DARK MATTER and LONG-LIVED PARTICLES

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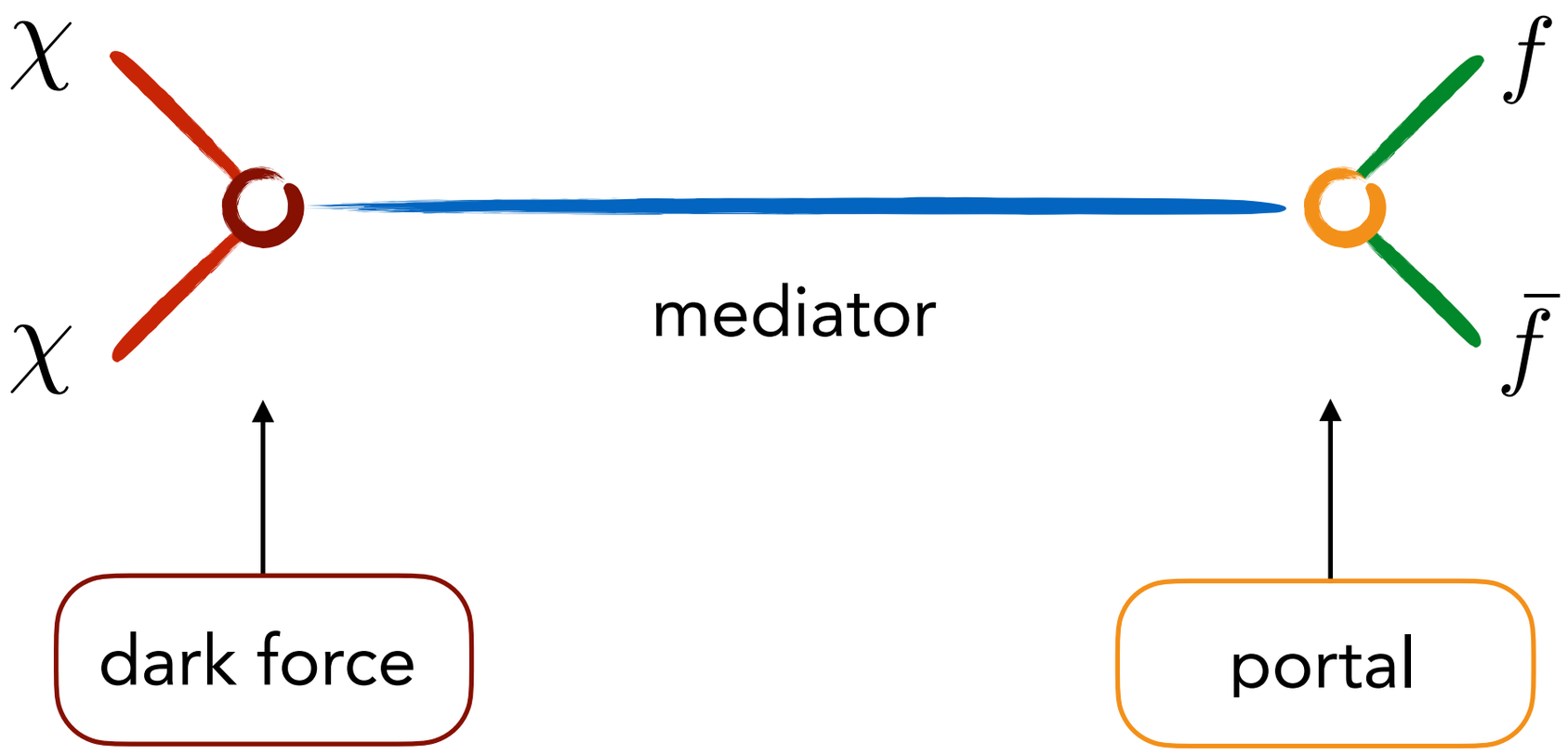
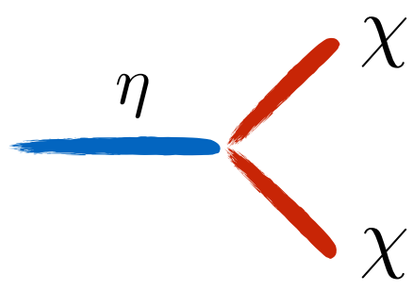
IPA 2022 ∘ Sep 5-9 ∘ Vienna

Dark and bright matter



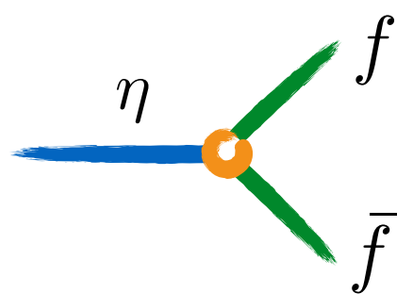
Mediator decays

dark:



$m_\eta > 2m_\chi$

visible:



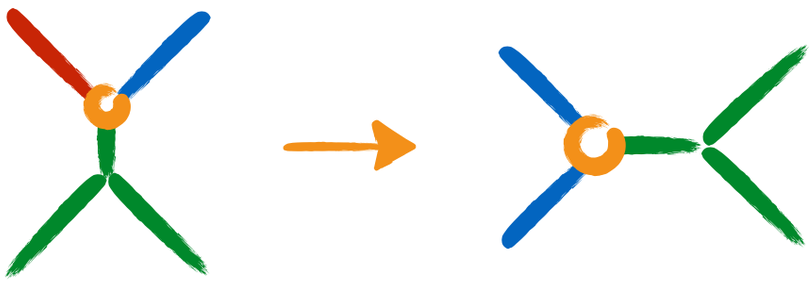
$m_\eta < 2m_\chi$

suppressed decay - long lifetime:

$$\tau = \frac{1}{\Gamma} \sim \frac{1}{\epsilon^2}$$

Dark matter relics: freeze-out

- early universe: co-scattering



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

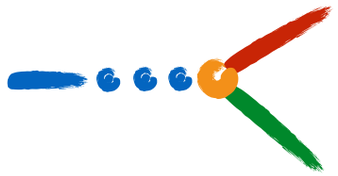
- number densities → compressed spectrum

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

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

- observed abundance for → long-lived mediators

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

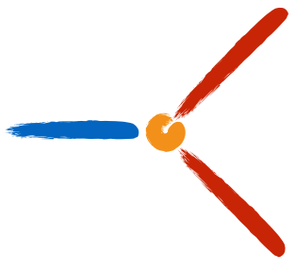


$$c\tau_\eta \sim \frac{1}{g_\chi^2 m_\eta} \left(\frac{m}{\Delta m}\right)^n$$

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

Dark matter relics: freeze-in

- early universe: mediator decays



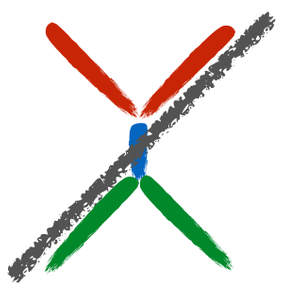
$$\Omega_\chi h^2 \sim \frac{m_\chi}{\mathrm{GeV}} \frac{M_P \Gamma_\eta}{T_{fi}^2}$$

- freeze-in temperature → split spectrum

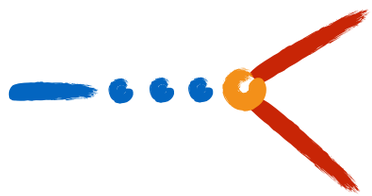
$$T_{fi} \approx m_\eta/3$$

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

- DM out of equilibrium → long-lived mediators



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



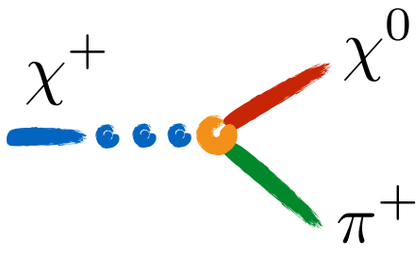
$$c\tau_\eta \sim \frac{m_\chi}{m_\eta^2}$$

Hall et al. 0911.1120

Dark sectors across the scales

- 100 GeV: electroweakinos

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



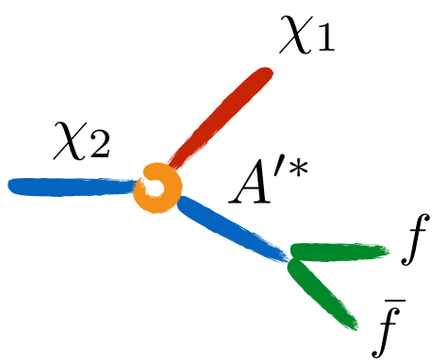
$$c\tau_{\chi^+} \approx 1\,\mathrm{cm} \left(\frac{6\times10^{-5}}{g_\chi}\right)^2 \left(\frac{20\,\mathrm{GeV}}{m_{\chi^+}-m_{\chi^0}}\right)^5 \left(\frac{m_{\chi^+}}{80\,\mathrm{GeV}}\right)^4$$

Blekman, SW et al. 2007.03708

- 100 MeV: inelastic dark matter

Tucker-Smith, Weiner hep-ph/0101138

Izaguirre et al. 1508.03050

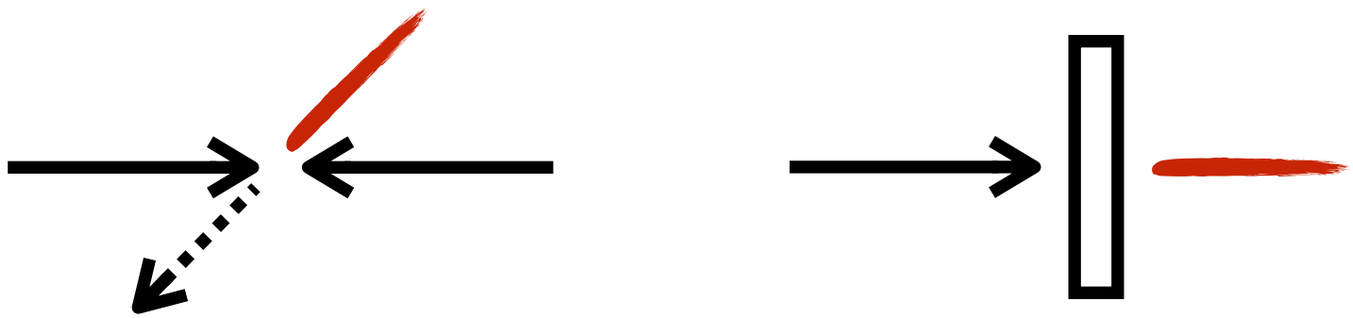


$$c\tau_{\chi_2} \sim \frac{1}{\epsilon^2 m_\chi}\left(\frac{m_1}{m_2-m_1}\right)^5\left(\frac{m_{A'}}{m_1}\right)^4 \gtrsim \mathcal{O}(\mathrm{km})$$

