UNIVERSITÄT BERN

The Neutrino Magnetic Moment Portal: Cosmology, Astrophysics, and Direct Detection

Admir Greljo

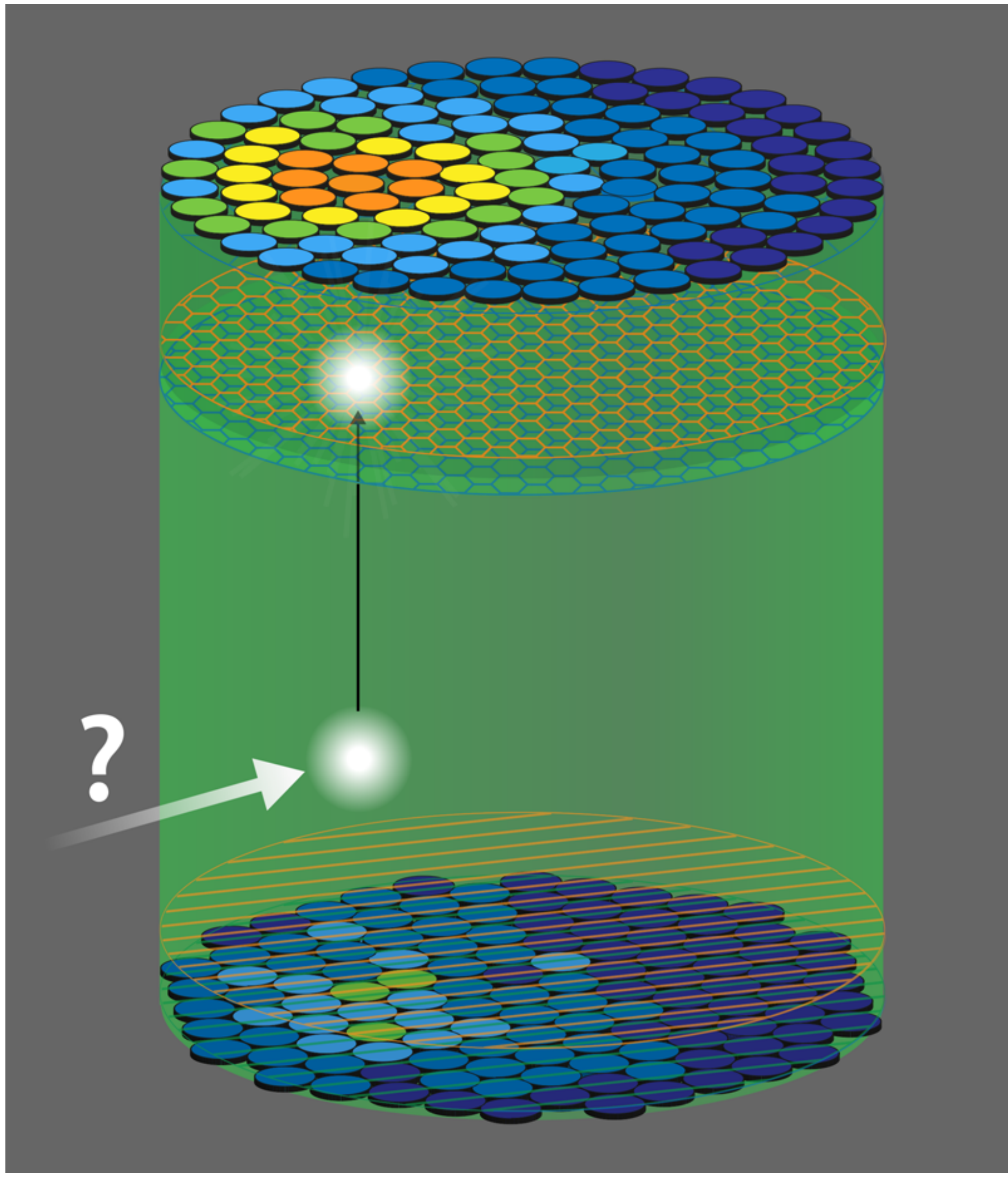
*Thanks to Toby Opferkuch for many slides.

IJS, 15.10.2020

Motivation

Dark matter direct detection experiments

- Underground laboratories waiting from the dark matter hits
- Electronic & nuclear recoils
  prompt scintillation (S1) and delayed electroluminescence (S2)
- Challenge: Low background rate, large target mass, and low energy threshold
- Quietest and darkest laboratory environments



XENON1T; adapted by APS/**Alan Stonebraker**

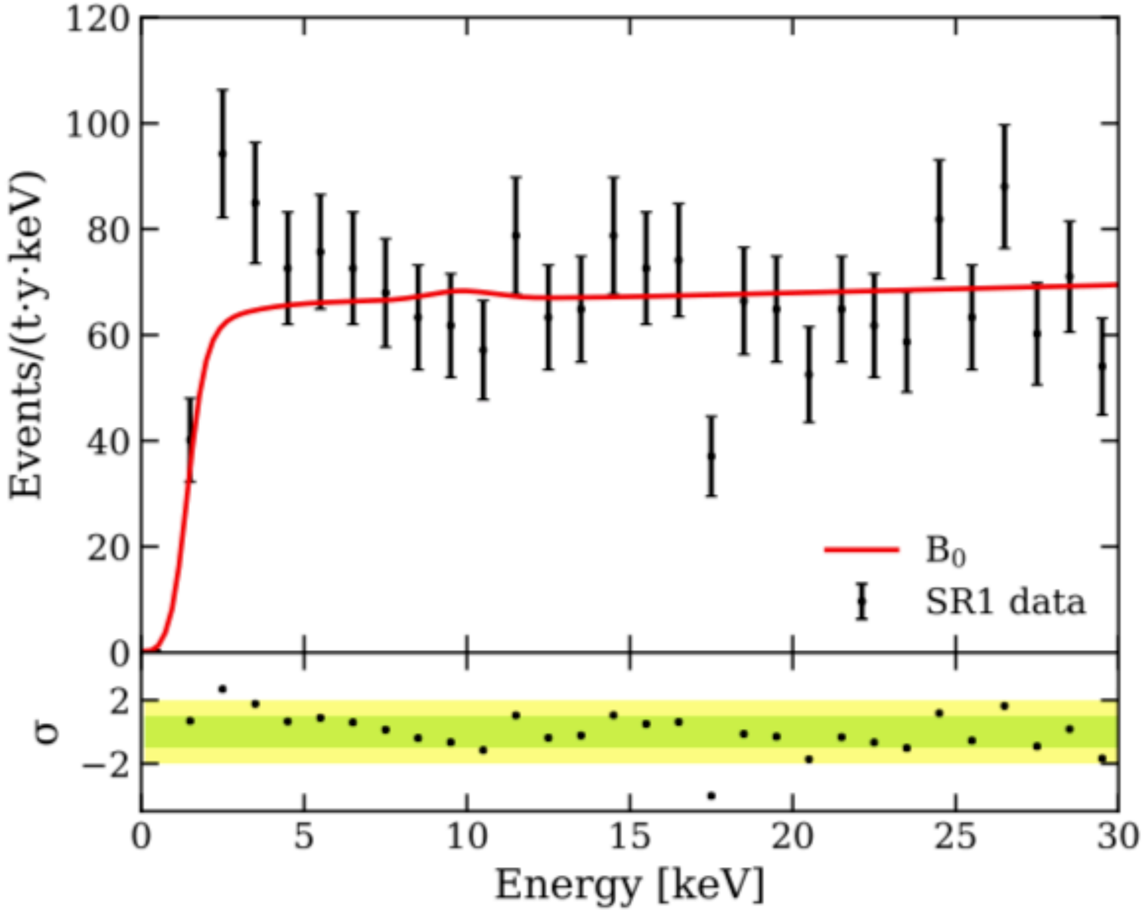
Enormous tank of purified liquid xenon surrounded by photomultiplier tubes.

Motivation

Dark matter direct detection experiments

- XENON1T **3.3 sigma** anomaly:
  - Large **e/γ** ratio (S2/S1) = Electronic recoils

2006.09721

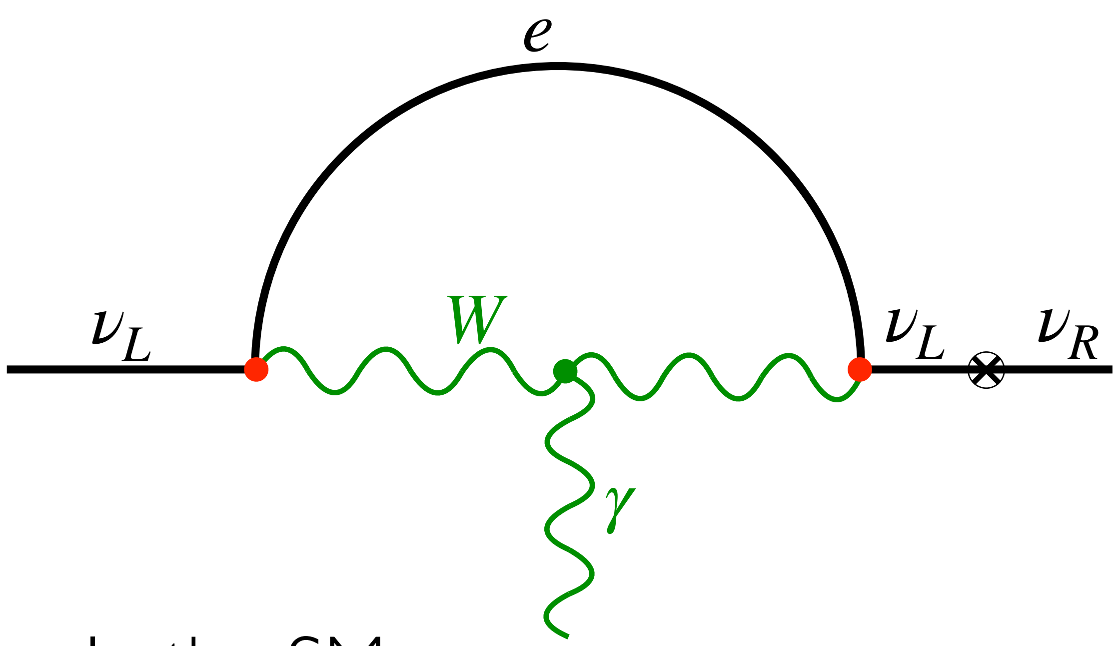


- Fluctuation, tritium, new physics?!

Neutrino magnetic moment

XENON1T, 2006.09721

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



In the SM

$$\mu_\nu^{SM} \sim 10^{-20}\ \mu_B$$

Neutrino magnetic moment

XENON1T, 2006.09721

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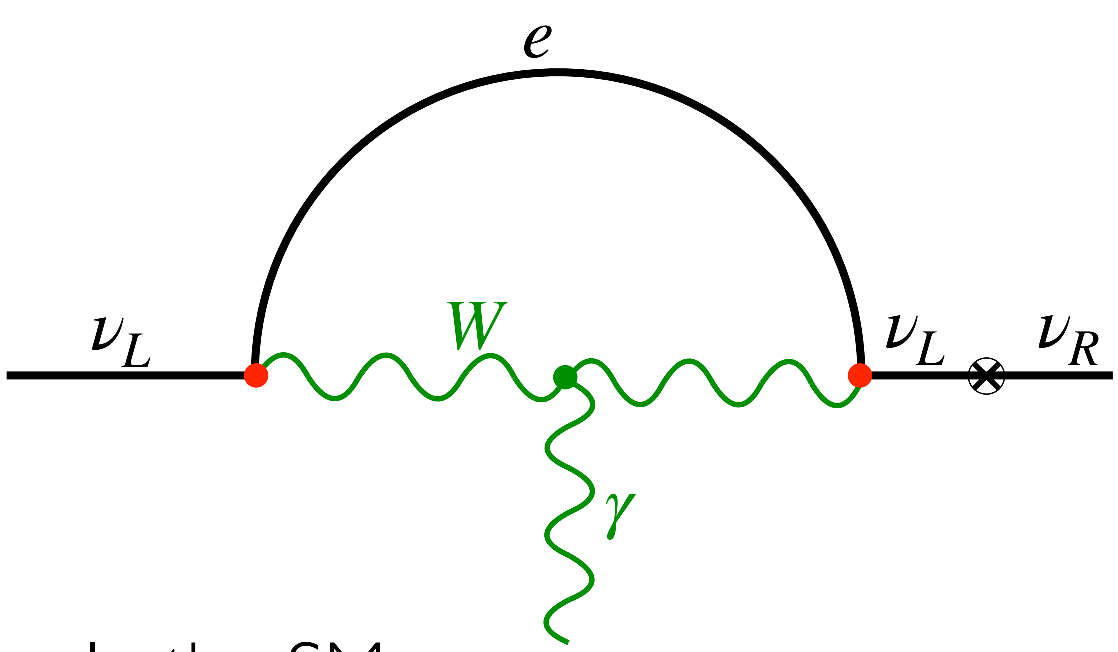

