cosmology in a symmetric world

without strong CP problem

andrea tesi

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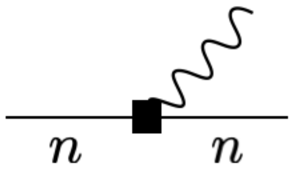
Sezione di Firenze

unobserved CP violation in the strong interactions



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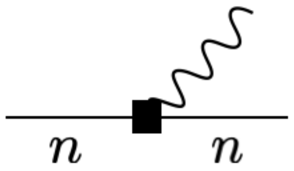

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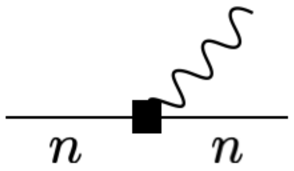

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physical combination CP violating
(two contributions related by a field redefinition)

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can we solve strong CP and find that DM is not an axion?

identify a model that solves the strong CP based on discrete symmetry

—> with spontaneous breaking

—> with a dark matter candidate

—> with the ingredients for baryogenesis cosmology of **parity** solutions of the strong CP problem

with Michele Redi, arXiv: 2307.03161

recently also:

[Craig et al '20;
Hisano et al '23;
Bonnefoy et al '23]

$\mathbb{P}$ symmetric world + color interactions

[Bonnefoy, Hall, Manzari, Scherb, 2303.06156]

$$\mathbb{P} = \mathrm{P} \times Z_2$$

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➡ for example:

$q \sim (3, 2, 1/6)$

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➡ Higgs and its copy

$$\langle H \rangle = v \qquad \langle \tilde{H} \rangle = \tilde{v}$$

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SM	$SU(3)$	$SU(2)$	$U(1)$
Q	3	2	1/6
U	$\bar{3}$	2	−2/3
D	$\bar{3}$	2	1/3
L	1	1	−1/2
E	1	1	1

$\widetilde{\mathrm{SM}}$	$\widetilde{\mathrm{SU}}(3)$	$\widetilde{\mathrm{SU}}(2)$	$\tilde{U}(1)$
$\tilde{Q}$	$\bar{3}$	2	−1/6
$\tilde{U}$	3	1	2/3
$\tilde{D}$	3	1	−1/3
$\tilde{L}$	1	2	1/2
$\tilde{E}$	1	1	−1

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theta-terms in the two sectors are equal and opposite*

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* in the frame where all the angle is in the topological term

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and of course also:

$$Y_u Q H U + Y_u^* \tilde{Q} \tilde{H} \tilde{U} + h.c.$$

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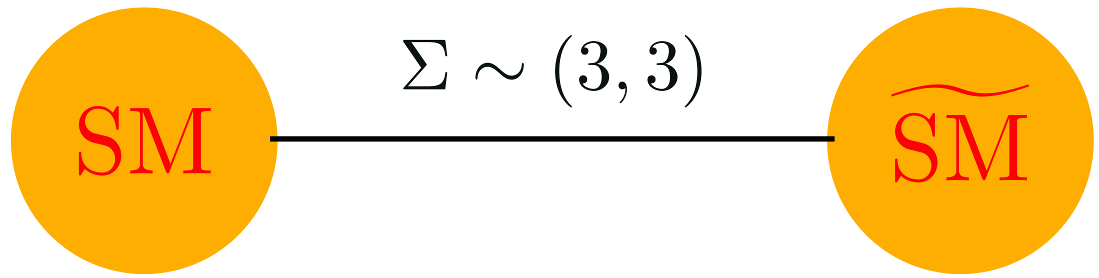
[Bonnefoy, Hall, Manzari, Scherb, 2303.06156]

crucial ingredient is the **breaking** of the two color factors to our QCD



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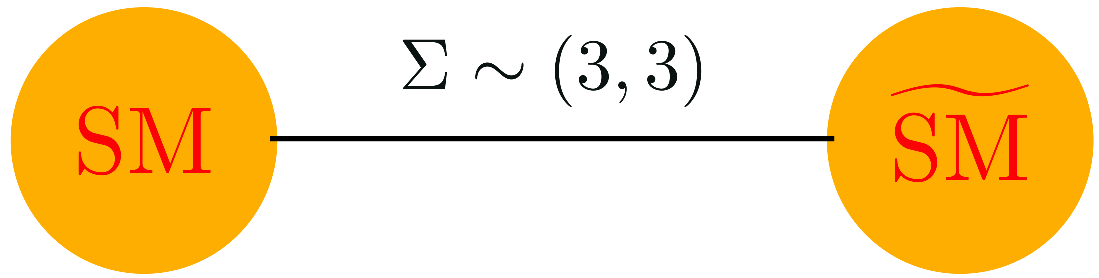

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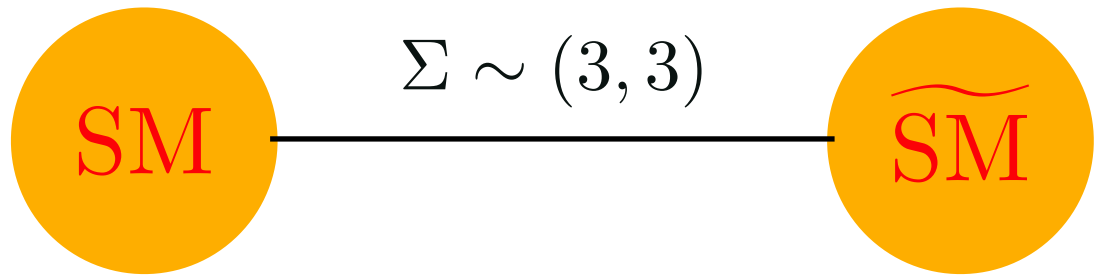

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➡ unbroken SU(3)c identified with our color group
➡ broken part, higgsed, massive color vector octect

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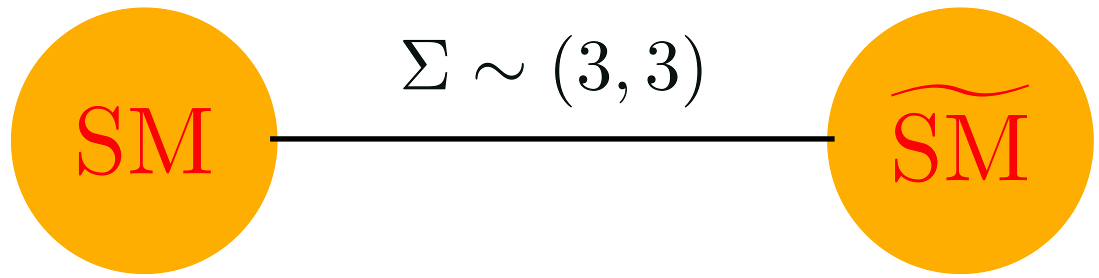

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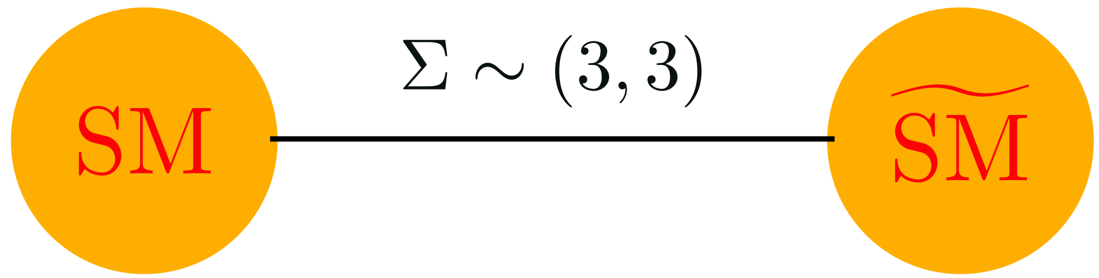

