Connecting neutrino physics with DM

Colombian Workshop on Dark Matter (MOCa) 2021

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Work in progress:
In collaboration with LMG de la Vega, L. Flores, N. Nath

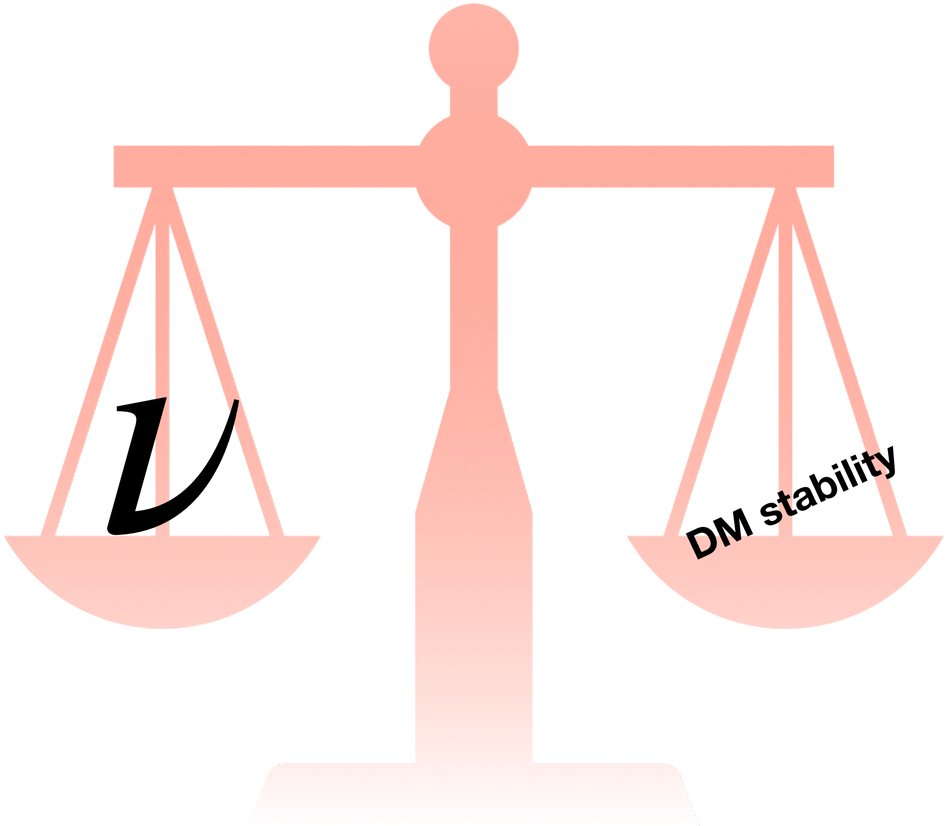
Dirección General de Asuntos del Personal Académico

CONACYT

Dirac or Majorana?

m_ν scale?

Hierarchy



Stable or long lived

Cosmological abundance

WIMP? Fermionic? Bosonic? Axionlike?

Talks by:
Bonilla, Carcamo, Cosme, Kumar, Lineros, Restrepo, Vicente…

ν nature and DM Stability

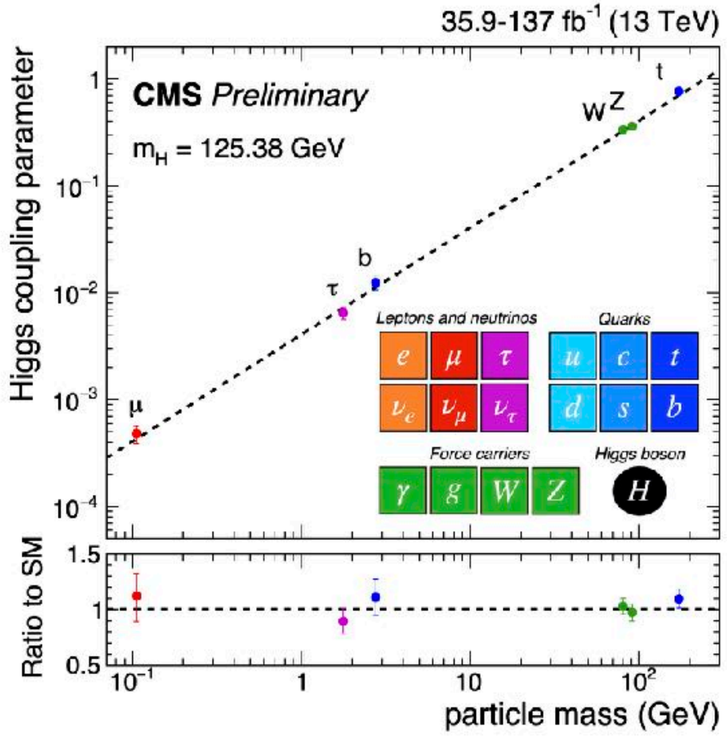
Any experimental complementarity?

Standard Model Masses

$$\mathcal{L} = i\overline{L'_{\alpha L}}\not{D}L'_{\alpha L} + i\,\overline{Q'_{\alpha L}}\not{D}Q'_{\alpha L} + i\overline{l'_{\alpha R}}\not{D}l'_{\alpha R}$$
$$+ i\overline{q'^{D}_{\alpha R}}\not{D}q'^{D}_{\alpha R} + i\overline{q'^{U}_{\alpha R}}\not{D}q'^{U}_{\alpha R} - \frac{1}{4}\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$
$$+ \left(D_\rho\Phi\right)^\dagger\left(D^\rho\Phi\right) + \mu^2\Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2$$
$$- \left(Y'^{l}_{\alpha\beta}\,\overline{L'_{\alpha L}}\,\Phi\,l'_{\beta R} + Y'^{l*}_{\alpha\beta}\,\overline{l'_{\beta R}}\,\Phi^\dagger\,L'_{\alpha L}\right)$$
$$- \left(Y'^{D}_{\alpha\beta}\,\overline{Q'_{\alpha L}}\,\Phi\,q'^{D}_{\beta R} + Y'^{D*}_{\alpha\beta}\,\overline{q'^{D}_{\beta R}}\,\Phi^\dagger\,Q'_{\alpha L}\right)$$
$$- \left(Y'^{U}_{\alpha\beta}\,\overline{Q'_{\alpha L}}\,(i\sigma_2\Phi^*)\,q'^{U}_{\beta R} + Y'^{U*}_{\alpha\beta}\,\overline{q'^{U}_{\beta R}}\,(-i\Phi^T\sigma_2)\,Q'_{\alpha L}\right)$$

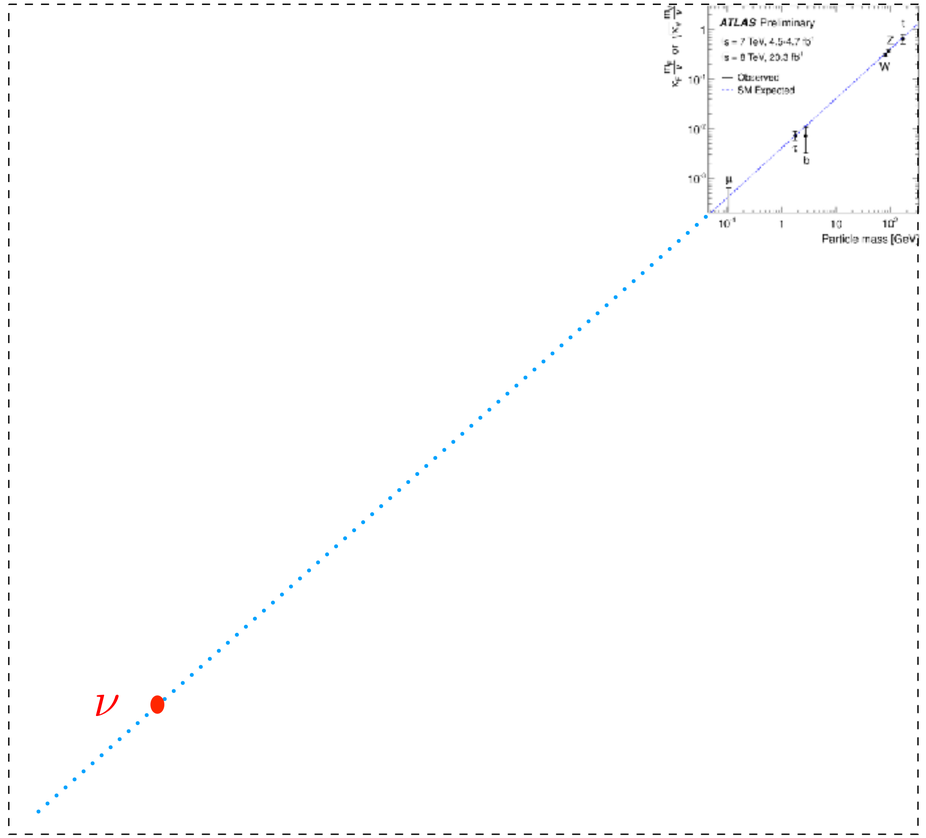
Fermion masses:

m_e	$.5\ MeV$
m_d	$4.8\ MeV$
m_u	$2.3\ MeV$
m_μ	$105\ MeV$
m_s	$95\ MeV$
m_c	$1.275\ GeV$
m_τ	$1.776\ GeV$
m_b	$4.18\ GeV$
m_t	$174\ GeV$



http://cds.cern.ch/record/2725728
CMS-PHO-GEN-2020-002

Coupling with Higgs



Particle mass

$$\sum m_\nu \leq 0.12\ eV$$

Cosmology

$$m_e^{eff} < 0.8\ eV$$

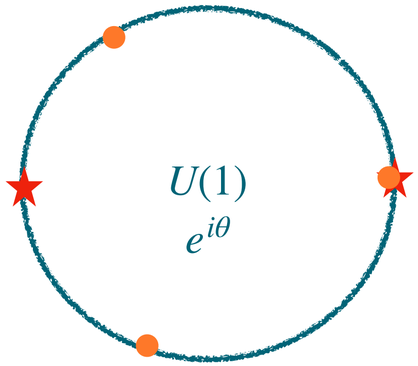
KATRIN 2021

¿Dirac o Majorana?
Hierarchy
CP violation

Dark Matter and neutrino nature $U(1)'$

$Z_2 \quad \pm 1$

$Z_3 \quad \omega^n \qquad \omega = e^{i2/3\pi}$



Krauss and Wilczek (1988)

Toy example

$$\phi \to e^{im\theta}\phi \qquad \chi \to e^{-in\theta}\chi$$

$$m < n \qquad V \supset \phi^y \chi$$

SSB $\langle \chi \rangle \neq 0$

$$V \supset \phi^y$$

Can be used for DM stability

Bonilla, Restrepo, …

$$U(1)' \to Z_N \qquad N = \frac{n}{m}$$

$U(1)'$ global or local

Nardi´s talk

Examples of breaking

$m = 1/3 \qquad n = 1$

$$V \supset \phi^3 \chi$$

$$\langle \chi \rangle = v$$

$$V \supset v\phi^3 \qquad U(1)' \to Z_3$$

$m = 1/2 \qquad n = 2$

$$V \supset \phi^4 \chi$$

$$\langle \chi \rangle = v$$

$$V \supset v\phi^4 \qquad U(1)' \to Z_4$$

Dark Matter and neutrino nature $U(1)'$

Bonilla, Centelles-Chulia, Cepedello EP, Srivastava PRD (2020)

Dirac or Majorana

$$U(1)_{B-L} \to \mathcal{Z}_m$$

$\mathcal{Z}_m \equiv \mathcal{Z}_{2n+1}$ with $n \in \mathbb{Z}^+$

Neutrinos are Dirac particles

$\mathcal{Z}_m \equiv \mathcal{Z}_{2n}$ with $n \in \mathbb{Z}^+$

Neutrinos can be Dirac or Majorana

$$L = \begin{pmatrix} \nu_L \\ l_L \end{pmatrix} \quad \begin{array}{l} \sim \omega^n \text{ under } \mathcal{Z}_{2n} \Rightarrow \text{Dirac Neutrinos} \\ \sim \omega^n \text{ under } \mathcal{Z}_{2n} \Rightarrow \text{Majorana Neutrinos} \end{array}$$

Bonilla's talk

Anomaly free

$$\nu_{R_i} \sim \begin{cases} (-1,-1,-1) & \bar{L}\tilde{H}\nu_R \quad \checkmark \\ (-4,-4,5) & \bar{L}\tilde{H}\nu_R \quad \times \quad \bar{L}H^c\chi_1\cdots\chi_i\nu_R, \end{cases}$$

Dark Matter and neutrino nature $U(1)'$

DM stability

Bonilla, Centelles-Chulia, Cepedello EP, Srivastava PRD (2020)

	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L}$	$\mathcal{Z}_6$
ions	L_i	$(\mathbf{2}, -1/2)$	-1	ω^4
	ν_{R_i}	$(\mathbf{1}, 0)$	$(-4, -4, 5)$	$(\omega^4, \omega^4, \omega^4)$

$$U(1)_{B-L} \to \mathcal{Z}_m \qquad \begin{matrix} m = 2n \\ n > 2 \end{matrix} \qquad Z_4,\ Z_6, \ldots$$

