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Neutrino and Dark Matter connection from spontaneous lepton number violation

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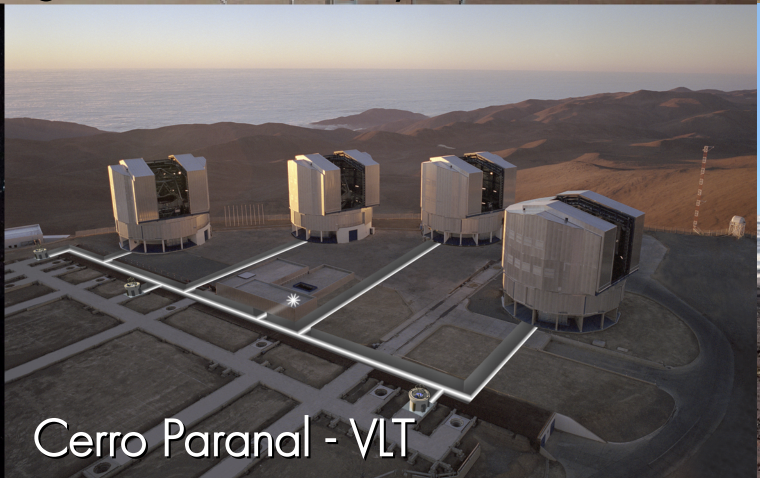
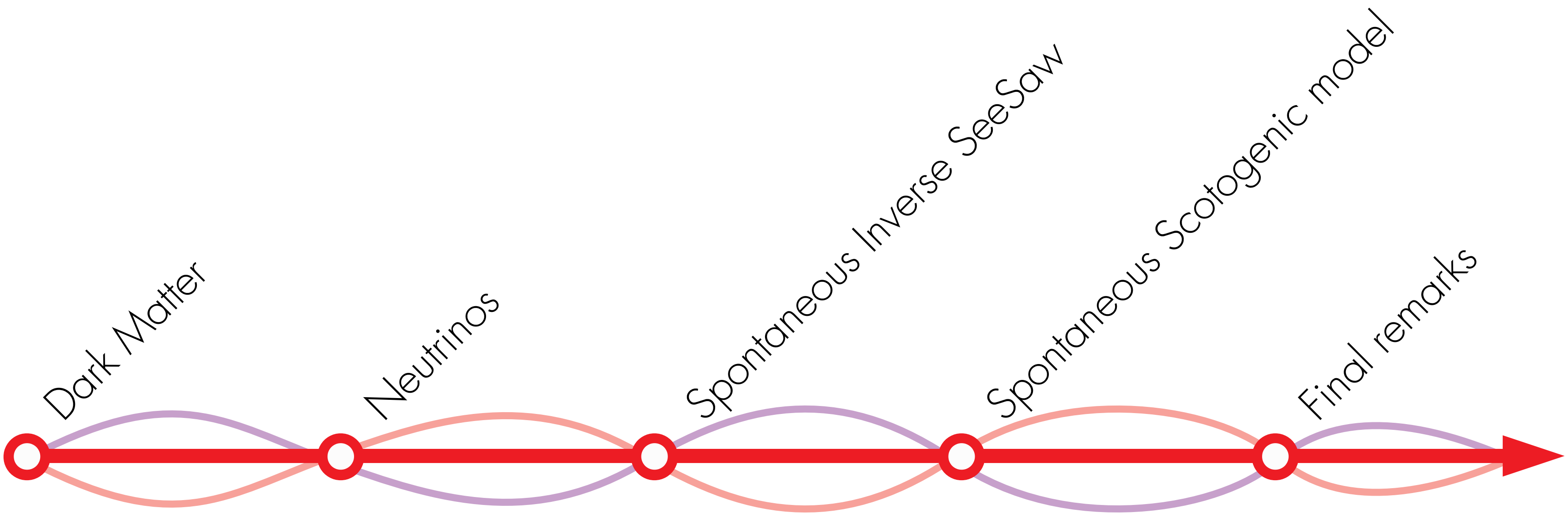
Dark Side of the Universe, UBA – 18 July 2019

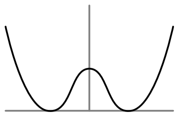
Science around Antofagasta

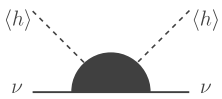


Outline



Dark Matter
Neutrinos
Spontaneous Inverse SeeSaw
Spontaneous Scotogenic model
Final remarks





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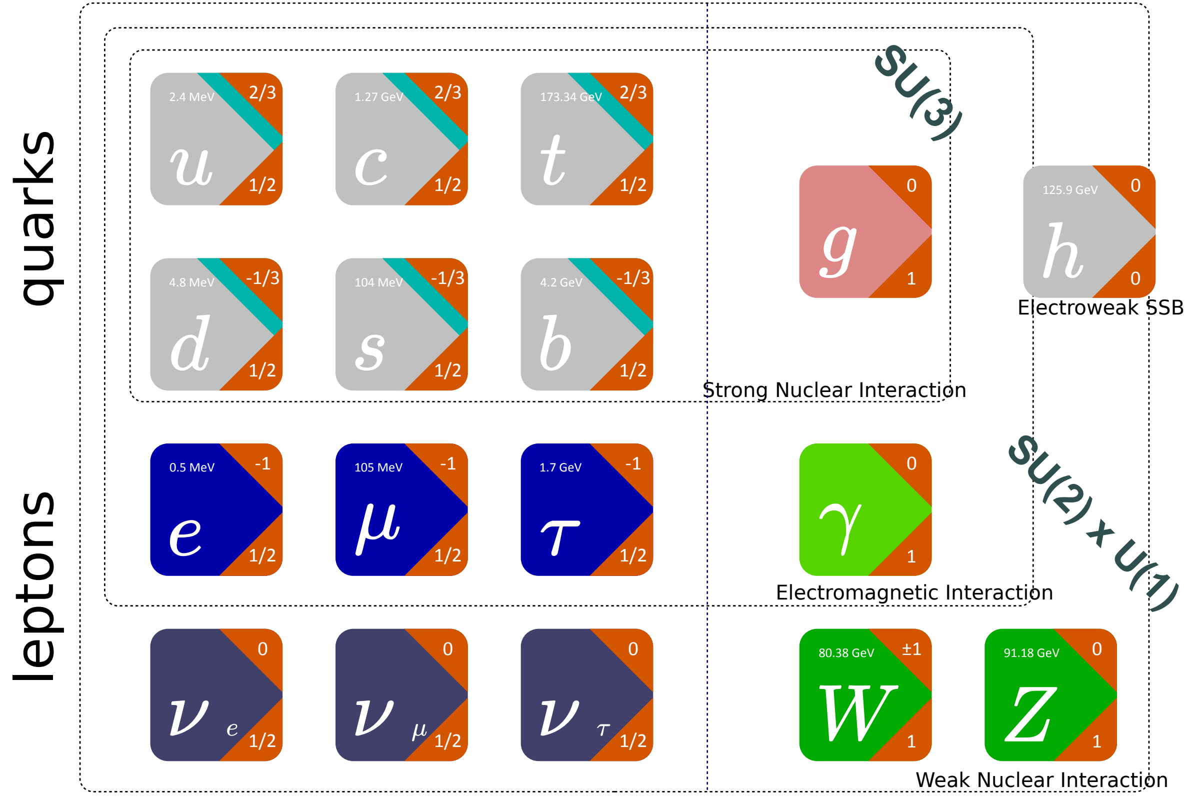
The Standard Model

