Collider signals of Scotogenic models

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There are MANY
Majorana neutrino mass models...

Tree-level

Radiative: 1-loop, 2-loop, 3-loop, ...

High scale

Low scale

Dimension-5: Weinberg operator

Higher dimensions: dim-7, dim-9, ...

There are MANY Majorana neutrino mass models...

Review: [Cai, Herrero-García, Schmidt, AV, Volkas, 2017]

Tree-level

Radiative: 1-loop, 2-loop, 3-loop, ...

High scale

Low scale

Dimension-5: Weinberg operator

Higher dimensions: dim-7, dim-9, ...

Loop suppression

Dark matter candidate

Collider signals

Outline

Introduction

Finished already!

The Scotogenic model

A quick review of the well-known Scotogenic model

Generalizing the Scotogenic model

A variant of the Scotogenic model with a richer LHC phenomenology

The Scotogenic model

Also known as...

The inert doublet model

The radiative seesaw

Ma's model

The Scotogenic model

[Ma, 2006]

σκότος

skotos = darkness

	gen	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
η	1	**2**	1/2	$-$
N	3	**1**	0	$-$

← Inert (or dark) doublet

← Singlet fermion ("HNL")

Dark Matter!

$$\mathcal{L}_N = \overline{N_i} \partial\!\!\!/ N_i - \frac{M_{R_i}}{2} \overline{N_i^c} N_i + y_{i\alpha} \eta \overline{N_i} \ell_\alpha + \text{h.c.}$$

$$\mathcal{V} = m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} \left(H^\dagger H\right)^2 + \frac{\lambda_2}{2} \left(\eta^\dagger \eta\right)^2 + \lambda_3 \left(H^\dagger H\right) \left(\eta^\dagger \eta\right)$$
$$+ \lambda_4 \left(H^\dagger \eta\right) \left(\eta^\dagger H\right) + \frac{\lambda_5}{2} \left[\left(H^\dagger \eta\right)^2 + \left(\eta^\dagger H\right)^2\right]$$

Radiative neutrino masses

[Ma, 2006]

Tree-level:

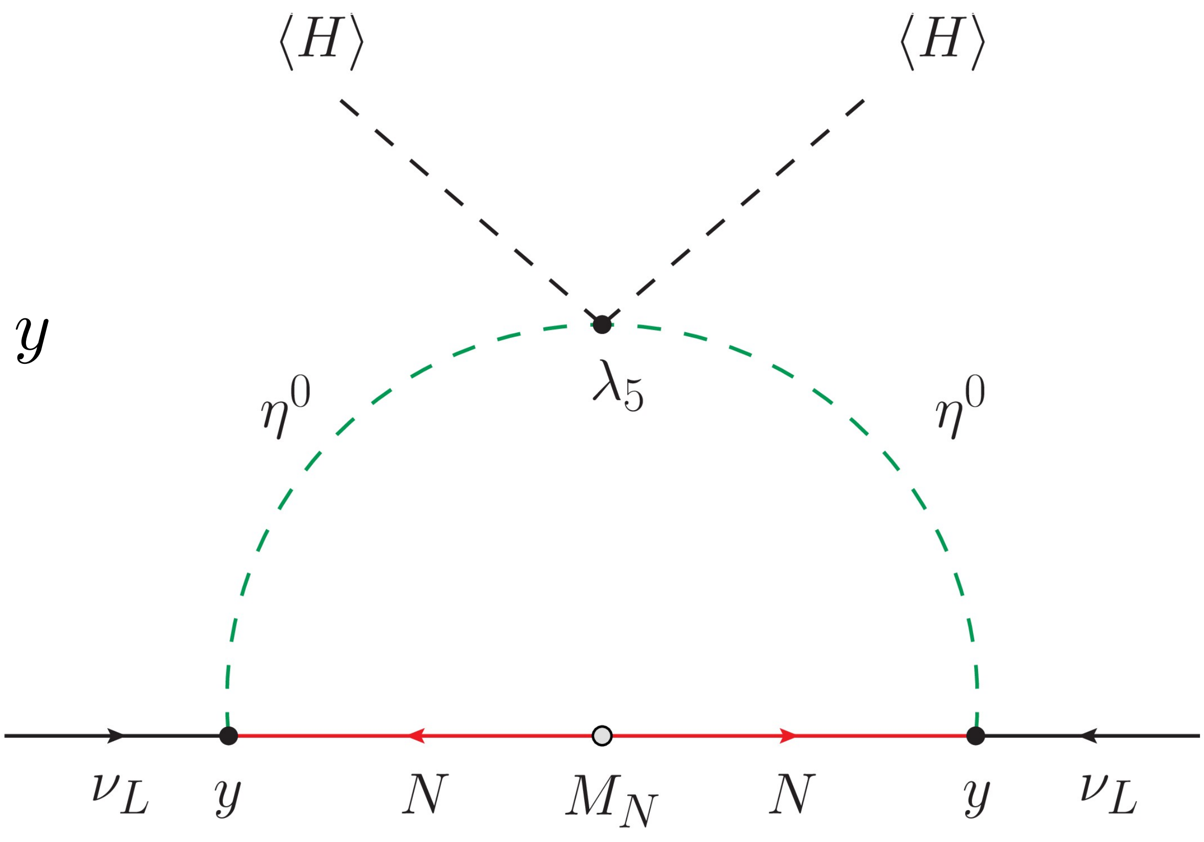
Forbidden by the $\mathbb{Z}_2$ symmetry

