6th PIKIO Meeting

Boosted Dark Matter Searches at Surface and Neutrino Experiments

Seodong Shin

THE UNIVERSITY OF CHICAGO

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1612.06867, 1712.07126, 1803.03264, 1804.07302, 1810.xxxxx

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

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

Boosted DM (BDM)

- BDM in multi-component DM scenarios

  Agashe, Cui, Necib, Thaler, 1405.7370

- Other scenarios possible: semi-annihilation, decaying DM

  Phenomenology is same

  Kopp, Liu, Wang, 1503.02669

  Bhattacharya et al., 1407.3280

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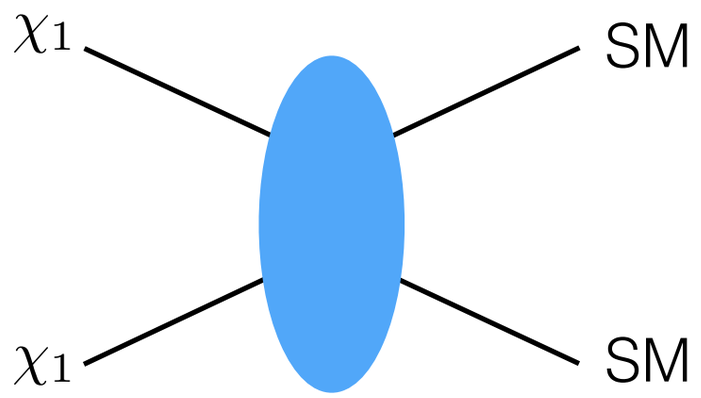
Separate the role of interactions

χ_0 χ_1

Gravitational int.

NASA/ESA/JPL-Caltech/Yale/CNRS

Weak (or other scale) int. with SM



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Secluded from the SM (avoid strong bounds)

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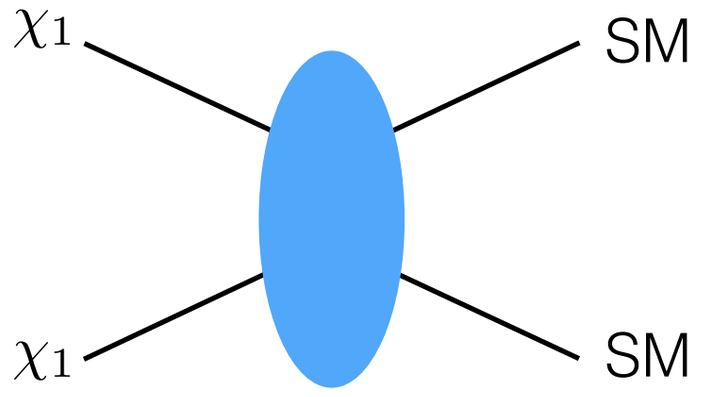
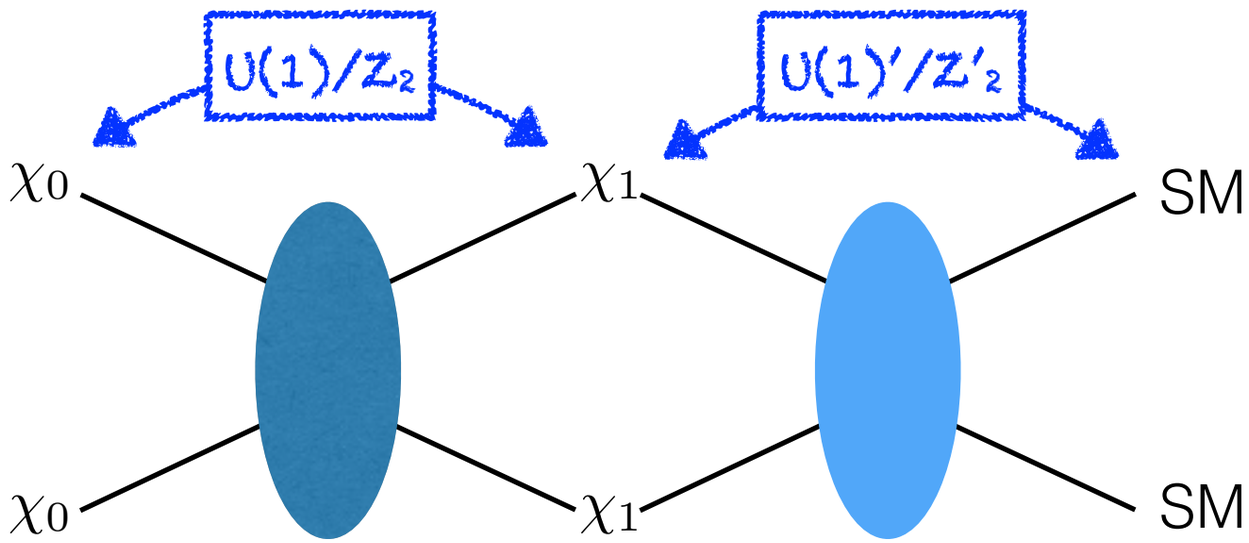


Boosted DM (BDM)

χ_0: heavy, χ_1: light



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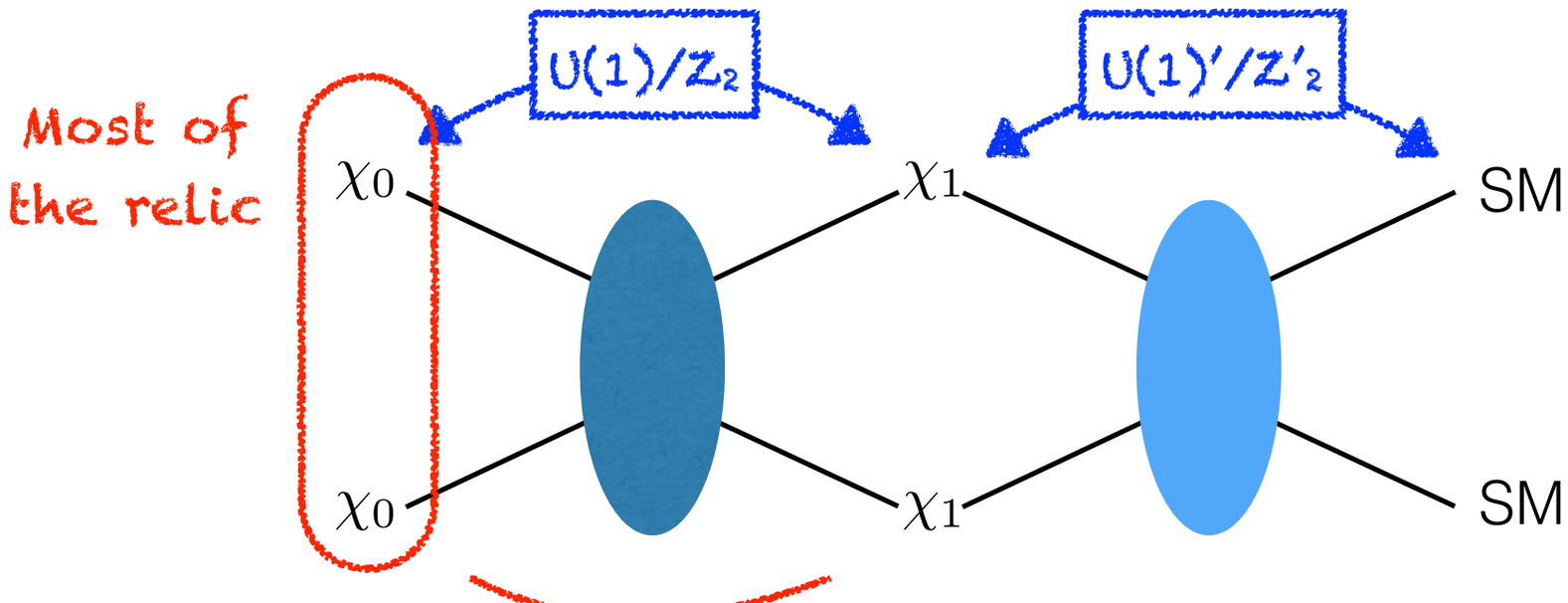

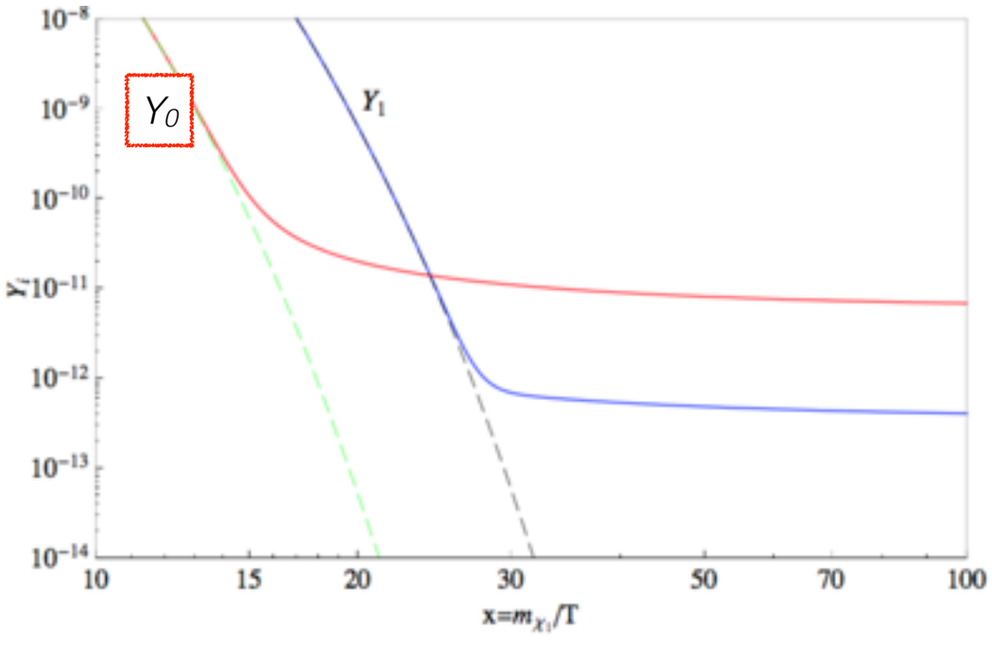

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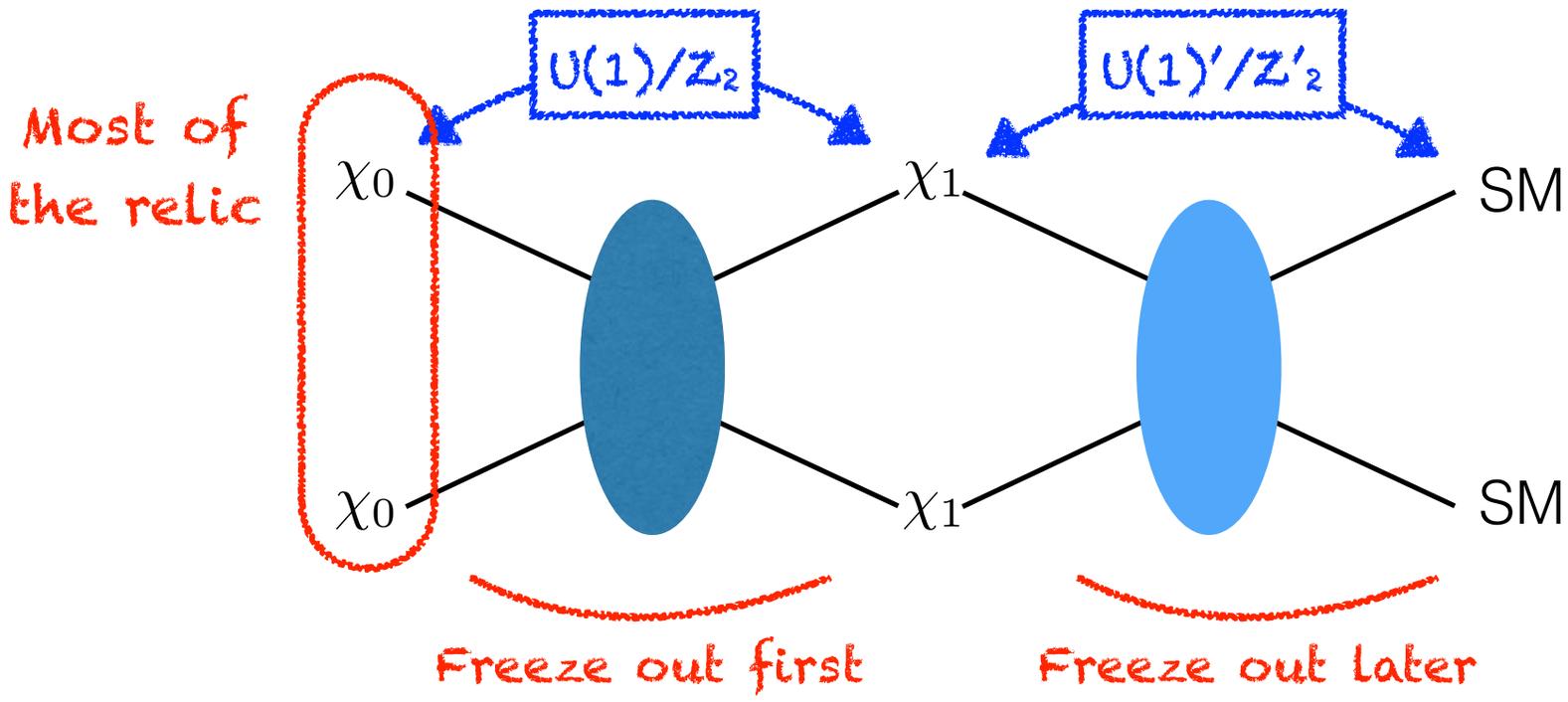

