Twin Quark Dark Matter from Cogenesis

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arxiv: 2109.03248

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Motivation

Quark Dark Matter

In many models with confining $\mathscr{G}$, DM candidate is composite (+ asymmetric)

If $\mathscr{G} \to \mathscr{G}' \times \cdots$, singlets χ under the residual confining $\mathscr{G}'$ can be DM

- χ can be symmetric or asymmetric

Having χ from $\mathscr{G}_c \to SU(3)_c \times \cdots$ in SM is non-trivial

We study the (fraternal) twin Higgs model as a benchmark

- Well-motivated from neutral naturalness
- $SU(3)_c \to SU(2)_c$ in the twin sector **BB, WH, CV [arXiv:2004.10761]**

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(Fraternal) Twin Higgs

ZC, HG, RH [hep-ph/0506256]
NC, AK, MS, RS [arXiv:1501.05310]

(Little) Hierarchy problem

- Twin Higgs Model provides a solution to "little" hierarchy problem between the cutoff of about TeV scale to the weak scale by introducing $\mathbb{Z}_2$ symmetric (twin) sector
    - Twin Higgs Model is phenomenologically rich
    - Top quark partner (twin top quark) is not charged under SM $SU(3)_C$
- Fraternal: only keep the first generation of fermions
    - Yukawa couplings except for twin top are not restricted (if $y_{i \neq t} \ll 1$)
    - DM in the original FTH model: twin bottom baryon ($b_B b_B b_B$) and/or twin tau

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Breaking Twin Color

BB, WH, CV [arXiv:2004.10761]

Extends both sectors by introducing new colored triplet scalars $\phi_{A,B}$

$$\langle \phi_A \rangle = 0 \qquad \langle \phi_B \rangle^T = \begin{pmatrix} 0 & 0 & f_\phi + \varphi_B \end{pmatrix}$$

$$SU(3)_A \to SU(3)_A \qquad SU(3)_B \to SU(2)_B$$

$q_B \to \hat{q}_B$ ($SU(2)_B$ doublet) + q_{3B} ($SU(2)_B$ singlet)

Stable states: $\hat{b}_B \hat{b}_B$ ($SU(2)_B$ baryon), b_{3B} ($SU(2)_B$ singlet)

- b_{3B} is (twin) quark dark matter
  - Can be symmetric or **asymmetric** (directly connected to M/AM asymmetry in the visible sector — cogenesis)

Twin Baryogenesis

MF, AM, CS [arXiv:1604.08211]

Introduce additional fermion $N_{A,B}$

N is singlet under SM and twin gauge groups and serves as an additional portal

$$\mathscr{L} \supset -\lambda_A \phi_A q_A q_A - \kappa_A \phi_A q_A N_A - \frac{1}{2} M_N \overline{N}_A N_B + (A \leftrightarrow B)$$

Ingredients for cogenesis (Twin Baryogenesis) from $N_{A,B}$ decays

Diagonal baryon number $B_B = Q_A^B - Q_B^B$

	q_A	ϕ_A	$\overline{N}_A$	q_B	ϕ_B	N_B
B_B	$1/3$	$2/3$	-1	$-1/3$	$-2/3$	1

Twin Baryogenesis

With Twin Color Breaking

Twin gluon and photon mixes

$$B'_B = B_B + \sqrt{3} B_\phi T^8 \qquad Q'^{EM}_B = \frac{1}{2}\sigma^3 + Y + \sqrt{3} Y_\phi T^8$$

$\hat{q}_B$ ($SU(2)_B$ doublet) loses B_B charge

CP-asymmetry only in q_{3B} (or quark dark matter)

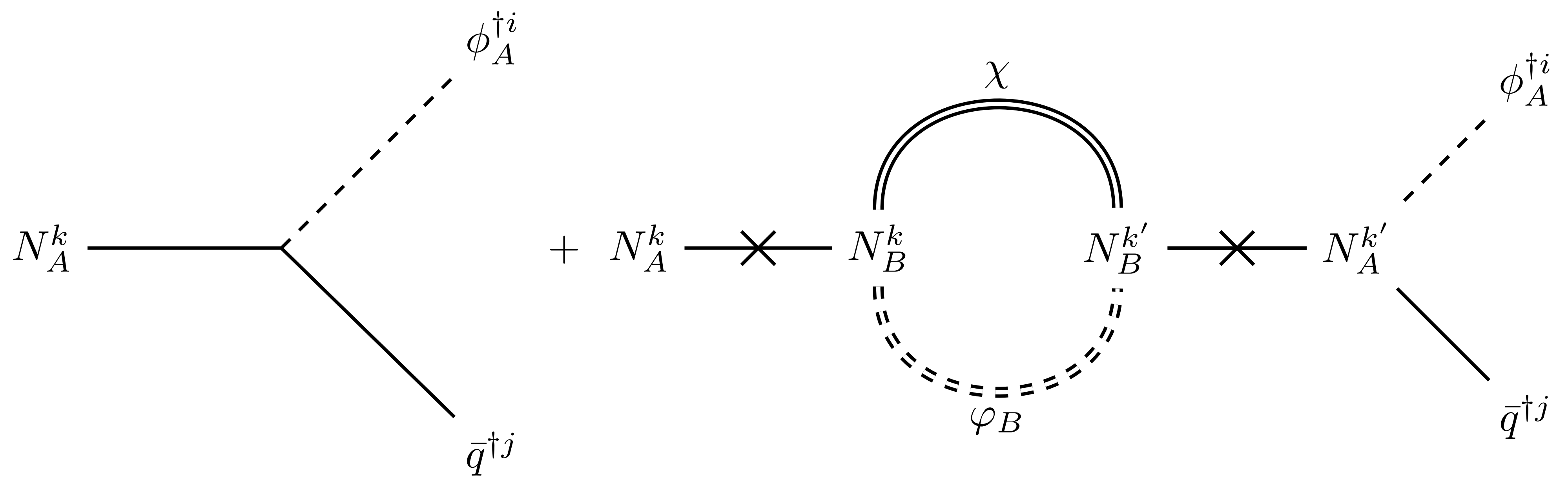
$Y(\phi_{A,B}) = +2/3$ is chosen for b_{3B} to be twin electric charged

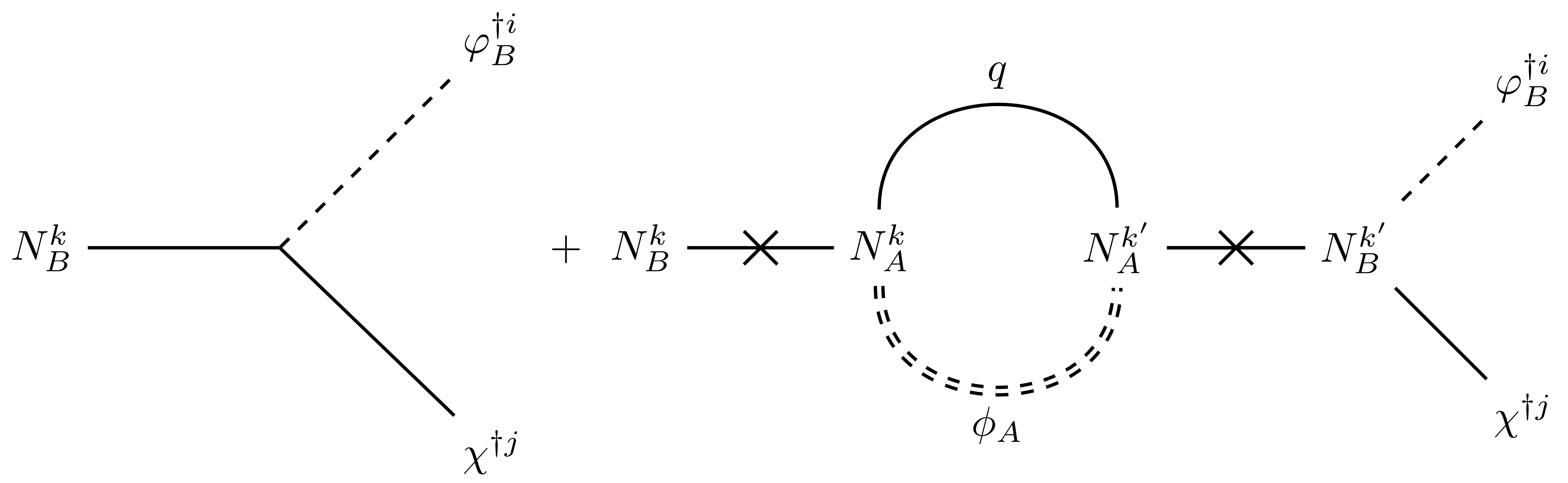
	$\widehat{Q}_B$	Q_{3B}	$\widehat{\overline{U}}_B$	$\overline{U}_{3B}$	$\widehat{\overline{D}}_B$	$\overline{D}_{3B}$	φ_B	$\overline{N}_B$
B_B	$\frac{1}{3}$	$\frac{1}{3}$	-$\frac{1}{3}$	-$\frac{1}{3}$	-$\frac{1}{3}$	-$\frac{1}{3}$	-$\frac{2}{3}$	1
B'_B	0	1	0	-1	0	-1	0	1
Q'^{EM}_B	(1,0)	(0,-1)	-1	0	0	1	0	0

