WIMP dark matter as radiative neutrino mass messenger

Joaquim Palacio
04/09/13

TAE - 2013

Universitat de València

IFIC Institut de Física Corpuscular

CSIC Consejo Superior de Investigaciones Científicas

MultiDark
Multimessenger Approach for Dark Matter Detection

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M. Hirsch, R.A. Lineros, S. Morisi, J. Palacio, N. Rojas, J.W.F. Valle.
arXiv:1307.8134

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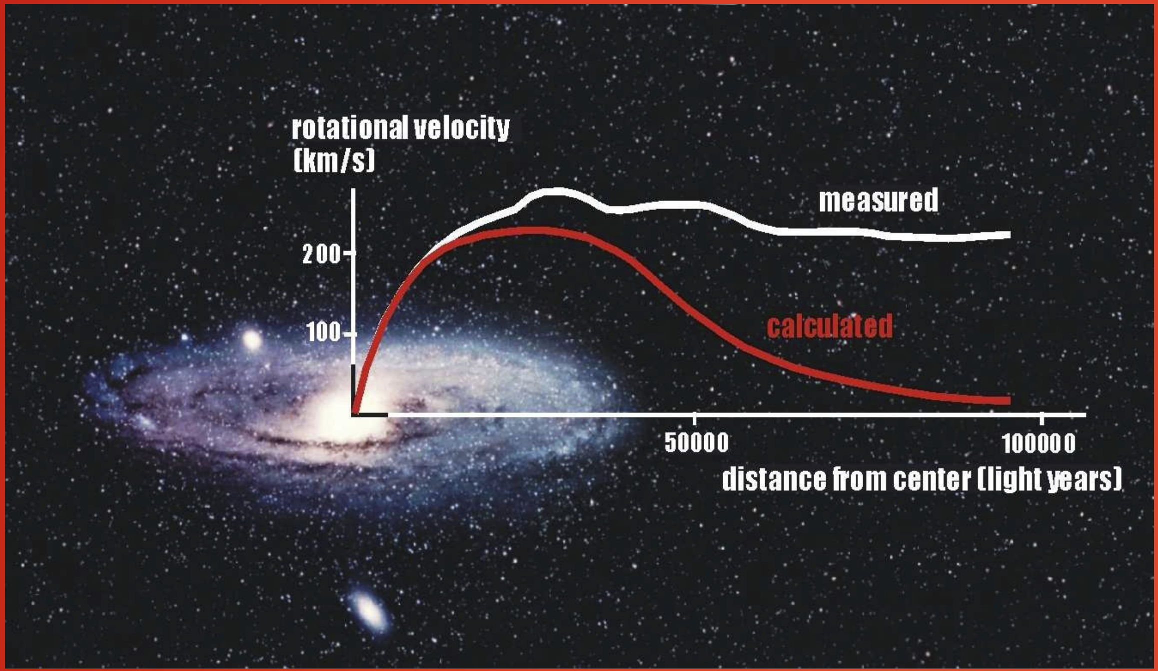
MultiDark Multimessenger Approach for Dark Matter Detection

Outline

- Dark Matter Evidences
  - WIMP candidate
- (Radiative) Neutrino Mass Models
- Dark Matter & Neutrino Masses
- The Model
  - Particle content
  - Study of the Model
  - Detection prospects
- Conclusions

DM evidences

At galactic scales



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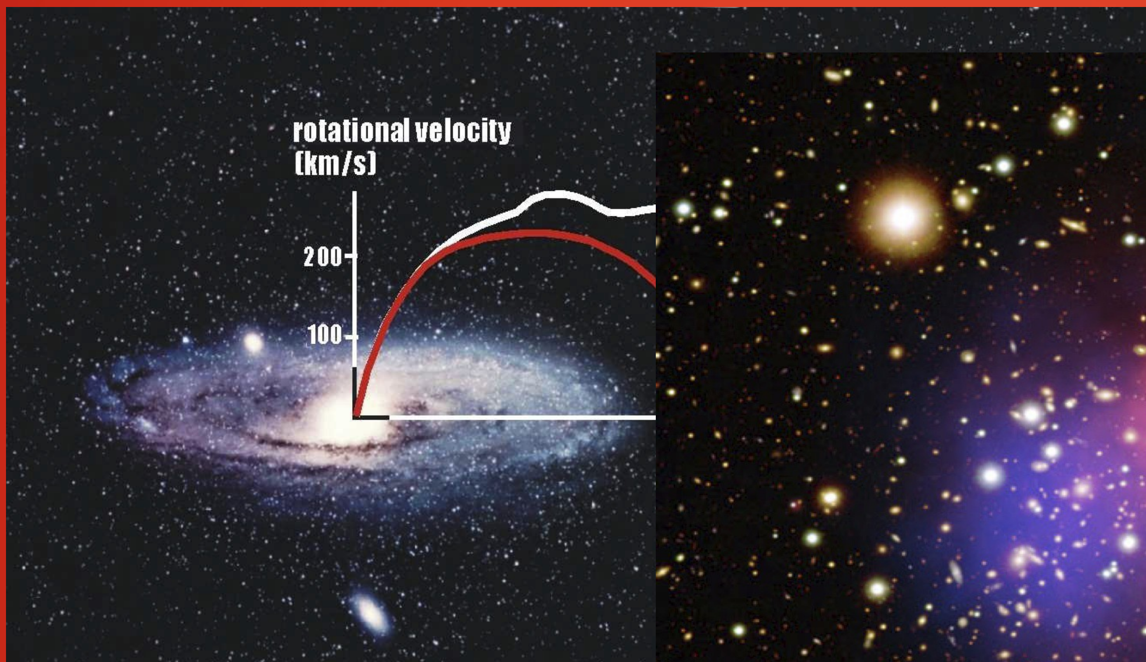

At galaxy cluster scales

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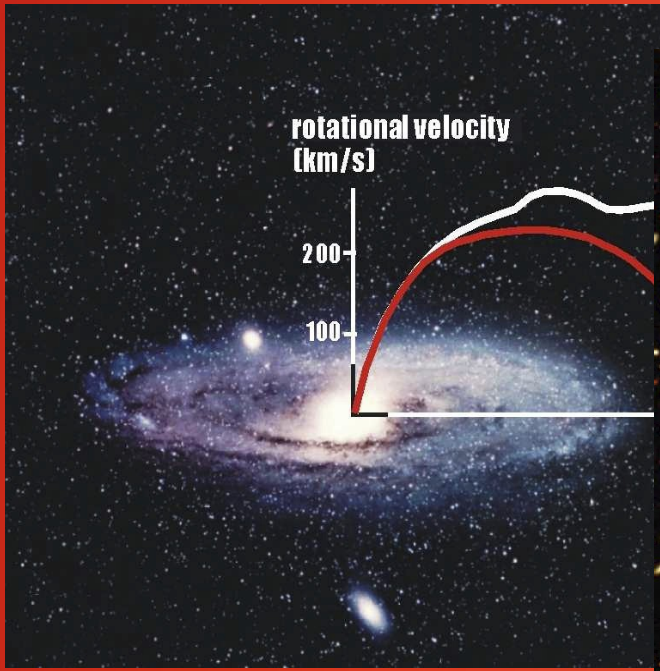

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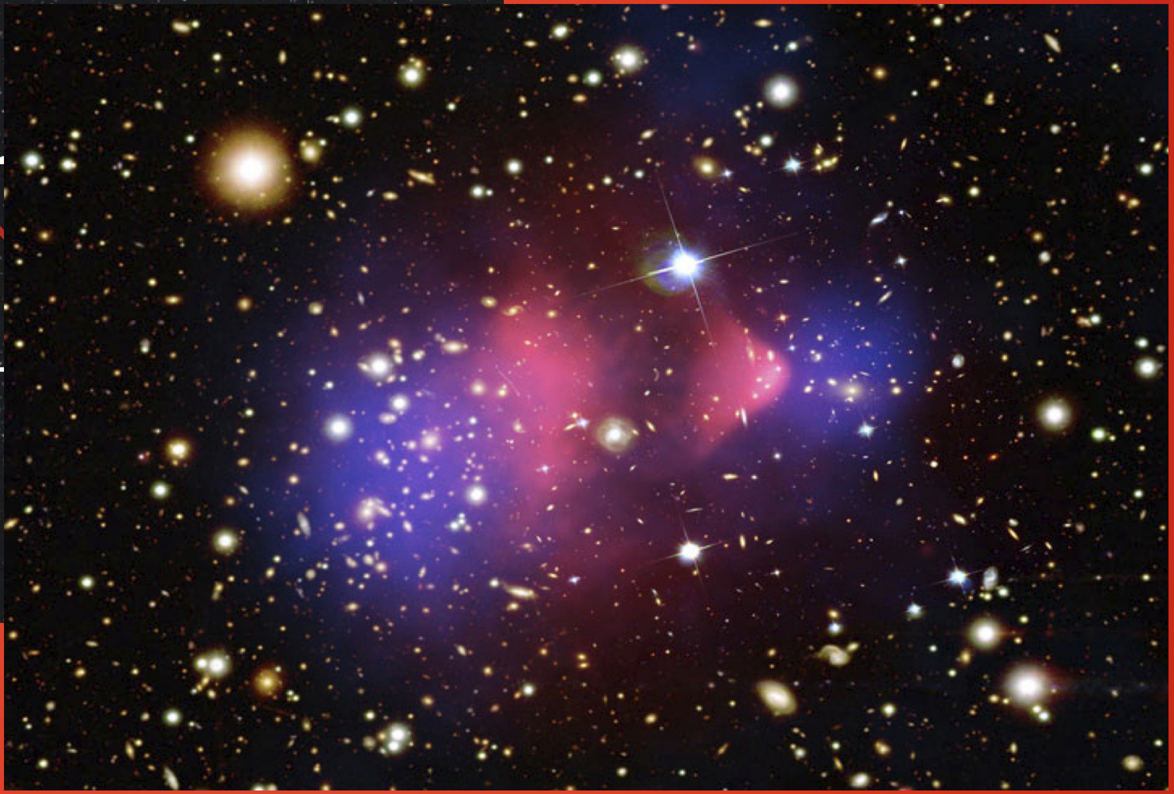
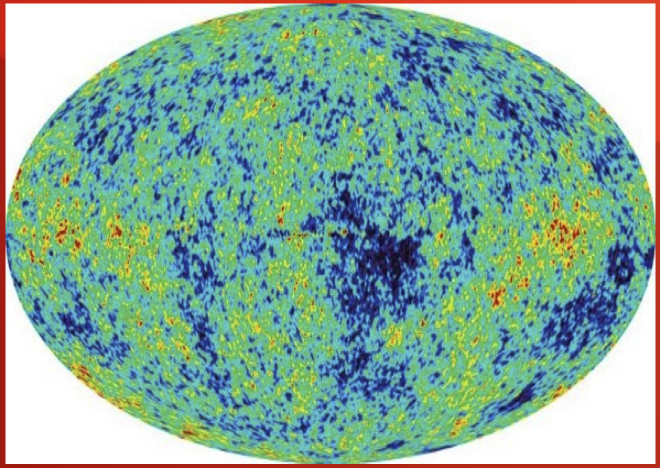


At cosmogical scales



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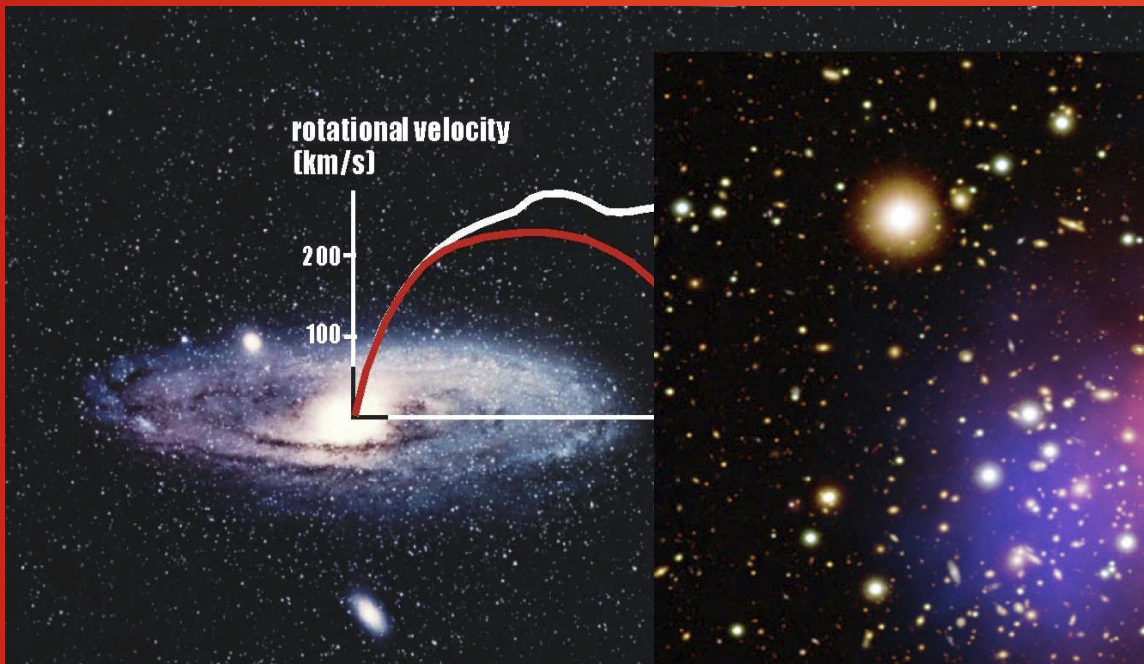

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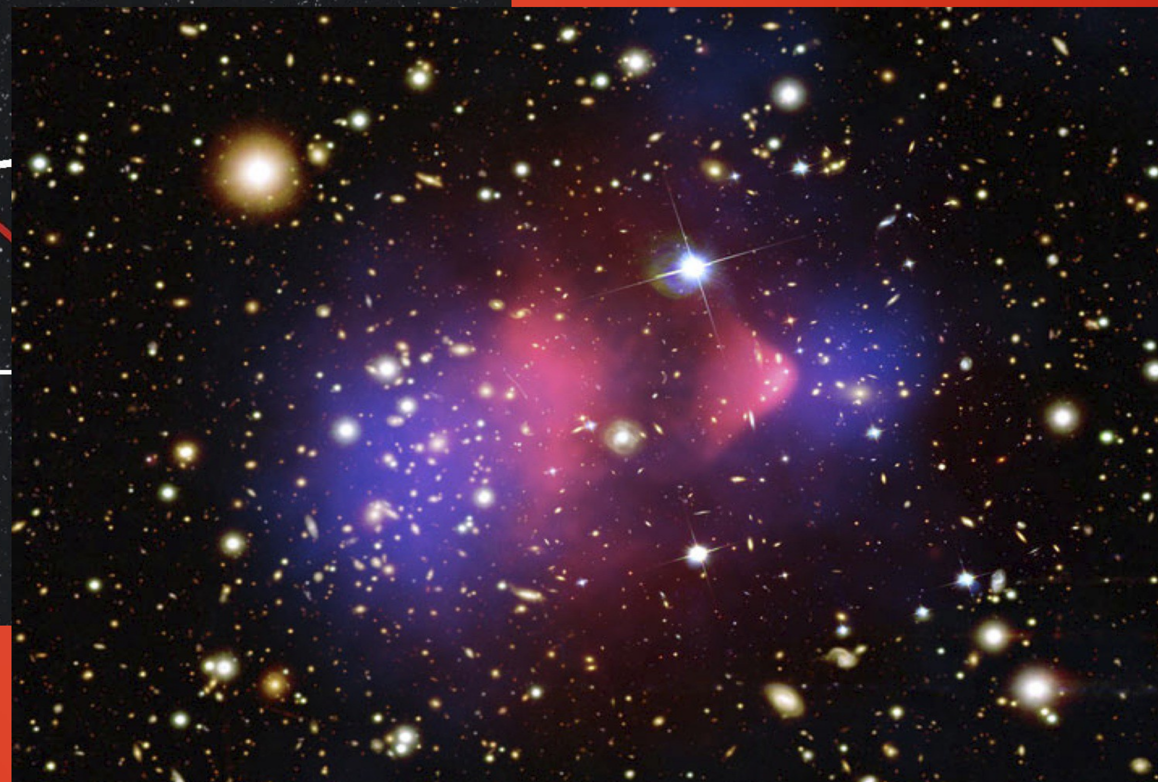

