Hints of Light New Physics at XENON1T and Muon g-2 Experiments

Téssio Melo

International Institute of Physics - UFRN

24 June 2021

PhenoBR Workshop 2021

Outline

1. XENON1T Anomaly
2. The model
3. Results
4. Accommodating $(g-2)_\mu$
5. Conclusions

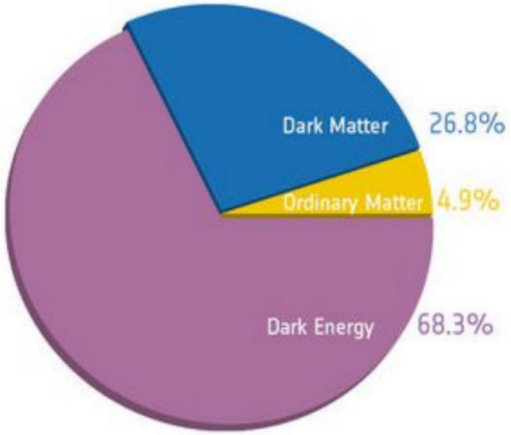
Based on work done in collaboration with :

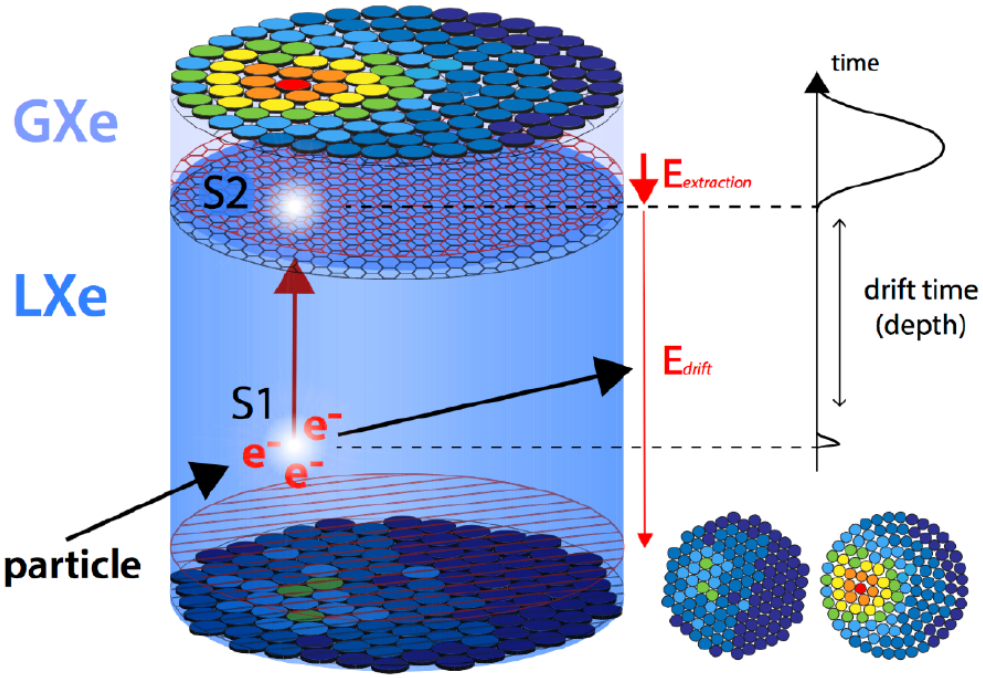
M. Lindner, Y. Mambrini & F. Queiroz
Phys. Lett. B 811 (2020)

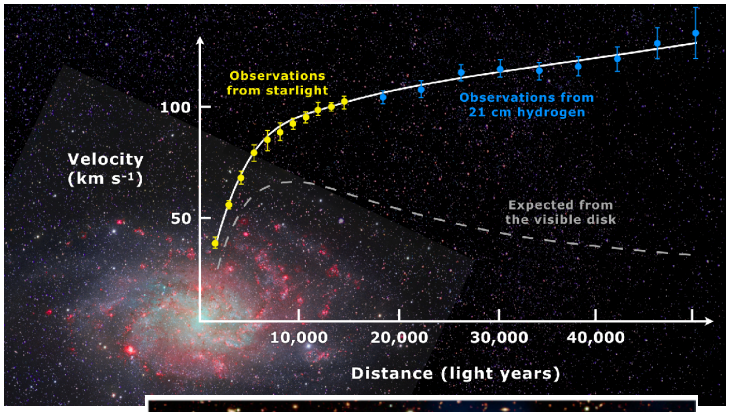
G. Arcadi, A. de Jesus, F. Queiroz & Y. Villamizar
arxiv :2104.04456

XENON1T Experiment

- Detector for direct Dark Matter searches
  - Designed to search for WIMPs
- Dual phase Xe detector with 1 tonne of liquid Xenon in fiducial volume
- S1 (scintillation) and S2 (ionization) signals allow the reconstruction of the event position

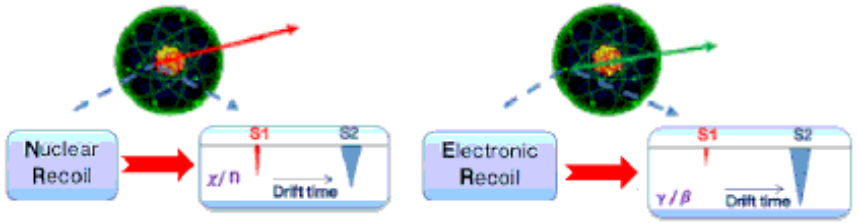


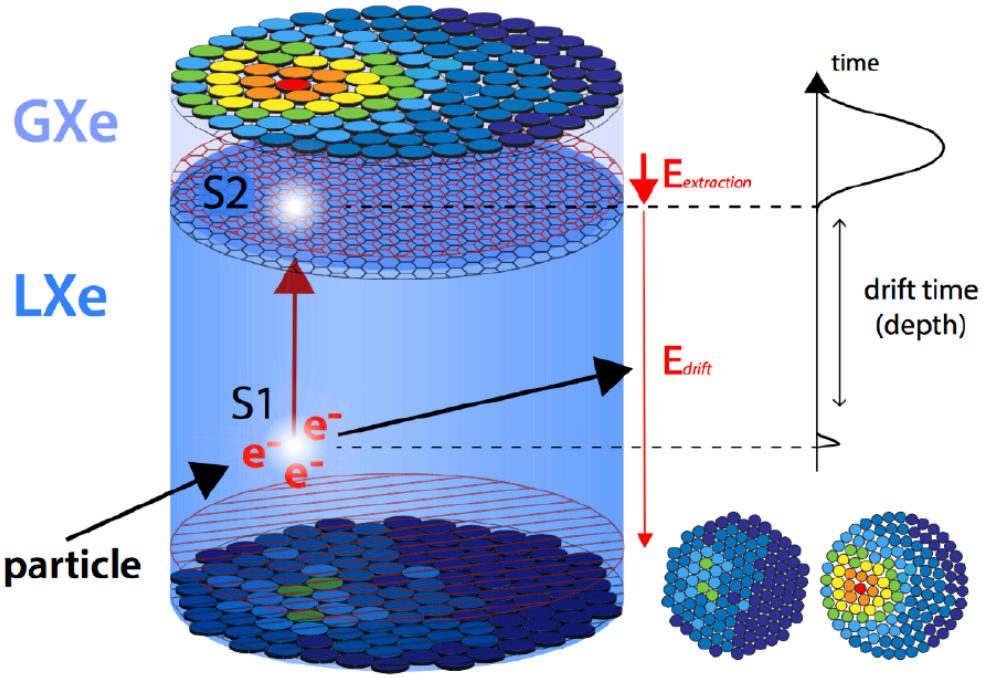


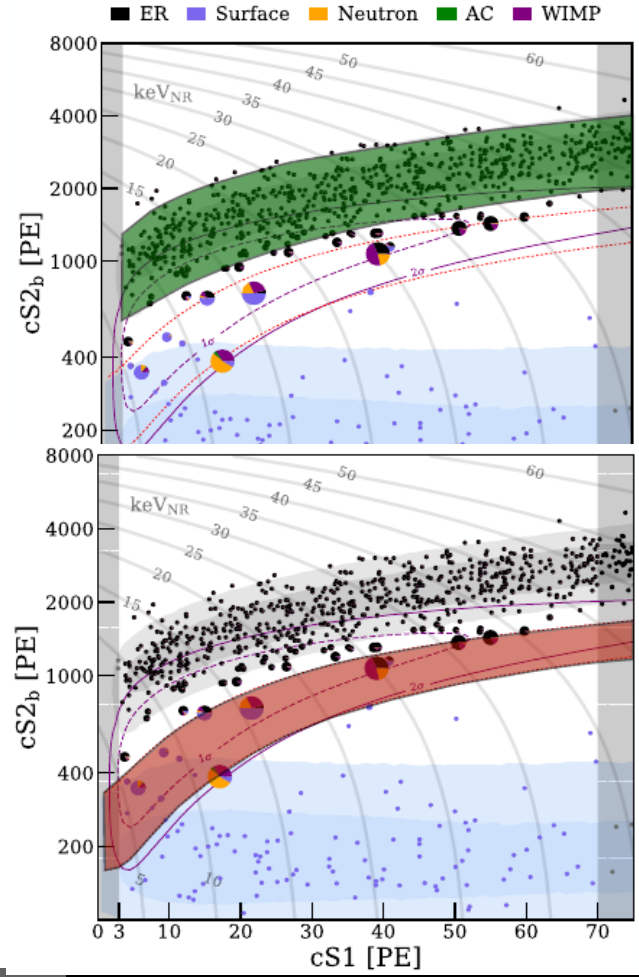


XENON1T Experiment

- S1 and S2 signals also allow the discrimination between nuclear and electron recoil events
- Electron and nuclei recoil bands
- WIMPs are expected to produce nuclear recoils

