Ineastic Boosted Dark Matter Searches at ICARUS – Gran Sasso

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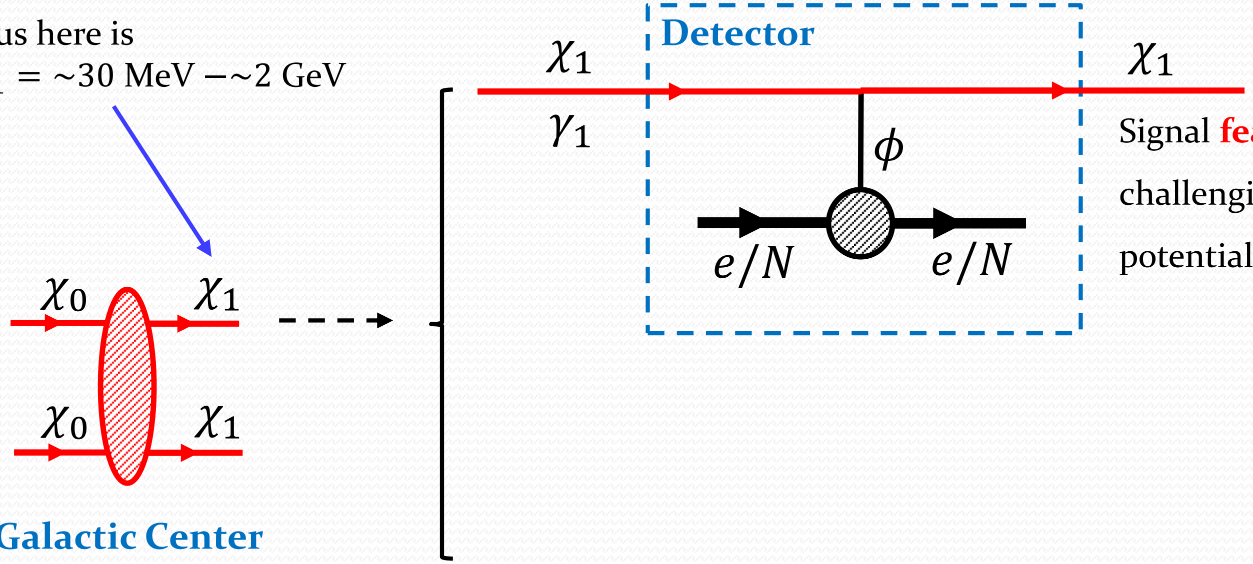
Generic BDM Signal Processes

(a) Elastic scattering (eBDM) (cf. eBDM at DUNE [Necib, Moon, Wongjirad, Conrad (2016); Alhazmi, Kong, Mohlabeng, Park (2016)])

Our focus here is
$m_0 = E_1 = \sim 30$ MeV $- \sim 2$ GeV



Signal **featureless**, hence challenging to separate from potential BGs

- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

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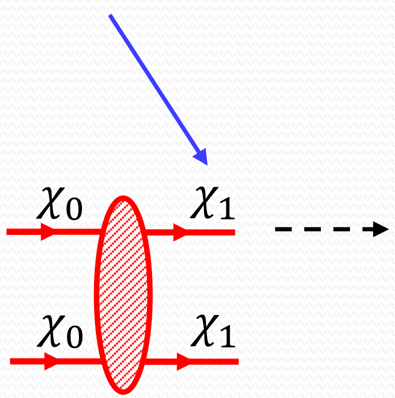
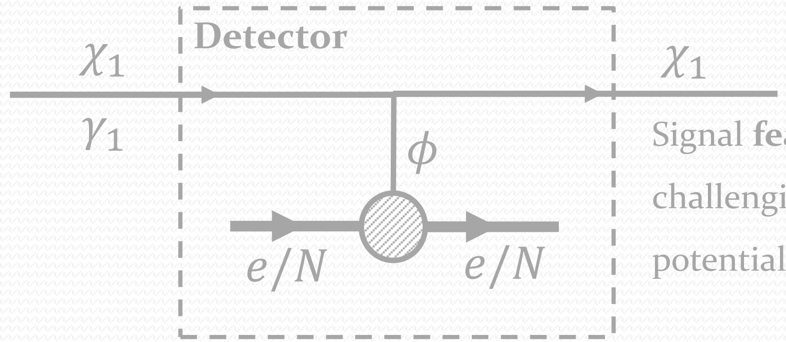
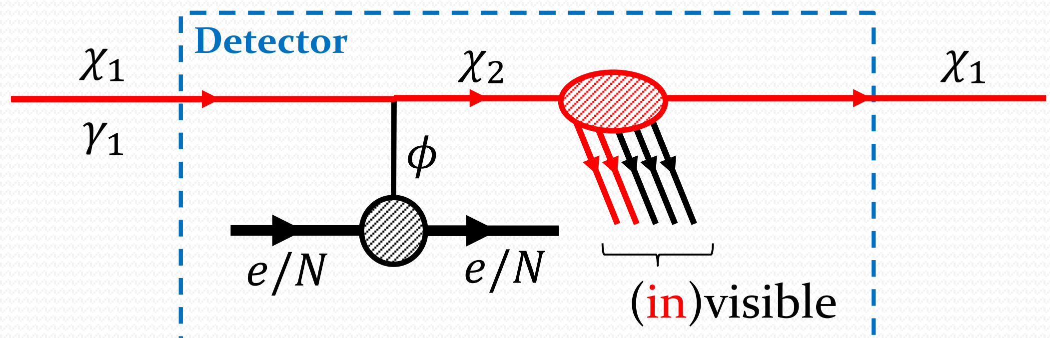