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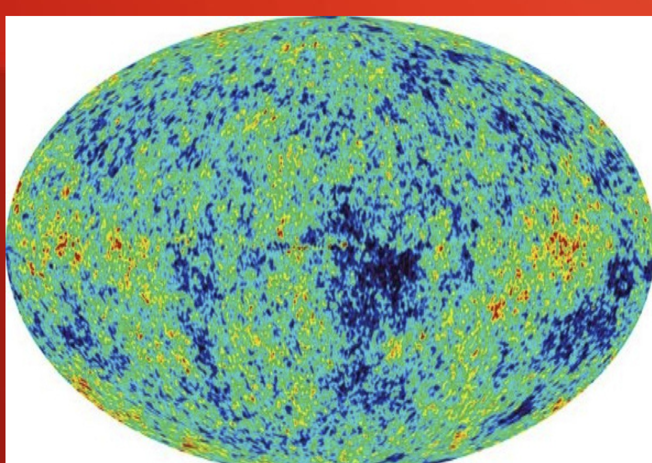


PDG (2012)

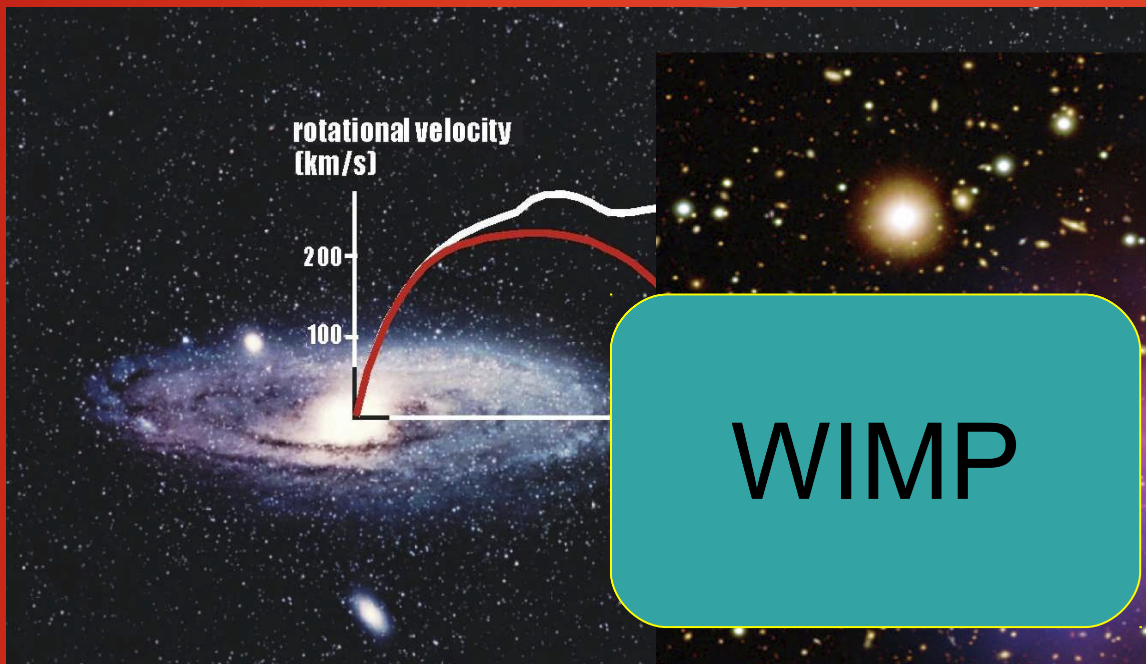
Ω_R	≤ 0.5
Ω_M	0.27
Ω_Λ	0.73
Ω_k	$\leq 10^{-2}$

→

$\Omega_b h^2$	0.0226
$\Omega_{DM} h^2$	0.111

DM evidences

At galactic scales



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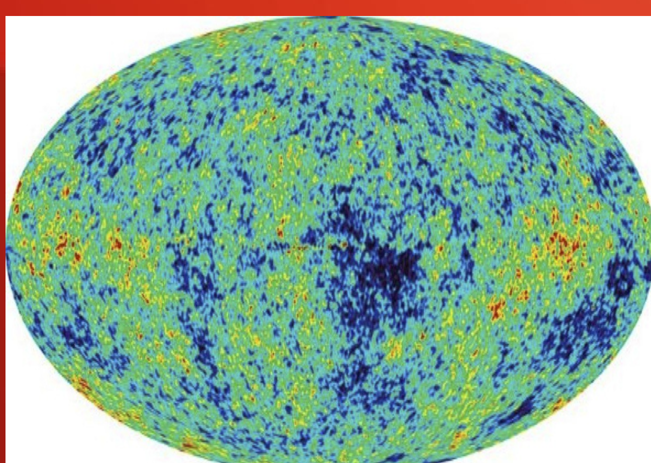
WIMP

At cosmogical scales



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WIMP candidate & Freeze Out

Try to solve the Boltzmann equation

$$\hat{L}[f] = \hat{C}[f]$$

Considering a FRW metric

$$\frac{dn}{dt} + 3\mathrm{Hn} = -\left(n^2 - n_{eq}^2\right) < \sigma_A v >$$

Approximations:

- -All species BUT ONE are in equilibrium
- -Boltzmann distribution
- -CP conservation
- -Isoentropic expansion → $sa^3 = cte$
- -Small chemical potential → μ << T

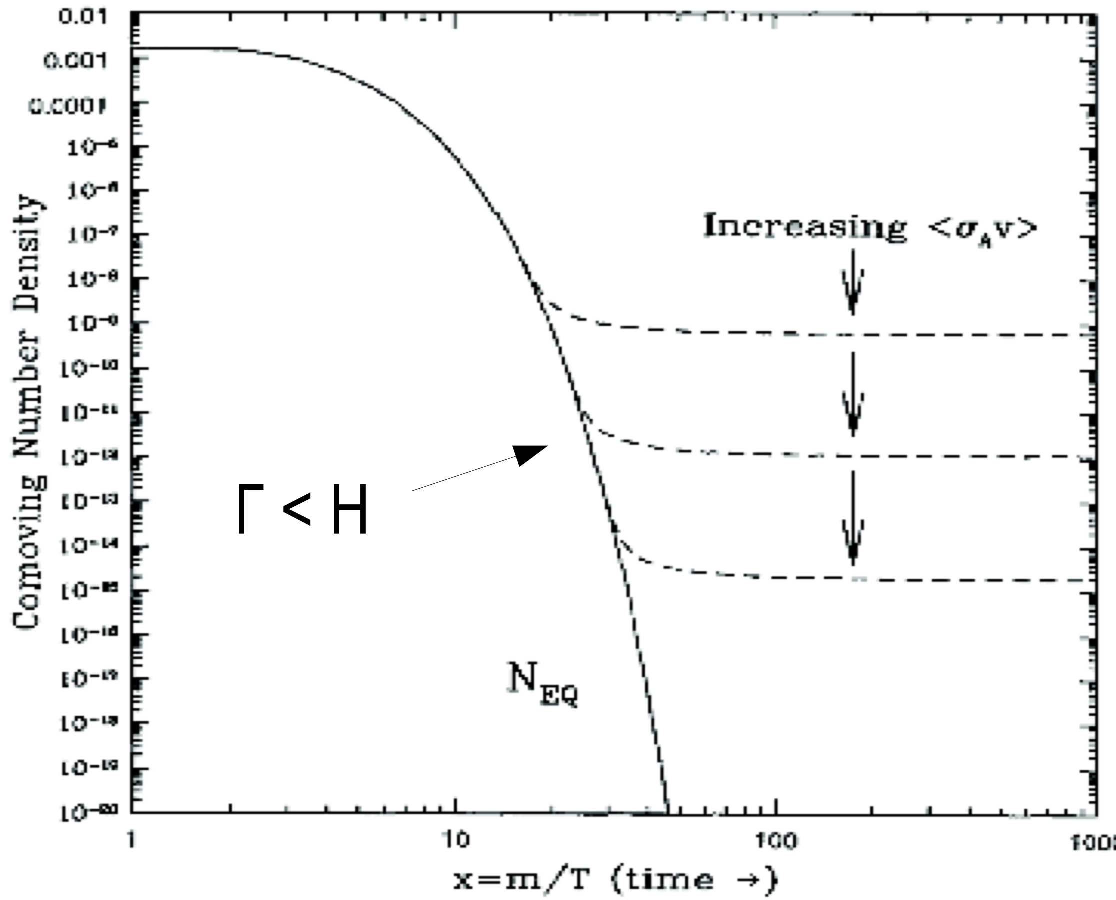
$$\frac{x}{Y_{eq}} \frac{dY}{dx} = \frac{-\Gamma_A}{H} \left[\left(\frac{Y}{Y_{eq}} \right)^2 - 1 \right]$$

$$x = \frac{m}{T}; \quad Y = \frac{n}{s}$$

$$\Gamma_A = n_{eq} < \sigma_A v >$$

$$\Omega_{DM} \propto m Y(\infty)_{T=0}$$

WIMP candidate & Freeze Out



$$\Omega_{CDM}h^2 \approx 0.1 \frac{3 \cdot 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle_{f.o.}}$$

Neutrino Masses

FORERO-TORTOLA-VALLE
Phys. Rev. D 86, 073012 (2012)

parameter	best fit	1σ range	2σ range	3σ range
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	7.62	7.43–7.81	7.27–8.01	7.12–8.20
$\|\Delta m^2_{31}\|\ [10^{-3}\mathrm{eV}^2]$	2.55 2.43	$2.46-2.61$ $2.37-2.50$	$2.38-2.68$ $2.29-2.58$	$2.31-2.74$ $2.21-2.64$
$\sin^2\theta_{12}$	0.320	0.303–0.336	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	0.613 (0.427)[a] 0.600	0.400-0.461 & 0.573–0.635 0.569–0.626	0.38–0.66 0.39–0.65	0.36–0.68 0.37–0.67
$\sin^2\theta_{13}$	0.0246 0.0250	0.0218–0.0275 0.0223–0.0276	0.019–0.030 0.020–0.030	0.017–0.033
δ	0.80π -0.03π	$0-2\pi$	$0-2\pi$	$0-2\pi$

Neutrino Masses

Effective dim 5 operator: Weinberg Operator

$$(\mathcal{O}_{ij}) = \frac{1}{\Lambda} L^c_{iL} \quad \widetilde{\phi}^* \widetilde{\phi}^\dagger L_{jL}$$

$$\text{where } L_i = (\nu_e, e), (\nu_\mu, \mu), (\nu_\tau, \tau);$$

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Extending the SM, 3 possible tree level Seesaw realizations,

	Field	Spin	SU(2)	Y
Type 1	N	1/2	1	0
Type 2	Δ	0	3	-2
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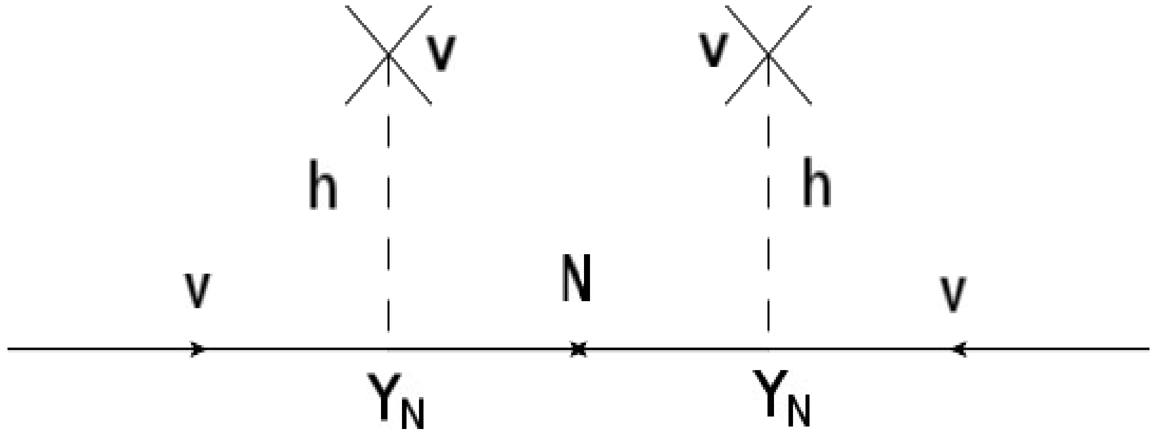

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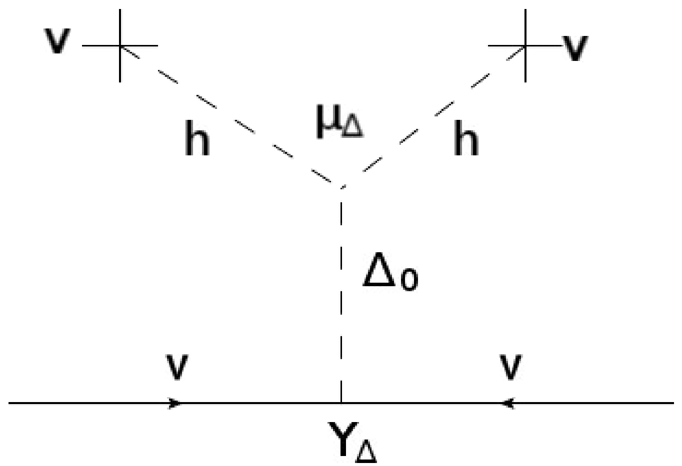