Twin Baryogenesis

Cogenesis

When $M_N > m_\phi$ and $T_B \lesssim m_\phi/25$





$\Delta B_B = +1$ $\qquad$ $\Delta B_B = -1$

Visible sector $\qquad$ Twin sector

B'_B charge conservation $\rightarrow \eta_A = \eta_B$

$Q_B^{\prime\mathrm{EM}}$ charge conservation $\rightarrow m_{b_B} + m_{\tau_B} = m_p \dfrac{\Omega_{\mathrm{DM}}}{\Omega_B} = 5\ \mathrm{GeV}$

Phenomenology

Full Lagrangian

$$\mathscr{L}_{\text{visible}} \supset -Y_L H_A^\dagger L_A \overline{E}_A - Y_U Q_A H_A \overline{U}_A - Y_D H_A^\dagger Q_A \overline{D}_A - \boxed{\frac{\lambda}{2}\phi_A^\dagger \overline{D}_A \overline{D}_A} + \text{H.c.}$$

$$\mathscr{L}_{\text{twin}} \supset -y_\tau H_B^\dagger L_B \overline{E}_B - y_t Q_B H_B \overline{U}_B - y_b H_B^\dagger Q_B \overline{D}_B + \text{H.c.} \ .$$

$$\mathscr{L}_{\text{portal}} \supset -M_N \overline{N}_A N_B - \boxed{\kappa_A \phi_A \overline{U}_A \overline{N}_A} - \boxed{\kappa_B \phi_B \overline{U}_B N_B} + \text{H.c.} \ ,$$

$$\boxed{\lambda_A \phi_A^\dagger \overline{D}_A \overline{D}_A \quad \kappa_A \phi_A \overline{U}_A \overline{N}_A \quad \kappa_B \phi_B \overline{U}_B N_B \quad \frac{\kappa_A \kappa_B f_\phi}{\sqrt{2} M_N} \phi_A \overline{U}_A \bar{t}_{3B}}$$

N_A and t_{3B} mixing from $\langle \phi_B \rangle = f_\phi$

Phenomenology

$\lambda_A \phi_A^\dagger \overline{D}_A \overline{D}_A \quad \kappa_A \phi_A \overline{U}_A \overline{N}_A \quad \kappa_B \phi_B \overline{U}_B N_B \quad \frac{\kappa_A \kappa_B f_\phi}{\sqrt{2} M_N} \phi_A \overline{U}_A \bar{t}_{3B}$

Signature

Collider searches

ϕ_A pair production: $\phi_A \to jj$ or $\phi_A \to j(t_A) t_B$ (identical to “stop/squark”)

Current constraint: $m_\phi \gtrsim 1.2\ \mathrm{TeV}$, HL-LHC projection: $m_\phi \lesssim 1.8\ \mathrm{TeV}$

ATLAS [arXiv:1909.03460] **XV et al [arXiv:1812.07831]**

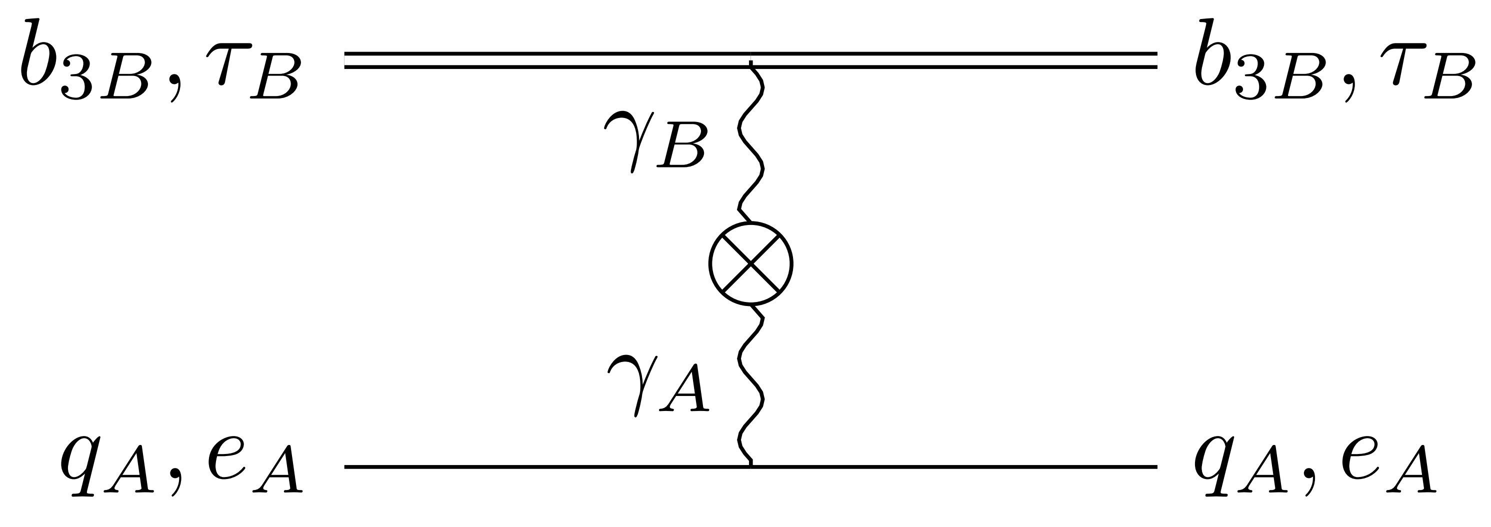
Direct detection

$m_{\gamma_B} \sim 1\ \mathrm{GeV}$ to annihilate the symmetric part + evade dark photon constraint

$m_{\gamma_B} = 0\ \mathrm{GeV}$ with increased α_B^{EM} is another option

b_{3B} and τ_B can scatter off nucleons due to the kinetic mixing

Current constraint: $\varepsilon < 10^{-3}$, Near future sensitivity: $\varepsilon \sim 10^{-4}$



