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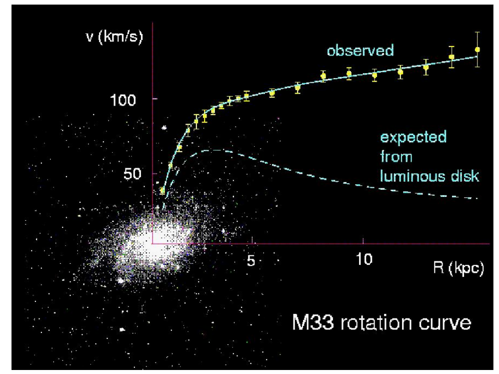
(IFIC Valencia - UV/CSIC)

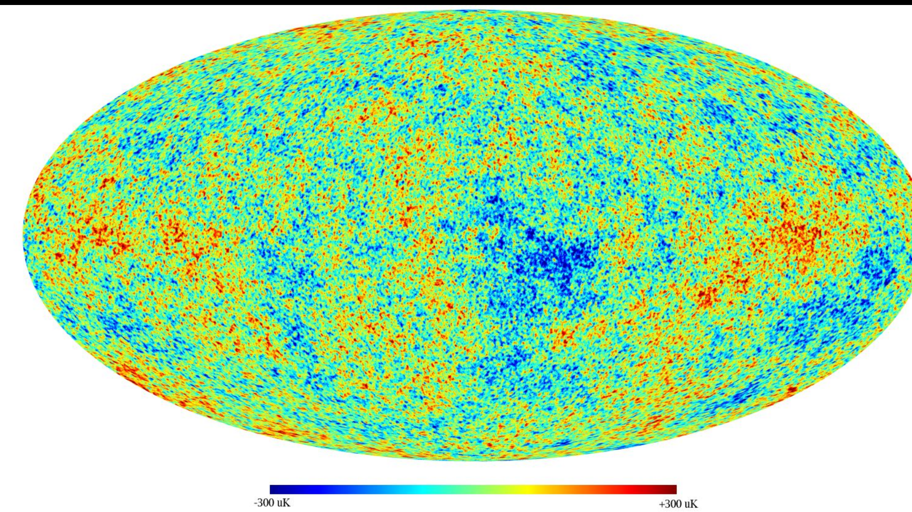
Hunting for Light Dark Matter with DUNE

15th MultiDark Consolider Workshop
Zaragoza
3-5 April 2019

Based on 1903.10505 in collaboration with K. Kelly and P. A. N. Machado

There is overwhelming evidence for the existence of dark matter:





CMB anisotropies,
Clusters (X-rays, lensing),
Large Scale Structures,
Galaxies (rotation curves, fits...)

The content of the Universe in terms of paellas (after Planck)

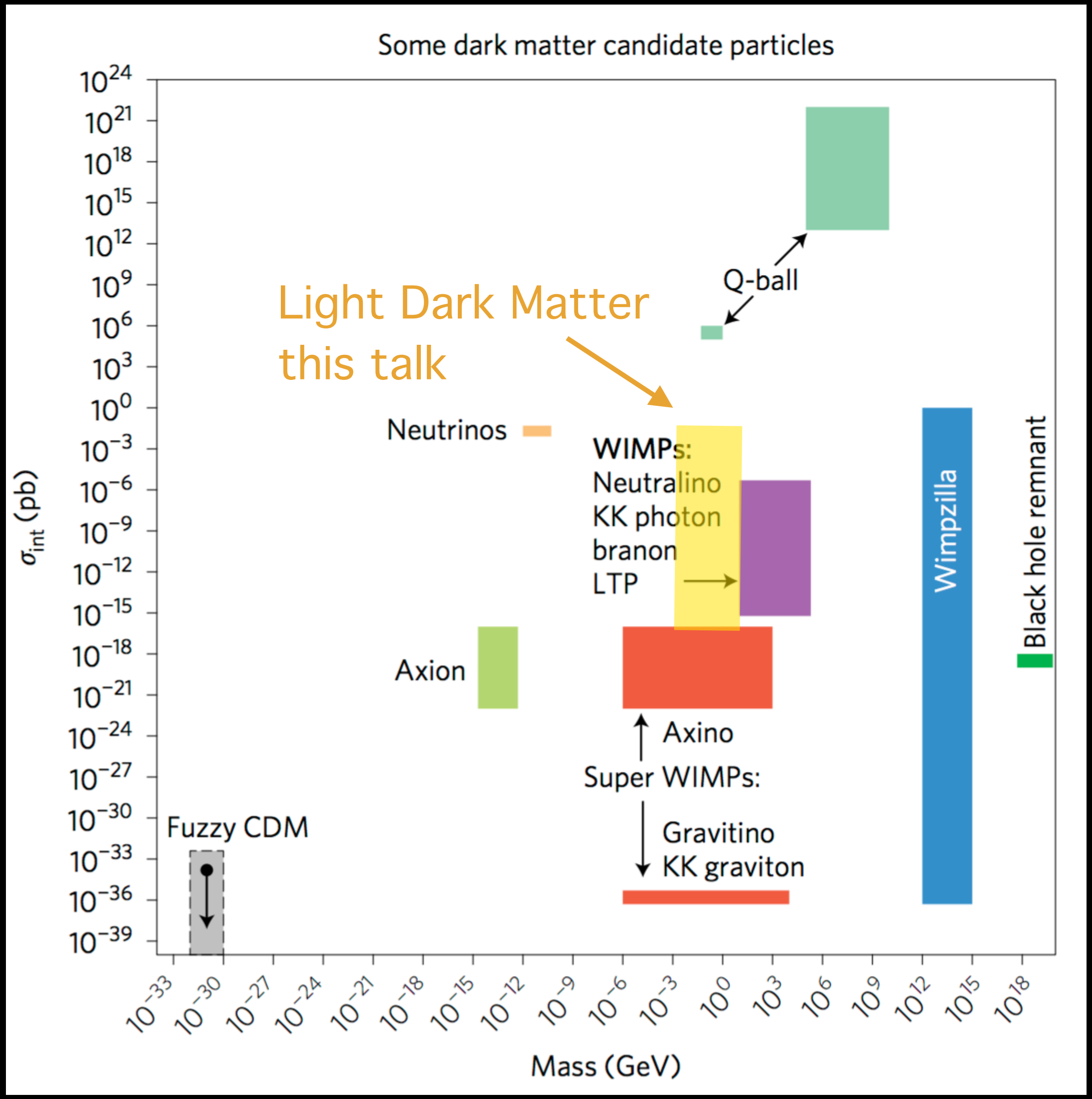
Cosmological
and astrophysical
observations

credit: R.A. Lineros

$$\Omega_{\mathrm{CDM}}h^2 = 0.1186 \pm 0.0020$$

What do we know about DM?

- Non-baryonic (BBN, CMB)
- Collisionless (bullet cluster)
- Stable on cosmological scales
  (or lifetime >> t_U ~13.8 Gyr)
- Neutral
- Massive
- Cold or Warm (structure formation)
- Not in conflict/excluded by DM experiments and cosmological data



Park, E.-K. DMSAG Report on the Direct Detection and Study of Dark Matter (2007)

not included in the Standard Model

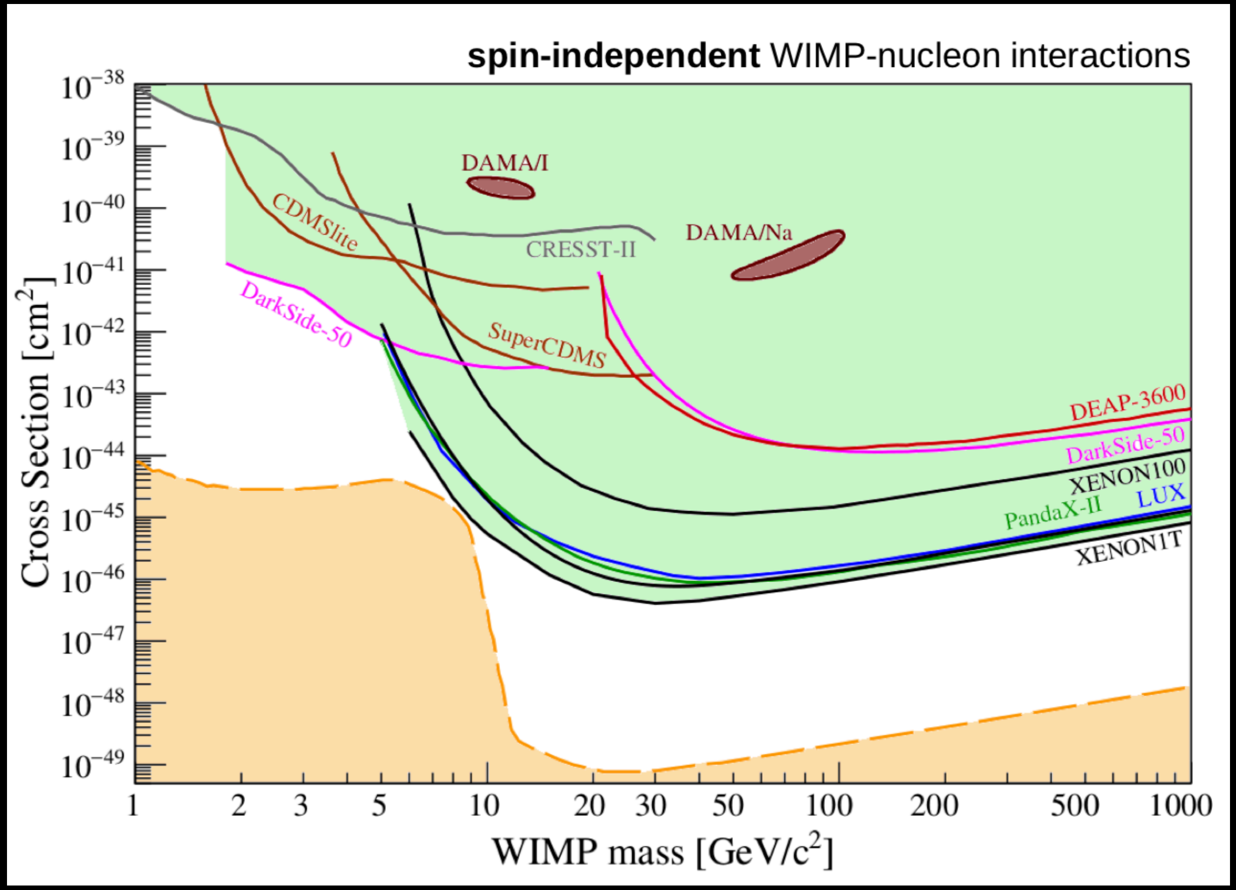
Many candidates in Particle Physics!

If DM is made of particles that interact among themselves and with SM particles we may hope to detect it. Two strategies:

