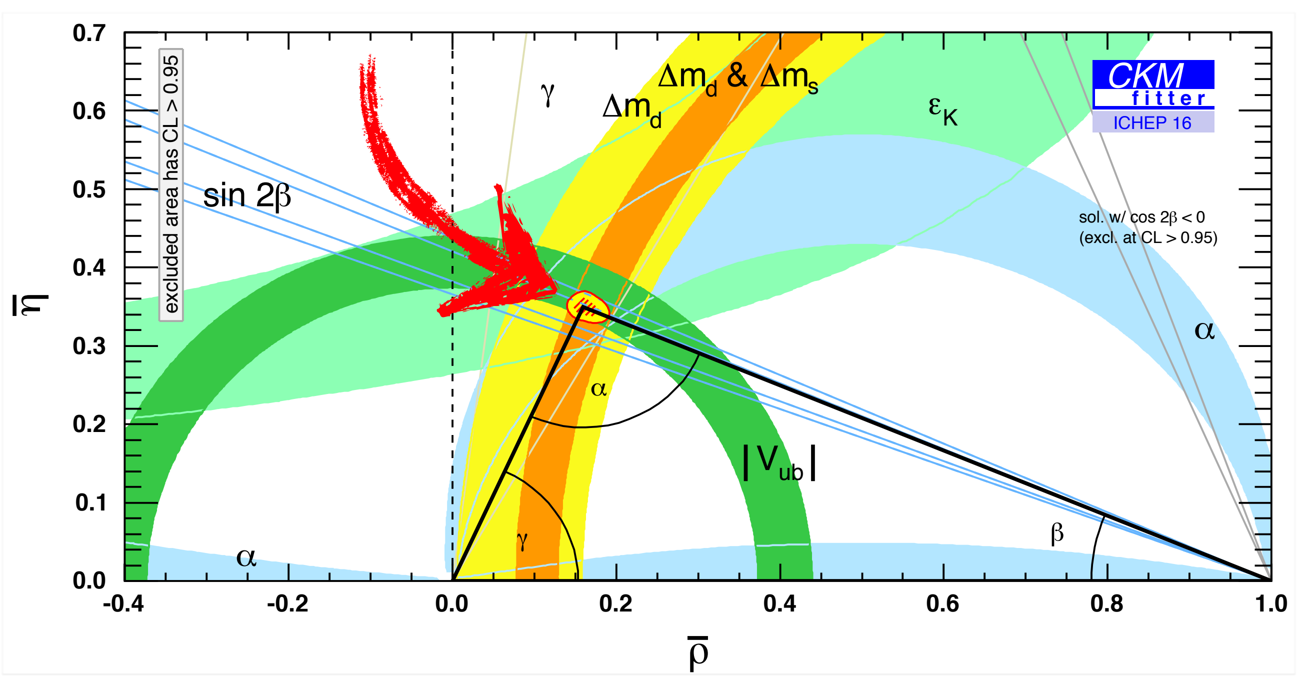
Neutrinos as a Window to New Physics

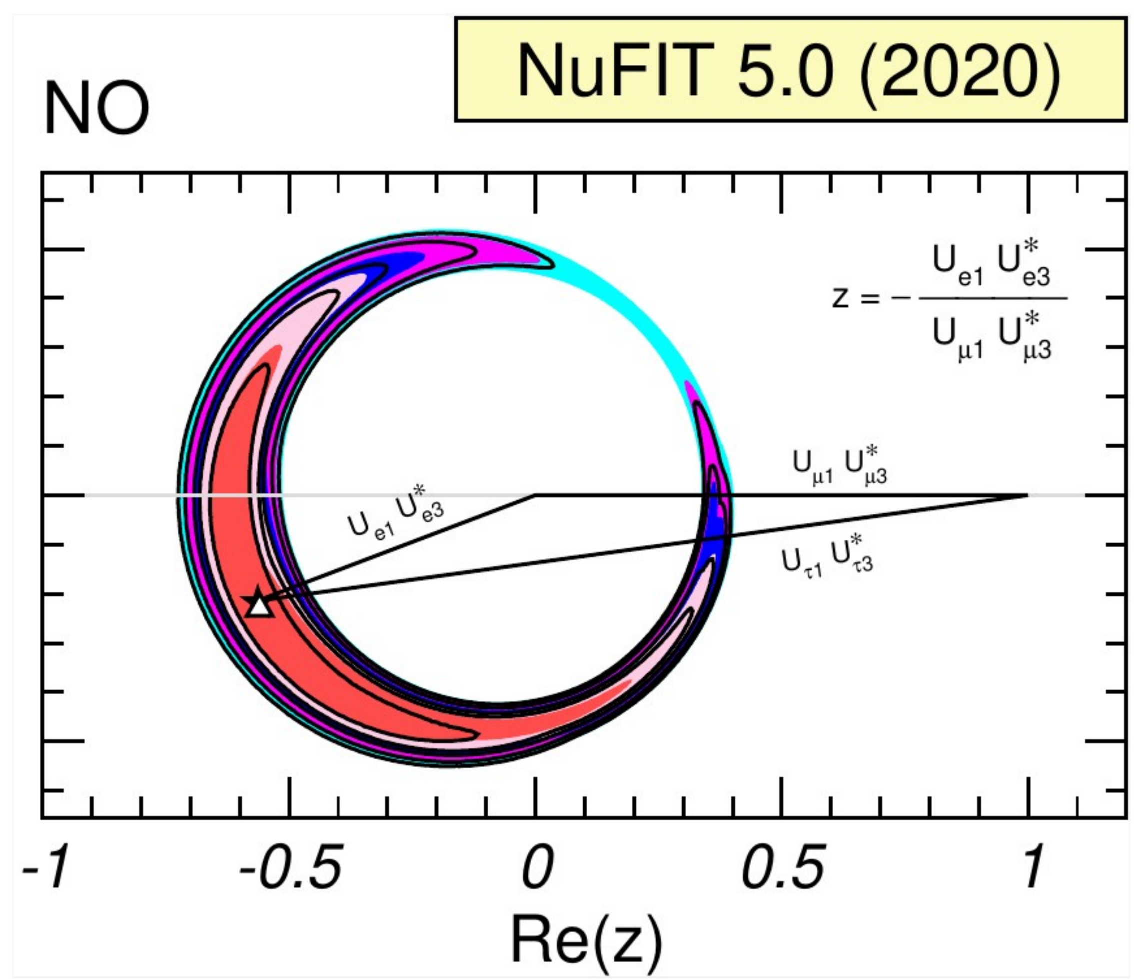
Joachim Kopp (CERN & JGU Mainz)
Planck 2021 Conference | 28–30 June 2021 | Durham, UK

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

The Neutrino Portal

SM singlet fermion

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

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The MiniBooNE Experiment

A search for $\nu_\mu \rightarrow N$ and $\nu_\mu \rightarrow \nu_e$ oscillations mediated by N

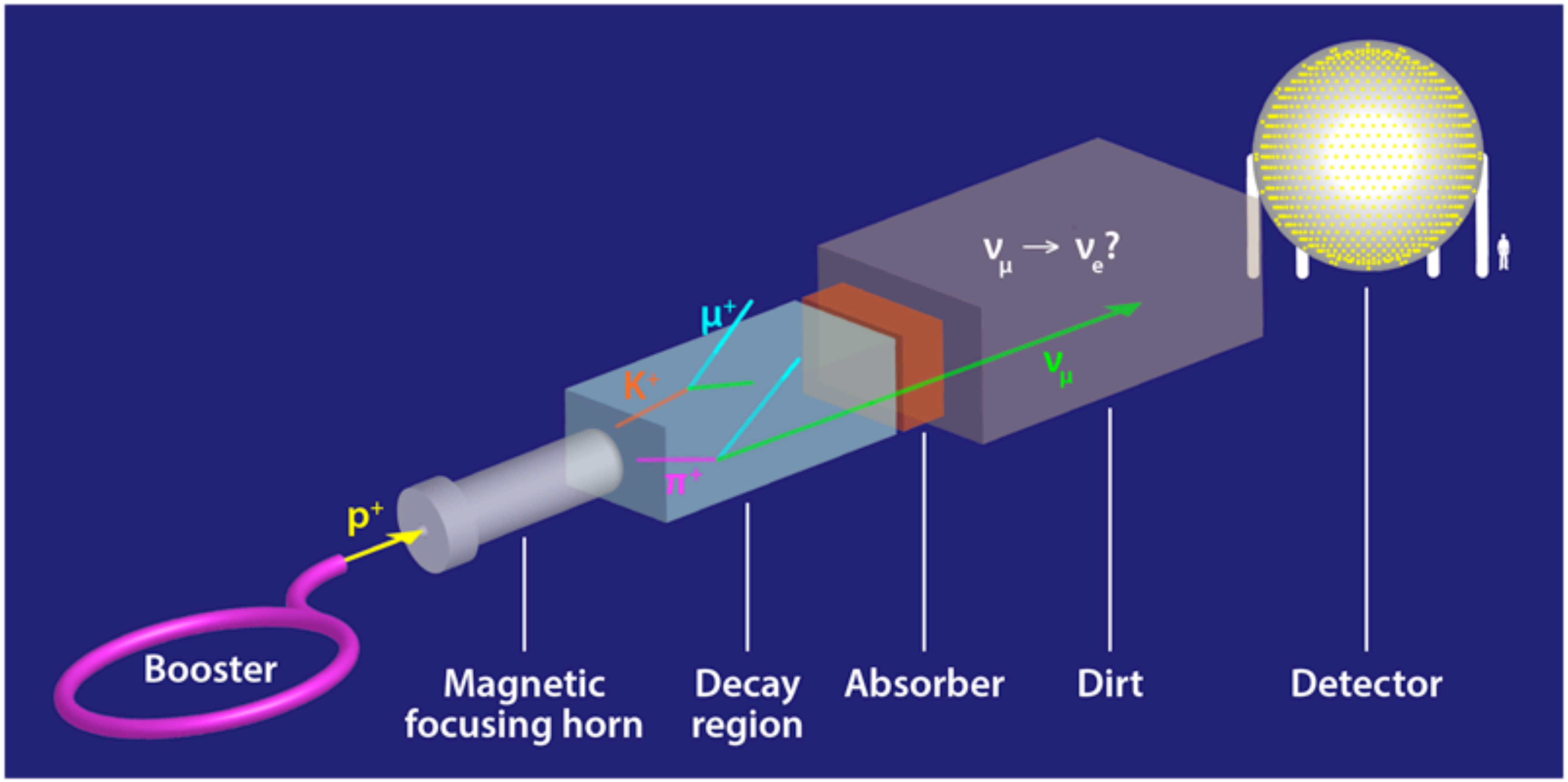
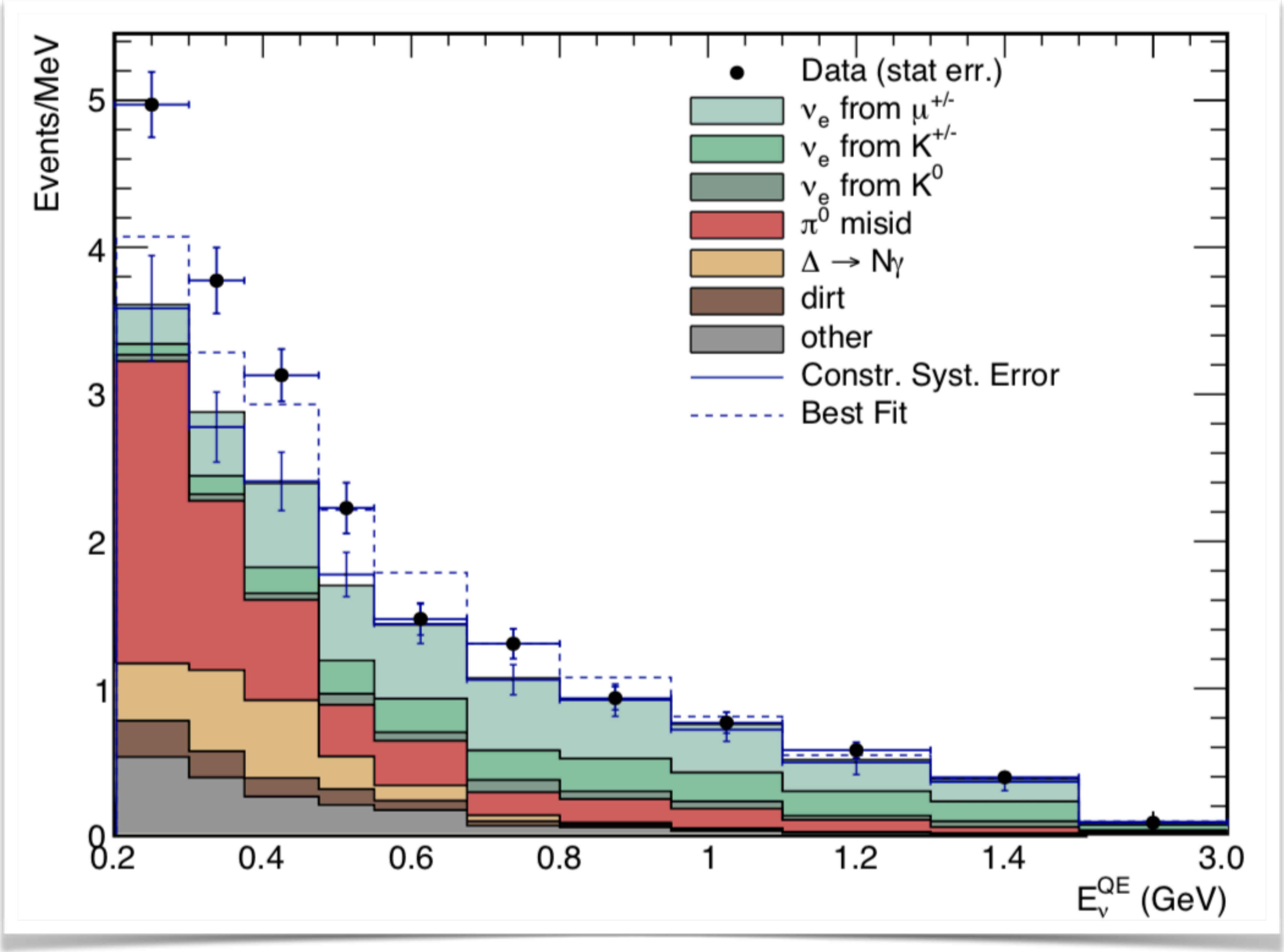


