Search for sub-GeV dark matter at the DUNE Near detector

Animesh Chatterjee
University of Texas at Arlington
PONDD, FNAL
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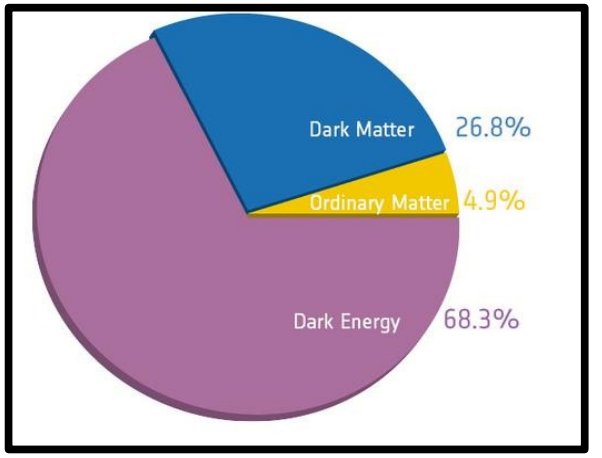
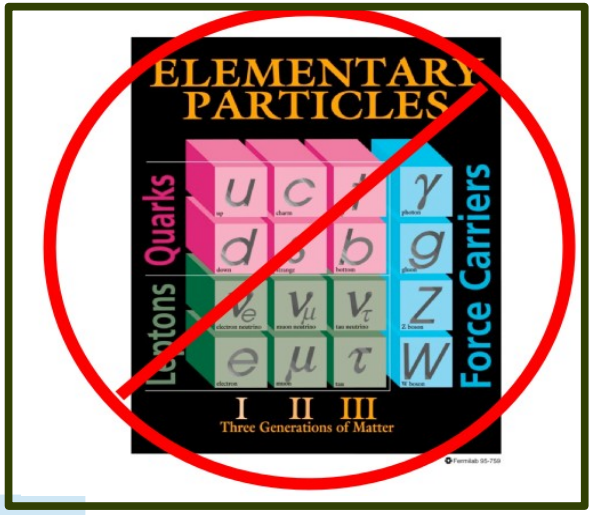
Outline

- Introduction
- Motivation : sub-GeV dark matter search
- Sub-GeV dark matter search at DUNE Near detector
- Outlook

We know that dark matter exists...
but we don't know much about it

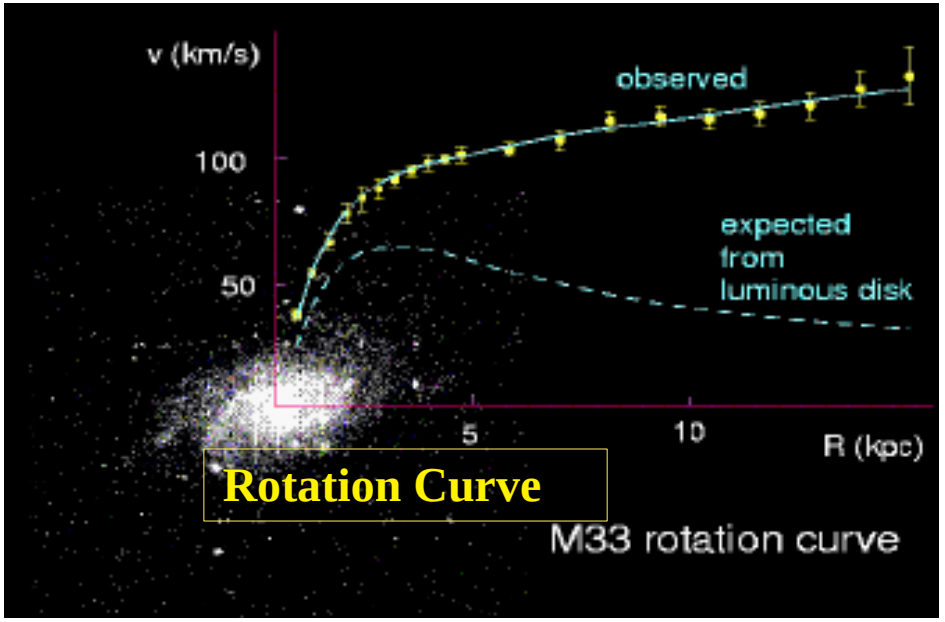
- Dark matter has manifested its presence so far only via gravitational interactions with surrounding baryonic matter
- Weakly Interacting Massive Particles(WIMPs) are the leading particle physics candidate for the dark matter
- What it's not :
  - → not luminous (hence “dark”)
  - → not short-lived
  - → not relativistic or “hot”
  - → not strongly interacting particle

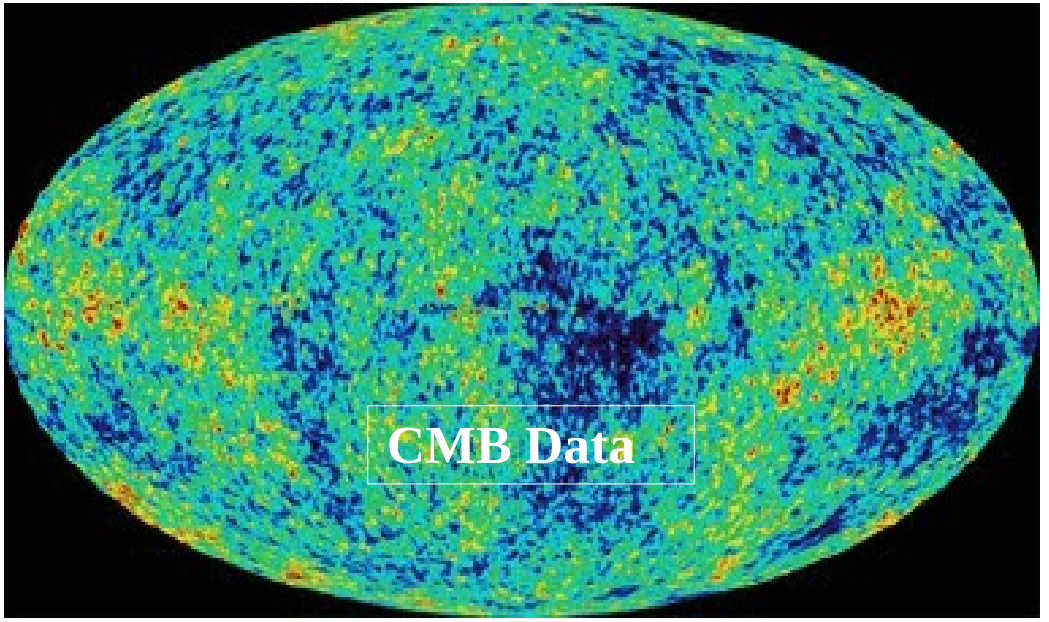


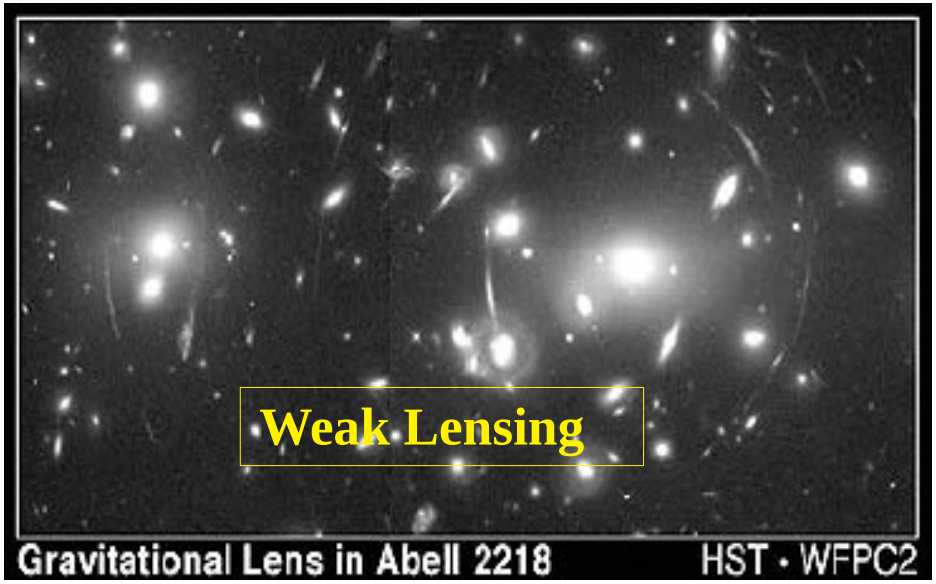


NOT STANDARD MODEL!
(need to go beyond SM)

Evidences of Dark matter from Astronomical Observations



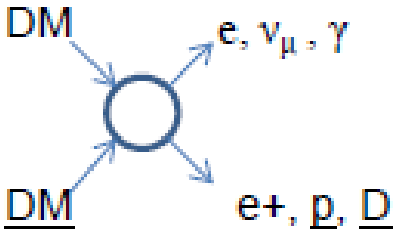




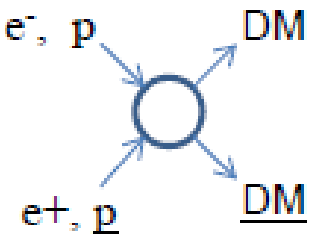
What is it made of ? Can we detect it in terrestrial laboratories ?