1. DIRECT DETECTION (looks for energy deposited within a detector by the DM-nuclei scattering)

2. INDIRECT DETECTION (looks for WIMP annihilation (or decay) products)

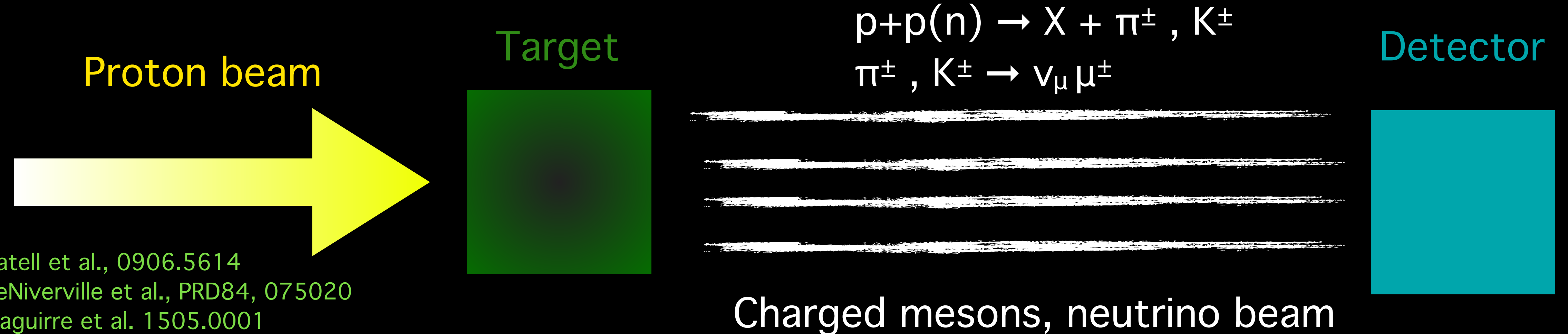
+ complementary searches at colliders



M. Schumann ZPW 2019

Light dark matter signals in neutrino detectors

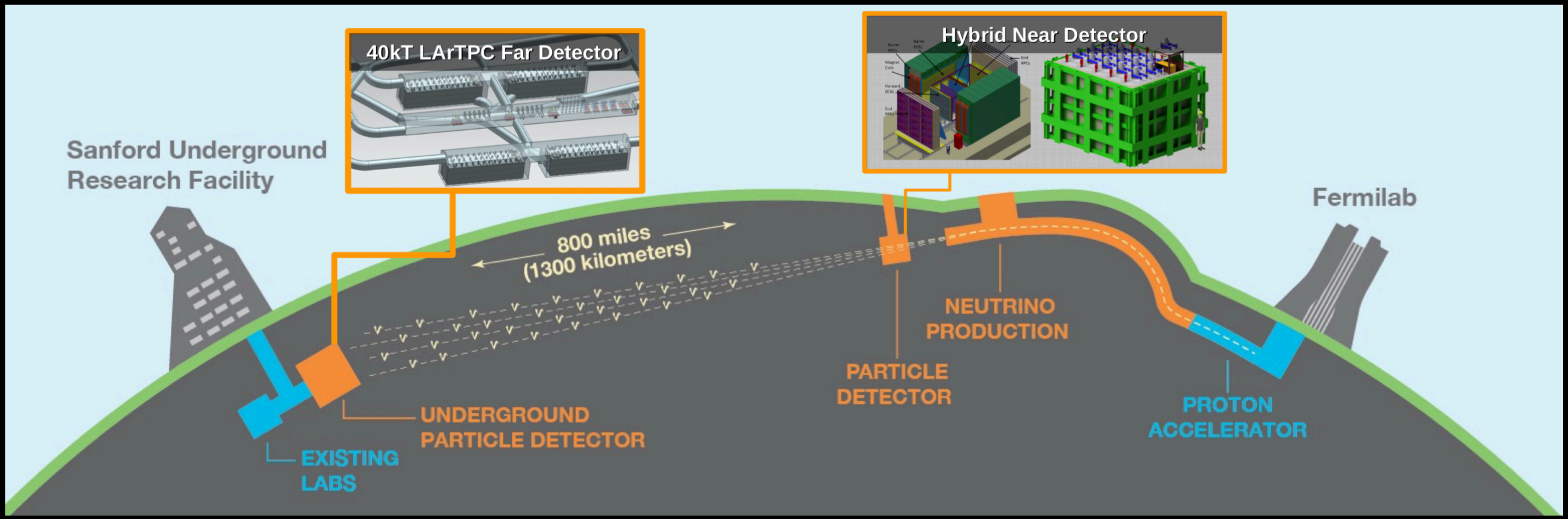
- Need of new experimental strategies
- Traditional direct detection experiments and the LHC have limited sensitivity to sub-GeV DM
- Neutrino facilities to probe light dark matter-nucleon interactions
- Experiments impact a target with $\sim 10^{21}$ protons/yr to produce a high intensity neutrino beam.
- Neutrinos produced from decays of charged mesons propagating through subsequent decay volume
    - Can select for neutrino or antineutrino beams through the use of magnetic focusing horns.
    - Non-neutrinos are removed from the beam before it reaches the detector to reduce background.



Batell et al., 0906.5614
deNiverville et al., PRD84, 075020
Izaguirre et al. 1505.0001
deNiverville et al., PRD95 035006
deNivervile, Frugiuele 1807.06501
++ ...

Light dark matter @ DUNE

- To search for DM with high mediator mass (1-10 GeV), we need high proton energy.
- Fermilab's Main Injector accelerator as a proton source of energy 120 GeV to make high energy neutrino beam.
- The Deep Underground Neutrino Experiment (DUNE) is the next generation long baseline neutrino experiment to provide a broad neutrino physics programme. It will consist of two detectors:
  - Far Detector: 40 kton liquid argon time-projection chamber (LArTPC) installed deep underground at the Sanford Underground Research Facility (SURF) 1300 km away
  - Near Detector: ~75 ton LAr placed at a distance of 574 m from the beam line.



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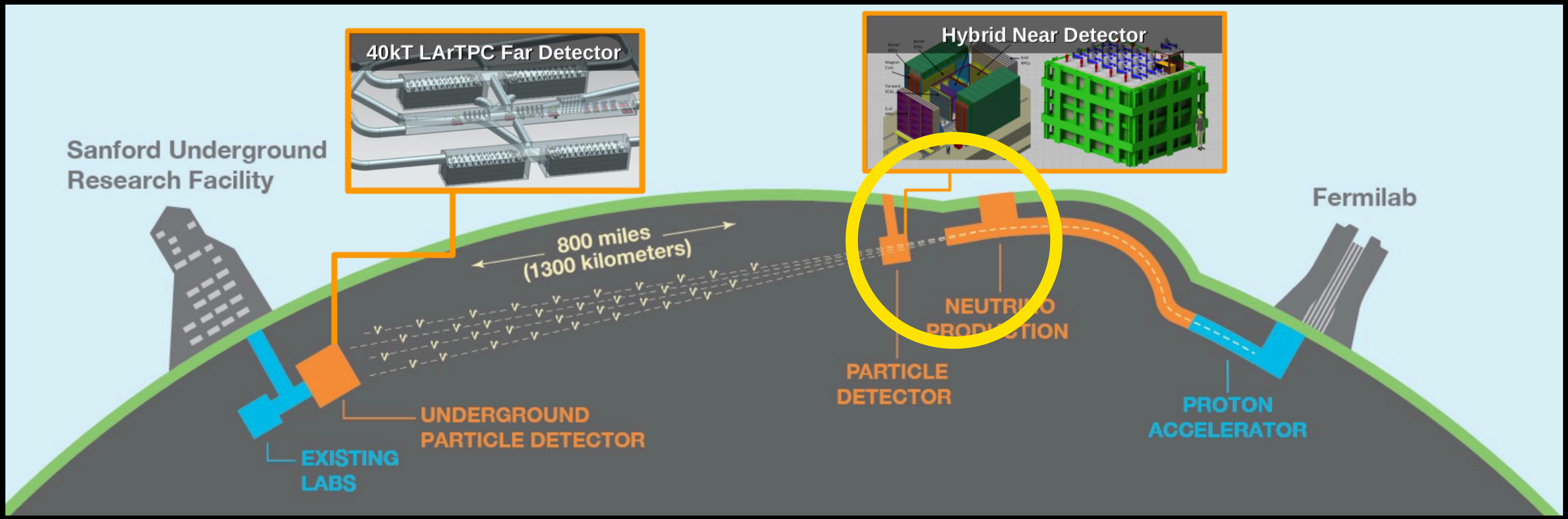
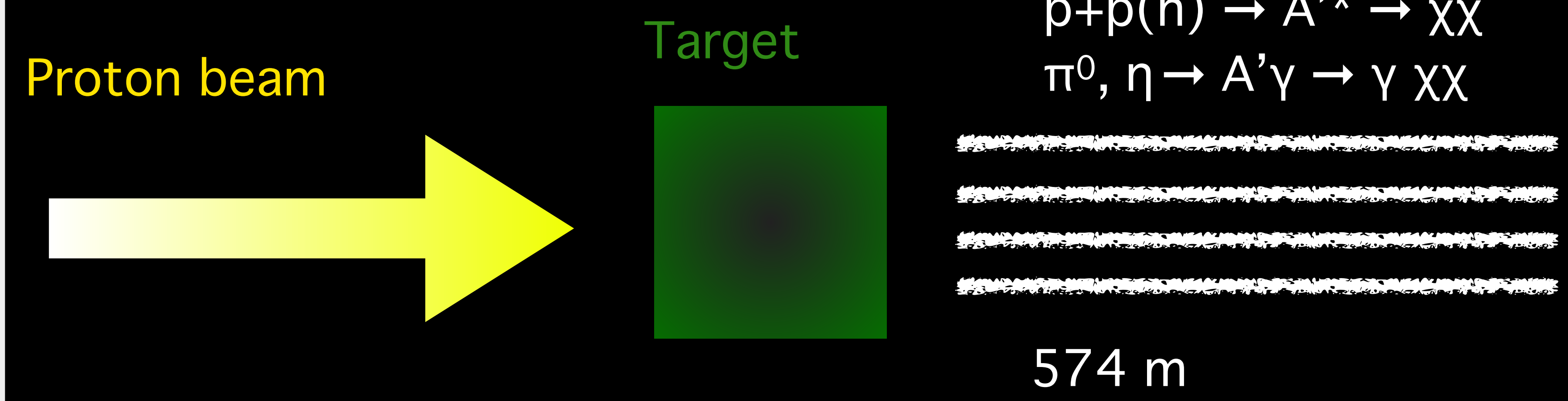
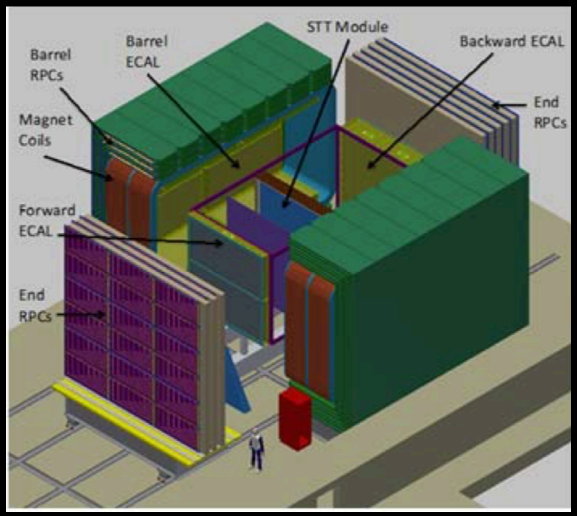


Light dark matter @ DUNE

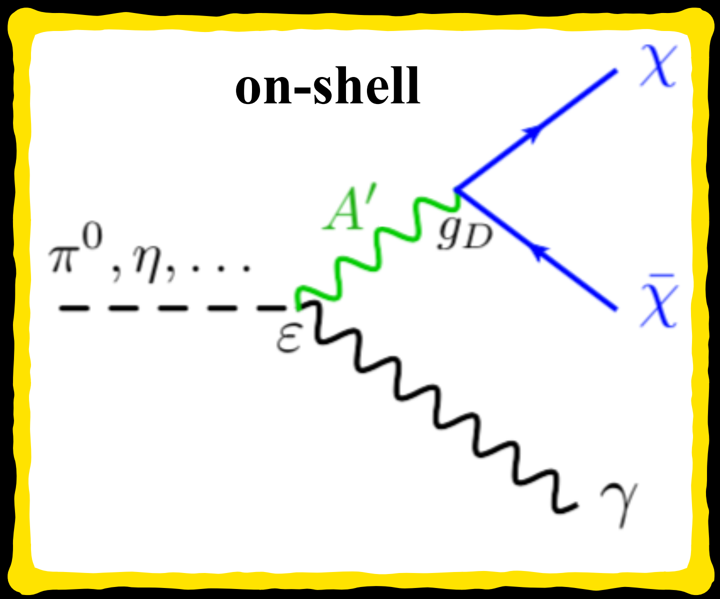


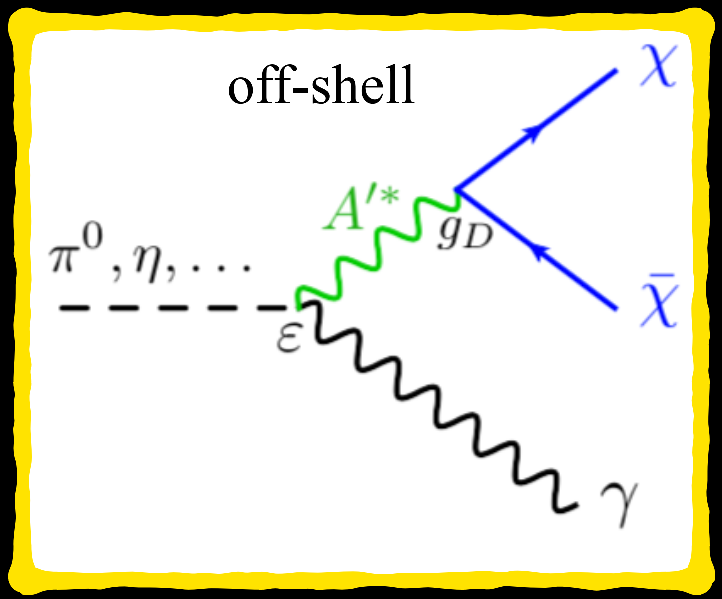
CDR reference design arXiv:1601.02984

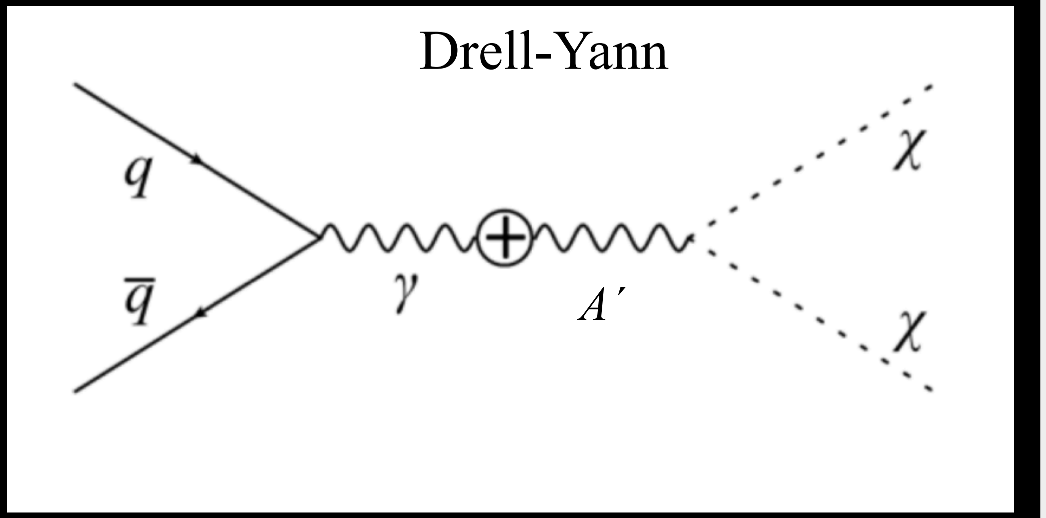


Near detector (75t LAr)

- DUNE near detector as a high intensity beam dump experiment
- High luminosity available (10^{21} POT/year)
- Allows for the production of a sizeable relativistic DM beam
- DM produced in the radiative decay of neutral hadrons or direct parton-level production







Light dark matter: dark photon portal

Extend the SM gauge group by including a new $U(1)_D$, spontaneously broken in a hidden sector.

