Light Z' and Dirac fermion dark matter at "Lifetime Frontier" Experiments

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Gauged $B - L$ Extension of Standard Model

- Global B-L symmetry in SM is gauged.
- N_R^i are necessary to cancel anomalies
- φ breaks B-L symmetry which generates Majorana masses for N_R^i and B-L gauge boson Z'.
- Seesaw Mechanism is automatically implemented to generate observed light neutrino masses.

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{B-L}$
q_L^i	3	2	$+1/6$	$+1/3$
u_R^i	3	1	$+2/3$	$+1/3$
d_R^i	3	1	$-1/3$	$+1/3$
ℓ_L^i	1	2	$-1/2$	-1
N_R^i	1	1	0	-1
e_R^i	1	1	-1	-1
H	1	2	$-1/2$	0
φ	1	1	0	$+2$

Dirac Dark Matter (DM) in $B - L$ Model

Symmetry/Fields	Q_L^i	u_R^i	d_R^i	L_L^i	e_R^i	N_R^i	H	ϕ	χ
$U(1)_{B-L}$	$1/3$	$1/3$	$1/3$	-1	-1	-1	0	2	Q

Dark Matter (χ) : $Q \neq \pm 1, \pm 3$

Stability of DM

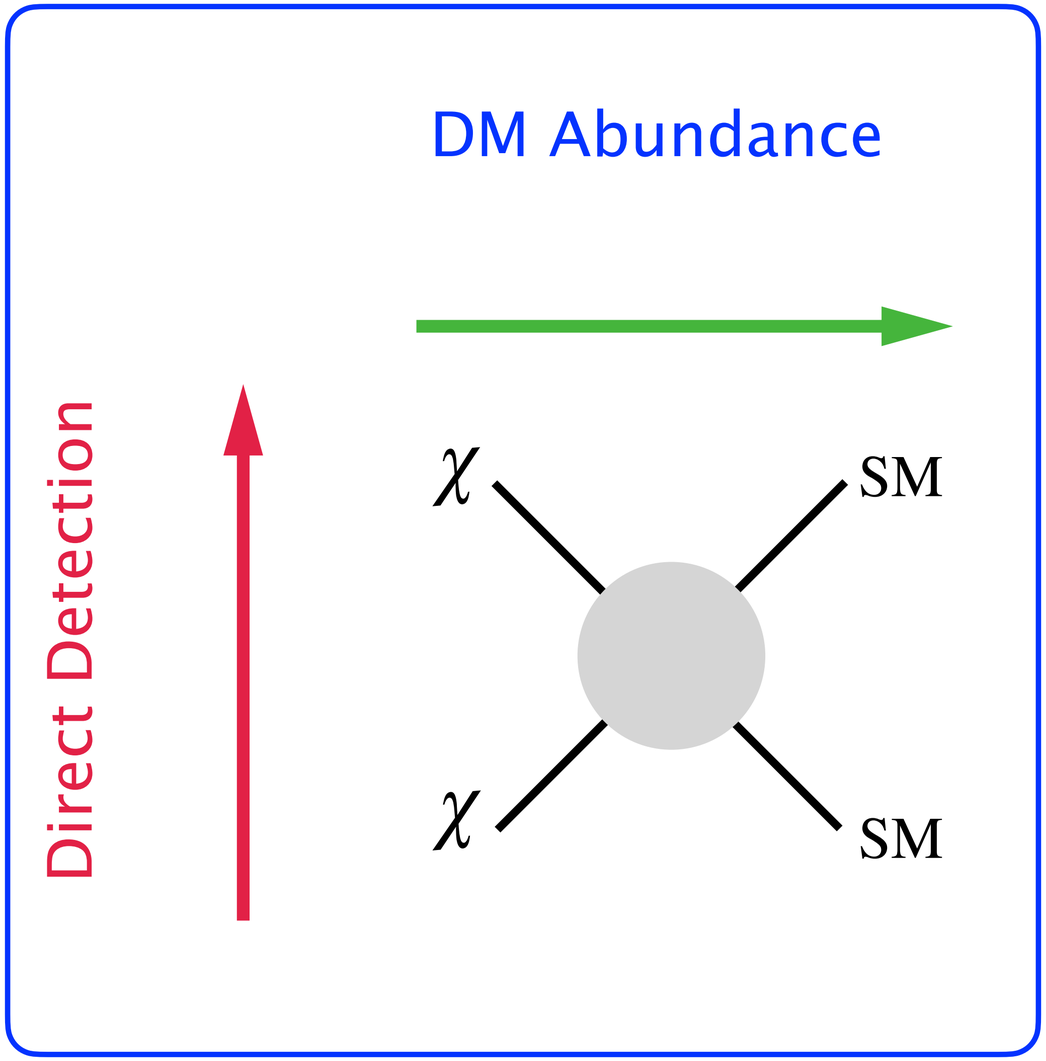
Z'- portal DM Interactions

$$\mathscr{L} \supset i g_{BL} Q \left(\bar{\chi}\gamma^{\mu}\chi\right) Z'_{\mu} \quad + \quad i g_{BL} Q_f \left(\bar{f}\gamma^{\mu} f\right) Z'_{\mu}$$

$$+ m_{\chi}\bar{\chi}\chi$$

Parameters: $Q,\ g_{BL},\ m_{Z'},\ m_{\chi}$

We focus on weakly couple light DM (sub GeV to GeV range).



