Realizations of minicharged particles: from neutrinos to dark matter

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22nd Lomonosov Conference on Elementary Particle Physics

Moscow State University, August 26, 2025

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Talk based on:

- "Neutrino masses and mixing from milli-charged dark matter"
  [Michael Klasen, Sudip Jana,Vishnu P.K., Luca P Wiggering: arXiv:2406.18641 (*JCAP 02 (2025) 011*)]

- "How charged can neutrinos be?"
  [Michael Klasen, Sudip Jana,Vishnu P.K.: arXiv:2504.20044]

Electric Charge (De)quantization

Is electric charge is quantized?

Many theoretical frameworks suggest charge quantization:

- Grand unified theories, Magnetic monopoles,....
- So far no evidence

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Electric charge is not quantized in the standard model!

- Conditions imposed by gauge invariance and gauge anomaly cancellations can fix some of the hypercharge assignments, but not all
- May be a hint!

Minicharged Particles: Within and Beyond SM

Definition: particles of charge $|Q| \ll 1$

Within SM:

- ☐ Viable candidates: neutral gauge bosons, Higgs boson, and neutrinos
- ☐ Gauge invariance forbid minicharged gauge bosons and Higgs boson
- ☑ Neutrinos can be charged

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Beyond SM:

- ☑ Viable candidate for dark matter
- ☐ Stable: ensured by electromagnetic gauge symmetry


Minicharged Neutrinos

Charged Neutrinos

Models of charged neutrinos would inherently be a realization of Dirac neutrinos

- "Diracness" is protected by electromagnetic gauge symmetry
- Unlike various other realizations of Dirac neutrinos, no additional symmetries required

Non-standard interactions for neutrinos:

- Coupling with photons
- Could be probed in various experiments

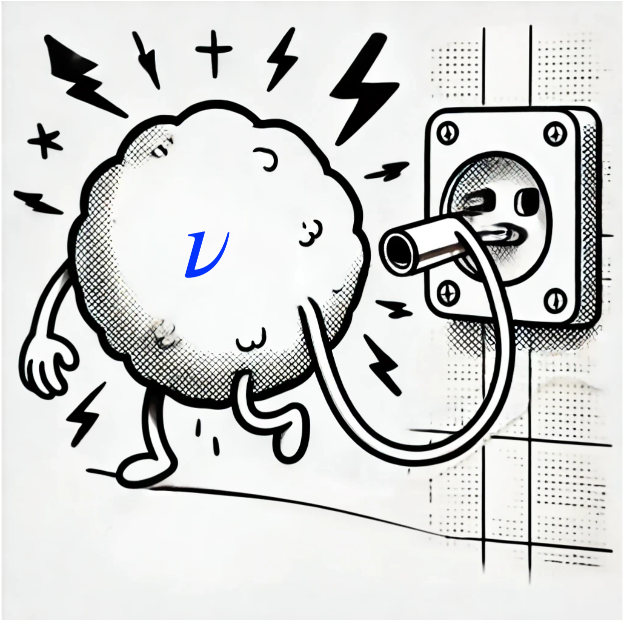
Gauge invariance implies non-standard charges for charged leptons and/or quarks:

- Charged neutrons and charged matter!
- Stringent constraints from neutrality tests

‘Charging’ Neutrinos

Electric charge is dequantized in a theory if it holds a guagable global symmetry, which is not the same as the SM hypercharge symmetry

[R. Foot, G. C. Joshi, H. Lew, R. R. Volkas, 1990],
[R. Foot, 1991],
[K. S. Babu, R. R. Volkas, 1992],
[R. Foot, H. Lew, R. R. Volkas, 1993]



Setup: Models that possess a gaugable global symmetry $U(1)_X$ under which neutrinos transform non trivially (with X_ν quantum number)

Procedure: Instead of gauging the SM hypercharge generator Y, gauge a linear combination of Y and X. Then spontaneous symmetry breaking of modified electroweak gauge $SU(2)_L \times U(1)_{Y+\epsilon X}$ yields an unbroken electromagnetic symmetry $U(1)_Q$ with neutrinos of charge ϵX_ν

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times \{U(1)_X\} \rightarrow SU(3)_C \times SU(2)_L \times U(1)_{Y+\epsilon X} \rightarrow SU(3)_C \times U(1)_Q \Rightarrow Q = Q_{st} + \epsilon X$$

Models of Minicharged Neutrinos

Requirements on $U(1)_X$

1. $U(1)_X$ symmetry has to comply with all the gauge anomaly conditions
2. $U(1)_X$ symmetry is neither explicitly nor spontaneously broken
3. Under $U(1)_X$ symmetry, the SM leptons should transforms non-trivially

$Q = Q_{st} + \epsilon X$

$Q_\nu \neq 0$

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$Q_\nu \neq 0$

Based on the $U(1)_X$ symmetry, models of charged neutrinos can be classified into two categories:

1. Charged neutrinos from **flavor-dependent** $U(1)_X$ scenarios
2. Charged neutrinos from **flavor-universal** $U(1)_X$ scenarios

Charged neutrinos: flavor dependent $U(1)_X$

Different flavors of the SM have different charges under the $U(1)_X$ symmetry

Symmetries include $U(1)_{L_i-L_j}$, $U(1)_{B_i-L_j}$

Charged neutrinos from $U(1)_{L_i-L_j}$:

- Anomaly free within SM — Condition 1✓
- Symmetry is unbroken — Condition 2✓
- SM leptons are charged under $U(1)_{L_i-L_j}$ — Condition 3✓

$$SU(3)_C \times SU(2)_L \times U(1)_{Y+\epsilon(L_i-L_j)} \Rightarrow Q = Q_{st} + \epsilon(L_i - L_j) \Rightarrow U(1)_{L_\mu-L_\tau} \begin{cases} Q_{\nu_\mu} = \epsilon, \quad Q_{\nu_\tau} = -\epsilon \\ Q_\mu = -1+\epsilon, \quad Q_\tau = -1-\epsilon \end{cases}$$

