New μ Forces from ν/μ Sources

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IMCC 2024 - Physics Session

March 14, 2024

Illustrations by Stable Diffusion

MUON COLLIDERS

A quick reminder of what makes muon colliders so special:

High Energy

Second Generation Particles

Now is the time to think creatively about what new theories we can probe

Motivation

The commonality between these two works is *muon-specific* couplings, but illustrate a few ways in which we can search for new physics

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New μ forces from ν_μ sources

CC, Kahn, Krnjaic, Rocha, Spitz ’23

Physics from proton beam at MuC?

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New μ forces from ν_μ sources

CC, Kahn, Krnjaic, Rocha, Spitz ’23

Physics from proton beam at MuC?

Leptophilic Dark Matter at Future Lepton Colliders

CC, Krnjaic (WIP)

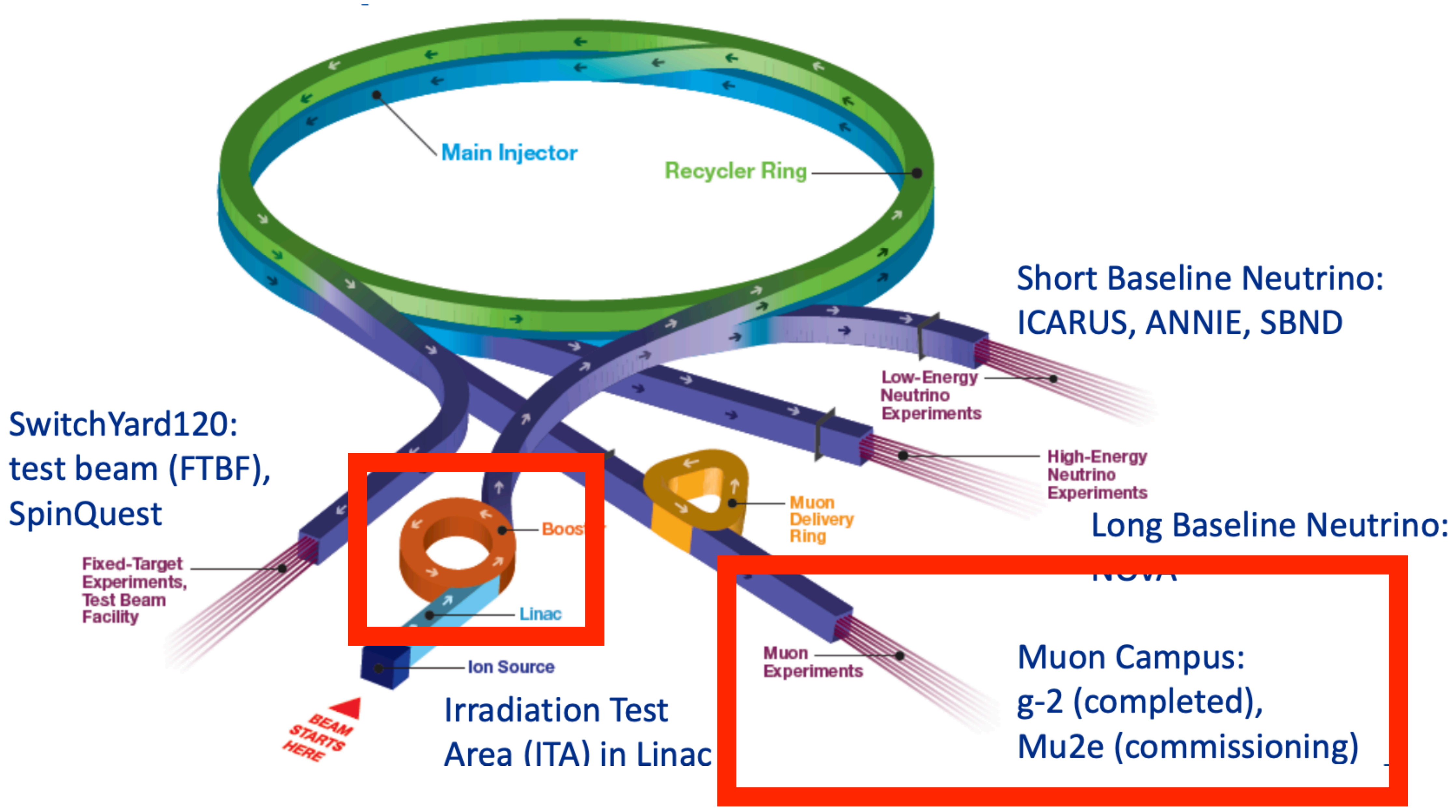
Physics from collisions of leptons

Part I: New μ forces from ν_μ sources

A muon collider necessitates a proton source.

Is there any new physics we can probe with minimal instrumentation?

This work can be considered **proof-of-concept** for possible future demonstrators, staging options, or full MuC collider



(Or as stand-alone result that's interesting because of muons)

CC, Kahn, Krnjaic, Rocha, Spitz '23

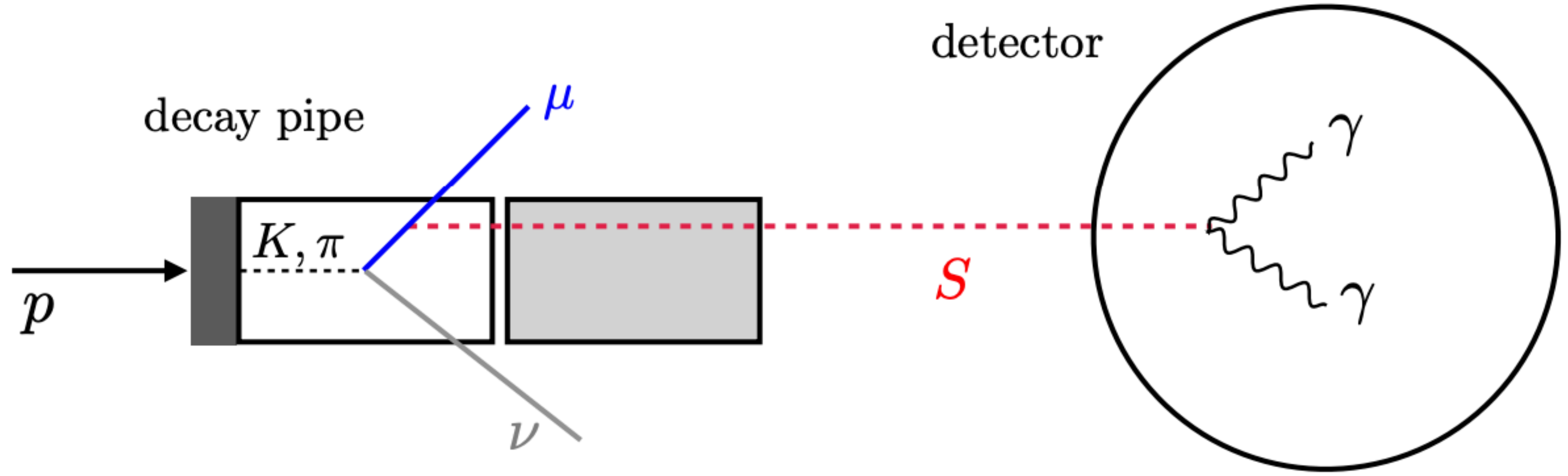
EXISTING ν_μ SOURCES

Whenever we have ν sources (from proton-on-target), there are **muons**

We consider Mini/MicroBooNE, but one could also consider ESSνSB, DUNE, etc.

Detector already exists

Beam already exists



Just Recast!

Data was already taken

CC, Kahn, Krnjaic, Rocha, Spitz '23

Muon-philic Forces

E

$$\mathscr{L}_{eff} \supset \frac{y}{v} S H^{\dagger} L \mu_R^c + hc$$

$$\mathscr{L}_{int} \supset y S \mu \bar{\mu}$$

CC, Kahn, Krnjaic, Rocha, Spitz ’23

Muon-philic Forces

$$\mathscr{L}_{UV} \supset y_\psi H^\dagger L_2 \psi^c + \kappa\psi\mu^c + (M_\psi + y'S)\psi\bar{\psi} + hc$$

New vector-like fermion

$$+\psi \sim (1,1)_1$$

E

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CC, Kahn, Krnjaic, Rocha, Spitz '23

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$$\mathscr{L}_{UV} \supset y_\psi H^\dagger L_2 \psi^c + \kappa\psi\mu^c + (M_\psi + y'S)\psi\bar{\psi} + hc$$

$E \ll M_\psi$

New vector-like fermion

$+\psi \sim (1,1)_1$

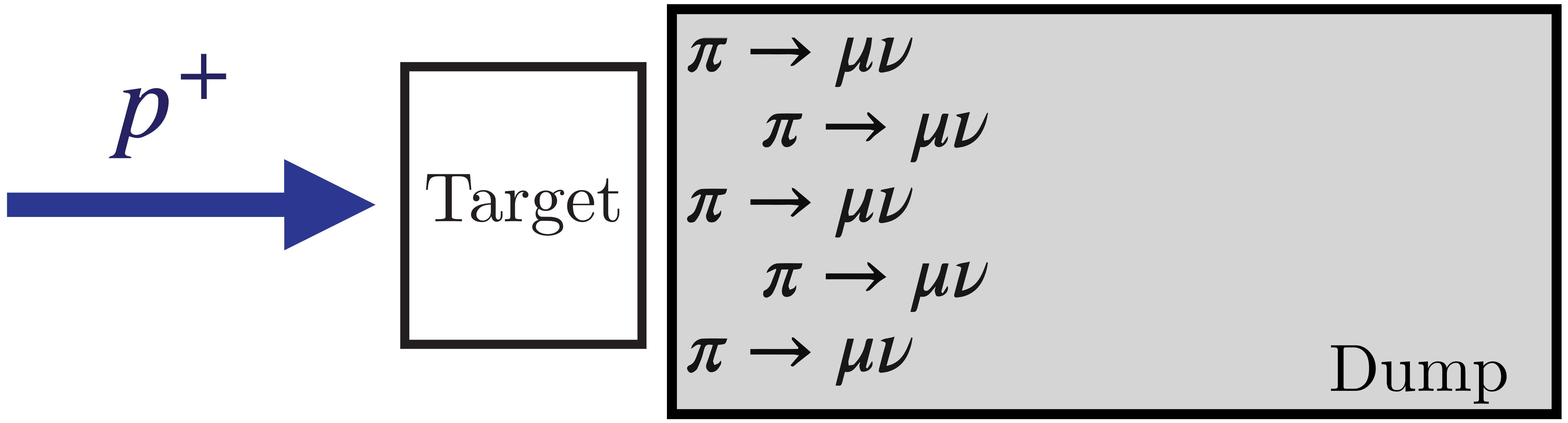
$$\mathscr{L}_{eff} \supset \frac{y' y_\psi \kappa}{M_\psi^2} S H^\dagger L \mu_R^c + hc$$

(SSB)