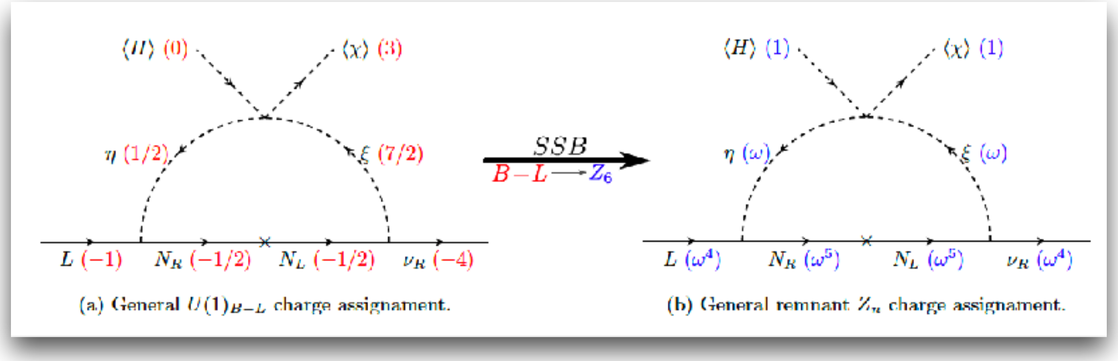
If SM leptons even power

DM (F or S) transforming as odd
Automatically stable

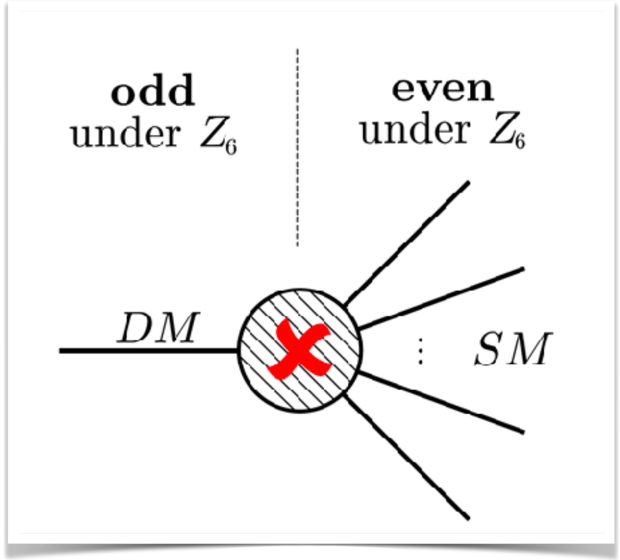
If SM leptons odd power

Scalar DM transforming as odd
Automatically stable

Fermionic DM transforming as even
Automatically stable

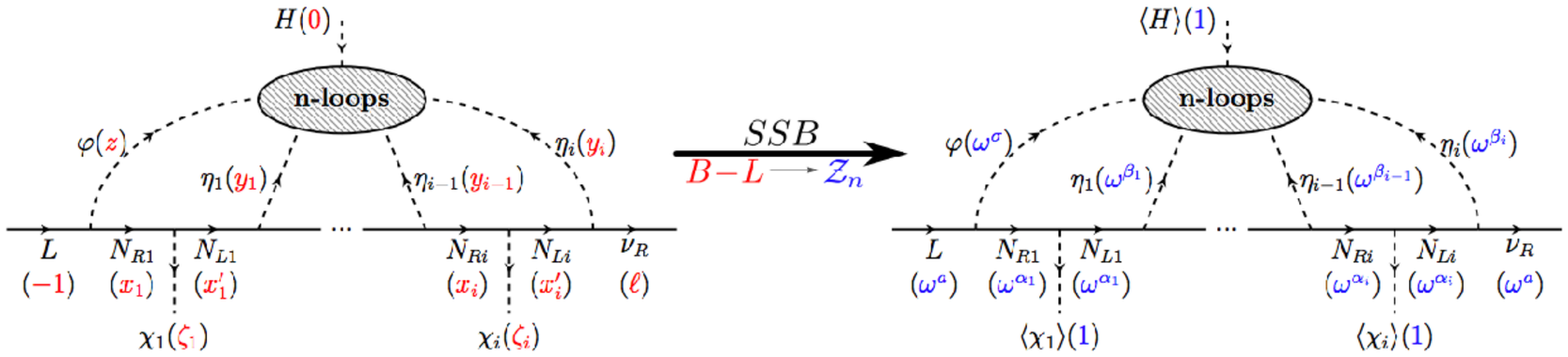


(a) General $U(1)_{B-L}$ charge assignament. (b) General remnant Z_n charge assignament.



For Majorana neutrinos Centelles-Chulia, Cepedello EP, Srivastava (2020)
For more details also: Bonilla, EP, Srivastava (2020)

Dark Matter and neutrino nature $U(1)'$



(a) General $U(1)_{B-L}$ charge assignment.

(b) General residual $\mathcal{Z}_n$ charge assignment.

If SM leptons even power

DM (F or S) transforming as odd
Automatically stable

If SM leptons odd power

Scalar DM transforming as odd
Automatically stable

Fermionic DM transforming as even
Automatically stable

Bonilla, Centelles-Chulia, Cepedello EP, Srivastava PRD (2020)

Bonilla, EP, Srivastava (2020)

Light Vector Boson from $U(1)'$

$$\mathscr{L} \supset \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + i g' Z'_{\mu} (Q_f \bar{f} \gamma^{\mu} f)$$

SSB

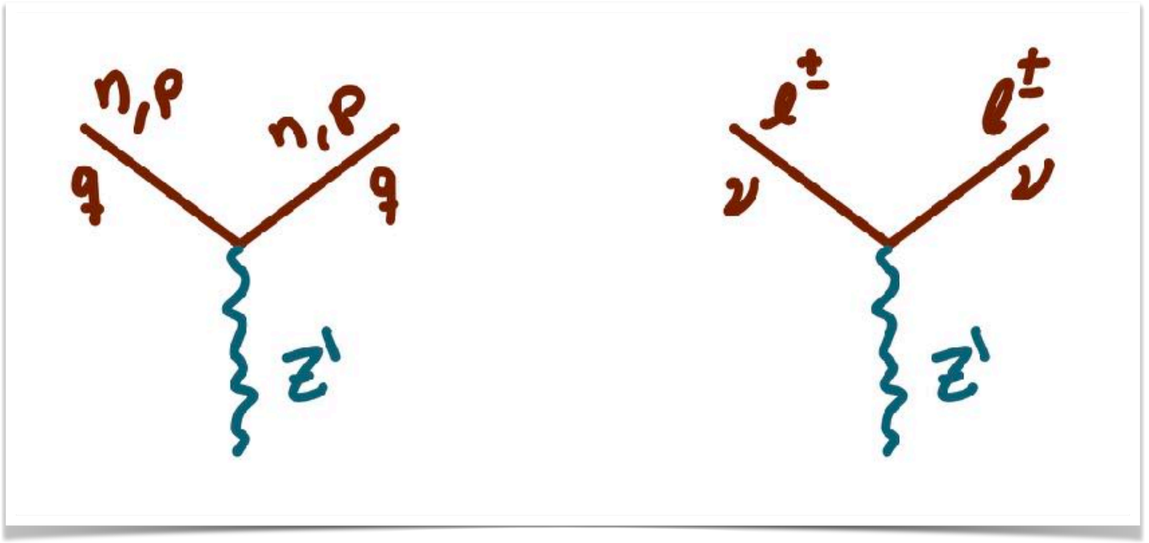
$$\langle \phi_i \rangle = \frac{v_i}{\sqrt{2}}$$

$$m_{Z'}^2 = \sum_i g' Q_i^2 v_i^2$$

Small

Low scale

If $Q_f \neq 0$ for quarks



If $Q_f \neq 0$ for leptons

Up to now only COHERENT SNS detected

14.6 Kg **CsI** 134 events (~300 day)

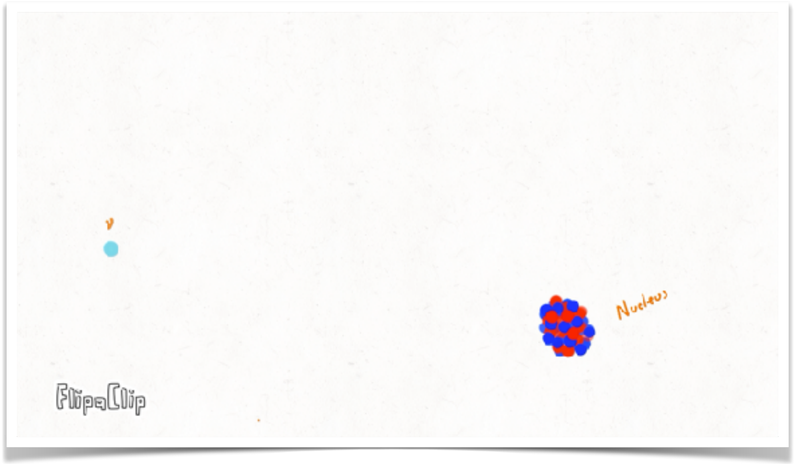
24 Kg **Ar** 159 events (~ 240 days)

Ar will continue …

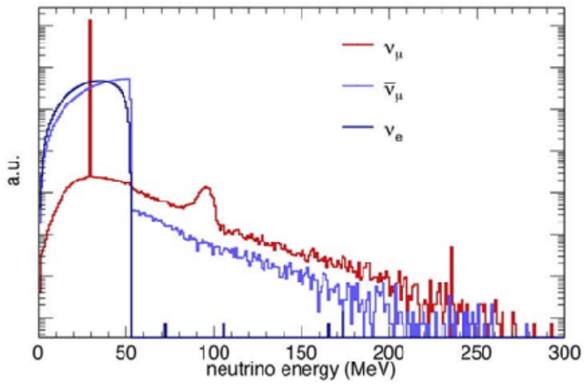
$$p \longrightarrow Hg \rightarrow \pi^- \quad (99.9\,\%\ captured\ by\ Hg)$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu(29.9\ MeV)$$

