Sub-GeV thermal relics enabled by a light Higgs portal

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Light Dark World 2025, IFT UAM/CSIC-Madrid

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Universität Münster

institut für theoretische physik

Talk based on:

- “Minimal realization of light thermal dark matter”

  [Johannes Herms, Sudip Jana, Vishnu P.K., Shaikh Saad: arXiv:2203.05579 (*Phys.Rev.Lett. 129 (2022) 9, 9*)]

- “Light neutrinophilic dark matter from a scotogenic model”

  [Johannes Herms, Sudip Jana, Vishnu P.K., Shaikh Saad: arXiv:2307.15760 (*Phys.Lett.B 845 (2023) 138167*)]

- “Neutrino masses and mixing from milli-charged dark matter”

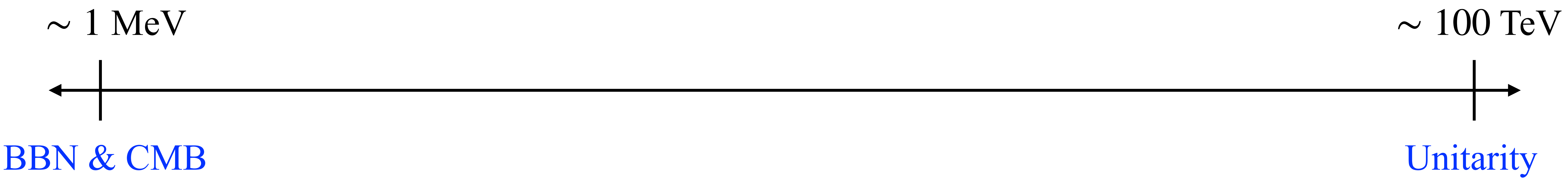
  [Michael Klasen, Sudip Jana,Vishnu P.K., Luca P Wiggering: arXiv:2406.18641 (*JCAP 02 (2025) 011*)]

Outline

- Light Thermal Dark Matter
  - General features and constraints
  - Viable scenarios
- Forbidden Dark Matter
  - General features and minimal realization
  - How to probe?
- Neutrinophilic Dark Matter
  - General features and realization within neutrino mass models
  - How to probe?
- Summary

Thermal dark matter

Thermal relics: particles that were once in equilibrium with SM bath $\Longrightarrow$
- Simplest cosmology
- Testable predictions
- …



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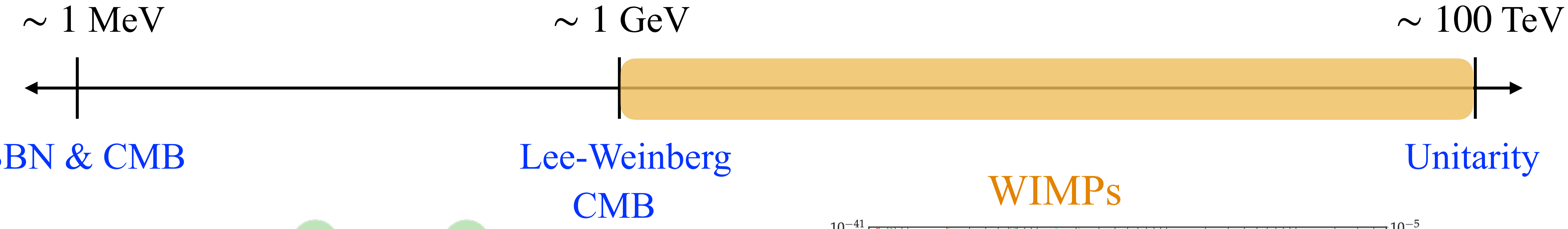
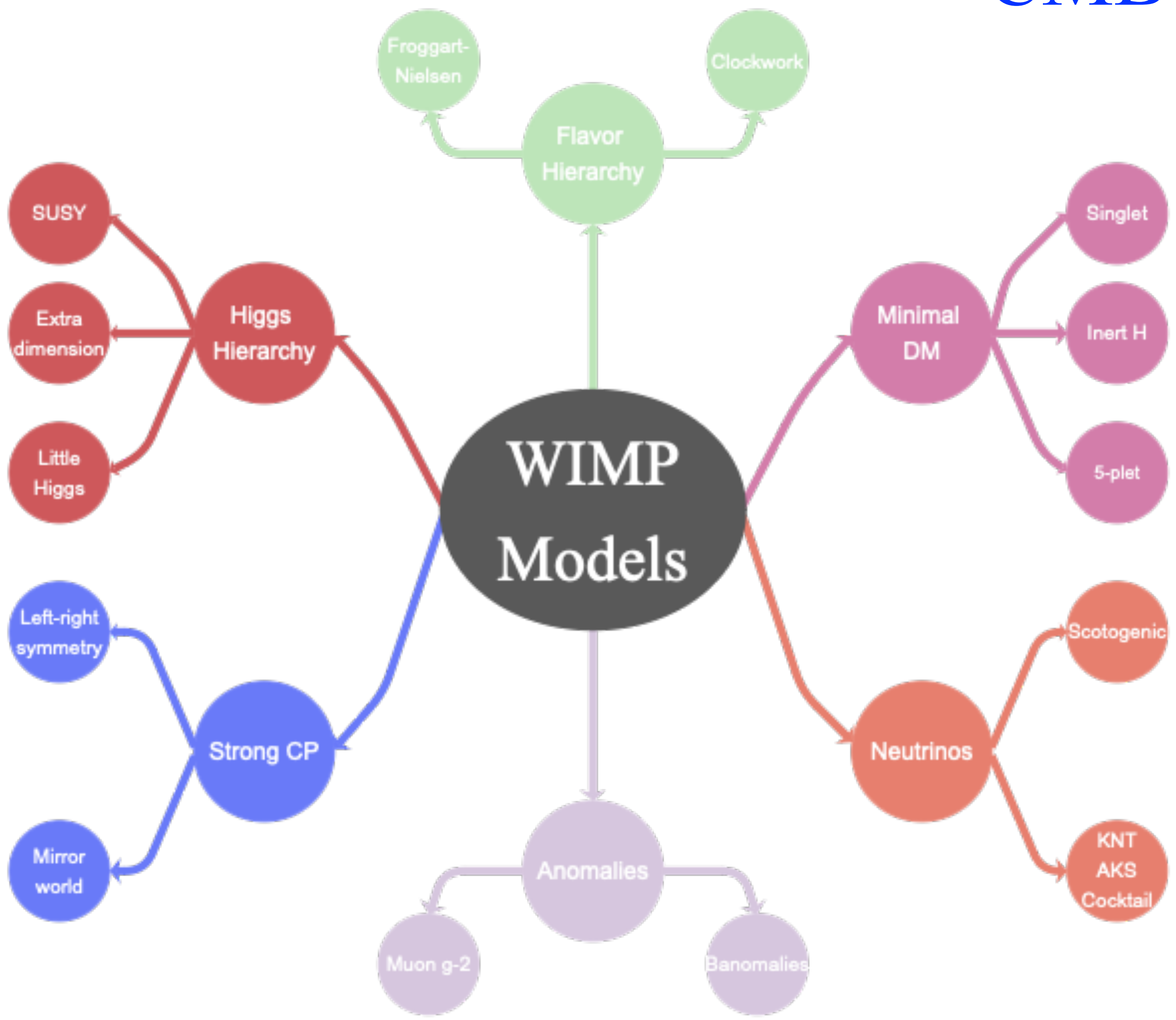
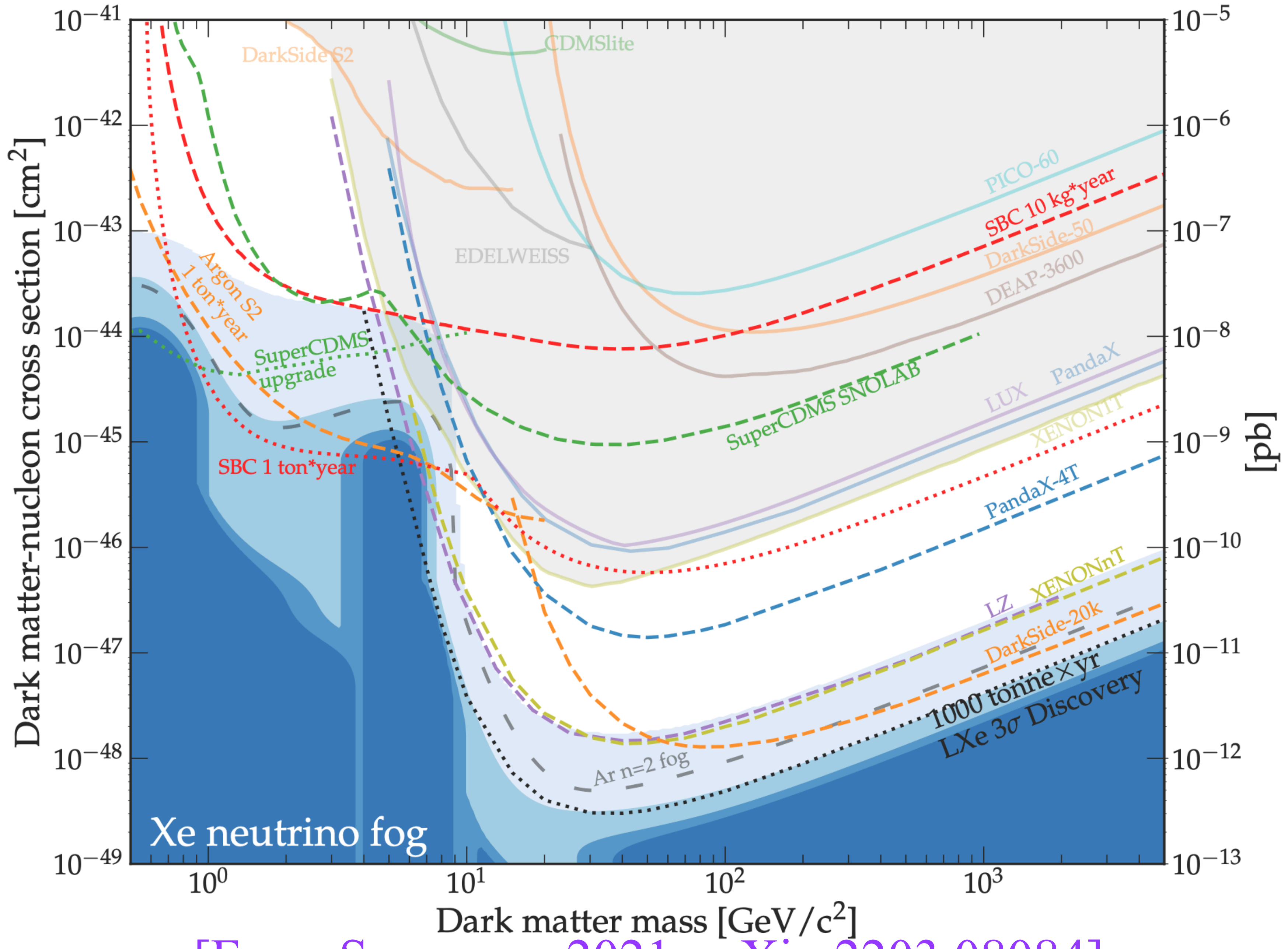


WIMPs





[From Snowmass2021, arXiv:2203.08084]

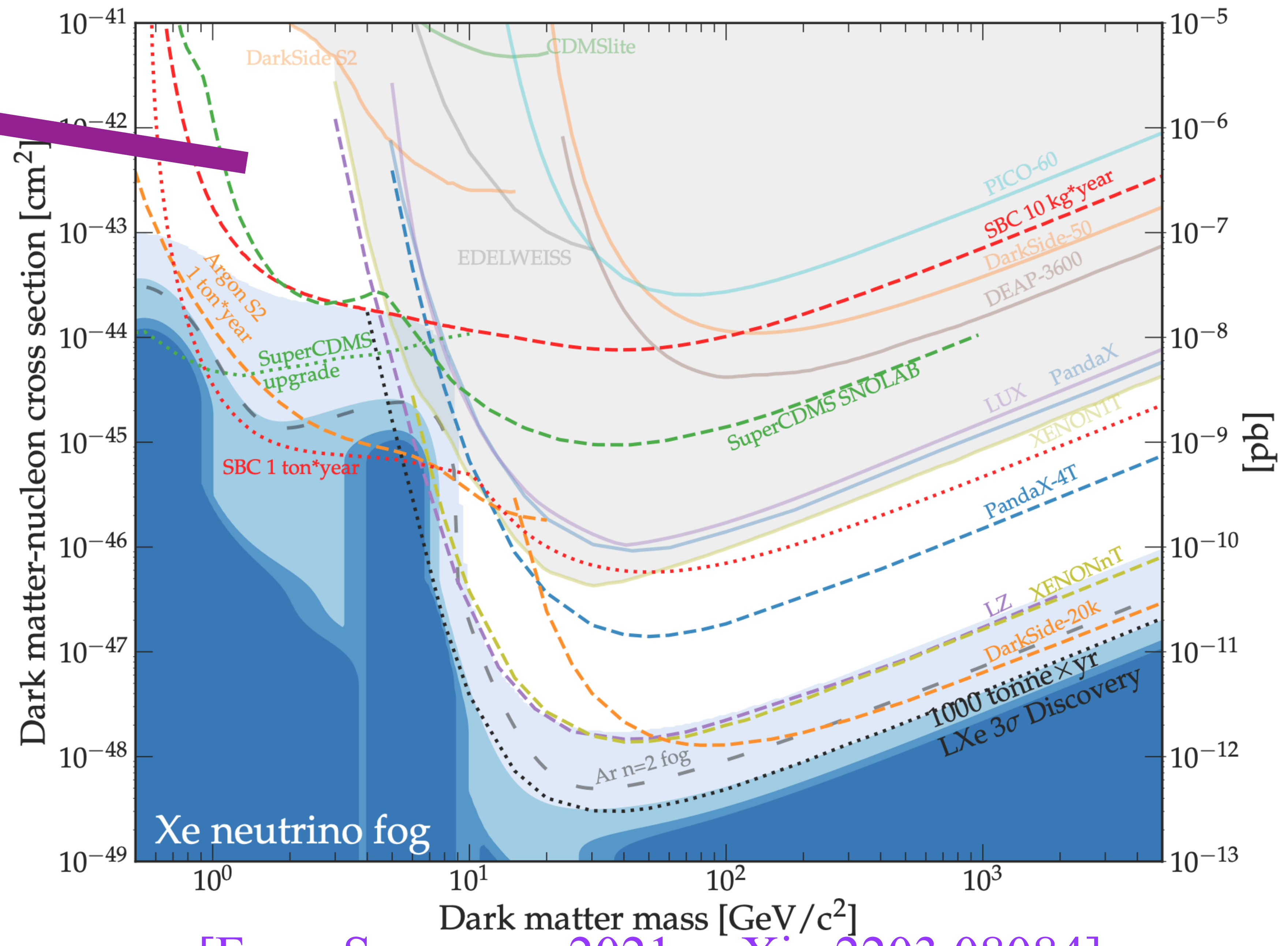
Thermal dark matter

Thermal relics: particles that were once in equilibrium with SM bath $\Longrightarrow$ { Simplest cosmology; Testable predictions; … }

