Summer Institute 2019

Inelastic Boosted Dark Matter

Seodong Shin

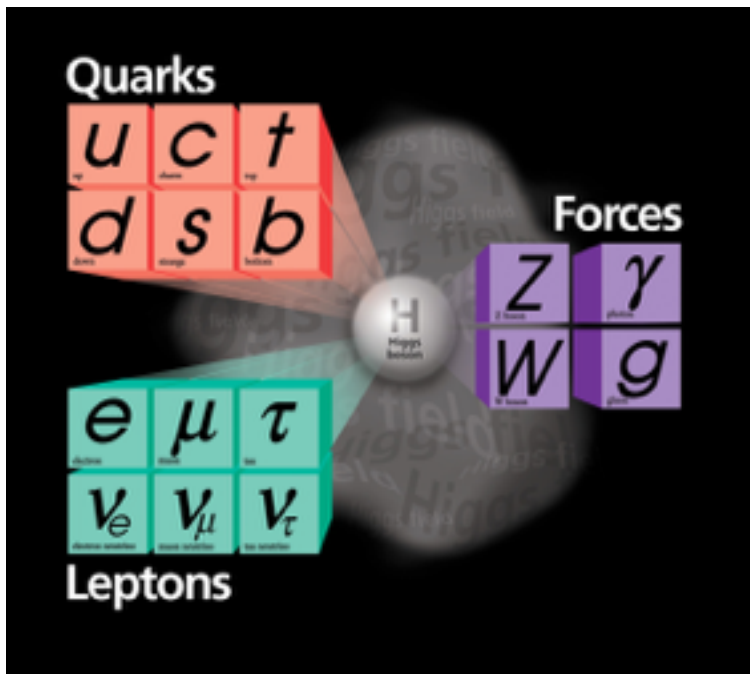
1612.06867, 1712.07126, 1803.03264, 1804.07302, 1903.05087, 1908.xxxxx

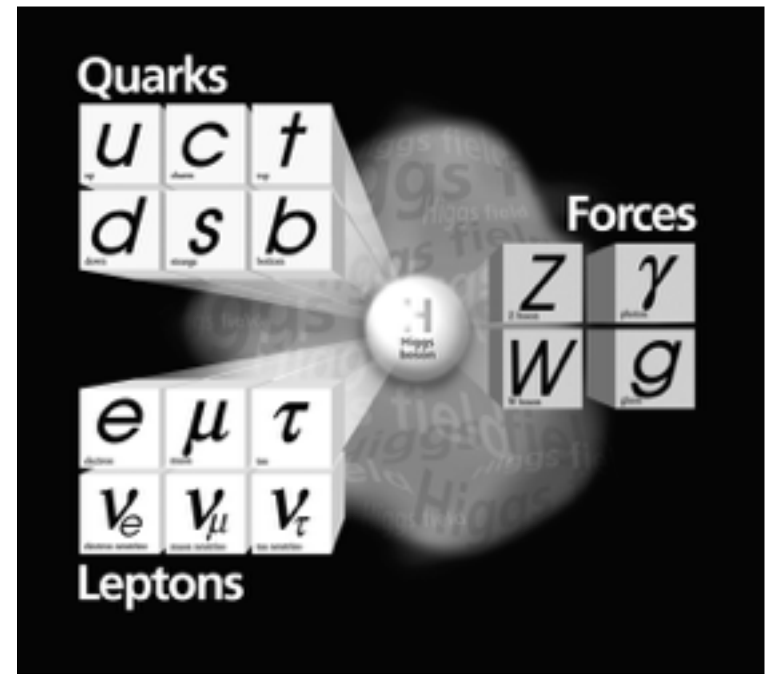
Gian F. Giudice, Doojin Kim, Kyoungchul Kong, Pedro A. N. Machado, Jong-Chul Park

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

Not simple dark sector

"WIMP may be an oversimplification of dark sector."





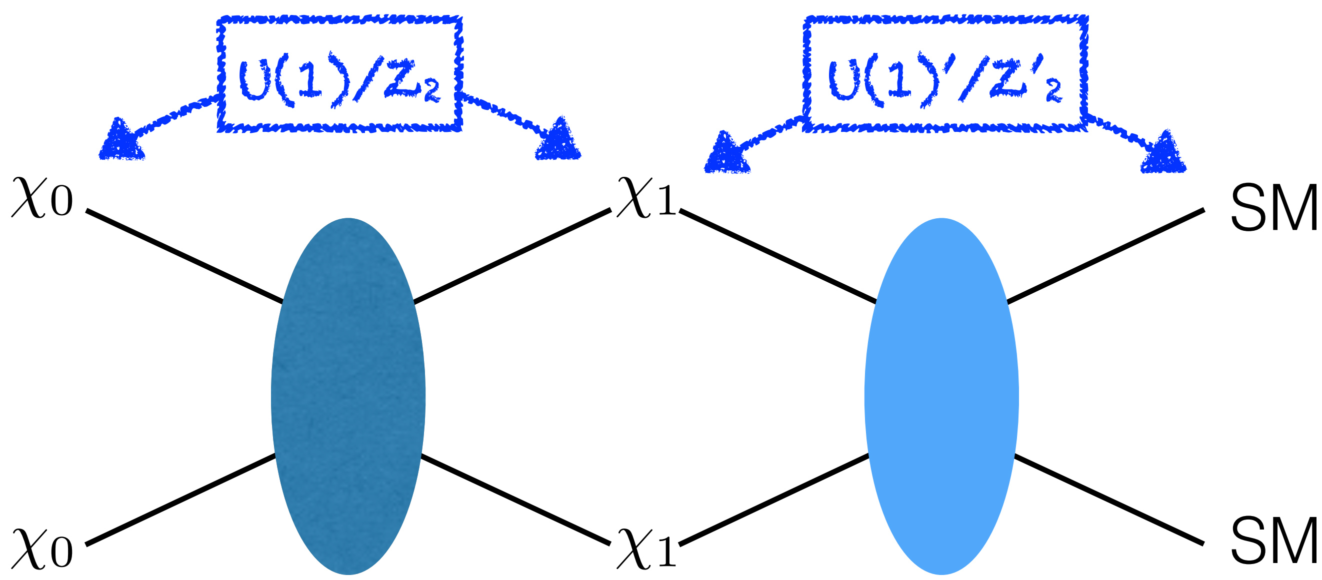
e.g., copy of SM or more complex?

See also lectures by Hitoshi, Tongyan

- Multi-component? dark p or e or ν ?
- Relativistically moving? dark e or ν ?
- Dark gauge symmetry? U(1), SU(2), SU(3)?
- Different flavor? dark e, μ ?

Multi-component Boosted DM (BDM)

χ_0: heavy, χ_1: light



Agashe, Cui, Necib, Thaler,1405.7370

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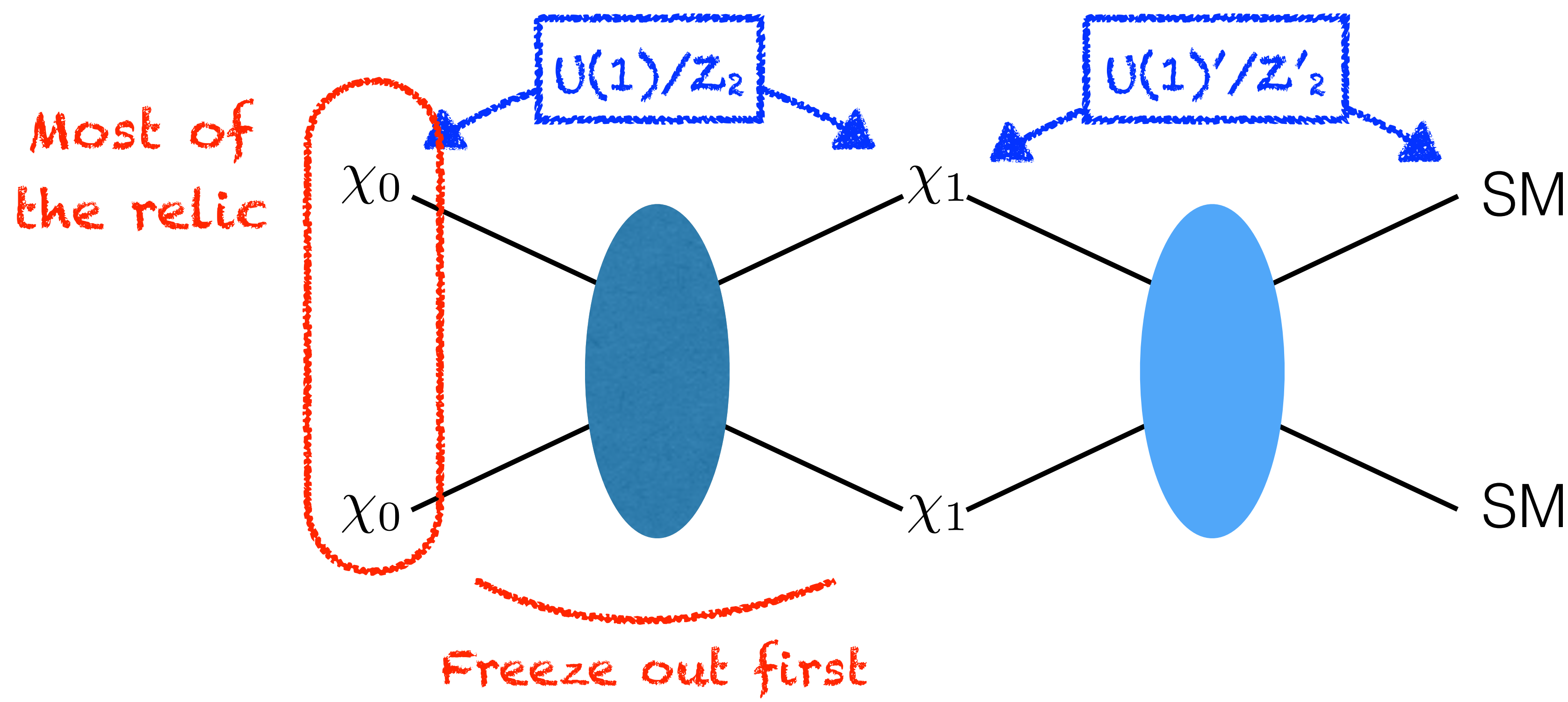

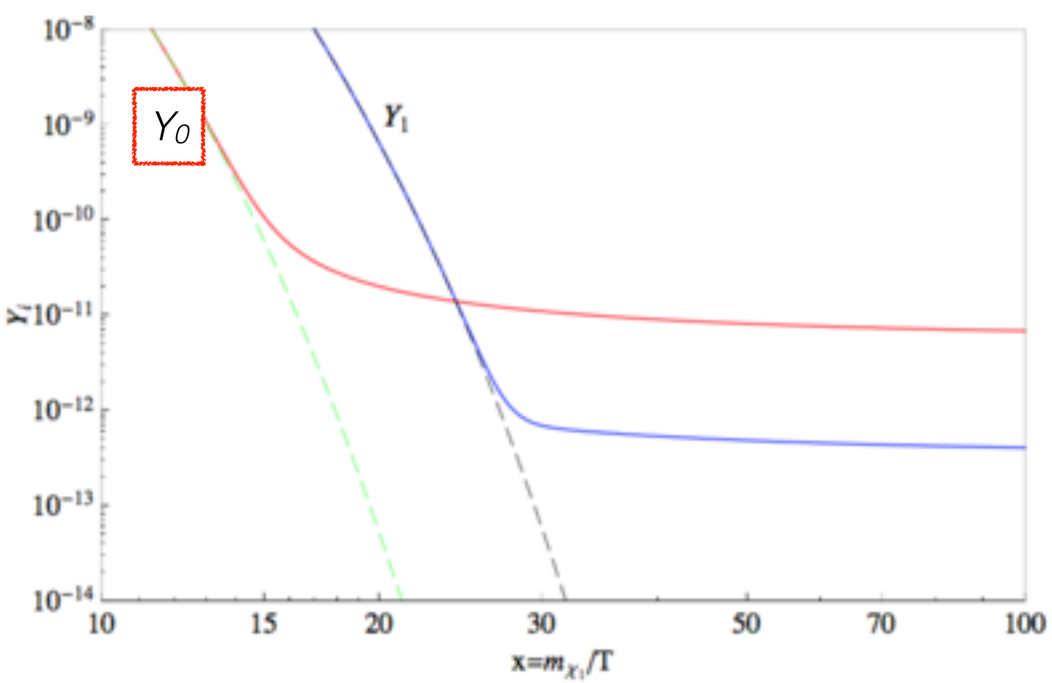

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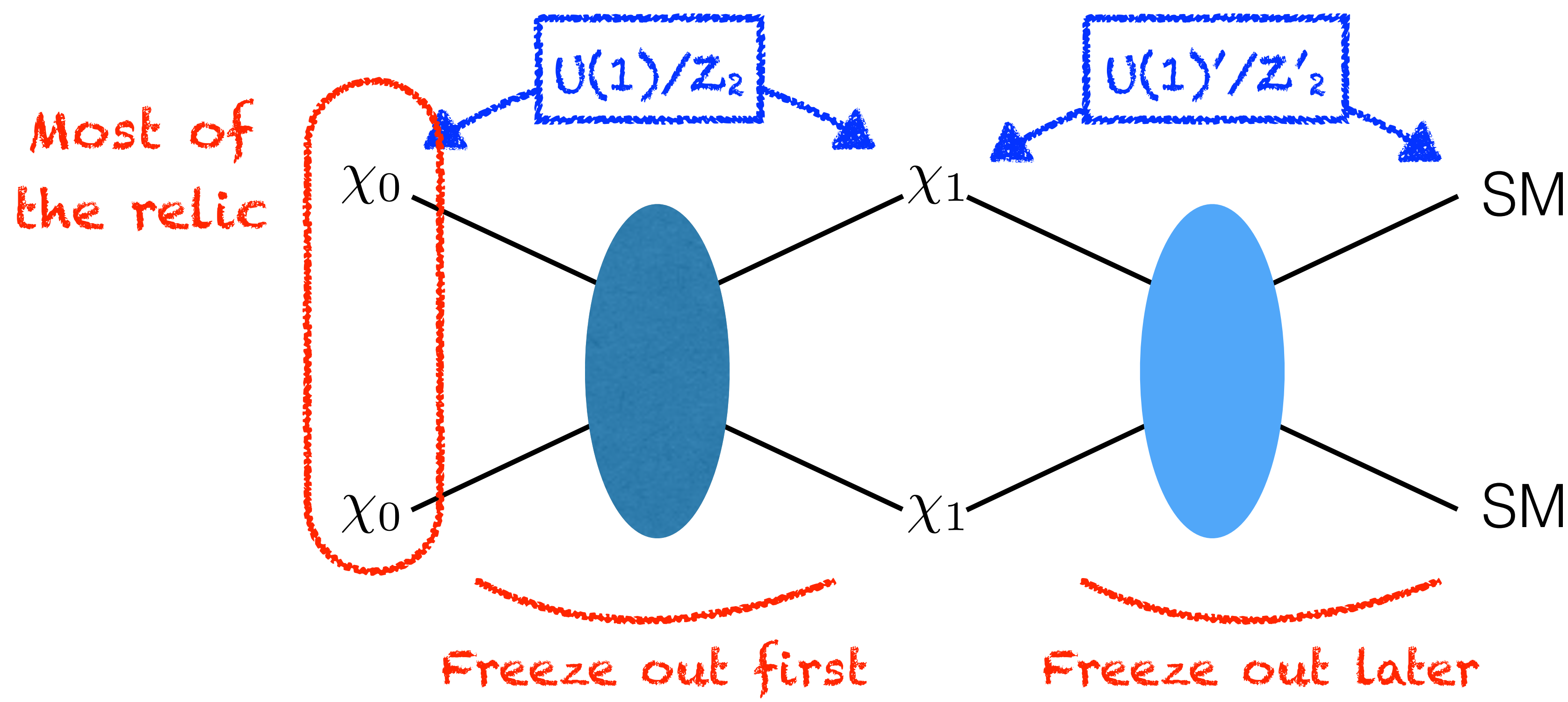