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Charged neutrinos from $U(1)_{B_i-L_j}$:
- Condition 1 — Requires one RH-neutrino ν_R
- Condition 2 — Majorana mass terms are not allowed
- SM leptons are charged under $U(1)_{B_i-L_j}$ — Condition 3✓

$$SU(3)_C \times SU(2)_L \times U(1)_{Y+\epsilon(B_i-L_j)} \Rightarrow Q = Q_{st} + \epsilon(B_i - L_j) \Rightarrow U(1)_{B_3-L_3} \begin{cases} Q_{\nu_\tau} = -\epsilon, \quad Q_\tau = -1-\epsilon \\ Q_t = \frac{2}{3} + \frac{\epsilon}{3}, \quad Q_b = -\frac{1}{3} + \frac{\epsilon}{3} \end{cases}$$

Charged neutrinos: flavor dependent $U(1)_X$

Despite the success in accommodating the charged neutrinos, these scenarios are not compatible with various experimental data

Charged neutrinos from $U(1)_{L_i - L_j}$: $\begin{cases} \text{Neutrino mixings are forbidden} \\ \text{Two neutrinos are massless} \end{cases} \Longrightarrow$ Neutrino oscillation data $\times$

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Charged neutrinos from $U(1)_{B_i-L_j}$: $\begin{cases}\text{Mixing between } \nu_j \text{ \& } \{\nu_{i\neq j}\} \text{ are forbidden}\\ \text{Mixing between } q_i \text{ \& } \{q_{j\neq i}\} \text{ are forbidden}\end{cases} \Longrightarrow$ Neutrino oscillation data ×; Observed quark mixings ×

Similar conclusion holds in general for other flavor dependent $U(1)_X$ scenarios

Charged neutrinos: flavor universal $U(1)_X$

SM flavors have same charge under the $U(1)_X$ symmetry

Symmetries include $U(1)_{B-L}$, $U(1)_L$

Charged neutrinos from $U(1)_{B-L}$:
- Condition 1 — Requires three RH-neutrino ν_R
- Condition 2 — Majorana mass terms are not allowed
- SM leptons are charged under $U(1)_{B-L}$ — Condition 3✓

$$SU(3)_C \times SU(2)_L \times U(1)_{Y+\epsilon(B-L)} \Rightarrow Q = Q_{st} + \epsilon(B-L) \Rightarrow \begin{cases} Q_{\nu_\ell} = -\epsilon, \quad Q_\ell = -1-\epsilon \\ Q_u = \frac{2}{3} + \frac{\epsilon}{3}, \quad Q_d = -\frac{1}{3} + \frac{\epsilon}{3} \end{cases}$$

Charges of both SM leptons and quarks are altered from standard value $\Rightarrow$ charged matter and neutron!

- ☑ Compatible with neutrino oscillation data: $\mathscr{L}_Y \supset Y_\nu \overline{\ell_L} \widetilde{H} \nu_R + h.c.$
- ☑ Compatible with observed quark mixings

Charged neutrinos: flavor universal $U(1)_X$

Charged neutrinos from $U(1)_L$: condition 3 is automatically satisfied

Anomaly cancellation requires (condition 1):

$$\nu_{R_i} \sim (1,0,1), \quad i = 1-3,$$

$$\psi_L^{1,2} = \begin{pmatrix} \psi_1^{1,2} \\ \psi_2^{1,2} \end{pmatrix}_L \sim (2, \pm a, -\frac{3}{2}),$$

$$\psi_{1R}^{1,2} \sim (1, \pm a + \frac{1}{2}, -\frac{3}{2}), \quad \psi_{2R}^{1,2} \sim (1, \pm a - \frac{1}{2}, -\frac{3}{2}),$$

Majorana mass terms for neutrinos are not allowed: condition 2

$$SU(3)_C \times SU(2)_L \times U(1)_{Y+\epsilon(L)} \Rightarrow Q = Q_{st} + \epsilon(L) \Rightarrow Q_{\nu_\ell} = \epsilon, \quad Q_\ell = -1 + \epsilon$$

Only charges of SM leptons are altered from standard value: no constraint from neutrality test of neutrons

- ☑ Compatible with neutrino oscillation data: $\mathscr{L}_Y \supset Y_\nu \overline{\ell_L} \widetilde{H} \nu_R + h.c.$
- ☑ Compatible with observed quark mixings

Current Status of Charged Neutrinos

Neutarlity tests: indirectly impose stringent constraints on neutrino electric charge

$$\left\{\begin{array}{l}\text{Neutron} \Rightarrow U(1)_{B-L} \\ \text{Matter} \Rightarrow U(1)_{L_e-L_\mu}, U(1)_{L_e-L_\tau}, U(1)_L, U(1)_{B-L}\end{array}\right. \Longrightarrow |Q_\nu| < 10^{-21}e$$

Neutrino scattering experiments: directly probe electric charge of neutrinos

$$\left\{\begin{array}{l}\text{Reactor } \nu \text{ expts (GEMMA, TEXONO, CONUS, Dresden-II)} \Rightarrow |Q_\nu| \lesssim 10^{-12}e \\ \text{Accelerator } \nu \text{ expts (LSND,DONUT,COHERENT)} \Rightarrow |Q_\nu| \lesssim 10^{-10}e \\ \text{Solar } \nu \text{ expts (LZ,XENONnT,PandaX-4T)} \Rightarrow |Q_\nu| \lesssim 10^{-13}e\end{array}\right.$$

Astrophysics considerations:

$$\left\{\begin{array}{l}\text{SN1987A} \Rightarrow |Q_\nu| \lesssim \left(10^{-17}, 10^{-15}\right) e \\ \text{Solar cooling} \Rightarrow |Q_\nu| \lesssim 10^{-14}e \\ \text{TRGB} \Rightarrow |Q_\nu| \lesssim 10^{-15}e \\ \text{Magnetars} \Rightarrow |Q_\nu| \lesssim \left(10^{-12}, 10^{-11}\right) e \\ \text{Pulsars} \Rightarrow |Q_\nu| \lesssim 10^{-19}e\end{array}\right.$$

See refrs within [C. Giunti, K. Kouzakov, Y.-F. Li, A. Studenikin, 2024], [M. Klasen, S. Jana, VPK, 2025]