Image: APS

MiniBooNE ν_e Appearance Search

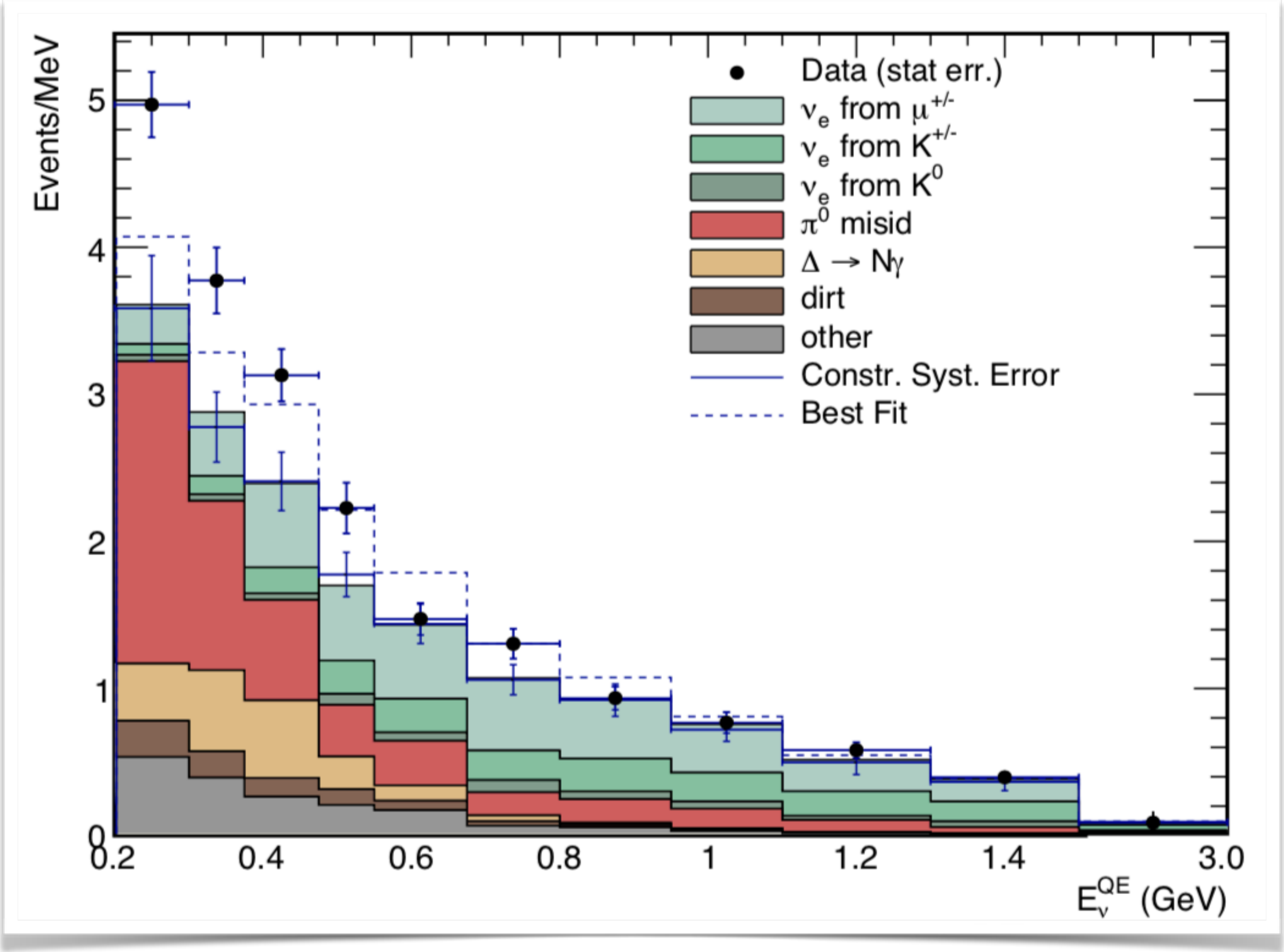


MiniBooNE 2018

Precision Neutrino Physics

> "With great precision comes great responsibility."
>
> *Tim Linden, WIN 2021*

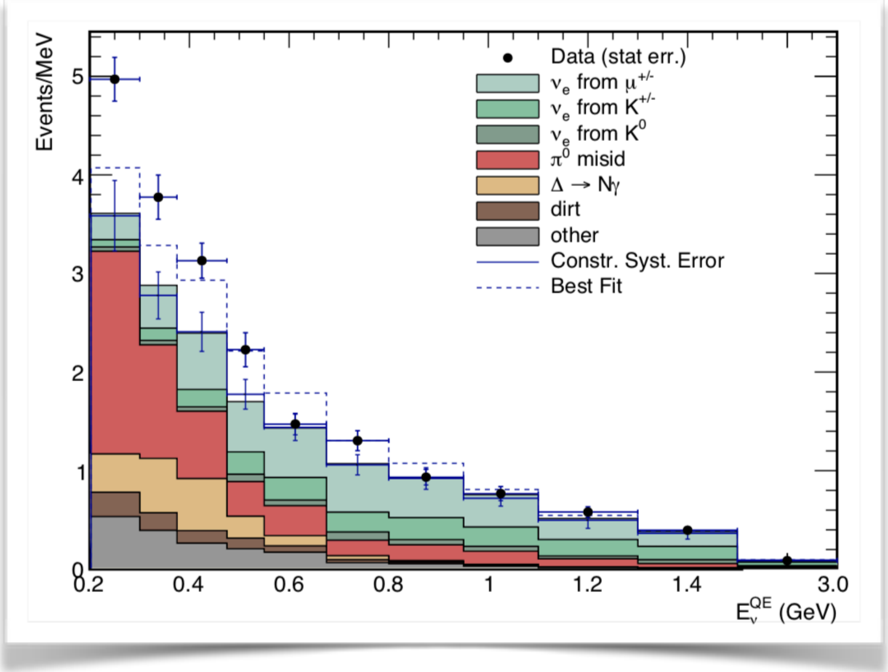
The MiniBooNE Anomaly



MiniBooNE 2018

$\Delta \to \gamma N$

- Neutral current neutrino interaction:
  $\nu + n/p \to \nu + \Delta(1232)$
- $\Delta(1232)$ mostly decays to $\pi + n/p$
- But a rare decay exists to $\gamma + n/p$
- MiniBooNE cannot distinguish
  γ and $e^{\pm}$ ➠ potential background



Δ → γ N

- Neutral current neutrino interaction:
  ν + n/p → ν + Δ(1232)
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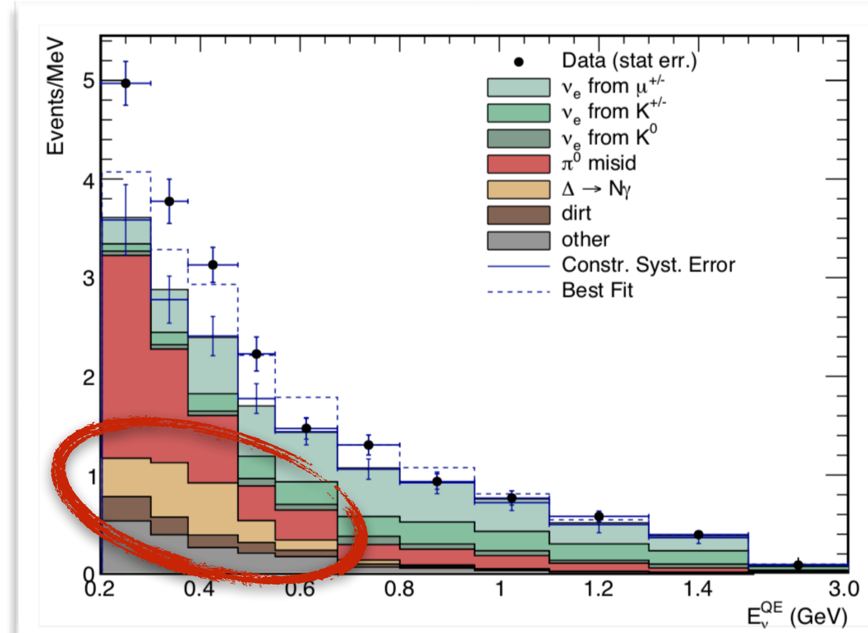
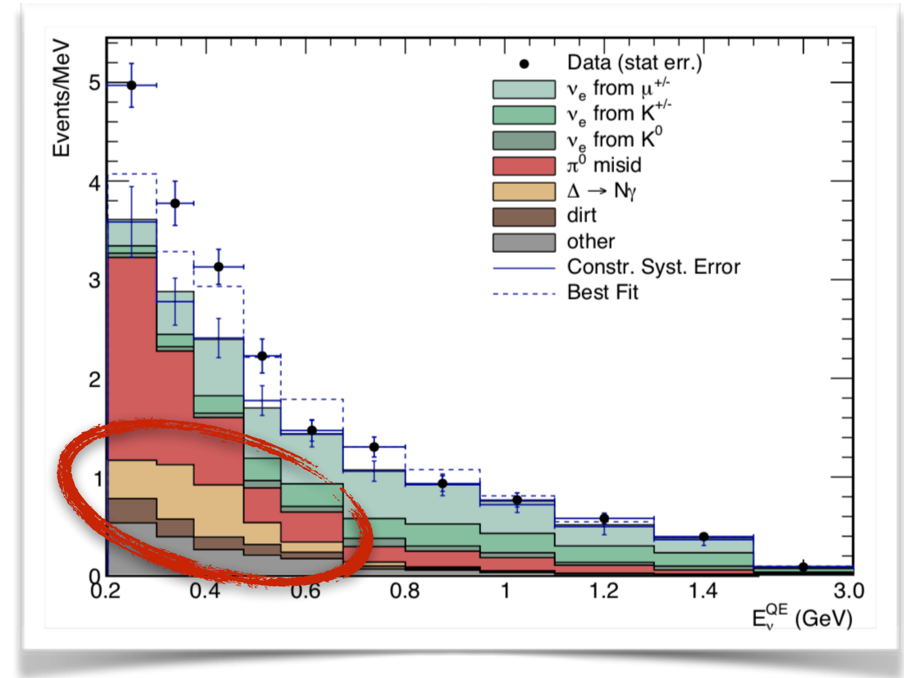


$\Delta \to \gamma N$

- Δ production rate measured in $\Delta \to \pi + n/p$
- Pions may be absorbed on their way out of the nucleus
  - may excite another Δ resonance
    - ➠ $\Delta \to \gamma$ n/p enhanced
    - ➠ background prediction enhanced
  - or may be absorbed
    - ➠ control region suppressed
    - ➠ background prediction enhanced

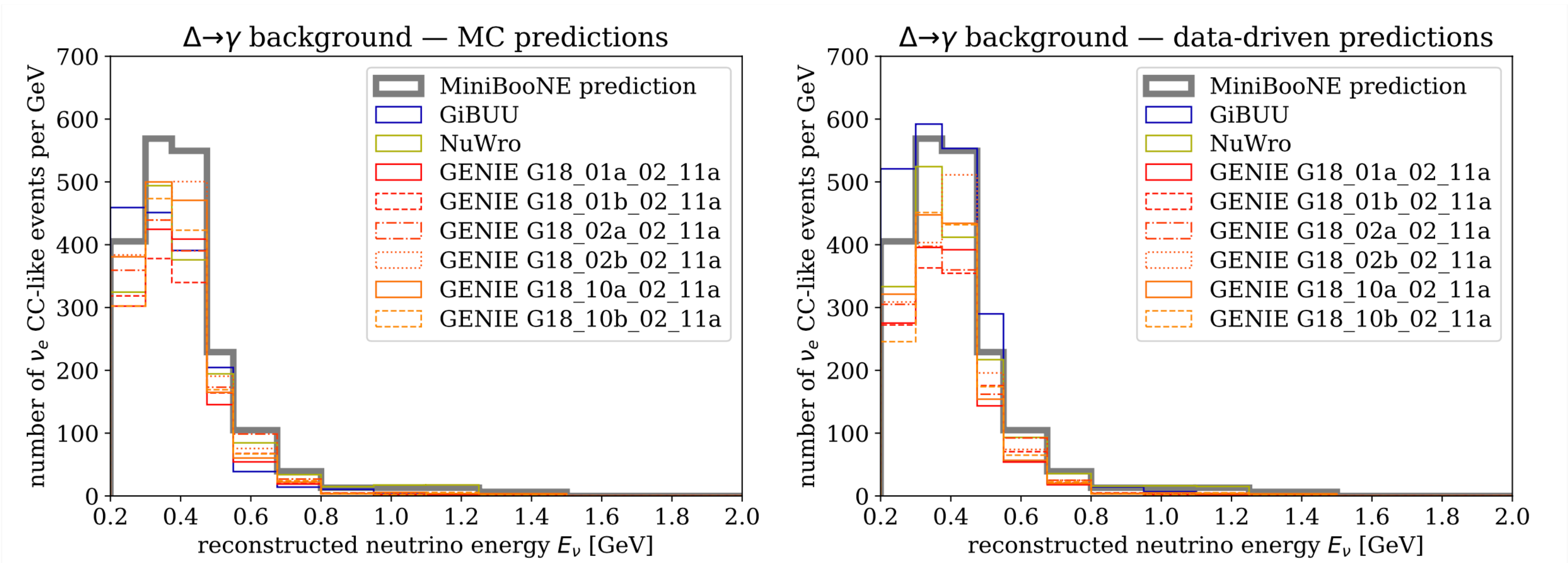


Ioannisian 1909.08571
Giunti Ioannisian Ranucci 1912.01524
Brdar JK, *in preparation*

