Neutrino Masses and Mixings from Milli-charged Dark Matter

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Collaboration with Sudip Jana, Michael Klasen, and Luca Paolo Wiggering
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institut für theoretische physik

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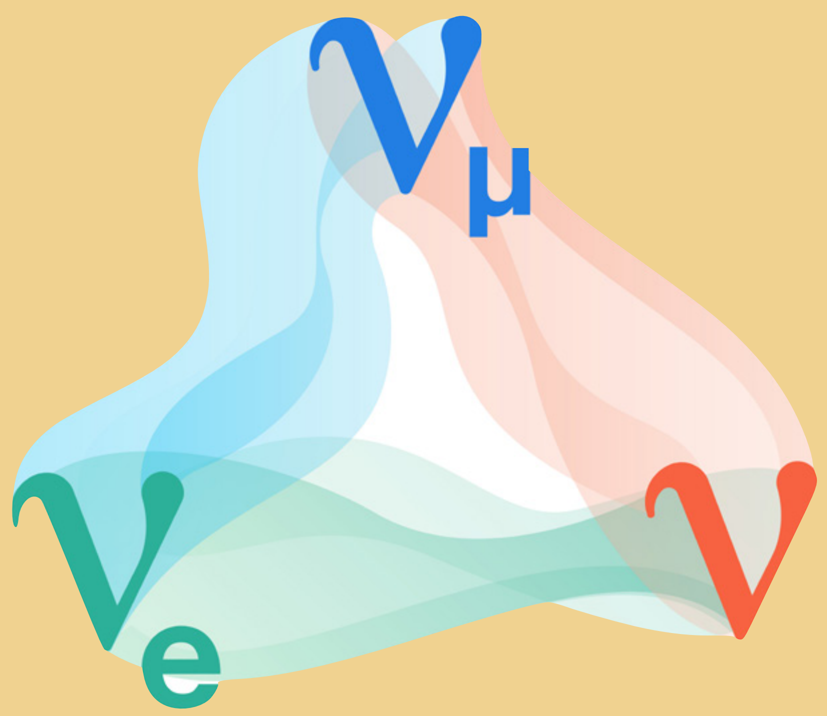
14 -18 October 2024, Hyderabad, India

Introduction

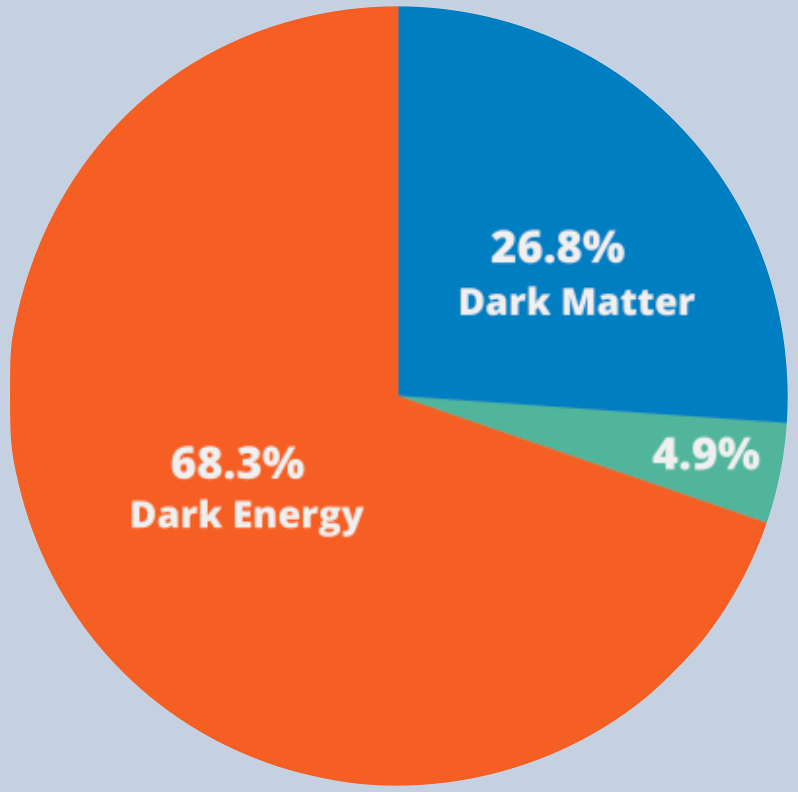
Neutrino masses and mixings



Neutrino oscillation data show:

- Neutrinos have tiny, but non-zero masses
- Direct evidence for physics beyond the SM

Dark matter



Data show:

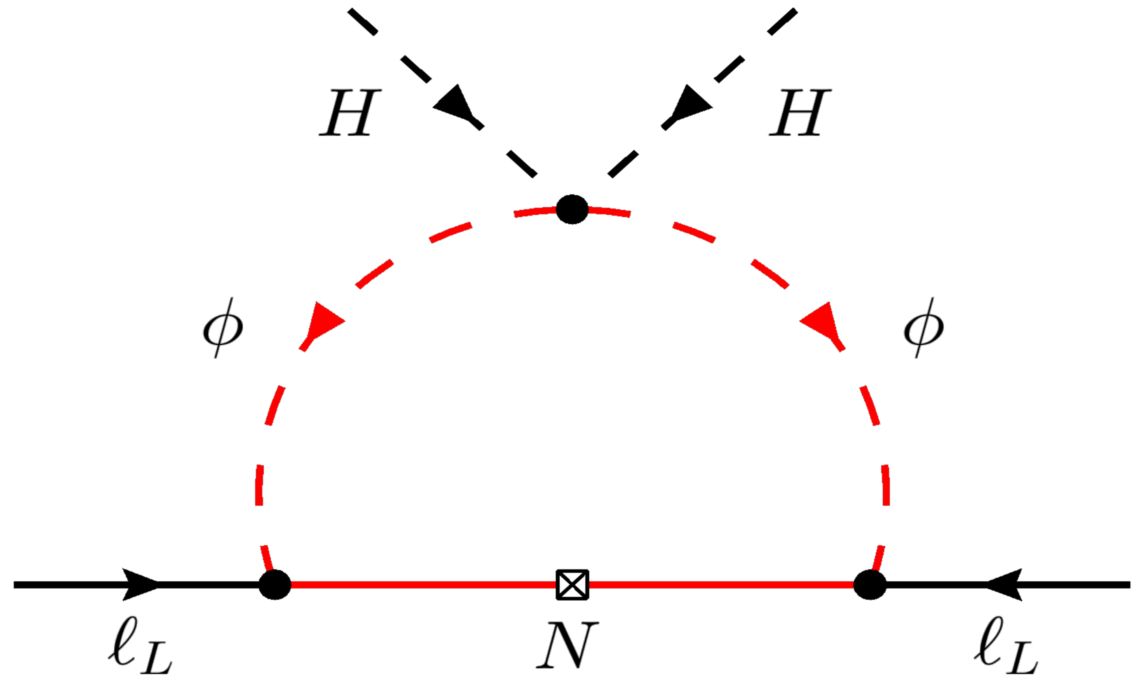
- Dark matter constitutes 27% of energy budget of Universe
- No suitable candidate within the SM

Scotogenic mechanism

Neutrino mass is generated radiatively by dark sector particles:

$N_{1,2} \sim (1,1;\, -\,)$

$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \sim (1,2,\frac{1}{2};\, -\,)$



Requires a new symmetry to stabilize dark matter

Z. Tao (1996)
E. Ma (2006)

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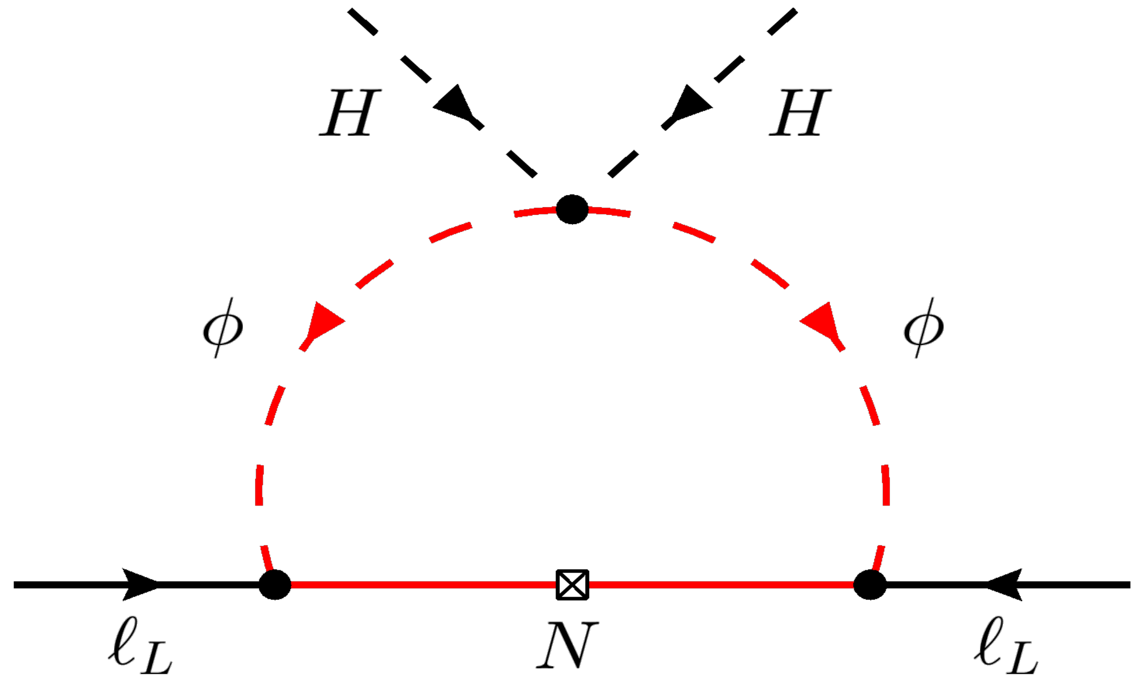

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Can the SM gauge symmetry alone stabilize dark matter within the scotogenic setup?

