Sub-GeV dark matter search at ILC beam dumps

Workshop on Very Light Dark Matter 2023
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Daiki Ueda (KEK)

Based on arXiv:2301.03816
with Kento Asai, Sho Iwamoto, Maxim Perelstein, and Yasuhito Sakaki

Introduction

- Sub-GeV (MeV-GeV) new particles with feeble coupling to the SM can be thermal **Dark Matter (DM)** by light mediator

  - escape direct detection in nuclear recoil searches because of detection threshold

    ※ Inelastic DM scenario can escape even electron recoil search by small mass difference

  - collider constraint is not severe because of feeble coupling

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

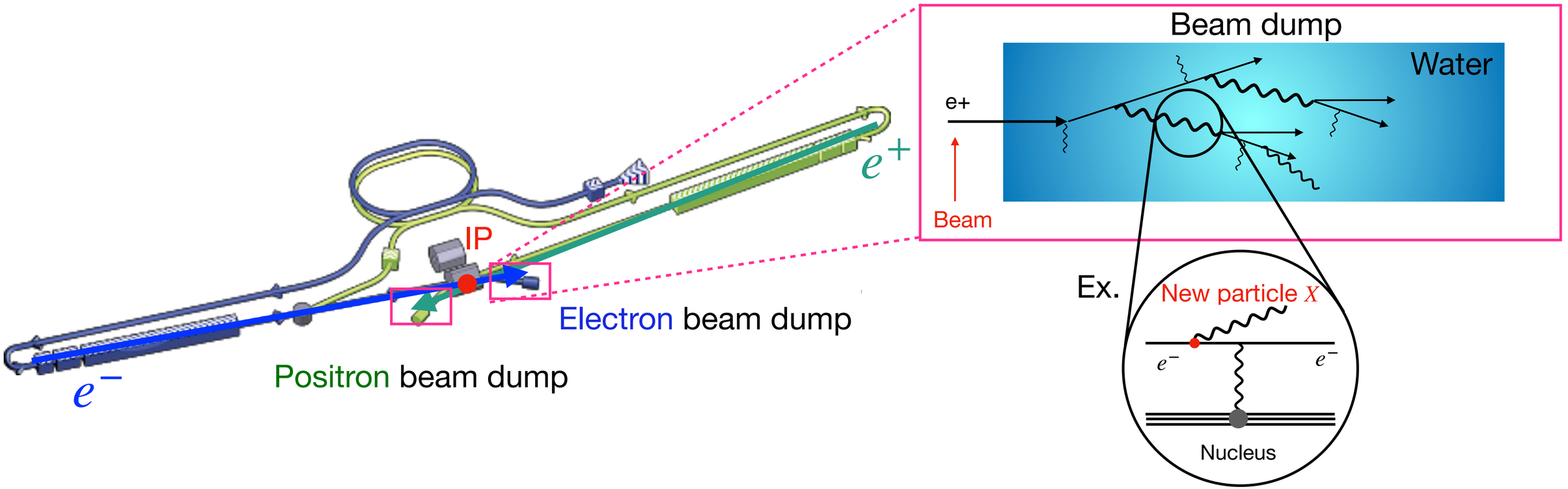
- **High-energy** sub-GeV particles can deposit enough energy in detector

- **High-intensity** beams 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



- Almost all $e^{\pm}$ beams go into the main beam dump after passing through the IP

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

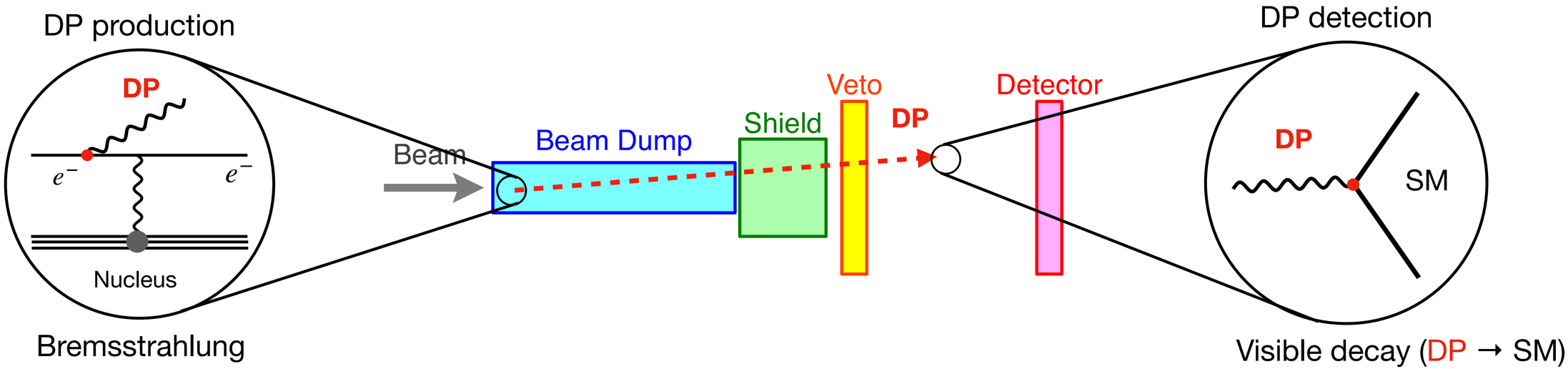
⇒ Large amount of EM showers are produced in the beam dumps

The EM showers can produce boosted sub-GeV new particle

Introduction

- It was proposed to set a shield, veto, and detector behind the main beam dump

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



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

where ϵ is **dark photon (DP)**-SM coupling strength, and m_X is DP mass

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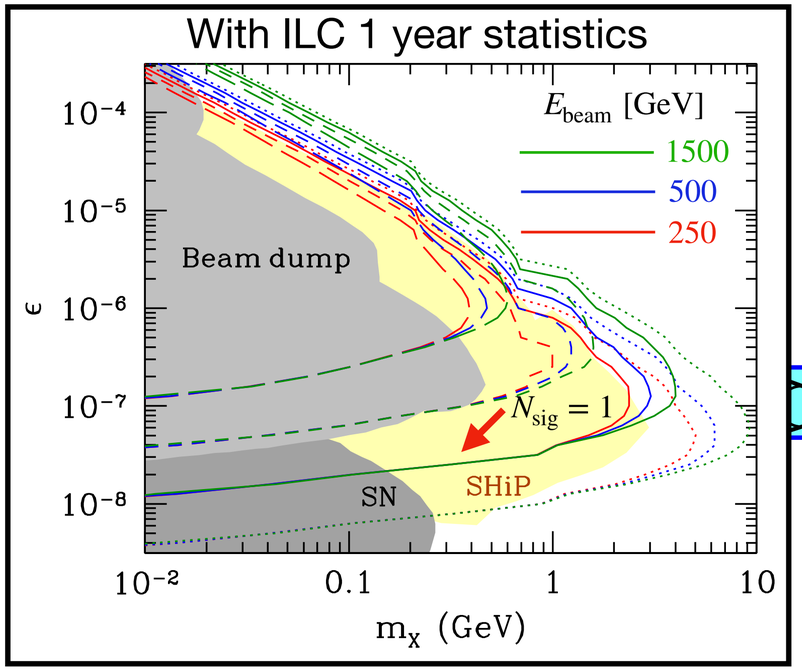

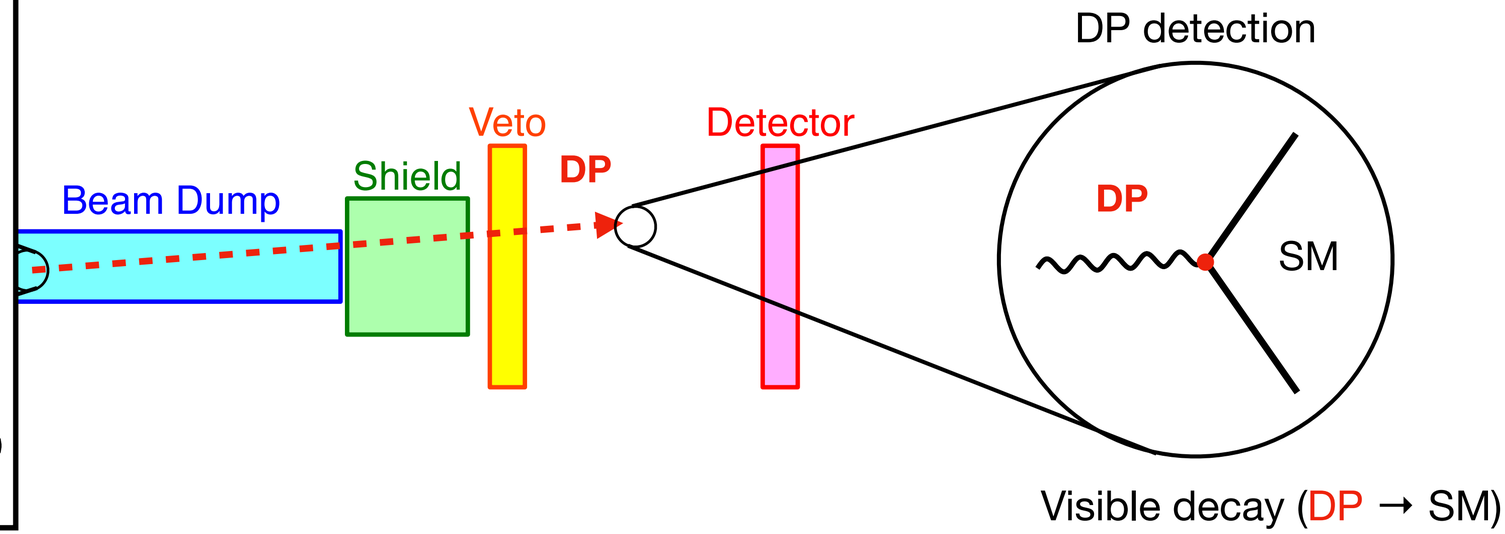

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where ϵ is **dark photon (DP)**-SM coupling strength, and m_X is DP mass

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

※ Visible decay searches for various models also have been studied

Axion-like particle, light scalar [arXiv: 2105.13768], Leptophilic gauge boson [arXiv:2205.11766], Heavy neutral lepton [arXiv:2206.13523], etc