$\sim$ 1 MeV — $\sim$ 1 GeV — $\sim$ 100 TeV

BBN & CMB — Light DM — Lee-Weinberg CMB — WIMPs — Unitarity

There exists a sizable, potentially interesting portions of thermal DM parameter space that eludes DM–nuclear scattering constraints yet remains testable through various other probes



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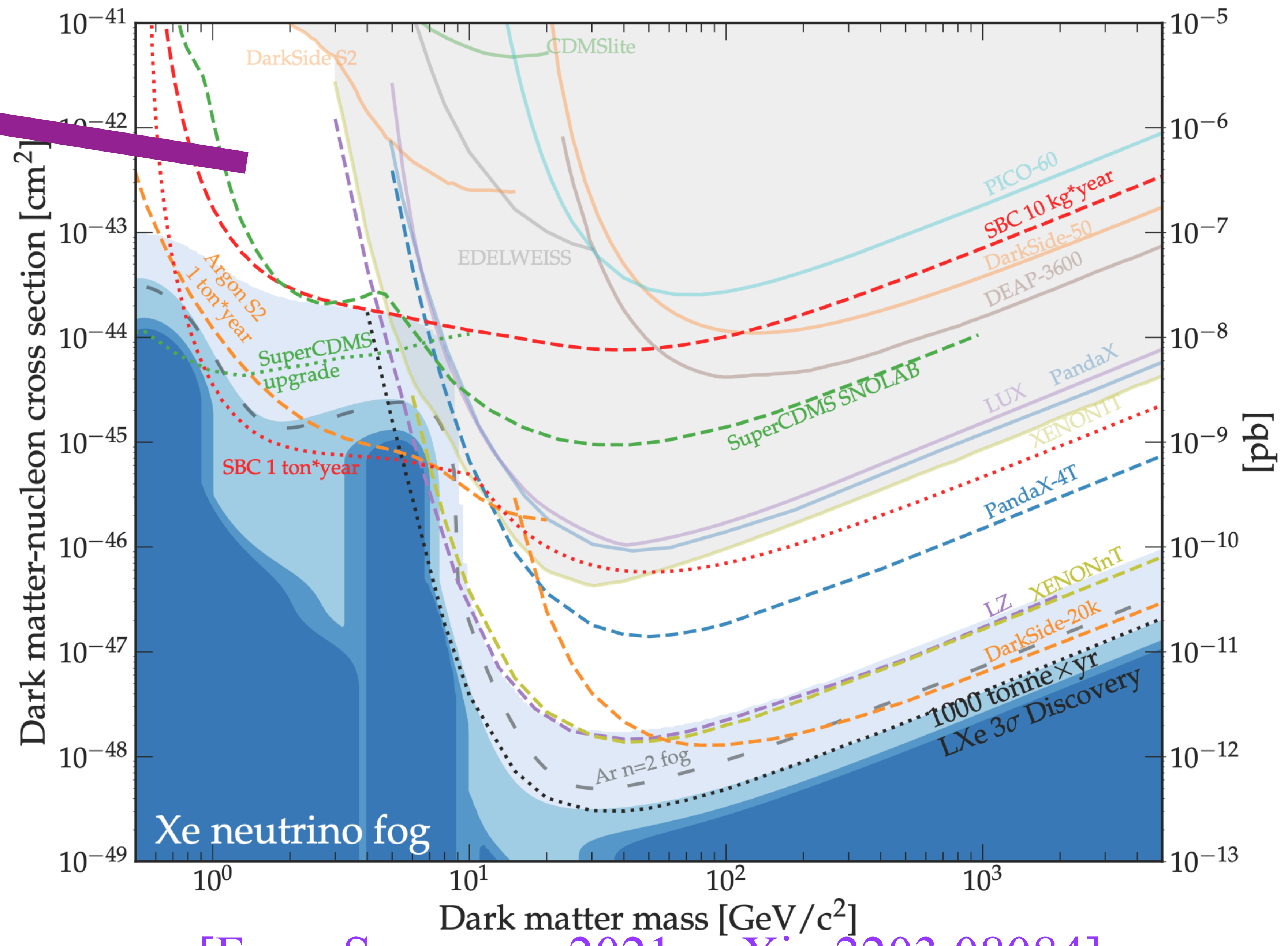
Challenges:

- Lee-Weinberg bound
- Indirect detection constraints



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Light thermal dark matter

Requirement of a light mediator state:

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

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- ☐ ALPs
- ☐ Singlet scalar
- ☑ Higgs doublet(s)

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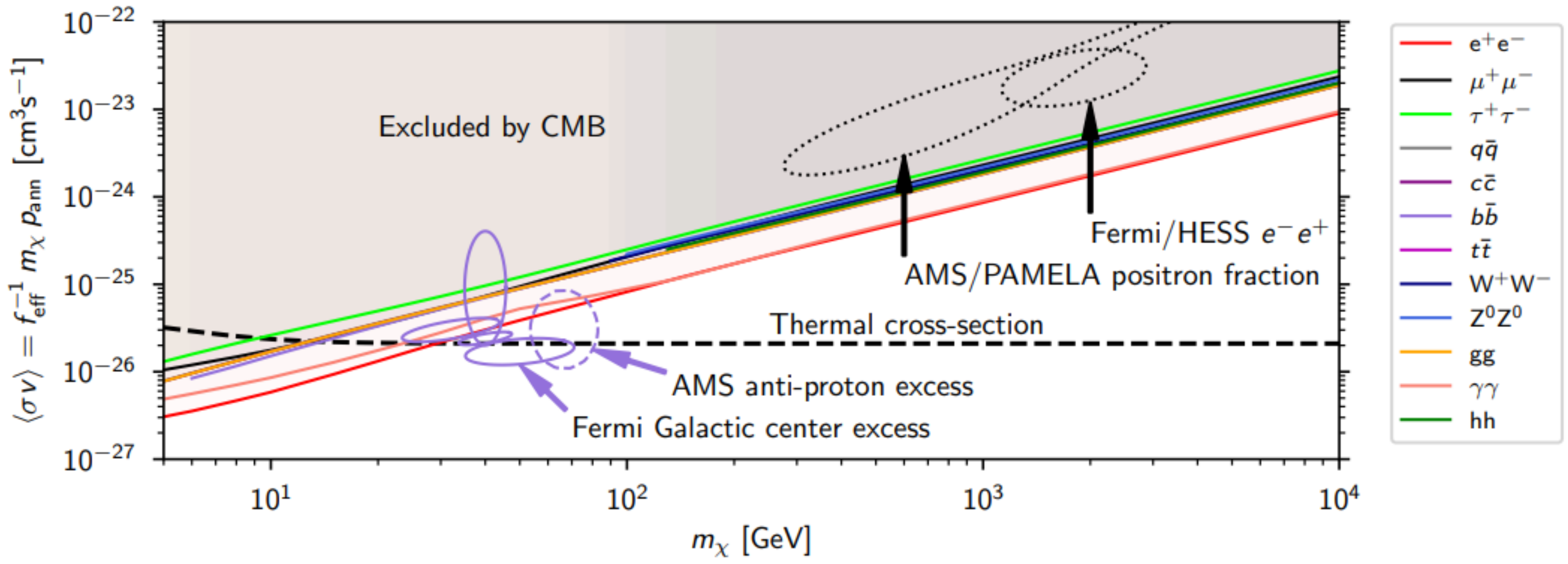
Stringent constraints from CMB measurements

- ☐ Thermal dark matter with s-wave annihilation
- ☑ Requires $\langle\sigma v\rangle_{\rm today} \ll \langle\sigma v\rangle_{\rm freeze-out}$



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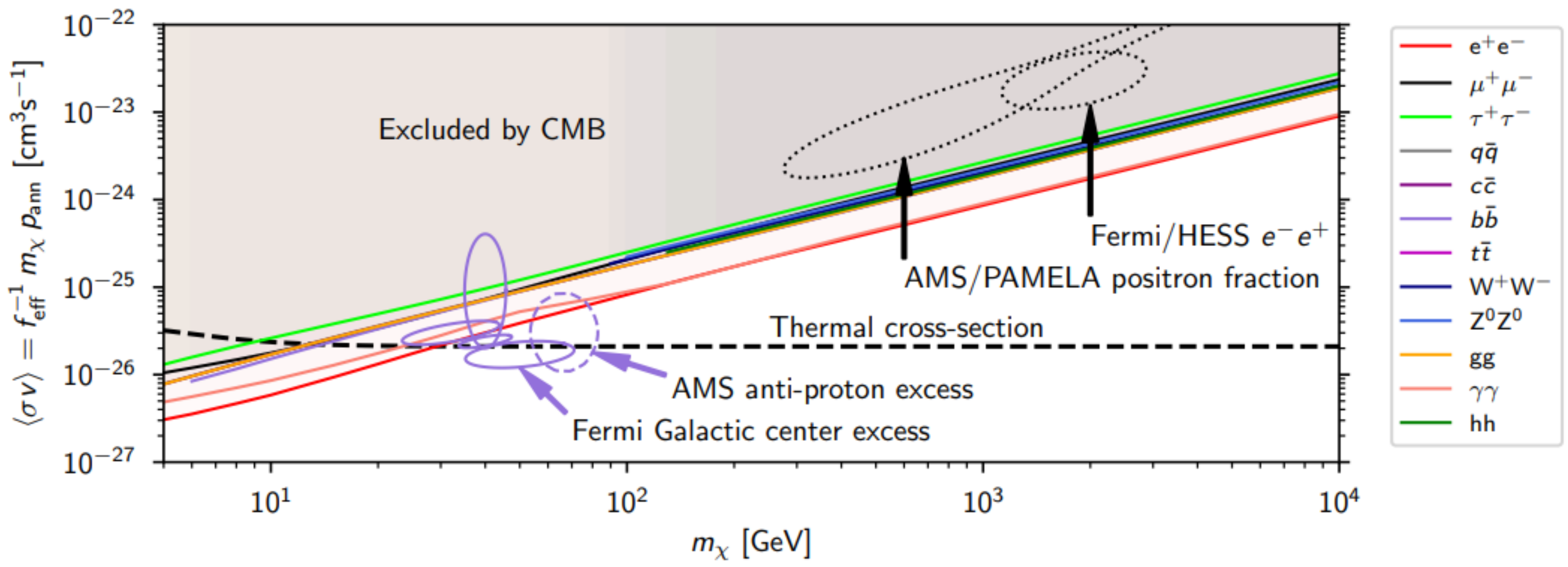

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Possible exceptions:

- ☐ Secluded dark matter [M. Pospelov, A. Ritz, M B. Volosin, 2007],…
- ☐ Dark matter with dominant annihilation through p-wave
- ☐ Forbidden dark matter [R. T. D'Agnolo, J. T. Ruderman, 2015], [K. Griest, D. Seckel, 1991]
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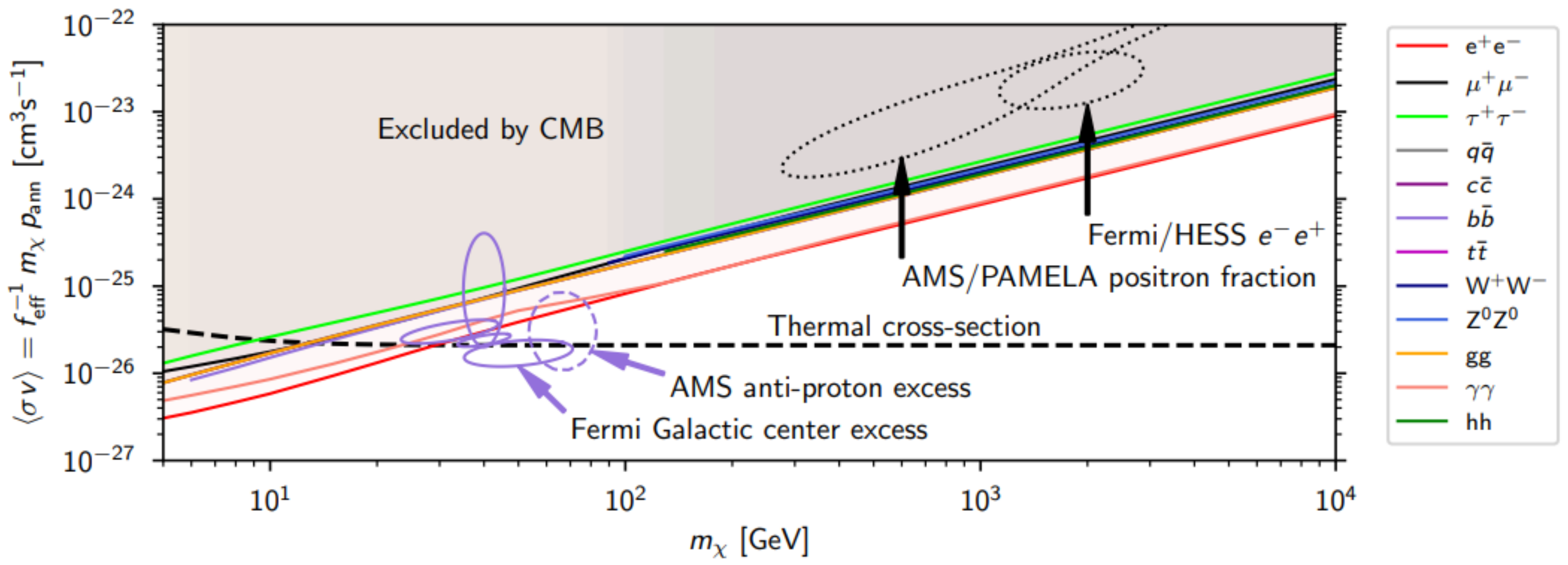