- MiniBooNE are modelling such effects, but uncertainties are large and hard to quantify

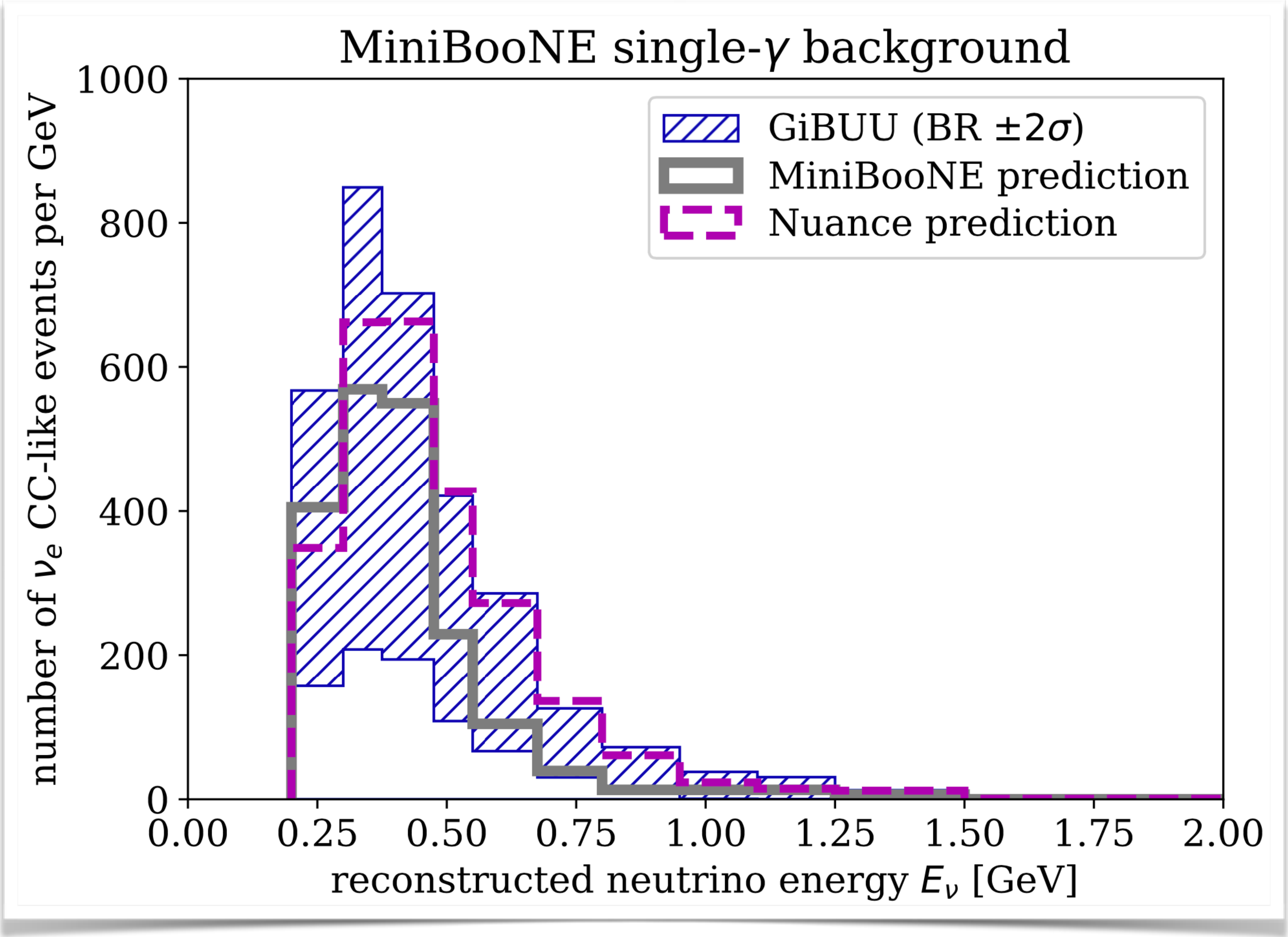
Δ → γ N: Comparison of Generators

Brdar JK, *in preparation*



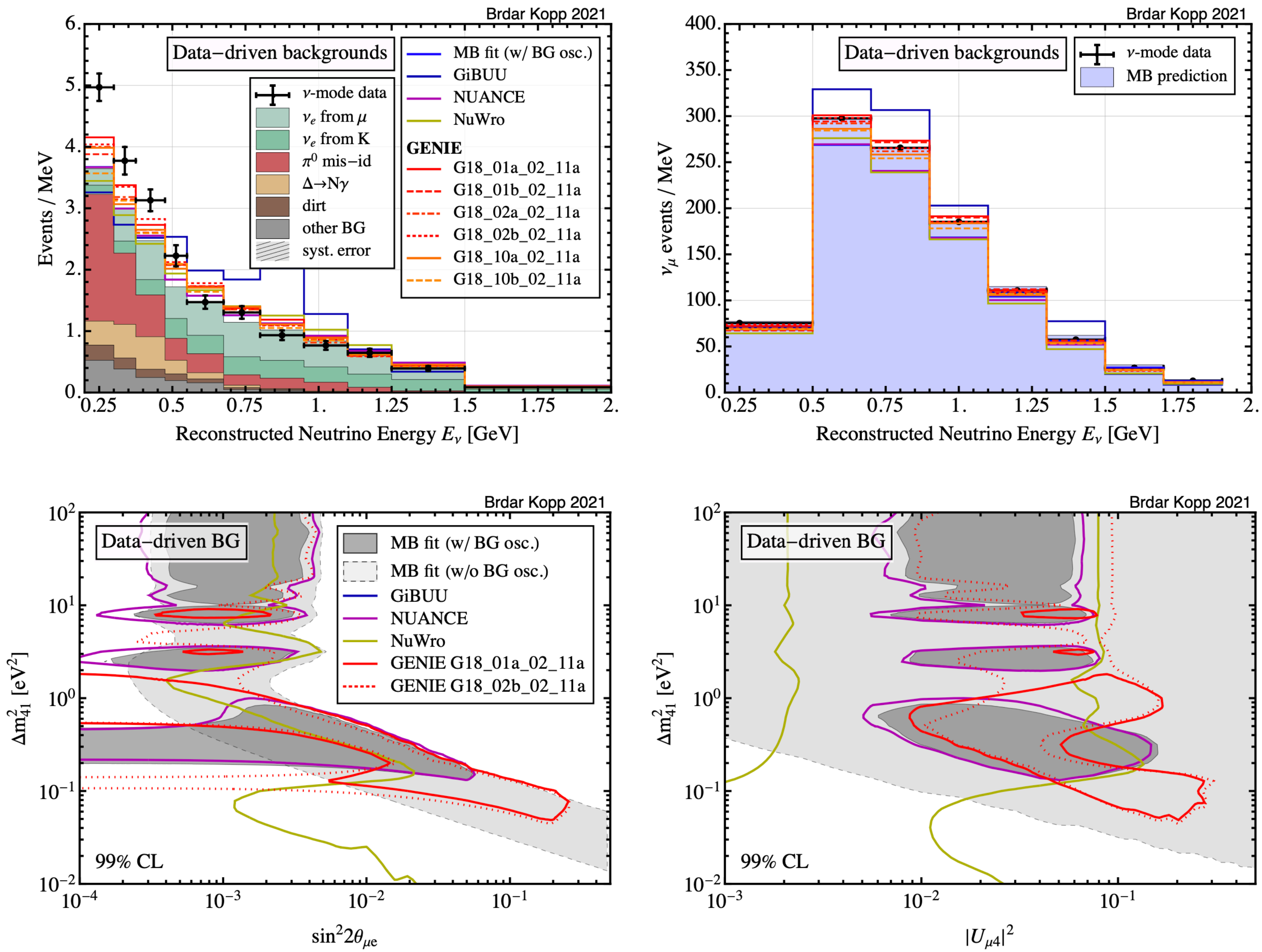
- ☑ histograms calibrated to NUANCE (the generator used by MiniBooNE)
- ☑ using our own implementation of radiative resonance decays in GiBUU, NuWro, NUANCE

Δ → γ N: Branching Ratio Uncertainties



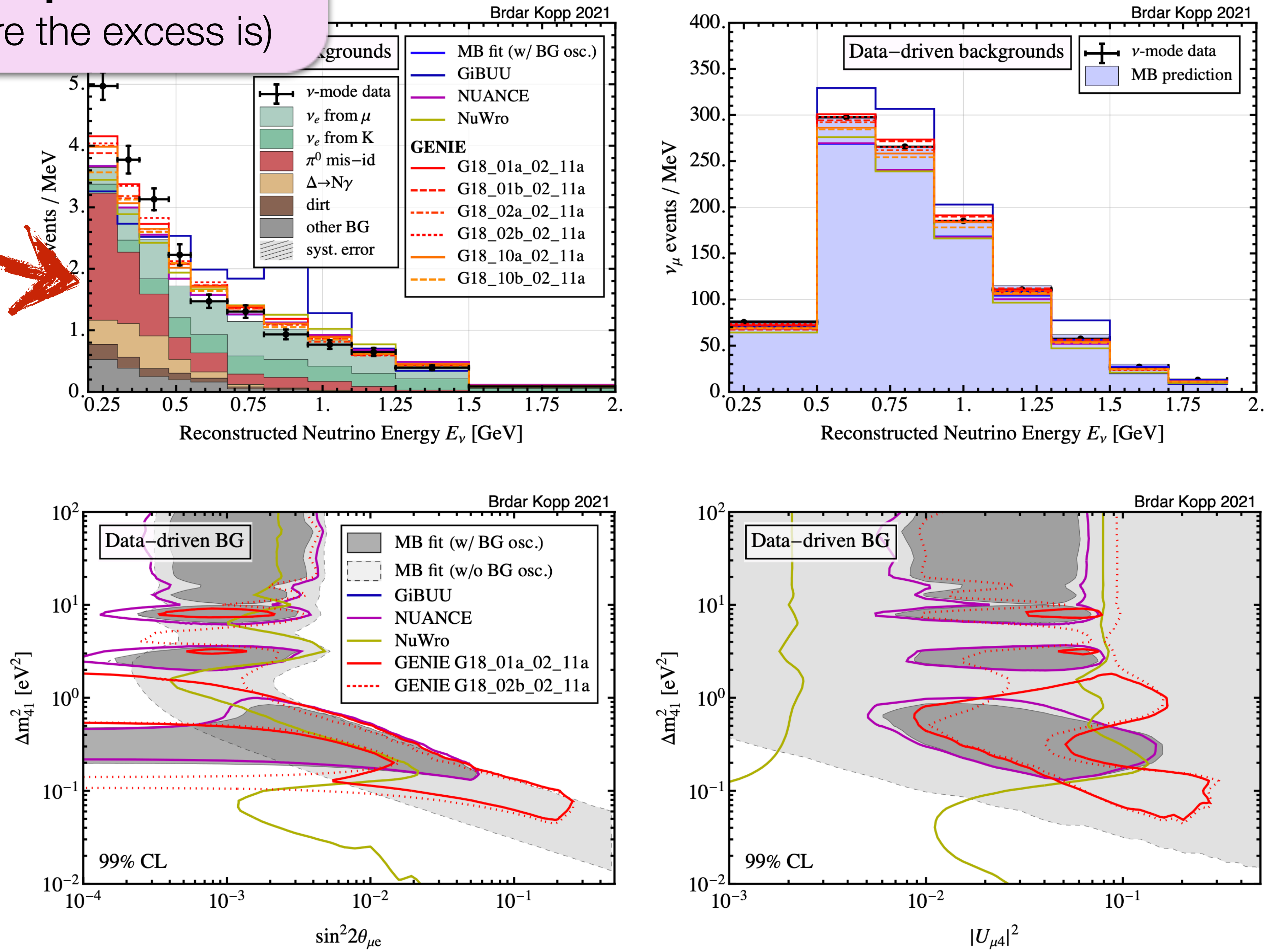
Brdar JK, *in preparation*

3+1 Models in MB: Comparison of Generators



3+1 Models in MB: Comparison of Generators

ν_e spectrum
(where the excess is)



