Dark Matter Identification 2019

Boosted Dark Matter and the signal probes at Neutrino and Direct Detection 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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detection

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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

$$\chi_0 \longleftrightarrow \chi_1$$

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

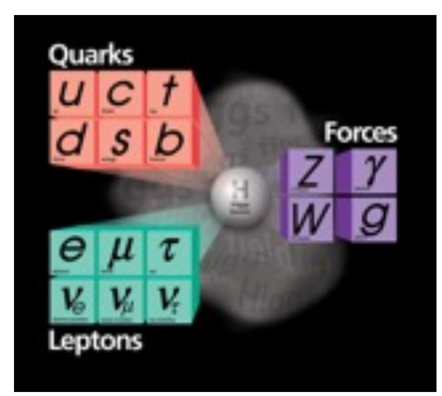
Simple two-component DM

$\langle \sigma v \rangle_{\chi_0 \bar{\chi}_0 \to \chi_1 \bar{\chi}_1}$ 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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χ_0

Gravitational int.

χ_1

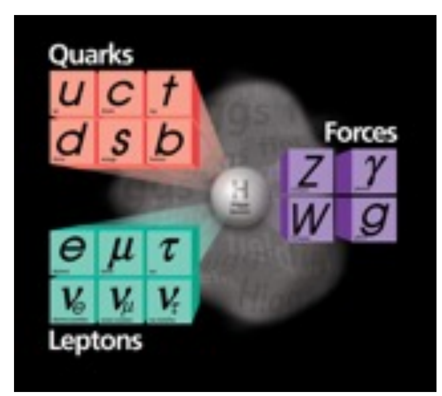
Negligible relic

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

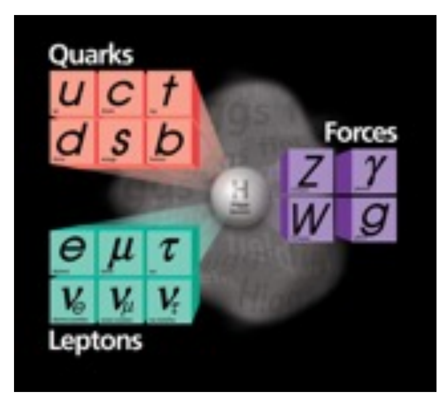
$\langle \sigma v \rangle_{\chi_0 \bar{\chi}_0 \to \chi_1 \bar{\chi}_1}$ determines $\Omega_{\rm DM} \simeq \Omega_{\chi_0}$

Easy set-up!

heavy		light
χ_0	⟷	χ_1
Gravitational int.		Weak (or other scale) int. with SM

Assisted freeze-out

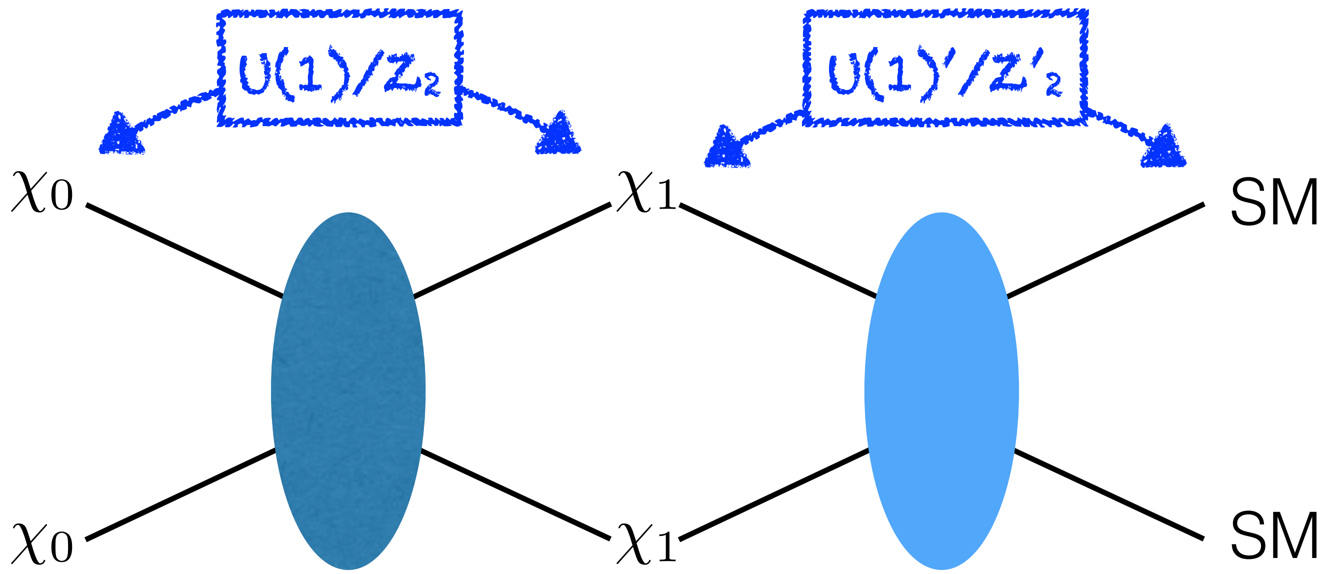
Belanger, Park, 1112.4491



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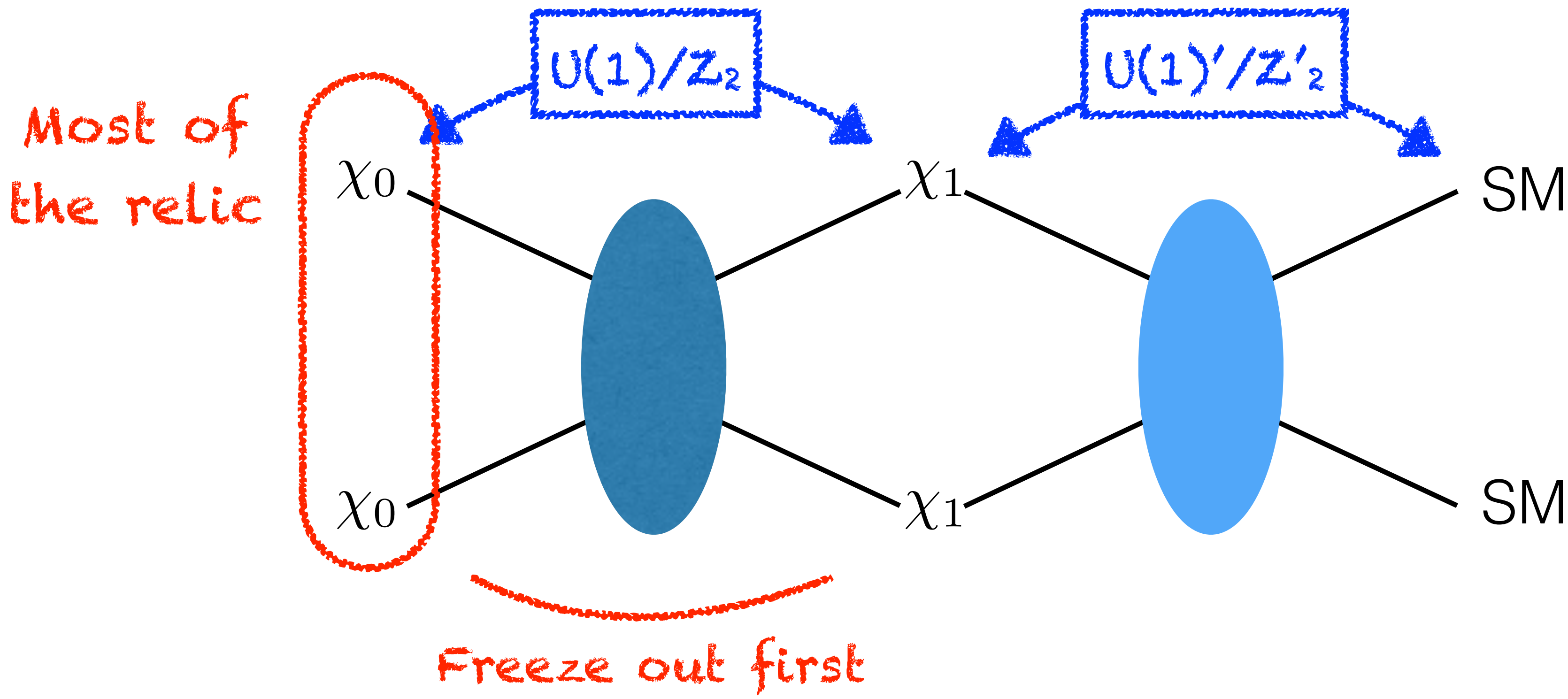

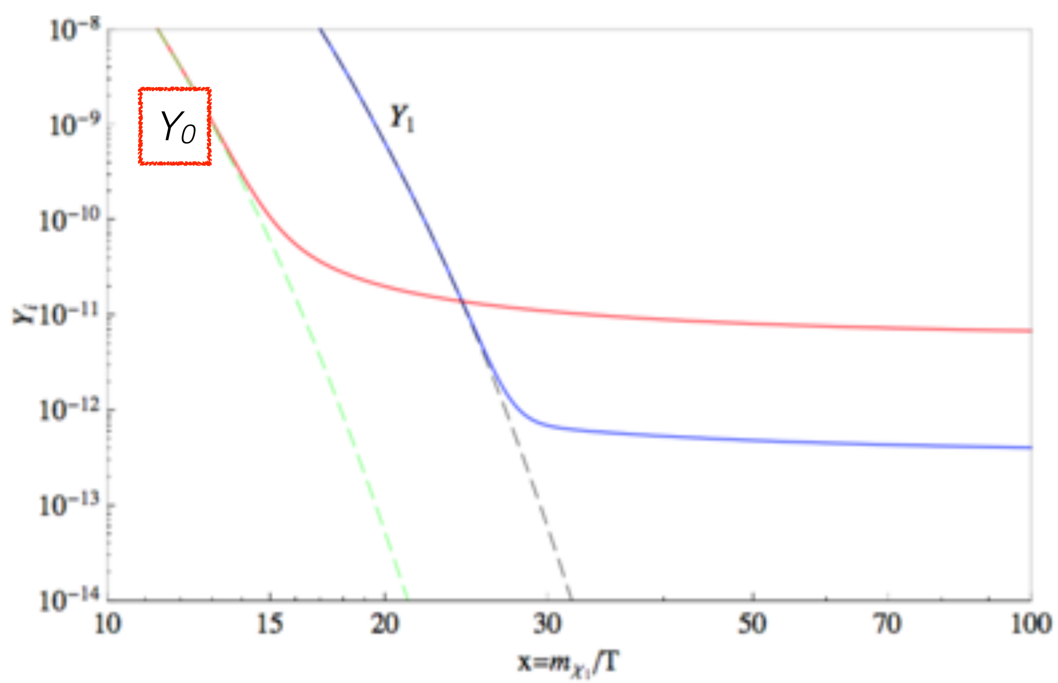

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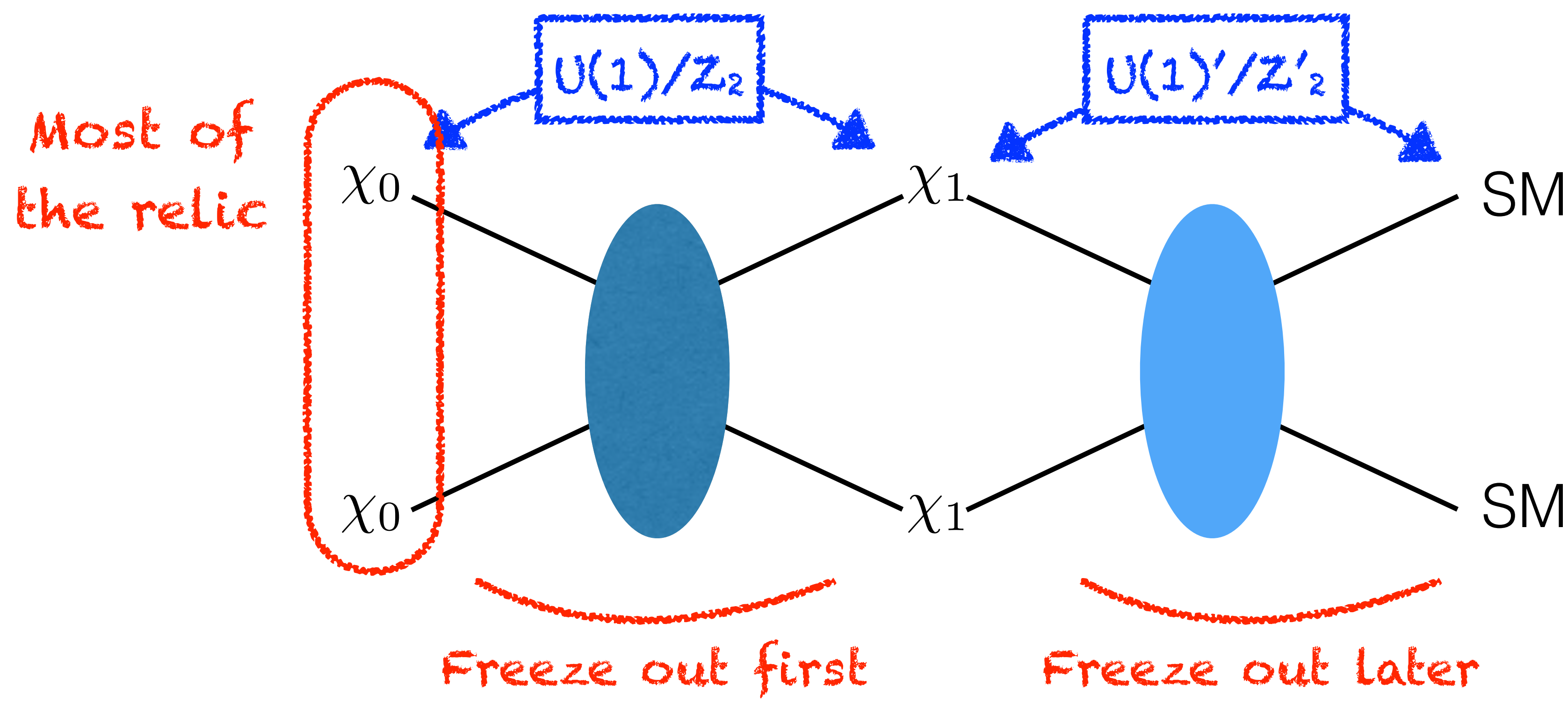

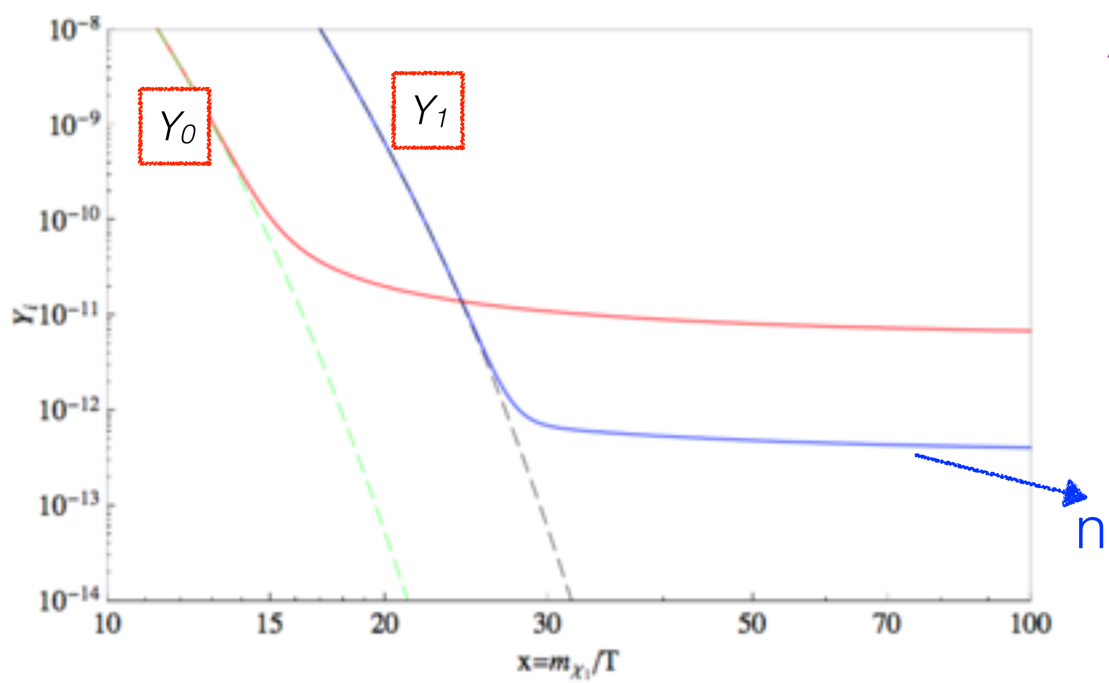

Agashe, Cui, Necib, Thaler,1405.7370

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

Assume: NFW

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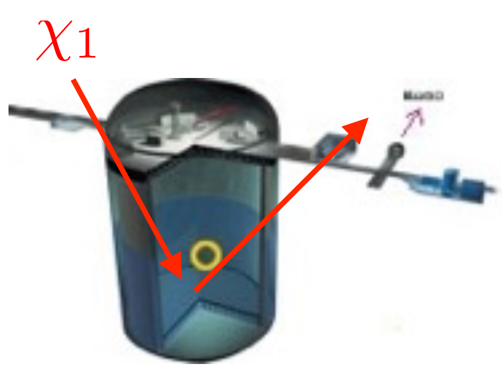
Assume: NFW