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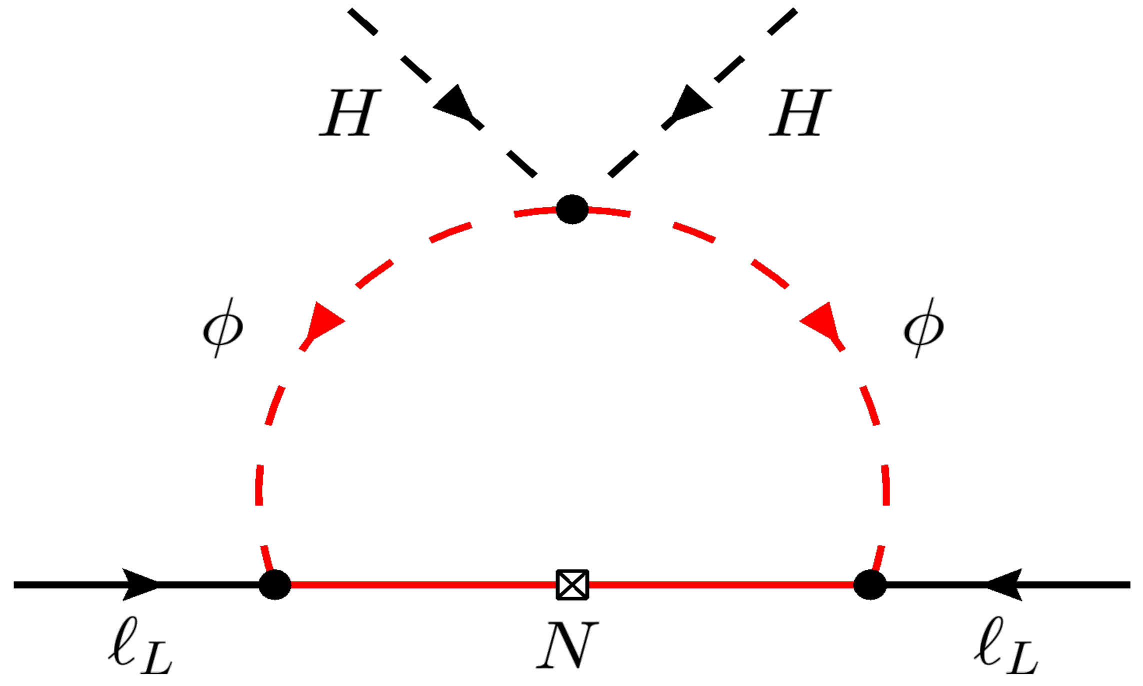

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Higher representations of $SU(2)_L$ symmetry

- Dark matter stability: ensured by an accidental symmetry

M. Cerilli, N. Fornengo, A. Strumia (2006)
M. Cerilli, A. Strumia (2009)

- But: typically requires imposition of an approximate symmetry; requires large no.of multiplets
- Higher dimensional terms could leads to dark matter decay

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K. Kumericki, I. Picek and B. Radovcic (2012)
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Y. Cai and M. A. Schmidt (2016)

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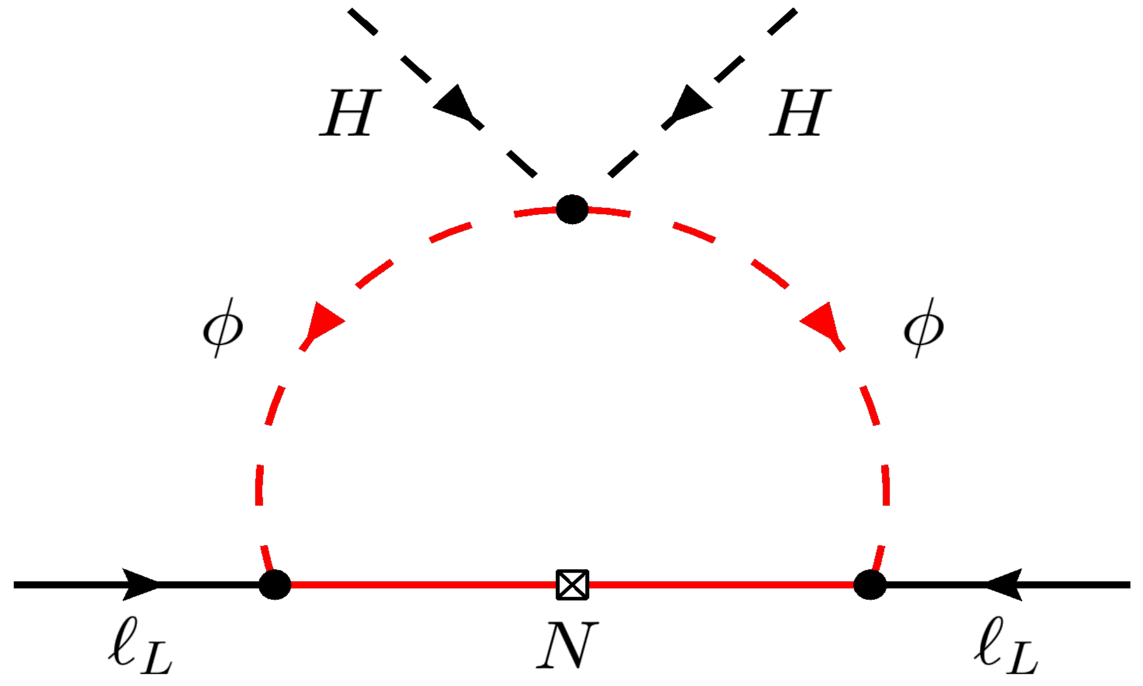

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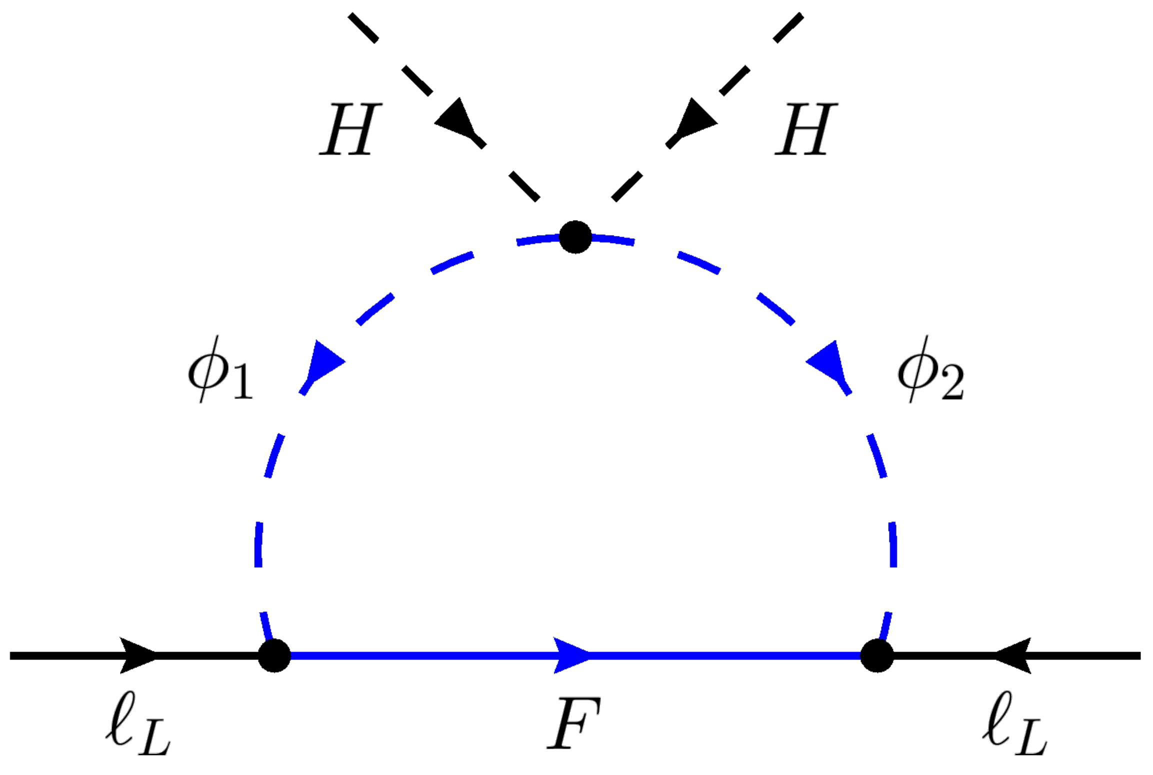
Milli-charged dark matter

- Dark matter stability: ensured by electromagnetic gauge symmetry
- Stablility is protected upto all orders in the EFT expansion
- Model content: more minimal

Neutrino mass from milli-charged dark matter

Neutrino mass is generated at one-loop level:



$F \sim (1,1,\epsilon)$

$$\phi_1 = \begin{pmatrix} \phi_1^{1+\epsilon} \\ \phi_1^{\epsilon} \end{pmatrix} \sim (1,2,\frac{1}{2}+\epsilon)$$

$$\phi_2 = \begin{pmatrix} \phi_2^{1-\epsilon} \\ \phi_2^{-\epsilon} \end{pmatrix} \sim (1,2,\frac{1}{2}-\epsilon)$$

- The lightest milli-charged particle is stable, can be a viable candidate for dark matter
- To be consistent with various constraints, $\epsilon \ll 1$ (wait for next slide)
- Electric charge dequantization! Charge is not quantized in the SM: may be a hint!

R. Foot (1991)
R. Foot, G. C. Joshi, H. Lew, and R. R. Volkas (1990)

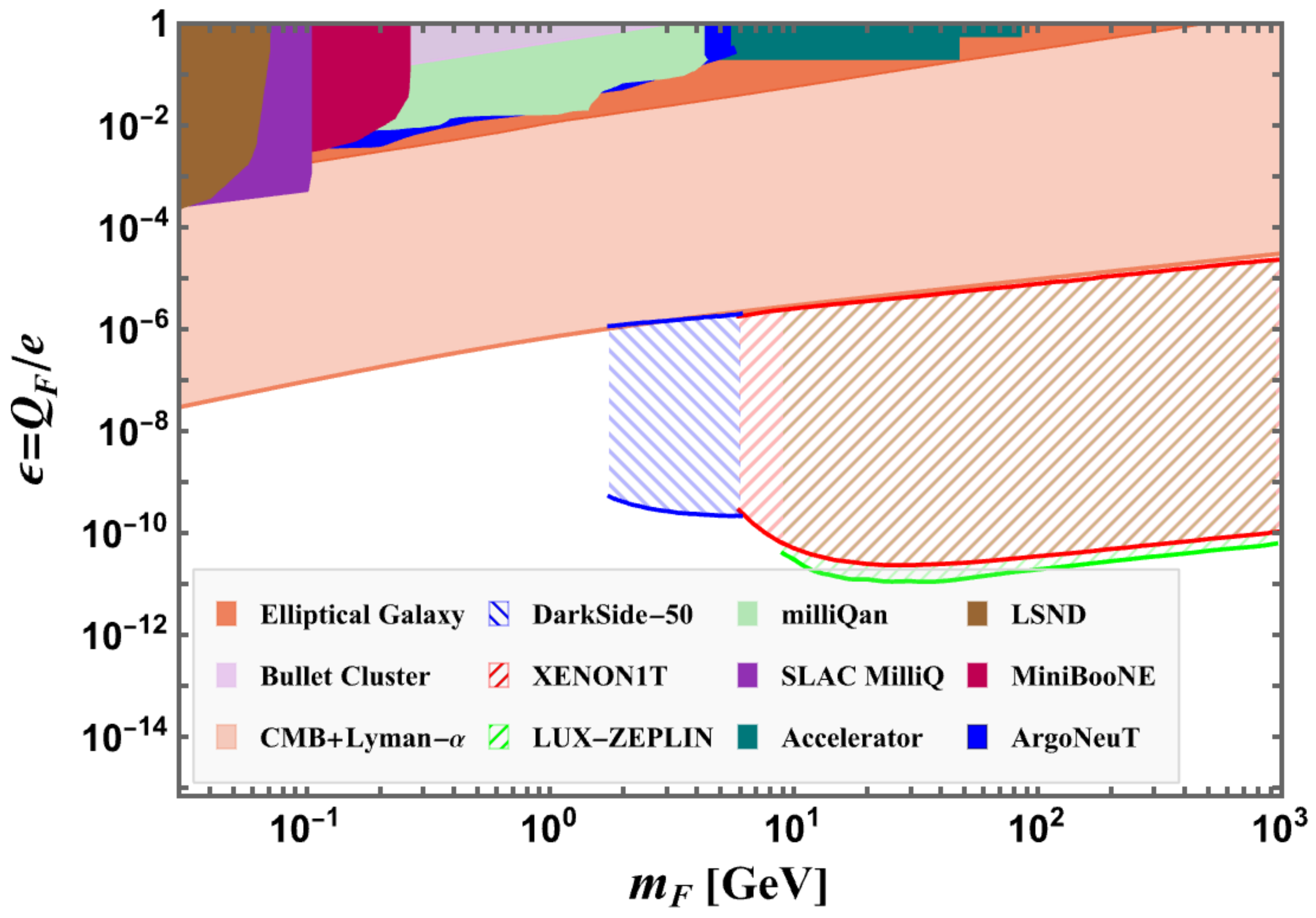
Status of milli-charged dark matter searches

DM direct detection expts.

