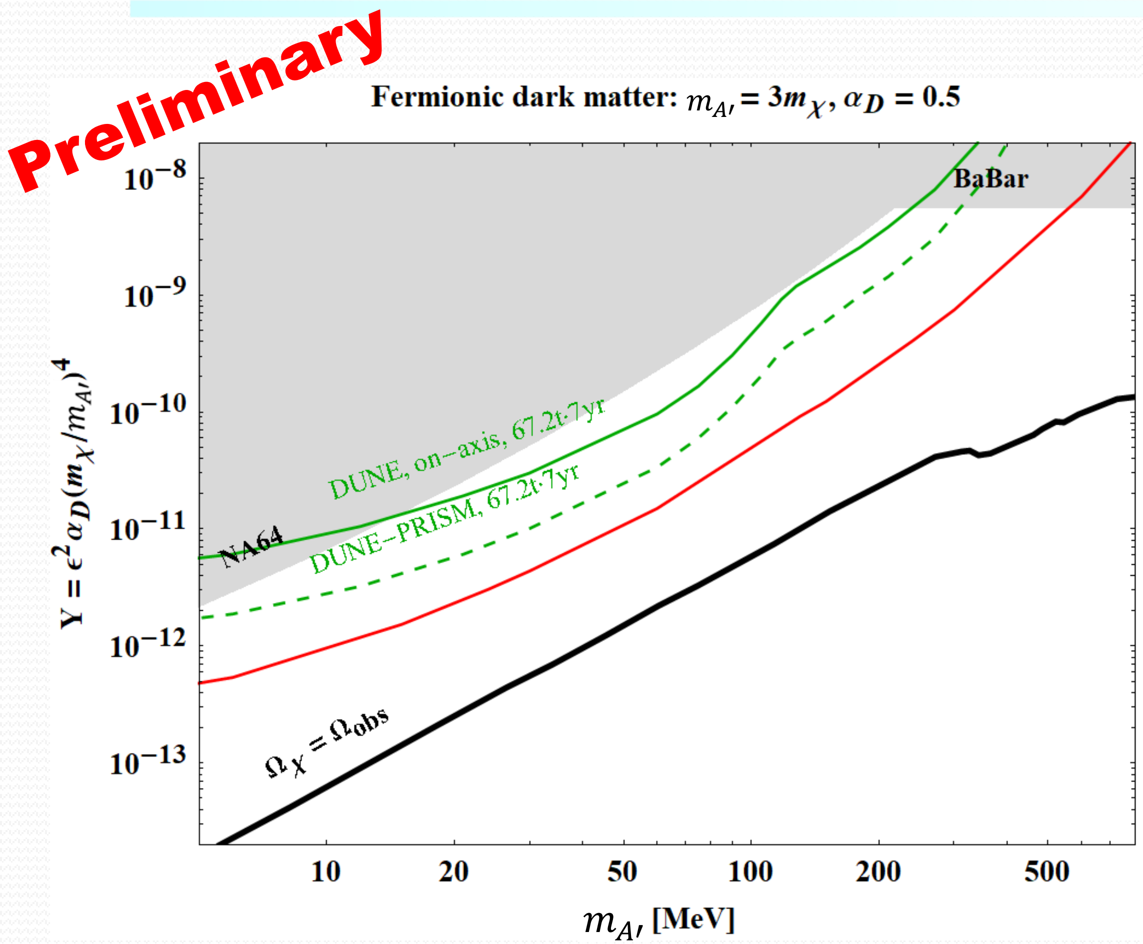
Chris M. Marshall,[1] Kevin S. McFarland,[2] and Callum Wilkinson[3]

