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Neutrino and Dark Matter connection from spontaneous lepton number violation

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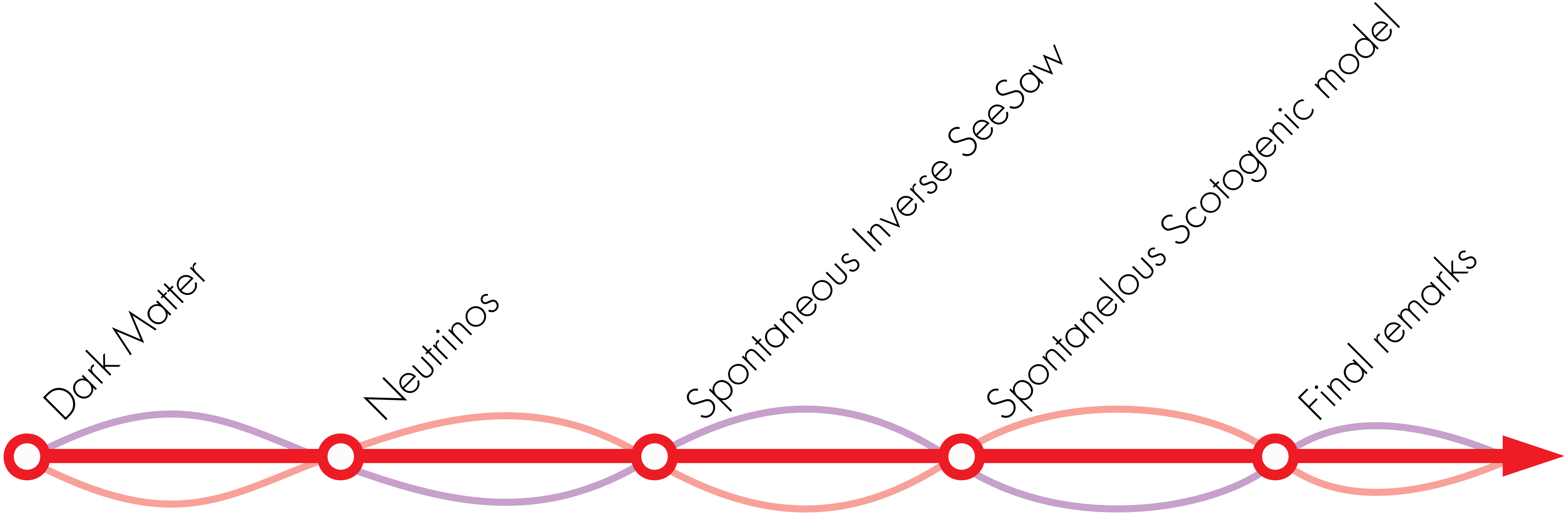
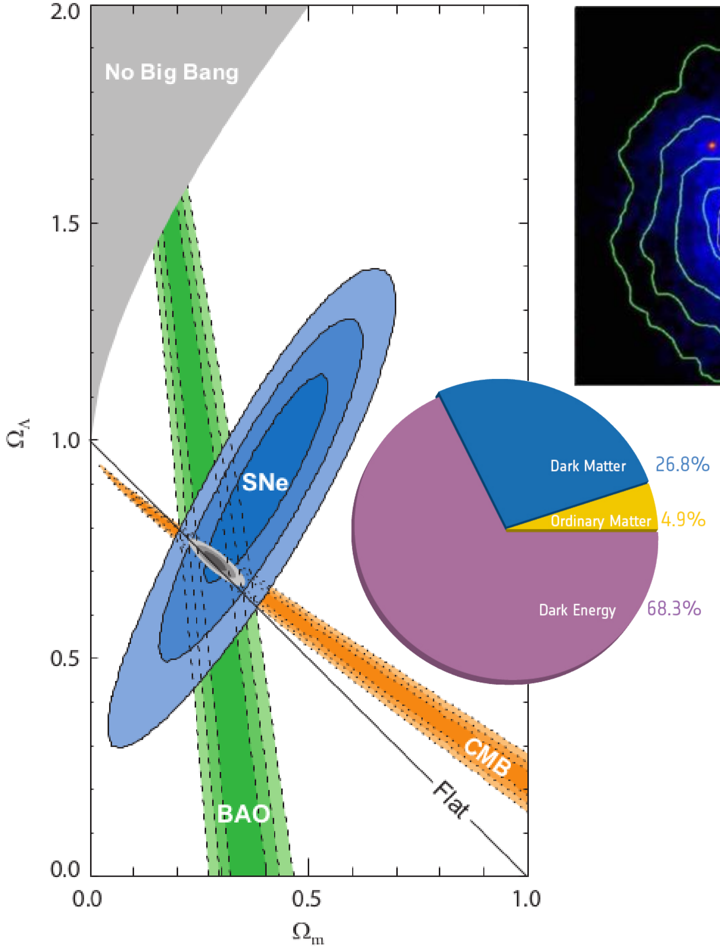
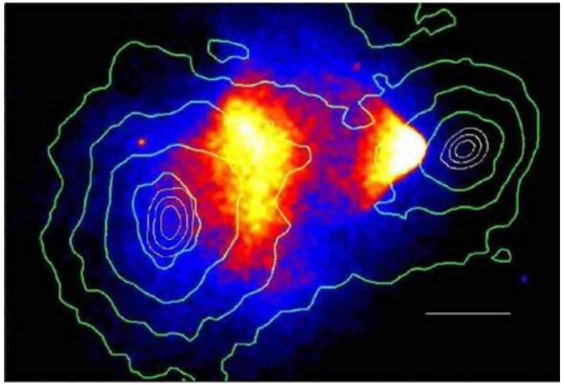
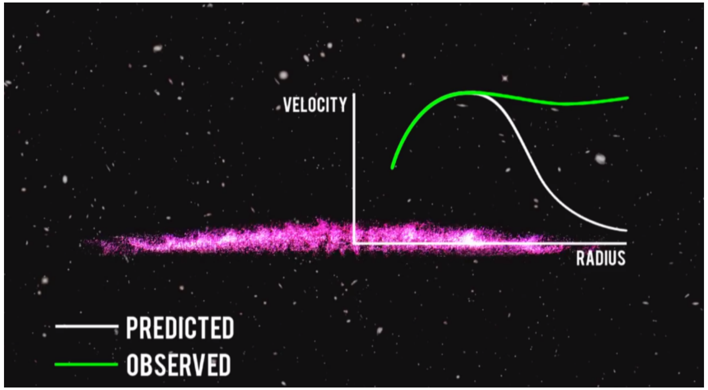
Outline