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

Sources of long-lived particles

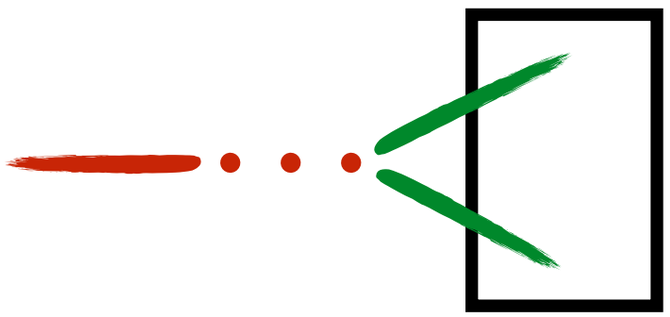
- on earth: colliders fixed target



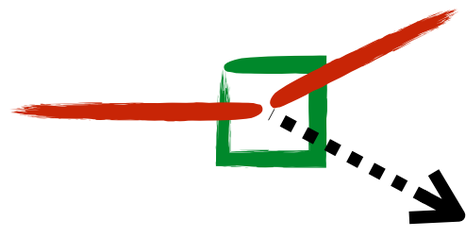
- in space: atmosphere relic abundance

Detection of long-lived particles

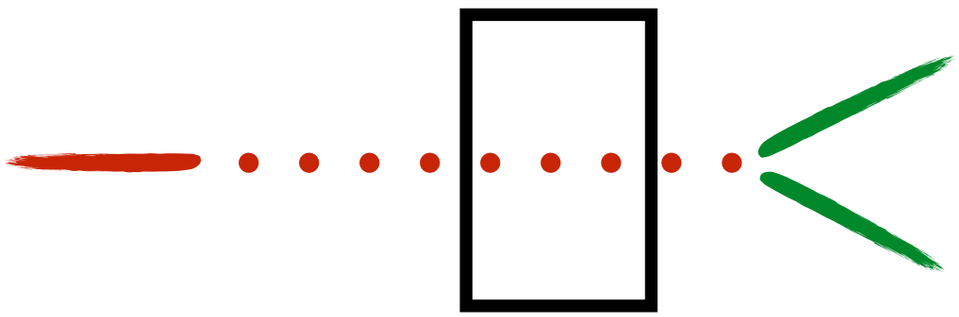
displaced decay



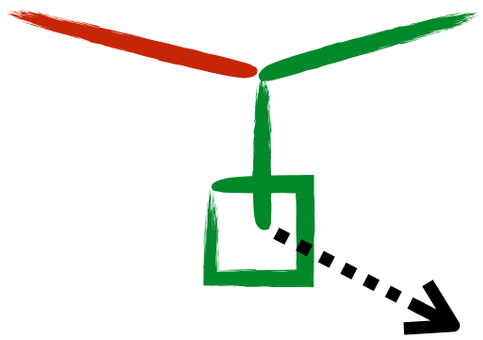
(up)scattering



missing energy

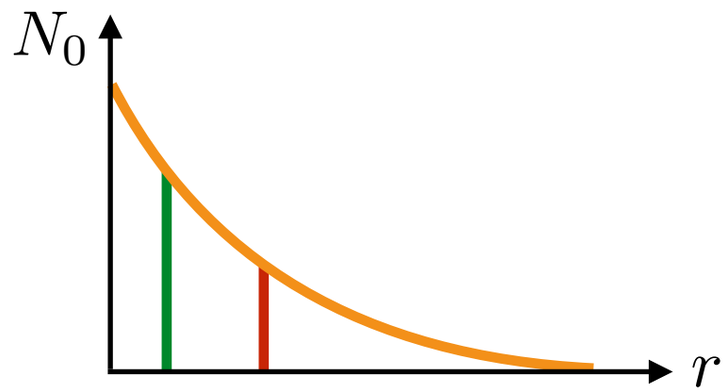


conversion



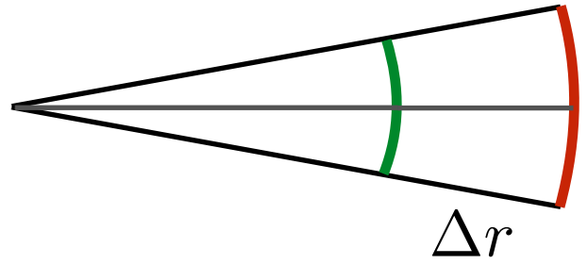
Long-lived particles at colliders

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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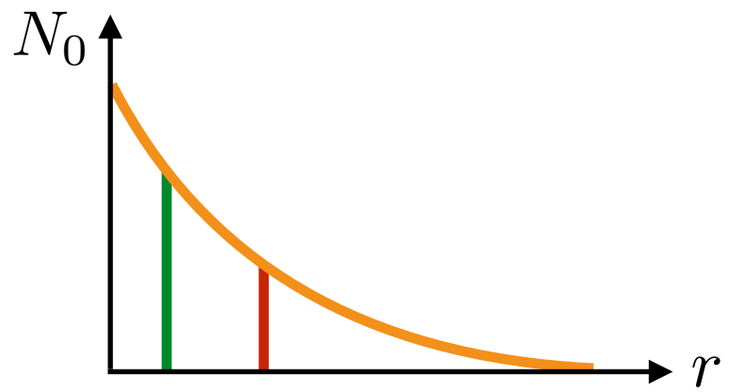

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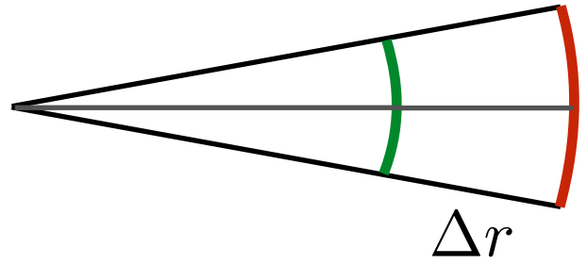


- boost

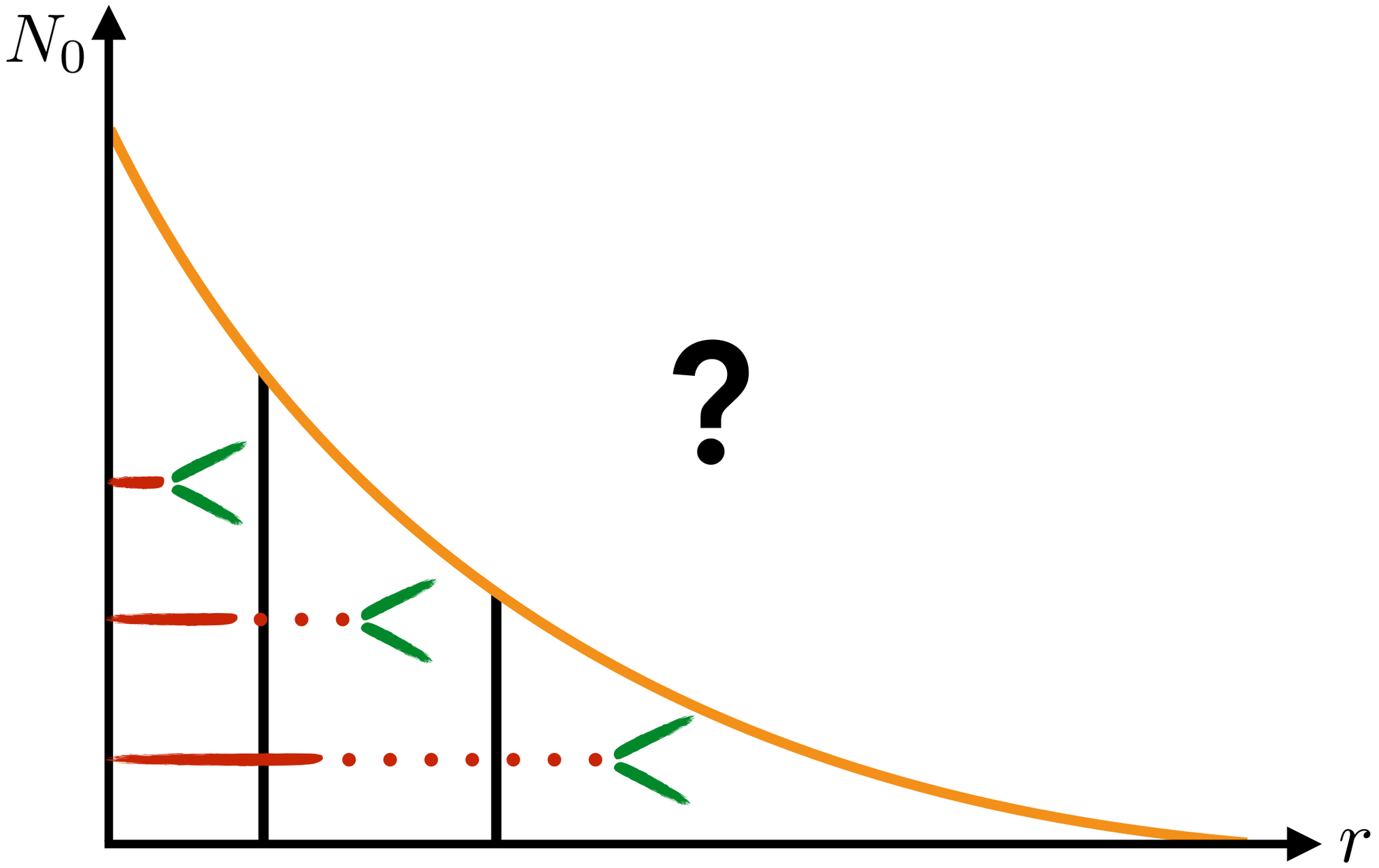
B meson

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

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

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

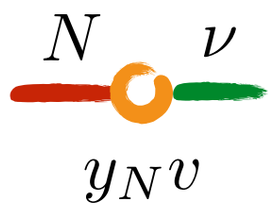
Prompt - displaced - invisible

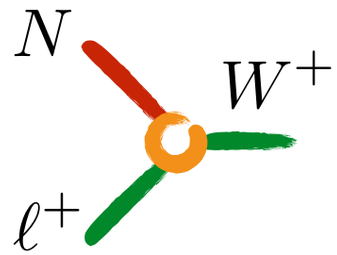


Portals

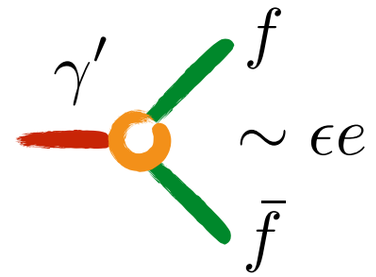
couple one new particle without touching SM symmetries

Neutrino portal: $\mathcal{L} = y_N(\overline{L}H)N + h.c.$

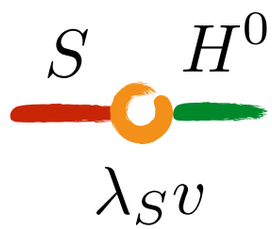


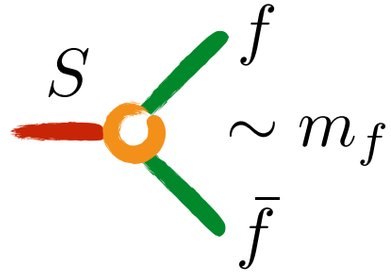


Vector portal: $\mathcal{L} = \epsilon\, F^{\mu\nu} F'_{\mu\nu}$

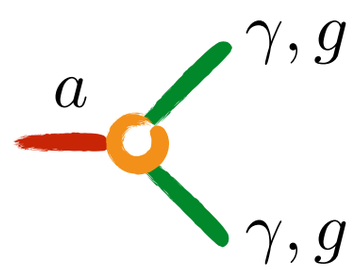


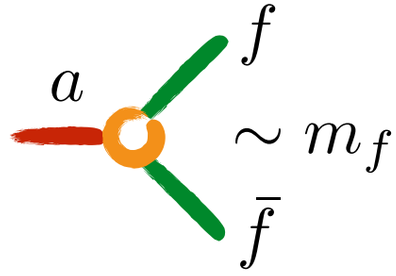
Higgs portal: $\mathcal{L} = \lambda_S(H^\dagger H)S$





ALP: $\mathcal{L}_{\text{eff}} = c_V \frac{a}{\Lambda} V_{\mu\nu}\widetilde{V}^{\mu\nu} + c_f \frac{\partial_\mu a}{\Lambda}(\bar{f}\gamma^\mu\gamma_5 f)$

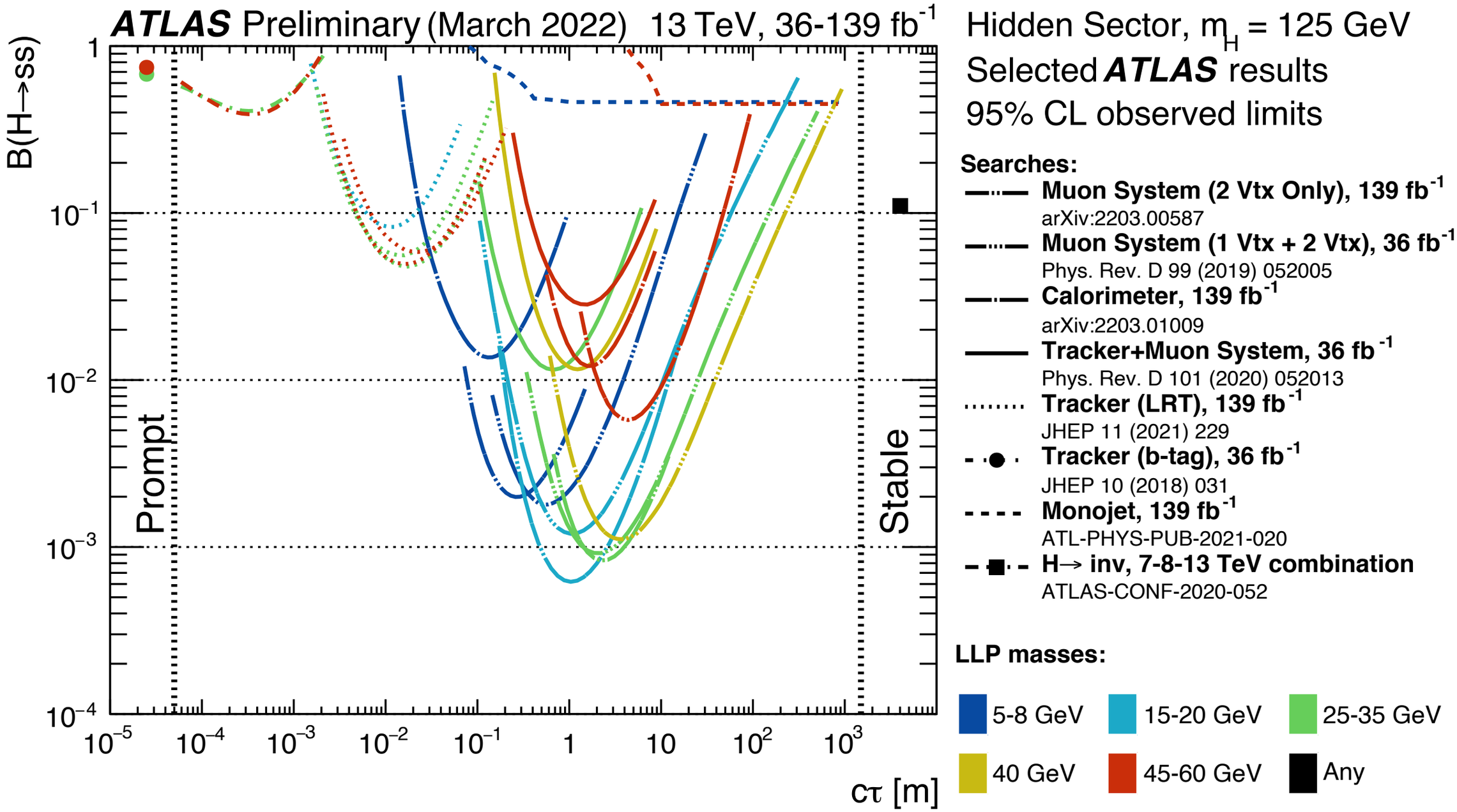




Georgi, Kaplan, Randall Phys.Lett.B 169 (1986) 73-78; Pospelov, Ritz, Voloshin 0711.4866

