Aspen winter conference 2019

Boosted Dark Matter at Neutrino Experiments

Seodong Shin

1612.06867, 1712.07126, 1803.03264, 1804.07302, 1903.05087, 1904.xxxxx

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

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

Contents

- Multi-component boosted dark matter (BDM)
- Inelastic BDM (iBDM) and darkstrahlung
- Signal probe
- Conclusions

Multi-component boosted dark matter (BDM)

Search for WIMP (non-gravitational)

Direct detection

Indirect detection

Collider search

http://www.hap-astroparticle.org

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- Keep probing the rest of the corners of parameter space

- Non-conventional DM scenario & search strategy

(chance for new theory development!!)

Alternative of WIMP?

Easy set-up

- Keep the gravitational interaction as observed: keep ΛCDM
- Non-gravitational interaction: out of the originally targeted weak scale

→ My current focus: Multi-component boosted DM

Simple two-component DM

χ_0 χ_1

Just like the SM particles: proton and electron

Simple two-component DM

$\langle \sigma v \rangle_{\chi_0 \bar{\chi}_0 \to \chi_1 \bar{\chi}_1}$ determines $\Omega_{\rm DM} \simeq \Omega_{\chi_0}$

Most of the relic

χ_0 ⟷ χ_1

Gravitational int.

Just like the SM particles: proton and electron

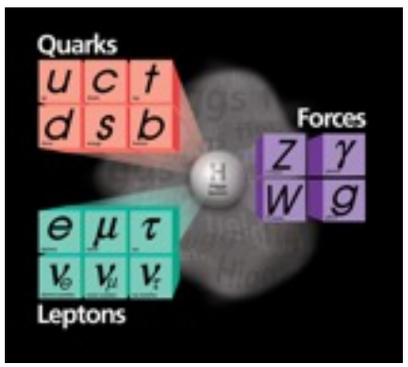
Simple two-component DM

$\langle \sigma v \rangle_{\chi_0 \bar{\chi}_0 \to \chi_1 \bar{\chi}_1}$ determines $\Omega_{\rm DM} \simeq \Omega_{\chi_0}$

χ_0 ⟷ χ_1 Negligible relic

Gravitational int.

Weak (or other scale) int. with SM



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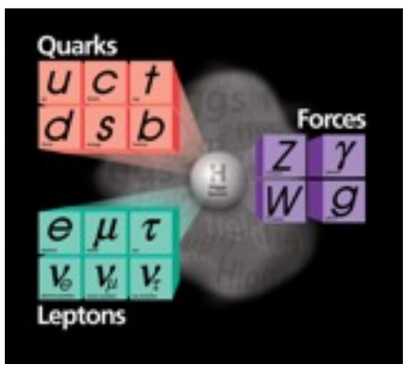
Gravitational int.

Weak (or other scale) int. with SM

Assisted freeze-out

Belanger, Park, 1112.4491



- Indirect interaction: elusive nature of DM
- No effect to ΛCDM

Simple two-component DM

$\langle \sigma v \rangle_{\chi_0 \bar{\chi}_0 \to \chi_1 \bar{\chi}_1}$ determines $\Omega_{\rm DM} \simeq \Omega_{\chi_0}$

heavy χ_0 ⟷ light χ_1

Gravitational int.

Weak (or other scale) int. with SM

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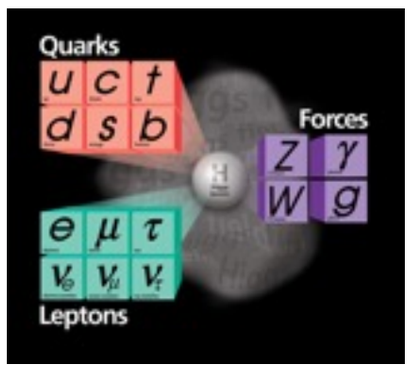
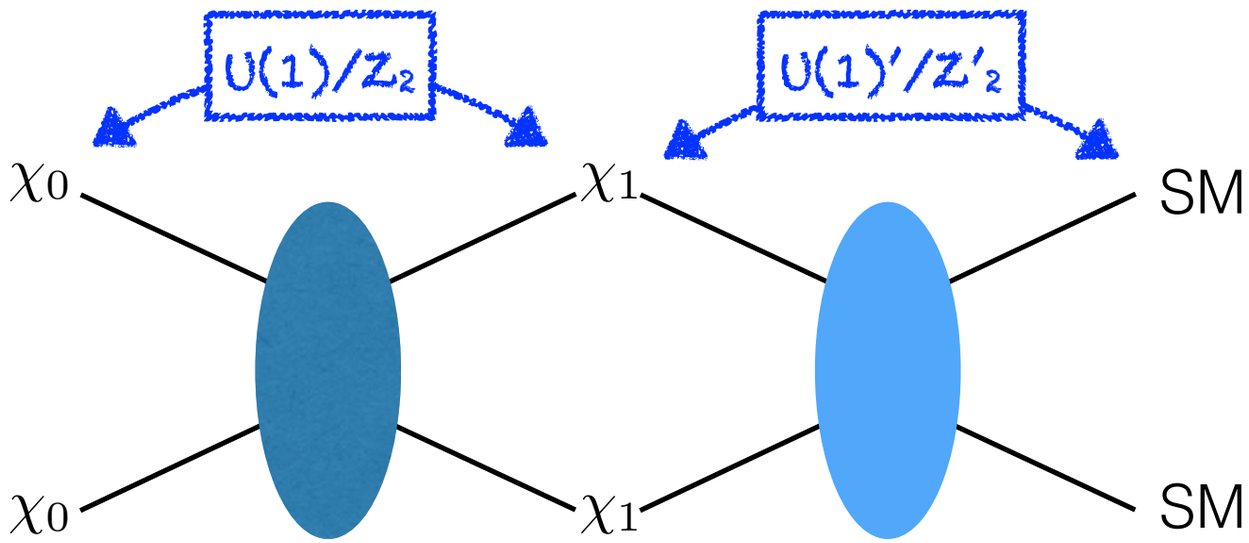
Belanger, Park, 1112.4491



- Indirect interaction: elusive nature of DM
- No effect to ΛCDM
- Extraordinary signal (relativistic DM scattering)

Multi-component Boosted DM (BDM)

χ_0: heavy, χ_1: light



Agashe, Cui, Necib, Thaler,1405.7370

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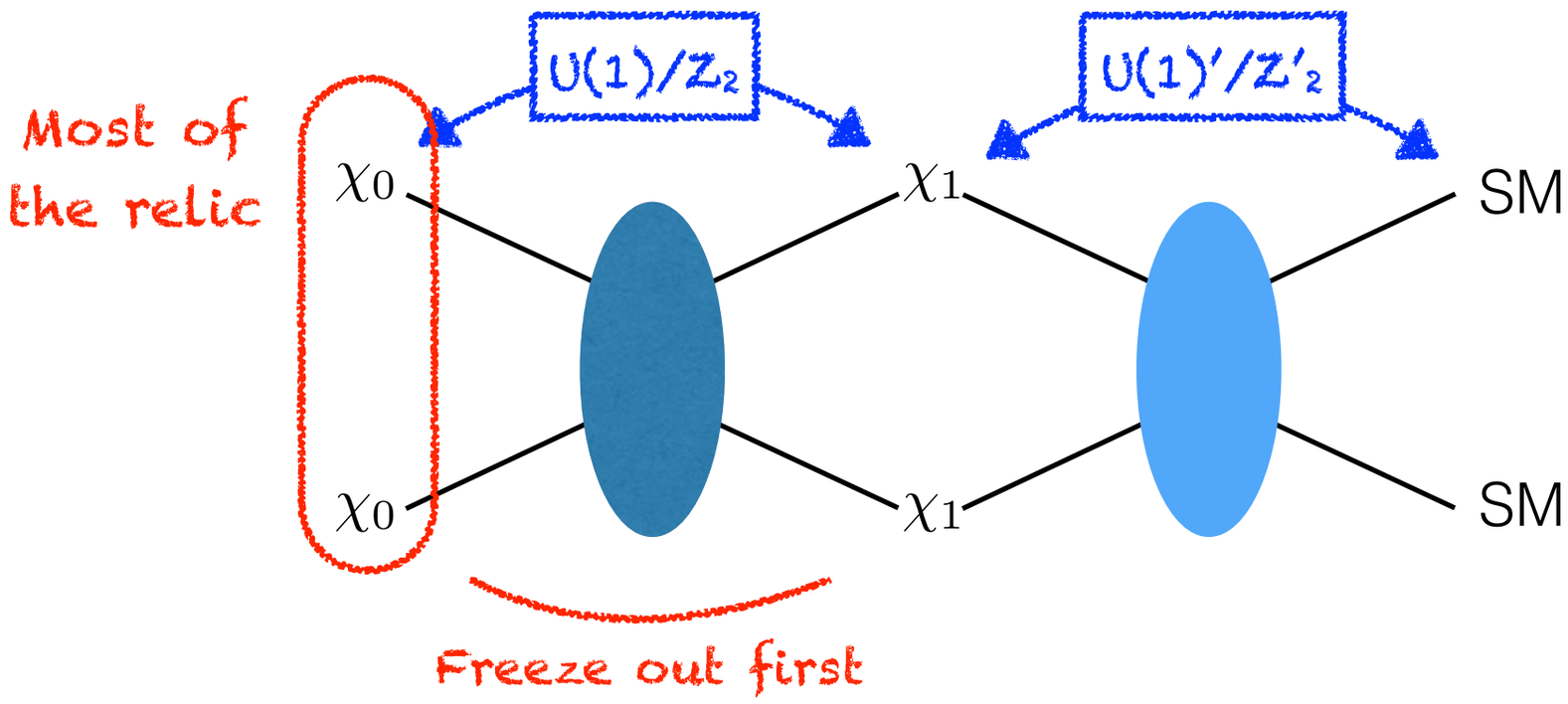

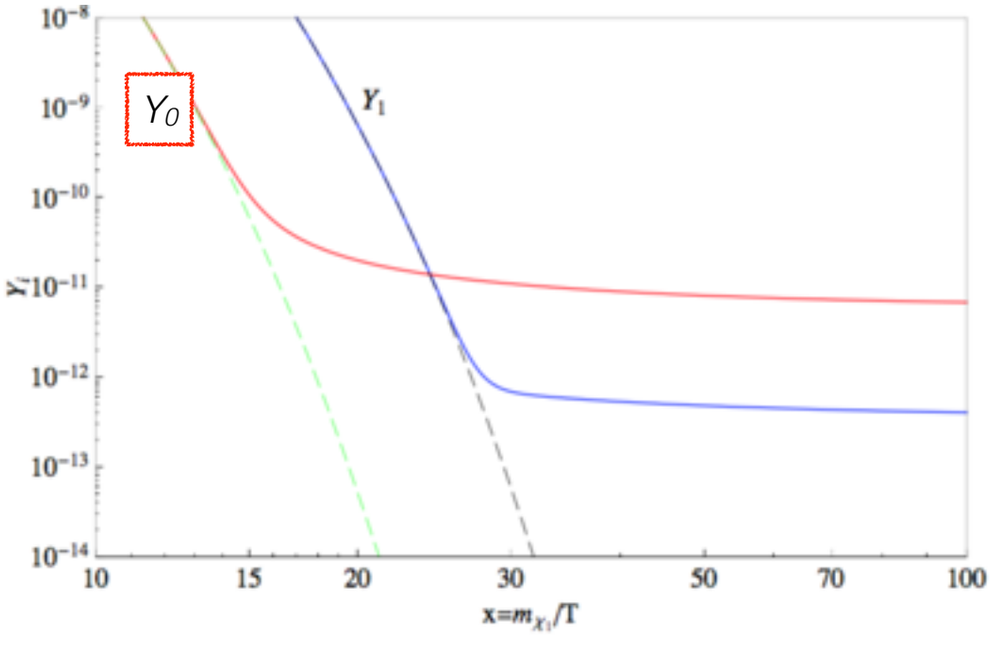

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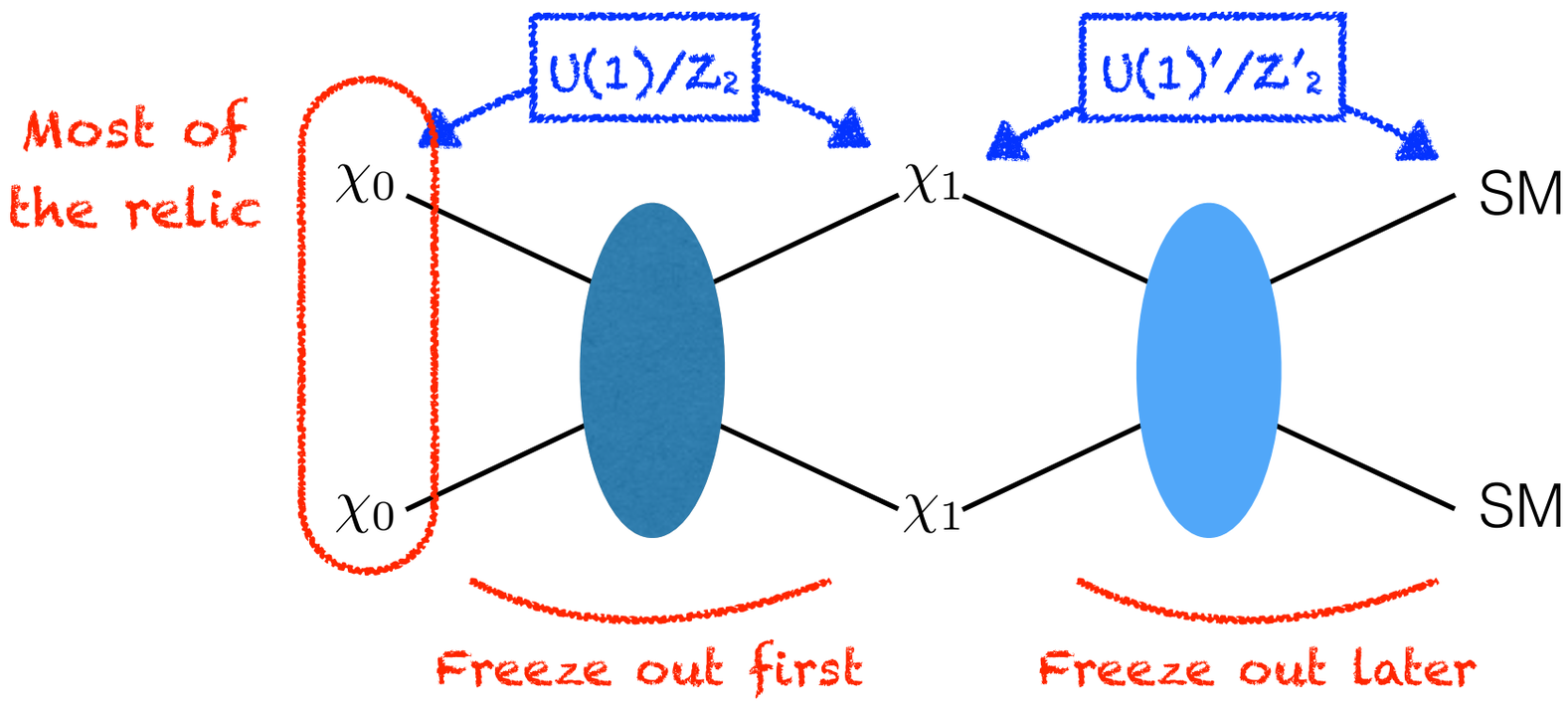

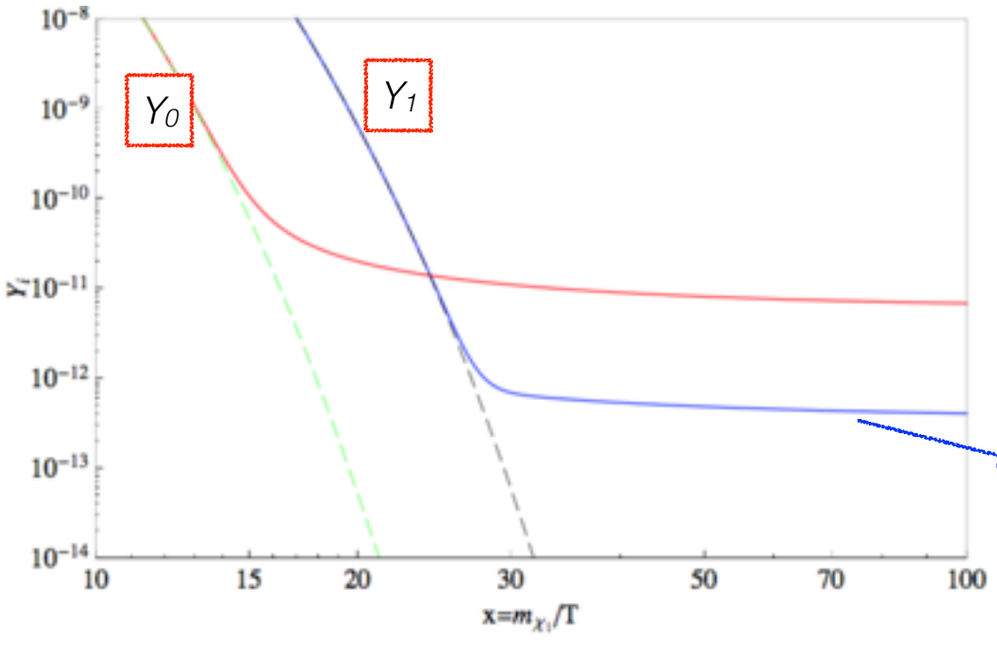

Agashe, Cui, Necib, Thaler,1405.7370

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)