Dark Matter
Neutrinos
Spontaneous Inverse SeeSaw
Spontanelous Scotogenic model
Final remarks

Dark Matter





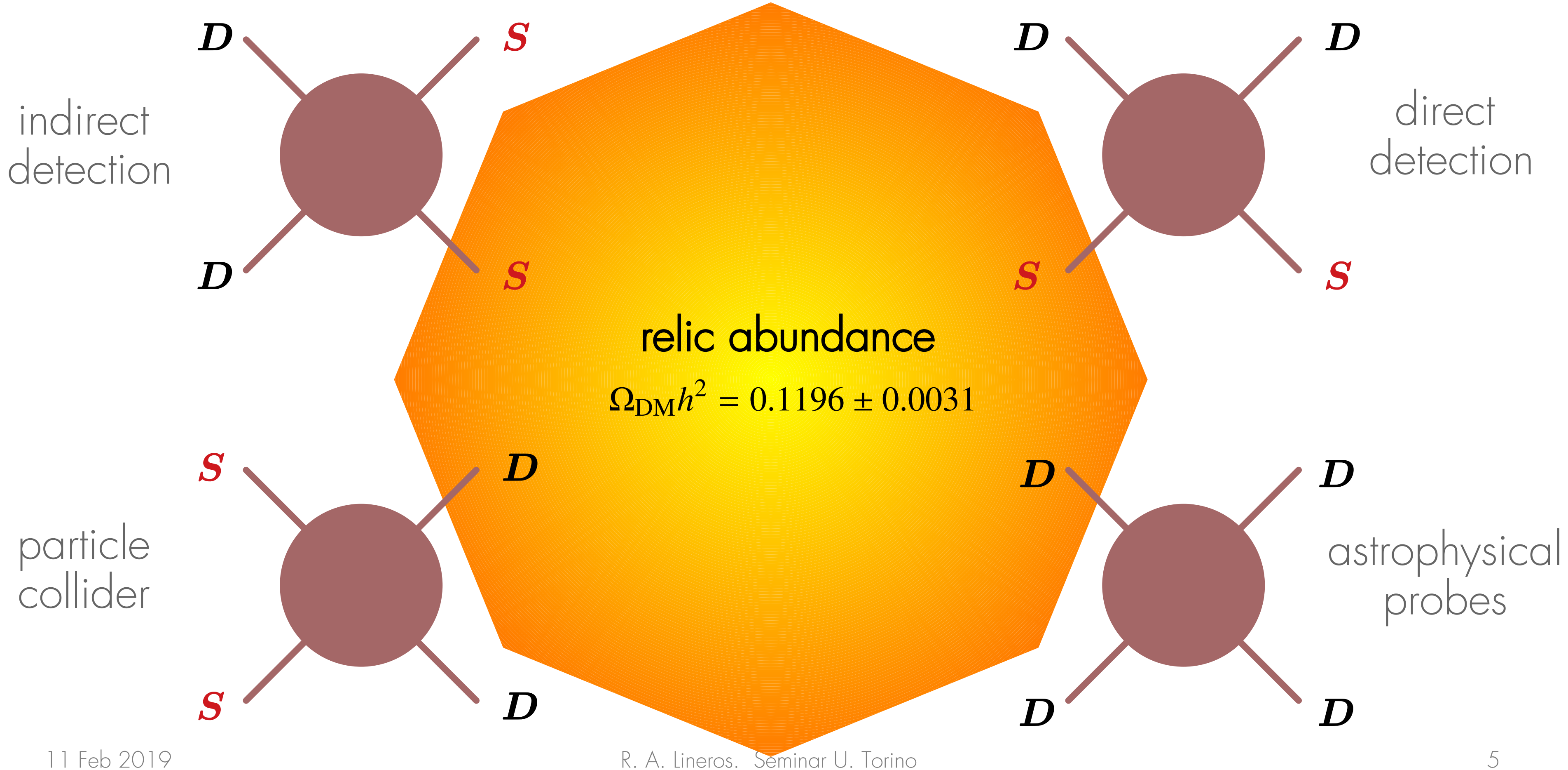


Observations support Dark Matter

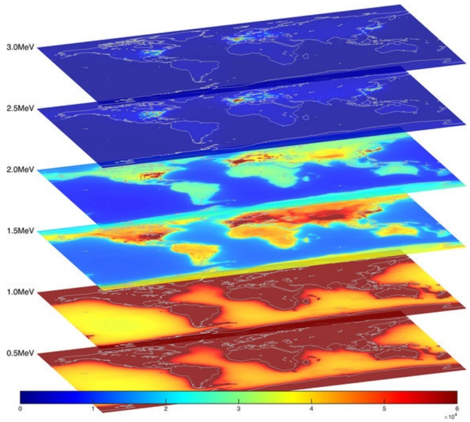
- Dynamics of clusters and galaxies
- Structure formation
- CMB anisotropies
- Baryon Acoustic Oscillation