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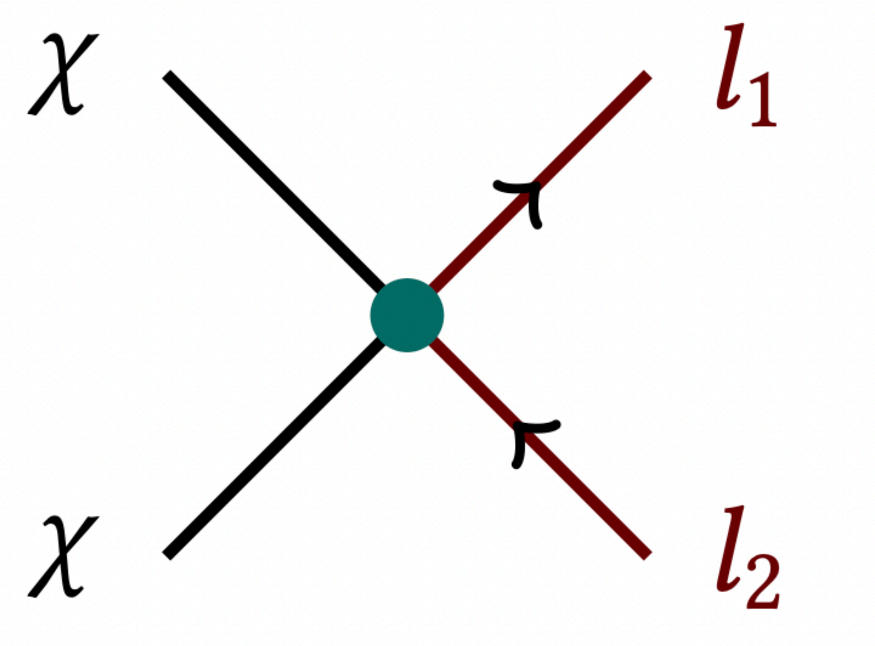
Forbidden Dark Matter

Forbidden dark matter

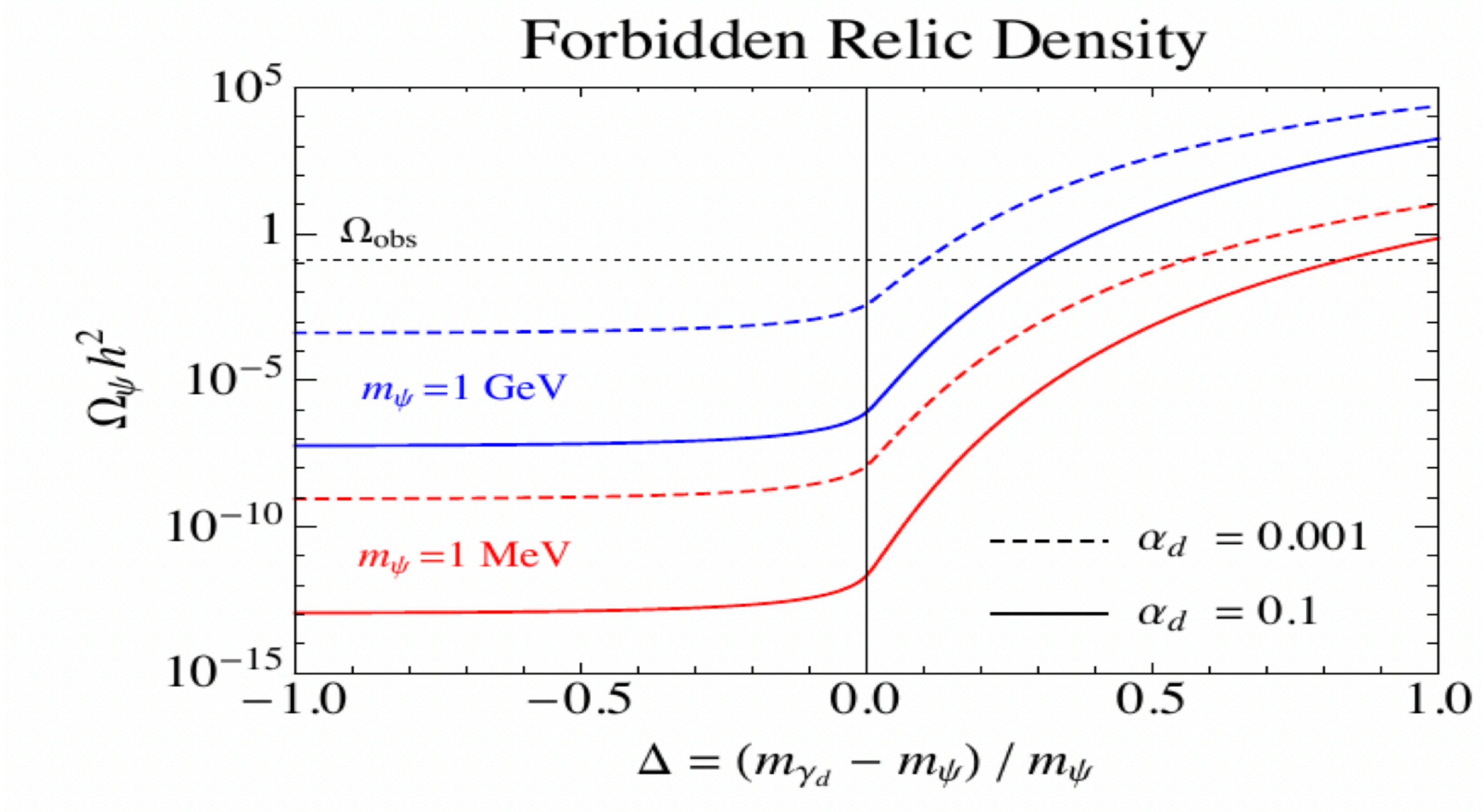
Annihilation proceed through kinematically <u>forbidden channels</u> (*forbidden only at* $T = 0$): $2m_\chi < m_{\ell_1} + m_{\ell_2}$

[K. Griest, D. Seckel, 1991], [R. T. D'Agnolo, J. T. Ruderman, 2015]



$\langle \sigma v \rangle$ is suppressed by mass splitting:

$$\langle \sigma v \rangle_{\chi\chi \to \ell_1 \ell_2} = \langle \sigma v \rangle_{\ell_1 \ell_2 \to \chi\chi} e^{\frac{-2\Delta m_\chi}{T}}$$



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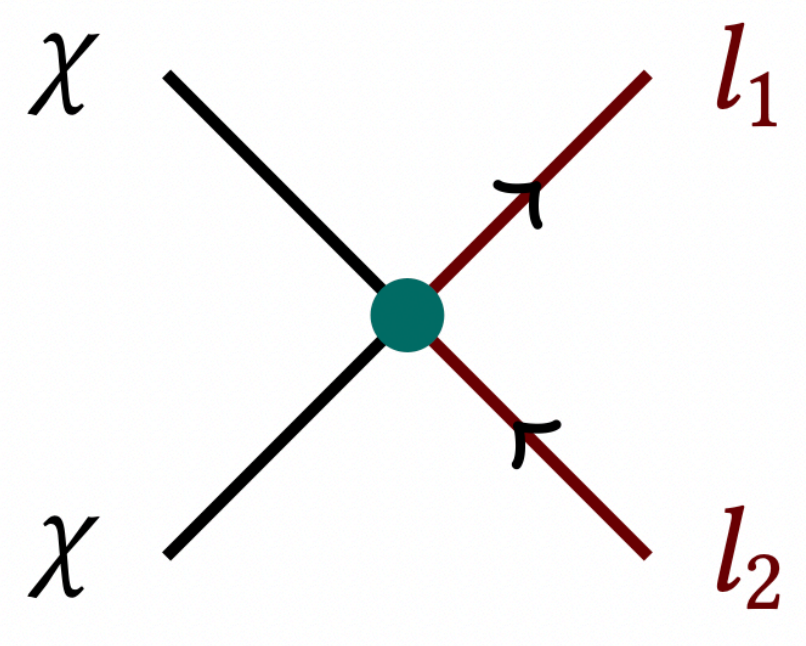

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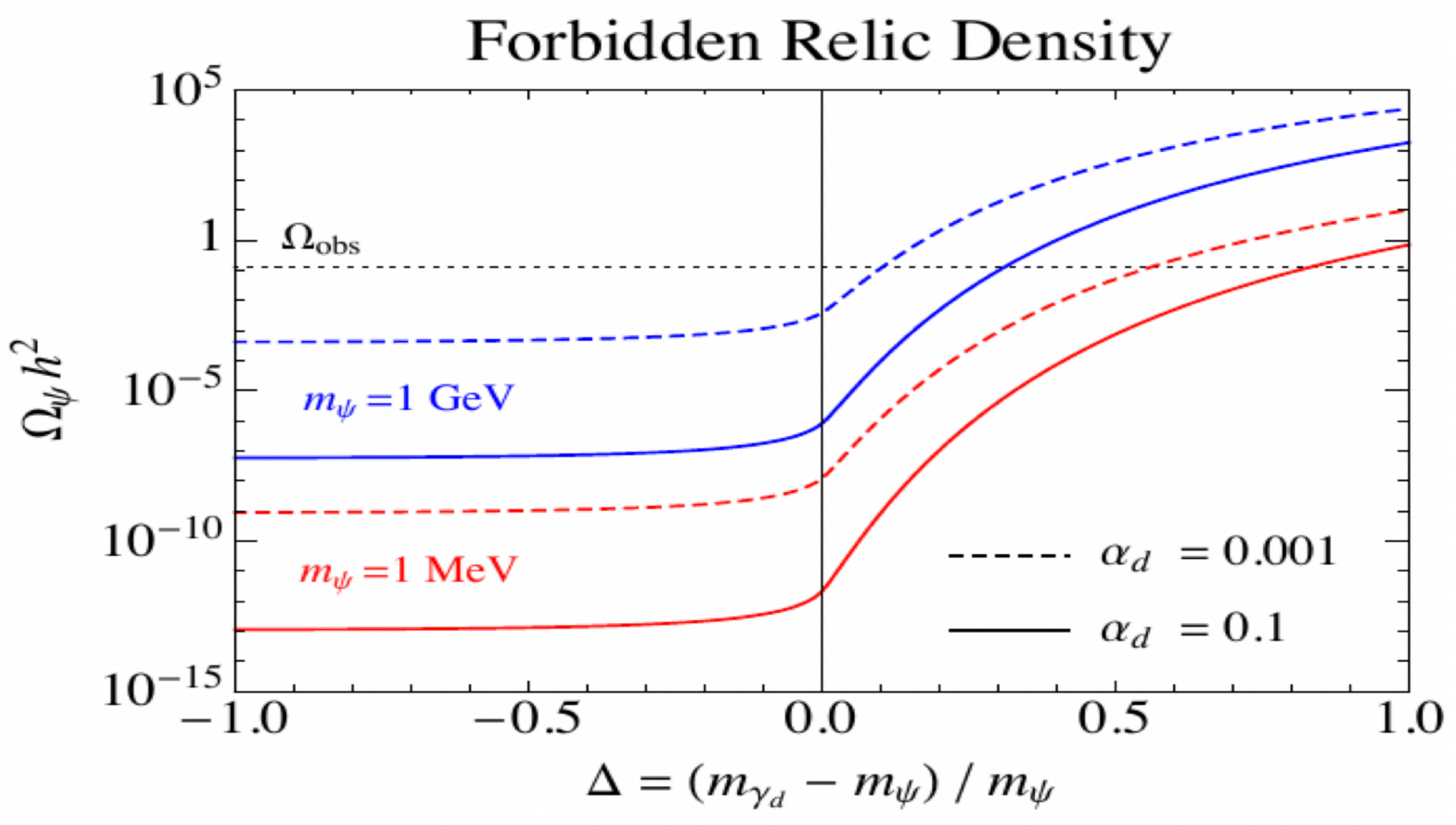
$$\langle\sigma v\rangle_{\chi\chi\to\ell_1\ell_2} \xrightarrow{T\to 0} 0$$: sastisfy ID const.



