ILC Beam Dump Experiment and New Physics Search

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Mini-workshop in Theory & Experiment and Detector,

IAS Program on High Energy Physics (HEP2023) @ HKUST IAS

February 13, 2023

Outline

1, Introduction

Brief theoretical review of BSM search in forward direction

2, ILC beam dump experiment

Motivations and setup

3, New physics search @ ILC beam dump

1, Long-lived particle

"New physics search at ILC positron and electron beam dumps", **K. Asai**, S. Iwamoto, Y. Sakaki, and D. Ueda, JHEP 09 (2021) 183, arXiv:2107.07487

2, Sub-GeV dark matter

"Sub-GeV dark matter search at ILC beam dumps", **K. Asai**, S. Iwamoto, M. Perelstein, Y. Sakaki, and D. Ueda, arXiv:2301.03816

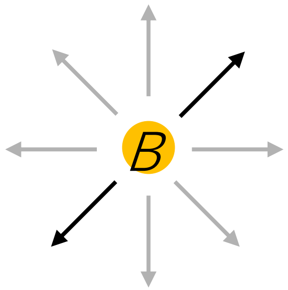
Introduction

Why forward region?

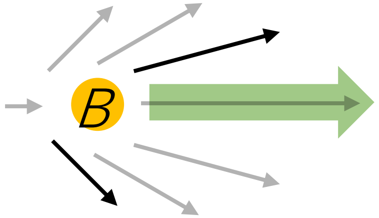
- Light particles produced at particle beam experiments fly in forward direction because of boost factor

Ex.) $B \rightarrow K + \phi$

in rest frame



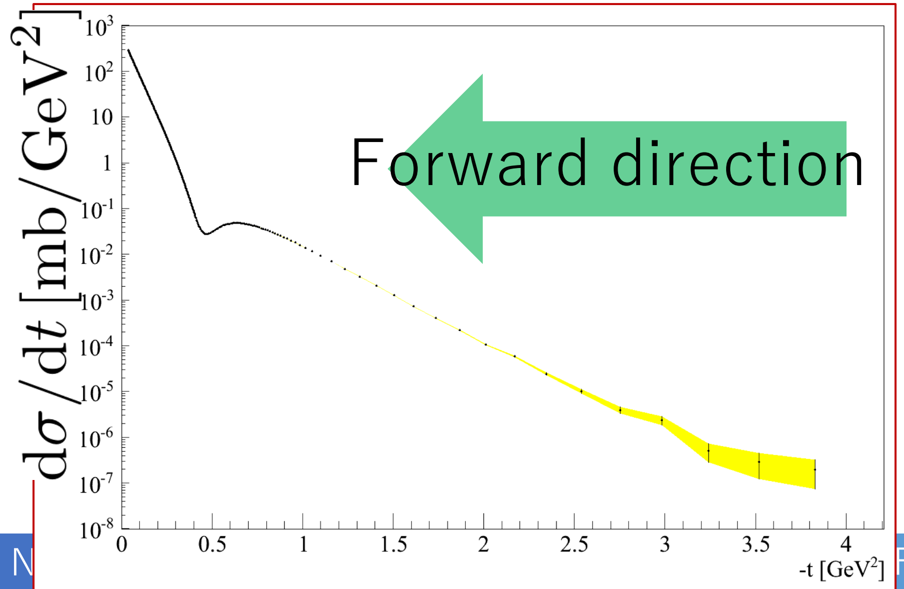
in lab frame



- pp-reaction cross section @ LHC is very large in the direction of beam axis

Inelastic scattering cross section of pp collision @ 13TeV LHC

TOTEM Collaboration, EPJC 79 (2019) 10, 861



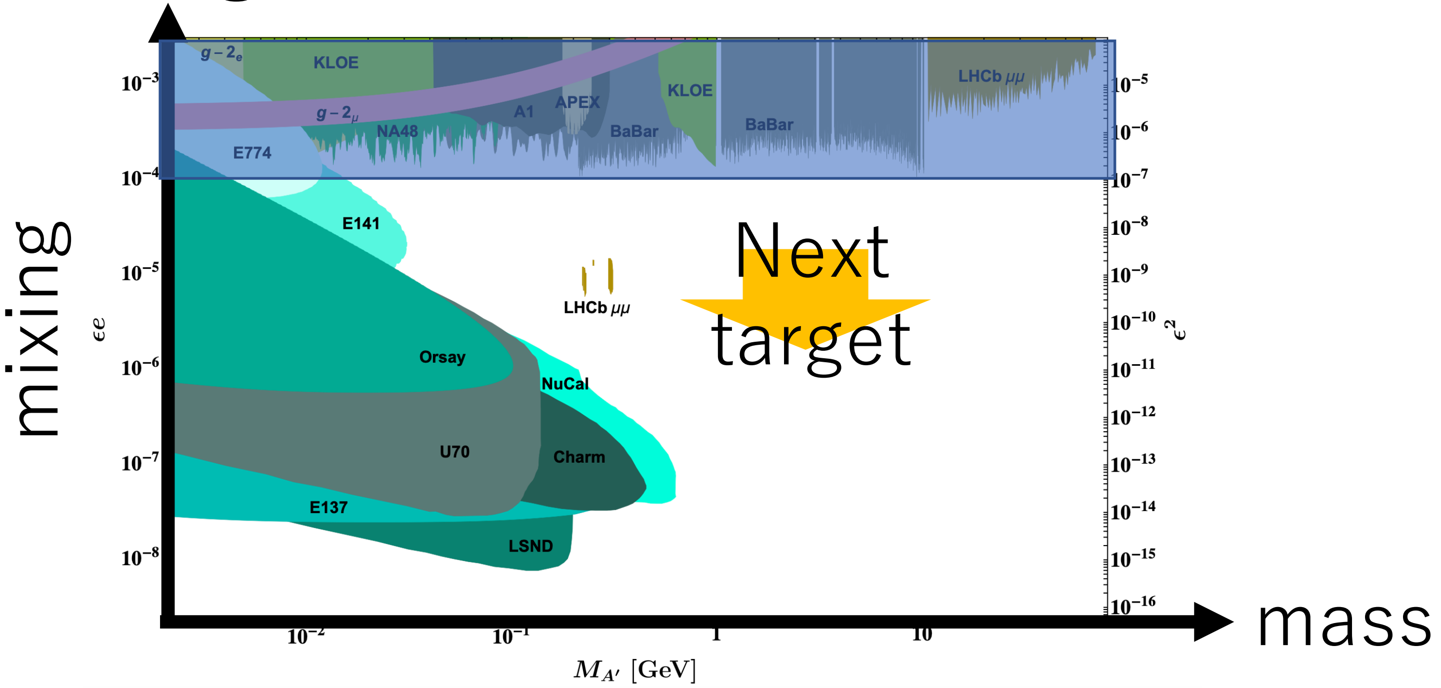
$-t = p^2\theta^{*2}[\mathrm{GeV}^2]$

Why long-lived particles?

- Strong coupling between SM & BSM particle has been already excluded for light mass case

Ex.) Dark photon

M. Bauer, P. Foldenauer, and J. Jaeckel, JHEP **2018** (2018) 94



- For background reduction, thick shield needs

Ex.) muons with EM/HD shower

Various experiments

Fixed target	Place	Year	Beam	Shield length
CHARM	CERN	1979	p, 400GeV	480m
ν-Cal I	Serpkhov	1989	p, 68.6GeV	64m
E137	SLAC	1988	e^-, 20GeV	179m
BDX	JLab	2027?	e^-, 11GeV	20m
SHiP	CERN	LHC Run4	p, 400GeV	120m
ILC beam dump	Iwate ?	?	e^-/ e^+, 125GeV	70m

Beam-beam	Place	Year	Beam $\sqrt{s}$	Distance
FASER	ATLAS	Present	p, 14TeV	480m
FASER2	ATLAS	HL-LHC	p, 14TeV	620m?

Various future experiments in forward region

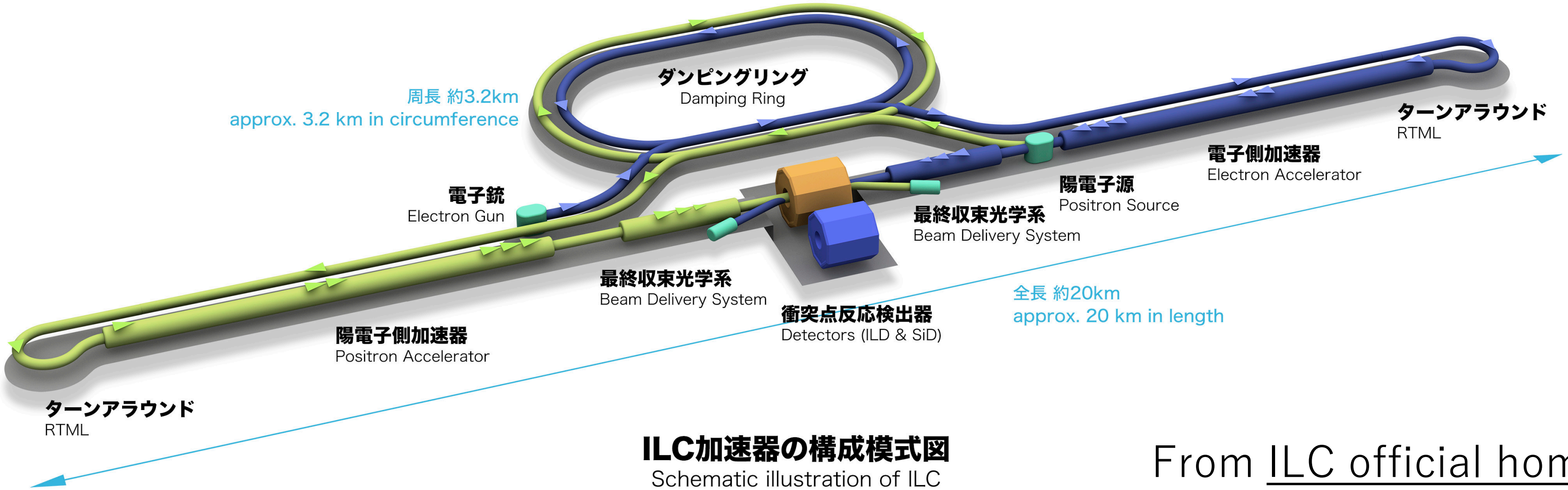
Light & feebly interacting particles will become hotter!