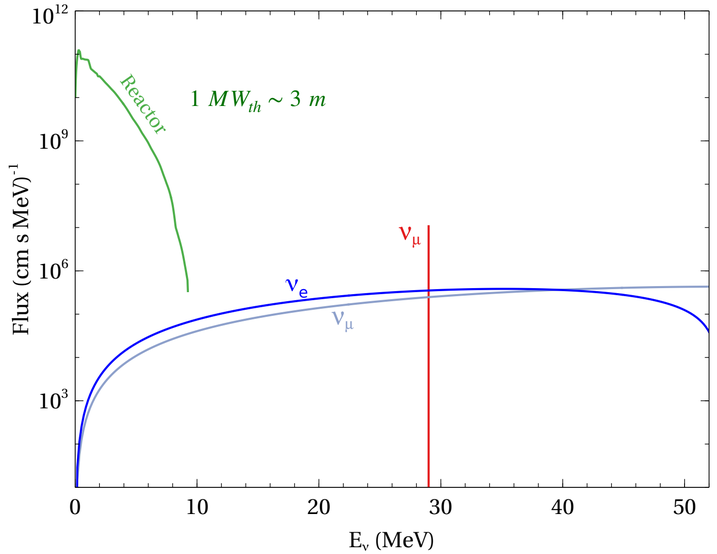
$$e^+ + \bar{\nu}_\mu + \nu_e$$



Aristizabal, Vazquez-Jáuregui talks



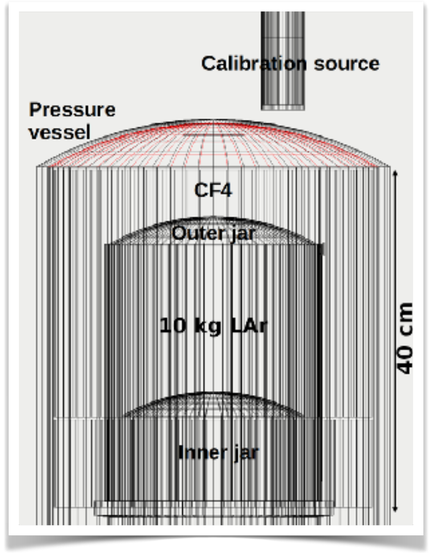
$$T_{max} = 2\frac{E_\nu^2}{M}$$



Many Proposals: CONNIE and CONUS, **TEXONO**, **SBC**, **etc.**

SBC collaboration

L. Flores, et. al. SBC collaboration (2021)



E. Alfonso-Pita

10 kg liguid Argon
bubble chamber
similar to PICO
detector

T~90-130 ^{o}K
P~2 atm

100 eV threshold

Vazquez-Jáuregui talk

Currently under construction

10 kg at 3 m a 1-MW_{th} reactor

A TRIGA Mark III research

~8 neutrino events/day

~2,900 neutrino events in 1 year

~320 background events
cosmogenic

~140 background events
Neutrons from reactor

100 kg at 30 m from a 2000-MW_{th} power reactor

Laguna Verde

~1570 neutrino events/day

~570 K neutrino events in 1 year

~68 K background events
cosmogenic

Light Vector Boson from $U(1)'$

$$\mathscr{L} \supset \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + i g' Z'_{\mu} (Q_f \bar{f} \gamma^{\mu} f)$$

SSB

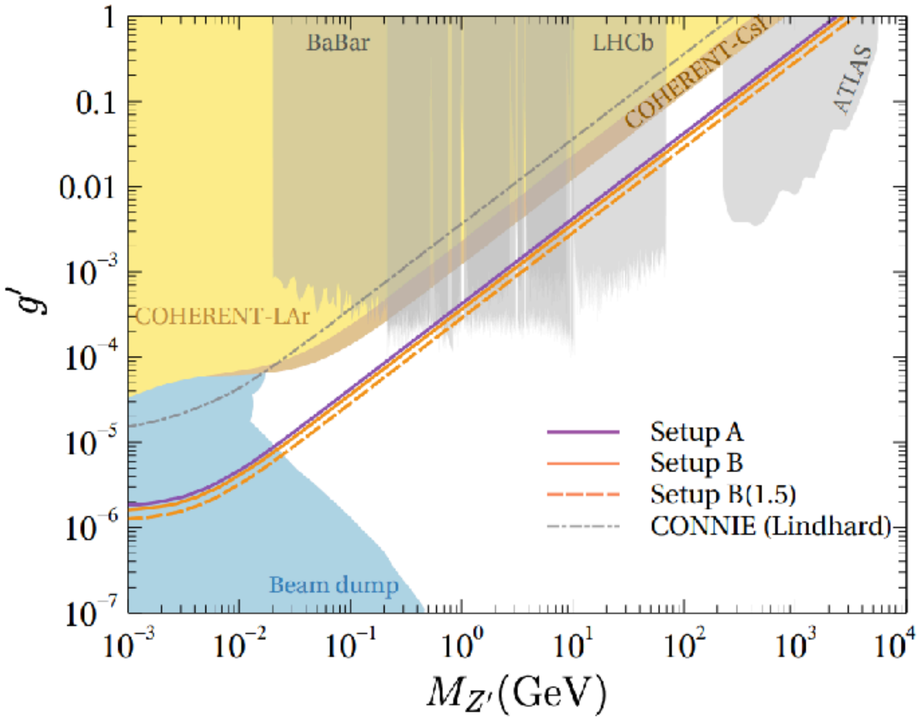
$$\langle \phi_i \rangle = \frac{v_i}{\sqrt{2}} \qquad m_{Z'}^2 = \sum_i g' Q_i^2 v_i^2$$

$$U(1)_{B-L}$$

NSI

$$\mathcal{L}_{\text{eff}} = -\frac{g'^2 Q_l Q_q}{q^2 + M_{Z'}^2} \left[\sum_{\alpha} \bar{\nu}_{\alpha} \gamma^{\mu} P_L \nu_{\alpha} \right] \left[\sum_{q} \bar{q} \gamma_{\mu} q \right]$$

Aristizabal's talk



Vazquez-Jauregui's talk

L. Flores, et. al. SBC collaboration (2021)

Dark Matter from $U(1)_{B-L}$

Extend the SM with a Dirac fermion χ with $Q_\chi = 1/3$

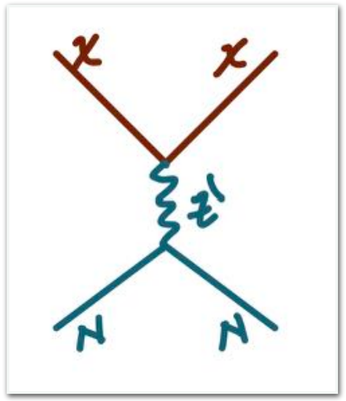
$$\mathscr{L} \supset M_D \bar{\chi}\chi + \bar{\chi}\gamma^\mu(\partial_\mu + ig' Q_\chi Z'_\mu)\chi$$

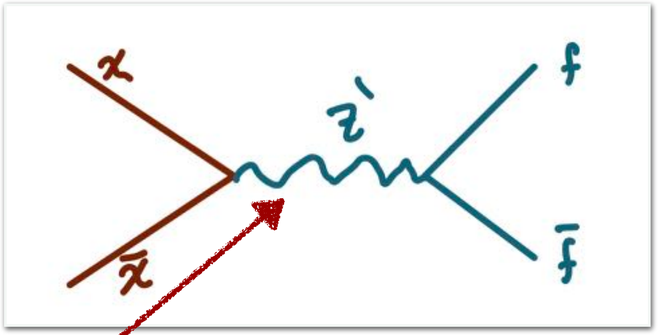
Will need a scalar field ϕ for SSB

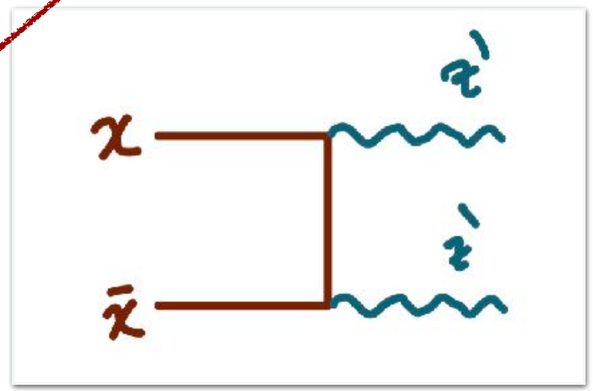
$Q_\phi =$ 1 → Dirac neutrinos

$Q_\phi =$ 2 → Majorana neutrinos $\phi \bar{N}^c N$

Resonant annihilation $M_\chi \simeq M_{z'}/2$







Lepton flavored $U(1)' = U(1)_{B-2L_\alpha-L_\beta}$

L. Flores, N. Nath, EP, JHEP (2020)

Gauge $U(1)_{B-2L_\alpha-L_\beta}$

Anomaly free

3 RH neutrinos

2 U(1) breaking scalar fields

$$\frac{1}{2}M_{Z'}^2 = g'^2\ \frac{1}{2}(v_1^2 + 4v_2^2)$$

$\langle\phi_1\rangle$ $\langle\phi_2\rangle$

	ϕ_1	ϕ_2
$U(1)$	1	2

Neutrino phenomenology

$$-\mathcal{L}_{Majorana} = \frac{1}{2}M_1\overline{N_1^c}N_1 + \frac{1}{2}y_1^N\overline{N_1^c}N_2\phi_1 + \frac{1}{2}y_2^N\overline{N_1^c}N_3\phi_2 + \frac{1}{2}y_3^N\overline{N_2^c}N_2$$

