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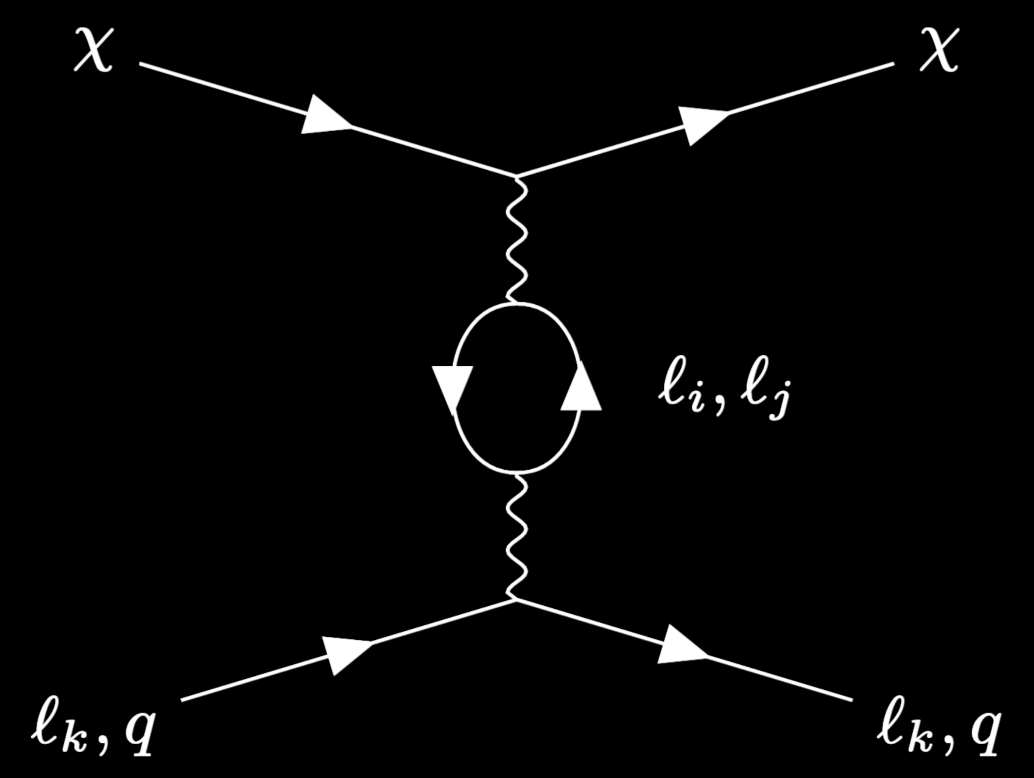
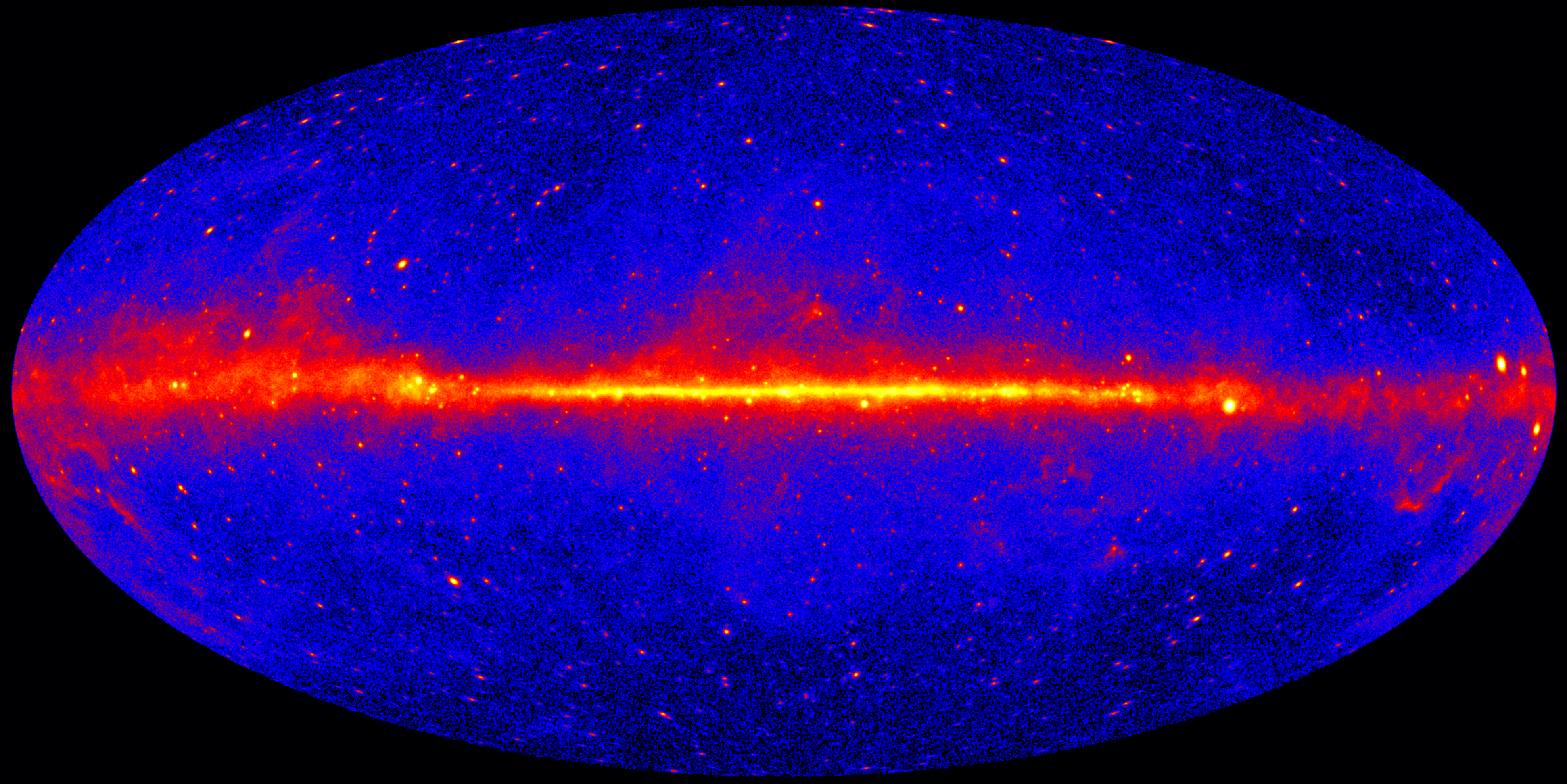
RPP 2026

March 12th, 2026



The Galactic Centre Excess via leptophilic dark matter in $U(1)_{L_i-L_j}$ models

Based on JK, Di Mauro, *Phys.Rev.D* 112 (2025) 115016



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Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

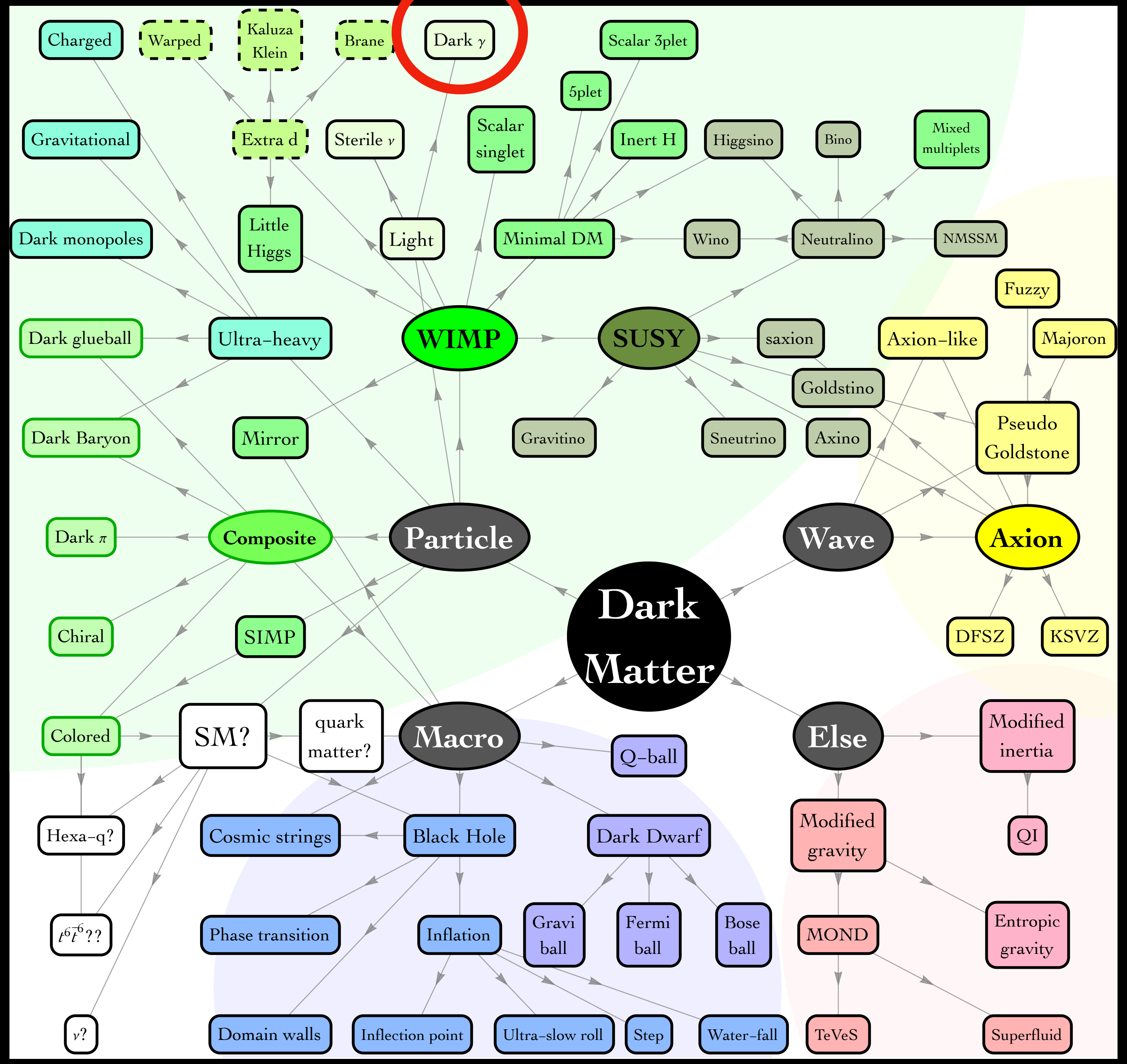
INFN
TORINO

Constraining BSM theories with DM

Dark matter is not part of the Standard Model

There exist a set of theories BSM that adds a DM candidate that can interact with SM particles through a mediator: simplified models

Some of them are particularly motivated as they gauge accidental global symmetries of the SM:



Cirelli, Strumia & Zupan (2024) [2406.01705]

e.g., $U(1)_{L_\mu - L_\tau}$, $U(1)_{L_e - L_\tau}$, $U(1)_{L_\mu - L_e}$, $U(1)_{B-L}$

(dark photon)

$U(1)_{L_i-L_j}$ models

Introduction

- Gauging $L_i - L_j$ is anomaly free without adding other fermions. New boson X_μ
- Minimal extension of the SM, with the possibility of adding DM with X_μ being its portal to the SM

Kinetic mixing — DM & portal

$$\mathscr{L} = \mathscr{L}_{\text{SM}} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{\epsilon}{2}\hat{B}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu - m_\chi^2\bar{\chi}\chi - g_X q_X \bar{\chi}\gamma_\mu\chi X^\mu$$

$$-g_X\left(\bar{\ell}_i\gamma_\mu\ell_i + \bar{\nu}_i\gamma_\mu\nu_i - \bar{\ell}_j\gamma_\mu\ell_j - \bar{\nu}_j\gamma_\mu\nu_j\right)X^\mu$$

$U(1)_{L_i-L_j}$ models

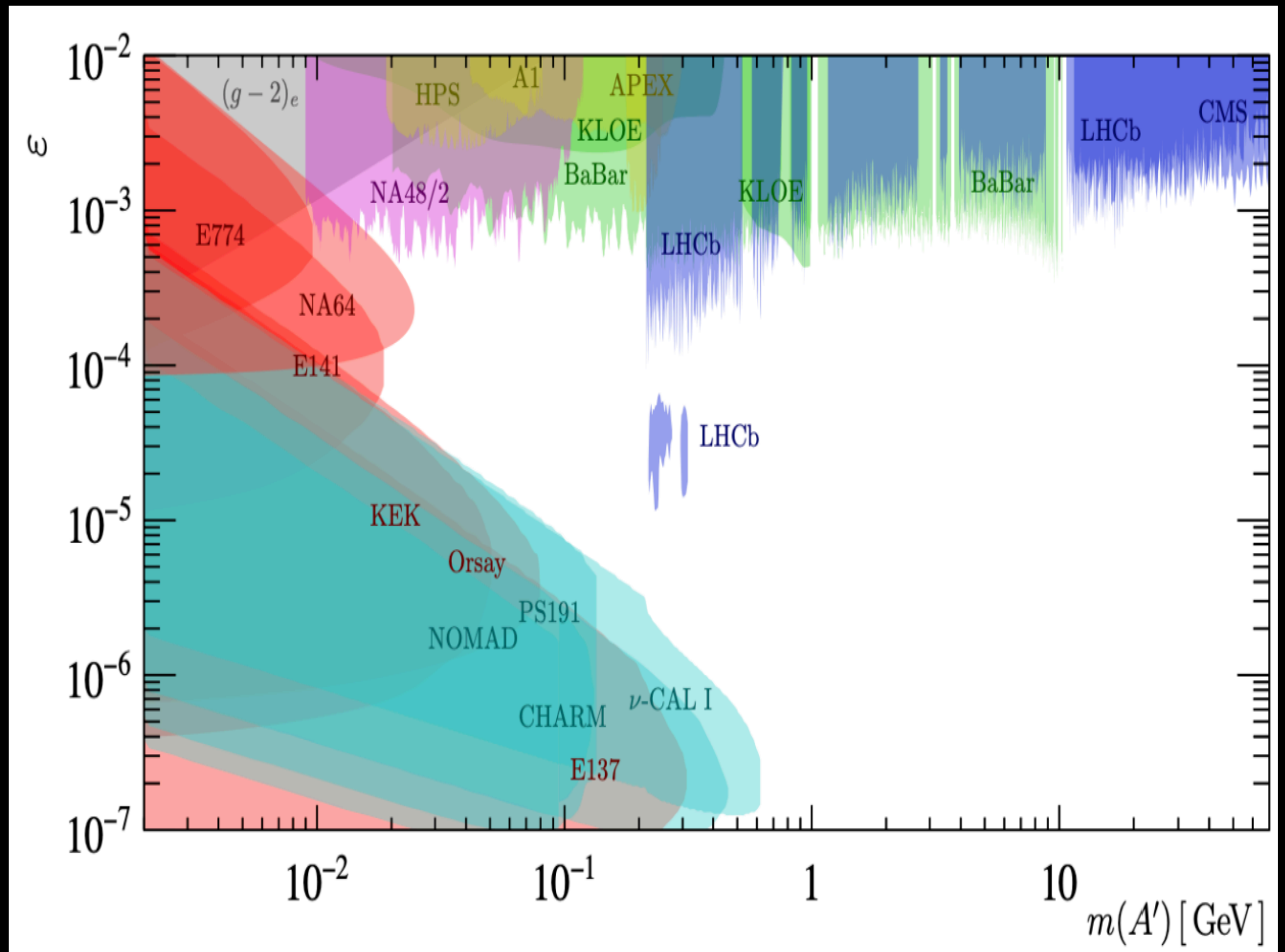
Introduction

$$\xi \simeq \frac{\epsilon \sin\theta_W}{1-\delta} \qquad \delta = \frac{m_X^2}{m_{Z^0}^2}$$

- After the rotation of the fields (normalisation and EWSB):

$$\mathcal{L}_{\rm int} \approx -eA_\mu J^\mu_{\rm EM} - Z_\mu \left[g_Z J^\mu_Z + g_X \sin\xi J^\mu_X\right]$$
$$-A'_\mu\left[g_X J^\mu_X - e\epsilon\cos\theta_W J^\mu_{\rm EM} + g_Z(\epsilon\sin\theta_W - \sin\xi)J^\mu_Z\right]$$

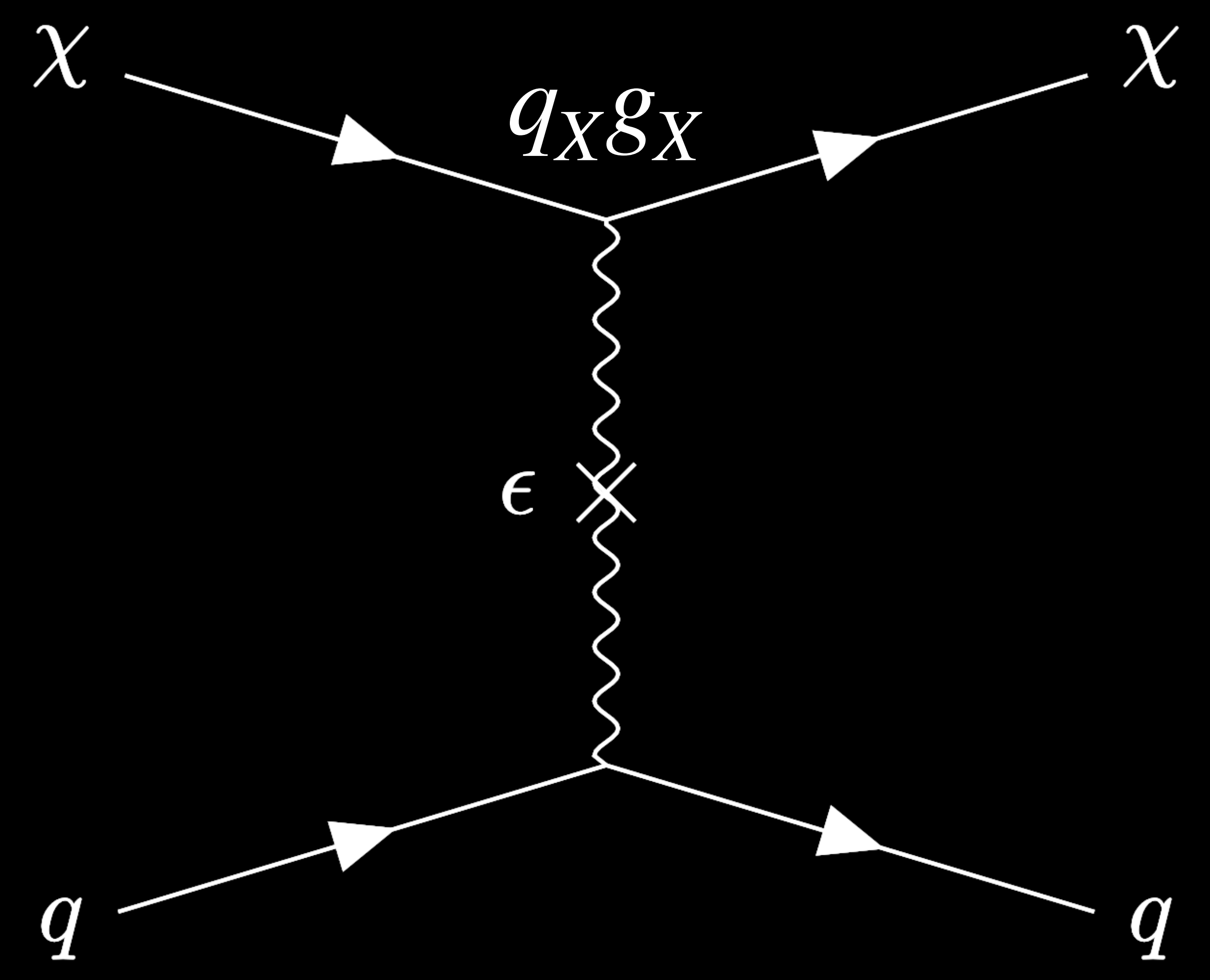
Dark photon is coupled to q and ℓ_k



Cirelli, Strumia & Zupan (2024) [2406.01705]

