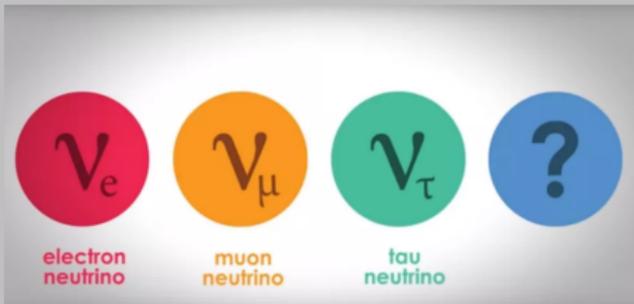


# The Neutrino Magnetic Moment Portal: Terrestrial Experiments and Astrophysical Probes



Vedran Brdar (CERN-TH)

# Magnetic Moment for Massive Neutrinos

$$\mathcal{L} \supset \frac{1}{2} \mu_{\nu}^{\alpha\beta} \bar{\nu}_L^{\alpha} \sigma^{\mu\nu} \nu_R^{\beta} F_{\mu\nu}$$

- ▶ neutrinos are massless in the Standard Model

$$\implies \mu_{\nu}^{\alpha\beta} = 0$$

- ▶ adding  $\nu_R$  to the Standard Model generates Dirac mass  $m_{\nu} \bar{\nu}_L \nu_R$  which generates nonzero  $\mu_{\nu}$

$$\mu_{\nu}^{\text{diag}} = \frac{3eG_F m_{\nu}}{8\sqrt{2}\pi^2} \approx 3 \times 10^{-20} \mu_B \left( \frac{m_{\nu}}{0.1 \text{ eV}} \right)$$

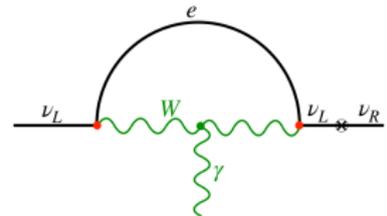
- ▶ for Majorana neutrinos, only non-diagonal elements are nonzero

$$\mu_{\nu}^{ij} = -\frac{3eG_F(m_i+m_j)}{16\sqrt{2}\pi^2} \sum_k \text{Im} [U_{ki}^* U_{kj}] \frac{m_k^2}{m_W^2} \lesssim 10^{-23} \mu_B \quad \mu_B = \frac{e}{2m_e}$$

- ▶ **not testable**  $\implies$  more BSM physics required

Three Generations of Matter (Feynman) spin 1/2

	I	II	III	spin 0
quarks	u up	c charm	t top	g gluons
quarks	d down	s strange	b bottom	$\gamma$ photon
quarks	$\nu_u$ up neutrino	$\nu_c$ charm neutrino	$\nu_t$ top neutrino	Z boson
quarks	$\nu_d$ down neutrino	$\nu_s$ strange neutrino	$\nu_b$ bottom neutrino	H Higgs boson
leptons	e electron	$\mu$ muon	$\tau$ tau	W boson
leptons	$\nu_e$ electron neutrino	$\nu_{\mu}$ muon neutrino	$\nu_{\tau}$ tau neutrino	spin 0

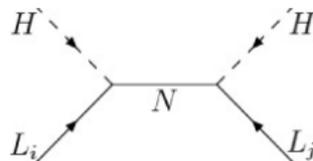


# Sterile Neutrinos

## Type-I Seesaw



Minkowski, Mohapatra, Senjanović,  
Gell-Mann, Ramond, Slansky, Yanagida



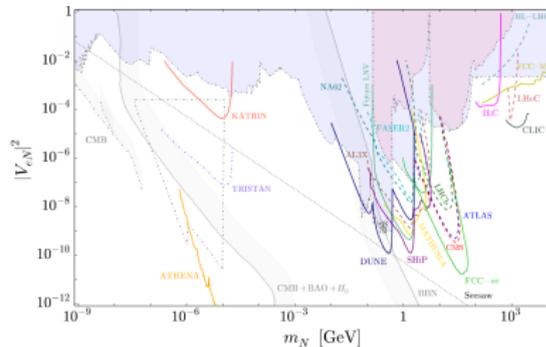
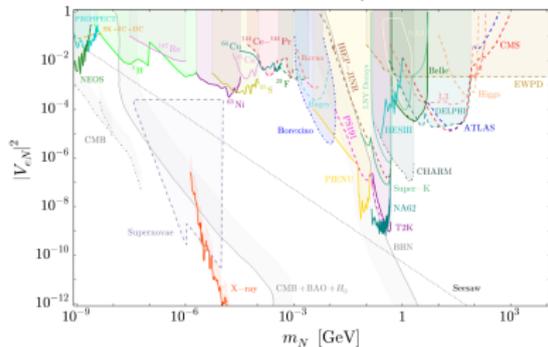
$$\mathcal{M} = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

$$m_\nu = -M_D M_R^{-1} M_D^T$$

$$\theta = M_D / M_R$$

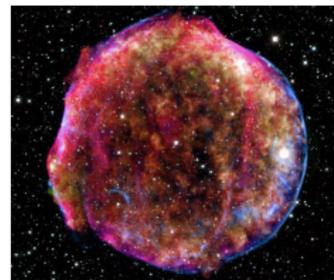
$$\mathcal{L} \supset \frac{1}{2} \bar{N}^c M_R N + \bar{L} Y_\nu \tilde{H} N + \text{h.c.}$$