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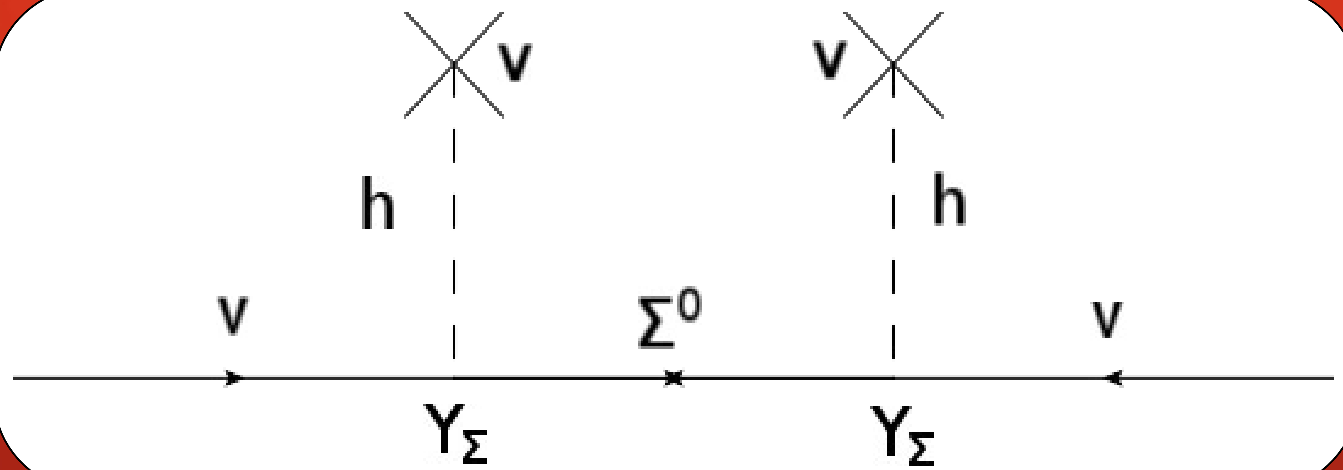

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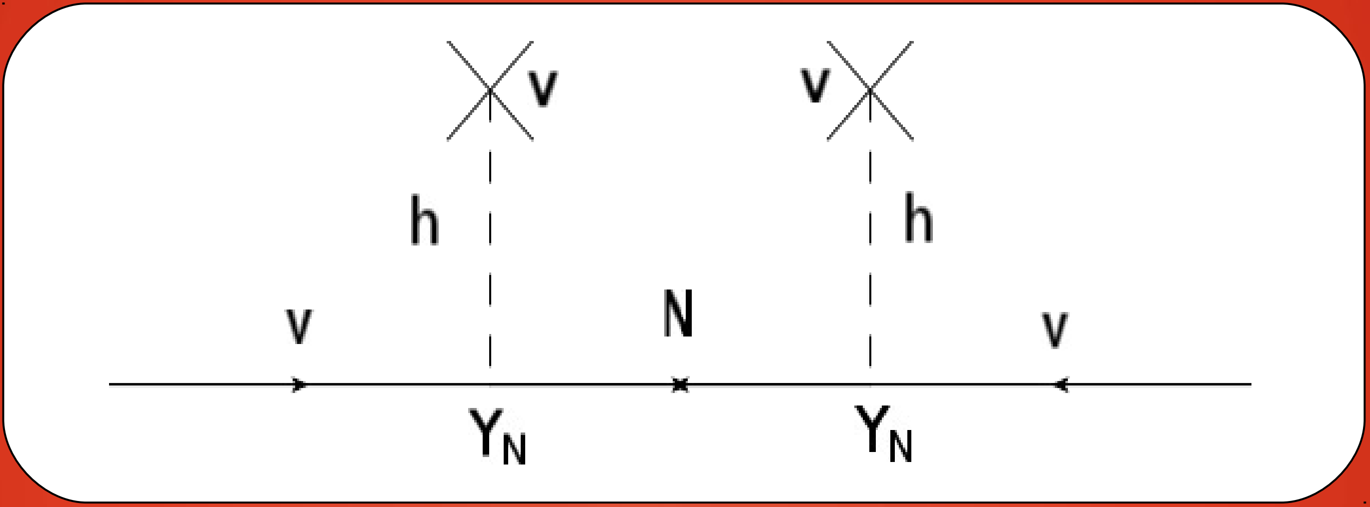
It was then realised that based on the same matter content, neutrino masses could arise at loop level, providing an interesting link between Dark Matter and Neutrino masses generating mechanism.

Neutrino Masses

As an example, Radiative Type 1



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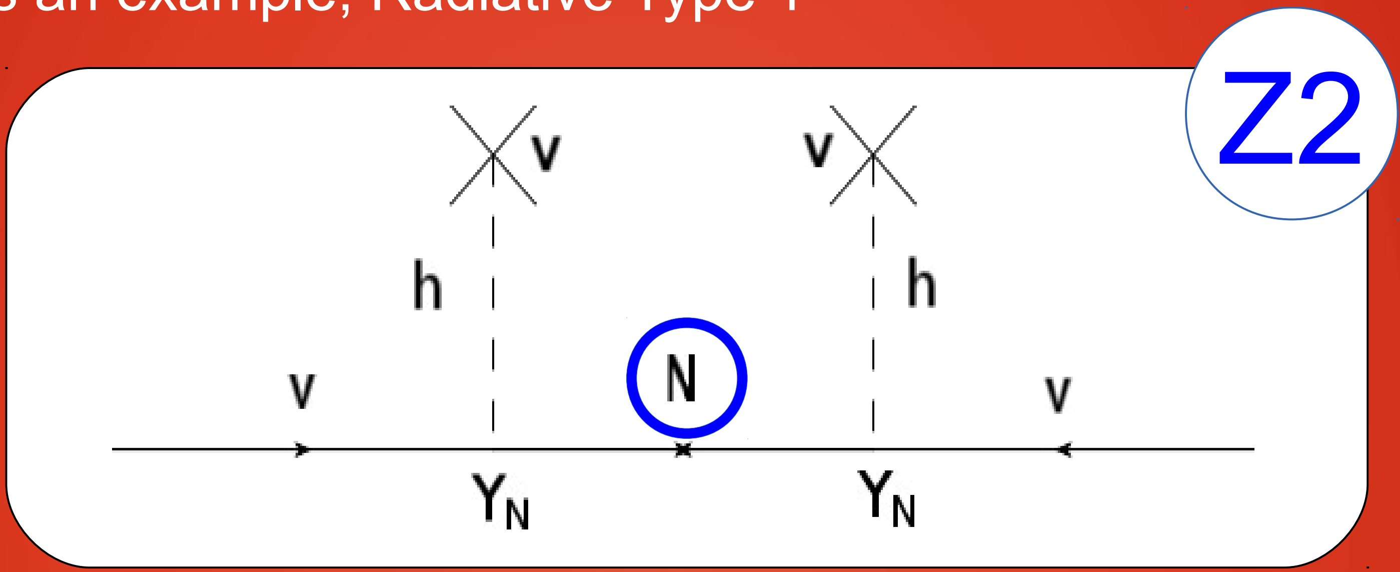

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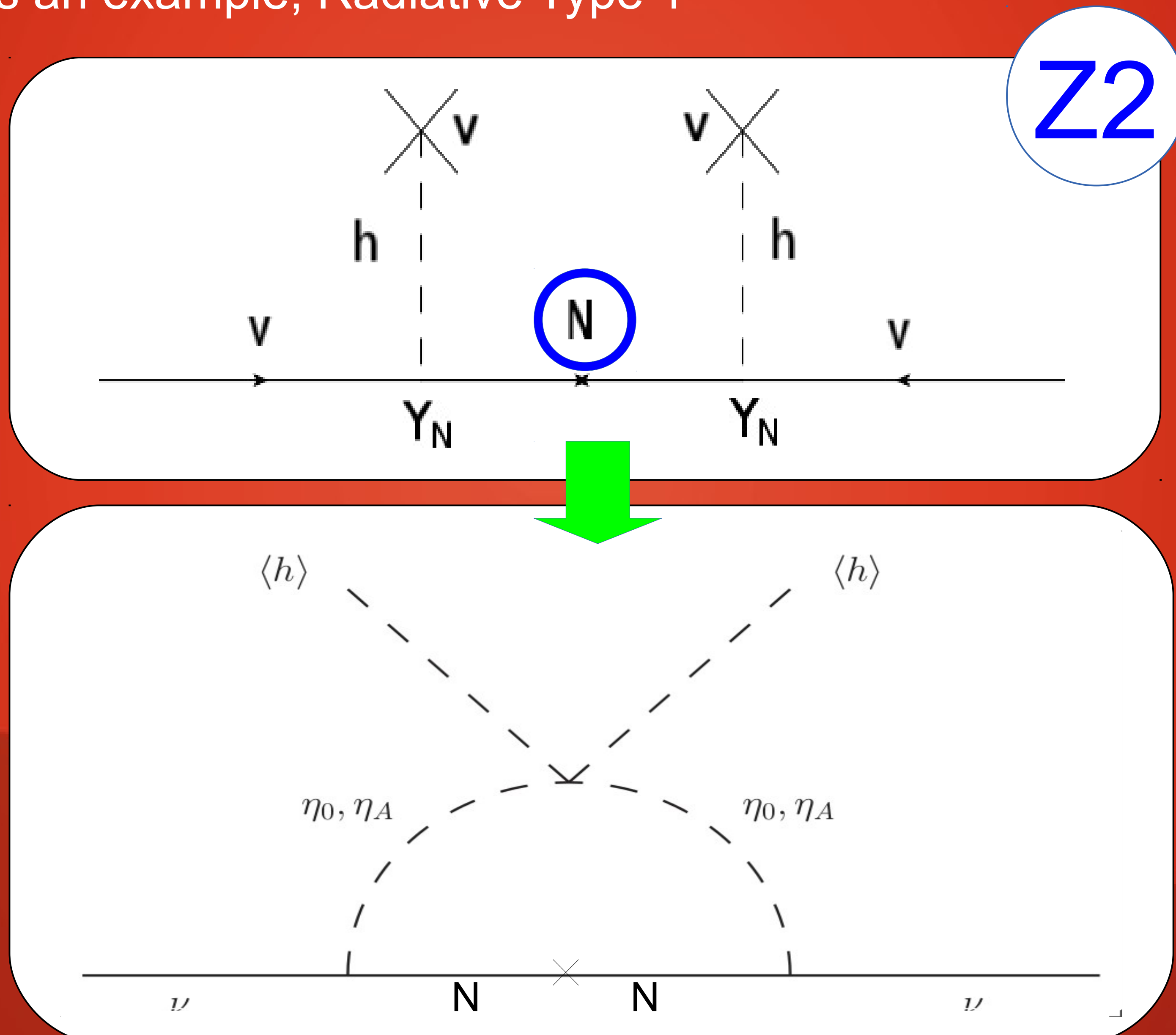
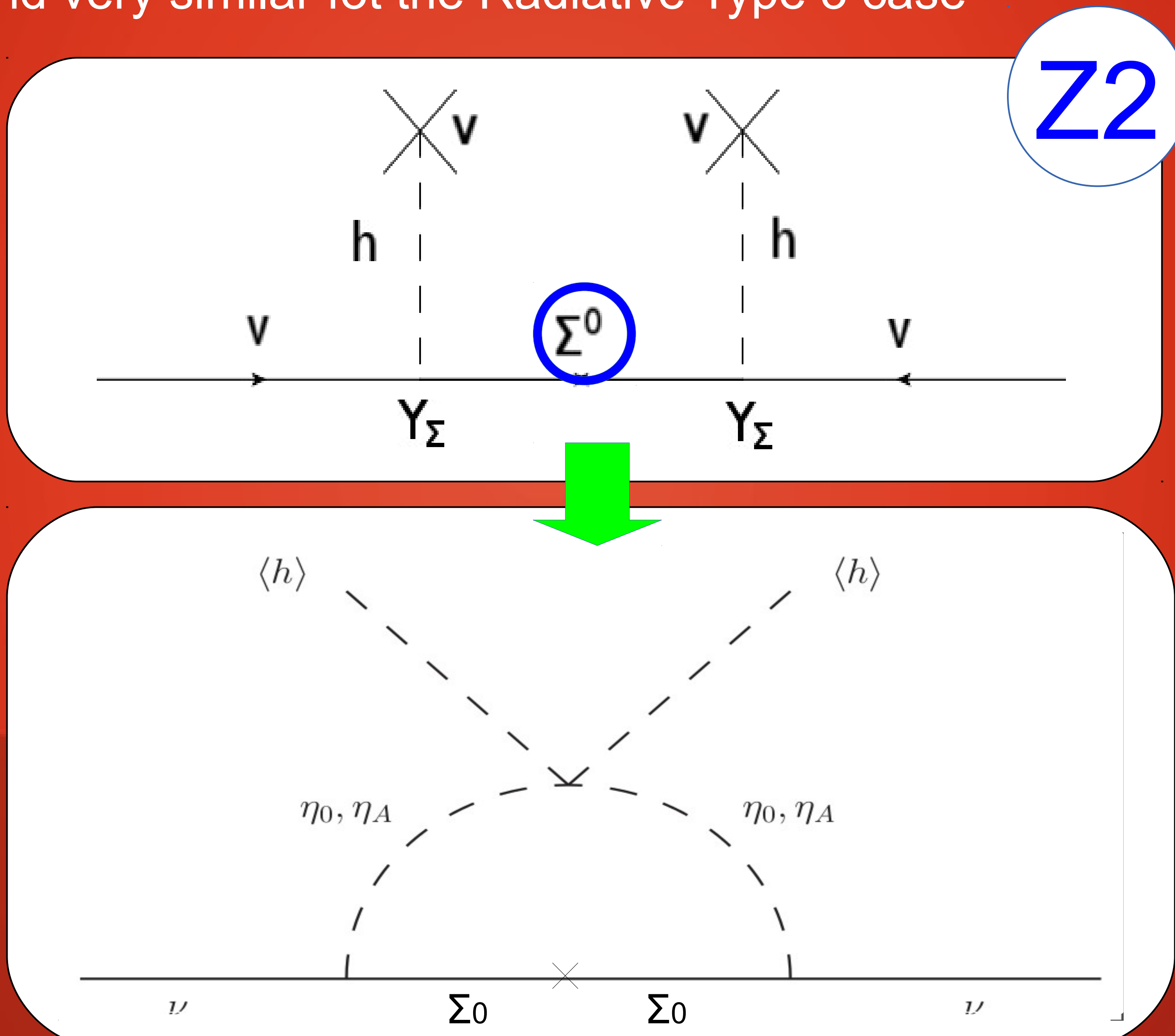
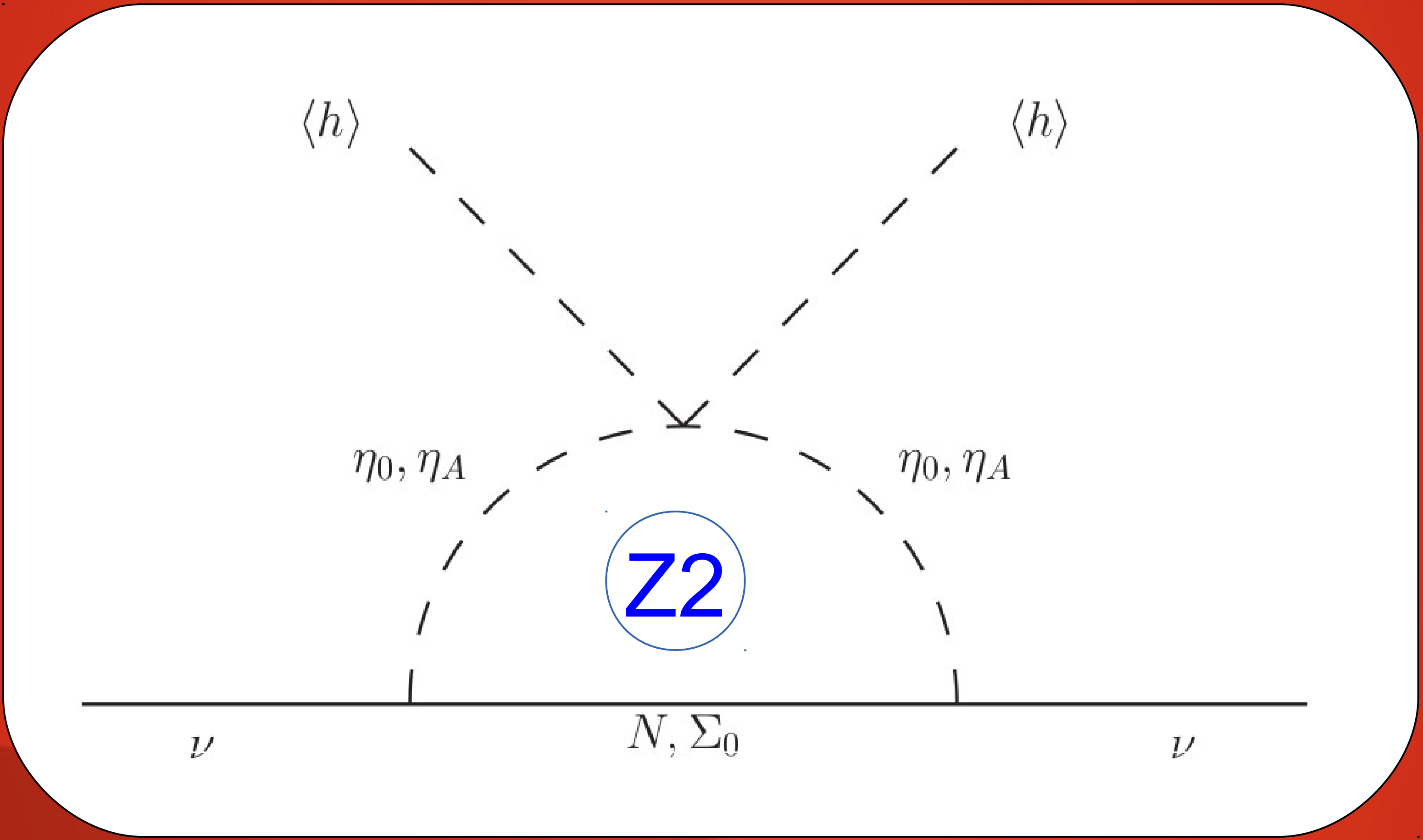


