New physics search at ILC-BDX experiment

ECFA HF WG1: 1st Workshop of the WG1-SRCH group
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Based on on-going work
with Kento Asai, Sho Iwamoto, Maxim Perelstein, and Yasuhito Sakaki

Introduction

- Sub-GeV new particles with feeble coupling to the SM:

  ⇒ Axion-like particles (ALPs), light SM-singlet scalars from generalized Higgs sectors, etc

  ⇒ Dark matter

  - escape direct detection in nuclear recoil search

    ※ recoil energy is smaller than detection threshold

  - collider constraint is not severe because of feeble coupling

- We need high-intensity boosted new particle beams to detect such particles

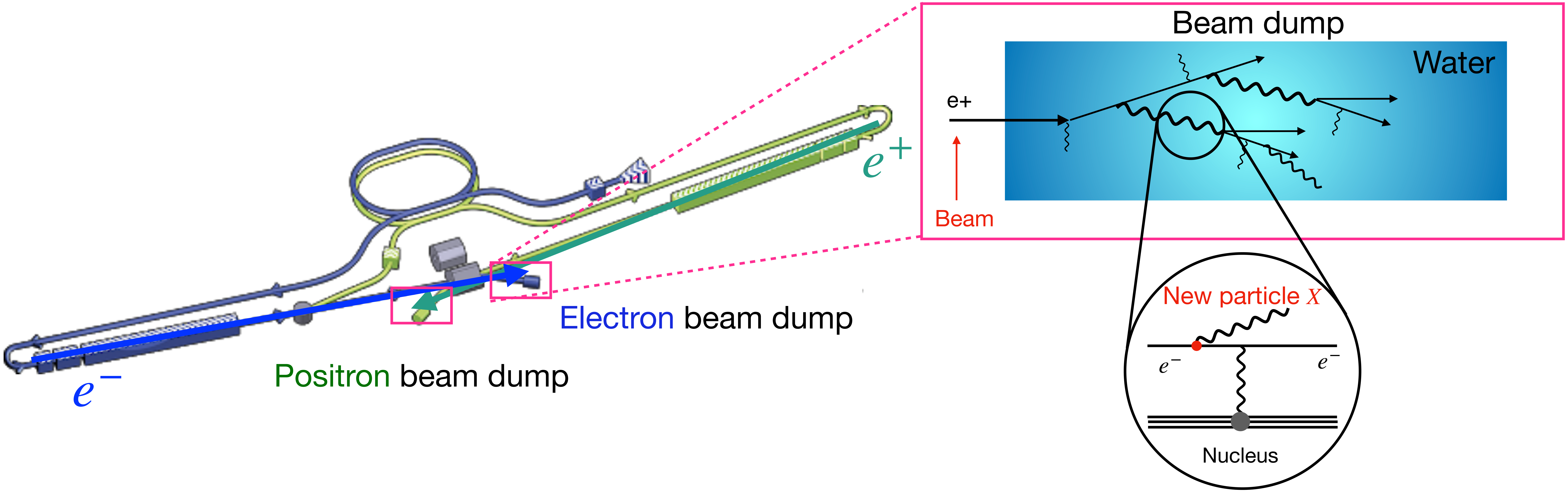
  - High energy sub-GeV particles can deposit enough energy in detector

  - High-intensity beam can produce many new particles with feeble coupling

ILC beam dump experiment can produce high-intensity boosted new particle beams

Introduction

- ILC is linear collider experiment using high energy electron and positron beams



- Linear Collider Experiment ⇒ After beam collisions almost all beams are discarded in main beam dump ※ To avoid radiation contamination

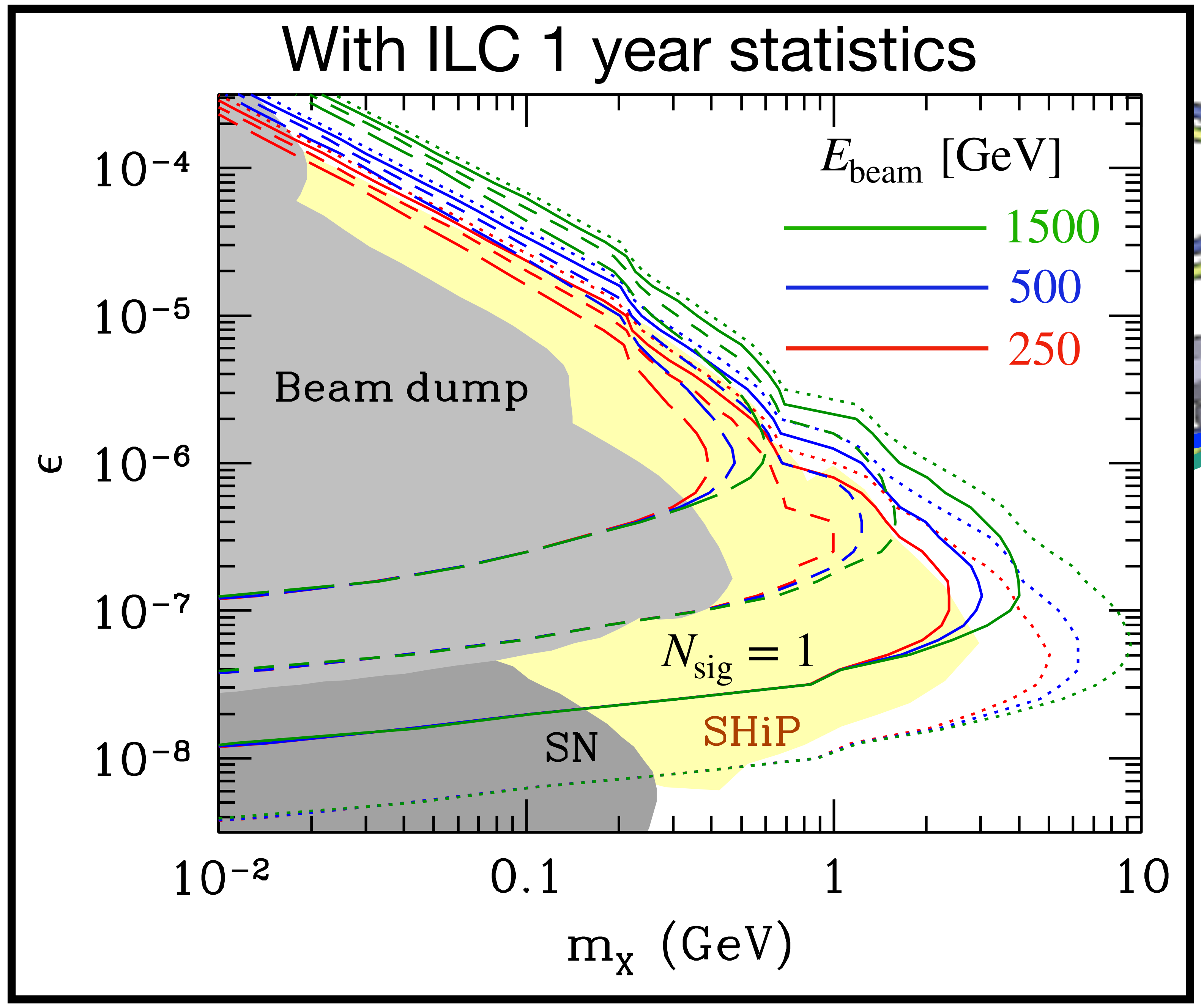
ILC-250 ⇒ Energy in Lab frame: $125\ \mathrm{GeV}$, Flux: $4 \times 10^{21}/\mathrm{year}$

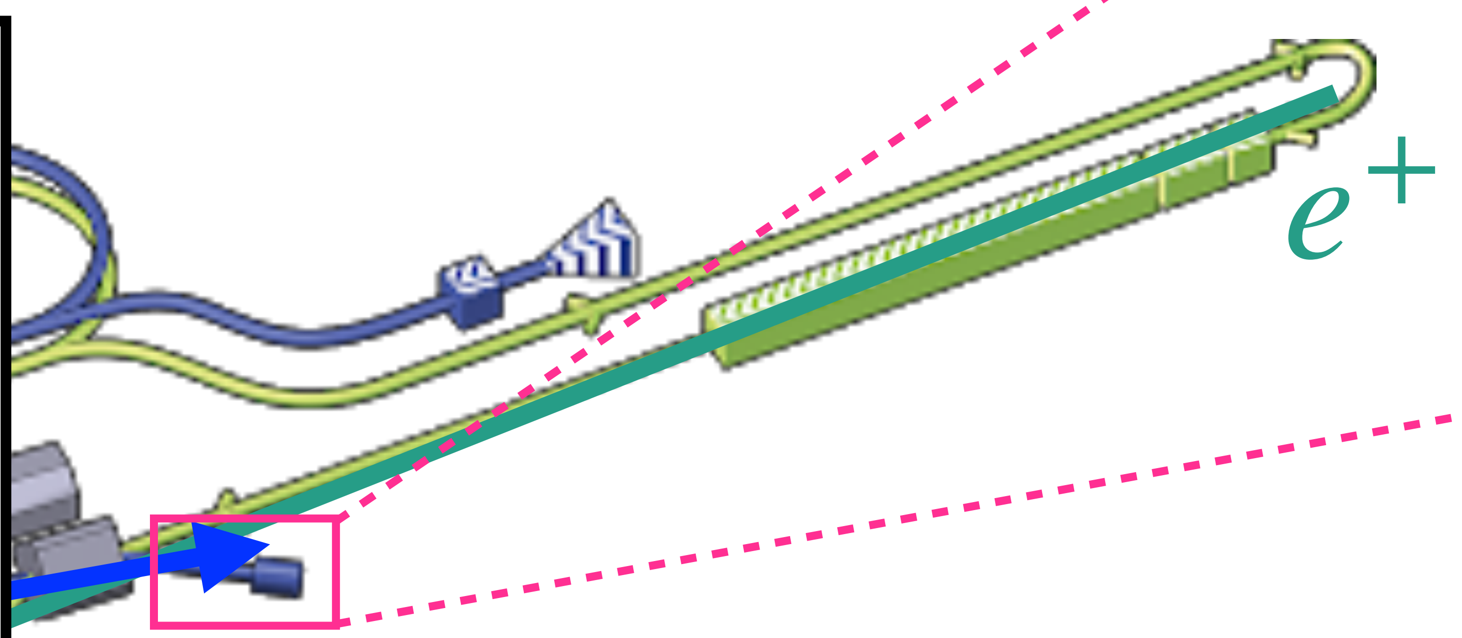
The discarded beams can be converted into new particle beams

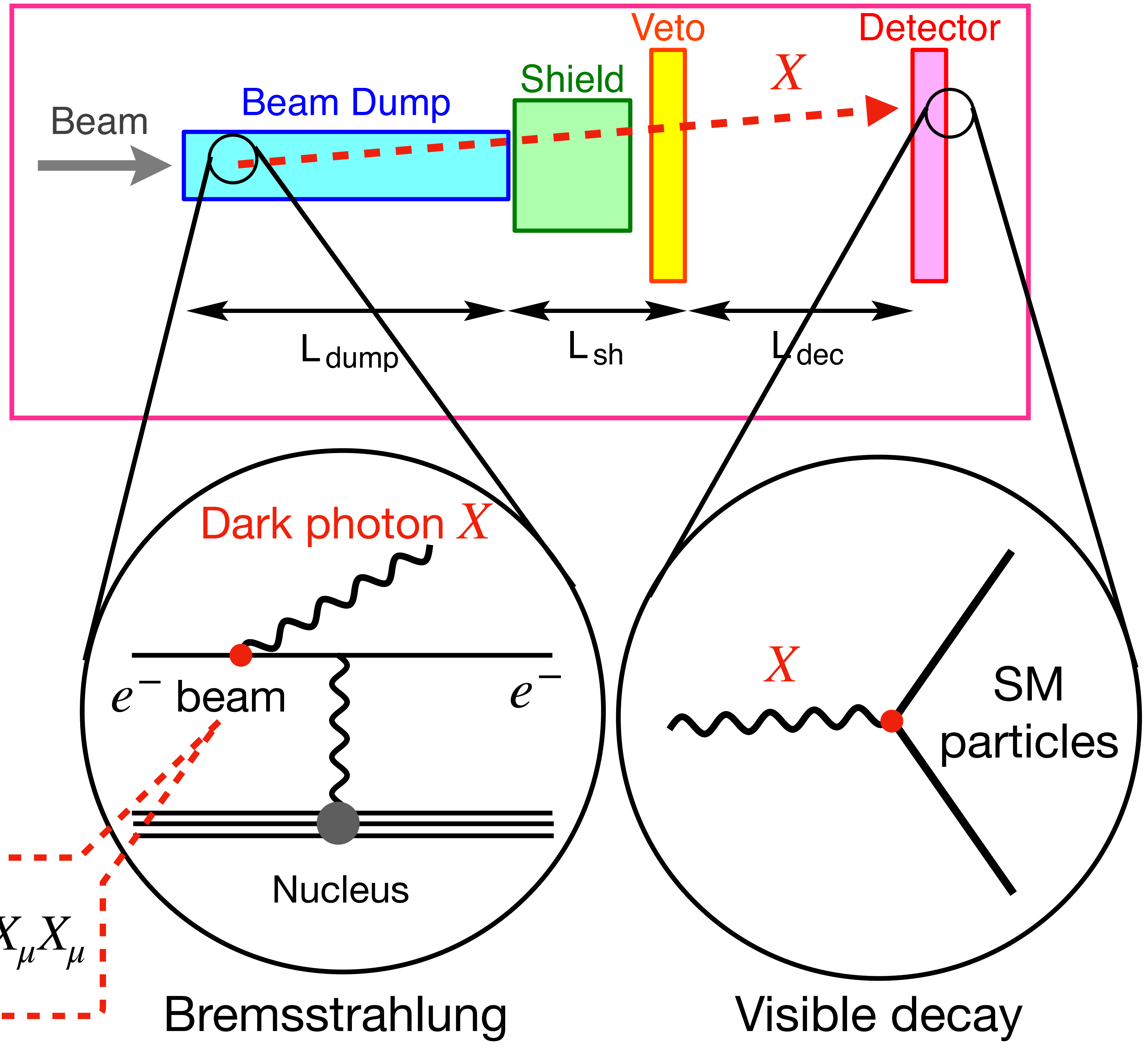
Introduction

- Using the main beam dump, fixed-target experiments were proposed

[S. Kanemura, T. Moroi, T. Tanabe. arXiv:1507.02809]







$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}F^X_{\mu\nu}F^X_{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F^X_{\mu\nu} + \frac{m_X^2}{2}X_\mu X_\mu$$