LHC: lifetime scan with detector layers

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

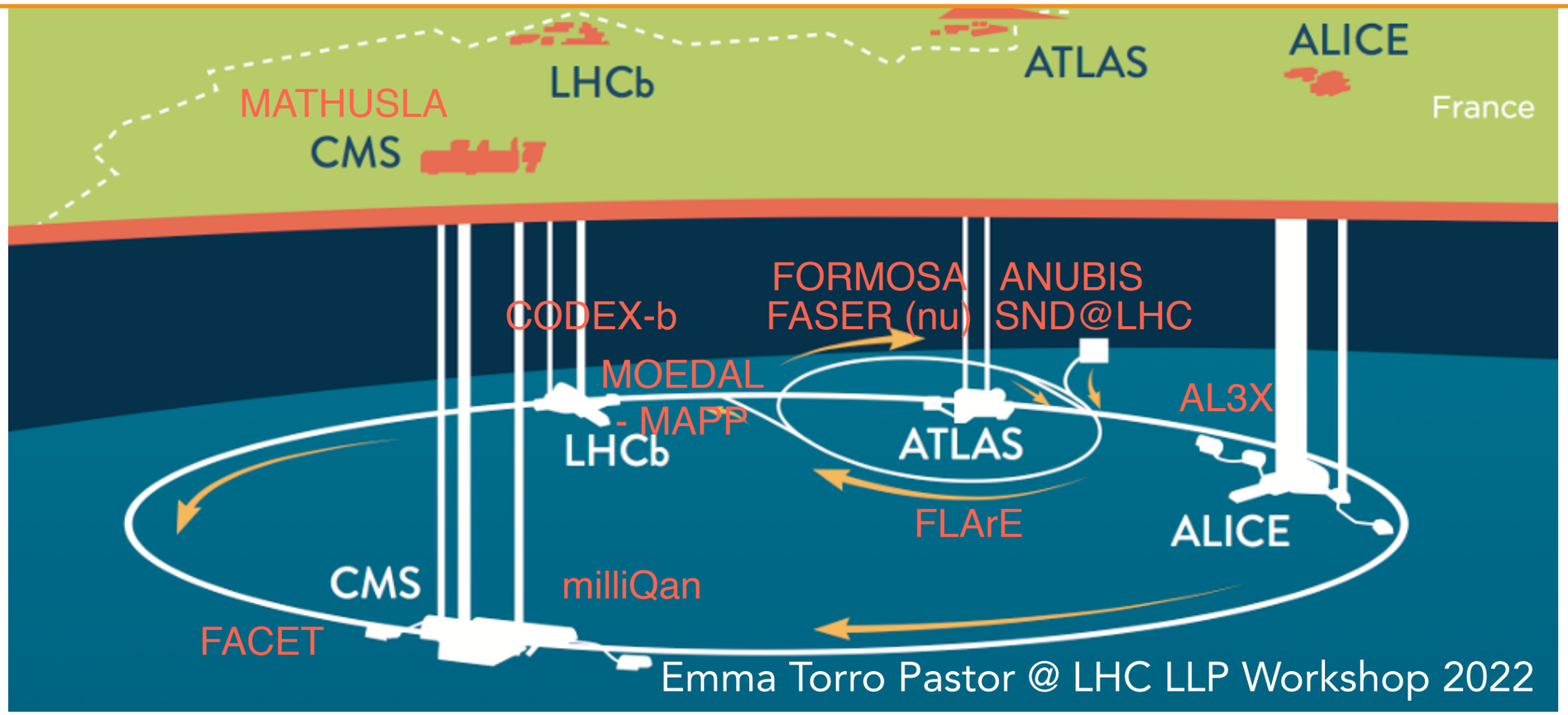


→ talk by Cristiano Alpigiani

Long lifetimes: far detectors

gain over near detectors *if*

- low background
- high geometric coverage



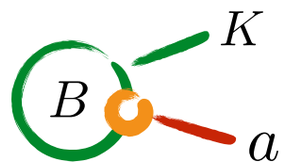
- LHC: Forward Physics Facility — Feng et al. 2203.05090
- Belle II: GAZELLE — Dreyer, SW et al. 2105.12962
- ILC: transverse far detectors — Schaefer, Tillinger, SW 2202.11714

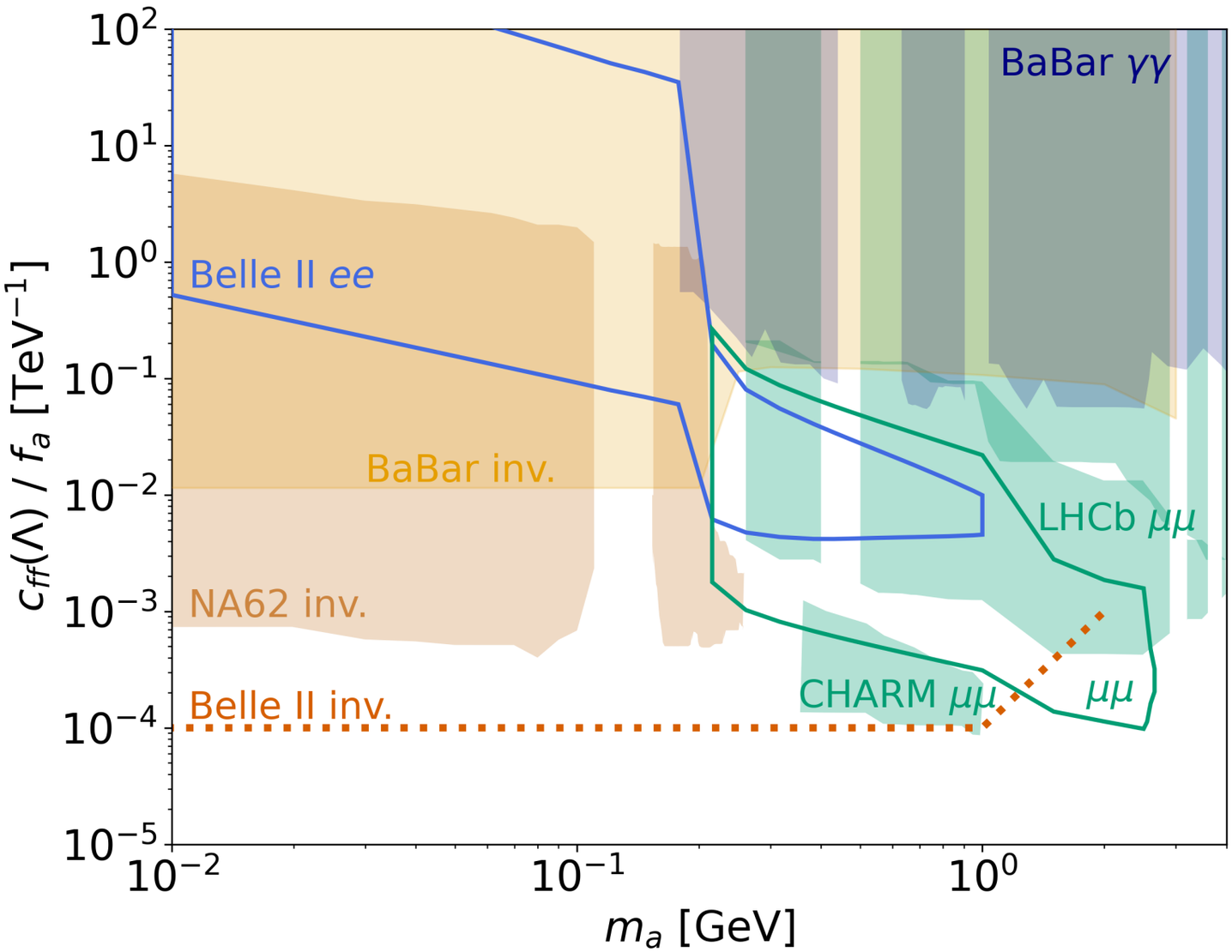
→ FASER: talk by Monica D'Onofrio

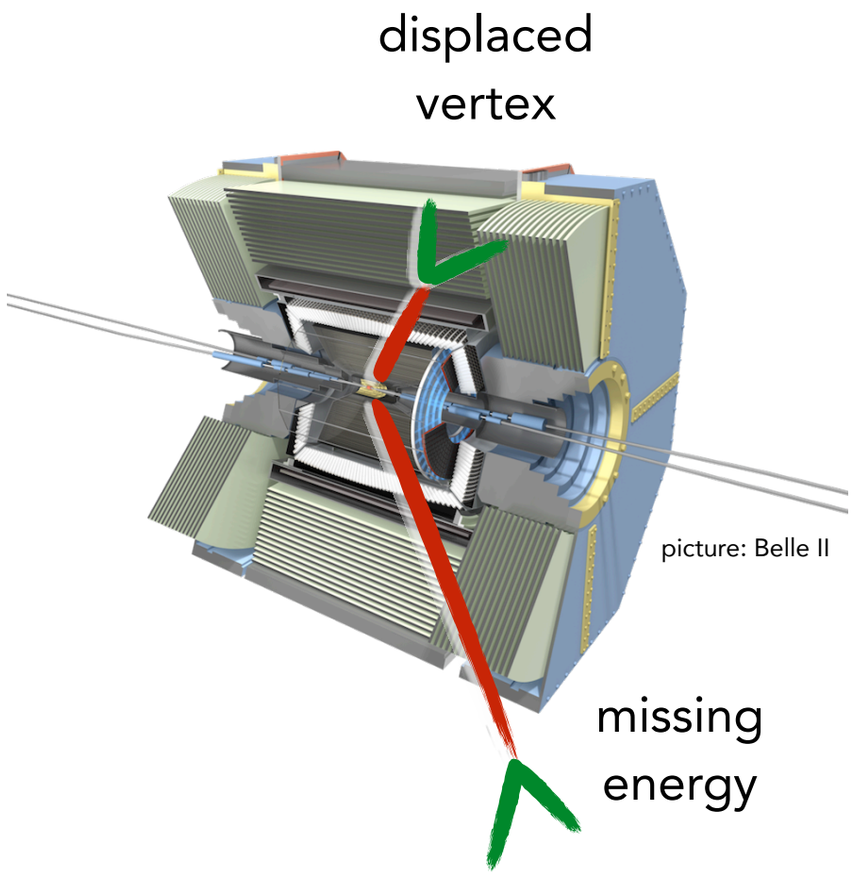
Belle II: displaced versus invisible

- axion-like particle:

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







Ferber, Filimonova, Schaefer, SW 2201.06580

Belle II: displaced versus invisible

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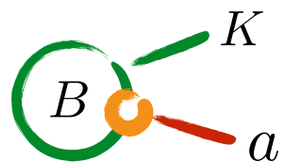
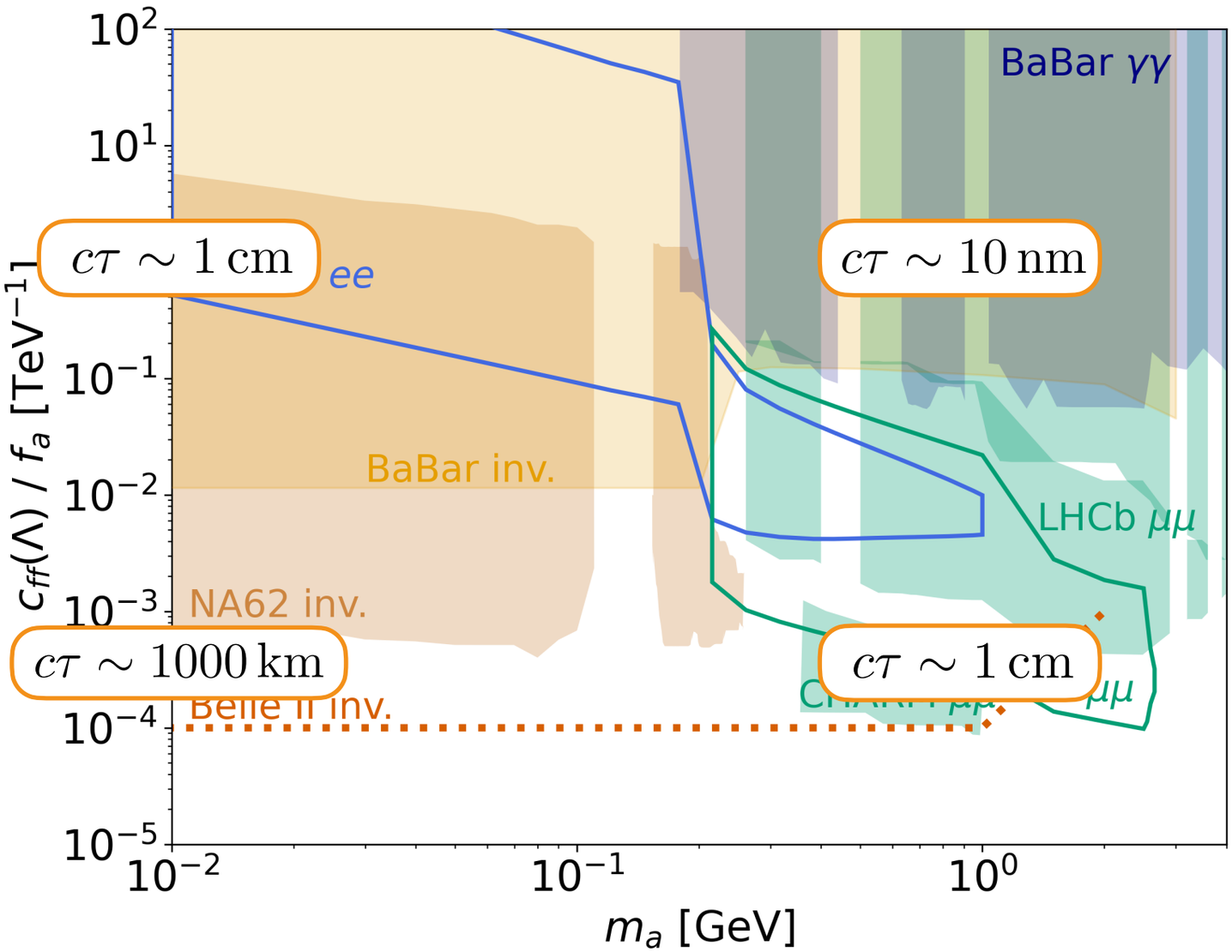
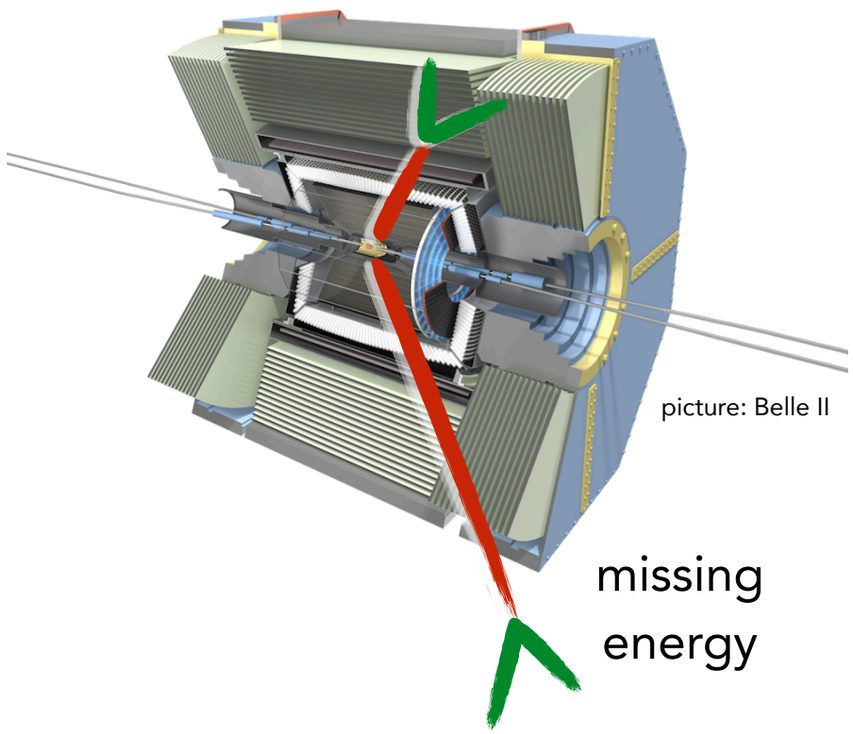


