

dark matter in a symmetric world

without strong CP problem

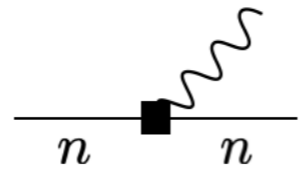
andrea tesi



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Sezione di Firenze

strong CP problem: numbers & parameters

unobserved CP violation in the strong interactions



The diagram shows a horizontal line representing a neutron, labeled with 'n' at both ends. A small black square is placed on the line, with a wavy line (representing a gluon) extending upwards from it.

$$\frac{d_n}{e \text{ cm}} \lesssim 10^{-26}$$

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at odds with the SM:

$$\theta_0 \frac{\alpha_s}{16\pi} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu}^a G_{\rho\sigma}^a + (Y_u Q H U + Y_d Q H^* D + h.c)$$

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

$$\frac{d_n}{e \text{ cm}} \lesssim 10^{-26} \times \frac{\theta}{10^{-10}}$$

strong CP problem: symmetry solutions

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QCD axion *vs* rest of the world ?

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- ➔ IR solution
- ➔ DM candidate

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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;
Bonnetfoy et al '23]

\mathbb{P} symmetric world + color interactions

[Bonnetfoy, Hall, Manzari, Scherb, 2303.06156]

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

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fundamental symmetry of an extended sector
~ **parity exchange SM with its copy**~

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→ for example:

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

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

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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{SM}	$\widetilde{SU(3)}$	$\widetilde{SU(2)}$	$\widetilde{U(1)}$
\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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acts non trivially on the gauge fields

\mathbb{P} symmetric world + color interactions

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

$$\bar{\theta} \left[\frac{\alpha_3}{16\pi} \epsilon^{\mu\nu\rho\sigma} G_{\mu\nu} G_{\rho\sigma} - \frac{\tilde{\alpha}_3}{16\pi} \epsilon^{\mu\nu\rho\sigma} \tilde{G}_{\mu\nu} \tilde{G}_{\rho\sigma} \right]$$

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

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and of course also:

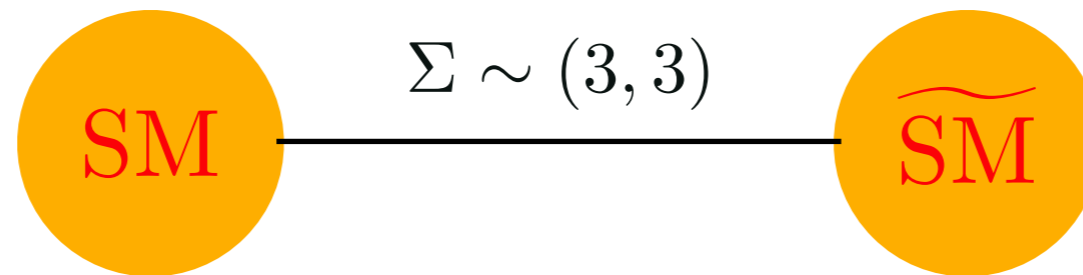
$$Y_u Q H U + Y_u^* \tilde{Q} \tilde{H} \tilde{U} + h.c.$$

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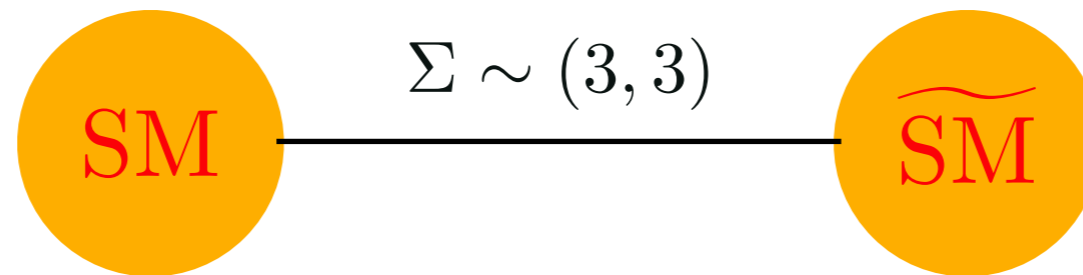
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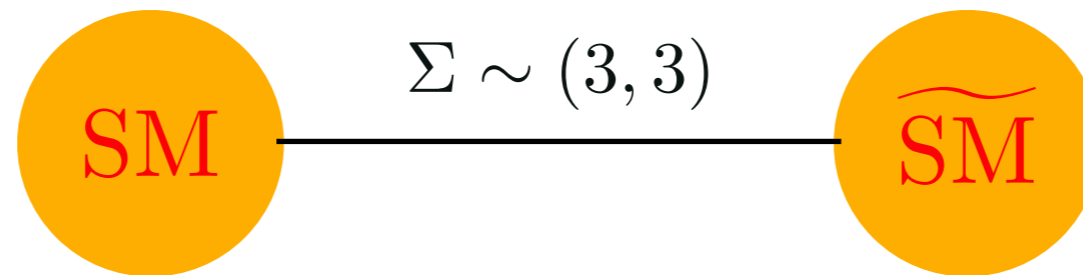


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$$\frac{1}{g_s^2(M_\Sigma)} = \frac{1}{g_3^2(M_\Sigma)} + \frac{1}{\tilde{g}_3^2(M_\Sigma)}$$

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

spectrum and constraints

the new sector is **colored** below Σ

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➔ all the mirror quarks are **colored**

$$m_{\tilde{u}} = 800 \text{ GeV} \left(\frac{\tilde{v}}{10^8 \text{ GeV}} \right)$$