	Experiment/Method	Charge of neutrino in $[e]$ $U(1)_{L_e-L_\mu}$	$U(1)_{L_e-L_\tau}$	$U(1)_{L_\mu-L_\tau}$	$U(1)_{B-L}$	$U(1)_{L}$
Neutrality test	Neutron	—	—	—	$= (0.4 \pm 1.1) \times 10^{-21}$	—
	Matter	$= (-0.2 \pm 2.3) \times 10^{-21}$	$= (-0.2 \pm 2.3) \times 10^{-21}$	—	$= (0.2 \pm 2.1) \times 10^{-21}$	$= (-0.2 \pm 2.3) \times 10^{-21}$
Reactor ν experiment	TEXONO (2002)	$< 3.7 \times 10^{-12}$	$< 3.7 \times 10^{-12}$	—	$< 3.7 \times 10^{-12}$	$< 3.7 \times 10^{-12}$
	GEMMA	$< 1.5 \times 10^{-12}$	$< 1.5 \times 10^{-12}$	—	$< 1.5 \times 10^{-12}$	$< 1.5 \times 10^{-12}$
	TEXONO (2014)	$< 2.1 \times 10^{-12}$	$< 2.1 \times 10^{-12}$	—	$< 2.1 \times 10^{-12}$	$< 2.1 \times 10^{-12}$
	CONUS	$< 3.3 \times 10^{-12}$	$< 3.3 \times 10^{-12}$	—	$< 3.3 \times 10^{-12}$	$< 3.3 \times 10^{-12}$
	Dresden-II	$\in (-9.3, 9.5) \times 10^{-12}$	$\in (-9.3, 9.5) \times 10^{-12}$	—	$\in (-9.3, 9.5) \times 10^{-12}$	$\in (-9.3, 9.5) \times 10^{-12}$
	CONUS+	$\in (-1.8, 1.9) \times 10^{-12}$	$\in (-1.8, 1.9) \times 10^{-12}$	—	$\in (-1.8, 1.9) \times 10^{-12}$	$\in (-1.8, 1.9) \times 10^{-12}$
Accelerator ν experiment	LSND	$< 3 \times 10^{-9}$	—	$< 3 \times 10^{-9}$	$< 3 \times 10^{-9}$	$< 3 \times 10^{-9}$
	DONUT	—	$< 4 \times 10^{-6}$	$< 4 \times 10^{-6}$	$< 4 \times 10^{-6}$	$< 4 \times 10^{-6}$
	COHERENT	$\in (-1.9, 1.9) \times 10^{-10}$	$\in (-5.0, 5.0) \times 10^{-10}$	$\in (-1.9, 1.9) \times 10^{-10}$	$\in (-1.9, 1.9) \times 10^{-10}$	$\in (-1.9, 1.9) \times 10^{-10}$
Solar ν experiment	XMAS-I	$< 7.3 \times 10^{-12}$	$< 7.3 \times 10^{-12}$	$< 1.1 \times 10^{-11}$	$< 5.4 \times 10^{-12}$	$< 5.4 \times 10^{-12}$
	LUX-ZEPLIN	$\in (-2.1, 2.0) \times 10^{-13}$	$\in (-2.1, 2.0) \times 10^{-13}$	$\in (-2.8, 2.8) \times 10^{-13}$	$\in (-2.1, 2.0) \times 10^{-13}$	$\in (-2.1, 2.0) \times 10^{-13}$
	XENONnT	$\in (-6.2, 6.1) \times 10^{-13}$	$\in (-5.4, 5.2) \times 10^{-13}$	$\in (-5.4, 5.2) \times 10^{-13}$	$\in (-5.4, 5.2) \times 10^{-13}$	$\in (-5.4, 5.2) \times 10^{-13}$
	PandaX-4T	$\in (-1.3, 1.6) \times 10^{-12}$	$\in (-1.3, 1.6) \times 10^{-12}$	$\in (-2.2, 2.2) \times 10^{-12}$	$\in (-1.3, 1.6) \times 10^{-12}$	$\in (-1.3, 1.6) \times 10^{-12}$
Beam Dump	BEBC	—	$< 4 \times 10^{-4}$	$< 4 \times 10^{-4}$	$< 4 \times 10^{-4}$	$< 4 \times 10^{-4}$
$(g-2)_\ell$	Muon $(g-2)$	$< 10^{-7}$	—	$< 10^{-7}$	$< 10^{-7}$	$< 10^{-7}$
	Electron $(g-2)$	$< 10^{-11}$	$< 10^{-11}$	—	$< 10^{-11}$	$< 10^{-11}$
Astrophysics	SN1987A	$\lesssim 10^{-17} - 10^{-15}$	$\lesssim 10^{-17} - 10^{-15}$	—	$\lesssim 10^{-17} - 10^{-15}$	$\lesssim 10^{-17} - 10^{-15}$
	Solar cooling	$\lesssim 4 \times 10^{-14}$	$\lesssim 4 \times 10^{-14}$	$\lesssim 4 \times 10^{-14}$	$\lesssim 3 \times 10^{-14}$	$\lesssim 3 \times 10^{-14}$
	TRGB	$< 6.3 \times 10^{-15}$	$< 6.3 \times 10^{-15}$	$< 6.3 \times 10^{-15}$	$< 6.3 \times 10^{-15}$	$< 6.3 \times 10^{-15}$
	Magnetars	$< 10^{-12} - 10^{-11}$	$< 10^{-12} - 10^{-11}$	$< 10^{-12} - 10^{-11}$	$< 10^{-12} - 10^{-11}$	$< 10^{-12} - 10^{-11}$
	Pulsars	$< 10^{-19}$	$< 10^{-19}$	$< 10^{-19}$	$< 10^{-19}$	$< 10^{-19}$


Minicharged Dark Matter

Minicharged Dark Mater

Minicharged under $U(1)_Y$ symmetry: $\mathscr{L}_{\rm mDM} = i\bar{\psi}\left(\gamma^\mu\partial_\mu - i\epsilon e\gamma^\mu B_\mu + m_{\rm F}\right)\psi$

