Neutrinos as a Window to New Physics

Joachim Kopp (CERN & JGU Mainz)
KITP Santa Barbara | March 30, 2022

CERN

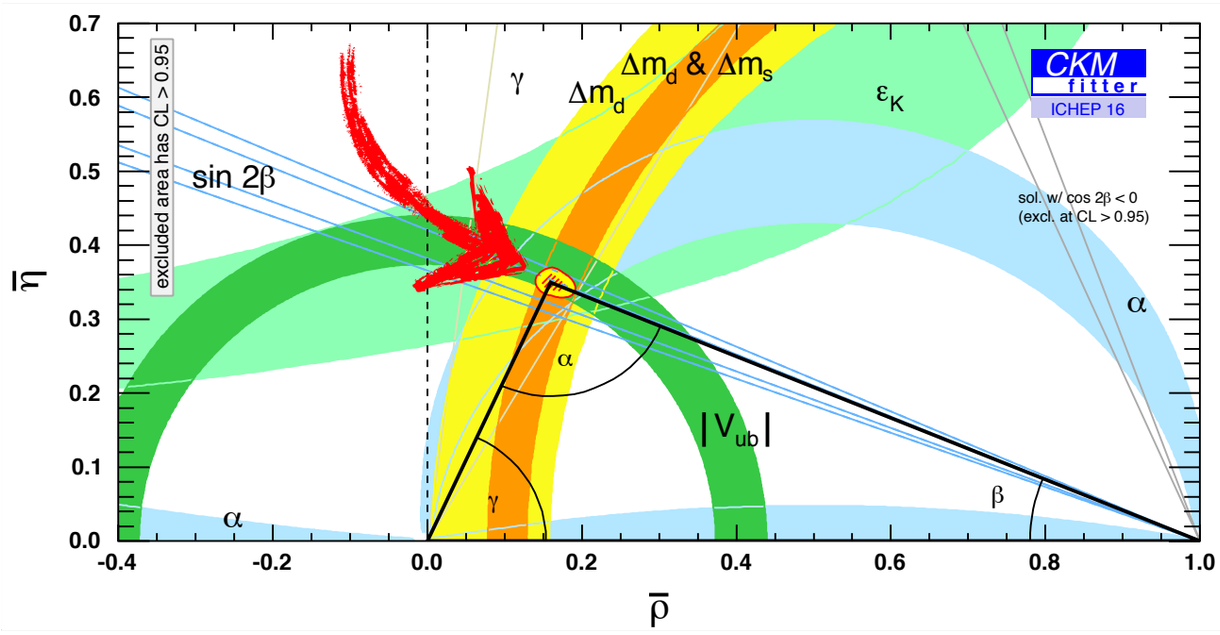
Neutrino PLATFORM

erc

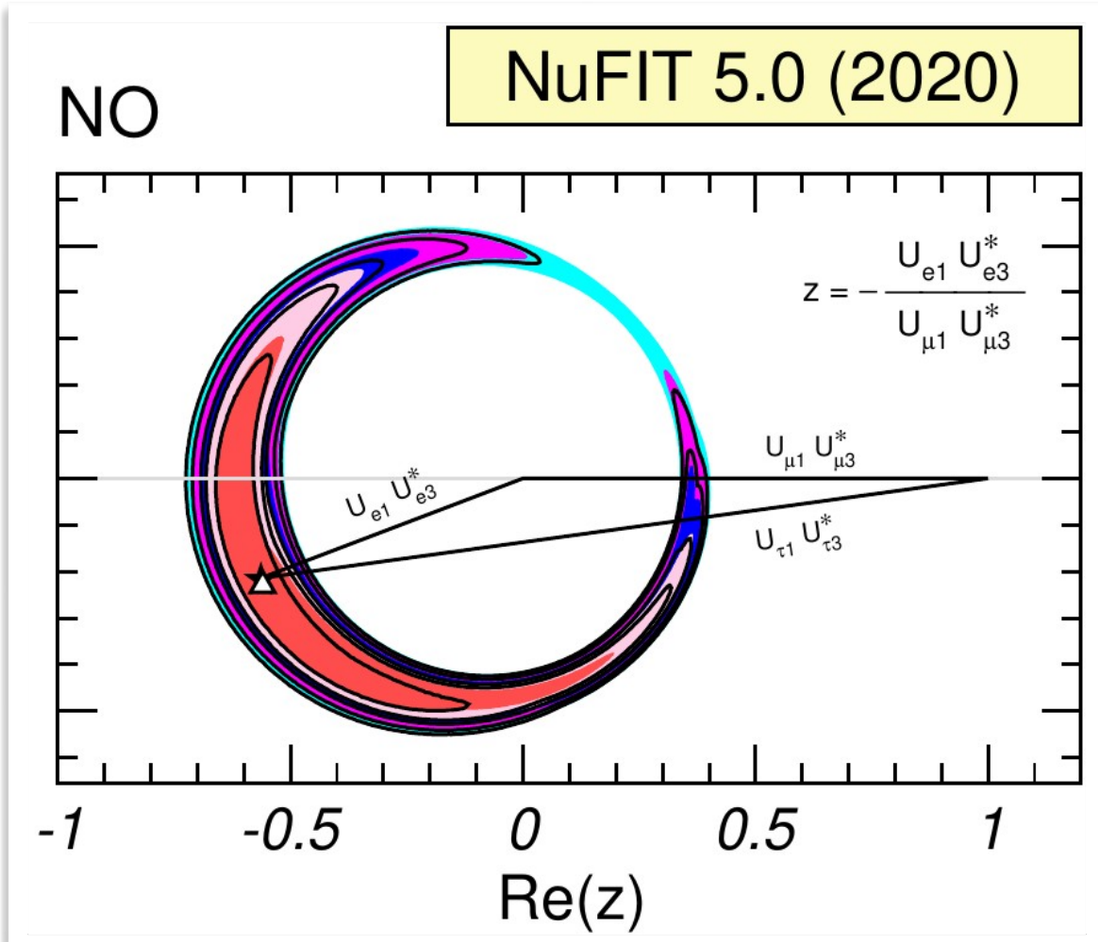
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Unitarity Triangles

Quarks



Leptons



How can high-precision neutrino experiments constrain physics beyond the SM?

Outline

dim-4: the Neutrino Portal

dim-5: Neutrino Magnetic Moments

dim-6: Neutrinos in SMEFT

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dim-4: the Neutrino Portal

dim-5: Neutrino Magnetic Moments

dim-6: Neutrinos in SMEFT

The Neutrino Portal

$$\mathcal{L} \supset y\, \bar{L}\, (i\sigma^2 H^*)\, N$$

- ☑ the only renormalizable coupling to a singlet fermion
- ☑ leads to mass mixing between ν and *N*
  - ➠ *N* production in neutrino interactions
  - ➠ active–sterile neutrino oscillations
- ☑ Widely discussed in the context of short-baseline anomalies

The Neutrino Portal

SM singlet fermion
(sterile neutrino)

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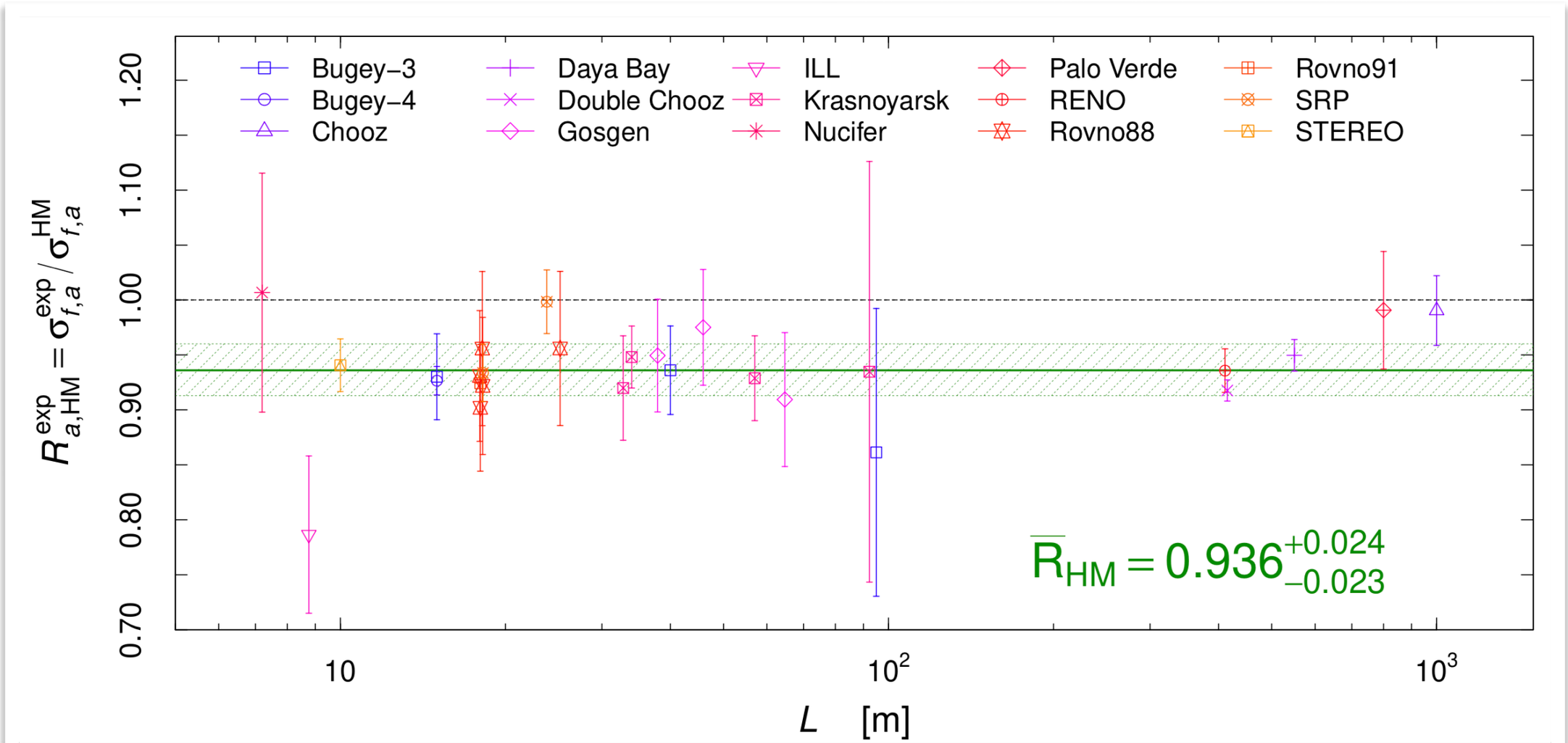
Anomaly #1: Reactor Neutrino Fluxes

With updated input data to flux calculation
(new β spectra from ^{235}U fission)



Kopeikin Skorokhvatov Titov arXiv:2103.01684
Berryman Huber arXiv:2005.01756
Giunti Li Ternes Xin arXiv:2110.06820

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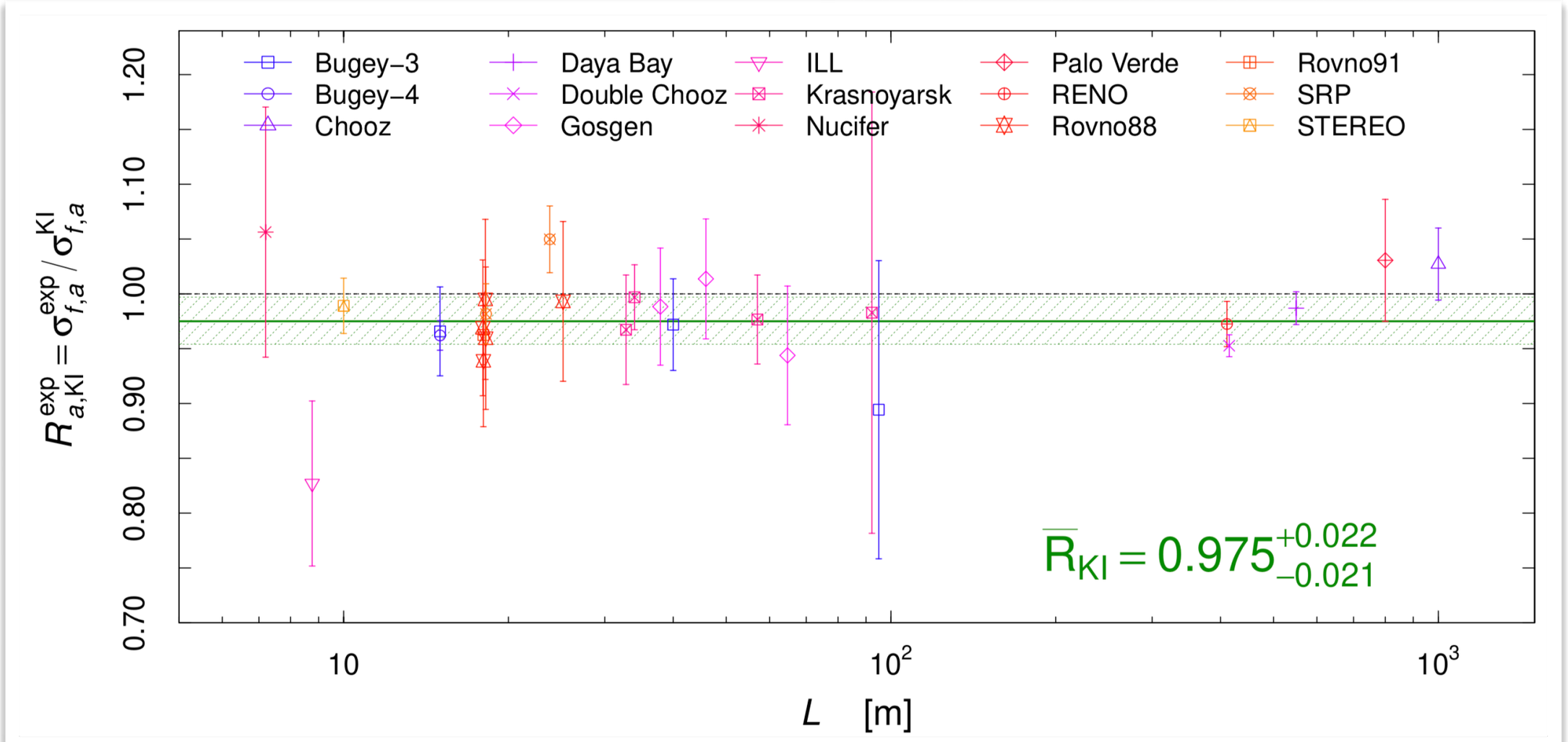

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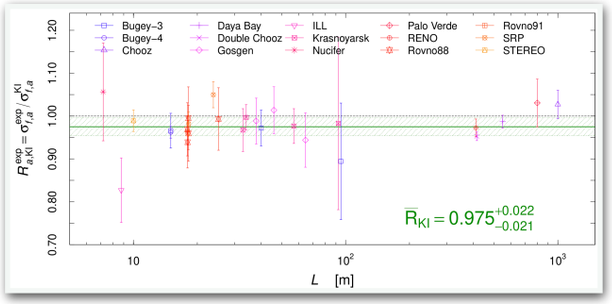
Short-Baseline Anomalies



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resolved with new input data
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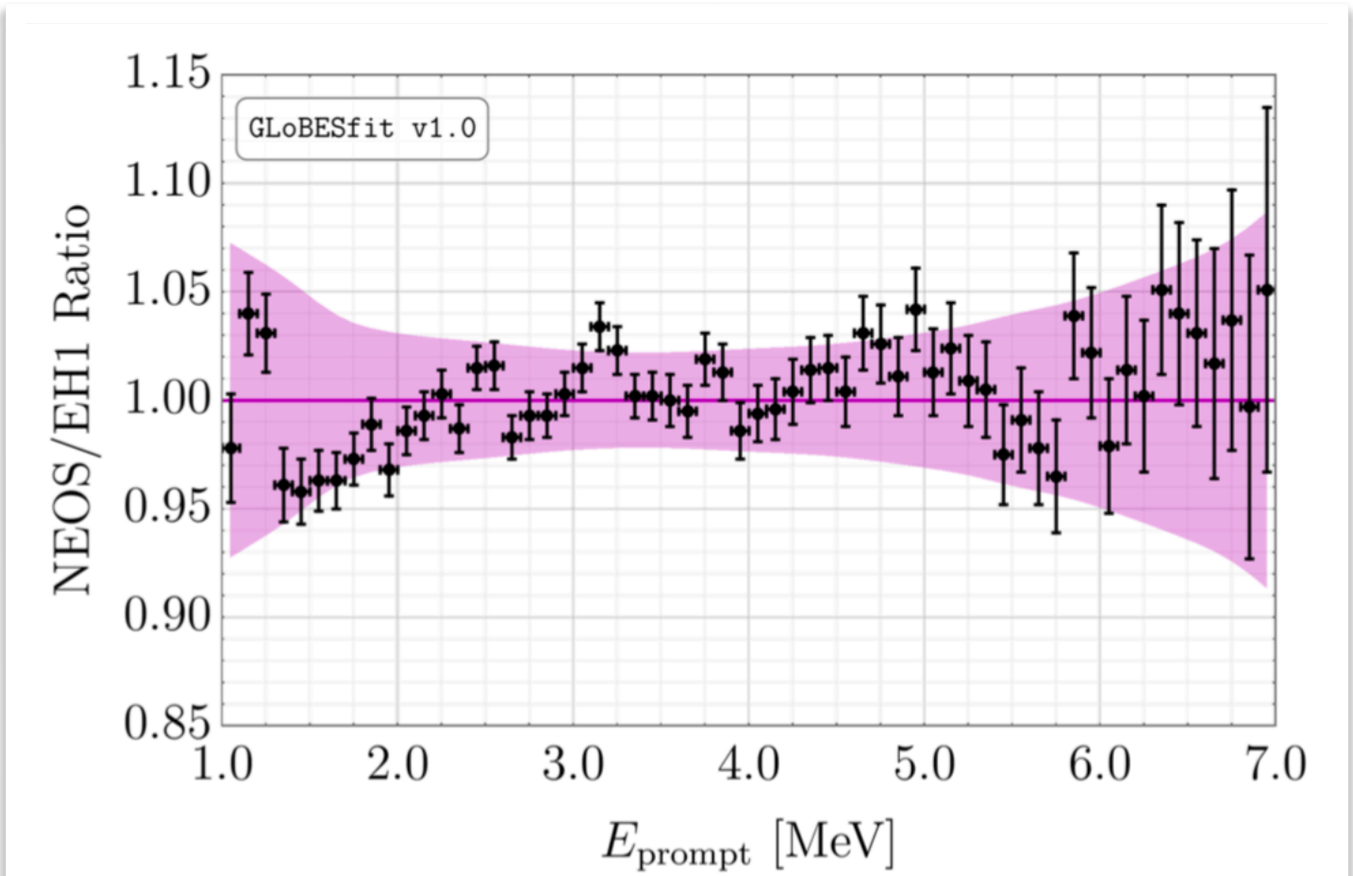
Anomaly #2: Reactor Spectra



- ☑ spectral “wiggles” in several experiments
  - can be interpreted as signal of neutrino oscillations
- ☑ Use ratios of spectra at different baselines
  - makes results independent of flux predictions

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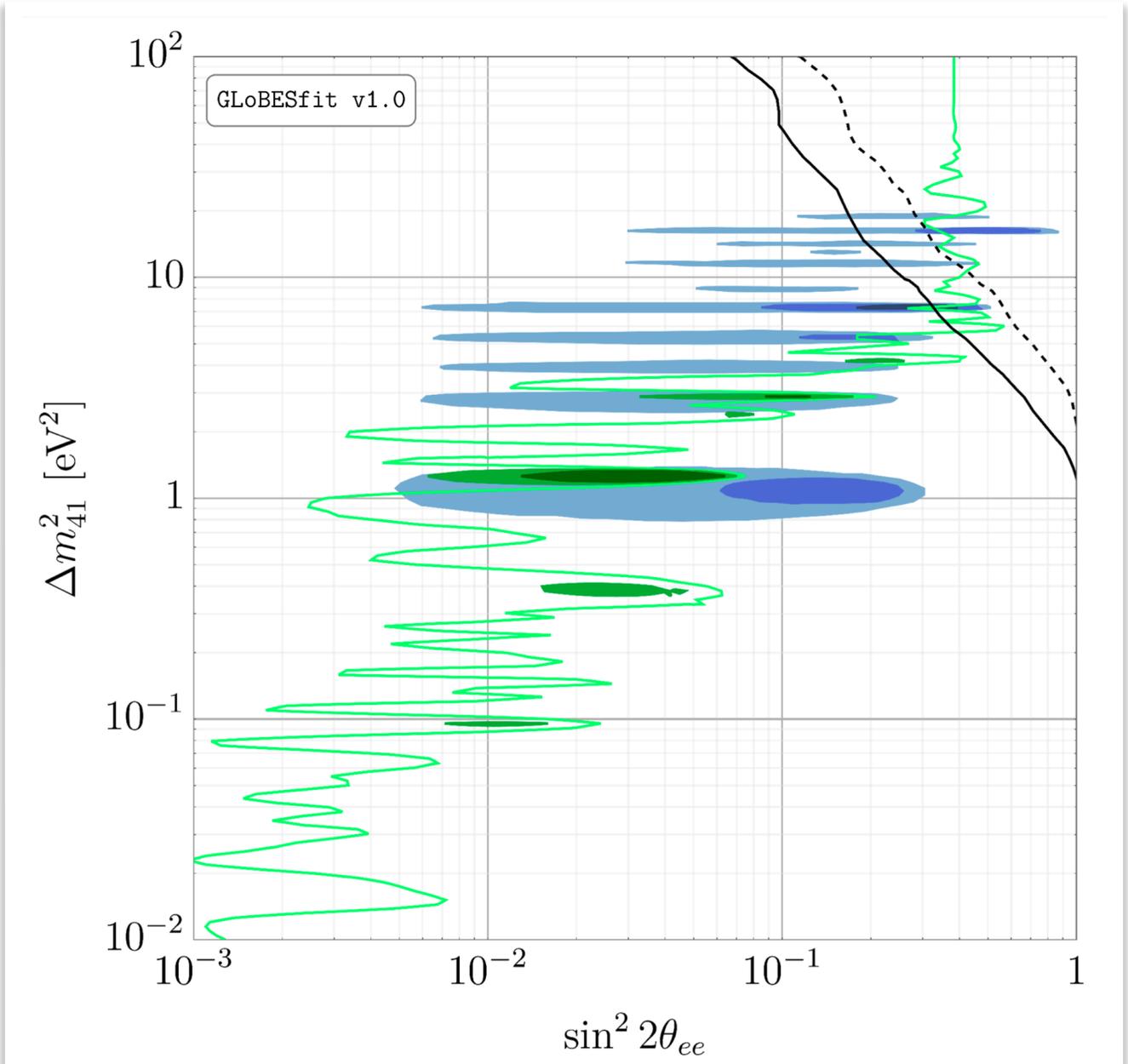

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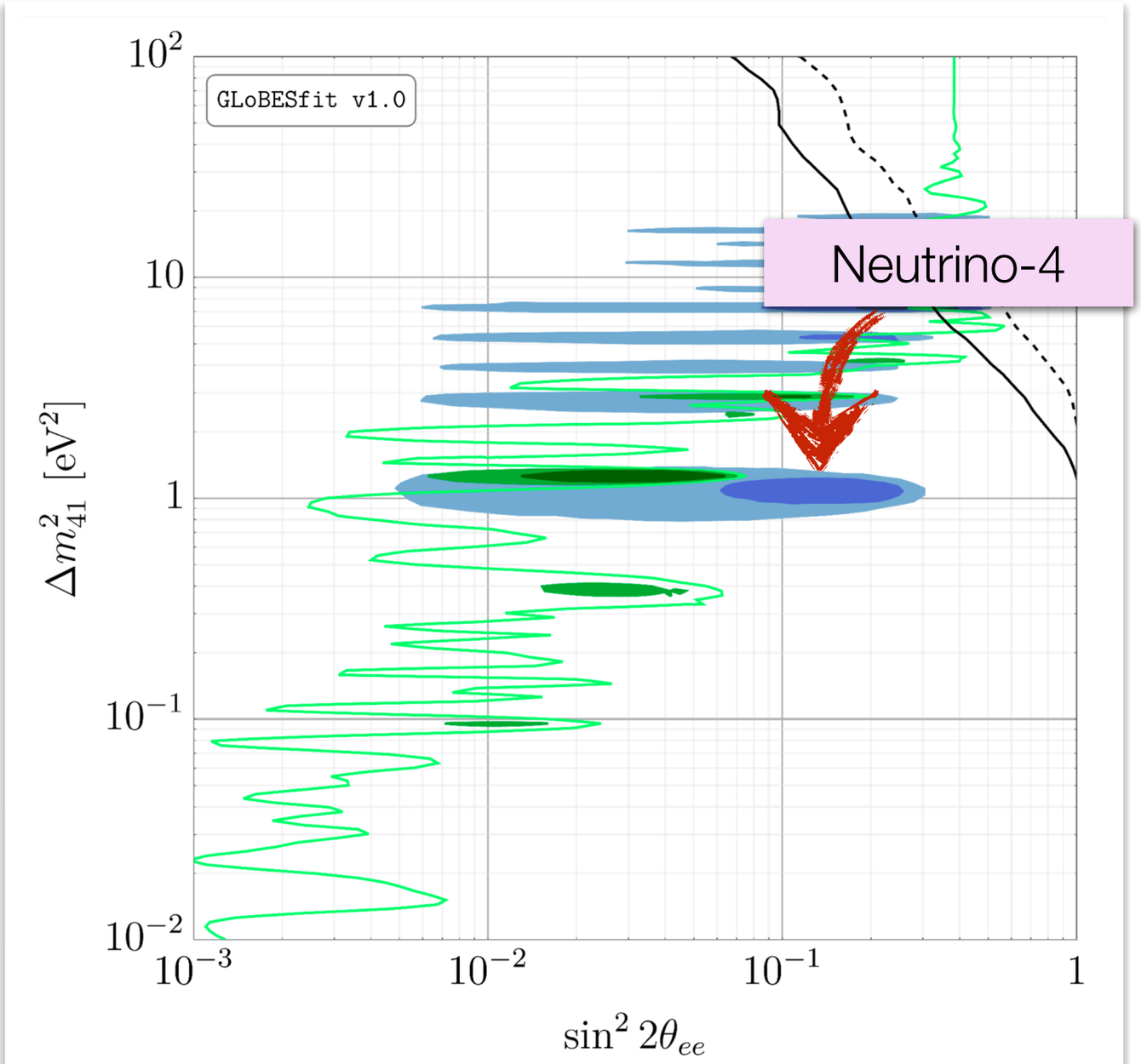

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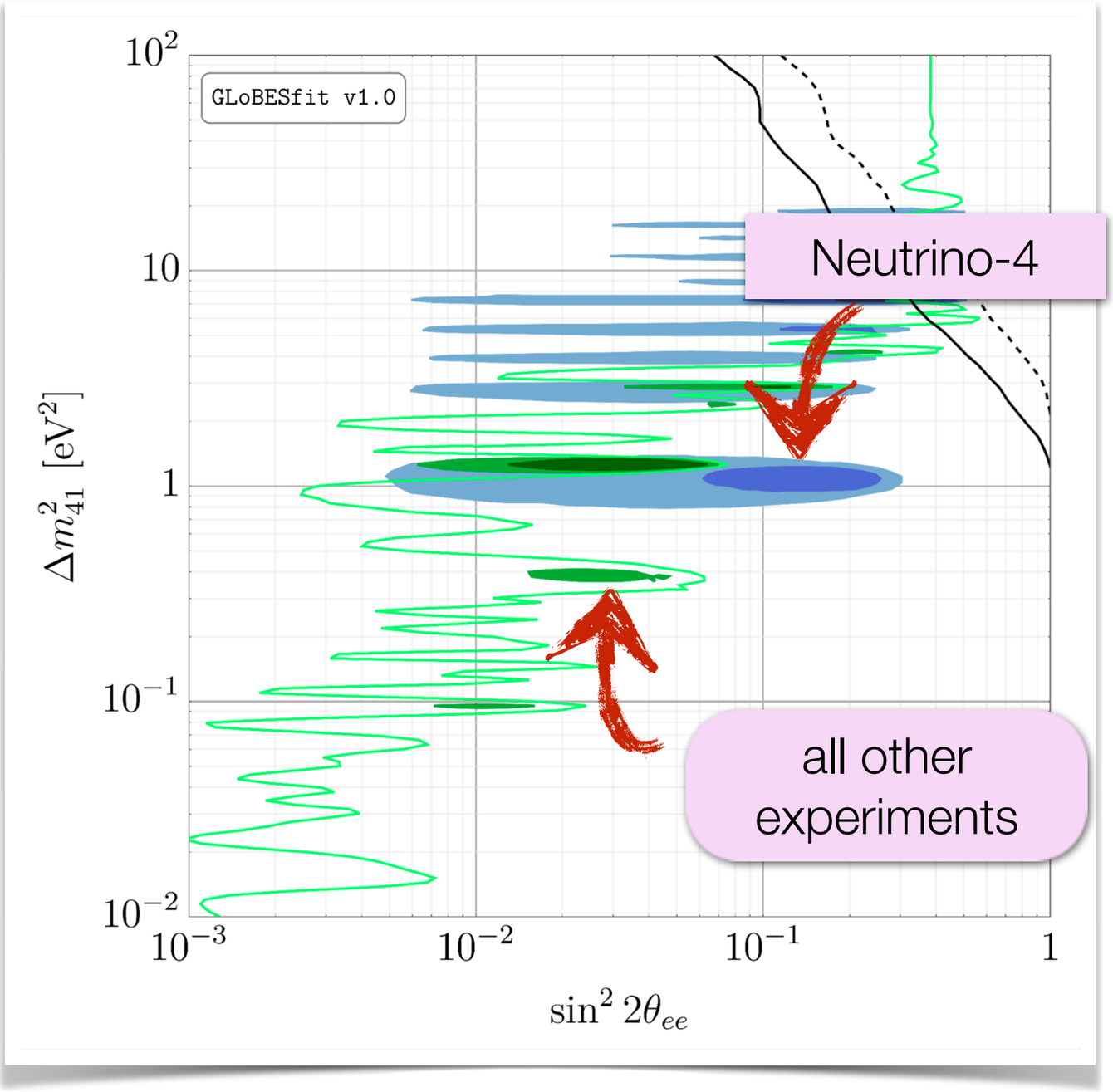