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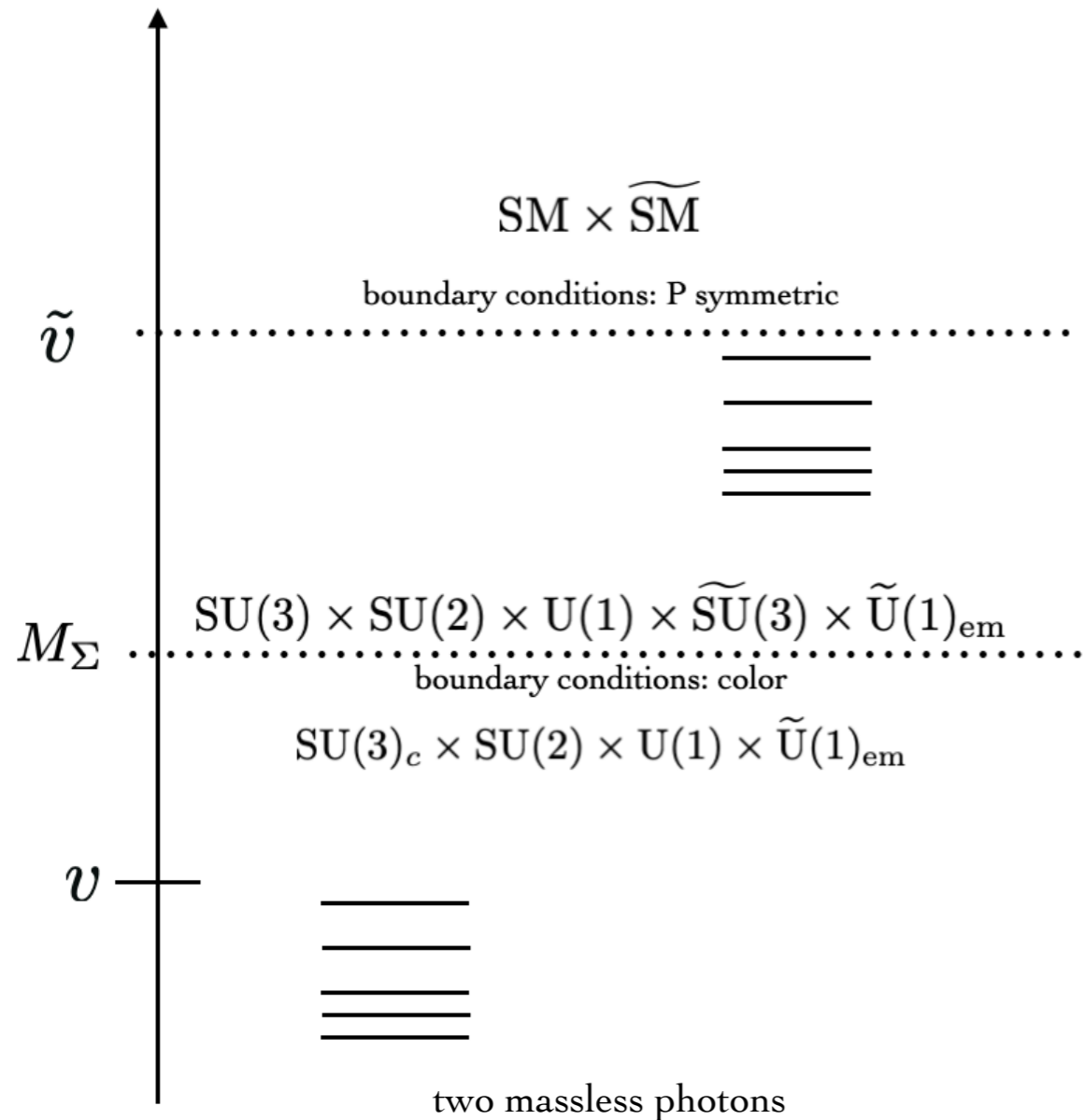
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[big difference with the
“mirror world literature”]



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challenges

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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can the new field Σ and the mirror sector
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similar ideas in

[Blinov and Hook, [1605.03178](#)]

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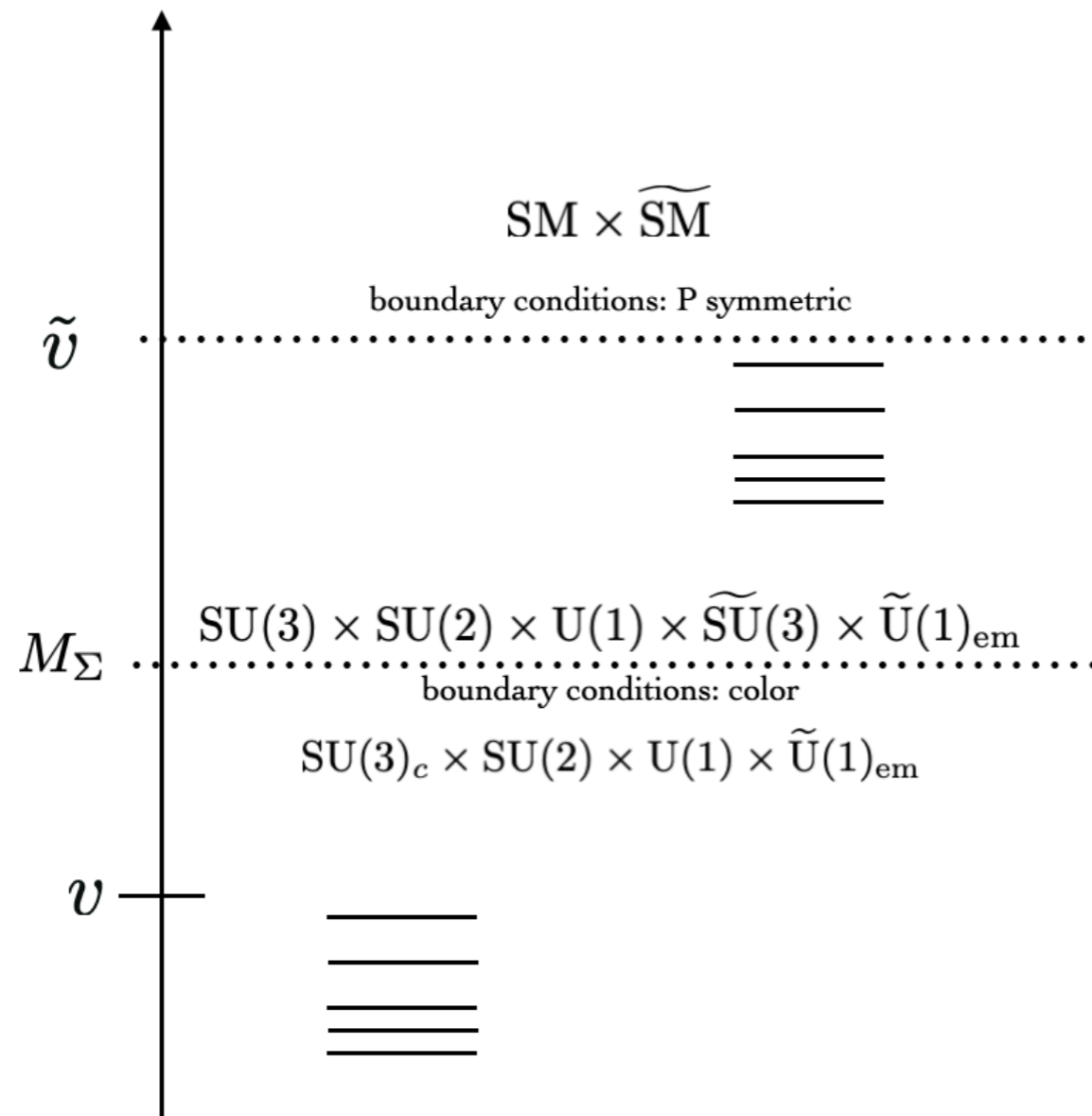
➔ look for new minimum before M_{Pl} , consistent with low energy boundary conditions

similar ideas in

[Blinov and Hook, [1605.03178](#)]

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spontaneous breaking possible by inspecting the SM Higgs **effective potential**