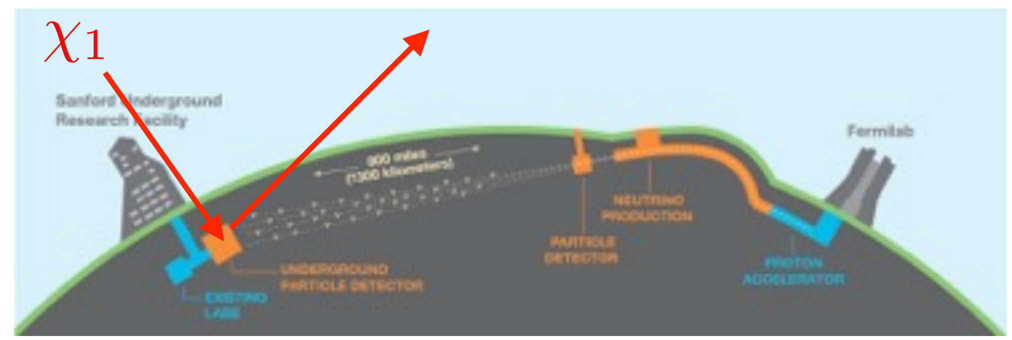
Fixed ~ 1 if s-channel annihilation dominates

10,000 times smaller than the flux of atmospheric neutrino

Huge detector if $m_{\chi_0} \gtrsim O(10\ \mathrm{GeV})$

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





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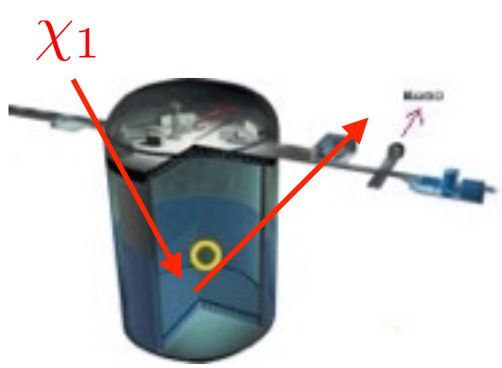
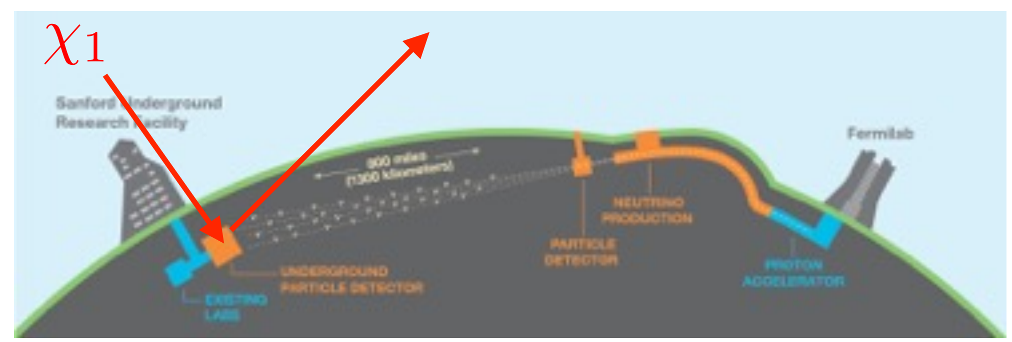




Subtraction of
major background (ν)

- 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

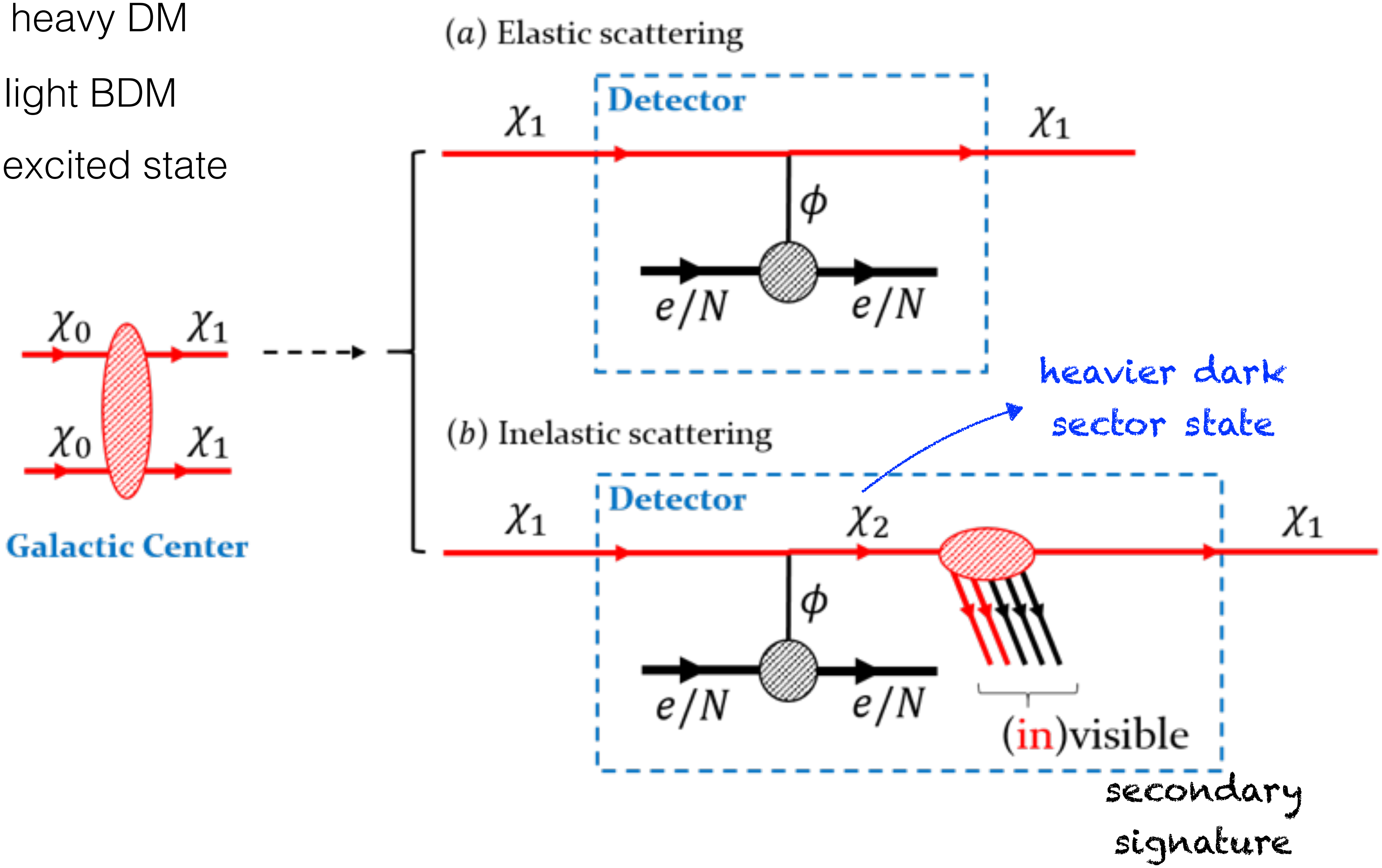
Inelastic BDM (iBDM) and darkstrahlung

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)

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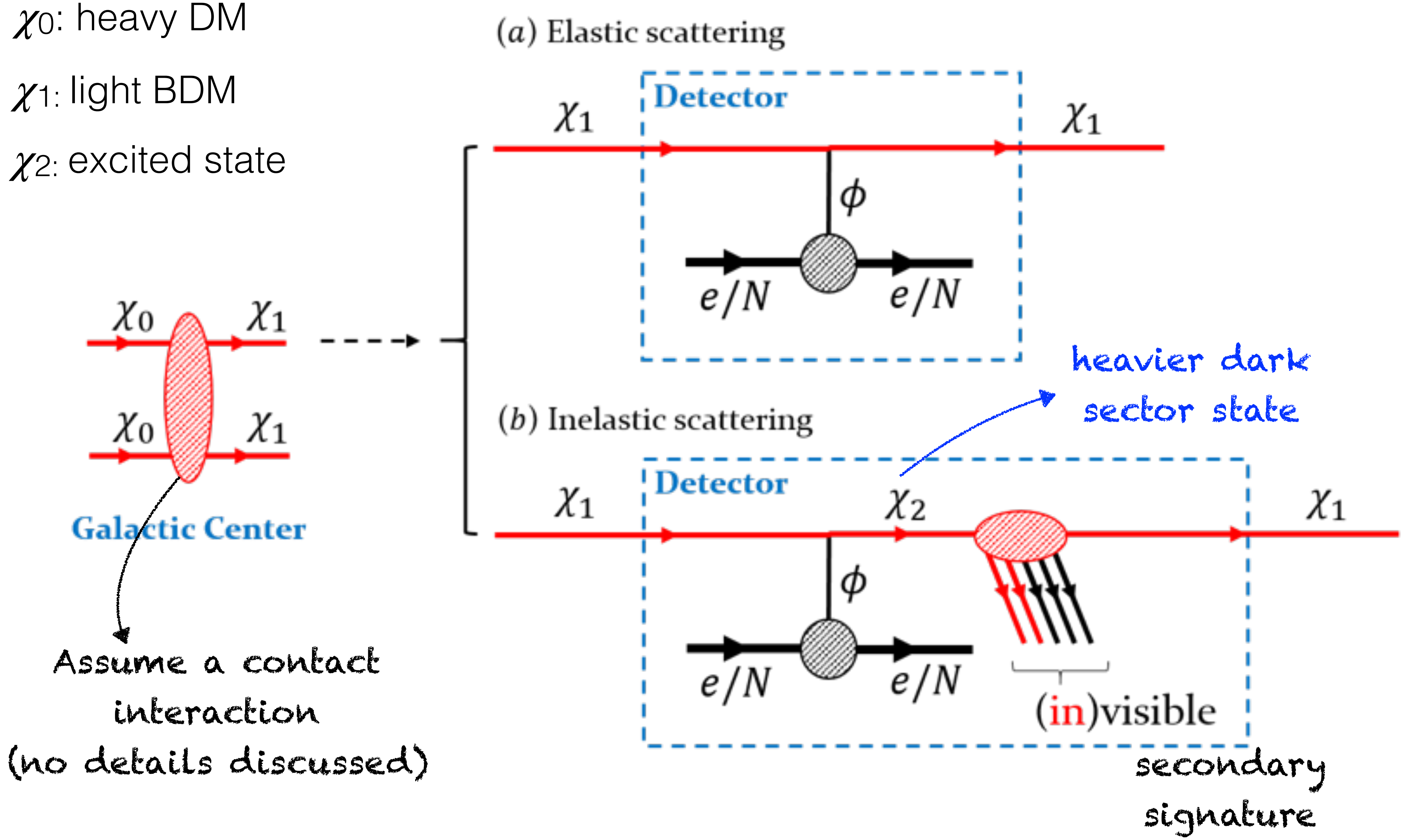

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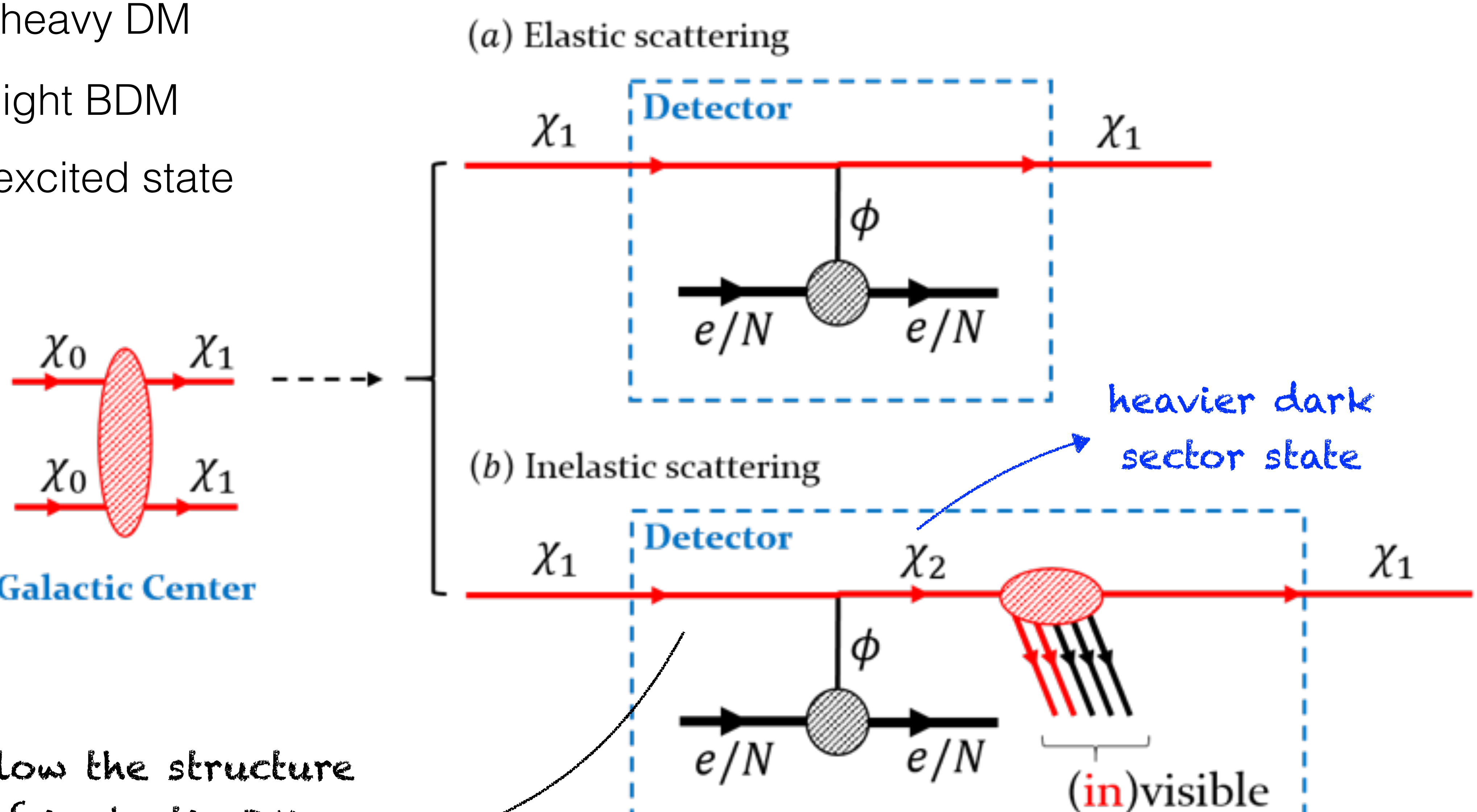

heavier dark sector state

Follow the structure of inelastic DM e.g., pseudo-Dirac fermion, dark photon

secondary signature

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

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

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 $U(1)_X$

Reference Model

Dark photon (X_μ) mediator

(Pseudo-) Dirac fermionic DM

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

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

↓ kinetic mixing ↓ eBDM ↓ iBDM

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

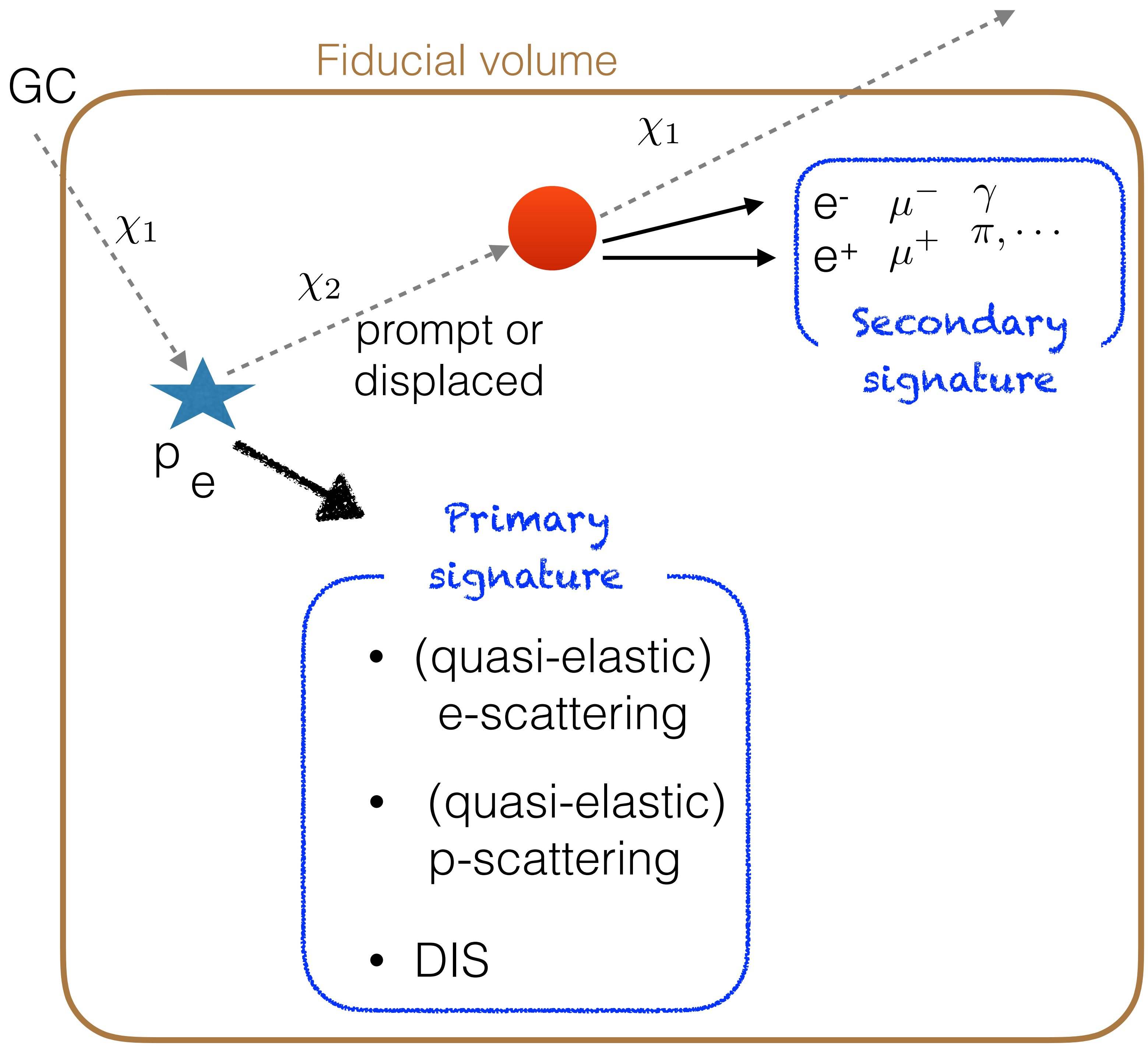
Comple-mentary

iDM + de-excitation (in the current universe) astro-ph/0702587 0903.1037 1312.1363