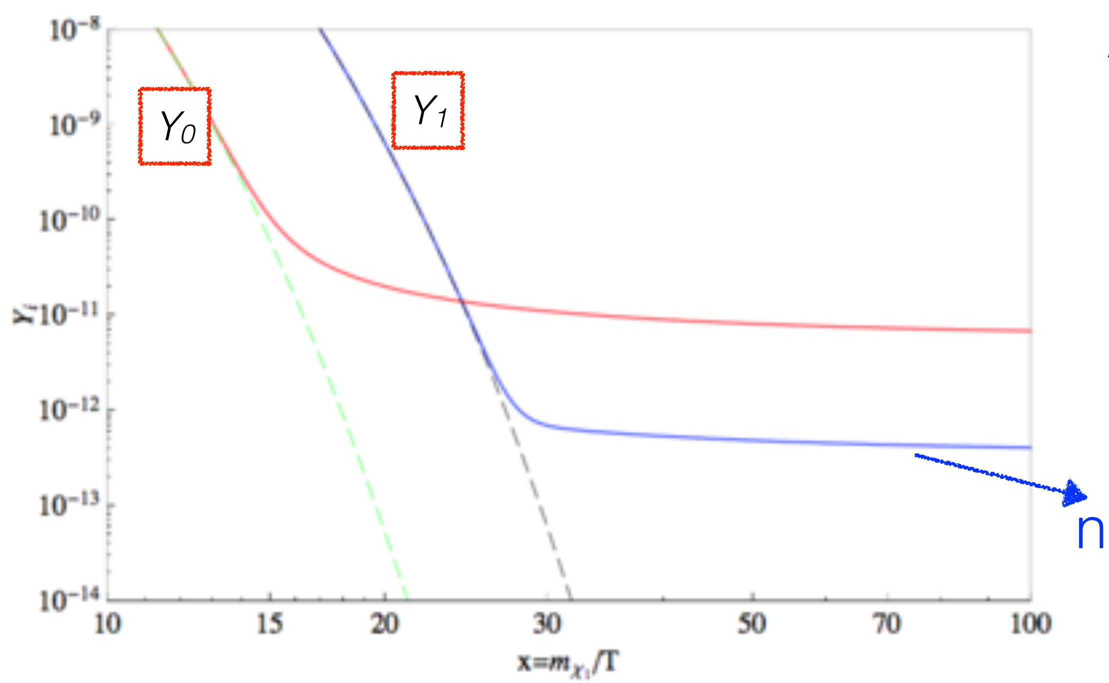

Agashe, Cui, Necib, Thaler,1405.7370

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

(indirect detection of χ_0)

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

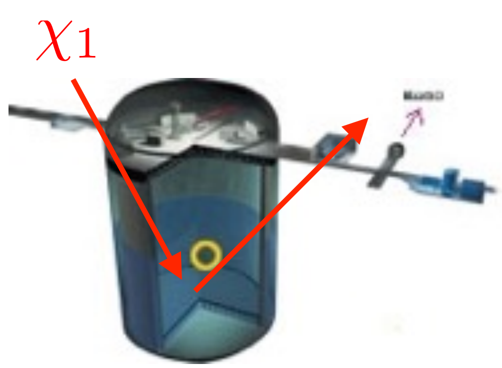
Assume: NFW

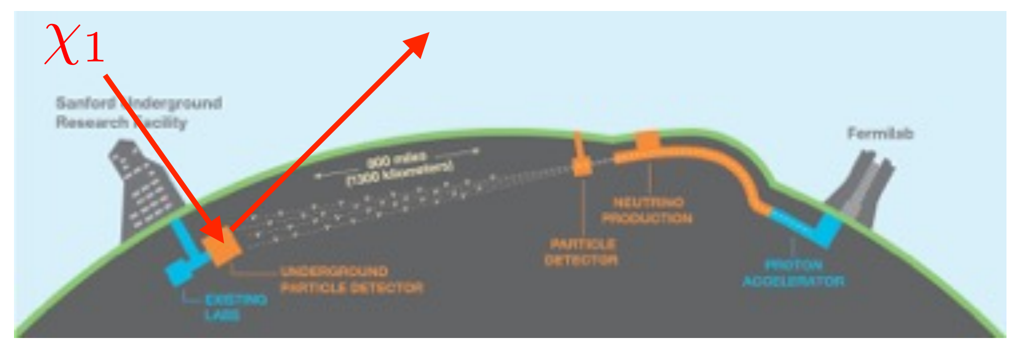
Fixed ~ 1 if s-channel annihilation dominates

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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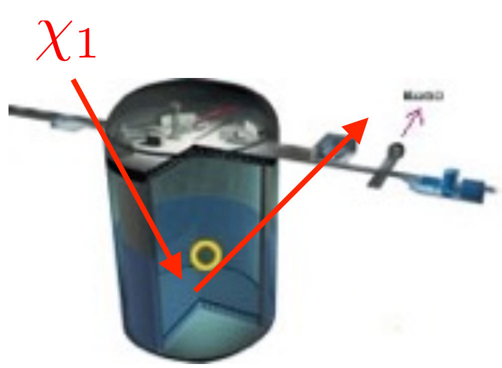

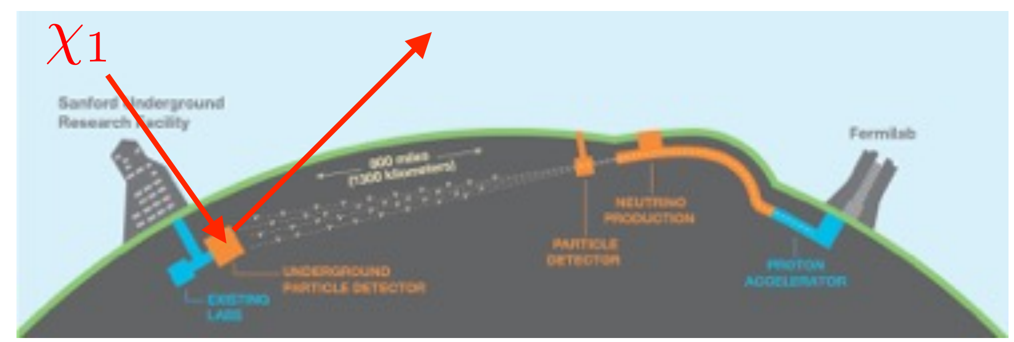

Subtraction of
major background (ν)

Important for all cosmogenic
BSM signals

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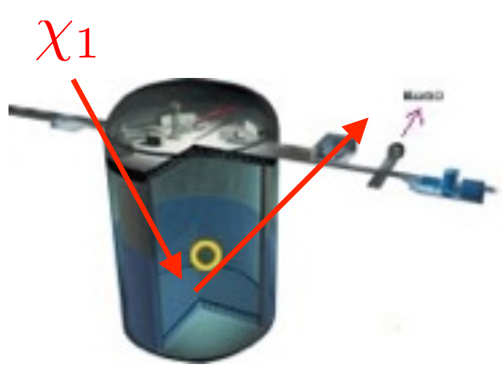
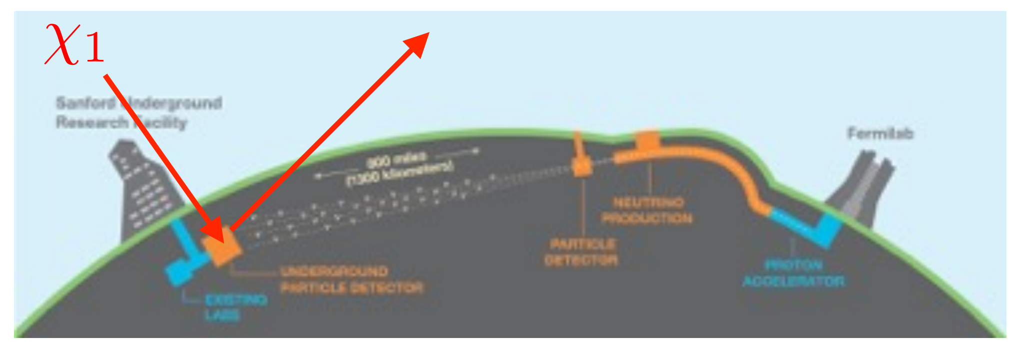
Flux: small & Energy of χ_1: large ⟶ Large volume ν experiments





Subtraction of
major background (ν)

Important for all cosmogenic
BSM signals

- Directional information:
  e.g., GC, Sun, dSphs
- Signal with unique feature

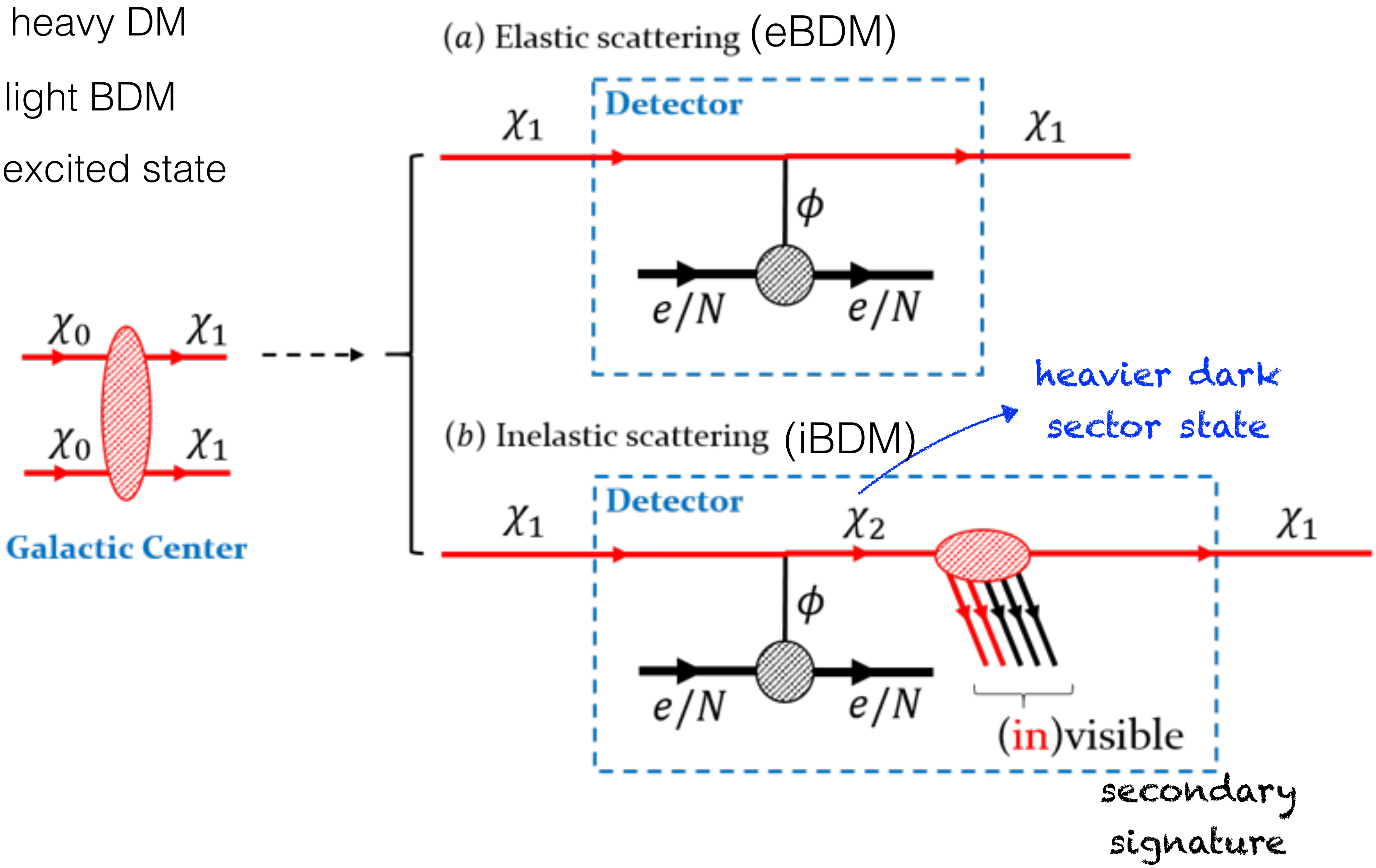
Open up novel possibilities of BDM search in many experiments

