PONDD, Fermilab

Search for Inelastic Boosted Dark Matter in DUNE far detector

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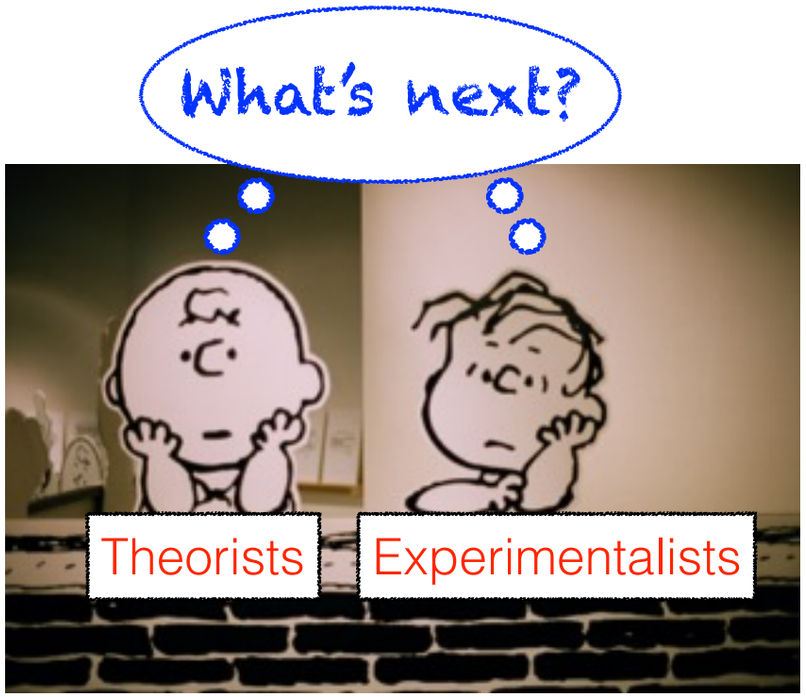
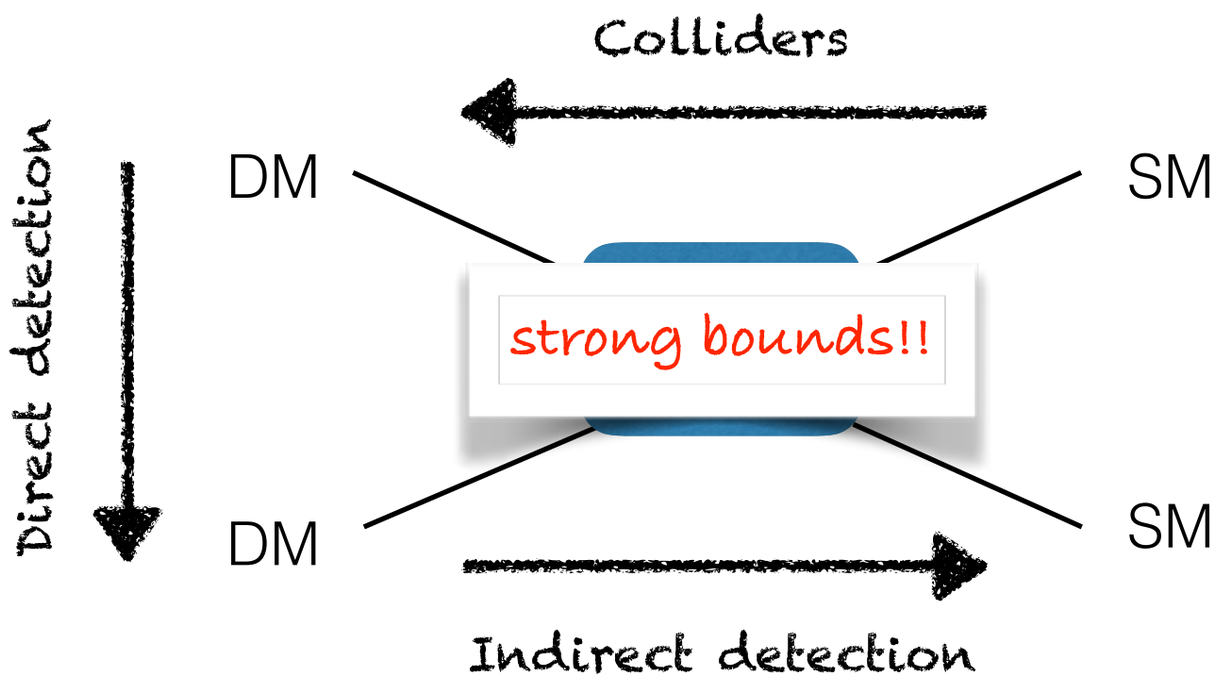
1612.06867, 1712.07126, 1803.03264, 1804.07302, 1812.xxxxx

Gian F. Giudice, Doojin Kim, Kyoungchul Kong, Pedro A. N. Machado, Jong-Chul Park

DUNE experimentalists : Chatterjee, De Roeck, Moghaddam, Whitehead, Yu

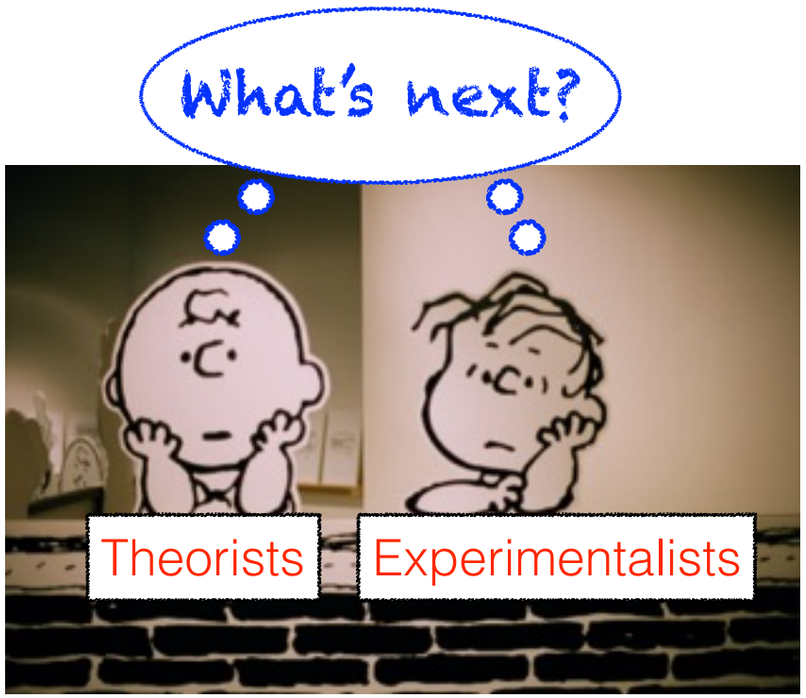
WIMP search

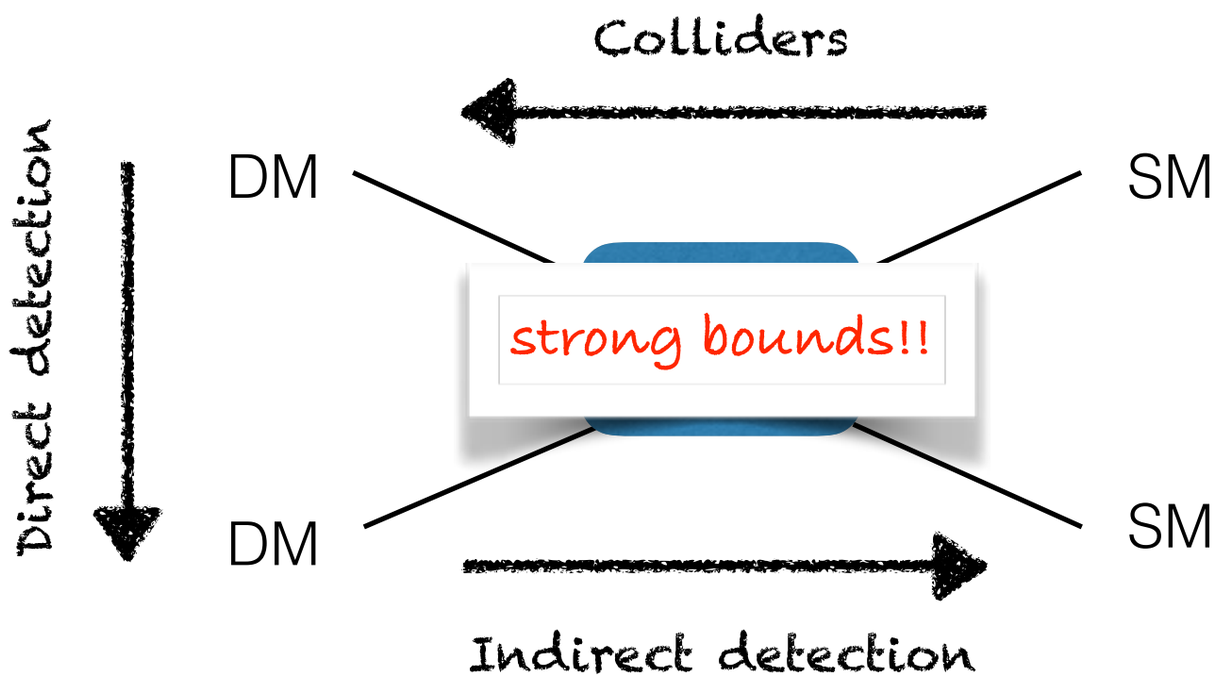




- Keep probing the rest of the corners of parameter space
- Non-conventional DM scenario & search strategy

WIMP search





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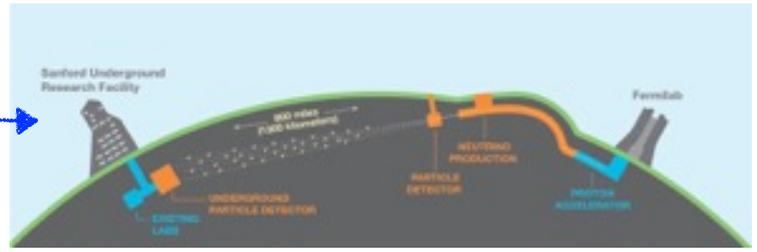
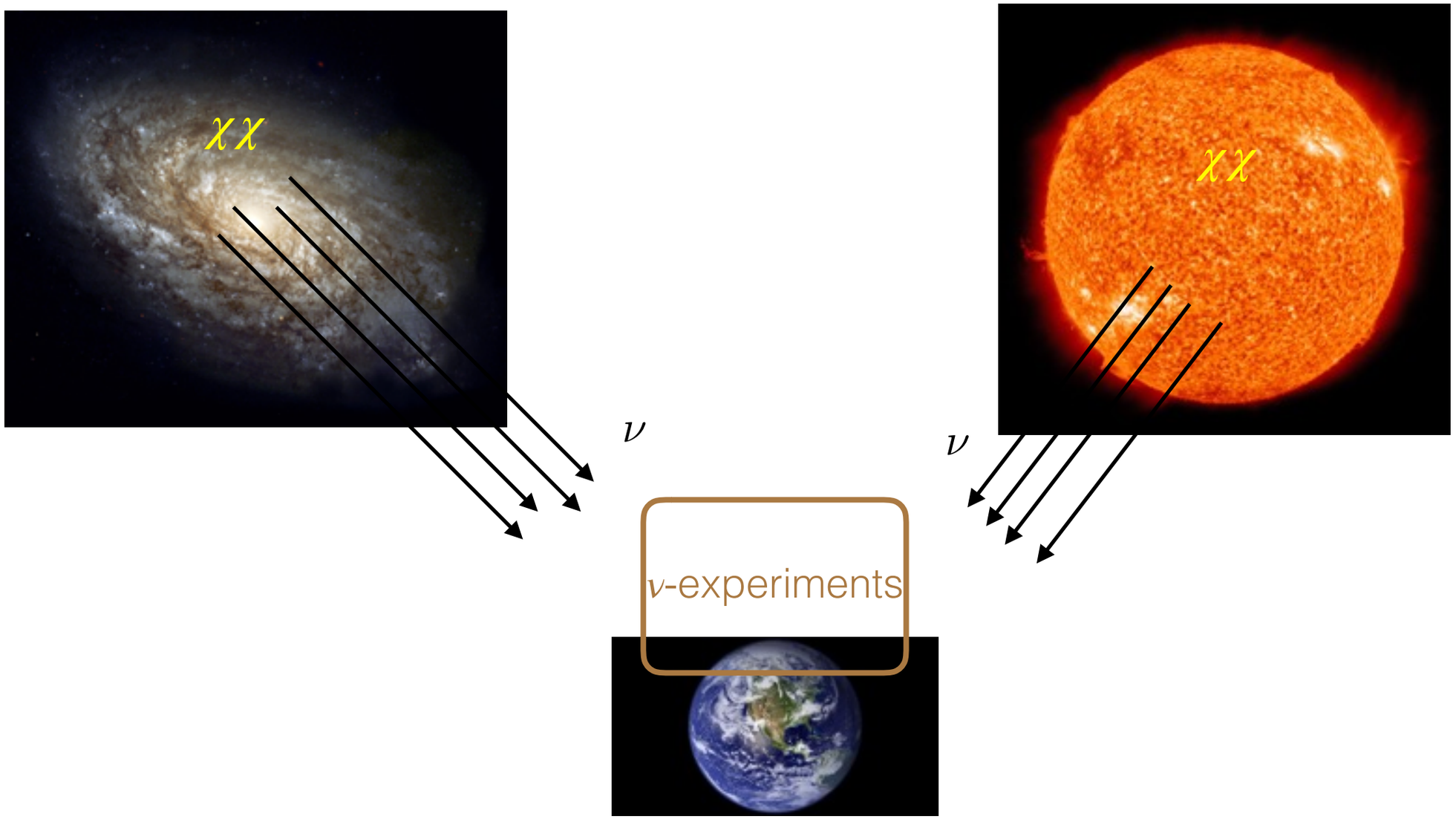
Physics opportunities in neutrino experiments

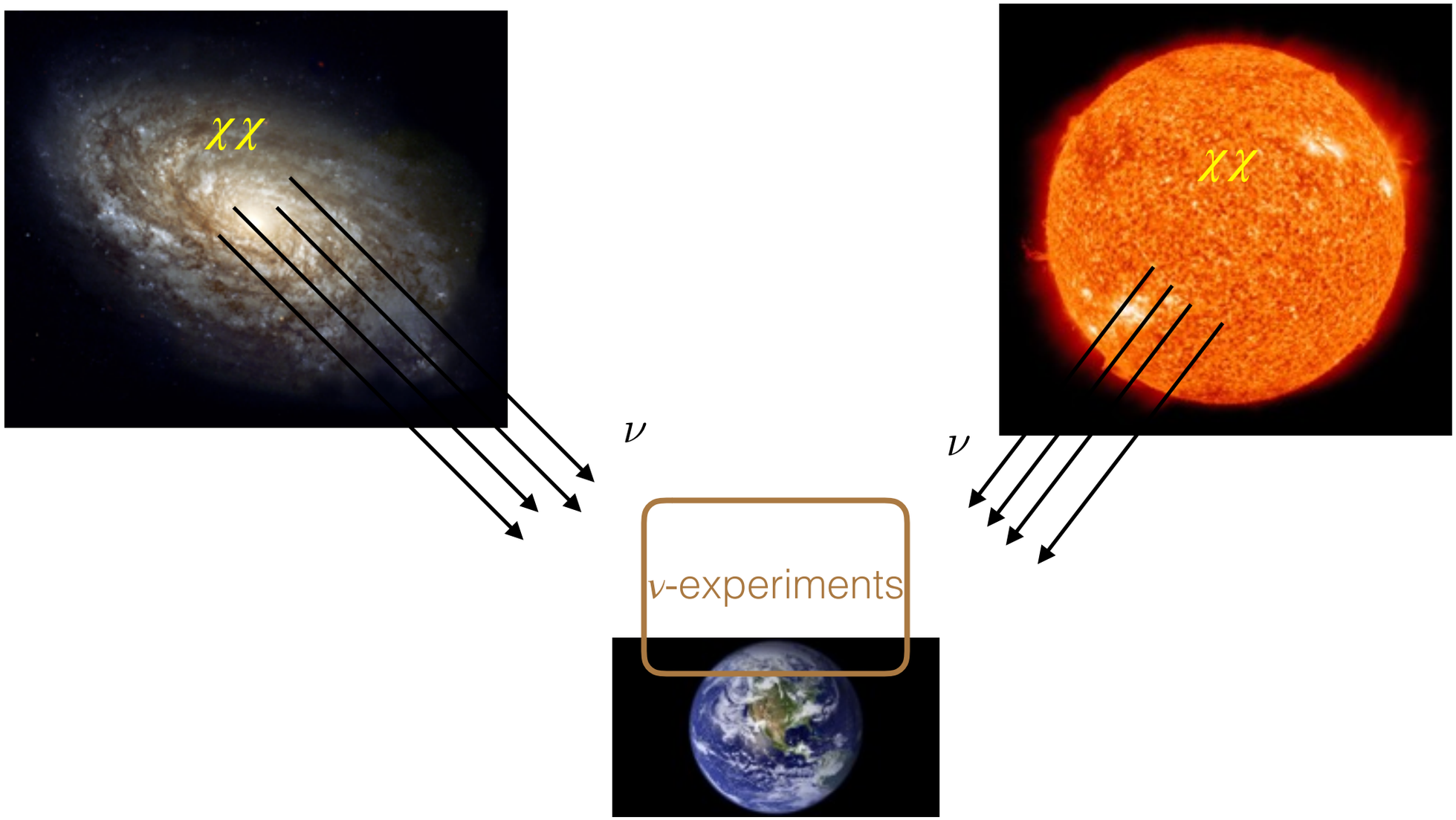


DM searches in ν-experiments



- Neutrino measurements from the annihilation/decay of DM (indirect detection)
- Give some information on (spin-dependent) cross section off nucleon
- Directly measure DM signal?

DM search in ν-experiments



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Boosted DM (BDM)

What if DM has a relativistic velocity?