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

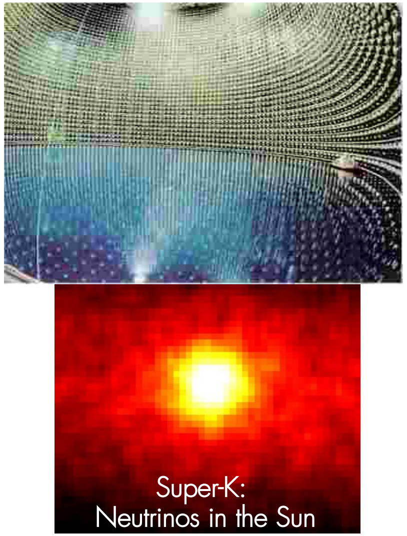
Dark Matter Searches



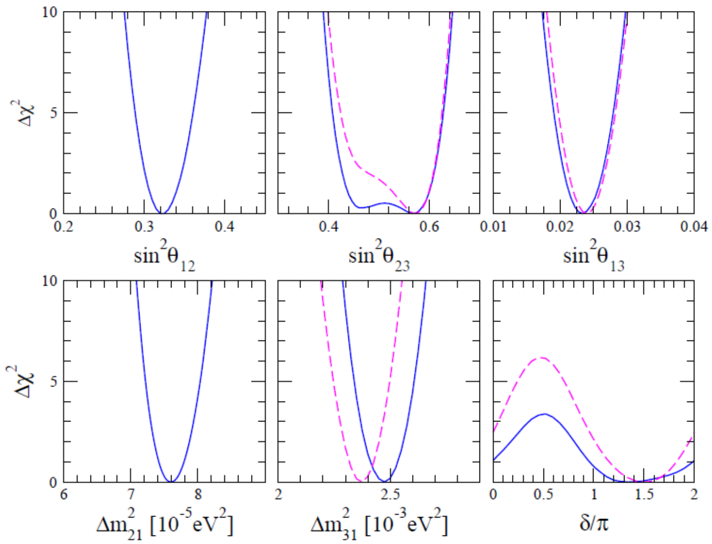
Neutrinos



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

(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 breaks lepton number in 2 units

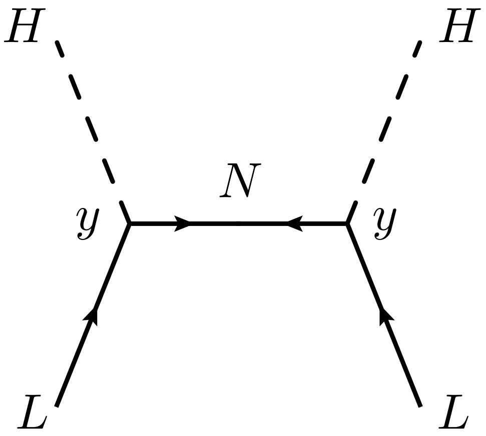
$$\mathcal{O}_{5ij} = \frac{v^2}{\Lambda}\nu_i \nu_j$$

Neutrino mass mechanisms

The commonly known schemes are see-saw mechanisms

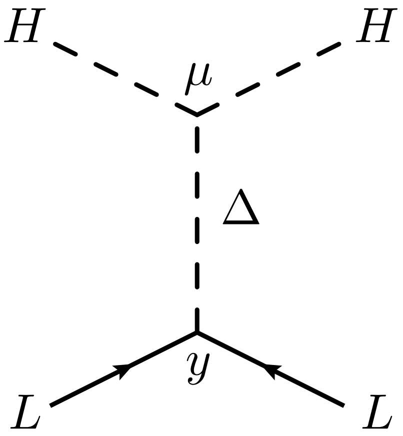
$\mathcal{O}_{5ij}$

Type-I



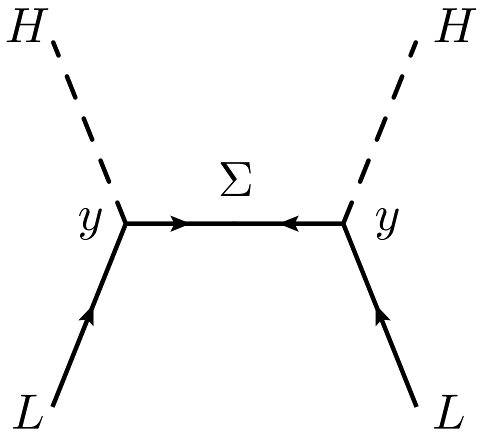
$$m_\nu \propto \frac{v^2 y^2}{M_N}$$

Type-II



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

Type-III

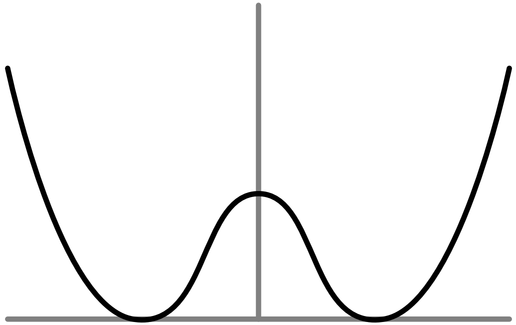


$$m_\nu \propto \frac{v^2 y^2}{M_\Sigma}$$

Enters the Majoron

The Type-I seesaw can be generated by the spontaneous breaking of the U(1) lepton number symmetry

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



$$\mathcal{L} \supset -y_L \underset{-1}{\overline{L}} \underset{0}{H} \underset{1}{N^c} - \frac{y_S}{2} \underset{2}{S} \underset{-1}{\overline{N^c}} \underset{-1}{N} + h.c.$$

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

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

and 2 scalars: σ and J

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

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

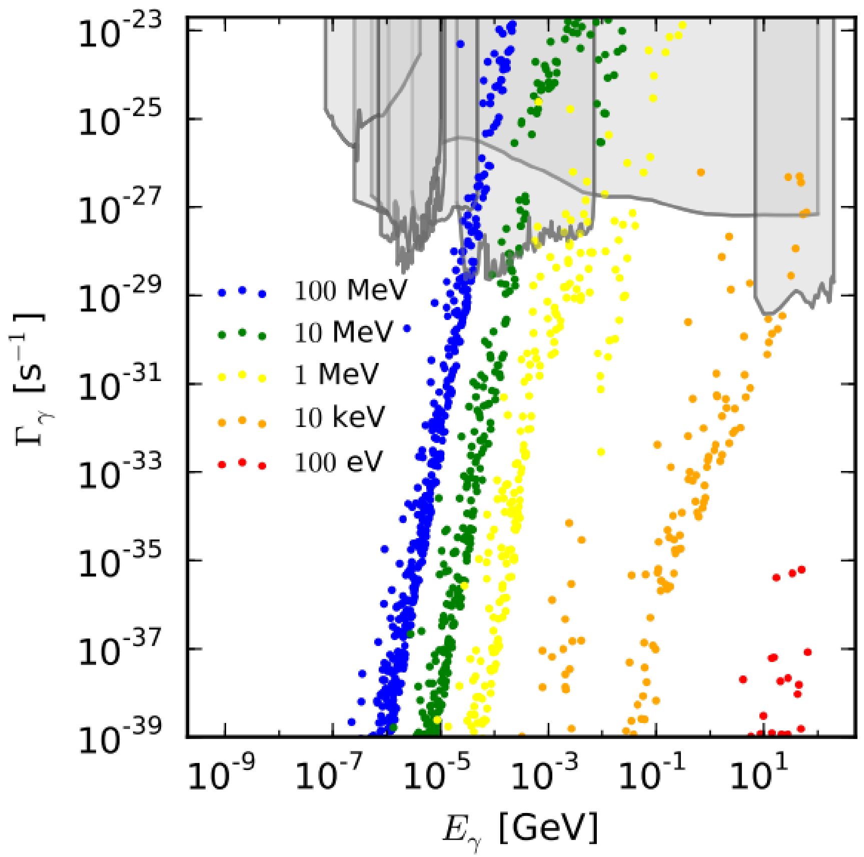
$$\mathcal{L} \supset -m_D \bar{\nu}_{\rm L} N^c - \frac{M_N}{2} \overline{N^c} N + h.c.$$