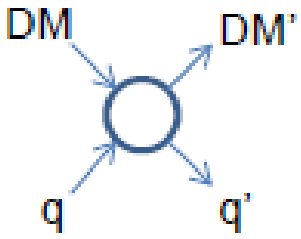
Detecting dark matter

- **Indirect Detection :**
  - **Observation of WIMP annihilation or decay products**
    - **Gamma Ray Telescopes(MAGIC, HESS, VERITAS, EGRET etc.)**
    - **Anti-matter experiments (PAMELA, HEAT etc.)**
    - **Neutrino detectors. Telescope (ICECUBE,AMANDA, SK etc.)**



- **Collider Experiment (Indirect detection) :**
  - **missing energy/ transverse momenta in collision**



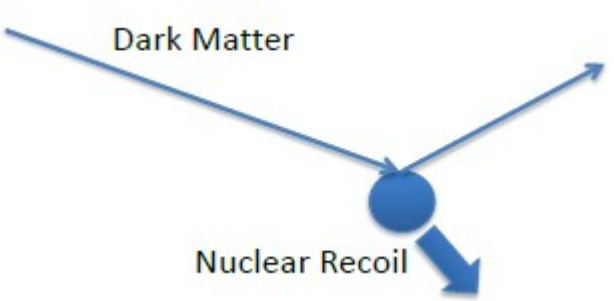


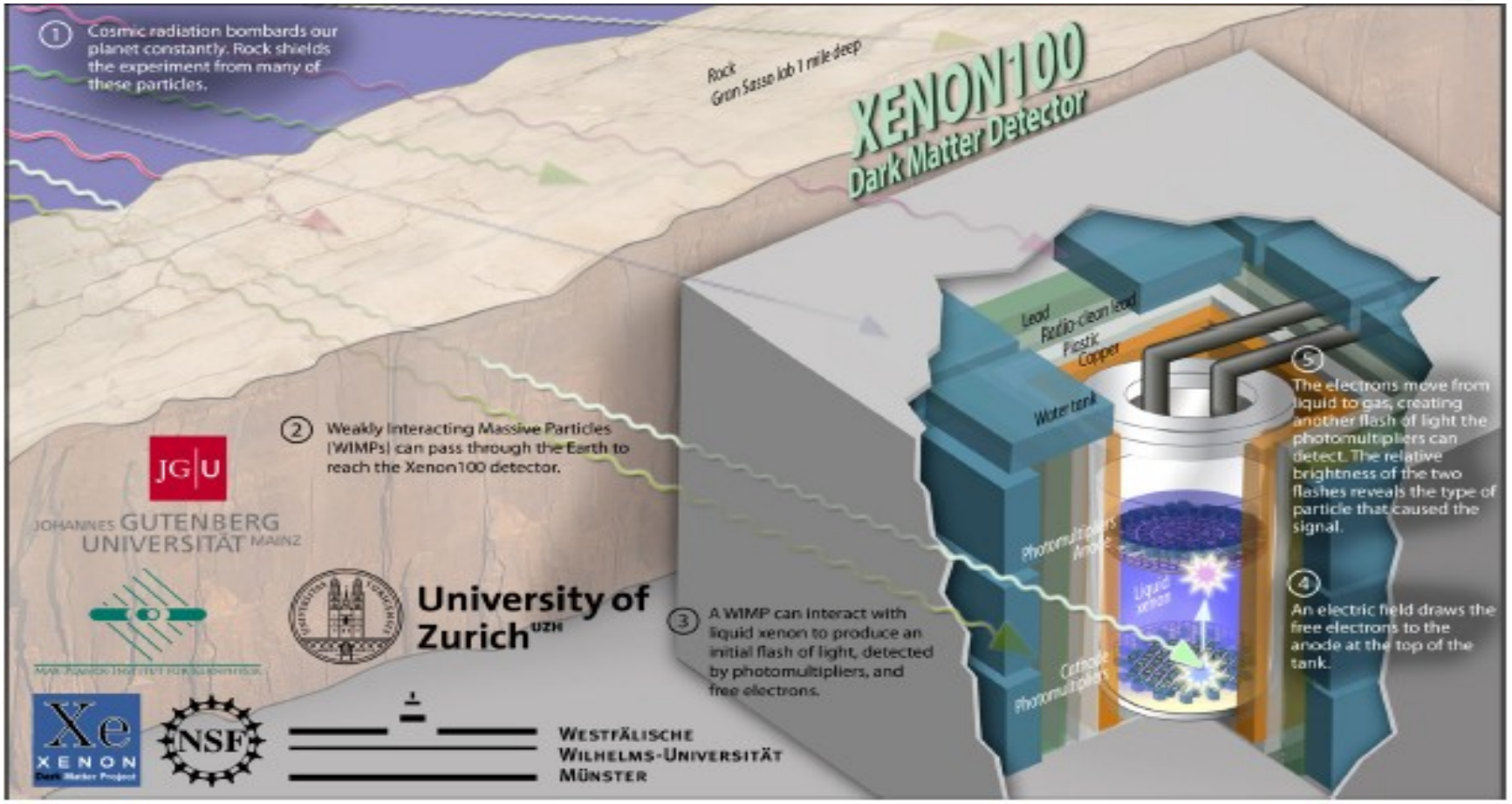
- **Direct Detection :**
  - **WIMP Nuclear recoil**
  - **Axion Searches**

Standard Direct detection

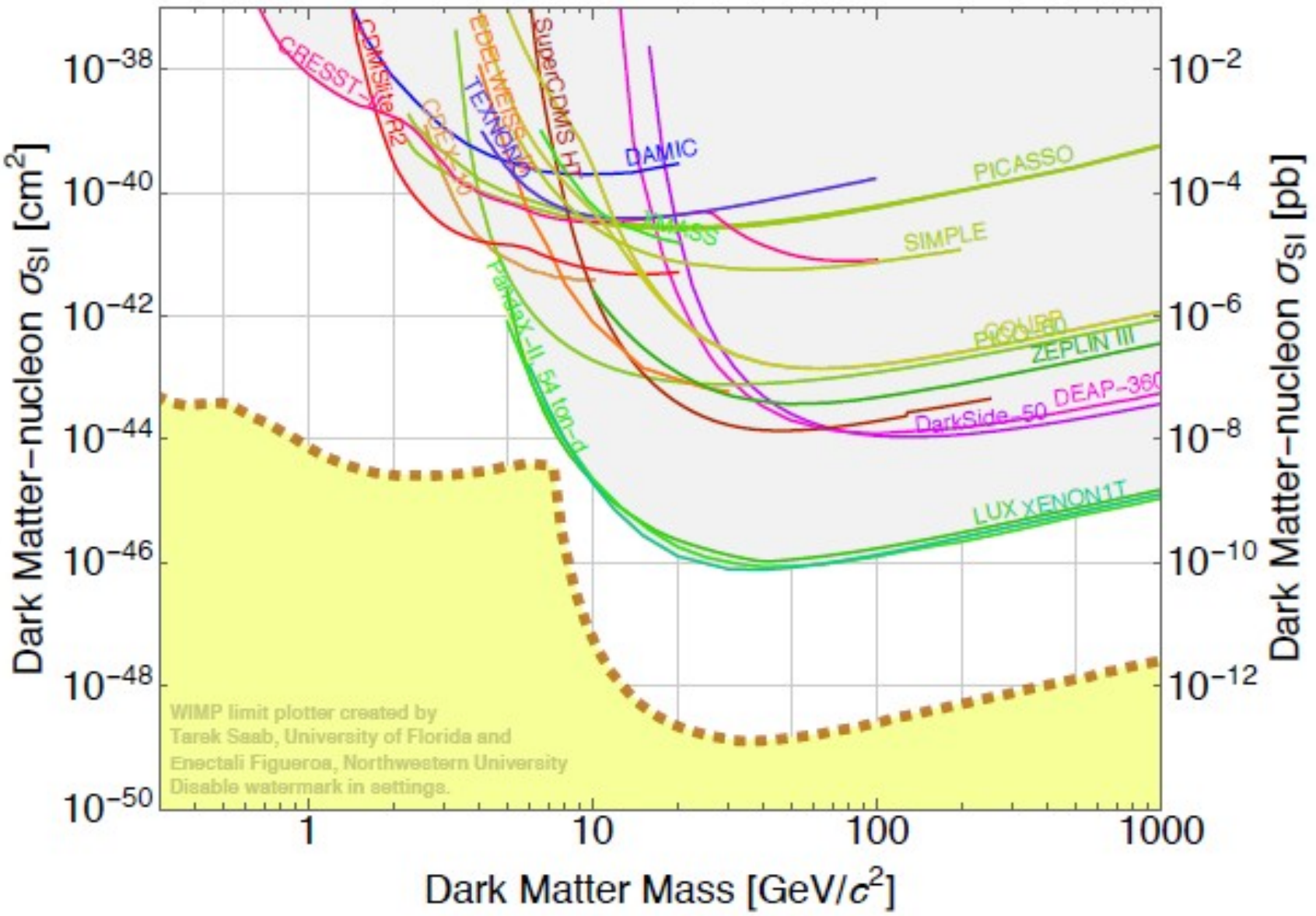
- **Direct Searches :** Observe Nuclear Recoils

