# Ineastic Boosted Dark Matter Searches at ICARUS – Gran Sasso

**Doojin Kim**

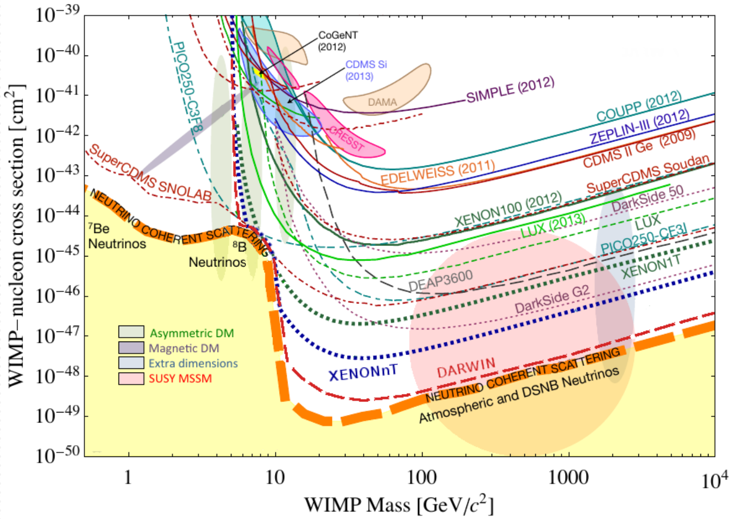
**Outline**

1. Physics Motivation
2. Signatures and General Strategies
3. Phenomenology: Experimental Sensitivities

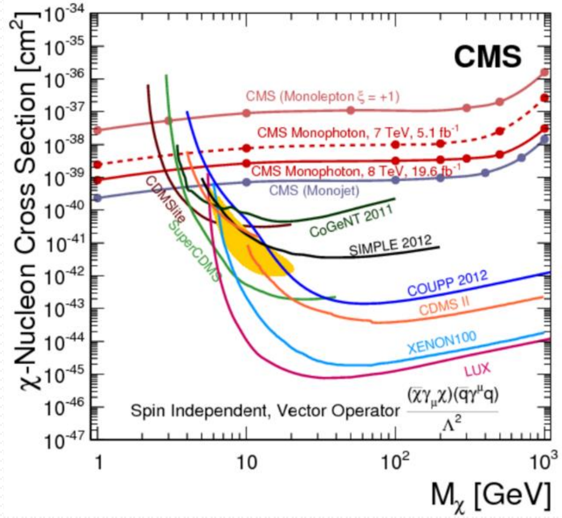
# Physics Motivation

# Current Status of DM Searches

- **No observation** of DM signatures via non-gravitational interactions (many searches/interpretations designed/performed under **WIMP/minimal dark-sector** scenarios) ⇒ merely excluding more parameter space in dark matter models




[P. Cushman, C. Calbiati and D. N. McKinsey, (2013); L. Baudis (2014)]




[CMS mono-photon search (2014)]

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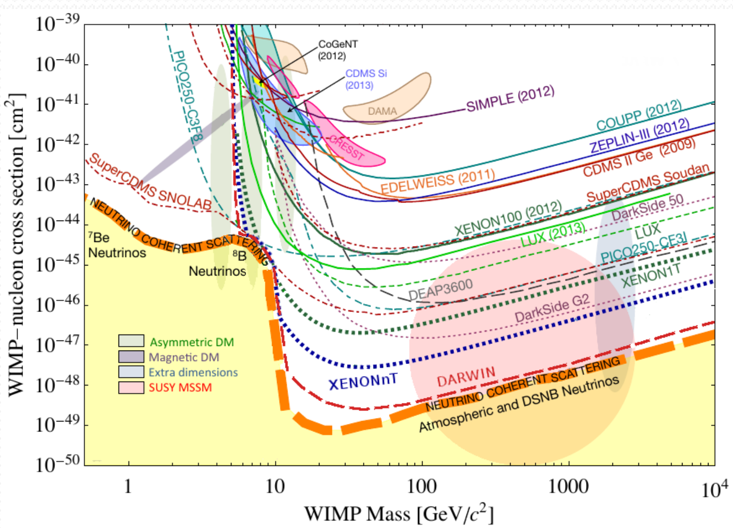


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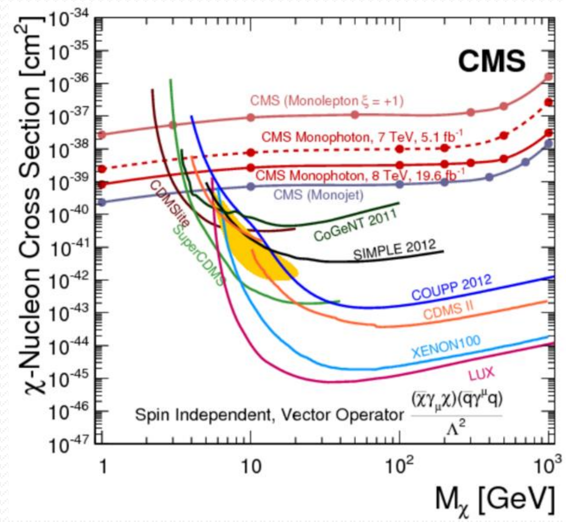


[CMS mono-photon search (2014)]

**Time to change our approach?!**

# Conventional Approach

- Traditional approaches for DM searches:
  - ✓ Weak-scale mass
  - ✓ Weakly-coupled
  - ✓ Minimal dark sector
  - ✓ Elastic scattering
  - ✓ Non-relativistic

# Conventional vs. Nonconventional Approach

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- Modified approaches for DM searches:
  - ✓ Other mass scale: e.g., PeV, sub-GeV, MeV, keV, meV, …
  - ✓ Weaker coupling to the SM: e.g., vector portal (dark photon), scalar portal, axion portal, …
  - ✓ "Flavorful" dark sector: e.g., more dark matter species, unstable heavier dark sector states, …
  - ✓ Inelastic scattering (i.e., up-scatter to an "excited" state)
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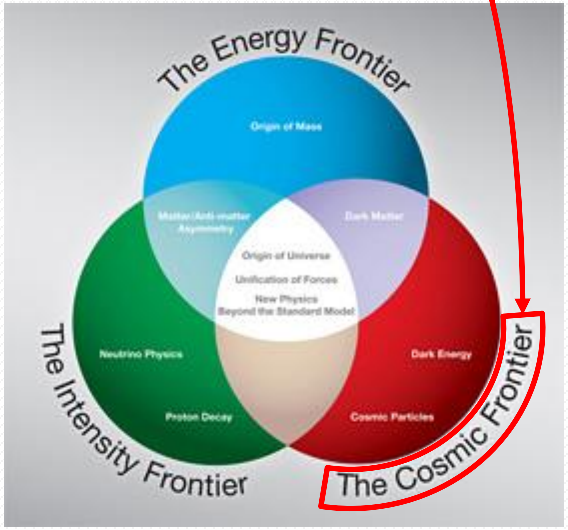
# DM Search Strategies

| Scattering \ $v_{DM}$ | Non-relativistic ($v_{DM} \ll c$) |
|---|---|
| elastic | Direct detection |
| *in*elastic | inelastic DM (iDM) |

Very well-studied

# DM Search Strategies

| Scattering \ $v_{DM}$ | Non-relativistic ($v_{DM} \ll c$) | Relativistic ($v_{DM} \sim c$) |
|---|---|---|
| elastic | Direct detection | Boosted DM (eBDM) |
| *in*elastic | inelastic DM (iDM) | inelastic BDM (*i*BDM) |

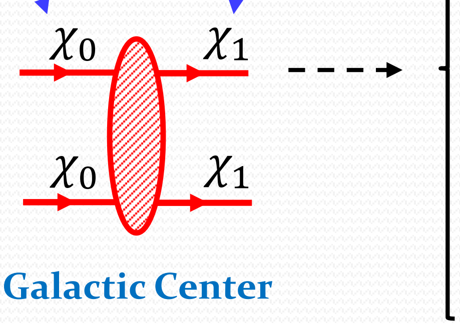


# Signatures and General Strategies

# Generic Boosted Dark Matter (BDM) Event Topologies

$m_0 = E_1 = \sim 30$ MeV $- \sim 20$ GeV
with $\mathcal{F}_{\chi_1} = \sim 10^{-1} - 10^{-7}\ \text{cm}^{-2}\text{s}^{-1}$