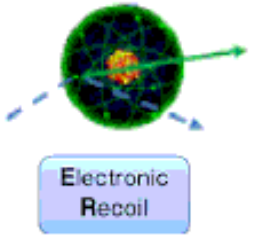


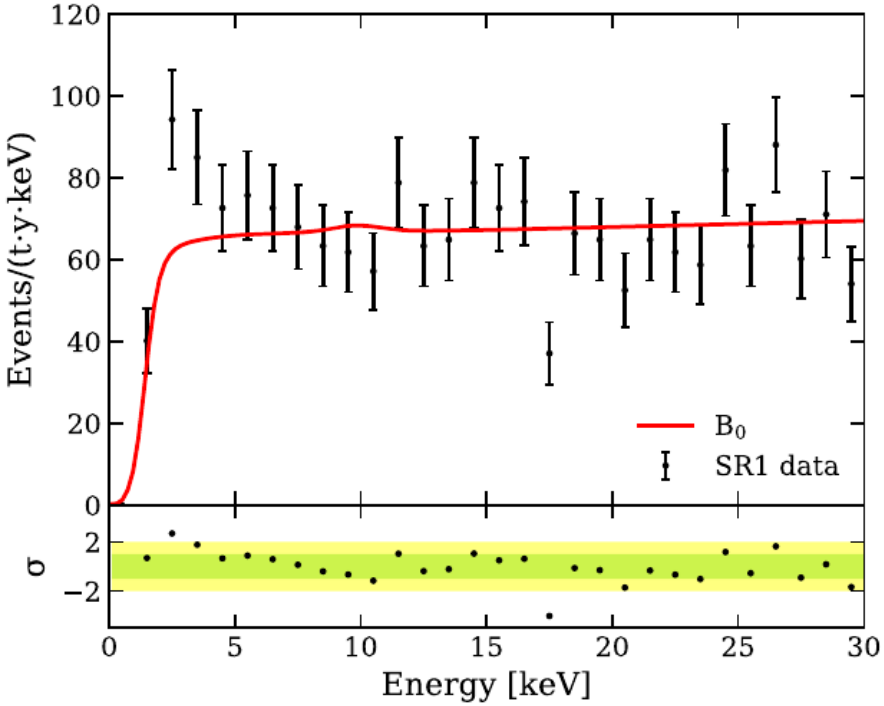


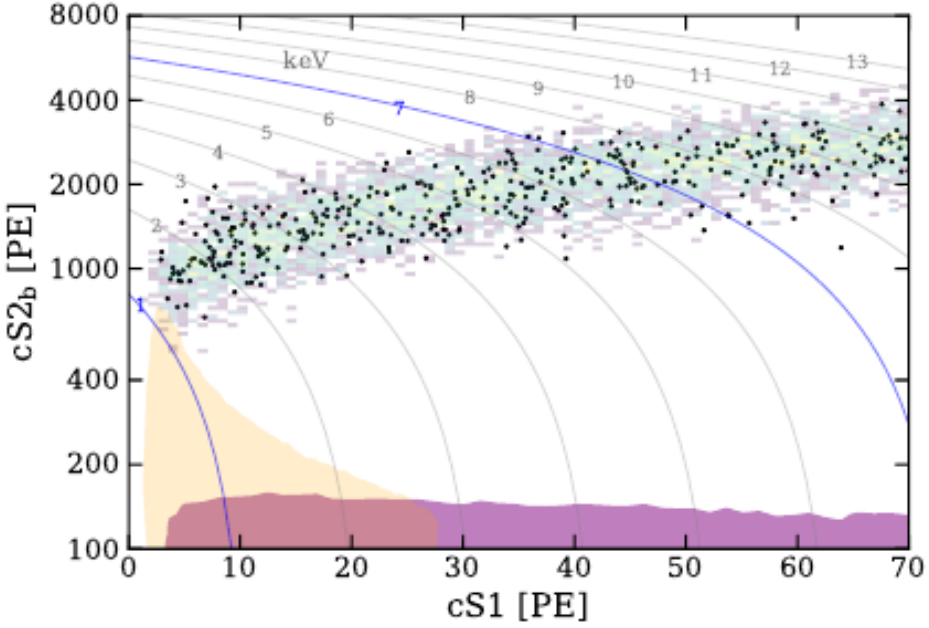


XENON1T Anomaly

- 3.3 σ excess in the low energy electron recoils
- 285 events observed in the region between 1-7 keV
  - 235 $\pm$ 15 events were expected

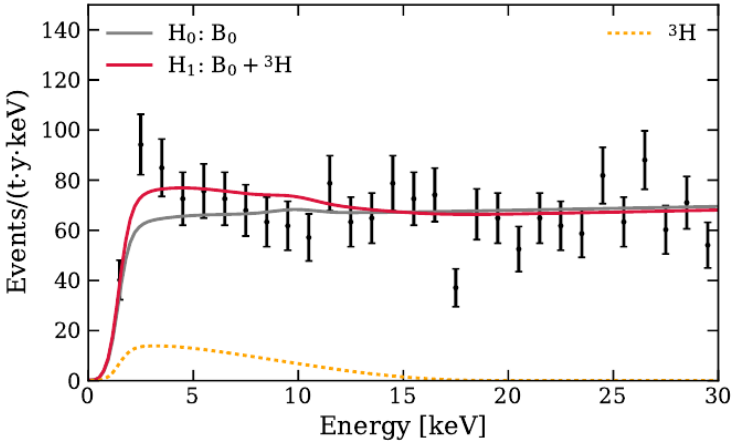






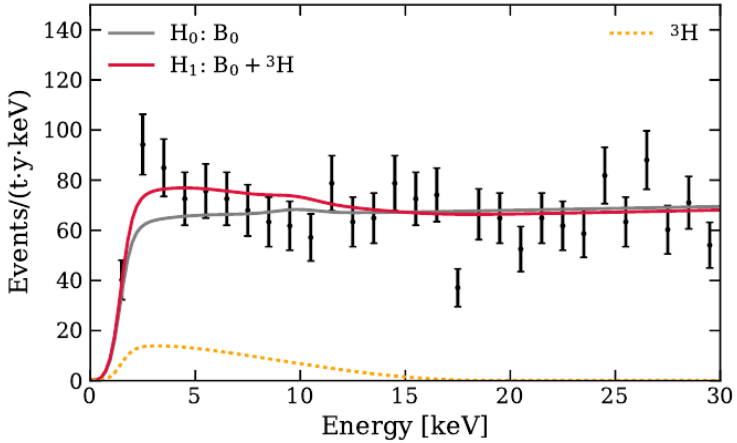
What is behind this excess ?

- Background ?
  - Tritium β-decay
  - Concentration : $(6.2\pm$ 2.0) $\times 10^{-25}$ mol/mol (3 atoms of tritium per kg of xenon)
  - Could account for 159 ± 51 events

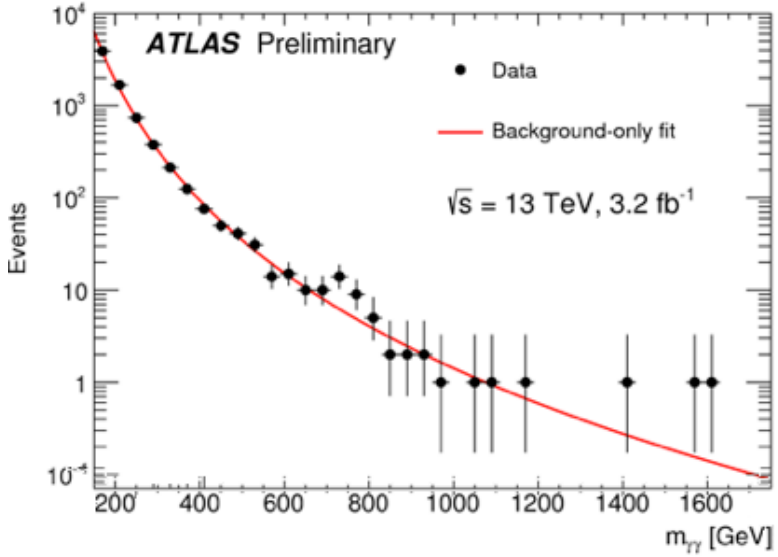


What is behind this excess ?

- Background ?
  - Tritium β-decay
  - Concentration : $(6.2 \pm 2.0) \times 10^{-25}$ mol/mol (3 atoms of tritium per kg of xenon)
  - Could account for 159 ± 51 events

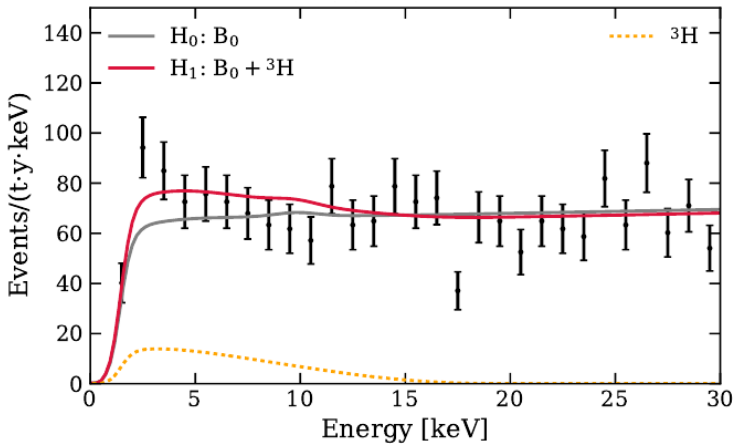


- Statistical fluctuation ?

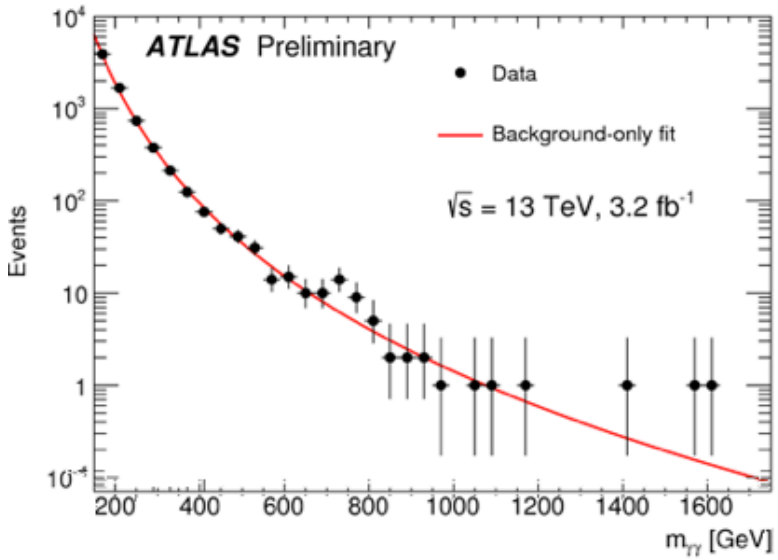


What is behind this excess ?