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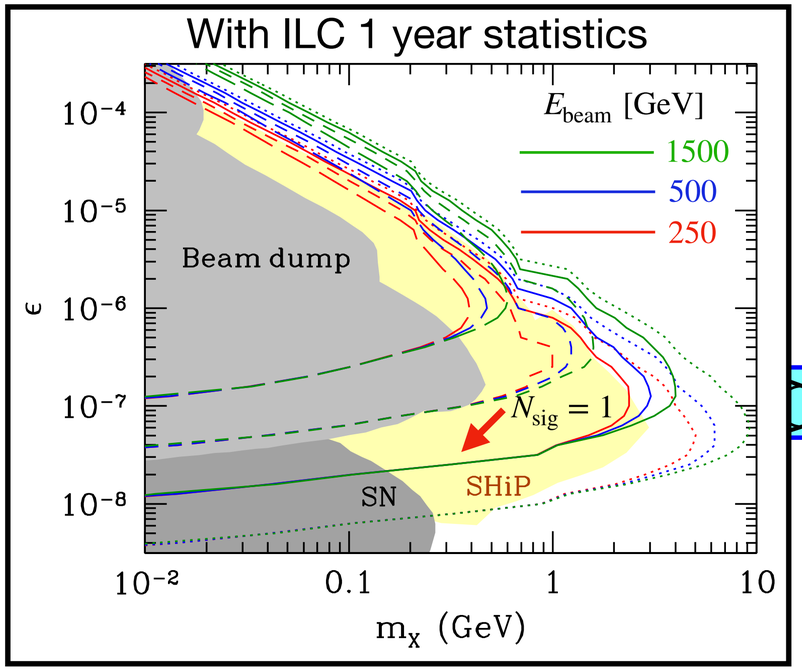

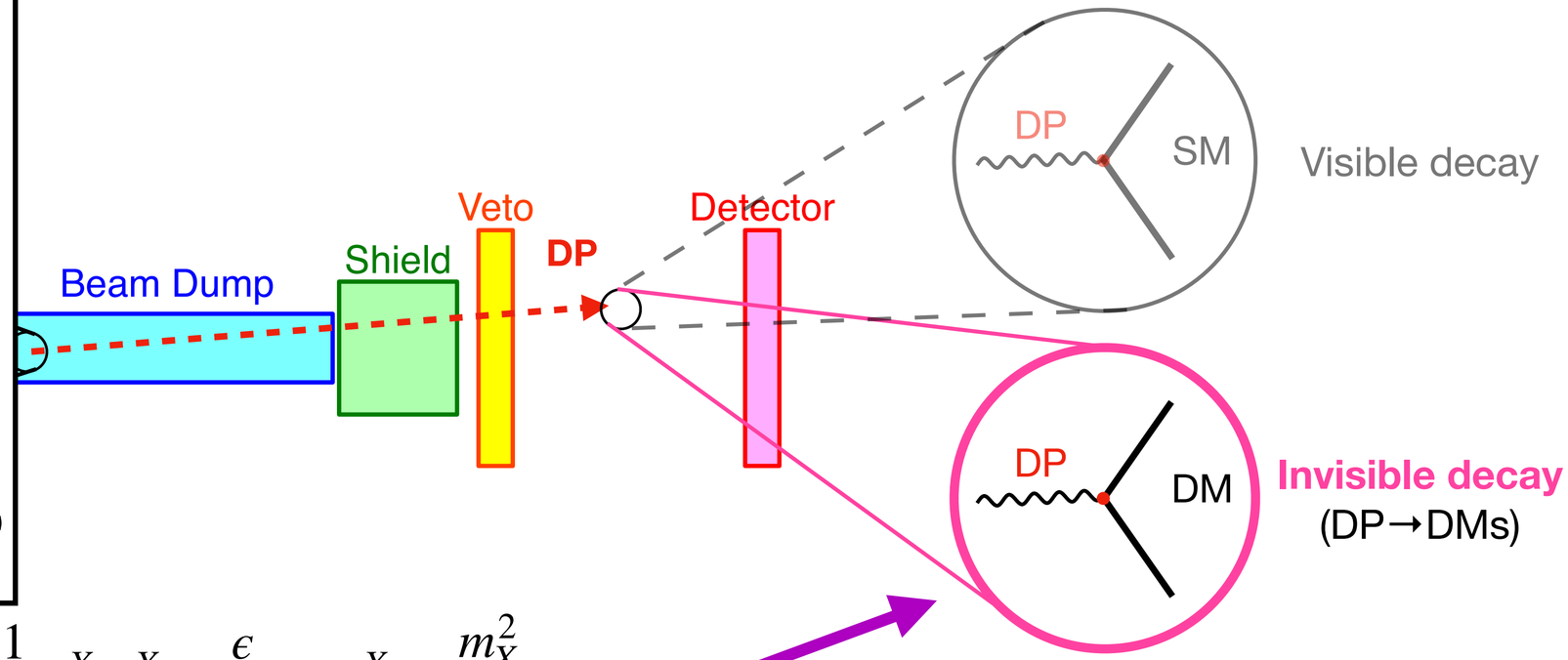

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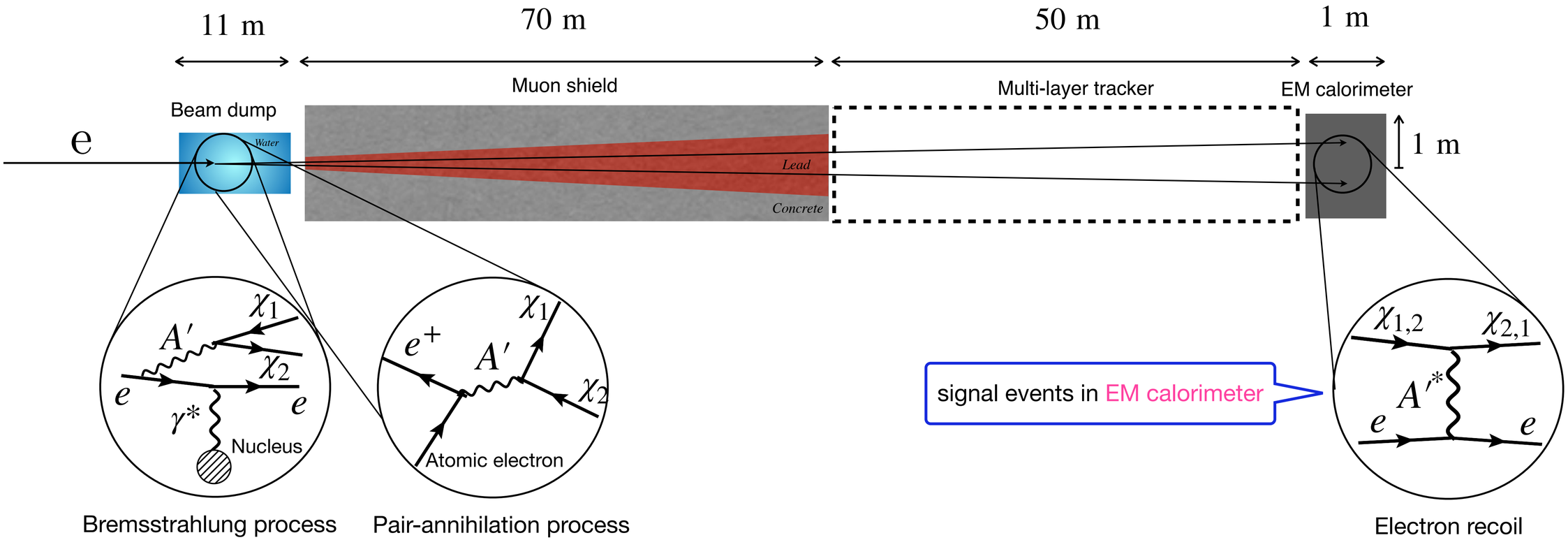
where ϵ is **dark photon (DP)**-SM coupling strength, and m_X is DP mass

What about **invisible decay** (DP→DMs) search in ILC beam dump experiment?

Setup and signal events

- We adopted a similar setup as visible decay searches [M.M. Nojiri, Y.Sakaki, K. Tobioka, DU. arXiv:2206.13523]
  - Muon lead shield ⇒ reduce background, Multi-layer tracker ⇒ detect charged tracks

    EM calorimeter ⇒ detect EM showers



Benchmark Model (1): $\mathscr{L} \supset -g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + \mathrm{H.c.}) + \epsilon \cdot e A'_\mu J^\mu_{\mathrm{EM}}$ with $\Delta = m_{\chi_2} - m_{\chi_1} < 2m_e$

Dark photon

Pseudo-Dirac DM

(**small mass difference**)

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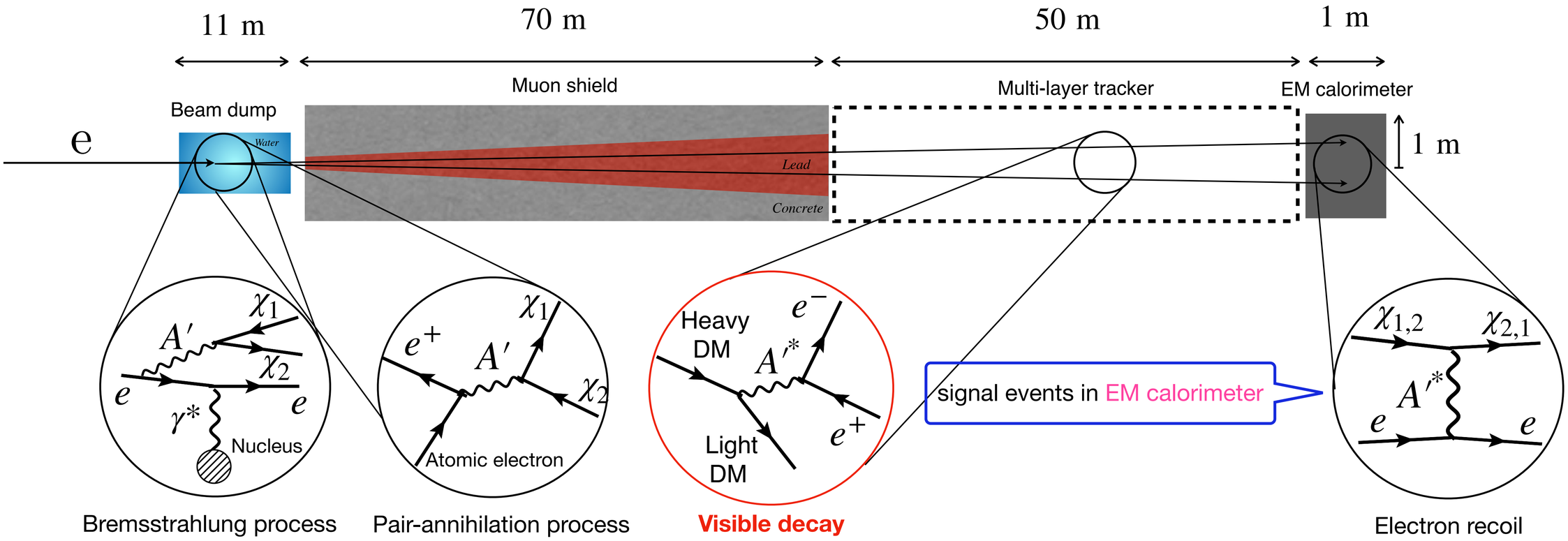

