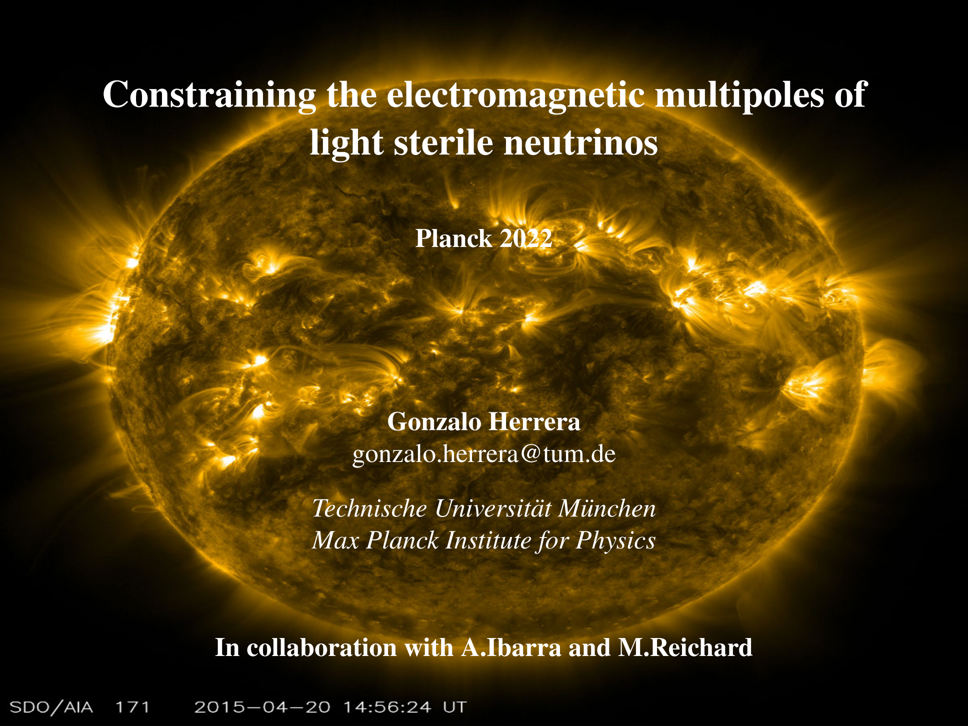
Constraining the electromagnetic multipoles of light sterile neutrinos

Planck 2022

Gonzalo Herrera
gonzalo.herrera@tum.de

Technische Universität München
Max Planck Institute for Physics

In collaboration with A.Ibarra and M.Reichard



Outline

- **Motivation:** Light sterile neutrinos, neutrino electromagnetic properties.
- The sterile neutrino **flux** at Earth.
- **Constraints** from XENON1T and complementary searches.
- A **model** with enhanced sterile neutrino electromagnetic multipoles.
- **Conclusions**.

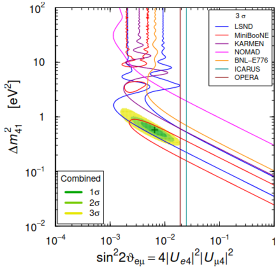
Light sterile neutrinos

- Sterile neutrinos constitute a simple extension of the SM introducing an appealing left-right symmetry.
- In some seesaw models with several right handed neutrino fields, not all of them need to be very heavy.

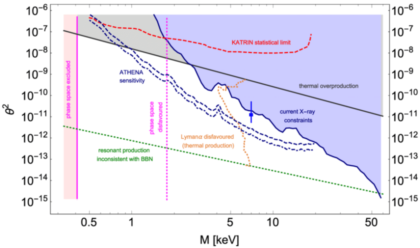
Light sterile neutrinos

- Sterile neutrinos constitute a simple extension of the SM introducing an appealing left-right symmetry.
- In some seesaw models with several right handed neutrino fields, not all of them need to be very heavy.

