

New Physics Searches at the ILC positron and electron beam dumps

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Based on

KA, S. Iwamoto, Y. Sakaki, D. Ueda, arXiv : [2105.13768](https://arxiv.org/abs/2105.13768) [hep-ph]



Introduction

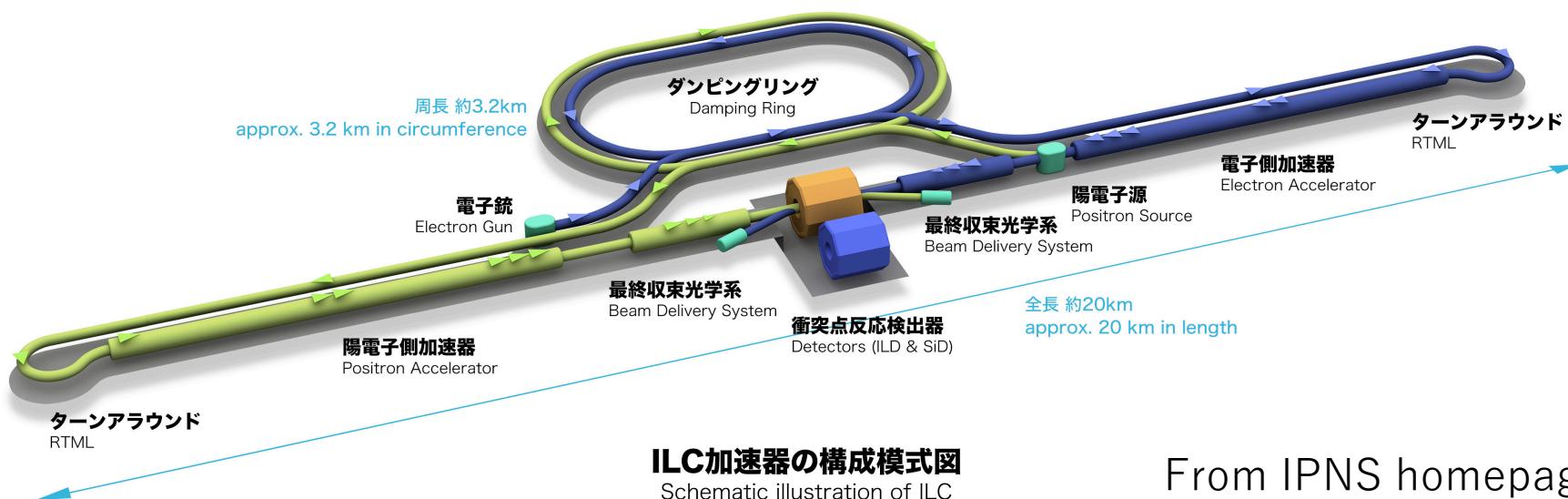
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International Linear Collider

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 IPNS homepage

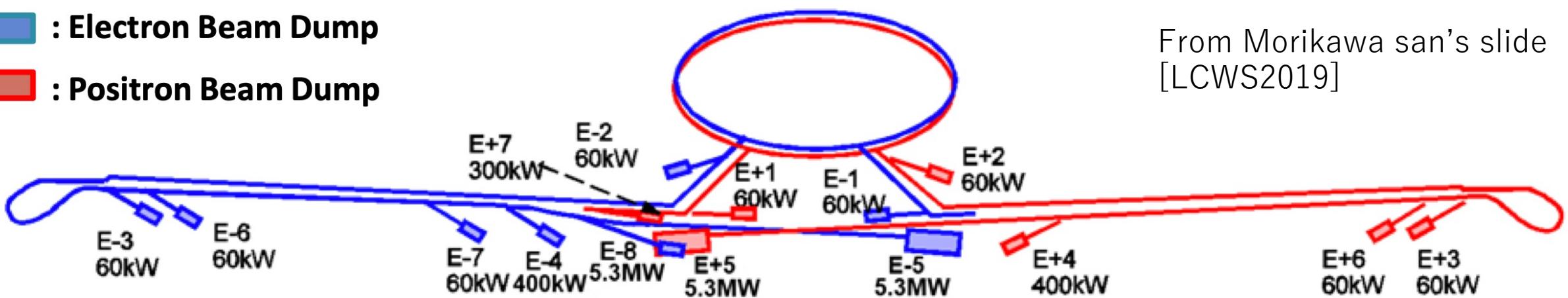
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Beam dumps in ILC

Total 15 beam dumps in ILC

- : Electron Beam Dump
- : Positron Beam Dump



From Morikawa san's slide
[LCWS2019]

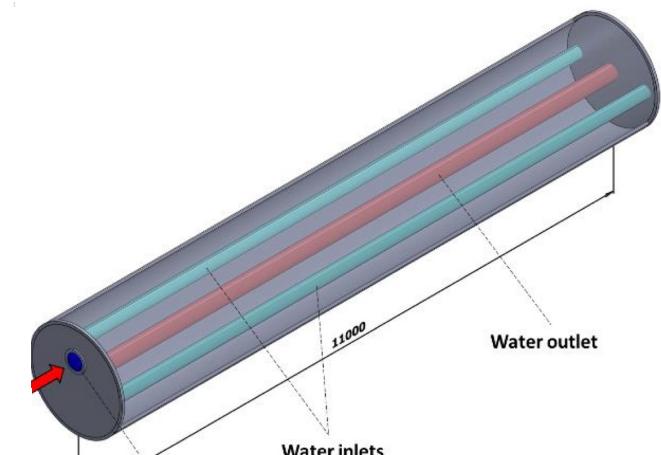
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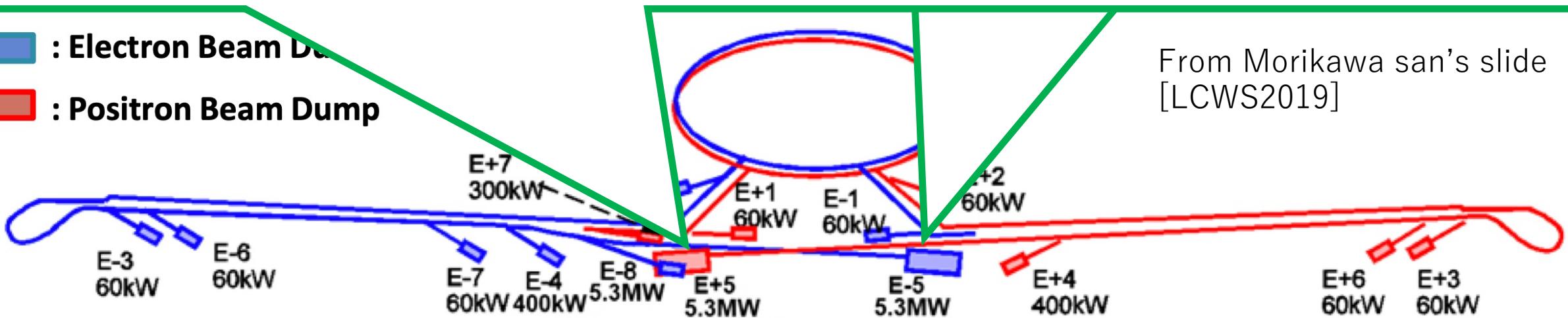
Main beam dump

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



 : Electron Beam Dump

 : Positron Beam Dump



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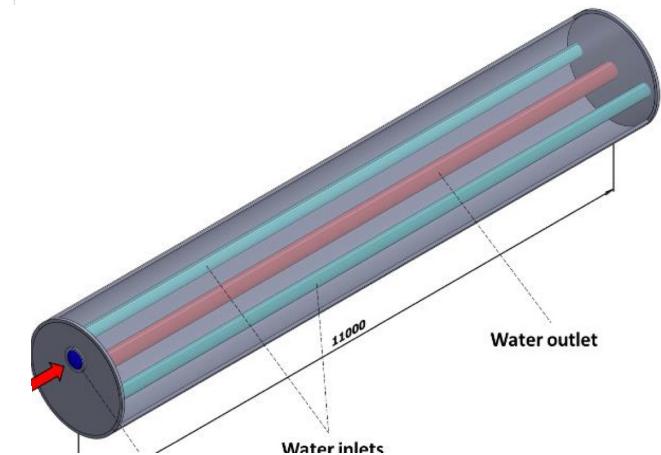
Beam dumps in ILC

Main beam dump

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

What a waste !!

