ILC Beam Dump Experiment and New Physics Search

Kento Asai

(ICRR, the University of Tokyo)

New Trends in High-Energy and Low-x Physics

@ Sfântu Gheorghe, România

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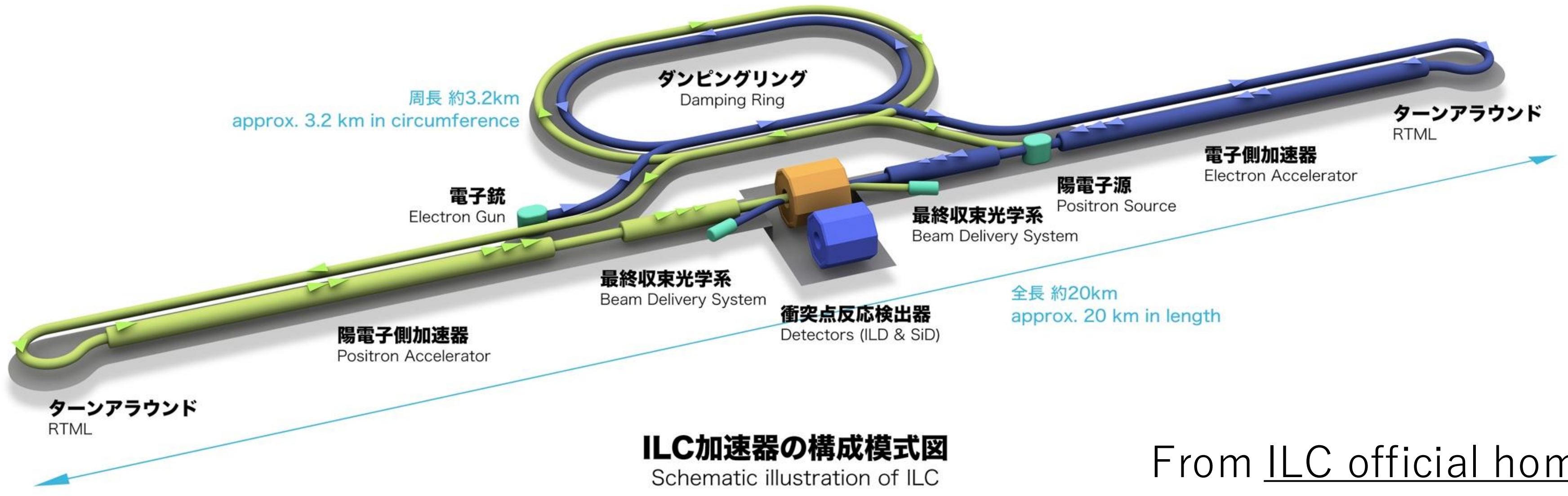
Based on **KA**, S. Iwamoto, Y. Sakaki, D. Ueda, JHEP 09 (2021) 183, arXiv:2105.13768[hep-ph]
KA, S. Iwamoto, M. Perelstein, Y. Sakaki, D. Ueda, JHEP 02 (2024) 129, arXiv:2301.03816[hep-ph]

International Linear Collider

ILC (International Linear Collider)

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



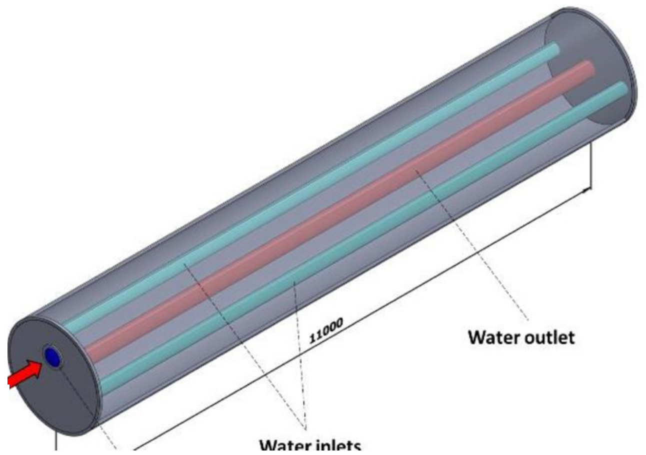
From ILC official homepage

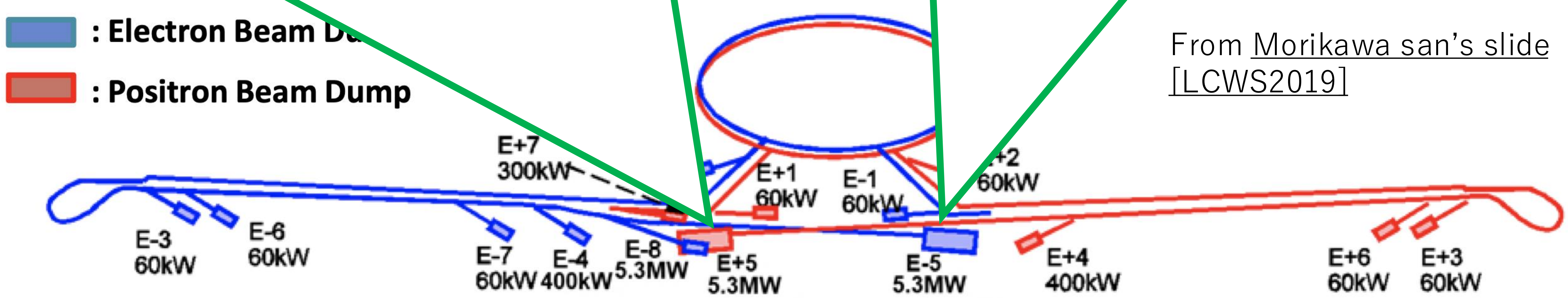
International Linear Collider

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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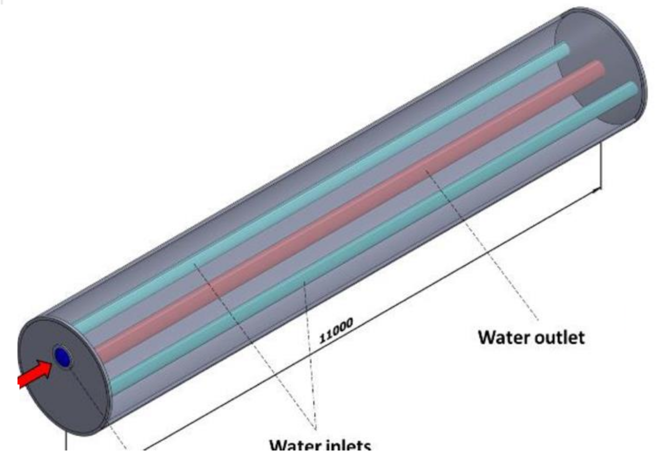