$$\mathscr{L}_{int} \supset yS\mu\bar{\mu}$$

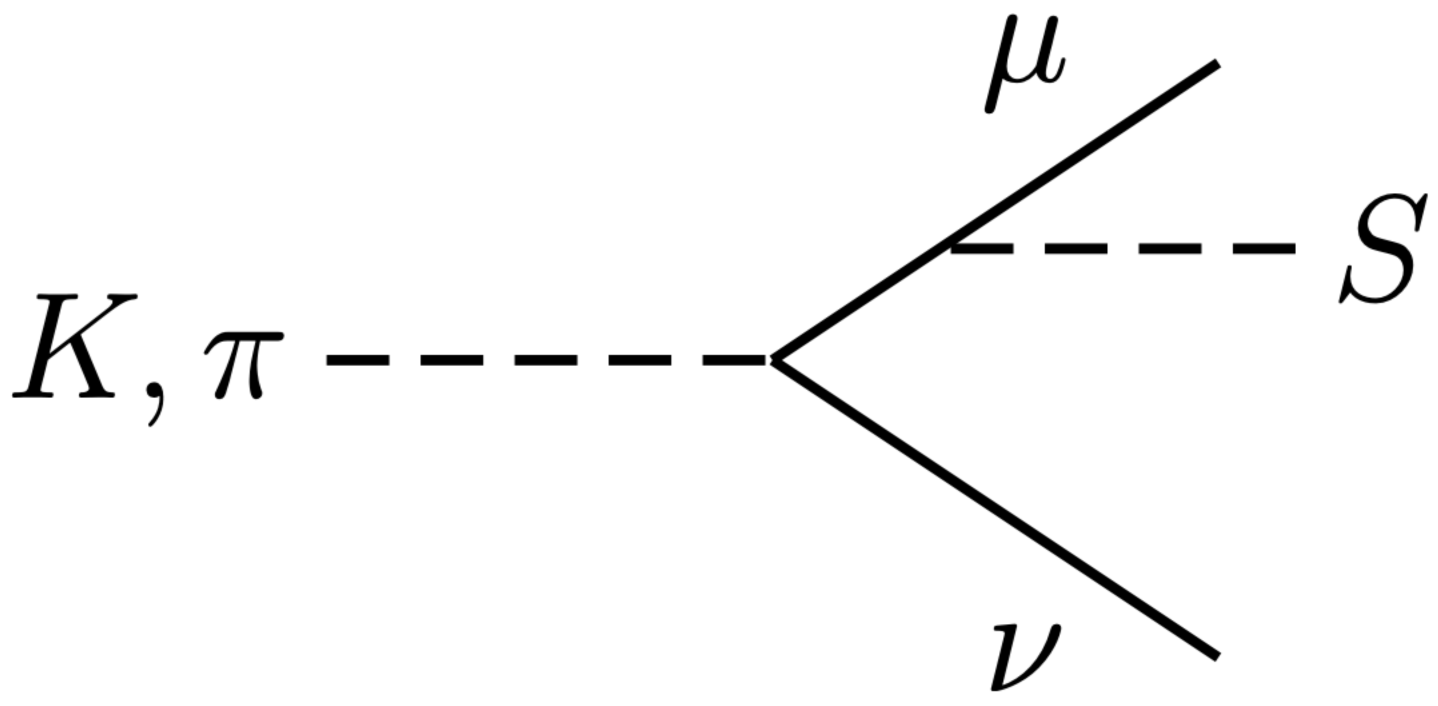
CC, Kahn, Krnjaic, Rocha, Spitz '23

Signatures with Proton Beam-on-target

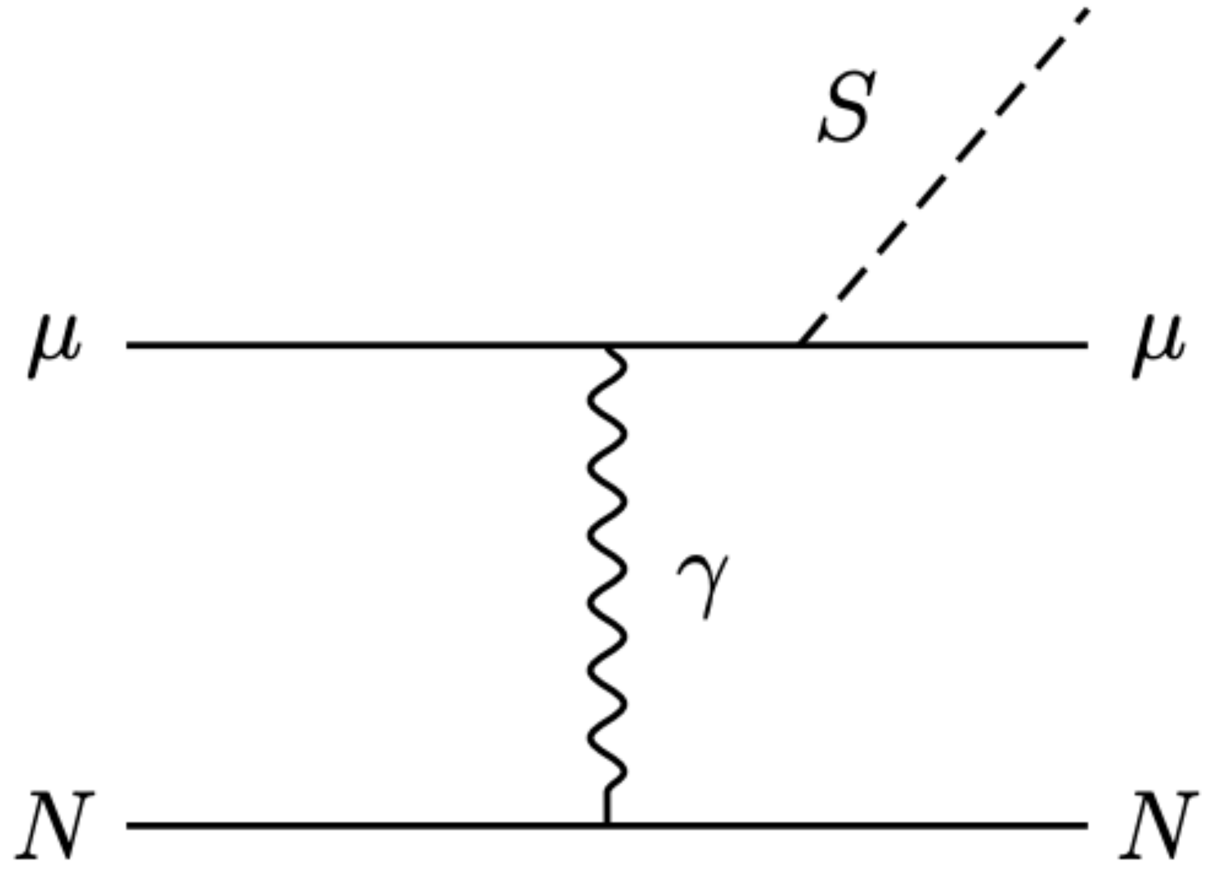


$$\mathscr{L}_{int} \supset yS\mu\bar{\mu}$$

Rare decays of mesons



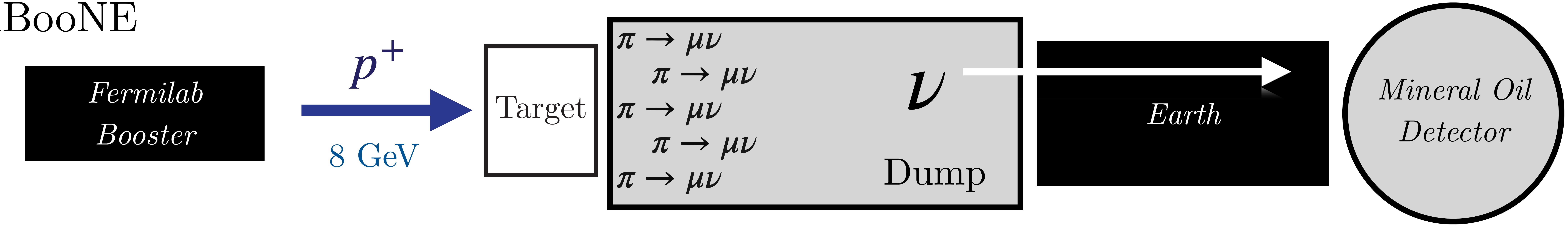
Scattering of muons in material



CC, Kahn, Krnjaic, Rocha, Spitz '23

Mini/MicroBooNE

MiniBooNE



500 m

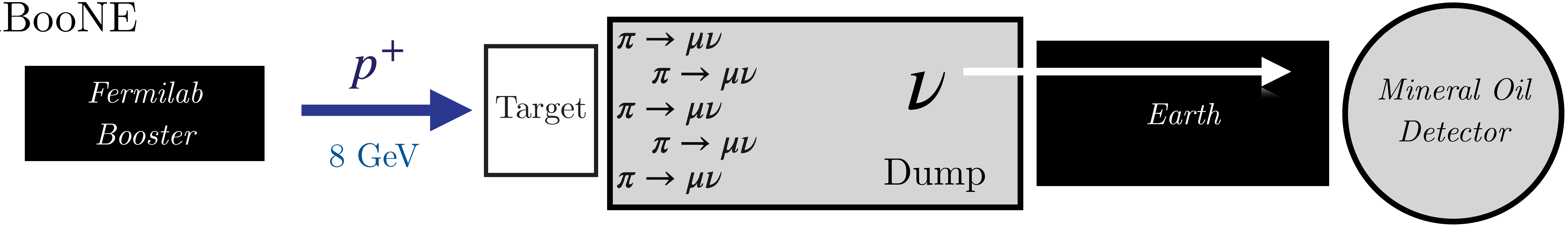
(Upgrade to Micro)

$\sim$ *SBND*

CC, Kahn, Krnjaic, Rocha, Spitz '23

MINI/MICROBOONE

MiniBooNE

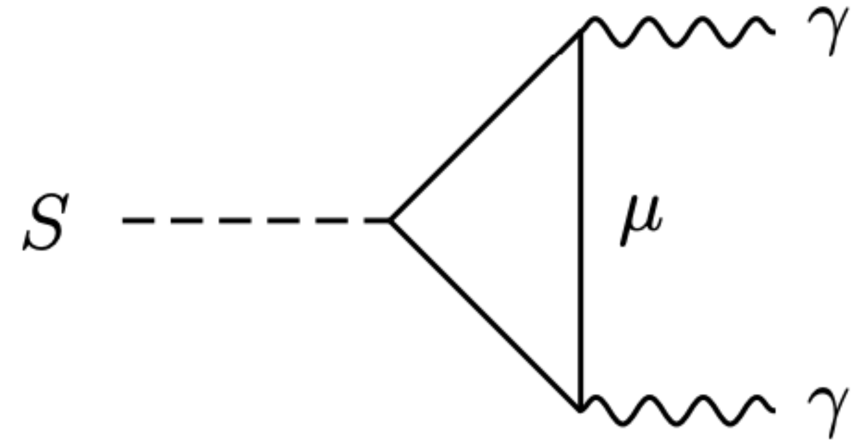


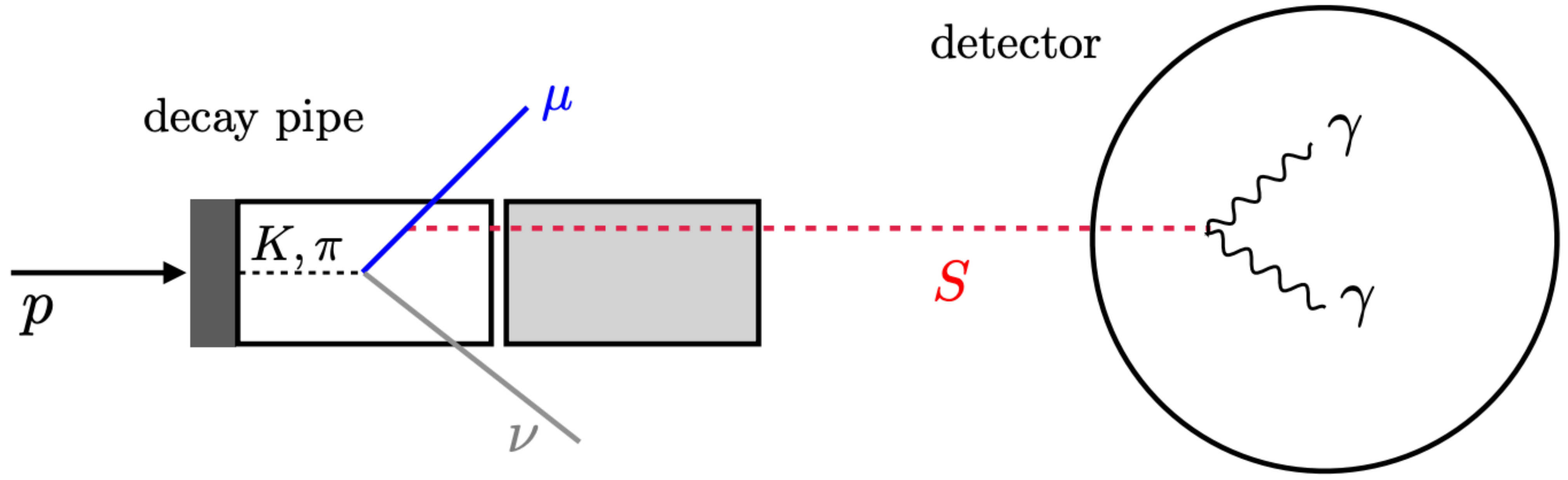
500 m

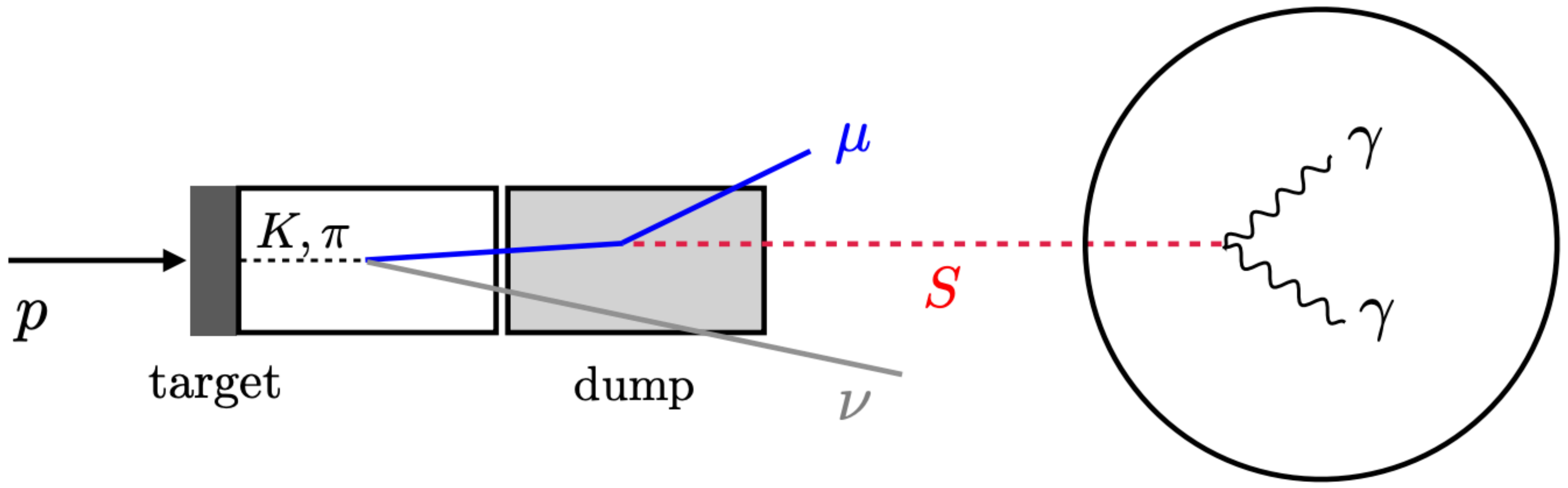
(Upgrade to Micro)