DM Abundance

I. Freeze-Out

II. Freeze-In

Parameters: $Q,\ g_{BL},\ m_{Z'},\ m_{\chi}$

Direct Detection Bound

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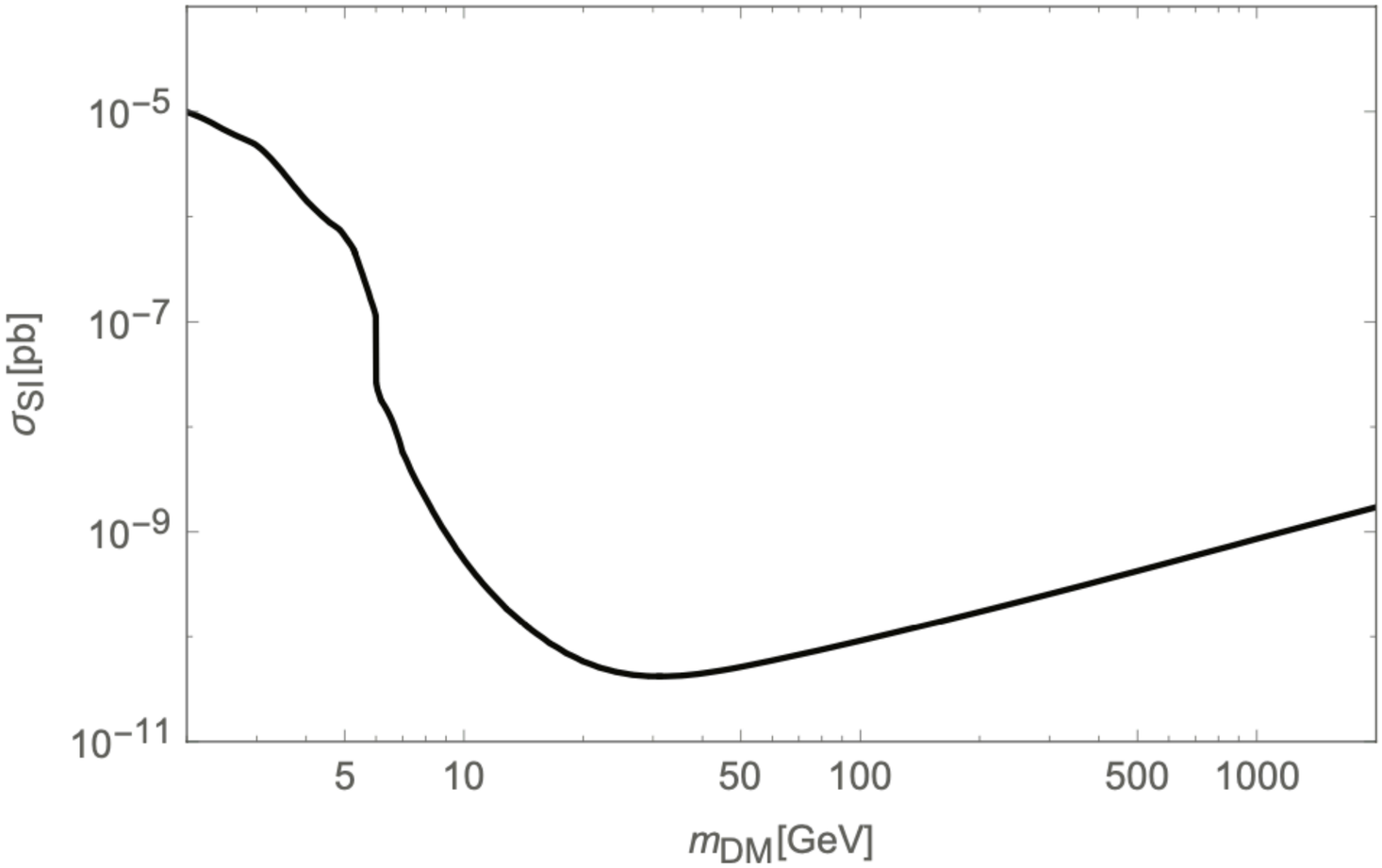
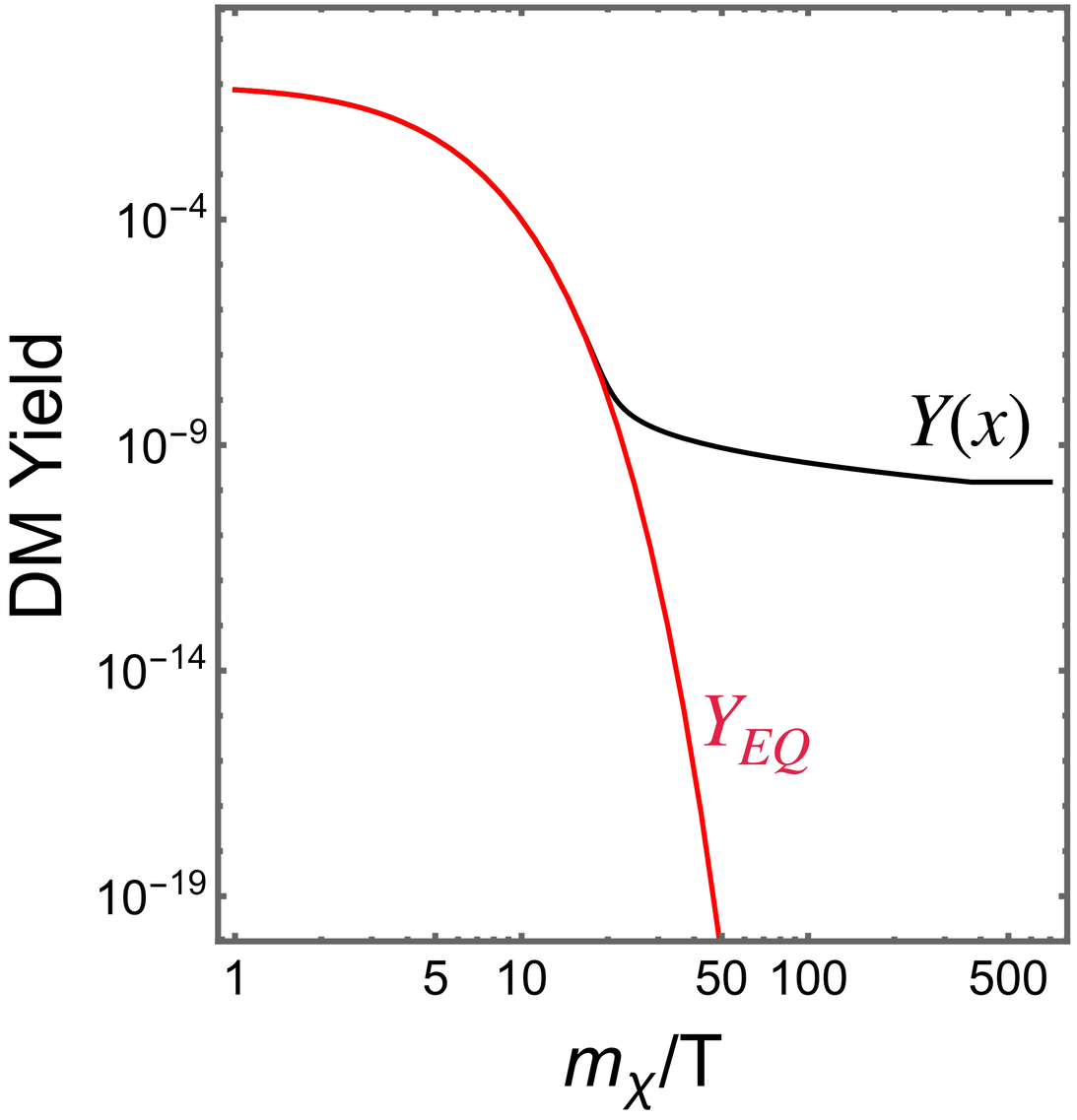