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

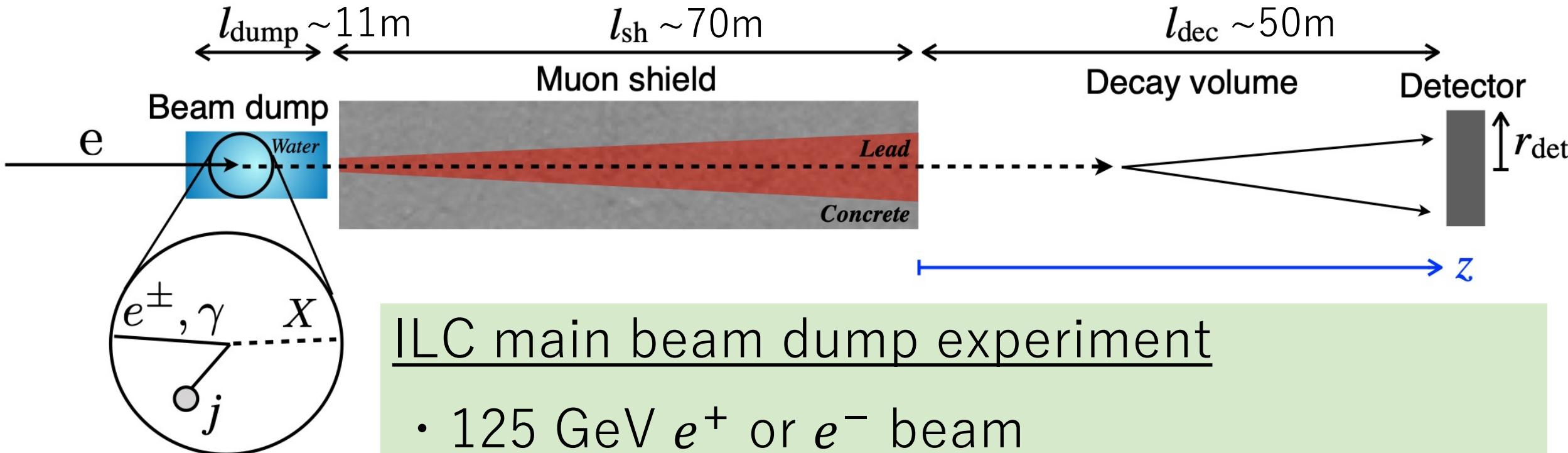


→ Use them as beams in beam dump experiment

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Beam dump experiment in ILC



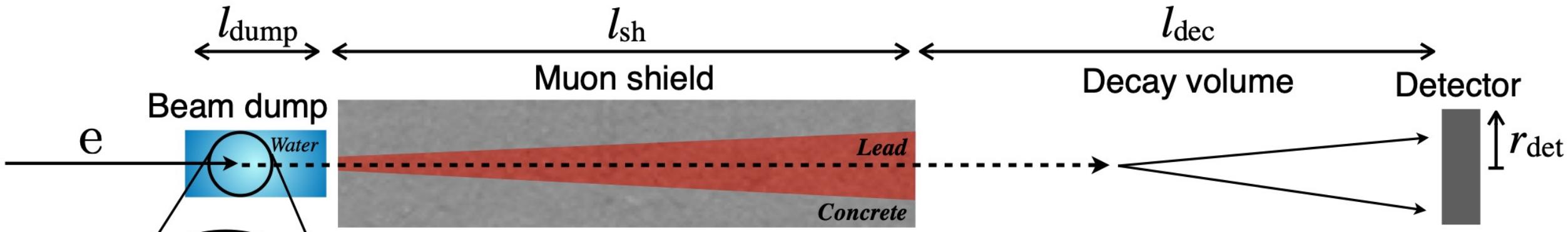
ILC main beam dump experiment

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

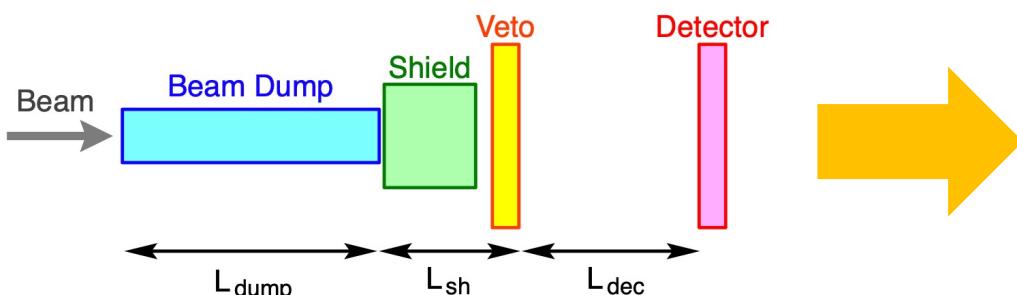
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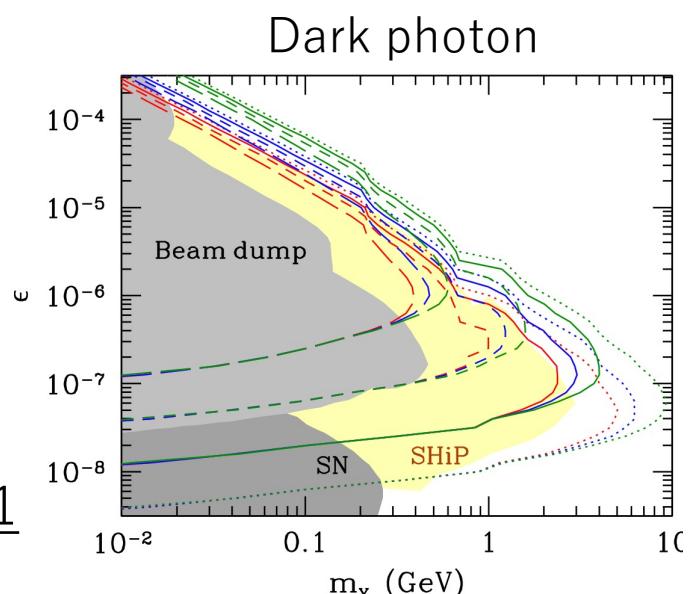
Beam dump experiment in ILC



Previous works



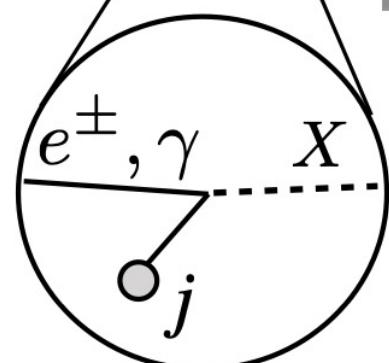
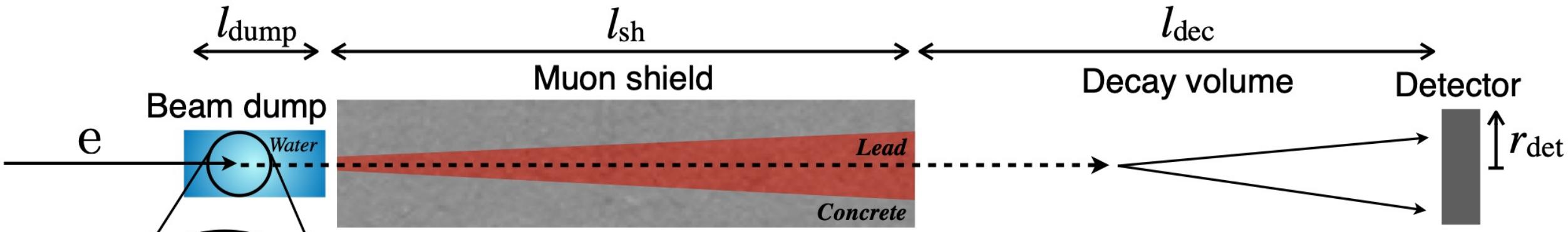
S. Kanemura, T. Moroi, T. Tanabe, PLB 751
(2015) 25-28, arXiv : 1507.02809 [hep-ph]



Introduction

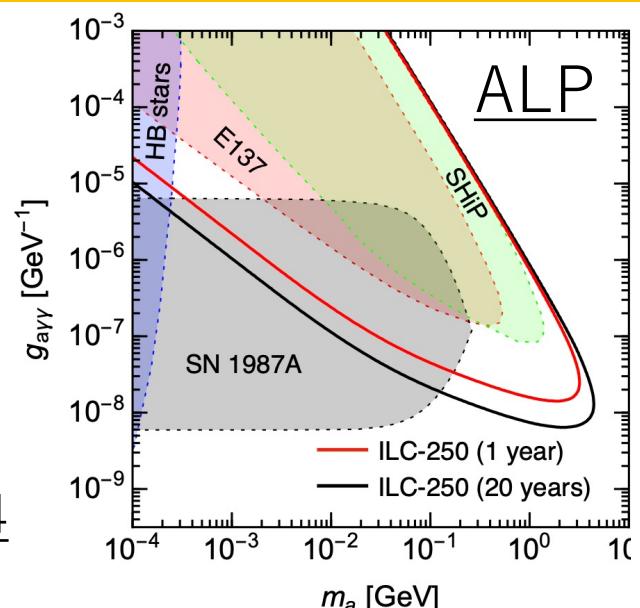
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Beam dump experiment in ILC



Previous works

Y. Sakaki, D. Ueda, PRD 103 (2021) 3, 035024
arXiv : 2009.13790 [hep-ph]



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Beam dump experiment in ILC

Advantage

- Can explore **intensity frontier** (light weakly coupled new physics [-> long lived])



Energy frontier (heavy strongly coupled new physics, large energy deposit)



Target of ILC

- **Cheep** construction & run costs

Beams, beam dump, and muon shield can be used as they are.

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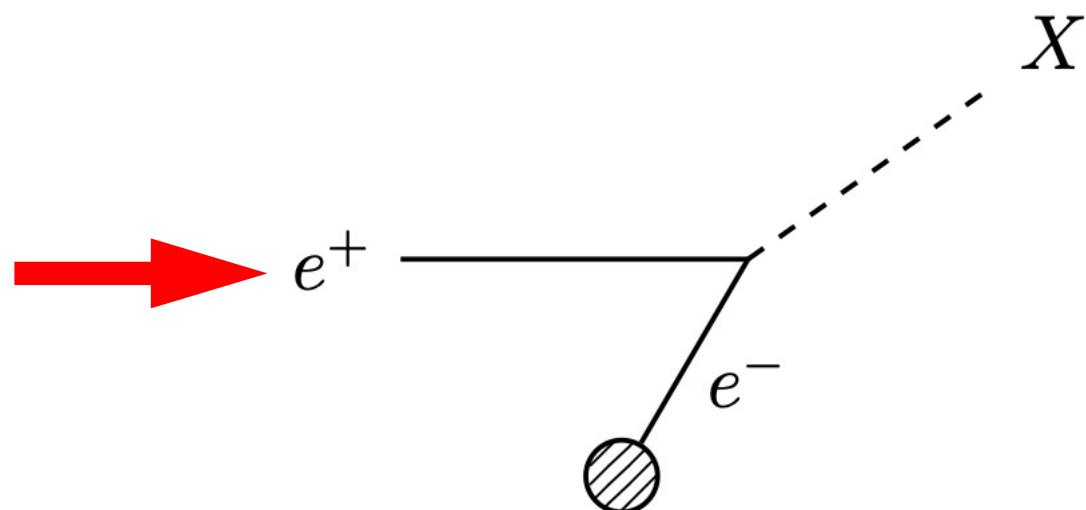
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Beam dump experiment in ILC

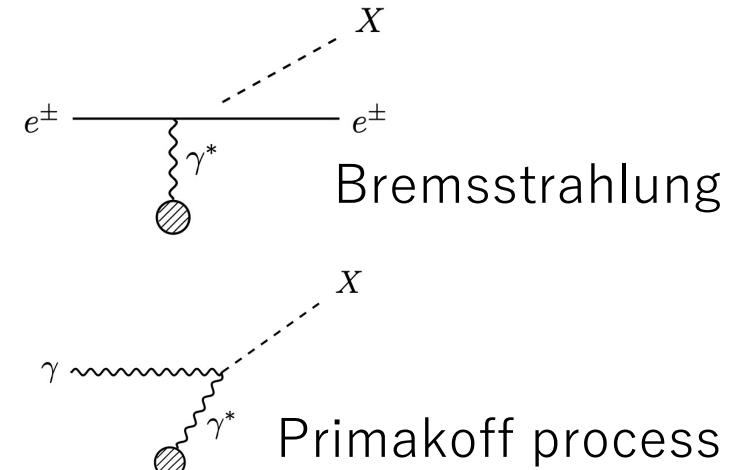
Advantage

- Can use **positron beam**

→ Pair annihilation process



Other process



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Production Process

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

leptophilic gauge boson →

Next Niki san's talk !

Beam Dump Experiment

Beam Dump Experiment

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Number of interaction

Luminosity

$$\mathcal{L} = N_{e^\pm} n_j \frac{dl_i}{dE_i}$$

N_{e^\pm} : Number of incident e^\pm into beam dump
($\sim 10^{21}$ / year @ ILC)

n_j : Number density of j in target

$$\left(n_{\text{nuclear}} = \frac{N_{\text{Avogadro}} \rho_{\text{H}_2\text{O}}}{A_{\text{H}_2\text{O}}}, \quad n_e = Z_{\text{H}_2\text{O}} n_{\text{nuclear}} \right)$$

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Number of interaction

Luminosity

$$\mathcal{L} = N_{e^\pm} n_j \frac{dl_i}{dE_i}$$

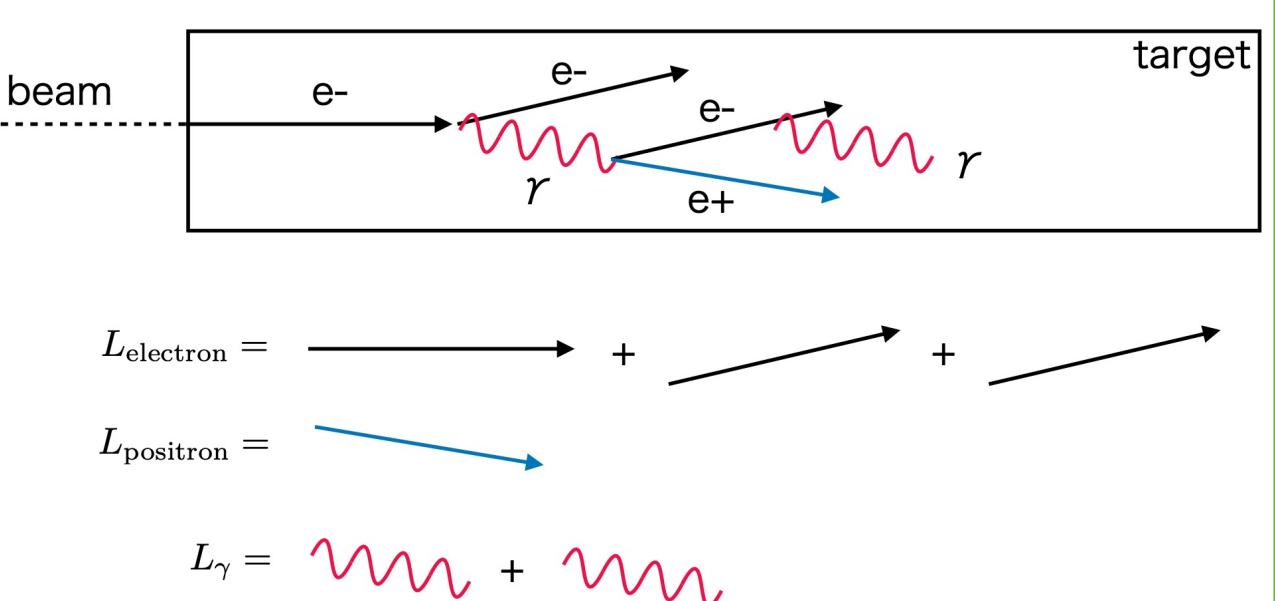
$\frac{dl_i}{dE_i}$: Track length of i
(Averaged total flight length of i
in target with energy range $[E, E + dE]$)

