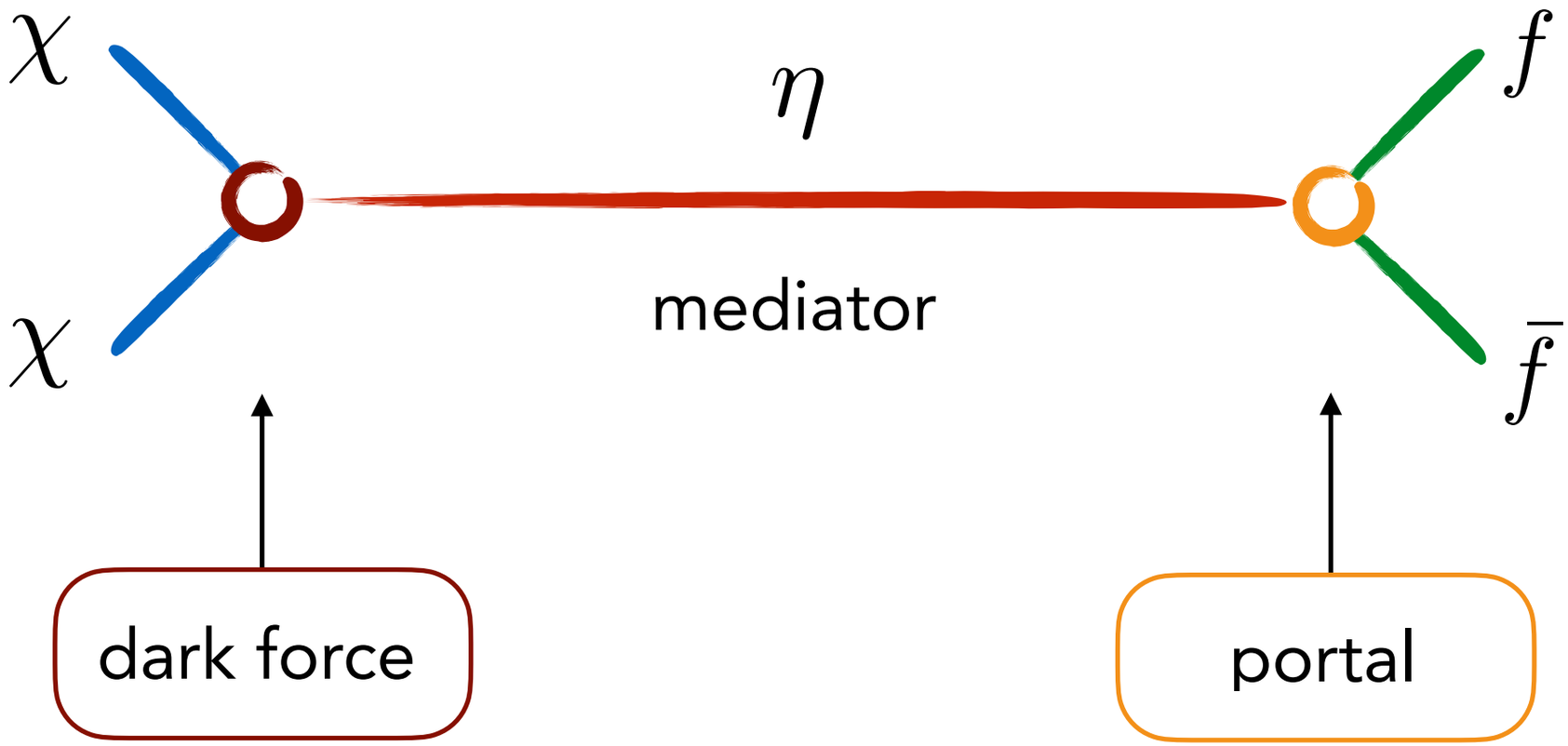
DARK MATTER and LONG-LIVED PARTICLES

Susanne Westhoff
Radboud University | Nikhef

webinar • July 5, 2022 • HIDDeN ITN network

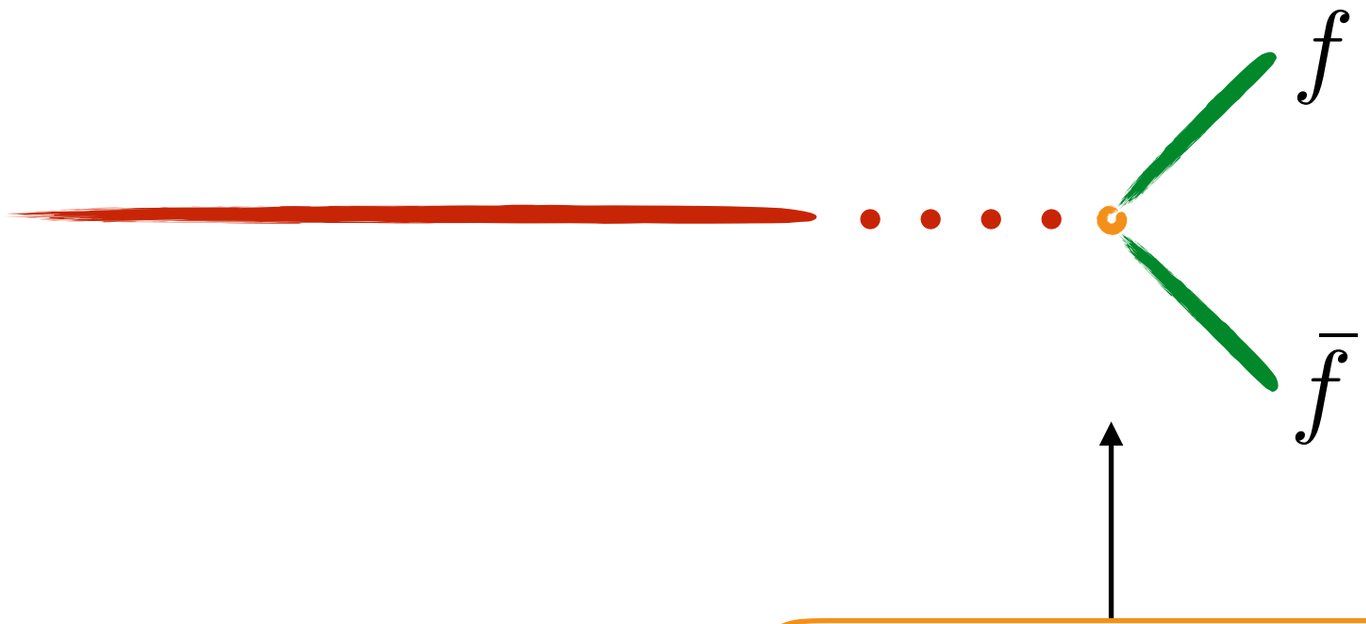
Dark and bright matter



Pospelov, Ritz, Voloshin 0711.4866

Long-lived mediators

$$\tau = \frac{1}{\Gamma}$$

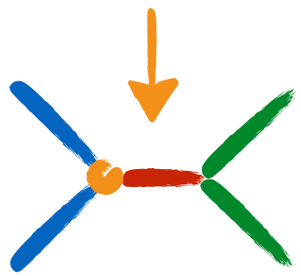


suppressed decay

Feeble dark matter interactions

Freeze-out: $$\Omega_\chi h^2 \sim \frac{m_\chi}{T_{fo}} \frac{\mathrm{GeV}^{-1}}{M_P \langle \sigma v \rangle}$$

- resonance:



$$\sigma \sim \frac{g^2}{m_\eta^2 - s}$$

Feeble dark matter interactions

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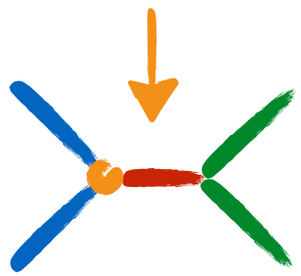
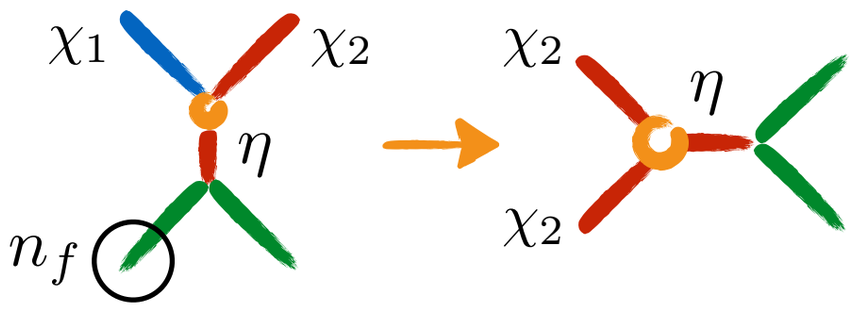


- co-scattering:



$$g^2 \sim e^{-\frac{m_\chi}{T_{fo}}} g^2_{\mathrm{WIMP}}$$

$$\Delta = \frac{m_2 - m_1}{m_1} \ll 1$$

Feeble dark matter interactions

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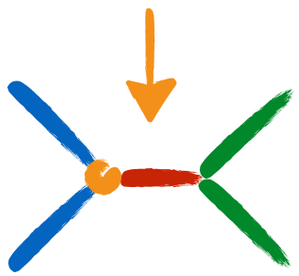
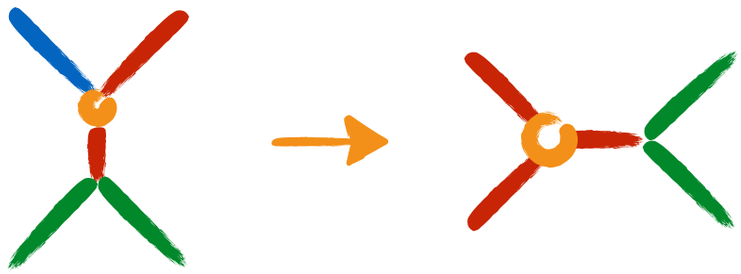
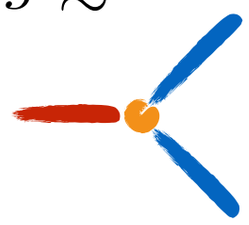


- co-scattering:



Freeze-in: $$\Omega_\chi h^2 \sim \frac{m_\chi}{\mathrm{GeV}} \frac{M_P \Gamma_\eta}{T_{fi}^2}$$

$g \lesssim 10^{-7}$

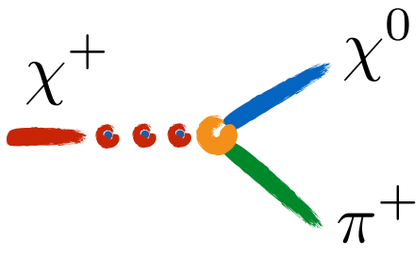


$$\frac{m_\eta^2}{m_\chi} \sim 10^9\,\mathrm{GeV}$$

Dark sectors across the scales

- 100 GeV: electroweakinos

Arkani-Hamed, Delgado, Giudice hep-ph/0601041



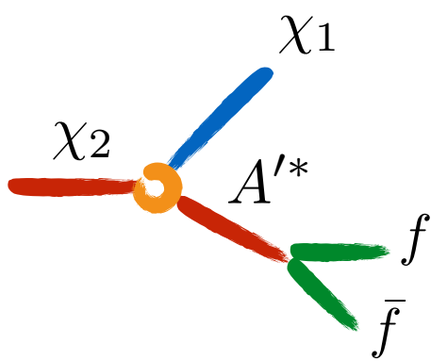
$$c\tau_{\chi^+} \approx 1\,\mathrm{cm} \left(\frac{6\times10^{-5}}{g_\chi}\right)^2 \left(\frac{20\,\mathrm{GeV}}{m_{\chi^+}-m_{\chi^0}}\right)^5 \left(\frac{m_{\chi^+}}{80\,\mathrm{GeV}}\right)^4$$