Galactic Center



Signal **featureless**, hence challenging to separate from potential BGs

(b) Inelastic scattering (iBDM) (cf. iBDM at DUNE [**DK**, Park, Shin (2016)])



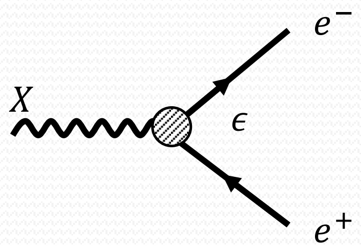
Many signal **features**, helping veto BGs

- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

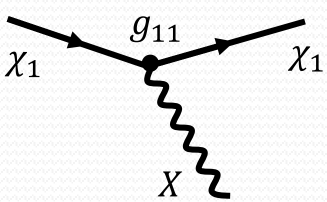
Benchmark Model: Building Blocks

$$\mathcal{L}_{\rm int} \ni -\frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} + g_{11}\bar{\chi}_1\gamma^\mu\chi_1 X_\mu + g_{12}\bar{\chi}_2\gamma^\mu\chi_1 X_\mu + \text{h.c.} + (\text{others})$$

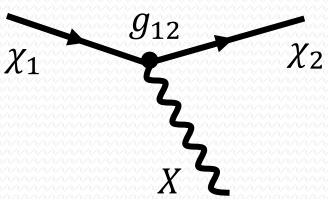
- Vector portal (e.g., dark gauge boson scenario) [Holdom (1986)]



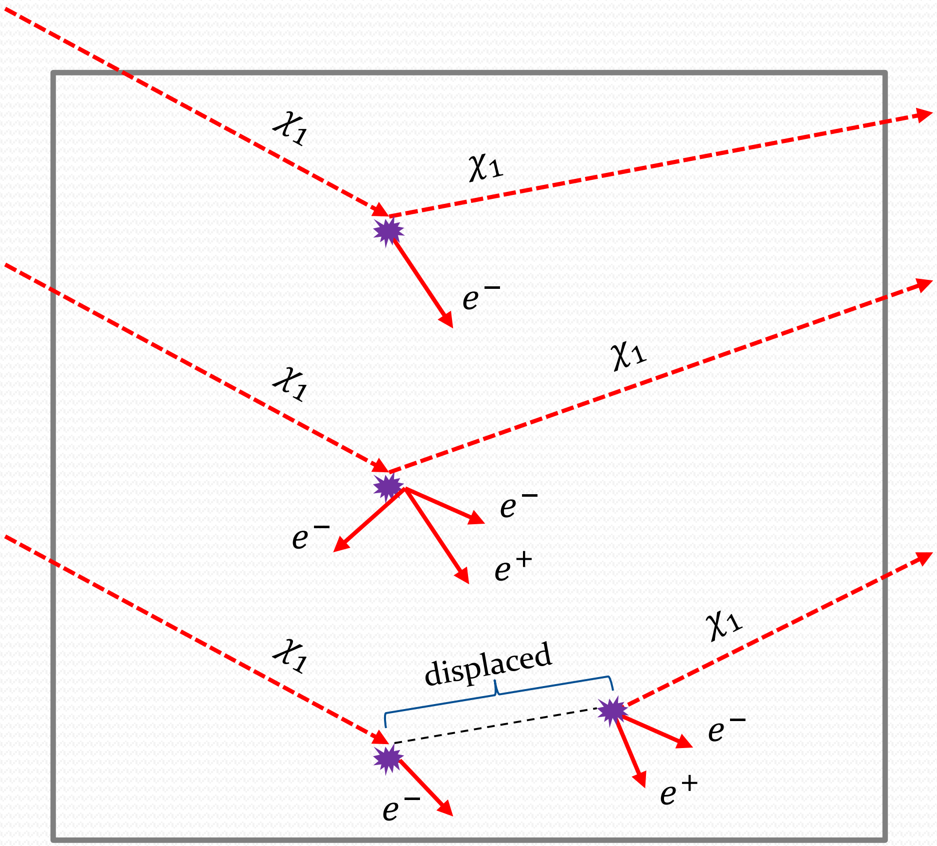
- Fermionic DM
  - χ_2: a heavier (unstable) dark-sector state
  - Flavor-conserving neutral current ⇒ elastic scattering