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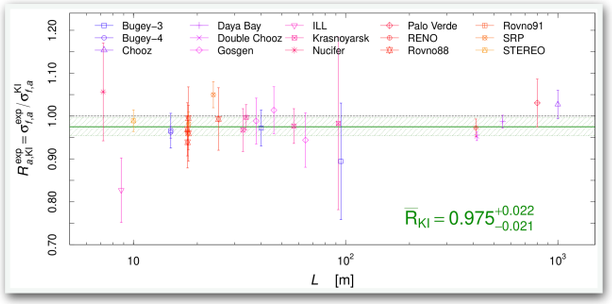
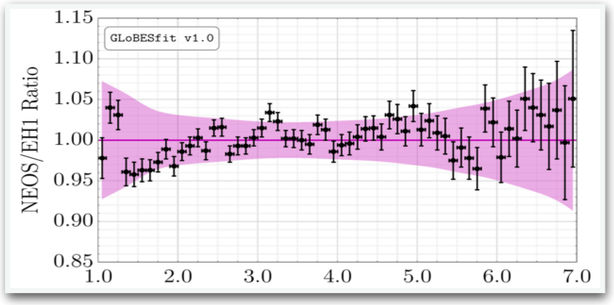




reactor flux anomaly:
resolved with new input data
to flux calculation

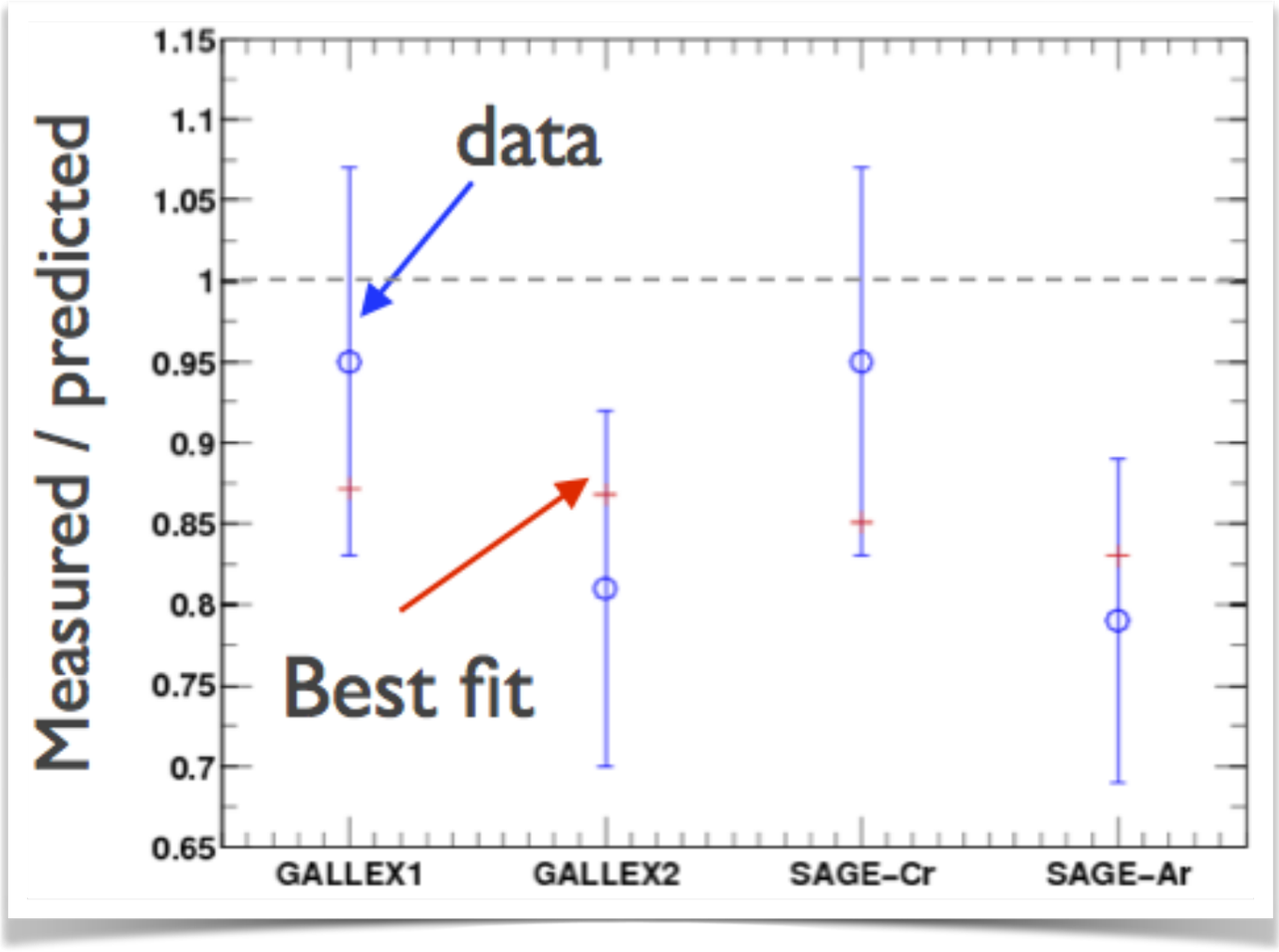
reactor spectra:
unresolved

Anomaly #3: the Gallium Anomaly

- ☑ Experiments with intense radioactive sources
- ☑ Neutrino detection via

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$

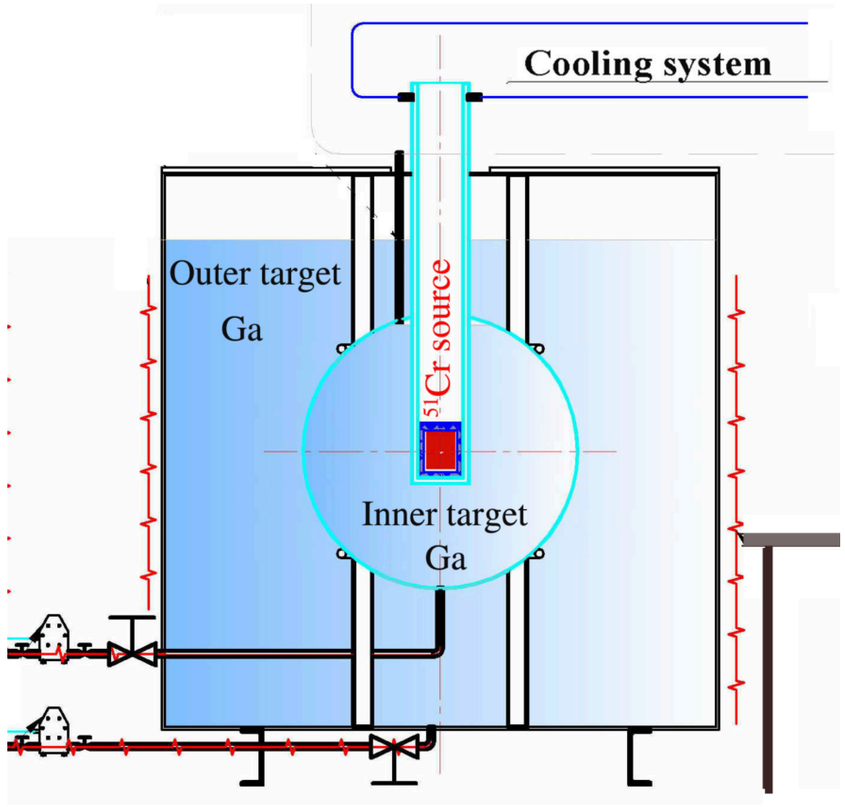
- ☑ ~3σ deficit
- ☑ ν_e disappearance into sterile state?
- ☑ would require very large mixing
  (conflict with reactor observations)



Giunti Laveder 1006.3244

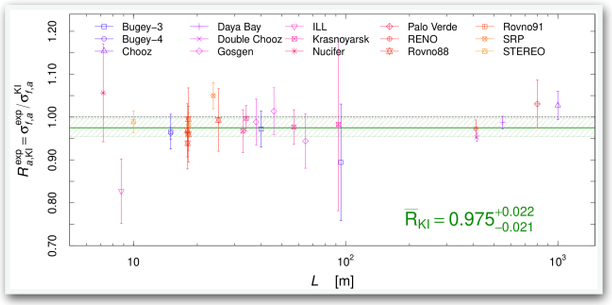
Anomaly #3: the Gallium Anomaly

- ☑ recently confirmed by BEST
- ☑ two independent target volumes
  (hoping to see oscillation pattern)
- ☑ radiochemistry similar to
  other gallium experiments
  (correlated systematics?)
- ☑ but: past experiments
  cross-calibrated with solar neutrinos



BEST arXiv:2109.11482
Barinov Gorbunov arXiv:2109.14654

Short-Baseline Anomalies



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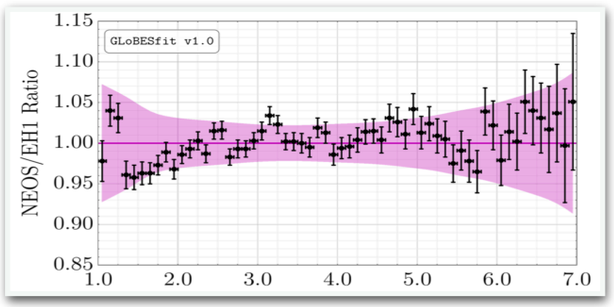

reactor spectra:
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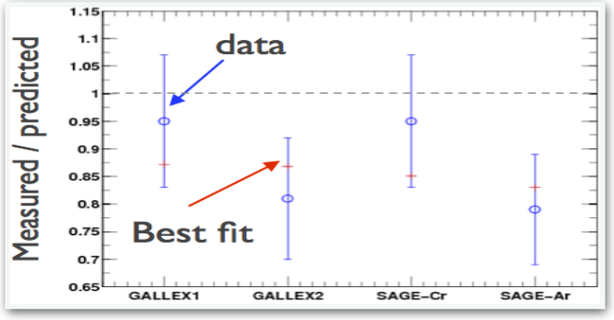
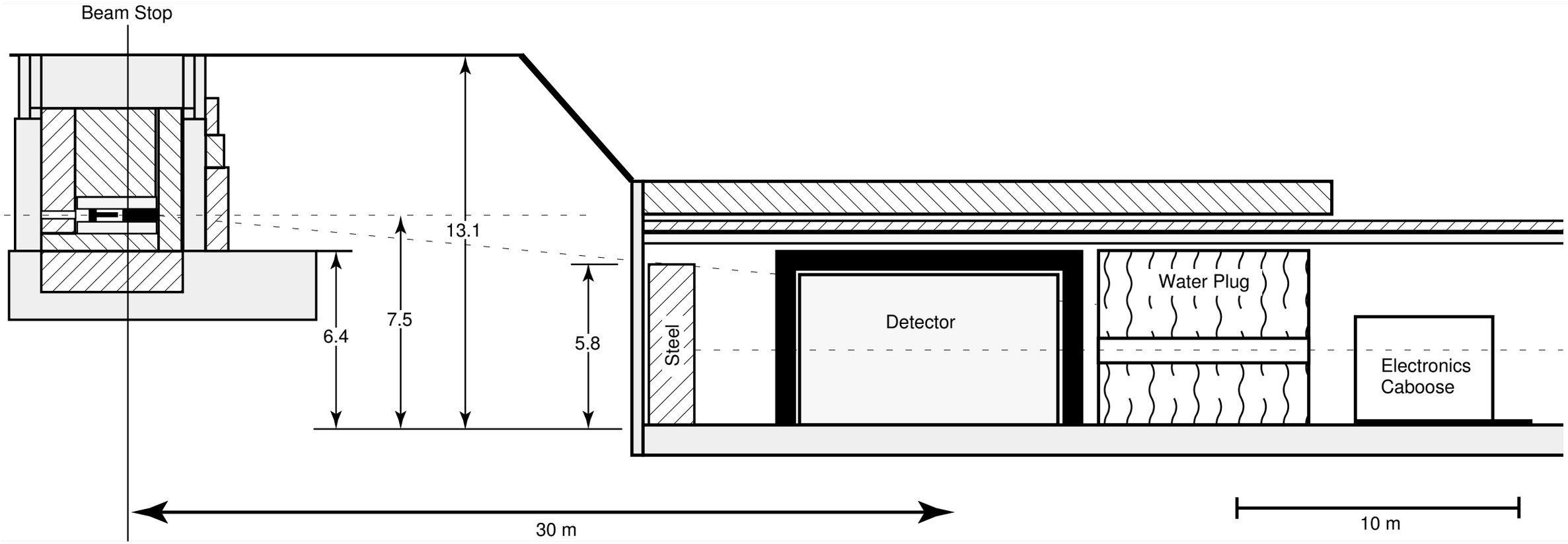


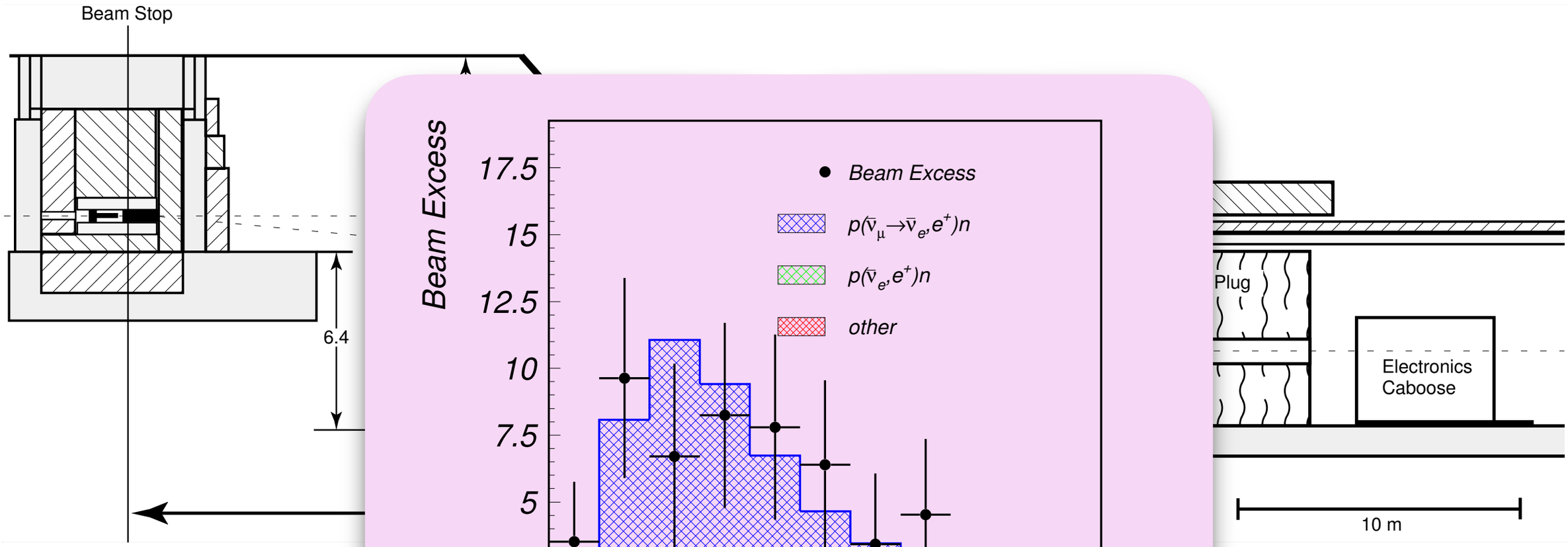
gallium anomaly:
unresolved, recently reinforced

Anomaly #4: LSND



- ☑ $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam
- ☑ Source—detector distance (“baseline”) ~ 30 m
- ☑ $\nu_\mu \rightarrow \nu_e$ oscillations?

Anomaly #4: LSND



LSND Collaboration, hep-ex/0104049

- ☑ $\bar{\nu}_e$ appeara
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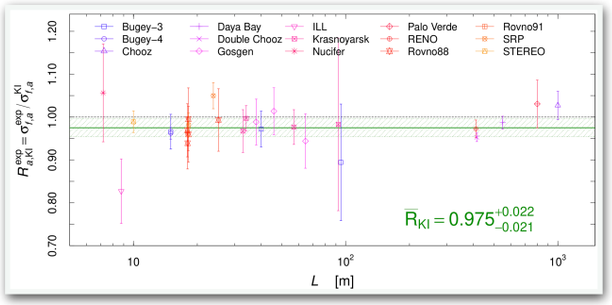
Short-Baseline Anomalies



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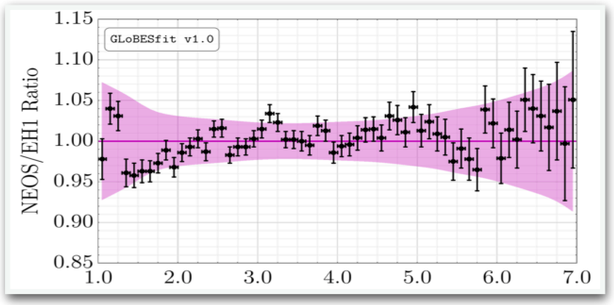
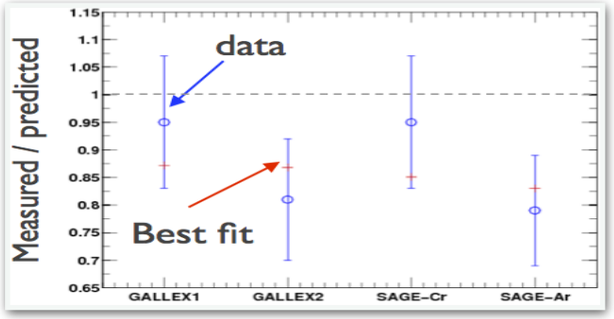


reactor spectra:
unresolved



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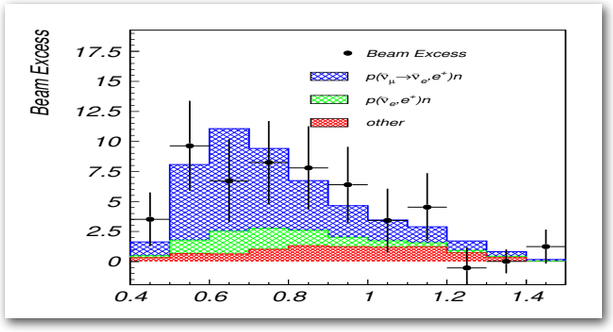
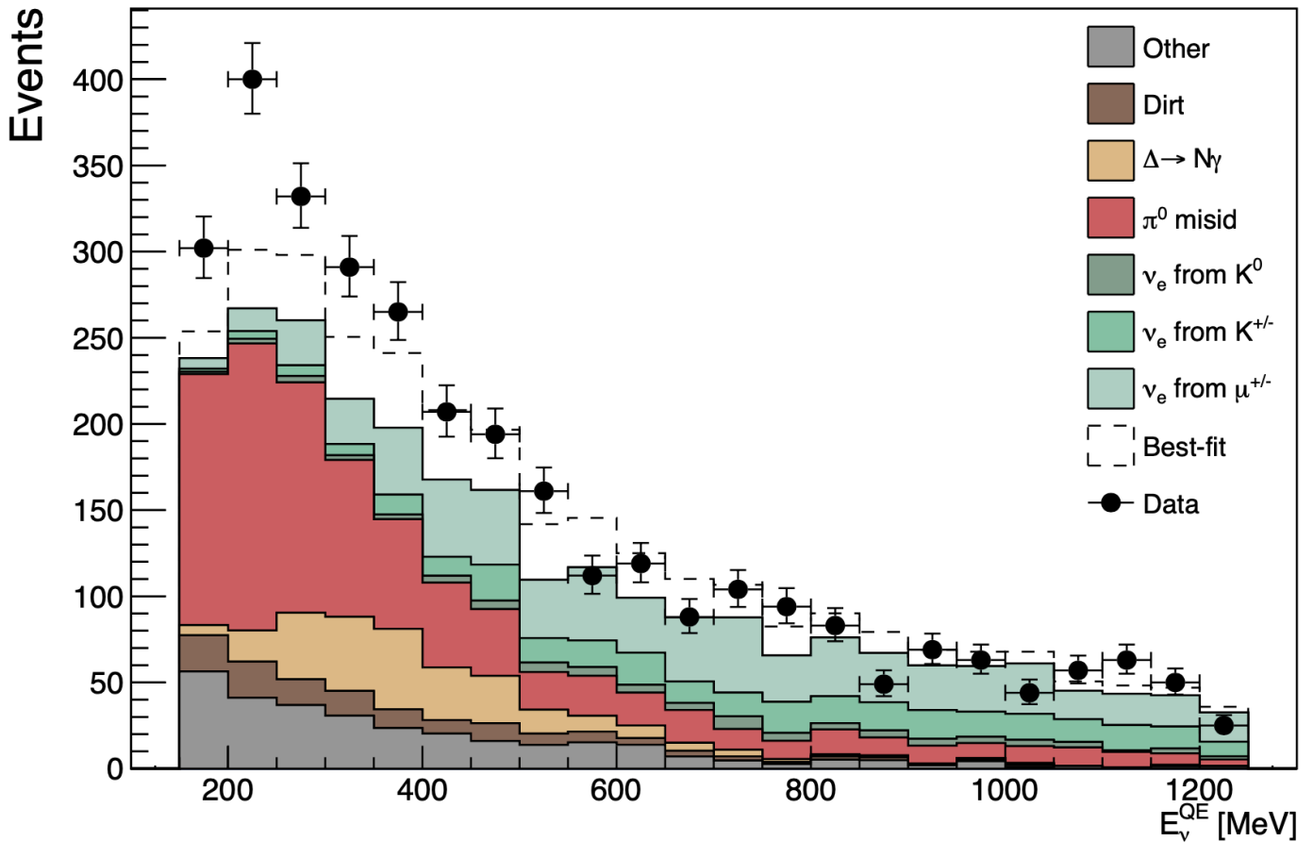


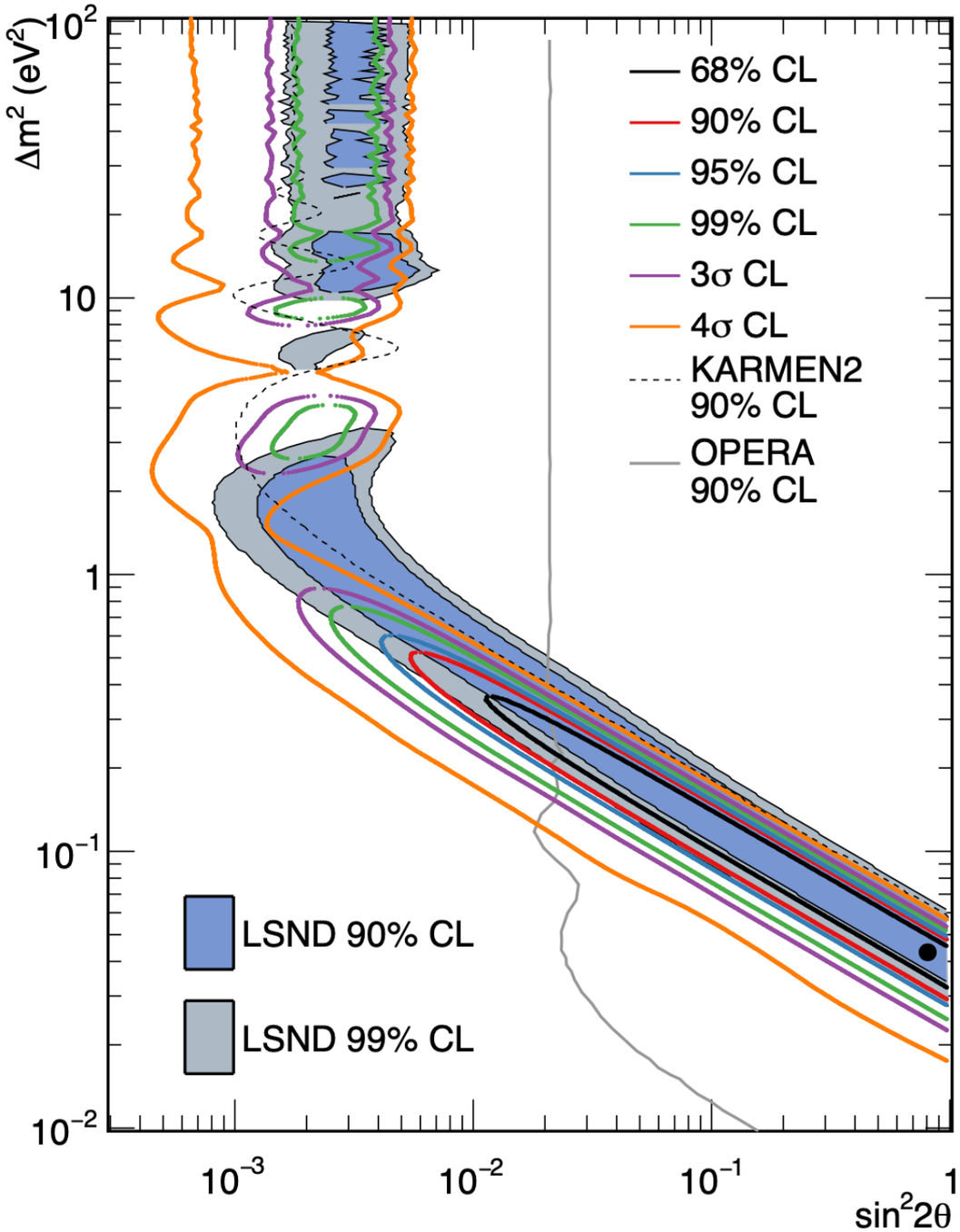
$\bar{\nu}_e$ appearance in LSND
unresolved

Anomaly #5: MiniBooNE

- ☑ Unexplained low-*E* excess
- ☑ Consistent with LSND
- ☑ L/E too small for std. oscillations (wrong Δm^2)



MiniBooNE Collaboration arXiv:2006.16883



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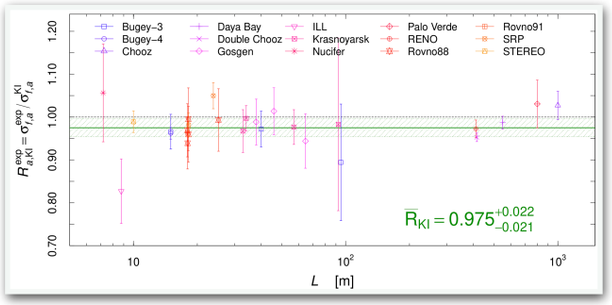

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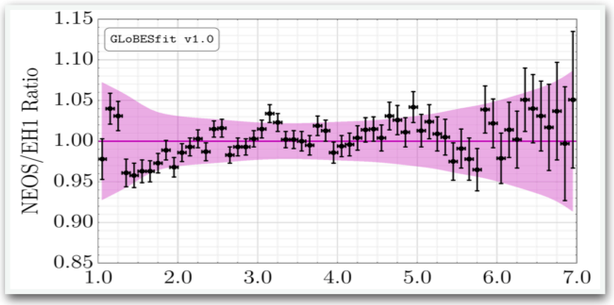

reactor spectra:
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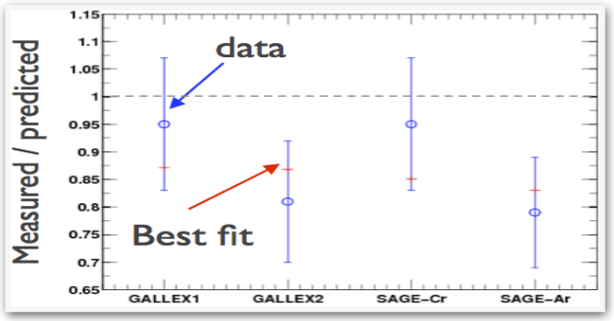

gallium anomaly:
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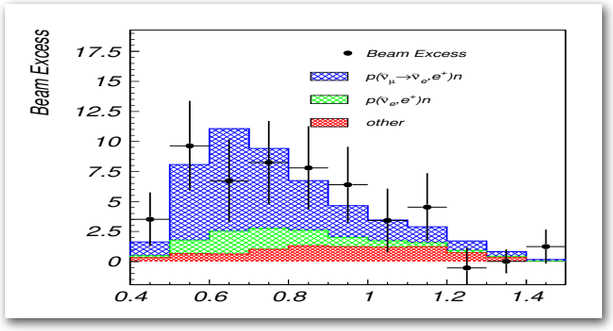

$\bar{\nu}_e$ appearance in LSND
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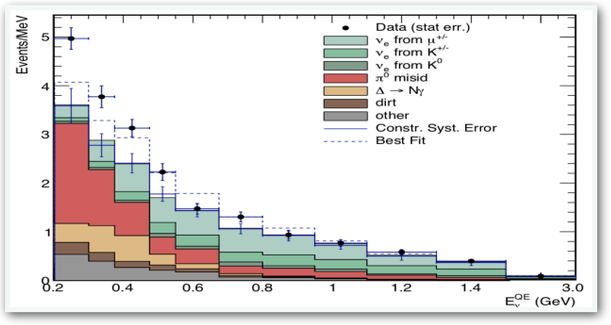
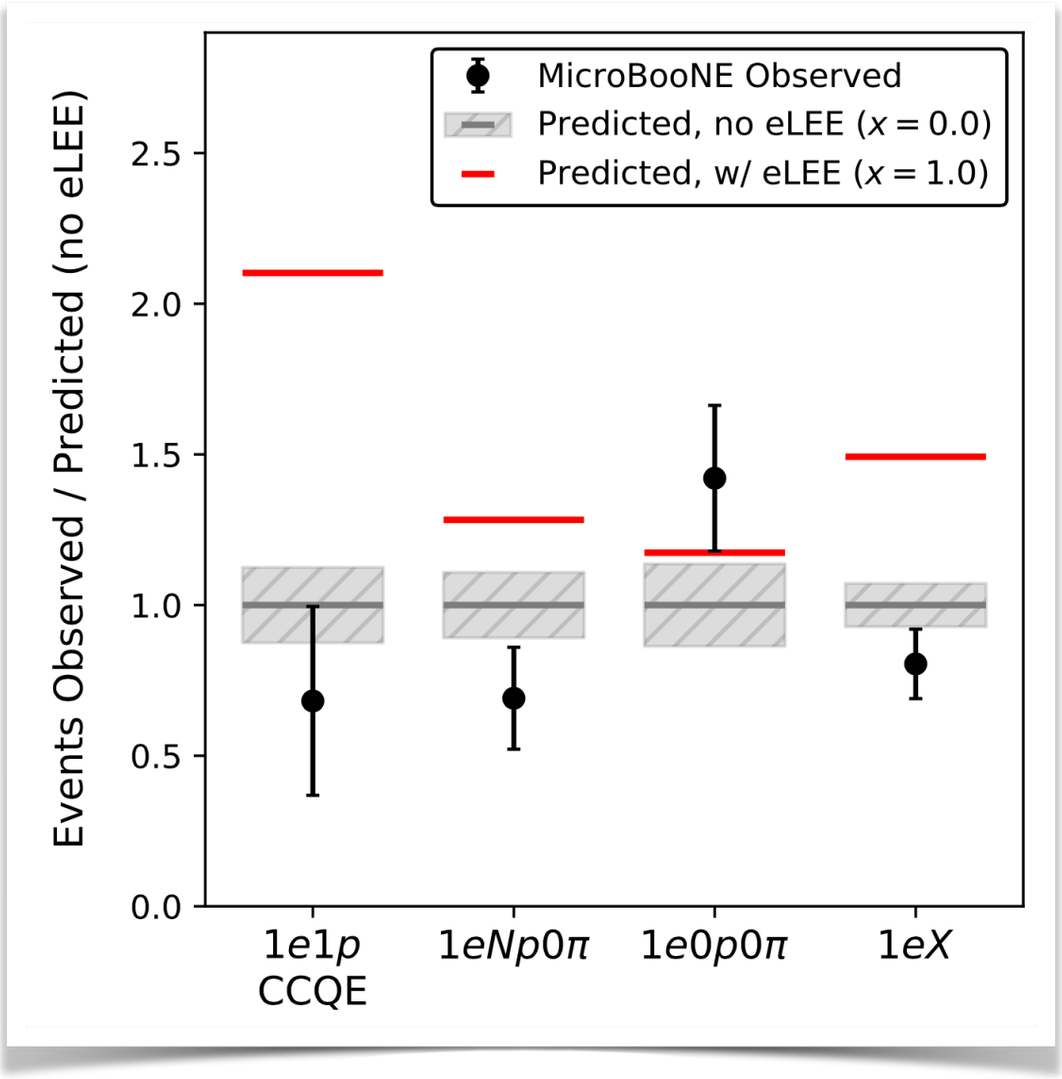


MiniBooNE
unresolved

A True ν_e signal?

