Hitting the Thermal Target with Leptophilic Dark matter

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WG1 Parallel Session

ECFA 2024

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MIT CTP Postdoc Fellow

What are the open questions in particle physics today?

OPEN QUESTIONS

Many open questions remain in the SM & beyond

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- Higgs properties?
- EWSB? EW Sector?
- Neutrino masses?
- Origin of Flavor?

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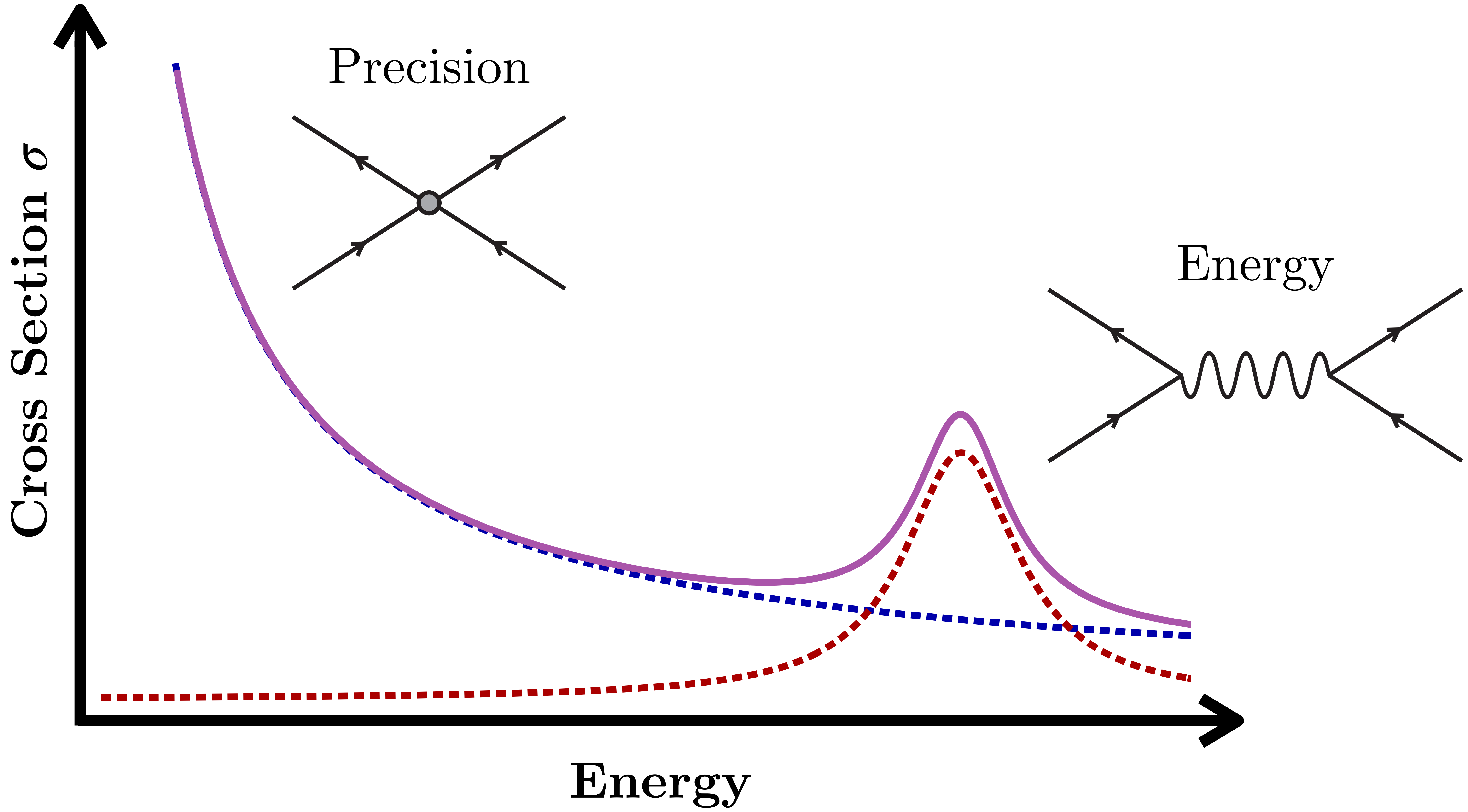
- Dark matter?
- Above 10 TeV?
- Hidden Sectors?
- Anomalies?
- BAU?

OPEN QUESTIONS

Two avenues to make progress: Precision & Energy



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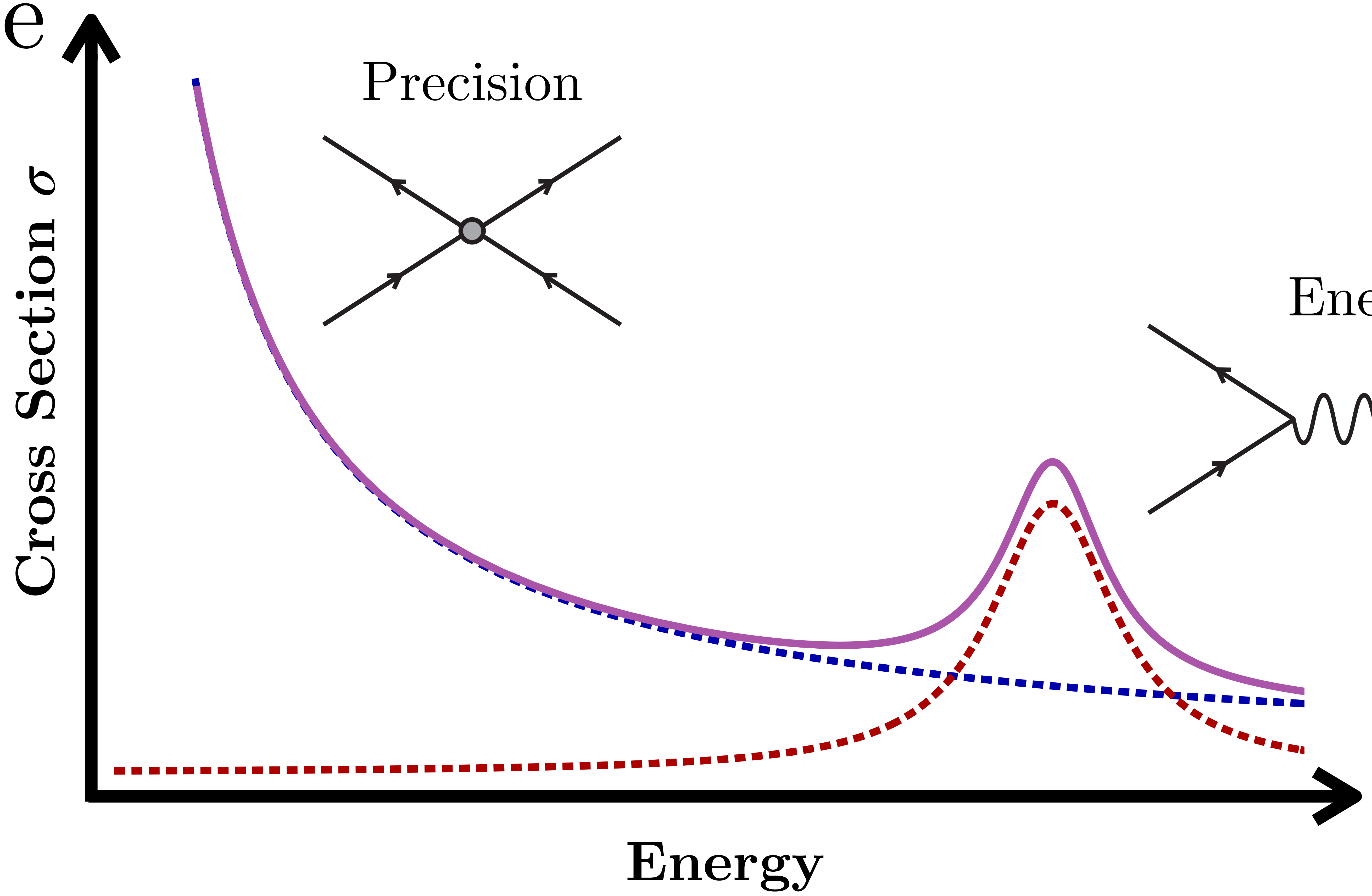
OPEN QUESTIONS

Two avenues to make progress:

Precision & Energy

e^+e^- Machine



High-energy Machine

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LEPTOPHILIC DARK MATTER

Consider an *ideal* model to search for at colliders

The coupling of a new particle to leptonic sector are proportional to the Higgs SM Yukawa couplings

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l} \qquad\qquad g_l = g_e \frac{m_l}{m_e}$$

D' Ambrosio, Giudice, Isidori, Strumia '02

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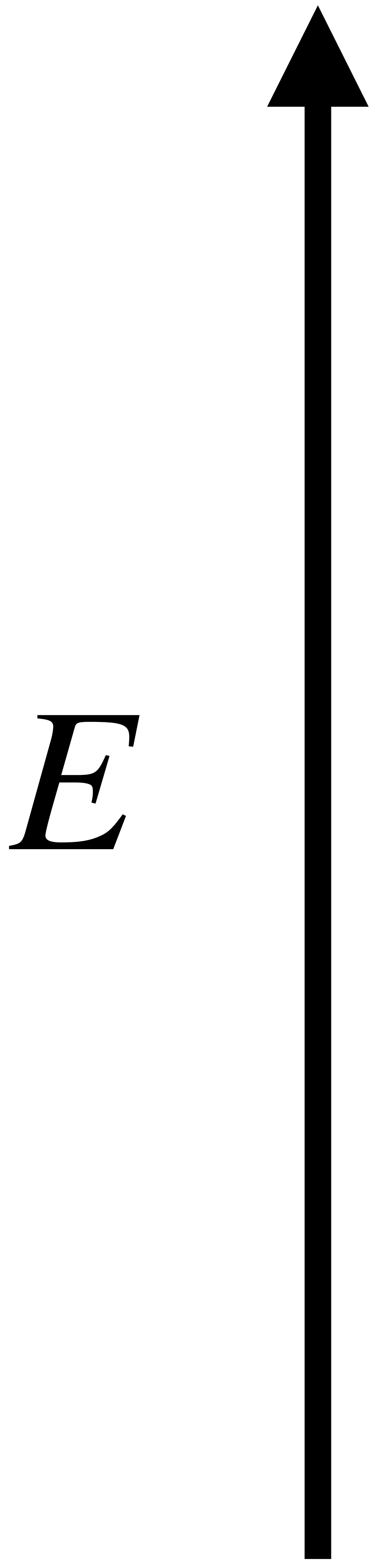
LEPTOPHILIC DARK MATTER