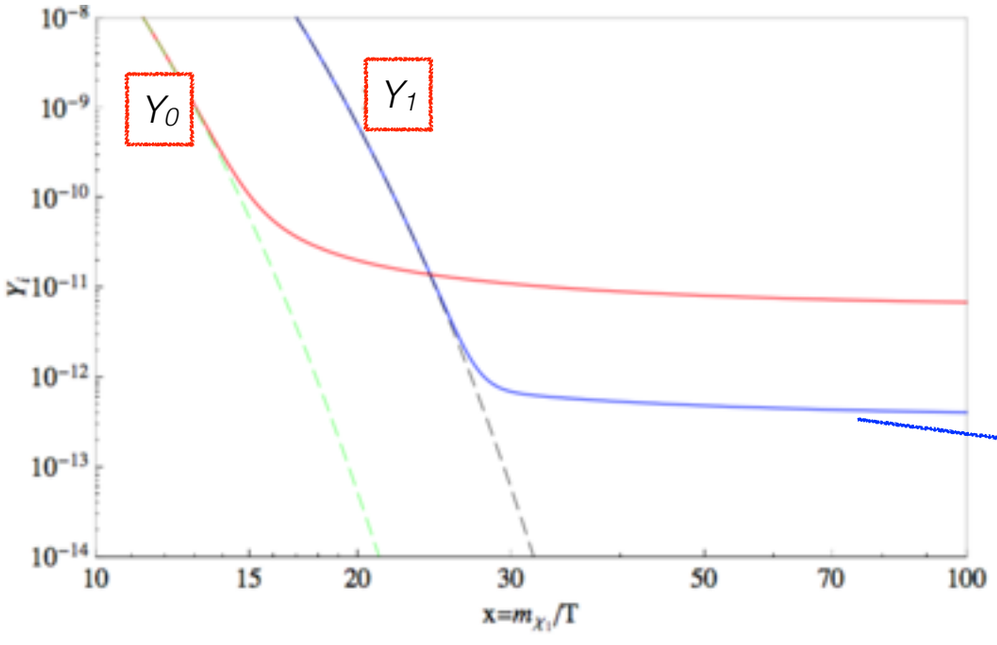

Belanger, Park, 1112.4491

Assisted freeze-out mechanism

→ non-relativistic relic χ_1

$Y_0 \gg Y_1$

Boosted DM (BDM)

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

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

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Observe relativistic χ_1 scattering with target with $E > E_{th}$

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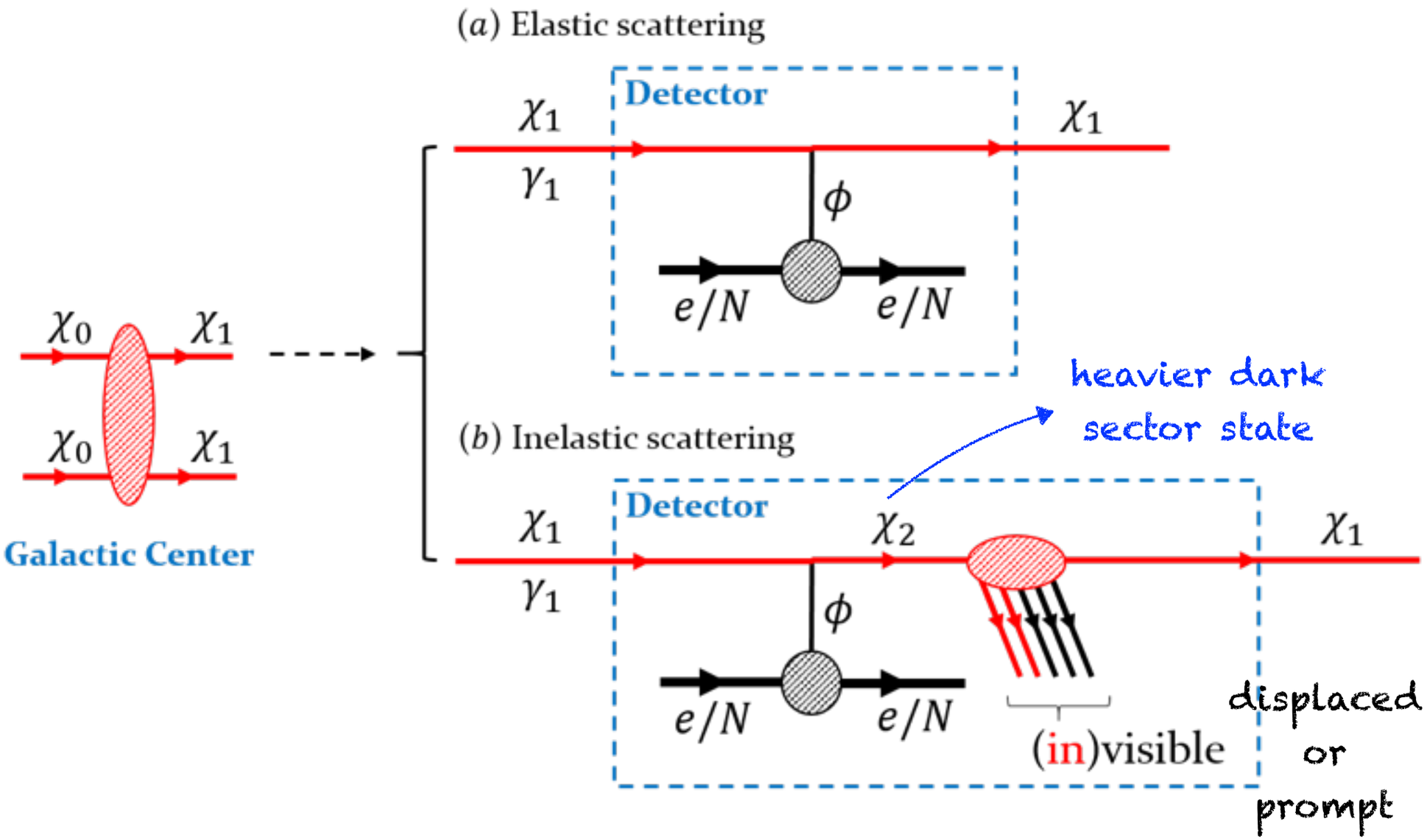
Subtraction of
major background (ν)

- Directionality information:
  e.g., GC, Sun, dSphs
  1405.7370 1410.2246 1610.03486
  1611.09866 1411.6632

- Signal with unique feature

inelastic BDM (iBDM)



Kim, Park, **SS**, 1612.06867

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

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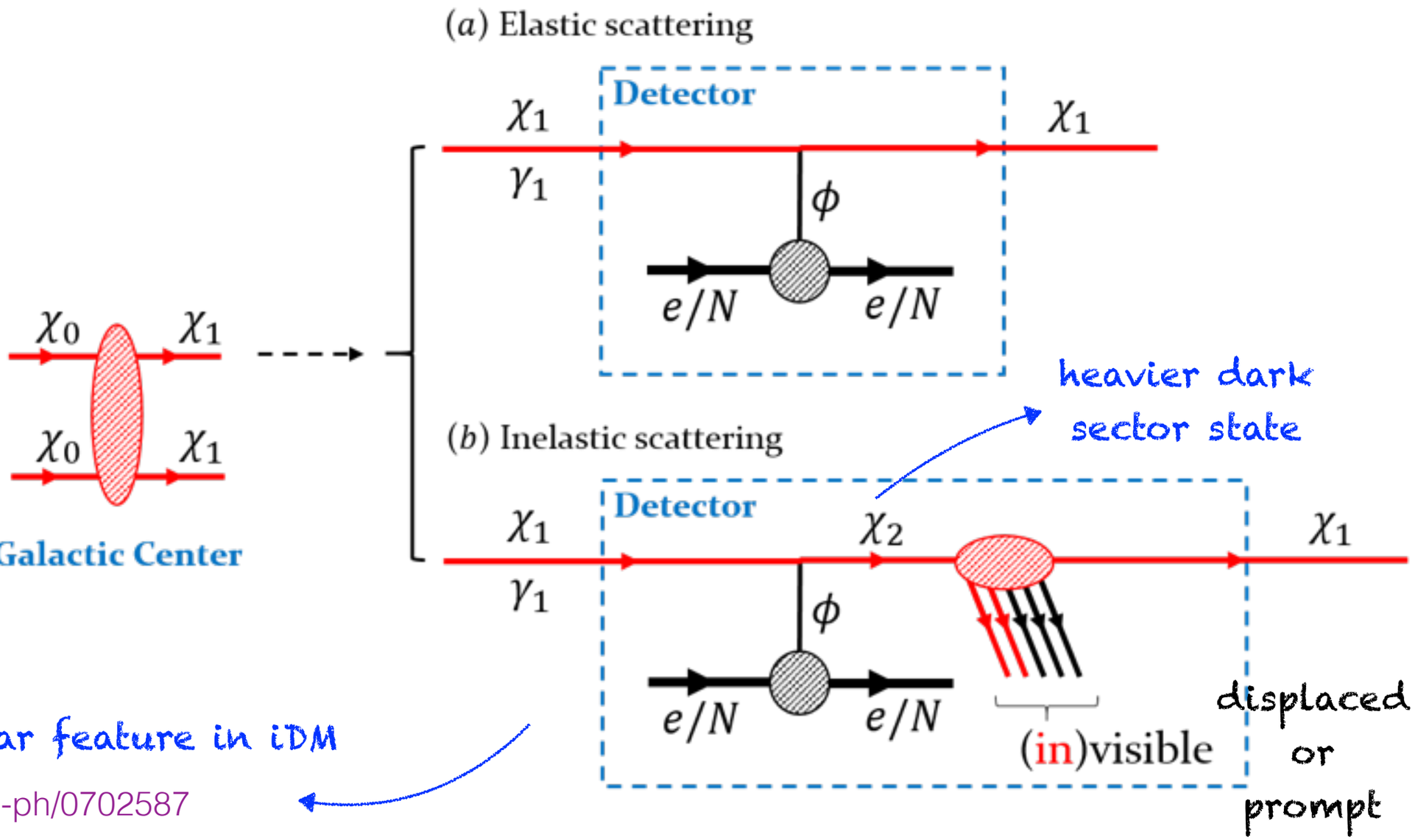