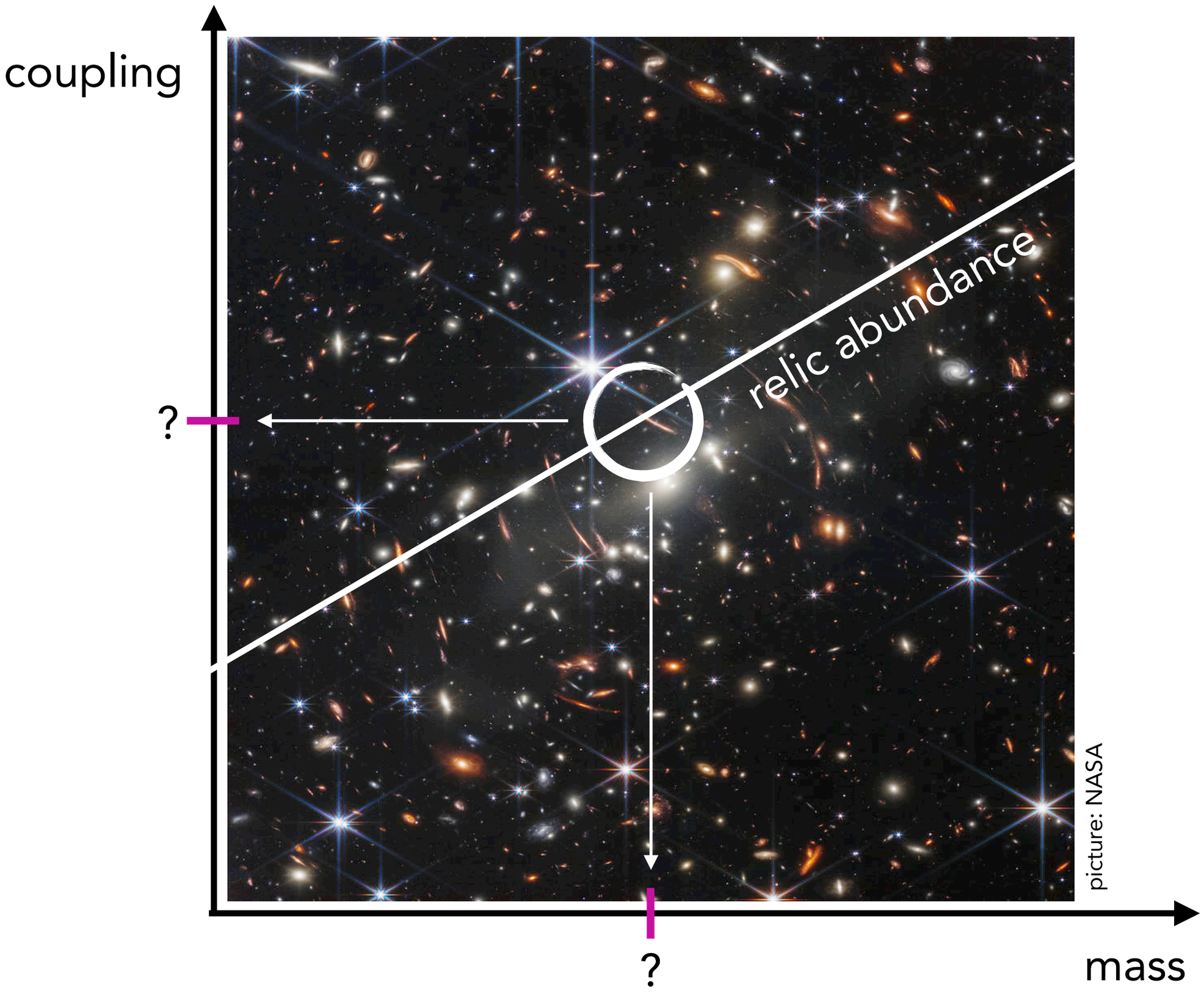


displaced vertex



Ferber, Filimonova, Schaefer, SW 2201.06580

Scale of dark matter?

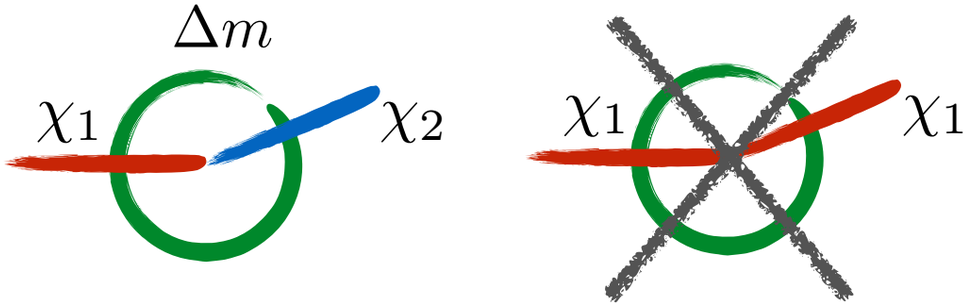


Inelastic Dark Matter

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

- only *inelastic* nucleon scattering

Tucker-Smith, Weiner hep-ph/0101138



→ hidden from direct detection

Inelastic Dark Matter

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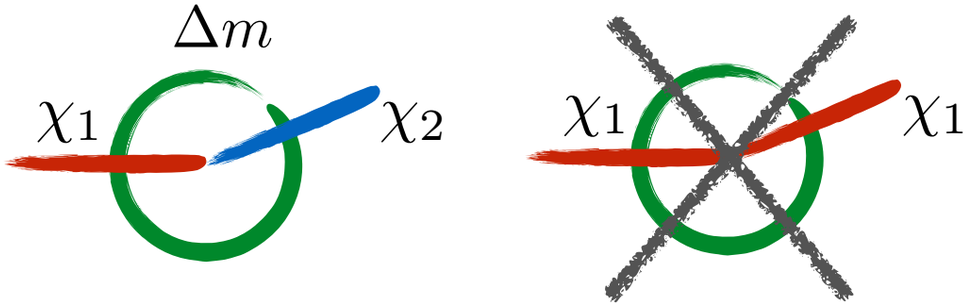
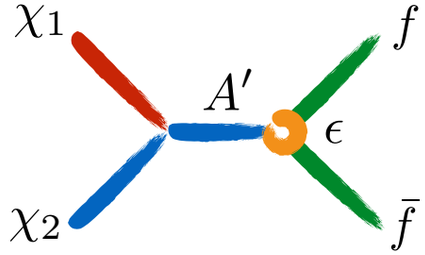


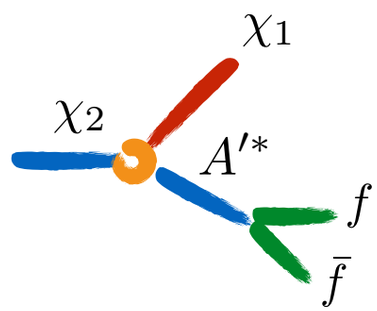
→ hidden from direct detection

- relic abundance:



co-annihilation

- phenomenology:

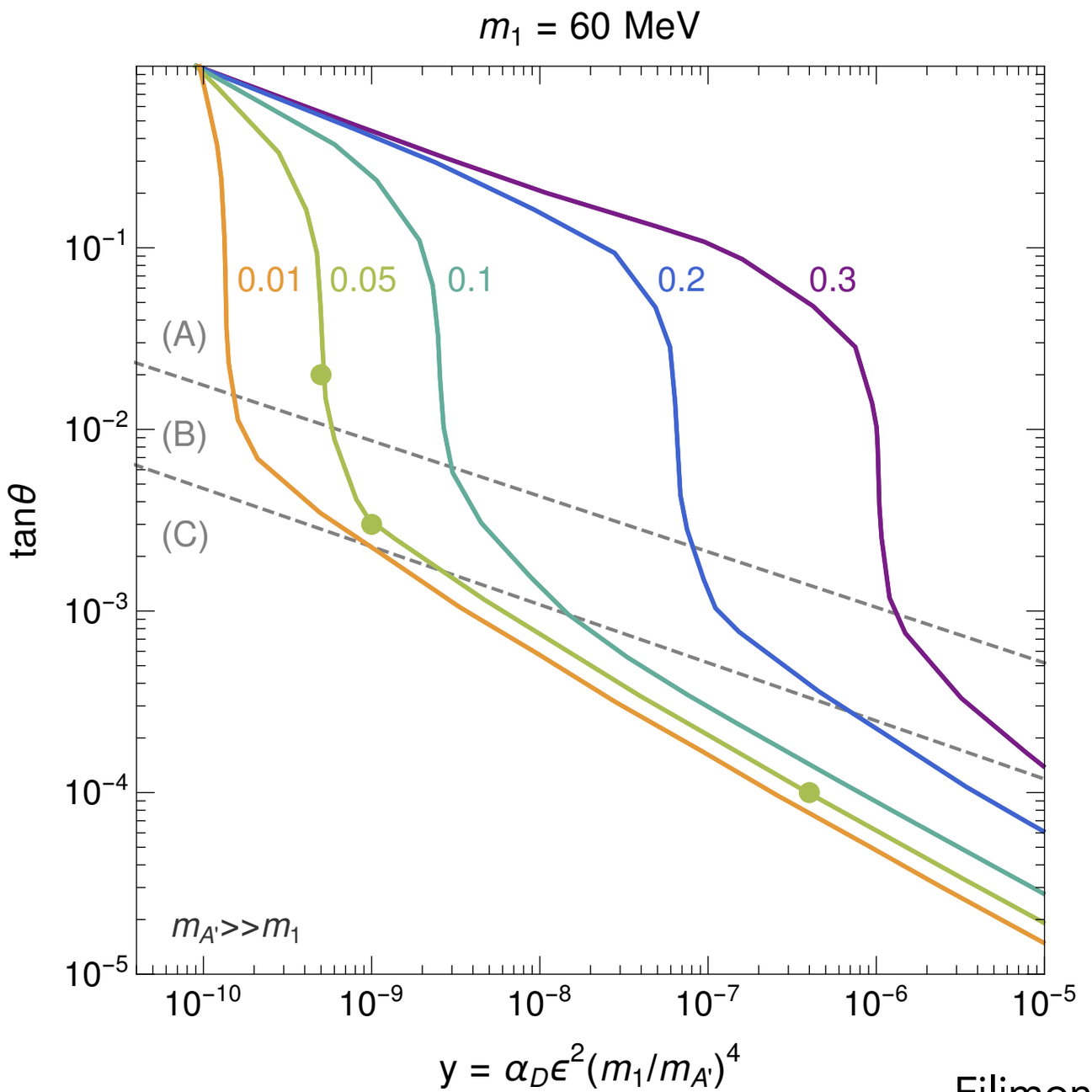


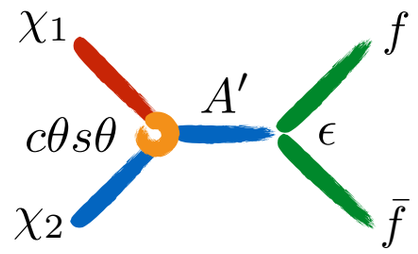
decay

Izaguirre et al. 1505.00011

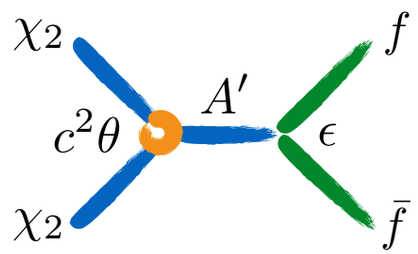
Inelastic Dirac Dark Matter

$$\mathcal{L}_{\rm i2DM} \supset -g_D A'_\mu \left[s^2\theta(\bar{\chi}_1\gamma^\mu\chi_1) - s\theta c\theta(\bar{\chi}_1\gamma^\mu\chi_2 + h.c.) + c^2\theta(\bar{\chi}_2\gamma^\mu\chi_2) \right]$$