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

  ※ relic χ_1 is non-relativistic

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Observe χ_1 scattering off target with $E_1 > E_{th}$

(indirect detection of χ_0)

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Flux of χ_1 $\simeq 1.6 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \times \left(\dfrac{\langle\sigma v\rangle_{0\to1}}{5\times10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times \left(\dfrac{100\,\mathrm{GeV}}{m_0}\right)^2$

Assume: NFW

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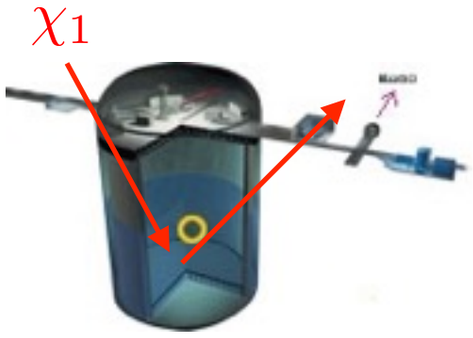
Assume: NFW

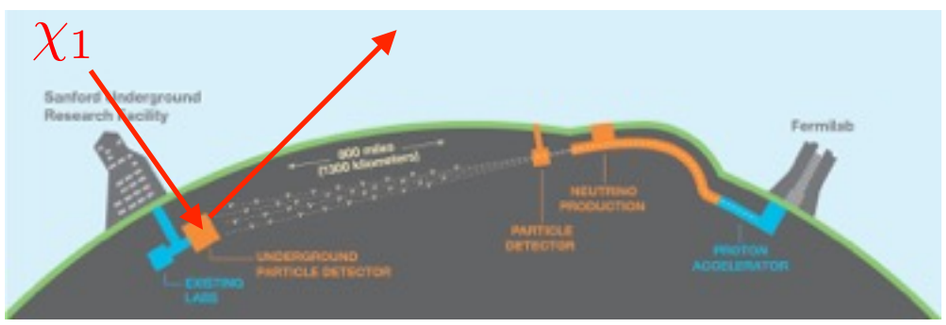
Fixed ~ 1 if s-channel annihilation dominates

10,000 times smaller than the flux of atmospheric neutrino

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

Flux: small & Energy of χ_1: large ⟶ Large volume ν experiments





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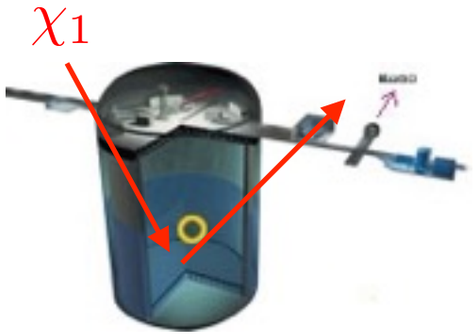
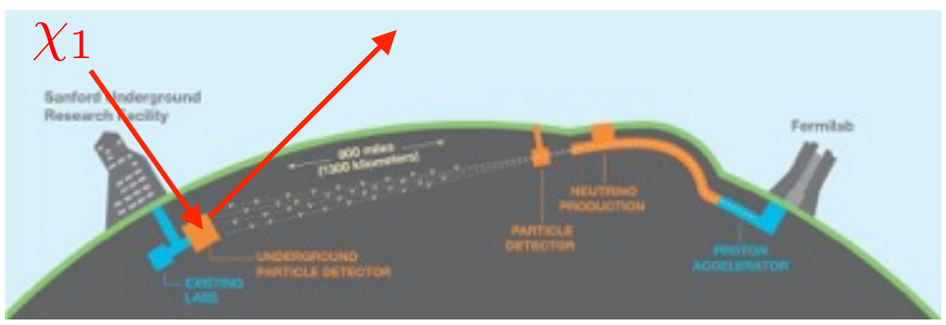




Subtraction of major background (ν)

- Directional 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

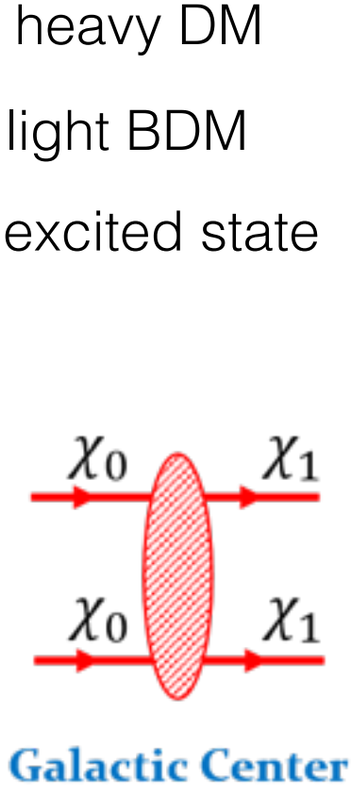
Inelastic BDM (iBDM) and darkstrahlung

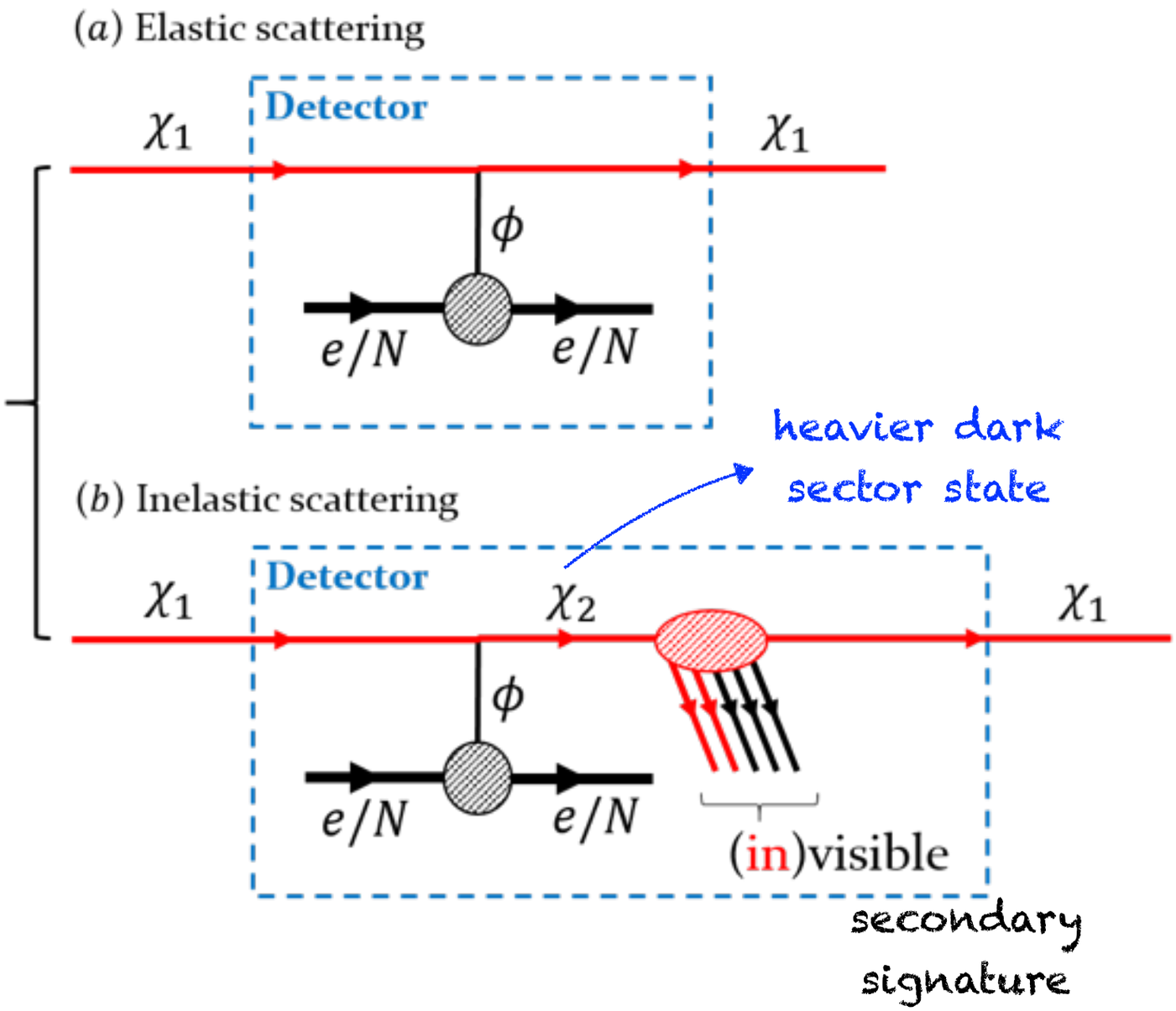
Inelastic BDM (iBDM)

χ_0: heavy DM

χ_1: light BDM

χ_2: excited state





Kim, Park, **SS**, PRL 119, 161801 (2017)

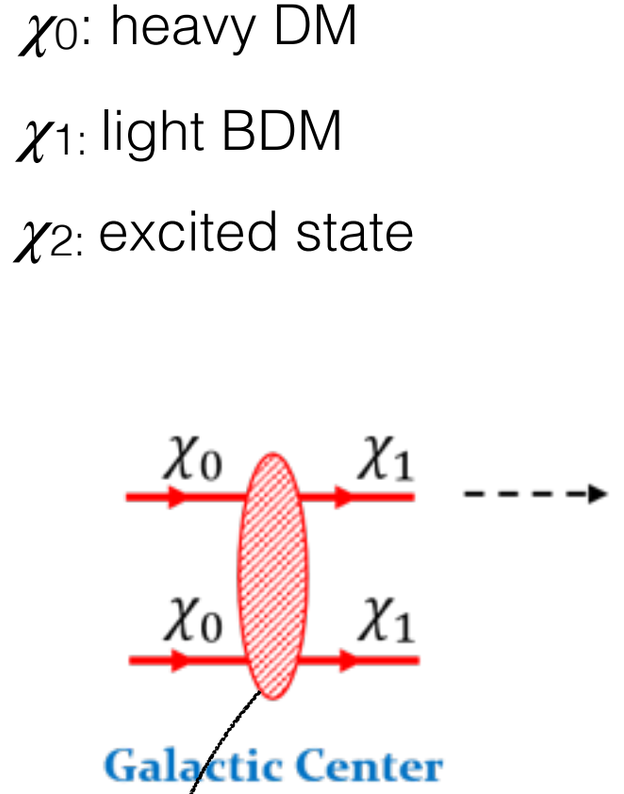
Giudice, Kim, Park, **SS**, PLB 780, 543 (2018)

Inelastic BDM (iBDM)

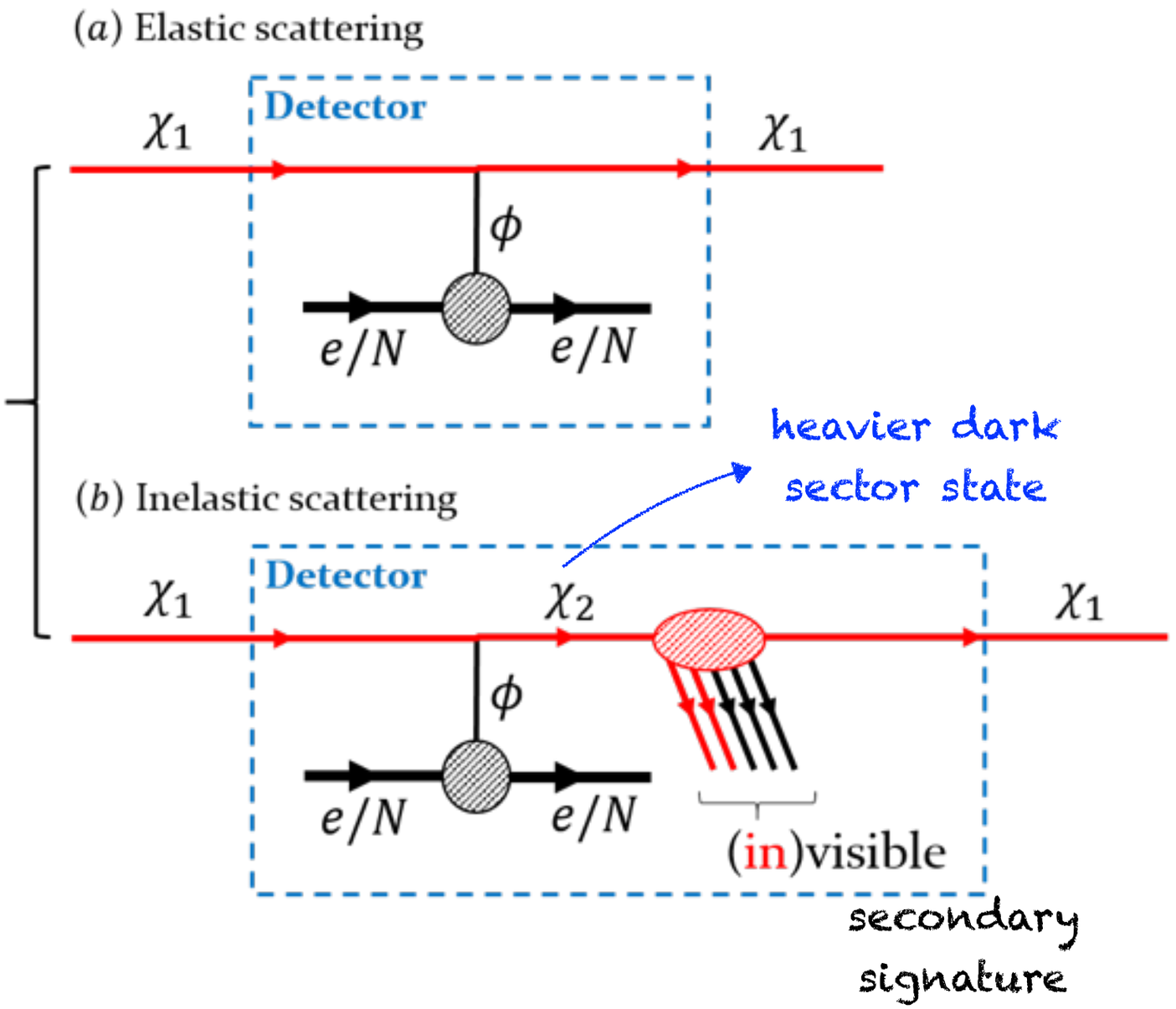
χ_0: heavy DM

χ_1: light BDM

χ_2: excited state



Assume a contact interaction (no details discussed)



secondary signature

Kim, Park, **SS**, PRL 119, 161801 (2017)

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Inelastic BDM (iBDM)