Agashe, Cui, Necib, Thaler, 1405.7370

- DM coming from the universe has energy > E_{th} in ν-experiments
- Model building: right relic abundance of DM, mechanism boosting DM
  - Multi-component model — Belanger, Park, 1112.4491
  - Semi-annihilation model — D'Eramo, Thaler, 1003.5912

Josh's talk

Boosted DM (BDM)

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Josh's talk

- Decaying multi-component DM Bhattacharya et al., 1407.3280
  Kopp, Liu, Wang, 1503.02669
- High velocity (semi-relativistic) DM

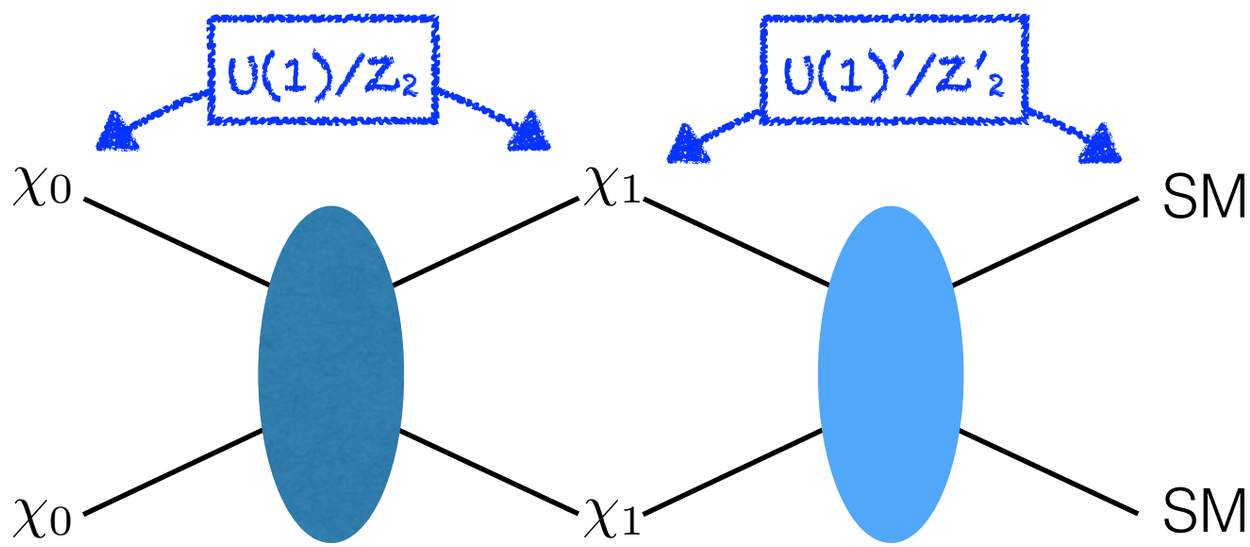
Same phenomenology

Anti-DM from DM-induced nucleon decay in the Sun
Huang, Zhao, 1312.0011

Energetic cosmic-ray induced DM Yin, 1809.08610
Bringmann, Pospelov, 1810.10543 Ema, Sala, Sato, 1811.00520

Multi-component BDM

χ_0: heavy, χ_1: light



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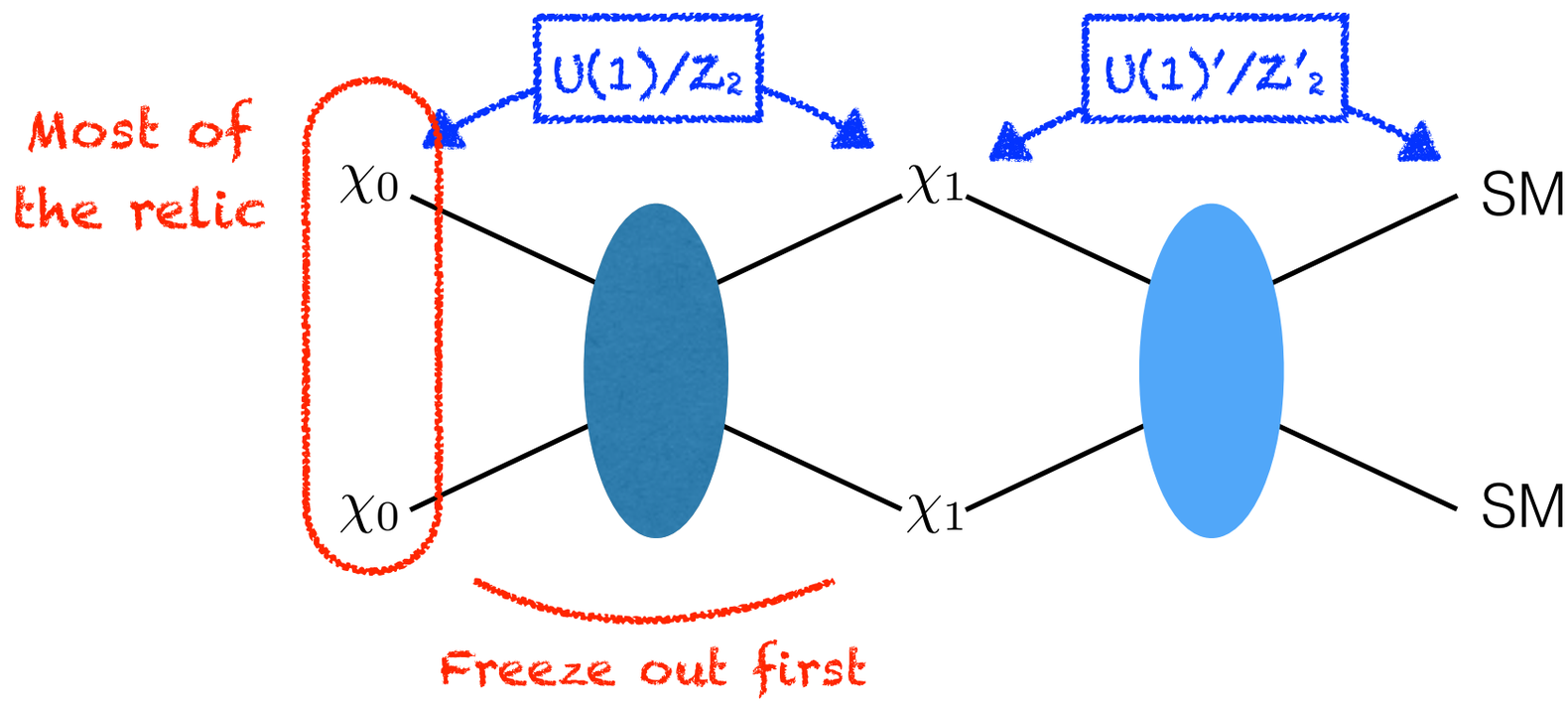

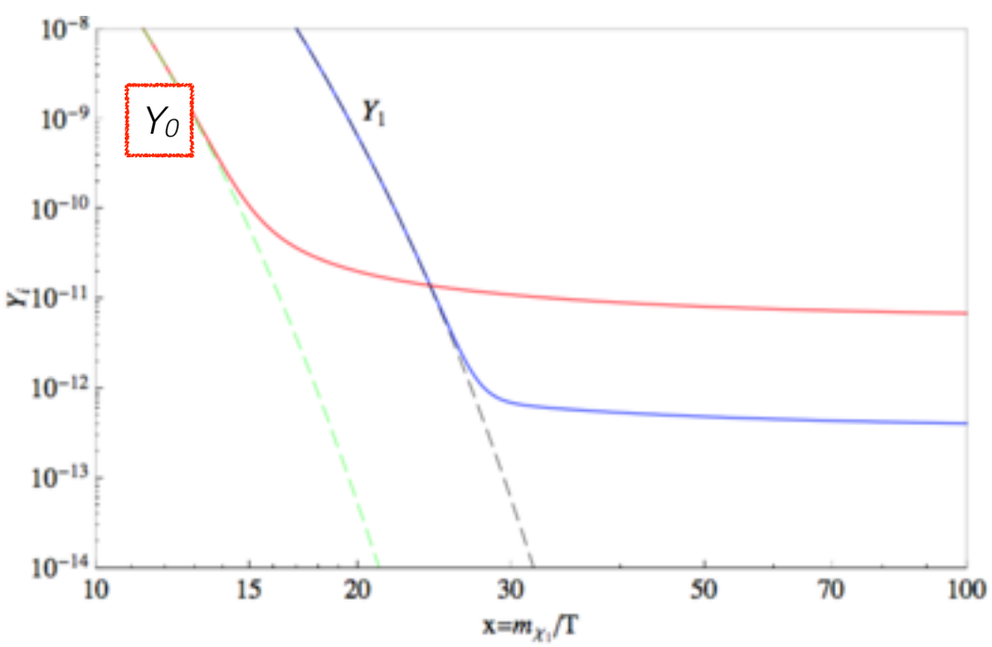

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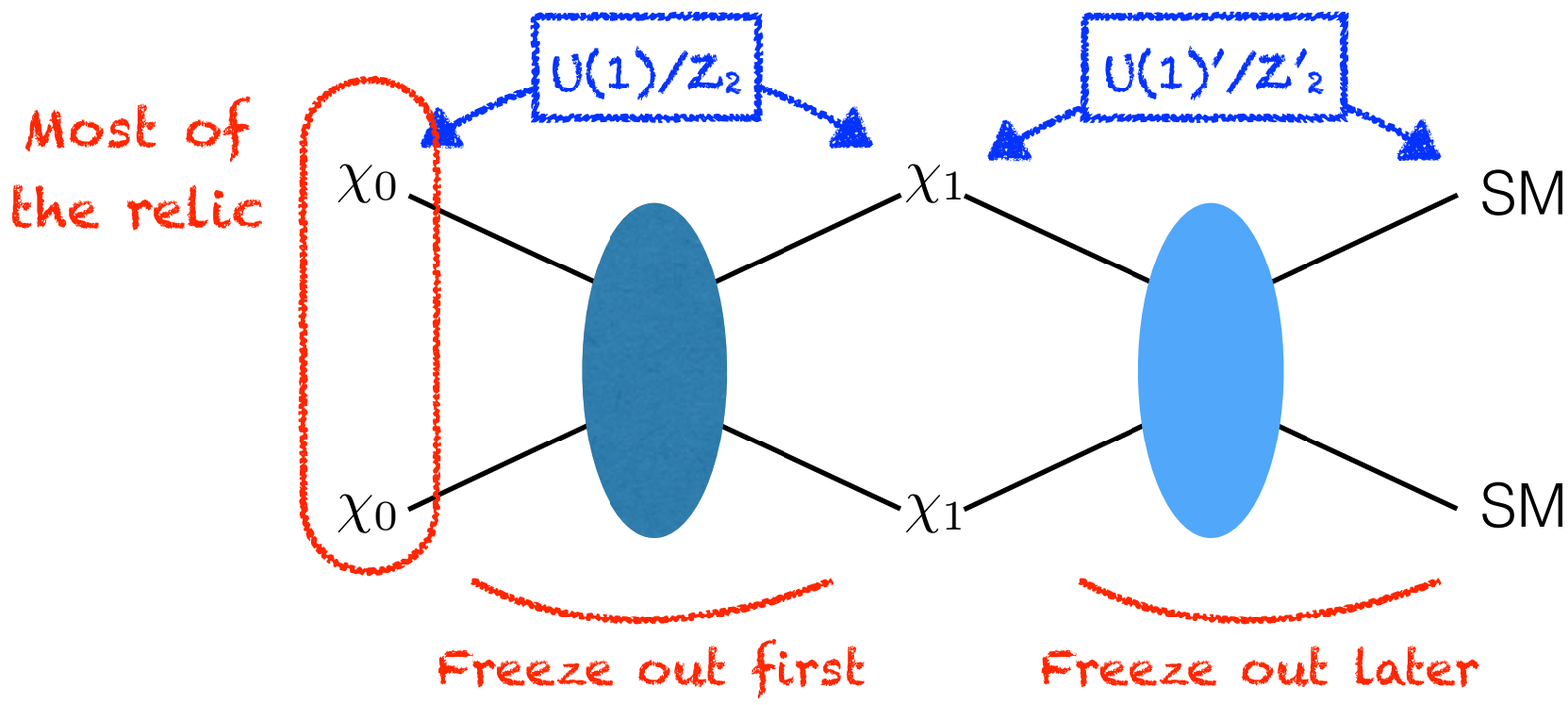

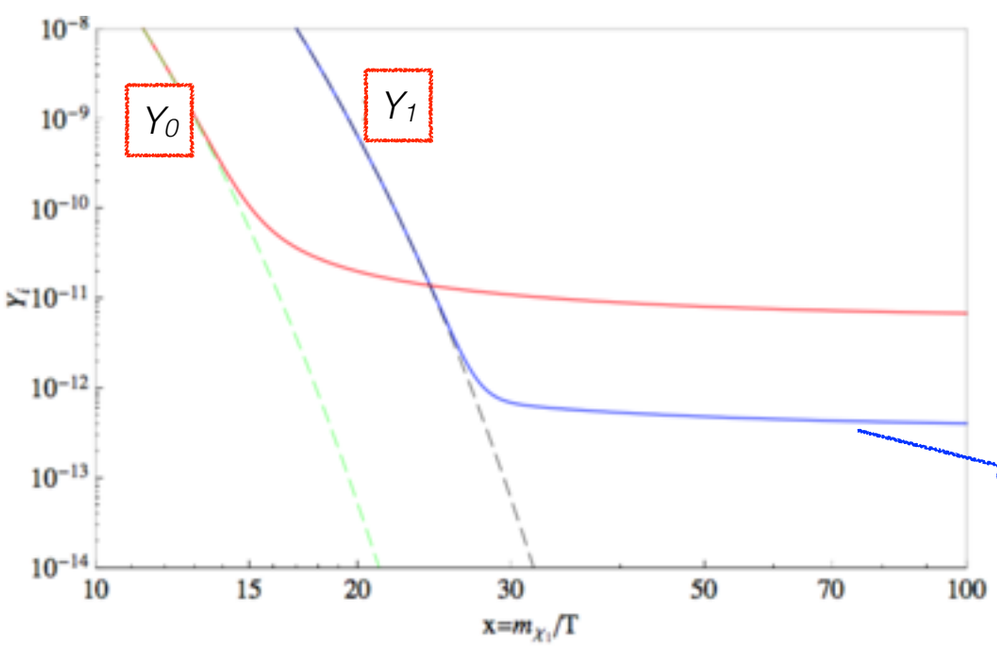

Belanger, Park, 1112.4491

Assisted freeze-out mechanism

non-relativistic relic χ_1 (negligible)

$Y_0 \gg Y_1$

Multi-component BDM

- χ_0 : gravitationally WIMP accumulated
  (GC, Sun, dSphs)

- $\chi_0 \chi_0 \rightarrow \chi_1 \chi_1$ (current universe) relativistic

  ※ relic χ_1 is non-relativistic

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Observe relativistic χ_1 scattering with target with $E > E_{th}$
(indirect detection of χ_0)

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Flux of χ_1 $\simeq 1.6 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \times \left(\frac{\langle \sigma v \rangle_{0\to 1}}{5 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}} \right) \times \left(\frac{100\,\mathrm{GeV}}{m_0} \right)^2$

Assume: NFW

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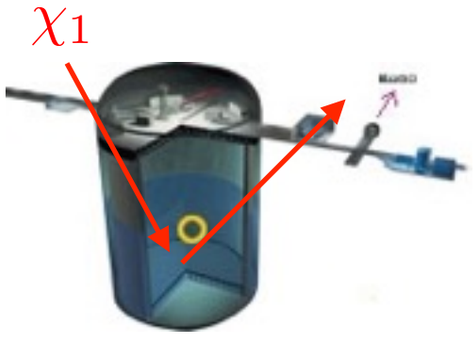
Assume: NFW

Fixed ~ 1 if s-channel annihilation dominates

10,000 times smaller than the flux of atmospheric neutrino

Huge detector if $m_{\chi 0} \gtrsim O(10\ \text{GeV})$

Large volume neutrino experiments



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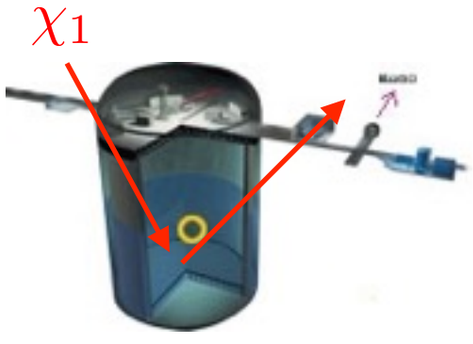


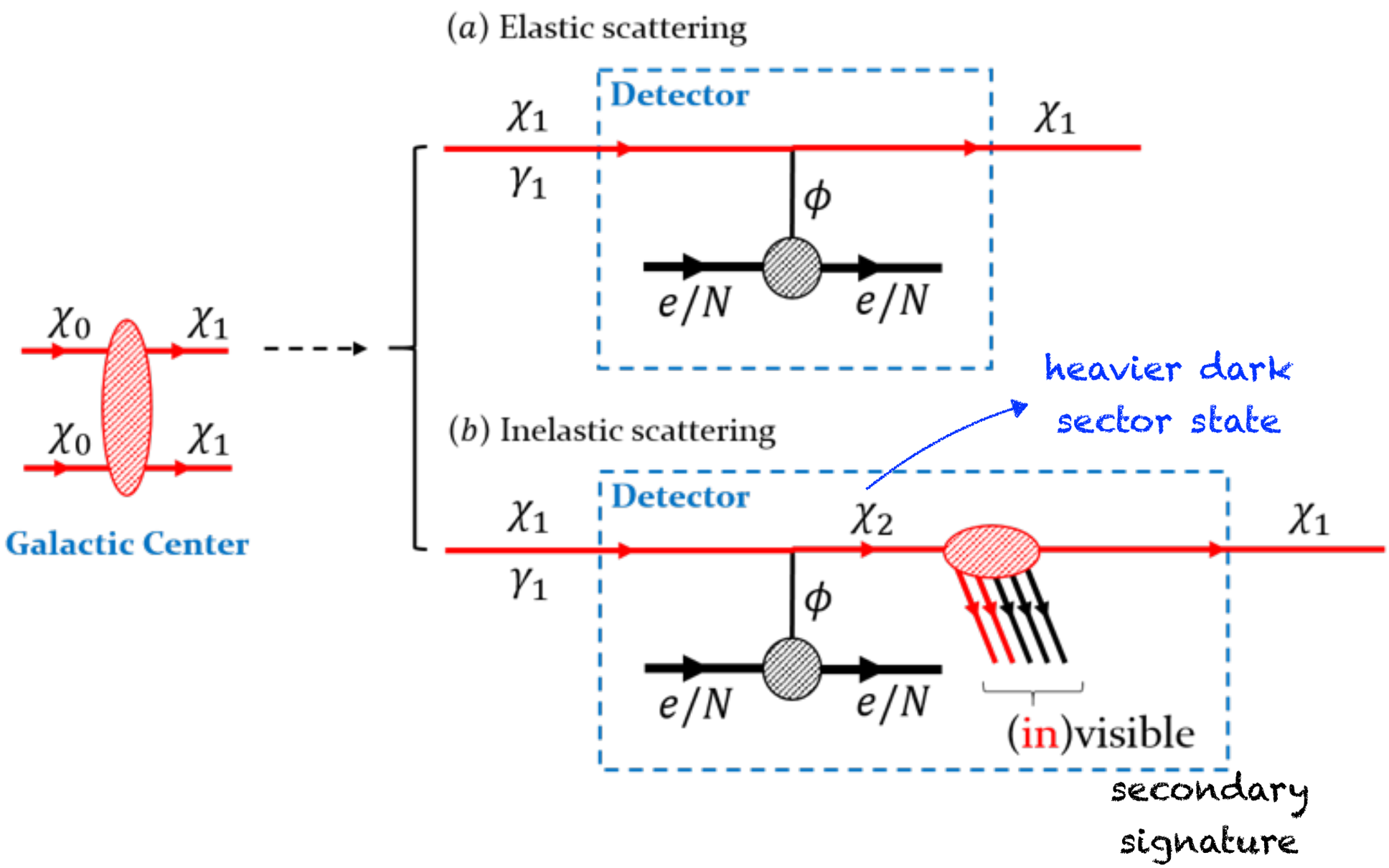
Subtraction of
major background (ν)

True for any BDM models

- Directionality information:
  e.g., GC, Sun, dSphs
  1405.7370 1410.2246 1610.03486
  1611.09866 1411.6632 1804.07302
- Signal with unique feature