3+1 Models in MB: Comparison of Generators

ν_e spectrum
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ν_μ spectrum
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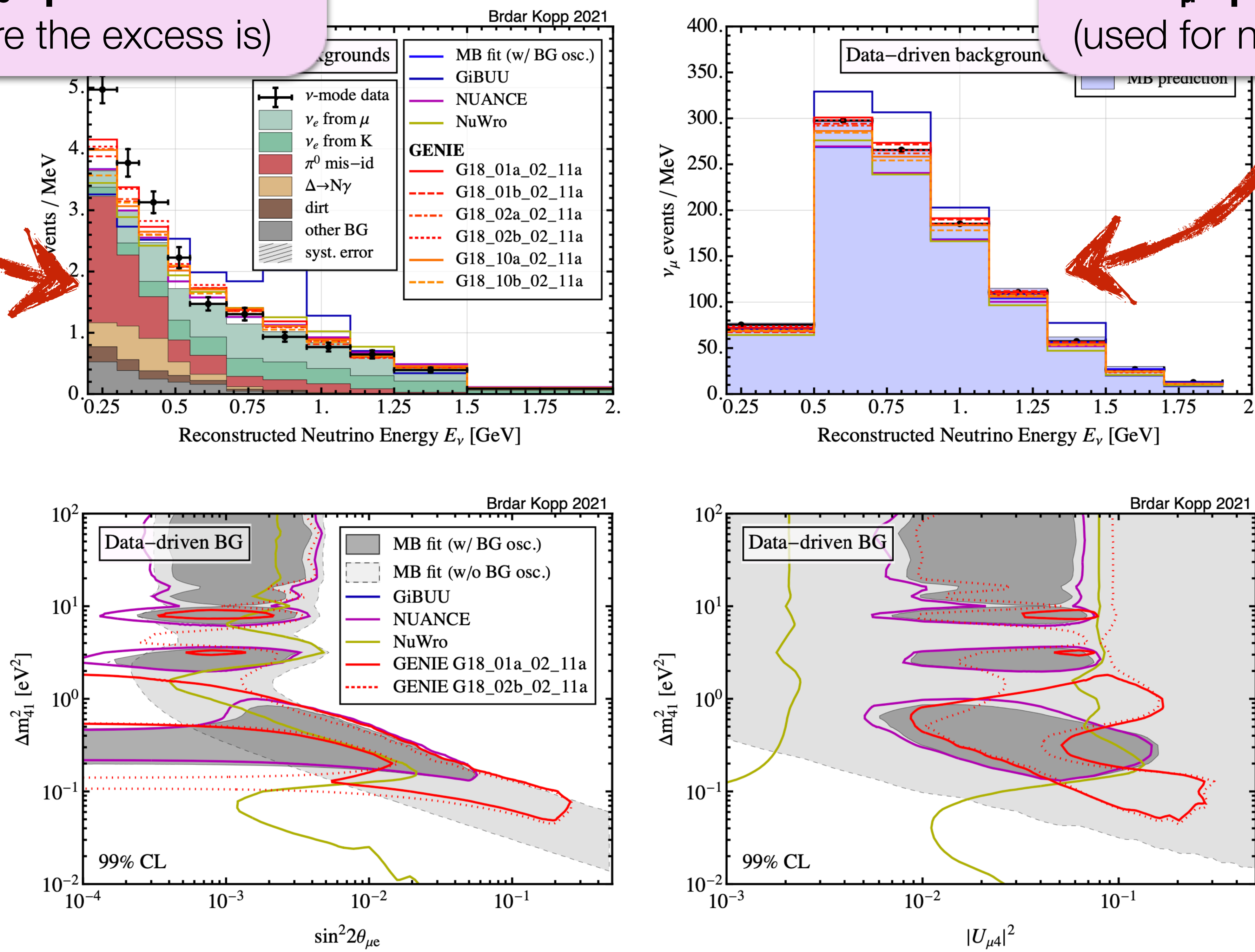

3+1 Models in MB: Comparison of Generators

ν_e spectrum
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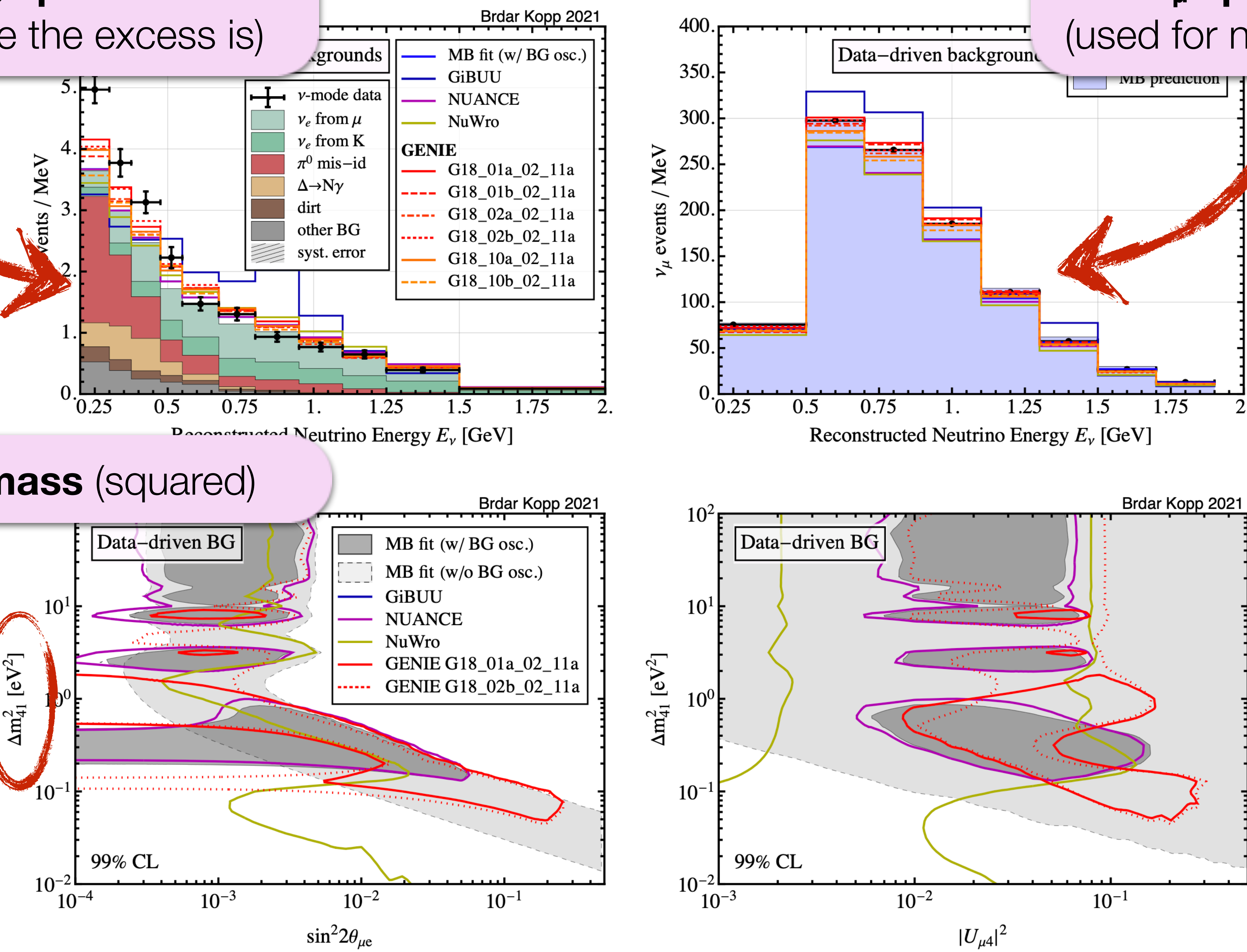
ν_s mass (squared)



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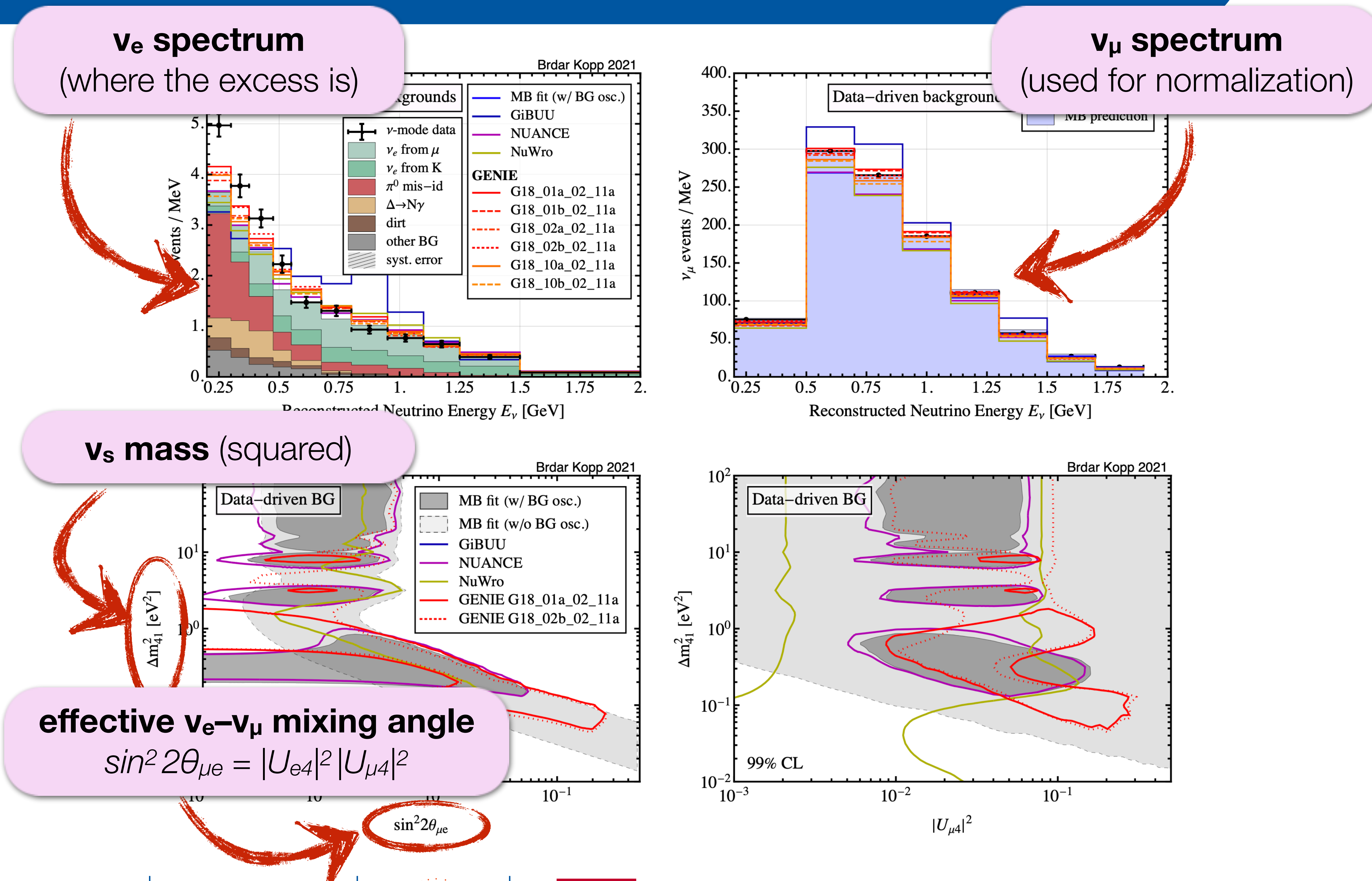

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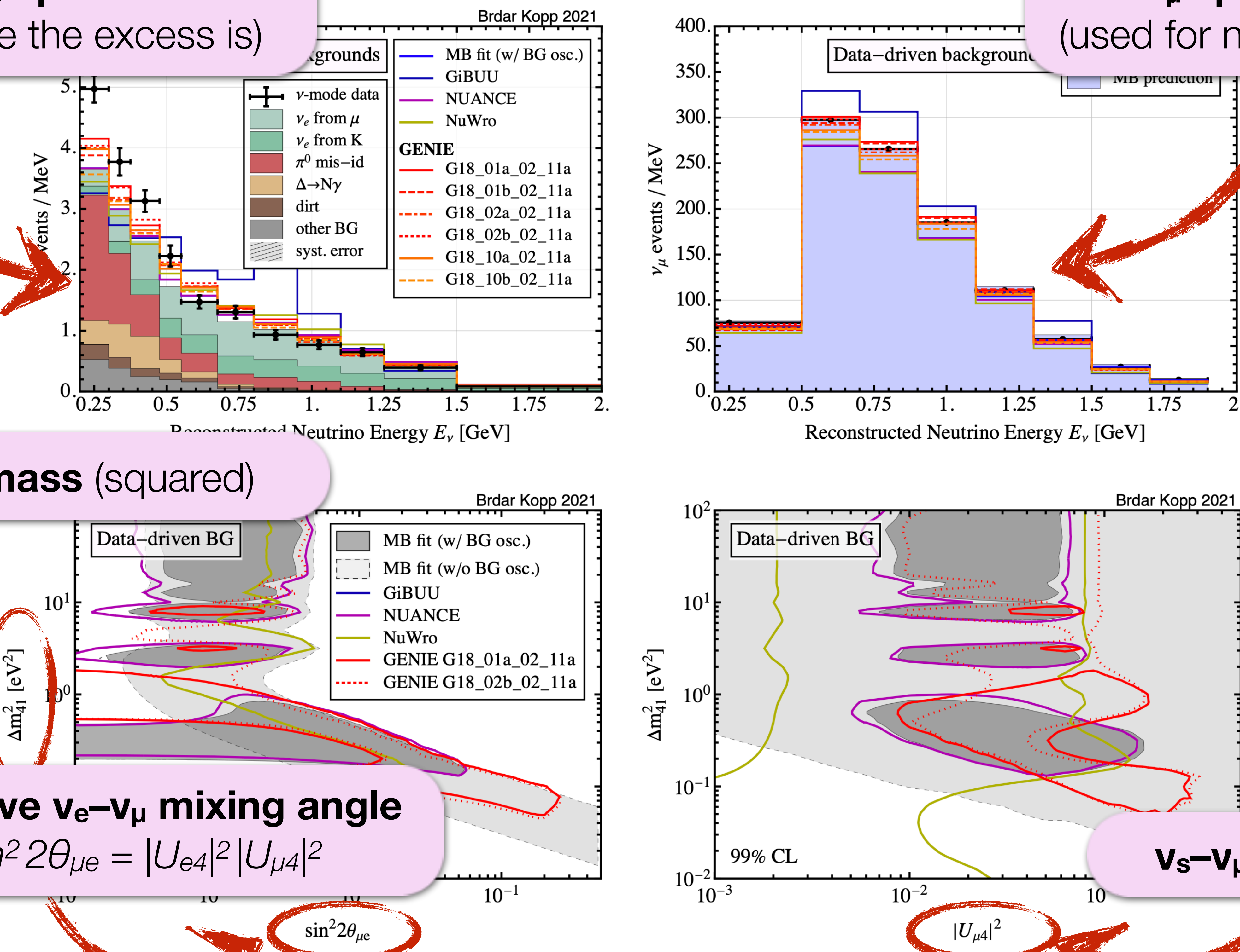
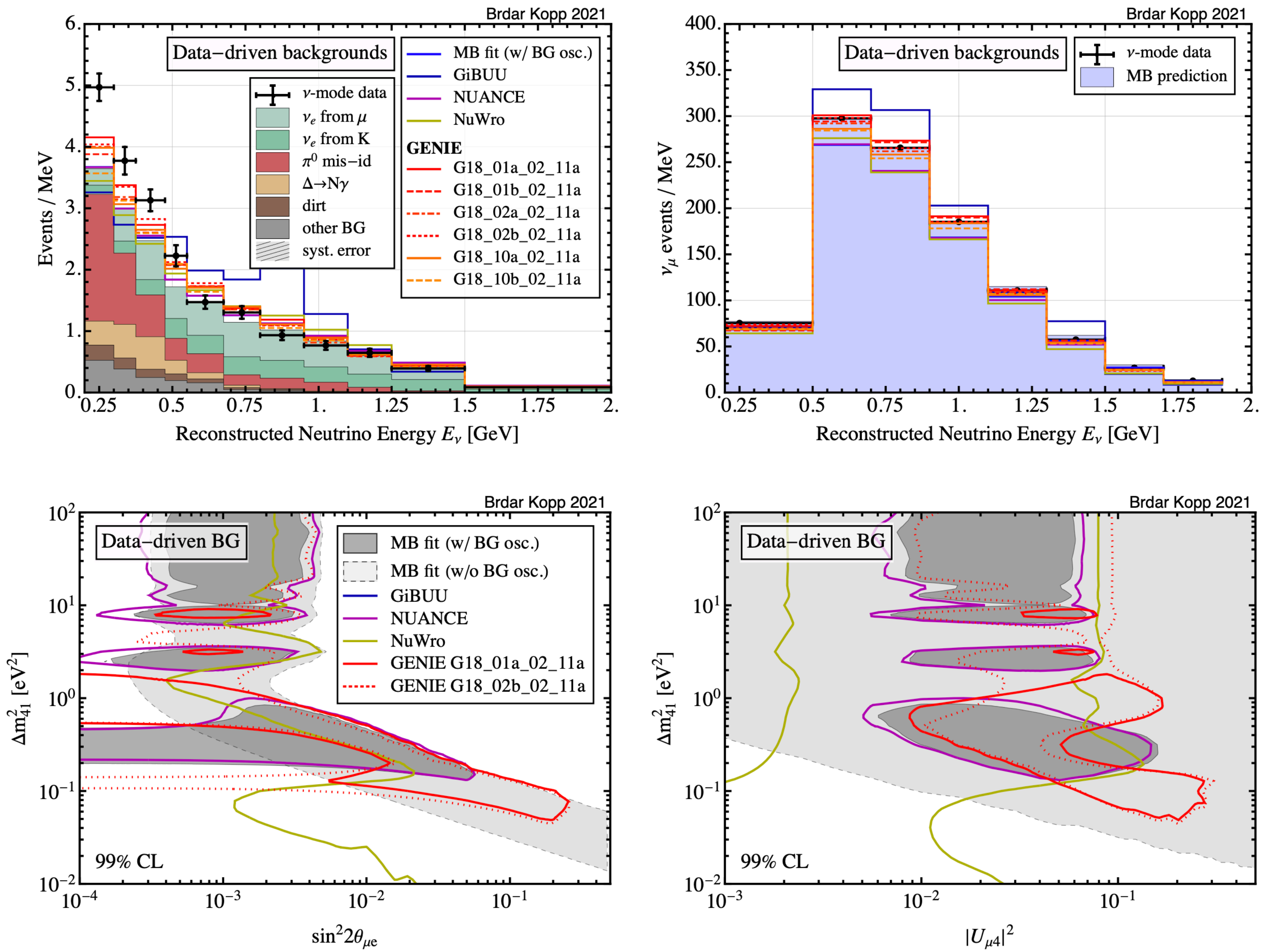