Similar feature in iDM

astro-ph/0702587

0903.1037

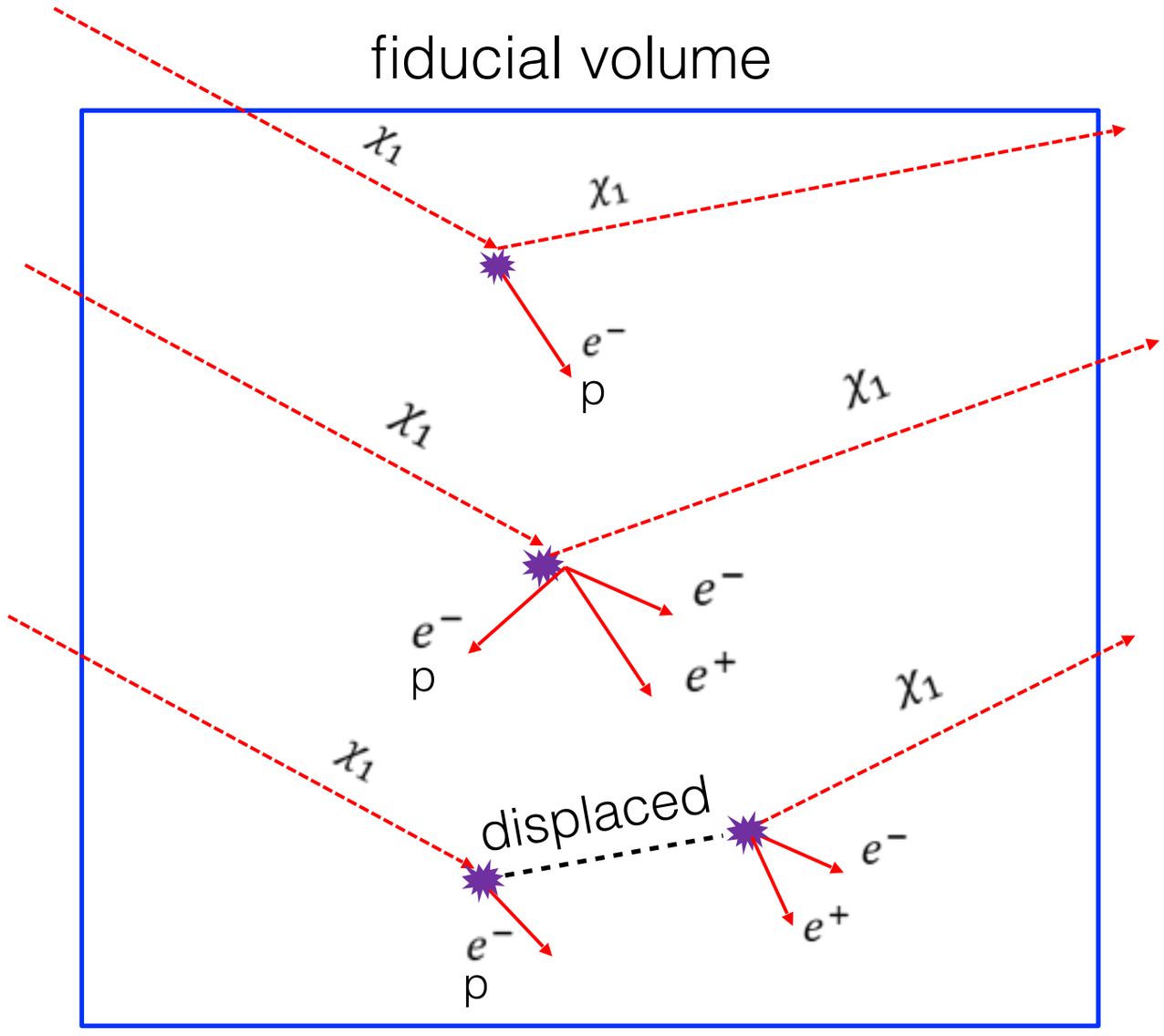
1309.0825

1312.1363 1403.6826

Kim, Park, **SS**, 1612.06867

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

Expected signatures



- Elastic scattering: eBDM
- Inelastic scattering: prompt iBDM
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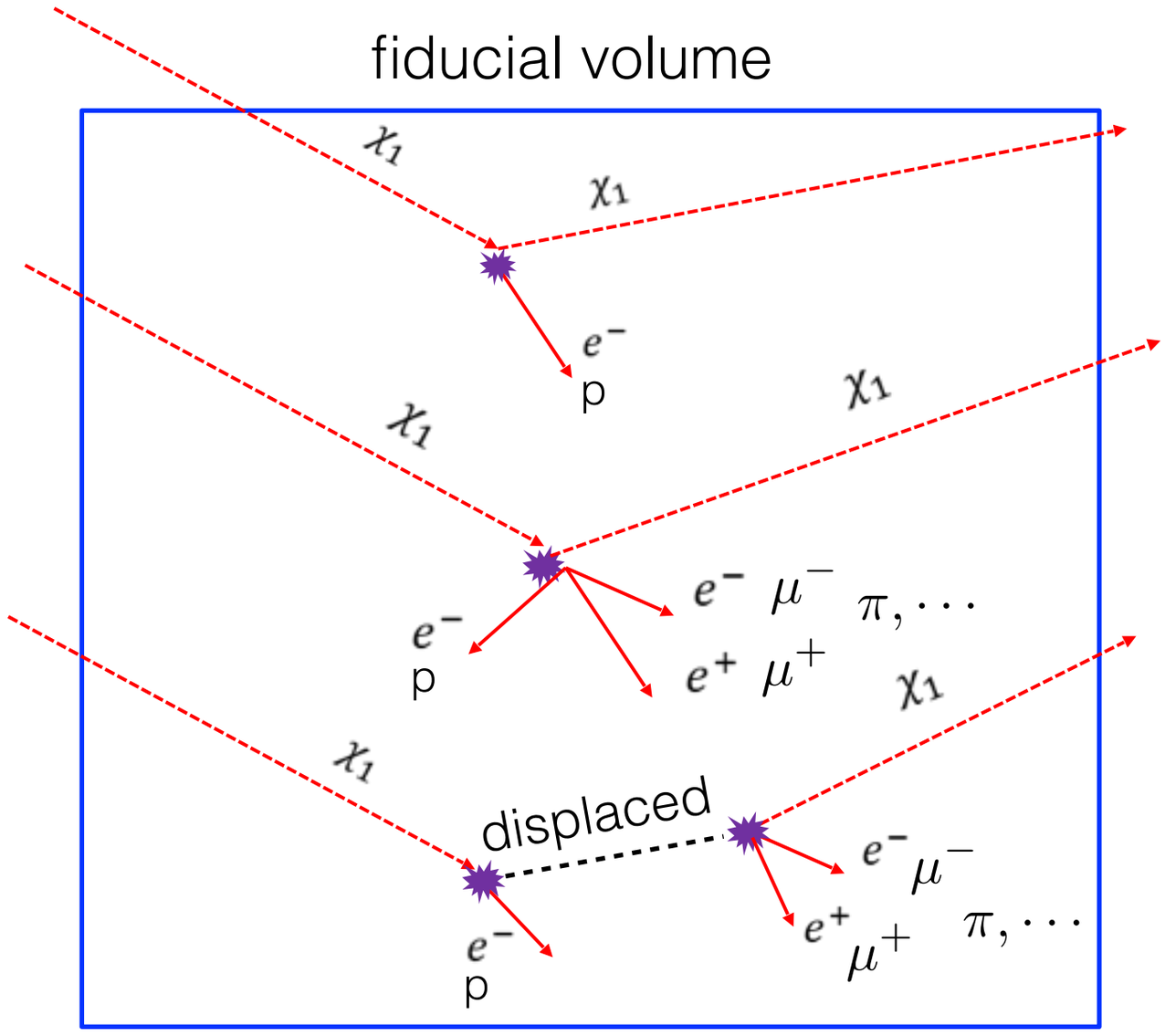

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Strategy of signal probe

	eBDM	iBDM
Surface ν exp.		
Underground ν exp.		

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SK, IceCube, Borexino, …

HK/KNO, DUNE, JUNO, …

600 m ~ 2 km (earth crust)

Cosmic-ray backgrounds much suppressed

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Background	eBDM	iBDM
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Signals?	Directionality of the scattering	Particle identification
	Berger, Cui, Zhao, 1410.2246 Necib, Moon et al., 1610.03486 Kong, Mohlabeng, Park, 1411.6632 + 1611.09866 with Alhazmi	Kim, Park, **SS**, 1612.06867 + 1712.07126 with Giudice + 1810.xxxxx with Machado (Maybe) zero-bkg achievable

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ICARUS, MicroBooNE, SBND
(SBNP at Fermilab)

ProtoDUNE, NOvA, …

O(1m) (+ overburden)

Cosmic-ray backgrounds abundant

$N_\mu \sim 10^{10}/\mathrm{m}^2/\mathrm{yr}$ at sea level

E > 10 MeV
PDG

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Earth shielding

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

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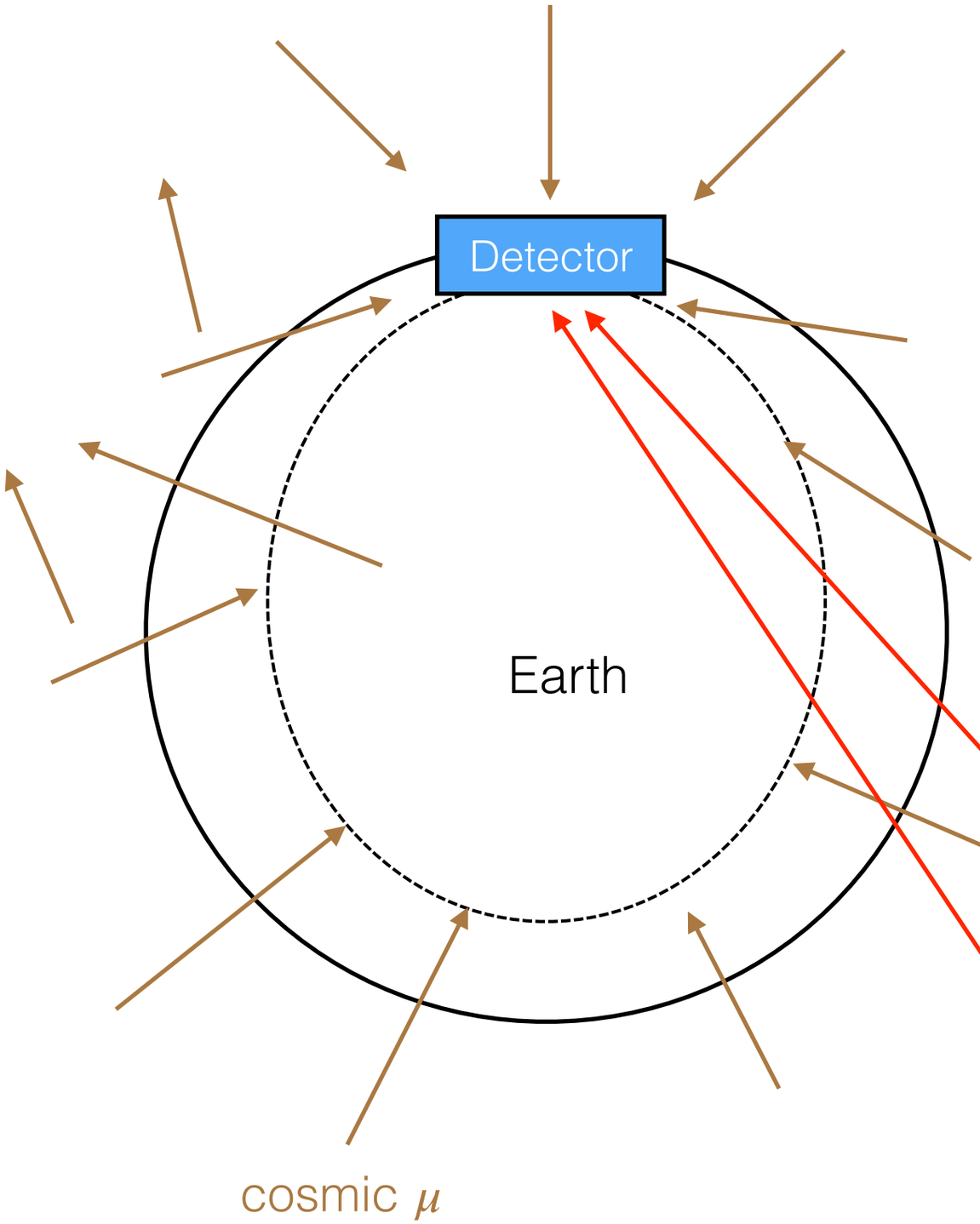
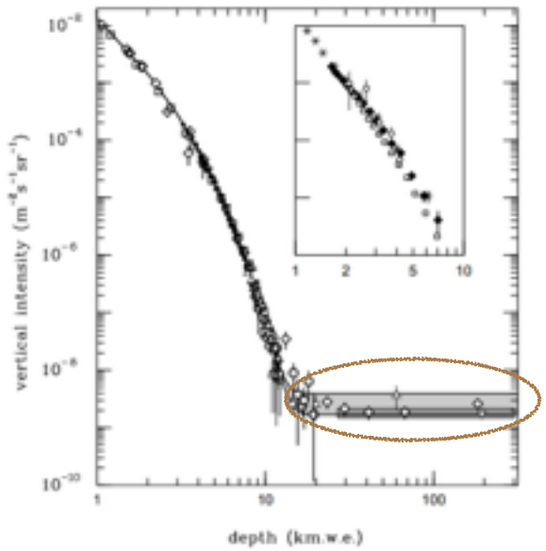