  - Flavor-changing neutral current ⇒ inelastic scattering



Expected Signatures with Electron Recoil



- ❑ Ordinary elastic scattering: electron recoil (ER) only, i.e., single track
- ❑ "Prompt" inelastic scattering: ER + e^+e^- pair (from the decay of on-shell X), i.e., **three tracks**
- ❑ "Displaced" inelastic scattering: ER + e^+e^- pair (typically from a three-body decay of χ_2), i.e., again **three tracks**
- ❑ Note that **tracks will pop up inside the fiducial volume**.
- ❑ Straightforwardly applicable to proton recoil (up to form factor, DIS etc.)

Model-independent Reach

- **Non-trivial** to find appropriate parameterizations for providing **model-independent reaches** due to many parameters involved in the model
- Number of signal events $N_{\rm sig}$ is

$$N_{\rm sig} = \sigma_\epsilon \mathcal{F} A \, t_{\rm exp} N_e \,, \qquad (3)$$

  - σ_ϵ: scattering cross section between χ_1 and (target) electron
  - $\mathcal{F}$: flux of incoming (boosted) χ_1
  - A: acceptance
  - $t_{\rm exp}$: exposure time
  - N_e: total # of target electrons

Controllable! (once a detector is determined) — applies to $t_{\rm exp}$ and N_e

Here determined by distance between the primary (ER) and the secondary vertices, other factors such as cuts, energy threshold, etc are absorbed into σ_ϵ. Depending on analyses, some factors can be reabsorbed into A.

Model-independent Reach: Comprehensive

Two completely separated modules are assumed.