☑ Tested by MicroBooNE in several channels

☑ No support for interpretation of MiniBooNE excess as ν_e



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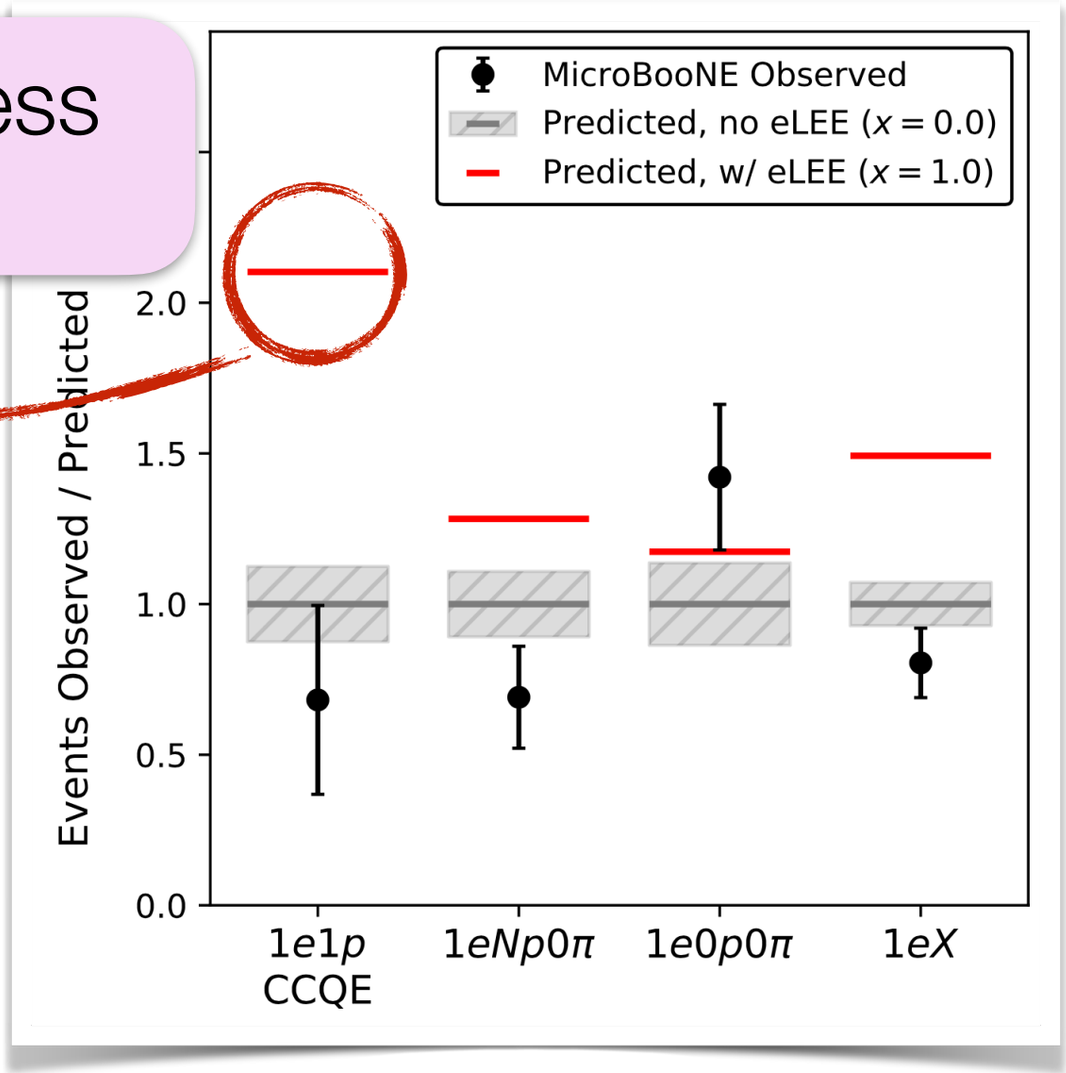
MiniBooNE excess
central value



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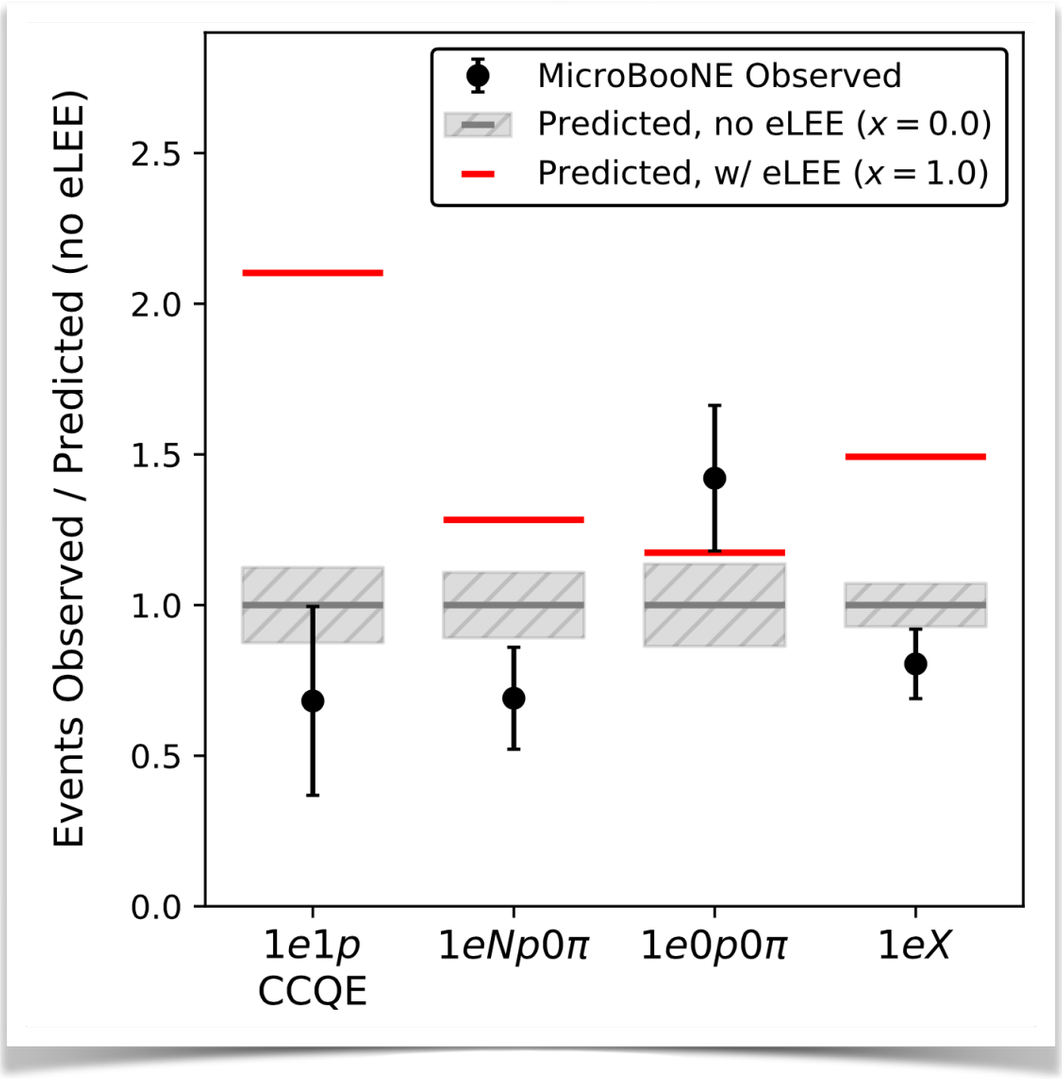
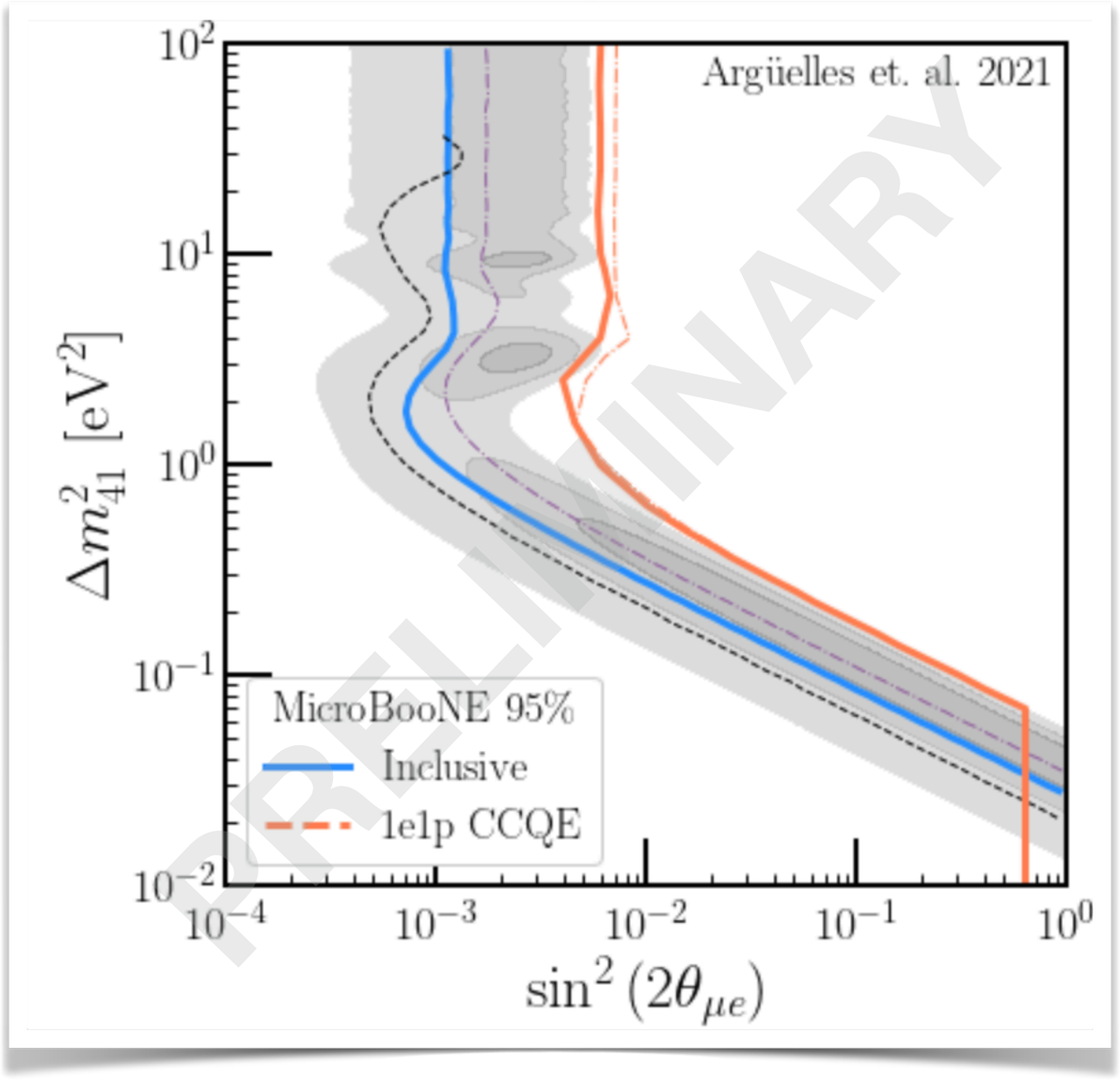
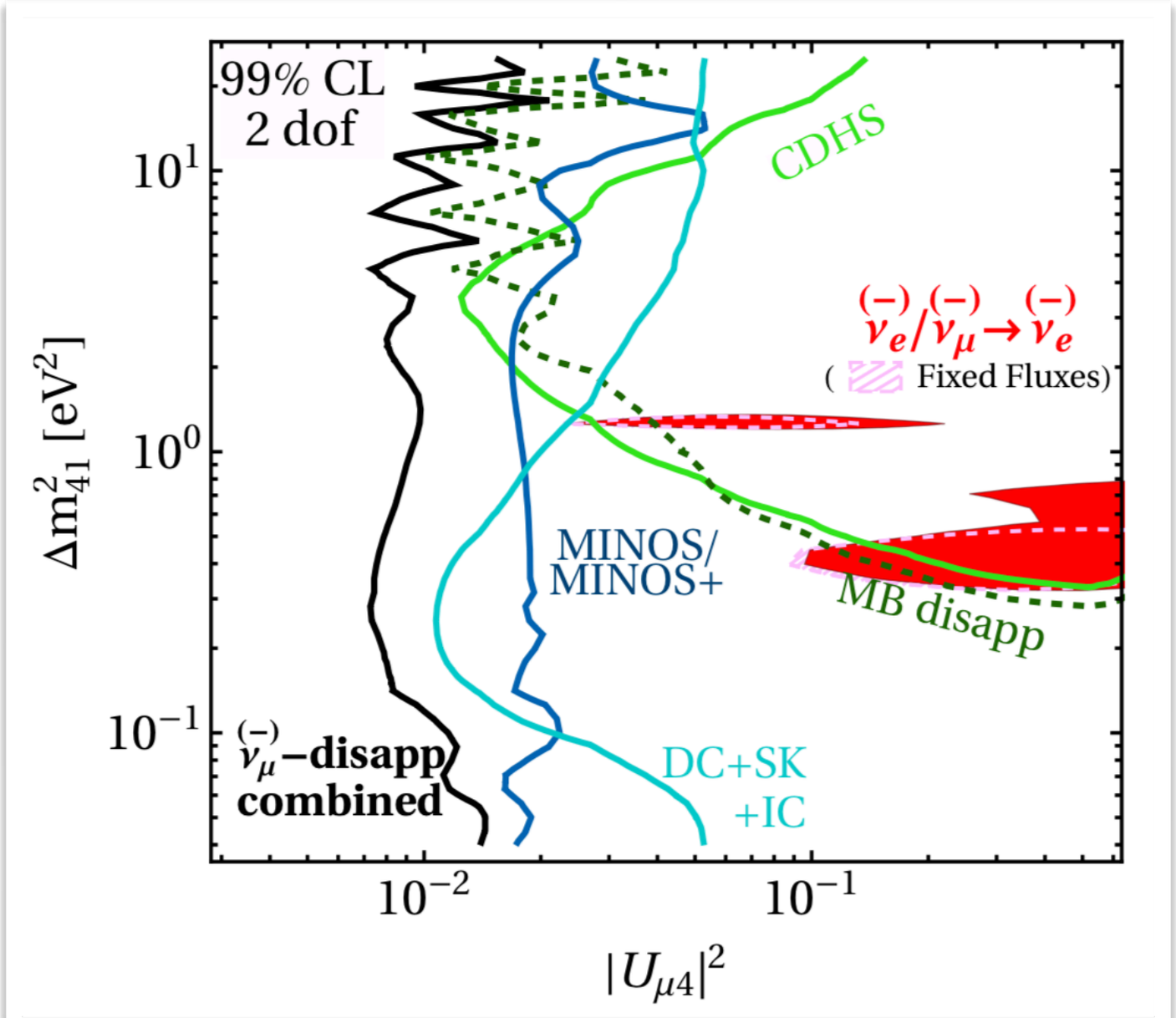


Compatibility Between MiniBooNE and μBooNE



- ☑ 2σ regions overlap
- ☑ relatively good sensitivity driven by downward fluctuation

Sterile Neutrinos?

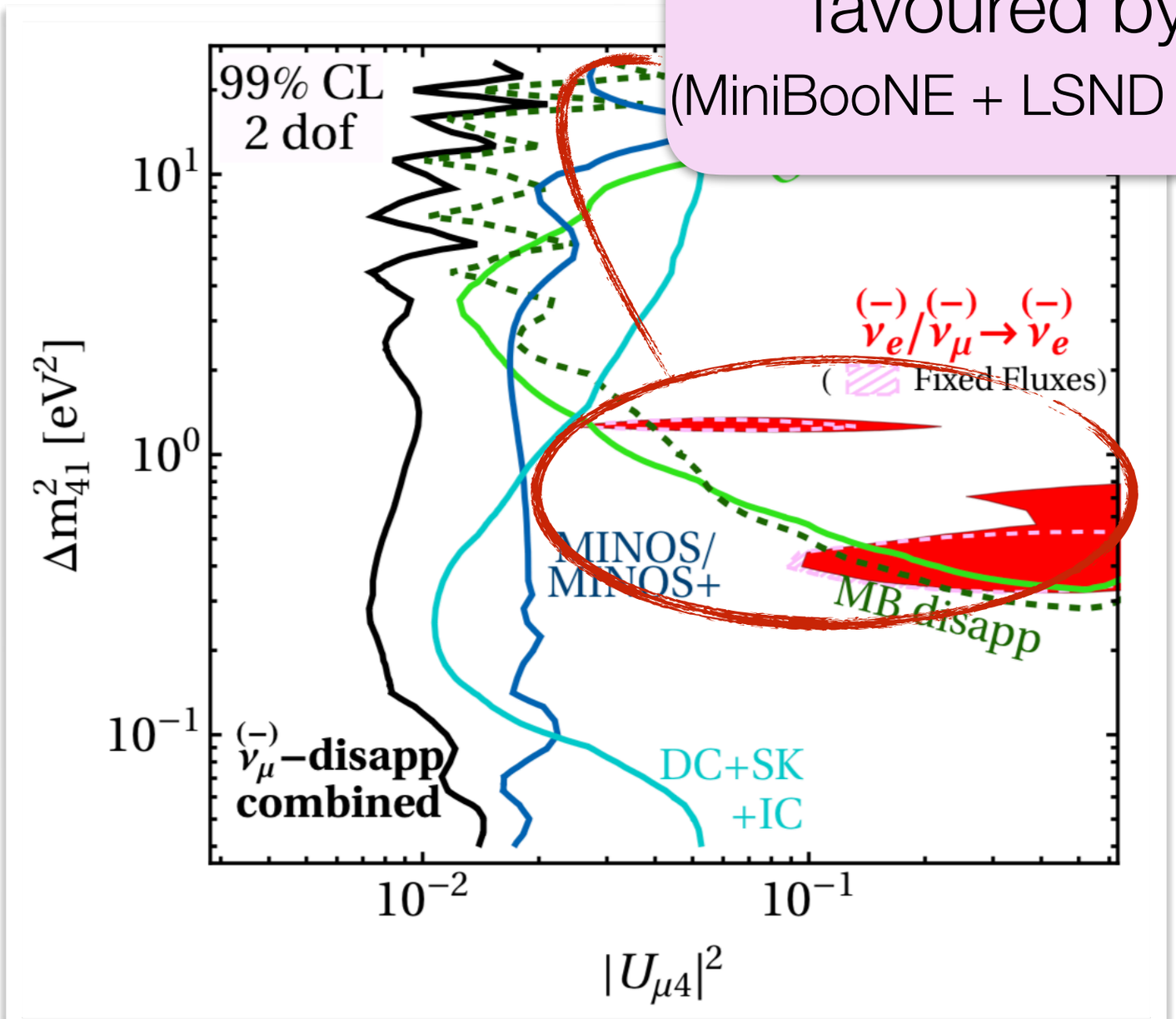


Dentler Hernandez JK Machado Maltoni Martinez Schwetz, 1803.10661
see also works by Collin Argüelles Conrad Shaevitz, 1607.00011
Gariazzo Giunti Laveder Li, 1703.00860

Sterile Neutrinos?

favoured by anomalies

(MiniBooNE + LSND + reactors + gallium



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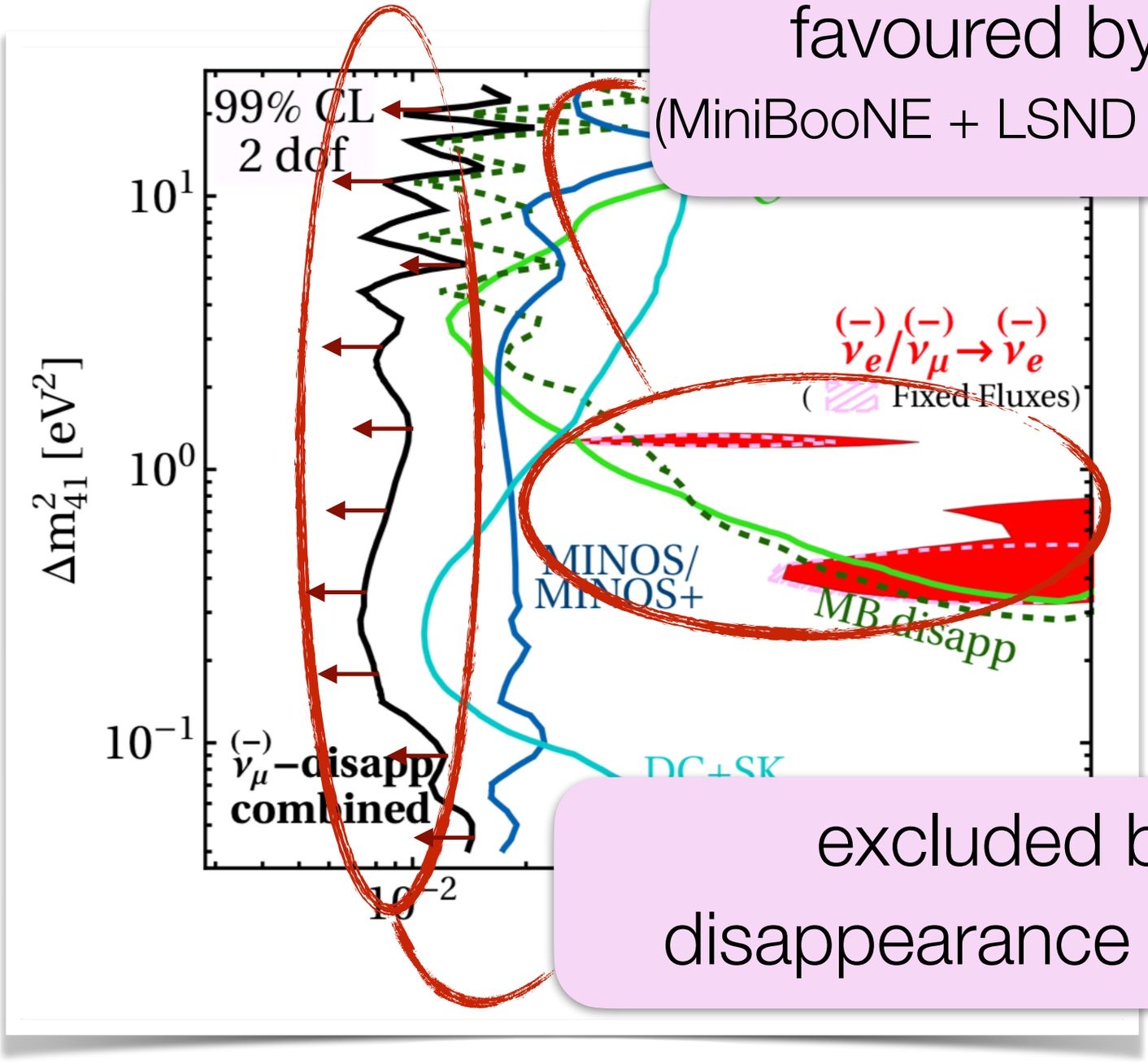

excluded by ν_μ disappearance searches

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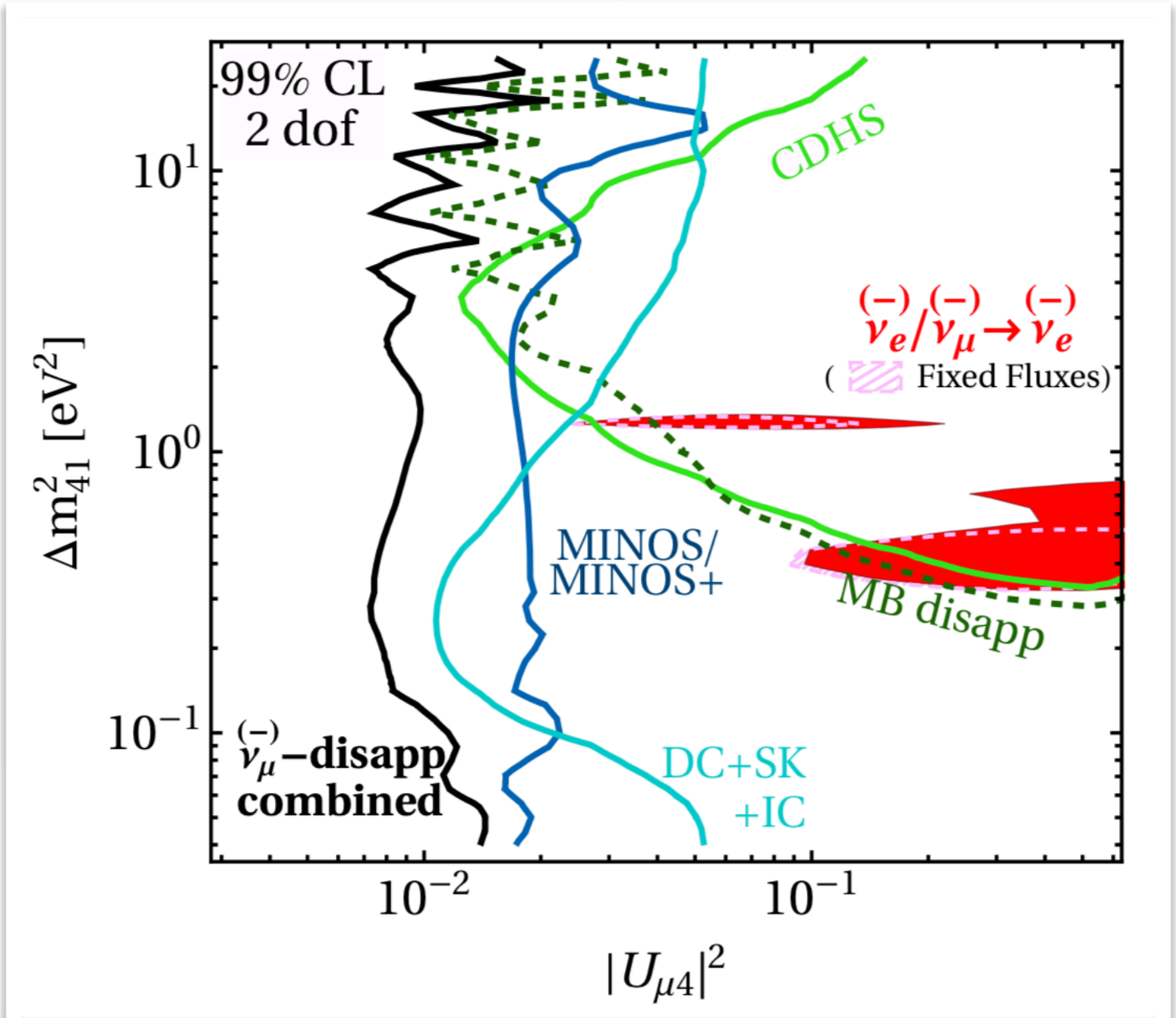