ν_s mass (squared)

effective ν_e–ν_μ mixing angle
$\sin^2 2\theta_{\mu e} = |U_{e4}|^2 |U_{\mu 4}|^2$

ν_s–ν_μ mixing

3+1 Models in MB: Comparison of Generators



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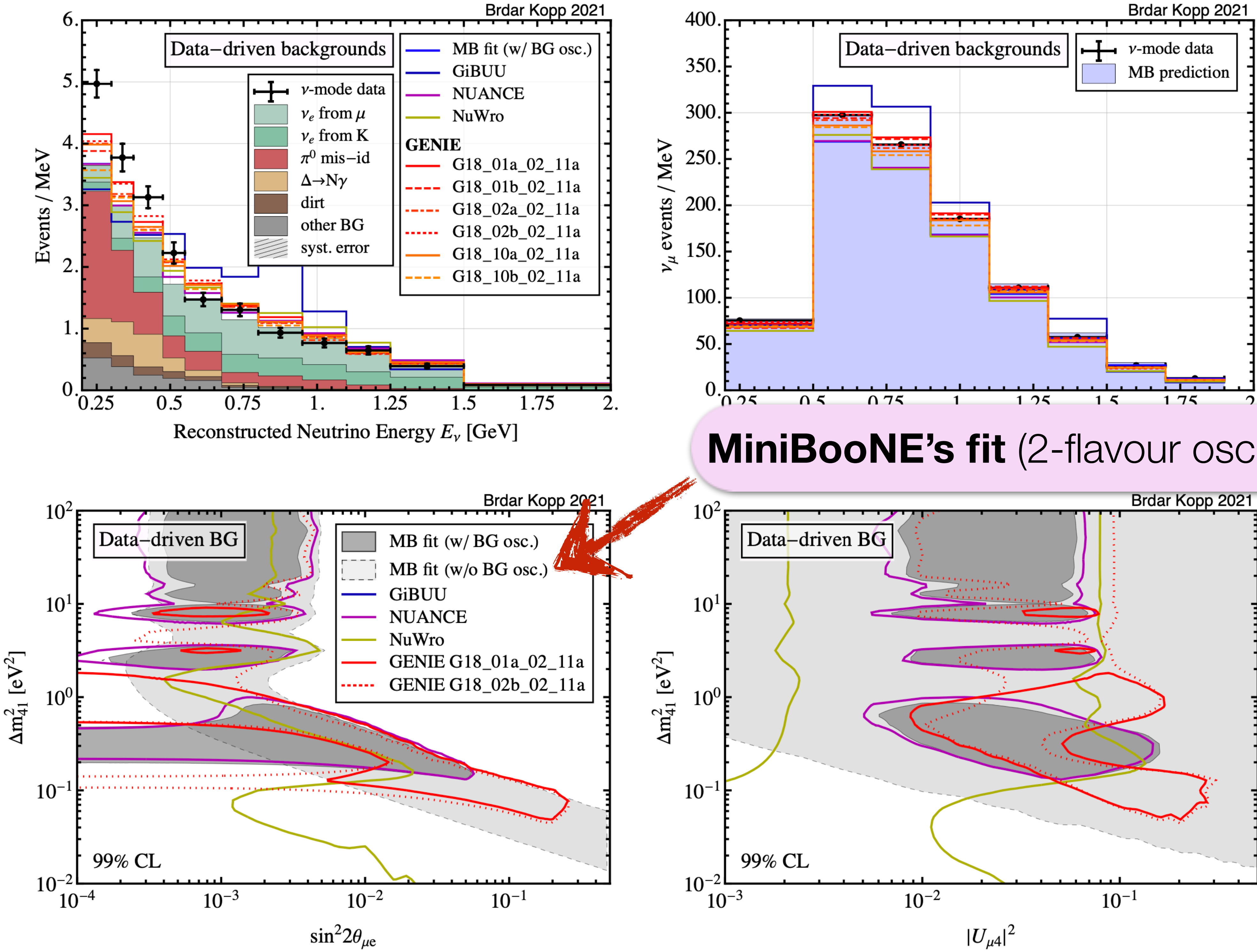
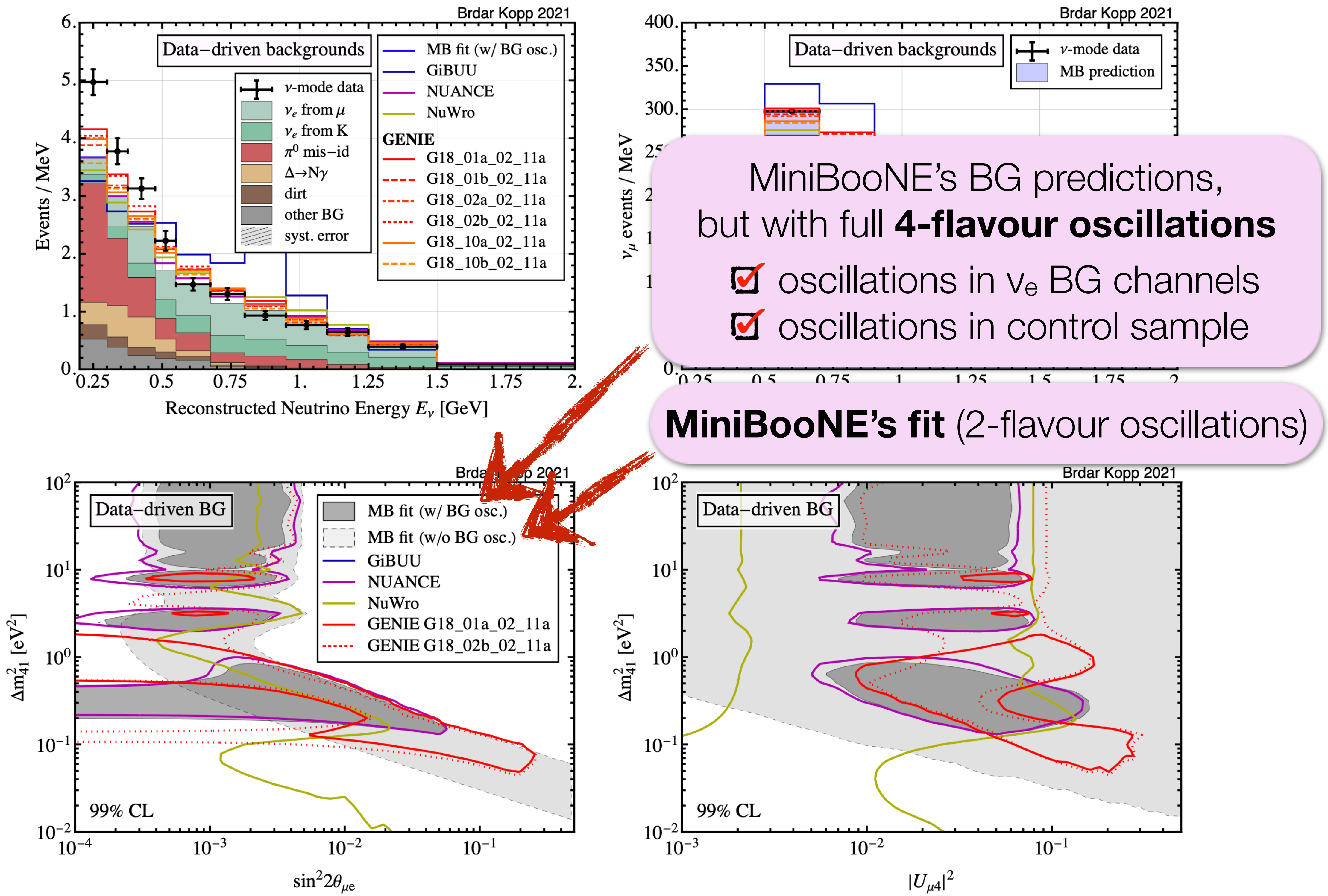


MiniBooNE's fit (2-flavour oscillations)

3+1 Models in MB: Comparison of Generators

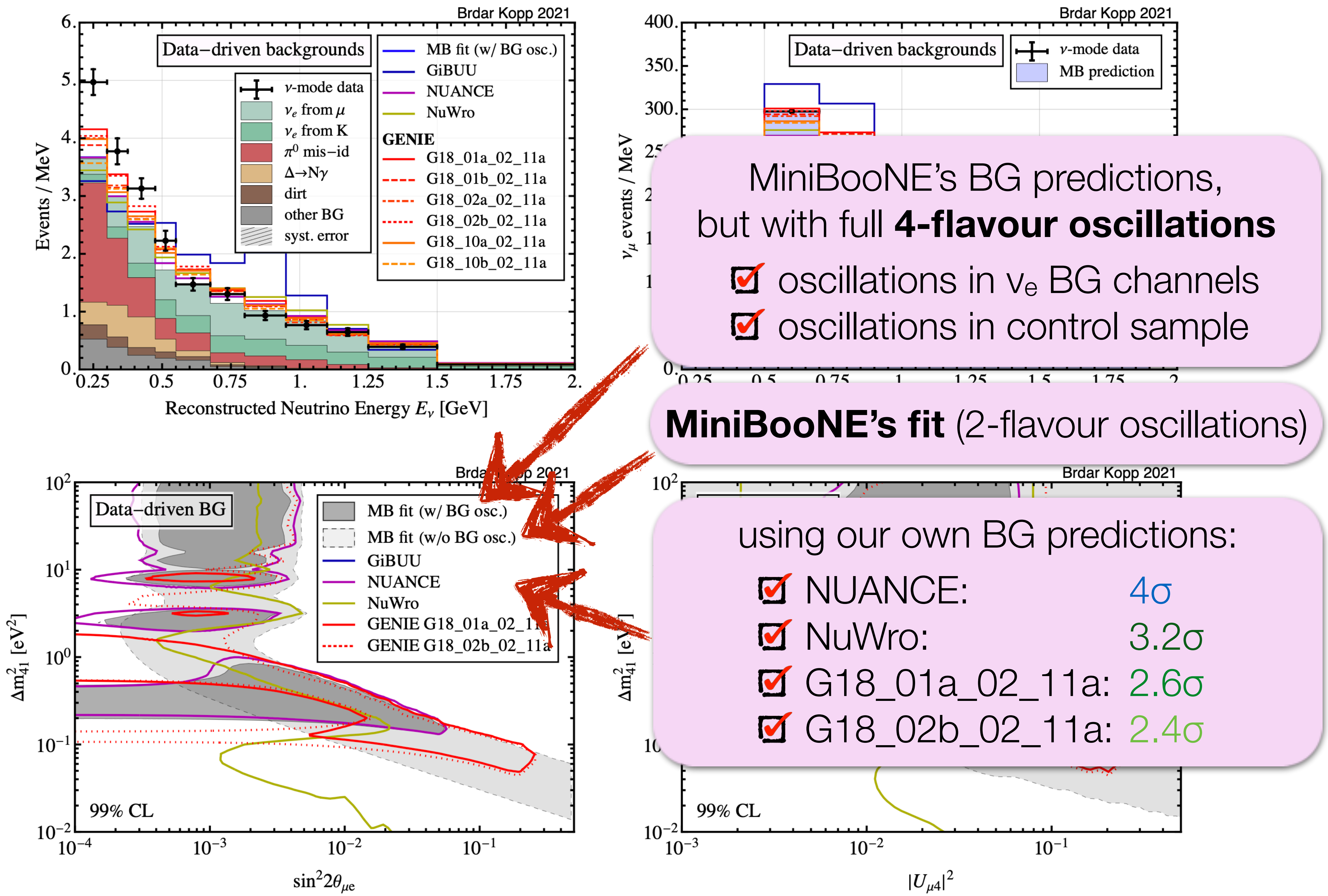


MiniBooNE's BG predictions, but with full **4-flavour oscillations**

- ☑ oscillations in ν_e BG channels
- ☑ oscillations in control sample

MiniBooNE's fit (2-flavour oscillations)