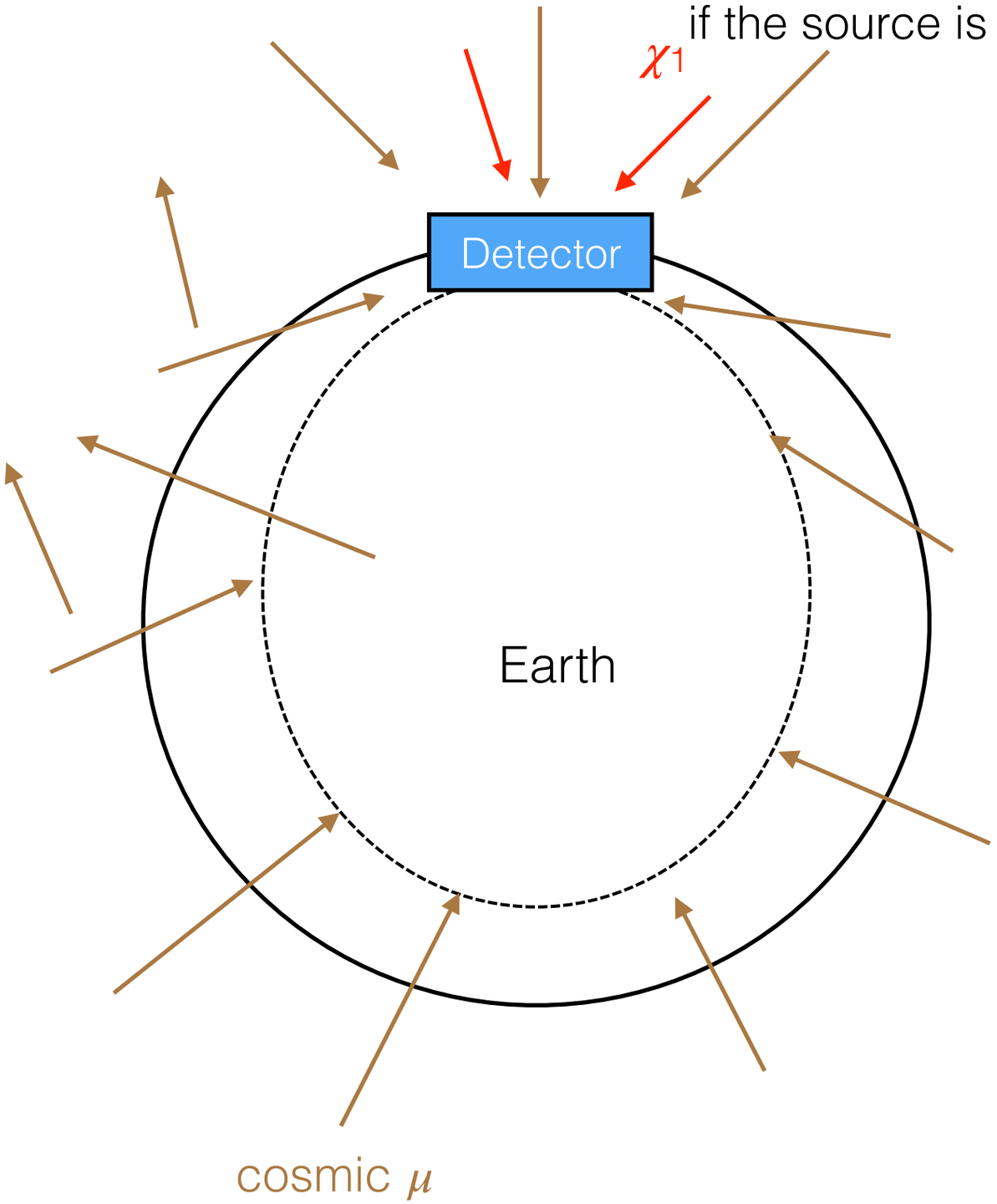


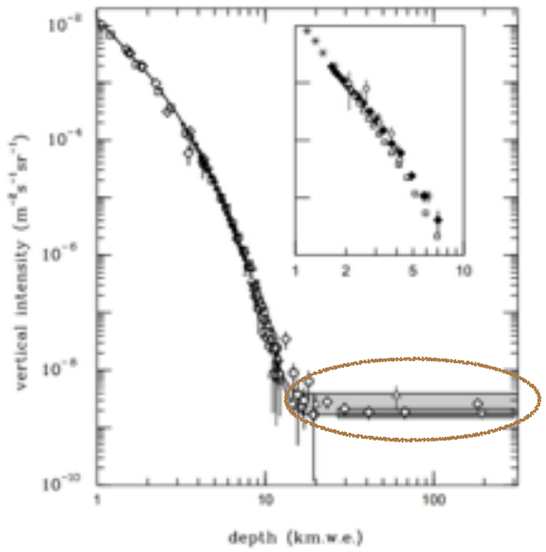
Dashed: 7km below sea level

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

χ_1 if the source is here

Earth shielding





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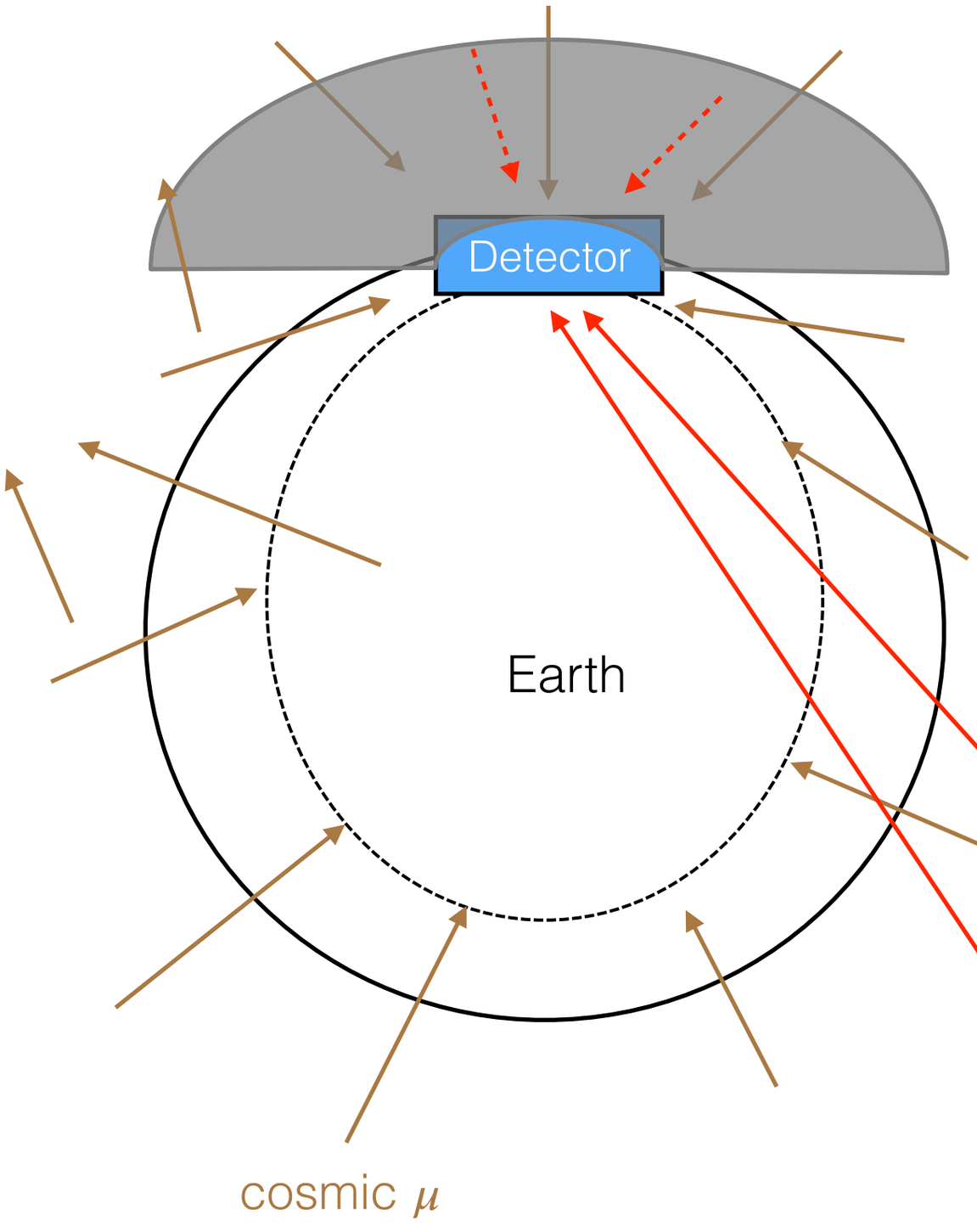
Hard to subtract the cosmic-ray background in this case

Earth shielding



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

Strategy of signal probe

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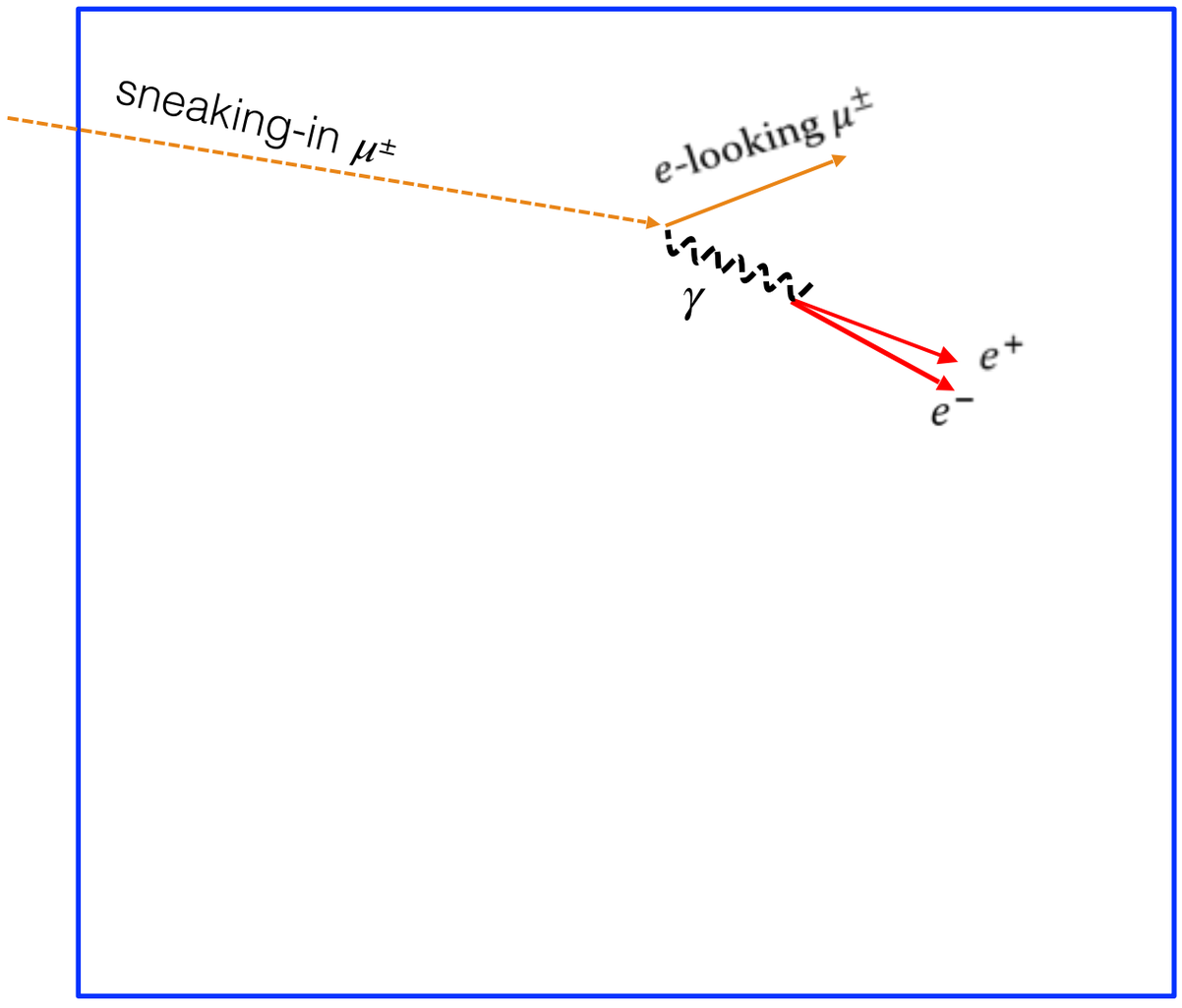
Surface ν exp.	+ ~~Cosmic-rays~~	+ (Very) rare ~~cosmic-ray~~ induced processes
Underground ν exp.	ν-scattering	(Very) rare ν-induced πs
Signals?	Directionality of ν-scattering + Earth shielding Kong, Kim, Park, **SS**, 1804.07302	Particle identification Unique event topology Kim, Park, **SS**, DUNE experimentalists, 1803.03264

iBDM bkg: 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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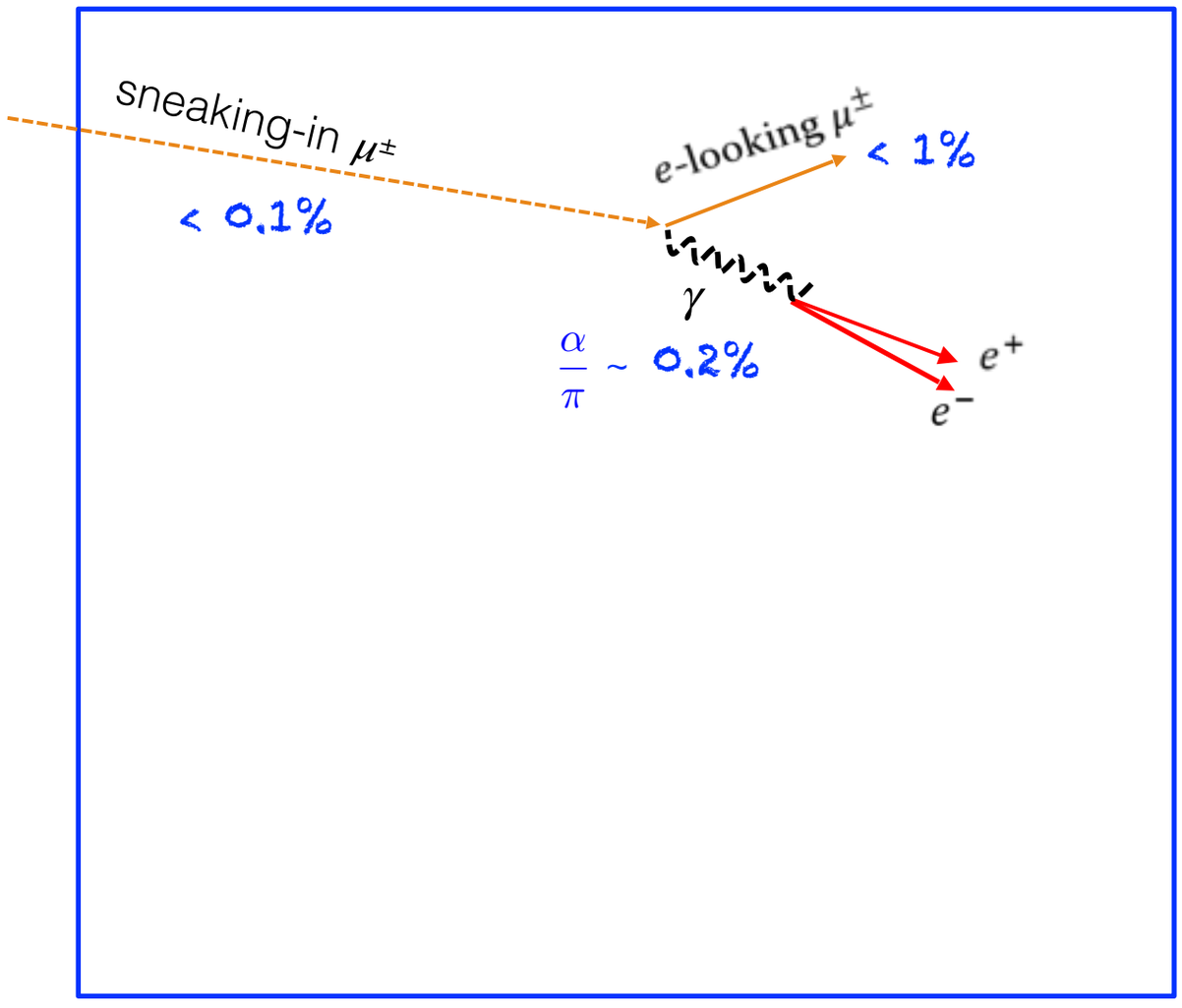