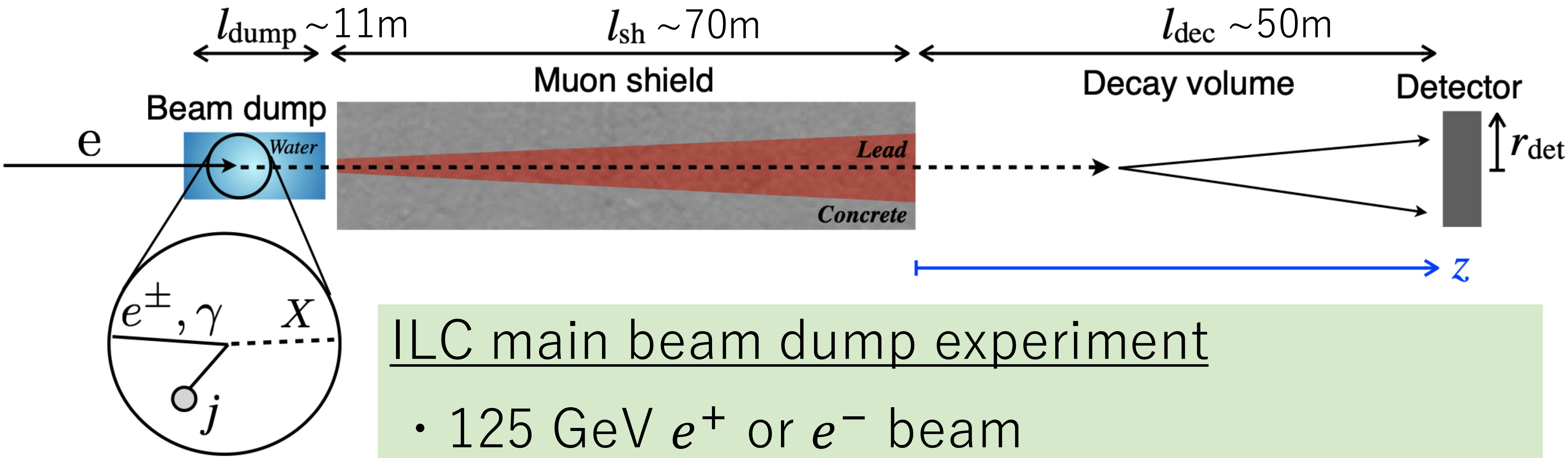
What a waste !!

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

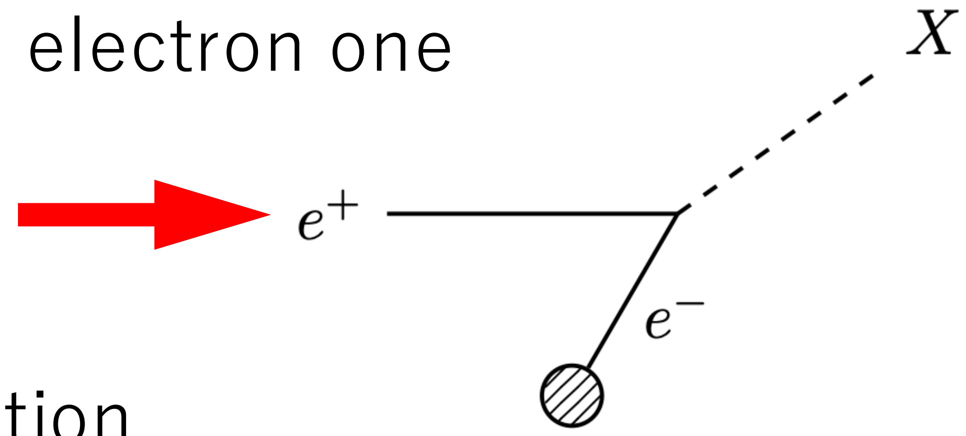
- Possible to use beams and beam dumps for ILC main experiment

ILC beam dump experiment

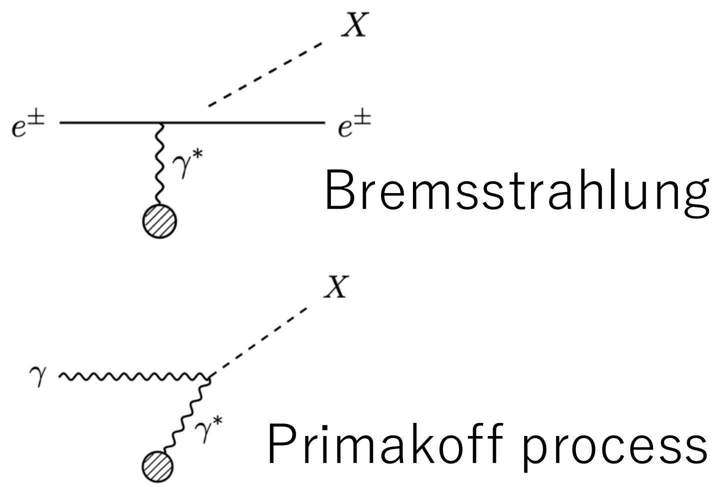
Advantage

- 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



Our question

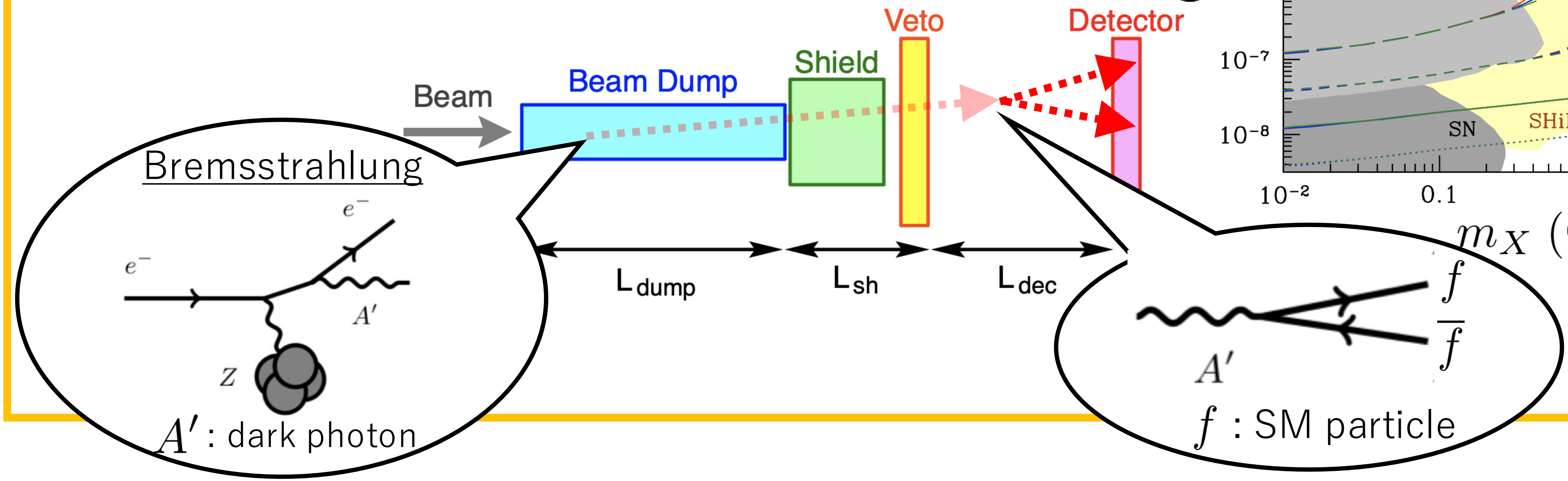
How much better does positron beam dump perform than electron one ?