Giunti, Lasserre, 19'



Boyarsky, Drewes, Lasserre, Mertens, Ruchayskiy, 18'



- Some short baseline oscillation and reactor experiments seem to favour a 3+1 scheme with an eV sterile neutrino.
- keV sterile neutrinos could account for the dark matter abundance and explain anomalous X-ray observations.

Neutrino electromagnetic interactions

Effective interaction vertex between a photon and a neutrino:

$$\mathcal{M}_\mu^{i\to f}(q) = (\gamma_\mu - q_\mu \not{q}/q^2)\left[f_Q^{fi}(q^2) + f_A^{fi}(q^2)q^2\gamma_5\right] - i\sigma_{\mu\nu}q^\nu\left[f_M^{fi}(q^2) + i f_E^{fi}(q^2)\gamma_5\right]$$

$f_Q^{fi}(0) = e_{fi}$ charge

$f_M^{fi}(0) = \mu_{fi}$ magnetic moment

$f_E^{fi}(0) = \epsilon_{fi}$ electric moment

$f_A^{fi}(0) = a_{fi}$ anapole moment

For ultrarelativistic neutrinos ($\gamma_5 \to -1$), the charge and anapole form factors have a similar phenomenology:

$$\langle r_\nu^2 \rangle = 6\left.\frac{df_Q(q^2)}{dq^2}\right|_{q^2=0} = -6a$$

Majorana: $e_{ii} = \mu_{ii} = \epsilon_{ii} = 0$, $e_{ij} = 0$

Dirac: $\epsilon_{ii} = 0$

Laboratory constraints on the moments of neutrinos

PDG, 21'

Electric charge:
$(e_\nu, e_N) \lesssim (10^{-12}, -) \times e$

Magnetic moment:
$(\mu_{\nu\nu}, \mu_{\nu N}, \mu_{NN}) \lesssim (10^{-11}, 10^{-10}, -) \times \mu_B$

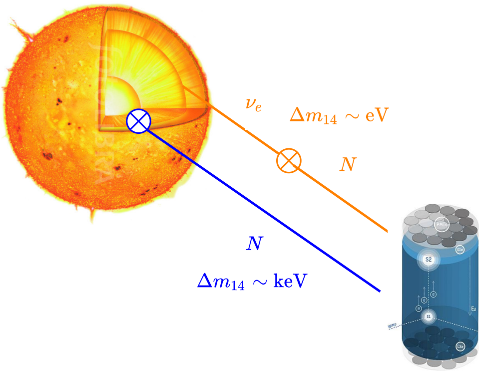
while the predicted value for active neutrinos is $\mu \sim 10^{-19} \frac{m_\nu}{1\mathrm{eV}} \mu_B$

Anapole moment:
$(a_{\nu\nu}, a_{\nu N}, a_{NN}) \lesssim (10^{-33}, 10^{-32}, 10^{-32}) \times \mathrm{cm}^2$

while the predicted value for active neutrinos is $a \sim 10^{-34}\,\mathrm{cm}^2$

The electromagnetic properties of sterile neutrinos are less constrained than for active neutrinos.

The solar sterile neutrino flux



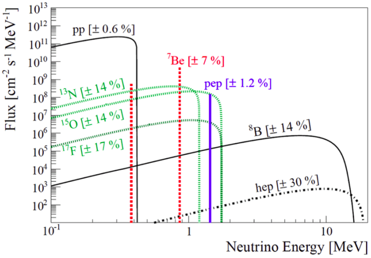
- The flux of solar eV-scale sterile neutrinos is given by the conversion probability of an ν_e into a N on its way to Earth.

- keV-scale sterile neutrinos are produced directly in the Sun.

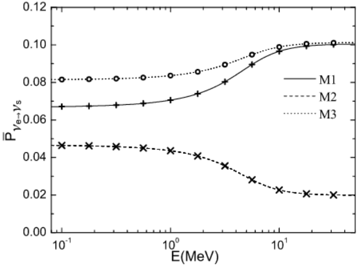
The solar sterile neutrino flux

- The largest flux of neutrinos (ν_e) at Earth comes from the proton-proton (pp) chain.
- Matter effects for pp neutrinos do not have an impact on the flux.

