The Neutrino Magnetic Moment Portal

Joachim Kopp (CERN & JGU Mainz)
Physics of the Flavorful Universe | Portorož | 22 September 2021

Introduction

Then: DM physics as a spin-off of neutrino physics

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

"We study detection of MeV-scale neutrinos through elastic scattering on nuclei […]"

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

"We consider the possibility that the […] neutrino detector recently proposed by Drukier and Stodolsky could be used to detect […] dark matter."

Introduction

Now: neutrino physics as a spin-off of DM physics

Now: neutrino physics as a spin-off of DM physics

Solar and Atmospheric Neutrinos: Background Sources for the Direct Dark Matter Searches

A. Gütlein, C. Ciemniak, F. von Feilitzsch, N. Haag, M. Hofmann, C. Isaila, T. Lachenmaier, J. [illegible] L. Oberauer, S. Pfister, W. Potzel, S. Roth [illegible] R. Strauß, and A. Zöller

Exploring ν signals in dark matter detectors

Roni Harnik[1,*] Joachim Kopp[1,†] and Pedro A. N. Machado[1,2,3‡]

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

Vedran Brdar,[1, a] Admir Greljo,[2, b] Joachim Kopp,[2, 3, c] and Toby [illegible]

Physics from solar neutrinos in dark matter direct detection experiments

David G. Cerdeño,[1] Malcolm Fairbairn,[2] Thomas Jubb,[1] [illegible][3,4] Aaron C. Vincent,[1] and Céline Bœhm[1,5]

Neutrino Discovery Limit of Dark Matter Direct Detection experiments in the presence of Non-Standard Interactions

[illegible] Yuber F. Perez-Gonzalez[e,f] and [illegible]

Neutrino physics with dark matter detectors

Bhaskar Dutta and Louis E. Strigari

Pre-Supernova Neutrinos in Large Dark Matter Direct Detection Experiments

[illegible] Raj,[1,*] Volodymyr Takhistov,[2,†] and Samuel J. Witte[3,‡]

Solar Neutrinos as a Signal and Background in Direct-Detection Experiments [illegible] for Sub-GeV Dark Matter With Electron Recoils

[illegible] Sholapurkar,[1,†] and Tien-Tien Yu[2,3,‡]

Direct Detection Experiments at the Neutrino Dipole Portal Frontier

Ian M. Shoemaker and Jason Wyenberg

Introduction

This talk:
neutrino magnetic moment constraints
from direct detection and elsewhere

Outline

- ☑ Neutrino Magnetic Moments
- ☑ Direct Detection Constraints
- ☑ Other Constraints
- ☑ Model-Building Considerations

Neutrino Magnetic Moments

Neutrino Magnetic Moments in the SM

Neutrino Magnetic Moments in the SM

- Magnetic Moment Operator

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

Neutrino Magnetic Moments in the SM

- Magnetic Moment Operator

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

electromagnetic field strength tensor

Neutrino Magnetic Moments in the SM

Couples LH and RH neutrinos

☑ Magnetic Moment Operator

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

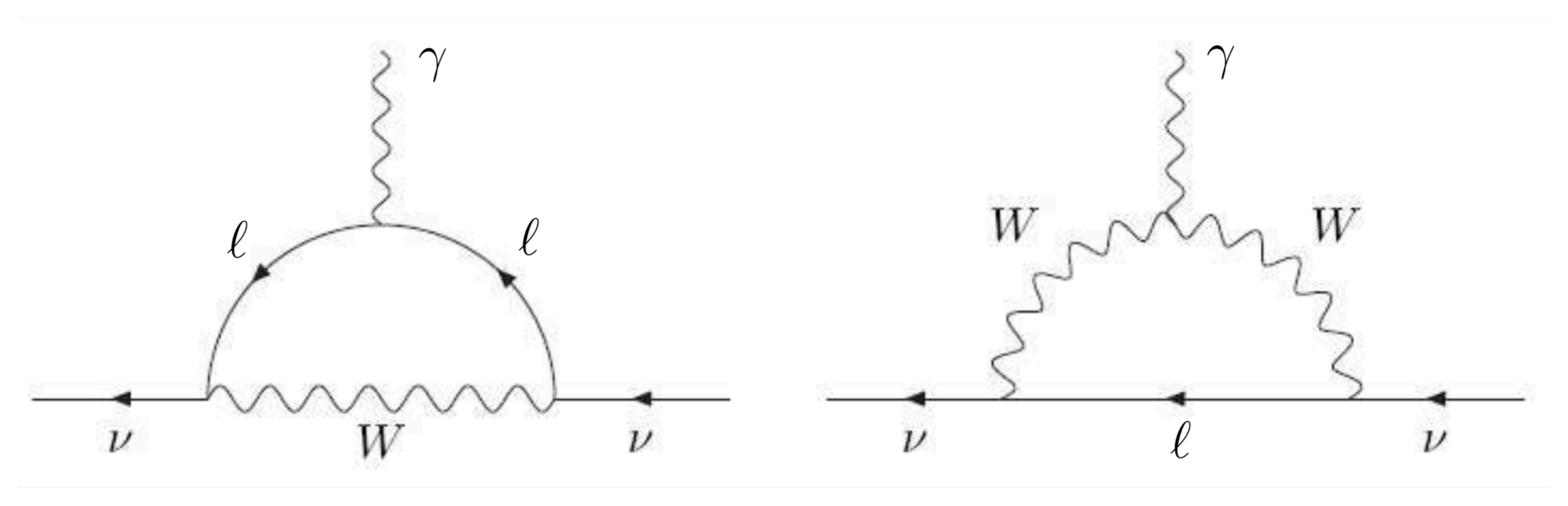
electromagnetic field strength tensor

Neutrino Magnetic Moments in the SM

- Magnetic Moment Operator

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

- In the SM: generated by loop diagrams



- Numerically tiny: $< 10^{-19}\ \mu_B$

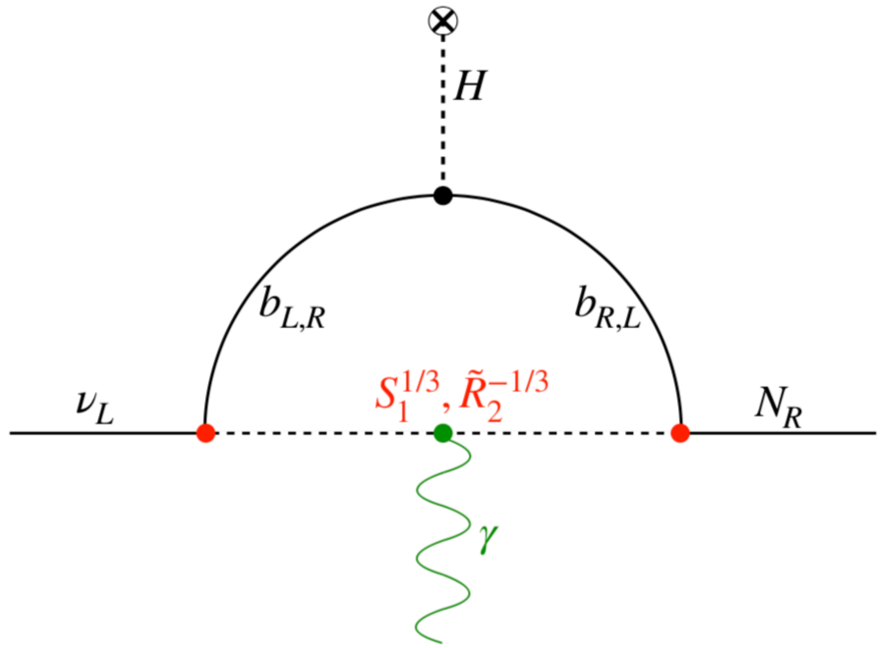
Petcov 1977
Fujikawa Shrock 1980

Neutrino Magnetic Moments Beyond the SM

- ☑ Numerically tiny: $< 10^{-19}\ \mu_B$
- ☑ Can be significantly enhanced in BSM theories
  - new loop diagrams, and/or
  - new "sterile" neutrino states N_R