In the SM

$$\mu_\nu^{SM} \sim 10^{-20}\ \mu_B$$

Neutrino solution

- The source of incoming particles is known.
- However, the expected signal is tiny in the SM (the neutrino floor).
- How to lift up the neutrino floor?
  - * Modifying neutrino properties

Neutrino magnetic moment

XENON1T, 2006.09721

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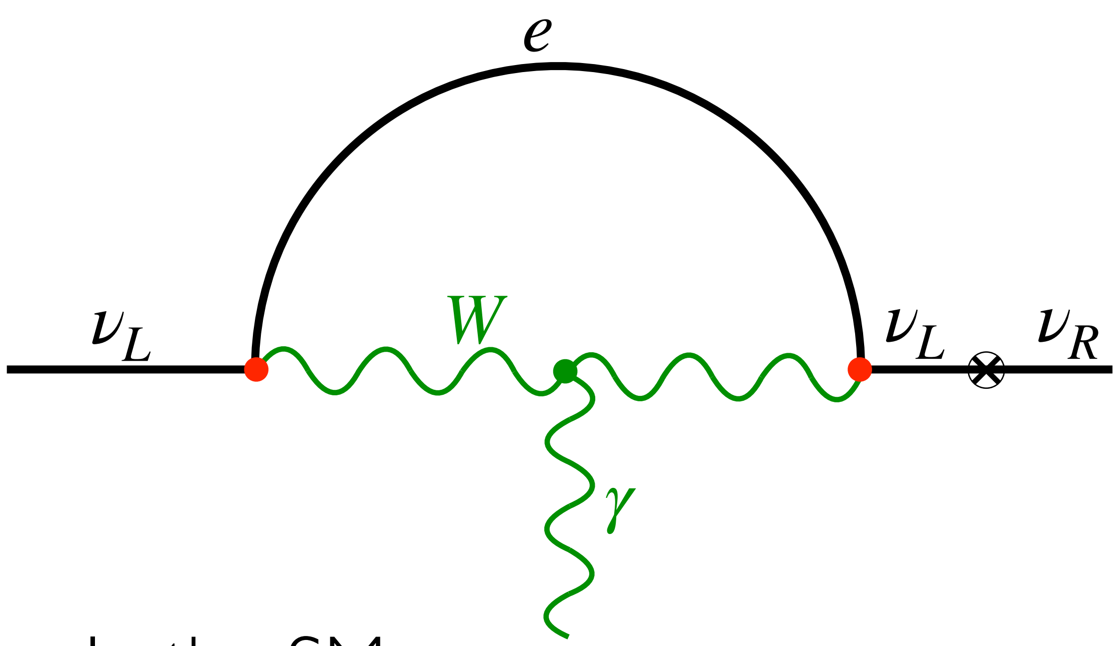

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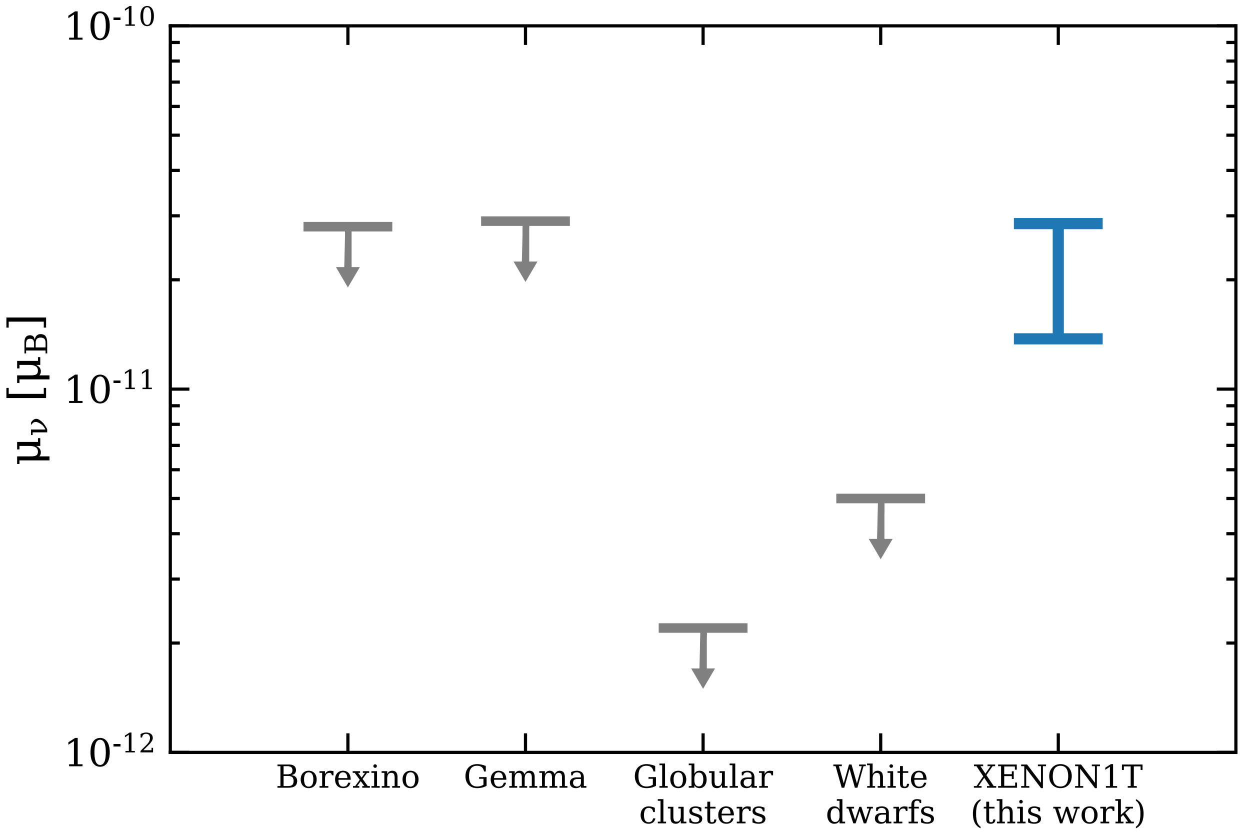

- *Magnetic moments of active flavours ruled out by stellar cooling constraints*

Vedran Brdar (MPIK Heidelberg), Admir Greljo, Joachim Kopp, Toby Opferkuch (CERN)

We wanted to fix the problem; ended up answering some interesting questions in

- ***Neutrino physics***

Questions

- What dark matter direct detection experiments tell us about the electromagnetic properties of neutrinos?

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- Is it possible to observe the signal in present/future experiments, given complementary constraints from astrophysics and cosmology?

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- What dark matter direct detection experiments tell us about the electromagnetic properties of neutrinos?
- Is it possible to observe the signal in present/future experiments, given complementary constraints from astrophysics and cosmology?
- Is there a viable model which predicts the observable signal, while still consistent with known neutrino masses and other phenomenology?

Transition magnetic moment

- Problem
  Magnetic moments of active flavours ruled out by stellar cooling constraints

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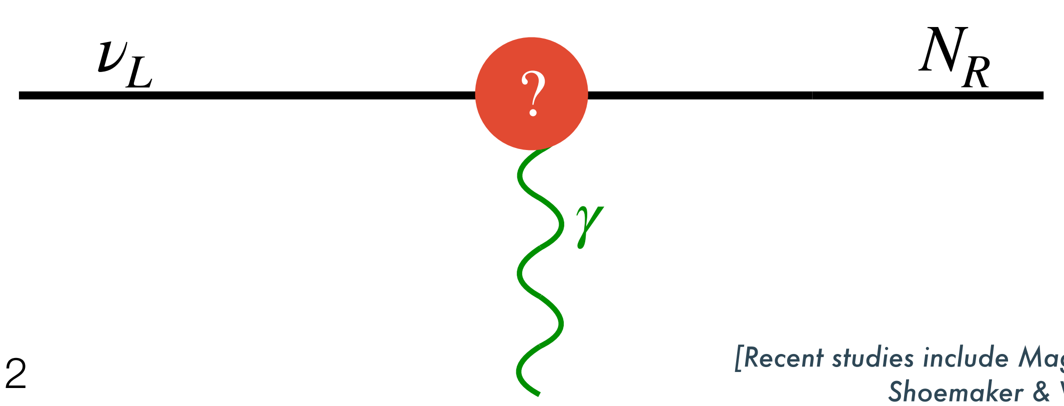
  Magnetic moments of active flavours ruled out by stellar cooling constraints

- Idea

- Heavy sterile neutrino N_R with mass M_N

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



[Recent studies include Magill et. al. 1803.03262, Shoemaker & Wyenberg 1811.12435]

Transition magnetic moment

- Problem
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- Idea
  New sterile neutrino
  1) Heavy enough to avoid cooling

$$\gamma^* \longrightarrow \nu_L + N \quad m_{\gamma^*} \propto T_{\rm star}$$

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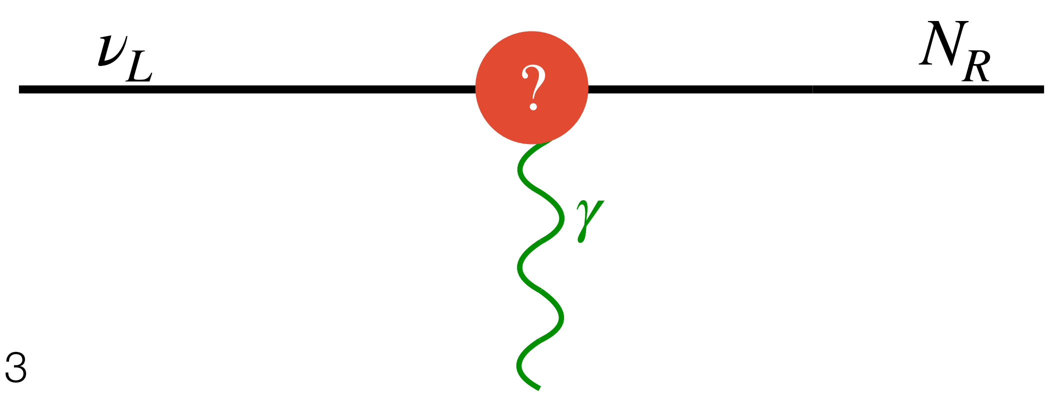
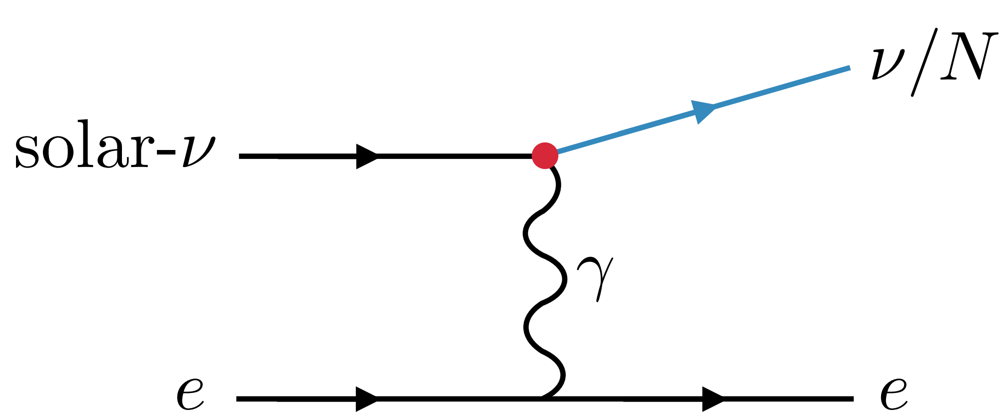