Type III 2HDM

$H_1 \sim (1,2)_{1/2}$ $\quad +S \sim (1,1)_0$
$H_2 \sim (1,2)_{-1/2}$

$$\mathscr{L} \supset \lambda_u H_1 Q \bar{u} + \lambda_d H_1^\dagger Q \bar{d} + \lambda_\ell H_2 L \bar{e}$$

$$V(H_1, H_2, S) = S\left(\mu_{11} H_1^\dagger H_1 + \mu_{12} H_1 H_2 + \mu_{12}^* H_2^\dagger H_1^\dagger + \mu_{22} H_2^\dagger H_2\right)$$

Each get vev v_1, v_2

Diagonalize into SM Higgs h and heavy Higgs H

Work in regime of parameters, esp $\tan\beta \equiv \frac{v_2}{v_1} \gg 1$

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l \bar{l}$$

$$g_l = g_e \frac{m_l}{m_e}$$

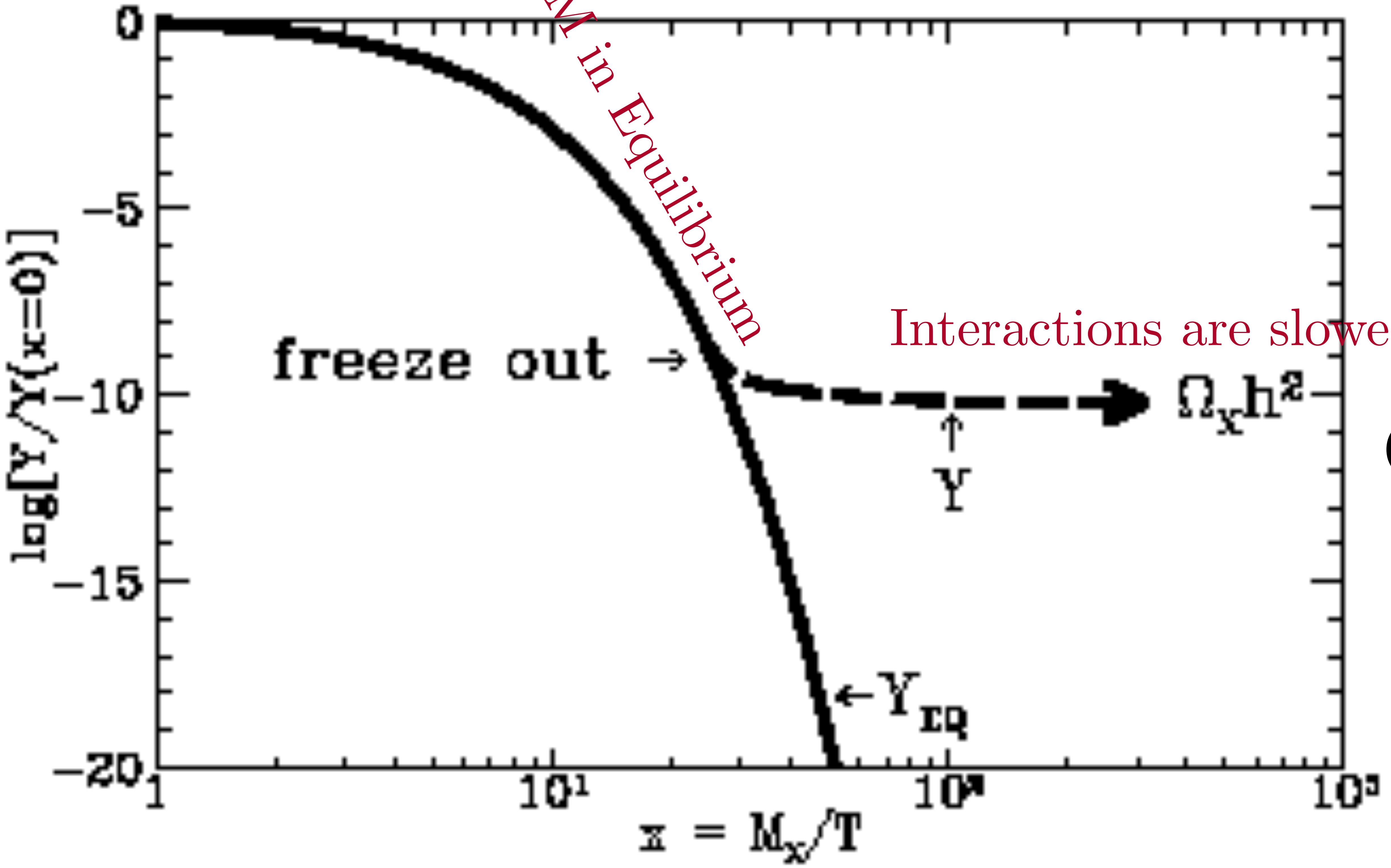
RELIC ABUNDANCE OF DM

Leptophilic Dark Matter

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l}$$

χ is DM

φ is portal



DM in Equilibrium

Interactions are slower than expansion

Observed relic abundance Ω_χ sets relations between parameters

CC & Krnjaic '24

RELIC ABUNDANCE OF DM

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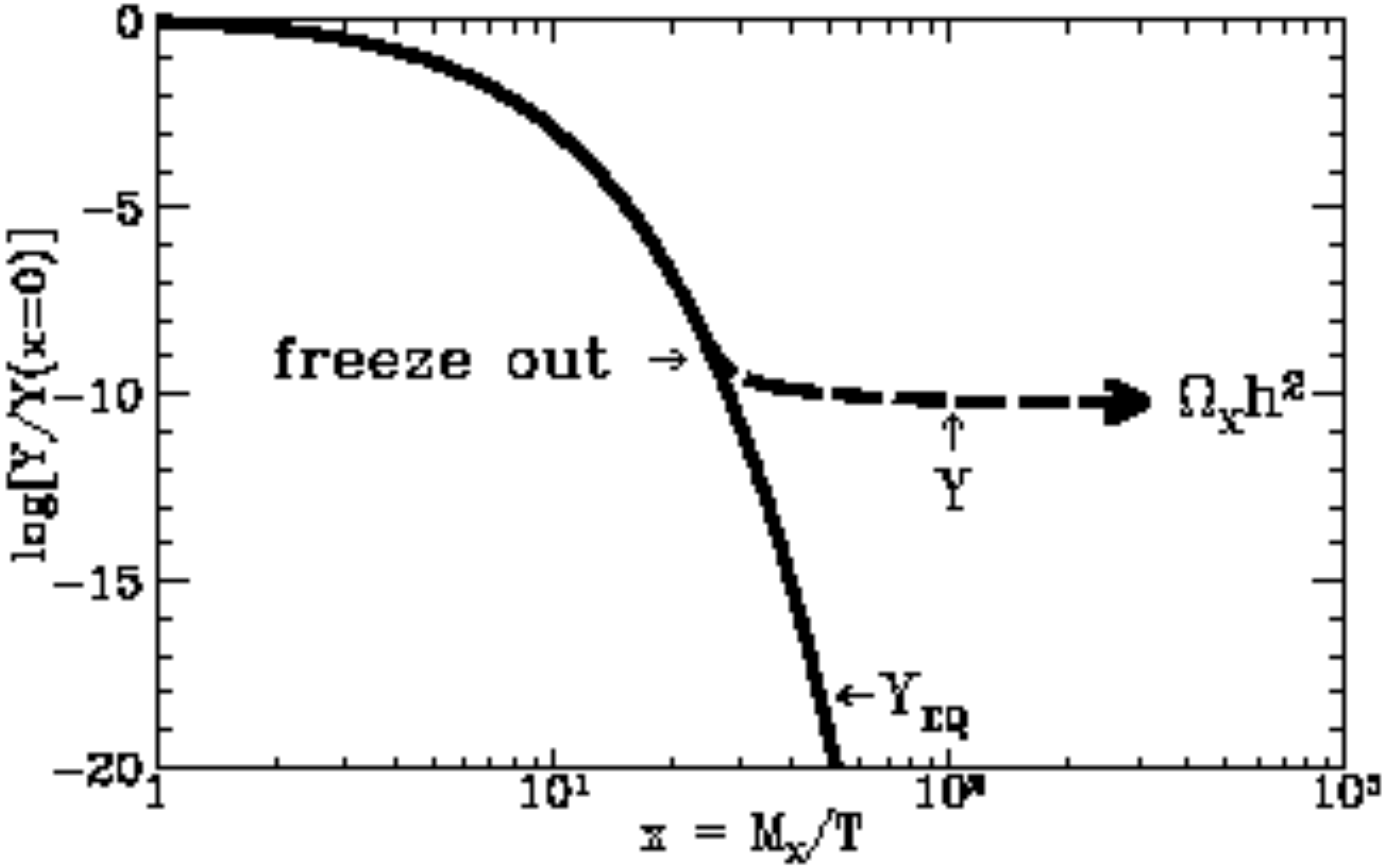

Solve Boltzmann Equation

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle[n_\chi^2 - (n_\chi^{\text{eq}})^2]$$

$$\sigma v_{\chi\chi\to\ell\ell} = \frac{g_\chi^2 g_\ell^2 m_\chi^2 v^2}{8\pi(m_\varphi^2 - 4m_\chi^2)^2} \propto g_\chi^2 g_\ell^2 \left(\frac{m_\chi}{m_\varphi}\right)^4 \frac{1}{m_\chi^2}$$