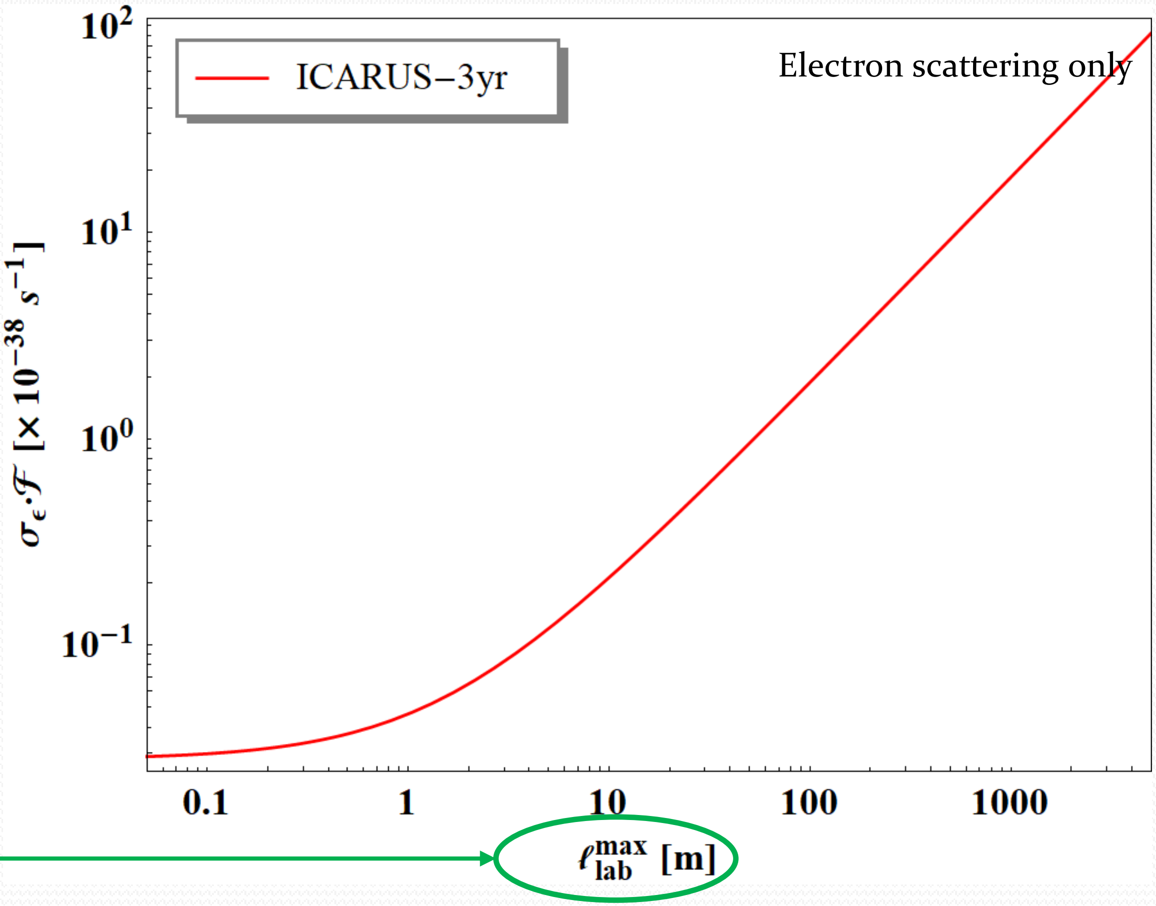
90% C.L. with zero BG

$$\sigma_\epsilon \mathcal{F} > \frac{2.3}{A(\ell_{\rm lab}) t_{\rm exp} N_e}, \quad (4)$$

Calculable

Evaluated under the assumption of cumulatively isotropic χ_1 flux

$\ell_{\rm lab}$ different event-by-event, so taking $\ell_{\rm lab}^{\rm max}$ for more conservative limit



Model-independent Reach: More Familiar Form

- More familiar parameterization possible with the below modification!

$$\sigma_\epsilon \geq \frac{2.3}{\mathcal{F} \cdot A \cdot t_{\text{exp}} \cdot N_e}$$

set to be 5×10^{-26} cm^{3}s^{-1}

$$\mathcal{F} = 1.6 \times 10^{-4}\,\text{cm}^{-2}\text{s}^{-1} \times \left(\frac{\langle \sigma v \rangle_{0\to 1}}{5 \times 10^{-26}\,\text{cm}^3\text{s}^{-1}}\right) \times \left(\frac{\text{GeV}}{m_0}\right)^2, \quad (1)$$