$$\chi + N \rightarrow \chi + N$$

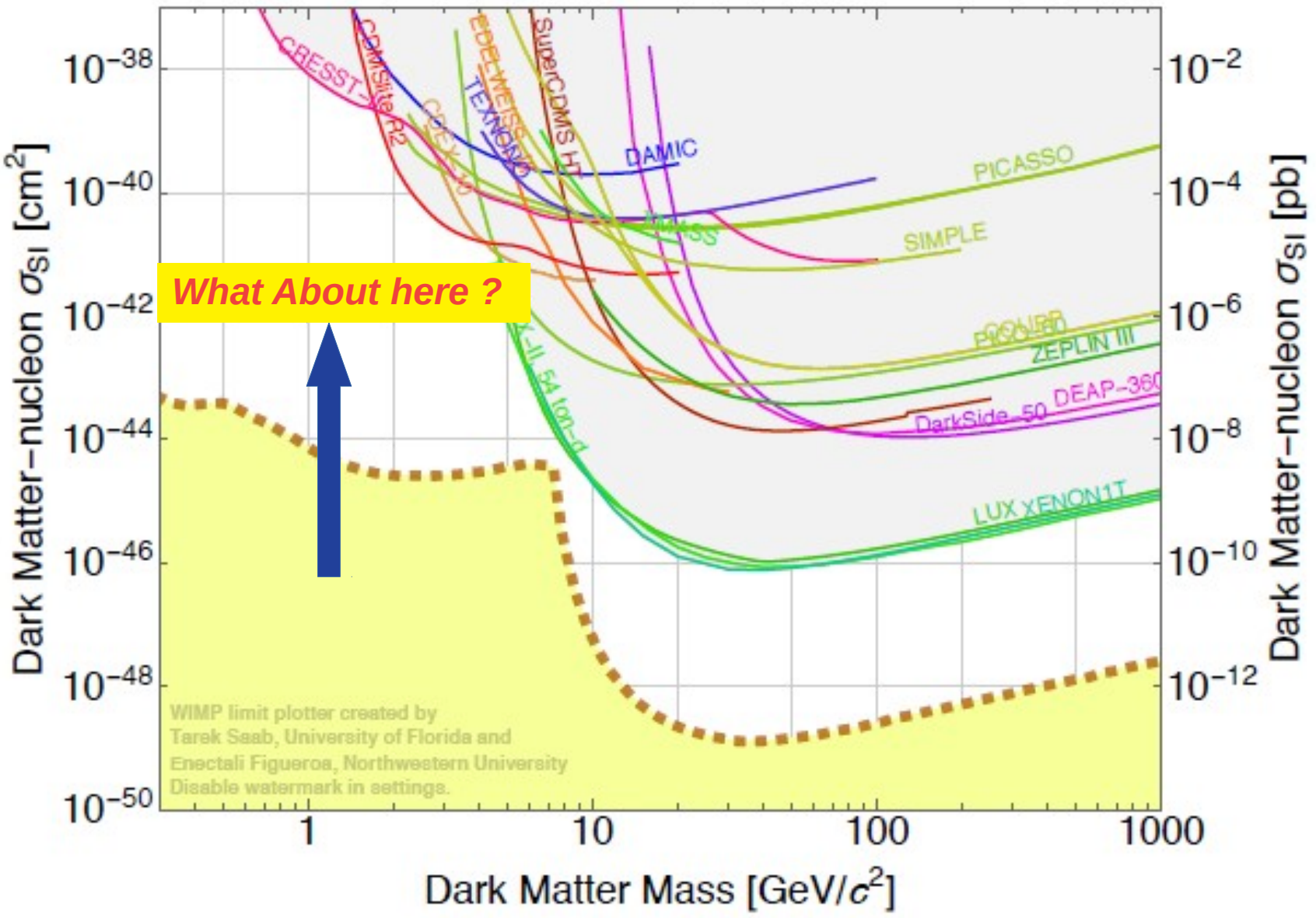




Current Direct detection Limits

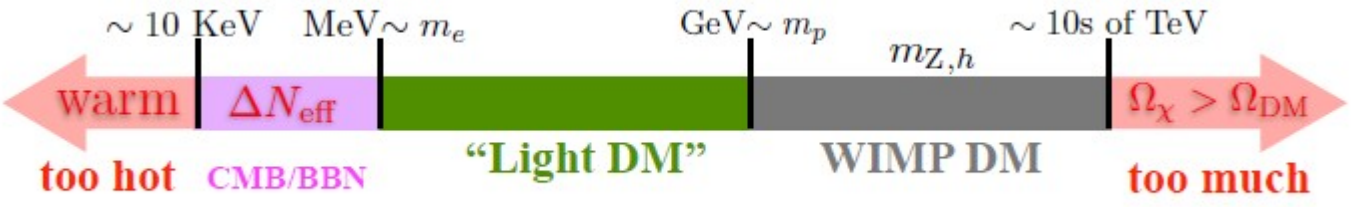


Current Direct detection Limits

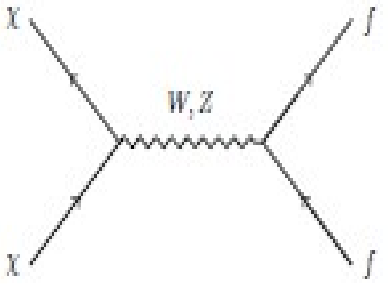


Motivation: sub-GeV Dark Matter

- **Direct detection experiments >GeV mass threshold due to slow moving galactic halo DM, and low energy detection limits**
- **Solve by producing boosted DM with proton beamline. Method has experienced much recent theoretical and experimental activity.**



Light DM requires new, comparably light mediators to achieve required annihilation cross-section for thermal relics



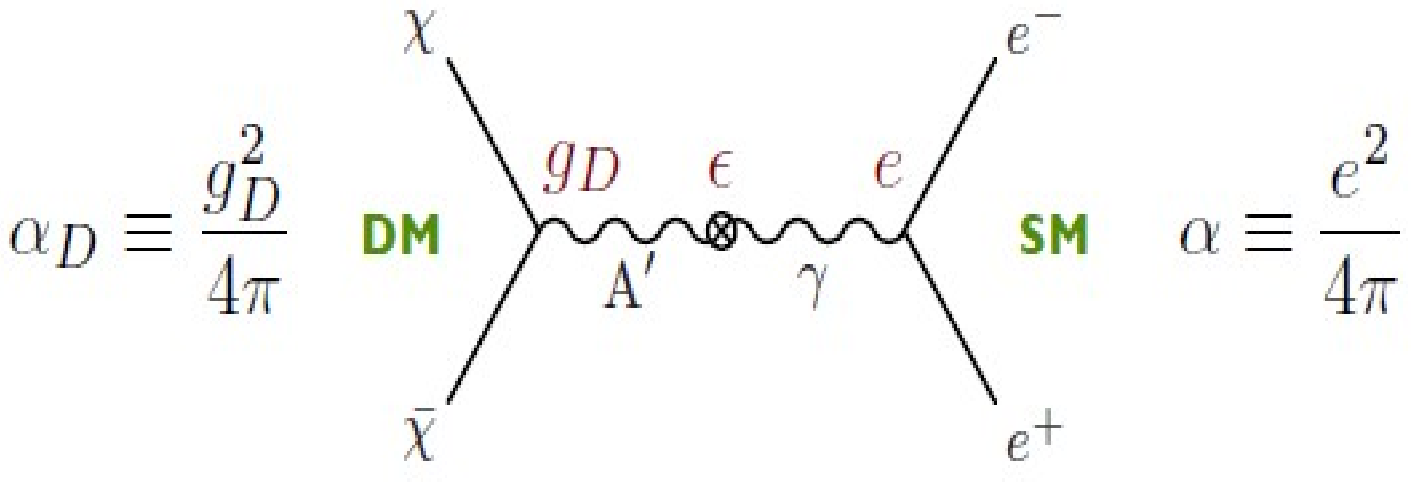
$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\,\mathrm{cm}^3\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