Viable candidate for dark matter

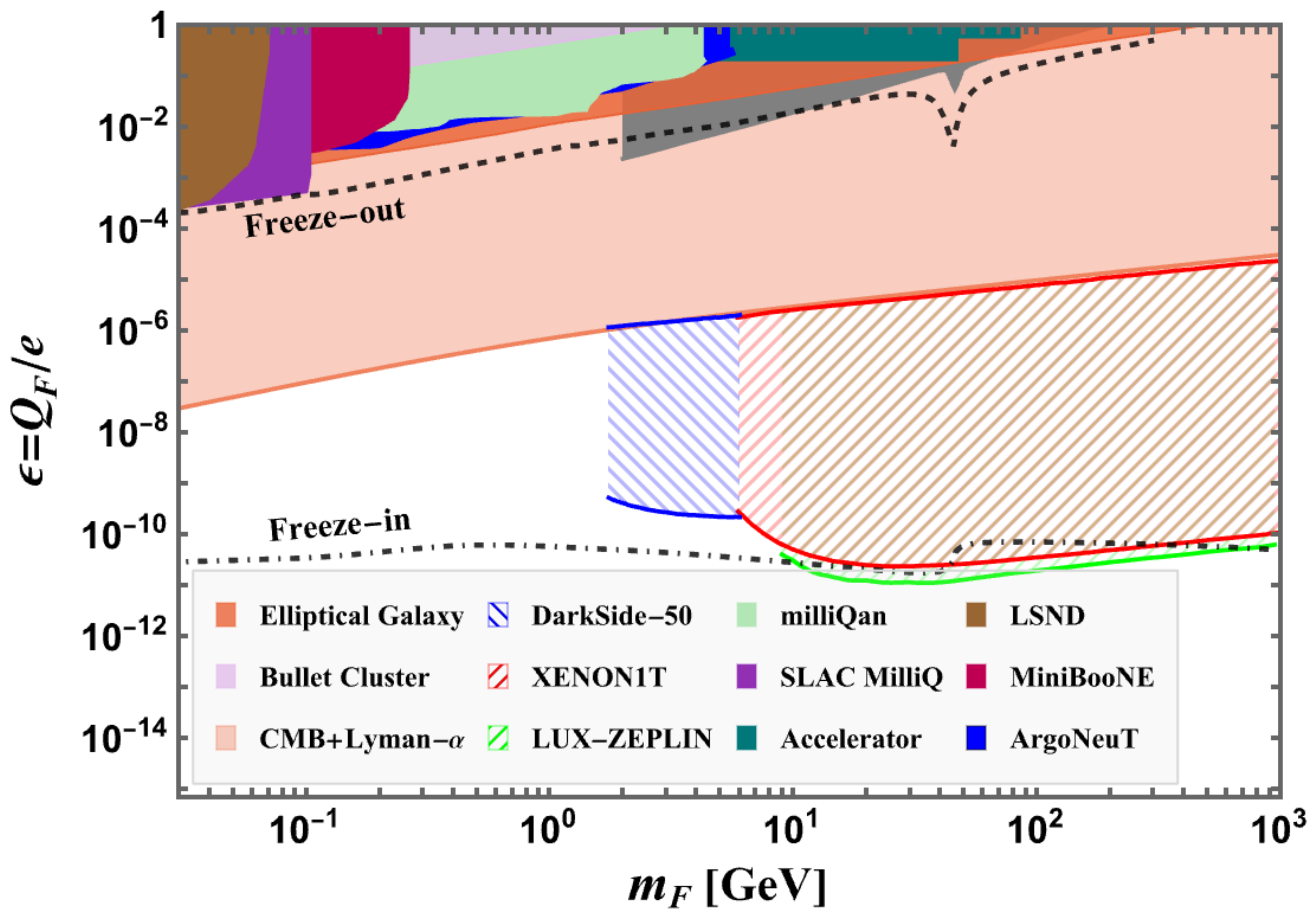
- Dark matter stability is ensured by electromagnetic gauge symmetry
- Stability is protected upto all orders in EFT expansion

Tree-level coupling with photons:

- Could be probed/constrained in/by various expts.

Relic abundance:

- Freeze-out: alaready excluded by CMB constraints
- Typically requires additional portals
- Freeze-in could work



Neutrino masses and mixings

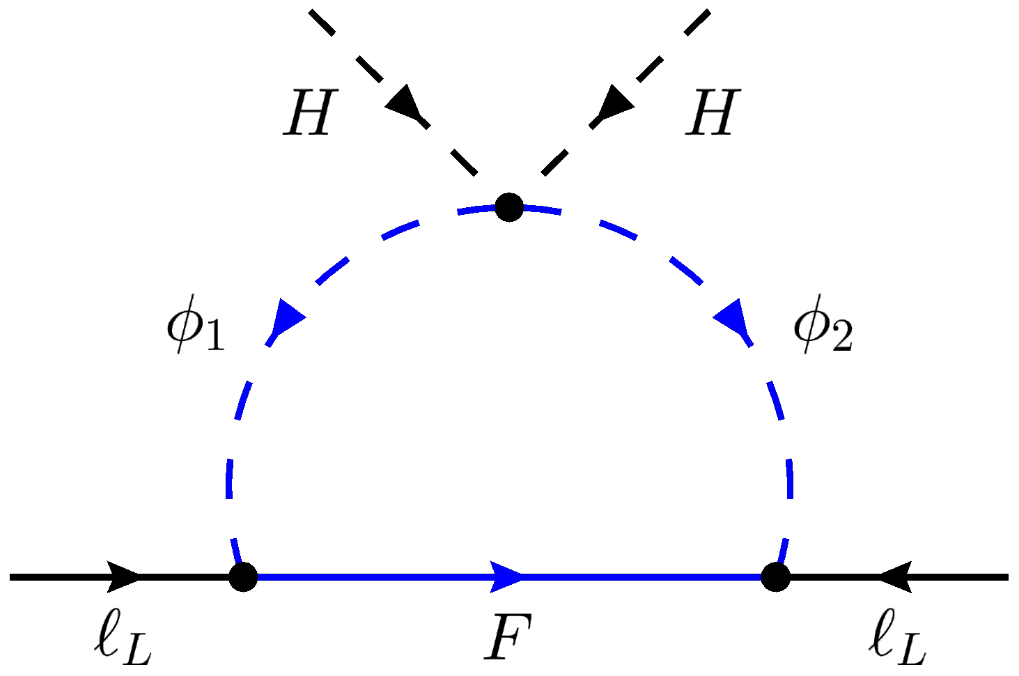
NuFIT 6.0 (2024)