- Background ?
  - Tritium β-decay
  - Concentration : $(6.2 \pm 2.0) \times 10^{-25}$ mol/mol (3 atoms of tritium per kg of xenon)
  - Could account for 159 ± 51 events



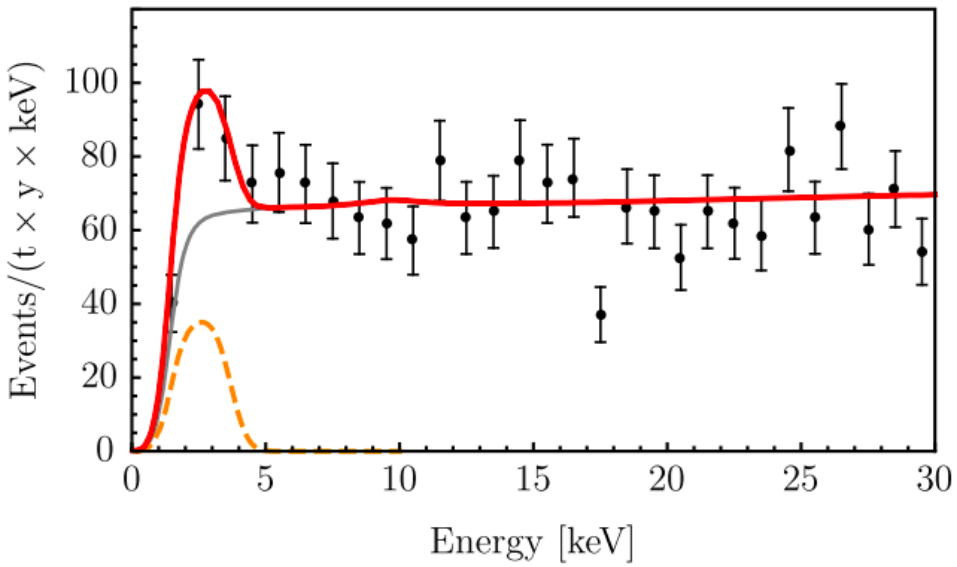
- Statistical fluctuation ?



New Physics !??

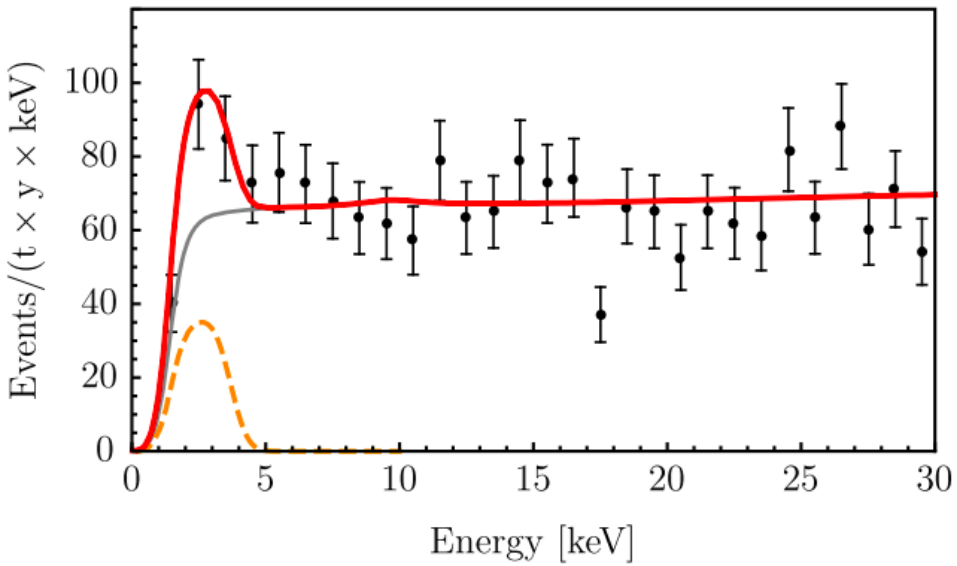
What Kind of New Physics : a WIMP ?

- Boosted DM [B. Fornal, P. Sandick, J. Shu, et. al., 2006.11264]
  - $m_\chi \gg m_e$ (~ 10 GeV)
  - Boosted component with velocity ($v \sim 0.05c$) much greater than the DM velocity in the halo ($v \sim 0.001c$)

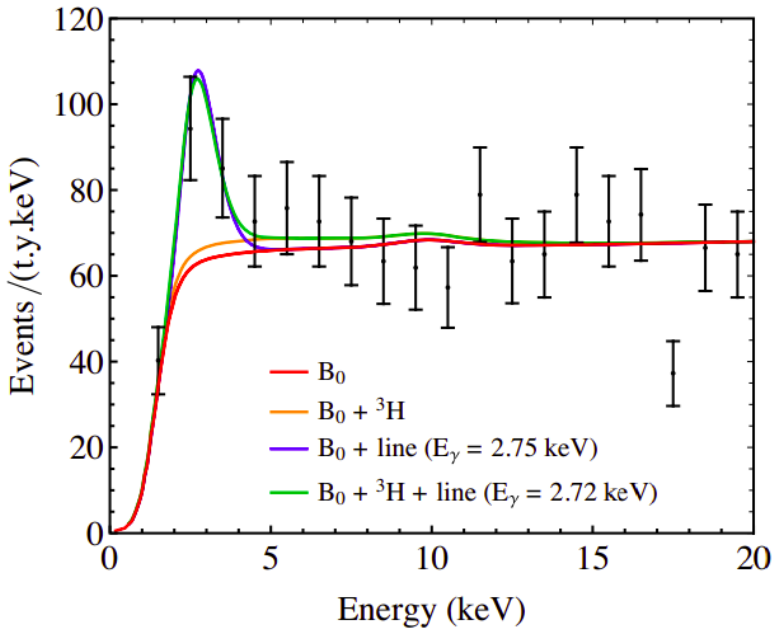


What Kind of New Physics : a WIMP ?

- Boosted DM [B. Fornal, P. Sandick, J. Shu, et. al., 2006.11264]
  - $m_\chi \gg m_e$ (~ 10 GeV)
  - Boosted component with velocity ($v \sim 0.05c$) much greater than the DM velocity in the halo ($v \sim 0.001c$)

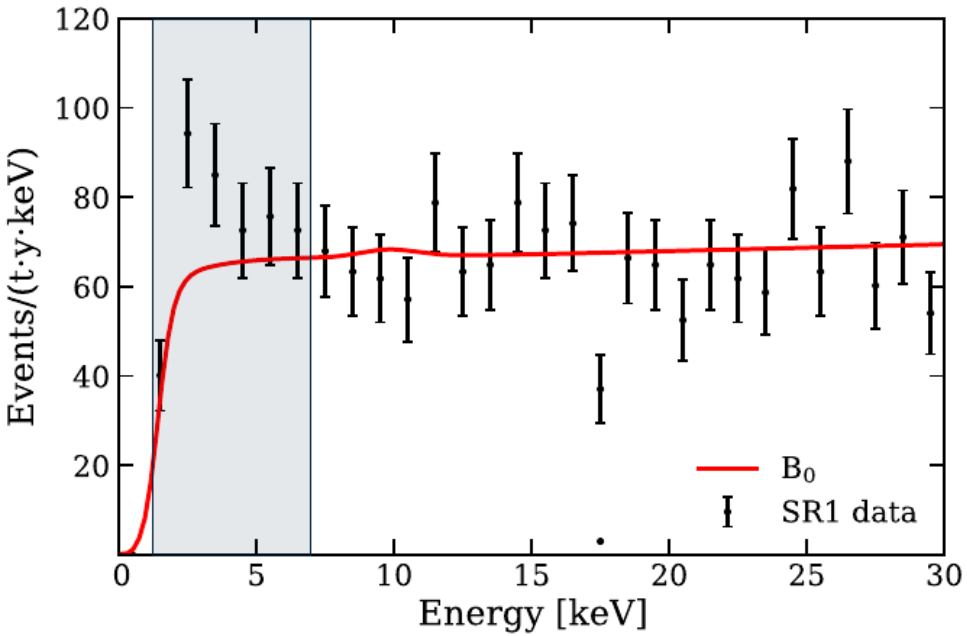


- Inelastic DM [N. Bell, J. Dent, B. Dutta, et. al., 2006.12461]
  - DM scatters inelastically in the detector producing a heavier dark state
  - Mass split : $\Delta m = 2 - 3$ keV



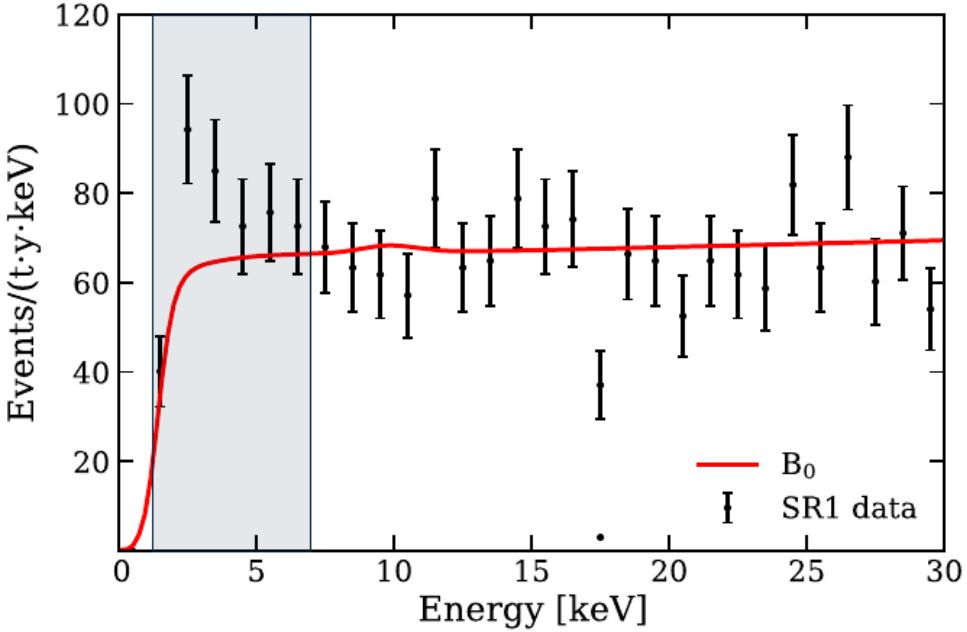
What Kind of New Physics : Neutrinos ?

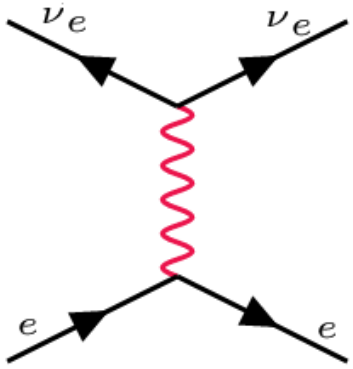
- The excess is located near the detector threshold

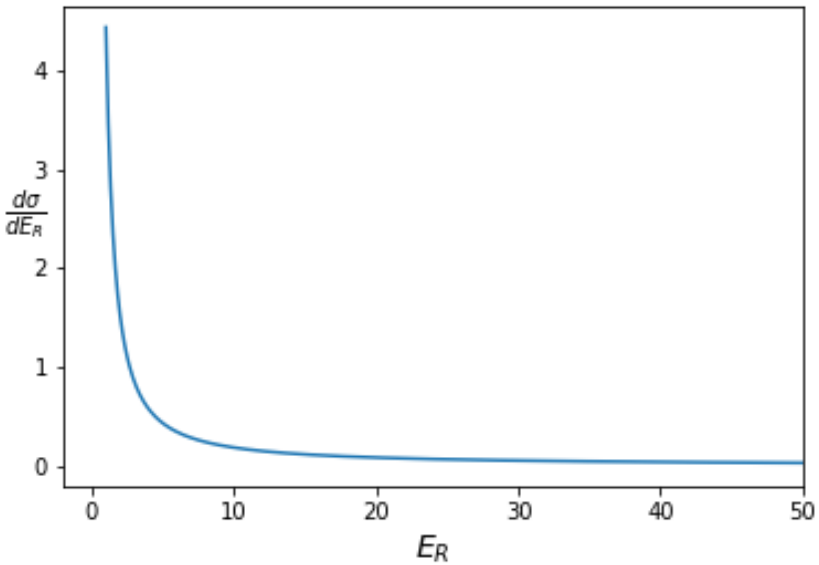


What Kind of New Physics : Neutrinos ?