Transition magnetic moment

- Problem
  Magnetic moments of active flavours ruled out by stellar cooling constraints
- Idea
  New sterile neutrino
  1) Heavy enough to avoid cooling
  2) Light enough to be produced in the up-scatering

$$\gamma^* \longrightarrow \nu_L + N \quad m_{\gamma^*} \propto T_{\rm star}$$



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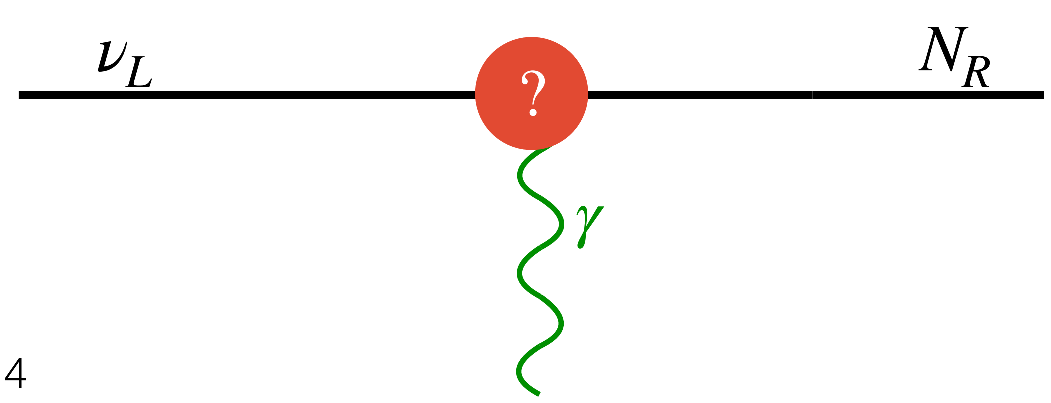
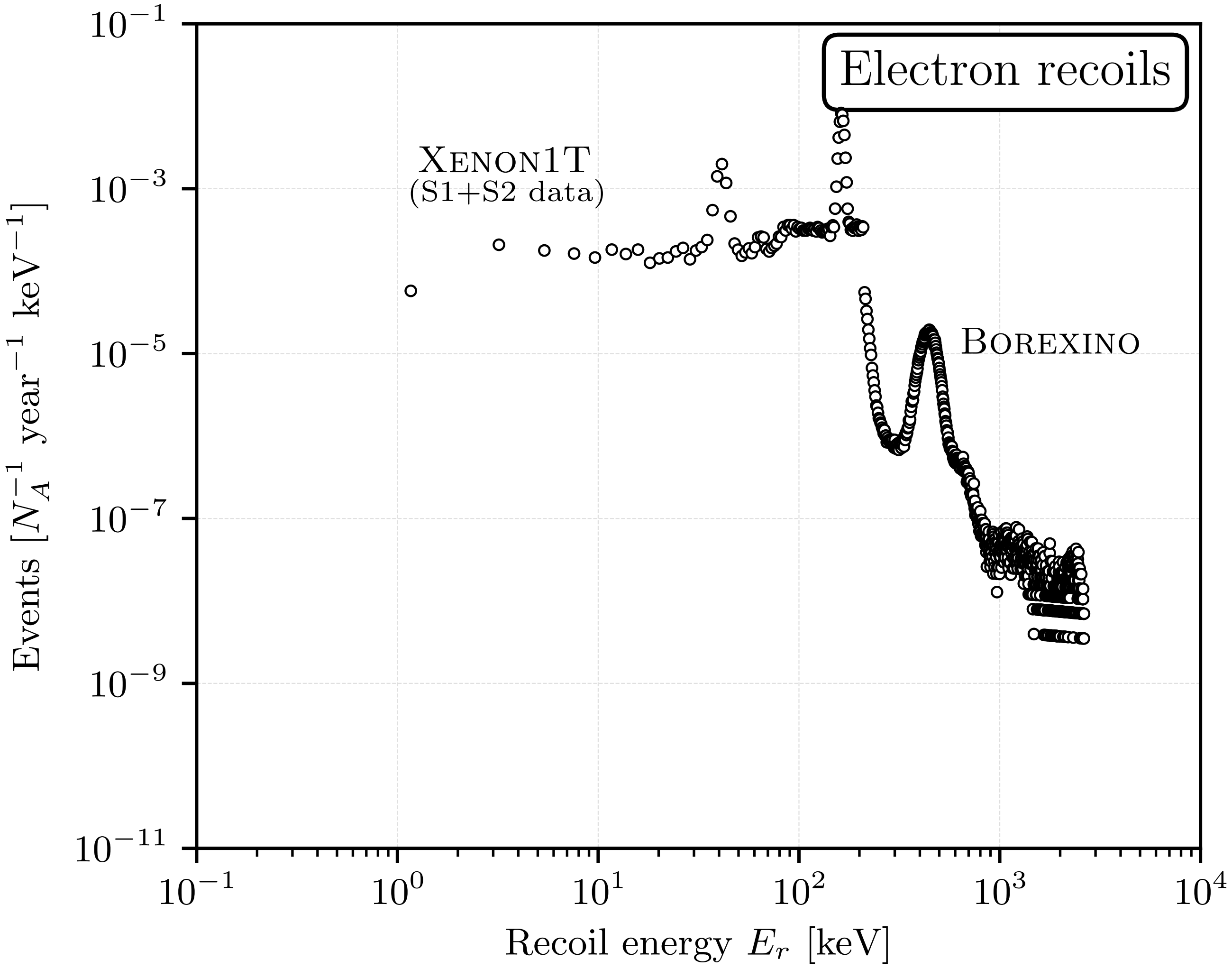


Neutrino (up-)scattering in the detector

Electronic recoil signal

DATA

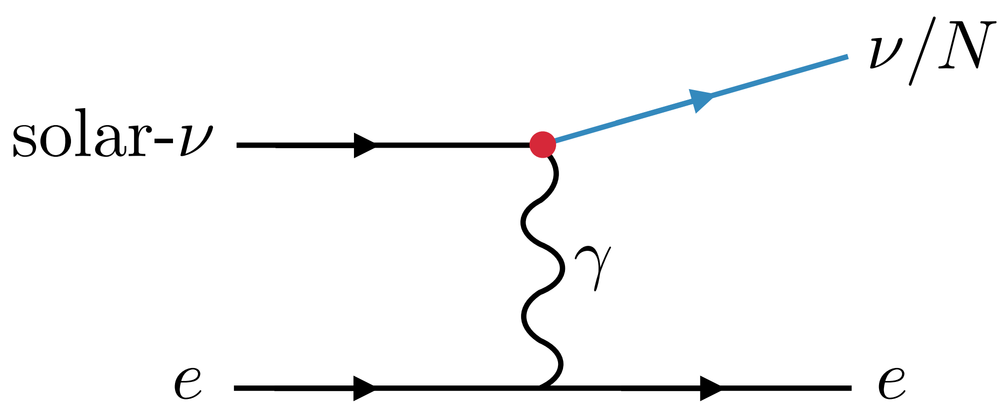


We consider the entire measured range

Electronic recoil signal

Differential event rate:

$$\frac{\Delta R}{\Delta E_r} = N_T \epsilon(E_r) \int_{E_\nu^a}^{E_\nu^b} \mathrm{d}E_\nu \frac{\mathrm{d}\Phi}{\mathrm{d}E_\nu} \frac{\mathrm{d}\sigma}{\mathrm{d}E_r}$$



[Pospelov 1103.3261, Harnik et. al 1202.6073]

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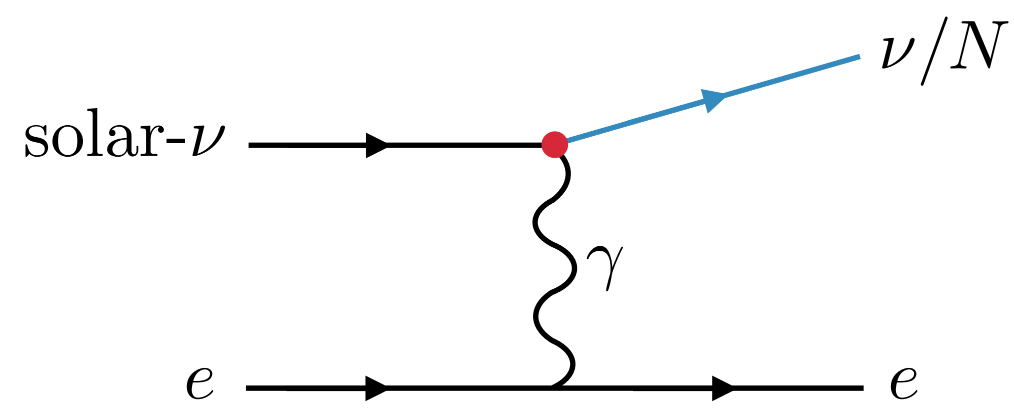
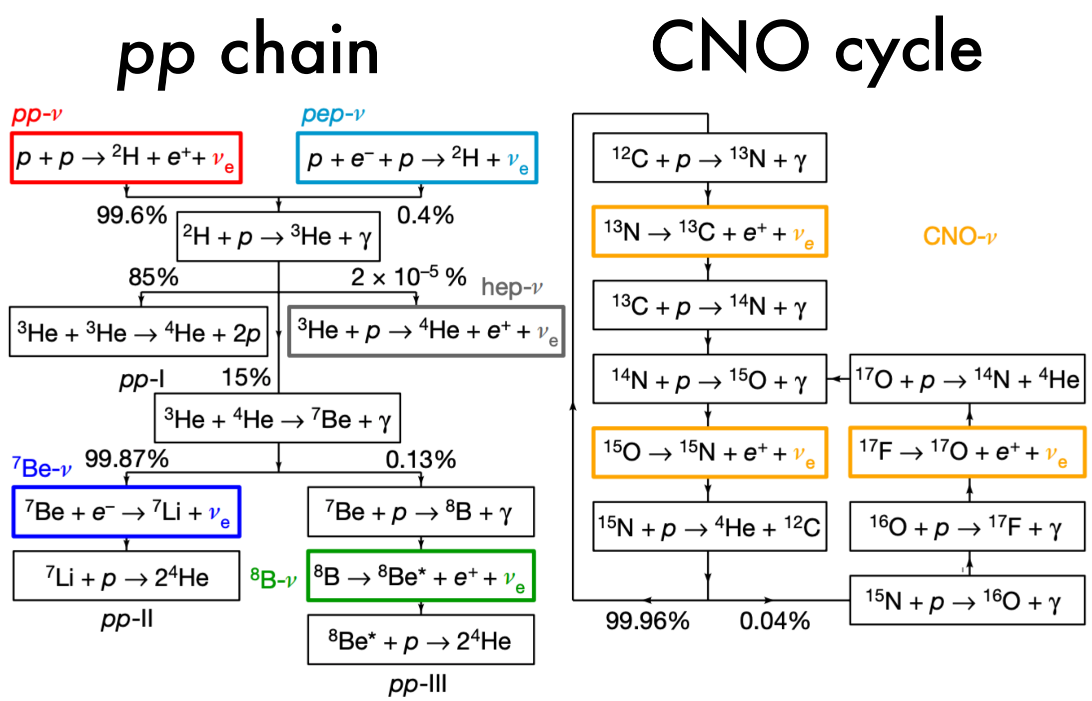


[Pospelov 1103.3261, Harnik et. al 1202.6073]