~ SBND

RECAST



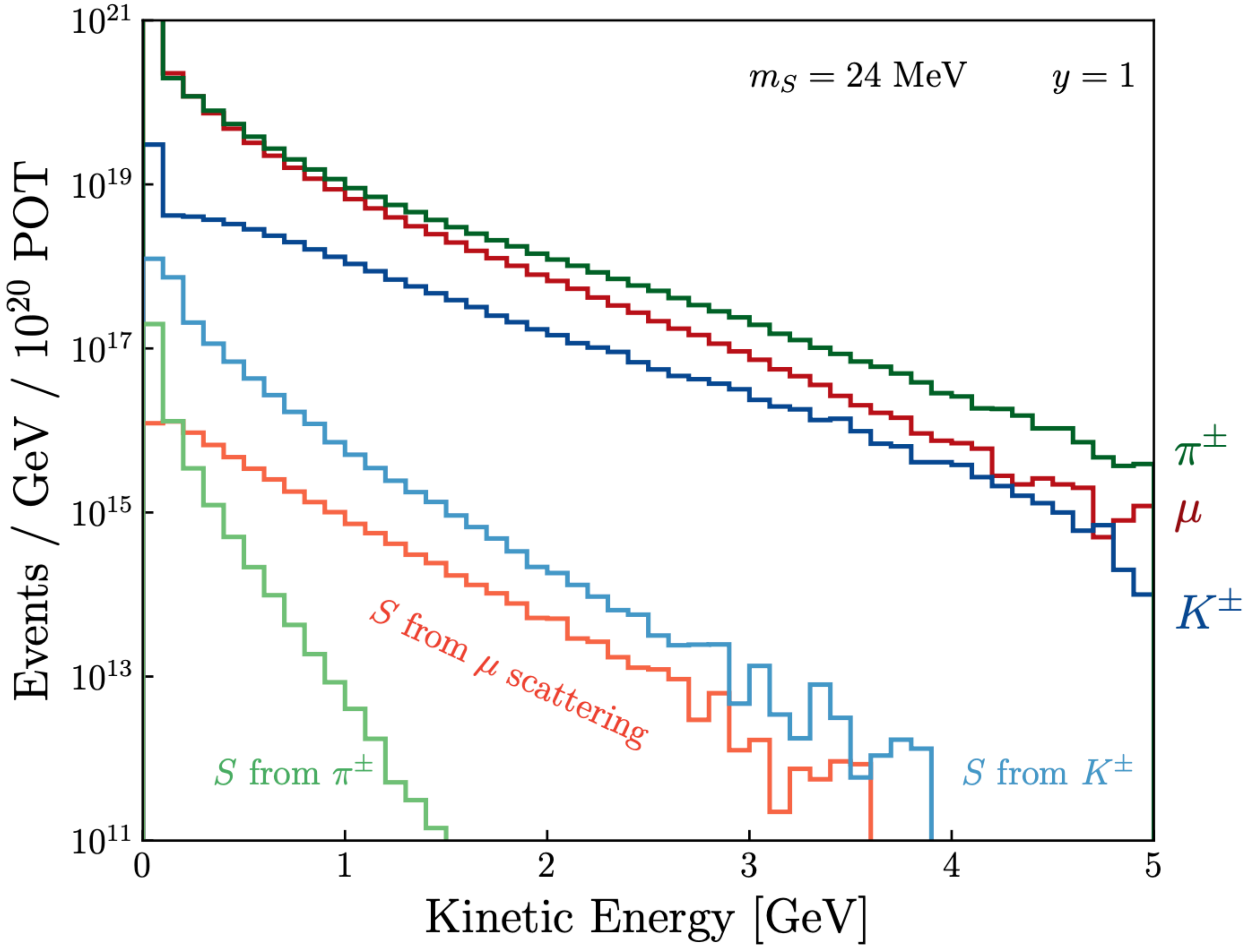




Chen, Pospelov, Zhong '17

CC, Kahn, Krnjaic, Rocha, Spitz '23

S production and Background



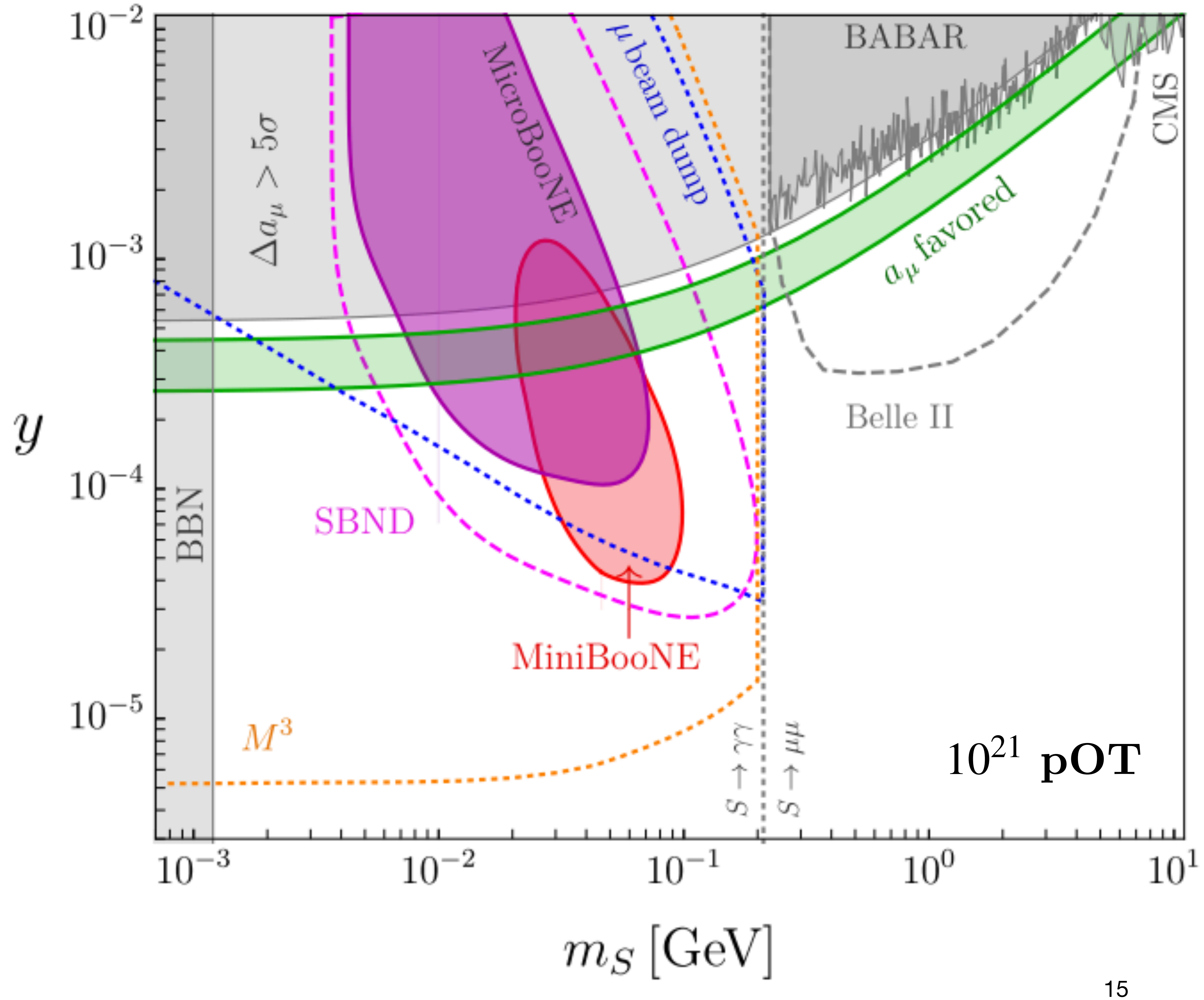
Immediate recast is possible because the BooNEs measured neutrino induced NC π^0 production, with $m_{\gamma\gamma}$ reported

$$\nu_\mu N \to \nu_\mu N \pi^0 (\pi^0 \to \gamma\gamma)$$

We have our data set and our background!

CC, Kahn, Krnjaic, Rocha, Spitz '23

RESULTS



MiniBooNE / MicroBooNE results

SBND (set to run this year?) sensitivity

See if this kind of experiment is compatible with MuC proton beam or ν facility

CC, Kahn, Krnjaic, Rocha, Spitz '23

Part II: New μ forces from μ sources

Let's shift our attention from muon-philic forces to MFV forces

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

CC, Krnjaic '24 (to come)

Part II: New μ forces from μ sources

E

Type III 2HDM

$H_1 \sim (1,2)_{1/2}$
$H_2 \sim (1,2)_{-1/2}$

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

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

$+S \sim (1,1)_0$

Each get vev v_1, v_2

Diagonalize into SM Higgs h and heavy Higgs H

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

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

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

CC, Krnjaic '24 (to come)

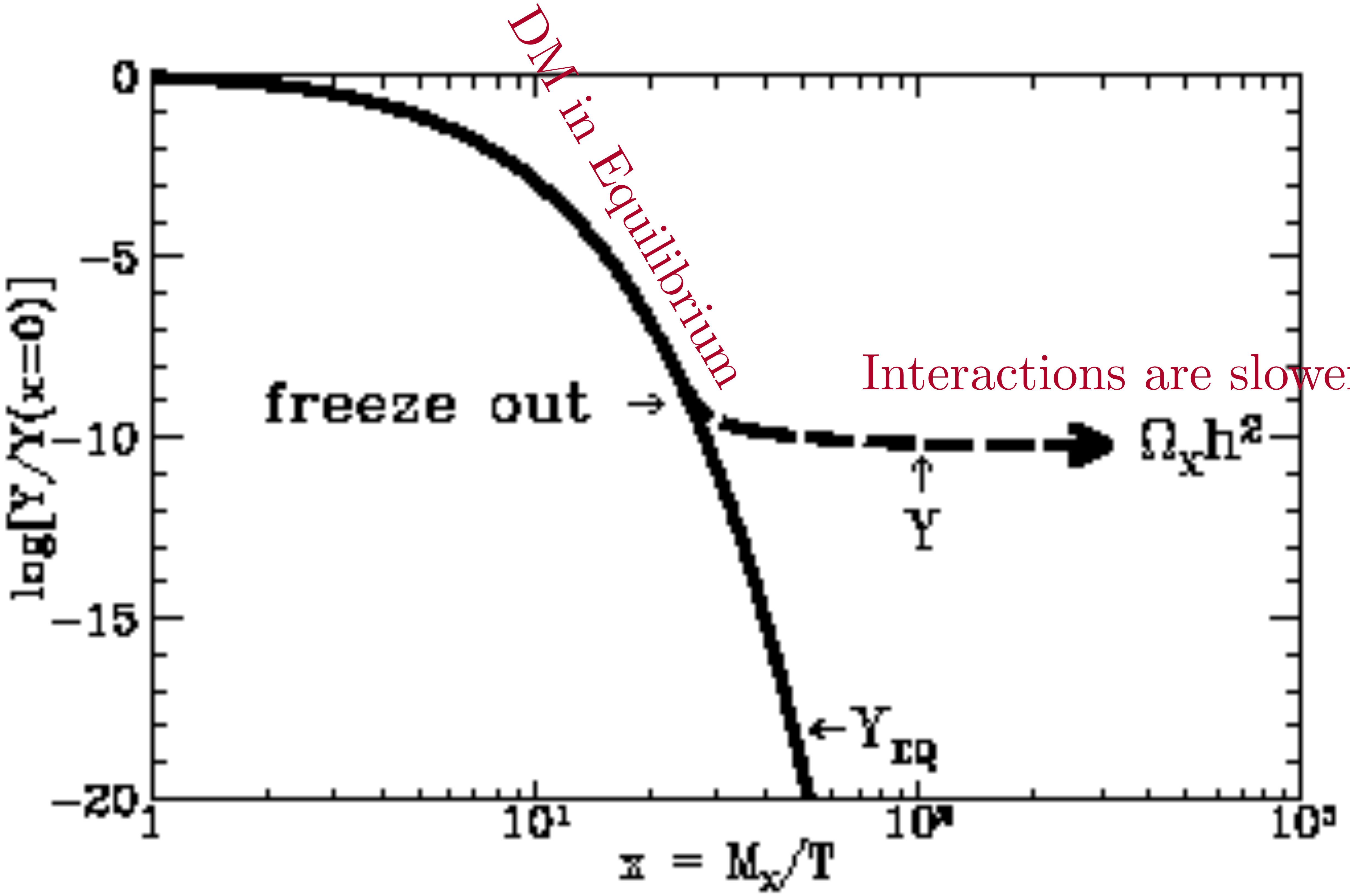
Relic Abundance of Leptophilic DM

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



Observed relic abundance Ω_χ sets relations between parameters

CC, Krnjaic '24 (to come)

Relic Abundance of Leptophilic DM

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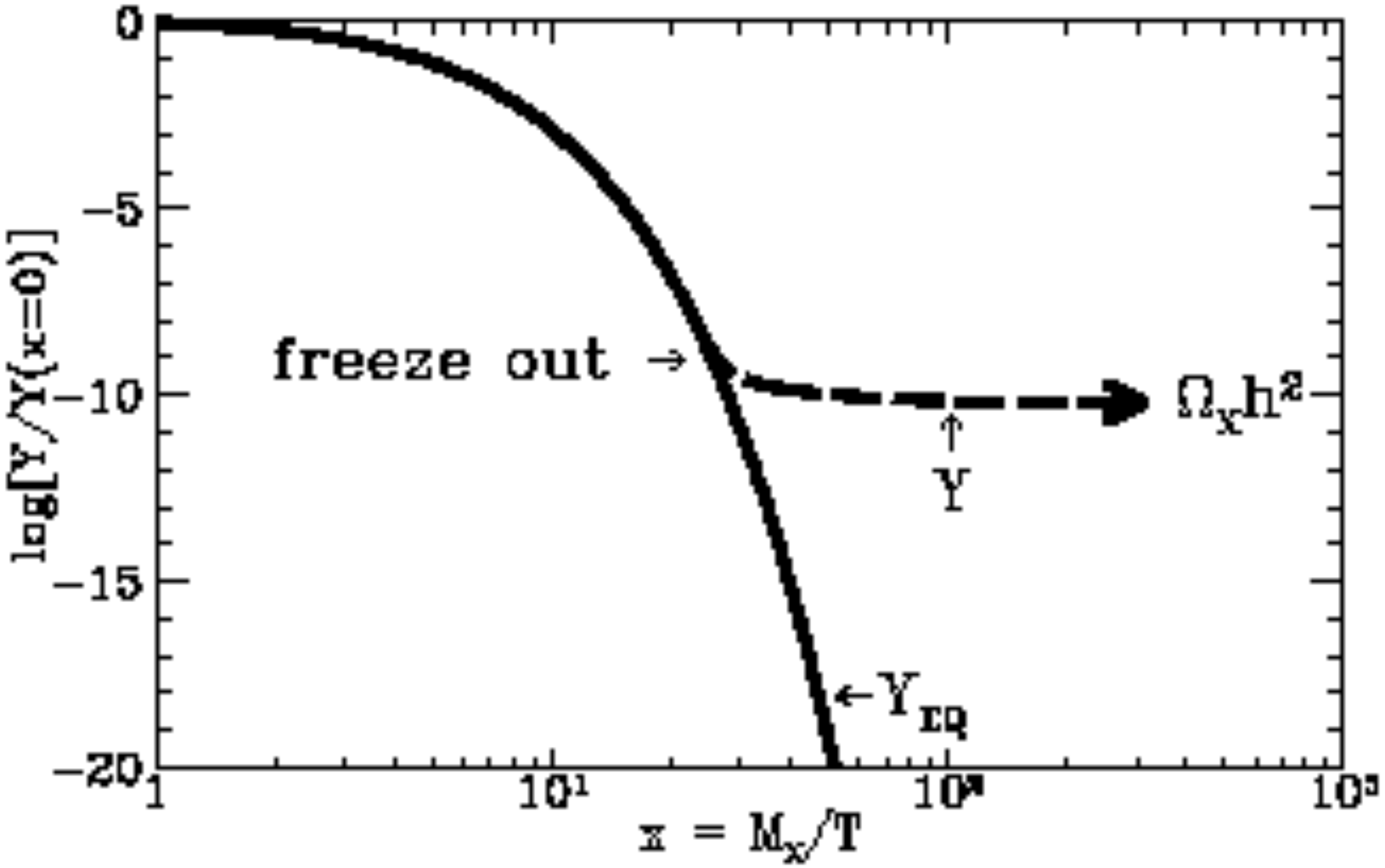