Bolton et al., JHEP 2020



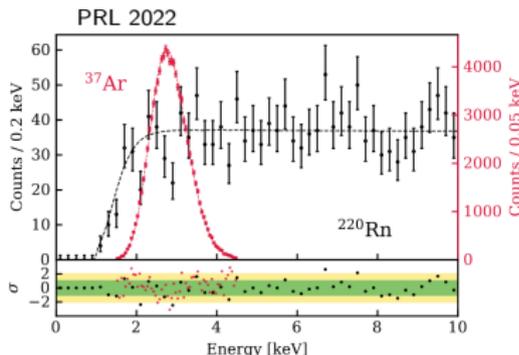
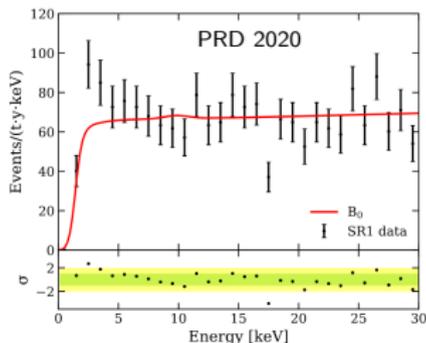
# Active-to-Sterile Neutrino Transition Magnetic Moment

$$\mathcal{L} \supset \frac{1}{2} \mu_N \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R F_{\mu\nu}$$

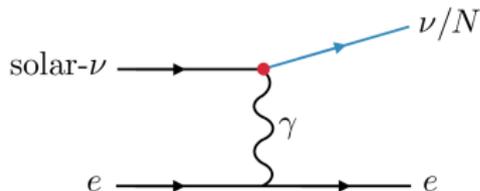


# Transition Magnetic Moment at Dark Matter Experiments

- ▶ detectors like XENONnT and LUX-ZEPLIN can record electron and nuclear recoils



- ▶ signal induced by magnetic moment interaction



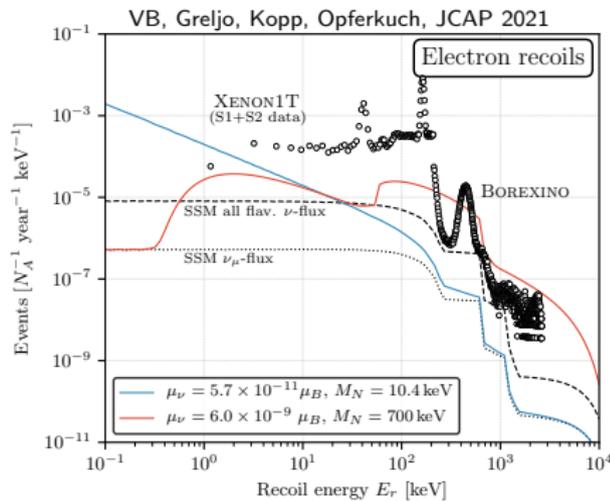
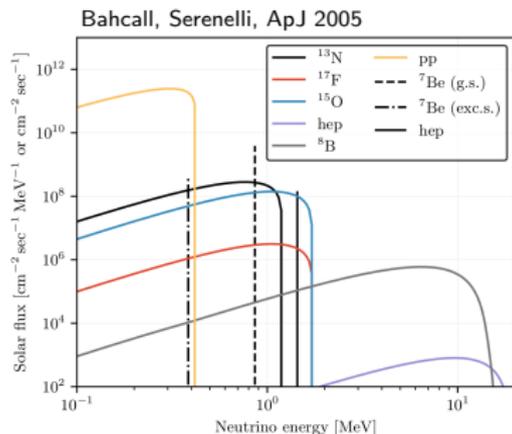
$$\frac{d\sigma_{\mu}(\nu_L e \rightarrow N_R e)}{dE_r} = \alpha \mu_{\nu}^2 \left[ \frac{1}{E_r} - \frac{1}{E_{\nu}} + M_N^2 \frac{E_r - 2E_{\nu} - m_e}{4E_{\nu}^2 E_r m_e} + M_N^4 \frac{E_r - m_e}{8E_{\nu}^2 E_r^2 m_e^2} \right]$$

$$\frac{d\sigma_{\mu}(\nu_L X_Z^A \rightarrow N_R X_Z^A)}{dE_r} = \alpha \mu_{\nu}^2 Z^2 F_1^2(E_r) \left[ \frac{1}{E_r} - \frac{1}{E_{\nu}} + M_N^2 \frac{E_r - 2E_{\nu} - m_X}{4E_{\nu}^2 E_r m_X} + M_N^4 \frac{E_r - m_X}{8E_{\nu}^2 E_r^2 m_X^2} \right]$$

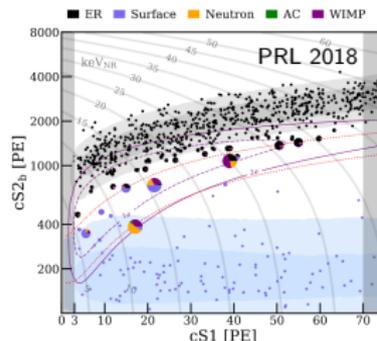
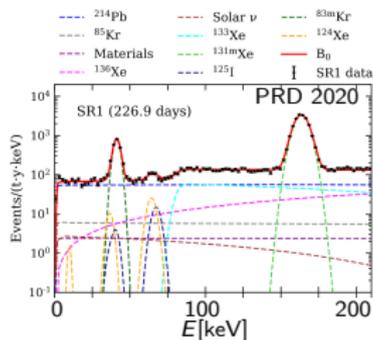
# Transition Magnetic Moment at Dark Matter Experiments

- ▶ scattering targets and detection efficiency
- ▶ solar neutrino flux
- ▶ cross-sections for scattering via magnetic moment