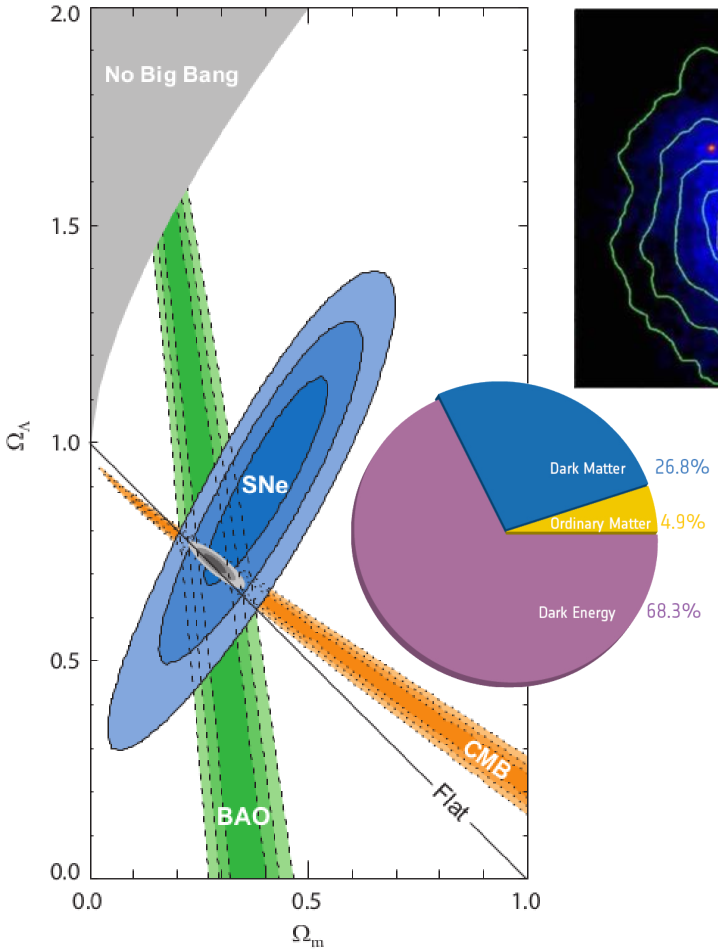
SM matter families

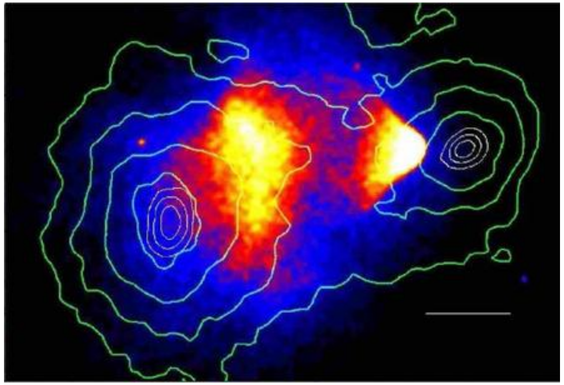


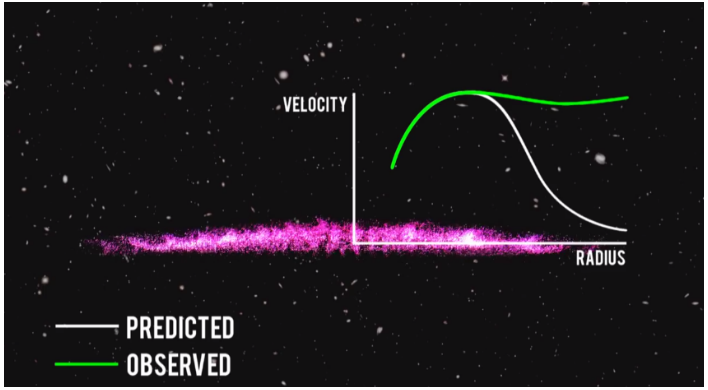
- Massless and left handed neutrinos
- Lepton number conserved
- Baryon number conserved

Dark Matter and Neutrino masses are signs of new physics

Dark Matter





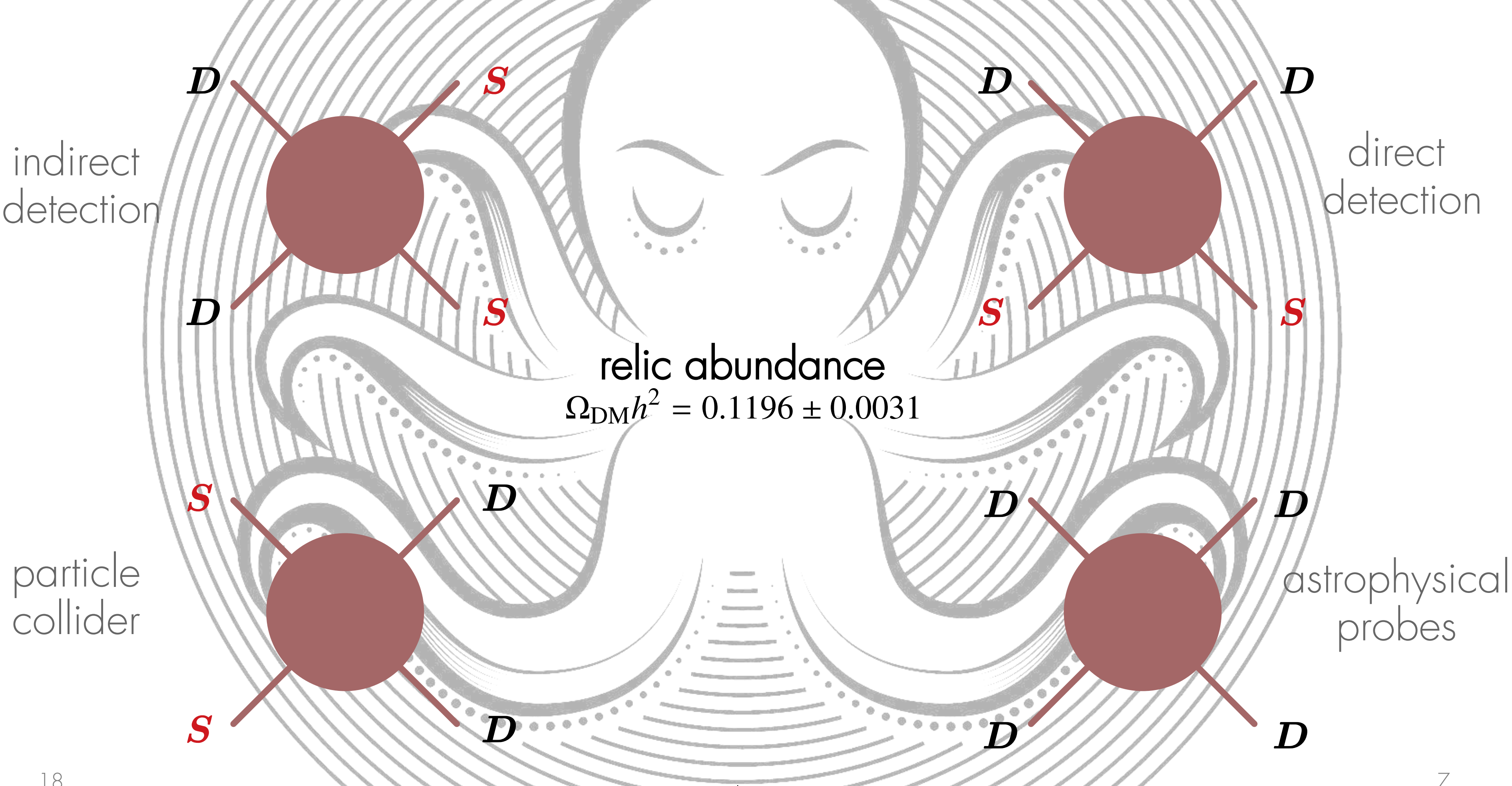


Observations support Dark Matter

- Dynamics of clusters and galaxies
- Structure formation
- CMB anisotropies
- Baryon Acoustic Oscillation