Solve Boltzmann Equation

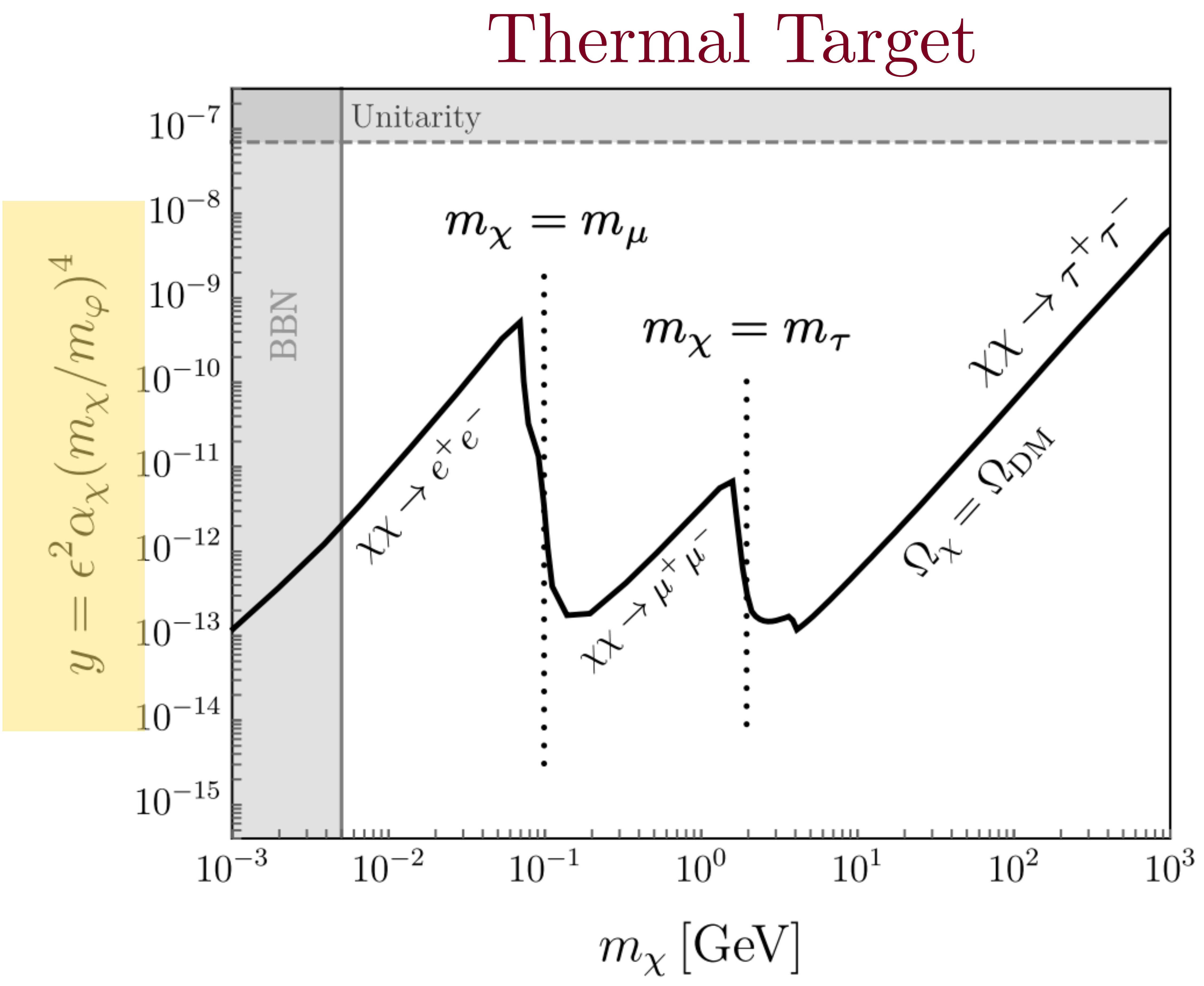
$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle[n_\chi^2 - (n_\chi^{\text{eq}})^2]$$

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

CC, Krnjaic '24 (to come)

Thermal Target

Leptophilic Dark Matter



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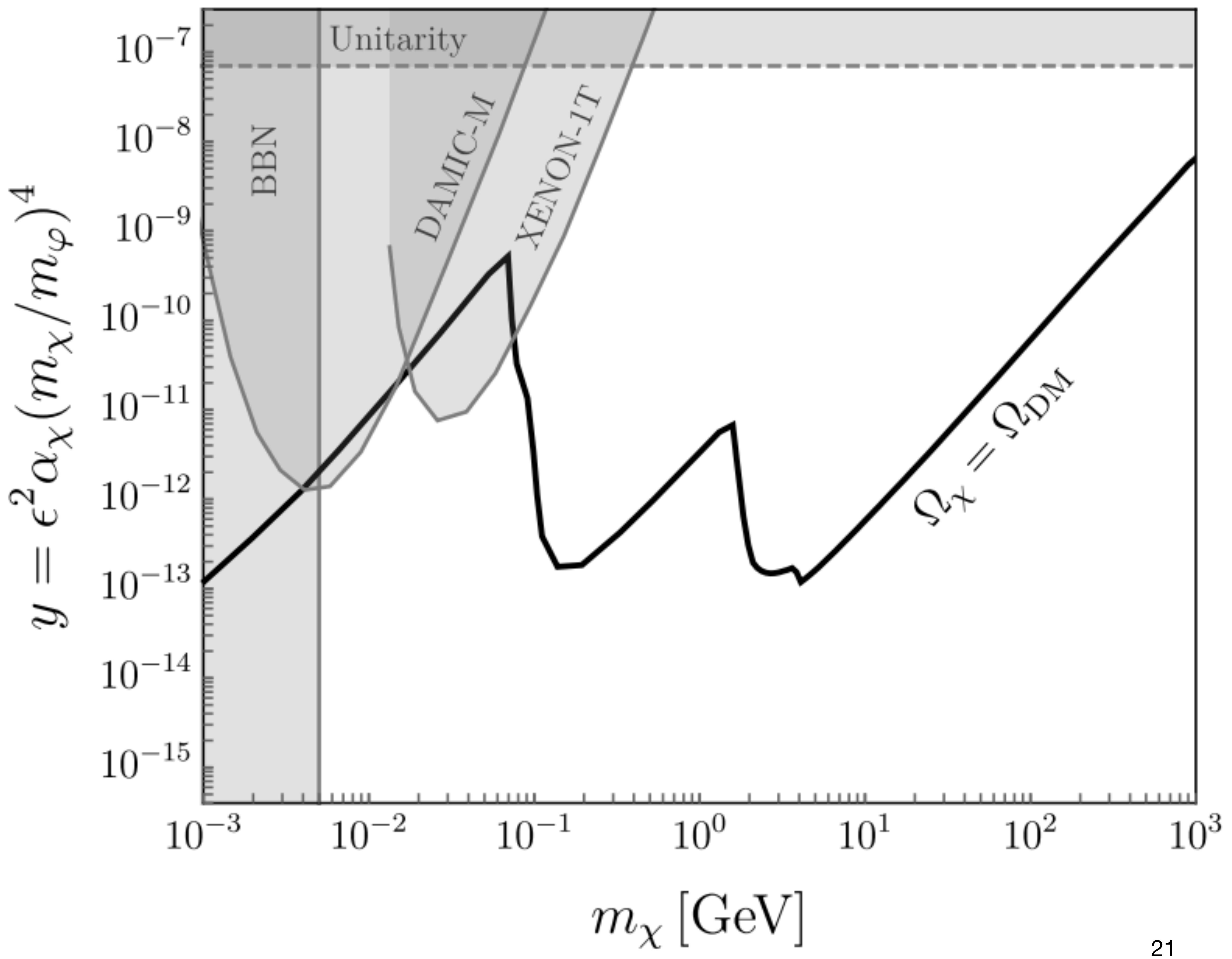
$$\propto \frac{y}{m_\chi^2}$$

CC, Krnjaic '24 (to come)

Other bounds



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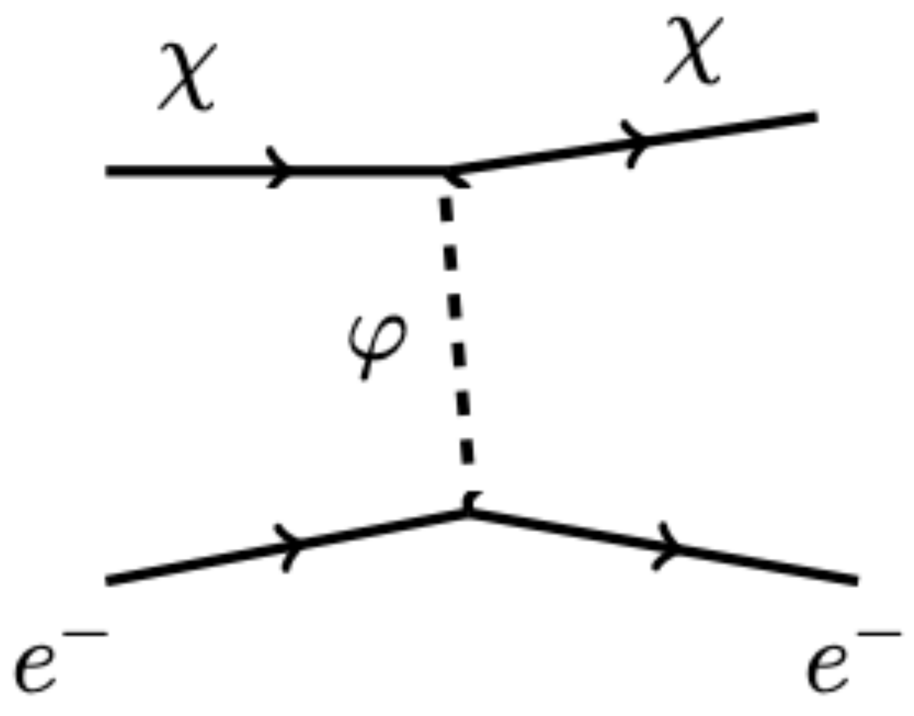


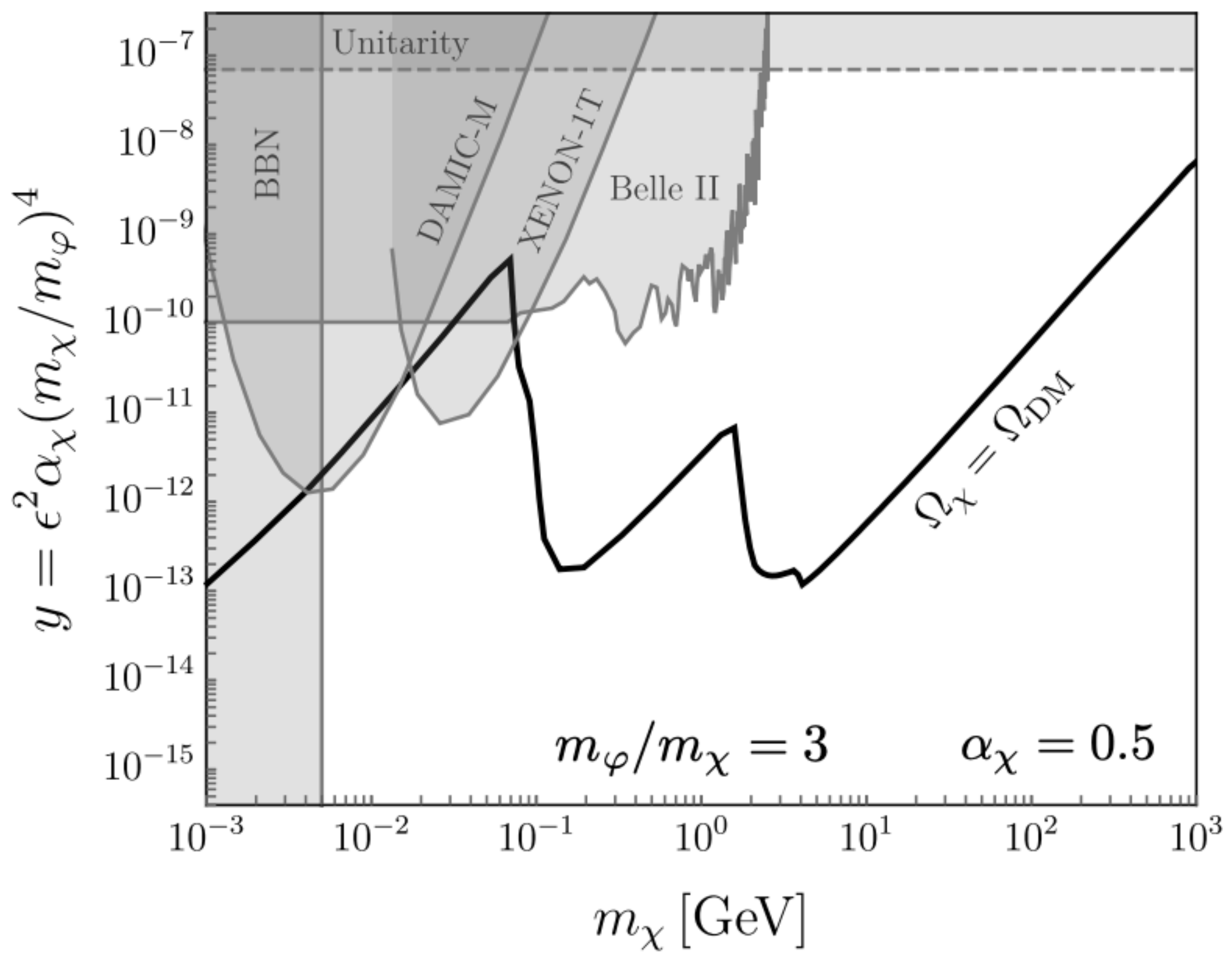
Direct Detection

DAMIC-M 2302.02372

XENON-IT 2112.12116

CC, Krnjaic '24 (to come)