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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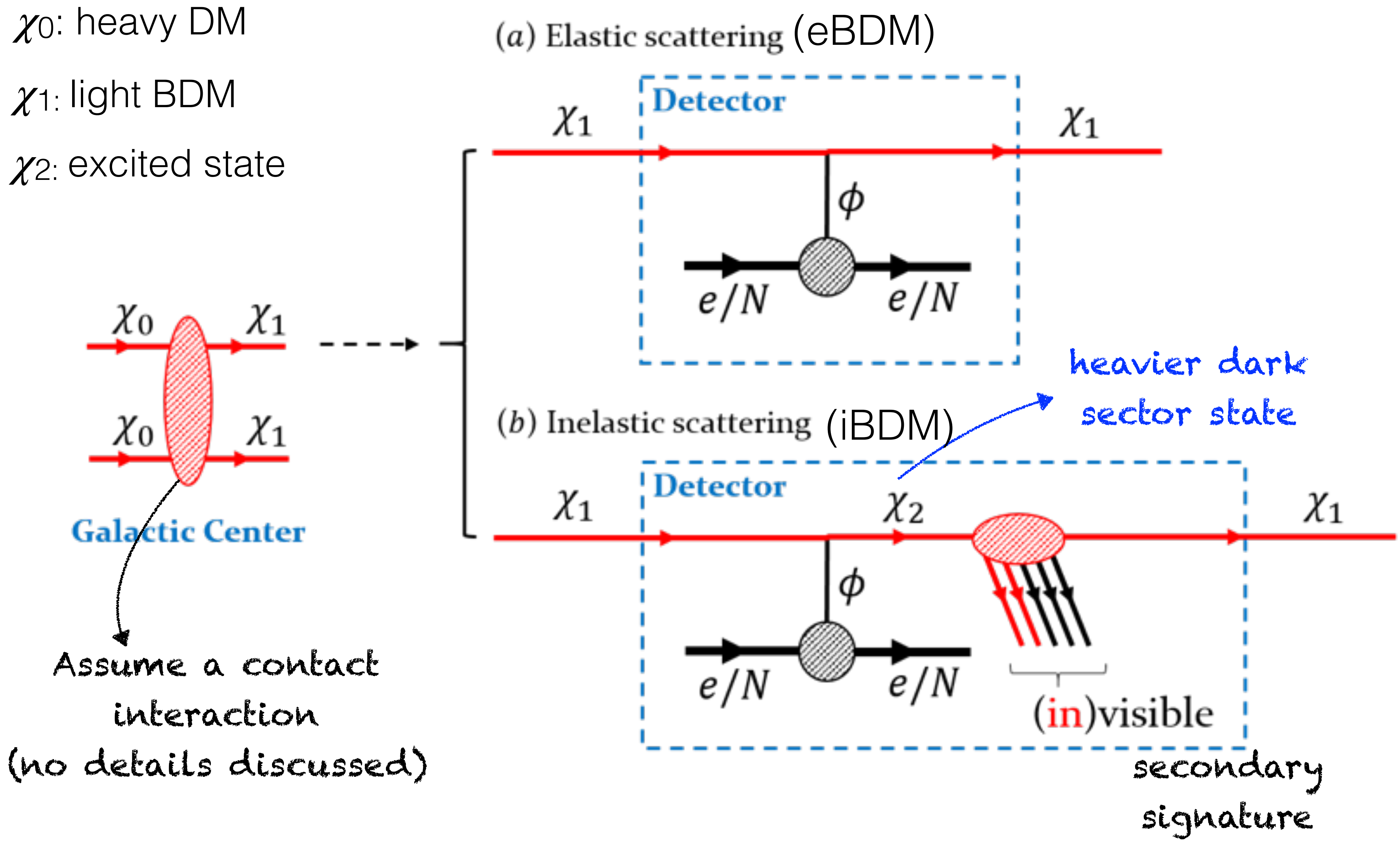

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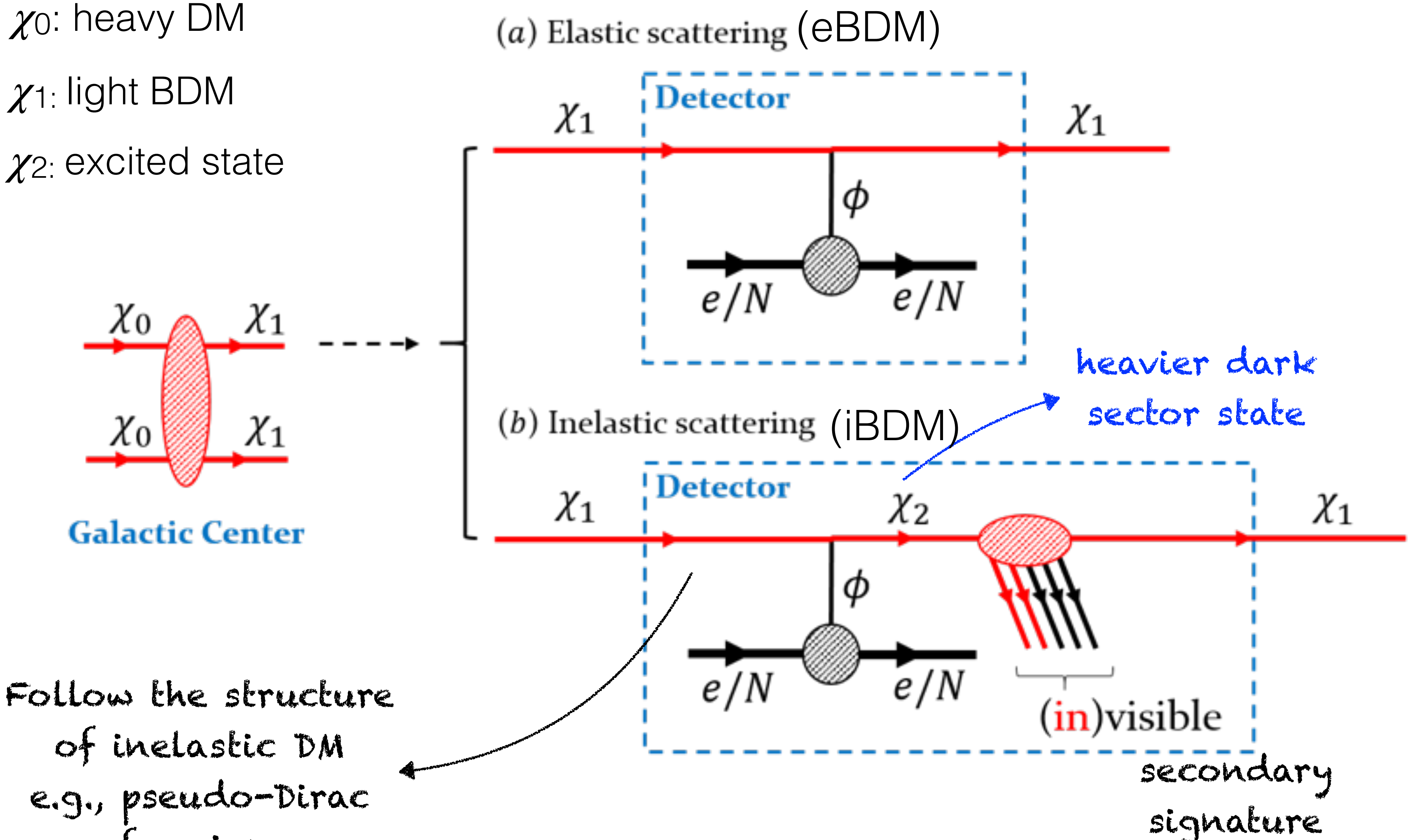

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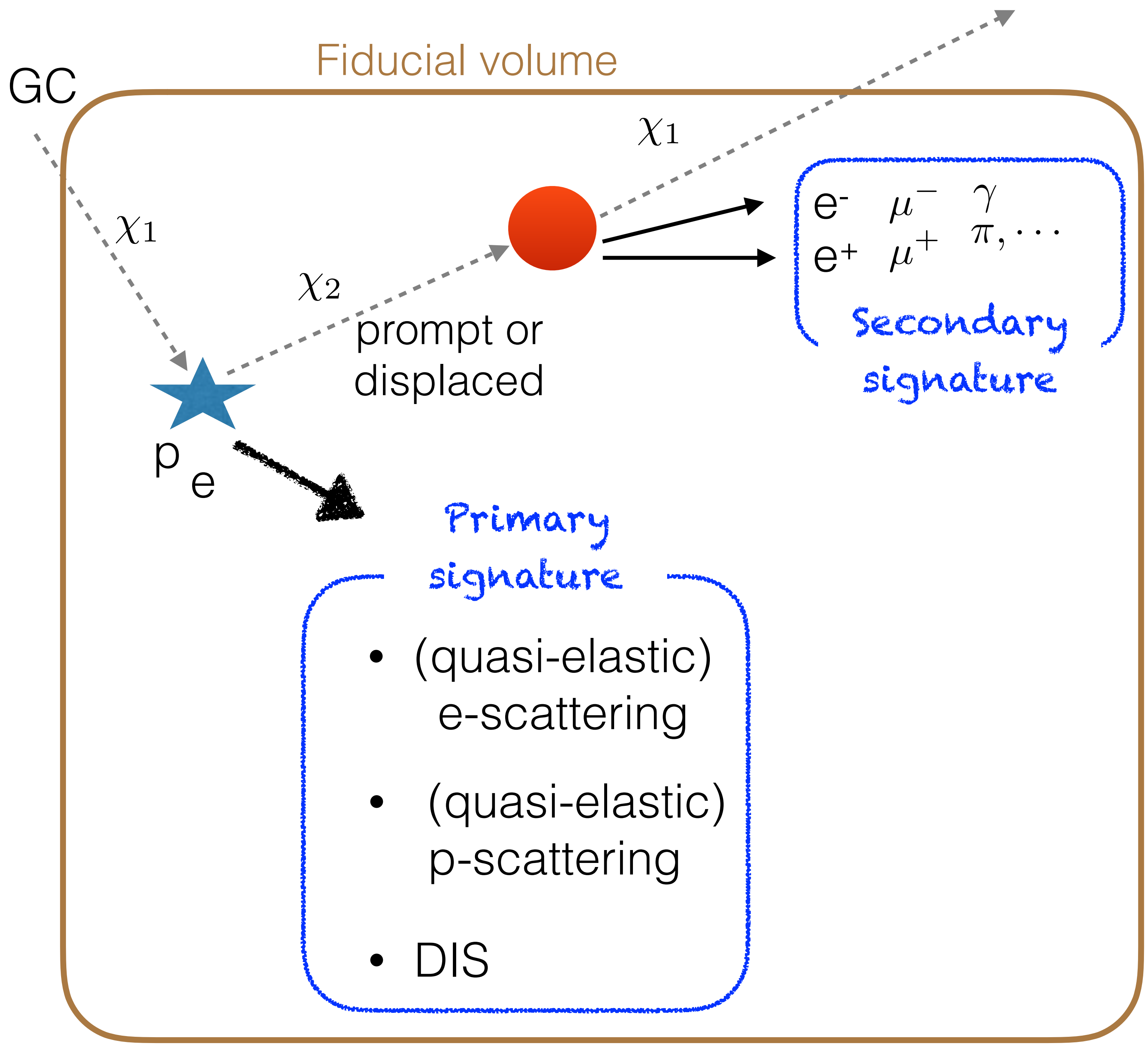
Signals inside a fiducial volume



χ_1: light BDM, χ_2: excited state

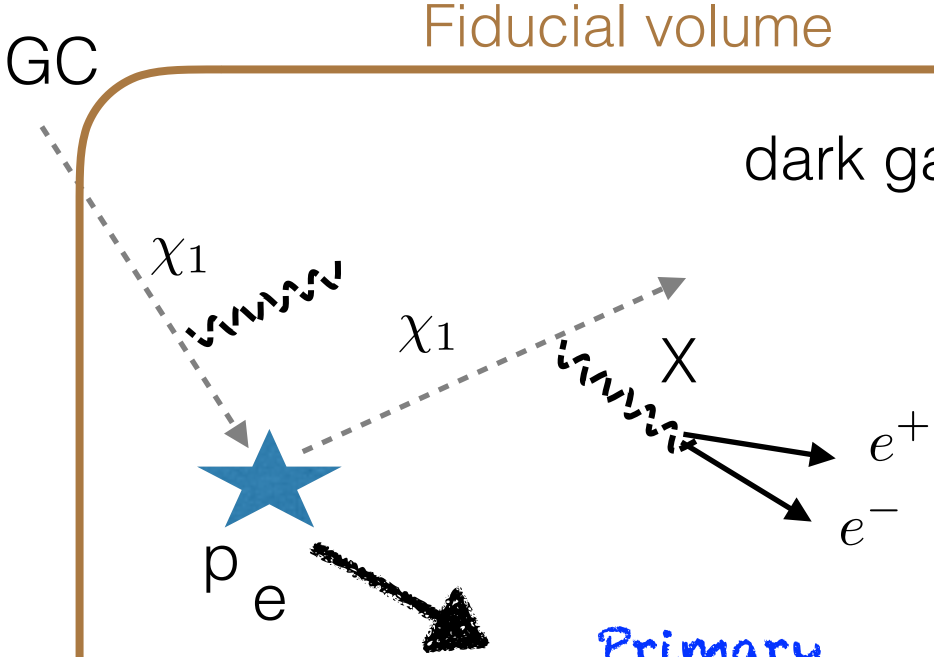
iBDM

- Tracks pop-up inside fiducial volume
- Track observation & time correlation can reject bkg.