	Normal Ordering ($\Delta\chi^2 = 0.6$)		Inverted Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$0.430 \to 0.596$	$0.562^{+0.012}_{-0.015}$	$0.437 \to 0.597$
$\theta_{23}/^\circ$	$48.5^{+0.7}_{-0.9}$	$41.0 \to 50.5$	$48.6^{+0.7}_{-0.9}$	$41.4 \to 50.6$
$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$0.02023 \to 0.02376$	$0.02224^{+0.00056}_{-0.00057}$	$0.02053 \to 0.02397$
$\theta_{13}/^\circ$	$8.52^{+0.11}_{-0.11}$	$8.18 \to 8.87$	$8.58^{+0.11}_{-0.11}$	$8.24 \to 8.91$
$\delta_{\rm CP}/^\circ$	177^{+19}_{-20}	$96 \to 422$	285^{+25}_{-28}	$201 \to 348$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.534^{+0.025}_{-0.023}$	$+2.463 \to +2.606$	$-2.510^{+0.024}_{-0.025}$	$-2.584 \to -2.438$

Minicharged Dark Matter assisted Neutrino Mass

Unlike the conventional scotogenic models, this scheme doesn't requires any BSM symmetry to ensure dark matter stability

Neutrino mass generated at one-loop level



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

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

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

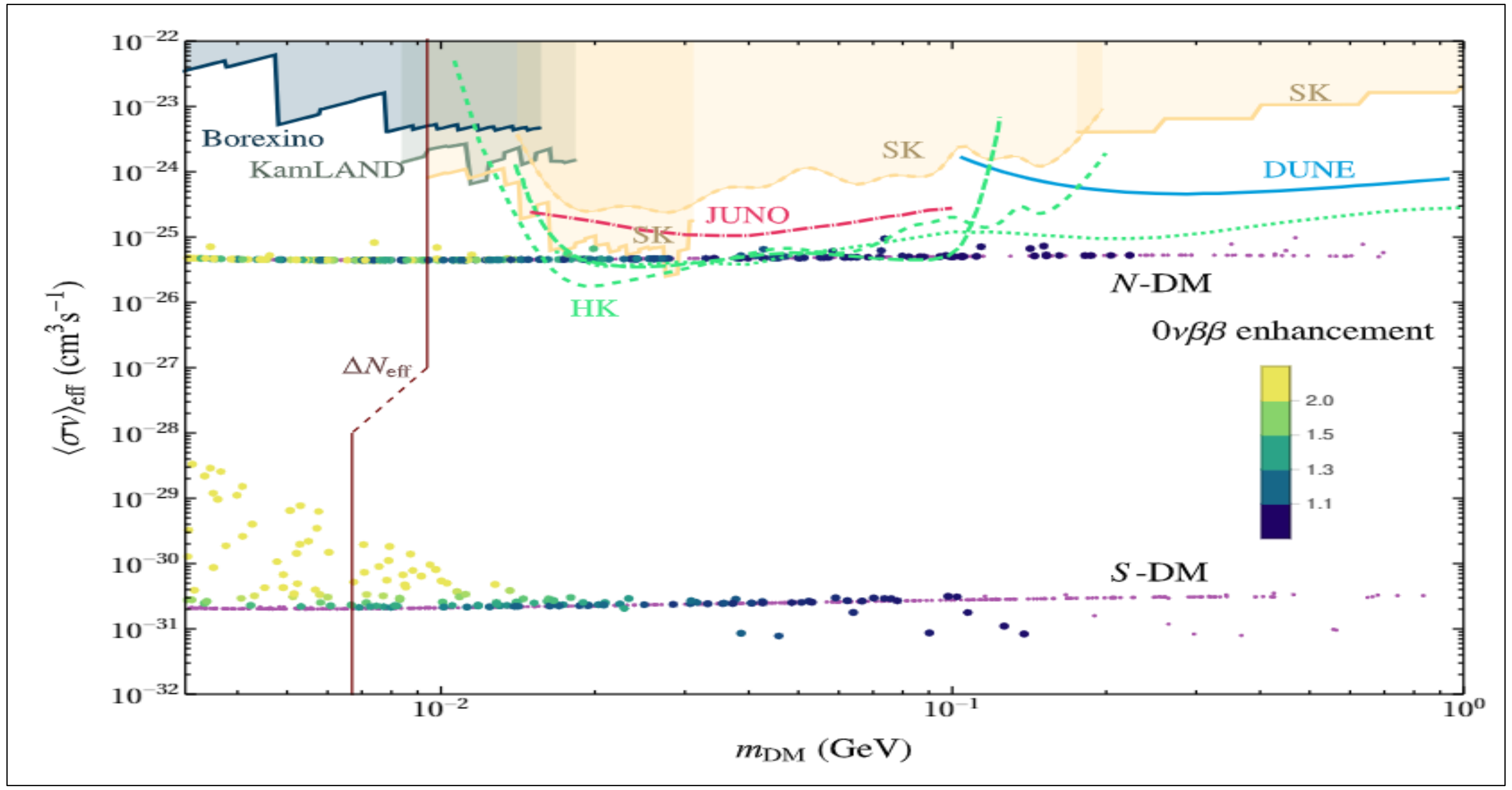
The lightest minicharged particle is stable: can be a viable candidate for dark matter