Other bounds



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B Factories

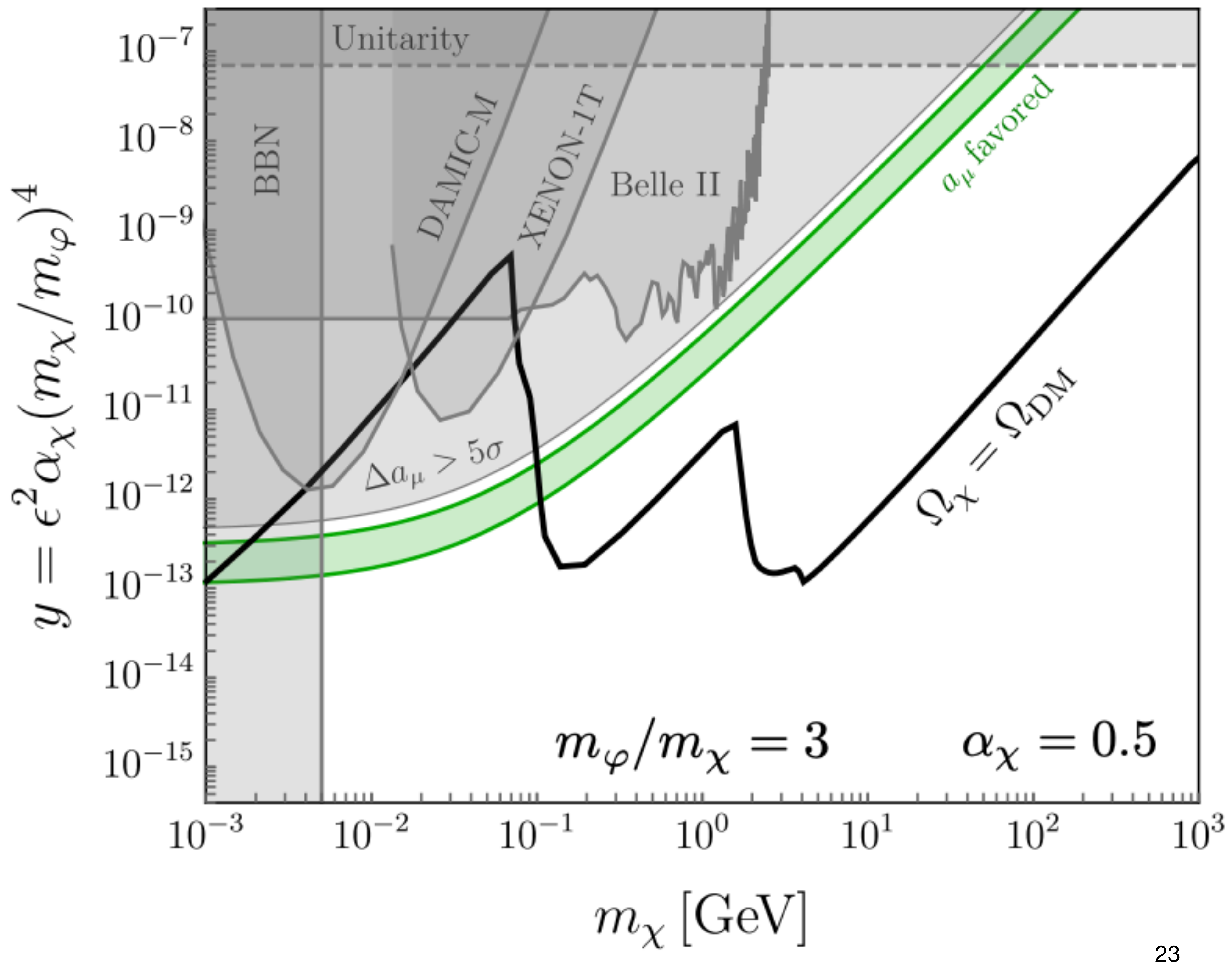
$$e^+e^- \to \mu^+\mu^-\varphi$$

(Dimuon + missing energy)

Belle II Collaboration 2212.03066

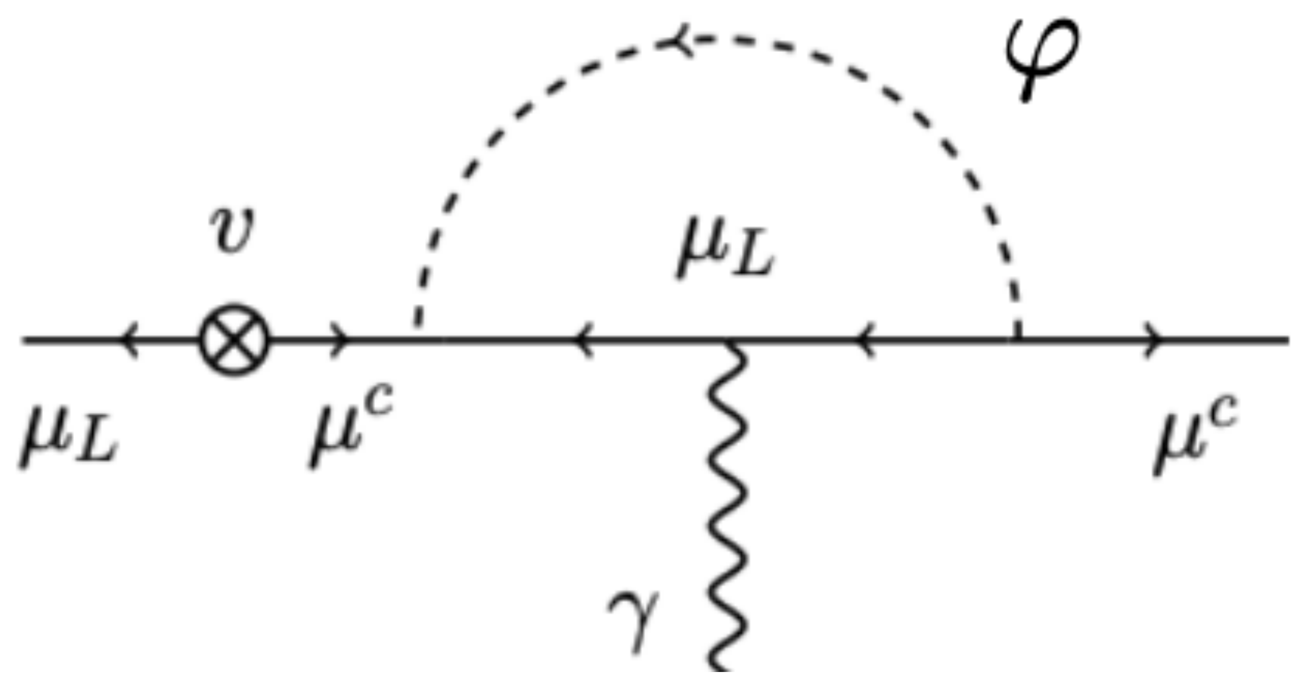
CC, Krnjaic '24 (to come)

Other bounds



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

Muon g-2



Muon *g-2* 2311.08282

CC, Krnjaic '24 (to come)

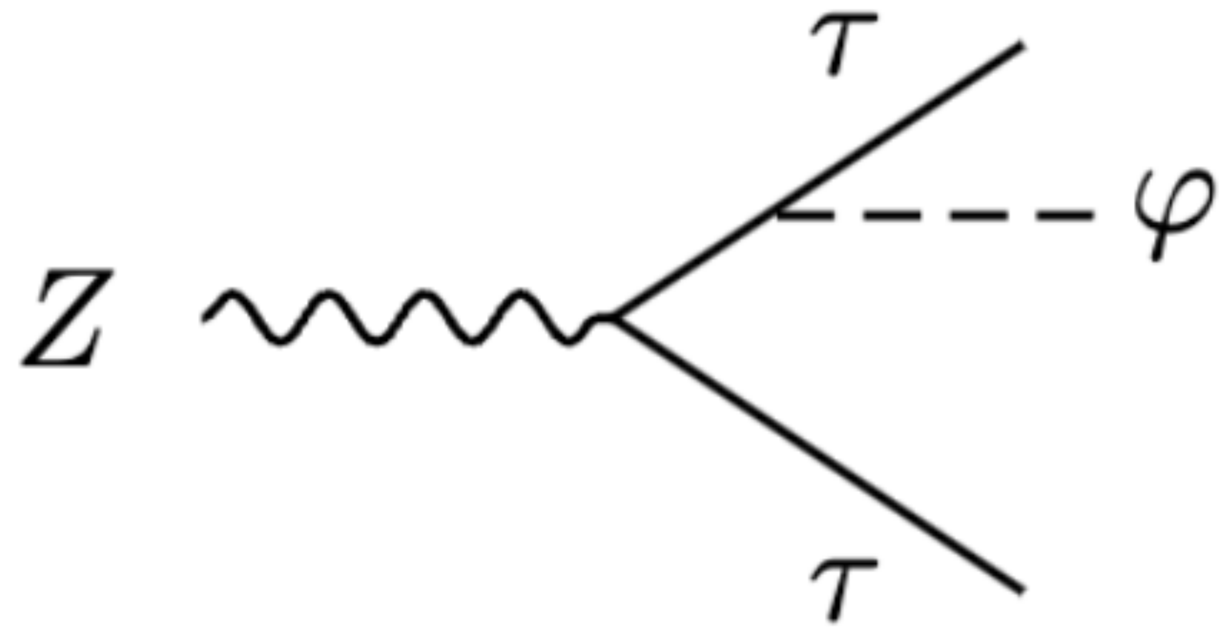
Bounds from FCCee

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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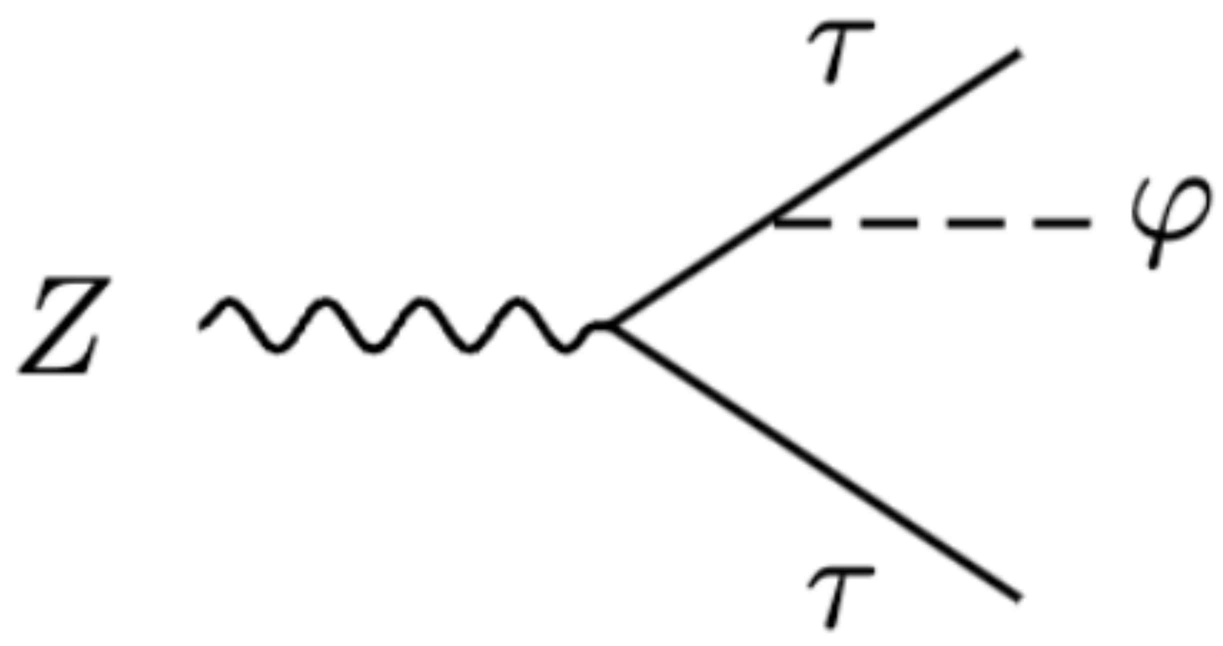

Previous LEP: $(1.7 \times 10^7\ Z\text{'s})$

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

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

Assume primary improvements come from statistics

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

CC, Krnjaic '24 (to come)