Lee/Weinberg '79

T.Nelson, Dark Interactions 2018

Benchmark Scenario : Dark Photons

- A dark photon A', can mix with SM photon, with a coupling of ε with the SM fermions



$\varepsilon \approx 10^{-4} - 10^{-2}$

α_D is the coupling between Dark matter and dark photon

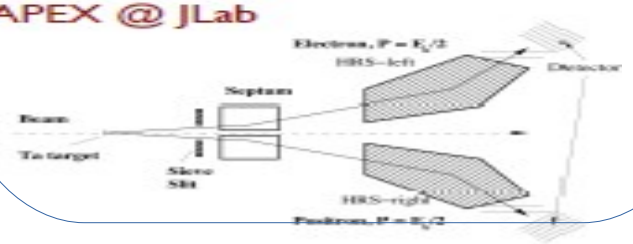
Fixed target experiments

e fixed target

$N \propto \epsilon^2$

- dark bremsstrahlung
- $e+e^- \rightarrow A'\gamma$

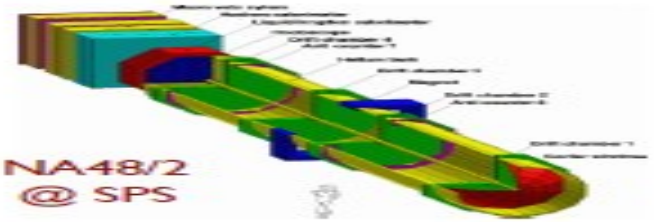
APEX @ JLab



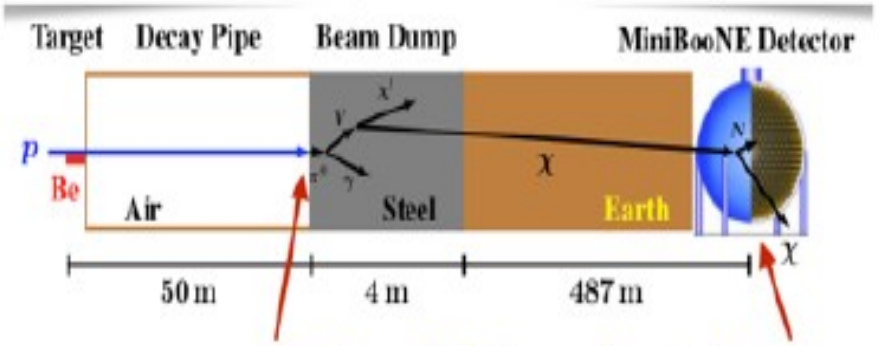
p fixed target

$N \propto \epsilon^2$

- meson decays
- dark bremsstrahlung

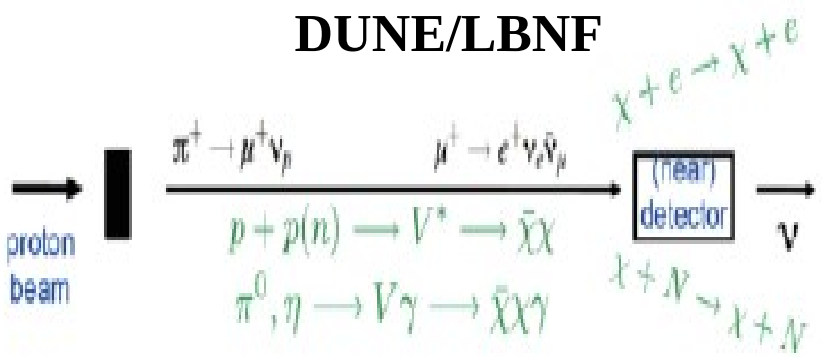


Proton / electron beam dump



Probes DM interaction twice

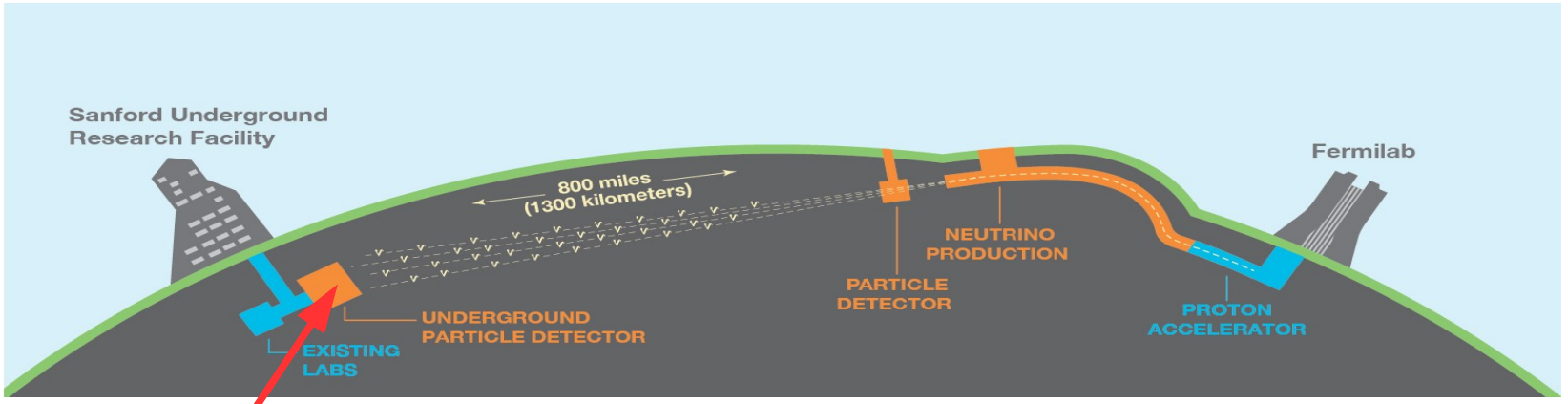
DUNE/LBNF



DUNE

- **Deep Underground Neutrino Experiment**

A next generation experiment for neutrino science, nucleon decay, and supernova physics



Far detector at Sanford Underground Research Facility (SURF)

Neutrino beam and near detector at Fermilab

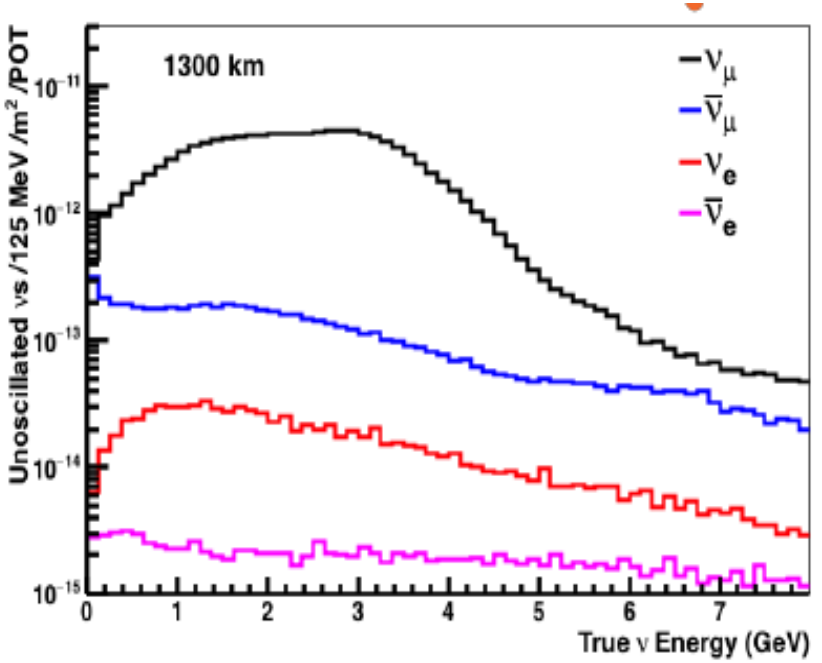
Primary Physics goals

- ν oscillation physics
  - * Precise measurements of the oscillation parameters θ_{23}, θ_{13}, Δm^2_{31}
  - * Neutrino mass hierarchy
  - * Octant of θ_{23}
  - * CP Violation and measurement of δ_{cp}
- Nucleon decay
- Supernova neutrinos
- Physics beyond the standard model