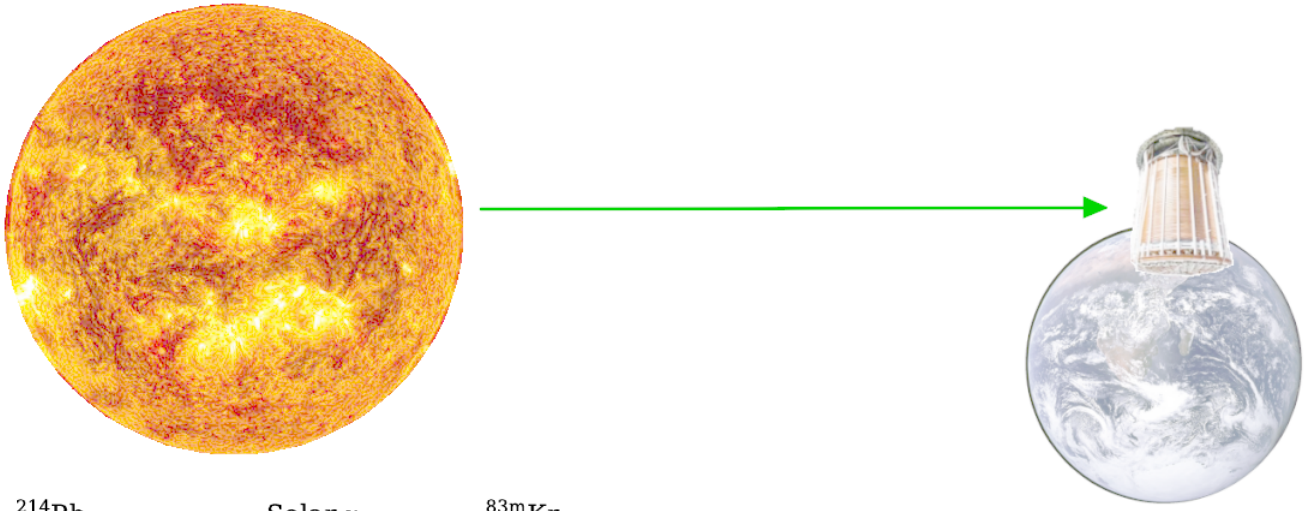
- The excess is located near the detector threshold

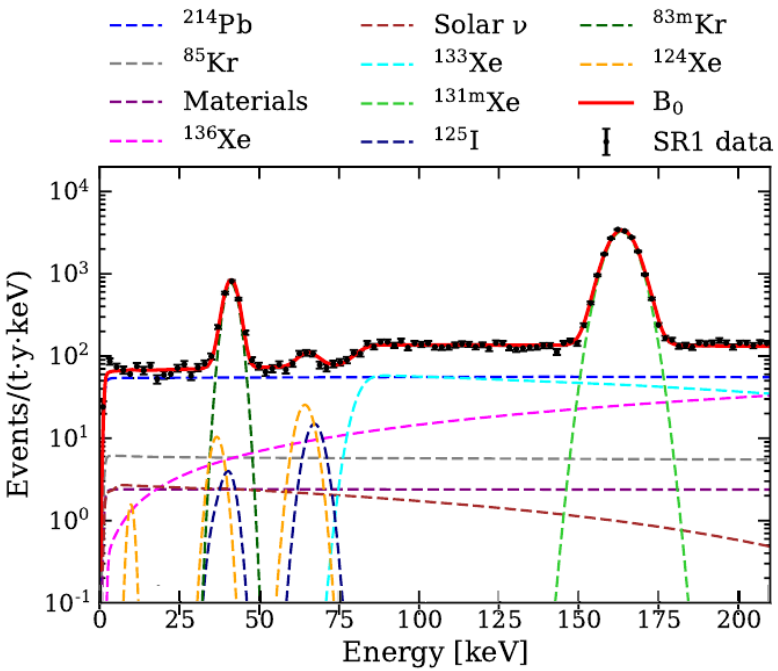


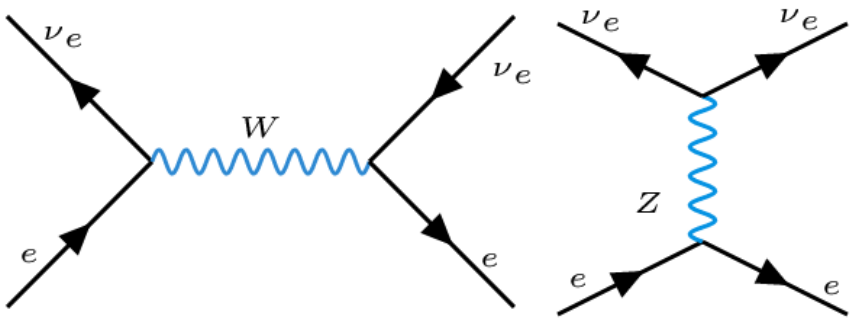




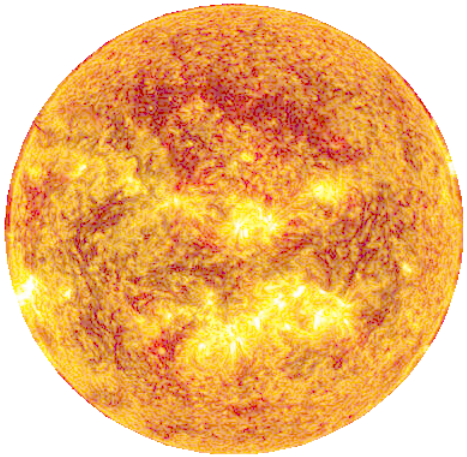
Where the Neutrinos Come From ? The Sun

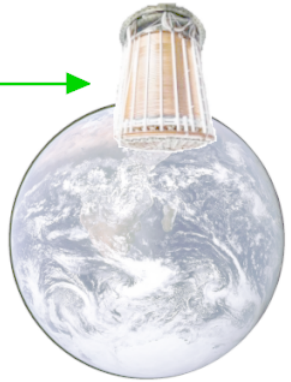


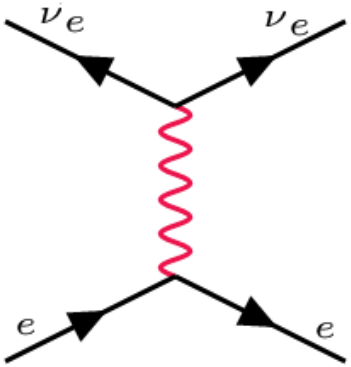


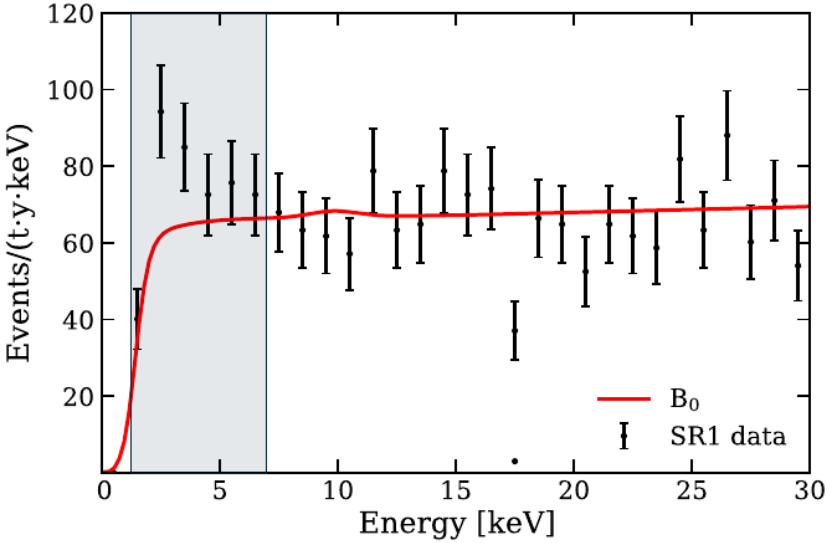


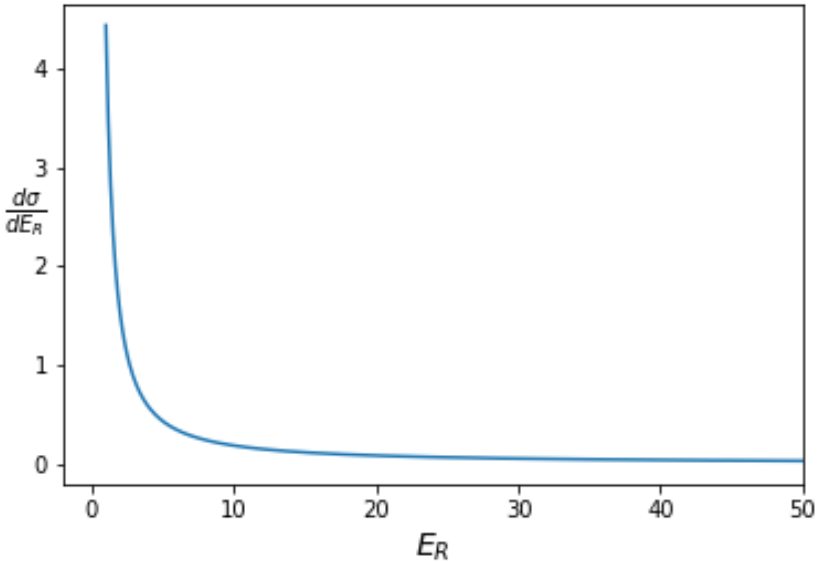
Solar Neutrinos + New Interaction







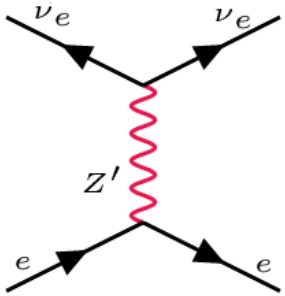




A Simplified Model : Light Z'