Cosmological DM, Assumed no direct couple to SM




Galactic Center

- $\chi_0$: heavier DM
- $\chi_1$: lighter DM
- $\gamma_1$: boost factor of $\chi_1$
- $\chi_2$: massive unstable dark-sector state
- $\phi$: mediator/portal particle

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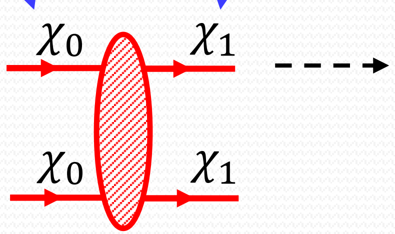


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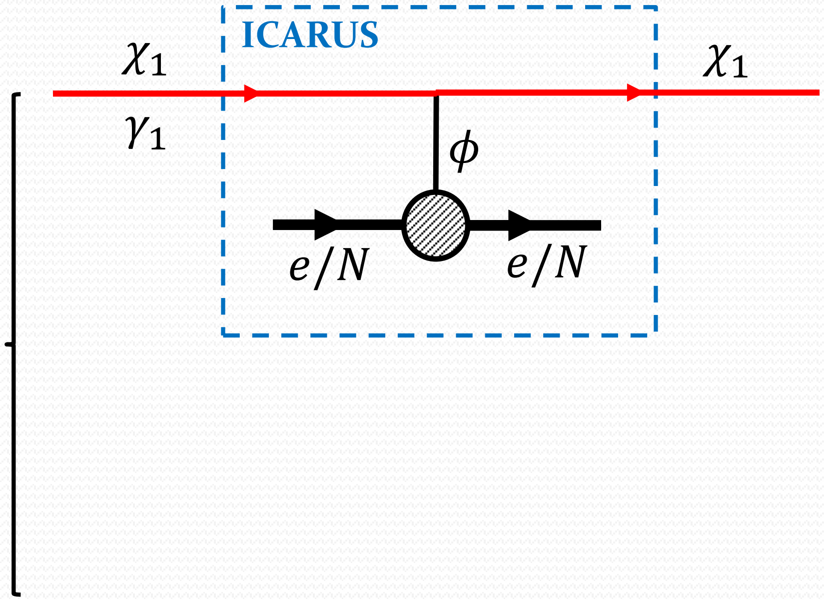


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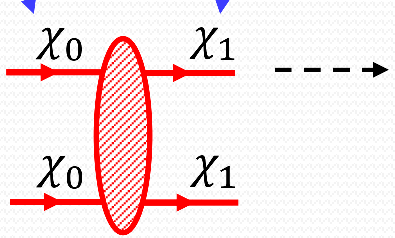


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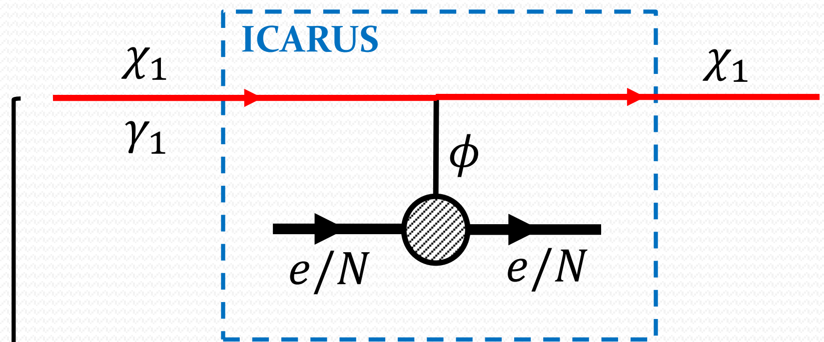


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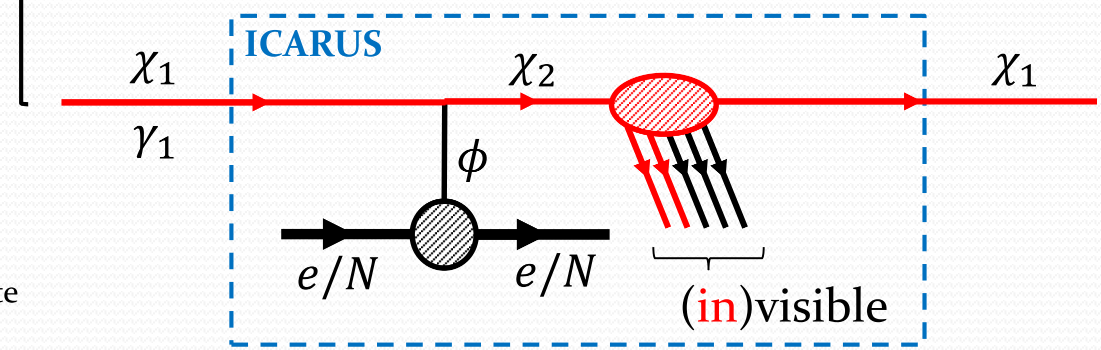


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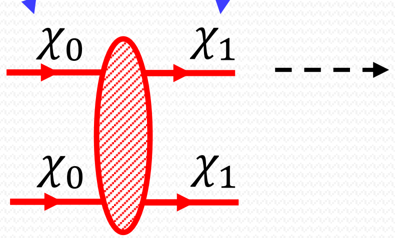


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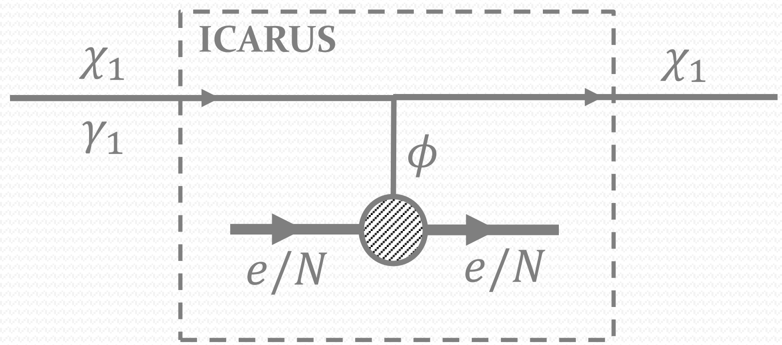


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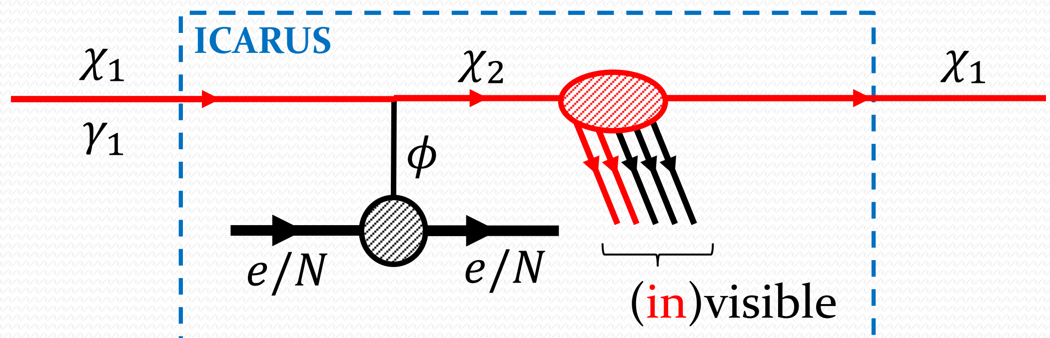