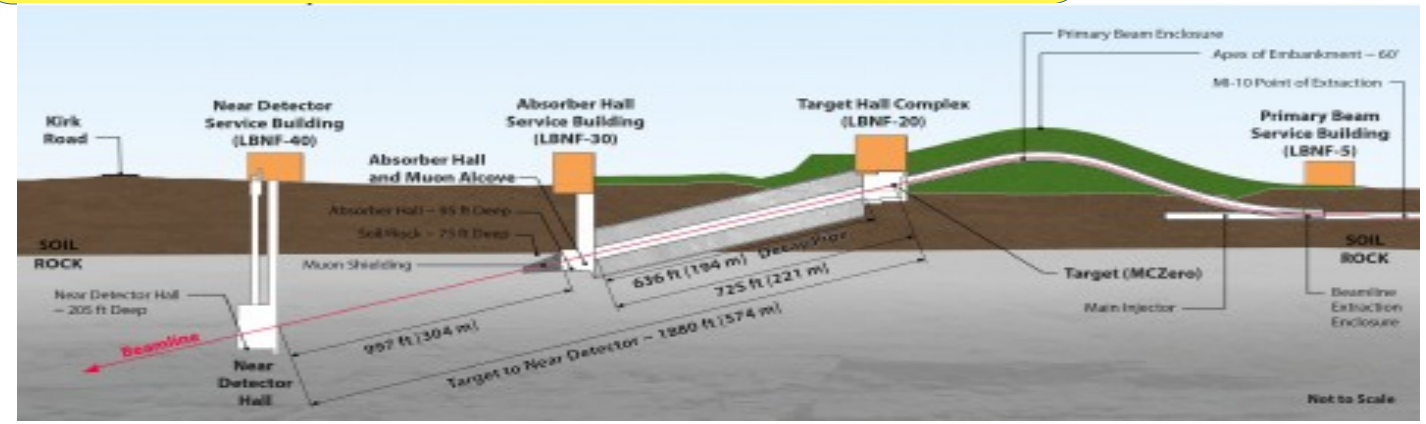
LBNF Beamline

* Most intense neutrino beam : "LBNF"
* 60–120 GeV protons from Fermilab Main Injector

* Initial power: 1.2 MW; plan(2032) to upgrade to 2.4 MW

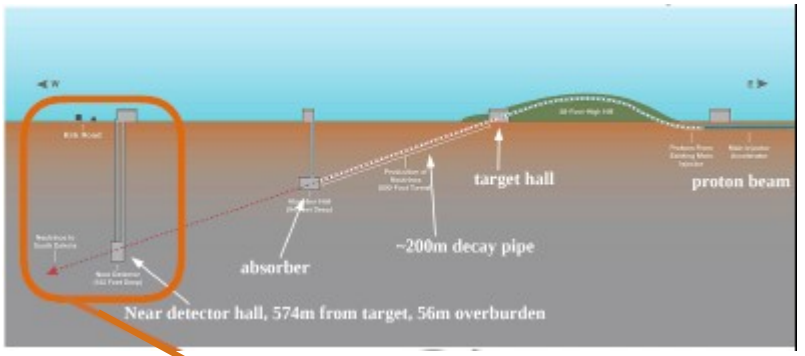


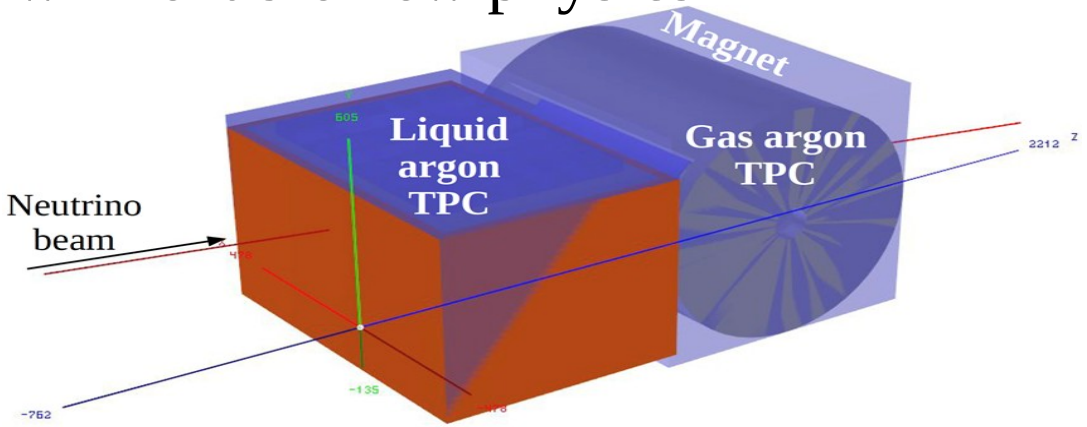
*Wideband beam enhances the possibility of probing new BSM phenomena

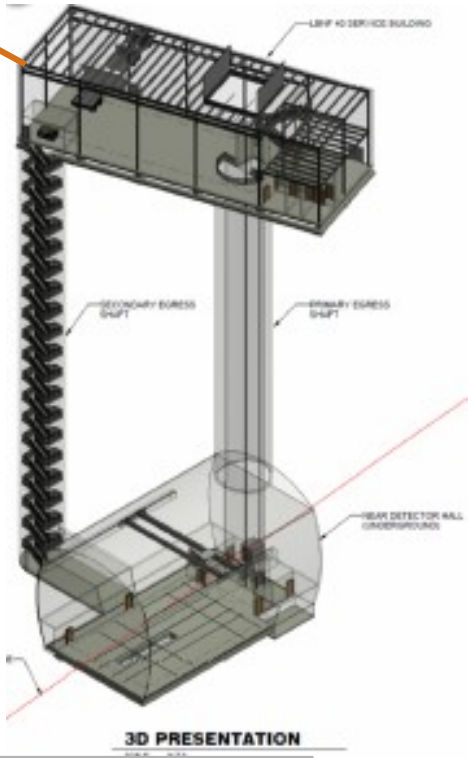


DUNE Near Detector

- Highly-capable ND located at 574 m downstream of production target, will constrain systematic uncertainties
- ND concept design include multiple detectors
  - → Finely segmented LArTPC
  - → Magnetized multi-purpose tracker
- 10 million/Year neutrino interactions in Ar will enable new physics







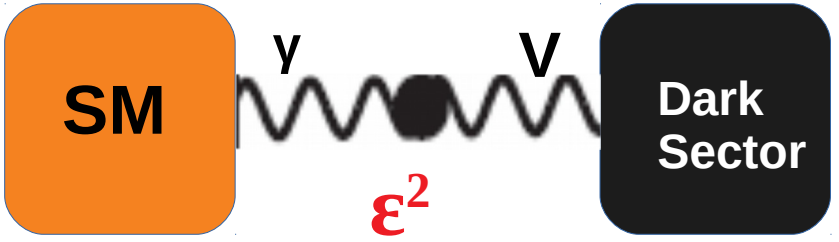
*** In the case of sub-GeV dark matter search we have considered LArTPC detector only (no Gas argon TPC or other detector)**

- **Sub-GeV dark matter search @DUNE ND**

(Simplest model and preliminary results)

The model: "Vector portal"

- Models of sub-GeV dark matter typically involve scalar or fermion DM and vector or scalar mediators
- Maybe the simplest model is known as the "dark photon" model. The mediator is a new gauge field which "mixes" with the SM photon through ε



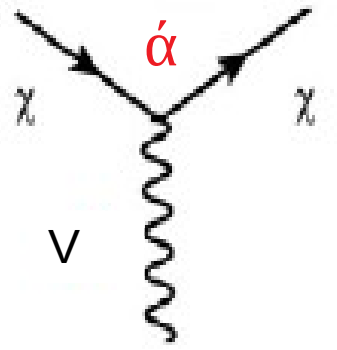
- 4 free parameters

→ **Mass of the dark photon m_V**

→ **Mass of the dark matter m_χ**

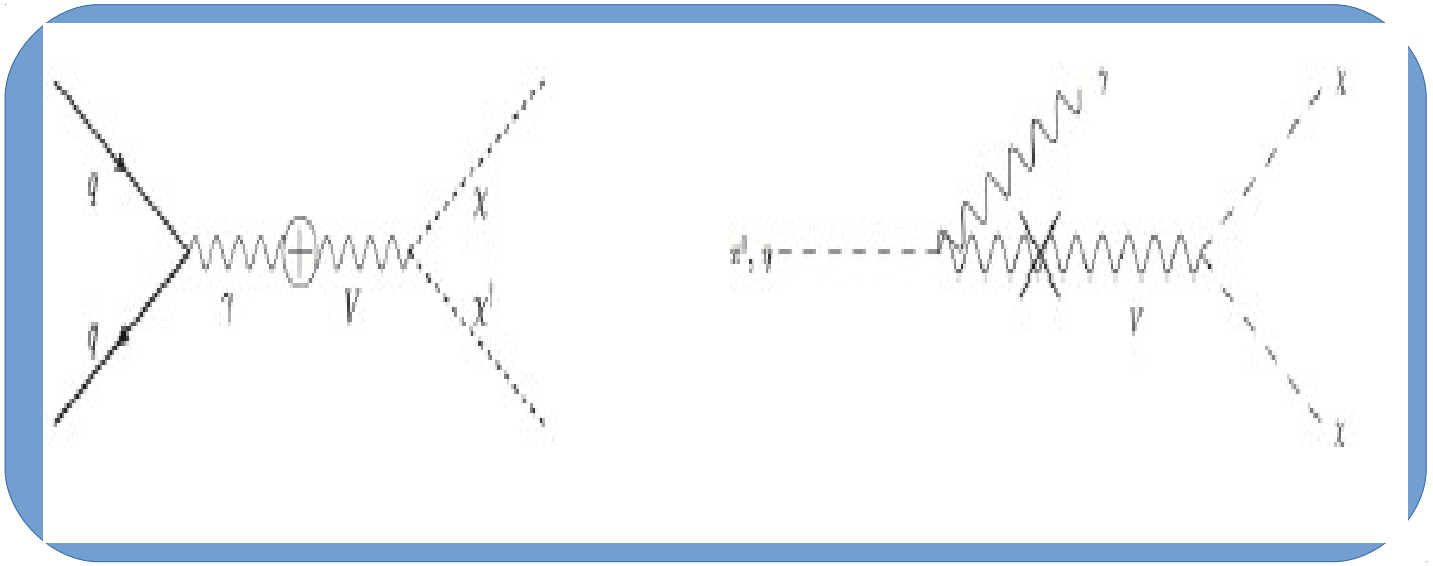
→ **Mixing between SM and dark sector ε**