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

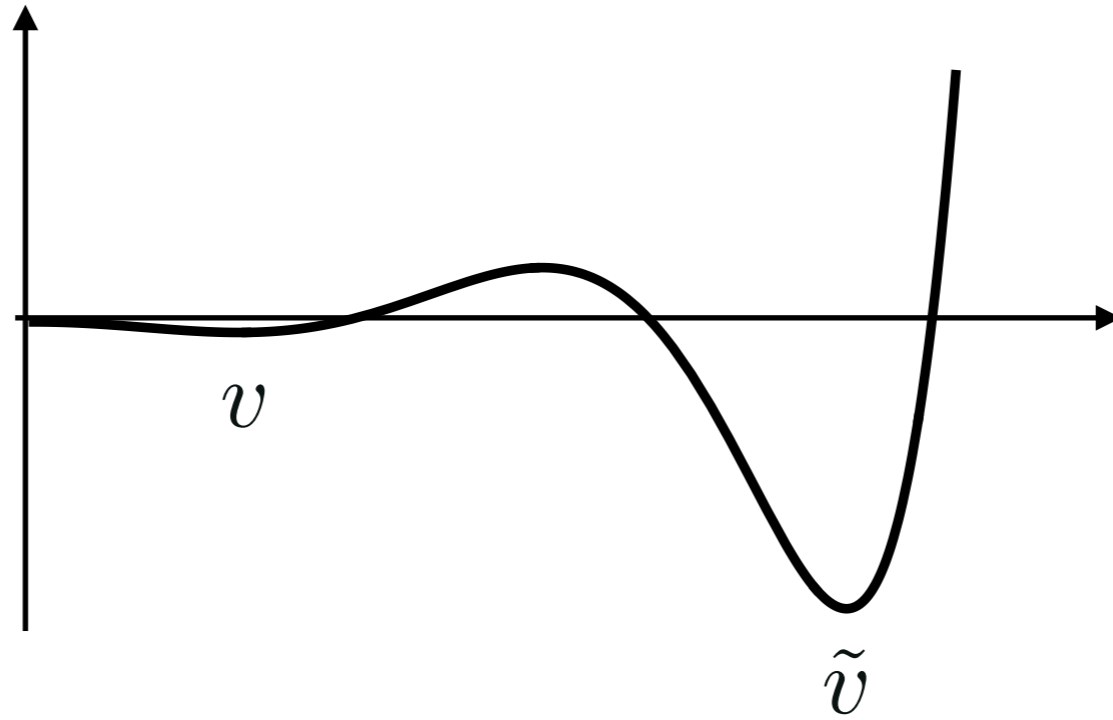
$$\Delta\beta_{g_3} = \frac{g_3^3}{(4\pi)^2} \frac{1}{2} + \frac{g_3^5}{(4\pi)^4} 11$$

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

[SM equations from: Buttazzo et al '13]

higgs potential with two minima before the Planck scale

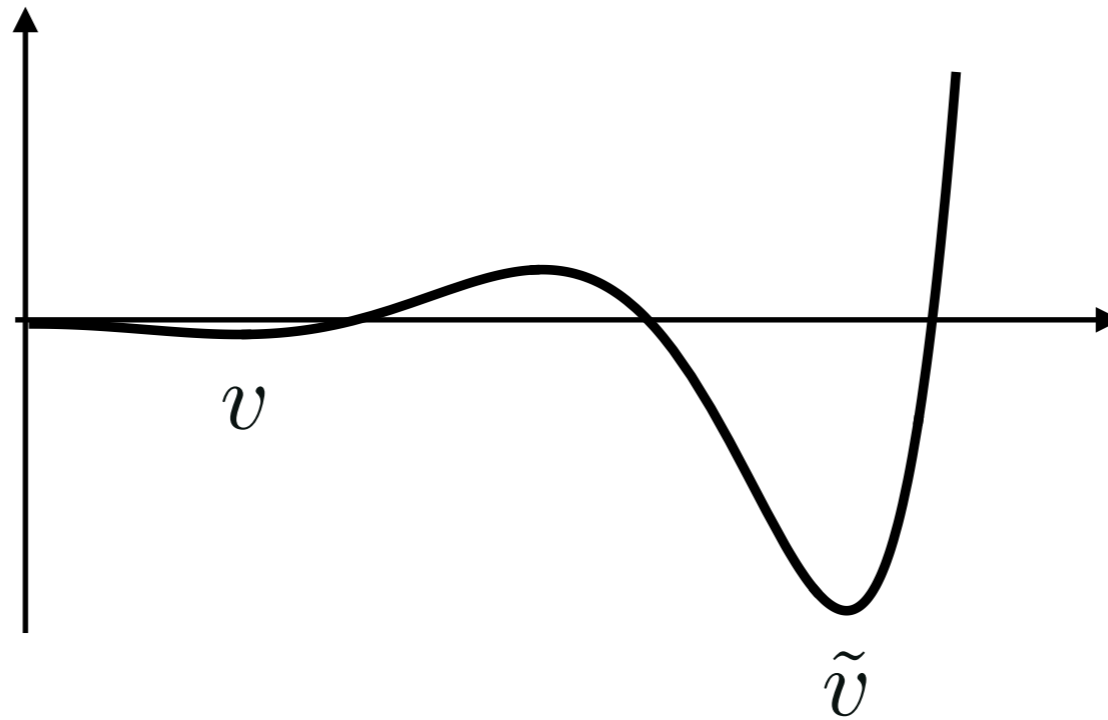
we found that the parity symmetric scenario allows for a second minimum



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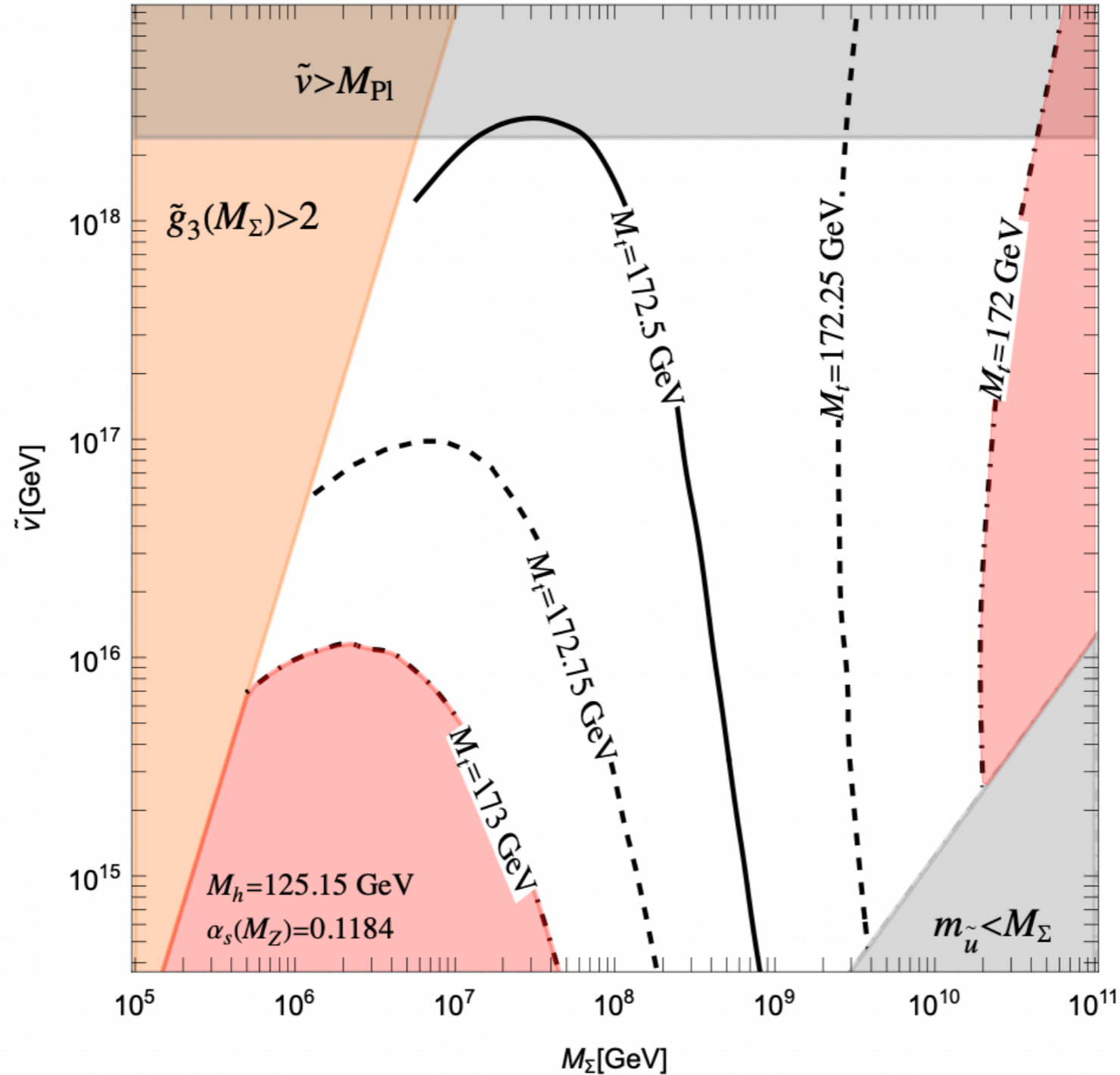
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➔ domain wall problem: symmetry must be broken during inflation