Borexino, 14'

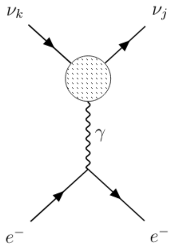


Giunti, Li, 09'

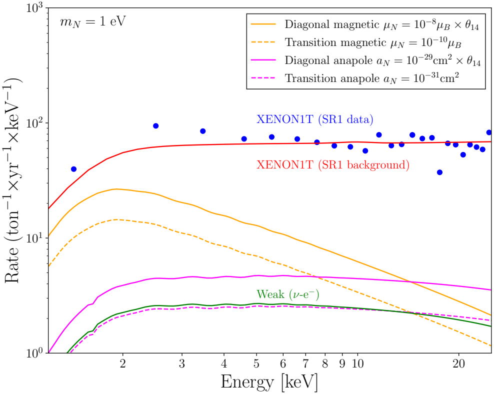


For both eV and keV masses, the flux scales as θ^2.

Recoil rate of sterile neutrino scatterings with electrons

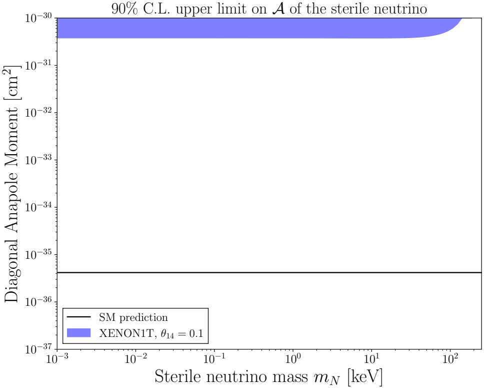


Effective EM interaction



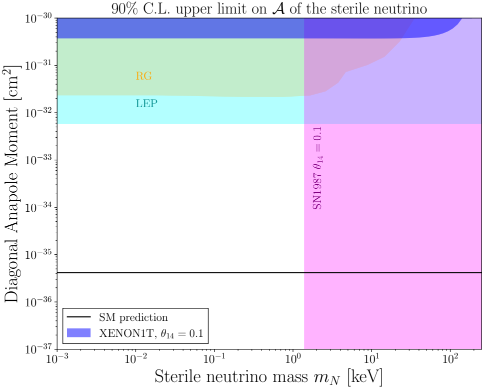
- **Anapole**: Flat at low energies, and same energy dependence as the weak scatterings of active neutrinos in the SM.
- **Magnetic**: Diverges at low energies, and different energy dependence than known SM backgrounds.

A constraint on the diagonal anapole moment



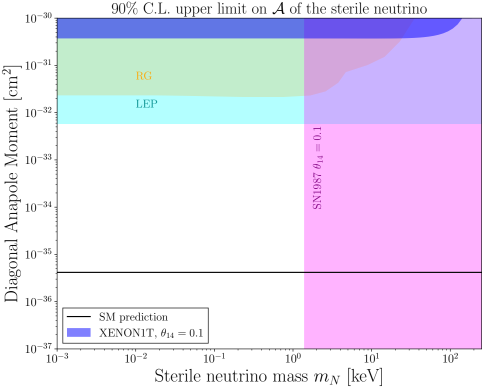
- The constraint from XENON1T on the diagonal anapole moment is far from the **SM prediction**.

A constraint on the diagonal anapole moment



- The constraint from XENON1T on the diagonal anapole moment is far from the **SM prediction**.
- It is close to astrophysical and collider constraints.
  Chu, Pradler, Semmelrock, 18'
  Raffelt, Zhou, 11'

A constraint on the diagonal anapole moment



Are there models where the expected values of the sterile neutrino moments become testable?