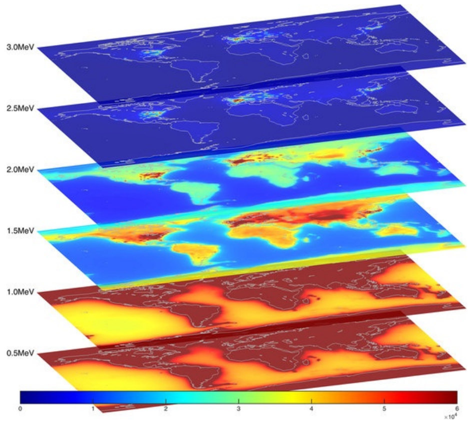
$$\Omega_{\rm DM}h^2 = 0.1196 \pm 0.0031$$

Dark Matter Searches

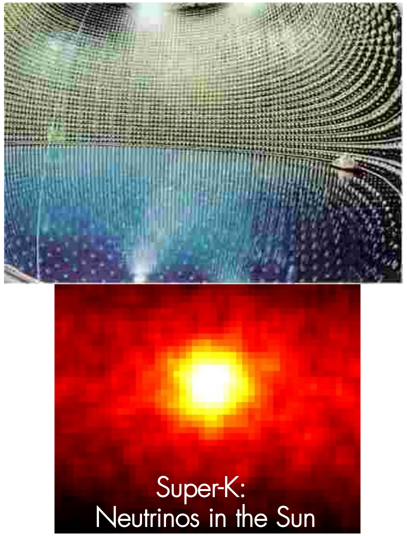


Design Credits: Vecteezy!

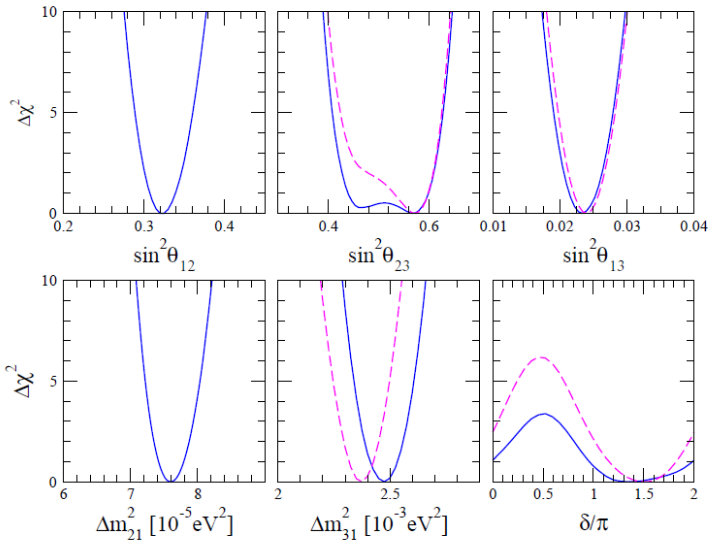
Neutrinos



AGM2015: Antineutrino Global Map 2015



Forero, Tortola and Valle PRD 90 (2014) 093006



The SM predicts zero neutrino mass

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

Case 1

A (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

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

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

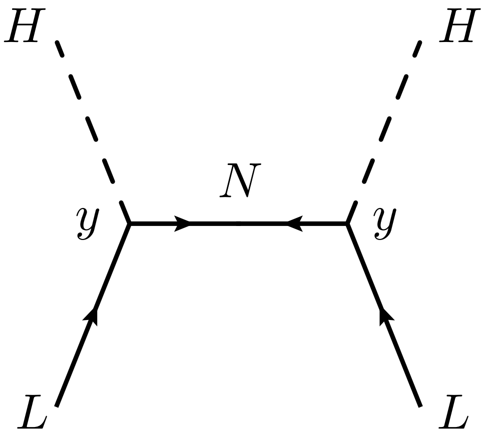
$$\mathcal{O}_{5ij} = \frac{v^2}{\Lambda}\nu_i \nu_j = M_{ij}\nu_i \nu_j$$

Neutrino mass mechanisms

The most known schemes are see-saw mechanisms

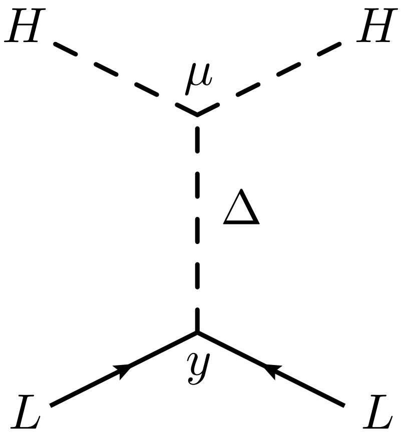
$\mathcal{O}_{5ij}$

Type-I



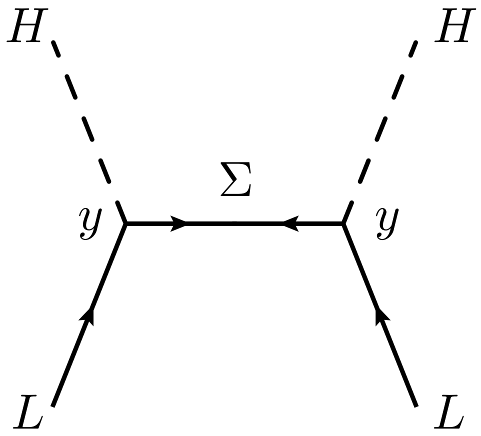
$$m_\nu \propto \frac{v^2 y^2}{M_N}$$

Type-II



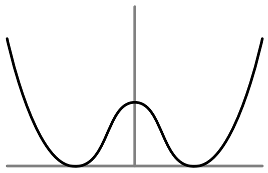
$$m_\nu \propto \frac{v^2 y \mu}{M_\Delta^2}$$

Type-III



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

Minimal Majoron Model



The Type-I seesaw can be generated via the spontaneous breaking of the global $\mathrm{U}(1)$ lepton symmetry

$$\mathcal{L} \supset -y_L \overline{L} H N^c - \frac{y_S}{2} S \overline{N^c} N + h.c.$$