- *DM can scatter off the nuclei at tree level via photon exchange*
- *The null results from these expts constraints the charge of the DM*

Collider or fixed target expts.

- *Milli-charged DM can be produced via the Drell-Yan process or via the decay of various mesons*
- *The null results from these searches constraints the parameter space*



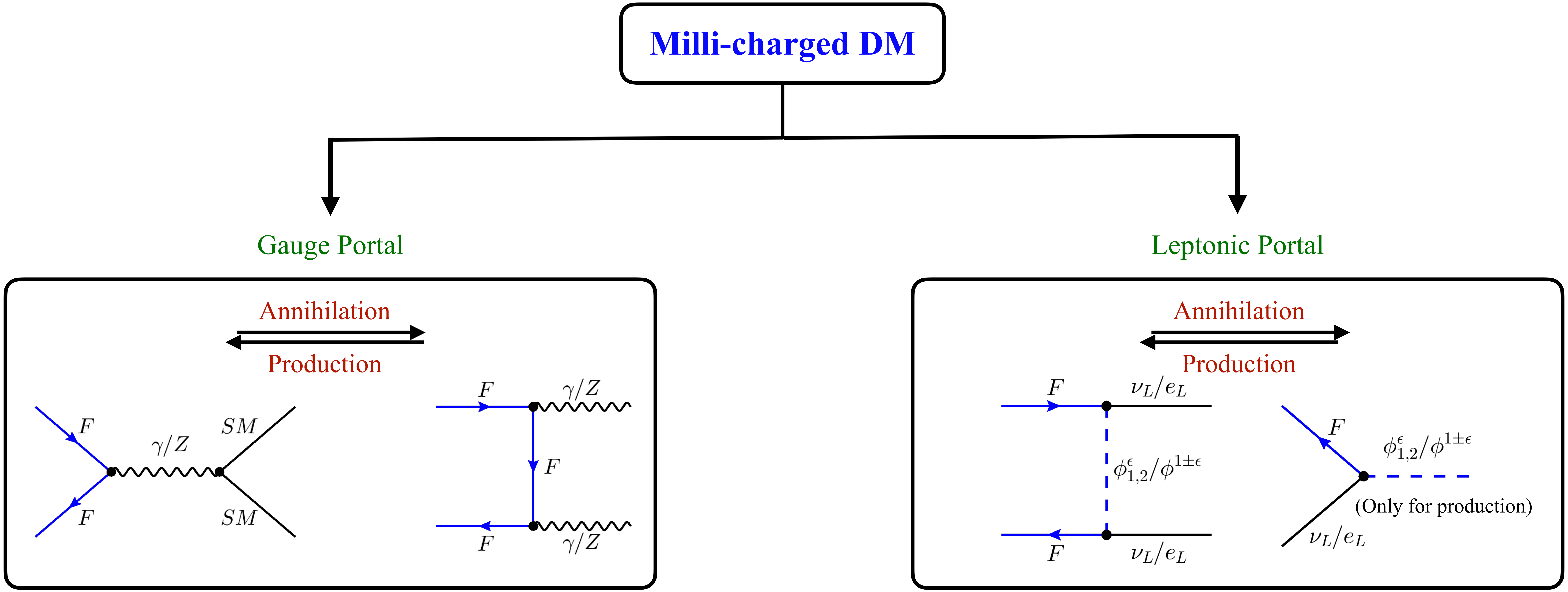
DM self -interactions

- *Milli-charged DM can have sizeable self-interactions*
- *Such interactions are constrained from bullet cluster and elliptical glaxy*

CMB data

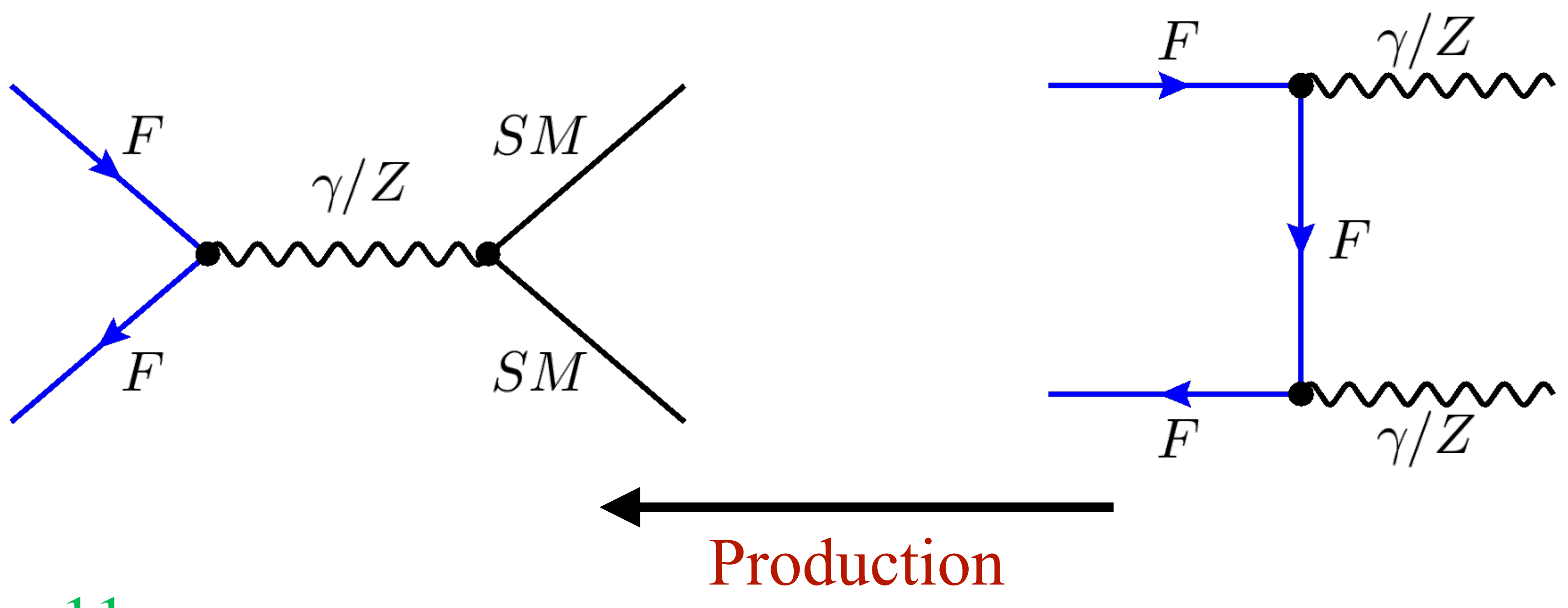
- *Milli-charged DM can couple tightly with photon-baryon plasma even at the low temperature*
- *Such coupling during recombination era could affect CMB observables significantly*

Different portals

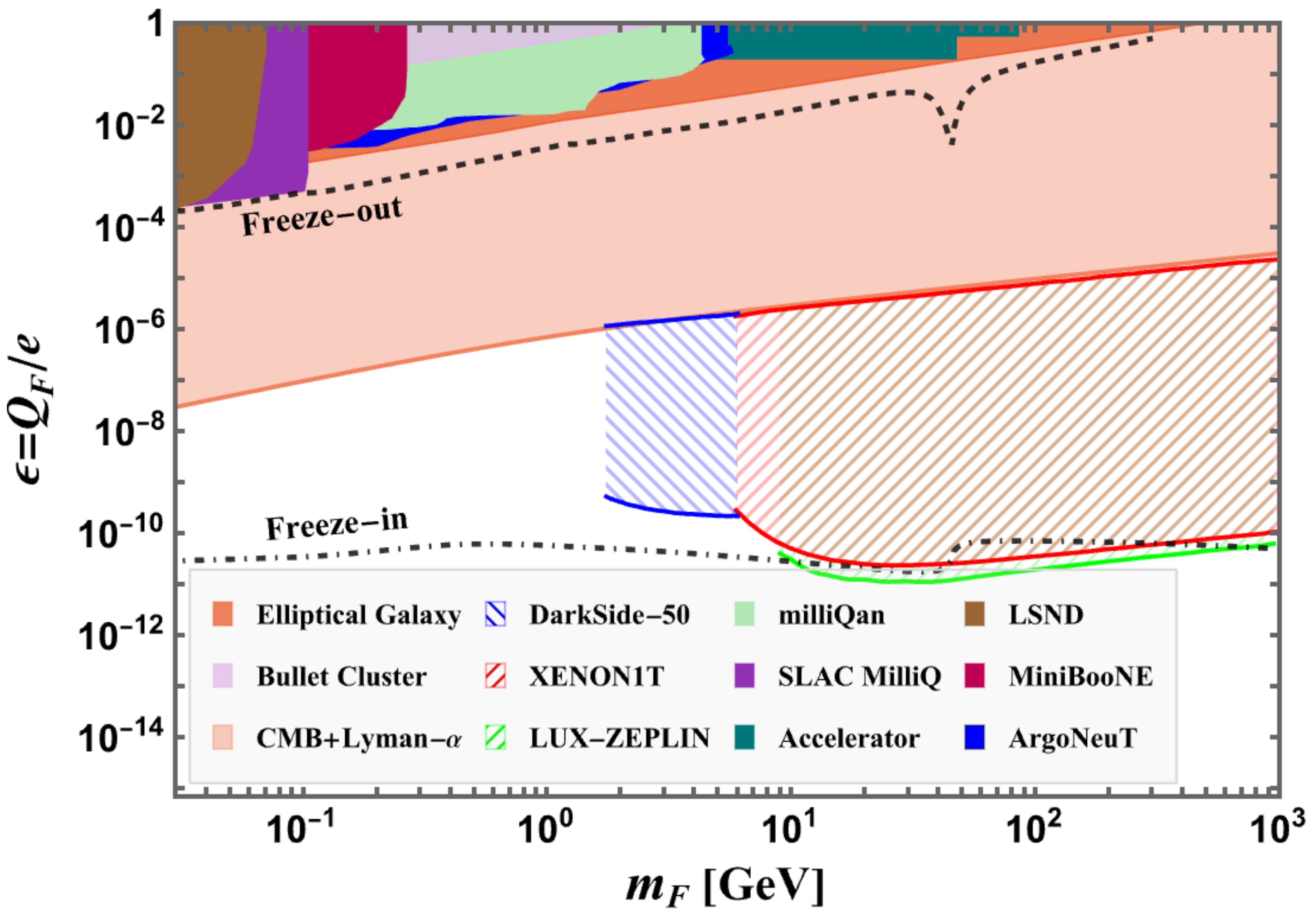


Freeze-in scenario

- Gauge portal: dominant production via annihilation of SM particles



$\epsilon \simeq 10^{-11}$ is required to satisfy correct relic abundance; consistent with out-of-equilibrium condition



