

# The Neutrino Magnetic Moment Portal

based on 2007.15563, JCAP01(2021)039

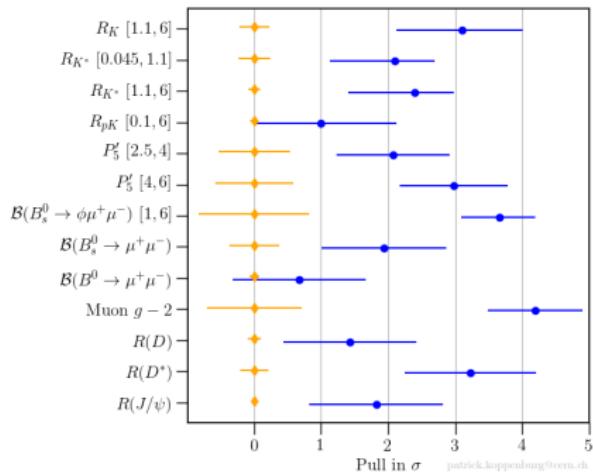
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Vedran Brdar

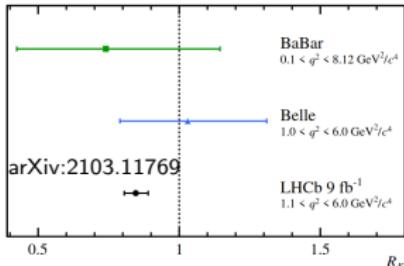


Northwestern  
University

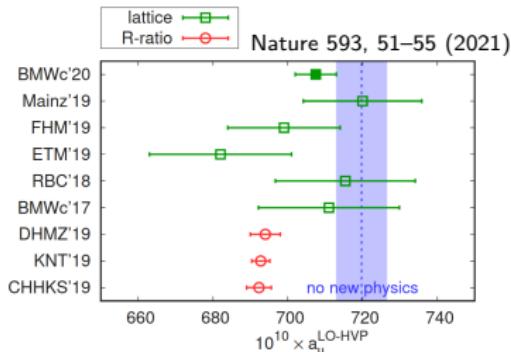
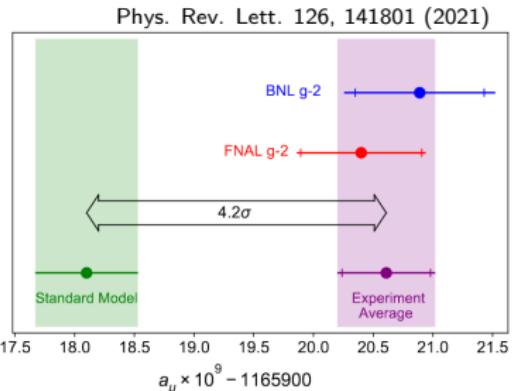
# B-anomalies and Muon $g - 2$



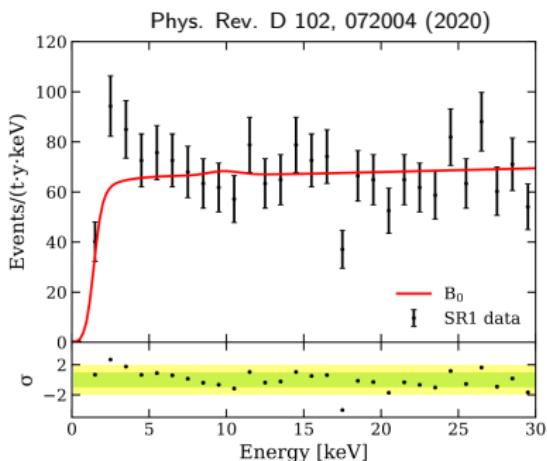
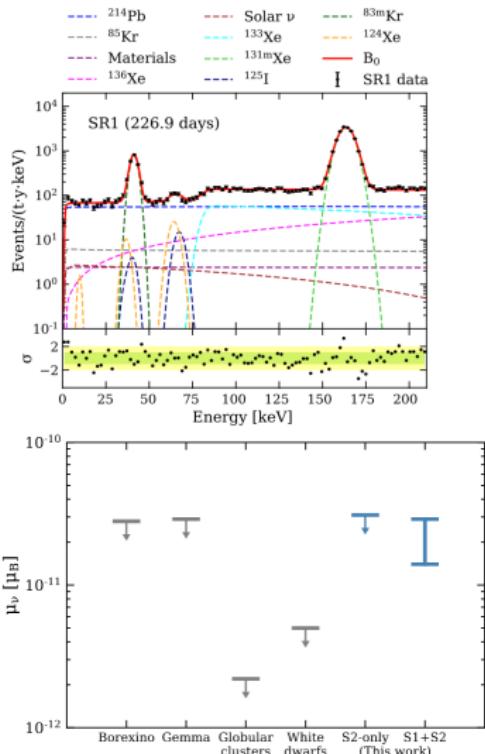
[http://www.scholarpedia.org/article/Rare\\_decays\\_of\\_b\\_hadrons](http://www.scholarpedia.org/article/Rare_decays_of_b_hadrons)