and 2 scalars: σ and J ← DM candidate

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

Majoron as DM (pros)

- Neutral
- Weakly coupled to the SM
- Long lived



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 (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

Majoron as DM (our proposal)

ArXiv:1703.03416

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 $\mu \ll m_D \ll M$

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

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

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

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

$$m_N = M - \frac{m_D^2}{M} - \frac{\mu}{2}$$

Inverse seesaw

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

Some numerology:

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

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

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

Spontaneous Inverse seesaw

To generate the inverse seesaw scheme we need 2 complex scalars

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

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

Spontaneous Inverse seesaw

To generate the inverse seesaw scheme we need 2 complex scalars

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

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

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	$1-x$	$2x$

$\boxed{x = 3/5}$

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

Scalar potential

The assignment fixes the potential

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

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

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

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

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

ζ_1 ζ_2 ζ_3 ζ_4 ζ_5 → higgs-like

Massless

$$M_J^2 = \frac{v_S^2}{2\omega}\lambda_{\rm cp}(1+9\omega^2)$$

Heavy scalars

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

Majoron DM stability

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

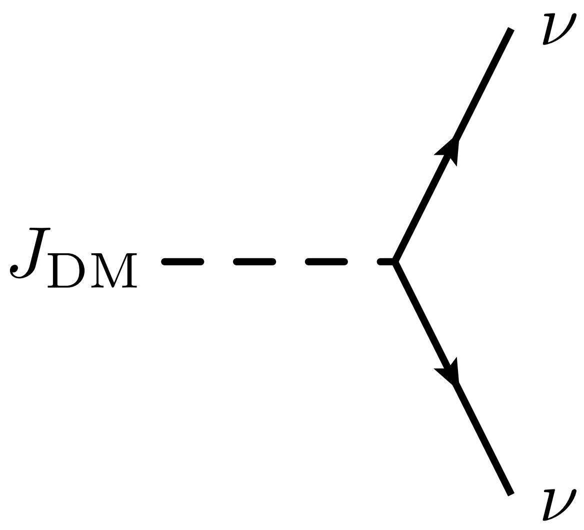
$$\zeta_2 = J_{\rm DM}$$

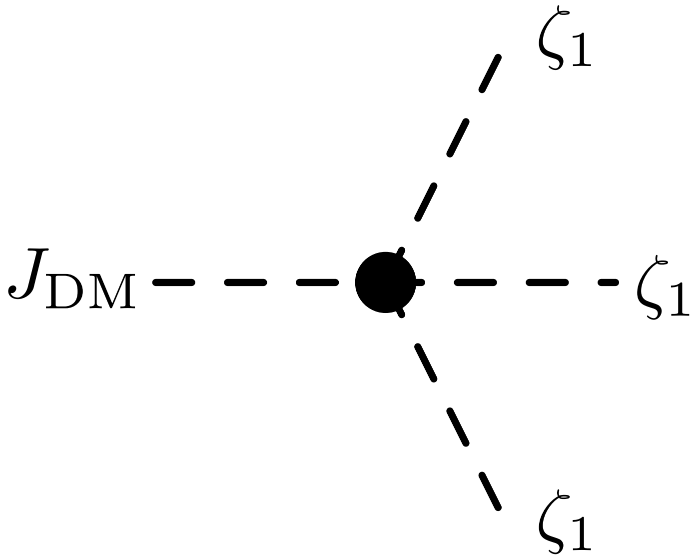
We still has to satisfy the stability condition keV decaying DM:

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

Decay modes

There are potentially dangerous decay modes:





Decay into neutrinos

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

The decay rate vanishes for:

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

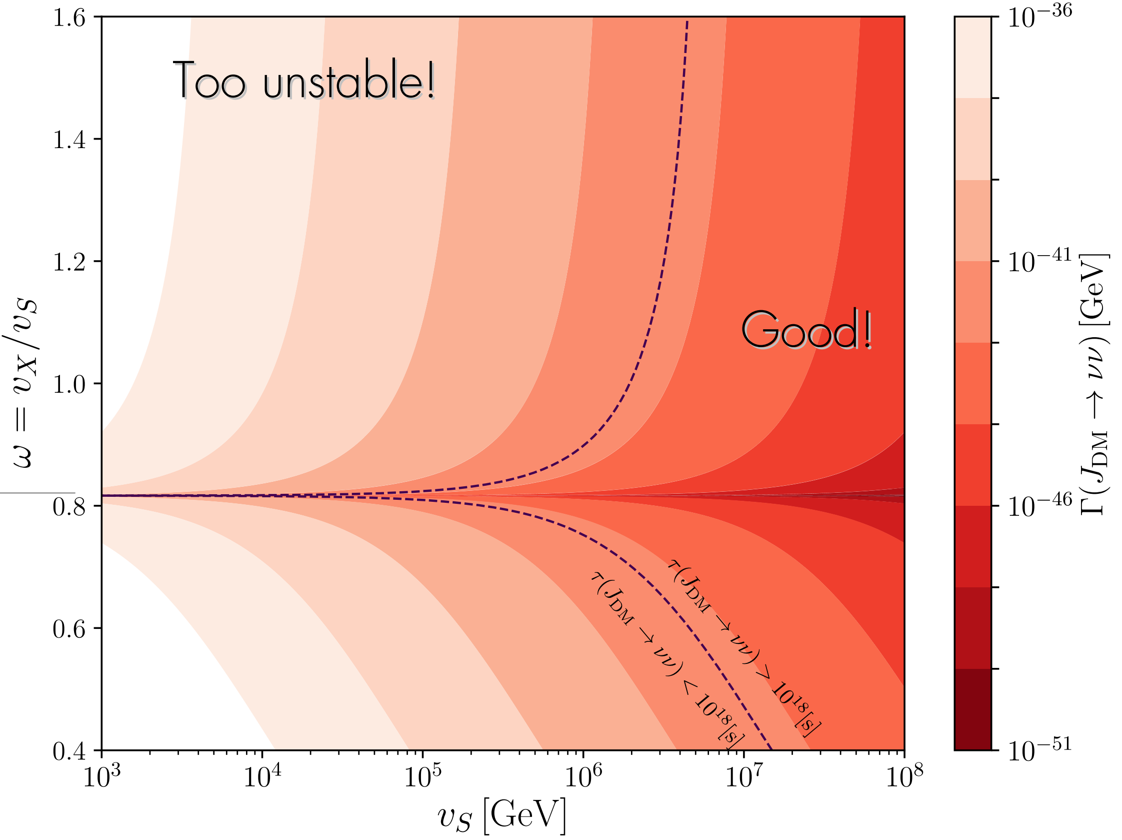
$$\Gamma_\nu = \Gamma_{0\nu}(\omega_0)\, 4\alpha^2$$