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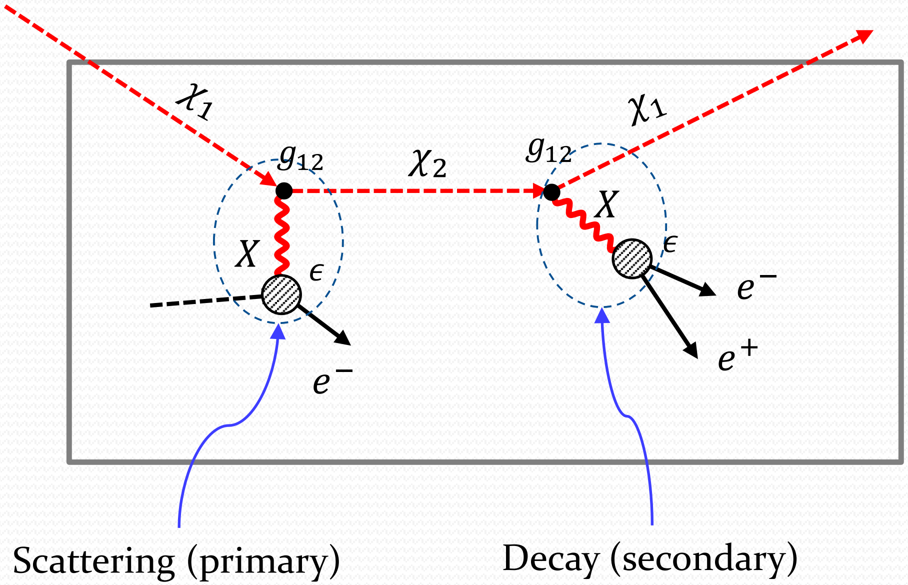
# Expected Signatures with a Dark Photon Scenario




- ❑ Benchmark model to describe interactions between dark-sector and SM-sector particles: dark photon ($X$) model.
- ❑ $m_2 > m_1 + 2m_e$
- ❑ **Three electron tracks** with two possibilities
  - ✓ "Prompt" *i*BDM: scattering (primary) and decay (secondary) arise at the same point.
  - ✓ "Displaced" *i*BDM: primary and secondary interaction points appear displaced (often due to long-lived $\chi_2$)

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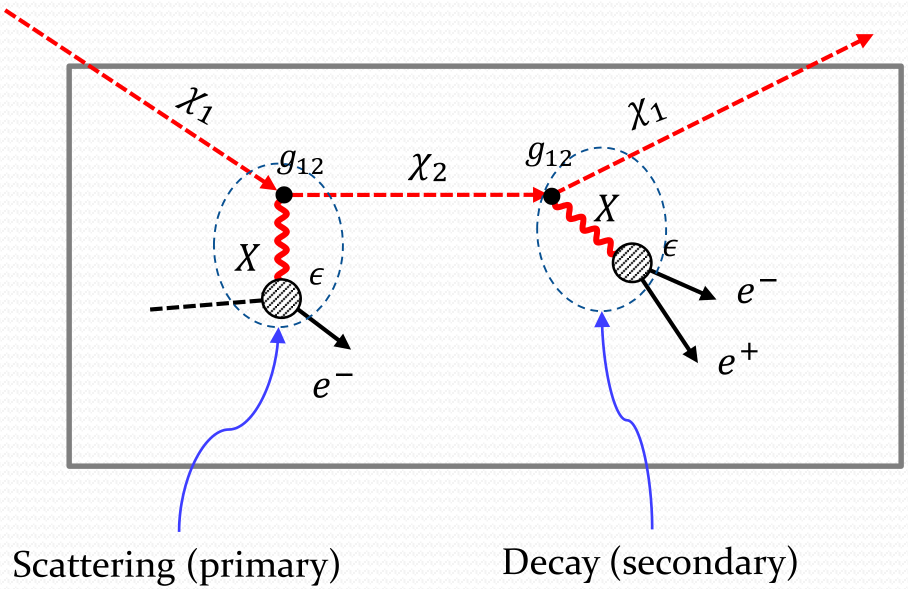


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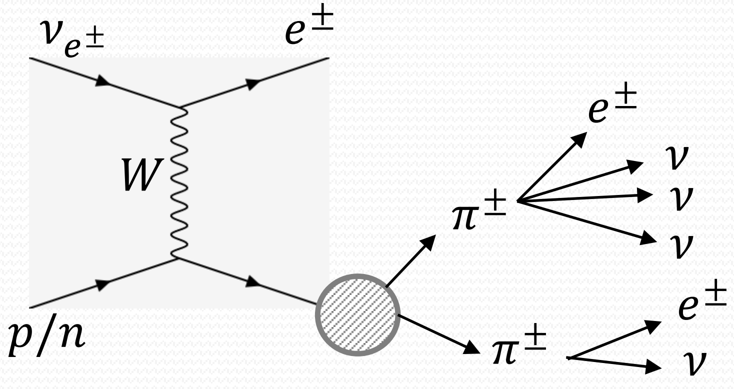
- ❑ Note that **tracks will pop up inside the fiducial volume**.
- ❑ Straightforwardly applicable to proton recoil (up to form factor, DIS etc.)

# Expected Number of ν-induced Events

- Atm.-$\nu$ may induce multi-track events (which could be backgrounds)
- The dominant source
  - ✓ **$\nu_e$-induced C.C.** events

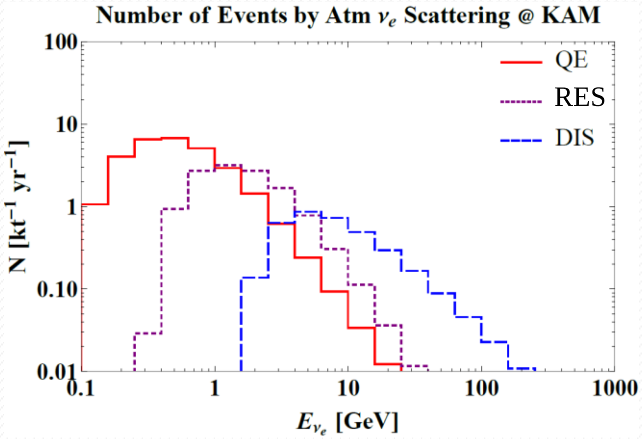


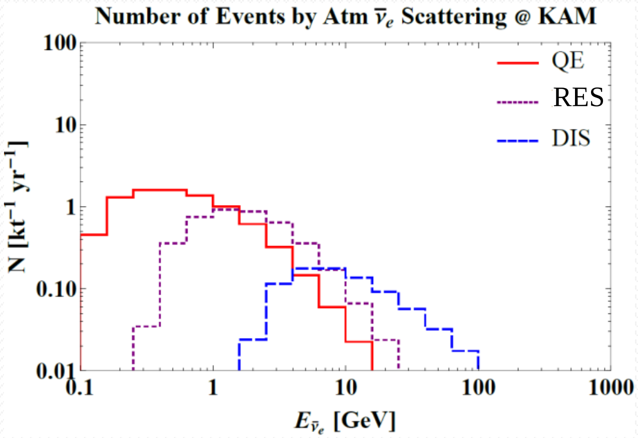

e.g. $\pi^\pm \to \mu^\pm\nu \to e^\pm\nu\nu\nu$, $\pi^\pm \to e^\pm\nu$

- Other subdominant sources
  - ✓ N.C. events: smaller cross section
  - ✓ $\nu_\tau$-induced: too small flux, hence negligible
  - ✓ $\nu_\mu$-induced C.C.: leaving an energetic (primary) muon (which can be tagged easily)

# Expected Number of ν-induced Events

- $\nu_e$-flux [SK Collaboration, 1502.03916] ⊗ $\nu_e$-cross section [Formaggio, Zeller, 1305.7513]