-1 0 1 2 -1 -1

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

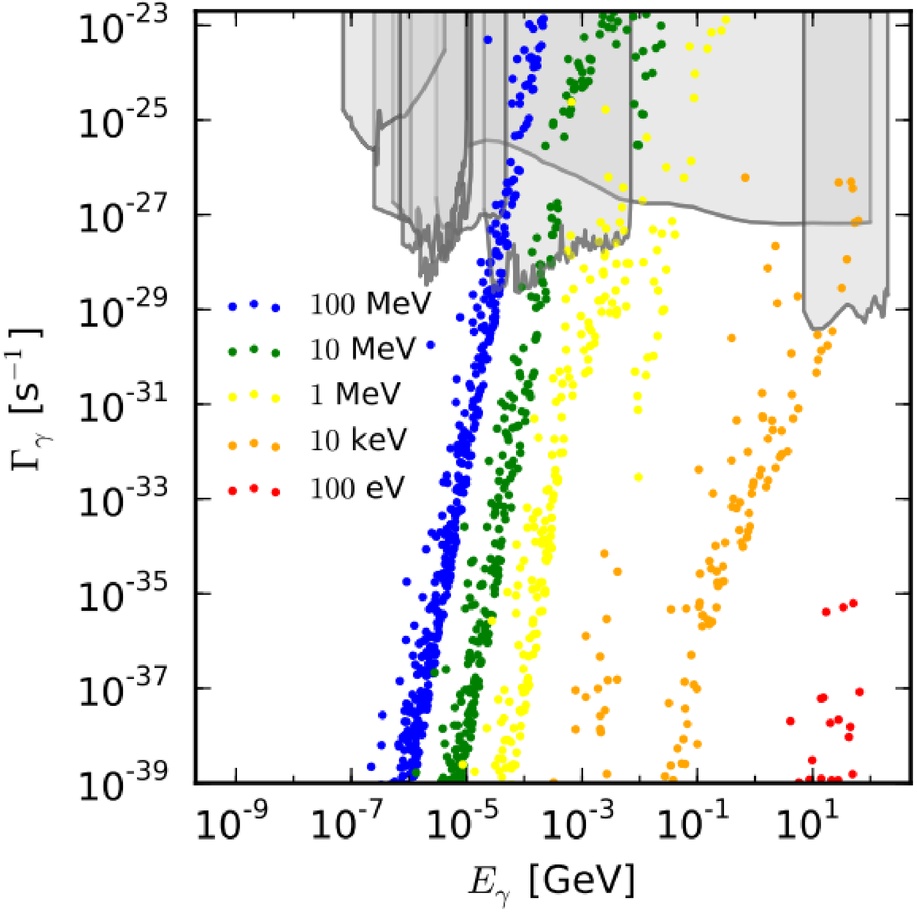
majoron

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

Majoron as DM

- Weakly coupled to the SM
- Long lived
- Decay to neutrinos
- Decay to photons

- Massless



Details in arxiv:1406.0004

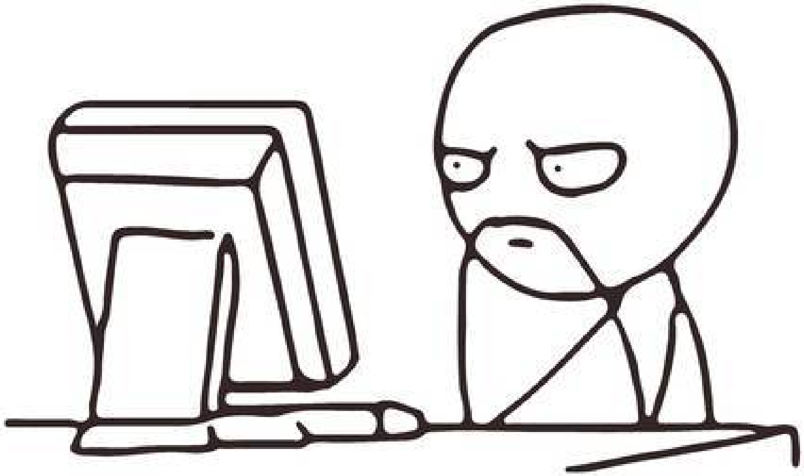
$$\Gamma_{J\to\nu\nu} = \frac{m_J}{32\pi}\frac{\sum_i (m_i^\nu)^2}{2v_1^2} \qquad \Gamma_{J\to\gamma\gamma} = \frac{\alpha^2 m_J^3}{64\pi^3}\left|\sum_f N_f Q_f^2 \frac{2v_3^2}{v_2^2 v_1}(-2T_3^f)\frac{m_J^2}{12 m_f^2}\right|^2$$

Majoron as DM (our proposal)

ArXiv:1703.03416

What we want of a majoron DM candidate?

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



Inverse seesaw

The standard inverse seesaw

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

$$\mathcal{L} = -\frac{1}{2} n_L^T C \mathcal{M} n_L + h.c. \qquad \mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

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

$$m_\nu = \left(\frac{m_D}{M}\right)^2 \mu \qquad m_{\mathcal{N}'} = M - \frac{m_D^2}{M} + \frac{\mu}{2}$$

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

Lepton number violating term

Inverse seesaw

The usual inverse seesaw hierarchy: $\mu \ll m_D \ll M$

Some numerology:

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

$$m_\nu \sim 0.1\,\mathrm{eV}$$

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

Spontaneous Inverse seesaw

To generate the inverse seesaw scheme we need 2 complex scalars

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

The charge assignments do not correspond to the one of a standard Inverse See Saw

	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	$1-x$	$2x$

5 options only, we use $x = 3/5$ fractional lepton number

Scalar potential

The assignment fixes the potential

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

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

$$V_{\text{I}} = \lambda_J e^{i\delta} X S^{\dagger^3} + \text{h.c.}$$

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

Mass spectrum

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

4 related to L breaking + 1 related to EW breaking

ζ_1 ζ_2 ζ_3 ζ_4 ζ_5

ζ_5 → very higgs-like

ζ_1 → Massless majoron

ζ_2 → Majoron DM

$$M_J^2 = \frac{v_S^2}{2\omega}\lambda_J\left(1+9\omega^2\right)$$

ζ_3, ζ_4 → Heavy scalars TeV–EeV

$$M^2_{\zeta_{3,4}} \sim \mathcal{O}(v_S^2)$$

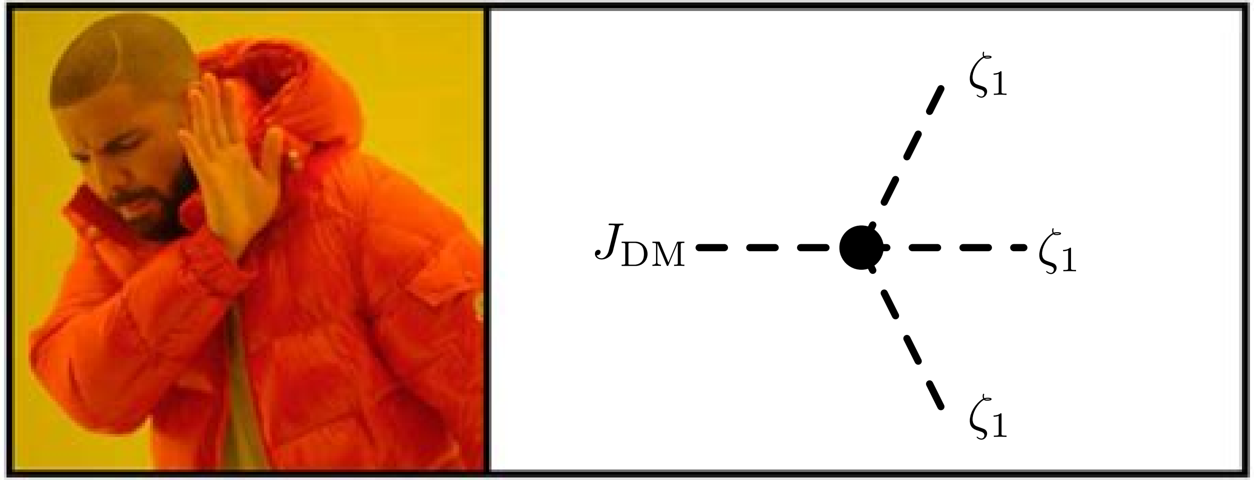
Majoron DM stability

The suitable candidate is the lightest **massive** scalar $\zeta_2 = J_{\mathrm{DM}}$