3+1 Models in MB: Comparison of Generators



MiniBooNE's BG predictions, but with full **4-flavour oscillations**

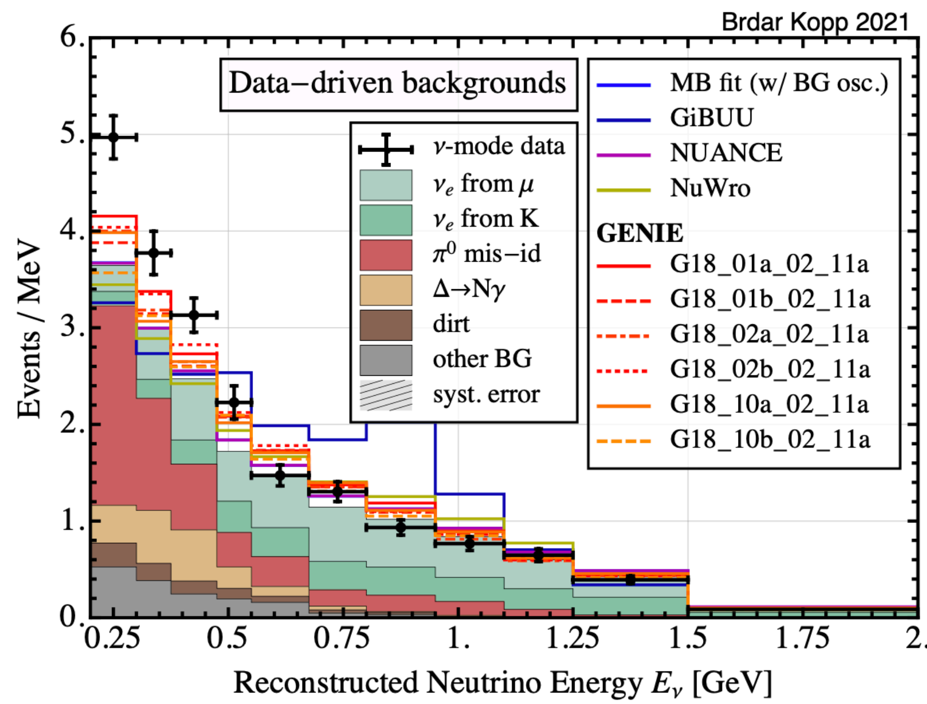
- ☑ oscillations in ν_e BG channels
- ☑ oscillations in control sample

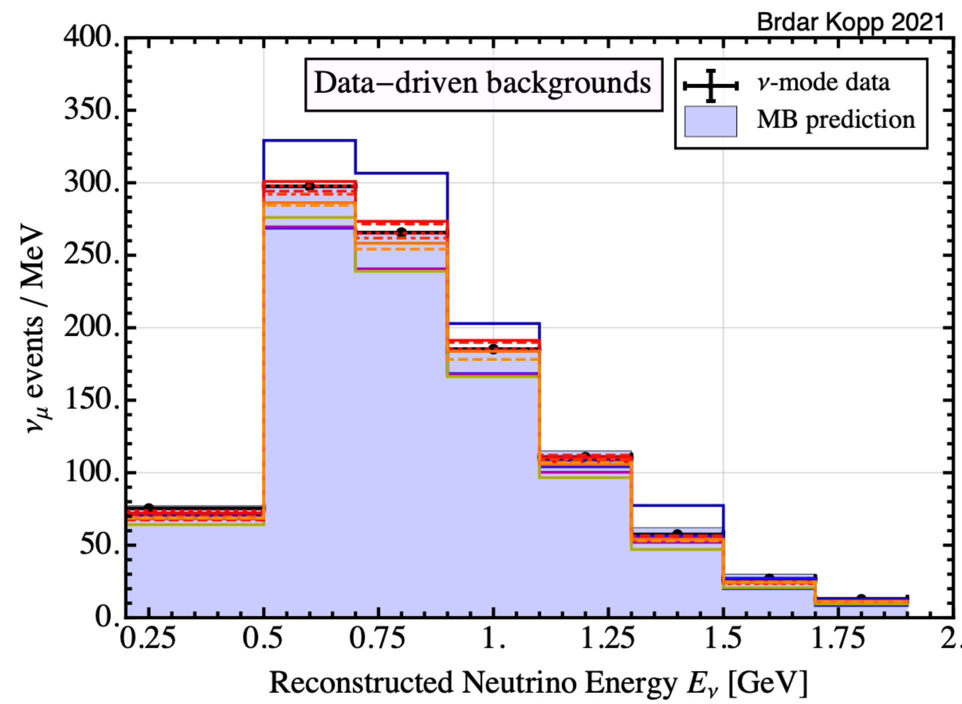
MiniBooNE's fit (2-flavour oscillations)

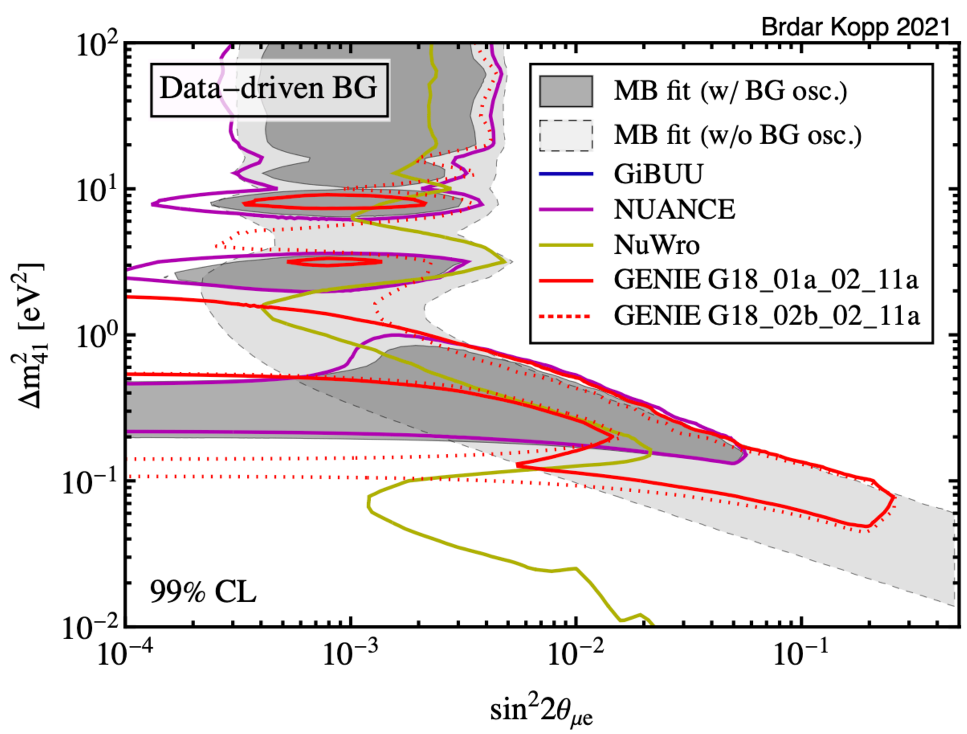
using our own BG predictions:

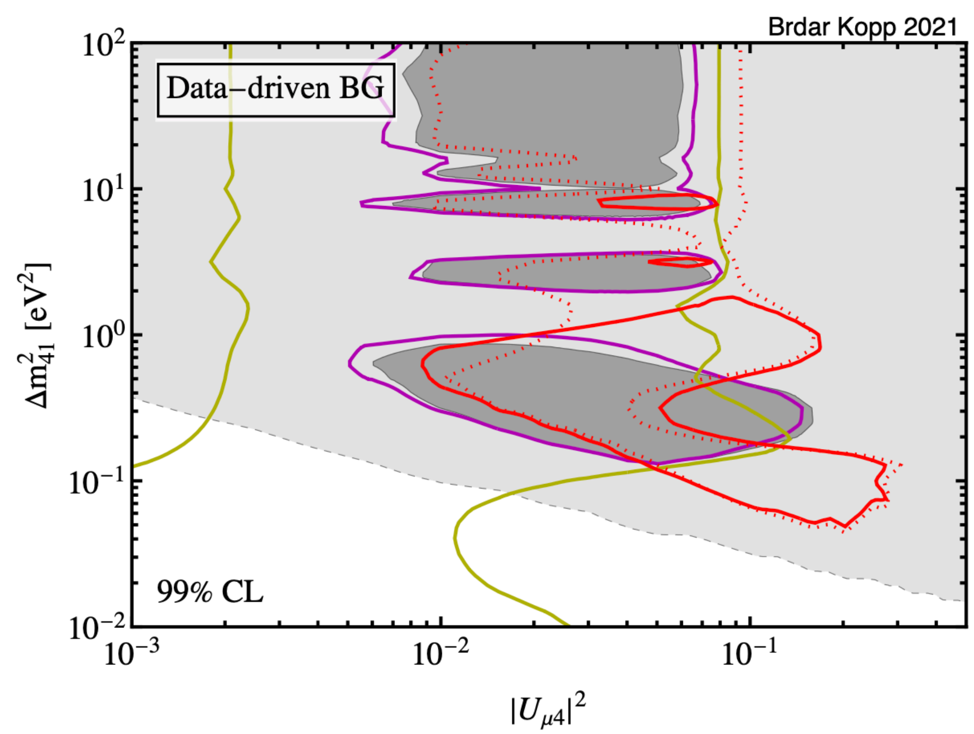
- ☑ NUANCE: 4σ
- ☑ NuWro: 3.2σ
- ☑ G18_01a_02_11a: 2.6σ
- ☑ G18_02b_02_11a: 2.4σ

3+1 Models in MB: Comparison of Generators









Light Sterile Neutrinos?

- ☑ Add extra neutrino flavor, promote mixing matrix to 4×4
- ☑ Oscillation channels are related:

$$P_{\nu_e \to \nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

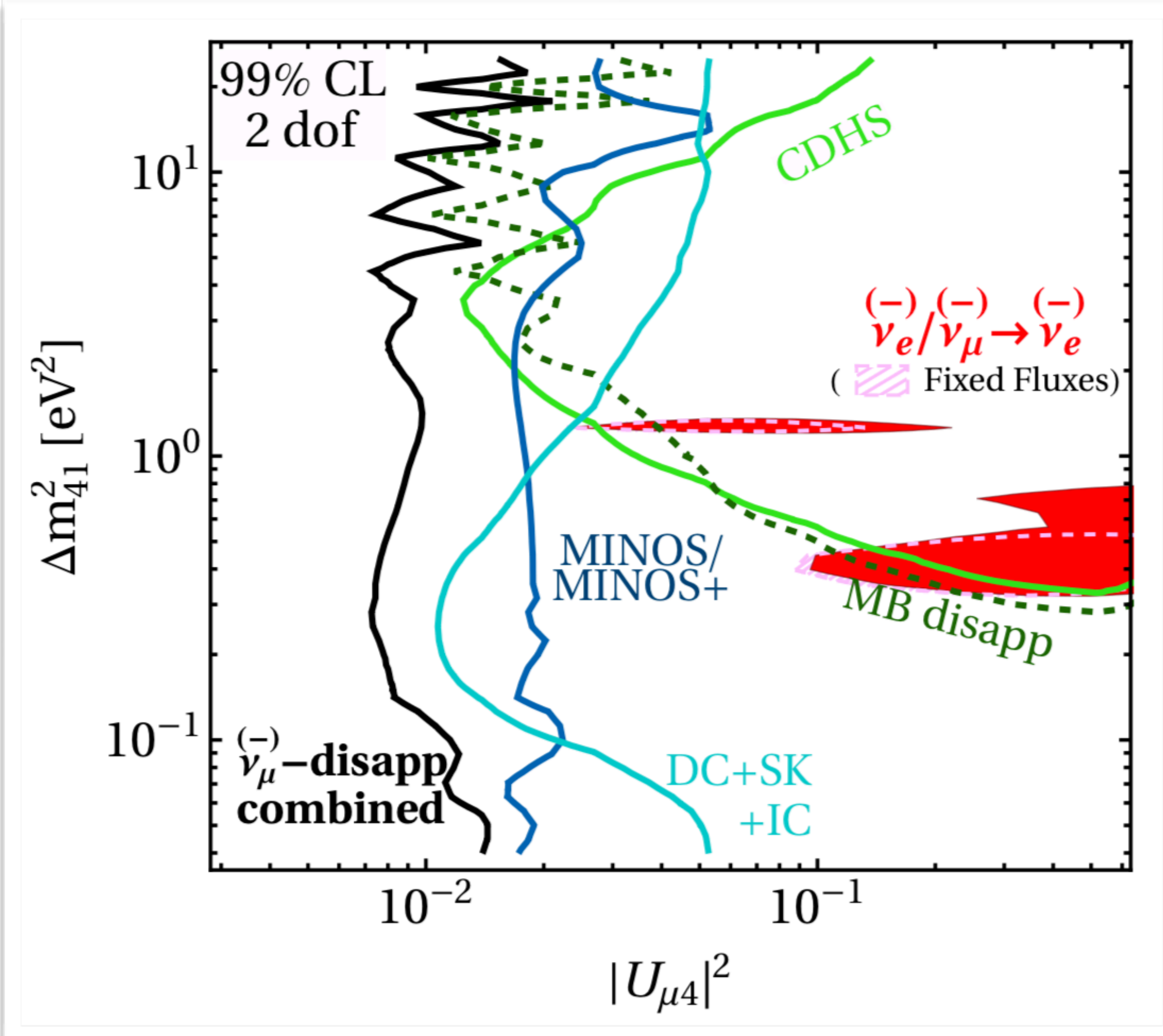
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

$$P_{\nu_\mu \to \nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

(for $4\pi E/\Delta m^2_{41} \ll L \ll 4\pi E/\Delta m^2_{31}$)