Blekman, SW et al. 2007.03708

- 100 MeV: inelastic dark matter

Tucker-Smith, Weiner hep-ph/0101138

Izaguirre et al. 1508.03050

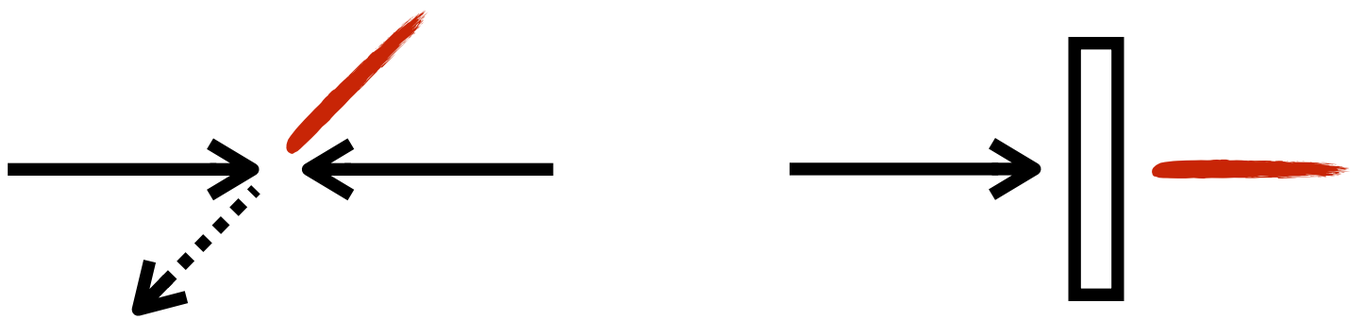


$$c\tau_{\chi_2} \sim \frac{1}{\epsilon^2 m_\chi}\left(\frac{m_1}{m_2-m_1}\right)^5\left(\frac{m_{A'}}{m_1}\right)^4 \gtrsim \mathcal{O}(\mathrm{km})$$

for comparison: B meson $c\tau_B \sim 1\,\mathrm{mm}$

Sources of long-lived particles

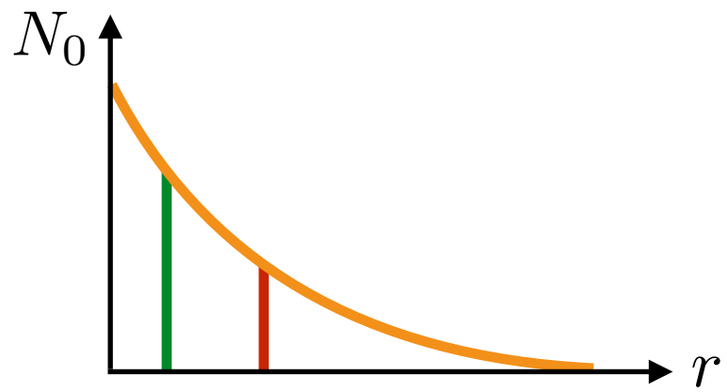
- on earth: colliders fixed target



- in space: atmosphere relic abundance

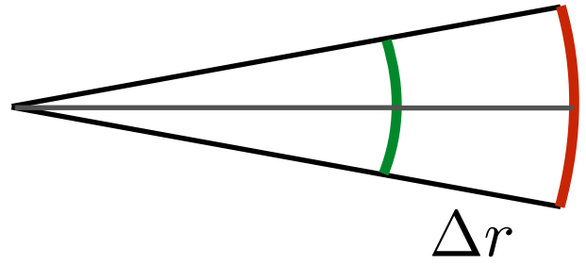
Long-lived particles at colliders

decay length $d = \beta\gamma c\tau$



- detector geometry

$$N(\Delta V) = N_0 \frac{\Delta\Omega}{4\pi}\left[\exp\left(-\frac{r}{d}\right) - \exp\left(-\frac{r+\Delta r}{d}\right)\right]$$



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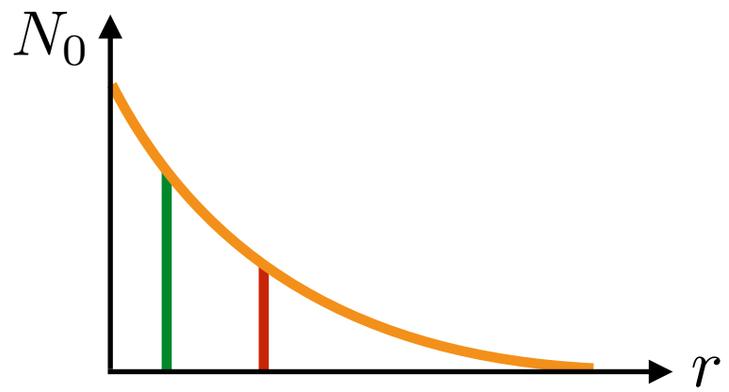

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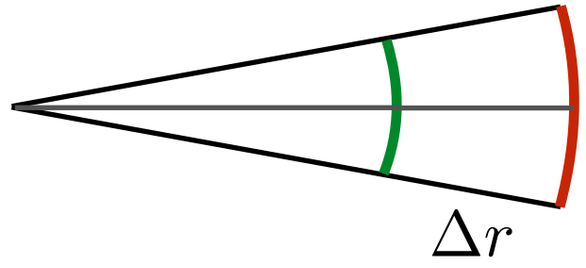


- boost

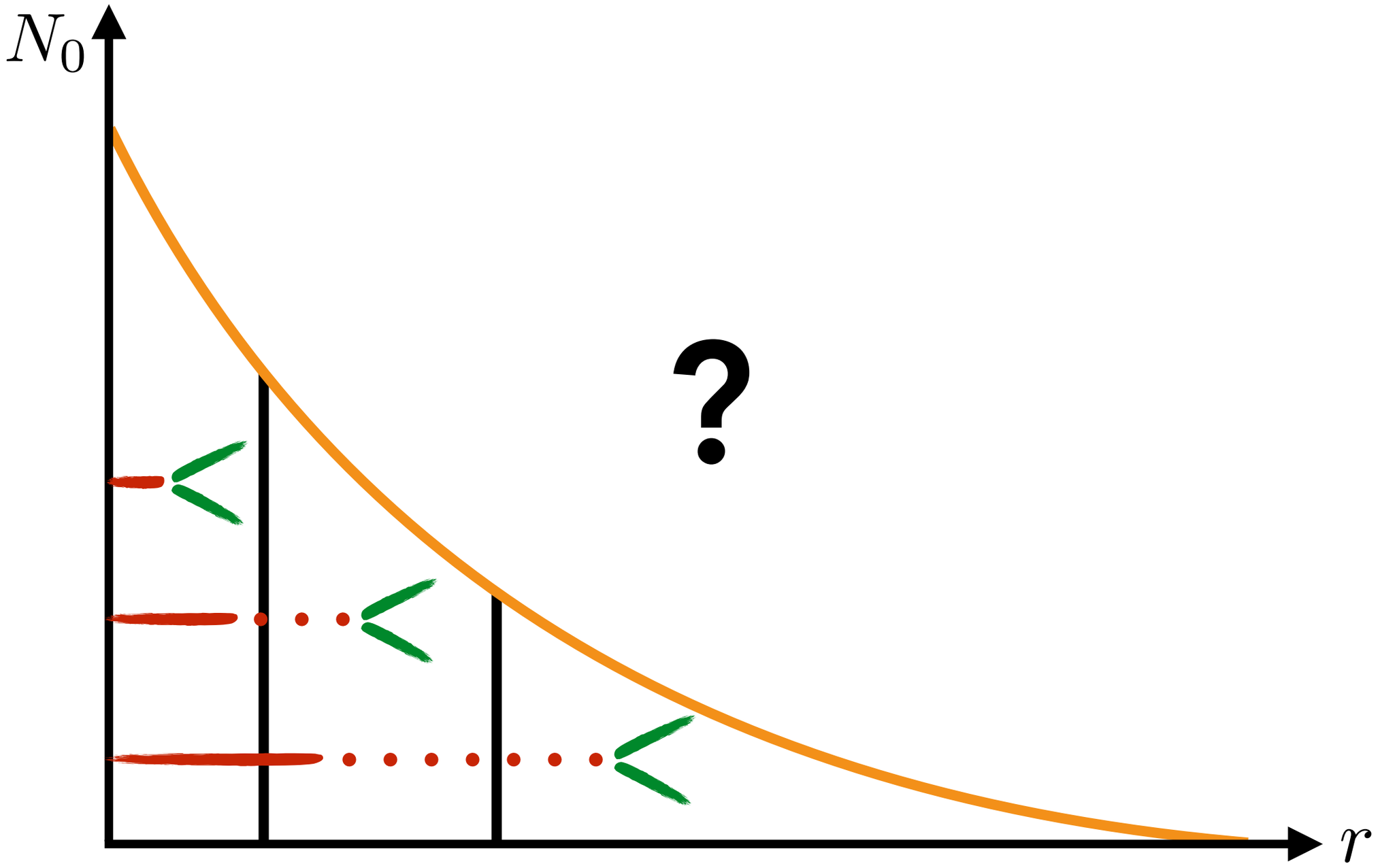
B meson

$c\tau \sim 1\,\mathrm{mm}$

LHC: $\gamma = \dfrac{500\,\mathrm{GeV}}{m_B} = 100,\ \beta \approx 1$ → $d \approx 10\,\mathrm{cm}$

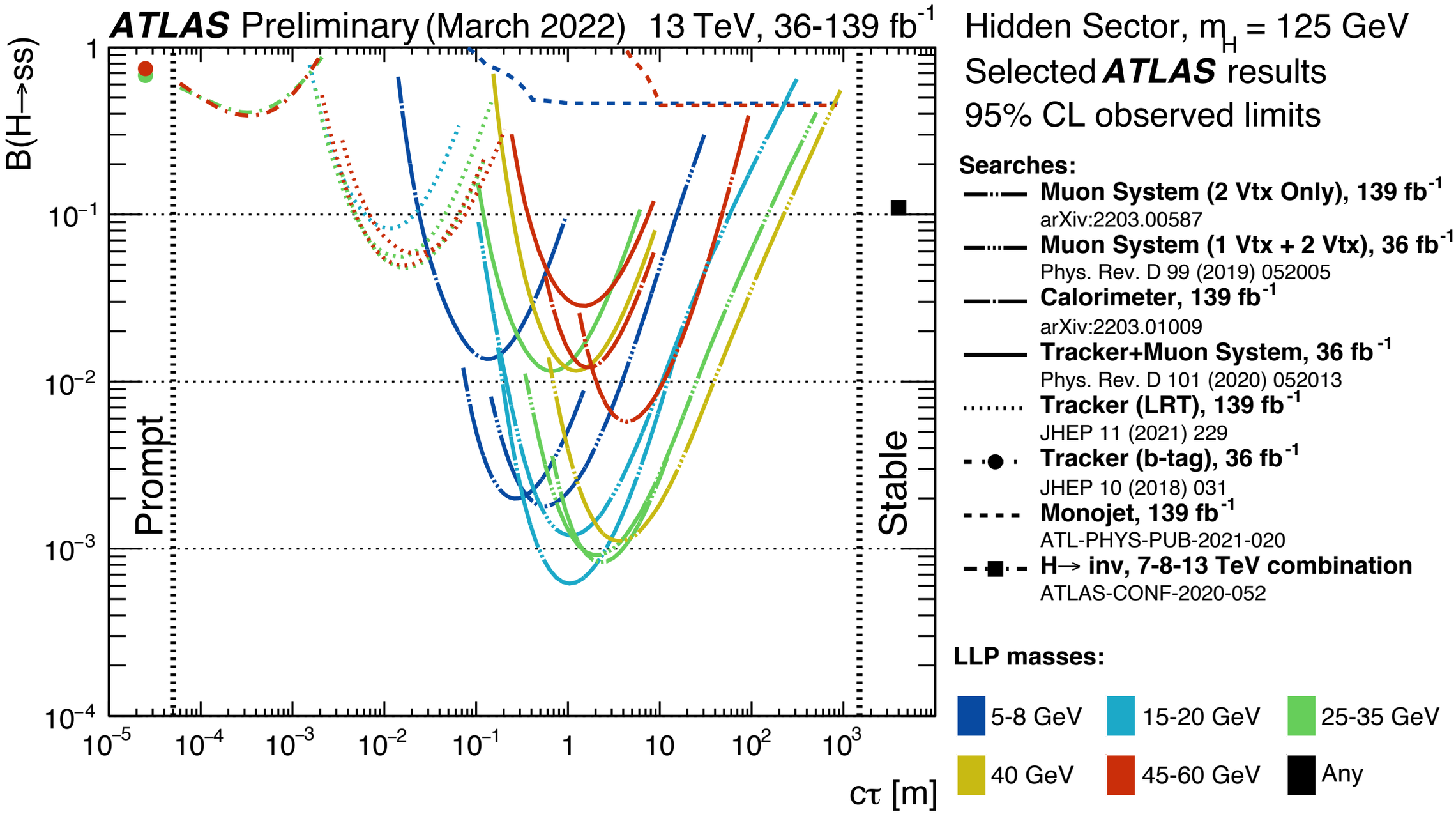
Belle II: $\gamma = \dfrac{5\,\mathrm{GeV}}{m_B} = 1,\ \beta \approx 0$ → $d \ll 1\,\mathrm{mm}$

Prompt - displaced - invisible



LHC: lifetime scan with detector layers

- long-lived scalars: $h \to ss \to X$

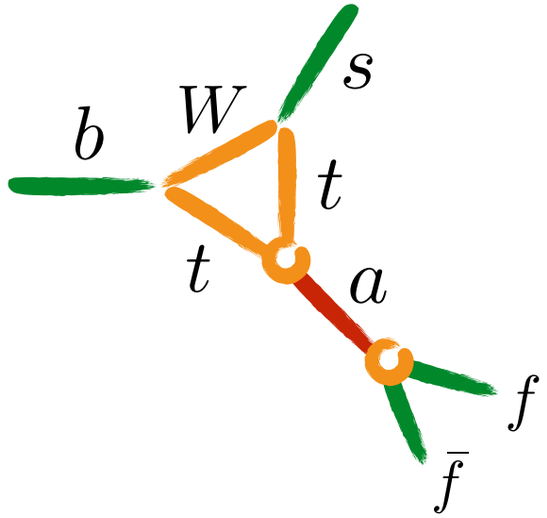


Belle II: long-lived ALPs

- axion-like particle:

$$\mathcal{L}_{\text{eff}}(\mu > \mu_w) = \sum_f \frac{c_{ff}(\mu)}{2} \frac{\partial^\mu a}{f_a} (\bar{f}\gamma_\mu\gamma_5 f)$$