$$R(K^{(*)}) \equiv \frac{\text{BR}(B \rightarrow K^{(*)}\mu^+\mu^-)}{\text{BR}(B \rightarrow K^{(*)}e^+e^-)} \Big|_{q^2_{\min} < q}$$



# XENON1T Excess



- ▶ new physics in  $\nu - e$  scattering?
- ▶ significance of various new physics hypotheses depends on whether cosmogenic  $^3H$  is included in the fit

new physics for XENON1T excess in tension with stellar cooling constraints

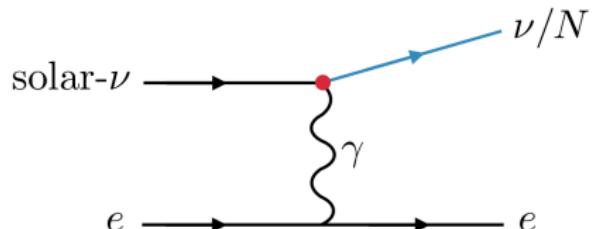
# Transition Magnetic Moments Between $\nu$ and $N_R$

- ▶ XENON1T collaboration considered magnetic moments involving only light neutrinos in the context of the excess
- ▶ such scenario can explain the excess at the expense of violating stellar cooling bounds
- ▶ to address that, we introduce **right-handed neutrinos** and the transition magnetic moments between those and light neutrinos; when  $M_N > T_{\text{star}}$  cooling bounds go away

$$\mathcal{L}_\mu = \frac{\mu_\nu^\alpha}{2} F_{\mu\nu} \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R + \text{h.c.}$$

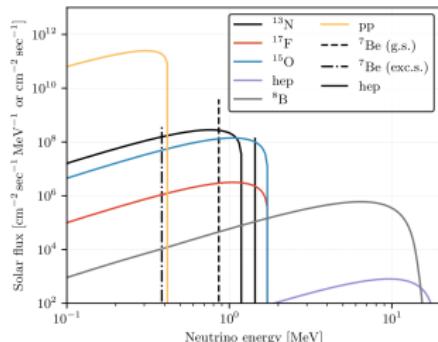
$$\frac{dR}{dE_r} = N_T \epsilon(E_r) \int_{E_\nu^{\min}} dE_\nu \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_r}$$

- ▶ scattering targets
- ▶ solar neutrino flux
- ▶ cross-sections for scattering via magnetic moment operator