Beam Dump Experiment

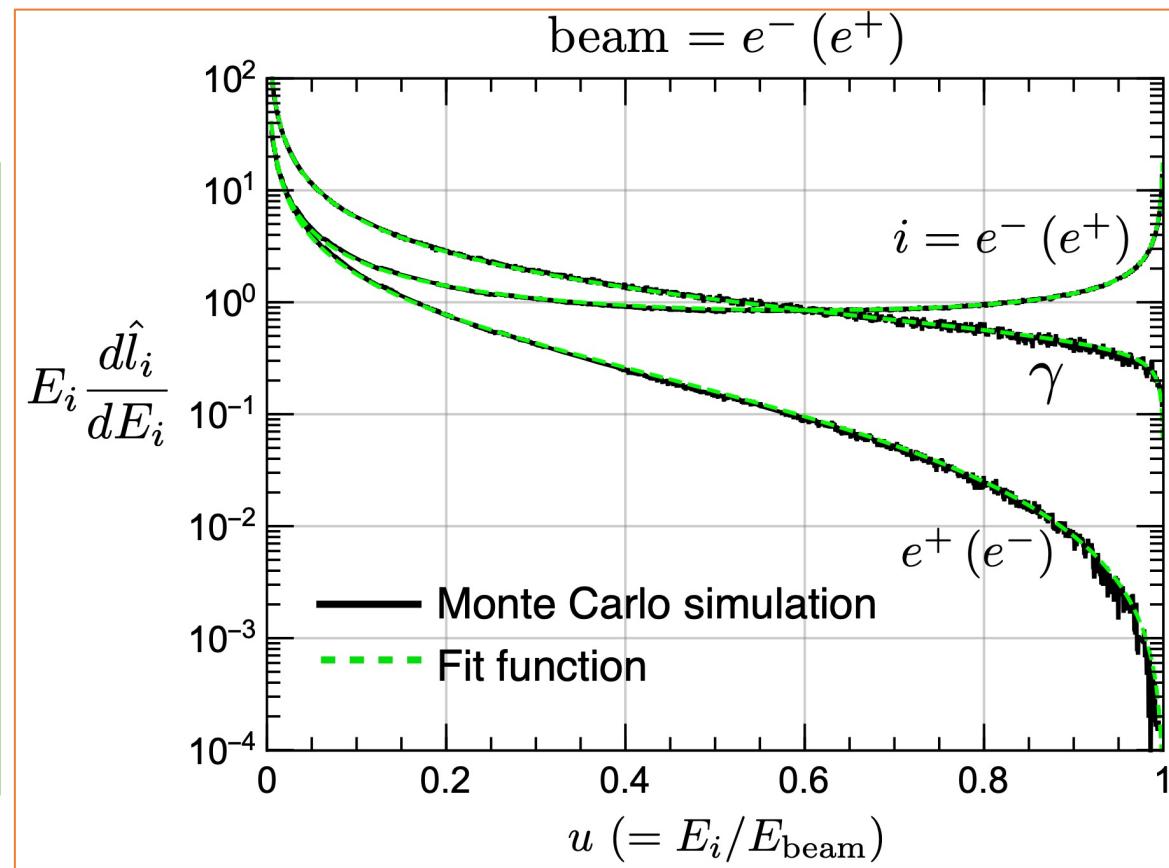
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Number of interaction

Track length



From Sakaki san's slide



Beam Dump Experiment

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Number of interaction

Production number of light bosons

$$N = \int_0^{E_{\text{beam}}} dE_i N_{e^\pm} n_j \frac{dl_i}{dE_i} \sigma_{\text{prod}}(E_i)$$

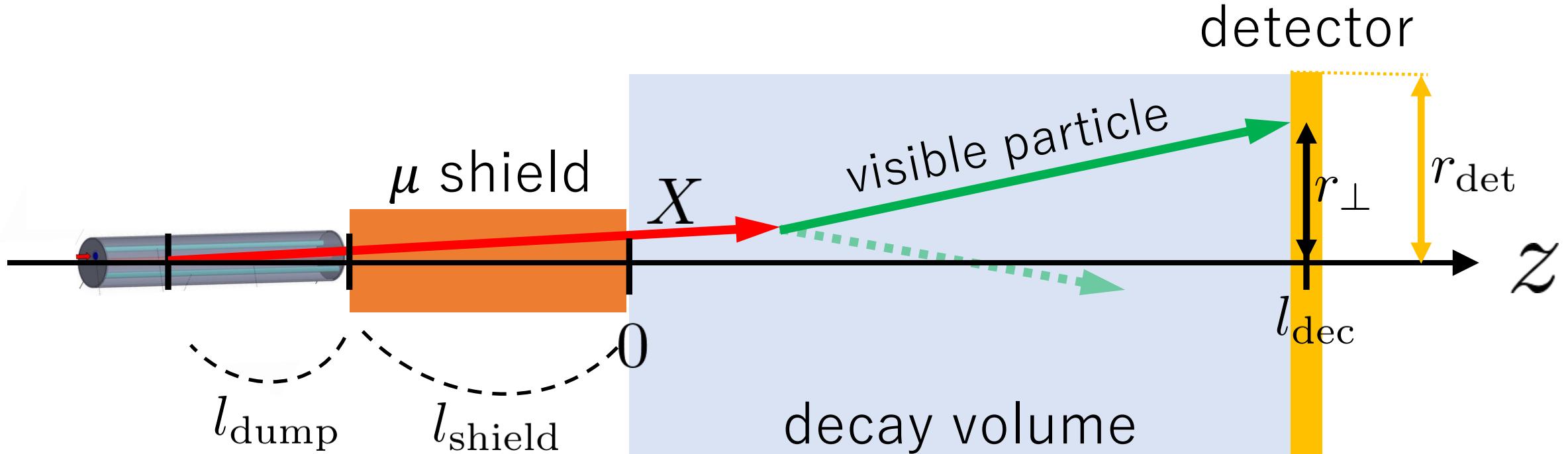
luminosity

$\sigma_{\text{prod}}(E_i)$: Production cross section of light bosons

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Geometrical Acceptance



Acceptance

$$\text{Acc}(X) = \int_0^{l_{\text{dec}}} dz \frac{dP_{\text{dec}}}{dz} \cdot \Theta(r_{\text{dec}} - r_{\perp})$$

$\frac{dP_{\text{dec}}}{dz}$: decay probability

Beam Dump Experiment

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Number of signal events

Number of signal events @ detector

$$N = \int_0^{E_{\text{beam}}} dE_i N_{e^\pm} n_j \frac{dl_i}{dE_i} \sigma_{\text{prod}}(E_i) \text{Acc}(X)$$

Acceptance

$$\text{Acc}(X) = \int_0^{l_{\text{dec}}} dz \frac{dP_{\text{dec}}}{dz} \cdot \Theta(r_{\text{dec}} - r_\perp)$$

Decay probability

$$\frac{dP_{\text{dec}}}{dz} = \frac{1}{l_X^{(\text{lab})}} \exp \left(-\frac{l_{\text{dump}} + l_{\text{shield}} + z}{l_X^{(\text{lab})}} \right)$$

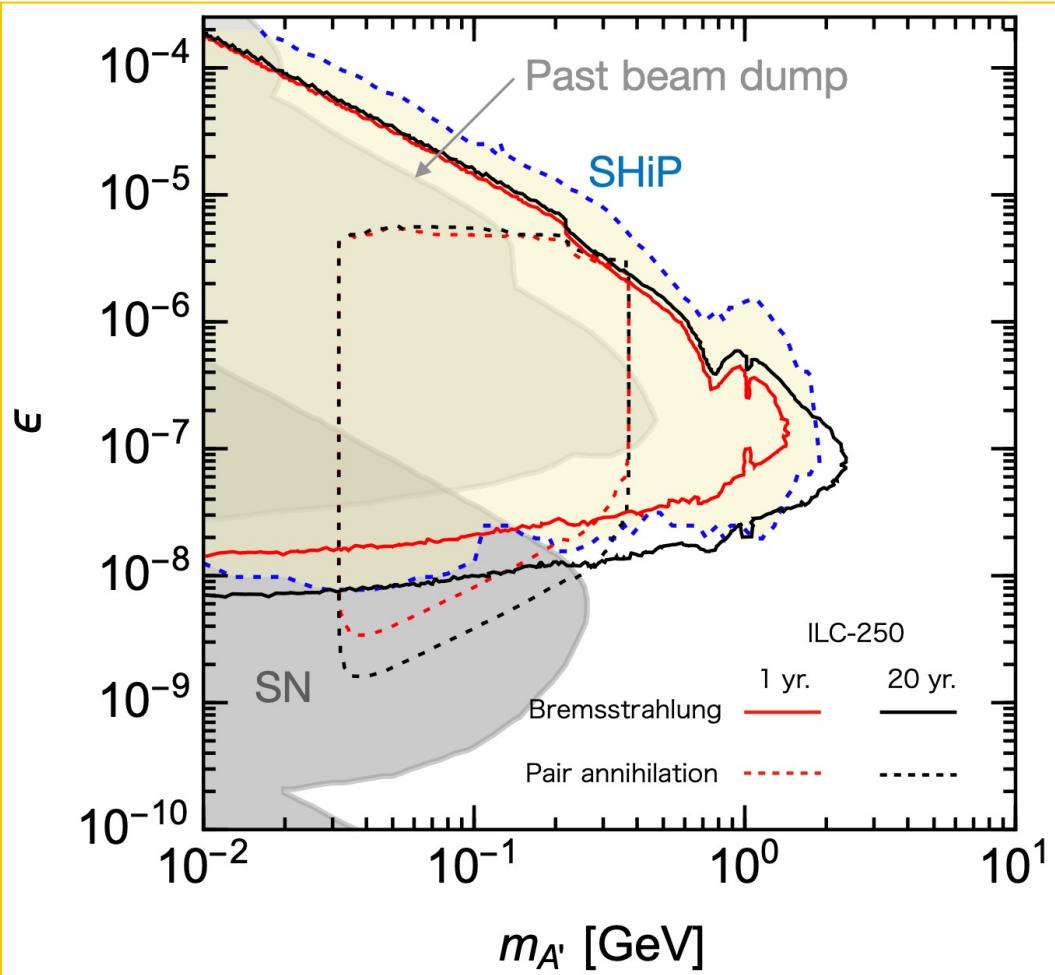
$l_X^{(\text{lab})}$: decay length
in lab frame