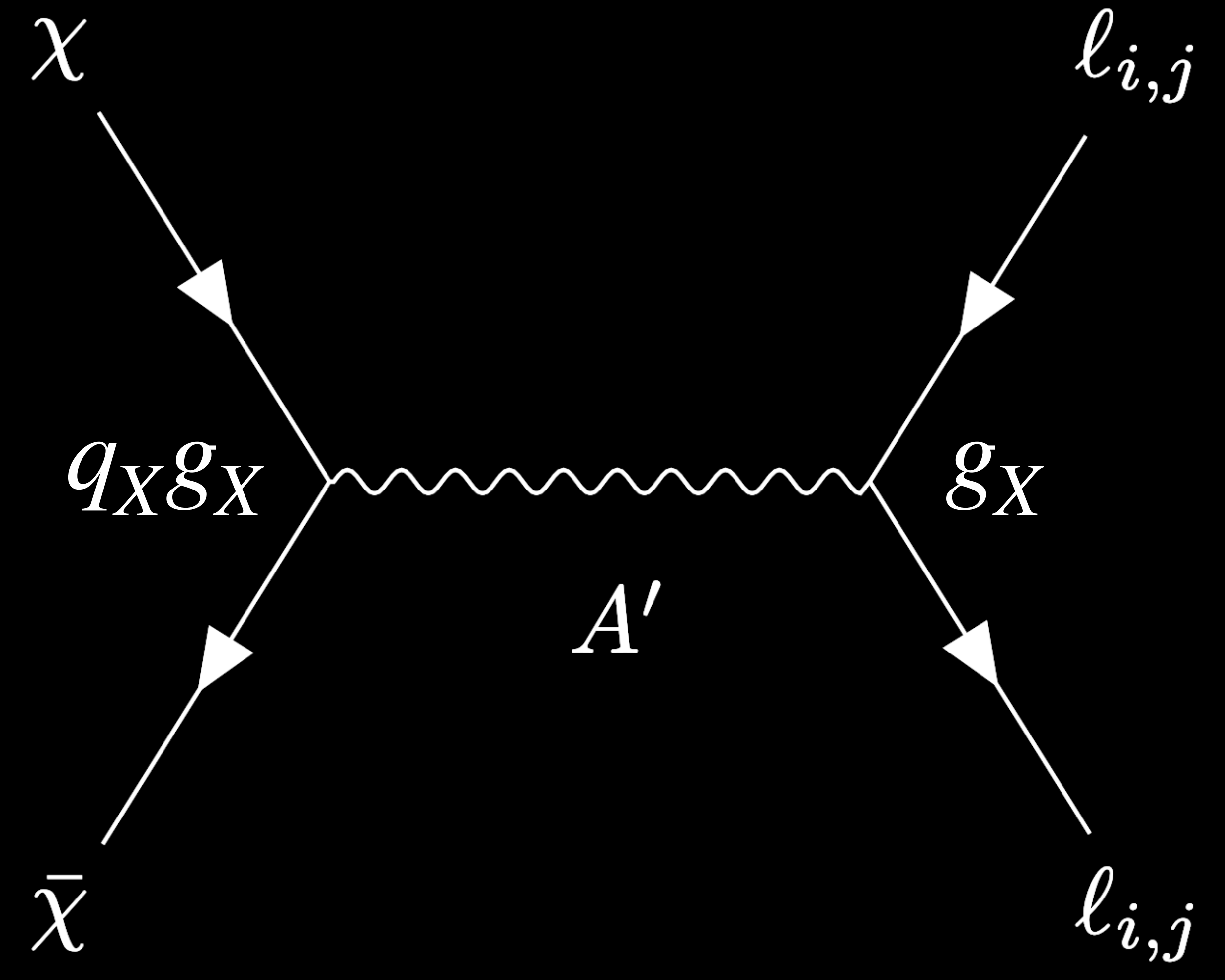
- We expect $\epsilon \ll 1$, colliders set strong constraints

$U(1)_{L_i - L_j}$ models
Introduction



Probed by DD
$\sigma_{\chi N} \propto q_X^2 g_X^2 \epsilon^2$

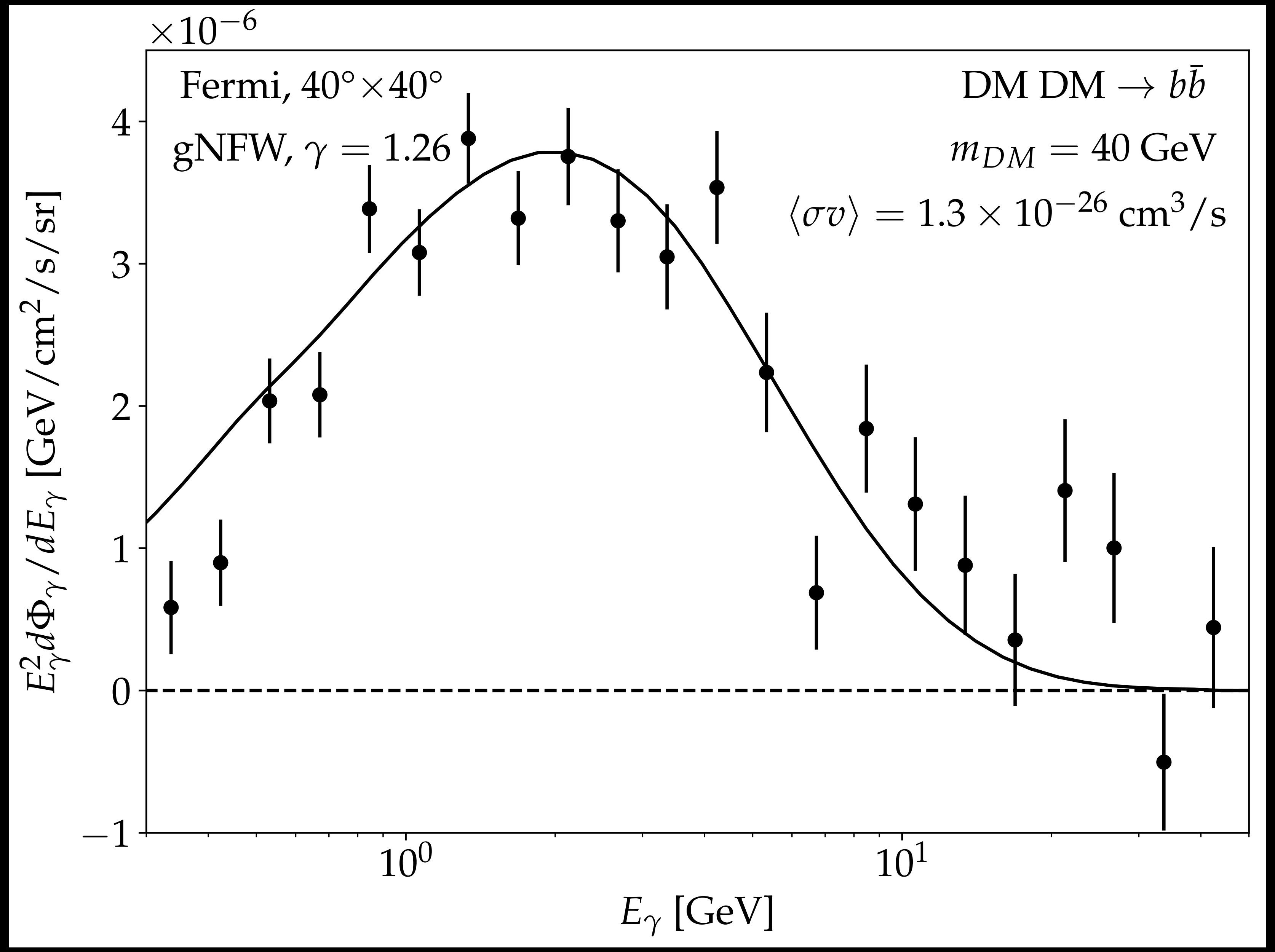
$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{(m_{A'}^2 - 4m_\chi^2)^2 + m_{A'}^2 \Gamma_{A'}^2}$$



Probed by ID and relic abundance
$\langle \sigma v \rangle \propto q_X^2 g_X^4$

A target of DM ID: The Galactic Centre

γ-ray excess at the GC: $0.5 - 5$ GeV extending out to $10° - 20°$ reported by Fermi-LAT



Two compelling possibilities:

- DM DM → hadronic for $m_\chi \approx 50$ GeV with $\langle \sigma v \rangle$ compatible for DM as thermal relic and cusped profile
- Old population of unresolved millisecond pulsars

Setup

For each $U(1)$ model:

1) We fix m_χ and $\langle \sigma v \rangle$ by fitting the flux of DM-produced γ-rays to the GCE

Allowed region in the $g_X / m_{A'}$ parameter space

2) We cross-check if m_χ and $\langle \sigma v \rangle$ are not excluded by positron data from AMS-02

3) For the fixed m_χ we figure the $g_X / m_{A'}$ parameter space that satisfies:

- Thermal relic (Allowance line)
- Anomalous magnetic moments (Upper limit)
- Direct detection constraints (Upper limit)
- Collider contraints (Upper limit)

Relevant observables

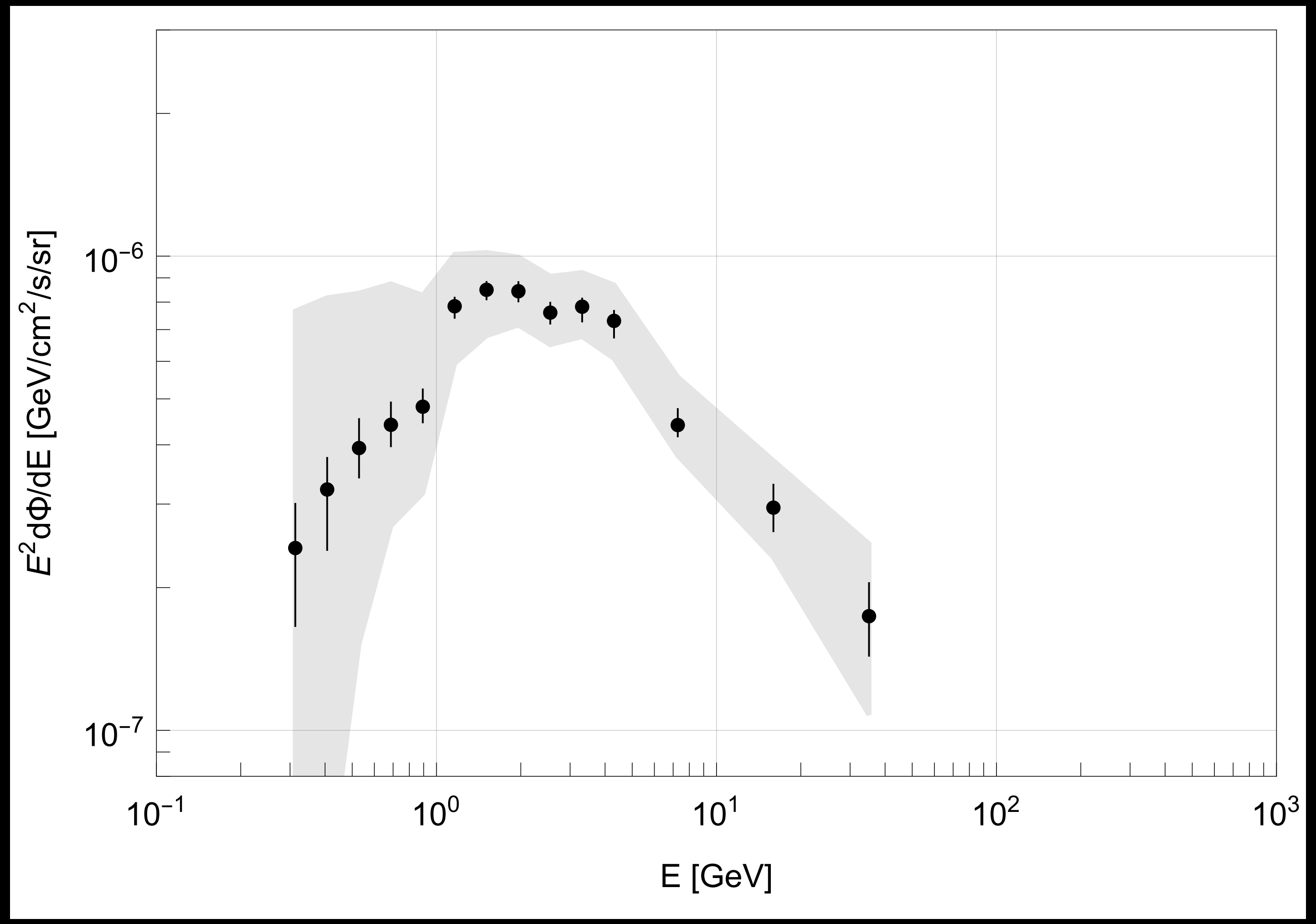
Galactic Centre excess

Most up-to-date characterisation of the GCE from interstellar emission template fitting:

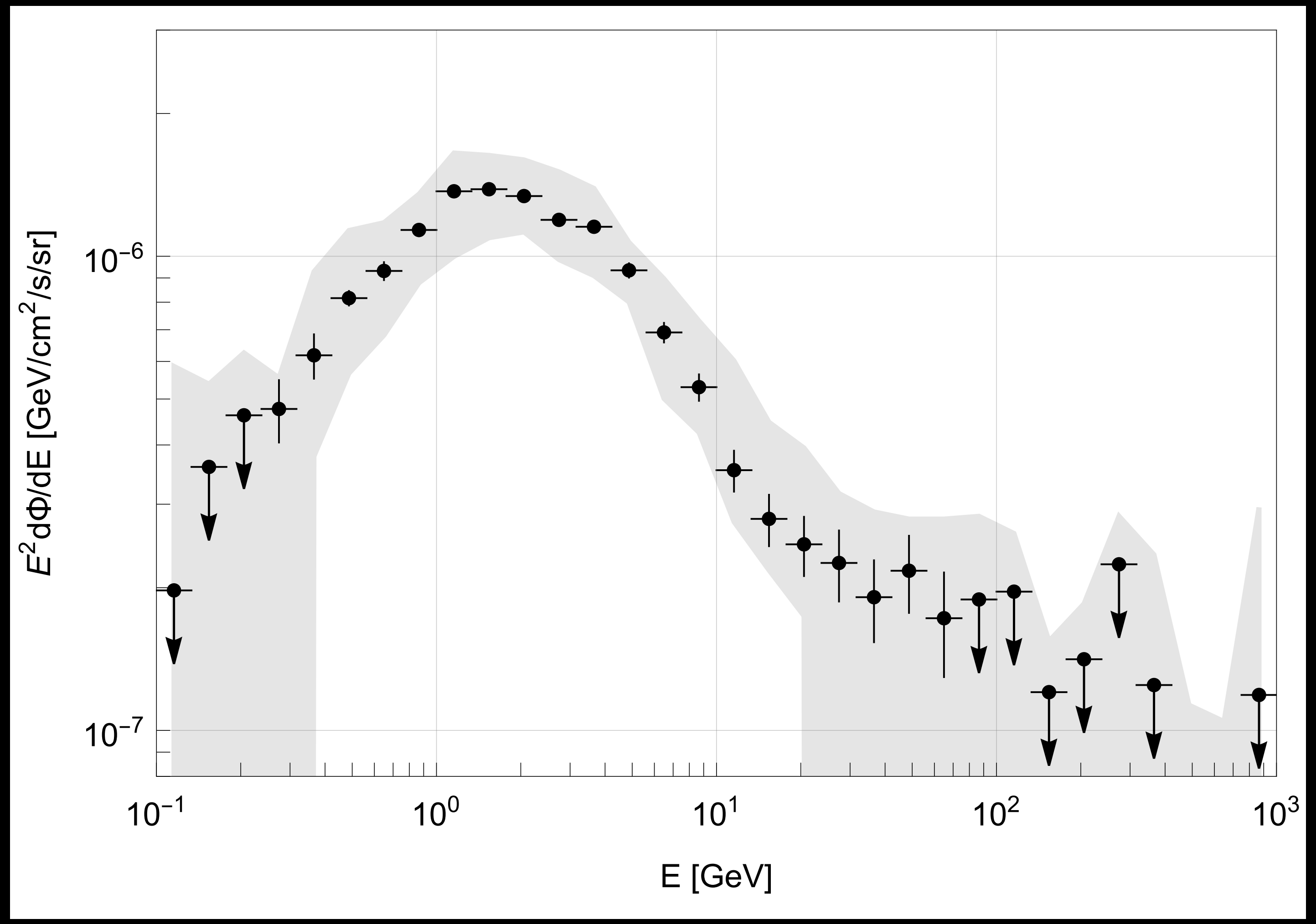
- Cholis+22 ($40^\circ \times 40^\circ$, $|b| < 2^\circ$ and resolved point sources masked)
- Di Mauro+21 ($40^\circ \times 40^\circ$)

Astrophysical uncertainties up to 60% in the normalisation

Using both of the datasets → systematic uncertainty on m_χ and $\langle \sigma v \rangle$



Cholis et al., *Phys.Rev.D* 105 (2022) 103023



Di Mauro, *Phys.Rev.D* 103 (2021) 063029

Relevant observables

Galactic Centre excess

Relevant observables

gNFW: $\rho_{\rm NFW}(r) = \rho_s \left(\frac{r_s}{r}\right)^{\gamma} \left(1 + \frac{r}{r_s}\right)^{\gamma-3}$

Einasto: $\rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}$

Galactic Centre excess

Prompt emissions: $\frac{d\Phi_\gamma^{\rm prompt}}{dE_\gamma} = \frac{1}{4}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{m_\chi}\right)^2 \overline{\mathcal{J}}\langle\sigma v\rangle \sum_f {\rm BR}_f \frac{dN_\gamma^f}{dE_\gamma}$

J-factor: $\overline{\mathcal{J}} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} \frac{ds}{r_\odot}\left(\frac{\rho_{\rm DM}(r(s,\Omega))}{\rho_\odot}\right)^2$

Other systematic uncertainty source for $\langle\sigma v\rangle$

Label	DM profile	slope (γ/α)	ρ_s [GeV/cm^3]	r_s [kpc]	$\rho_\odot$ [GeV/cm^3]	$\overline{\mathcal{J}}_{\rm Di\ Mauro+21}$	$\overline{\mathcal{J}}_{\rm Cholis+22}$
MIN	gNFW	1.20	0.416	12.87	0.300	120	67.9
MED	gNFW	1.30	0.449	12.67	0.345	209	89.6
MAX	Einasto	0.13	0.864	5.51	0.390	422	179