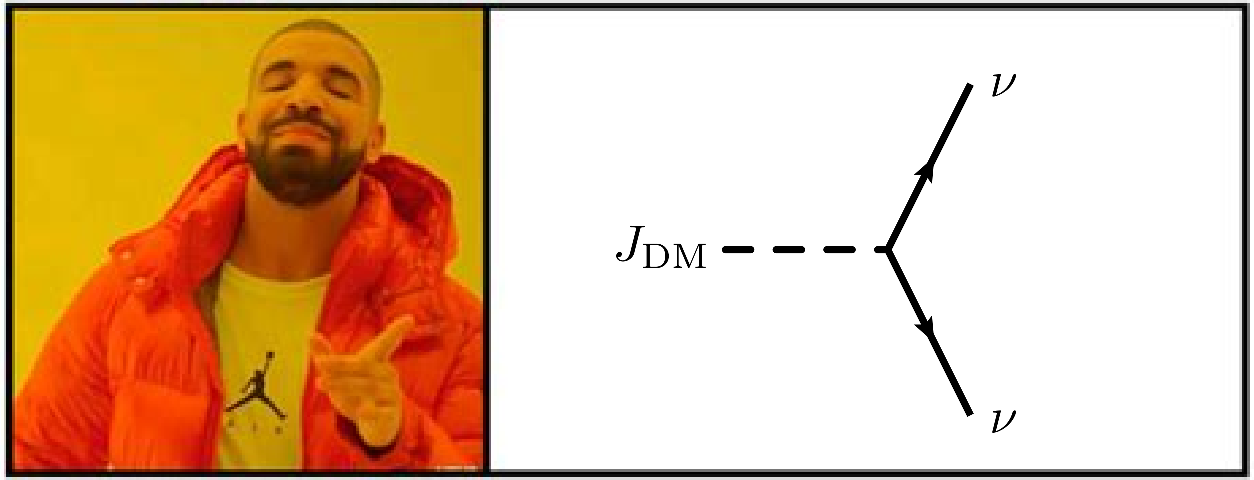
It still has to satisfy the stability condition for a **keV** decaying DM:

$$\Gamma_{\mathrm{DM}} < 10^{-43}\,\mathrm{GeV} \leftrightarrow \tau_{\mathrm{DM}} > 10^{19}\,\mathrm{s}$$

Decay modes



$$\Gamma_{3\zeta} = \frac{1}{(64\pi)^3} M_J \left\| \lambda^{\mathrm{eff}}_{2111} \right\|^2$$



$$\Gamma_{\nu} = \frac{M_J}{32\pi} f\left(m_\nu, m_D, M, v_S\right)$$

Decay into neutrinos

$$J_{\rm DM} \to \nu\nu$$

The decay rate vanishes for:

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

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

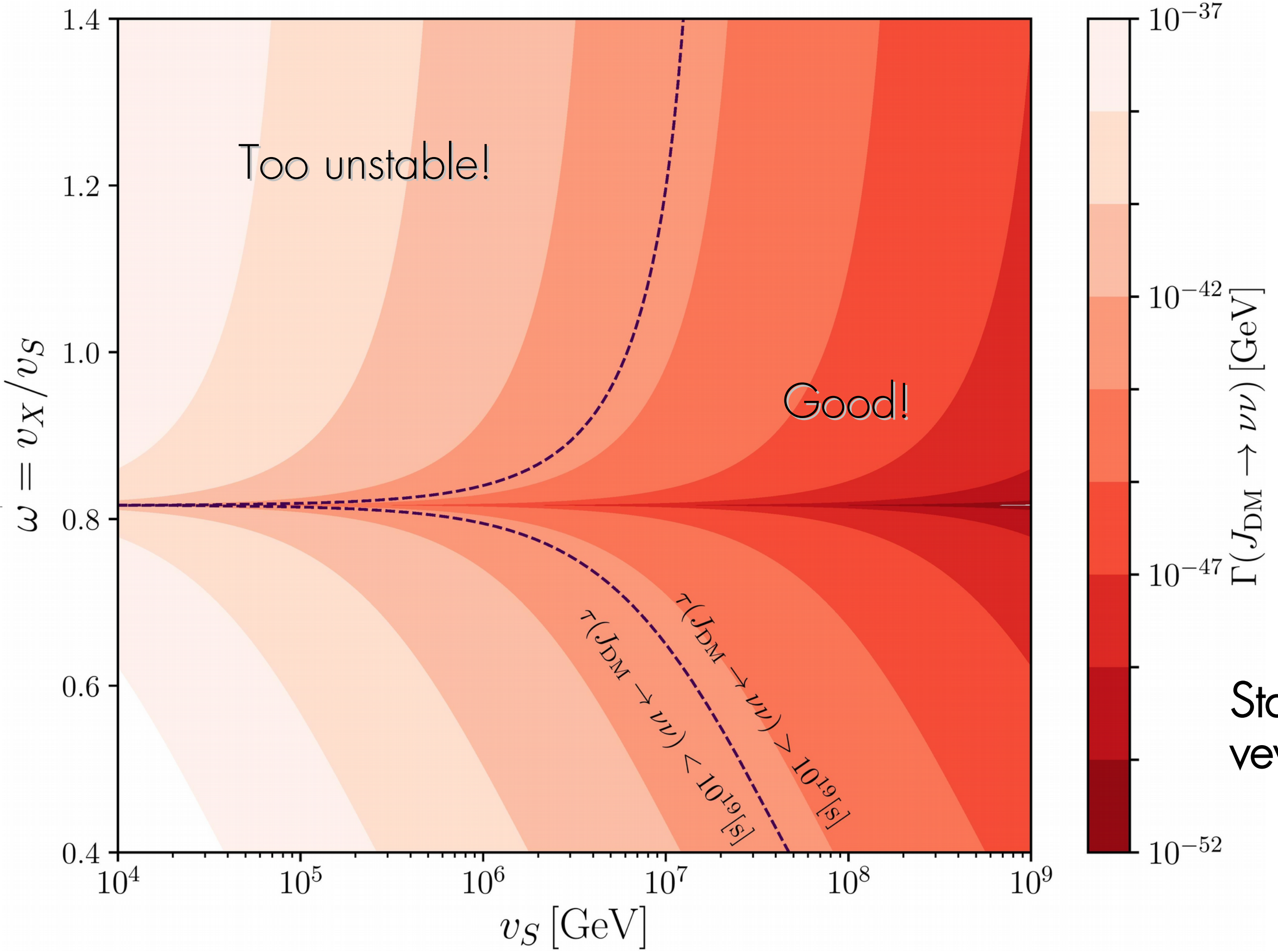
$$\Gamma_\nu = \Gamma_{0\nu}(\omega_0)\, 4\alpha^2$$

$$\Gamma_{0\nu}\,(\omega_0) \simeq 10^{-42}\,\text{GeV}\left(\frac{m_\nu}{0.1\text{eV}}\right)^2\left(\frac{M_J}{1\text{keV}}\right)\left(\frac{v_S}{10^6\text{GeV}}\right)^{-2}$$