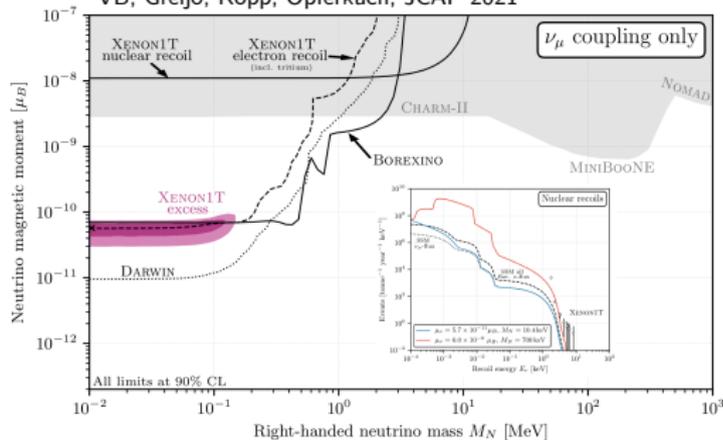
$$\frac{dR}{dE_r} = N_T \epsilon(E_r) \int_{E_\nu^{\min}} dE_\nu \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_r}$$



# Transition Magnetic Moment at XENON1T



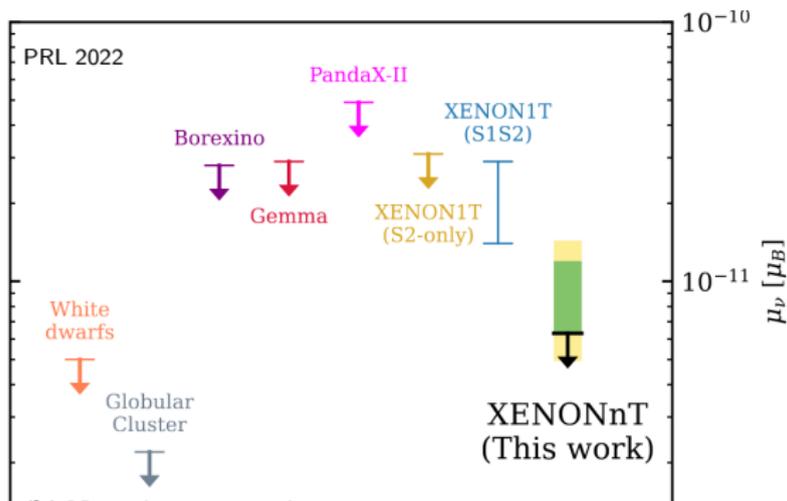
VB, Greljo, Kopp, Opferkuch, JCAP 2021



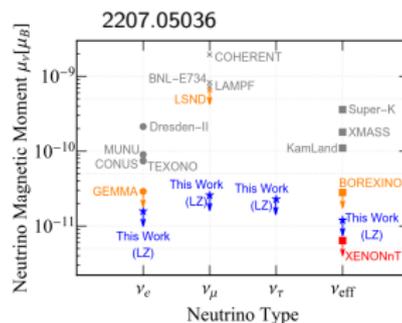
$\mu_\nu \gtrsim 7 \times 10^{-11} \mu_B$   
is disfavored

$$\mu_B = \frac{e}{2m_e}$$

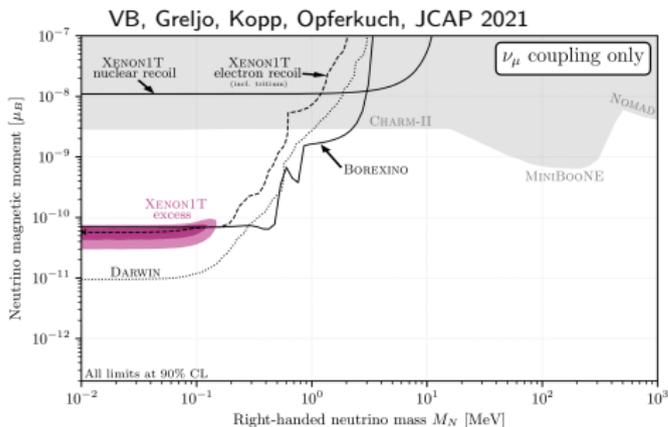
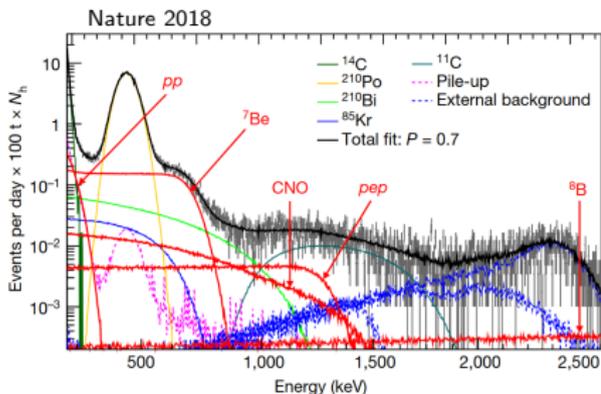
# Recent Results from XENONnT and LZ



- improvement by a factor of 2-3 in  $\mu_\nu$



# Transition Magnetic Moment at Neutrino Experiments

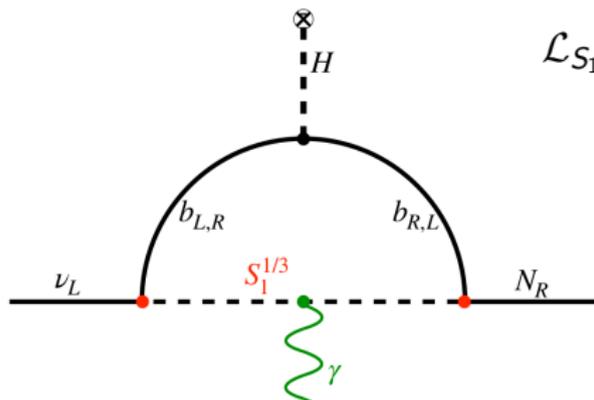


- ▶ larger  $N_T$  and  $\epsilon(E_r)$  but higher  $E_r$  energy threshold than DM experiments
- ▶ better limits at higher  $M_N$

$$E_\nu^{\min}(E_r) = \frac{1}{2} \left[ E_r + \sqrt{E_r^2 + 2m_e E_r} \right] \left( 1 + \frac{M_N^2}{2E_r m_e} \right)$$