- produced in B meson decays:



$$\mathcal{B}(B^+ \to K^+ a) = 0.03\, c_{ff}^2 (4\pi f_a)$$

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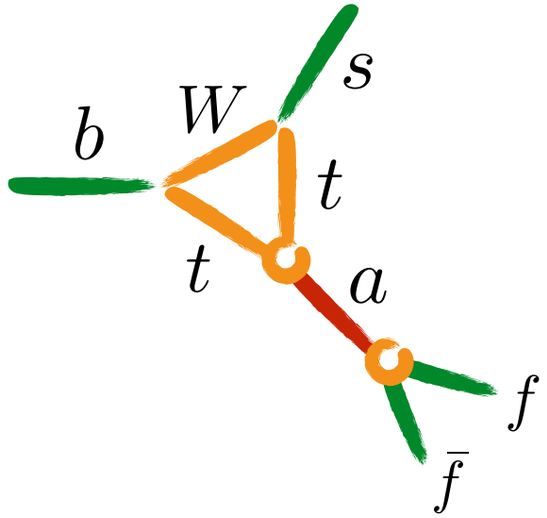

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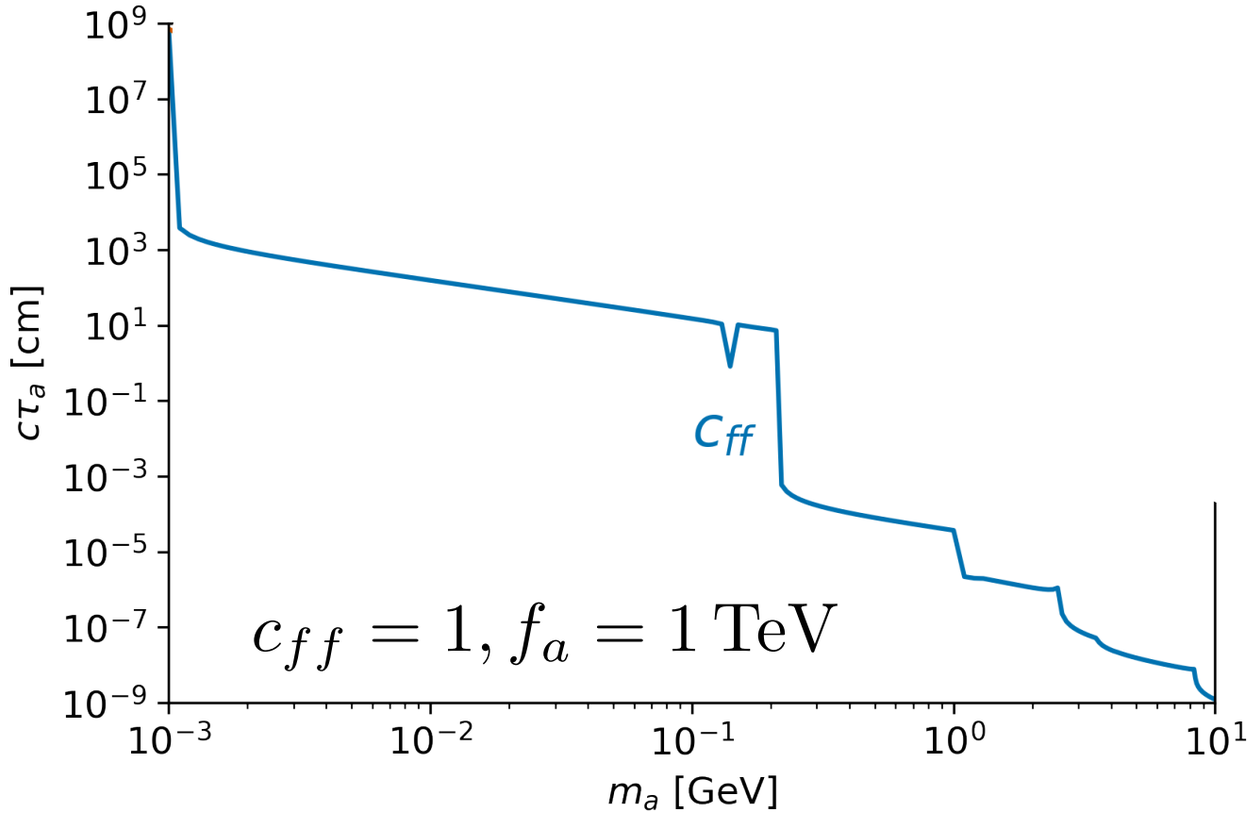
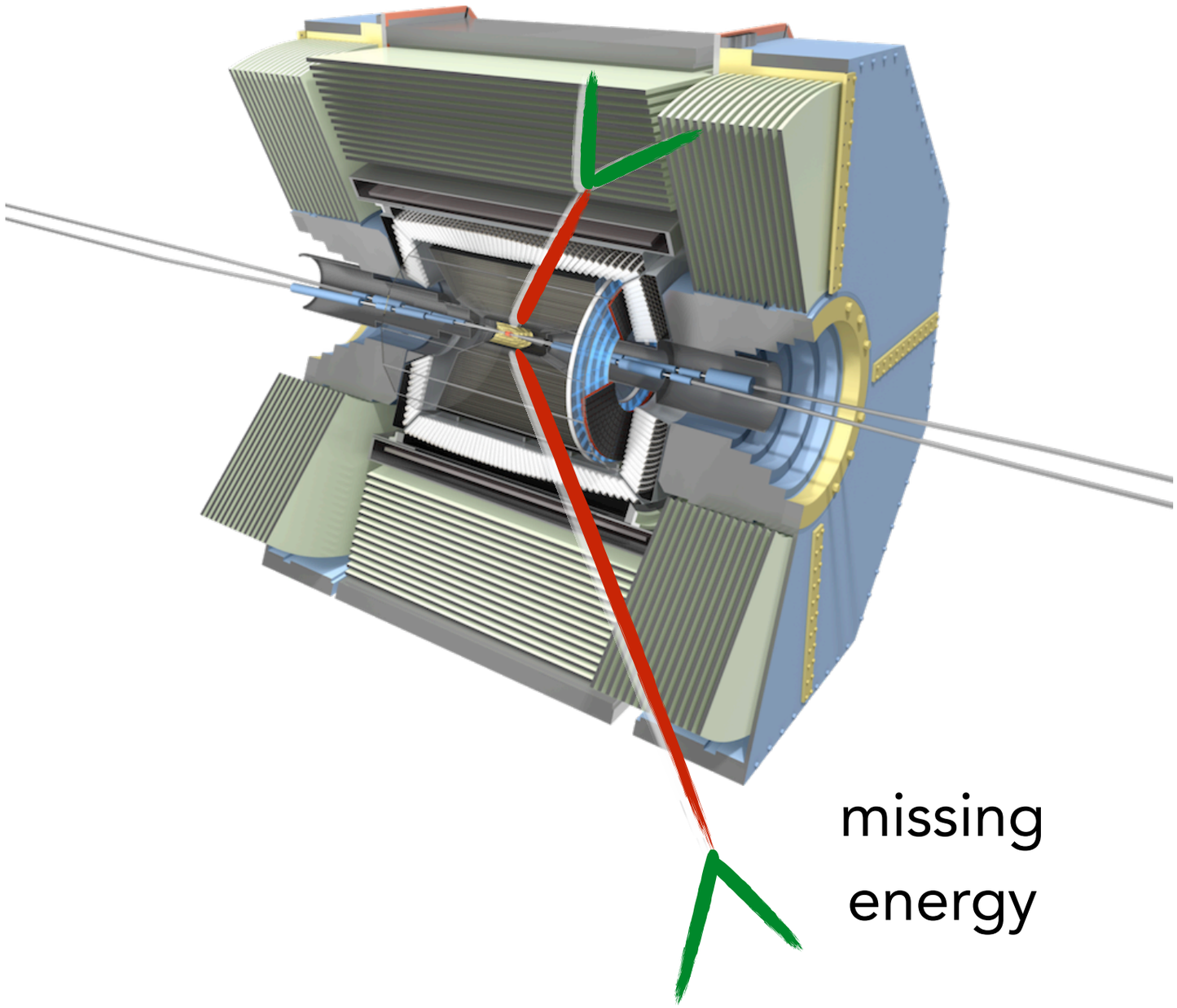
- proper lifetime:



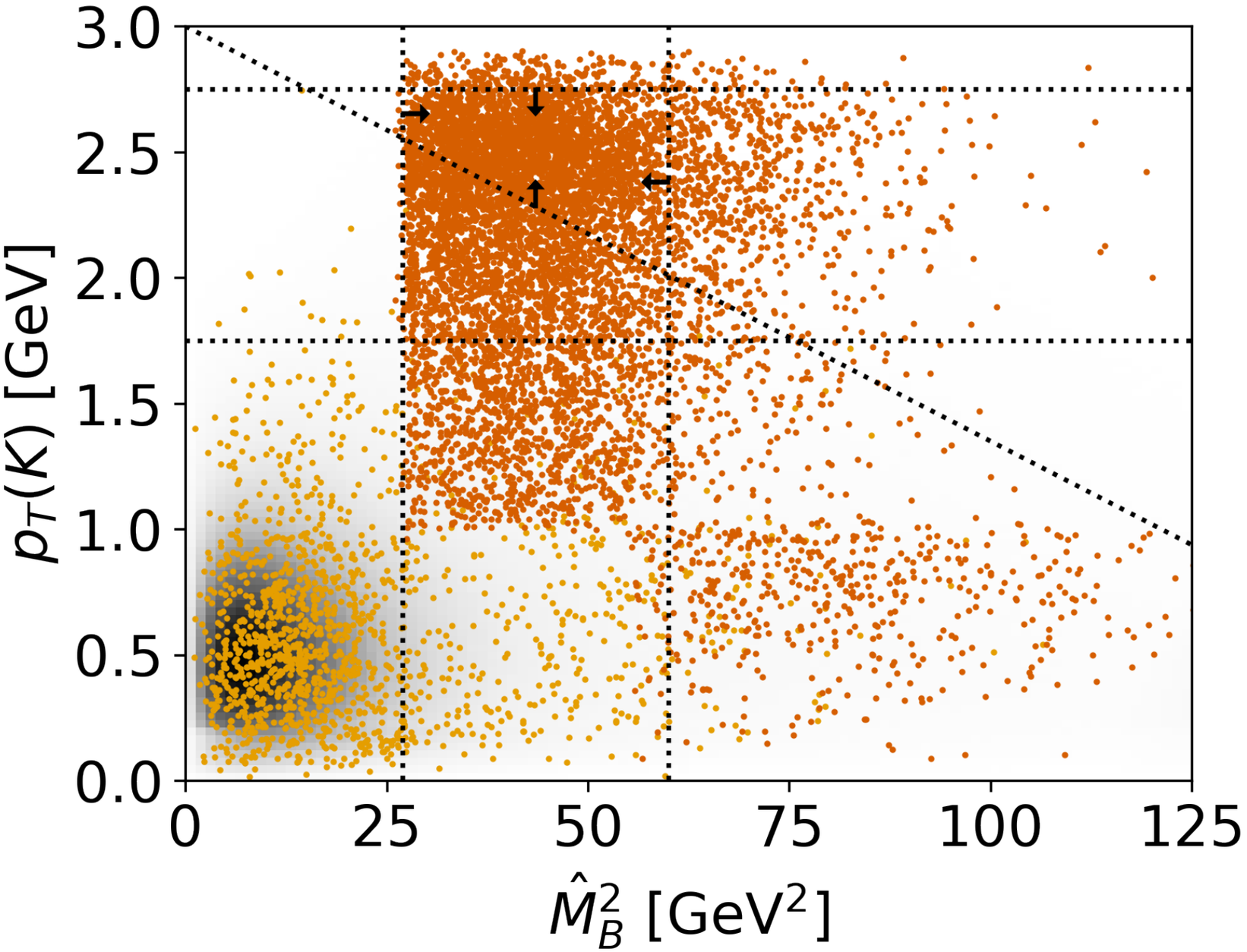
Displaced or invisible?