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Forbidden annihilations into SM particles

Particularly interesting to consider scenarios where dark matter annihilates to SM particles

- Definitive prediction for dark matter mass: $m_{\rm DM} \sim \dfrac{(m_{\ell_1} + m_{\ell_2})}{2}$

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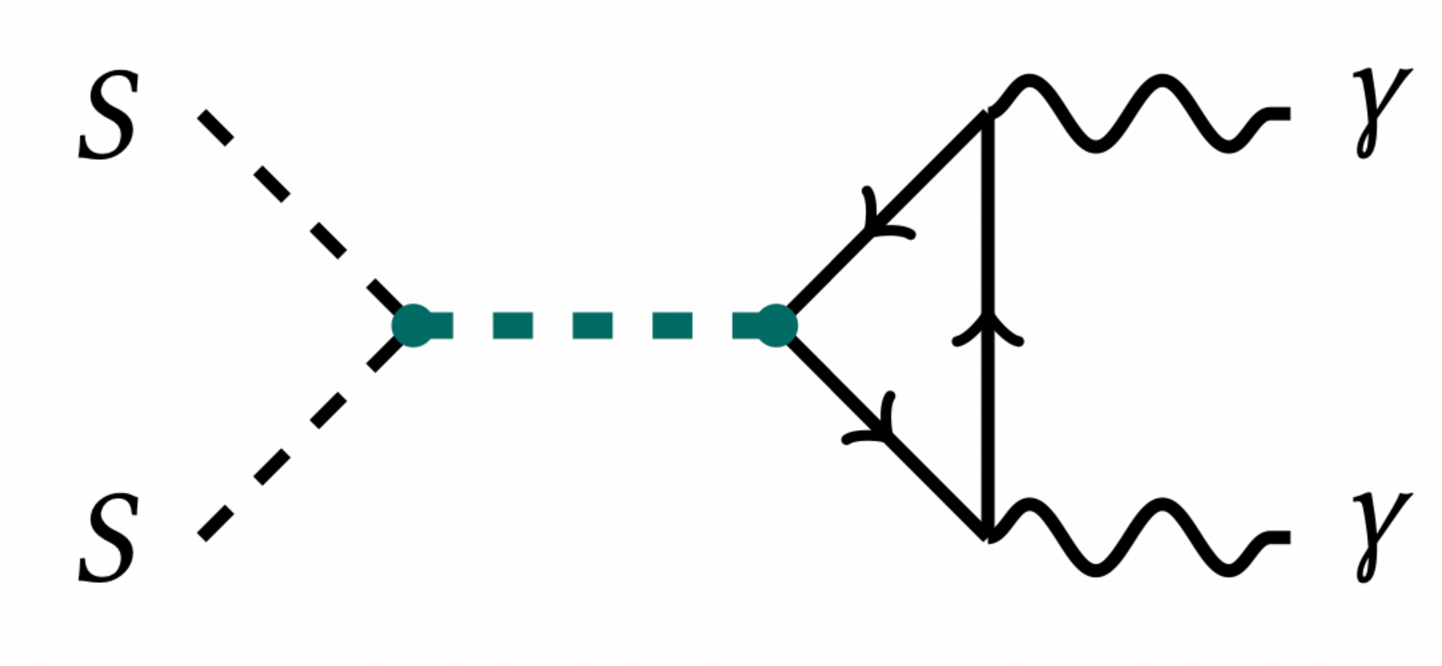
- Positive identification:

  [J. Herms, S. Jana, **VPK**, S. Saad, 2022]



Galactic gamma ray lines just below the lepton masses are a specific prediction of the scenario

Could be probed future MeV gamma ray missions like the AMEGO and e-ASTROGAM

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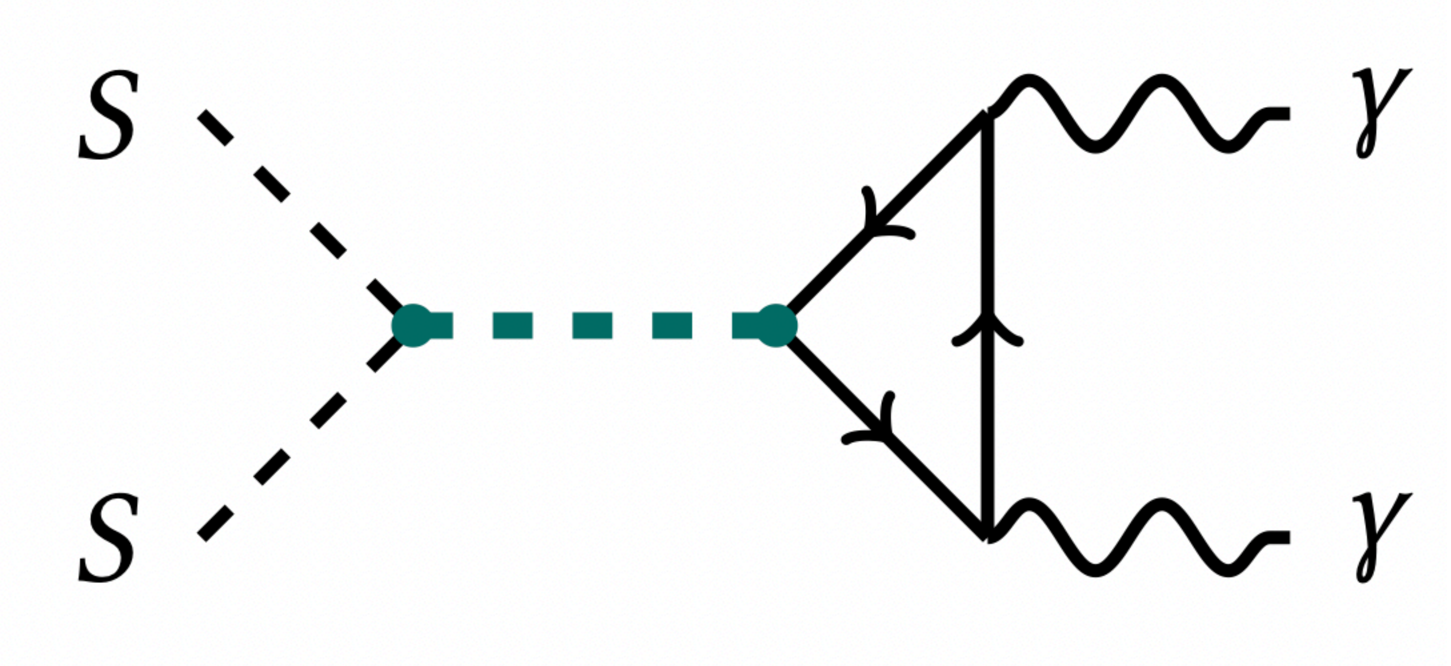

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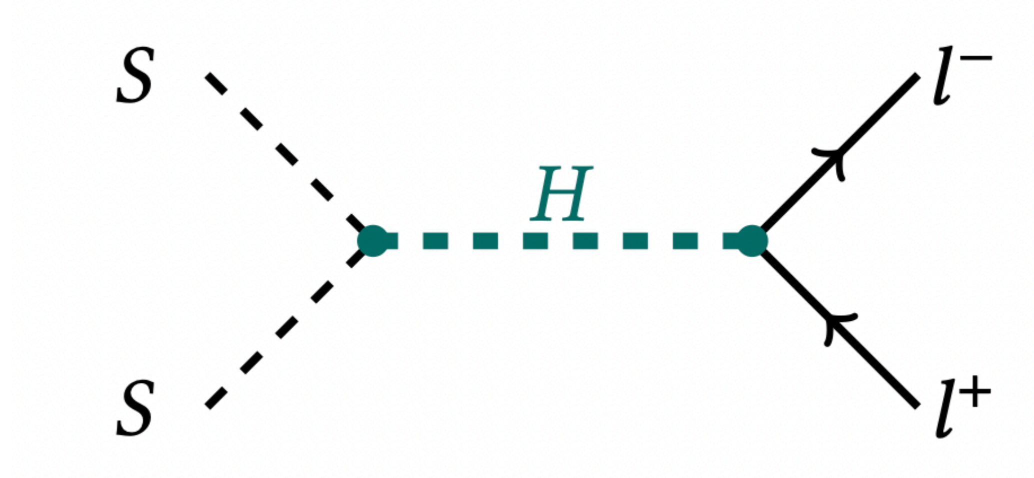
Minimal realization within 2HDM framework

[J. Herms, S. Jana, **VPK**, S. Saad, 2022]



Sub – GeV $scalar\ H \in 2HDM$

Two Higgs doublet model

2HDM: An extension of the SM scalar sector with an additional Higgs doublet

$$H_1 = \begin{pmatrix} G^+ \\ \frac{(v + \phi_1^0 + iG^0)}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{(H + iA)}{\sqrt{2}} \end{pmatrix}$$

Scalar Potential:

$$\mathscr{V}(H_1, H_2) = \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 - \{\mu_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.}\} + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2)$$
$$+ \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{ \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \mathrm{h.c.} \right\} + \left\{ \left[\lambda_6 (H_1^\dagger H_1) + \lambda_7 (H_2^\dagger H_2)\right] H_1^\dagger H_2 + \mathrm{h.c.} \right\}.$$

Physical states in the alignment limit:

$$h_{\mathrm{SM}} \simeq \phi_1^0, \quad H_{\mathrm{new}} = \{H, A, H^\pm\}$$

Light Higgs in 2HDM

BSM scalars: $H_{\rm new} = \{H, A, H^\pm\}$

Phenomenologically consistent choice of mass heirarchy: $m_H \ll m_A \simeq m_{H^\pm} \simeq \mathcal{O}(100)\,\text{GeV}$

- Z-decay width constraints
  - $Z \to HA : m_A > 90\,\text{GeV}$
- LEP constraints
  - $m_{H^\pm} > 100\,\text{GeV}$
- Electroweak precision constraints
  - $$T = \frac{1}{16\pi^2 \alpha_{\rm em}(M_Z) v^2}\left\{\mathcal{F}(m_{H^+}^2, m_H^2) + \mathcal{F}(m_{H^+}^2, m_A^2) - \mathcal{F}(m_H^2, m_A^2)\right\},$$
    $$\text{where } \mathcal{F}(m_1^2, m_2^2) \equiv \frac{1}{2}(m_1^2 + m_2^2) - \frac{m_1^2 m_2^2}{m_1^2 - m_2^2}\ln\left(\frac{m_1^2}{m_2^2}\right)$$
  - Suppressed for $m_A \simeq m_{H^\pm}$

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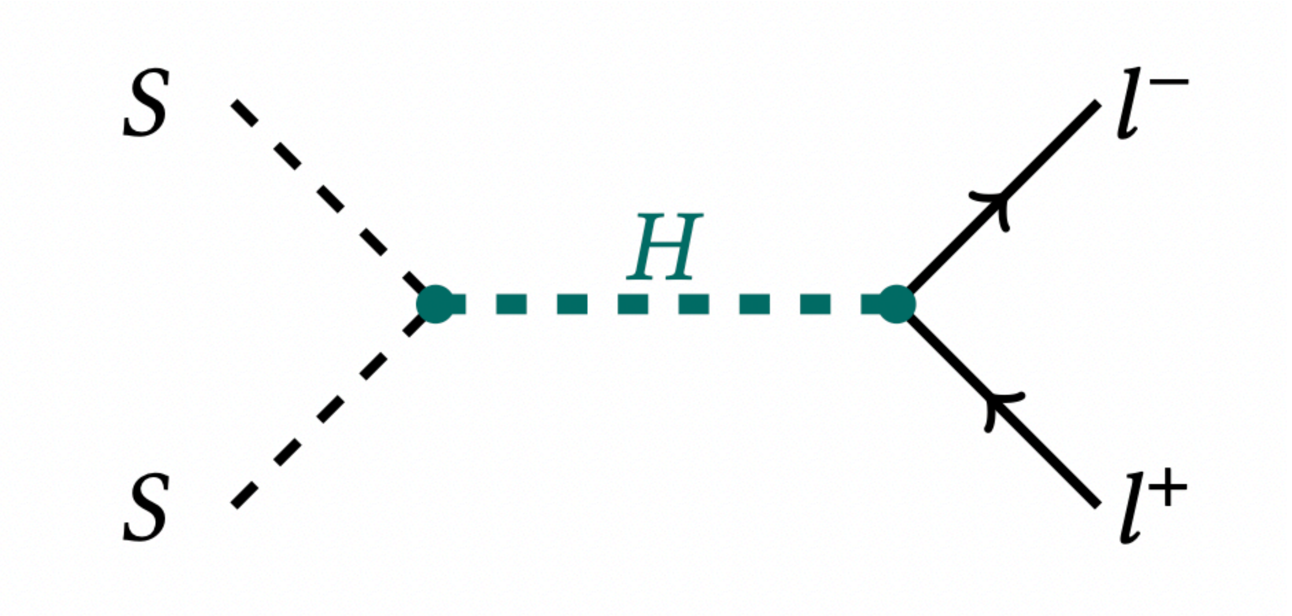
- Z-decay width constraints
- LEP constraints
- Electroweak precision constraints
- SM Higgs phenomenology
  - $h \to HH \to l^+l^-l^+l^-/\text{invisible} : \mathscr{V} \supset \frac{v_{EW}}{2} hH^2 \left(\lambda_3 + \lambda_4 + \lambda_5\right) \Rightarrow \lambda_3 \simeq -(\lambda_4 + \lambda_5) \propto \frac{m^2_{H^\pm}}{v^2_{EW}}$
  - $h \to \gamma\gamma : \mathscr{V} \supset \lambda_3 v_{EW} hH^+H^- \Longrightarrow R_{\gamma\gamma} < 1$, LHC data prefer $R_{\gamma\gamma} \gtrsim 1$
- Pertubativity conditions
  - $|\lambda| < \sqrt{4\pi} \Rightarrow m_{A,H^\pm} < 460\,\text{GeV}$: all BSM states lie $\lesssim$ EW – scale

Light Higgs portal for forbidden dark matter

Scalar state H provides a portal for light thermal DM:



Dark matter coupling with the light scalar state H:

$$\mathscr{V} \supset \frac{\kappa_{12}}{2} S^2 H_2^\dagger H_1 + \mathrm{h.c.}$$

Coupling of mediator state with SM light fermions:

$$-\mathscr{L}_{\mathrm{Y}uk} \supset \widetilde{Y} \overline{\ell}_L H_1 \ell_R + Y \overline{\ell}_L H_2 \ell_R + \mathrm{h.c.}$$

- $\widetilde{Y} = \mathrm{diag}(m_e, m_\mu, m_\tau)/v_{EW}$ (alignment limit)
- Y detemines the dark matter phenomenology

Light Higgs portal for forbidden dark matter

Possible annihilation channels:

$$Y = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{e\mu} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{e\tau} & Y_{\mu\tau} & Y_{\tau\tau} \end{pmatrix} : \quad Y_{ij} \Longrightarrow SS \to \ell_i^{\pm} \ell_j^{\mp}$$