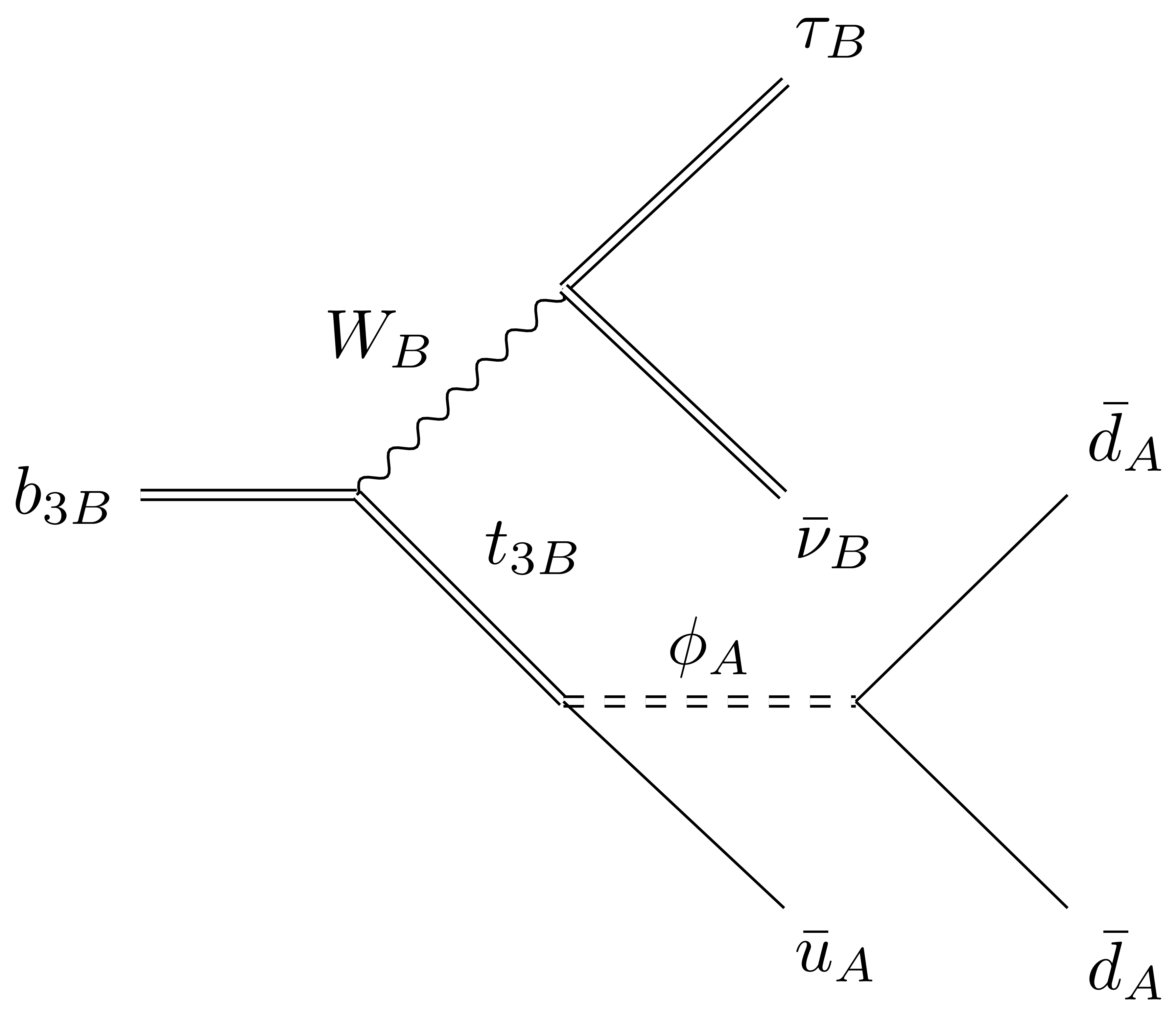
Phenomenology

Signatures

$$\lambda_A \phi_A^\dagger \overline{D}_A \overline{D}_A \quad \kappa_A \phi_A \overline{U}_A \overline{N}_A \quad \kappa_B \phi_B \overline{U}_B N_B \quad \frac{\kappa_A \kappa_B f_\phi}{\sqrt{2} M_N} \phi_A \overline{U}_A \bar{t}_{3B}$$

DM decay indirect detection

- If $|m_{b_{3B}} - m_{\tau_B}| < m_p$, DM is stable
- If $|m_{b_{3B}} - m_{\tau_B}| \geq m_p$
  - b_{3B} has $B'_B = -1$: $b_{3B} \to \bar{q}\bar{q}\bar{q}$
  - From Fermi-LAT: $\tau_\chi \gtrsim 5 \times 10^{27}$ sec $(\bar{u}u)$ — highly conservative
  - **Fermi-LAT [arXiv:1410.3696]**



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Conclusion

Summary and Outlook

(Dark) Quark itself can be DM by spontaneous color breaking, without confinement

As a concrete example, we extend the fraternal Twin Higgs model

- Colored scalars in the SM and twin sectors
  - Twin colored scalar can acquire a vev and spontaneously break the twin color group down to $SU(2)_B$
- Gauge singlet fermions that provide a new portal btw the two sectors
  - Initiates the baryogenesis in both sectors
- After the twin color breaking, singlet quarks under the residual $SU(2)_B$ becomes (asymmetric) quark dark matter

Conclusion

Summary and Outlook

3 puzzles are addressed — naturalness puzzle, M/AM puzzle and the DM puzzles

There exist large areas of parameter space where this model can address the puzzles in question, while remaining consistent with all existing experimental constraints

- Di-jet and "stop/squark" collider searches, dark photon, direct detection, decaying DM, etc.

Future searches will have sensitivity to the available parameter space of the model

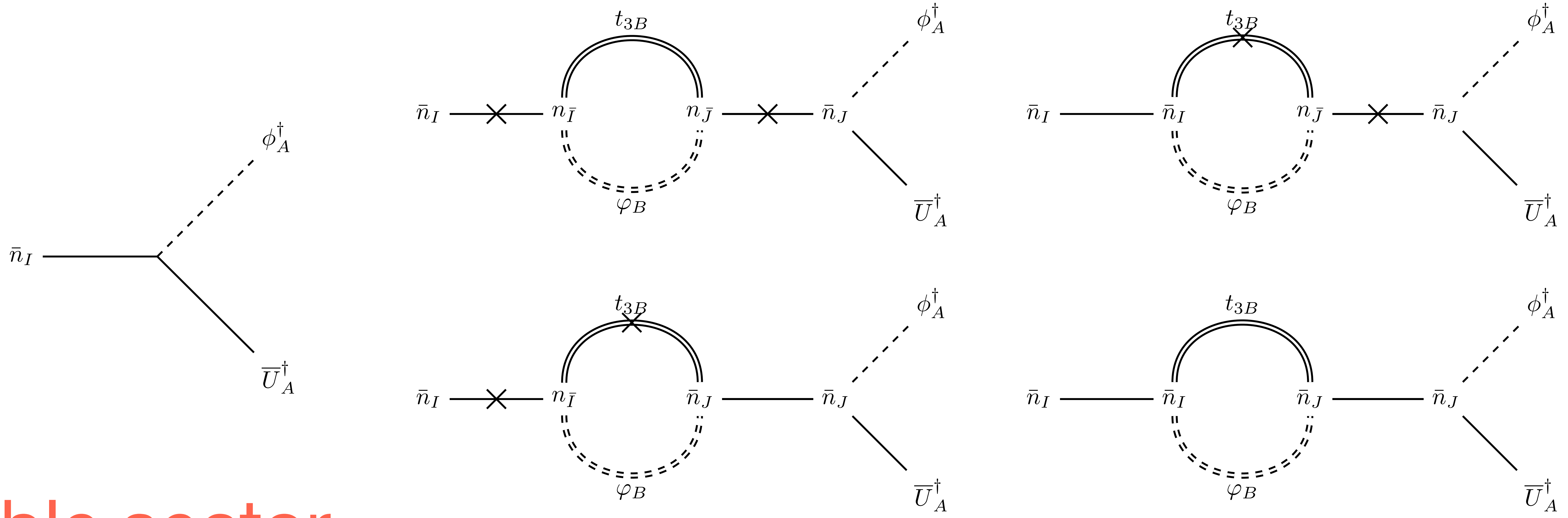
Thank you for listening!

Supplements

Twin Baryogenesis

With Twin Color Breaking

Additional diagrams due to twin color breaking, suppressed by m_{t_B}/M_N



Visible sector

t_{B3} decays into b_{3B} and $\tau_B \rightarrow m_{b_B} + m_{\tau_B} = m_p \dfrac{\Omega_{\text{DM}}}{\Omega_B} = 5 \text{ GeV}$

Phenomenology

Full Lagrangian

$$Y(\phi_{A,B}) = +\frac{2}{3}$$

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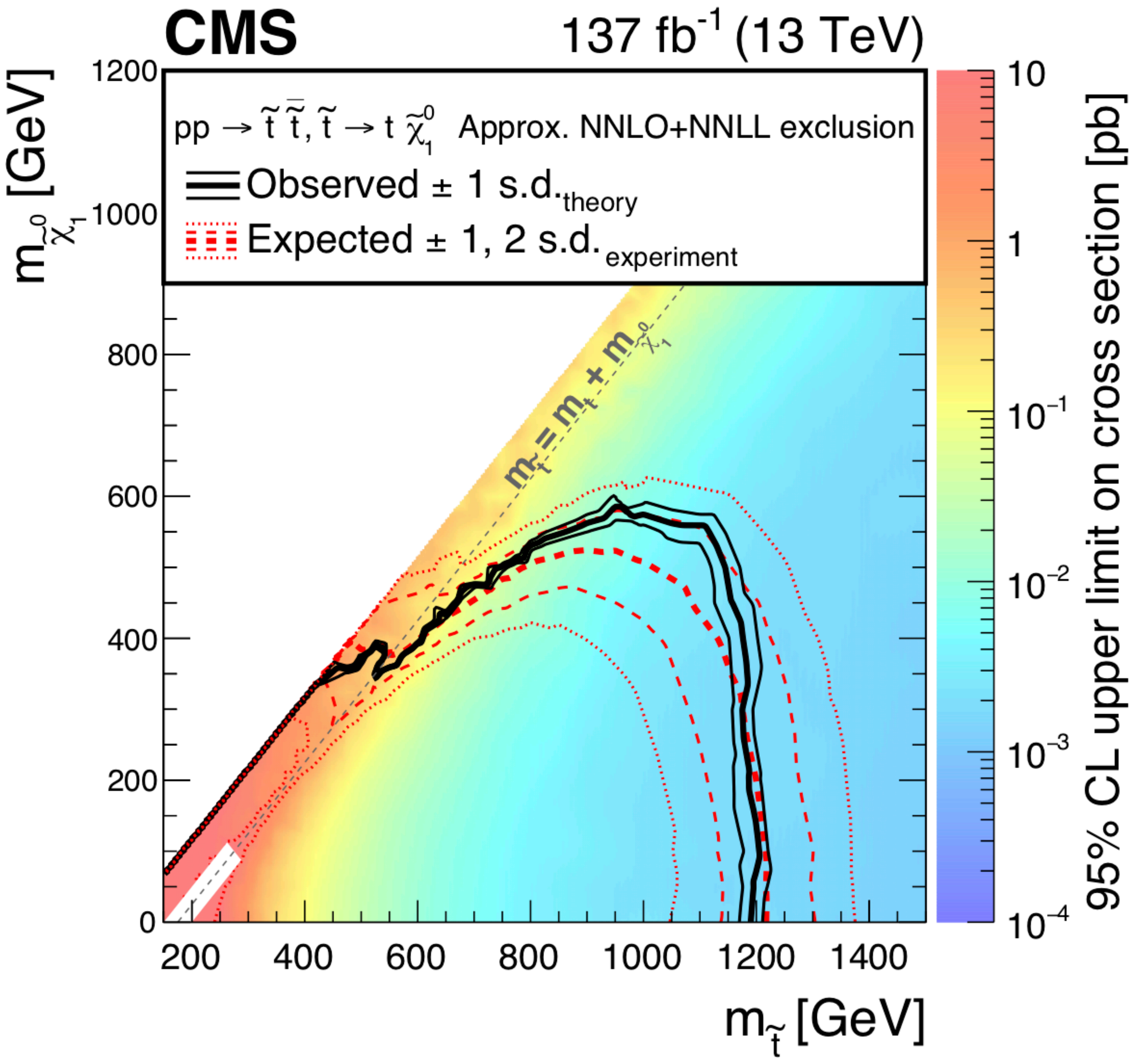
Phenomenology