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

leptoquark model, inspired by B physics anomalies

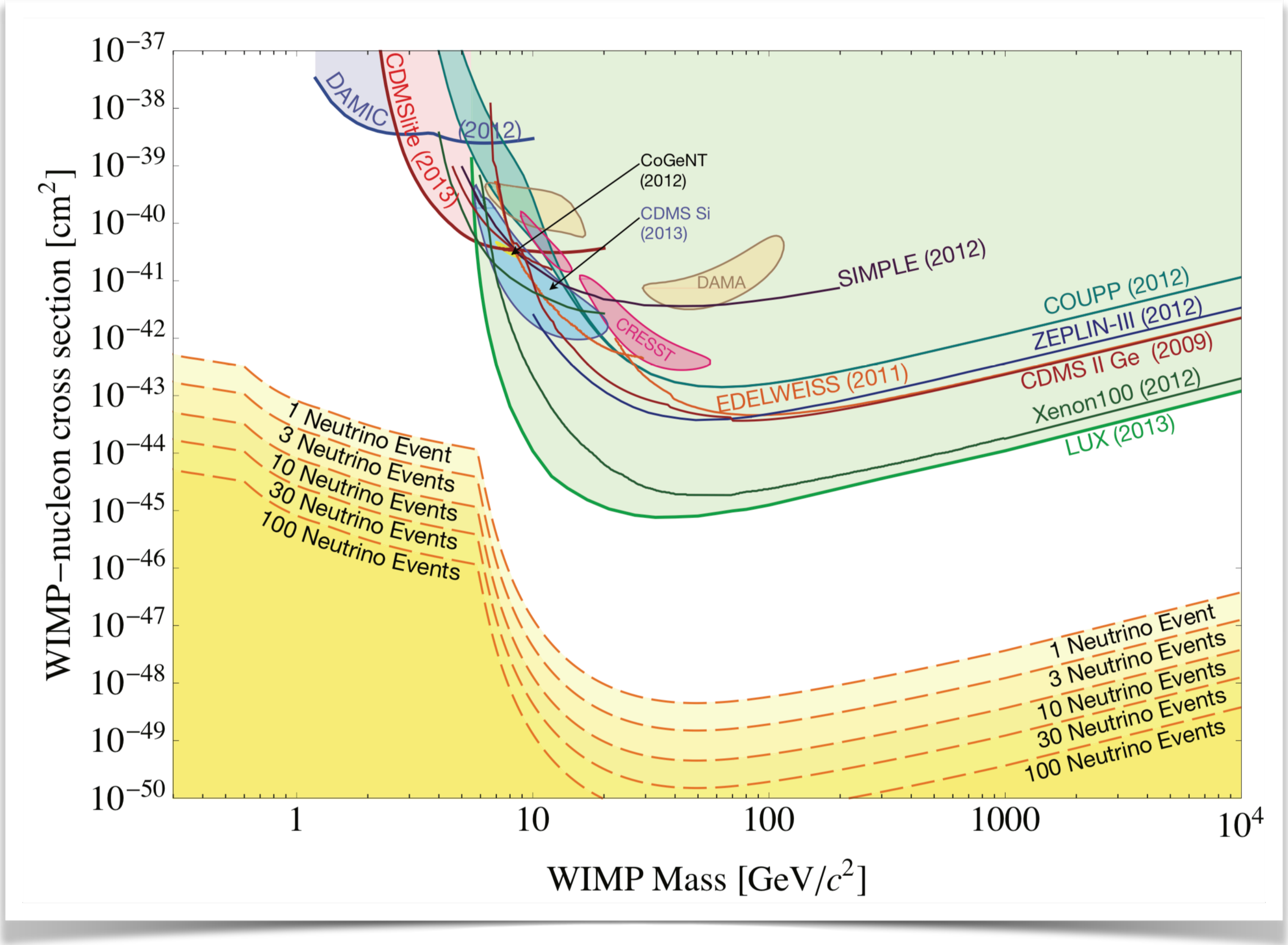


Brdar Greljo JK Opferkuch
2007.15563

Direct Detection Constraints

Signals in Direct Detection Experiments

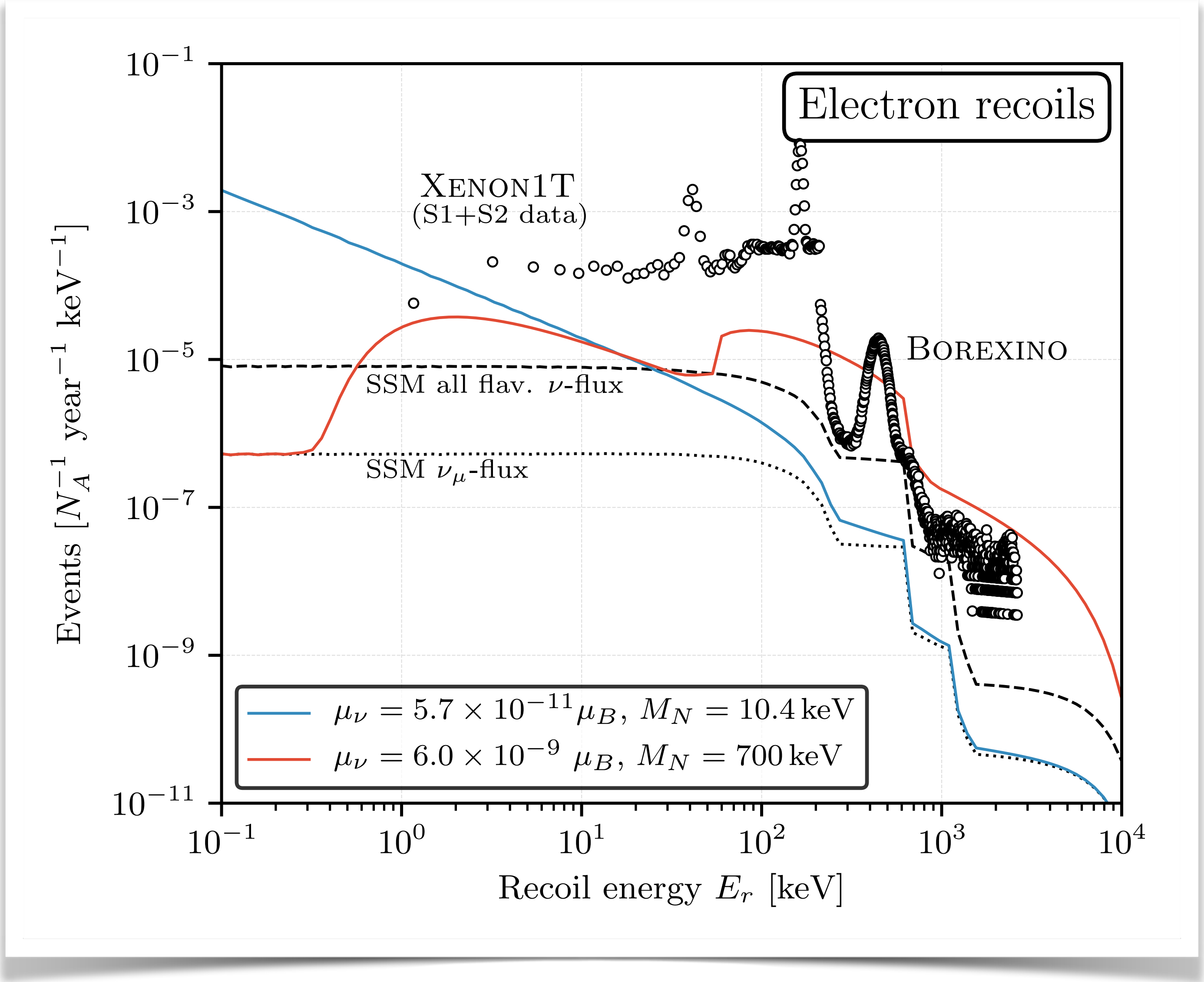
☑ solar ν always present in direct detection experiments

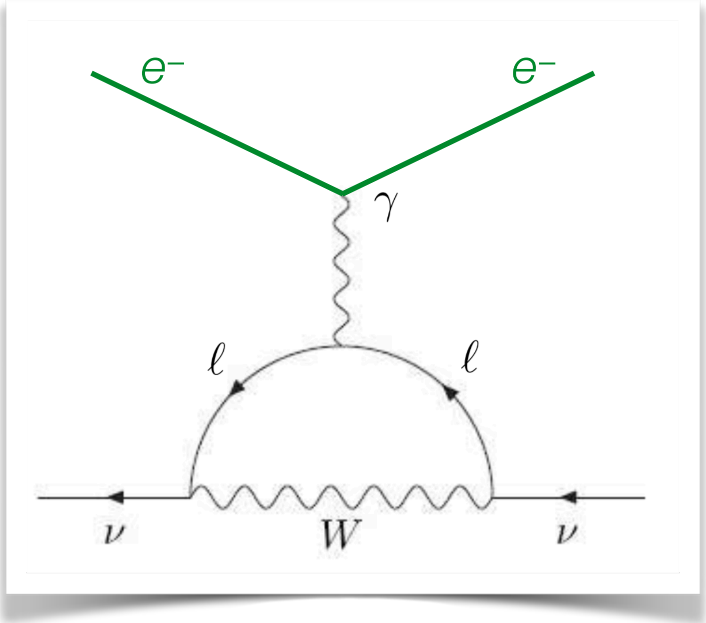


Gütlein et al. arXiv:1003.5530
Billard Strigari Figueroa-Feliciani arXiv:1307.5458

Signals in Direct Detection Experiments

- ☑ solar ν always present in direct detection experiments
- ☑ enhanced e^- recoil rate from μ_ν-induced scattering

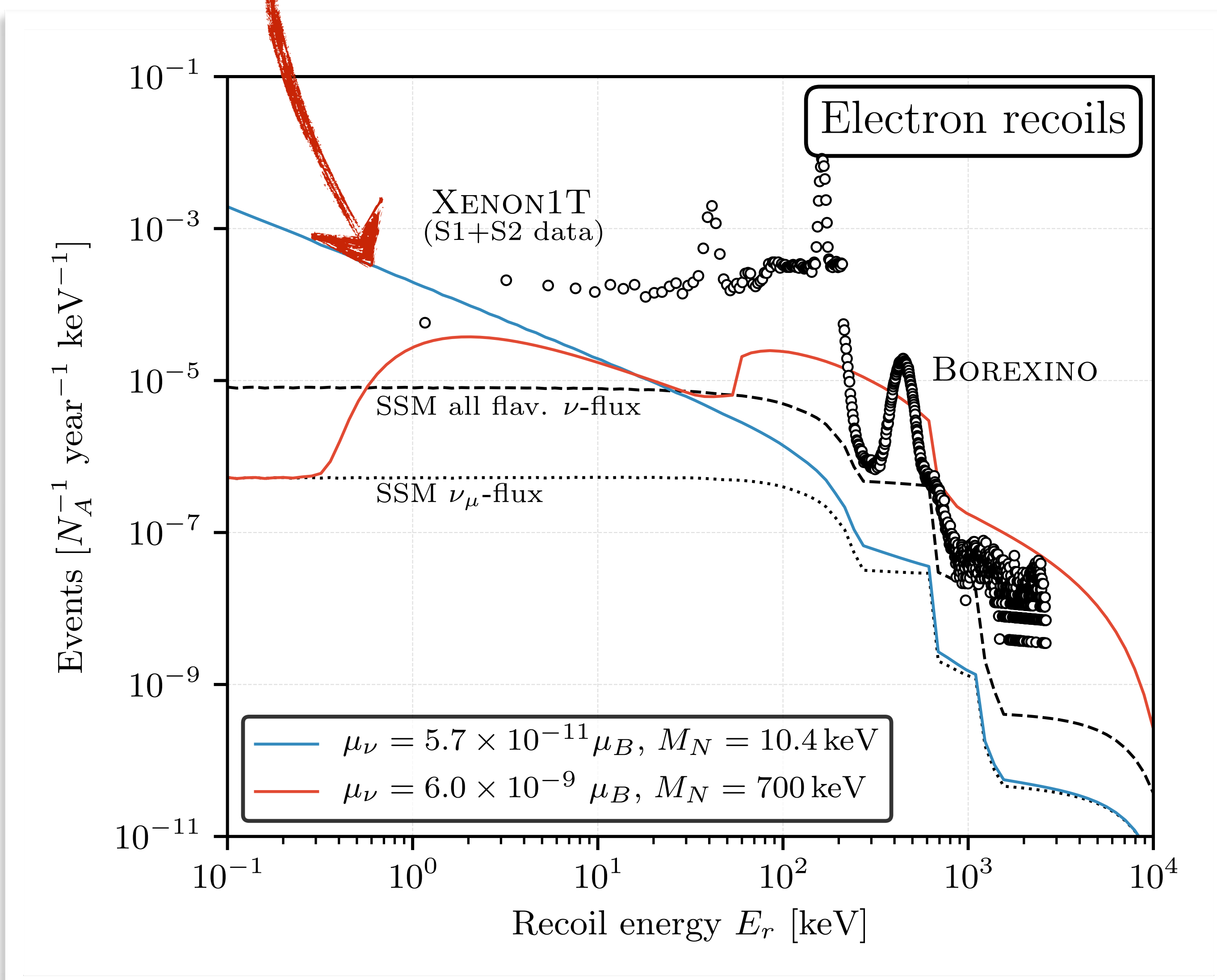


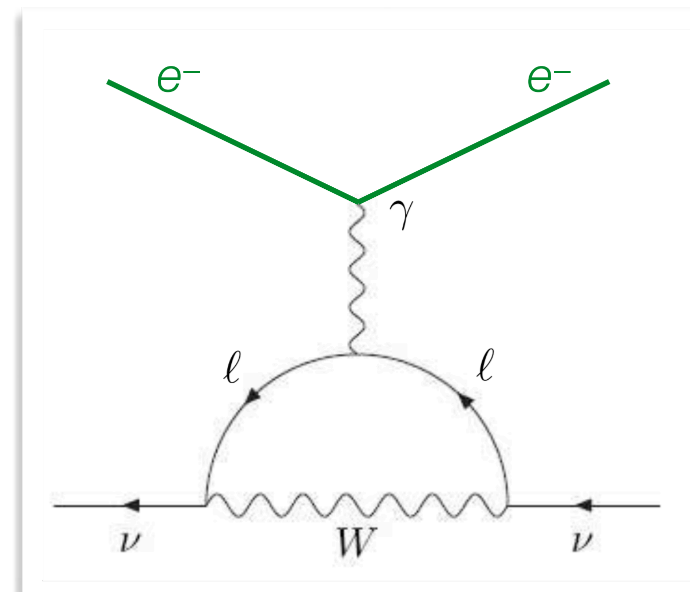


Signals in Direct Detection Experiments

- ☑ so… …ct detection experiments
- ☑ enhanced e⁻ recoil rate from μ_ν-induced scattering