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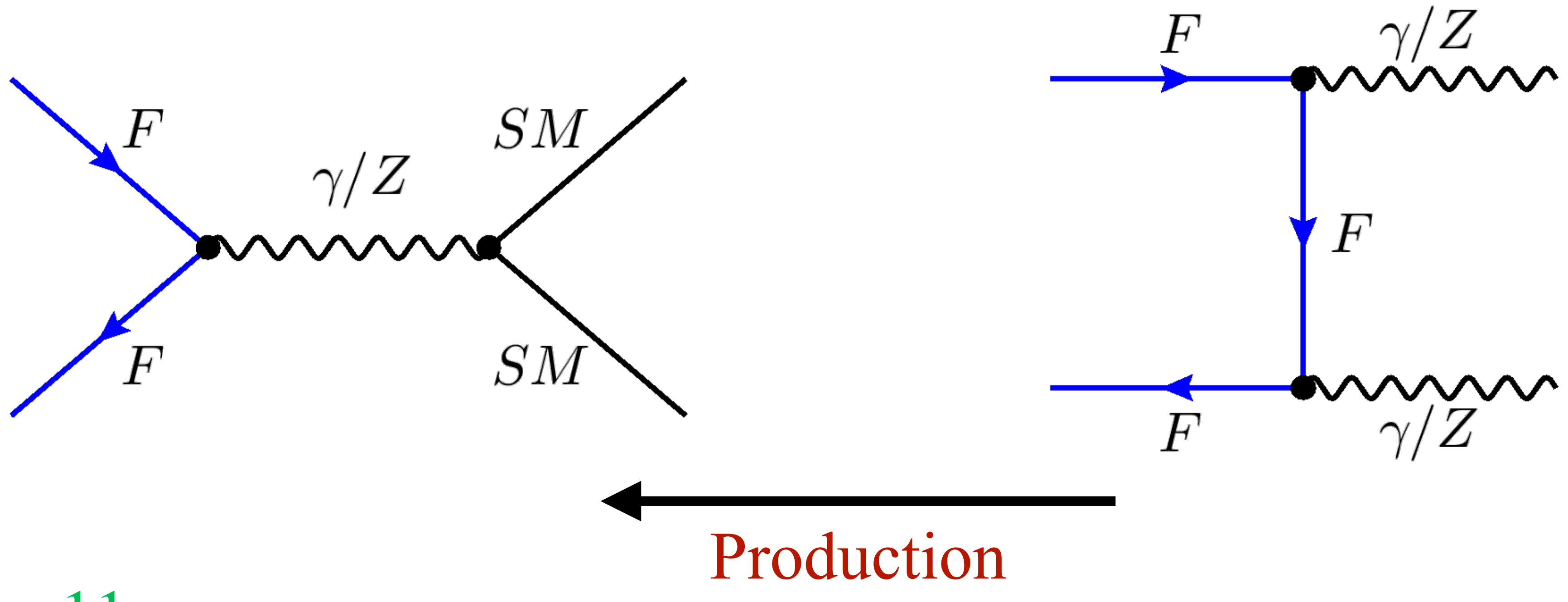

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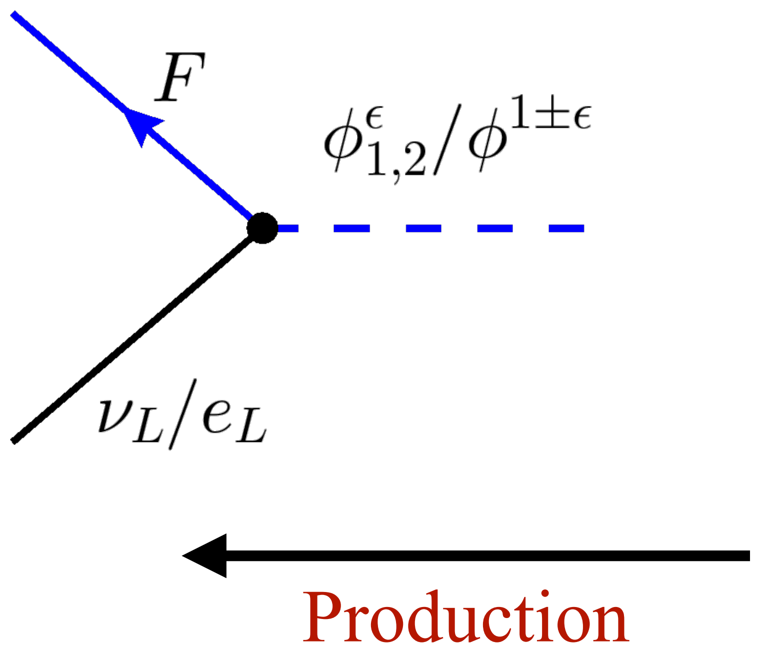
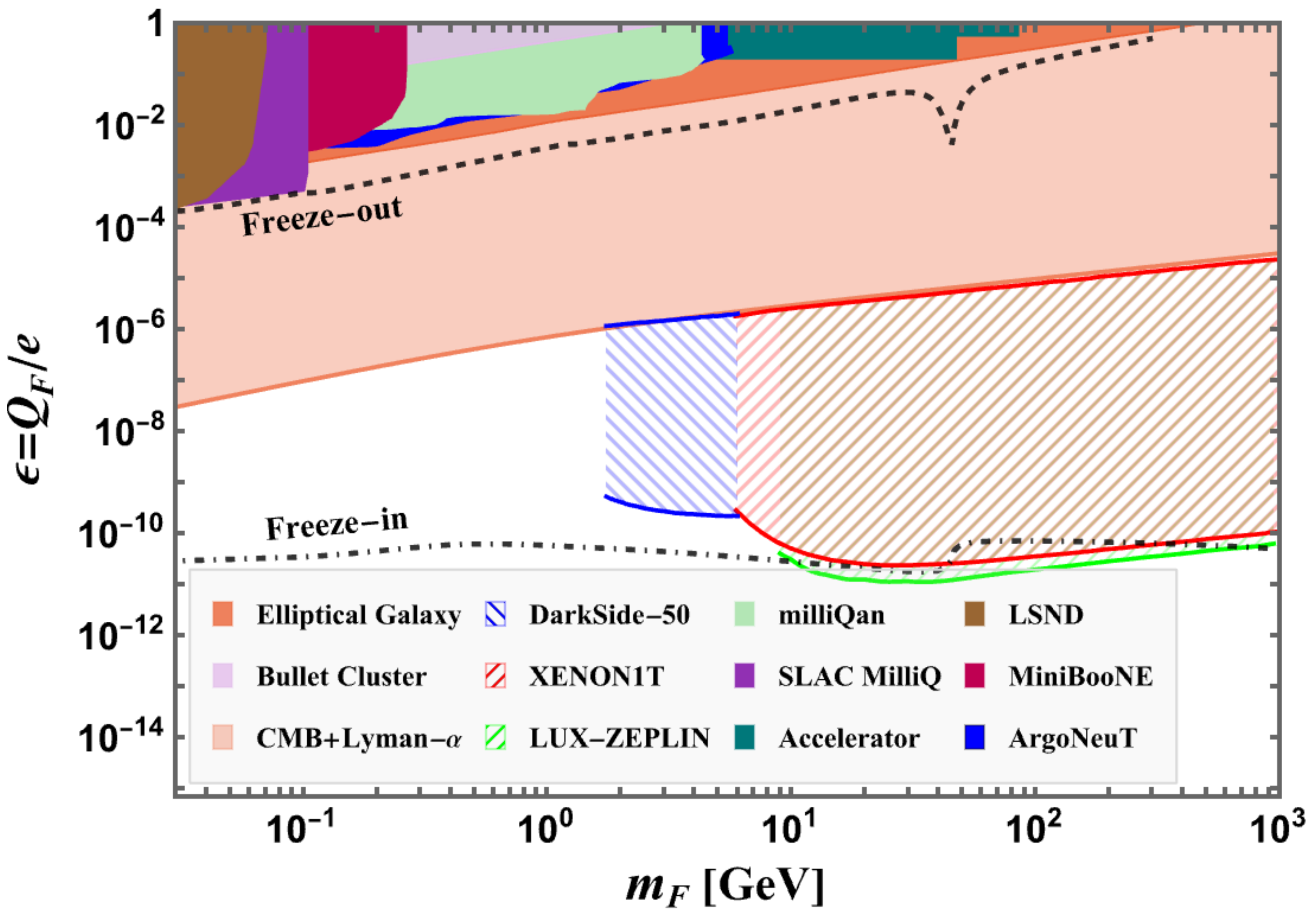
- Leptonic portal: dominant production via decay of BSM scalars





Out-of-equilibrium condition requires

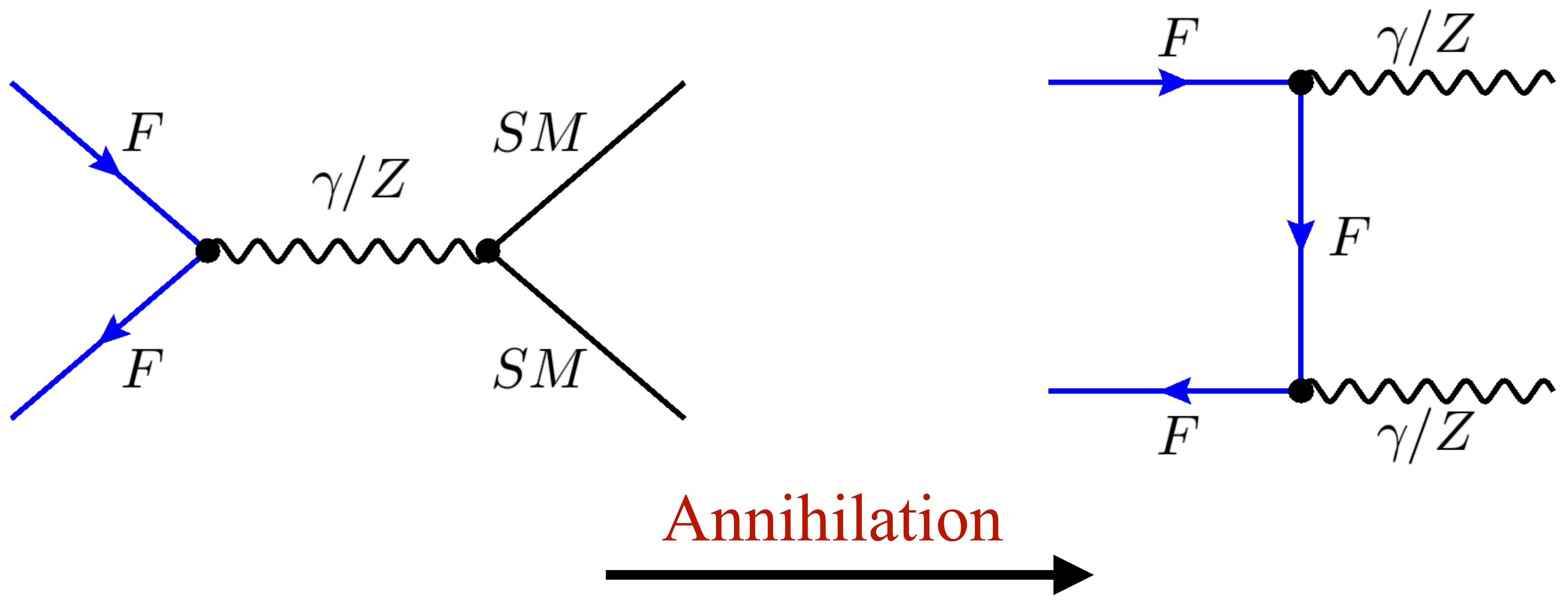
$$\Gamma(\phi \to F\ell) \lesssim H|_{T\simeq m_\phi} \Longrightarrow |Y_{1,2}| \lesssim 10^{-8}\sqrt{\frac{m_{\phi_{1,2}}}{100\,\mathrm{GeV}}}$$

$$M_\nu \simeq \begin{cases} 10^{-9}\mathrm{eV}\left(\frac{\mathrm{m_F}}{1\mathrm{GeV}}\right)\left(\frac{\sin 2\theta}{1}\right) & m_{S_{1,2}} \sim \mathcal{O}(100)\mathrm{GeV}, \\ 10^{-11}\mathrm{eV}\left(\frac{\mathrm{m_F}}{1\mathrm{GeV}}\right)\left(\frac{\lambda_{\mathrm{H}\phi_1\phi_2}}{2}\right) & m_{S_{1,2}} \sim \mathcal{O}(100)\mathrm{TeV}, \end{cases}$$