# The 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



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

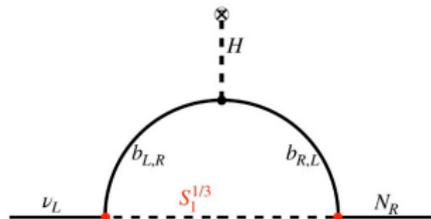
$$\mu_\nu \approx \frac{e y_1 y_2}{8\pi^2 m_{LQ}^2} m_b \log \frac{m_b^2}{m_{LQ}^2}$$

- ▶ for  $m_{LQ} = 1$  TeV and  $y_1 y_2 \simeq 0.05$  we obtain  $\mu_\nu \approx 10^{-10} \mu_B$  that is in the ballpark of previously discussed limits

# 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 EW scale  $\Lambda \implies m_{\nu N} \simeq \mathcal{O}(1)$  MeV and type-I seesaw **does not** yield  $m_\nu \sim 0.1$  eV

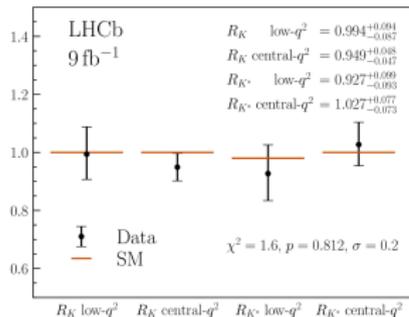
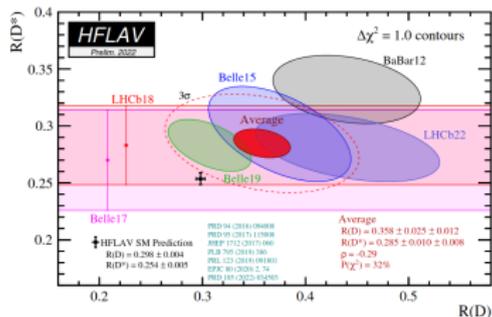


$$m_\nu = \frac{m_{\nu N}^2}{M_N}$$

## Solutions:

- ▶ radiatively induced  $m_{\nu N}$  approximately cancels against tree-level  $y_\nu v_H / \sqrt{2}$
- ▶ employing the symmetry (Voloshin mechanism)

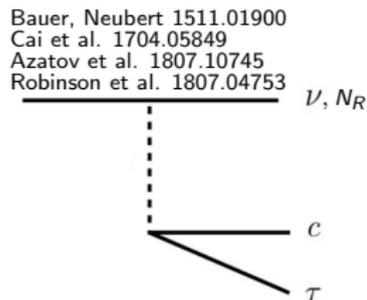
# B-meson Anomalies



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

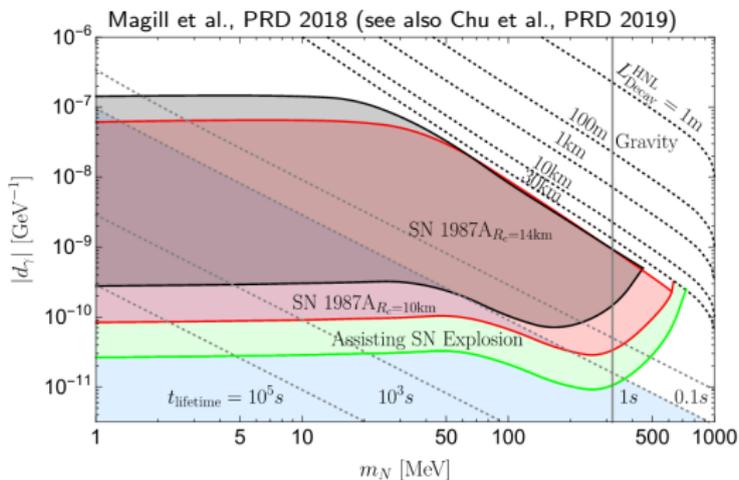
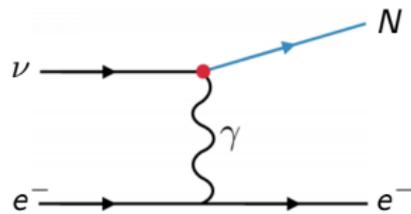
$$\mathcal{L}_{S_1} \supset y_1 \bar{b}_R^c N_R S_1 + y_2 \bar{Q}_L^3 L_L^c S_1^\dagger + \text{h.c.}$$

- ▶ (i) dominant decay into  $\nu_\tau \Rightarrow y_1 \ll y_2$  and  $y_2 \simeq \mathcal{O}(1)$  with TeV-scale  $S_1$  can explain  $R(D^{(*)})$
- ▶ (ii) dominant decay into  $N_R \Rightarrow y_1 > y_2$  and  $y_1 \sim \mathcal{O}(1)$  explains the anomaly



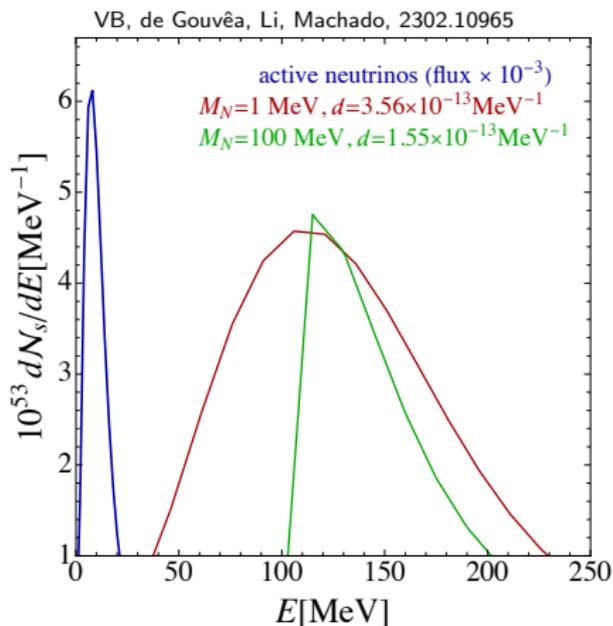
# Towards Smaller $\mu_\nu$ : Supernovae