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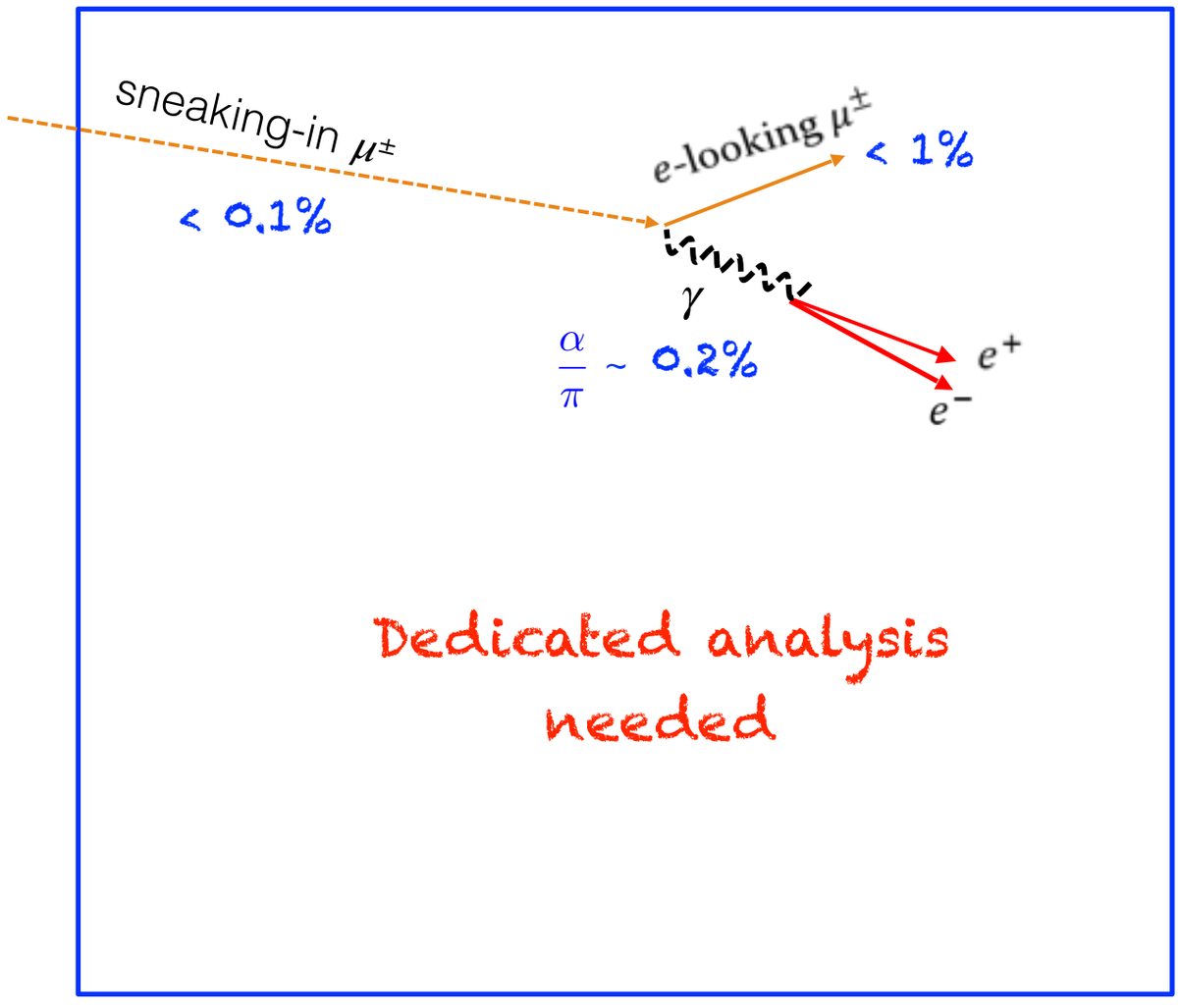

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N_{BG}~100 (crazy upper limit) ← if 0.06%

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Detector type

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

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

Conclusions

- Underground experiments proper to search BDM signals

Signal type	eBDM	iBDM
e-scattering	SK, HK/KNO	DUNE but comparable
p-scattering	DUNE	DUNE

- Search possible in surface experiments: ProtoDUNE, SBNP

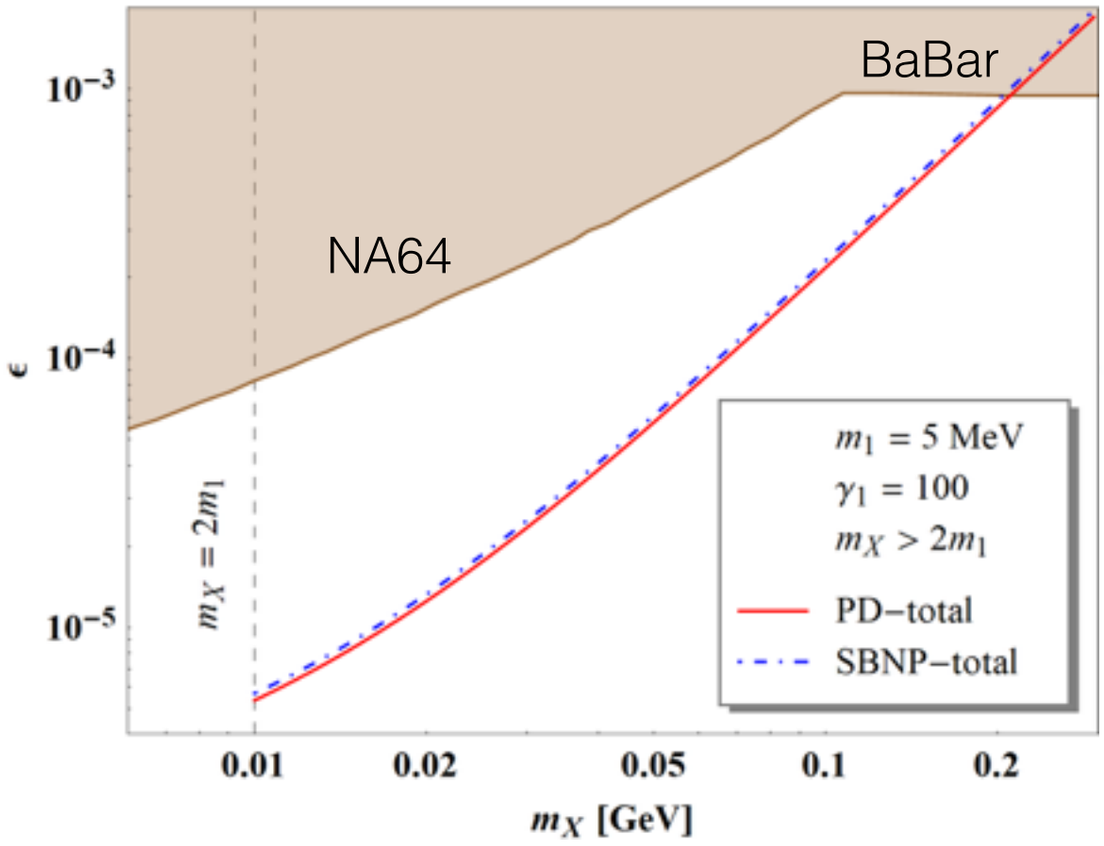
- More analysis will be in DUNE TDR

Proposal may be accepted

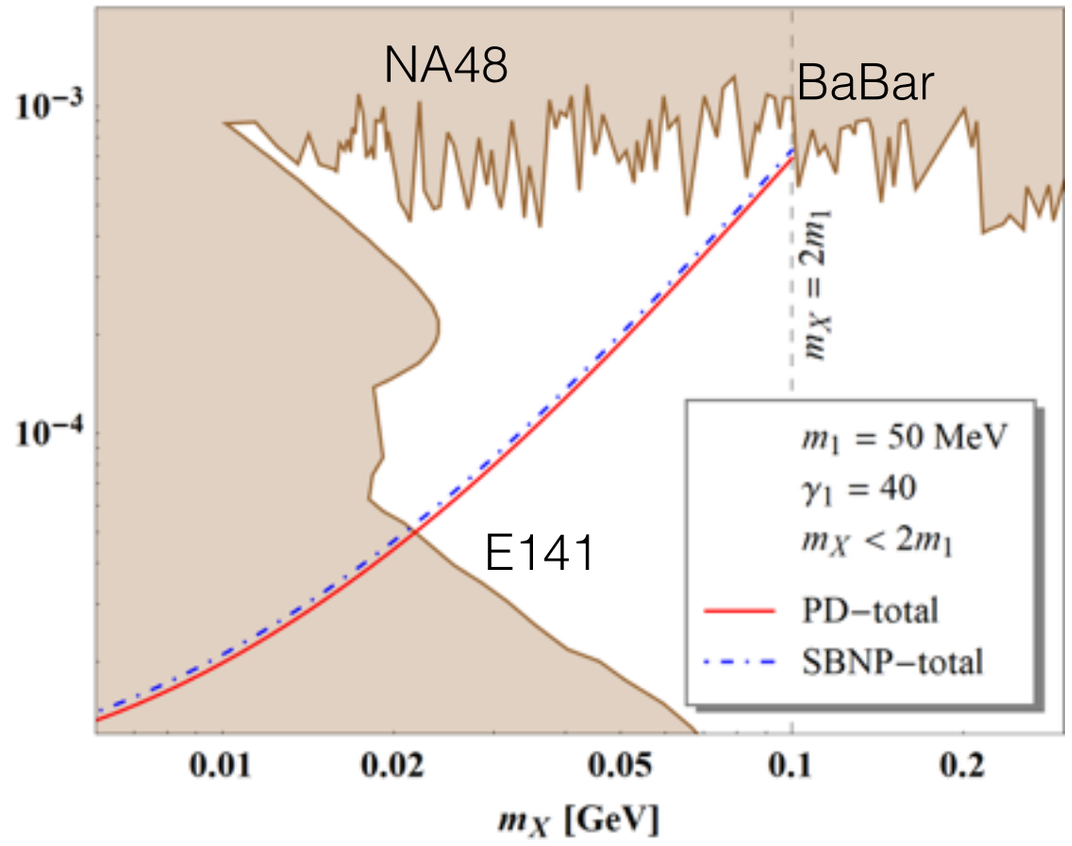
Dark photon parameter reach

eBDM at surface experiments

X→invisible



X→e^+e^-



1 yr exposure, i.e., 0.69 yr (ProtoDUNE) and 0.66 yr (SBNP)

An order of magnitude stronger coverage (model dependent) possible

Search of BDM signals

$\chi_0\chi_0 \rightarrow \chi_1\ \chi_1$

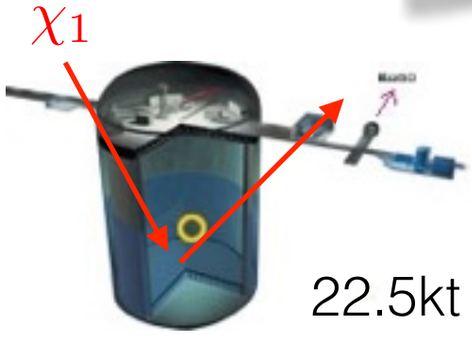
- Flux of χ_1 $\quad (n_{\chi_0})^2 \propto 1/(m_{\chi_0})^2$
- Detector resolutions

m_{χ_0}	Flux of χ_1
O(10) GeV	$\mathcal{O}(10^{-7}\,\mathrm{cm}^{-2}\mathrm{s}^{-1})$

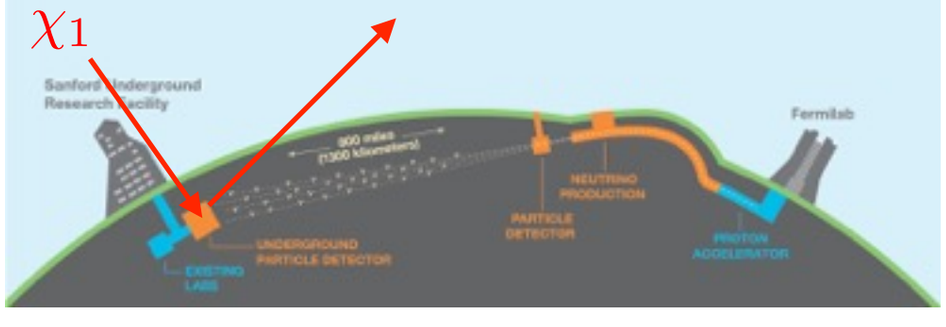
NFW

$\langle\sigma v\rangle_0 \sim 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$

Large volume ν experiments



22.5kt



40kt

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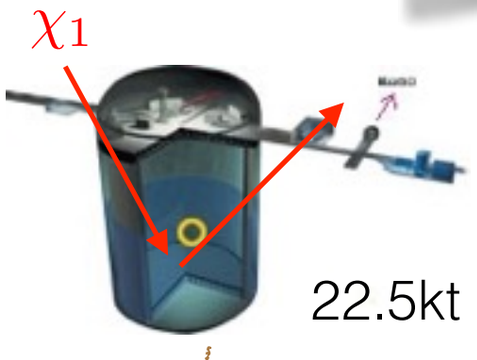