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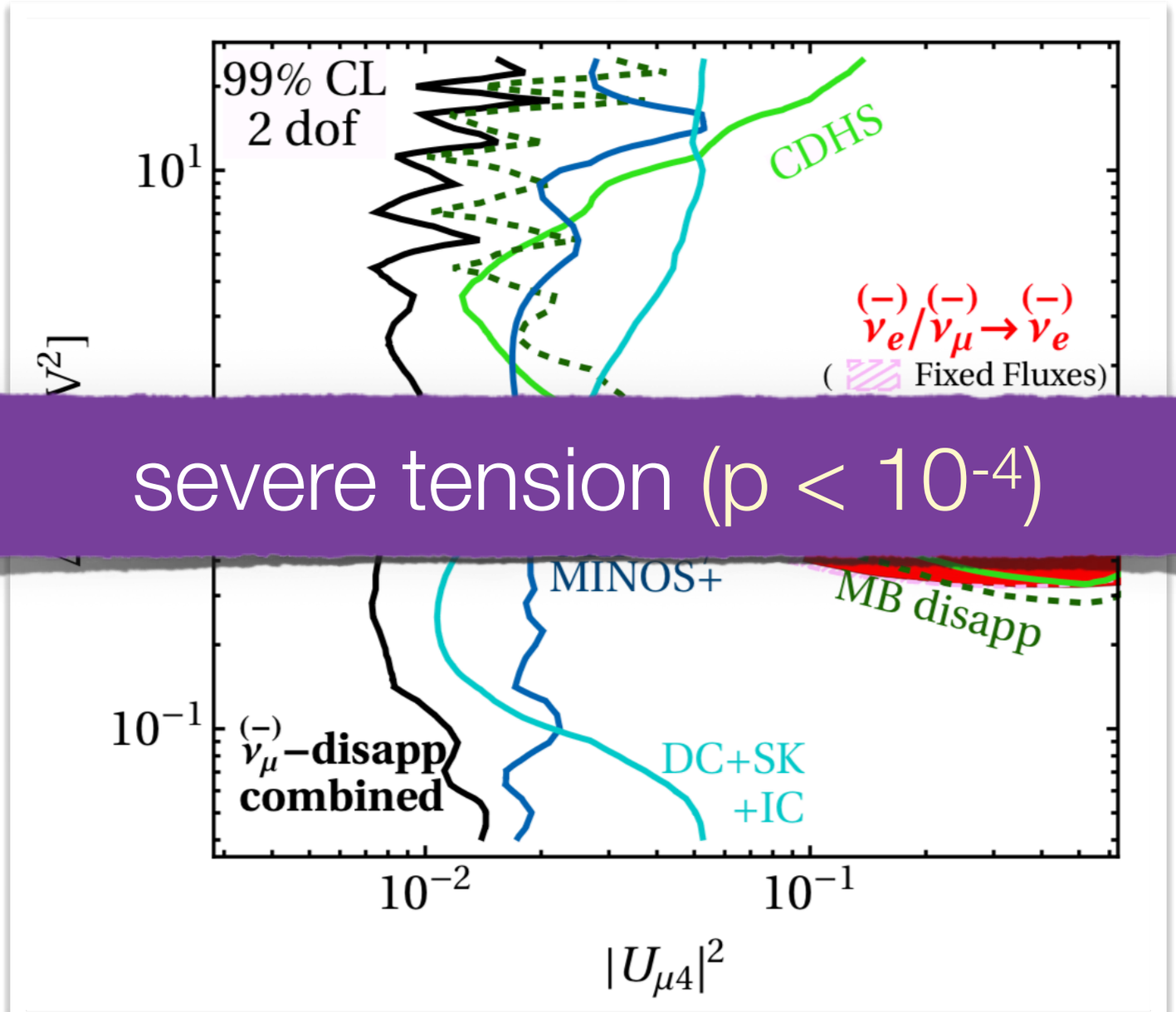

severe tension ($p < 10^{-4}$)

Dentler Hernandez JK Machado Maltoni Martinez Schwetz, 1803.10661
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Gariazzo Giunti Laveder Li, 1703.00860

To Do List for Neutrino Anomalies

- ★ scrutinize anomalies for unknown systematics
  (need 4 independent effects!)
- ★ scrutinize also null results!
- ★ extended models?
  → next talk by Matheus Hoster

Outlook

dim-4: the Neutrino Portal

dim-5: Neutrino Magnetic Moments

dim-6: Neutrinos in SMEFT

Outlook

dim-4: the Neutrino Portal

☑ upcoming experiments may resolve (some) anomalies
☑ … and lead to improved modelling of neutrino interactions

dim-5: Neutrino Magnetic Moments

dim-6: Neutrinos in SMEFT

Outline

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Neutrino Magnetic Moments in the SM

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☑ Magnetic Moment Operator

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

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electromagnetic field strength tensor

Neutrino Magnetic Moments in the SM

Couples LH and RH neutrinos

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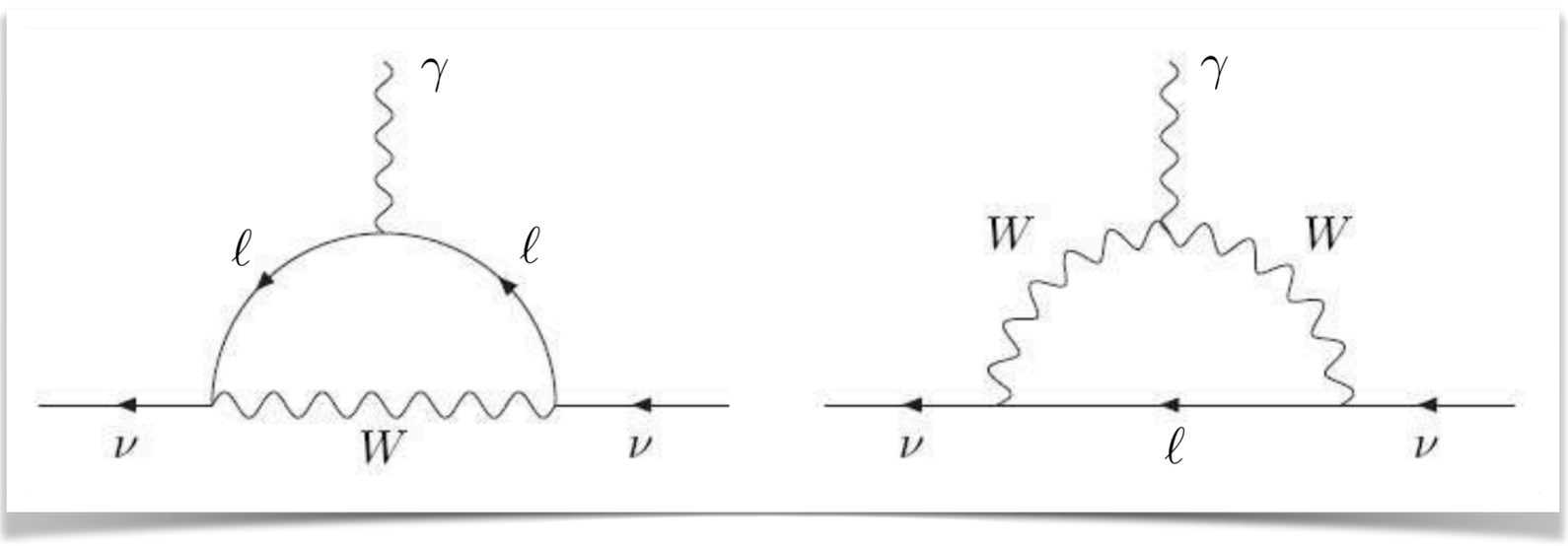
☑ In the SM: generated by loop diagrams



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

Petcov 1977
Fujikawa Shrock 1980

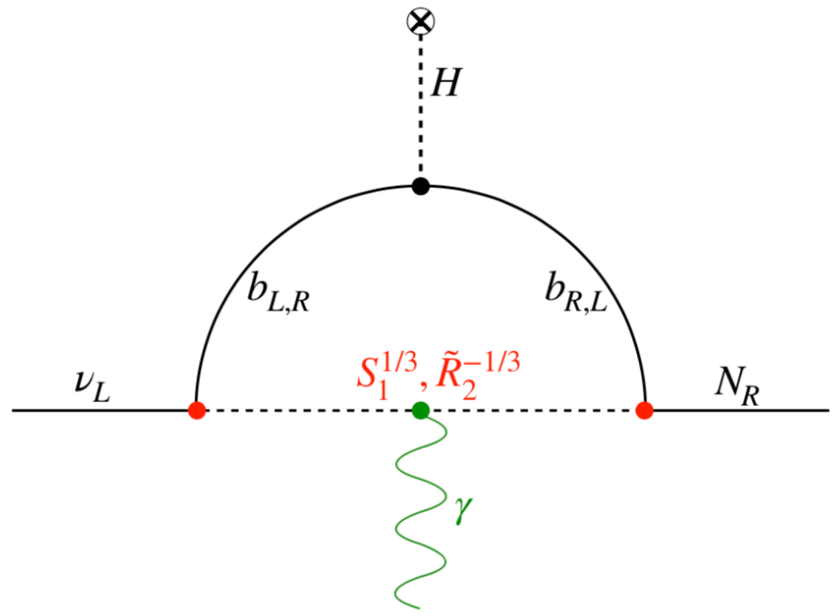
Neutrino Magnetic Moments Beyond the SM

☑ 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

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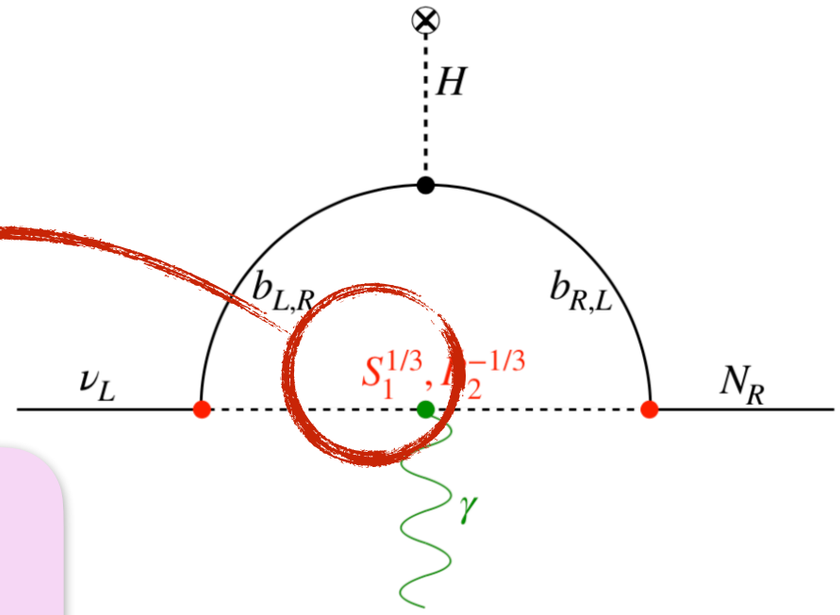
$$\mathcal{L} \supset \frac{1}{2}\mu_N \, \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R F_{\mu\nu}$$

leptoquark model, inspired by B physics anomalies

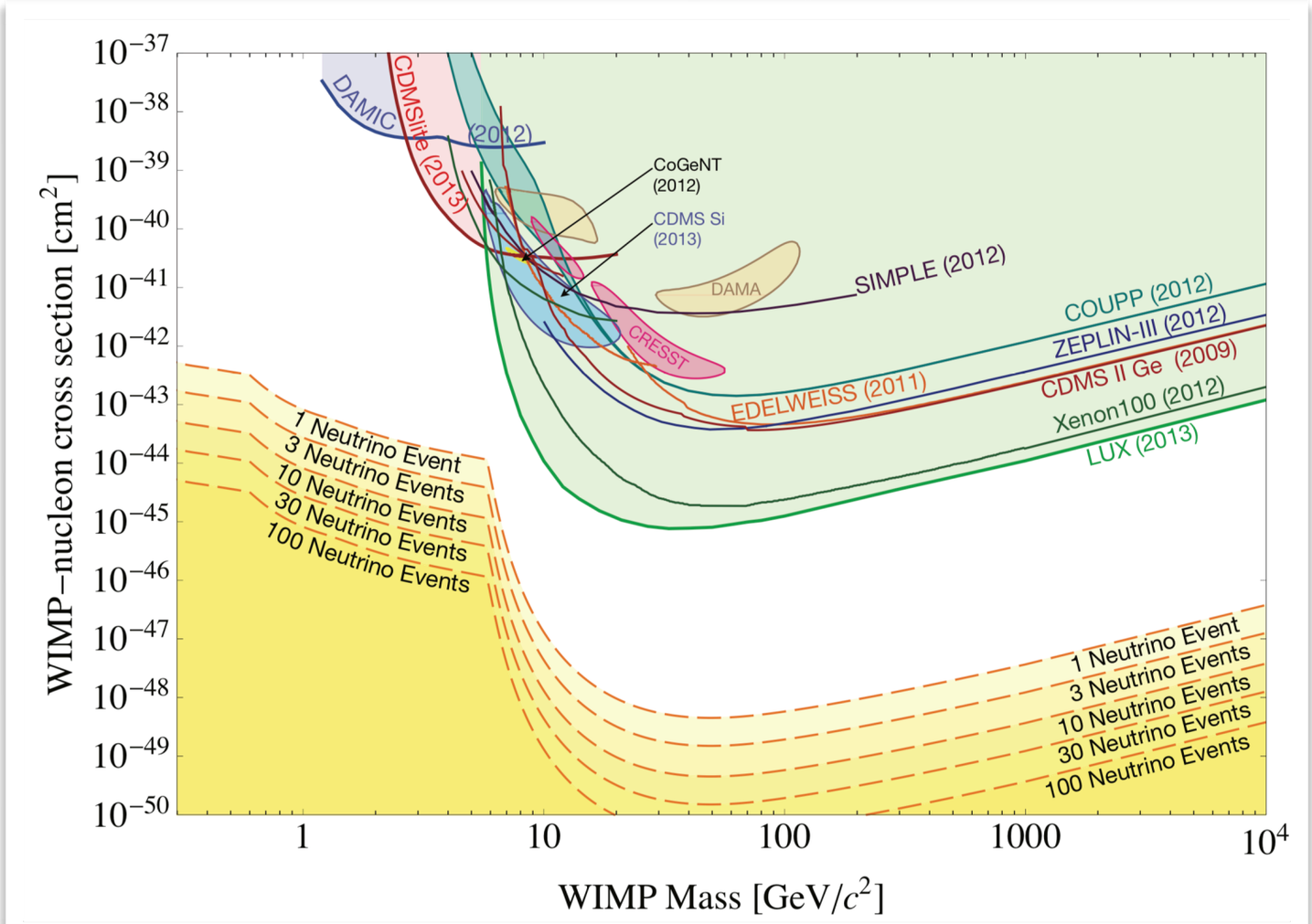


Brdar Greljo JK Opferkuch 2007.15563

can explain
$R(D^*)$ and $(g–2)_\mu$ anomalies.
(see later)

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

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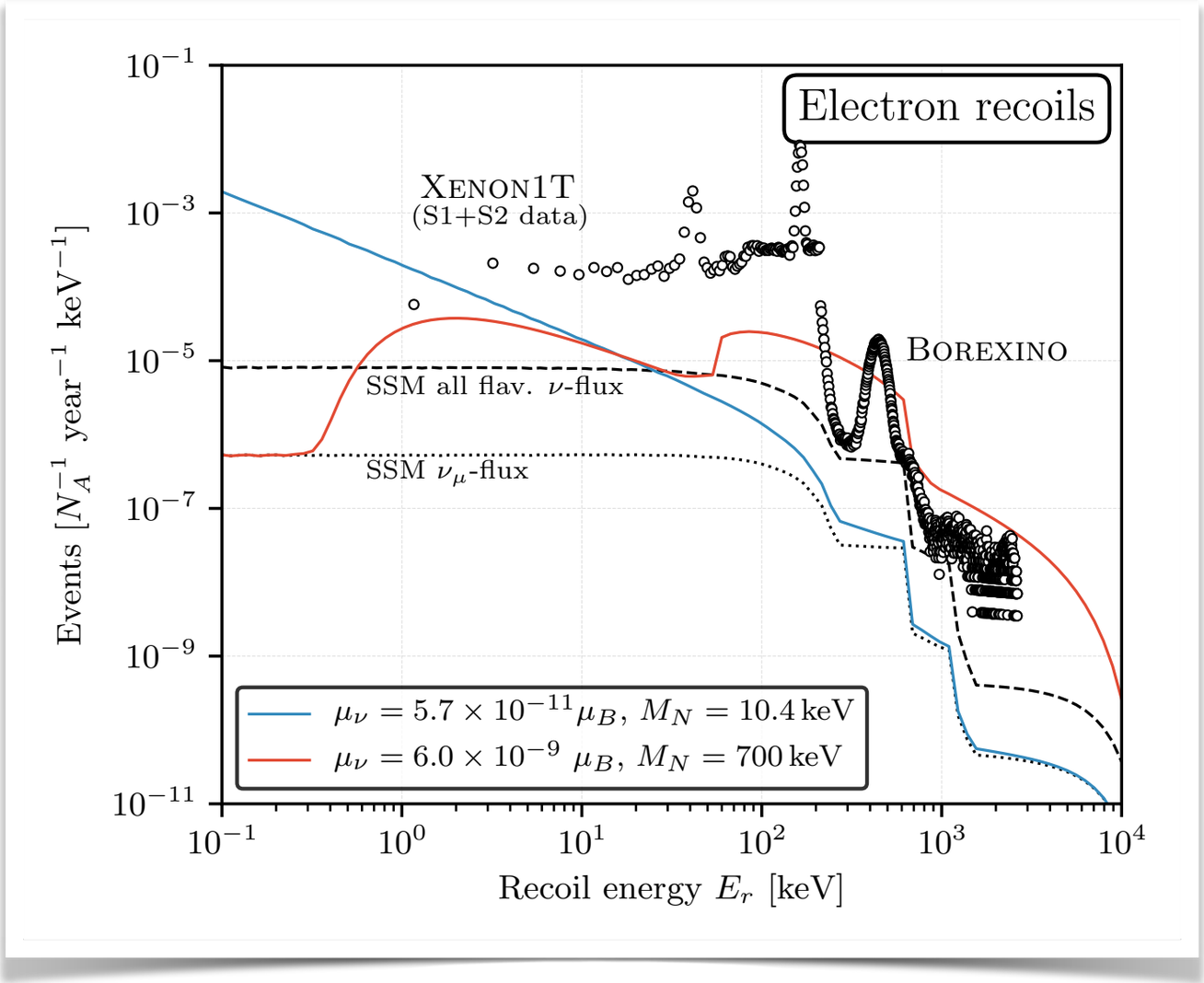
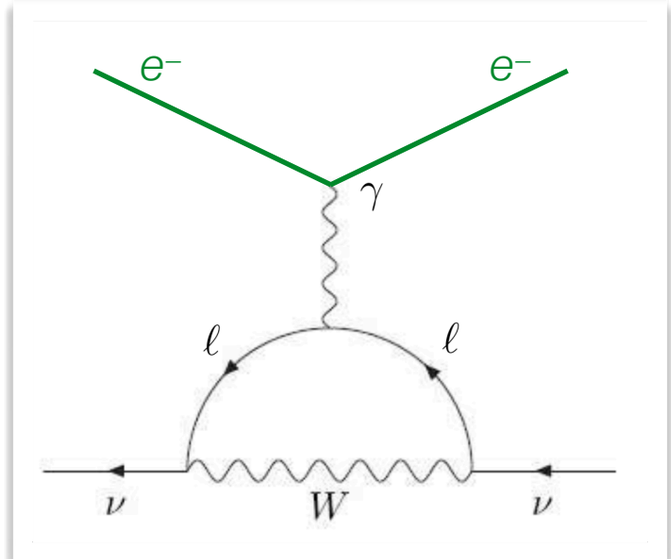
☑ enhanced e^- recoil rate from μ_ν-induced scattering

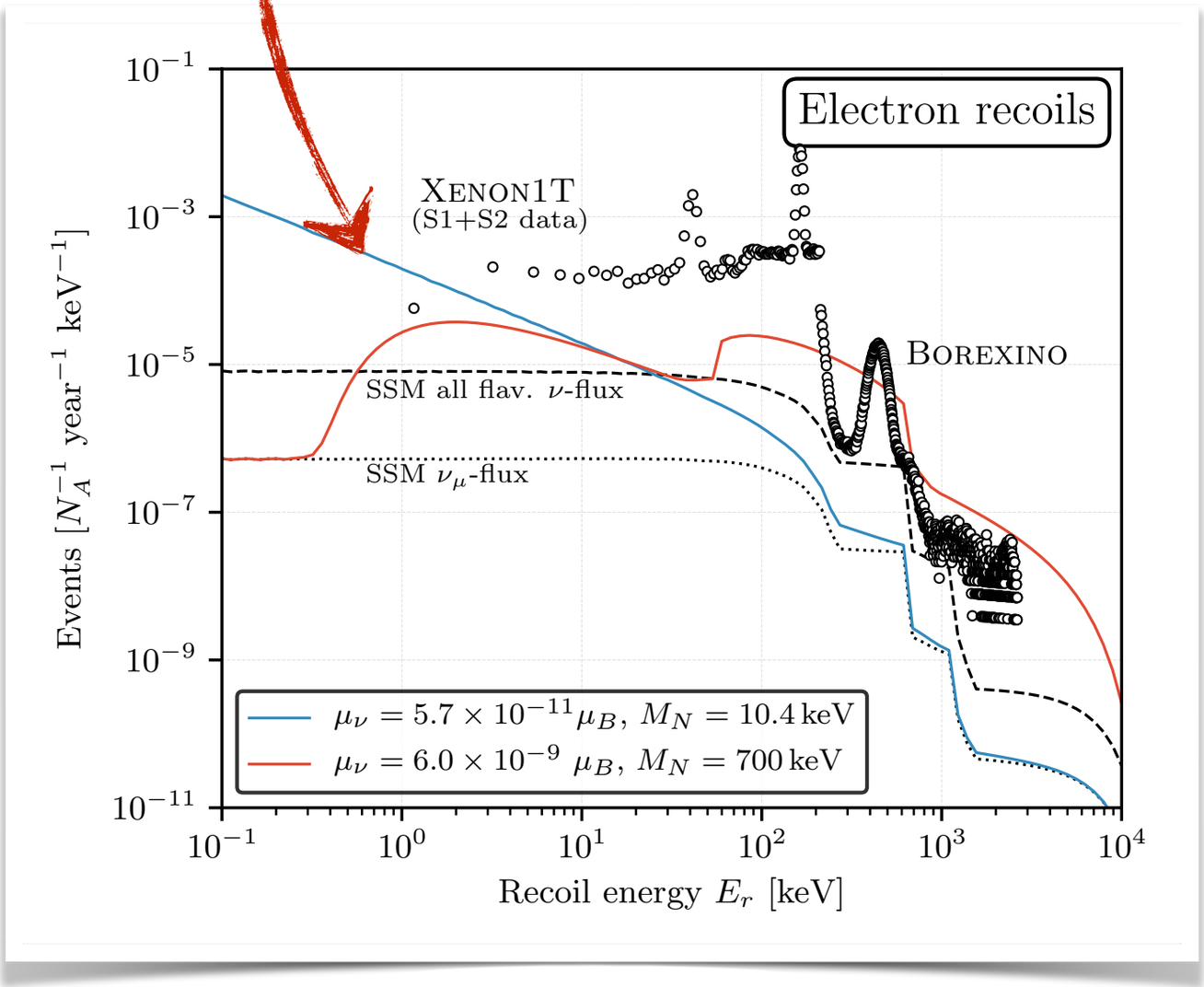


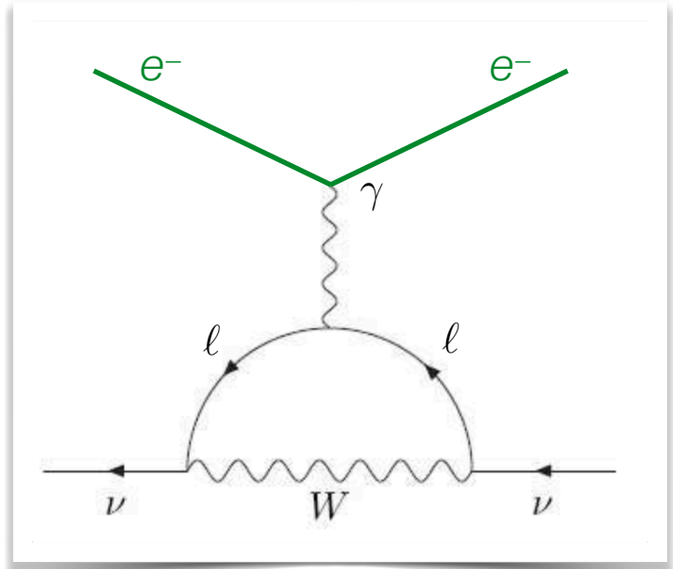


Signals in Direct Detection Experiments

- ☑ so[illegible]ct detection experiments
- ☑ enhanced e^- recoil rate from μ_ν-induced scattering

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





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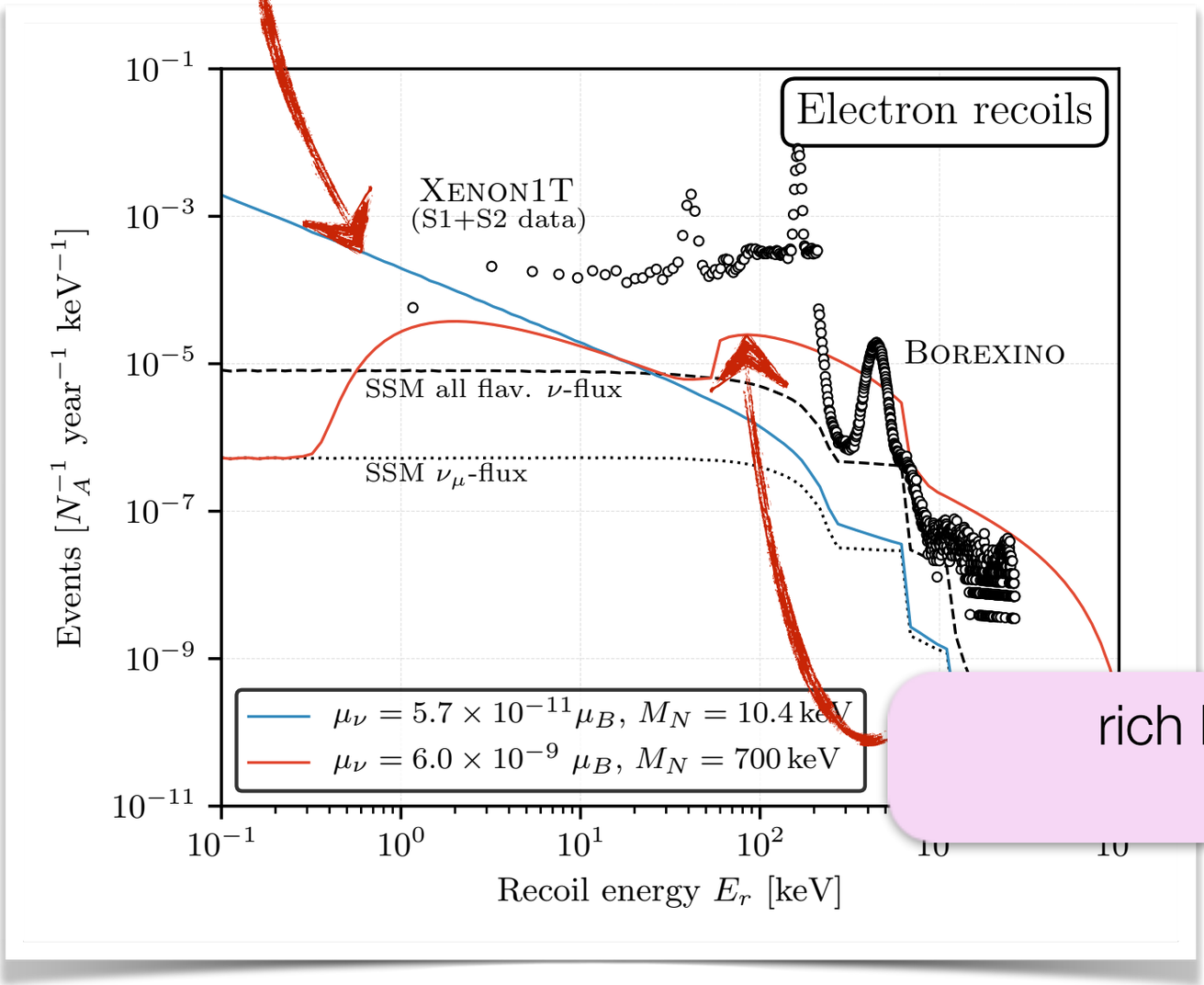
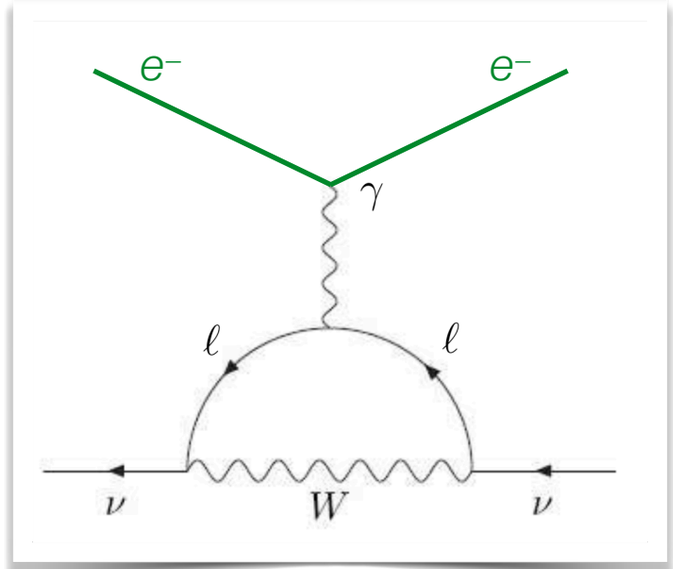
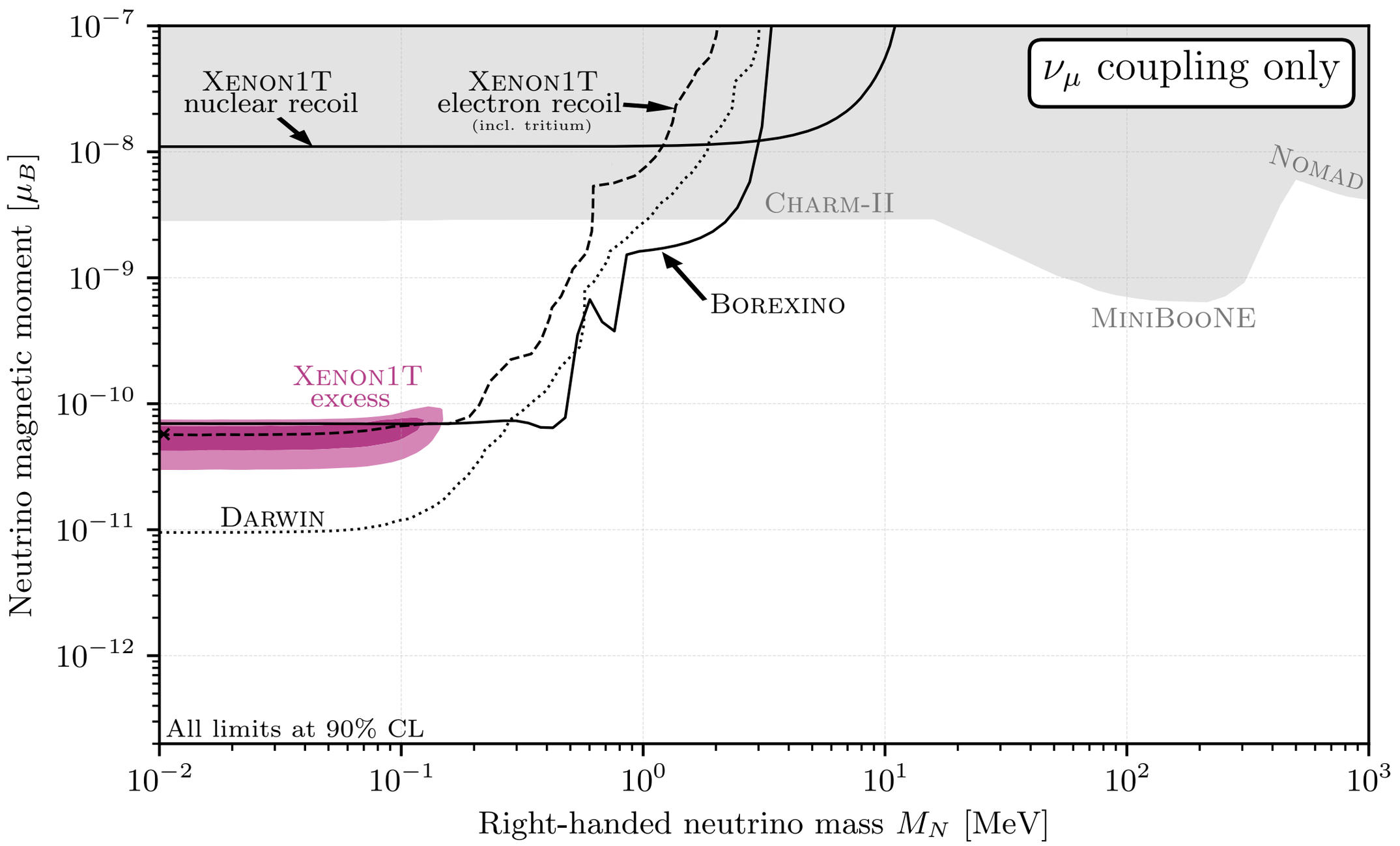