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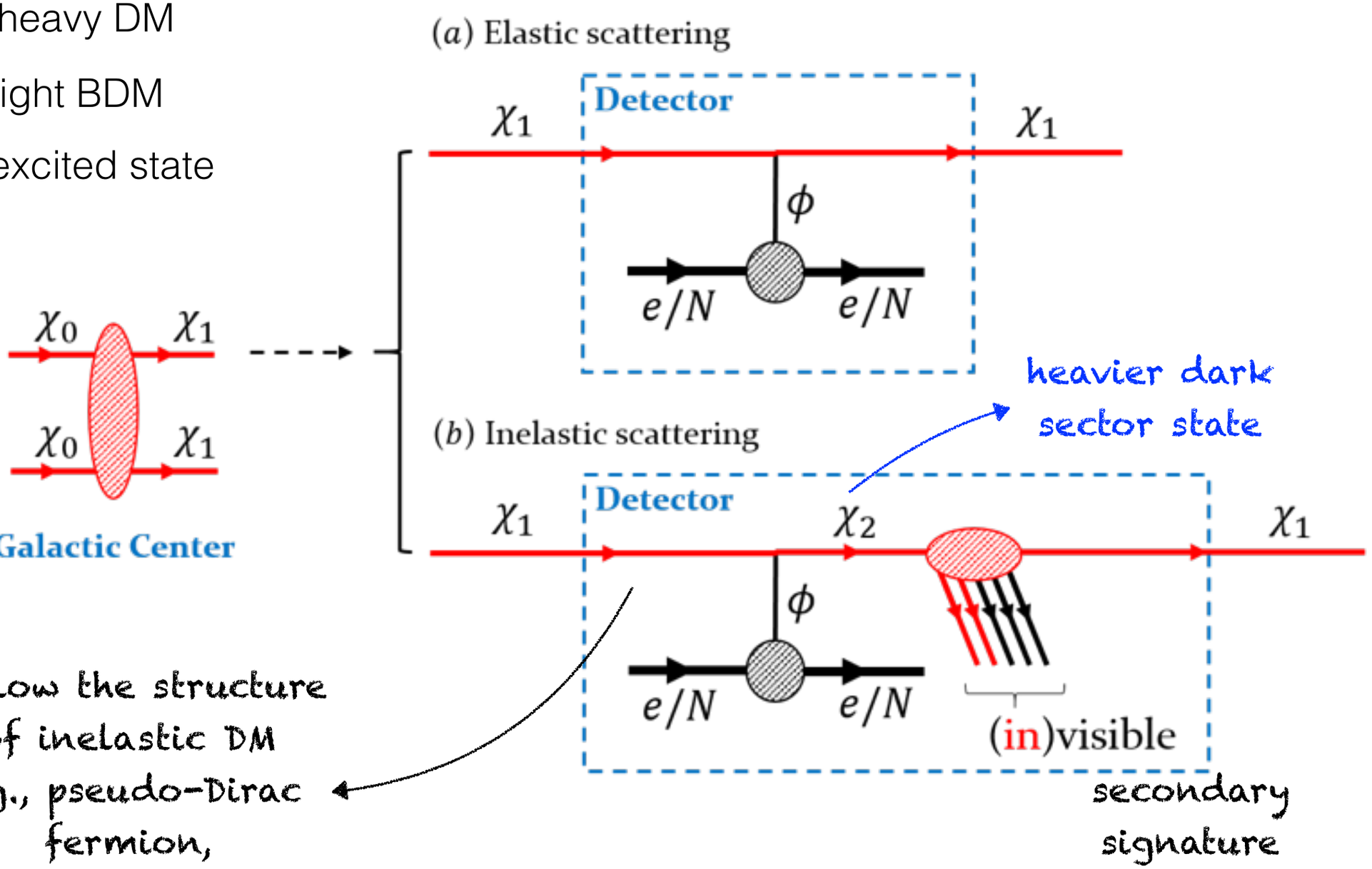
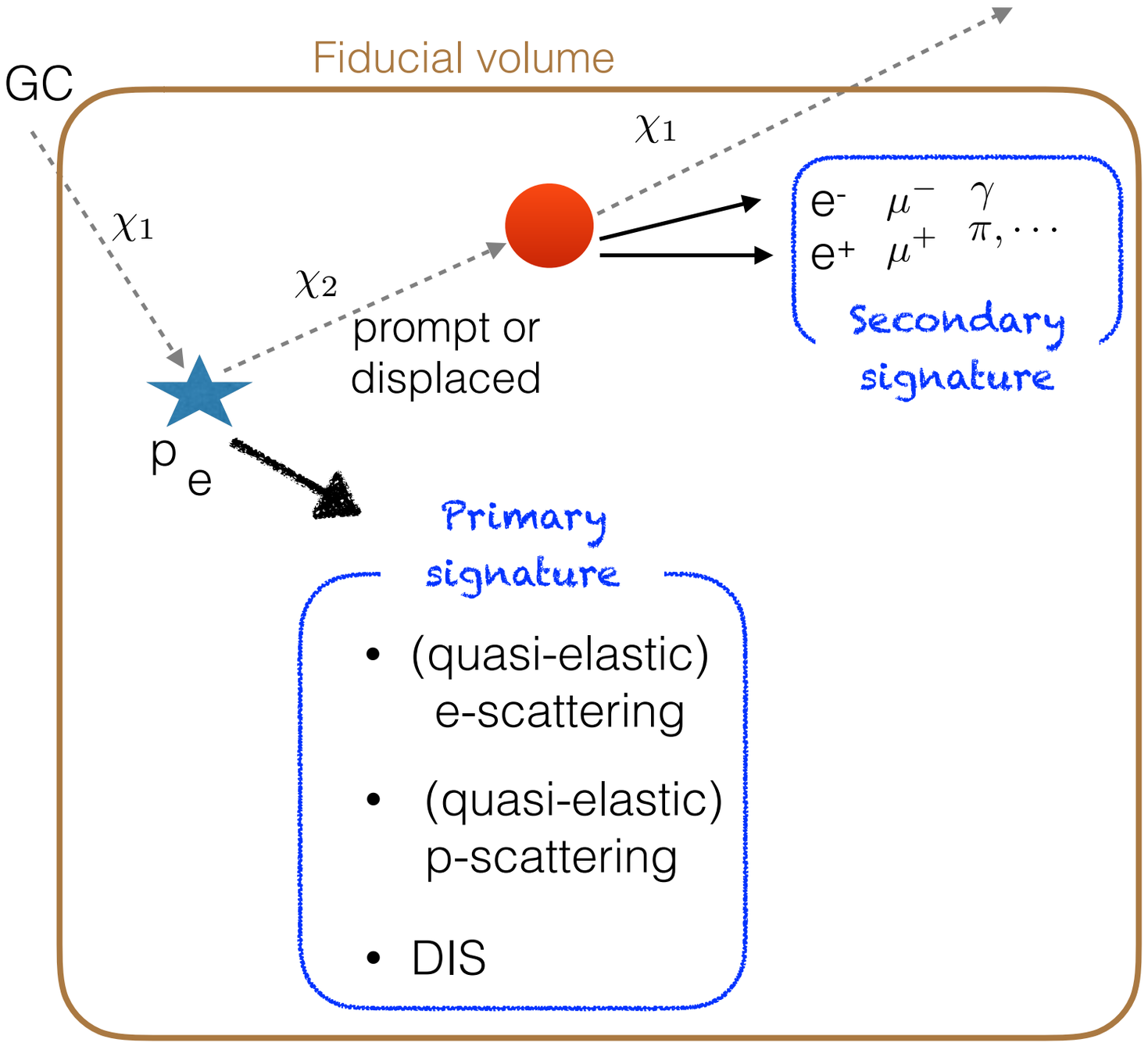


Follow the structure of inelastic DM e.g., pseudo-Dirac fermion, dark photon (details at backup)

Kim, Park, **SS**, PRL 119, 161801 (2017)

Giudice, Kim, Park, **SS**, PLB 780, 543 (2018)

Signals inside a fiducial volume



χ_1: light BDM, χ_2: excited state

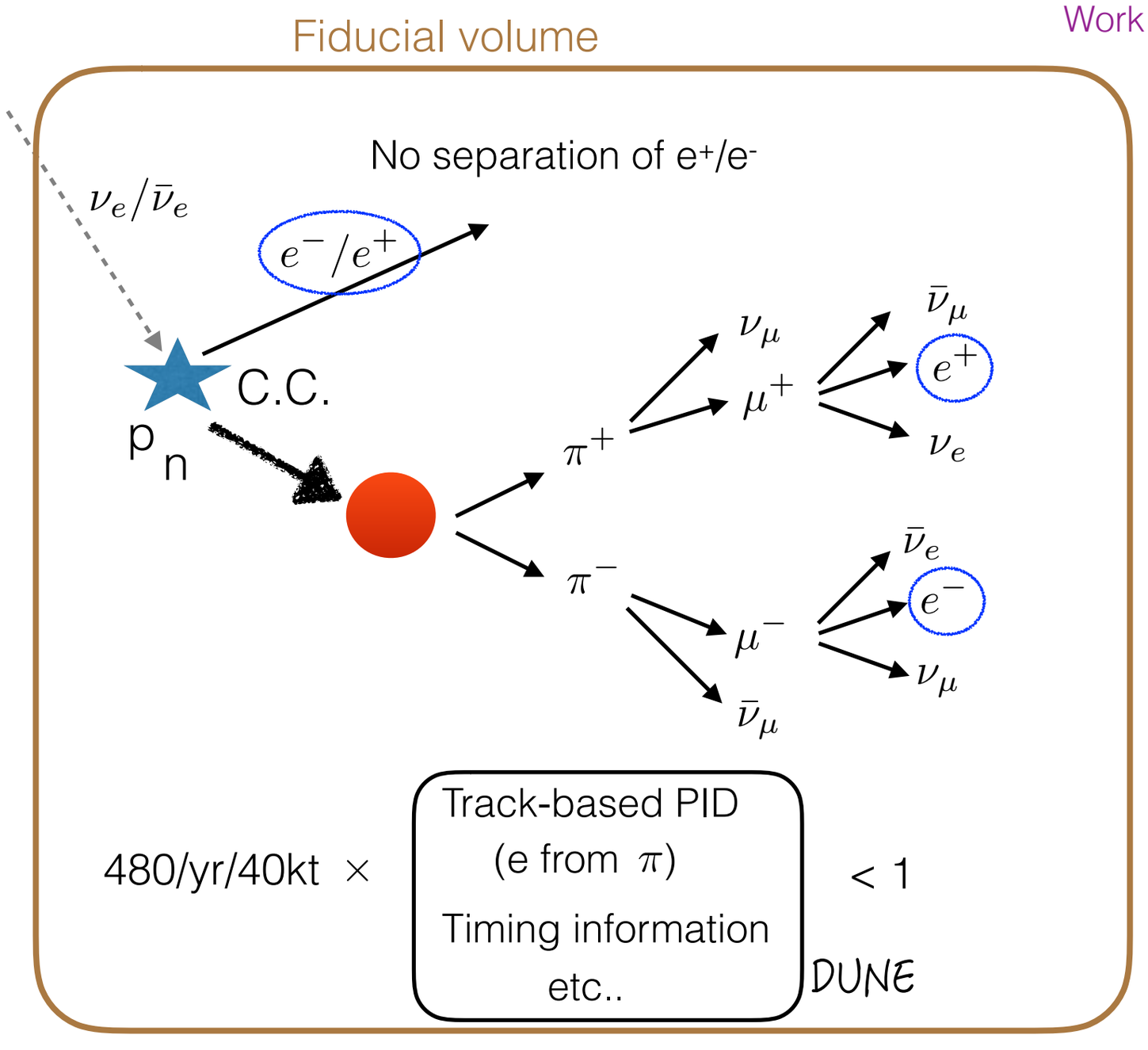
iBDM

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

Background candidate: underground

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

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

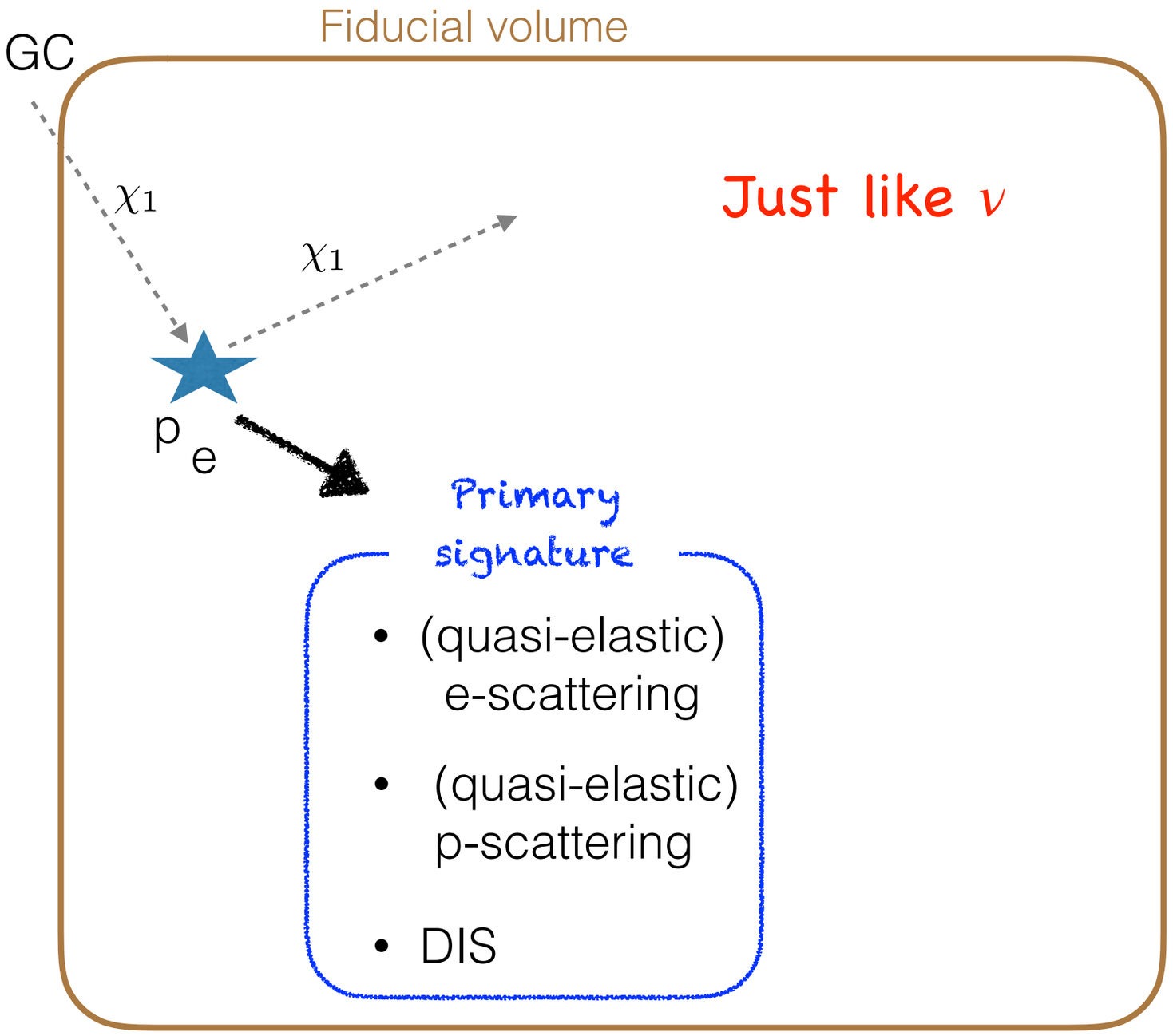
- (quasi-elastic) proton scattering: less bkg.