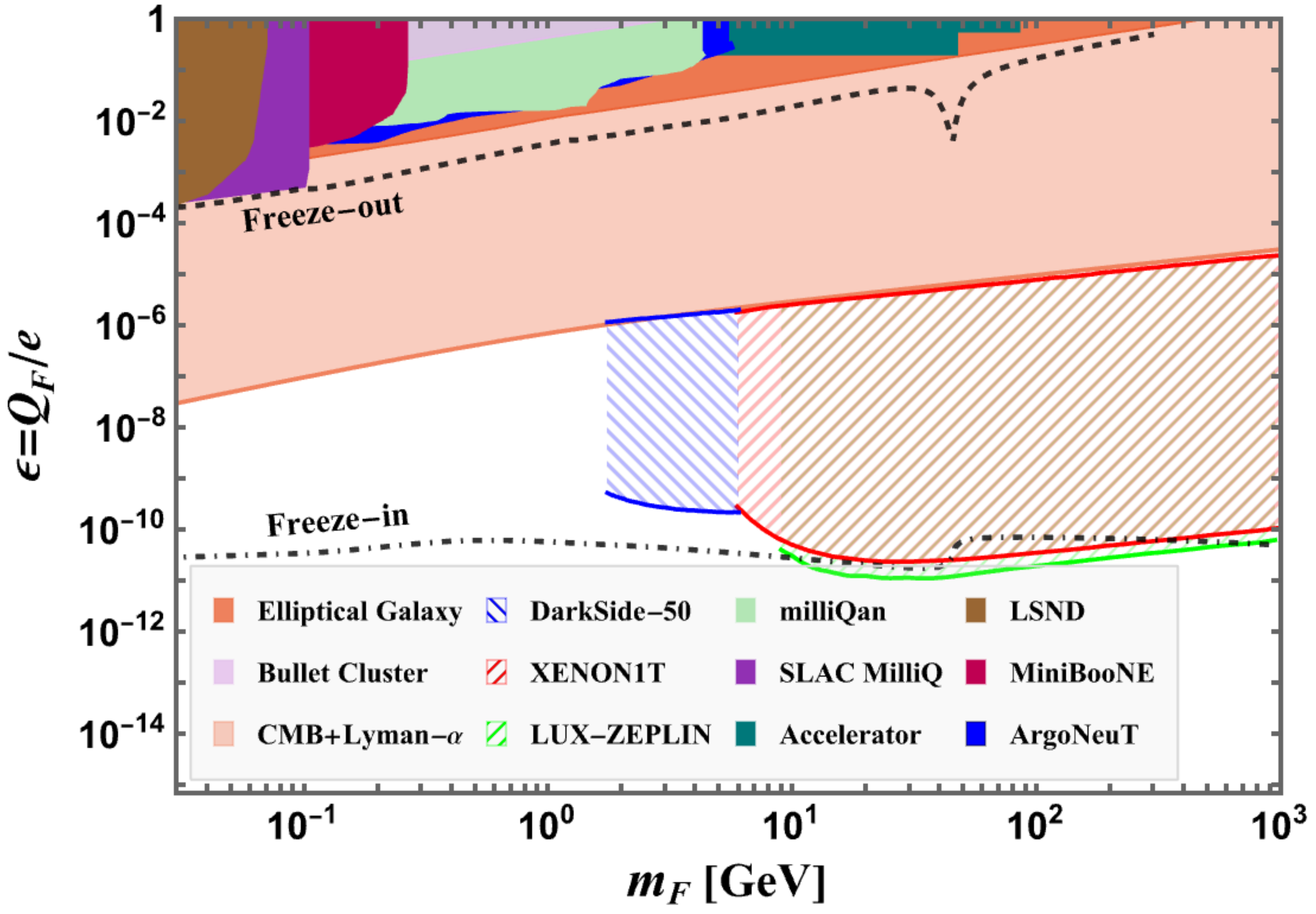
Freeze-in scenario is incompatoble with neutrino mass mechanism

Freeze-out scenario

- Gauge portal: dominant contribution to annihilation cross section via



ϵ is required to be large to be consistent with correct relic abundance, which is excluded by various constraints; contributions from gauge portal channels are suppressed



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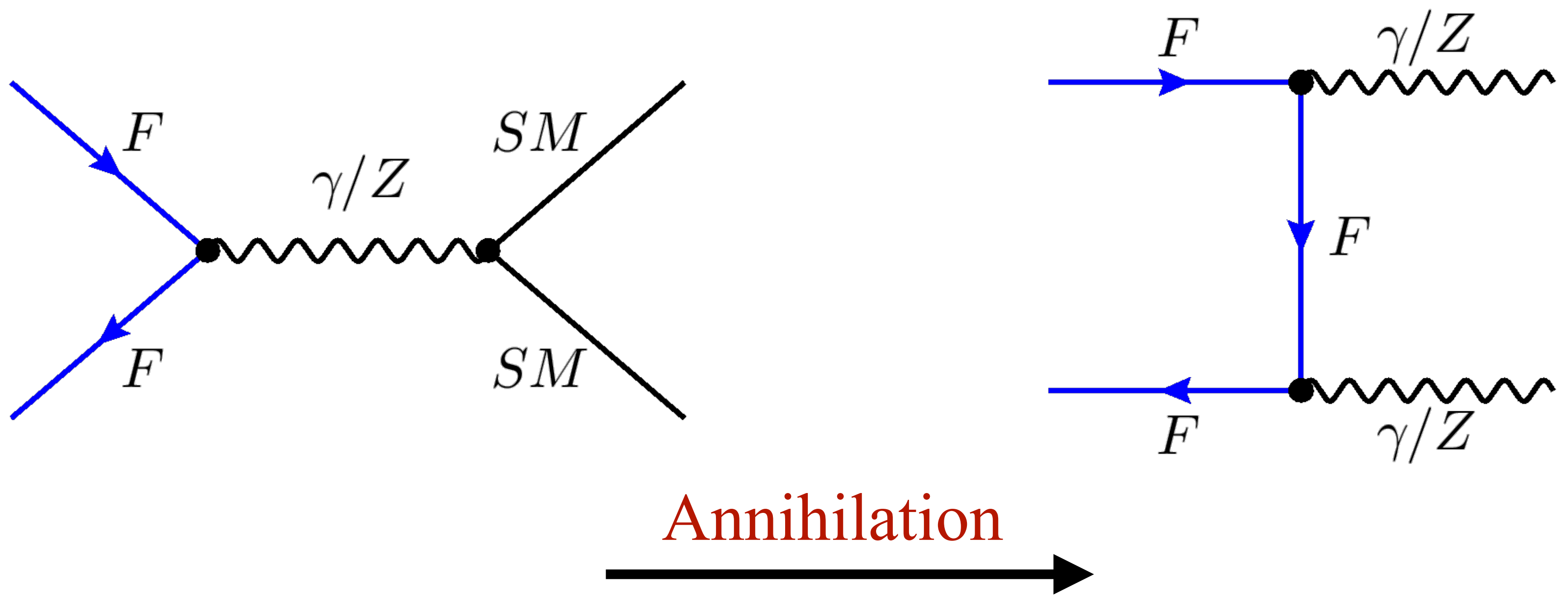

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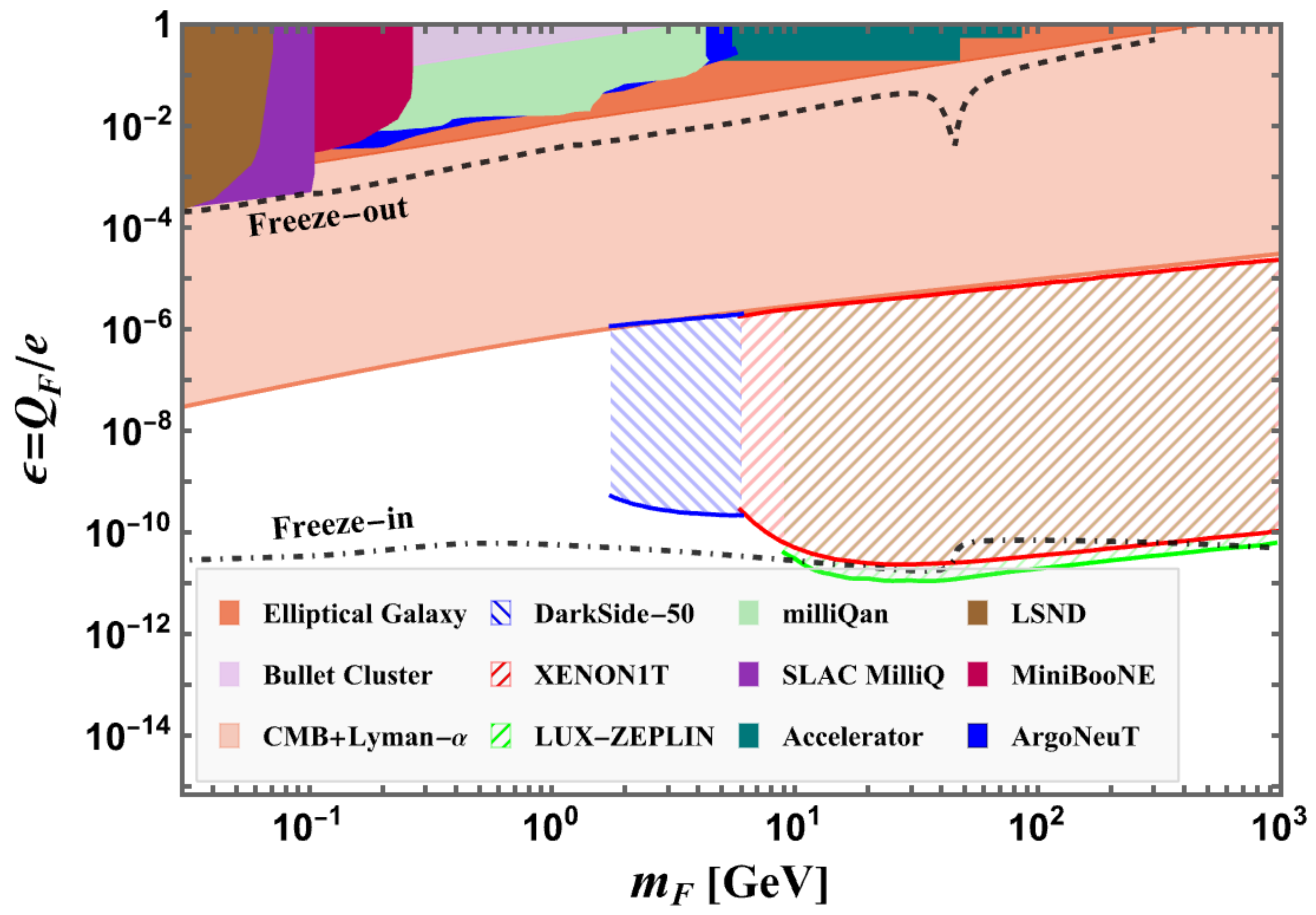
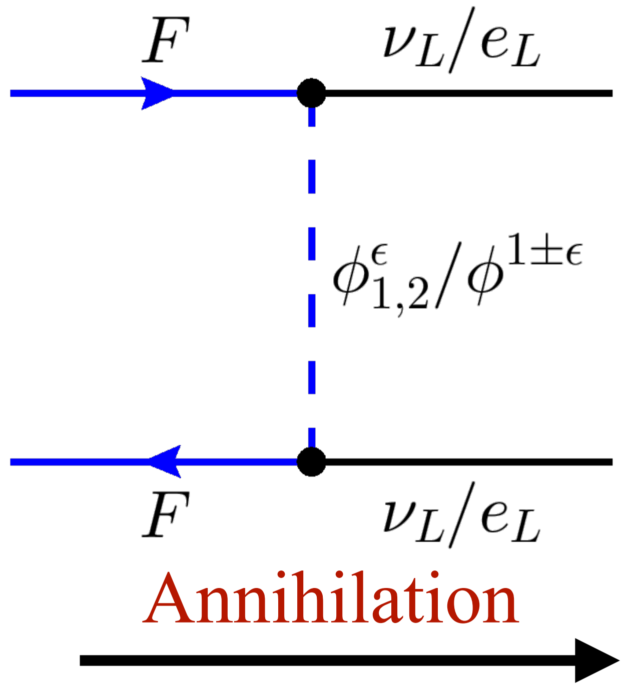