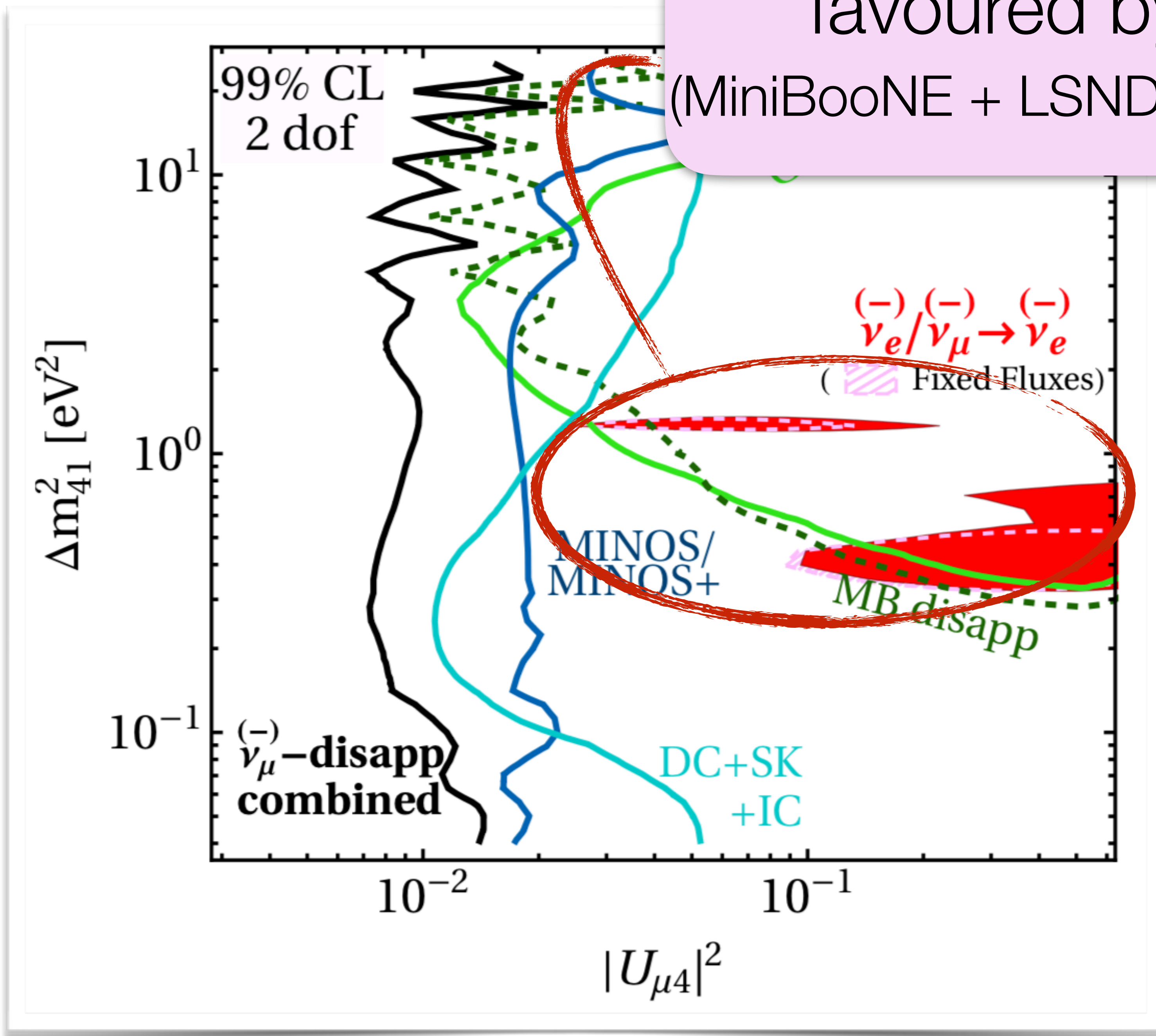
- ☑ Models can be over-constrained.

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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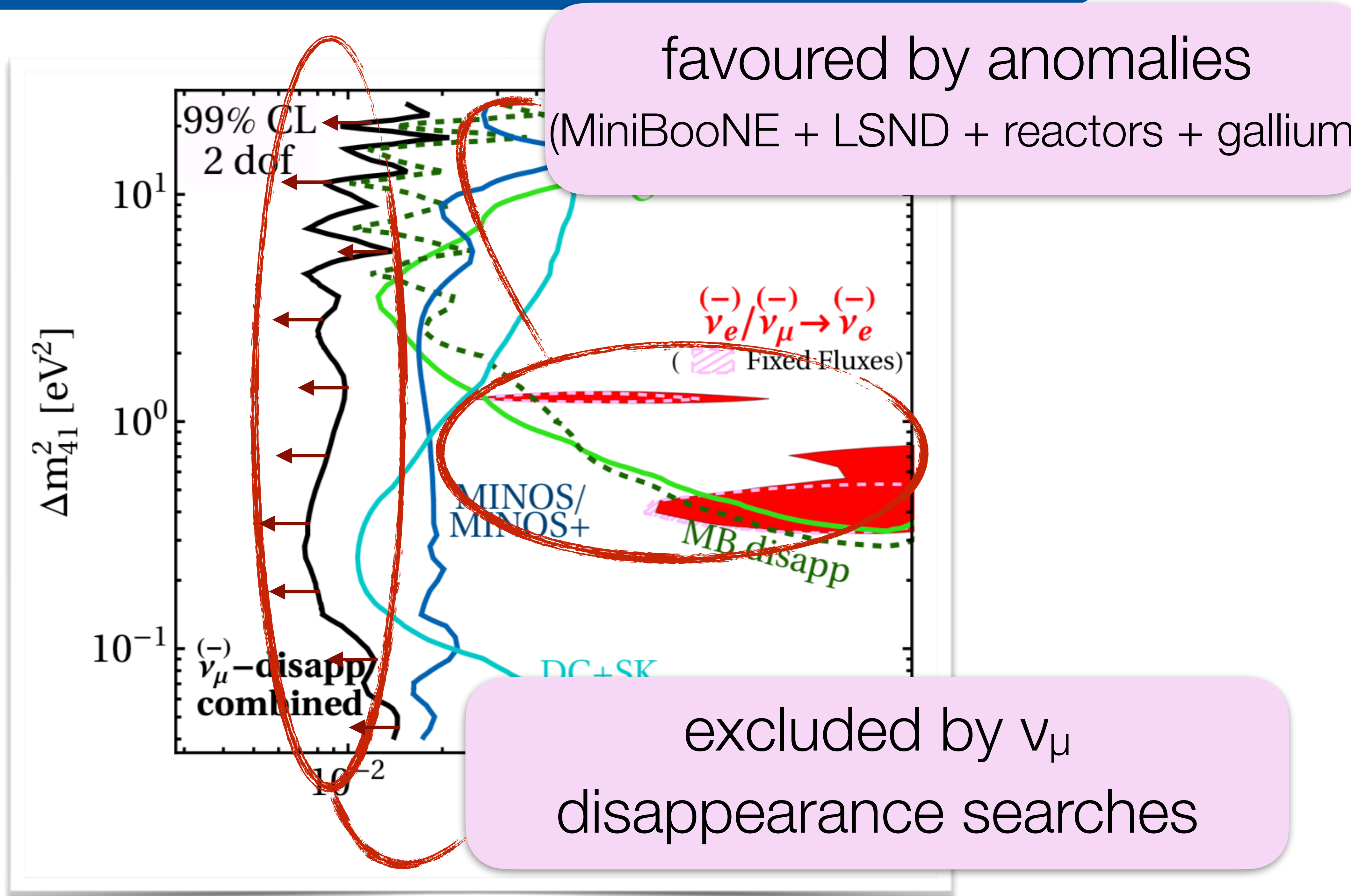

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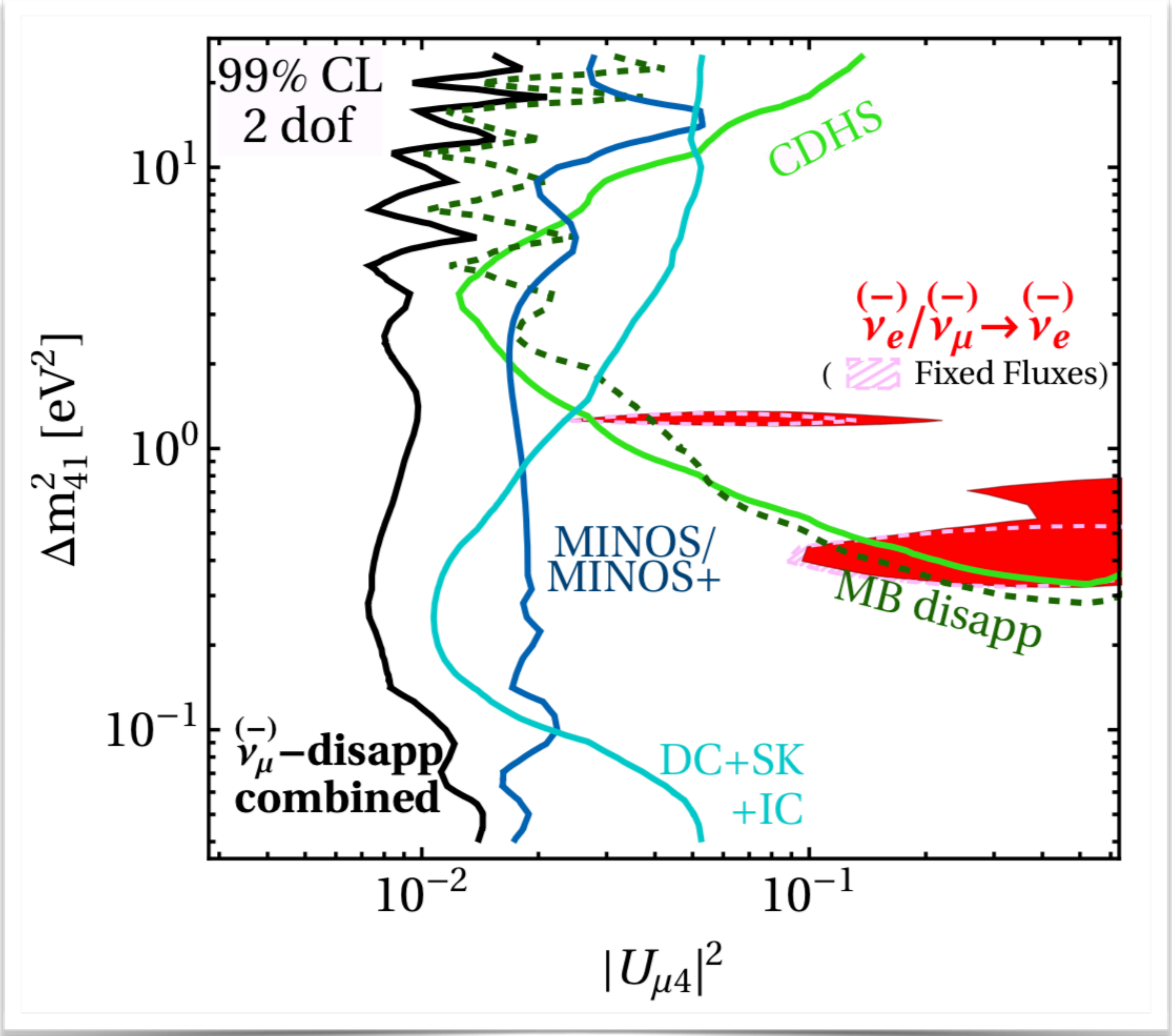