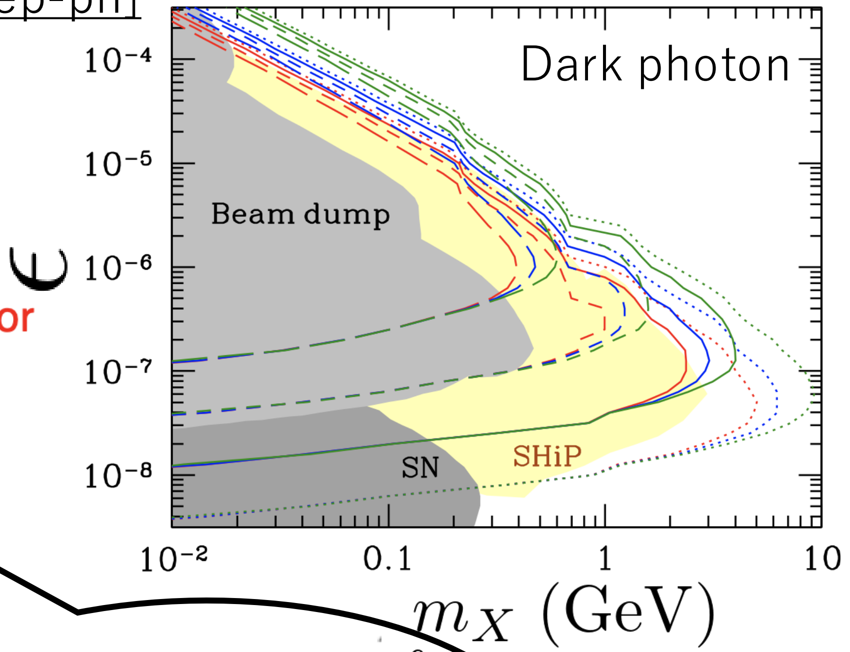
Pioneering work

S. Kanemura, T. Moroi, T. Tanabe, PLB 751 (2015) 25-28,
arXiv : 1507.02809 [hep-ph]

Dark photon search by ILC electron beam

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} F^{(X)}_{\mu\nu} F^{(X)}_{\mu\nu} - \frac{\epsilon}{2} F^{(\rm em)}_{\mu\nu} F^{(X)}_{\mu\nu} + \frac{m_X^2}{2} X_\mu X_\mu$$





LLP search at ILC

blue curve
→ bound from T2K 10-year run

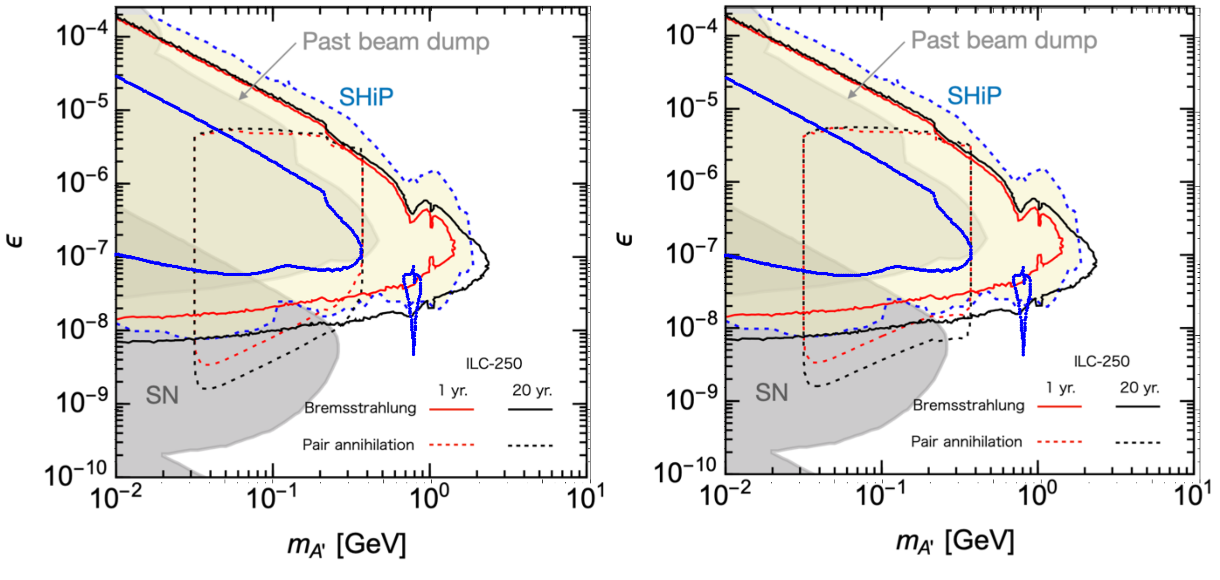
T. Araki, **KA,** T. Iizawa, H. Otono, T. Shimomura, Y. Takubo , JHEP 11 (2023) 056

New physics search (previous)

- Dark photon, ALP, light scalar

K. Asai, S. Iwamoto, Y. Sakaki, and D. Ueda, JHEP 09 (2021) 183, arXiv:2107.07487

● Dark photon



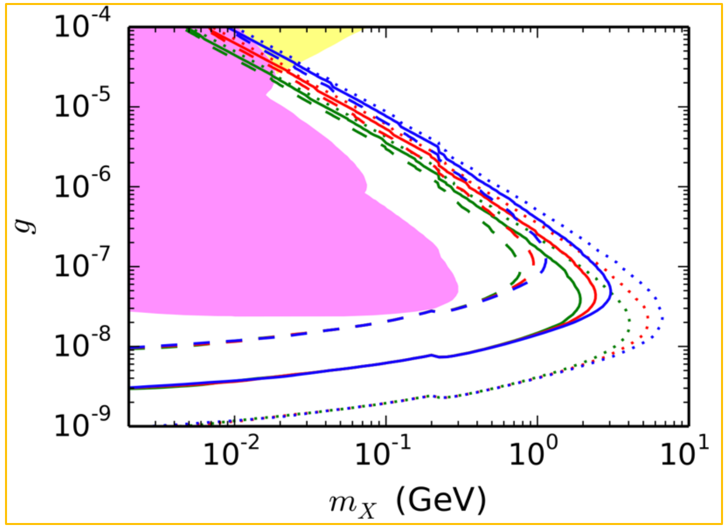
(a) electron beam dump (b) positron beam dump

- $U(1)_{L_i-L_j}$ gauge boson

K. Asai, T. Moroi, and A. Niki, PLB 818 (2021) 136374, arXiv:2104.00888

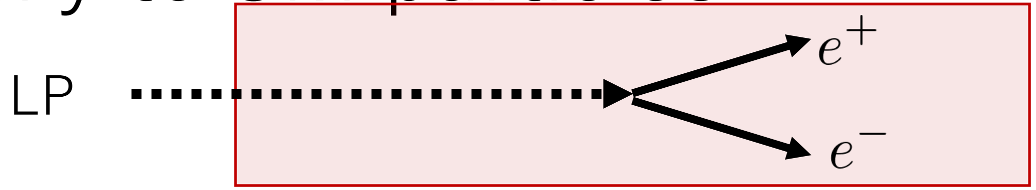
T. Moroi, and A. Niki, JHEP 05 (2023) 016, arXiv:2205.11766

● $U(1)_{e-\mu}$ gauge boson



Light Particle + Dark Matter

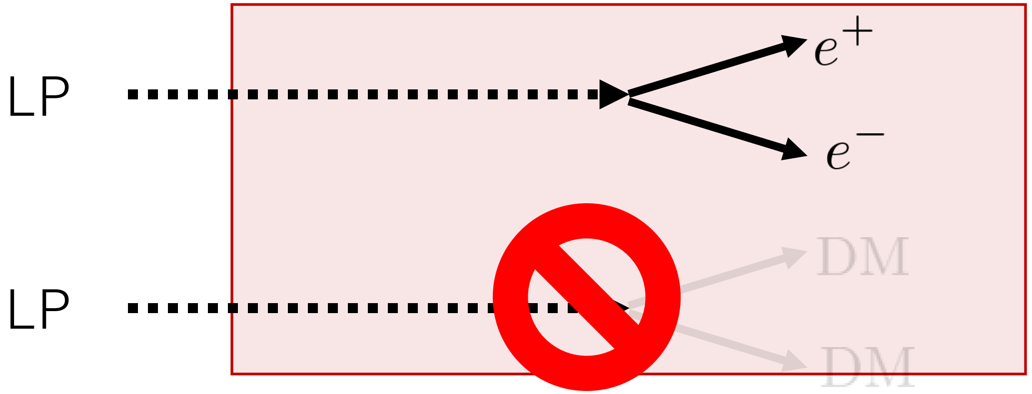
In light particle (LP) search at ILC bean dump, it is assumed that they couple only to SM particles



LP Detectable

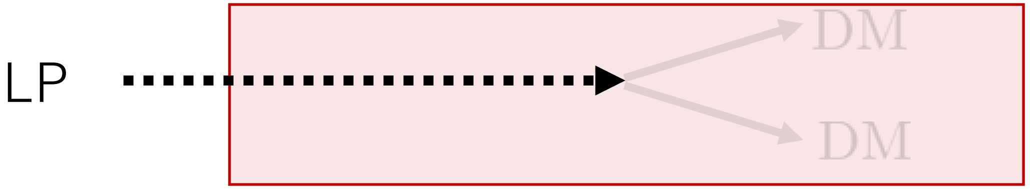
If light particles dominantly decay into DMs,

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



LP Detectable

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



No visible signal !