ILC beam dump experiment

International Linear Collider

ILC (International Linear Collider)

- Electron-positron linear collider
- 250 GeV center-of-mass energy (-> upgrade to 500 GeV, 1TeV)
- 250 $\mathbf{fb^{-1}}$ integrated luminosity



ILC加速器の構成模式図
Schematic illustration of ILC

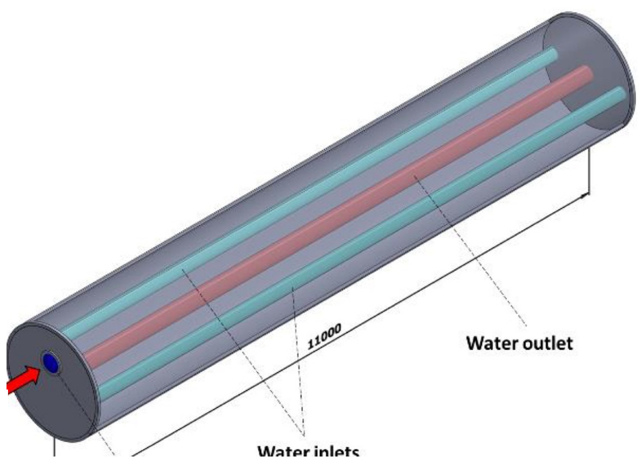
From ILC official homepage

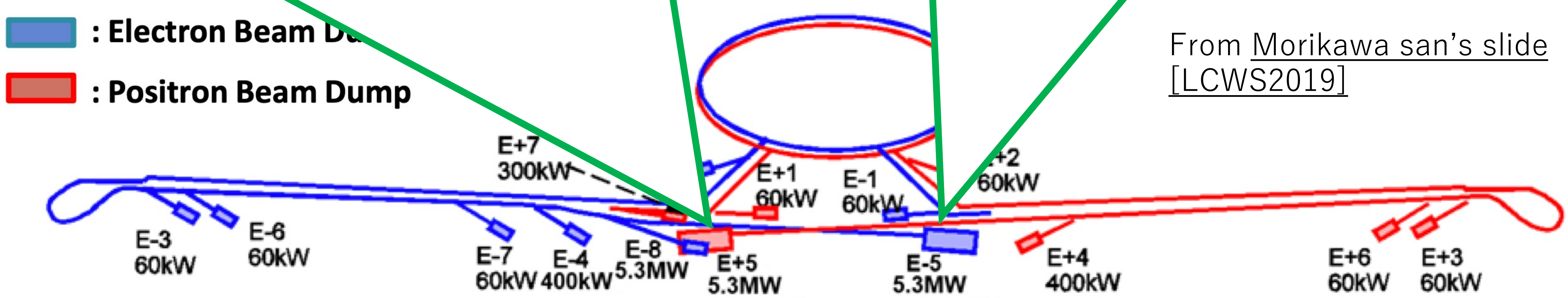
International Linear Collider

Beam dumps at ILC

Main beam dump

- Absorber : liquid water
- Covered by iron shield and concrete
- 11 m length





From Morikawa san's slide [LCWS2019]

International Linear Collider

Beam dumps at ILC

Main beam dump

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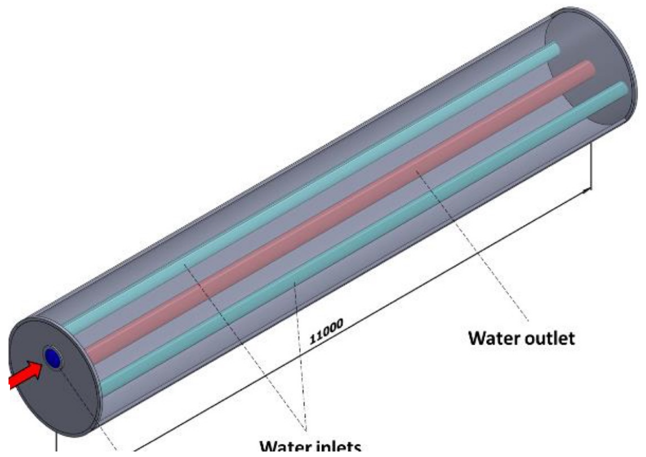


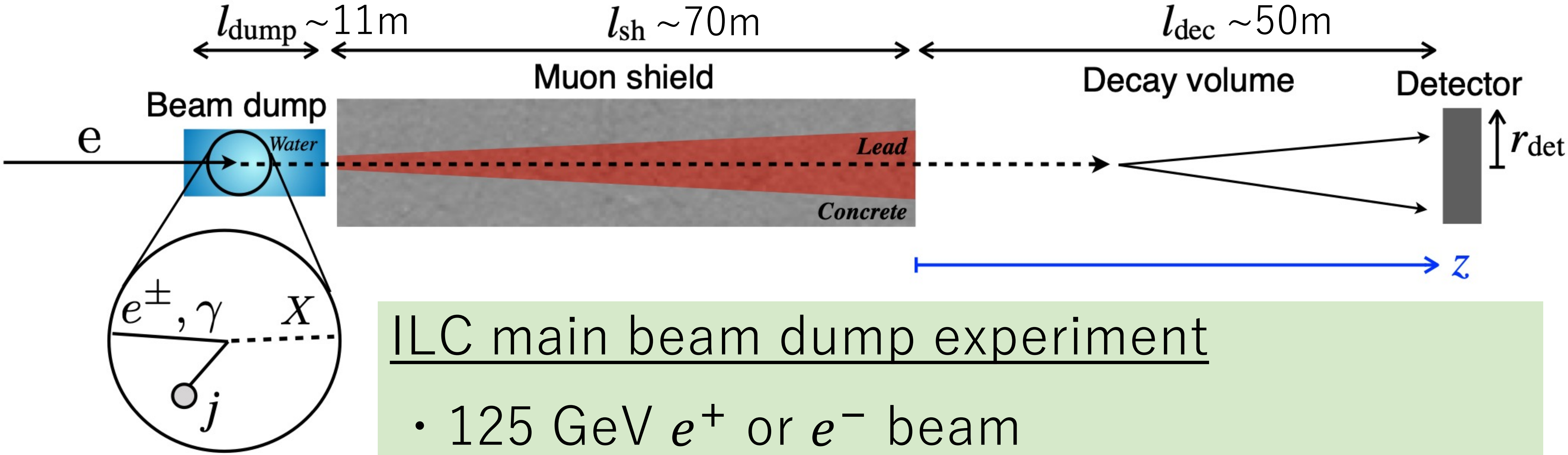
What a waste !!

Almost all e^+ & e^- are dumped at main beam dump

➡ Use them for beam dump experiment

ILC beam dump experiment

Beam dump experiment at ILC



ILC main beam dump experiment

- 125 GeV e^+ or e^- beam
- Liquid water target
- Thick muon shield for removing background

ILC beam dump experiment

Advantage

○ Intensity frontier

- Produce large number of light weakly-interacting BSM particles by high-intensity beam & fixed target

ILC beam dump experiment and ILC main experiment are in complementary relation

ILC experiment

○ Energy frontier

- Produce heavy interactive BSM particle by high energy beam

○ Low cost of construction and operation

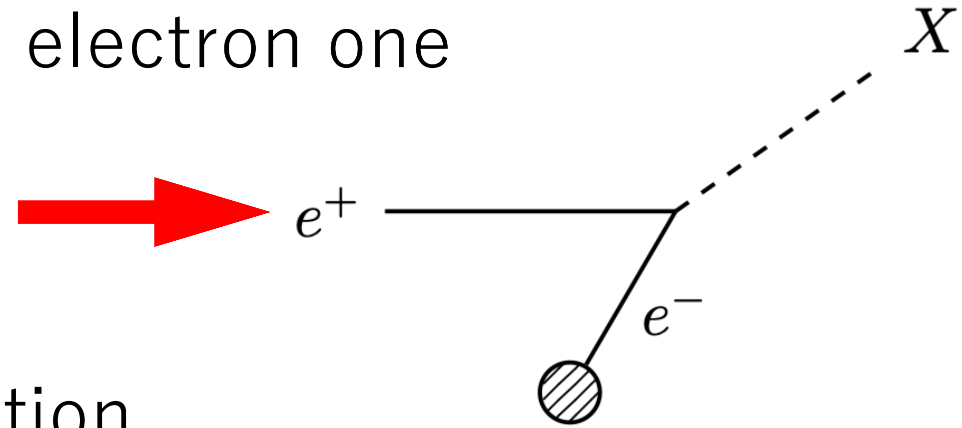
- Possible to use beams and beam dumps for ILC main experiment

ILC beam dump experiment

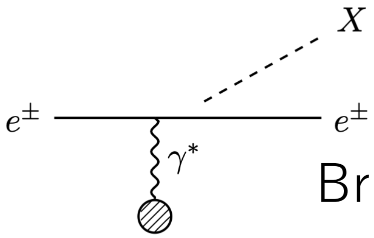
Advantage

- Can use positron beam
  - Production by pair annihilation between e^+ beam and e^- in H_2O

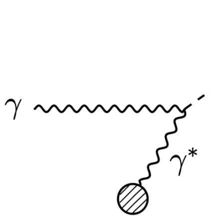
➡ Proton beam dump has higher sensitivity than electron one



Other process



Bremsstrahlung



Primakoff process

Our question

How much better does positron beam dump perform than electron one ?