→ **Coupling between dark photon and dark matter $\acute{\alpha}$**



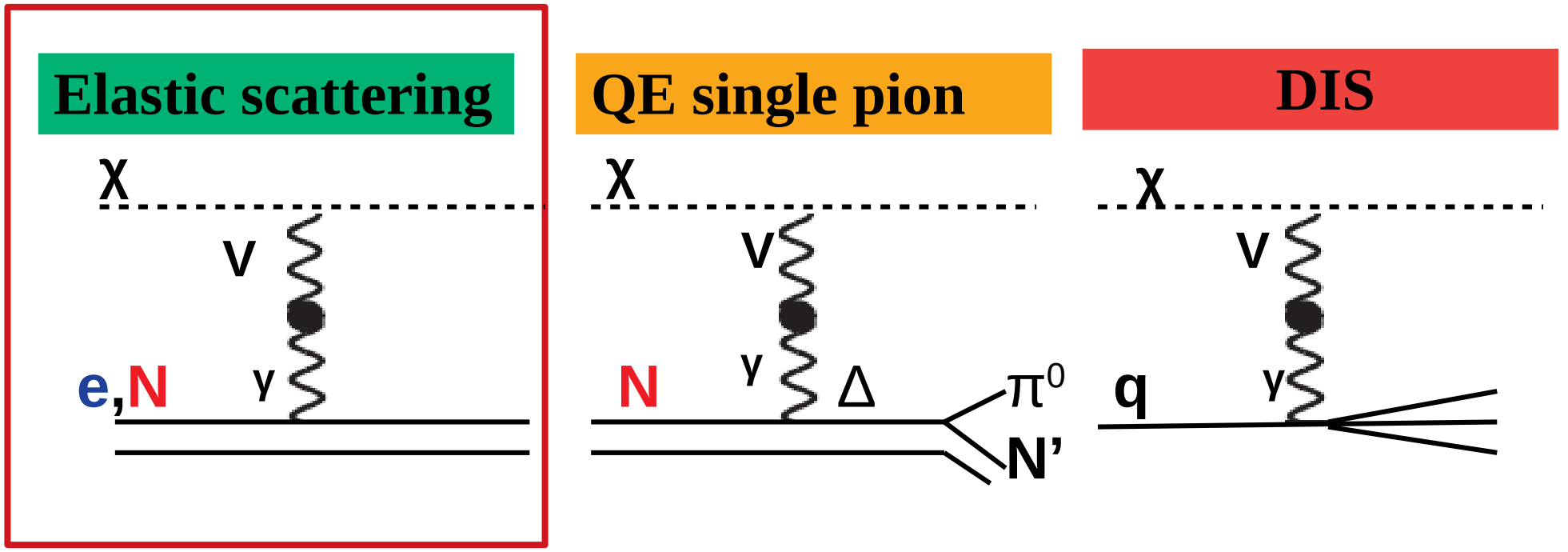
Dark Matter production at LBNF Beamline

- Production proceeds directly (pp(n) → V*) and indirectly (through meson decays):



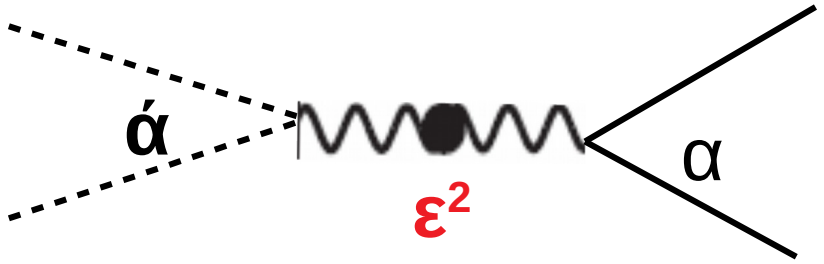
- At the LBNF with the Proton Energy 80 GeV or 120 GeV, the direct production process will dominate
- We are particularly interested in the sub-GeV range DM coming from the decay of on-shell V
- We consider $m_V = 3\ m_x$, which will also be effective for direct production of dark matter

Dark Matter Interactions at the Detector



- Interactions look like just neutrino interactions
- All interactions are neutral current (since mediator is not charged)
- **In this analysis we consider only Electron Elastic scattering**
- DUNE ND will be designed to detect such interactions

Cross-section variable (Y)



The Annihilation cross section goes as

$$\sigma v \approx \acute{\alpha}\, \varepsilon^2\, \alpha\, (m_x^2 / m_v^4)$$

Define New variable

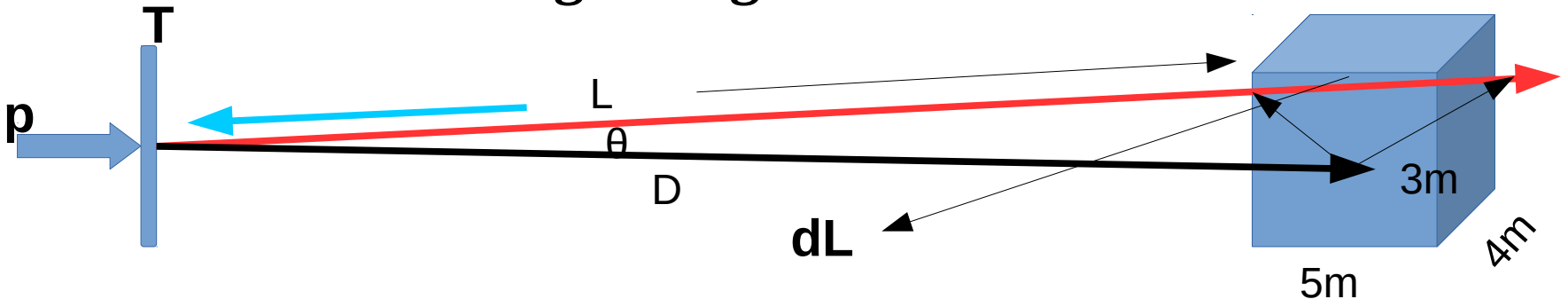
$$Y = \acute{\alpha}\, \varepsilon^2\, (m_x / m_v)^4$$

Annihilation cross-section in-terms of Y

$$\sigma v \approx \alpha\, (Y / m_x^2)$$

DM Simulation at DUNE ND

- **We have the following configuration**



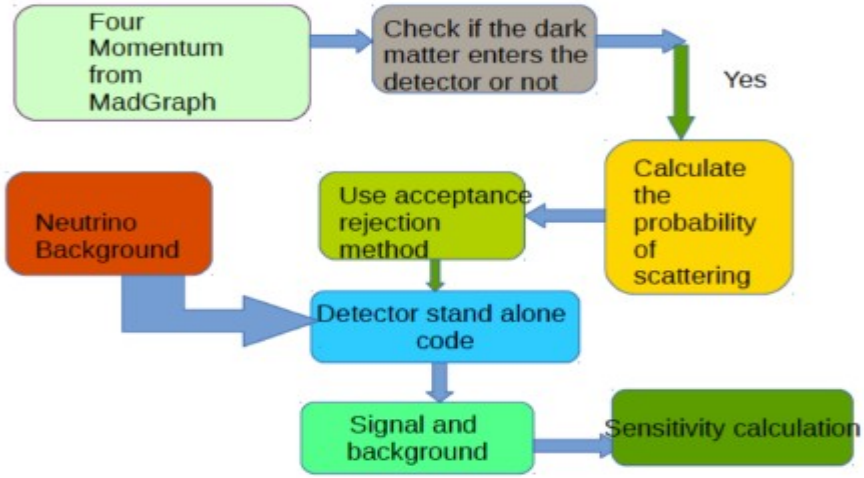
- **We generate DM events using MadGraph5* MC generator in Fixed Target mode**
- **The detector is located at a distance D = 574 m from target**
- **The fiducial volume of the detector is 4m(W) x 3m(H) x 5m(L)**
- **The distance DM crosses the detector is dL**