Result

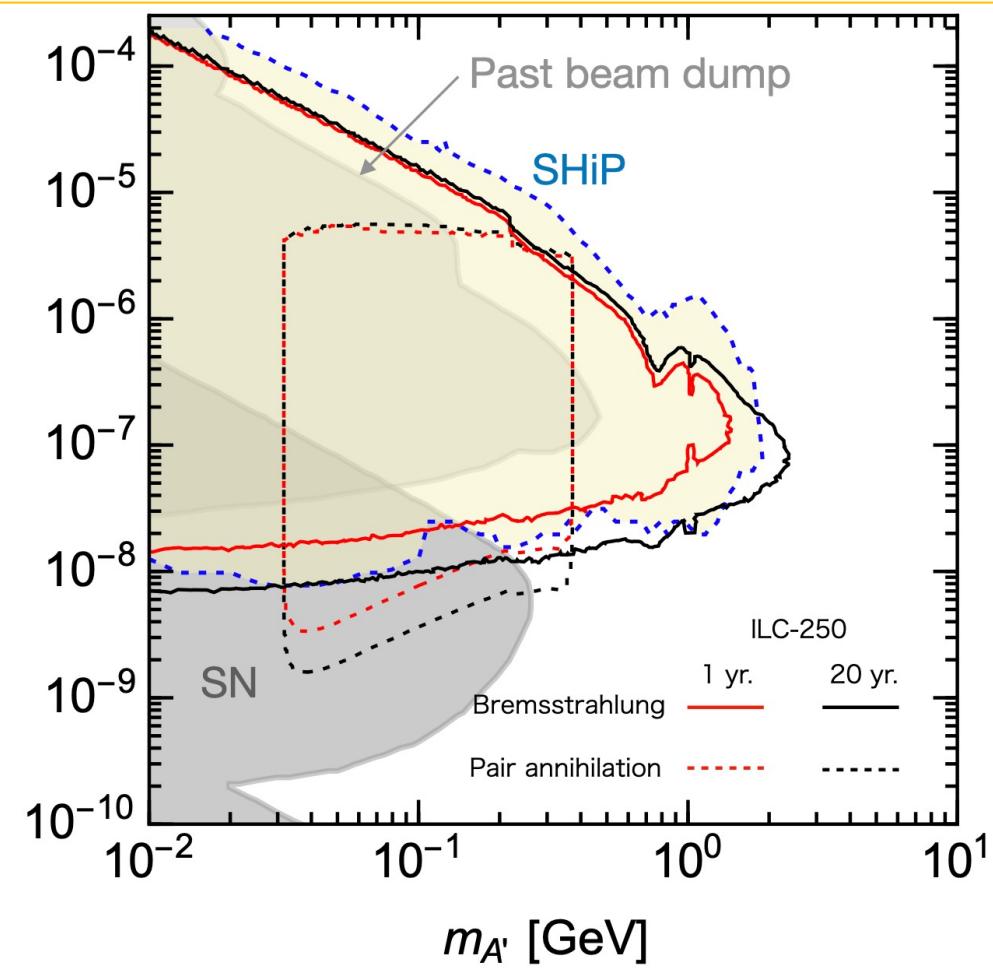
Result

Dark photon case

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(a) electron beam dump

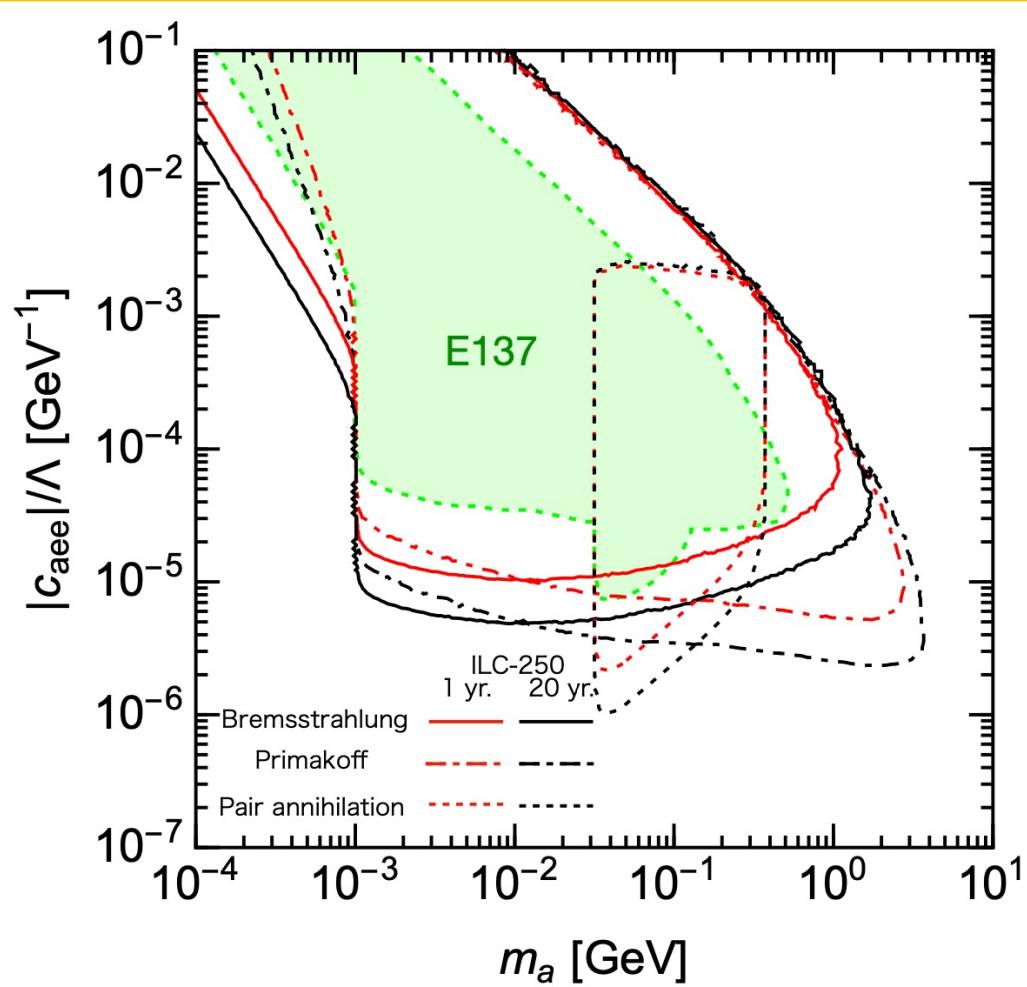


(b) positron beam dump

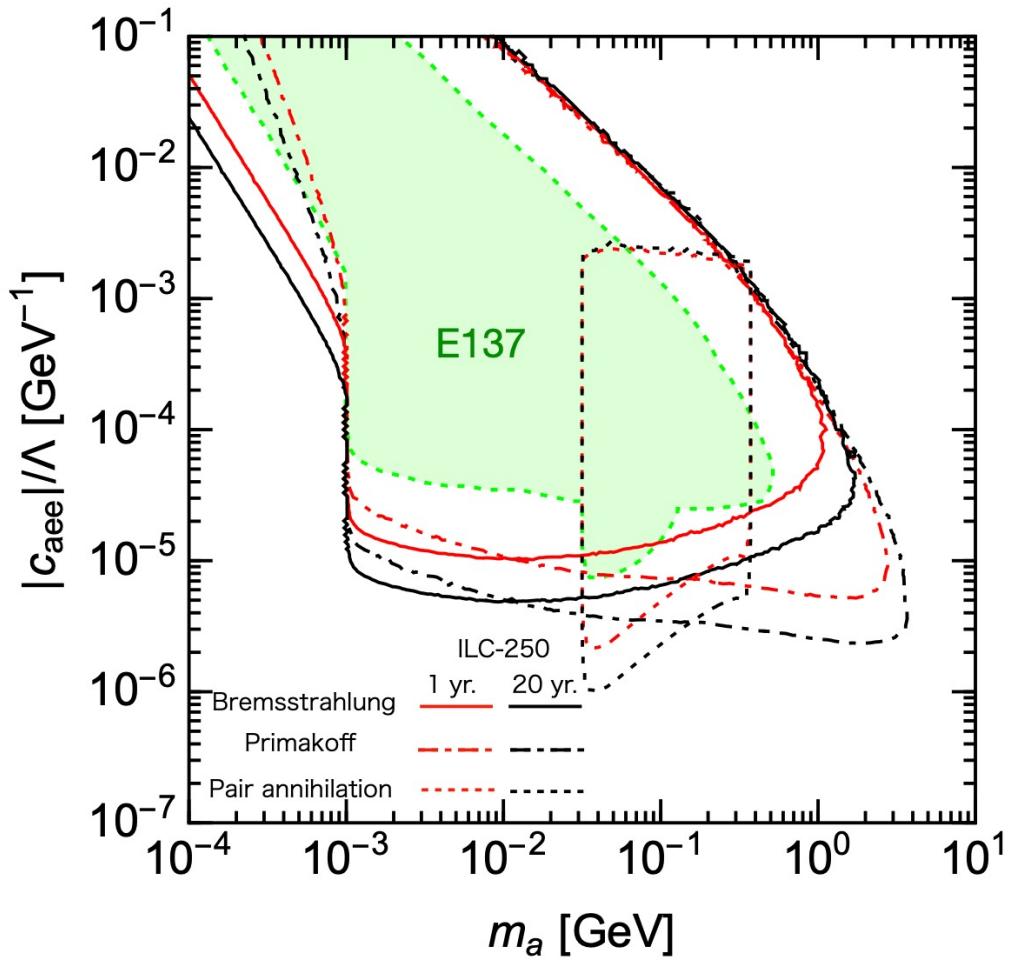
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ALP case (model 1)

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(a) electron beam dump

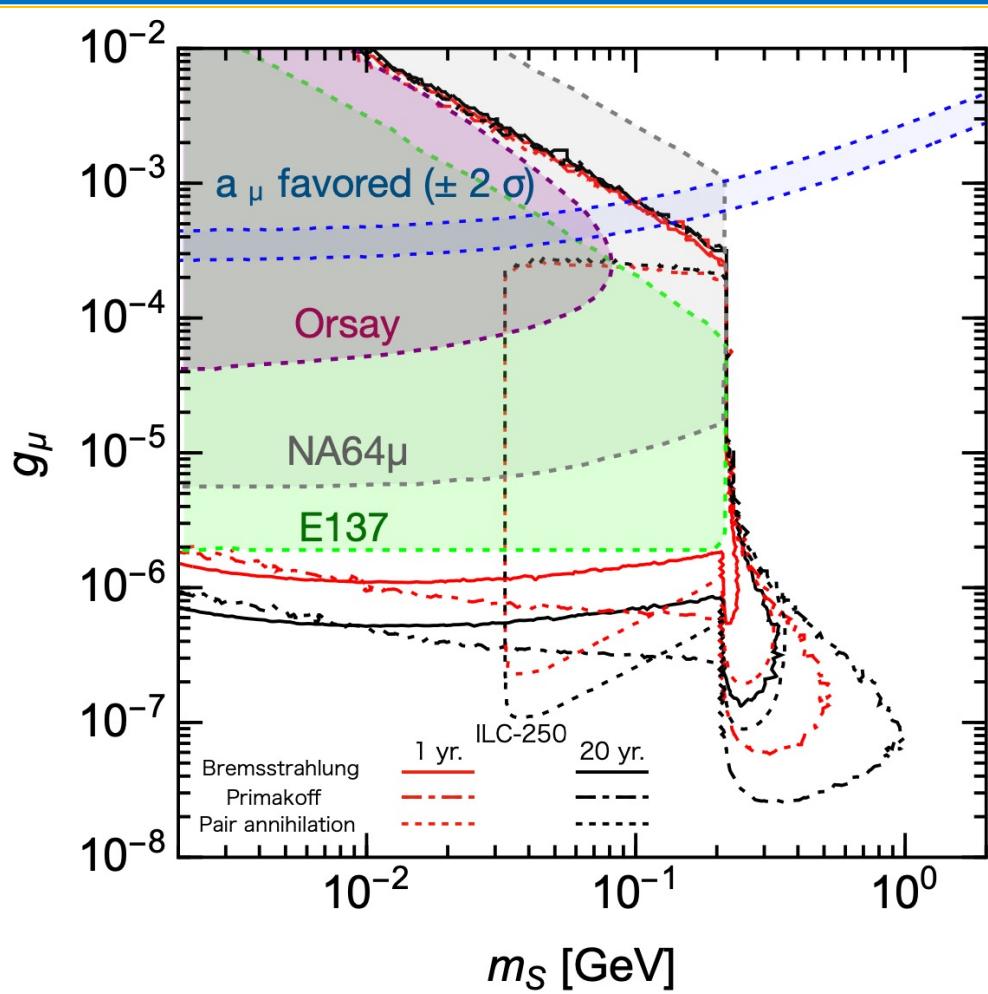


(b) positron beam dump

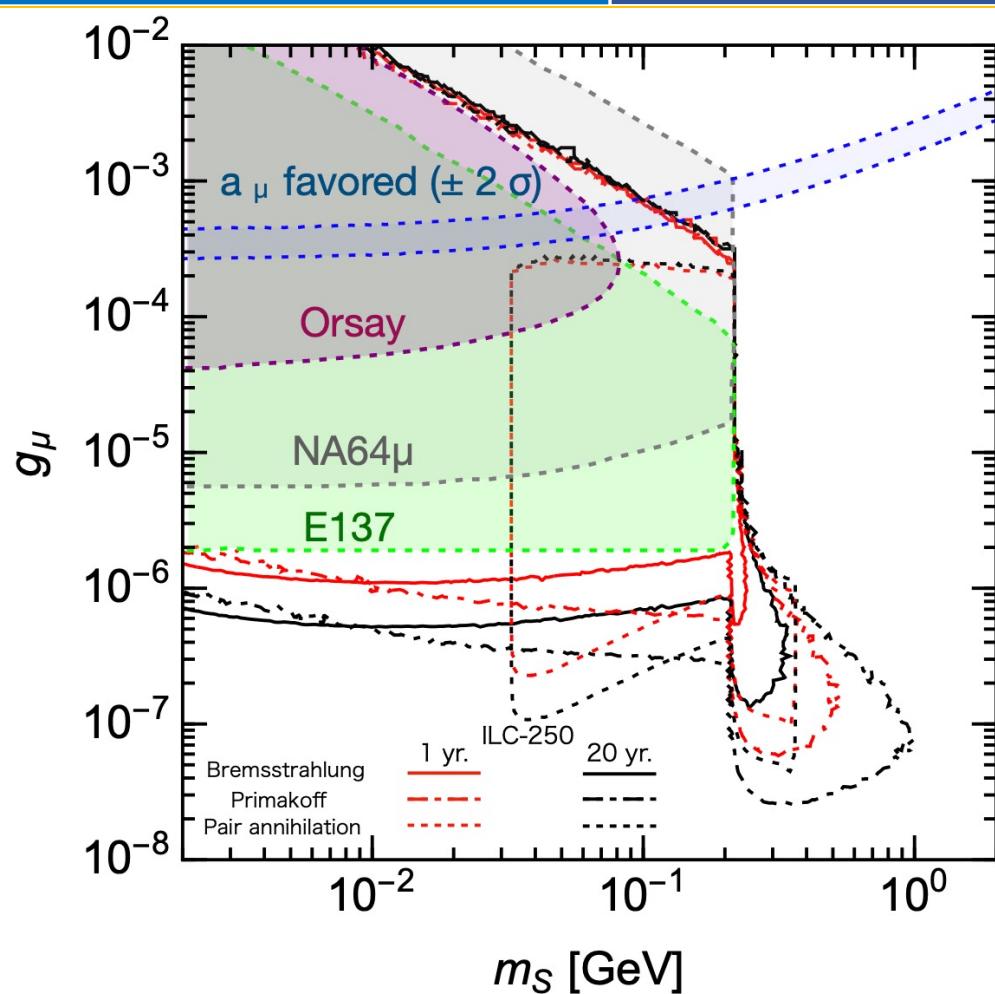
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Scalar case