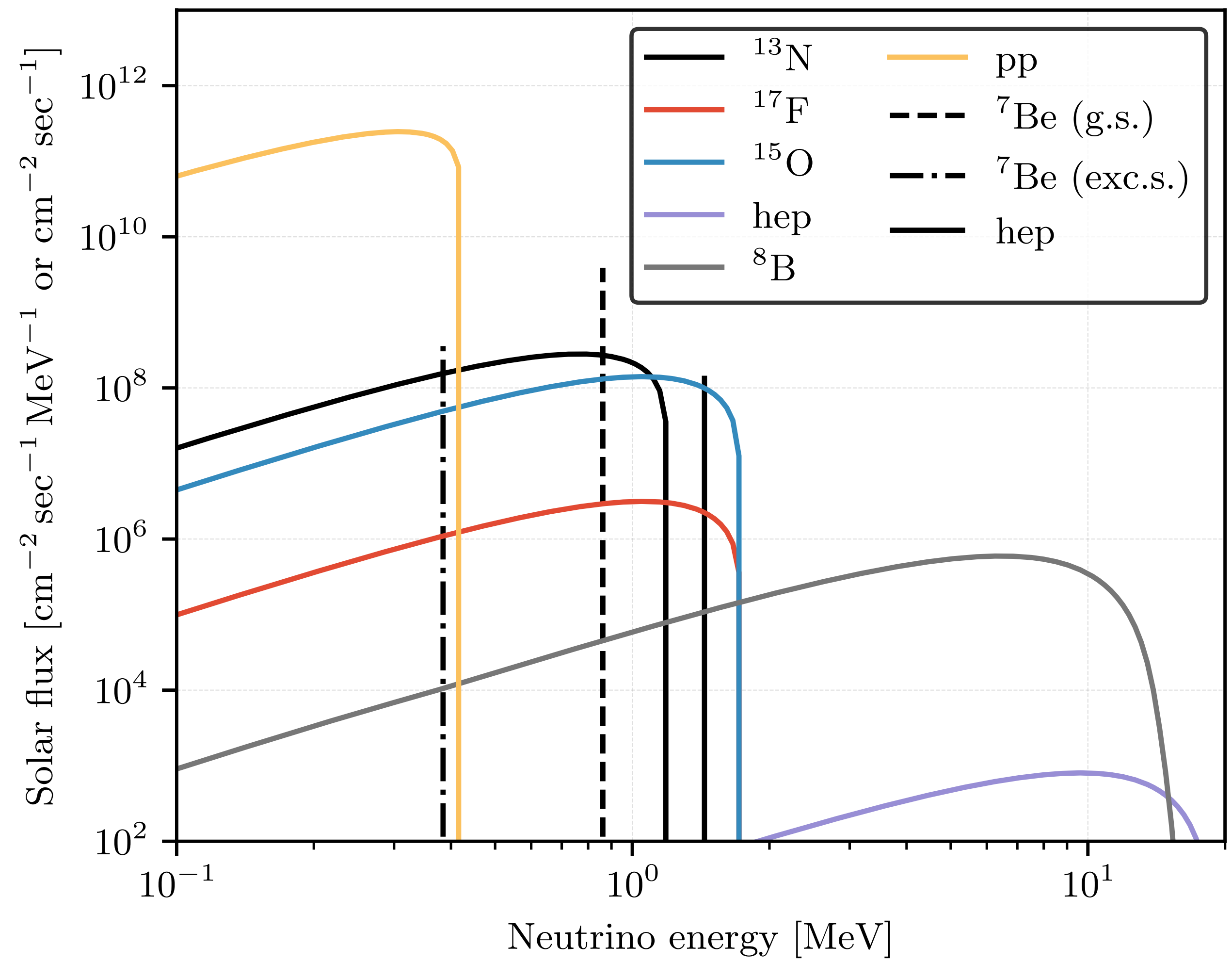
- Scattering targets
- Solar neutrino flux
- Neutrino cross-sections and kinematics

Solar neutrino flux

Two branches:



[Comprehensive measurement of pp-chain solar neutrinos Borexino Collaboration 2018]



Both continuous and monochromatic spectra. Input: theoretical model BS05(OP)

[Bahcall, Serenelli and Basu 2005]

Differential cross sections

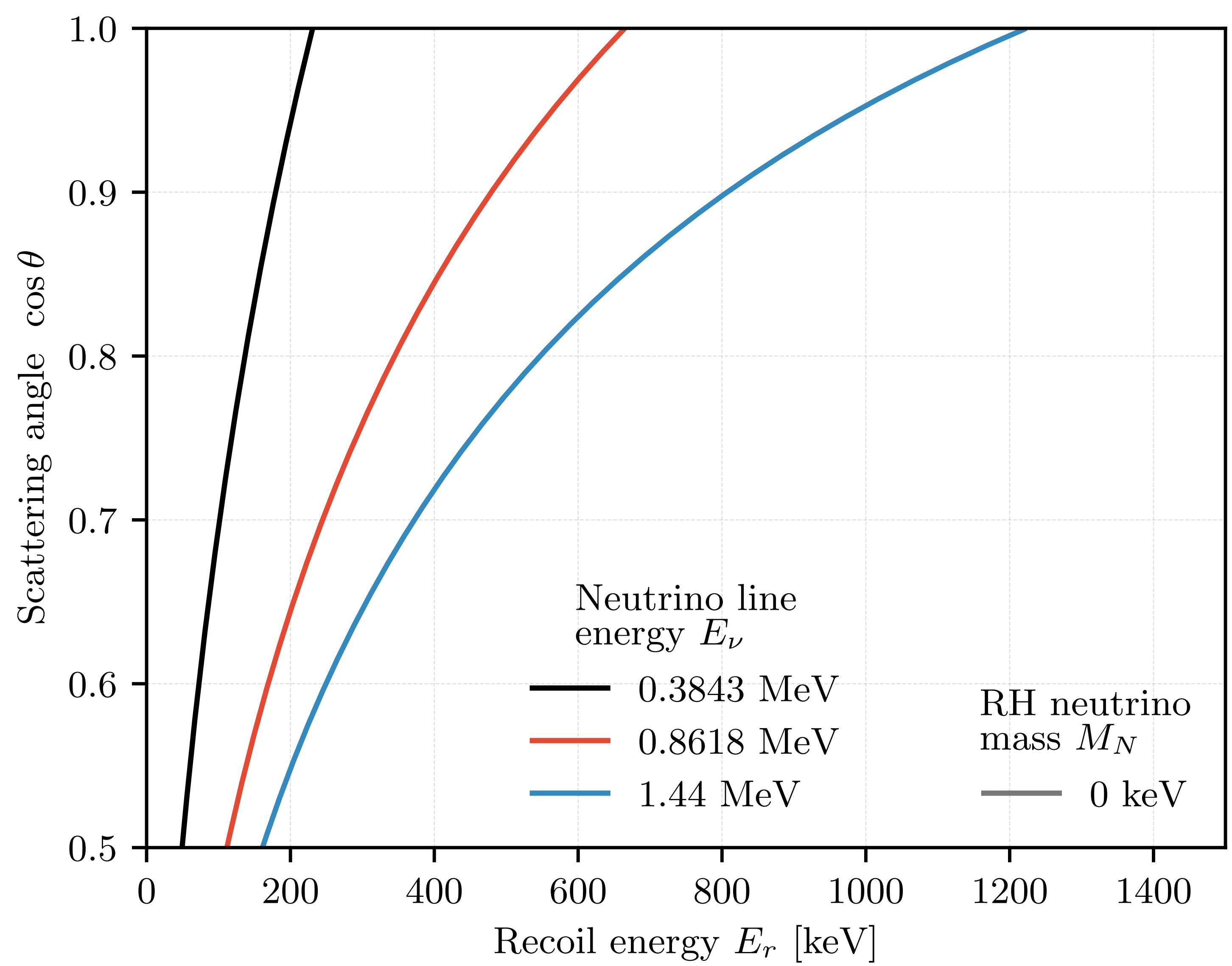
$$\frac{d\sigma_\mu(\nu_L e \to \nu_R e)}{dE_r} = \alpha \mu_\nu^2 \left[\frac{1}{E_r} - \frac{1}{E_\nu}\right]$$

Kinematics:

$$\cos\theta = \frac{E_r(E_\nu + m_e)}{E_\nu \sqrt{E_r(2m_e + E_r)}}$$

angle between outgoing electron and incoming neutrino

$$(E_r^{\min}, E_r^{\max}) = \left(0, \frac{2E_\nu^2}{m_e + 2E_\nu}\right)$$



Differential cross sections

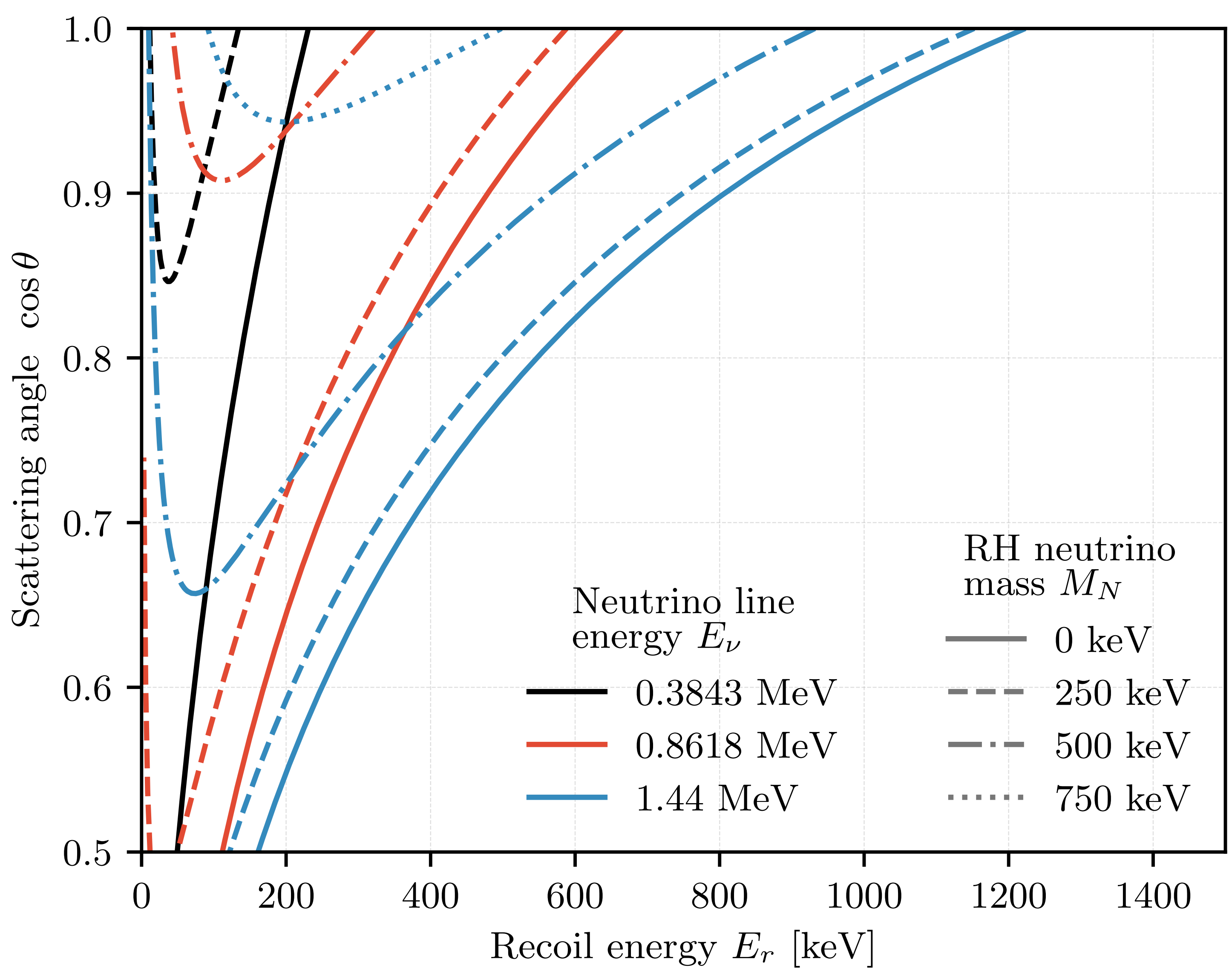
$$\frac{d\sigma_\mu(\nu_L e \to N_R e)}{dE_r} = \alpha \mu_\nu^2 \left[\frac{1}{E_r} - \frac{1}{E_\nu} + M_N^2 \frac{E_r - 2E_\nu - m_e}{4E_\nu^2 E_r m_e} + M_N^4 \frac{E_r - m_e}{8 E_\nu^2 E_r^2 m_e^2} \right]$$

Kinematics:

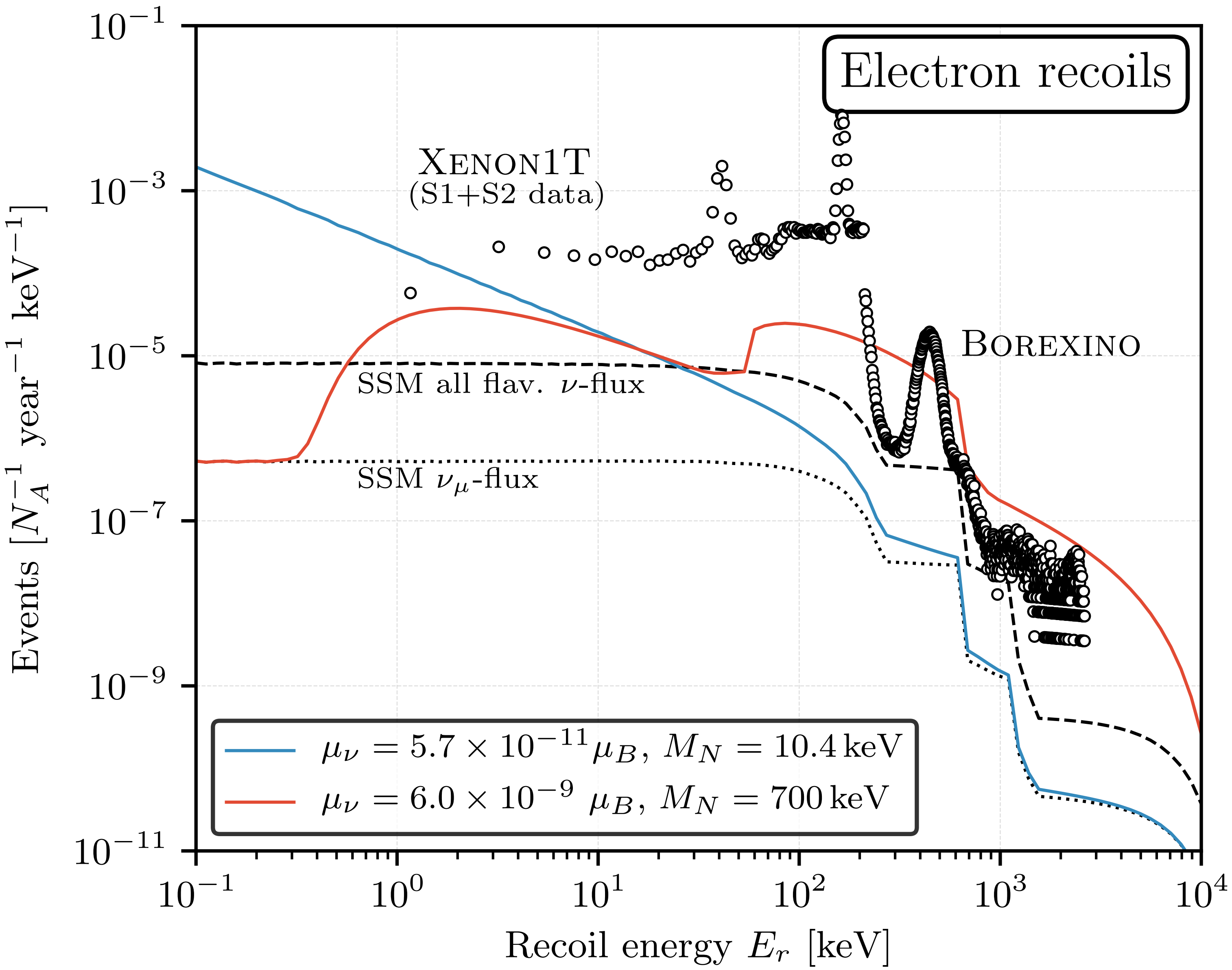
$$\cos\theta = \frac{E_r(E_\nu + m_e) + M_N^2}{E_\nu \sqrt{E_r(2m_e + E_r)}}$$

angle between outgoing electron and incoming neutrino

$$E_r^{\min} \simeq \frac{M_N^2}{2(m_e + M_N)} > 0$$



The predicted spectra



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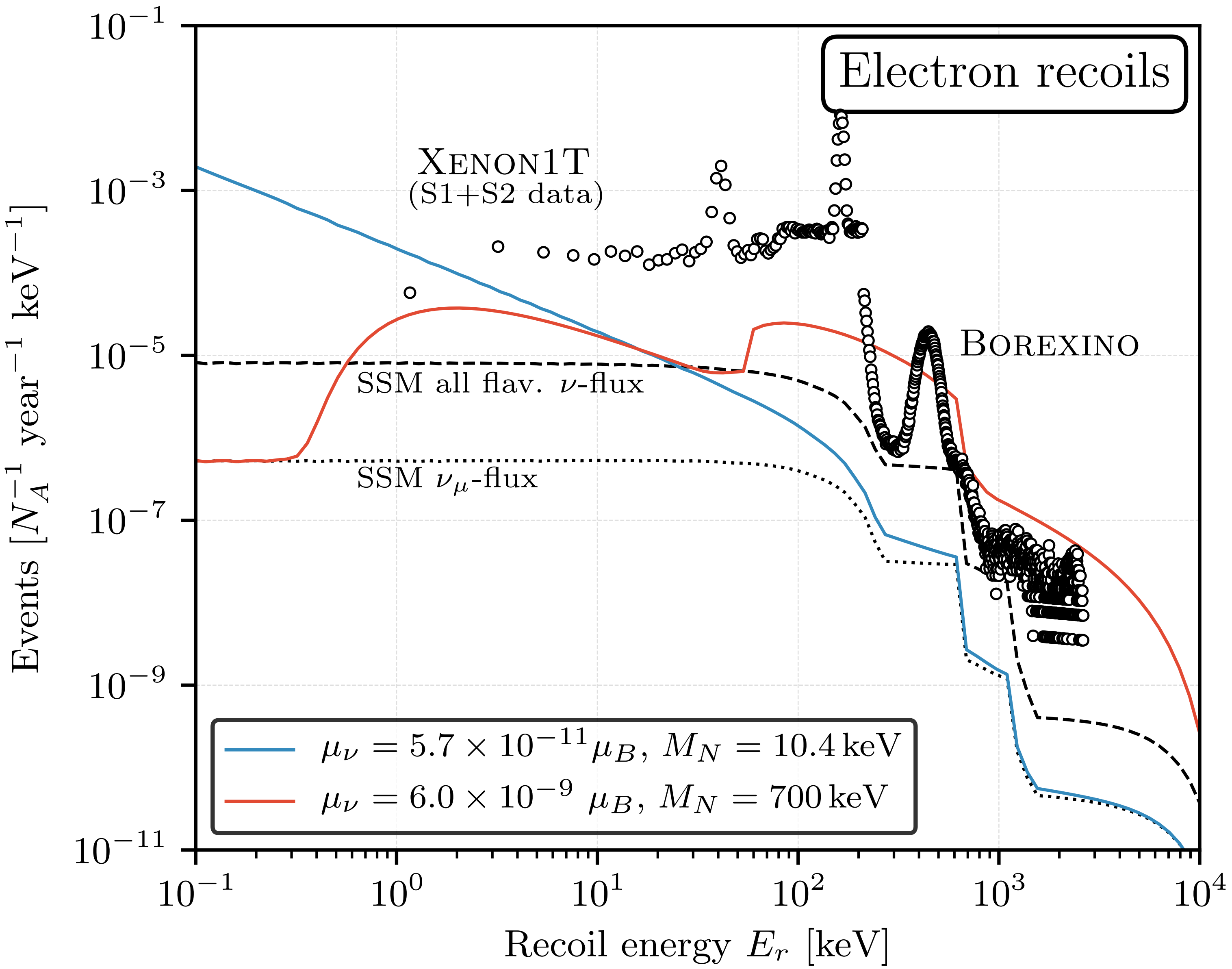
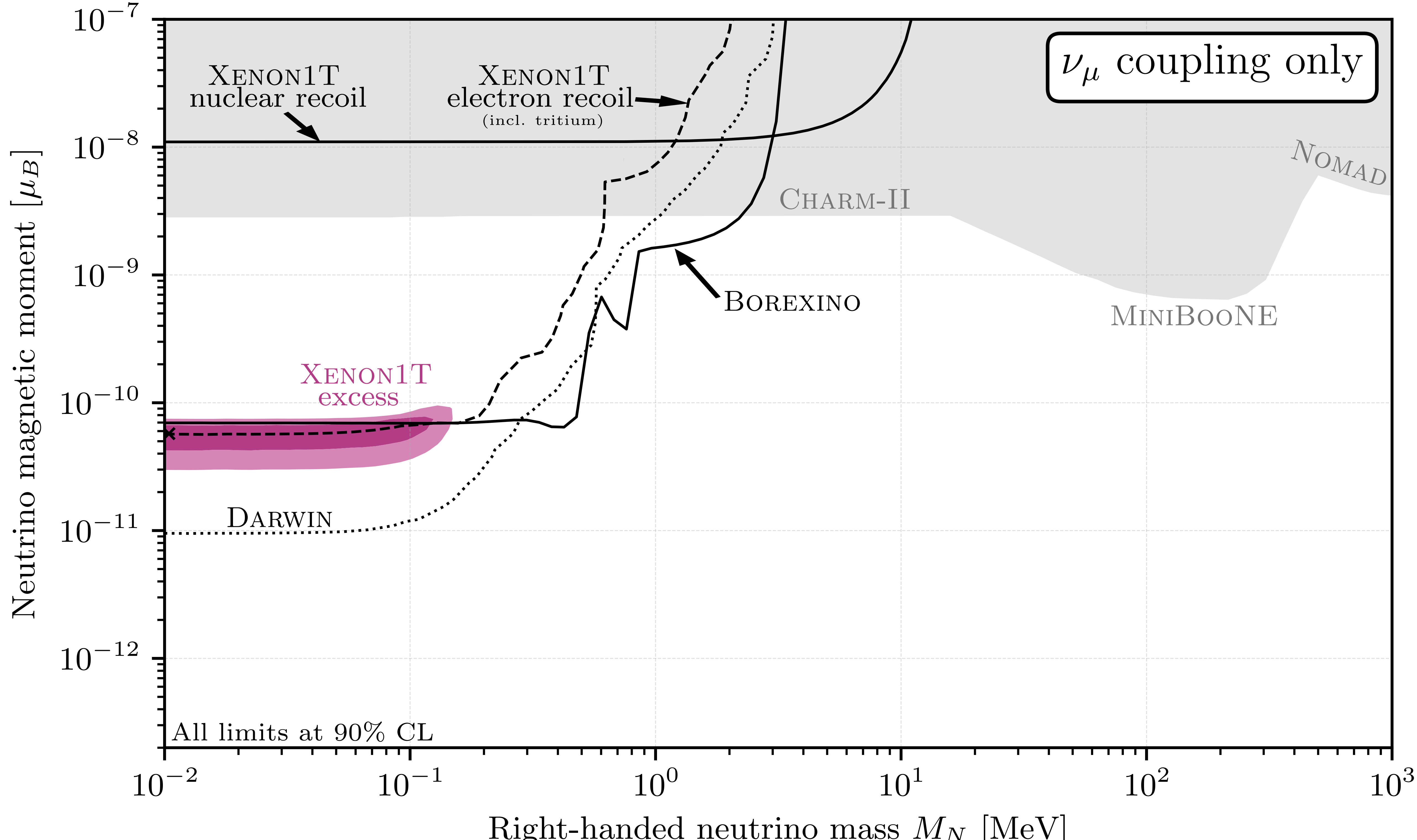


We did a binned likelihood fit to all data:

- Full recoil energy range
- Systematics for the solar flux
- Reproduced Xenon1T and Borexino limits on the magnetic moment of active neutrinos

Results



ν_μ coupling only
XENON1T nuclear recoil
XENON1T electron recoil (incl. tritium)
BOREXINO
CHARM-II
NOMAD
MINIBOONE
XENON1T excess
DARWIN
All limits at 90% CL
Neutrino magnetic moment $[\mu_B]$
Right-handed neutrino mass M_N [MeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Astrophysics

Stellar cooling

- Plasmon decays in dense charged medium kinematically allowed

$$\gamma^* \longrightarrow \nu_L + N \qquad \textbf{where} \qquad m_{\gamma^*} \propto T_{\rm star}$$

- This additional energy loss mechanism affects stellar evolution — increased fuel burning rate!