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

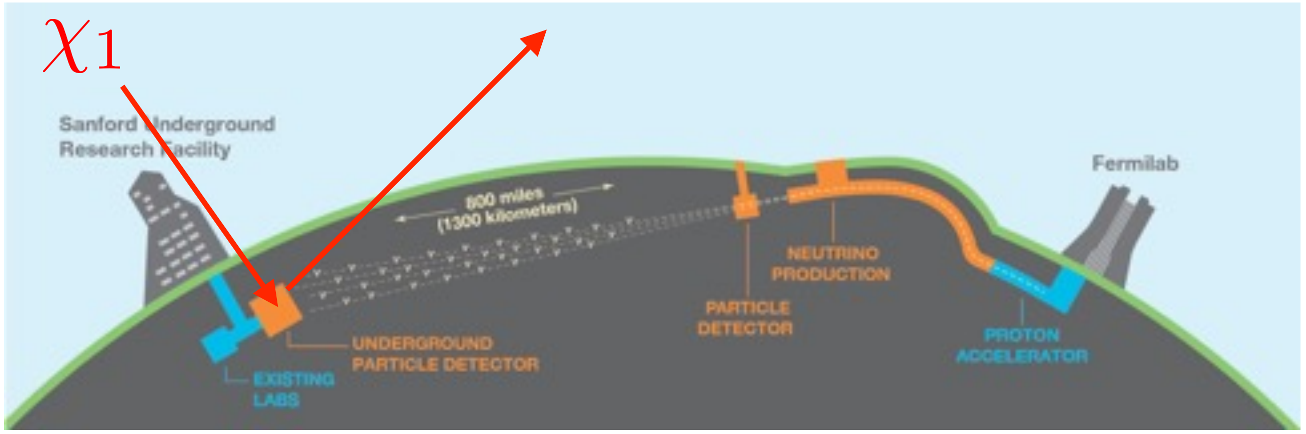
eBDM: elastically scattering BDM

- Different from DM → $\nu\ \nu$
- NLO but O(10-20%) of LO possible (impossible for beam produced DM)
- Efficient for large N_{BG} (cosmogenic BSM signal)

Signal probe

- DUNE: Search for both iBDM & eBDM   TRD (soon)

De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, work in progress



Signal probe

- DUNE: Search for both iBDM & eBDM   TRD (soon)

De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, work in progress

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

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

Assume: NFW

Signal probe

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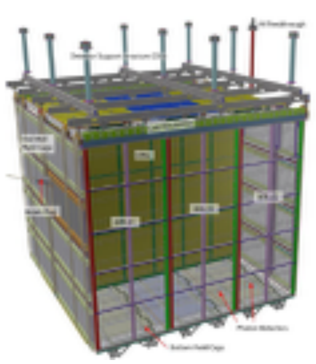
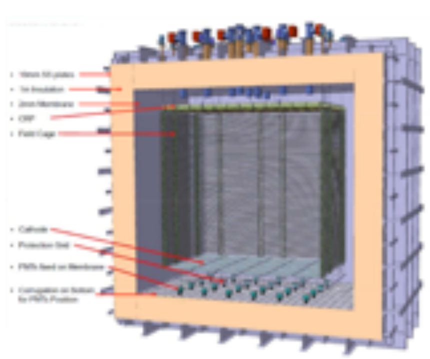
- Moderate volume surface-based neutrino experiments:
  Short-baseline neutrino program, ProtoDUNE

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

Chatterjee, De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, Yu, 1803.03264





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

Signal probe

- DUNE: Search for both iBDM & eBDM TRD (soon)

De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, work in progress

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

- Ton-scale DM direct detection experiments:
  XENON1T, DarkSide-20k, COSINE-100

First iBDM search result

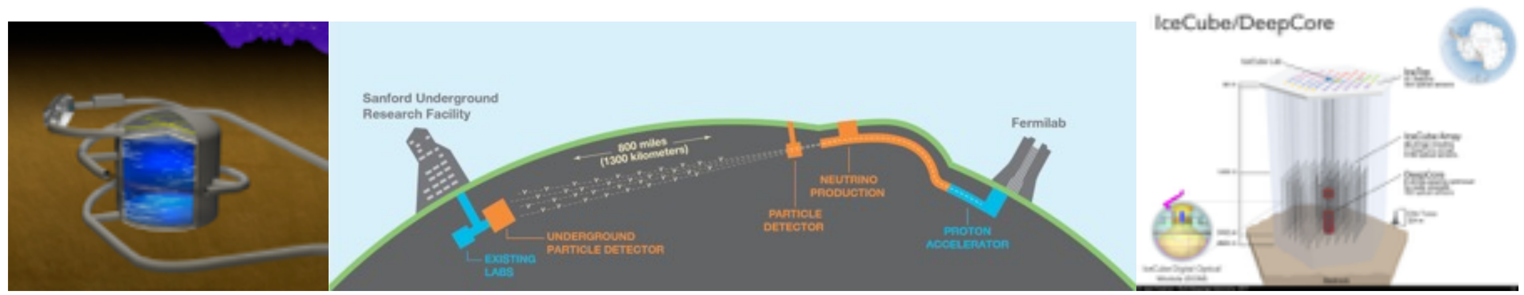
PRL 2019

106kg array of 8 ultra-pure NaI(Tl) crystals

surrounded by 2200L of liquid scintillator (~ 2 ton)

Observed: 21 events, Background expected: 16.4 ± 2.1

Complementary searches

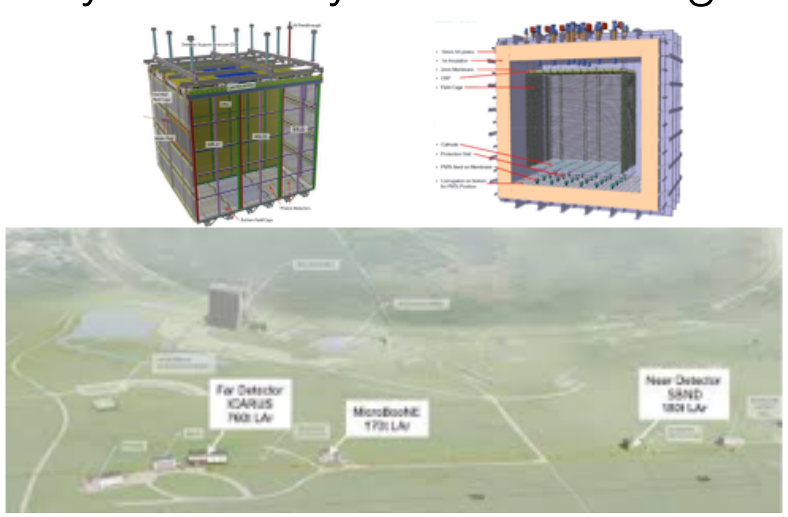


Large volume ν experiments (underground)

signal observation

background subtraction

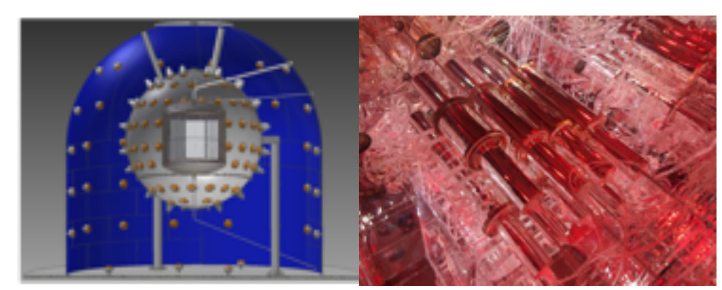
Early discovery & less ν background



Moderate volume surface ν experiments

Better resolution (E_{th}, angle)

Sensitive for smaller $E_1 = m_0$



Ton scale DM direct detection experiments (underground)

Applications of dark sector structure

- Positron excess (TeV) Kim, Park, **SS**, 1702.02944

Heurtier, Kim, Park, **SS**, 1905.13223

- High Energy cosmic-ray signals: IceCube (PeV), ANITA (EeV)

Heurtier, Kim, Park, Park, **SS**, in progress

- Light DM searches in fixed target experiments: e.g, ν-experiments

Subtraction of
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Arrival time to detectors
&
Recoil energy

Dutta, Kim, Liao, Park, **SS**, Strigari,
1906.10745 & in progress

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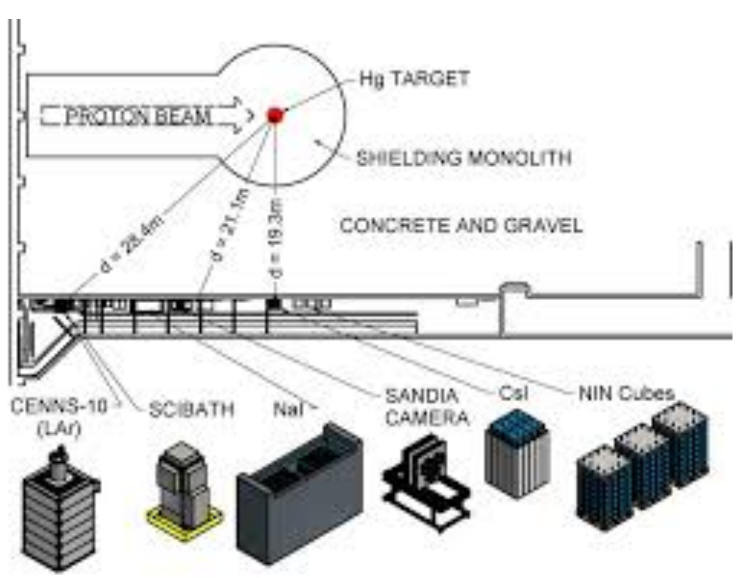

Arrival time to detectors
&
Recoil energy

Dutta, Kim, Liao, Park, **SS**, Strigari, 1906.10745 & in progress

$$\pi^+ \to \underline{\nu_\mu} \mu^+ \to \nu_\mu e^+ \underline{\bar{\nu}_\mu \nu_e}$$

prompt delayed

Applications of dark sector structure

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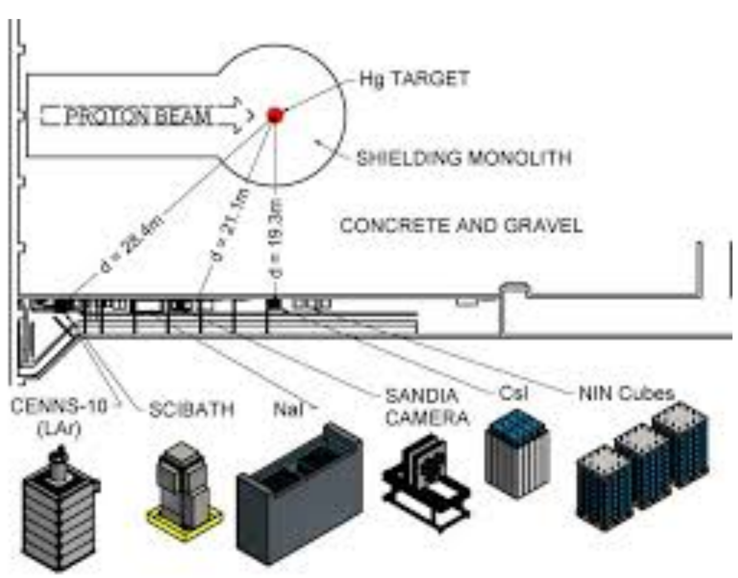

$$\pi^- + p \to X + n$$

$$X \to \chi\bar{\chi}$$

Arrival time to detectors
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Dutta, Kim, Liao, Park, **SS**, Strigari, 1906.10745 & in progress

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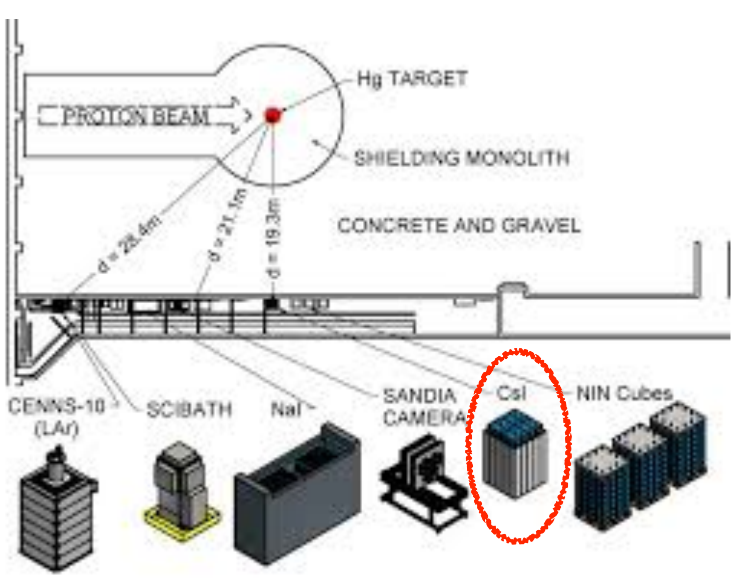


COHERENT, 2018 CsI data

$$\pi^- + p \to X + n$$

$$X \to \chi\bar{\chi}$$

Arrival time to detectors
&
Recoil energy

Dutta, Kim, Liao, Park, **SS**, Strigari, 1906.10745 & in progress

3σ (2.4σ) statistical deviation
for Rn = 5.5fm (4.7fm)

Conclusions

- BDM (iBDM & eBDM) is a candidate of Dark World beyond WIMP

  New DM search strategies required!

- Unique signal feature helps to reject ν background:

  i) iBDM

  ii) Darkstrahlung for eBDM

- Complementary searches in various experiments

Backup: other energetic DM scenarios

- Semi-annihilation model

D'Eramo, Thaler, 1003.5912

- 3 → 2 model

Carlson, Machaceck, Hall, Astrophys J. (1992)