χ_1: light BDM, χ_2: excited state

Signals inside a fiducial volume

Minimal case

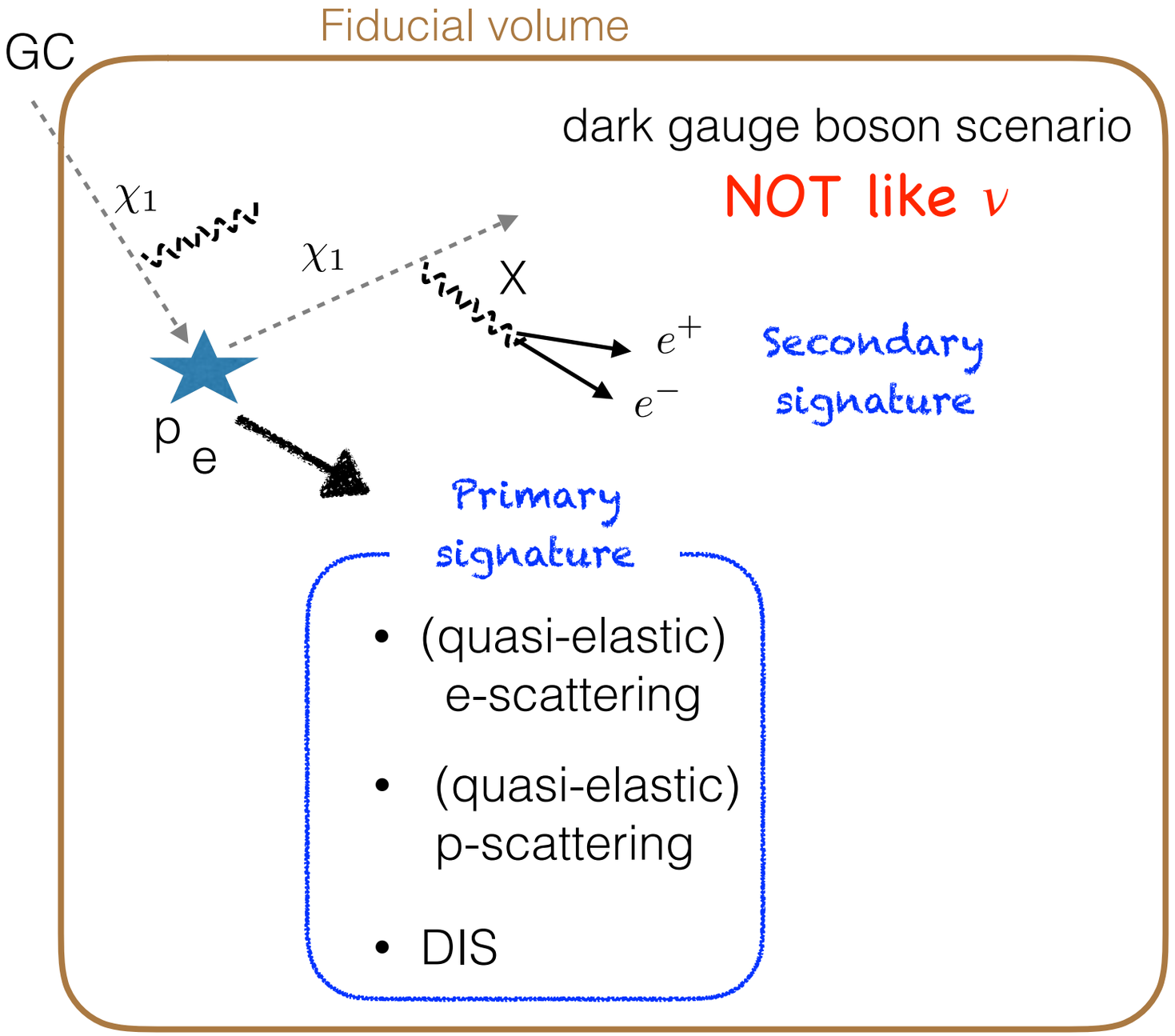
eBDM: elastically scattering BDM



χ_1: light BDM

New method in eBDM search: darkstrahlung

Kim, Park, **SS**, 1903.05087



χ_1: light BDM

Minimal case

eBDM: elastically scattering BDM

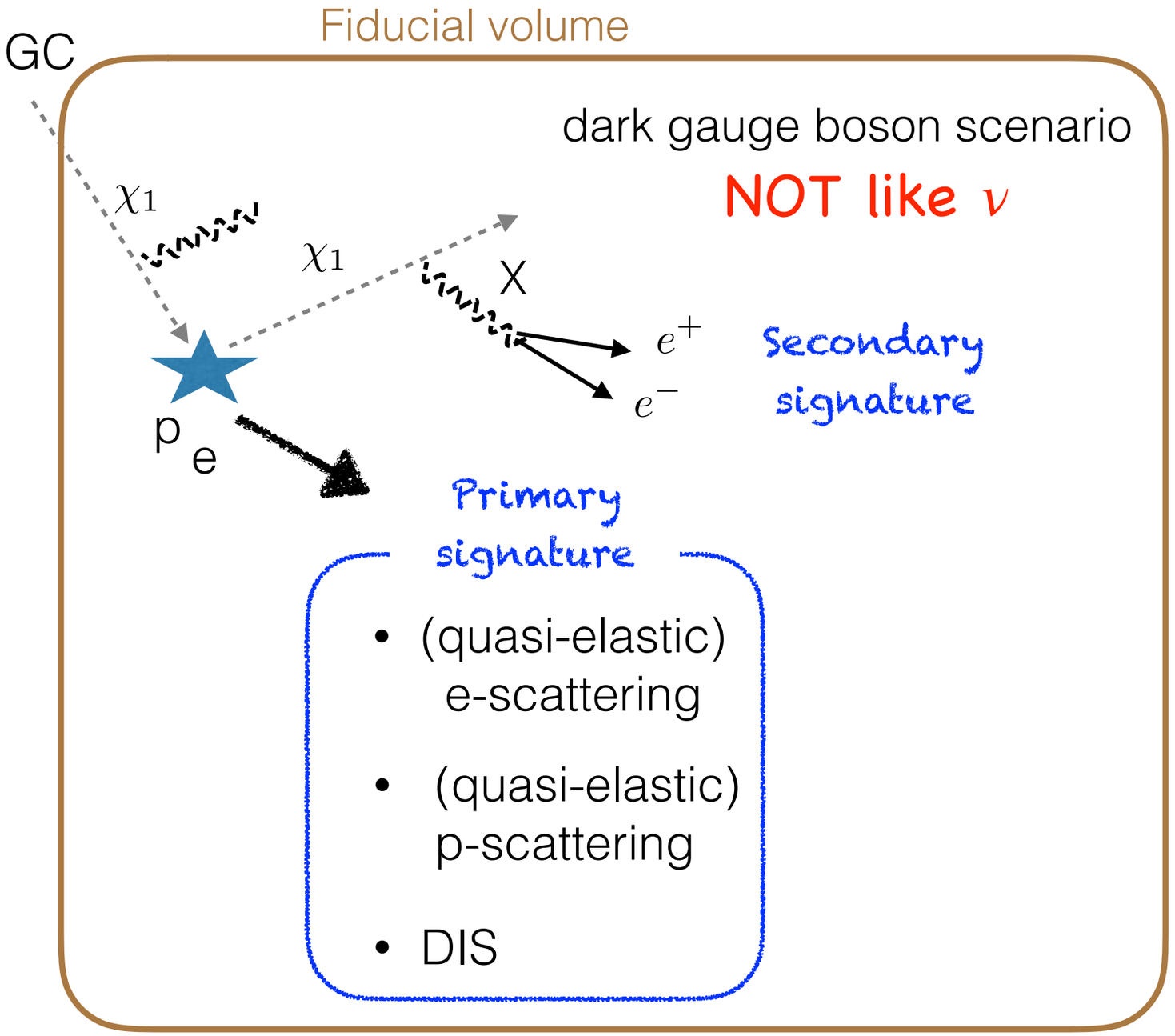
- Different from DM → $\nu\,\nu$
- Next-leading order but O(10-20%) of the leading-order possible

Dark trident, 1809.06388

LHC 1504.01385, 1504.01395, 1612.02850

New method in eBDM search: darkstrahlung

Kim, Park, **SS**, 1903.05087



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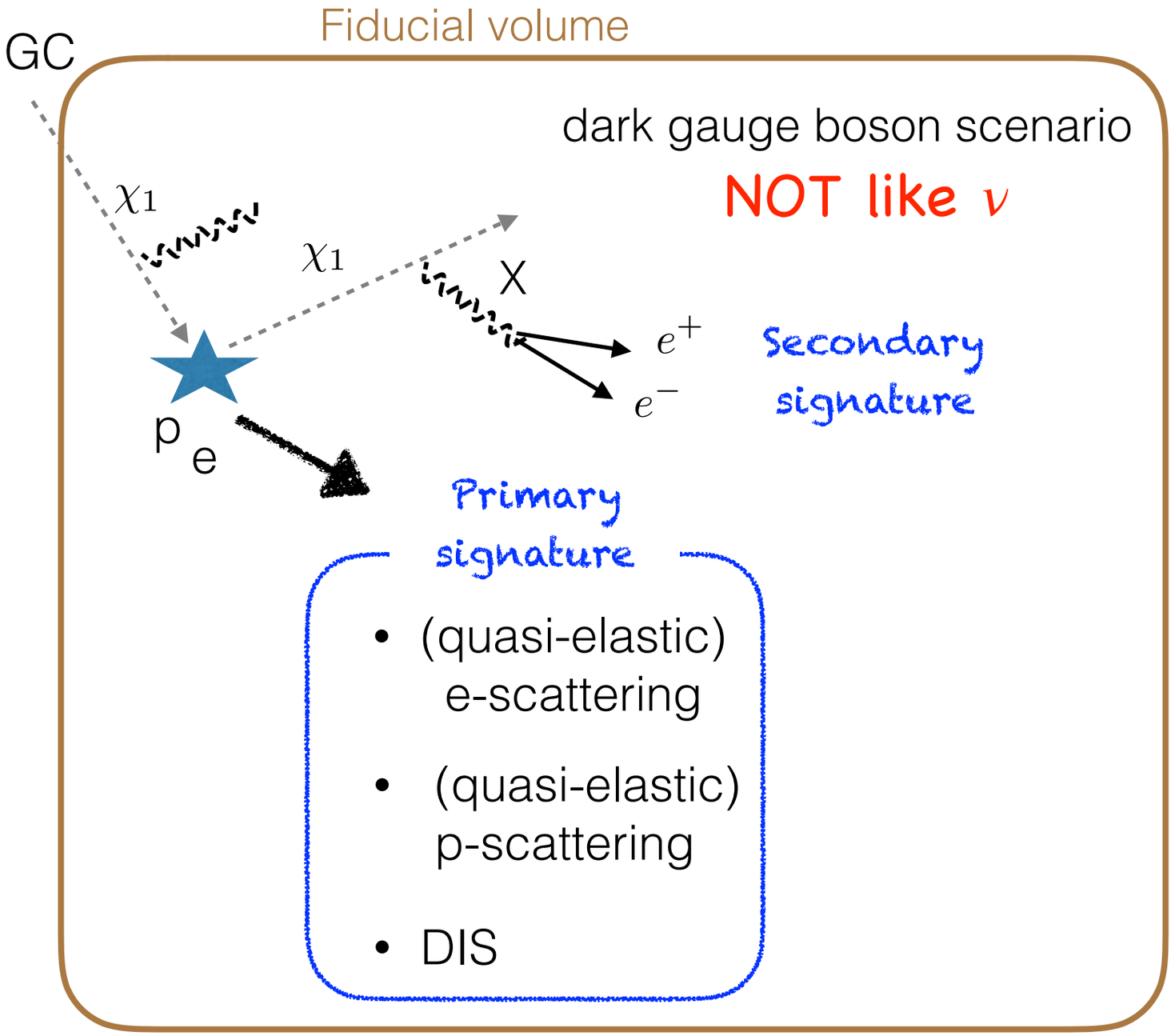


χ_1: light BDM

Minimal case

eBDM: elastically scattering BDM

- Different from DM → $\nu\,\nu$

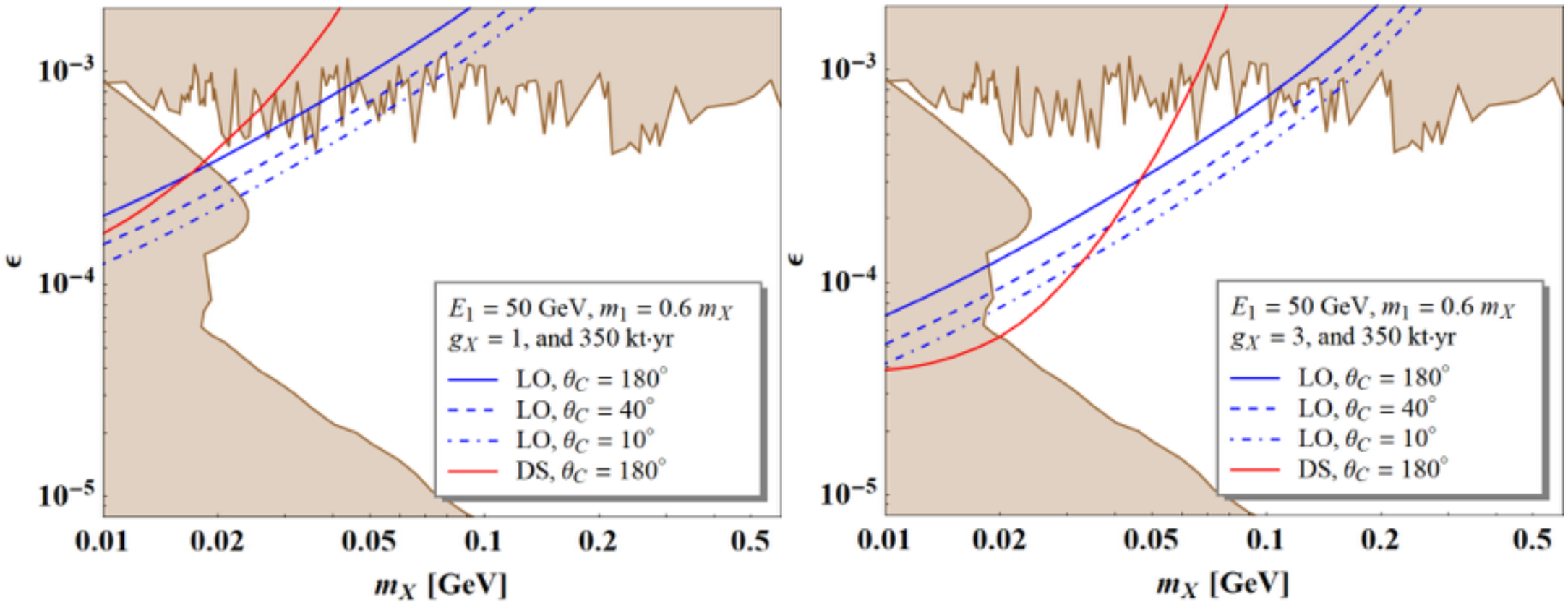
- Next-leading order but O(10-20%) of the leading-order possible

- Efficient for large N_{BG} (cosmogenic BSM signal)

Dark trident, 1809.06388

LHC 1504.01385, 1504.01395, 1612.02850

New method in eBDM search: darkstrahlung



θ_C: cone angle around the GC

DS and LO sensitivities are comparable or better (for larger N_{BG})

DS effective for larger E_1, g_X and smaller m_1, m_X

Signal probe

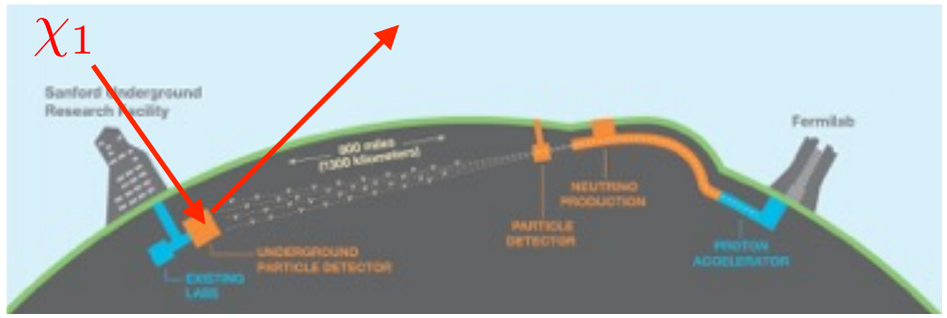
- Large volume deep underground ν-experiments
- Moderate volume surface based ν-experiments
- Ton scale WIMP direct detection experiments

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

$$\text{Flux of } \chi_1 \simeq 1.6 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \times \left(\frac{\langle \sigma v \rangle_{0\to 1}}{5 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times \left(\frac{100\,\mathrm{GeV}}{m_0}\right)^2$$

Assume: NFW

Large volume ν experiments (underground except NOvA)



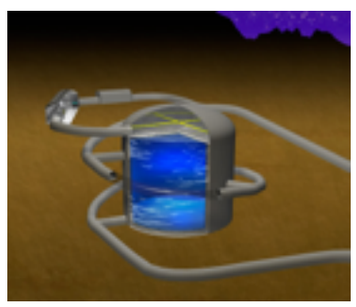
DUNE far detector

DUNE TDR (coming up)

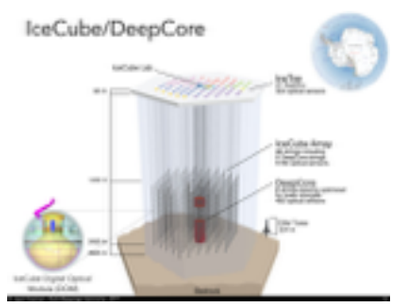
Most of BDM papers

Super-K

1711.05278



Hyper-K/KNO



IceCube/DeepCore

Smaller size good if $m_{\chi 0} \lesssim$ O(1 GeV)

Flux of $\chi_1 \simeq 1.6 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \times \left(\frac{\langle\sigma v\rangle_{0\to 1}}{5\times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times \left(\frac{100\,\mathrm{GeV}}{m_0}\right)^2$

Assume: NFW

- Moderate volume surface based ν-experiments:
  Short-baseline neutrino program, ProtoDUNE, …

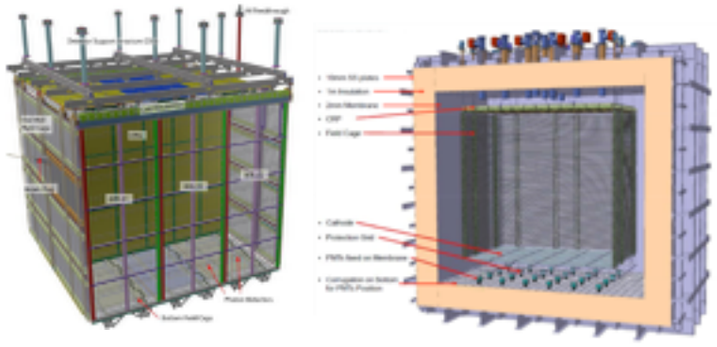
- Ton scale WIMP direct detection experiments:
  DarkSide-20k, COSINE-100 (including passive volume),
  LUX-ZEPLIN, XENON-nT, …