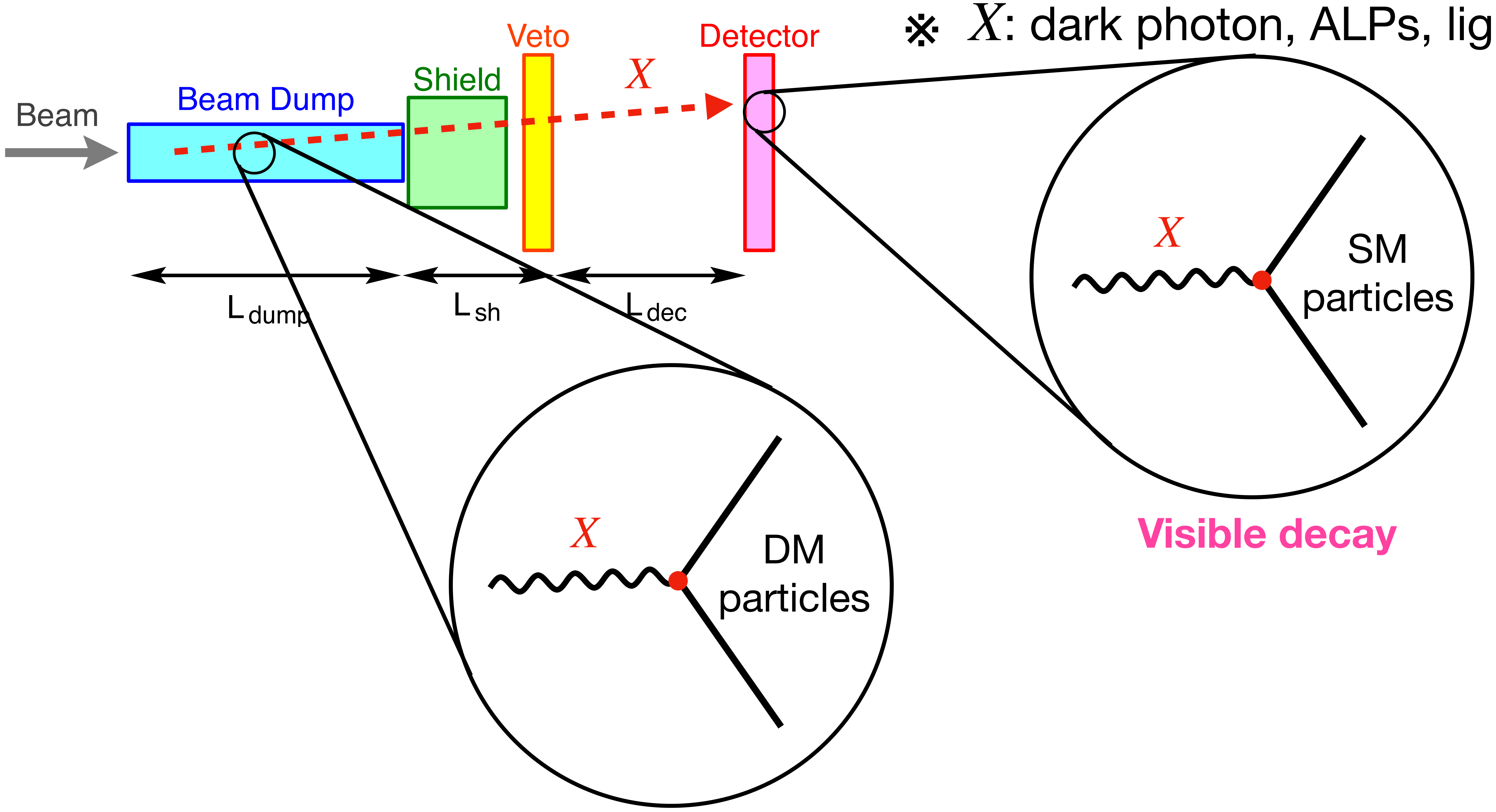
ILC beam dump experiment has higher sensitivity than past beam dump experiments

Introduction

- Visibly-decaying particle search using ILC main beam dump have been studied

[S. Kanemura, T. Moroi, T. Tanabe. arXiv:1507.02809, Y. Sakaki, DU. arXiv:2009.13790,…]

※ X: dark photon, ALPs, light scalar,…



Visible decay

Invisible decay

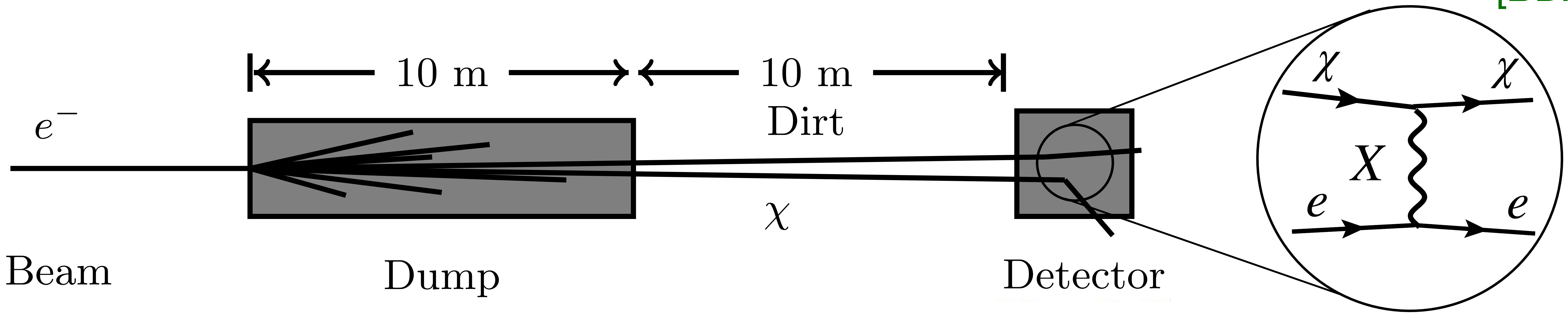
- When X has a coupling with DMs, Invisibly-decay can takes place

How about sensitivity of ILC beam dump experiment to DM particles?

Introduction

- BDX experiment planned at JLAB is similar to ILC beam dump setup

[BDX, arXiv:1607.01390]



- Electron recoil events are detectable in EM calorimeter

- ILC beam dump experiment have similar statics and higher beam energy

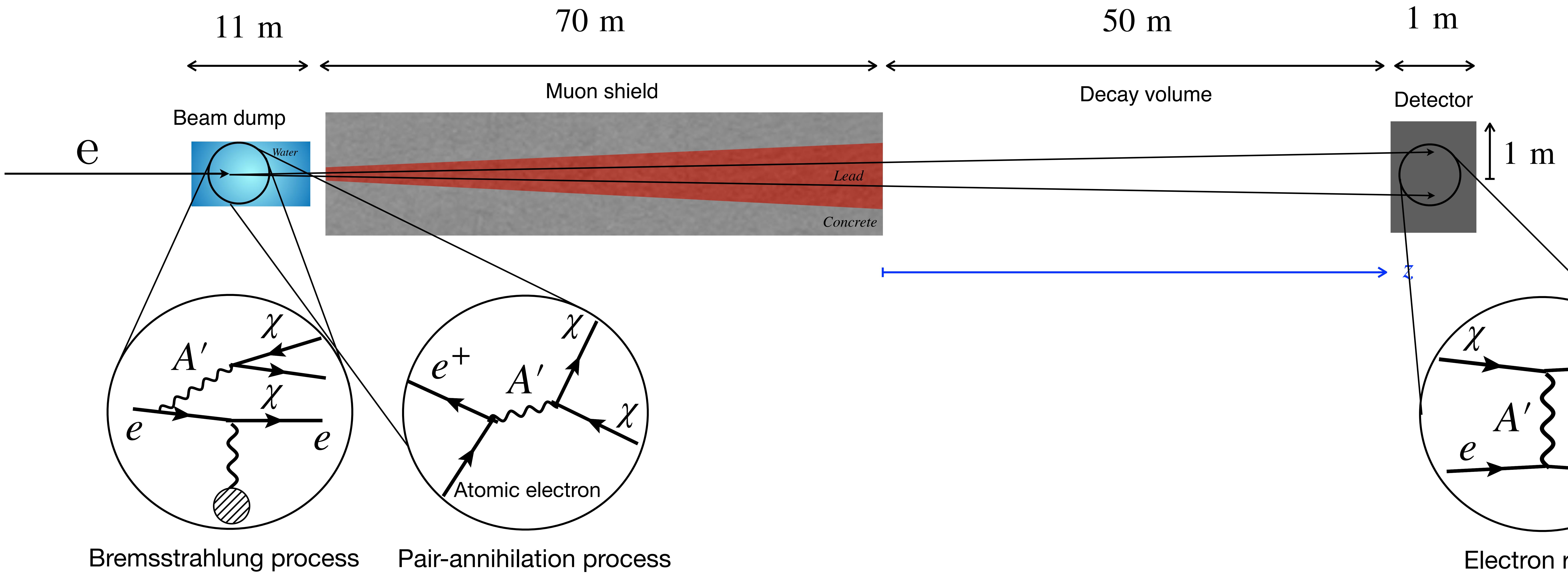
※ BDX: EOT $= 10^{22}$/year, $E_{\rm beam} = 11$ GeV, ILC: EOT $= 4 \times 10^{21}$/year, $E_{\rm beam} = 125$ GeV

⇒ More DMs are produced because of larger amount of electromagnetic showers

How about sensitivity of ILC-BDX experiment to DM particles?

ILC-BDX setup

- We adopted the same setup as [Y. Sakaki, DU. arXiv:2009.13790, K. Asai, S. Iwamoto, Y. Sakaki, DU. arXiv:2105.13768]
  - Installing cheap muon lead shield was proposed ⇒ reduce background



signal events in EM calorimeter

A benchmark Model (2): $\mathscr{L} \supset -\frac{1}{4}F^{A'}_{\mu\nu}F^{A'}_{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F^{A'}_{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'_\mu + (g_D A'_\mu \bar{\chi}_2 \gamma^\mu \chi_1 + \mathrm{h.c.}) + m_1\bar{\chi}_1\chi_1 + m_2\bar{\chi}_2\chi_2$

Dark photon

Two fermion DM with mass m_1 and m_2

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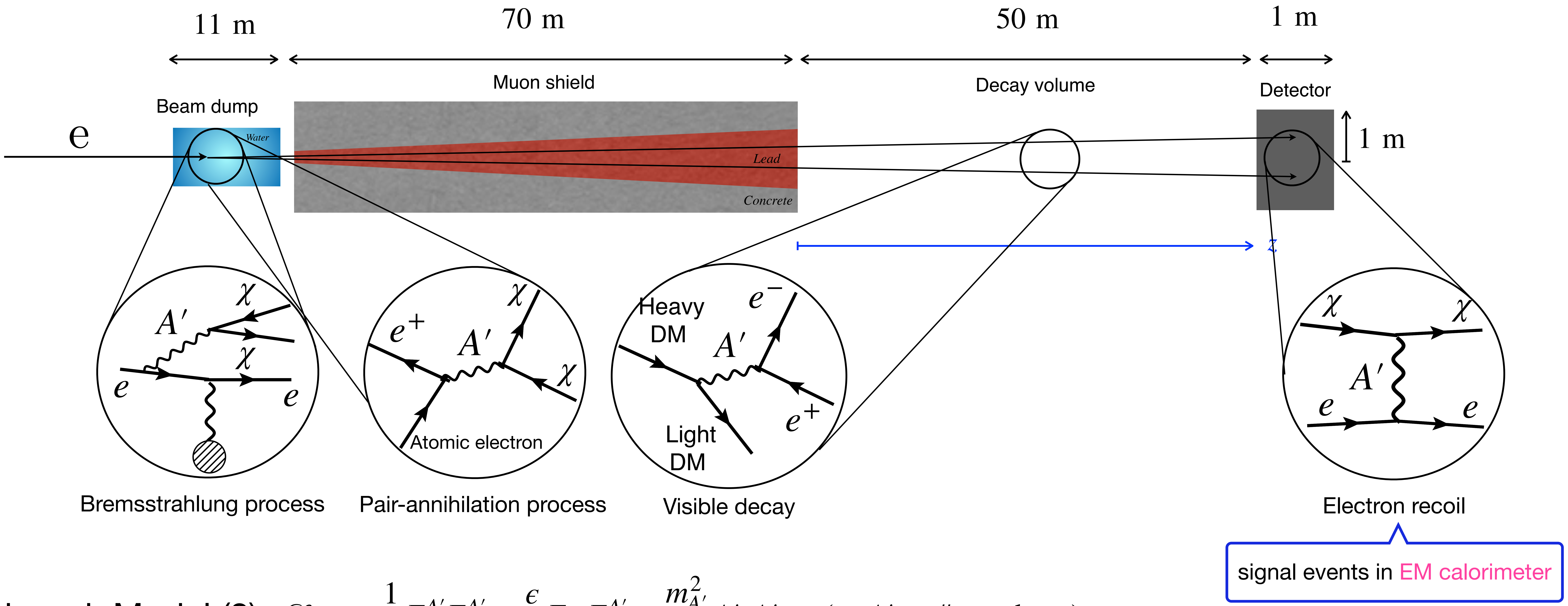

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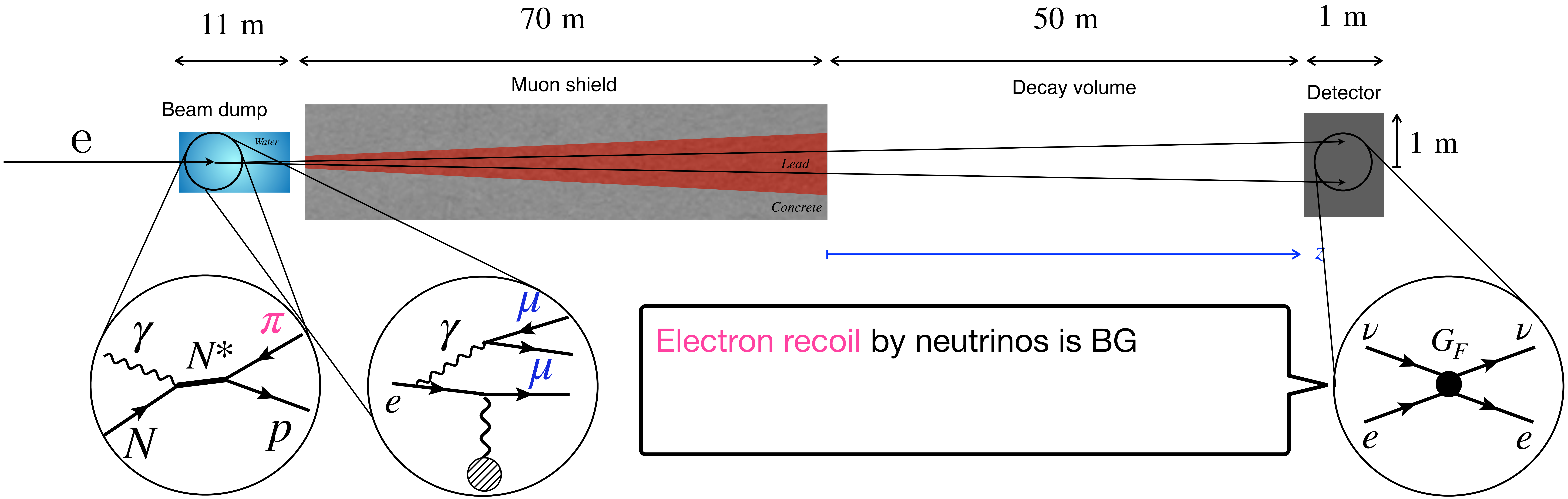
Background

- Beam related background:
  - neutrinos are produced by decay of pion, muon,… in beam dump

Ex. $\pi^+ \to \mu^+ + \nu_\mu, \;\; \mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e, \ldots$ ※ neutron, muon,.. are removed by muon lead shield