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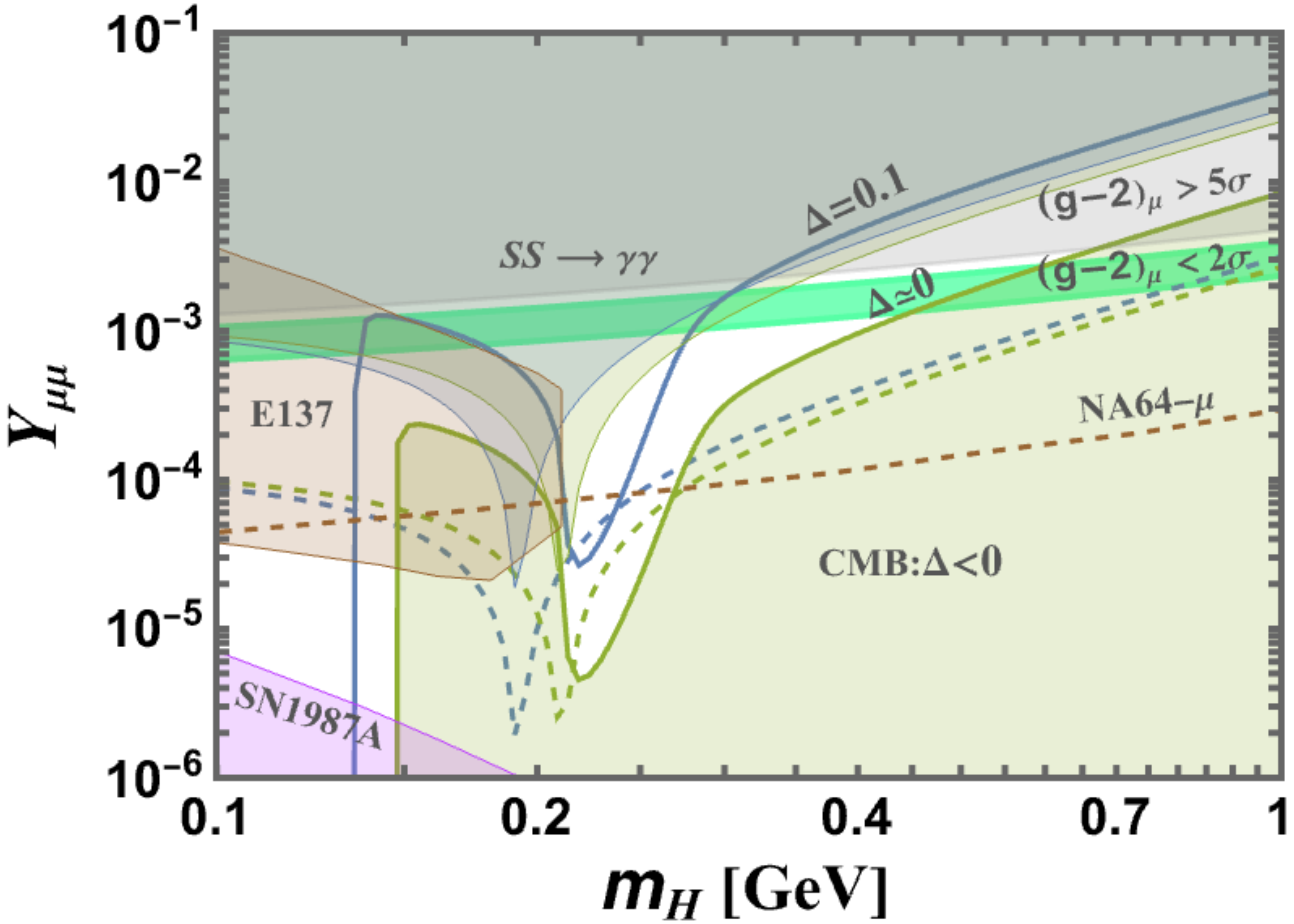
$SS \to e^+e^-$: $m_{\rm DM} < m_e$, exlcuded by BBN and CMB data

$SS \to \ell^{\pm}e^{\mp}$: leads to $\ell \to eSS$, most of the parameter space excluded by $\ell \to e\bar{\nu}\nu$ measurements

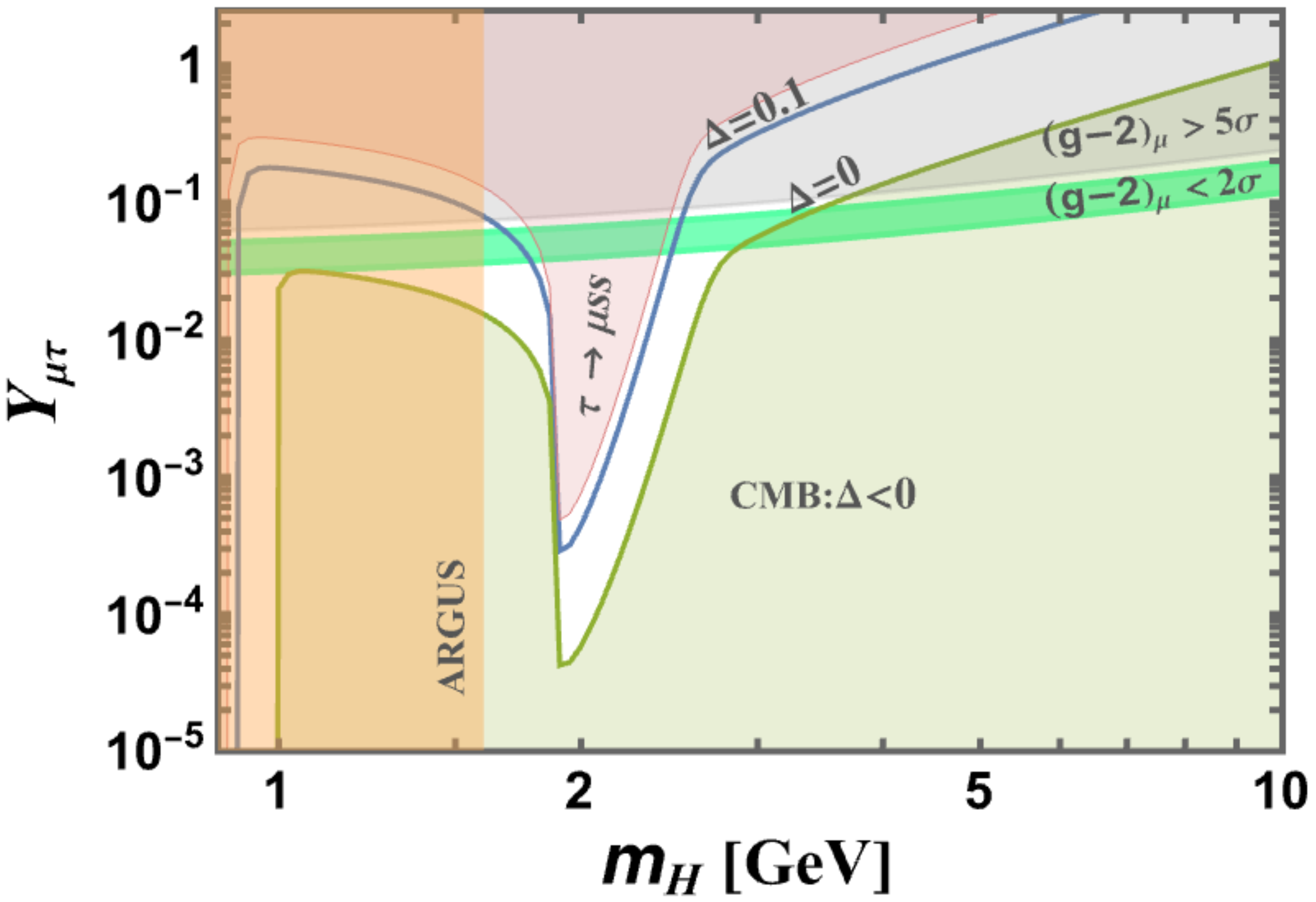
Viable scenarios: $SS \to \{\mu^+\mu^-, \mu^{\pm}\tau^{\mp}, \tau^+\tau^-\}$

Results-$\mu\mu$



- Muon g-2:
  - H contributes positively to Δa_μ
  - $\Delta a_\mu > 0 \sim 4.2\sigma$ [FNAL, 2021], [WP, 2020]
  - Below 1σ [FNAL, 2025], [WP, 2025]
- Supernovae cooling
  - H can contributes to energy loss [D. Croon+, 2006.13942]
- Beam dump experiments:
  - E137 electron beam dump [B. Batell+, 1712.10022]
  - NA64-μ muon beam dump [C.-Y. Chen+, 1807.03790]
  - NA64-μ muon beam dump [NA64, 2024]

Results-$\mu\tau$



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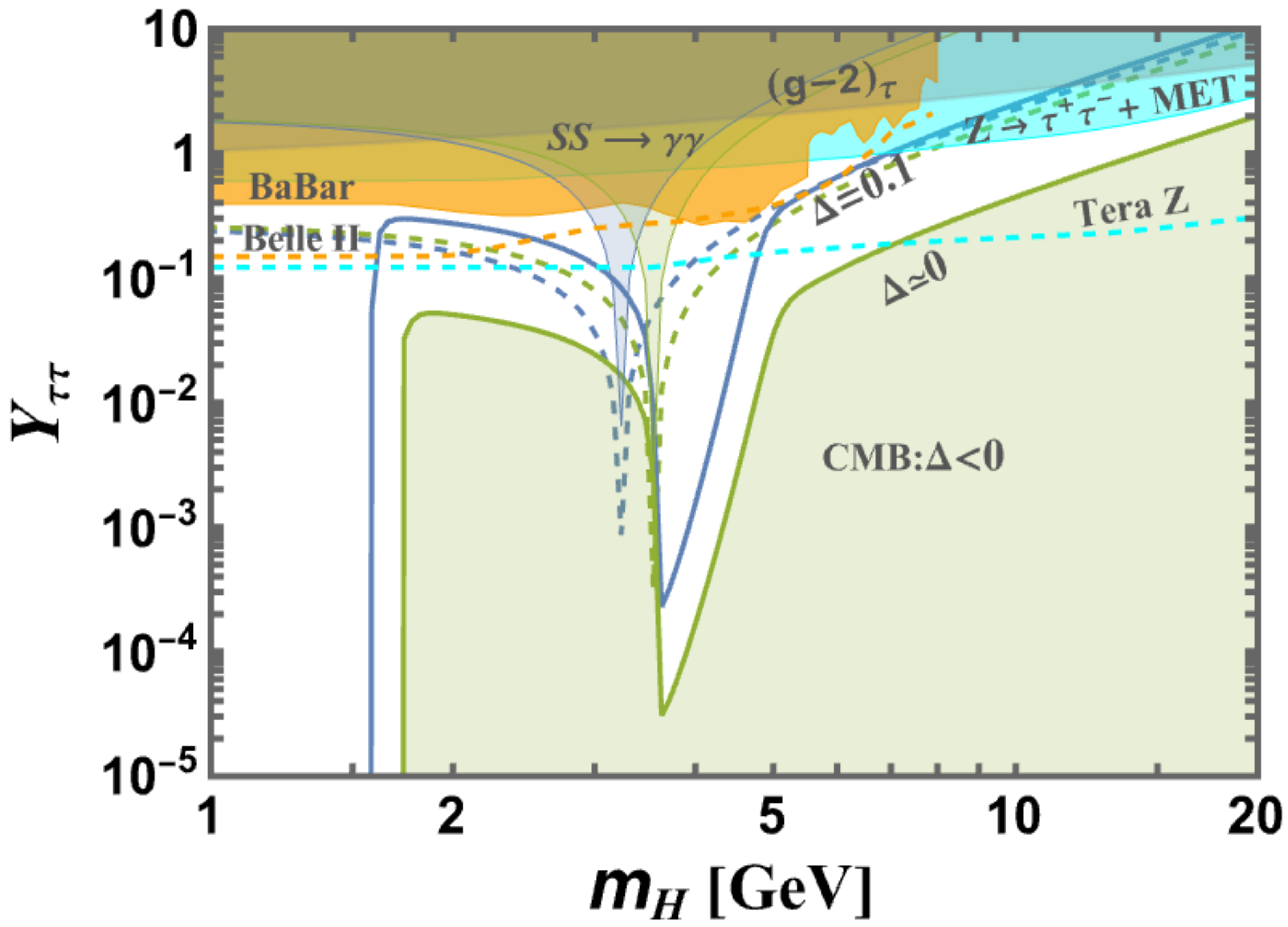
- Tau decay:
  - $\tau \to \mu H$: LFV two-body decay [ARGUS, 1995]
    $\Longrightarrow m_\tau - m_\mu < m_H$
  - $\tau \to \mu SS$: adds to expt. $\Gamma(\tau \to \mu\nu_\tau\bar{\nu}_\mu)$
    $\Longrightarrow \Delta < 0.126$

Results-$\tau\tau$



- Z decay:
  - $Z \to \tau^+\tau^- H$ adds to expt. Br($Z \to \tau^+\tau^-$)

[C.-Y. Chen+, 1807.03790]

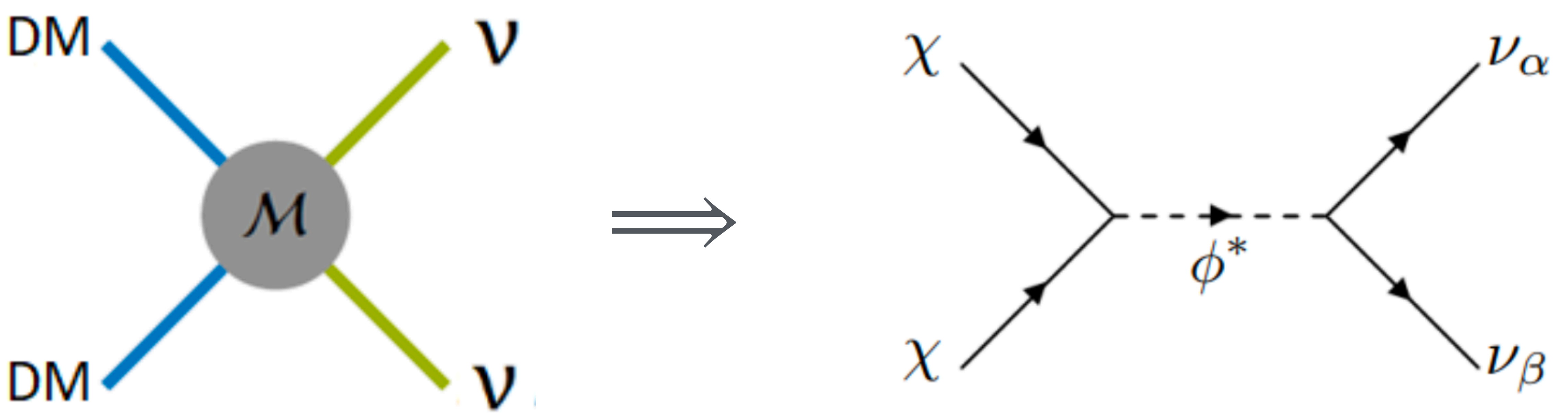
- Collider constraints:
  - $e^+e^- \to \gamma H$ with $H \to$ dark from BaBar
  - For the same process, Belle-II