6 possible choices for α and β

$\alpha=\mu$ and $\beta=\tau$

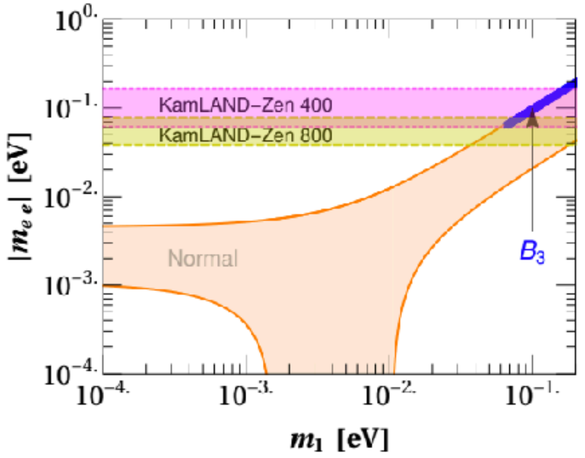
$$M_N = \begin{pmatrix} M_1 & y_1^N\langle\phi_1\rangle & y_2^N\langle\phi_2\rangle \\ y_1^N\langle\phi_1\rangle & y_3^N\langle\phi_2\rangle & 0 \\ y_2^N\langle\phi_2\rangle & 0 & 0 \end{pmatrix}$$

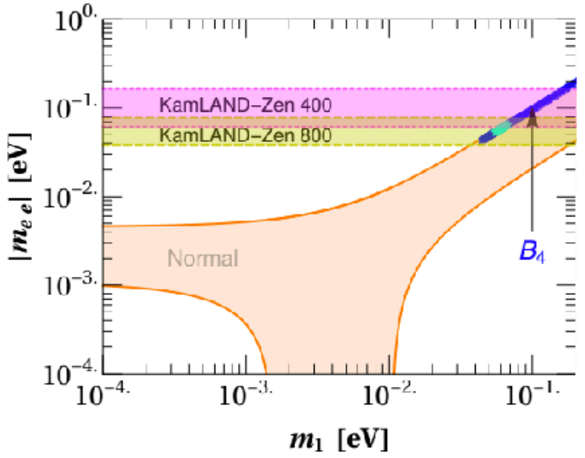
Charged leptons diagona

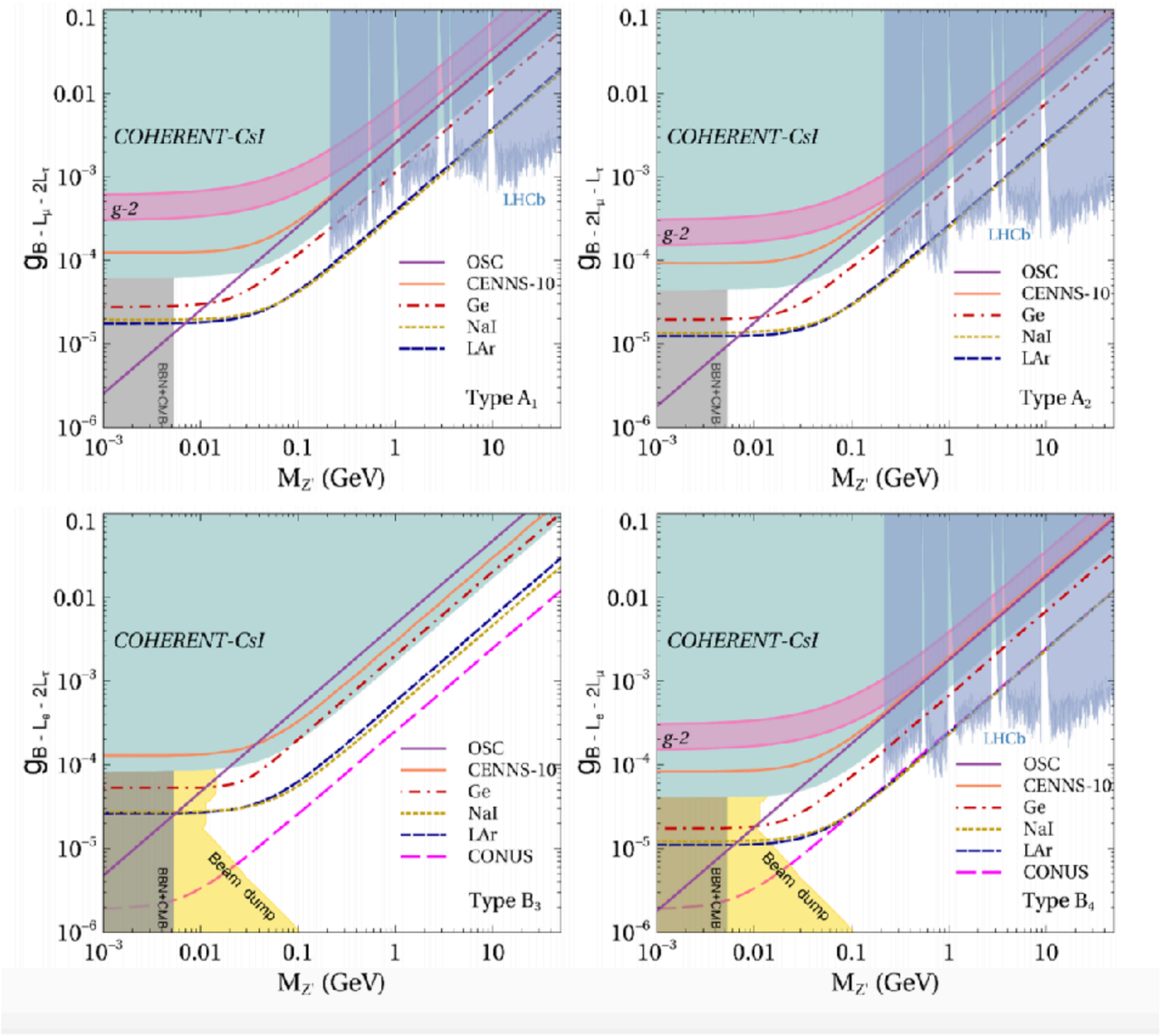
x_e	x_μ	x_τ	Neutrino mass matrix	Type	NSI parameters
0	-1	-2	$\begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}$	A_1	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
0	-2	-1	$\begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$	A_2	$\varepsilon_{\mu\mu}$ & $\varepsilon_{\tau\tau}$
-1	0	-2	$\begin{pmatrix} \times & 0 & \times \\ 0 & 0 & \times \\ \times & \times & \times \end{pmatrix}$	B_3	ε_{ee} & $\varepsilon_{\tau\tau}$
-1	-2	0	$\begin{pmatrix} \times & \times & 0 \\ \times & \times & \times \\ 0 & \times & 0 \end{pmatrix}$	B_4	ε_{ee} & $\varepsilon_{\mu\mu}$
-2	-1	0	$\begin{pmatrix} \times & \times & \times \\ \times & \times & 0 \\ \times & 0 & 0 \end{pmatrix}$	$\times$	ε_{ee} & $\varepsilon_{\mu\mu}$
			$\begin{pmatrix} \times & \times & \times \end{pmatrix}$		

Better agreement

Good pheno







$$\frac{1}{2}M_{Z'}^2 = g'^2 \ \frac{1}{2}(v_1^2 + 4v_2^2)$$

$$M_{Z'} = 0.1\,\text{GeV}$$

$$g' = 2.8 \times 10^{-5}$$

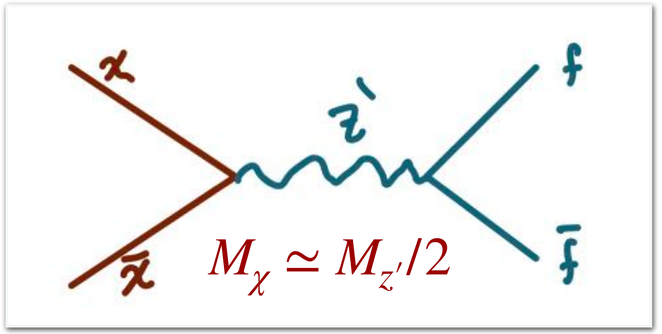
$$v_1 \approx 3\,\text{TeV} \quad v_2 \approx 1\,\text{TeV}$$