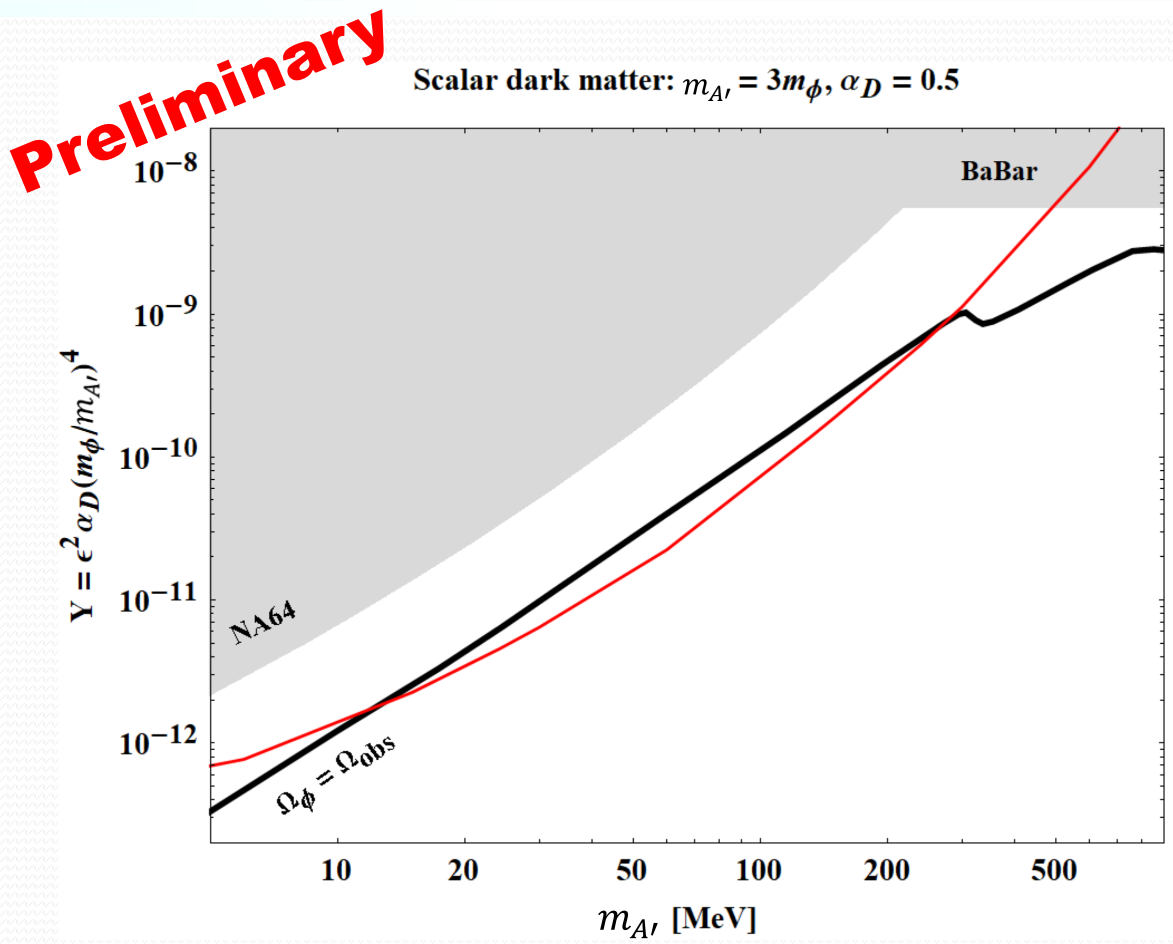
[1] *Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[2] *University of Rochester, Rochester, New York, USA*
[3] *University of Bern, Bern, Switzerland*

TABLE I: Number of $E_\nu$ template, and template binning for all detectors and beam configurations considered. The binning was decided by requiring ≥500 events/template in the GENIE prediction. The predicted event rates given are the total number of neutrino-electron events in five years of running in the nominal 1.2 MW beam for each detector.