Smaller size good if $m_{\chi 0} \lesssim$ O(1 GeV)

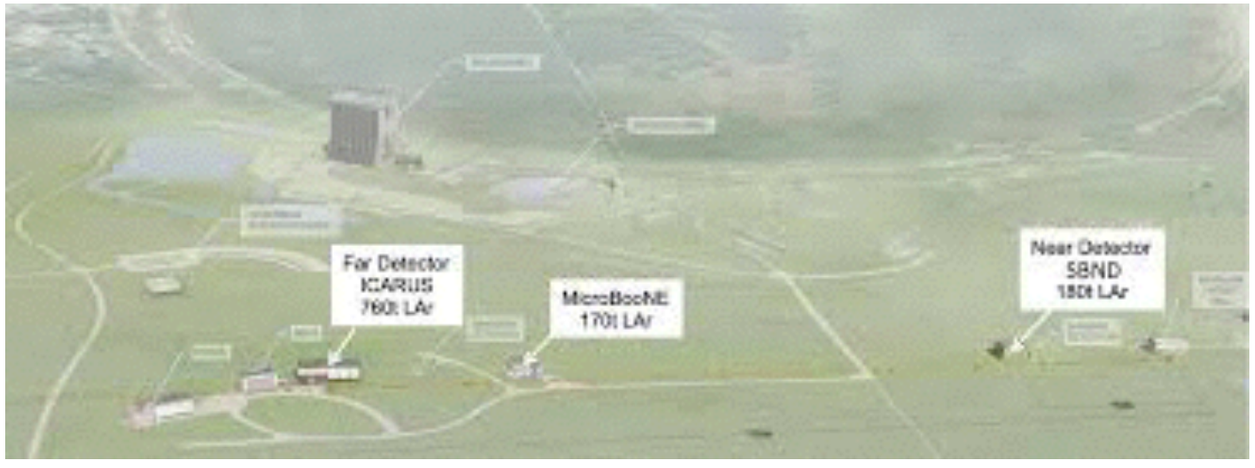
Surface-based ν experiments (Cosmic-ray backgrounds)

- iBDM: unique signal topology, decent detector ability
  (machine learning would help)
  Chatterjee, De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, Yu, 1803.03264
- eBDM: interesting idea i) darkstrahlung (unique signal topology)
  Kim, Park, **SS**, 1903.05087
  ii) Earth shielding (upward signal only)
  Kim, Kong, Park, **SS**, 1804.07302

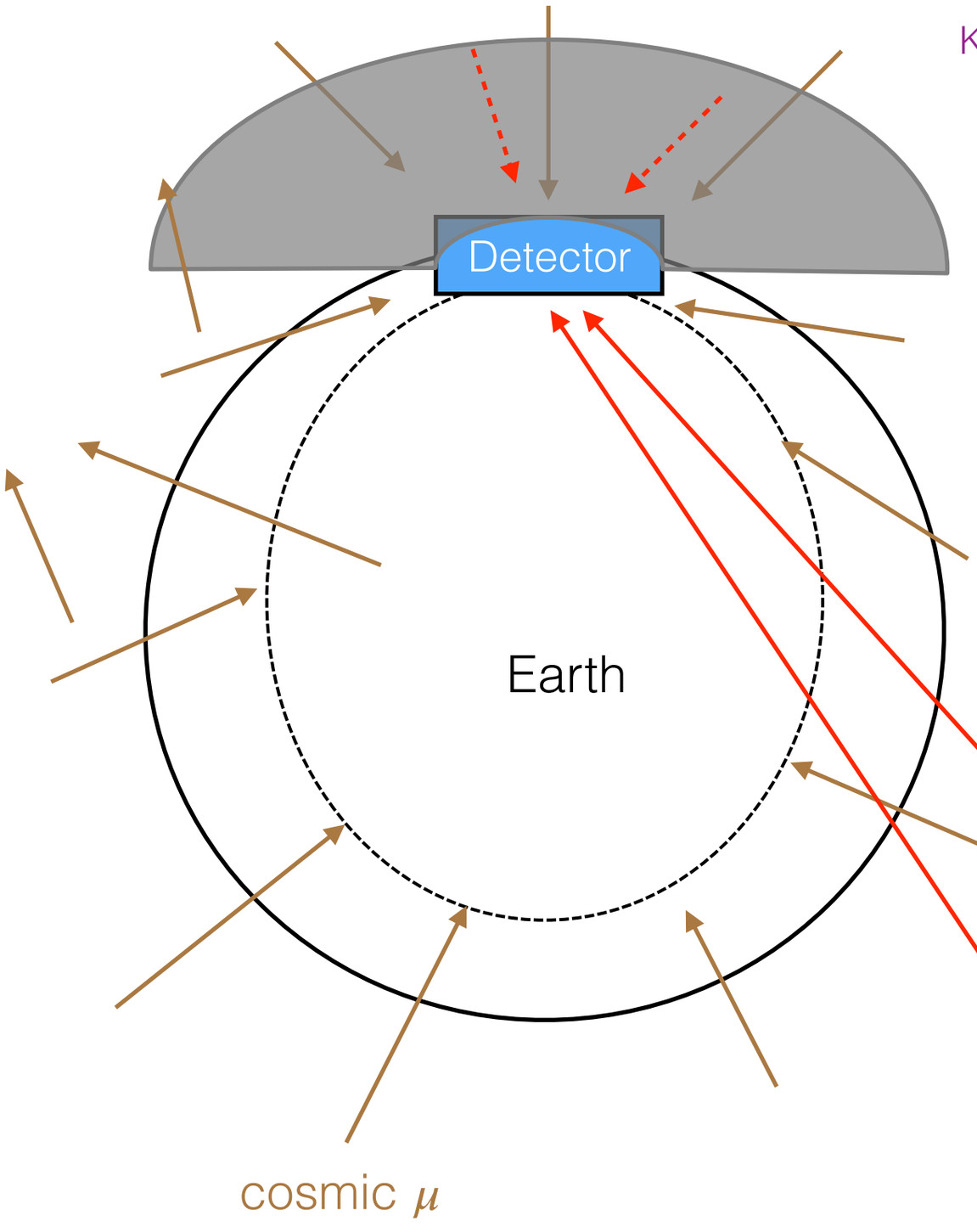
ProtoDUNE



SBNP



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

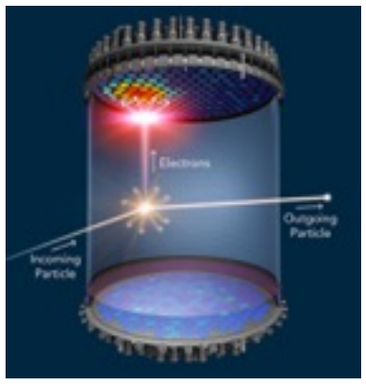
Smaller size good if $m_{\chi 0} \lesssim$ O(1 GeV)

DM direct detection experiments

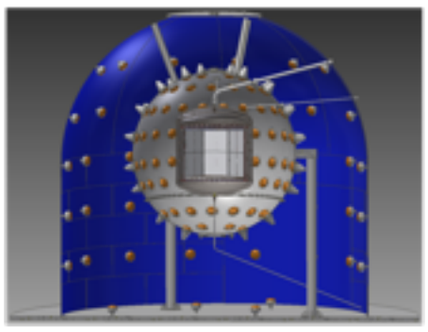
- Need special strategies: PMT saturation (ionization signal)
- Pattern of scintillation signals (identify two displaced vertices)
- Double scattering signal in the array-type detectors (COSINE-100)

→ First iBDM search result

1811.09344



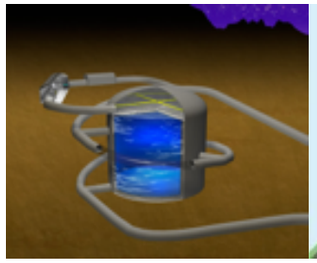
LUX-ZEPLIN
or Xenon NT

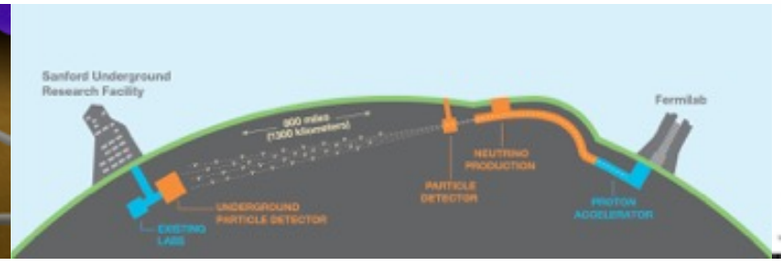


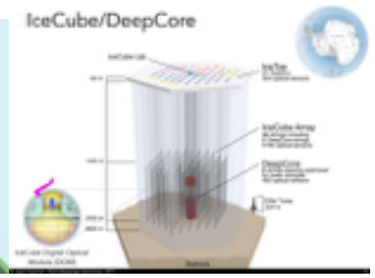
DarkSide-20k

COSINE-100

Complementary searches



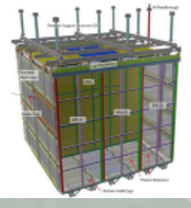


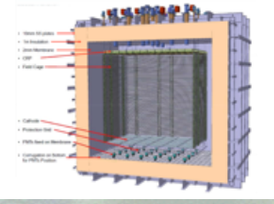


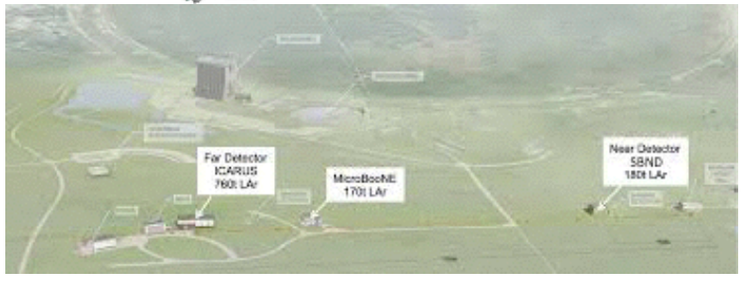
Large volume ν experiments (underground)

signal observation

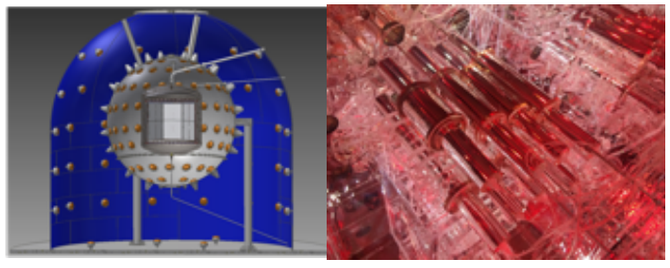
background subtraction





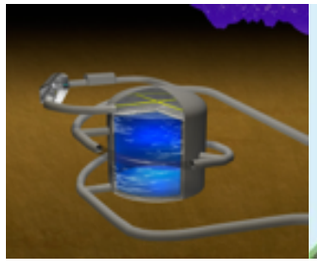


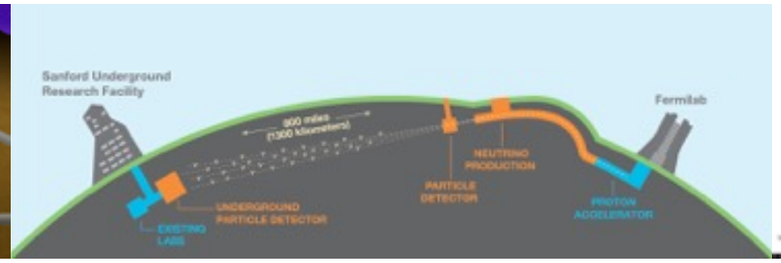
Moderate volume surface ν experiments

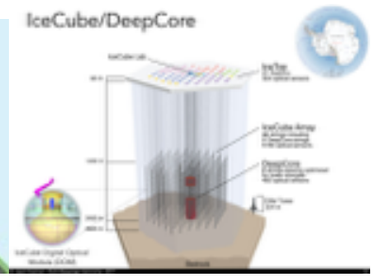


Ton scale DM direct detection experiments (underground)

Complementary searches





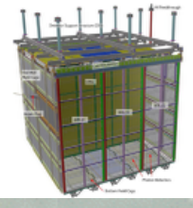


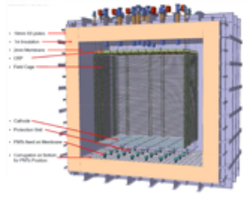
Large volume ν experiments (underground)