Long-lived Particle @ ILC beam dump

Based on
"New physics search at ILC positron and electron beam dumps", **K. Asai**, S. Iwamoto, Y. Sakaki, and D. Ueda, JHEP 09 (2021) 183, arXiv:2107.07487

Basic strategy

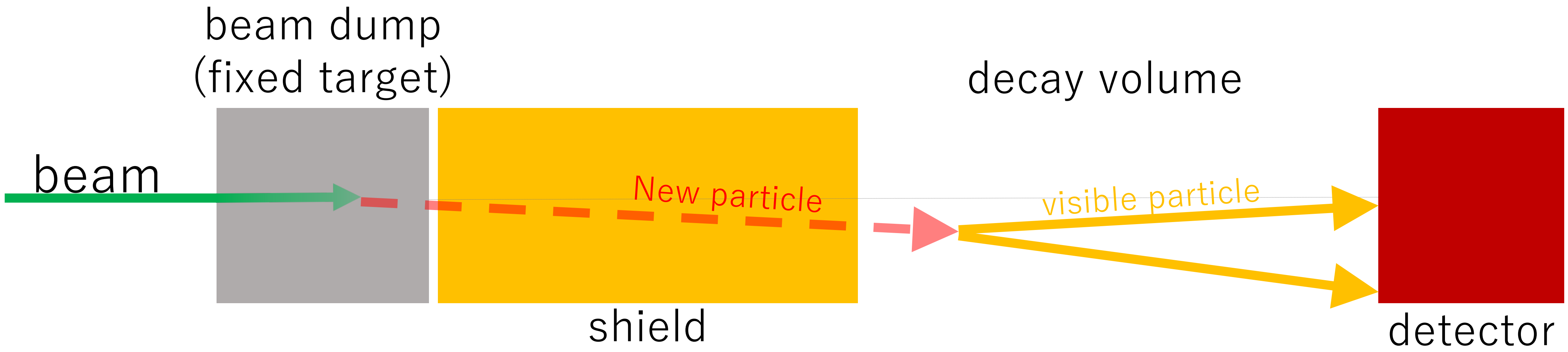
Production & Detection

1, LLPs are produced and fly in forward direction

2, LLPs pass through long shied

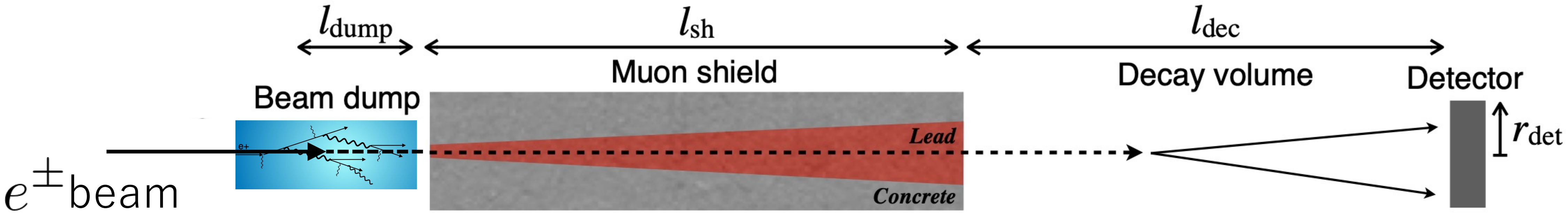
3, LLPs decay into SM visible particles in decay volume

4, Visible particles are detected at detectors



Long-lived particle search

Calculation of event number

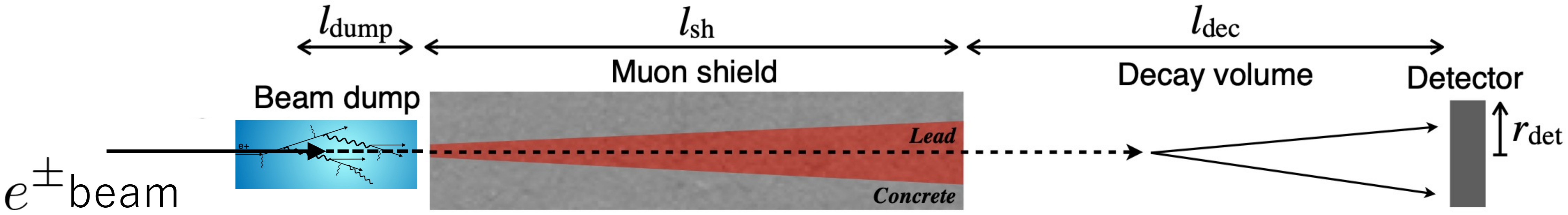


(# of signal event)

= (# of produced BSM particles) × (Acceptance) × (Branching ratio)

Long-lived particle search

Calculation of event number

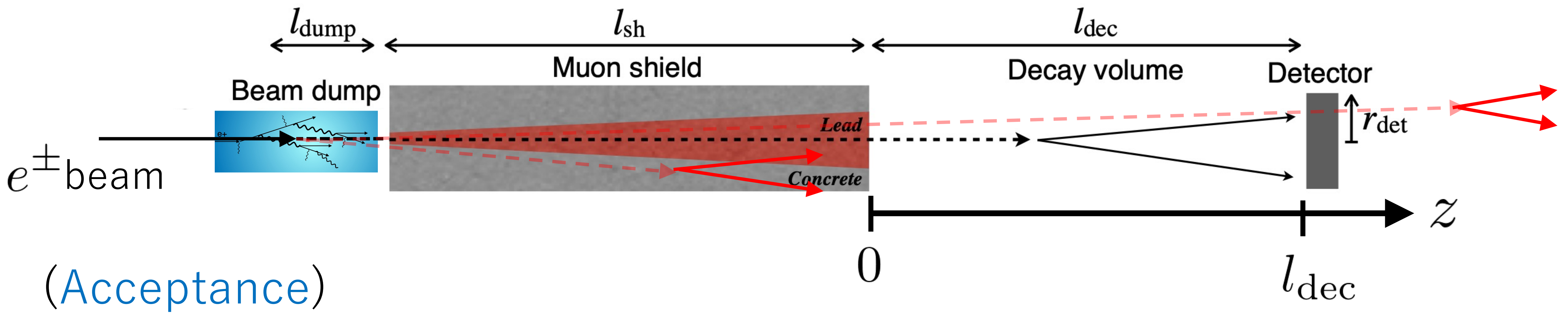


(Acceptance)

= (Probability of decay in decay volume) × (Angular cut)

Long-lived particle search

Calculation of event number



(Acceptance)

= (Probability of decay in decay volume) × (Angular cut)

BSM particles reach decay volume and are detected by decay into visible particles

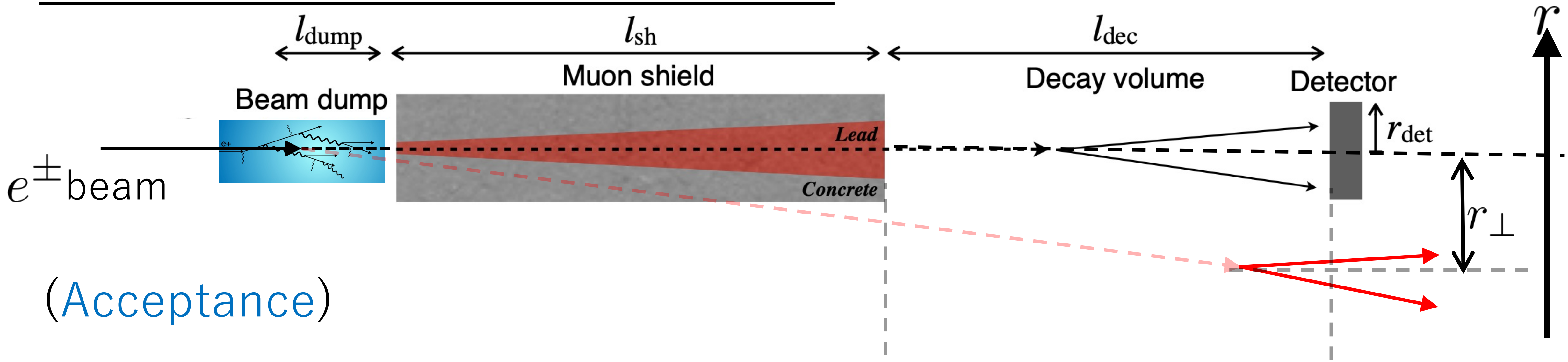
➡ Probability of decay between $0 \sim l_{\rm dec}$

$$\frac{{\rm d}P_{\rm dec}}{{\rm d}z} = \frac{1}{l_X^{\rm (lab)}} \exp\left(- \frac{l_{\rm dump} + l_{\rm sh} + z}{l_X^{\rm (lab)}} \right)$$

$l_X^{\rm (lab)}$: Decay length in laboratory frame

Long-lived particle search

Calculation of event number



(Acceptance)

= (Probability of decay in decay volume) × (Angular cut)