| Beam | Detector | Rate | N. bins | $E_\nu$ binning (GeV) |
|---|---|---|---|---|
| FHC ($\nu$-mode) | 30t LAr | 22458 | 28 | 0.0, 1.25, 1.5, 1.75, 2.0, 2.125, 2.25, 2.375, 2.5, 2.625, 2.75, 2.875, 3.0, 3.125, 3.25, 3.5, 3.75, 4.0, 4.25, 4.625, 5.125, 5.875, 6.875, 8.5, 10.0, 12.0, 14.5, 18.5, 100 |
| RHC ($\bar{\nu}$-mode) | 30t LAr | 15885 | 18 | 0, 1.25, 1.625, 1.875, 2.125, 2.375, 2.625, 2.875, 3.125, 3.375, 3.625, 4.0, 4.375, 5.0, 6.0, 7.75, 10.5, 14.0, 100 |

# Expected Sensitivity Reaches



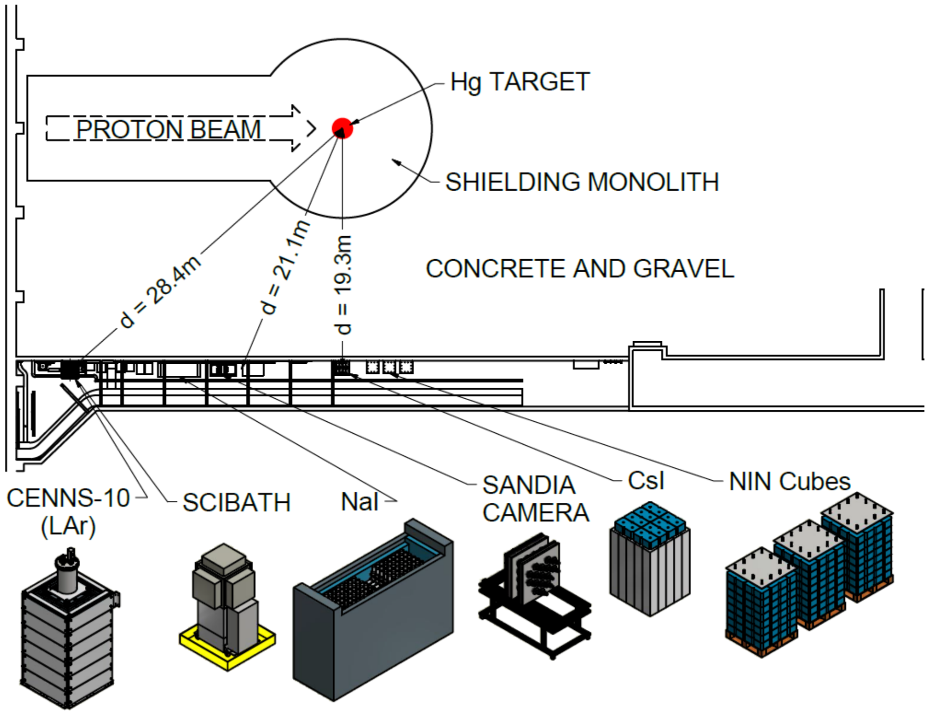



# Conclusions

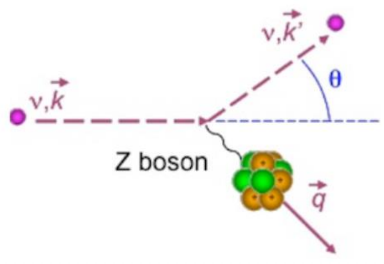
- Null signal observation at conventional dark matter detection experiments motivates us to look into mass scales other than that of WIMP.
- Models with light mediators and dark matter are interesting and receiving rising attention.
- Not only energy spectrum but also timing spectrum can be utilized in the search for light dark matter-induced signals in the low-energy neutrino beam experiments: A combination of timing and energy cuts can eliminate SM neutrino backgrounds efficiently.
- A more dedicated estimate of the photon flux allows us to estimate sensitivity reaches more precisely: A modified plan of DUNE-PRISM might be needed, given additional sources (e.g., cascade photons) of the dark matter flux.
- More interesting results coming up. Stay tuned!