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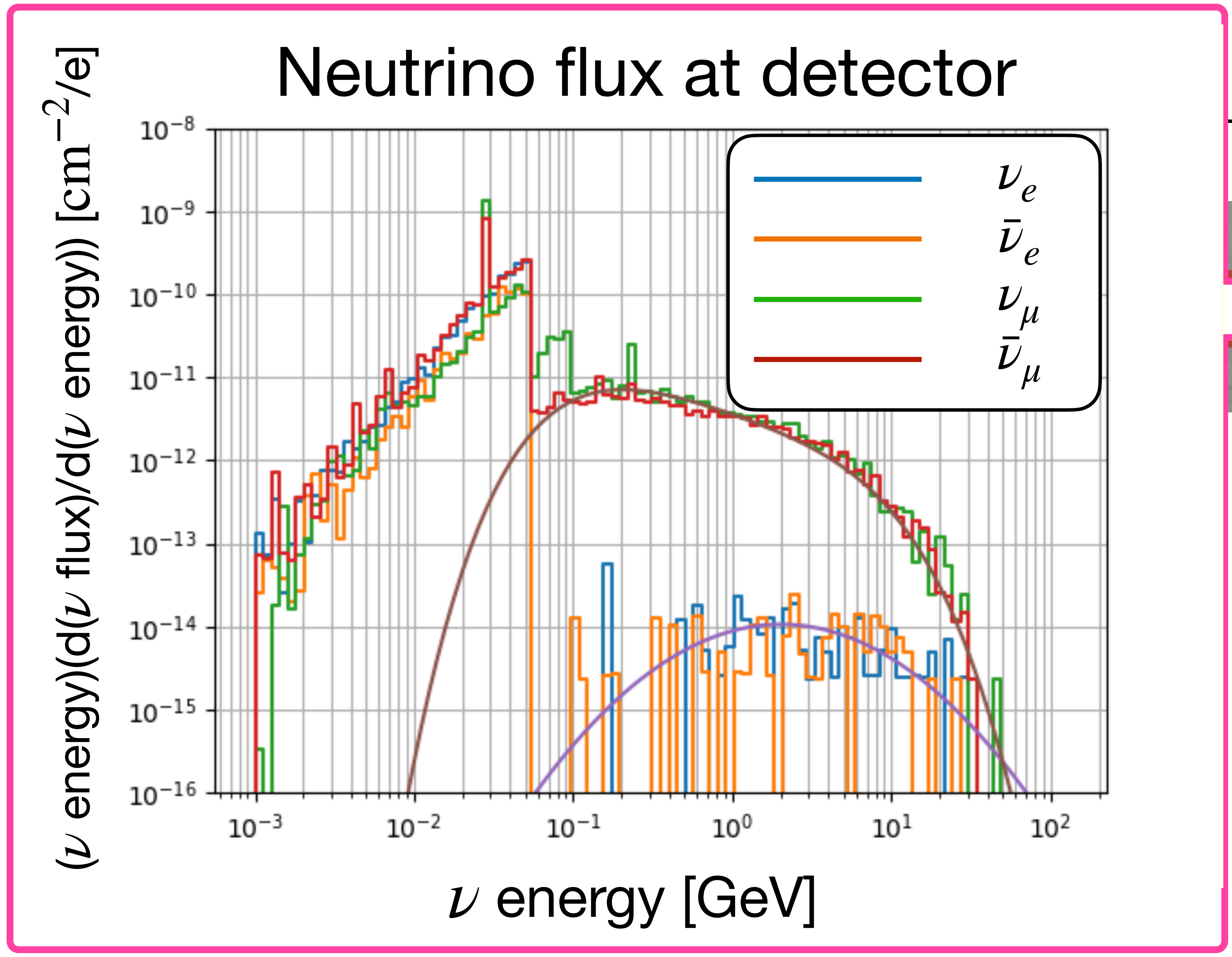
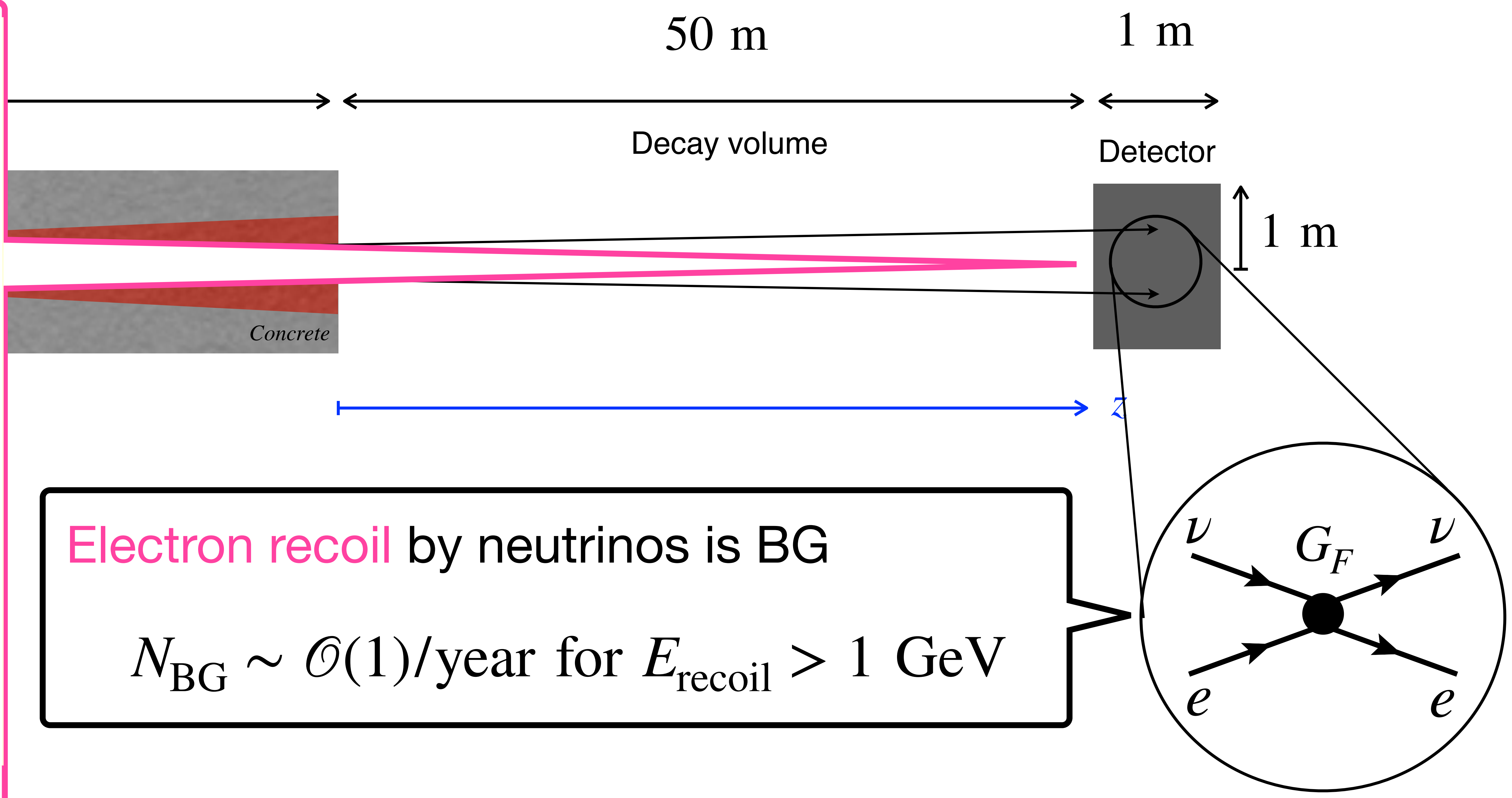




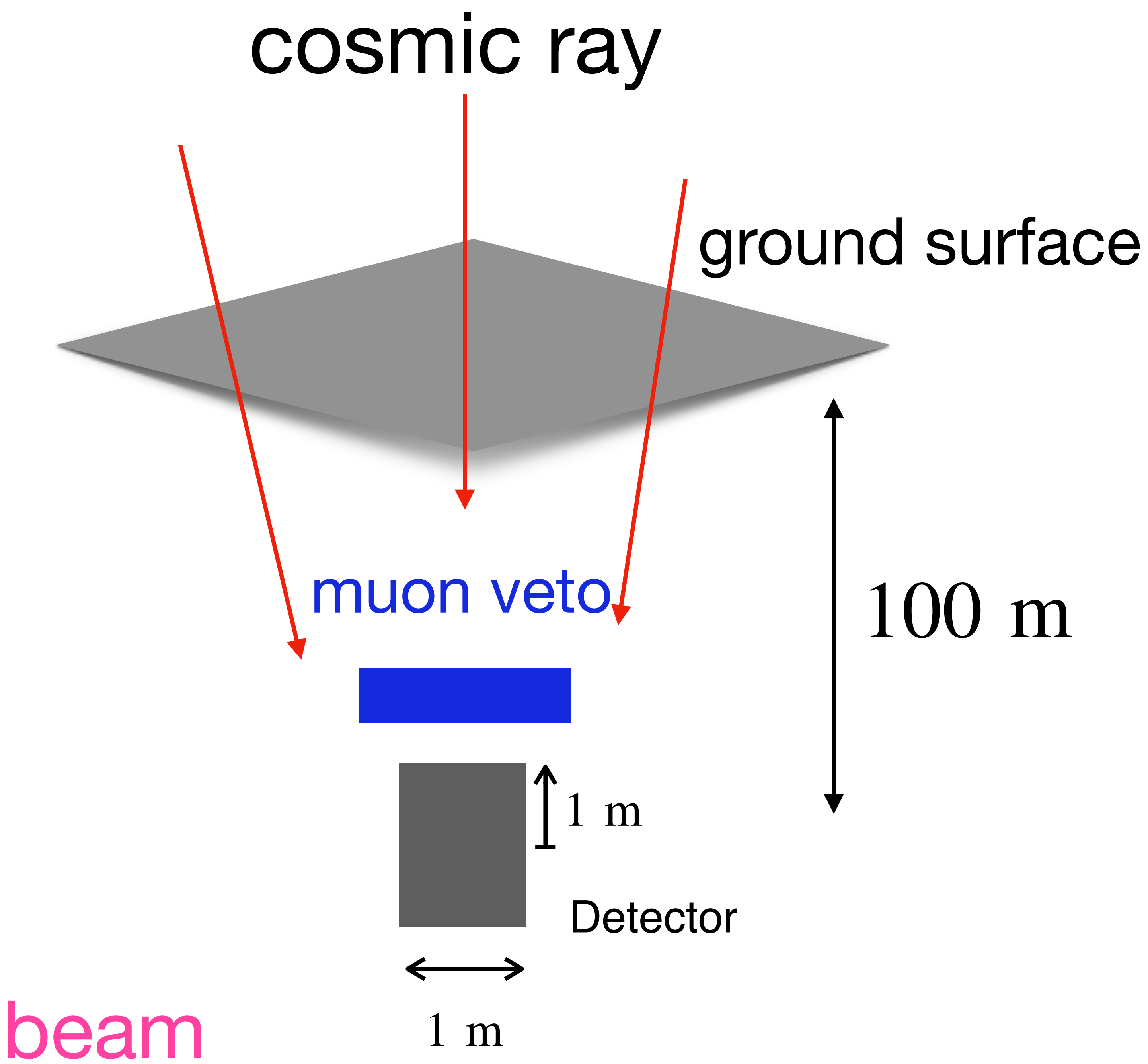
Electron recoil by neutrinos is BG

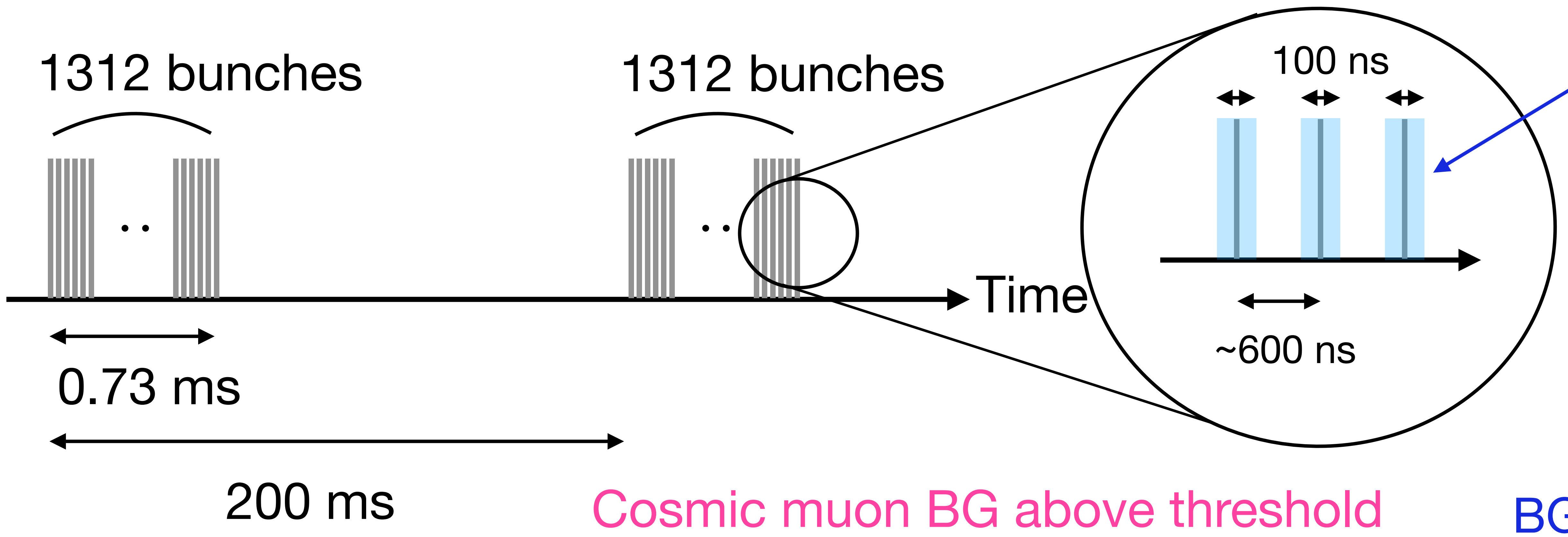
$N_{\rm BG} \sim \mathcal{O}(1)$/year for $E_{\rm recoil} > 1$ GeV

※ Calculated by Monte Carlo simulation

Background

- Beam unrelated background:
  - cosmic ray(muon, neutron,…) can be background events
    - Cosmic muon: strong penetration power ⇒ reach detector
      - reduction of cosmic muon by veto
      - cosmic muon BG is reduced by time window because of ILC pulsed beam