- Then having

$$\sigma_\epsilon \text{ vs. } m_0 (= E_1 = \gamma_1 m_1)$$

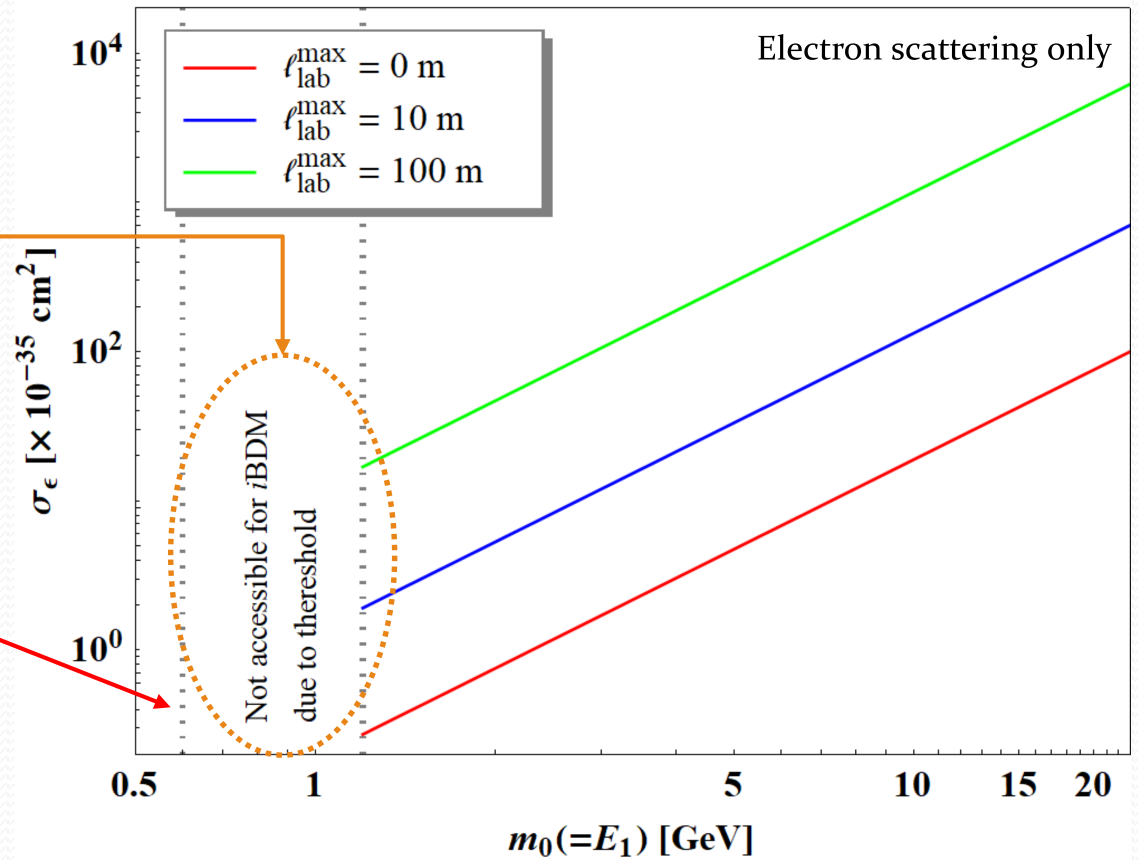
just like σ vs. m_{DM} in conventional WIMP searches

Model-independent Reach: More Familiar Form

3-year data collection assumed.

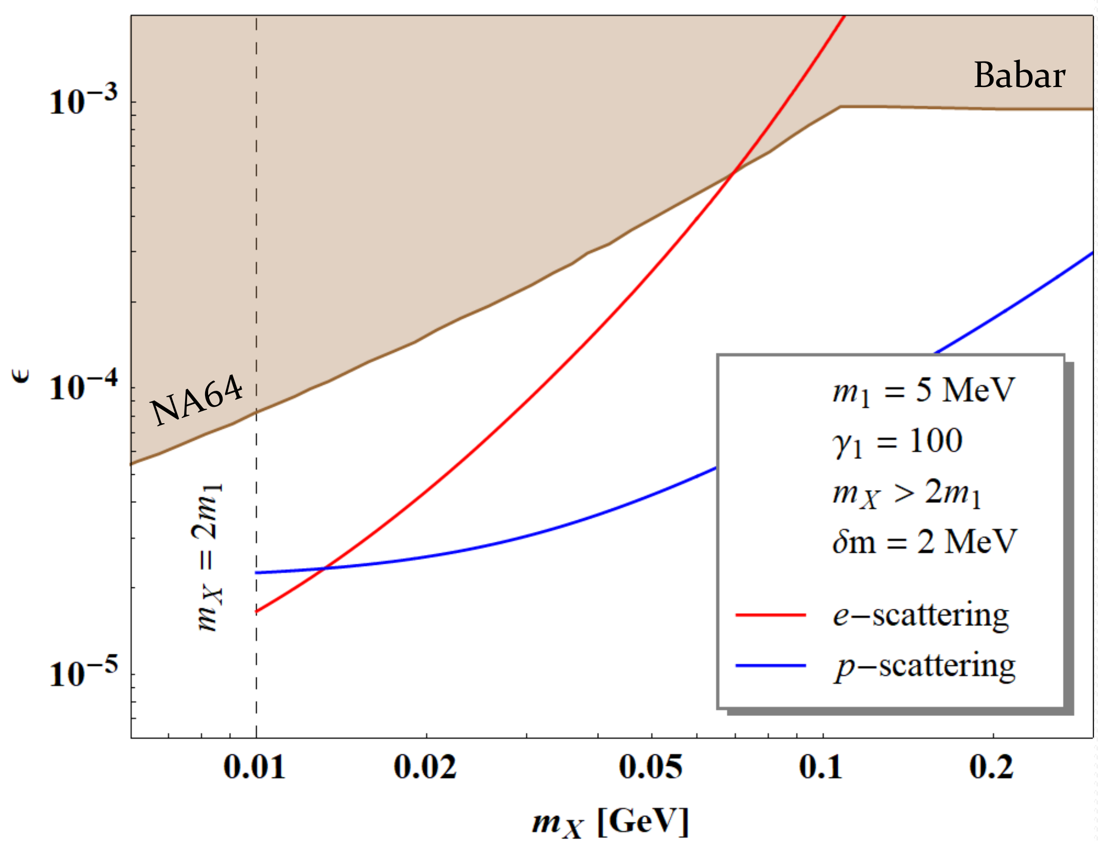
Absolute lower bound for visible tri-track events due to the threshold energy of 400 MeV. (The actual lower bound may involve minor model-dependence.)