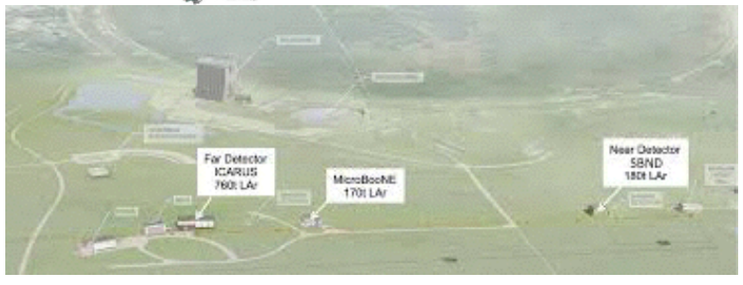
signal observation

background subtraction

Early discovery & less ν background

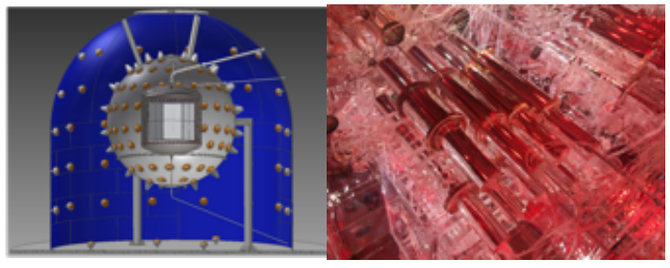






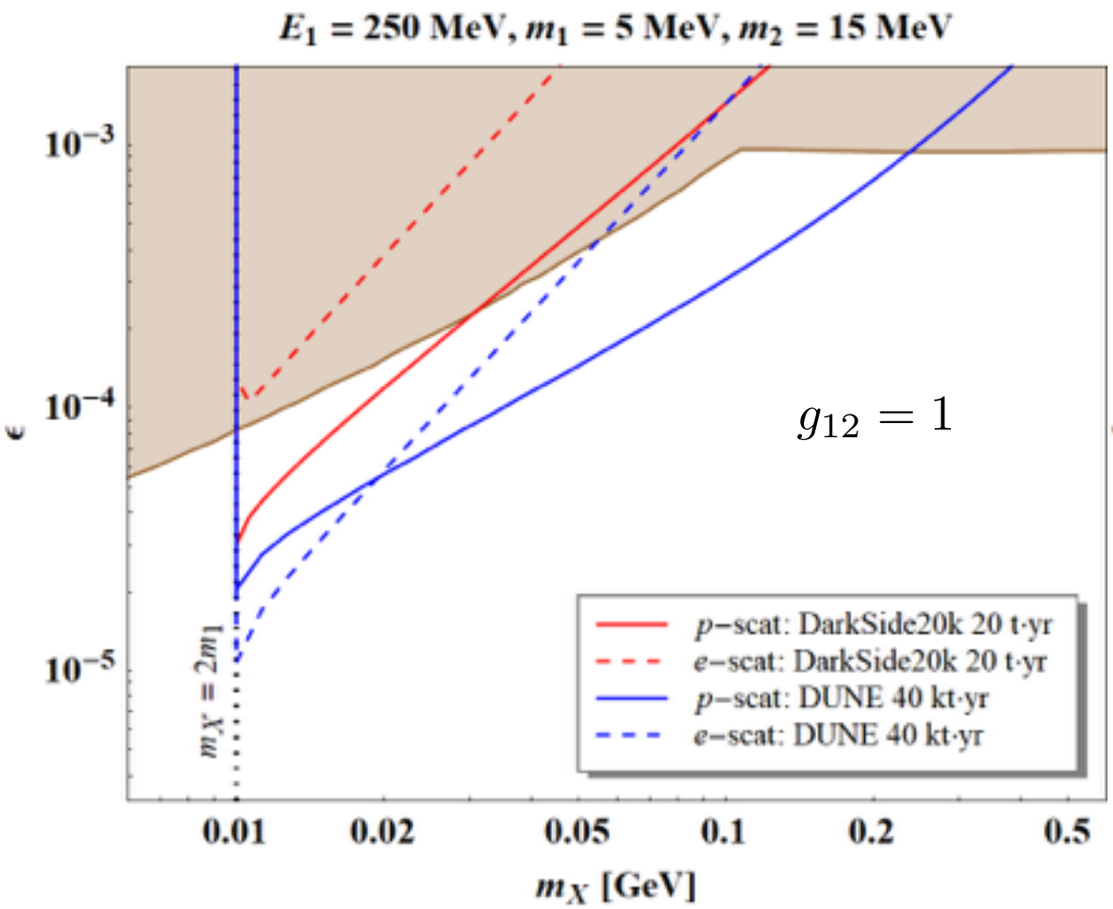
Moderate volume surface ν experiments

Better resolution (E_{th}, angle)
Sensitive for smaller $E_1=m_0$

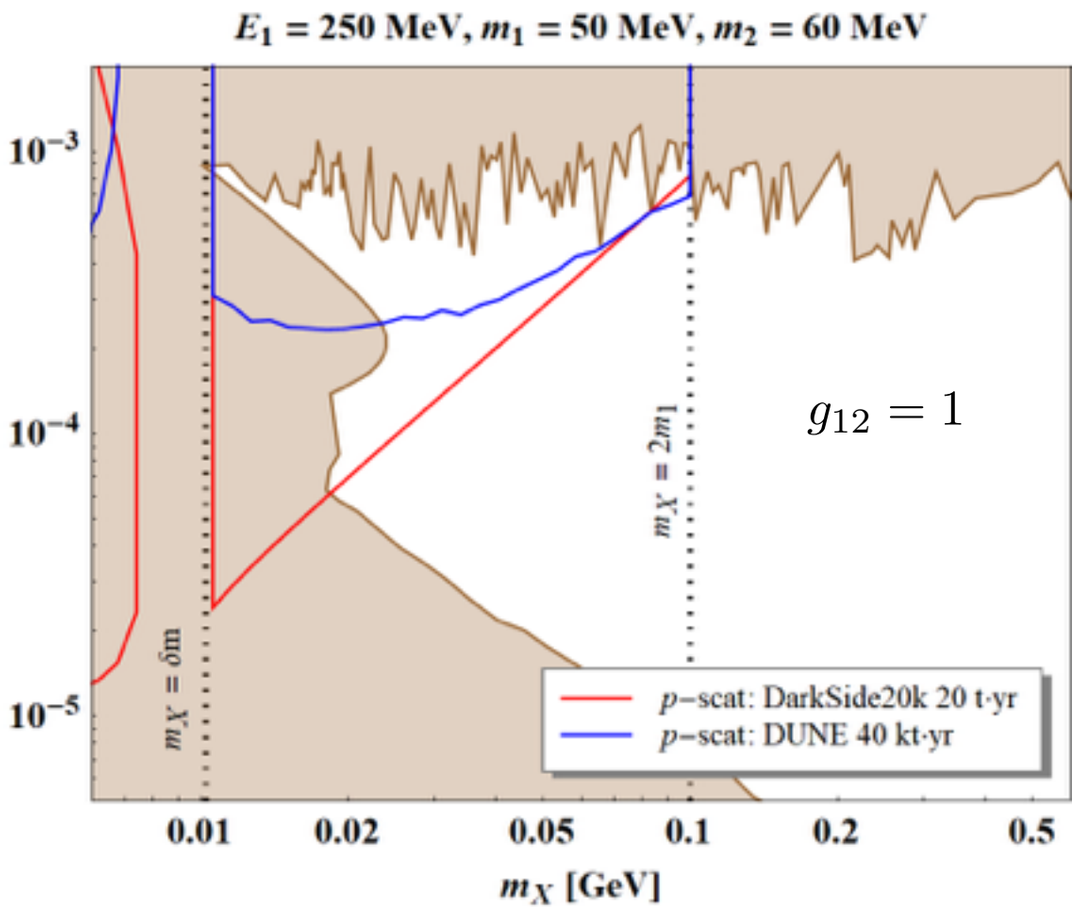


Ton scale DM direct detection experiments (underground)

Sensitivities at DUNE vs DarkSide



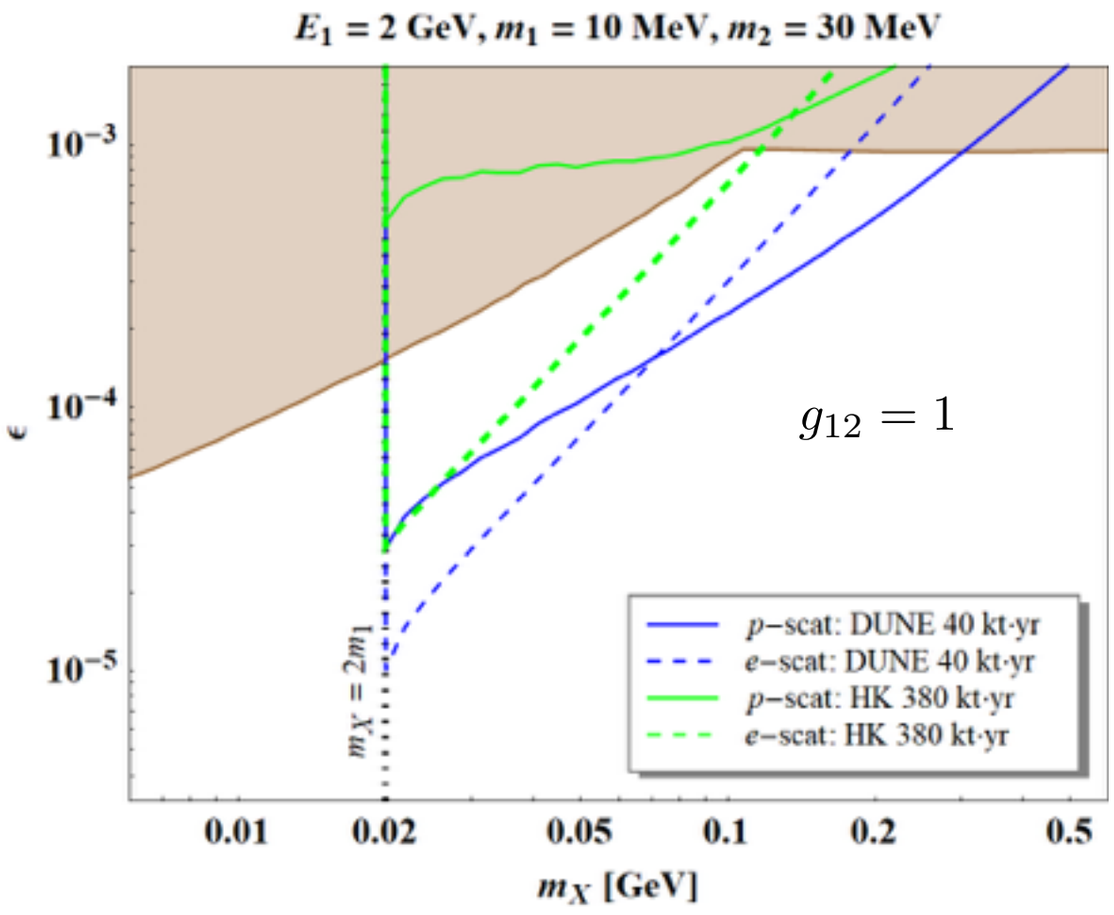
$m_X > 2m_1$ $\quad \chi_2 \to X^* \chi_1 \to e^+ e^- \chi_1$



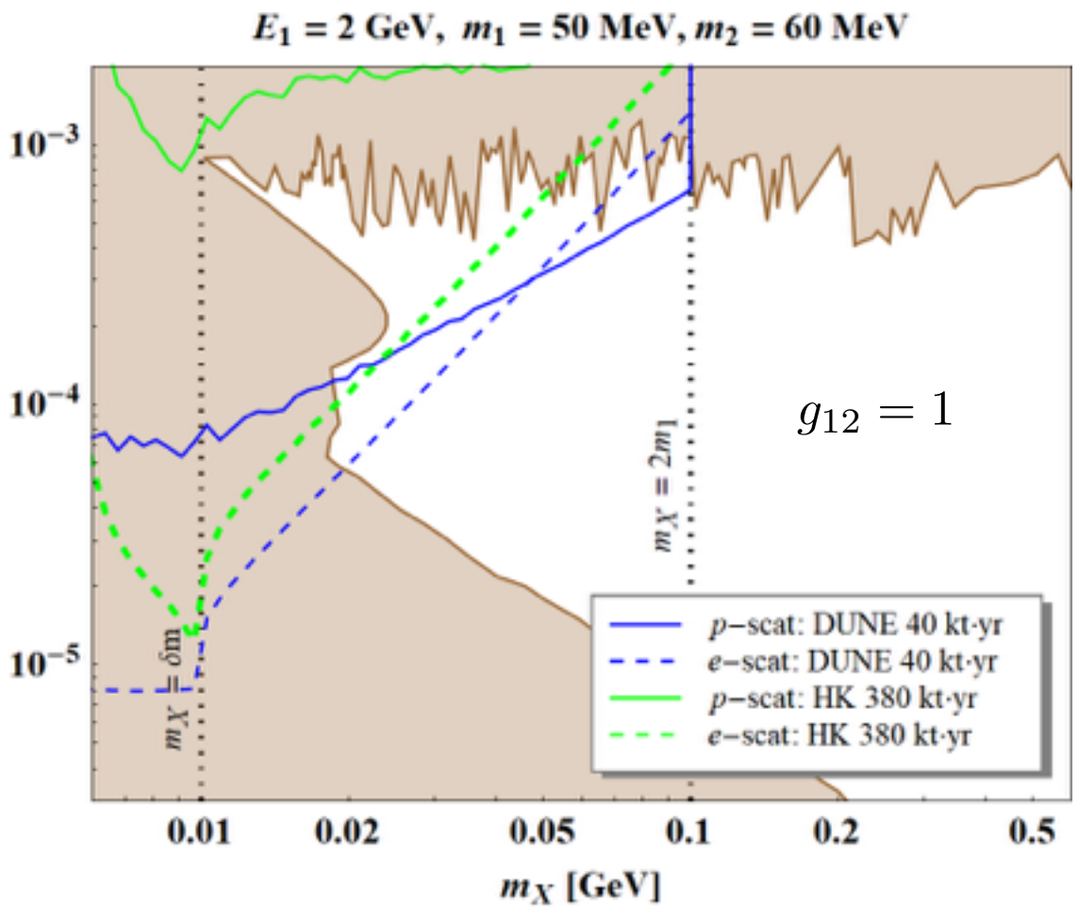
$m_X < 2m_1$ $\quad \chi_2 \to X^{(*)} \chi_1 \to e^+ e^- \chi_1$

- p-scattering larger than e-scattering as increasing m_X
- DarkSide-20k gets sensitive for smaller m_X (longer decay length)
- DarkSide-20k can be competitive over DUNE when E_1 and m_X is small (E_{th})

Sensitivities at DUNE vs HK



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



$m_X < 2m_1$ $\quad \chi_2 \to X^{(*)} \chi_1 \to e^+ e^- \chi_1$

- 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

  → Better for larger E_1
- Difference huge for p-scattering

Conclusions

- BDM (iBDM & eBDM) is an excellent alternative of conventional WIMP
  & requires new DM search strategies

- Unique signal feature helps to reject ν background:

  i) iBDM

  ii) Darkstrahlung for eBDM

- Complementary searches in various experiments

  1. Large (underground) ν experiments

  2. Moderate surface ν experiments: early discovery, less ν background

  3. Ton scale DM direct detection experiments: smaller E_1, lower E_{th}

Backup: Other BDM scenarios

Model building: right relic abundance of DM, mechanism boosting DM

Agashe, Cui, Necib, Thaler, 1405.7370

- Multi-component model — Belanger, Park, 1112.4491
- Semi-annihilation model — D'Eramo, Thaler, 1003.5912
- $3 \to 2$ model — Carlson, Machaceck, Hall, Astrophys J. (1992); Hochberg, Kuflik, Volansky, Wacker, 1402.5143

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

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

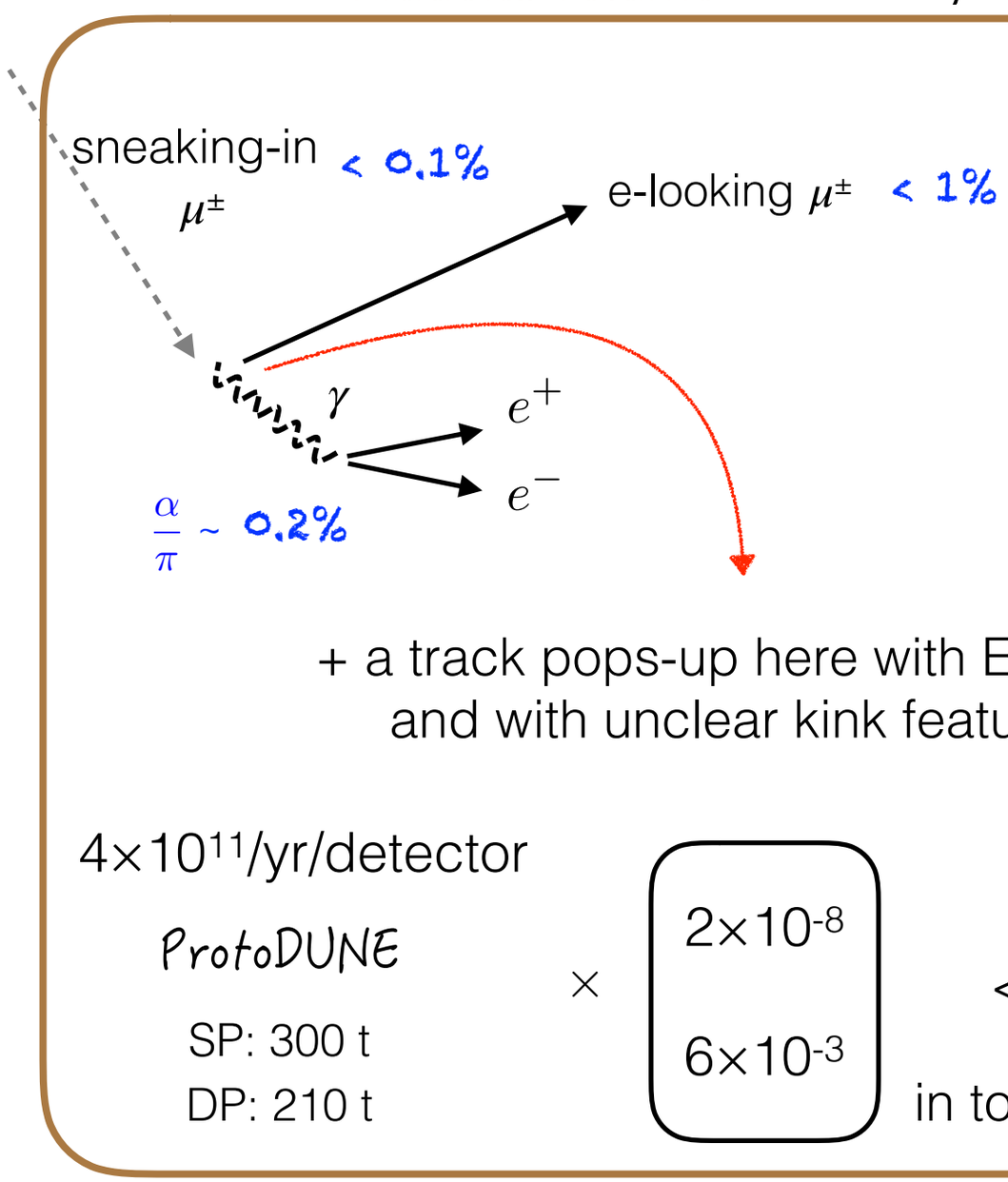
  Energetic cosmic-ray induced DM — Yin, 1809.08610; Bringmann, Pospelov, 1810.10543; Ema, Sala, Sato, 1811.00520

Same phenomenology

Backup: cosmic-ray background

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

Fiducial volume cosmic μ events (> 400 MeV) ≃ 94/m²/s/sr at sea level



- Dominant background: sneaking-in muon (rare events but many cosmic-muons)
- Assume the unknown probability ~ 0.6%