spontaneous breaking for SM measured parameters



exploiting renormalizable portal couplings \rightarrow larger parameter space

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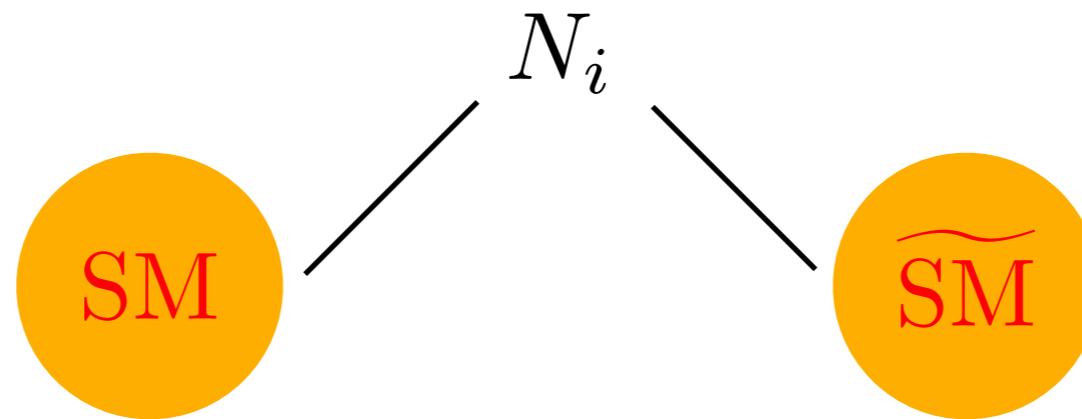
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we find that the DM abundance is
linked to the cosmology of neutrinos from the mirror world

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

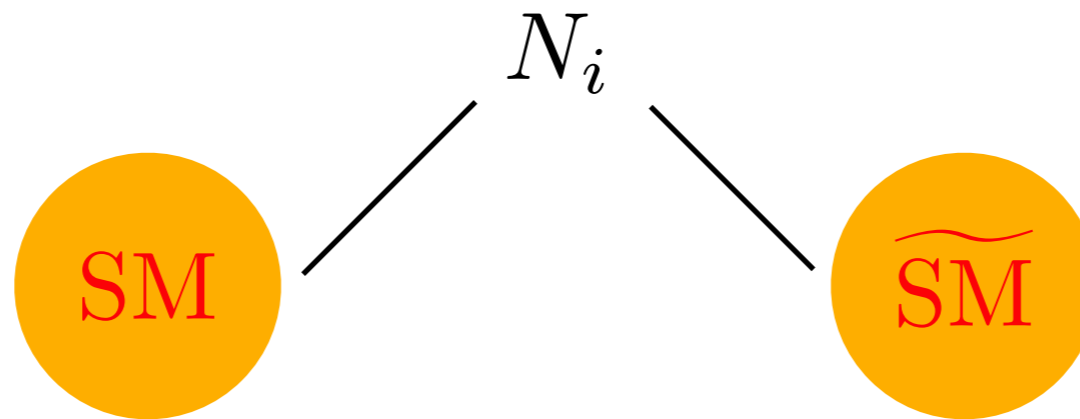
neutrino masses and sterile neutrinos

right handed neutrinos respect the \mathbb{P} symmetry



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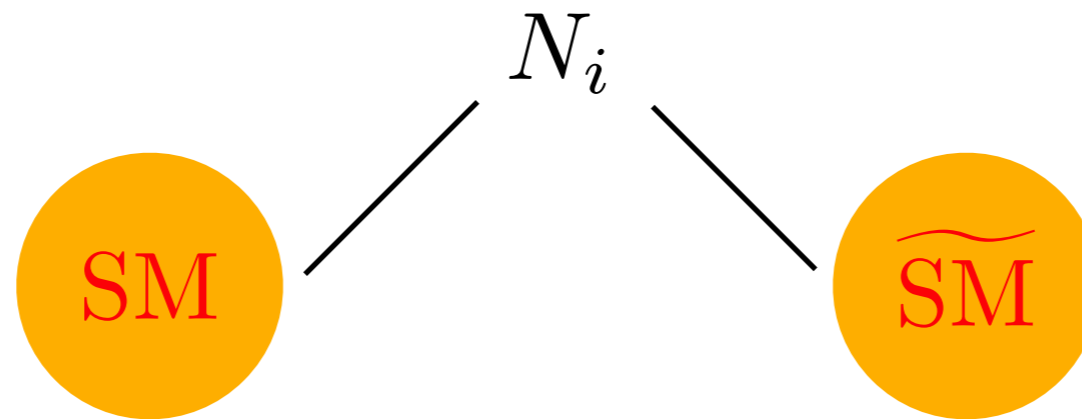
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visible and sterile neutrinos are **majorana**