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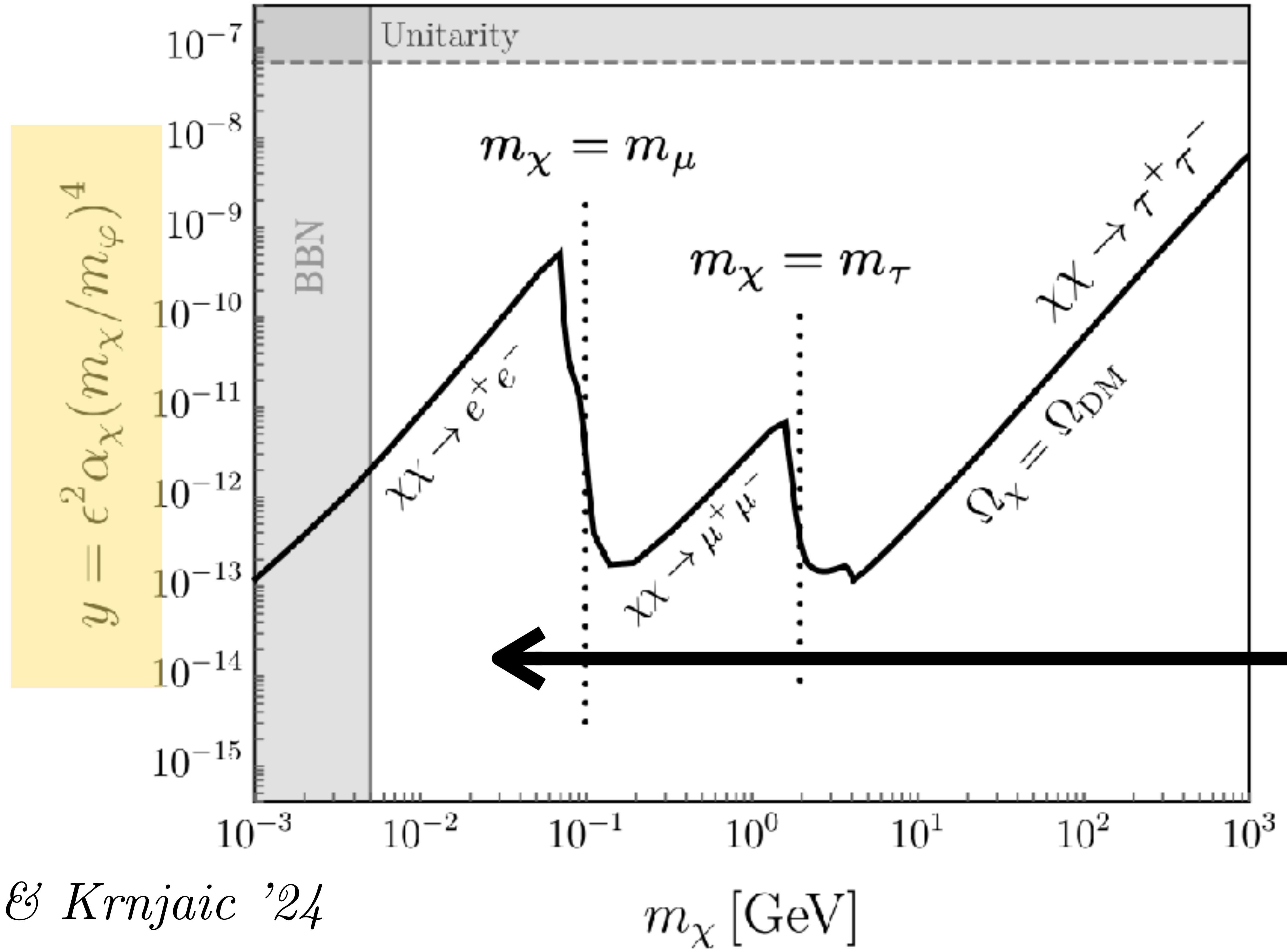
THERMAL TARGET

Leptophilic Dark Matter

Thermal Target



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$$\propto \frac{y}{m_\chi^2}$$

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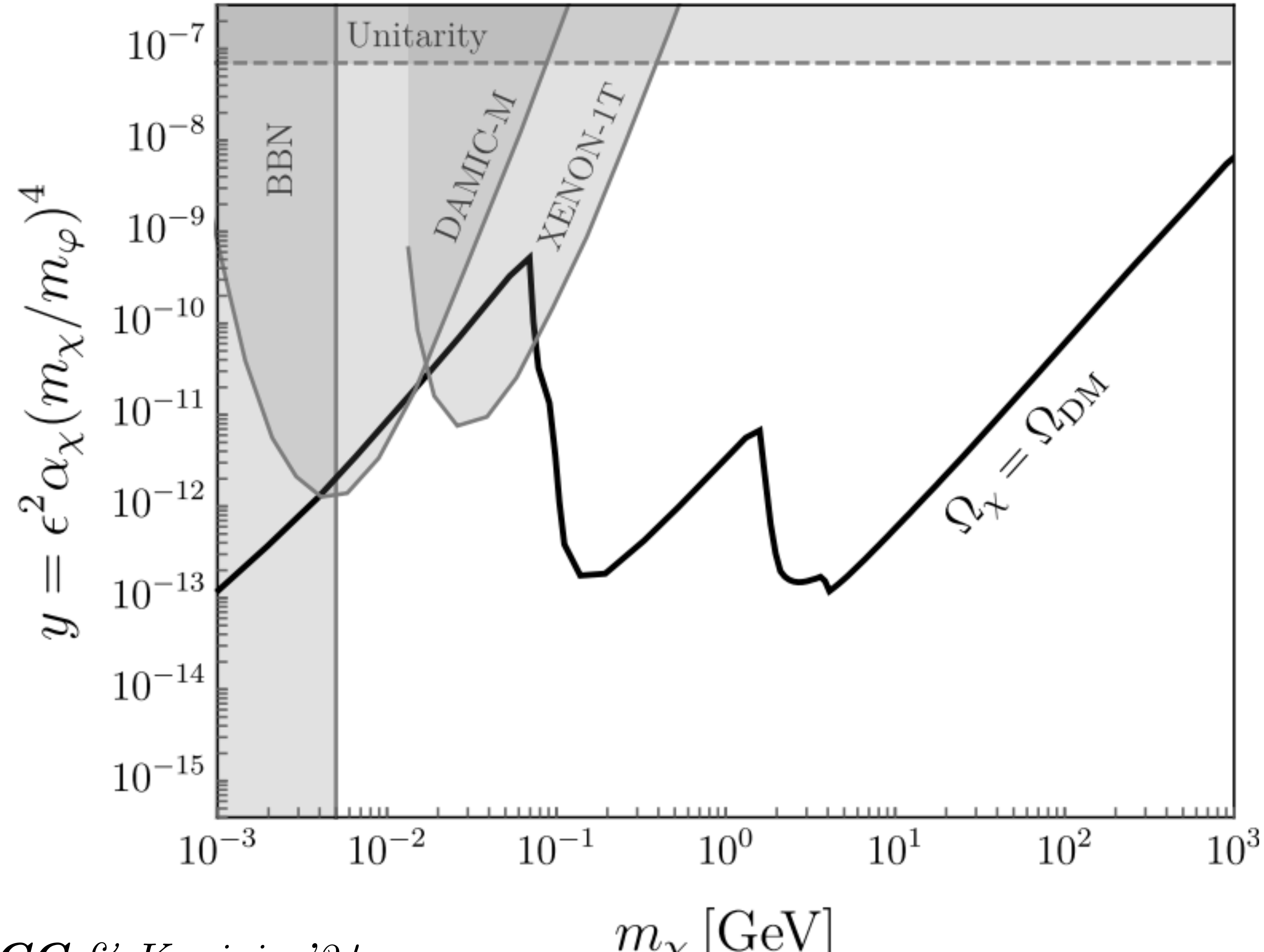
OTHER BOUNDS