A dark matter particle χ (or Φ) interacts with the SM particles through a massive dark photon A' and its kinetic mixing with the photon.

- DM is a light WIMP
- stable because new interactions are such that the DM can only be pair produced.

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M_{A'}^2}{2} A'_\mu A'^\mu + \overline{\chi} i \gamma^\mu \left(\partial_\mu - i g_D A'_\mu \right) \chi - M_\chi \overline{\chi} \chi$$

- Fermion DM

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M_{A'}^2}{2} A'_\mu A'^\mu + |D_\mu \phi|^2 - M_\phi^2 \, |\phi|^2$$

- Scalar DM

- ε kinetic mixing parameter between the SM $U(1)_Y$ and the new $U(1)_D$
- g_D gauge coupling associated to the dark $U(1)_D$
- $\alpha_D \equiv g_D^2/(4\pi)$, dark fine structure constant

Okun Sov. Phys JTEP 56, 502
Holdom PLB 166 196
Pospelov et al. Phys. Lett. B662 (2008) 53-61
Pospelov Phys. Rev. D80 (2009) 095002

Constraints

- Theoretical
- CMB and BBN
- Direct detection
- B-factories
- LEP, LHC
- Beam-dump exps
- Self interactions
- Supernovae

C. Boehm & P. Fayet, Nucl. Phys. B683 (2004) 219
C. Boehm et al., Phys. Rev. Lett. 92 (2004) 101301
Izaguirre et al. 1505.00011

Slatyer et al., PRD80 043526
Finkbeiner et al. PRD85 043522
Lin et al. PRD85 063503
Galli et al. PRD84 027302 +++

Essig et al. PRL109 021301, PRD96 043017

BABAR collab., Phys. Rev. Lett. 113 (2014) 201801, Phys. Rev. Lett. 119, 131804 (2017)

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Batell et al. PRD80 095024
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Batell et al. PRL 113 171802
Yahn et al. PRD91 055006
Aguilar-Arevalo et al.PRD9811, 112004
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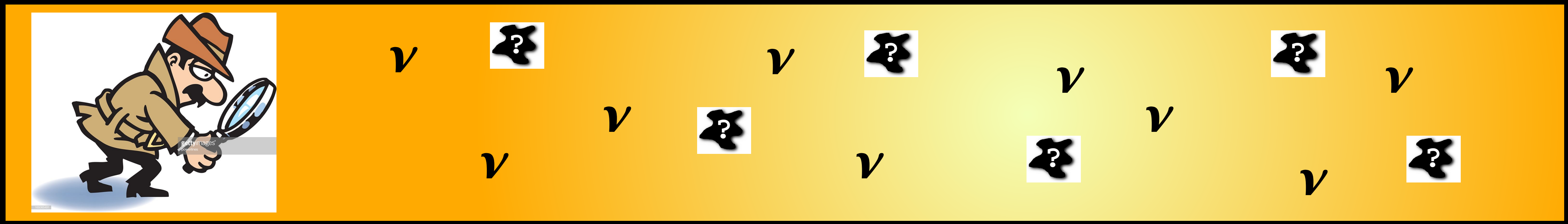
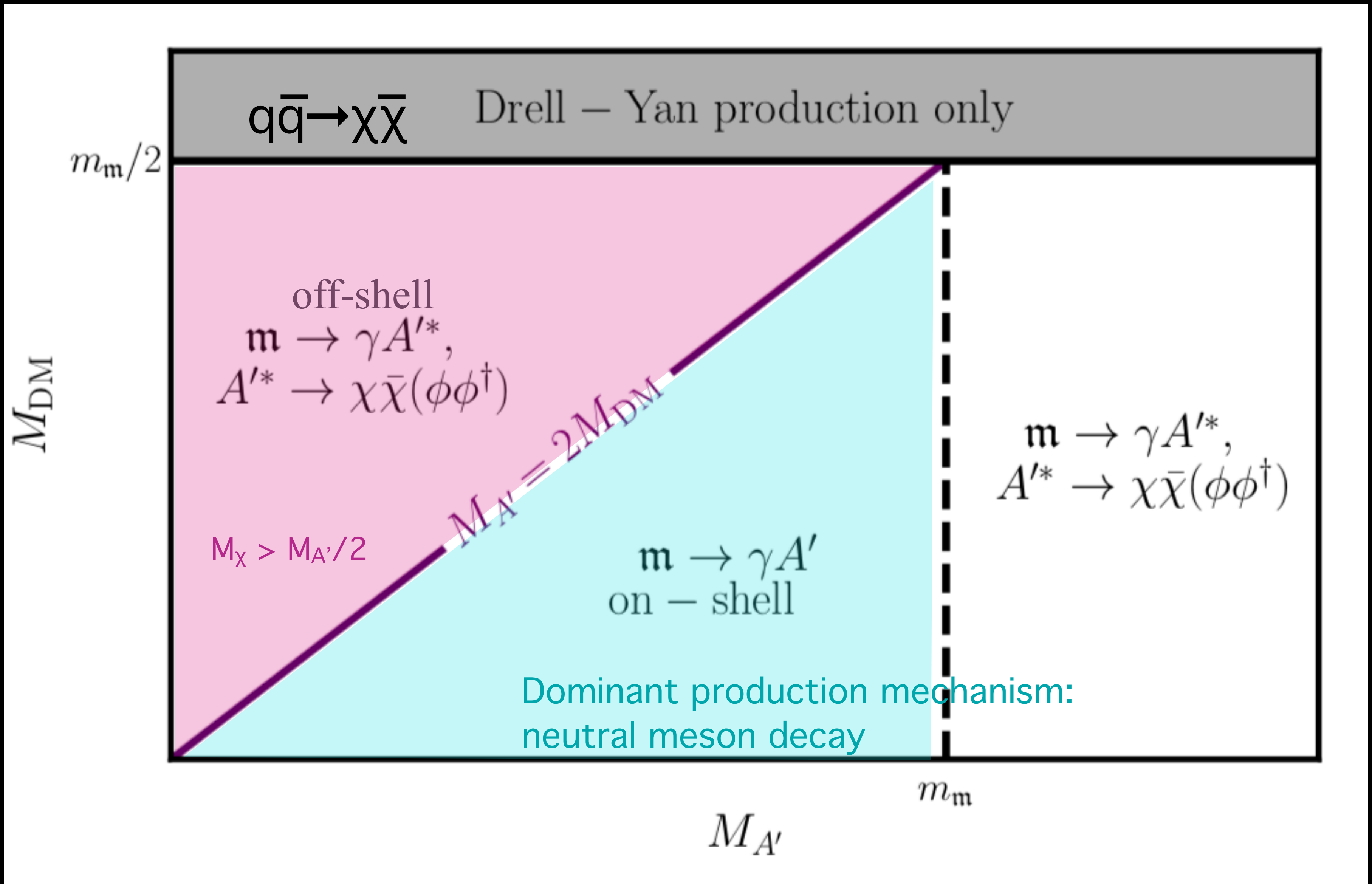


Light dark matter @ DUNE

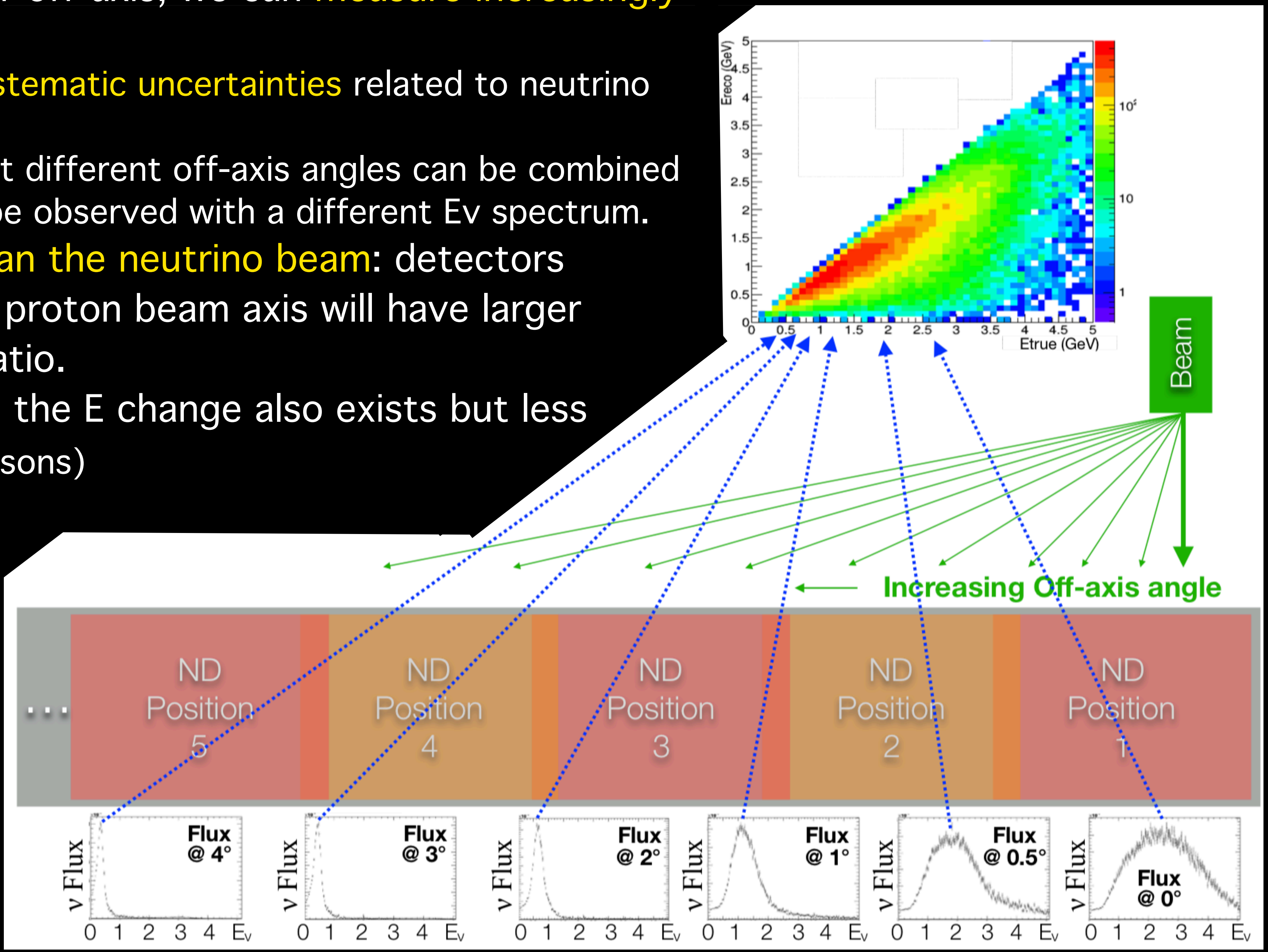
- Any process in which photons participate at a neutrino facility can lead to A' or DM production.
- For DM heavier than mediator, t-channel annihilation into two mediators typically dominates over the s-channel processes.