LHC 1109.4144 1311.6169 1504.01385 1508.03050 1810.01879

Fixed target experiments 1403.6826 1804.00661

Signals inside a fiducial volume



iBDM

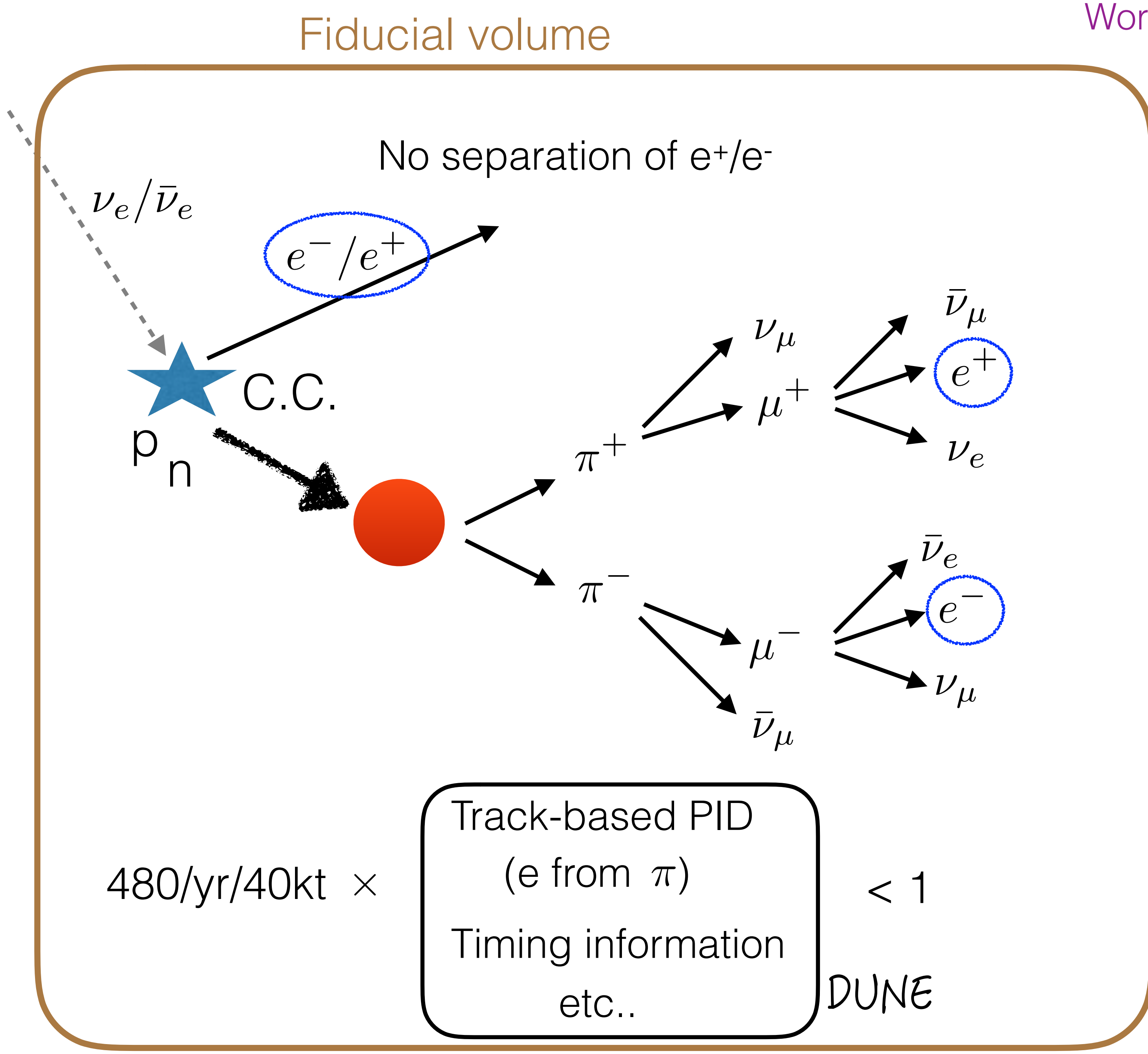
- Tracks pop-up inside fiducial volume (depending on parameter choice)
- Track observation & time correlation can reject bkg.

χ_1: light BDM, χ_2: excited state

Background candidate: underground

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

Work in progress



χ_1: light BDM, χ_2: excited state

- Other subdominant bkg. negligible

  N.C. events (smaller)

  ν_μ: accompanying μ

  ν_τ: too small flux

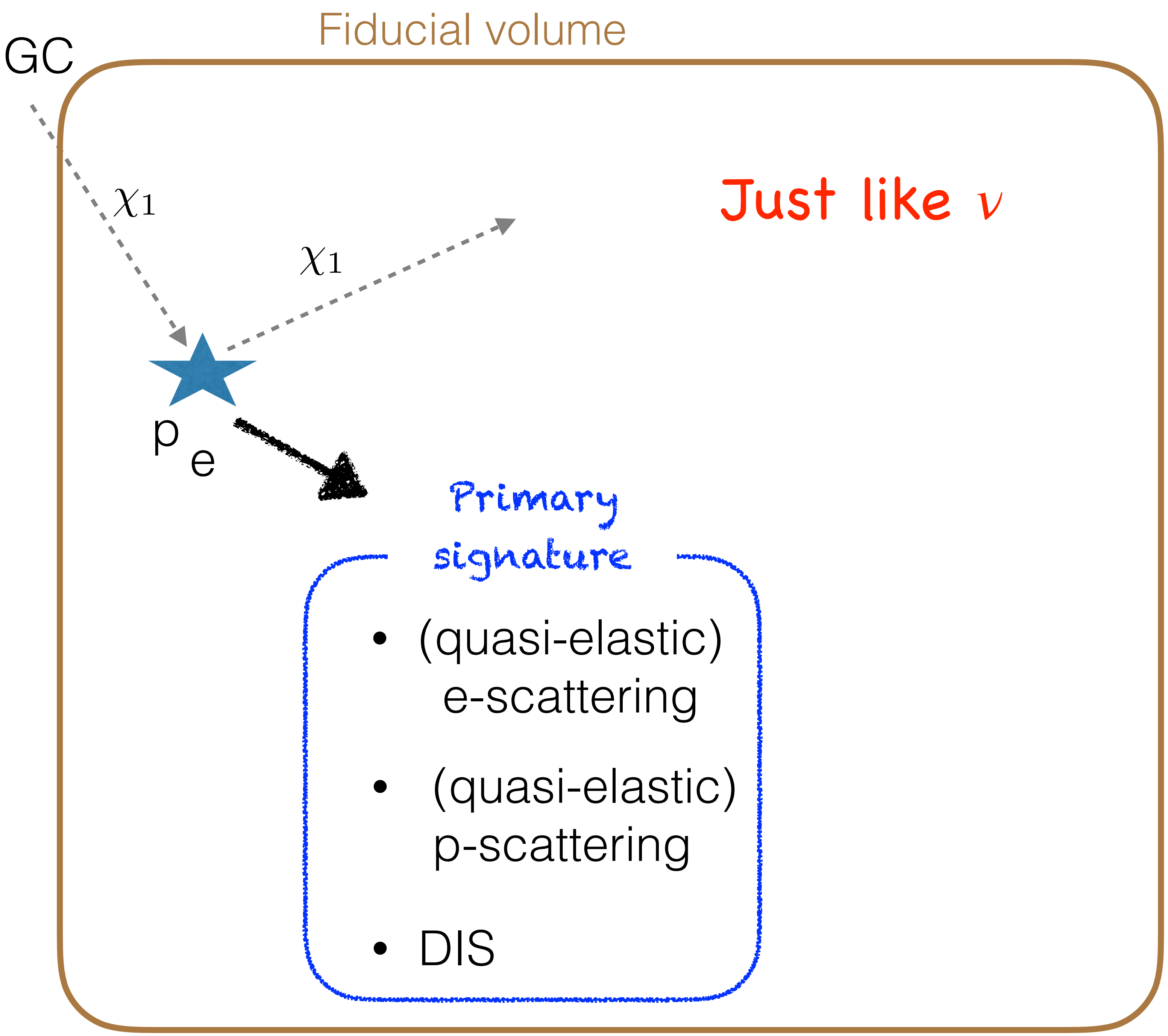
- Zero-bkg. is easily achievable

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

Signals inside a fiducial volume

Minimal case

eBDM: elastically scattering BDM



χ_1: light BDM

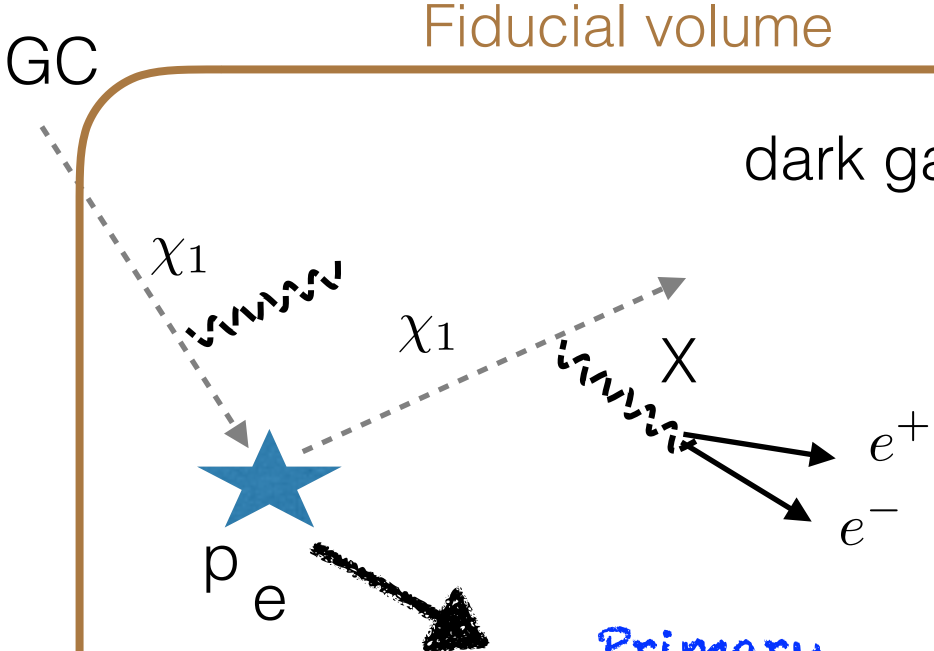
New method in eBDM search: darkstrahlung

Kim, Park, **SS**, 1903.05087

Fiducial volume

dark gauge boson scenario

NOT like ν



Secondary signature

Primary signature

- (quasi-elastic) e-scattering
- (quasi-elastic) p-scattering
- DIS

χ_1: light BDM

Minimal case

eBDM: elastically scattering BDM

- Different from DM → ν ν

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

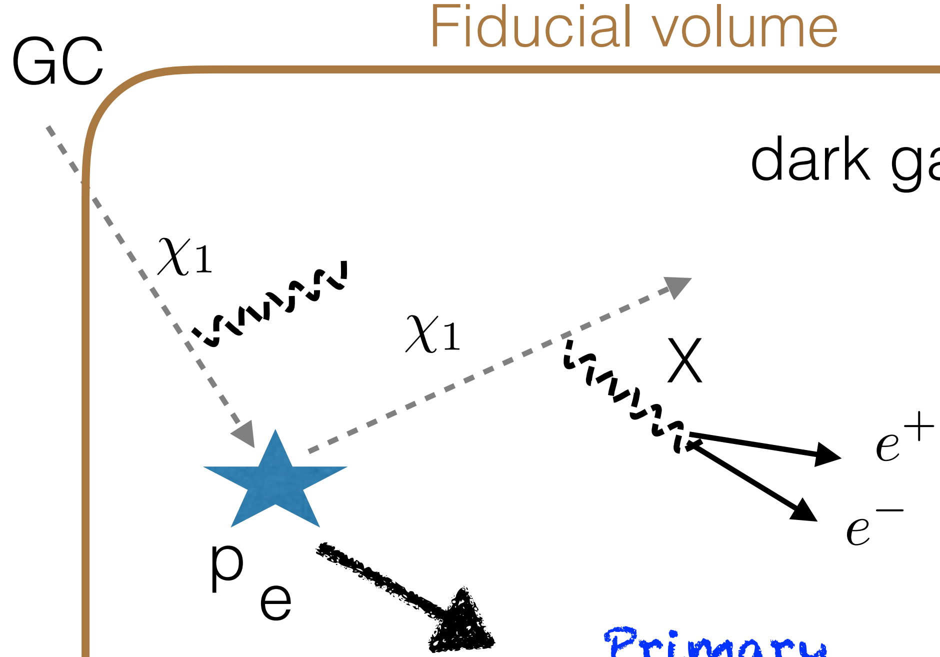
Dark trident, 1809.06388

LHC 1504.01385 1504.01395 1612.02850

New method in eBDM search: darkstrahlung

Kim, Park, **SS**, 1903.05087

Fiducial volume



dark gauge boson scenario

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Secondary signature

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- (quasi-elastic) e-scattering
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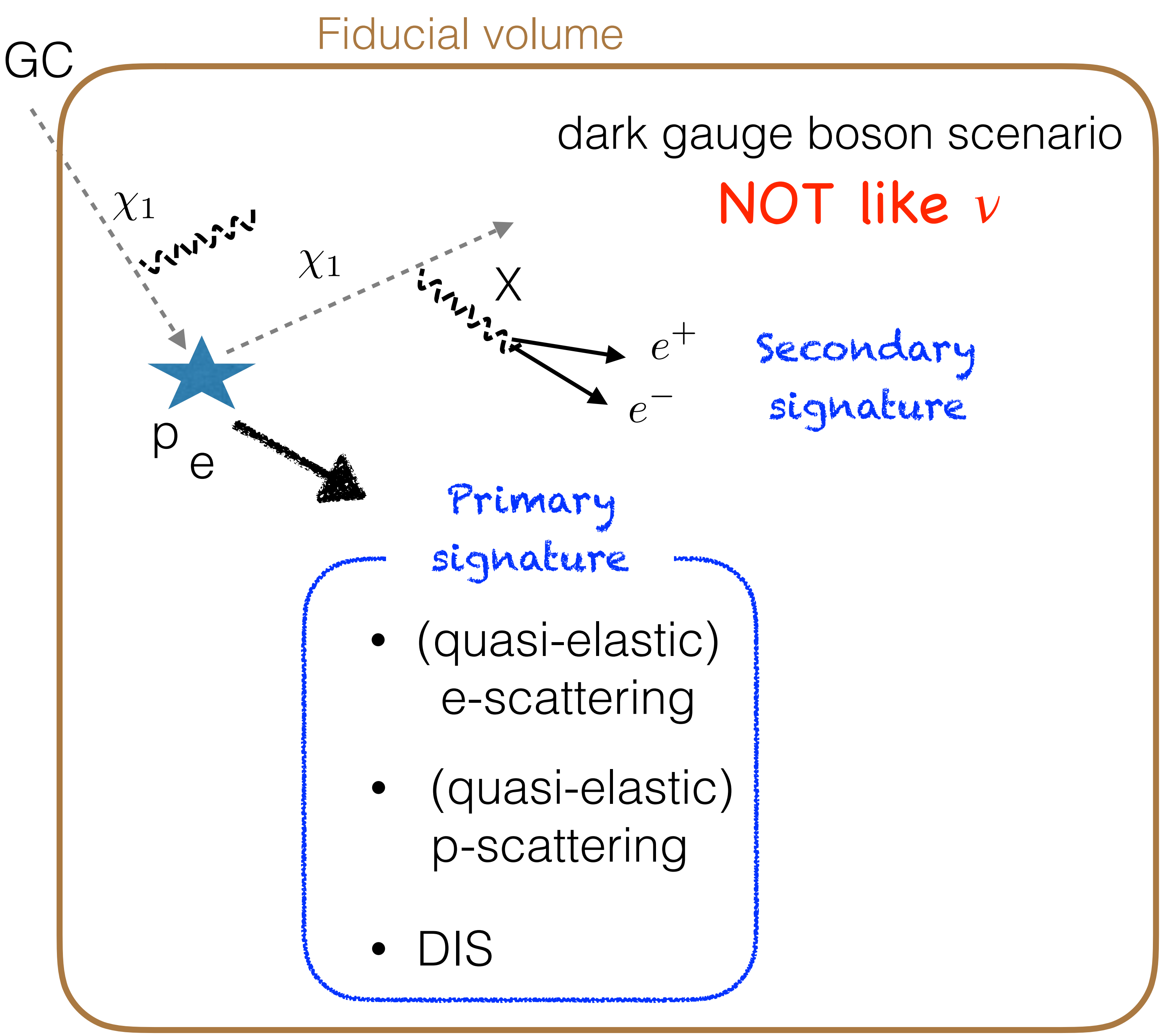