L. Flores, N. Nath, EP, JHEP (2020)

CEvNS and DM searches complementarity

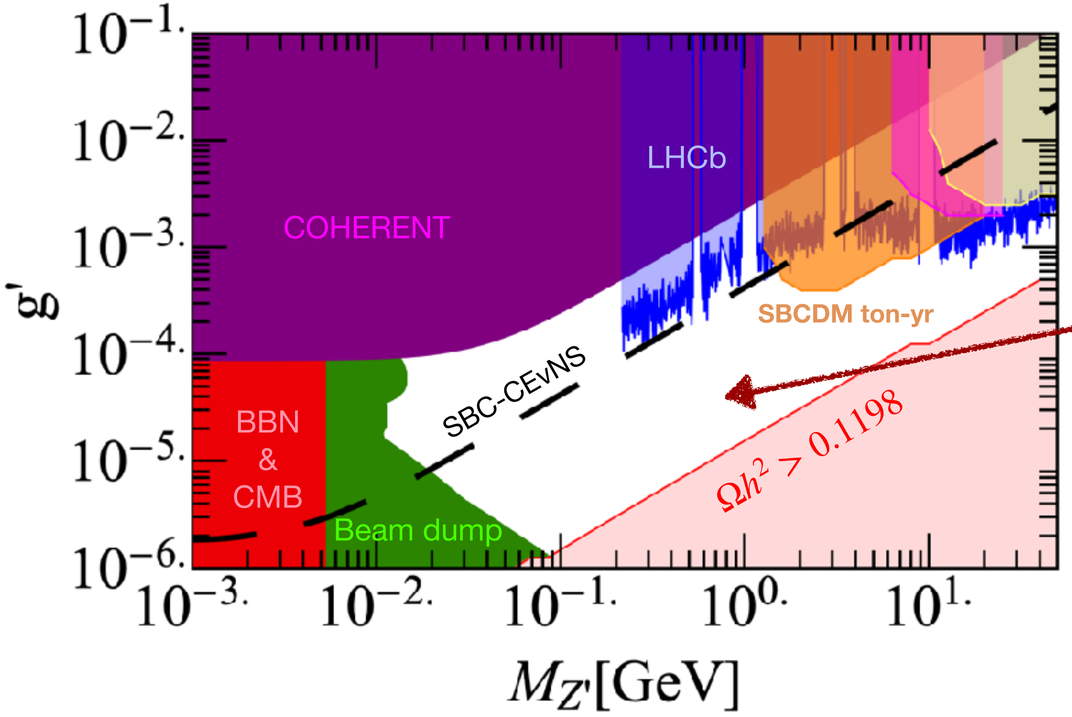
Work in progress LMG de la Vega, L. Flores, N. Nath