Hochberg, Kuflik, Volansky, Wacker, 1402.5143

- 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

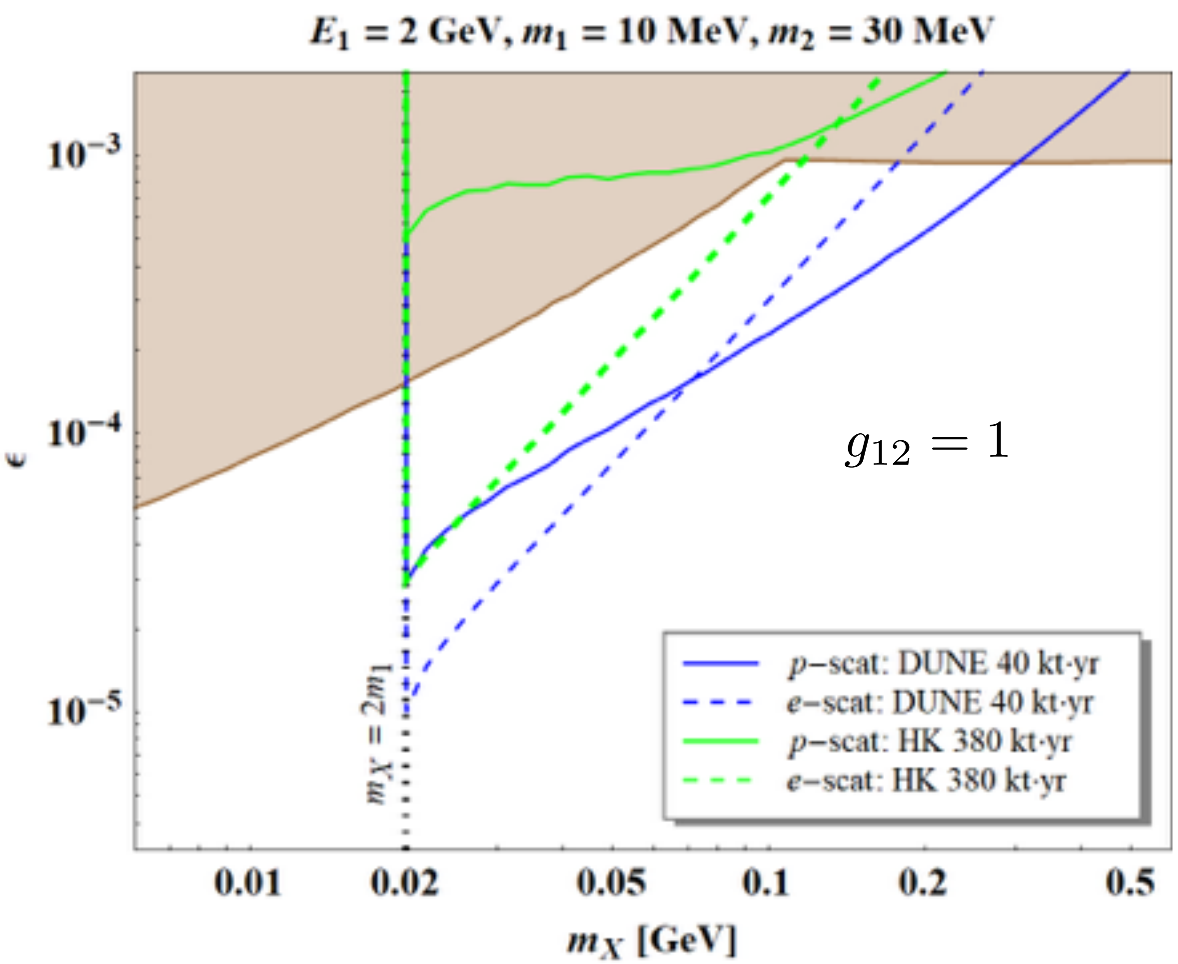
Ultra High Energetic Cosmic-Ray induced DM

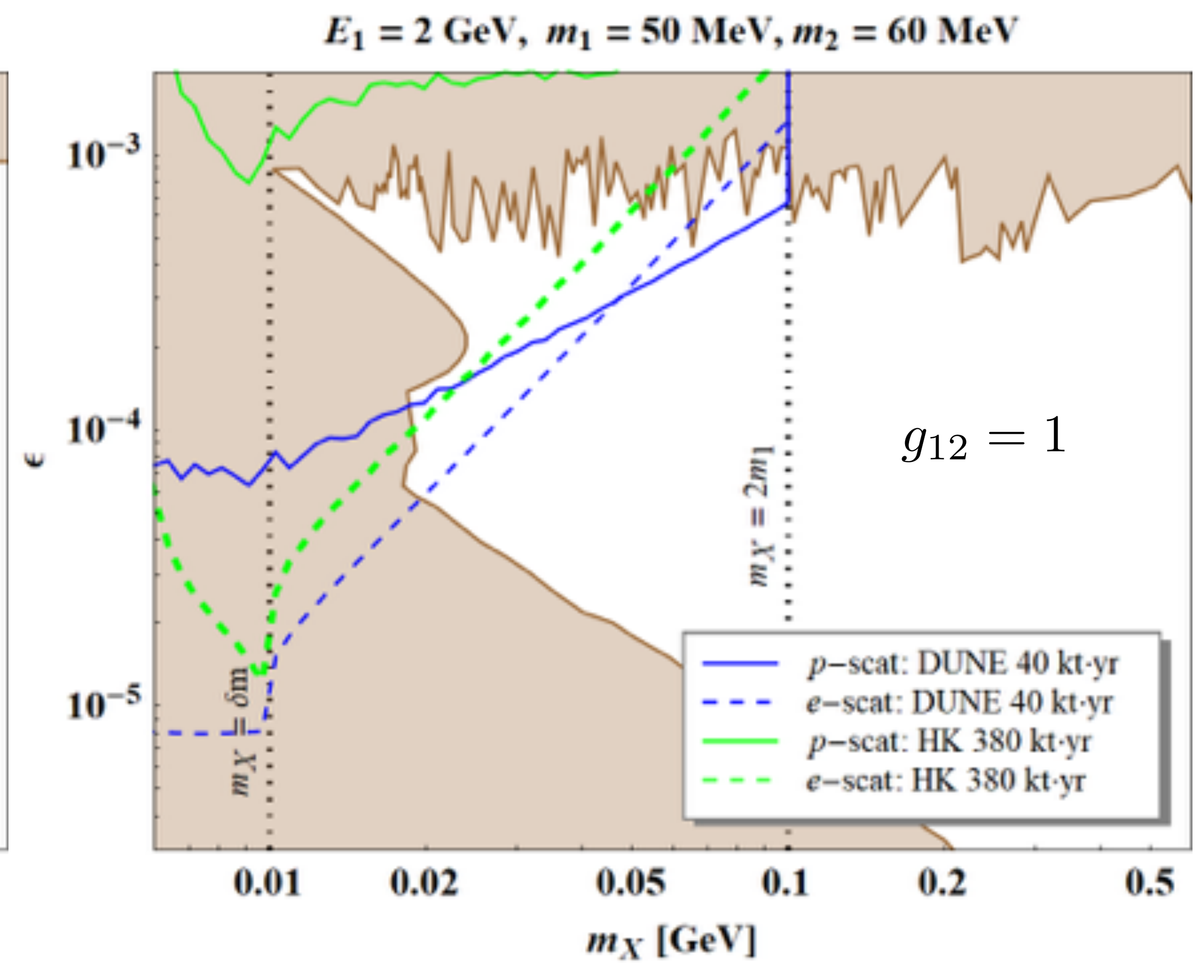
Bringmann, Pospelov, 1810.10543 Ema, Sala, Sato, 1811.00520 Yin, 1809.08610

Cappiello, Ng, Beacom, 1810.07705 Cappiello, Beacom, 1906.11283

Same phenomenology

Backup: Sensitivities at DUNE vs HK





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

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

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

  Better for larger E_1

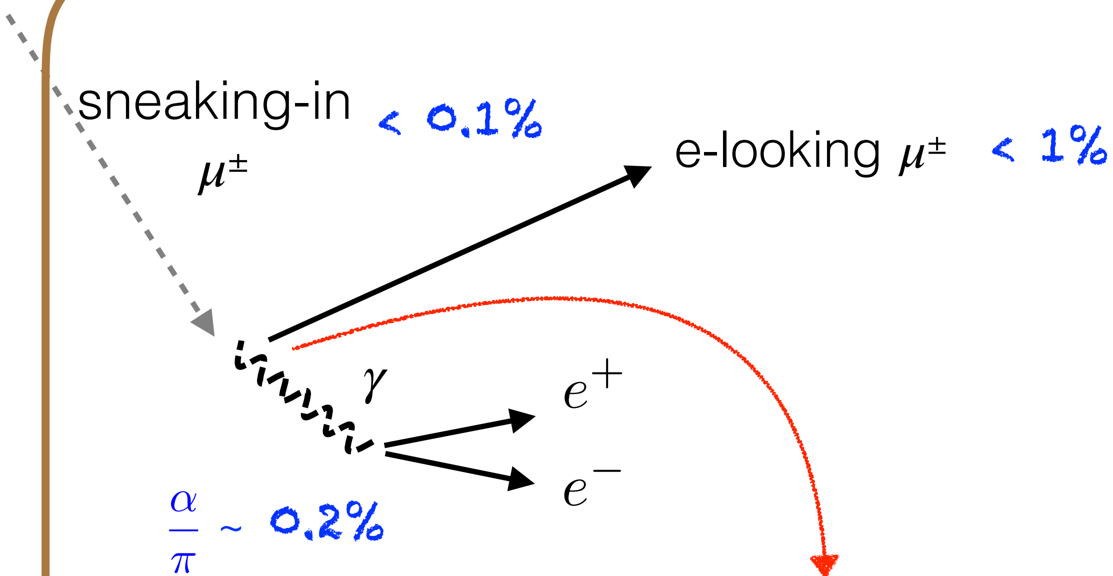
- Difference is huge for p-scattering

Kim, Machado, Park, **SS**, To appear soon

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



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

4×10¹¹/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)

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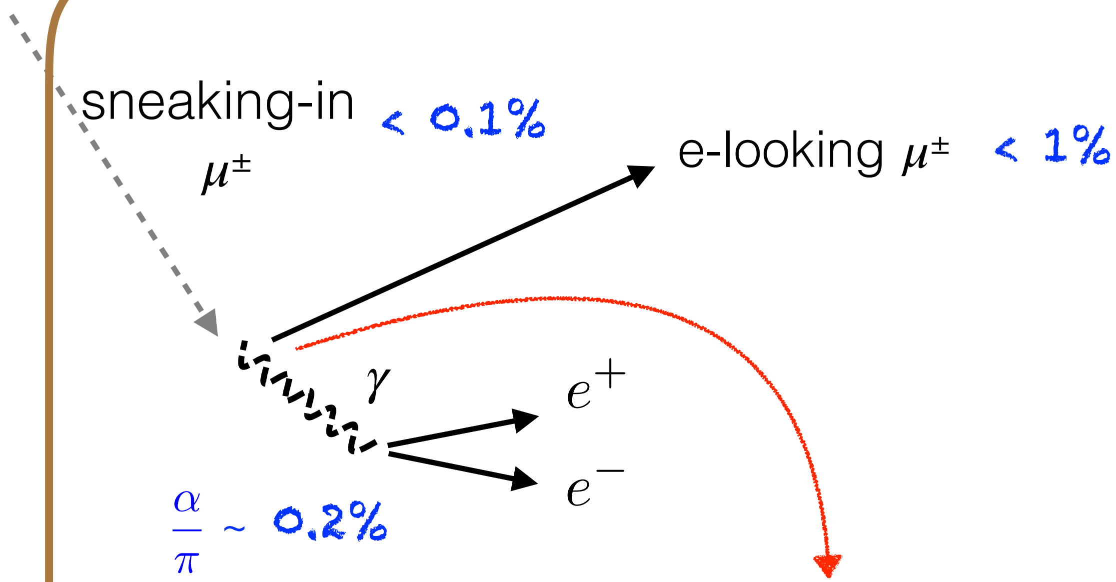

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4×10^{11}/yr/detector

ProtoDUNE

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×

2×10^{-8}
6×10^{-3}

< 100

in total detectors

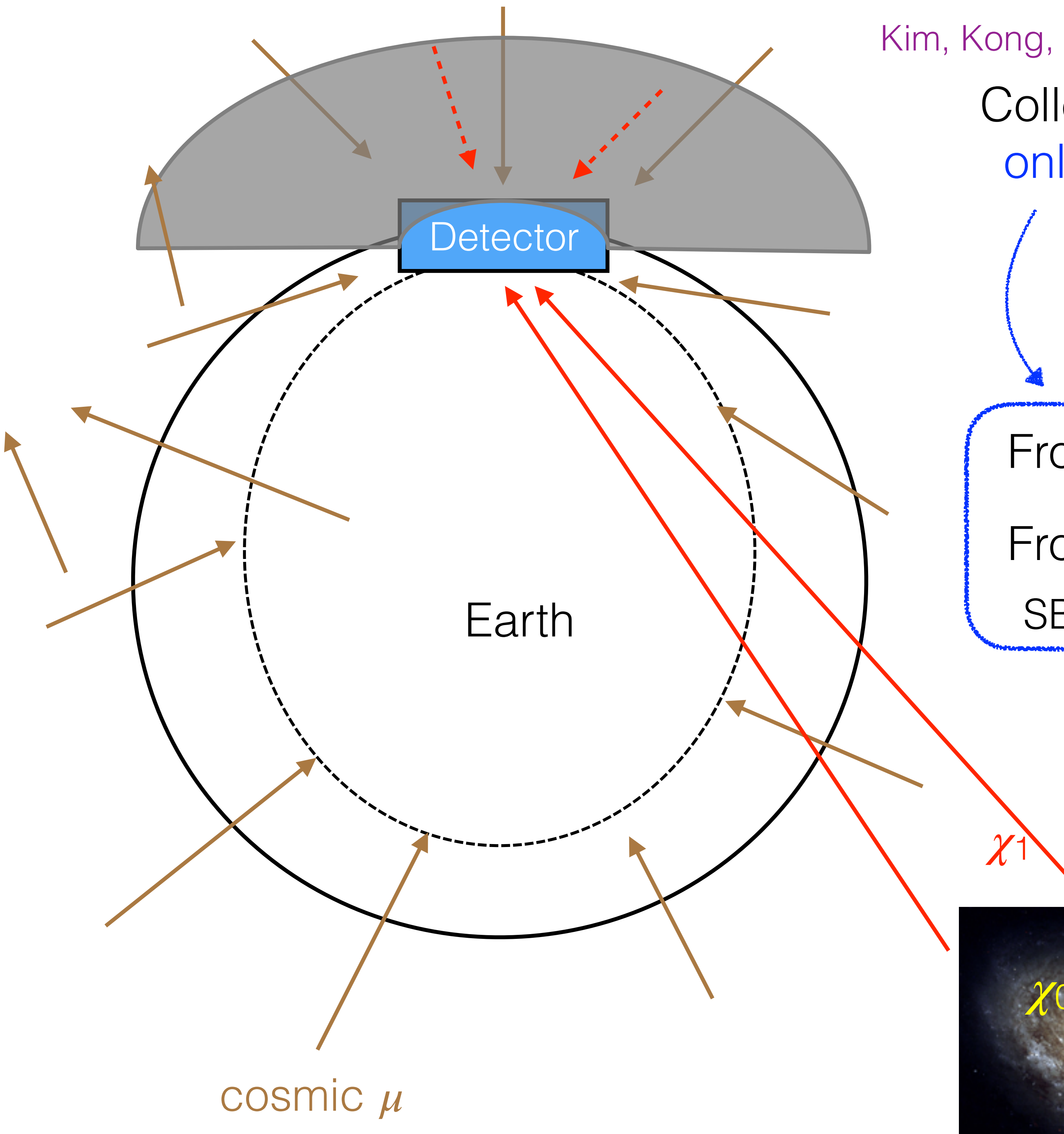
- Dominant background: sneaking-in muon (rare events but many cosmic-muons)
- Assume the unknown probability ~ 0.6%
- Pattern analysis by machine learning will decrease further (N_{bkg}: negligible)

Work in progress

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

Backup: Earth shielding

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:

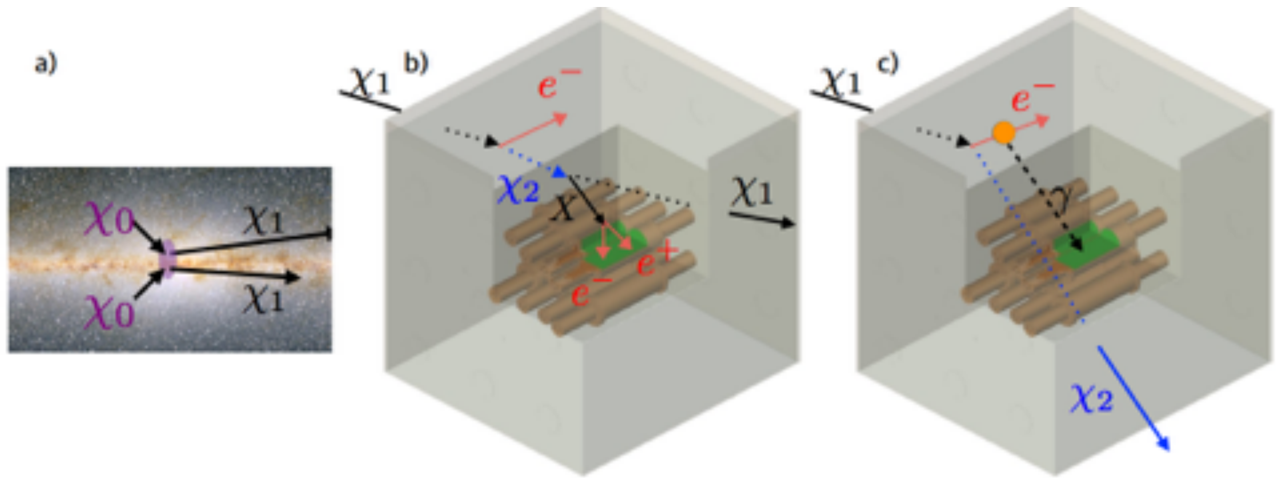
SBNP: 0.66, ProtoDUNE: 0.69

Backup: COSINE-100 result

COSINE-100, 1811.09344

Based on theoretical study

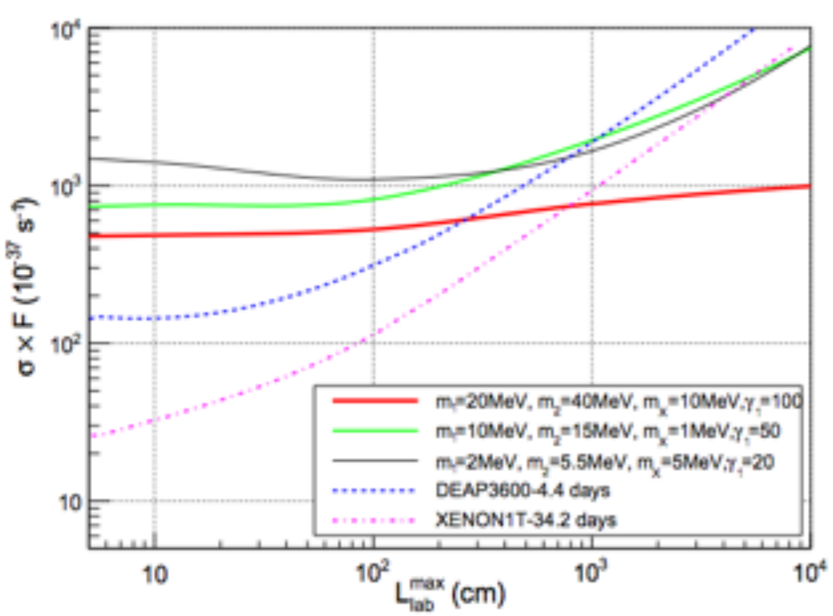
Giudice, Kim, Park, **SS**, 1712.07126

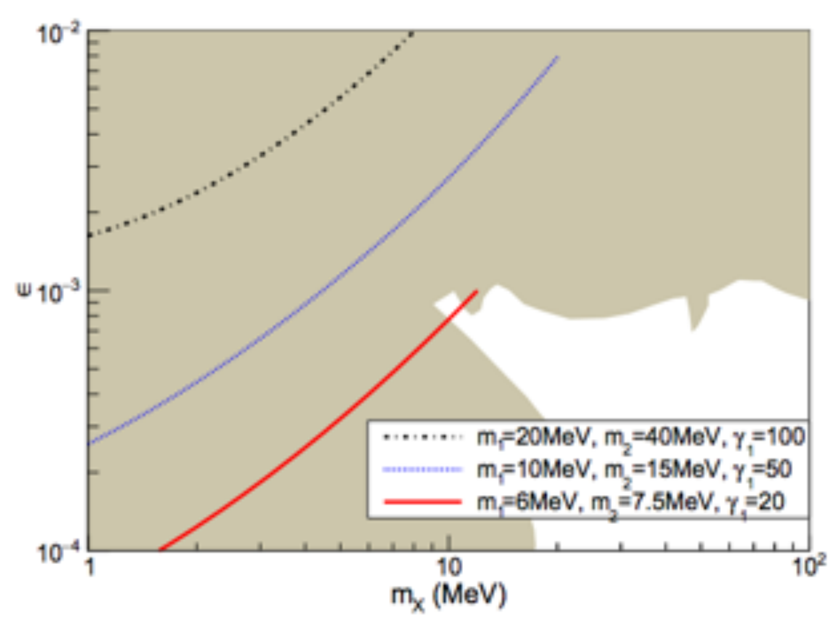


2200L of liquid scintillator
(~ 2 ton)

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

Observed: 21 events, Background expected: 16.4 ± 2.1





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
- $\mathcal{F}$: 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)

} Fixed for a given experiment ($t_{\rm exp}$, N_T)

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 — with signal efficiency
- $\mathcal{F}$: 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

Both primary and secondary inside the fiducial volume

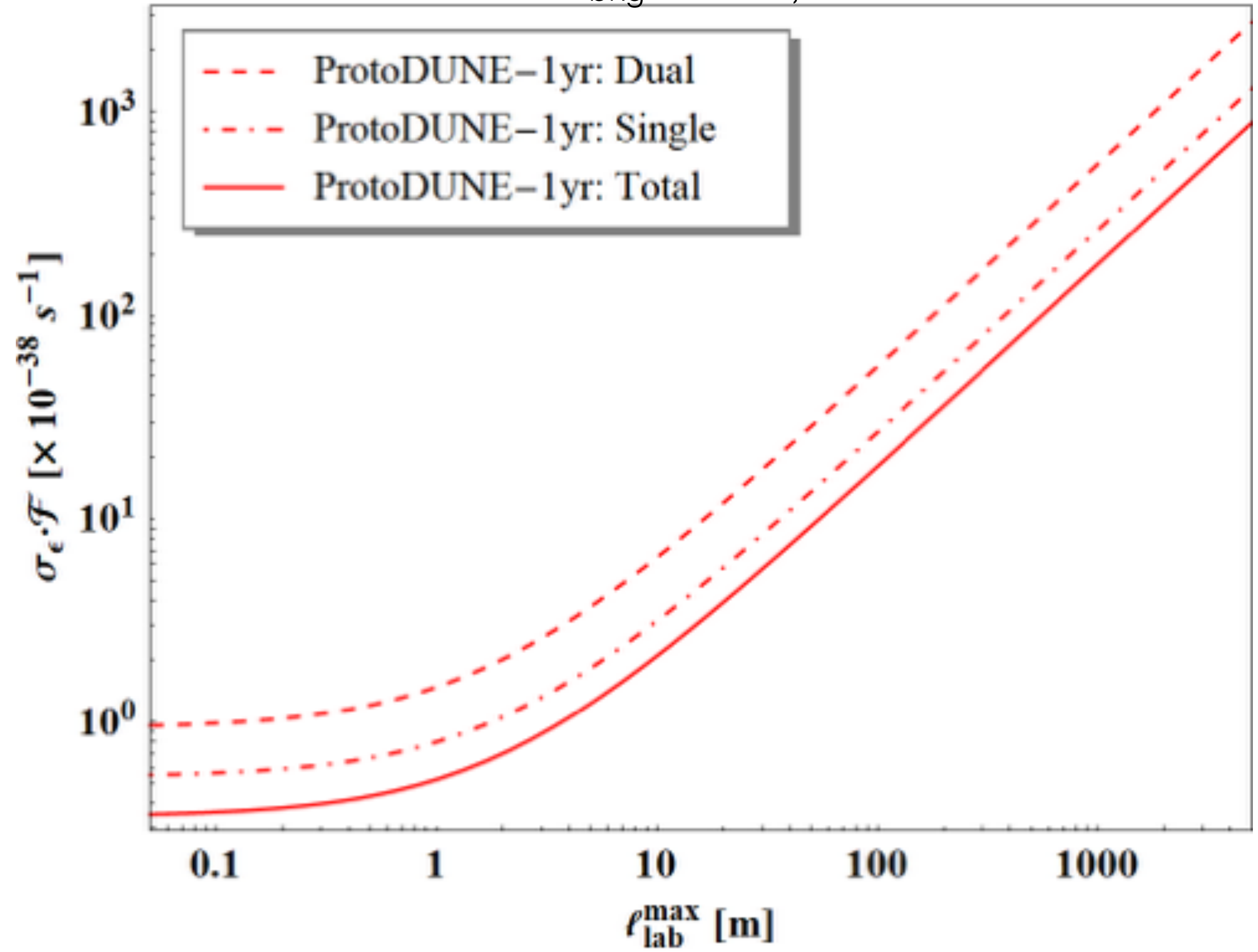
- Function of decay length of χ_2 (event generation assuming cumulatively isotopic flux of χ_1)
- Conservatively, we calculate the maximum mean decay length in the laboratory frame for each parameter set

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



(Almost) Model independent sensitivity

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

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

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

Fix (then use NFW)

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

e.g., ProtoDUNE (worst case)
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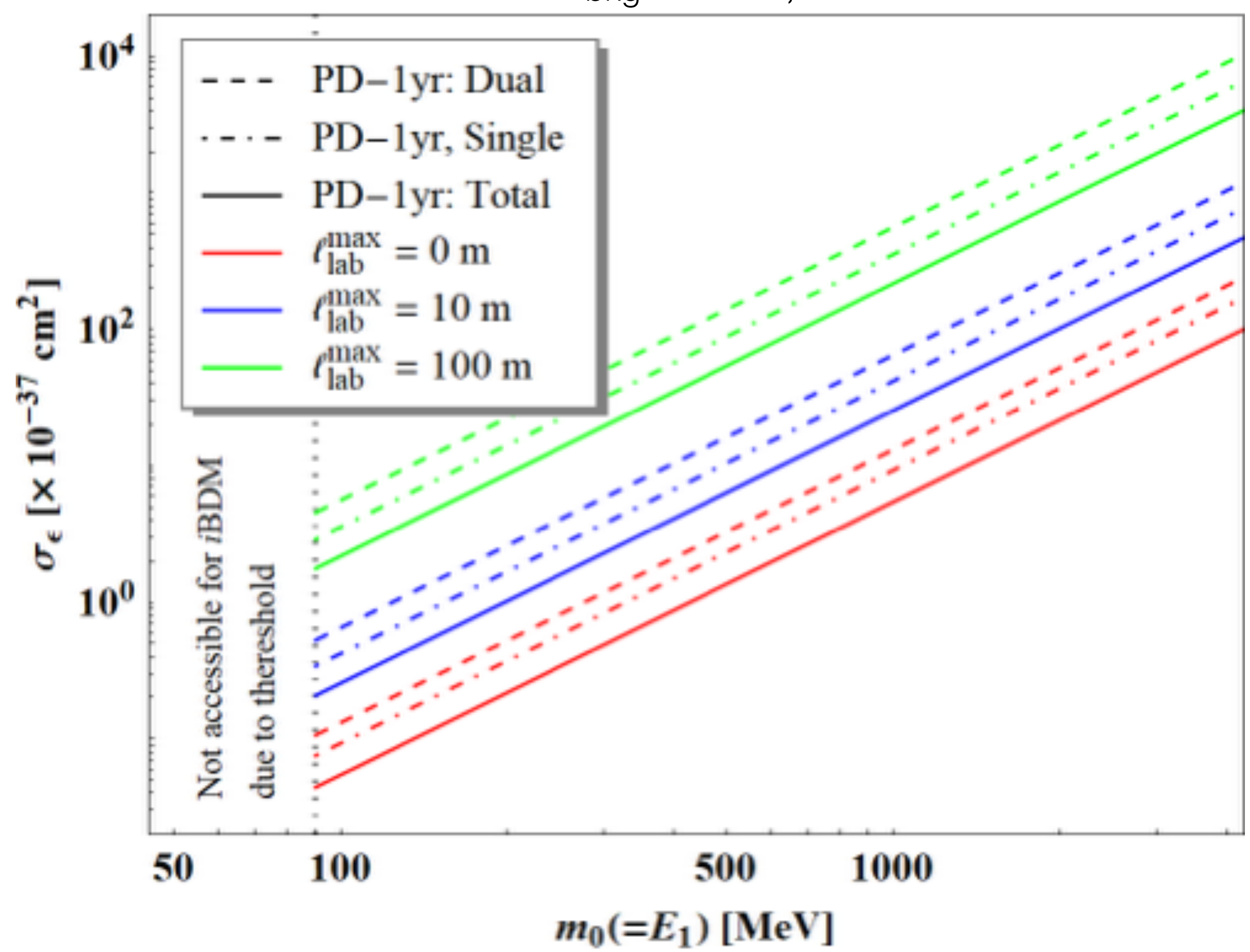