Decay into neutrinos

$J_{\mathrm{DM}} \to \nu\nu$

$\omega = \sqrt{\frac{2}{3}}$



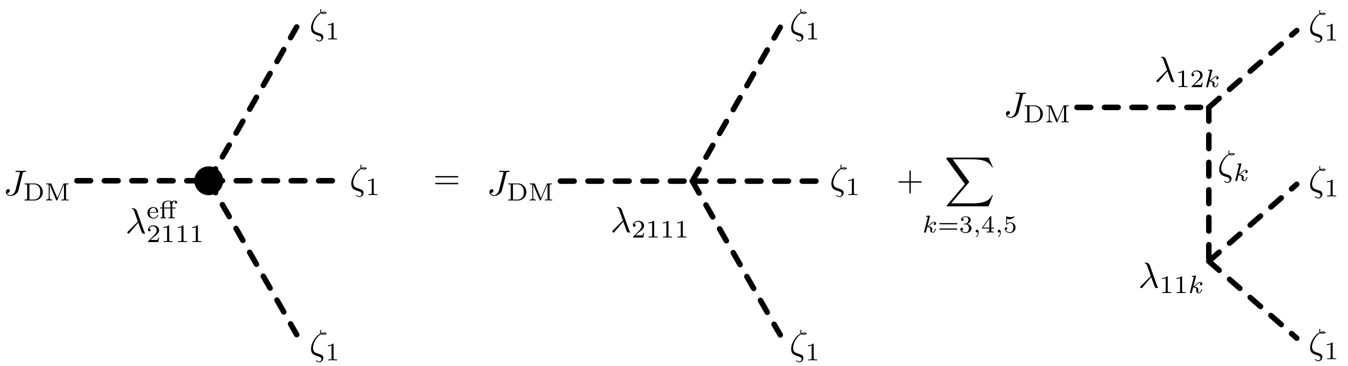
Stability thanks to vev alignment

Decay into scalars

$J_{\rm DM} \to \zeta' {\rm s}$

Without a protective symmetry, this channel is not suppressed

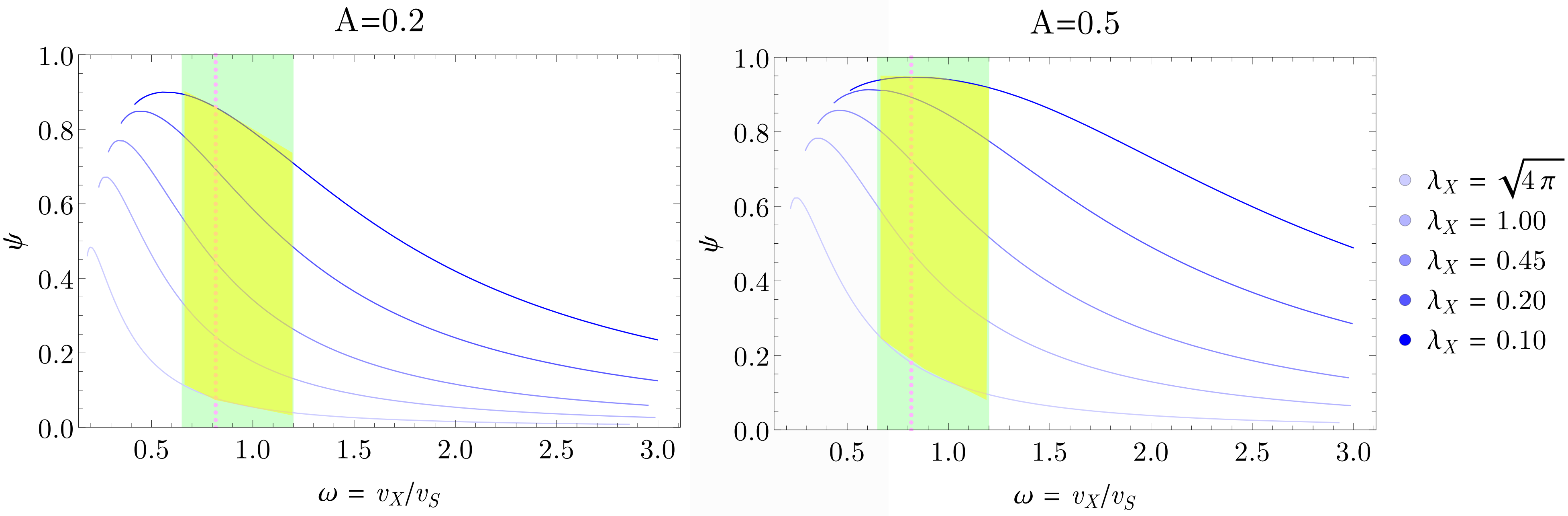
However we find the parameter space where the mode vanishes



Contribution from higgs modes: $\Gamma_{3\zeta} \sim 10^{-12} \left(\frac{M_J}{1{\rm keV}}\right) \left(\frac{M_J}{v_S}\right)^8 {\rm GeV} \sim 10^{-108} {\rm GeV}$

Decay into scalars

$J_{\rm DM} \to \zeta' {\rm s}$



- The interplay of different diagrams allows to vanish the decay mode
- There is a large volume in the parameter space that satisfy this condition

Conclusions (of this part)

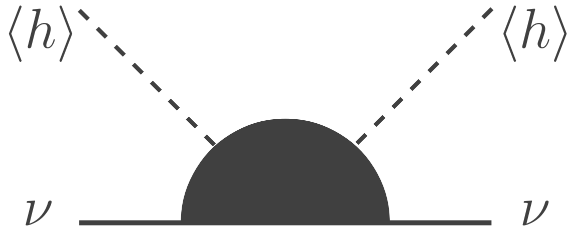
- The spontaneous inverse seesaw provides a well suited majoron DM candidate
- Our majoron DM is phenomenologically equivalent to the PNGB without invoking QG
- The vev alignment has a relevant role in the DM stability

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 loop level
- An extra symmetry is needed to protect the loop
- Dark Matter becomes stable when it runs in the loop

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

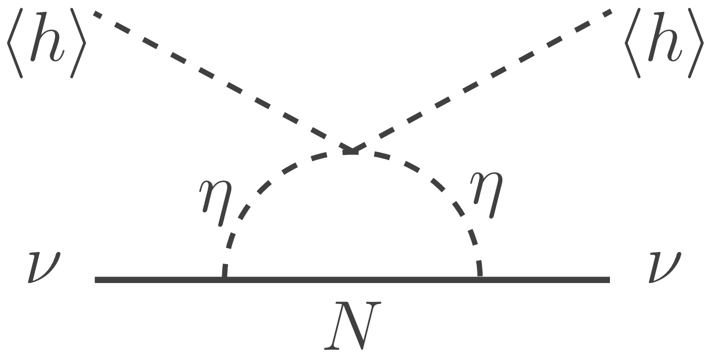
Lepton number is explicitly broken

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

Scotogenic model

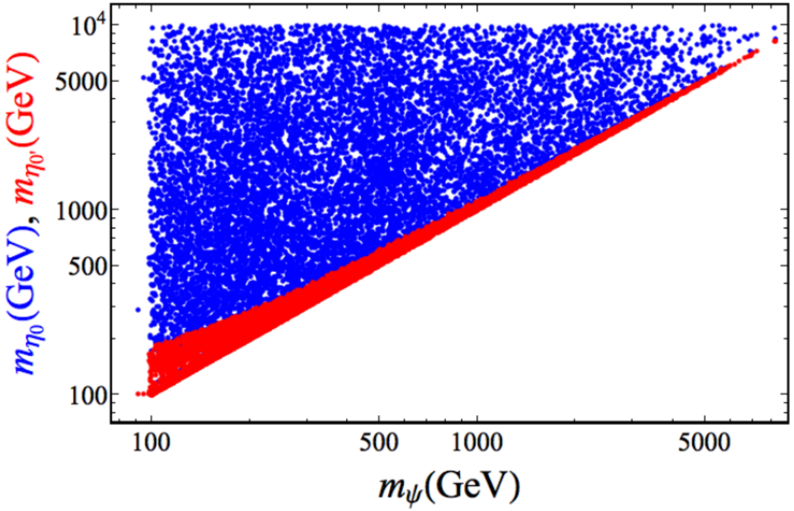
The simplest scotogenic model is the Type-I

$$(\mathcal{M}_\nu)_{ij} = \sum_{k=1}^{3} \frac{Y^\nu_{ik} Y^\nu_{kj} m_{N_k}}{16\pi^2} \left[\frac{m^2_{\eta R}}{m^2_{\eta R} - m^2_{N_k}} \log \frac{m^2_{\eta R}}{m^2_{N_k}} - \frac{m^2_{\eta I}}{m^2_{\eta I} - m^2_{N_k}} \log \frac{m^2_{\eta I}}{m^2_{N_k}} \right]$$