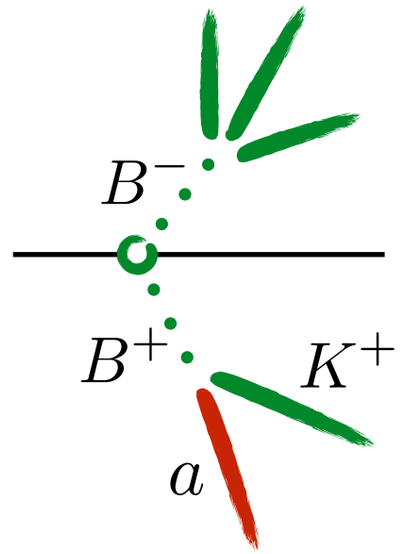
displaced
vertex



missing
energy

ALP kinematics

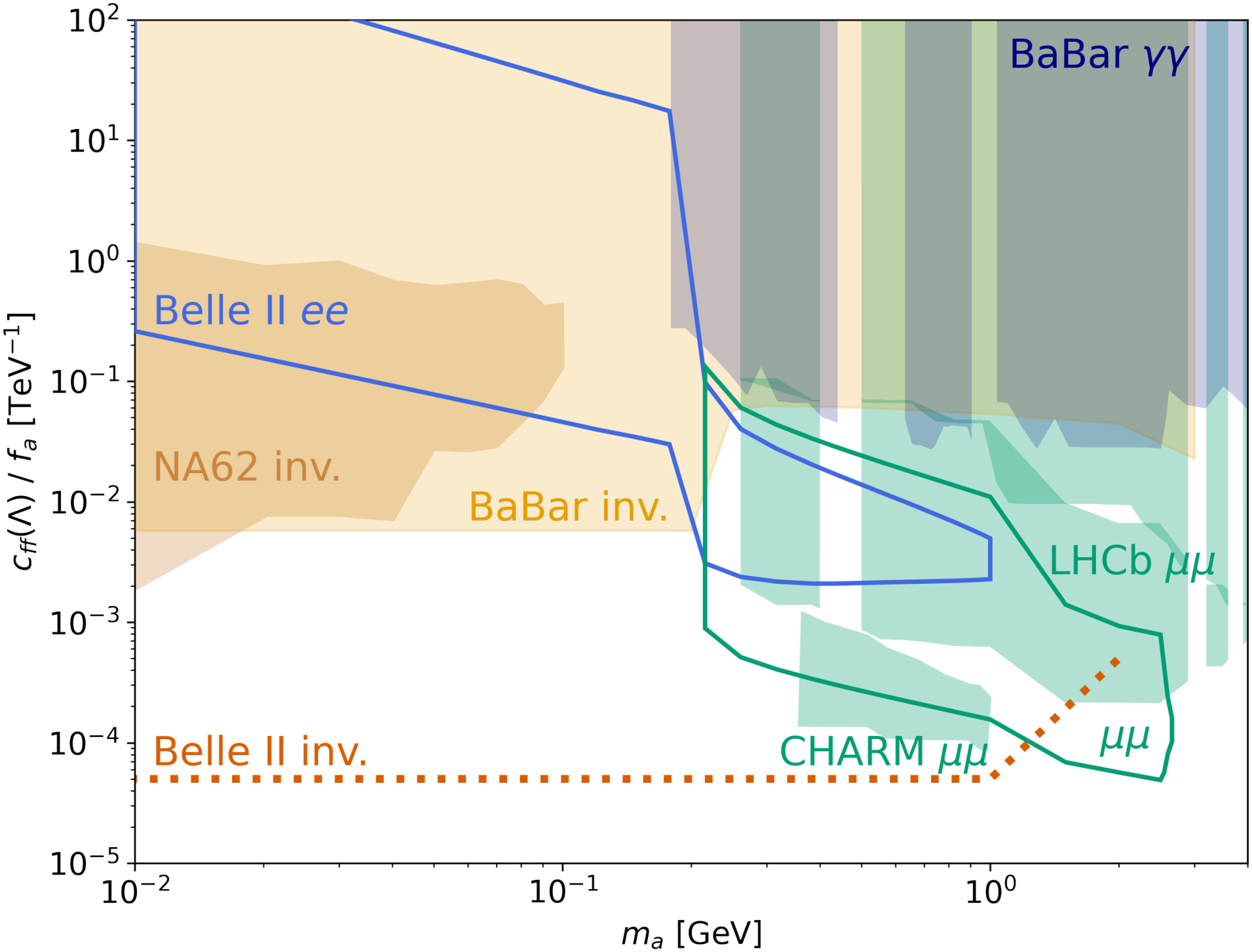




- ALP signal
- misrec. ALP-K pair
- background

Ferber, Filimonova, Schaefer, SW 2201.06580

Displaced versus invisible



Ferber, Filimonova, Schaefer, SW 2201.06580

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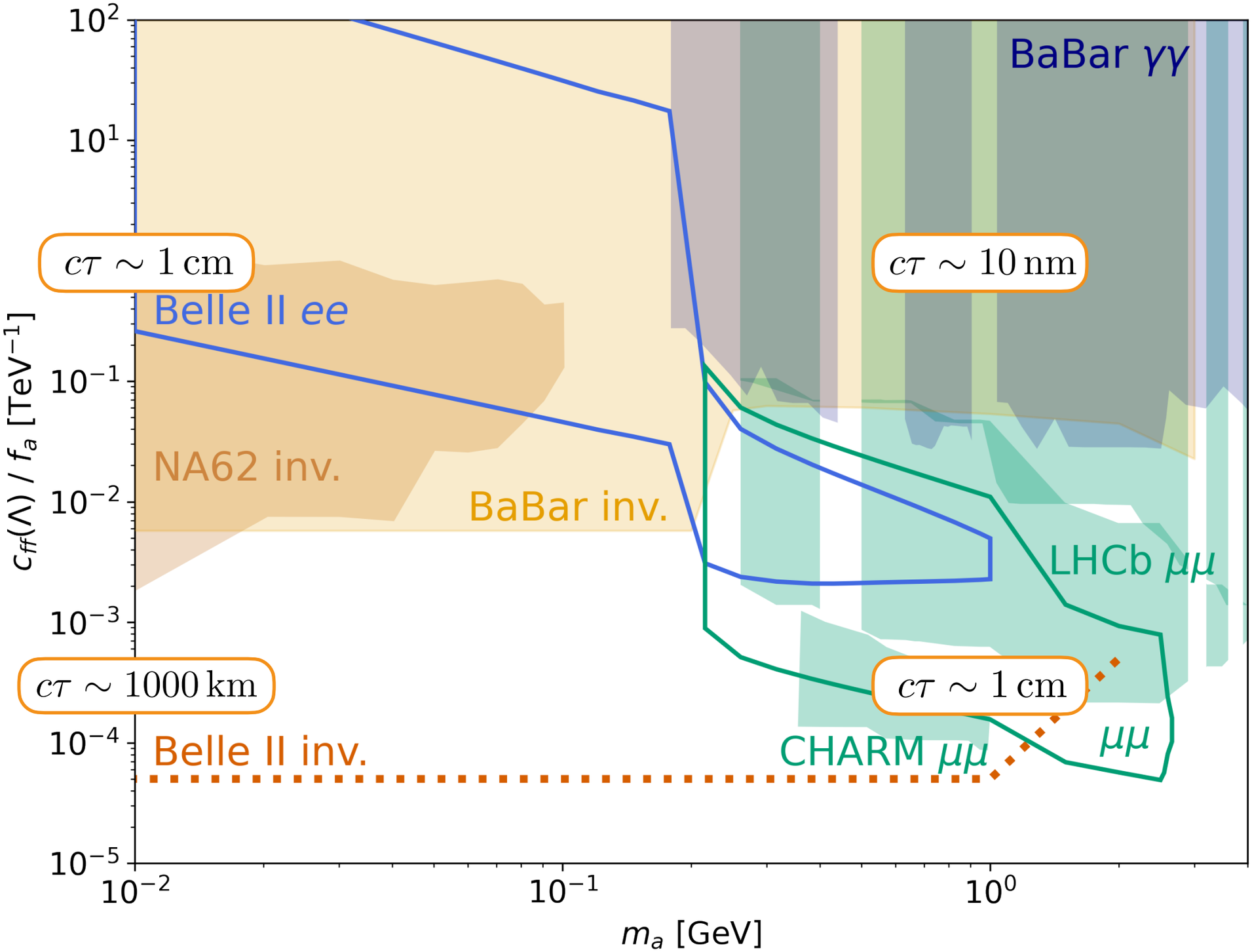
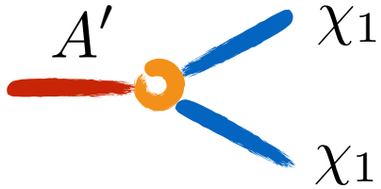


Ferber, Filimonova, Schaefer, SW 2201.06580

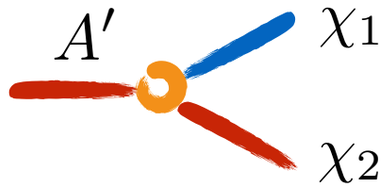
And dark matter?

Inelastic Dirac Dark Matter (i2DM)

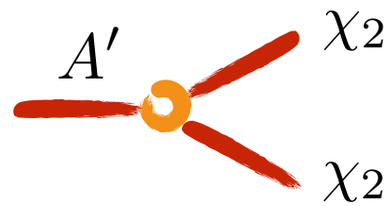
$$\mathcal{L} \supset \; e\epsilon A'_\mu \sum_f Q_f \bar{f}\gamma^\mu f - g_D\left(A'_\mu + \epsilon\,\frac{s_W}{c_W} Z_\mu\right)\left(\sin^2\theta J_1^\mu - \sin\theta\cos\theta J_{12}^\mu + \cos^2\theta J_2^\mu\right)$$



$J_1^\mu = \bar{\chi}_1\gamma^\mu\chi_1$



$J_{12}^\mu = \bar{\chi}_1\gamma^\mu\chi_2 + h.c.$



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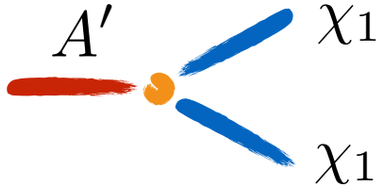

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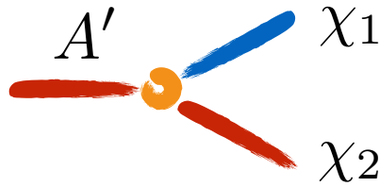

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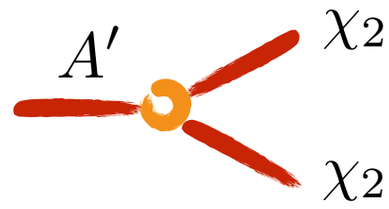
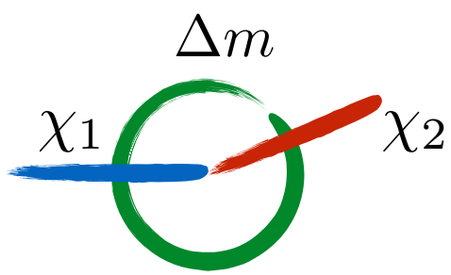


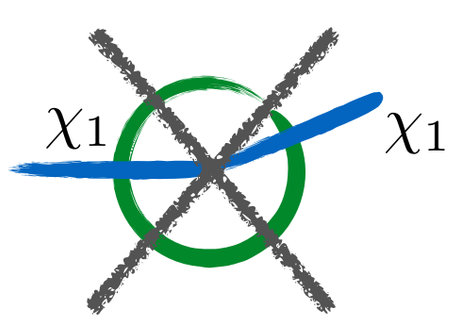
$J_2^\mu = \bar{\chi}_2\gamma^\mu\chi_2$

$\theta \to 0$:

- *inelastic* nucleon scattering

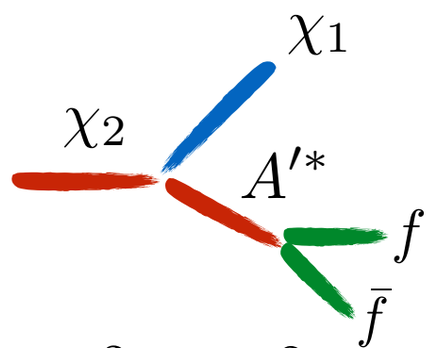


$\sin^2\theta\cos^2\theta$



$\sin^4\theta$

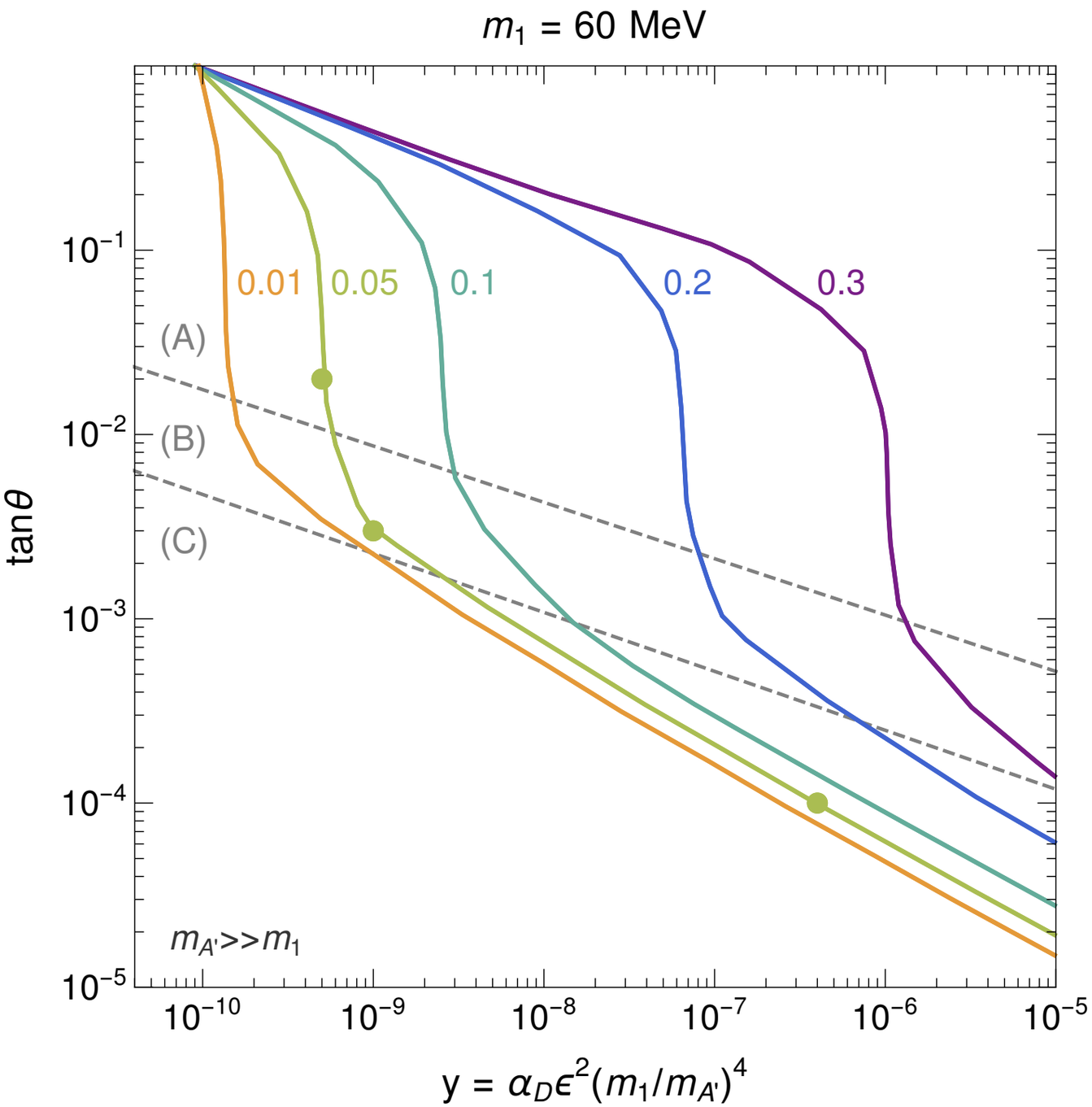
- long-lived partners

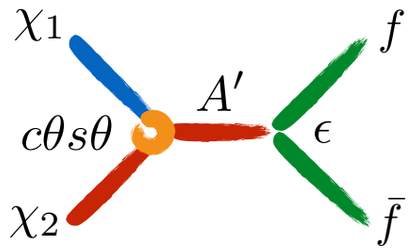


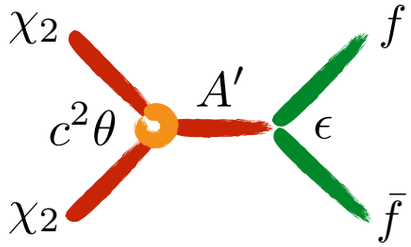
$\sin^2\theta\cos^2\theta$

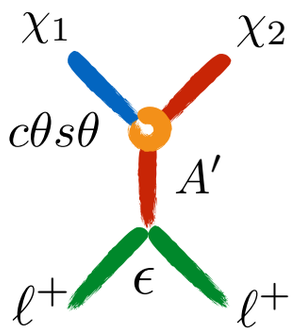
Filimonova, Junius, Lopez-Honorez, SW 2201.08409

Freeze-out cosmology









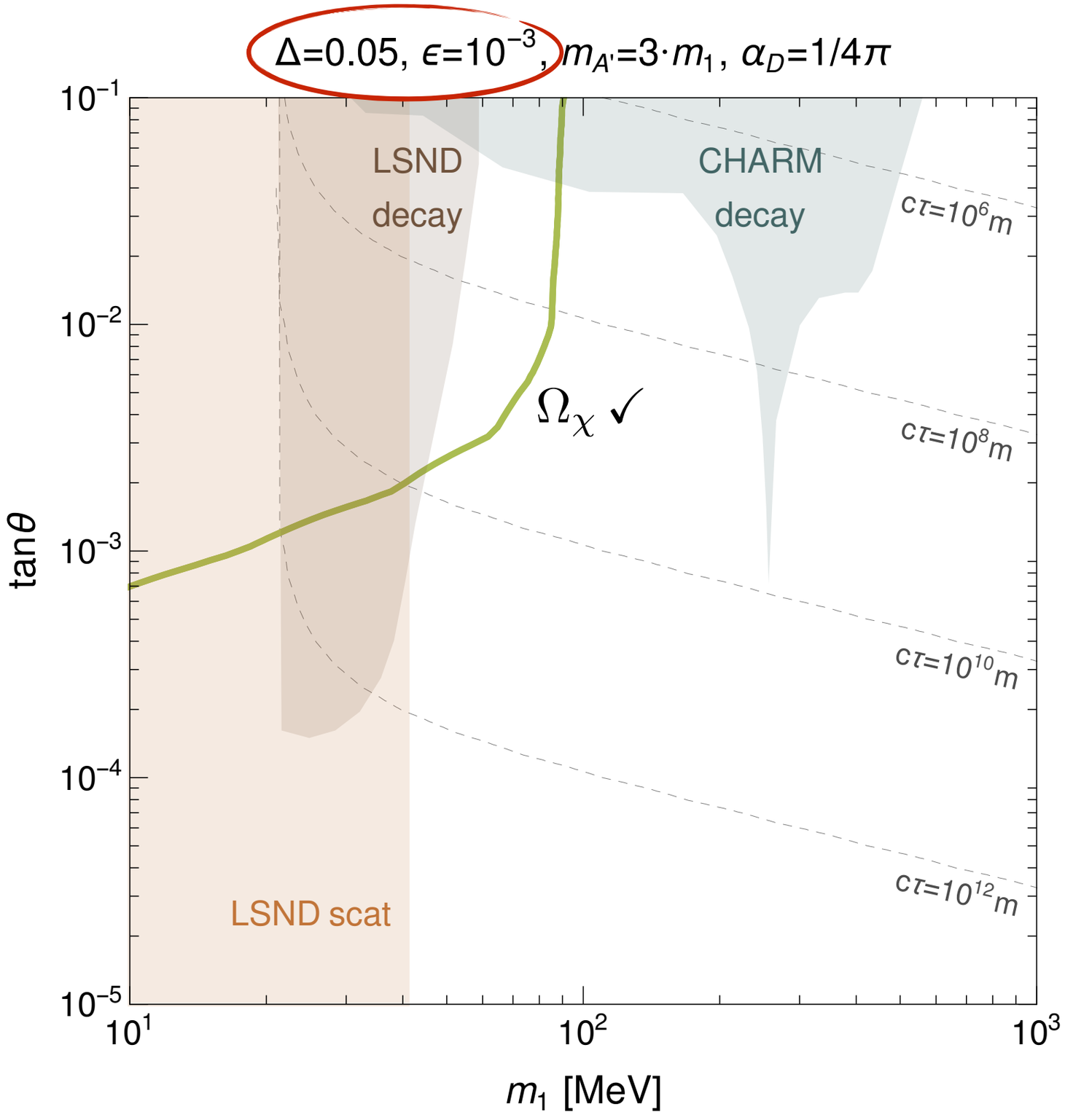
co-annihilation

partner annihilation

co-scattering

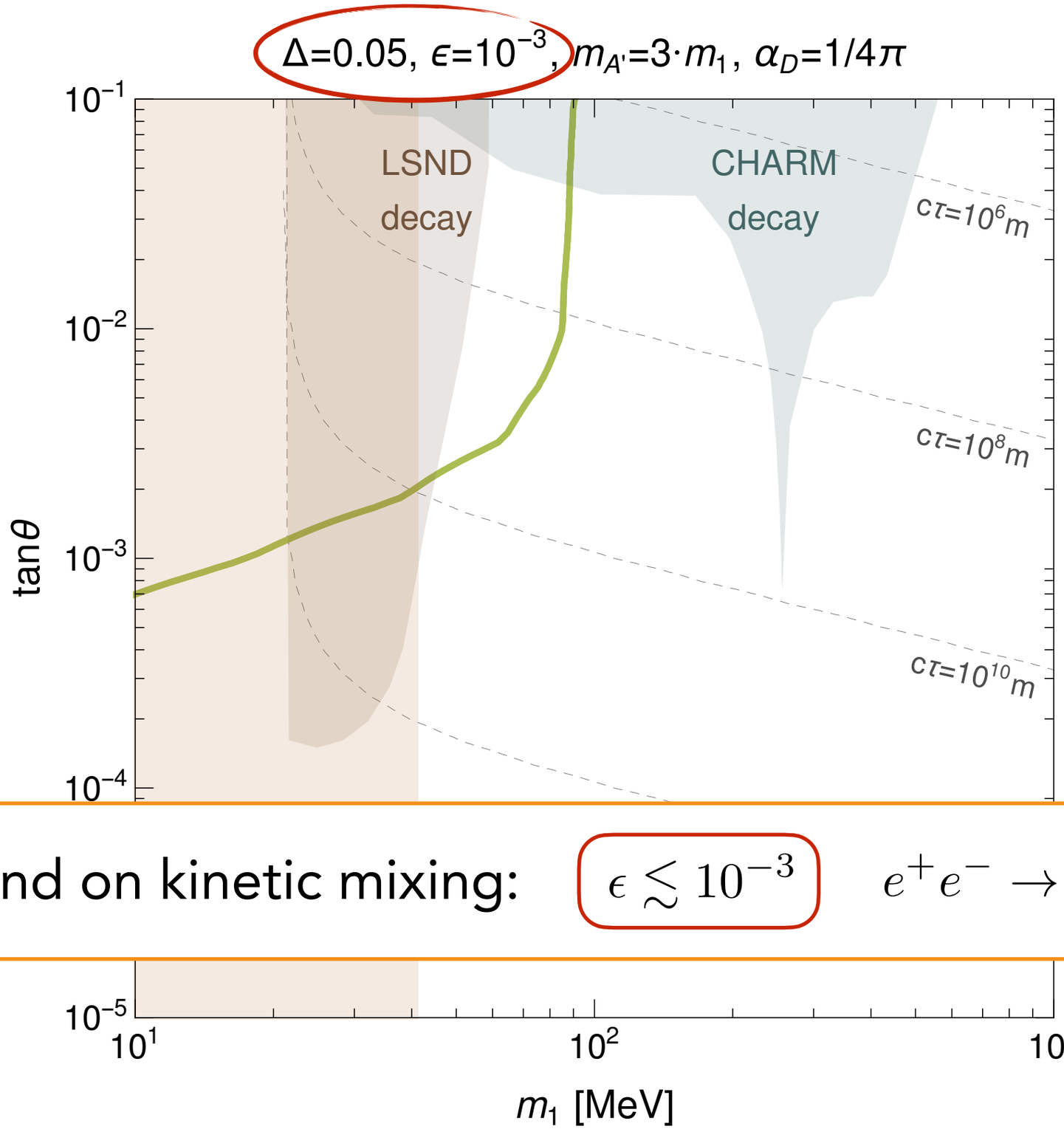
Filimonova, Junius, Lopez-Honorez, SW 2201.08409