Open up novel possibilities of BDM search in many experiments

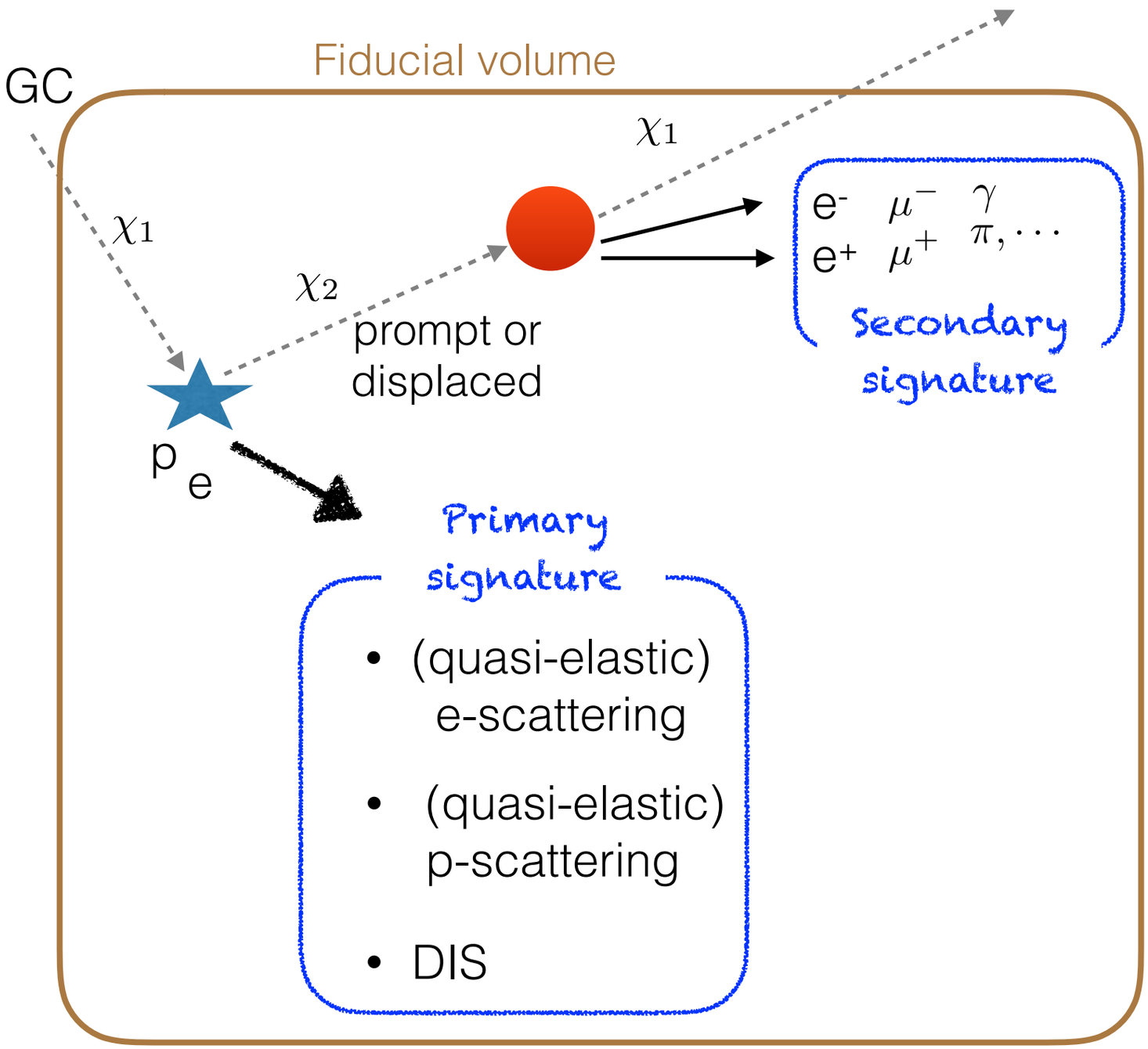
Inelastic BDM (iBDM)



Kim, Park, **SS**, 1612.06867

Giudice, Kim, Park, **SS**, 1712.07126

Signals at DUNE far detector



- Tracks pop-up inside fiducial volume (depending on parameter choice)
- Track observation & time correlation can reject bkg.
- eBDM: elastic

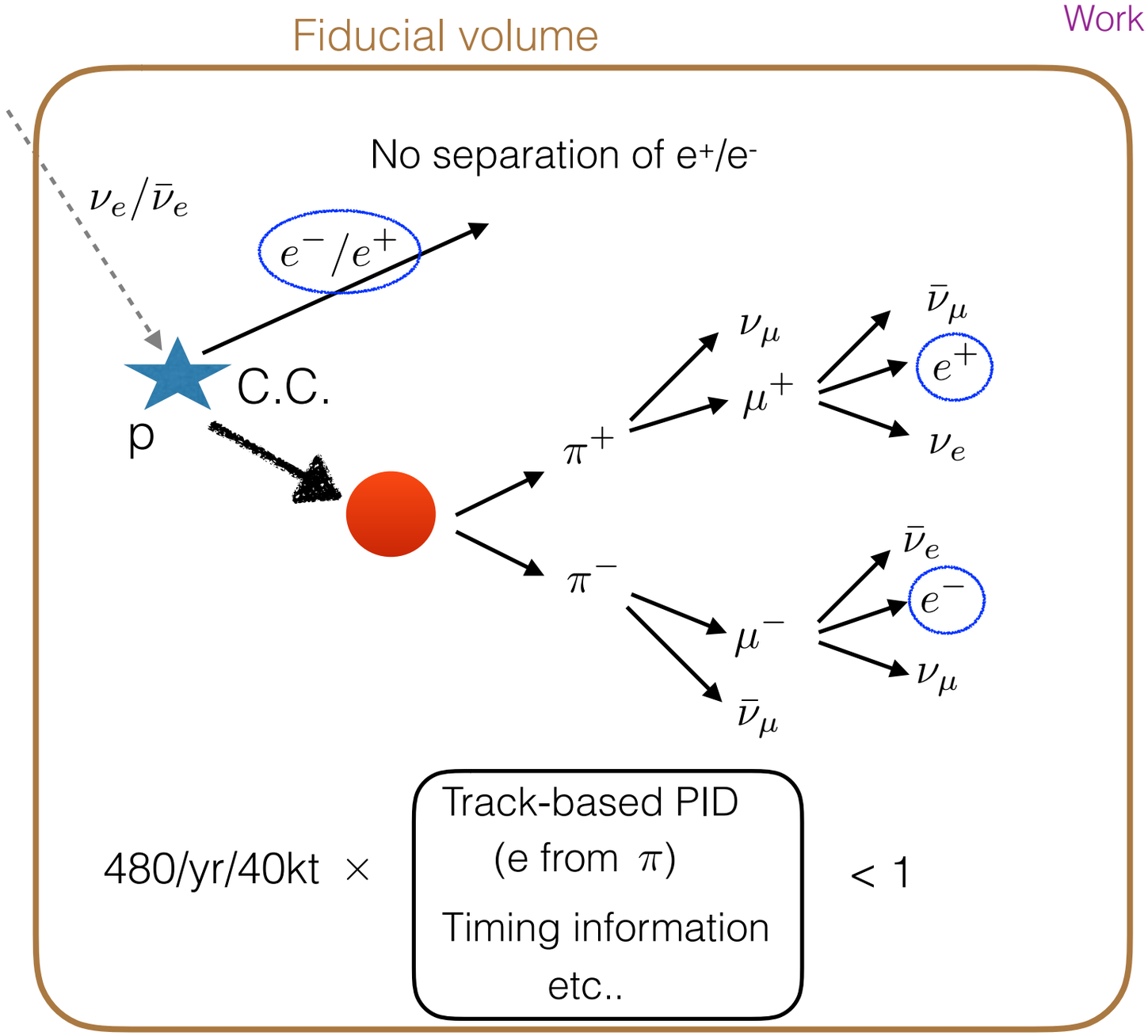
  or loose 2nd signature

  e.g., outside fid. vol. decay invisibly

Background candidate at DUNE far detector

e.g., primary: e-scattering, secondary e^+ e^-

Work in progress



- Other subdominant bkg. negligible

  N.C. events (smaller)

  ν_μ: accompanying μ

  ν_τ: too small flux

- Zero-bkg. is easily achievable

- (quasi-elastic) proton scattering: less bkg.

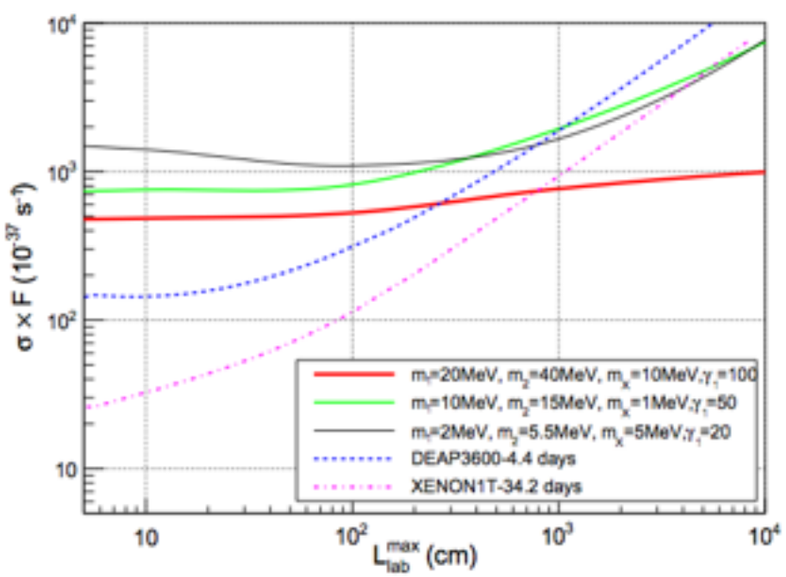
Experimental efforts

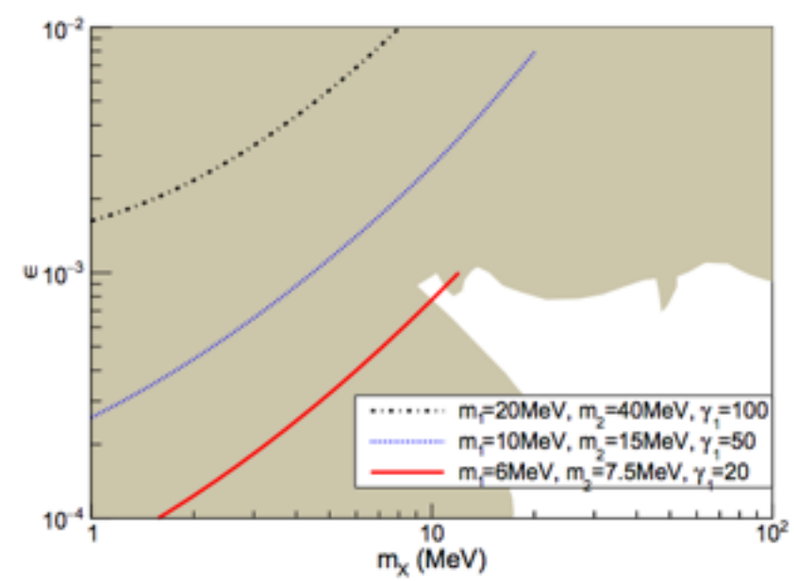
DM direct detection experiments (m_0: sub GeV)

- Theoretical study Giudice, Kim, Park, **SS**, 1712.07126

- COSINE-100 COSINE-100 collaboration, 1811.09344

First direct search for iBDM





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  First direct search for iBDM

Surface ν experiments (Cosmic-ray backgrounds)

- ProtoDUNE Chatterjee, De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, Yu, 1803.03264 (PRD 98, 075027)

  Proposal submitted to ProtoDUNE collaboration (first NP search at PD)

- Short-Baseline Neutrino program (ICARUS, MicroBooNE, SBND)
  Kim, Kong, Park, **SS**, 1804.07302 (eBDM using Earth shielding)

  Discussion with ICARUS (for iBDM, Gran Sasso + future)

Experimental efforts

Underground ν experiments

- DUNE Kim, Park, **SS**, work in progress with experimentalists

  DUNE TDR

- Summary of possible phenomenology in other experiments

  Kim, Machado, Park, **SS**, 1812.xxxxx

  Hyper-Kamiokande, IceCube, DarkSide-20k, ……

Reference Model

Dark photon (X_μ) mediator

(Pseudo-) Dirac fermionic DM

Kim, Park, **SS**, 1612.06867

Giudice, Kim, Park, **SS**, 1712.07126

$$\mathcal{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{11} \bar{\chi}_1 \gamma^\mu \chi_1 X_\mu + g_{12} \bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + \text{h.c.}$$

$\downarrow$ kinetic mixing

$\downarrow$ eBDM

$\downarrow$ iBDM

cf inelastic DM hep-ph/0101138

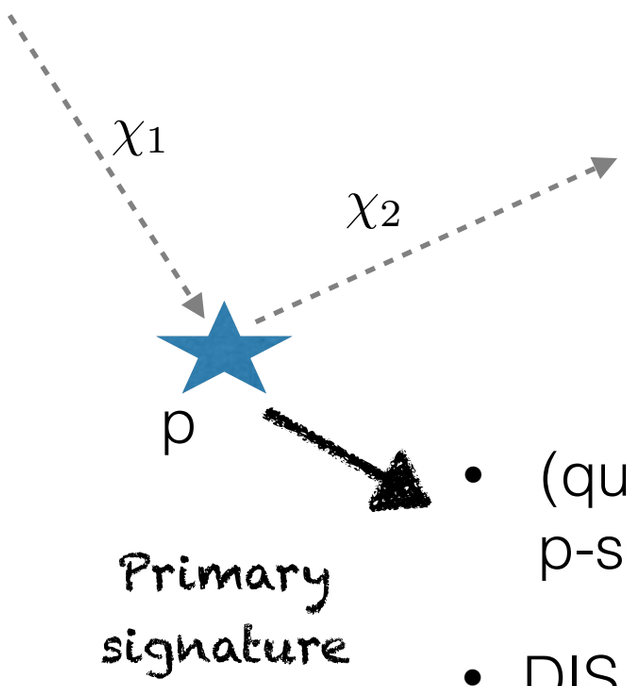
iDM + de-excitation (in the universe) astro-ph/0702587 0903.1037 1309.0825

iDM at the LHC 1109.4144

Phenomenology at fixed target experiments 1312.1363 1403.6826

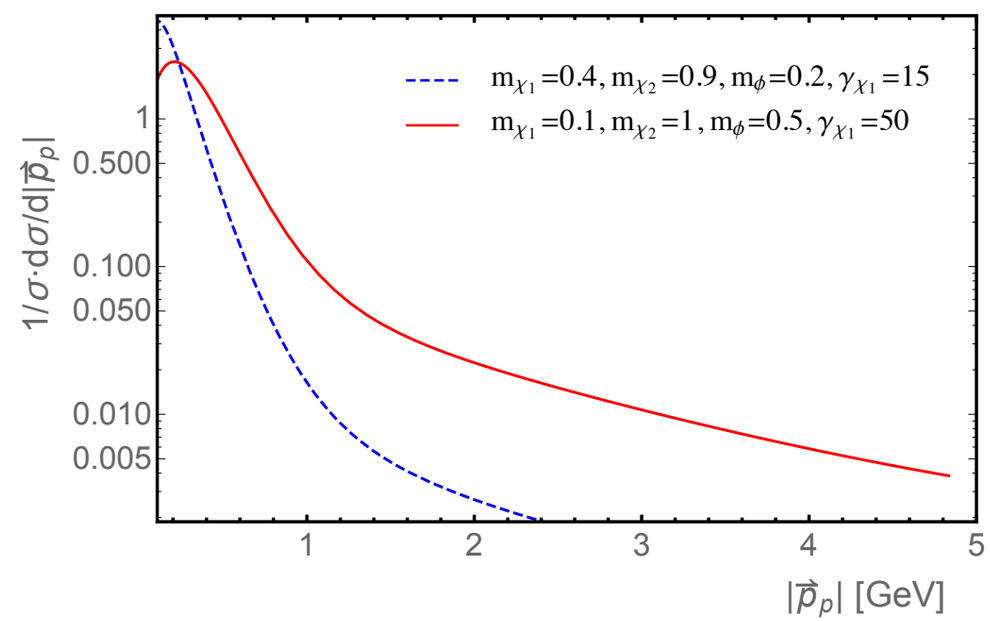
Signals at DUNE far detector: p vs DIS

(quasi-elastic) p-scattering vs DIS



- (quasi-elastic) p-scattering
- DIS

Kim, Park, **SS**, 1612.06867



PRD79, 112010 (2009)

- Differential cross section peaks ≪ 1 GeV: the exact value not important

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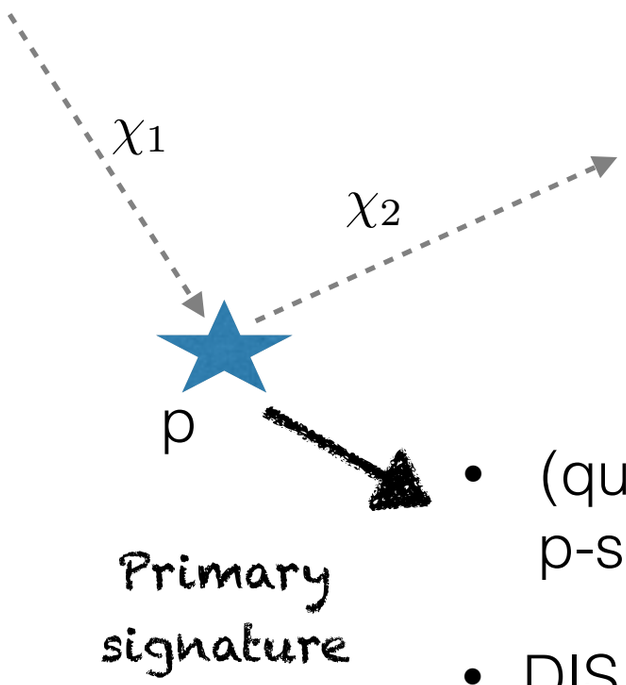

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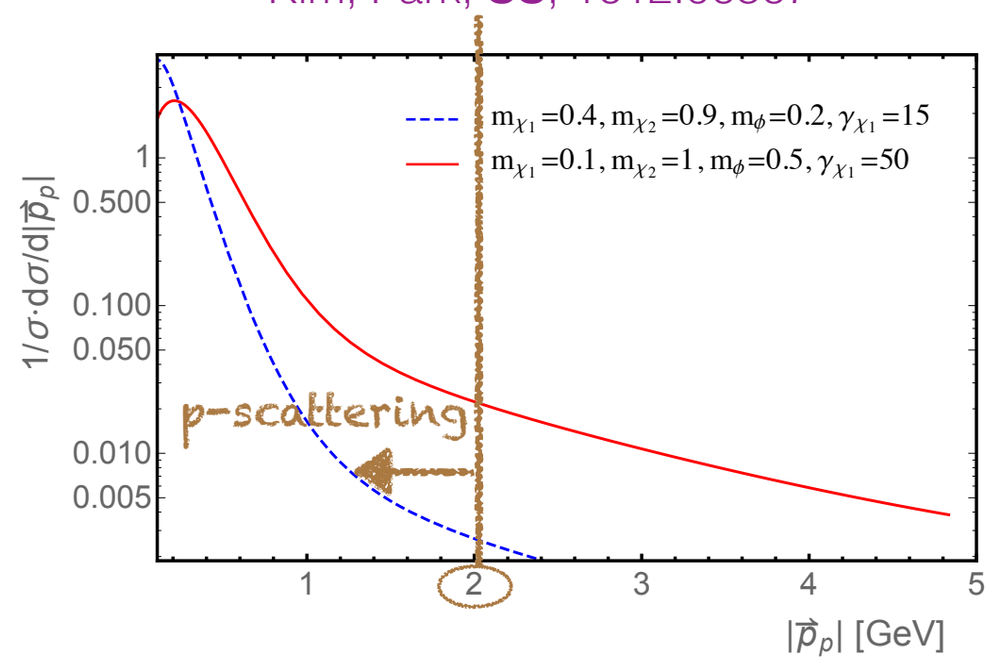
Kim, Park, **SS**, 1612.06867



- Super-Kamiokande simulation study: 50% of the events accompany π^0 or charged secondary p_p ~ 2 GeV

  PRD79, 112010 (2009)