- Energy loss per unit volume

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

$$K = \sqrt{\omega^2 - k^2}$$

Plasmon energy and momentum

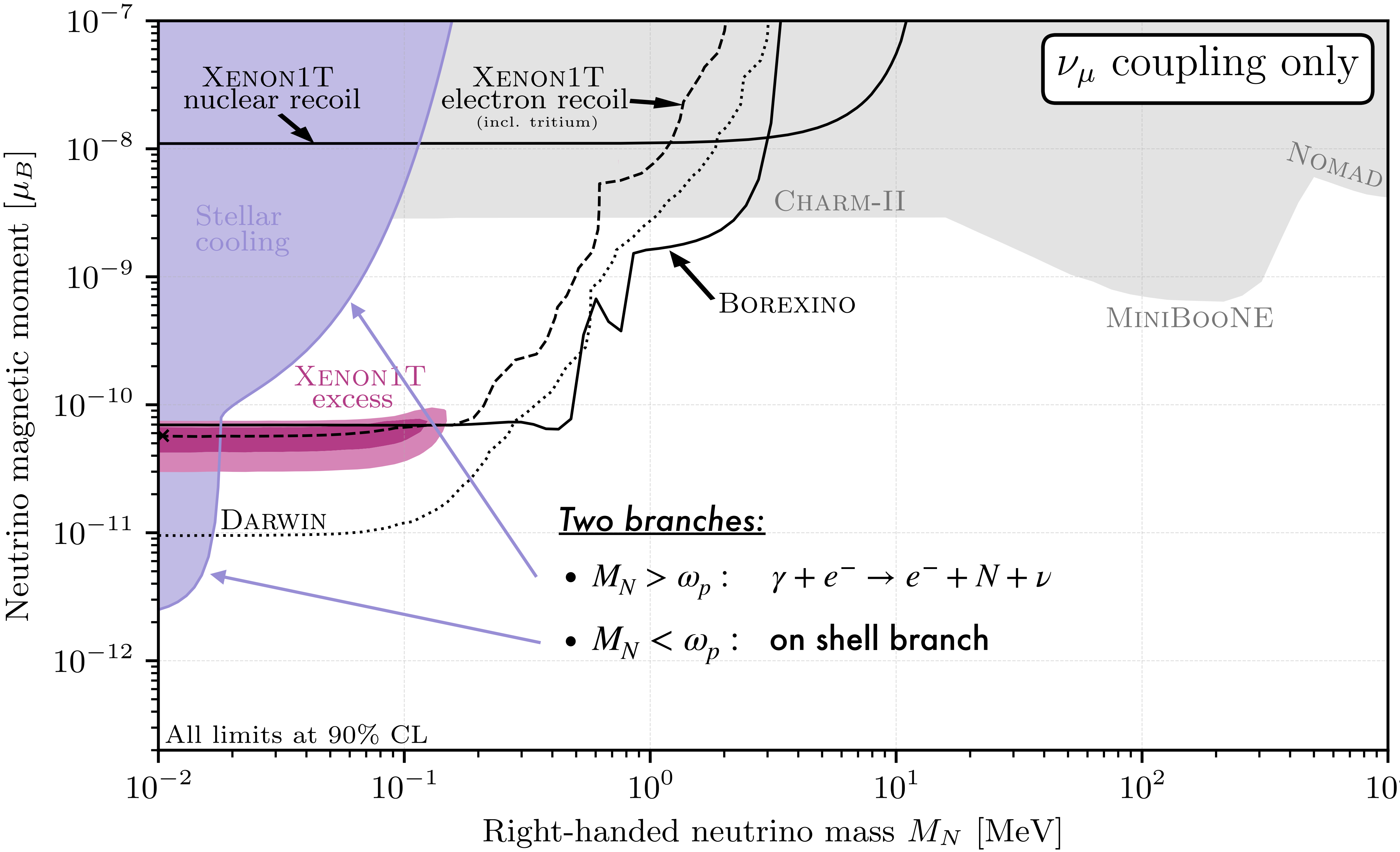
Plasmon width $$\Gamma_{\gamma^*} = \frac{|\mu_\nu|^2 K^4}{24\pi\,\omega}\left(1-\frac{M_N^2}{K^2}\right)^2\left(1+2\,\frac{M_N^2}{K^2}\right)\theta(K-M_N)$$

Thomson scattering rate $$\Gamma_T = \frac{8\pi\alpha^2 n_e}{3m_e^2}$$

Limit set via energy-loss comparison with the $M_N = 0$ case where $\mu_\nu < 2.2\times 10^{-12}\mu_B$

[Arceo-Díaz et. al. 1910.10568]

Stellar cooling

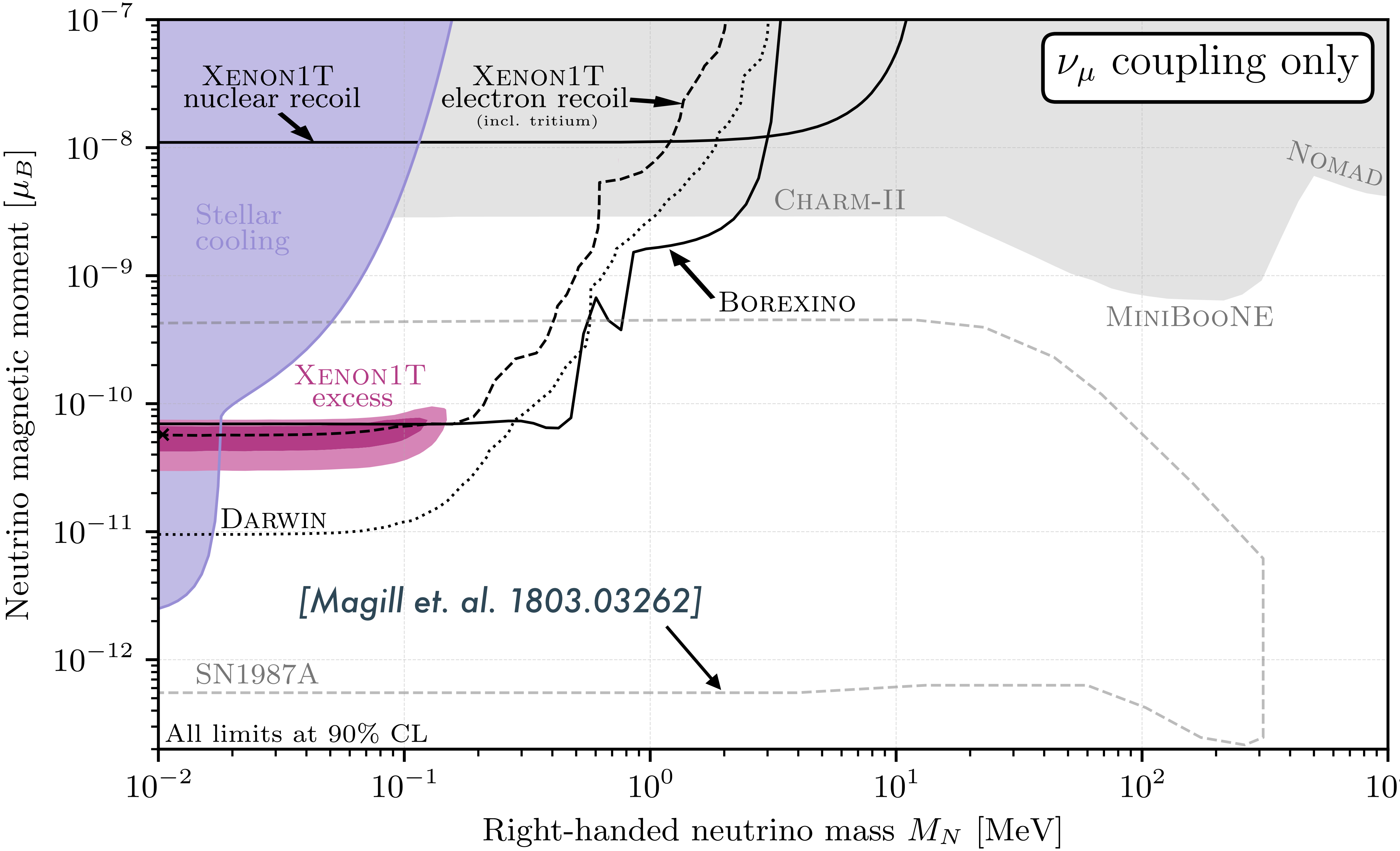


Two branches:

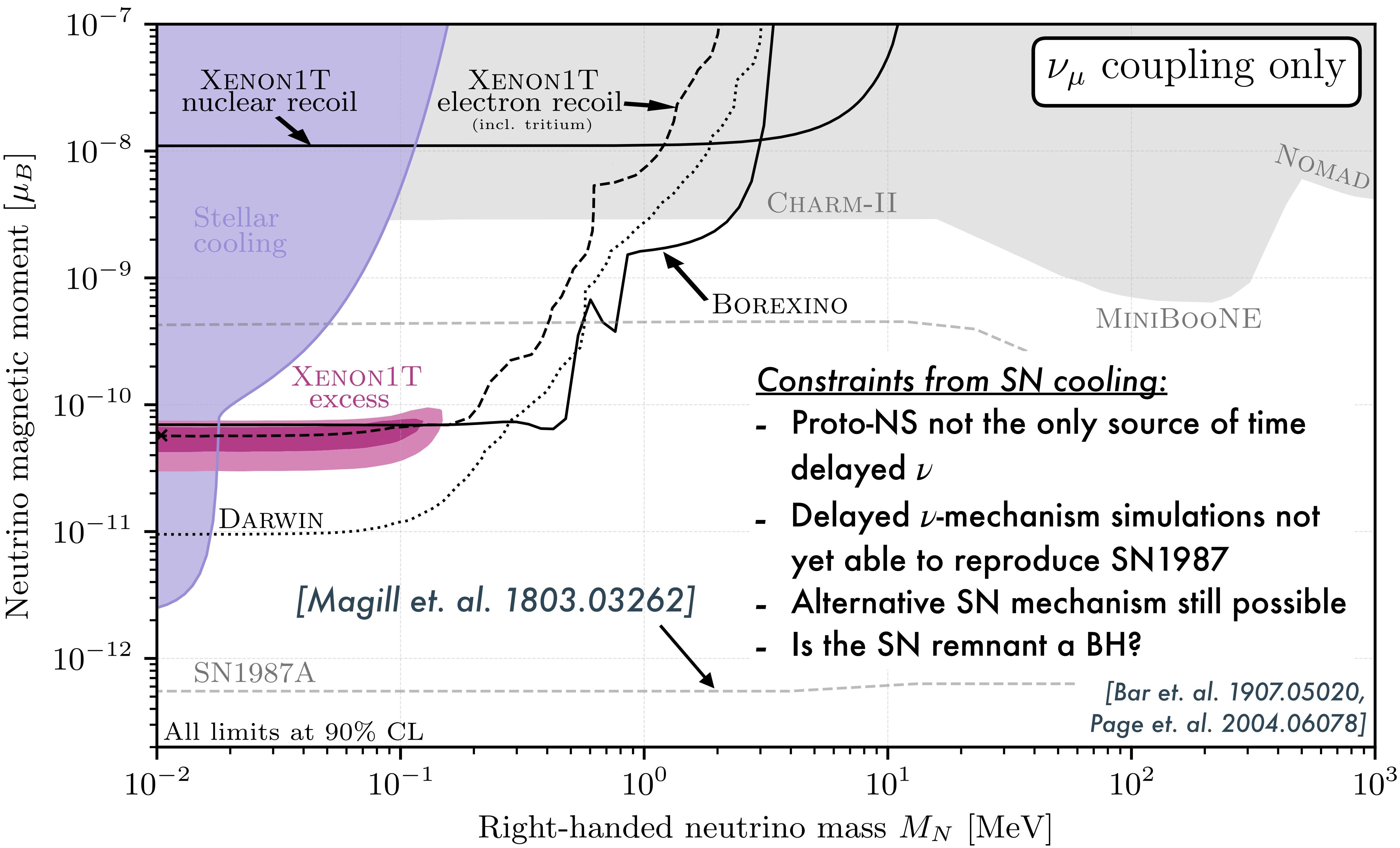
- $M_N > \omega_p$: $\gamma + e^- \to e^- + N + \nu$
- $M_N < \omega_p$: on shell branch

Use following RG parameters $\omega_p = 18\,\mathrm{keV}$, $T_\gamma = 8.6\,\mathrm{keV}$ and $n_e = 3 \times 10^{29}\,\mathrm{cm}^{-3}$

Supernova constraints



Supernova constraints



<u>*Constraints from SN cooling:*</u>

- Proto-NS not the only source of time delayed ν
- Delayed ν-mechanism simulations not yet able to reproduce SN1987
- Alternative SN mechanism still possible
- Is the SN remnant a BH?