Collider signatures

$\lambda_A \phi_A^\dagger \overline{D}_A \overline{D}_A$ $\kappa_A \phi_A \overline{U}_A \overline{N}_A$ $\kappa_B \phi_B \overline{U}_B N_B$ $\frac{\kappa_A \kappa_B f_\phi}{\sqrt{2} M_N} \phi_A \overline{U}_A \bar{t}_{3B}$

Collider searches: possible at the LHC

- ϕ_A pair production: $\phi_A \to jj$ or $\phi_A \to j(t_A)t_B$
- $m_\phi \gtrsim 1.2\ \mathrm{TeV}$ (ATLAS, CMS)
- $m_\phi \gtrsim 1.8\ \mathrm{TeV}$ (HL-LHC)
- Dijet resonance: $\lambda \lesssim 0.1$ for $m_\phi \approx 2\ \mathrm{TeV}$
- Displaced vertex: $m_\phi \gtrsim 1.8\ \mathrm{TeV}$
- N needs to wait until 100 TeV FCC.



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Phenomenology

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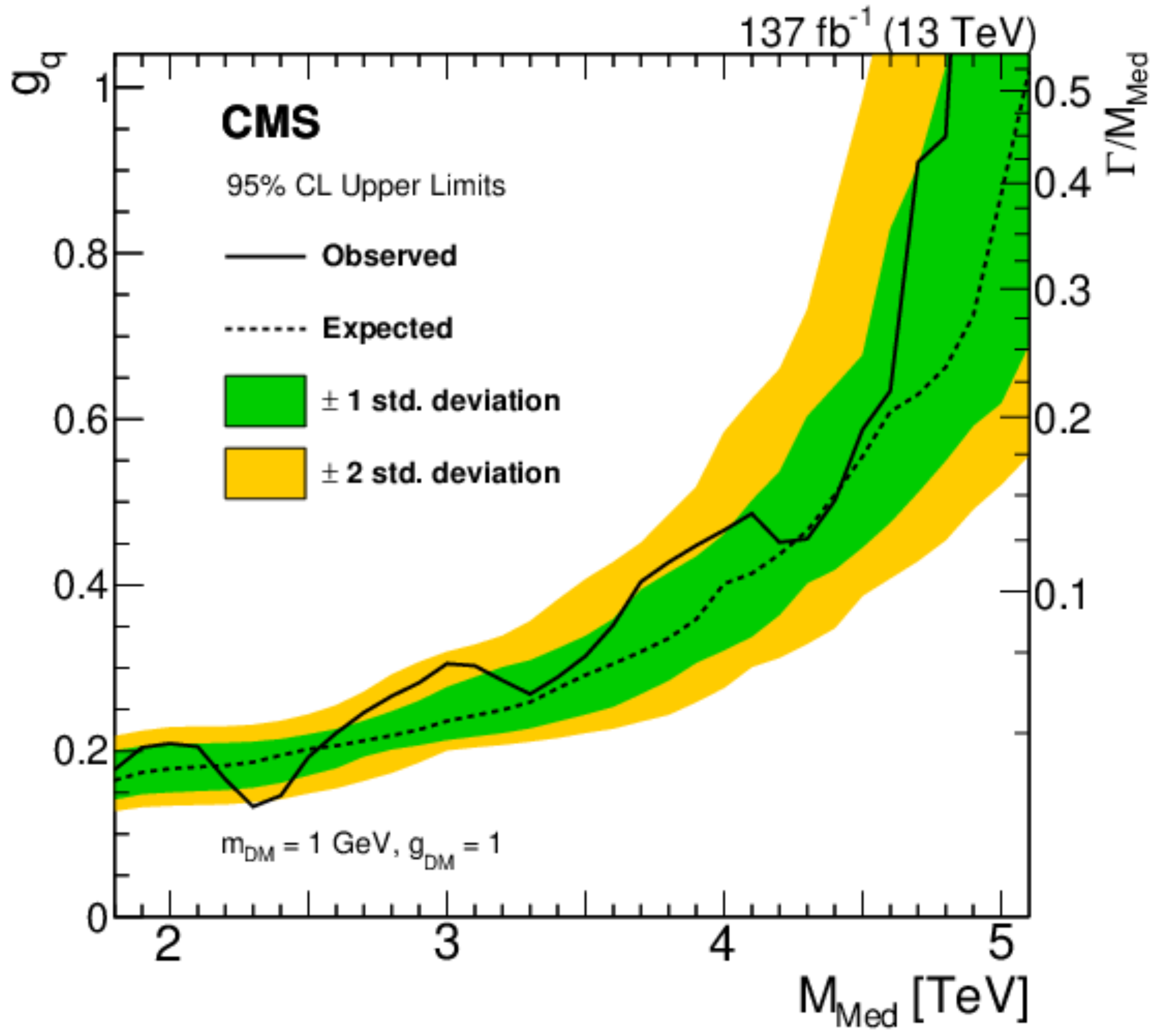

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Phenomenology

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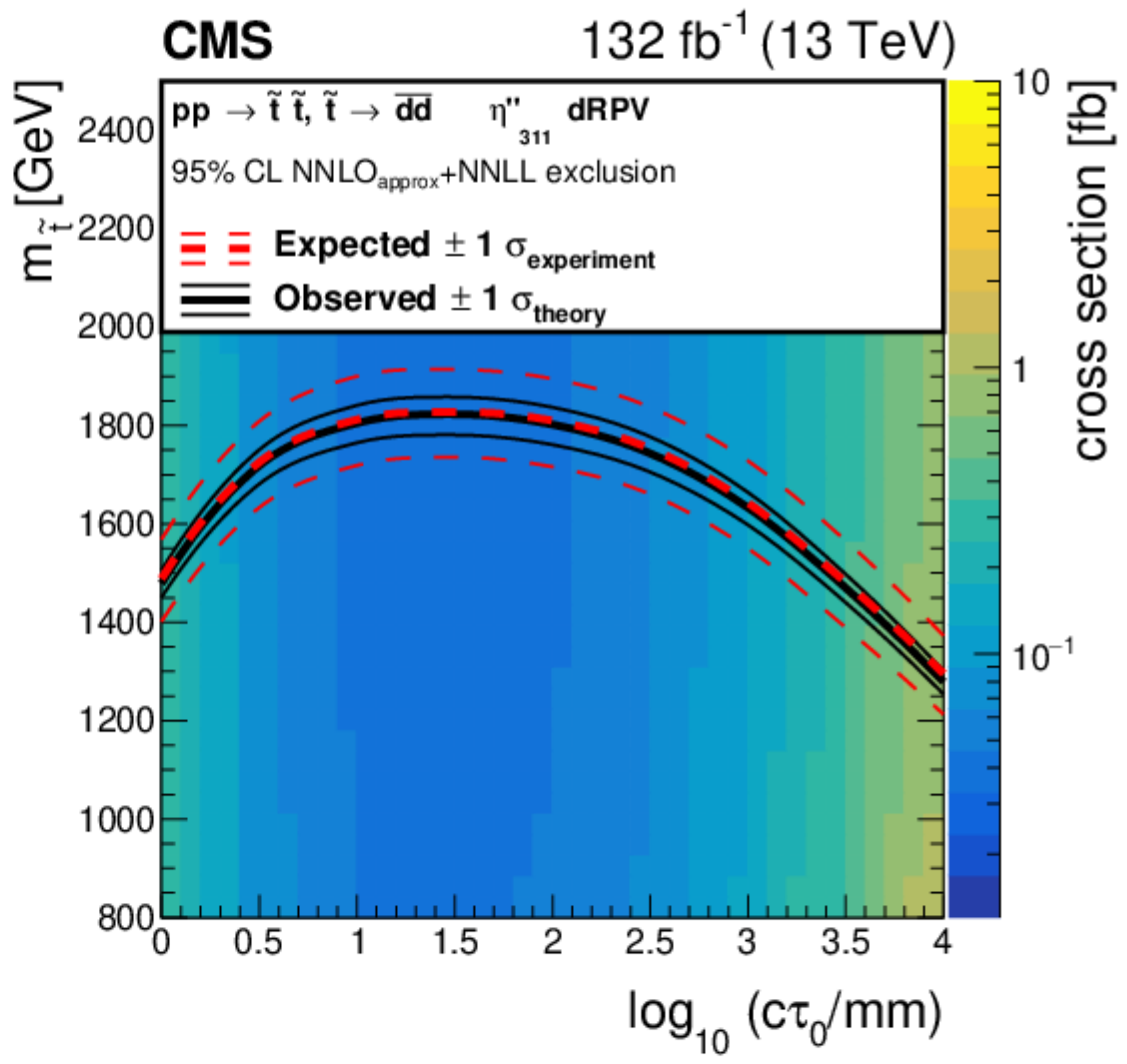