1/E enhancement due to massless *t*-channel mediator





Signals in Direct Detection Experiments

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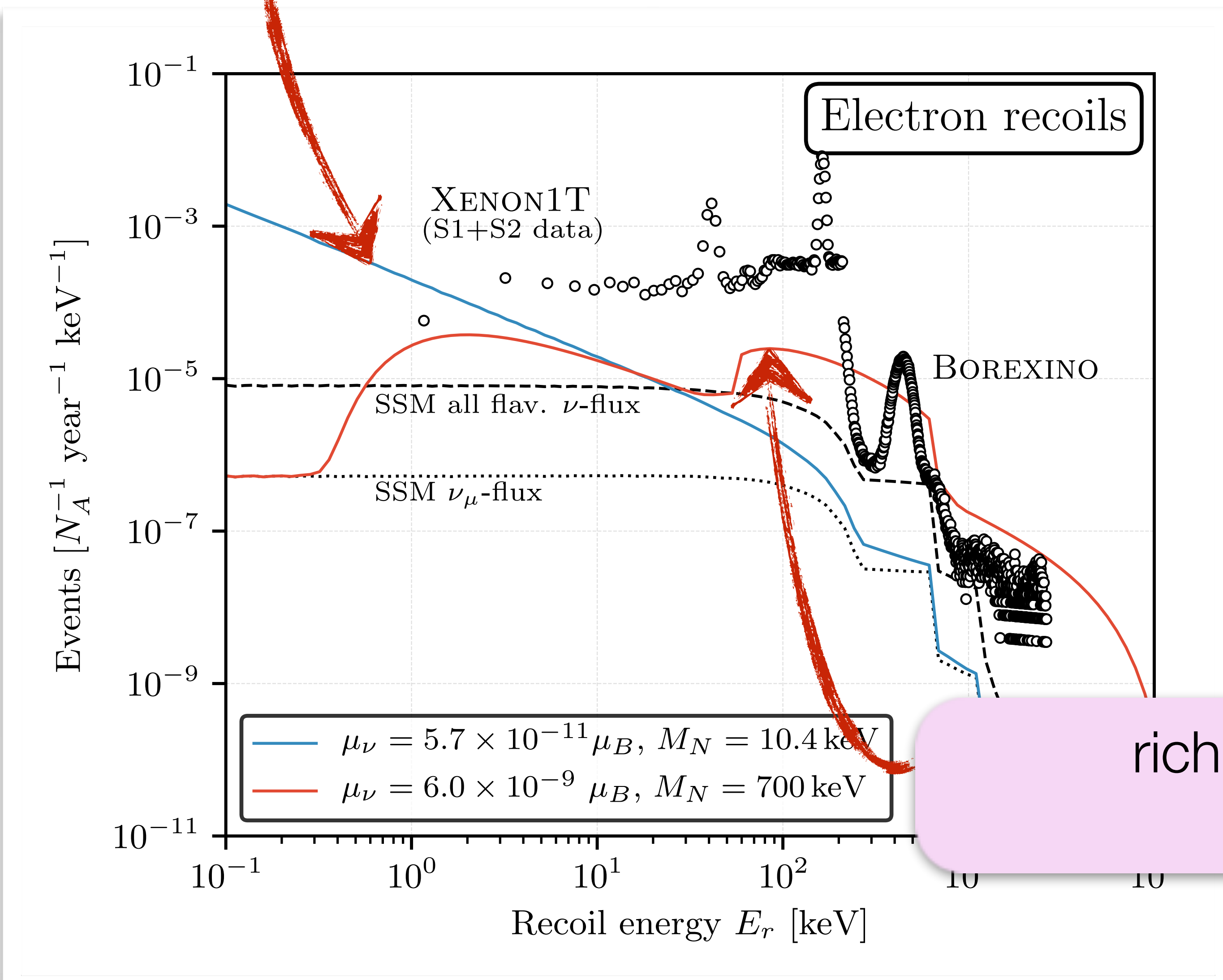
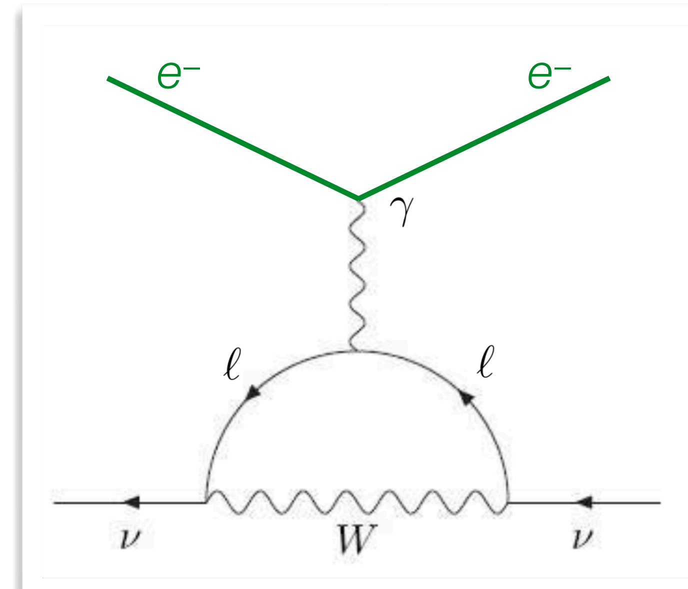
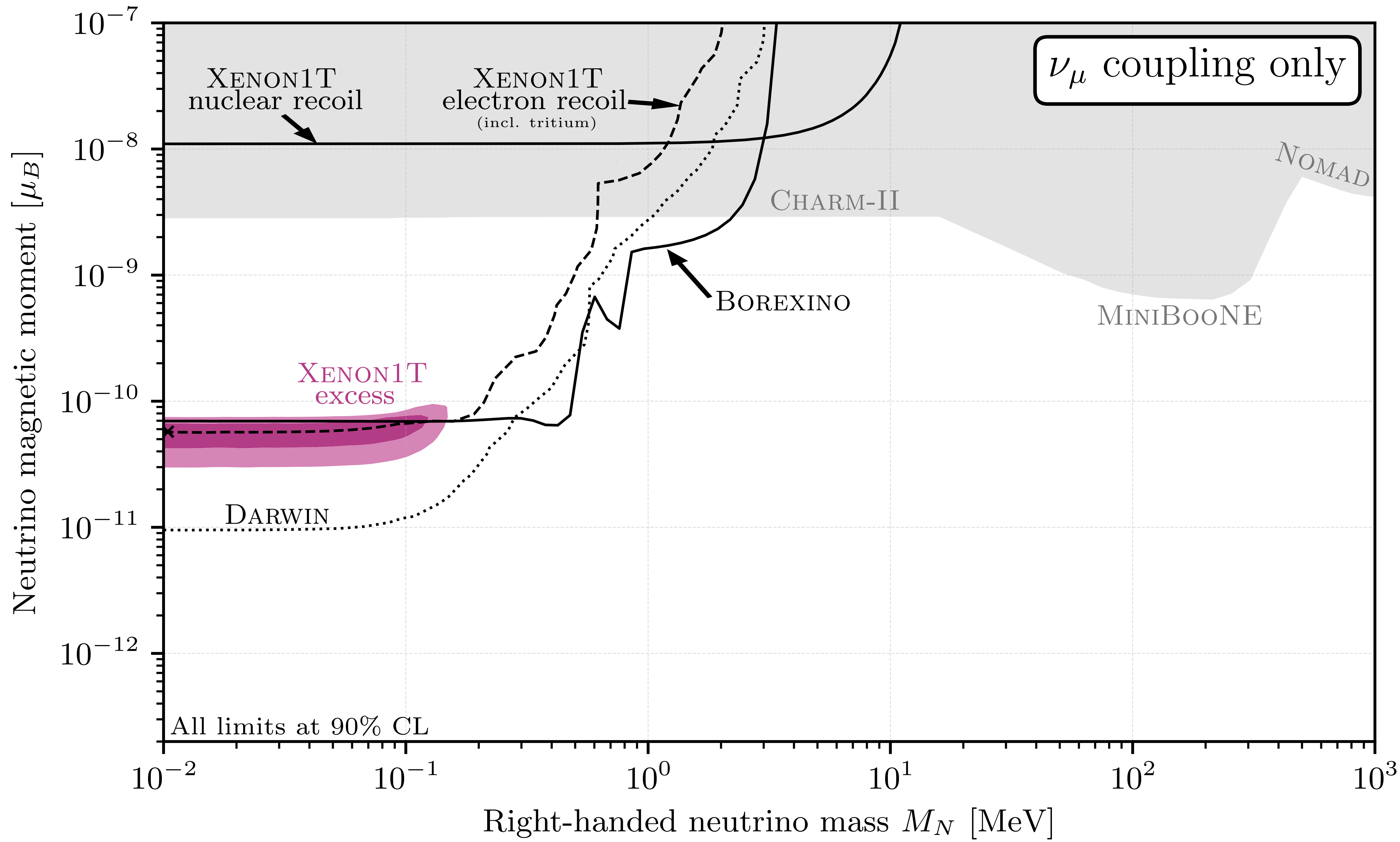




rich kinematic features for heavy N_R

Summary of Terrestrial Constraints



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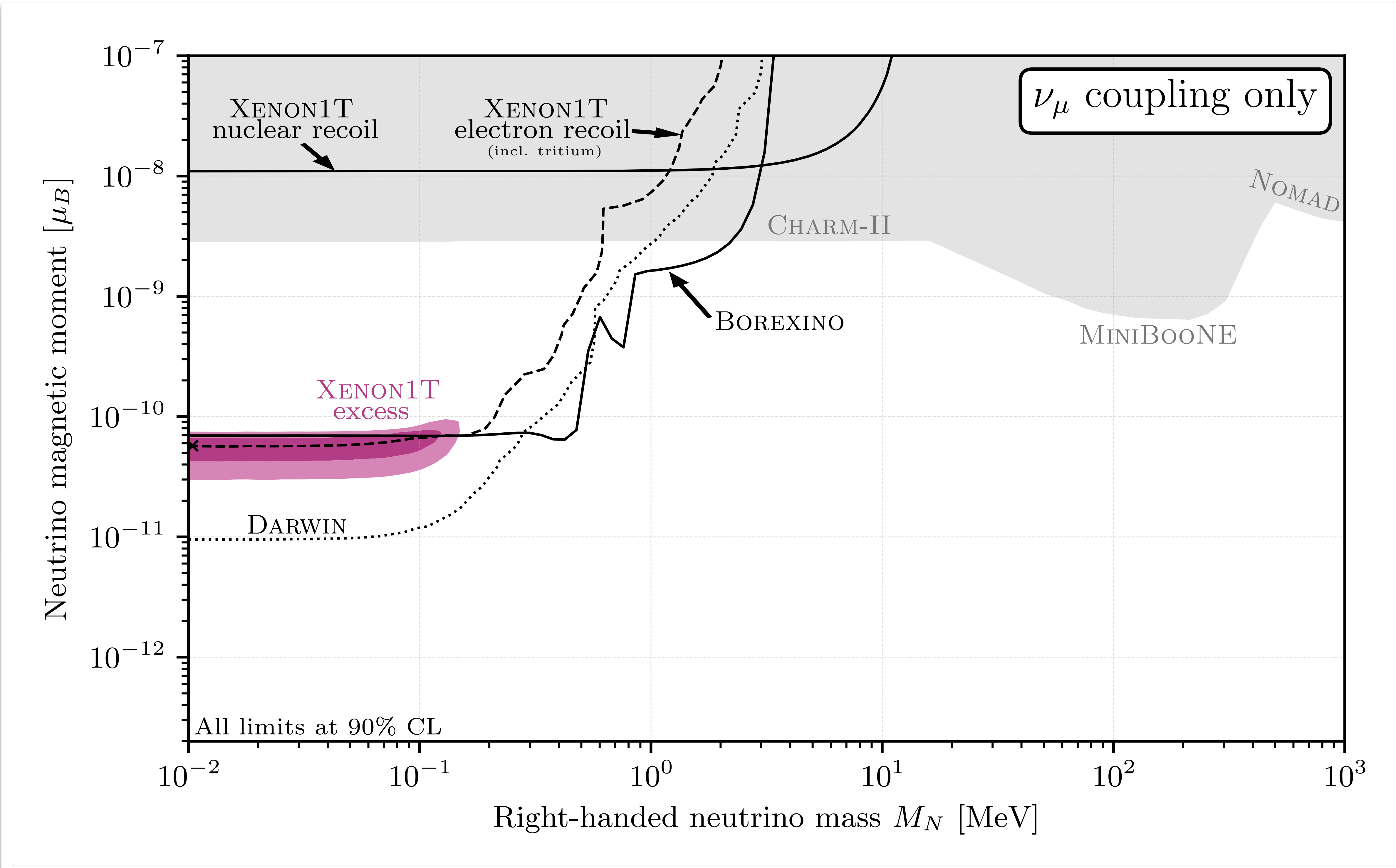
Other Constraints

Stellar Cooling

- Inside hot stellar plasma:
  - modified photon dispersion relation (≃ effective mass)
    ➠ Plasmons γ^*
  - $\gamma^* \to \nu_L N_R$ and $\gamma^* e^- \to \nu_L N_R e^-$ allowed
  - extra energy loss mechanism
  - modified stellar evolution, star uses up its fuel faster

Raffelt 1996, 1999

Stellar Cooling



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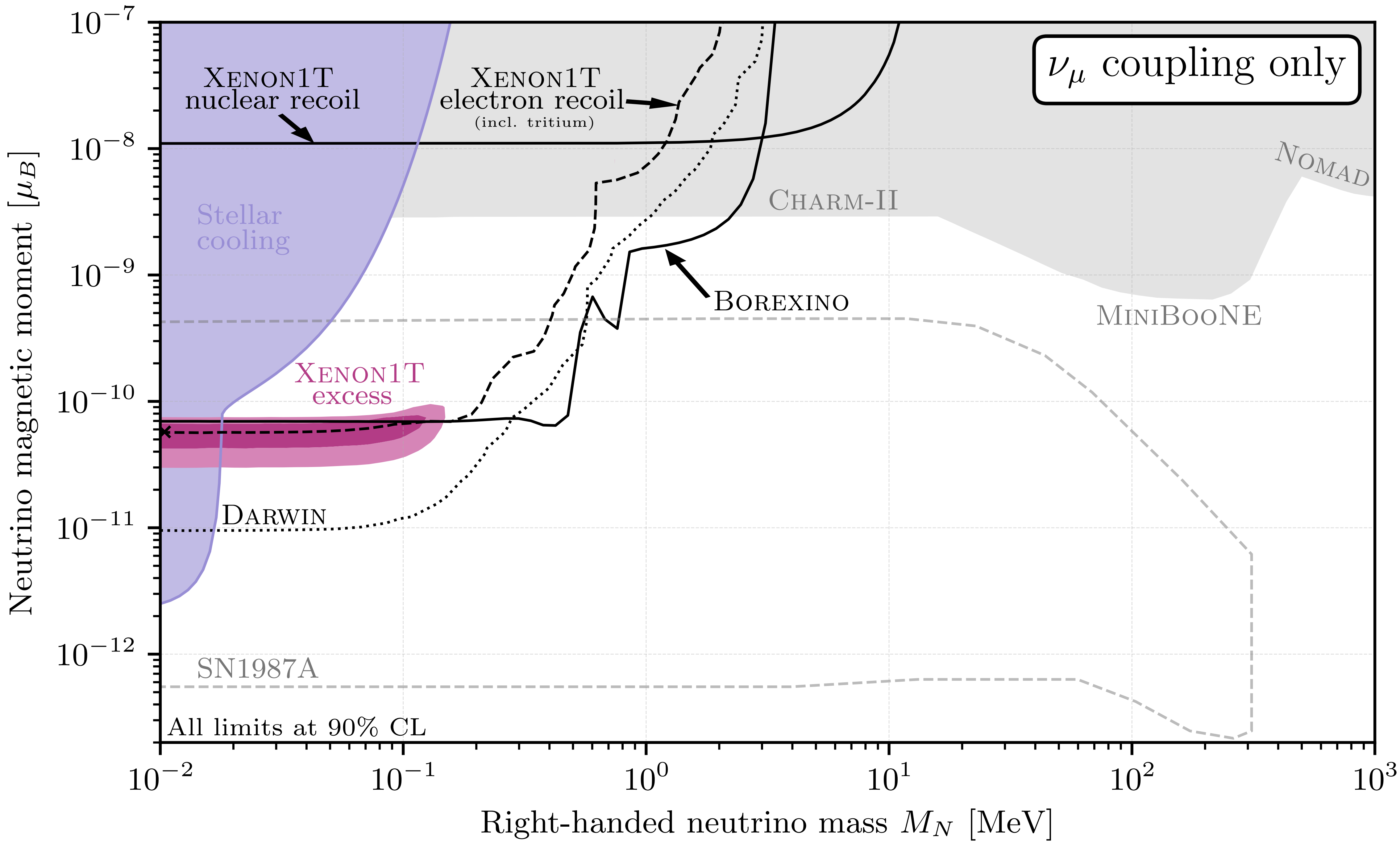
Stellar Cooling