Relevant observables

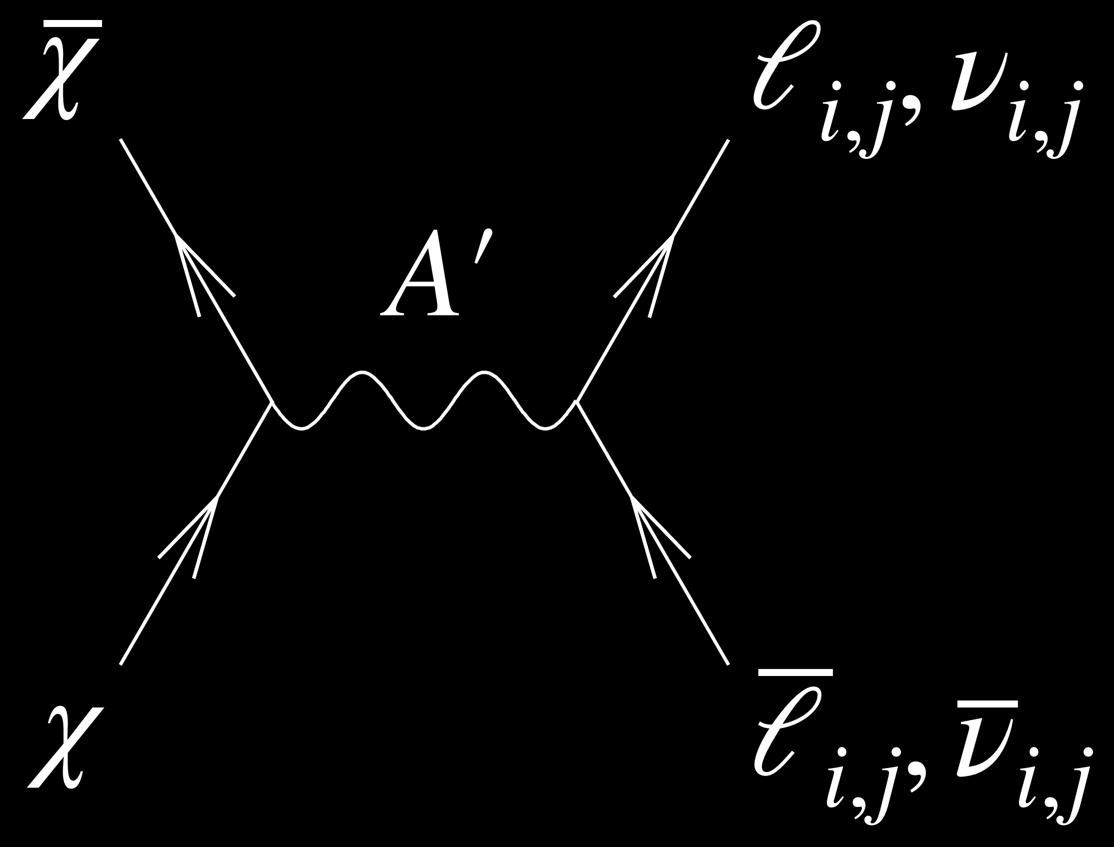
$$\langle\sigma v\rangle \simeq \sum_f \frac{q_X^2 g_X^4 k_f}{2\pi} \frac{m_\chi^2}{(m_{A'} - 4m_\chi^2)^2 + m_{A'}^2\Gamma_{A'}^2} \times$$

2-body

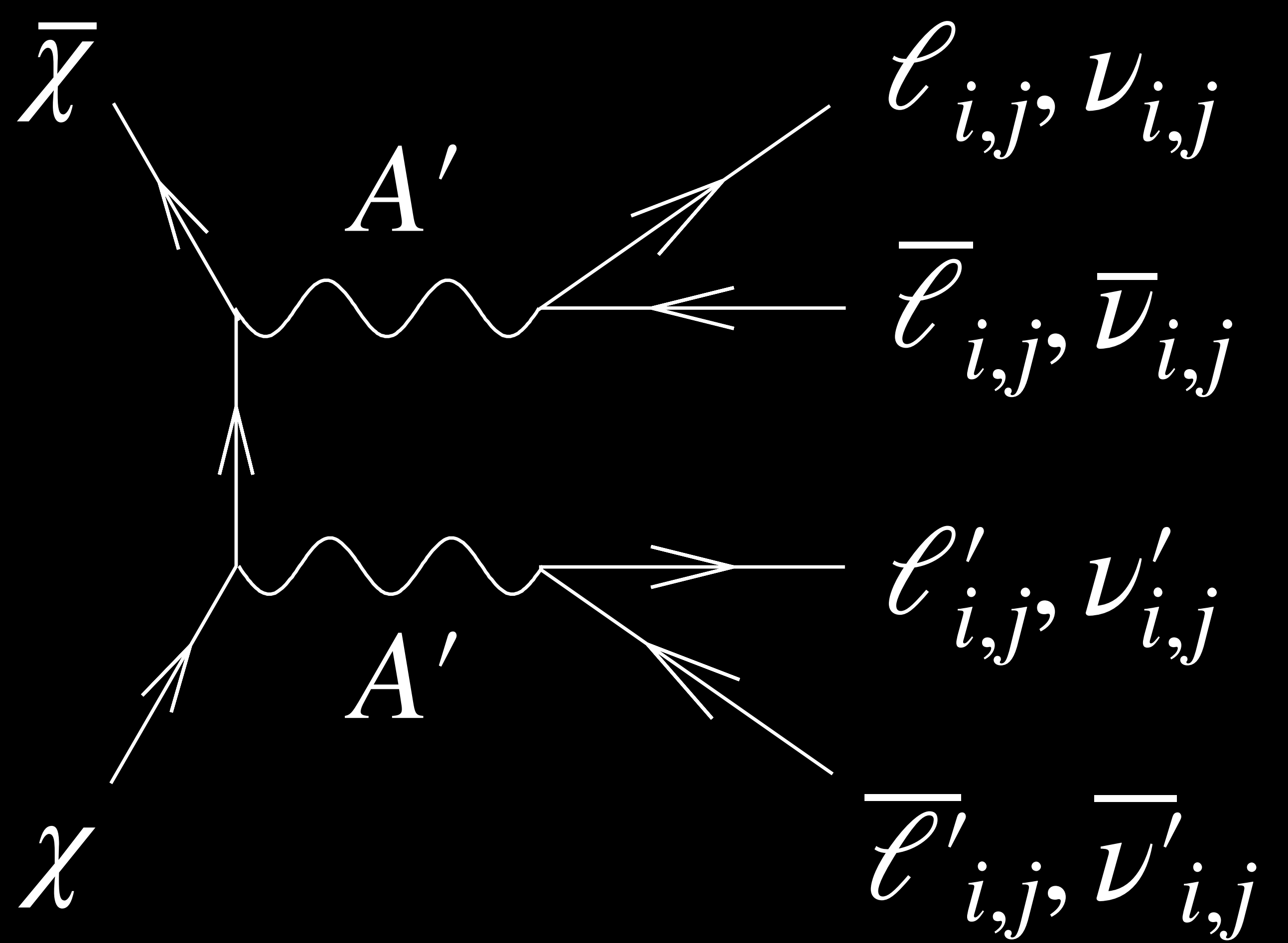
$$\times \sqrt{1 - \frac{m_f^2}{m_\chi^2}} \left(1 + \frac{m_f^2}{2m_\chi^2}\right) + \mathcal{O}(v^2)$$

Galactic Centre excess

Relevant diagrams for DM annihilation



$\langle\sigma v\rangle \propto q_X^2 g_X^4$



Open for $m_\chi > m_{A'}$ but $\langle\sigma v\rangle \propto q_X^2 g_X^8$

MadDM

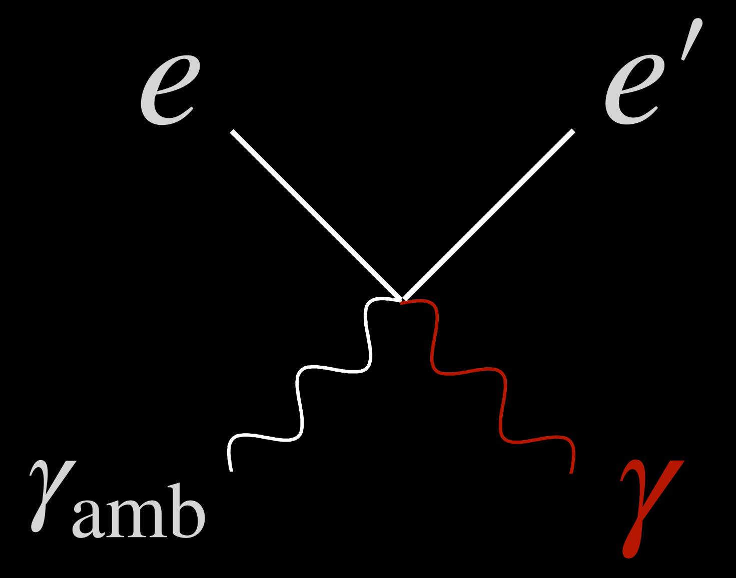
For a given m_χ and g_X

- Evaluates $\langle\sigma v\rangle_f$ for each channel $\rightarrow \mathrm{BR}_f$ and $\langle\sigma v\rangle$
- Evaluates dN_γ^f/dE_γ using MadGraph5_aMC@NLO

Relevant observables

Galactic Centre excess

Inverse-Compton scattering



Secondary emissions: $$\frac{d\Phi_\gamma^{\rm ICS}}{dE_\gamma} = \frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{m_\chi}\right)^2 \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} \frac{ds}{r_\odot} \times$$
$$\times \int_{m_e}^{m_\chi} dE_e\, f_{e^\pm}(E_e, \vec{x}(s,\Omega))\mathscr{P}_{\rm ICS}(E_\gamma, E_e, \vec{x}(s,\Omega))$$

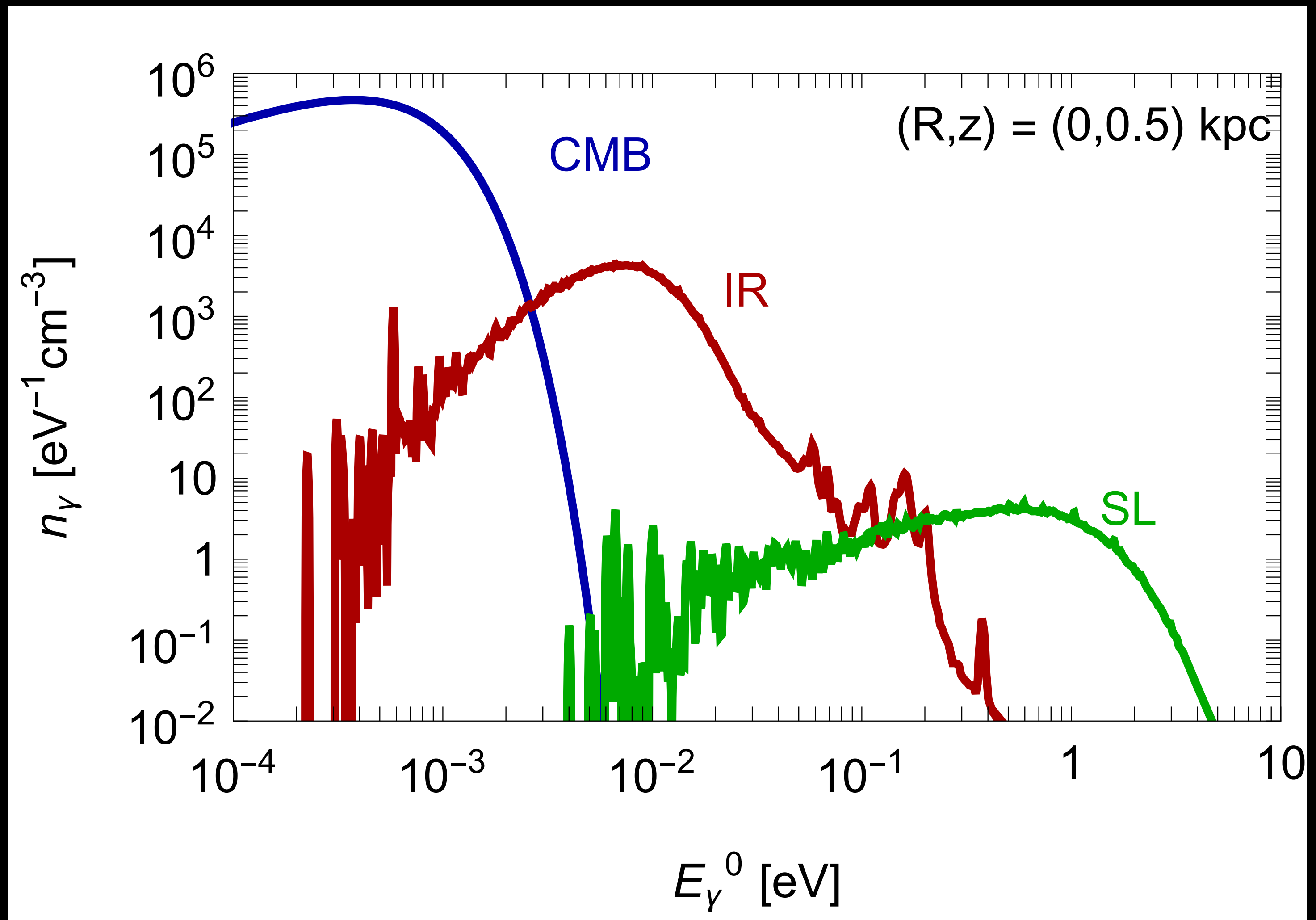
Diffusion-loss equation:

$$\vec{\nabla}\left(D\,\vec{\nabla} f_{e^\pm} - \vec{v}_c f_{e^\pm}\right) + \frac{\partial}{\partial K_e}\left(b_{\rm loss} f_{e^\pm} + \beta^2 D_{pp}\frac{\partial f_{e^\pm}}{\partial K_e}\right) + Q_{e^\pm}^{\rm DM} = 0$$

spatial diffusion | convection | energy losses | momentum space diffusion | source

Relevant observables

Galactic Centre excess



In the GC, energy losses dominate over everything else: ICS happens on the spot

Encodes the ambient photon density and the Klein-Nisihina cross section

$$\frac{d\Phi_\gamma^{\rm ICS}}{dE_\gamma} = \frac{1}{2}\frac{r_\odot}{4\pi}\left(\frac{\rho_\odot}{m_\chi}\right)^2 \overline{\mathcal{J}}\langle\sigma v\rangle \sum_f \int_{m_e}^{m_\chi} dE_e \frac{\mathcal{P}_{\rm ICS}(E_\gamma, E_e)}{b_{\rm loss}(E_e)} \int_{E_e}^{m_\chi} dE'_e \, {\rm BR}_f \frac{dN_e^f}{dE'_e}$$

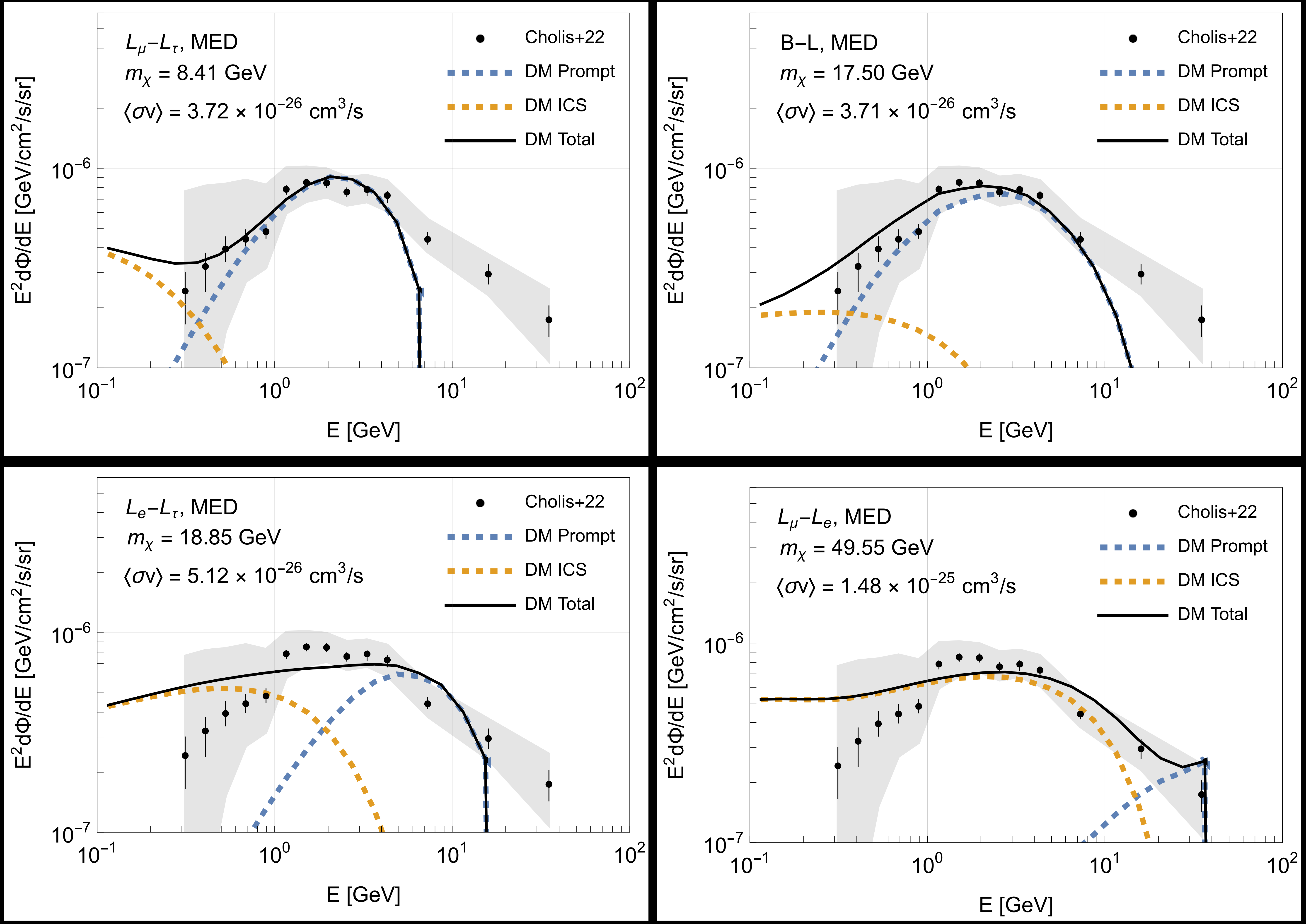
Encodes the energy losses
$b_{\rm loss} \propto E_e^{1.8-2.0}$

MadDM

Relevant observables

Galactic Centre excess

Model	Dataset	m_χ [GeV]	$\langle\sigma v\rangle$ [cm^3/s]	χ^2/d.o.f.
$L_\mu - L_\tau$	Di Mauro+21	6.73	2.14×10^{-26}	3.84
	Cholis+22	8.41	3.72×10^{-26}	0.41
$L_e - L_\tau$	Di Mauro+21	12.33	2.56×10^{-26}	4.68
	Cholis+22	18.85	5.12×10^{-26}	0.28
$L_\mu - L_e$	Di Mauro+21	38.00	7.42×10^{-26}	2.12
	Cholis+22	49.55	1.48×10^{-25}	0.05
$B - L$	Di Mauro+21	13.28	1.95×10^{-26}	1.99
	Cholis+22	17.50	3.72×10^{-26}	0.31



Relevant observables

Positron flux from DM

Relevant observables

Positron flux from DM

$$Q^{\rm DM}_{e^\pm}(E_e, \vec{x}) = \frac{\langle \sigma v \rangle}{2} \left(\frac{\rho_{\rm DM}(\vec{x})}{m_\chi} \right)^2 \frac{dN_{e^\pm}}{dE_e}$$