Neutrino Masses

And very similar fot the Radiative Type 3 case



Neutrino Masses



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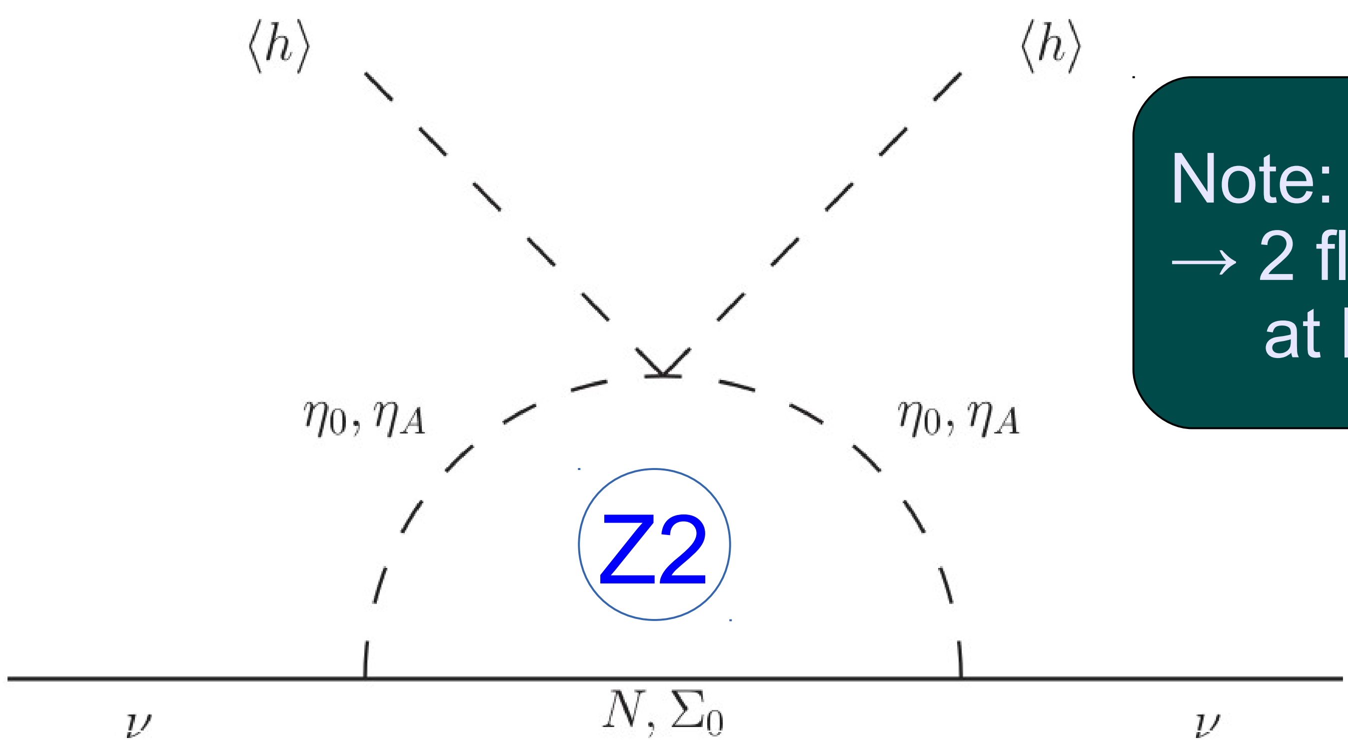
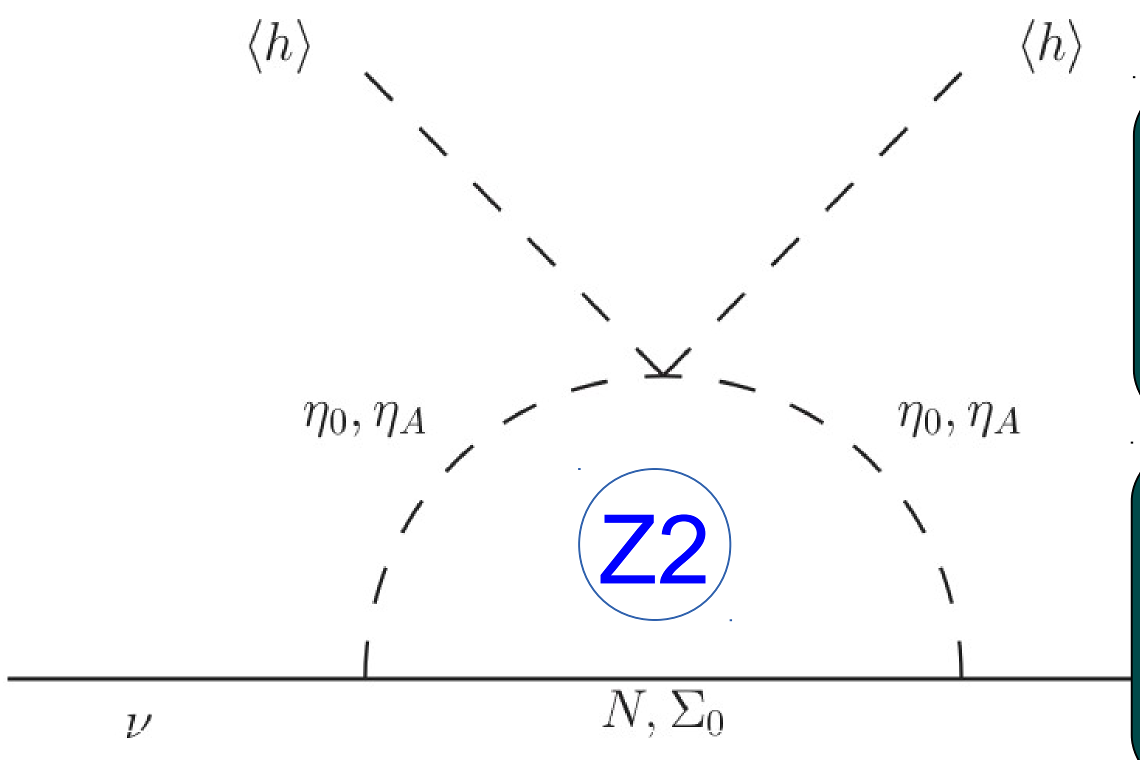


Note:
→ 2 flavours at least

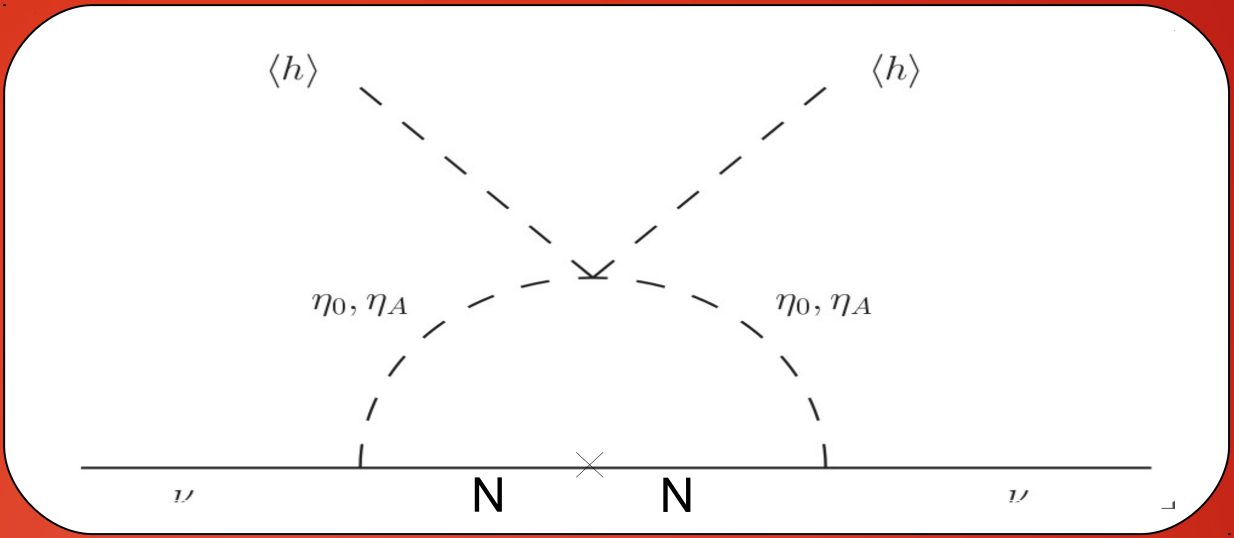
Neutrino Masses



Note:
→ 2 flavours at least

Dark Matter:
→ Scalar or Fermionic

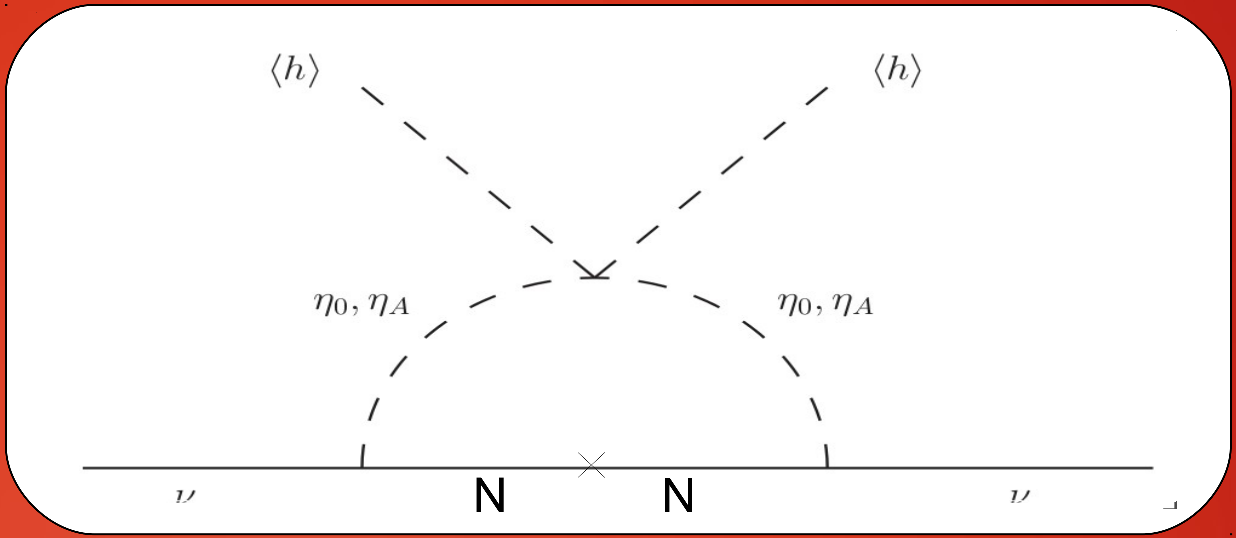
Radiative type 1



Scalar DM

The phenomenology is very close to the inert doublet DM model*. But* the relation with neutrinos is not very strong.

Radiative type 1



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Tightly related to neutrino masses.

