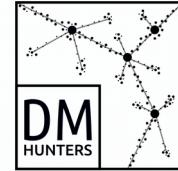


$$1 + 2 + 3 + 4 + 5 + 6 + 7 + \dots + \infty = -\frac{1}{12}$$



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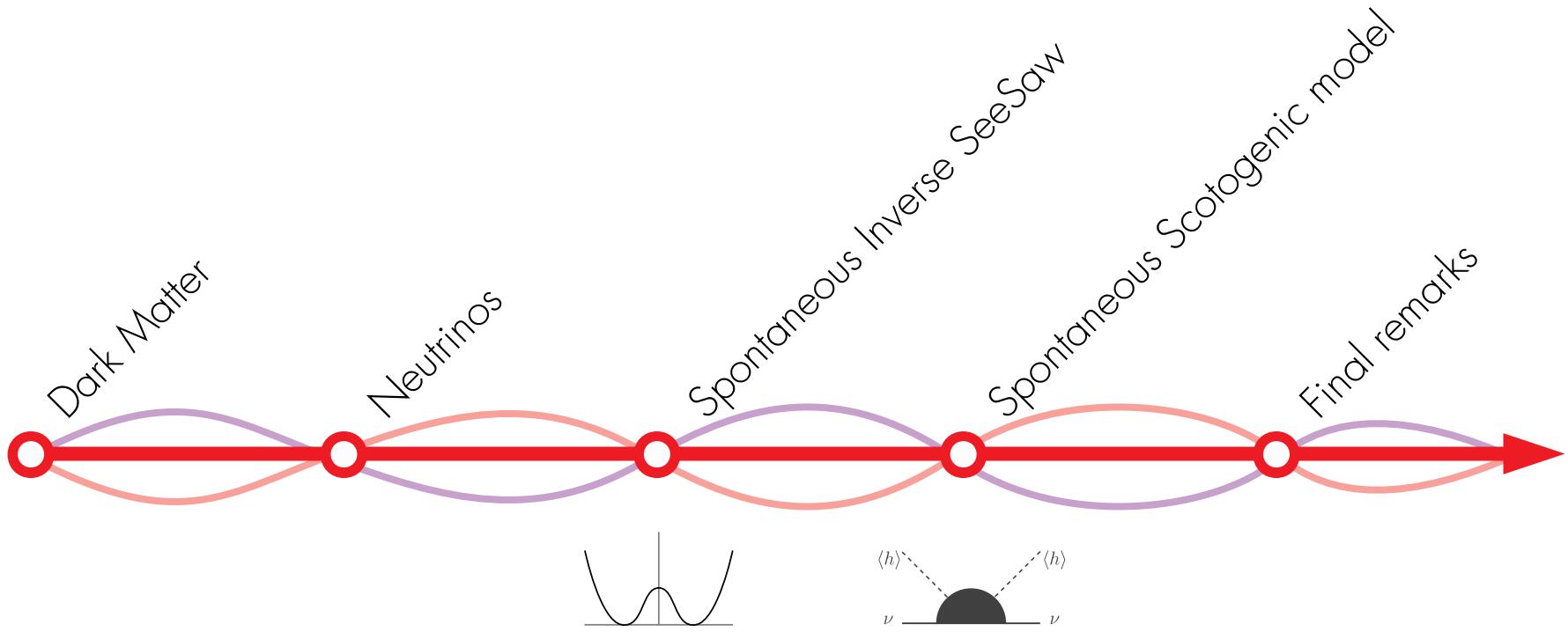
Neutrino and Dark Matter connection from spontaneous lepton number violation

Roberto A. Lineros

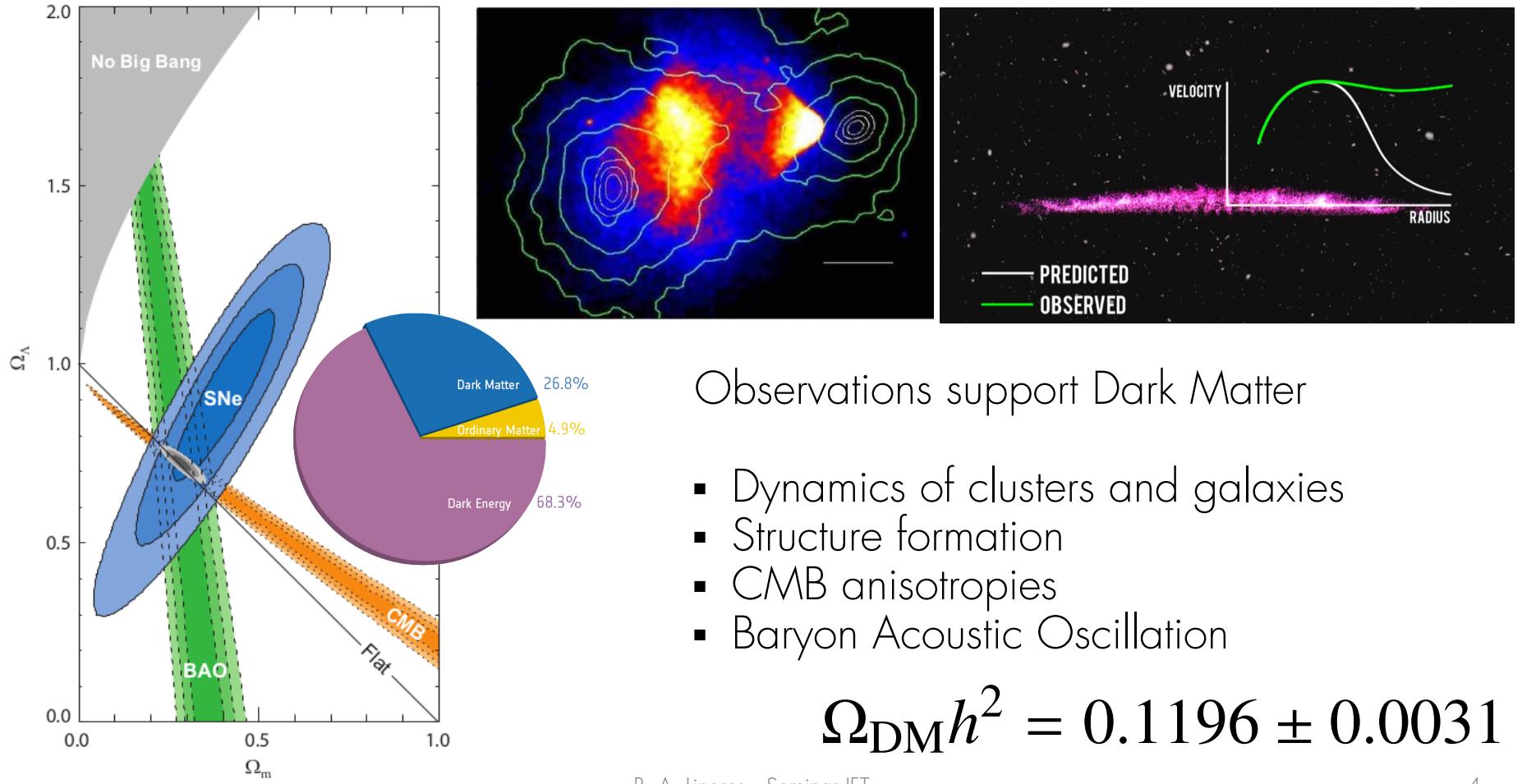
Departamento de Física, Universidad Católica del Norte