DUNE PRISM

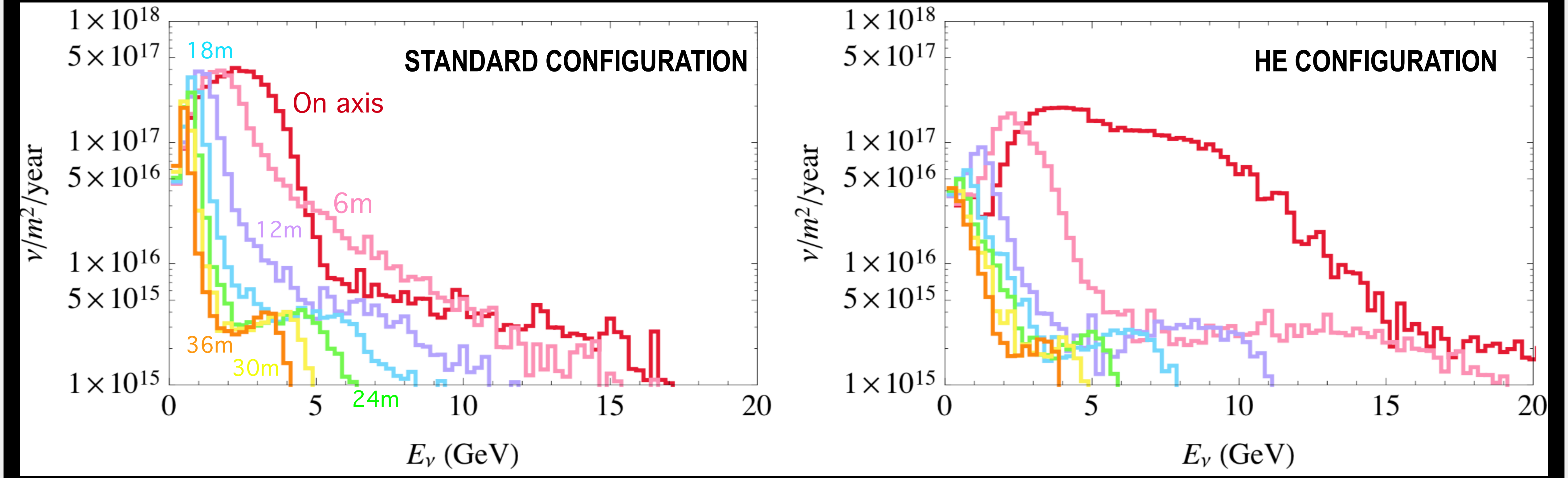
- The DUNE PRISM concept proposes to move the near detector between 0 and 36 m transverse to the beam direction.
- By moving the detector off-axis, we can measure increasingly lower Ev spectra.
  - Advantage: reduce systematic uncertainties related to neutrino cross sections.
  - Interaction observed at different off-axis angles can be combined to mimic what would be observed with a different Ev spectrum.
- DM beam is broader than the neutrino beam: detectors located away from the proton beam axis will have larger signal to background ratio.
- For the DM production, the E change also exists but less pronounced (neutral mesons)

credit: M. Wilking, DUNE PRISM design group



DUNE HE configuration

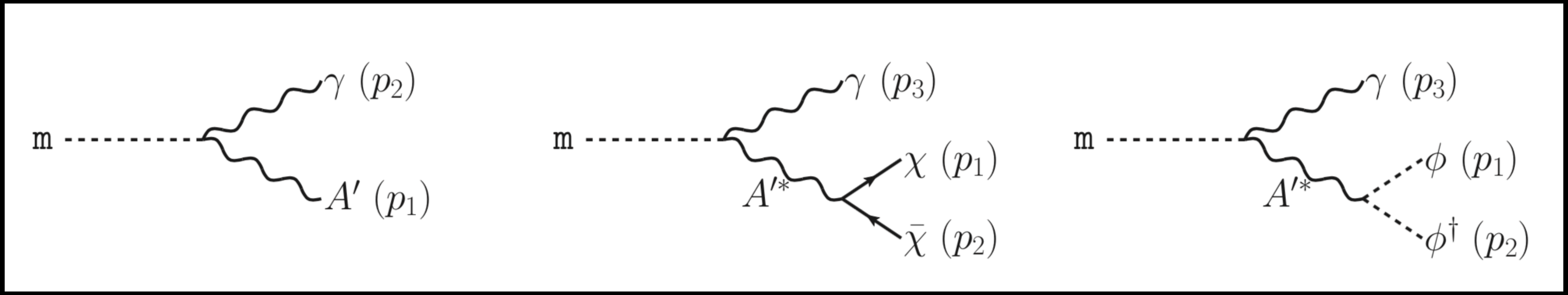
- DUNE will operate in two horn currents, focusing positive and negative mesons that produce mostly neutrinos and antineutrinos
- Additionally, a HE configuration has also been considered mainly for the study of tau neutrinos at the far detector.



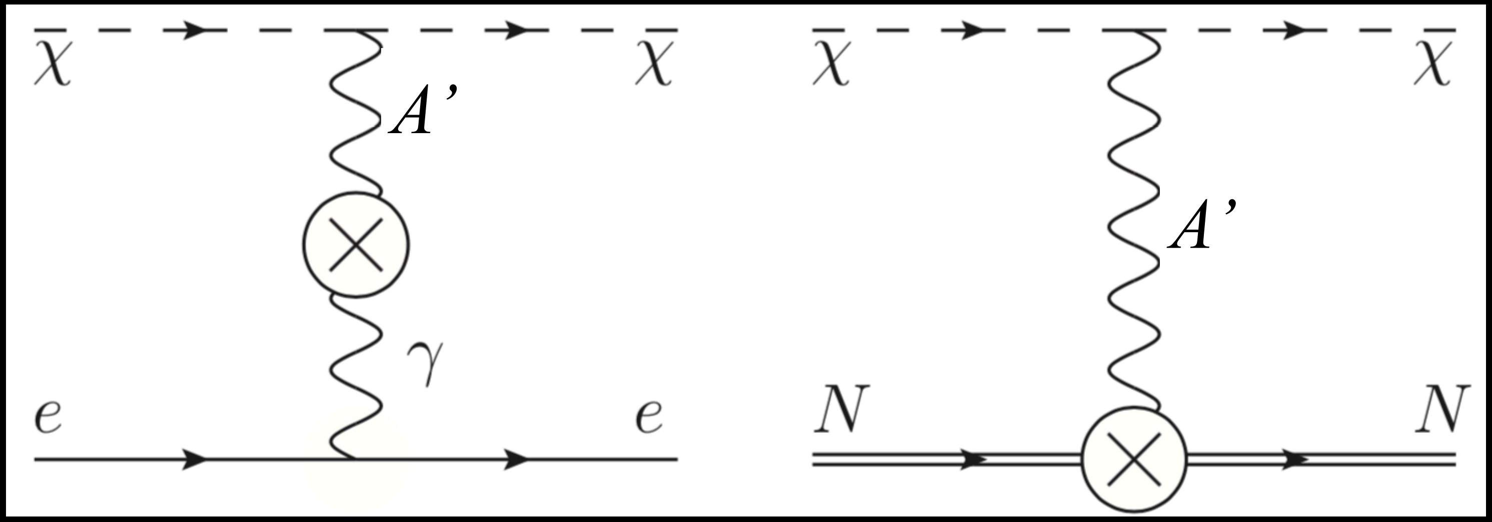
fluxes from Laura Fields http://home.fnal.gov/~ljf26/DUNEFluxes/

Detecting Dark Matter with DUNE

- We consider a 120 GeV proton beam striking a graphite target and simulate the production of meson m = π^0, η using PYTHIA8.
- We simulate the DUNE DM angular distributions and energy spectra from π^0, η decays on an event-by-event basis.



Production

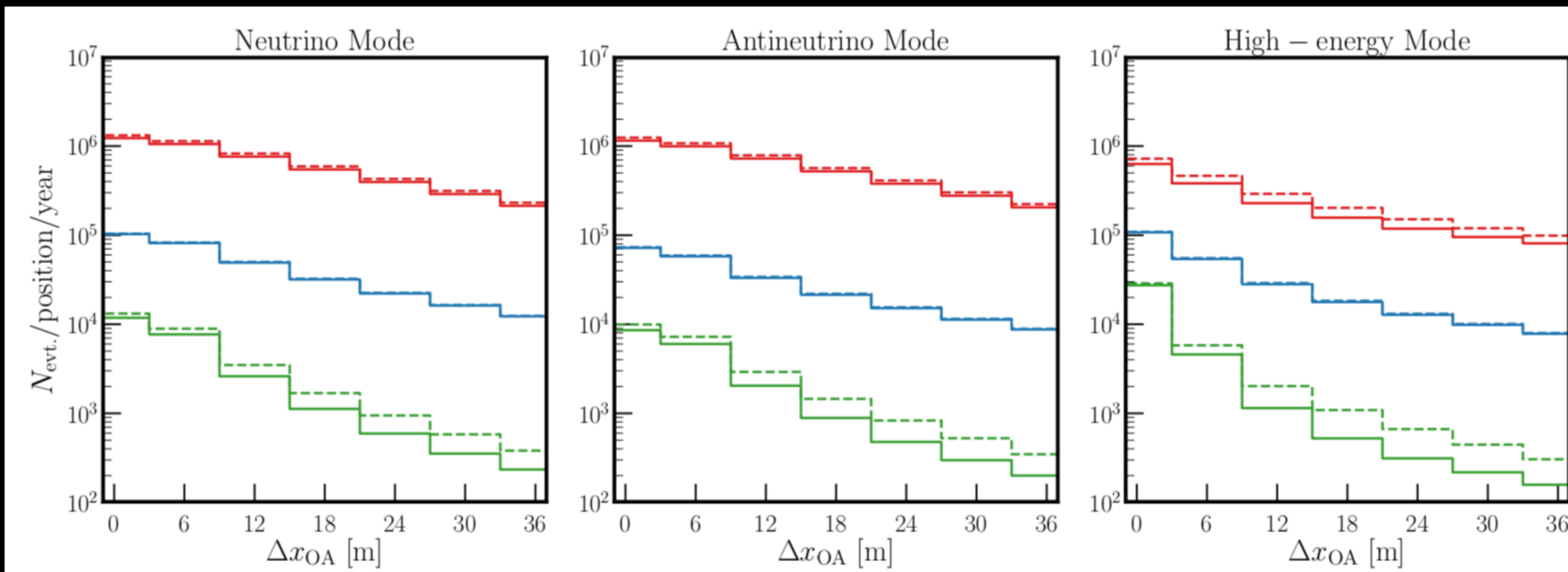


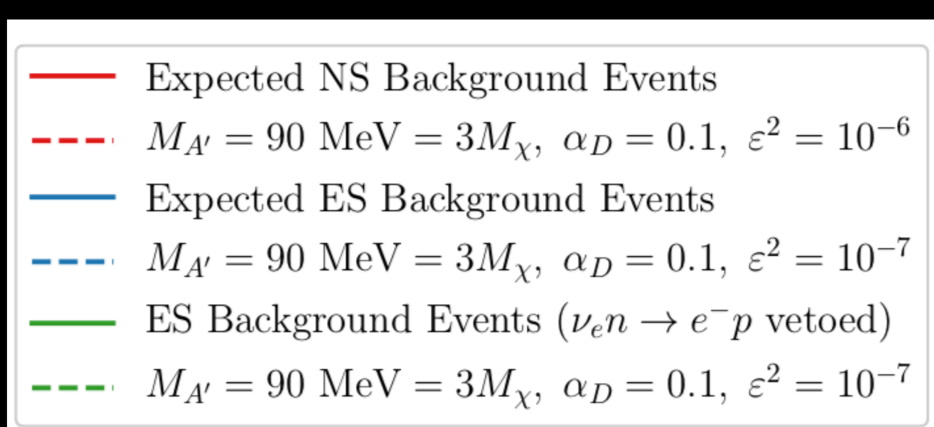
Signatures

- Nucleon scattering (NCQE)
- Electron scattering

Detecting Dark Matter with DUNE

- Expected number of events per year of data collection





Three backgrounds:

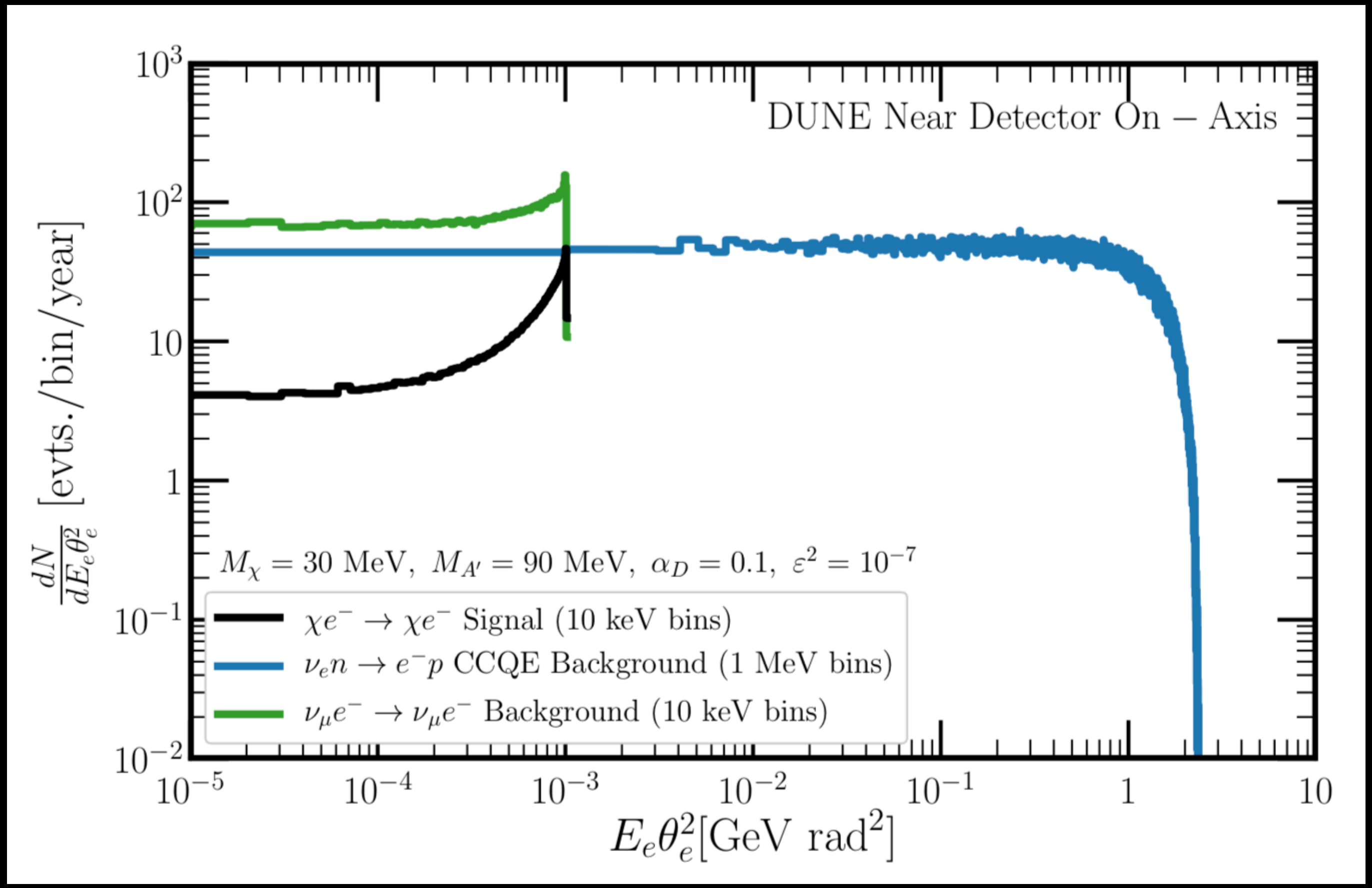
- neutrino-nucleon scattering (NC) $\nu N \to \nu N$
- neutrino-electron scattering (NC) $\nu_\mu e^- \to \nu_\mu e^-$
- neutrino-nucleon scattering (CC) $\nu_e n \to e^- p$

Background reduction for CCQE scattering

Performing solely a counting experiment, the largest background is from electron neutrino beam contamination with CCQE scattering, $\nu_e n \to e^- p$ or $\nu_e p \to e^+ n$, where the final-state hadronic system is unidentified.

Since the initial and final states are distinct (and nucleons), the electron will tend to scatter at large angles.

Place a cut on the outgoing energy and angle of the final electron retaining all of our signal, all of the $\nu_\mu e^- \to \nu_\mu e^-$ background, and less than 0.1% of the CCQE background.



Statistical analysis

Combine all channels and beam configurations as independent experiments.

- On-axis: all data collected on axis, 3.5 yr nu mode, 3.5 yr anu mode (r_1 =3.5, r_i = 0).
- DUNE-PRISM: data collected at equal time for each off-axis position, 3.5 yr nu mode, 3.5 yr anu mode (r_i = 0.5).
- DUNE-PRISM-HE: data collected at equal time for each off-axis position, 3 yr nu mode, 3 yr anu mode, 1yr HE mode (r_i = 3/7 for nu and anu, r_i = 1/7 for HE).

$$-2\Delta\mathcal{L} = \sum_i \frac{r_i^m\left(\left(\frac{\varepsilon}{\varepsilon_0}\right)^4 N_i^\chi + (A-1)N_i^\nu\right)^2}{A\left(N_i^\nu + (\sigma_{f_i} N_i^\nu)^2\right)} + \frac{(A-1)^2}{\sigma_A^2}.$$

Benchmarks	$r^{\nu}_{\rm on}$	$r^{\overline{\nu}}_{\rm on}$	$r^{\nu}_{{\rm off},i}$	$r^{\overline{\nu}}_{{\rm off},i}$	$r^{{\rm HE}\nu}_k$
On-axis	3.5	3.5	0	0	0
DUNE-PRISM	0.5	0.5	0.5	0.5	0
DUNE-PRISM-HE	3/7	3/7	3/7	3/7	1/7

Three sources of uncertainty: statistical, correlated systematic (σf_i =1%) and uncorrelated systematic (σ_A =10%).

Nüisance parameter A (different for each mode) modifies the number of nu-related background events in each bin (with Gaussian uncertainty = 10%).
Any single-position measurement will be systematic-limited.

Sensitivity improvement from e- kinematics

Sensitivity can be improved by including information about the final-state electron kinematics for the signal and background distributions.

Depending on the DM/A′ masses, the DM-electron scattering spectrum can appear significantly different than the $\nu_\mu e^- \to \nu_\mu e^-$ background.

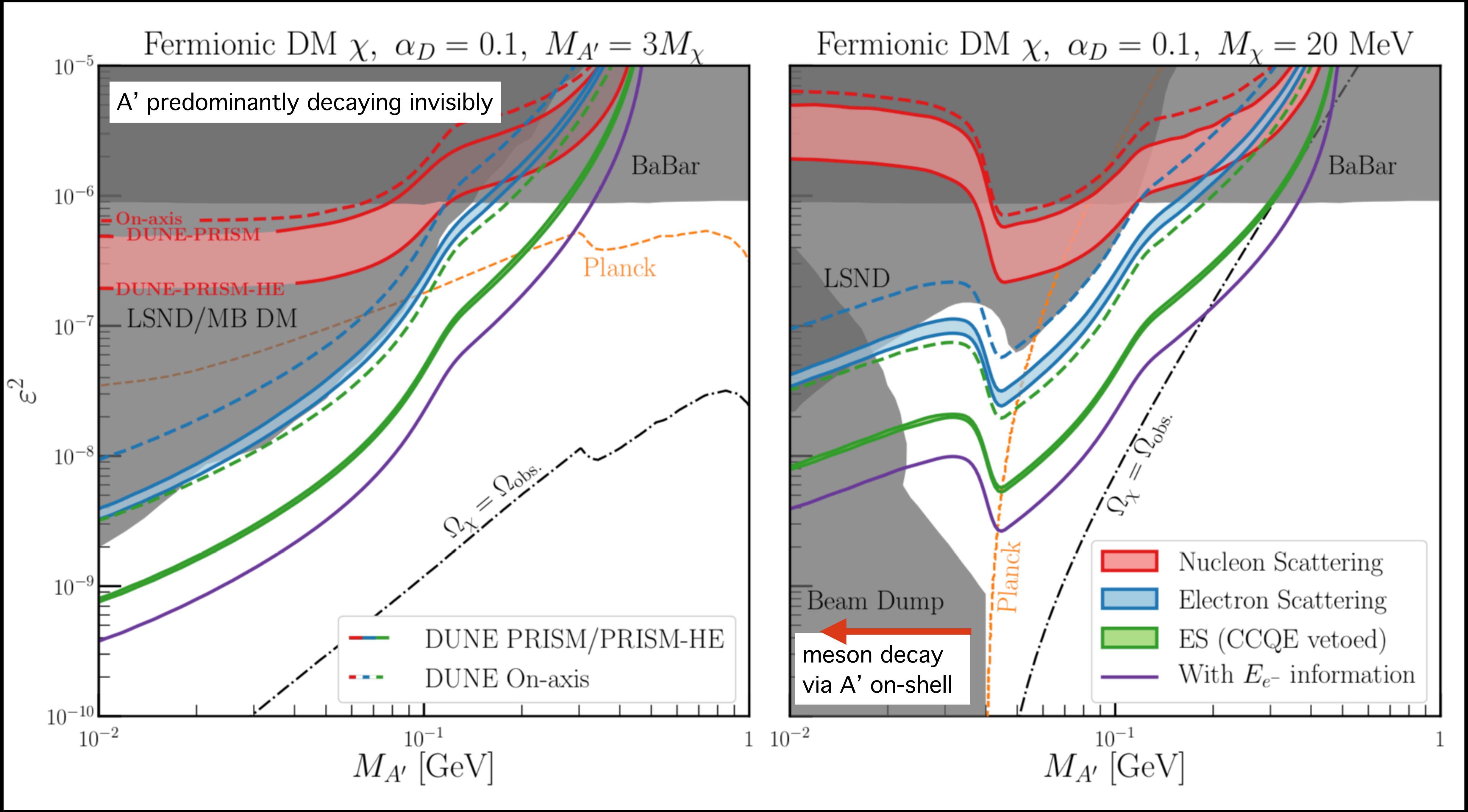
$$\mathcal{L}_{ij} \to -A * f_i \left(\left(\frac{\varepsilon}{\varepsilon_0} \right)^4 N_{ij}^{\chi} + N_{ij}^{\nu} \right) + N_{ij}^{\nu} \ln \left(A * f_i \left(\left(\frac{\varepsilon}{\varepsilon_0} \right)^4 N_{ij}^{\chi} + N_{ij}^{\nu} \right) \right) - \ln \left(N_{ij}^{\nu}! \right),$$

$$-2\Delta\mathcal{L} = \sum_{i=1} \left[\sum_{j=1} (-2\mathcal{L}_{ij}) + \frac{(f_i - 1)^2}{\sigma_{f_i}^2} \right] + \frac{(A-1)^2}{\sigma_A^2}.$$

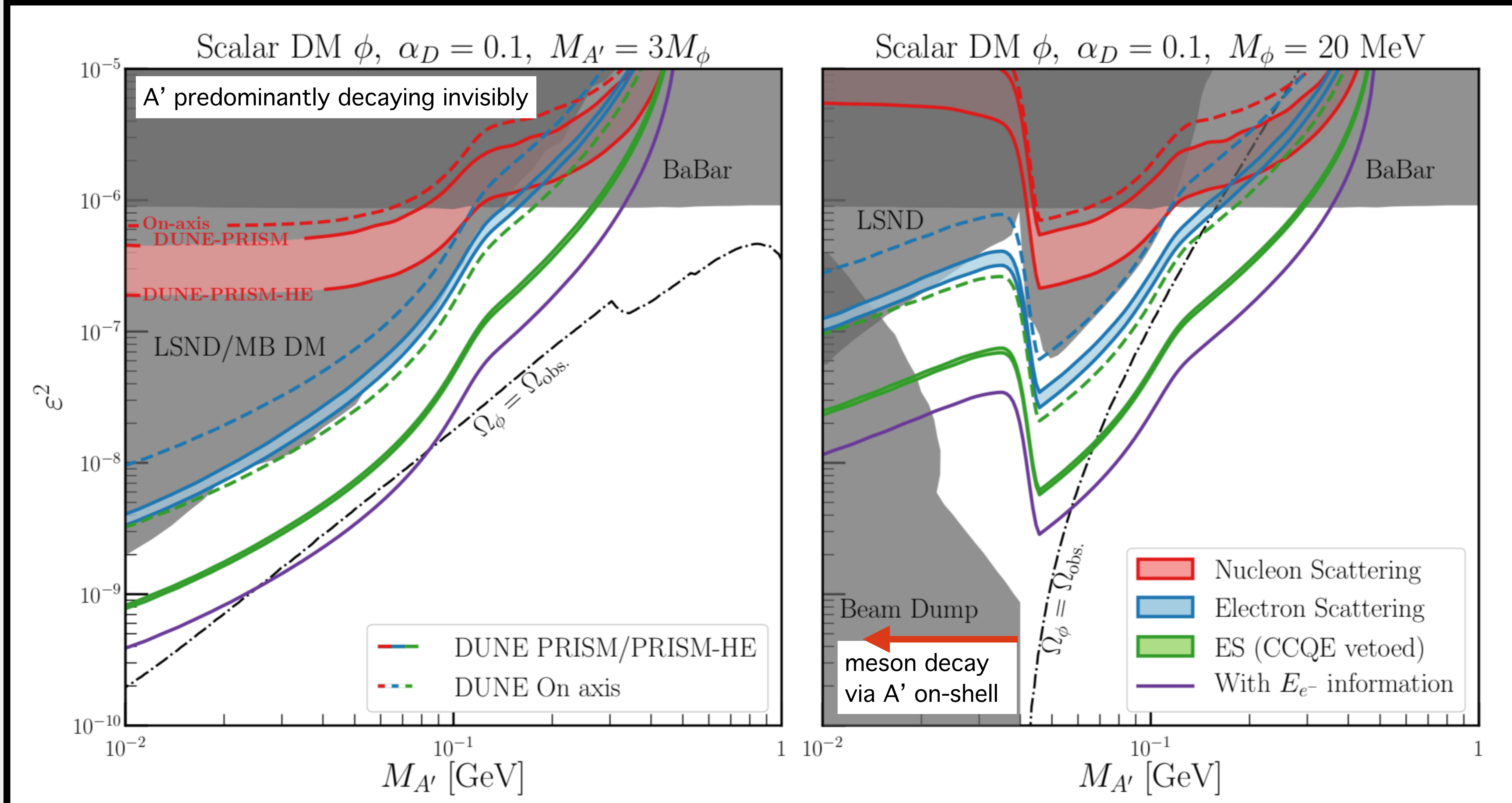
i: position
j: energy bin

The improvement obtained when considering electron energy leads to roughly a factor of 2 stronger limits on ε^2 are expected for A′ and χ masses of interest