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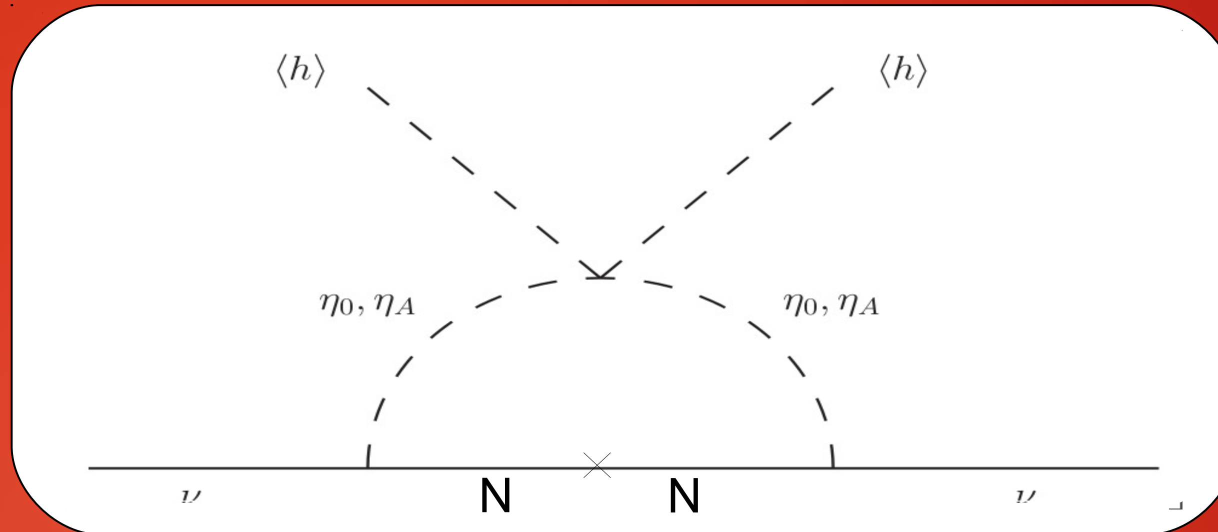

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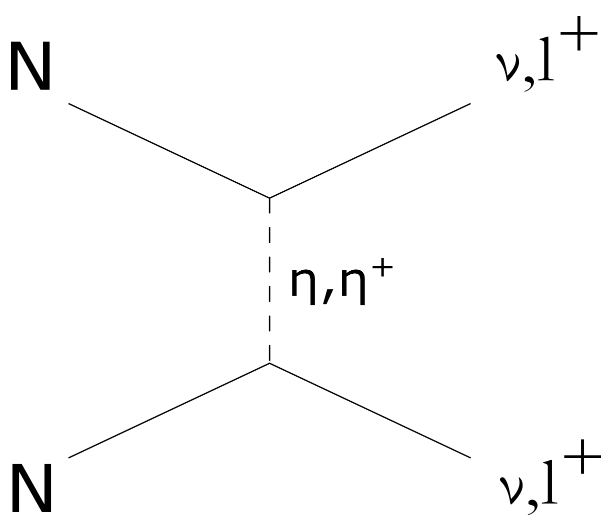
Relic density / Indirect searches



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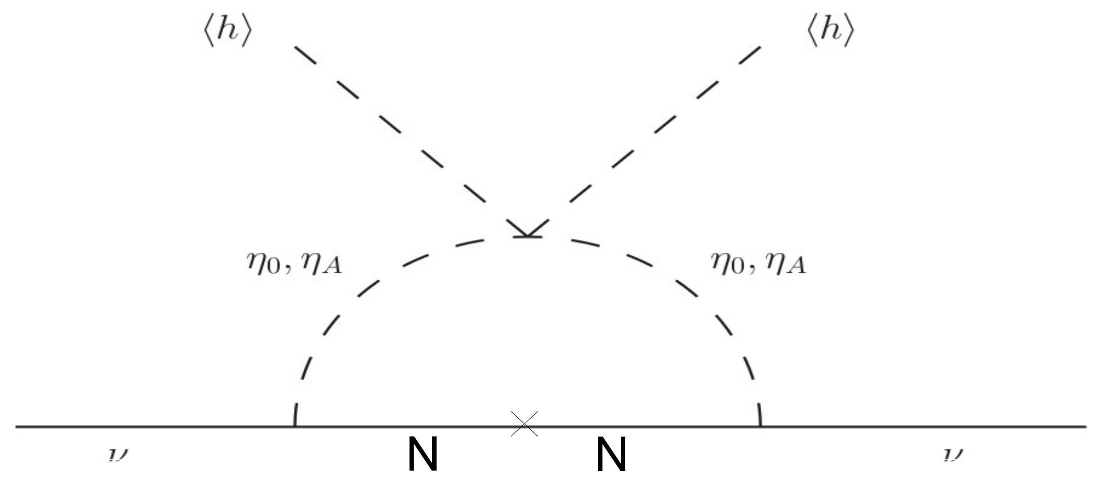

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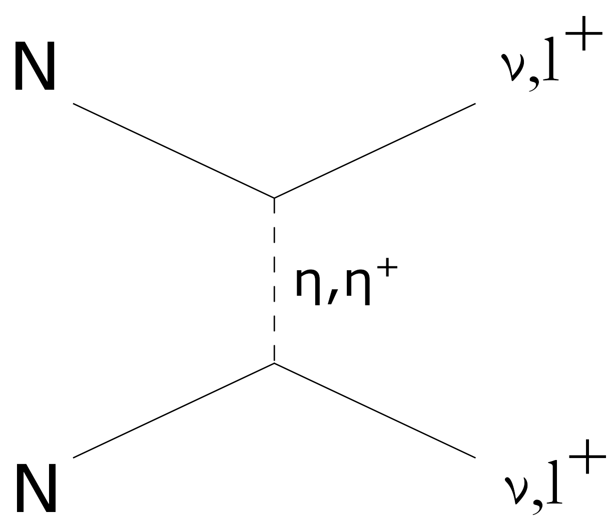
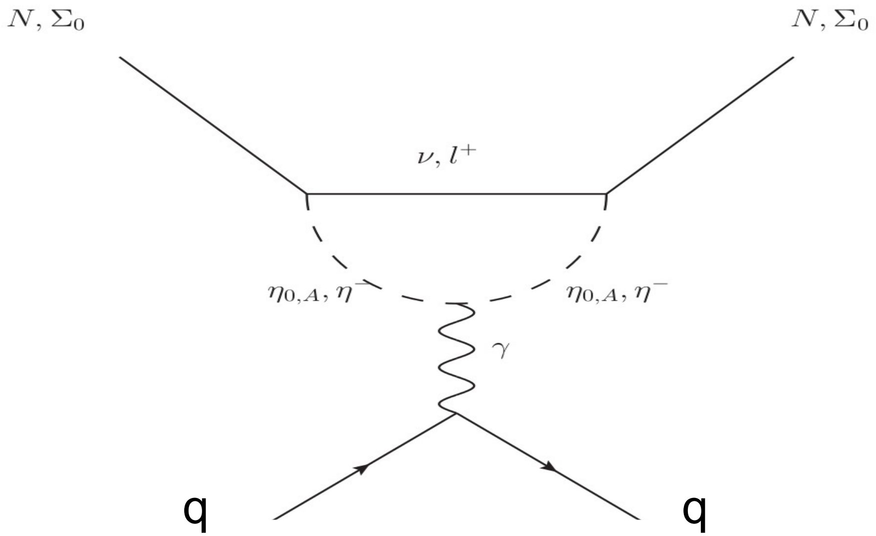
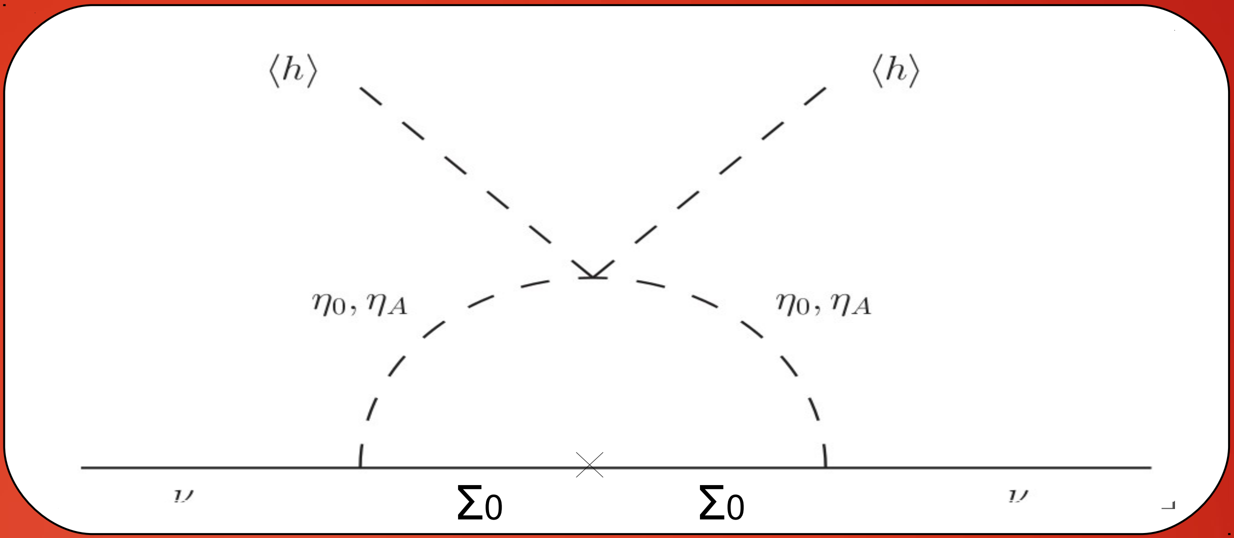


Direct searches



Radiative type 3



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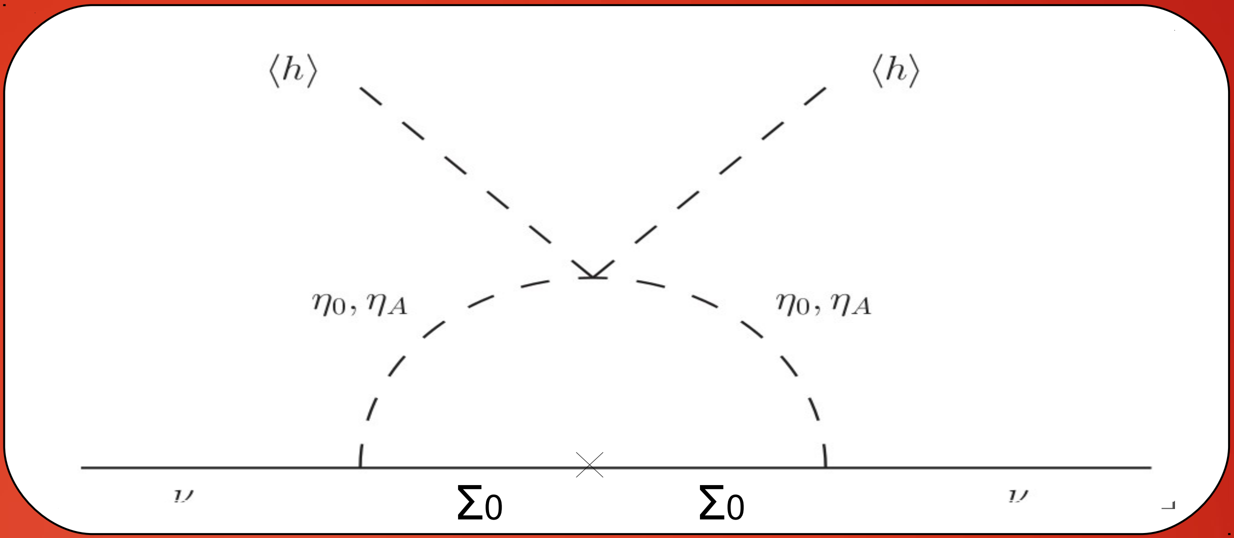

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Th DM mass appears at ~2.7 TeV.

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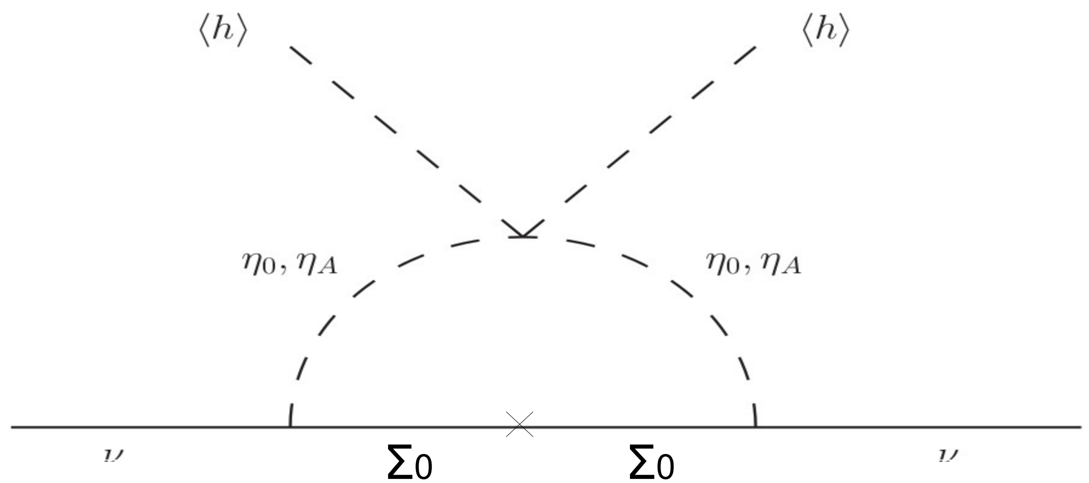

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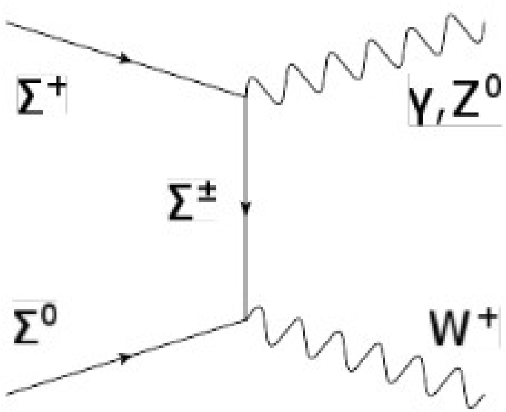

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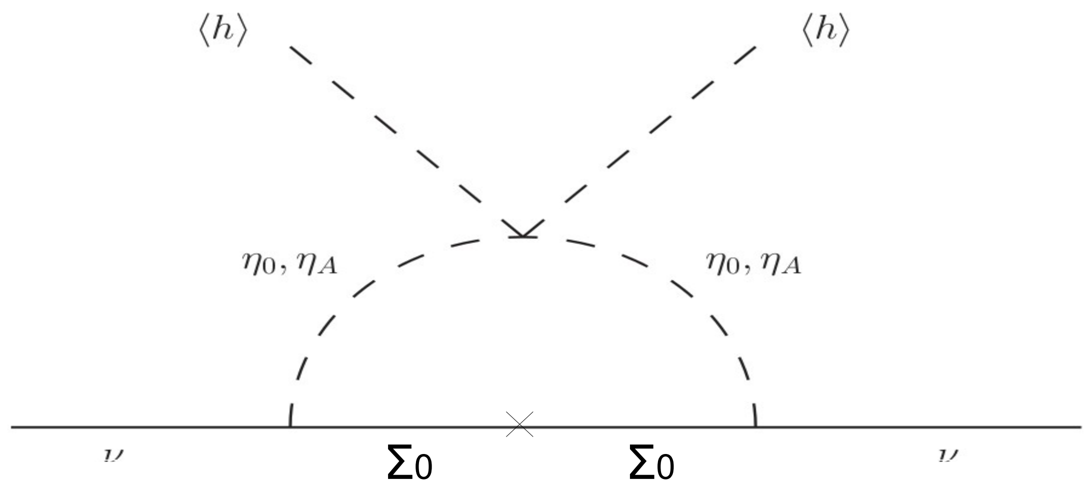