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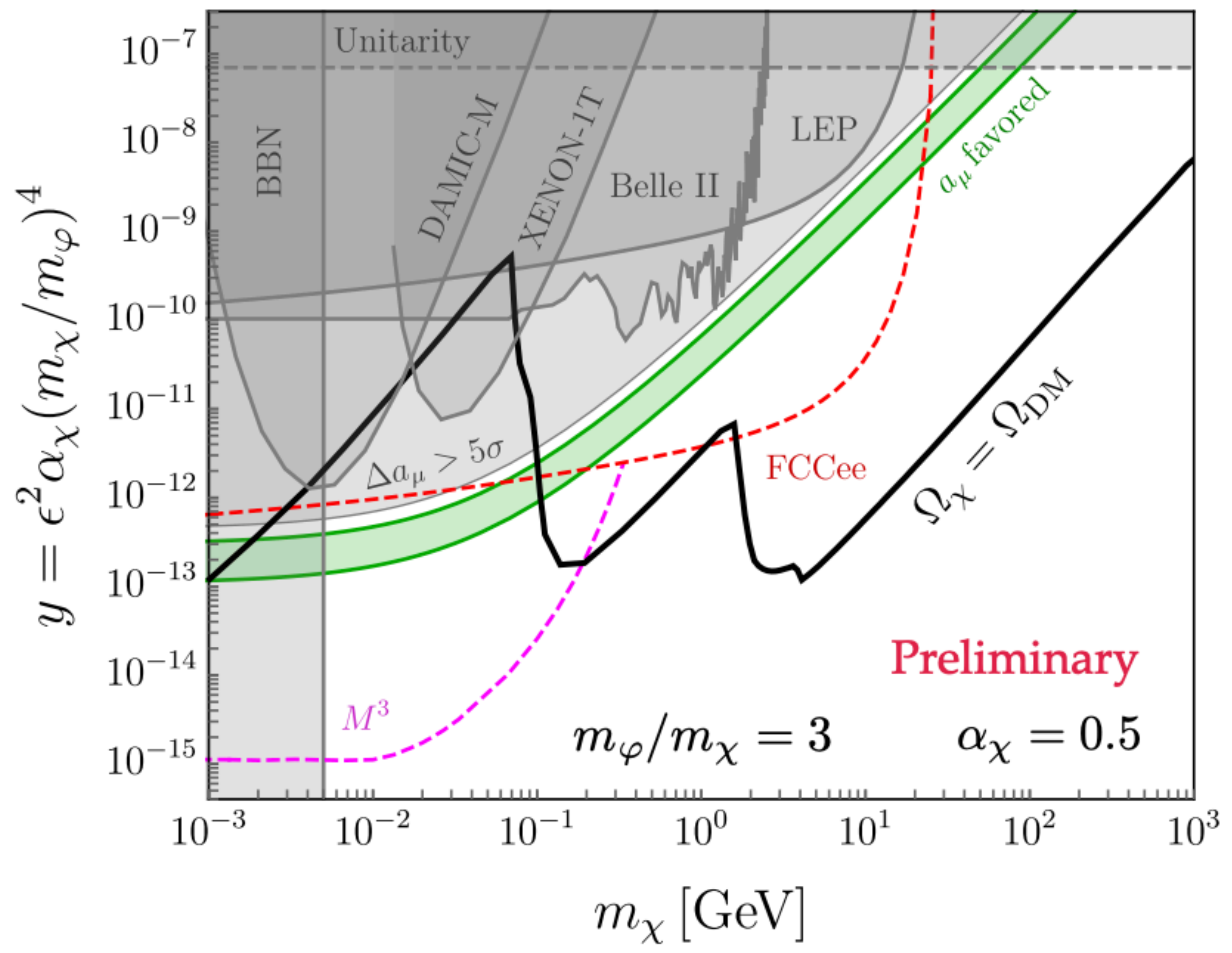
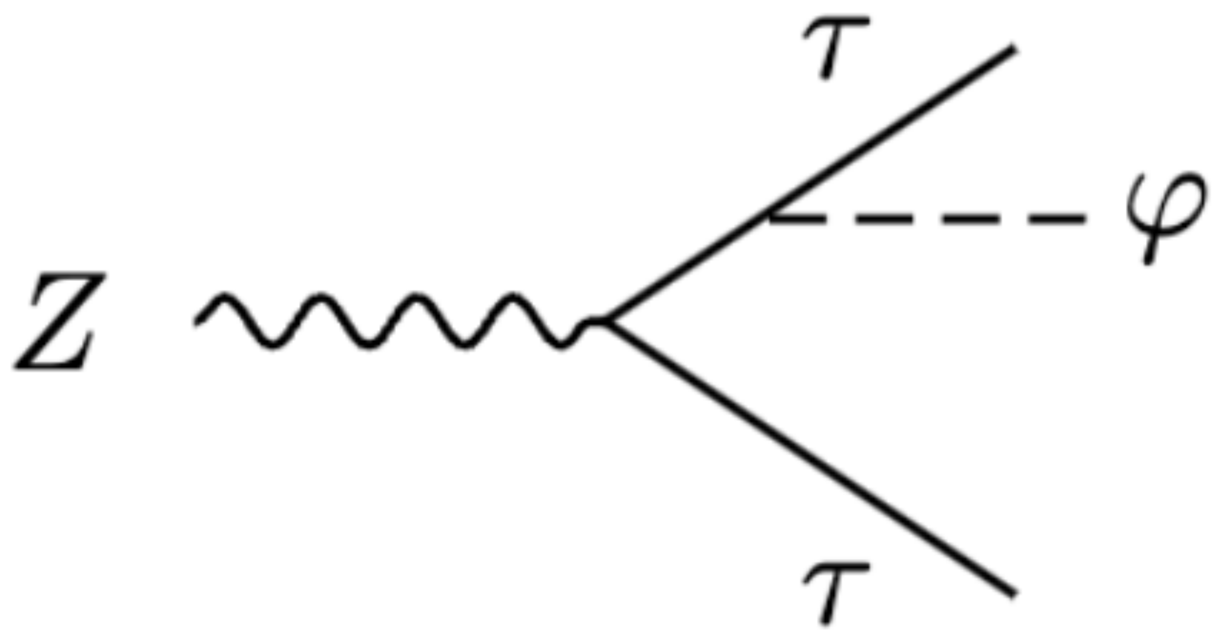


2σ in $\Delta\Gamma(Z \to \tau\tau)$



CC, Krnjaic '24 (to come)

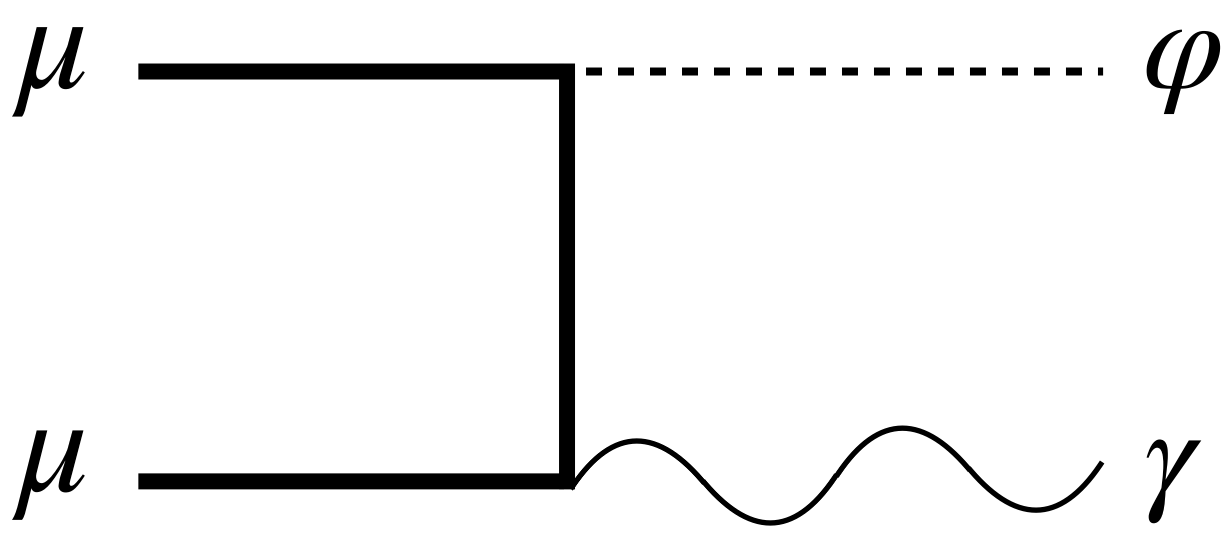
Bounds from 3 TeV MuC

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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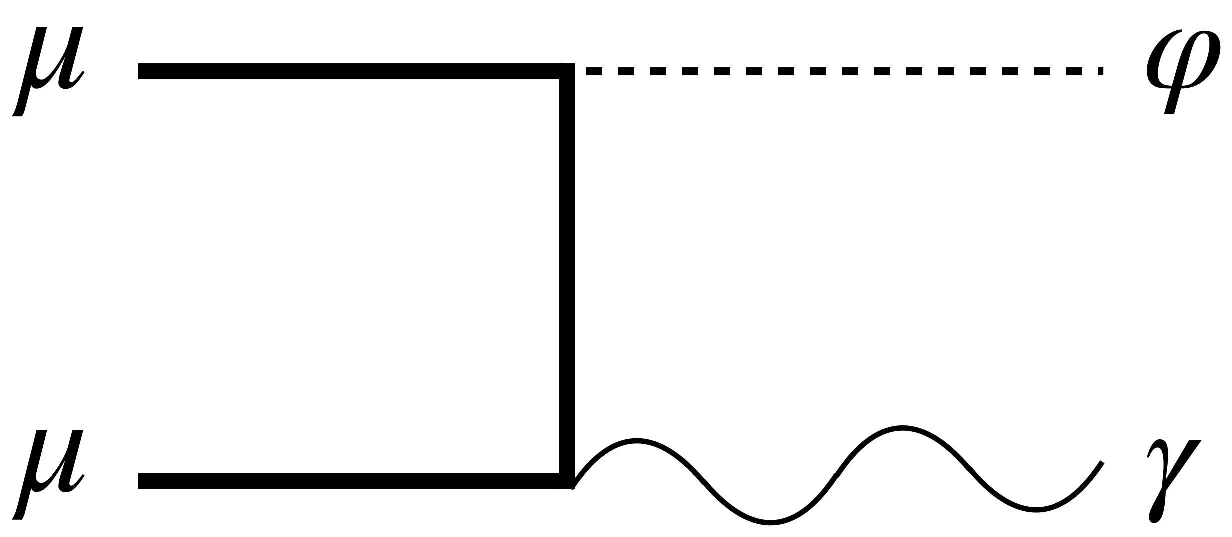

$$\sqrt{s} = 3\text{ TeV}$$
$$\sigma_E = 3\%$$
$$\mathcal{L} = 1\text{ab}^{-1}$$
$$|\eta| < 2.5$$

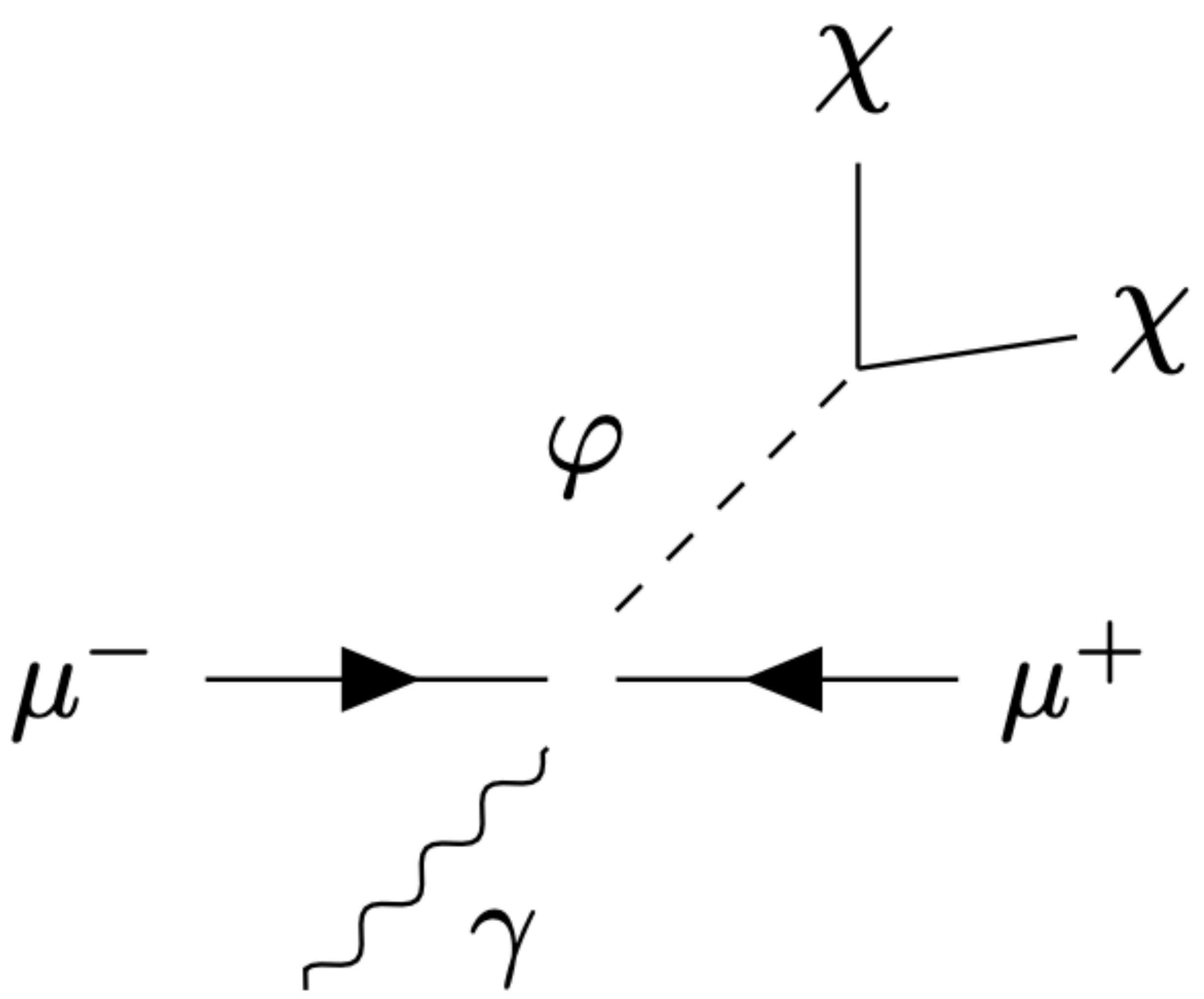

Image: Krnjaic

Primary Background:

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

CC, Krnjaic '24 (to come)