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(a) electron beam dump



(b) positron beam dump

Summary

- ILC beam dump experiment can search for the regions where interactions with SM particles are small, and in such regions, new physics may be hidden.
- As a benchmark, we comprehensively study sensitivities to dark photon, ALPs and light scalar boson, using ILC positron and electron beam dumps.
- ILC beam dump experiment has an order of magnitude better performance than other beam dump experiments

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Lagrangian

Dark photon model

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

Light scalar boson model

$$\mathcal{L} = \frac{1}{2}(\partial_{\mu}S)^2 - \frac{1}{2}m_S^2S^2 - \sum_{\ell=e,\mu,\tau} g_{\ell}S\bar{\ell}\ell - \frac{1}{4}g_{S\gamma\gamma}SF_{\mu\nu}F^{\mu\nu}$$

$$g_e/m_e = g_{\mu}/m_{\mu} = g_{\tau}/m_{\tau}$$



Loop induced

Model

Lagrangian

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ALP model

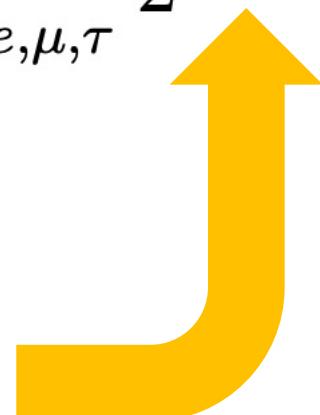
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2 + \sum_{\ell=e,\mu,\tau} \frac{1}{2}c_{a\ell\ell}\frac{\partial_\mu a}{\Lambda}\bar{\ell}\gamma^\mu\gamma_5\ell - \frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

Case 1

$$c_{aee} \neq 0, \quad c_{a\mu\mu} = c_{a\tau\tau} = 0$$

Case 2

$$c_{aee} = c_{a\mu\mu} = c_{a\tau\tau}$$

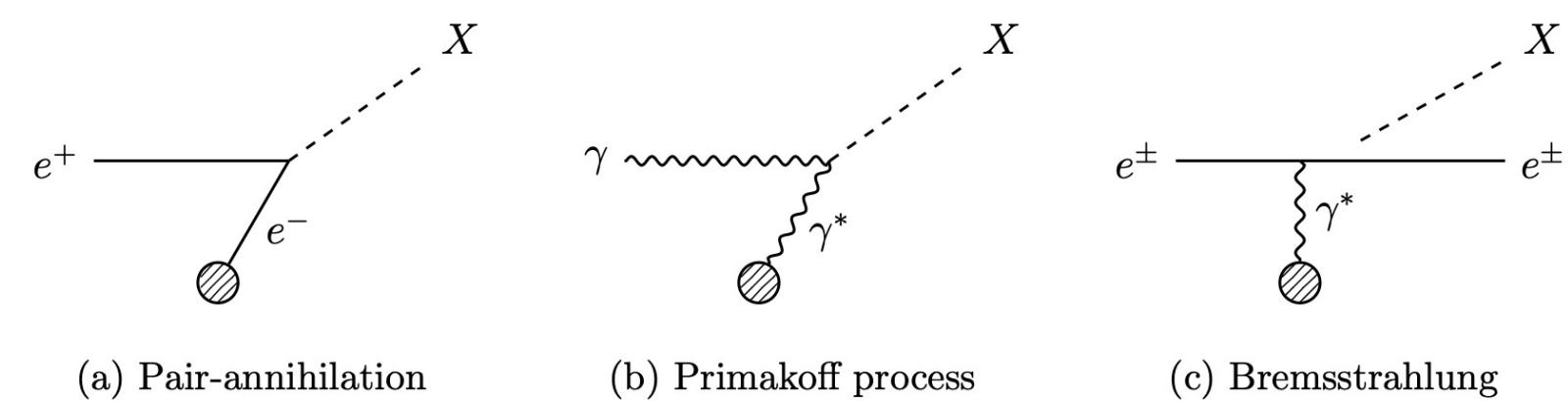


Loop induced

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Number of signal events

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$$N_{\text{signal}}^{(a)} = N_{e^\pm} \int dE_{e^+} \frac{dl_{e^+}}{dE_{e^+}} \cdot n_{e^-} \cdot \sigma(e^+ e^- \rightarrow X) \cdot \text{Acc}(X),$$

$$N_{\text{signal}}^{(b)} = N_{e^\pm} \int dE_\gamma \frac{dl_\gamma}{dE_\gamma} \cdot n_N \int_0^\pi d\theta_X \frac{d\sigma(\gamma N \rightarrow X N)}{d\theta_X} \cdot \text{Acc}(X),$$

$$N_{\text{signal}}^{(c)} = N_{e^\pm} \sum_{i=e^-, e^+} \int dE_i \frac{dl_i}{dE_i} \cdot n_N \int dE_X \int_0^\pi d\theta_X \frac{d^2\sigma(i N \rightarrow i X N)}{dE_X d\theta_X} \cdot \text{Acc}(X)$$

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Production cross section

Pair annihilation

$$\sigma(e^+e^- \rightarrow A') \simeq \frac{2\pi^2\alpha\epsilon^2}{m_e} \delta\left(E_i - \frac{m_{A'}^2}{2m_e} + m_e\right) ,$$

$$\sigma(e^+e^- \rightarrow a) \simeq \frac{\pi m_e}{4} \left(\frac{c_{aee}}{\Lambda}\right)^2 \delta\left(E_i - \frac{m_a^2}{2m_e} + m_e\right) ,$$

$$\sigma(e^+e^- \rightarrow S) \simeq \frac{\pi g_e^2}{4m_e} \delta\left(E_i - \frac{m_S^2}{2m_e} + m_e\right)$$

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Production cross section

Primakoff process

$$\frac{d\sigma(\gamma N \rightarrow aN)}{d\theta_a} \simeq \frac{\alpha g_{a\gamma\gamma}^2 E_i^4 \theta_a^3}{4t^2} G_2(t),$$

$$\frac{d\sigma(\gamma N \rightarrow SN)}{d\theta_S} \simeq \frac{\alpha g_{S\gamma\gamma}^2 E_i^4 \theta_S^3}{4t^2} G_2(t),$$

where

$G_2(t)$: electric form factor

$$t = -q^2 \simeq E_i^2 \theta_X^2 + \frac{m_X^4}{4E_i^2} \quad (q : \text{momentum transfer})$$

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Production cross section

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Bremsstrahlung

$$\frac{d^2\sigma(e^\pm N \rightarrow e^\pm X N)}{dx d\theta_X} = \frac{g_{Xee}^2 \alpha^2}{2\pi} x(1-x) E_i^2 \beta_X \frac{\mathcal{A}^X|_{t=t_{\min}}}{\tilde{u}^2} \chi,$$

where $x = E_X/E_i$

$$\tilde{u} = -x E_i^2 \theta_X^2 - m_X^2 \frac{1-x}{x} - m_e^2 x$$

$$\beta_X = \sqrt{1 - m_X^2/E_i^2} \quad \chi : \text{effective flux of photon}$$

$$\mathcal{A}^{A'}|_{t=t_{\min}} = 2 \frac{2-2x+x^2}{1-x} + 4(m_{A'}^2 + 2m_e^2) \frac{\tilde{u}x + m_{A'}^2(1-x) + m_e^2 x^2}{\tilde{u}^2},$$

$$\mathcal{A}^a|_{t=t_{\min}} = \frac{x^2}{1-x} + 2m_a^2 \frac{\tilde{u}x + m_a^2(1-x) + m_e^2 x^2}{\tilde{u}^2},$$

$$\mathcal{A}^S|_{t=t_{\min}} = \frac{x^2}{1-x} + 2(m_S^2 - 4m_e^2) \frac{\tilde{u}x + m_S^2(1-x) + m_e^2 x^2}{\tilde{u}^2},$$

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Angular acceptance

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Angle of initial particle i

$$\theta_1 = \begin{cases} 16 \text{ mrad} \cdot \text{GeV}/E_{e^\pm} & (\text{for shower electrons and positrons}), \\ 8 \text{ mrad} \cdot \text{GeV}/E_\gamma & (\text{for shower photons}) \end{cases}$$

Production angle of new light particle

$$\theta_2 = \begin{cases} \theta_X & (\text{for Primakoff process \& bremsstrahlung}) \\ 0 & (\text{for pair annihilation}) \end{cases}$$

Decay angle of SM particle from X

$$\theta_3 = \frac{\pi m_X}{2 E_X}$$

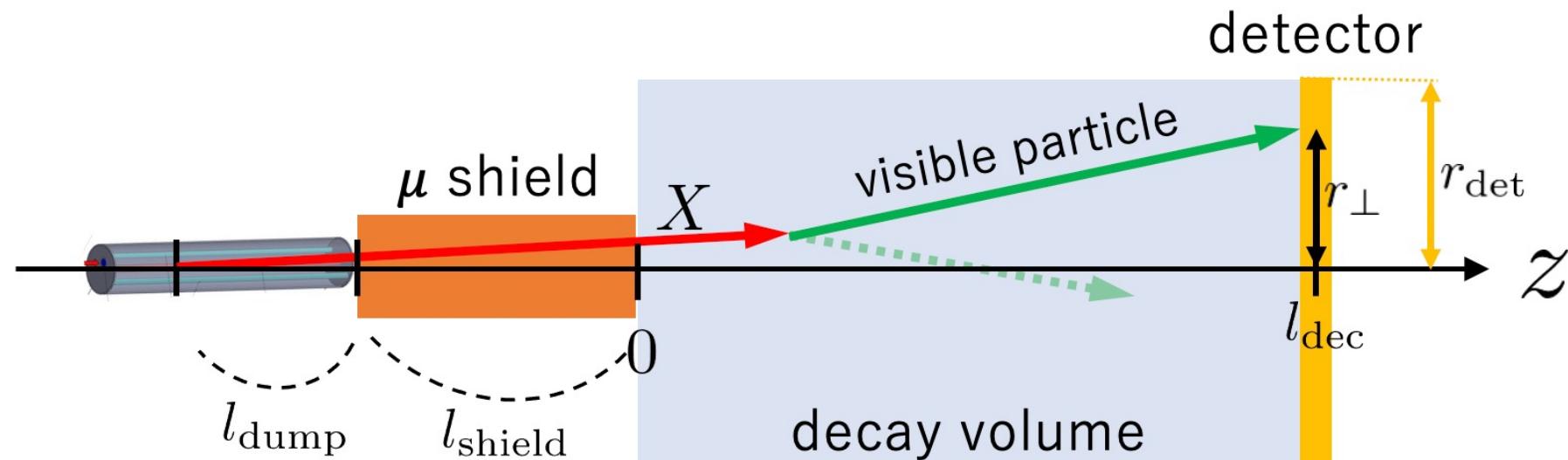
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Typical deviation of emitted SM particle from beam axis

$$r_{\perp}(z) = \sqrt{\theta_1^2(l_{\text{dump}} + l_{\text{shield}} + l_{\text{dec}})^2 + \theta_2^2(l_{\text{dump}} + l_{\text{shield}} + l_{\text{dec}})^2 + \theta_3^2(l_{\text{dec}} - z)^2}$$