# Bonus Slides

# COHERENT Experiment: Primer



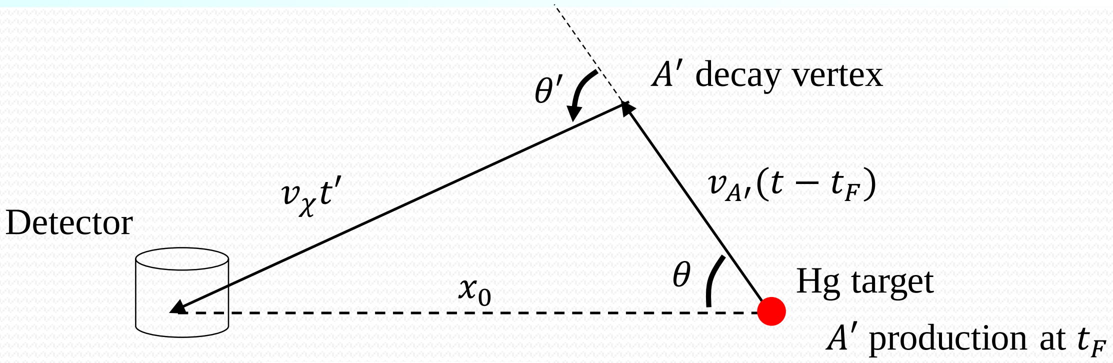

- ✓ Main mission: first direct measurement of Coherent Elastic Neutrino-Nucleus Scattering (CEνNS).




  - Prompt ν's: $\pi \to \mu + \nu_\mu$
  - Delayed ν's: $\mu \to e + \nu_\mu + \nu_e$

- ✓ ~1 GeV proton beam on Mercury target (pulse duration: 380 ns FWHM 60 Hz)
- ✓ $5 \times 10^{20}$ protons-on-target (POT) delivered per day

# Timing Spectrum of Dark-Matter Events




**Dark matter flux at the detector**: $f(T) = dN_\chi/dT$

$$f(T) = \int_{-1}^{1} d\cos\theta \int_0^{t_F^{\max}} dt_F \left|\frac{dT}{dt}\right|^{-1} \frac{d^2N_{A'}}{dt\,d\cos\theta} \cdot w(\cos\theta') \cdot \mathcal{F}(t_F)$$

Model of $\pi^-$ production timing ($\propto$ POT)

$$T = t + v_\chi^{-1}\sqrt{x_0^2 + v_{A'}^2(t-t_F)^2 - 2x_0 v_{A'}(t-t_F)\cos\theta}$$

$$\frac{d^2N_{A'}}{dt\,d\cos\theta} = \frac{1}{2}\cdot\frac{1}{\tau_{A'}}e^{-\frac{t-t_F}{\tau_{A'}}}\Theta(t-t_F)$$ ← from the decay law

$$w(\cos\theta') = \frac{1}{2\pi(v_\chi t')^2}\left|\frac{d\cos\theta'}{d\cos\theta^*}\right|^{-1}\frac{dN_{A'\to\chi}}{d\cos\theta^*}$$ ← Probability that DM travels towards the detector

# Application to Existing CsI Data

- Data released by COHERENT: CsI 14.5 kg × 308 days = 4,466 kg·day [Akimov et al, 1804.09459]

- Analysis scheme (also following [Dutta, Liao, Sinha, Strigari (2019)] for background estimate)
  - Fix the size of neutron distribution to $R_n = 4.7$ fm
  - 14 keV $< E_r <$ 26 keV, $T < 1.5\ \mu$s

$$F_N^{\text{Helm}}(q^2) = \frac{3 j_1(qR_0)}{qR_0} \exp(-\frac{q^2 s^2}{2})$$
$$R_n^2 = R_0^2 + 5s^2$$