Radiative generation of neutrino masses

$$m_\nu = \frac{\lambda_5 v^2}{32\pi^2} \, y^T \, M_R^{-1} f_{\rm loop} \, y$$

Dark particles in the loop

1-loop neutrino masses



Collider signals

$\mathbb{Z}_2$ $\Longrightarrow$ The singlet fermions do not mix with the LH neutrinos and remain as pure singlets $\Longrightarrow$ The usual searches for HNLs are no longer valid

$\longrightarrow$ Talk by Xabi Marcano

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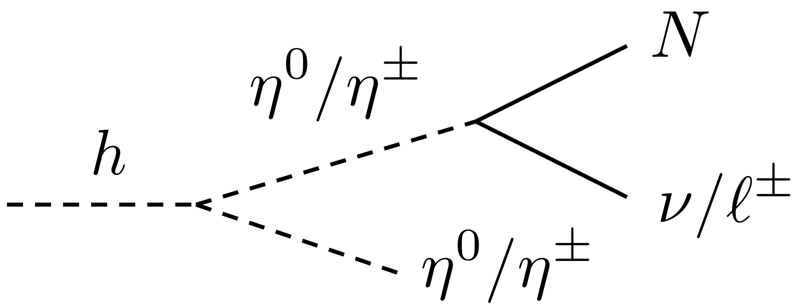
→ Talk by Xabi Marcano

☆ **Higgs boson decays** [Ho, Tandean, 2013]

→ Leptons and/or MET



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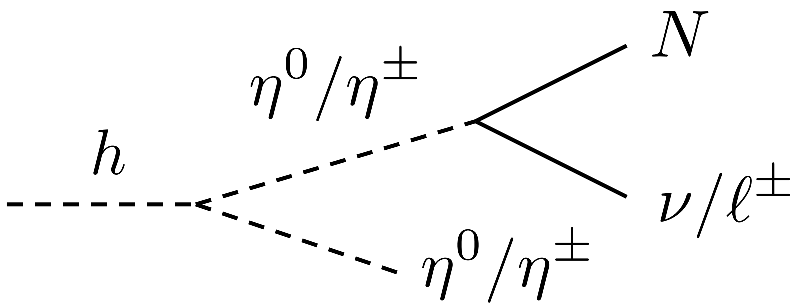
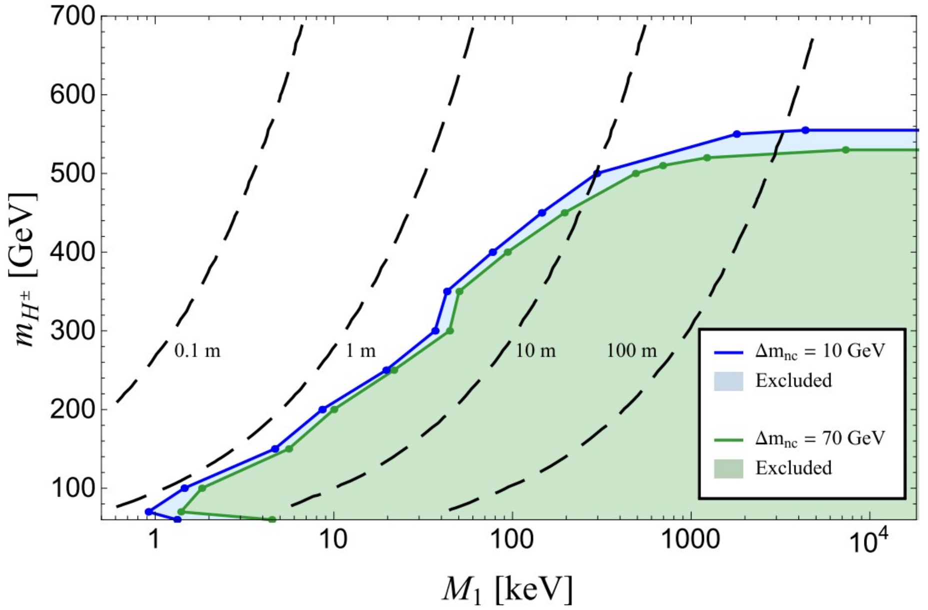


☆ **FIMP @ LHC** [Hessler et al, 2016]

⟶ Assume N produced by freeze-in

⟶ $\eta^\pm$ produced by DY or η^0 decays

⟶ $\eta^\pm \to N\,\ell^\pm$ with charged track



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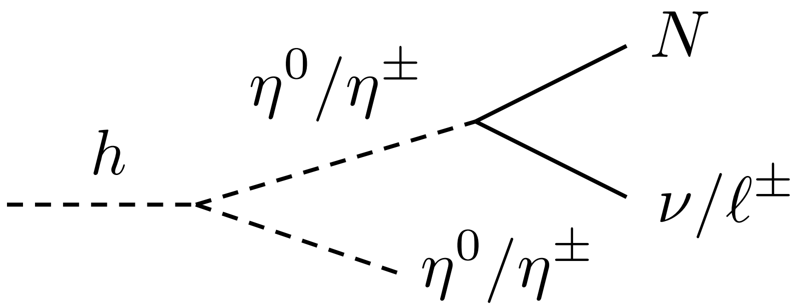