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Angular acceptance

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Averaged angled of initial particles

$$\theta_1 = \begin{cases} 16 \text{ mrad} \cdot \text{GeV}/E_{e^\pm} & \text{(for shower electrons and positrons),} \\ 8 \text{ mrad} \cdot \text{GeV}/E_\gamma & \text{(for shower photons)} \end{cases}$$

→ Shower γ (e^\pm) with $E_\gamma < 0.52 \text{ GeV}$ ($E_{\gamma(e^\pm)} < 1.05 \text{ GeV}$) always result in $r_\perp > r_{\text{det}}$

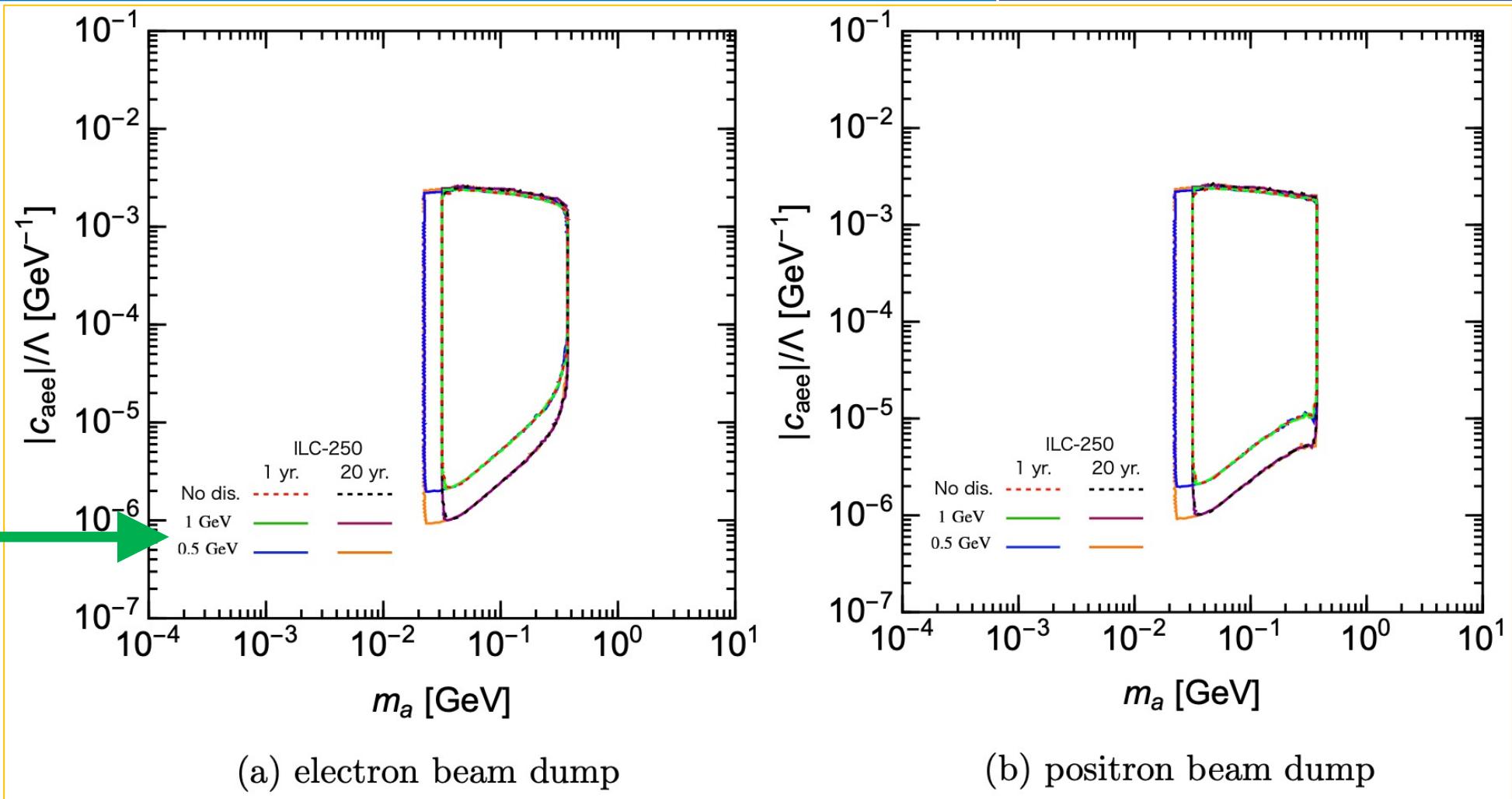
→ In reality, θ_1 has a distribution, and shower particles with smaller momentum may pass the angular cut

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Angular acceptance

ALP model (Case 1)

E_{th} : minimal energy
for detection

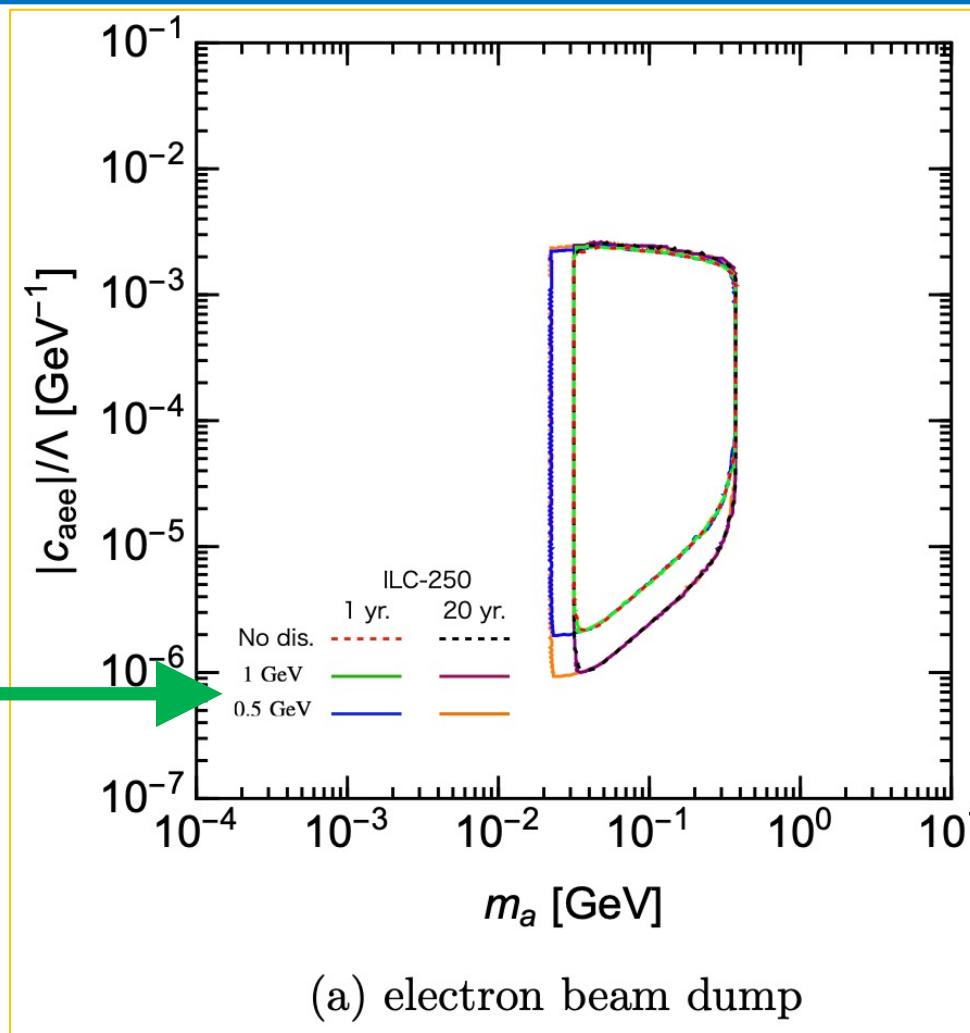


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Angular acceptance

ALP model (Case 1)

E_{th} : minimal energy
for detection



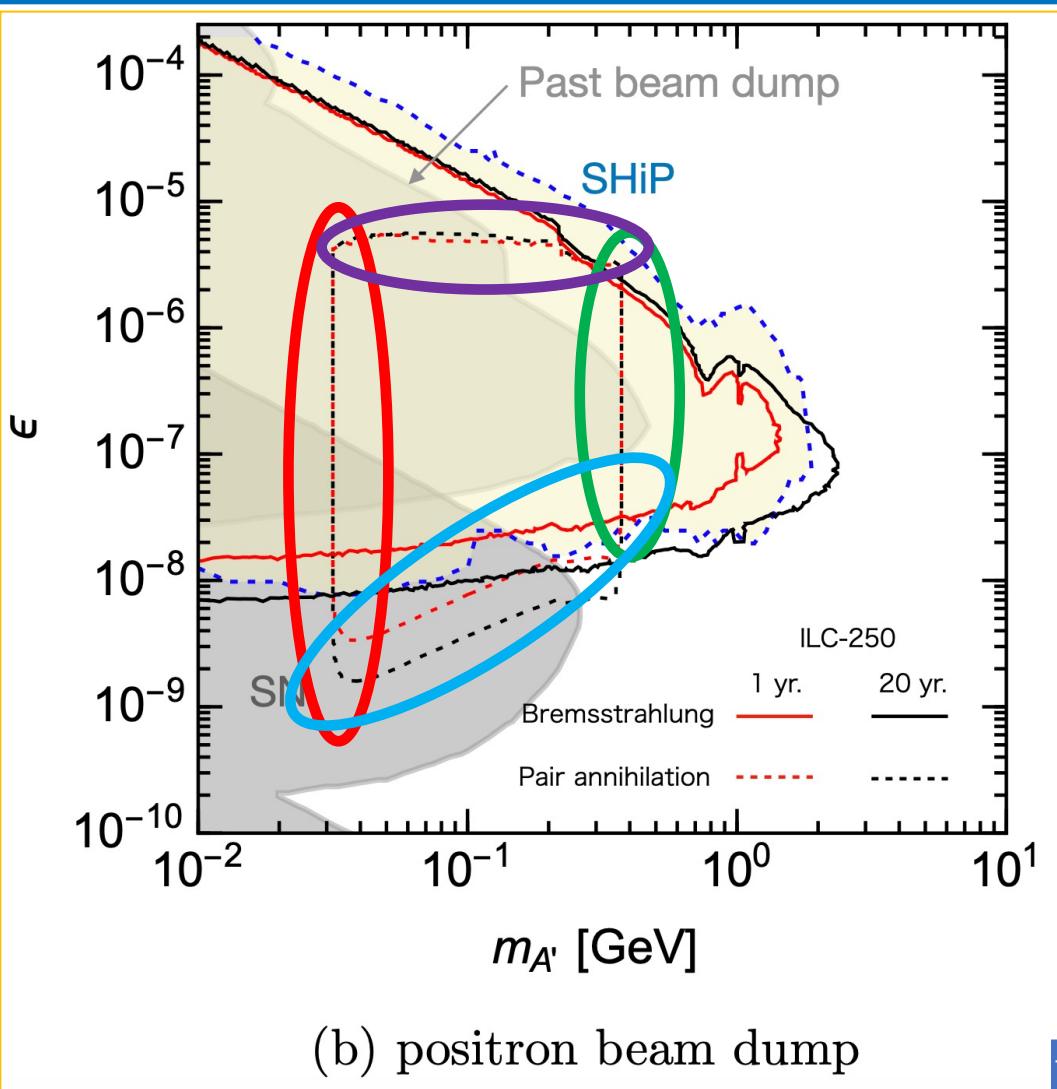
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Low mass boundary is sensitive
to energy threshold

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Dark photon case

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Pair annihilation

Low-mass boundary

Angular acceptance
(energy threshold for detection)