- Leptonic portal: both DM annihilation and coannihilation processes play crucial roles in reproducing correct relic abudance

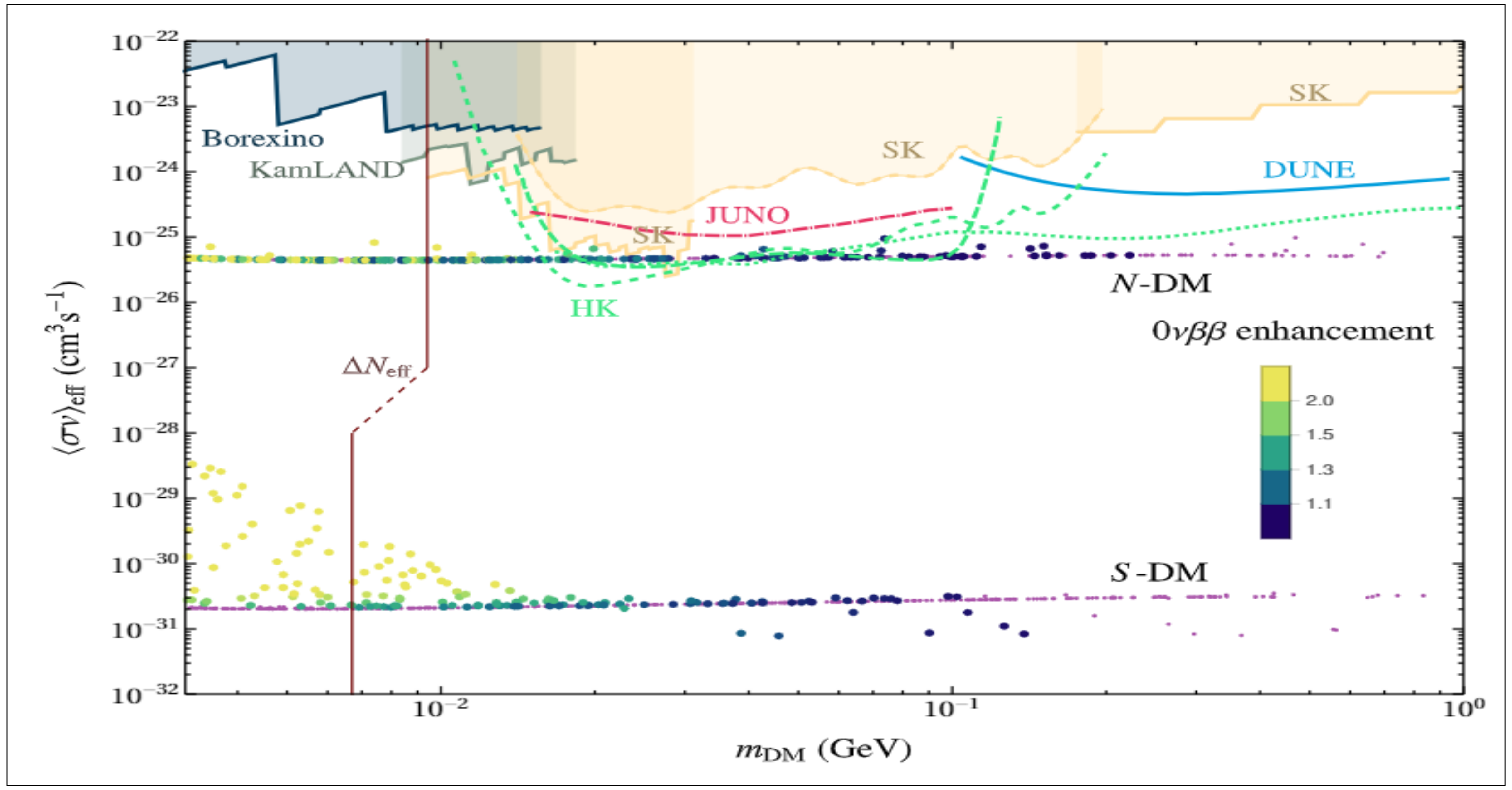


Light thermal dark matter

- Requires a light mediator state for generating sufficently large contribution to annihilation cross section

$$\langle \sigma v \rangle \simeq \frac{m_{\rm DM}^2 g^4}{M^4}, m_{\rm DM} = 100\,{\rm MeV} \begin{cases} 100\,{\rm GeV\ mediator\ g} = 1 \\ 100\,{\rm MeV\ mediator\ g} = 10^{-3} \end{cases}$$

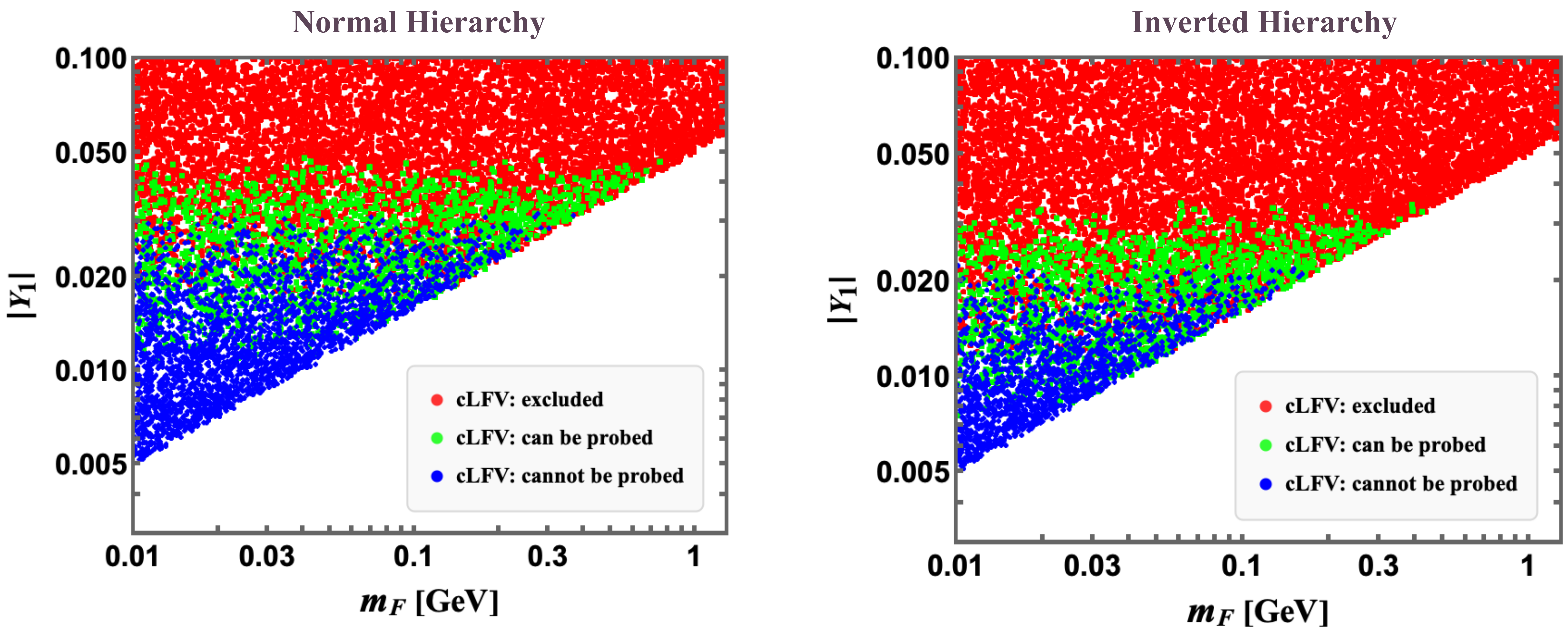
- Scalars $\{\phi_1^\epsilon, \phi_2^\epsilon\}$ can be a viable light mediator (only one can be light!): neutrinophilic dark matter



J. Herms, S. Jana, VPK, and S. Saad (2023)

Can be probed in various next generation neutrino telescopes

Relic abundance: NH and IH



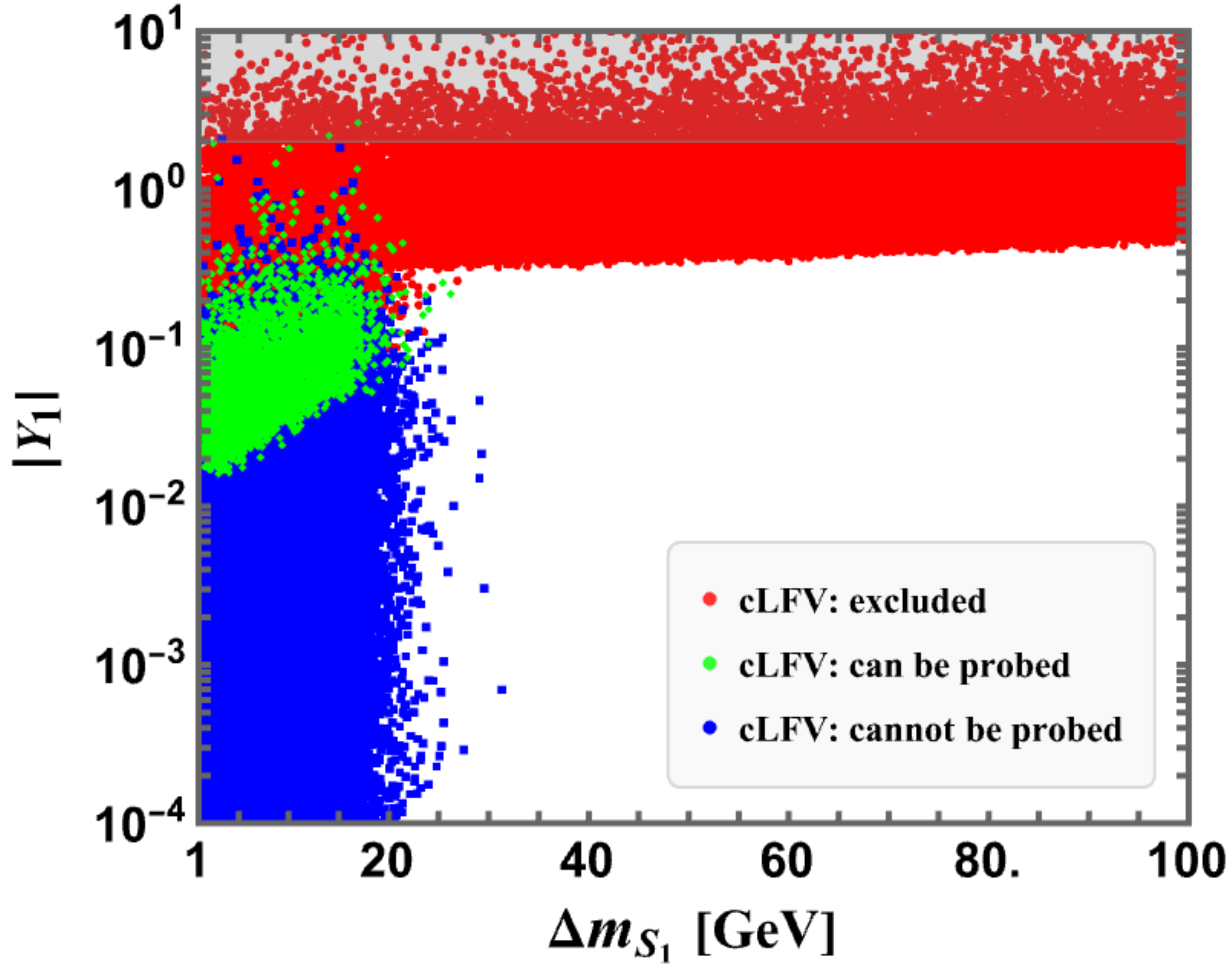
- For larger DM masses, sizeable values of Yukawa couplings are required to be consistent with relic density constraint
- Large values of Yukawa couplings are excluded by cLFV constraints: $m_{\mathrm{DM}} > 0.8\,\mathrm{GeV}$ (NH) and $m_{\mathrm{DM}} > 0.5\,\mathrm{GeV}$ (IH)