Direct Detection



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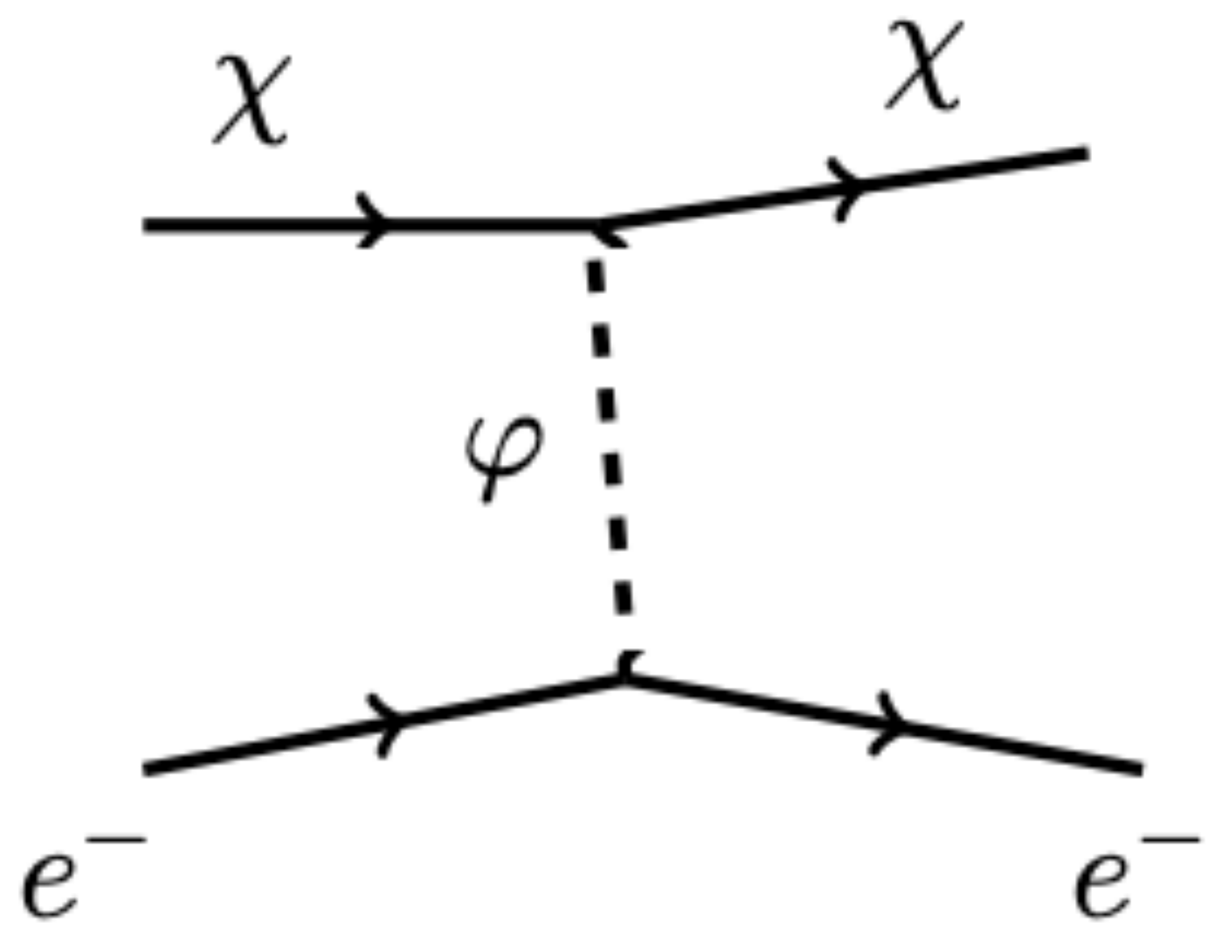
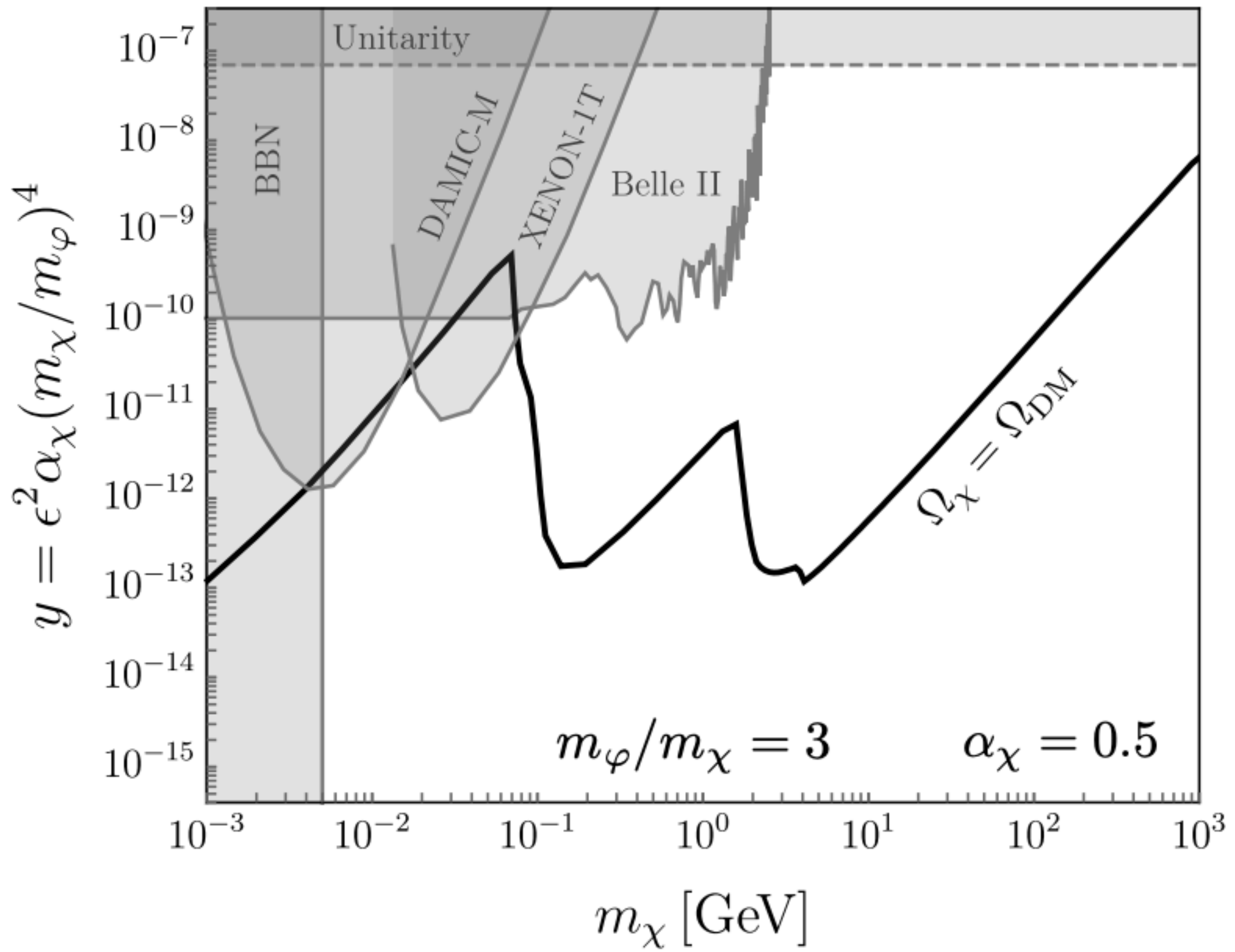


DAMIC-M 2302.02372
XENON-IT 2112.12116

OTHER BOUNDS

B Factories



$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l}$$

$$e^+e^- \to \mu^+\mu^-\varphi$$

(Dimuon + missing energy)

Belle II Collaboration 2212.03066

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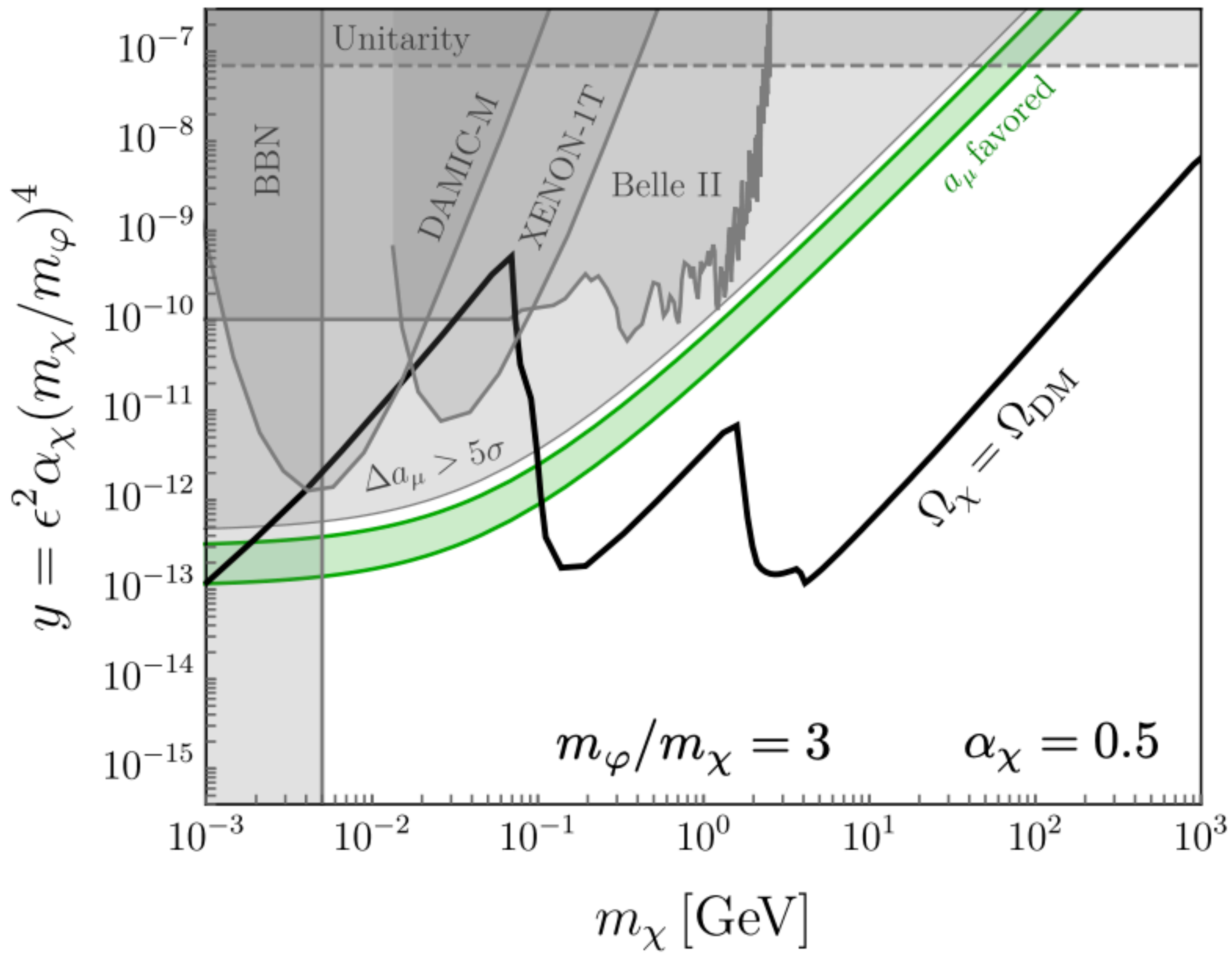
OTHER BOUNDS