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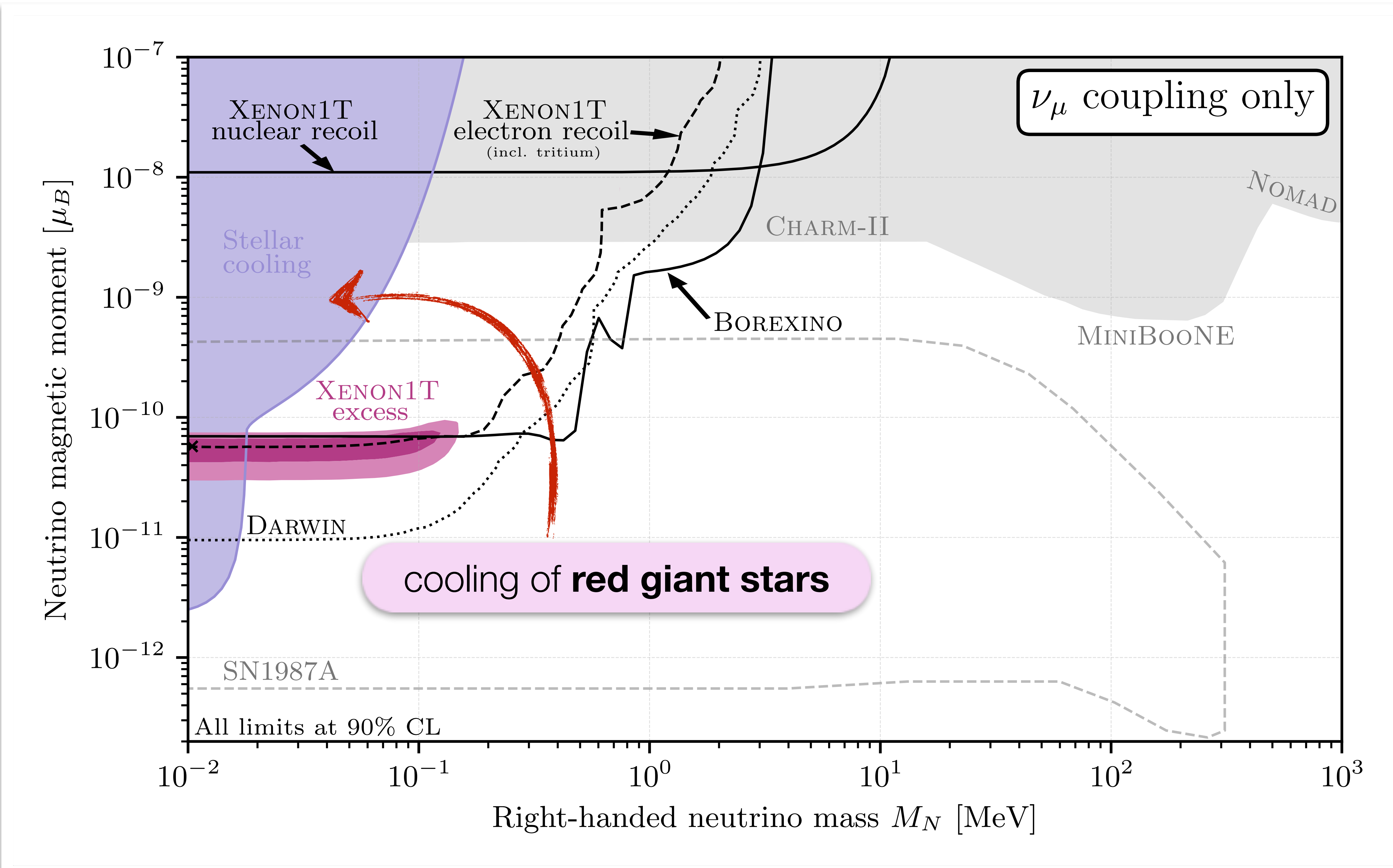
Stellar Cooling



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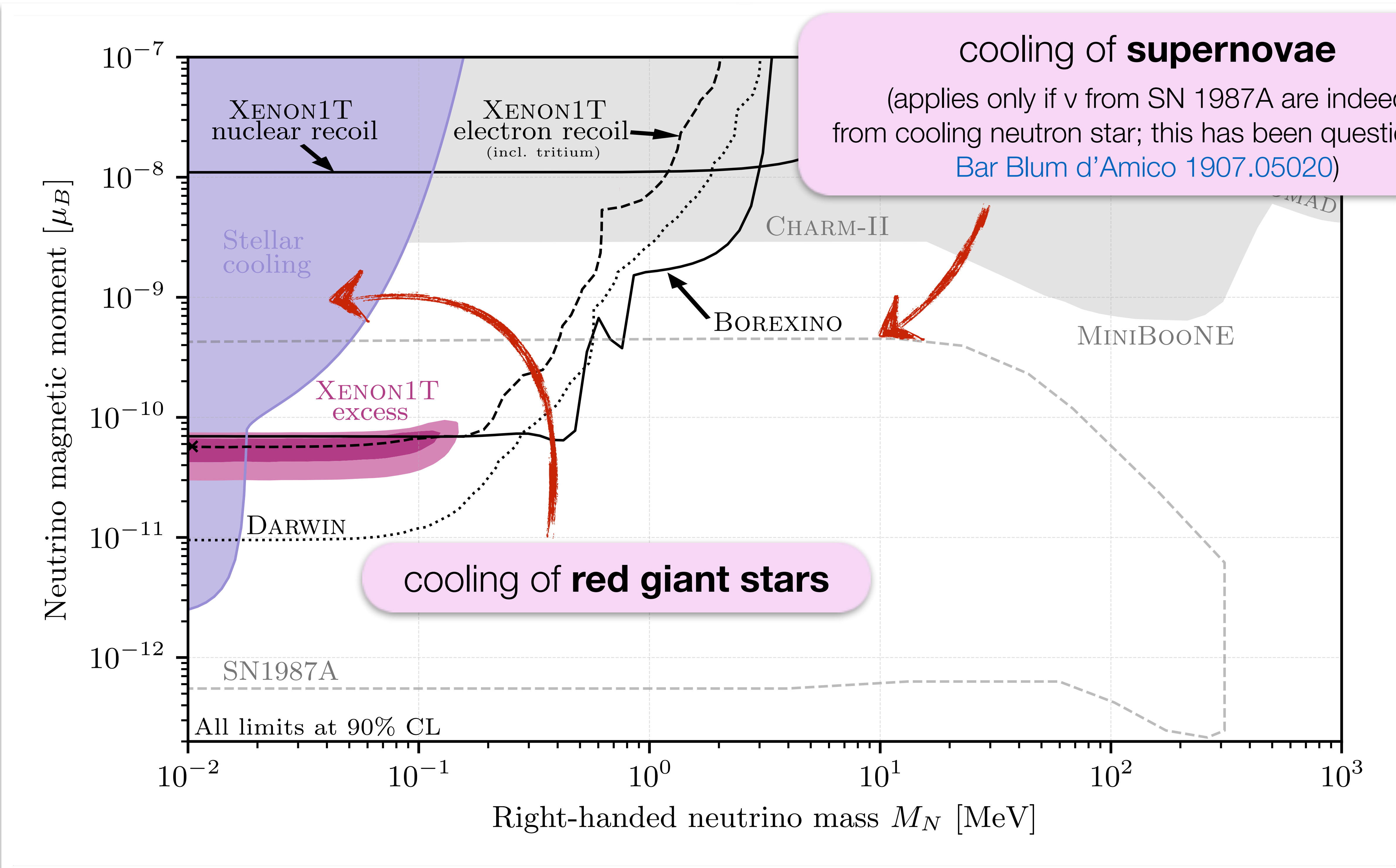
Stellar Cooling



cooling of **supernovae**

(applies only if ν from SN 1987A are indeed from cooling neutron star; this has been questioned: Bar Blum d’Amico 1907.05020)

cooling of **red giant stars**

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Cosmology

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based on codes developed by
Arbey Auffinger Hickerson Jenssen (2018)
and Depta Hufnagel Schmidt-Hoberg (2020)

Cosmology

☑ BBN

- presence of light N_R during BBN alters N_{eff}
- N_R decay ($N_R \Rightarrow \nu_L + \gamma$) after BBN alters baryon-to-photon ratio η.

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Cosmology

- ☑ BBN
  - presence of light N_R during BBN alters N_{eff}
  - N_R decay ($N_R \Rightarrow \nu_L + \gamma$) after BBN alters baryon-to-photon ratio η.
- ☑ CMB
  - N_R decay ($N_R \Rightarrow \nu_L + \gamma$) after ν decoupling changes N_{eff}