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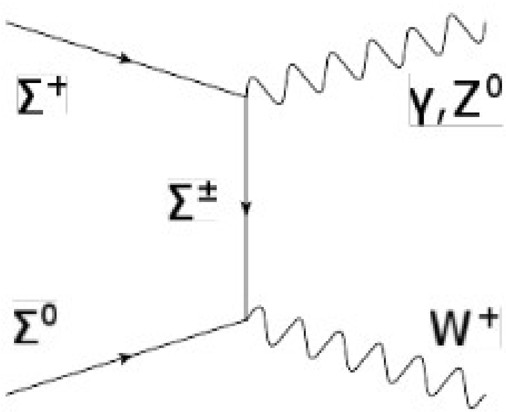
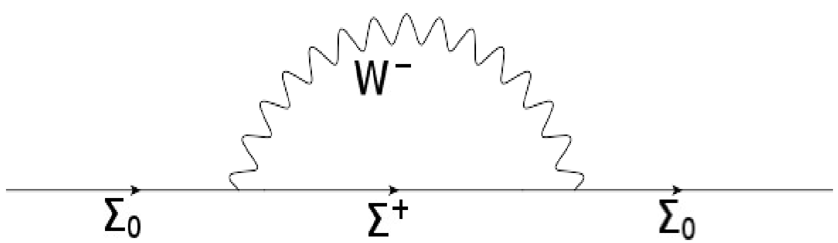
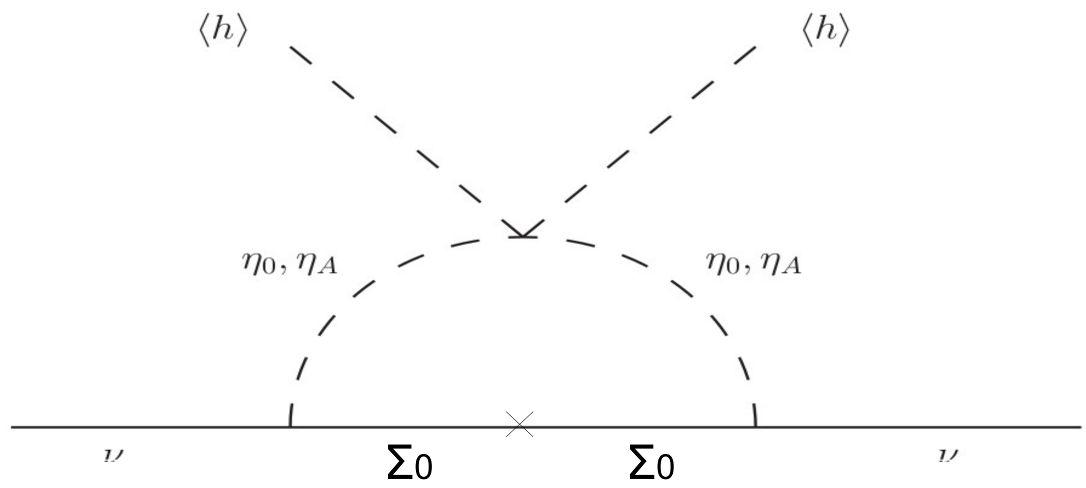




~O(100) MeV

Radiative type 3



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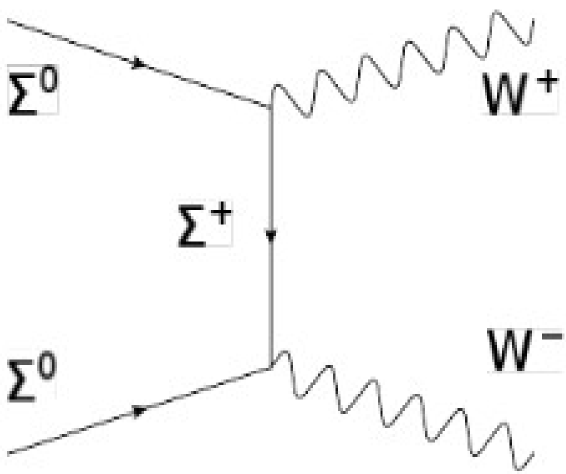

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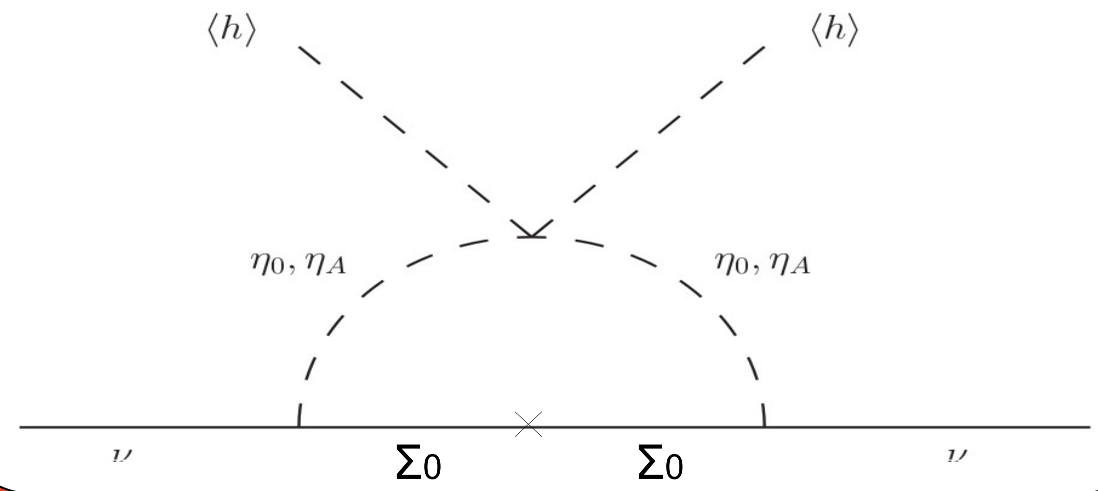

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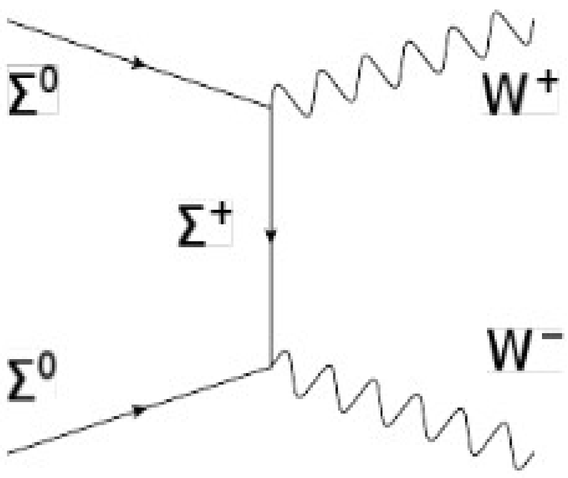

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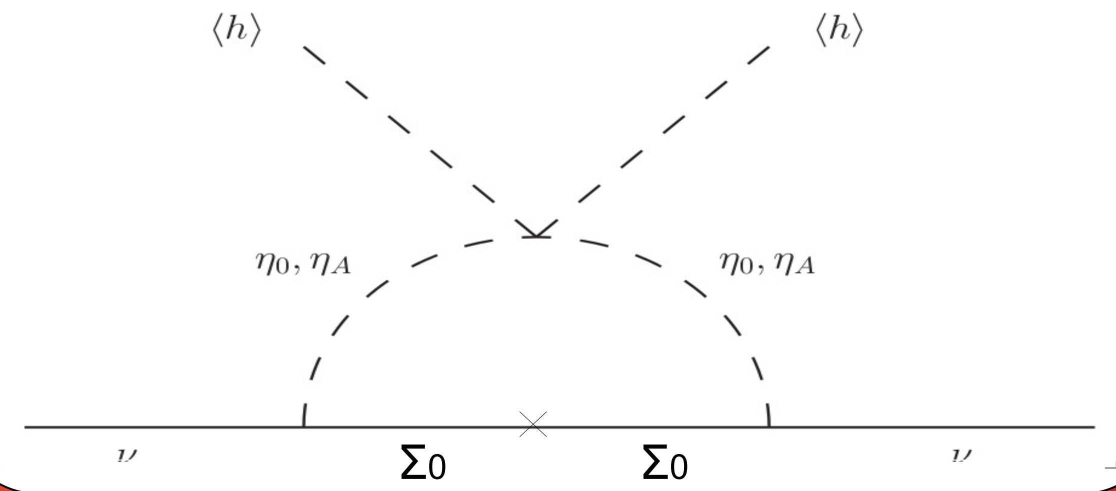

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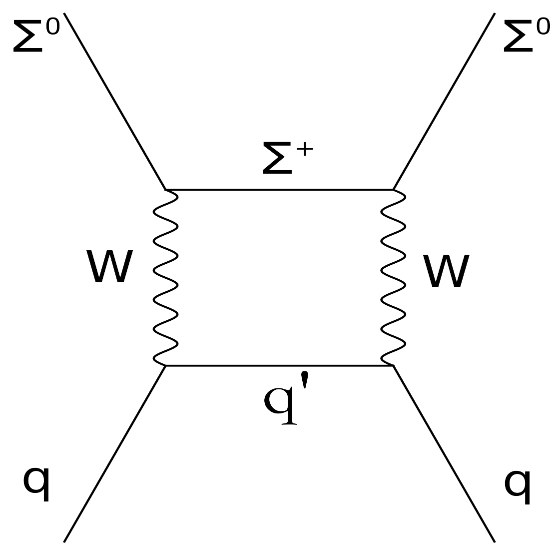

The Model

We would like to join de advantatges of both scenario:

->Light DM for the singlet

->Rich phenomenology

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->Light DM for the singlet

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This could be achieved by breaking the mass degeneracy of the triplet component.

The Model

We considered a mixture scenario

Fields	Standard Model			Fermions		Scalars	
	L	e	ϕ	Σ	N	η	Ω
$SU(2)$	2	1	2	3	1	2	3
Y	-1	-2	1	0	0	1	0
Z_2	$+$	$+$	$+$	$-$	$-$	$-$	$+$

The Model

$$
\begin{aligned}
V \;=\; & -m_1^2\phi^\dagger\phi + m_2^2\eta^\dagger\eta + \frac{\lambda_1}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 + \lambda_3\left(\phi^\dagger\phi\right)\left(\eta^\dagger\eta\right) \\
+\; & \lambda_4\left(\phi^\dagger\eta\right)\left(\eta^\dagger\phi\right) + \frac{\lambda_5}{2}\left(\phi^\dagger\eta\right)^2 + h.c. - \frac{M_\Omega^2}{4}Tr\left(\Omega^\dagger\Omega\right) + \left(\mu_1\phi^\dagger\Omega\phi + h.c.\right) \\
+\; & \lambda_1^\Omega\phi^\dagger\phi\, Tr\left(\Omega^\dagger\Omega\right) + \lambda_2^\Omega\left(Tr(\Omega^\dagger\Omega)\right)^2 + \lambda_3^\Omega Tr(\left(\Omega^\dagger\Omega\right)^2) + \lambda_4^\Omega\left(\phi^\dagger\Omega\right)\left(\Omega^\dagger\phi\right) \\
+\; & \left(\mu_2\eta^\dagger\Omega\eta + h.c.\right) + \lambda_1^\eta\eta^\dagger\eta\, Tr\left(\Omega^\dagger\Omega\right) + \lambda_4^\eta\left(\eta^\dagger\Omega\right)\left(\Omega^\dagger\eta\right) .
\end{aligned}
$$

$$
\phi = \begin{pmatrix} \varphi^+ \\ (h + v_h + i\varphi)/\sqrt{2} \end{pmatrix}
$$

Z2

$$
\eta = \begin{pmatrix} \eta^+ \\ (\eta_0 + i\eta_A)/\sqrt{2} \end{pmatrix}
$$

$$
\Omega = \begin{pmatrix} (\Omega_0 + v_\Omega) & \sqrt{2}\,\Omega^+ \\ \sqrt{2}\,\Omega^- & -(\Omega_0 + v_\Omega) \end{pmatrix}
$$

The Model

$$\mathcal{L} = -Y_{\alpha\beta}\,\overline{L}_\alpha e_\beta \phi - Y_{\Sigma_\alpha}\overline{L}_\alpha^{c}\,{}'\Sigma^\dagger\tilde{\eta} - \frac{1}{4}M_\Sigma \mathrm{Tr}\left[\overline{\Sigma}^c\Sigma\right] +$$

$$-Y_\Omega \mathrm{Tr}\left[\overline{\Sigma}\Omega\right] N - Y_{N_\alpha}\overline{L}_\alpha\tilde{\eta}N - \frac{1}{2}M_N\overline{N^c}N + h.c.$$

where $\alpha, \beta = 1, 2, 3;$

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$$M_{\chi 2} = \cos(\theta_f)^2 M_N + \sin(\theta_f)^2 M_\Sigma + 2v_\Omega Y_\Omega \cos(\theta_f)\sin(\theta_f)$$

$$\text{where } \tan(2\theta_f) = \frac{-4Y_\omega v_\Omega}{M_\Sigma - M_N}$$

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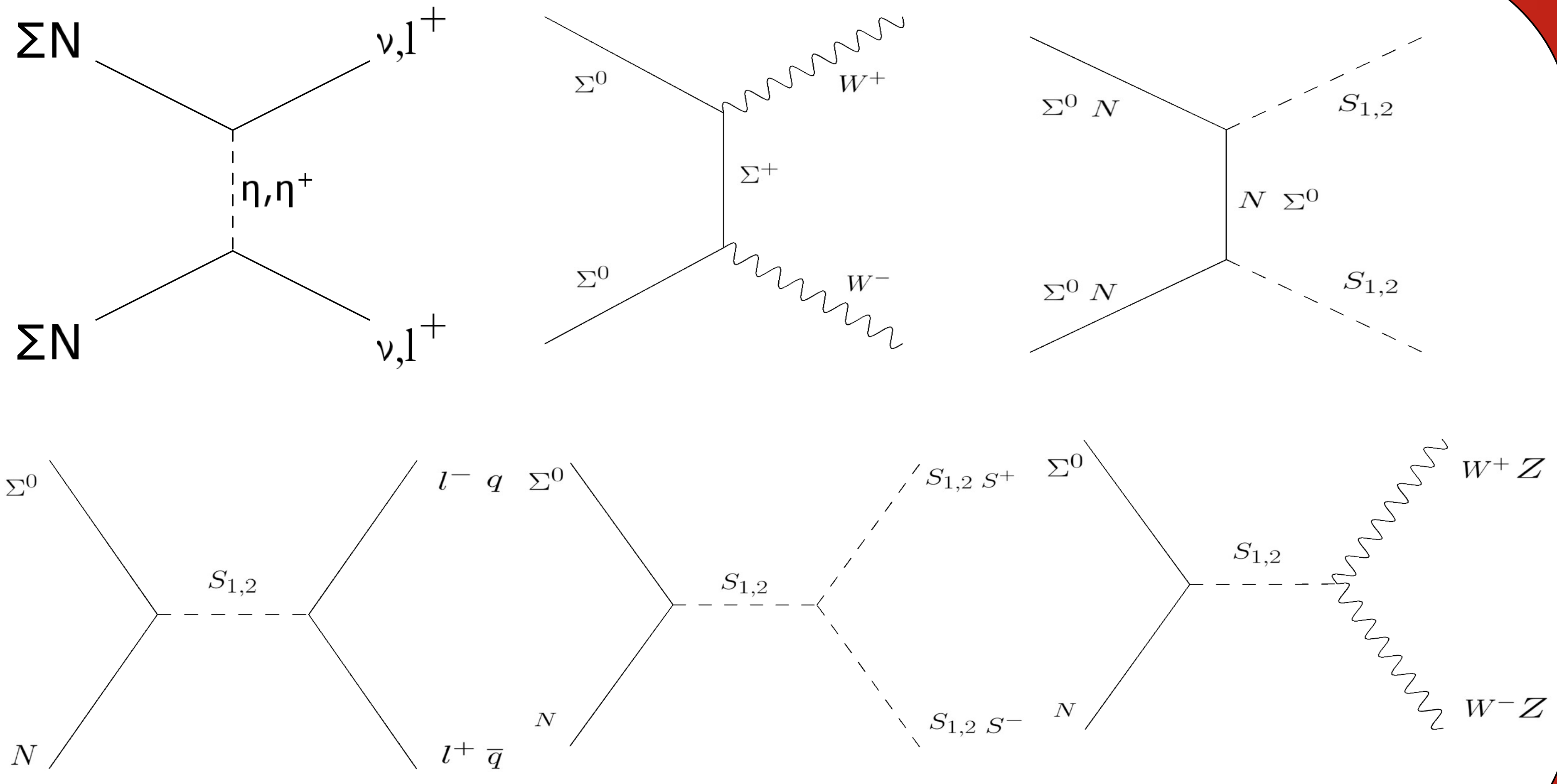
M. Hirsch, R.A. Lineros, S. Morisi, J. Palacio, N. Rojas, J.W.F. Valle.
arXiv:1307.8134

(Co-)Annihilation diagrams



We recover the two extreme regimes.