- Differential cross section peaks ≪ 1 GeV: the exact value not important

Signals at DUNE far detector: p vs DIS

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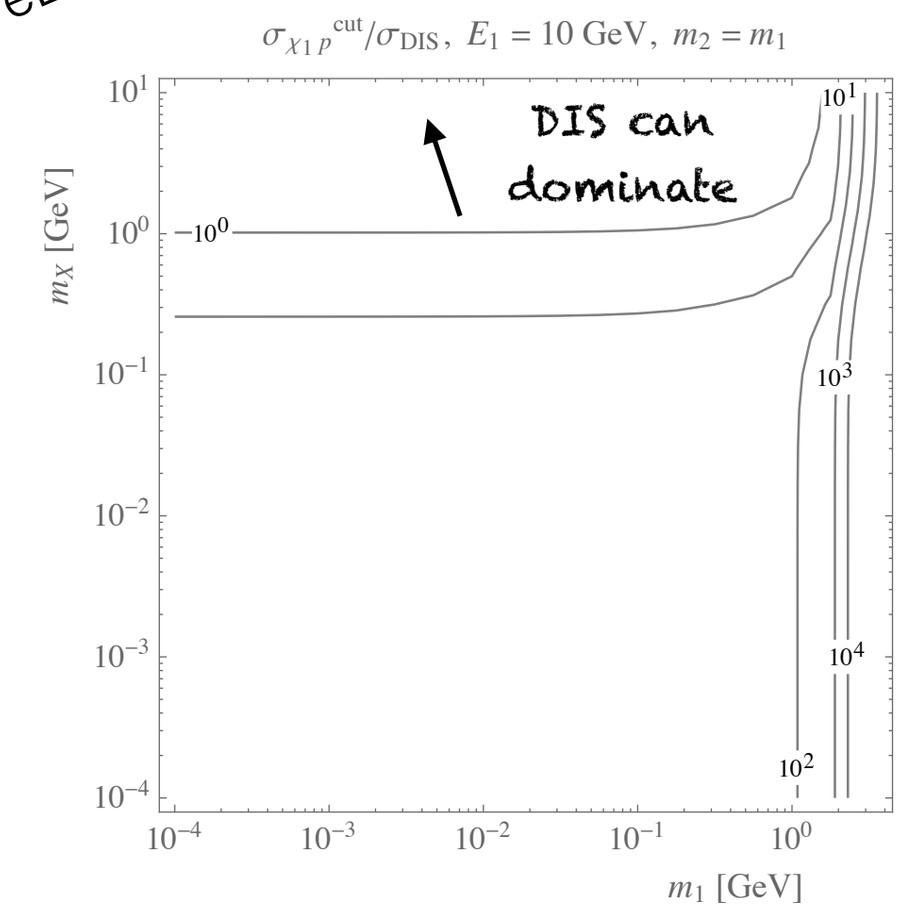
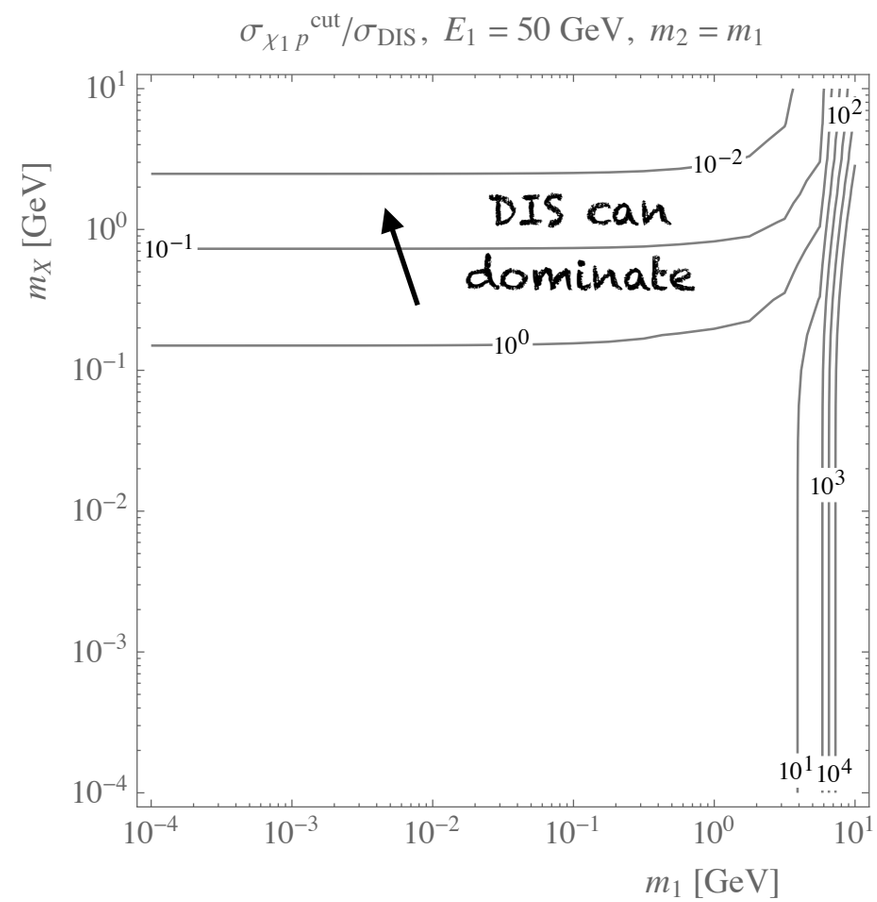
Kim, Machado, Park, **SS**, 1812.xxxxx

eBDM





- Penalty on p-scattering E_{th} > 21 MeV (conservative): $\sigma^{\rm cut}_{\chi_1 p}$

  ArgoNeuT, 1405.4261

- Still, p-scattering dominates for m_X < 1 GeV

Signals at DUNE far detector: p vs DIS

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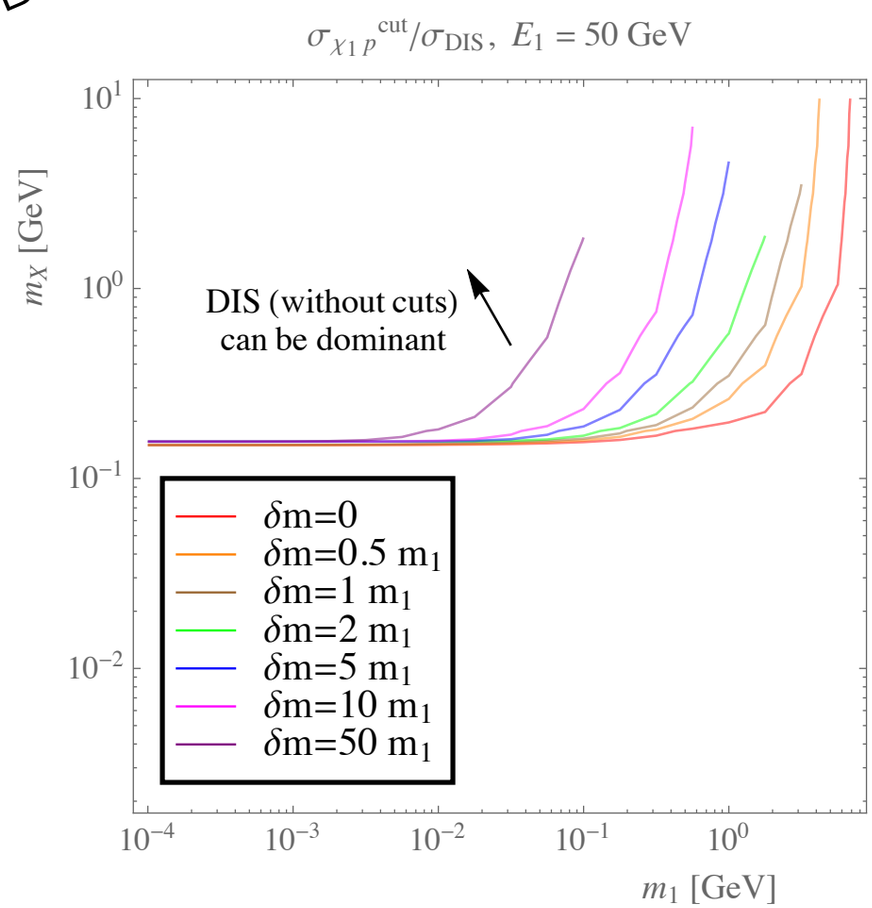
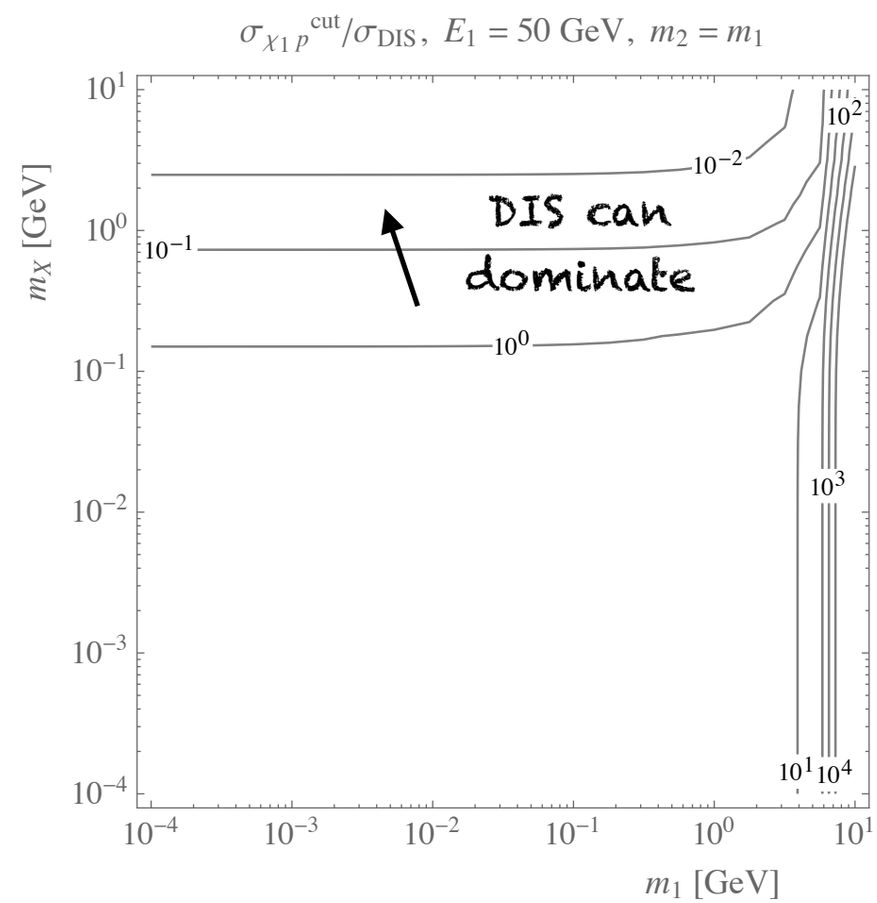
Kim, Machado, Park, **SS**, 1812.xxxxx

iBDM





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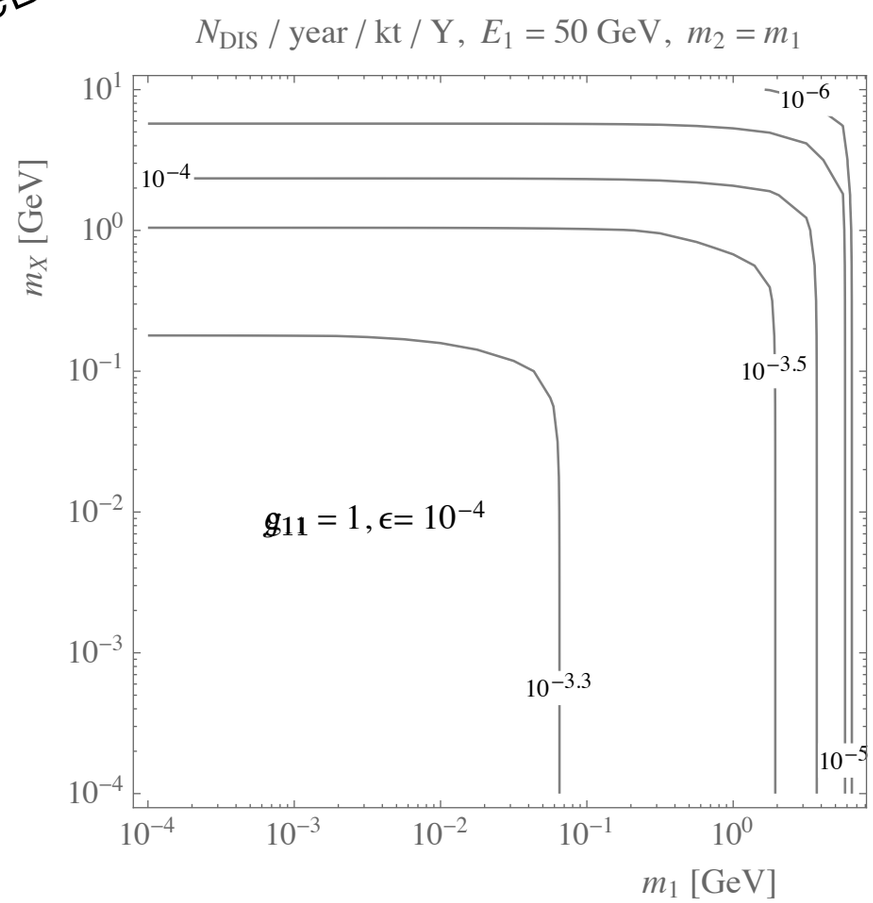

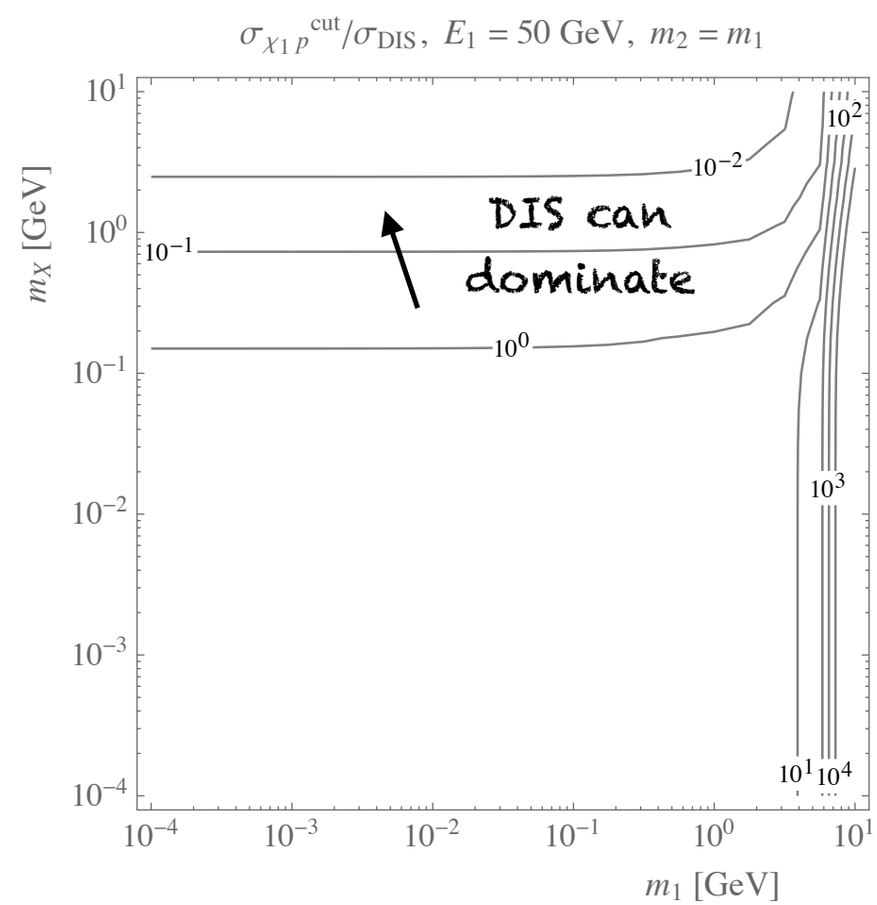

- Number of DIS induced events (Y = atomic number/atomic weight)

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Kim, Machado, Park, **SS**, 1812.xxxxx

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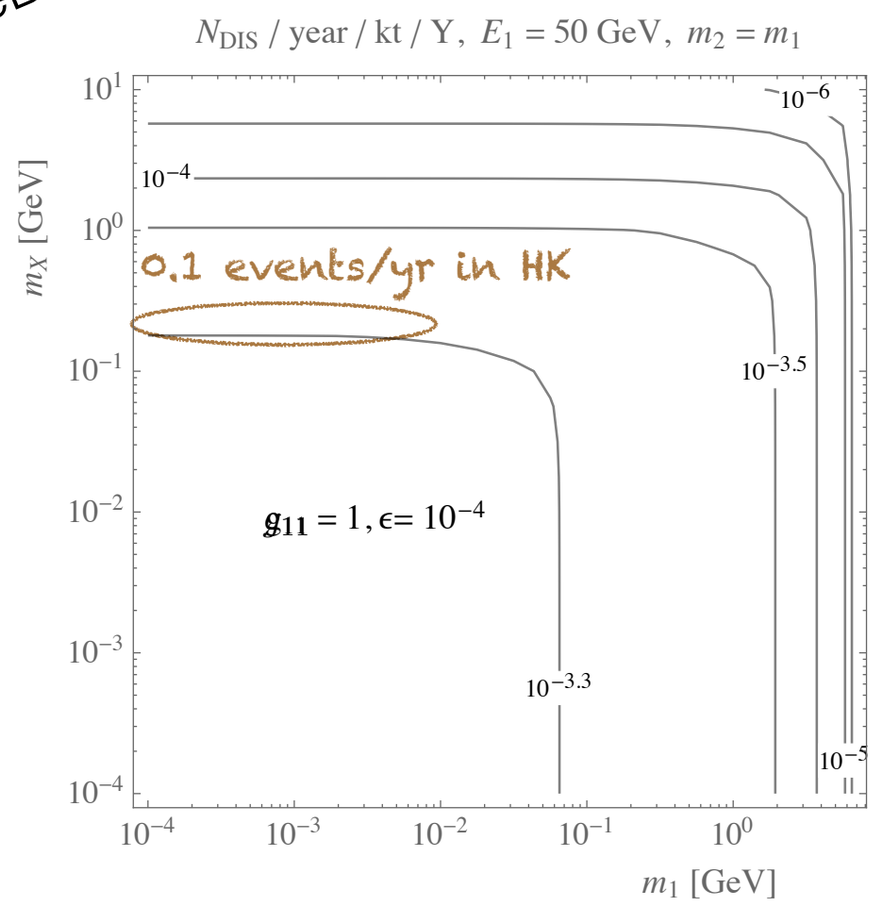
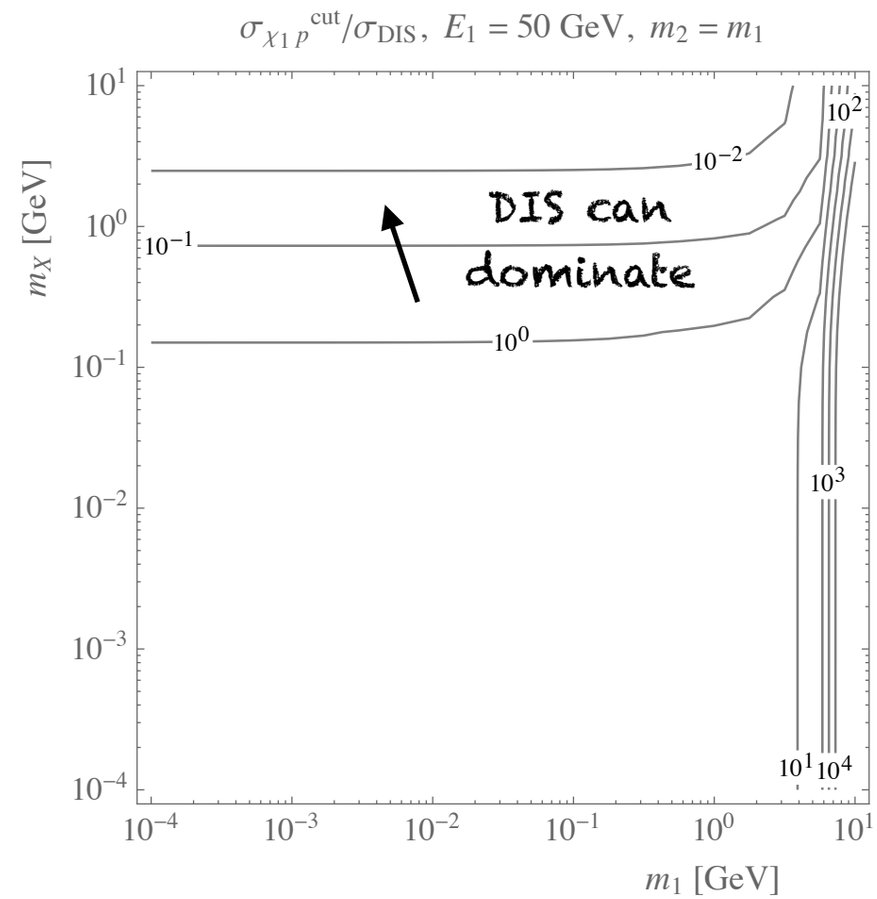