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Phenomenology

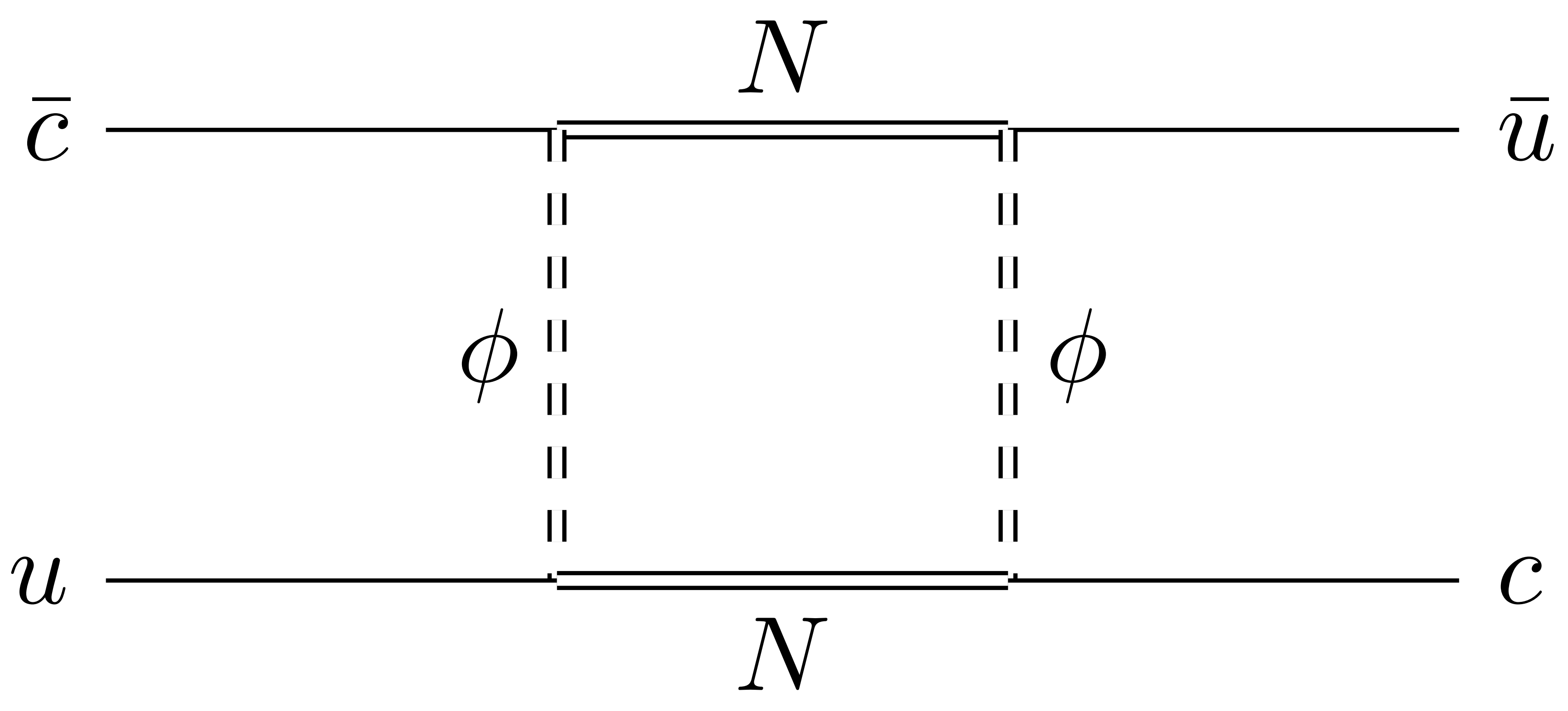
Precision measurement

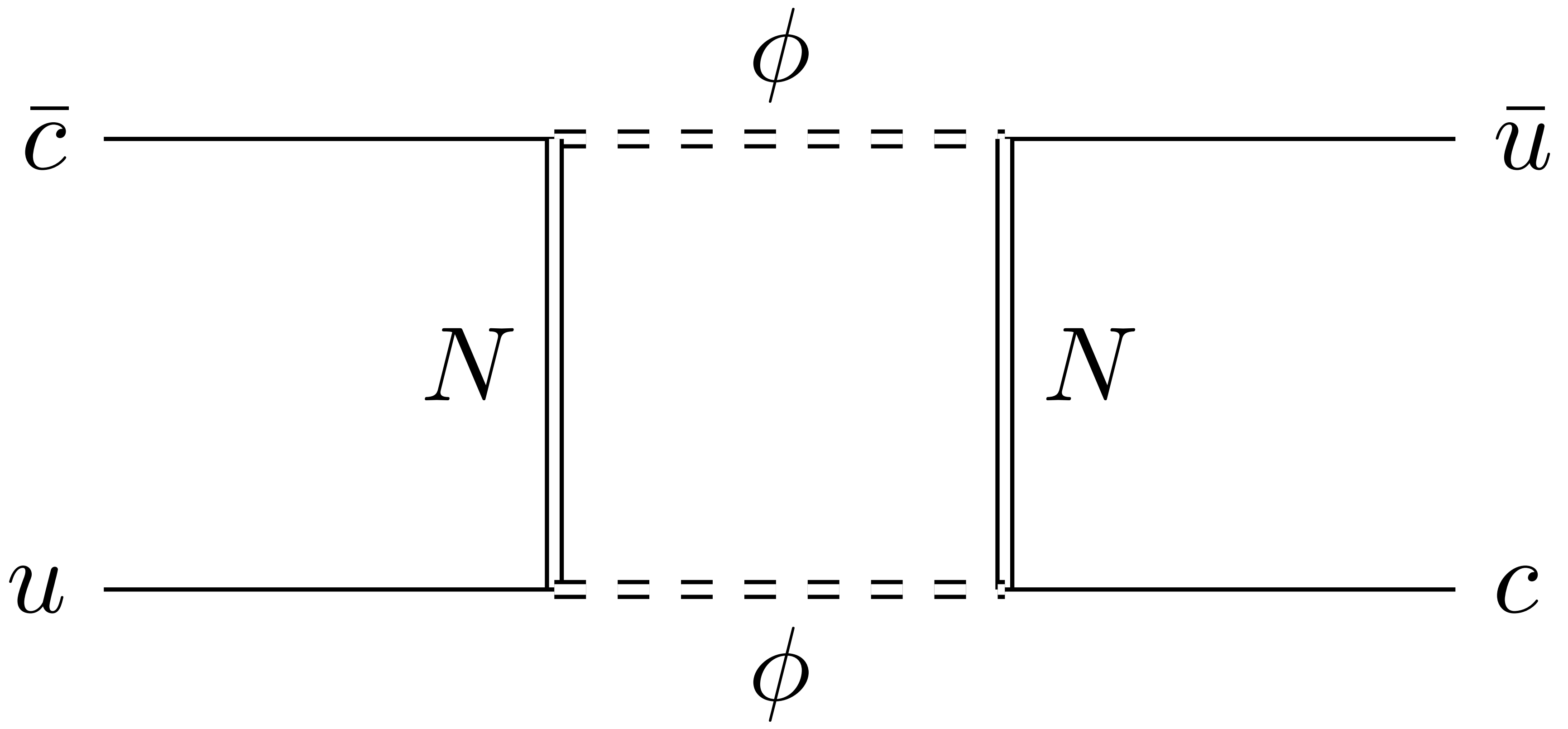
$\lambda_A \phi_A^\dagger \overline{D}_A \overline{D}_A$ $\quad$ $\kappa_A \phi_A \overline{U}_A \overline{N}_A$ $\quad$ $\kappa_B \phi_B \overline{U}_B N_B$ $\quad$ $\frac{\kappa_A \kappa_B f_\phi}{\sqrt{2} M_N} \phi_A \overline{U}_A \bar{t}_{3B}$