97 : total events
– 49 : classified as the steady-state (SS) background
– 19 : identified as delayed neutrino events (SM)
– 0 : identified as prompt neutrino events (SM)
– 3 : beam-related neutron (BRN) backgrounds

26 : "Excess"

Significance ($R_n = 4.7$ fm): **2.4 $\sigma$**

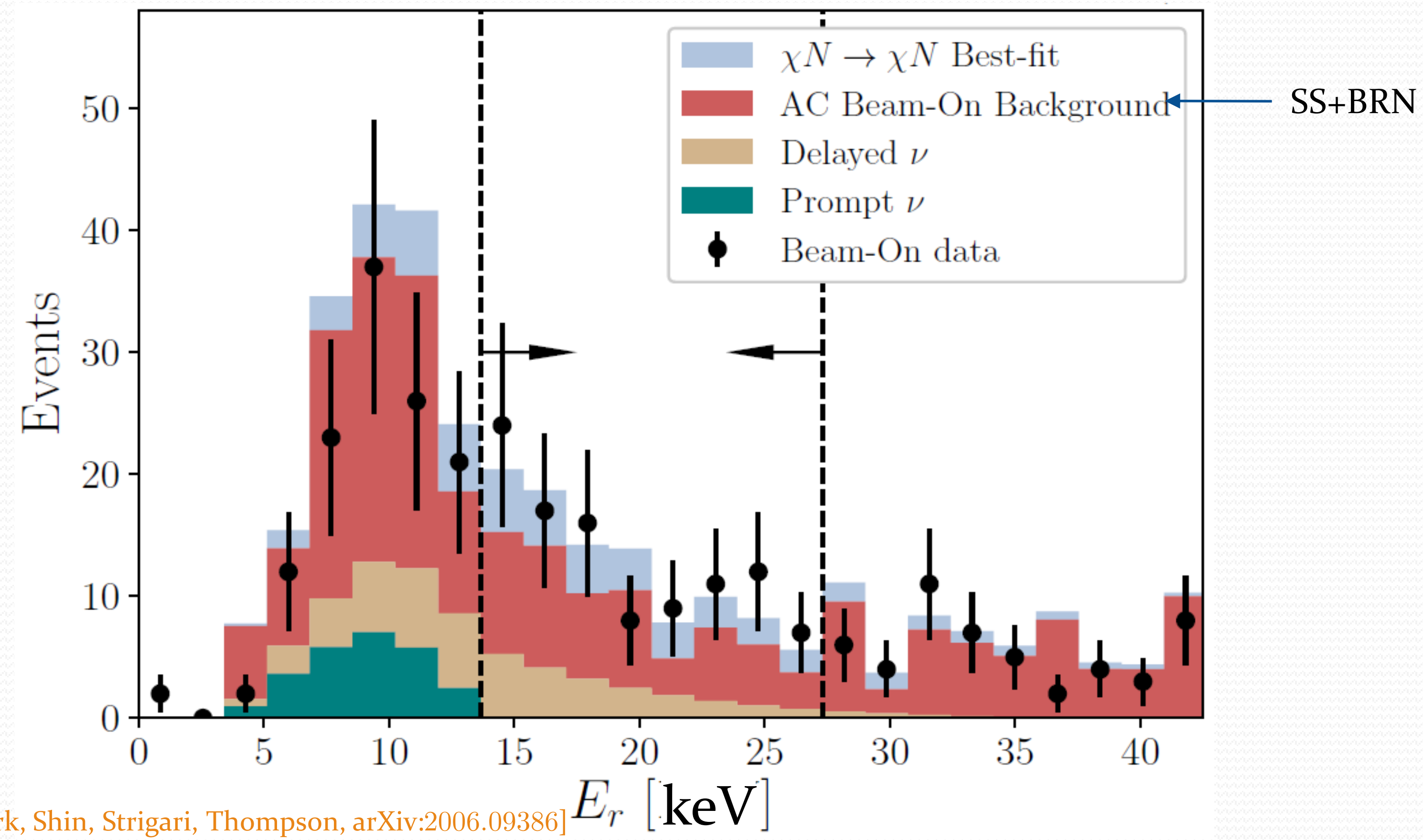
Significance ($R_n = 5.5$ fm): **3.0 $\sigma$**

$$\text{Significance} = \frac{\text{Excess}}{\sqrt{2\text{SS}+\text{BRN}+\text{SM}}}$$ [COHERENT, 1708.01294]