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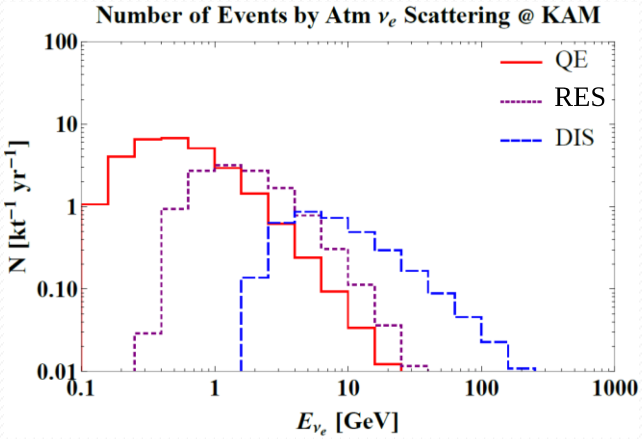
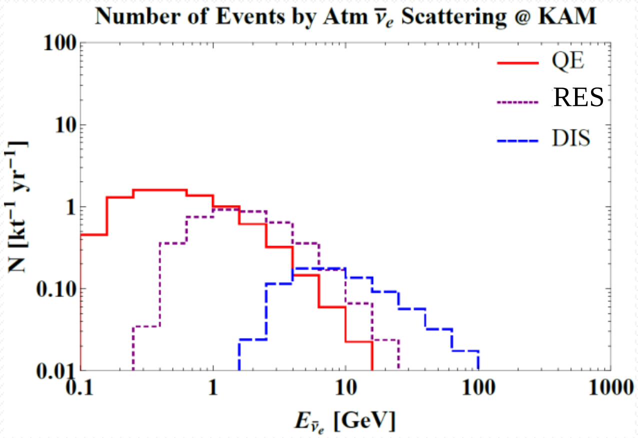
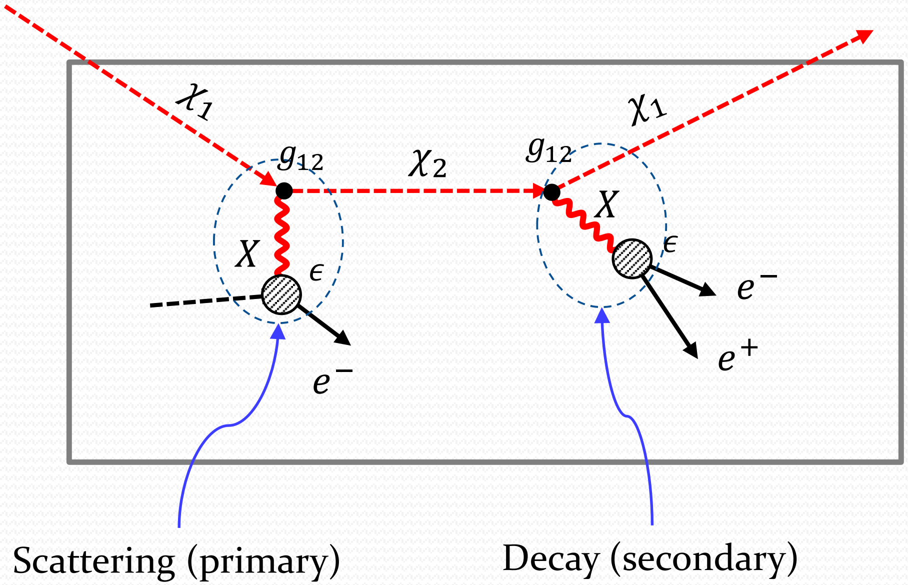



- Most DIS events result in messy final states, not mimicking signal events, while a majority of resonance events may create a few mesons in the final state [Formaggio, Zeller, 1305.7513].
  - ⇒ **12.2** events/kt/yr are potentially relevant, i.e., **18** events/3-yr for **0.48 kt**
- (quality) track-based particle identification etc at ICARUS LArTPC detectors can suppress such events significantly. → **Zero BG is achievable**!

# Phenomenology: Experimental Sensitivities

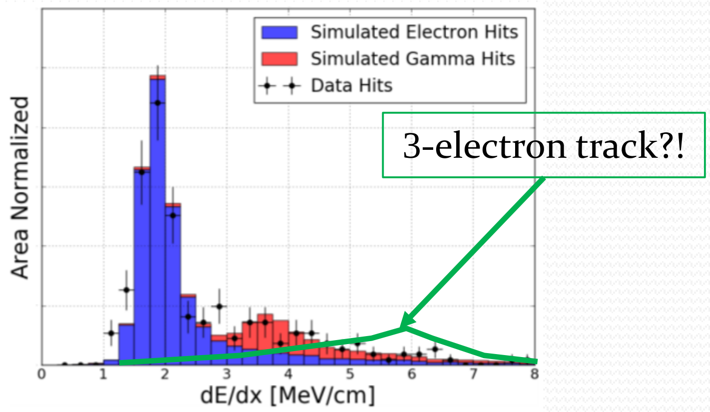
# Reminder for the Signal of Interest




- ❑ Remember that dark photon is a "player" in the benchmark model, allowing us to study phenomenology of dark photon!

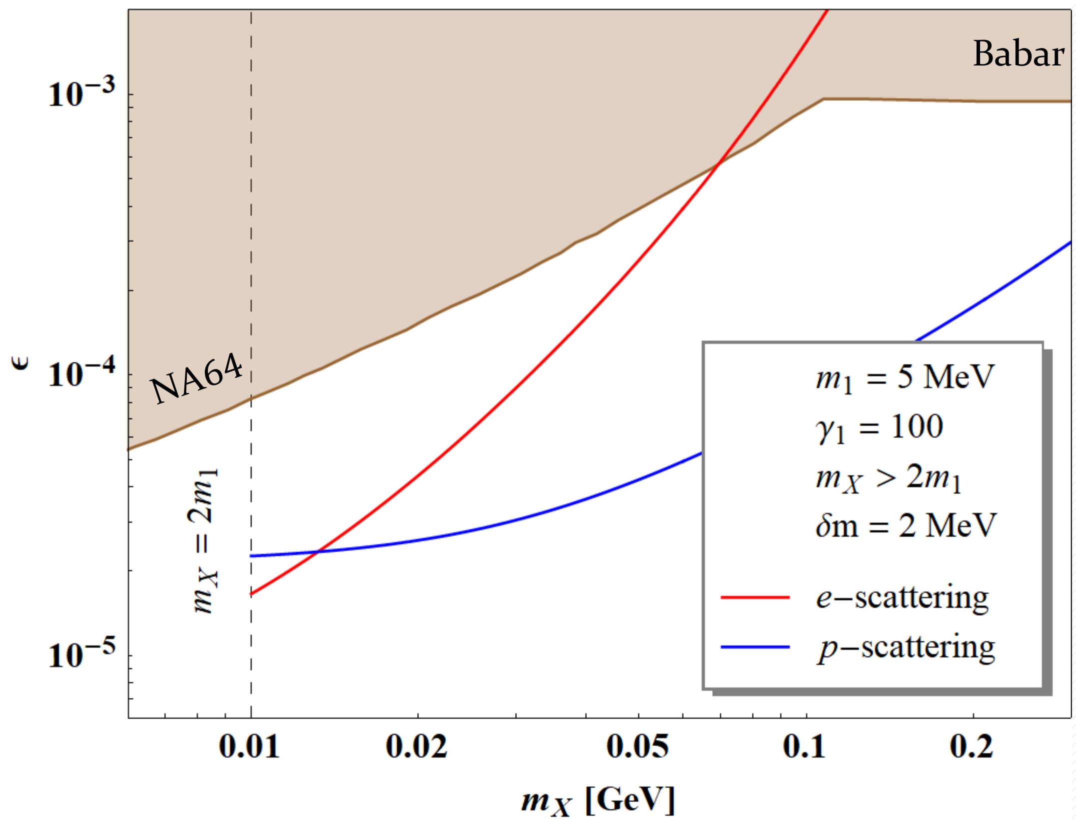
# Proposed Search Strategy

- It may be hard for each of three tracks to exceed the threshold energy unless the heavier (cosmological) dark mass is heavy enough (at the price of signal flux).
  - $\Rightarrow$ All three visible particles are likely to be collimated (due to a large boost factor of $\chi_1$).
  - $\Rightarrow$ However, such (single-track-like) collective/"fat" objects can overcome the threshold, hence we accept the associated events.
  - $\Rightarrow$ dE/dx analysis can allow to distinguish collimated objects from true single track events, i.e., three tracks overlaid (signal) vs. two tracks overlaid (signal, cf. "near-stationary" pion-induced photons leave two overlaid tracks, but do not overcome the threshold) vs. electron track (background)