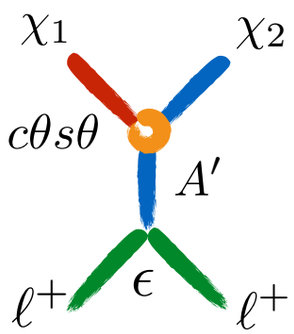




co-annihilation



partner annihilation



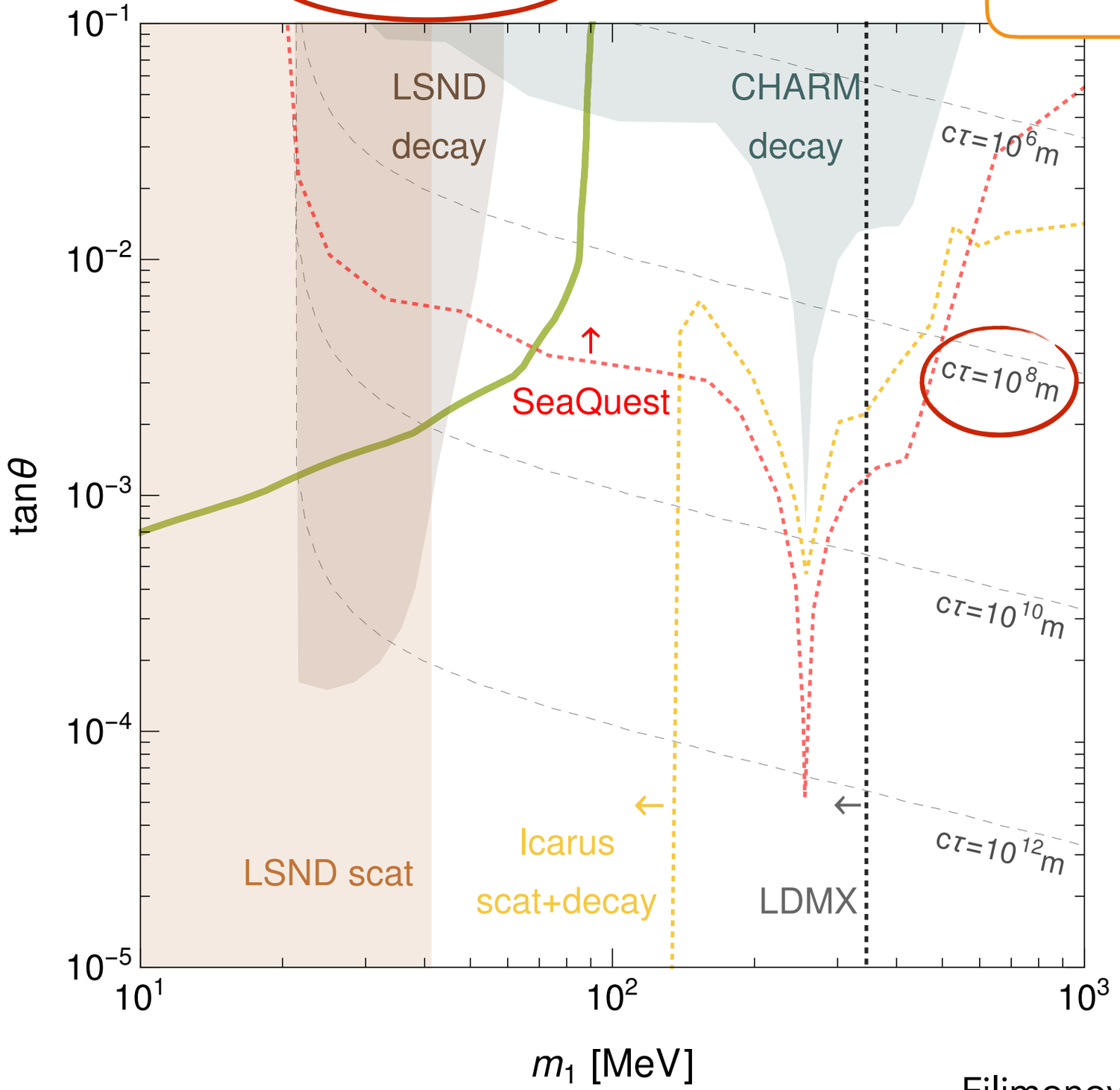
co-scattering

Filimonova, Junius, Lopez-Honorez, SW 2201.08409

Evade mono-photon searches

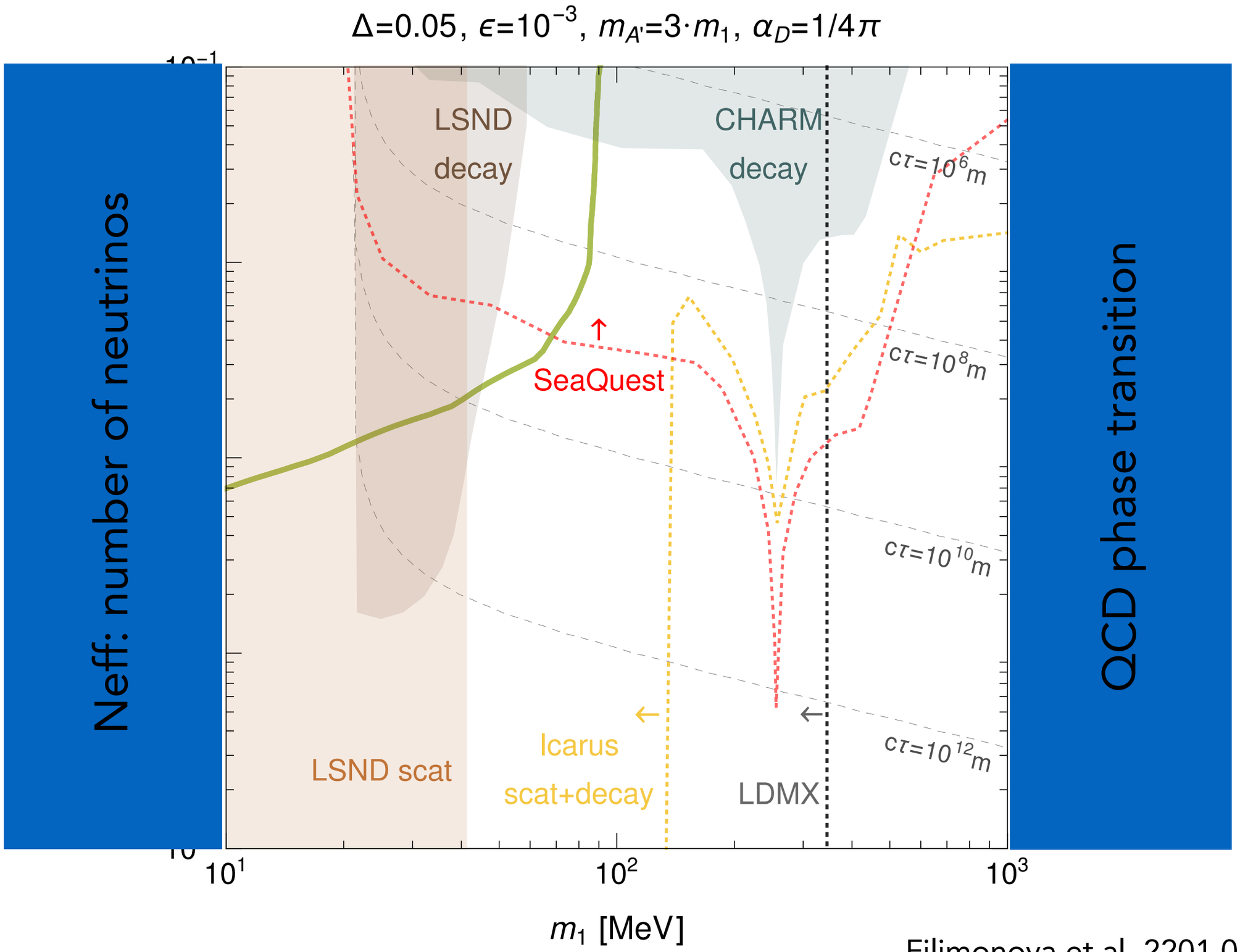
Δ=0.05, ϵ=10^{-3}, $m_{A'}$=3·m_1, α_D=1/4π

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



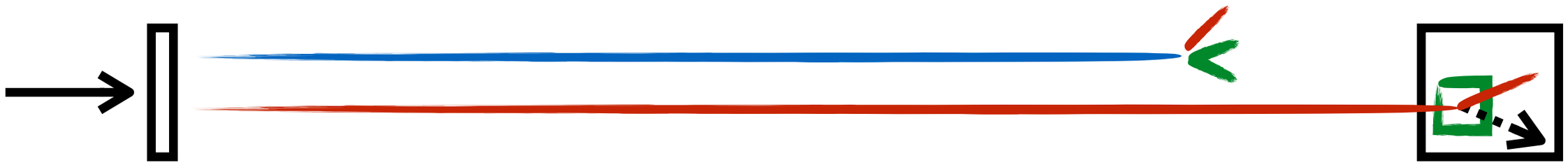
Filimonova et al. 2201.08409

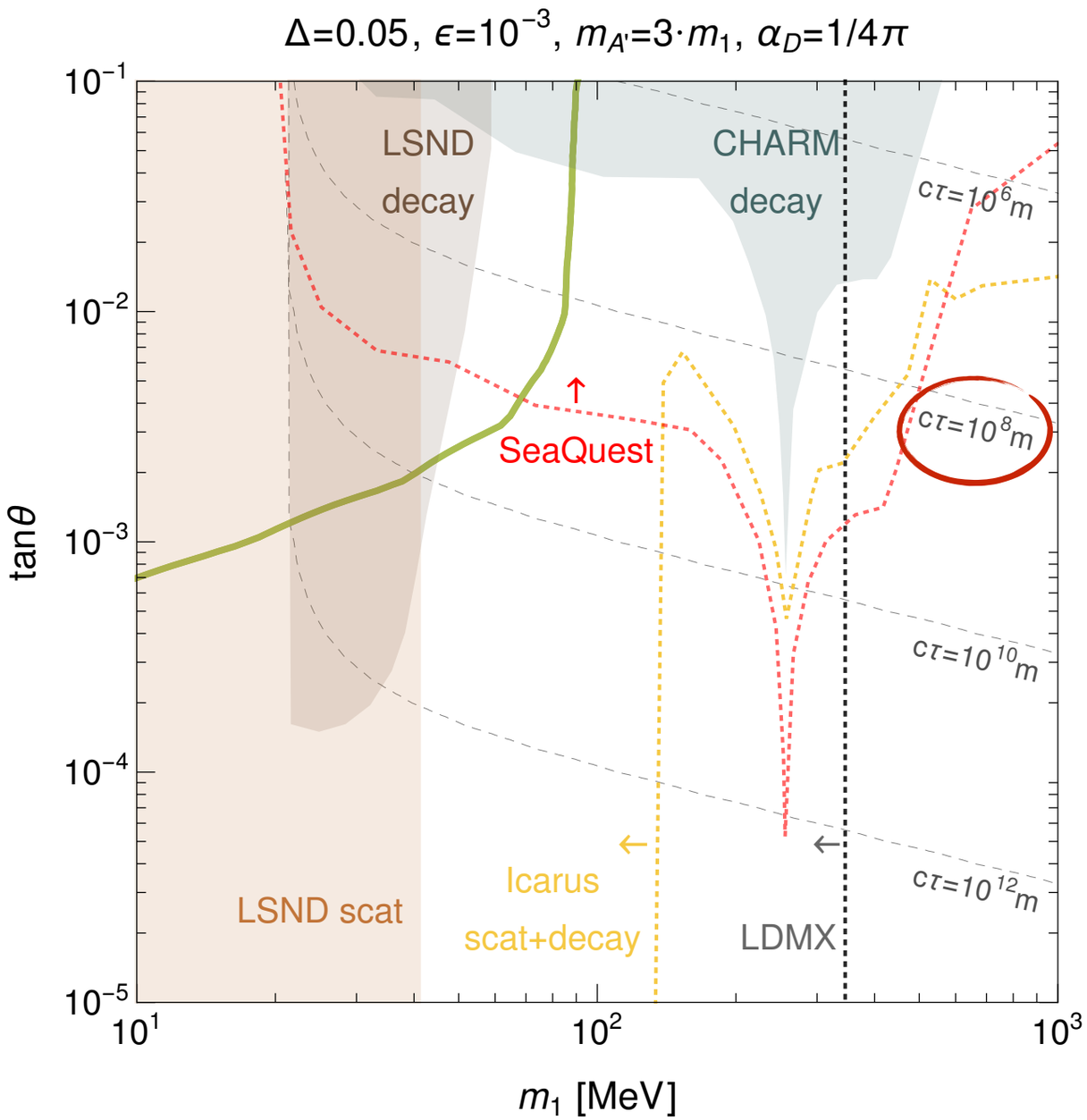
Cosmology leaves a mass window



Filimonova et al. 2201.08409

Long baseline





- 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:

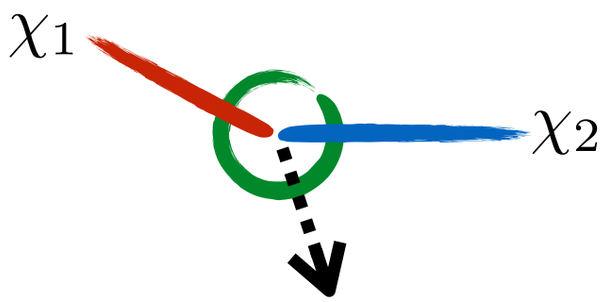
$$\chi_1 N \to \chi_2 N \to \chi_1 \ell^+\ell^- N$$

Filimonova et al. 2201.08409

Long-lived particles from space

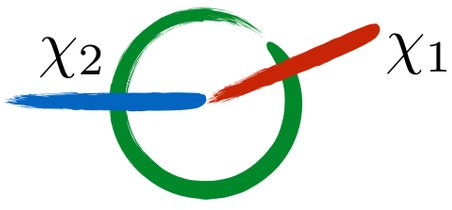
- production in the atmosphere:

Bringmann, Pospelov 1810.10543

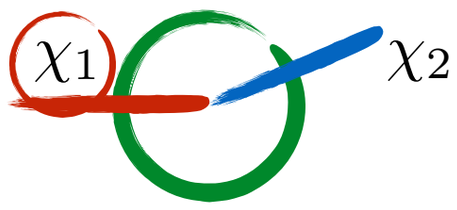


upscattering

- detection underground:

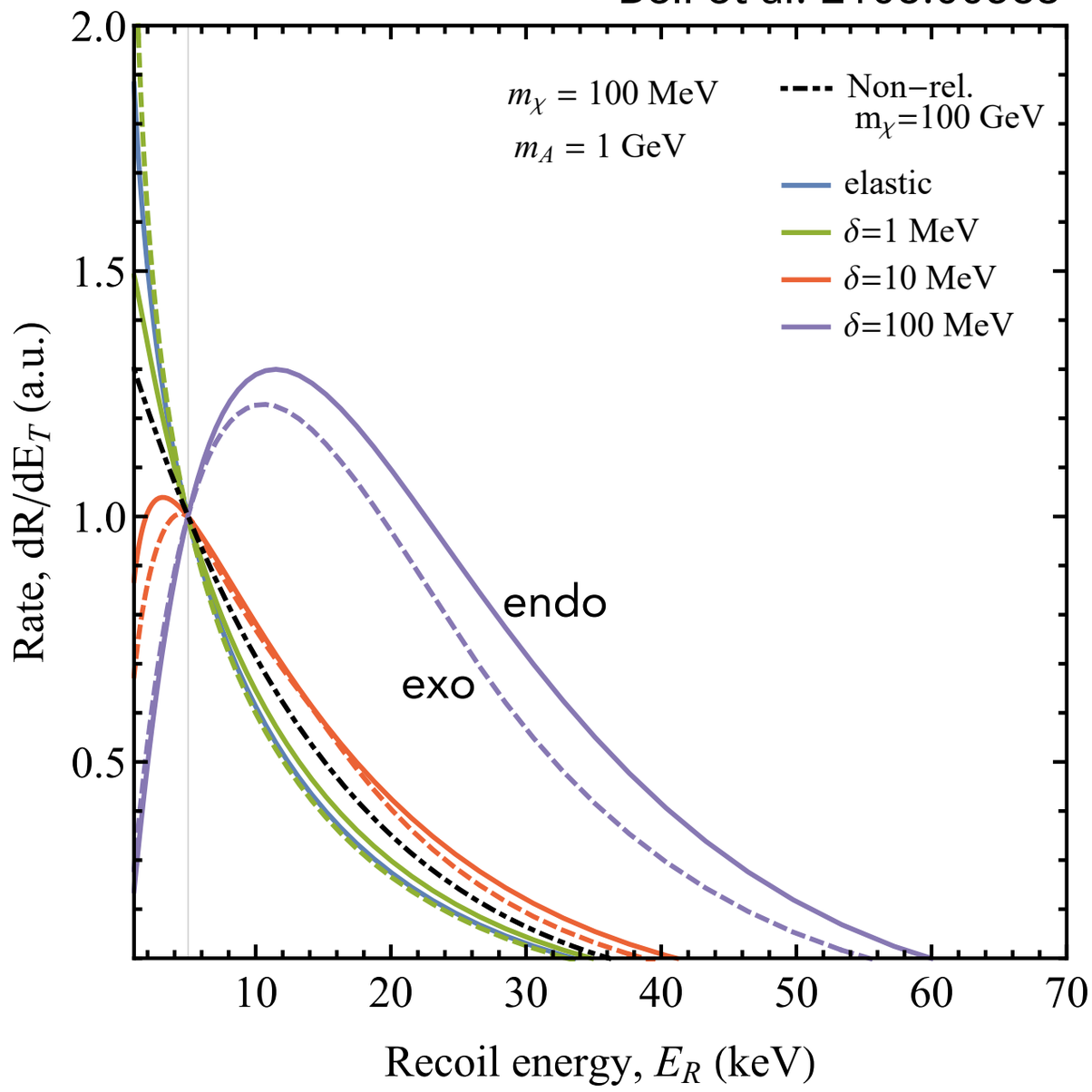


exothermic

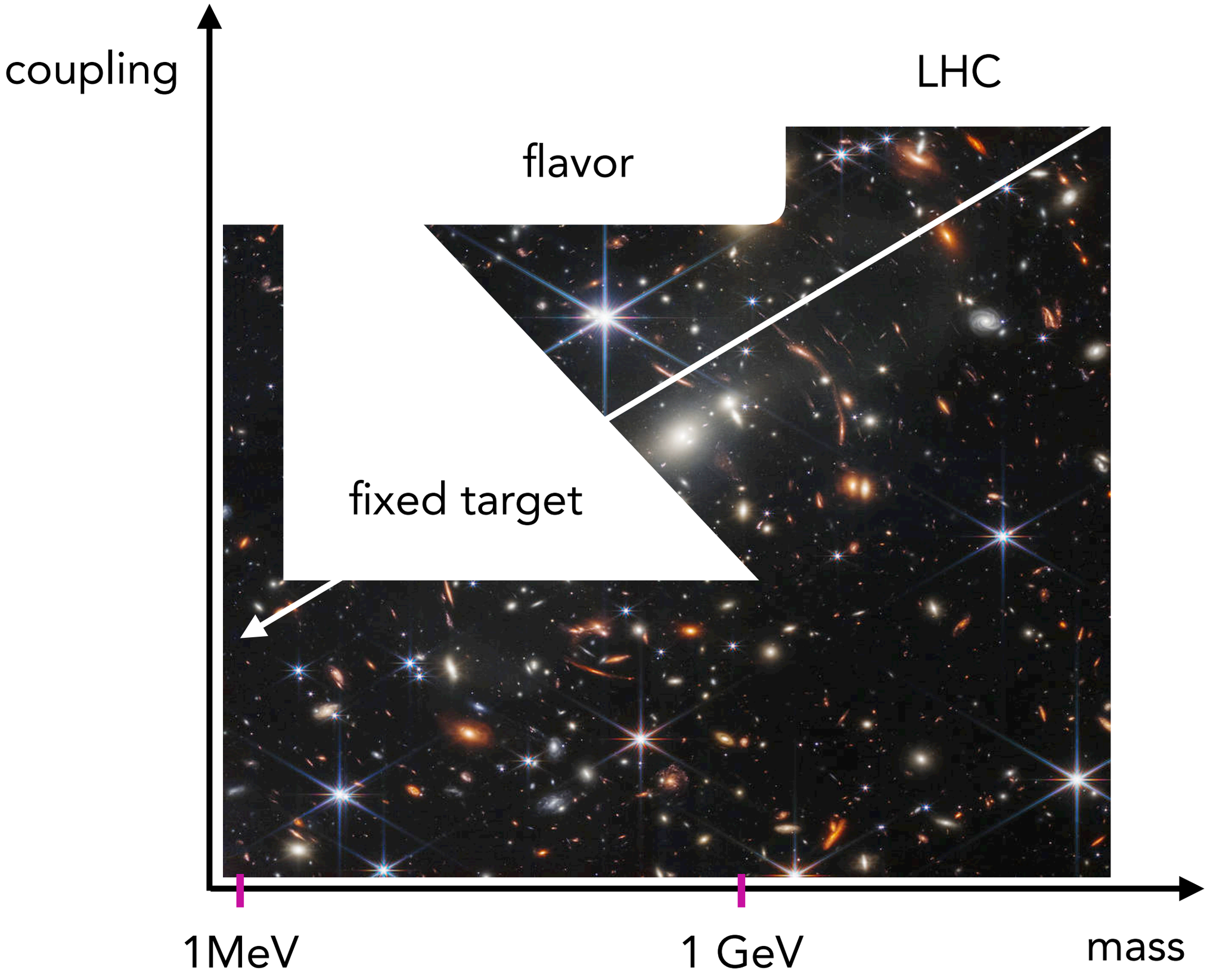


endothermic

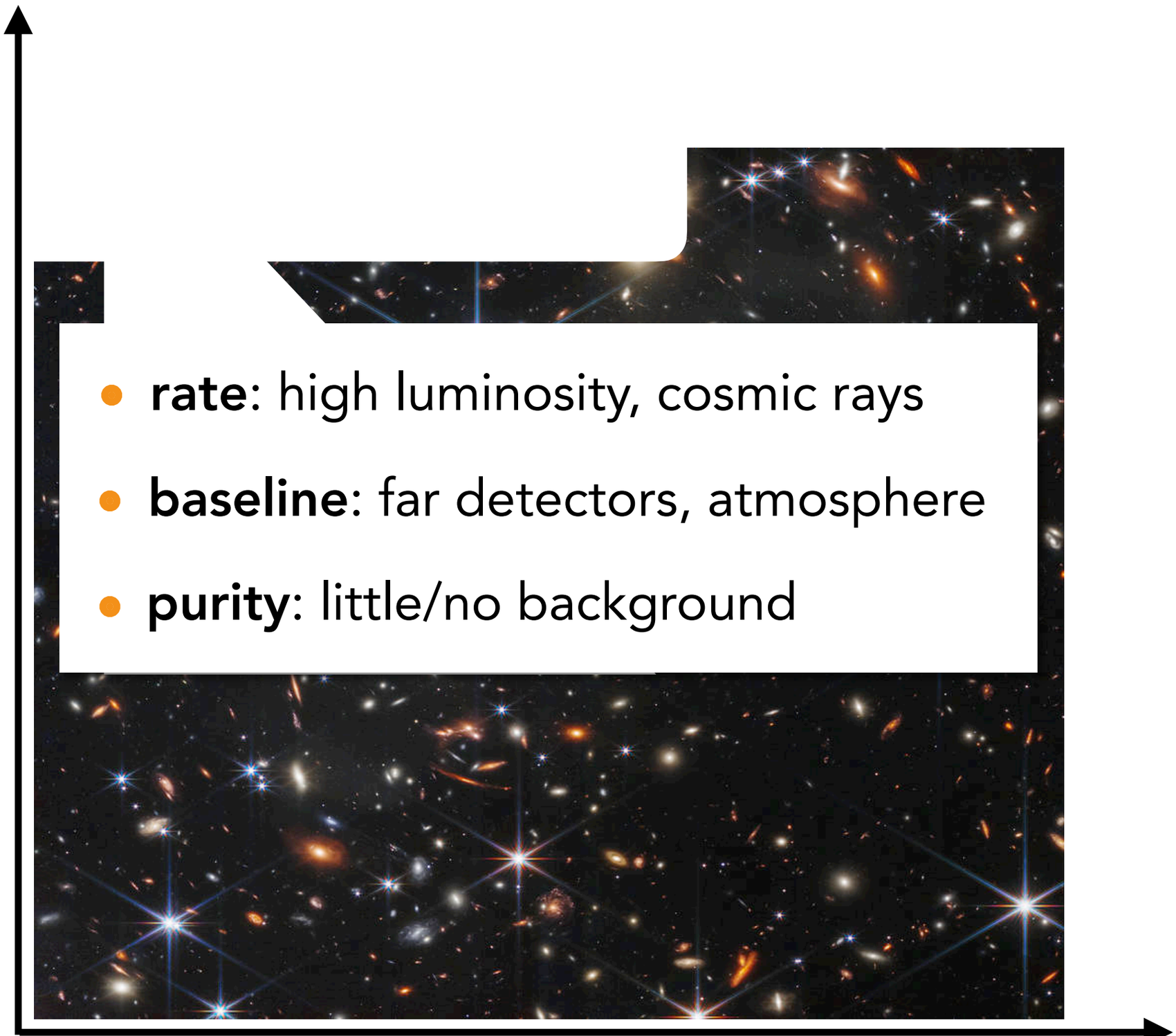
Bell et al. 2108.00583



Summary: feebly interacting dark matter

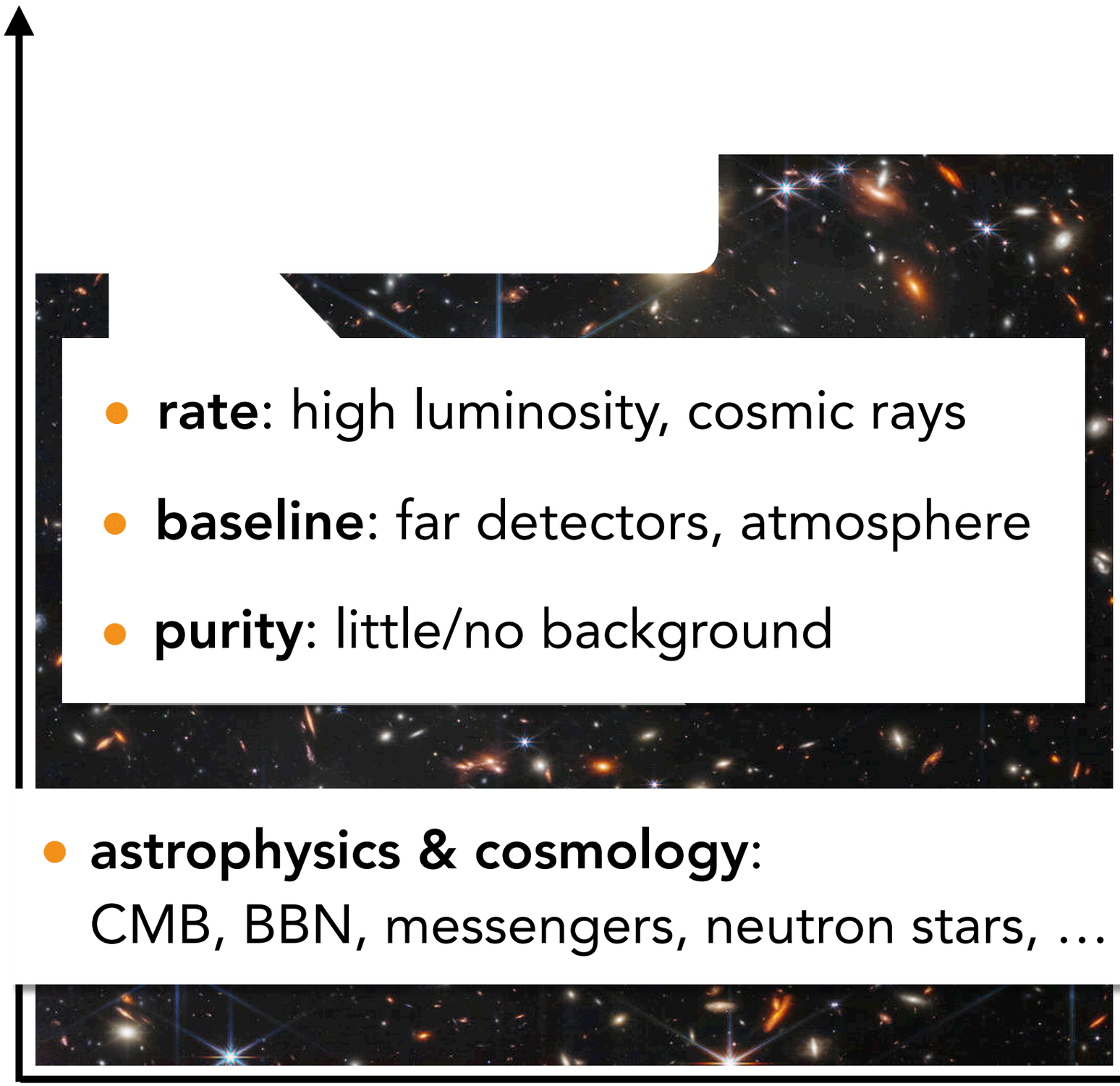


Summary: feebly interacting dark matter



- **rate**: high luminosity, cosmic rays
- **baseline**: far detectors, atmosphere
- **purity**: little/no background