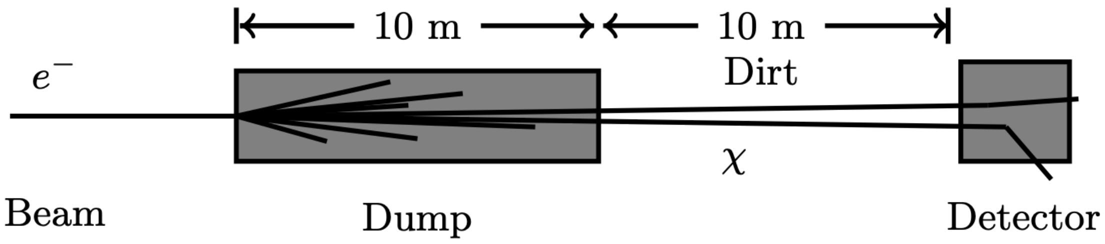
DM can be detected at ILC beam dump experiment ?

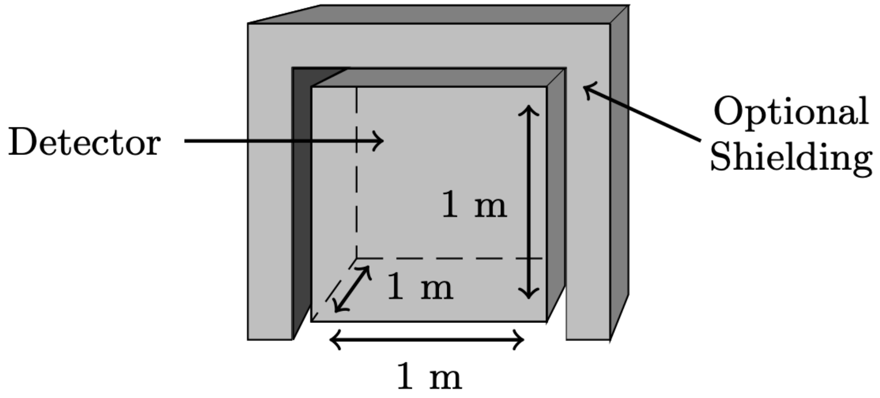
BDX (Beam Dump eXperiment)

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

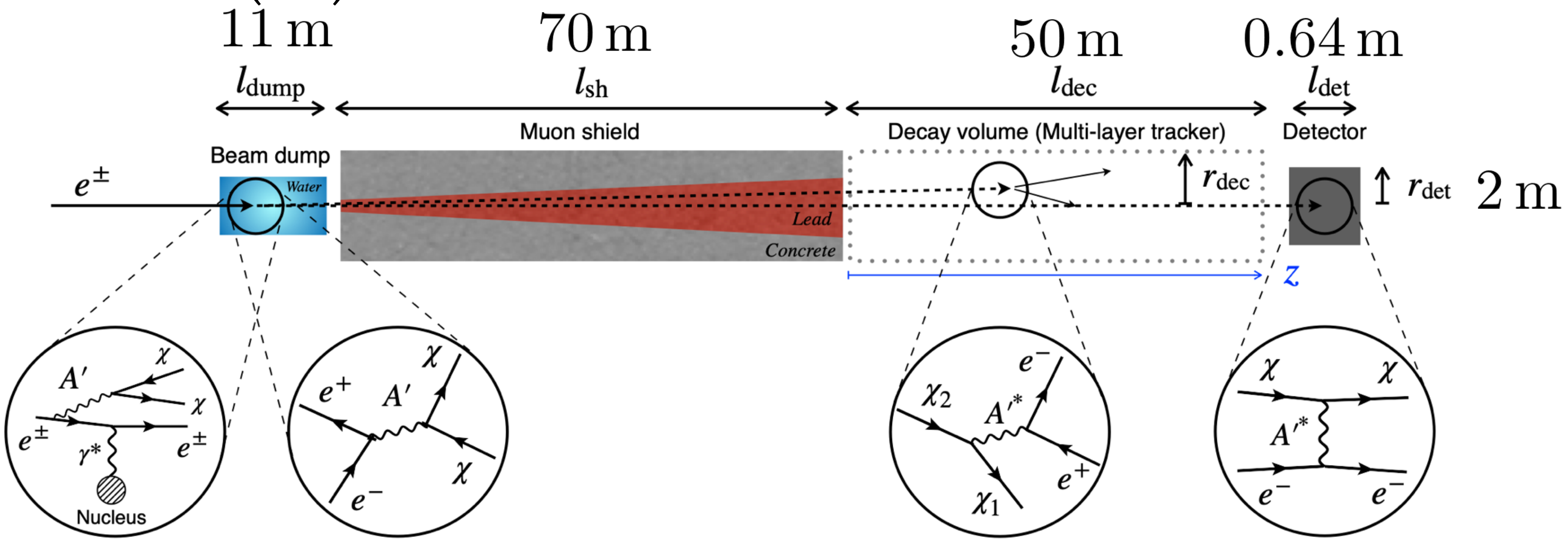
➡ Powerful DM search like BDX @ ILC beam dump !

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

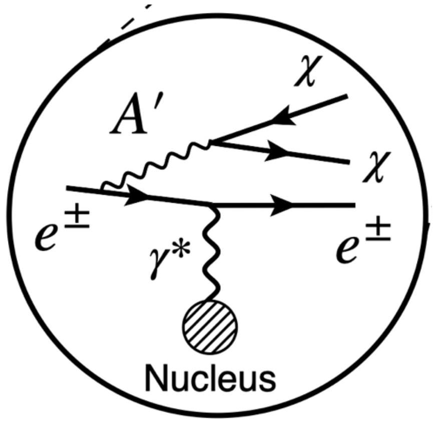


ILC-BDX

Two types of DM production

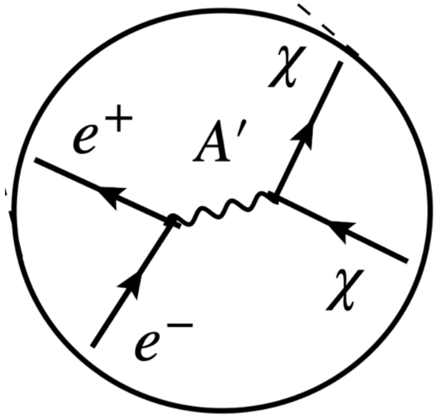
① $e^{\pm}$ bremsstrahlung

Beam and shower $e^{\pm}$ scatter with nucleus in $\mathrm{H_2O}$ molecules and produce dark matters through $e^{\pm}$ bremsstrahlung process