A model with enhanced sterile neutrino moments

Sterile neutrinos couple to a new scalar and fermion charged under a dark $U(1)$, giving rise to one-loop diagrams generating the electromagnetic moments.

$$\mathcal{L} = \bar{N}\,[c_L P_L + c_R P_R]\, S^* f + \text{h.c.}$$

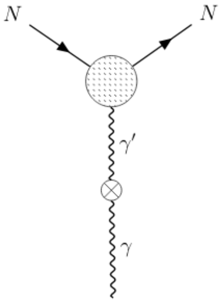
Some benchmark values:

$m_S \sim 1$ MeV

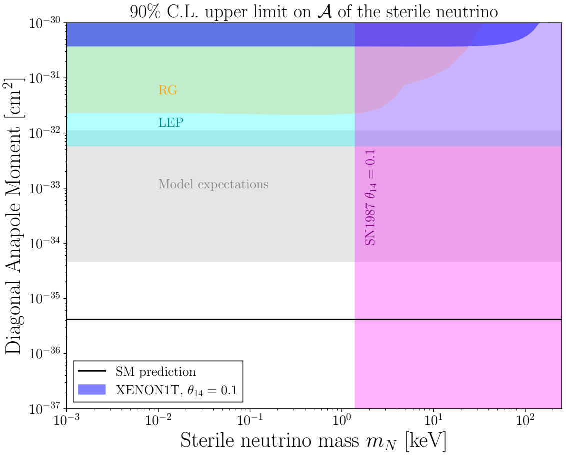
$m_f \sim 100$ MeV

$c_L, c_R \sim 1$

$\epsilon \sim 10^{-6}$



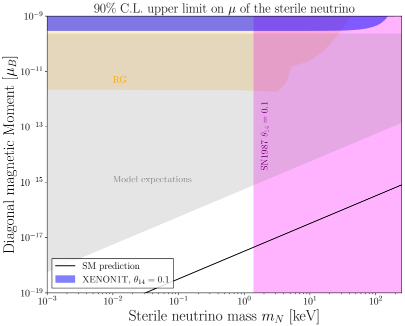
For an ultralight hidden photon γ', the new particles in the dark sector are poorly constrained.

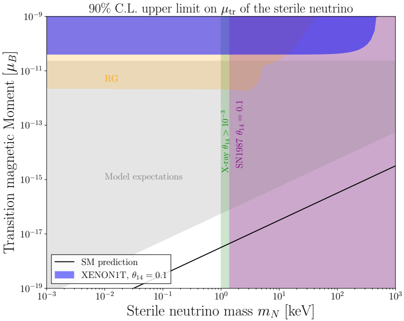


Are there models where the expected values of the sterile neutrino moments become testable?

✓ Yes, and we have provided an example of these.

Constraints and predictions on the magnetic moment





- The constraint from XENON1T on the off-diagonal magnetic moment is only ~ 1 order of magnitude weaker than the one from Red Giants.
- For allowed values of our model parameters, the predicted magnetic moments will be testable in the near future (XENONnT, SENSEI...).