Muon g-2



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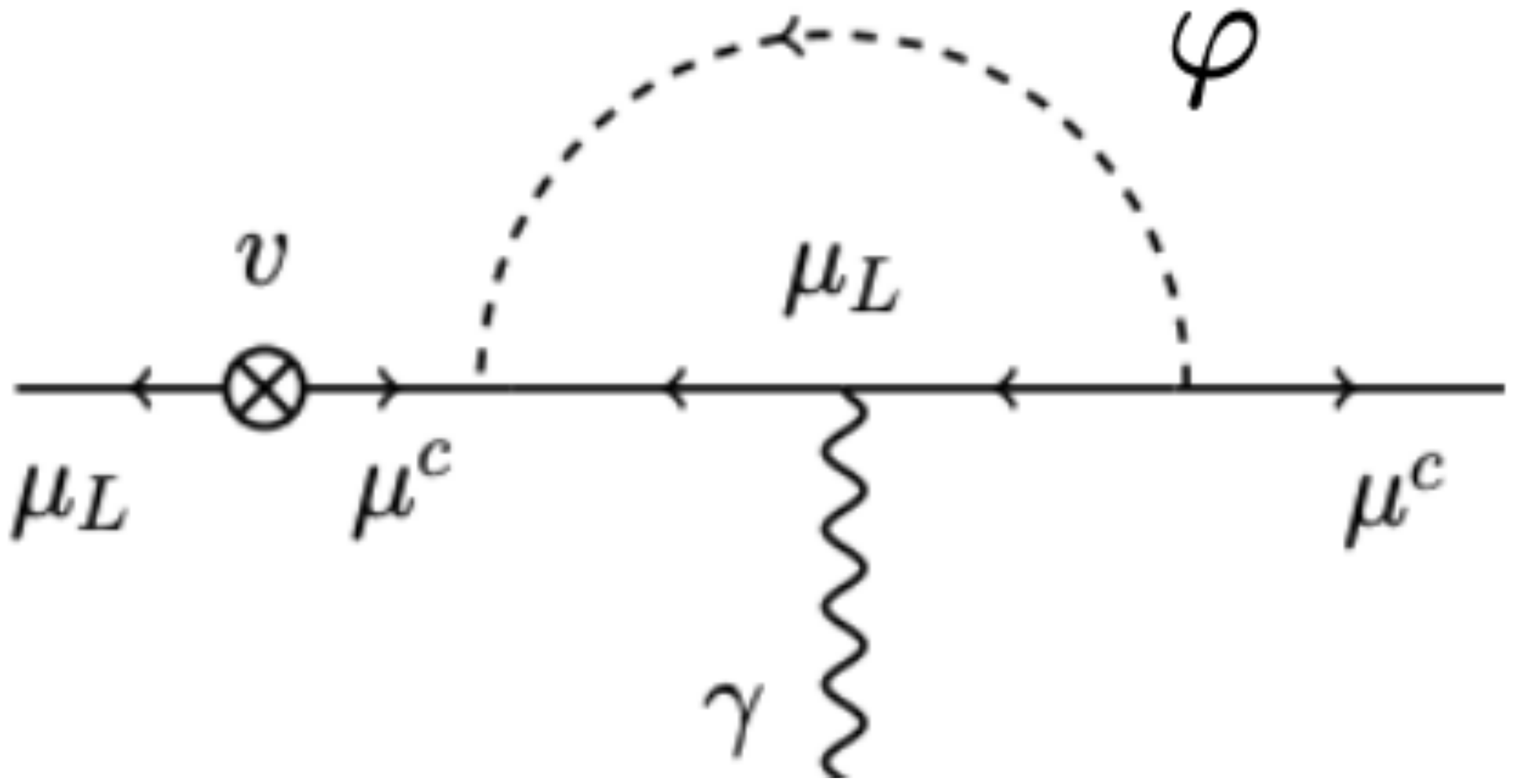


Muon *g-2* 2311.08282

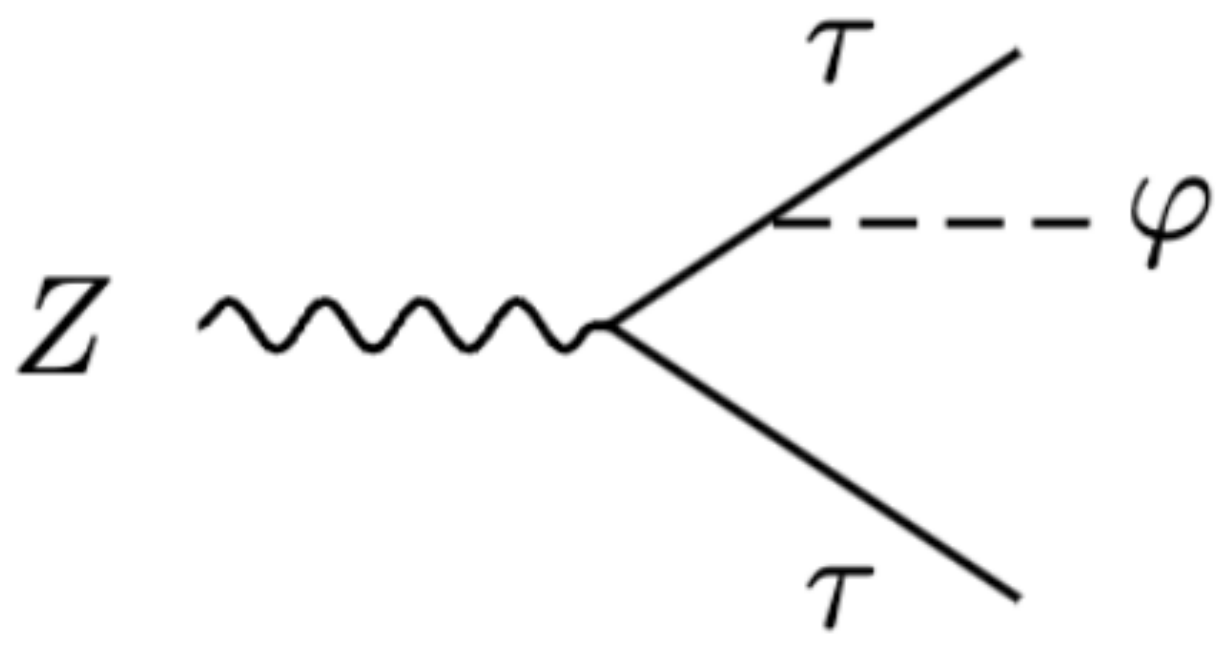
REACH AT FCC-EE

Tera-Z run at FCCee can also set significant bounds from rare Z decays

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi\sum_{l=e,\mu,\tau} g_l l\bar{l}$$

Strongest bound set by couplings to $Z \to \tau\tau$

Bound set by uncertainty in BR



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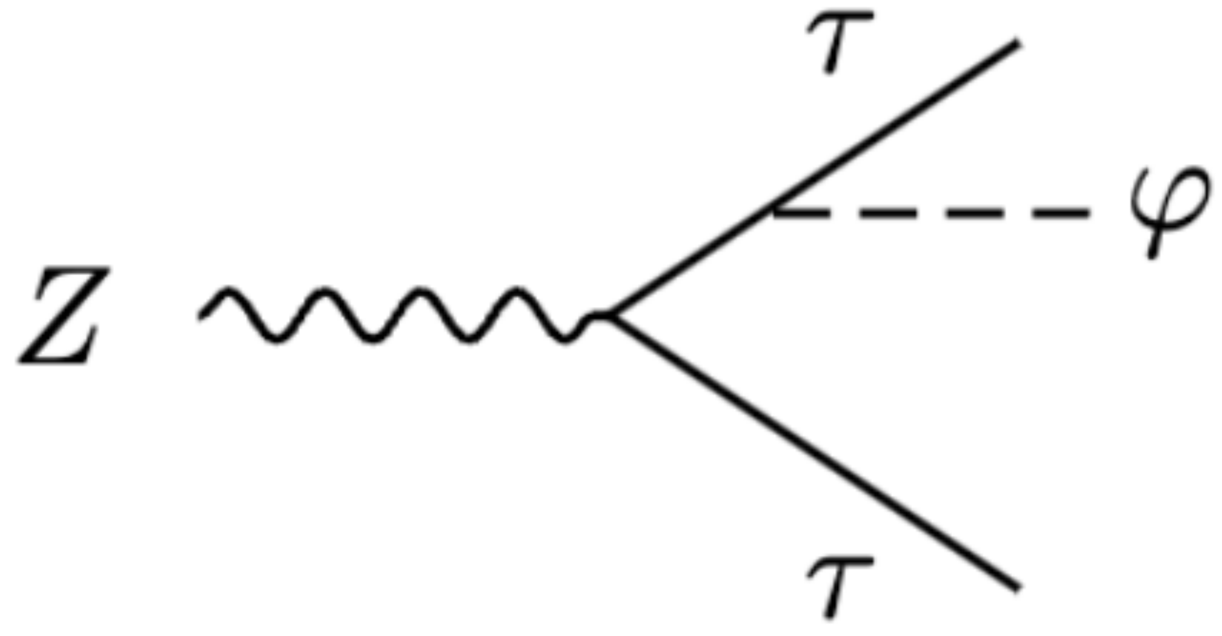