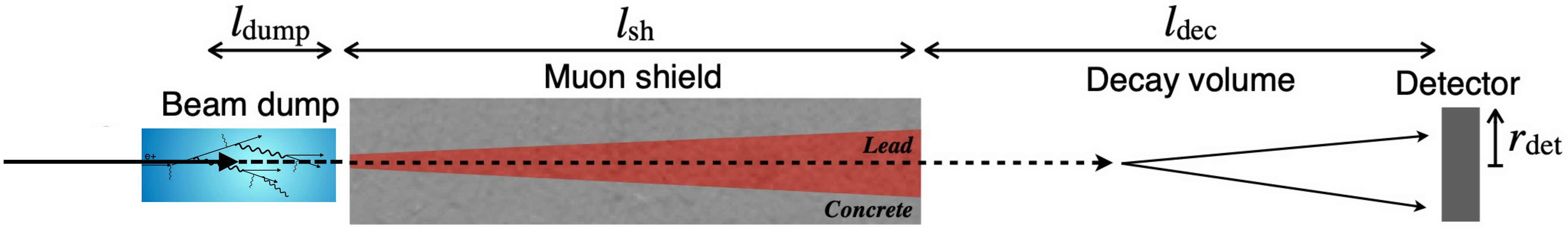
Produced particles have angles with respect to initial particles

➡ For large angle (deviation from beam axis $r_{\perp}$), visible particles in decay volume do not hit detector

➡ Angular cut : $\Theta(r_{\mathrm{det}} - r_{\perp})$

Long-lived particle search

Calculation of event number ($e^{\pm}$ beam dump experiment)



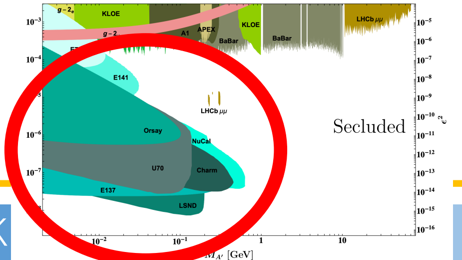
(Number of signals)

= (# of produced new particles) × (Acceptance) × (Branching ratio)

$$= N_{e^{\pm}} n_j \int \mathrm{d}E_i \frac{\mathrm{d}l_i}{\mathrm{d}E_i} \int \mathrm{d}E_X \int_0^{\pi} \mathrm{d}\theta_X \frac{\mathrm{d}^2\sigma(i+j \to X + \mathrm{others})}{\mathrm{d}E_X \mathrm{d}\theta_X} \times \int_{z_1}^{z_2} \mathrm{d}z \frac{1}{l_{\mathrm{dec}}} e^{-z/l_{\mathrm{dec}}} \Theta(r_{\mathrm{det}} - r_{\perp}) \times \mathrm{Br}(X \to \mathrm{visible})$$

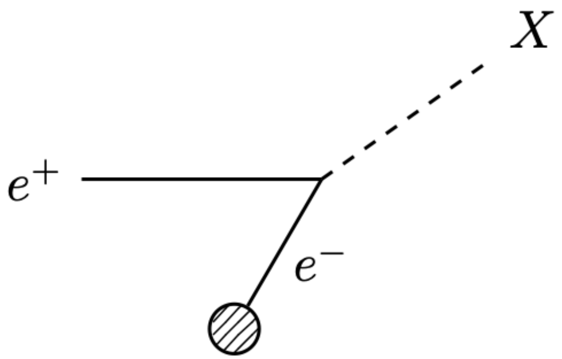
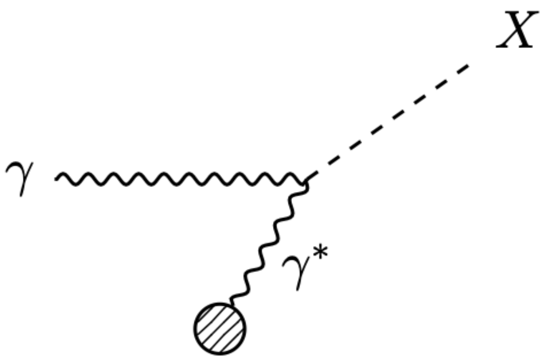
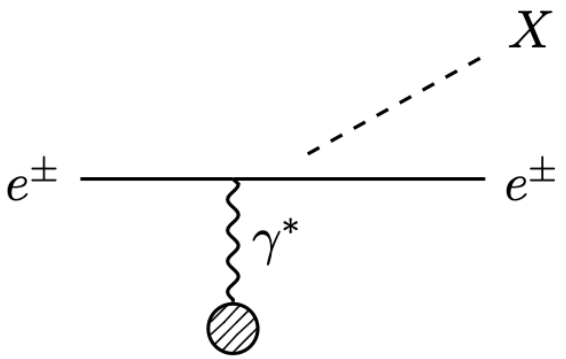
Coupling to SM ⤴ ⟶ # of production ⤴ Acceptance (lifetime) ⤵

➡ # of signals is defined by competition of two effects



LLP search at ILC beam dump

Production Process

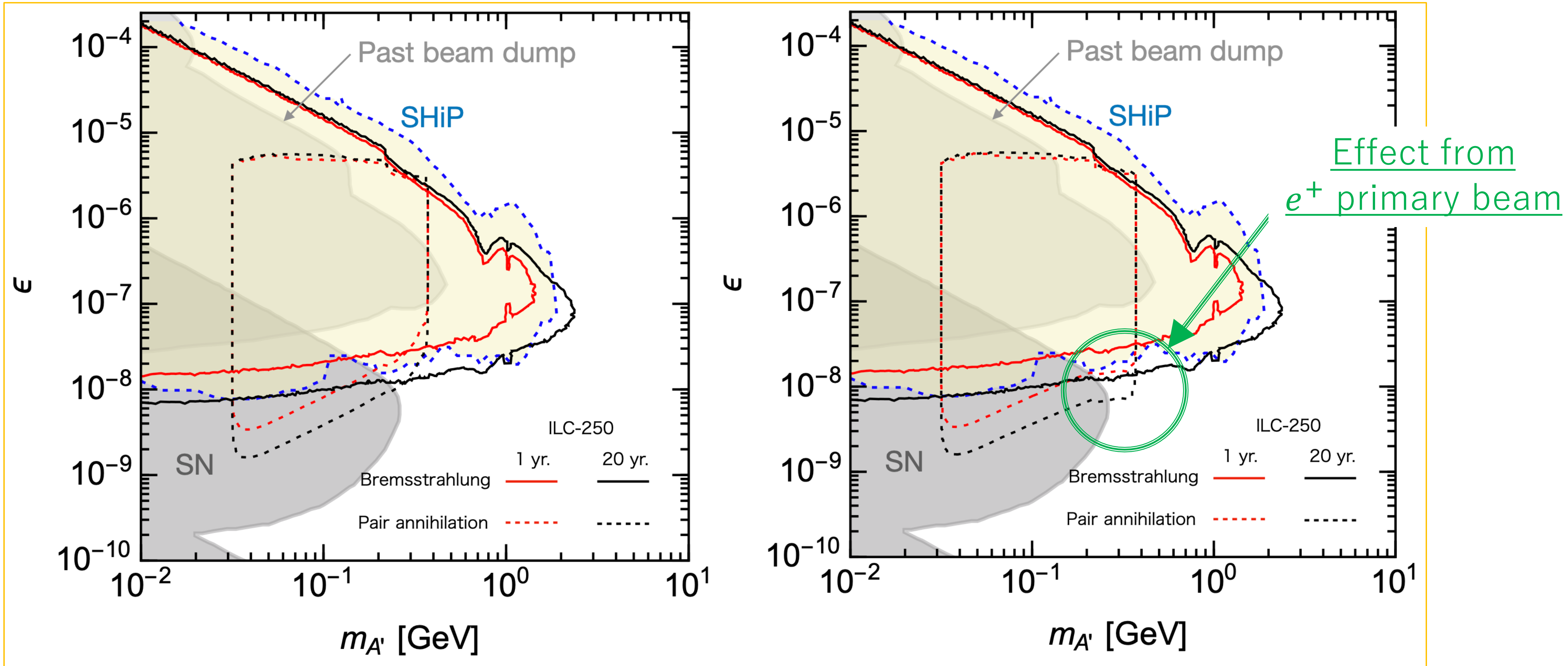
	 (a) Pair-annihilation	 (b) Primakoff process	 (c) Bremsstrahlung
dark photon	✓		✓
ALP	✓	✓	✓
scalar	✓	✓	✓

LLP search at

Dark photon

$$\mathcal{L} \supset -\frac{1}{4}F^{(A')}_{\mu\nu}F^{(A')\mu\nu} - \frac{\epsilon}{2}F^{(\mathrm{em})}_{\mu\nu}F^{(A')\mu\nu} + \frac{m^2_{A'}}{2}A'_{\mu}A'^{\mu}$$

Sensitivity region



Electron beam

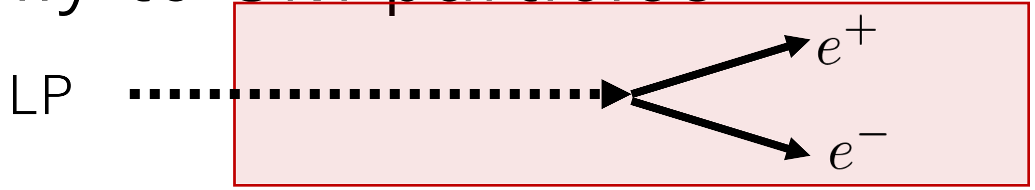
Positron beam

Sub-GeV Dark Matter @ ILC beam dump

Based on
"Sub-GeV dark matter search at ILC beam dumps", **K. Asai**, S. Iwamoto, M. Perelstein, Y. Sakaki, and D. Ueda, arXiv:2301.03816