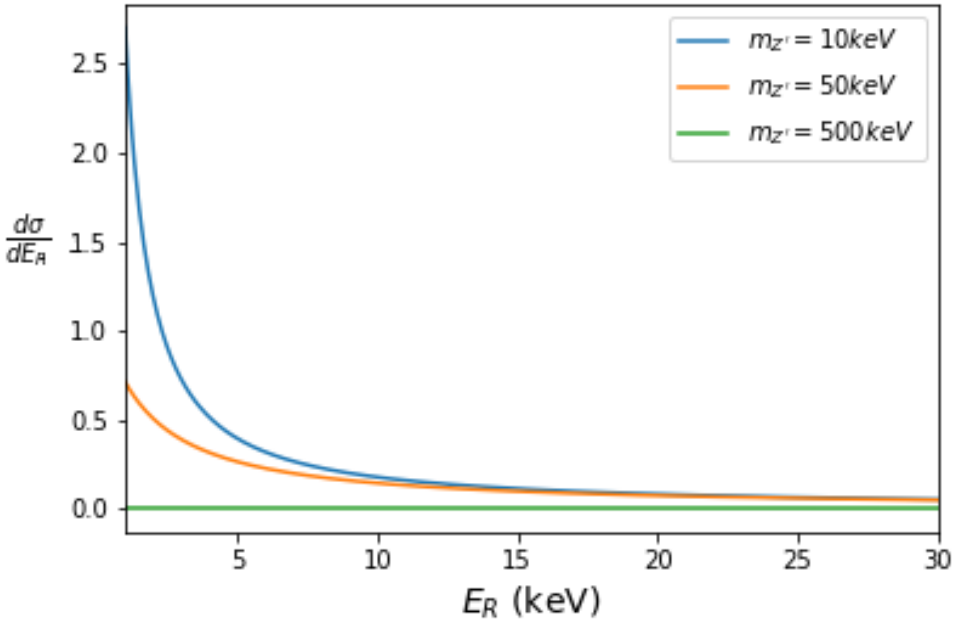
- Simplified Lagrangian :

$$\mathcal{L}_{Z'ff} \supset (\frac{g_\nu}{4}\bar{\nu}\gamma^\mu\nu + \frac{g_e}{4}\bar{l}\gamma^\mu l)Z'$$



- Cross section :

$$\frac{d\sigma_\nu}{dE_R} \simeq \frac{m_e g_\nu^2 g_e^2}{512\pi(2E_R m_e + m_{Z'}^2)^2}$$

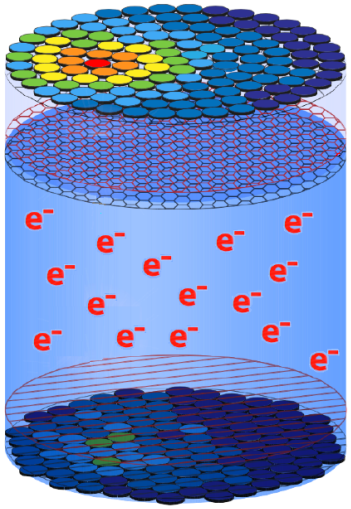


A Simplified Model : Light Z'

- Differential rate : $$\frac{dR}{dE_R} = N_T \int dE_\nu \frac{d\phi}{dE_\nu} \frac{d\sigma_\nu}{dE_R}$$

A Simplified Model : Light Z'

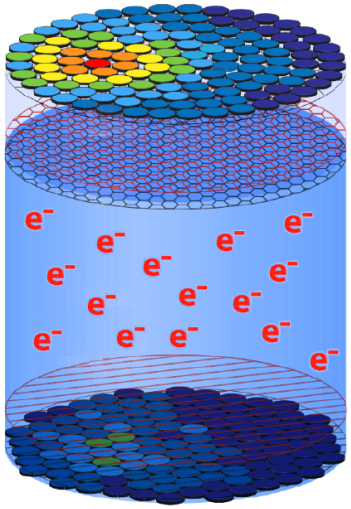
- Differential rate : $$\frac{dR}{dE_R} = N_T \int dE_\nu \frac{d\phi}{dE_\nu} \frac{d\sigma_\nu}{dE_R}$$

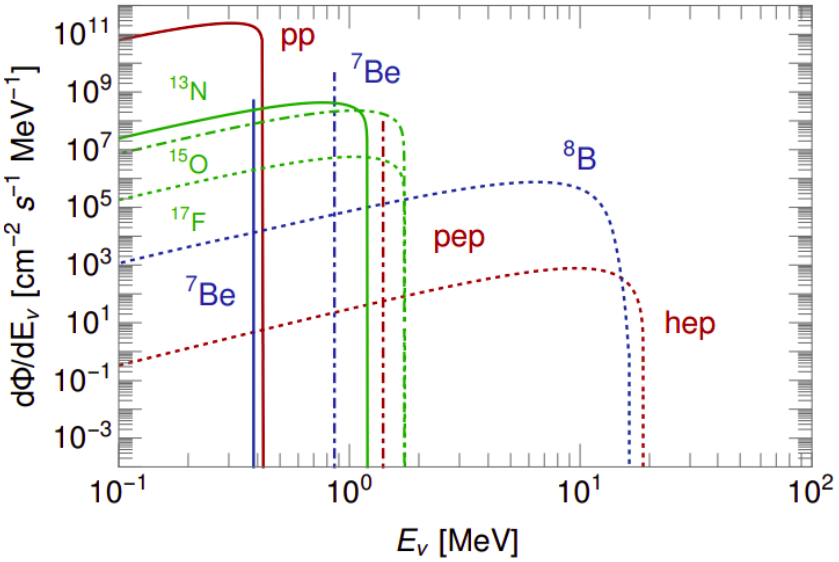


Target electrons : $N_T \sim 10^{29} t^{-1}$

A Simplified Model : Light Z'

- Differential rate : $$\frac{dR}{dE_R} = N_T \int dE_\nu \frac{d\phi}{dE_\nu} \frac{d\sigma_\nu}{dE_R}$$



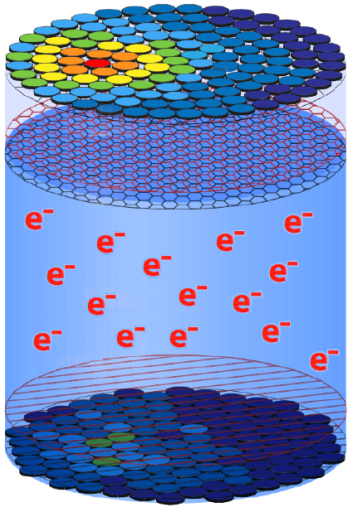


$N_T \sim 10^{29} t^{-1}$

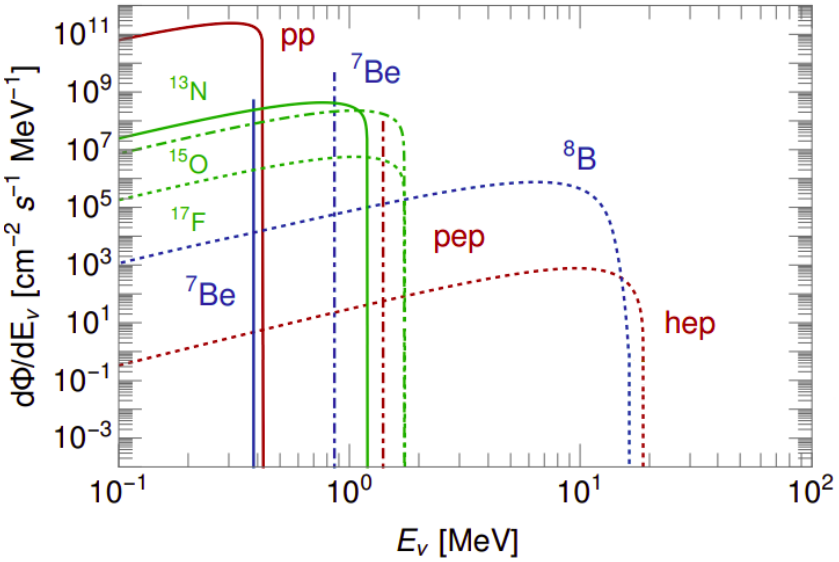
Solar neutrino flux : $\Phi_\nu \sim 10^2 y^{-1} keV^{-2}$

A Simplified Model : Light Z'

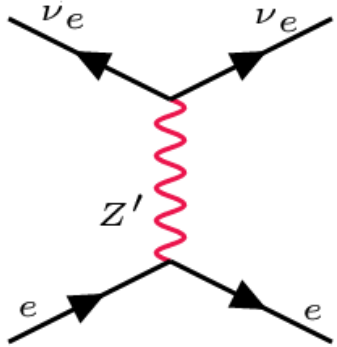
- Differential rate : $$\frac{dR}{dE_R} = N_T \int dE_\nu \frac{d\phi}{dE_\nu} \frac{d\sigma_\nu}{dE_R}$$



$N_T \sim 10^{29} t^{-1}$



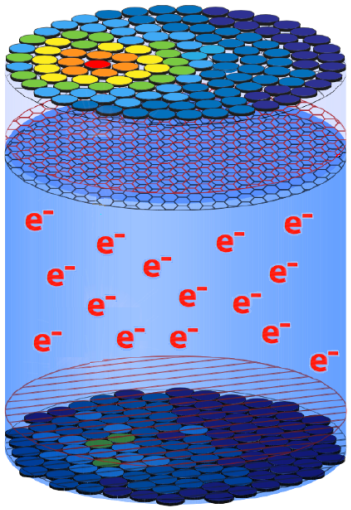
$\Phi_\nu \sim 10^2 y^{-1} keV^{-2}$

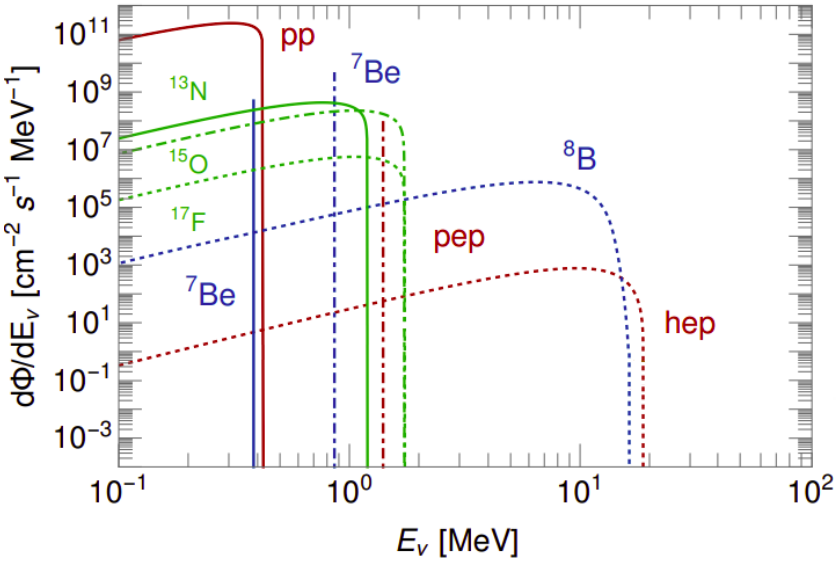


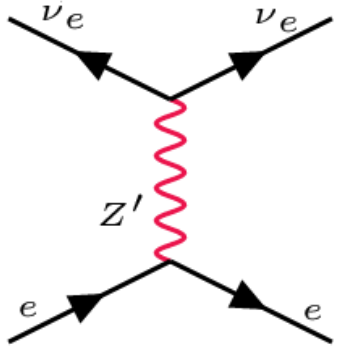
$$\frac{d\sigma_\nu}{dE_R} \sim 10^{-7} \frac{g_\nu^2 g_e^2}{E_R^2}$$