# Dark Photon Parameter Space: Invisible X Decay

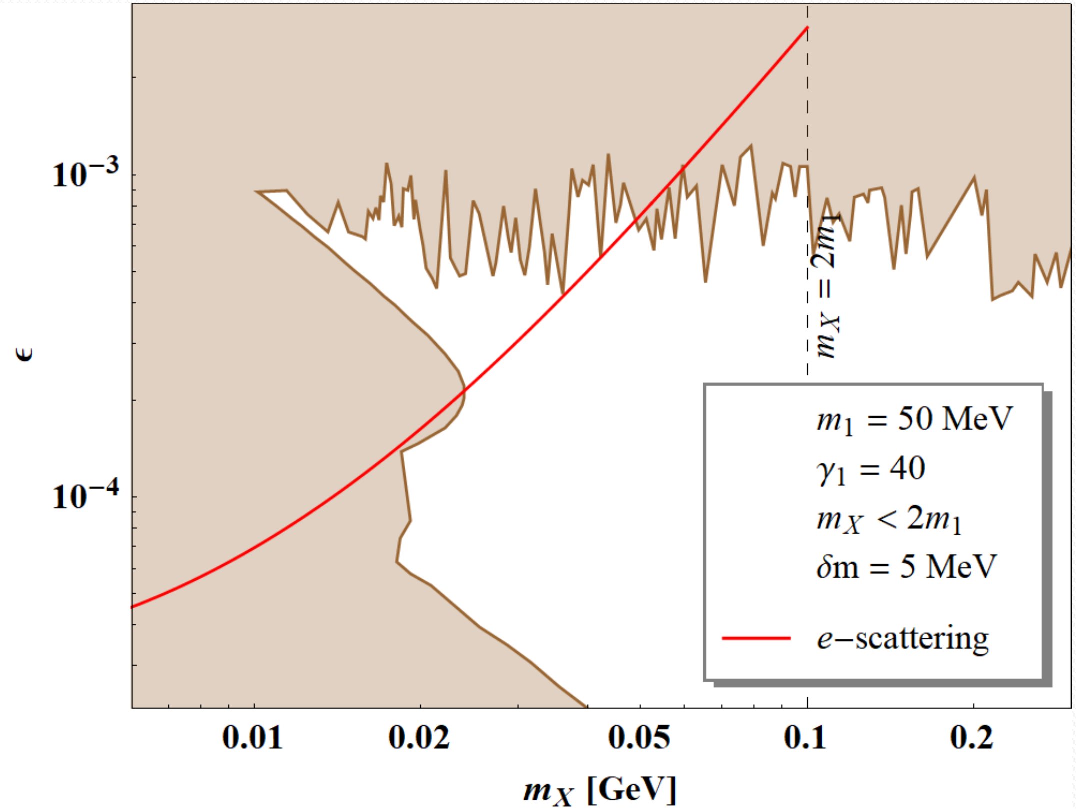
- Case study 1: mass spectra for which dark photon decays into DM pairs, i.e., $m_X > 2m_1$




- 3-year data collection under the zero background is assumed.
- 400 MeV threshold and proposed search strategy are assumed.
- ICARUS can probe the uncovered parameter region by an order of magnitude in the $\epsilon$ 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 under the zero background is assumed.
- 400 MeV threshold and proposed search strategy are assumed.
- ICARUS can probe the uncovered parameter region by half order of magnitude in the $\epsilon$ axis.

# 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 $N_{\text{sig}}$ is

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

  - $\sigma_\epsilon$: scattering cross section between $\chi_1$ and (target) electron
  - $\mathcal{F}$: flux of incoming (boosted) $\chi_1$
  - $A$: acceptance
  - $t_{\text{exp}}$: exposure time
  - $N_e$: total # of target electrons

**Controllable!** (once a detector is determined)

Here determined by distance between the primary (ER) and the secondary vertices (often secondary vertex only overcomes the threshold), other factors such as cuts, energy threshold, etc are absorbed into $\sigma_\epsilon$. Depending on analyses, some factors can be reabsorbed into $A$.

# Model-independent Reach: Comprehensive

Two completely separated modules are assumed.

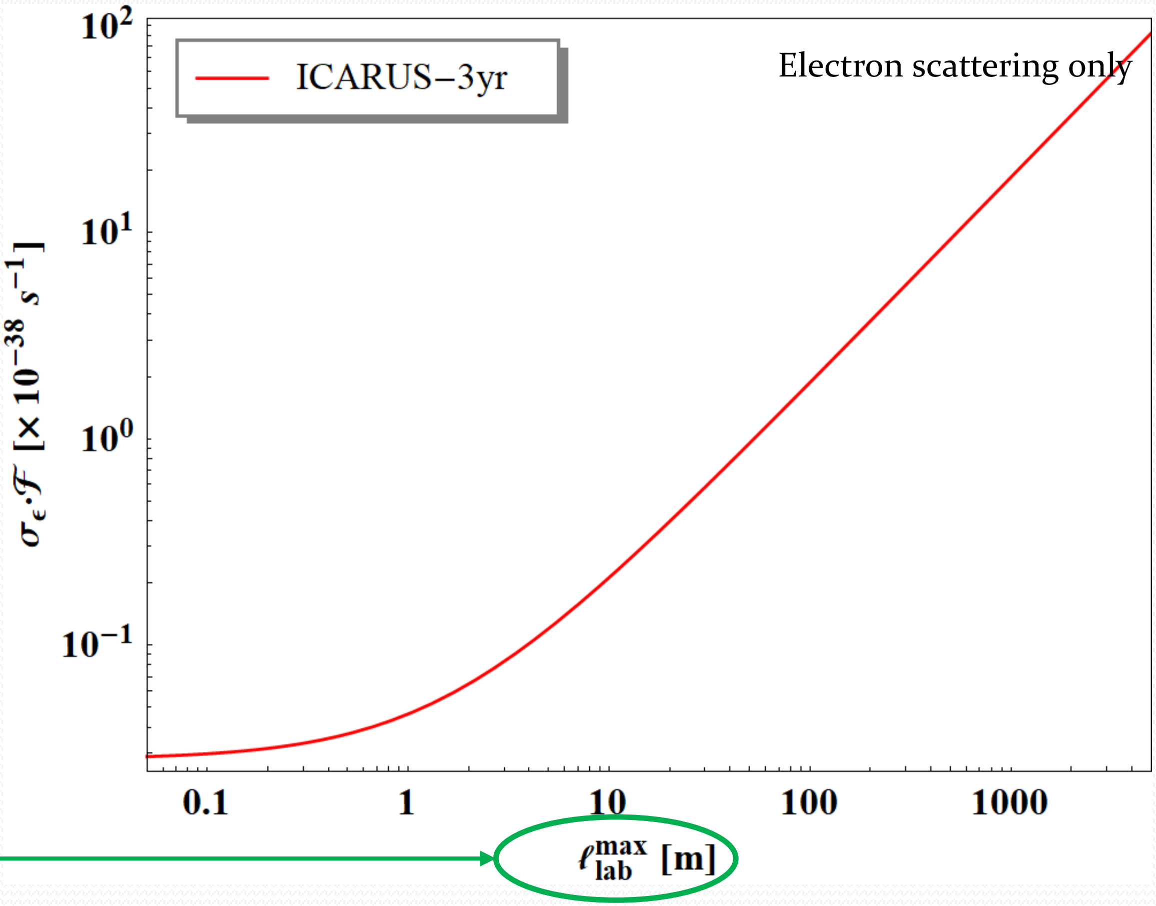
90% C.L. with zero BG

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

Calculable

Evaluated under the assumption of cumulatively isotropic $\chi_1$ 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!