② Pair annihilation

Beam and shower e^{+} annihilate with e^{-} in $\mathrm{H_2O}$ molecules and produce dark matters through $e^{+}e^{-}$ pair annihilation process

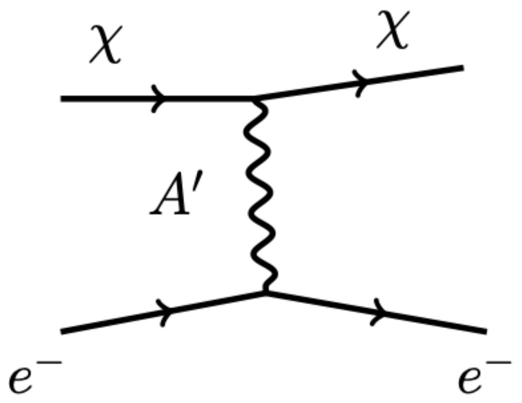


ILC-BDX

Two types of DM signals

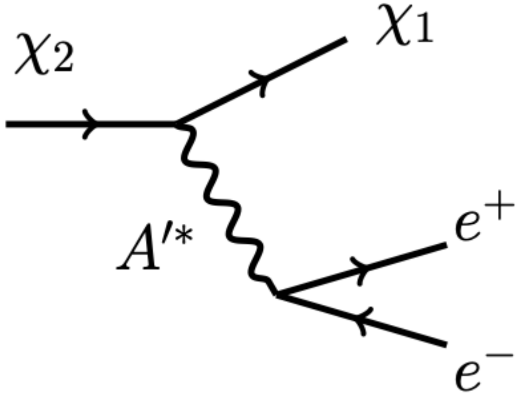
① Electron recoil

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



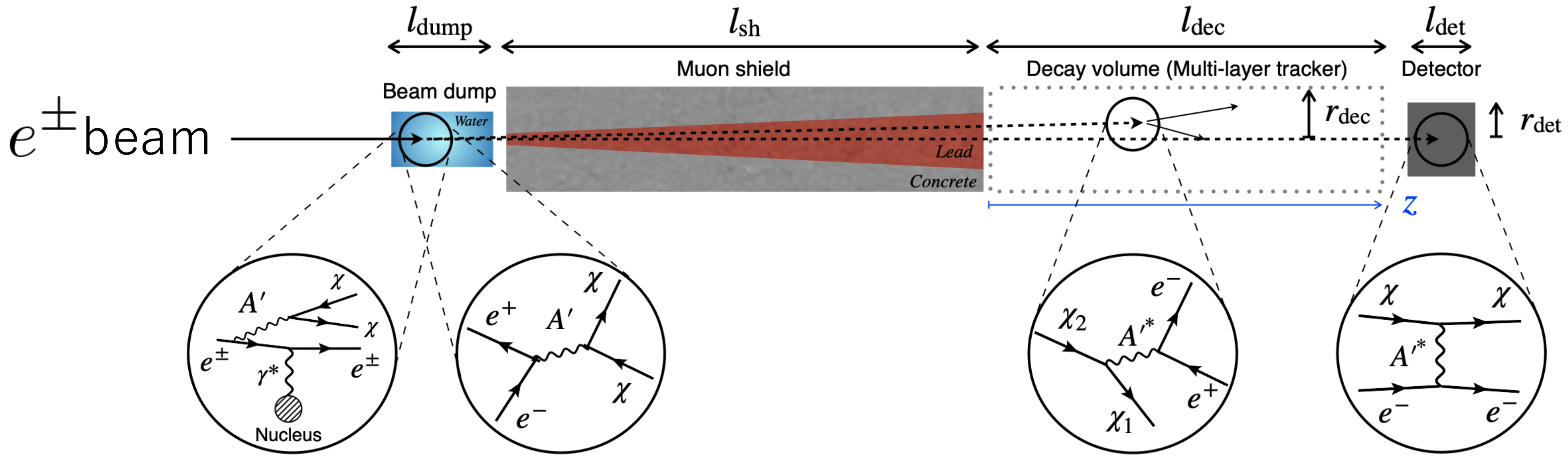
② Visible decay

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)

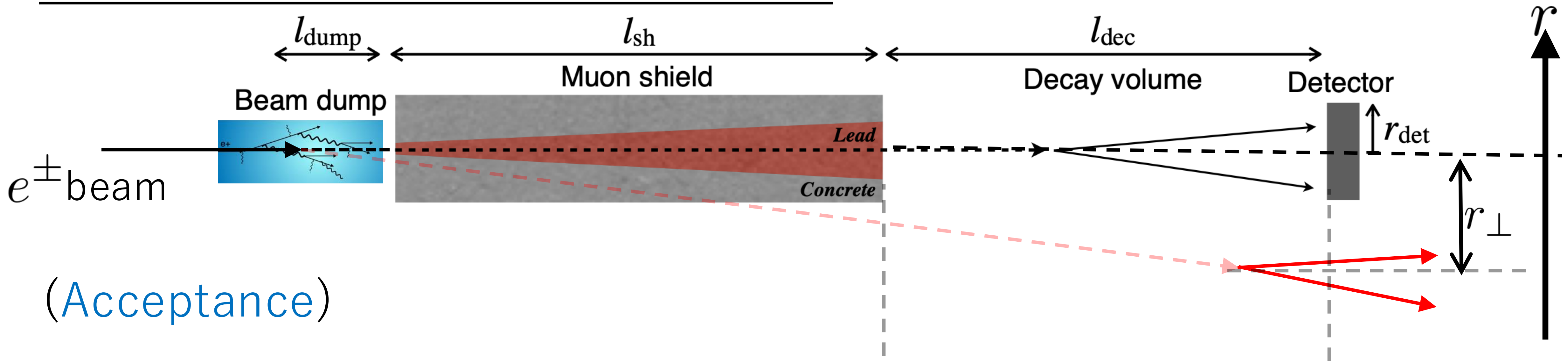
= (Probability of reaction with visible SM particles) × (Angular cut)

Visible decay ➡ probability of heavy dark state decay

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

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 : $\Theta(r_{\rm det} - r_{\perp})$