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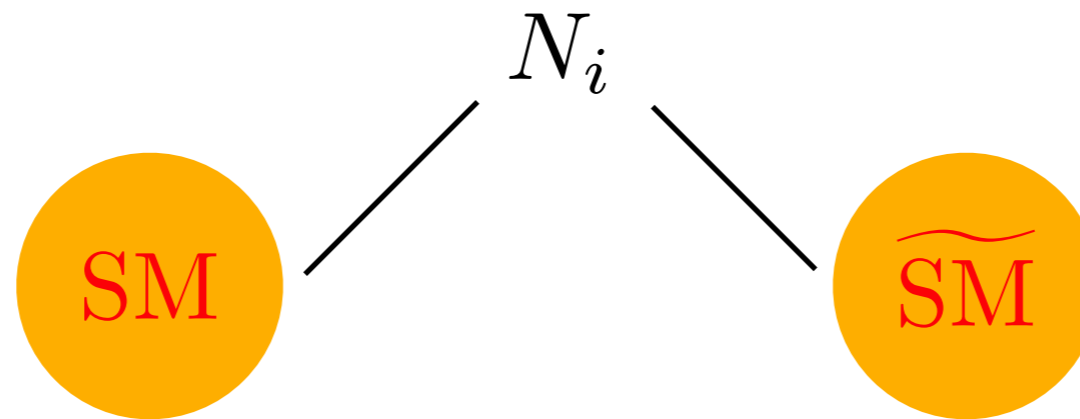


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$$\frac{\tilde{m}_i}{\tilde{v}^2} \delta_{ij} L^i H L^j H + \frac{\tilde{m}_i}{\tilde{v}^2} \delta_{ij} \tilde{L}^i \tilde{H} \tilde{L}^j \tilde{H} + \frac{\Delta_{ij} \tilde{m}_j}{\tilde{v}^2} L^i H \tilde{L}^j \tilde{H} + h.c.$$

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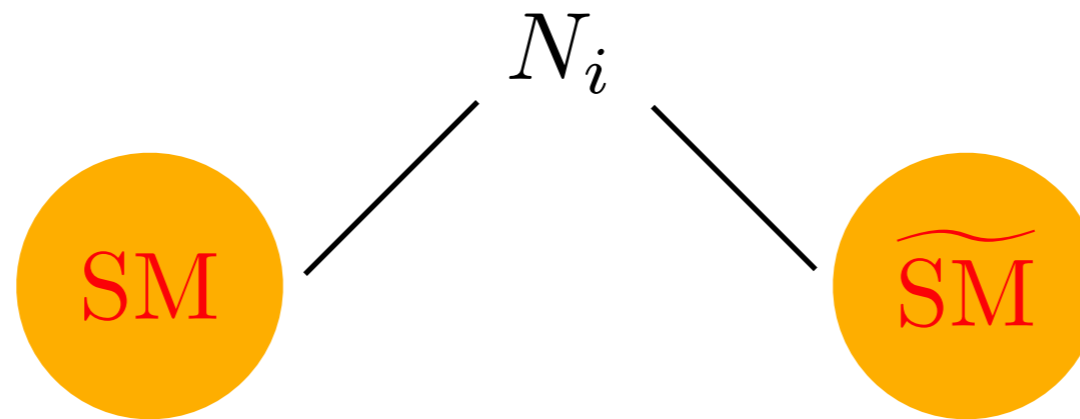
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inverted or normal ordering affects the mass spectrum

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inverted or normal ordering affects the mass spectrum

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

cosmology of sterile neutrinos

in the right ballpark, sterile neutrinos at the GeV scale

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

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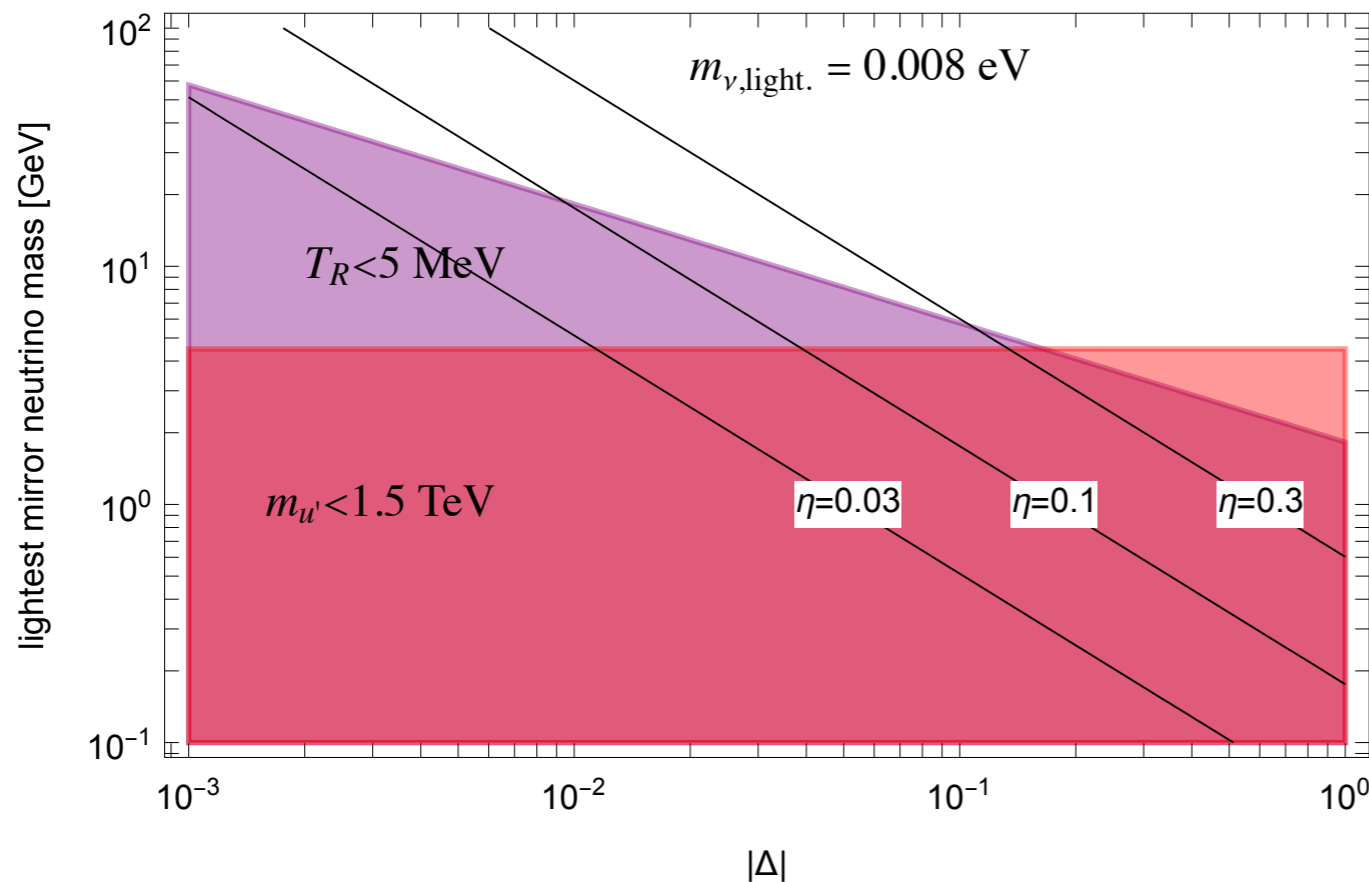
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matter dominated phase that can **reheat** the universe