Neutrinophilic Dark Matter

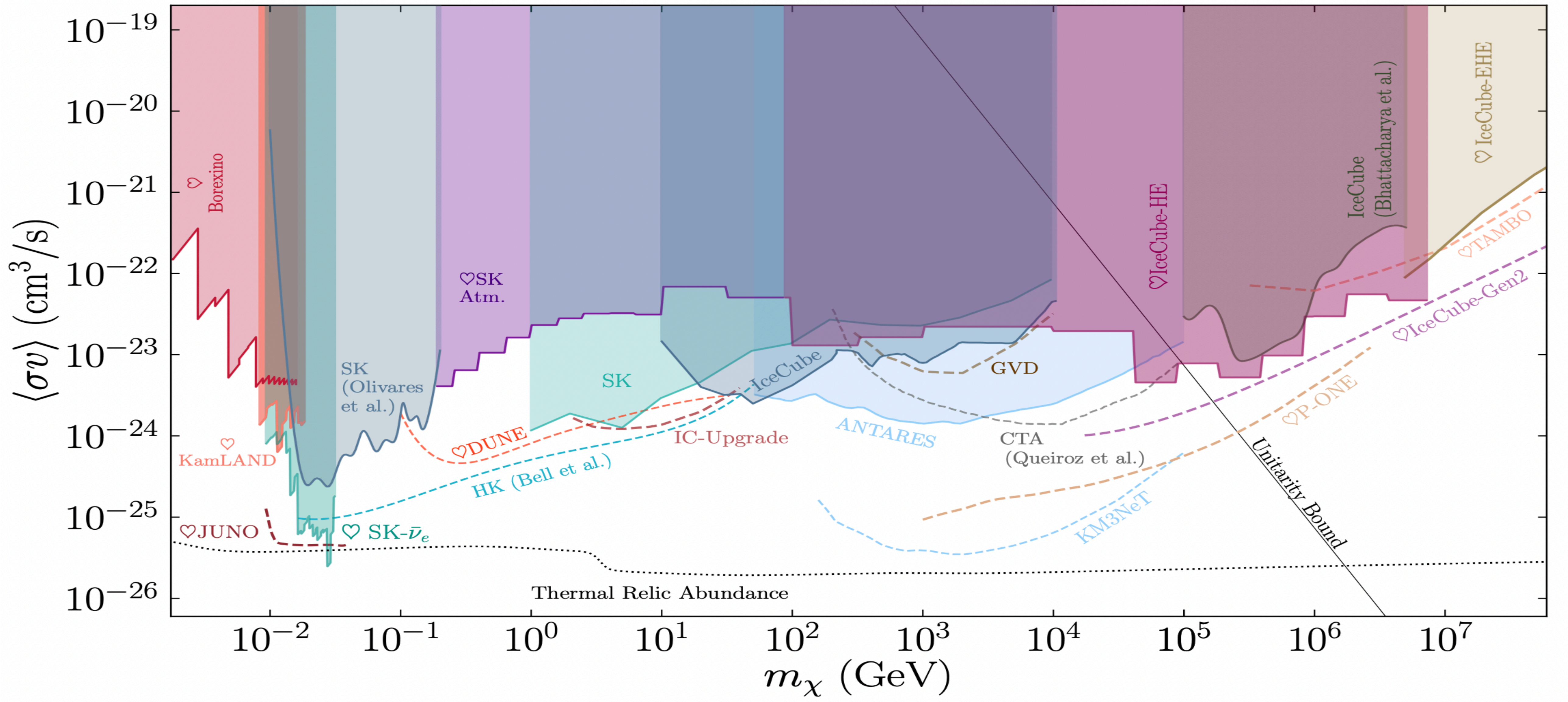
Image credit:quanta magazine

Neutrinophilic dark matter

Dark matter predominantly annihilates to neutrinos:



Sub-GeV neutrinophilic dark matter has promising prospects in various next generation neutrino telescopes



[From arXiv:1912.09486]

Neutrino masses and mixings

NuFIT 6.0 (2024)

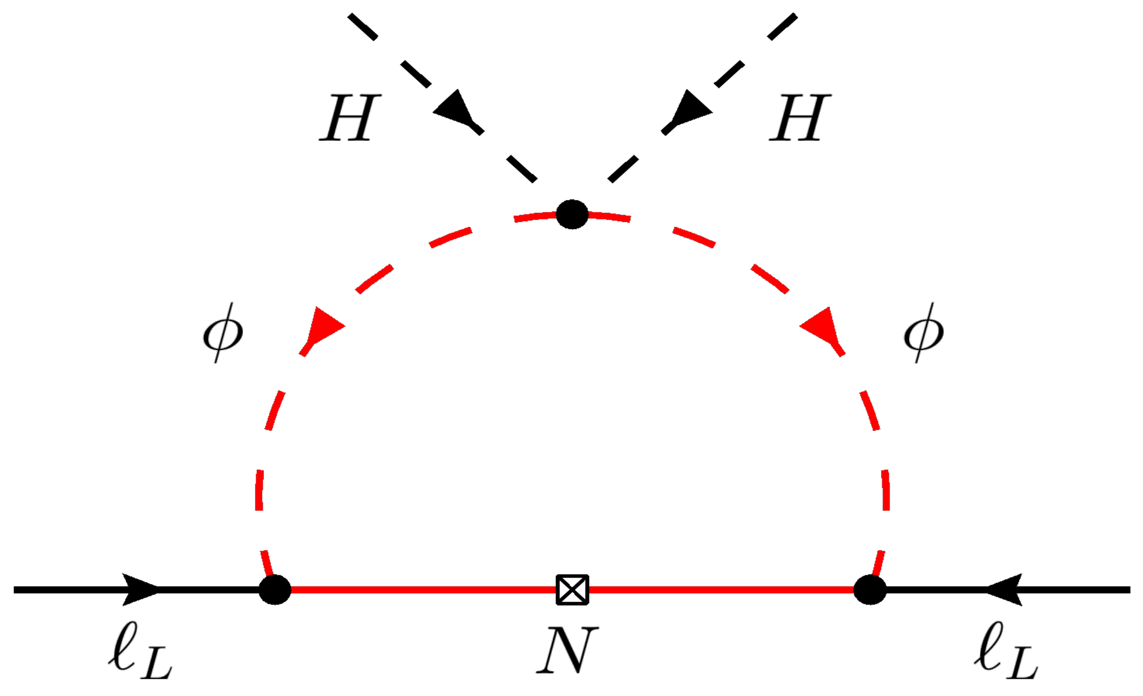
	Normal Ordering ($\Delta\chi^2 = 0.6$)		Inverted Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$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

It would be nice if sub-GeV neutrinophilic dark matter can be realized within neutrino mass models

Scotogenic models

Models in which neutrino mass generated radiatively assisted by dark matter candidates

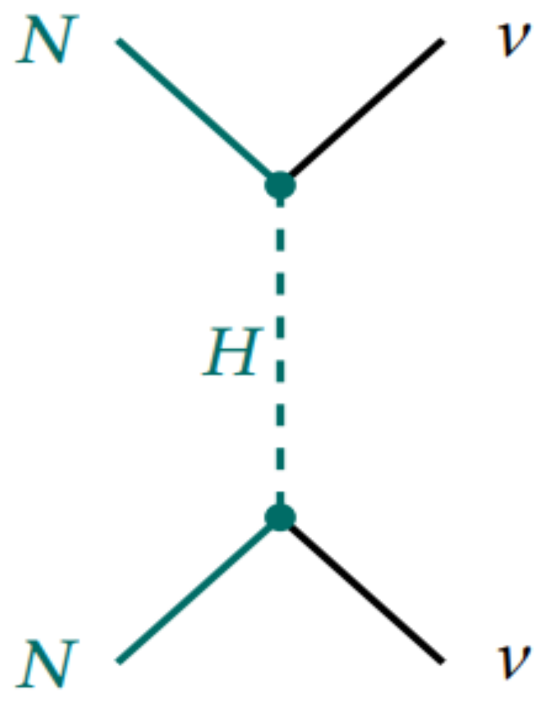
Minimal model: [Z. Tao, 1996], [E. Ma, 2006]



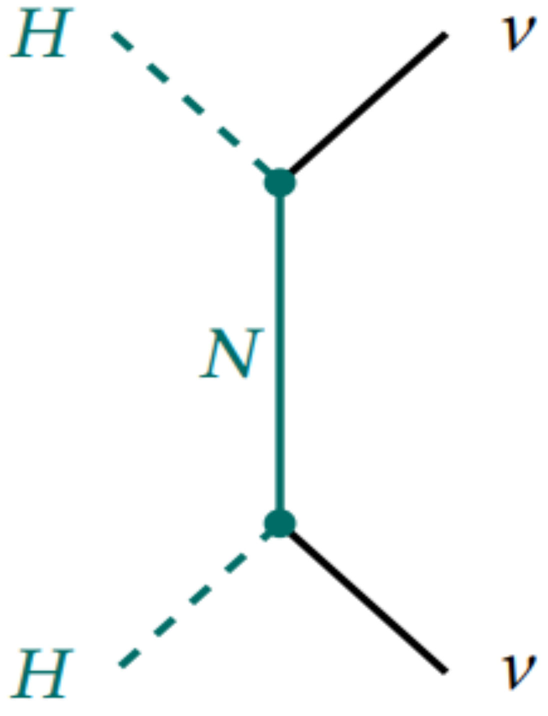
$N_{1,2} \sim (1,1;\ -\ )$

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

Dark matter can be neutrinophilic. But can it be light?



Fermionic DM

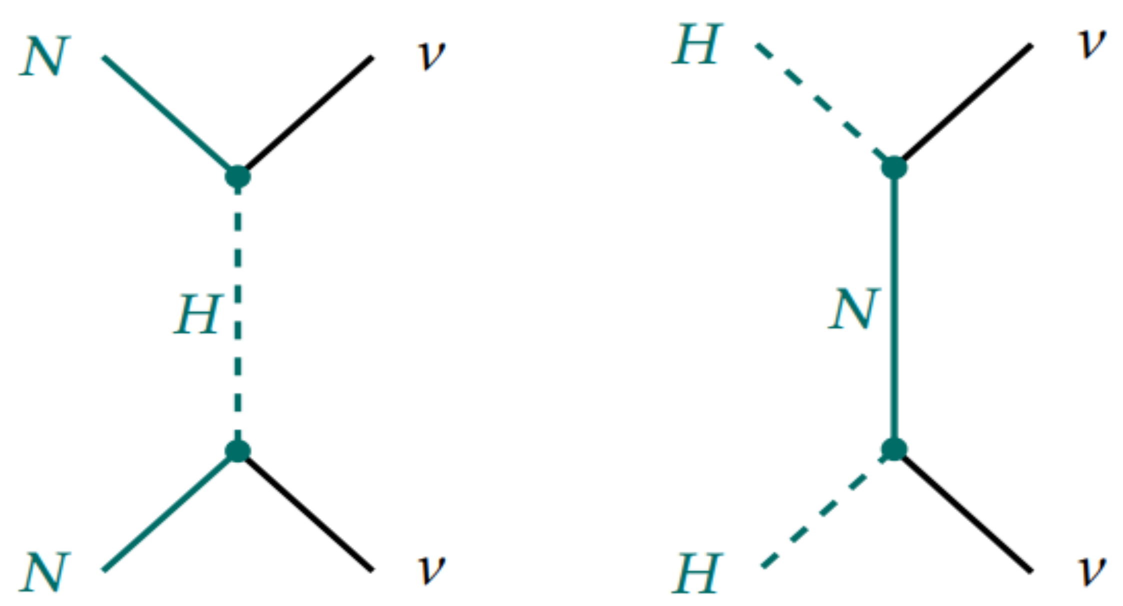


Scalar DM

Realization within minimal scotogenic model

Requirement of a light scalar from Higgs doublet: can be done!

To generate correct relic abudance, Yukawa couplings required to be large



$\Longrightarrow \langle \sigma v \rangle \propto Y^4$

Realization within minimal scotogenic model

Requirement of a light scalar from Higgs doublet: can be done!

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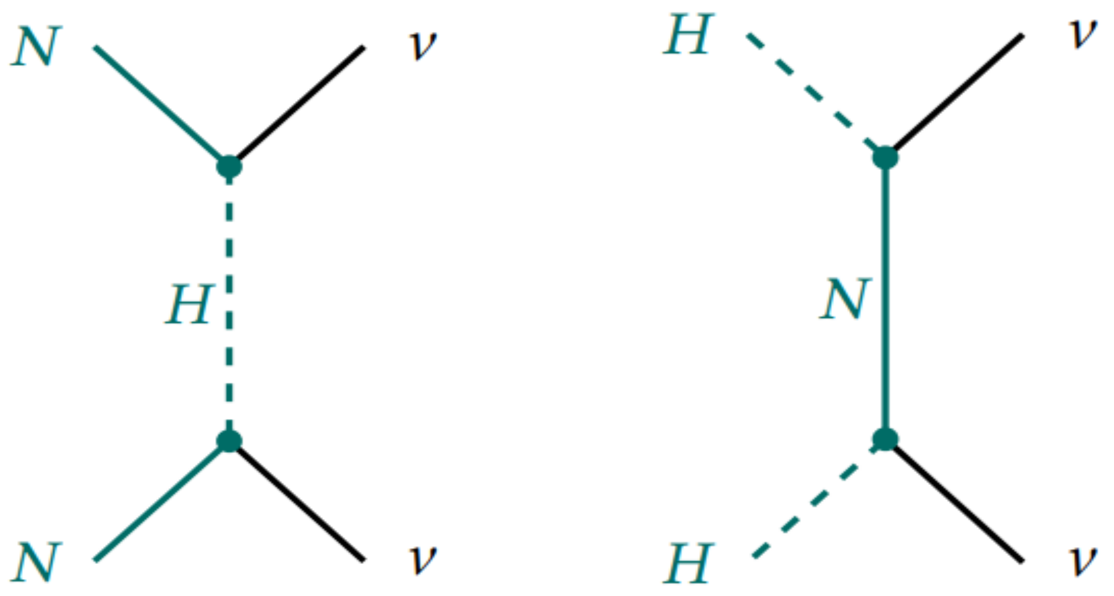
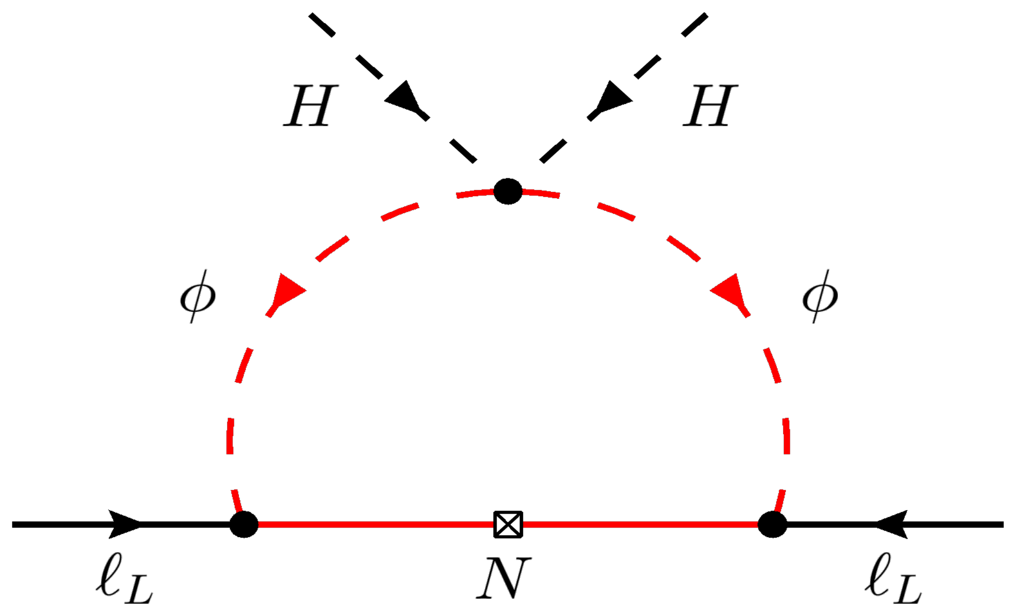