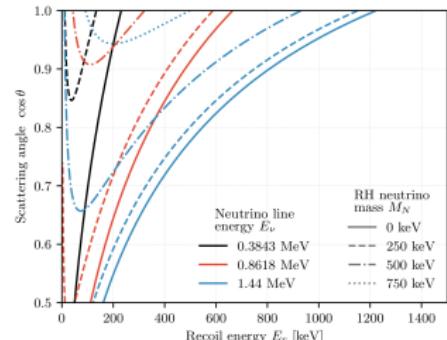


# Transition Magnetic Moment and XENON1T

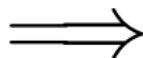
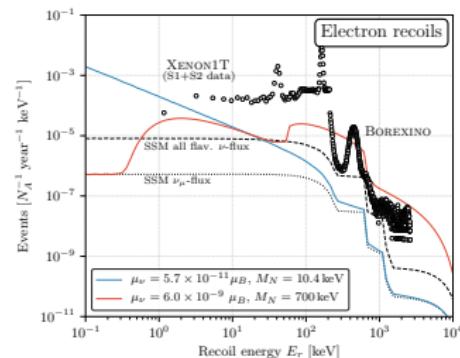
solar flux



$$\frac{d\sigma \mu(\nu_L e \rightarrow N_R e)}{dE_r} = \alpha \mu_\nu^2 \left[ \frac{1}{E_r} - \frac{1}{E_\nu} + M_N^2 \frac{E_r - 2E_\nu - m_e}{4E_\nu^2 E_r m_e} + M_N^4 \frac{E_r - m_e}{8E_\nu^2 E_r^2 m_e^2} \right]$$



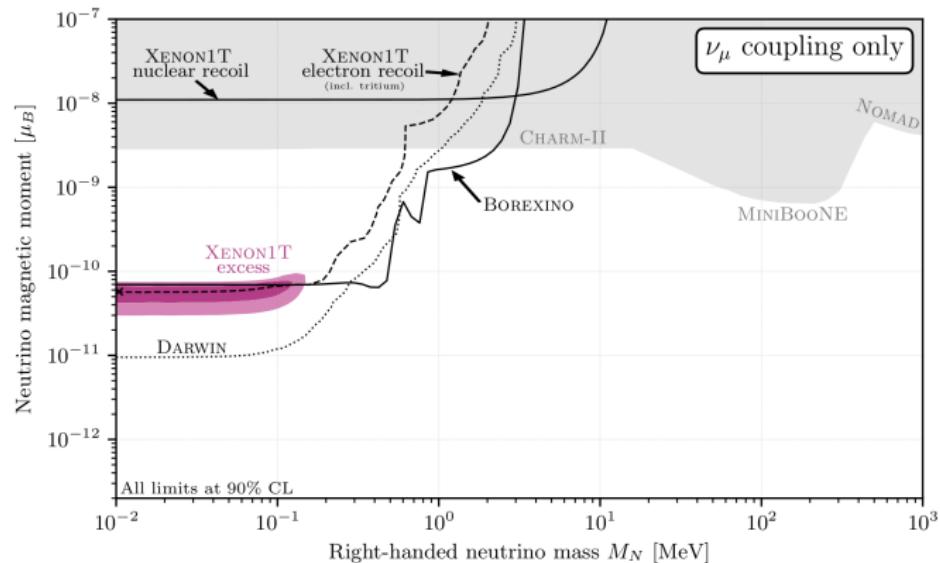
final  
spectra



fit

# Transition Magnetic Moment and XENON1T

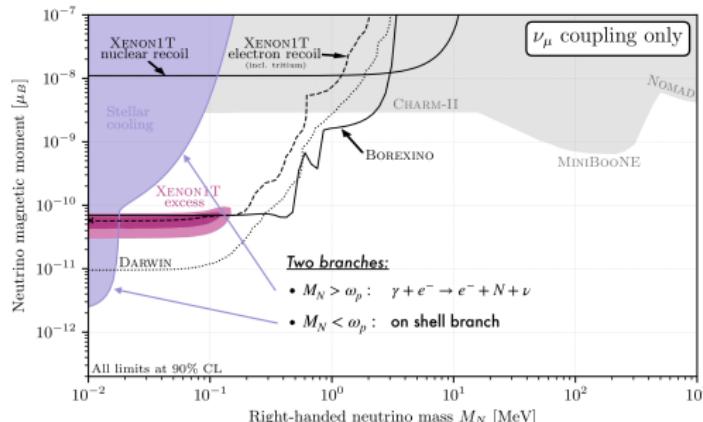
- ▶ result of binned fits to XENON1T and Borexino data