χ_1: light BDM

Minimal case

eBDM: elastically scattering BDM

- Different from DM → ν ν

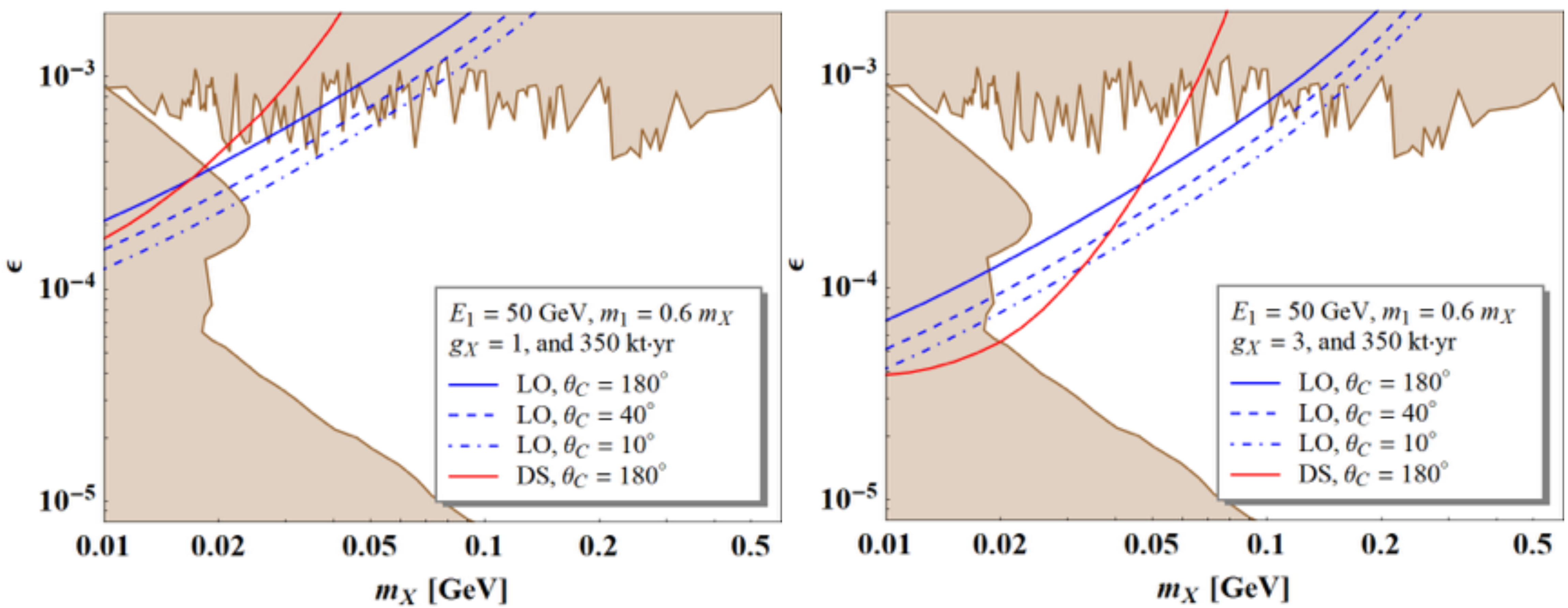
- Next-leading order but O(10-20%) of the leading-order possible

- 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

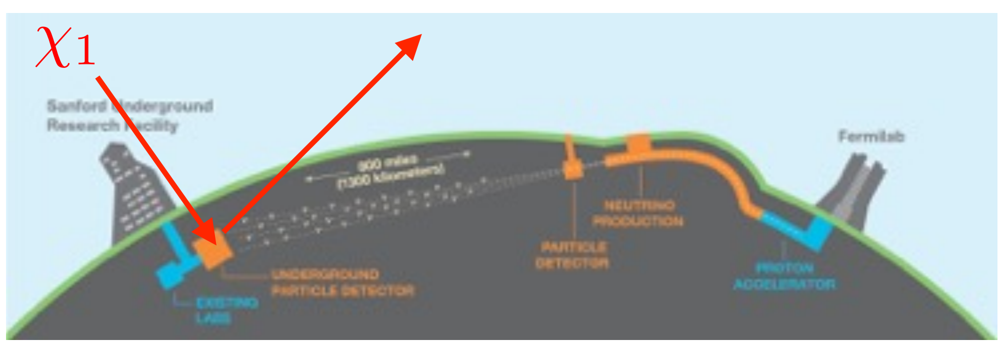
- Large volume deep underground ν-experiments
- Moderate volume surface based ν-experiments
- Ton scale WIMP direct detection experiments

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

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

Assume: NFW

Large volume ν experiments (underground except NOvA)



DUNE far detector

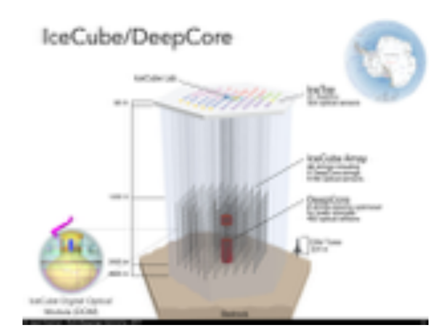
DUNE TDR (coming up)

Most of BDM papers

Super-K

1711.05278

Hyper-K/KNO



IceCube/DeepCore

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

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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, …

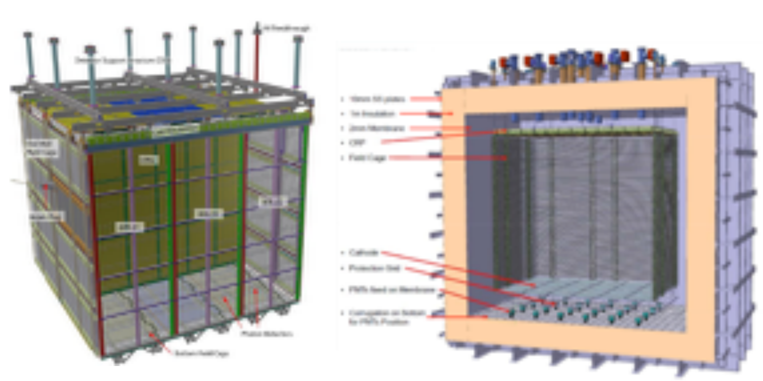
Smaller size good if $m_{\chi 0} \lesssim O(1\ \text{GeV})$

Surface-based ν experiments (Cosmic-ray backgrounds)

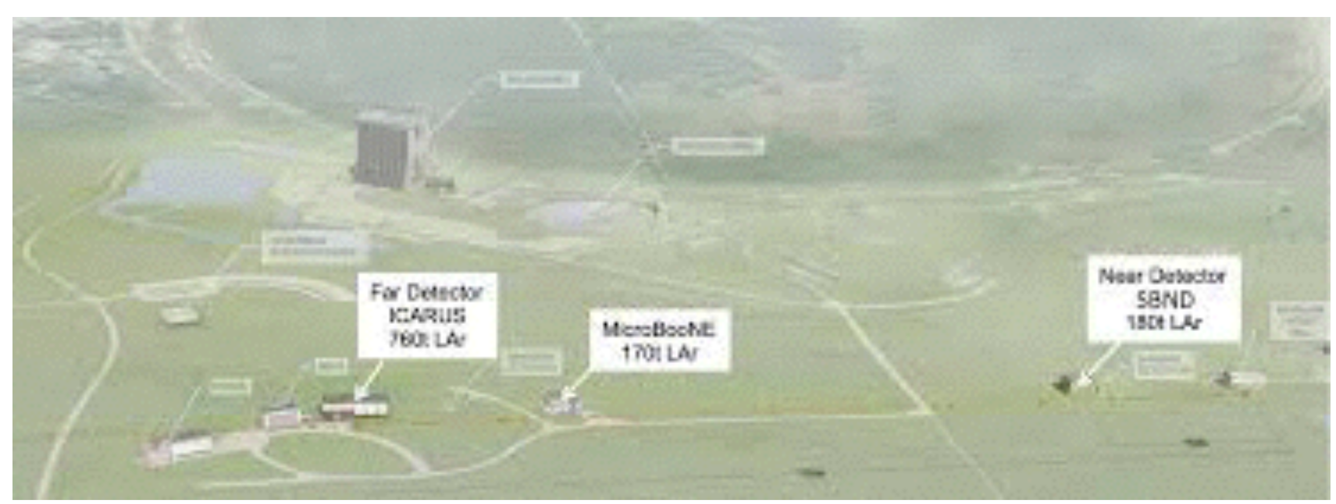
- iBDM: unique signal topology, decent detector ability
  (machine learning would help)
  Chatterjee, De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, Yu, 1803.03264

- eBDM: interesting idea i) darkstrahlung (unique signal topology)
  ii) Earth shielding (upward signal only)

ProtoDUNE



SBNP



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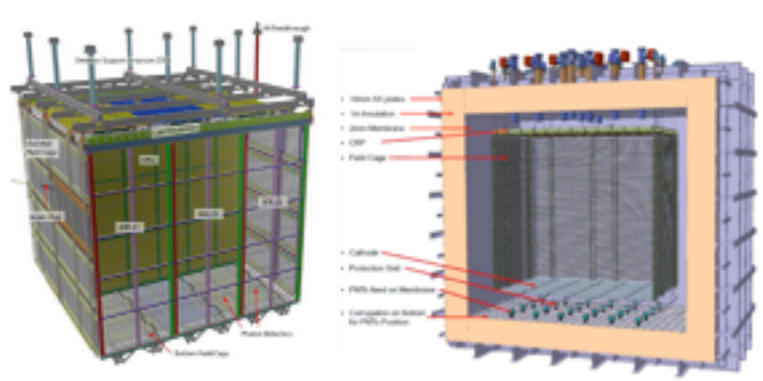
First idea searching for NP here.
Proposal submitted to take 3 yr comic data.

ProtoDUNE



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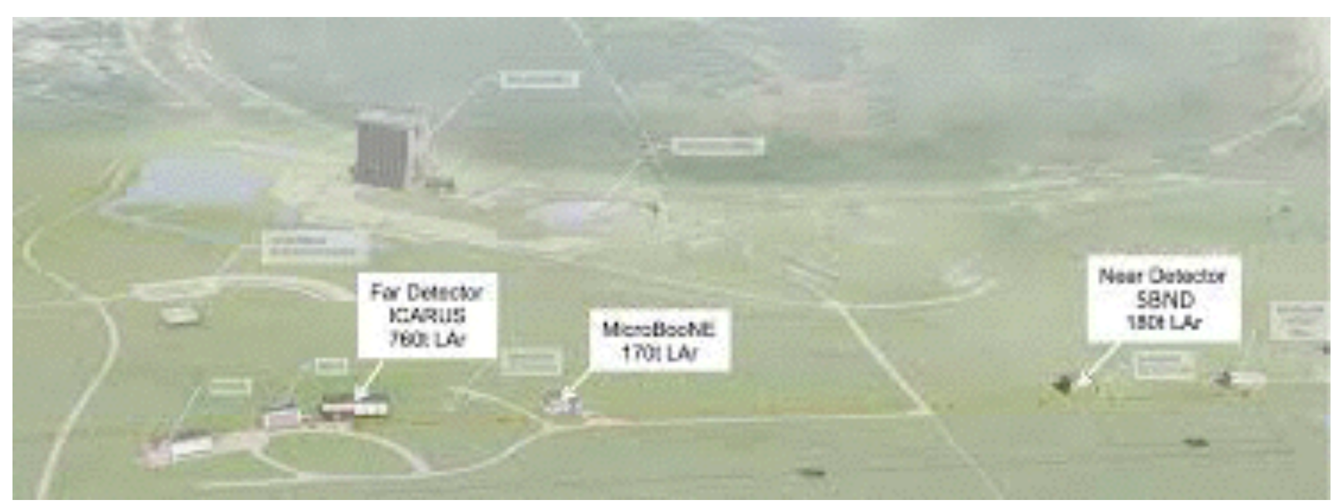

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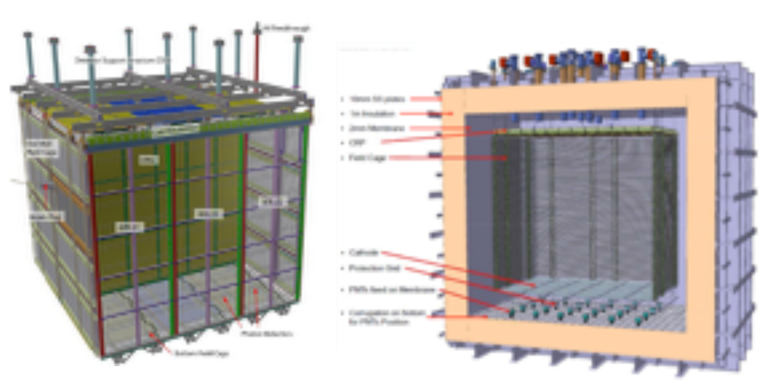
  Kim, Kong, Park, **SS**, 1804.07302