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

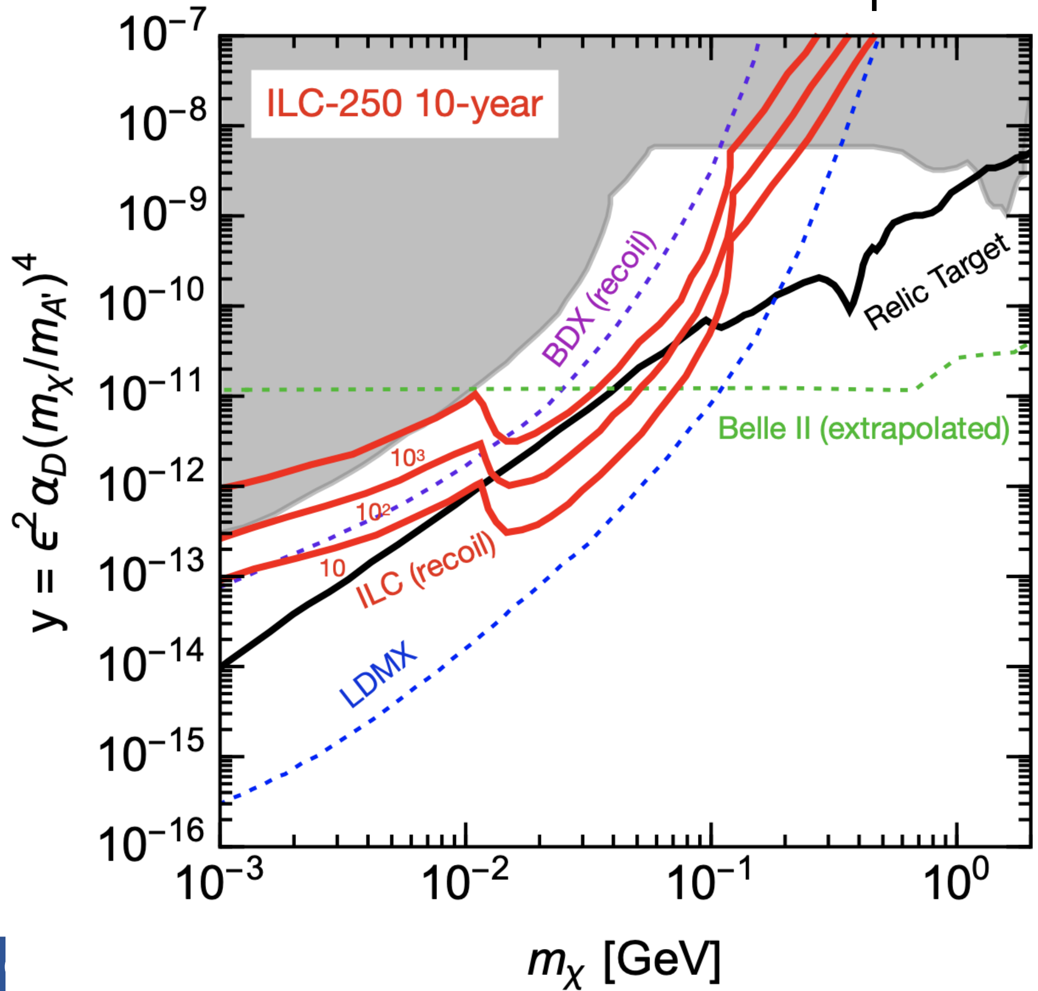
$$J^\mu_\chi = i\bar{\chi}_2 \gamma^\mu \chi_1 + \mathrm{H.c.}$$