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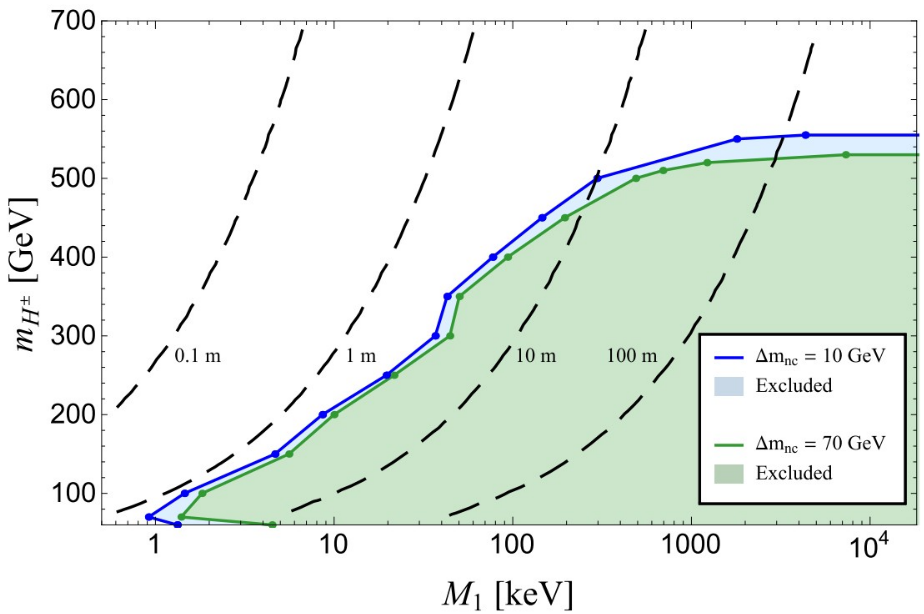


☆ **Effects in e^+e^- colliders** [Ho, Tandean, 2013] **+ Inert Doublet Model at colliders** [...]

Generalizing the Scotogenic model

Chuck Norris fact of the day

Chuck Norris counted to infinity. Twice.

Beyond the Scotogenic model

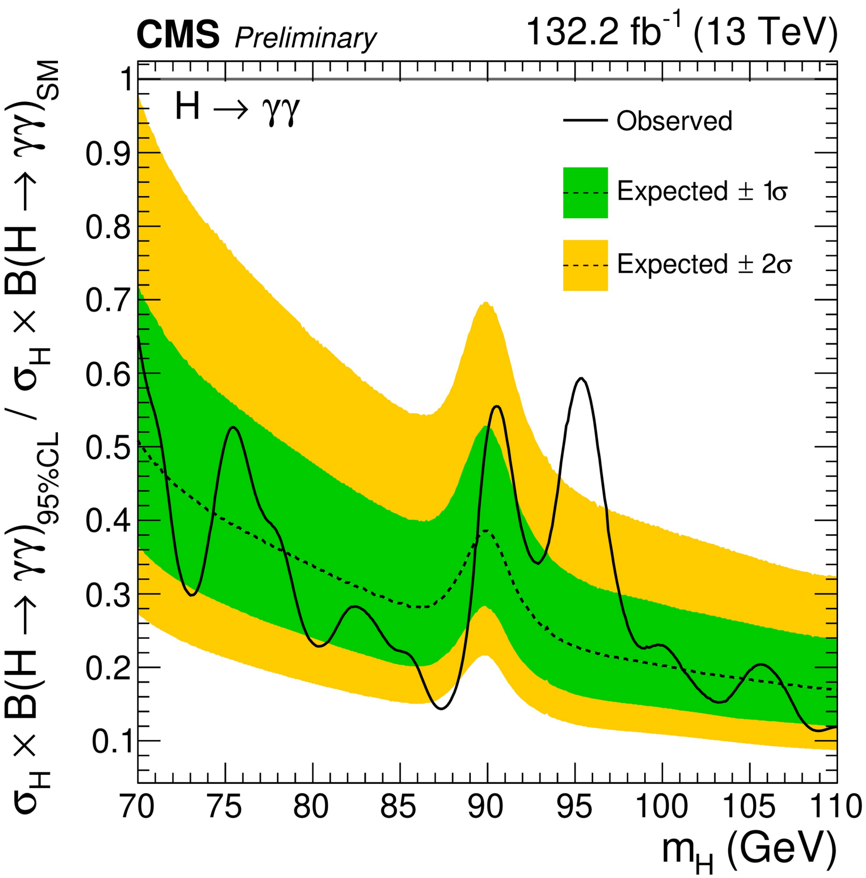
From “model” to “paradigm”

There are multiple Scotogenic paths to explore:

- Number of generations of each Scotogenic state
- Representations under the gauge group
- Additional Scotogenic states
- Spontaneous violation of lepton number
- ...

The 95 GeV excess

[CMS-PAS-HIG-20-002]



$\mathbf{2.9}\,\boldsymbol{\sigma}$ (local) at $\mathbf{95.4}\,\mathrm{GeV}$

$$\mu_{\gamma\gamma}^{\rm CMS} = \frac{\sigma^{\rm exp}(gg \to X \to \gamma\gamma)}{\sigma^{\rm SM}(gg \to H \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}$$

[Gascon-Shotkin, MoriondEW 2023]

[Biekötter et al, 2023]

+ **ATLAS** *mild excess* at 95 GeV ($\sim \mathbf{1}\,\boldsymbol{\sigma}$)

+ *hints* (also at 95 GeV) in $\begin{cases} b\bar{b} & \text{(LEP)} \\ \tau^+\tau^- & \text{(CMS)} \end{cases}$