Seminar IFT – 21 February 2019

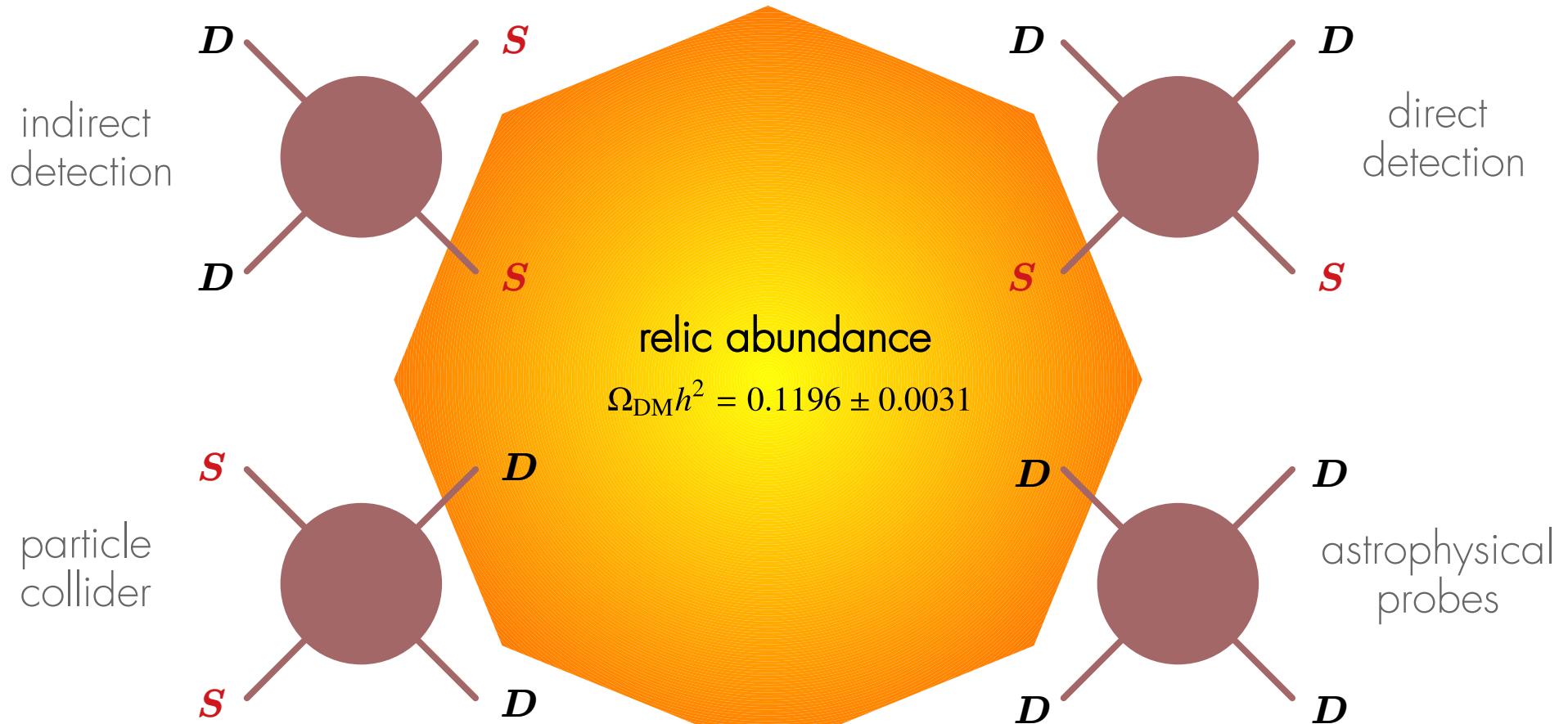
Outline



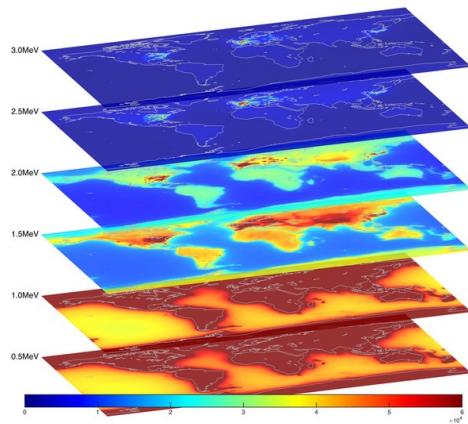
Dark Matter



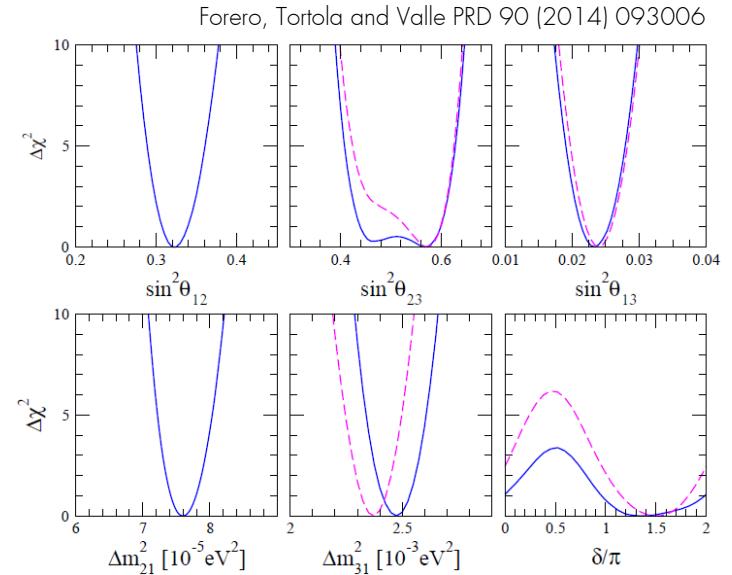
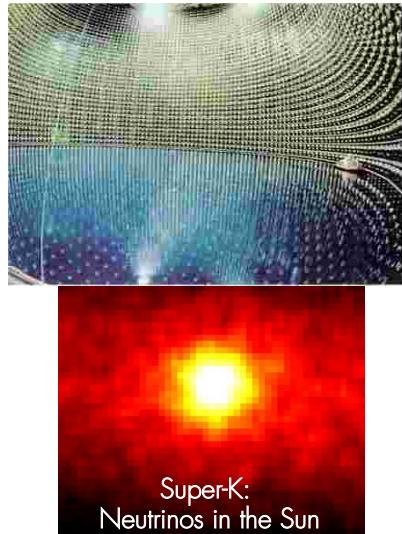
Dark Matter Searches



Neutrinos



AGM2015: Antineutrino Global Map 2015



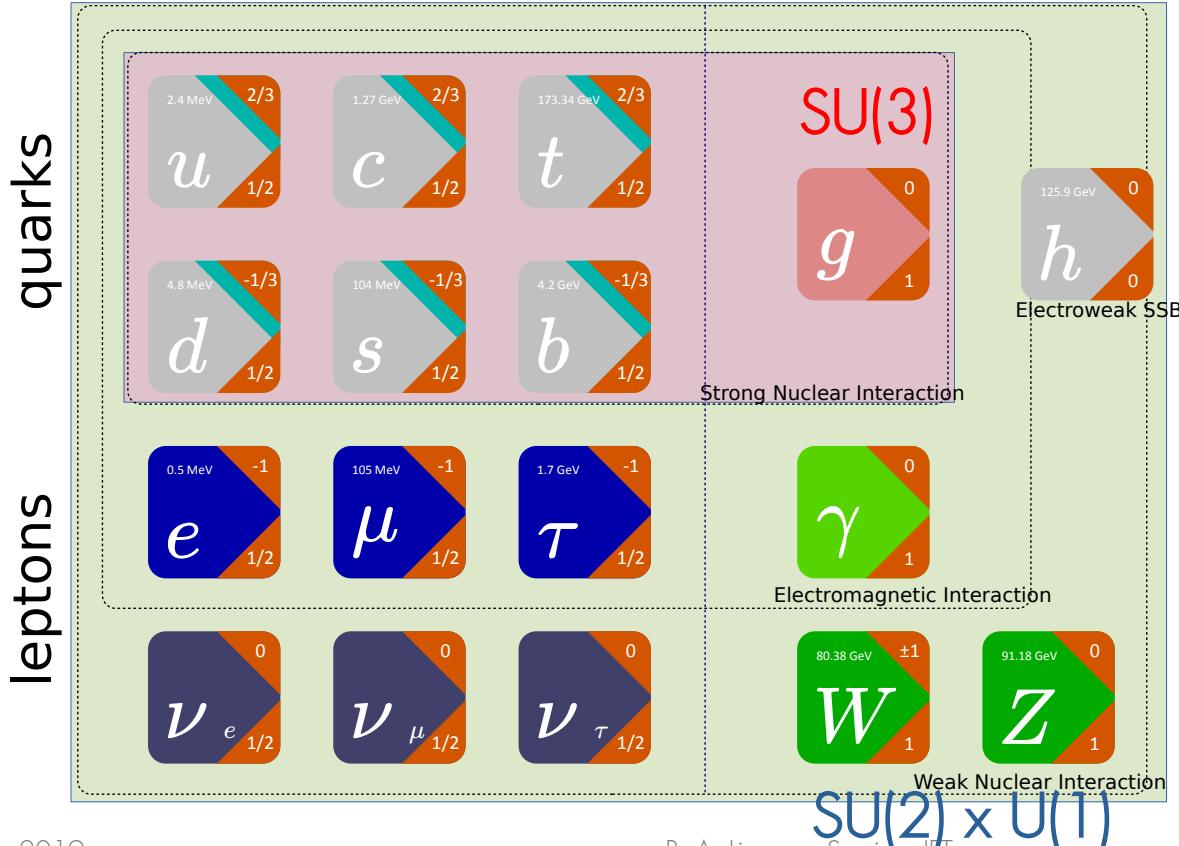
The SM predicts zero neutrino mass

Beyond SM physics is required to explain mass spectrum and mixing angles

The Standard Model

(so far)