rich kinematic features
for heavy N_R

Summary of Terrestrial 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

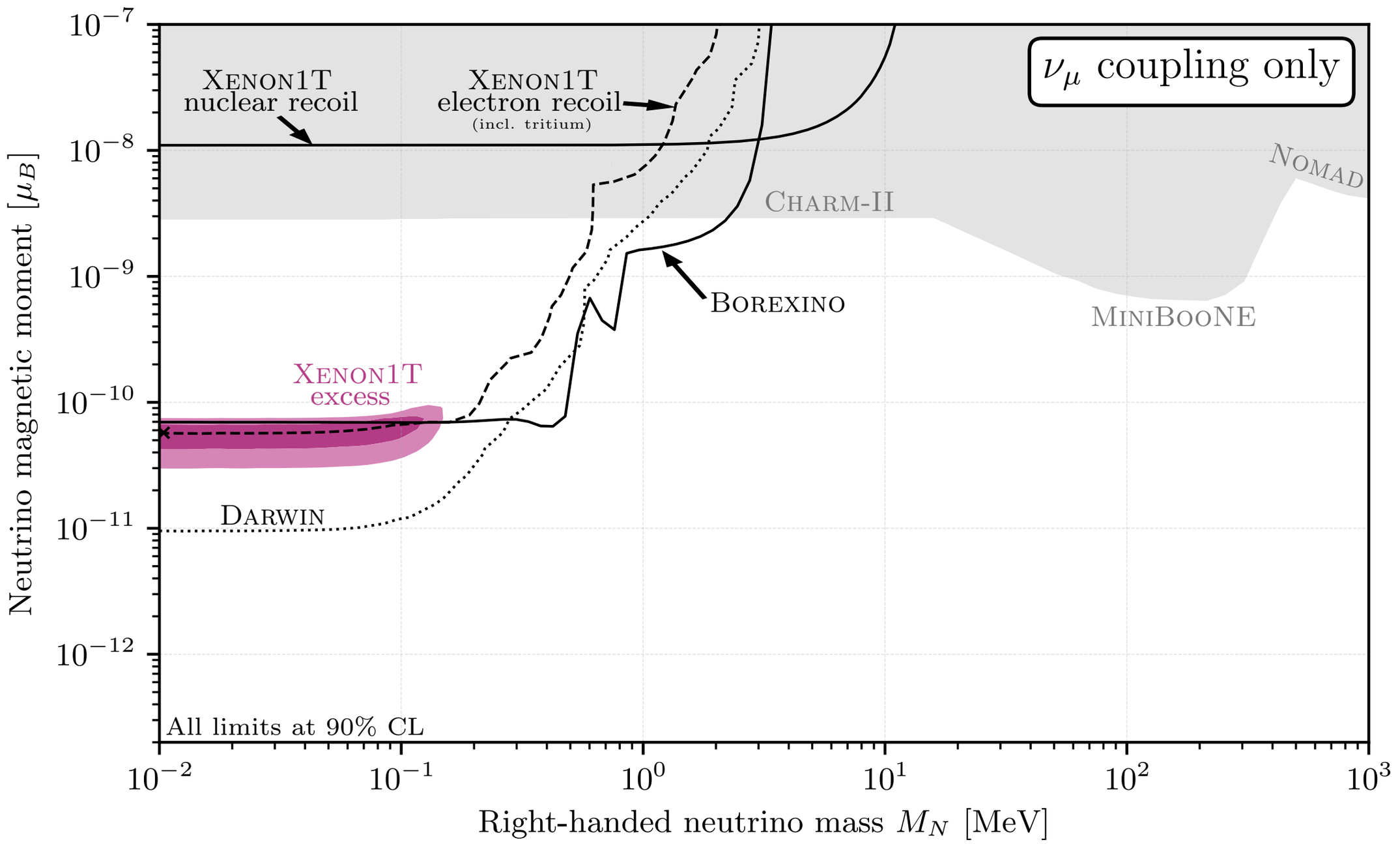
Stellar Cooling

☑ 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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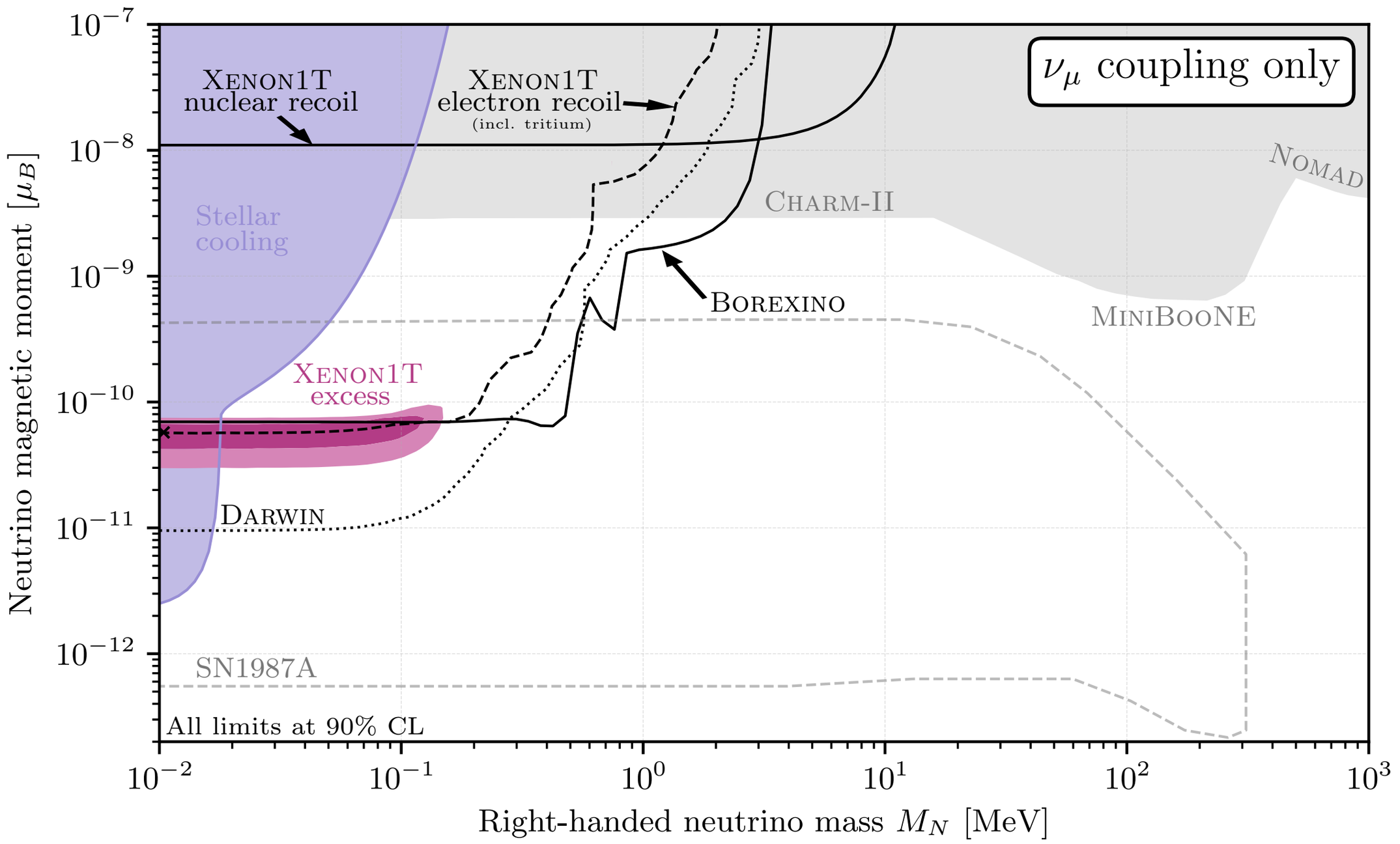

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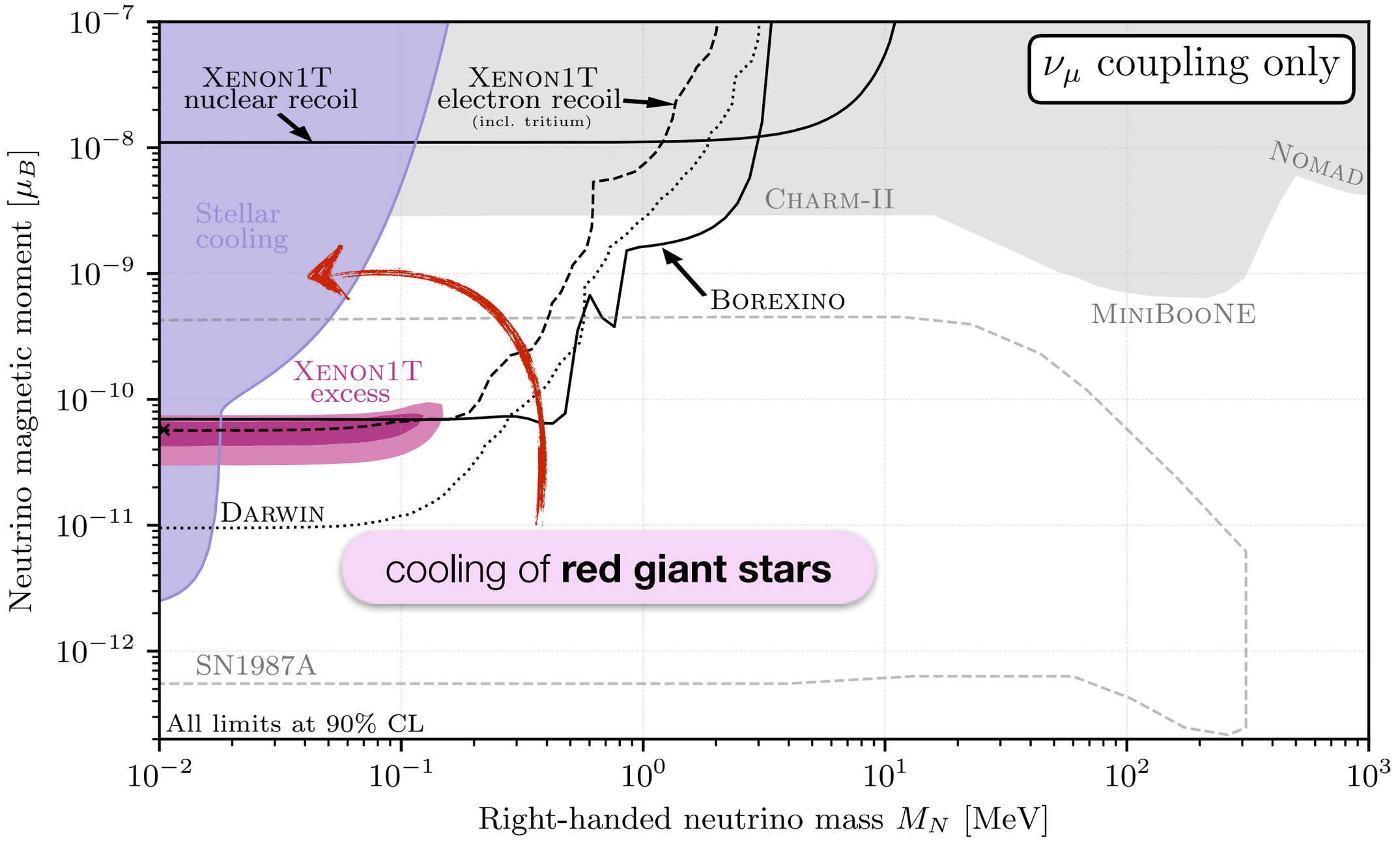

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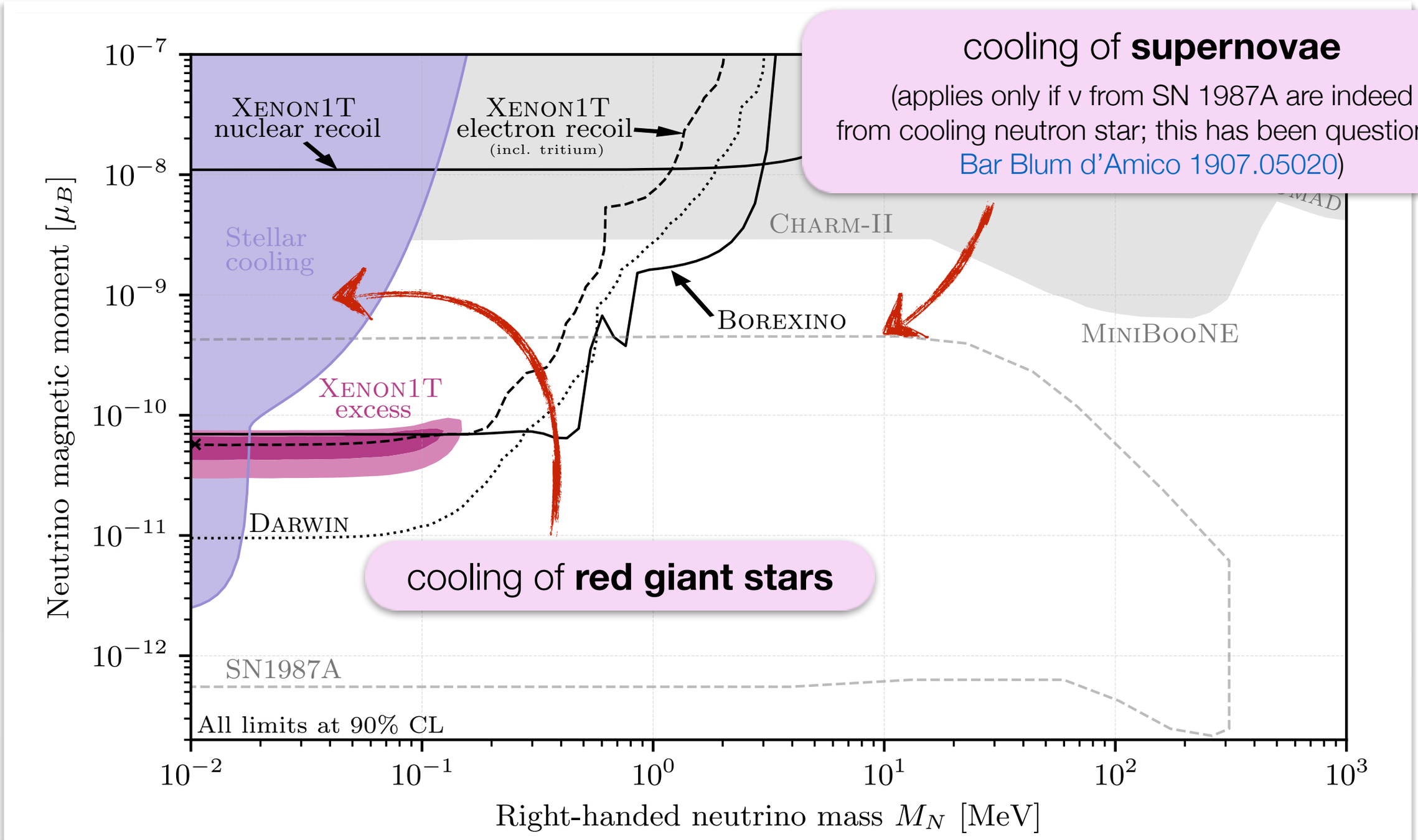

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Cosmology

Brdar Greljo JK Opferkuch 2007.15563
using codes adapted from
Arbey Auffinger Hickerson Jenssen 1806.11095
and Depta Hufnagel Schmidt-Hoberg 2002.08370

Cosmology

☑ BBN

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

Brdar Greljo JK Opferkuch 2007.15563
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☑ technical details ➡ backup slides

Brdar Greljo JK Opferkuch 2007.15563
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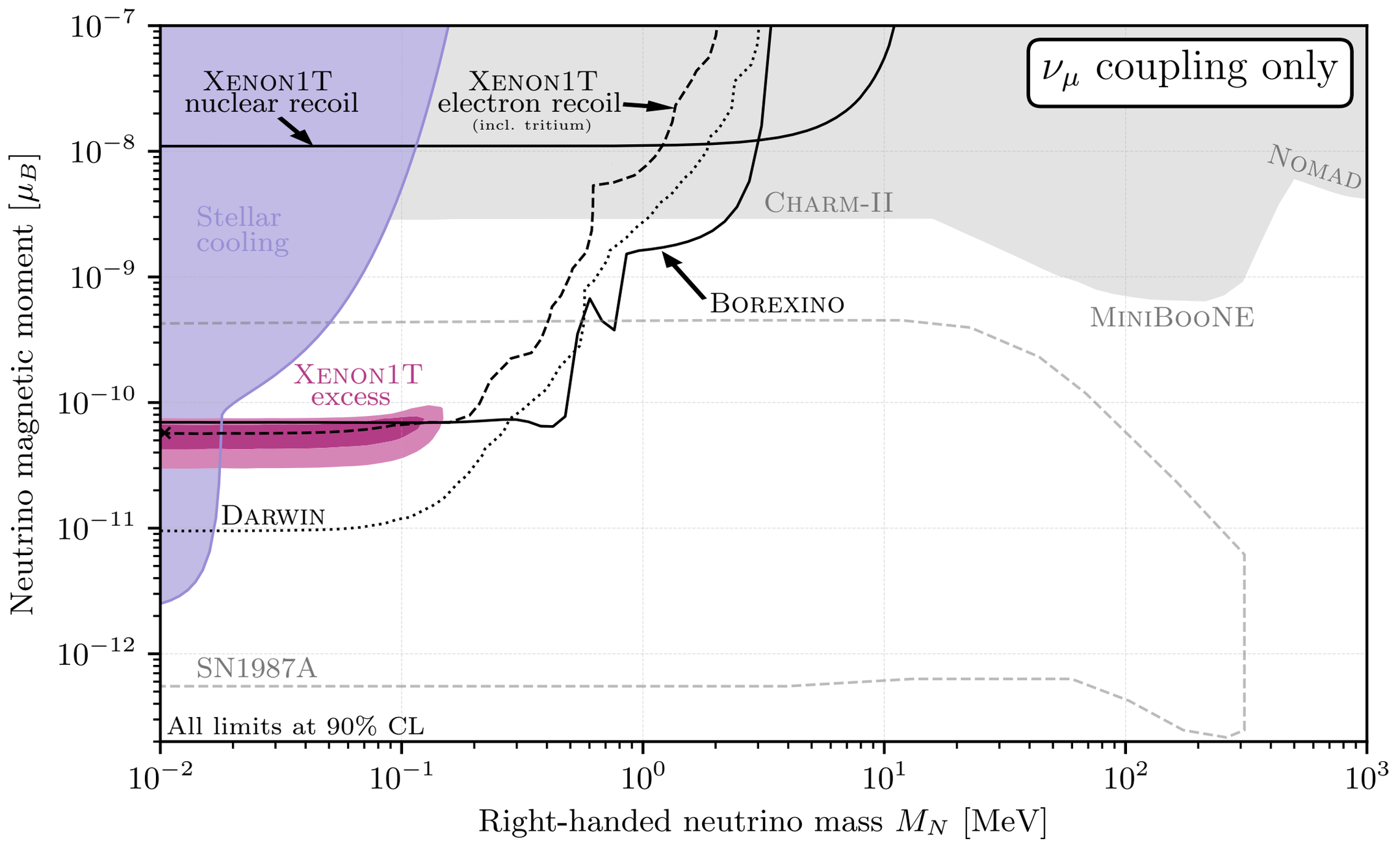
Summary of Constraints



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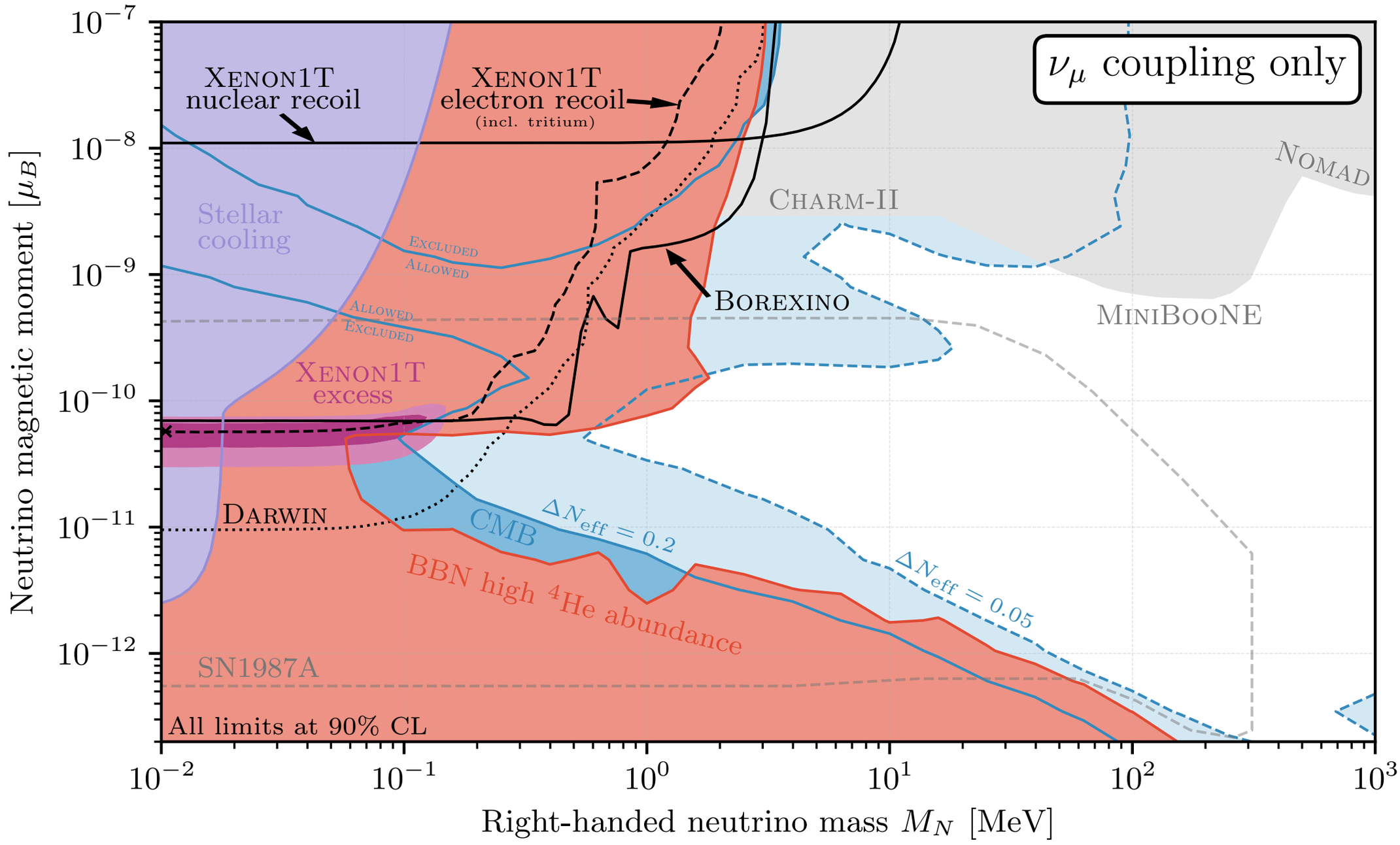

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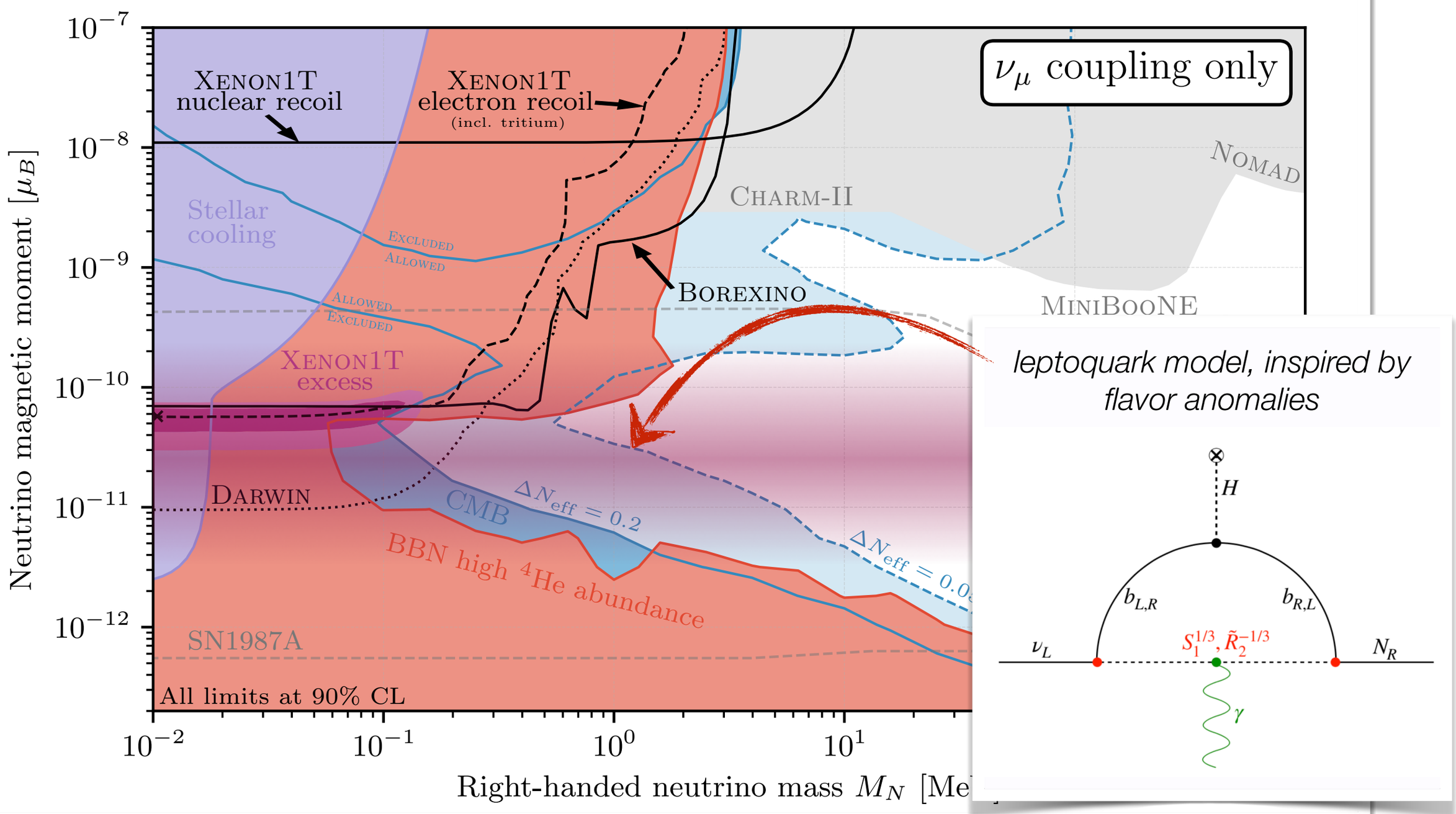

leptoquark model, inspired by flavor anomalies

Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
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Outlook

dim-4: the Neutrino Portal

dim-5: Neutrino Magnetic Moments

dim-6: Neutrinos in SMEFT

Outlook

dim-4: the Neutrino Portal

dim-5: Neutrino Magnetic Moments

- ☑ impact on supernova neutrinos
- ☑ impact on high-energy astrophysical neutrinos

dim-6: Neutrinos in SMEFT

Outline

dim-4: the Neutrino Portal

dim-5: Neutrino Magnetic Moments

dim-6: Neutrinos in SMEFT

New Neutrino Interaction

Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109
Biggio Blennow Fernandez-Martinez arXiv:0907.0097