Heavy thermal dark matter

- For larger DM masses, DM annihilation into SM leptons via the *t*- channel processes is excluded through the cLFV constraints

- However, the coannihilations with the new scalars are less severely constrained by these constraints

Coannihilation Partner: S_1^ϵ



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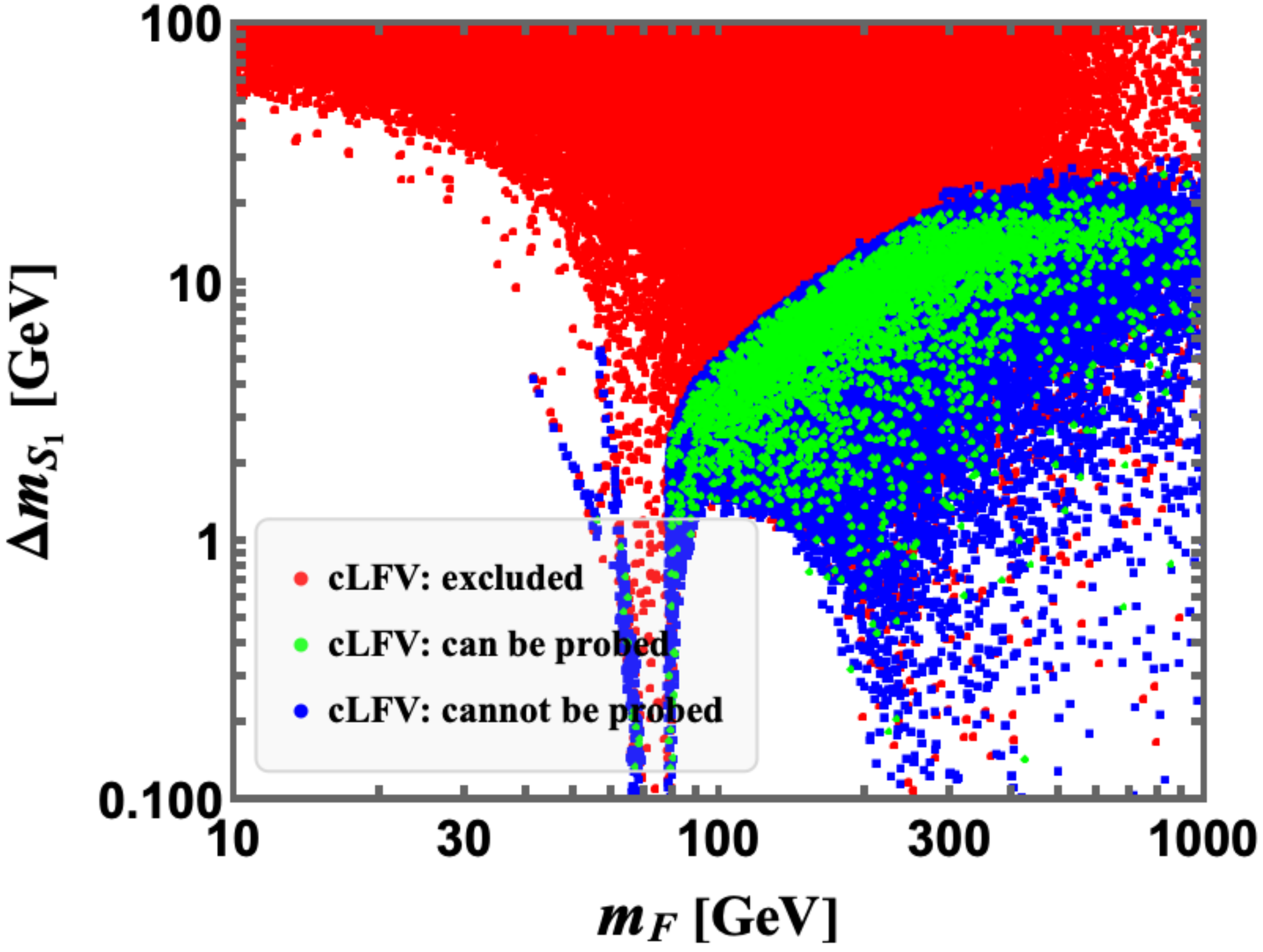

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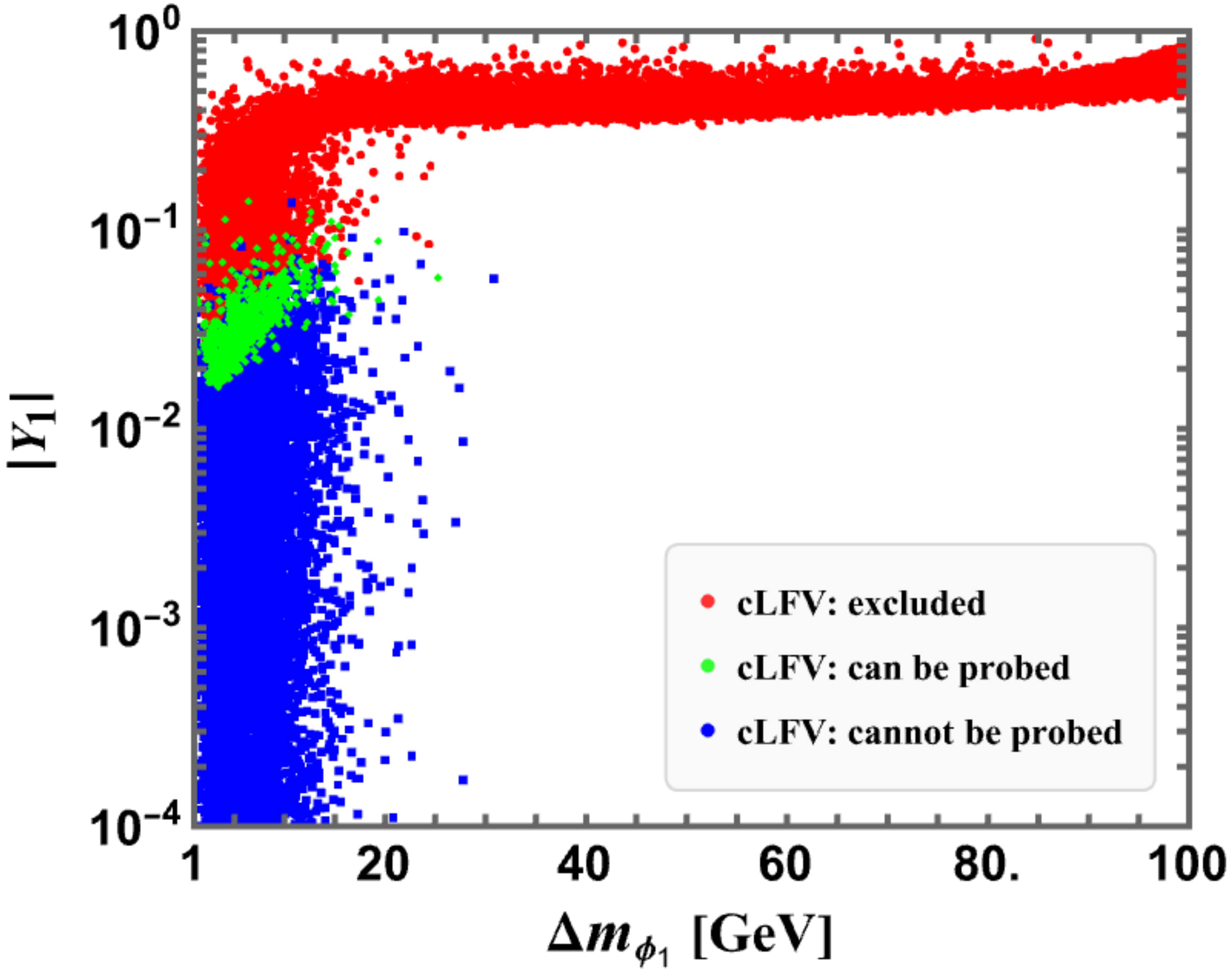

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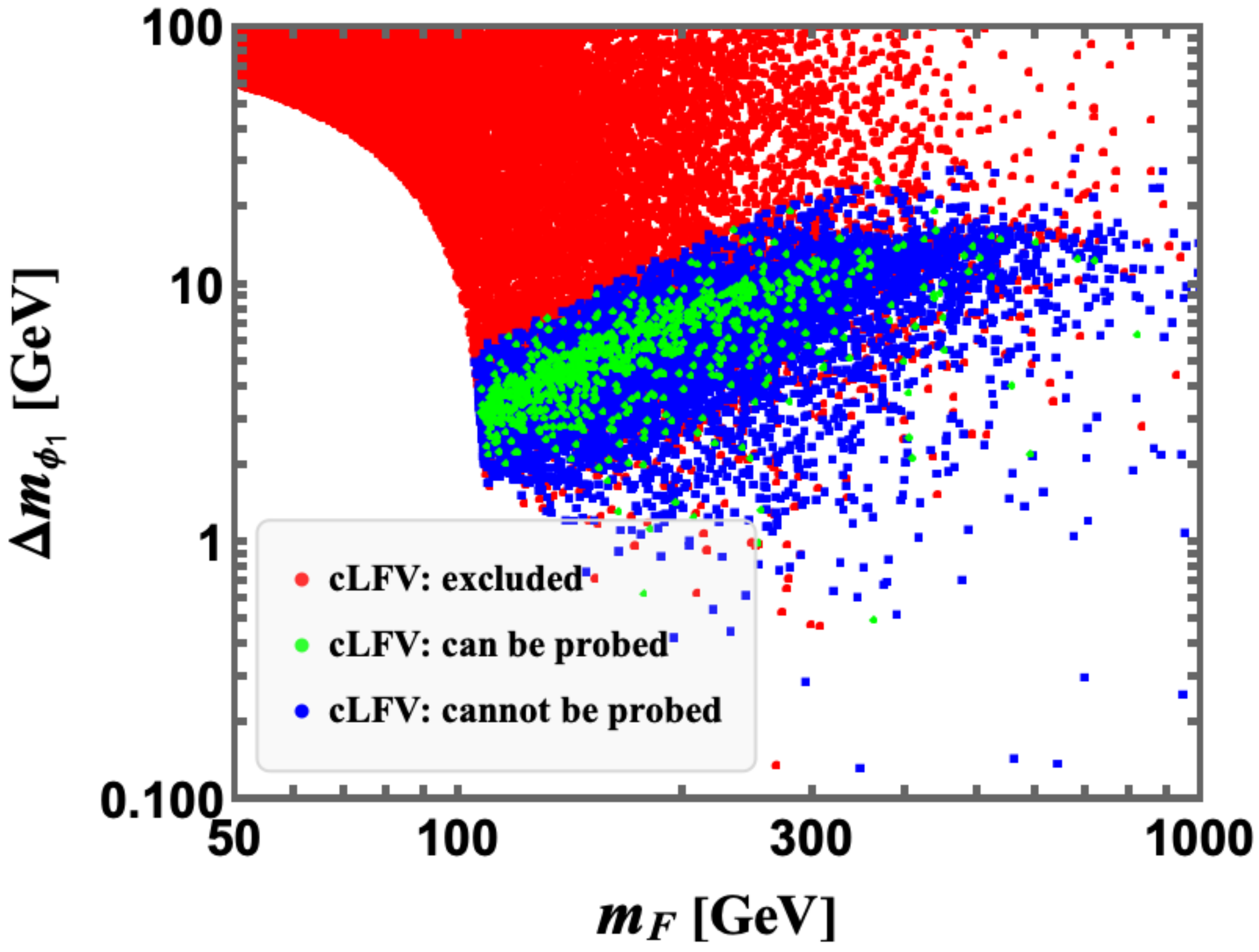