SM matter families

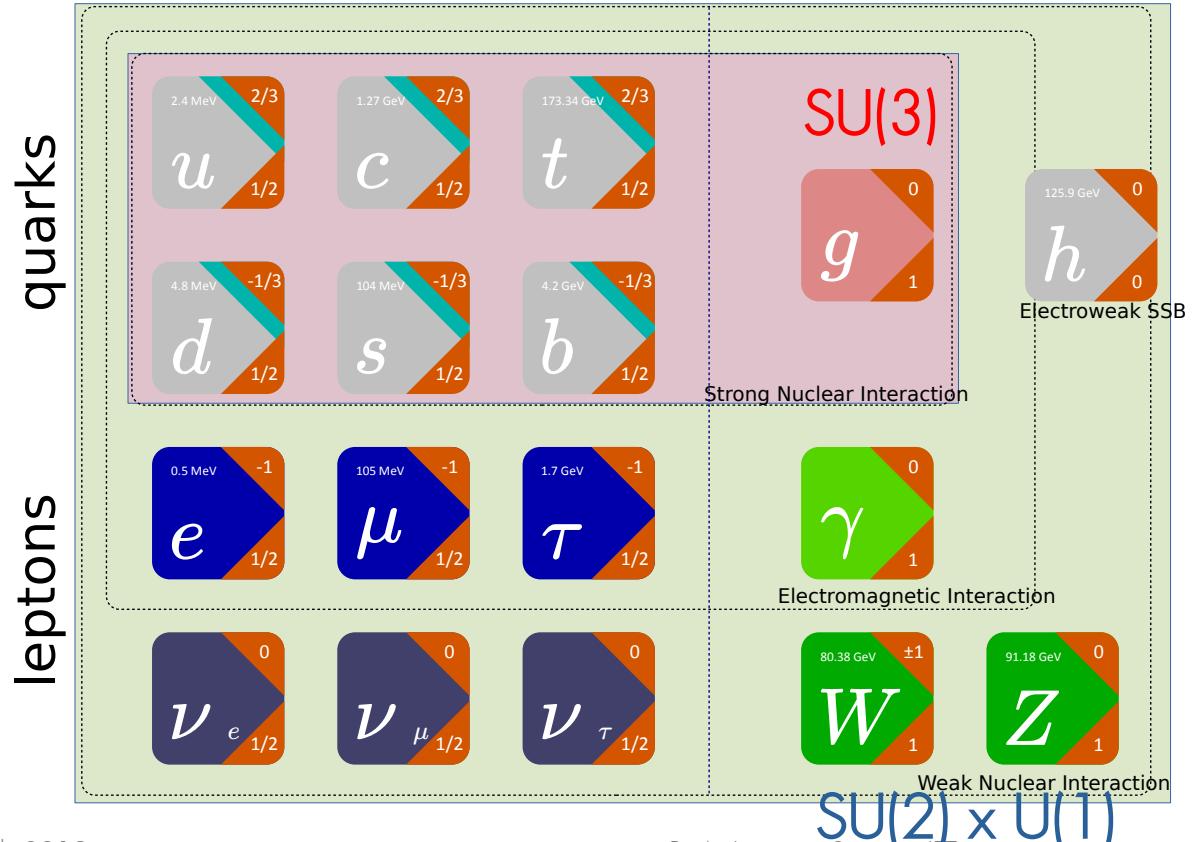


- Massless neutrinos
- Lepton number conserved
- Baryon number conserved

The Standard Model

(so far)

SM matter families



Beyond SM



Case 1

(light) Dark Matter candidate
and neutrino masses

Majoron dark matter from a spontaneous inverse seesaw model.
N. Rojas, R. A. Lineros, F. Gonzalez-Canales. [[arxiv:1703.03416](#)]

Neutrino mass mechanisms

A large fraction of the models uses the 5-dim Weinberg operator to generate majorana neutrino masses

$$\mathcal{O}_{5ij} = \frac{1}{\Lambda} (L_i H)^T (L_j H)$$

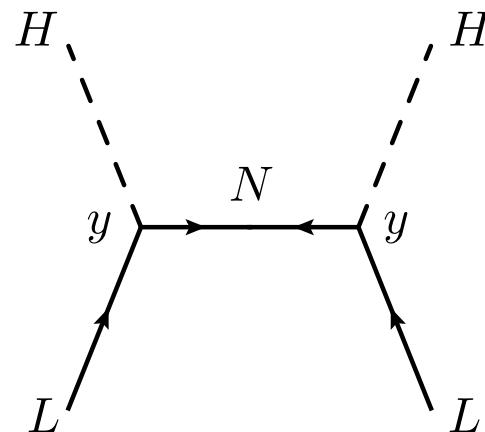
This operator preserves SM symmetries but it breaks lepton number in 2 units

$$\mathcal{O}_{5ij} = \frac{v^2}{\Lambda} \nu_i \nu_j = M_{ij} \nu_i \nu_j$$

Neutrino mass mechanisms

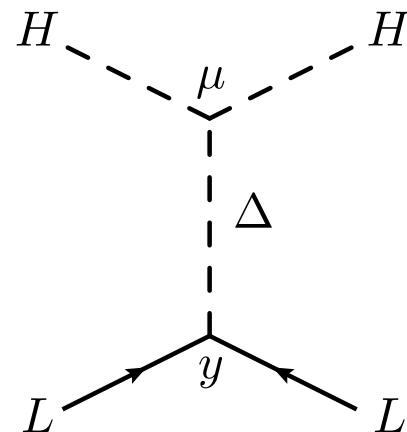
The commonly known schemes are **see-saw mechanisms**

Type-I



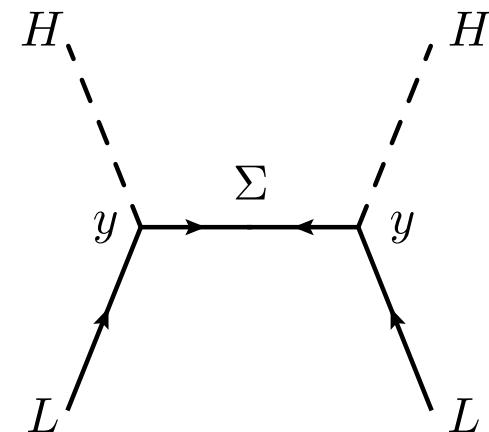
$$m_\nu \propto \frac{v^2 y^2}{M_N}$$

Type-II



$$m_\nu \propto \frac{v^2 y \mu}{M_\Delta^2}$$

Type-III



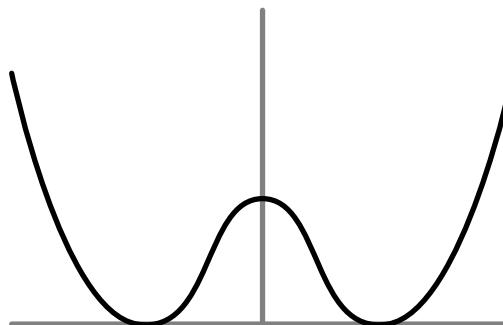
$$m_\nu \propto \frac{v^2 y^2}{M_\Sigma}$$

Enters the Majoron

The Type-I seesaw can be generated via the **spontaneous** breaking of the **global U(1) lepton** symmetry

$$\mathcal{L} \supset -y_L \begin{matrix} \bar{L} \\ -1 \end{matrix} H \begin{matrix} N^c \\ 0 \end{matrix} - \frac{y_S}{2} \begin{matrix} S \\ 2 \end{matrix} \begin{matrix} \bar{N}^c \\ -1 \end{matrix} N + h.c.$$

$$S = \frac{v_S + \sigma + iJ}{\sqrt{2}}$$



Enters the Majoron

$$m_D = \frac{y_L v_H}{\sqrt{2}}$$

$$M_N = \frac{y_S v_S}{\sqrt{2}}$$

After the SSB, we get the Type-I seesaw

$$\mathcal{L} \supset -m_D \bar{\nu}_L N^c - \frac{M_N}{2} \overline{N^c} N + h.c.$$

and 2 scalars: σ and J

$$m_\sigma \simeq v_S \quad m_J = 0$$

Enters the Majoron

$$m_D = \frac{y_L v_H}{\sqrt{2}}$$

$$M_N = \frac{y_S v_S}{\sqrt{2}}$$

After the SSB, we get the Type-I seesaw

$$\mathcal{L} \supset -m_D \bar{\nu}_L N^c - \frac{M_N}{2} \overline{N^c} N + h.c.$$

and 2 scalars: σ and J  DM candidate

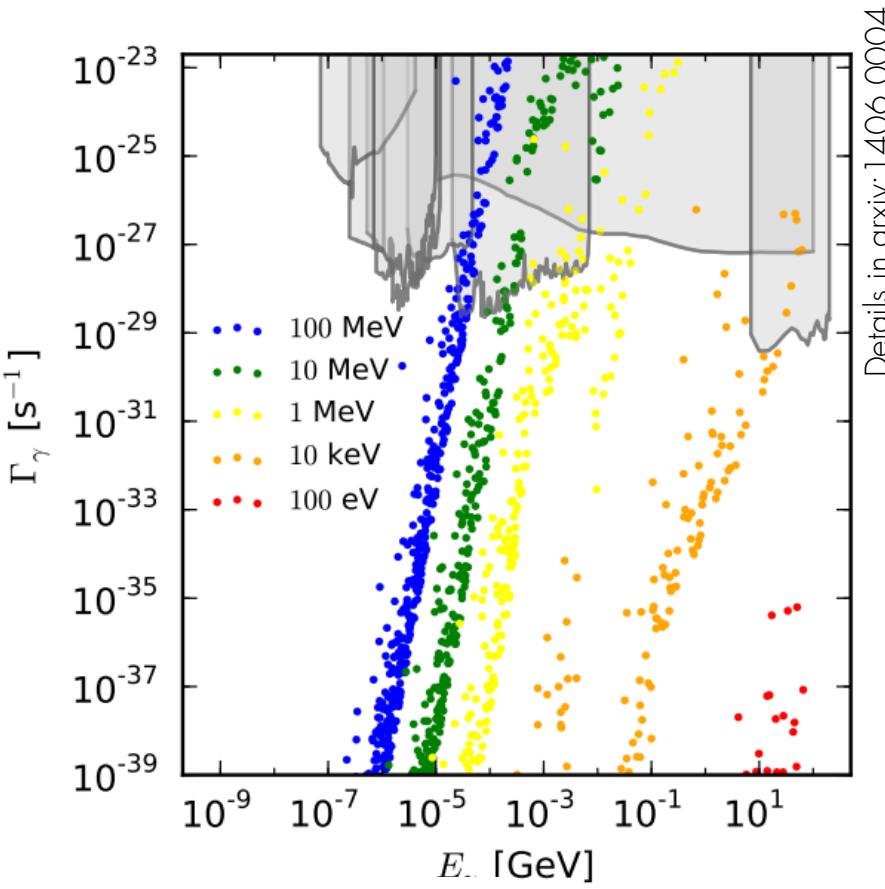
$$m_\sigma \simeq v_S \quad m_J = 0$$

Majoron as DM (pros)