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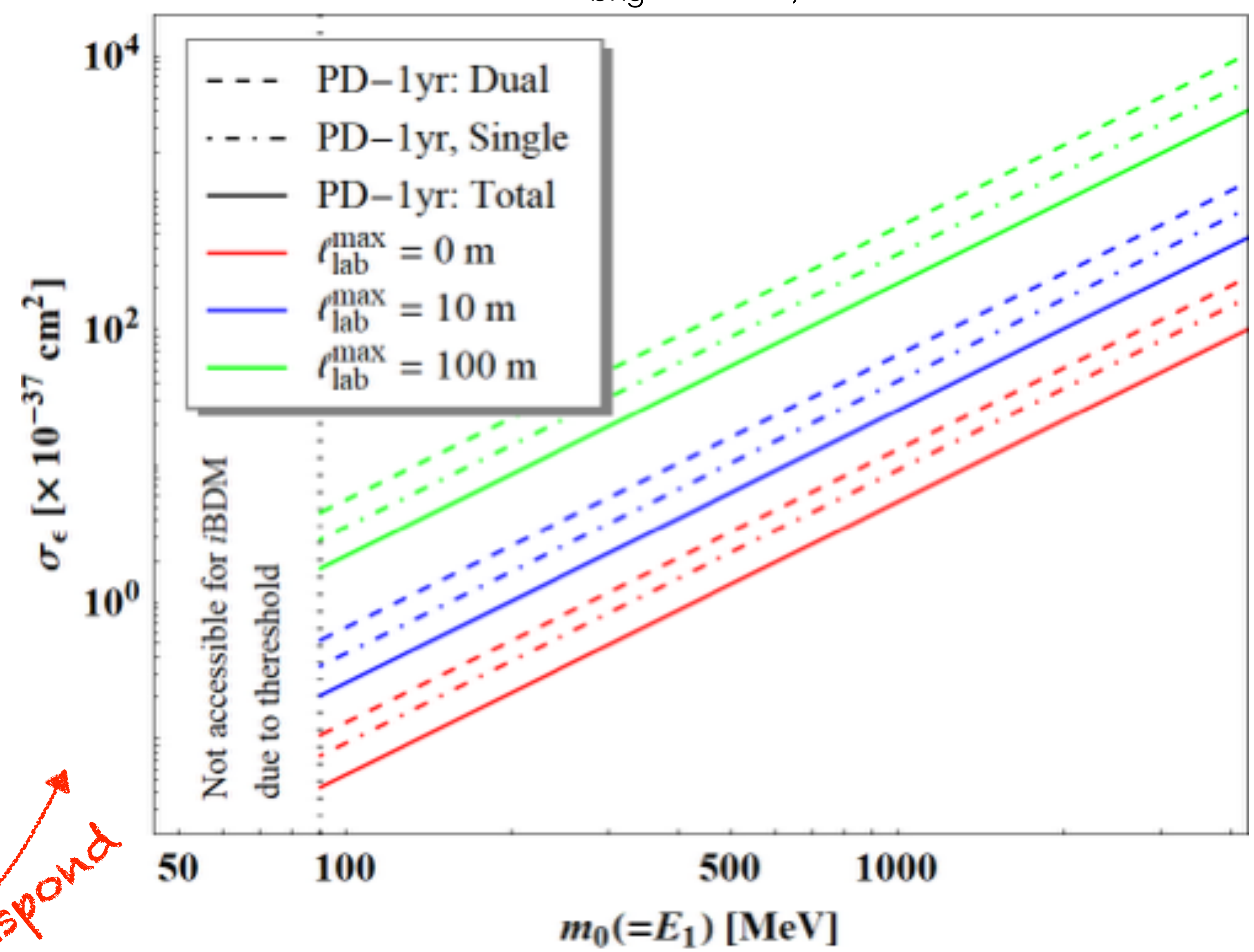
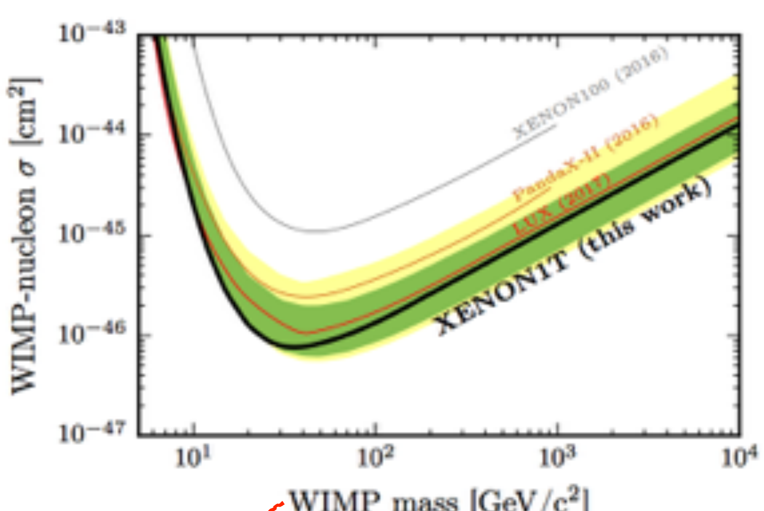


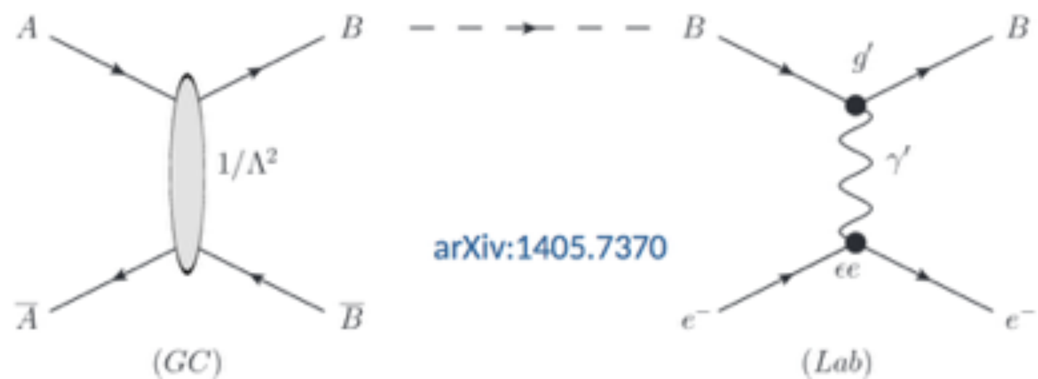


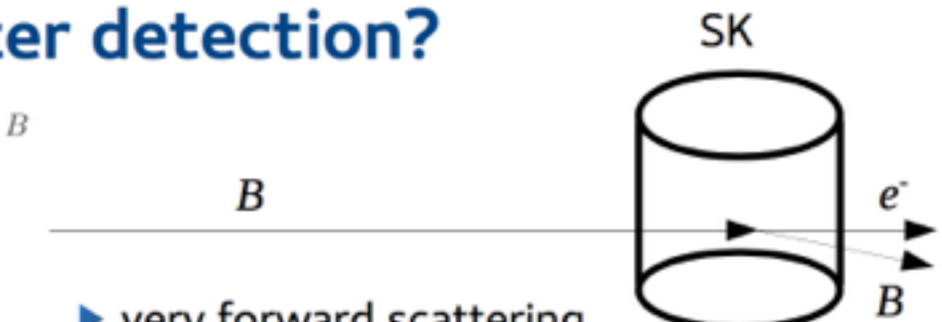
correspond

information of energy and flux

Backup: SK

(In)direct dark matter detection?

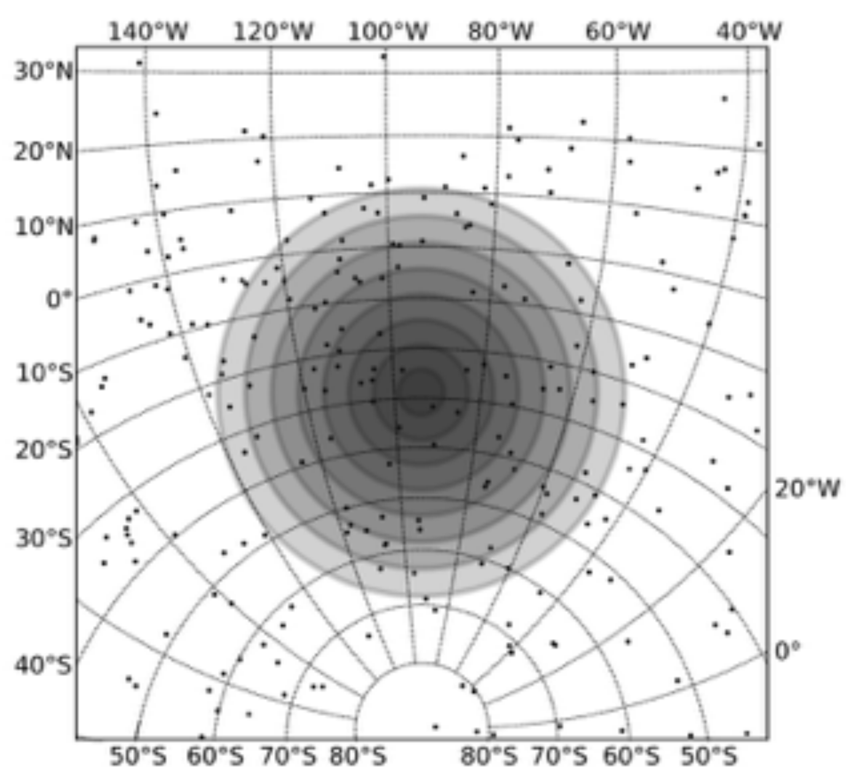




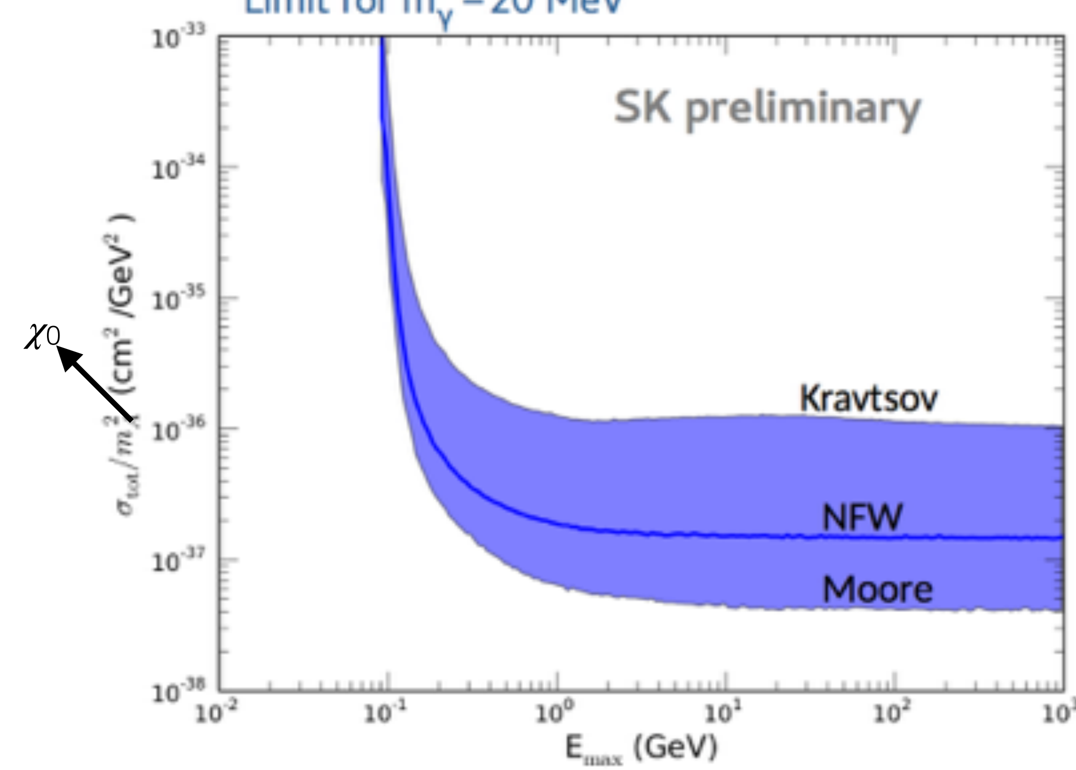
- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