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based on codes developed by
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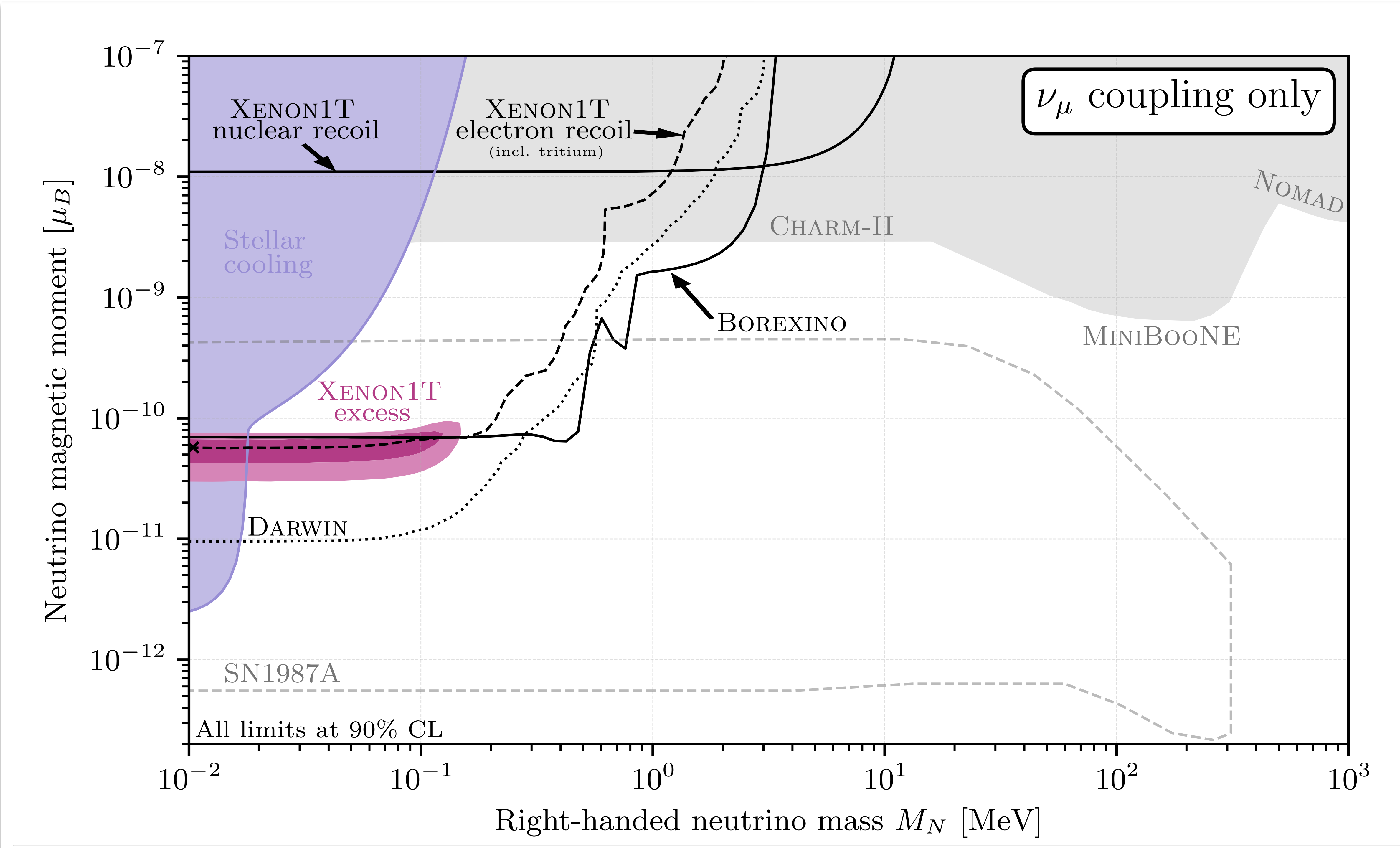
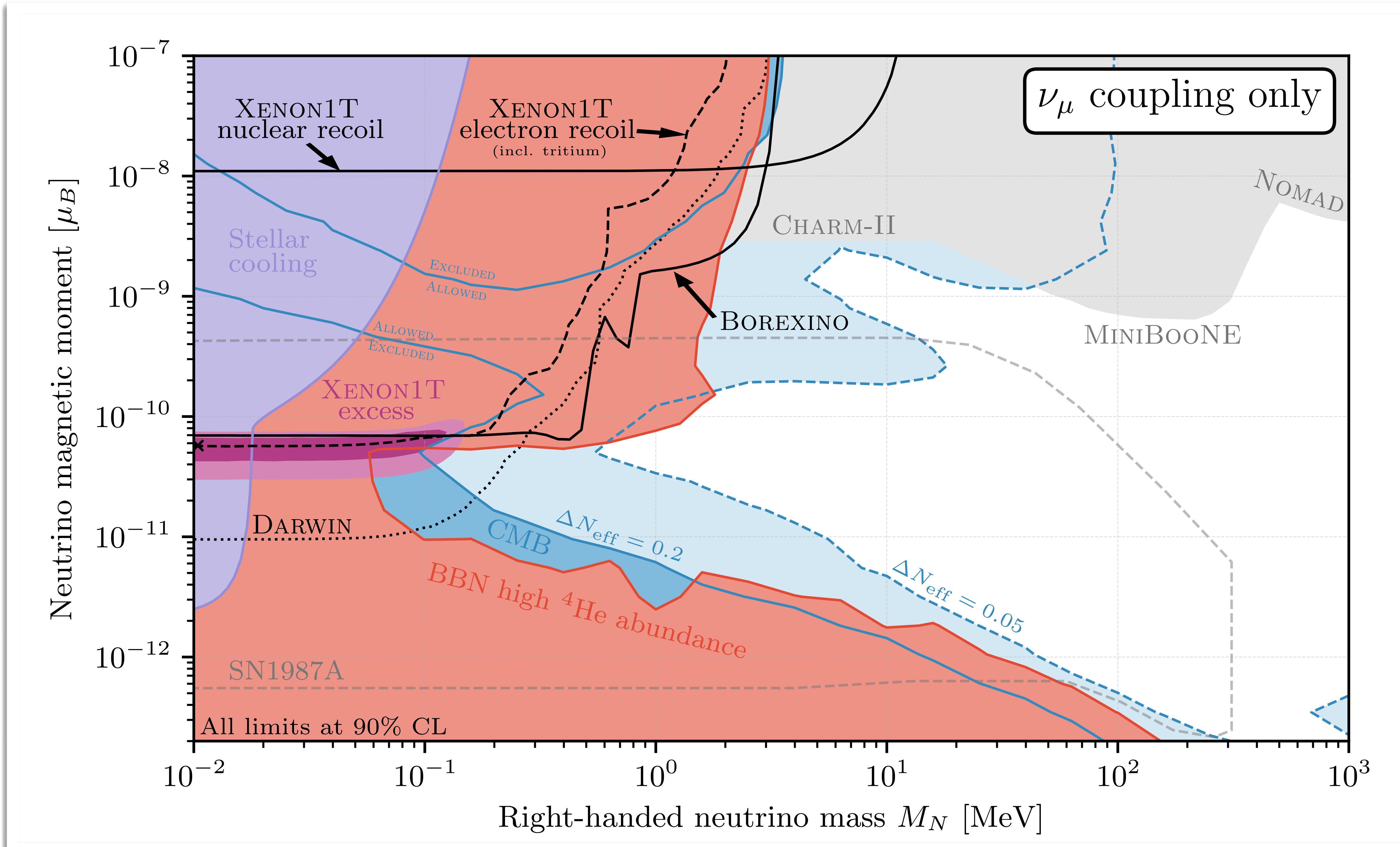
Summary of Constraints



Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

Summary of Constraints



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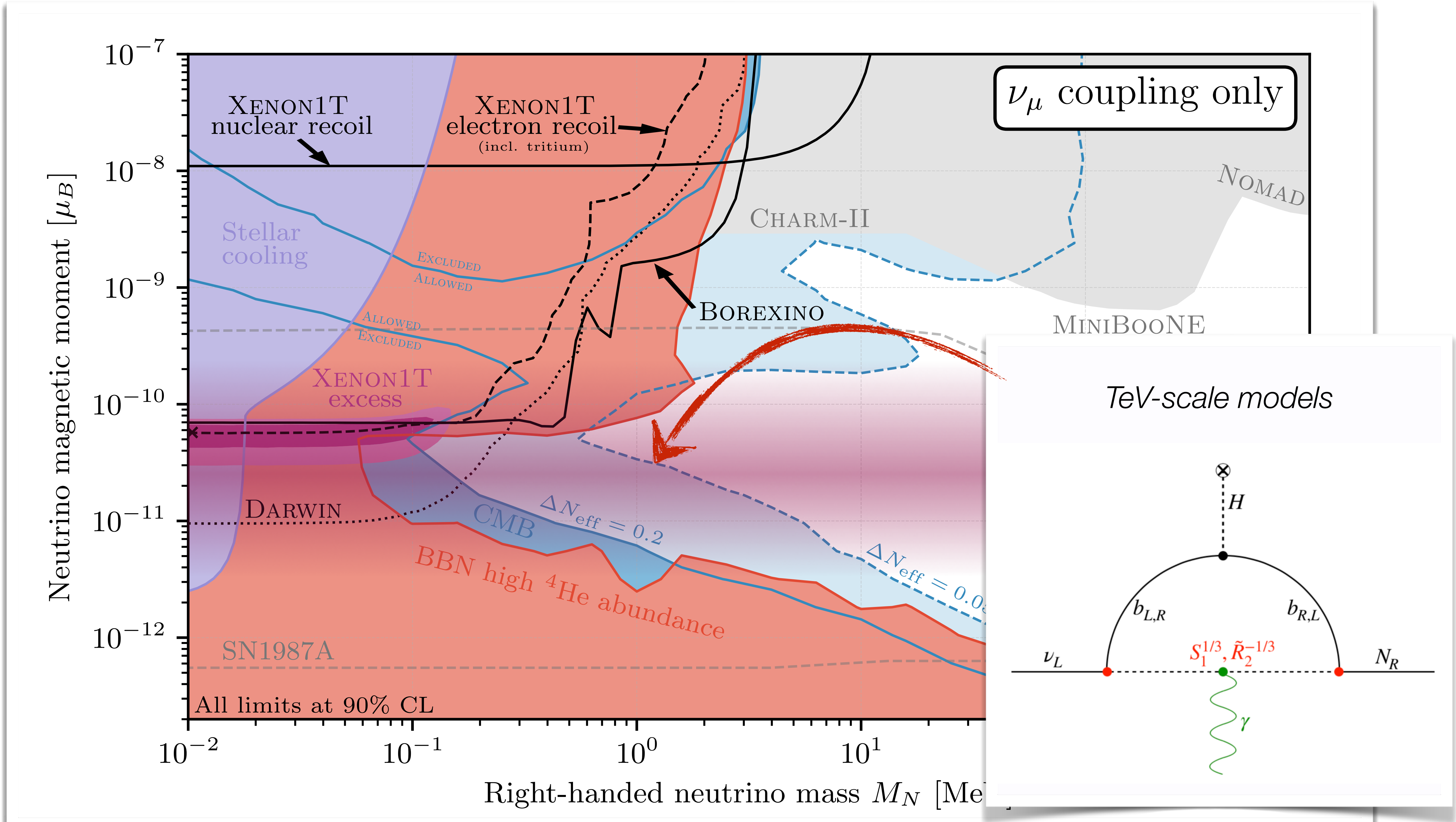

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New Ideas for the Future

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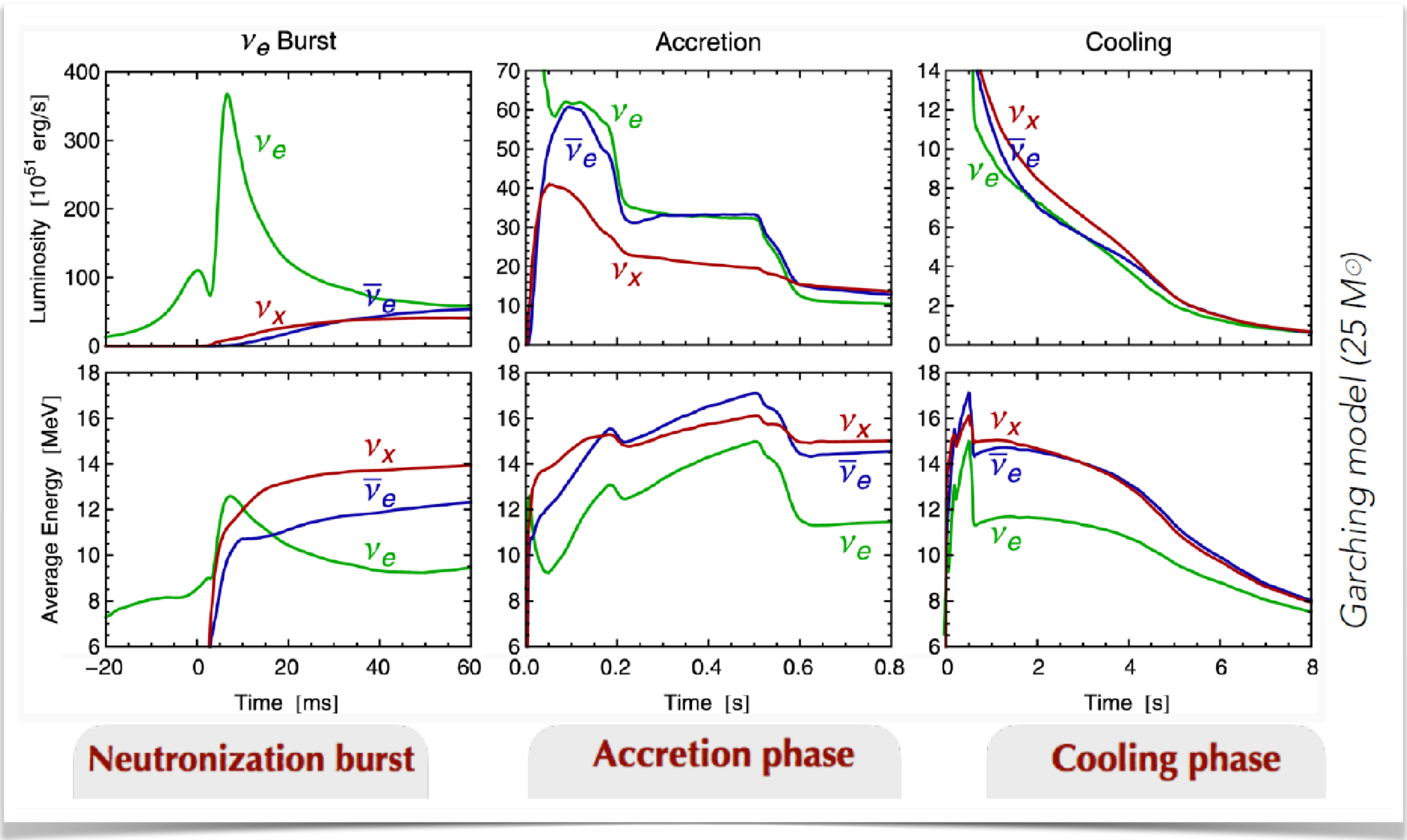
The Next Galactic Supernova

Three phases:



from a slide by Amanda Weinstein,
based on a model by the Garching group

JK Opferkuch Wang, *in preparation*

The Next Galactic Supernova

- ☑ Three phases (ν_e burst, accretion, cooling)
- ☑ Precise (~10%) prediction for flux during ν_e burst
- ☑ Galactic magnetic fields convert $\nu_L \to \nu_R$
- ☑ Expect ν_L deficit
- ☑ Expected limit:

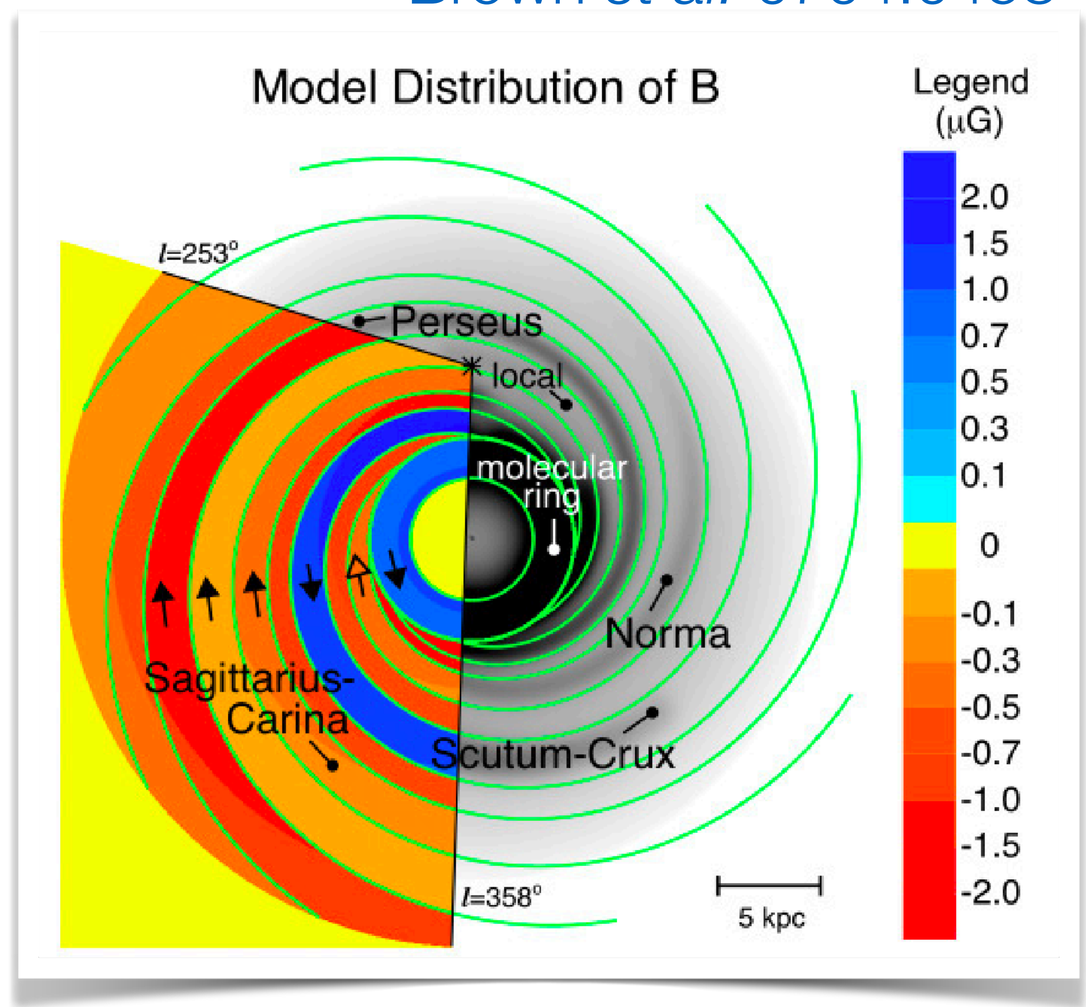
$$\mu_\nu < 10^{-13}\,\mu_B$$

(for Dirac neutrinos)

- ☑ 1–2 orders of magnitude better than existing limits

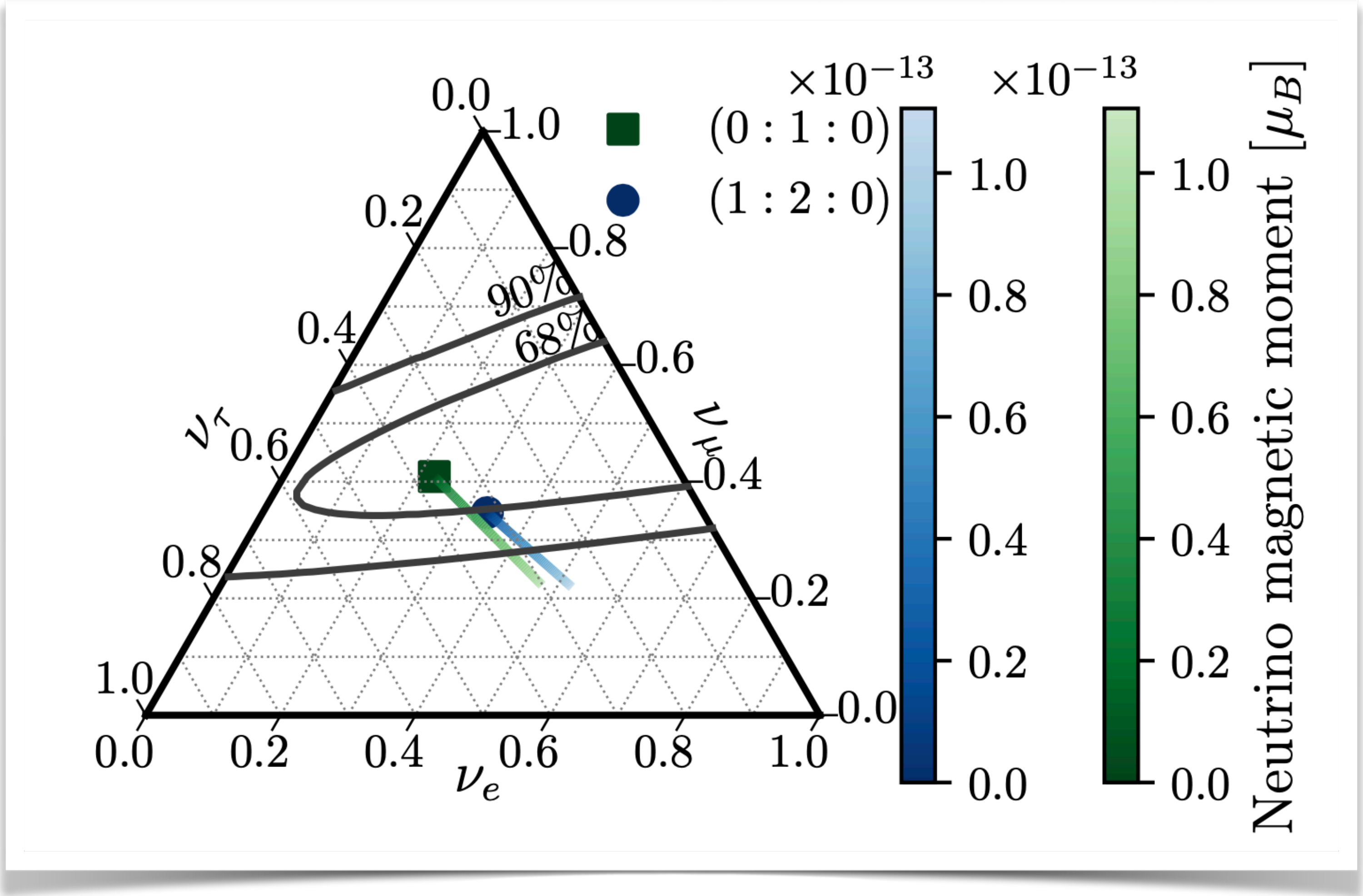
JK Opferkuch Wang, *in preparation*

Brown *et al.* 0704.0458



Ultra-High Energy Astrophysical Neutrinos

- Flux deficit
  - ➠ unobservable because initial flux is not known
- Modified flavour ratios

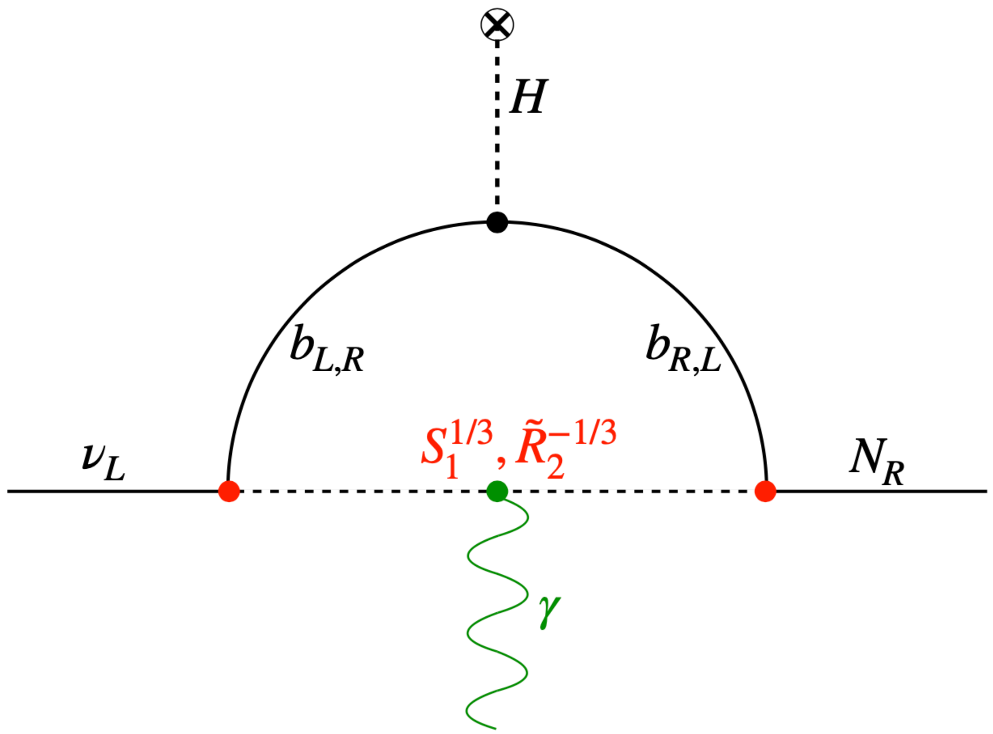


JK Opferkuch Wang, *in preparation*

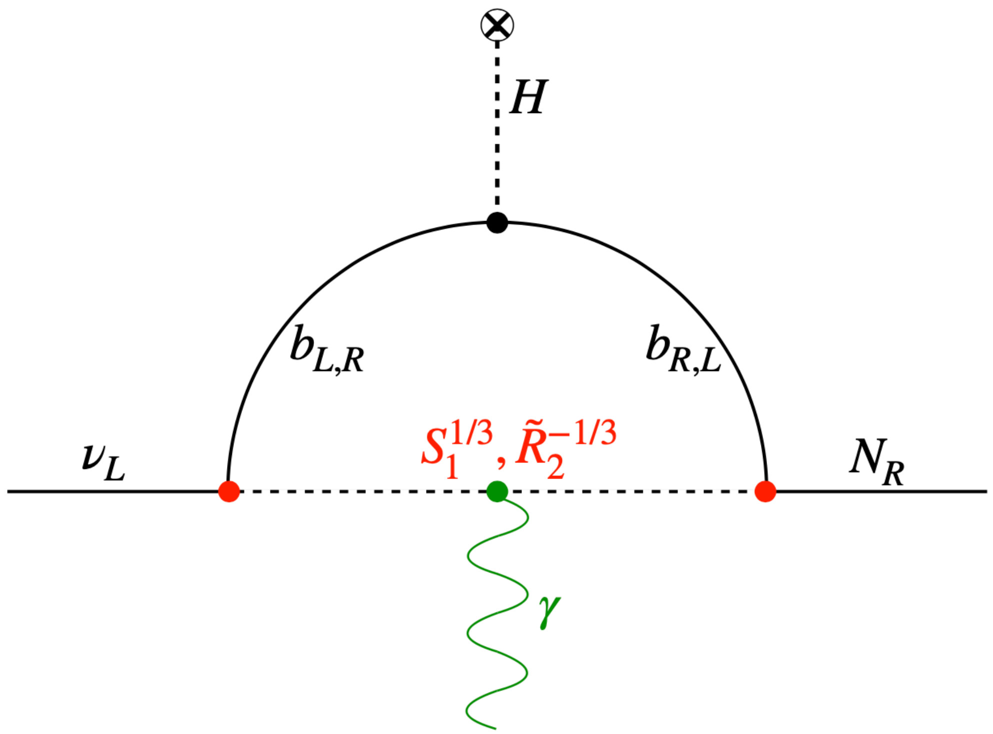
Model Building Considerations

Neutrino Masses vs. Magnetic Moments

- Diagrams that generate μ_ν are closely related to diagrams generating neutrino masses
  (remove the photon)



Neutrino Masses vs. Magnetic Moments



- Generic relation:

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

- For new physics: at 100 GeV: $\mu_\nu \sim 10^{-10}\,\mu_B \Leftrightarrow m_\nu \sim$ MeV