Conclusions

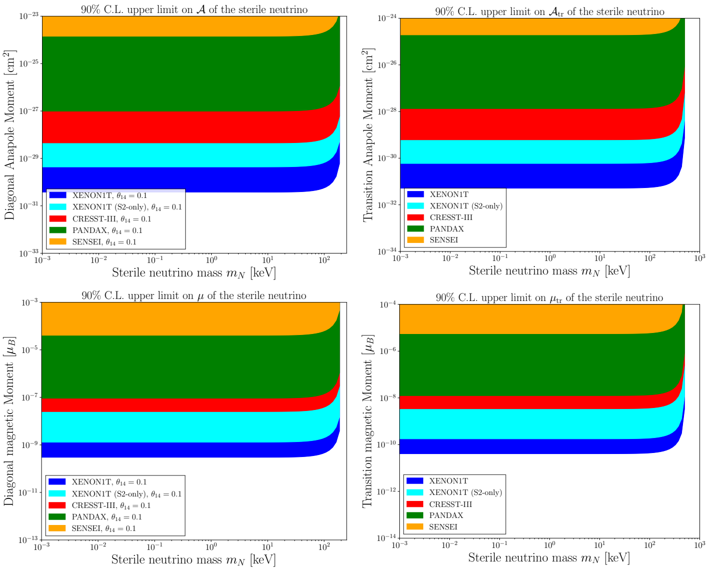
- In minimal extensions of the Standard Model with light sterile neutrinos, these are expected to carry electromagnetic moments, which are different for Majorana and Dirac particles.
- The electromagnetic moments of light sterile neutrinos are less constrained than those of active neutrinos, and their predicted values are model dependent.
- We have derived novel constraints on the diagonal anapole and magnetic moments of solar sterile neutrinos with XENON1T electron recoil data.
- We have proposed a model where the electromagnetic moments of the light sterile neutrinos will be testable in the near future.

Thanks for your attention

gonzalo.herrera@tum.de

Back-up slides

Constraints from different experiments



Cross section for the magnetic and anapole interactions

$$\frac{d\sigma_{\text{ana}}}{dT} = \alpha \mathcal{A}^2 \frac{\left(Tm_N^2 - Tm_e^2 + m_e(T^2 + 2E_\nu^2 - 2TE_\nu - 2m_N^2)\right)}{(E_\nu^2 - m_N^2)} \tag{1}$$

$$\frac{d\sigma_{\text{ana,tr}}}{dT} = \alpha \mathcal{A}_{\text{tr}}^2 \frac{\left(m_N^2(T - 2E_\nu) - 2Tm_e^2 + m_e(4E_\nu^2 - 4TE_\nu + 2T^2 - m_N^2)\right)}{2E_\nu^2}, \tag{2}$$

$$\frac{d\sigma_{\text{mag}}}{dT} = \alpha\mu^2 \frac{2m_e(E_\nu^2 - TE_\nu - m_N^2) + Tm_N^2}{2m_e T(E_\nu^2 - m_N^2)} \tag{3}$$

$$= \frac{\alpha\mu^2}{E_\nu^2 - m_N^2}\left[\frac{E_\nu^2}{T} - E_\nu + m_N^2\left(\frac{1}{2m_e} - \frac{1}{T}\right)\right] \tag{4}$$

$$\frac{d\sigma_{\text{mag,tr}}}{dT} = \alpha\mu_{\text{tr}}^2\left[\frac{1}{T} - \frac{1}{E_\nu} - \frac{m_N^2}{2E_\nu T m_e}\left(1 - \frac{T}{2E_\nu} + \frac{m_e}{2E_\nu}\right) + \frac{m_N^4(T - m_e)}{8E_\nu^2 T^2 m_e^2}\right] \tag{5}$$

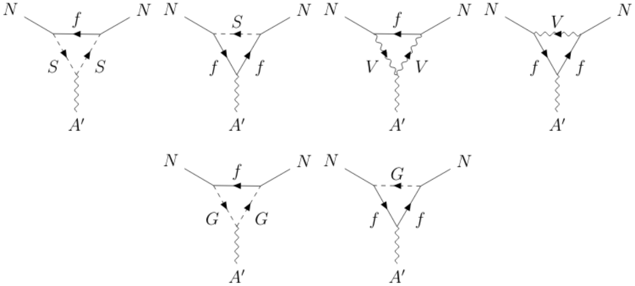
The recoil rate formula

$$\frac{dR}{dT_{rec}} = N_0 t \int_{T_{\min}}^{T^{\max}} dT \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \frac{d\phi}{dE_\nu} \frac{d\sigma}{dT} \epsilon(T_{rec}) G(T_{rec}, T) \quad (6)$$

$$E_\nu^{\min} = \frac{T}{2} + \frac{1}{2}\sqrt{T^2 + 4m_e T + 2m_N^2}. \quad (7)$$