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

→ **No clusters visible**



Limit for m_{γ}'=20 MeV



Backup: SK

0.1 GeV < p_e < 1 TeV

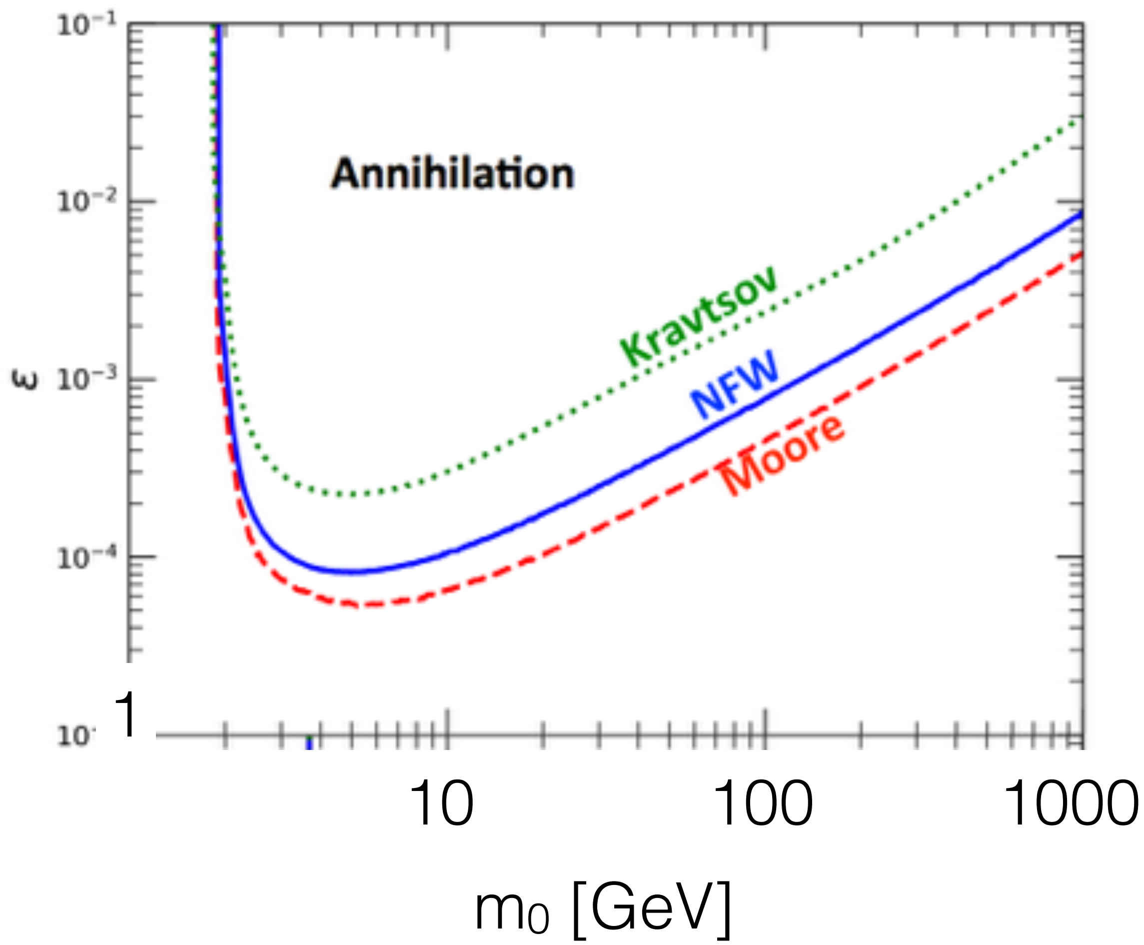
p_e^{th} with angular resolution 3°

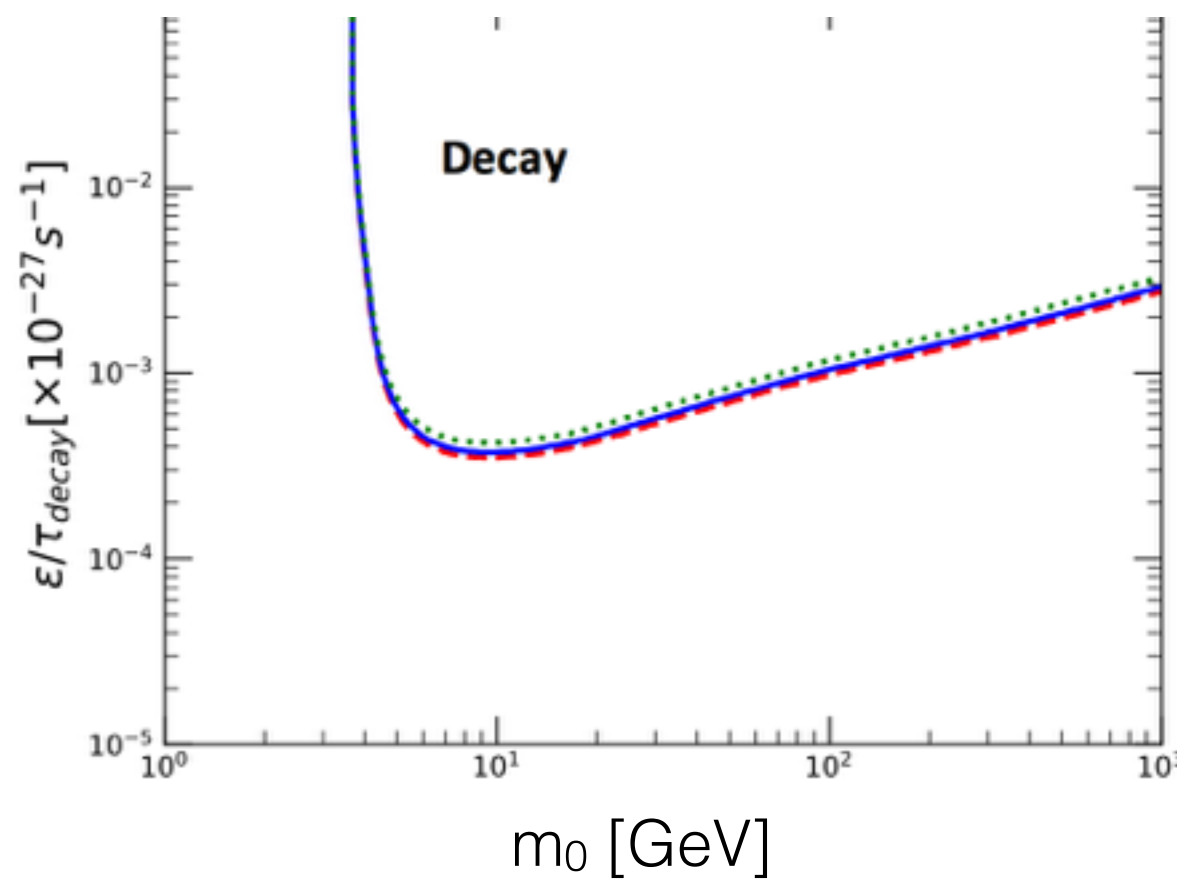
GC & Sun

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

SK, 1711.05278

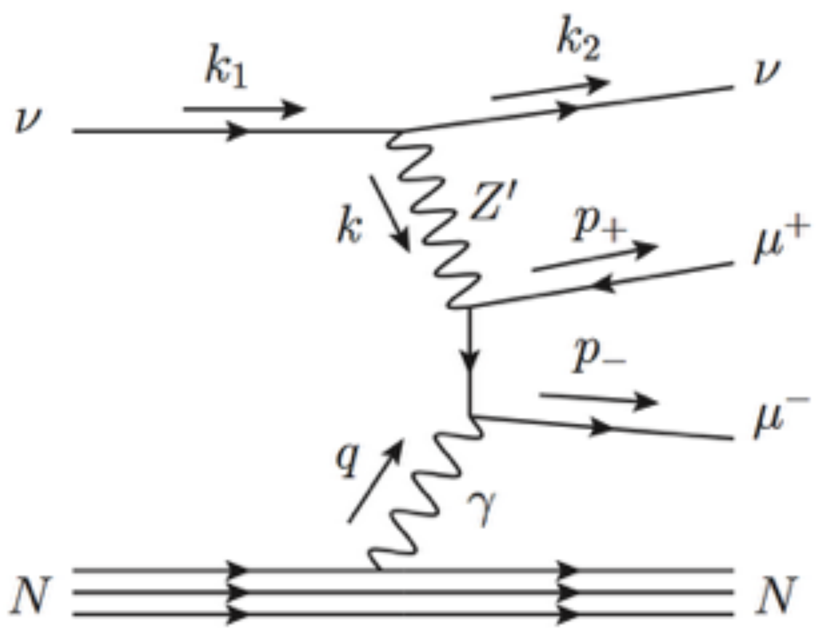
90% bound



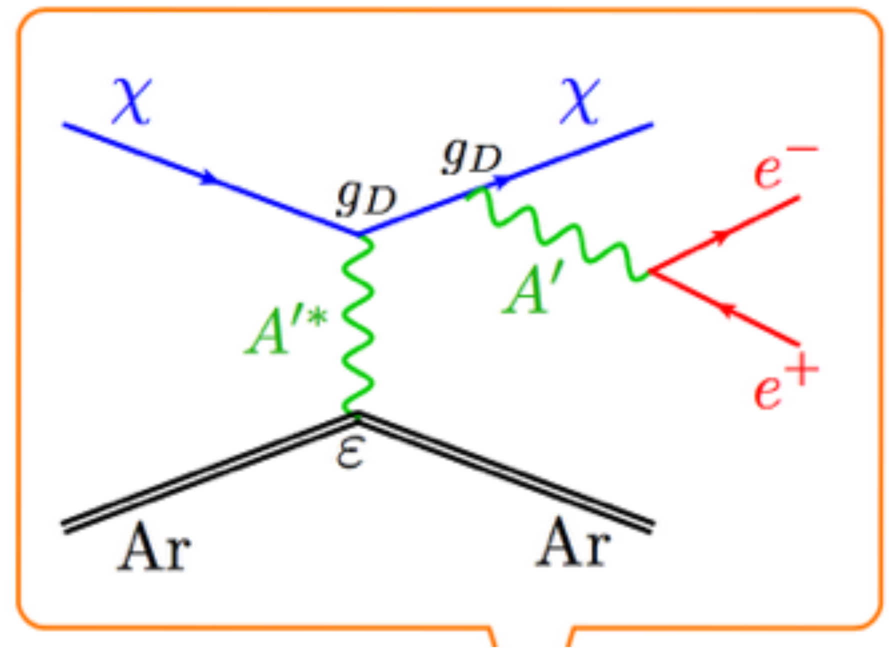


m_1 =200 MeV, m_X = 20 MeV, g_{11}=0.5

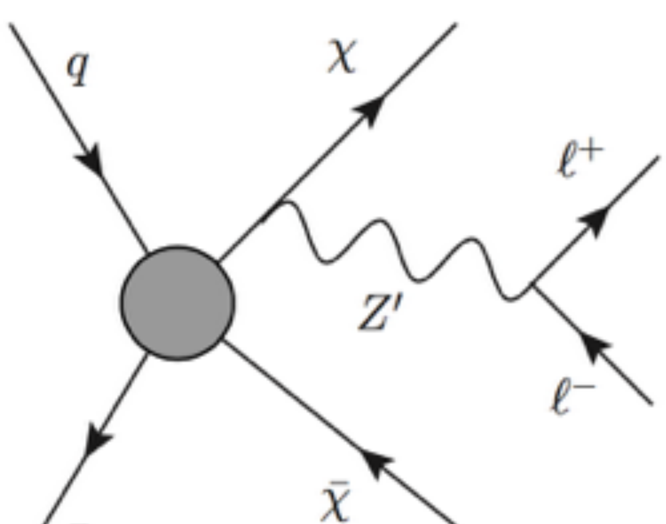
Backup: Darkstrahlung topology



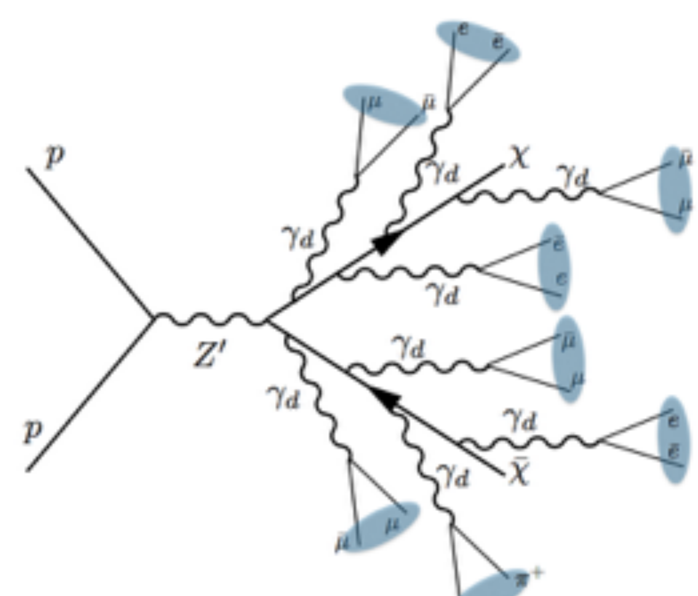
Altmannshofer, Gori, Pospelov, Yavin, 1406.2332



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

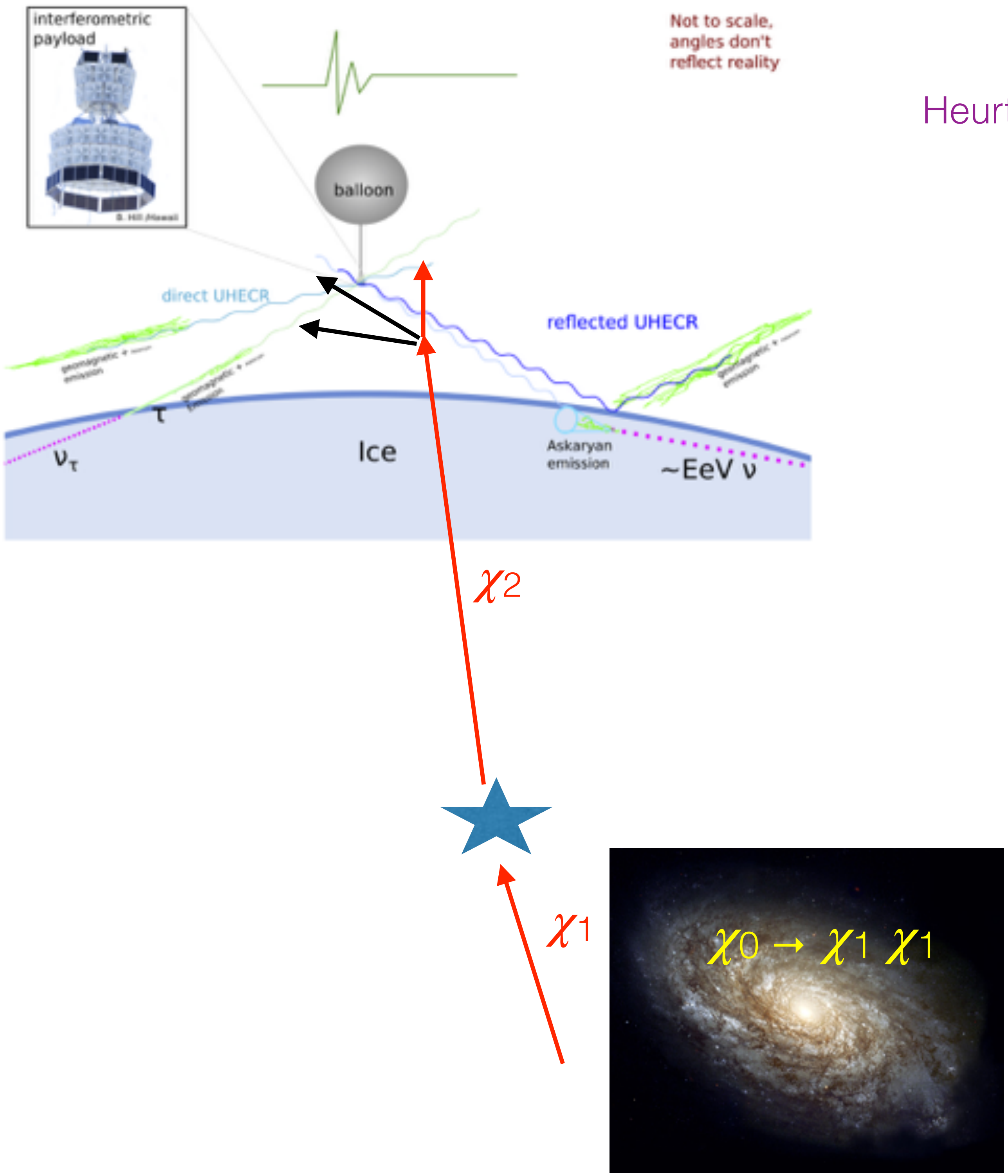


Gupta, Primulando, Saraswat, 1504.01385



Kim, Lee, Park, Zhang, 1612.02850

Backup: Higher Energy?



Heurtier, Kim, Park, **SS**, 1905.13223