Light Particle + Dark Matter

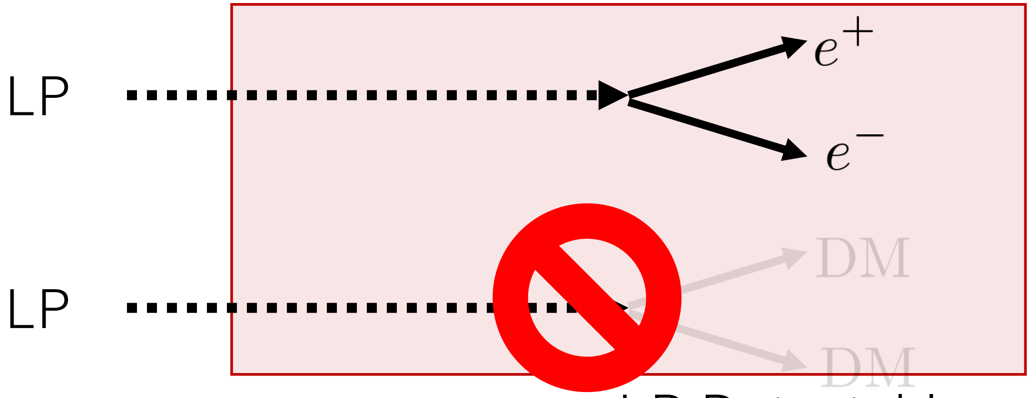
In light particle (LP) search at ILC bean dump, it is assumed that they couple only to SM particles



LP Detectable

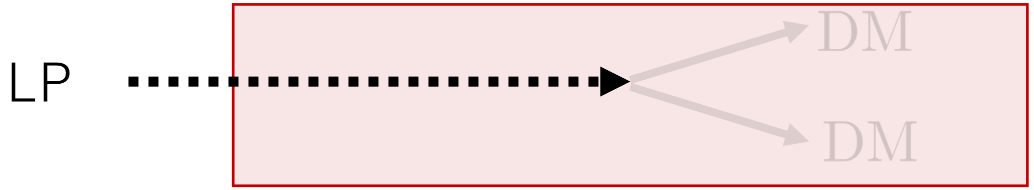
If light particles dominantly decay into DMs,

(i) $m_{\rm LP} < 2m_{\rm DM}$ case



LP Detectable

(ii) $m_{\rm LP} \geq 2m_{\rm DM}$ case



No visible signal !

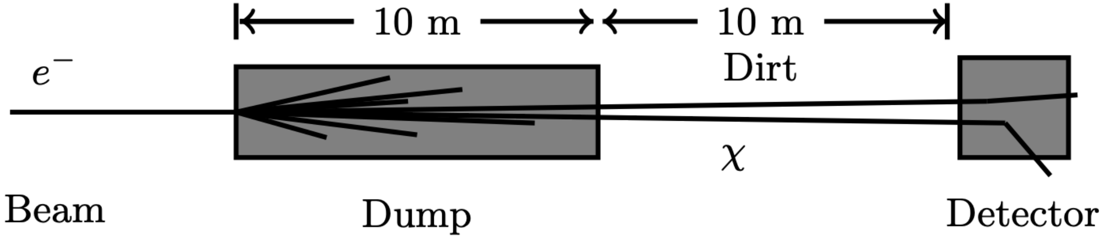
DM can be detected at ILC beam dump experiment ?

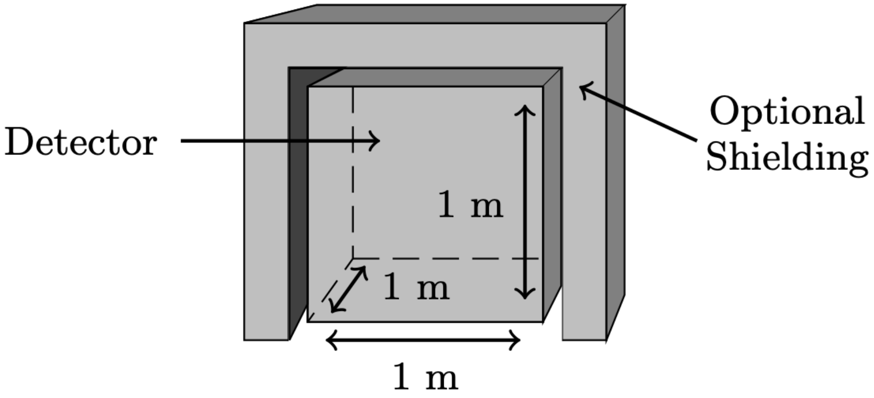
BDX (Beam Dump eXperiment)

MeV-GeV dark matter search experiment @ JLab

- ○ DMs are produced in electron beam dump
- ○ 11 GeV electron beam
- ○ 10^{22} electron on target
- ○ 1m^3 CsI (Tl) scintillator

BDX collaboration (2016), arXiv:1607.01390





ILC beam dump

125 GeV $e^{\pm}$ beam,

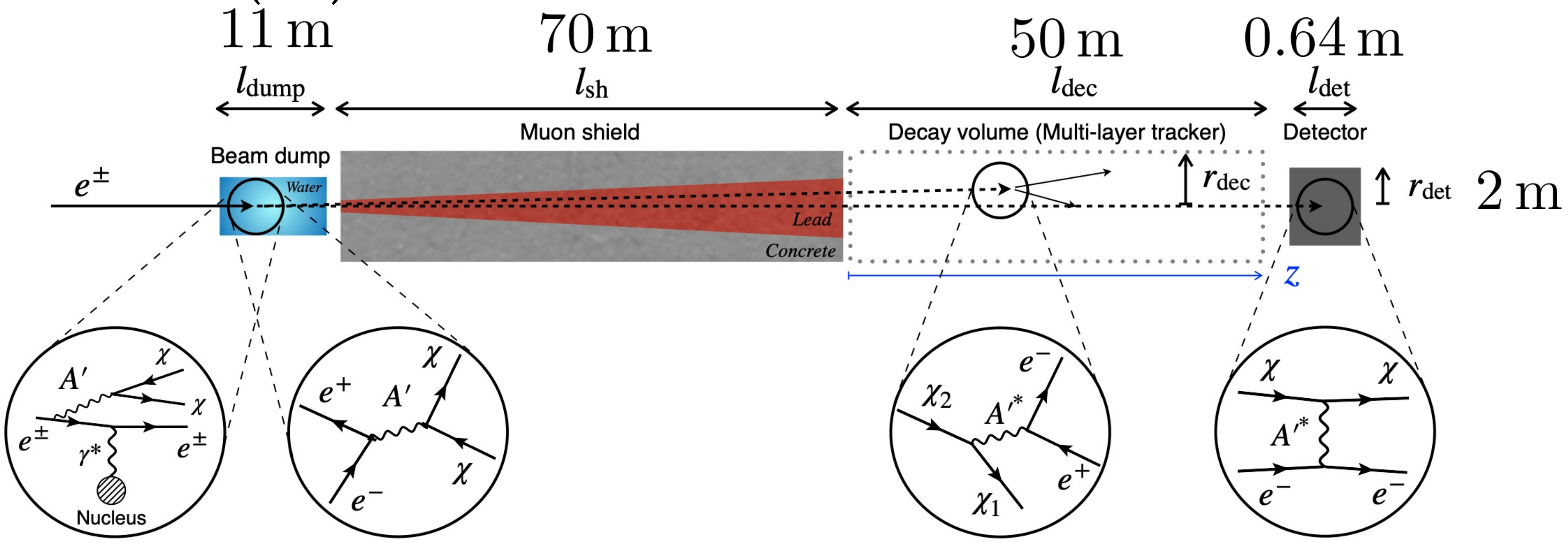
4×10^{21}/year $e^{\pm}$ on target

➡ Powerful DM search like BDX @ ILC beam dump !

ILC-BDX

MeV-GeV dark matter search experiment @ ILC beam dump

- ○ DMs are produced in $e^{\pm}$ beam dump
- ○ 125 GeV $e^{\pm}$ beam
- ○ 4×10^{21}/year $e^{\pm}$ on target
- ○ cylindrical CsI (Tl) scintillator

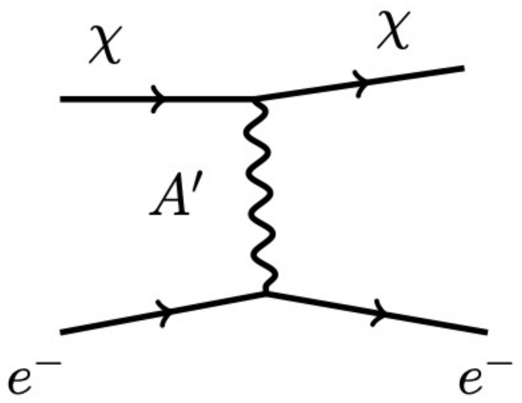


ILC-BDX

Two types of DM signals

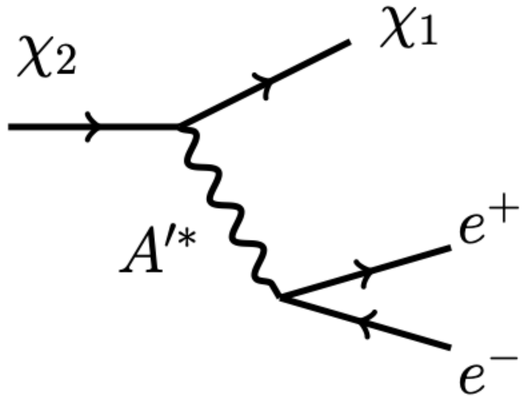
① Electron recoil

DMs scatter with electrons in detector material elastically, and recoil electrons are detected.