ProtoDUNE



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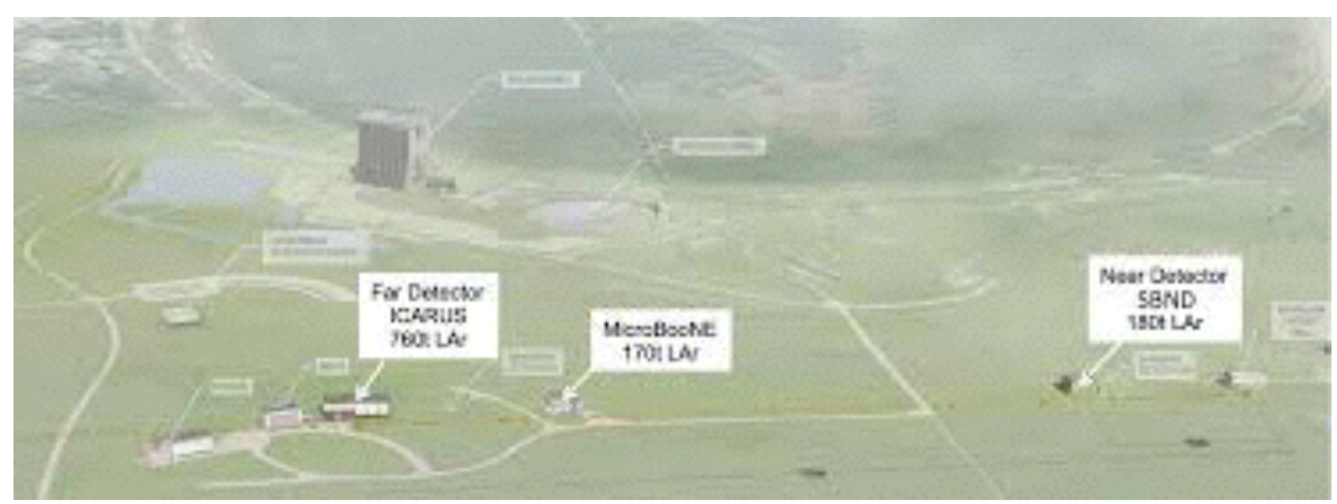
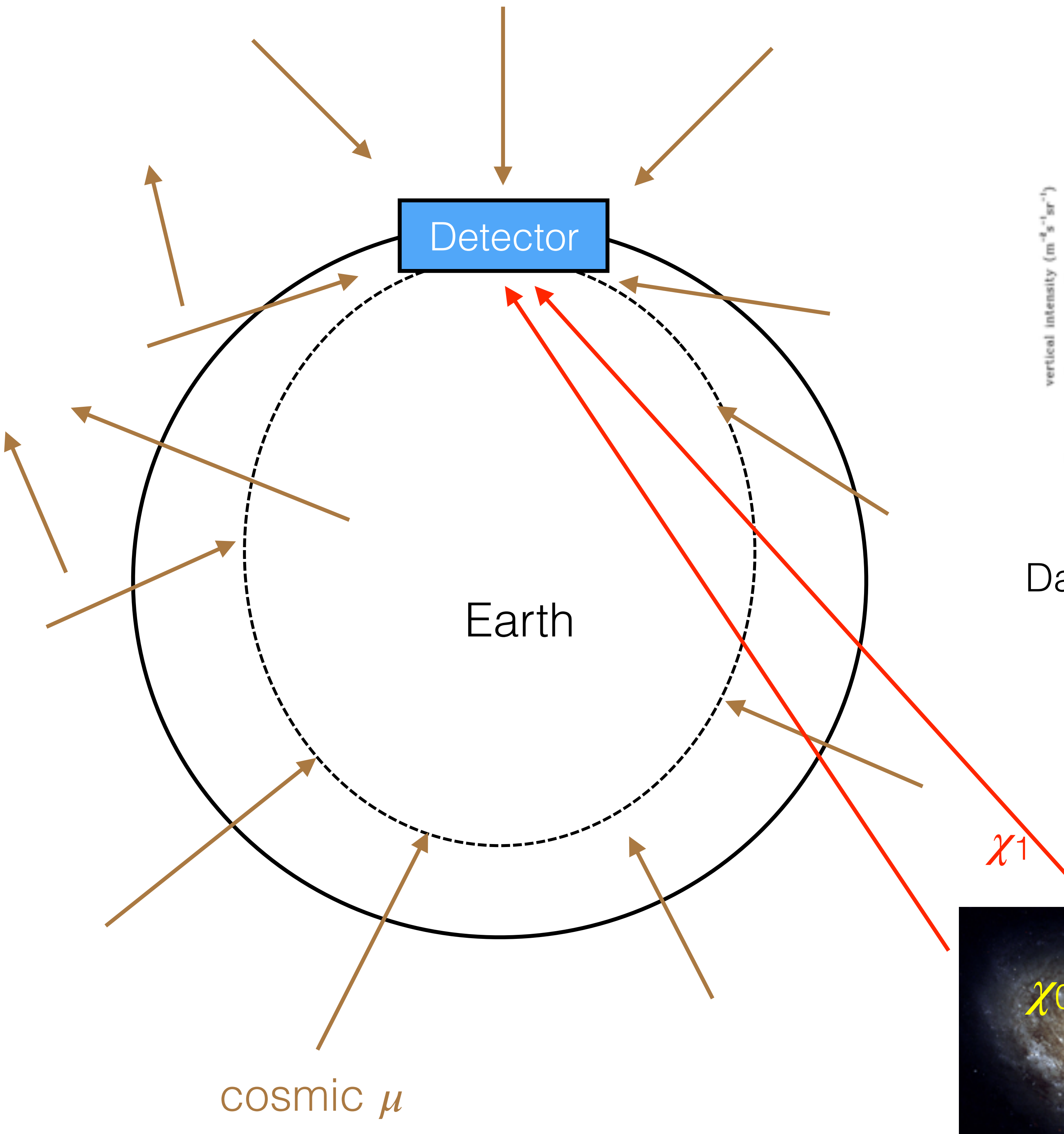
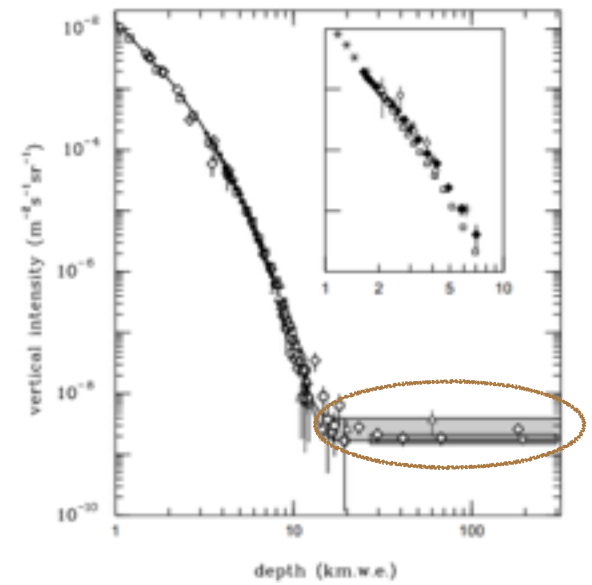


Earth shielding



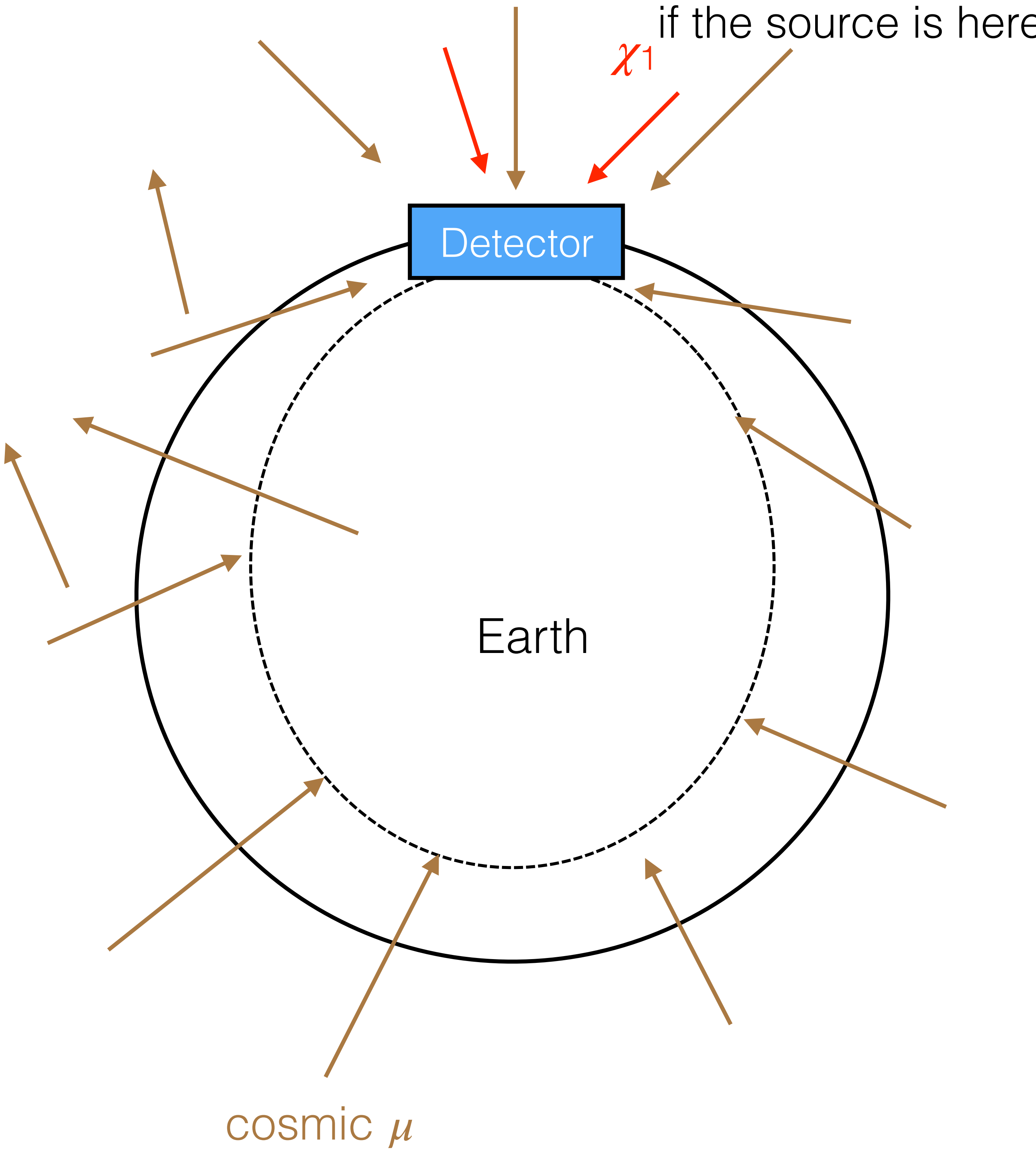


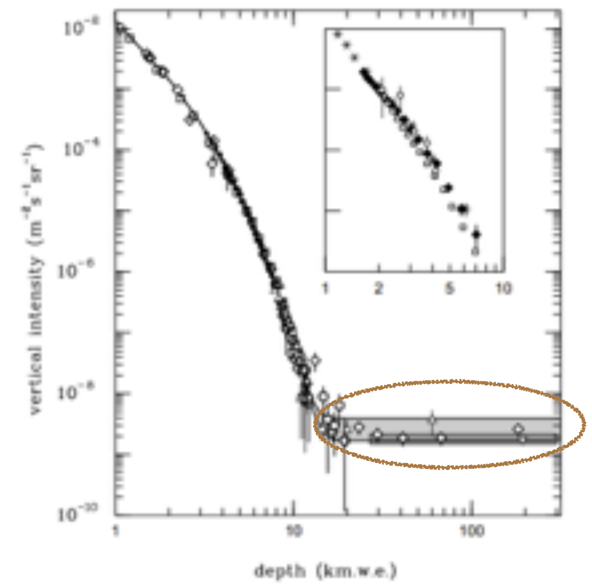
Dashed: 7km below sea level

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

if the source is here

Earth shielding





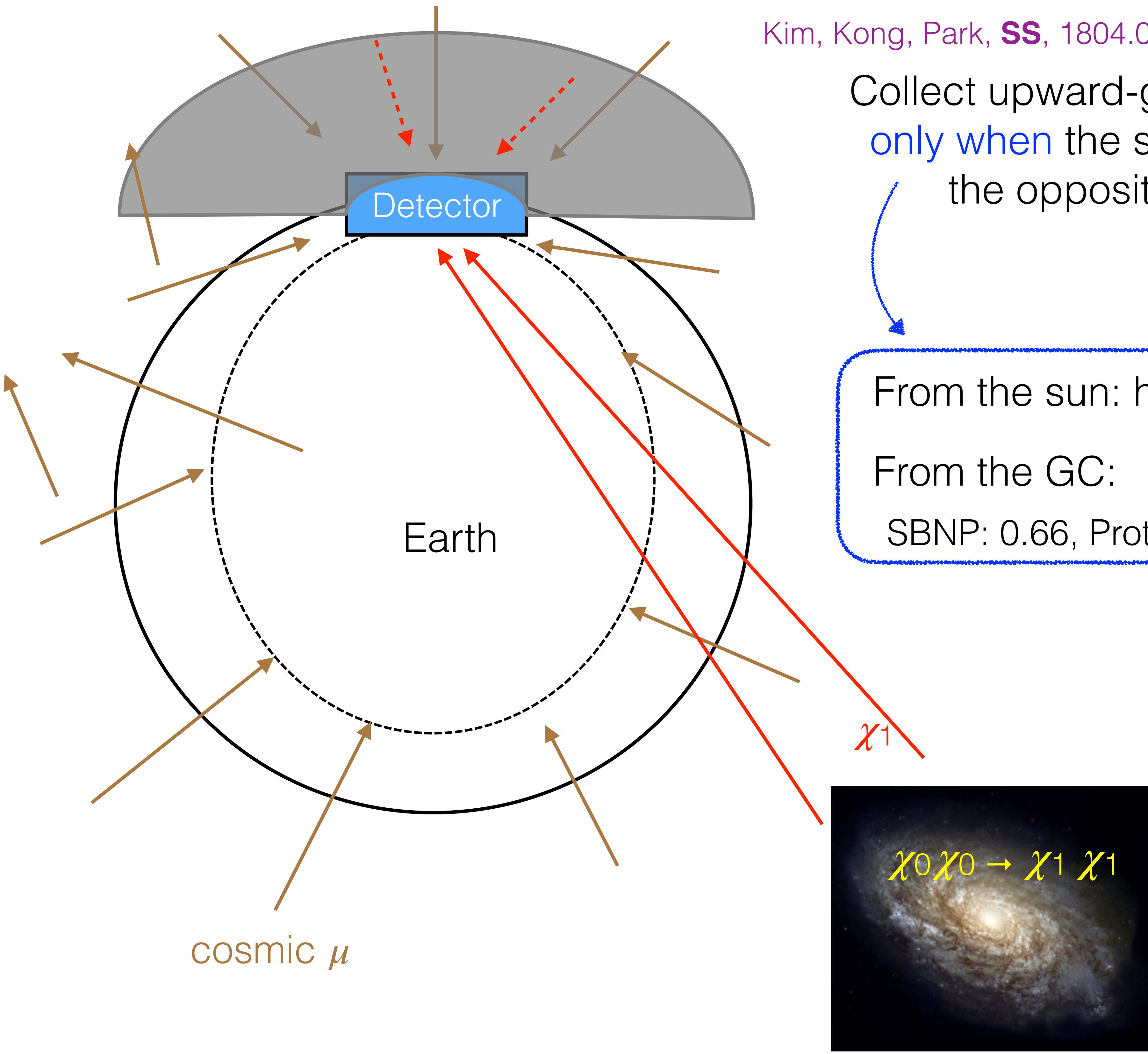
Dashed: 7km below sea level

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

Hard to subtract the
cosmic-ray background
in this case

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

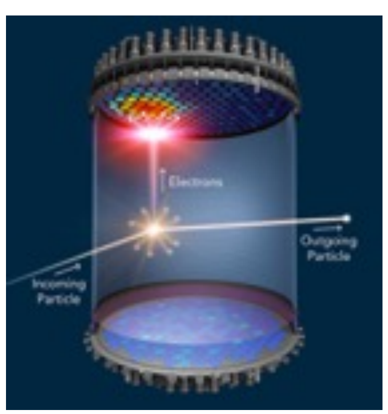
From the GC:

SBNP: 0.66, ProtoDUNE: 0.69

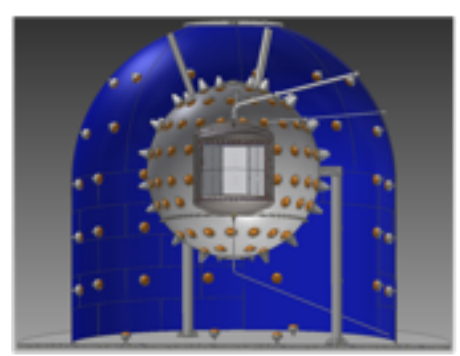
Smaller size good if $m_{\chi^0} \lesssim O(1\ \mathrm{GeV})$

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)



LUX-ZEPLIN
or Xenon NT



DarkSide-20k

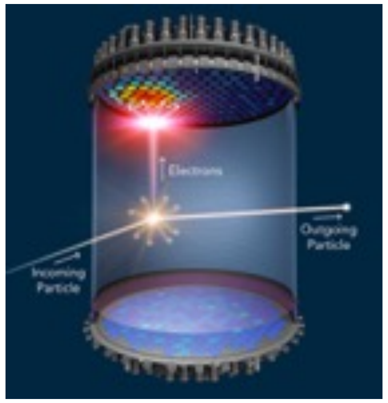
Smaller size good if $m_{\chi 0} \lesssim O(1\ \mathrm{GeV})$

DM direct detection experiments

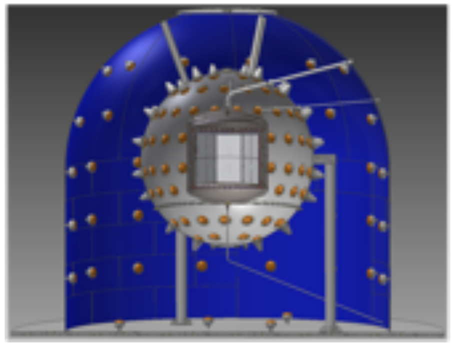
- Need special strategies: PMT saturation (ionization signal)
- Pattern of scintillation signals (identify two displaced vertices)
- Double scattering signal in the array-type detectors (COSINE-100)