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Dark photon

Pseudo-Dirac DM

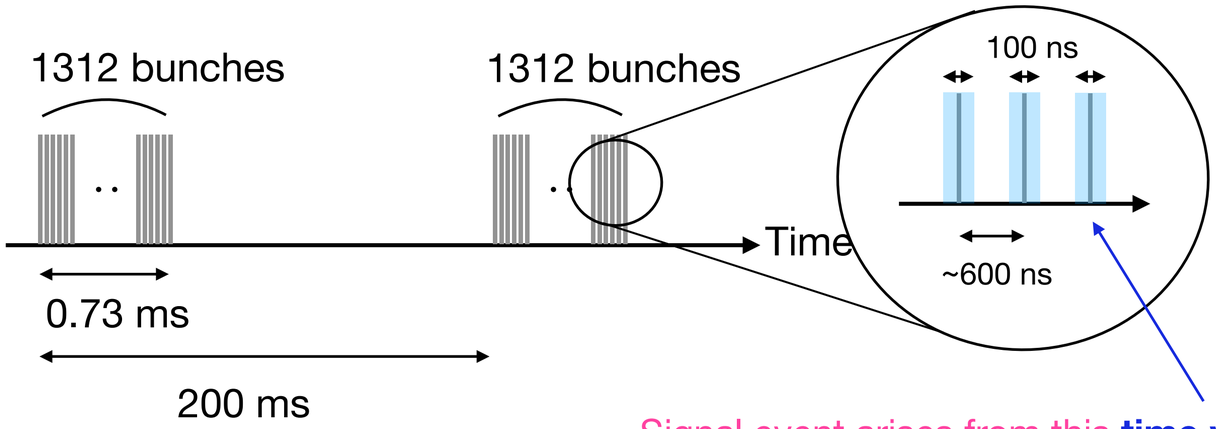
(**Large mass difference**)

Background

- Beam-unrelated background: cosmic muons

  - deep underground location (120 m) of detector

  - time window based on ILC pulsed beam

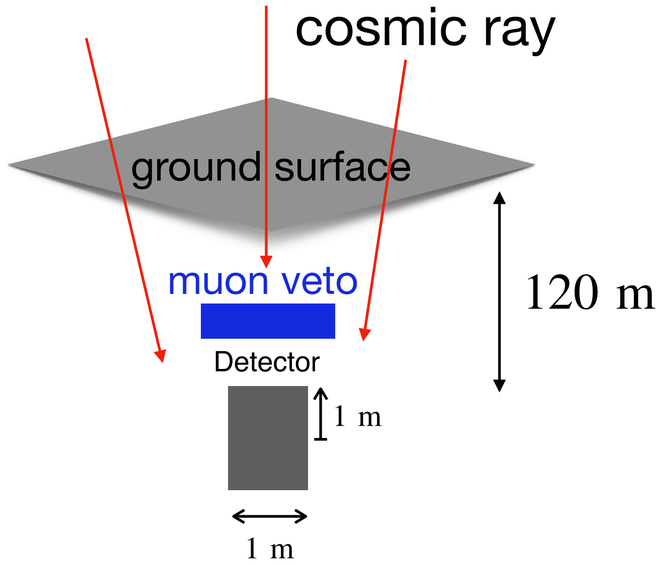


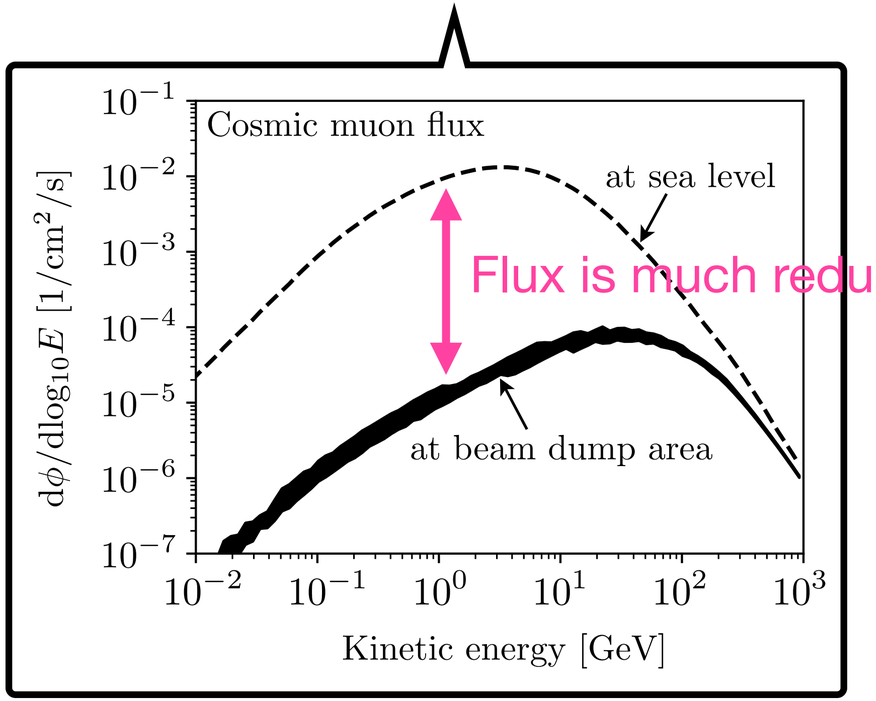
Signal event arises from this **time window**

We impose **time window = 100 ns**

  - muon veto

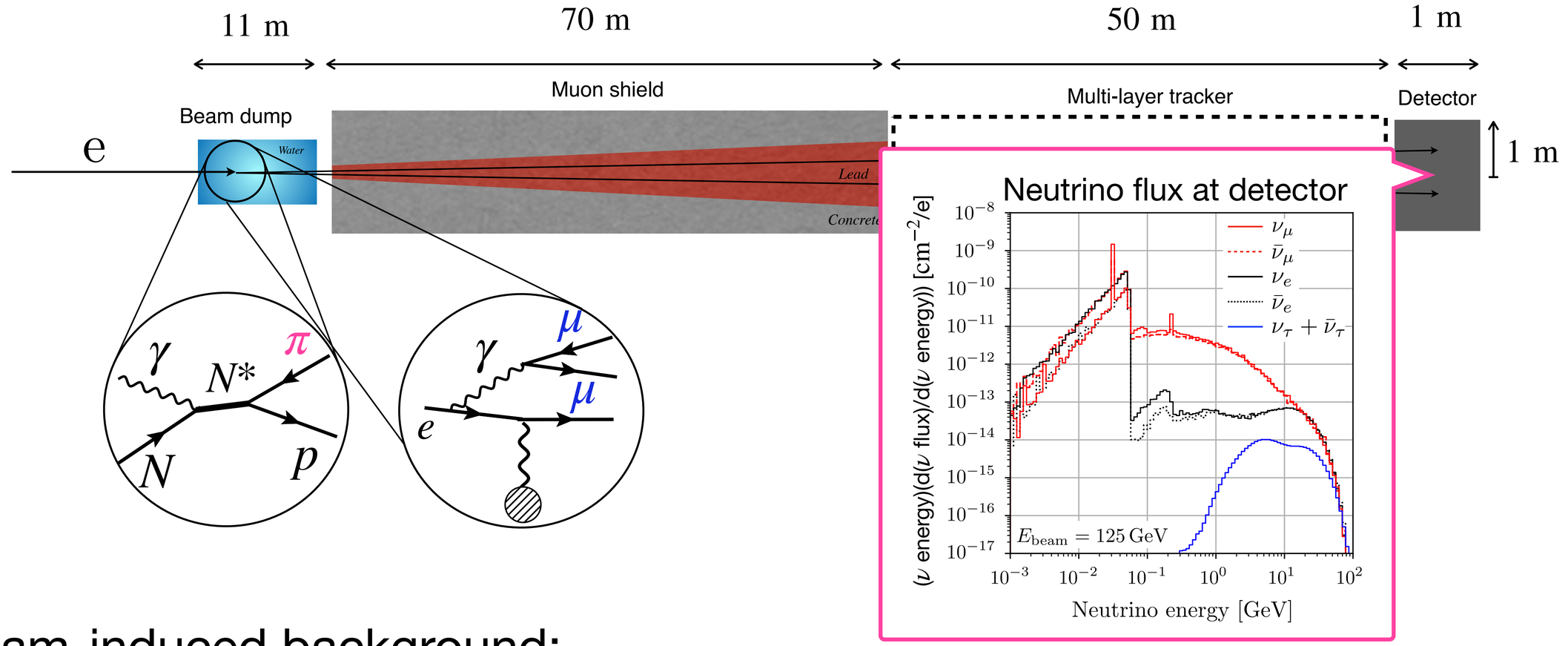
⇒ cosmic-ray backgrounds are negligible





Results of Monte Carlo simulation (EXPACS + PHITS)

Background



Results of Monte Carlo simulation (PHITS)

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

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

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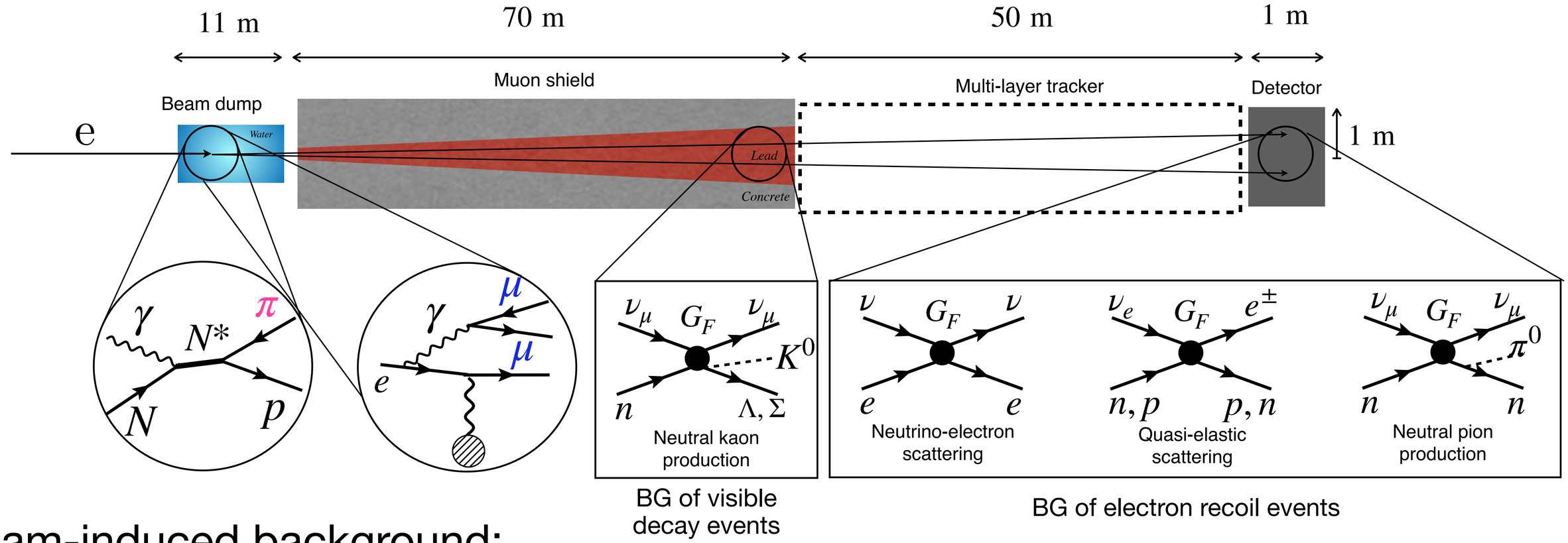