- Number of DIS induced events (Y = atomic number/atomic weight)
- 380kt water (HK) Y=10/18, at most 0.1 events/yr

  No detector effects (hence, realistic number is even smaller)

Signals at DUNE far detector: p vs DIS

(quasi-elastic) p-scattering vs DIS

Kim, Machado, Park, **SS**, 1812.xxxxx

- N_{DIS} negligible unless a much larger detector or flux exists (model dependent)

Josh's talk

- p-scattering dominates for smaller $m_X < 1$ GeV even for $E_1 > 50$ GeV
  (unlike neutrino scattering events: mediator W, Z)

$$\frac{d\sigma_{\chi_1 p}}{dp_p} \propto \frac{1}{(p_p^2 + m_X^2)^2}$$

Differential cross section peaks
$p_p \ll 1$ GeV

$$\frac{d\sigma_{\rm DIS}}{dxdy} \propto \frac{1}{(Q^2 + m_X^2)^2}$$

$$Q > 1.5\,\mathrm{GeV}$$

Signals at DUNE far detector: p vs e

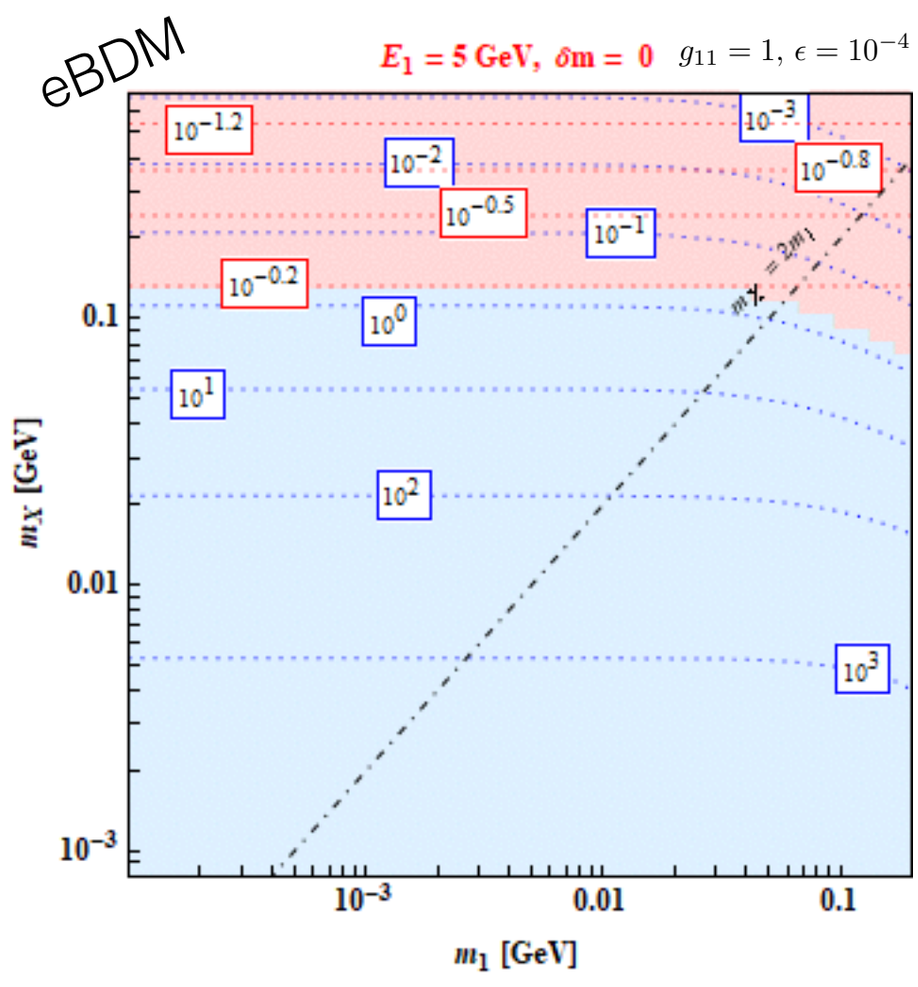
- Theoretical calculation: p-scattering wins unless $m_X \lesssim$ keV
- Realistic effects such as E_{th},angular resolutions, and event acceptance added

i) $p_e > 30$ MeV, $200\,\text{MeV} < p_p < 2\,\text{GeV}$,

ii) $\Delta\theta_{e-i} > 1^\circ$, $\Delta\theta_{p-i} > 5^\circ$ with i denoting the other visible final state particles, and

iii) both primary and secondary vertices should appear in the detector fiducial volume.

iv) Secondary signature: $e^- e^+$



- Red: p-scattering preferred
  Blue: e-scattering preferred
- For smaller m_X, a further suppression of $\sigma_{\chi_1 p}$ by p_p effective

$$\frac{d\sigma_{\chi_1 p}}{dp_p} \propto \frac{1}{(p_p^2 + m_X^2)^2} \qquad \frac{d\sigma_{\chi_1 e}}{dp_e} \propto \frac{1}{(m_e p_e + m_X^2)^2}$$

- Contours: N_{events} by p-scattering (red)
  e-scattering (blue)

  Note: bkg. should be subtracted

Signals at DUNE far detector: p vs e

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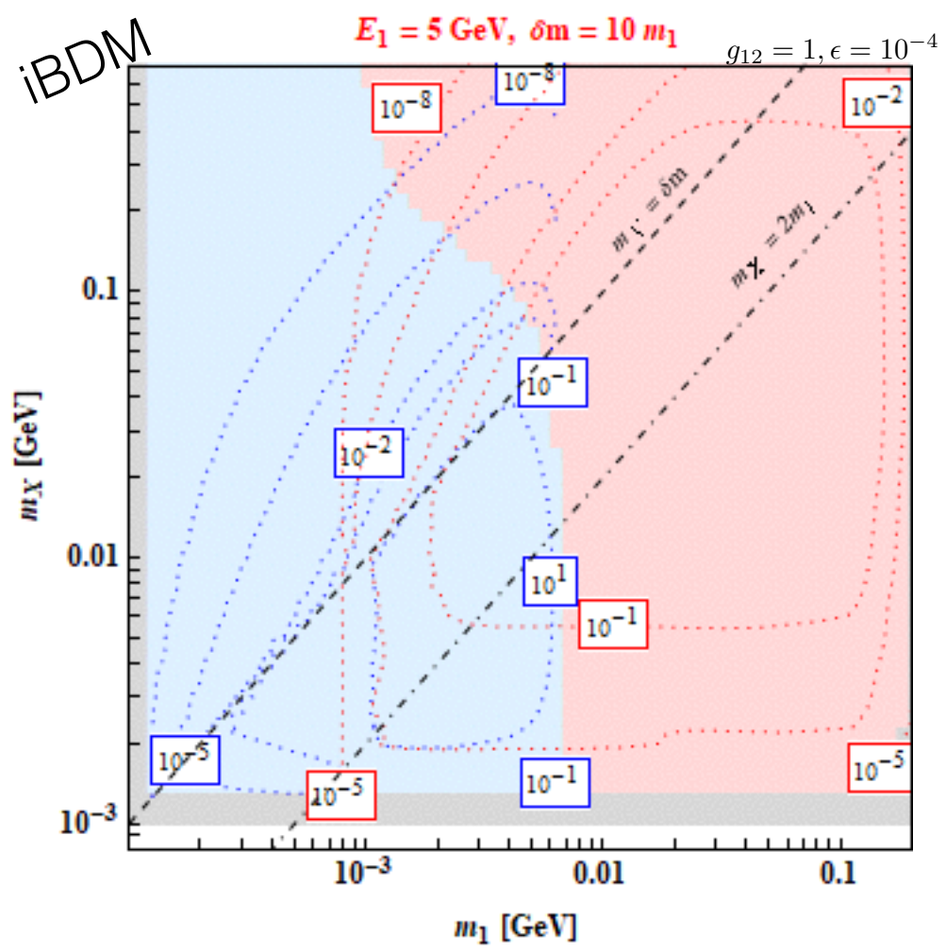

- e-scattering more preferred for smaller m_1: angular cut for secondary $e^- e^+$
  ∵ recoiling p has less energy, i.e., χ_2 has more energy
- e-scattering is limited for larger δm
- gray: $e^- e^+$ is too soft for small δm or m_X

Signals at DUNE far detector: p vs e

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- Realistic effects such as E_{th},angular resolutions, and event acceptance added

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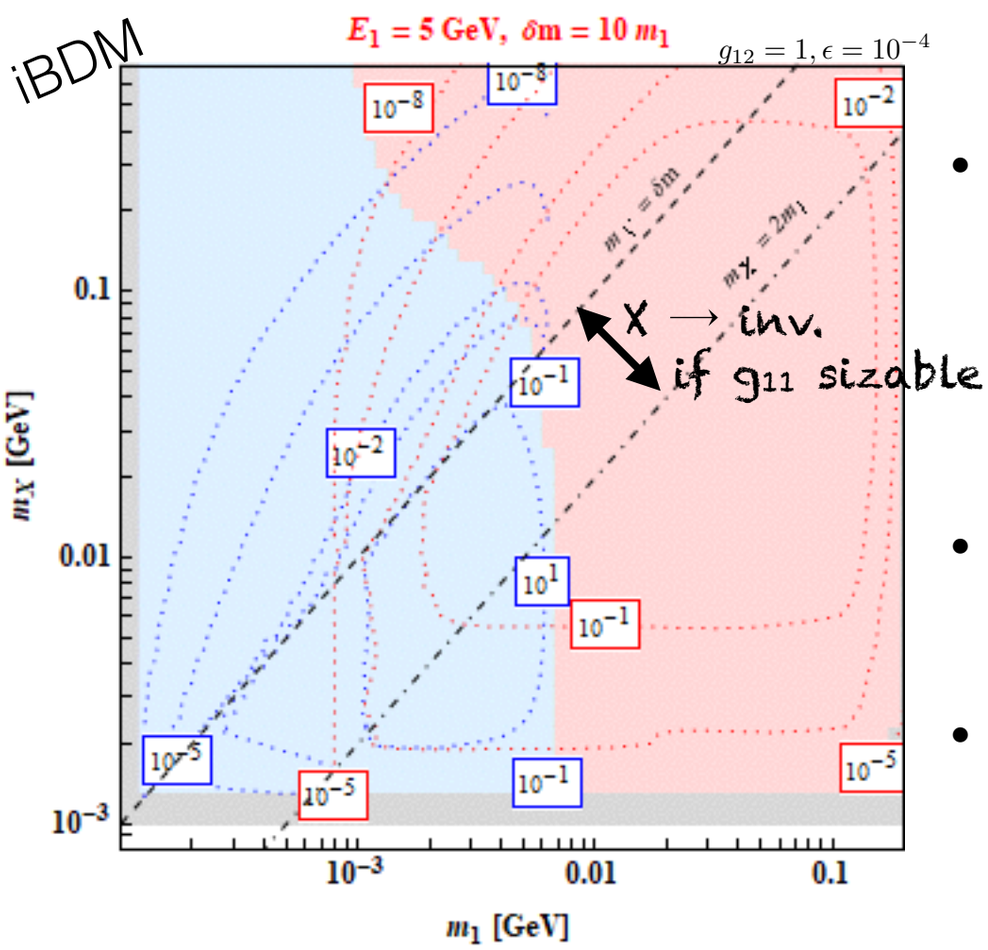
  iv) Secondary signature: $e^- e^+$



- e-scattering more preferred for smaller m_1: angular cut for secondary $e^- e^+$
  ∵ recoiling p has less energy, i.e., χ_2 has more energy
- e-scattering is limited for larger δm
- gray: $e^- e^+$ is too soft for small δm or m_X

Signals at DUNE far detector: p vs e

- Theoretical calculation: p-scattering wins unless mX ≲ keV
- Realistic effects such as E_{th},angular resolutions, and event acceptance added

  i) $p_e > 30$ MeV, $200\,\text{MeV} < p_p < 2\,\text{GeV}$,

  ii) $\Delta\theta_{e-i} > 1^\circ$, $\Delta\theta_{p-i} > 5^\circ$ with i denoting the other visible final state particles, and

  iii) both primary and secondary vertices should appear in the detector fiducial volume.

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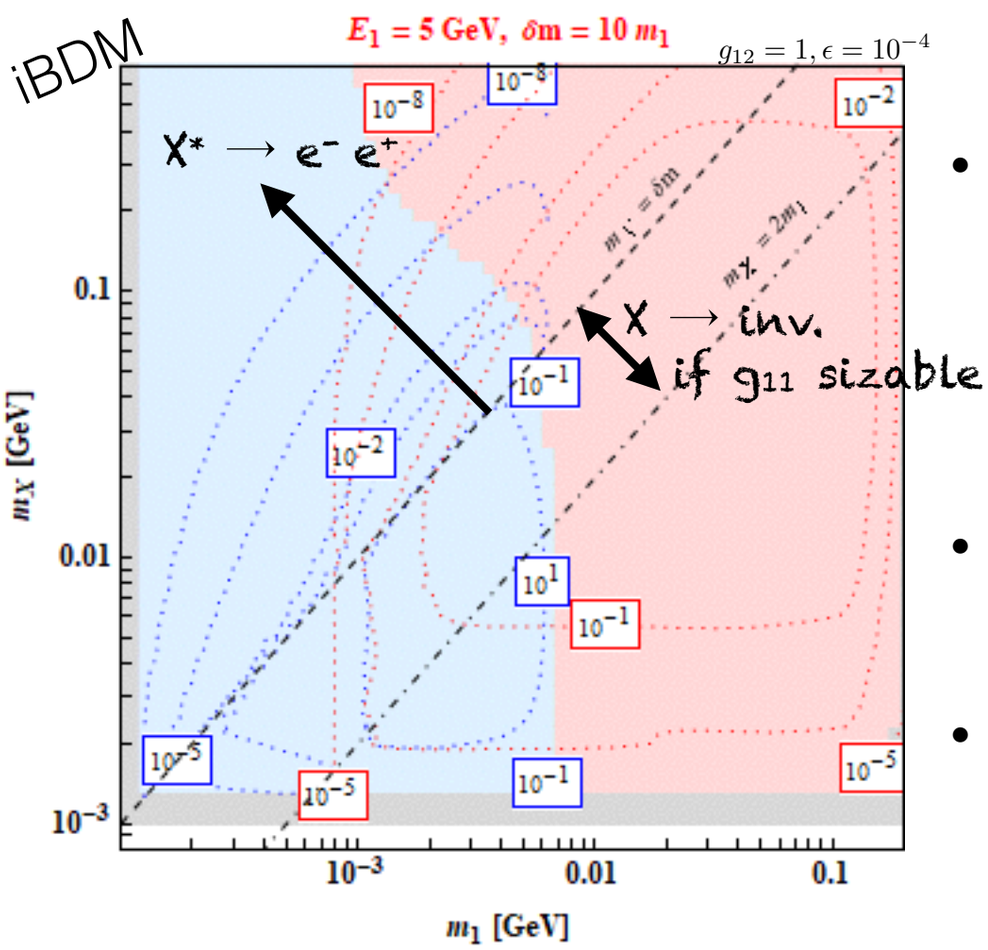