- Neutral
- Weakly coupled to the SM
- Long lived

$$\Gamma_{J \rightarrow \nu\nu} = \frac{m_J}{32\pi} \frac{\sum_i (m_i^\nu)^2}{2v_1^2}$$

$$\Gamma_{J \rightarrow \gamma\gamma} = \frac{\alpha^2 m_J^3}{64\pi^3} \left| \sum_f N_f Q_f^2 \frac{2v_3^2}{v_2^2 v_1} (-2T_3^f) \frac{m_J^2}{12m_f^2} \right|^2$$



Majoron as DM (cons)

$$m_J = 0 \quad !!!$$

... but global symmetries are not protected under gravity effects

Therefore

$$m_J \neq 0$$

... and the majoron DM is just a *pseudo Nambu-Goldstone boson*

What defines a majoron DM?

- It is a (pseudo)scalar
- It is part of the neutrino mass mechanism
- Its signature is the decay into neutrinos
- It is massive

Inverse seesaw

The **standard** inverse seesaw

$$\mu \ll m_D \ll M$$

$$\mathcal{L} = -\frac{1}{2} n_L^T C \mathcal{M} n_L + h.c.$$

$$n_L^T = (\nu_L, N_1^c, N_2)$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

Inverse seesaw

The **standard** inverse seesaw

$$\mu \ll m_D \ll M$$

$$\mathcal{L} = -\frac{1}{2} n_L^T C \mathcal{M} n_L + h.c.$$

$$n_L^T = (\nu_L, N_1^c, N_2)$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

Lepton number
violating term

Inverse seesaw

The **standard** inverse seesaw

$$\mu \ll m_D \ll M$$

Active neutrinos

$$m_\nu = \left(\frac{m_D}{M} \right)^2 \mu$$

Heavy neutrinos

$$m_{\mathcal{N}'} = M - \frac{m_D^2}{M} + \frac{\mu}{2}$$

$$m_{\mathcal{N}} = M - \frac{m_D^2}{M} - \frac{\mu}{2}$$

Inverse seesaw

The **usual** inverse seesaw hierarchy:

$$\mu \ll m_D \ll M$$

Some numerology:

$$M \sim 100 \text{ TeV} \quad m_D \sim 10 \text{ GeV} \quad \mu \sim 10 \text{ MeV}$$

$$m_\nu \sim 0.1 \text{ eV}$$

$$\alpha = \frac{\mu}{M} \sim 10^{-7}$$

Spontaneous Inverse seesaw

To generate the inverse seesaw scheme we need 2 complex scalars

$$\mathcal{L} = -y_L \bar{L} H N_1^c - y_S S^\dagger \overline{N_2} N_1^c - \frac{y_X}{2} X^\dagger \overline{N_2^c} N_2 + h.c.$$

$$m_D = \frac{y_L v_h}{\sqrt{2}}, M = \frac{y_S v_S}{\sqrt{2}}, \text{and } \mu = \frac{y_X v_X}{\sqrt{2}}$$

Spontaneous Inverse seesaw

To generate the inverse seesaw scheme we need 2 complex scalars

$$\mathcal{L} = -y_L \bar{L} H N_1^c - y_S S^\dagger \overline{N_2} N_1^c - \frac{y_X}{2} X^\dagger \overline{N_2^c} N_2 + h.c.$$

$$v_S > 50 \text{ TeV} \quad v_X > 5 \text{ MeV}$$

Spontaneous Inverse seesaw

But the **charge assignments** do not follow the typical one of the ISS

	L	N_1	N_2	S	X
$SU(2)_L$	2	1	1	1	1
$U(1)_Y$	1/2	0	0	0	0
$U(1)_l$	1	-1	x	$1-x$	$2x$

$$x = 3/5$$

$$\mathcal{L} = -y_L \bar{L} H N_1^c - y_S S^\dagger \overline{N_2} N_1^c - \frac{y_X}{2} X^\dagger \overline{N_2^c} N_2 + h.c.$$

Scalar potential

The **assignment** fixes the potential

$$\omega = \frac{v_X}{v_S}$$

$$V_{\text{scalar}} = V_{XS} + V_{HXS} + V_I$$

$$V_I = \lambda_{\text{cp}} e^{i\delta} X S^{\dagger 3} + h.c.$$

$$S = \frac{v_S e^{i\theta} + \sigma_S + i\chi_S}{\sqrt{2}} \quad X = \frac{v_X e^{i\tau} + \sigma_X + i\chi_X}{\sqrt{2}}$$

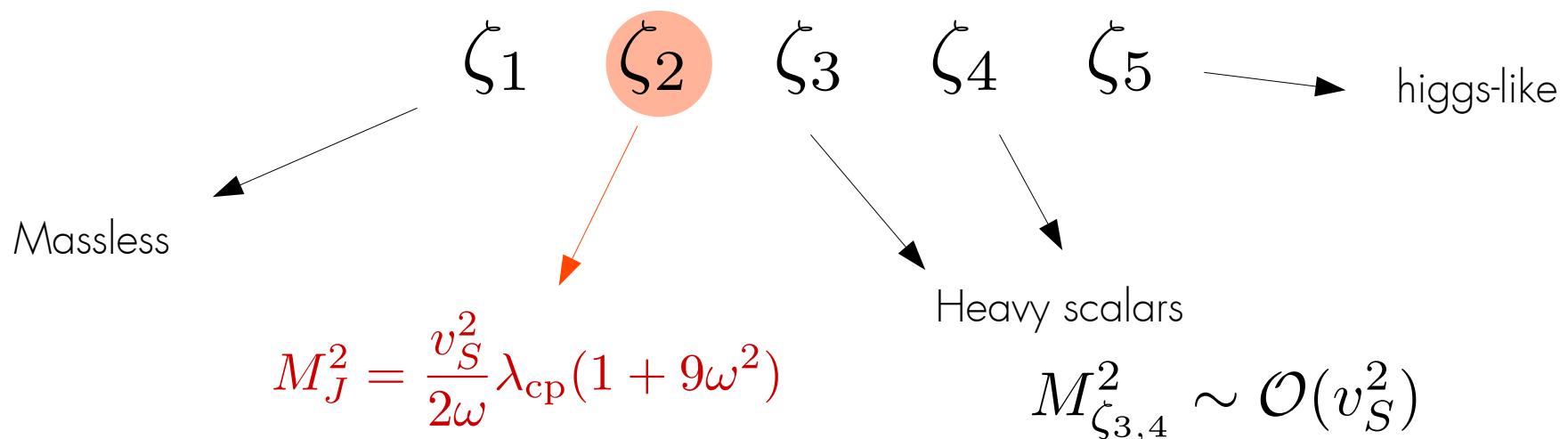
The tadpole equations relate the CP phases:

$$\tau = 3\theta - \delta - \pi$$

Mass spectrum

$$\omega = \frac{v_X}{v_S}$$

Now we have 5 spin-0 fields: 4 related to L breaking
1 related to EW breaking



Majoron DM stability

The only candidate is the **lightest massive scalar** i.e.

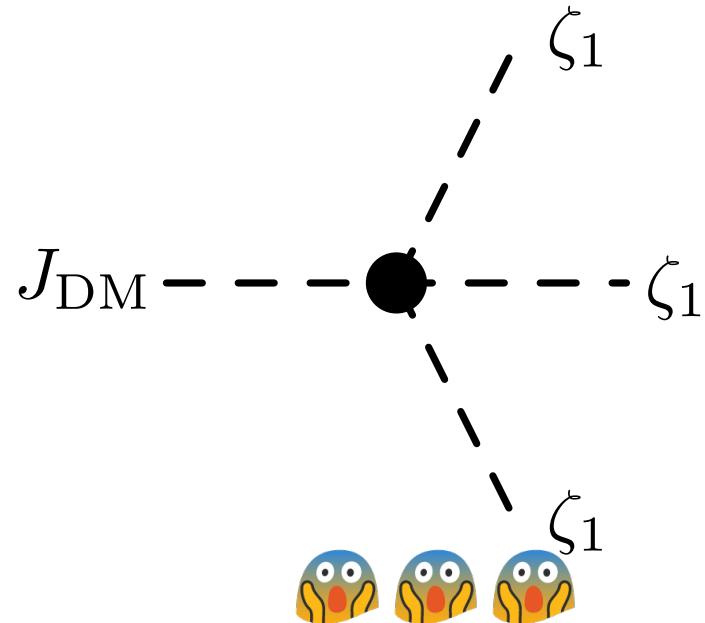
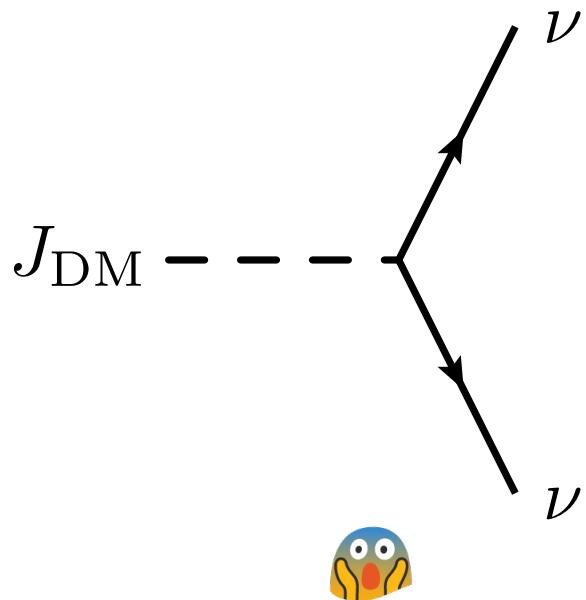
$$\zeta_2 = J_{\text{DM}}$$