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

set to be $5 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$

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

- Then having

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

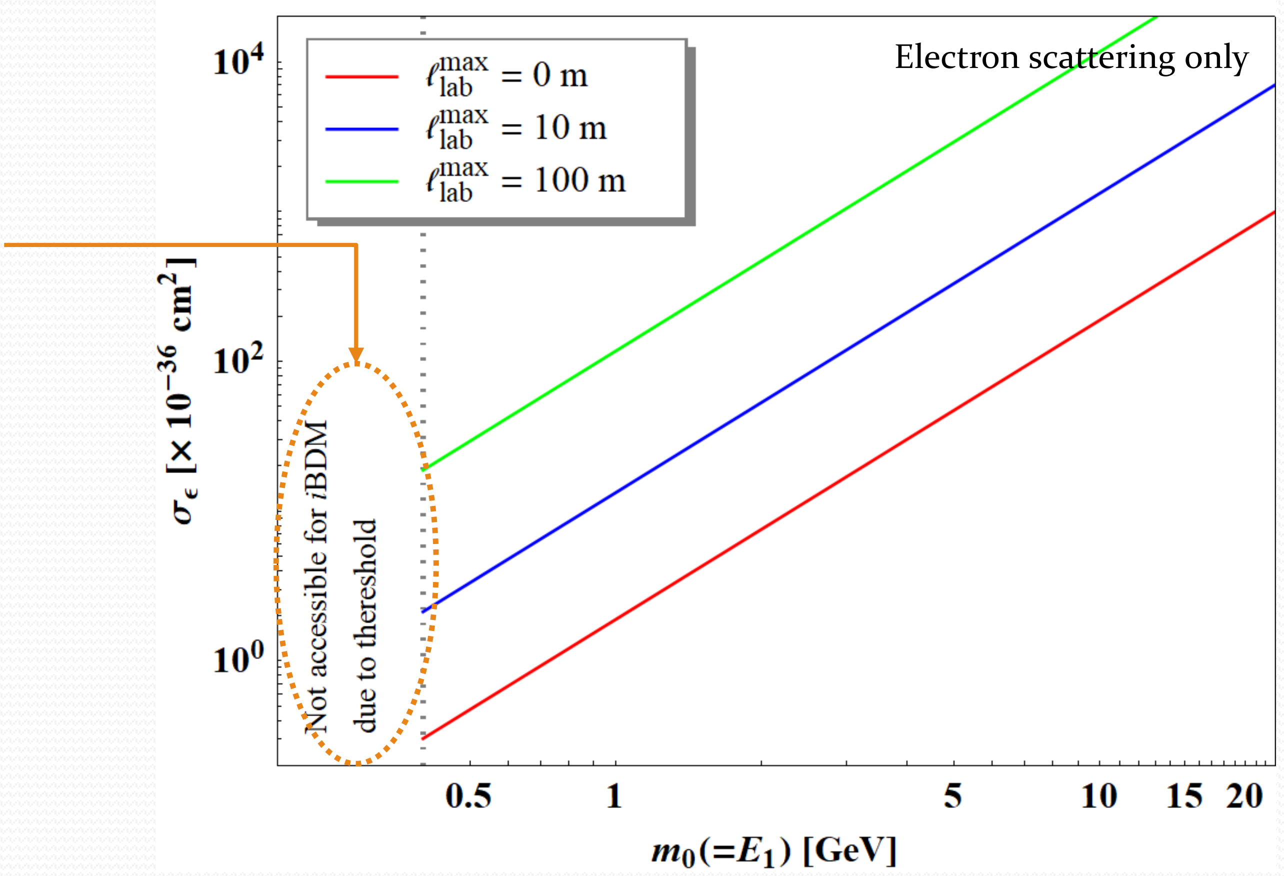
just like $\sigma$ vs. $m_{\rm DM}$ in conventional WIMP searches

# 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.



# Conclusions and Outlook

| Scattering \ $v_{DM}$ | Non-relativistic ($v_{DM} \ll c$) | Relativistic ($v_{DM} \sim c$) |
|---|---|---|
| elastic | Direct detection | Boosted DM (eBDM) |
| *in*elastic | inelastic DM (iDM) | **inelastic BDM (*i*BDM)** |

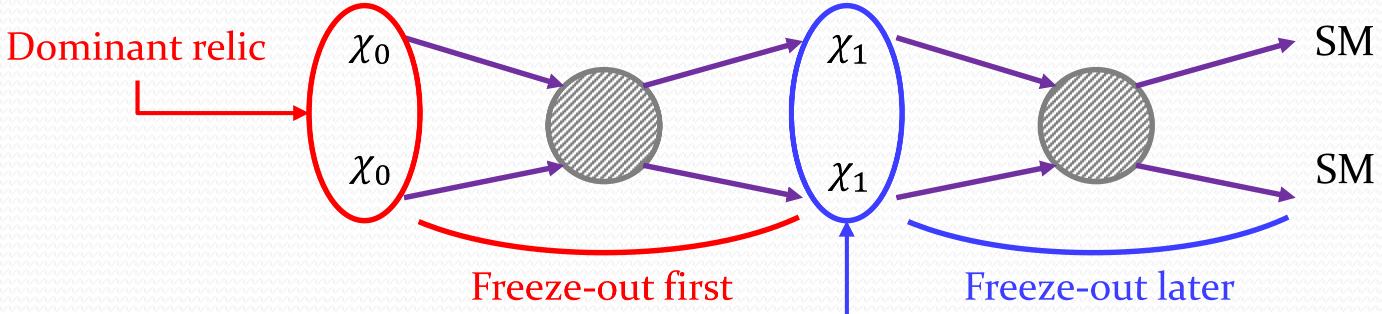
- The boosted (light) DM search is **promising** and provides a **new direction** to study DM phenomenology.
- Theoretical/phenomenological studies have been actively conducted and in progress.
- These ideas can be tested with the actual data taken by **ICARUS experiment** at Gran Sasso.

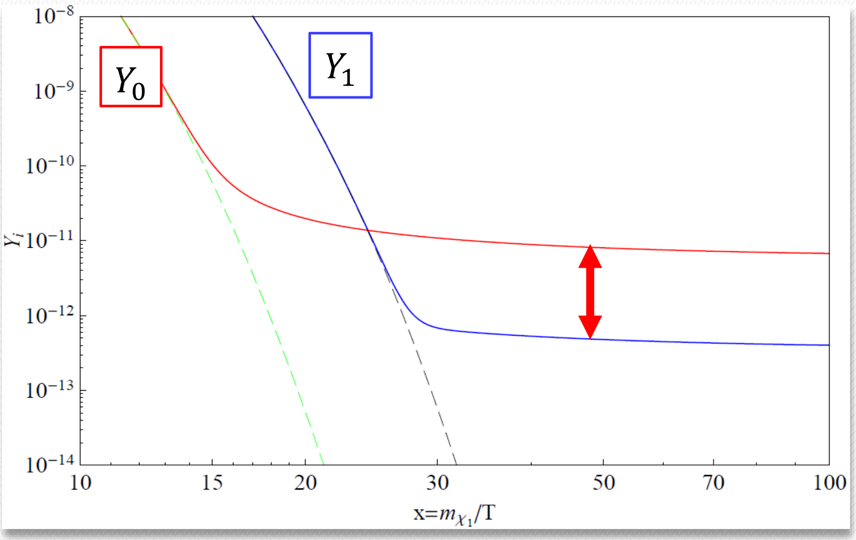
*thank you !*

# Back-up

# Two-component Boosted DM Scenario

- A possible relativistic source: BDM scenario (cosmic frontier), stability of the two DM species ensured by separate symmetries, e.g., $Z_2 \otimes Z_2'$, $U(1) \otimes U(1)'$, etc.

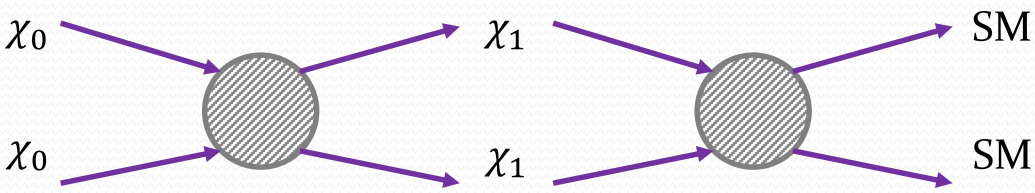


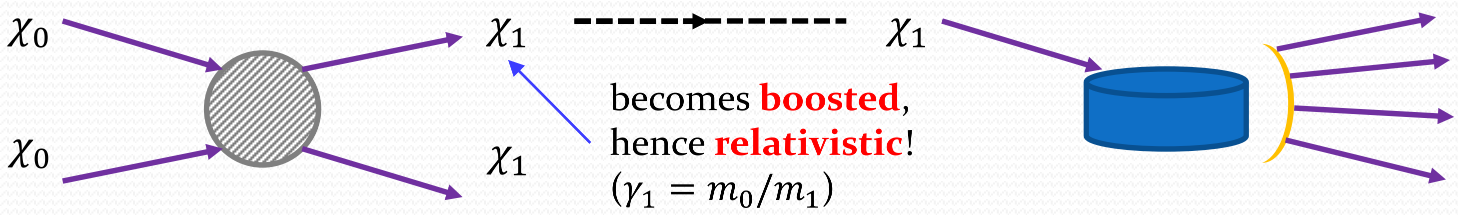

<u>"Assisted" freeze-out</u> mechanism

[Belanger, Park (2011)]