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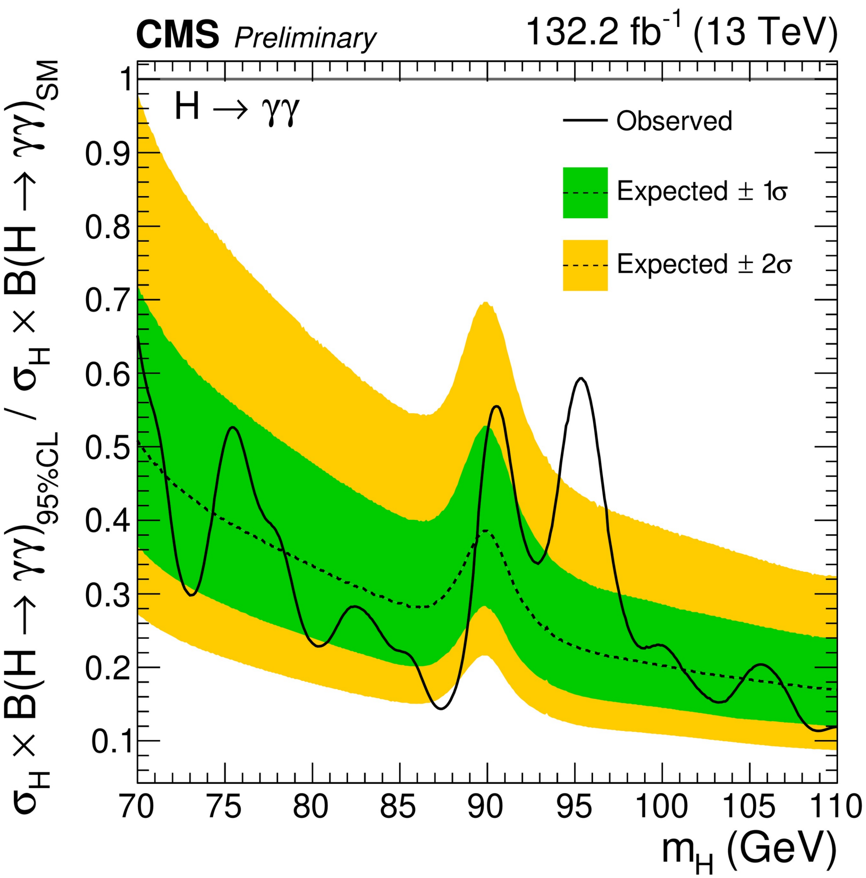

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Careful: remember any recent diphoton excess?

A Scotogenic explanation for the 95 GeV excess

[Escribano, Martin Lozano, AV, in progress]

	gen	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
η	n_η	$\mathbf{2}$	$1/2$	$-$
S	1	$\mathbf{1}$	0	$+$
N	n_N	$\mathbf{1}$	0	$-$

η ← Variable number of generations

S ← Real scalar singlet

N ← Variable number of generations

[Escribano, Reig, AV, 2020]

$$\mathcal{L} \supset -\frac{M_{R_n}}{2} \overline{N_n^c} N_n + \kappa_n S \overline{N_n^c} N_n + y_{na\alpha} \eta_a \overline{N_n} \ell_\alpha + \text{h.c.}$$
$$-\lambda_1 \left(H^\dagger H\right)^2 - \frac{\lambda_S}{4} S^4 - \frac{\lambda^{HS}}{2} \left(H^\dagger H\right) S^2 - \lambda_3^{ab} \left(H^\dagger H\right)\left(\eta_a^\dagger \eta_b\right) - \frac{\lambda_3^{\eta S,ab}}{2} \left(\eta_a^\dagger \eta_b\right) S^2$$
$$-\mu \left(\eta_a^\dagger \eta_b\right) S + \ldots$$

Rich scalar sector with multiple states ⇒ idea

$$\begin{cases} h_1 = h_{95} \\ h_2 = h_{125} \end{cases}$$

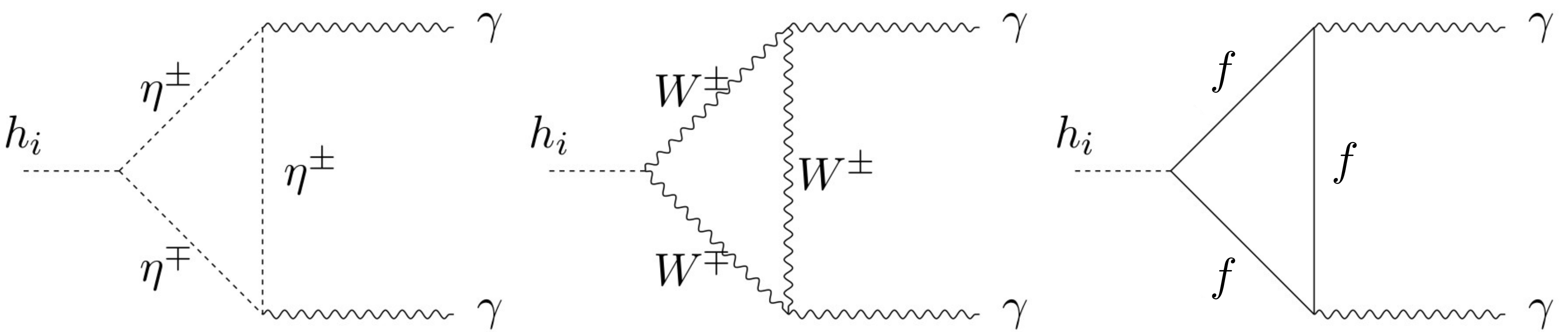
A Scotogenic explanation for the 95 GeV excess