A Simplified Model : Light Z'

- Differential rate : $$\frac{dR}{dE_R} = N_T \int dE_\nu \frac{d\phi}{dE_\nu} \frac{d\sigma_\nu}{dE_R}$$







$$N_T \sim 10^{29} t^{-1}$$

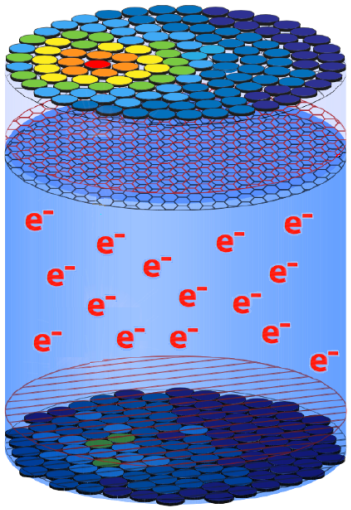
$$\Phi_\nu \sim 10^2 y^{-1} keV^{-2}$$

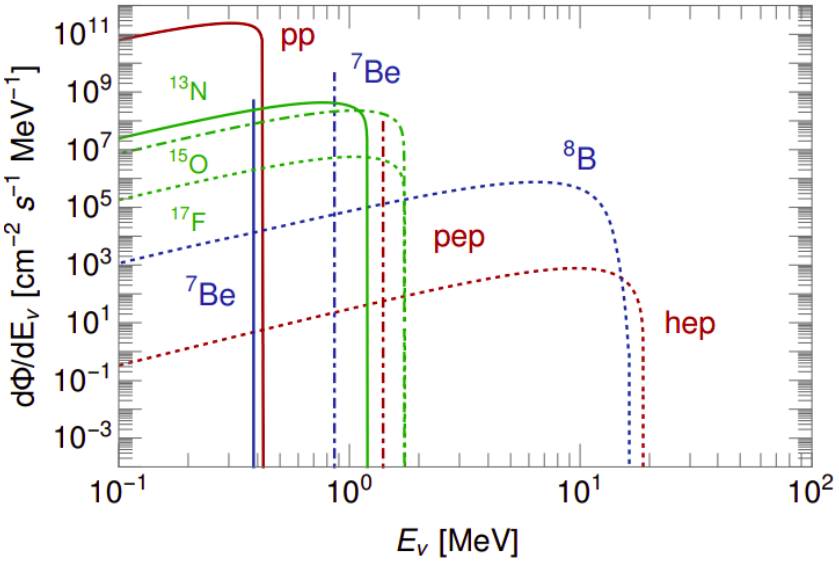
$$\frac{d\sigma_\nu}{dE_R} \sim 10^{-7} \frac{g_\nu^2 g_e^2}{E_R^2}$$

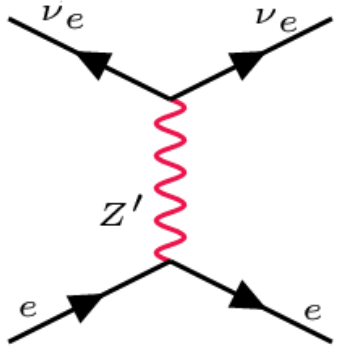
$$\sqrt{g_\nu g_e} \simeq 10^{-6} \left(\frac{E_R}{1\ \text{keV}}\right)^{\frac{1}{2}} \left(\frac{dR/dE_R}{10\ \text{Events}}\right)^{\frac{1}{4}}$$

A Simplified Model : Light Z'

- Differential rate : $$\frac{dR}{dE_R} = N_T \int dE_\nu \frac{d\phi}{dE_\nu}\frac{d\sigma_\nu}{dE_R}$$







$N_T \sim 10^{29} t^{-1}$

$\Phi_\nu \sim 10^2 y^{-1} keV^{-2}$

$$\frac{d\sigma_\nu}{dE_R} \sim 10^{-7}\frac{g_\nu^2 g_e^2}{E_R^2}$$

$$\sqrt{g_\nu g_e} \simeq 10^{-6}\left(\frac{E_R}{1\text{ keV}}\right)^{\frac{1}{2}}\left(\frac{dR/dE_R}{10\text{ Events}}\right)^{\frac{1}{4}}$$

- To generate the excess we need $m_{Z'} \ll m_e$ and $\sqrt{g_\nu g_e} \sim 10^{-6}$

Two Higgs Doublet Model (2HDM)

Two Higgs doublets :

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

A motivation to introduce the $U(1)$ symmetry in the 2HDM is the flavor problem

General Yukawa Lagrangian with two scalar doublets :

$$\begin{aligned} -\mathcal{L}_{Y_{\text{2HDM}}} &= y^{1d}\bar{Q}\Phi_1 d_R + y^{1u}\bar{Q}\widetilde{\Phi_1} u_R + y^{1e}\bar{L}\Phi_1 e_R + \\ &+ y^{2d}\bar{Q}\Phi_2 d_R + y^{2u}\bar{Q}\widetilde{\Phi_2} u_R + y^{2e}\bar{L}\Phi_2 e_R + h.c. \end{aligned}$$

Mass matrix :

$$M^d_{ij} = y^{1d}_{ij}\frac{v_1}{\sqrt{2}} + y^{2d}_{ij}\frac{v_2}{\sqrt{2}}$$

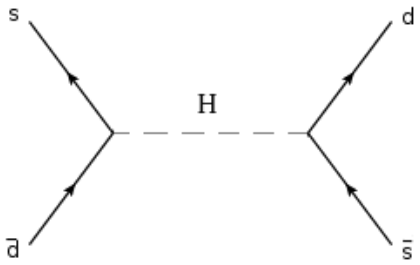
In the physical basis :

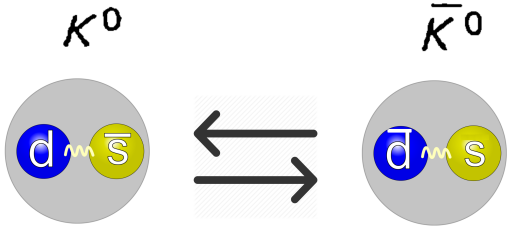
- M^d_{ij} is diagonal
- y^{1d}_{ij} and y^{2d}_{ij} **are not diagonal** $\longrightarrow$ **Yukawa neutral interactions mix flavors**

2HDM - Flavor Changing Problem

Neutral scalars mediate flavor changing neutral interactions at tree level

$\mathcal{L}_{\text{Ydown}} \supset y_{dd} H\bar{d}d + y_{ss} H\bar{s}s + y_{ds} H\bar{d}s$:





Four possibilities of Yukawa interaction :

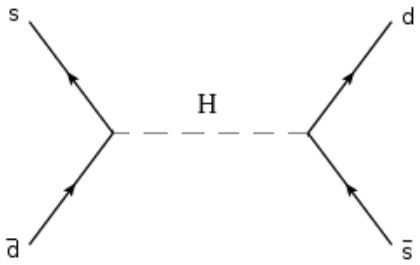
2HDM	u_R	d_R	e_R
Tipo I	Φ_2	Φ_2	Φ_2
Tipo II	Φ_2	Φ_1	Φ_1
Tipo X	Φ_2	Φ_2	Φ_1
Tipo Y	Φ_2	Φ_1	Φ_2

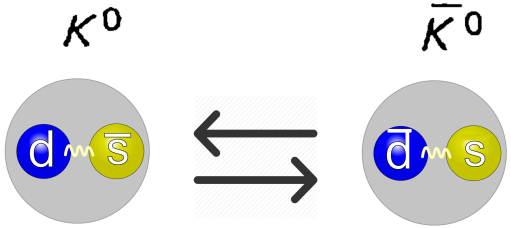
$$-\mathcal{L}_{Y_{\text{2HDM}}} = y^{1d}\bar{Q}\Phi_1 d_R + y^{1u}\bar{Q}\widetilde{\Phi}_1 u_R + y^{1e}\bar{L}\Phi_1 e_R + \\ + y^{2d}\bar{Q}\Phi_2 d_R + y^{2u}\bar{Q}\widetilde{\Phi}_2 u_R + y^{2e}\bar{L}\Phi_2 e_R + h.c.$$

2HDM - Flavor Changing Problem

Neutral scalars mediate flavor changing neutral interactions at tree level

$\mathcal{L}_{\text{Ydown}} \supset y_{dd} H \bar{d} d + y_{ss} H \bar{s} s + y_{ds} H \bar{d} s$:





Four possibilities of Yukawa interaction :

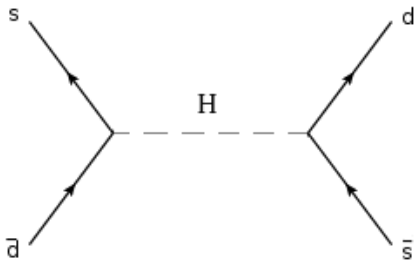
2HDM	u_R	d_R	e_R
Tipo I	Φ_2	Φ_2	Φ_2
Tipo II	Φ_2	Φ_1	Φ_1
Tipo X	Φ_2	Φ_2	Φ_1
Tipo Y	Φ_2	Φ_1	Φ_2

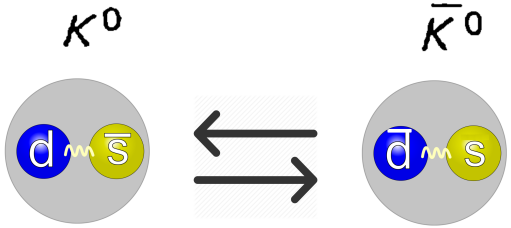
$$-\mathcal{L}_{Y_{\text{2HDM}}} = \cancel{y^{1d}\bar{Q}\Phi_1 d_R} + \cancel{y^{1u}\bar{Q}\widetilde{\Phi}_1 u_R} + \cancel{y^{1e}\bar{L}\Phi_1 e_R} + \\ + y^{2d}\bar{Q}\Phi_2 d_R + y^{2u}\bar{Q}\widetilde{\Phi}_2 u_R + y^{2e}\bar{L}\Phi_2 e_R + h.c.$$

2HDM - Flavor Changing Problem

Neutral scalars mediate flavor changing neutral interactions at tree level

$\mathcal{L}_{\text{Ydown}} \supset y_{dd} H \bar{d} d + y_{ss} H \bar{s} s + y_{ds} H \bar{d} s$:





Four possibilities of Yukawa interaction :

2HDM	u_R	d_R	e_R
Tipo I	Φ_2	Φ_2	Φ_2
Tipo II	Φ_2	Φ_1	Φ_1
Tipo X	Φ_2	Φ_2	Φ_1
Tipo Y	Φ_2	Φ_1	Φ_2

$$-\mathcal{L}_{Y_{\text{2HDM}}} = y^{1d}\bar{Q}\Phi_1 d_R + \cancel{y^{1u}\bar{Q}\widetilde{\Phi}_1 u_R} + y^{1e}\bar{L}\Phi_1 e_R + \\ + \cancel{y^{2d}\bar{Q}\Phi_2 d_R} + y^{2u}\bar{Q}\widetilde{\Phi}_2 u_R + \cancel{y^{2e}\bar{L}\Phi_2 e_R} + h.c.$$

2HDM-$U(1)_{B-L}$

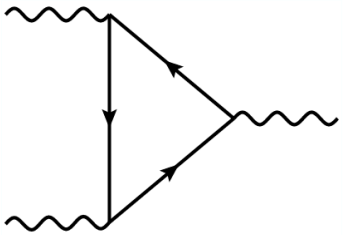
- To avoid FCNC at tree level we impose a $U(1)_{B-L}$ symmetry

Particles	u_R	d_R	Q_L	L_L	e_R	N_R	Φ_2	Φ_1	Φ_S
$U(1)_{B-L}$ Charges	$1/3$	$1/3$	$1/3$	-1	-1	-1	0	2	2

2HDM-$U(1)_{B-L}$

- To avoid FCNC at tree level we impose a $U(1)_{B-L}$ symmetry

Particles	u_R	d_R	Q_L	L_L	e_R	N_R	Φ_2	Φ_1	Φ_S
$U(1)_{B-L}$ Charges	$1/3$	$1/3$	$1/3$	-1	-1	-1	0	2	2



- Extra features :
  - 3 right-handed neutrinos N_R for anomaly cancellation
  - Scalar singlet Φ_S coupled to neutrinos

$$-\mathcal{L}_\nu \supset y^D \bar{L}\widetilde{\Phi}_2 N_R + Y^M \overline{N_R^c}\Phi_s N_R$$

  - Neutrinos become massive after $U(1)$ breaking $\Longrightarrow$ Type I seesaw mechanism

2HDM-$U(1)_{B-L}$

Z ′ Interactions with leptons :

$$\mathcal{L}_{Z'ff} = \frac{1}{2}\left(g_{BL}\bar{\nu}\gamma^\mu\nu + g_{BL}\bar{l}\gamma^\mu l\right) Z'_\mu + ...$$

Equal couplings to electrons and neutrinos : $g_\nu = 2g_{BL} \quad , \quad g_e = 2g_{BL}$

2HDM-$U(1)_{B-L}$

Z ′ Interactions with leptons :

$$\mathcal{L}_{Z'ff} = \frac{1}{2}\left(g_{BL}\bar{\nu}\gamma^\mu\nu + g_{BL}\bar{l}\gamma^\mu l\right) Z'_\mu + ...$$

Equal couplings to electrons and neutrinos : $g_\nu = 2g_{BL} \quad , \quad g_e = 2g_{BL}$

$$\Longrightarrow \sqrt{g_\nu g_e} = 2g_{BL} \sim 10^{-6}$$

2HDM-$U(1)_{B-L}$

Z ′ Interactions with leptons :

$$\mathcal{L}_{Z'ff} = \frac{1}{2}\left(g_{BL}\bar{\nu}\gamma^\mu\nu + g_{BL}\bar{l}\gamma^\mu l\right) Z'_\mu + ...$$

Equal couplings to electrons and neutrinos : $g_\nu = 2g_{BL} \quad , \quad g_e = 2g_{BL}$

$$\Longrightarrow \sqrt{g_\nu g_e} = 2g_{BL} \sim 10^{-6}$$

Z ′ Mass : Proportional to the $U(1)_{B-L}$ symmetry breaking scale v_s and to g_{BL}.
$m_{Z'}$ and g_{BL} are not independent.

$$m_{Z'} \sim g_{BL} v_s$$

2HDM-$U(1)_{B-L}$

Z ′ Interactions with leptons :

$$\mathcal{L}_{Z'ff} = \frac{1}{2}\left(g_{BL}\bar{\nu}\gamma^\mu\nu + g_{BL}\bar{l}\gamma^\mu l\right) Z'_\mu + ...$$

Equal couplings to electrons and neutrinos : $g_\nu = 2g_{BL} \quad , \quad g_e = 2g_{BL}$

$$\Longrightarrow \sqrt{g_\nu g_e} = 2g_{BL} \sim 10^{-6}$$

Z ′ Mass : Proportional to the $U(1)_{B-L}$ symmetry breaking scale v_s and to g_{BL}.
$m_{Z'}$ and g_{BL} are not independent.

$$m_{Z'} \sim g_{BL} v_s$$

For $g_{BL} = 10^{-6}$, $v_S = 1$ TeV $\quad \Longrightarrow \quad m_{Z'} \sim 1$ MeV

2HDM-$U(1)_{B-L}$

Z ′ Interactions with leptons :

$$\mathcal{L}_{Z'ff} = \frac{1}{2}\left(g_{BL}\bar{\nu}\gamma^\mu\nu + g_{BL}\bar{l}\gamma^\mu l\right) Z'_\mu + ...$$

Equal couplings to electrons and neutrinos : $g_\nu = 2g_{BL} \quad , \quad g_e = 2g_{BL}$

$$\Longrightarrow \sqrt{g_\nu g_e} = 2g_{BL} \sim 10^{-6}$$

Z ′ Mass : Proportional to the $U(1)_{B-L}$ symmetry breaking scale v_s and to g_{BL}.
$m_{Z'}$ and g_{BL} are not independent.

$$m_{Z'} \sim g_{BL} v_s$$

For $g_{BL} = 10^{-6}$, $v_S = 1$ TeV $\quad \Longrightarrow \quad m_{Z'} \sim 1$ MeV Too heavy for our purpose...

2HDM-$U(1)_{B-L}$

Z ′ Interactions with leptons :

$$\mathcal{L}_{Z'ff} = \frac{1}{2}\left(g_{BL}\bar{\nu}\gamma^\mu\nu + g_{BL}\bar{l}\gamma^\mu l\right) Z'_\mu + ...$$

Equal couplings to electrons and neutrinos : $g_\nu = 2g_{BL} \quad , \quad g_e = 2g_{BL}$

$$\Longrightarrow \sqrt{g_\nu g_e} = 2g_{BL} \sim 10^{-6}$$

Z ′ Mass : Proportional to the $U(1)_{B-L}$ symmetry breaking scale v_s and to g_{BL}.
$m_{Z'}$ and g_{BL} are not independent.

$$m_{Z'} \sim g_{BL} v_s$$

For $g_{BL} = 10^{-6}$, $v_S = 1$ TeV $\quad \Longrightarrow \quad m_{Z'} \sim 1$ MeV Too heavy for our purpose...

$U(1)_Y \otimes U(1)_{B-L}$ **Kinetic mixing** : $\epsilon \hat{F}'_{\mu\nu}\hat{F}^{\mu\nu}$

2HDM-$U(1)_{B-L}$

Z ′ Interactions with leptons :

$$\mathcal{L}_{Z'ff} = \frac{1}{2}\left(g_{BL}\bar{\nu}\gamma^\mu\nu + g_{BL}\bar{l}\gamma^\mu l\right) Z'_\mu + ...$$

Equal couplings to electrons and neutrinos : $g_\nu = 2g_{BL} \quad , \quad g_e = 2g_{BL}$

$$\Longrightarrow \sqrt{g_\nu g_e} = 2g_{BL} \sim 10^{-6}$$

Z ′ Mass : Proportional to the $U(1)_{B-L}$ symmetry breaking scale v_s and to g_{BL}.
$m_{Z'}$ and g_{BL} are not independent.

$$m_{Z'} \sim g_{BL} v_s$$

For $g_{BL} = 10^{-6}$, $v_S = 1$ TeV $\quad \Longrightarrow \quad m_{Z'} \sim 1$ MeV Too heavy for our purpose...

$U(1)_Y \otimes U(1)_{B-L}$ **Kinetic mixing** : $\epsilon \hat{F}'_{\mu\nu}\hat{F}^{\mu\nu}$

$$\mathcal{L}_{Z'ff} = -\epsilon e J^\mu_{em} Z'_\mu \qquad \Longrightarrow \qquad g_\nu = 2g_{BL} \quad , \quad g_e = 2g_{BL} + 4\epsilon e$$

Results

- χ^2-fit for the 29 bins in the range $1-30$ keV of electron recoil energy

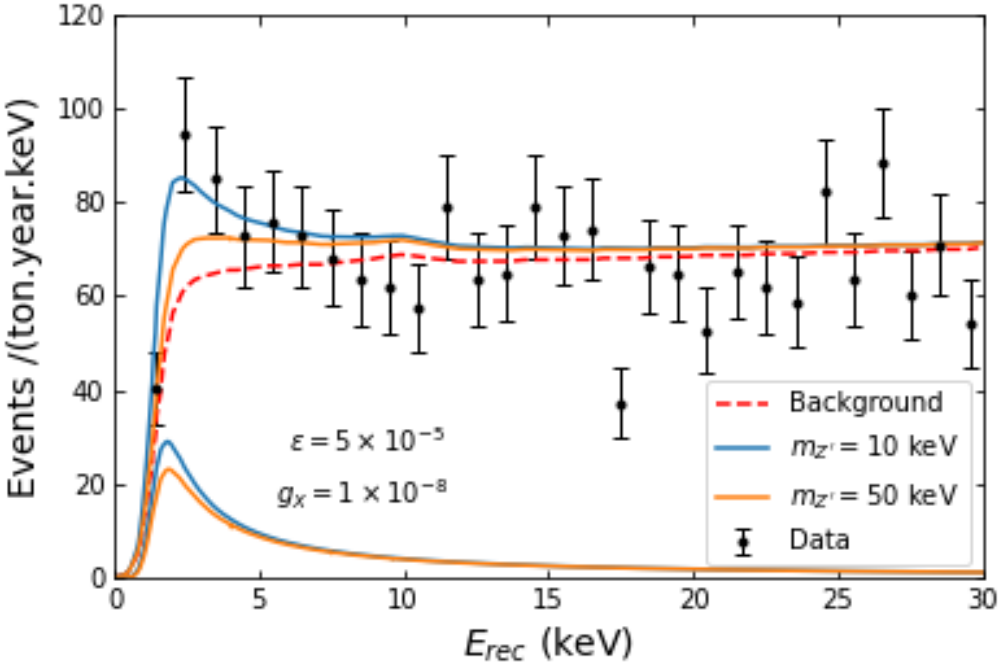
$$\chi^2 = \sum_i \frac{1}{\sigma_i^2}\left[\left(\frac{dR^{\text{th}}}{dE_{rec}}\right)_i - \left(\frac{dR^{exp}}{dE_{rec}}\right)_i\right]^2$$