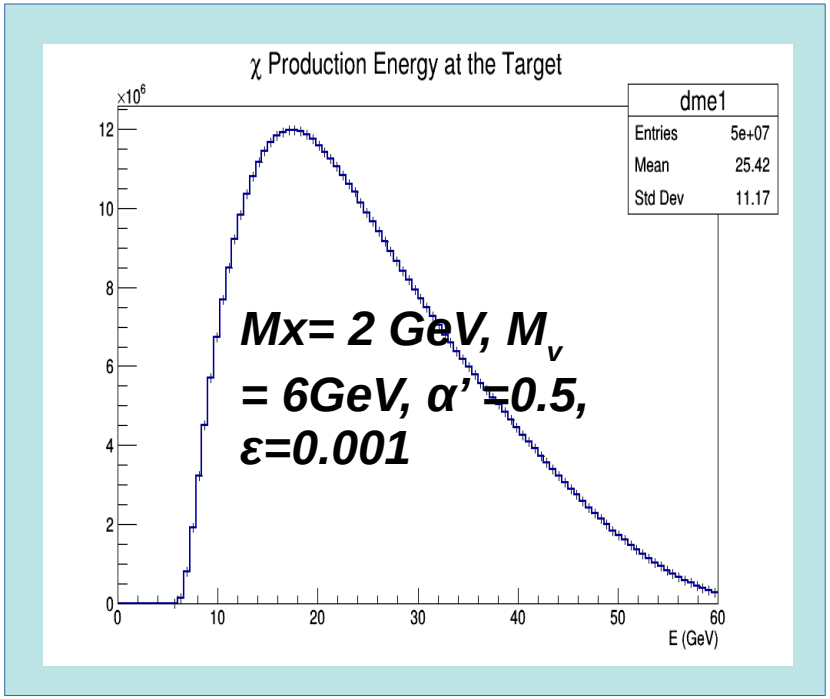
3

DM Simulation

- **Production at the target :**

Flow chart :





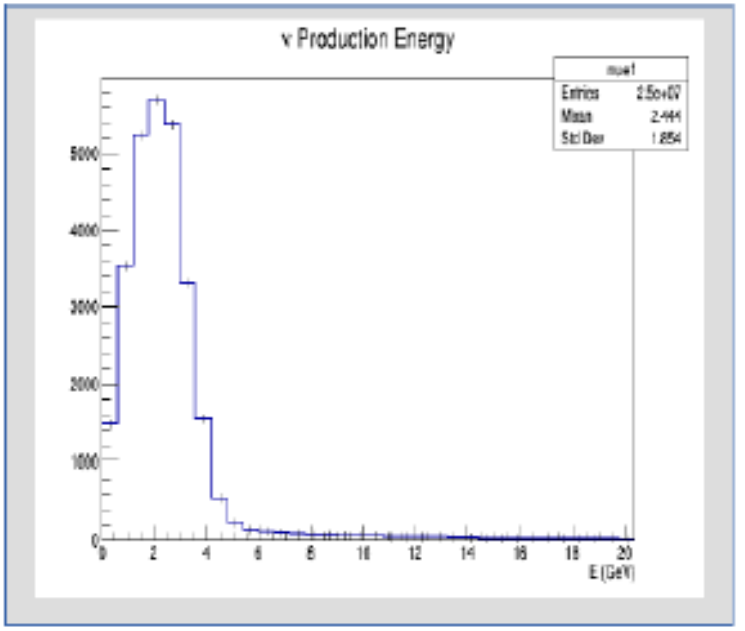
Electron scattering :

$$\frac{d\sigma}{dE_e} = 4\pi\varepsilon^2\alpha\alpha' m_e \frac{4m_e m_\chi^2 E_e + [m_\chi^2 + m_e E_\chi]^2}{(m_A^2 + 2m_e E_e)^2 (m_\chi^2 + 2m_e E_0)^2}$$

- Cross-section generated for each energy and theta bin
- Acceptance-Rejection method used to select scattered event

What about the Neutrinos ?

- Neutrinos are the dominant background



- The background to the signal for the DM-Electron scattering consist of any processes involving an electron recoil

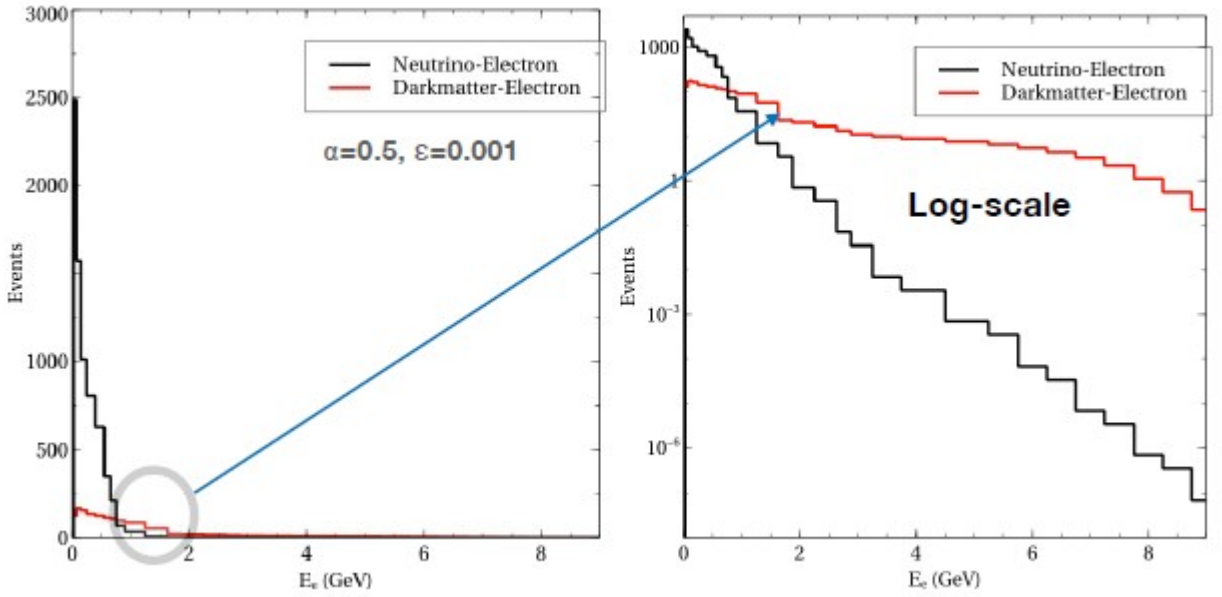
  - Assuming no cosmic background (vetoed by trigger and timing), the possible source of backgrounds are

    → ν_μ induced N.C. events
    → ν_e induced both C.C. and N.C. events
    → ν_e induced quasi-elastic events

  - In this analysis we have not considered ν_e induced quasi-elastic events just for simplicity

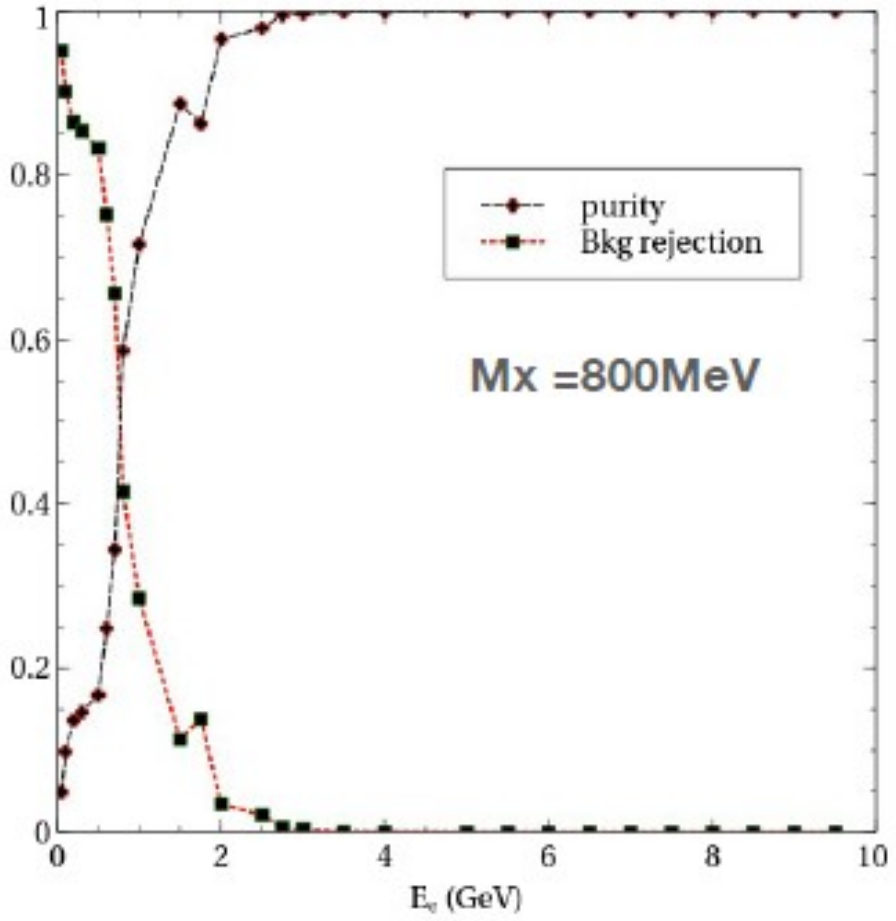
Background Estimation

- Background events are very large at low energies(below 1 GeV)
- Signal events are very small compared to background at low energy
- Signal events are also small at higher energy