[Escribano, Martin Lozano, AV, in progress]

h_1 production

Only via H-S mixing ⇒ Suppressed by $\sin^2\alpha$

h_1 decays

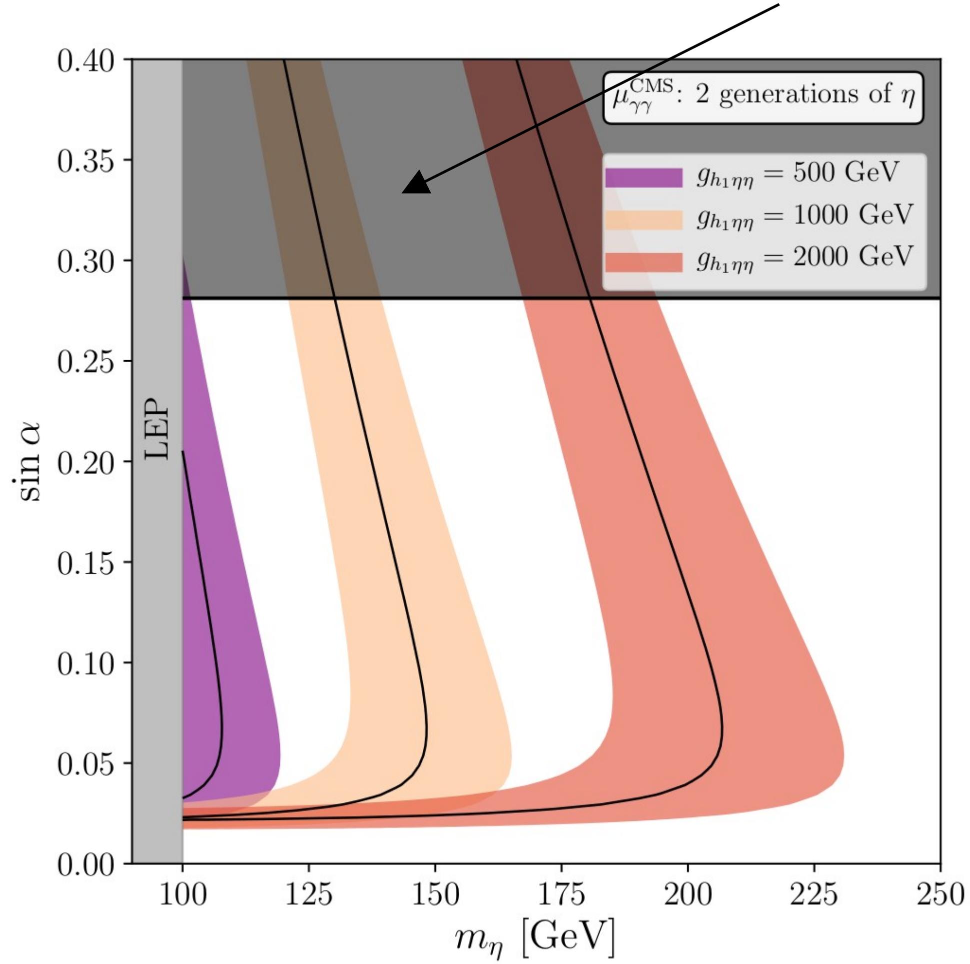


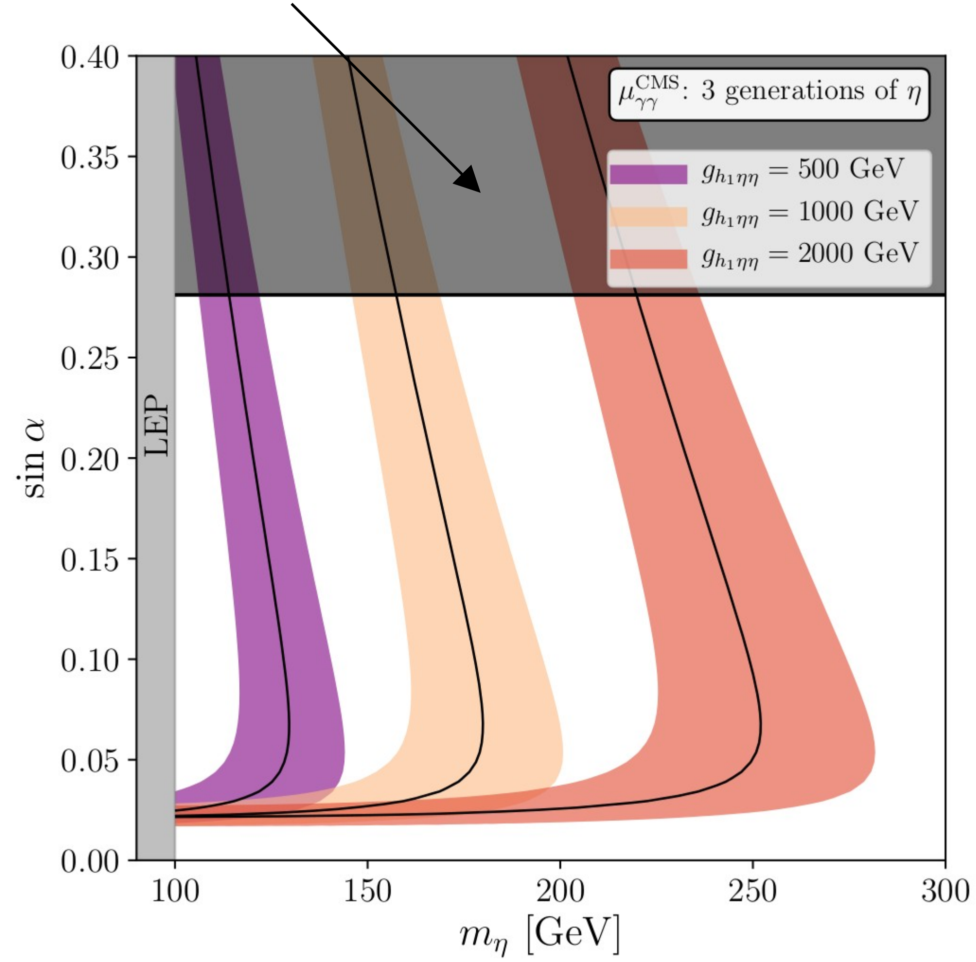
Scotogenic contribution!