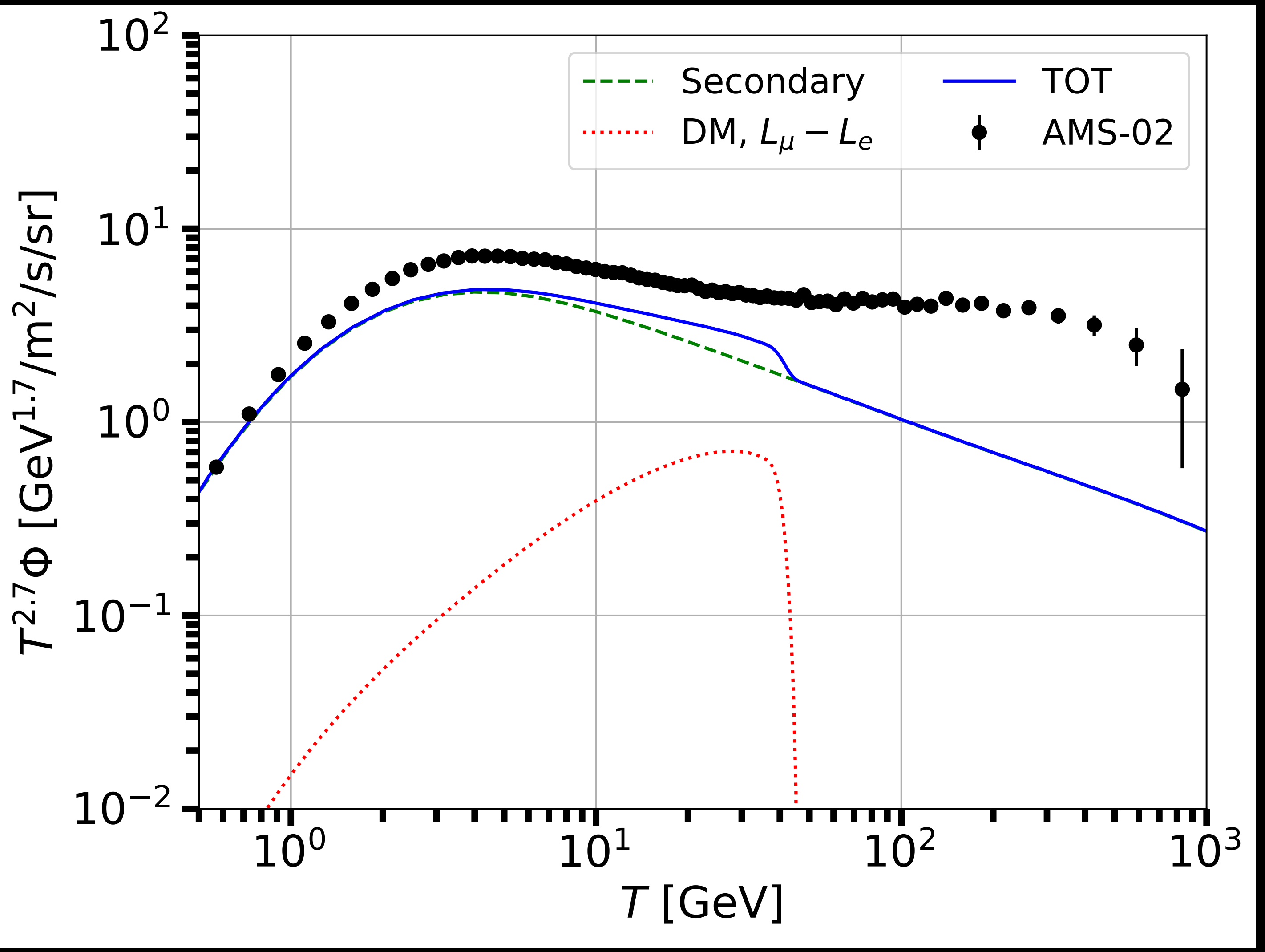
Diffusion-loss equation:

$$\vec{\nabla}\left(D\,\vec{\nabla} f_{e^\pm} - \vec{v}_c f_{e^\pm}\right) + \frac{\partial}{\partial K_e}\left(b_{\rm loss} f_{e^\pm} + \beta^2 D_{pp} \frac{\partial f_{e^\pm}}{\partial K_e} \right) + Q^{\rm DM}_{e^\pm} = 0$$

spatial diffusion | convection | energy losses | momentum space diffusion | source

GALPROP: obtain the positron flux at Earth

We set then an UL on $\langle \sigma v \rangle$ using AMS-02 positron data



Relevant observables

$$\langle\sigma v\rangle \simeq \sum_f \frac{q_X^2 g_X^4 k_f}{2\pi} \frac{m_\chi^2}{(m_{A'} - 4m_\chi^2)^2 + m_{A'}^2\Gamma_{A'}^2} \times$$
$$\times \sqrt{1 - \frac{m_f^2}{m_\chi^2}} \left(1 + \frac{m_f^2}{2m_\chi^2}\right) + \mathcal{O}(v^2)$$

DM relic density

We need to solve $\dfrac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$ for given g_X and $m_{A'}$ (m_χ fixed)

micrOMEGAs

Approximation: $\Omega_\chi^2 \simeq \dfrac{m_\chi s_0 Y_0}{\rho_c} \approx 1.07 \times 10^9\ \mathrm{GeV}^{-1} \dfrac{x_f}{\sqrt{g_*} M_{\mathrm{Pl}}} \dfrac{1}{\langle\sigma v\rangle}$

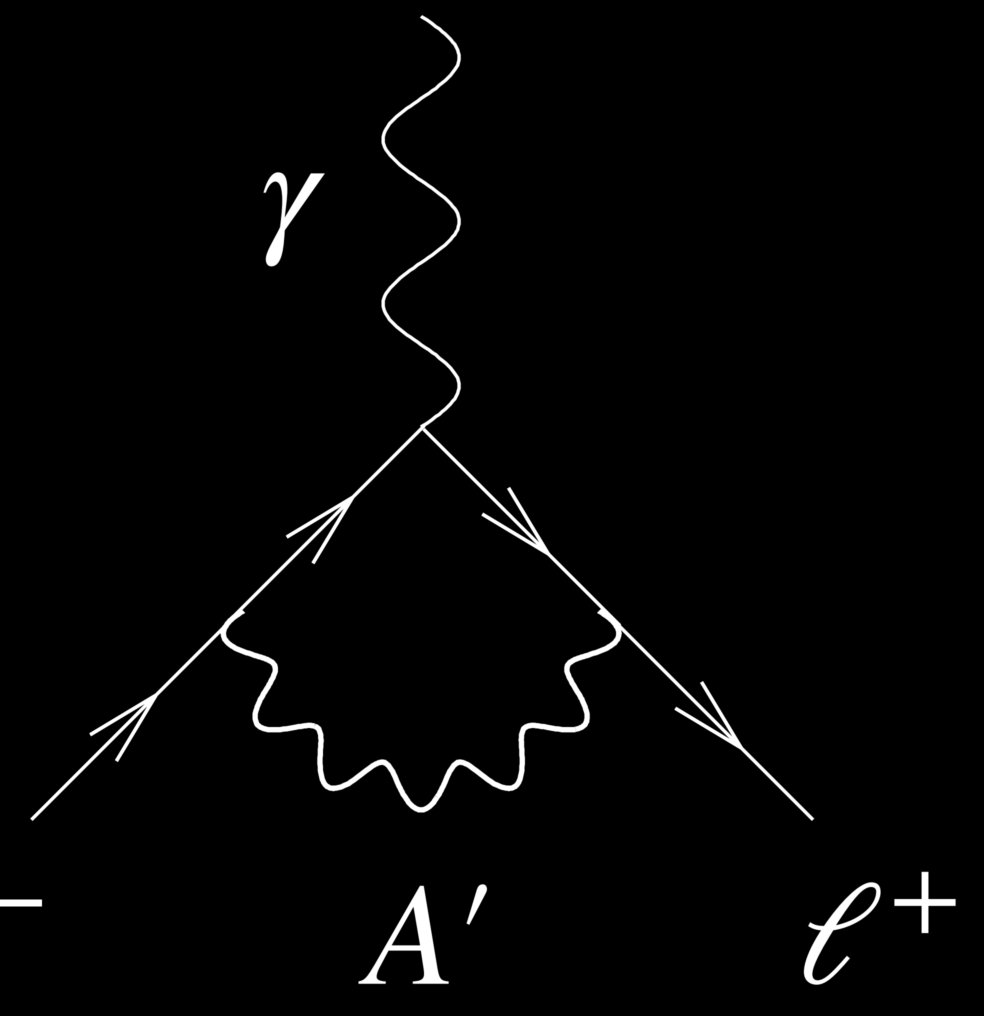
Value measured by Planck: $\Omega_\chi h^2 = 0.120 \pm 0.001$

$$\langle\sigma v\rangle \approx 3 \times 10^{-26}\ \mathrm{cm^3/s} \left(\frac{x_f}{25}\right)\left(\frac{90}{g_*}\right)^{1/2}$$

Relevant observables

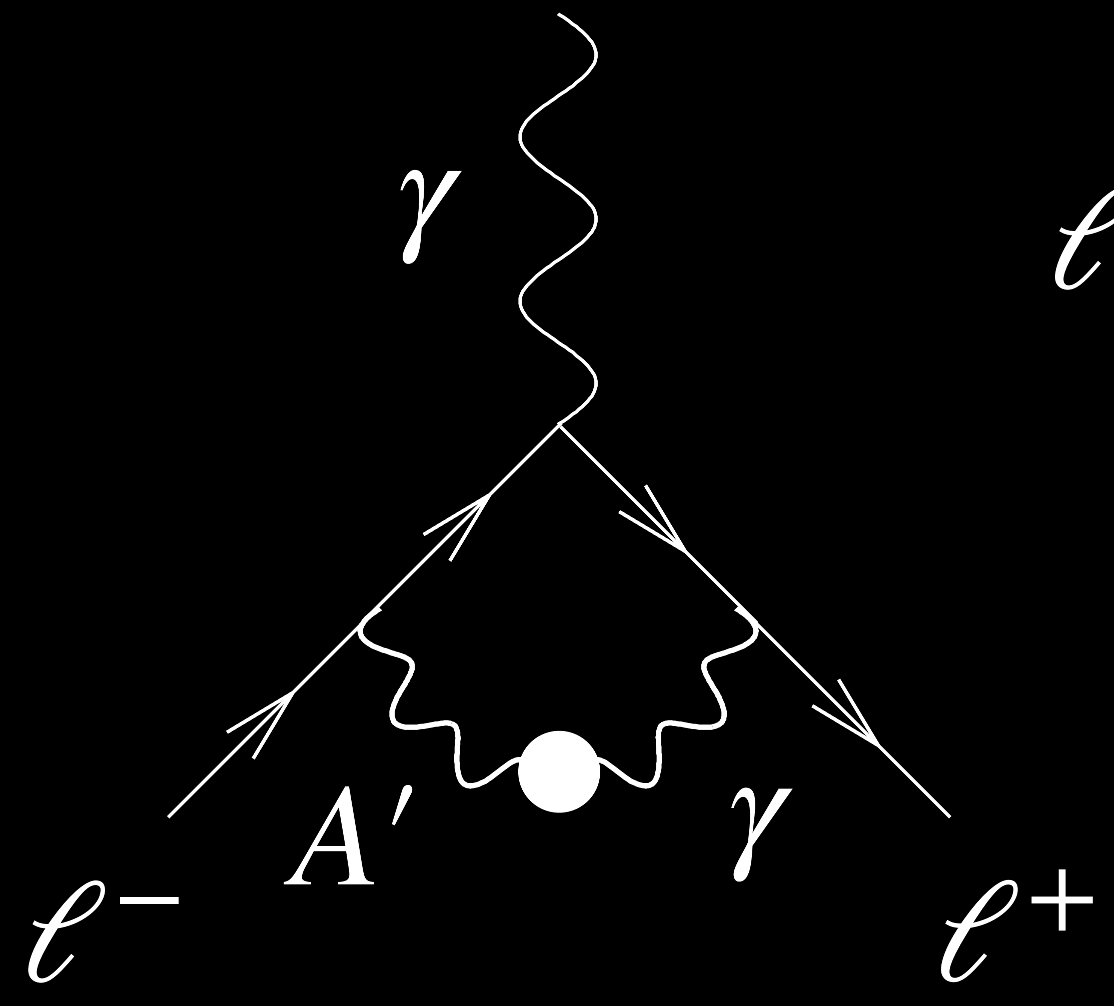
Anomalous magnetic moments

$$a_\ell = \frac{g_\ell - 2}{2}$$

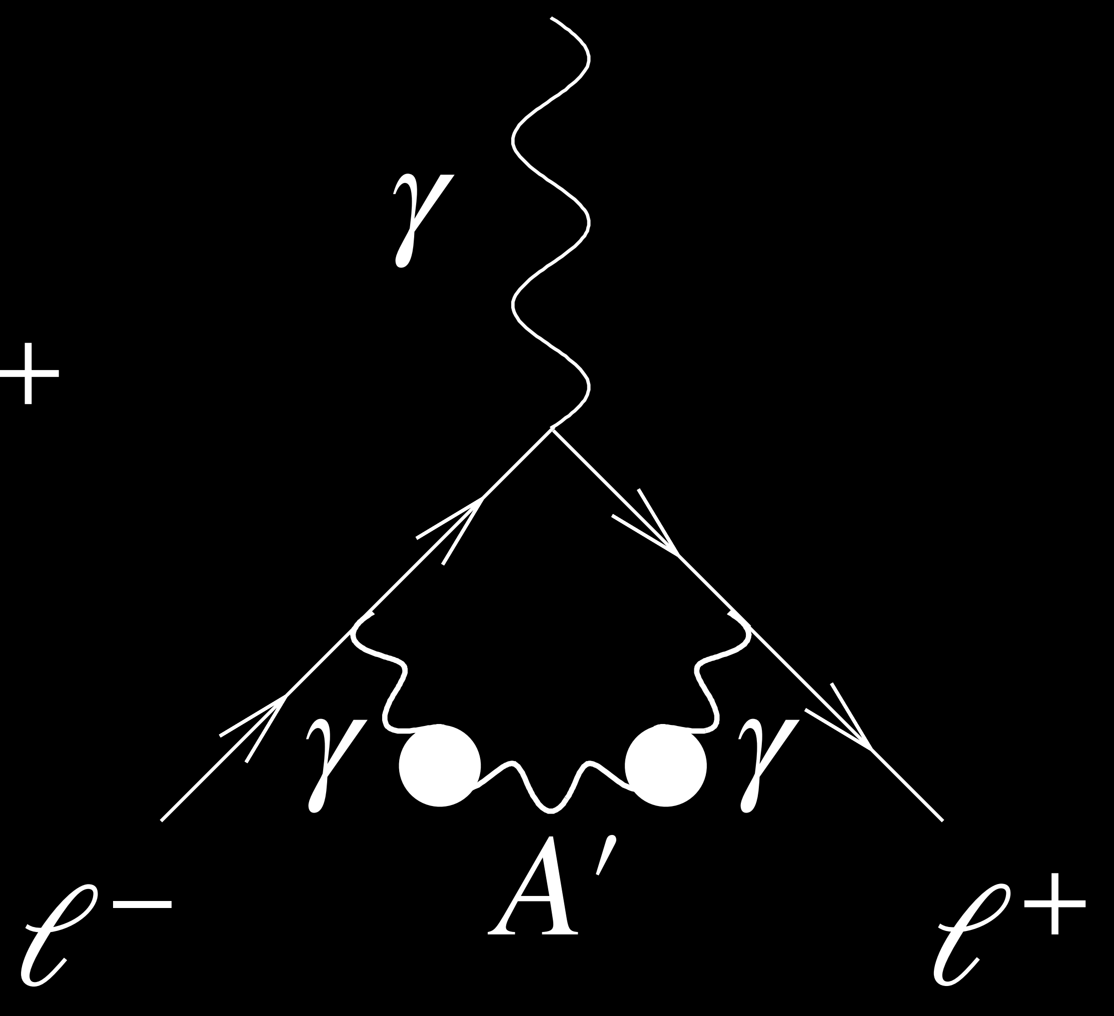


$$\Delta a_e = a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}} = (-1.44 \pm 0.72) \times 10^{-12}$$

$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (38 \pm 63) \times 10^{-11}$$



$$\Delta a_\ell^{A'} = \frac{(g_X + e\epsilon)^2}{4\pi^2} \int_0^1 dz \frac{m_\ell^2 z^2 (1-z)}{m_{A'}^2 (1-z) + m_\ell^2 z^2}$$



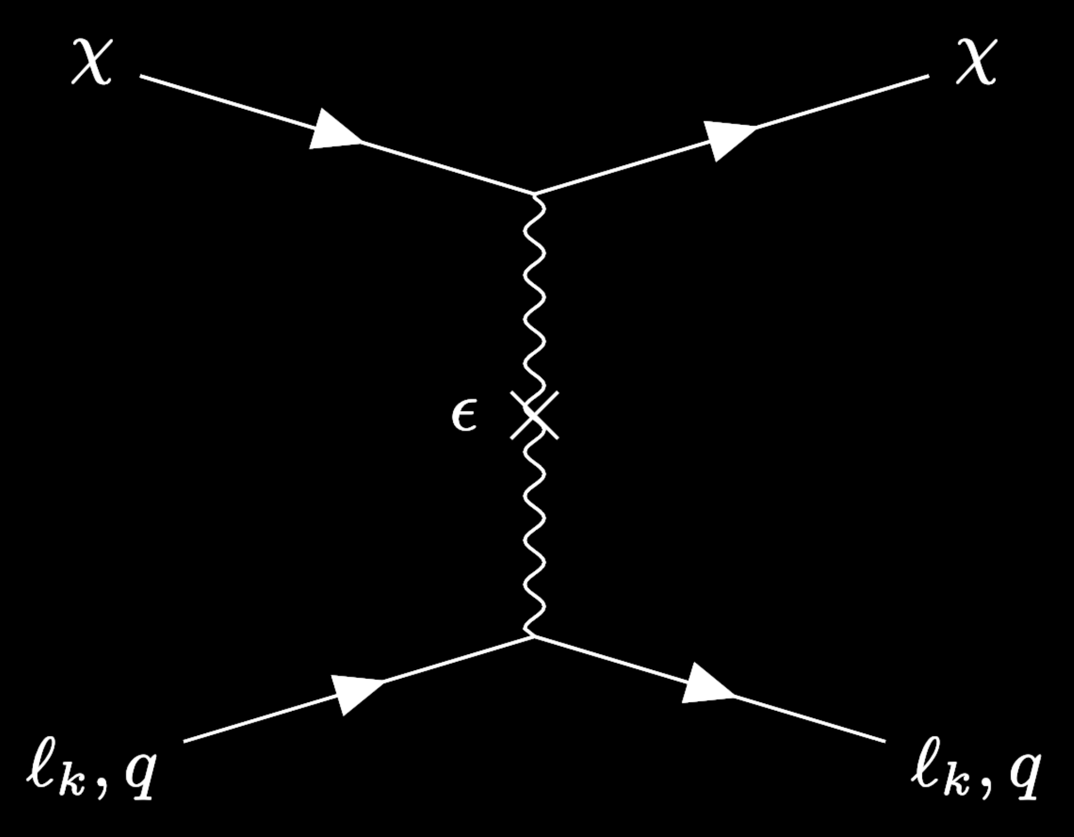
$U(1)_{L_e-L_\tau}$ and $U(1)_{L_\mu-L_e}$ can contribute to Δa_e