$$\mathscr{L}_{\rm FCNC} \supset -\tilde{C}^{uc} (\bar{c}\bar{\sigma}_\mu u)(\bar{u}\bar{\sigma}^\mu c) + \text{H.c.}$$

$$\tilde{C}^{uc} \simeq \frac{\kappa_{A,1\bar{I}} \kappa^*_{A,2I} \kappa_{A,2\bar{J}} \kappa^*_{A,1J}}{8\pi^2 M_N^2}$$

$$\kappa \lesssim \mathcal{O}(0.1)$$





Phenomenology

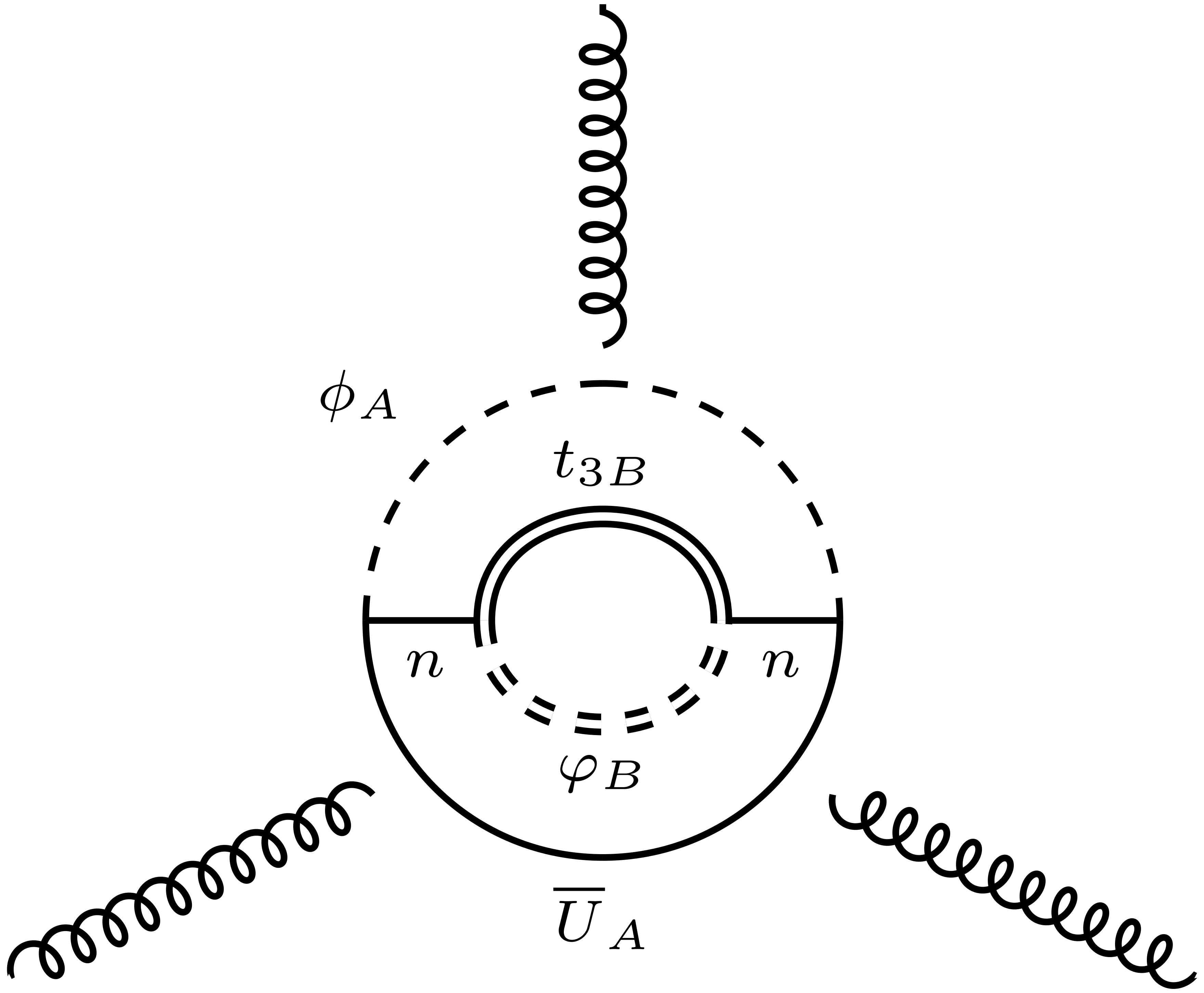
$\lambda_A \phi_A^\dagger \overline{D}_A \overline{D}_A$ $\kappa_A \phi_A \overline{U}_A \overline{N}_A$ $\kappa_B \phi_B \overline{U}_B N_B$ $\frac{\kappa_A \kappa_B f_\phi}{\sqrt{2} M_N} \phi_A \overline{U}_A \bar{t}_{3B}$

Precision measurement

$$\mathscr{L}_{\not{CP}} = -\frac{1}{3} \tilde{C}_G f^{ABC} \epsilon^{\mu\nu\rho\sigma} G^A_{\mu\lambda} G^{B\lambda}_{\nu} G^C_{\rho\sigma}$$

$$\frac{3g_s^3}{(16\pi^2)^3} \frac{\kappa^4}{M_N^2}$$

$$\kappa \lesssim \mathcal{O}(1)$$



Phenomenology

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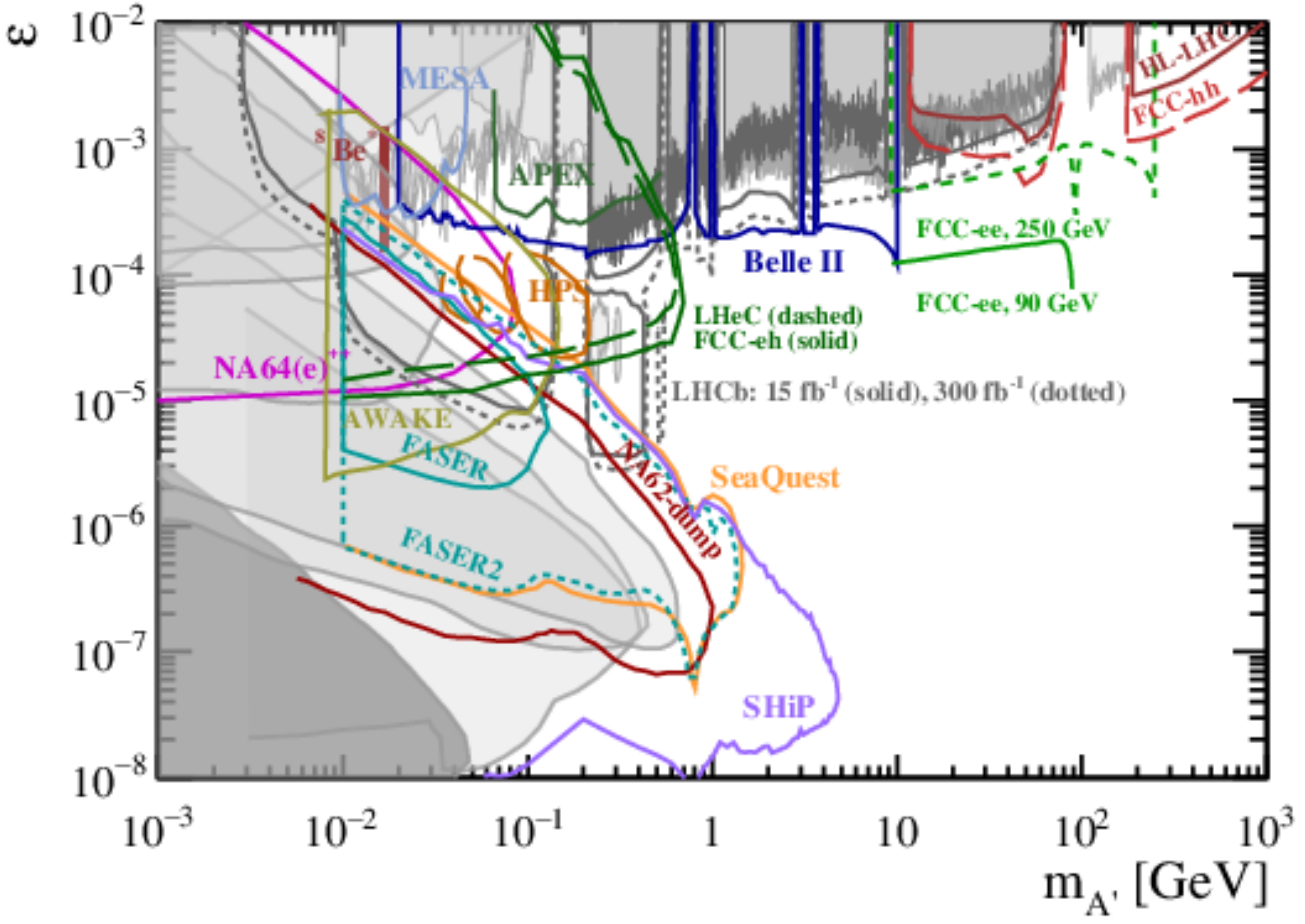
Dark Photon