$$\mu_{\gamma\gamma} = \frac{\sigma(gg \to h_1)}{\sigma_{\rm SM}(gg \to H)} \times \frac{{\rm BR}(h_1 \to \gamma\gamma)}{{\rm BR}_{\rm SM}(H \to \gamma\gamma)} = \sin^2\alpha \, \frac{{\rm BR}(h_1 \to \gamma\gamma)}{{\rm BR}_{\rm SM}(H \to \gamma\gamma)}$$

A Scotogenic explanation for the 95 GeV excess

Excluded by Higgs (h_2) data





Bottom line: the excess can be easily accommodated

Final discussion

Scotogenic neutrino mass models constitute an economical class of models addressing the dark matter and neutrino mass problems. There are plenty of ways to go beyond the minimal model with observable collider signals

- One generally expects leptons and MET in final states
- Modified Higgs phenomenology
- A possible Scotogenic explanation for the 95 GeV excess

Final discussion

Scotogenic neutrino mass models constitute an economical class of models addressing the dark matter and neutrino mass problems. There are plenty of ways to go beyond the minimal model with observable collider signals

- ☆ One generally expects leptons and MET in final states
- ☆ Modified Higgs phenomenology
- ☆ A possible Scotogenic explanation for the 95 GeV excess

Thanks for your attention!

Backup slides

The Scotogenic model

[Ma, 2006]

$$\mathcal{V} = m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} \left(H^\dagger H\right)^2 + \frac{\lambda_2}{2} \left(\eta^\dagger \eta\right)^2 + \lambda_3 \left(H^\dagger H\right) \left(\eta^\dagger \eta\right)$$
$$+\lambda_4 \left(H^\dagger \eta\right) \left(\eta^\dagger H\right) + \frac{\lambda_5}{2} \left[\left(H^\dagger \eta\right)^2 + \left(\eta^\dagger H\right)^2\right]$$

Inert scalar sector: $\eta^\pm$ $\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$

$$m_{\eta^+}^2 = m_\eta^2 + \lambda_3 \langle H^0 \rangle^2$$
$$m_R^2 = m_\eta^2 + (\lambda_3 + \lambda_4 + \lambda_5) \langle H^0 \rangle^2$$
$$m_I^2 = m_\eta^2 + (\lambda_3 + \lambda_4 - \lambda_5) \langle H^0 \rangle^2$$

$\Rightarrow$

$$\mathrm{m}_R^2 - m_I^2 = 2\,\lambda_5\,\langle H^0 \rangle^2$$

Dark matter

The lightest particle charged under $\mathbb{Z}_2$ is stable: dark matter candidate

Fermion Dark Matter: N_1

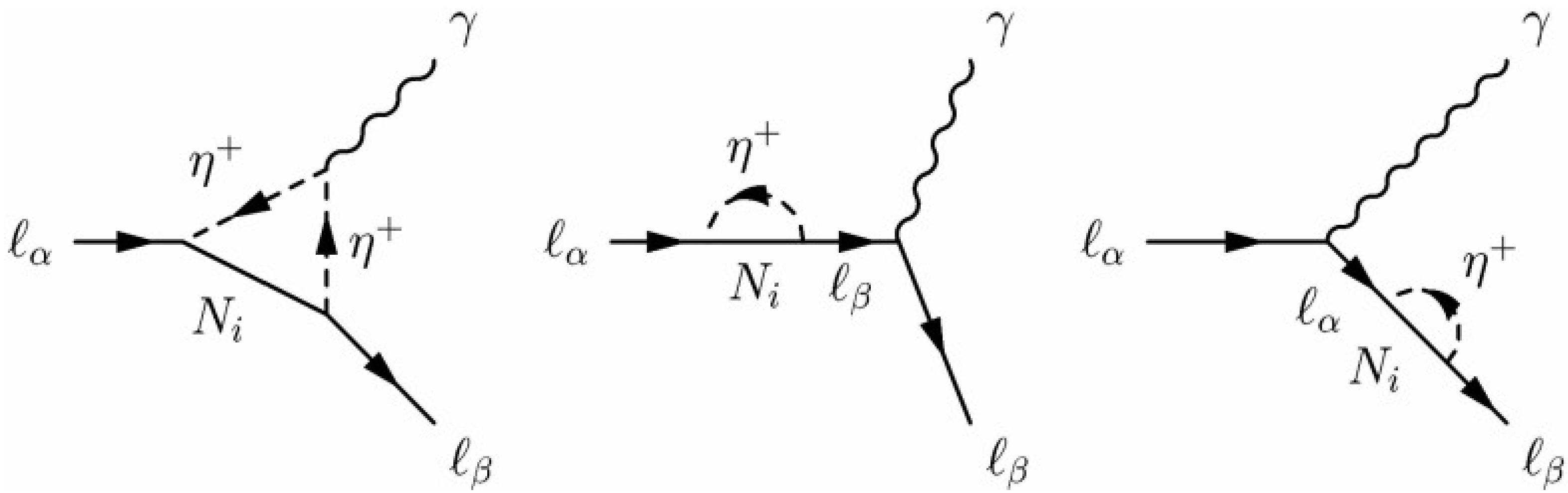
- It can only be produced via Yukawa interactions
- Potential problems with lepton flavor violation: is it compatible with the current bounds?