Light thermal dark matter

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

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

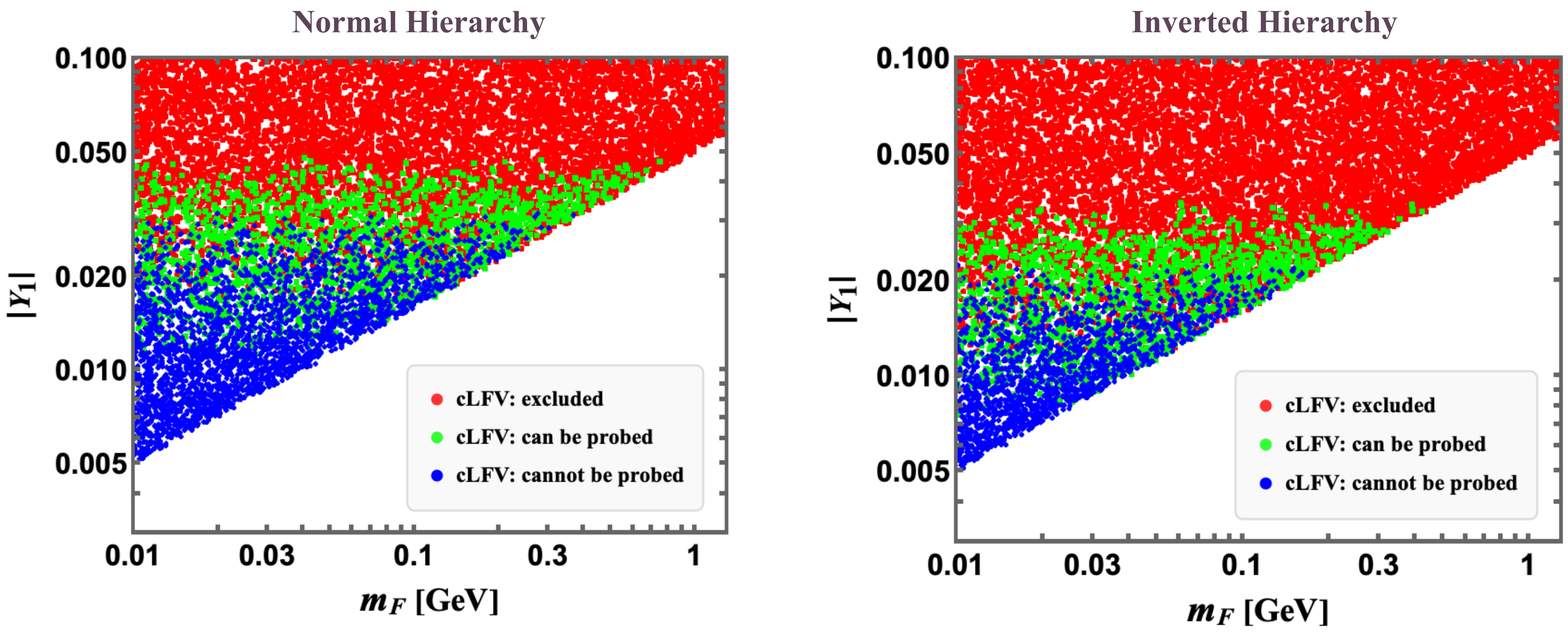
- Scalars $\{\phi_1^\epsilon, \phi_2^\epsilon\}$ can be a viable light mediator (only one can be light!): neutrinophilic dark matter



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

Can be probed in various next generation neutrino telescopes

Relic abundance: NH and IH

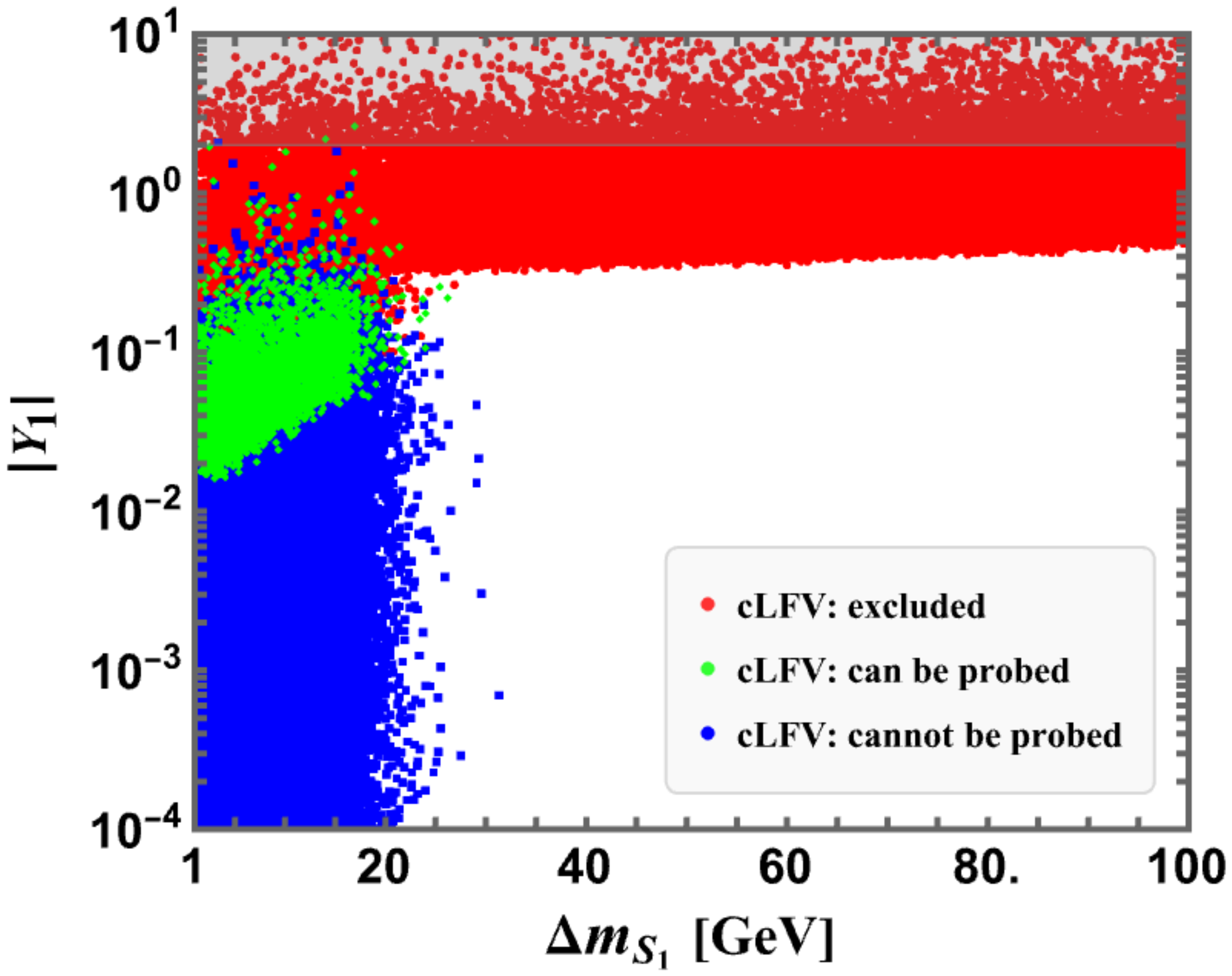


- For larger DM masses, sizeable values of Yukawa couplings are required to be consistent with relic density constraint
- Large values of Yukawa couplings are excluded by cLFV constraints: $m_{DM} > 0.8$ GeV (NH) and $m_{DM} > 0.5$ GeV (IH)