Smaller thresholds allow to probe smaller cosmological dark matter mass.



Dark Photon Parameter Space: Invisible X Decay

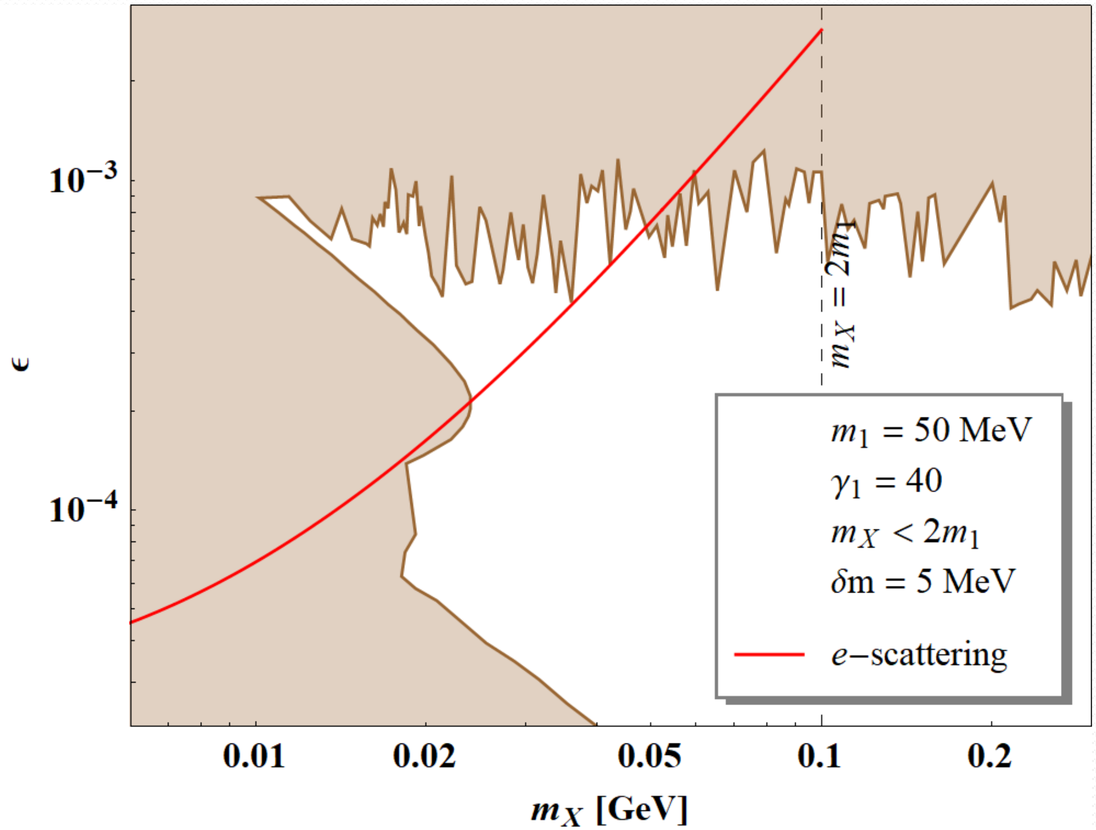
- Case study 1: mass spectra for which dark photon decays into DM pairs, i.e., $m_X > 2m_1$



- 3-year data collection is assumed.
- 400 MeV threshold is assumed.
- ICARUS can probe the uncovered parameter region by an order of magnitude in the ϵ axis.
- p-scattering is preferred for heavier dark photon masses [DK, Machado, Park, Shin, in progress]

Dark Photon Parameter Space: Visible X decay

- ❑ Case study 2: mass spectra for which dark photon decays into lepton pairs, i.e., $m_X < 2m_1$



- ❑ 3-year data collection is assumed.
- ❑ 400 MeV threshold is assumed.
- ❑ ICARUS can probe the uncovered parameter region by half order of magnitude in the ϵ axis.