Summary: feebly interacting dark matter



- **rate**: high luminosity, cosmic rays
- **baseline**: far detectors, atmosphere
- **purity**: little/no background

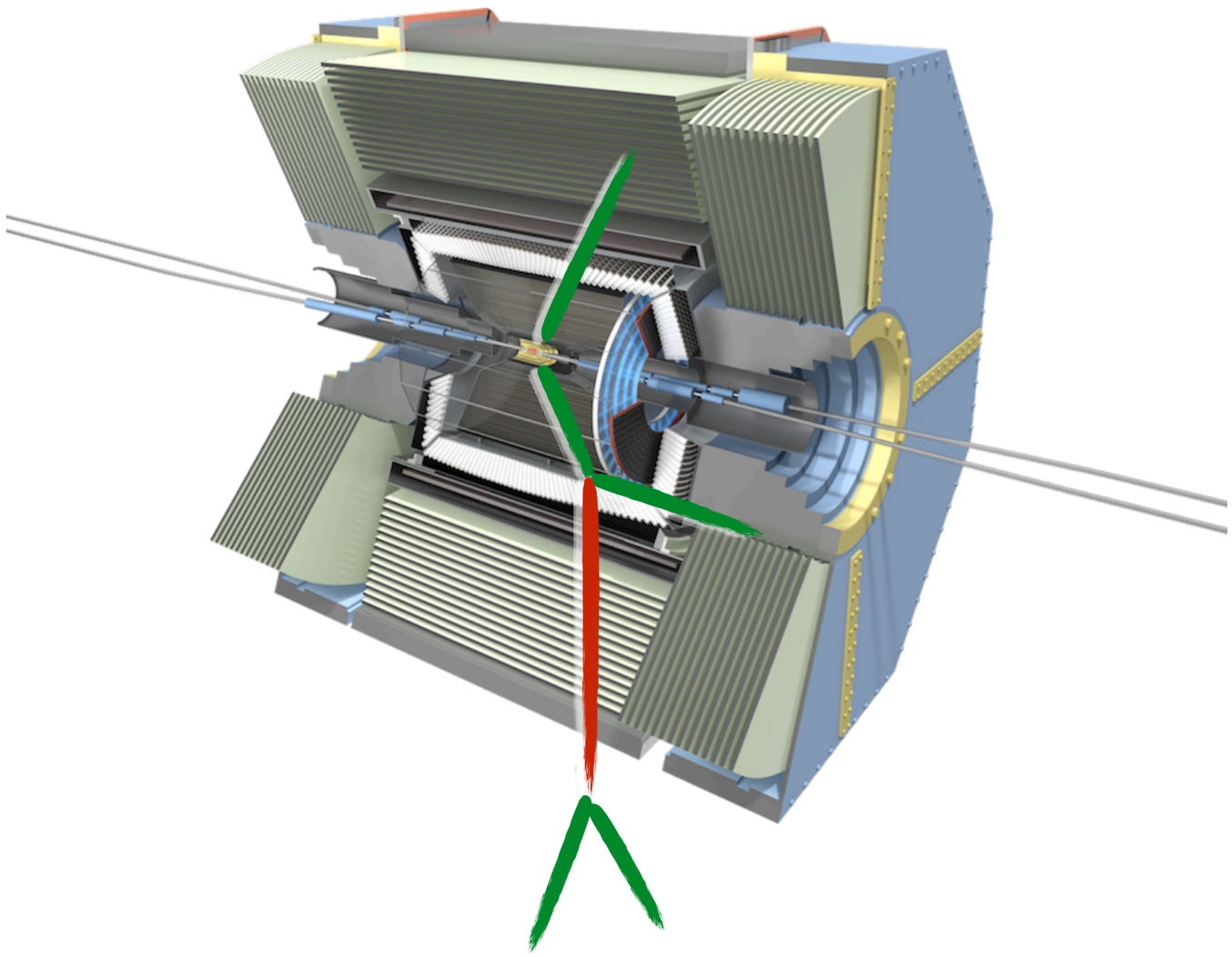
- **astrophysics & cosmology**:
  CMB, BBN, messengers, neutron stars, …

Thank you!

Backup

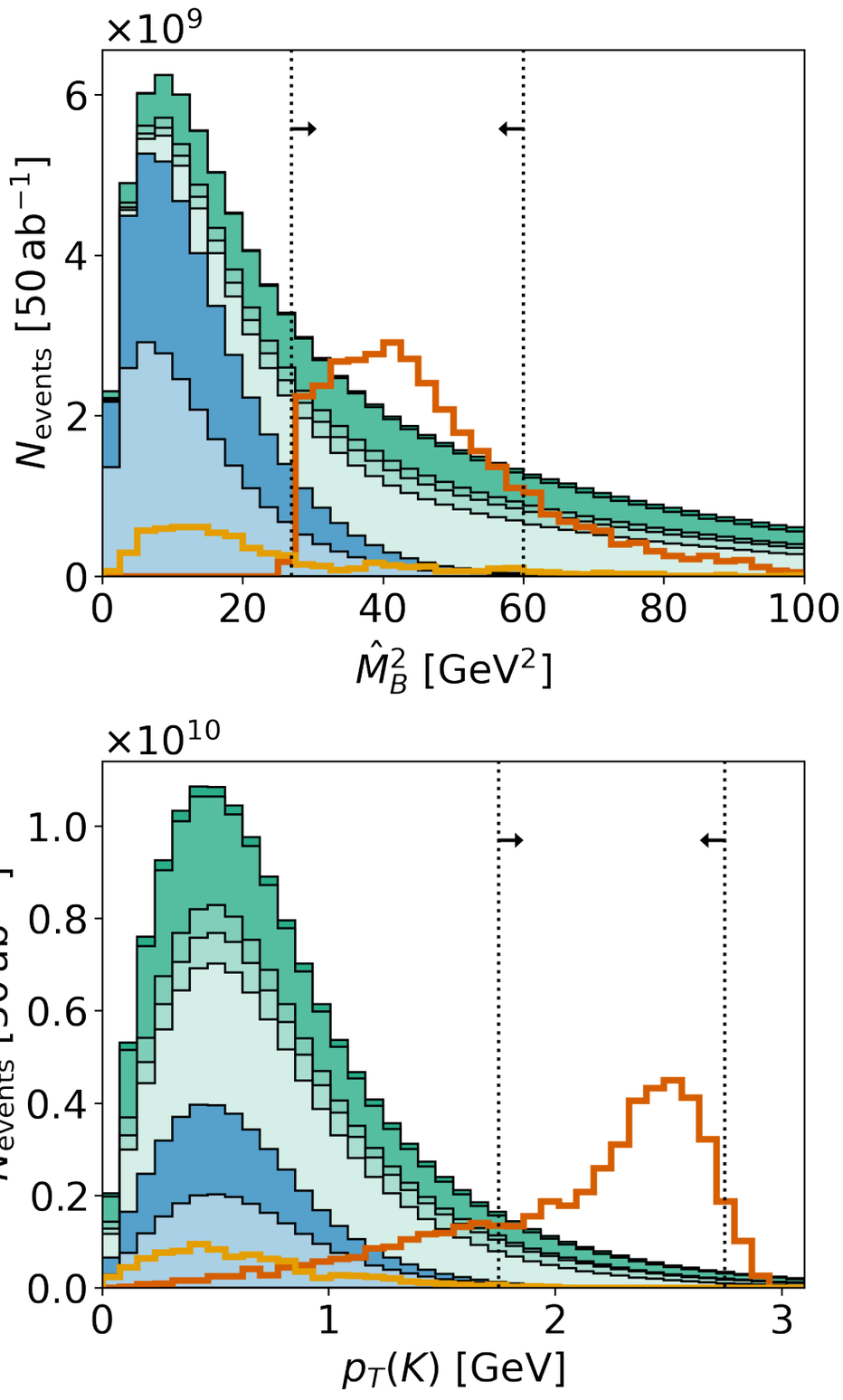
Missing energy from B decays at Belle II