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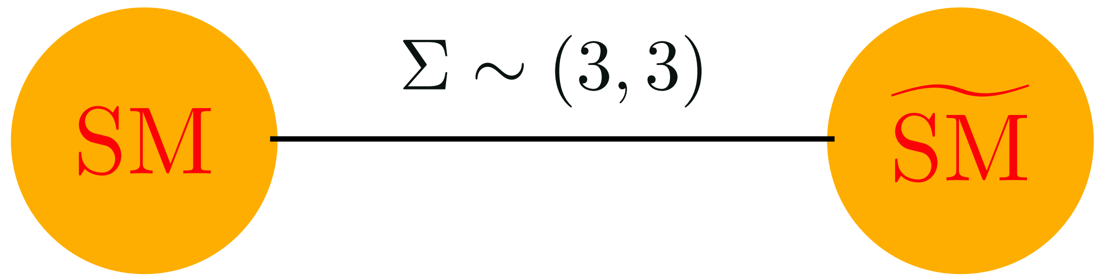

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$$\frac{1}{g_s^2(M_\Sigma)} = \frac{1}{g_3^2(M_\Sigma)} + \frac{1}{\tilde{g}_3^2(M_\Sigma)}$$

low energy as in
[Barr, Chang, Senjanovic '90s]

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spectrum and constraints

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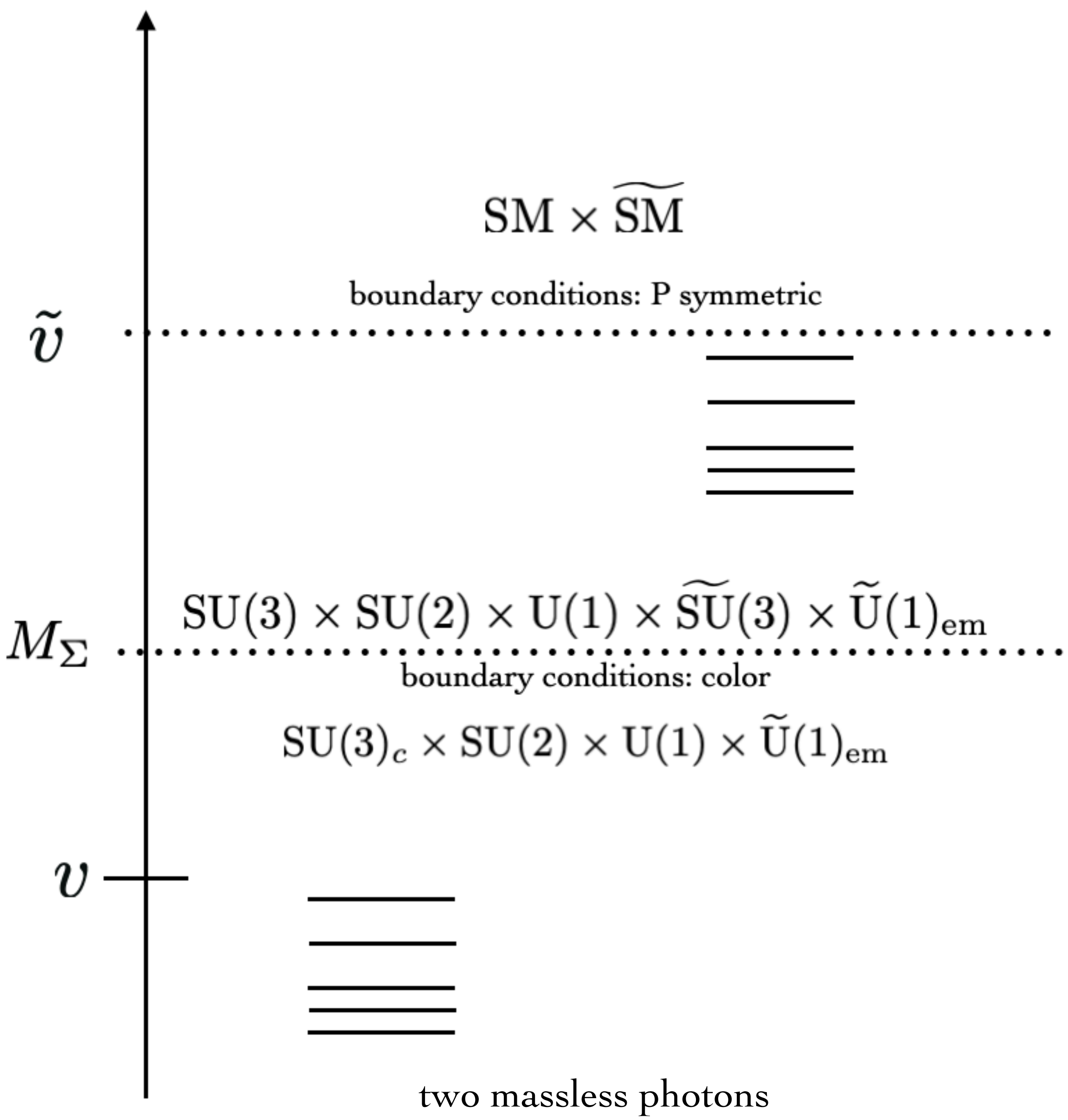
[big difference with the
"mirror world literature"]



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aim of our work was to show the following results

- **Spontaneous breaking of $\mathbb{P}$**
- **Dark Matter candidate**
- **Viable neutrino physics**

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similar ideas in

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➡ look for new minimum before M_{Pl}, consistent with low energy boundary conditions