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

Decay into neutrinos

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

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



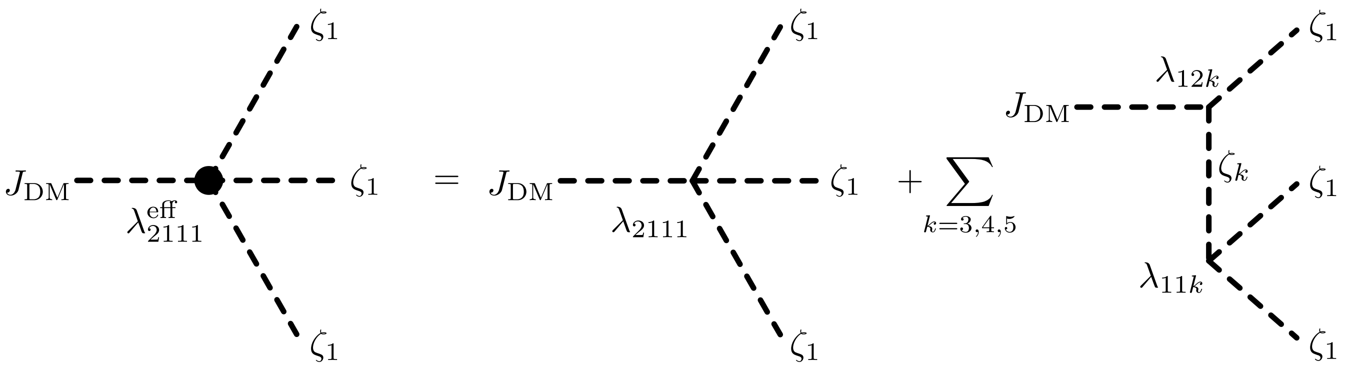
Stability thanks to vev alignment

Decay into scalars

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

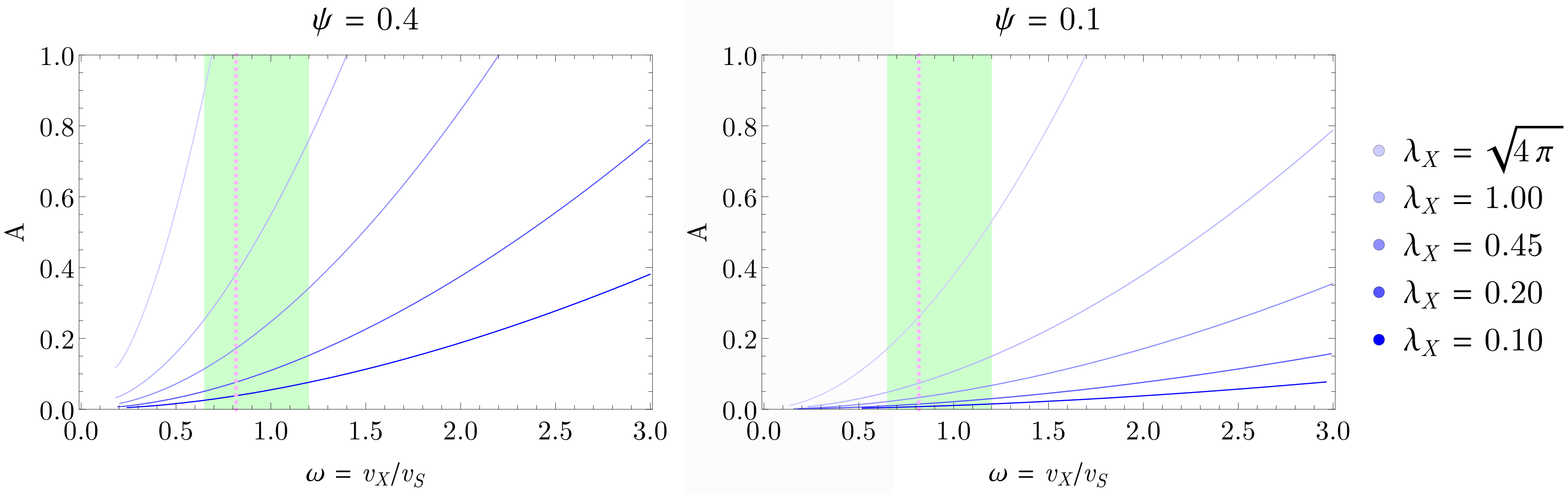
Without a protective symmetry, this channel is not suppressed