Need a proper selection criteria

Background Reduction



Purity = # signal events / total events

Bkg rejection = #Bkg events / total events

Background rejection technique :

- Bkg rejection with 2 kinematic variable
- Recoil energy
- Recoil theta
- Maximize the sensitivity where purity is equal or higher than bkg rejection

Analysis

The simulated data fitted with Gaussian distribution

$$\chi^2(\xi_k) = \sum_i \frac{(N_i^{th}(std) + \sum_{k=1}^{npull} c_i^k \xi_k - N_i^{ex})^2}{N_i^{ex}} + \sum_{k=1}^{npull} \xi_k^2$$

Where $N^{th} = N^{sig} + N^{bkg}$ and $N^{ex} = N^{bkg}$

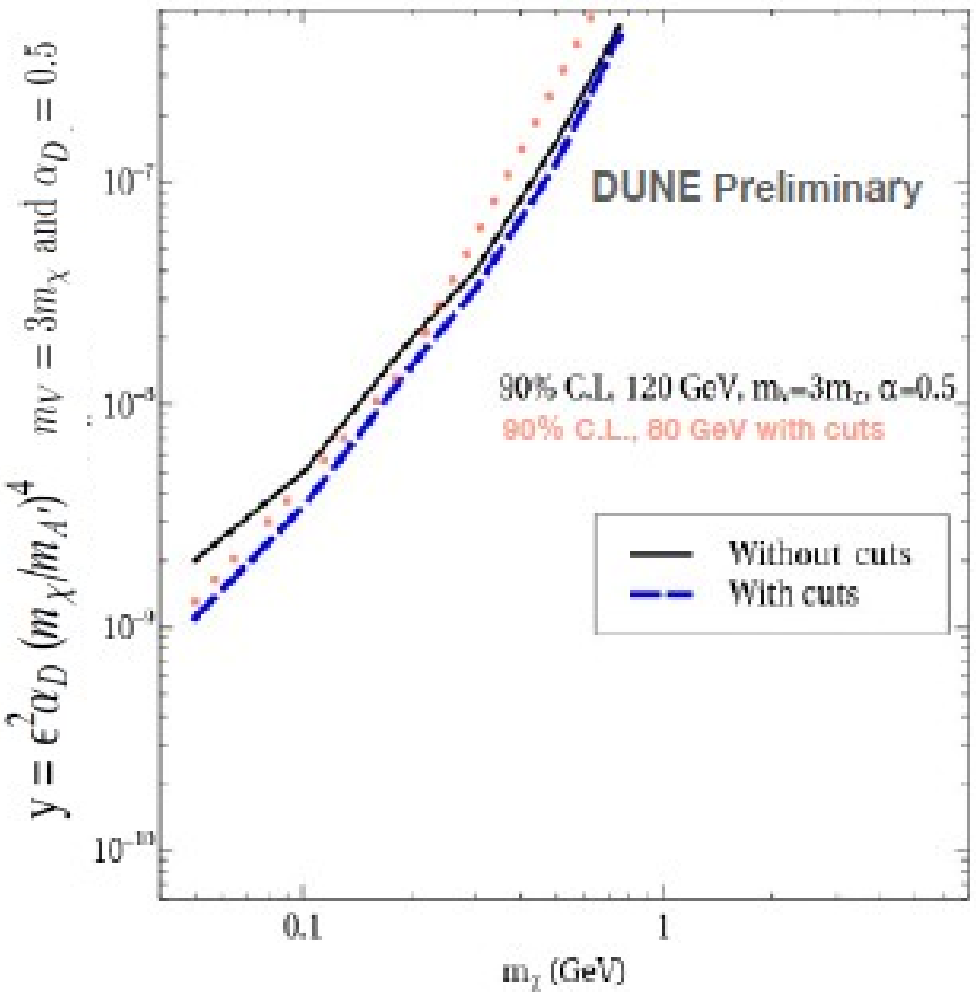
- **Uncertainties used:**
- Flux =20%
- Cross-section = 10%
- Scattering angle of electron = 5%
- Detector sys = 5%

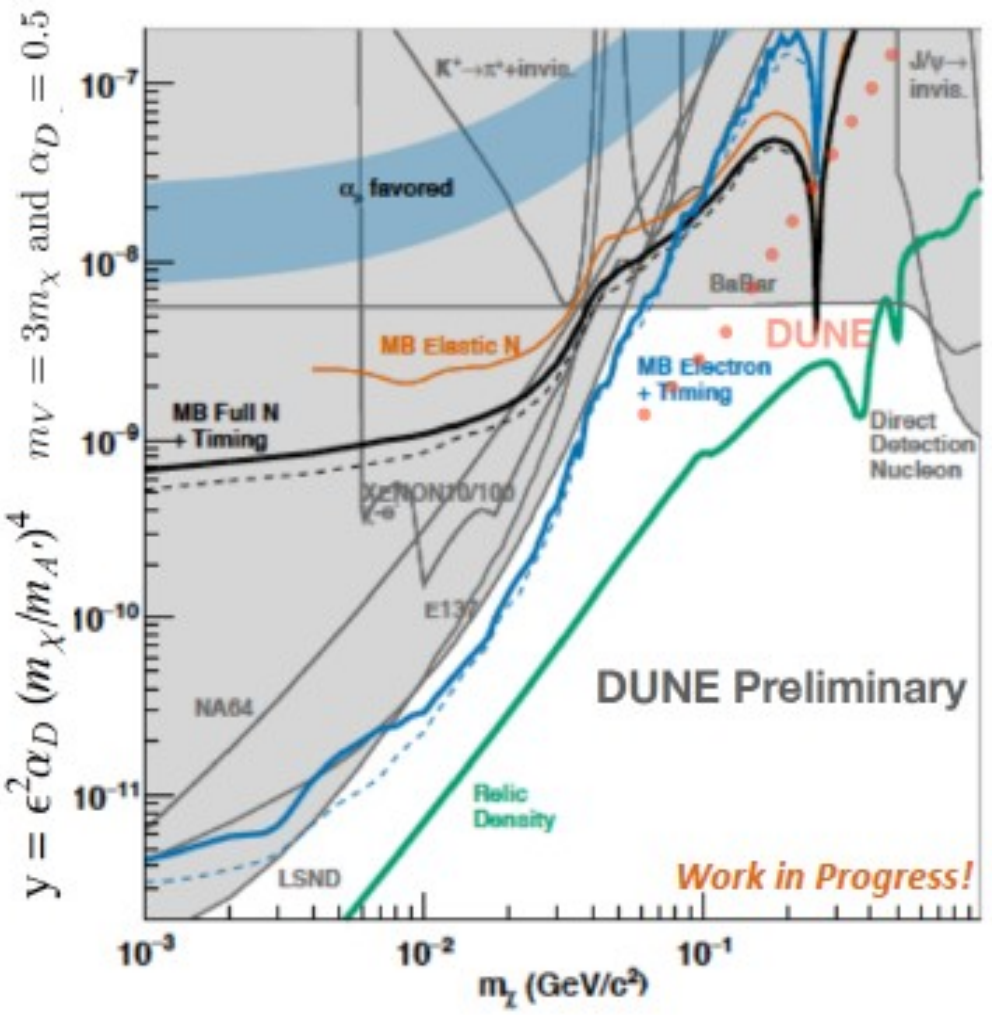
- **Detector properties :**
- **Efficiency 80%**
- $\sigma = 5\%/\sqrt{E}$

- **Re-weighting of neutrino and dark matter events : corresponded to same POT**

- **The analysis done with 1.2 MW of beam power with 50% duty cycle**
- **3.5 Years of data**

Sensitivity : 90% C.L





DUNE ND sensitivity better than other experiments can exclude Relic density

Outlook

- Accelerator based fixed target experiment will be helpful to probe sub-GeV dark matter
- With excellent energy resolution, 3D reconstruction efficiency LArTPC as ND will be suitable for dark matter search
- LBNF beamline with wide-band of energy is useful for sub-GeV range
- Preliminary result looks promising, result will enhance once other channel included
- To reduce neutrino background, “beam dump” mode or other ideas will be interesting

Thank you!

Backup