We still has to satisfy the stability condition keV decaying DM:

$$\Gamma_{\text{DM}} < 10^{-43} \text{GeV}$$

Decay modes

There are potentially dangerous decay modes:



Decay into neutrinos

$$\alpha = \frac{\mu}{M} \sim 10^{-7}$$

The decay rate vanishes for:

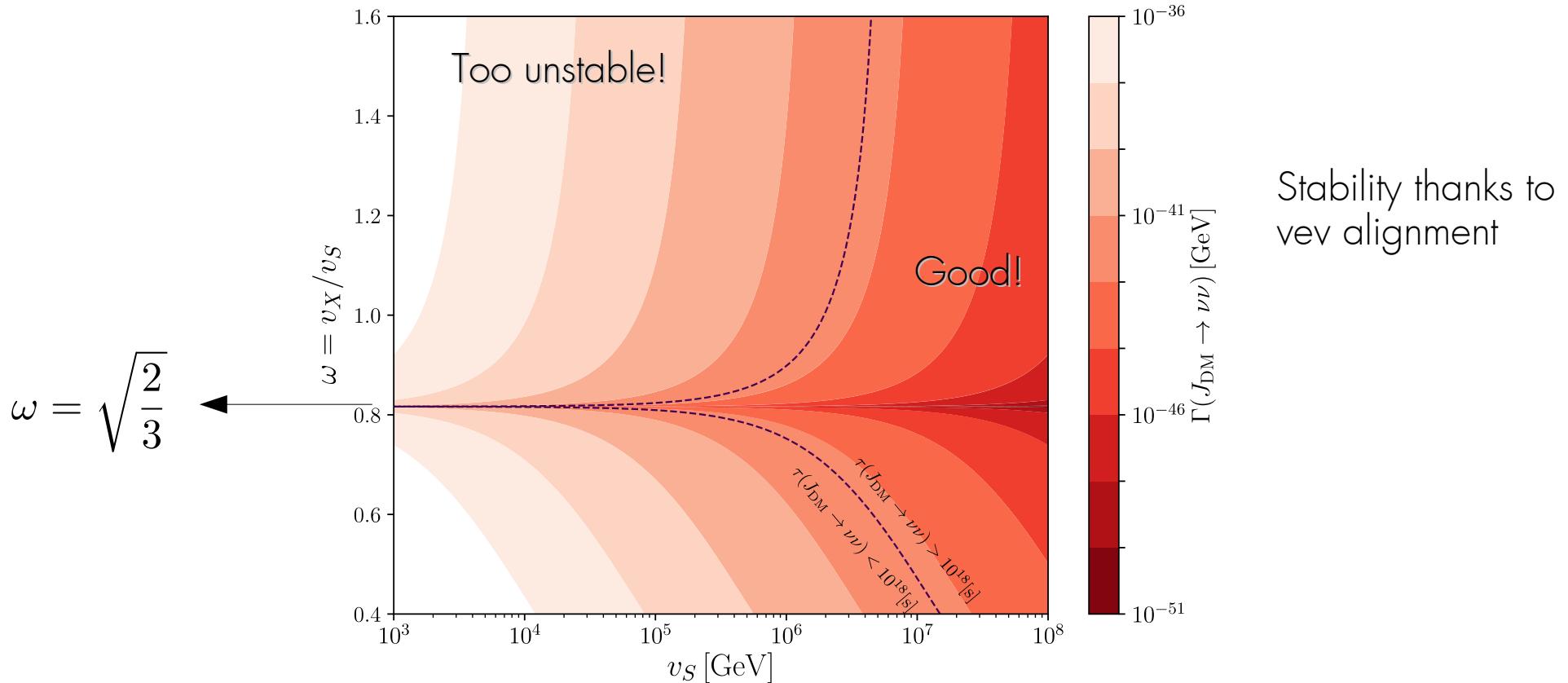
$$\omega_0 = \sqrt{2/3}$$

$$\Gamma_\nu = \Gamma_{0\nu}(\omega_0) 4\alpha^2$$

$$\Gamma_{0\nu}(\omega_0) \simeq 10^{-40} \text{ GeV} \left(\frac{m_\nu}{0.1 \text{ eV}} \right)^2 \left(\frac{M_J}{1 \text{ keV}} \right) \left(\frac{v_S}{100 \text{ TeV}} \right)^{-2}$$

Decay into neutrinos

$$J_{\text{DM}} \rightarrow \nu\nu$$

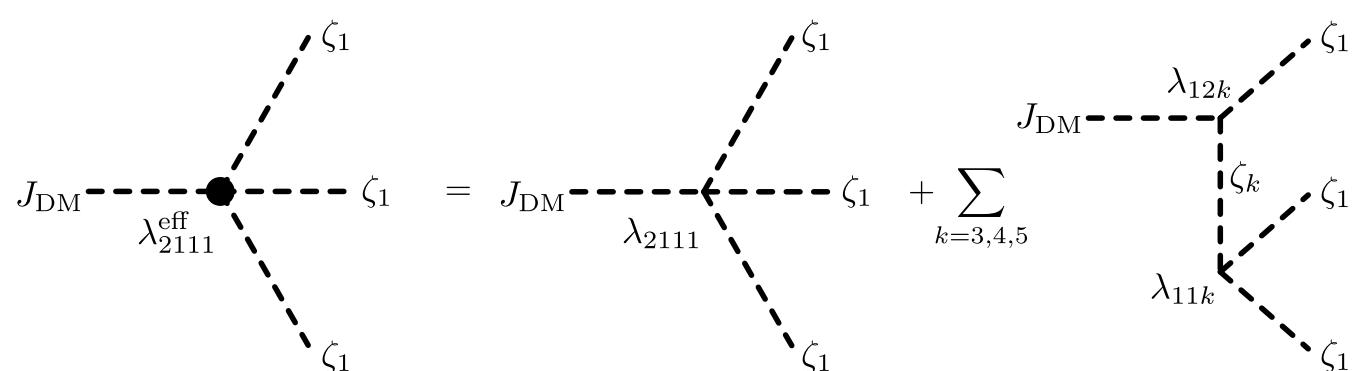


Decay into scalars

$$J_{\text{DM}} \rightarrow \zeta' \text{s}$$

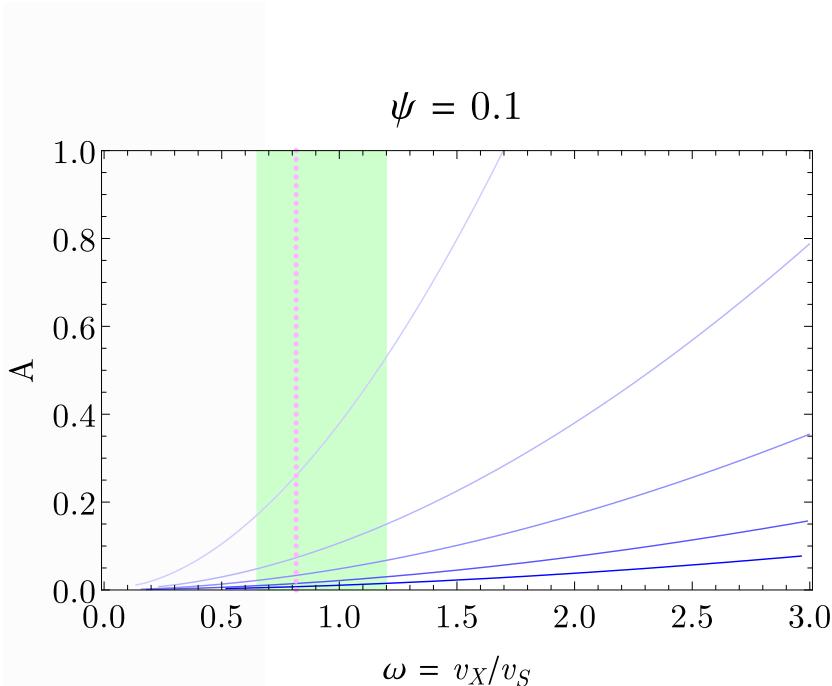
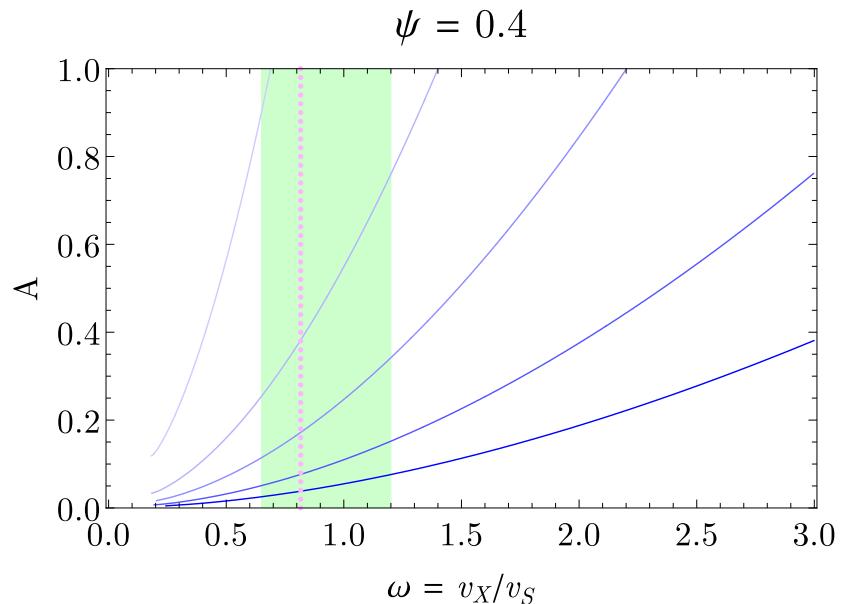
Without a protective symmetry, this channel is not suppressed