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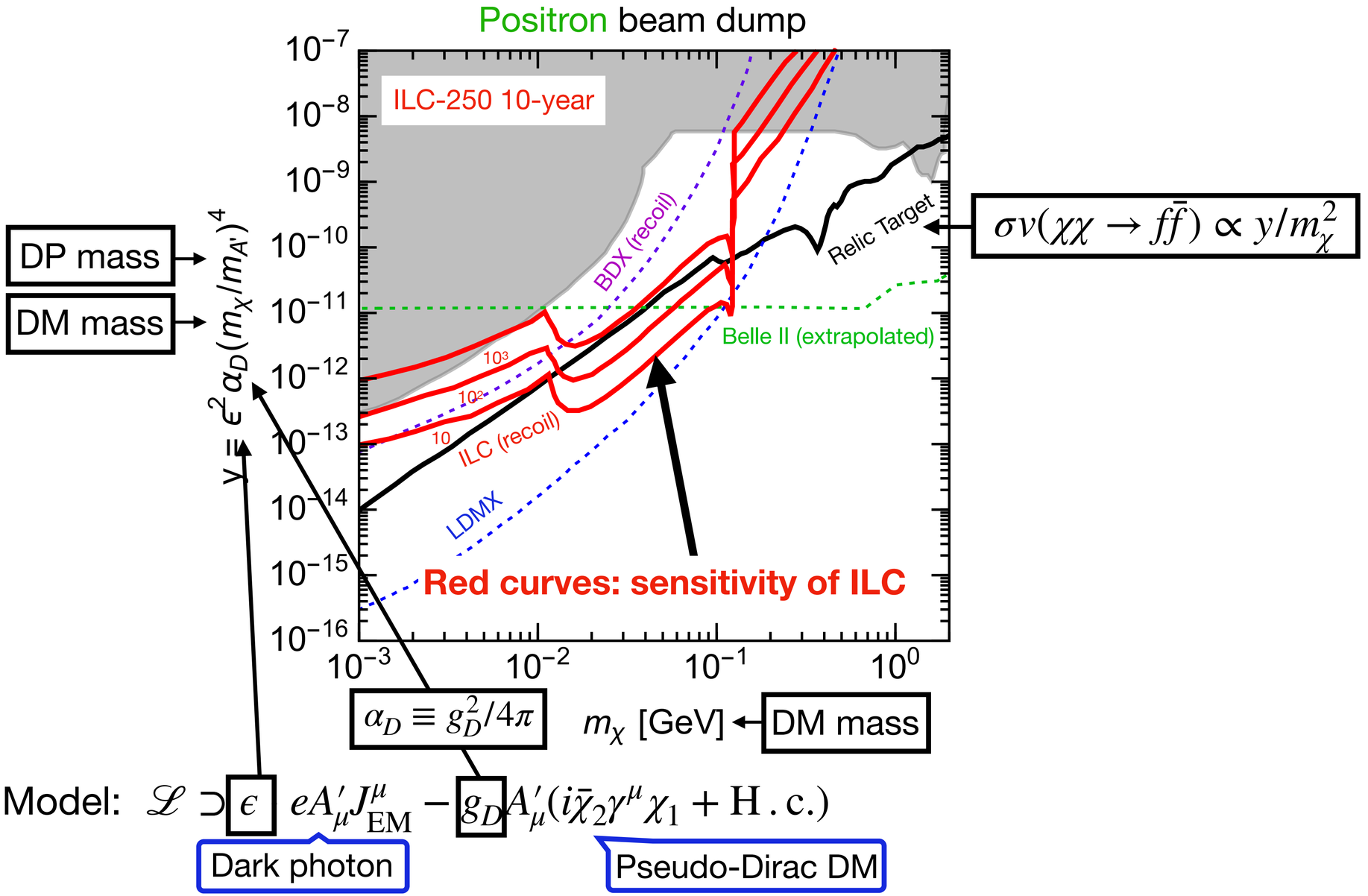
We take into account the neutrino-induced BG events

Sensitivity of ILC beam dump experiments (1)



Benchmark choice (1): $\alpha_D \equiv g_D^2/4\pi = 0.5,\ m_{A'} = 3m_\chi,\ \Delta = m_{\chi_2} - m_{\chi_1} < 2m_e$

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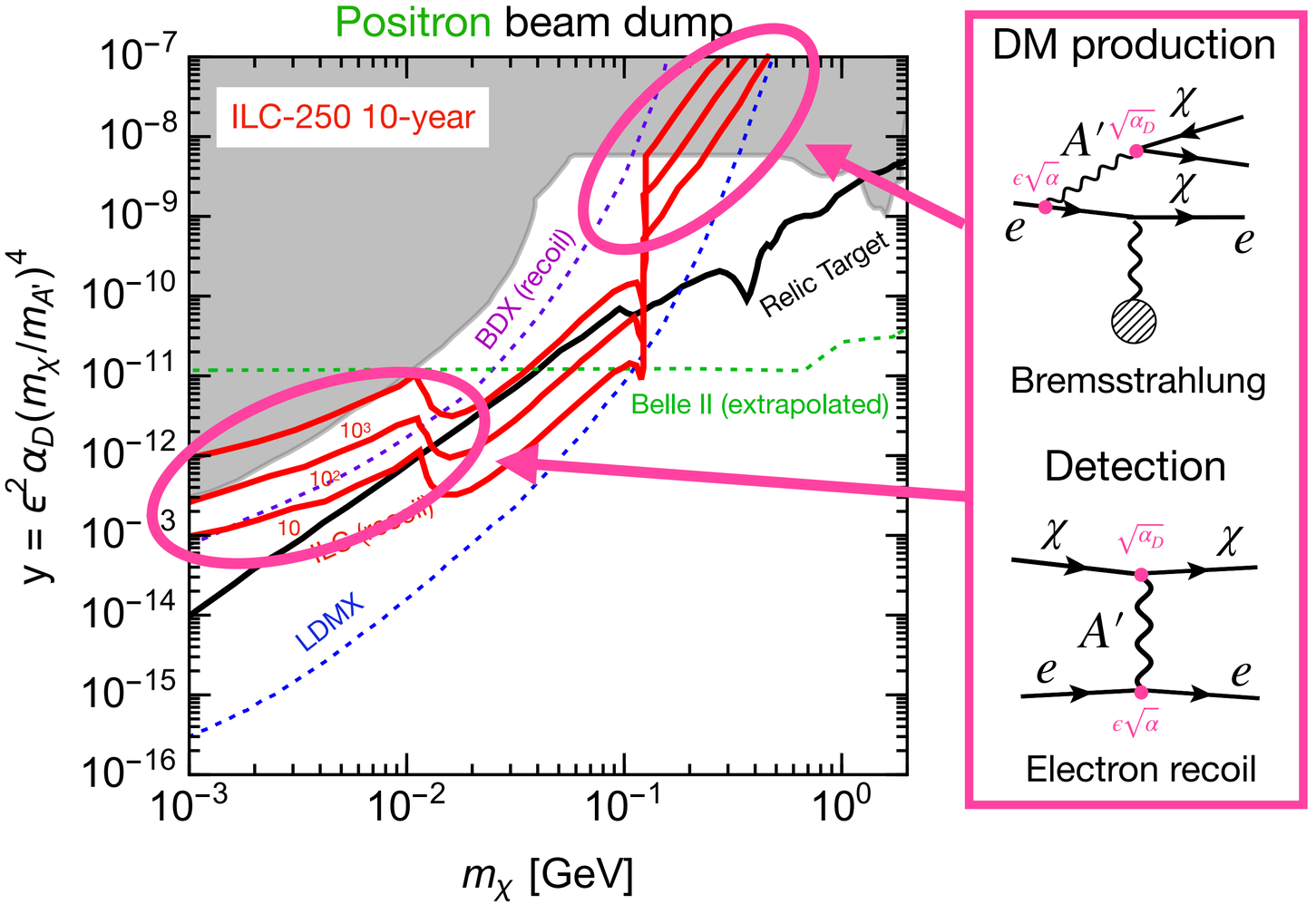