→ First iBDM search result

1811.09344



LUX-ZEPLIN or Xenon NT



DarkSide-20k

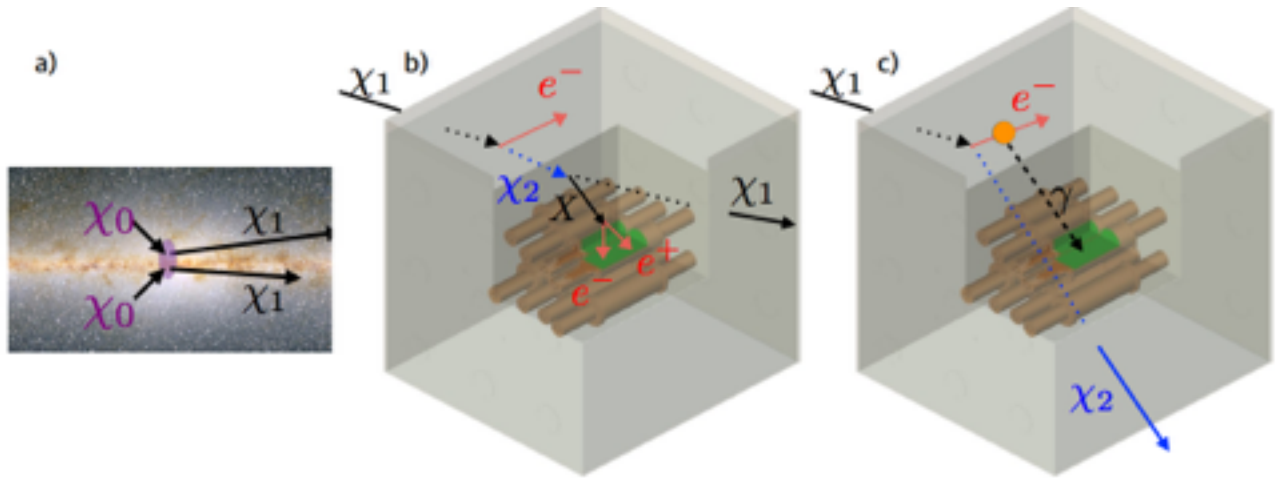
COSINE-100

COSINE-100 result

COSINE-100, 1811.09344

Based on theoretical study

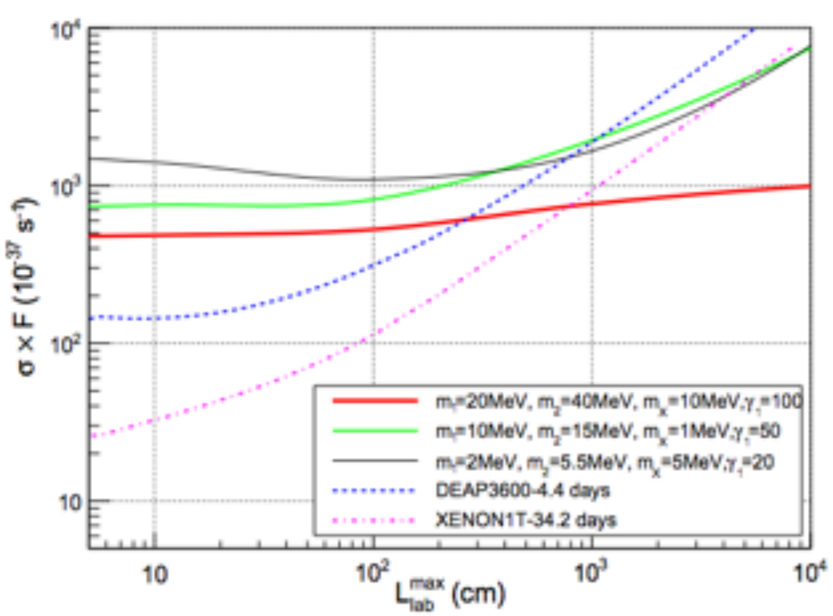
Giudice, Kim, Park, **SS**, 1712.07126

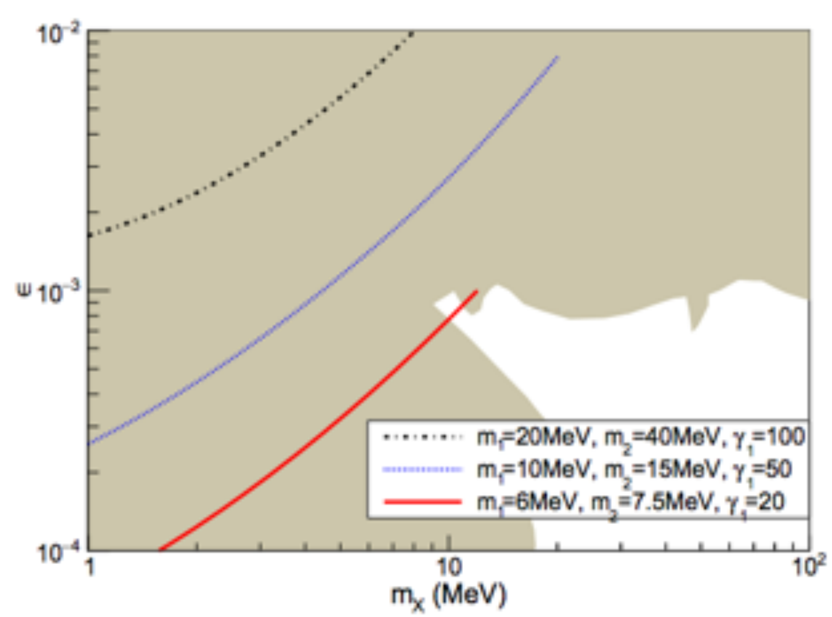


2200L of liquid scintillator
(~ 2 ton)

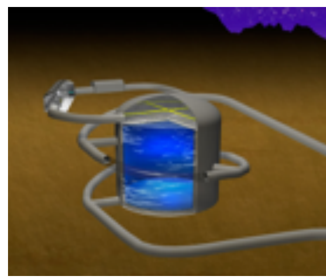
106kg array of 8 ultra-pure NaI(Tl) crystals
immersed in an active veto detector

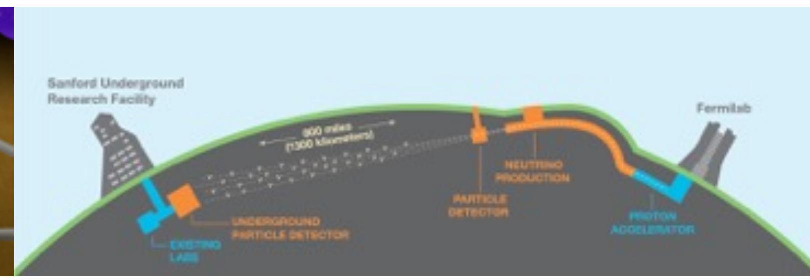
Observed: 21 events, Background expected: 16.4 ± 2.1

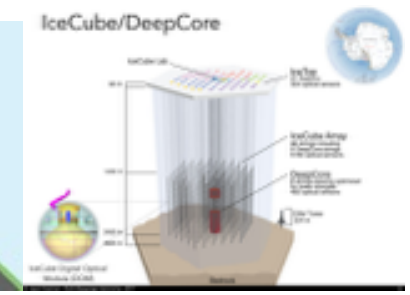




Complementary searches



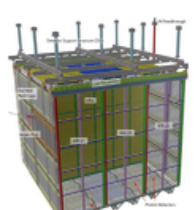


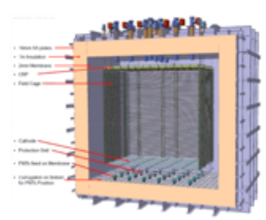


Large volume ν experiments (underground)

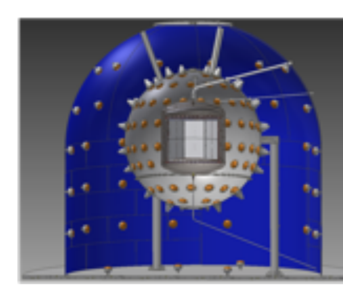
signal observation

background subtraction



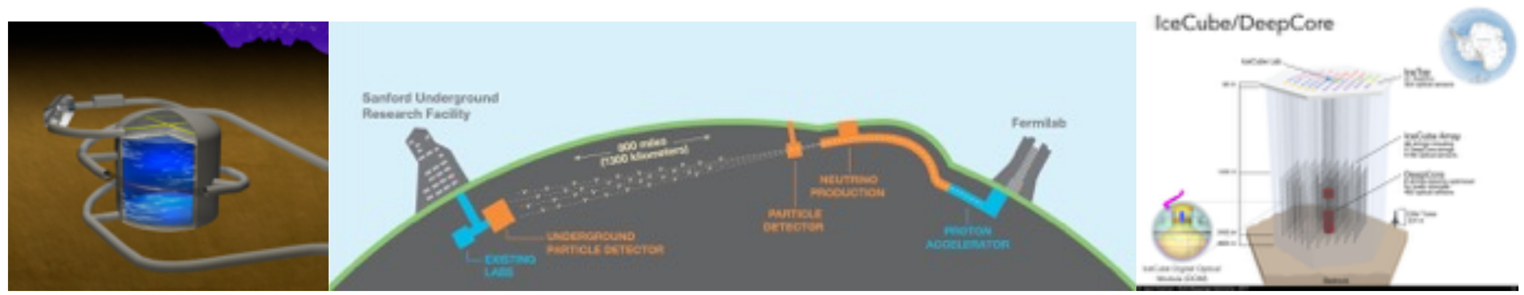


Moderate volume surface ν experiments



Ton scale DM direct detection experiments (underground)

Complementary searches

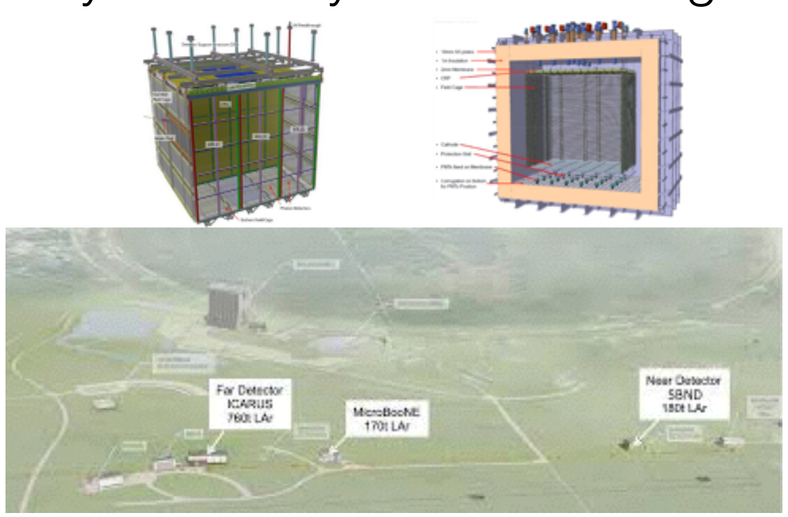


Large volume ν experiments (underground)

signal observation

background subtraction

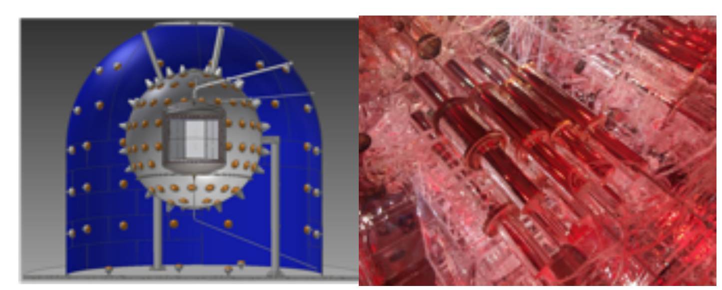
Early discovery & less ν background



Moderate volume surface ν experiments

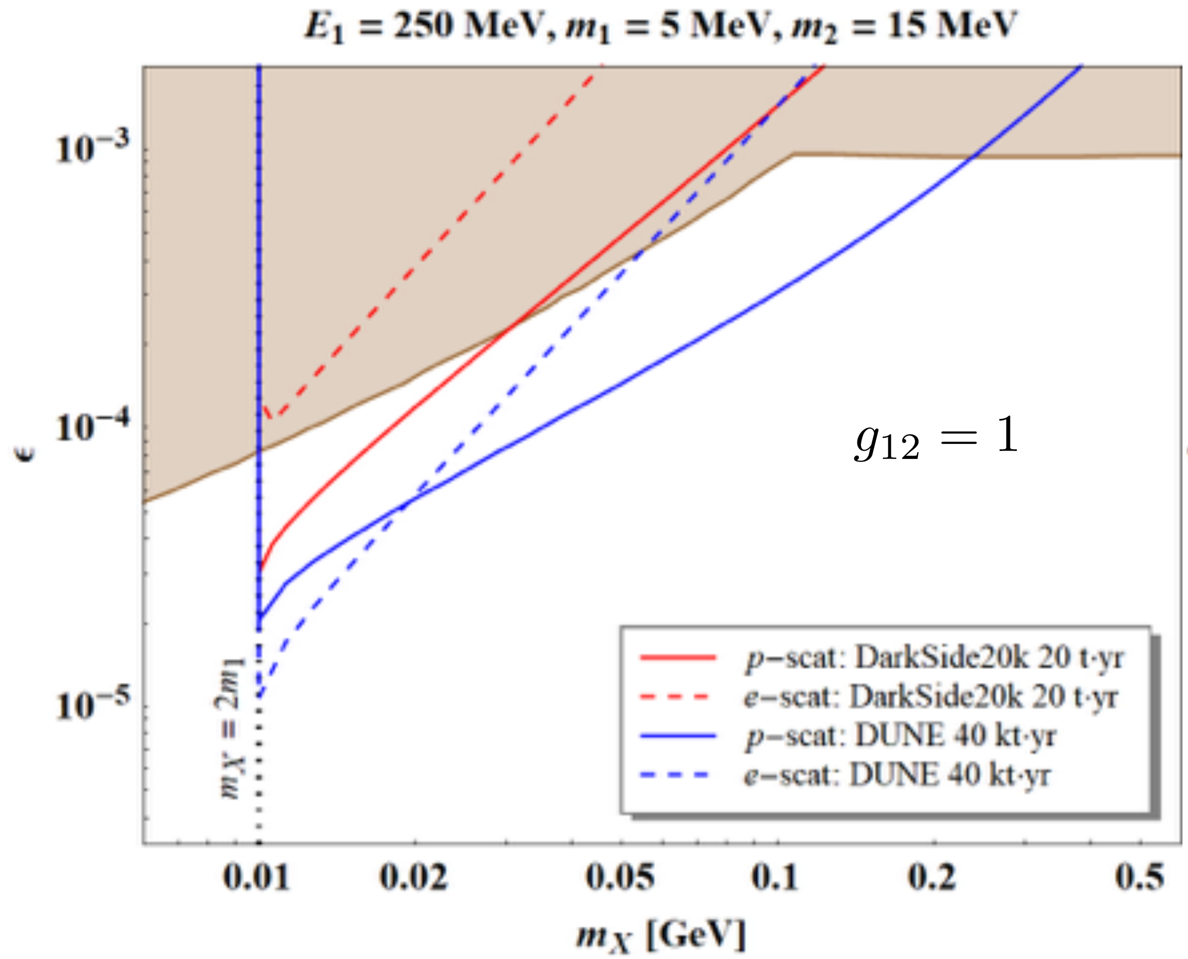
Better resolution (E_{th}, angle)

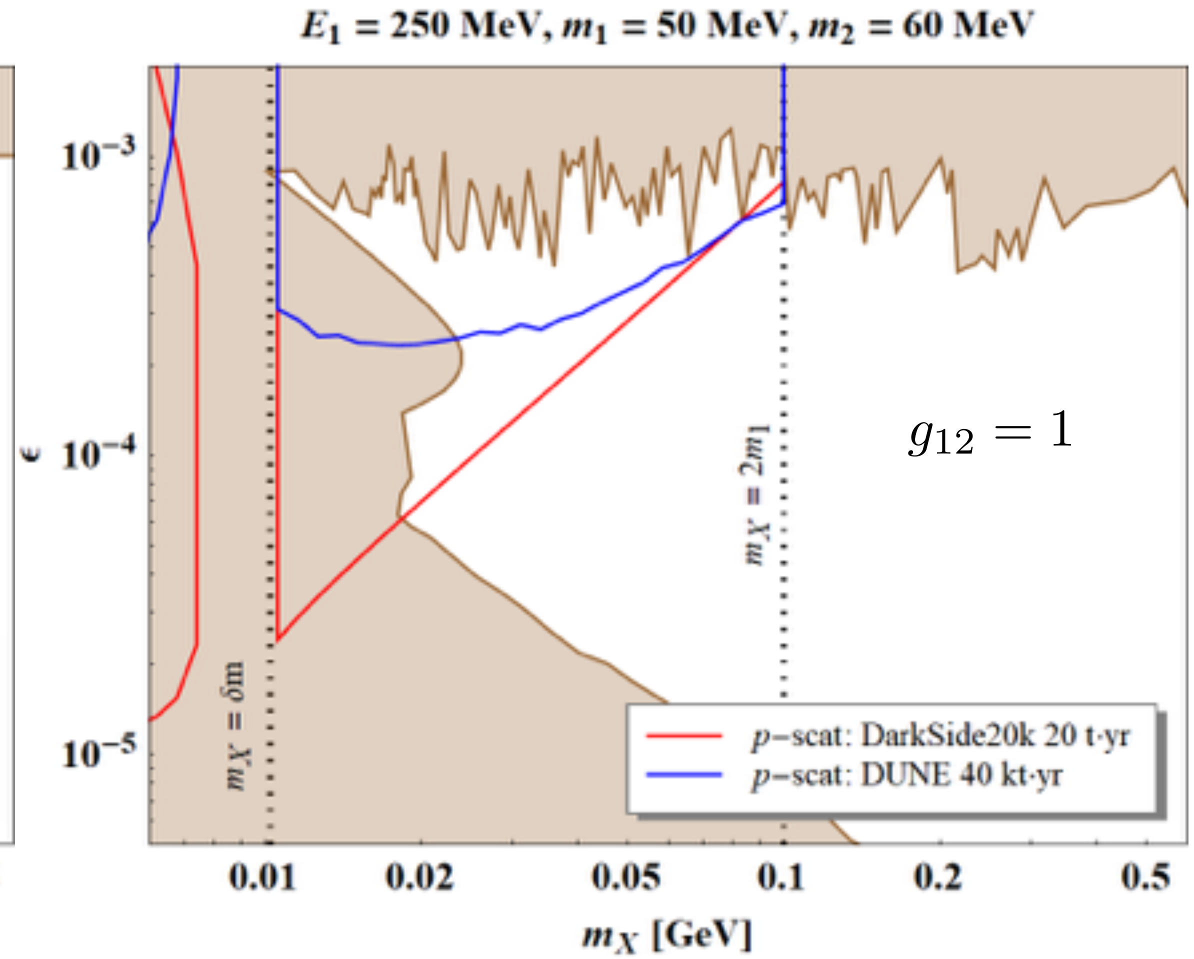
Sensitive for smaller $E_1 = m_0$



Ton scale DM direct detection experiments (underground)