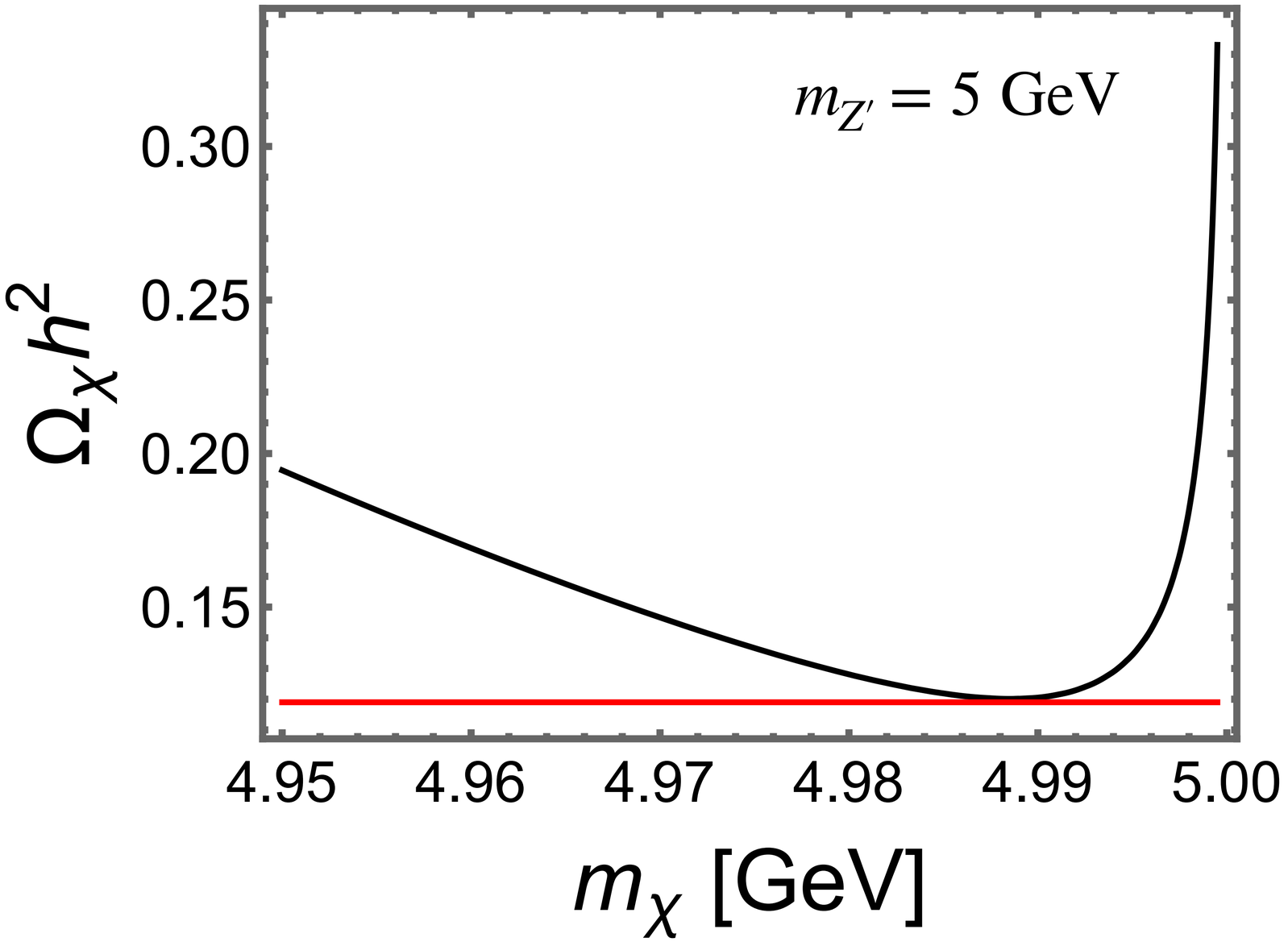
$$\sigma_{SI} \simeq \frac{1}{\pi}\left(\frac{\mu}{m_{Z'}^2} Q g_{BL}^2\right)^2$$