similar ideas in

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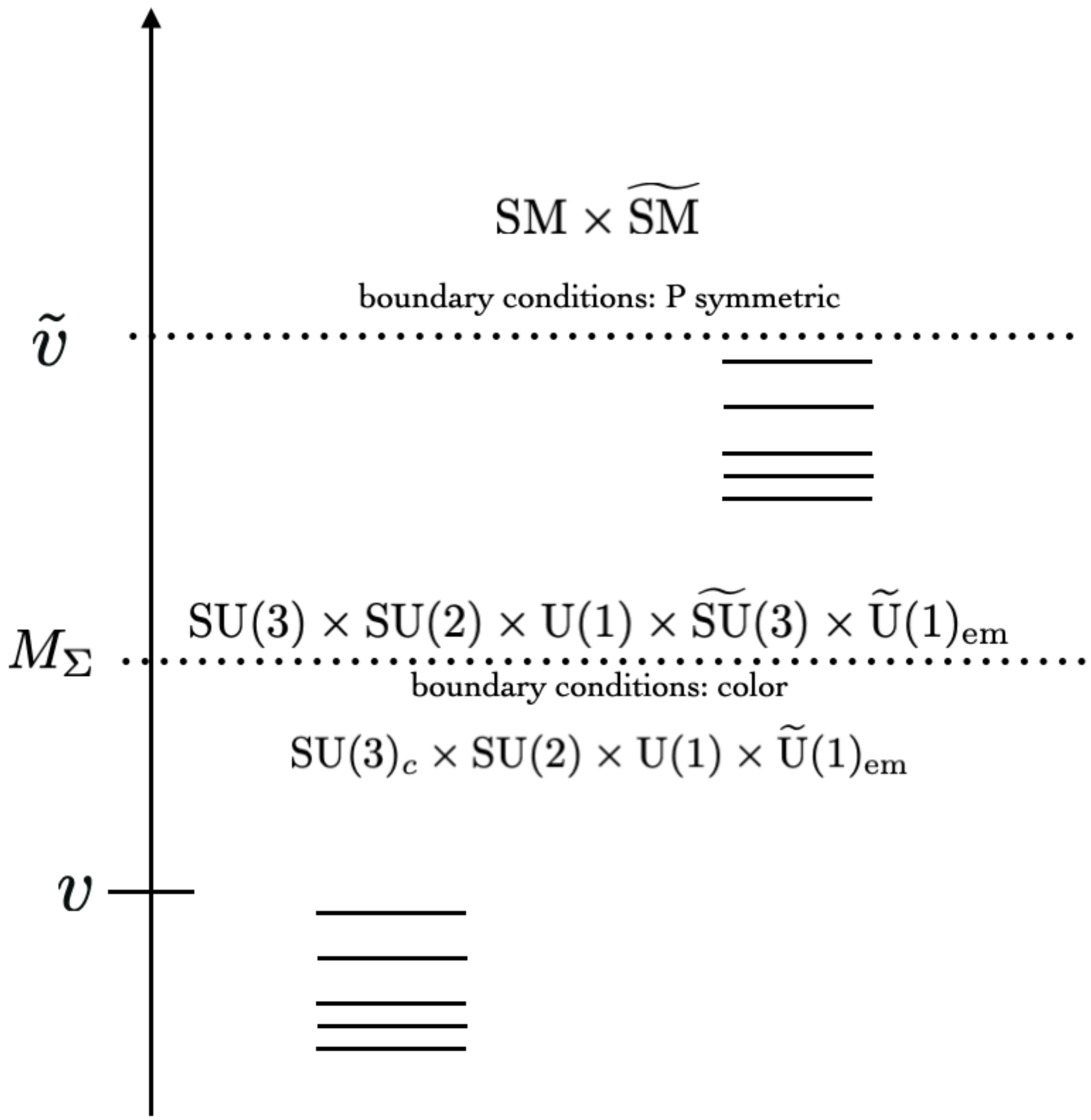

$$g_i(\tilde{v}) = \tilde{g}_i(\tilde{v})$$

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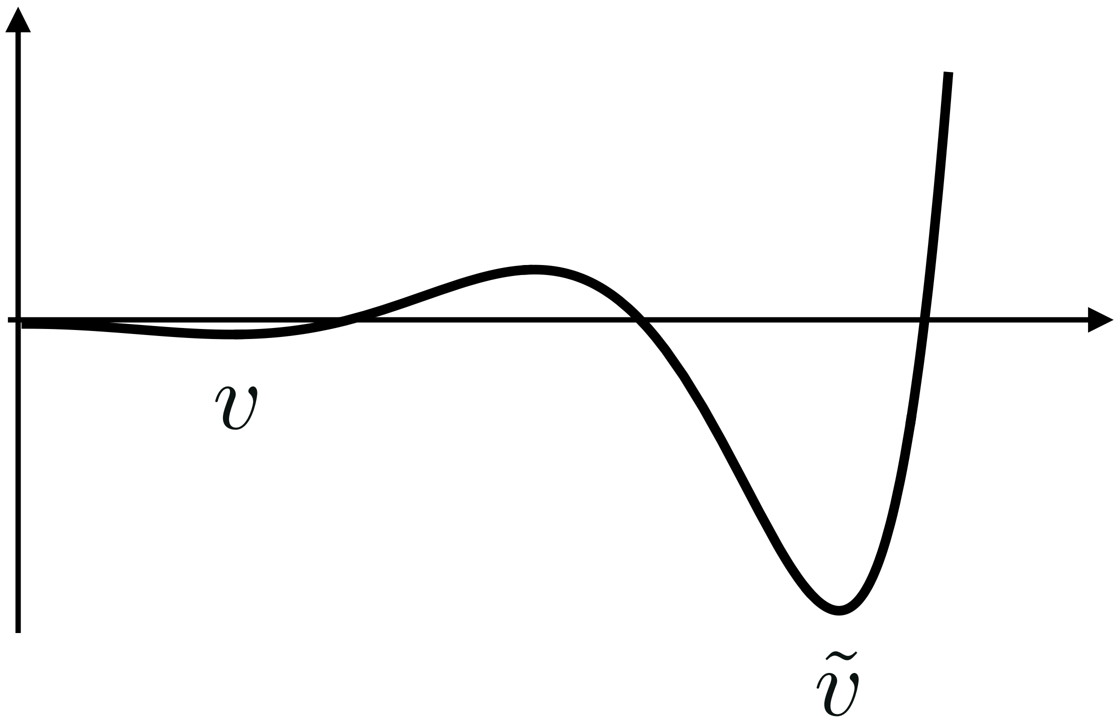
[SM equations from: Buttazzo et al '13]

we found that the parity symmetric scenario allows for a second minimum



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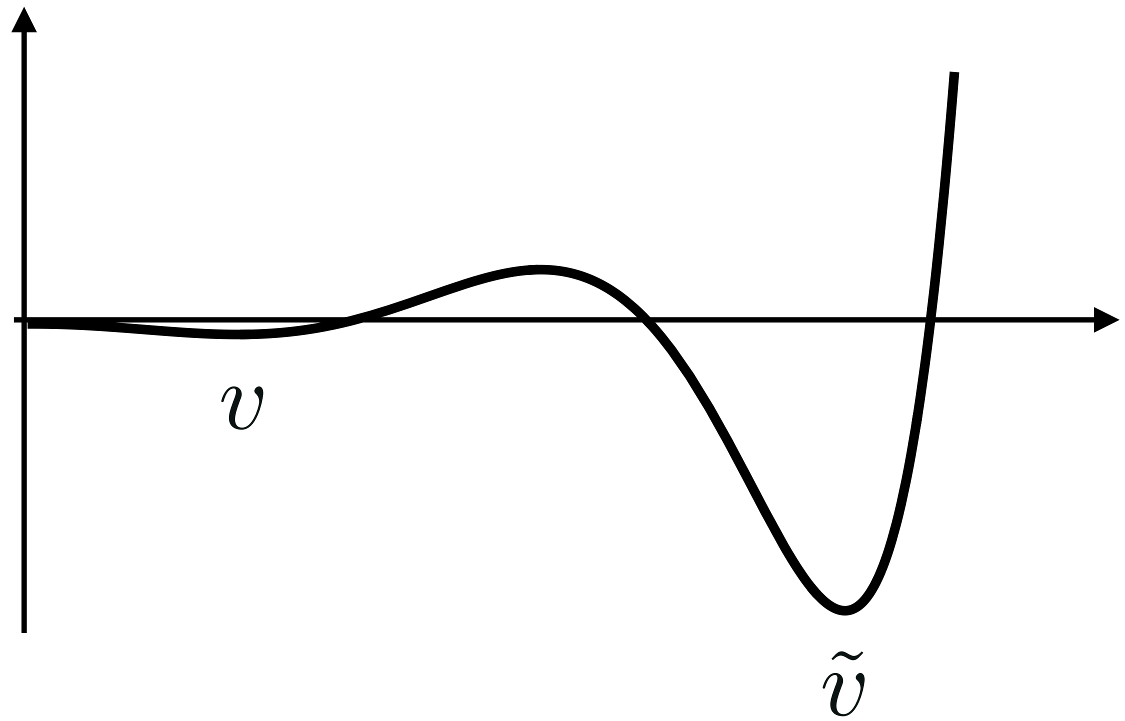