$\Longrightarrow \langle \sigma v \rangle \propto Y^4$

However, such large Yukawa couplings generate unacceptably large neutrino mass



$\Longrightarrow M_\nu \propto Y^2 \Longrightarrow \langle \sigma v \rangle \propto M_\nu^2$

Optimal scenario:

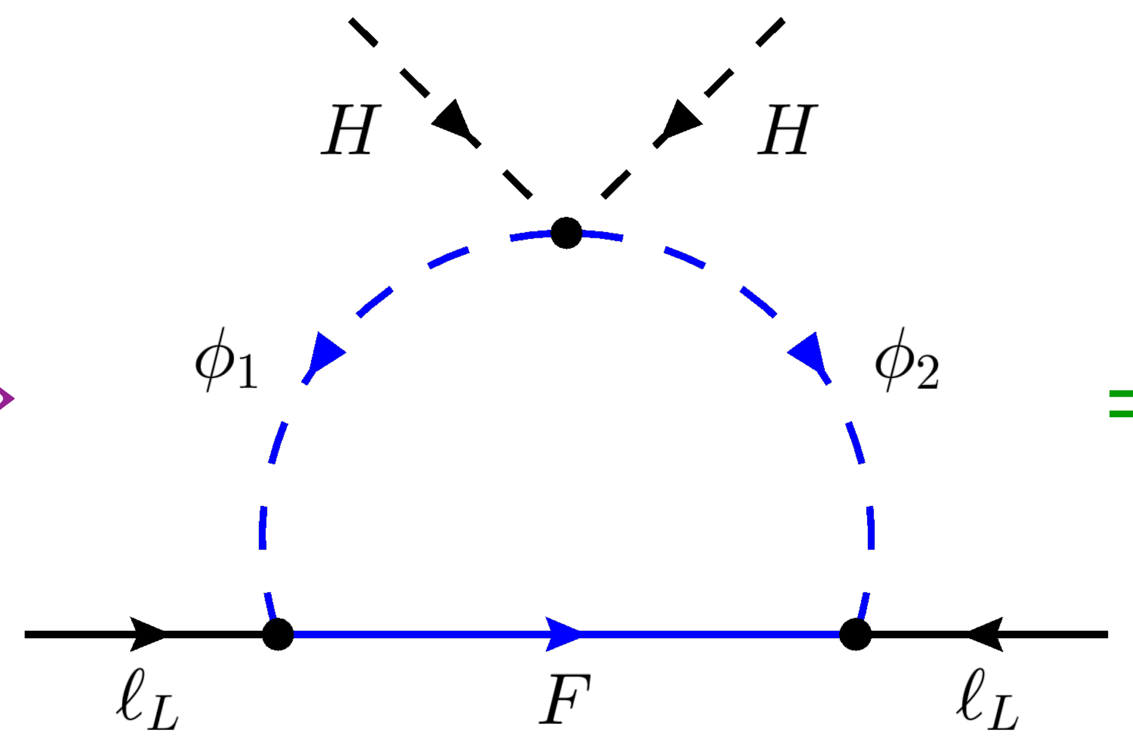
[J. Herms, S. Jana, **VPK**, S. Saad, 2023]

$$m_{\rm DM} = \sqrt{\frac{M_\nu}{0.1 \rm eV}} \times \begin{cases} 1.2\,\text{MeV} & R-\text{DM} \\ 0.5\,\text{MeV} & N-\text{DM} \end{cases} \Longrightarrow \text{Excluded by } N_{eff}$$

A different approach

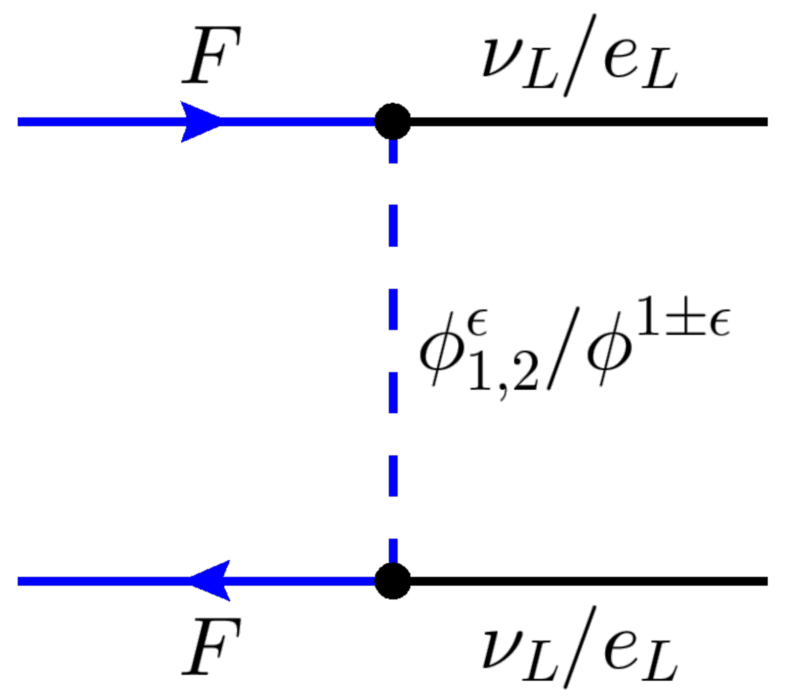
Framework:

$$-\mathscr{L}_{\text{Yuk}} \supset Y_1 \bar{\ell}_L \widetilde{\phi}_1 F + Y_2 \overline{\ell^c_L} \epsilon \phi_2 F + h.c. \Longrightarrow$$



$$\Longrightarrow M_\nu \propto Y_1 Y_2$$

Heirarchial Yukawa couplings: $|Y_1| \gg |Y_2| \Longrightarrow$



$$\Longrightarrow \langle \sigma v \rangle \propto Y_1^4$$

Models:

$F \sim (1,1,0;\omega)$, $\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \sim (1,2,\frac{1}{2};\omega)$, $\phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \sim (1,2,\frac{1}{2};\omega^{n-1})$

DM stability : $\mathscr{Z}_n, n > 2$

[C. Hagedorn, J. Herrero-Garcıa, E. Molinaro, M. A. Schmidt, 2018]
[J. Herms, S. Jana, **VPK**, S. Saad, 2023]

$F \sim (1,1,\epsilon)$, $\phi_1 = \begin{pmatrix} \phi_1^{1+\epsilon} \\ \phi_1^{\epsilon} \end{pmatrix} \sim (1,2,\frac{1}{2}+\epsilon)$, $\phi_2 = \begin{pmatrix} \phi_2^{1-\epsilon} \\ \phi_2^{-\epsilon} \end{pmatrix} \sim (1,2,\frac{1}{2}-\epsilon)$

DM stability : $U(1)_{\text{EM}}$

[M. Klasen, S. Jana, **VPK**, L. P. Wiggering, 2024]

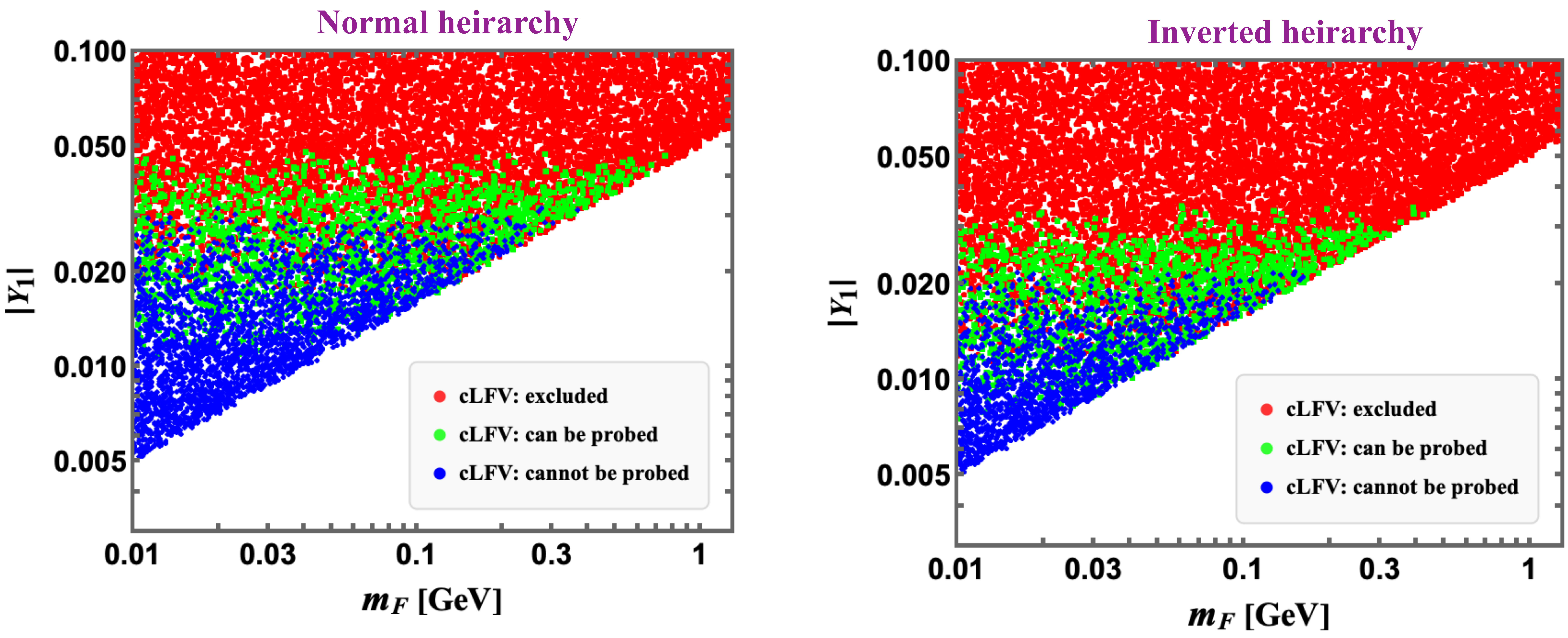
Light Higgs

BSM scalars: $H_{\text{new}} = \underbrace{S_1, S_2}_{\text{mix } \phi_1^0 \,\&\, \phi_2^0}, \phi_1^\pm, \phi_2^\pm$

Phenomenologically consistent choice of parameters: $m_{S_1} \ll m_{S_2} \simeq m_{\phi_1^\pm} \simeq m_{\phi_2^\pm} \simeq \mathcal{O}(100)\,\text{GeV} \,\&\, \theta \simeq \frac{\pi}{4}$

- Z-decay width constraints
  - $Z \to S_1^* S_1 : \Gamma_Z \propto \cos^2 2\theta$, suppressed for $\theta \simeq \frac{\pi}{4}$
  - $Z \to S_1 S_2 : m_{S_2} > 90\,\text{GeV}$
- LEP constarints
  - $m_{\phi_{1,2}^\pm} > 100\,\text{GeV}$
- Electroweak precision constraints
  - $m_{S_2} \simeq m_{\phi_1^\pm} \simeq m_{\phi_2^\pm} \implies T \propto \cos^2 2\theta$, suppressed for $\theta \simeq \frac{\pi}{4}$
- SM Higgs phenomenology
  - $h \to \gamma\gamma : R_{\gamma\gamma} \simeq 0.8$, consistent with LHC data at 3σ level