- ▶ in Supernovae, sterile neutrinos can be efficiently produced via  $\nu e^- \rightarrow N_R e^-$
- ▶ properties of detected SN1987A neutrino events impose that  $N$  can take as much as  $\gtrsim 10\%$  of the total energy output



$$\mu_B = 296 \text{ GeV}^{-1}$$

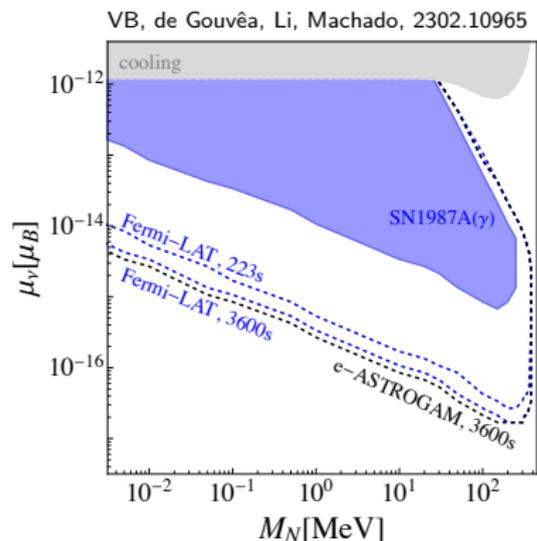
# Sterile Neutrino Production in Supernovae



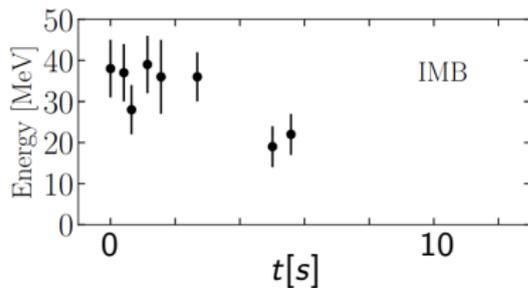
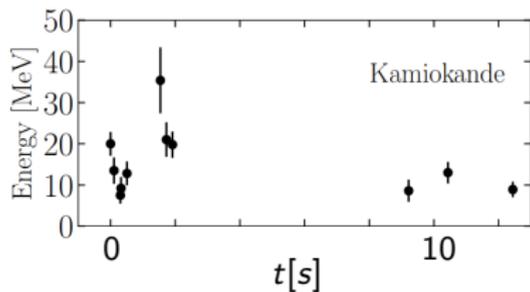
- ▶ sterile neutrinos are produced in a dense  $T \sim 100 \text{ MeV}$  core and, for sufficiently small  $\mu_\nu$ , leave the star without further interactions
- ▶  $N \rightarrow \gamma \nu$  decay via magnetic moment

# $\gamma$ -ray Detection

- ▶ **Gamma-Ray Spectrometer** observed  $\mathcal{O}(10^3)$  events in  $\Delta t \lesssim 223$  sec following SN1987A neutrino burst
- ▶ for the future galactic SN, experiments like **Fermi-LAT** and **e-ASTROGAM** can detect  $\gamma$  from  $N_R$  decay

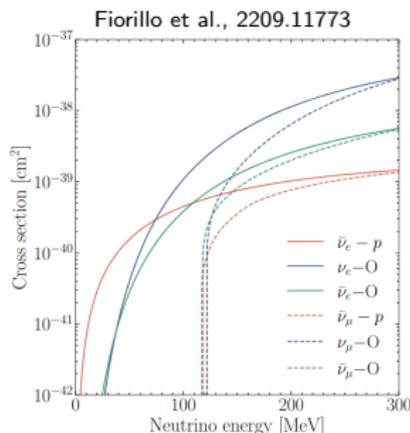


# Neutrino Detection

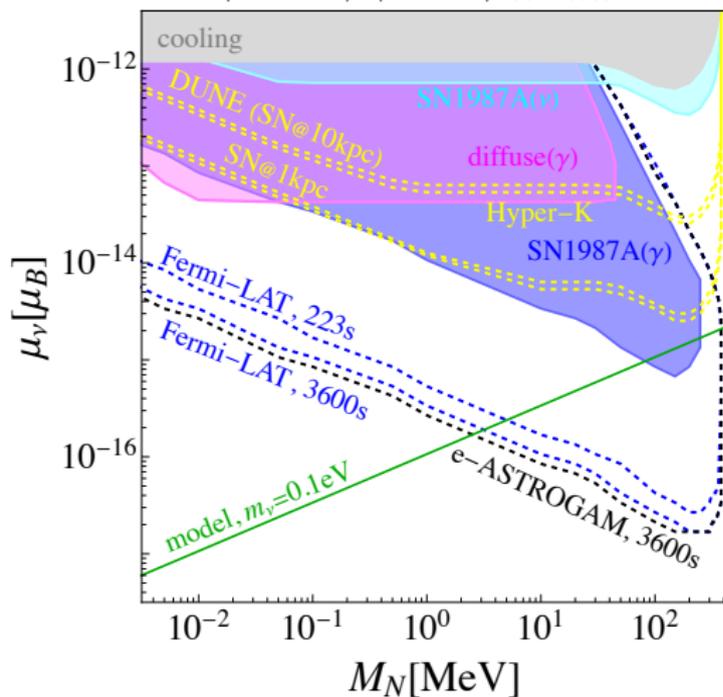


- ▶ no significant excess was observed by Kamiokande-II and IMB for  $E_\nu \gtrsim 50$  MeV
- ▶ at such energies, both  $\nu$  and  $\bar{\nu}$  contribute

$$N_\nu^{\text{BSM}} = N_{\text{target}} \int dE_\nu \frac{dN_\nu}{dE_\nu dA} (E_\nu) \sigma(E_\nu)$$