Viable i2DM candidates



2201.08409

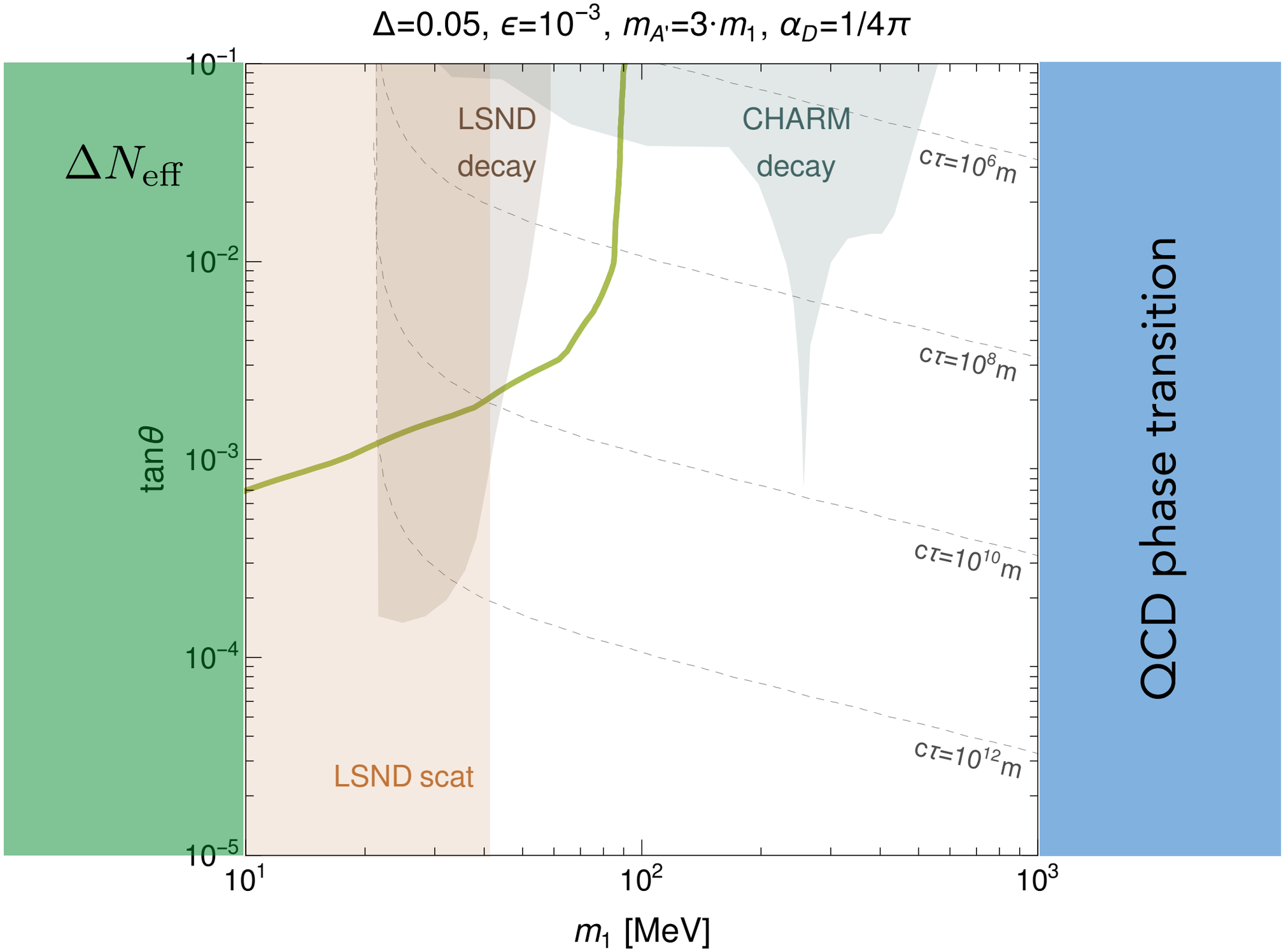
(No) missing energy at colliders



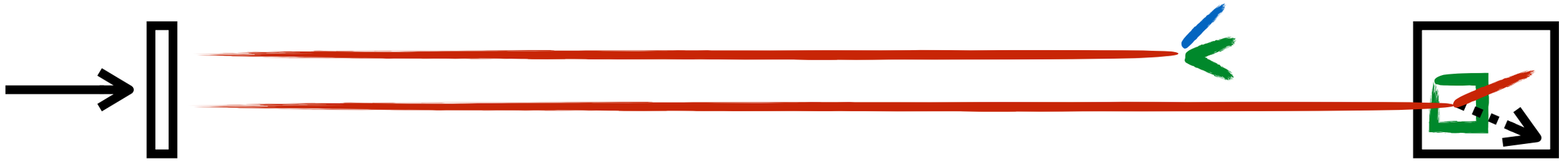
bound on kinetic mixing: $\epsilon \lesssim 10^{-3}$ $e^+e^- \to \gamma A' \to \gamma \not{E}$

BaBar 1702.03327

Mass bounds from cosmology



Long-baseline experiments



- production:

$$A' \to \chi_1\chi_2, \chi_2\chi_2$$

- decay:

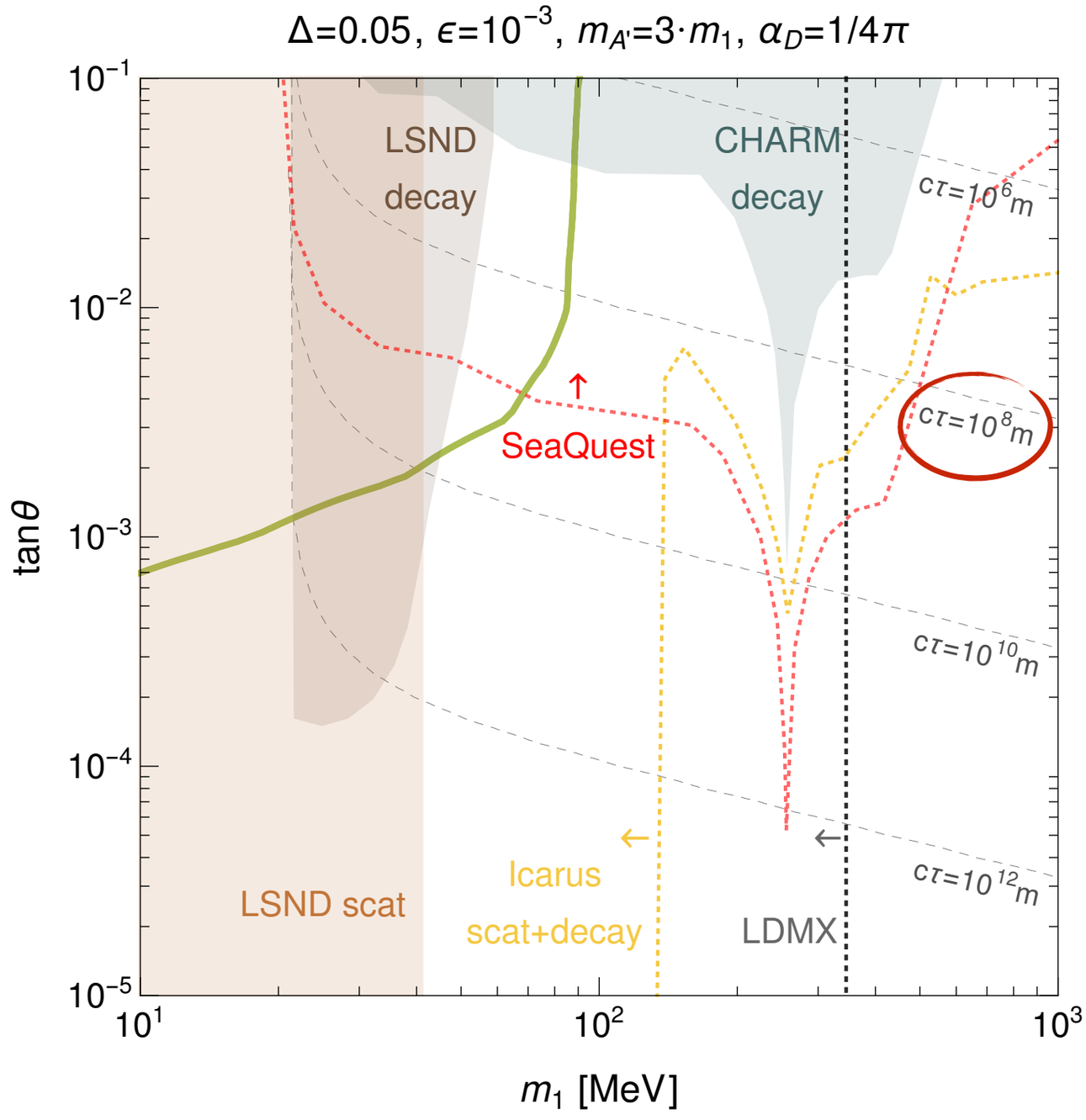
$$\chi_2 \to \chi_1 \ell^+ \ell^-$$

- scattering:

$$\chi_2 N \to \chi_2 N$$

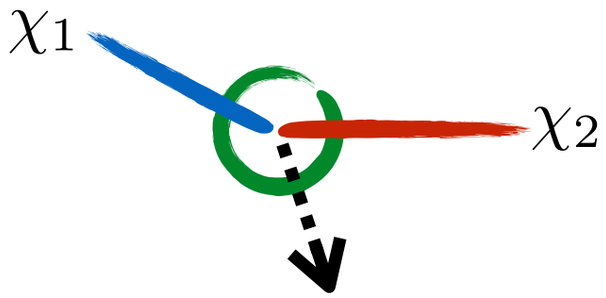
- upscattering + decay:

$$\chi_1 N \to \chi_2 N \to \chi_1 \ell^+ \ell^- N$$



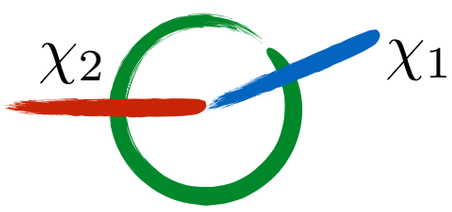
Long-lived particles from space

- production in the atmosphere: Bringmann, Pospelov 1810.10543

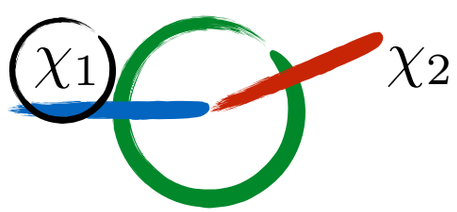


upscattering

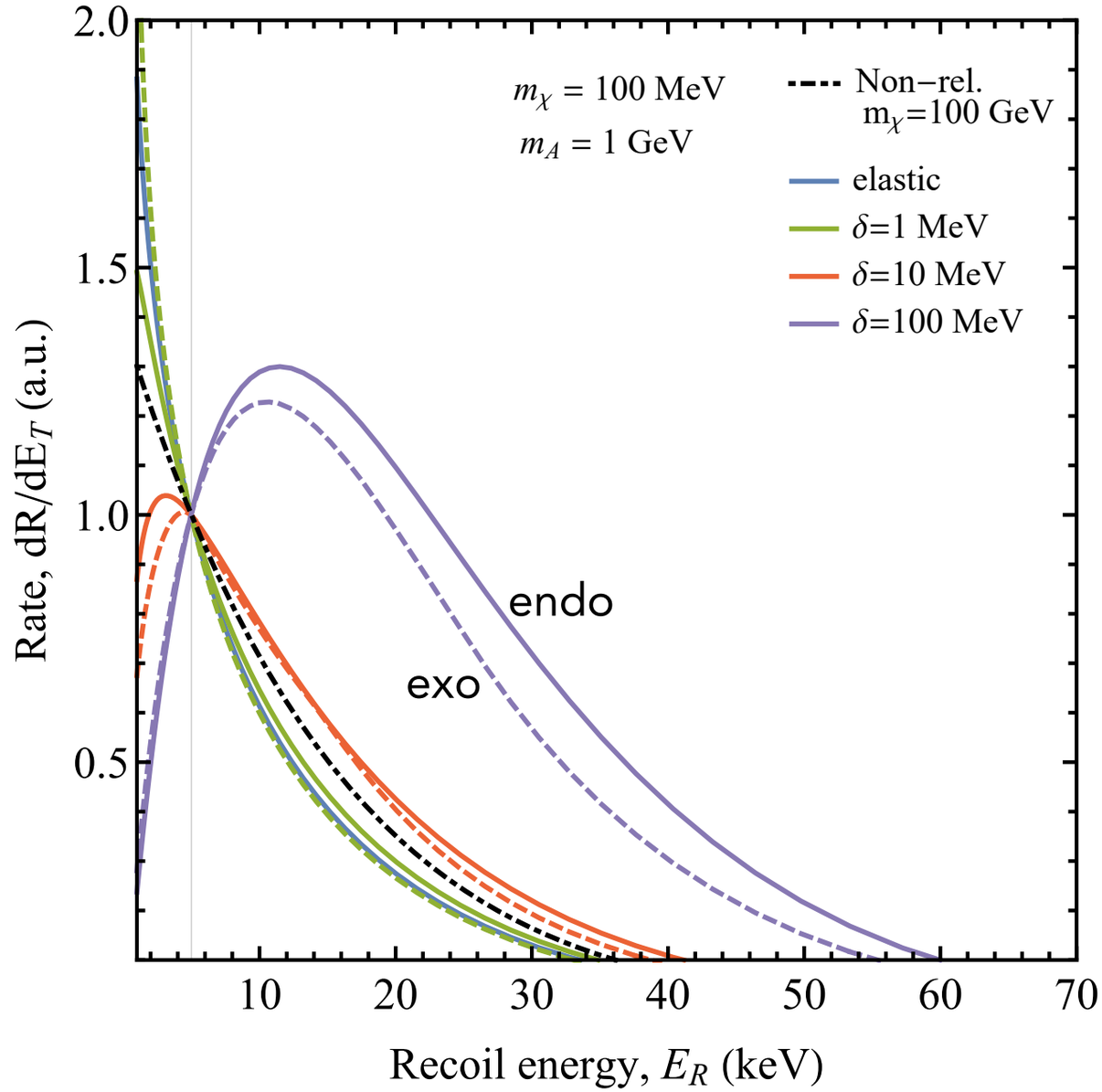
- detection underground:



exothermic



endothermic



Bell et al. 2108.00583

Summary

- **feeble** dark matter **interactions** - long-lived mediators

- **colliders**: multi-GeV particles with decay length < m

- **long-baseline**: sub-GeV particles with decay length >> m

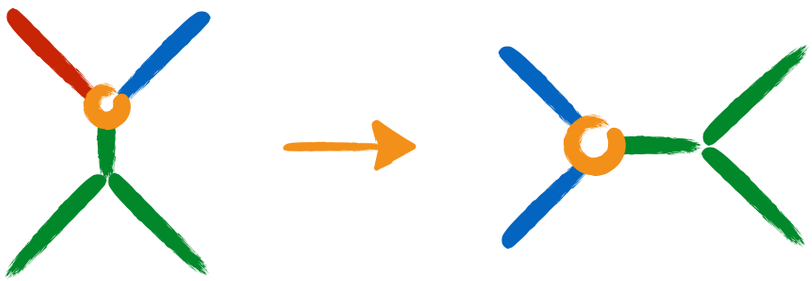
- **alternatives**: far detectors, atmosphere, cosmology

Thank you!