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Dark photon

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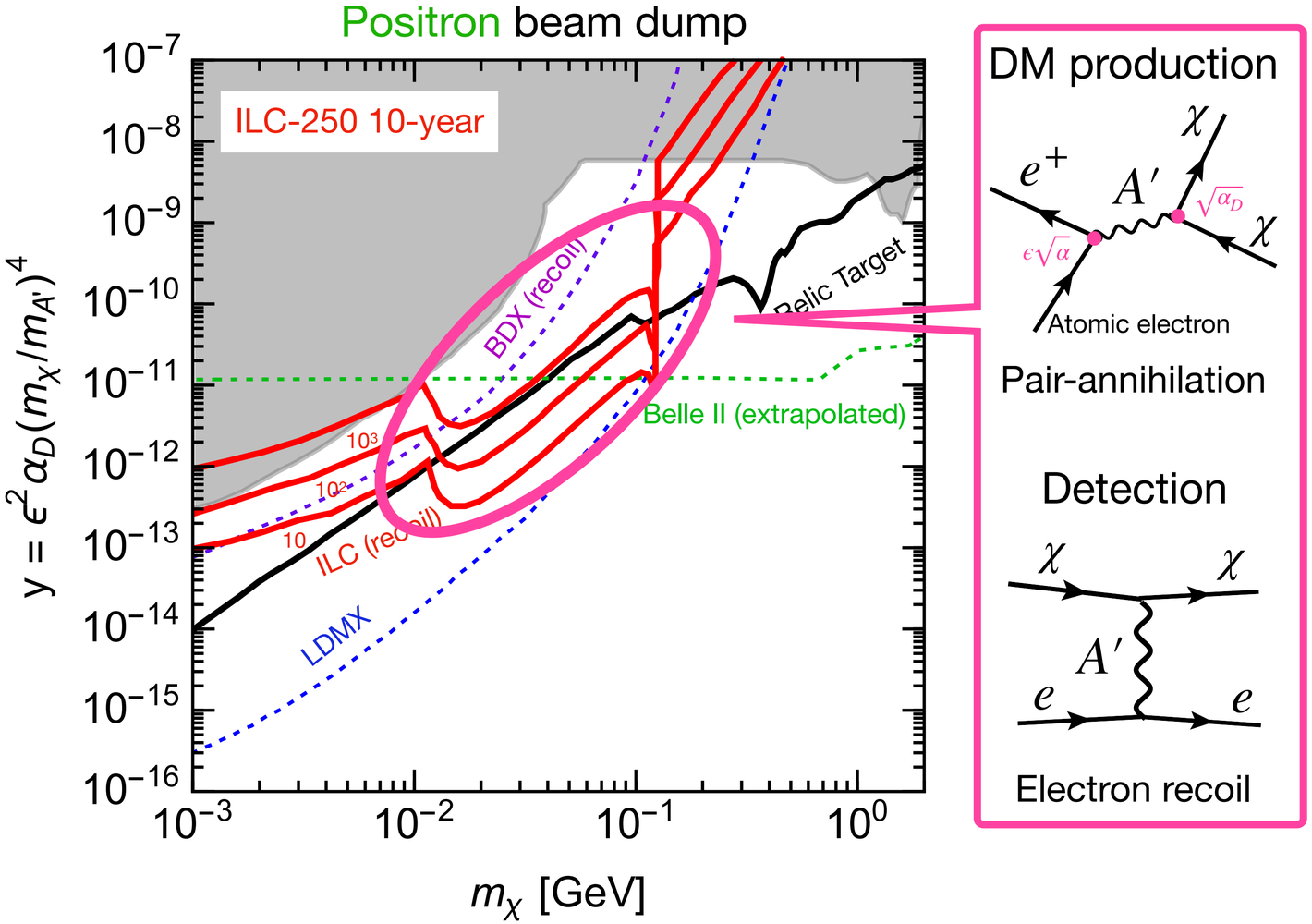

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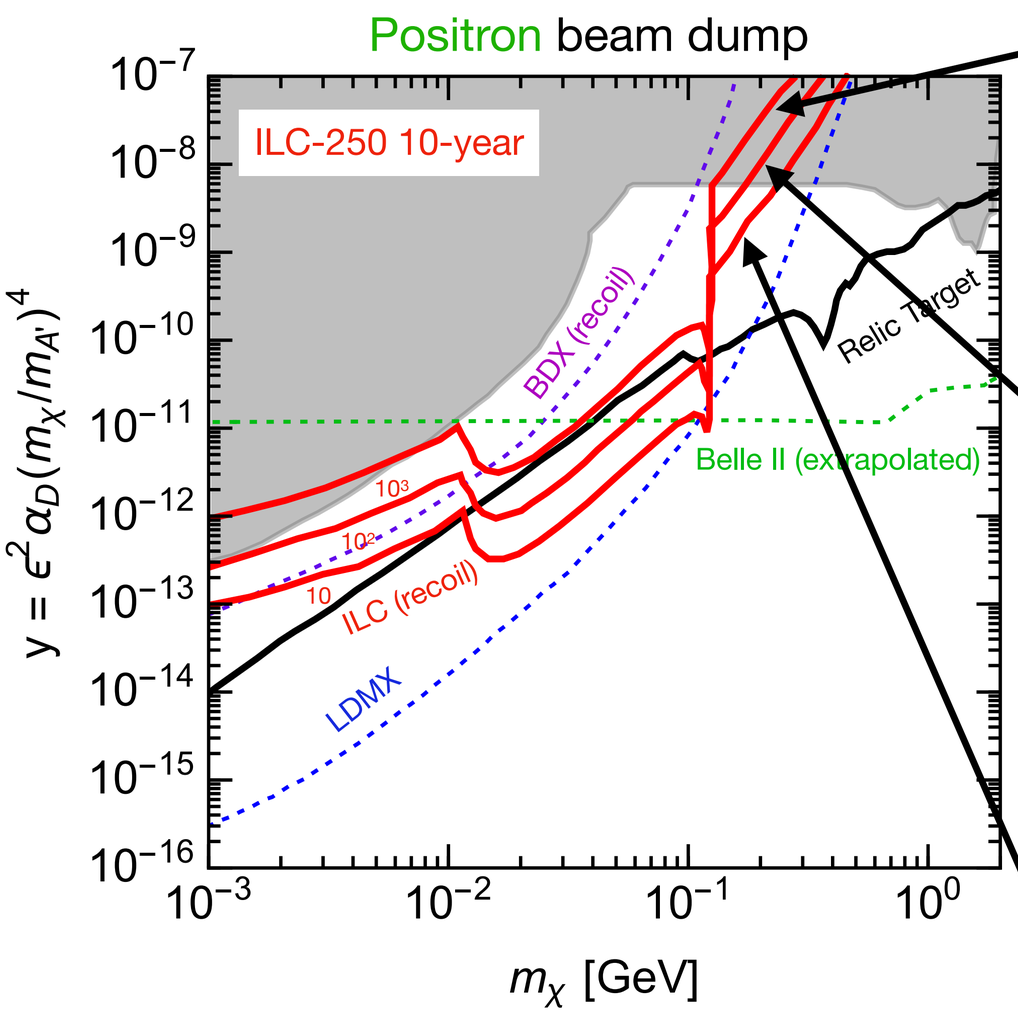
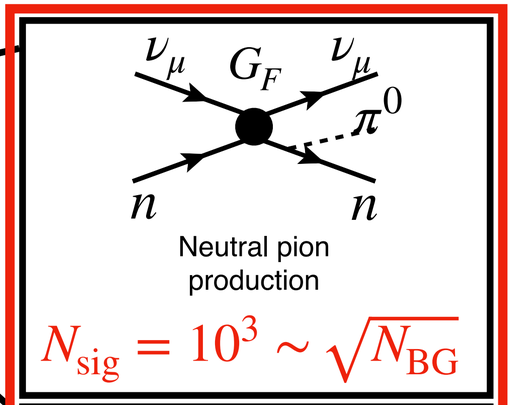
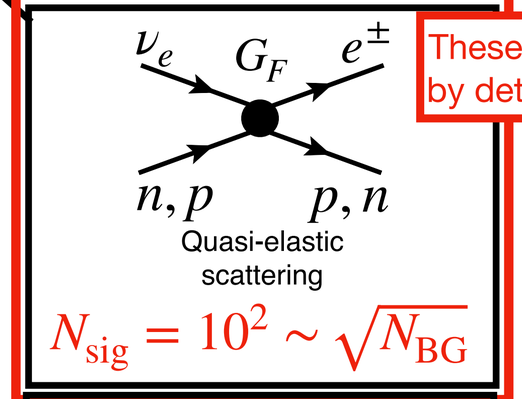
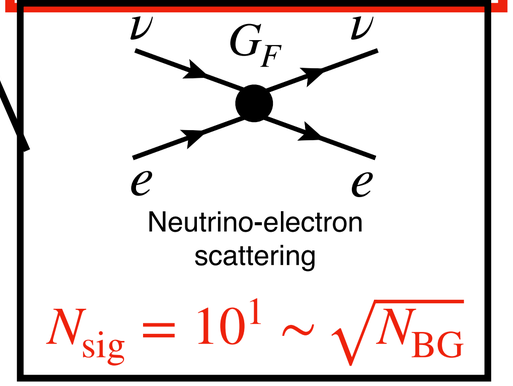