Previous LEP: $(1.7 \times 10^7\ Z\text{'s})$

$$\Gamma(Z \to \tau\tau) = 84.08 \pm 0.22\ \text{MeV}$$

FCCee Tera-Z: $(10^{12}\ Z\text{'s})$

Assume primary improvements come from statistics

$$\Delta\Gamma \times \sqrt{N_{LEP}/N_{FCC}}$$

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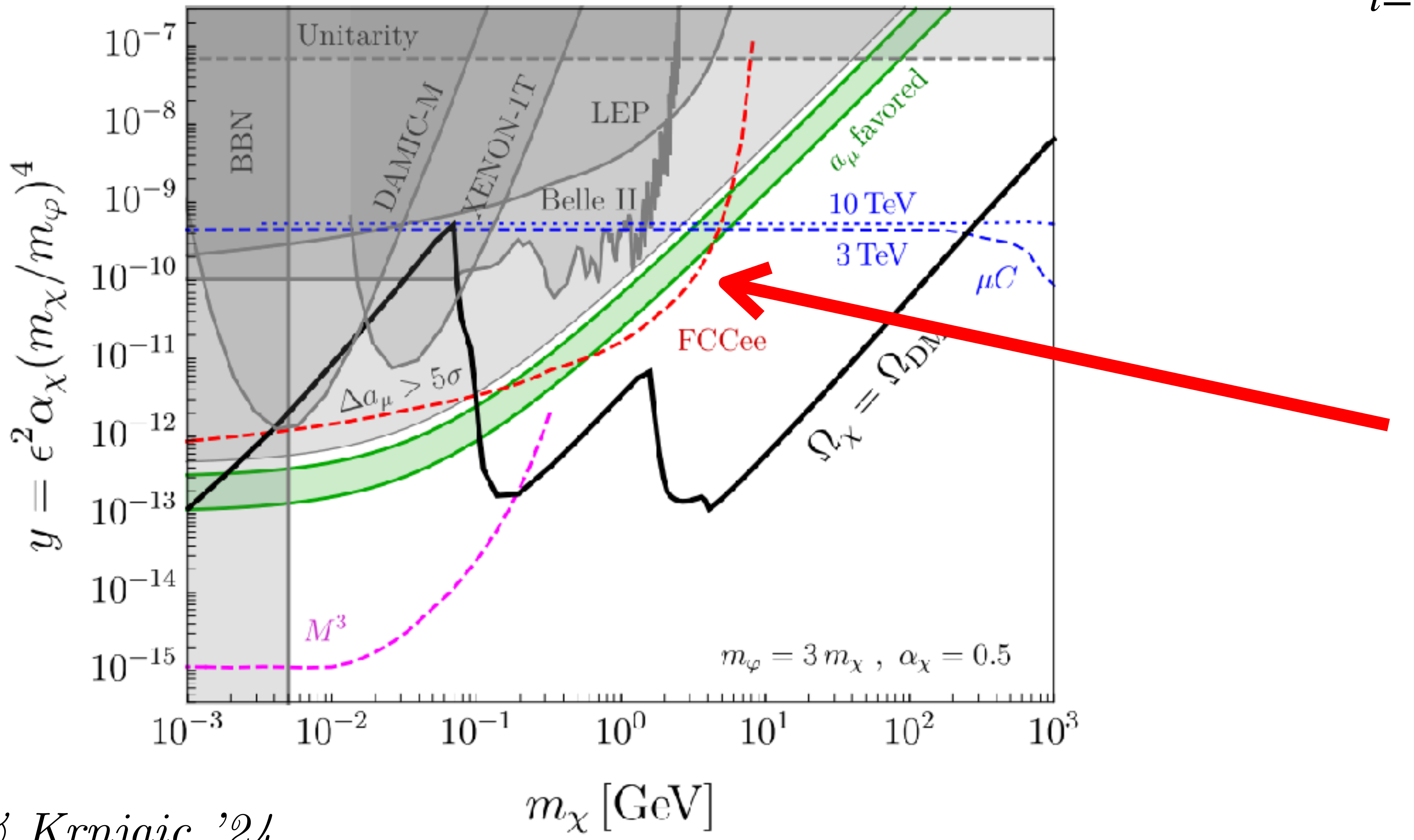
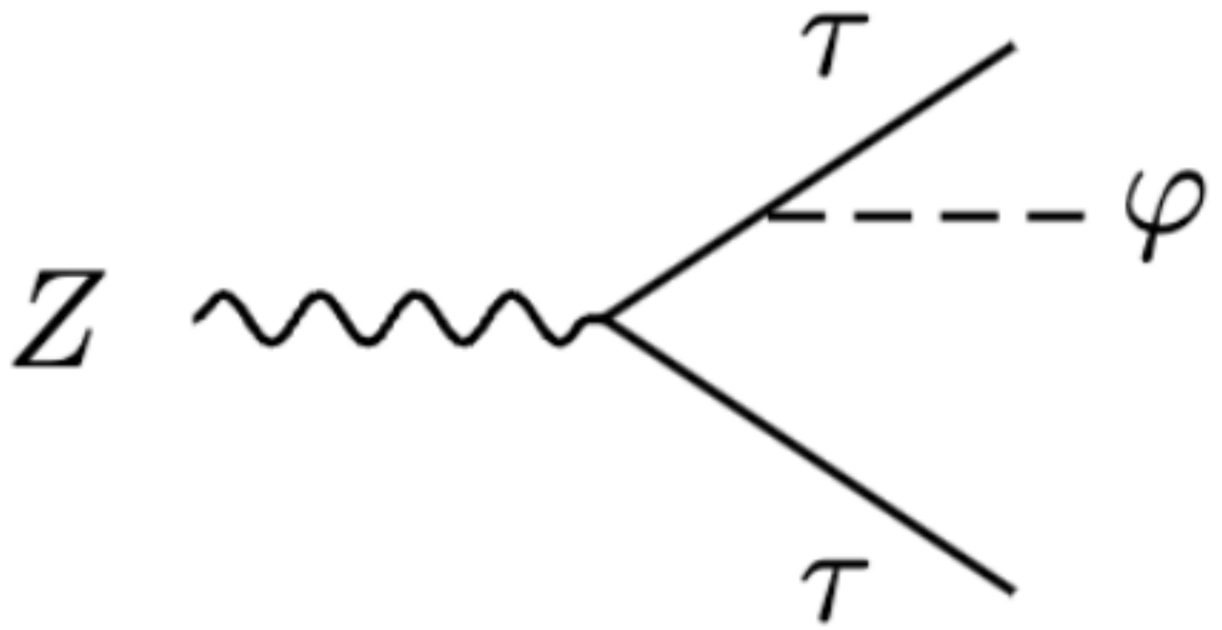


2σ in $\Delta\Gamma(Z \to \tau\tau)$



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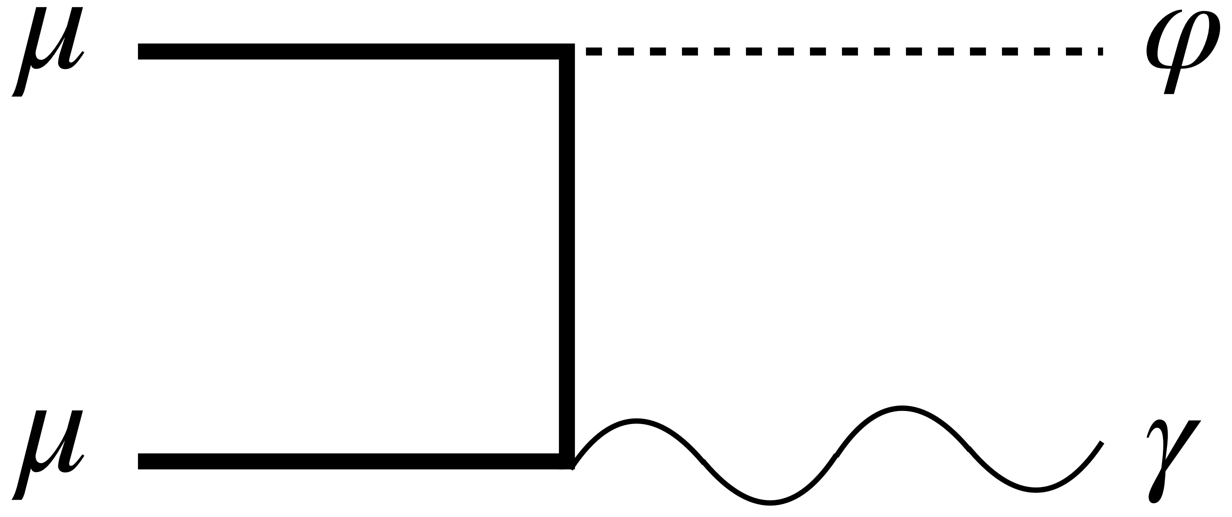
REACH AT MUC

For Muon Collider, our sensitivity is going to be to **heavy** states.

$$\mathscr{L}_{int} \supset -\frac{g_\chi}{2}\varphi\chi\chi - \varphi \sum_{l=e,\mu,\tau} g_l l\bar{l}$$