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

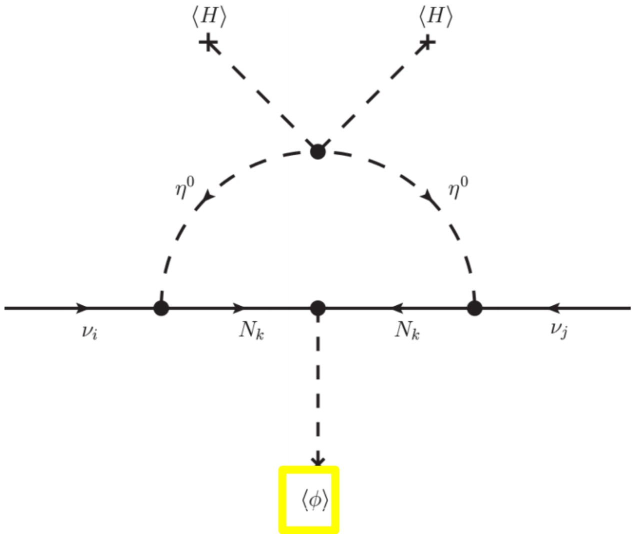
"Type-I"



Arxiv:1804.04117

$m_N > 100\,\mathrm{GeV}$

Spontaneous Scotogenic

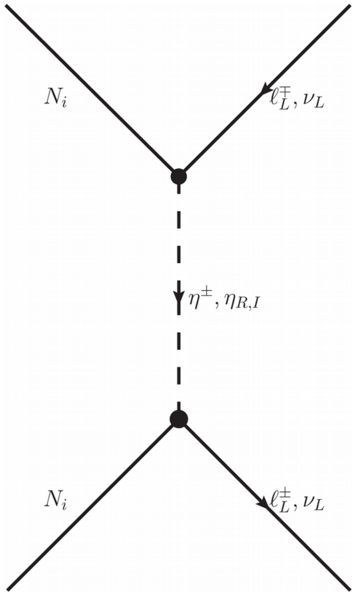


$$(\mathcal{M}_\nu)_{ij} \simeq \frac{\lambda_5 v_h^2}{16\pi^2} \sum_k \frac{Y^\nu_{ik} Y^\nu_{jk}}{m_{N_k}}$$

- The scotogenic model emerge when Lepton symmetry is spontaneously broken
- The new scalar opens new annihilation channels

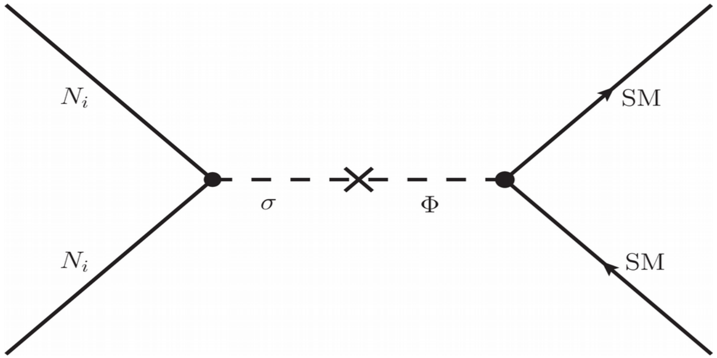
	$\bar{L}_i$	ℓ_i	H	η	N_i	ϕ
SU(2)	2	1	2	2	1	1
$U(1)_L$	1	-1	0	0	-1	2
Z_2	+	+	+	−	−	+