Sensitivities at DUNE vs DarkSide



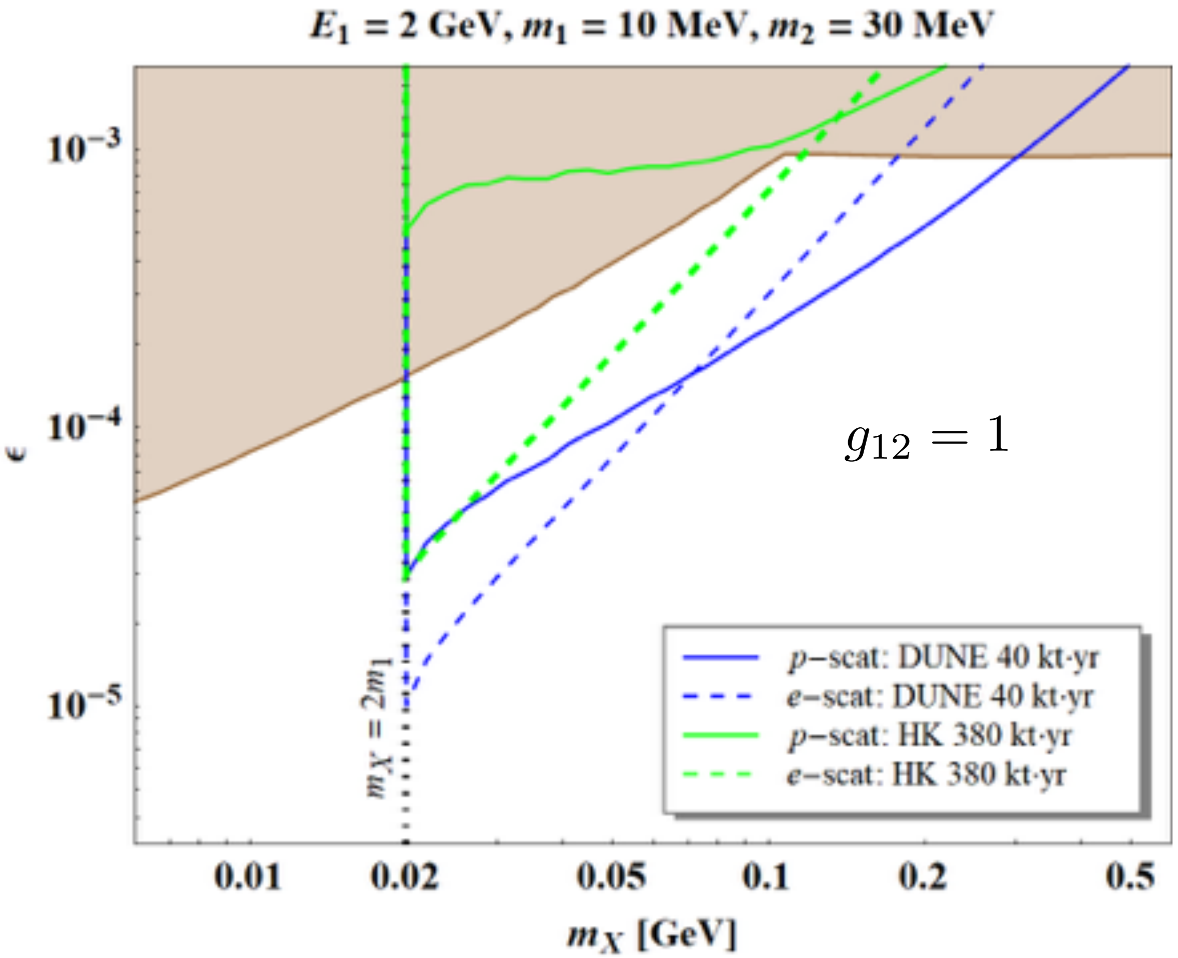


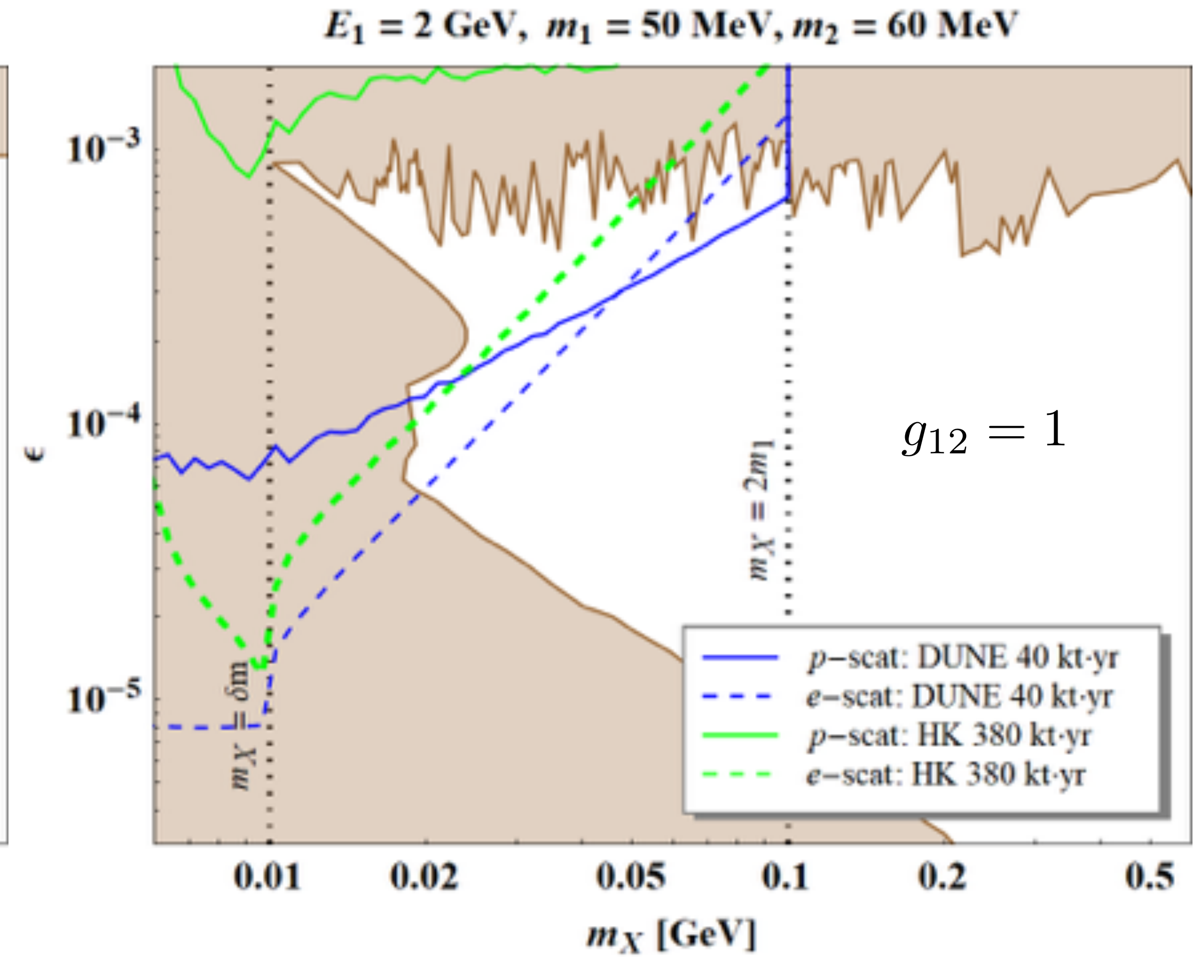
$m_X > 2m_1 \quad \chi_2 \to X^* \chi_1 \to e^+ e^- \chi_1$

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

- 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





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

- 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

     DUNE TDR, SK BDK search, HK/KNO...

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

     ProtoDUNE, ICARUS, ...

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

     COSINE-100, DarkSide-20k, ...

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

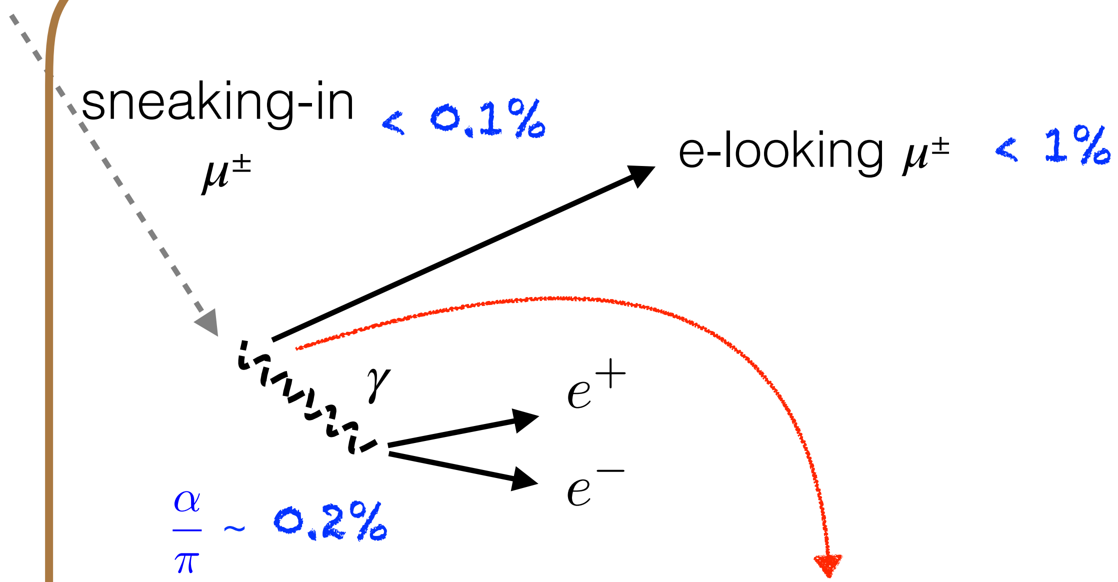
  Energetic cosmic-ray induced DM — Yin, 1809.08610; Bringmann, Pospelov, 1810.10543; Ema, Sala, Sato, 1811.00520

Same phenomenology

Backup: cosmic-ray background

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

Fiducial volume   cosmic μ events (> 400 MeV) ≃ 94/m^2/s/sr at sea level



+ a track pops-up here with E > E_{th}
and with unclear kink feature

4×10^{11}/yr/detector

ProtoDUNE

SP: 300 t

DP: 210 t

×

2×10^{-8}
6×10^{-3}

< 100

in total detectors

- 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)

Backup: cosmic-ray background

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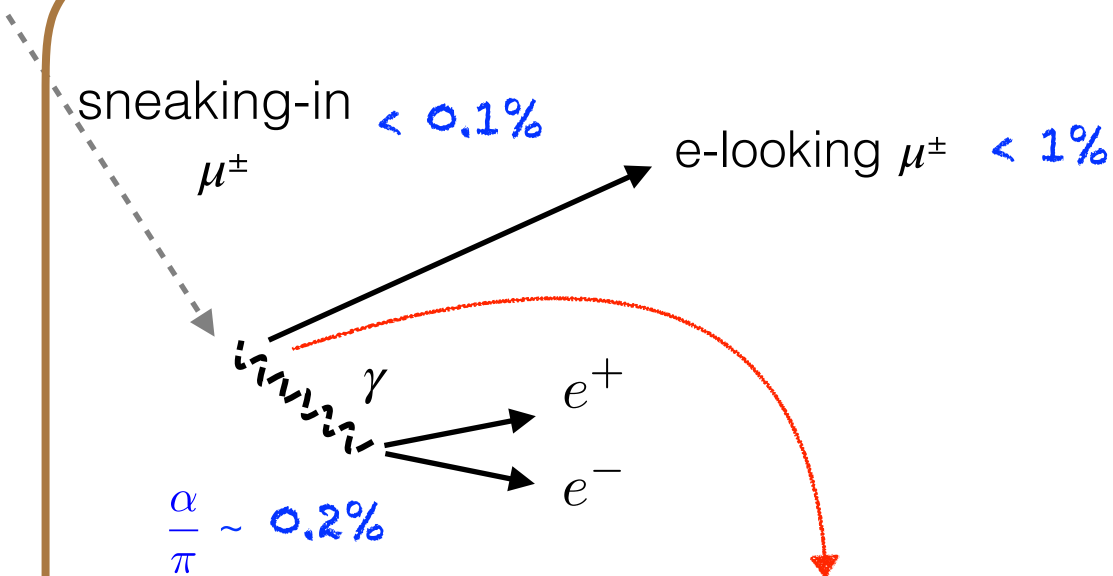
Fiducial volume

cosmic μ events (> 400 MeV) ≃ 94/m^2/s/sr at sea level



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SP: 300 t

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×

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6×10^{-3}

< 100

in total detectors

- 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: sensitivity

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

- 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)

} Fixed for a given experiment

Backup: sensitivity

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

- σ_ϵ: scattering cross section between χ_1 and (target) electron
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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

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

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

- 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)
- $t_{\rm exp}$: 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

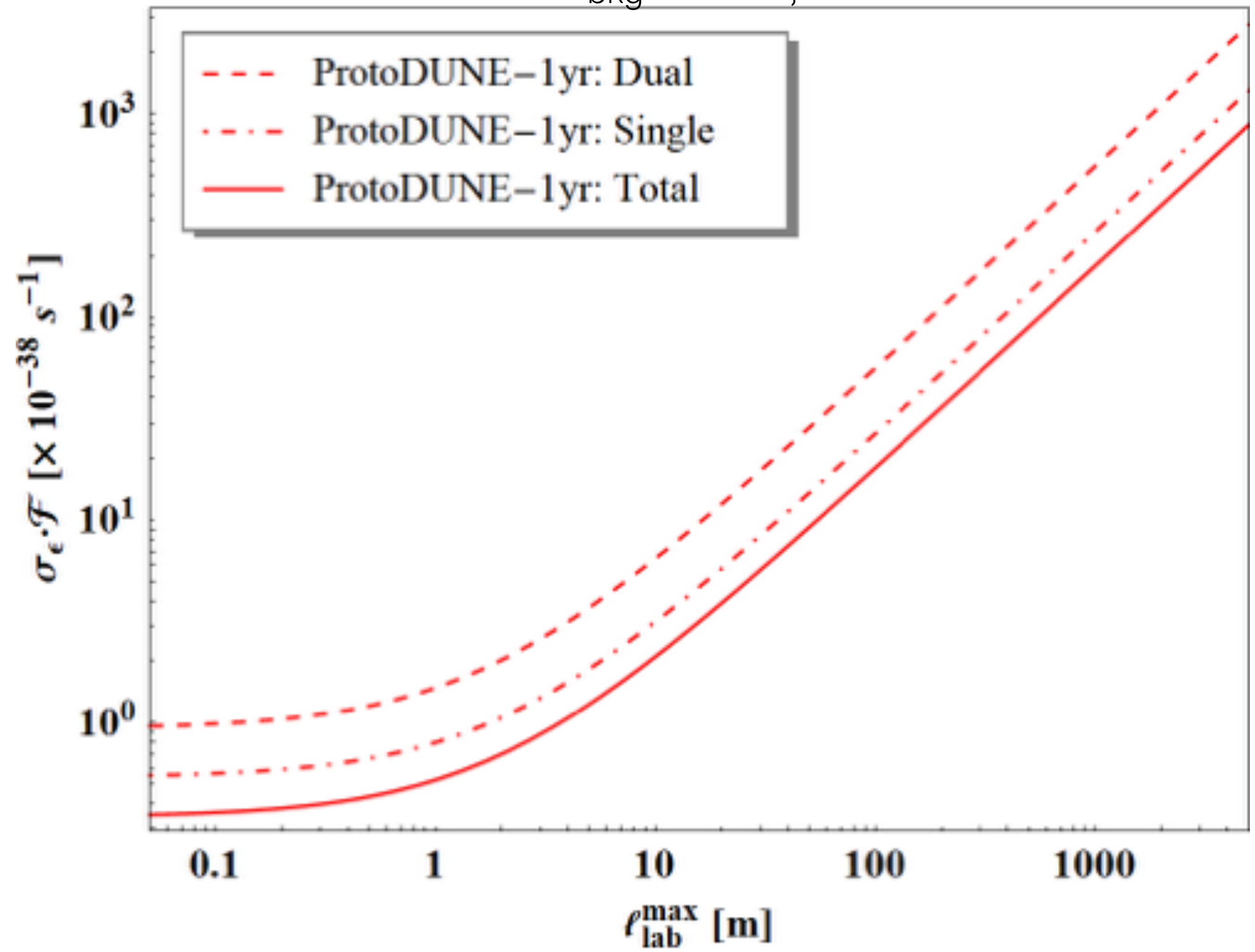
- Function of decay length of χ_2 (event generation assuming cumulatively isotopic flux of χ_1)
- Conservatively, we calculate the maximum mean decay length in the laboratory frame for each parameter set