New Neutrino Interaction

☑ EFT below the electroweak scale

$$\mathcal{L}_{\text{NSI,NC}} = \sum_{f,\alpha,\beta} 2\sqrt{2} G_F \varepsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f} \gamma^\mu P f) + \text{h.c.}$$

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dim-6 operators

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dimensionless coefficients
(strength of new interactions
relative to SM weak interactions)

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dimensionless coefficients
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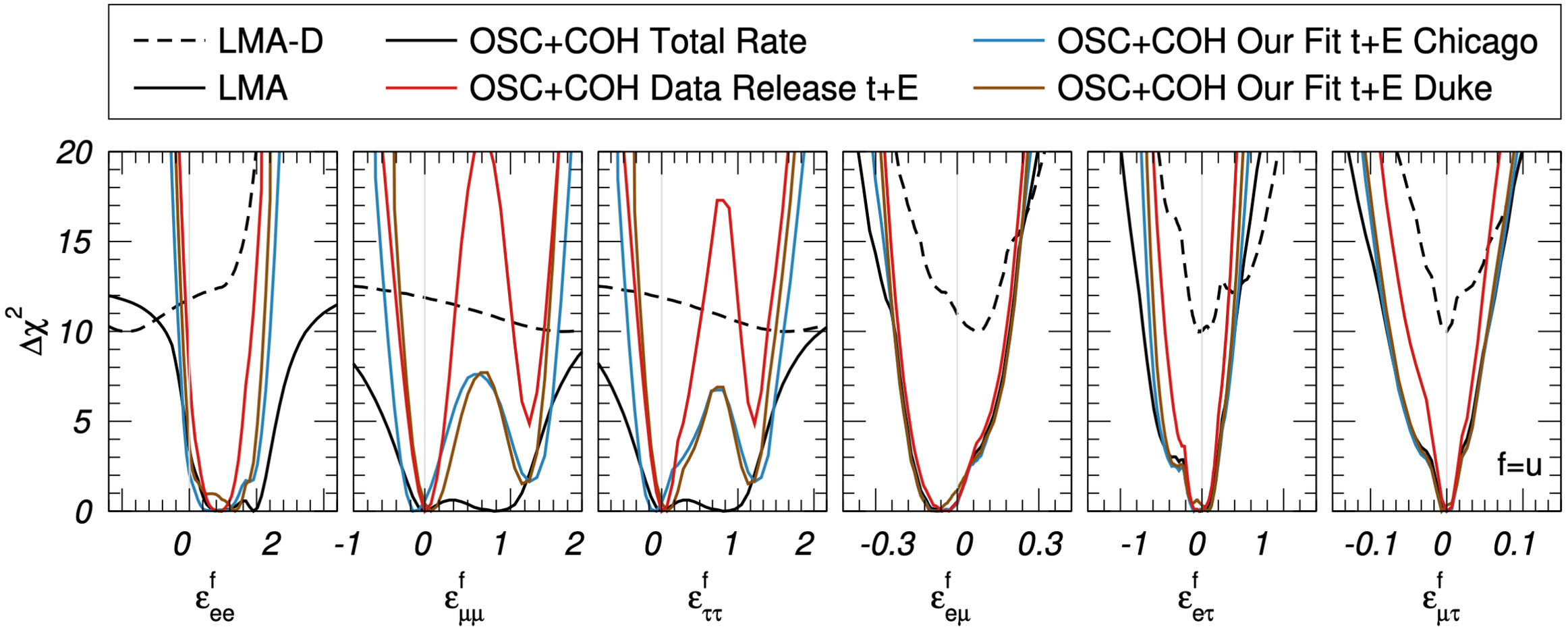
☑ NC: non-standard matter effects

☑ CC: anomalous production and detection

Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109
Biggio Blennow Fernandez-Martinez arXiv:0907.0097

Anomalous Neutral Currents in Oscillations



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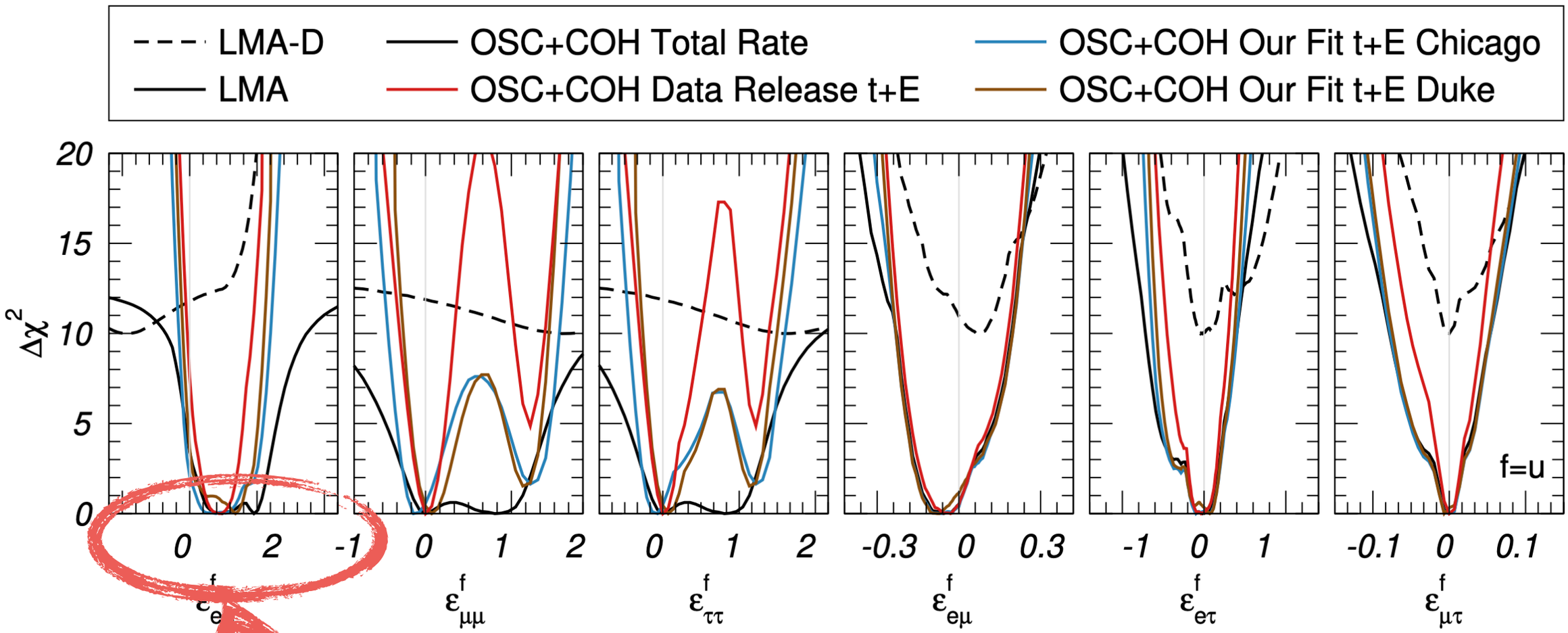
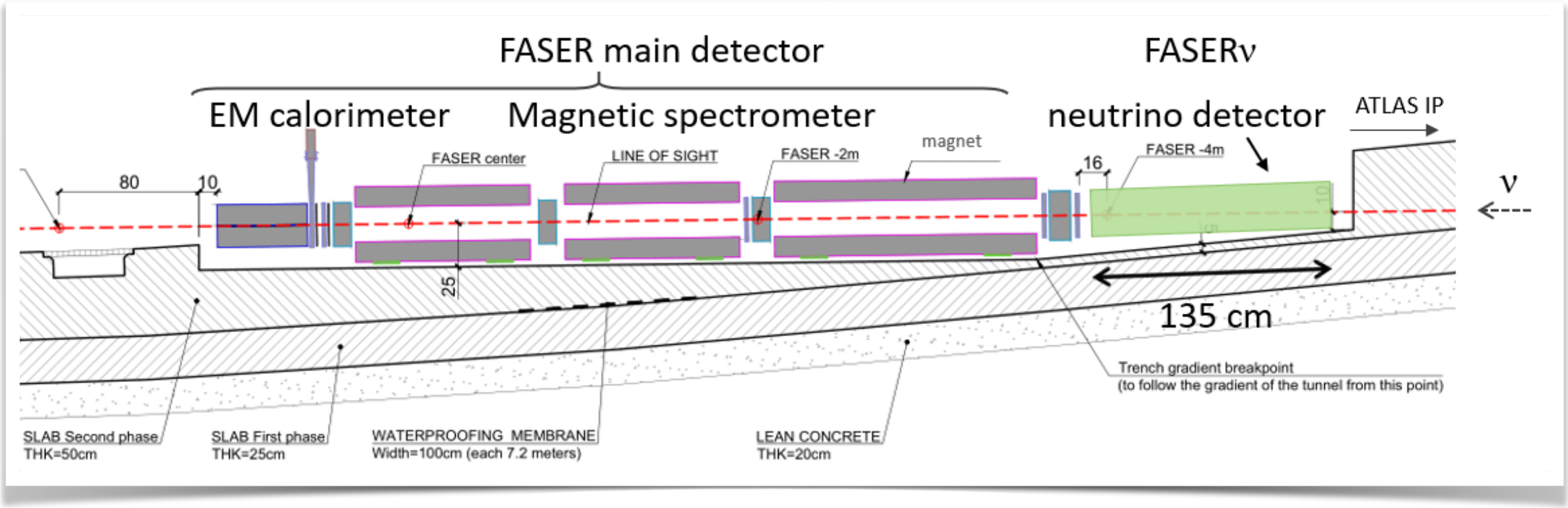


Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109

sensitivity to interactions
similar in strength to
SM weak interactions

Anomalous Charged Currents

☑ Interesting new opportunity: FASERν at the LHC



https://faser.web.cern.ch/about-the-experiment/detector-design/fasernu

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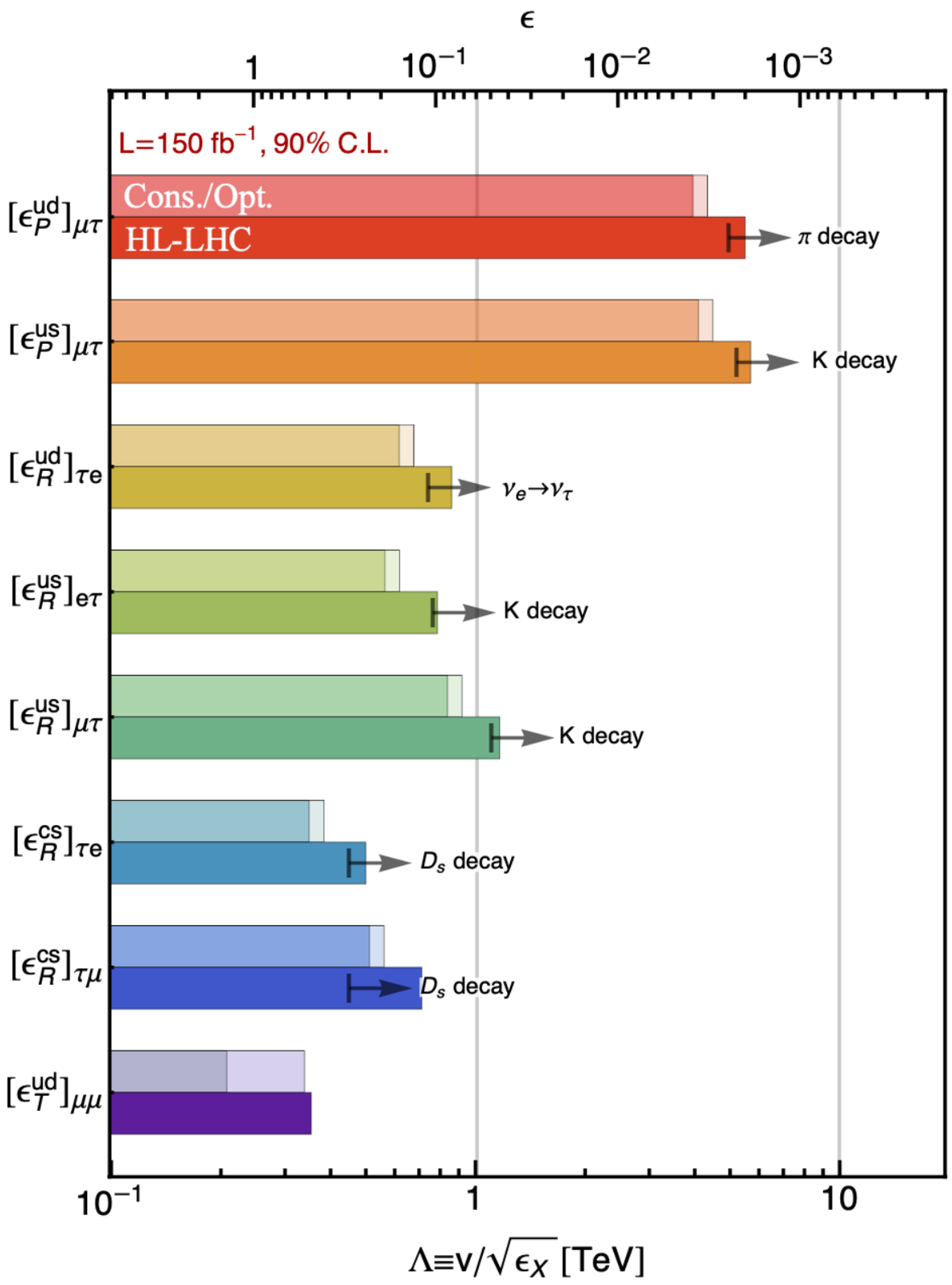

owski González-Alonso JK
Soreq Tabrizi, arXiv:2105.12136

Outlook

dim-4: the Neutrino Portal

dim-5: Neutrino Magnetic Moments

dim-6: Neutrinos in SMEFT

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dim-4: the Neutrino Portal

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- ☑ extend formalism to lower energies (Lee–Yang)
- ☑ implement in simulation tools

Summary

Outlook

dim-4: the Neutrino Portal

- ☑ upcoming experiments may resolve (some) anomalies
- ☑ … and lead to improved modelling of neutrino interactions

dim-5: Neutrino Magnetic Moments

- ☑ impact on supernova neutrinos
- ☑ impact on high-energy astrophysical neutrinos

dim-6: Neutrinos in SMEFT

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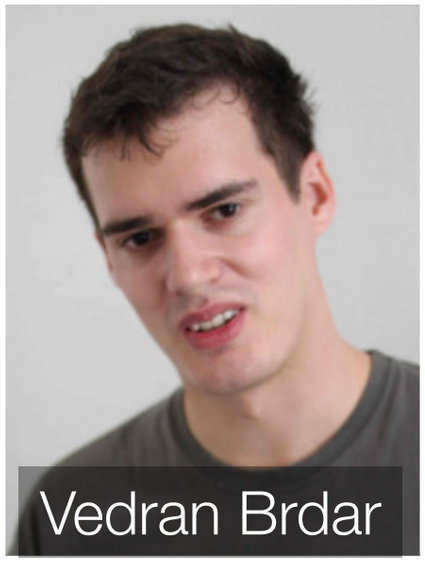
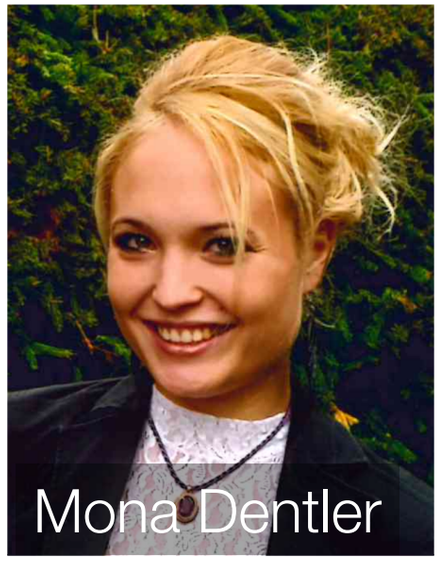
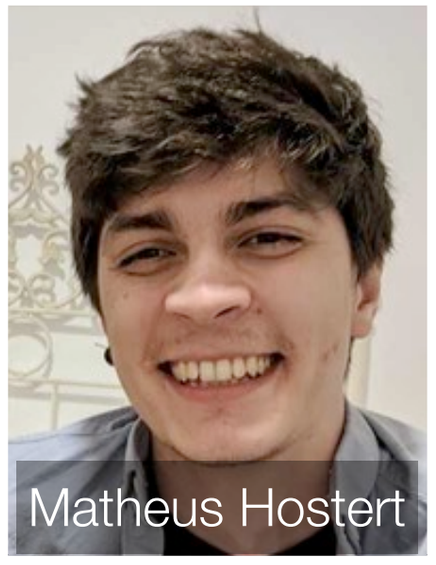
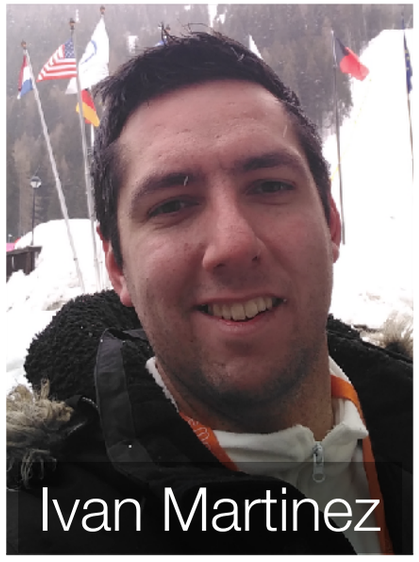
Thank You!

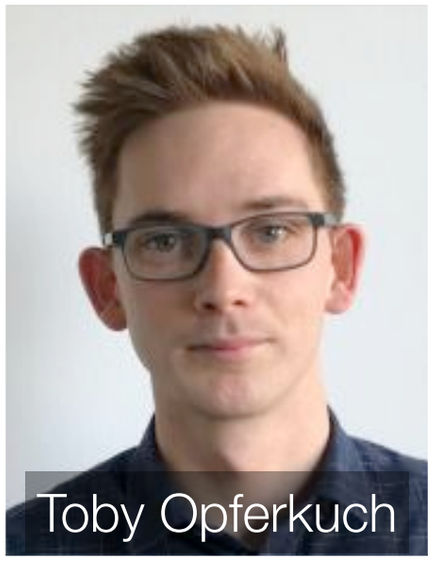

Vedran Brdar

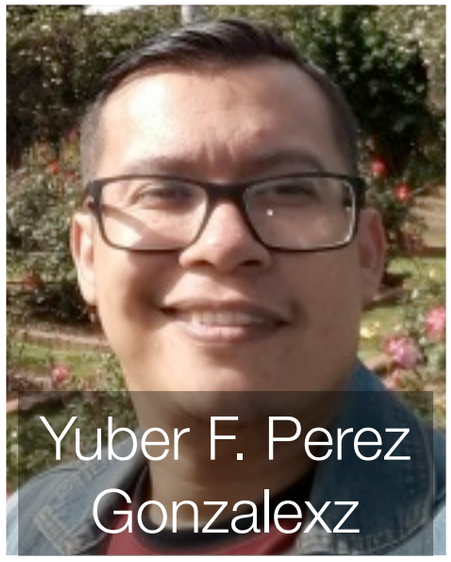

Mona Dentler


Ivan Esteban


Matheus Hostert


Ivan Martinez


Toby Opferkuch


Yuber F. Perez Gonzalexz


Zahra Tabrizi

Bonus Slides

CERN | Neutrino PLATFORM | erc | JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Oscillation Anomalies

CERN

Neutrino PLATFORM

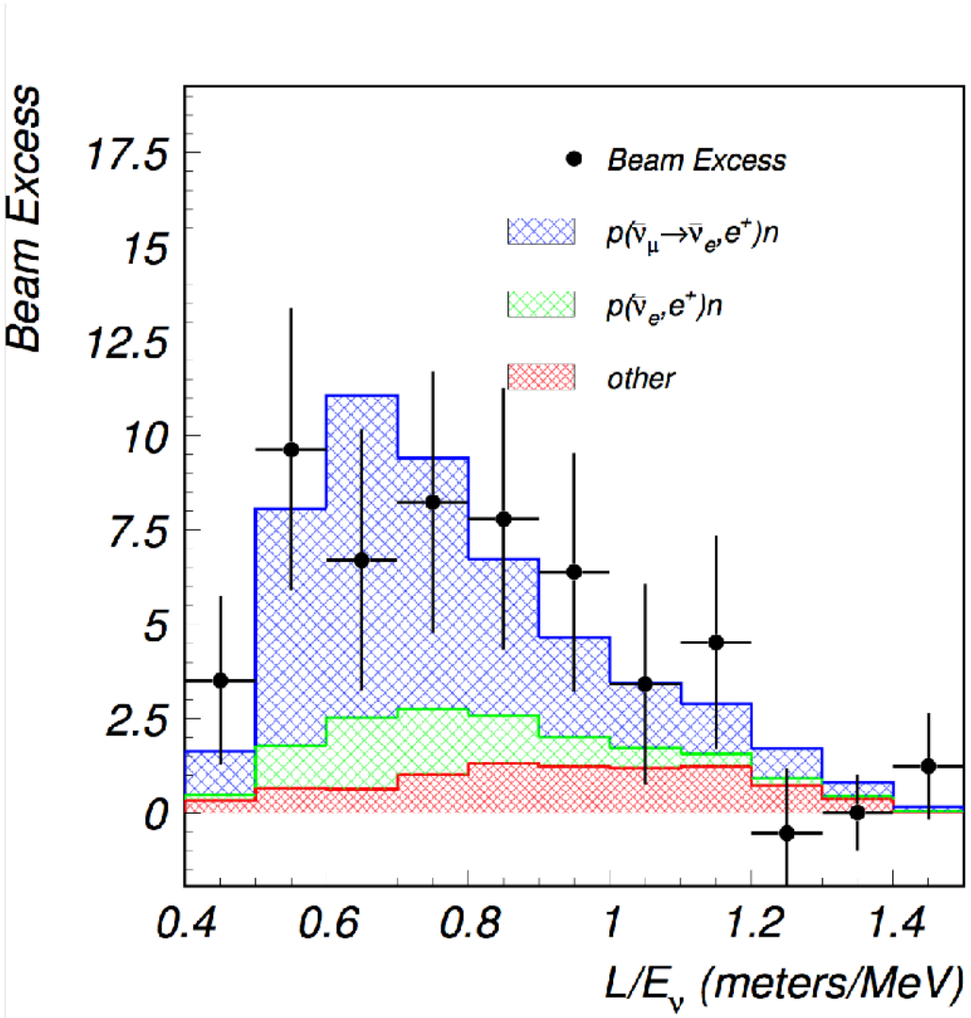
erc

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

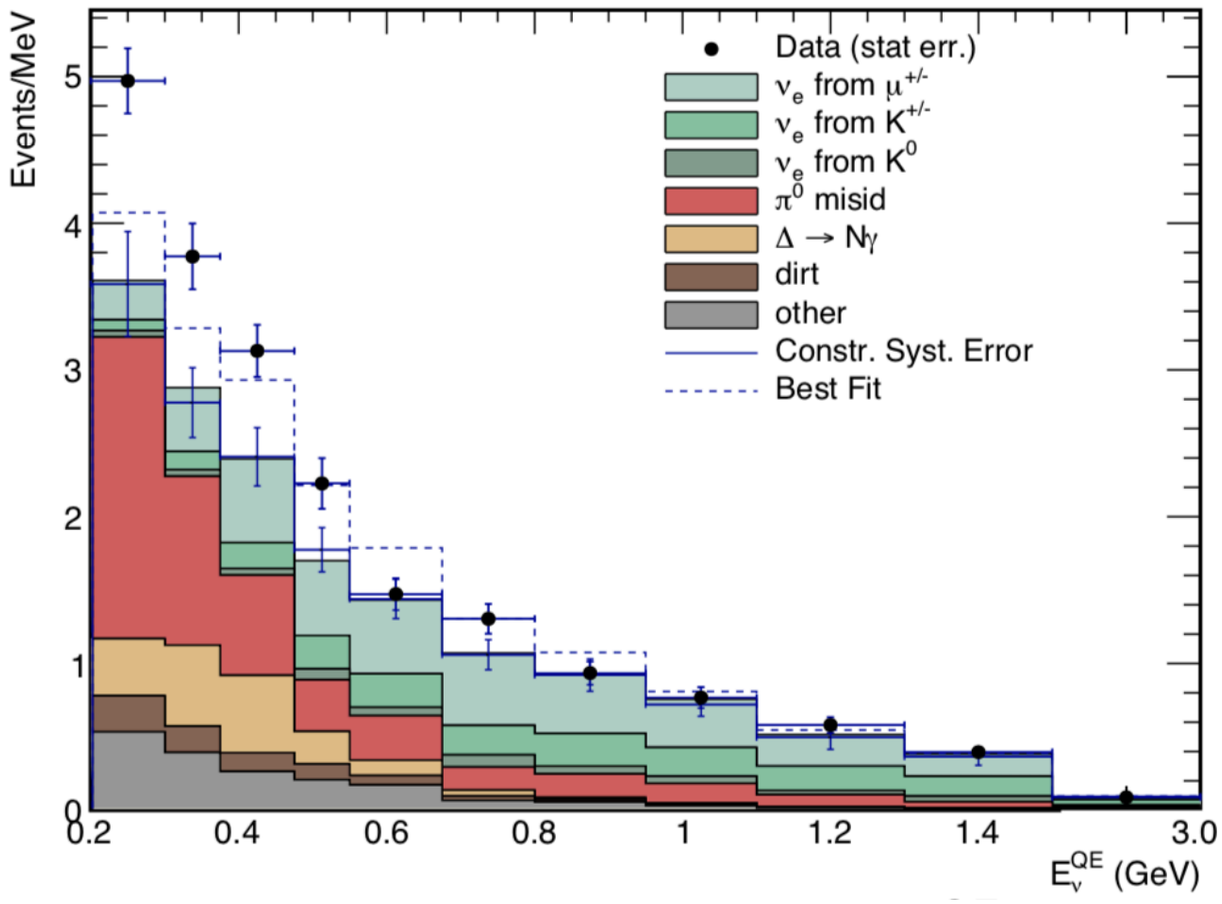
Anomalies in Short Baseline Oscillations