The Model

M. Hirsch, R.A. Lineros, S. Morisi, J. Palacio, N. Rojas, J.W.F. Valle.
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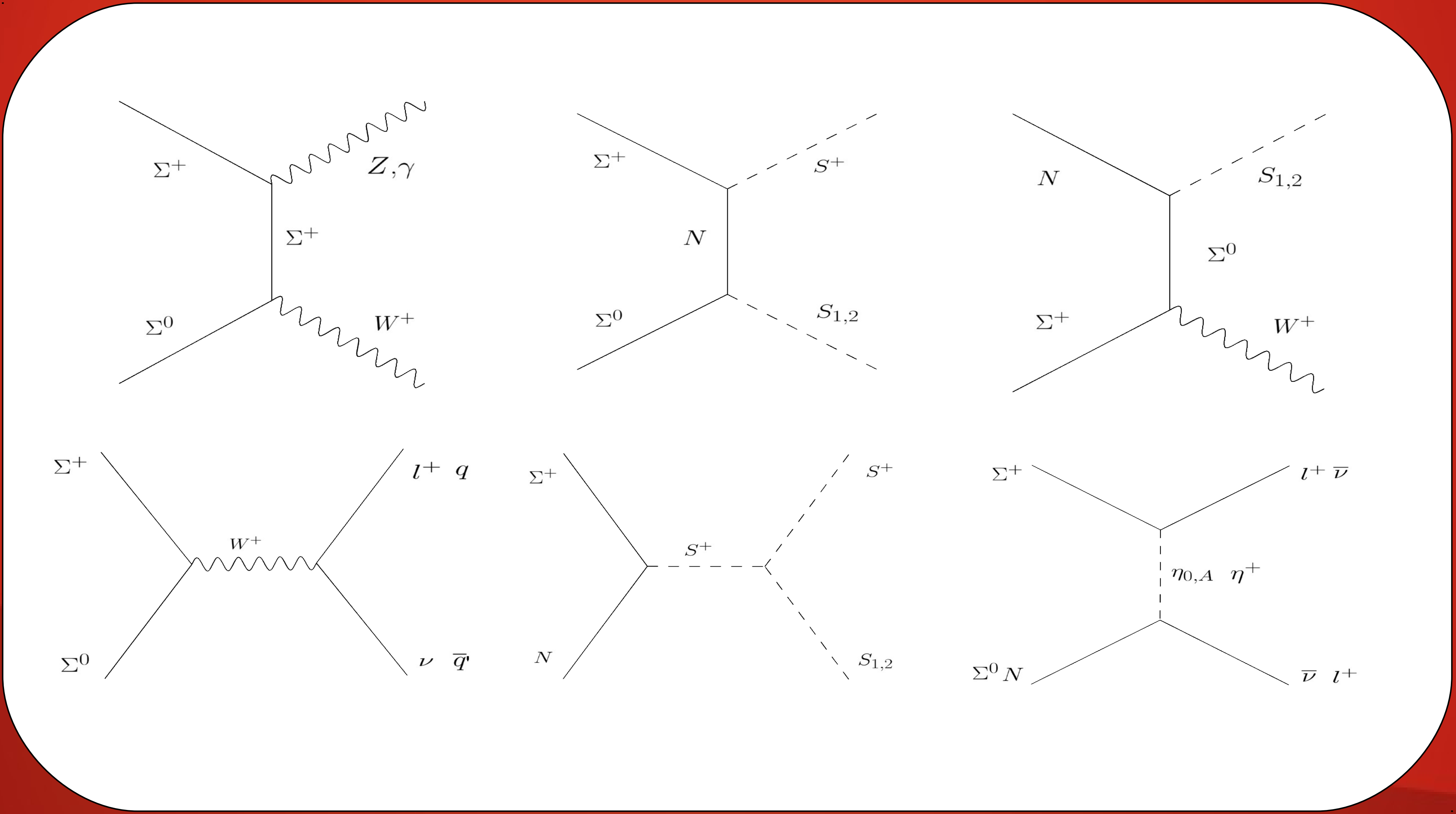
Charged co-Annihilation diagrams



We ALSO recover the two extreme regimes.

The Scan

We used micrOMEGAs to do a parameter scan

G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov, arXiv:1305.0237 [hep-ph]

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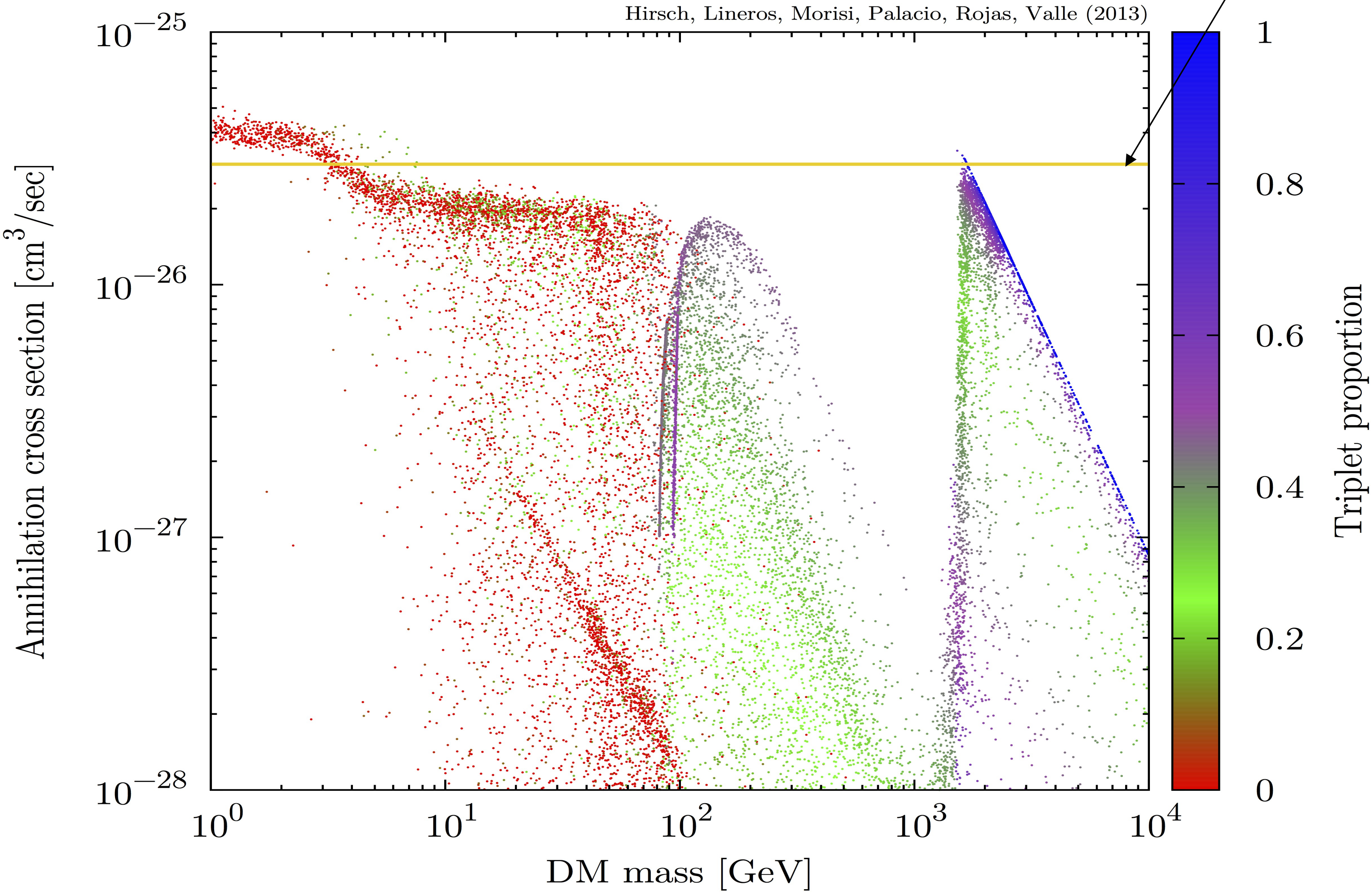
Searches of new physics:

Parameter	Range
M_N (GeV)	$1 - 10^5$
M_Σ (GeV)	$100 - 10^5$
$m_{\eta^\pm}$ (GeV)	$100 - 10^5$
m_{η^0} (GeV)	$1 - 10^5$
$M_\pm$ (GeV)	$100 - 10^4$
$\lvert\lambda_i\rvert$	$10^{-4} - 1$
$\lvert Y_i\rvert$	$10^{-4} - 1$

The Model

Annihilation cross section



$$\Omega_{CDM}h^2 \approx 0.1 \frac{3 \cdot 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle_{f.o.}}$$

The Model

$$
\begin{aligned}
V \;=\;& -m_1^2\phi^\dagger\phi + m_2^2\eta^\dagger\eta + \frac{\lambda_1}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 + \lambda_3\left(\phi^\dagger\phi\right)\left(\eta^\dagger\eta\right) \\
+\;& \lambda_4\left(\phi^\dagger\eta\right)\left(\eta^\dagger\phi\right) + \frac{\lambda_5}{2}\left(\phi^\dagger\eta\right)^2 + h.c. - \frac{M_\Omega^2}{4}Tr\left(\Omega^\dagger\Omega\right) + \left(\mu_1\phi^\dagger\Omega\phi + h.c.\right) \\
+\;& \lambda_1^\Omega\phi^\dagger\phi\, Tr\left(\Omega^\dagger\Omega\right) + \lambda_2^\Omega\left(Tr(\Omega^\dagger\Omega)\right)^2 + \lambda_3^\Omega Tr(\left(\Omega^\dagger\Omega\right)^2) + \lambda_4^\Omega\left(\phi^\dagger\Omega\right)\left(\Omega^\dagger\phi\right) \\
+\;& \left(\mu_2\eta^\dagger\Omega\eta + h.c.\right) + \lambda_1^\eta\eta^\dagger\eta\, Tr\left(\Omega^\dagger\Omega\right) + \lambda_4^\eta\left(\eta^\dagger\Omega\right)\left(\Omega^\dagger\eta\right)\,.
\end{aligned}
$$

$$
\begin{aligned}
\phi &= \begin{pmatrix} \varphi^+ \\ (h + v_h + i\varphi)/\sqrt{2} \end{pmatrix} \\
\eta &= \begin{pmatrix} \eta^+ \\ (\eta_0 + i\eta_A)/\sqrt{2} \end{pmatrix} \\
\Omega &= \begin{pmatrix} (\Omega_0 + v_\Omega) & \sqrt{2}\,\Omega^+ \\ \sqrt{2}\,\Omega^- & -(\Omega_0 + v_\Omega) \end{pmatrix}
\end{aligned}
$$

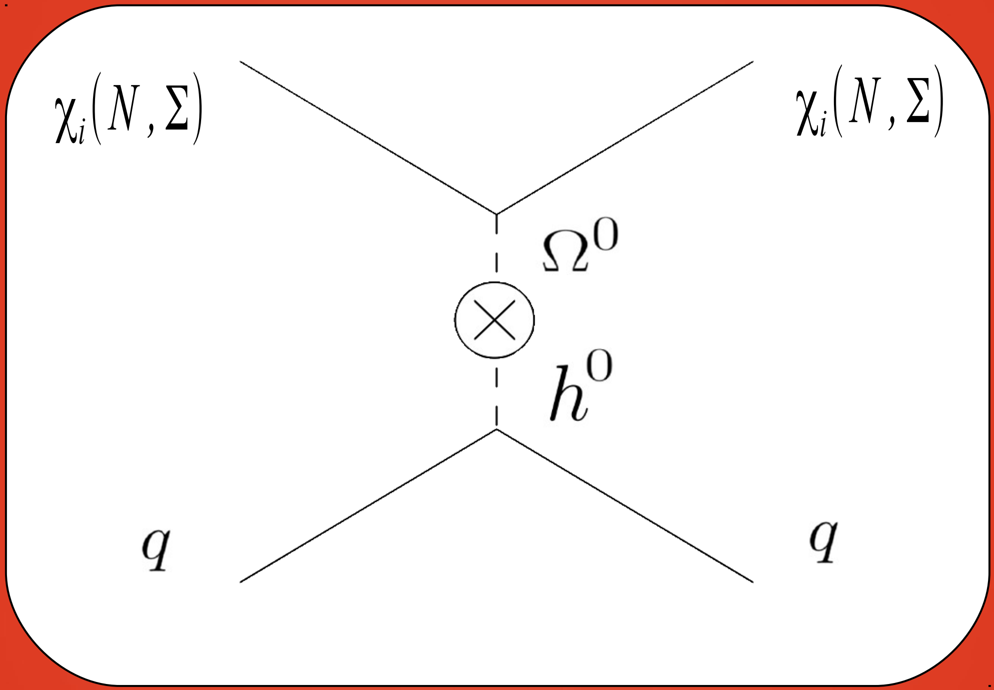
The Model

$$\begin{aligned} V &= -m_1^2\phi^\dagger\phi + m_2^2\eta^\dagger\eta + \frac{\lambda_1}{2}\left(\phi^\dagger\phi\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 + \lambda_3\left(\phi^\dagger\phi\right)\left(\eta^\dagger\eta\right) \\ &+ \lambda_4\left(\phi^\dagger\eta\right)\left(\eta^\dagger\phi\right) + \frac{\lambda_5}{2}\left(\phi^\dagger\eta\right)^2 + h.c. - \frac{M_\Omega^2}{4}Tr\left(\Omega^\dagger\Omega\right) + \left(\mu_1\phi^\dagger\Omega\phi + h.c.\right) \\ &+ \lambda_1^\Omega\phi^\dagger\phi\, Tr\left(\Omega^\dagger\Omega\right) + \lambda_2^\Omega\left(Tr(\Omega^\dagger\Omega)\right)^2 + \lambda_3^\Omega Tr(\left(\Omega^\dagger\Omega\right)^2) + \lambda_4^\Omega\left(\phi^\dagger\Omega\right)\left(\Omega^\dagger\phi\right) \\ &+ \left(\mu_2\eta^\dagger\Omega\eta + h.c.\right) + \lambda_1^\eta\eta^\dagger\eta\, Tr\left(\Omega^\dagger\Omega\right) + \lambda_4^\eta\left(\eta^\dagger\Omega\right)\left(\Omega^\dagger\eta\right) . \end{aligned}$$

$$\begin{aligned} \phi &= \begin{pmatrix} \varphi^+ \\ (h + v_h + i\varphi)/\sqrt{2} \end{pmatrix} \\ \eta &= \begin{pmatrix} \eta^+ \\ (\eta_0 + i\eta_A)/\sqrt{2} \end{pmatrix} \\ \Omega &= \begin{pmatrix} (\Omega_0 + v_\Omega) & \sqrt{2}\,\Omega^+ \\ \sqrt{2}\,\Omega^- & -(\Omega_0 + v_\Omega) \end{pmatrix} \end{aligned}$$