$$\mu^+\mu^- \to \varphi\gamma$$

$$E_\gamma \sim \sqrt{s}/2$$



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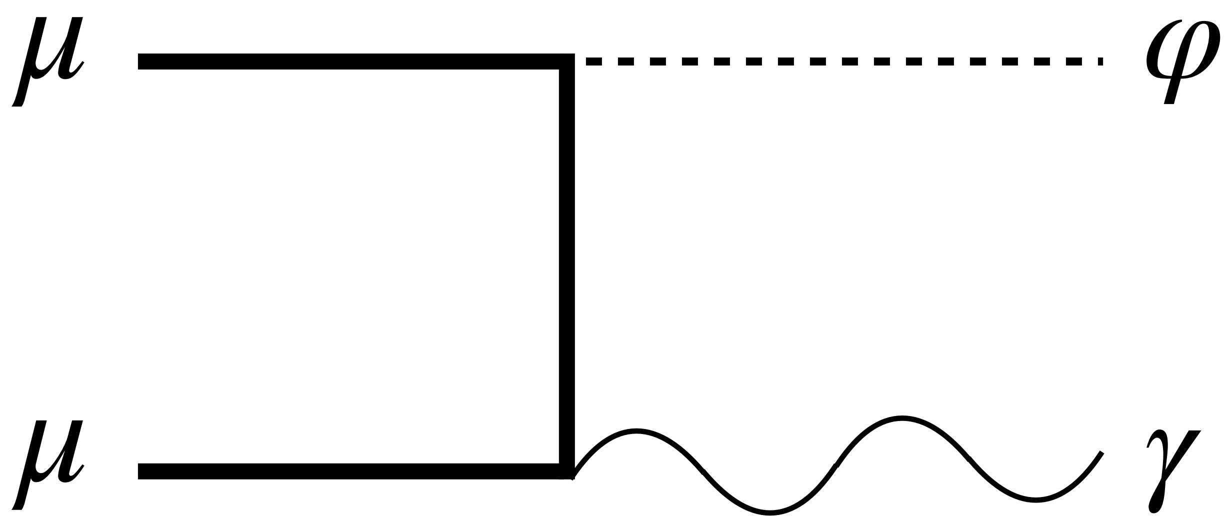
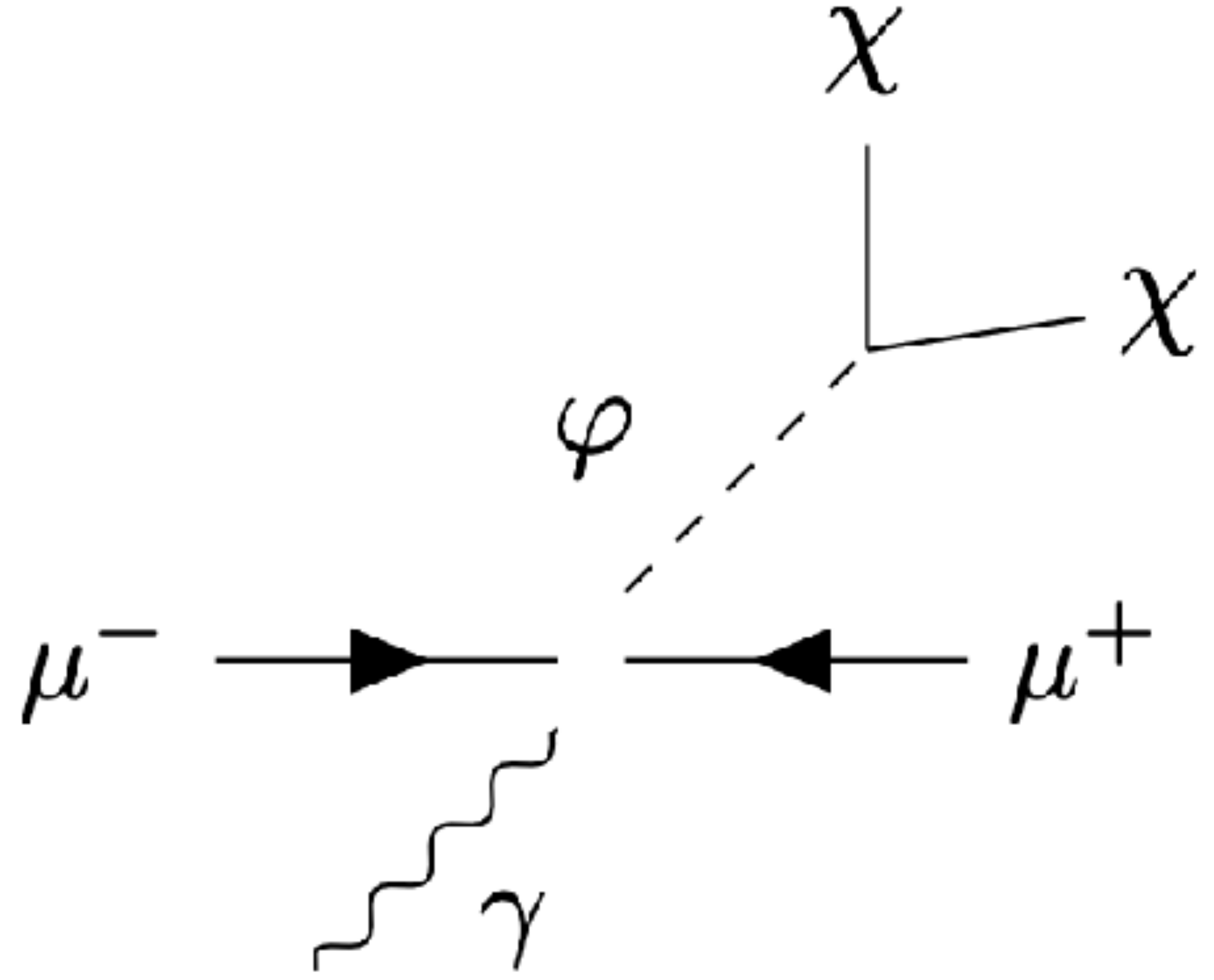


$\sqrt{s} = 3$ TeV

$\sigma_E = 3\%$

$\mathscr{L} = 1\text{ab}^{-1}$

$|\eta| < 2.5$



Primary Background:
$\mu^+\mu^- \to \nu\bar{\nu}\gamma$

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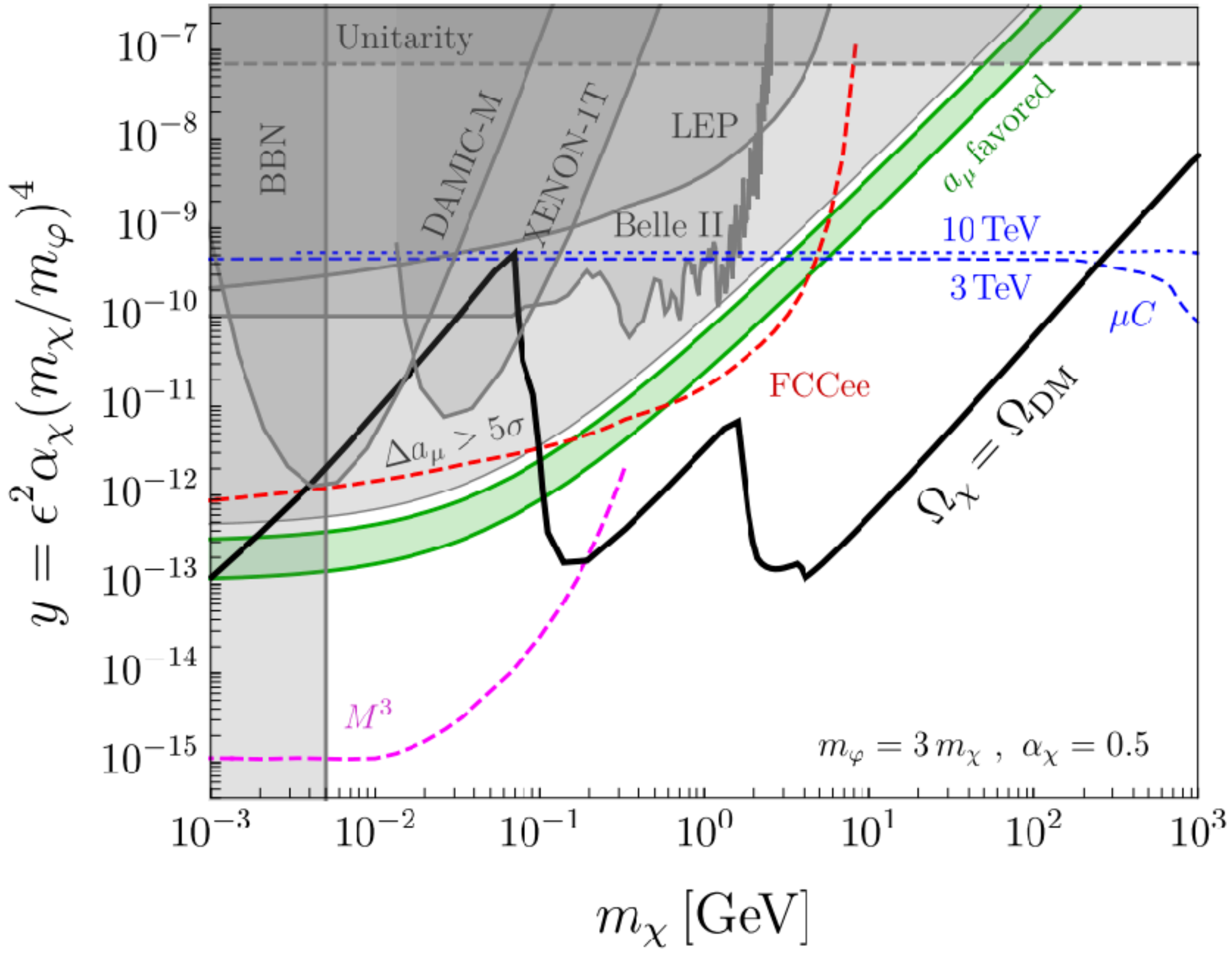