To annihilate the symmetric part,
$m_{\gamma_B} \sim 1 \text{ GeV}$

For γ_B to decay before BBN ~ 10 MeV
the kinetic mixing $\varepsilon \sim 5 \times 10^{-9}$



Phenomenology

Dark Photon

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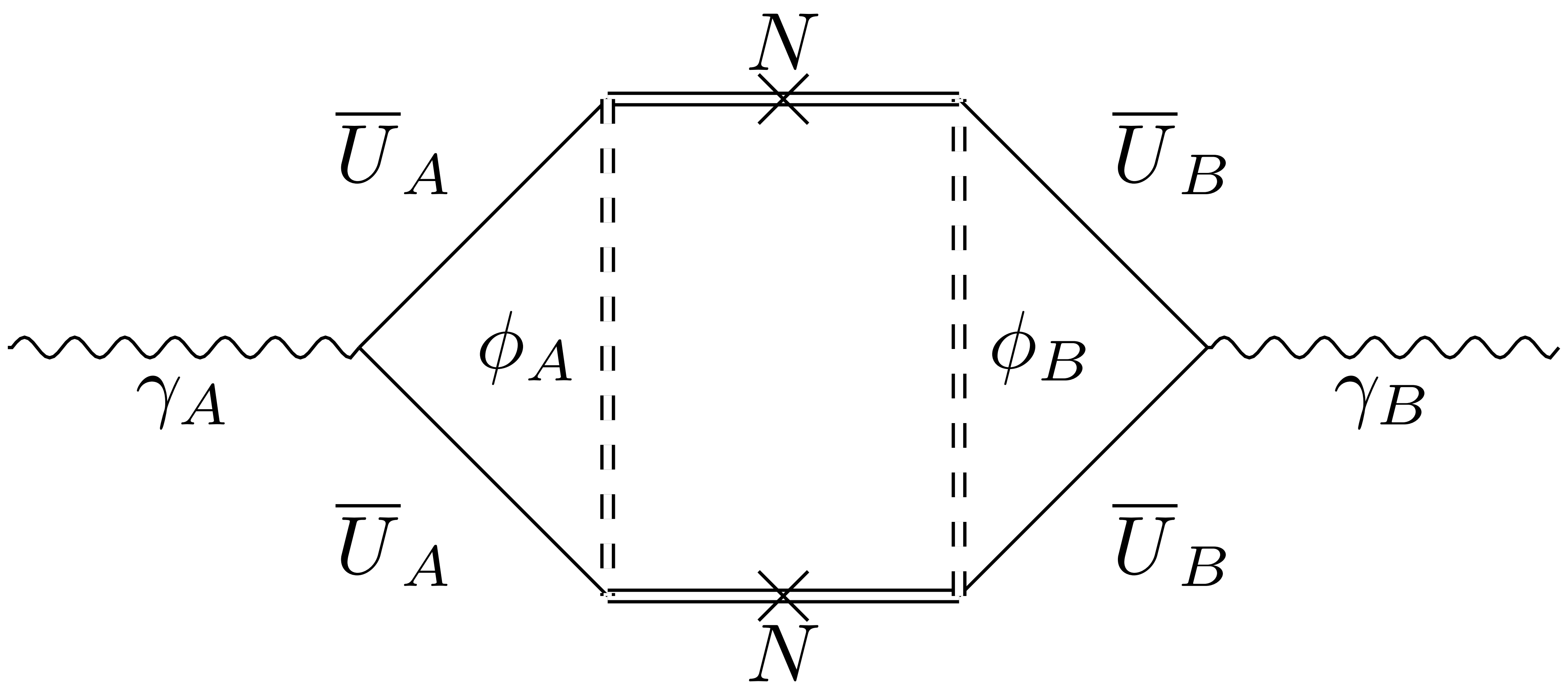
To annihilate the symmetric part,
$m_{\gamma_B} \sim 1\ \mathrm{GeV}$

For γ_B to decay before BBN ~ $10\ \mathrm{MeV}$
the kinetic mixing $\varepsilon \sim 5 \times 10^{-9}$

In Twin Higgs modes, $\varepsilon \sim 10^{-11}$,
induced at the four loop

$$\varepsilon_{\text{portal}} \sim \frac{e^2 \kappa^4}{(16\pi^2)^3} \approx 2.5 \times 10^{-8} \kappa^4$$



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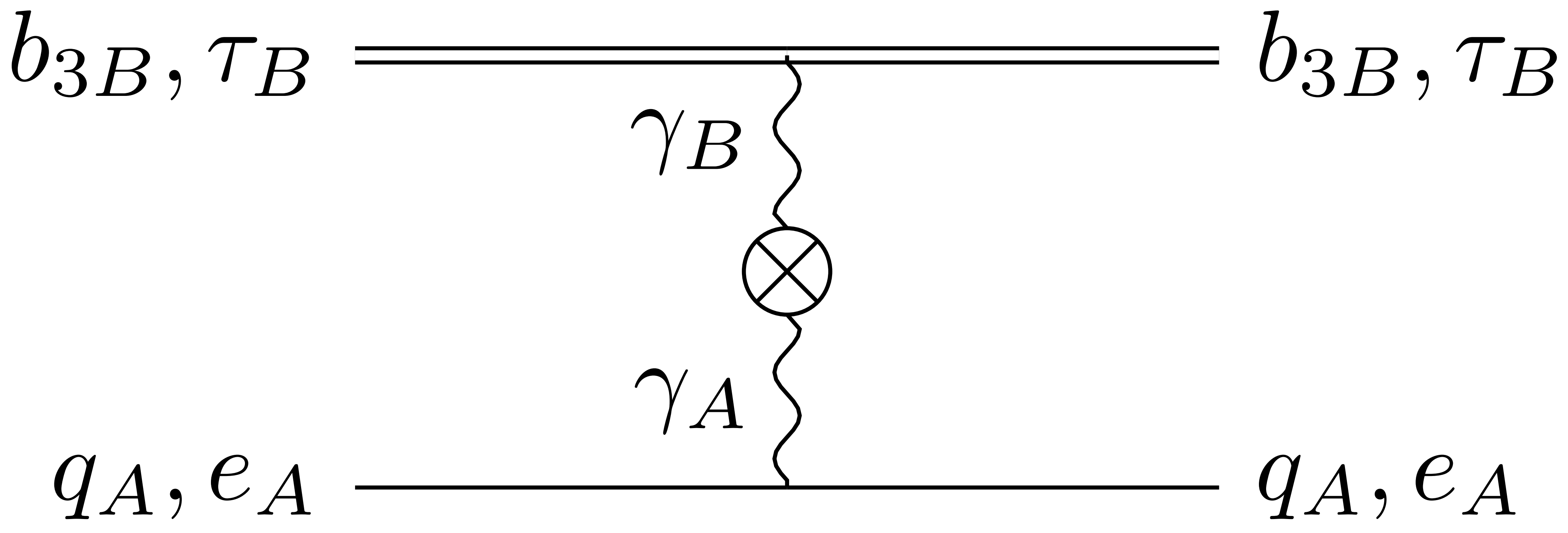
Direct Detection

b_{3B} and τ_B can scatter off nucleons due to the kinetic mixing

Current constraint: $\varepsilon < 10^{-3}$

Near future sensitivity: $\varepsilon \sim 10^{-4}$



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Twin Baryogenesis

Master Plot

$$\lambda_A \phi_A^\dagger \overline{D}_A \overline{D}_A \quad \kappa_A \phi_A \overline{U}_A \overline{N}_A \quad \kappa_B \phi_B \overline{U}_B N_B \quad \frac{\kappa_A \kappa_B f_\phi}{\sqrt{2} M_N} \phi_A \overline{U}_A \bar{t}_{3B}$$