[Bar et. al. 1907.05020, Page et. al. 2004.06078]

Cosmology

Cosmological constraints

Solve integrated Boltzmann equations:

$$\begin{aligned}
\dot\rho_\gamma &= \boxed{-4H\rho_\gamma +} \langle\sigma v\rangle_{ee}(n_e\rho_e - n_e^{\rm eq}\rho_e^{\rm eq}) + \frac{\Gamma_N}{2}(\rho_N - \rho_N^{\rm eq})\\
\dot\rho_e &= -s_e H\rho_e - \langle\sigma v\rangle_{ee}(n_e\rho_e - n_e^{\rm eq}\rho_e^{\rm eq})\\
\dot\rho_\nu &= -4H\rho_\nu + \frac{\Gamma_N}{2}(\rho_N - \rho_N^{\rm eq}) + \Gamma_{eN}(\rho_N - \rho_N^{\rm eq})\\
\dot\rho_N &= -s_N H\rho_N - \Gamma_N(\rho_N - \rho_N^{\rm eq}) - \Gamma_{eN}(\rho_N - \rho_N^{\rm eq})\,.
\end{aligned}$$

Dilution factors

Note: equilibrium densities for N_R function of both T_γ and T_ν i.e.

$$\rho_e^{\rm eq} = (2T_\gamma^4/\pi^2)J_f(m_e/T_\gamma)$$
$$\rho_N^{\rm eq} = (2T_R^4/\pi^2)J_f(M_N/T_R)$$

with $T_R \equiv \frac{1}{2}(T_\gamma + T_\nu)$

Rates:

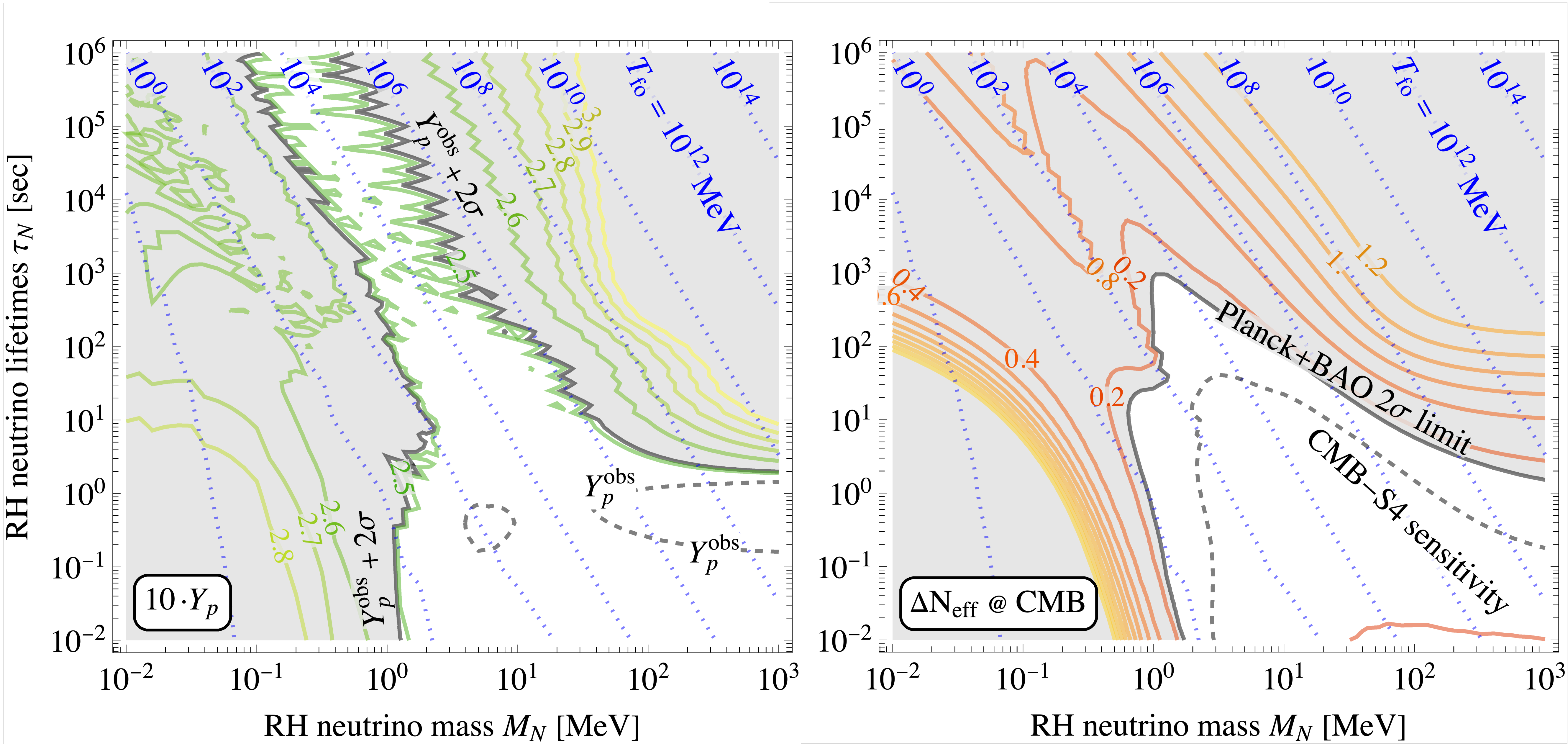
- Γ_N (Inverse) decays of N_R
- Γ_{eN} Electron up-scattering $e + N_R \to e + \nu_L$
- $\langle\sigma v\rangle_{ee}$ Standard model QED

Sanity check: simplified treatment reproduces ALP results

[Depta et. al. 2002.08370]

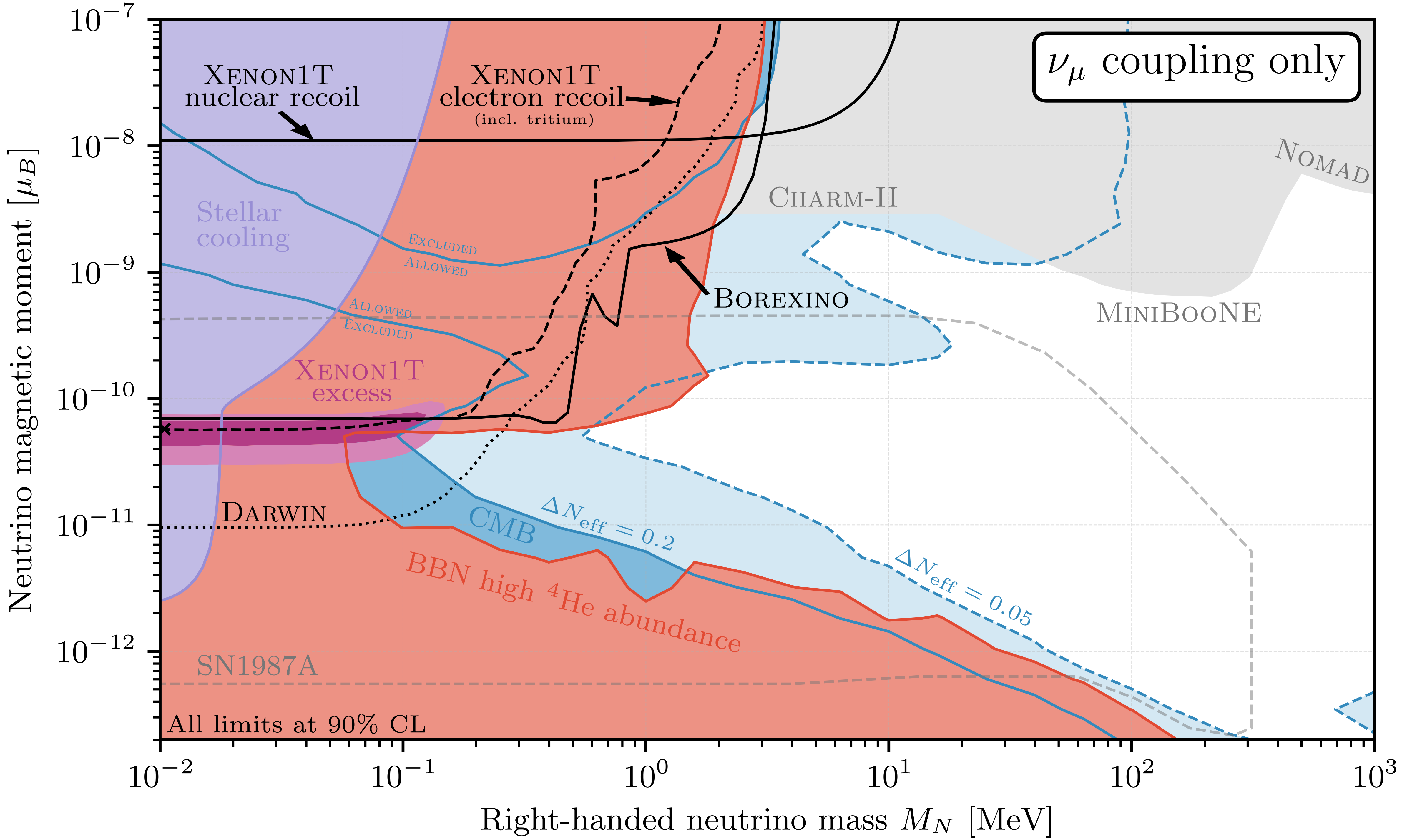
Code AlterBBN used.

Cosmological constraints



$$Y_p \equiv \rho(^4\mathrm{He})/\rho_b$$

The final plot



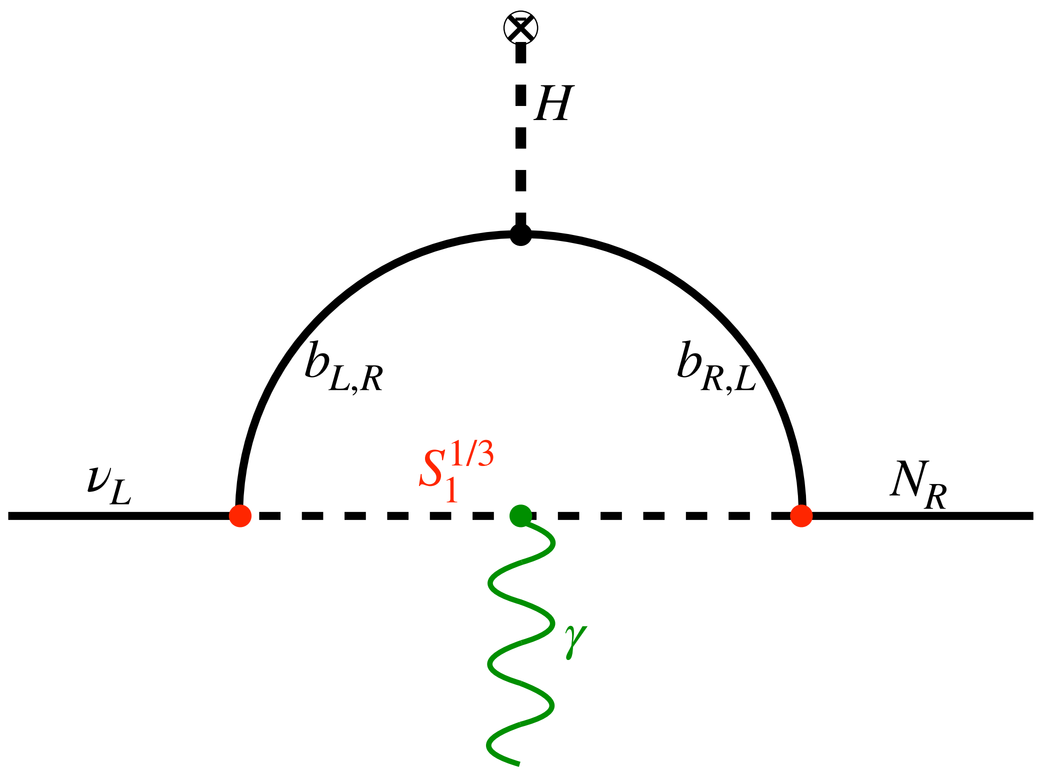
Model building

Neutrino masses

Natural relationship between $\boldsymbol{\mu_\nu}$ and Dirac mass $\boldsymbol{m_{\nu N}}$ term

$$\frac{\mu_\nu}{\mu_B} \approx \frac{m_e\, m_{\nu N}}{\Lambda^2} \qquad \Longrightarrow \qquad m_{\nu N} \sim \mathcal{O}(\mathrm{MeV}) \left(\frac{10^{-11}\,\mu_\mathrm{B}}{\mu_\nu}\right) \left(\frac{1\,\mathrm{TeV}}{\Lambda}\right)^2$$

Example:



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Assuming type-I seesaw: $M_N \sim \frac{m_{\nu N}^2}{m_\nu} \gg \mathrm{TeV}$ *Far far beyond reach of direct detection*

$M_N \sim$ MeV requires tuning tree level mass against this loop induced mass….