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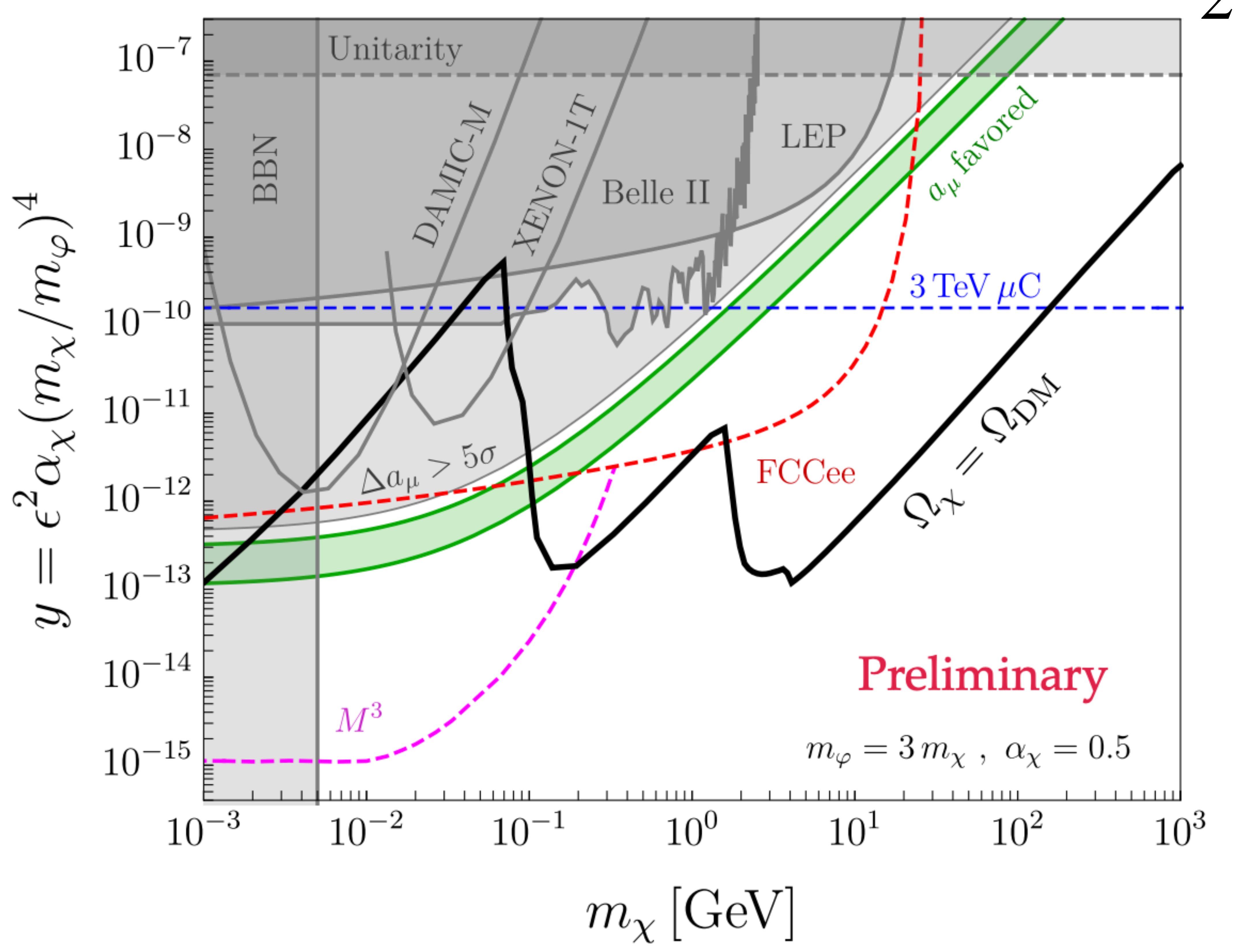

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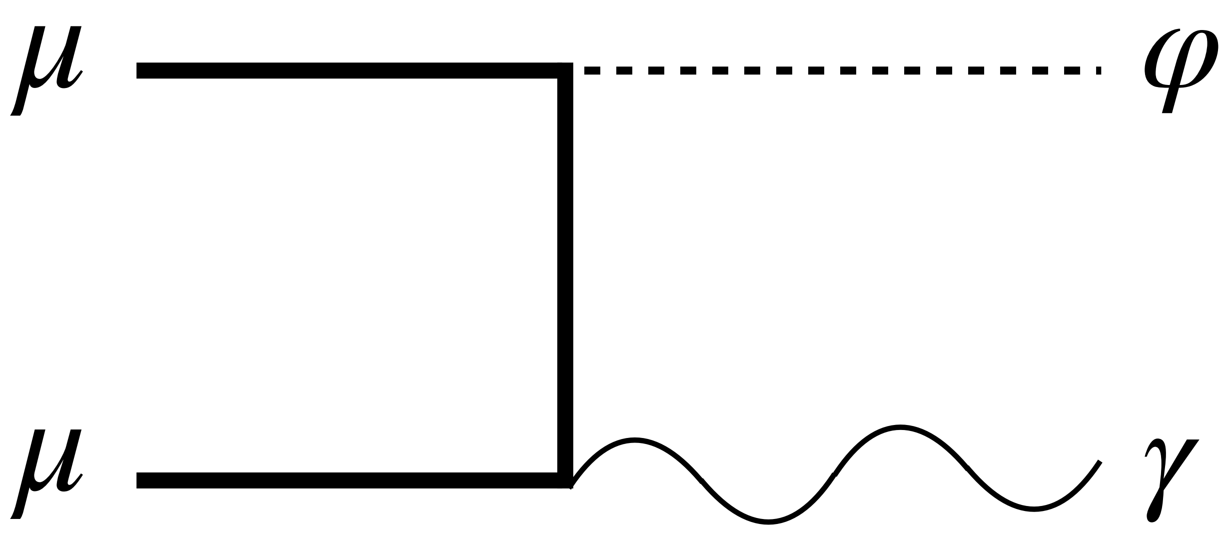

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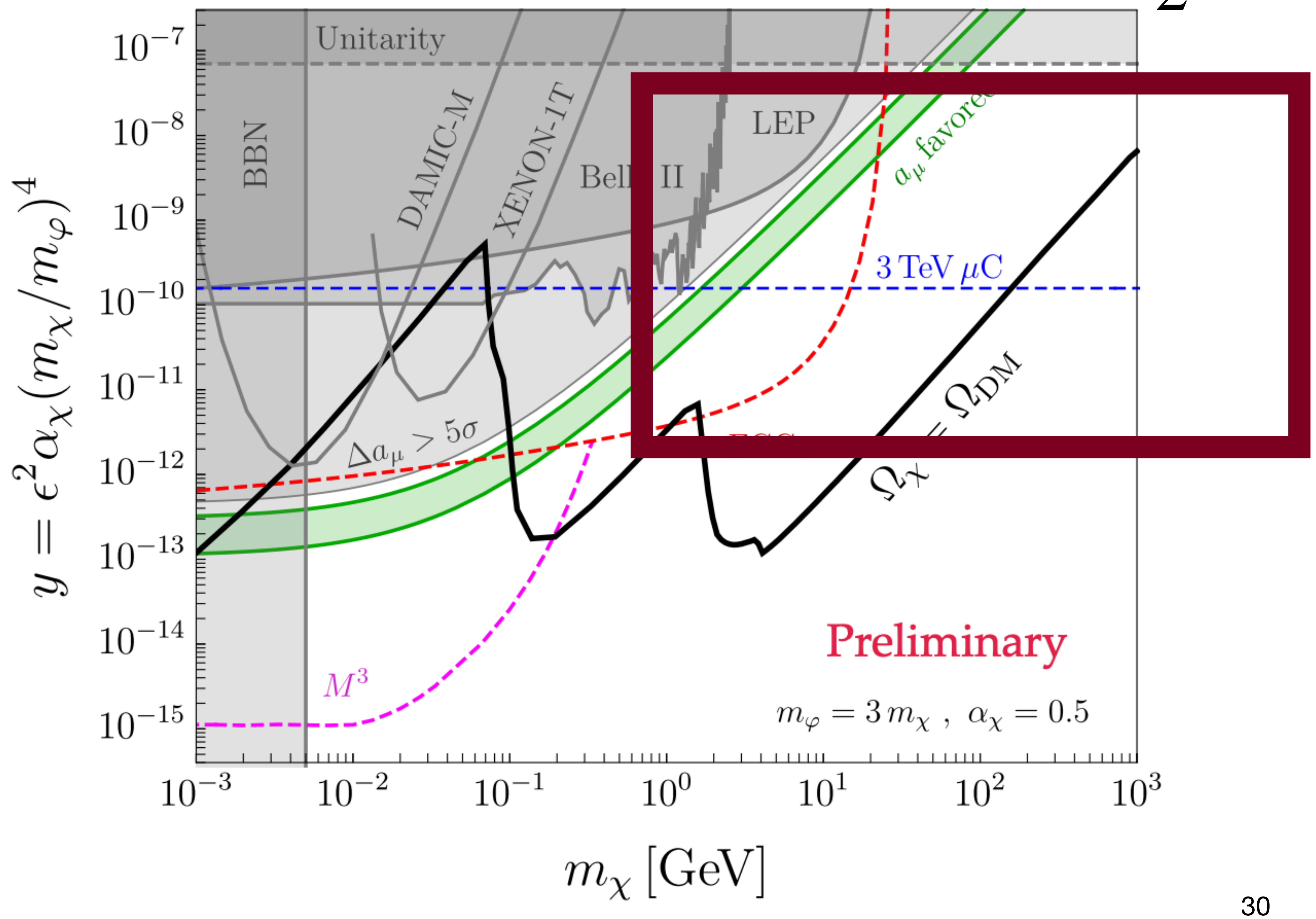

As is the theme of this workshop, a Muon Collider should be used to study heavy states!

CC, Krnjaic '24 (to come)

Conclusions

We should *modestly* instrument any extra beam (e.g. the chopper at Fermilab) to fully utilize the physics program at MuC

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FCCee and MuC can probe *different* physics

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We should *modestly* instrument any extra beam (e.g. the chopper at Fermilab) to fully utilize the physics program at MuC

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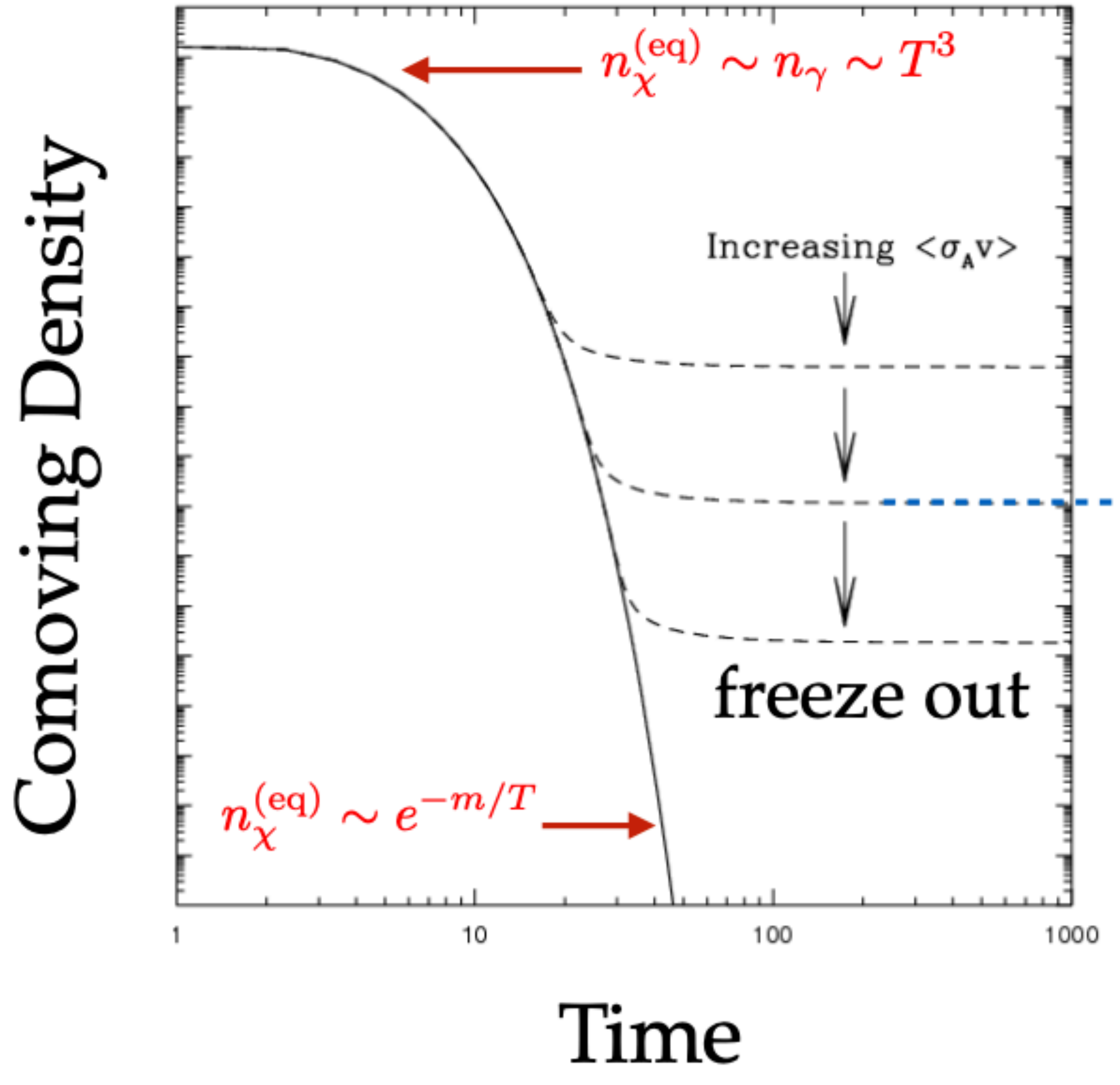
FCCee and MuC can probe *different* physics

Thanks!