Backup: model independent sensitivity

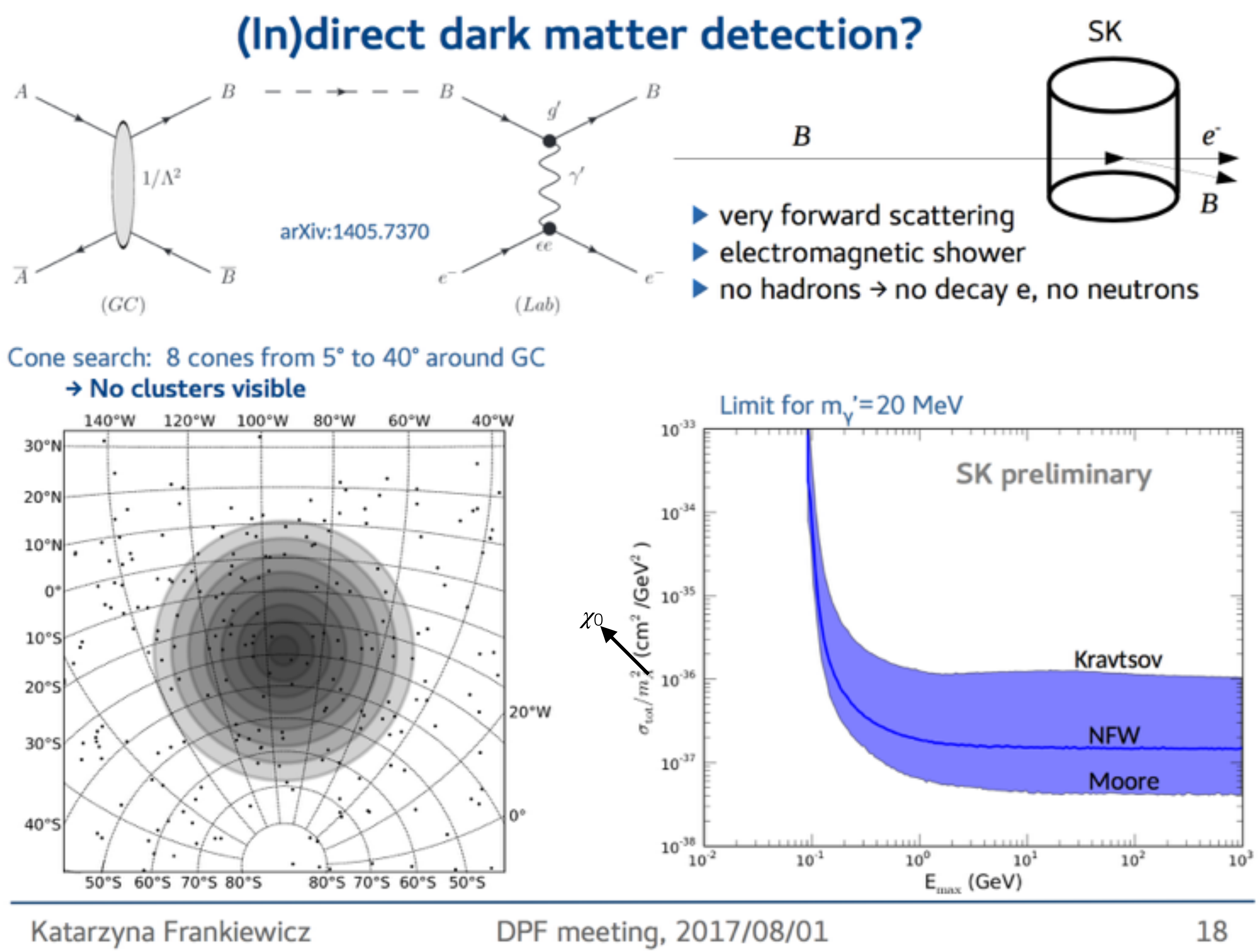
$$\sigma_\epsilon \cdot \mathcal{F} \geq \frac{2.3}{A(\bar{\ell}_{\rm lab}^{\rm max}) \cdot t_{\rm exp} \cdot N_T}$$

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

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



Backup: SK


(In)direct dark matter detection?
SK
A
B
B
B
$1/\Lambda^2$
g'
γ'
ϵe
$\bar{A}$
$\bar{B}$
e^-
e^-
(GC)
(Lab)
arXiv:1405.7370
B
e^-
B
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
140°W 120°W 100°W 80°W 60°W 40°W
30°N
20°N
10°N
0°
10°S
20°S
30°S
40°S
20°W
0°
50°S 60°S 70°S 80°S 80°S 70°S 60°S 50°S
Limit for m_{γ}'=20 MeV
SK preliminary
χ_0
σ_{tot}/m_χ^2 (cm² /GeV²)
Kravtsov
NFW
Moore
E_{max} (GeV)
Katarzyna Frankiewicz
DPF meeting, 2017/08/01
18

Backup: SK

$0.1\ \mathrm{GeV} < p_e < 1\ \mathrm{TeV}$

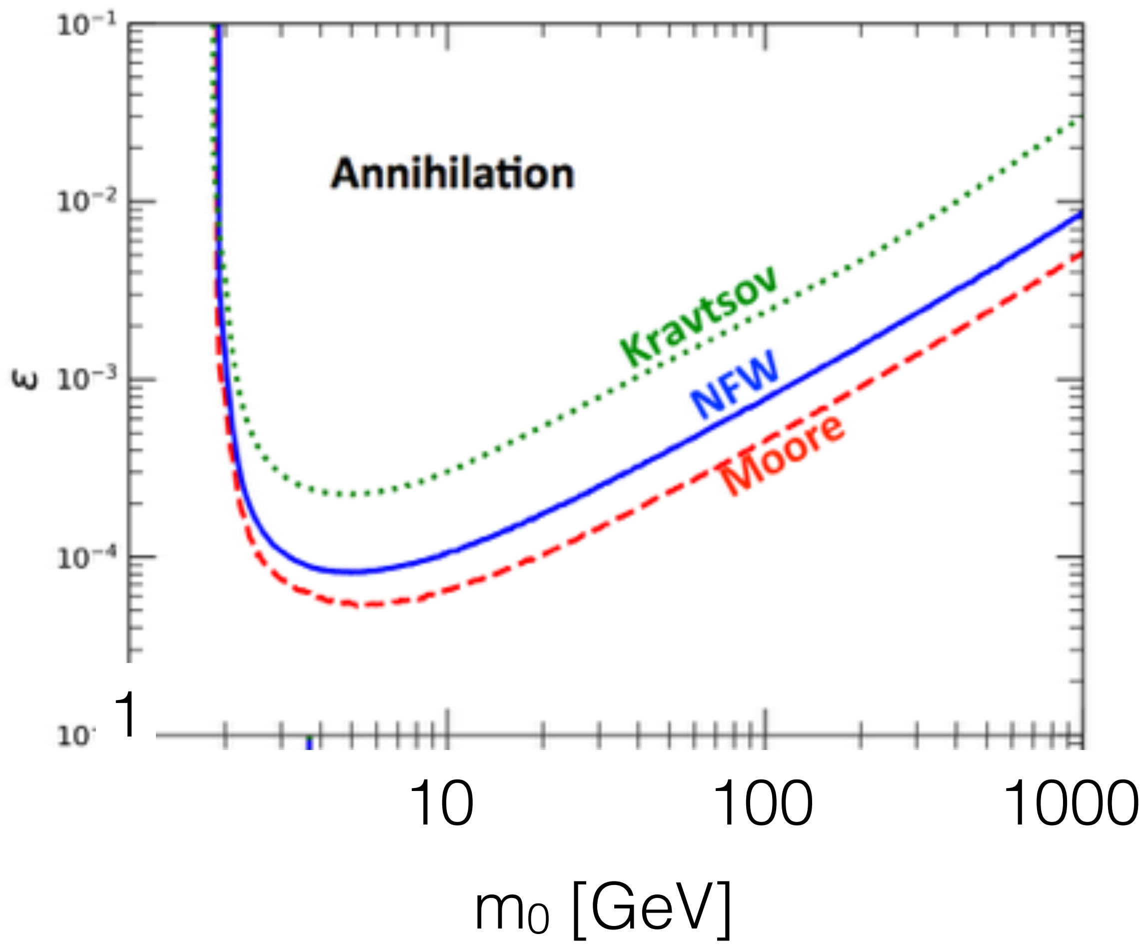
p_e^{th} with angular resolution 3°

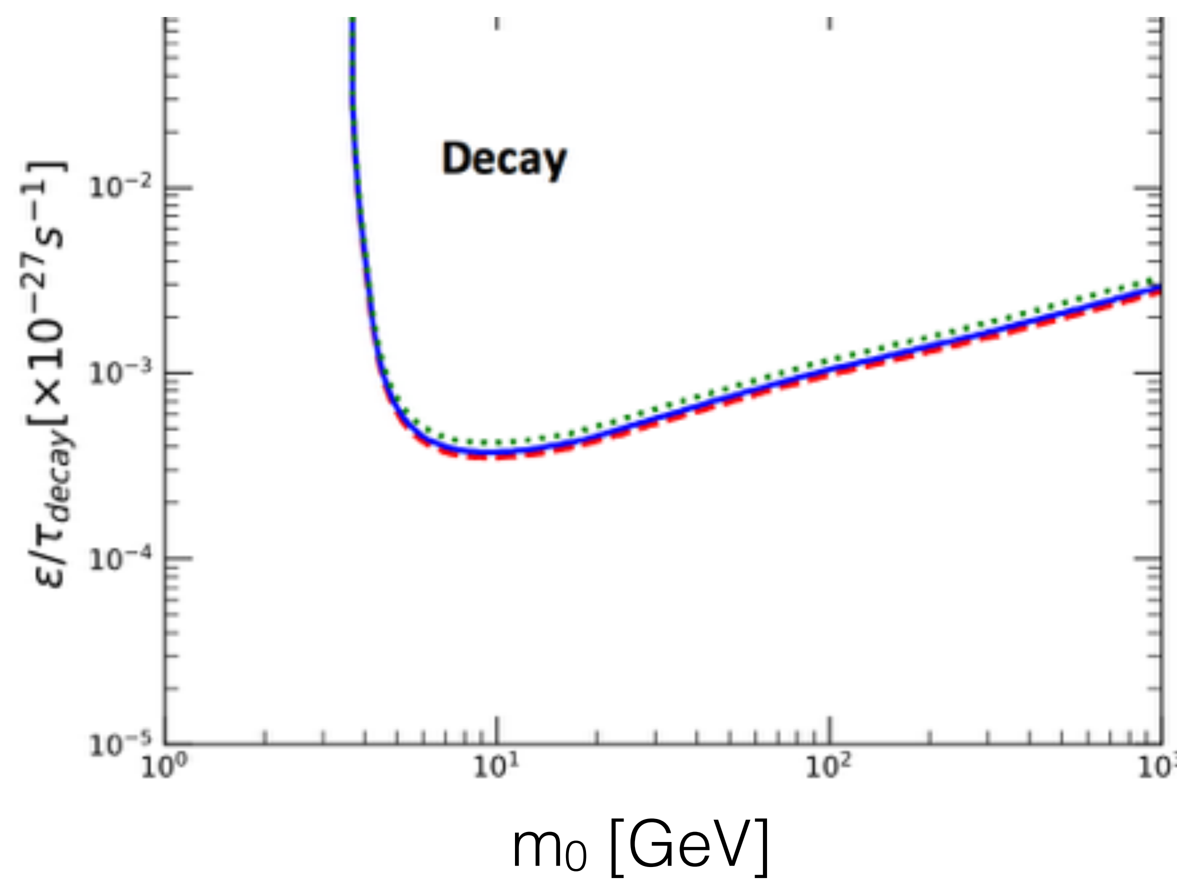
GC & Sun

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

SK, 1711.05278

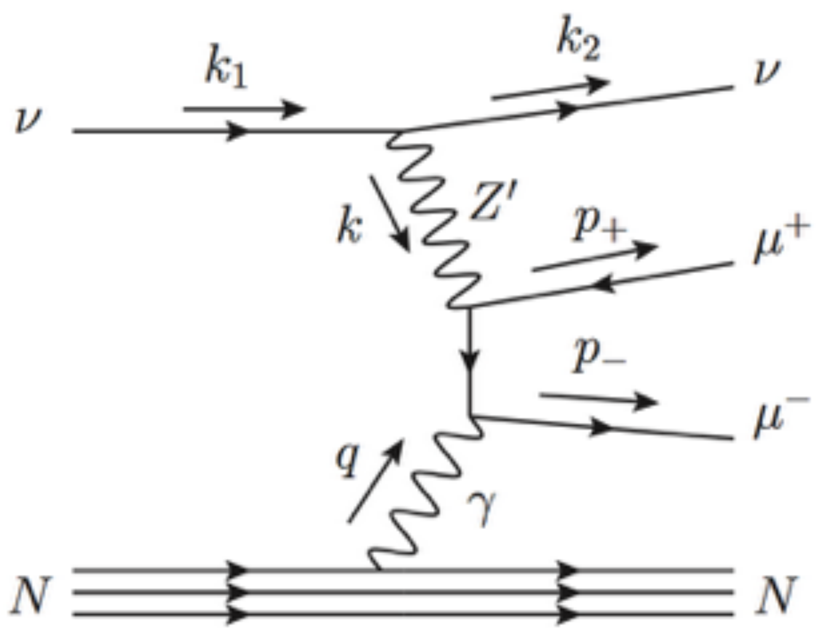
90% bound



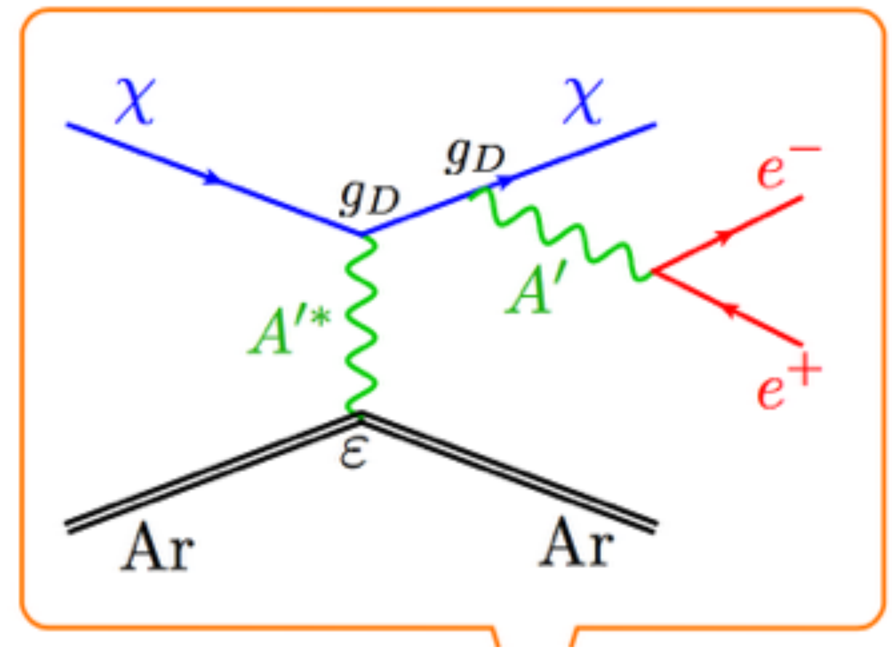


m_1 =200 MeV, m_X = 20 MeV, g_{11}=0.5

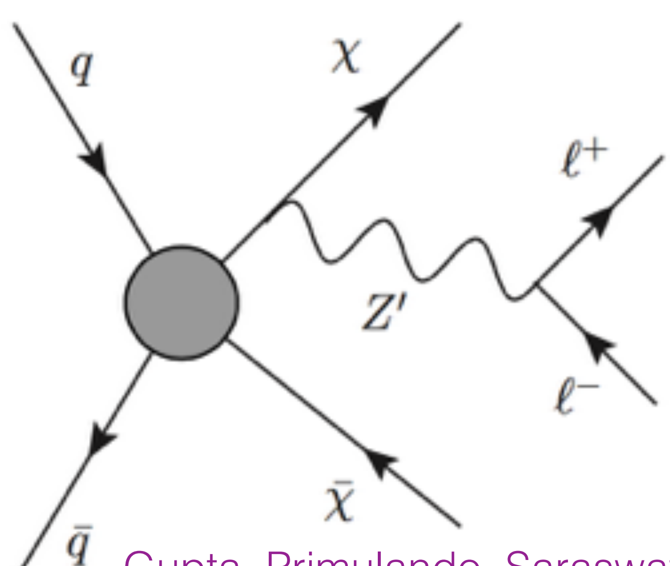
Backup: Darkstrahlung topology



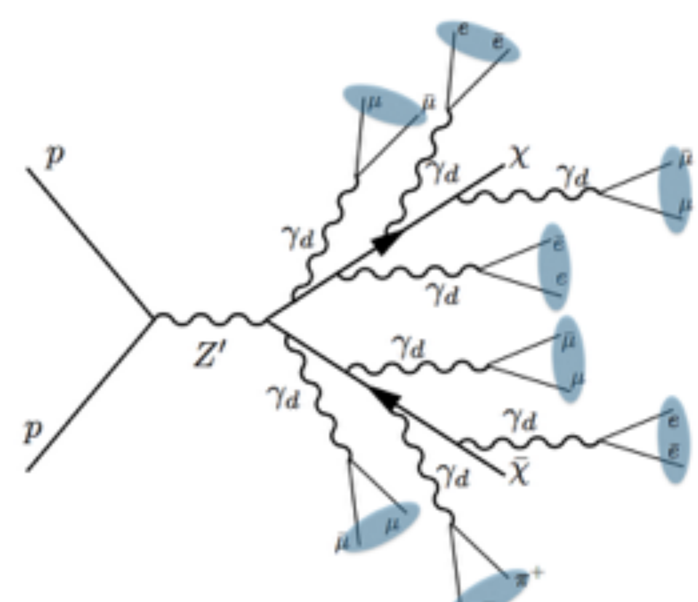
Altmannshofer, Gori, Pospelov, Yavin, 1406.2332



de Gouvea, Fox, Harnik, Kelly, Zhang, 1809.06388



Gupta, Primulando, Saraswat, 1504.01385



Kim, Lee, Park, Zhang, 1612.02850