These BG may be reduced by detecting nucleon recoil



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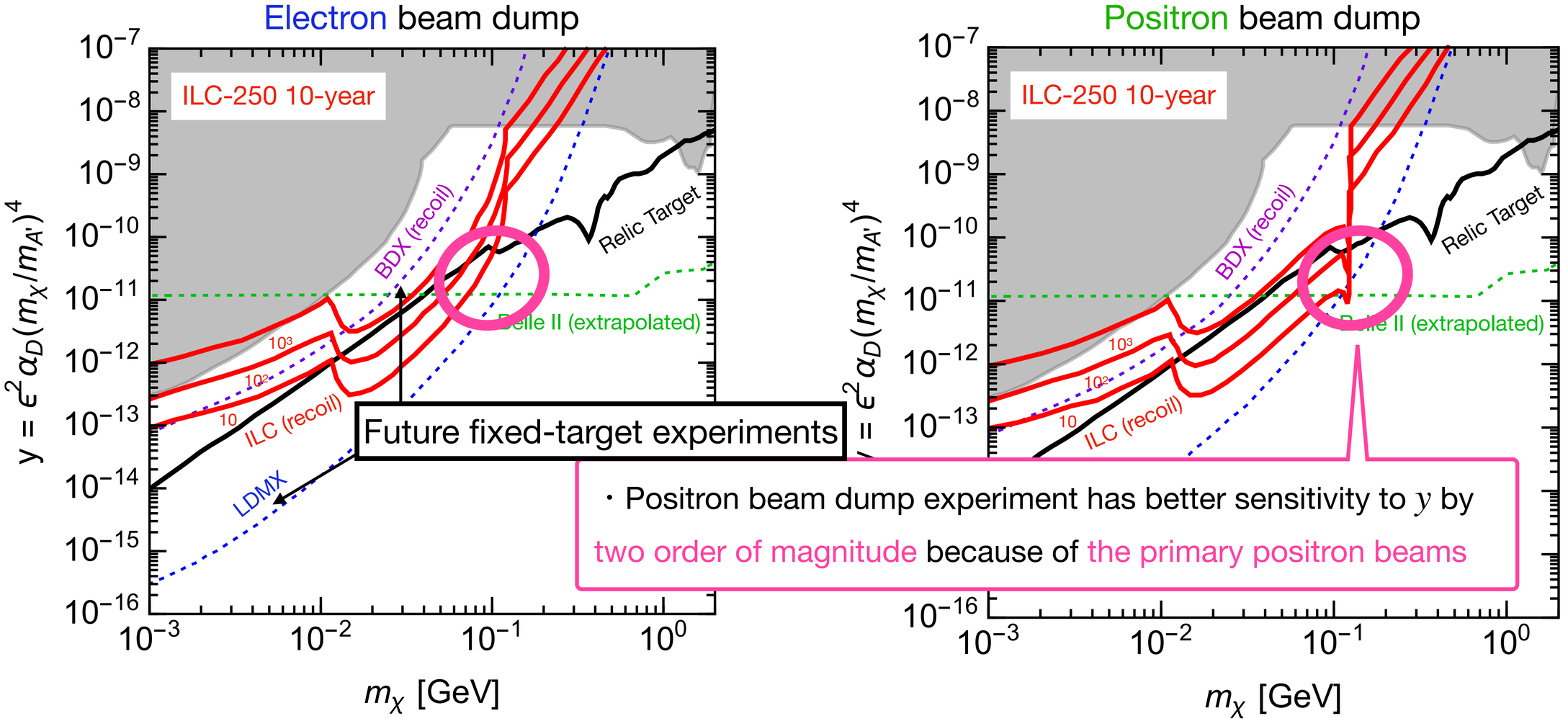
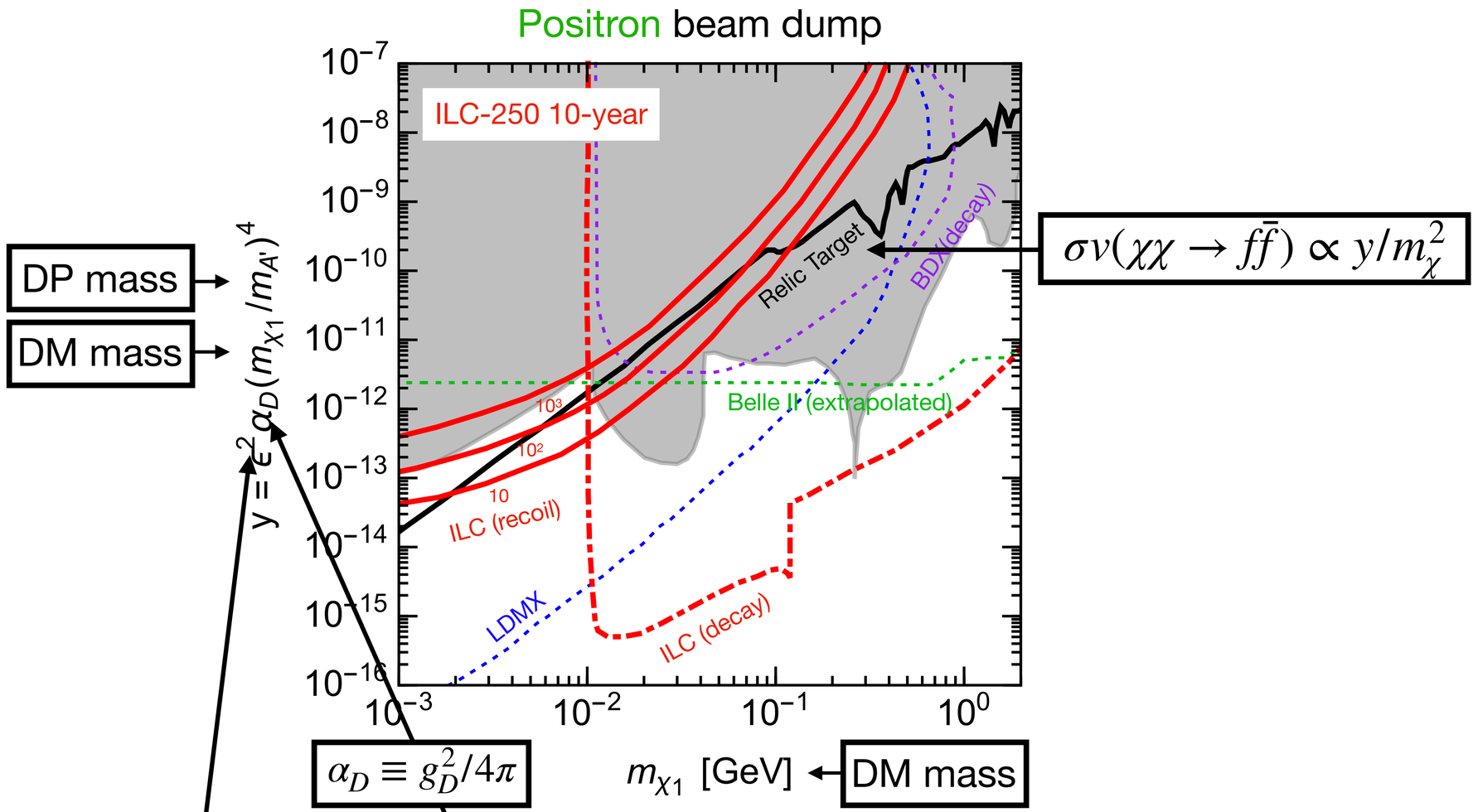


・Positron beam dump experiment has better sensitivity to y by two order of magnitude because of the primary positron beams

・ILC can have higher sensitivity than the BDX (electron recoil search) and reach the relic target

・ILC is complemental to the LDMX because the LDMX use the missing momentum technique

Sensitivity of ILC beam dump experiments (2)



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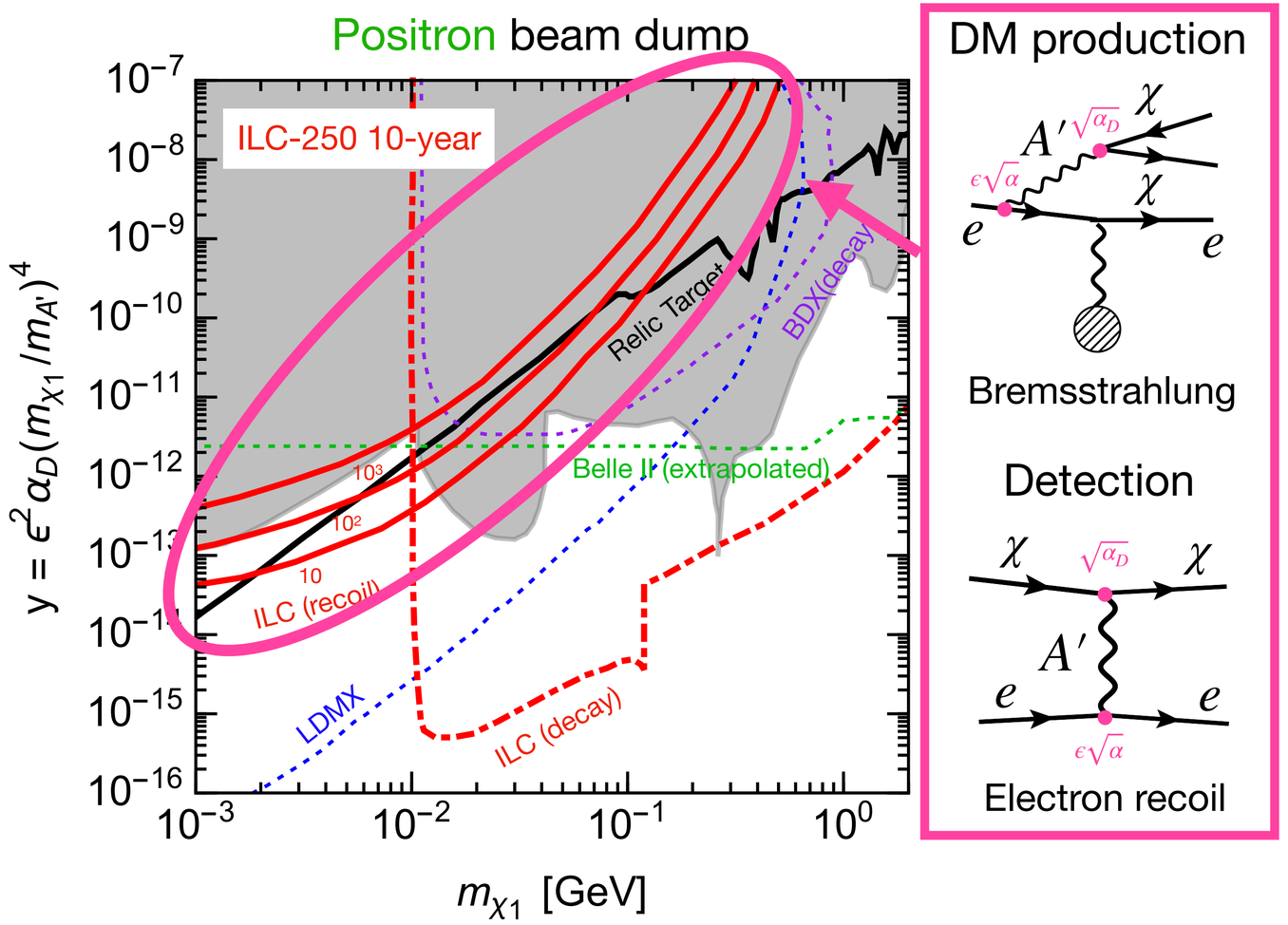