# "Relativistic" Dark Matter Search




- ✓ Heavier relic $\chi_0$: hard to detect it due to tiny/negligible coupling to SM
- ✓ Lighter relic $\chi_1$: hard to detect it due to small amount




(Galactic Center at **CURRENT** universe) (Laboratory)

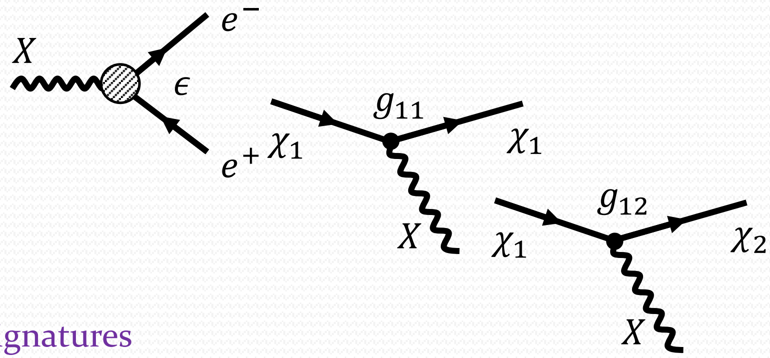
[Agashe, Cui, Necib, Thaler (2014)]

# Production of BDM & Benchmark Model

- Production of boosted DM at the universe: two-component boosted DM scenario [Agashe, Cui, Necib, Thaler (2014)]

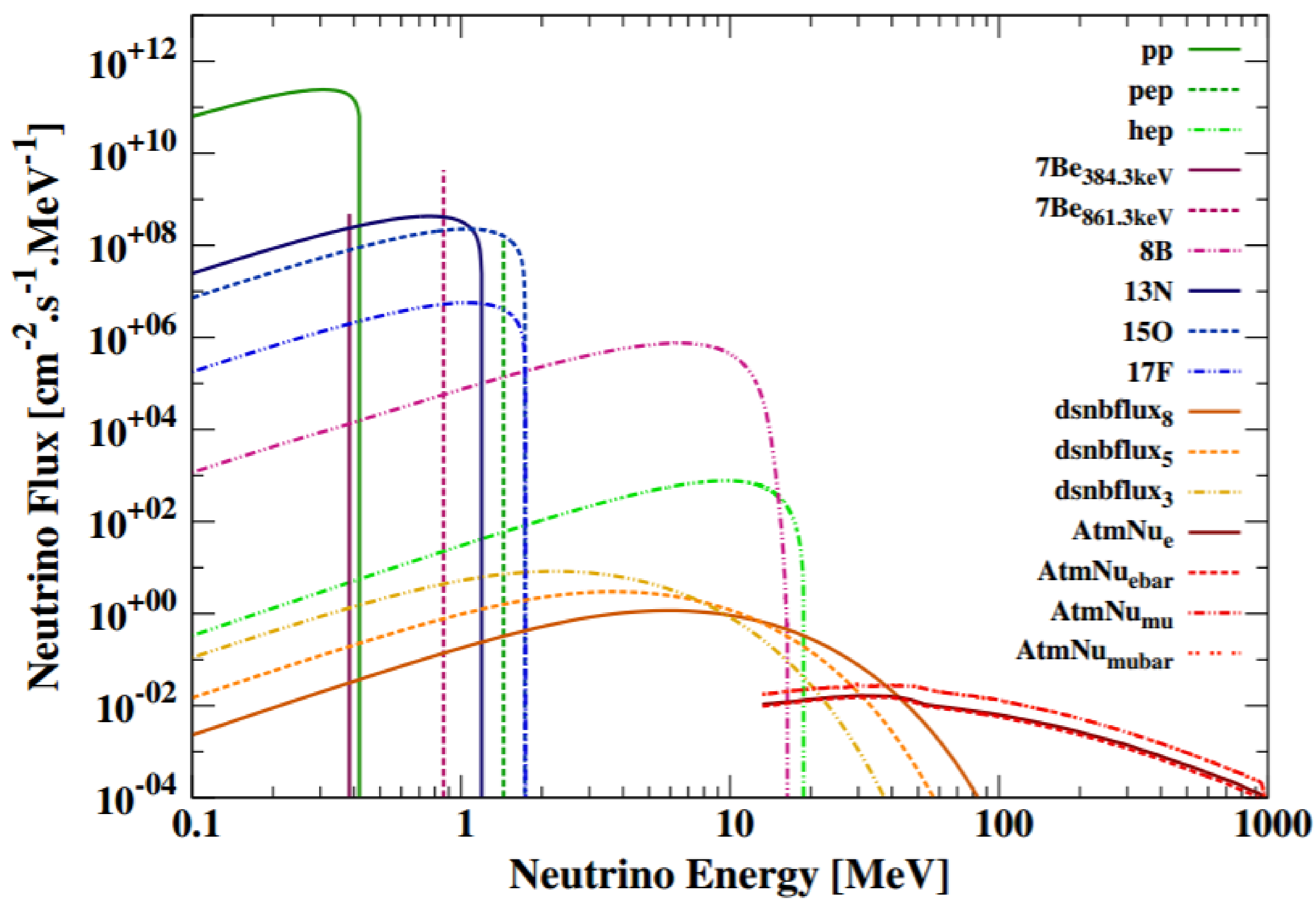
$$\mathcal{L}_{\rm int} \ni -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{11}\bar{\chi}_1 \gamma^\mu \chi_1 X_\mu + g_{12}\bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + \text{h.c.} + (\text{others})$$