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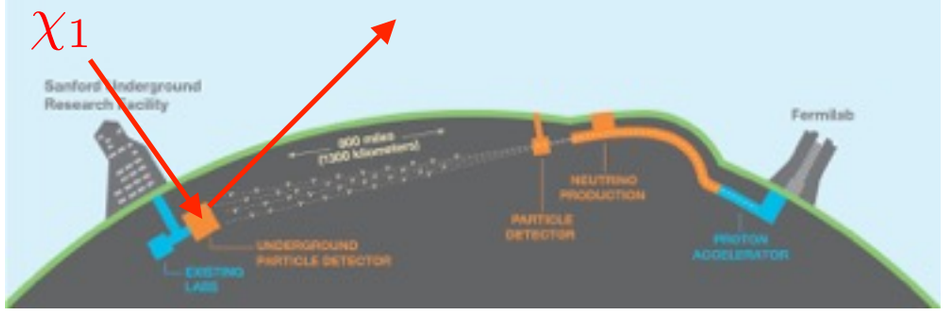
SK, 1711.05278



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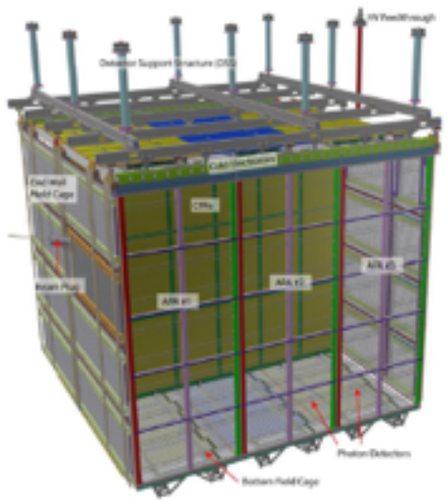
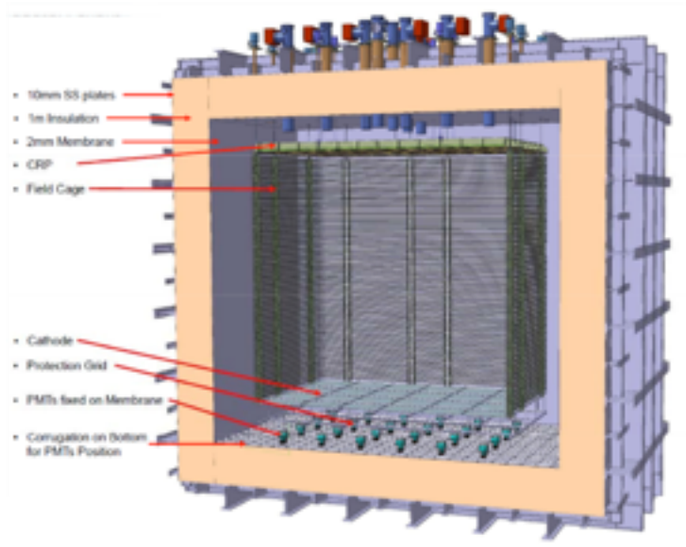
BDM at ProtoDUNE

single phase

420t





dual phase

300t

Prototype of DUNE far detector

- Constructed at CERN with initial operation plan in 2018
- Huge active volume: 720t
- Originally installed to test beam and cosmic-ray response (installed on the ground)

New physics search?

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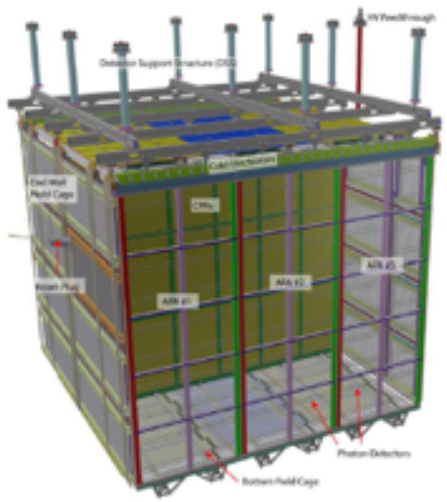

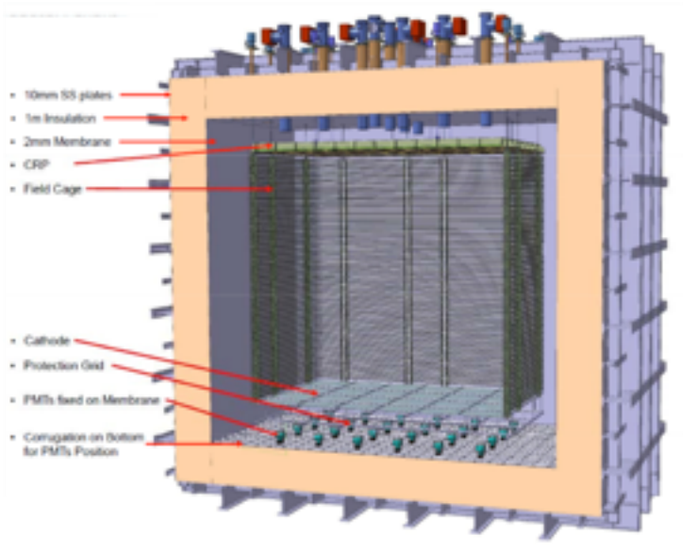

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iBDM: first physics study

1803.03264

Model independent reach

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

- σ_e: 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

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

- function of detector geometry: event generation

(cumulatively isotopic flux of χ_1)

Model independent reach

$$N_{\rm sig} = \sigma_e \cdot \mathcal{F} \cdot A \cdot t_{\rm exp} \cdot N_e$$

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

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with signal efficiency

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(cumulatively isotopic flux of χ_1)

Sensitivity: prompt decay/elastic scattering

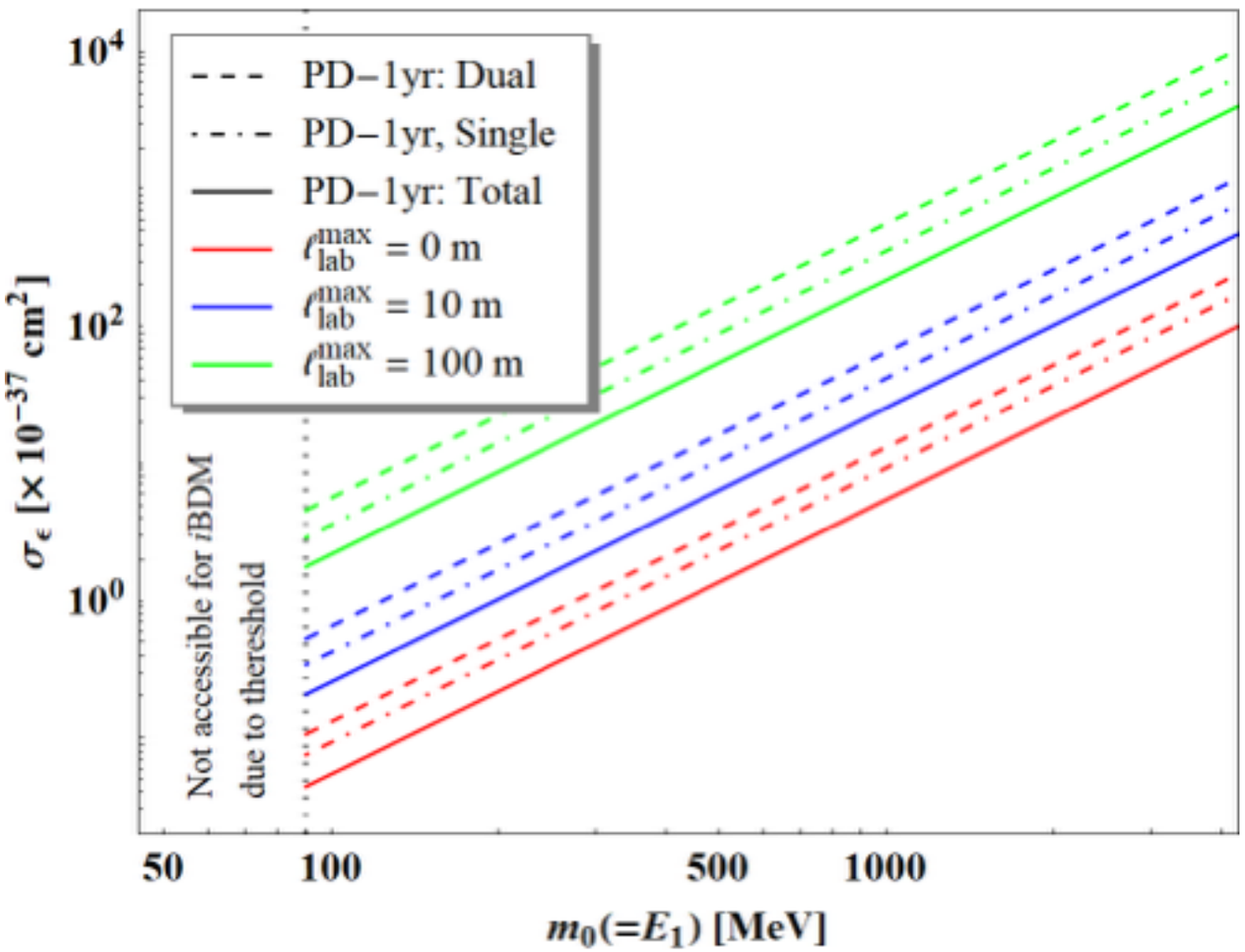
zero-background assumption (90% C.L.)

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

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

Fix (then use NFW)

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



Sensitivity: prompt decay/elastic scattering

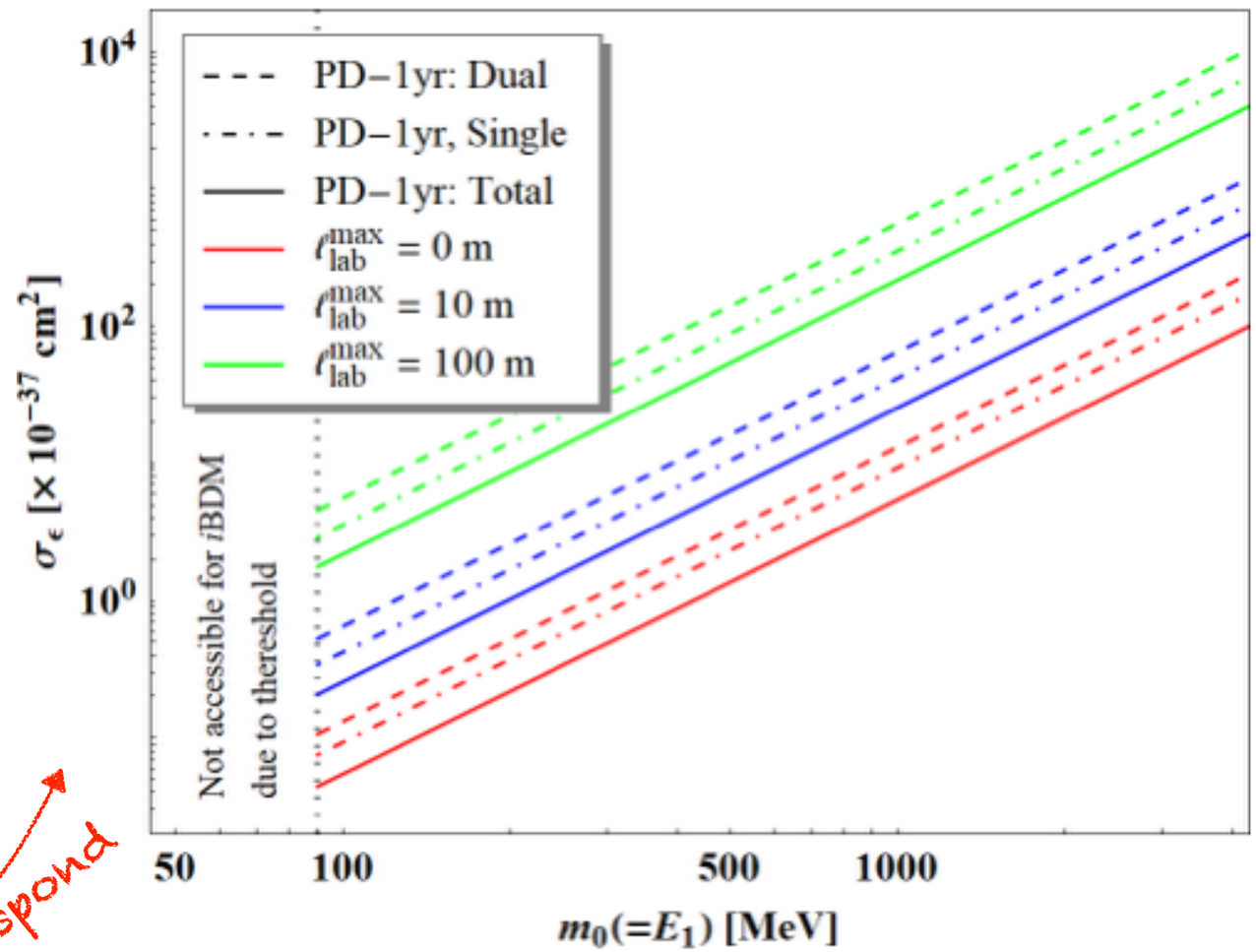
zero-background assumption (90% C.L.)