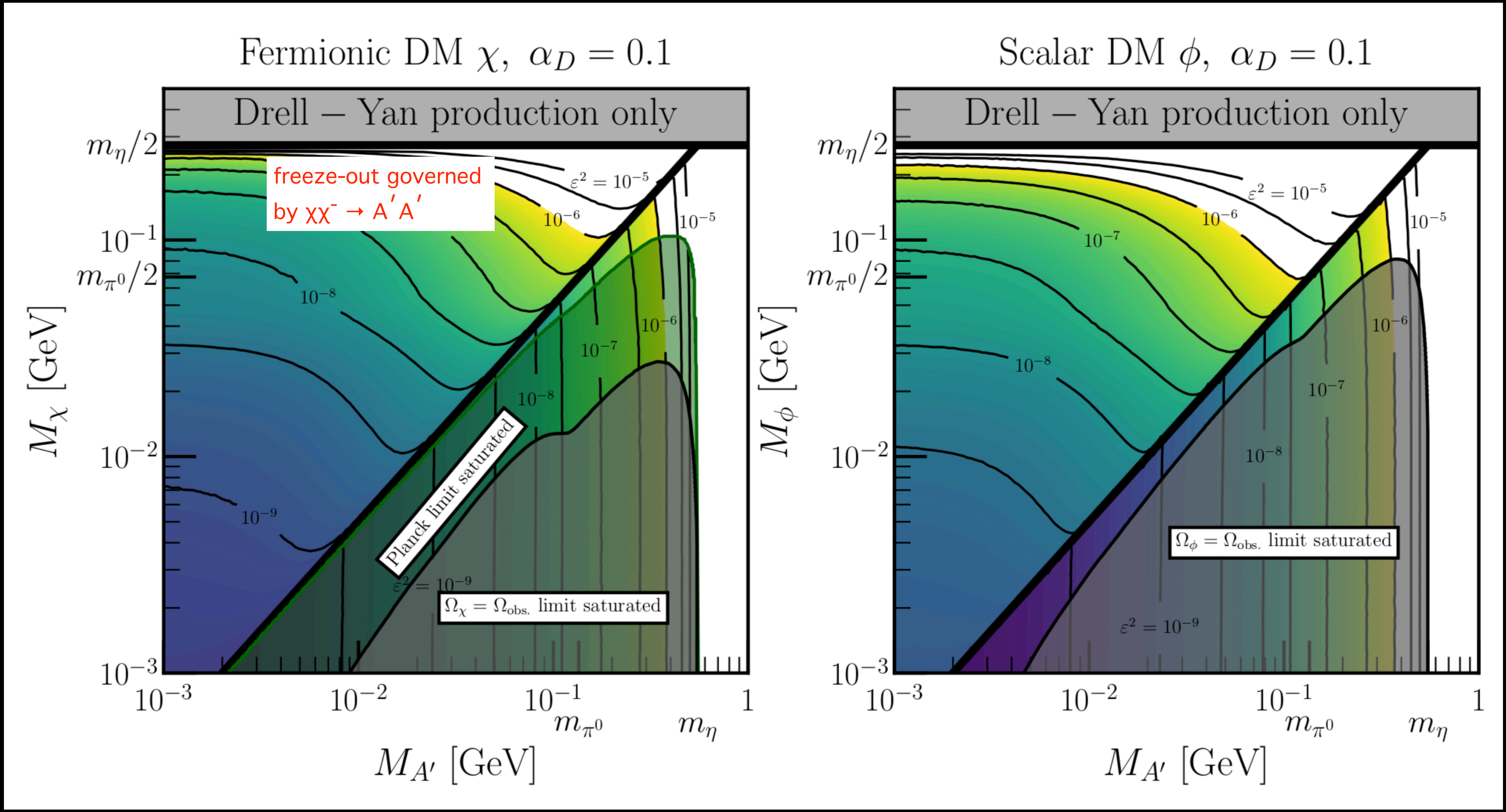
Results: fermionic DM



Results: scalar DM



Results: full parameter space



Electron scattering assuming the ν_e CCQE background has been vetoed and data are collected according to the DUNE-PRISM-HE scenario

Summary and outlook

- We have studied the prospects for detecting light dark matter at DUNE. Great complementarity to direct detection experiments and LHC searches.

- We have assumed a light dark matter (fermionic or scalar) (sub-GeV) with dark photon mediator.

- We investigated the impact on sensitivity limits at DUNE with both the DUNE-PRISM option and the HE configuration.

- Role of DUNE-PRISM:
  - neutrino induced backgrounds decrease faster than the DM signal
  - the on-axis measurement, being signal-rich, serves to constrain the neutrino flux with high statistics
  - → extend the reach in sensitivity on ε^2.

- Electron scattering allows for better sensitivity (compared to nucleon scattering) especially if the ν_e CCQE background can be removed.

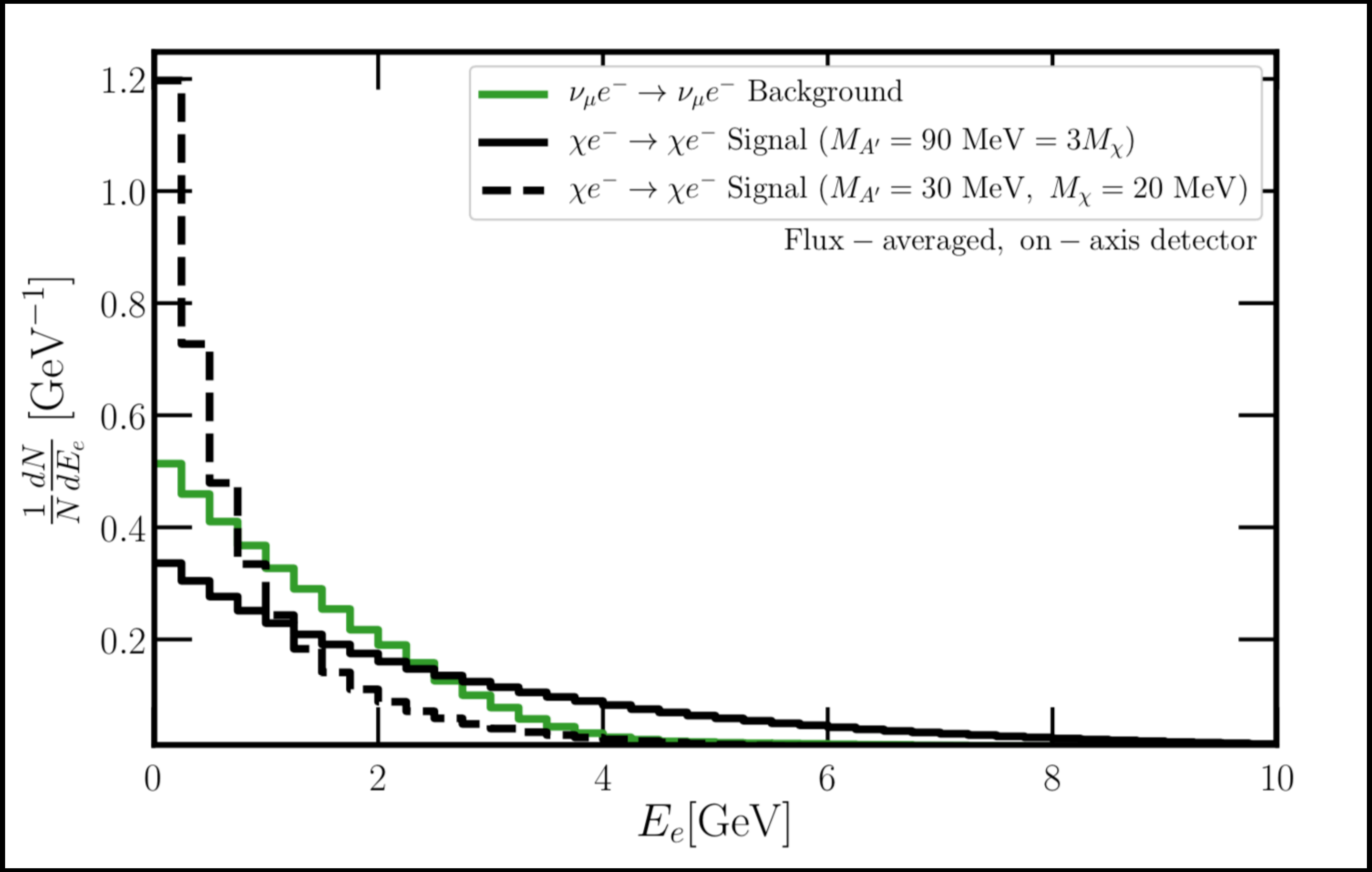
- DUNE-PRISM will be sensitive to values of ε^2 only a factor of ~ 3 higher than those probed by LDMX.
  LDMX Collaboration, T.Akesson et al. arXiv:1808.05219

- Competitive with dedicated experiments in probing light dark matter scenarios!!

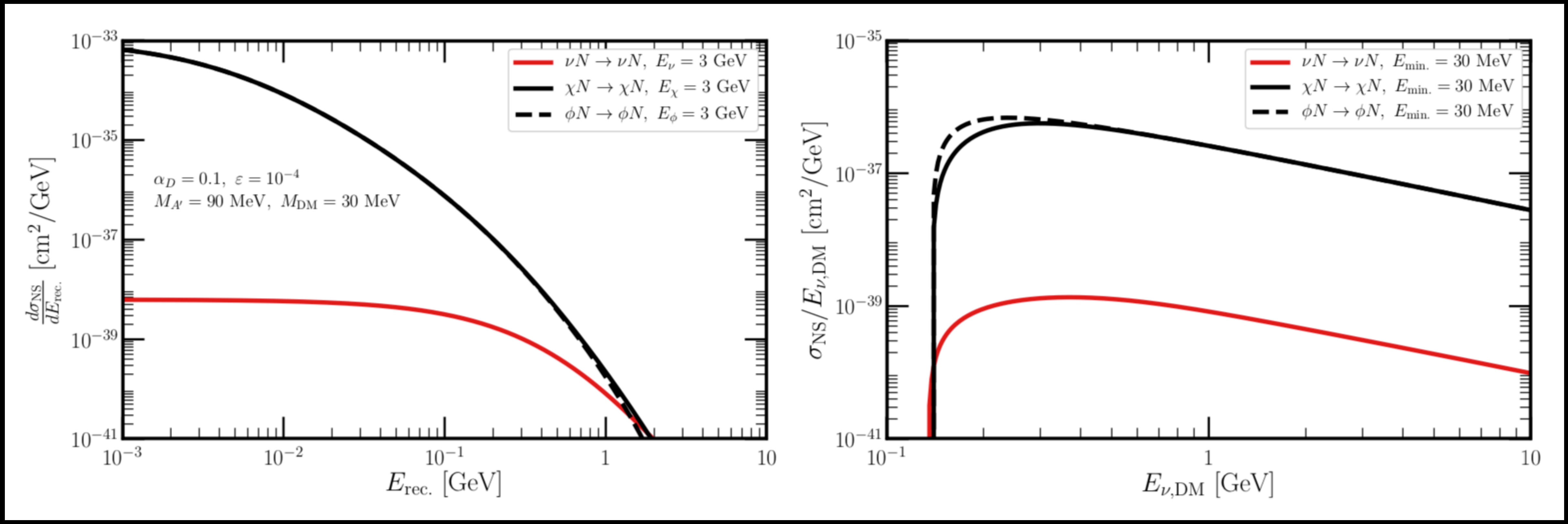
I acknowledge financial support by the "Juan de la Cierva Incorporacion" program (IJCI-2016-27736) funded by the Spanish MINECO, as well as partial support by the Spanish grants SEV-2014-0398, FPA2017-85216-P (AEI/FEDER, UE), PROMETEO/2018/165 (Generalitat Valenciana) and the Spanish Red Consolider MultiDark FPA2017-90566-REDC.