High-mass boundary

Center-of-mass energy

$$m_{A'} < \sqrt{s}$$

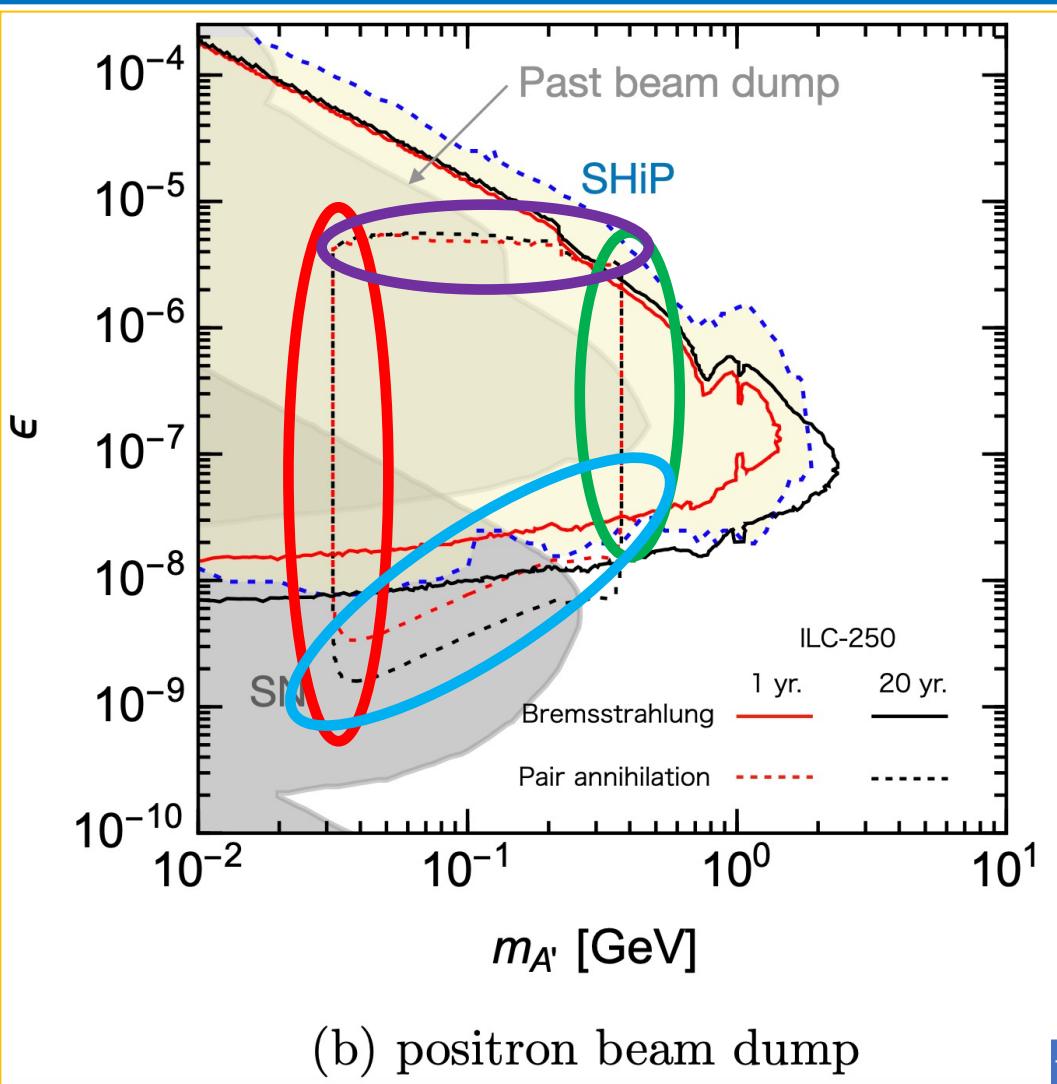
$$= \sqrt{2 E_{\text{beam}} m_e}$$

$$\simeq 0.35 \text{ GeV}$$

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Pair annihilation

Large coupling boundary

Decay probability

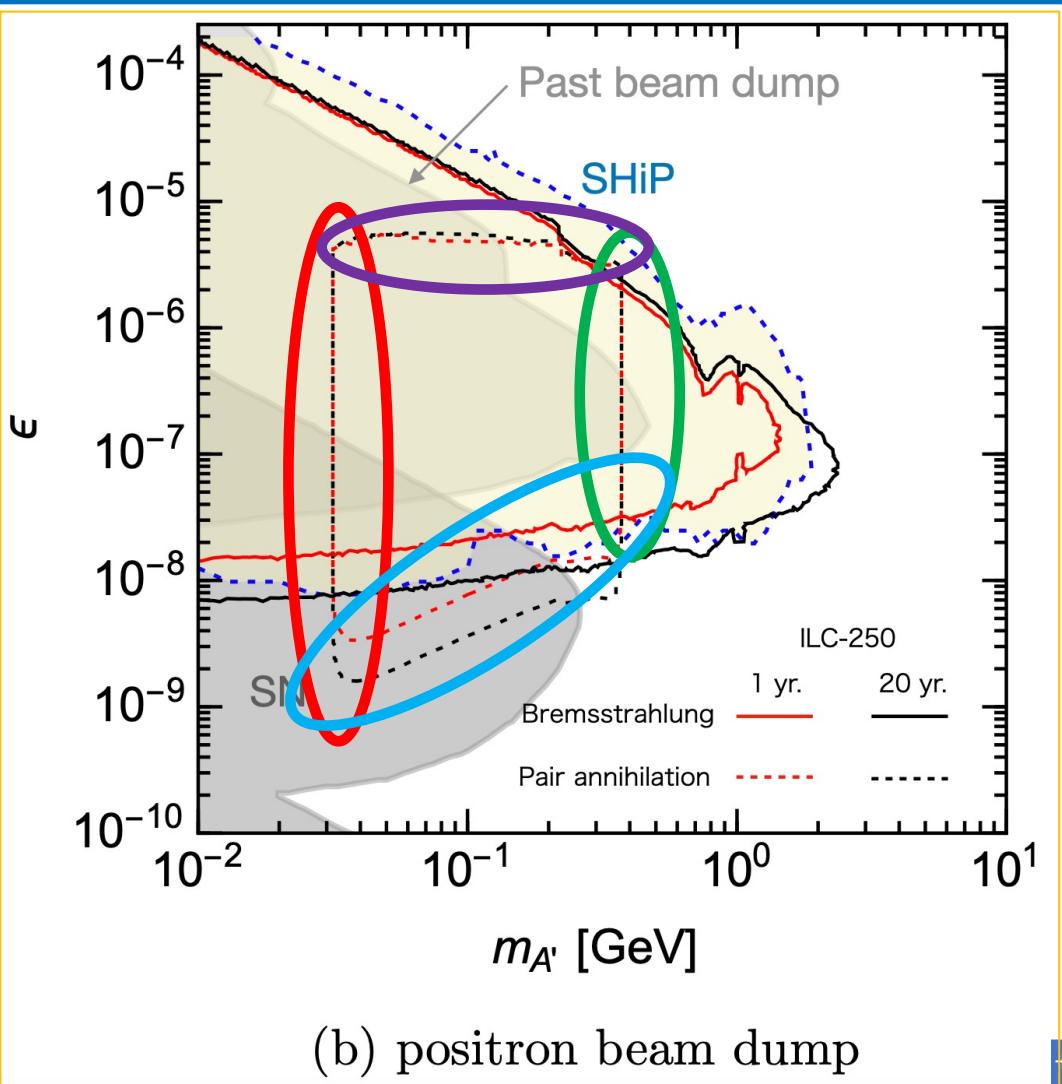
$$\frac{m_{A'} \Gamma_{A'}}{E_{A'}^{(\text{lab})}} (l_{\text{dump}} + l_{\text{sh}}) \sim \text{const}$$
$$\implies \epsilon^2 \sim \text{const}$$

Upper side of boundary does not depend on mass $m_{A'}$,

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Pair annihilation

Small coupling boundary

$$\frac{dl_{e^-}}{dE_{e^-}} \simeq \left(\frac{dl_{e^-}}{dE_{e^-}} \right)_{\text{shower}} \propto \frac{E_{\text{beam}}}{E_{e^-}^2}$$

$$\sigma(e^+ + e^- \rightarrow A') \propto \epsilon^2$$

$$(l_{A'}^{(\text{lab})})^{-1} \propto \frac{\epsilon^2 m_{A'}^2}{E_{A'}^{(\text{lab})}} \quad \text{for positron beam}$$

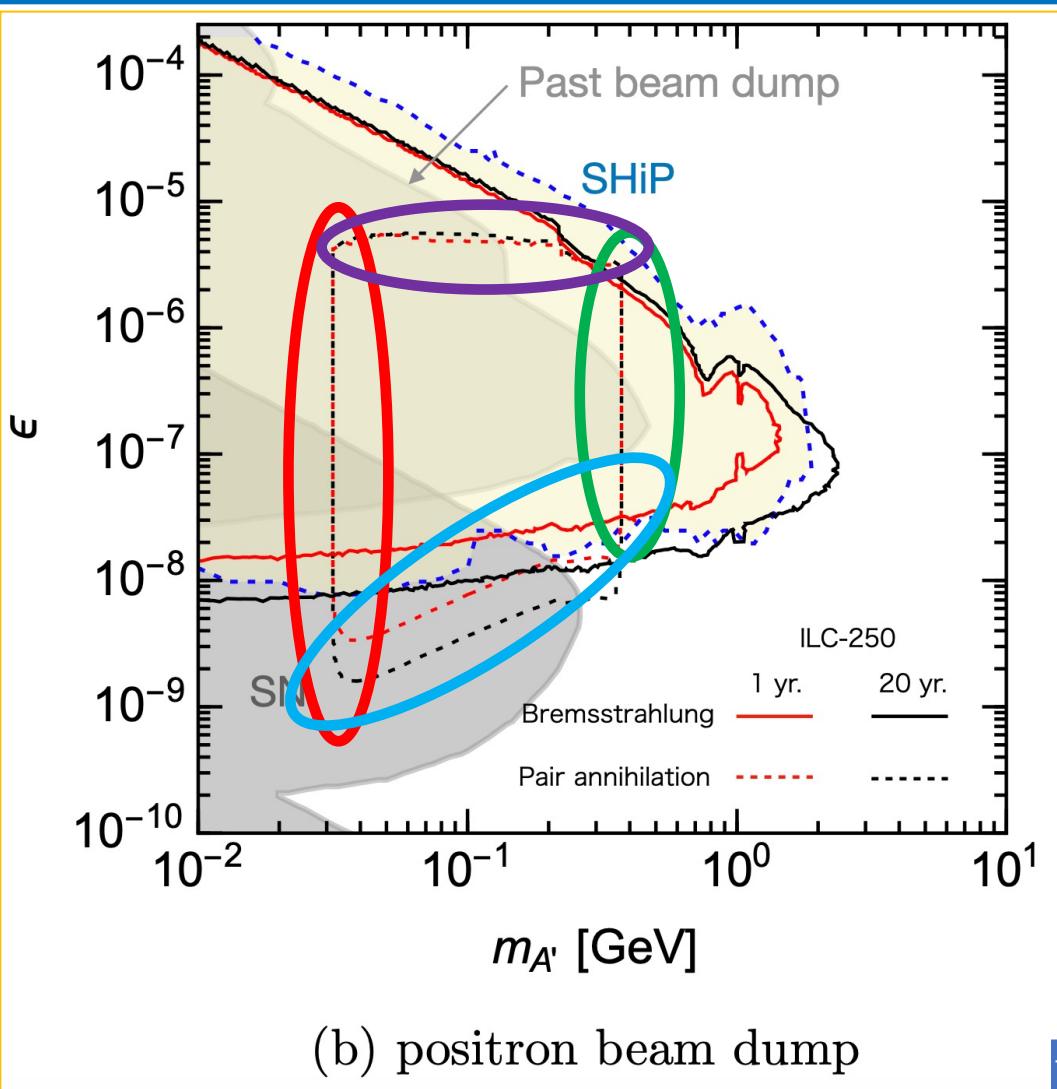
& $m_{A'} \lesssim \mathcal{O}(10^{-1}) \text{ GeV}$

$$N_{\text{signal}} \sim \left(\frac{N_{e^\pm}}{4 \times 10^{21}} \right) \left(\frac{E_{\text{beam}}}{125 \text{ GeV}} \right) \left(\frac{l_{\text{dec}}}{50 \text{ m}} \right) \left(\frac{\epsilon}{8 \times 10^{-9}} \right)^4 \left(\frac{0.1 \text{ GeV}}{m_{A'}} \right)^4$$