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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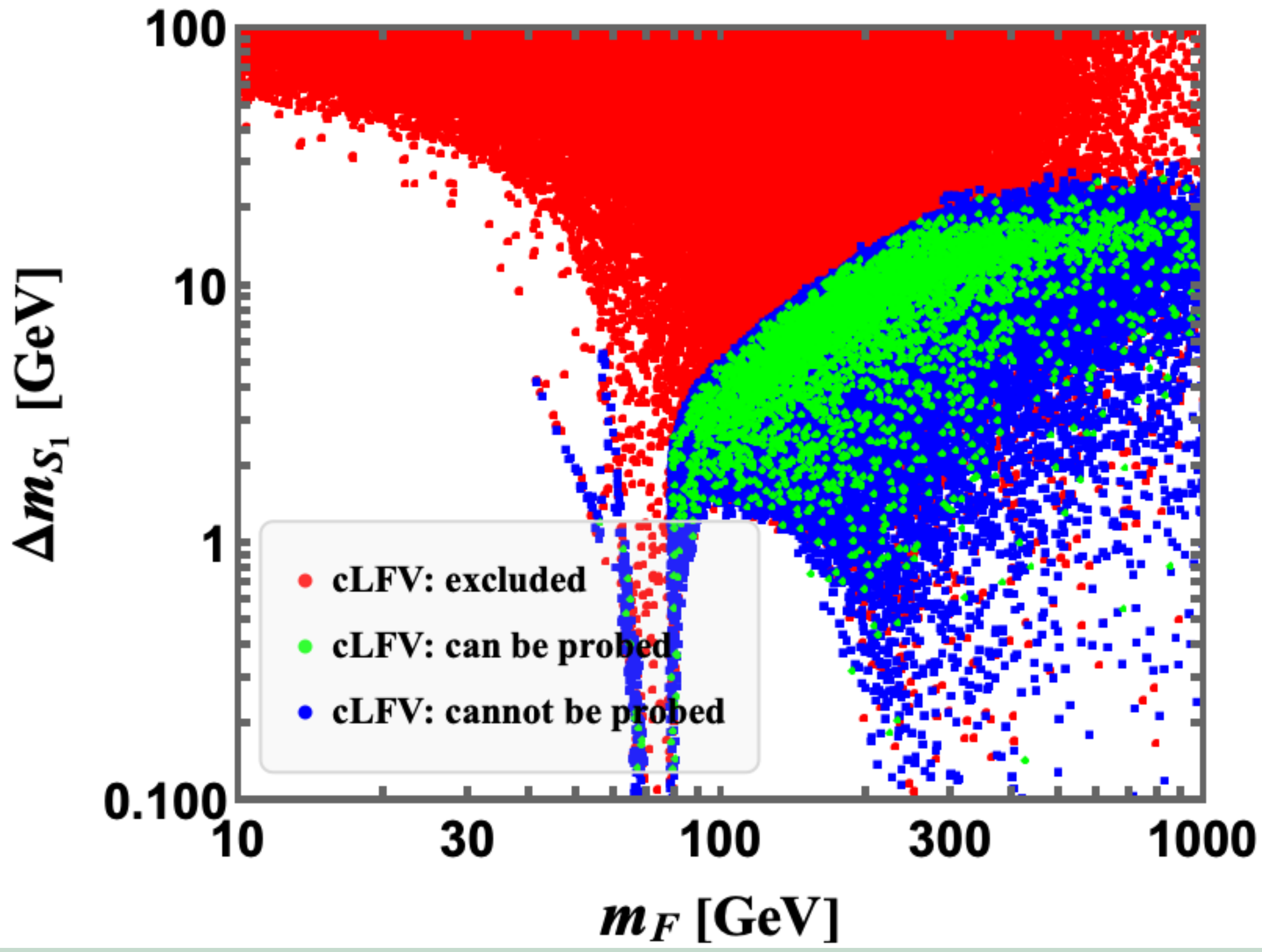

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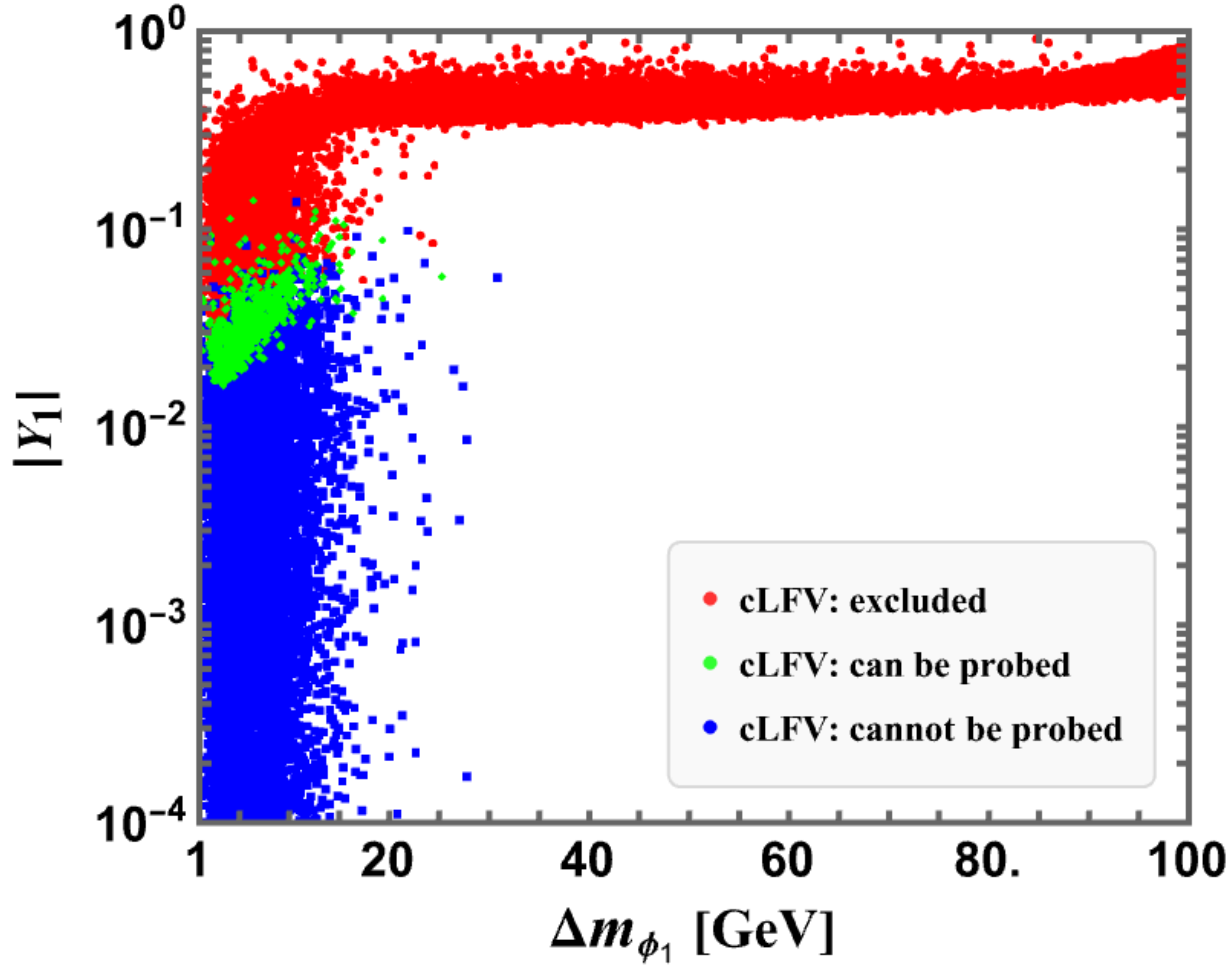
Coannihilation Partner: $\phi_1^{1+\epsilon}$