However we can find the parameter space where the mode vanishes



Decay into scalars

$$J_{\text{DM}} \rightarrow \zeta' s$$

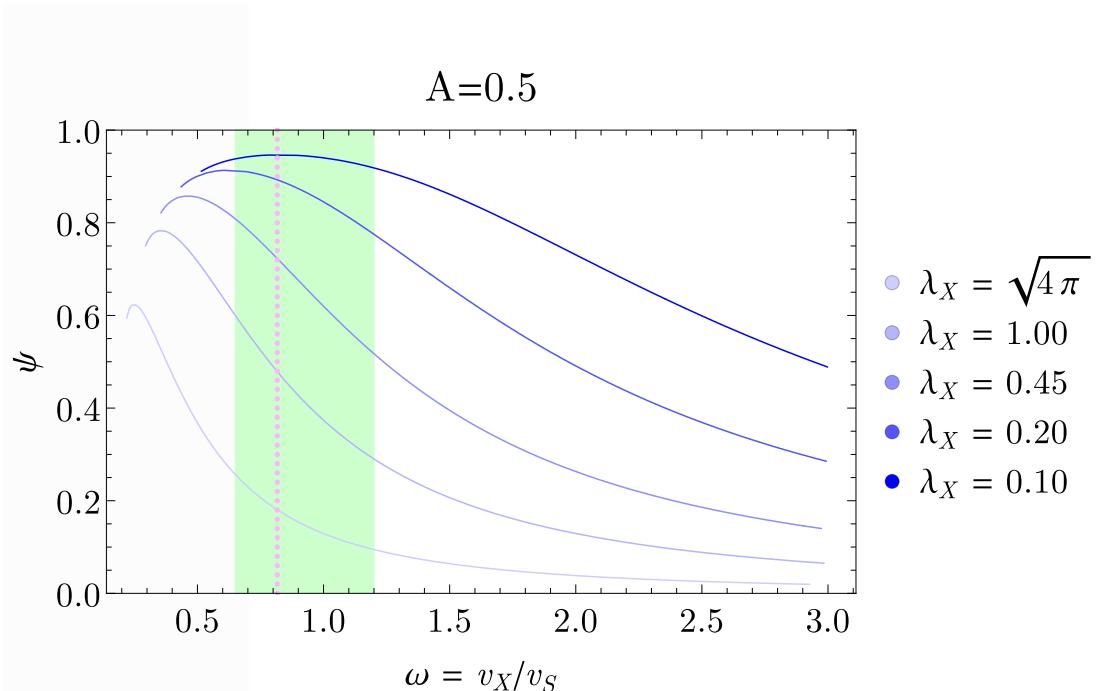
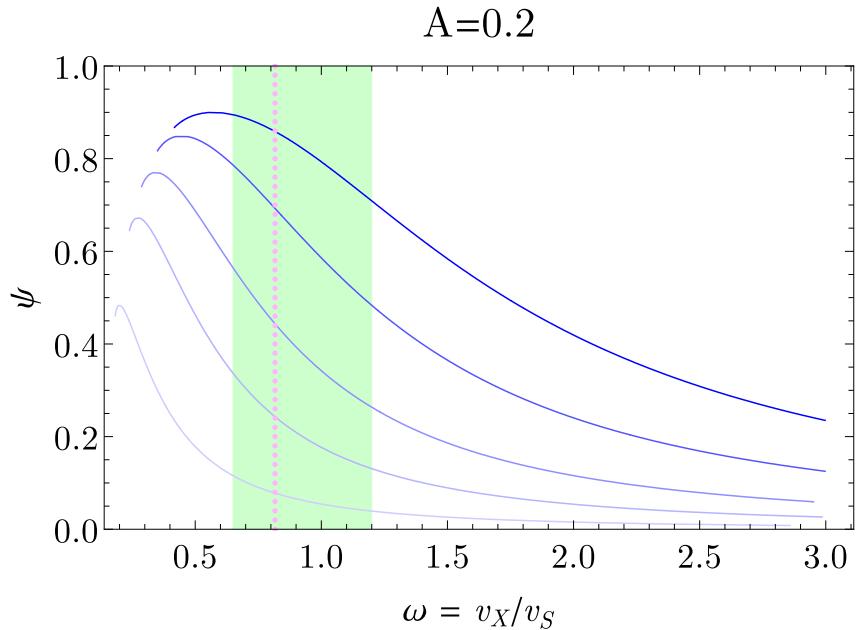


- $\lambda_X = \sqrt{4\pi}$
- $\lambda_X = 1.00$
- $\lambda_X = 0.45$
- $\lambda_X = 0.20$
- $\lambda_X = 0.10$

The interplay of different diagrams allows to vanish the decay mode

Decay into scalars

$$J_{\text{DM}} \rightarrow \zeta' \text{s}$$



There is a whole volume that satisfy this condition

Conclusions

(of this part)

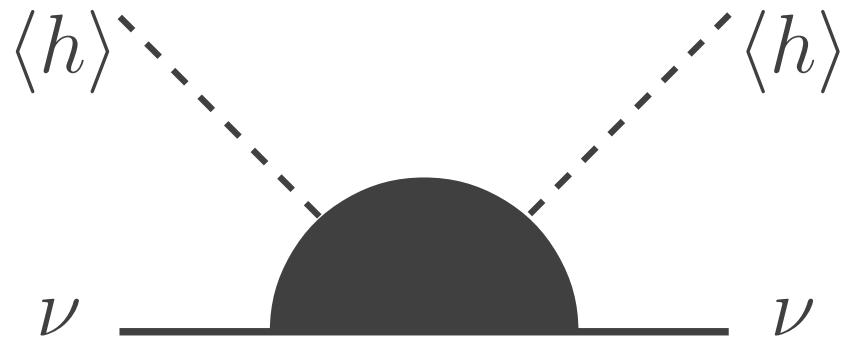
- The spontaneous inverse seesaw provides a well suited majoron DM candidate
- Our majoron DM is phenomenologically equivalent to the PNGB
- The vev alignment has a relevant role in the DM stability

Case 2

Spontaneously generated Scotogenic model

Fermion Dark Matter from Spontaneous Breaking of Lepton Number in the Scotogenic Model
C. Bonilla, L. dl Vega, J. M. Lamprea, R.L, E. Peinado [appearing soon]

Scotogenic model



Neutrino masses are generated at one loop

An extra symmetry is required to protect the loop

Dark Matter can be part of the loop

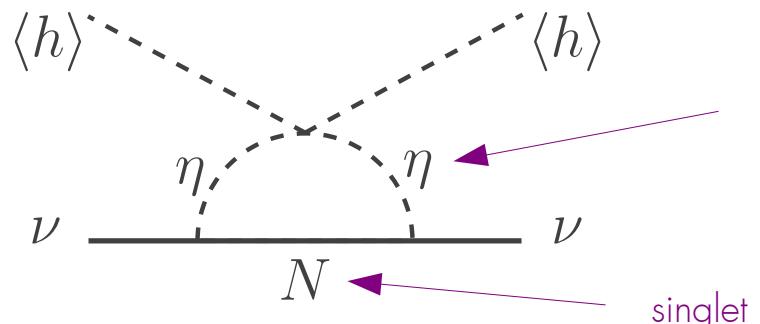
$$\mathcal{O}_{5ij} = \frac{1}{\Lambda} (L_i H)^T (L_j H)$$