Signal event arises from this **time window**

We impose **time window = 100 ns**

Cosmic muon BG above threshold

BG reduction by time window ~ 10^{-3}

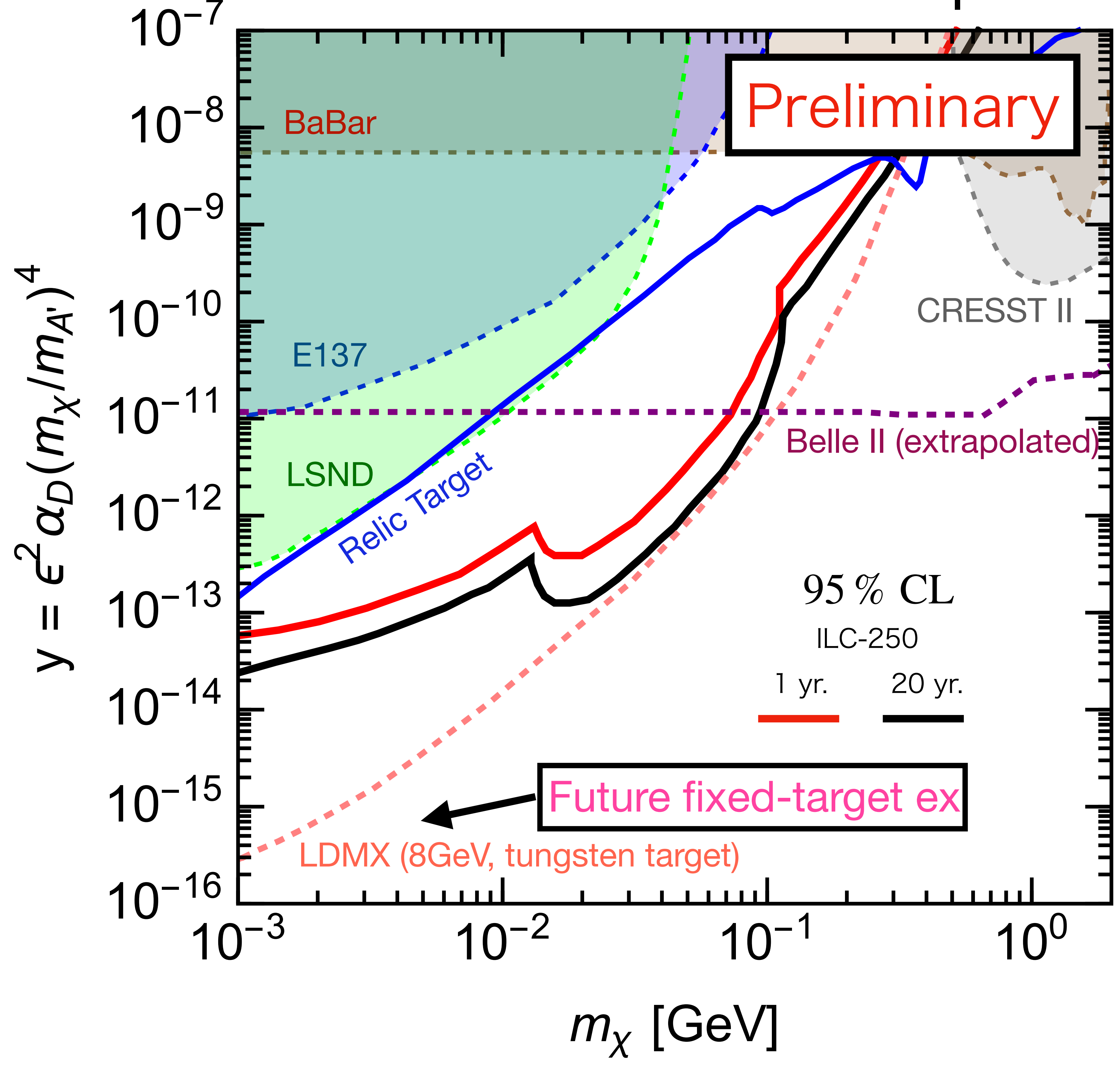
$$N^{BG}_{cos} \sim \left(\frac{\text{muon flux}}{10^{-3}\ \text{cm}^{-2}\cdot \text{s}^{-1}}\right)\left(\frac{\text{area}}{100^2\ \text{cm}^2}\right)\left(\frac{\text{runing time}}{1\ \text{year}}\right)\left(\frac{\text{BG per muon for } E_{th}>1\ \text{GeV}}{10^{-5}}\right)\left(\frac{\text{bunch}}{1312}\right)\left(\frac{200\ \text{ms}}{\text{Period of bunch}}\right)\left(\frac{\text{time window}}{100\ \text{ns}}\right)\times \epsilon_{veto} < \mathcal{O}(1)$$

Beam unrelated BG can be reduced by time window and veto

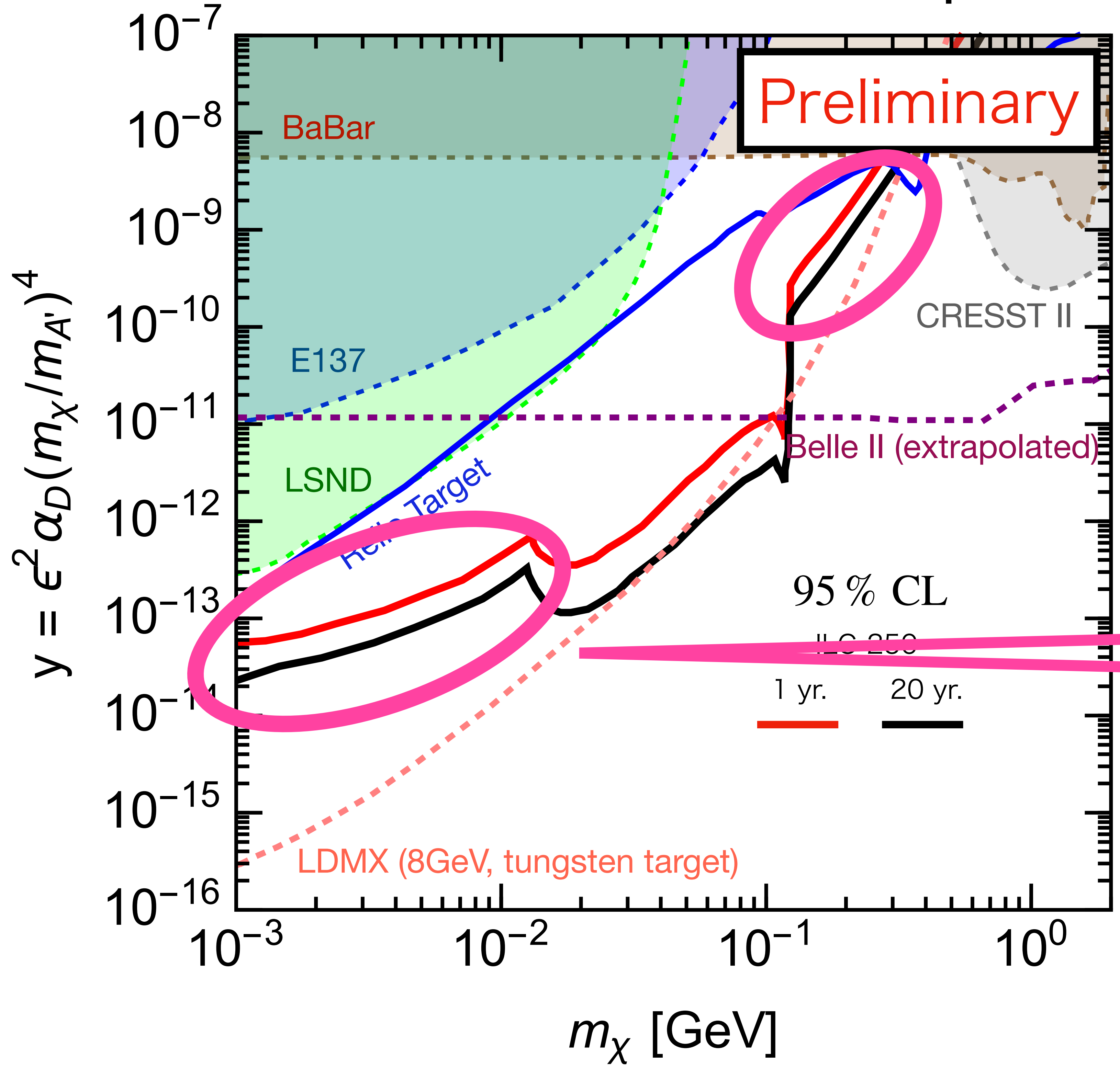
Results

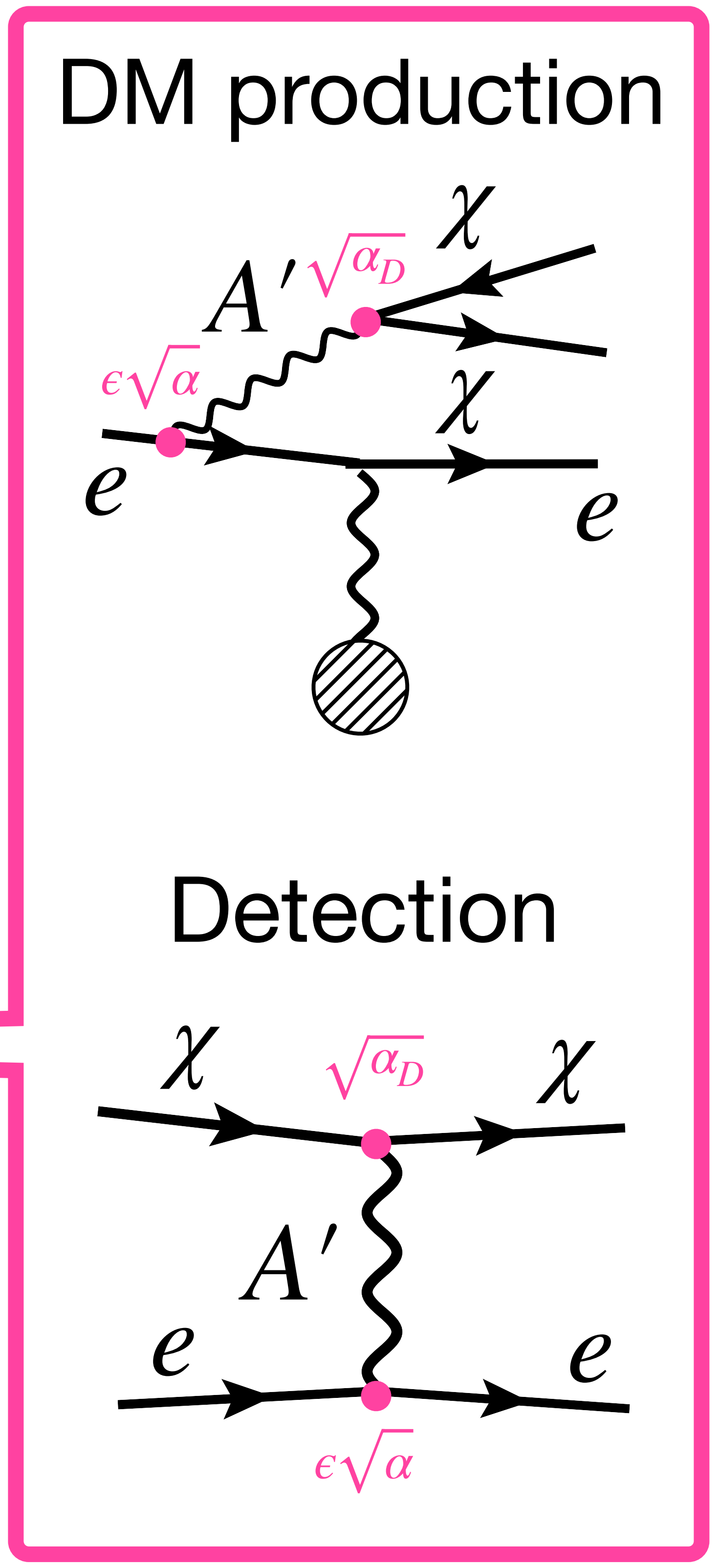
- Sensitivity comparison of positron and electron beam dump experiment
  - BG events are taken into account by Poisson statistics [K. Asai, S. Iwamoto, M. Perelstein, Y. Sakaki, DU.]

Electron beam dump



Positron beam dump





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Dark photon — Complex scalar DM

$\alpha_D \equiv g_D^2/4\pi = 0.5, \quad m_{A'} = 3m_\chi$

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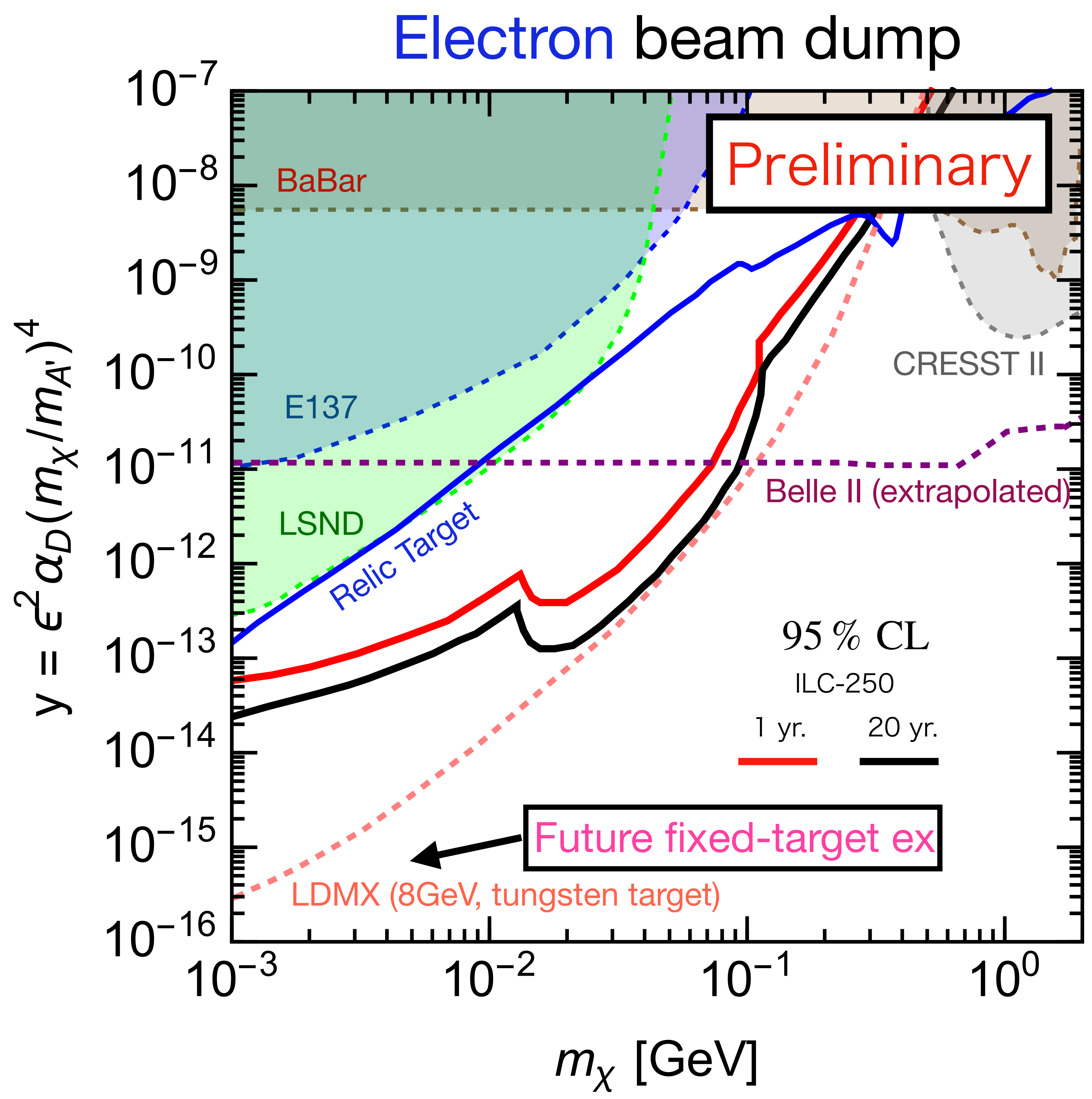