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

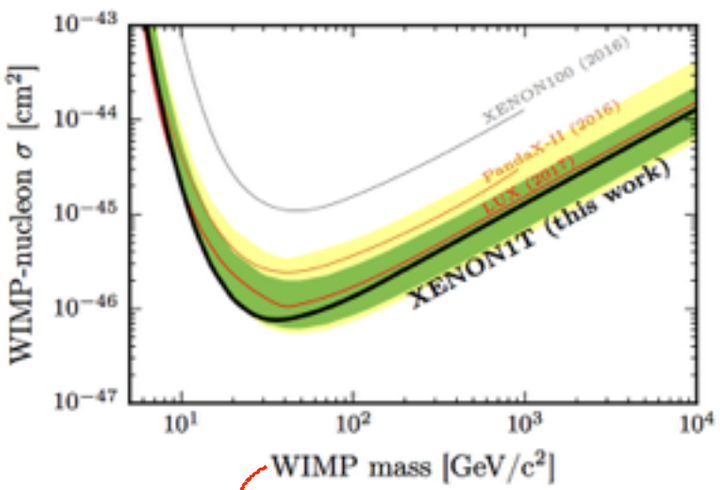
$$\mathcal{F} \propto \frac{\langle \sigma v \rangle_{\chi_0\chi_0 \to \chi_1\chi_1}}{m_0^2}$$

Fix (then use NFW)

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



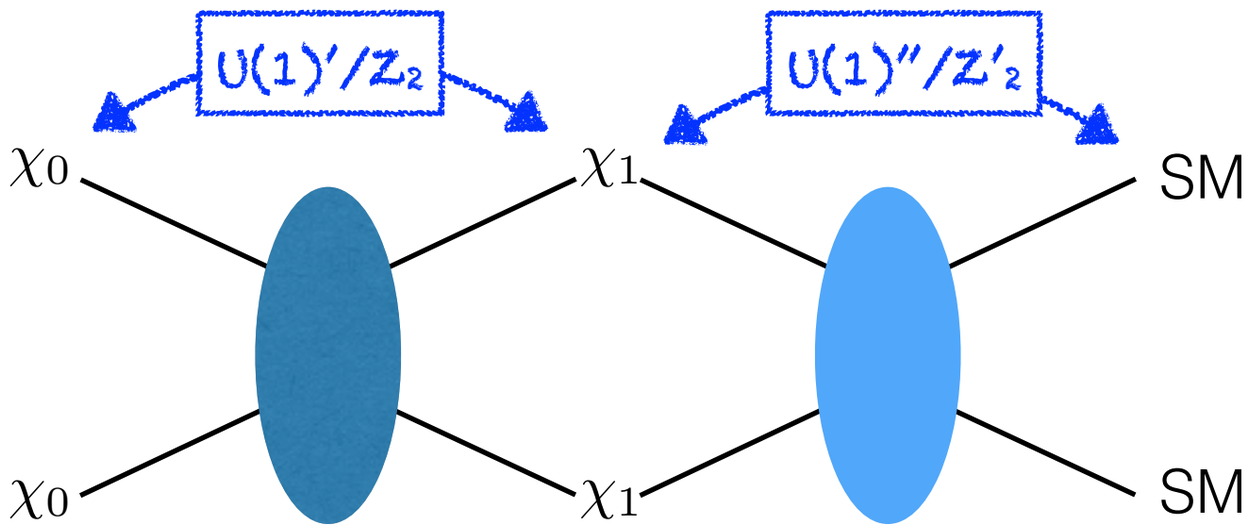
correspond



information of energy and flux

Back up

χ_0: heavy, χ_1: light



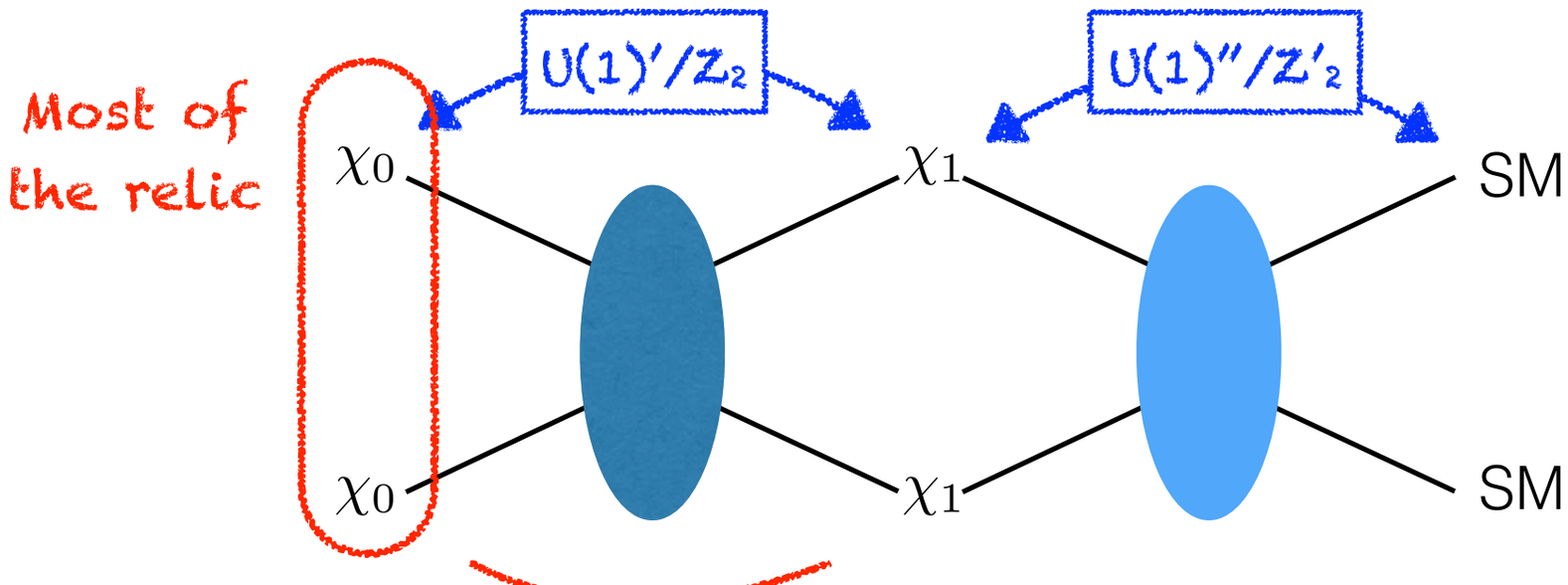
- Conventional WIMP model

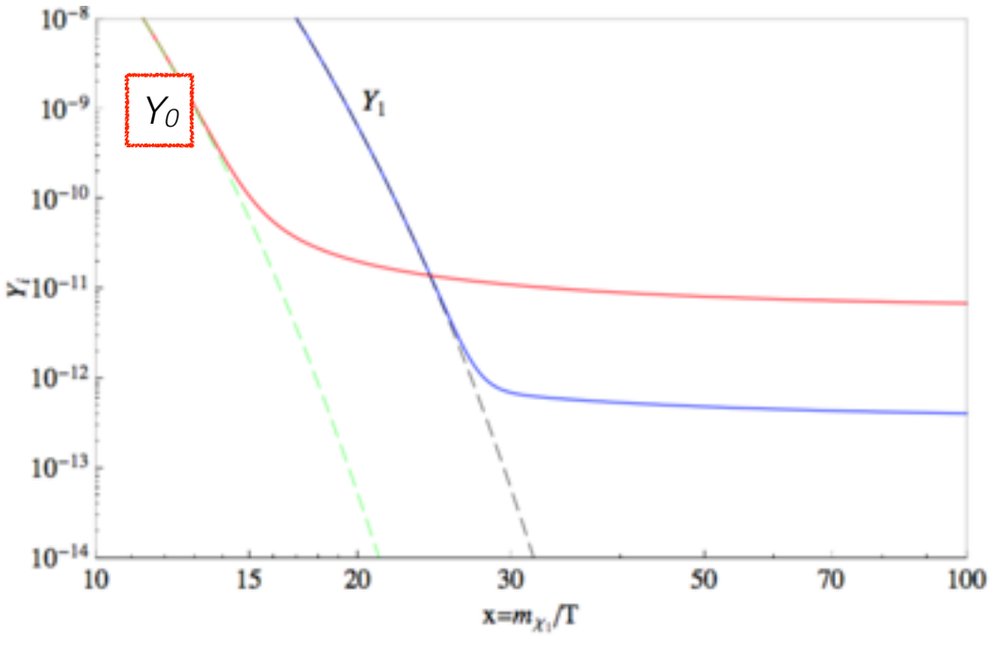
- BDM: multi-component DM with different int.
  - χ_0: only with χ_1
  - χ_1: with SM

e.g., SM
proton: heavy
neutrino: light
photon: EM int.