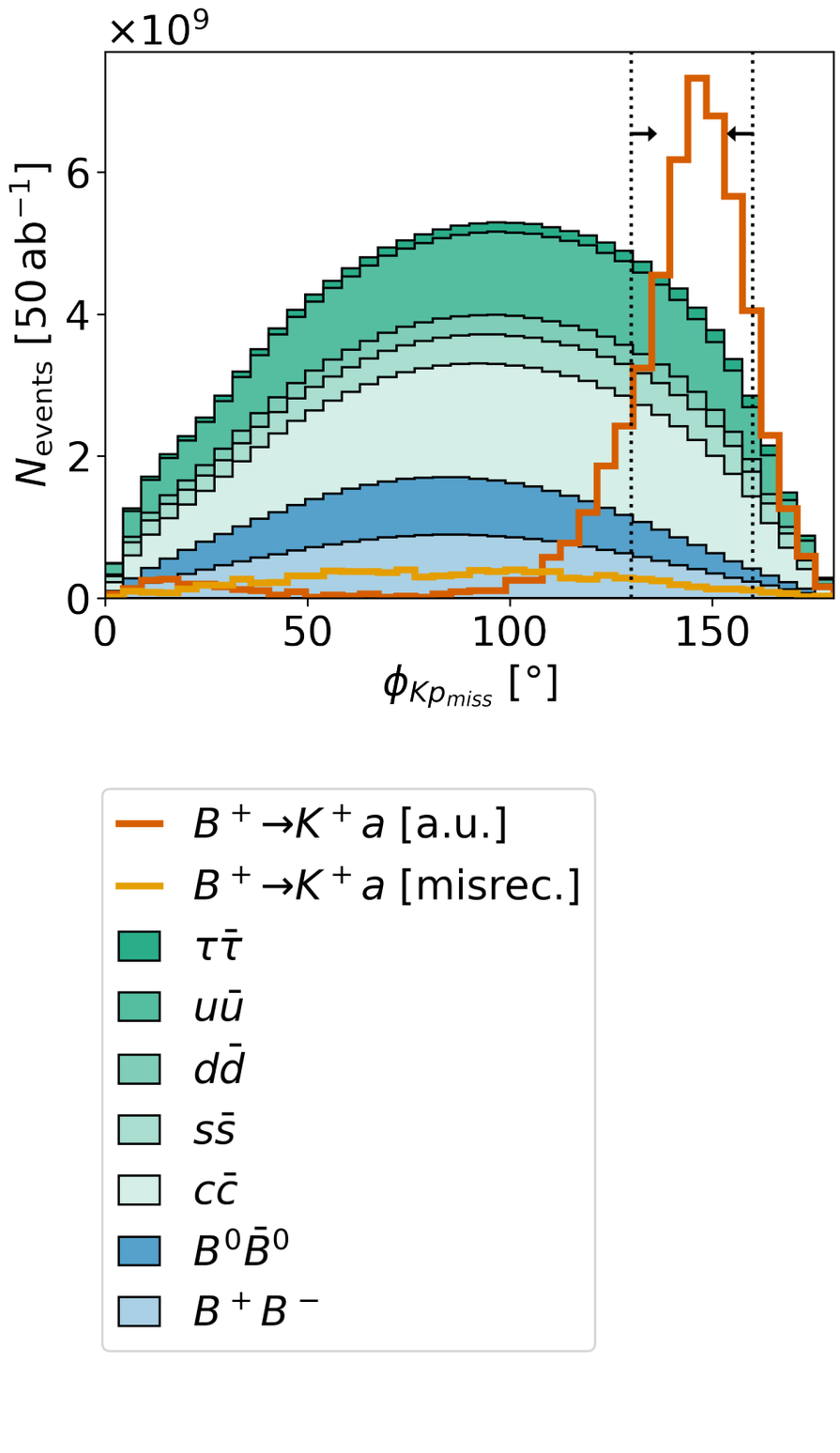
$$B \to X$$



$$B \to K a, a \to \not{E}$$

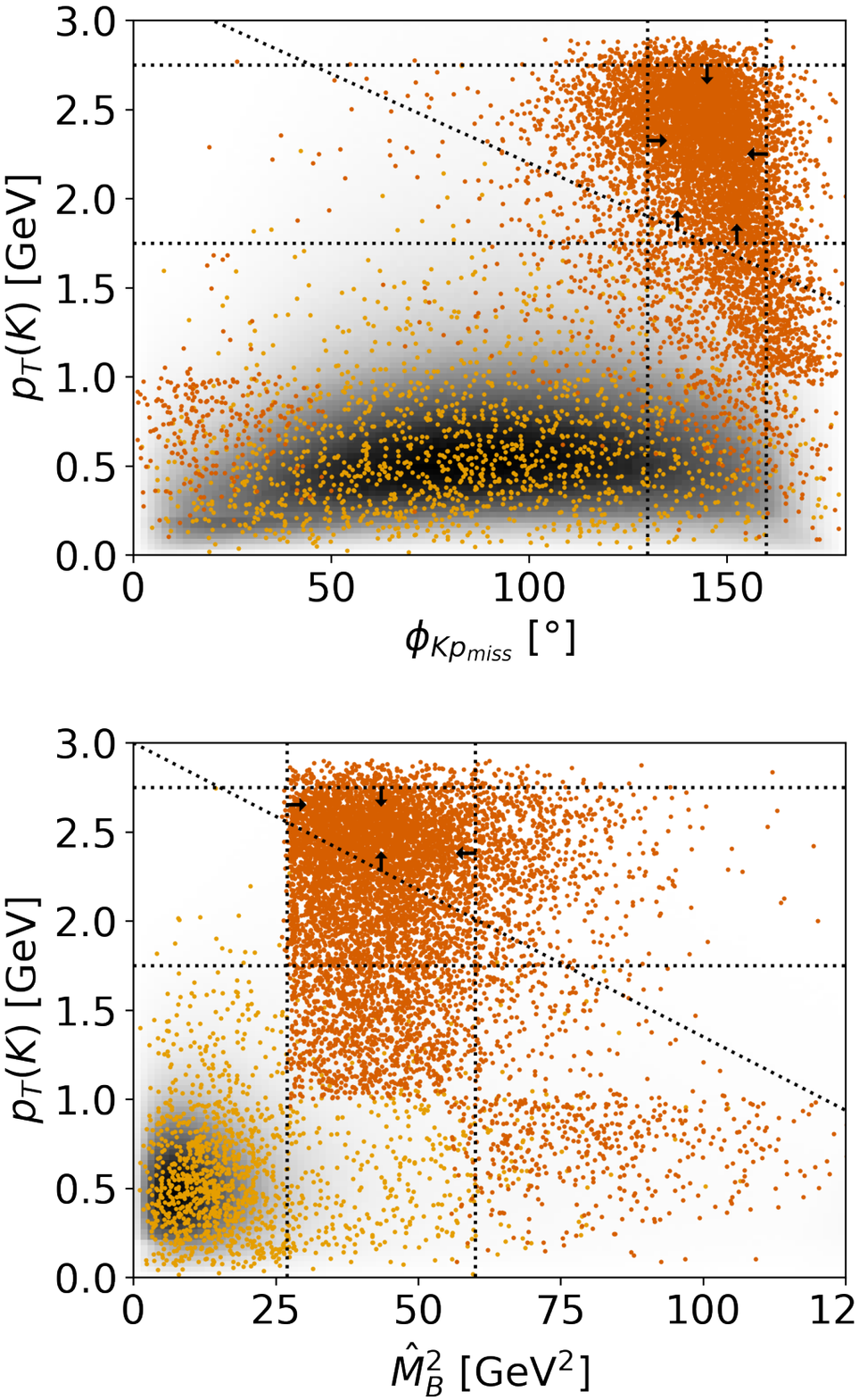
Missing energy from B decays at Belle II

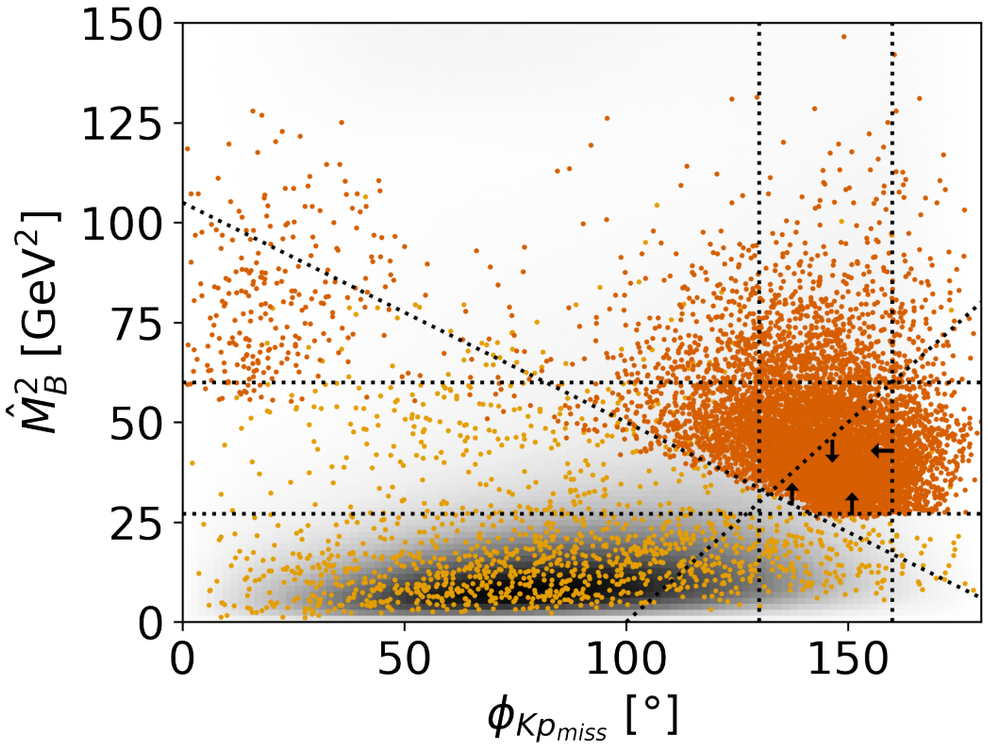


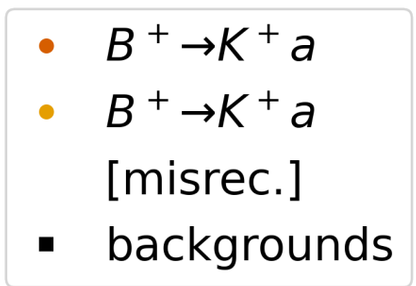


Ferber, Filimonova, Schaefer, SW 2201.06580

Missing energy from B decays at Belle II

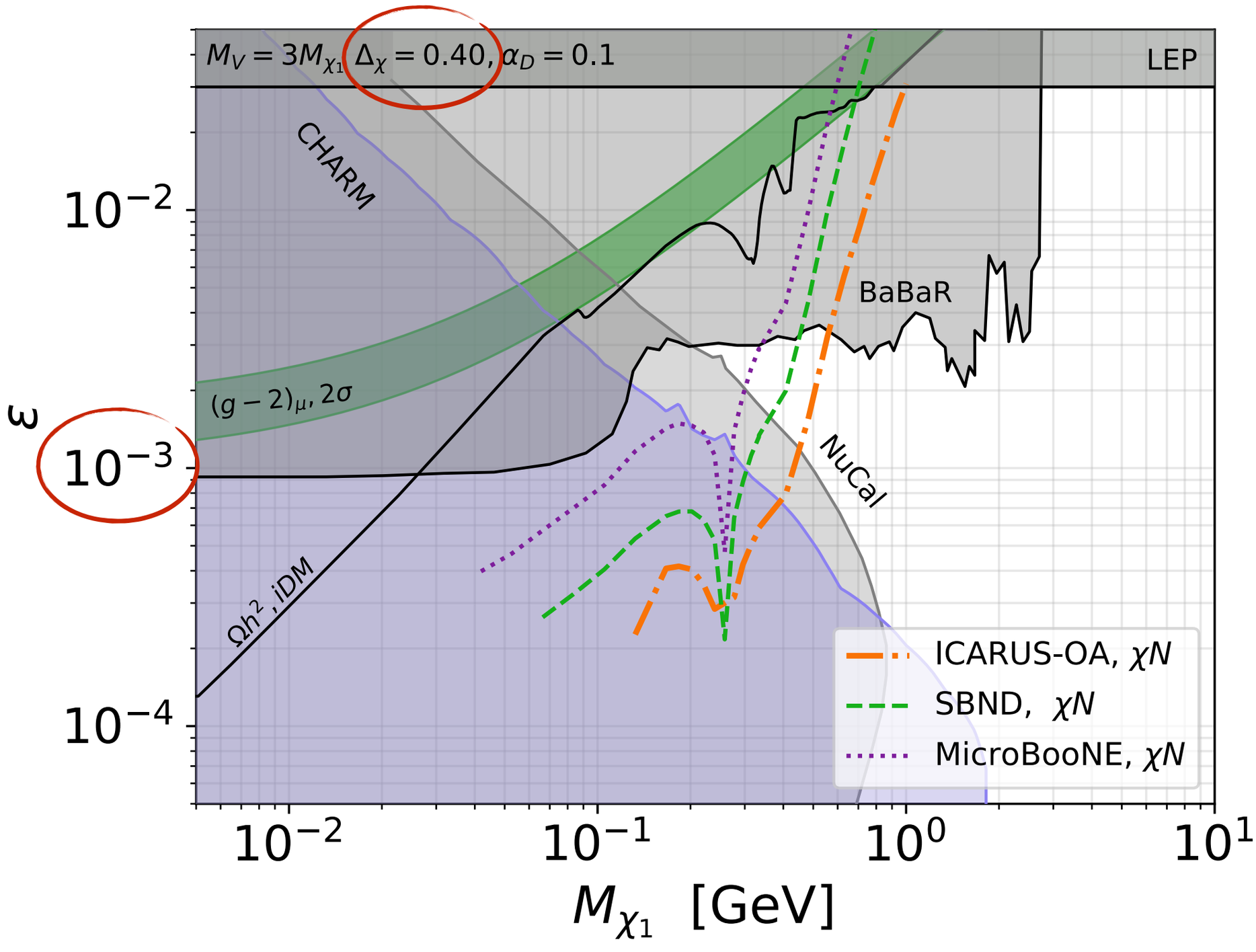






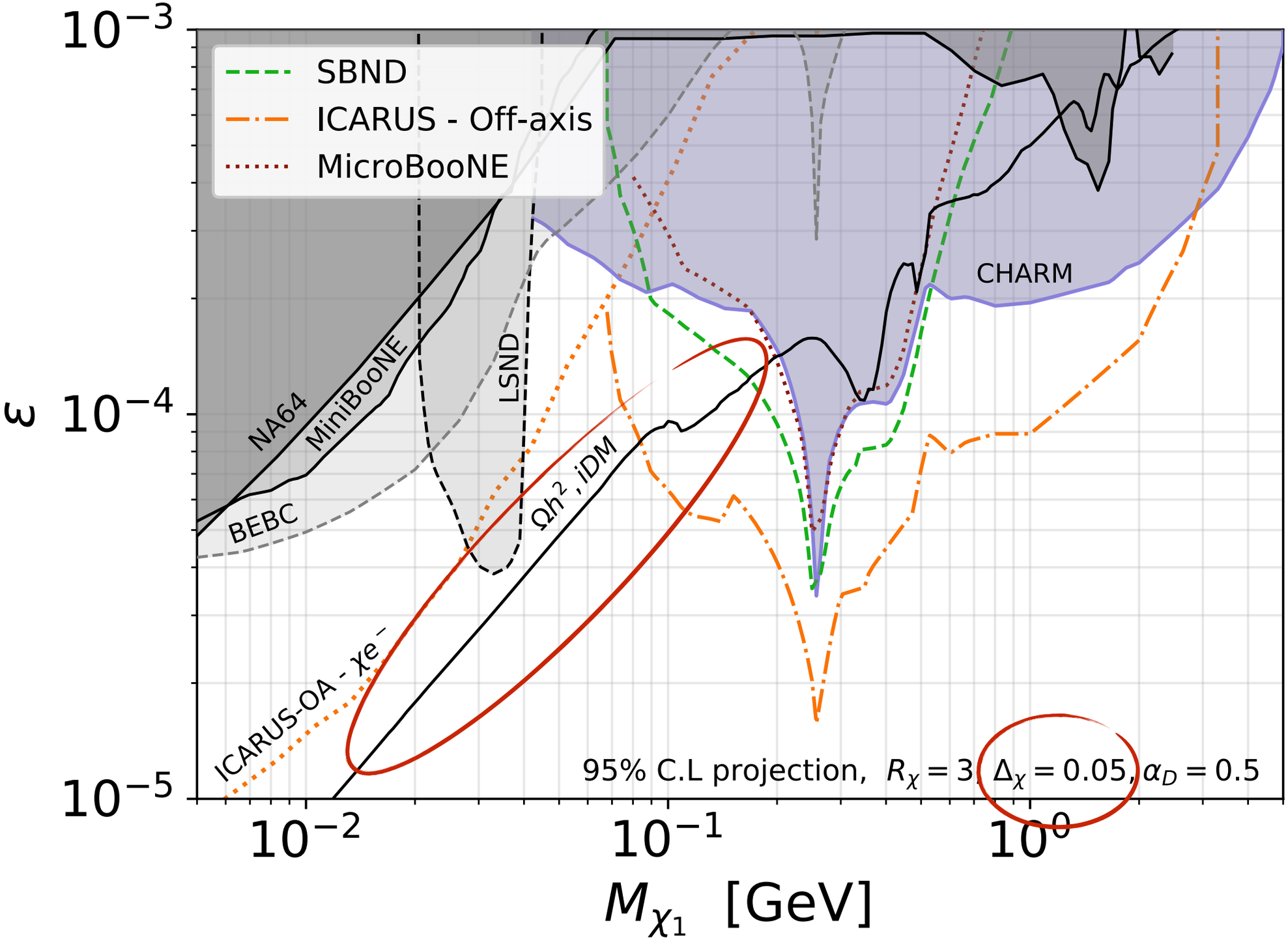
Ferber, Filimonova, Schaefer, SW 2201.06580

Inelastic Majorana Dark Matter



Batell, Berger, Darme, Frugiuele 2106.04584

Inelastic Majorana Dark Matter



Batell, Berger, Darme, Frugiuele 2106.04584