$U(1)_{B-L}$

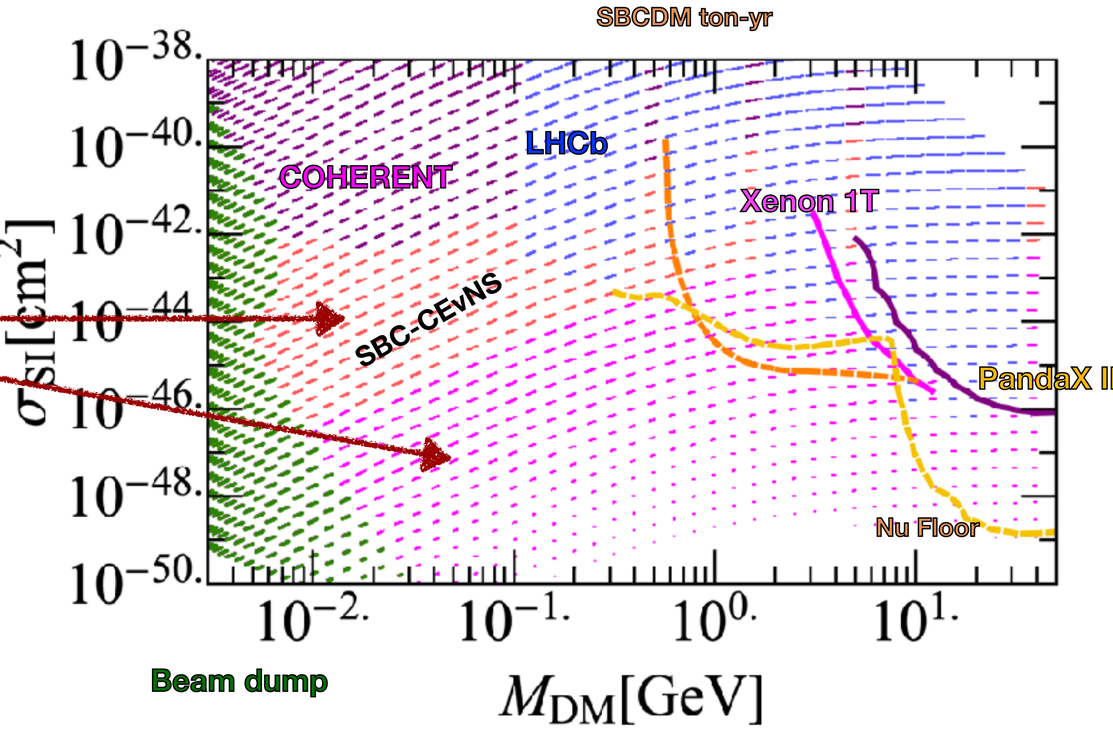


Xenon 1T

PandaX II



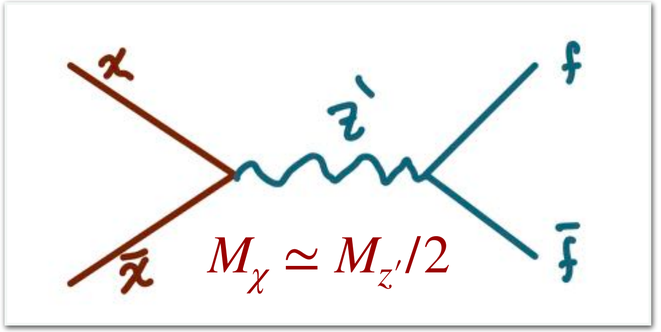
Allowed Region

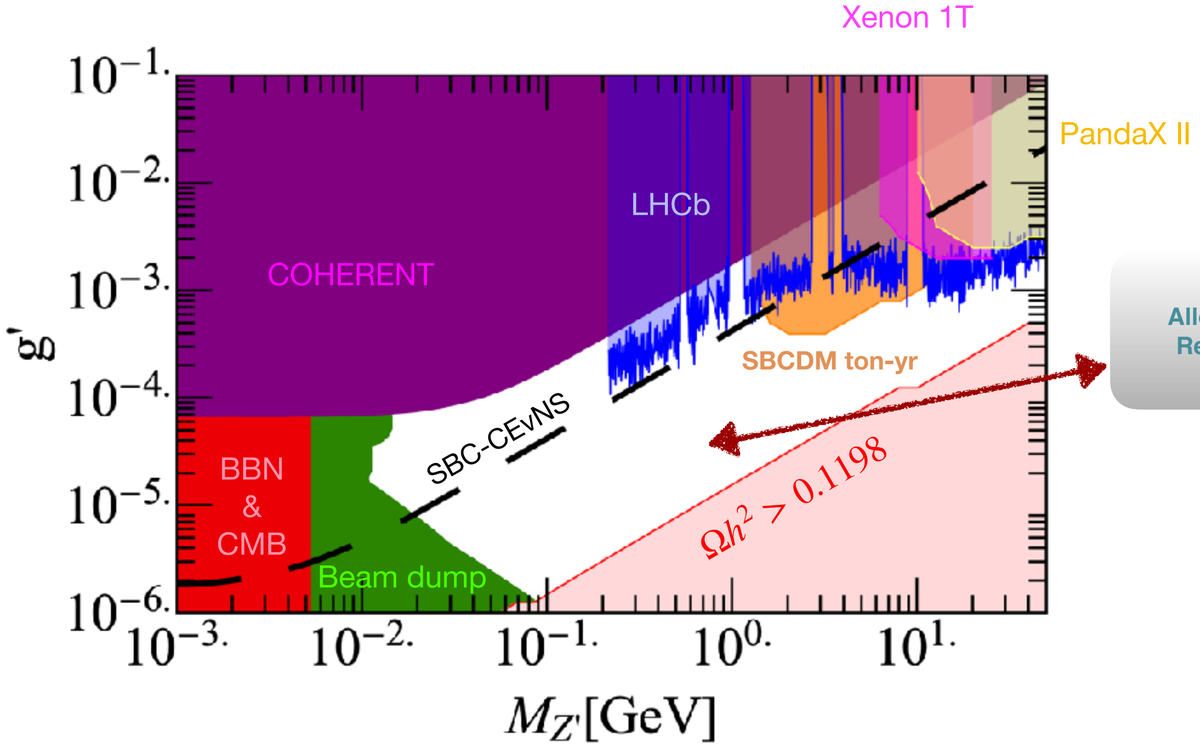


CEvNS and DM searches complementarity

Work in progress LMG de la Vega, L. Flores, N. Nath

$$U(1)_{B-L_e-2L_\mu}$$





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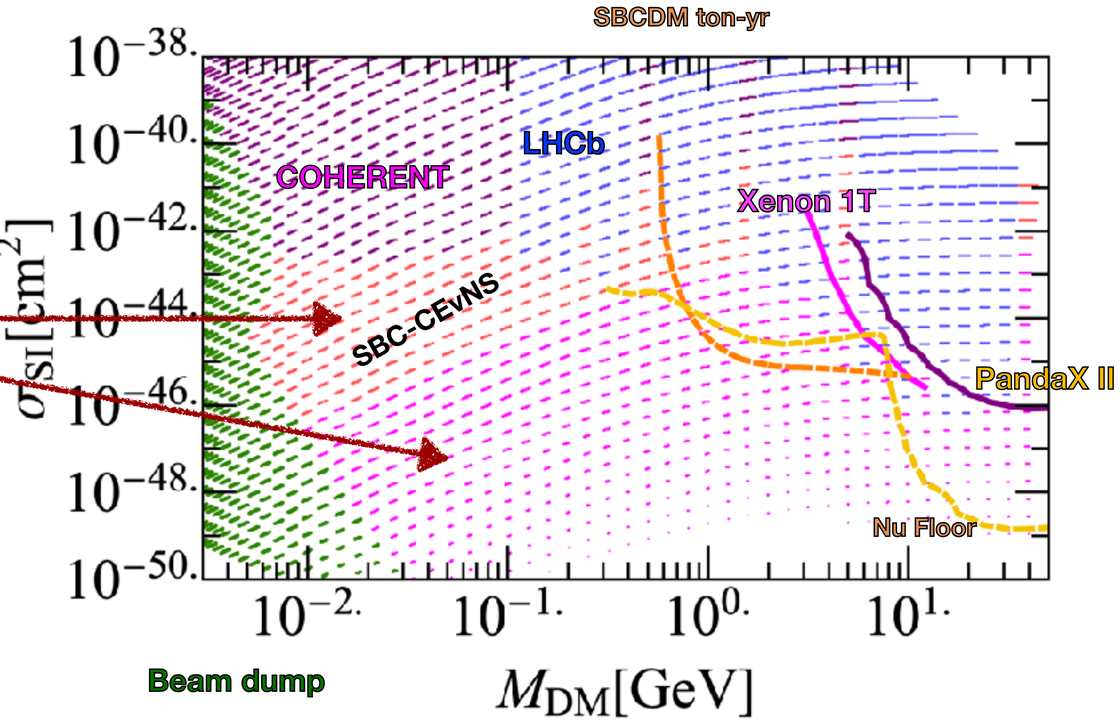
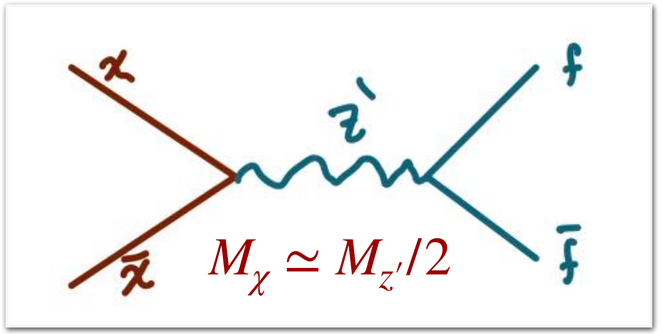
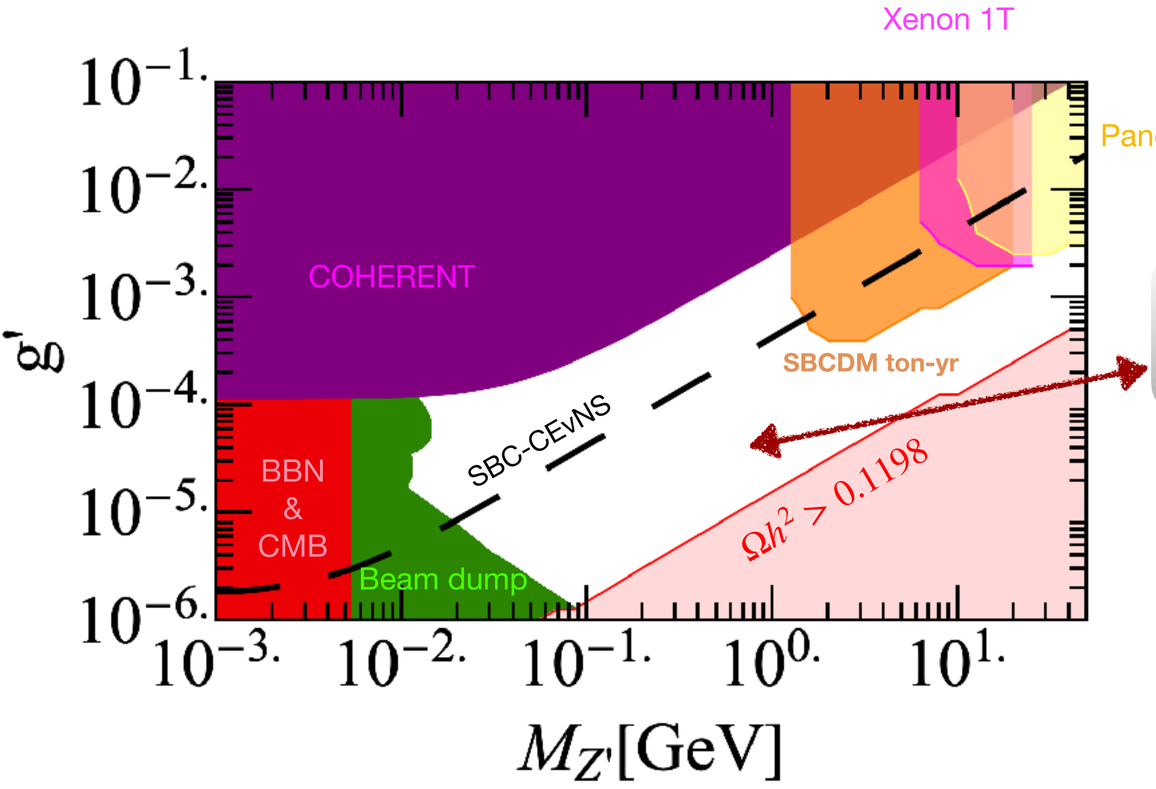