Anomalies in Short Baseline Oscillations

☑ LSND / MiniBooNE: anomalous $\nu_\mu \to \nu_e$ oscillations



LSND 2001



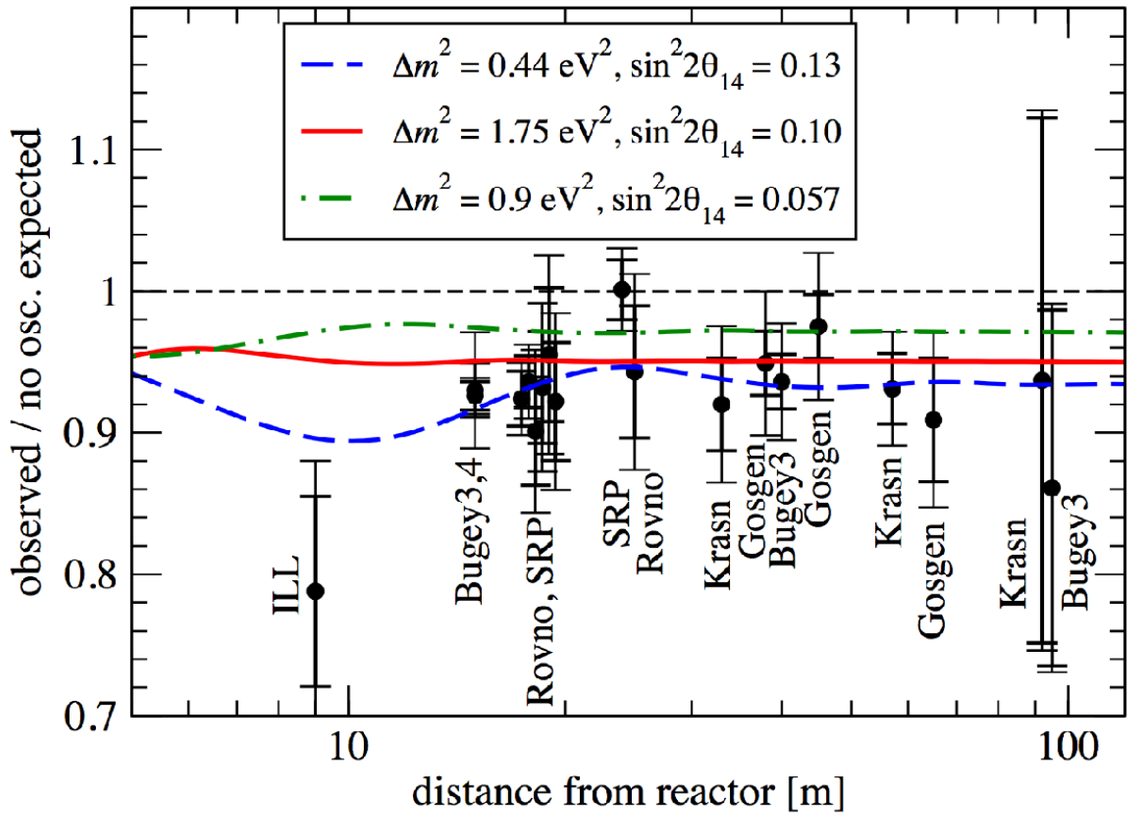
MiniBooNE 2018

Anomalies in Short Baseline Oscillations

☑ LSND / MiniBooNE: anomalous $\nu_\mu \to \nu_e$ oscillations

☑ Reactor & Gallium Experiments: anomalous ν_e disappearance

Mention et al., 1101.2755
Giunti Laveder, 1006.3244



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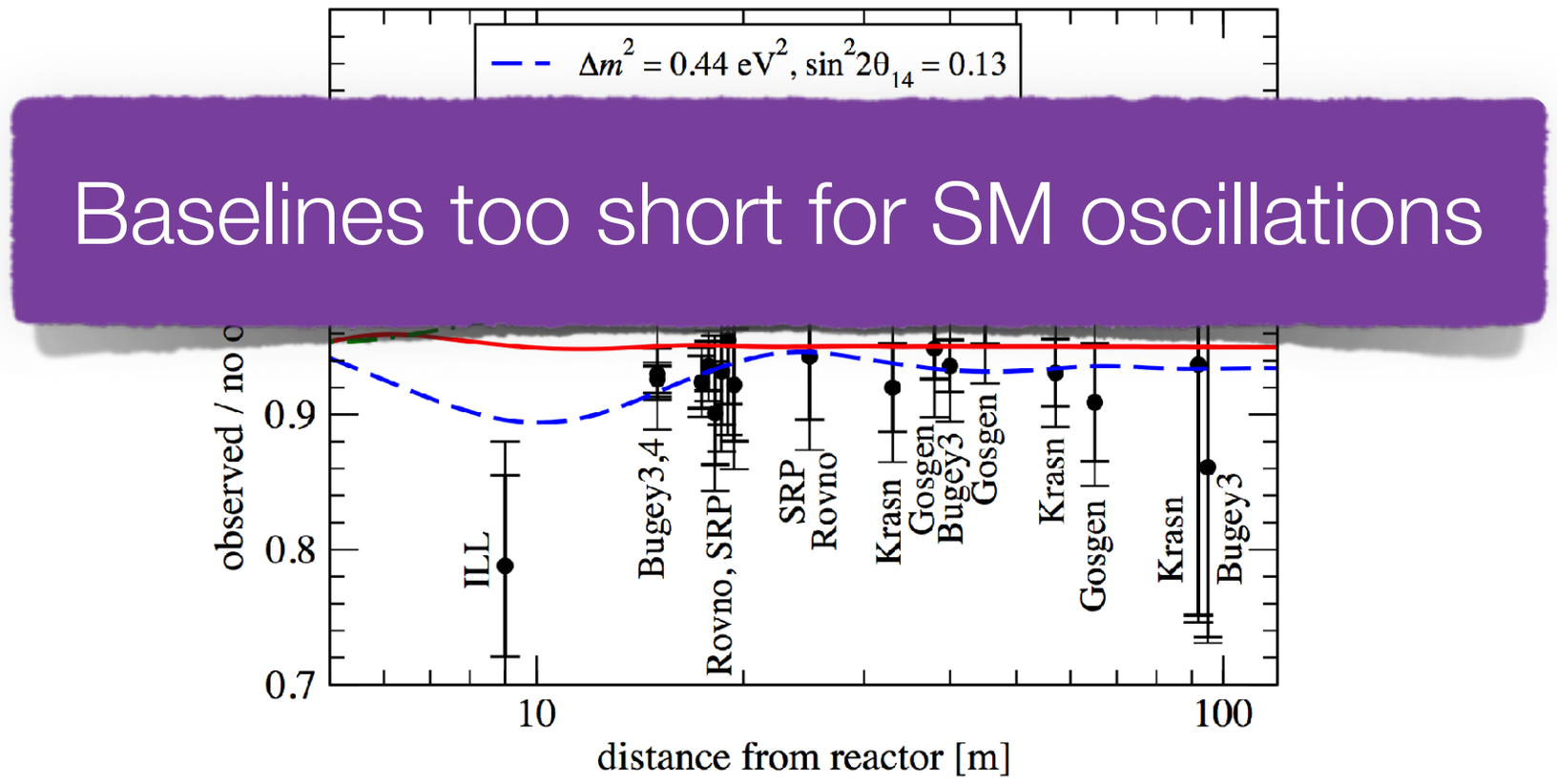
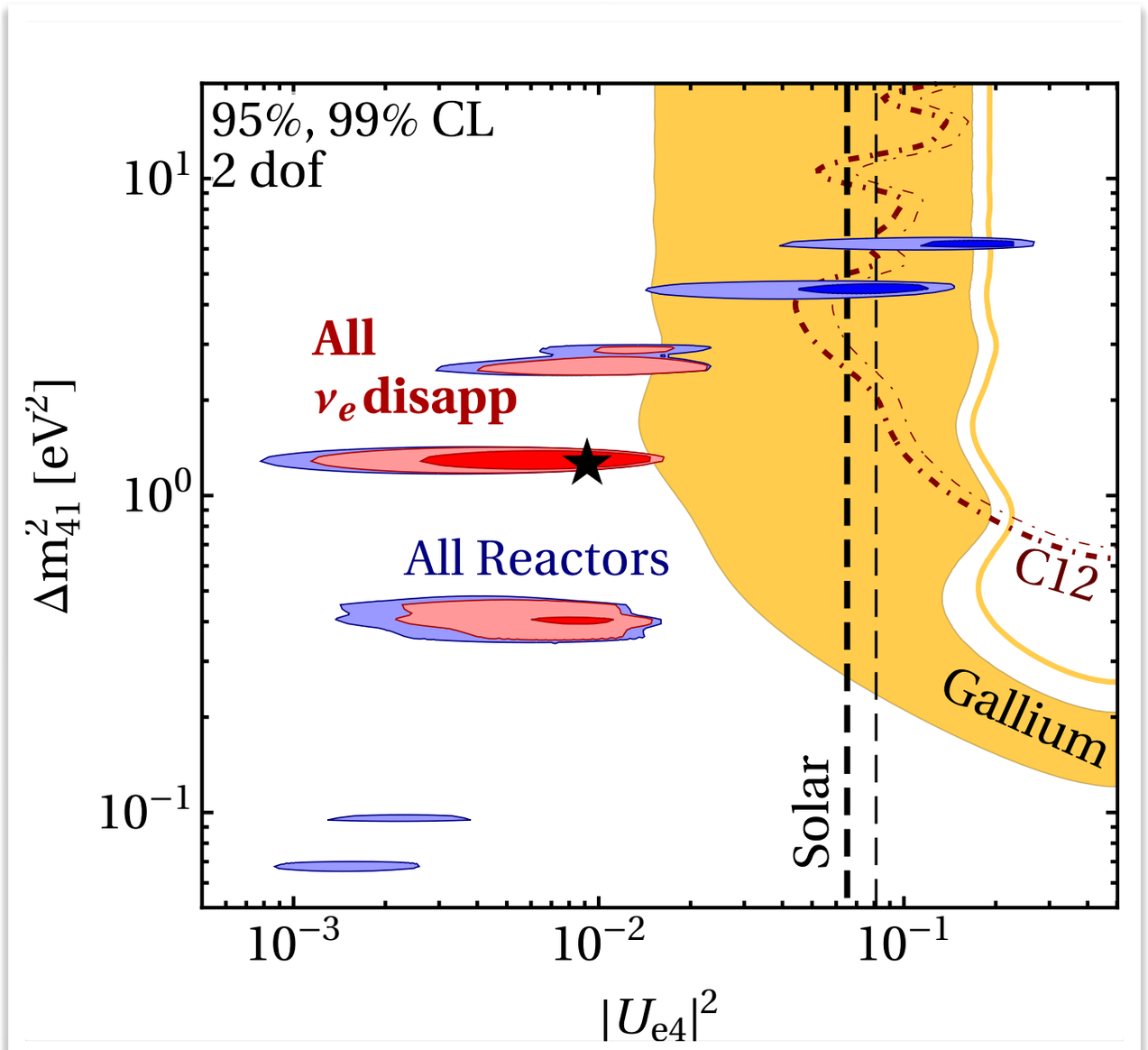


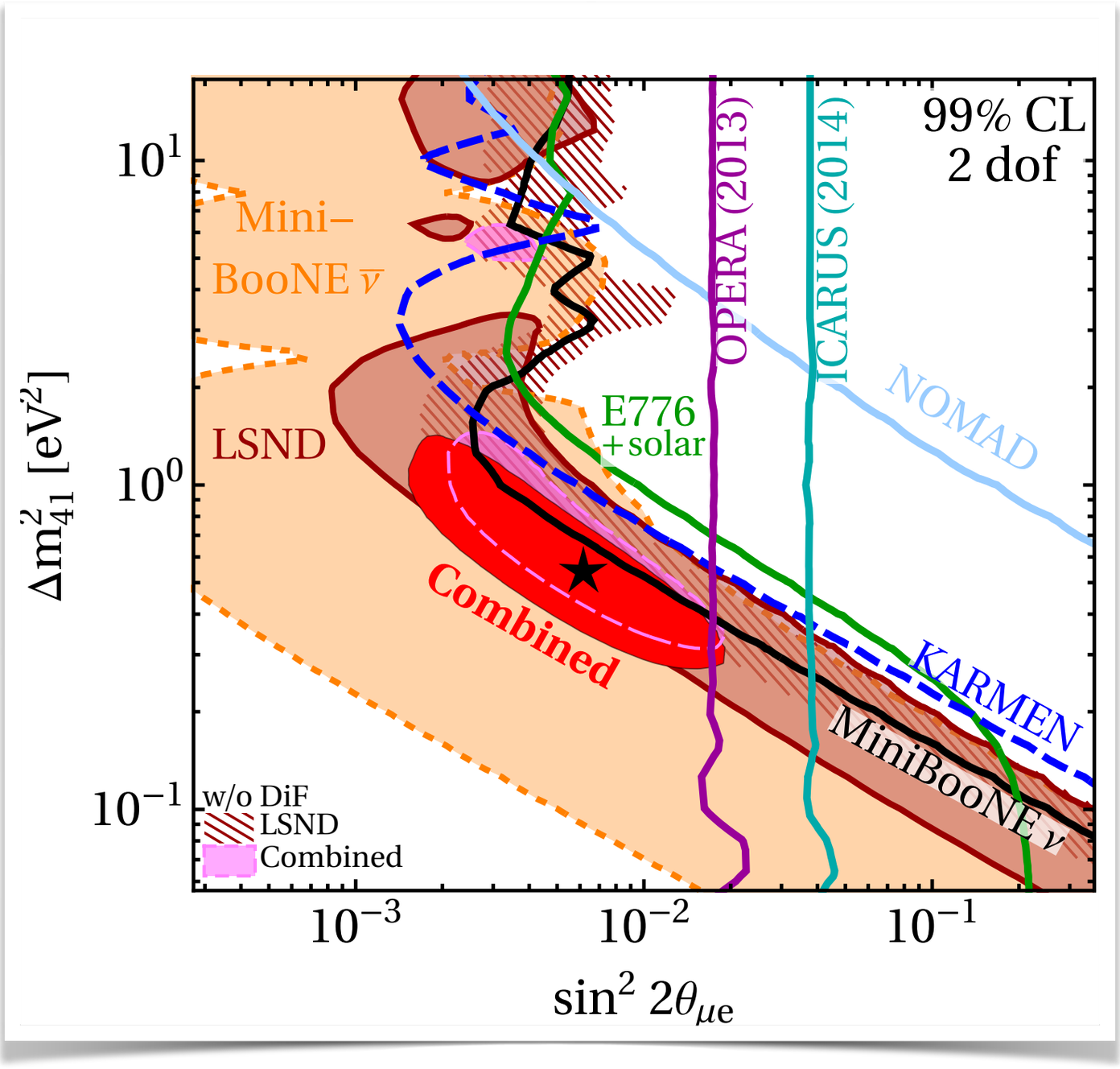
Baselines too short for SM oscillations

Global Fit to ν_e and $\bar{\nu}_e$ Disappearance



Dentler Hernández JK Maltoni Schwetz 1709.04294
Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*

$\nu_\mu \rightarrow \nu_e$ appearance



Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*

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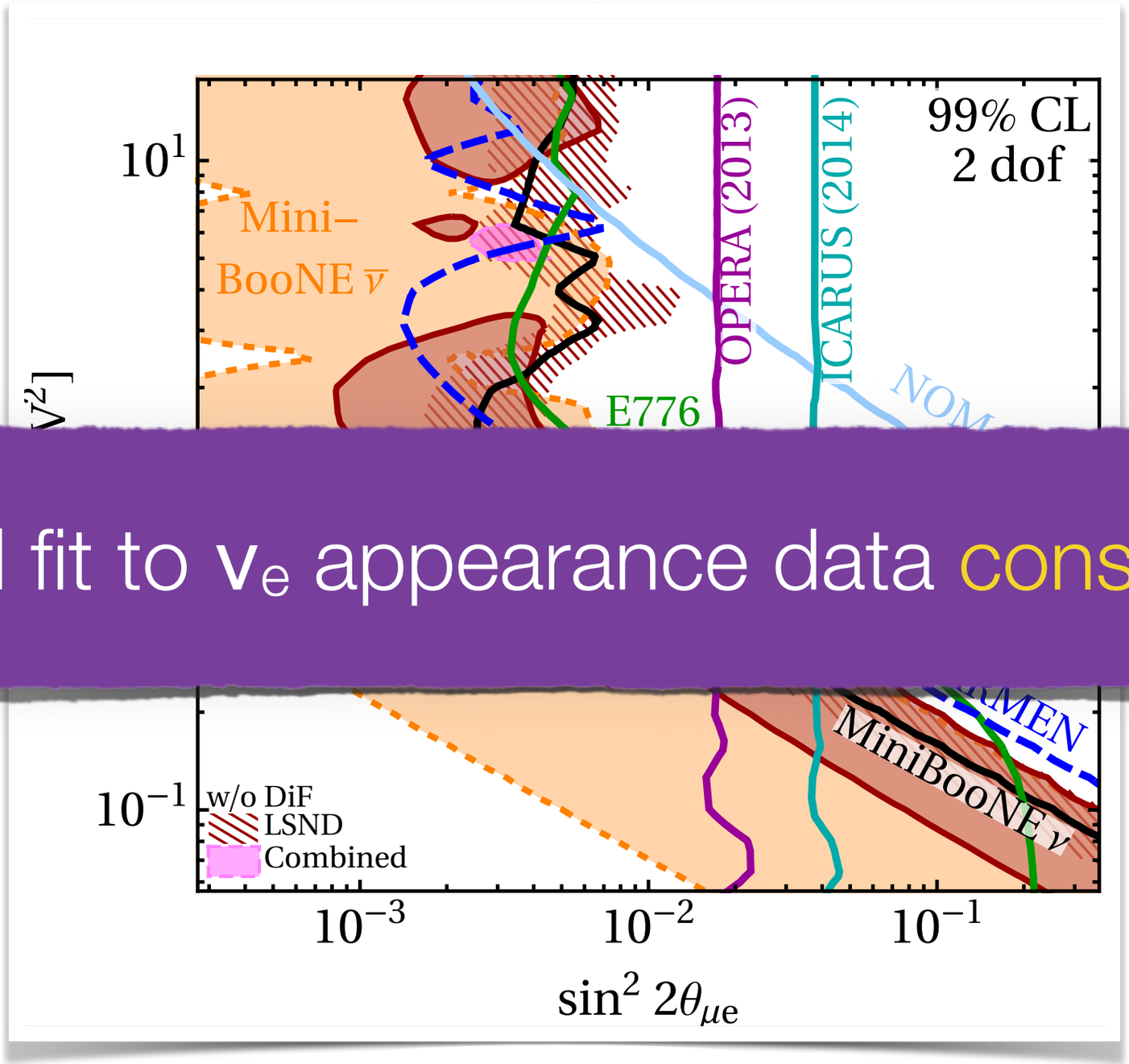
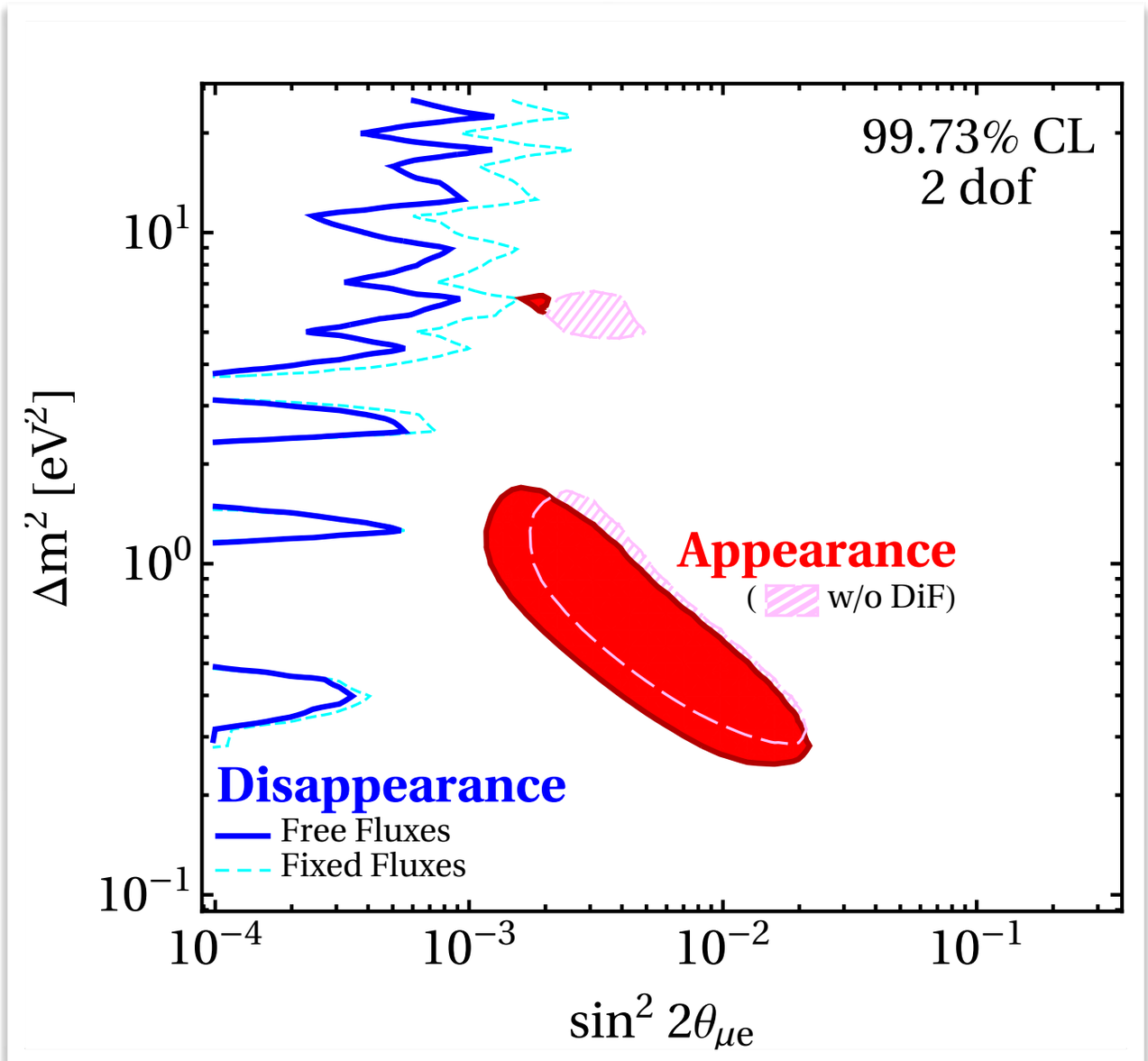


Global fit to ν_e appearance data consistent.

Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*

Appearance vs. Disappearance



Dentler Hernández JK Machado Maltoni Martinez Schwetz, *in preparation*
see also works by Collin Argüelles Conrad Shaevitz, e.g. 1607.00011,
Gariazzo Giunti Laveder Li, e.g. 1703.00860

Magnetic Moments

CERN

Neutrino PLATFORM

erc

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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:

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

Brdar Greljo JK Opferkuch 2007.15563

Big Bang Nucleosynthesis — Implementation

☑ Solve (integrated) Boltzmann equations:

Hubble expansion

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e^+e^- annihilation

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Big Bang Nucleosynthesis — Implementation

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e^+e^- annihilation

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Big Bang Nucleosynthesis — Implementation

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e^+e^- annihilation

e^+N_R scattering

N_R decay

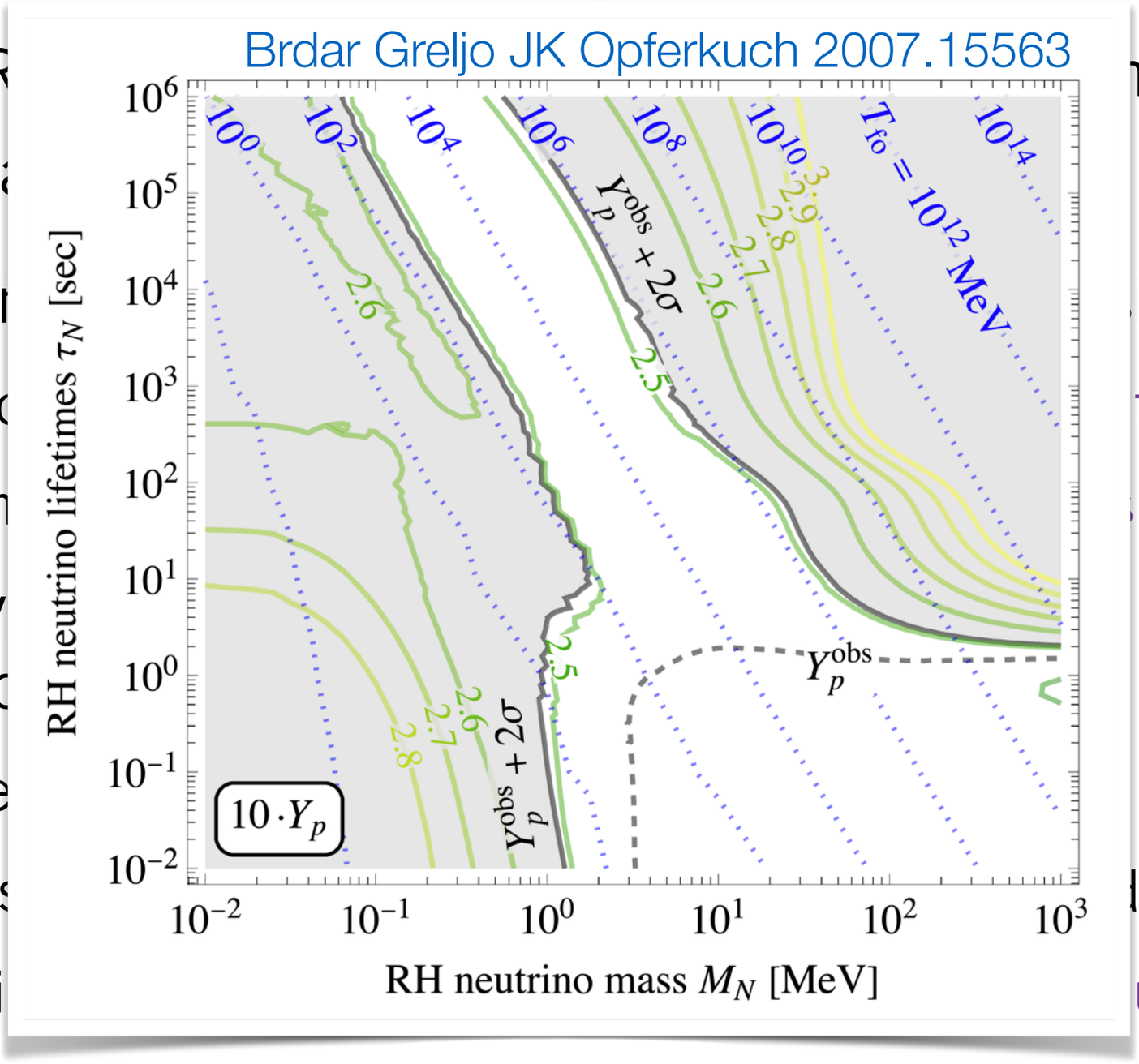
Brdar Greljo JK Opferkuch 2007.15563

Big Bang Nucleosynthesis — Results

Consider a R … nt μ_R .

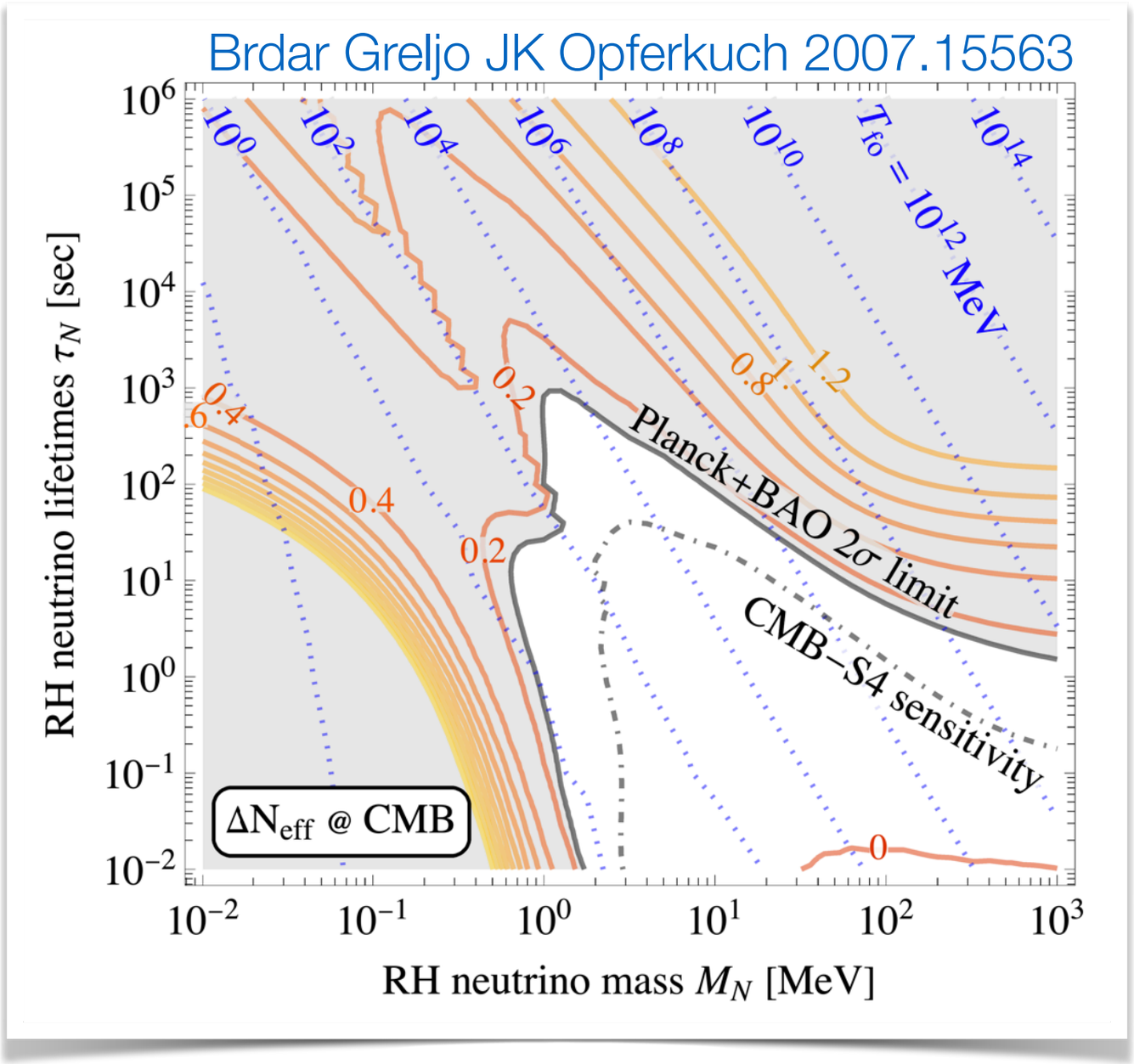
Assume deca …

- ☑ N_R presen … ion
  - $p \leftrightarrow n$ c … trons
  - Less tin …
- ☑ N_R decay … baryon-to …
  - η is pre …
  - Decreas … during BBN
  - Deuteri … utron-rich nuclei