Scalar Dark Matter: the lightest neutral η scalar, η_R or η_I

- It also has gauge interactions
- Not correlated to lepton flavor violation

$\ell_\alpha \to \ell_\beta \gamma$

[Kubo et al, 2006]
[Ma, Raidal, 2001]



$$\mathcal{L}_{\rm eff} = \left(\frac{\mu_{\beta\alpha}}{2}\right) \overline{\ell_\beta} \sigma^{\mu\nu} \ell_\alpha F_{\mu\nu}$$

$$\mu_{\beta\alpha} = e m_\alpha A_D / 2$$

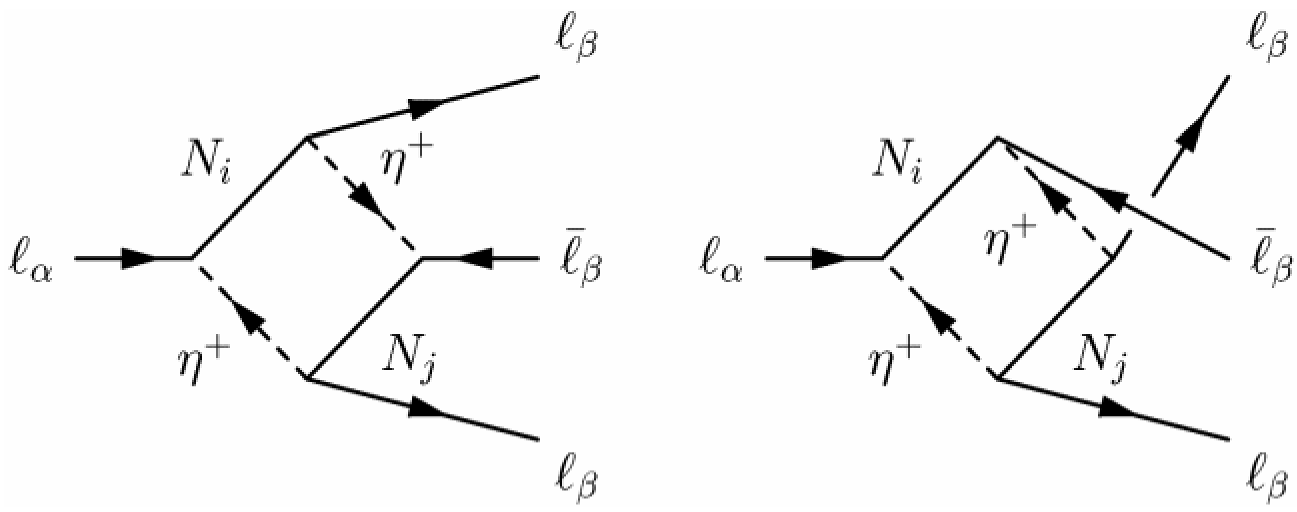
Transition magnetic moment

$$A_D = \sum_{i=1}^{3} \frac{y_{i\beta}^* y_{i\alpha}}{2(4\pi)^2} \frac{1}{m_{\eta^+}^2} F_2\left(\xi_i\right)$$

$\left(\xi_i \equiv m_{N_i}^2 / m_{\eta^+}^2\right)$

$\ell_\alpha \to 3\,\ell_\beta$

$\ell_\alpha(p) \to \ell_\beta(k_1)\bar{\ell}_\beta(k_2)\ell_\beta(k_3)$ [Toma, Vicente, 2013]



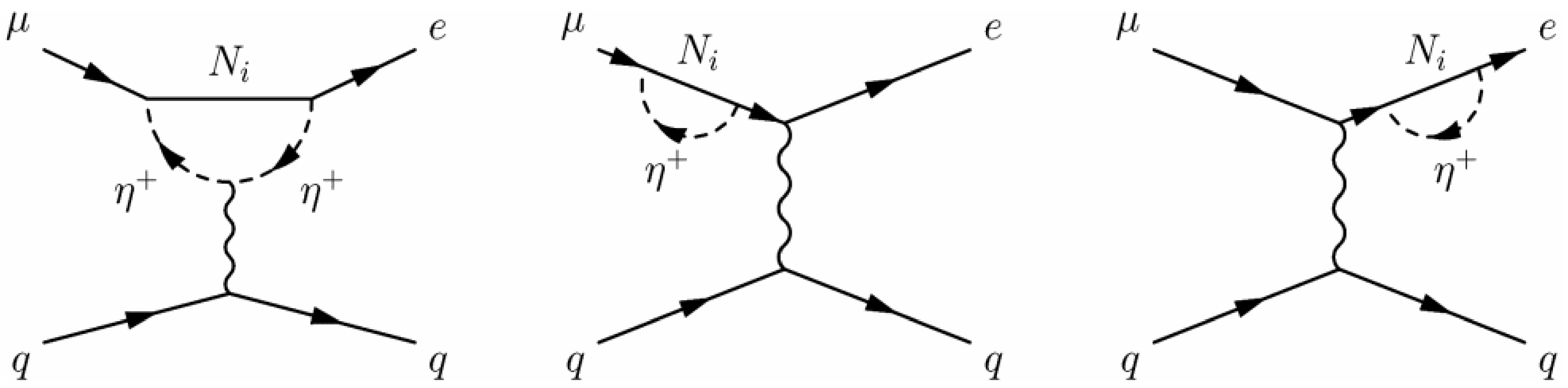
Boxes

$$i\mathcal{M}_{\rm box} = ie^2\, B\, \left[\bar{u}(k_3)\gamma^\mu P_L v(k_2)\right]\left[\bar{u}(k_1)\gamma_\mu P_L u(p)\right]$$