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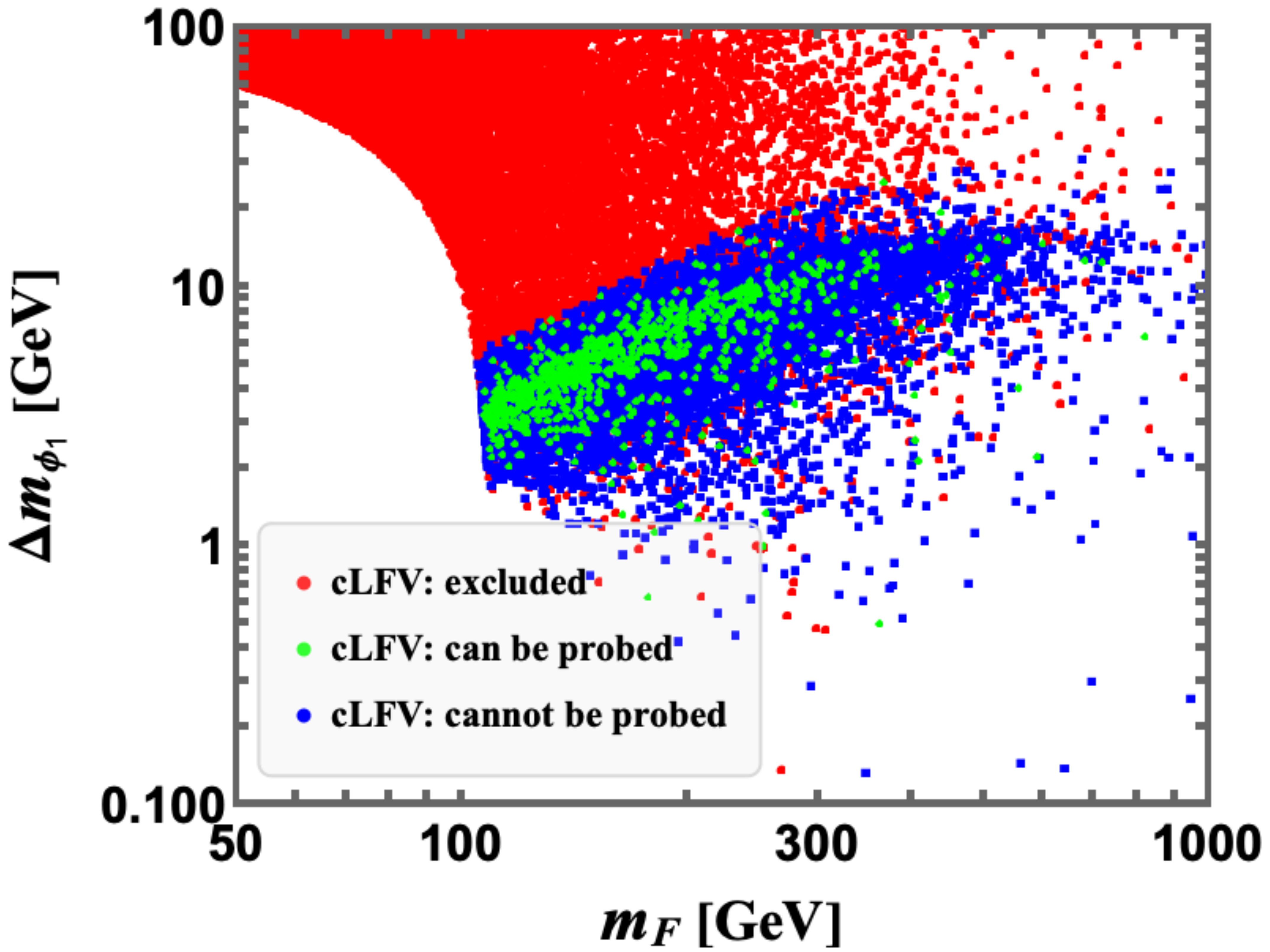

Summary

Theories of electric charge dequantization provide interesting avenues for BSM physics

Realization of minicharged particles:

- ☑ Within SM: neutrinos
- ☑ Beyond SM: viable candidate for dark matter

Minicharged neutrinos

- ☑ Presented various realization within the SM framework
- ☑ Demonstrated models of flavor dependent neutrino charges are incompatible with neutrino oscillation data
- ☑ Proposed a new UV complete model based on lepton number symmetry
- ☑ Presented currrent status for various models of charged neutrinos

Minicharged dark matter

- ☑ Presented a realization of minicharged dark matter assisted neutrino mass generation
- ☑ Unlike the conventional scotogenic scheme, this setup doesn't require any BSM symmetry for DM stability
- ☑ Could accommodate both light and heavy DM scenarios

Thank you for your attention!

Image credit:quanta magazine