➡ Inelastic DM

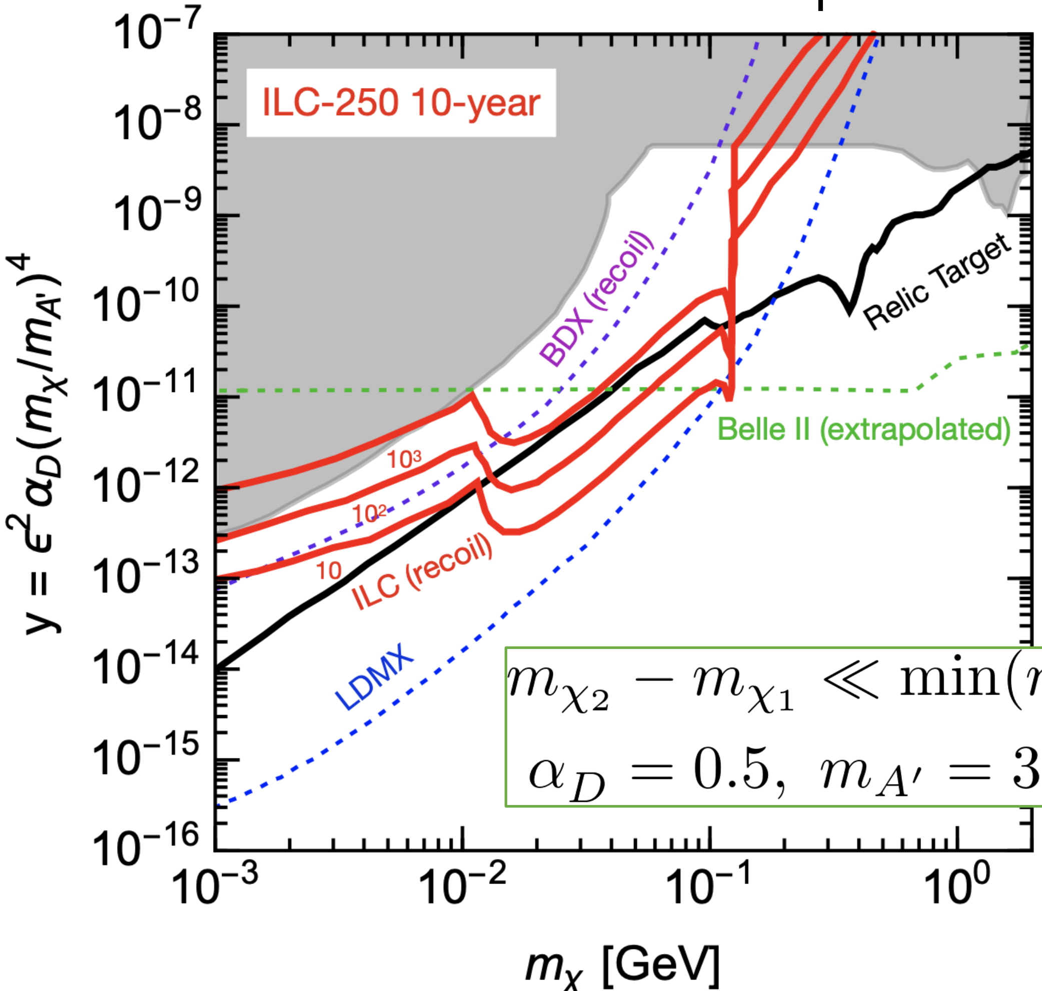
Projected sensitivity

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

e^- beam dump



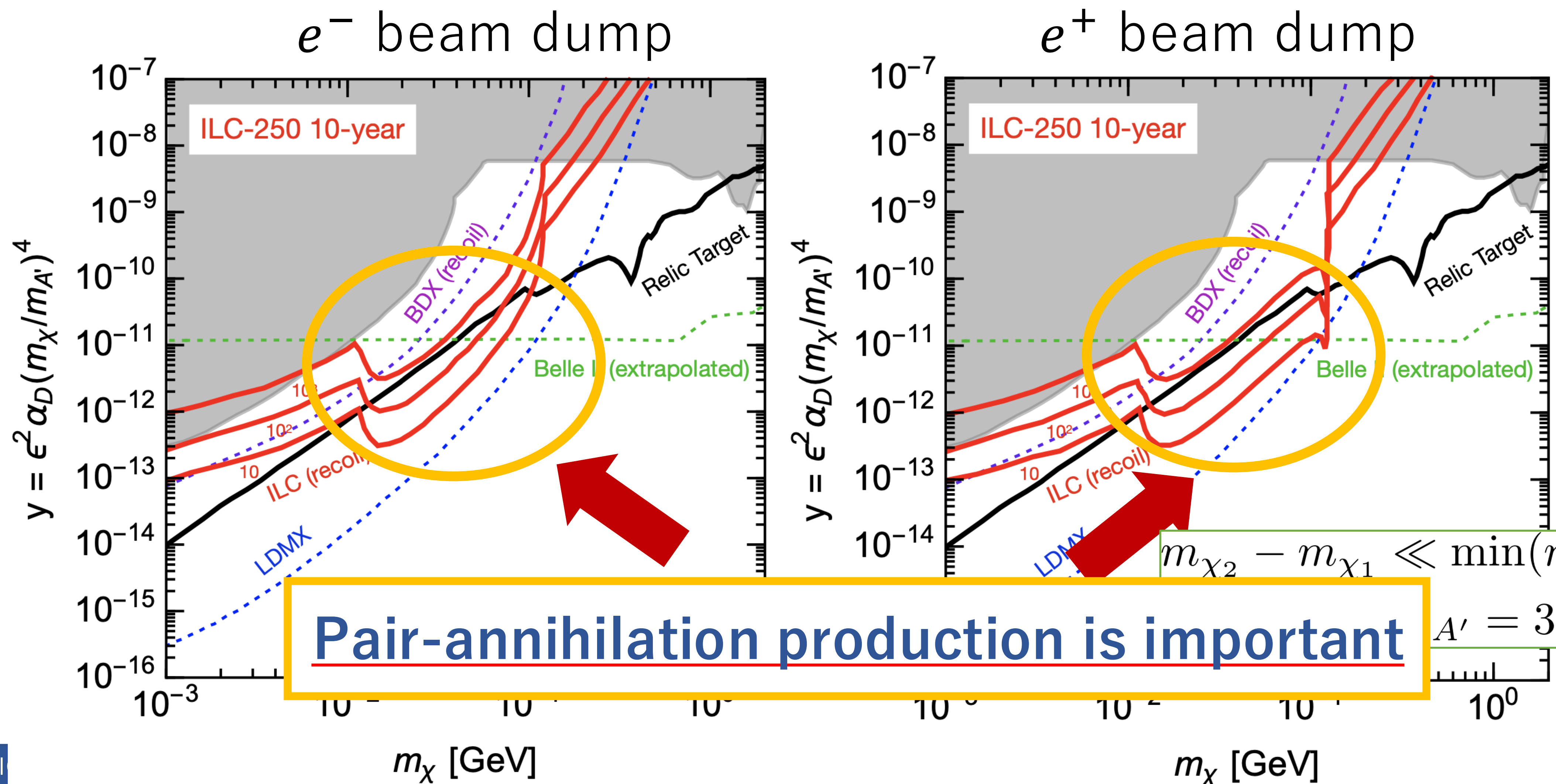
e^+ beam dump



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

Projected sensitivity

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



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

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

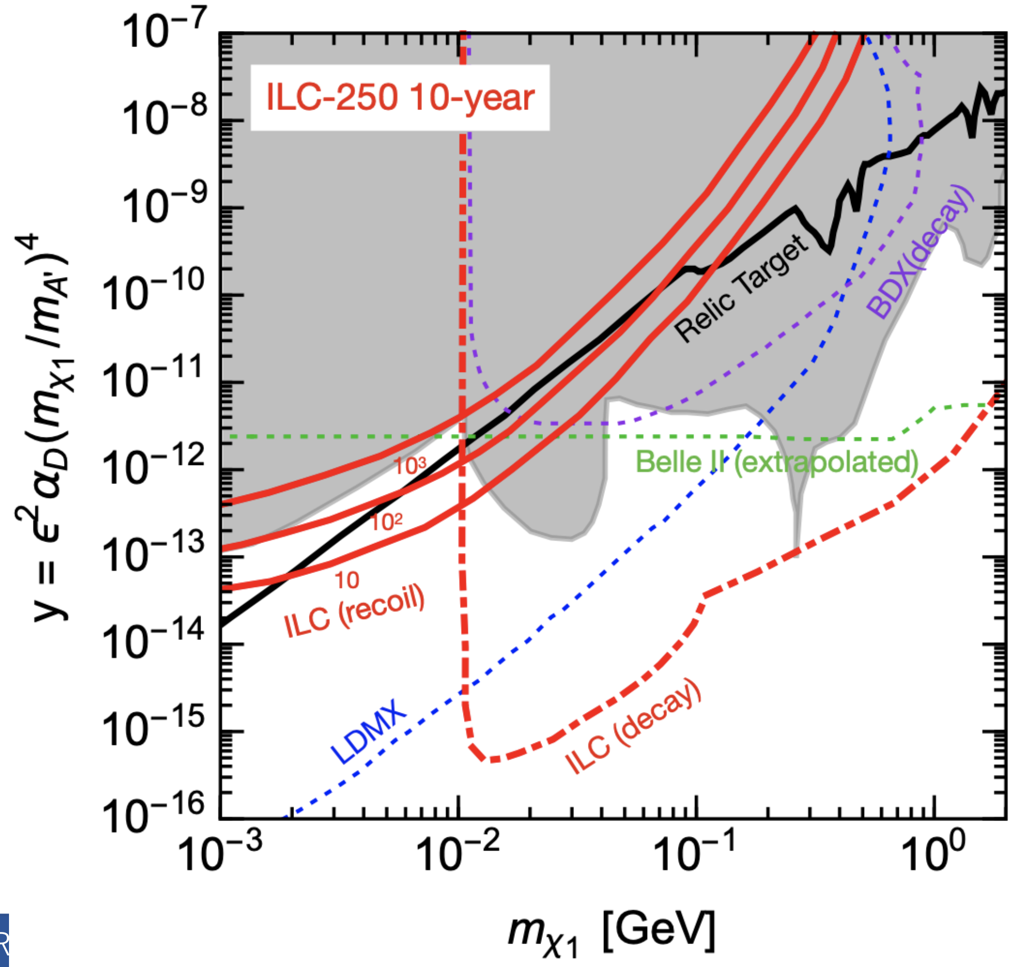
Pair-annihilation production is important

Projected sensitivity

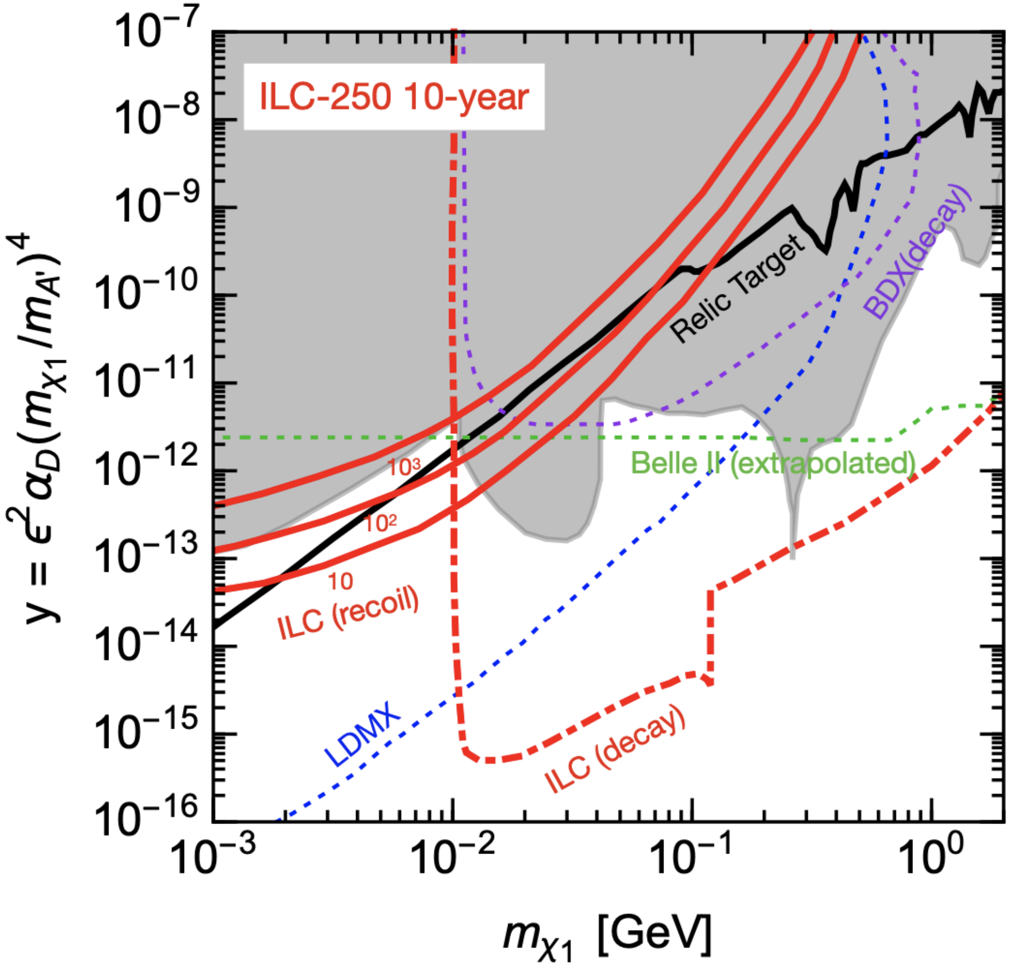
$m_{\chi_2} - m_{\chi_1} = 0.1 m_{\chi_1}$
$\alpha_D = 0.1, m_{A'} = 3 m_{\chi_1}$