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

entropy dilution

color keeps the two sectors
in thermal equilibrium

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

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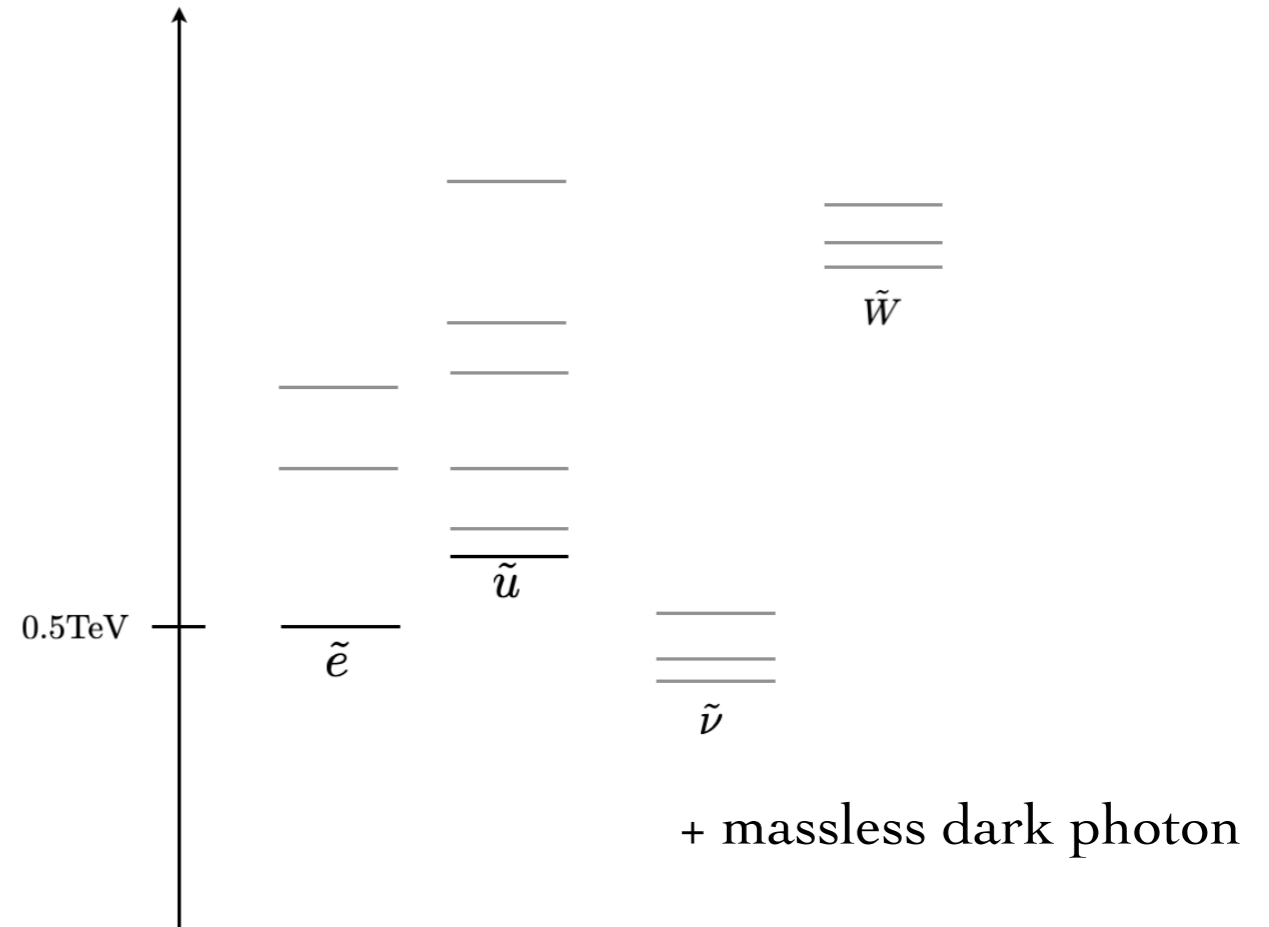
- **Baryon number**
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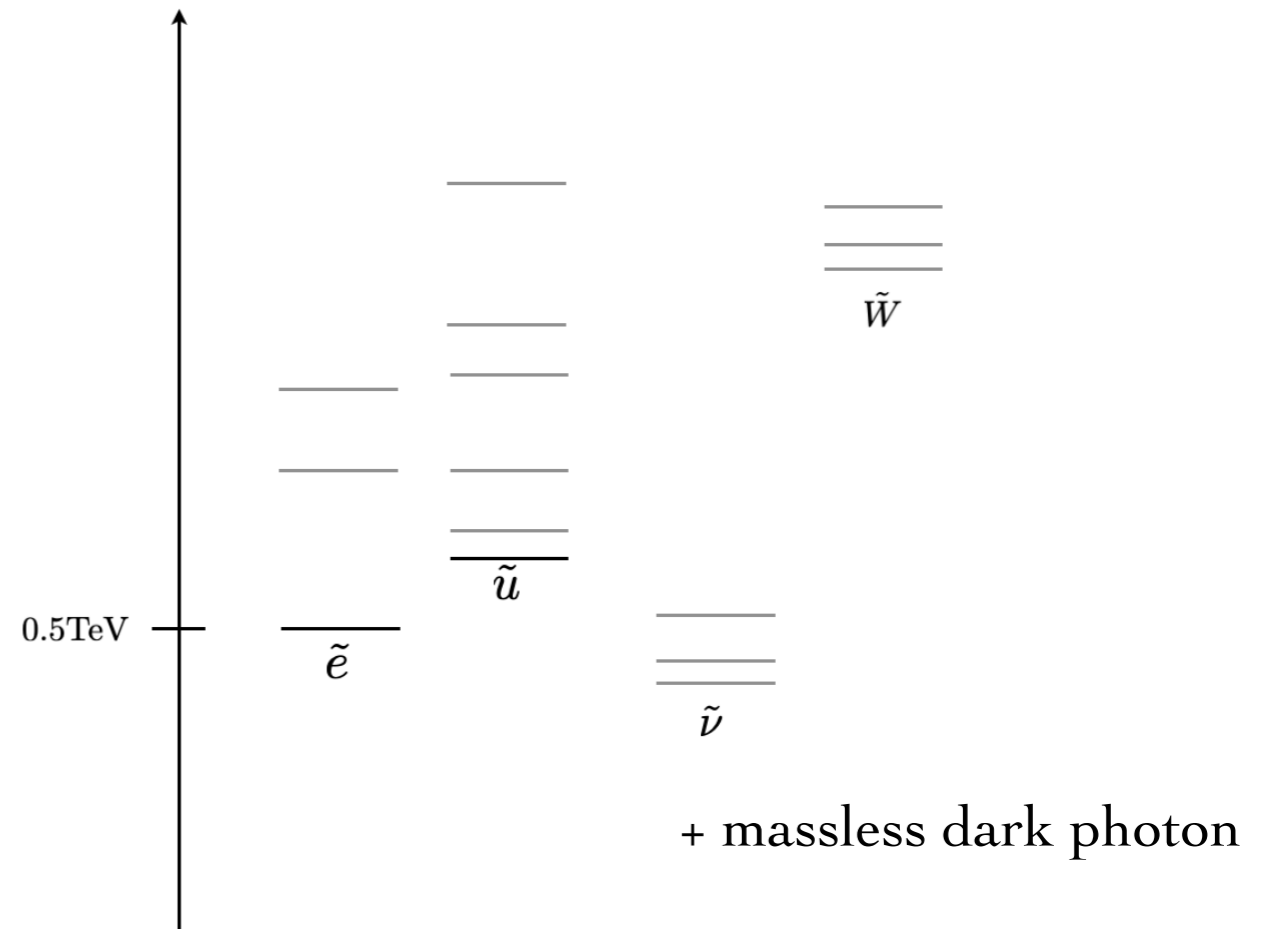