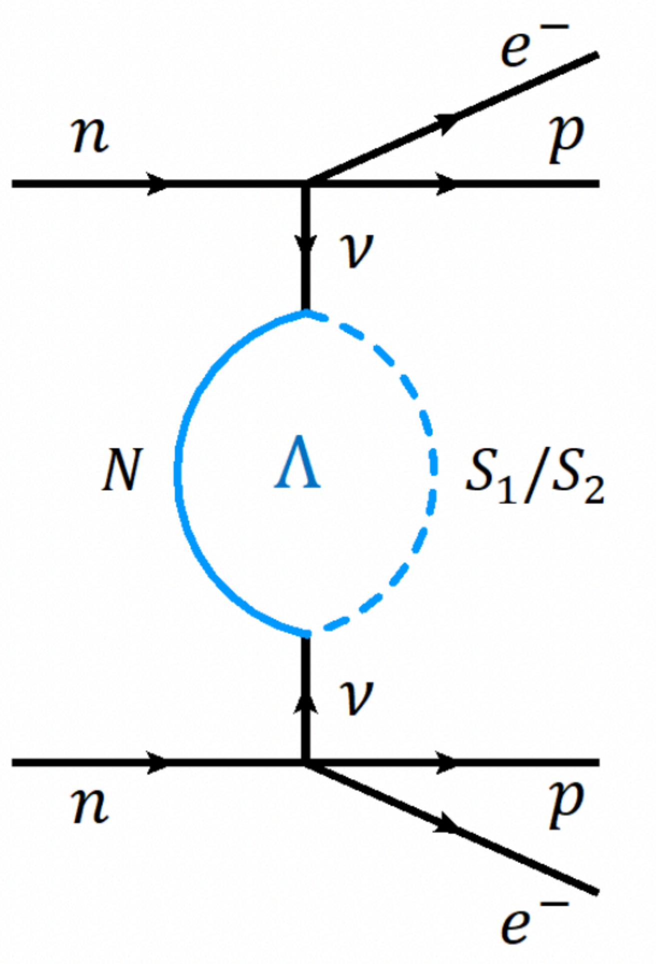
Results: relic abundance



Stringent bounds from charged lepton flavor violation constraints. For NH: $m_F < 0.8\,\text{GeV}$ and IH: $m_F < 0.5\,\text{GeV}$

Loop enhanced neutrinoless double beta decay

In radiative neutrino mass models, the rate of $0\nu\beta\beta$ decay process is modified by the neutrino self energy loop [W. Rodejohann, X. J. Xu, 2019]



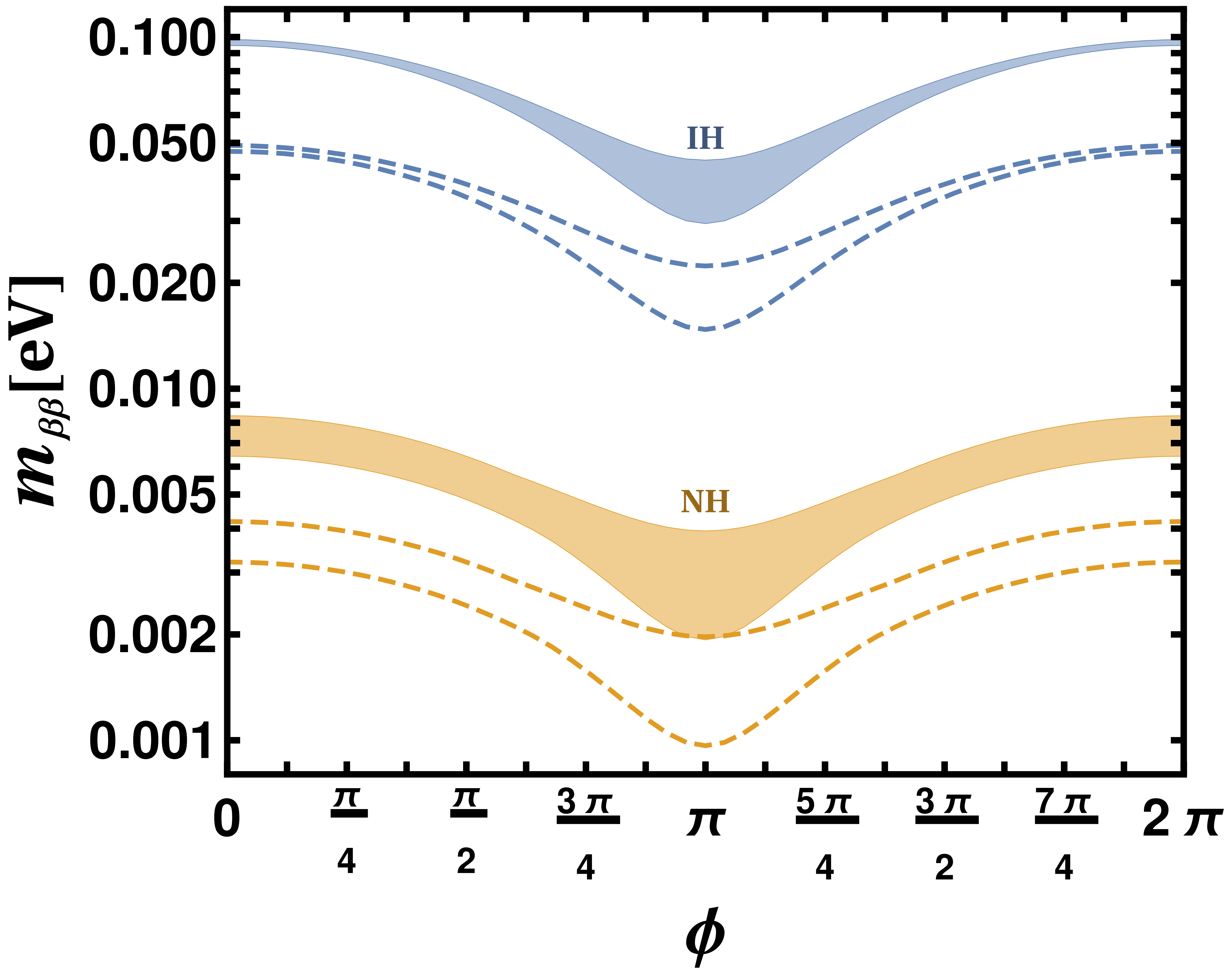
$$\Sigma(p) \simeq M_\nu \left(1 + \frac{p^2}{\Lambda^2}\right) \Longrightarrow m_{\beta\beta} \to m_{\beta\beta}\left(1 + \frac{p^2}{\Lambda^2}\right)$$

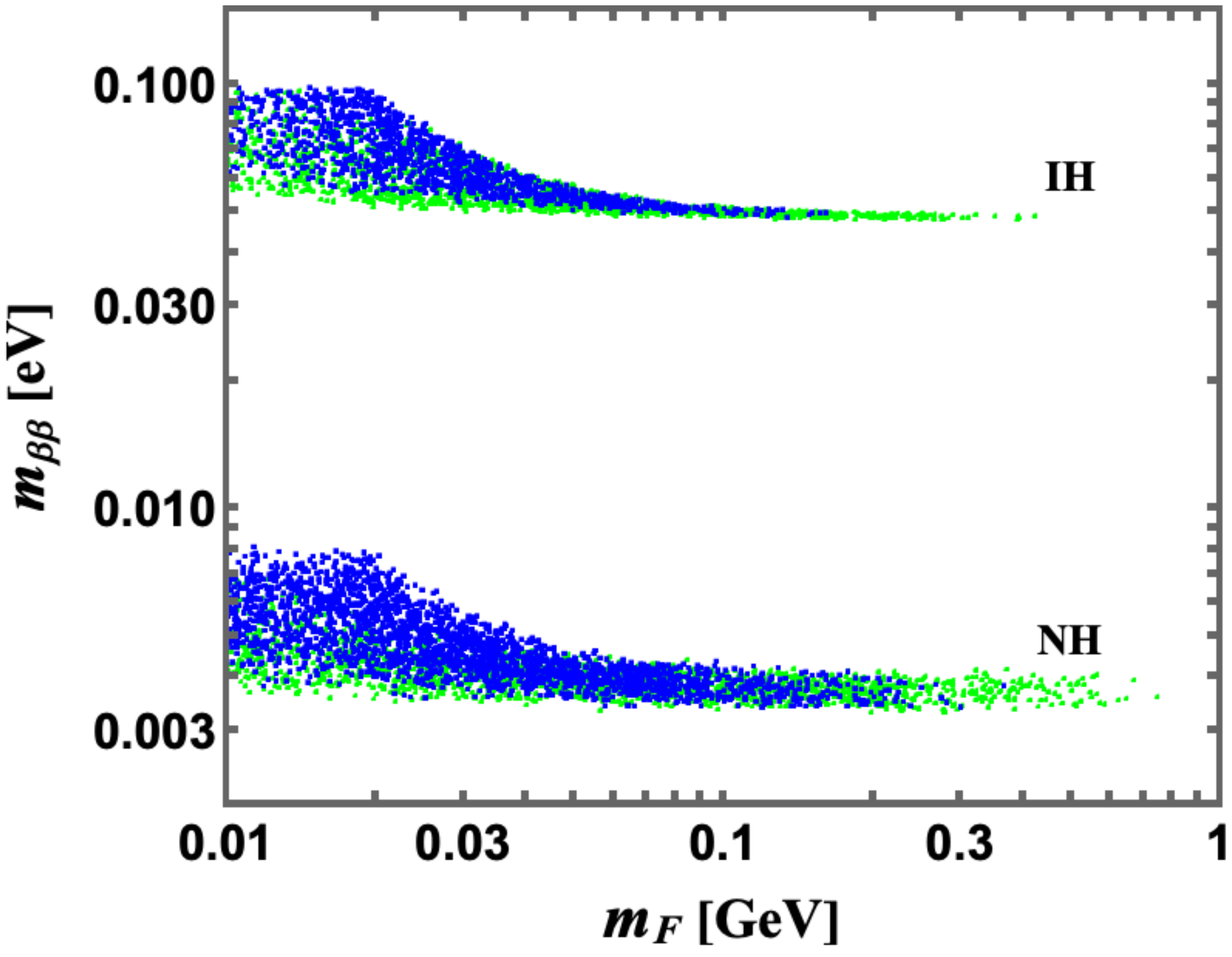
If the energy scale of the neutrino self energy is of the $\mathcal{O}(p) \Longrightarrow$ enhanced contribution to $m_{\beta\beta}$

In conventional radiative neutrino mass models, $\Lambda \simeq \mathcal{O}(100)$ GeV. For our scenario: $\Lambda \simeq \mathcal{O}(100)$ MeV, leads to enhanced contribution to $m_{\beta\beta}$

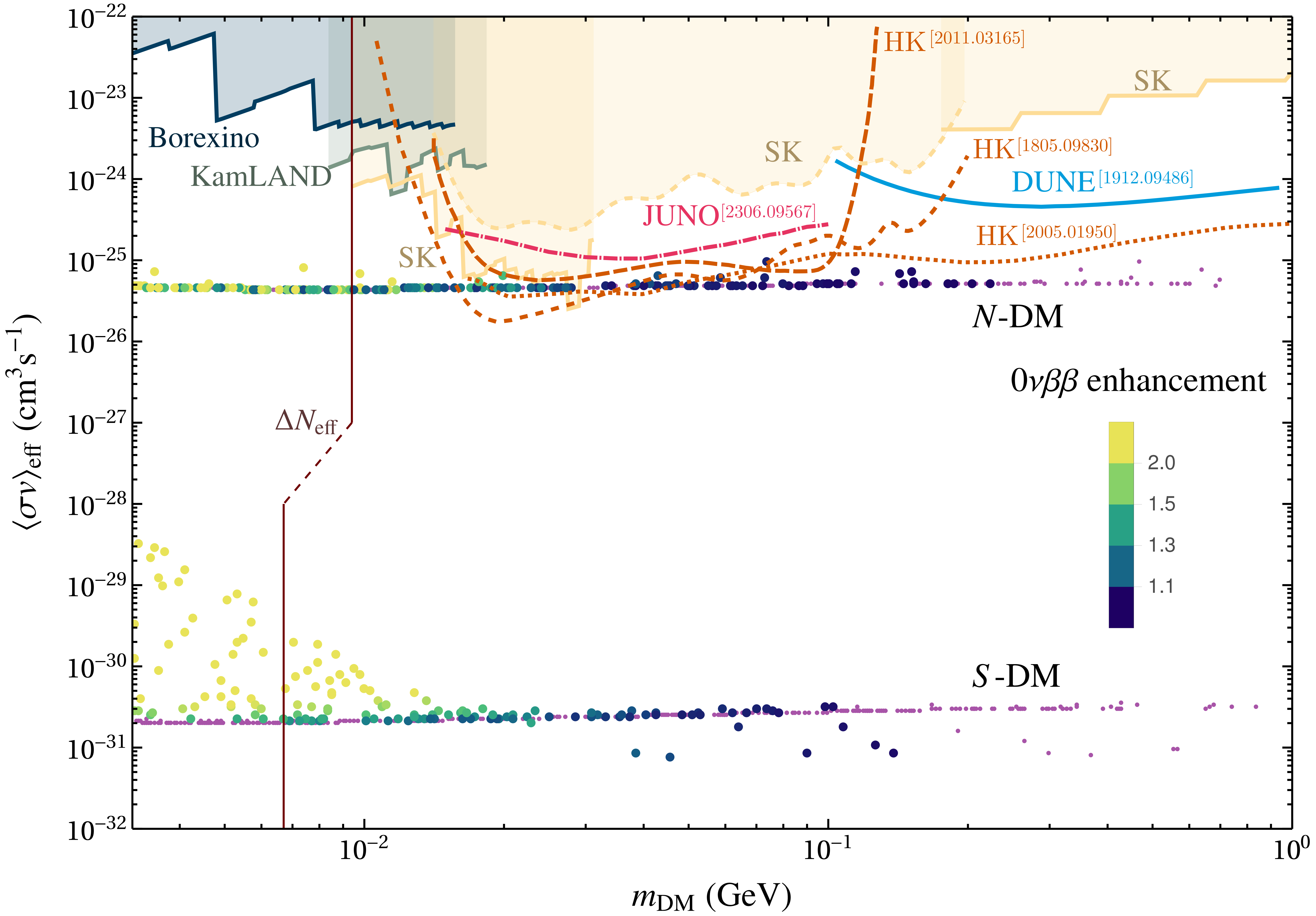
Can be probed in future/ongoing neutrinoless double beta decay experiments like LEGEND and CUPID

Results: enhanced $m_{\beta\beta}$





Neutrino telescopes



Could be probed in next generation neutrino telescopes, such as Hyper-Kamiokande

Summary

Dark matter could be a light thermal relics with mass lies in the sub-GeV regime

Dark matter indirect detection constraints can be circumvented for

- ☑ Forbidden DM
- ☑ Neutrinophilic DM

Forbidden dark matter

- ☑ Presented a minimal realization within 2HDM framework
- ☑ Radiative annihilation into two photons provides a positive identification of the scenario

Neutrinophilic dark matter

- ☑ Presented a realization within scotogenic models
- ☑ Enhanced contribution to neutrinoless double beta decay amplitude
- ☑ Could be probed in next generation neutrino telescopes

Image credit:quanta magazine