Channels



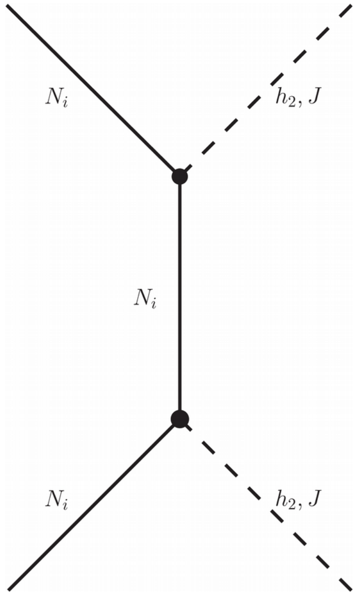
Leptophilic annihilation

Common to all scotogenic model



majoron-higgs portal

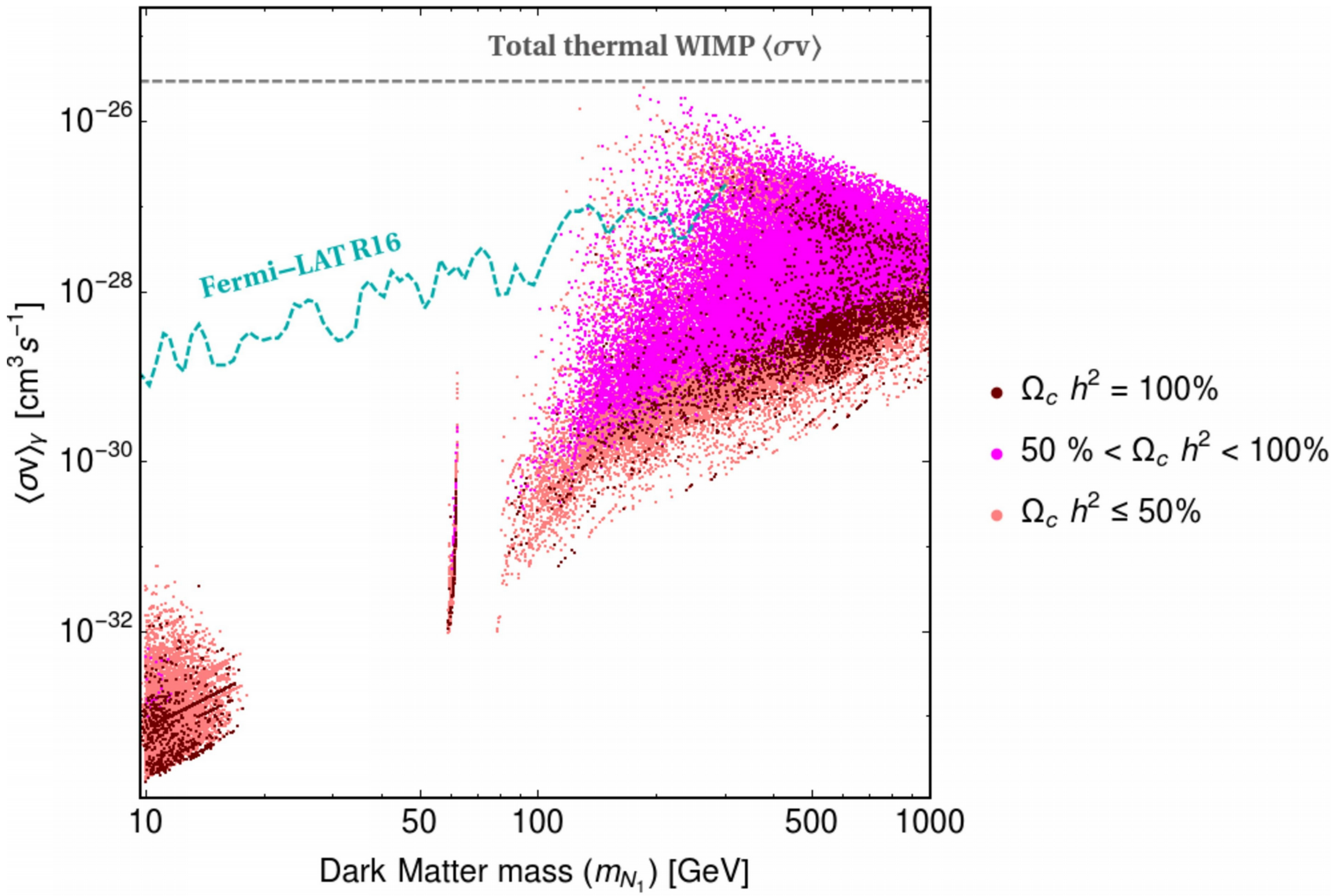
New!
Direct detection at tree level



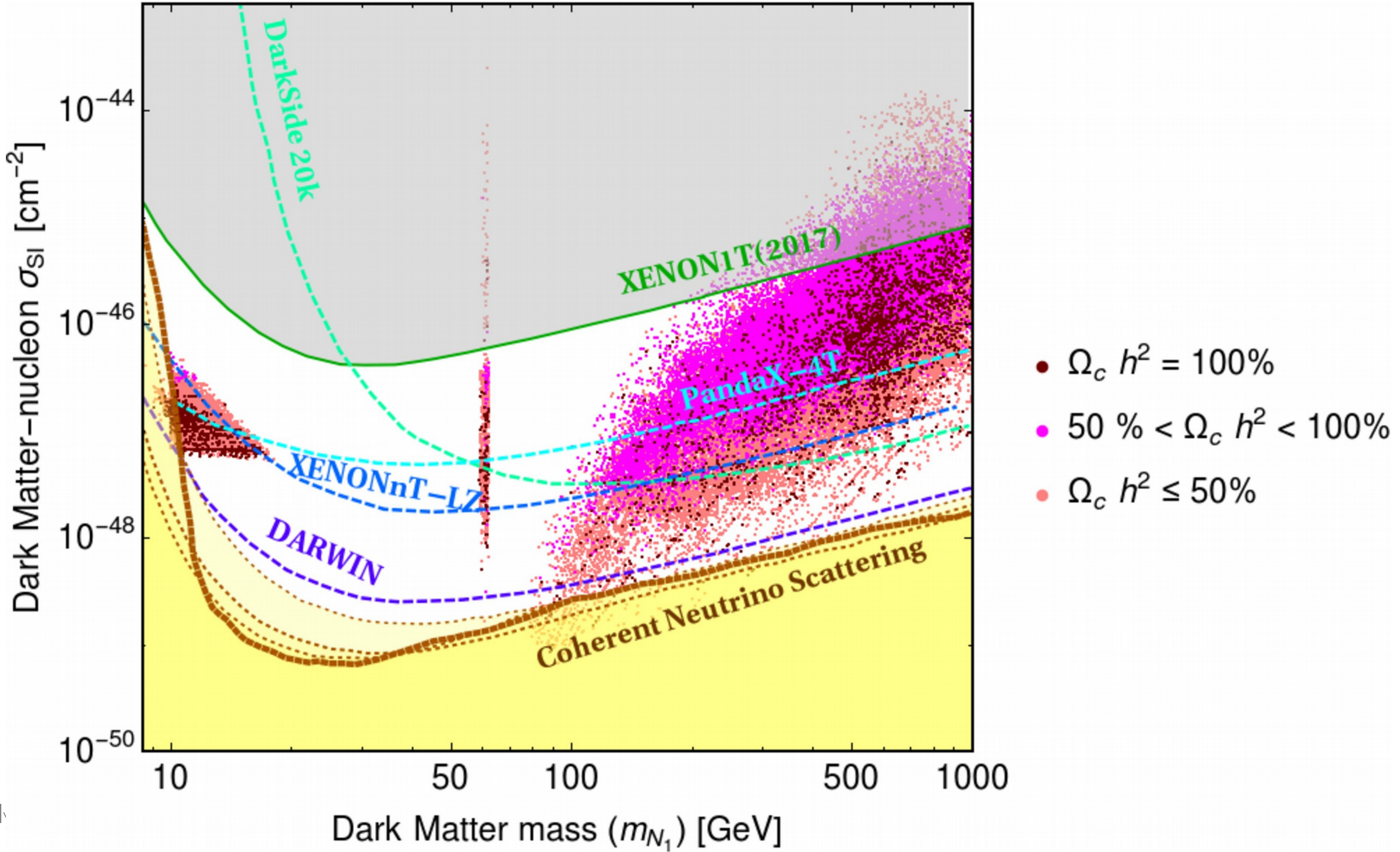
Annhilation into majorons

New!
Alleviate annihiliation constraints

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

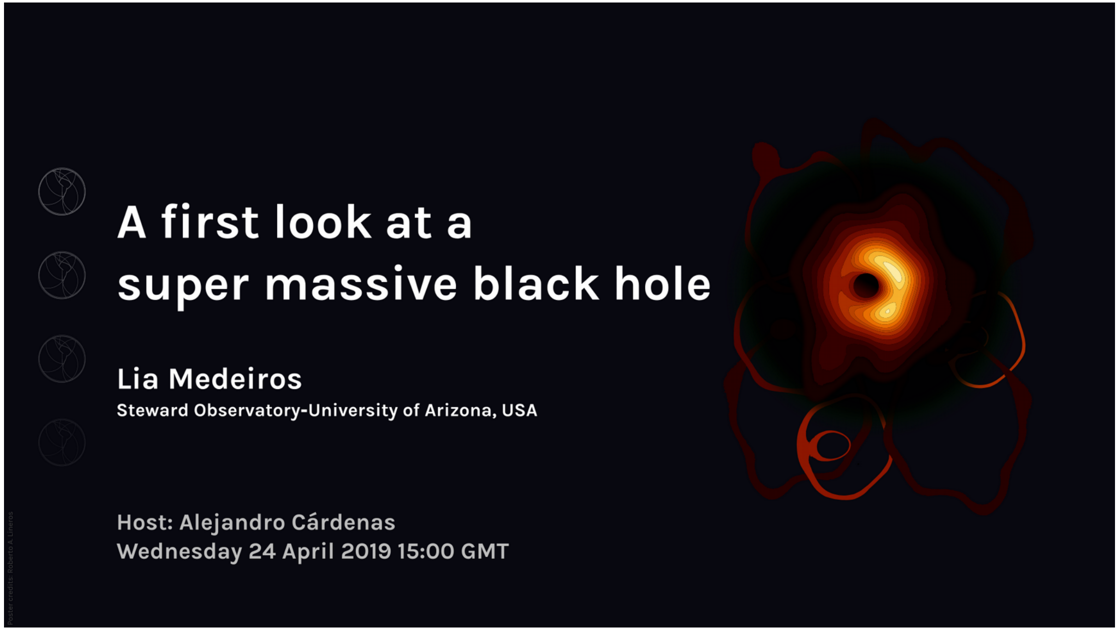
Final words

- Neutrinos observables and DM are keys to unveil New Physics

- Spontaneously broken lepton symmetry produces an appealing DM candidates

- Scotogenic mechanism connects DM stability and neutrino masses lawphysics

Latin American Webinars on Physics



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Thanks


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

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	$3/5$	$2/5$	$6/5$

m+n = 4

$$V_{\rm I} = \lambda_J \, e^{i\delta} X^m S^{\dagger n}$$

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

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

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

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	$10^3 - 10^8$ GeV
ω	0.4 – 1.6

$$\lambda_J \simeq \frac{M_J^2}{v_S^2} < 10^{-22}$$