$U(1)_{L_\mu-L_\tau}$ and $U(1)_{L_\mu-L_e}$ can contribute to Δa_μ

UL on $q_X g_X / m_{A'}$ using the 2σ uncertainties on Δa_ℓ

Relevant observables

DM direct detection



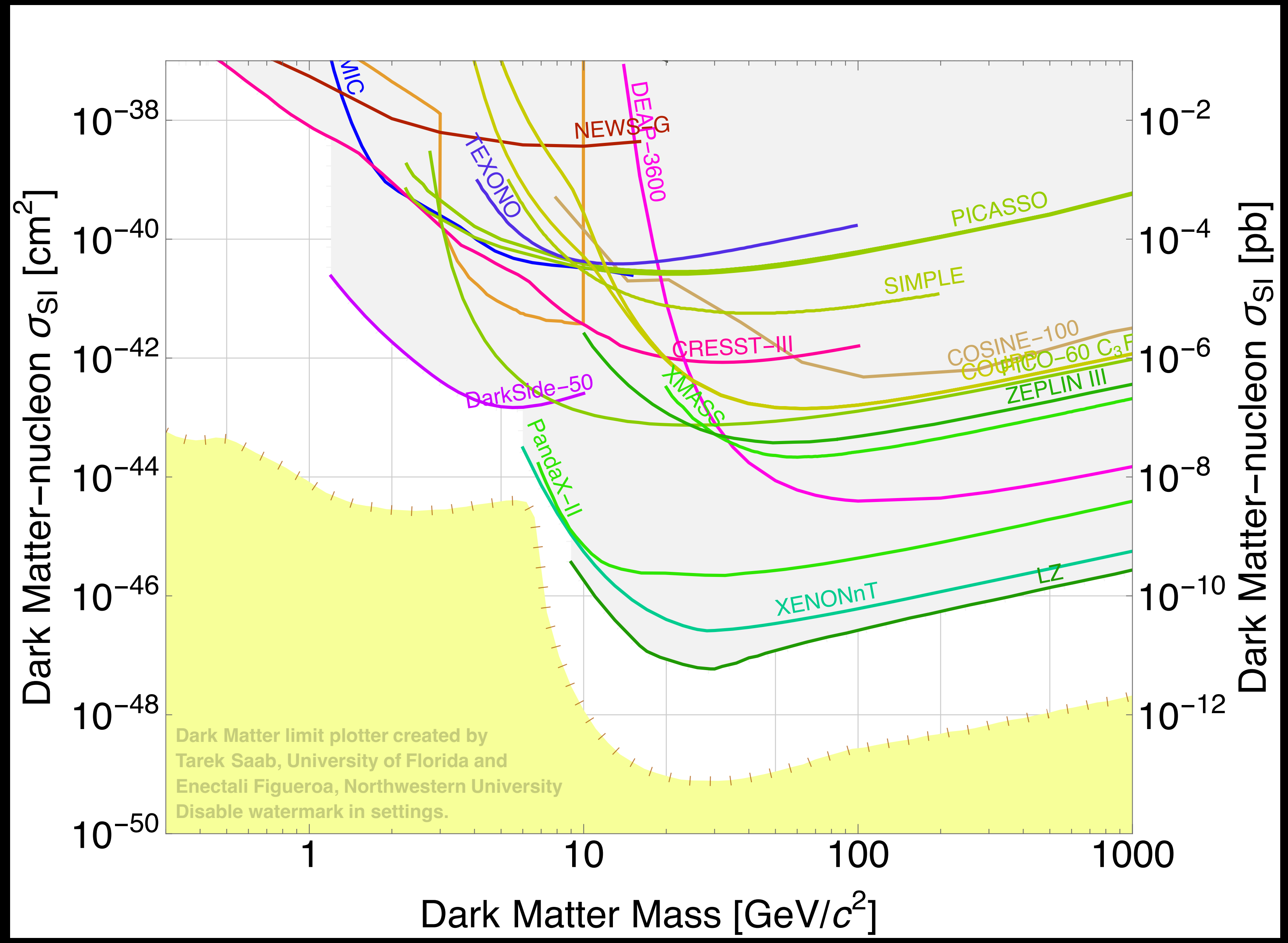
Nuclear scattering (start from $|\mathscr{M}|^2$)

$U(1)_{L_i - L_j}$ $$\sigma_{\chi N}(Q) = \frac{\mu_{\chi N}^2}{\pi} q_X^2 g_X^2 \epsilon^2(Q) F_{\rm Helm}^2(Q) \left| \frac{f_N^{A'}}{m_{A'}^2 + Q^2} - \frac{s_W f_N^Z}{m_Z^2 - m_{A'}^2} \right|^2$$

$U(1)_{B-L}$ $$\sigma_{\chi N}(Q) = \frac{\mu_{\chi N}^2}{\pi} \frac{q_X^2 g_X^4}{(m_{A'}^2 + Q^2)^2} F_{\rm Helm}^2(Q)$$

Most sensitive DD experiments for χN:

- XENONnT (Xe): 6 GeV $\lesssim m_\chi \lesssim 8.9$ GeV
- LUX-ZEPLIN (Xe): $m_\chi \gtrsim 8.9$ GeV



Relevant observables

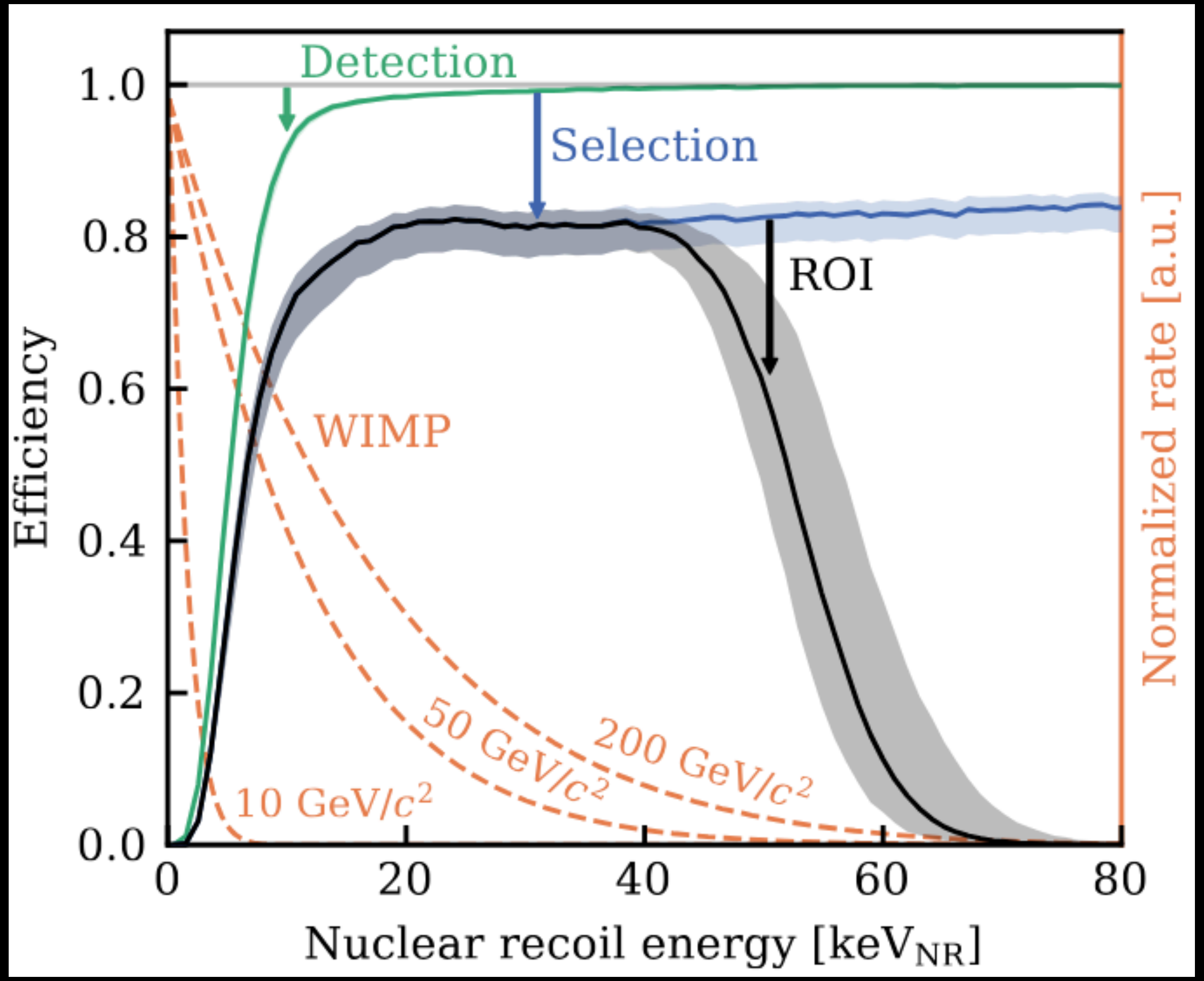
DM direct detection

DD experiments provide DM-nucleon cross-section upper limits assuming $Q = 0$

→ Compute the theoretical and experimental nuclear recoil rate to set a limit on g_X

$$R = \frac{A^2}{2\mu_{\chi N}^2}\left(\frac{\rho_\odot}{m_\chi}\right)\int_{E_R^{\min}}^{E_R^{\max}} \sigma_{\chi N}(Q(E_R))\omega(E_R)\eta(E_R)dE_R$$

$$\eta(E_R) = \int_{v_{\min}}^{v_{\rm esc}} \frac{f(\vec{v})}{|\vec{v}|} d^3\vec{v} \qquad E_R = \frac{Q^2}{2M_T}$$

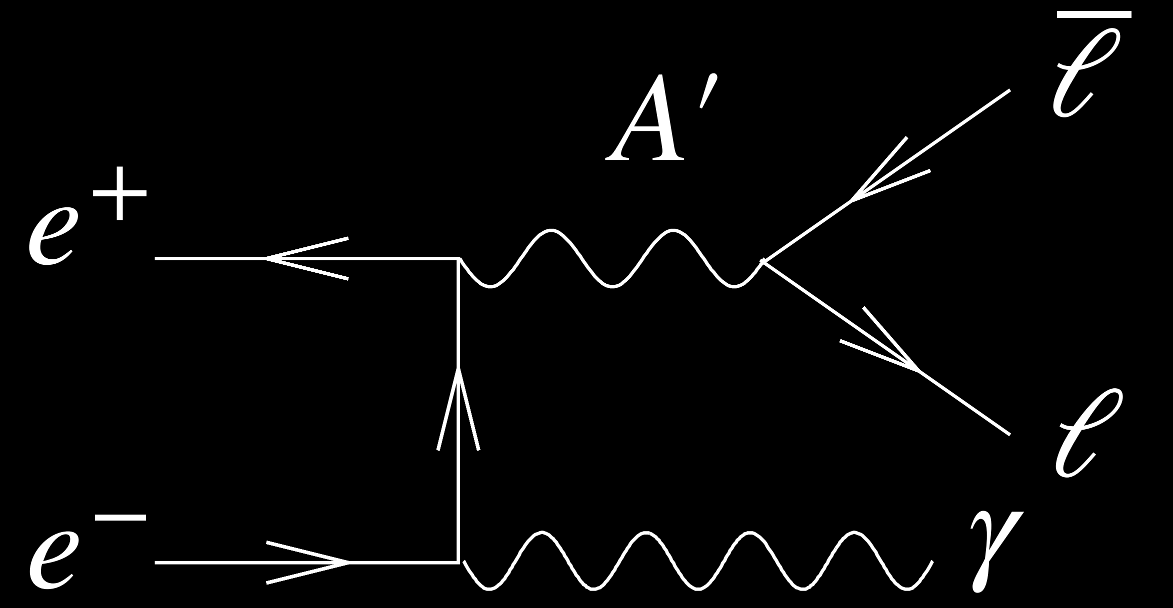


XENONnT Coll., *Phys.Rev.Lett.* 131 (2023) 041003

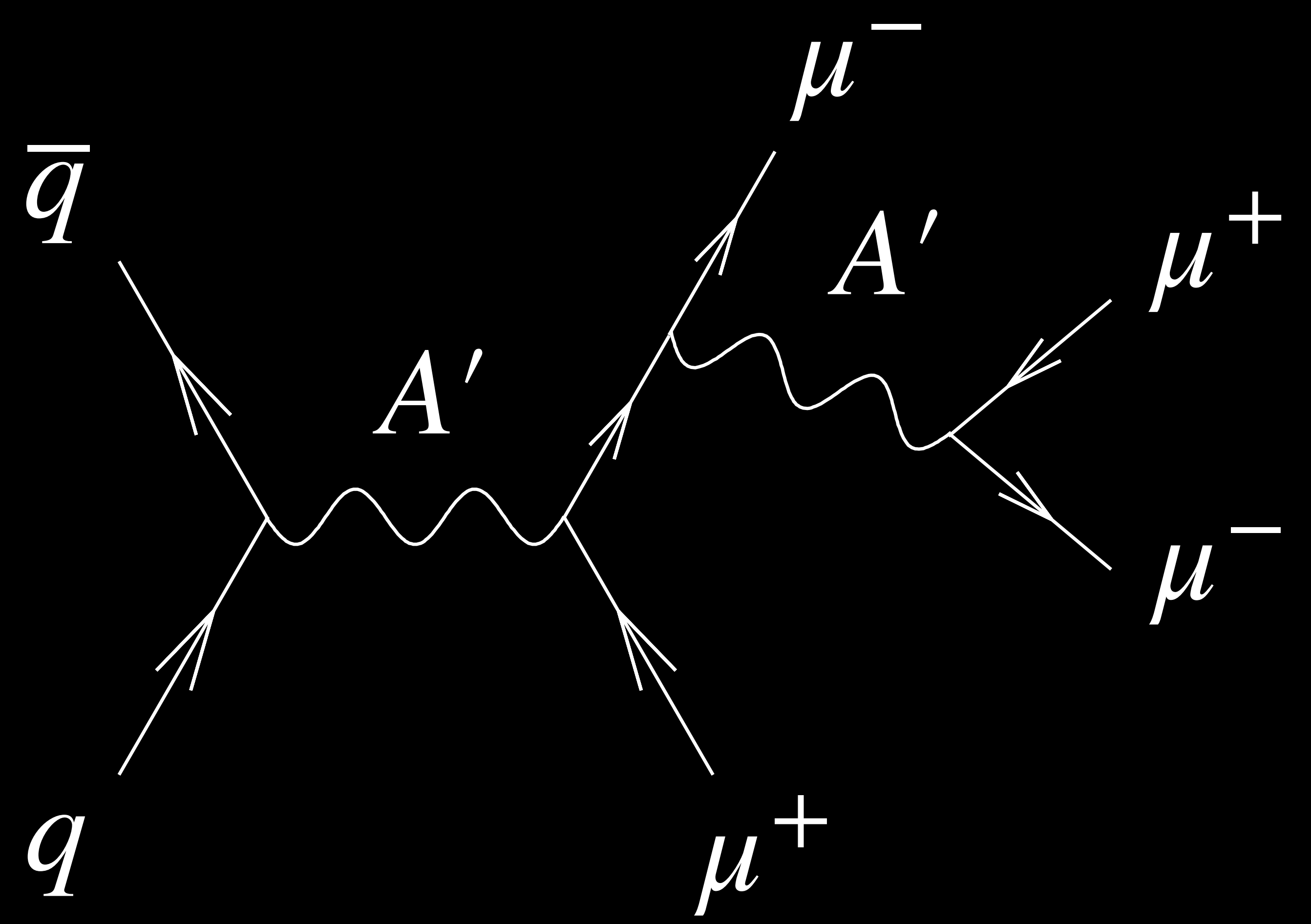
Relevant observables

Colliders

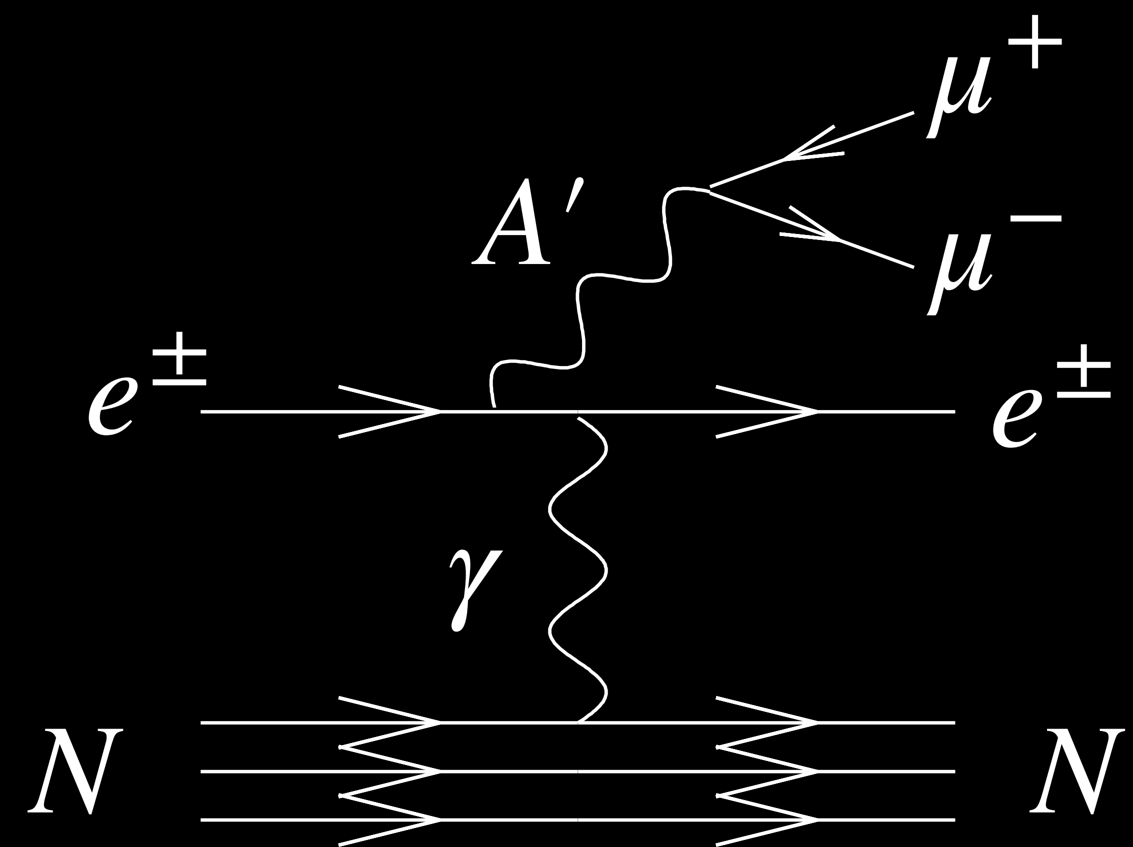
Most stringent constraints on g_X are obtained by trying to probe these processes (for relevant $m_{A'}$ masses)