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- ➡ mirror up quark
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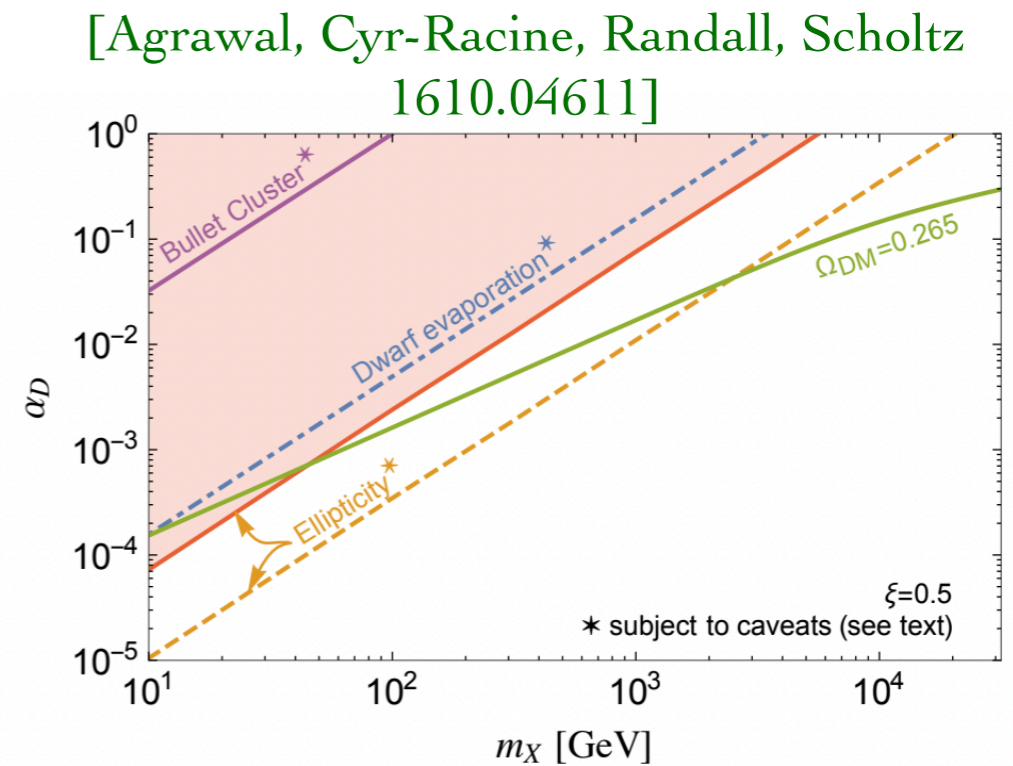
we focus on the **mirror electron as DM**

DM freeze out in a dark sector with a massless mediator

dark electron + dark photon

interestingly, DM with a massless dark photon is not excluded

➔ O(100 GeV) and typical coupling allowed

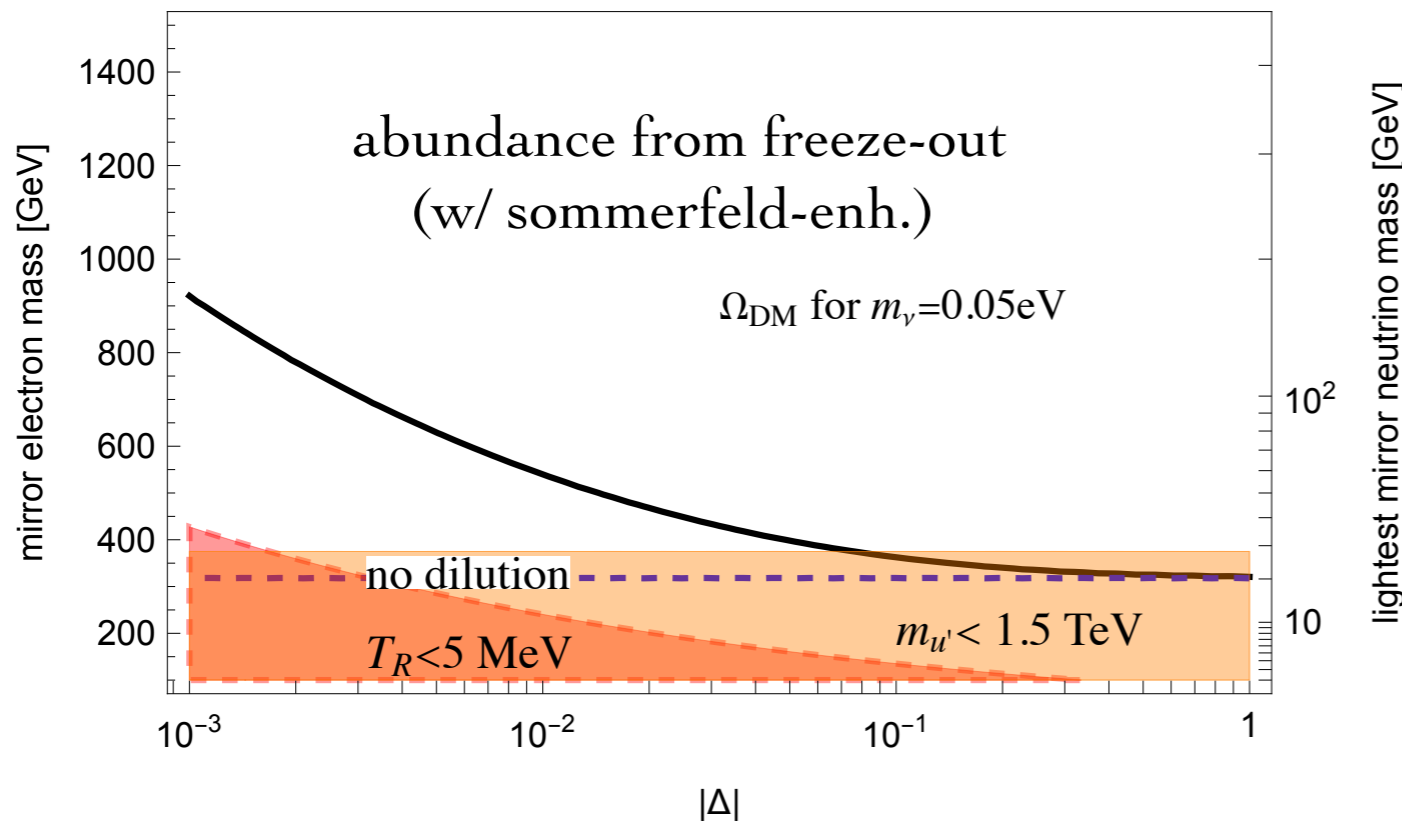
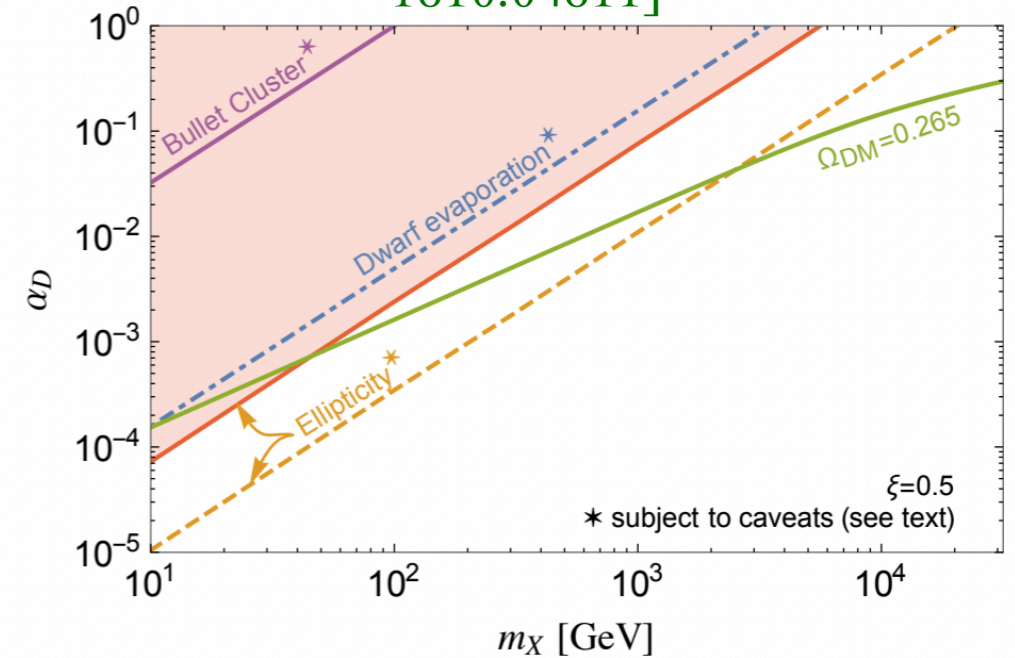