BACKUP

Dark matter relics: co-scattering

- freeze-out driven by co-scattering:



$$\Omega_\chi h^2 \sim \frac{m_\chi}{T_{fo}} \frac{\mathrm{GeV}^{-1}}{M_P \langle \sigma v \rangle}$$

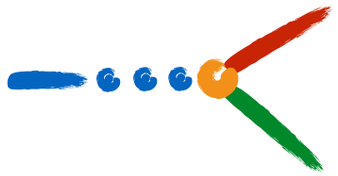
- number densities → compressed spectrum

$$\frac{n_\eta}{n_\chi} \sim e^{-\frac{\Delta m}{T}} \sim 1 \;@\; T_{fo} \sim \frac{m_\chi}{20}$$

$$\frac{\Delta m}{m} \ll 1$$

- observed abundance for → long-lived mediators

$$g_\chi^2 \sim e^{-\frac{m_\chi}{T}} g^2_{\mathrm{WIMP}} \ll 1$$

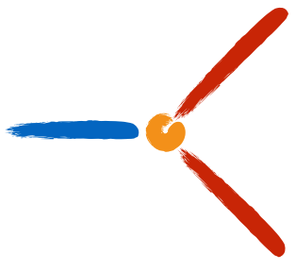


$$c\tau_\eta \sim \frac{1}{g_\chi^2 m_\eta} \left(\frac{m}{\Delta m}\right)^n$$

D'Agnolo et al. 1705.08450; Garny et al. 1705.09292

Dark matter relics: freeze-in

- early universe: mediator decays



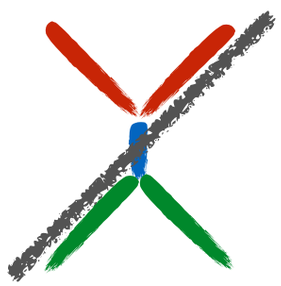
$$\Omega_\chi h^2 \sim \frac{m_\chi}{\mathrm{GeV}} \frac{M_P \Gamma_\eta}{T_{fi}^2}$$

- freeze-in temperature → split spectrum

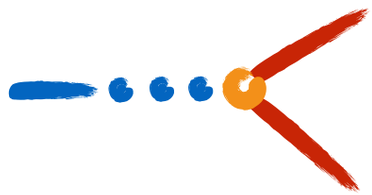
$$T_{fi} \approx m_\eta/3$$

$$\frac{m_\eta^2}{m_\chi} \sim 10^9\ \mathrm{GeV}$$

- DM out of equilibrium → long-lived mediators



$$g_\chi \lesssim 10^{-7}$$



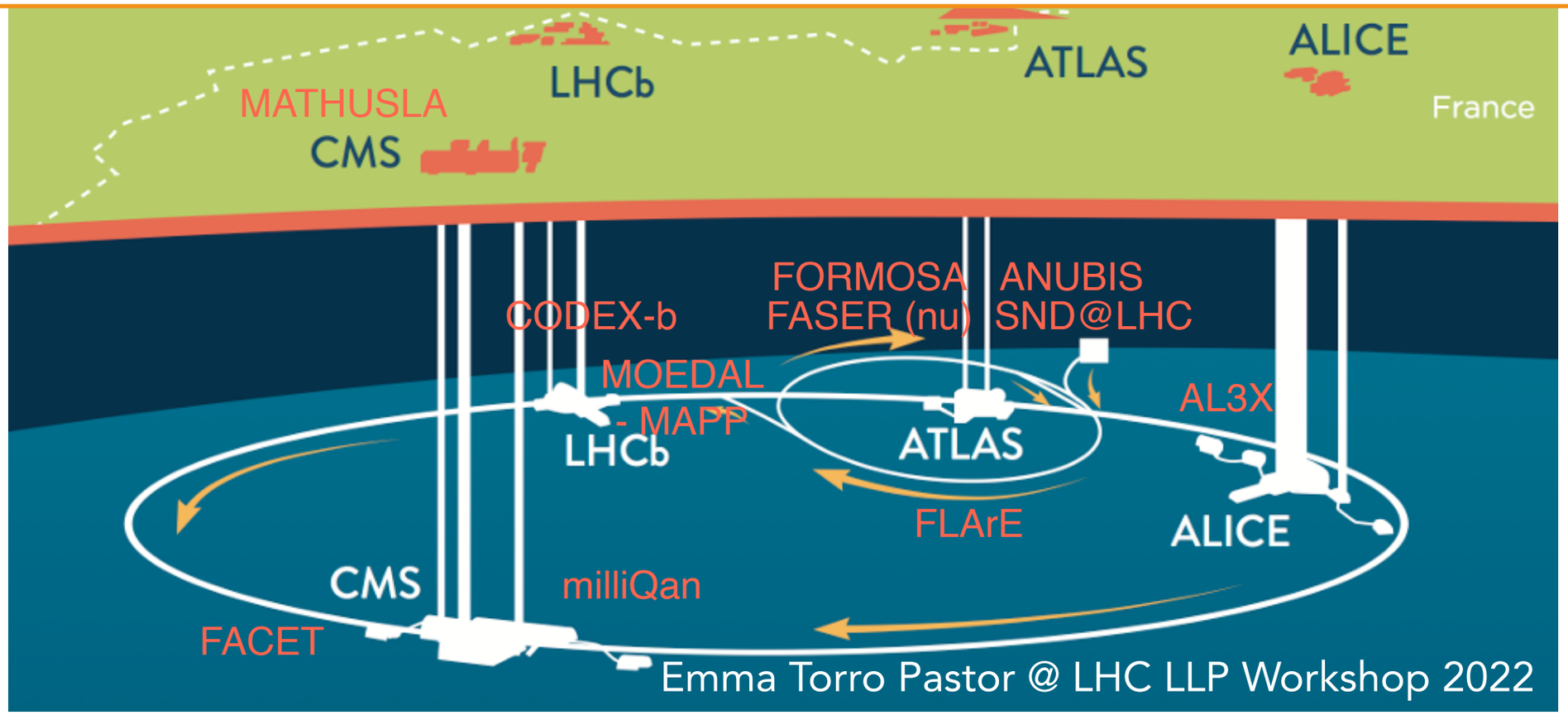
$$c\tau_\eta \sim \frac{m_\chi}{m_\eta^2}$$