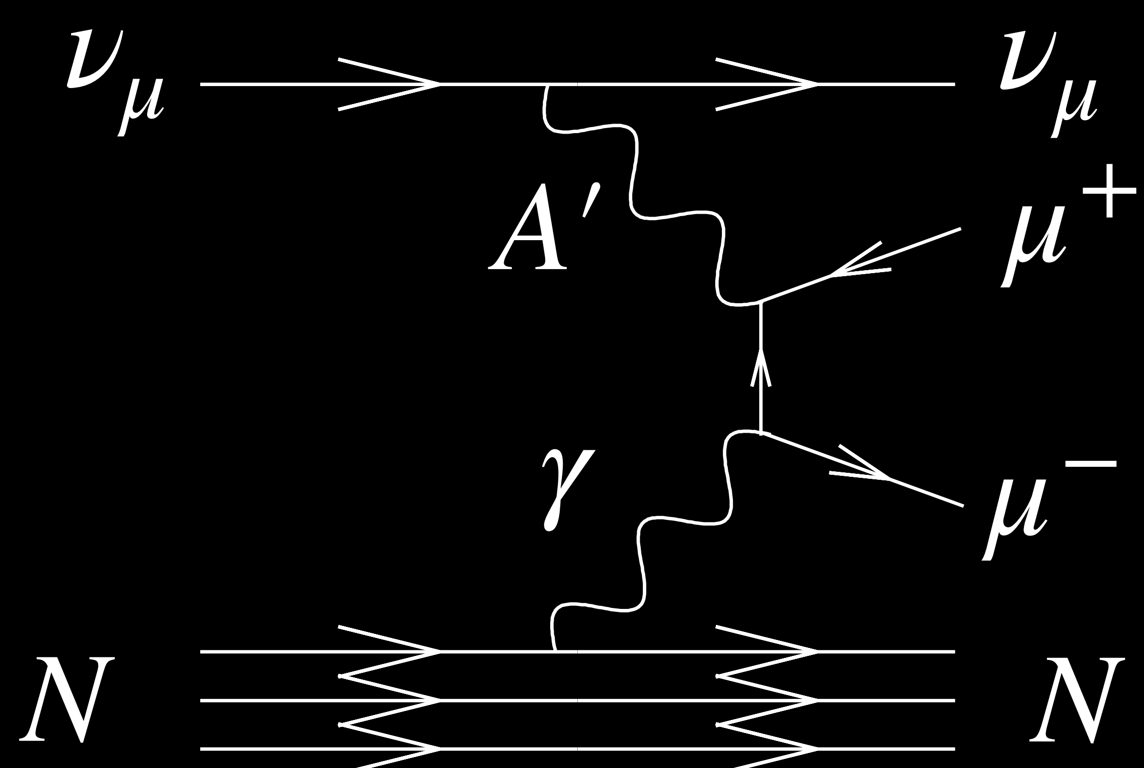


e^+e^- collisions
BaBar, Belle II



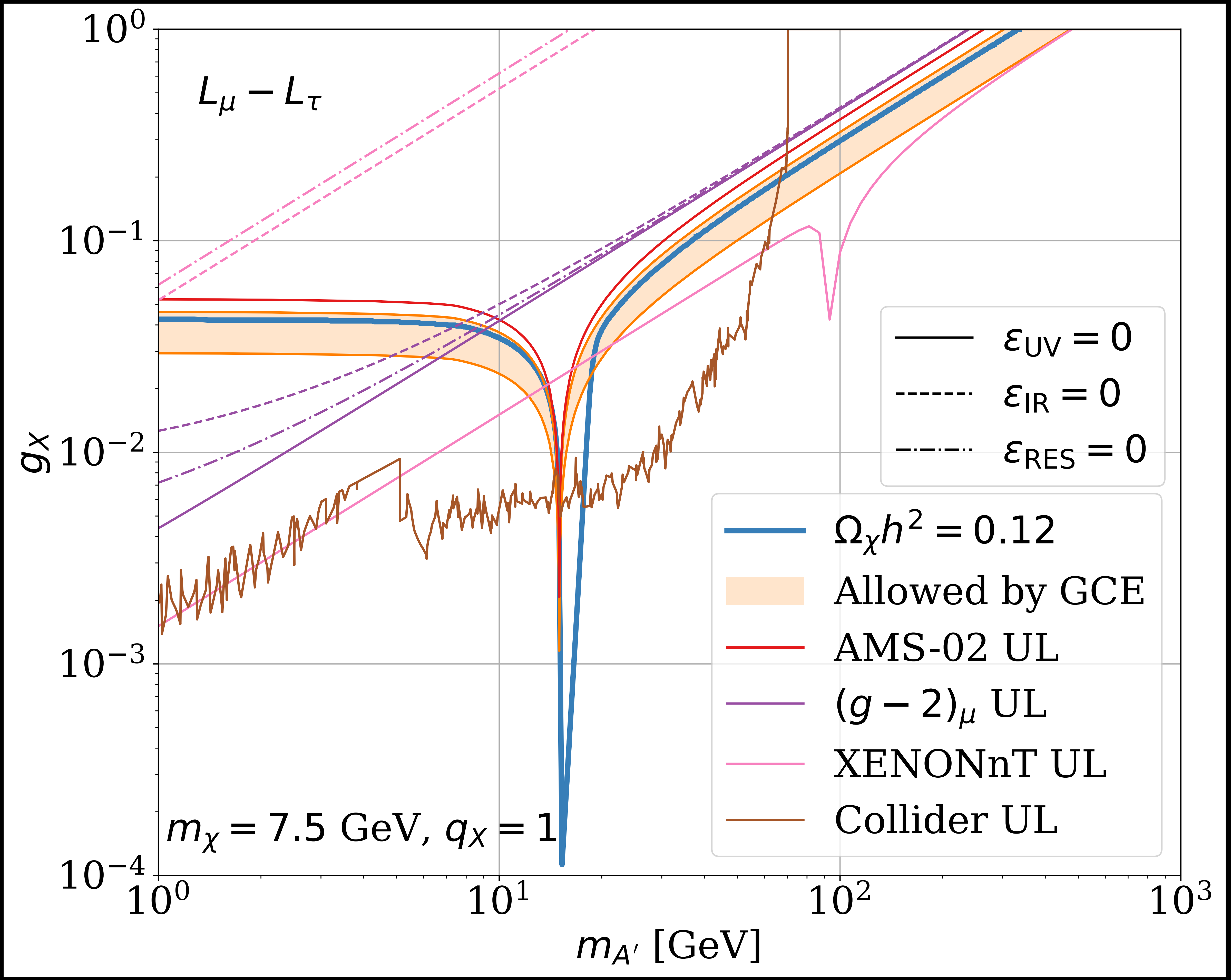
pp collisions
CMS, ATLAS



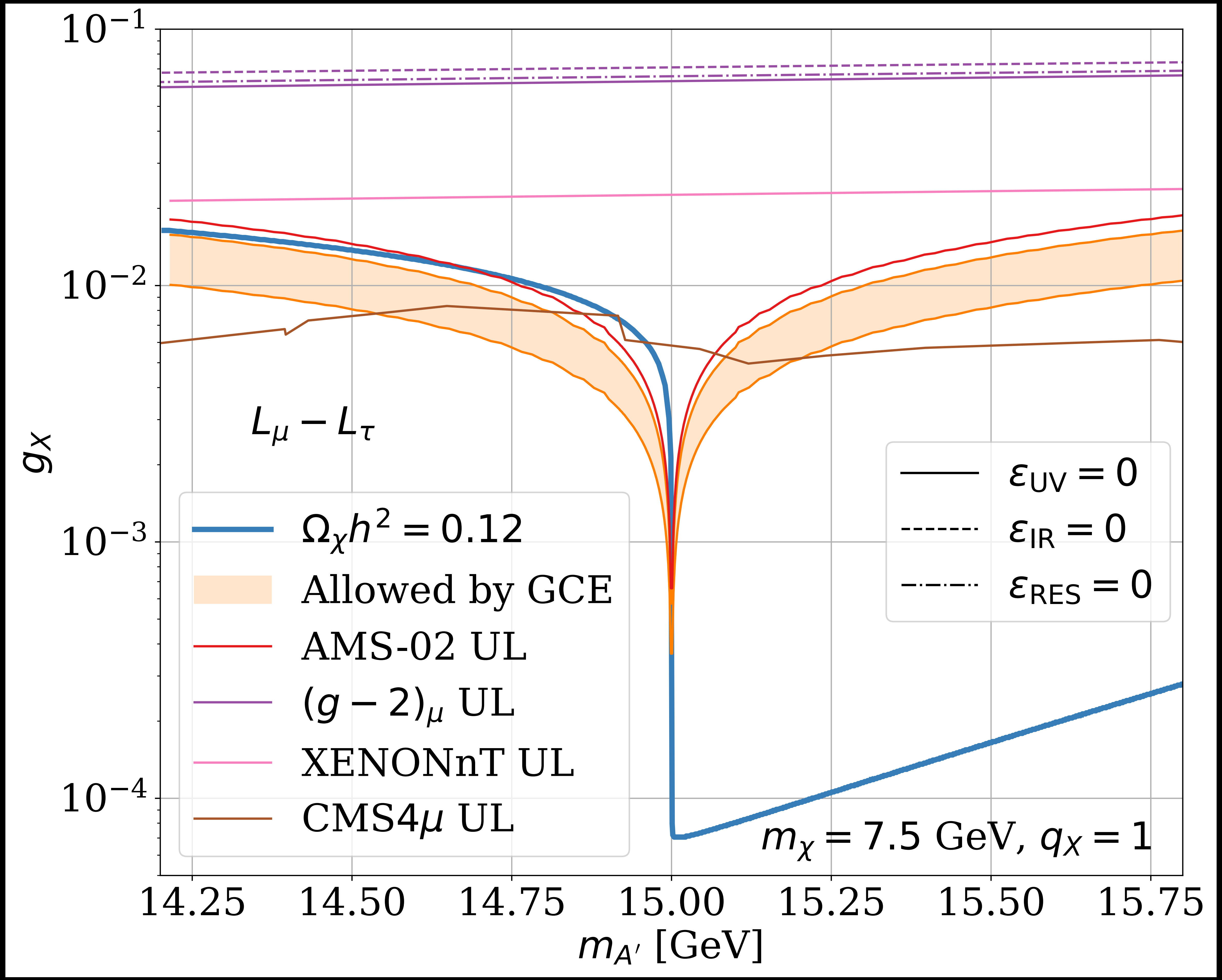


Fixed target
NA61, CCFR

Results

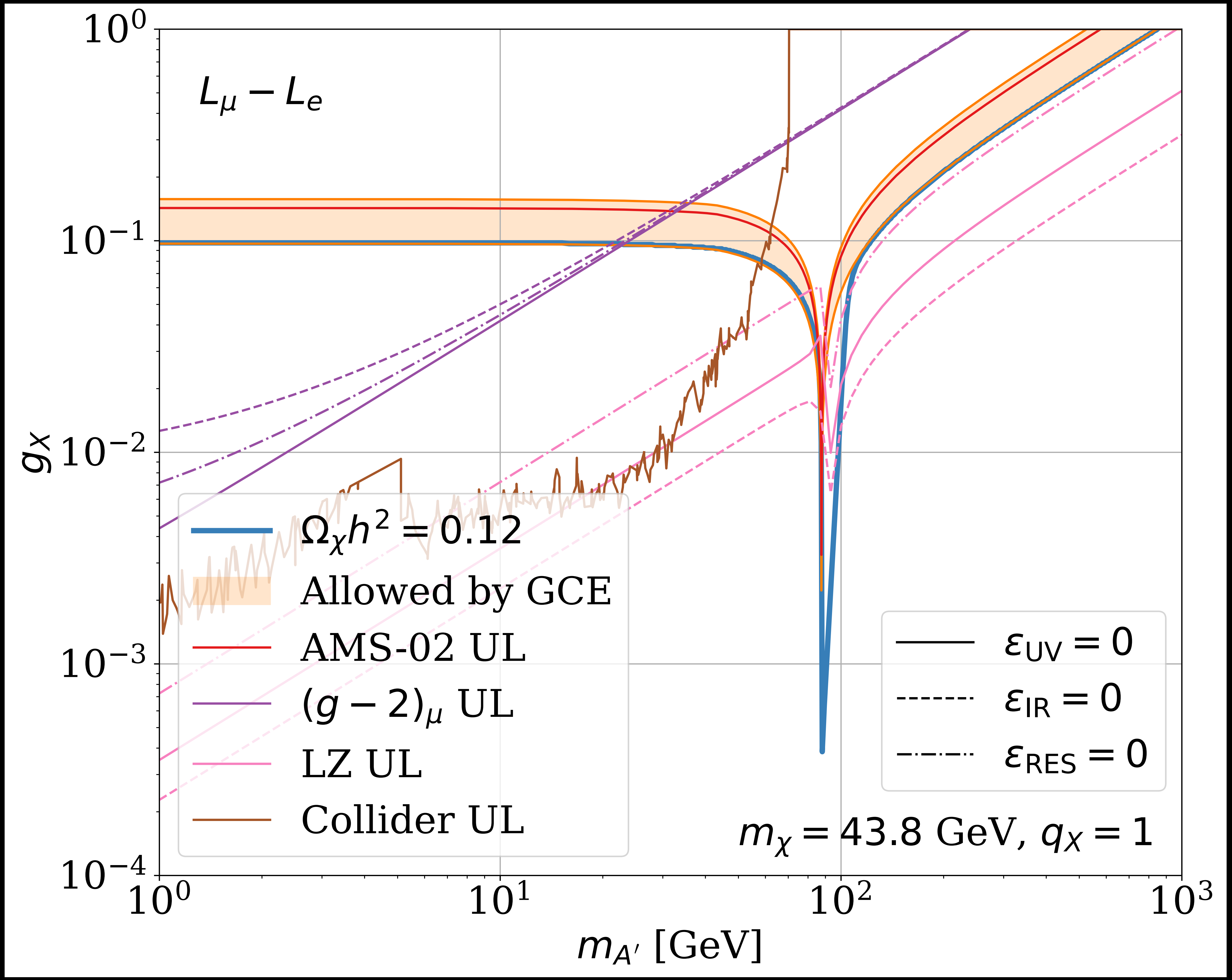


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
g_X
$L_\mu - L_\tau$
$\varepsilon_{UV} = 0$
$\varepsilon_{IR} = 0$
$\varepsilon_{RES} = 0$
$\Omega_\chi h^2 = 0.12$
Allowed by GCE
AMS-02 UL
$(g-2)_\mu$ UL
XENONnT UL
Collider UL
$m_\chi = 7.5$ GeV, $q_X = 1$
10^0
10^1
10^2
10^3
$m_{A'}$ [GeV]

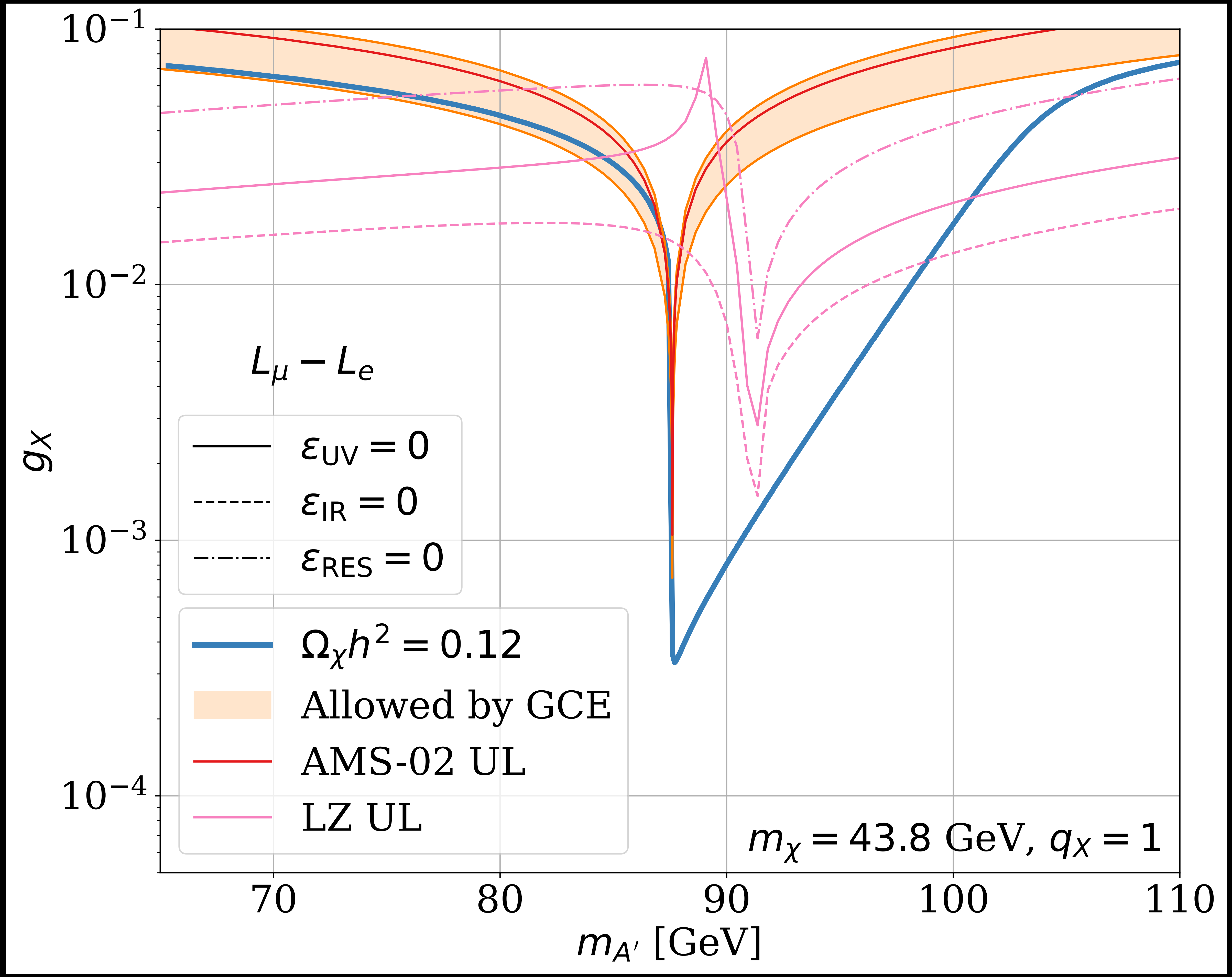


10^{-1}
10^{-2}
10^{-3}
10^{-4}
g_X
$L_\mu - L_\tau$
$\varepsilon_{UV} = 0$
$\varepsilon_{IR} = 0$
$\varepsilon_{RES} = 0$
$\Omega_\chi h^2 = 0.12$
Allowed by GCE
AMS-02 UL
$(g-2)_\mu$ UL
XENONnT UL
CMS4μ UL
$m_\chi = 7.5$ GeV, $q_X = 1$
14.25
14.50
14.75
15.00
15.25
15.50
15.75
$m_{A'}$ [GeV]

Results

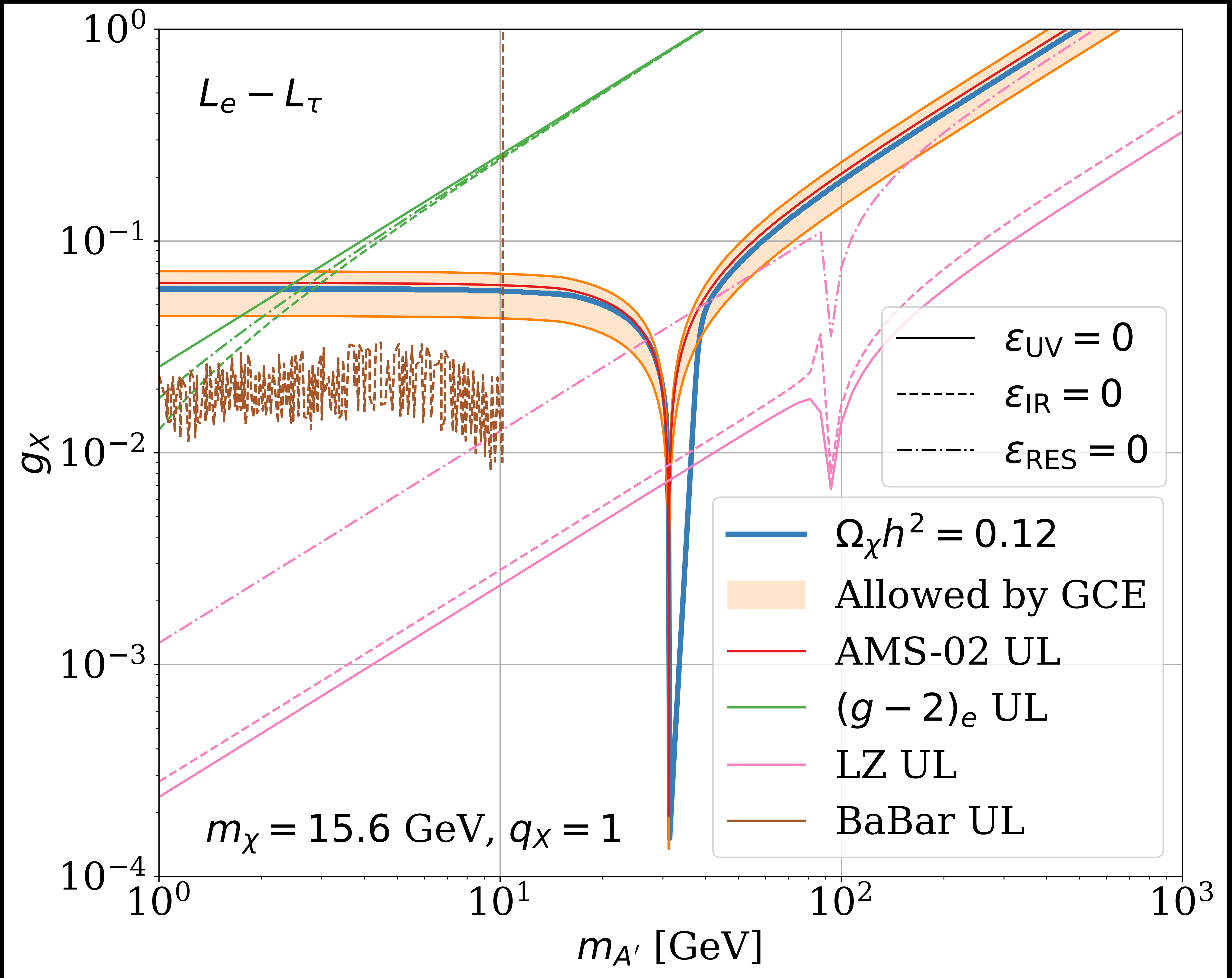


$L_\mu - L_e$
g_X
$m_{A'}$ [GeV]
$\Omega_\chi h^2 = 0.12$
Allowed by GCE
AMS-02 UL
$(g-2)_\mu$ UL
LZ UL
Collider UL
$\varepsilon_{\rm UV} = 0$
$\varepsilon_{\rm IR} = 0$
$\varepsilon_{\rm RES} = 0$
$m_\chi = 43.8$ GeV, $q_X = 1$