Conclusions

- A radiative neutrino mass model is presented, in which the particles within the loop carry small electric charges

- Unlike the conventional scotogenic setup, this scheme doesn't require imposition of any new symmetry to stabilize the dark matter candidate

- The proposed model could accommodate both light and heavy thermal dark matter scenarios

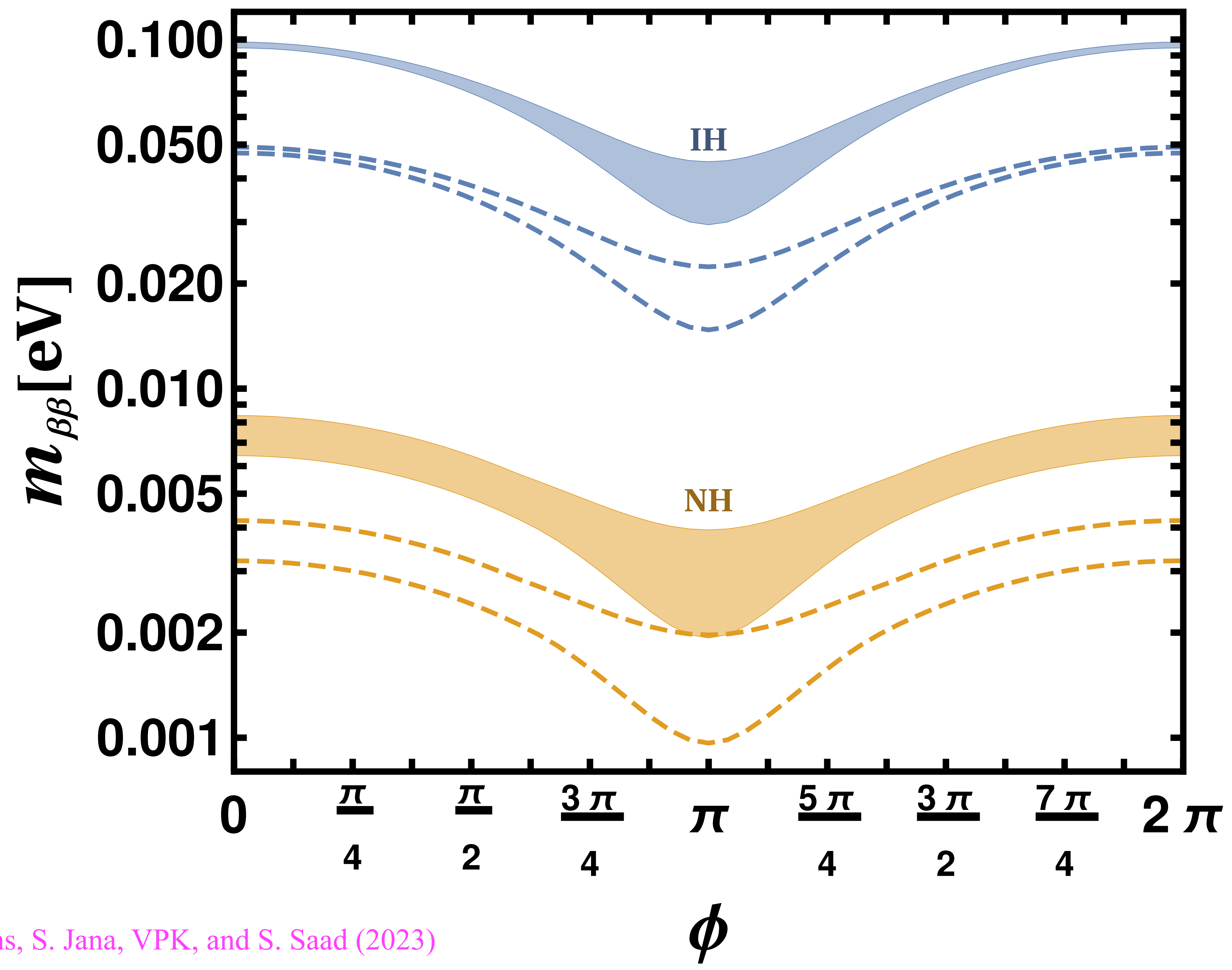
- The parameter space of the model can be probed in:

    - Various searches of milli-charged particles
    - Testable lepton flavor violating signals
    - Neutrino telescopes
    - Next generation $o\nu\beta\beta$ decay experiments

Thank you for your attention!

Image credit:quanta magazine

Loop enhanced neutrinoless double beta decay



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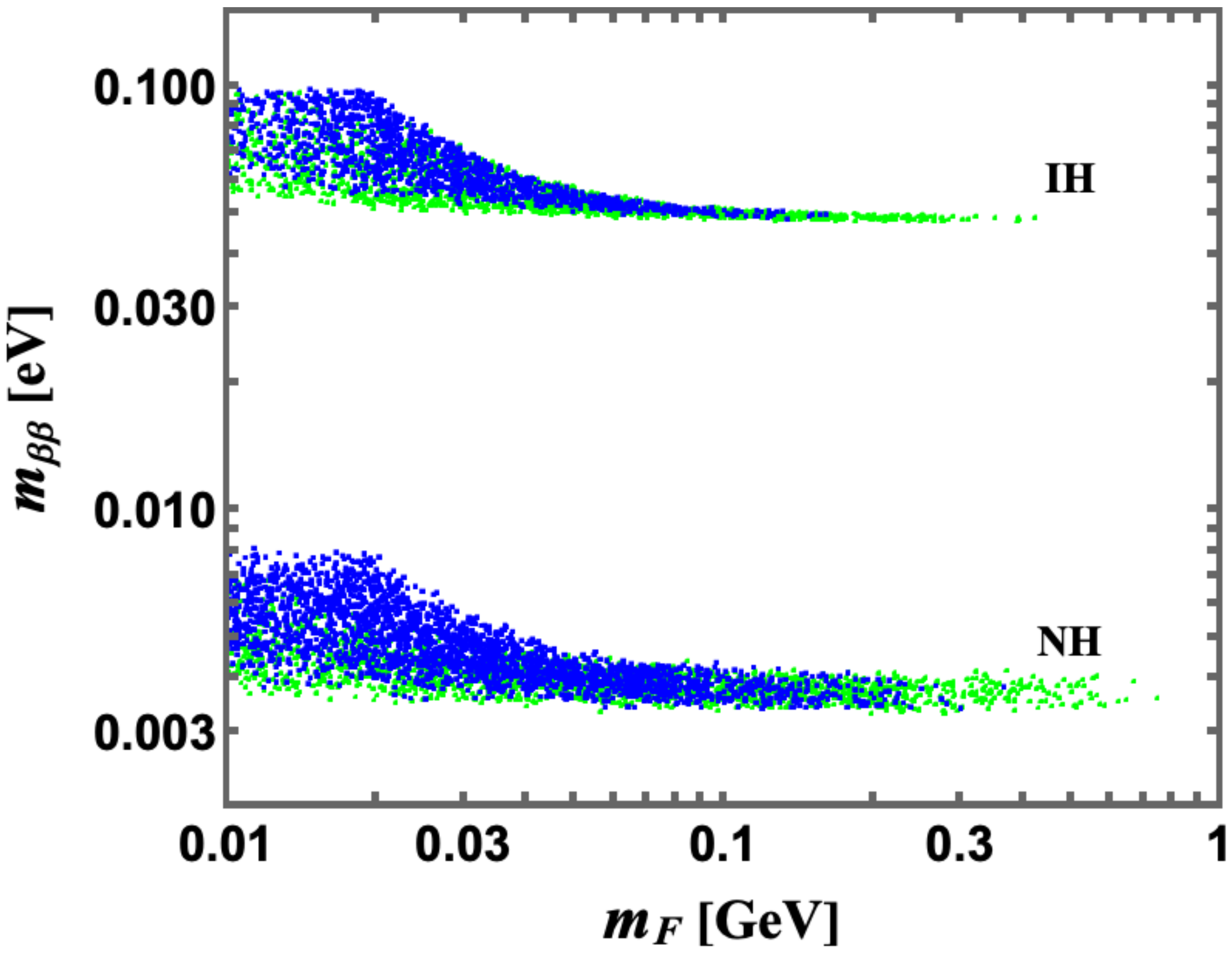

S. Jana, M. Klasen, VPK, and L. P. Wiggering (2023)

Enhanced contribution to $m_{\beta\beta}$: energy scale of neutrino self energy is similar order of momentum transfer of the $o\nu\beta\beta$ process

Light Mediator

Constraints

- Z-decay width measurements:
  - $Z \to S_1^* S_1$: $\Gamma_Z \propto cos^2 2\theta$ $\Longrightarrow$ Choosing $\theta \simeq \frac{\pi}{4}$
  - $Z \to S_1 S_2$: lower bound on mass of S_2 : $m_{S_2} > 90$ GeV
- W-decay measurements and LEP constraints::
  - Lower bound on mass of charged scalars: $m_{\phi_{1,2}^+} > 100$ GeV
- Electroweak precision observables:
  - To be consistent with other constraints, choose we mass hierarchy of the form $m_{S_1} \ll m_{S_2} = m_{\phi_1^+} = m_{\phi_2^+}$
  - T-parameter: $T = \frac{\cos^2 2\theta \mathcal{F}\left(m_{S_1}^2, m_{S_2}^2\right)}{8\pi^2 \alpha_{\text{em}}(M_Z) v^2}$ $\Longrightarrow$ suppressed for $\theta \simeq \frac{\pi}{4}$

Light Mediator

Other constraints: Higgs observables

- Invisible decay of Higgs:
  - SM Higgs $h \to S_1^* S_1$
  - $V \supset \frac{v}{2}(\lambda_{H\phi_1} + \lambda_{H\phi_2} + \lambda'_{H\phi_1} + \lambda'_{H\phi_2} - 2\lambda_{H\phi_1\phi_2}) h (S_1^* S_1)$

$$\Rightarrow \lambda_{H\phi_1} + \lambda_{H\phi_2} \simeq 2\lambda_{H\phi_1\phi_2} - (\lambda'_{H\phi_1} + \lambda'_{H\phi_2}) \propto \frac{2m_{\phi^\pm}^2}{v^2}$$

- $h \to \gamma\gamma$:
  - $V \supset \lambda_{H\phi_1} v (h \phi_1^+ \phi_1^-) + \lambda_{H\phi_2} v (h \phi_2^+ \phi_2^-)$:
  - Modify the Higgs signal strength into $\gamma\gamma$: $R_{\gamma\gamma} = \frac{Br(h\to\gamma\gamma)}{Br(h\to\gamma\gamma)_{SM}} \Rightarrow R_{\gamma\gamma} \simeq 0.8$