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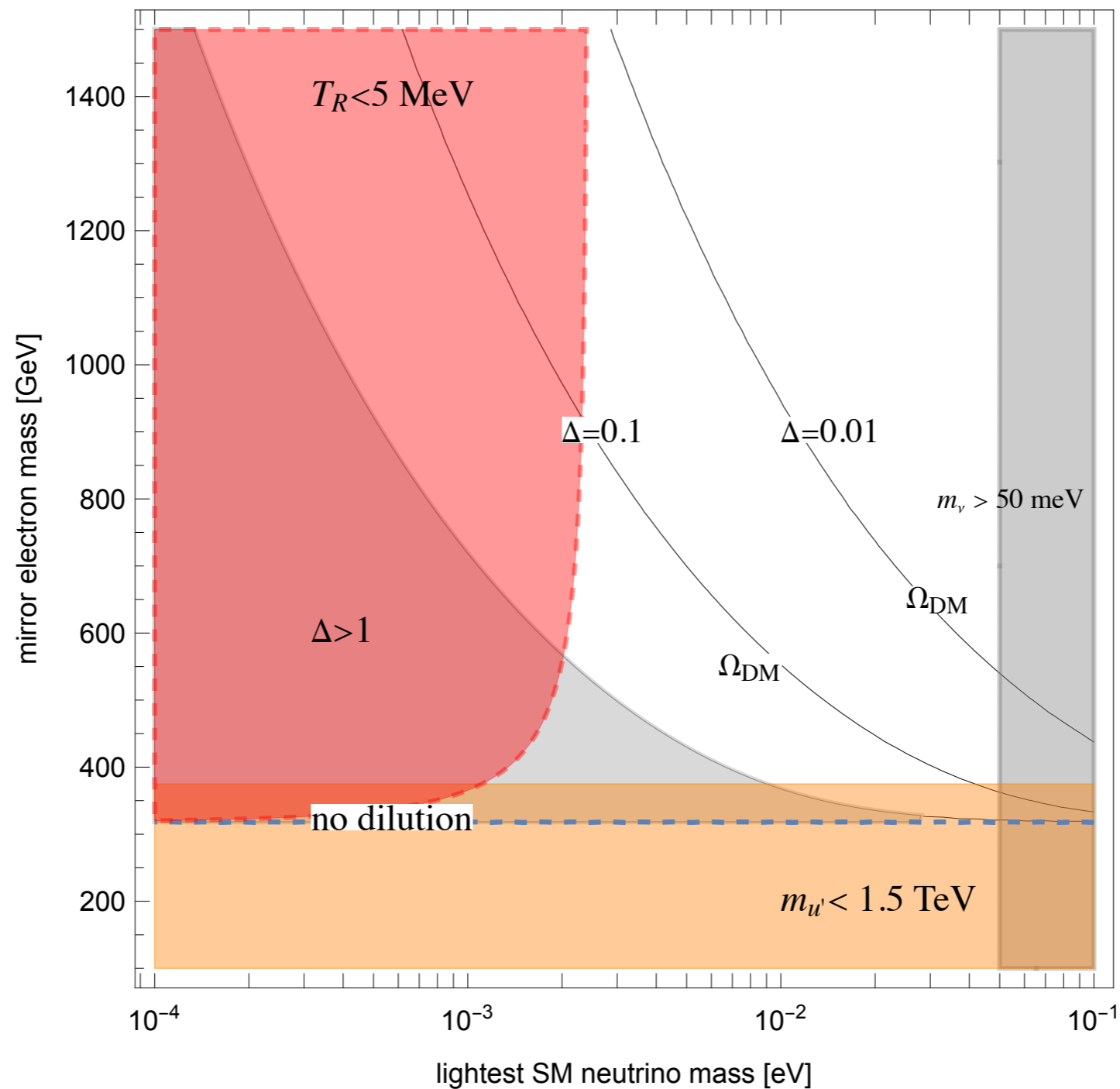
[Agrawal, Cyr-Racine, Randall, Scholtz 1610.04611]



➔ dilution from sterile neutrinos **critical**

cosmology and neutrino physics

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 \rightarrow milli-charged DM
- suppressed by four loops and limited running [Dunsky, Hall, Harigaya]

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

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

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

- **Massive dark photon**

- We explored massive dark photon with **P** symmetry
- Via breaking $U(1) \times \tilde{U}(1) \rightarrow U(1)_Y$ $\Sigma \sim (3, 3)_y$

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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 \mathbf{P}
- leptogenesis (all the ingredients available, connection with neutrino masses)

thank you!