However we can find the parameter space where the mode vanishes



Decay into scalars

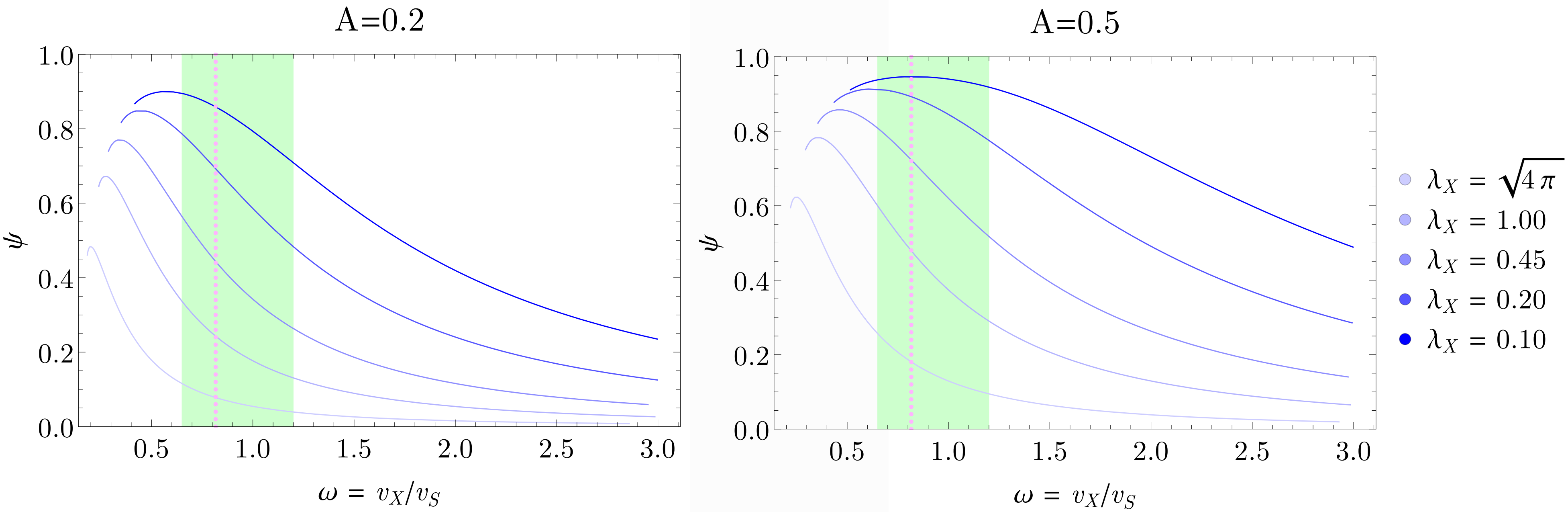
$J_{\mathrm{DM}} \to \zeta'\mathrm{s}$



The interplay of different diagrams allows to vanish the decay mode

Decay into scalars

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



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

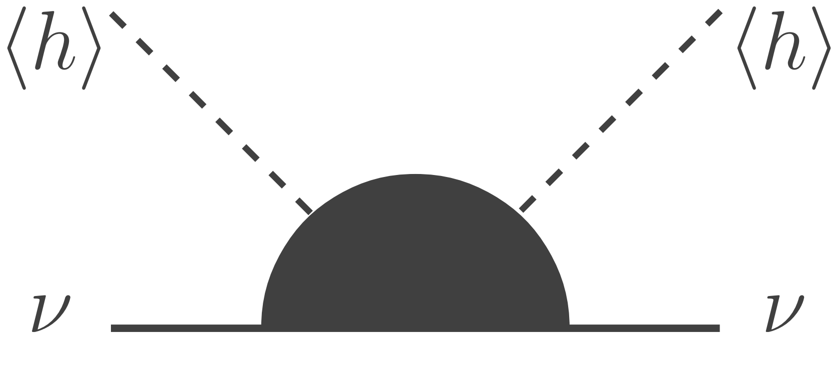
- The vev alignment has a relevent role in the DM stability

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

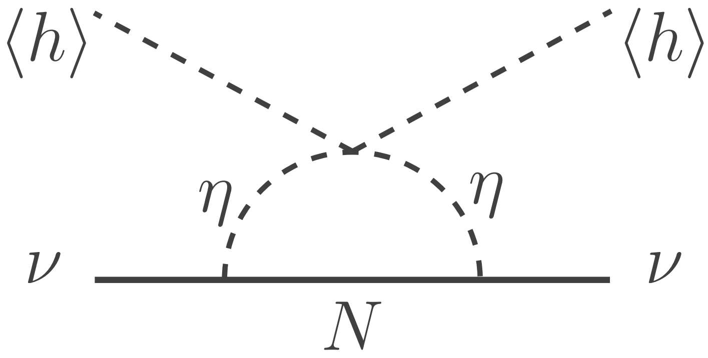
$$\mathcal{O}_{5ij} = \frac{1}{\Lambda}\left(L_i H\right)^T \left(L_j H\right)$$

Lepton number is explicitly broken

See Restrepo et al. arxiv:1308.3655

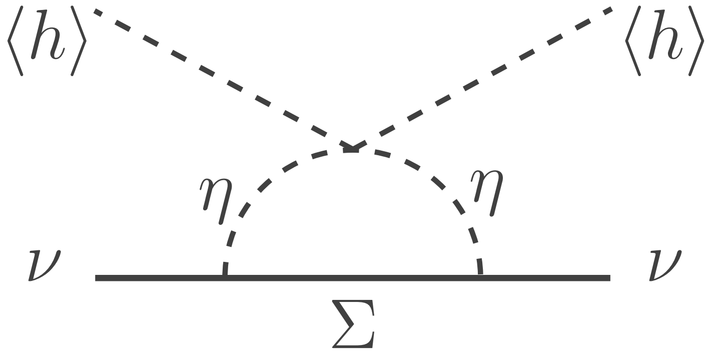
Scotogenic model

The simplest scotogenic models



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

"Type-I"

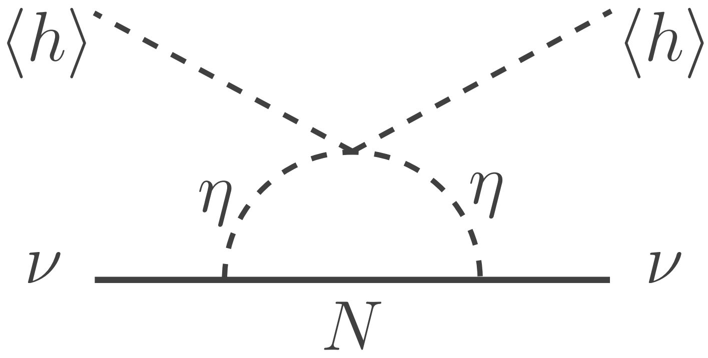


E. Ma, D. Suematsu Mod.Phys.Lett.A24:583-589,2009

"Type-II"