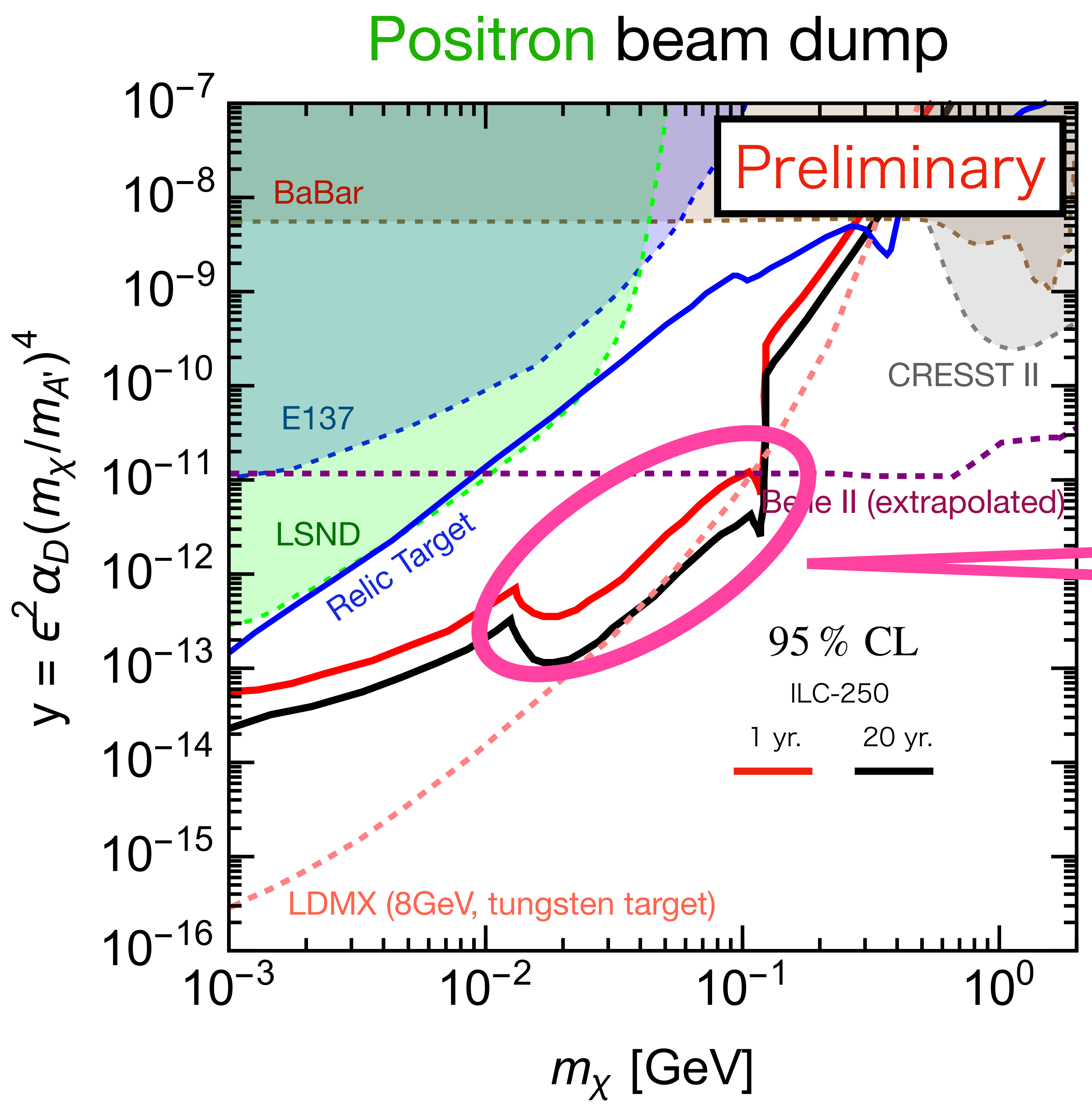

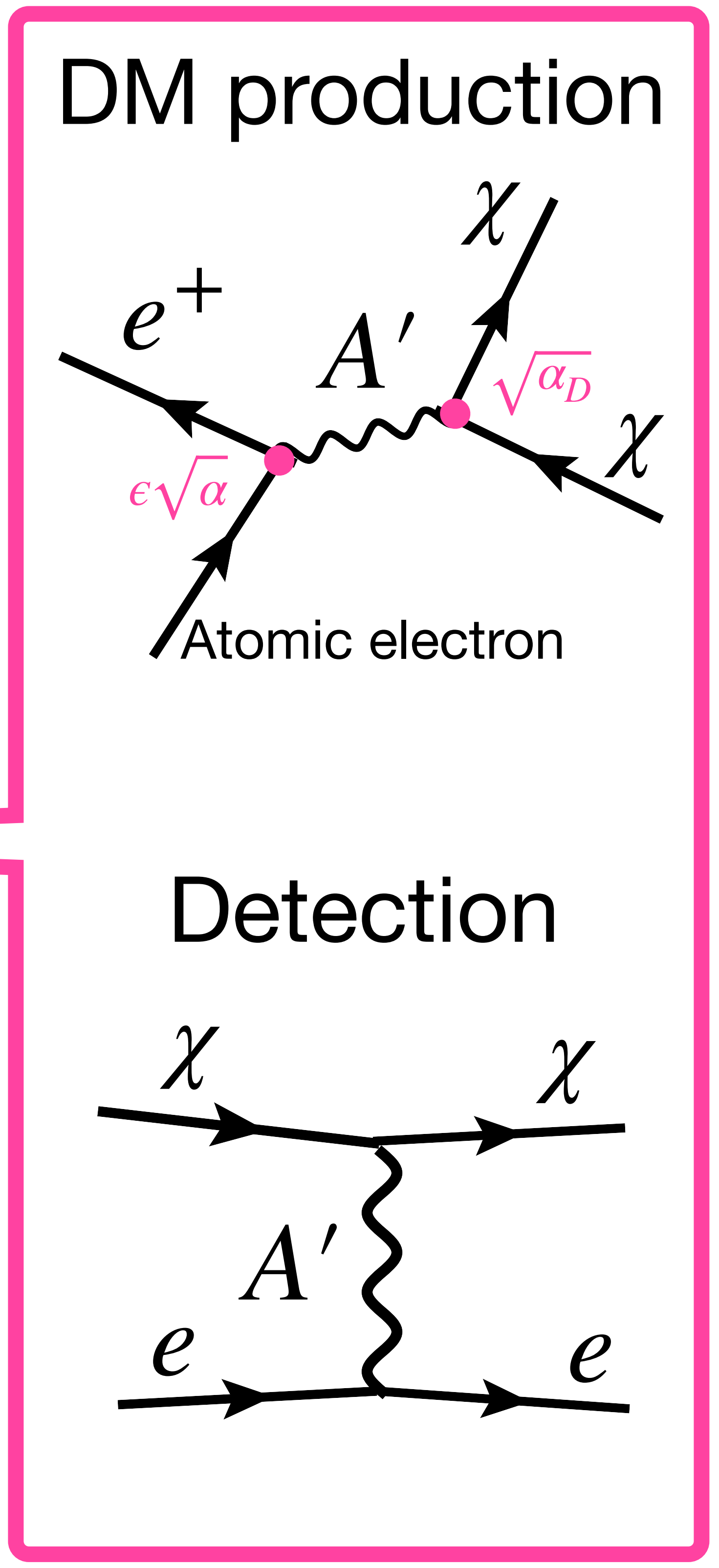

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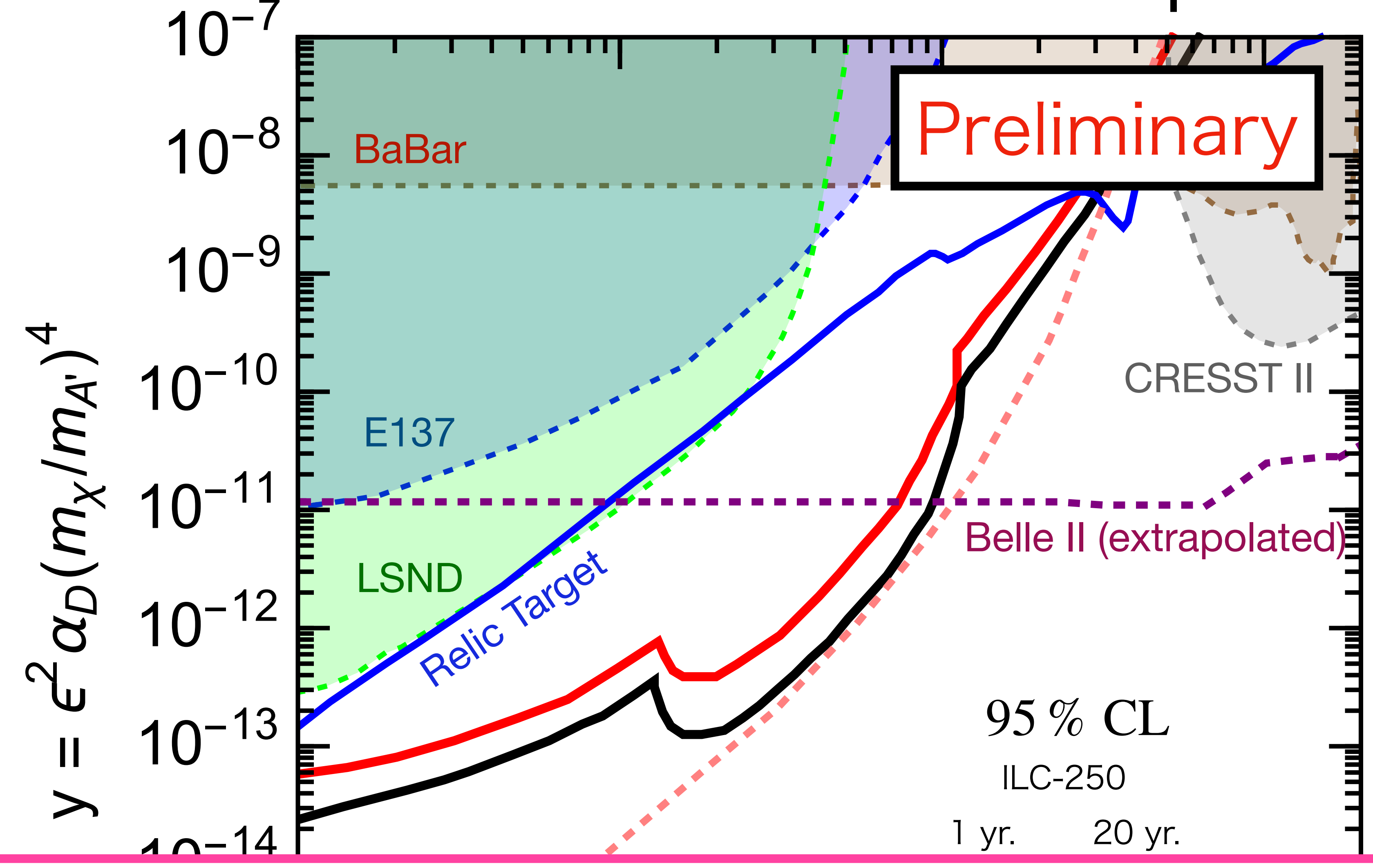

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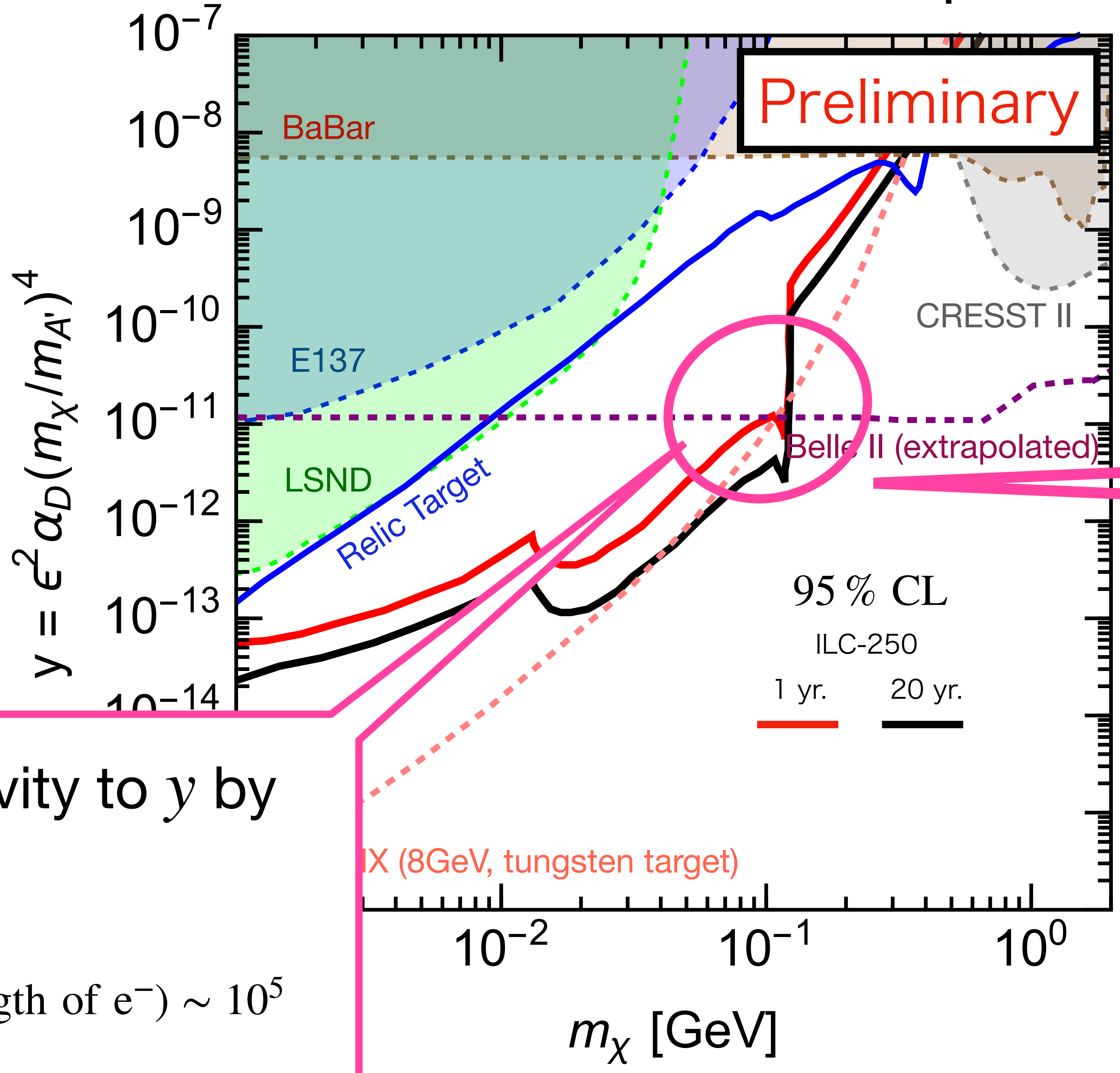
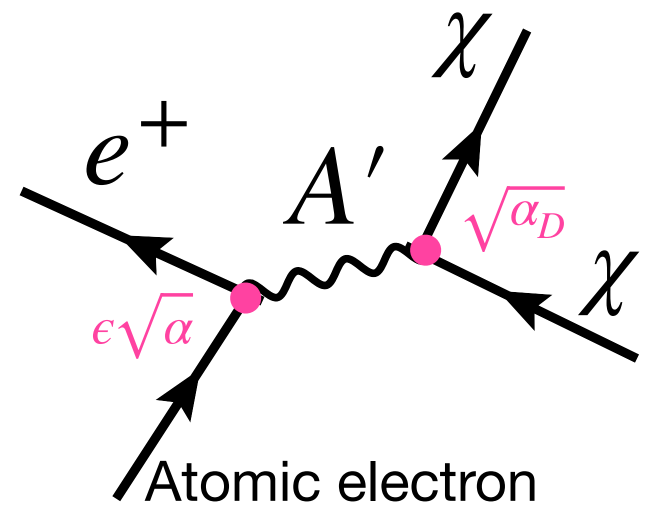