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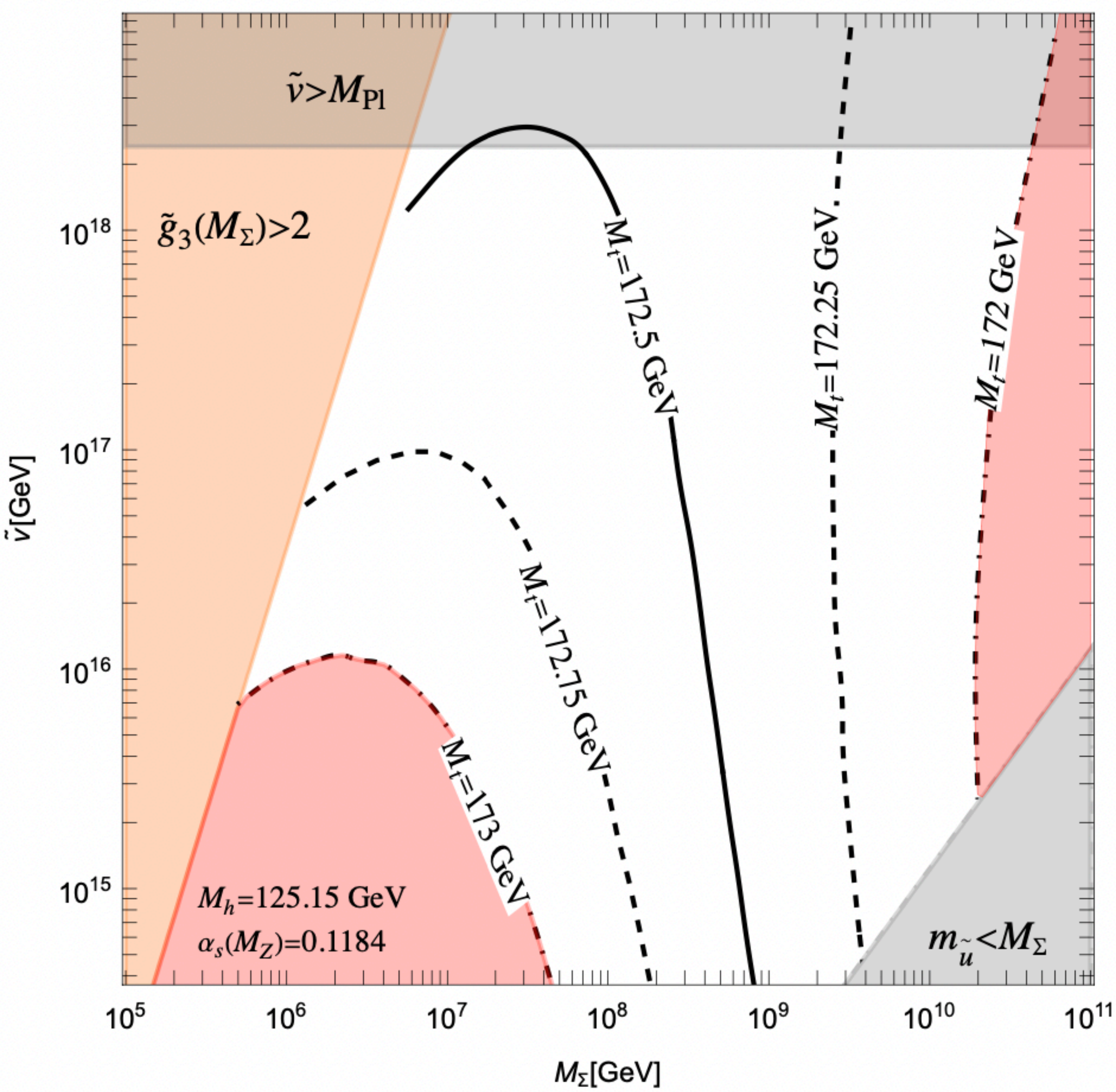
➡ domain wall problem: symmetry must be broken during inflation

spontaneous breaking for SM measured parameters



exploiting renormalizable portal couplings —> larger parameter space

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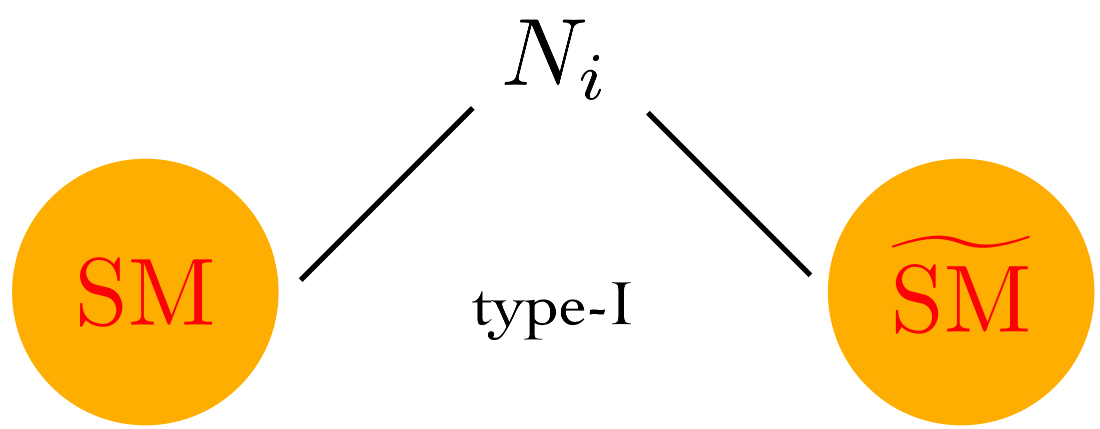
we find that the DM abundance is
linked to the cosmology of neutrinos from the mirror world

see also 'Higgs parity'
[Dunsky, Hall, Harigaya]

right handed neutrinos must also respect the $\mathbb{P}$ symmetry

$$\frac{1}{2}M_{ab}N_aN_b + h.c.$$



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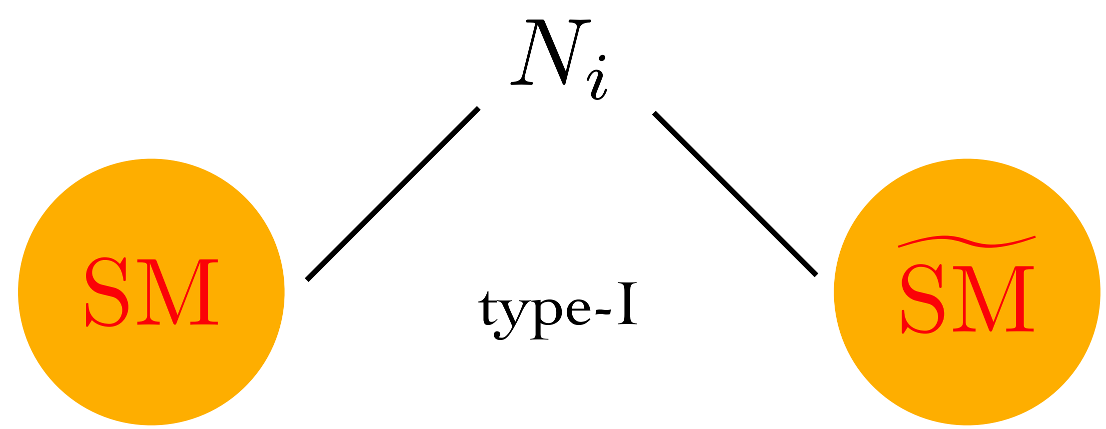