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

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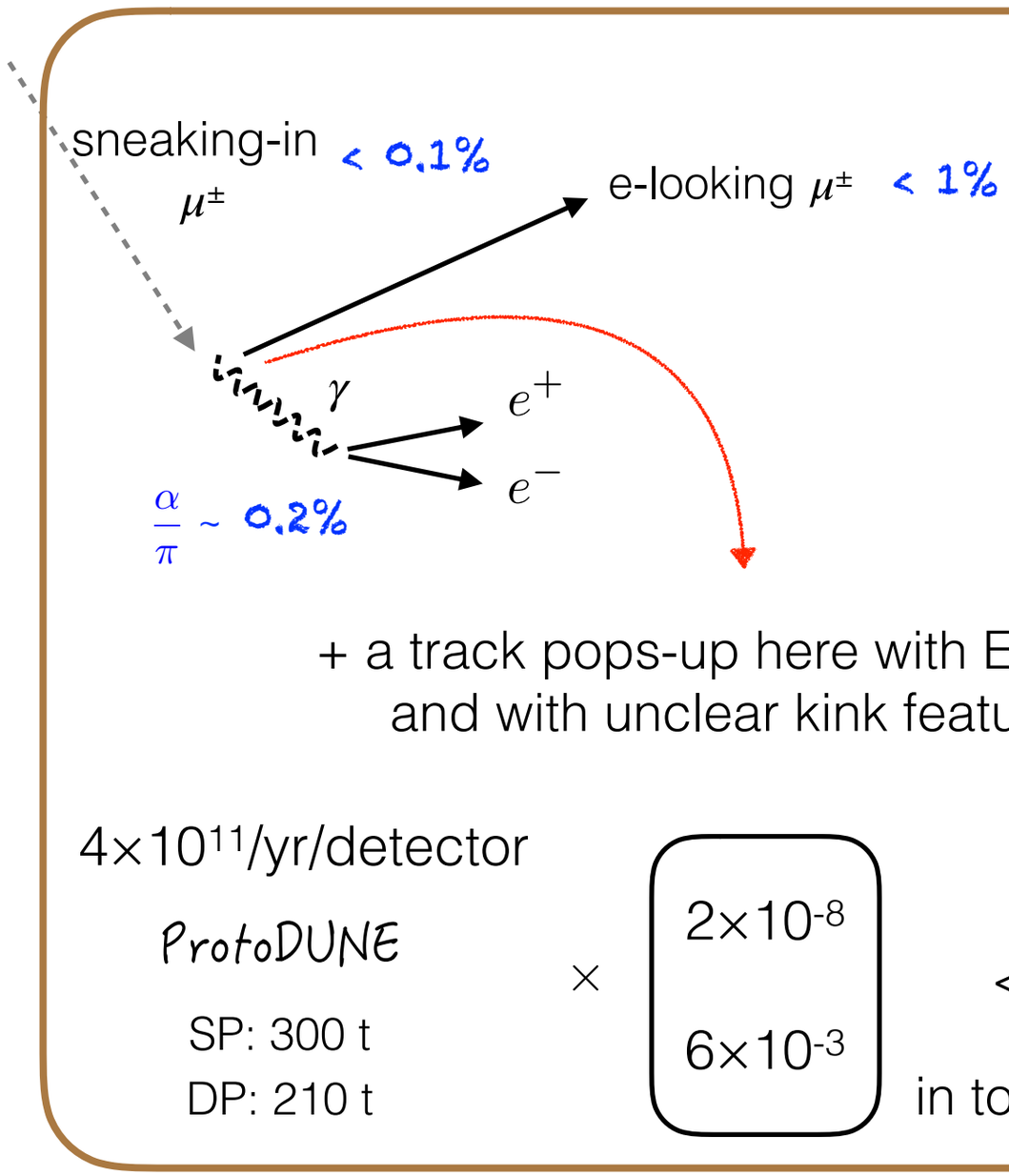
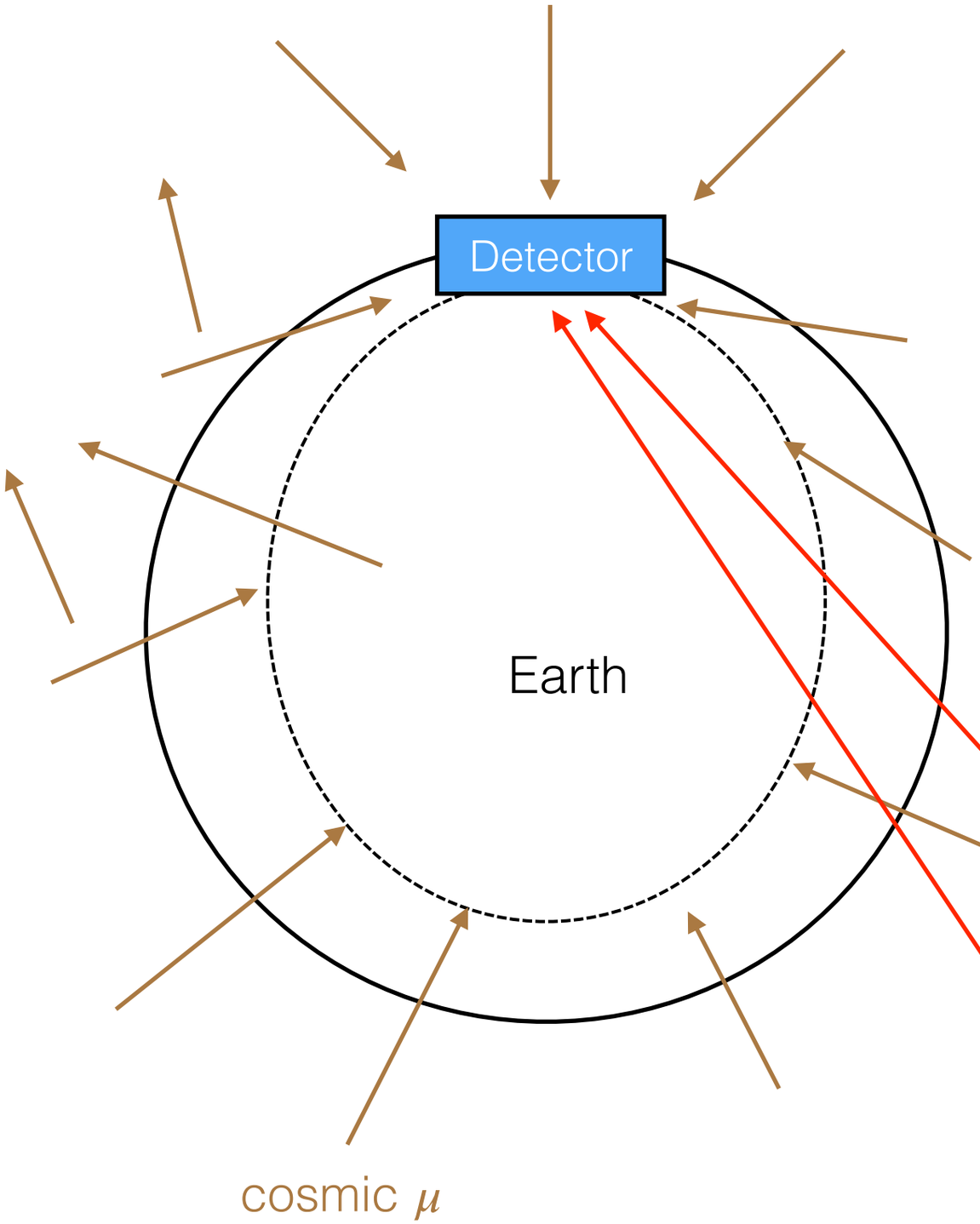


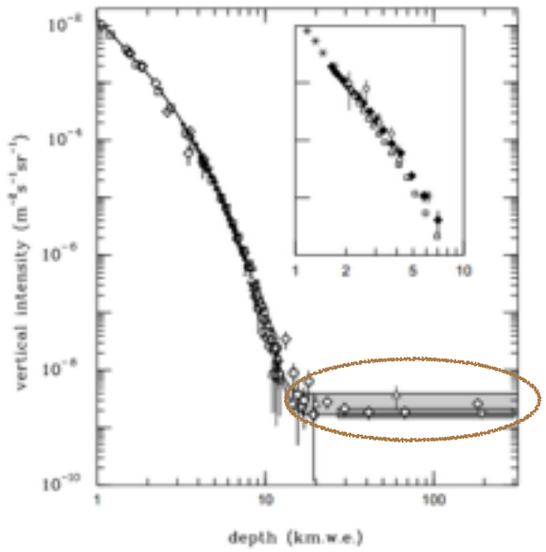
- Dominant background: sneaking-in muon (rare events but many cosmic-muons)
- Assume the unknown probability ~ 0.6%
- Pattern analysis by machine learning will decrease further (N_{bkg}: negligible)

Work in progress

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

Backup: Earth shielding





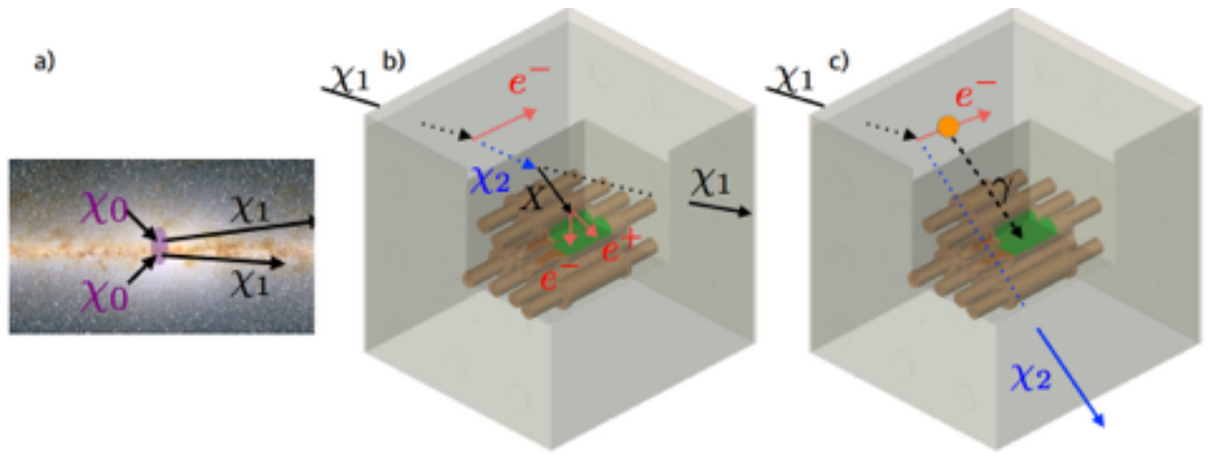
Dashed: 7km below sea level

$N_\mu \sim 0.1/\mathrm{m}^2/\mathrm{yr}$

χ_1 if the source is here

Backup: COSINE-100 result

COSINE-100, 1811.09344



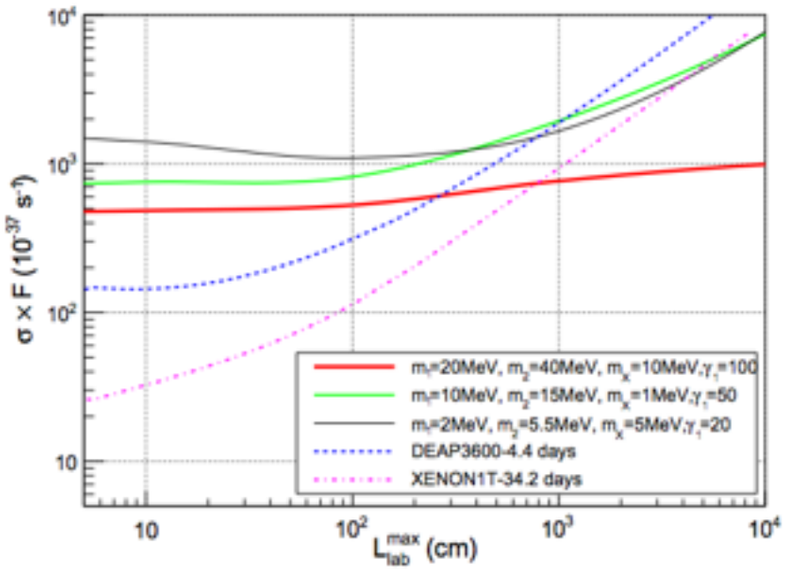
Based on theoretical study

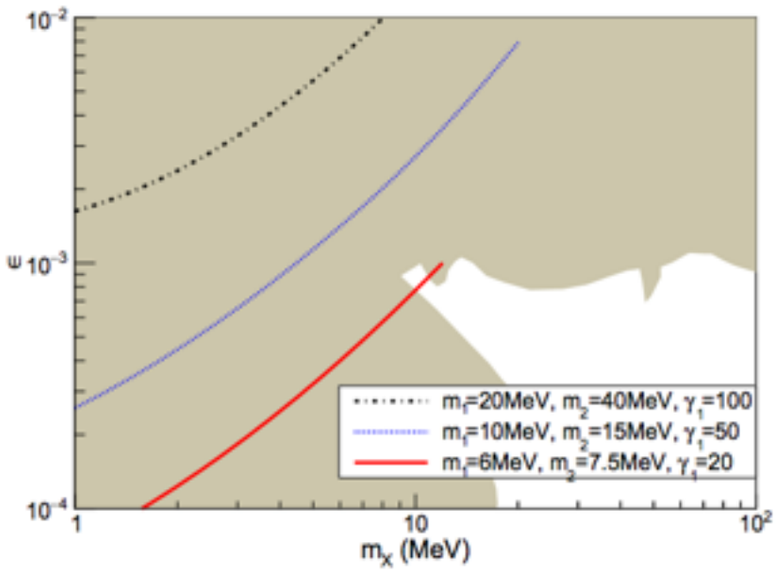
Giudice, Kim, Park, **SS**, 1712.07126

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

2200L of liquid scintillator
(~ 2 ton)

Observed: 21 events, Background expected: 16.4 ± 2.1





Backup: sensitivity

$$N_{\mathrm{sig}} = \sigma_e \cdot \mathcal{F} \cdot A \cdot t_{\mathrm{exp}} \cdot N_T$$

- σ_e: scattering cross section between χ_1 and (target) electron
- $\mathcal{F}$: flux of incoming (boosted) χ_1
- A: acceptance (detector geometry, only for iBDM)
- t_{exp}: exposure time
- N_T: total number of target (e,p,n)

) Fixed for a given experiment

Backup: sensitivity

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) Fixed for a given experiment

Both primary and secondary inside the fiducial volume

- Function of decay length of χ_2 (event generation assuming cumulatively isotopic flux of χ_1)
- Conservatively, we calculate the maximum mean decay length in the laboratory frame for each parameter set

Backup: sensitivity

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

σ^{fid} or σ^{vis}

- σ_ϵ: scattering cross section between χ_1 and (target) electron
- $\mathcal{F}$: flux of incoming (boosted) χ_1
- A: acceptance (detector geometry, only for iBDM)
- t_{exp}: exposure time
- N_T: total number of target (e,p,n)

with signal efficiency

Fixed for a given experiment

Both primary and secondary inside the fiducial volume

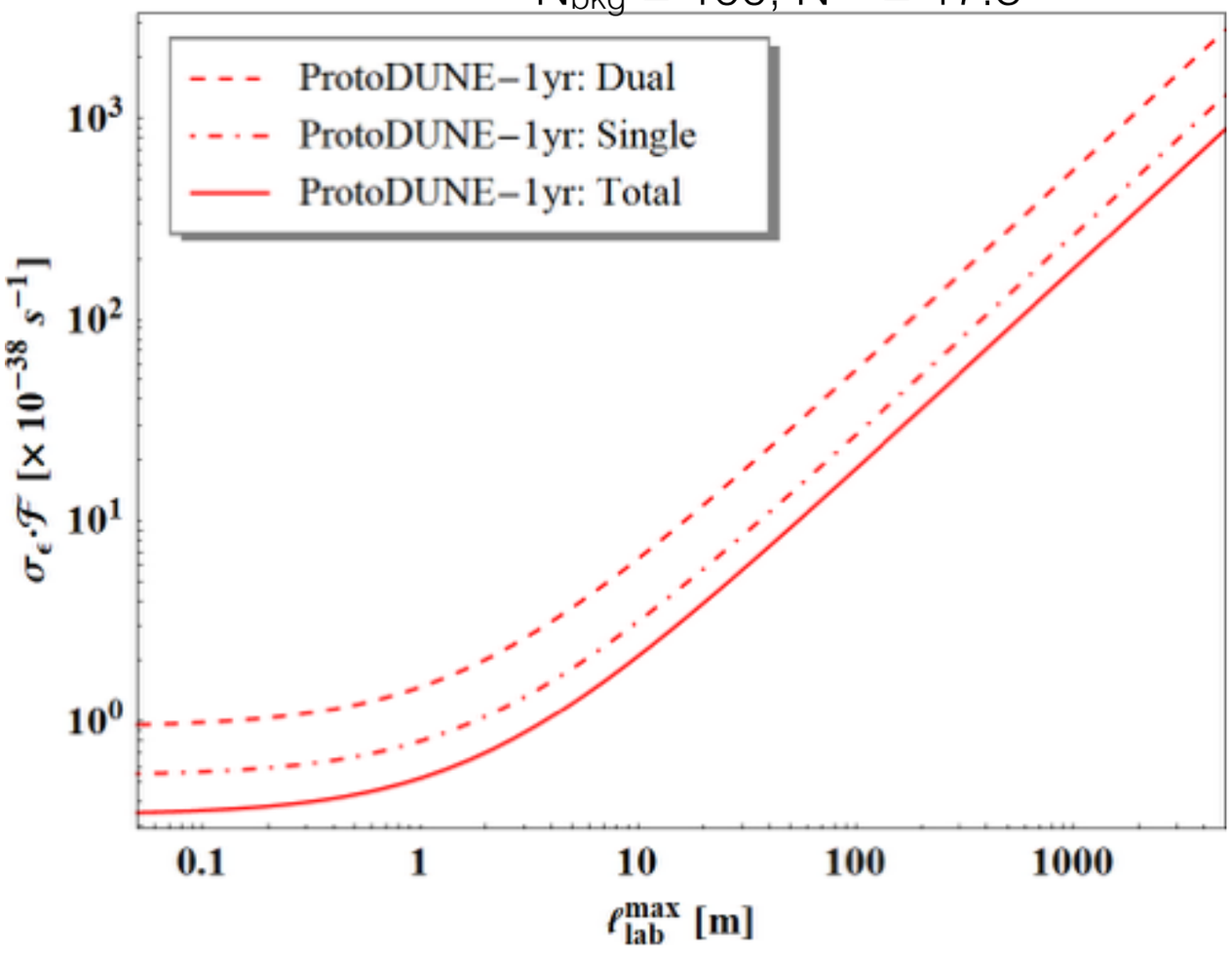
- Function of decay length of χ_2 (event generation assuming cumulatively isotopic flux of χ_1)
- Conservatively, we calculate the maximum mean decay length in the laboratory frame for each parameter set