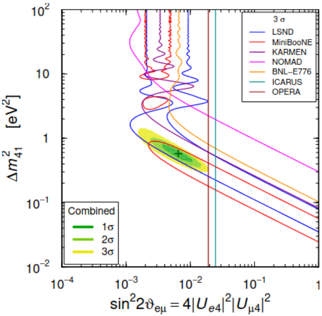
1-loop diagrams for the magnetic and anapole moment

$$\mathcal{L}_{\rm mag} = \frac{\mu}{2}\bar{N}\sigma^{\mu\nu}NF'_{\mu\nu} \quad \text{and} \quad \mathcal{L}_{\rm ana} = \frac{\mathcal{A}}{2}\bar{N}\gamma^{\mu}\gamma_5 N\partial^{\nu}F'_{\mu\nu}, \qquad (8)$$



eV sterile neutrinos

- In some seesaw models with several right handed neutrino fields, not all of them need to be very heavy
- The phenomenology of eV sterile neutrinos assumes that the heavy right handed neutrinos have negligible mixing with the lighter neutrinos



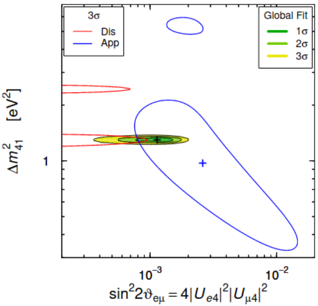
MiniBooNE reports an excess of 4.8σ favouring a 3+1 scheme with a ~ 1 eV sterile neutrino, and a 6.0σ significance when combined with LSND data.

Gallium and reactor anomalies also favor $\Delta m^2_{41} \geq 1$ eV^2

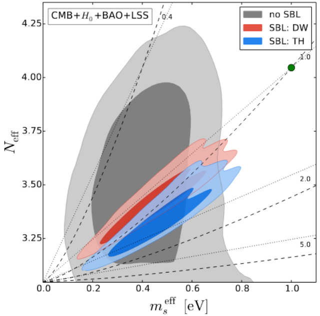
But...

- The non-observation of ν_μ disappearance in other experiments sets strong constraints on $\Delta m^2_{41} \sim 1\text{eV}^2$
- Global fits of appearance and disappearance data indicate that some experiment is wrong in their sterile neutrino interpretation.
- Cosmological data disfavor sterile neutrino masses at the eV scale and their full thermalization through active-sterile oscillations

Giunti, Lasserre, 19'



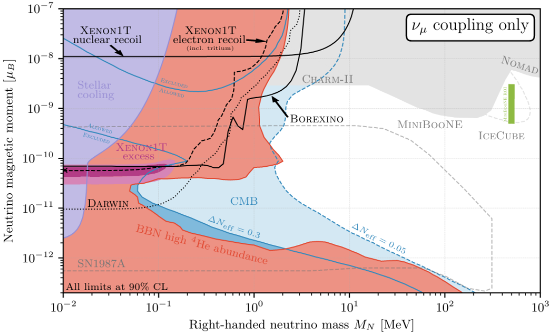
Gariazzo, 16'



SBL anomalies could be resolved in a few years: MicroBooNE, NEOS, IceCube, Katrin...

Cosmological constraints on the sterile neutrino magnetic moment

Brdar, Greljo, Kopp, Opferkuch, 21’



$N \to \nu + \gamma$ injects extra electromagnetic radiation.

N contributes to the expansion rate of the universe, increasing N_{eff}

Other models with sterile neutrino scatterings

- Sterile neutrinos can couple to the SM gauge bosons via right-handed CC and NC interactions:
  $\mathcal{L} = G_R(g_w/\sqrt{2})(\bar{l}_R\gamma^\rho \nu_{lR})W^- + NC$
- For eV sterile neutrinos, the strongest laboratory constraint comes from W decay width: $G_R \leq 6 \times 10^{-3}$