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

e^- beam dump



e^+ beam dump

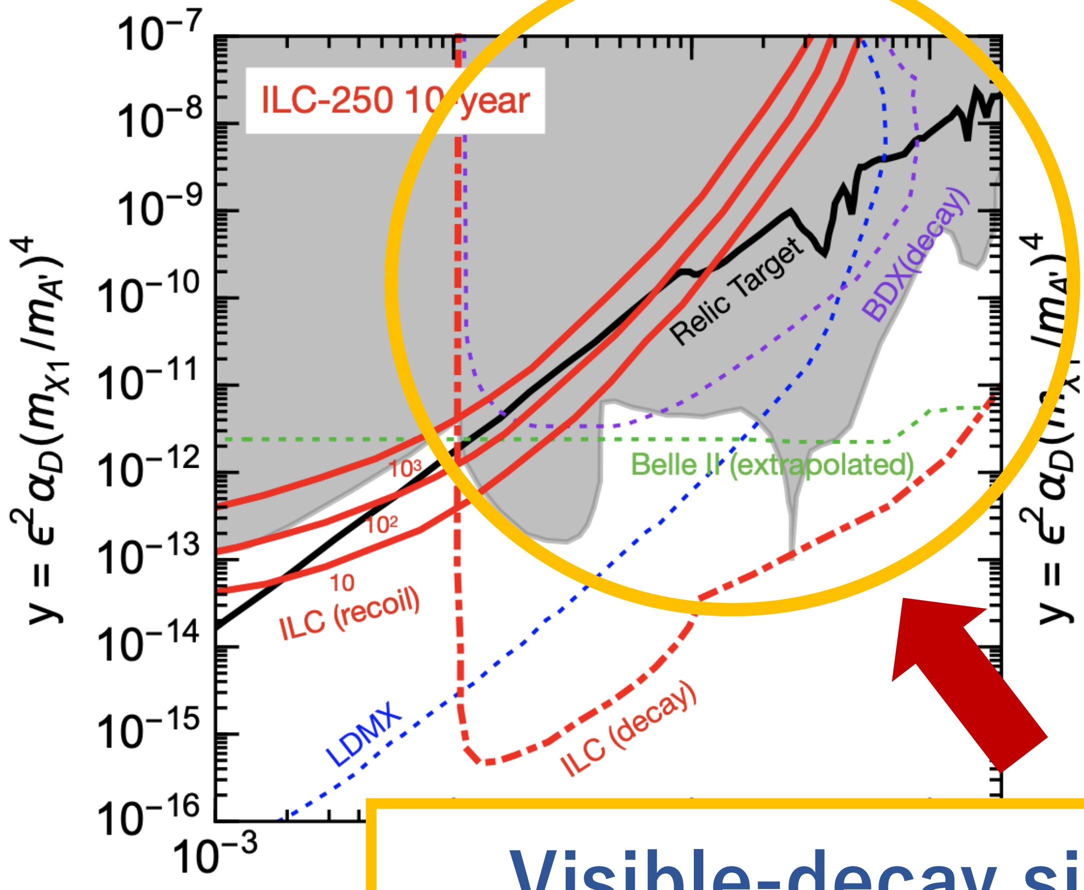


Projected sensitivity

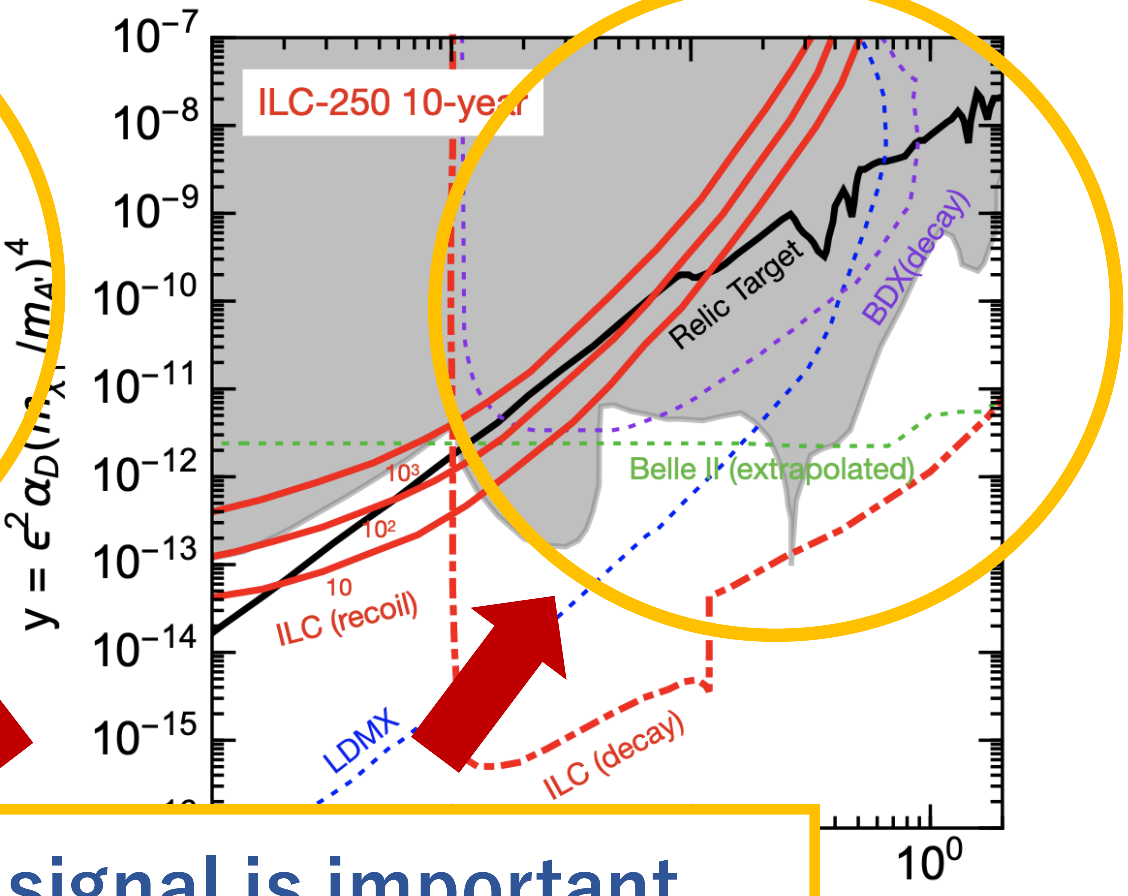
$$m_{\chi_2} - m_{\chi_1} = 0.1 m_{\chi_1}$$
$$\alpha_D = 0.1, m_{A'} = 3 m_{\chi_1}$$

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 !

Projected sensitivity

Ex.) Pseudo-Dirac DM @ e^+ beam dump