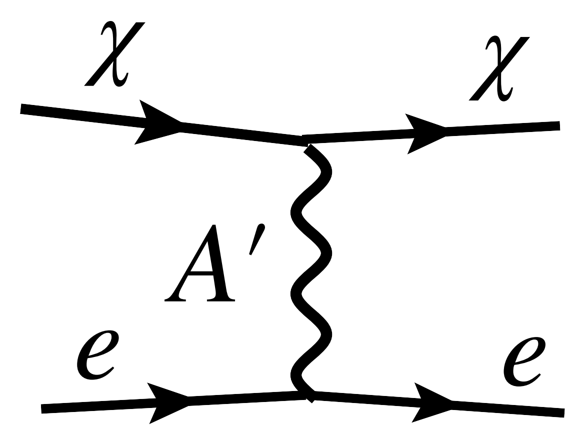
- Positron beam dump experiment has better sensitivity to y by **two order of magnitude**

※ $N_{\rm events}^{\rm (positron/electron)} \propto y^2$, $N_{\rm events}^{\rm (positron)}/N_{\rm events}^{\rm (electron)} \sim$ (Track length of e^+)/(Track length of e^-) $\sim 10^5$

DM production



Detection



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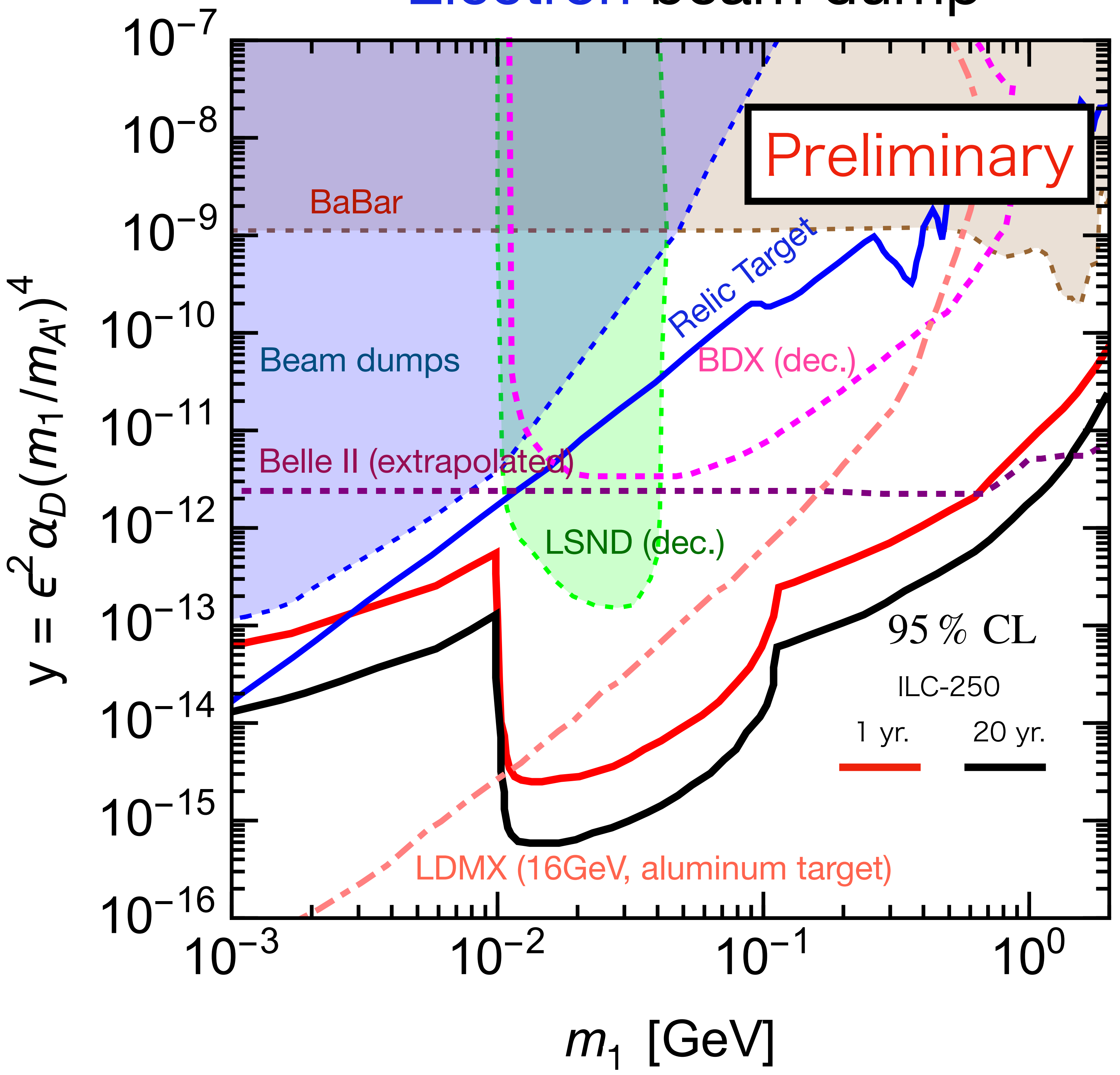

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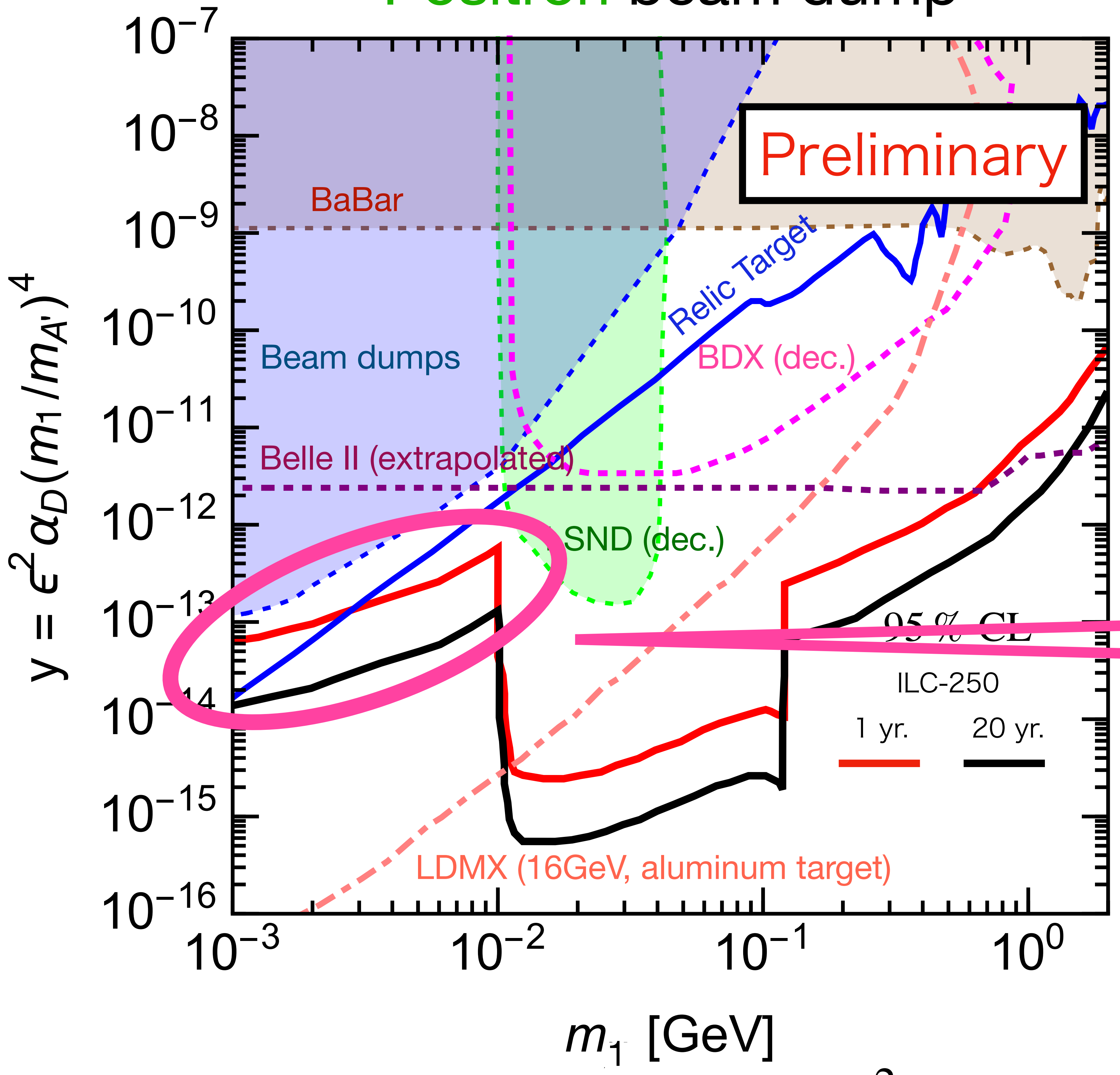

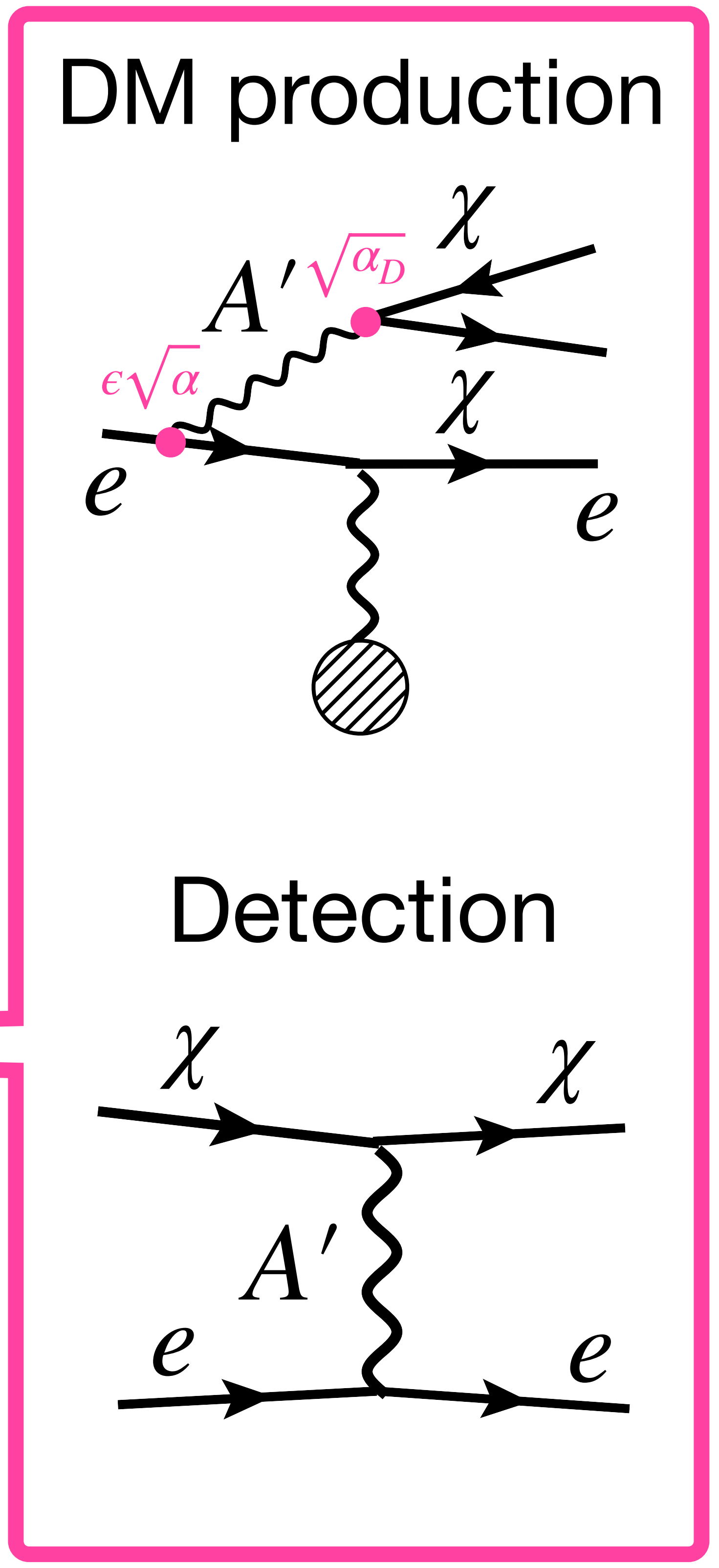

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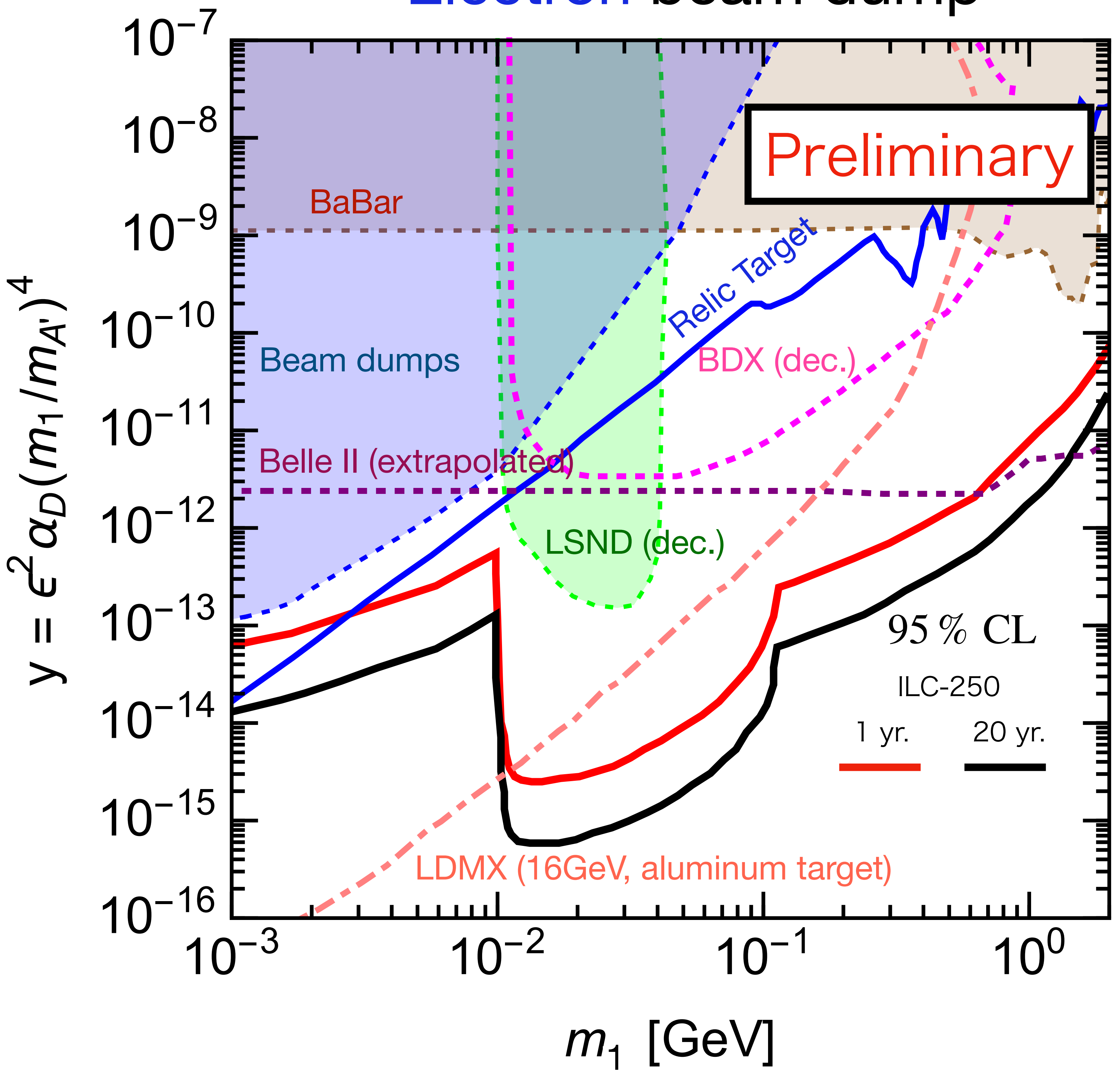