Scotogenic model

The simplest scotogenic models

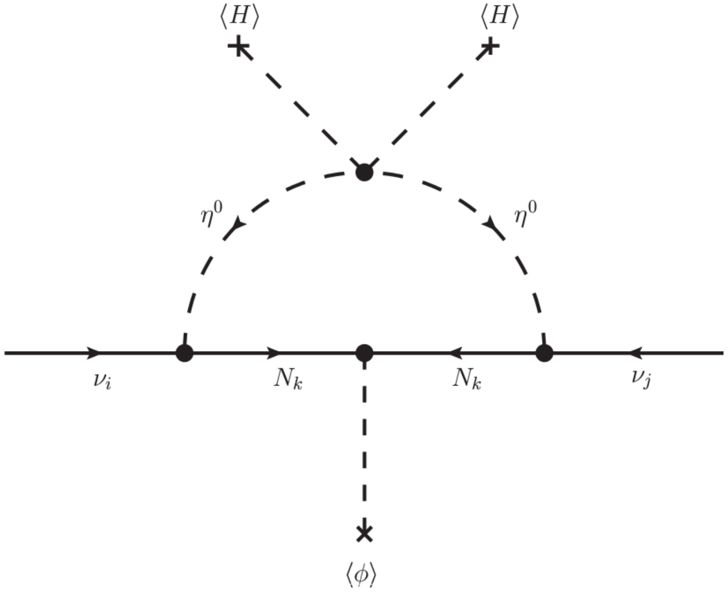


$$(\mathcal{M}_\nu)_{ij} = \sum_{k=1}^{3} \frac{Y^\nu_{ik} Y^\nu_{kj} m_{N_k}}{16\pi^2} \left[\frac{m^2_{\eta_R}}{m^2_{\eta_R} - m^2_{N_k}} \log \frac{m^2_{\eta_R}}{m^2_{N_k}} - \frac{m^2_{\eta_I}}{m^2_{\eta_I} - m^2_{N_k}} \log \frac{m^2_{\eta_I}}{m^2_{N_k}} \right]$$

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

"Type-I"

Spontaneous Scotogenic



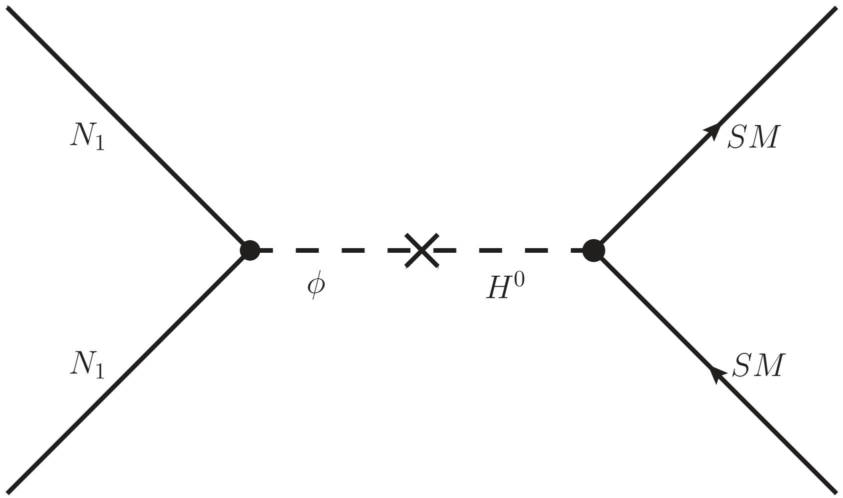
$$(\mathcal{M}_\nu)_{ij} \simeq \frac{\lambda_5 v_h^2}{16\pi^2} \sum_k \frac{Y^\nu_{ik} Y^\nu_{jk}}{m_{N_k}}$$

The scotogenic model emerge when lepton symmetry is spontaneously broken

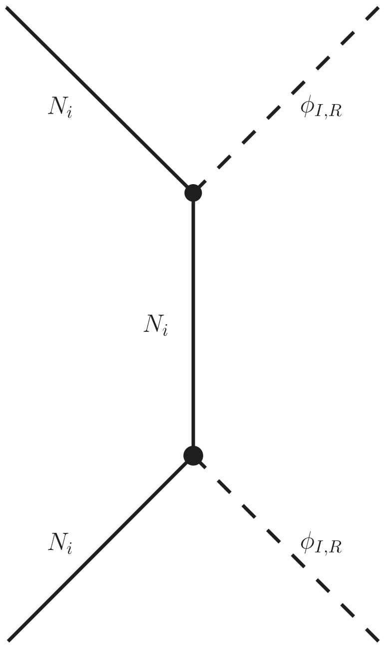
The new scalar opens new annihilation channels

	$\bar{L}_i$	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	$+$	$+$	$+$	$-$	$-$	$+$