[Dutta, **DK**, Liao, Park, Shin, Strigari, PRL124 (2020) 12, 121801]

# Sample Fit

- Timing cut, $T < 1.5\ \mu s$ is applied, and the chosen model point is $(Y, m_{A'}) = (6.7 \times 10^{-11}, 138\ \text{MeV})$.




[Dutta, **DK**, Liao, Park, Shin, Strigari, Thompson, arXiv:2006.09386]

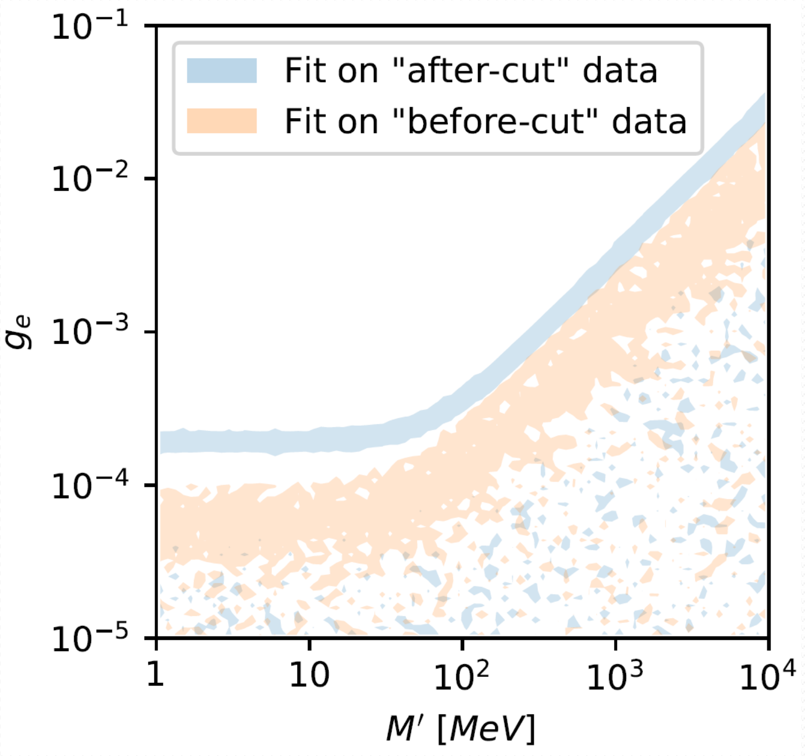
# Application to LAr Data of COHERENT

| Cut Scheme | Default PDF Excess | Best-fit PDF Excess |
|---|---|---|
| No Cuts | 1.62 | 2.56 |
| 10 < E < 30 keVee | 1.42 | 0.68 |
| t < 1.5mus, 10 < E < 30 keVee | 3.78 | 2.35 |
| t < 1.5mus, 10 < E < 30 keVee, F90 < 0.7 | 4.30 | 3.29 |

Preliminary

# If Mild Excess – Alternative Interpretation: NSI

- Example alternative new physics possibility, Non-Standard Interaction




- Benchmark case: non-zero coupling $g_e$, the NSI in the $\nu_e$ neutral-current interaction (along with a new mediator).
  - $\Rightarrow$ No overlapping regions, especially the prompt timing bin (i.e., $T < 1.5\ \mu$s) doesn't show a good fit. NSI affects the overall normalization of neutrino flux!
- The situation becomes even worse with $g_\mu \neq 0$, since it affects not only the delayed but the prompt spectrum.