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four possible assignments of $Z2$ for the right-handed neutrinos
(parity well defined on Majorana fermions)
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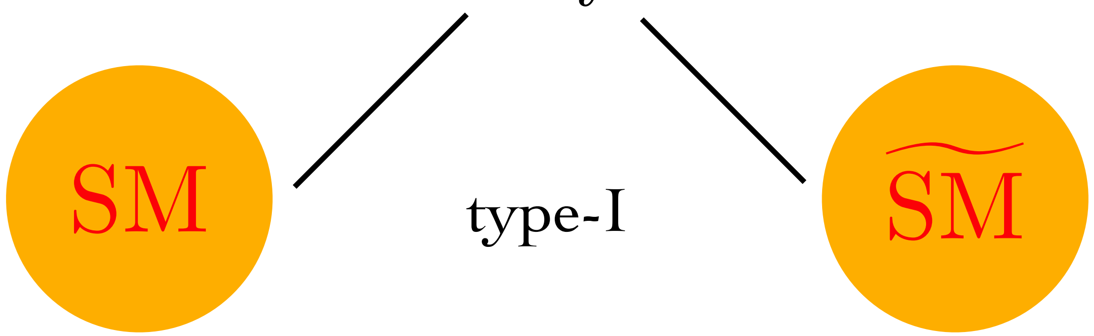

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$$\begin{pmatrix} N_1 \\ \dots \\ \dots \\ N_6 \end{pmatrix} \xrightarrow{Z_2} C \cdot \begin{pmatrix} N_1 \\ \dots \\ \dots \\ N_6 \end{pmatrix}, \qquad C^2 = \mathbf{1}_6 \,, \quad C \in Z_2$$

[work in progress]

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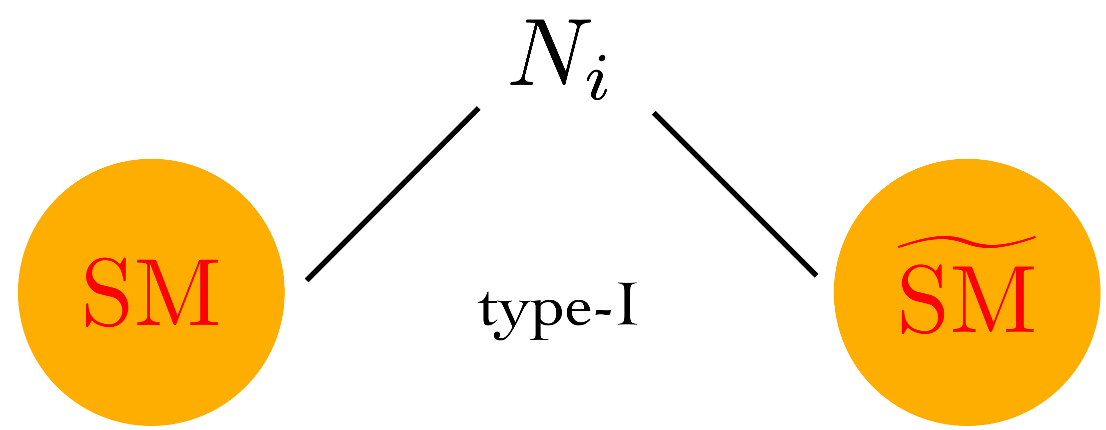

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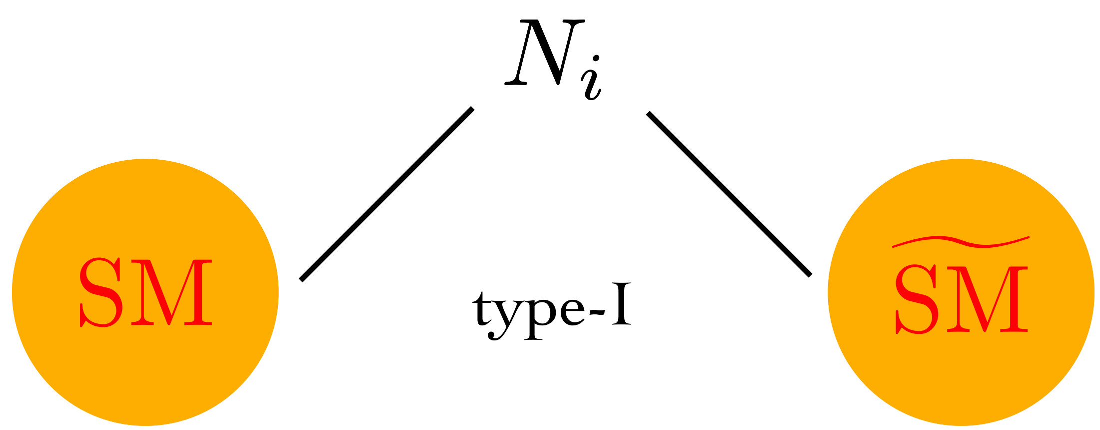

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[see Chacko, Craig, Fox, Harnik]

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$$\frac{\tilde{m}_i}{\tilde{v}^2}\delta_{ij}L^i H L^j H + \frac{\tilde{m}_i}{\tilde{v}^2}\delta_{ij}\tilde{L}^i\tilde{H}\tilde{L}^j\tilde{H} + \frac{\Delta_{ij}\tilde{m}_j}{\tilde{v}^2}L^i H\tilde{L}^j\tilde{H} + h.c.$$

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in the limit where the **see-saw scale is the largest one**:
visible and sterile neutrinos are **majorana**

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$$m_{\tilde{\nu}_i} = m_{\nu_i}\frac{\tilde{v}^2}{v^2} + O(\Delta^2) \qquad \theta_{ij} \sim \Delta_{ij}\frac{v}{\tilde{v}}$$

in the right ballpark, sterile neutrinos at the GeV scale

$$\Gamma_{\tilde{\nu}\to\mathrm{SM}} \approx 4.5 \times 10^5\,\mathrm{s}^{-1} \left(\frac{m_{\nu,\mathrm{light.}}}{0.008\,\mathrm{eV}}\right)\left(\frac{m_{\tilde{\nu}}}{10\mathrm{GeV}}\right)^4 \times \Delta^2$$