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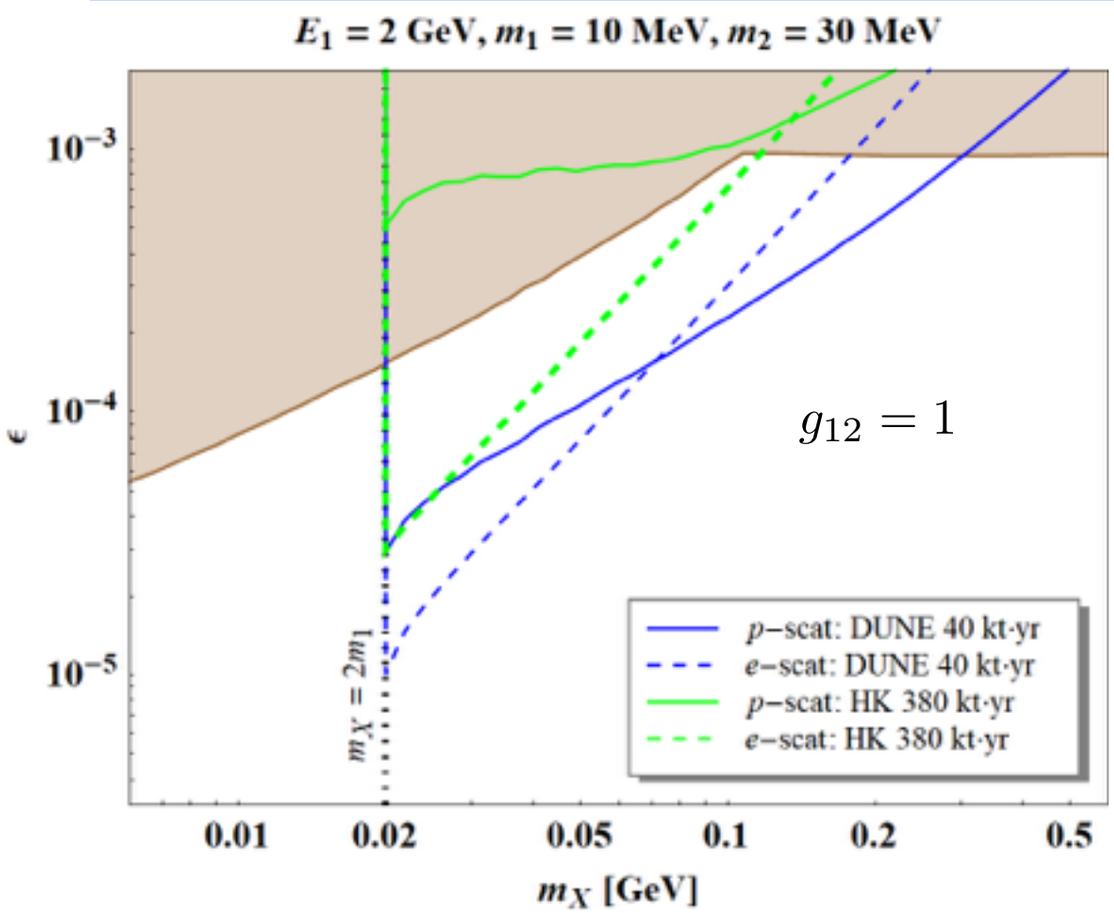
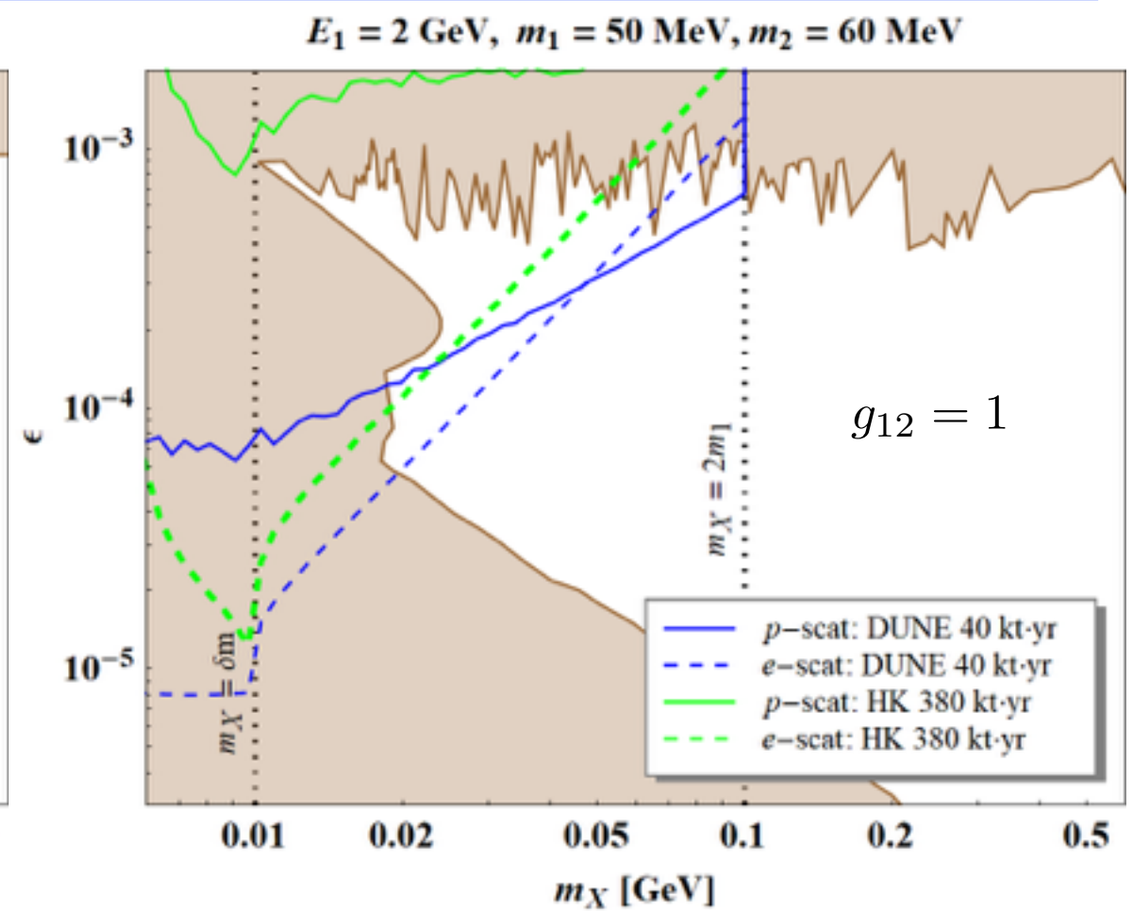
Sensitivities at DUNE far detector



$m_X > 2m_1 \quad \chi_2 \to X^* \chi_1 \to e^+ e^- \chi_1$



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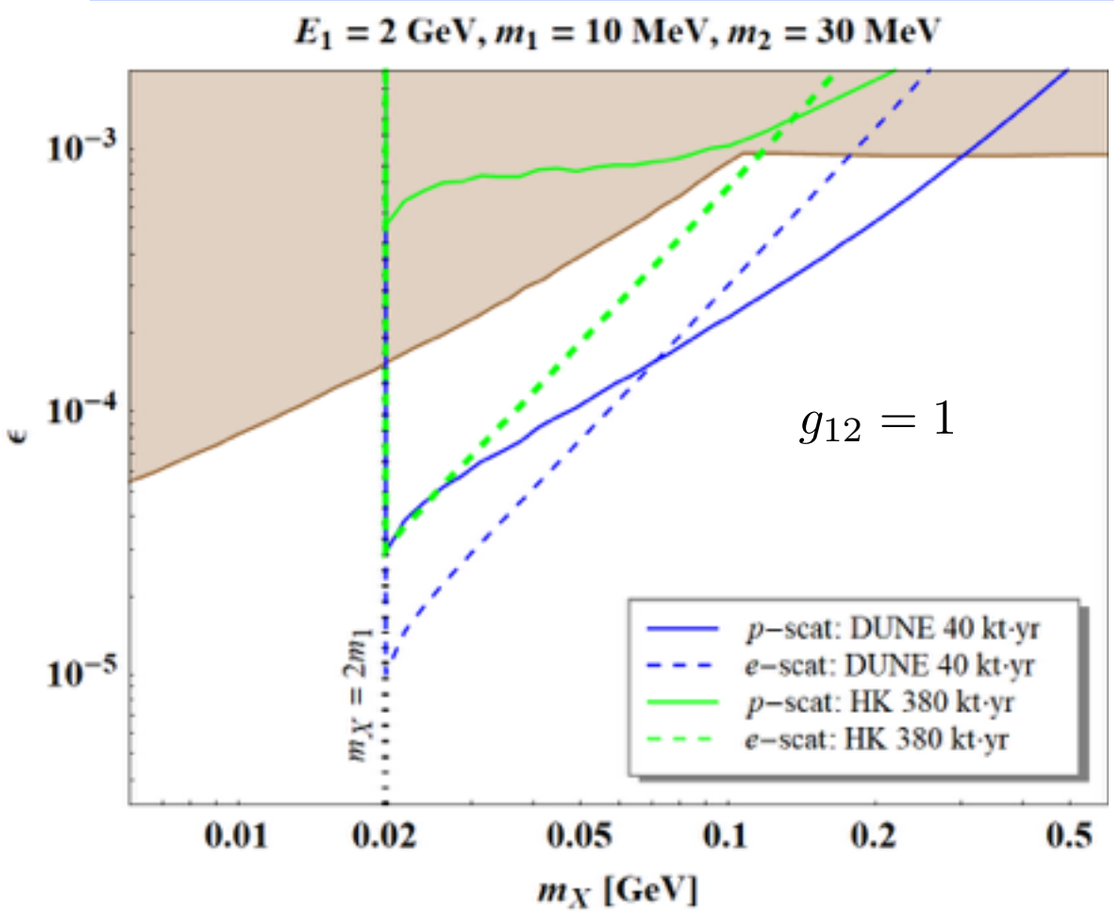

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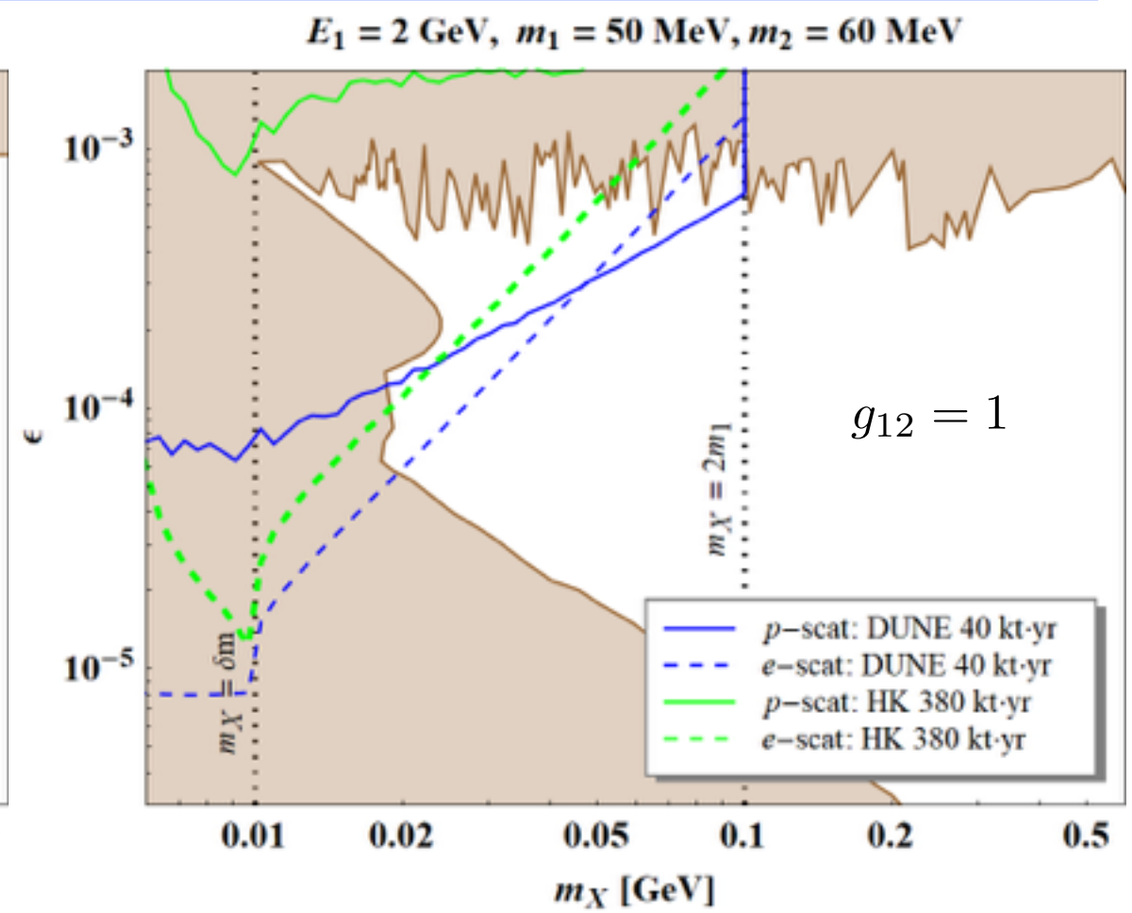

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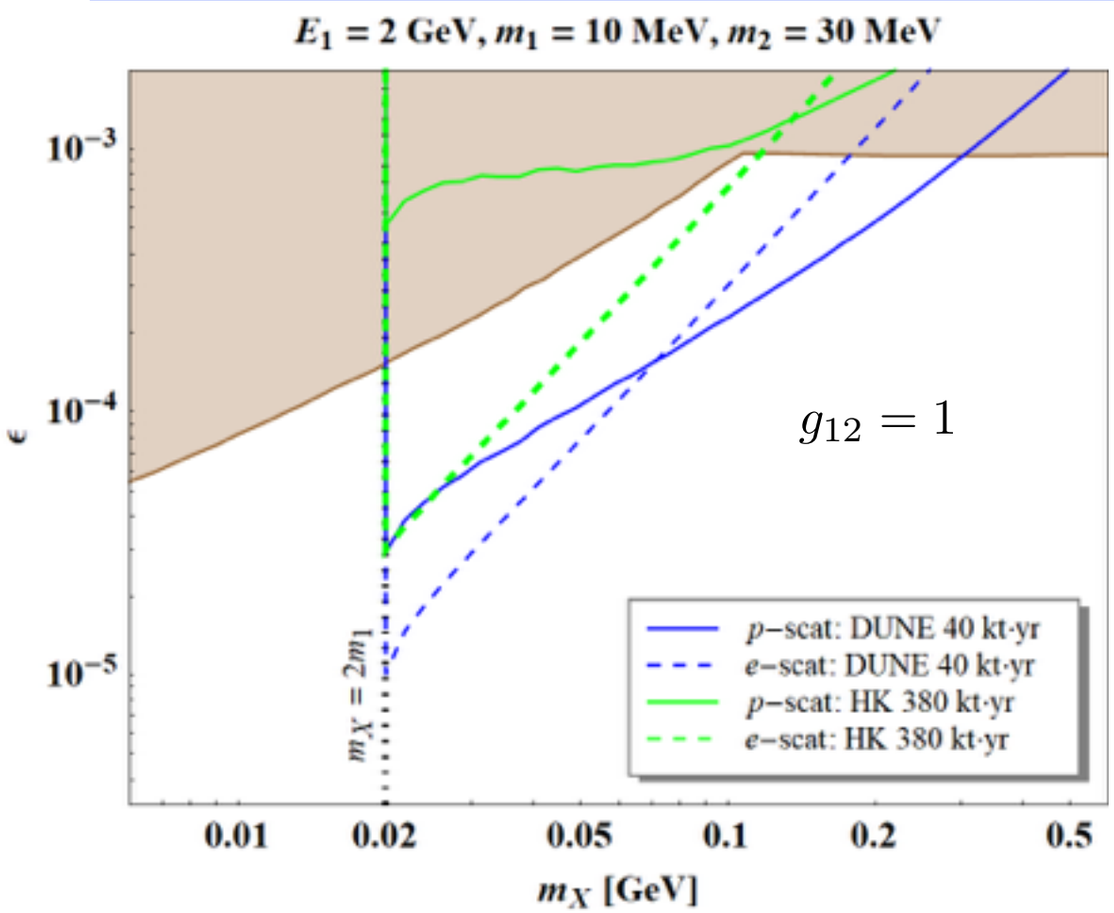
- p-scattering larger than e-scattering as increasing m_X
- DUNE preferred parameter region over HK (lower E_{th}, better resolution) although the size is ~ 1/10
- Difference huge for p-scattering

Sensitivities at DUNE far detector



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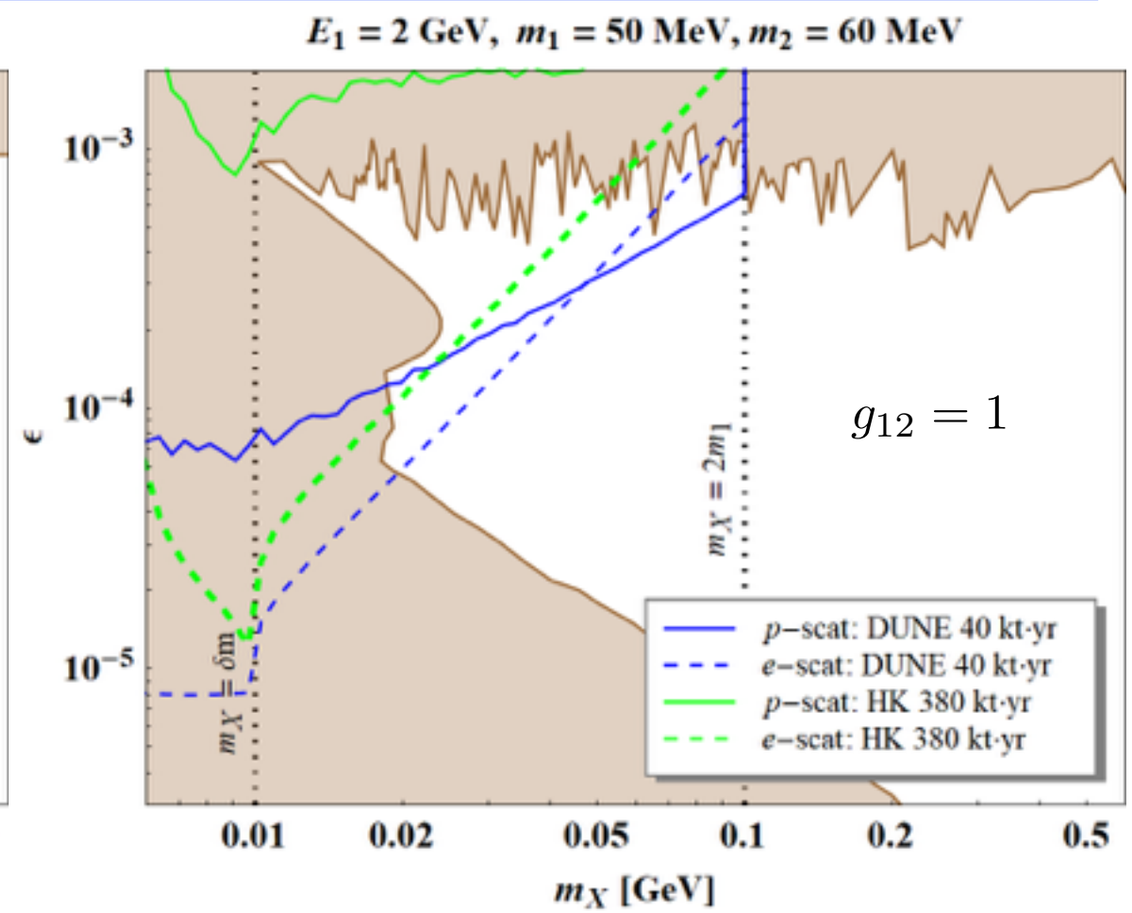

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- DUNE preferred parameter region over HK (lower E_{th}, better resolution) although the size is ~ 1/10

  Better for larger E_1
- Difference huge for p-scattering

Conclusions

- Searches for iBDM (+ eBDM) provide a new opportunity of DM search in DUNE far detectors

- Signal category: primary (e-scattering, p-scattering, DIS)
  secondary (visible SM particles e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, …)

- For iBDM, zero-background may be easily achievable

- Sensitivity at DUNE can be better than other experiments (e.g., HK) in some parameter space (in particular for p-scattering)

- Results will be in the follow-up papers and DUNE TDR

- Experimental observation signal by signal?
  (any theoretical model sharing a single signal)

Model independent reach

$$N_{\text{sig}} = \sigma_\epsilon \cdot \mathcal{F} \cdot A \cdot t_{\text{exp}} \cdot N_e$$

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

) Controllable

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- function of mean decay length of χ_2

$$\ell_{2,\rm lab} = \frac{c\gamma_2}{\Gamma_2} \sim 16.2\,{\rm cm} \times \left(\frac{10^{-3}}{\epsilon}\right) \times \left(\frac{1}{g_{12}}\right)^2 \times \left(\frac{m_X}{30\,{\rm MeV}}\right)^4 \left(\frac{10\,{\rm MeV}}{\delta m}\right)^5 \times \frac{\gamma_5}{10}$$

- function of detector geometry: event generation (cumulatively isotopic flux of χ_1)

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$\sigma^{\rm fid}$ or $\sigma^{\rm vis}$

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with signal efficiency

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Sensitivity: prompt decay/elastic scattering

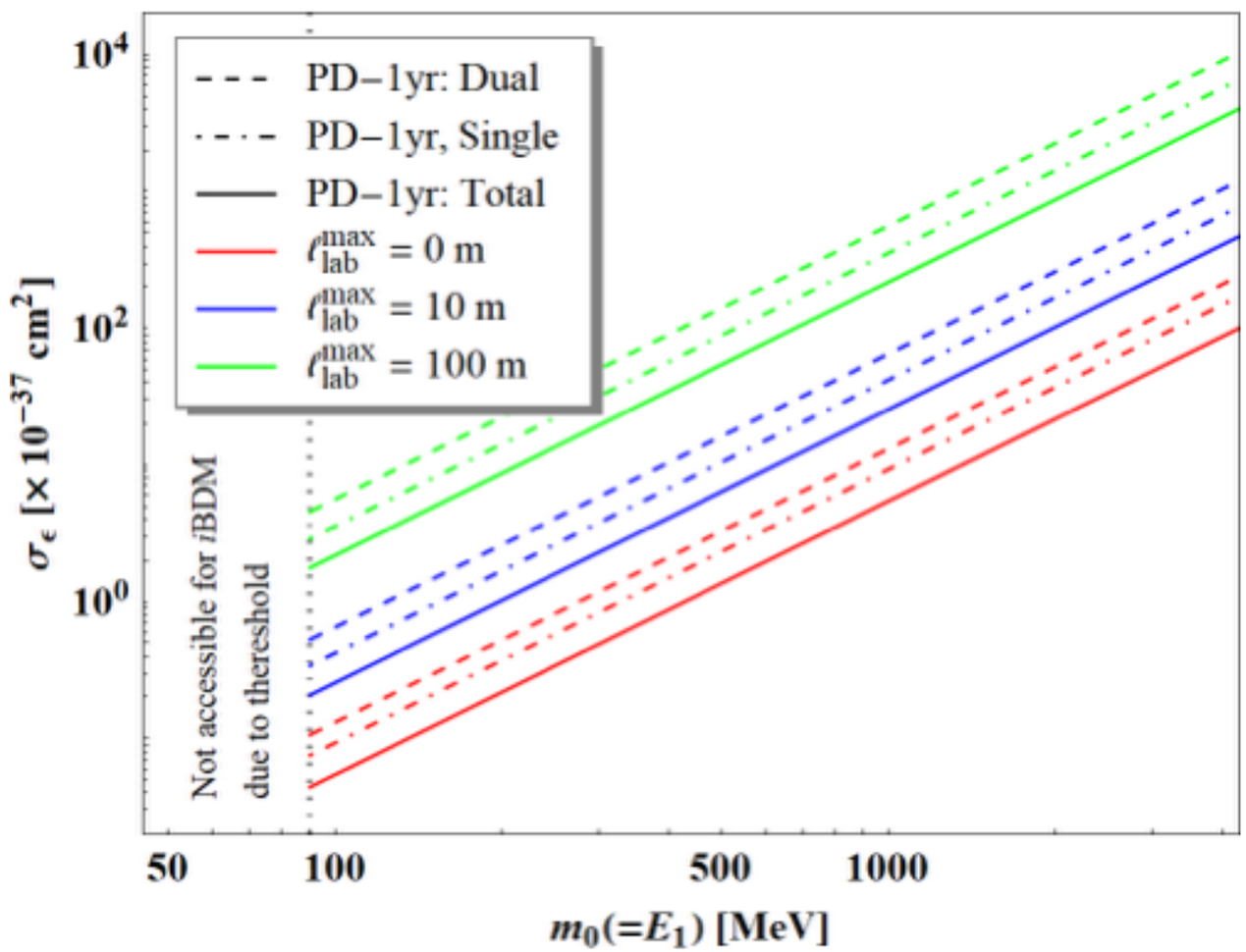
zero-background assumption
(90% C.L.)