- ▶ preferred  $1\sigma$  and  $2\sigma$  regions  $\rightarrow 7 \times 10^{-11} \mu_B \gtrsim \mu_\nu \gtrsim 3 \times 10^{-11} \mu_B$  and  $M_N \lesssim 100$  keV

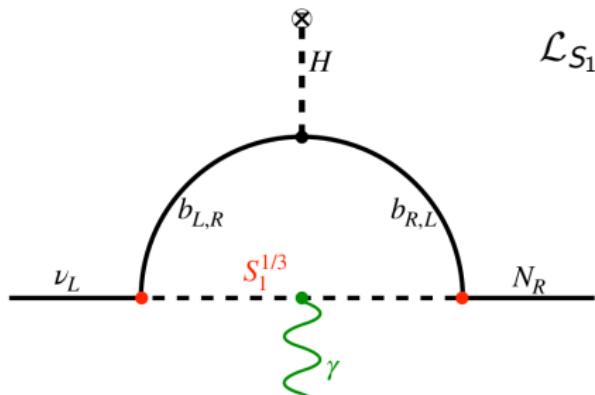
# Returning to Stellar Cooling Bounds

- ▶ in stars, plasmons can decay to  $N_R$  and  $\nu$  through magnetic moment operator (kinematically allowed if  $N_R$  is lighter than the core temperature of the star)
- ▶ such energy loss would be inconsistent with stellar evolution  
→ limits can be derived
- ▶ we obtain the constraint in  $(M_N, \mu_\nu)$  parameter space by employing arXiv:1910.10568 and their result for  $M_N \rightarrow 0$



# A Leptoquark Model

- ▶ we consider TeV-scale scalar leptoquark  $S_1 \sim (\bar{3}, 1, 1/3)$
- ▶ assumed dominant coupling with the third family of quarks
- ▶ benefits: (i) avoiding large Yukawa suppression in radiatively induced  $\mu_\nu$   
(ii) addressing flavor anomalies



$$\mathcal{L}_{S_1} \supset y_1 \overline{b_R^c} N_R S_1 + y_2 \overline{Q_L^3} L_L^i {}^c S_1^\dagger + \text{h.c.}$$

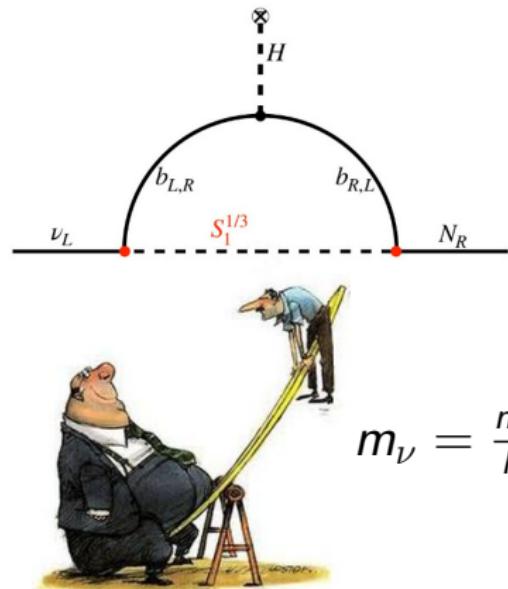
$$\mu_\nu \approx \frac{e y_1 y_2}{8\pi^2 m_{LQ}^2} m_b \log \frac{m_b^2}{m_{LQ}^2}$$

- ▶ for  $m_{LQ} = 1$  TeV and  $y_1 y_2 \simeq 0.05$  we obtain  $\mu_\nu \approx 10^{-10} \mu_B$  that is testable at XENON1T