Lepton number is explicitly broken

See a models zoology in Restrepo et al. arxiv:1308.3655

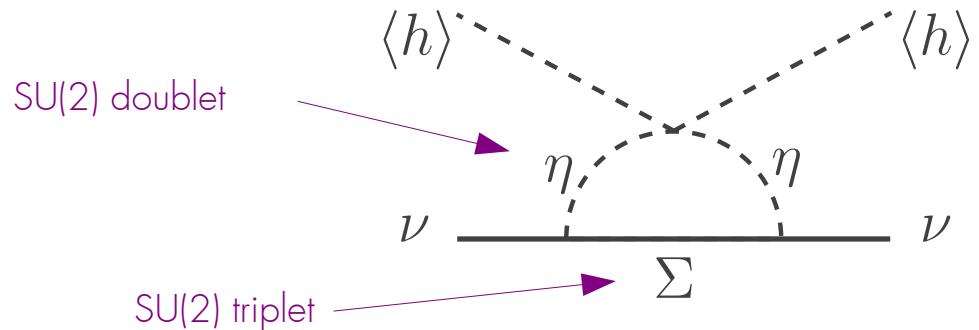
Scotogenic model

The simplest **scotogenic** models



E. Ma, Phys.Rev.D73:077301,2006

“Type-I”

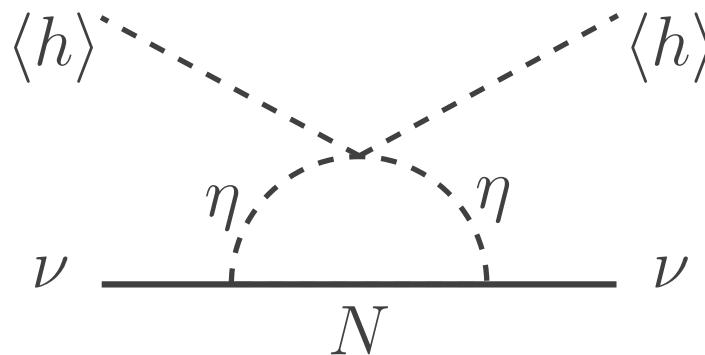


E. Ma, D. Suematsu Mod.Phys.Lett.A24:583-589,2009

“Type-III”

Scotogenic model

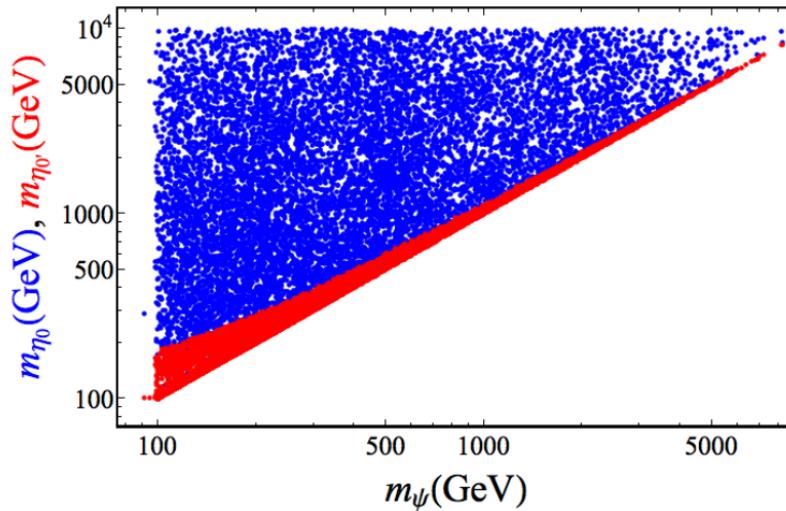
The simplest **scotogenic** models



E. Ma, Phys.Rev.D73:077301,2006

“Type-I”

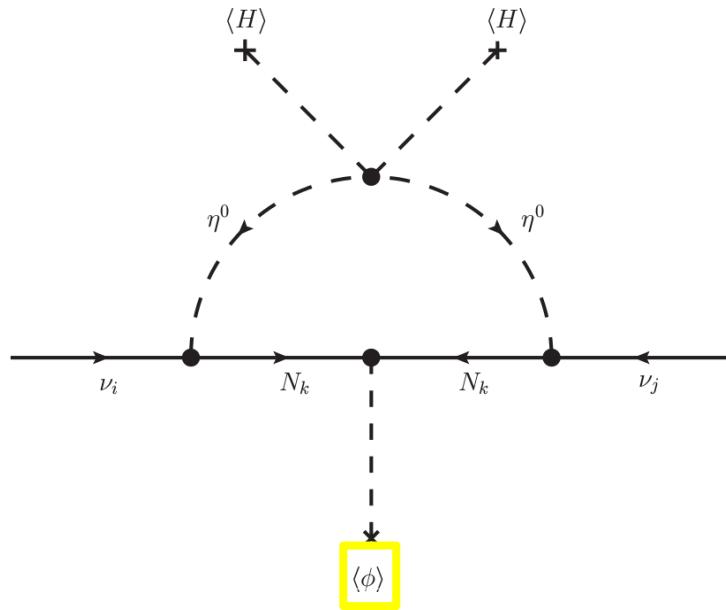
$$(\mathcal{M}_\nu)_{ij} = \sum_{k=1}^3 \frac{Y_{ik}^\nu Y_{kj}^\nu m_{N_k}}{16\pi^2} \left[\frac{m_{\eta_R}^2}{m_{\eta_R}^2 - m_{N_k}^2} \log \frac{m_{\eta_R}^2}{m_{N_k}^2} - \frac{m_{\eta_I}^2}{m_{\eta_I}^2 - m_{N_k}^2} \log \frac{m_{\eta_I}^2}{m_{N_k}^2} \right]$$



$$m_N > 100 \text{ GeV}$$

Arxiv: 1804.04117

Spontaneous Scotogenic



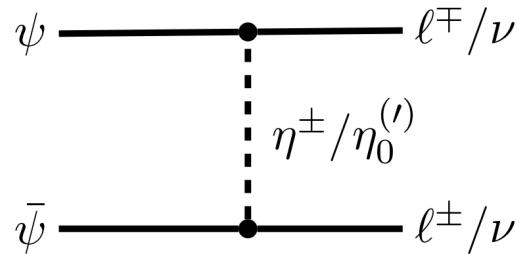
$$(\mathcal{M}_\nu)_{ij} \simeq \frac{\lambda_5 v_h^2}{16\pi^2} \sum_k \frac{Y_{ik}^\nu Y_{jk}^\nu}{m_{N_k}}$$

The scotogenic model emerge when lepton symmetry is spontaneously broken

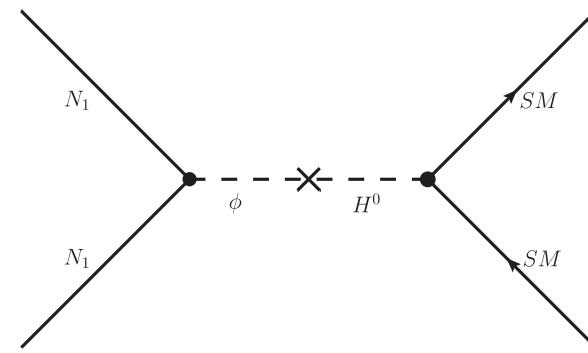
The new scalar opens new annihilation channels