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

$$\mathcal{F} \propto \frac{\langle \sigma v \rangle_{\chi_0\chi_0 \to \chi_1\chi_1}}{m_0^2}$$

Fix (then use NFW)

$$\langle \sigma v \rangle_{\chi_0\chi_0 \to \chi_1\chi_1} = 5 \times 10^{-26}\,{\rm cm}^3{\rm s}^{-1}$$



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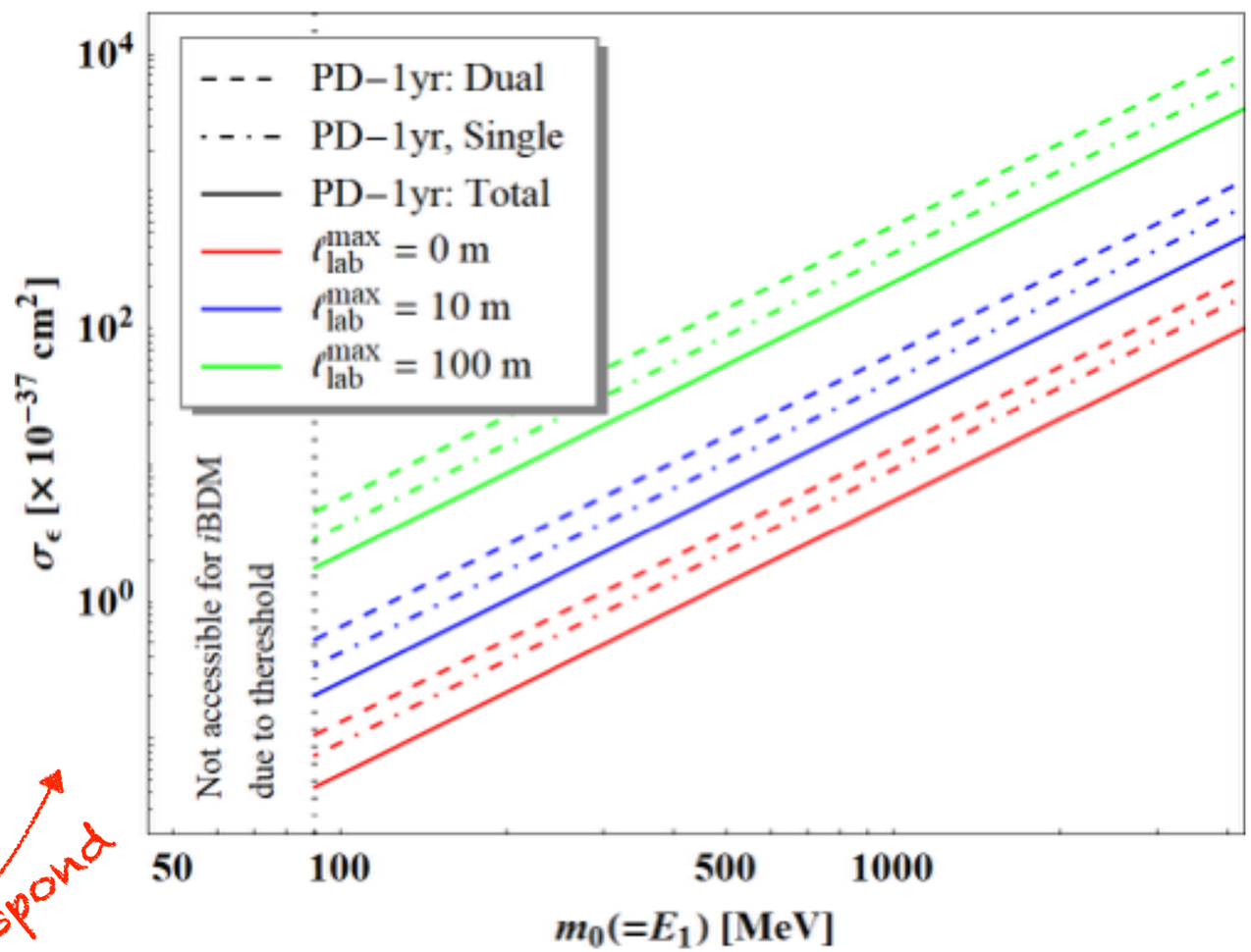
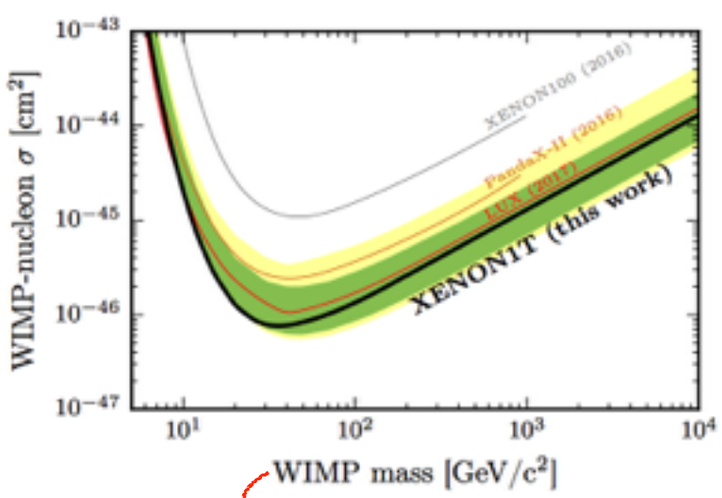


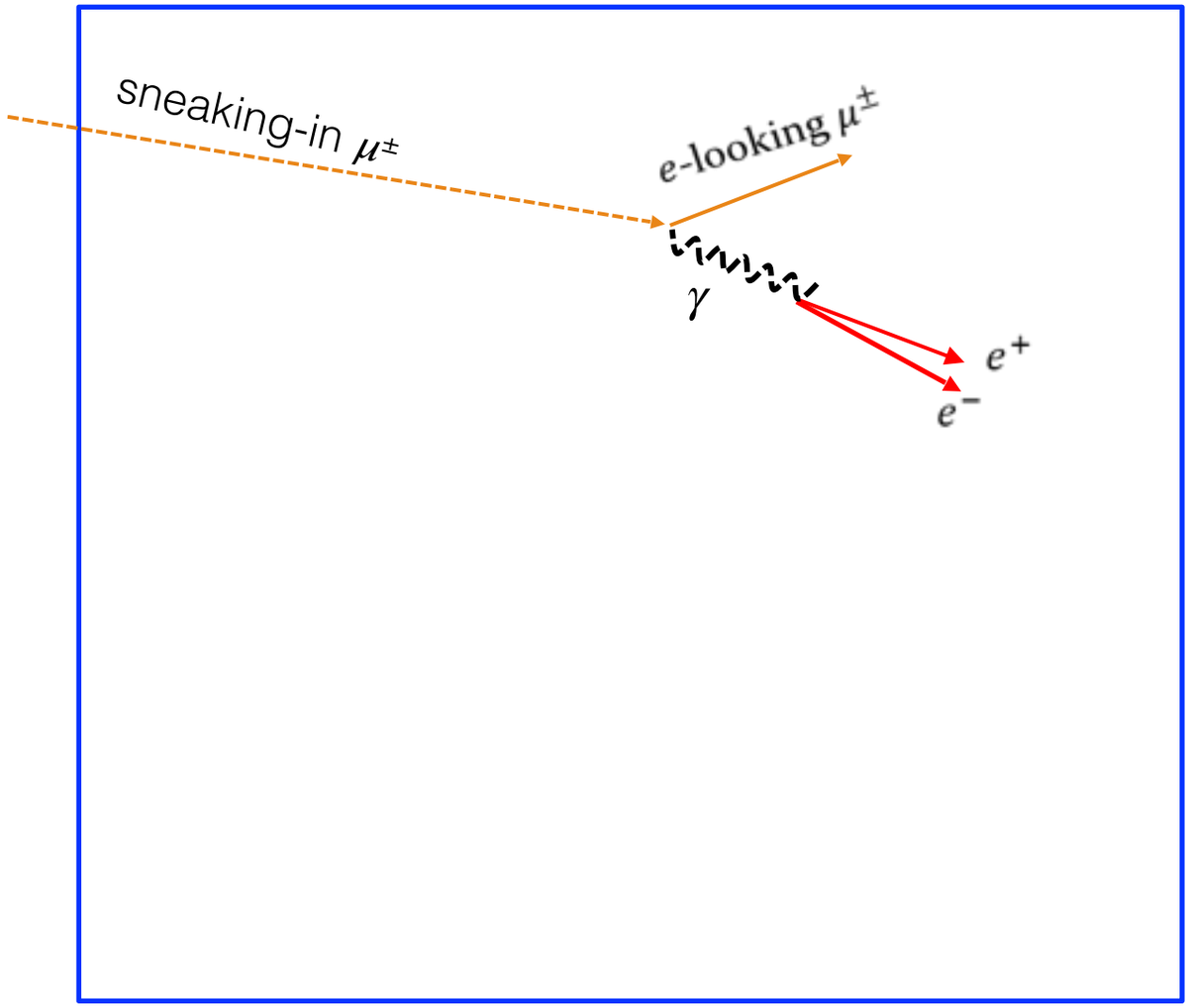


correspond

information of energy and flux

Back up: PD, sneaking-in μ

~ 10 energetic (> 500 MeV) cosmic μ events/ms ≃ 4×10^{11}/yr/detector (ProtoDUNE)



- Sneaking-in can be included in the events failed to be reconstructed as μ
- Hardly emitted photon
- A track pops-up there > E_{th} with unclear kink feature
- e-faking $\mu^{\pm}$
  (≪ e-faking γ rate: 7%)

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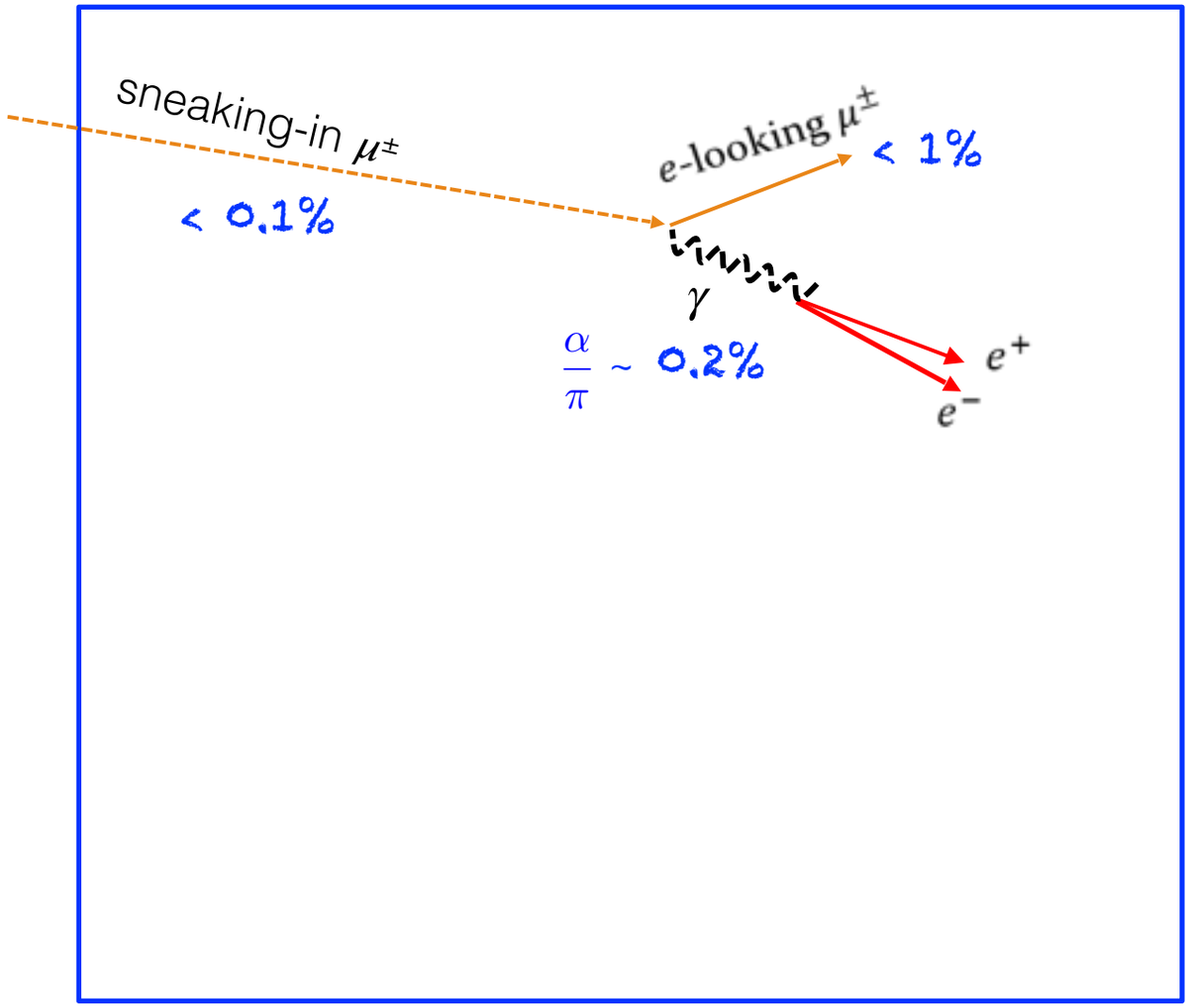

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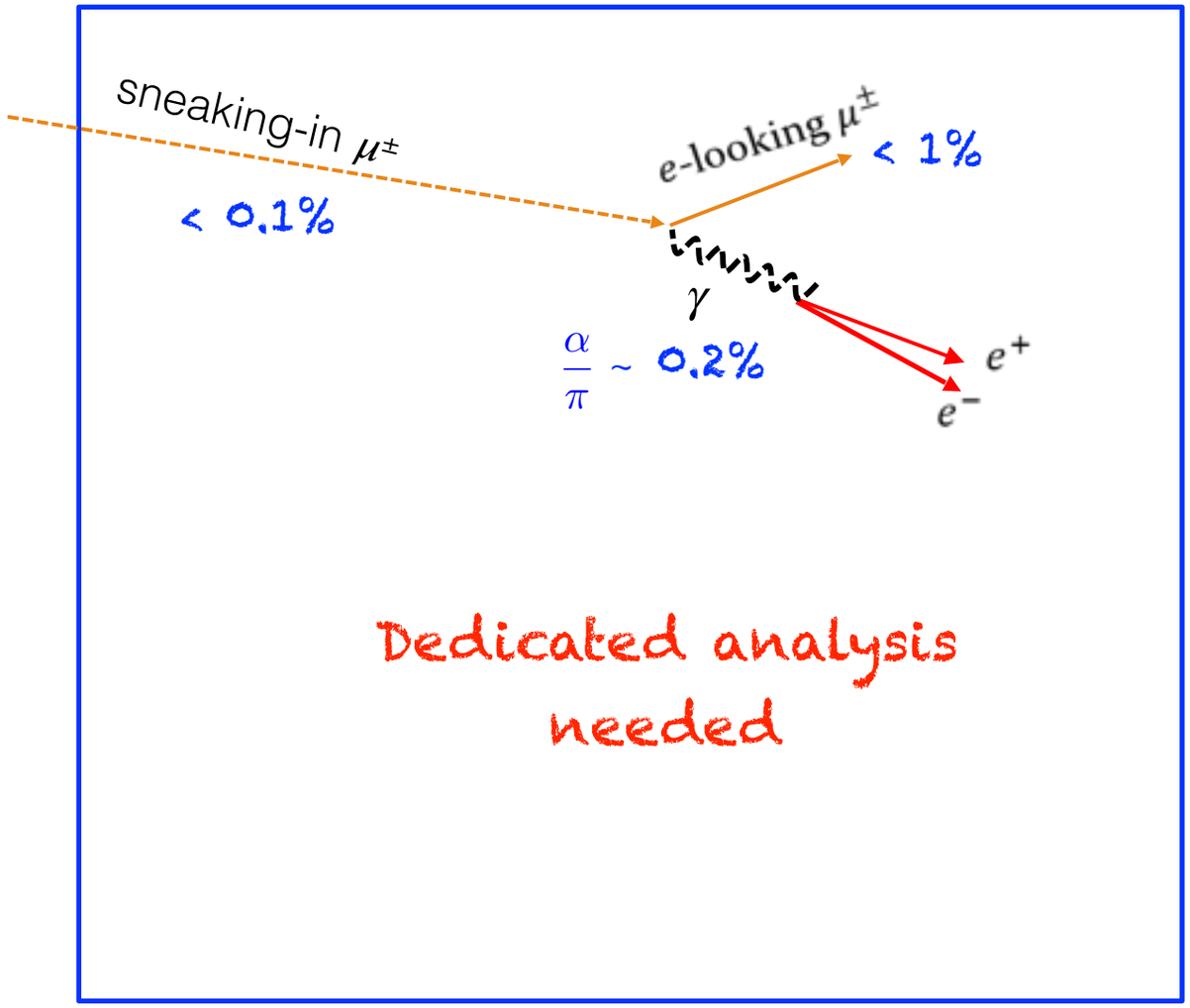