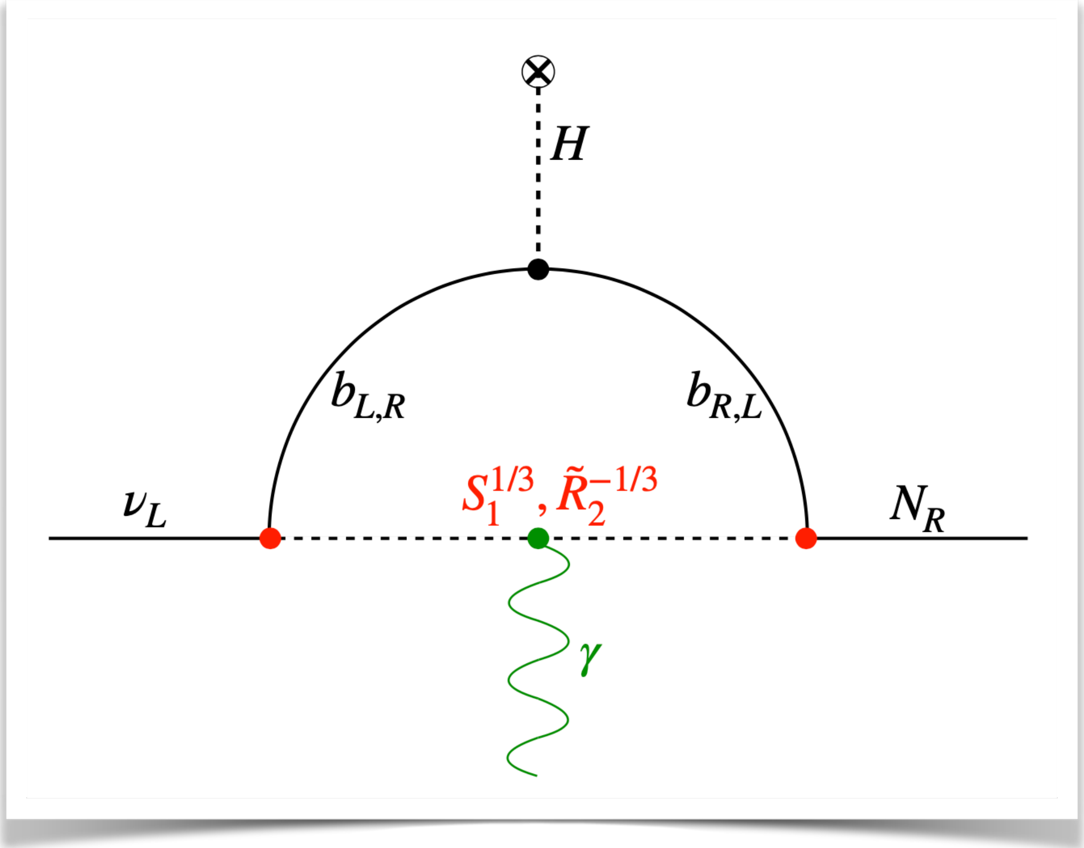
The Voloshin Mechanism

- ☑ (ν_L, N_R^c) as doublet of approximate global $SU(2)_H$
- ☑ Mass term: $\bar{N}_R \nu_L + \bar{N}_R^c \nu_L^c$ is forbidden
  Magnetic moment: $\bar{N}_R \nu_L - \bar{N}_R^c \nu_L^c$ is allowed

Voloshin 1988

A Leptoquark Model

- ☑ Add two leptoquarks (in a Voloshin $SU(2)_H$ doublet):
  - $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
  - $\tilde{R}_2 \sim (\mathbf{3}, \mathbf{2}, 1/6)$
- ☑ Interestingly, S_1 can explain the $R(D^*)$, $R(K^{(*)})$, and/or $(g-2)_\mu$ anomalies.



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

$$R(K^{(*)}) \equiv \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}\Bigg|_{q^2_{\mathrm{min}}<q^2<q^2_{\mathrm{max}}}$$

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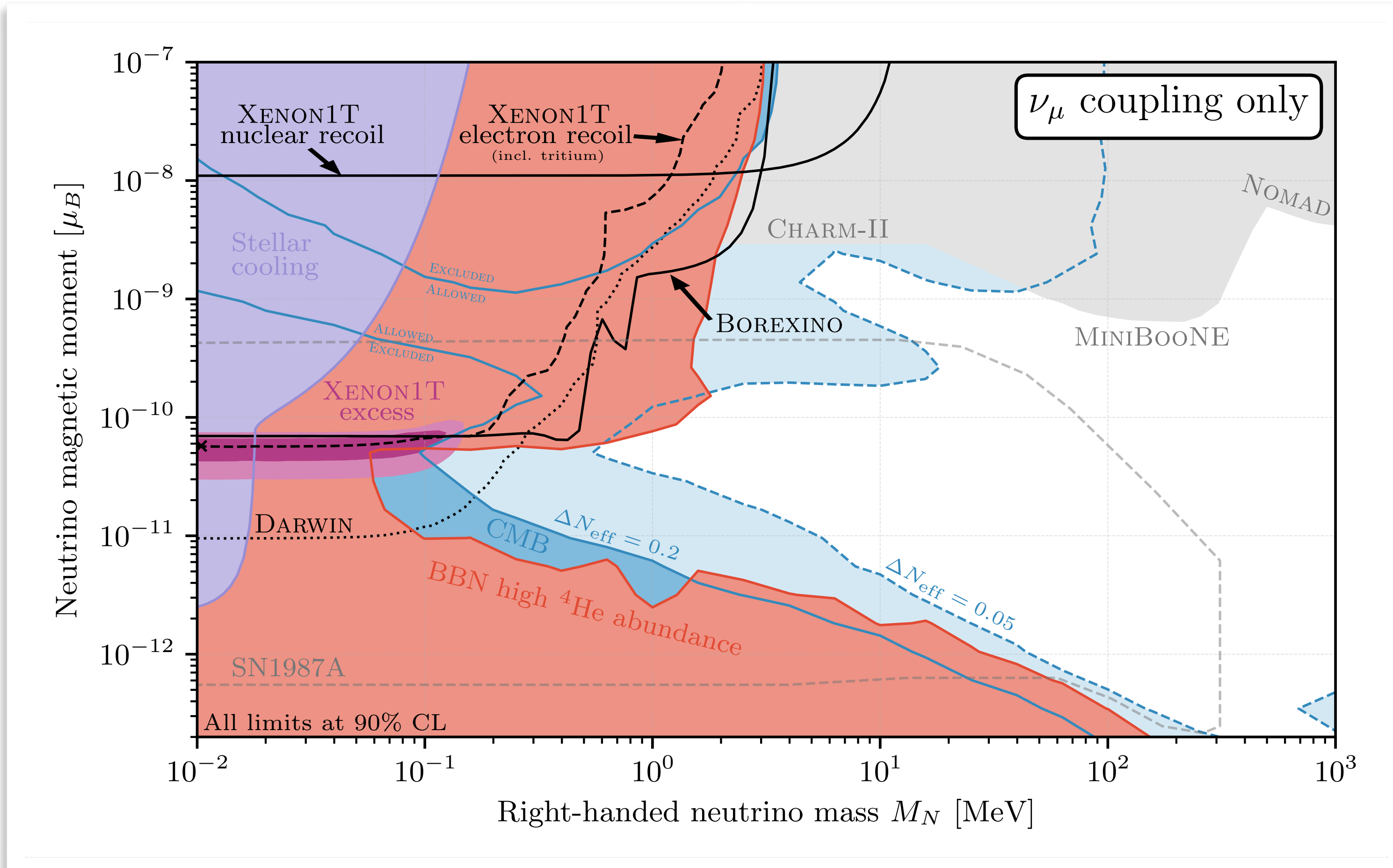
(+ references therein)

Conclusions

Conclusions



- ★ through neutrino magnetic moments, dark matter detectors are probing TeV scale physics
- ★ interesting interplay with astrophysics, cosmology, and maybe even flavour physics

Thank You!