Cosmic Microwave Background

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



New ν Physics

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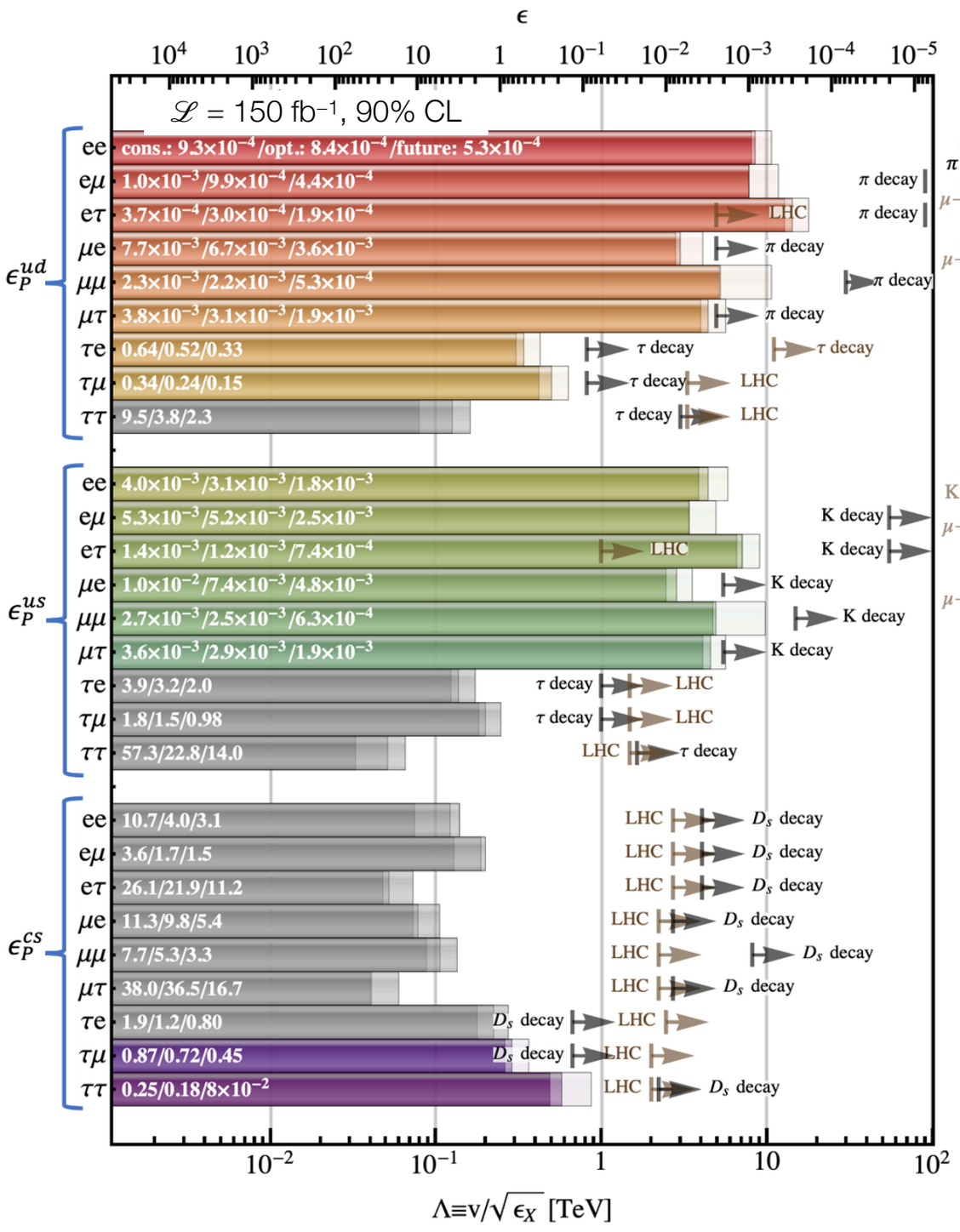
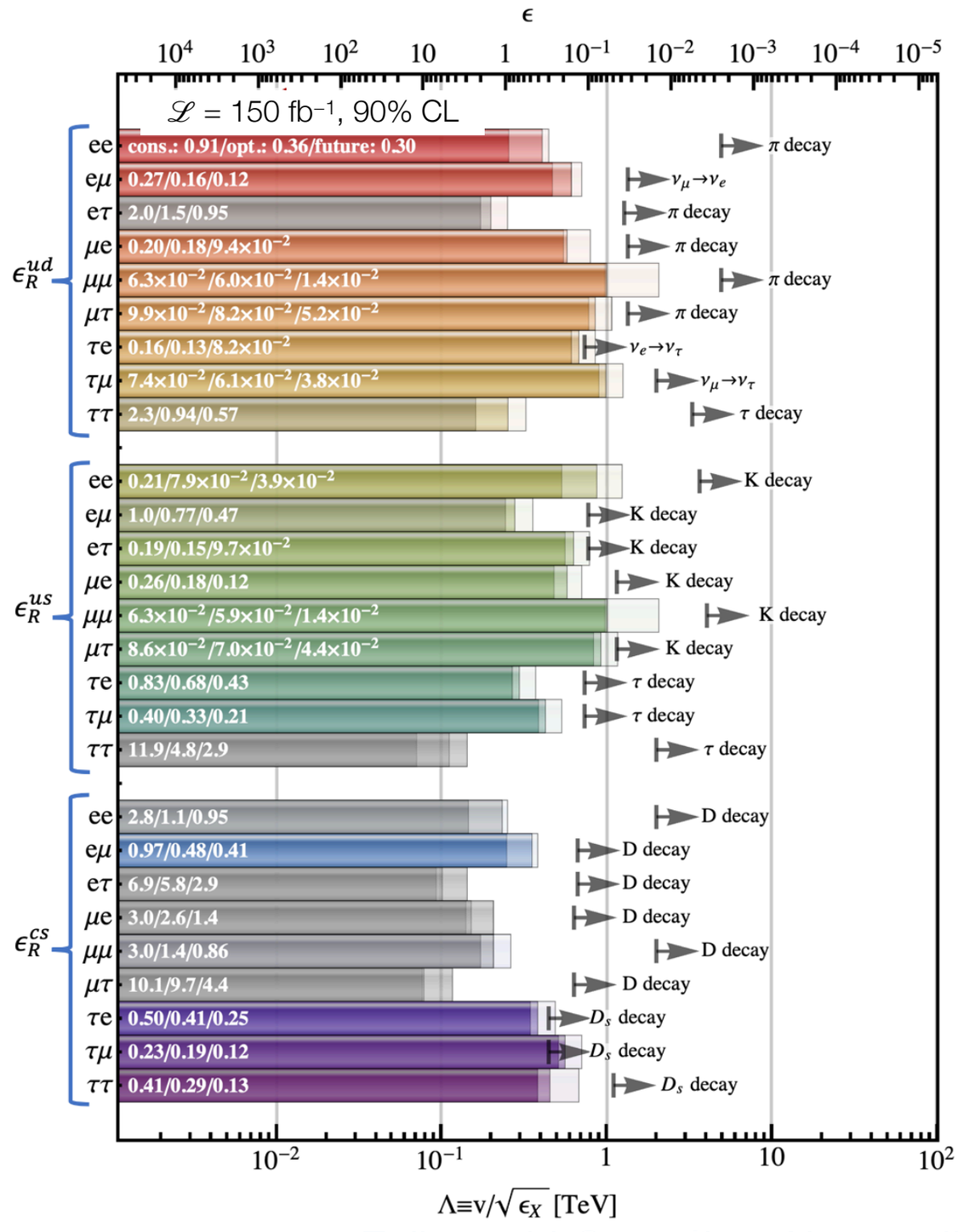
Anomalous Charged Currents





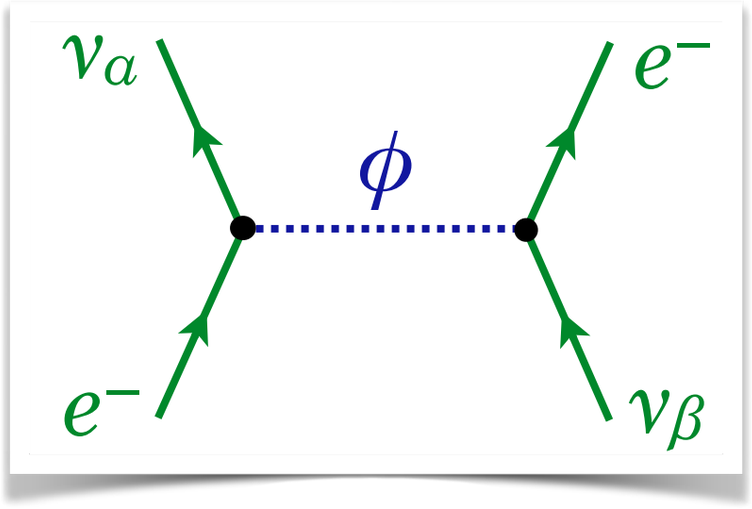
Falkowski González-Alonso JK
Soreq Tabrizi, arXiv:2105.12136

Are $\mathcal{O}(0.01\ G_F)$ Coupling Realistic?

☑ standard lore: because of $SU(2)_L$ invariance,
new neutrino interactions are accompanied by
similar couplings of charged leptons ➠ strong constraints

☑ but not always: consider charged $SU(2)_L$ singlet ϕ^+

$$\mathcal{L} \supset \frac{\xi^{\alpha\beta}}{2} \bar{L}_a^{c,\alpha} \epsilon_{ab} L_b^\beta \phi^+$$



$$\mathcal{L}_{\text{EFT}} \supset \frac{\xi^{\alpha\beta}\xi^{\gamma\delta *}}{4m_\phi^2} \left[\bar{L}_a^{c,\alpha} \epsilon_{ab} L_b^\beta\right] \left[\bar{L}_a^{c,\delta} \epsilon_{ab} L_b^\gamma\right]$$

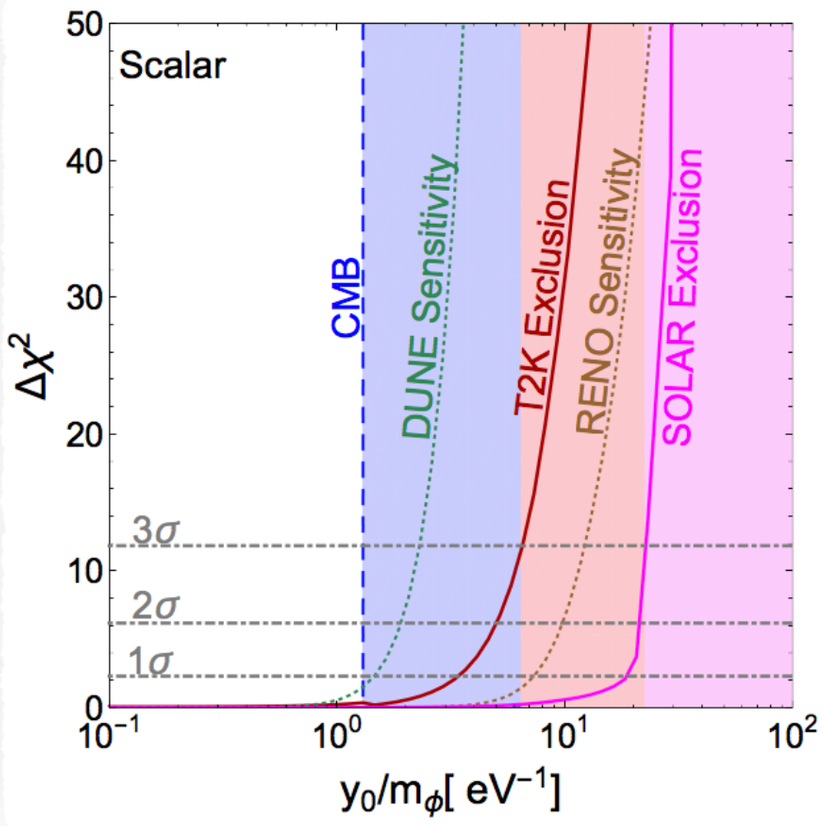
☑ coupling can arise naturally from TeV scale new physics

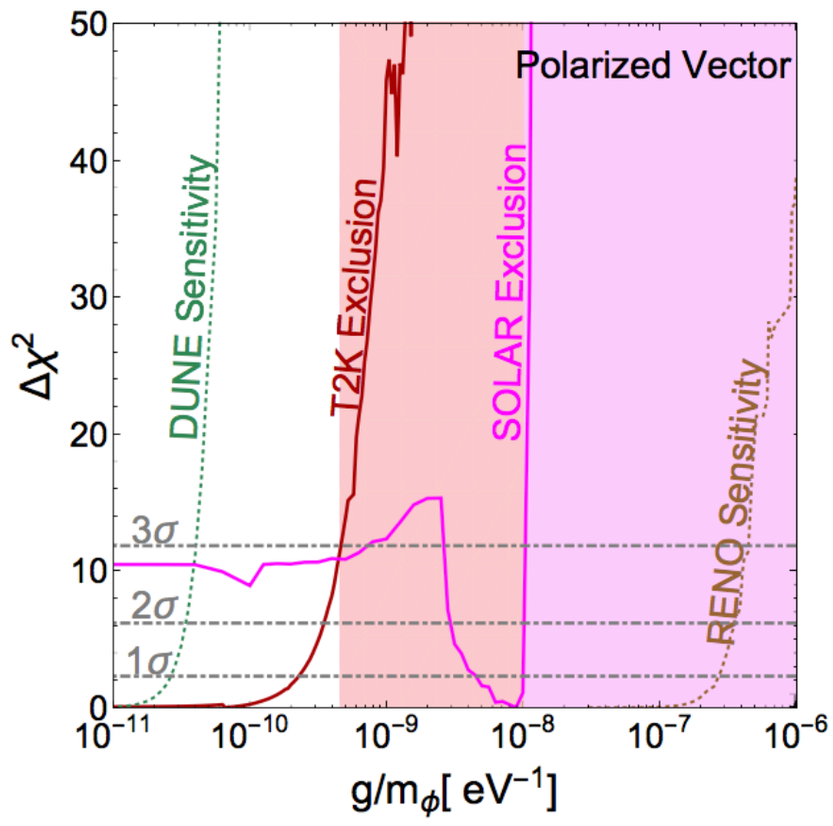
Crivellin Kirk Manzari Panizzi arXiv:2012.09845
Crivellin Esteban JK, *in preparation*

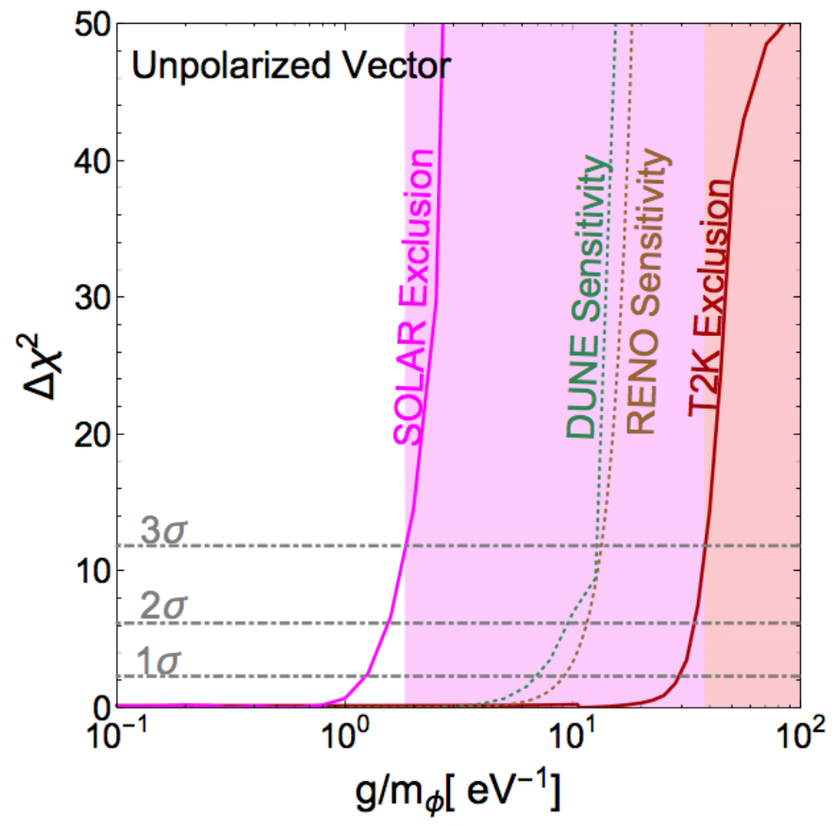
Neutrino—DM Interactions

- ☑ Coherent forward scattering of neutrinos on DM
  - an
  - Requires huge DM number density

Limits from Long-Baseline Experiments







Neutrino—DM Interactions

- ☑ Coherent forward scattering of neutrinos on DM
  - analogous to SM matter effects (“MSW effect”)
  - Requires huge DM number density
- ☑ Fuzzy Dark Matter
  - scalar or vector, $m < 10^{-20}$ eV
  - Compton wave length ~ pc
  - Interesting for small scale structure

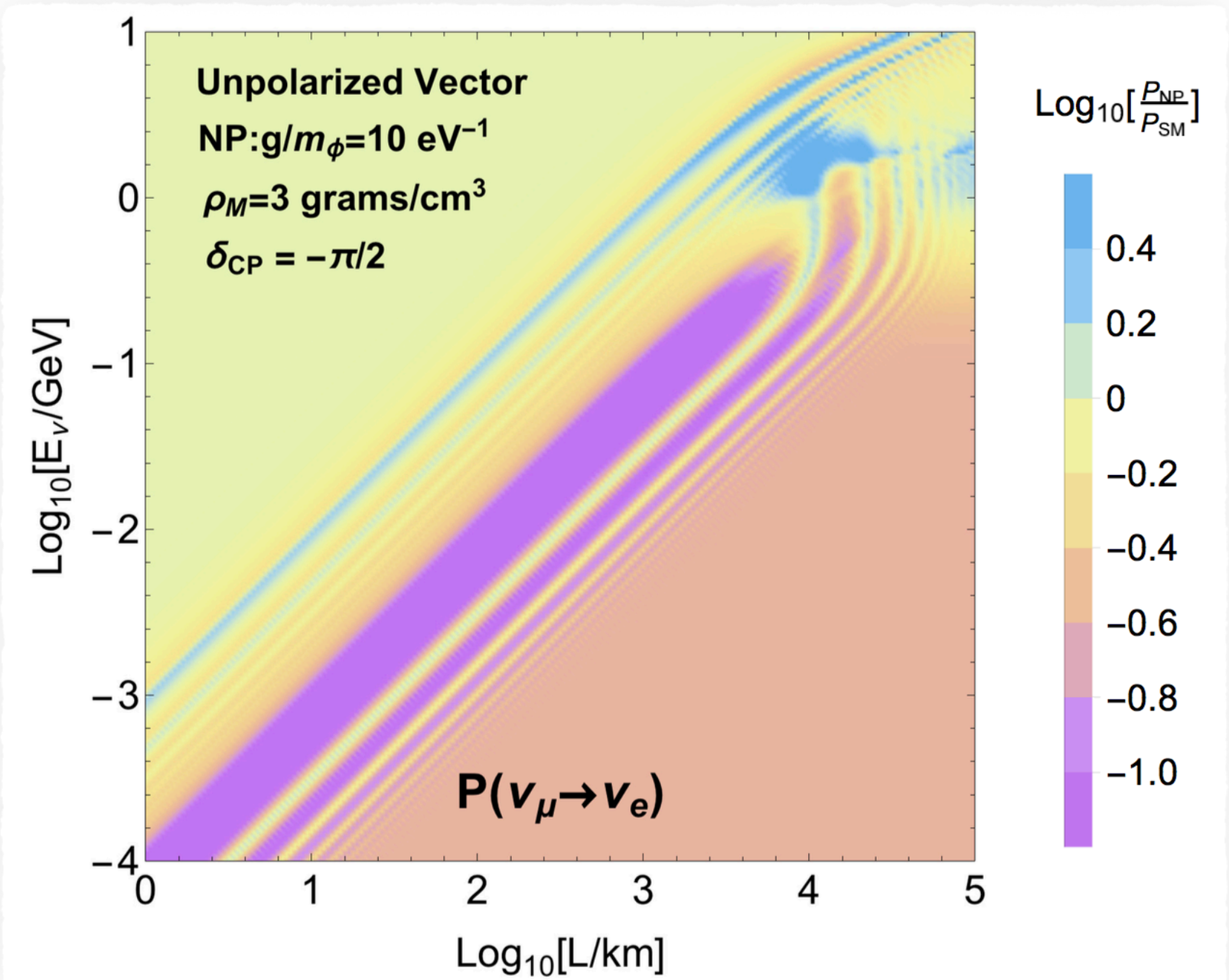
Krnjaic Machado Necib, 1705.06740
Brdar JK Liu Prass Wang, 1705.09455
Capozzi Shoemaker Vecchi 1804.05117

Neutrino—DM Interactions

Modified Oscillation Probabilities

- ☑ Coherent
  - ana
  - Req
- ☑ Fuzzy
  - scal
  - Con
  - Inte

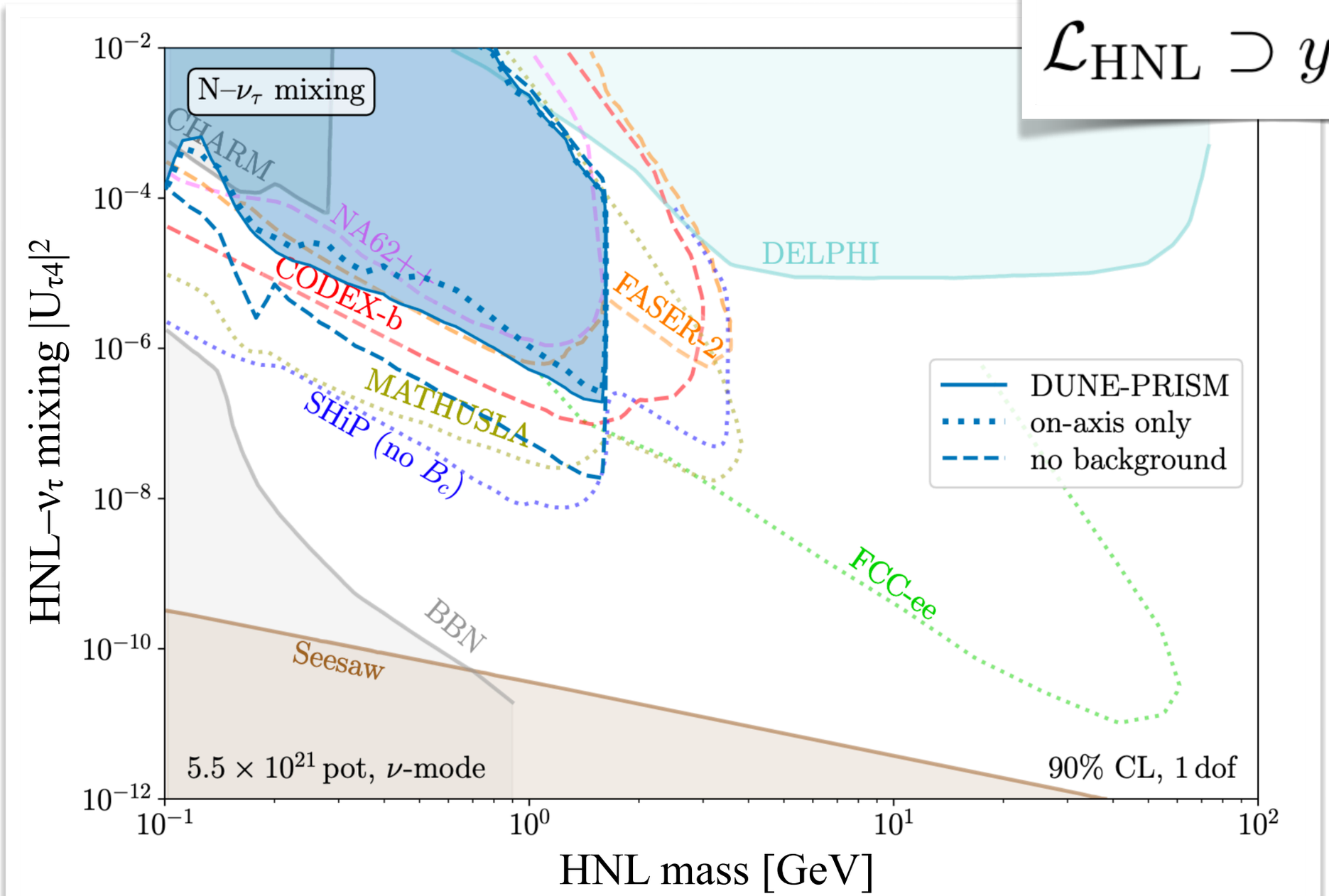
M



.06740
.09455
.05117

Example: Heavy Neutral Leptons

$$\mathcal{L}_{\text{HNL}} \supset y \bar{L} \tilde{H} N$$

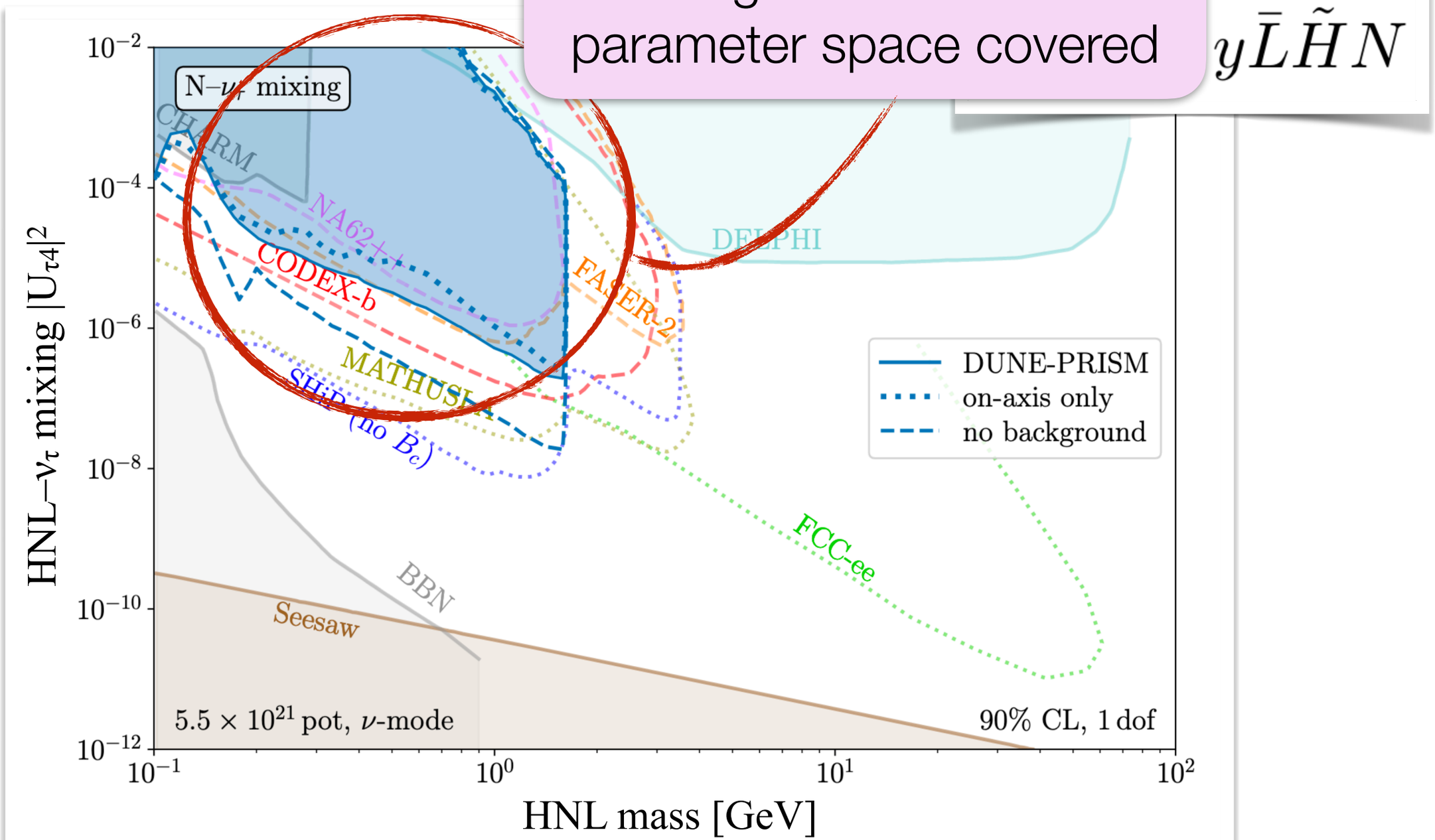


Breitbach Buonocore Frugiuele JK Mittnacht arXiv:2102.03383
see also works by Ballett Boschi Coloma Dobrescu Fernandez-Martinez Gonzalez-Lopez Harnik Hernandez-Martinez Pascoli Pavlovic

Example: Heavy Neutral Leptons

significant new
parameter space covered

$$y\bar{L}\tilde{H}N$$



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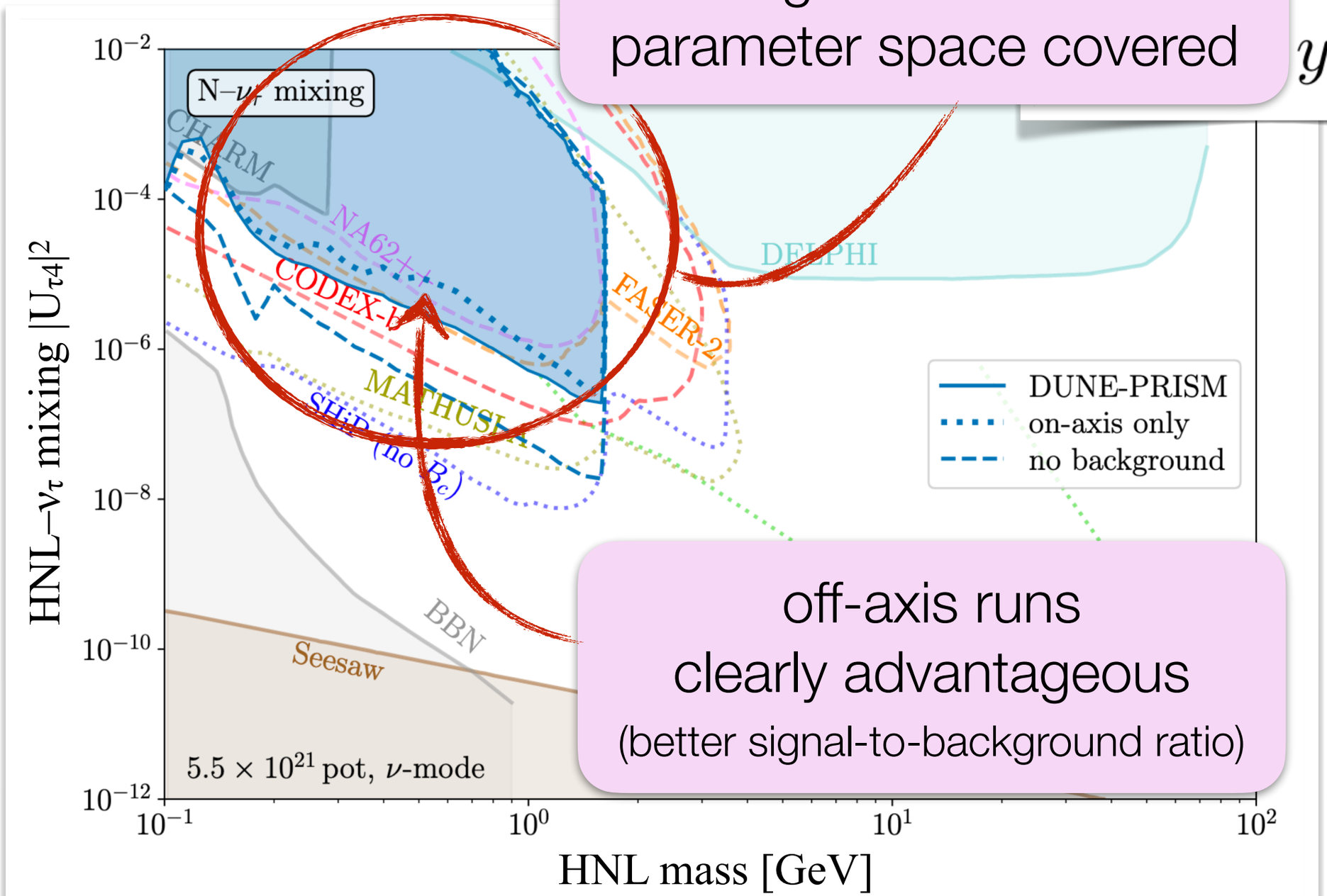

off-axis runs
clearly advantageous
(better signal-to-background ratio)

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