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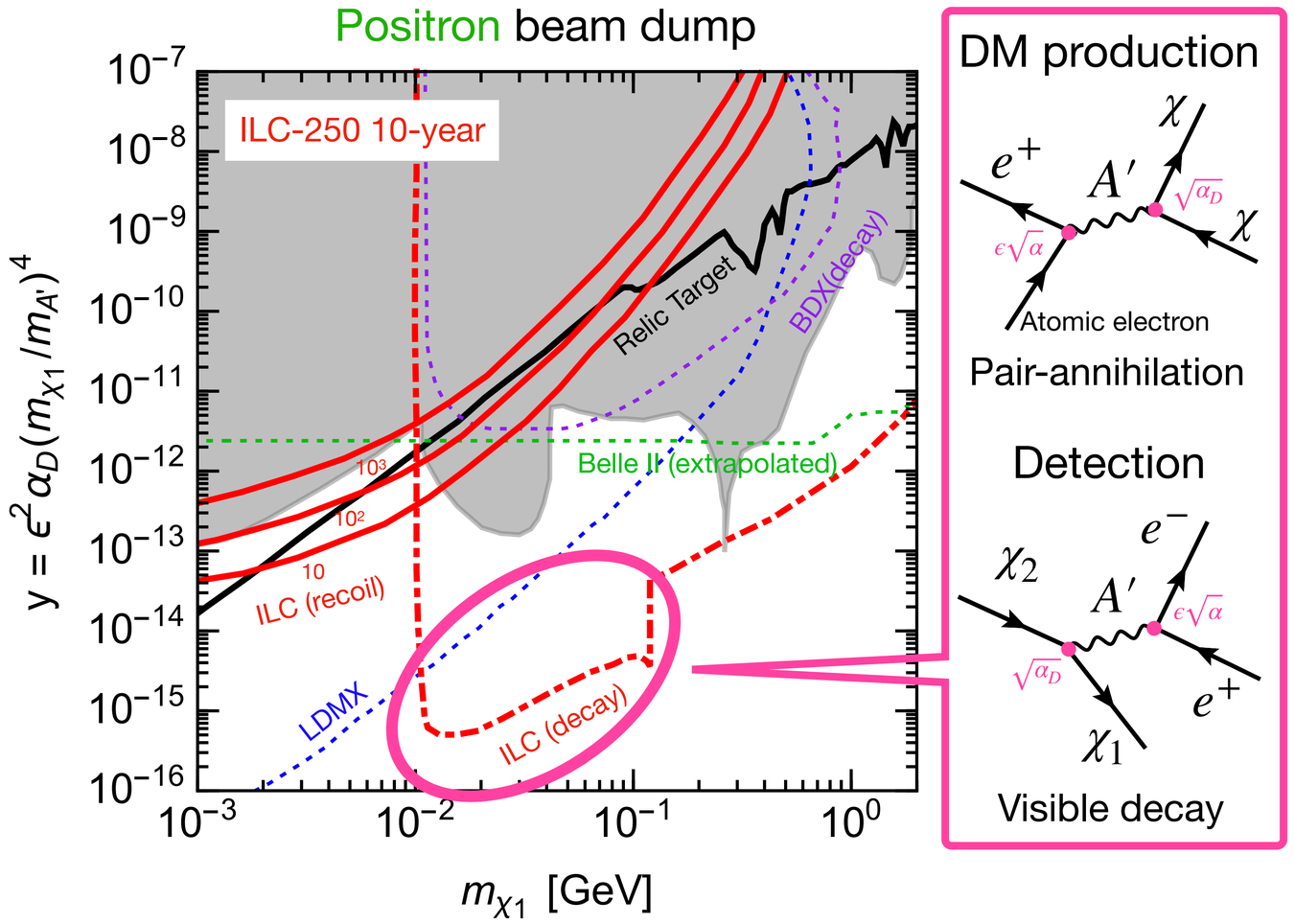

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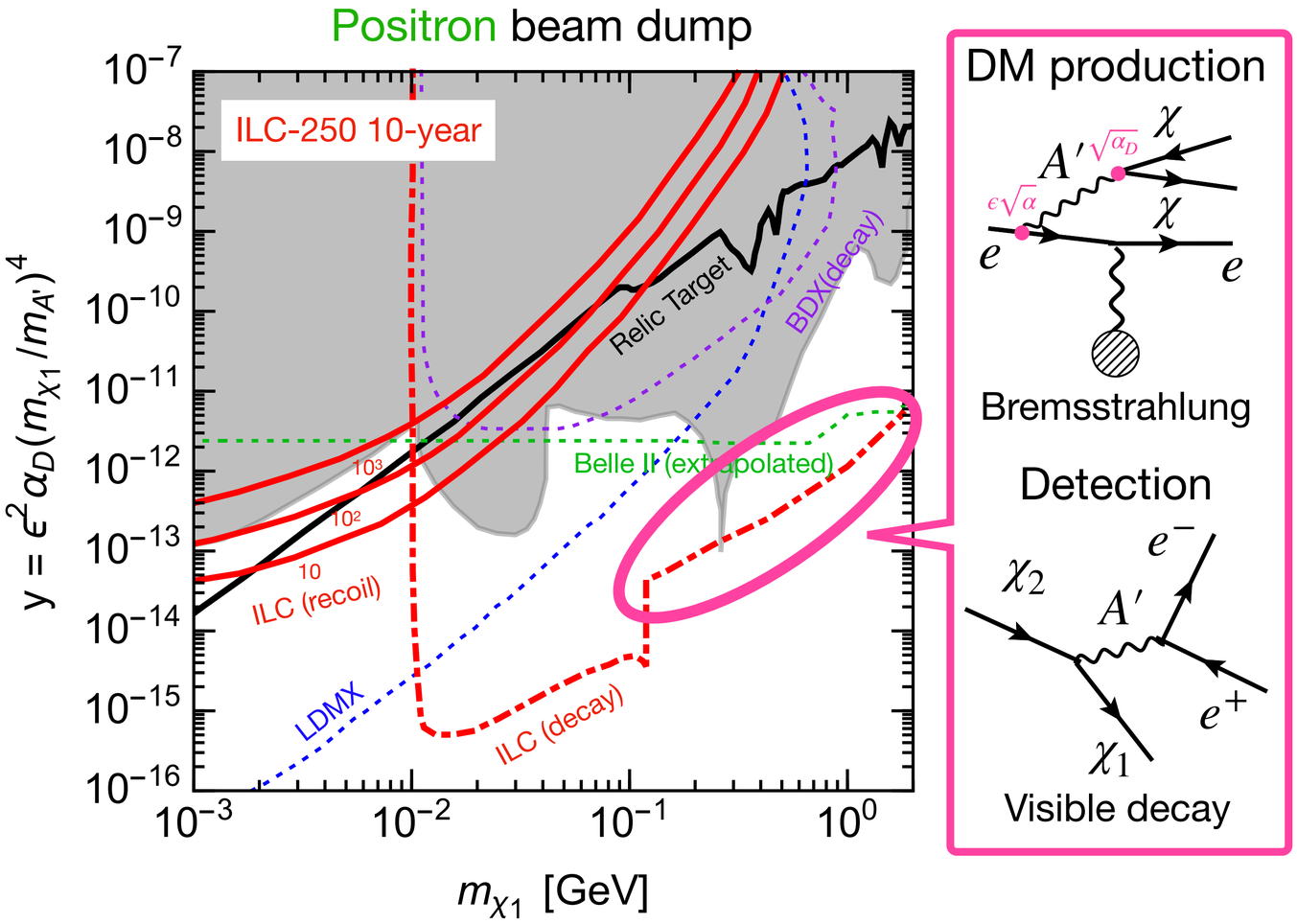

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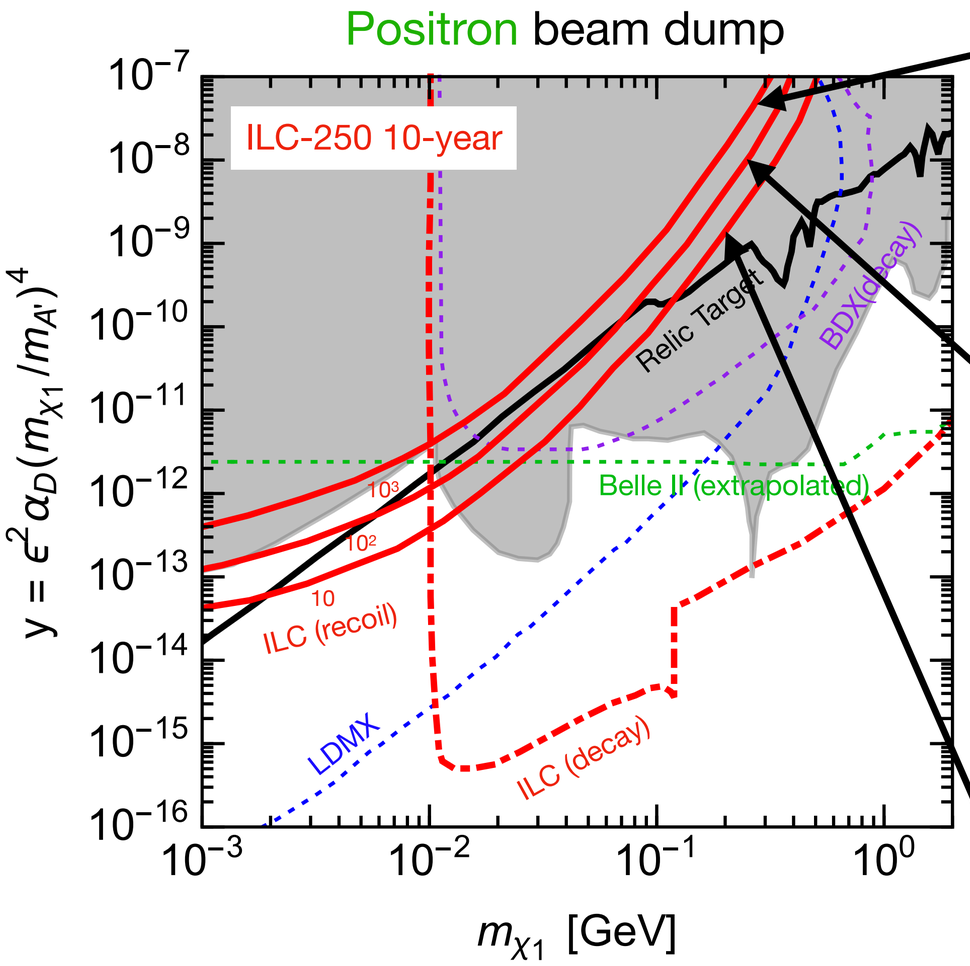
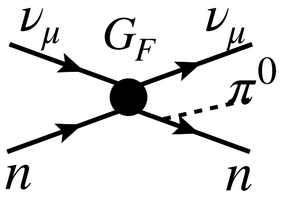
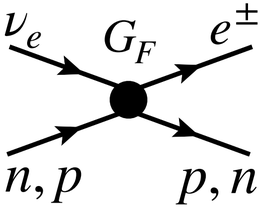




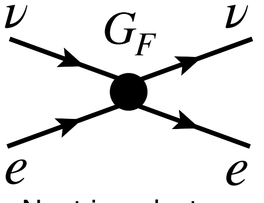
Neutral pion production

$N_{\rm sig} = 10^3 \sim \sqrt{N_{\rm BG}}$



Quasi-elastic scattering

$N_{\rm sig} = 10^2 \sim \sqrt{N_{\rm BG}}$



Neutrino-electron scattering

$N_{\rm sig} = 10^1 \sim \sqrt{N_{\rm BG}}$

Benchmark Model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\rm EM} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + {\rm H.c.})$