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Pair annihilation

Small coupling boundary

$$\frac{dl_{e^-}}{dE_{e^-}} \simeq \left(\frac{dl_{e^-}}{dE_{e^-}} \right)_{\text{primary}} \propto \frac{1}{E_{e^-}}$$

$$\sigma(e^+ + e^- \rightarrow A') \propto \epsilon^2$$

$$(l_{A'}^{(\text{lab})})^{-1} \propto \frac{\epsilon^2 m_{A'}^2}{E_{A'}^{(\text{lab})}} \quad \text{for positron beam}$$

& $m_{A'} \gtrsim \mathcal{O}(10^{-1}) \text{ GeV}$

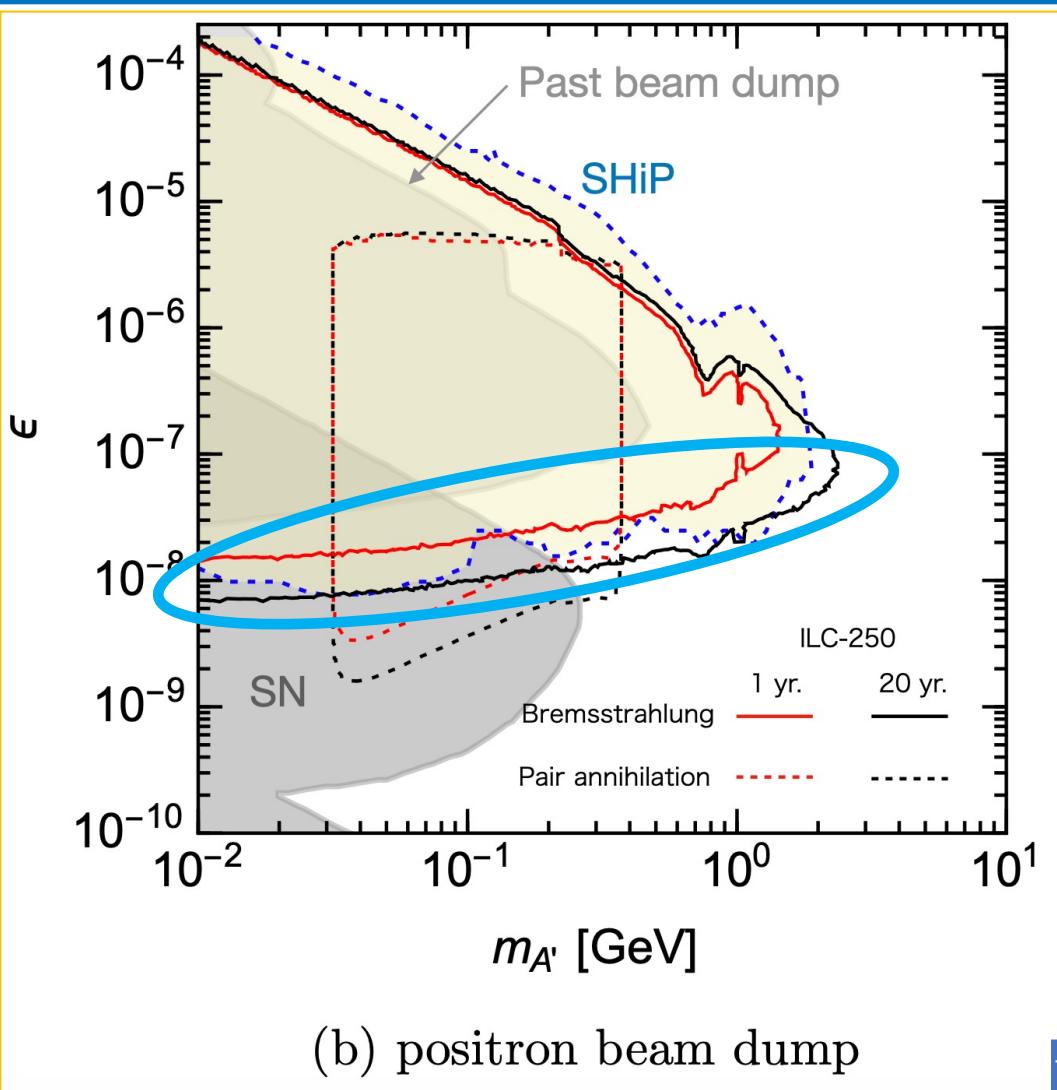


$$N_{\text{signal}} \sim \left(\frac{N_{e^\pm}}{4 \times 10^{21}} \right) \left(\frac{l_{\text{dec}}}{50 \text{ m}} \right) \left(\frac{\epsilon}{10^{-8}} \right)^4 \left(\frac{0.2 \text{ GeV}}{m_{A'}} \right)^2$$

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Bremsstrahlung

Small coupling boundary

$$\frac{dl_{e^\pm}}{dE_{e^\pm}} \simeq \left(\frac{dl_{e^\pm}}{dE_{e^\pm}} \right)_{\text{shower}} \propto \frac{E_{\text{beam}}}{E_{e^\pm}^2}$$

$$\sigma(e^\pm N \rightarrow e^\pm N A') \propto \frac{\epsilon^2}{m_{A'}^2}$$

$$(l_{A'}^{(\text{lab})})^{-1} \propto \frac{\epsilon^2 m_{A'}^2}{E_{A'}^{(\text{lab})}}$$

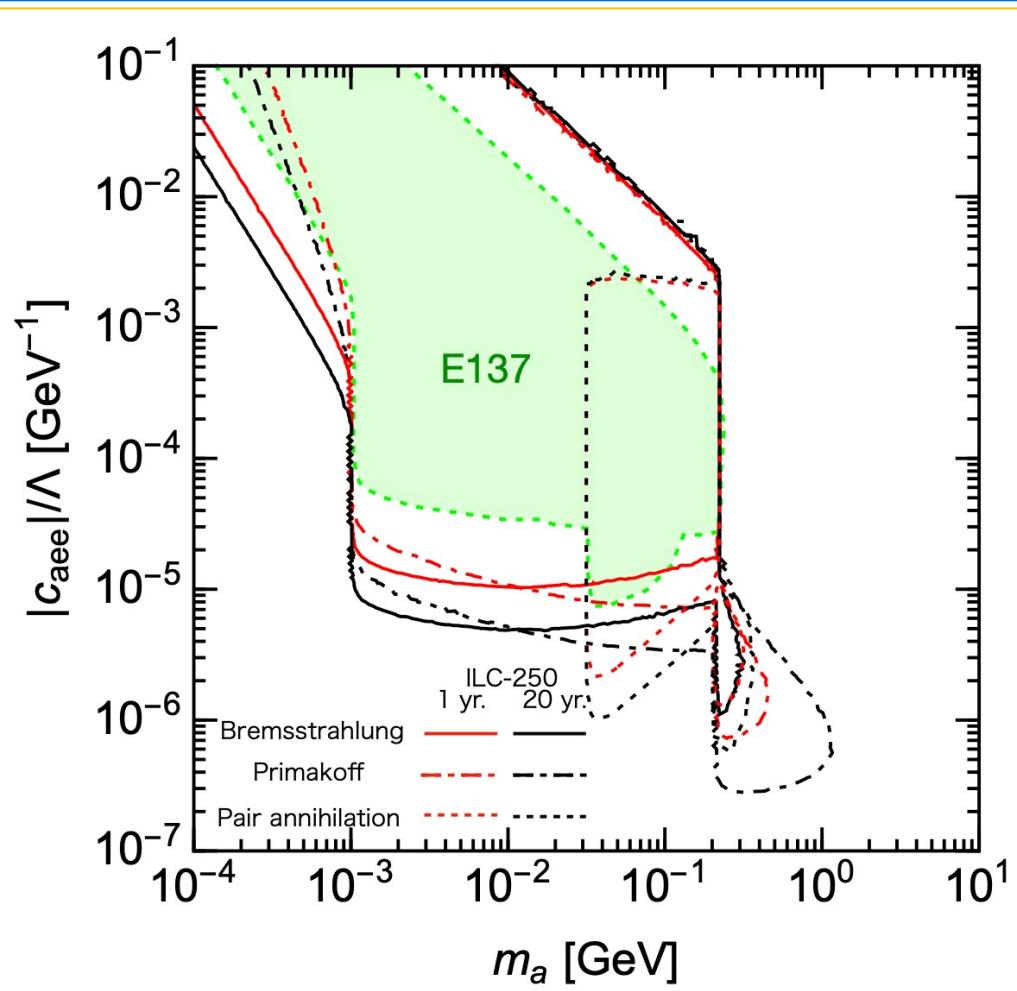


$$N_{\text{signal}} \sim \left(\frac{N_{e^\pm}}{4 \times 10^{21}} \right) \left(\frac{E_{\text{beam}}}{125 \text{ GeV}} \right) \left(\frac{l_{\text{dec}}}{50 \text{ m}} \right) \left(\frac{r_{\text{det}}}{2 \text{ m}} \right) \left(\frac{131 \text{ m}}{l_{\text{dump}} + l_{\text{sh}} + l_{\text{dec}}} \right) \left(\frac{\epsilon}{10^{-8}} \right)^4$$

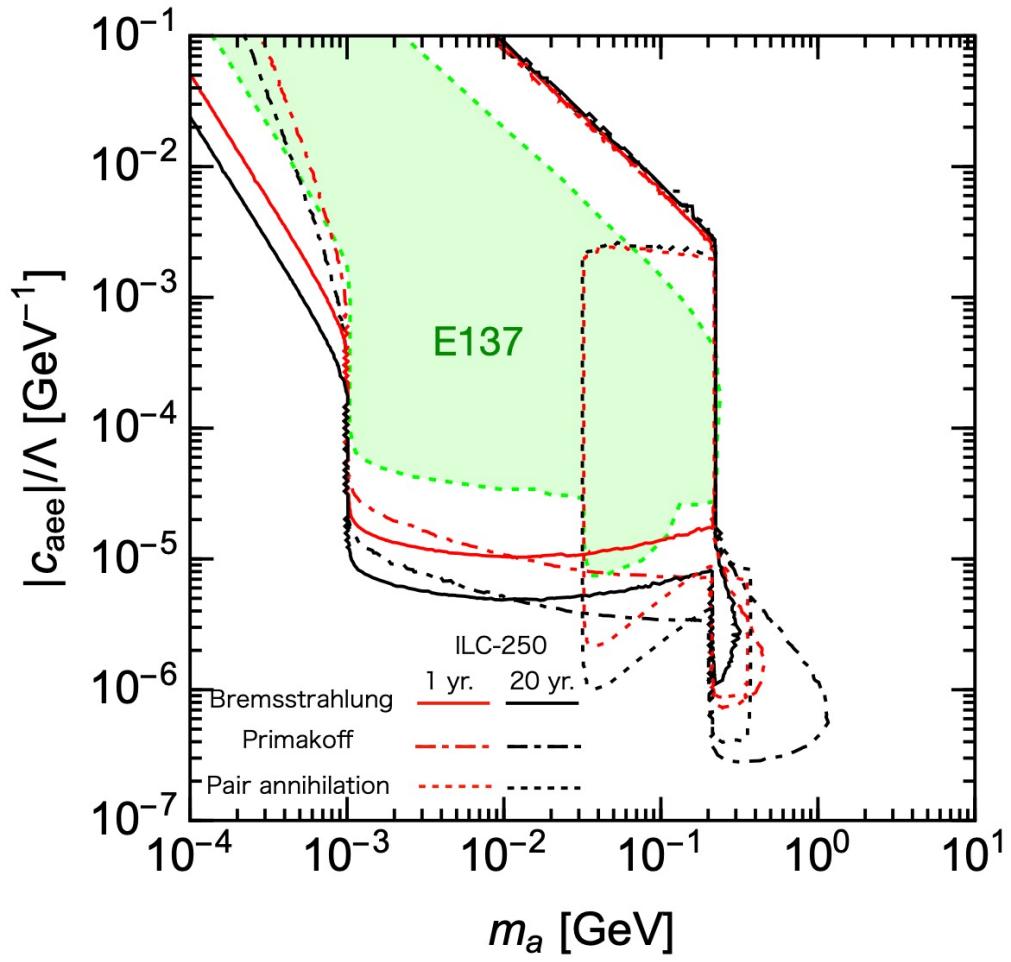
Appendix

ALP case (model 2)

- Introduction
- Beam Dump Experiment
- Result
- Appendix



(a) electron beam dump



(b) positron beam dump