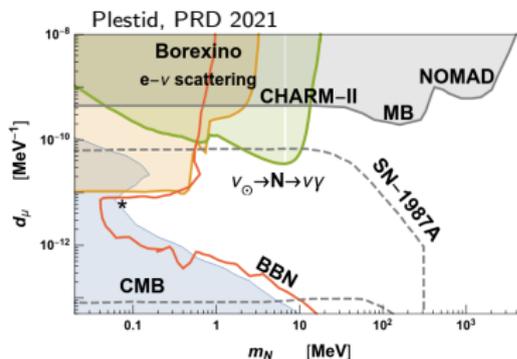
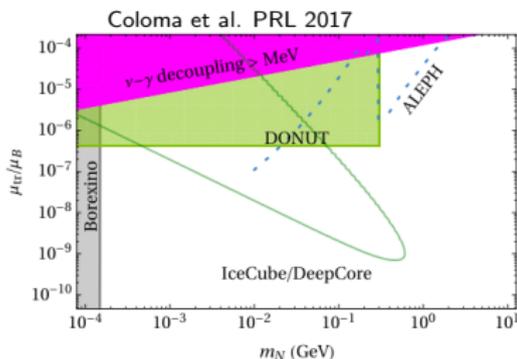
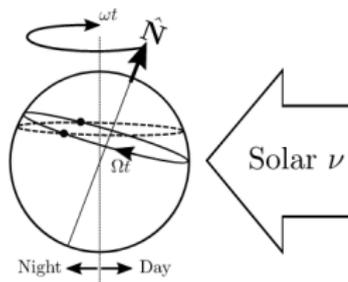
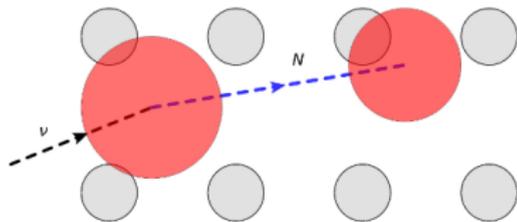
- ▶ multimessenger BSM opportunities for nearby supernova
- ▶ “natural” region of model’s parameter space will be probed

# Summary

- ▶ **Sterile neutrino** is a well-motivated extension of the Standard Model
- ▶ Interaction with the SM via the **magnetic moment portal**
- ▶ **Rich phenomenology**: neutrino experiments, dark matter direct detection experiments, supernovae...
- ▶ **Leptoquark TeV-scale UV completions** simultaneously generate testable transition magnetic moments and address flavor anomalies

# BACKUP

# More Opportunities at Neutrino Experiments



- ▶  $N$  produced in scattering of solar or atmospheric neutrinos
- ▶ subsequent decay to SM particles

# Stellar Cooling Bounds

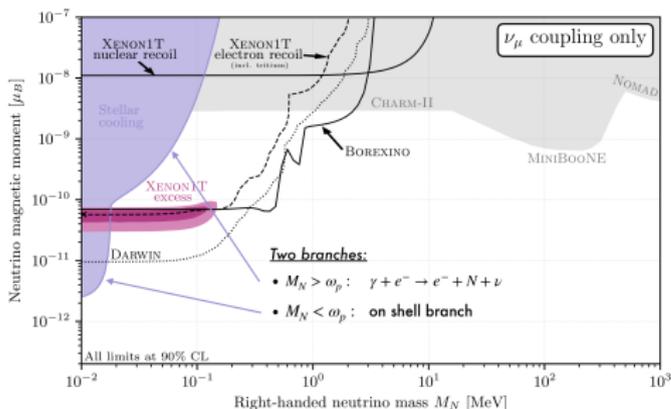
- ▶ in stars, transverse plasmons can decay into  $\nu + N_R$

$$\Gamma_{\gamma^*} = \frac{|\mu_\nu|^2 K^4}{24\pi\omega} \left(1 - \frac{M_N^2}{K^2}\right)^2 \left(1 + 2\frac{M_N^2}{K^2}\right) \theta(K - M_N) \quad K = \sqrt{\omega^2 - k^2}$$

- ▶ for  $M_N < \omega_{\text{plasma}}$ , plasmon decay dominate; instead, for  $M_N \gtrsim \omega_{\text{plasma}}$   $\gamma e^- \rightarrow e^- N_R \nu$  is important

- ▶ constraining energy loss

$$Q = \int_0^\infty \frac{k^2 dk}{\pi^2} \int_{M_N^2}^\infty \frac{d\omega^2}{\pi} \frac{\omega \Gamma_T}{(K^2 - \omega_p^2)^2 + (\omega \Gamma_T)^2} \frac{\omega \Gamma_{\gamma^*}}{e^{\omega/T_\gamma} - 1}$$



# Voloshin Mechanism

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

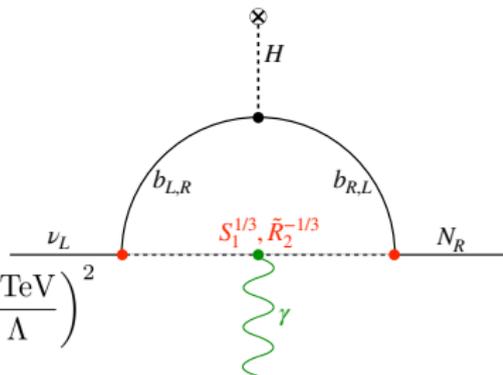
$$(\nu_L^c, N_R) \in \mathbf{2} \implies \begin{cases} \bar{N}_R \sigma^{\mu\nu} \nu_L - \bar{\nu}_L^c \sigma^{\mu\nu} N_R^c & SU(2) \text{ singlet} \\ \bar{N}_R \nu_L + \bar{\nu}_L^c N_R^c & SU(2) \text{ triplet} \end{cases}$$