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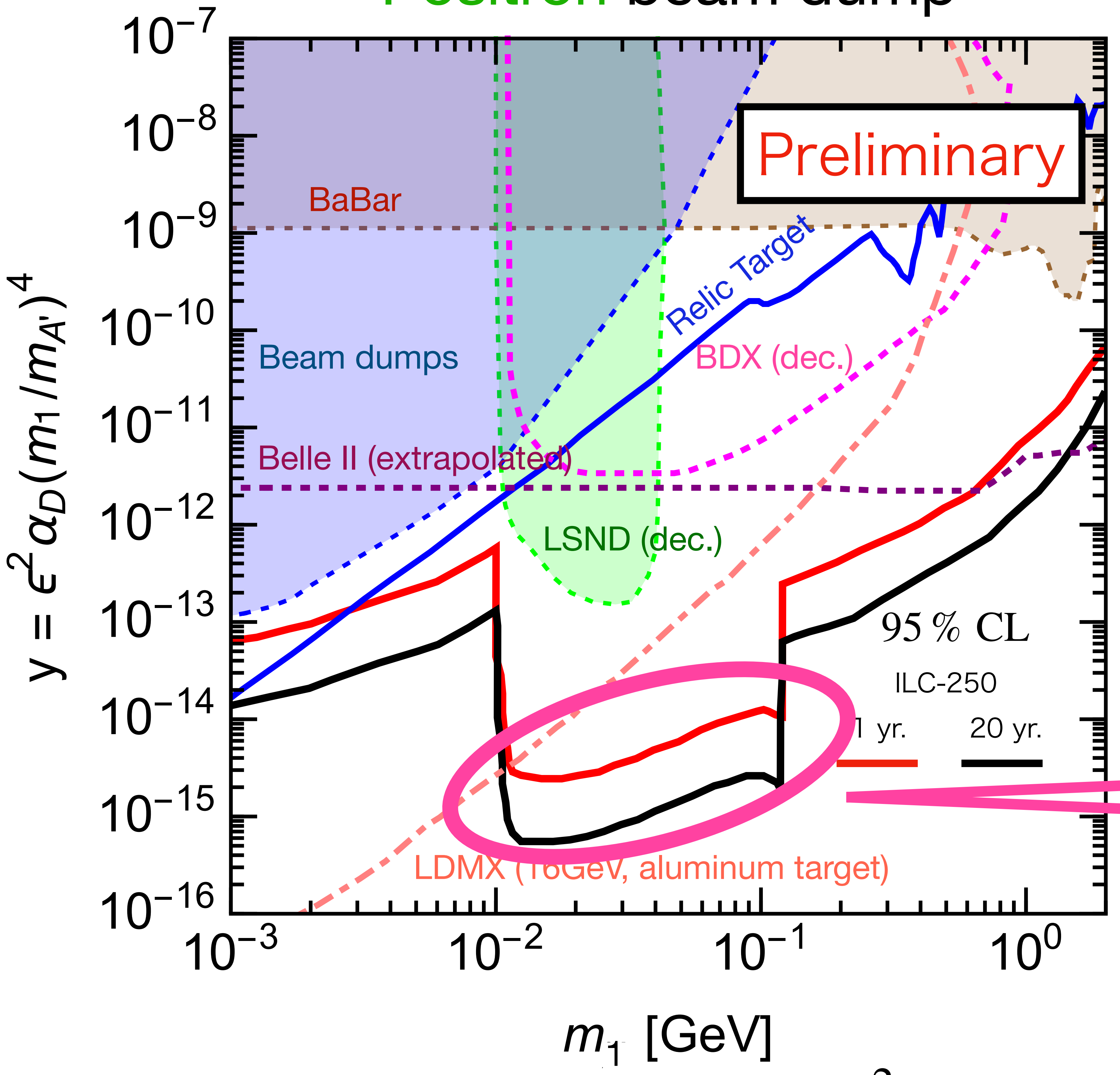

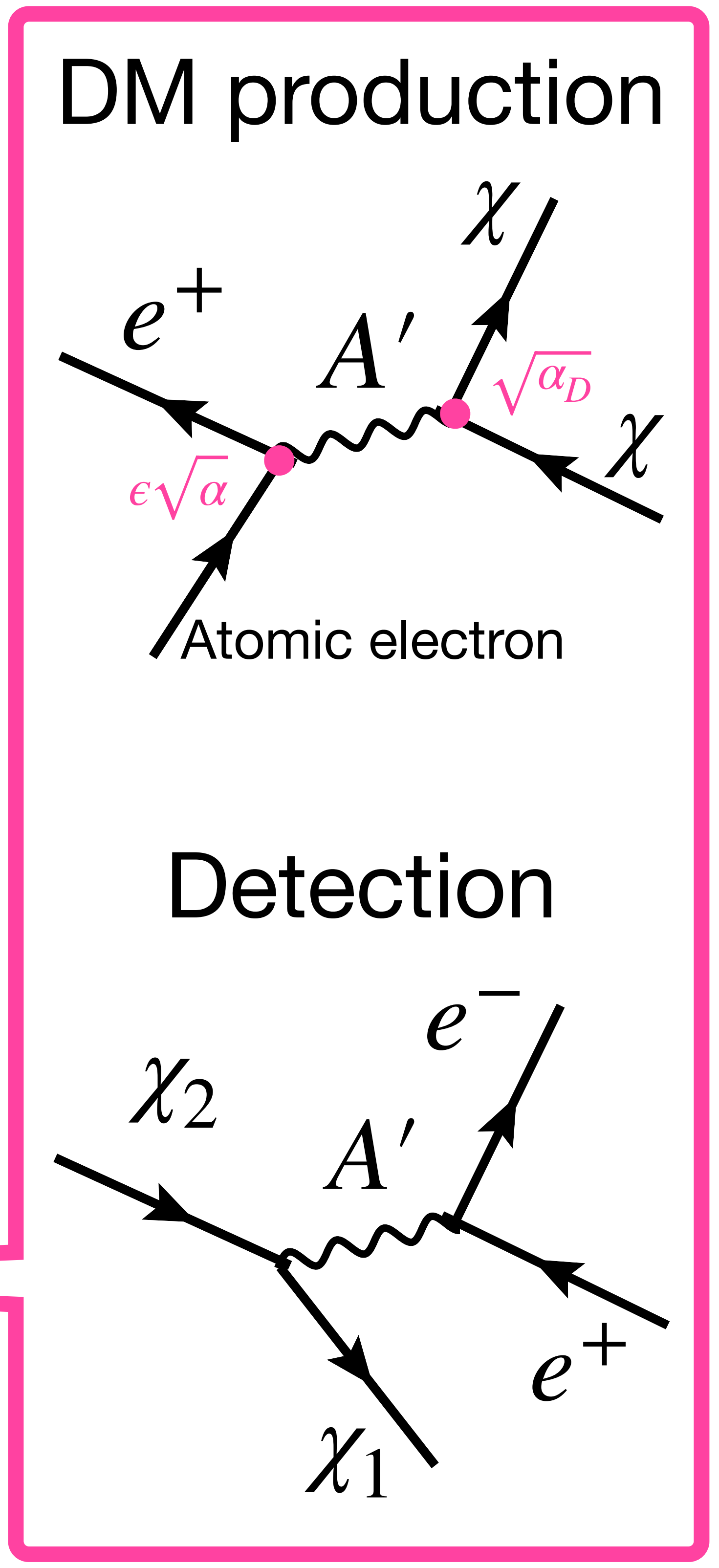

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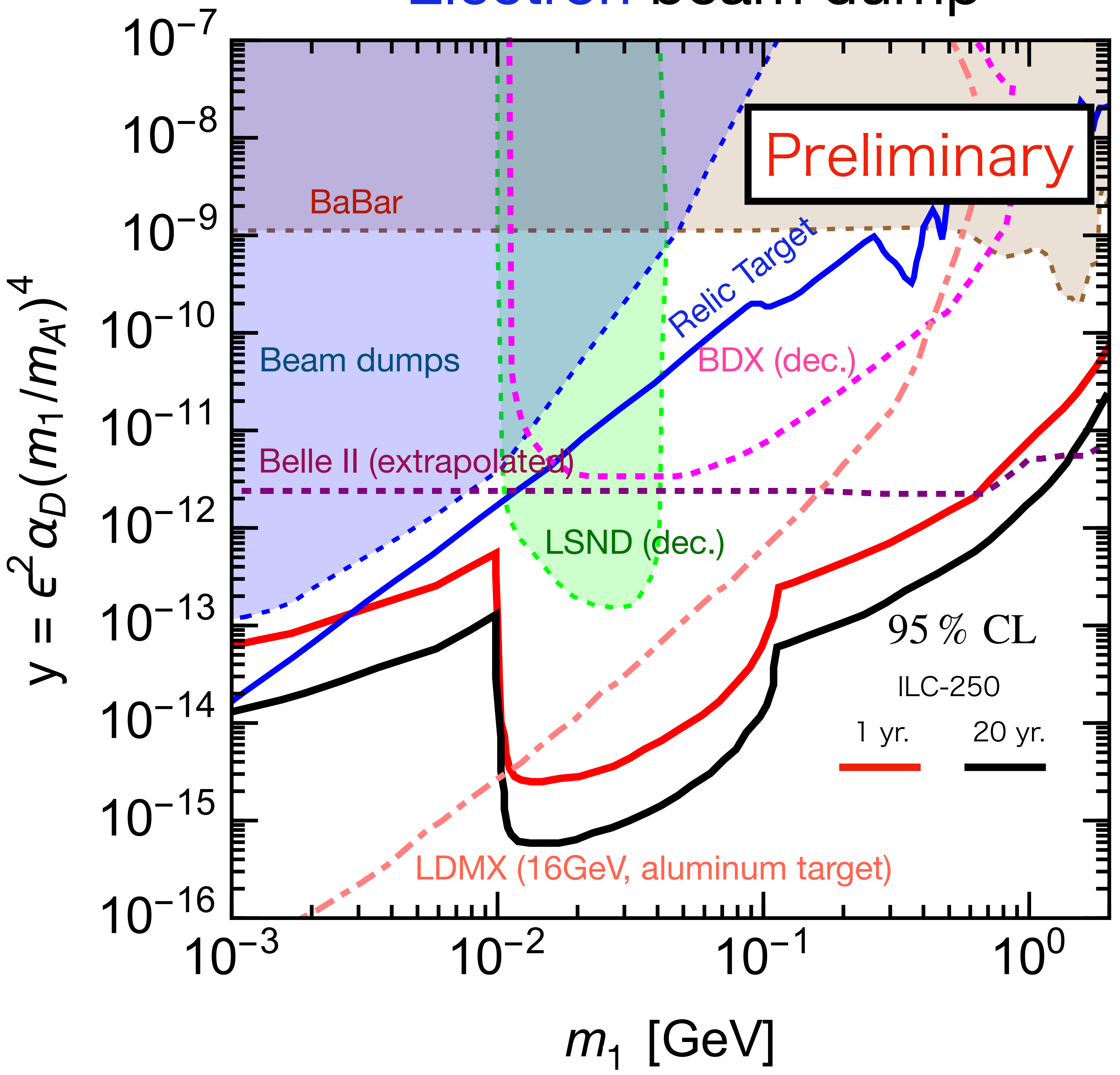

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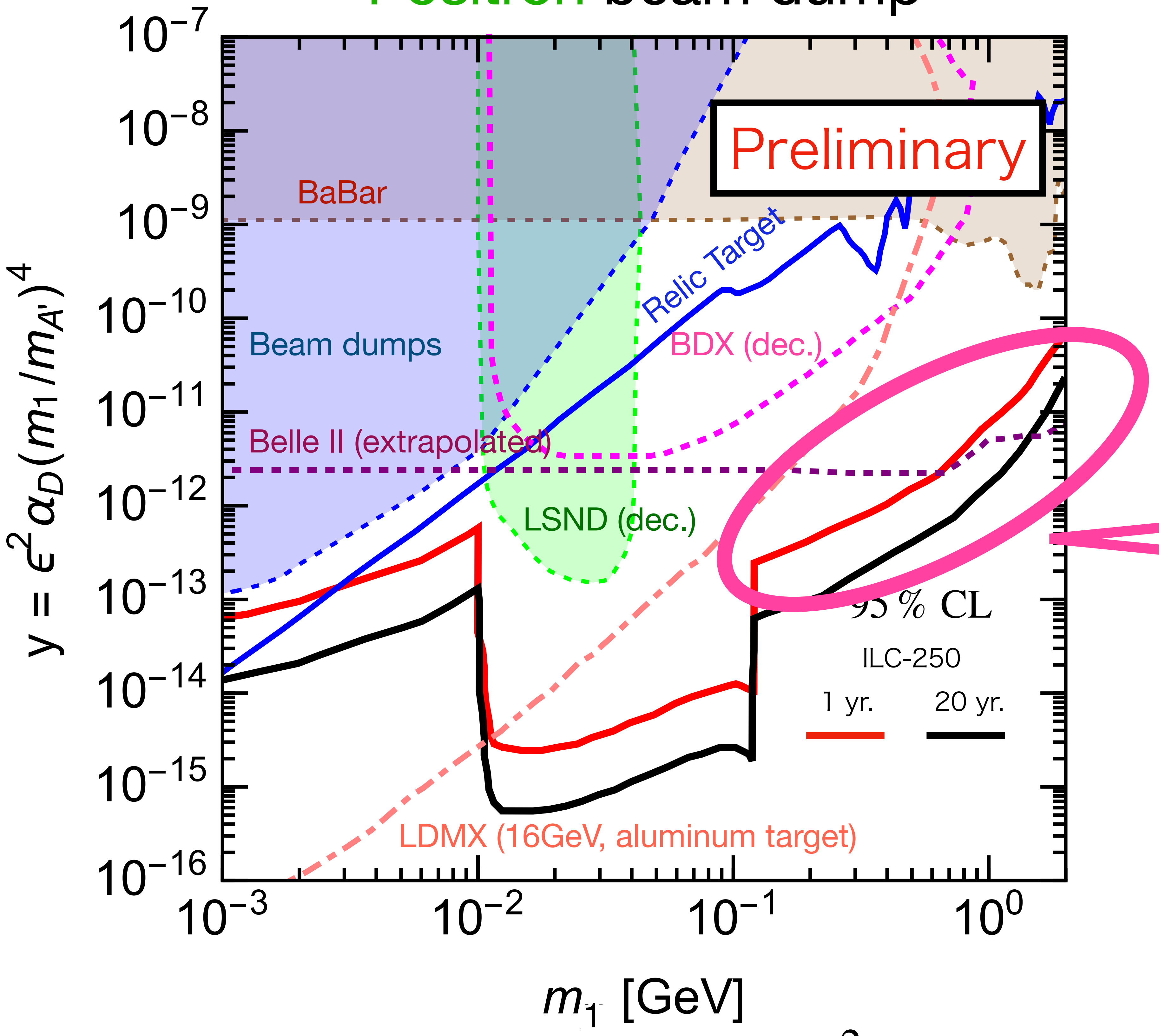