New channels

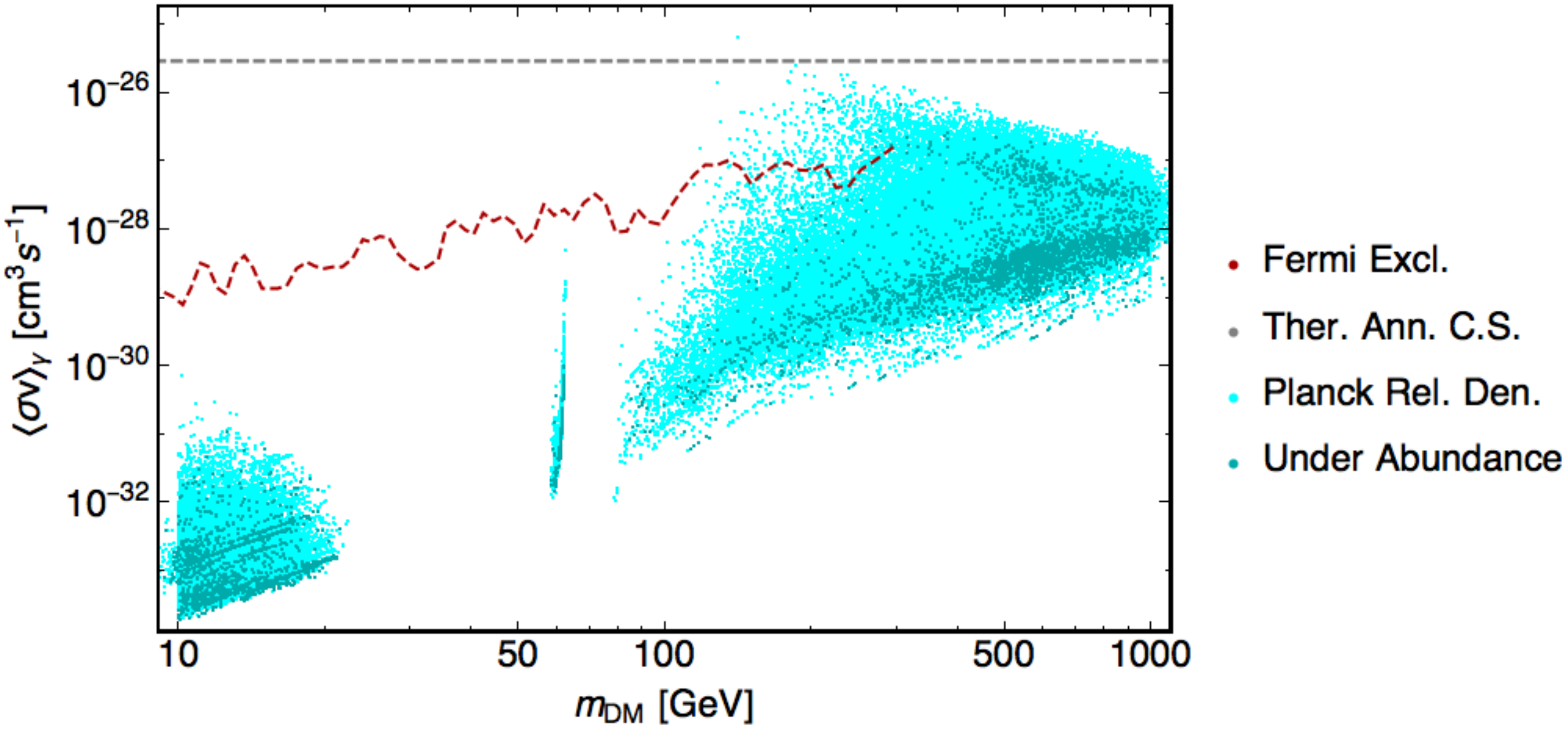


Higgs portal

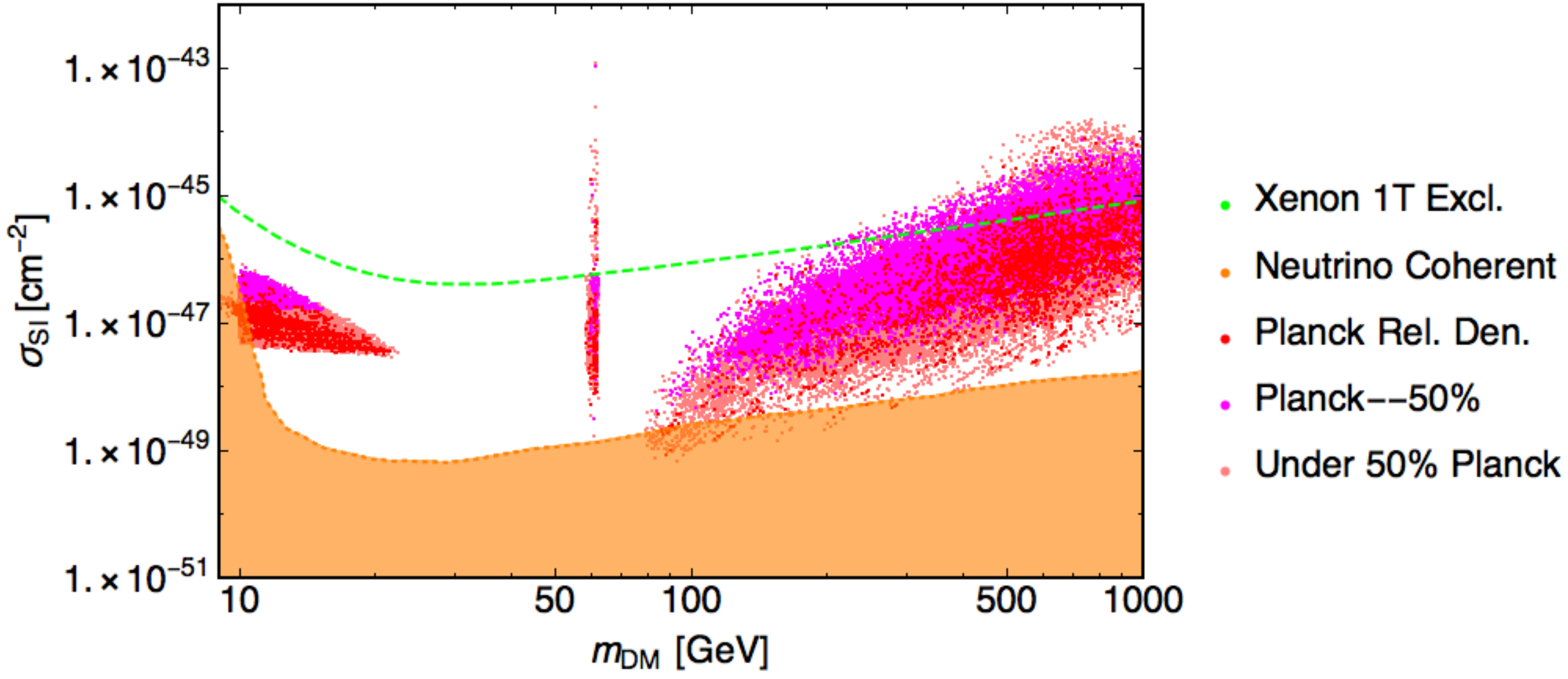


< 10%

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

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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

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

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

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

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

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	$0.4 - 1.6$

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