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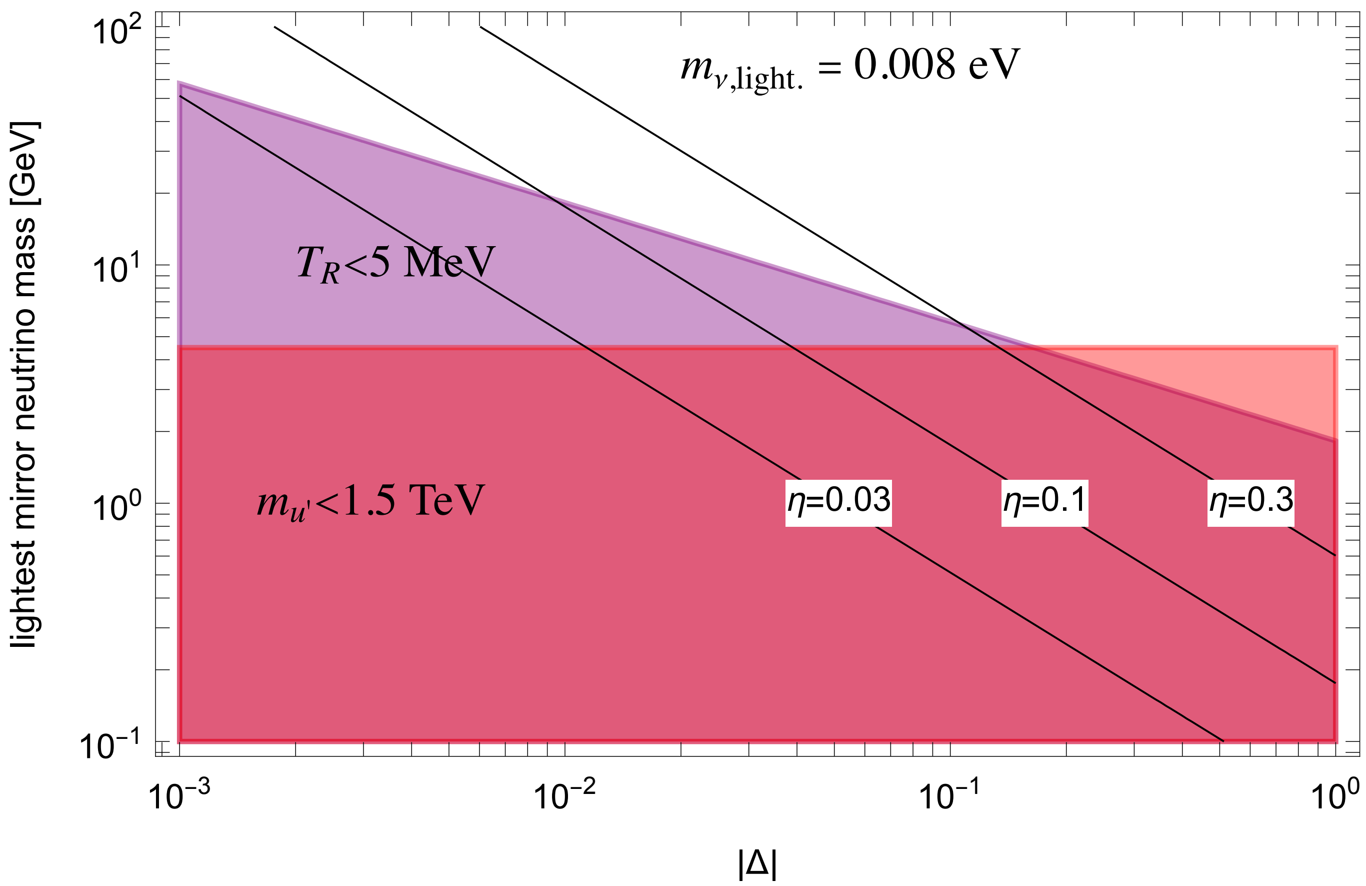

$$\eta \approx 0.04\,\Delta\sqrt{\frac{m_{\nu,\mathrm{light.}}}{0.01\,\mathrm{eV}}}\left(\frac{m_{\tilde{\nu}}}{\mathrm{GeV}}\right)$$

entropy dilution

color keeps the two sectors
in thermal equilibrium

$$T \lesssim m_{\tilde{u}}$$

the mirror sector has several **stable** states

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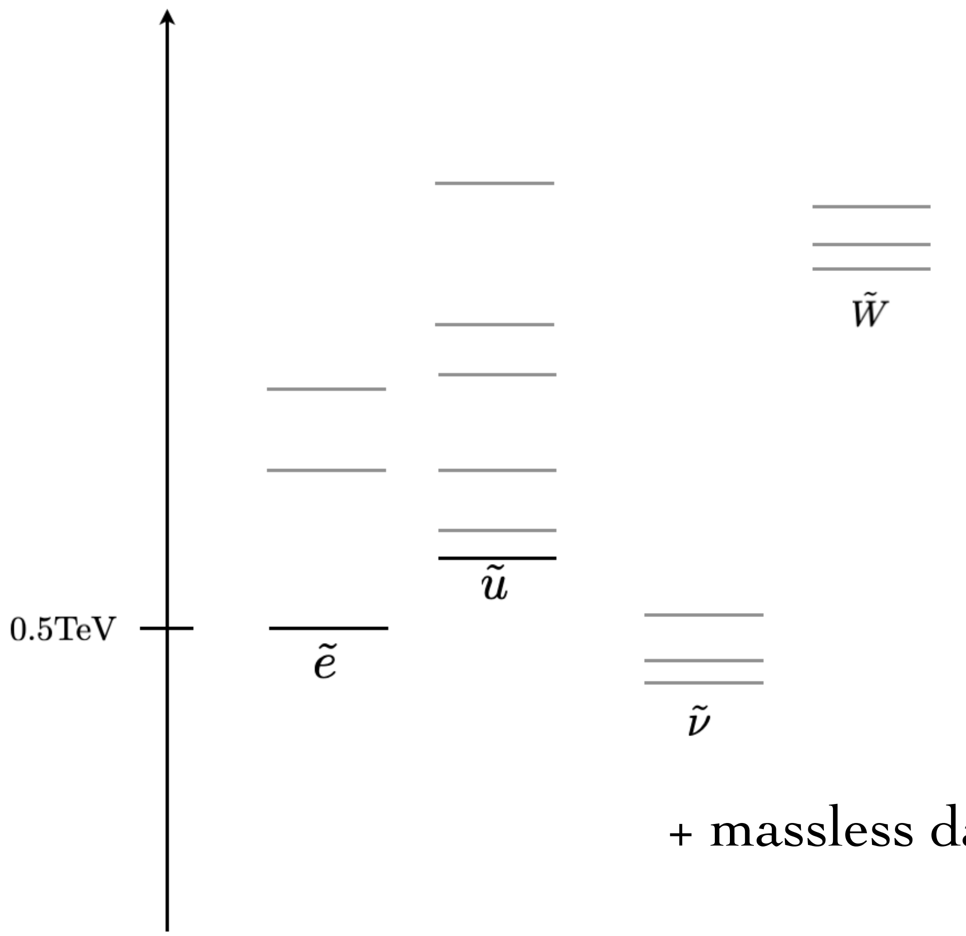

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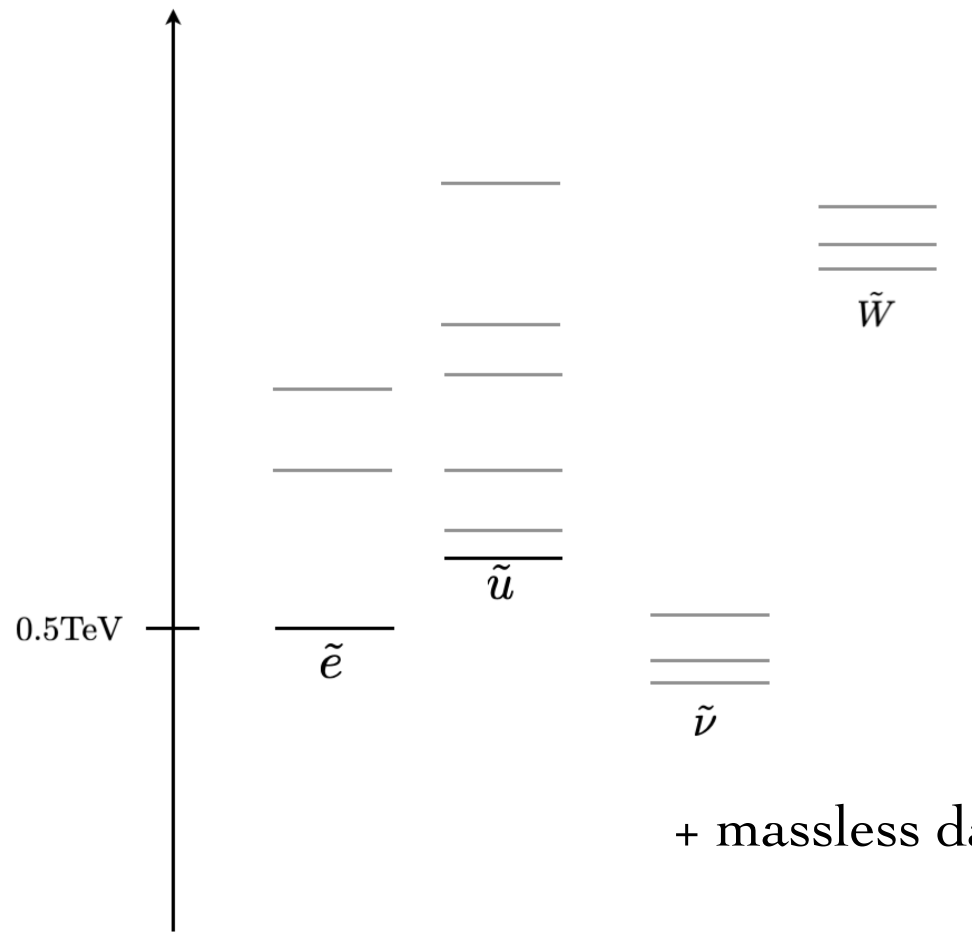