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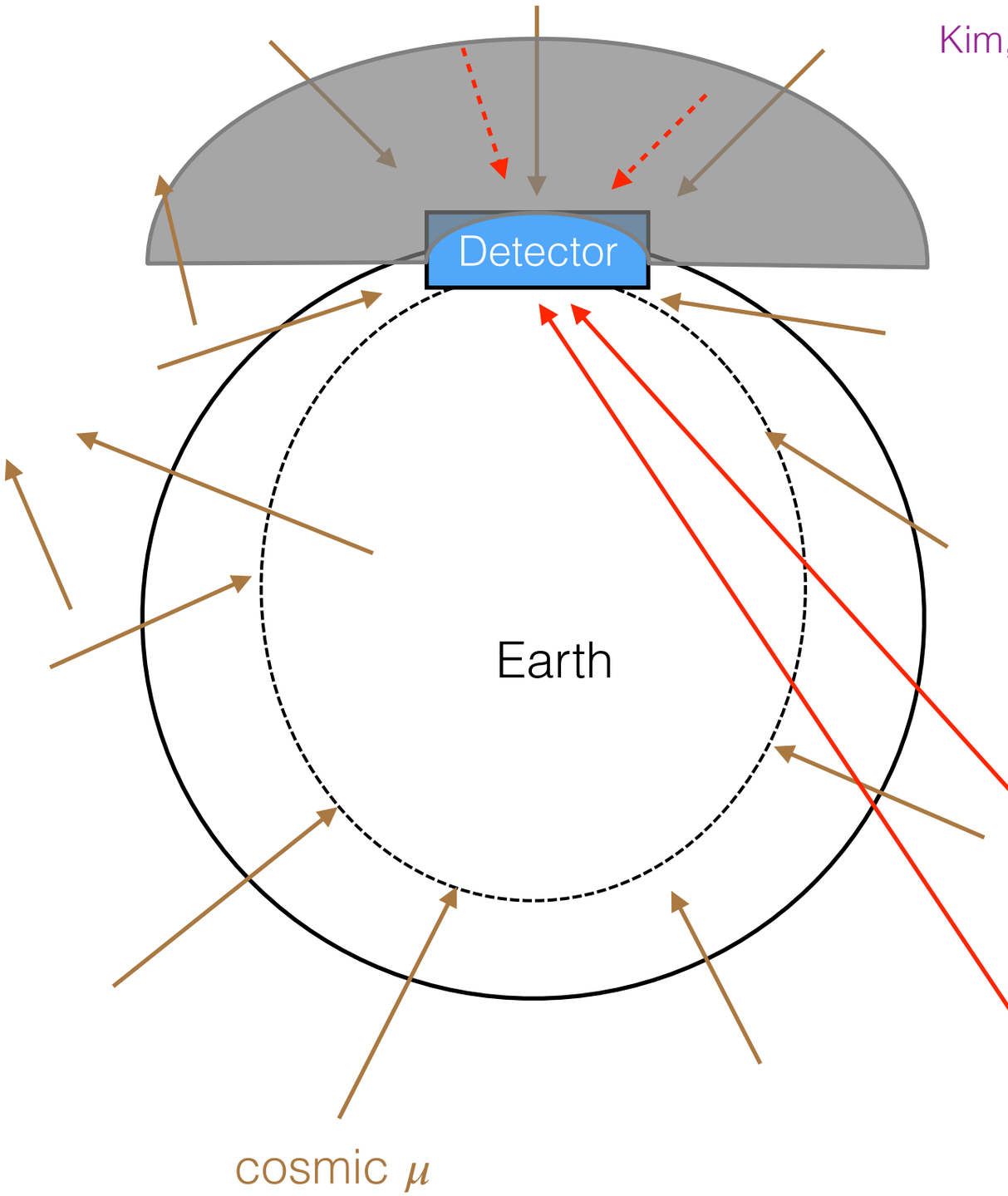
- ✓ e-faking $\mu^{\pm}$ (≪ e-faking γ rate: 7%)

N_{BG}~100 (crazy upper limit) ← if 0.06%

Back up: Earth shielding



Kim, Kong, Park, **SS**, 1804.07302

Collect upward-going signal only when the source is at the opposite side

From the sun: half

From the GC:

SBNP: 0.66, ProtoDUNE: 0.69

Back up: strategy

Signal probe	eBDM	iBDM
Surface ν exp.	+ Earth shielding	+ Unique topology
Underground ν exp.	Directionality of the scattering	Particle identification

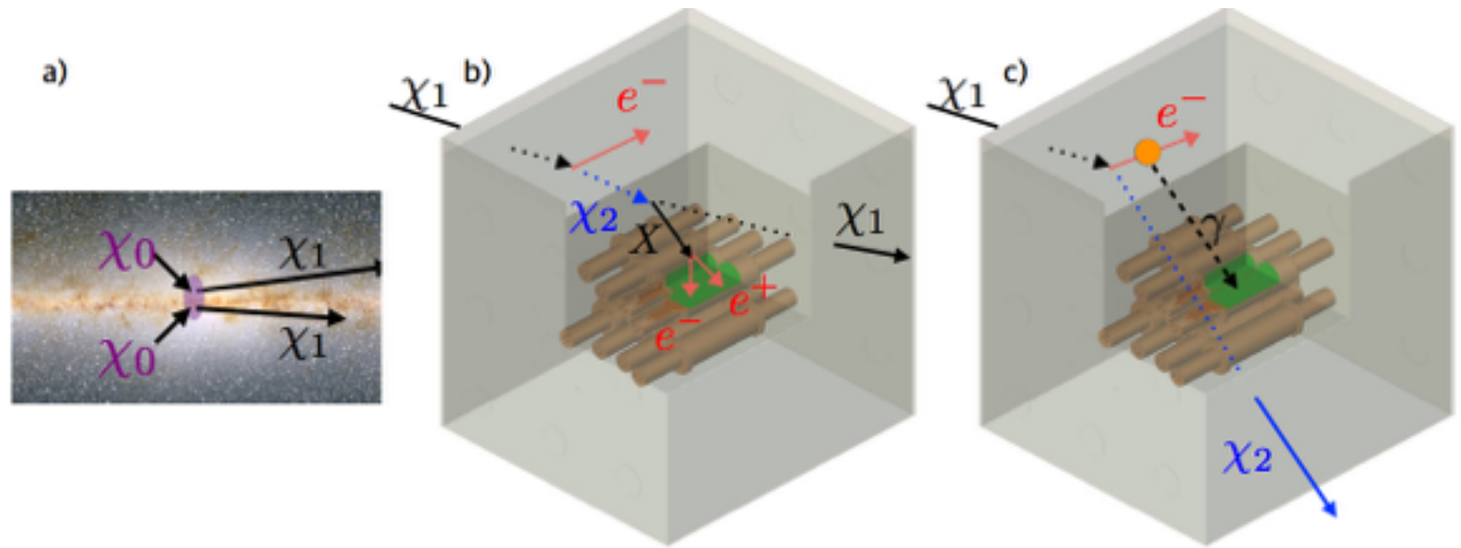
Detector type

LArTPC (DUNE, SBNP, …) → Better PID, resolutions

Cherenkov (SK, HK/KNO, …) → Larger volume

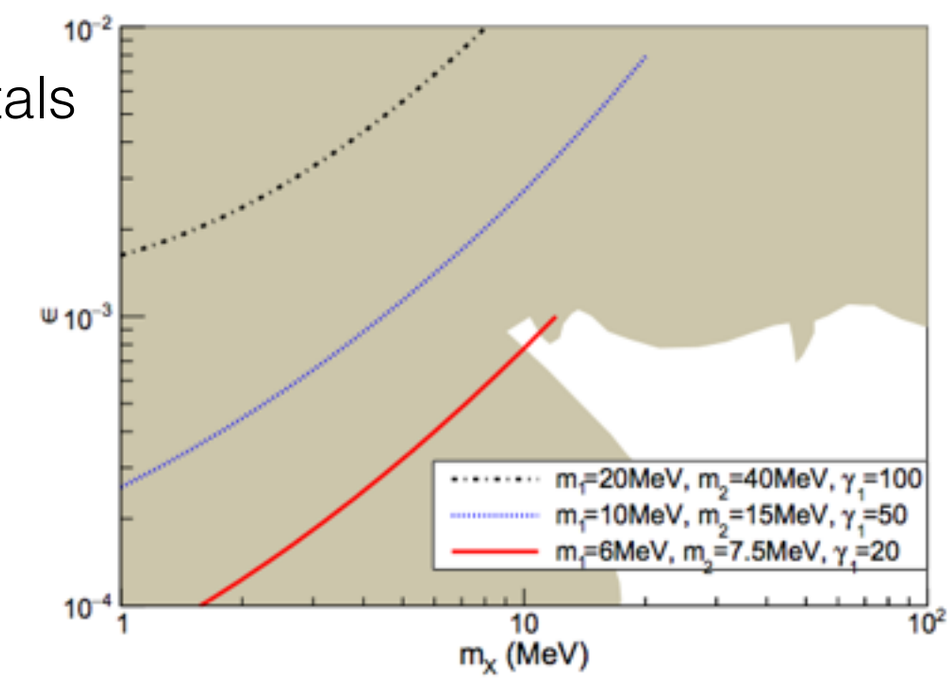
Back up

COSINE-100



106kg array of 8 ultra-pure NaI(Tl) crystals immersed in an active veto detector

2200L of liquid scintillator (~ 2 ton)



Back up

HK selection criteria

i) $p_e > 100$ MeV, 1.07 GeV $< p_p <$ 2 GeV,

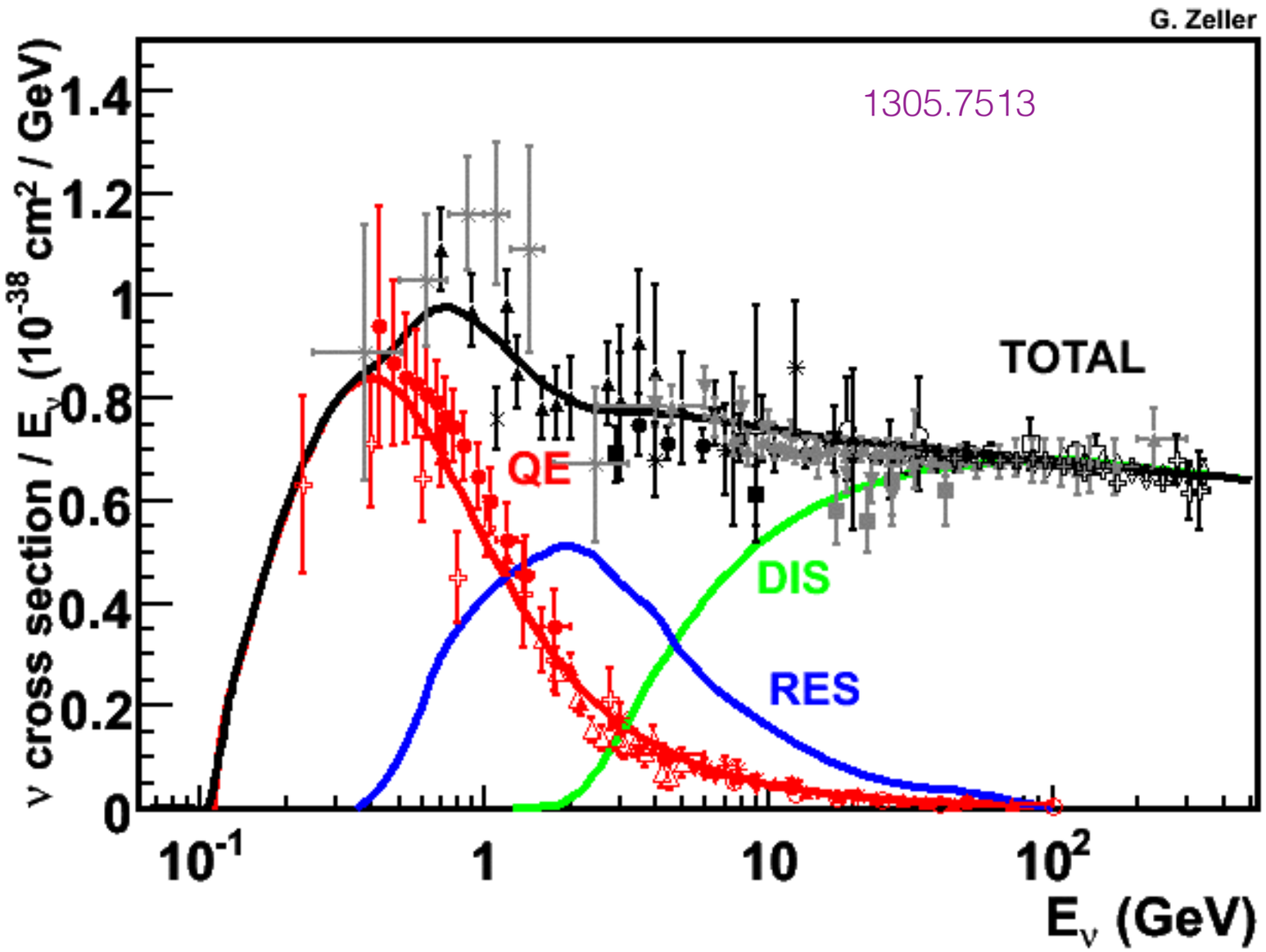
ii) $\Delta\theta_{e-i} > 3^\circ$, $\Delta\theta_{p-i} > 3^\circ$ with i running over the other visible final state particles, and

iii) both primary and secondary vertices should appear in the detector fiducial volume.

iv) Secondary signature: $e^- e^+$

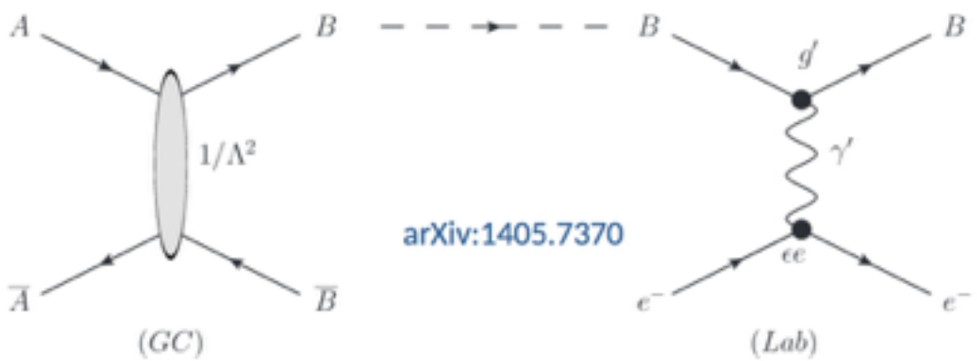
Back up

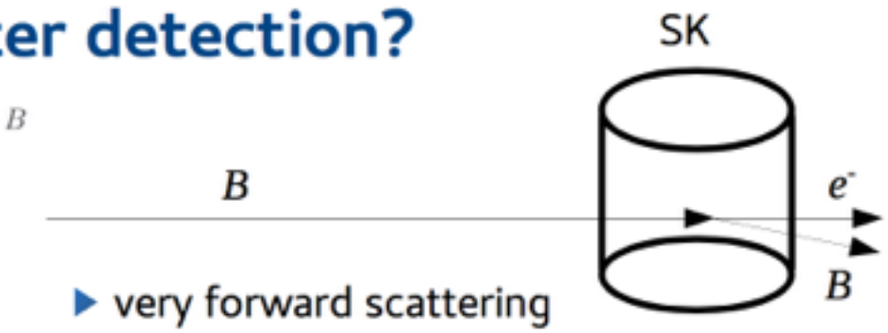
neutrino scattering



Back up

(In)direct dark matter detection?

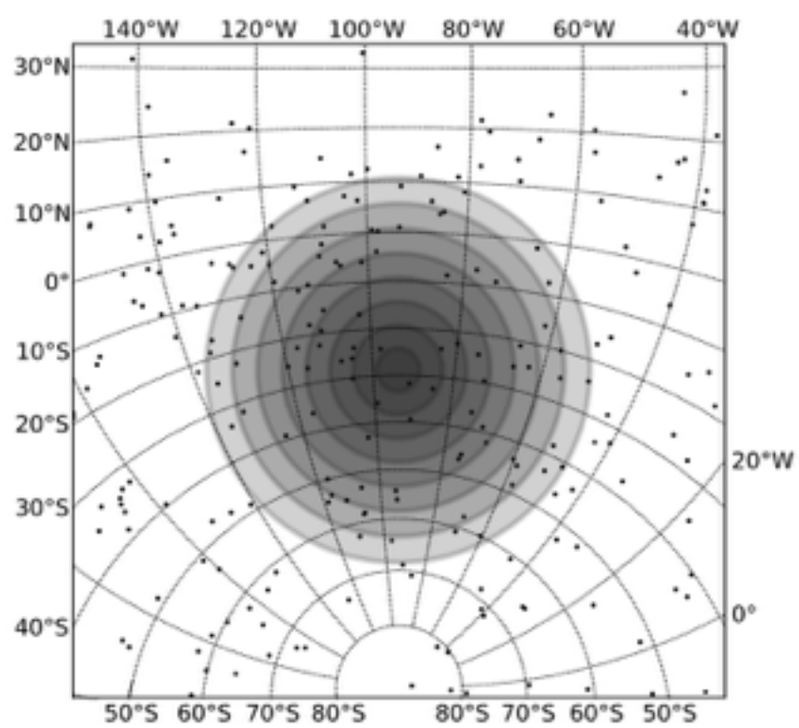
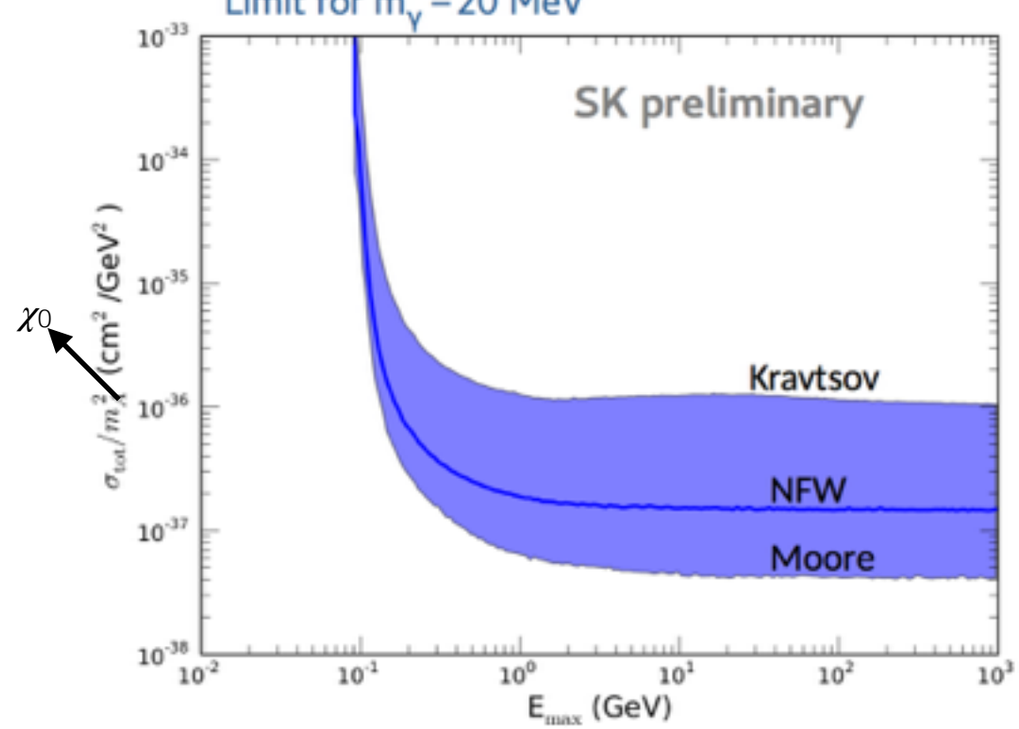




- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

Cone search: 8 cones from 5° to 40° around GC

→ No clusters visible



Limit for $m_{\gamma'}$=20 MeV