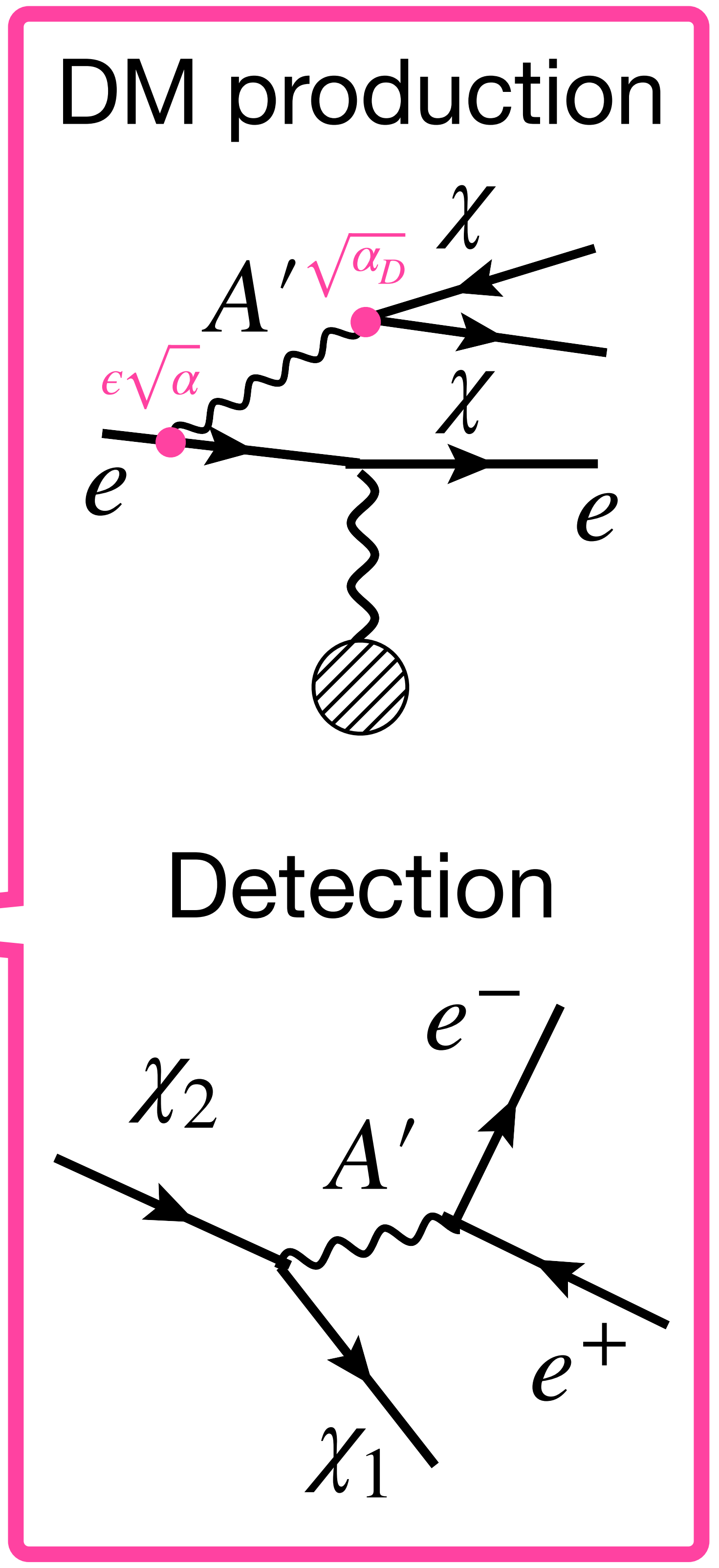

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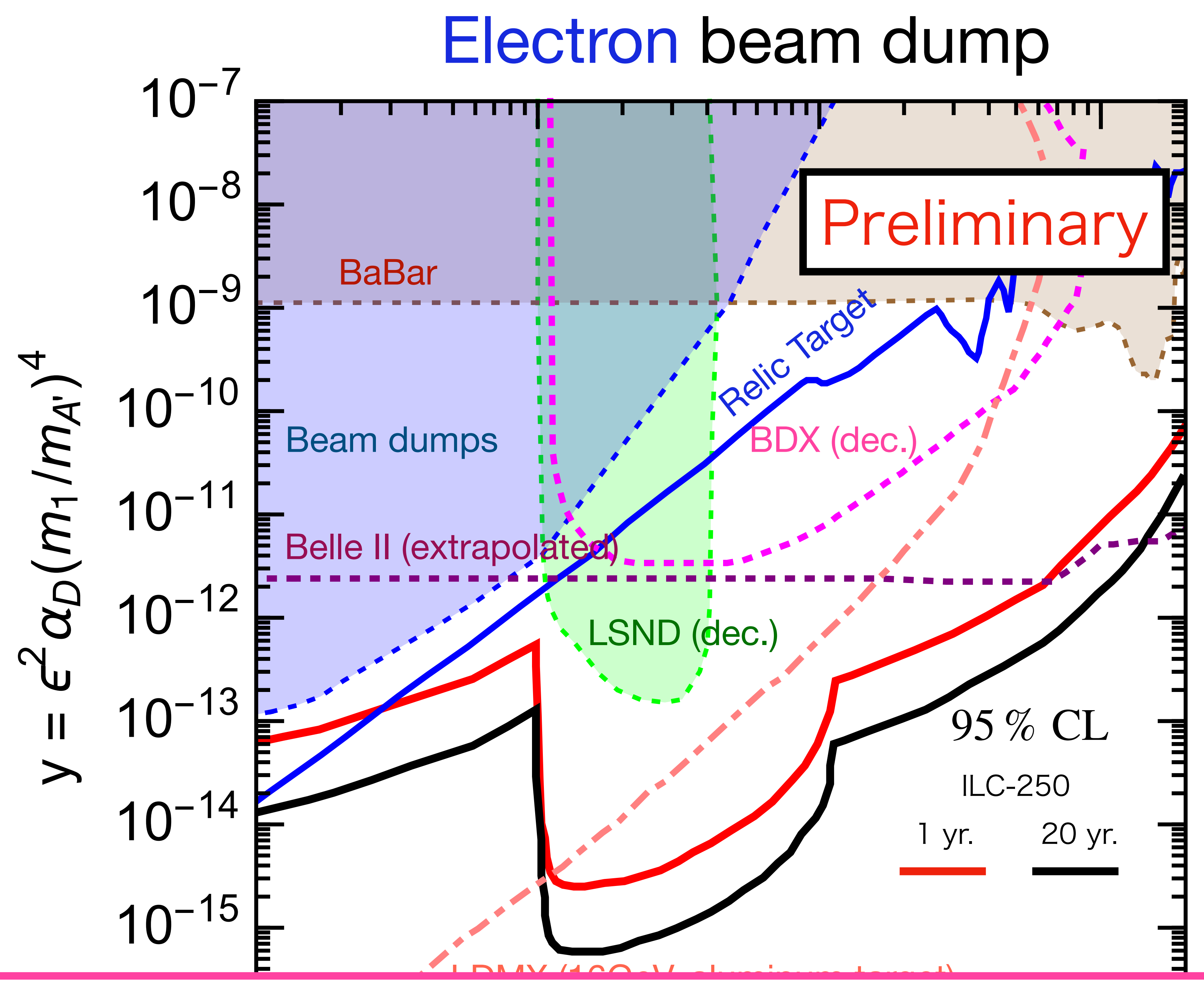

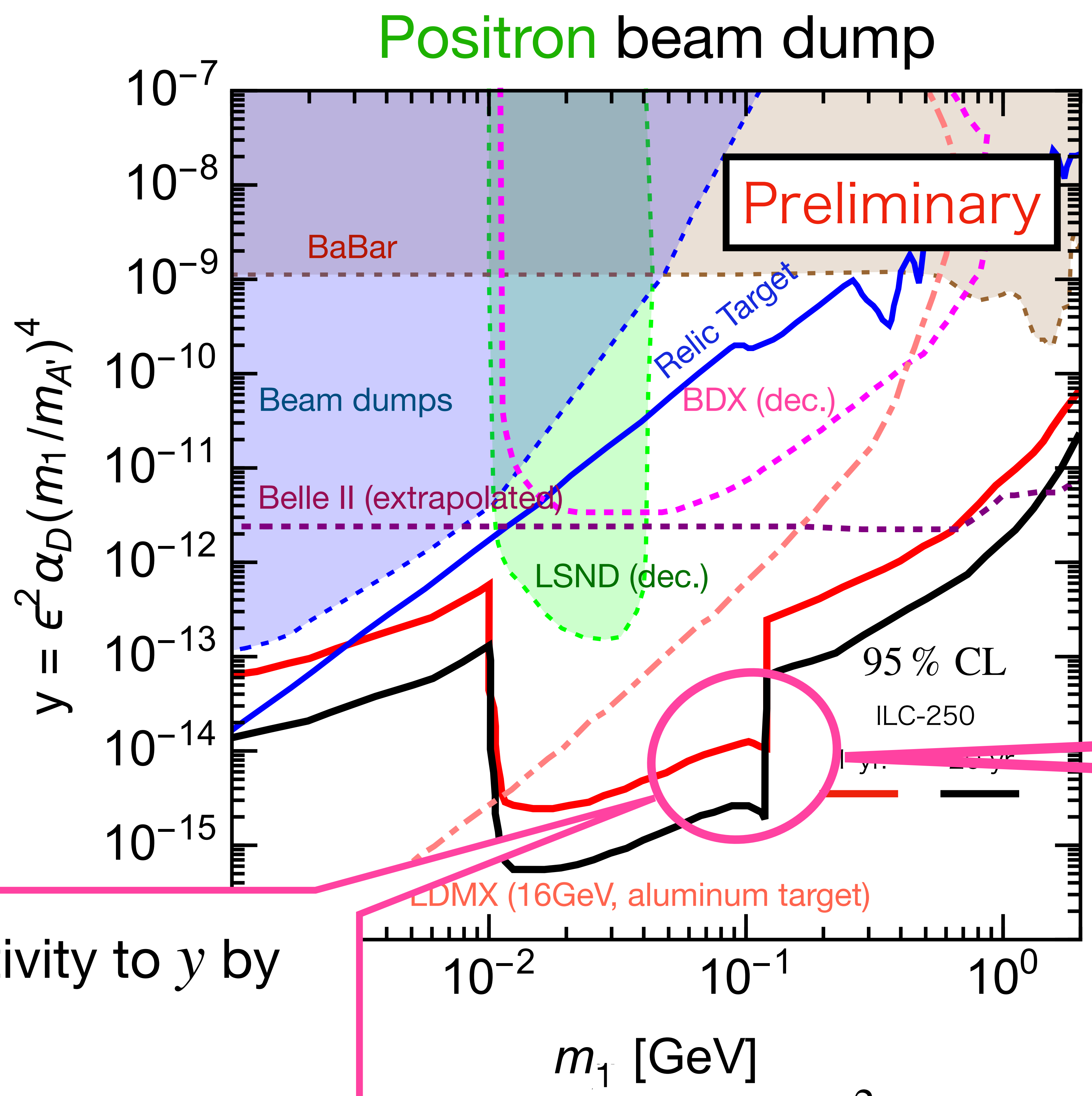

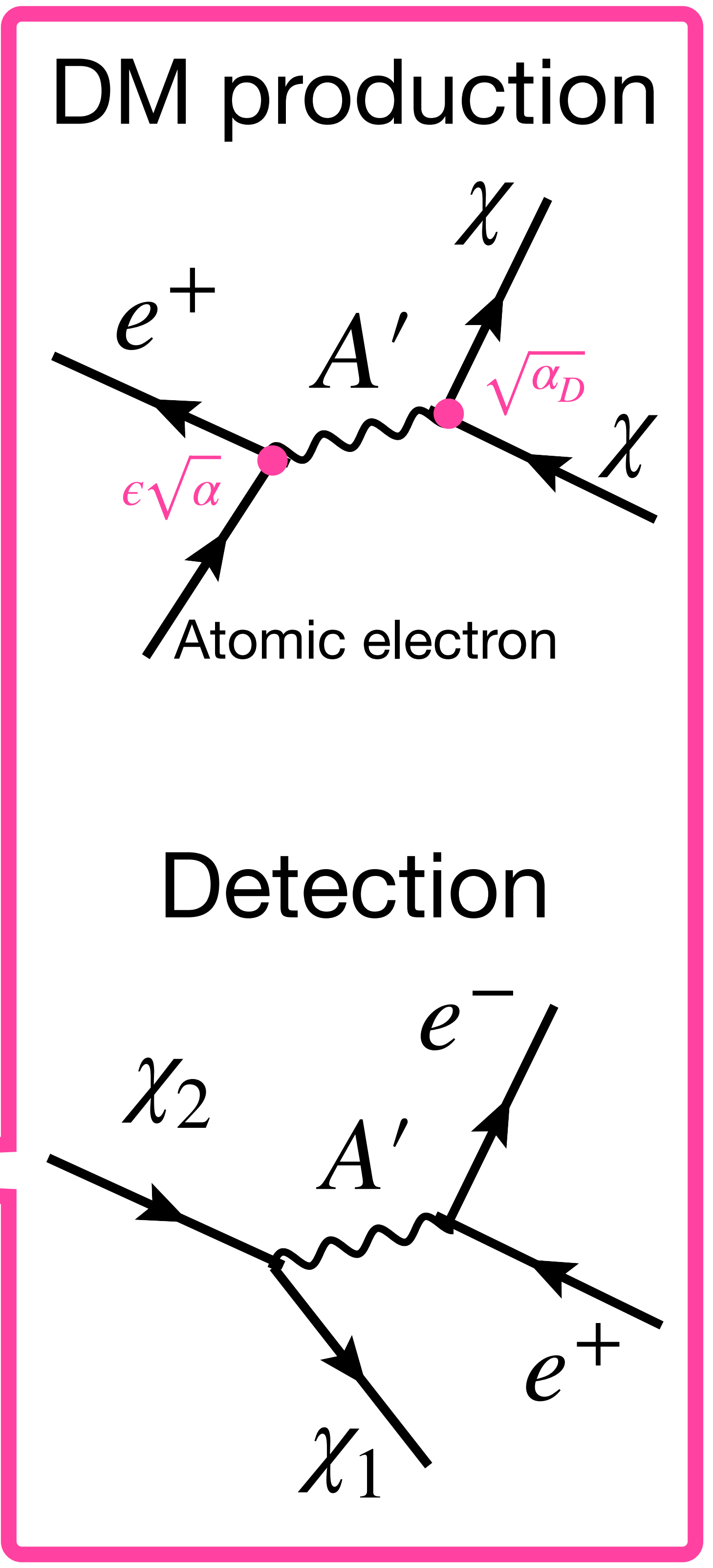

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Summary

- Primary positron beams produce new particles by pair-annihilation process, and positron beam dump experiment have better performance

- We performed a feasibility study by using a bench mark models: complex scalar DM and inelastic fermion DM

- In complex scalar DM model, ILC-BDX experiment has slightly better performance around 0.1 GeV than LDMX experiment

- In inelastic fermion DM model, ILC-BDX experiment has much better performance than future fixed-target experiment by visible decay signal