	\bar{L}_i	ℓ_i	H	η	N_i	ϕ
SU(2)	2	1	2	2	1	1
$U(1)_L$	1	-1	0	0	-1	2
Z_2	+	+	+	-	-	+

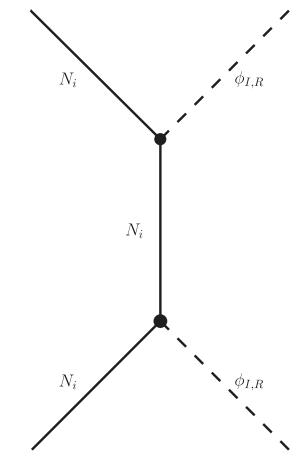
Channels



Leptophilic annihilation

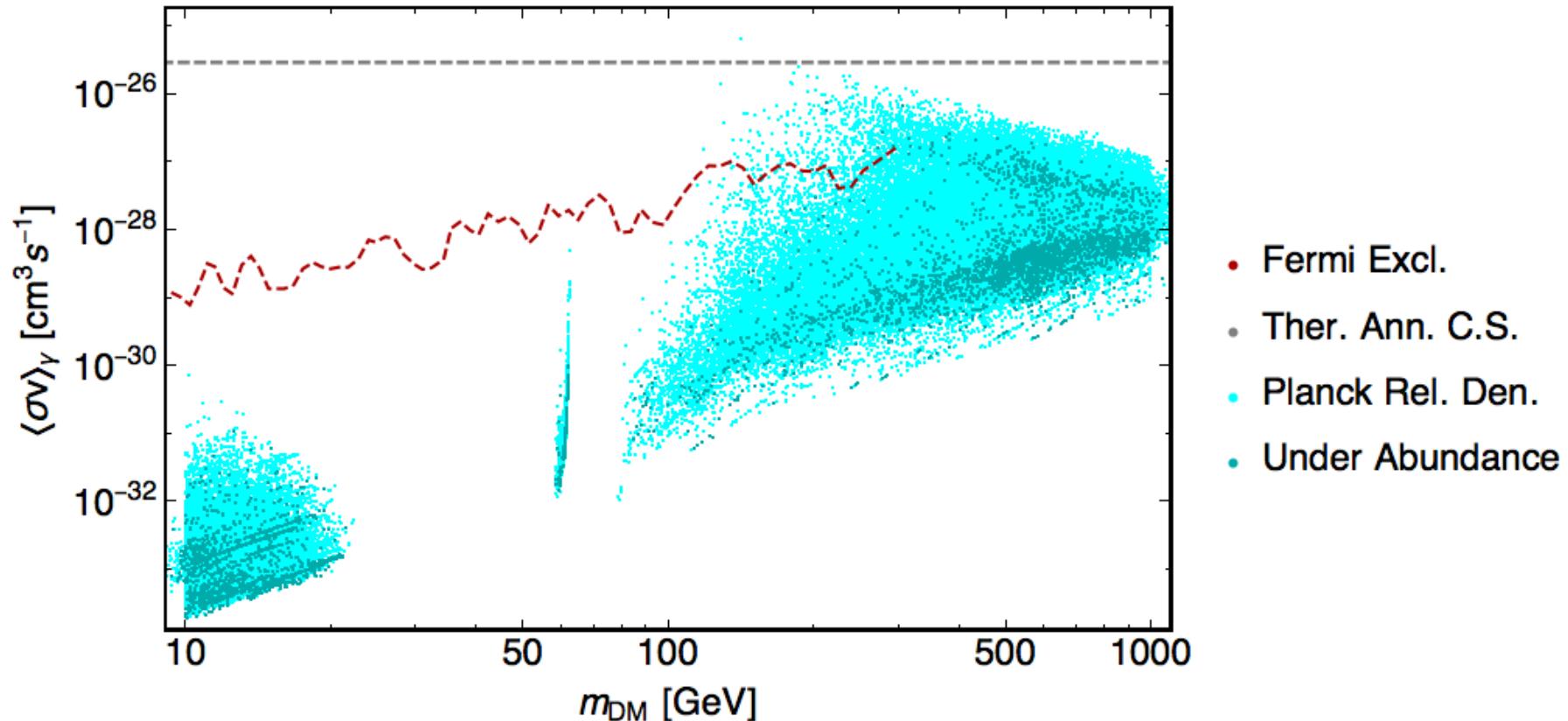


majoron-higgs portal

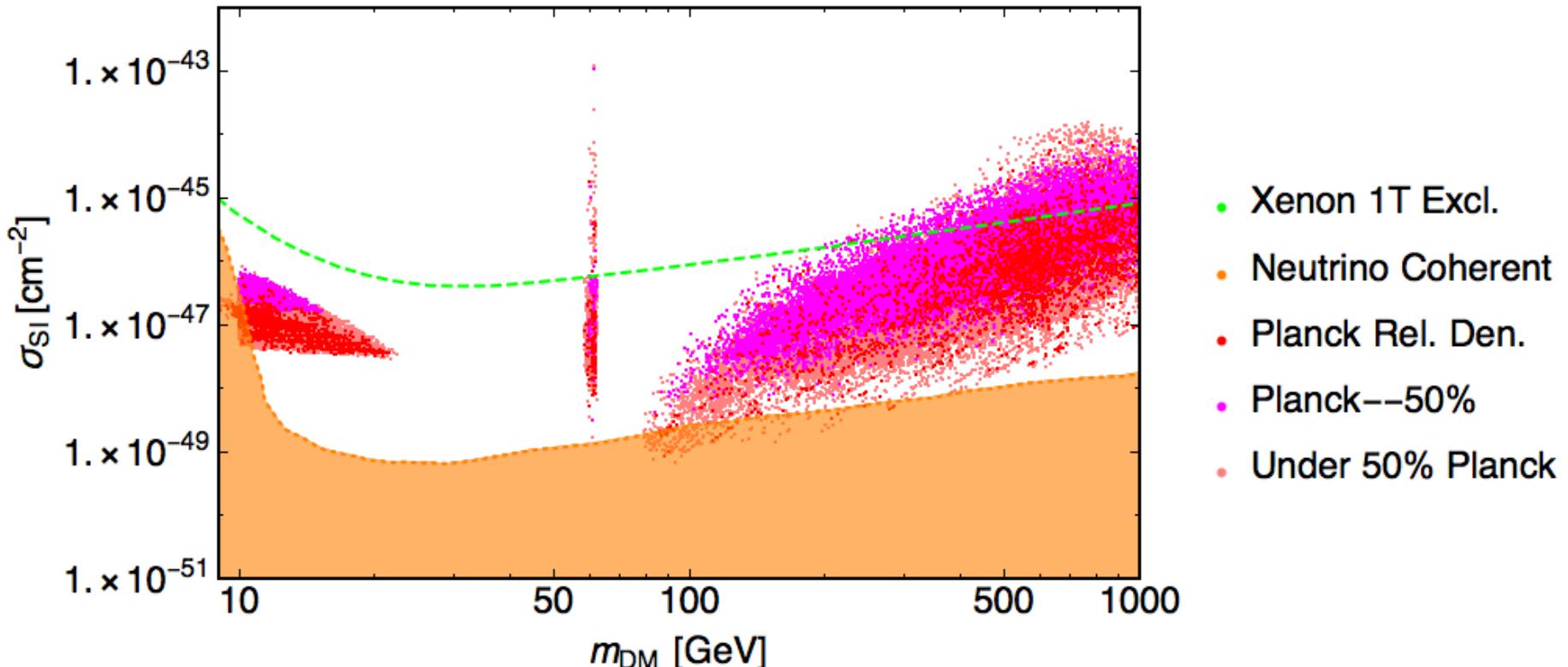


Annihilation into majorons
 $< 10\%$

Annihilation cross section



Direct detection



Conclusions

(of this part)

- Scotogenic mechanism for neutrino masses give an interplay with Dark Matter
- The spontaneous version opens DM phenomenology thanks the new channels

Final words

- Neutrinos observables and DM are keys to unveil New Physics
- Spontaneously broken lepton symmetry produces an appealing DM candidate
- Scotogenic mechanism connects DM stability and neutrino masses



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Latin American Webinars on Physics

Recent detections of gravitational waves

Isabel Cordero-Carrión
University of Valencia, Spain

Host: Joel Jones-Perez
Wednesday 13 December 2017 15:00 GMT

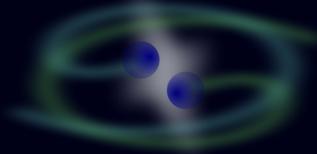


Foto: Alberto A. Lemos



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 lawphysics.wordpress.com

A wide-angle photograph of a nebula, likely the Lagoon Nebula (M8), showing its characteristic orange and yellow filaments against a darker blue and purple background. Numerous small white stars are scattered throughout the field.

Thanks

$$1 + 2 + 3 + 4 + 5 + 6 + 7 + \dots + \infty = -\frac{1}{12}$$

Charge assignments

5 possible models

	L	N_1	N_2	S	X
$n = 1$	1	-1	$1/7$	$6/7$	$2/7$
$n = 2$	1	-1	$1/3$	$2/3$	$2/3$
$n = 3$	1	-1	$3/5$	$2/5$	$6/5$

$$V_I = \lambda_{cp} e^{i\delta} X^m S^{\dagger n}$$

$$m+n=4$$

$$m+n=3$$

	L	N_1	N_2	S	X
$n = 1$	1	-1	$1/5$	$4/5$	$2/5$
$n = 2$	1	-1	$1/2$	$1/2$	1

The rest of the scalar potential

$$V_{SX} = -\mu_S^2 |S|^2 + \frac{\lambda_S}{4} |S|^4 - \mu_X^2 |X|^2 + \frac{\lambda_X}{4} |X|^4 + \lambda_5 |S|^2 |X|^2 + V_I$$

$$V_{HSX} = -\mu_H^2 H^\dagger H + \frac{\lambda_H}{4} (H^\dagger H)^2 + \lambda_{HS} |S|^2 H^\dagger H + \lambda_{HX} |X|^2 H^\dagger H$$

Mass spectrum

$$m_h^2 \simeq \frac{v_h^2}{2} \left\{ \frac{\lambda_H}{2} + 2 \left(\frac{\lambda_{HX}^2 \lambda_S + \lambda_{HS}^2 \lambda_X - 4 \lambda_5 \lambda_{HS} \lambda_{HX}}{4 \lambda_5^2 - \lambda_S \lambda_X} \right) \right\}$$

$$M_{\zeta_3}^2 \simeq \frac{v_S^2}{2} \left(\frac{-A + A\psi + 2\lambda_X \omega \psi}{2\psi} \right)$$

$$M_{\zeta_4}^2 \simeq \frac{v_S^2}{2} \left(\frac{A + A\psi + 2\lambda_X \omega \psi}{2\psi} \right)$$

$$\lambda_S = A + \lambda_X \omega^2$$

$$\lambda_5 = -A \left(\frac{\sqrt{1 - \psi^2}}{4\omega\psi} \right)$$

Numerology

Parameter	Value
M	100 TeV
μ	10 MeV
m_D	10 GeV
v_S	$10^8 - 10^{12}$ GeV
ω	0.4 – 1.6

$$\lambda_{\text{cp}} \simeq \frac{M_J^2}{v_S^2} < 10^{-22}$$