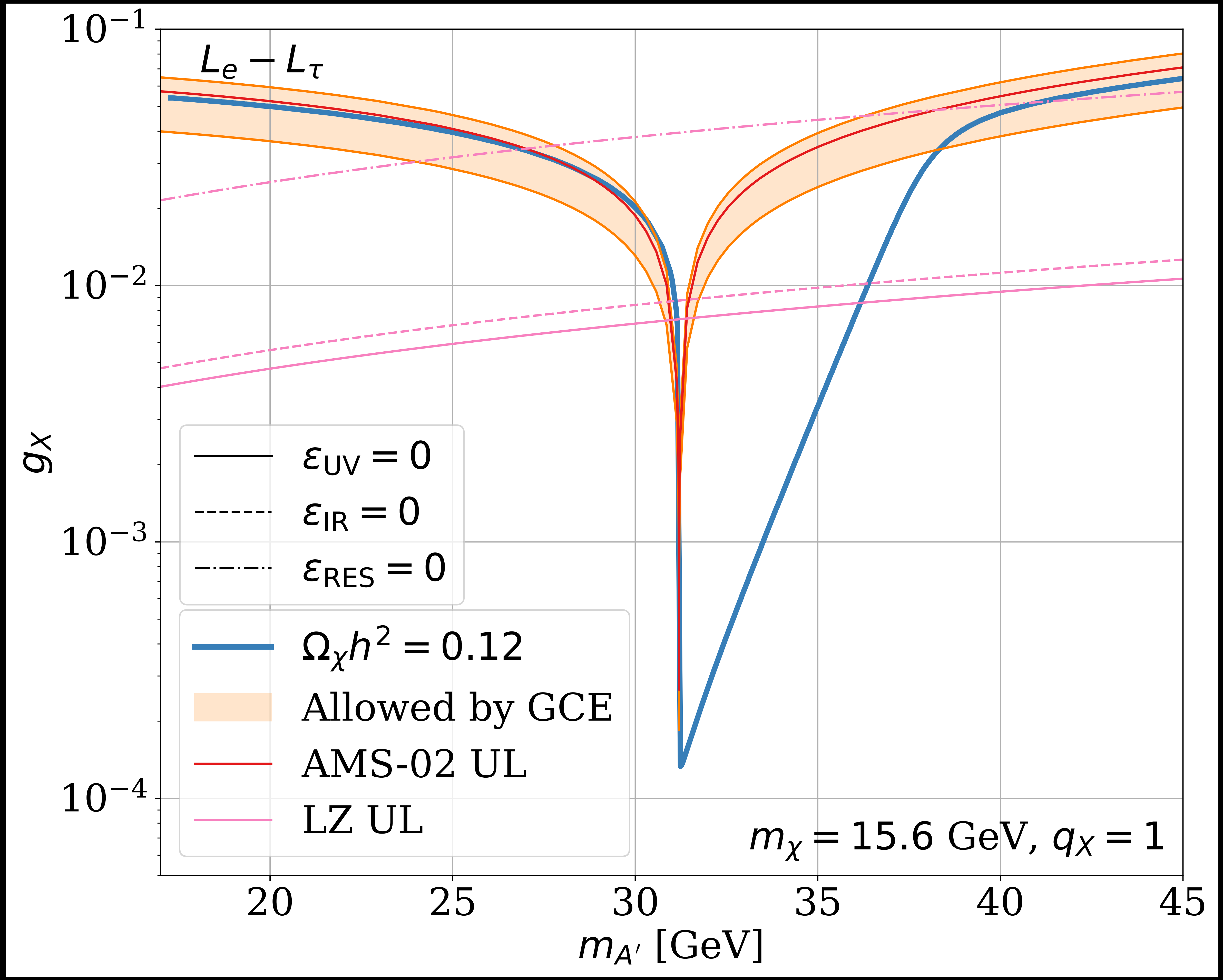


$L_\mu - L_e$
g_X
$m_{A'}$ [GeV]
$\varepsilon_{\rm UV} = 0$
$\varepsilon_{\rm IR} = 0$
$\varepsilon_{\rm RES} = 0$
$\Omega_\chi h^2 = 0.12$
Allowed by GCE
AMS-02 UL
LZ UL
$m_\chi = 43.8$ GeV, $q_X = 1$

Results

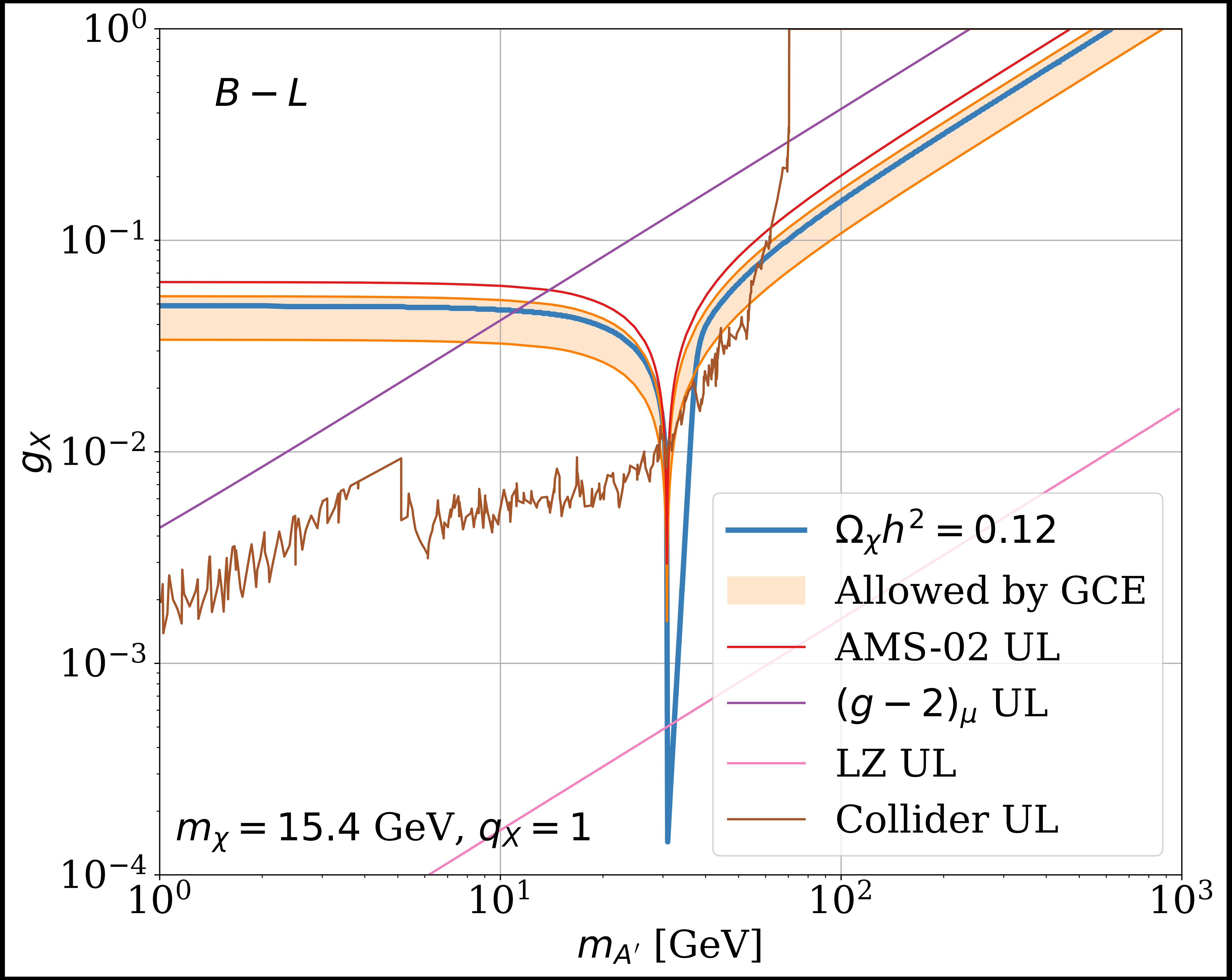


$L_e - L_\tau$
g_X
$m_{A'}$ [GeV]
$\varepsilon_{UV} = 0$
$\varepsilon_{IR} = 0$
$\varepsilon_{RES} = 0$
$\Omega_\chi h^2 = 0.12$
Allowed by GCE
AMS-02 UL
$(g-2)_e$ UL
LZ UL
BaBar UL
$m_\chi = 15.6$ GeV, $q_X = 1$

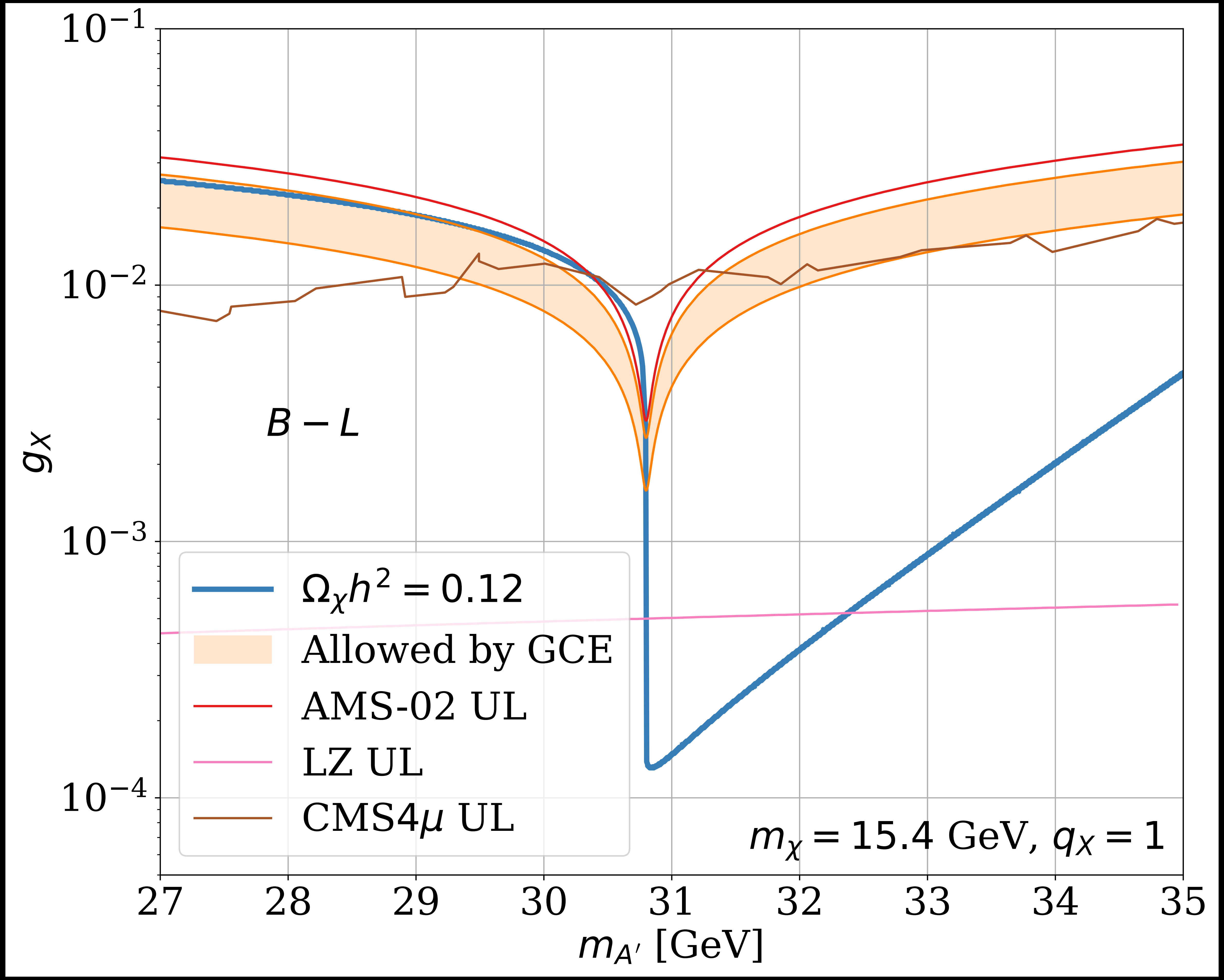


$L_e - L_\tau$
g_X
$m_{A'}$ [GeV]
$\varepsilon_{UV} = 0$
$\varepsilon_{IR} = 0$
$\varepsilon_{RES} = 0$
$\Omega_\chi h^2 = 0.12$
Allowed by GCE
AMS-02 UL
LZ UL
$m_\chi = 15.6$ GeV, $q_X = 1$

Results



$B-L$
$\Omega_\chi h^2 = 0.12$
Allowed by GCE
AMS-02 UL
$(g-2)_\mu$ UL
LZ UL
Collider UL
$m_\chi = 15.4$ GeV, $q_X = 1$
g_X
$m_{A'}$ [GeV]



$B-L$
$\Omega_\chi h^2 = 0.12$
Allowed by GCE
AMS-02 UL
LZ UL
CMS4μ UL
$m_\chi = 15.4$ GeV, $q_X = 1$
g_X
$m_{A'}$ [GeV]

Summary of the results

- If the GCE is explained by DM, we can severely constrain $U(1)_{L_i-L_j}$ models, leaving the near-resonance ($m_{A'} \lesssim 2m_\chi$) region unconstrained.
- Other regions of the parameter space are available, but up to the assumption on the value of the tree-level kinetic mixing.
- $U(1)_{B-L}$ is completely excluded.

Thank for your attention!

$U(1)_{B-L}$ model

Introduction

- Gauging $B - L$ is anomaly free if right-handed neutrinos are added. New boson X_μ
- Minimal extension of the SM, with the possibility of adding DM with X_μ being its portal to the SM

Kinetic mixing

DM & portal

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{\epsilon}{2}\hat{B}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu - m_\chi^2\bar{\chi}\chi - g_X q_X \bar{\chi}\gamma_\mu \chi X^\mu$$

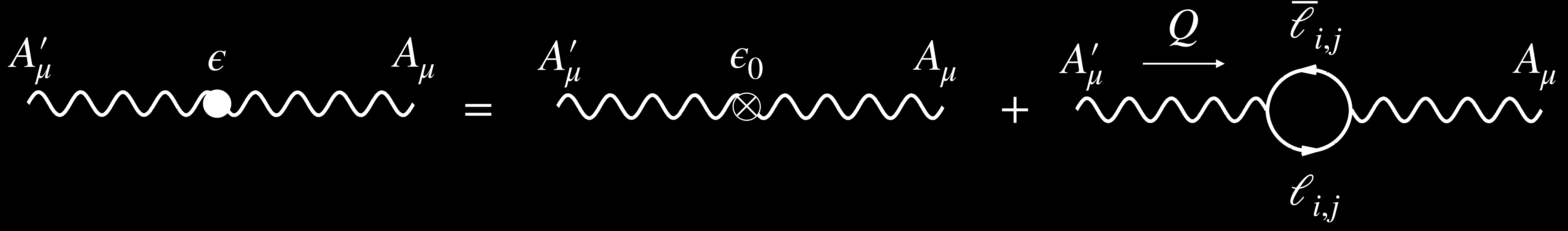
$$-g_X\left[\frac{1}{3}\sum_i \bar{q}_i\gamma_\mu q_i - \sum_j \bar{\ell}_j\gamma_\mu \ell_j\right] X^\mu$$

$U(1)_{L_i-L_j}$ models

Kinetic mixing

Since the leptons i, j are both charged under $U(1)_{L_i-L_j}$ and $U(1)_{\rm EM}$ after the EWSB, there are unavoidable loop corrections in the kinetic mixing to consider

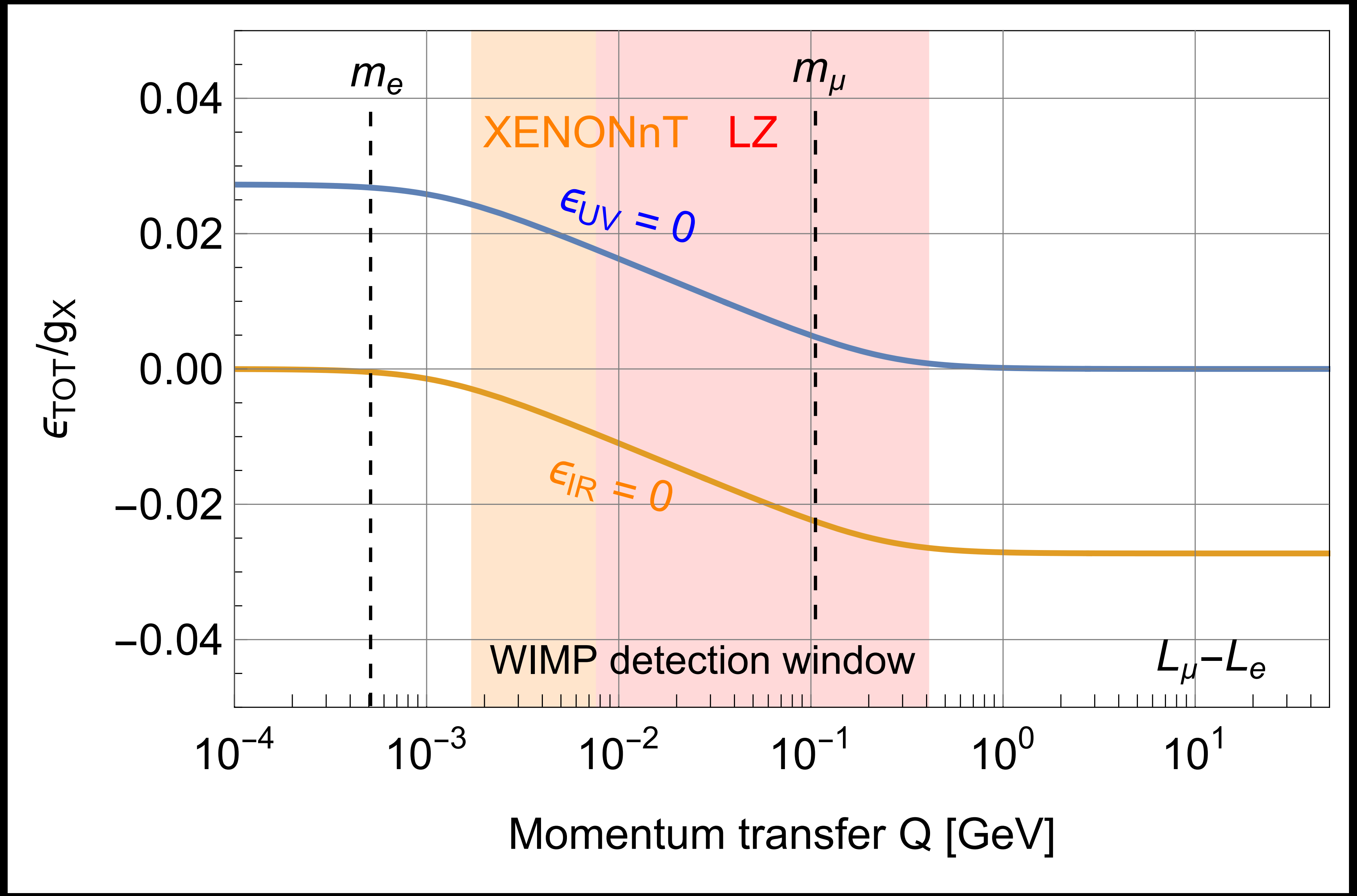
$$\epsilon(Q) = \epsilon_0 - \frac{e g_X}{2\pi^2}\int_0^1 dx\, x(1-x)\, \log\left(\frac{m_j^2 + Q^2 x(1-x)}{m_i^2 + Q^2 x(1-x)}\right)$$