Hall et al. 0911.1120

Far detectors

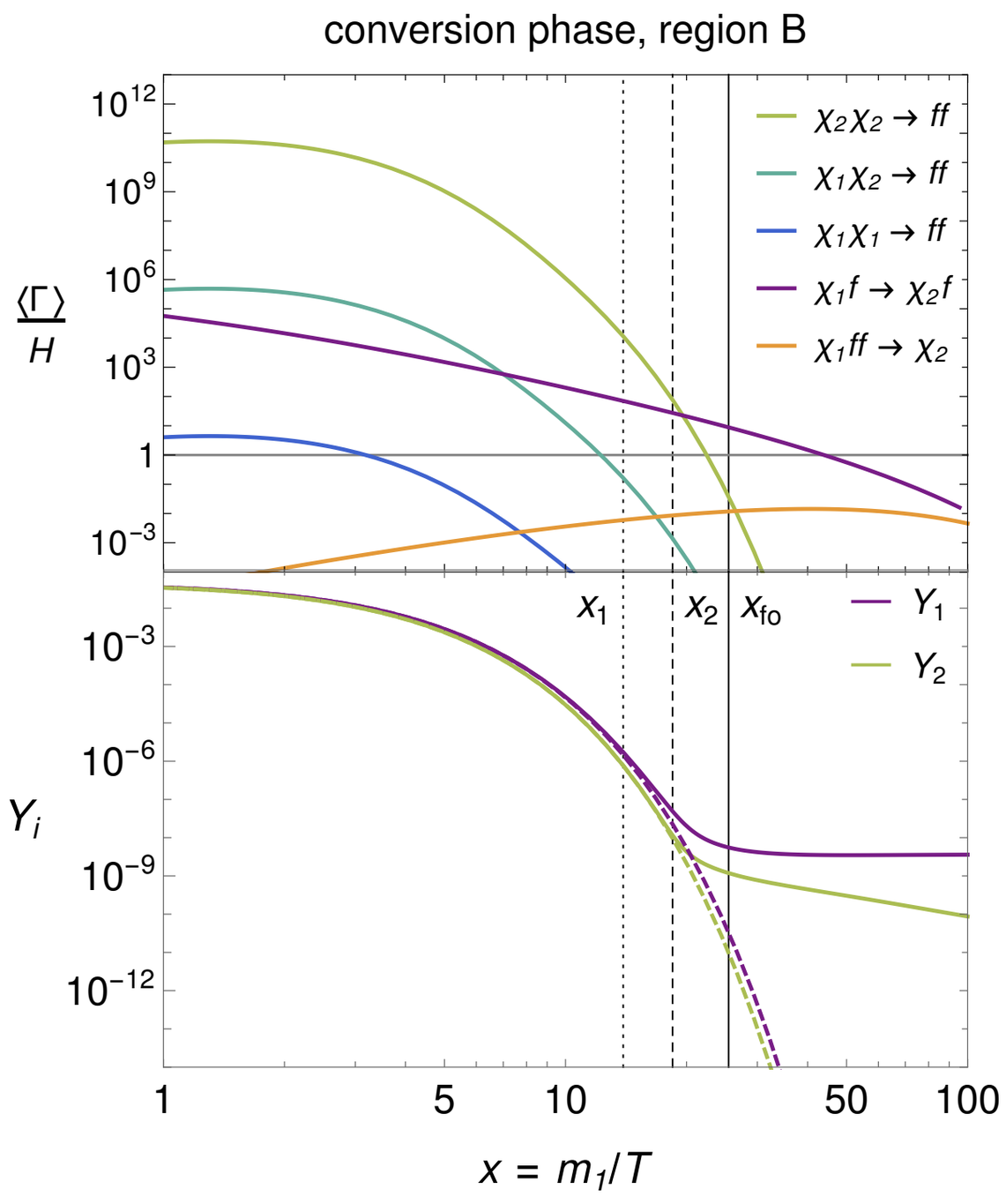
gain over near detectors *if*

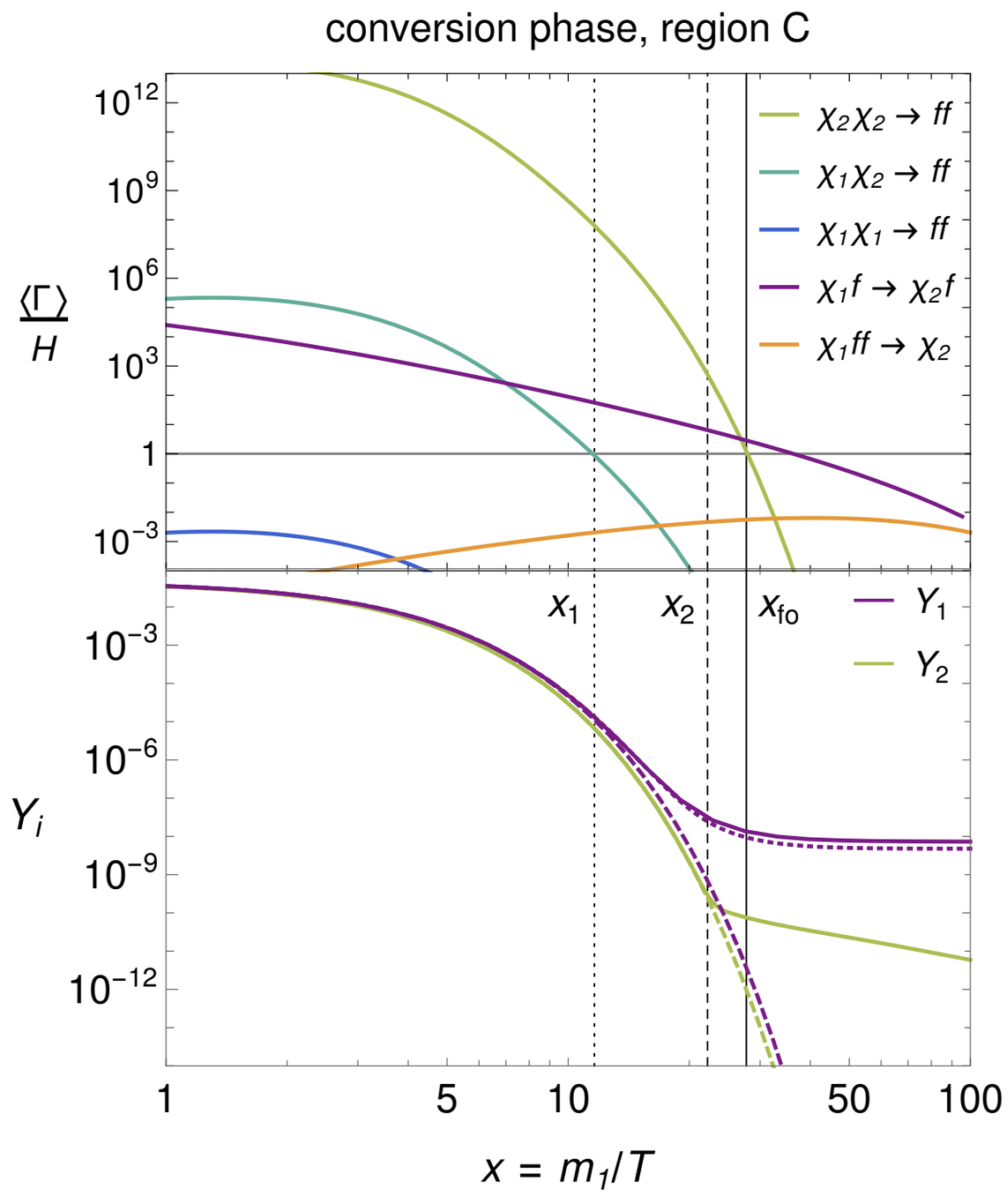
- low background
- high geometric coverage



- Forward Physics Facility — Feng et al. 2203.05090
- Belle II: GAZELLE — Dreyer, SW et al. 2105.12962
- ILC: transverse far detector options — Schaefer, Tillinger, SW 2202.11714

i2DM: freeze-out away from equilibrium



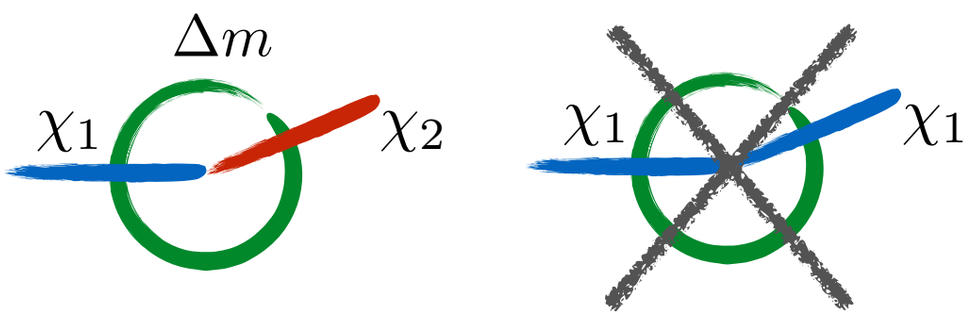


Filimonova, Junius, Lopez-Honorez, SW 2201.08409

Inelastic Dark Matter

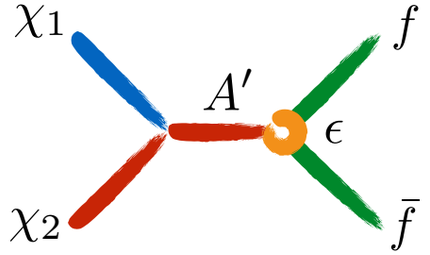
$$\mathcal{L}_{\rm iDM} \supset -ig_D A'_\mu(\chi_2^\dagger \bar{\sigma}^\mu \chi_1 - \chi_1^\dagger \bar{\sigma}^\mu \chi_2) + e\epsilon A'_\mu Q_f (\bar{f}\gamma^\mu f)$$

- only *inelastic* nucleon scattering



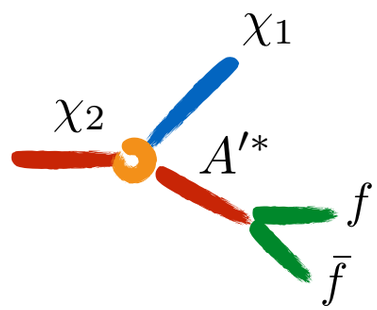
→ hidden from direct detection

- relic abundance:



co-annihilation

- phenomenology:

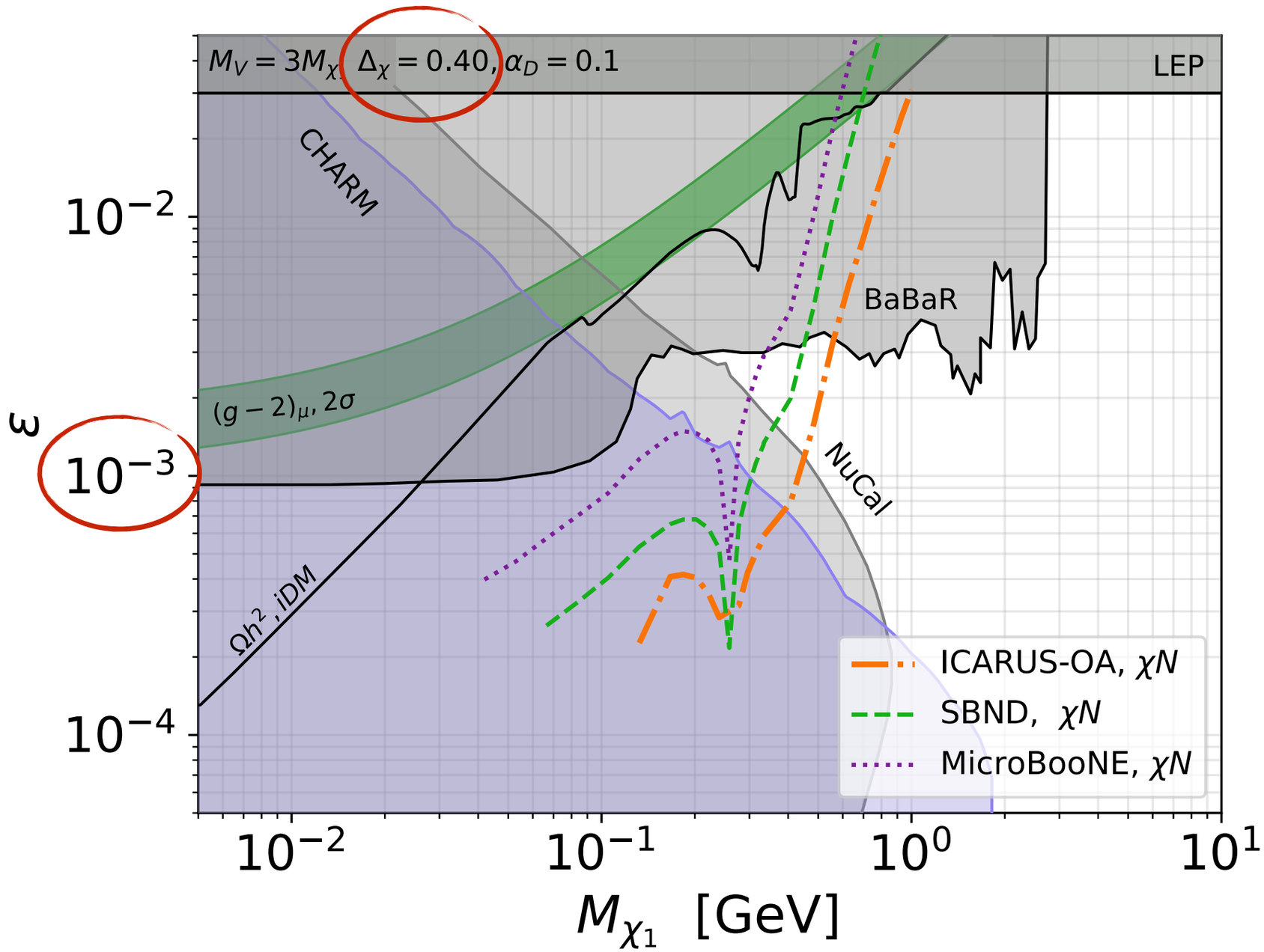


decay

Izaguirre et al. 1505.00011

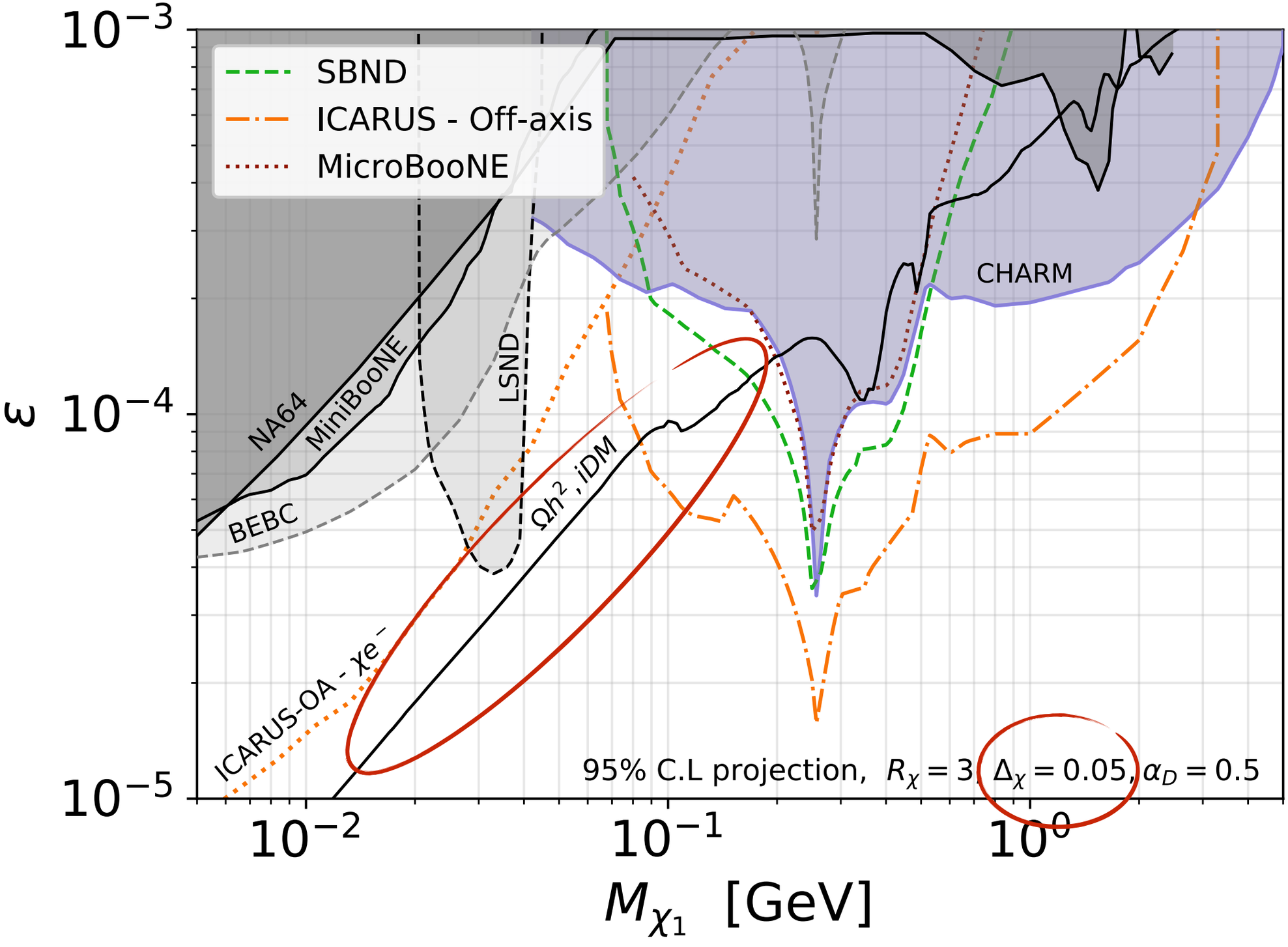
Evading mono-photon searches

$$e^+e^- \to \gamma A' \to \gamma \not{E}$$



Batell, Berger, Darme, Frugiuele 2106.04584

Sub-GeV inelastic dark matter



Batell, Berger, Darme, Frugiuele 2106.04584