Backup

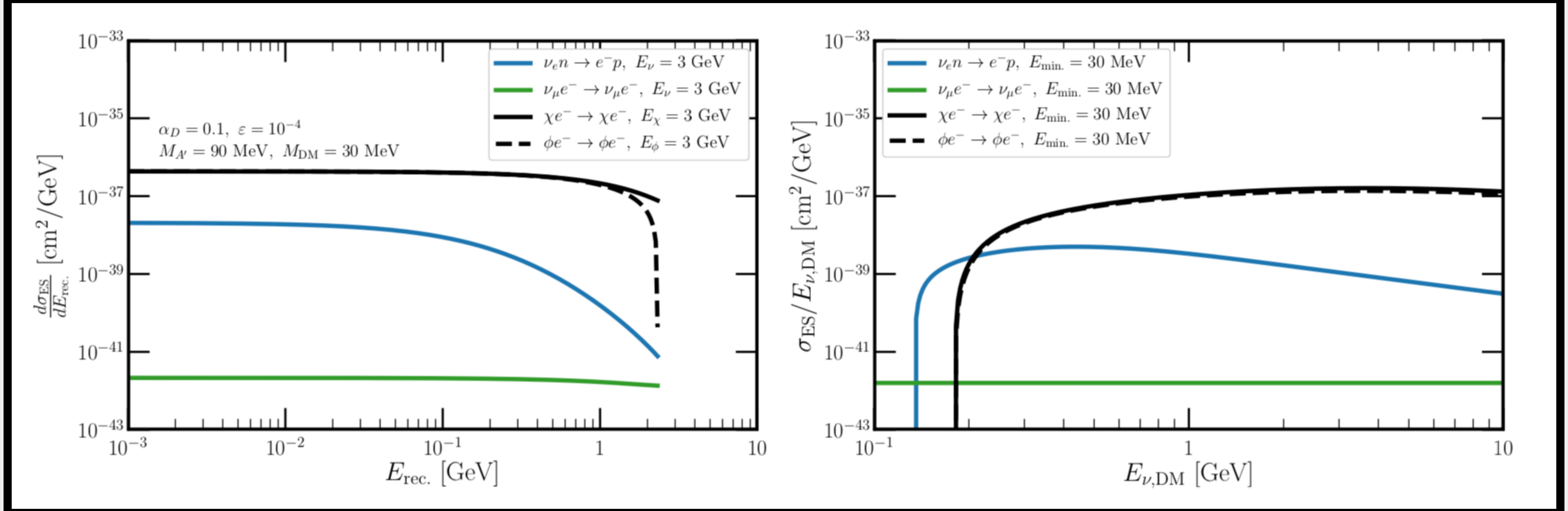
We will assume a conservative electron energy resolution of 250 MeV for these events, and we will consider electron events with energy between 0 and 10 GeV (40 bins total).



Differential and total cross sections for nucleon scattering



Differential and total cross sections for electron scattering



Meson Decay Branching Fractions

$$\mathrm{Br}(\mathfrak{m} \to \gamma\chi\bar{\chi}) = \mathrm{Br}(\mathfrak{m} \to \gamma\gamma) \times 2\varepsilon^2 \left(1 - \frac{M_{A'}^2}{m_{\mathfrak{m}}^2}\right)^3 \times \mathrm{Br}(A' \to \chi\bar{\chi}) \qquad (\mathrm{fermionic\ DM, on-shell}),$$

$$\mathrm{Br}(\mathfrak{m} \to \gamma\phi\phi^\dagger) = \mathrm{Br}(\mathfrak{m} \to \gamma\gamma) \times 2\varepsilon^2 \left(1 - \frac{M_{A'}^2}{m_{\mathfrak{m}}^2}\right)^3 \times \mathrm{Br}(A' \to \phi\phi^\dagger) \qquad (\mathrm{scalar\ DM, on-shell}).$$

$$\frac{\mathrm{Br}(\mathfrak{m} \to \gamma\chi\overline{\chi})}{\mathrm{Br}(\mathfrak{m} \to \gamma\gamma)} = \alpha_D\varepsilon^2 \times \frac{2}{3\pi} \int_{4x}^{1} \frac{(1-z)^3(2x+z)\sqrt{1-\frac{4x}{z}}}{(z-y)^2} dz,$$

$$\frac{\mathrm{Br}(\mathfrak{m} \to \gamma\phi\phi^\dagger)}{\mathrm{Br}(\mathfrak{m} \to \gamma\gamma)} = \alpha_D\varepsilon^2 \times \frac{1}{6\pi} \int_{4x}^{1} \frac{(1-z)^3 z \left(1-\frac{4x}{z}\right)^{3/2}}{(z-y)^2} dz.$$

Dark Matter Scattering Cross Sections

$$\frac{d\sigma(\chi N \to \chi N)}{dQ^2} = \frac{\pi \varepsilon^2 \alpha_{\text{EM}} \alpha_D}{4 m_N^3 \left(E_\chi^2 - M_\chi^2\right) \left(Q^2 + M_{A'}^2\right)^2} \times \qquad \text{(Fermionic DM)}$$
$$\left[16 E_\chi^2 m_N^3 F_1^2 + Q^4 \left(F_2(m_N(4F_1 + F_2) - 2E_\chi F_2) + 2F_1^2 m_N\right) \right.$$
$$\left. -4 m_N Q^2 \left(M_\chi^2 (F_1 + F_2)^2 + m_N^2 F_1^2 + 2 E_\chi m_N F_1^2 - E_\chi^2 F_2^2\right)\right],$$

$$\frac{d\sigma(\phi N \to \phi N)}{dQ^2} = \frac{\varepsilon^2 \alpha_{\text{EM}} \alpha_D}{16 m_N^4 \left(E_\phi^2 - M_\phi^2\right) \left(Q^2 + M_{A'}^2\right)^2} \times \qquad \text{(Scalar DM)}$$
$$\left[Q^6 F_2^2 + 64 E_\phi^2 m_N^4 F_1^2 - 4 Q^4 m_N F_2 \left((2E_\phi + m_N) F_2 + 2 m_N F_1\right) \right.$$
$$\left. -16 Q^2 m_N^2 \left(M_\phi^2 (F_1 + F_2)^2 + 2 E_\phi m_N F_1^2 - E_\phi^2 F_2^2\right)\right],$$

$$\frac{d\sigma(\chi e^- \to \chi e^-)}{dE_{\text{rec.}}} = \frac{4\pi \varepsilon^2 \alpha_D \alpha_{\text{EM}}}{E_\chi^2 - M_\chi^2} \frac{2E_\chi^2 m_e - (E_{\text{rec.}} - m_e)(M_\chi^2 + 2E_\chi m_e + 2m_e^2 - E_{\text{rec.}} m_e)}{\left(2E_{\text{rec.}} m_e + M_{A'}^2 - 2m_e^2\right)^2},$$

$$\frac{d\sigma(\phi e^- \to \phi e^-)}{dE_{\text{rec.}}} = \frac{4\pi \varepsilon^2 \alpha_D \alpha_{\text{EM}}}{E_\phi^2 - M_\phi^2} \frac{2E_\phi m_e \left(E_\phi - E_{\text{rec.}}\right) - M_\phi^2 E_{\text{rec.}}}{\left(2 m_e E_{\text{rec.}} + M_{A'}^2\right)^2}.$$

Constraints

- Theoretical:
  - sub-GeV thermal DM scenarios in general leads to overabundance (Lee-Weinberg limit)
  - Avoiding overproduction requires light mediator.
  - Scalar mediated light DM tightly constrained by B, K meson decays.

C. Boehm & P. Fayet, Nucl. Phys. B683 (2004) 219
C. Boehm et al., Phys. Rev. Lett. 92 (2004) 101301
Izaguirre et al. 1505.00011

- CMB and BBN
- Direct detection
- B-factories
- LEP, LHC
- Beam-dump exps
- Self interactions
- Supernovae

Constraints

- Theoretical
- CMB and BBN: residual annihilations can rehionize hydrogen and distort the high-ℓ CMB power spectrum.
  - Rules out thermal-relic Dirac fermion DM. For scalar DM p-wave suppression weaken the bound.
  - CMB energy injection bounds exclude symmetric fermionic DM, but not pseudo-Dirac, asymmetric, scalar DM.
  - Weaker bounds from ^{3}He abundance during BBN.

Slatyer et al., PRD80 043526
Finkbeiner et al. PRD85 043522
Lin et al. PRD85 063503
Galli et al. PRD84 027302 +++

- Direct detection
- B-factories
- LEP, LHC
- Beam-dump exps
- Self interactions
- Supernovae

Constraints

- Theoretical
- CMB and BBN

- Direct detection: limits on sub-GeV DM by Xenon from electron scattering (though background-limited).
  - Can be evaded if pseudo-Dirac DM

Essig et al. PRL109 021301, PRD96 043017

- B-factories
- LEP, LHC
- Beam-dump exps
- Self interactions
- Supernovae

Constraints

- Theoretical
- CMB and BBN
- Direct detection:

- B-factories: from BaBar (future BELLE II):
  - Searches for $\Upsilon \rightarrow \gamma + inv$ to constrain the process $e^+e^- \rightarrow \gamma + A'^{(*)} \rightarrow \gamma\chi\chi$. For on-shell A' scales as ε^2 insensitive to A'.
  - Search for a dark photon in the reaction $e^+e^- \rightarrow \gamma + A'$, $A' \rightarrow e^+e^-, \mu^+\mu^-$.

BABAR collab., Phys. Rev. Lett. 113 (2014) 201801, Phys. Rev. Lett. 119, 131804 (2017)

- LEP, LHC
- Beam-dump exps
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- Supernovae

Constraints

- Theoretical
- CMB and BBN
- Direct detection
- B-factories

- LEP, LHC:
  - EWPO constrain the existence of a new photon. Kinetic mixing induces a shift in the mass of the Z boson (mild bound, $\varepsilon<0.03$).
  - At LHC searches for mono-jet or mono-photon + missing ET (also weak bound).

Hook et al. 1006.0973
Curtin et al. JHEP 1502 157
CMS 1408.3583

- Beam-dump exps
- Self interactions
- Supernovae

Constraints

- Theoretical
- CMB and BBN
- Direct detection
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- LEP, LHC

- Beam-dump exps:
  - LSND strongest constraint below $m_{\pi 0}$ ($pN \to \pi^0 + X$, $\pi^0 \to \gamma\chi\chi$, then DM scattering off nucleon or electron).
  - E137 at SLAC sensitive to $eN \to eN\, A'$, $A' \to \chi\chi$. The bound scales as $\sim\varepsilon^4\alpha_D$.
  - MINIBOONE
  - NA64

Batell et al. PRD80 095024
Dobrescu et al. PRL 113 061801
Batell et al. PRL 113 171802
Yahn et al. PRD91 055006
Aguilar-Arevalo et al.PRD9811, 112004
+++

- Self interactions
- Supernovae

Constraints

- Theoretical
- CMB and BBN
- Direct detection
- B-factories
- LEP, LHC
- Beam-dump exps

- Self interactions: Bullet Cluster constrain the $\sigma_{self}/m_{DM} \lesssim$ cm^2/g ➡ bound on α_D relevant at low m_{DM}.