CEvNS and DM searches complementarity

Work in progress LMG de la Vega, L. Flores, N. Nath

$$U(1)_{B-L_e-2L_\tau}$$





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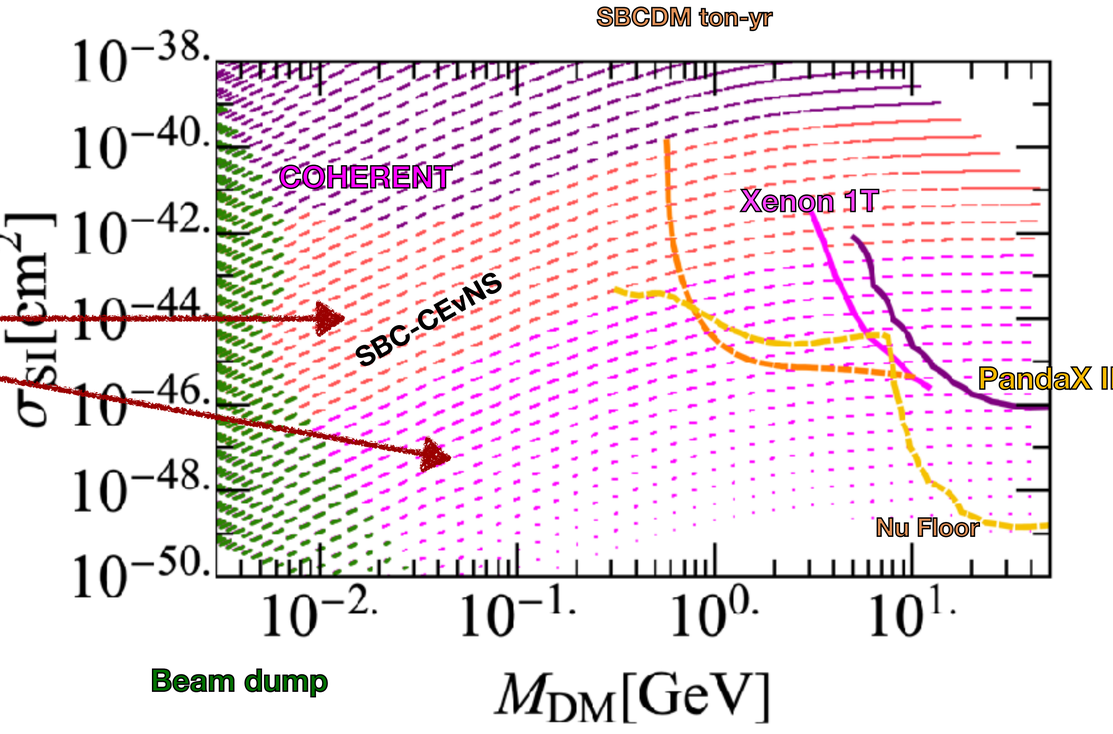

CEvNS and DM searches complementarity

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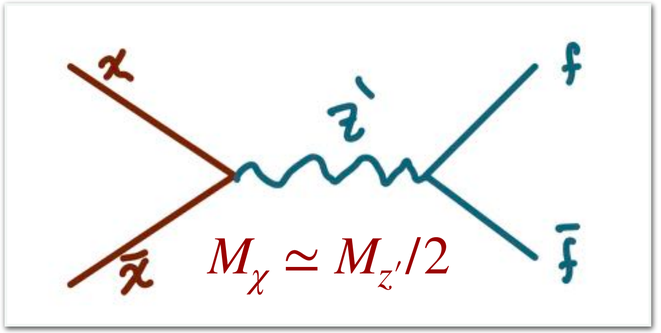
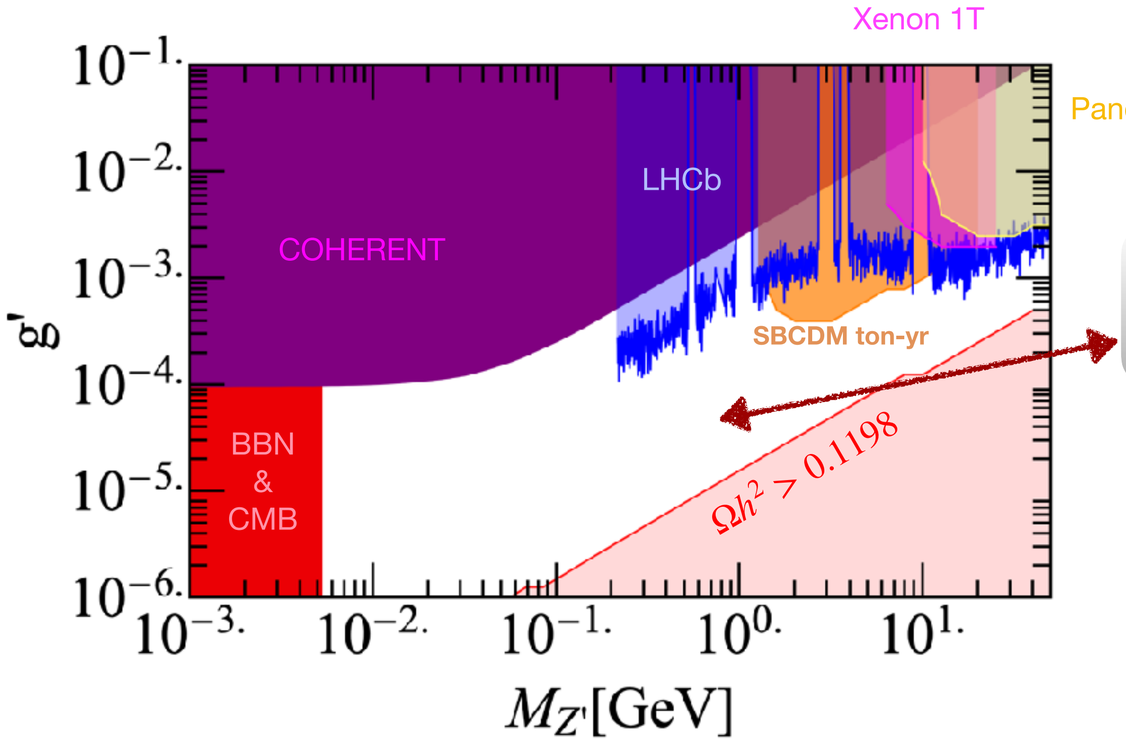
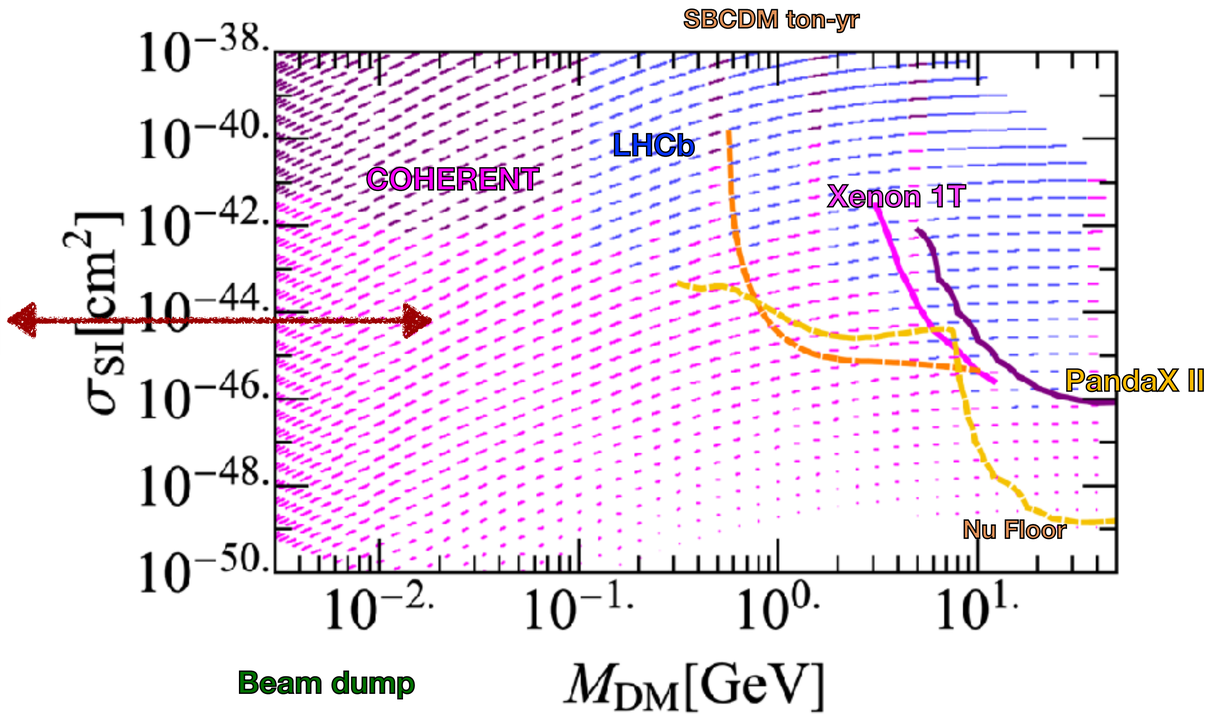
$$U(1)_{B-L_\mu-2L_\tau}$$





Allowed Region



Conclusions

- It is easy to incorporate DM in $U(1)'$ gauge models without extra symmetries.
- Lepton flavor models compatible with neutrino phenomenology in agreement with experiments.
- Complementarity between DM direct searches, collider and CEvNS experiments.

¡Gracias!