- ▶ to embed this in the leptoquark model we add  $\tilde{R}_2 \sim (3, 2, 1/6)$ ;  $(\tilde{R}_2^{-1/3}, S_1^\dagger) \in 2$

- ▶  $SU(2)_H$  broken by EW gauge interactions

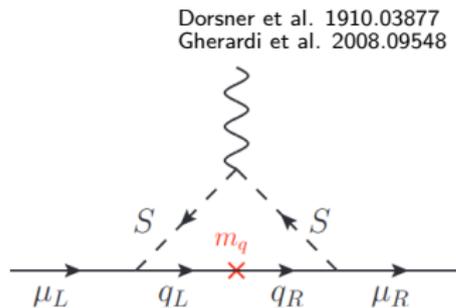
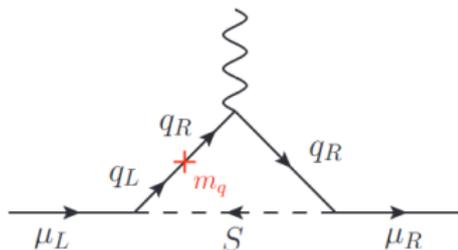
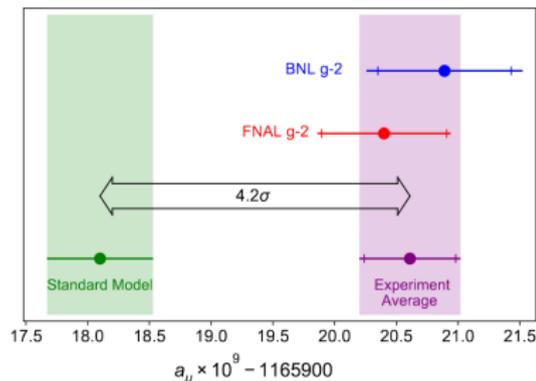
$$\frac{\mu_\nu}{\mu_B} \approx \frac{\alpha}{4\pi} \frac{m_e m_{\nu N}}{\Lambda^2} \implies m_{\nu N} \sim \mathcal{O}(\text{keV}) \left( \frac{10^{-11} \mu_B}{\mu_\nu} \right) \left( \frac{1 \text{ TeV}}{\Lambda} \right)^2$$

- ▶ with Voloshin mechanism, amount of fine-tuning is practically eliminated



# Muon g-2

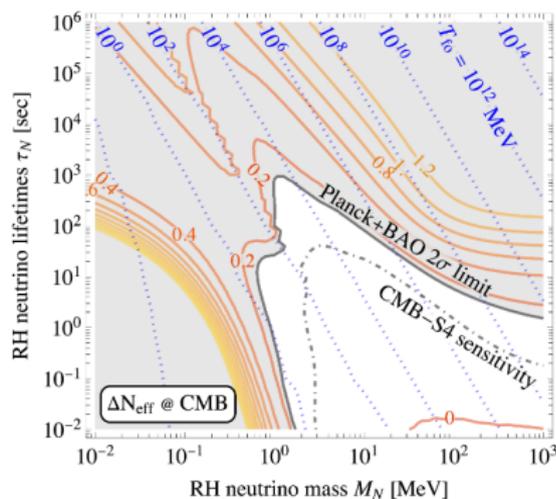
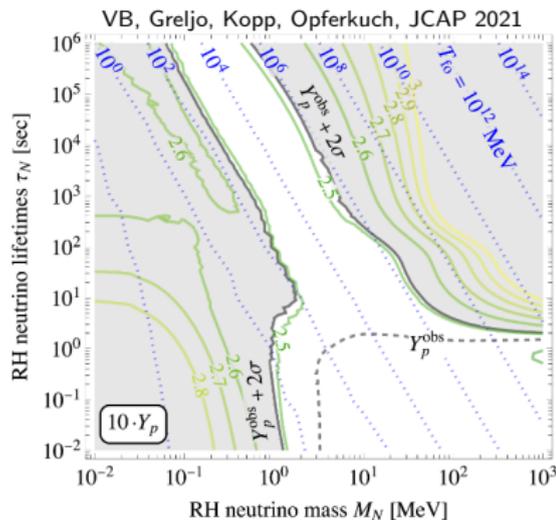
- ▶  $S_1$  coupling to both left- and right-handed quarks is required: in addition to  $y_2 \overline{Q}_L^3 L_L^c S_1^\dagger$  interaction, introduce  $y_1' \overline{t}_R^c e_R^i S_1$
- ▶ due to chiral enhancement from the top quark in the loop, small coupling  $y_1' \simeq 10^{-3}$  suffices