$U(1)_{L_i-L_j}$ models

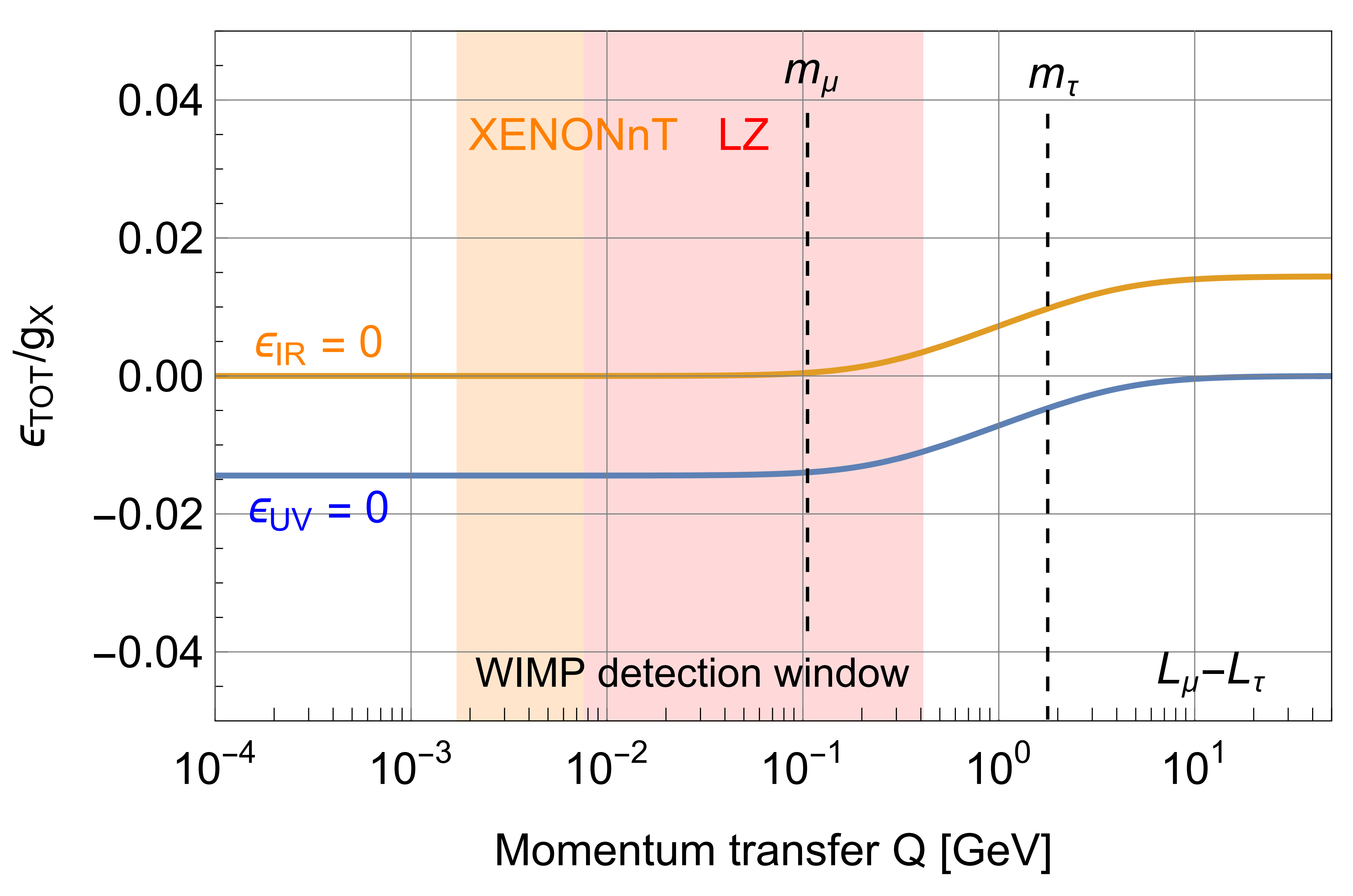
Kinetic mixing

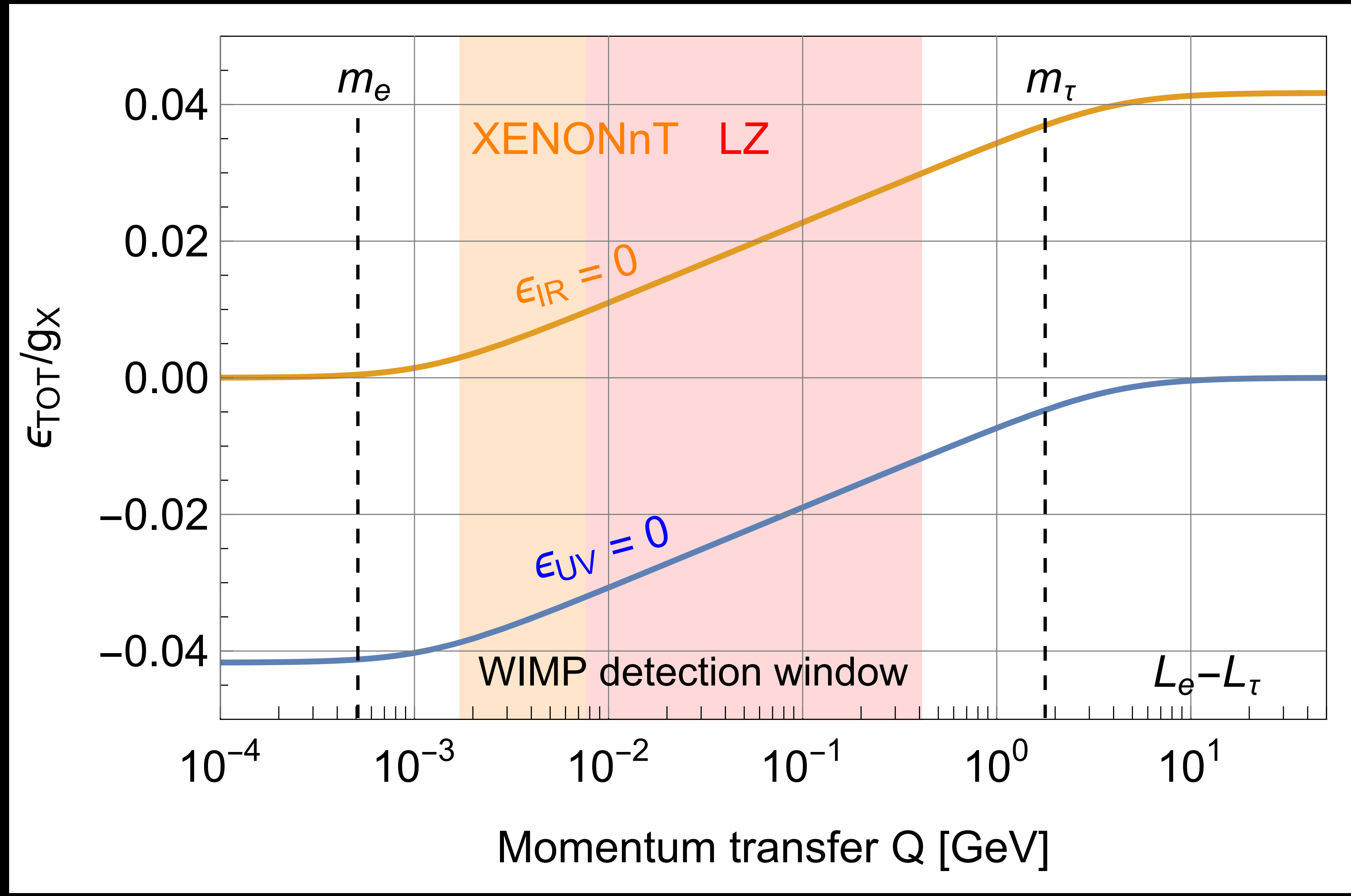
Case 1: $\epsilon_{\rm IR} = 0 \implies \epsilon_0 = \frac{e g_X}{12\pi^2} \log \frac{m_j^2}{m_i^2}$



Case 2: $\epsilon_{\rm UV} = 0$

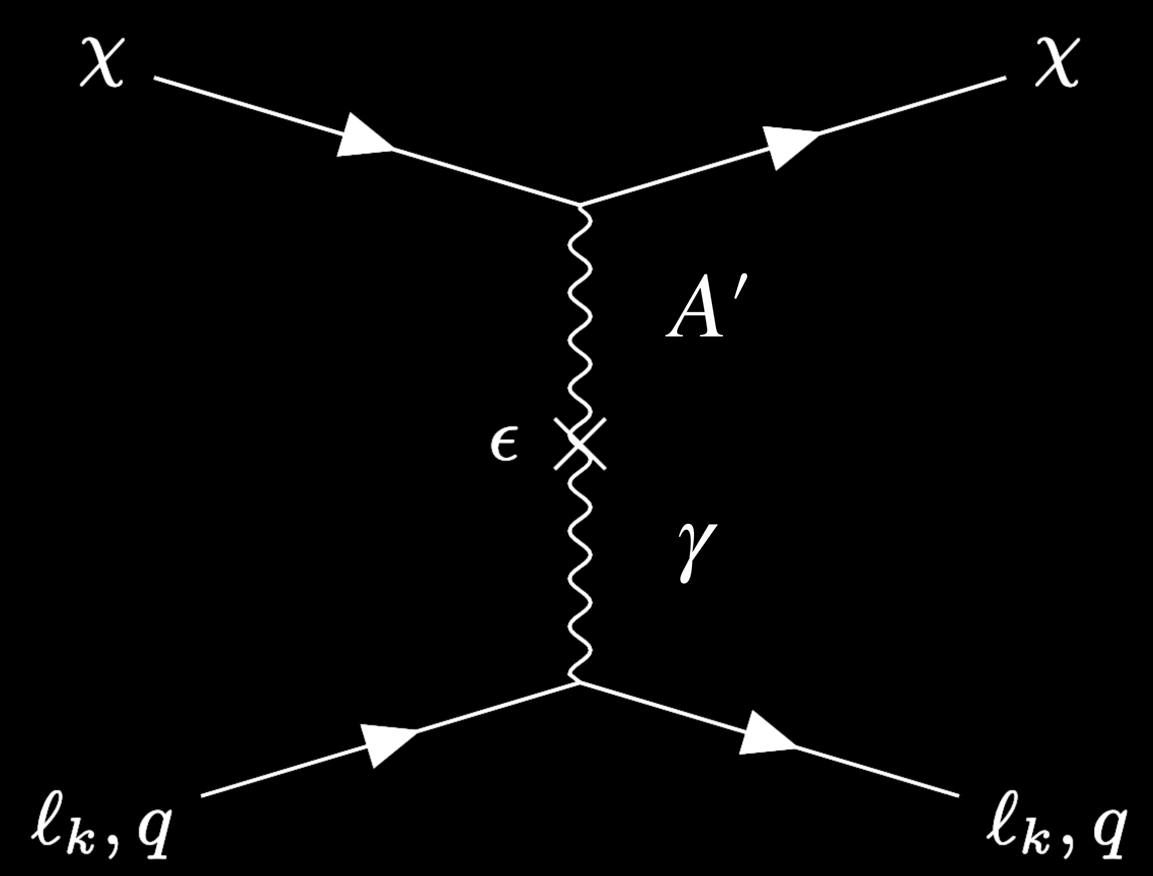
$\implies \epsilon_0 = 0$



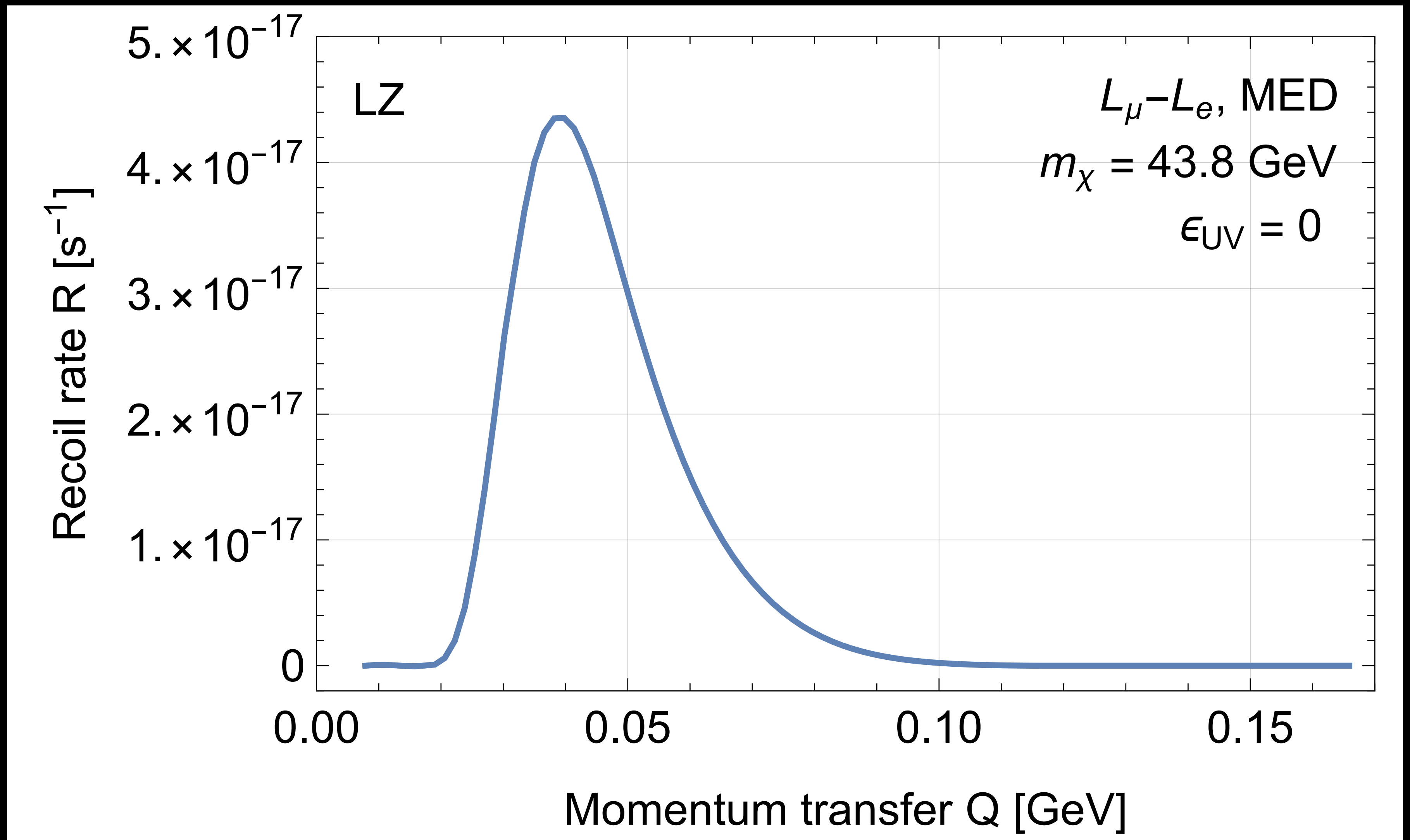


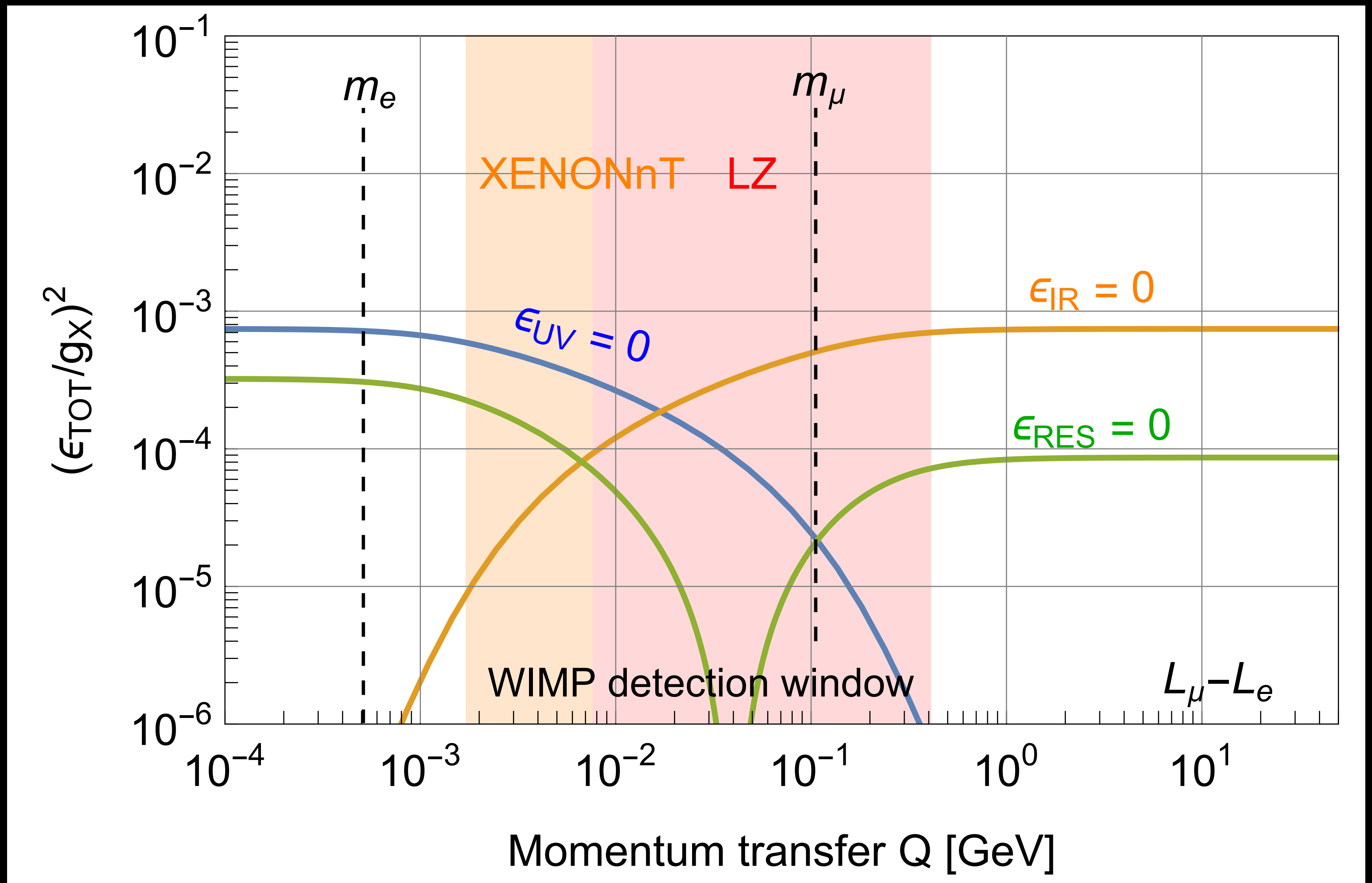
$U(1)_{L_i-L_j}$ models

Kinetic mixing



Case 3: What is the assumption we can make on ϵ_0 to evade as much as possible the DD limits?





For a given DM mass, we fix ϵ_0 so that $\epsilon(Q_{\max}) = 0$