Back up

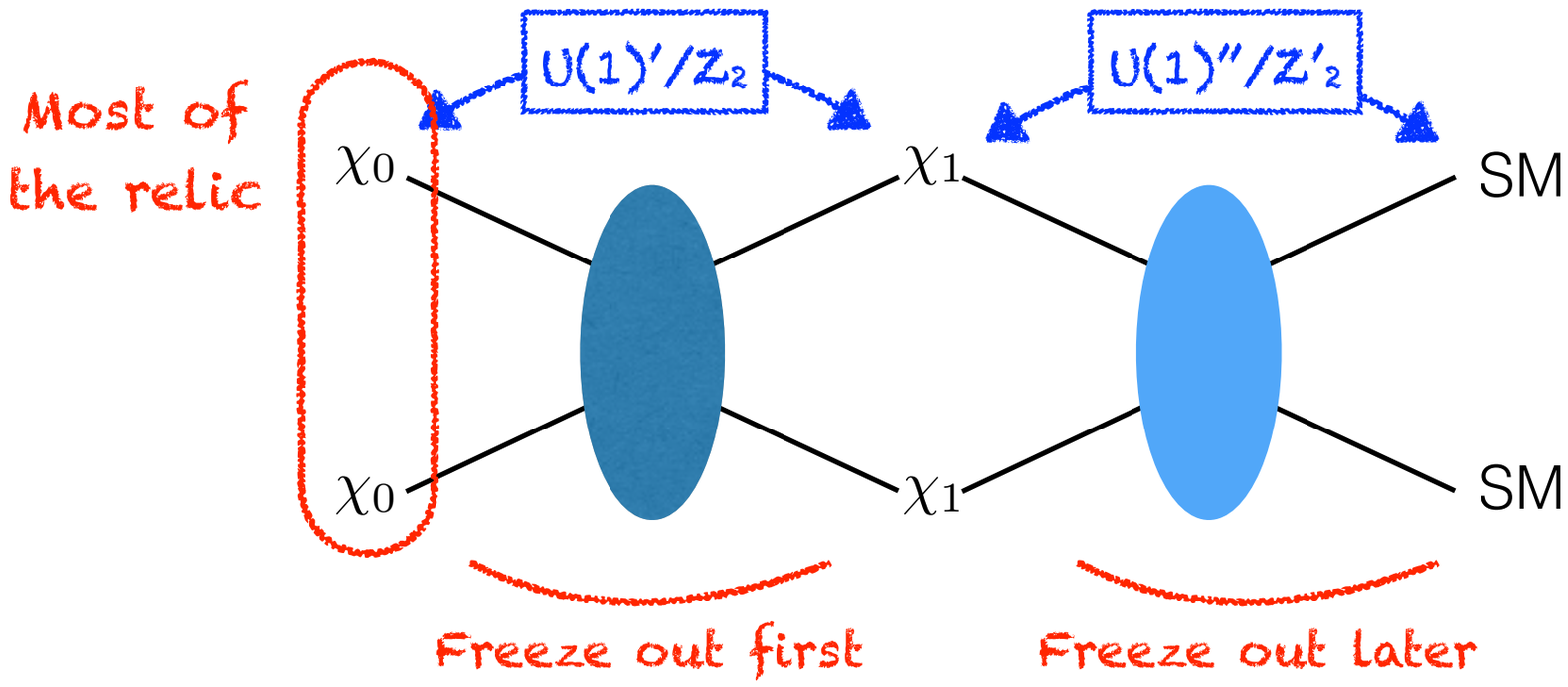
χ_0: heavy, χ_1: light

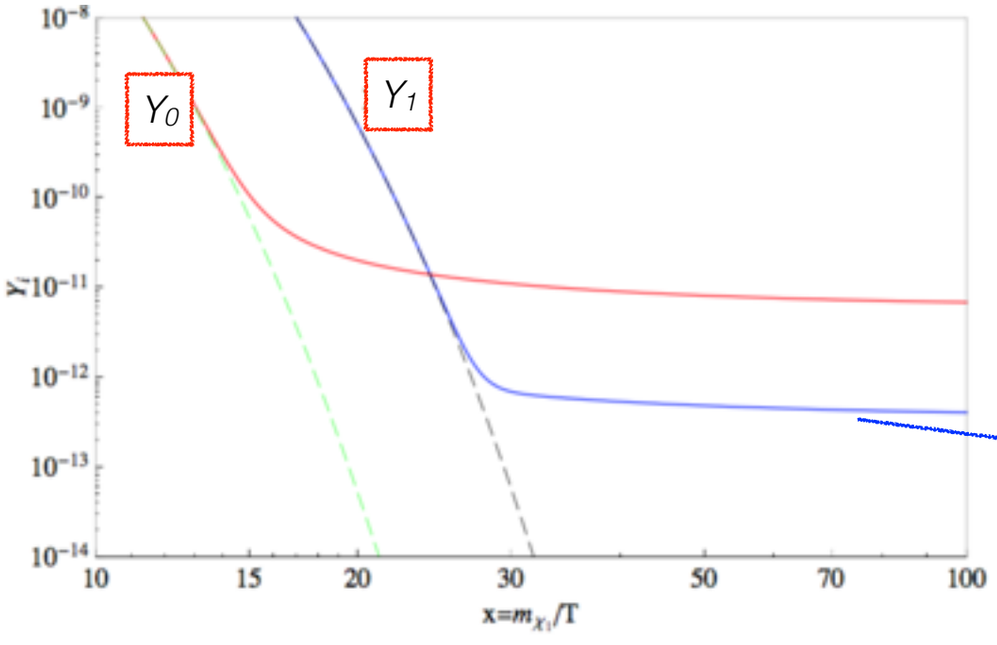




Back up

χ_0: heavy, χ_1: light





Belanger, Park, 1112.4491

Assisted freeze-out mechanism

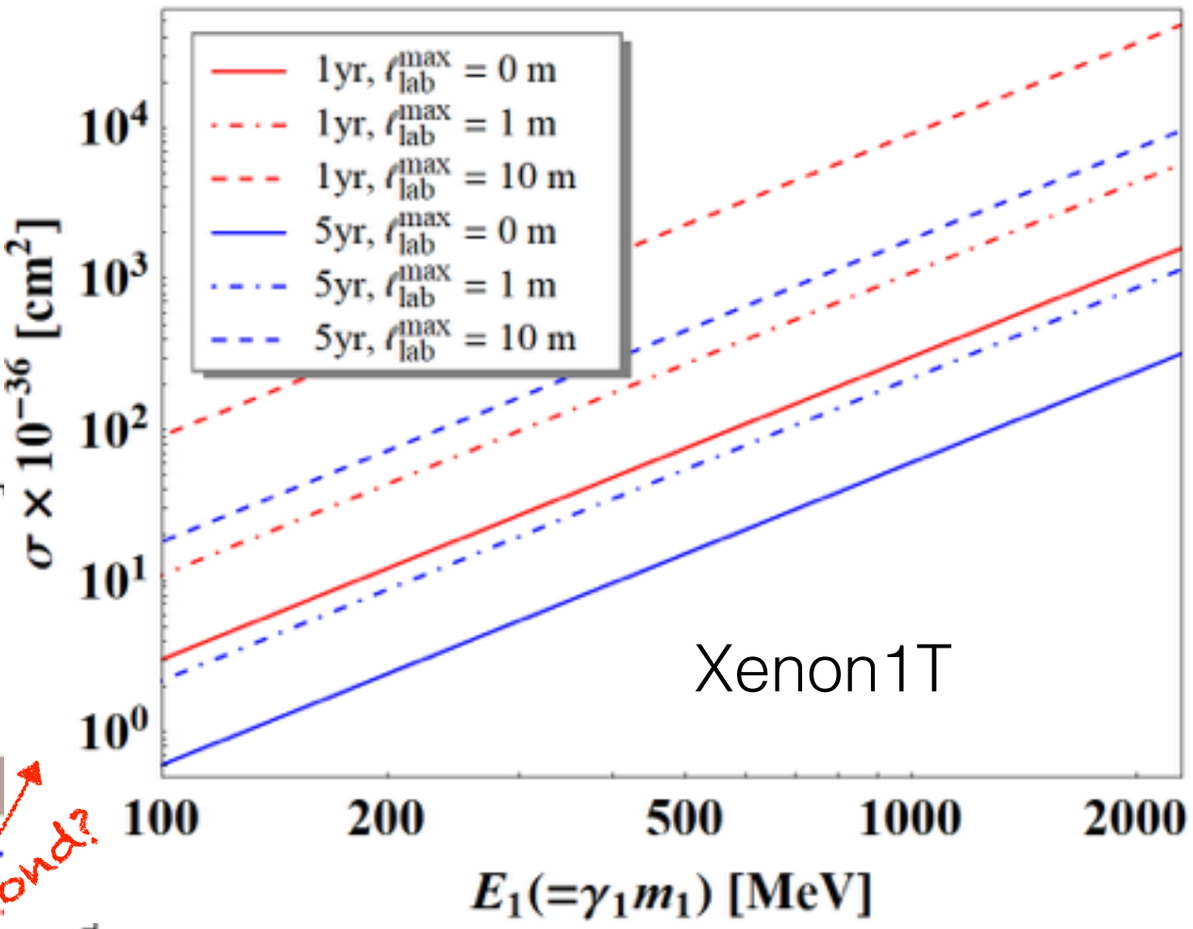
→ non-relativistic relic χ_1

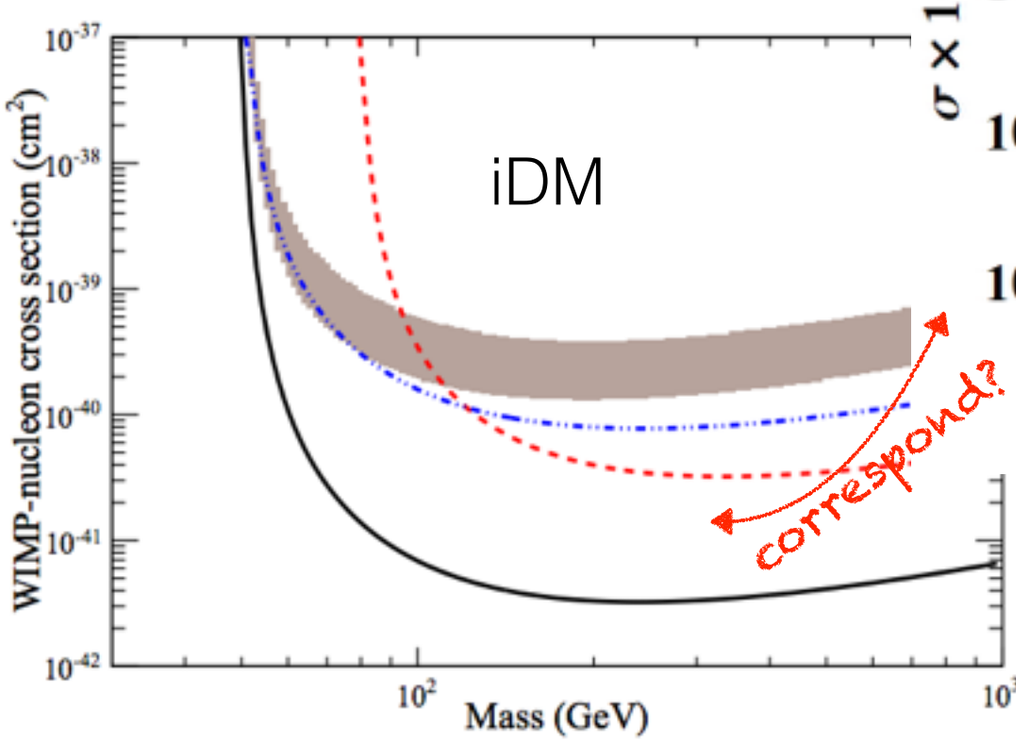
$Y_0 \gg Y_1$

Back up

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

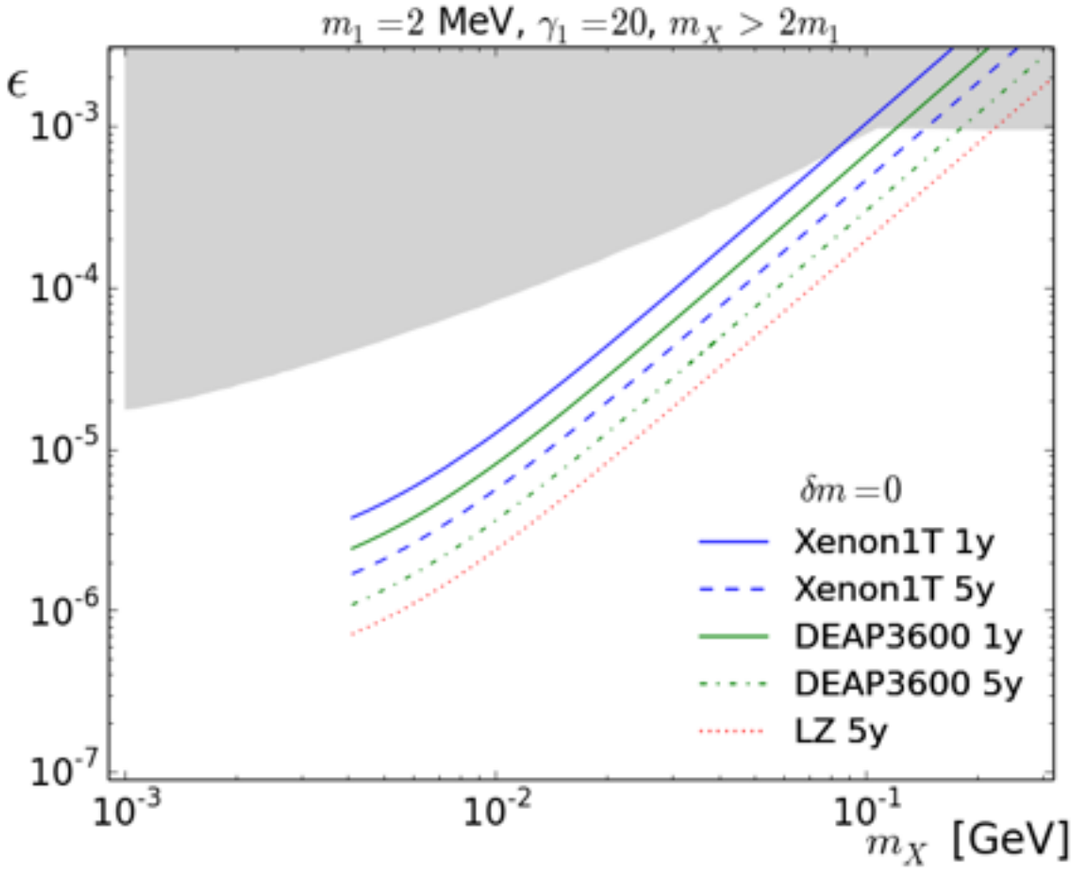
zero-background assumption



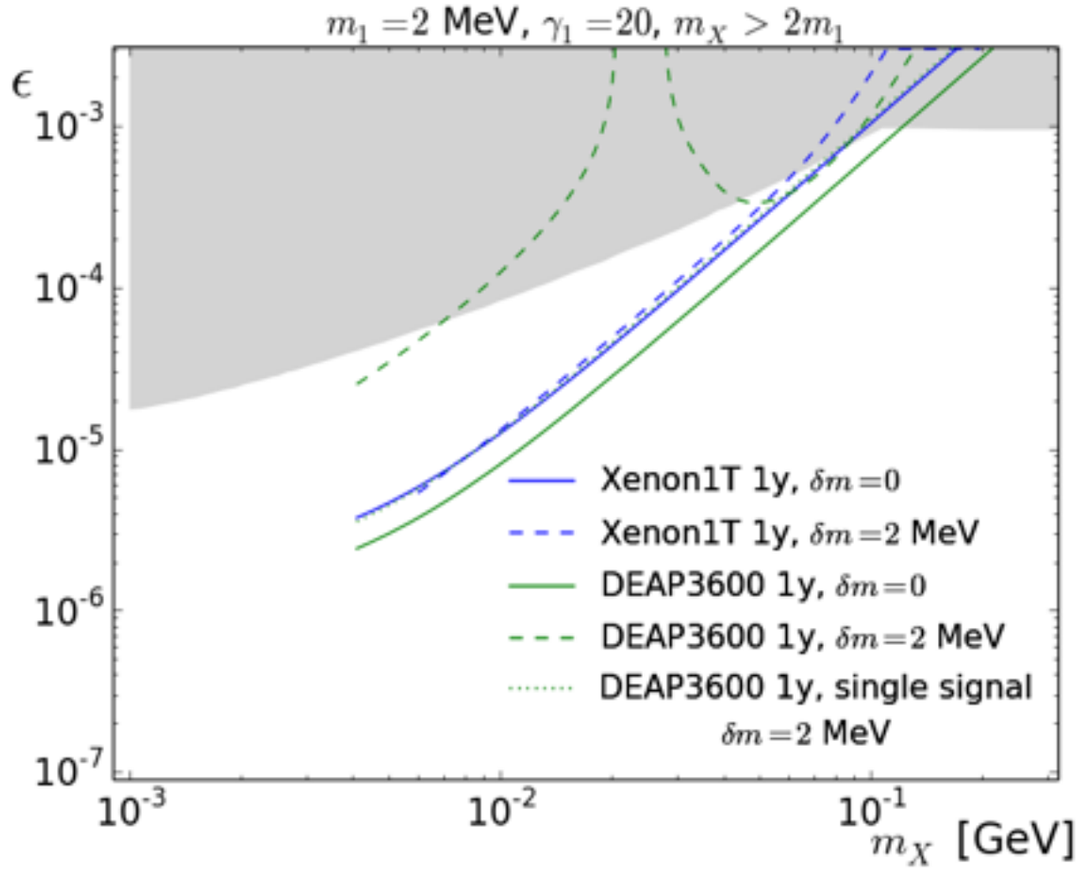


Back up

Elastic scattering



Comparison with iBDM



E_e > 10 MeV cut

- An order of magnitude stronger bounds!
- DEAP: effect of vertex resolution

Back up

Xenon1T	Borexino (solar ν)	COSINE-100, CUORE (array-type)
Ton size	100 ton size	Sub-ton size
Good angular/ position resolutions	Bad angular/position resolutions	Better in identifying displaced vertices
Less background (prompt/elastic)	More background (prompt/elastic)	No background (small size)
Lower energy range	Higher energy range 0.2MeV	Lower energy range
Smaller m_1 and E_1 Displaced vertex Post-discovery analysis	Larger m_1 and E_1	"Long" displaced vertex