+ massless dark photon

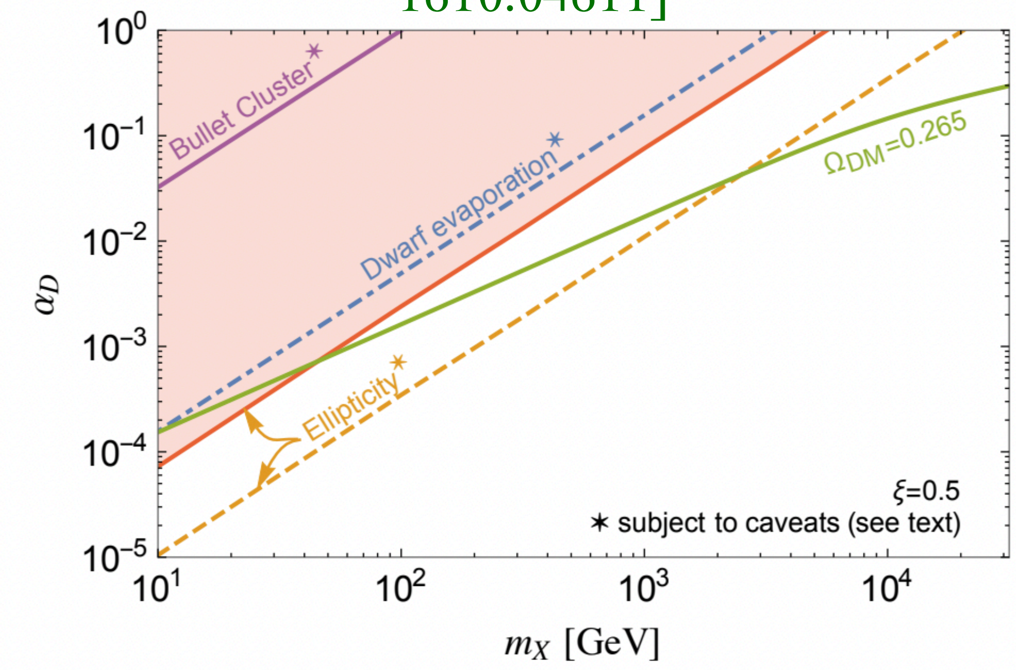
we focus on the **mirror electron as DM**

DM freeze out in a dark sector with a massless mediator

interestingly, DM with a massless dark photon is not excluded

➡ O(100 GeV) and typical coupling allowed

[Agrawal, Cyr-Racine, Randall, Scholtz 1610.04611]



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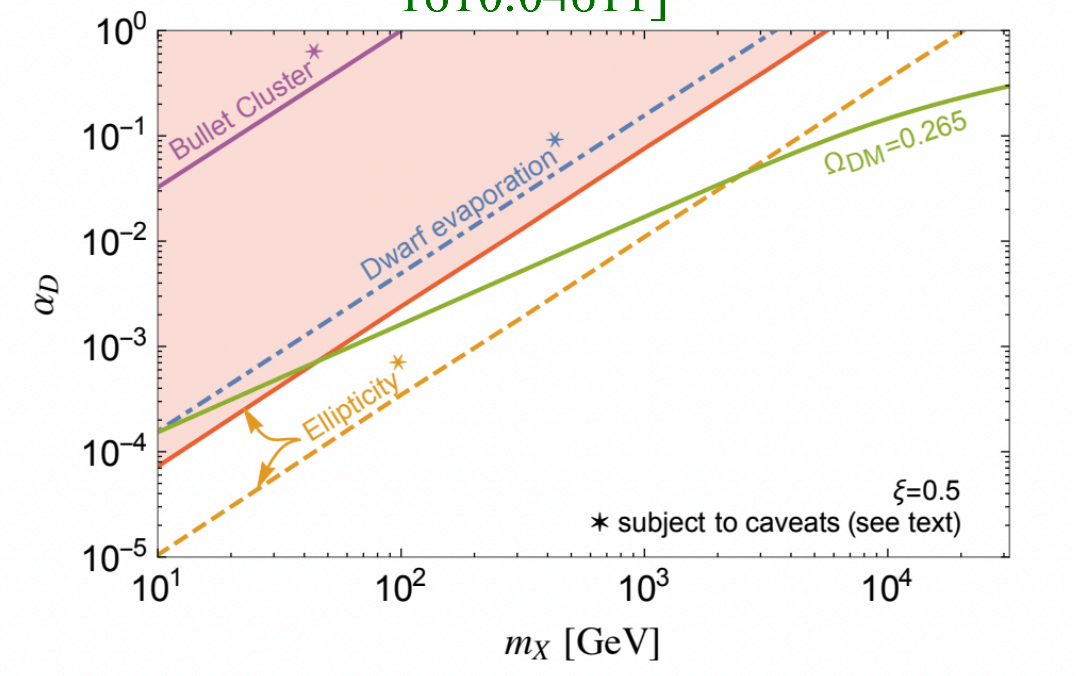