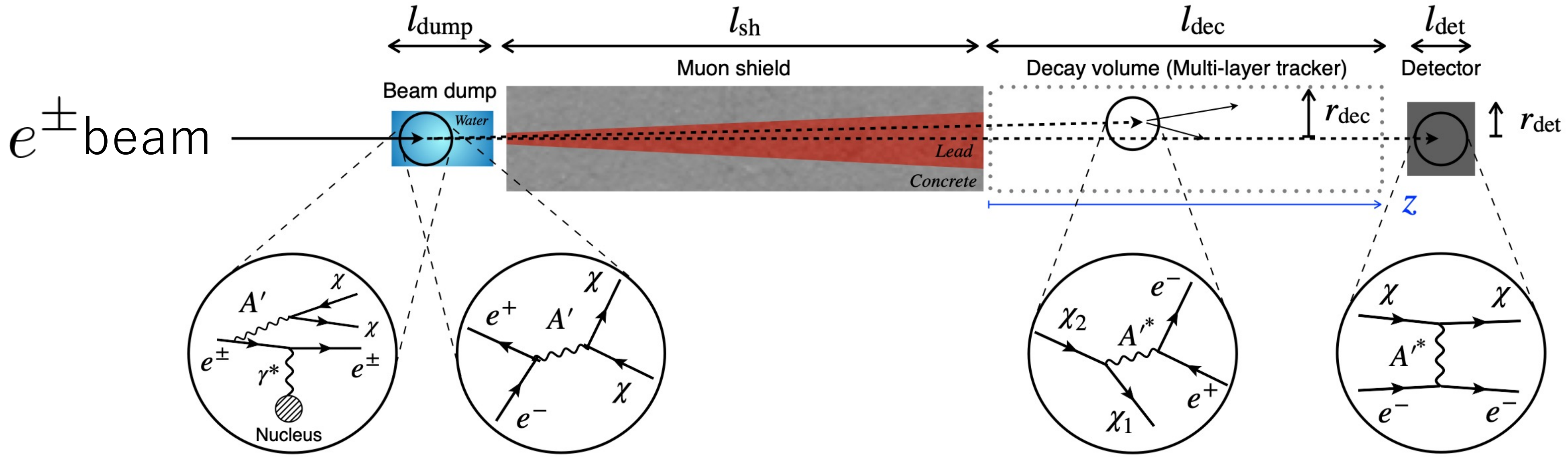
② Visible decay

Heavy DM state is produced at beam dump and decay into light DM state and SM particles. Visible daughter SM particles are detected.



Dark matter search

Calculation of event number（$e^{\pm}$ beam dump experiment)



(Acceptance)

= (Probability of reaction with visible SM particles) × (Angular cut)

Visible decay ➡ probability of heavy dark state decay

e^- recoil ➡ probability of e^--DM elastic scattering

Ex.) Pseudo-Dirac DM

Two-component Weyl fermion with nonzero dark U(1) charge

$$-\mathcal{L} \supset m_D \eta\xi + \frac{1}{2} m_M (\eta^2 + \xi^2) + \mathrm{H.c.}$$

in low-energy theory

For $m_D \gg m_M > 0$, DM mass eigenstates

$$\chi_1 = \frac{i}{\sqrt{2}}(\eta - \xi), \quad \chi_2 = \frac{1}{\sqrt{2}}(\eta + \xi)$$

with masses $m_{\chi_{1,2}} = m_D \mp m_M$

DM-dark photon coupling is off-diagonal

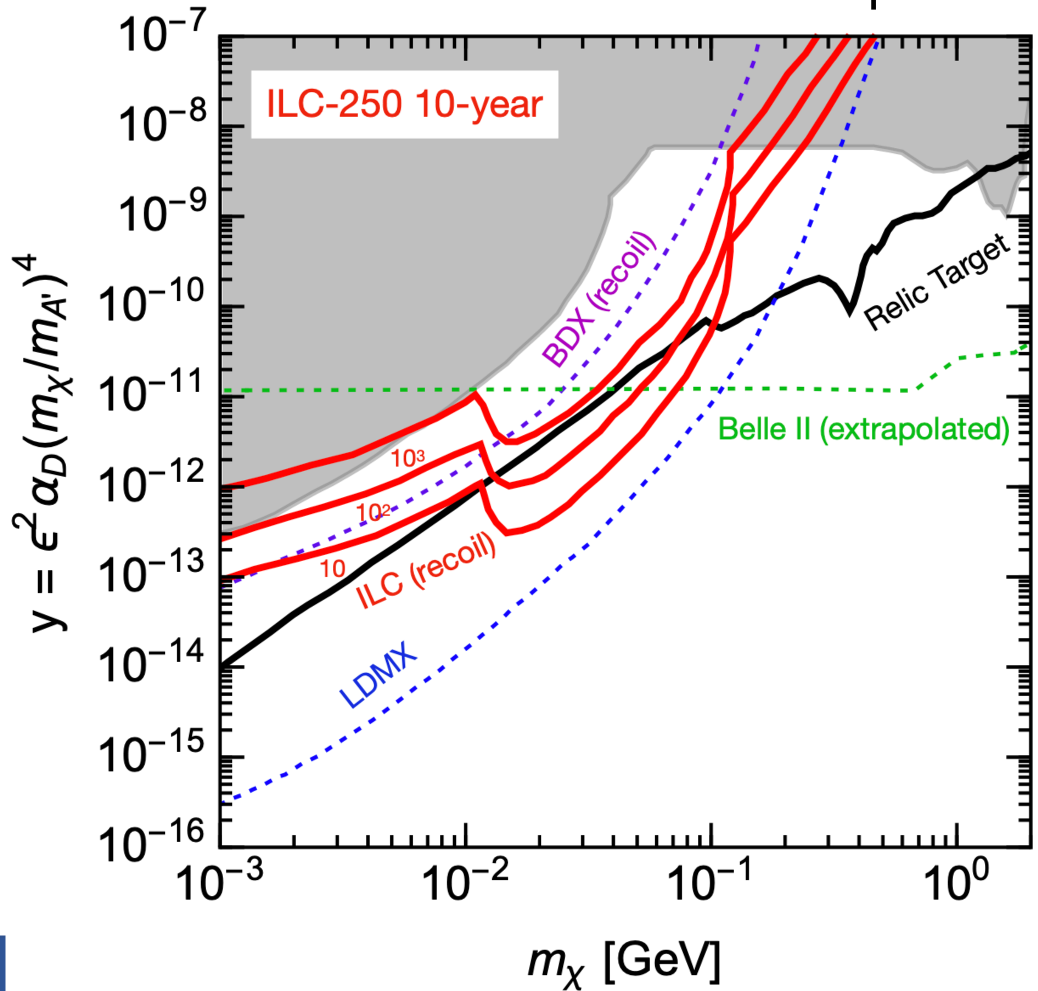
$$J_\chi^\mu = i\bar{\chi}_2 \gamma^\mu \chi_1 + \mathrm{H.c.}$$

➡ Inelastic DM

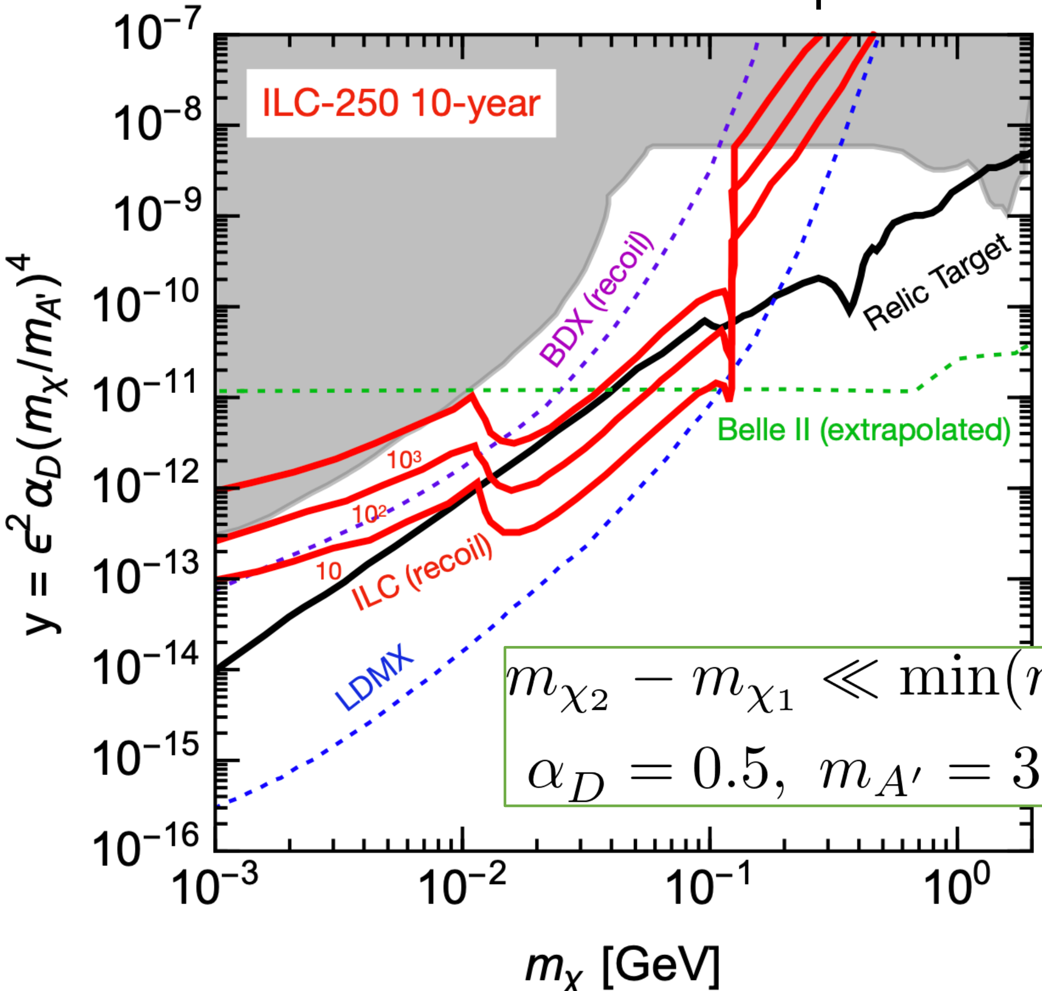
Projected sensitivity

Ex.) Pseudo-Dirac DM (small mass splitting)