$$\mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

(I) Freeze-Out Scenario



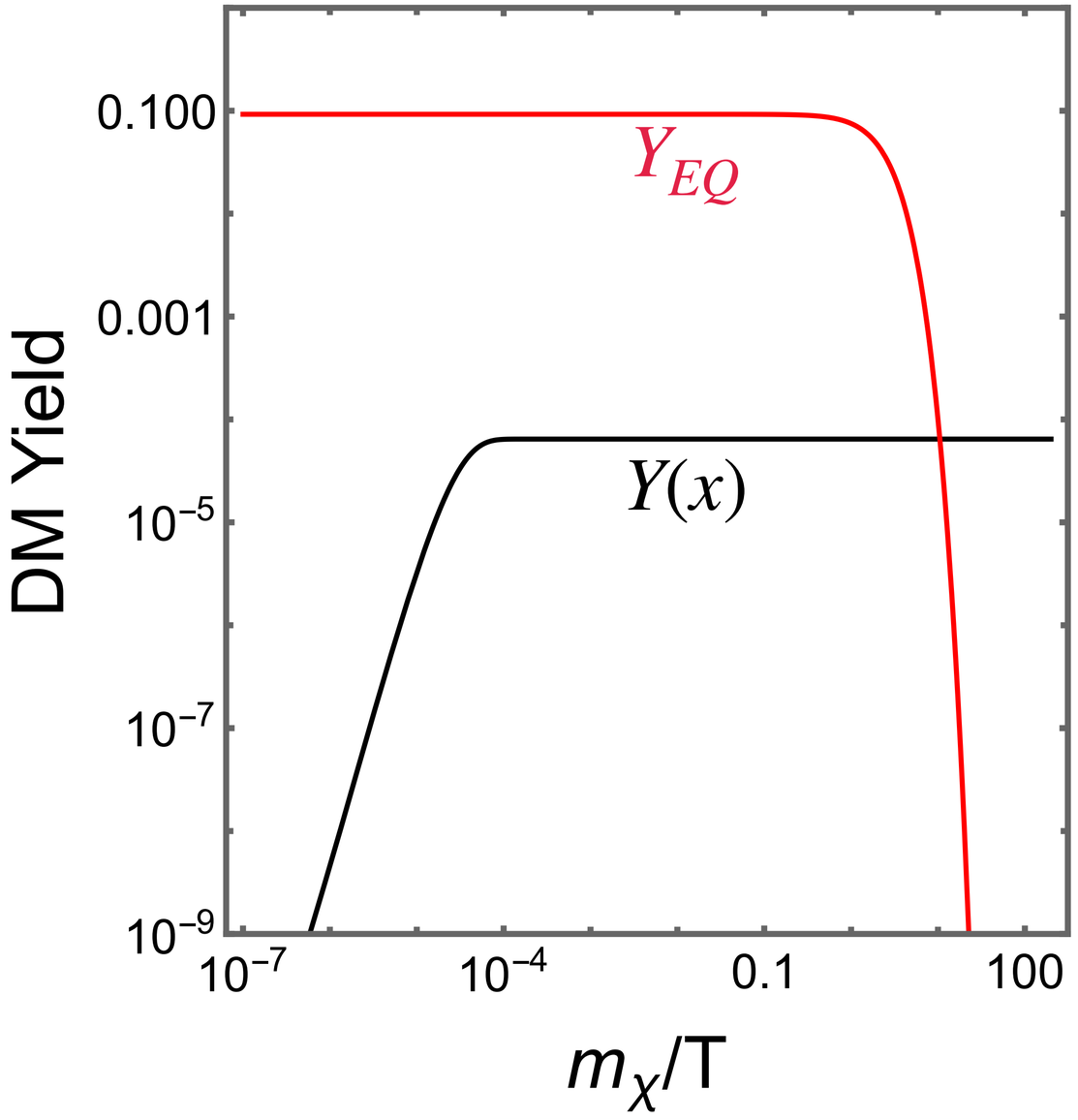
- DM interaction at early times is strong enough to keep it in thermal equilibrium with the plasma.
- At late times, the expansion rate of the universe dominates and the DM decouples or “freezes out”.



DM relic abundance is satisfied near the resonance:

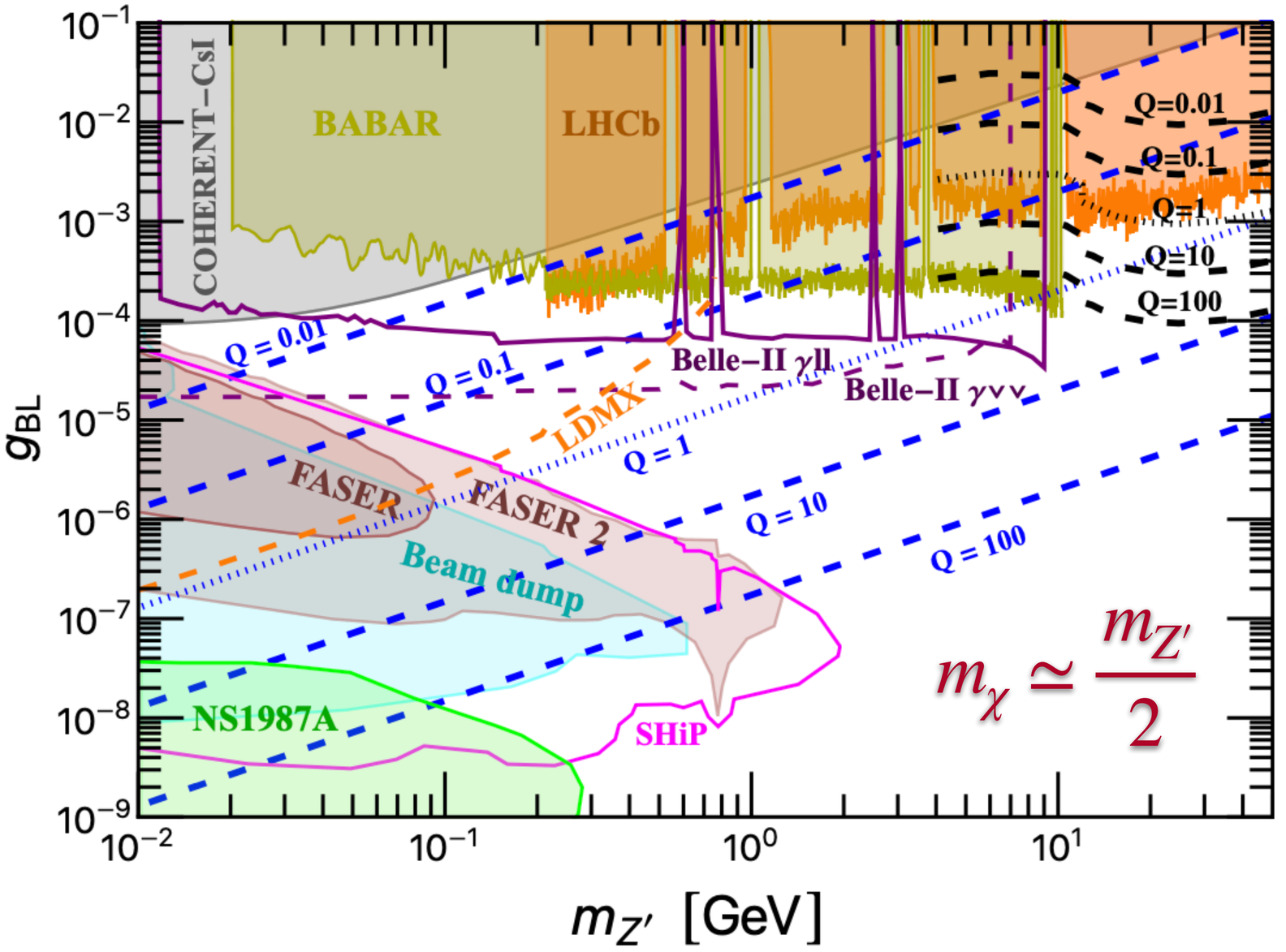
$$m_\chi \simeq \frac{m_{Z'}}{2}$$

(II) Freeze-In Scenario



- DM starts with zero abundance
- DM coupling is too small to achieve thermal equilibrium with the plasma.
- DM production stops at $T \sim m_\chi$ and its abundance "freezes-in".