# Neutrino Mass

- ▶ the diagram for  $\mu_\nu$  without a photon gives the radiative contribution to Dirac mass term  $m_\nu N \bar{\nu}_L N_R$

$$\frac{\mu_\nu}{\mu_B} \approx \frac{m_e m_\nu N}{\Lambda^2}$$



- ▶ for  $\mu_\nu \approx 10^{-10} \mu_B$  and with electroweak scale  $\Lambda$   
 $\implies m_\nu N \simeq \mathcal{O}(1) \text{ MeV}$
- ▶ for  $M_N$  testable at XENON1T type-I seesaw **does not** yield  $m_\nu \sim 0.1 \text{ eV}$
- ▶  $\mathcal{O}(\text{MeV})$  radiative  $m_{\nu N}$  should approximately cancel against  $y_\nu v_H / \sqrt{2}$  from tree-level  $y_\nu \bar{L}_L \tilde{H} N_R$  to give  $\sim 300 \text{ eV}$  Dirac mass

## Voloshin Mechanism

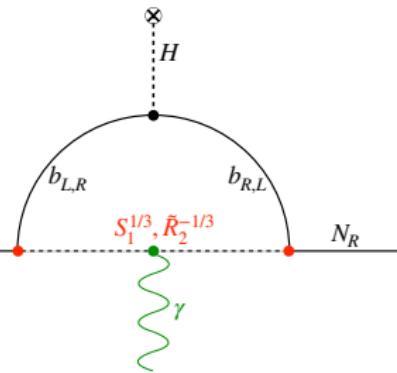
- ▶ Voloshin (1988) proposed the usage of a global  $SU(2)_H$  symmetry in order to break the relation between  $m_{\nu N}$  and  $\mu_\nu$

$$(\nu_L^c, N_R) \in \mathbf{2} \implies \begin{cases} \bar{N}_R \sigma^{\mu\nu} \nu_L - \overline{\nu_L^c} \sigma^{\mu\nu} N_R^c & SU(2) \text{ singlet} \\ \bar{N}_R \nu_L + \overline{\nu_L^c} N_R^c & SU(2) \text{ triplet} \end{cases}$$

- ▶ to embed this in the leptoquark model we add  $\tilde{R}_2$ ;  $(\tilde{R}_2^{-1/3}, S_1^\dagger) \in \mathbf{2}$
- ▶  $SU(2)_H$  broken by EW gauge interactions

$$\frac{\mu_\nu}{\mu_B} \approx \frac{\alpha}{4\pi} \frac{m_e m_{\nu N}}{\Lambda^2} \implies m_{\nu N} \sim \mathcal{O}(\text{keV}) \left( \frac{10^{-11} \mu_B}{\mu_\nu} \right) \left( \frac{1 \text{ TeV}}{\Lambda} \right)^2 \frac{\nu_L}{N_R}$$

- ▶ with Voloshin mechanism, amount of fine-tuning significantly reduced
- ▶ alternative options: inverse seesaw...



## B-meson anomalies

$$R(D^{(*)}) \equiv \frac{\text{BR}(B \rightarrow D^{(*)}\tau\nu)}{\text{BR}(B \rightarrow D^{(*)}\mu\nu)}$$

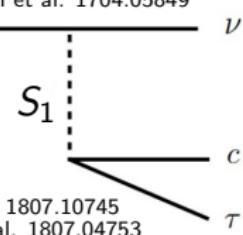
$$\mathcal{L}_{S_1} \supset y_1 \overline{b_R^c} N_R S_1 + y_2 \overline{Q_L^3} L_L^{i\,c} S_1^\dagger + \text{h.c.}$$

- ▶ effect on  $R(D^{(*)})$  is generated by tree-level  $S_1$  exchange ( $y_2$  coupling)
- ▶ (i) for dominant decay into  $\nu_\tau \Rightarrow y_1 \ll y_2$  required
- ▶  $y_2 \simeq \mathcal{O}(1)$  and TeV-scale  $S_1$  can explain  $R(D^{(*)})$
- ▶ (ii) for dominant decay into  $N_R \Rightarrow y_1 > y_2$  required
- ▶  $y_1 \sim \mathcal{O}(1)$