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



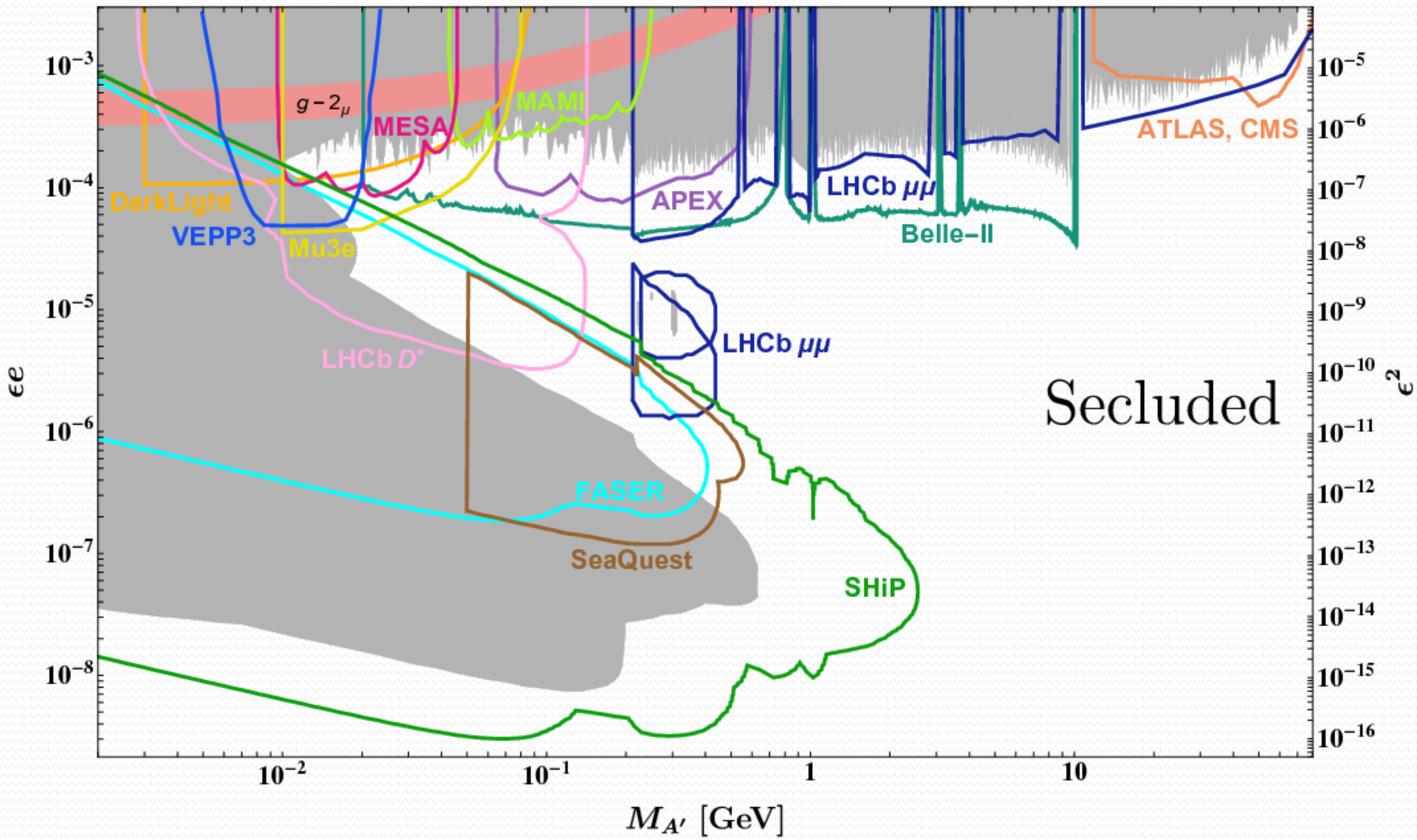

- Fermionic DM
  - $\chi_2$: a heavier (unstable) dark-sector state
  - Flavor-conserving neutral current ⇒ elastic scattering
  - Flavor-changing neutral current ⇒ inelastic scattering
- Not restricted to this model: various models conceiving BDM signatures
  - BDM source: galactic center, solar capture, dwarf galaxies, assisted freeze-out, semi-annihilation, fast-moving DM etc. [Agashe et al. (2014); Berger et al. (2015); Kong et al. (2015); Alhazmi et al. (2017); Super-K (2017); Belanger et al. (2011); D'Eramo et al. (2010); Huang et al. (2013)]
  - Portal: vector portal, scalar portal, etc.
  - DM spin: fermionic DM, scalar DM, etc.
  - iBDM-inducing operator: two chiral fermions, two real scalars, dipole moment interactions, etc. [Tucker-Smith, Weiner (2001); Giudice, **DK**, Park, Shin (2017)]

# Neutrino Fluxes




[Ruppin et al., (2014)]

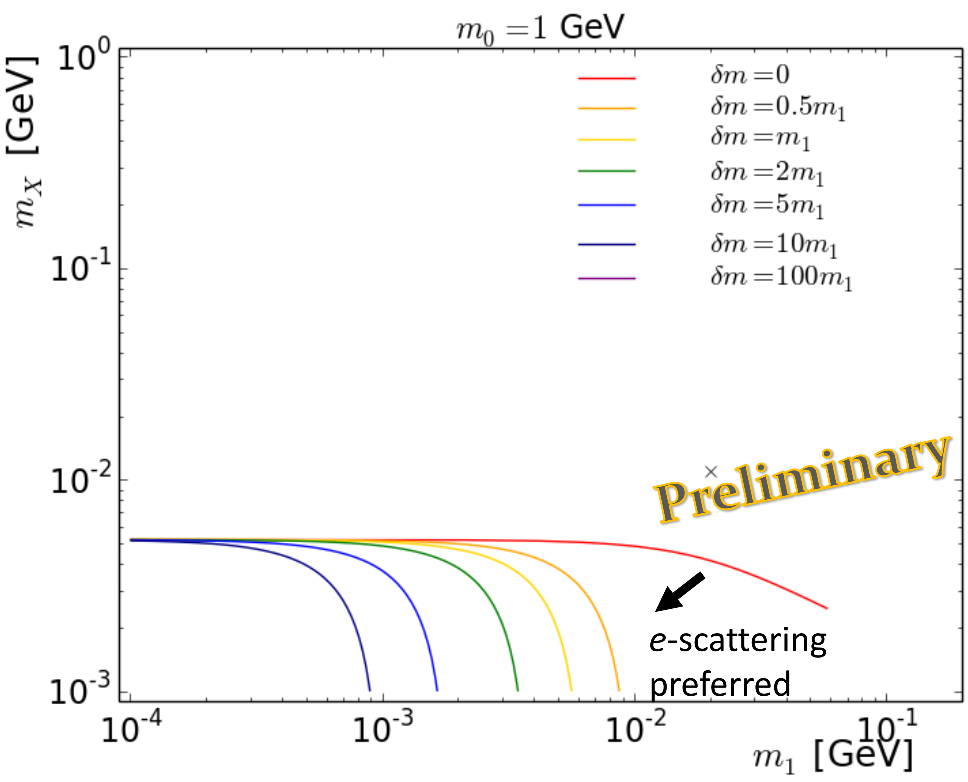
# Prospective Parameter Reaches for Visibly Decaying Dark Photon




[Bauer, Foldenauer, Jaeckel (2018)]

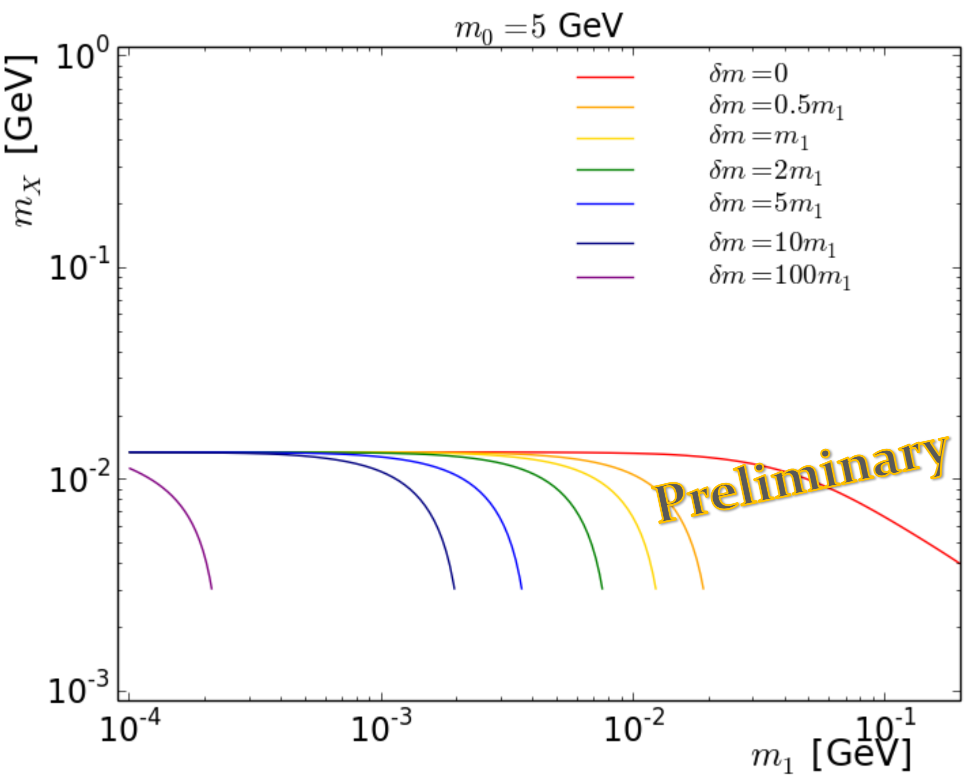
# *e*-scattering vs. *p*-scattering

- Comparison of cross sections via *e*-scattering and *p*-scattering




- As $m_X$ becomes negligible, *e*-scattering is more advantageous than *p*-scattering. ⇐ smaller suppression by the mass of target electron.
- "More" inelastic scattering shrinks the *e*-scattering preferred region. ⇐ *p*-scattering is better at accessing heavier dark sector states.

# *e*-scattering vs. *p*-scattering




- As $m_0$ becomes large, the *e*-scattering preferred region expands. ⇐ Difficulty in accessing heavier dark-sector states via *e*-scattering is relaxed by a larger boost factor of $\chi_1$.

# Worst Scenario Study

- One could take all SM single-track involving events as backgrounds: ~30 events/3 years are expected at ICARUS (Gran Sasso) considering SK atm. neutrino measurement.