Dark photon

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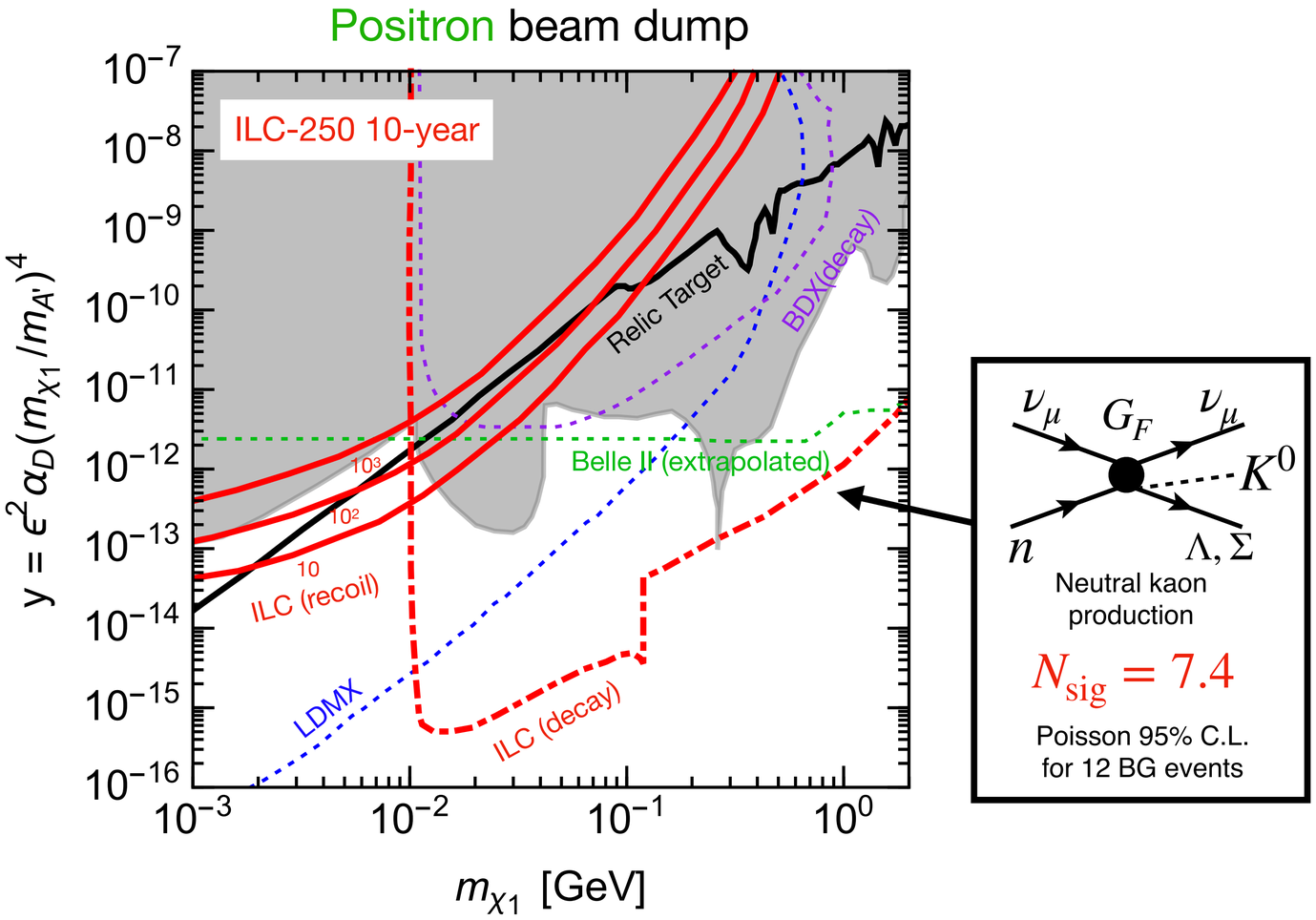

Neutral kaon production

$N_{\mathrm{sig}} = 7.4$

Poisson 95% C.L. for 12 BG events

Benchmark Model: $\mathscr{L} \supset \epsilon \cdot e A'_\mu J^\mu_{\mathrm{EM}} - g_D A'_\mu (i\bar{\chi}_2 \gamma^\mu \chi_1 + \mathrm{H.c.})$

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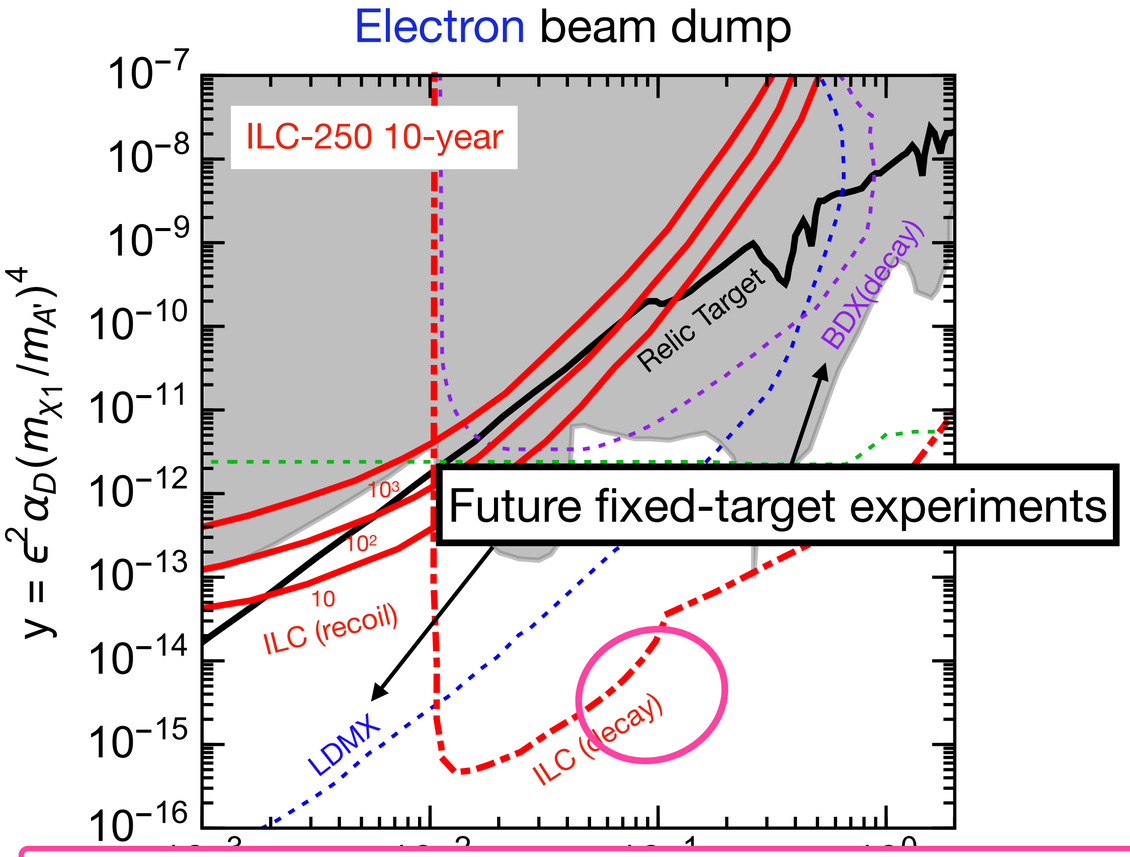
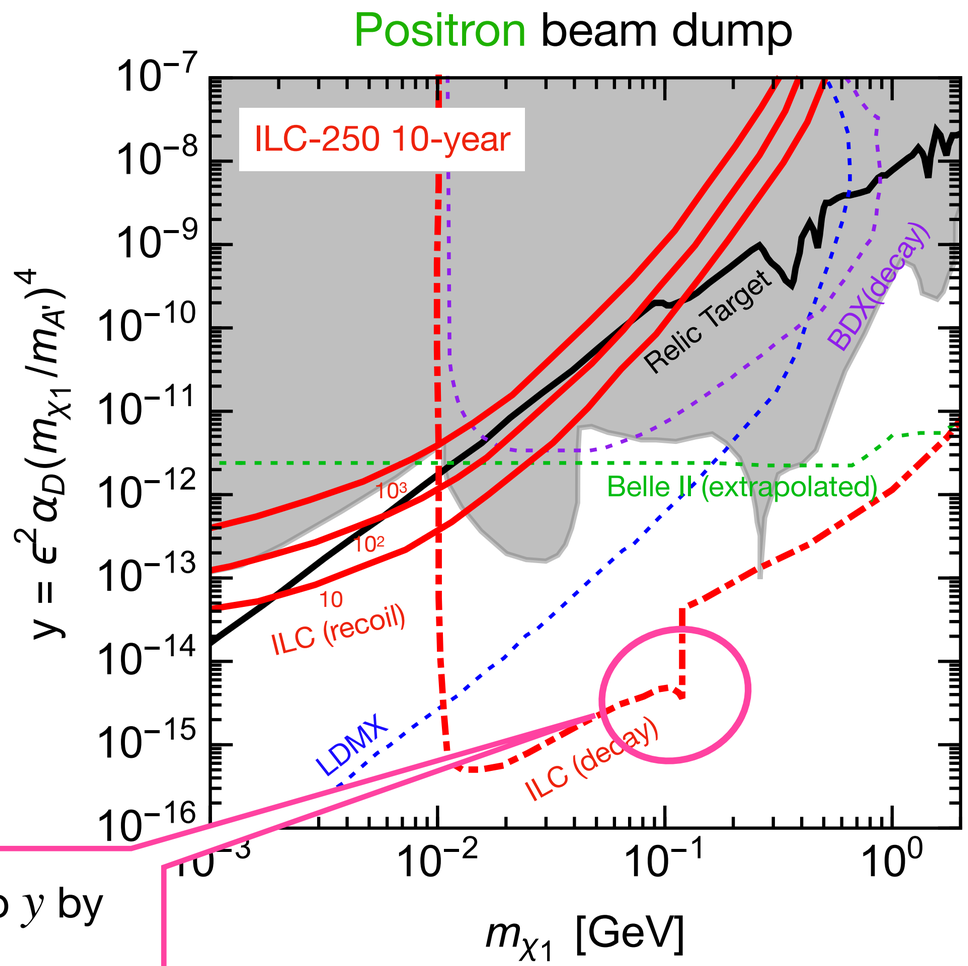
Comparison of electron and positron beam dump experiments (2)



Future fixed-target experiments



・Positron beam dump experiment has better sensitivity to y by two order of magnitude because of the primary positron beams

・ILC can reach the relic target

・ILC visible decay search has higher sensitivity than the LDMX (missing momentum technique)

Summary

- We performed a feasibility study of the ILC invisible decay search by using benchmark models: inelastic fermion DM, etc.

- Primary positron beams produce new particles by pair-annihilation process, and the positron beam dump experiment has better performance than the electron beam dump experiment

- For electron recoil searches, the ILC has better performance than the BDX experiment and can reach the relic target

- For visible decay searches, the ILC has better performance than the LDMX (missing momentum search)