Backup: model independent sensitivity

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

$$\sigma_\epsilon \cdot \mathcal{F} \geq \frac{2.3}{A(\bar{\ell}^{\max}_{\rm lab}) \cdot t_{\rm exp} \cdot N_T}$$

e.g., ProtoDUNE (worst case)
N_{bkg} = 100, N^{90} = 17.8



Backup: Reference Model

Dark photon (X_μ) mediator

(Pseudo-) Dirac fermionic DM

Kim, Park, **SS**, PRL 2017

Giudice, Kim, Park, **SS**, PLB 2018

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

kinetic mixing eBDM iBDM

$$-\mathcal{L}_m = m_L \psi_L^T C \psi_L + m_R \psi_R^T C \psi_R + 2 m_D \bar{\psi}_R \psi_L + \text{h.c.} = \Psi^T C M \Psi + \text{h.c.}$$

$$\Psi \equiv \begin{pmatrix} \psi_L \\ \psi_R^c \end{pmatrix} \qquad M \equiv \begin{pmatrix} m_L & m_D \\ m_D & -m_R \end{pmatrix},$$

Spontaneously broken U(1)$_X$

Backup: Reference Model

Dark photon (X_μ) mediator

(Pseudo-) Dirac fermionic DM

Kim, Park, **SS**, PRL 2017

Giudice, Kim, Park, **SS**, PLB 2018

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kinetic mixing — eBDM — iBDM

Extension possible: scalar DM, Higgs portal, dipole operator, …

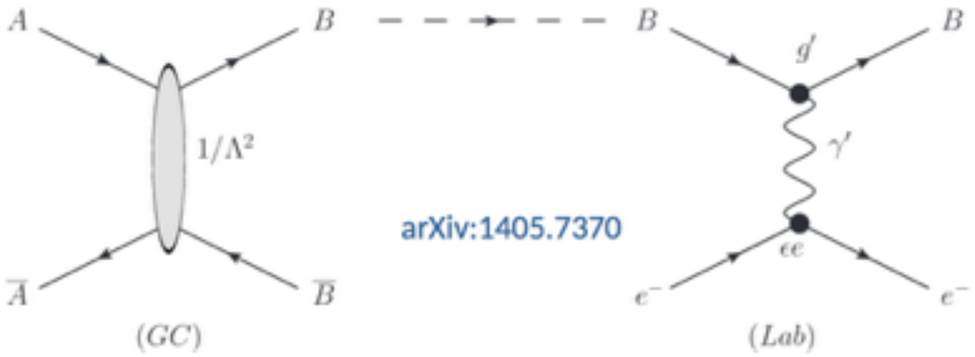
cf inelastic DM hep-ph/0101138 co-annihilation Binetruy, Girardi, Salati, NBP 1984; Mizuta, Yamaguchi, PLB 1993

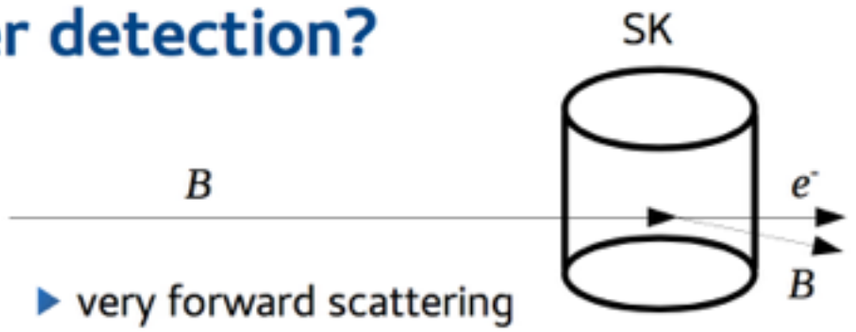
Comple-mentary

- iDM + de-excitation (in the current universe): astro-ph/0702587 0903.1037 1312.1363
- LHC: 1109.4144 1311.6169 1508.03050 1810.01879
- Fixed target experiments: 1403.6826 1804.00661

Backup: SK

(In)direct dark matter detection?

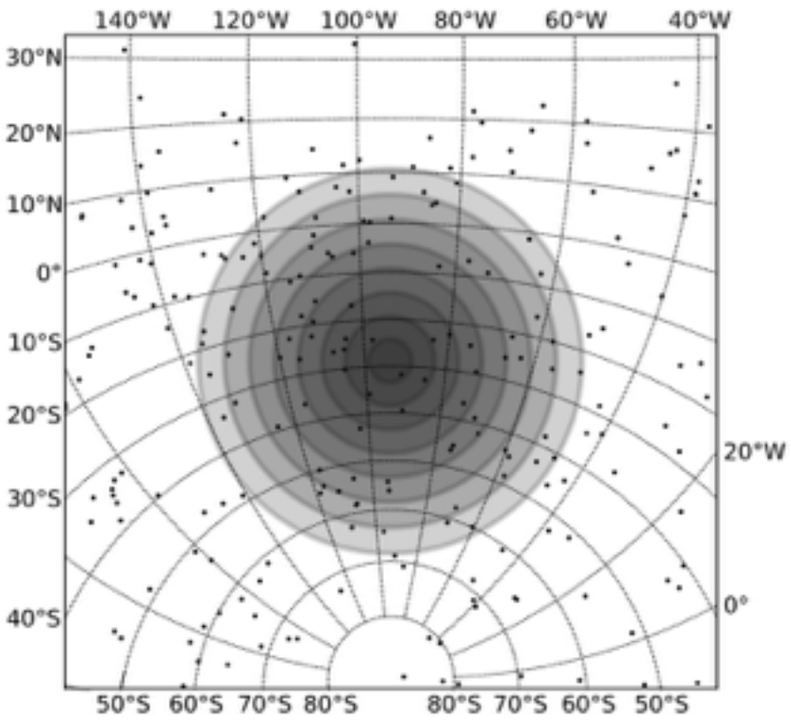


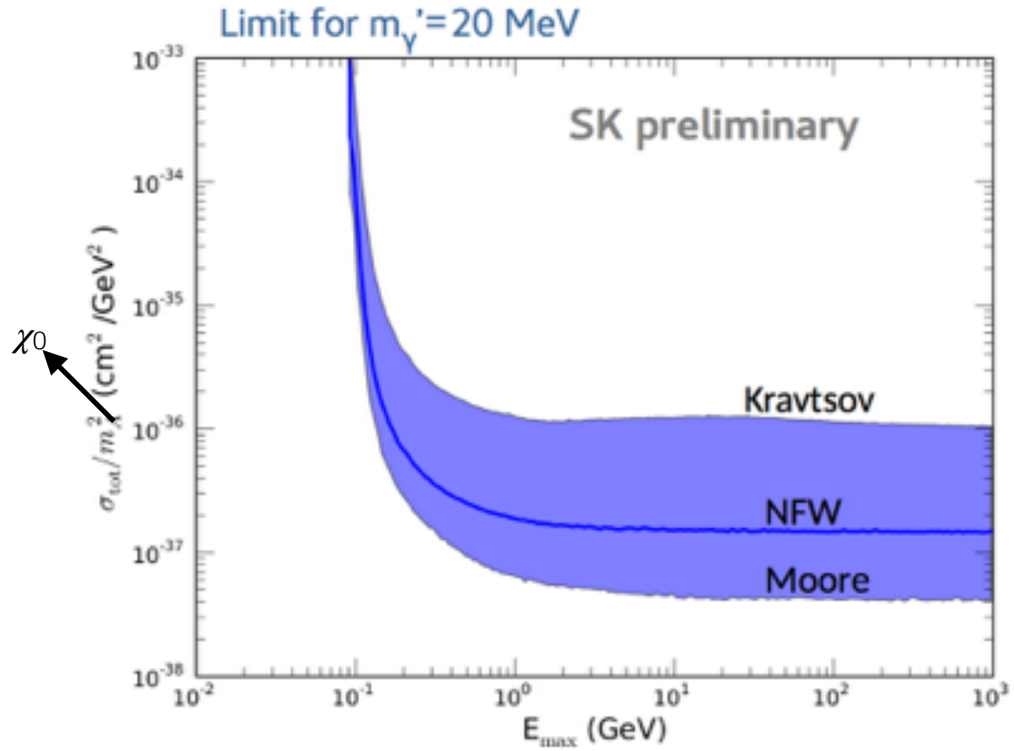


- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

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

→ No clusters visible





Backup: SK

0.1 GeV < p_e < 1 TeV

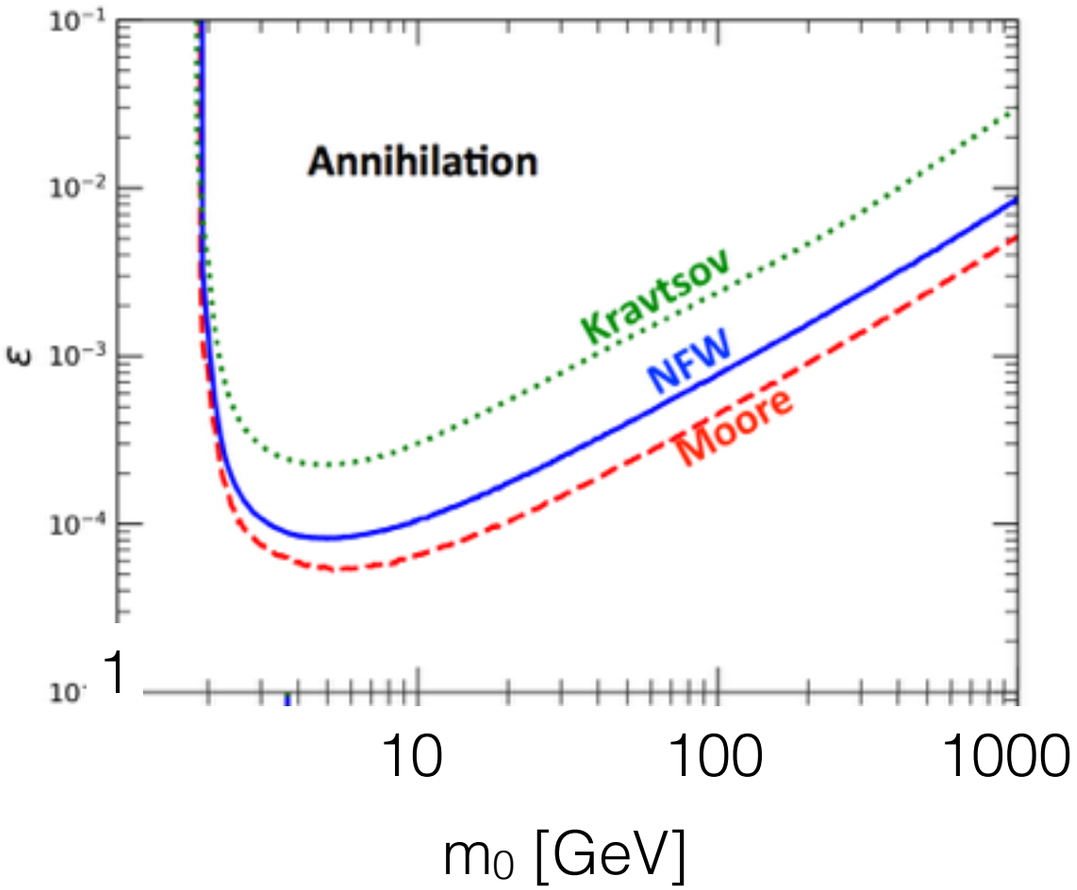
p_e^{th} with angular resolution 3°

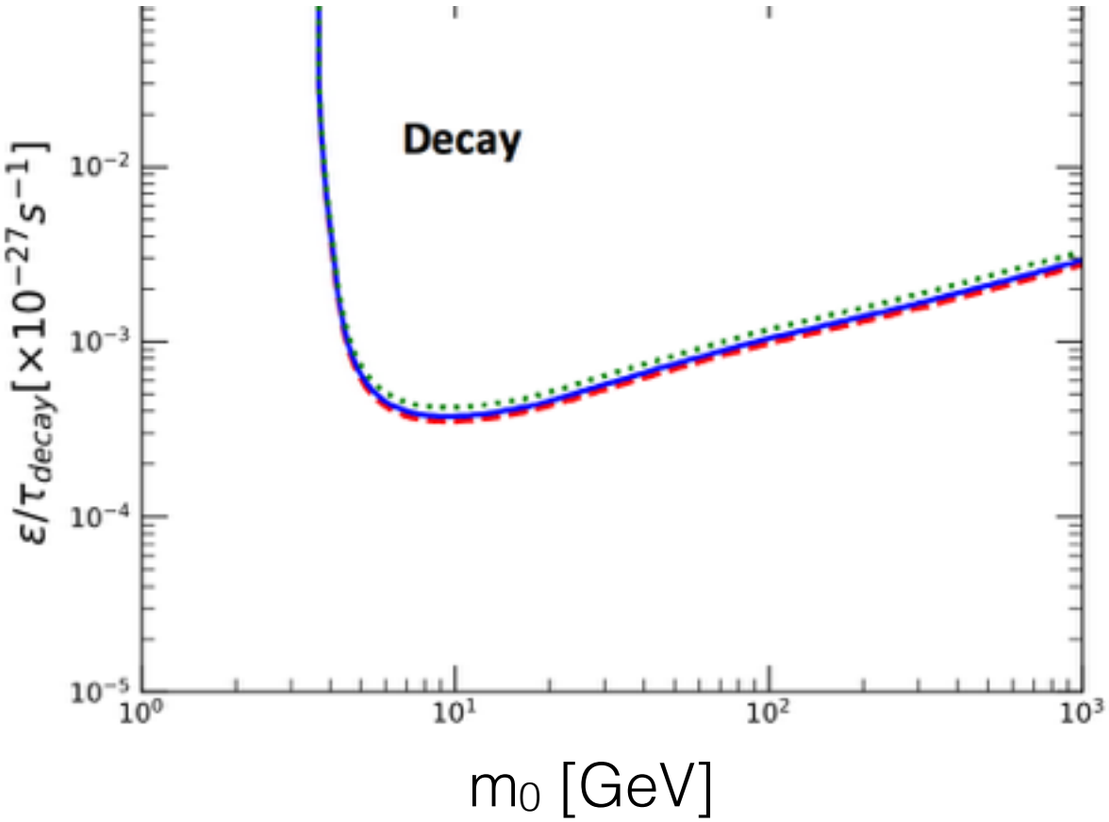
GC & Sun

1. 1-ring (if E_{vis} <100 GeV)
2. *e*-like
3. 0 decay electrons
4. 0 tagged neutrons

SK, 1711.05278

90% bound





m_1 =200 MeV, m_X = 20 MeV, g_{11}=0.5