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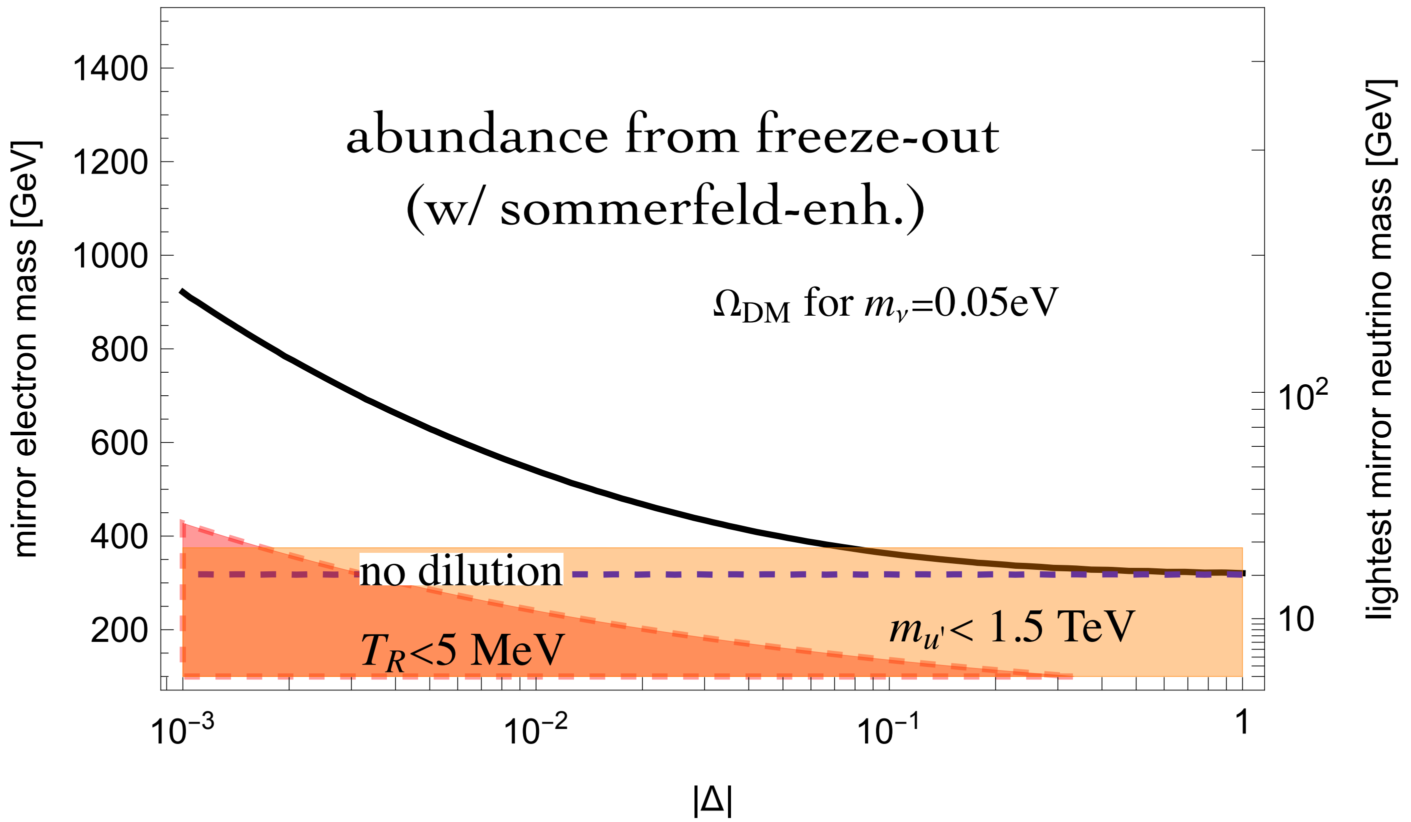
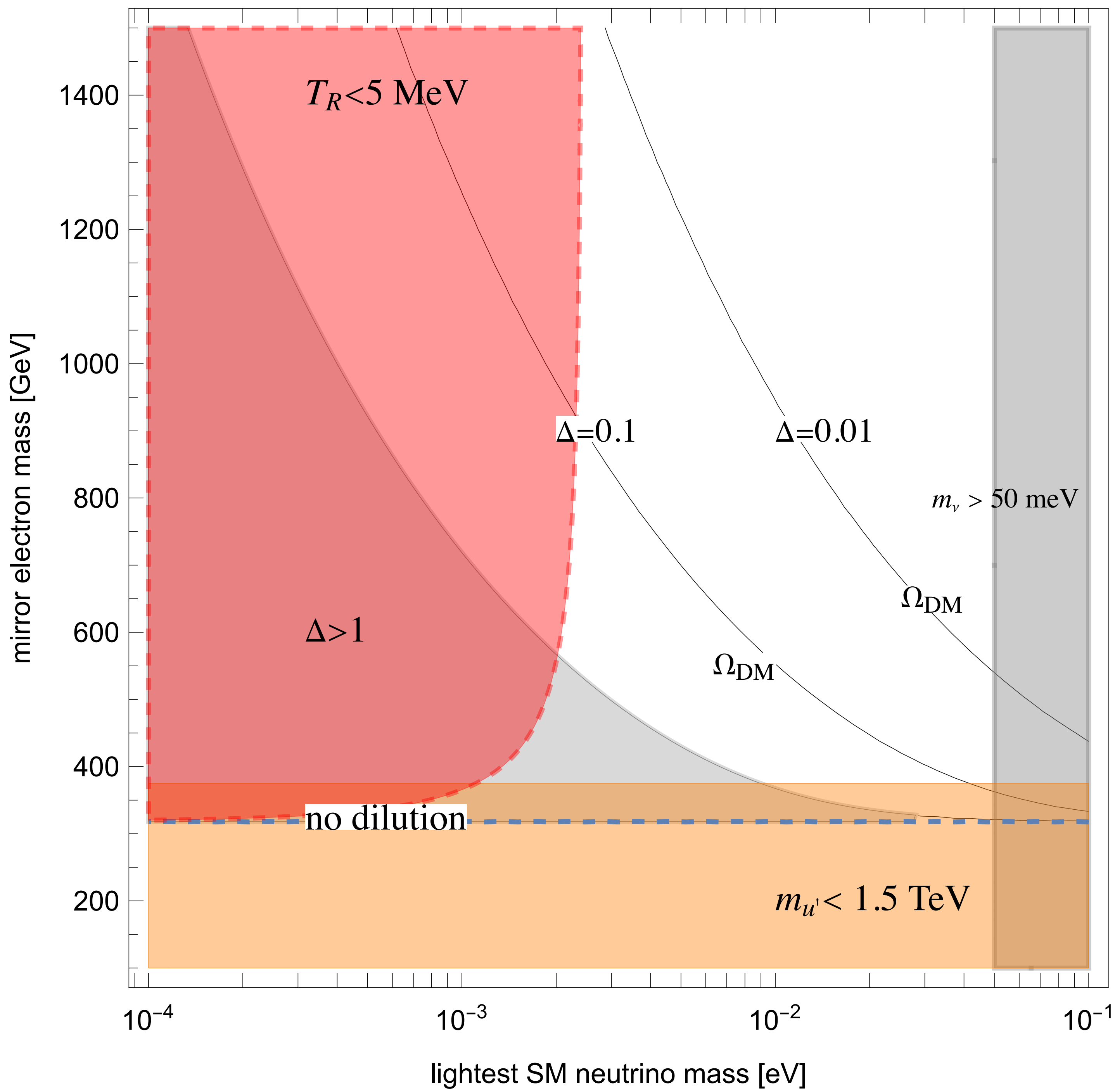


➡ dilution from sterile neutrinos **critical** the absence of free parameters besides DM and lightest neutrino mass gives us sharp predictions for the parameter space



- **Dark Matter direct detection**
  - kinetic mixing of visible and dark photon —> milli-charged DM
  - suppressed by four loops and limited running [Dunsky, Hall, Harigaya]

$$m_{\tilde{e}} \gtrsim 10\text{TeV}\left(\frac{\epsilon}{10^{-9}}\right)^2 \qquad \text{[Xenon1t]}$$

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$\tilde{u}\ q\ q \equiv \text{hadron}$ ➡ these are not the deepest bound states, crucial to compute their abundance

bounds from MAJORANA, MACRO, ICRRR depending upon $\beta\gamma \gg 1$

Outlook 2/2

- **Massive dark photon**
  - We explored massive dark photon with **P** symmetry
  - Via breaking $\mathrm{U}(1) \times \widetilde{\mathrm{U}}(1) \to \mathrm{U}(1)_Y$ $\quad \Sigma \sim (3,3)_y$

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- **in conclusion, some other directions**

  - completely dark mirror copy (need extra structure)
  - generic portals and larger parameter space for spontaneous breaking of **P**
  - **leptogenesis** (all the ingredients available, connection with neutrino masses)

thank you!