e^- beam dump



e^+ beam dump



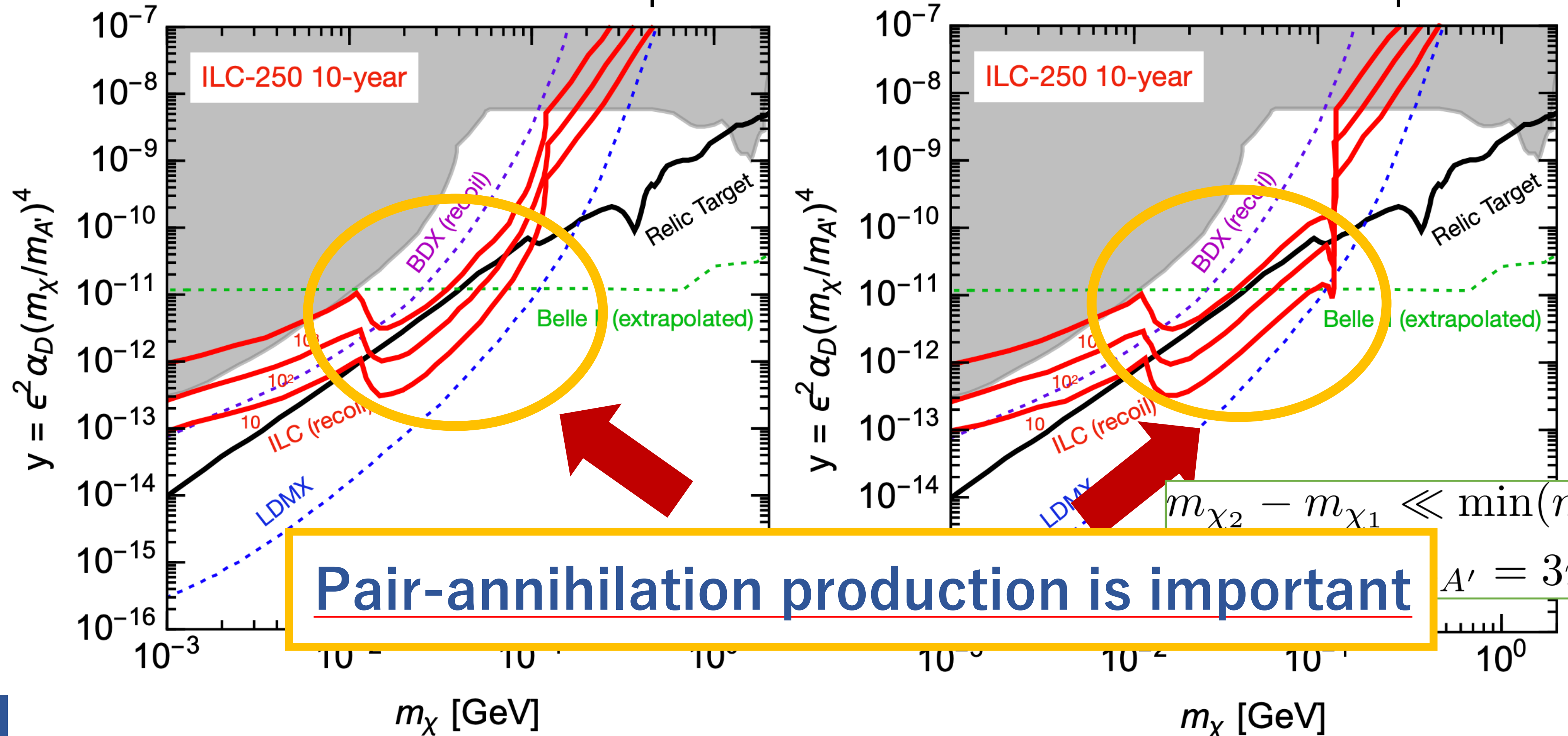
$$m_{\chi_2} - m_{\chi_1} \ll \min(m_e, m_{\chi_1})$$
$$\alpha_D = 0.5,\ m_{A'} = 3m_{\chi_1}$$

Projected sensitivity

Ex.) Pseudo-Dirac DM (small mass splitting)