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Two ways out:

Inverse seesaw:

- Destroys mixing-mass relationship
- Large mixing between active-sterile states

Voloshin mechanism:

- Requires an additional $SU(2)$ horizontal symmetry

Neutrino masses

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Two ways out:

Inverse seesaw:

- Destroys mixing-mass relationship
- Large mixing between active-sterile states

$$\mathcal{L} \supset -m_{\nu N}\bar{\nu}_L N_R - m_N \bar{N}_L N_R + \mathrm{h.c.}$$

(1 massless and 1 massive)

$$\tan\theta_{\nu N} = m_{\nu N}/m_N$$

Neutrino masses

Natural relationship between μ_ν and Dirac mass $m_{\nu N}$ term

- Interestingly large mixings are not excluded in terrestrial experiments for the MeV-mass sterile neutrino
- Still, we want the magnetic moment to dominate the phenomenology, not the mixing

Naive estimate of the relevant rates for cosmology*

$$\Gamma_{\mu_\nu} \sim \mu_\nu^2 T^3$$

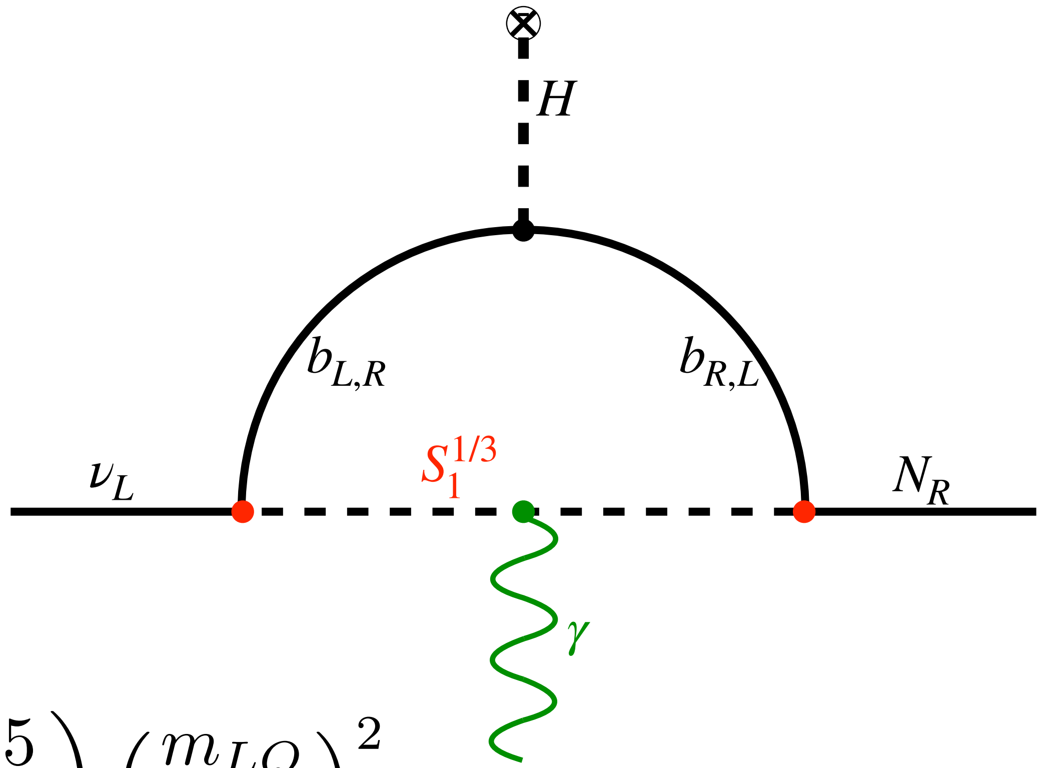
vs

$$\Gamma_\theta \sim G_F^2 T^5 \sin^2\theta$$

$$\Longrightarrow \quad \mu_\nu > G_F T \sin\theta \sim 10^{-11}\,\mu_B \left(\frac{\text{GeV}}{T}\right)\left(\frac{10^{-3}}{\sin\theta}\right)$$

- Large mixing between active-sterile states

Leptoquark model



Introduce a single scalar leptoquark
$S_1 \in (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

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

Naturally large magnetic moment

$$\mu_\nu \approx \frac{e\, y_1 y_2}{8\pi^2 m_{LQ}^2}\, m_b \log \frac{m_b^2}{m_{LQ}^2} \sim 3 \times 10^{-11}\, \mu_\text{B} \left(\frac{0.05}{y_1 y_2}\right) \left(\frac{m_{LQ}}{\text{TeV}}\right)^2$$

Leptoquark model

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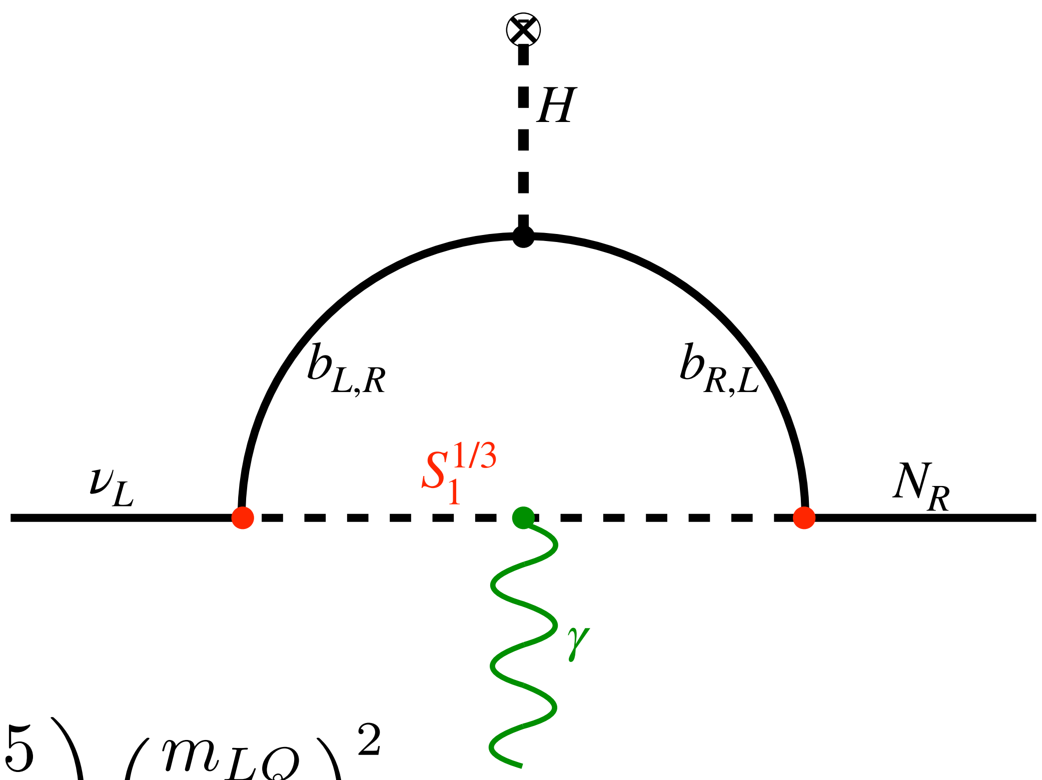

Naturally large magnetic moment

$$\mu_\nu \approx \frac{e\, y_1 y_2}{8\pi^2 m_{LQ}^2} m_b \log\frac{m_b^2}{m_{LQ}^2} \sim 3\times 10^{-11}\,\mu_{\rm B} \left(\frac{0.05}{y_1 y_2}\right)\left(\frac{m_{LQ}}{\rm TeV}\right)^2$$

Rich phenomenology:

- Unique collider signatures
- Contribution to $g-2$ of the muon
- Contributions to both neutral ($b \to s\ell\ell$) and charged current transitions ($b \to c\tau\nu$)
- Can also be embedded in RPV supersymmetry

Leptoquark model

Additional approximate $SU(2)$ symmetry

[Voloshin 1988 – typically mechanism is implemented using additional neutral scalars]

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

Dirac mass exactly zero (→ $SU(2)$ triplet)

Leptoquark model

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[Voloshin 1988 – typically mechanism is implemented using additional neutral scalars]

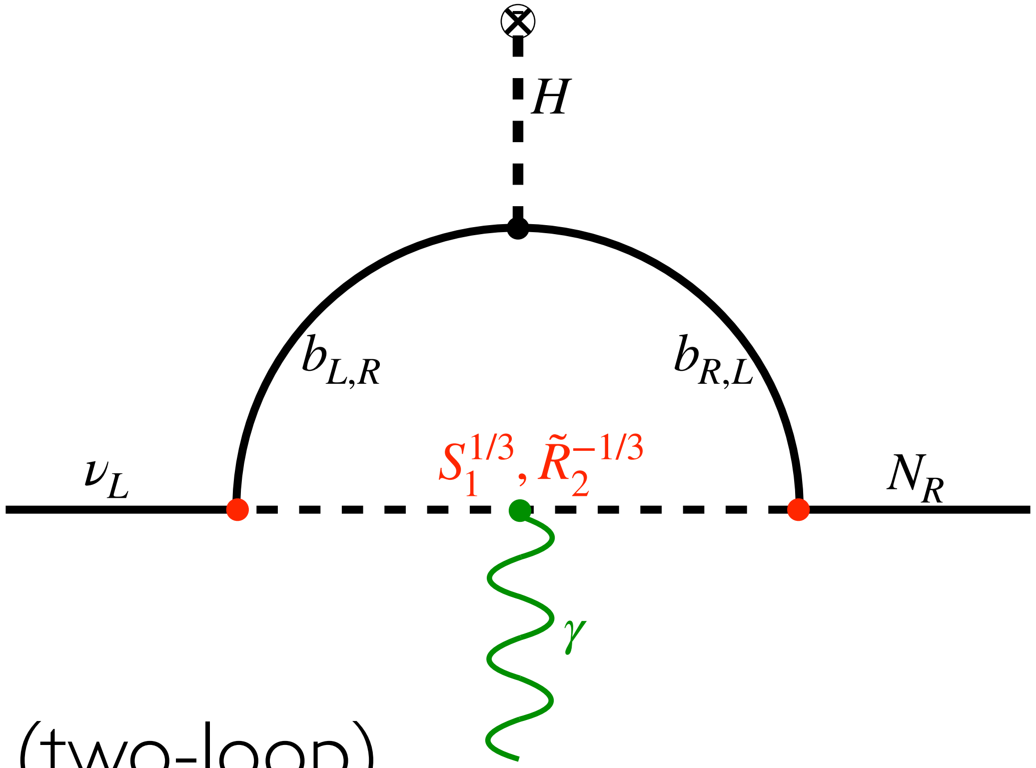
$$(\nu_L^c, N_R) \in \mathbf{2} \quad \Longrightarrow \begin{cases} \bar{N}_R \sigma^{\mu\nu} \nu_L - \overline{\nu_L^c} \sigma^{\mu\nu} N_R^c & SU(2) \text{ singlet} \\ \bar{N}_R \nu_L + \overline{\nu_L^c} N_R^c & SU(2) \text{ triplet} \end{cases}$$

Dirac mass exactly zero

Mechanism requires second leptoquark
$\tilde{R}_2 \in (\mathbf{3}, \mathbf{2}, 1/6)$

$$\mathcal{L}_{\tilde{R}_2} \supset -y_1 \, \tilde{R}_2^\dagger \, \overline{b_R^c} L_L^{ic} + y_2 \, \overline{Q_L^3} N_R \, \tilde{R}_2 + \text{h.c.}$$

with $\quad (\tilde{R}_2^{-1/3}, S_1^\dagger) \in \mathbf{2}$



Dominant breaking through EW corrections (two-loop)

Breaking from lepton Yukawa couplings is subdominant

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

*comment on the active neutrinos

Conclusions

- Active to sterile neutrino upscattering mediated by a transition magnetic moment in a neutrino or dark matter direct detection experiment.

- Complementary constraints from astrophysics and cosmology scrutinize most of the relevant parameter space.

- Model-building challenges arise in scenarios that feature large magnetic moments while keeping observed neutrino masses.