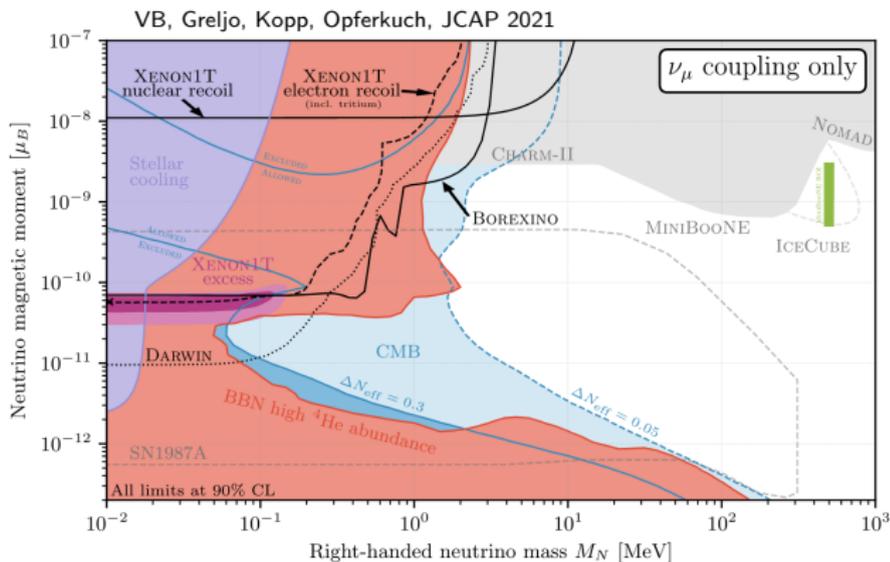
# Towards Smaller $\mu_\nu$ : Cosmology

- ▶ relativistic  $N_R$  contribute to  $N_{\text{eff}}$
- ▶  $N_R \rightarrow \nu\gamma$  inject extra photons into the Universe

$$\tau_N \simeq 3760 \text{ sec} \left( \frac{10^{-11} \mu_B}{\mu_\nu} \right)^2 \left( \frac{\text{MeV}}{M_N} \right)^3$$



# Towards Smaller $\mu_\nu$ : Cosmology



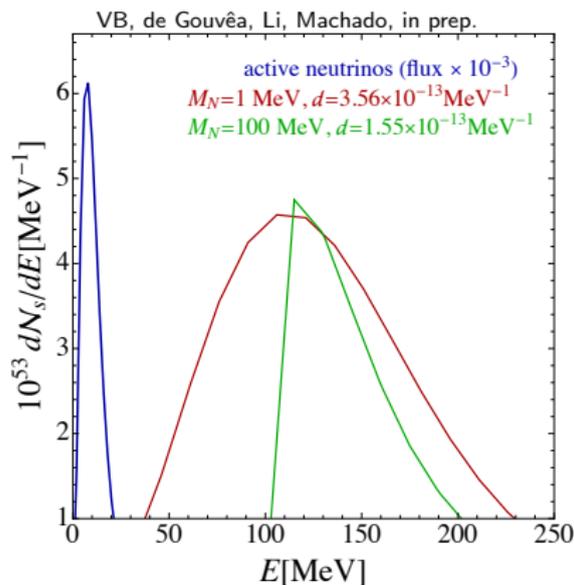
- ▶ limits are strong but are removed if  $T_{\text{RH}} < T_{\text{dec}}$  since then  $N_R$  have never been in thermal equilibrium

$$T_{\text{dec}} \simeq 1.28 \text{ GeV} \left( \frac{10^{-11} \mu_B}{\mu_\nu} \right)^2$$

# Sterile Neutrino Production in Supernovae

$$\frac{1}{4\pi r^2} \frac{\partial}{\partial r} \frac{\partial}{\partial t} \frac{dN_s}{dE_N} = \sigma n_e \frac{dn_\nu}{dE}$$

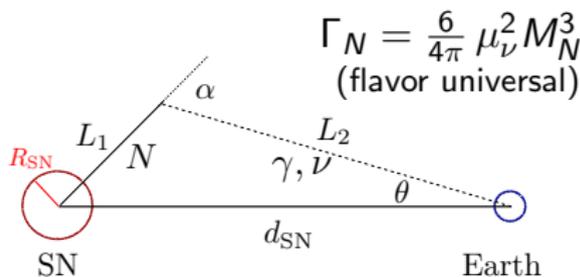
- ▶  $\sigma \propto \mu_\nu^2$
- ▶ data associated to a Garching group simulation of a  $8.8M_\odot$  progenitor star is employed
- ▶ sterile neutrinos are produced in a dense  $T \sim 100$  MeV core and leave subsequently the star without further interactions



# Sterile Neutrinos Decaying to $\gamma$ -rays and Neutrinos

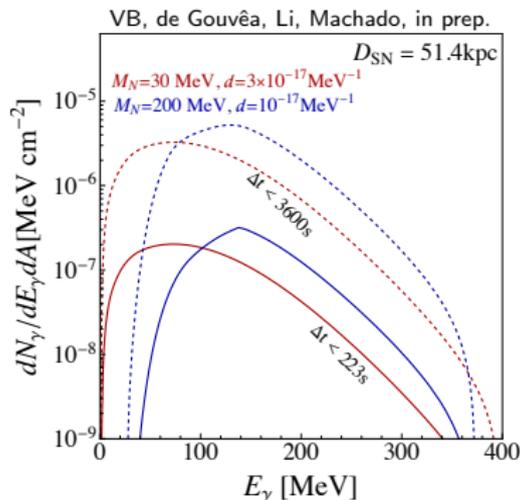
$$\cos \alpha = \frac{2E_N E_{\gamma/\nu} - M_N^2}{2E_{\gamma/\nu} \sqrt{E_N^2 - M_N^2}}$$

$$\Delta t = L_1/\beta + L_2 - d_{\text{SN}}$$



$$\frac{dN_{\gamma/\nu}}{dE_{\gamma/\nu} dA} \approx \int \frac{e^{-R_{\text{SN}}/L_N} - e^{-L_1^{\text{max}}/L_N}}{4\pi d_{\text{SN}}^2 E_N} \frac{dN_s}{dE_N} dE_N$$

$$L_N = \Gamma_N^{-1} (E_N/M_N) \sqrt{1 - M_N^2/E_N^2}$$



# Diffuse BSM-induced Photon and Neutrino Background

Lunardini, PRL 2009  
Caputo et al., PRD 2022

$$\frac{dn_N}{dE} = \frac{c}{4\pi} \int_0^\infty dz (1+z) n'_{cc}(z) \frac{dN_s}{dE} [(1+z)E]$$