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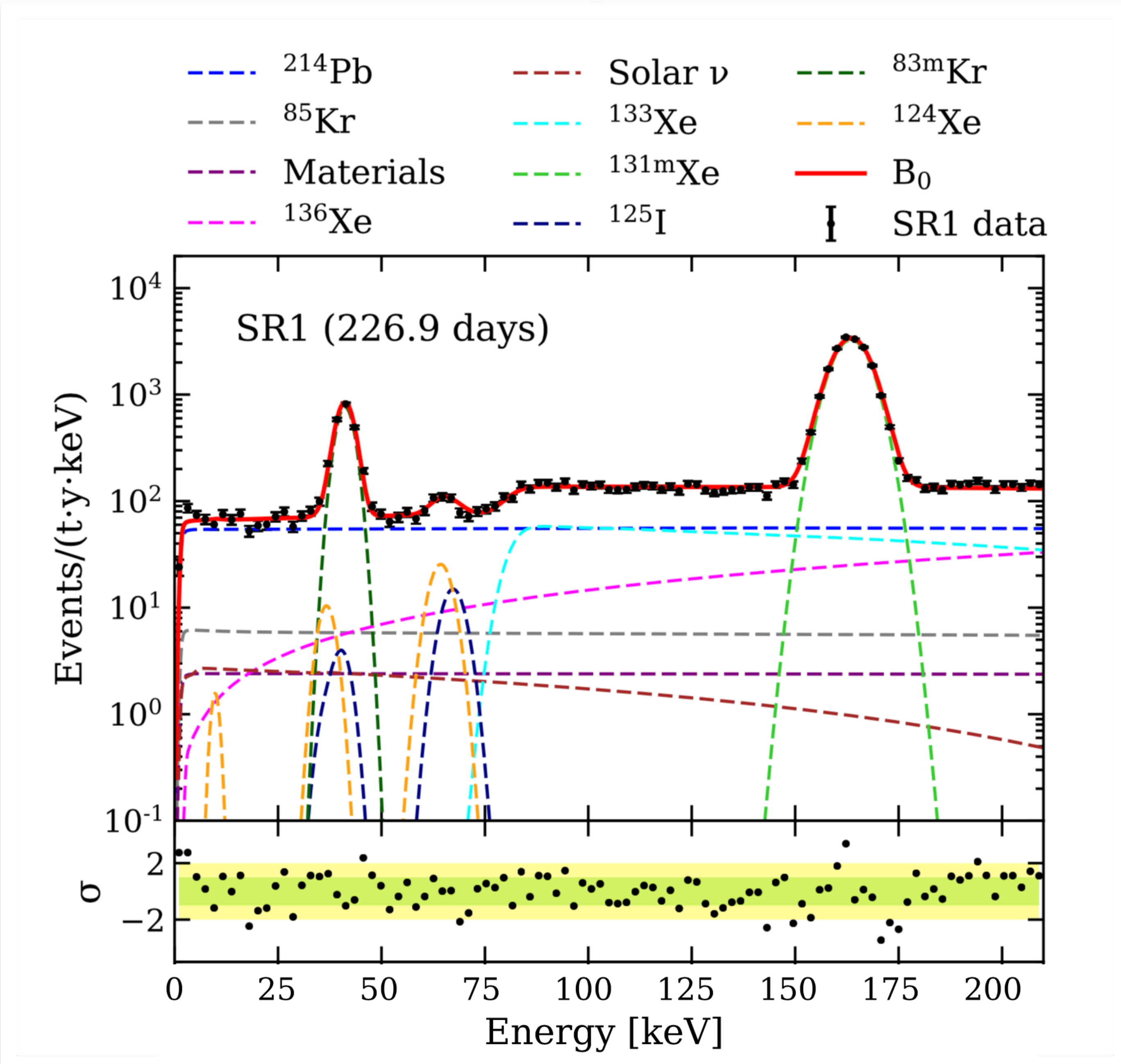
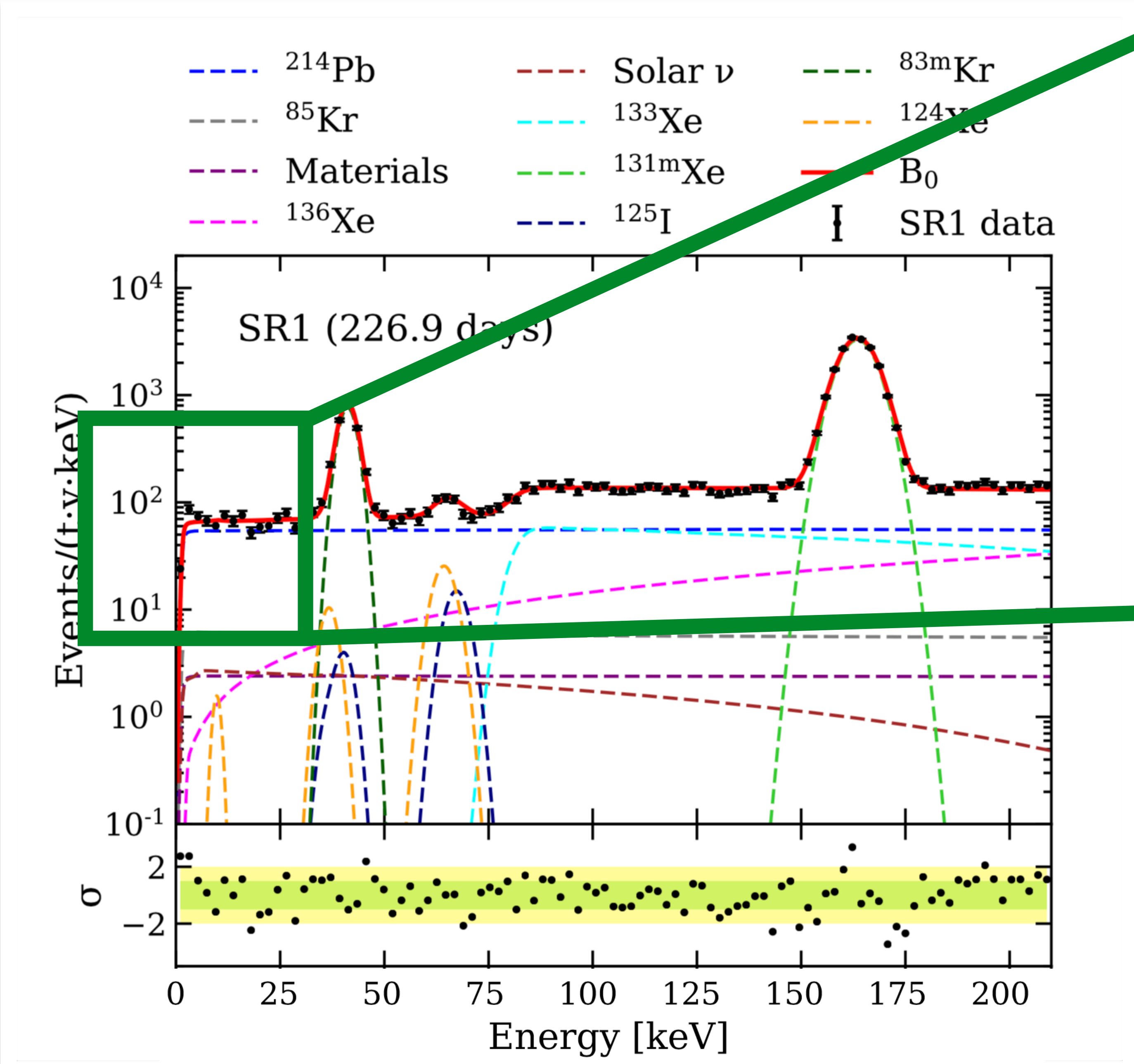
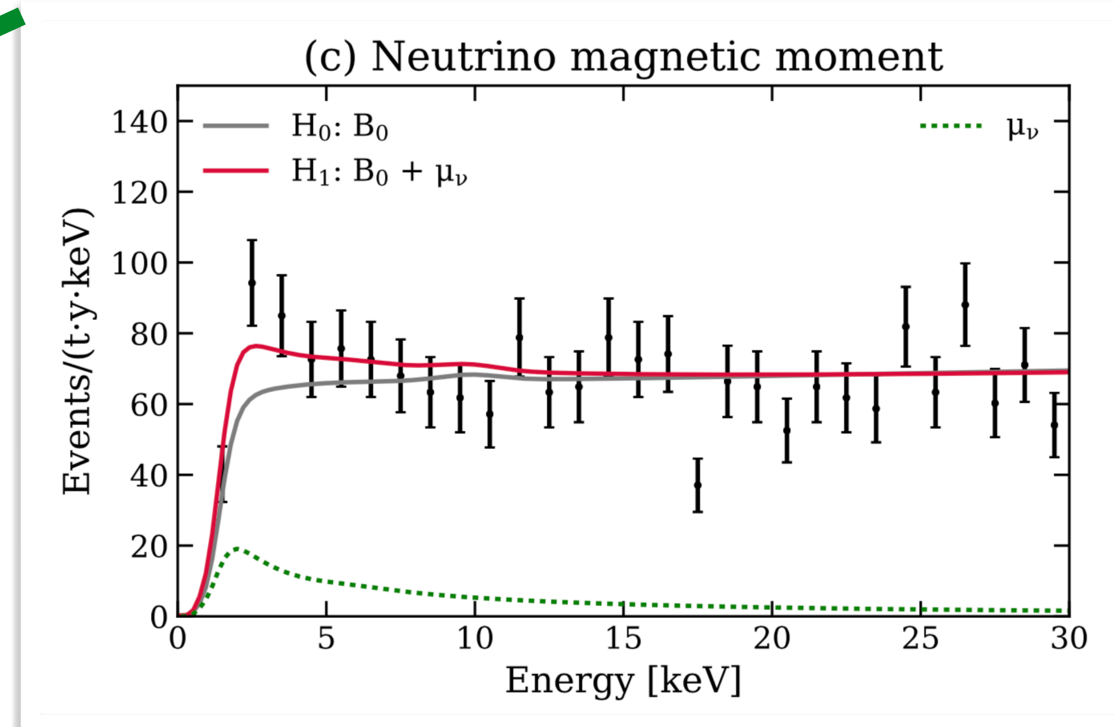
Bonus Slides

Xenon-1T Electron Excess



Xenon-1T Electron Excess





Xenon collaboration arXiv:2006.09721

see also Alonso-Álvarez et al. (2006.11243)
and An et al. (2006.13929)
for promising dark photon explanation

Big Bang Nucleosynthesis — Basic Concepts

Consider a RH neutrino N_R with magnetic moment μ_R .
Assume decays after BBN.

- ☑ N_R presence during BBN means faster expansion
  - $p \leftrightarrow n$ conversion freezes out sooner ➠ more neutrons
  - Less time for neutrons to decay ➠ more neutrons
- ☑ N_R decay (N_R ➠ $\nu_L + \gamma$) after BBN alters baryon-to-photon ratio η.
  - η is precisely measured at the CMB epoch
  - Decrease in η due to N_R decays implies larger η during BBN
  - Deuterium disintegration less efficient ➠ more neutron-rich nuclei

(For decays during BBN, similar arguments can be made.)

Big Bang Nucleosynthesis — Implementation

- ☑ Use modified version of AlterBBN

Arbey 1106.1363
Arbey Auffinger Hickerson Jenssen 1806.11095
Depta Hufnagel Schmidt-Hoberg 2002.08370

- ☑ Needed inputs (as a function of photon temperature T_γ):
  - time t
  - neutrino temperature T_ν
  - Hubble parameter H
  - Photon number density n_γ
- ☑ Solve (integrated) Boltzmann equations:

Big Bang Nucleosynthesis — Implementation

☑ Solve (integrated) Boltzmann equations:

$$\dot\rho_\gamma = -4H\rho_\gamma + \langle\sigma v\rangle_{ee}(n_e\rho_e - n_e^{\rm eq}\rho_e^{\rm eq}) + \tfrac{1}{2}\Gamma_N(\rho_N - \rho_N^{\rm eq}),$$
$$\dot\rho_e = -s_e H\rho_e - \langle\sigma v\rangle_{ee}(n_e\rho_e - n_e^{\rm eq}\rho_e^{\rm eq}),$$
$$\dot\rho_\nu = -4H\rho_\nu + \tfrac{1}{2}\Gamma_N(\rho_N - \rho_N^{\rm eq}) + \Gamma_{eN}(\rho_N - \rho_N^{\rm eq}),$$
$$\dot\rho_N = -s_N H\rho_N - \Gamma_N(\rho_N - \rho_N^{\rm eq}) - \Gamma_{eN}(\rho_N - \rho_N^{\rm eq}).$$

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Big Bang Nucleosynthesis — Implementation

☑ Solve (integrated) Boltzmann equations:

Hubble expansion

$$
\begin{aligned}
\dot{\rho}_\gamma &= -4H\rho_\gamma + \langle\sigma v\rangle_{ee}(n_e\rho_e - n_e^{\rm eq}\rho_e^{\rm eq}) + \tfrac{1}{2}\Gamma_N(\rho_N - \rho_N^{\rm eq})\,,\\
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\dot{\rho}_N &= -s_N H\rho_N - \Gamma_N(\rho_N - \rho_N^{\rm eq}) - \Gamma_{eN}(\rho_N - \rho_N^{\rm eq})\,.
\end{aligned}
$$

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Big Bang Nucleosynthesis — Implementation

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e^+e^- annihilation

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Big Bang Nucleosynthesis — Implementation

☑ Solve (integrated) Boltzmann equations:

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\dot\rho_\nu &= -4H\rho_\nu + \tfrac{1}{2}\Gamma_N(\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}
$$

e^+e^- annihilation

N_R decay

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Big Bang Nucleosynthesis — Implementation

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\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})\,,\\
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\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}$$

e^+e^- annihilation

e^+N_R scattering

N_R decay

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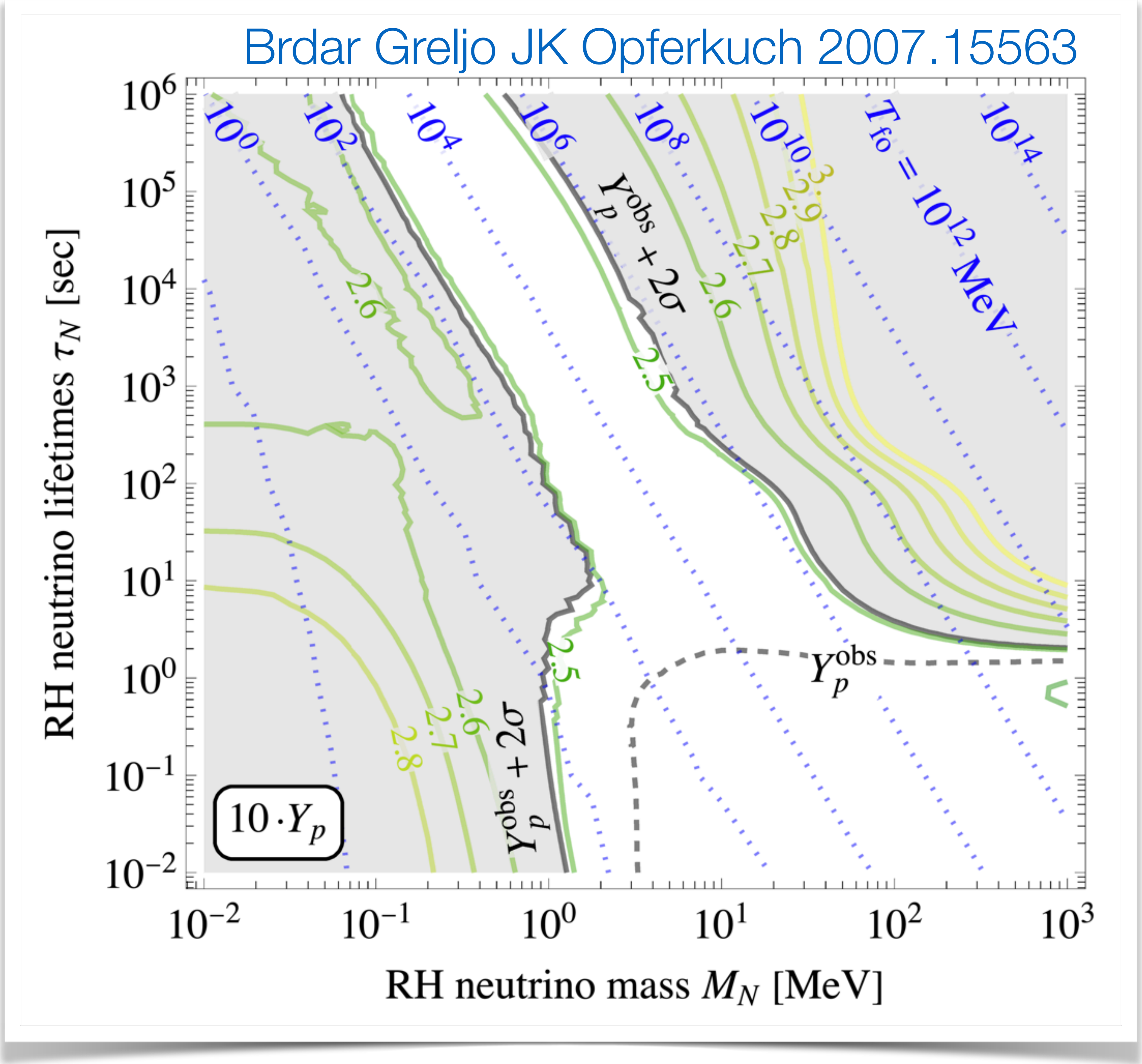
Big Bang Nucleosynthesis — Results



Cosmic Microwave Background

☑ N_R decay ($N_R \Rightarrow \nu_L + \gamma$) after ν decoupling changes N_{eff}