e^- beam dump

e^+ beam dump



$$m_{\chi_2} - m_{\chi_1} \ll \min(m_e, m_{\chi_1})$$

$$m_{A'} = 3m_{\chi_1}$$

Pair-annihilation production is important

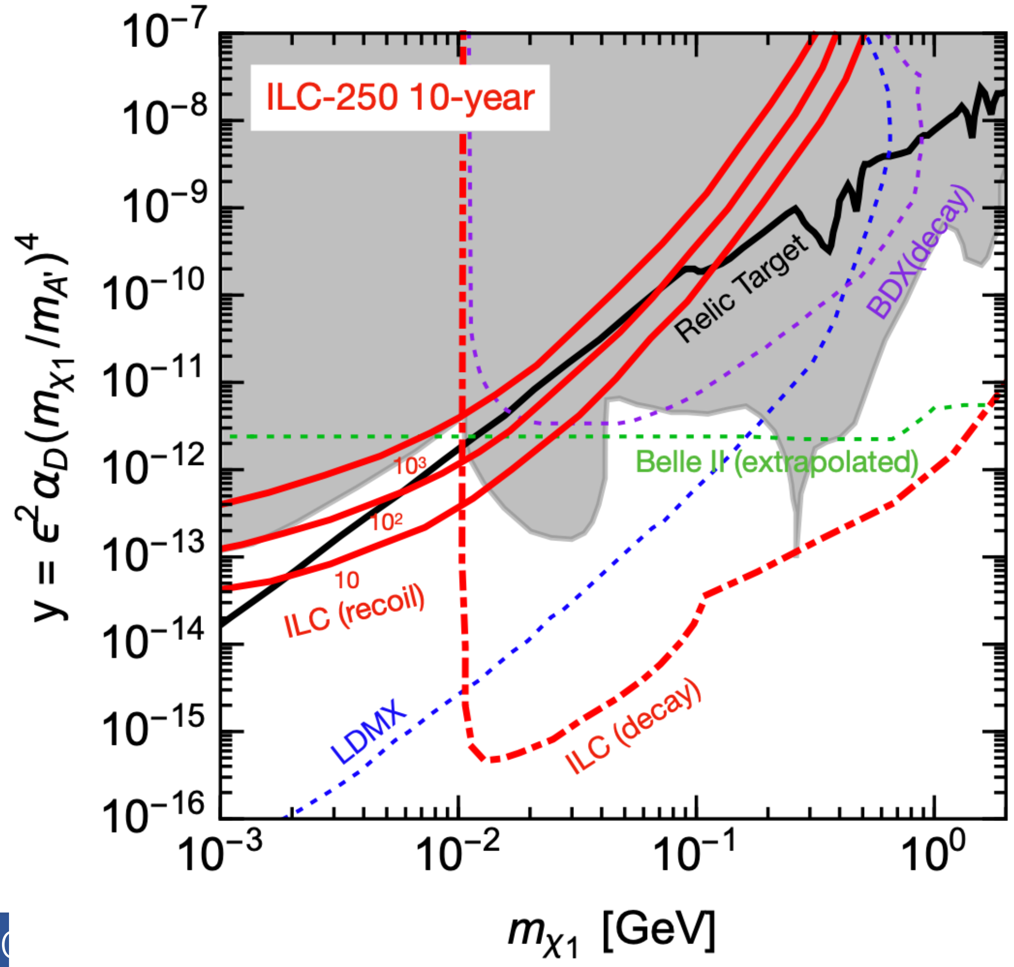
Projected sensitivity

$m_{\chi_2} - m_{\chi_1} = 0.1 m_{\chi_1}$

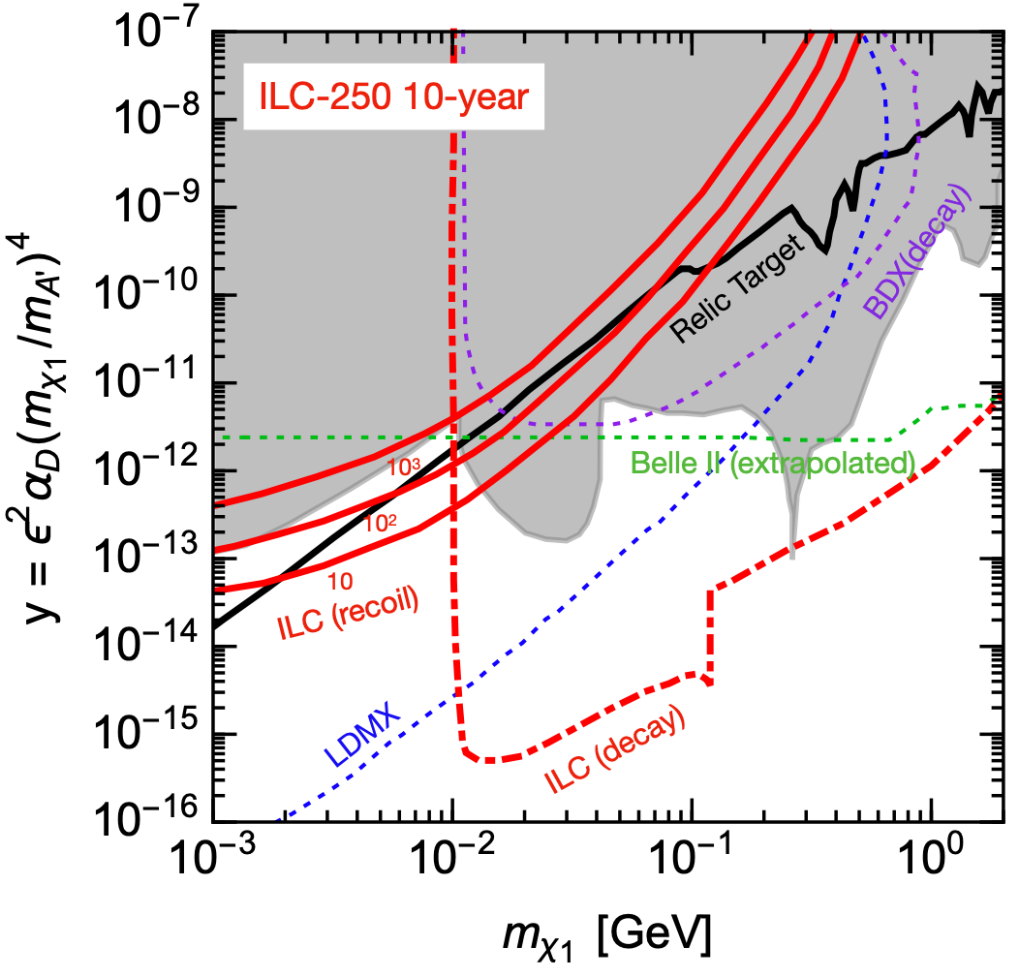
$\alpha_D = 0.1, m_{A'} = 3 m_{\chi_1}$

Ex.) Pseudo-Dirac DM (large mass splitting)

e^- beam dump



e^+ beam dump

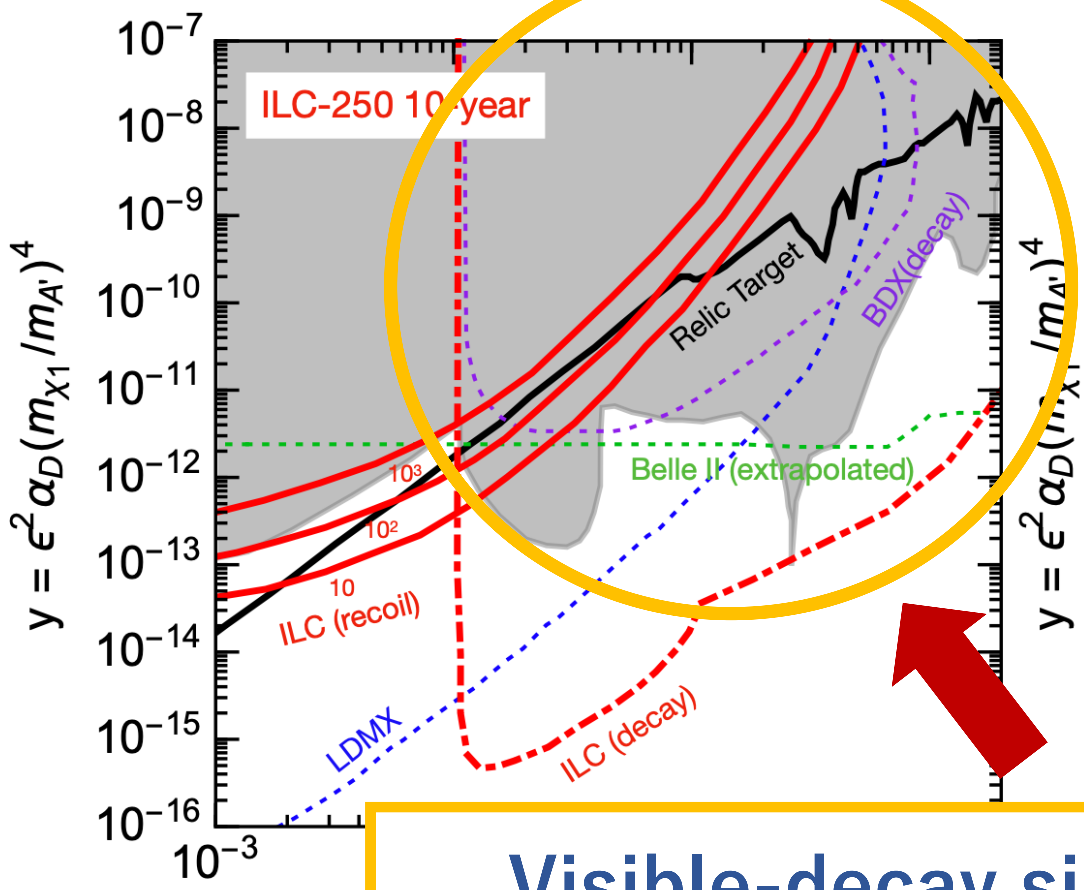


Projected sensitivity

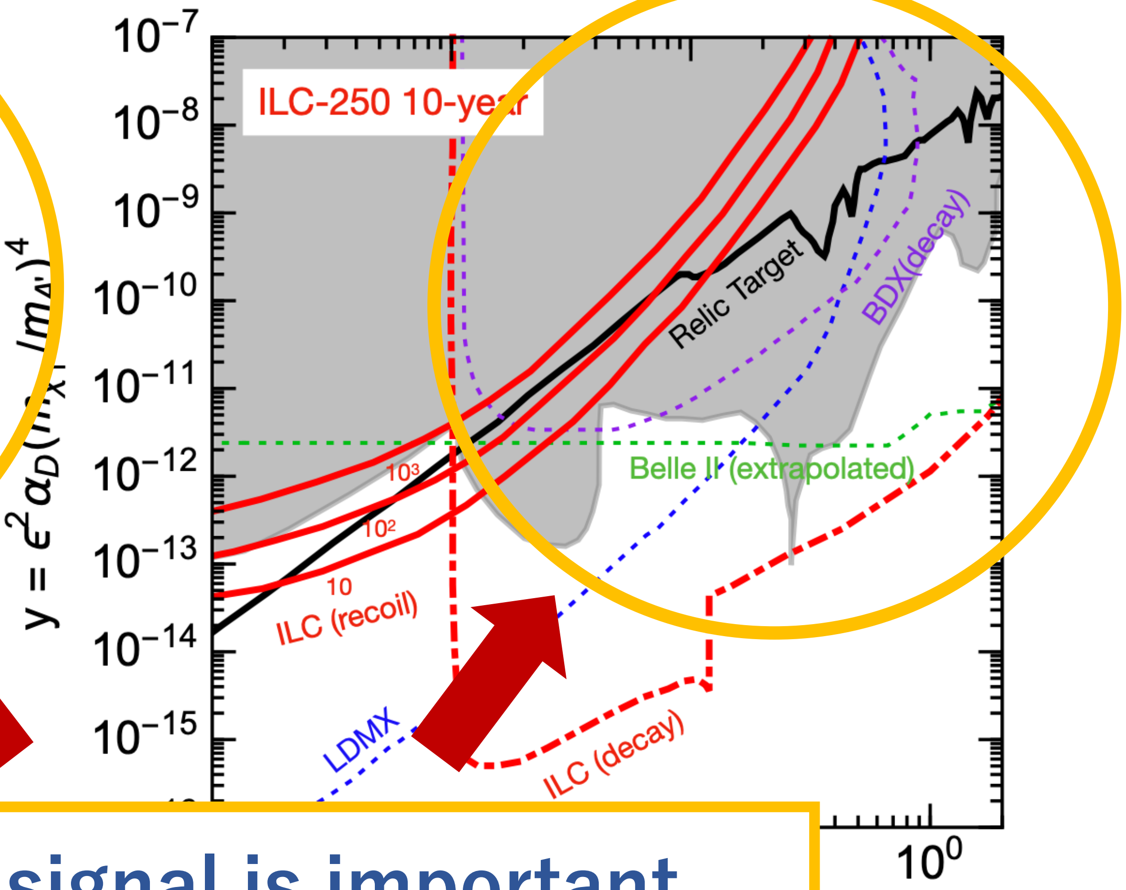
$$m_{\chi_2} - m_{\chi_1} = 0.1 m_{\chi_1}$$
$$\alpha_D = 0.1, m_{A'} = 3 m_{\chi_1}$$

Ex.) Pseudo-Dirac DM (large mass splitting)

e^- beam dump



e^+ beam dump



Visible-decay signal is important

Summary

- ILC $e^{\pm}$ beam dump experiment has higher sensitivity to light ($\lesssim 1\,\mathrm{GeV}$) weakly-interacting particles than past beam dump experiments
- ILC-BDX can probe interesting parameters of the sub-GeV DM model, and can reach the relic target.
- Although pair annihilation processes occur in both electron and positron beam dumps, positron case is more sensitive to heavy mass region because of primary e^{+} beam

Thank you for your attention !