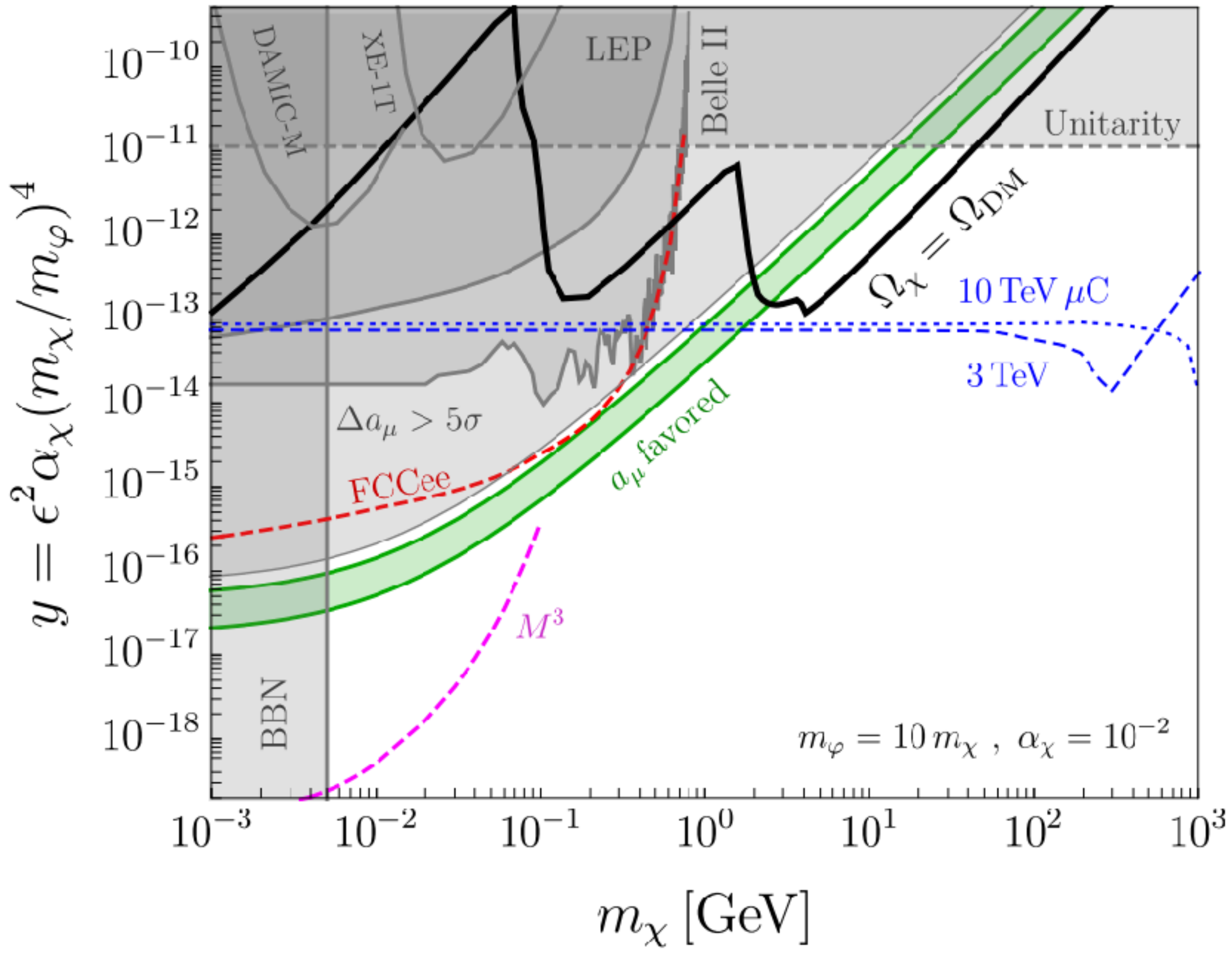

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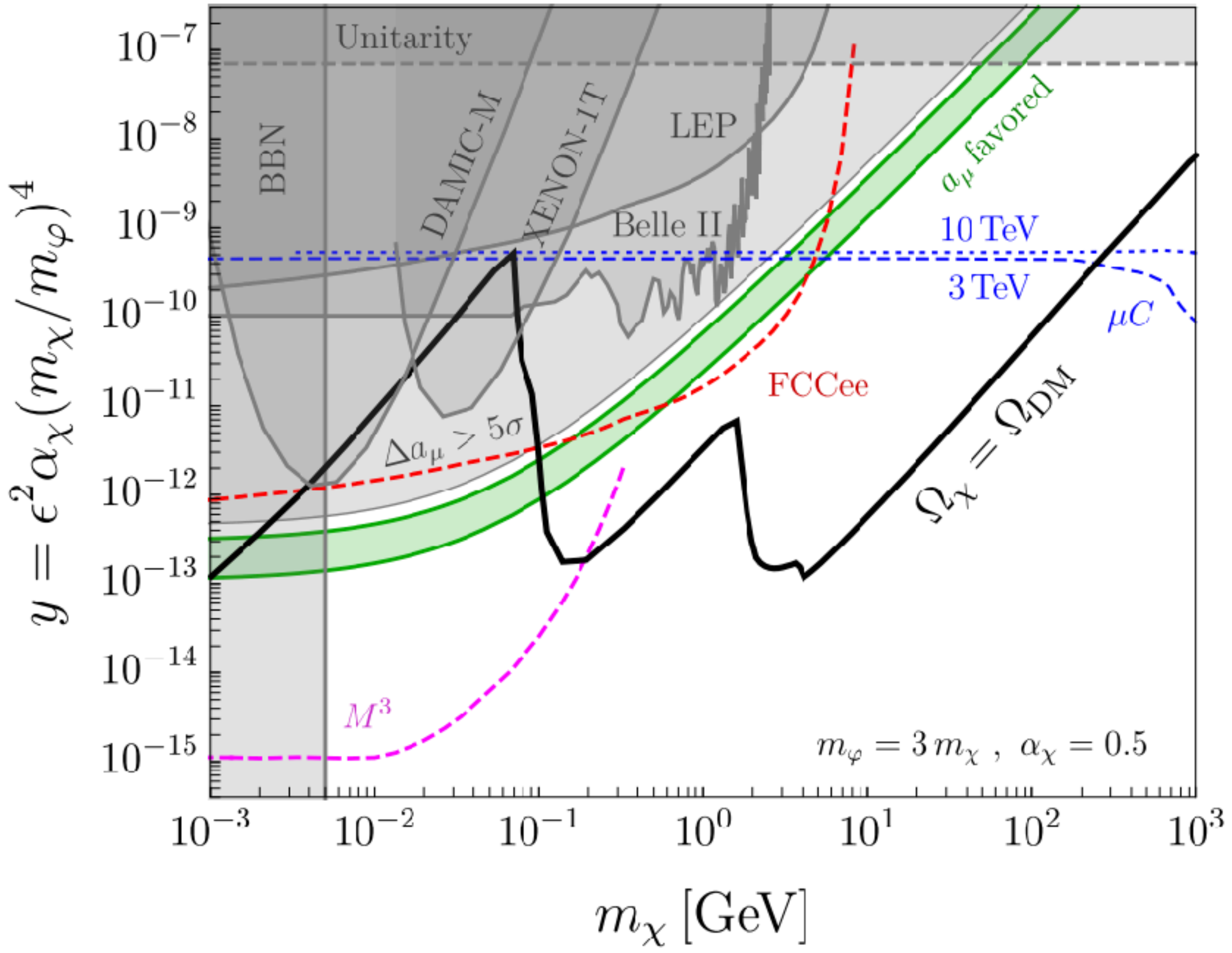
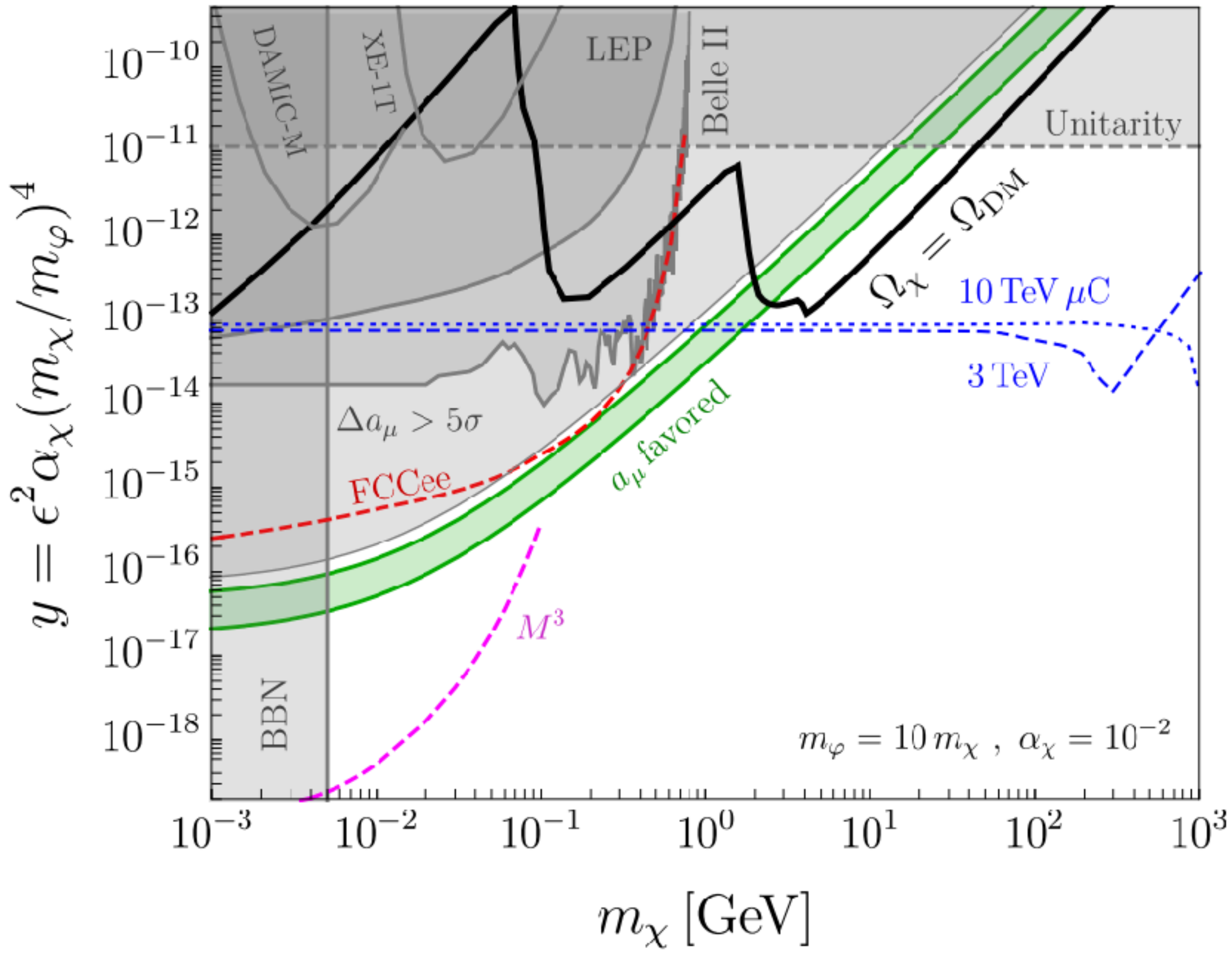
REACH AT FUTURE COLLIDERS

The physics reach of *precision* e^+e^- *machines* and *high-energy* colliders are *complementary*





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CONCLUSIONS

Precision vs. energy machines can probe *different* physics

Both are worth investing in

We will likely need both to have definitive answers regarding the big questions of particle physics