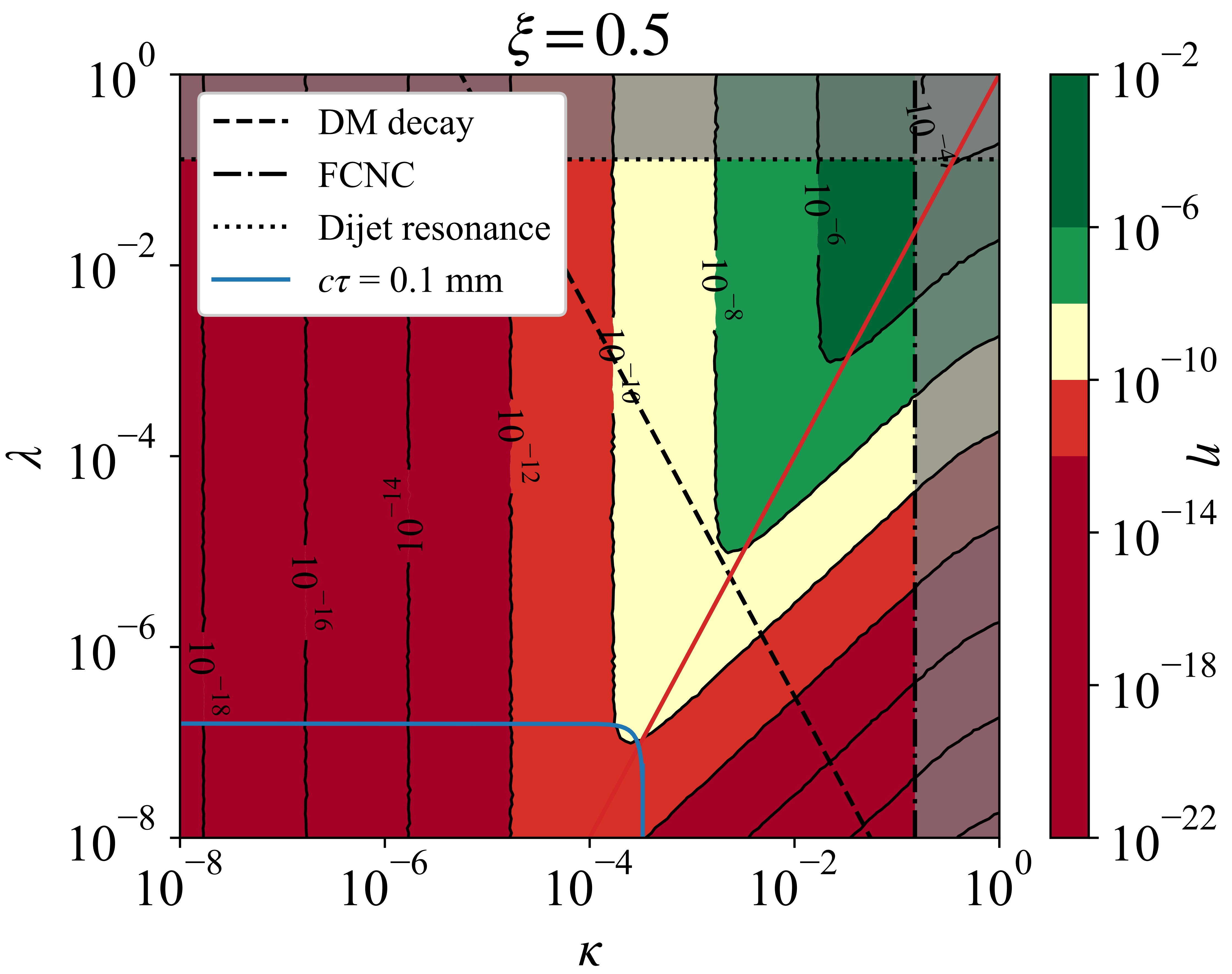
$$Y_{B_A} = Y_{B_B} = \eta Y_N \simeq 10^{-10}$$

$$Y_N \sim T_{\rm reh}/m_{\rm reh} \lesssim 10^{-1}$$

$$T_{\rm reh} \gtrsim \mathcal{O}(100)\ \text{GeV}$$

$$(M_N)_{\bar{I}J} = M_0 \left(\delta_{\bar{I}J} + \xi\ \sigma^3_{\bar{I}J}\right) + \frac{c_\Delta M_0}{16\pi^2} \left(\sum_i \kappa_{A,i\bar{I}} \kappa^*_{A,iJ} + \kappa^*_{B,\bar{I}} \kappa_{B,J} \right)$$

$$M_0 = f_\phi = 4\ \text{TeV},\ m_\phi = 2\ \text{TeV},$$
$$c_\Delta = 1$$



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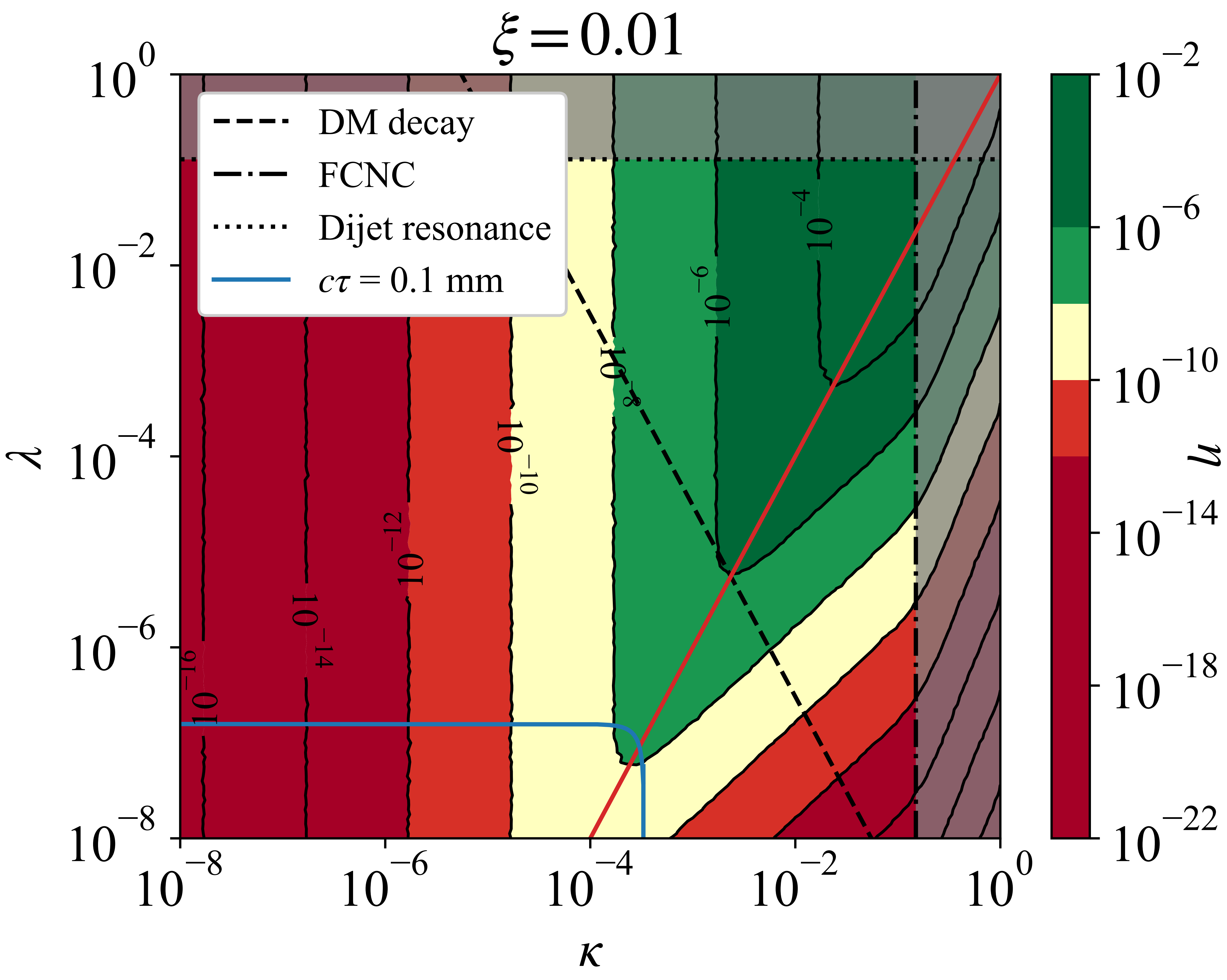

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