Results

- χ^2-fit for the 29 bins in the range $1-30$ keV of electron recoil energy

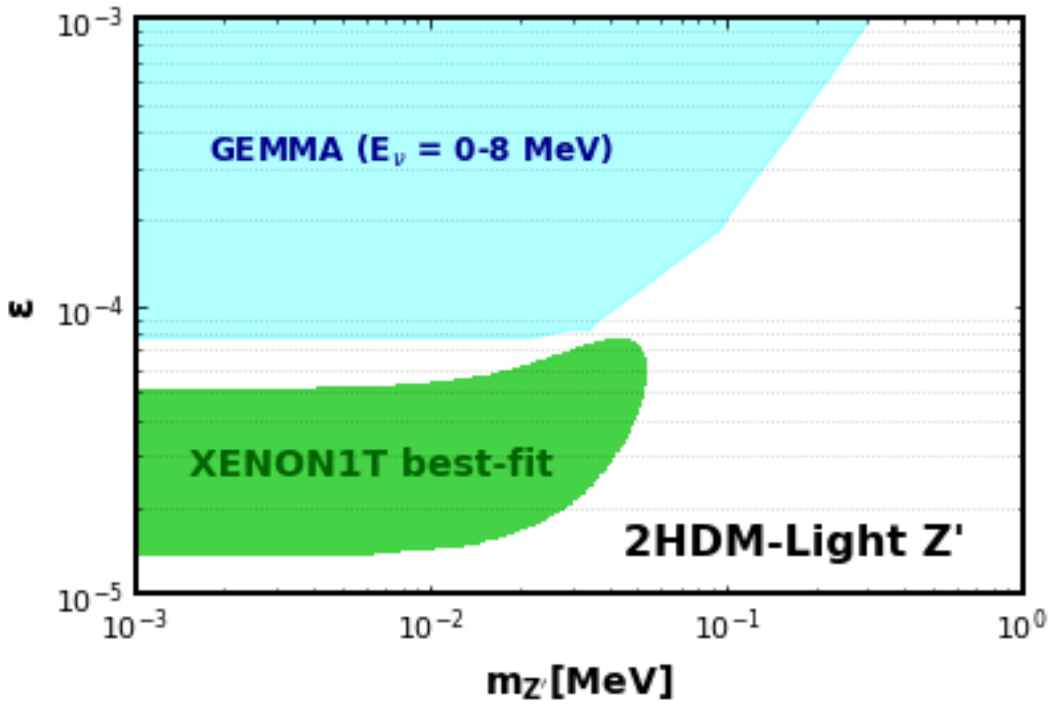
$$\chi^2 = \sum_i \frac{1}{\sigma_i^2}\left[\left(\frac{dR^{\text{th}}}{dE_{rec}}\right)_i - \left(\frac{dR^{exp}}{dE_{rec}}\right)_i\right]^2$$

- Sample signals for $m_{Z'} = 10keV$ and $m_{Z'} = 50keV$



Results

- Favored region in the plane $\epsilon \times m_{Z'}$, assuming fixed $g_{BL} = 1 \times 10^{-8}$



2HDM-$U(1)_{B-L}$ and $(g-2)_\mu$ Anomaly

- A 4.2σ discrepancy :

$$a_\mu^{exp} = 116592061(41) \times 10^{-11} \quad , \quad a_\mu^{SM} = 116591810(43) \times 10^{-11}$$

$$\Delta a_\mu = 251(59) \times 10^{-11}$$

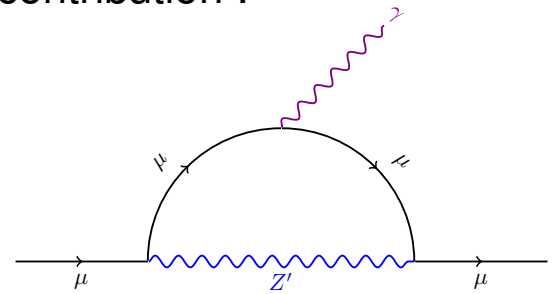
2HDM-$U(1)_{B-L}$ and $(g-2)_\mu$ Anomaly

- A 4.2σ discrepancy :

$$a_\mu^{exp} = 116592061(41) \times 10^{-11} \quad , \quad a_\mu^{SM} = 116591810(43) \times 10^{-11}$$

$$\Delta a_\mu = 251(59) \times 10^{-11}$$

- Z' contribution :



$$\Delta a_\mu = \frac{\epsilon^2 m_\mu^2}{8\pi^2} \int_0^1 \frac{2x^2(1-x)}{x^2 {m_\mu}^2 + (1-x) m_{Z'}^2} dx$$

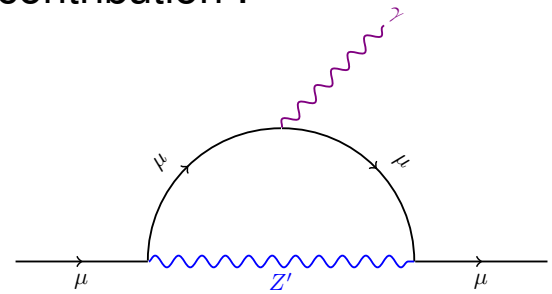
2HDM-$U(1)_{B-L}$ and $(g-2)_\mu$ Anomaly

- A 4.2σ discrepancy :

$$a_\mu^{exp} = 116592061(41) \times 10^{-11} \quad , \quad a_\mu^{SM} = 116591810(43) \times 10^{-11}$$

$$\Delta a_\mu = 251(59) \times 10^{-11}$$

- Z' contribution :



$$\Delta a_\mu = \frac{\epsilon^2 m_\mu^2}{8\pi^2} \int_0^1 \frac{2x^2(1-x)}{x^2 {m_\mu}^2 + (1-x) m_{Z'}^2} dx$$

- For $m_{Z'} \ll m_\mu$:

$$\Delta a_\mu \sim \frac{\epsilon^2}{8\pi^2} \qquad \Longrightarrow \qquad \epsilon \sim 10^{-3}$$

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

Particles	u	d	e	μ	τ	ν_e	ν_μ	ν_τ	Φ_2	Φ_1
$U(1)_{L_\mu - L_\tau}$ Charges	0	0	0	1	-1	0	1	-1	0	1

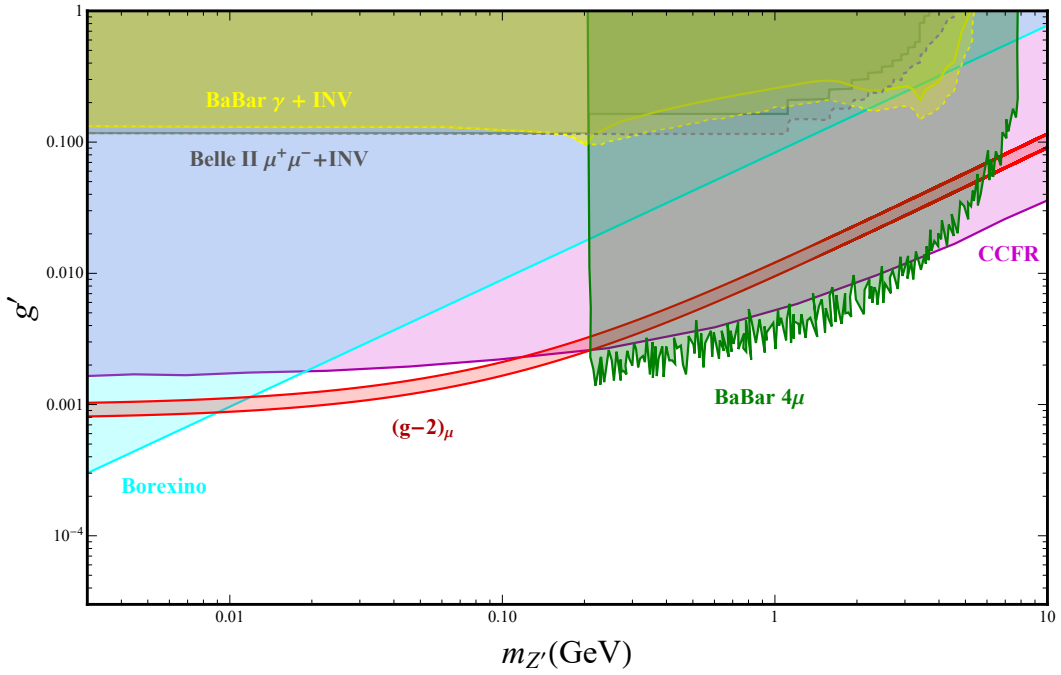
$$-\mathcal{L}_{Z'ff} = \frac{1}{2} g' \left(\bar{\mu}\gamma^\mu \mu - \bar{\tau}\gamma^\mu \tau\right) Z'_\mu + ...$$

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

Particles	u	d	e	μ	τ	ν_e	ν_μ	ν_τ	Φ_2	Φ_1
$U(1)_{L_\mu - L_\tau}$ Charges	0	0	0	1	-1	0	1	-1	0	1

$$-\mathcal{L}_{Z' f f} = \frac{1}{2} g' \left(\bar{\mu}\gamma^\mu \mu - \bar{\tau}\gamma^\mu \tau\right) Z'_\mu + \ldots$$

- Z' mass in the range $10\text{MeV} \lesssim m_{Z'} \lesssim 200\text{MeV}$



Summary

- XENON1T experiment has observed an excess on electronic recoils which is not the signal expected from a WIMP

Summary

- XENON1T experiment has observed an excess on electronic recoils which is not the signal expected from a WIMP
- It may be caused by solar neutrinos scattering off electrons inside the detector. The interaction is mediated by a light Z' gauge boson and enhanced at low energies

Summary

- XENON1T experiment has observed an excess on electronic recoils which is not the signal expected from a WIMP
- It may be caused by solar neutrinos scattering off electrons inside the detector. The interaction is mediated by a light Z' gauge boson and enhanced at low energies
- We propose a complete model that realizes this idea in the context of a 2HDM
- The $U(1)$ symmetry is well motivated in the 2HDM. The model is automatically free from FCNC and neutrinos are massive

Summary

- XENON1T experiment has observed an excess on electronic recoils which is not the signal expected from a WIMP
- It may be caused by solar neutrinos scattering off electrons inside the detector. The interaction is mediated by a light Z' gauge boson and enhanced at low energies
- We propose a complete model that realizes this idea in the context of a 2HDM
- The $U(1)$ symmetry is well motivated in the 2HDM. The model is automatically free from FCNC and neutrinos are massive
- A modified version of the model can accommodate the $(g-2)_\mu$ anomaly, although not both anomalies simultaneously