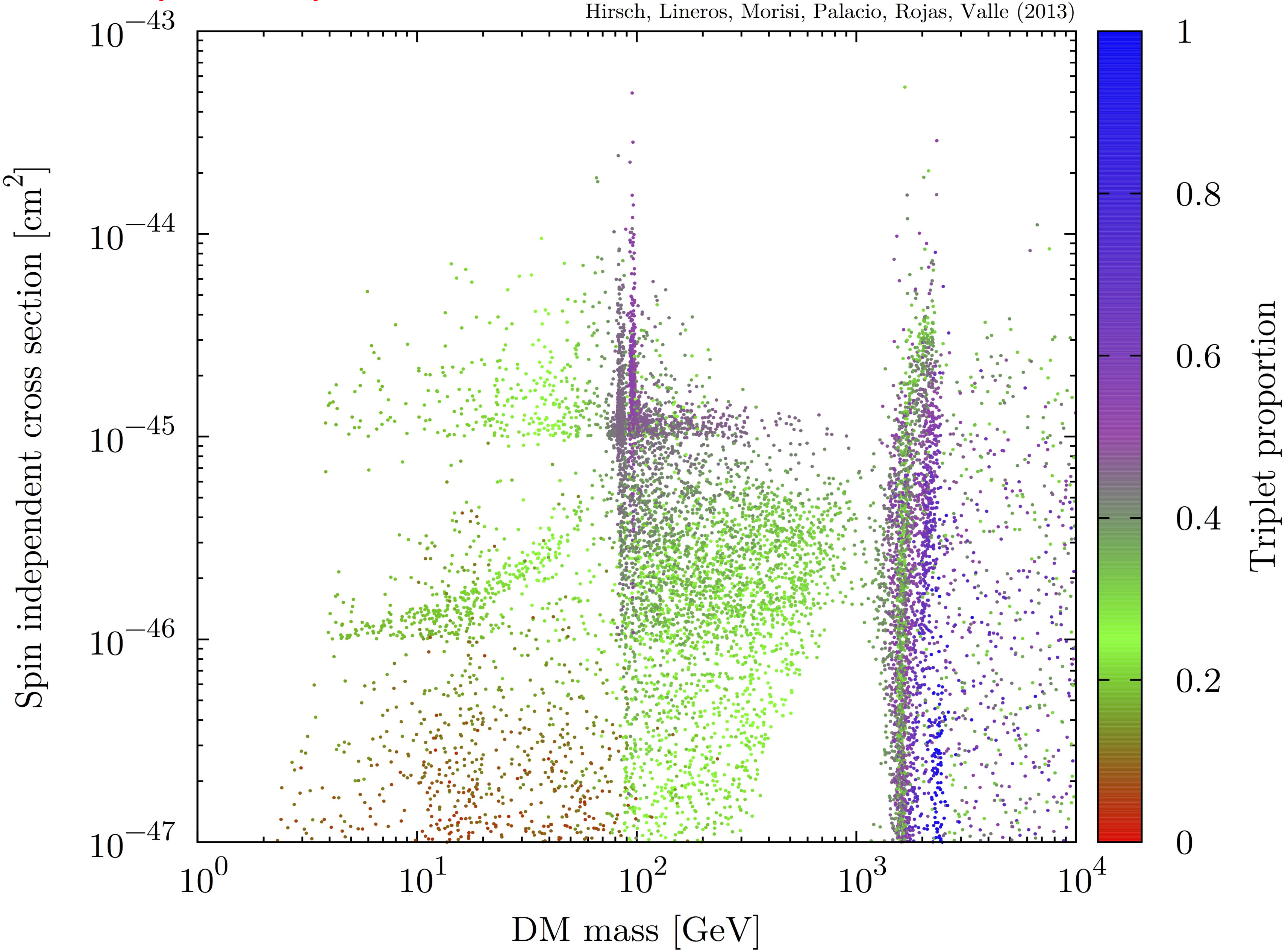
The Model

Direct signals



The Model

Spin independent cross section



Conclusions

Dark Matter and neutrino oscillations are the most robust evidence of physics beyond de Standard Model

We linked both phenomenas in this model: Neutrino mass-generating mechanism also stabilizes the Dark Matter.

The mixture scenario, Ω, gain the nice thinks of both pure Models: light DM with a rich phenomenology

The same mechanism that produces the fermion mixing also predicts a high interaction with quarks

Conclusions

Dark Matter and neutrino oscillations are the most robust evidence of physics beyond de Standard Model

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Thanks

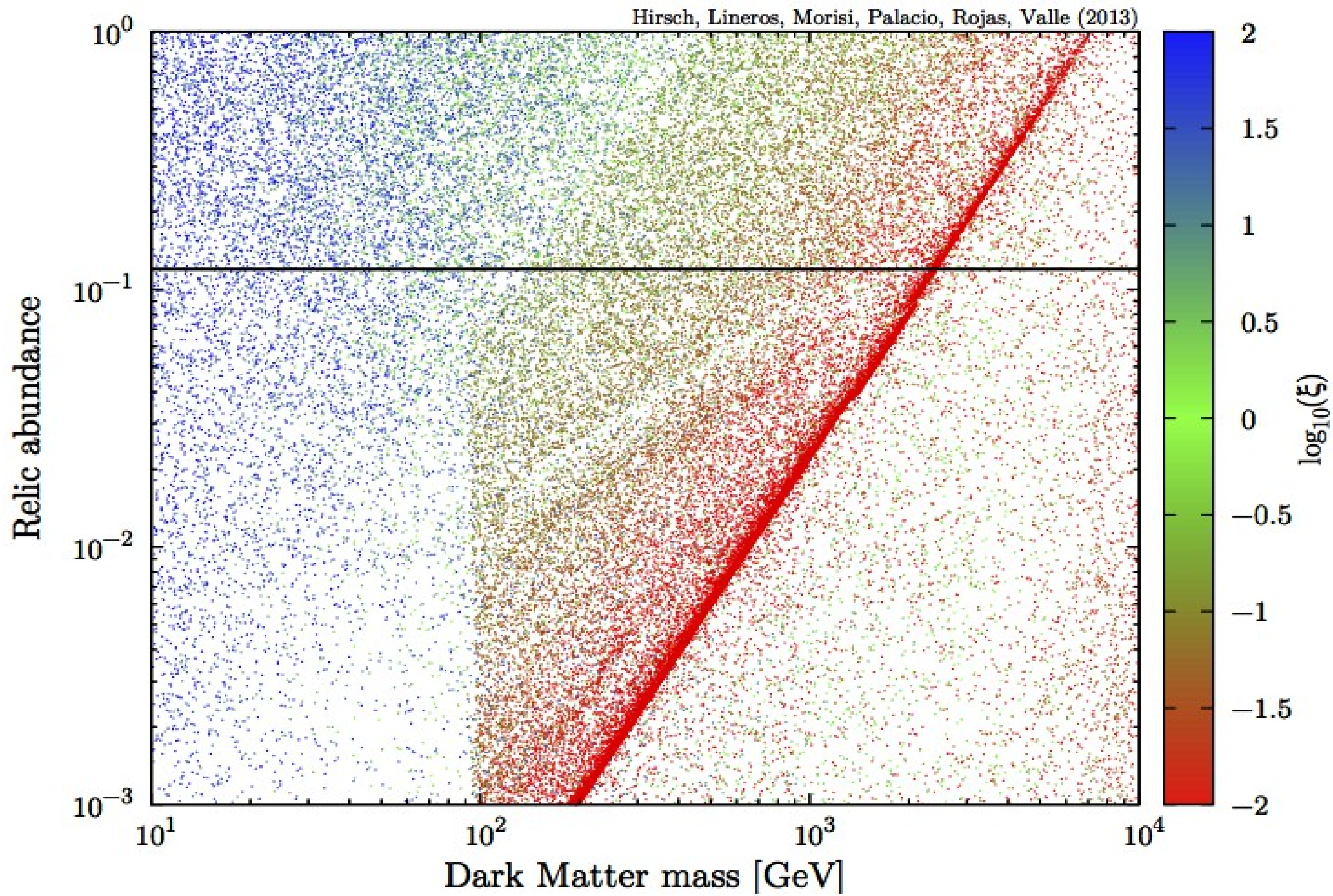
Back-up slides

Scalar sector

$$\mathcal{M}_s^2 = \begin{pmatrix} \lambda_1 v_h^2 + \frac{t_h}{v_h} & -2\mu_1 v_h + 4 v_h v_\Omega \left(\lambda_1^\Omega + \frac{\lambda_4^\Omega}{2}\right) \\ -2\mu_1 v_h + 4 v_h v_\Omega \left(\lambda_1^\Omega + \frac{\lambda_4^\Omega}{2}\right) & \frac{\mu_1 v_h^2}{v_\Omega} + 16 v_\Omega^2 \left(2\lambda_2^\Omega + \lambda_3^\Omega\right) + \frac{t_\Omega}{v_\Omega} \end{pmatrix}$$

$$\begin{aligned} M_{S1}^2 &= v_h^2 \lambda_1 \cos(\theta_0)^2 + 4 v_h \left[-v_\Omega \left(2\lambda_1^\Omega + \lambda_4^\Omega\right) + \mu_1\right] \cos(\theta_0)^2 \sin(\theta_0)^2 \\ &+ \left[16 v_\Omega^2 \left(2\lambda_2^\Omega + \lambda_3^\Omega\right) + \mu_1 v_h^2 / v_\Omega\right] \sin(\theta_0)^2 \\ M_{S2}^2 &= v_h^2 \lambda_1 \sin(\theta_0)^2 + 4 v_h \left[v_\Omega \left(2\lambda_1^\Omega + \lambda_4^\Omega\right) - \mu_1\right] \cos(\theta_0)^2 \sin(\theta_0)^2 \\ &+ \left[16 v_\Omega^2 \left(2\lambda_2^\Omega + \lambda_3^\Omega\right) + \mu_1 v_h^2 / v_\Omega\right] \cos(\theta_0)^2 \\ &\text{where } \tan(2\theta_0) = \frac{4 v_h \left[v_\Omega \left(2\lambda_1^\Omega + \lambda_4^\Omega\right) - \mu_1\right]}{16 v_\Omega^2 \left(2\lambda_2^\Omega + \lambda_3^\Omega\right) - v_h^2 \left(\lambda_1 - \mu_1 / v_\Omega\right)} \end{aligned}$$

Scan constrains



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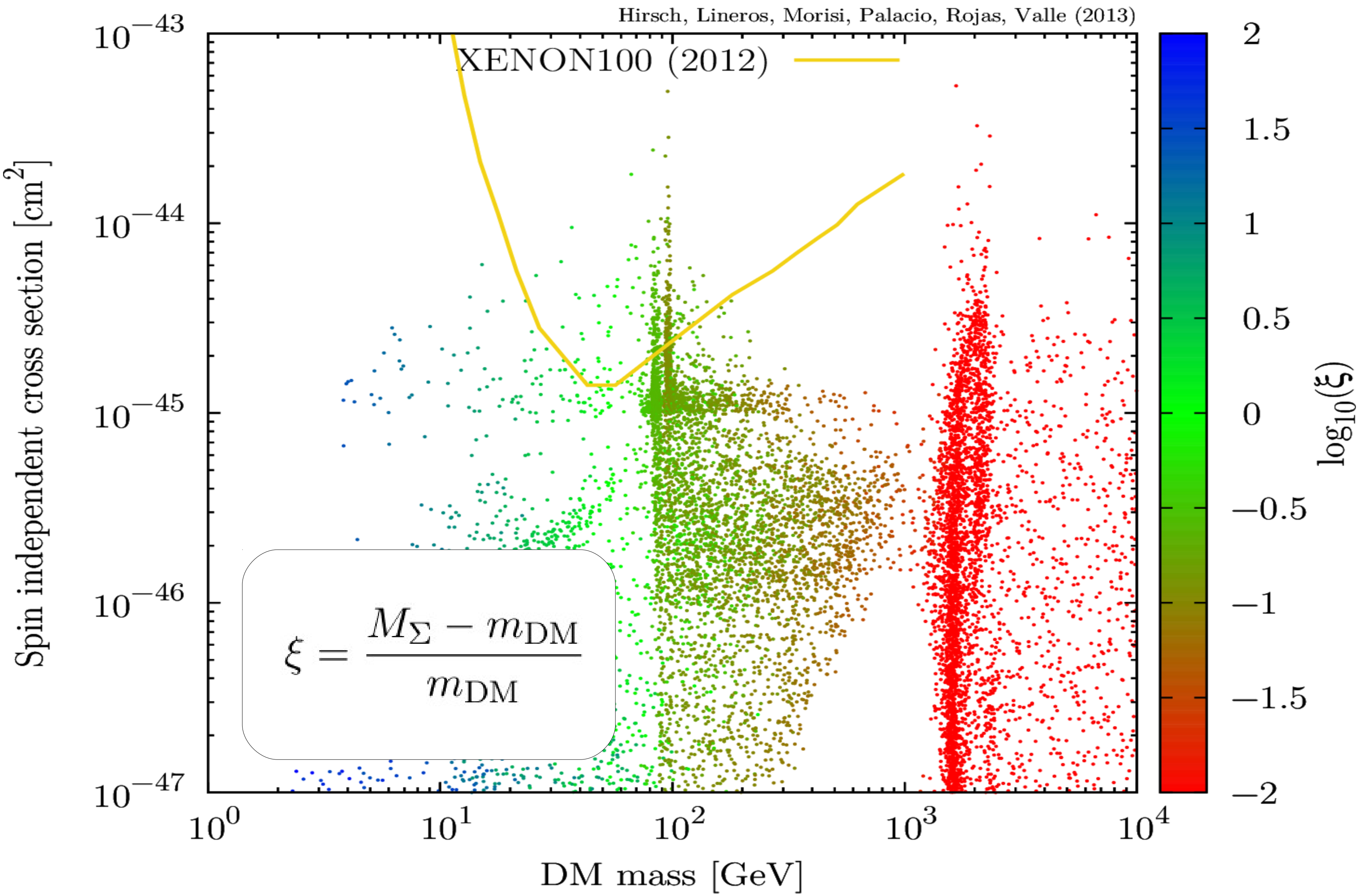

$$\xi = \frac{M_\Sigma - m_{\rm DM}}{m_{\rm DM}}$$

Scalar sector

-Z2

$$
\begin{aligned}
m_{\eta 0}^2 &= m_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 + \lambda_5\right) v_h^2 + \left(2\lambda_1^\eta + \lambda_4^\eta\right) v_\Omega^2 - 2\mu_2 v_\Omega\,, \\
m_{\eta A}^2 &= m_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 - \lambda_5\right) v_h^2 + \left(2\lambda_1^\eta + \lambda_4^\eta\right) v_\Omega^2 - 2\mu_2 v_\Omega\,, \\
m_{\eta \pm}^2 &= m_2^2 + \frac{1}{2}\lambda_3 v_h^2 + 2\mu_2 v_\Omega + \left(2\lambda_1^\eta + \lambda_4^\eta\right) v_\Omega^2\,.
\end{aligned}
$$

λ5 plays an important role in ν masses