Result: Freeze-Out

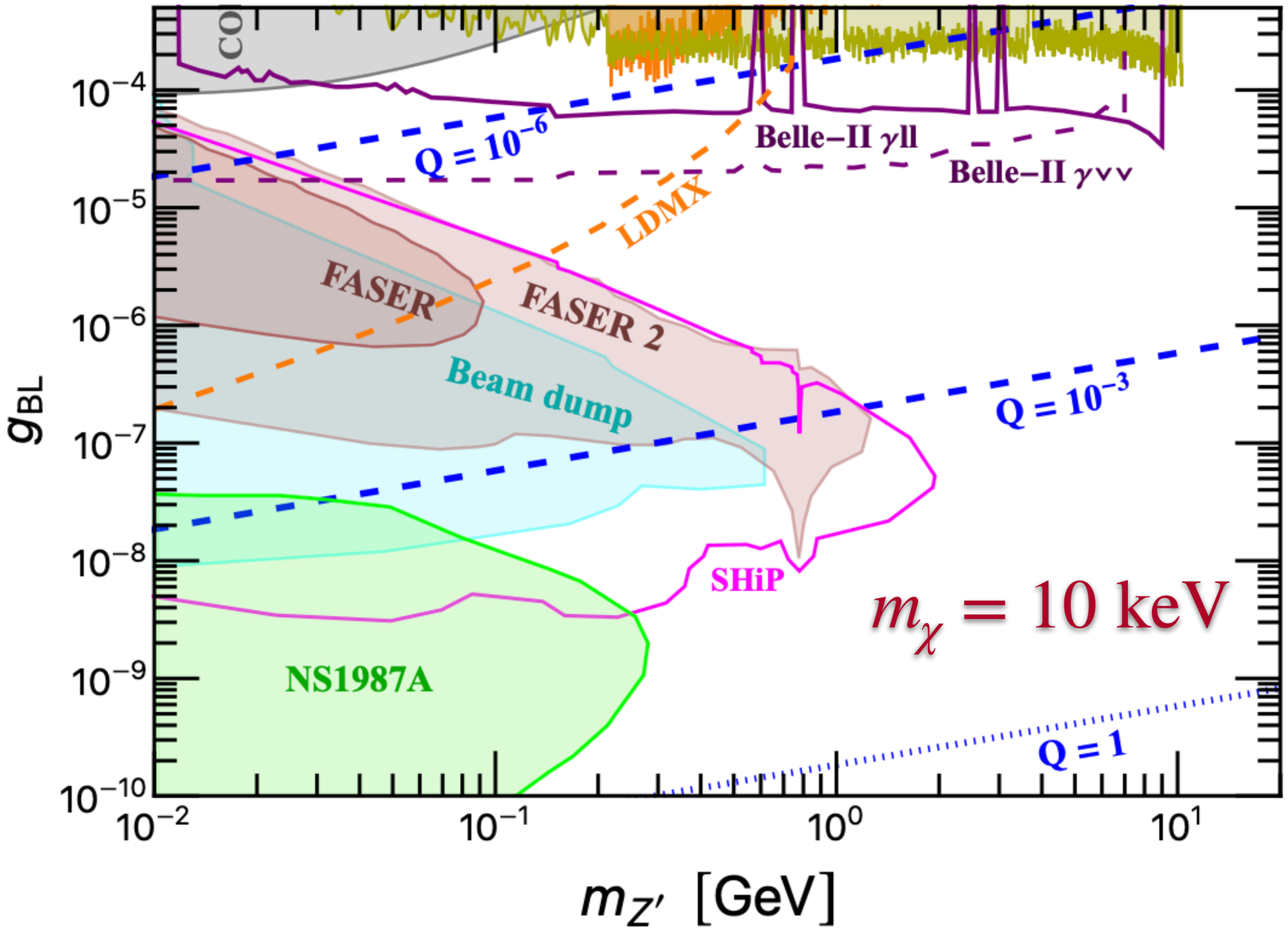


Direct Detection Bounds

Scaling Relation:

$$g_{BL} \times Q \simeq 1.7 \times 10^{-5} \left(\frac{m_{Z'}}{1\ \text{GeV}} \right)^{1.07}$$

Result: Freeze-In



Direct Detection bounds not applicable since the DM is very light

Scaling Relation:

$$g_{BL} \times Q \simeq 2.5 \times 10^{-12} \left(\frac{m_{Z'}}{m_\chi} \right)^{1/2}$$

Key Results:

- We have shown that a Z'- portal Dirac Fermion DM with B-L charge $Q \neq \pm 1, \pm 3$ and light (sub-GeV to KeV) mass can reproduce DM abundance in both freeze-out and freeze-in scenarios.

- In the Freeze-out the relic abundance is realized near the resonance.

- In the freeze-in scenario the Q values to realize observable g_{BL} values are found to be much smaller than that in the freeze-out scenario.

- The parameter space in both the scenarios can be tested at various planned/ proposed lifetime frontier experiments such as FASER, Belle-II, SHiP and LDMX.