Markevitch et al. APJ 606 819
Miralda-Escude et al. APJ 564 60

- Supernovae

Constraints

- Theoretical
- CMB and BBN
- Direct detection
- B-factories
- LEP, LHC
- Beam-dump exps
- Self interactions

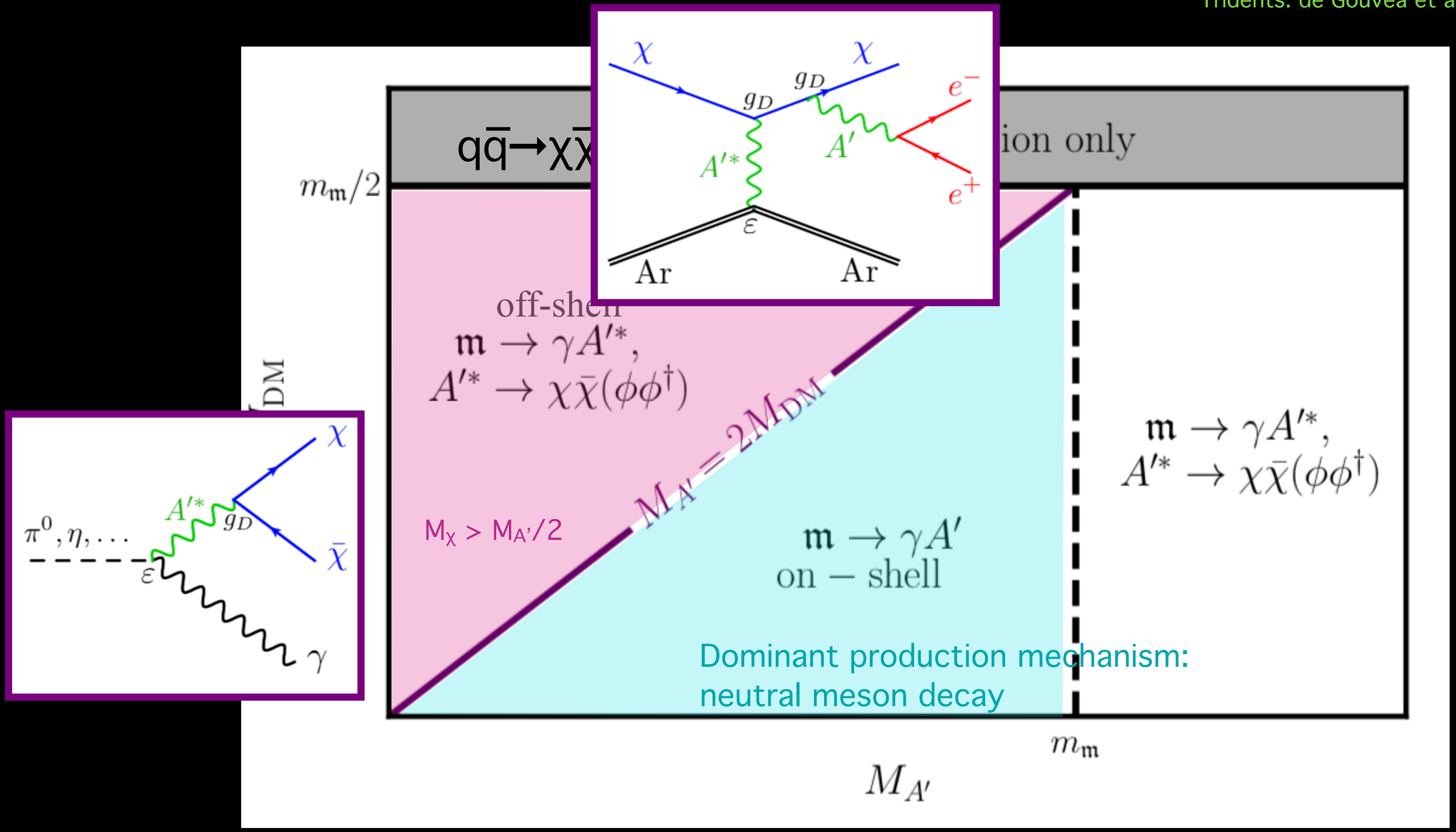
- Supernovae: free-streaming of DM pairs inside SN leads to constraint on combination of ε, α_D parameters. Typically important for mA'~mDM < 10 MeV.

Bionta et al. PRL58 1494
Hirata et al. PRL58 1490
Izaguirre et al. 1411.1404

Light dark matter @ DUNE

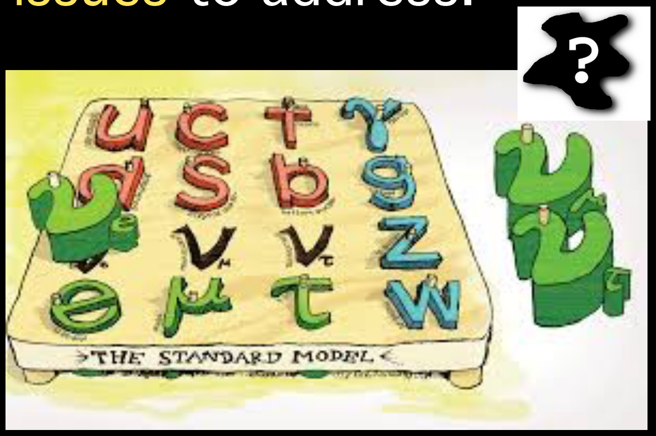
- Any process in which photons participate at a neutrino facility can lead to A' or DM production.
- For DM heavier than mediator, t-channel annihilation into two mediators typically dominates over the s-channel processes.

Tridents: de Gouvea et al. 1809.06388



New physics beyond the SM?

- The Standard Model can explain most of the experimental results. However, there are some theoretical and observational issues to address:
  - neutrino oscillations
  - dark matter
  - baryon asymmetry of the Universe



Symmetry Magazine

- Neutrino oscillations provide 1st laboratory evidence of New Physics
- The Standard Model must be extended (or embedded in larger framework)
  Many candidate models...
- New Physics actively searched for in many fronts:

- High energy colliders direct searches of new states
- High intensity facilities indirect searches (rare processes, deviations from SM)
- Cosmology & astroparticle physics observations (dark matter, inflation, ...)
- Neutrino experiments

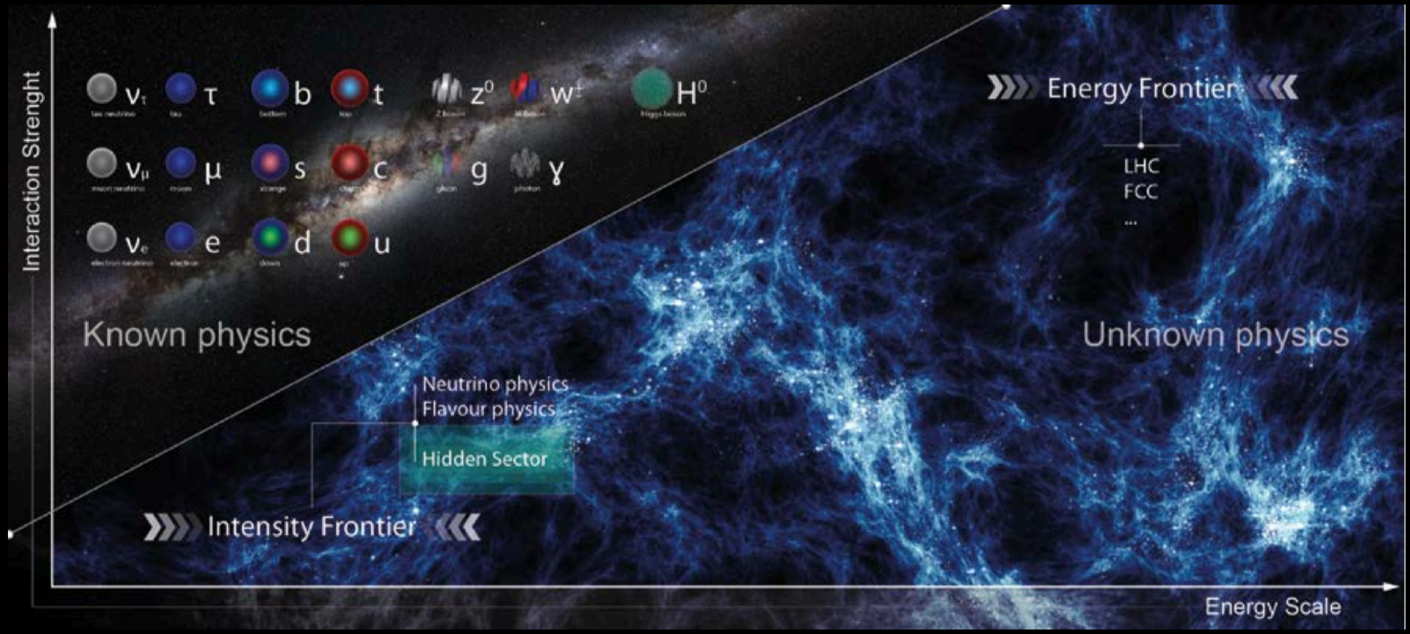


Image from CERN courier 2/2016

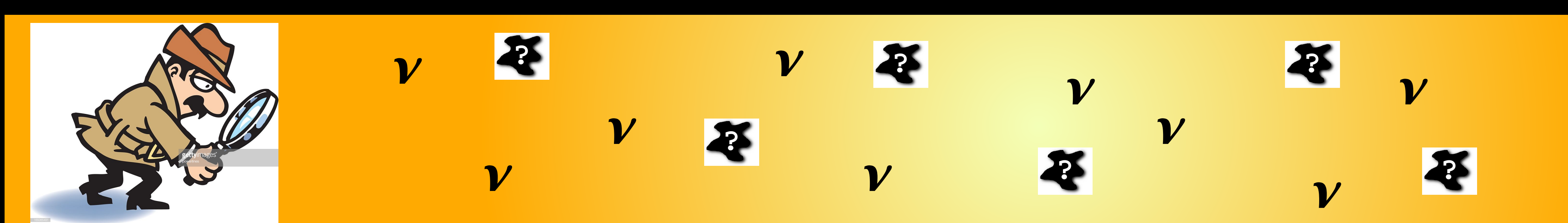
Outline

1) Searching for Dark Matter

2) Light dark matter signals in neutrino detectors

3) Dark photon portal scenario

4) Detecting Dark Matter with DUNE

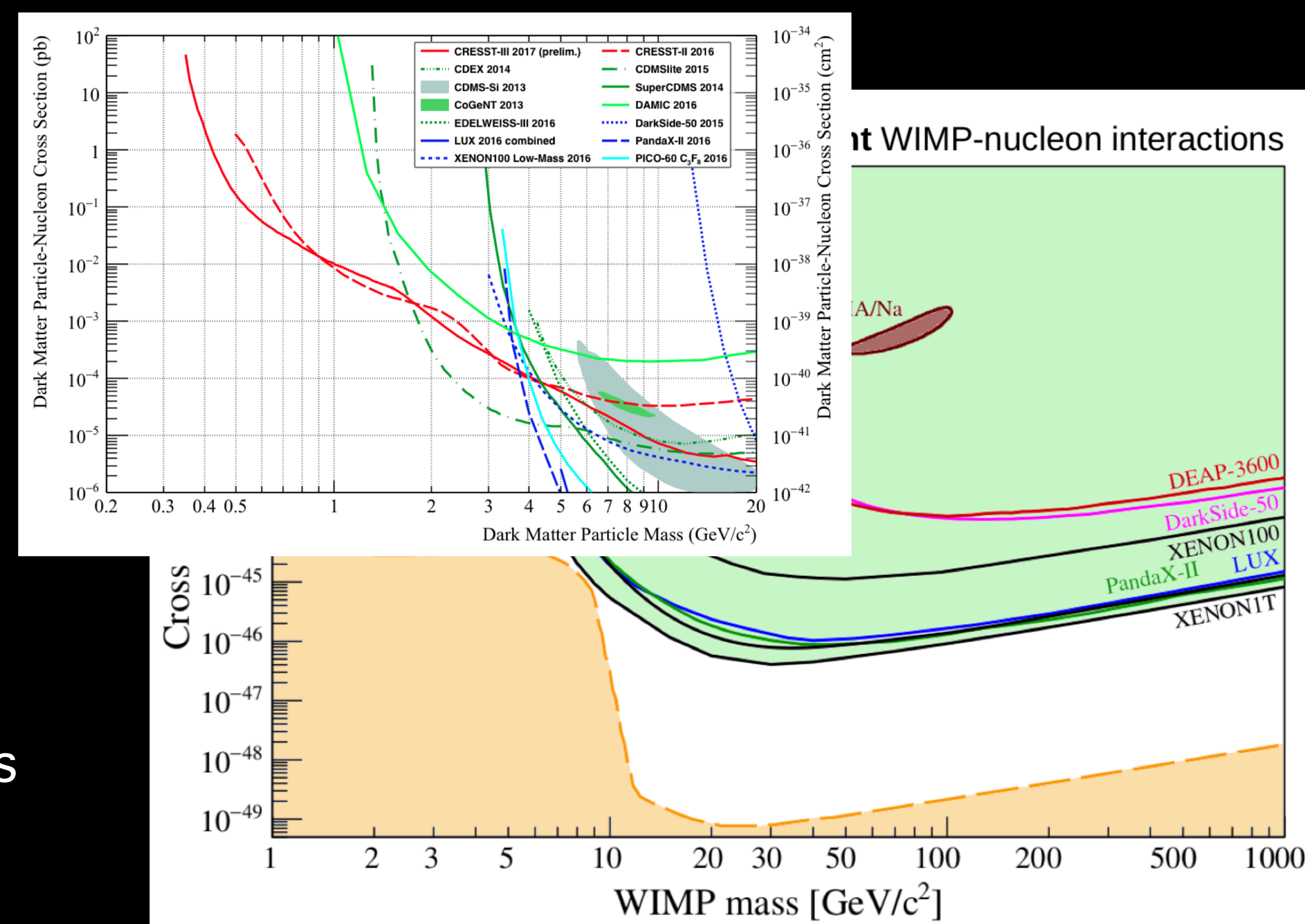


If DM is made of particles that interact among themselves and with SM particles we may hope to detect it. Two strategies:

1. DIRECT DETECTION (looks for energy deposited within a detector by the DM-nuclei scattering)

2. INDIRECT DETECTION (looks for WIMP annihilation (or decay) products)

+ complementary searches at colliders



M. Schumann ZPW 2019, CRESST-III exp