Back ups

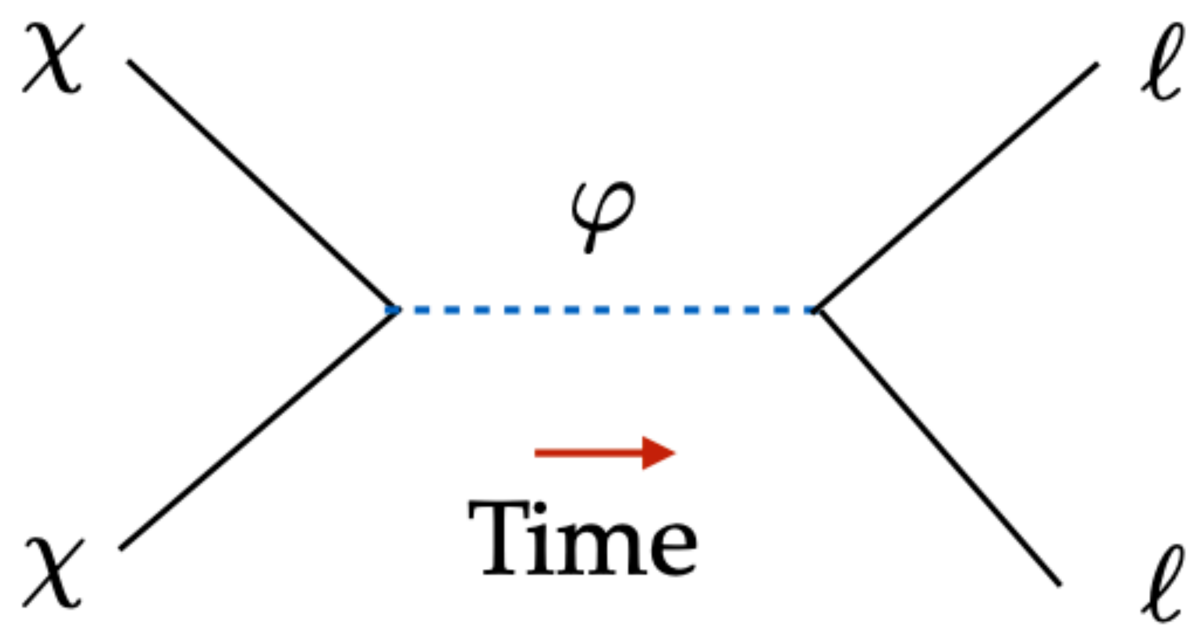
Cosmological History

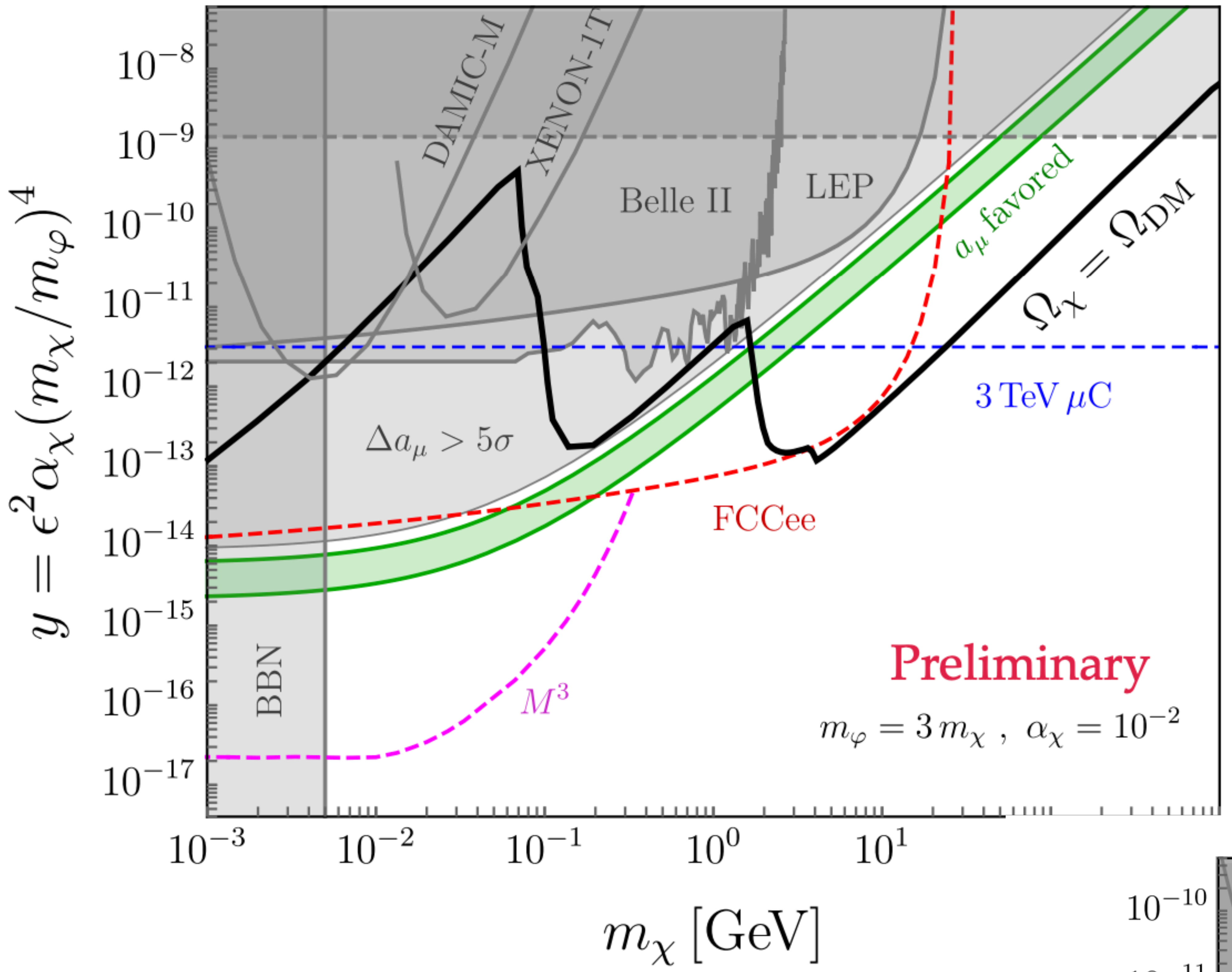
Equilibrium initially $n_\chi^{(\mathrm{eq})} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \propto \begin{cases} T^3 & (T \gg m) \\ e^{-m/T} & (T \ll m) \end{cases}$

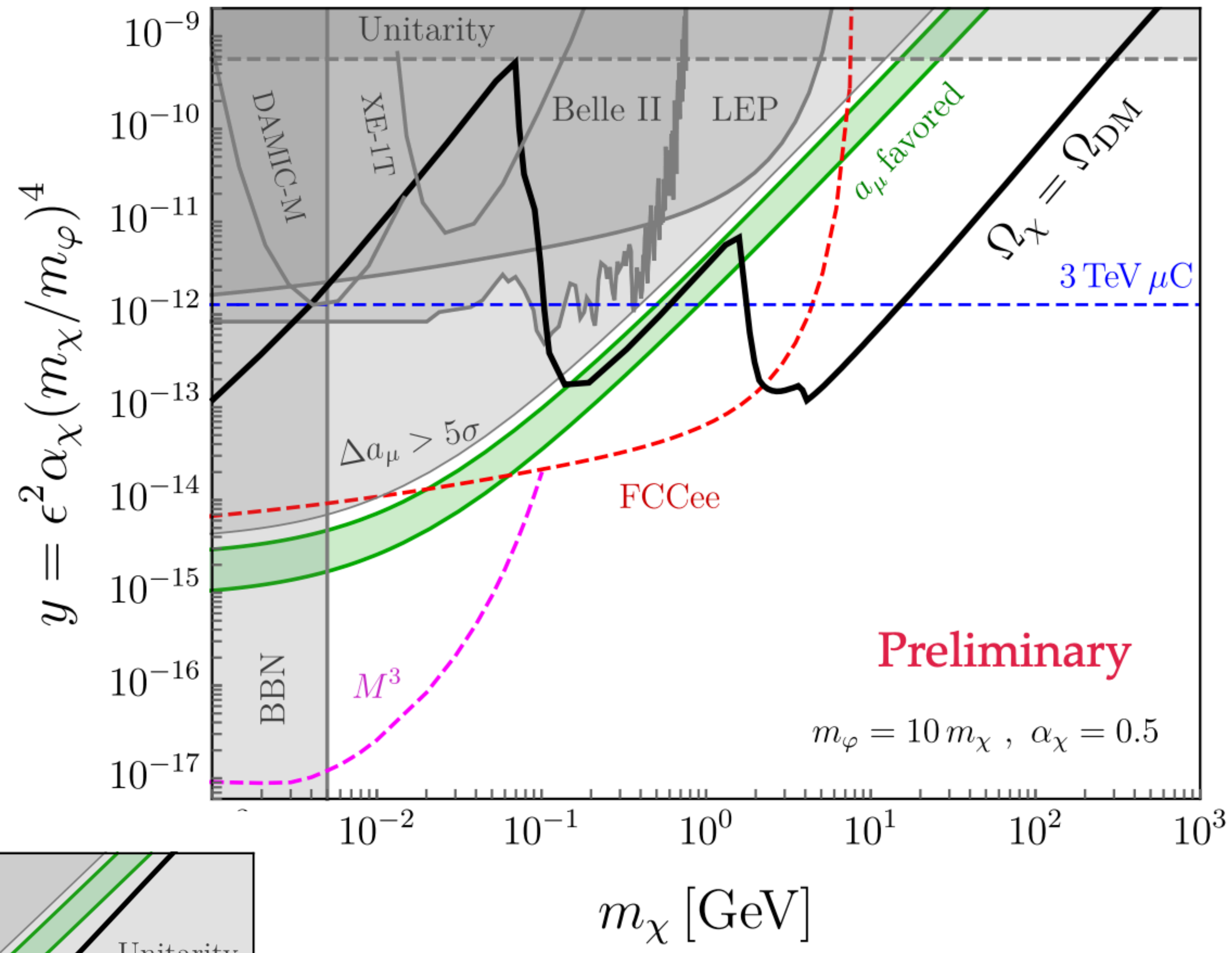


Observed density requires

$\sigma v \sim 2 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$




$y = \epsilon^2 \alpha_\chi (m_\chi/m_\varphi)^4$
m_χ [GeV]
DAMIC-M
XENON-1T
Belle II
LEP
a_μ favored
$\Omega_\chi = \Omega_{DM}$
3 TeV μC
$\Delta a_\mu > 5\sigma$
FCCee
BBN
M^3
Preliminary
$m_\varphi = 3\, m_\chi$, $\alpha_\chi = 10^{-2}$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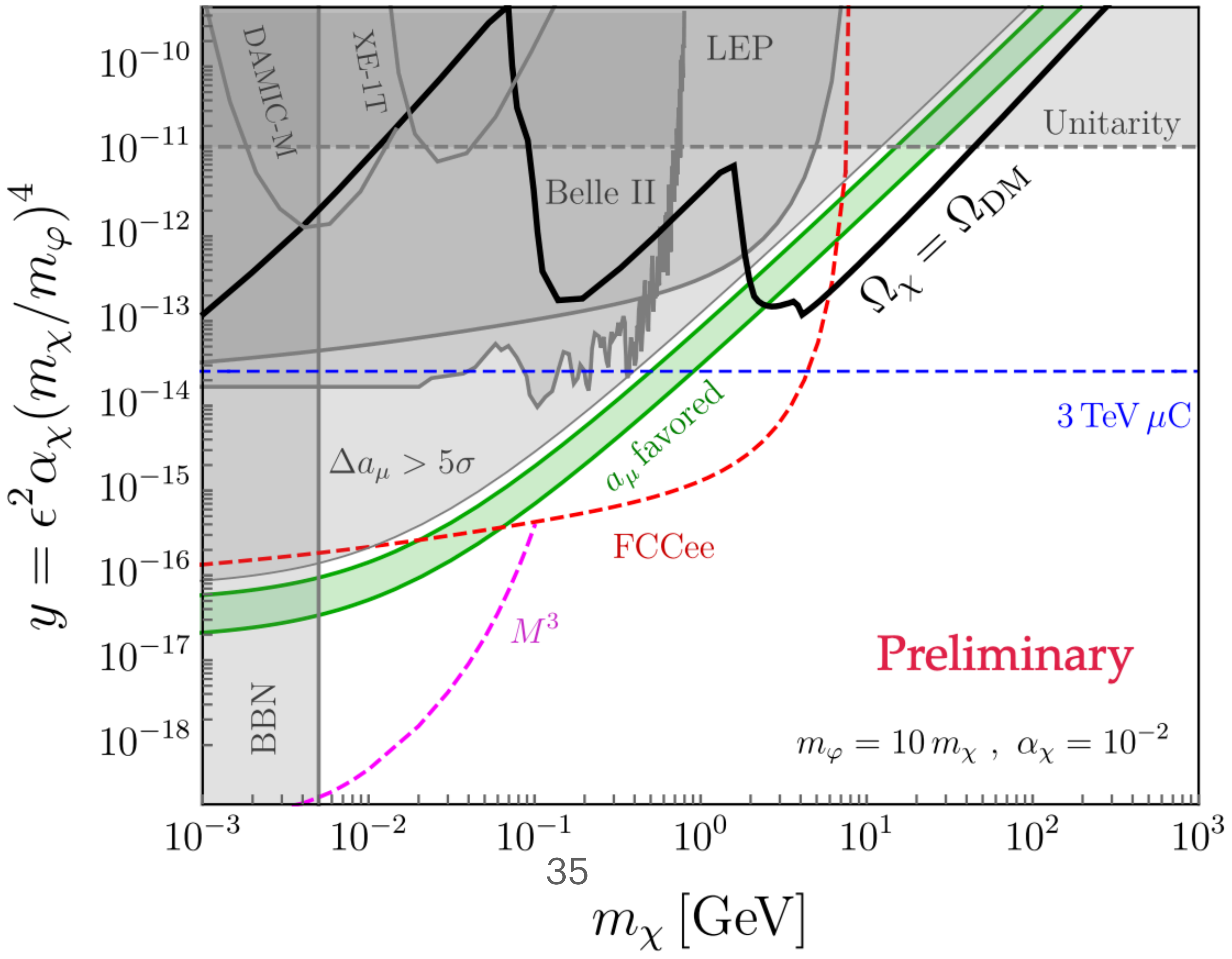
3 TeV μC
$\Delta a_\mu > 5\sigma$
FCCee
BBN
M^3
Preliminary
$m_\varphi = 10\, m_\chi$, $\alpha_\chi = 0.5$


$y = \epsilon^2 \alpha_\chi (m_\chi/m_\varphi)^4$
m_χ [GeV]
DAMIC-M
XE-1T
LEP
Unitarity
Belle II
$\Omega_\chi = \Omega_{DM}$
3 TeV μC
$\Delta a_\mu > 5\sigma$
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$m_\varphi = 10\, m_\chi$, $\alpha_\chi = 10^{-2}$