$$e^2 B = \frac{1}{(4\pi)^2 m_{\eta^+}^2}\sum_{i,\,j=1}^{3}\left[\frac{1}{2}D_1(\xi_i,\xi_j)y_{j\beta}^* y_{j\beta} y_{i\beta}^* y_{i\alpha} + \sqrt{\xi_i\xi_j}\,D_2(\xi_i,\xi_j)y_{j\beta}^* y_{j\beta}^* y_{i\beta} y_{i\alpha}\right]$$

$\mu - e$ conversion in nuclei

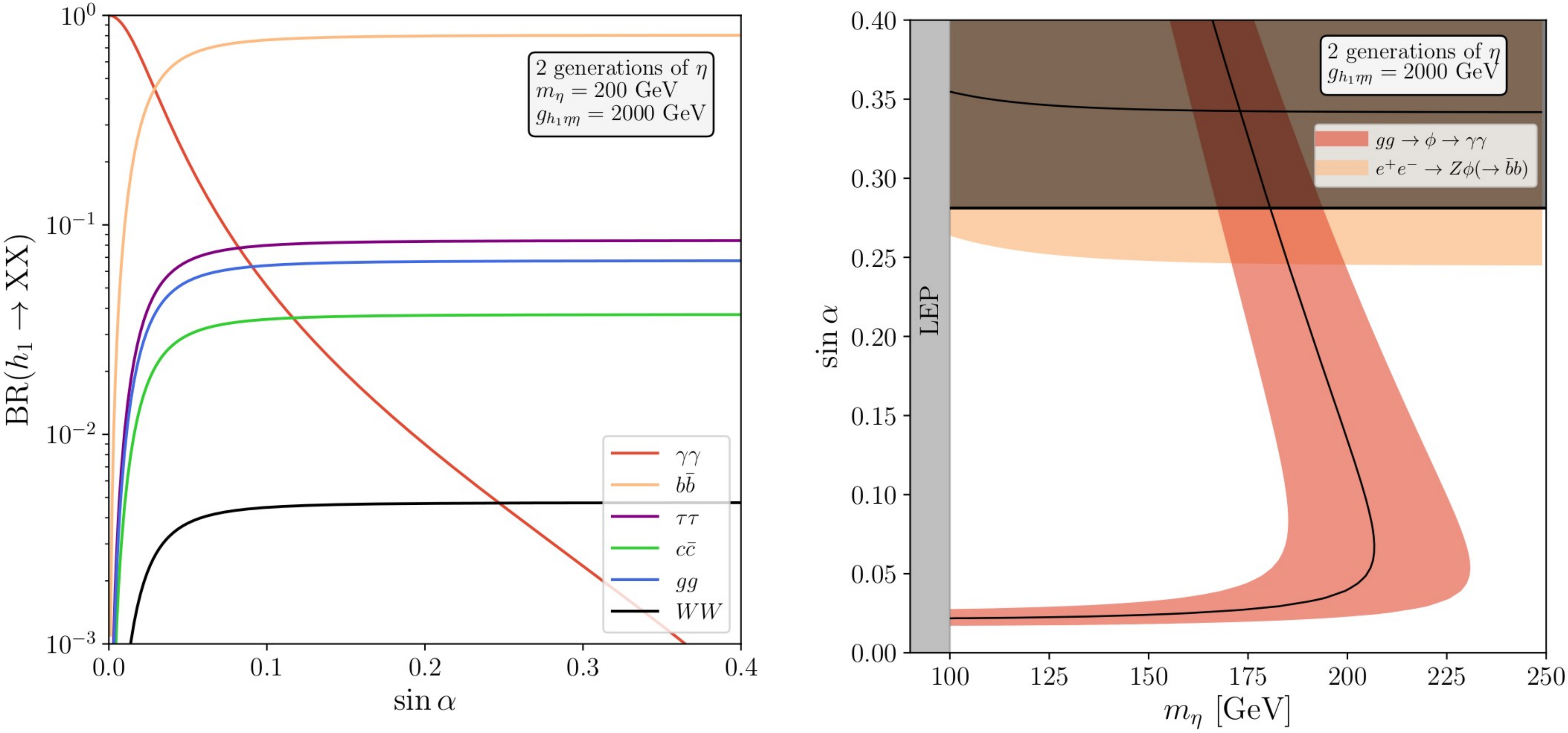
[Toma, Vicente, 2013]



- No box contributions from the inert doublet (they do not couple to the quark sector)

- The phenomenology is determined by photon penguin diagrams (Z penguins are negligible)

A Scotogenic explanation for the 95 GeV excess



A philosophical moment

Occam's razor:

The simplest explanation is the correct one

Occam's laser:

The most awesome explanation is the correct one

Occam's hammer:

My explanation is the correct one

All credit goes to
Alberto Aparici