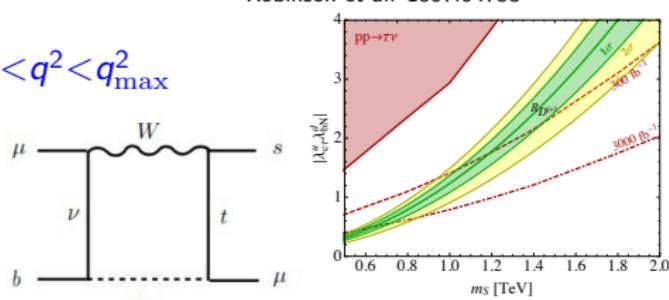
$$R(K^{(*)}) \equiv \left. \frac{\text{BR}(B \rightarrow K^{(*)}\mu^+\mu^-)}{\text{BR}(B \rightarrow K^{(*)}e^+e^-)} \right|_{q_{\min}^2 < q^2 < q_{\max}^2}$$

- ▶ loop induced  $\Rightarrow$  too large couplings required; including  $S_3$  LQ (2103.13991) is an option

Bauer, Neubert 1511.01900  
Cai et al. 1704.05849

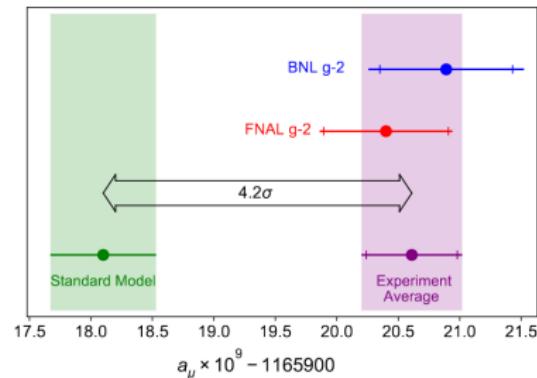
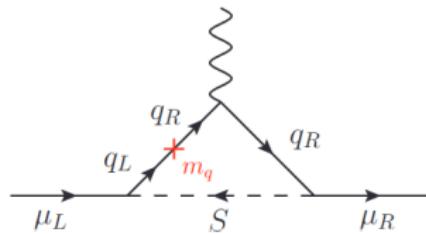


Azatov et al. 1807.10745  
Robinson et al. 1807.04753

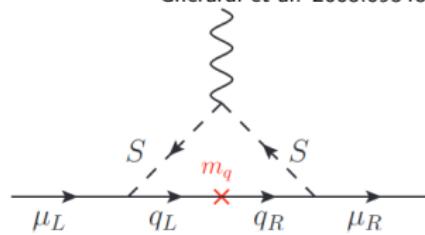


## g-2

- ▶ FNAL and BNL measurements for muon g-2 can be explained with  $S_1$
- ▶ we require  $S_1$  coupling to both left- and right-handed quarks of the same type
- ▶ in addition to  $y_2 \overline{Q_L^3} L_L^{i\,c} S_1^\dagger$  interaction,  $y'_1 \overline{t_R^c} e_R^i S_1$  appears
- ▶ due to chiral enhancement from the top quark in the loop, small coupling  $y'_1 \simeq 10^{-3}$  suffices



Dorsner et al. 1910.03877  
Gherardi et al. 2008.09548



# Conclusion

- ▶ we are still seeing hints for new physics:
  - (i) flavor anomalies are statistically significant
  - (ii) recent FNAL measurement of muon  $g-2 \sim 4\sigma$
  - (iii) excess in electron recoil events at XENON1T

## Common new physics explanation?

- ▶ a model with scalar leptoquark  $S_1$  and right-handed neutrinos  $N_R$
- ▶ successful explanation of above measurements in such minimal framework
- ▶ through neutrino magnetic moments, dark matter detectors are probing TeV-scale new physics
- ▶ hints of BSM physics at DM detectors may be reinforced at Belle II, LHCb and  $g - 2$  experiments and vice versa