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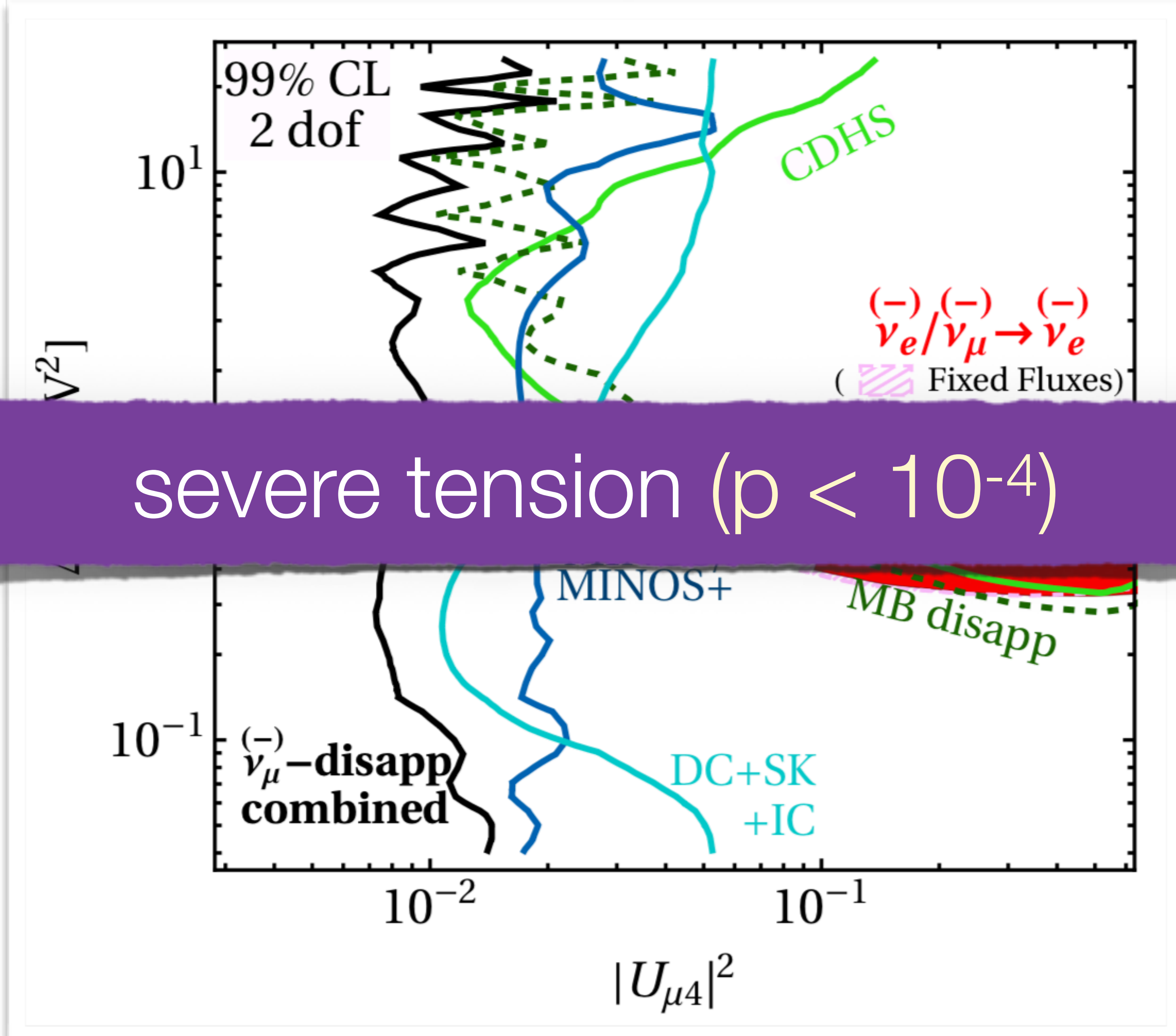

severe tension ($p < 10^{-4}$)

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

Extended Sterile Neutrino Models

- ☑ Sterile Neutrino production in the target, followed by $\nu_s \to \nu + \gamma$ decay in the detector
(MiniBooNE cannot distinguish $e^\pm$ and γ)

Fischer Hernández-Cabezudo Schwetz, 1909.09561

- ☑ Sterile Neutrino production in the detector, followed by $\nu_s \to \nu + \gamma$ decay

Gninenko, 1009.5536

- ☑ Sterile Neutrino production in the detector, followed by $\nu_s \to \nu + (A' \to e^+e^-)$ decay (on-shell or off-shell)

Bertuzzo Jana Machado Zukanovich-Funchal, 1807.09877
Ballett Pascoli Ross-Lonergan, 1808.02915

- ☑ Sterile Neutrino production in the target, followed by $\nu_s \to \nu_{e,\mu,\tau} + \varphi$ decay in flight

Dentler Esteban JK Machado, 1911.01427

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

dim-4: the Neutrino Portal

↓

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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

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electromagnetic field strength tensor

Neutrino Magnetic Moments in the SM

Couples LH and RH neutrinos

- ☑ Magnetic Moment Operator

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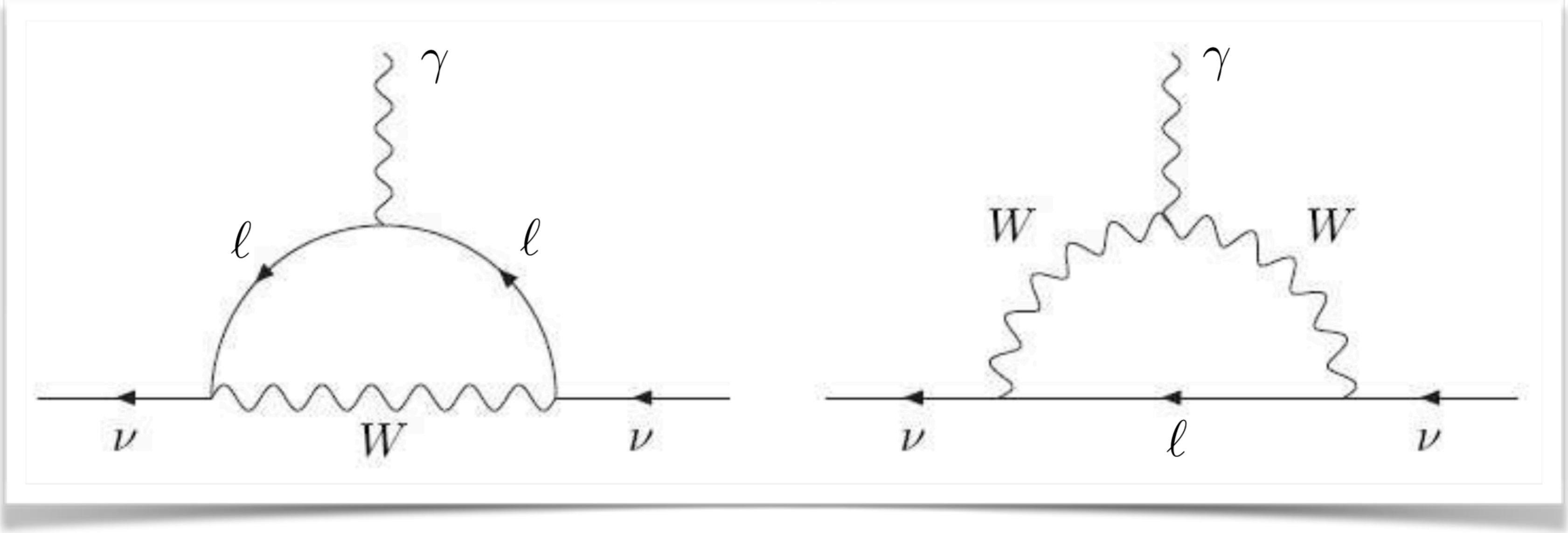
electromagnetic field strength tensor

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

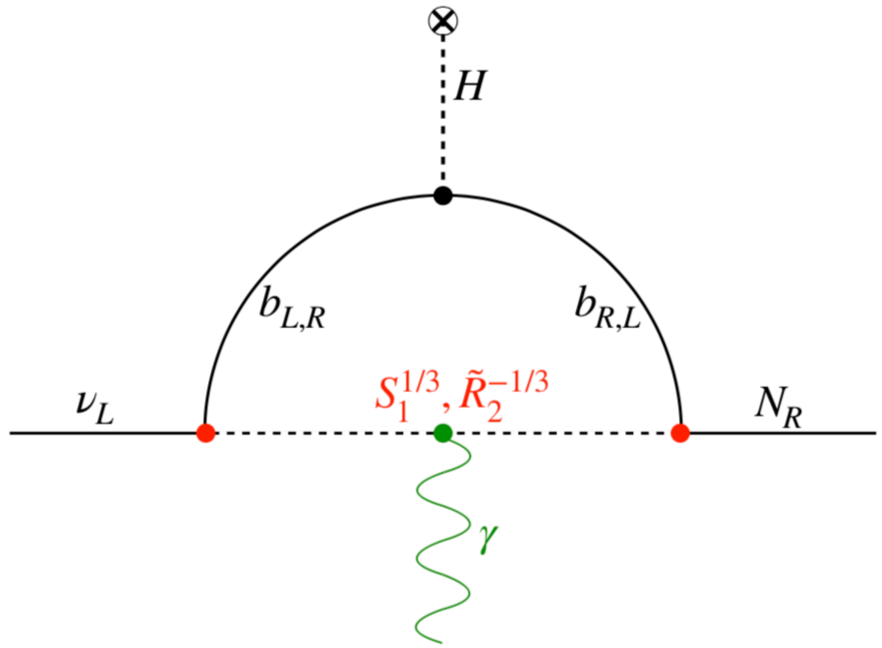
Petcov 1977
Fujikawa Shrock 1980

Neutrino Magnetic Moments Beyond the SM

- ☑ 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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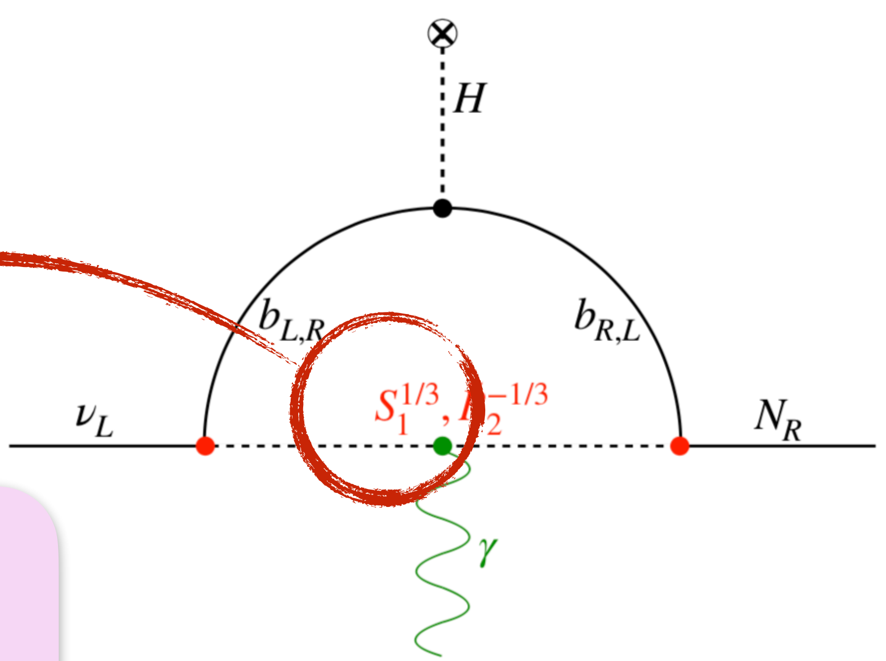
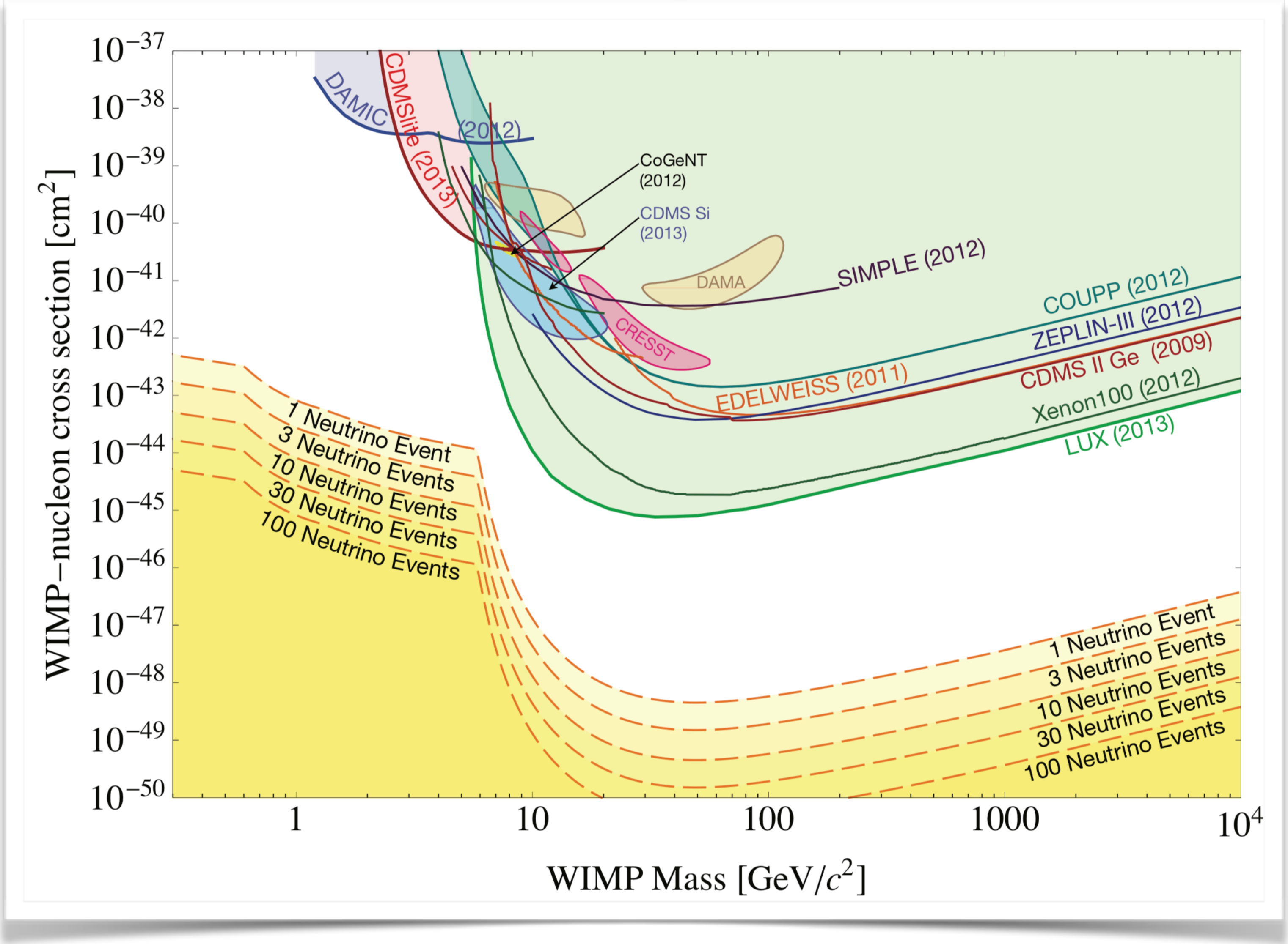


Brdar Greljo JK Opferkuch
2007.15563

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

Signals in Direct Detection Experiments

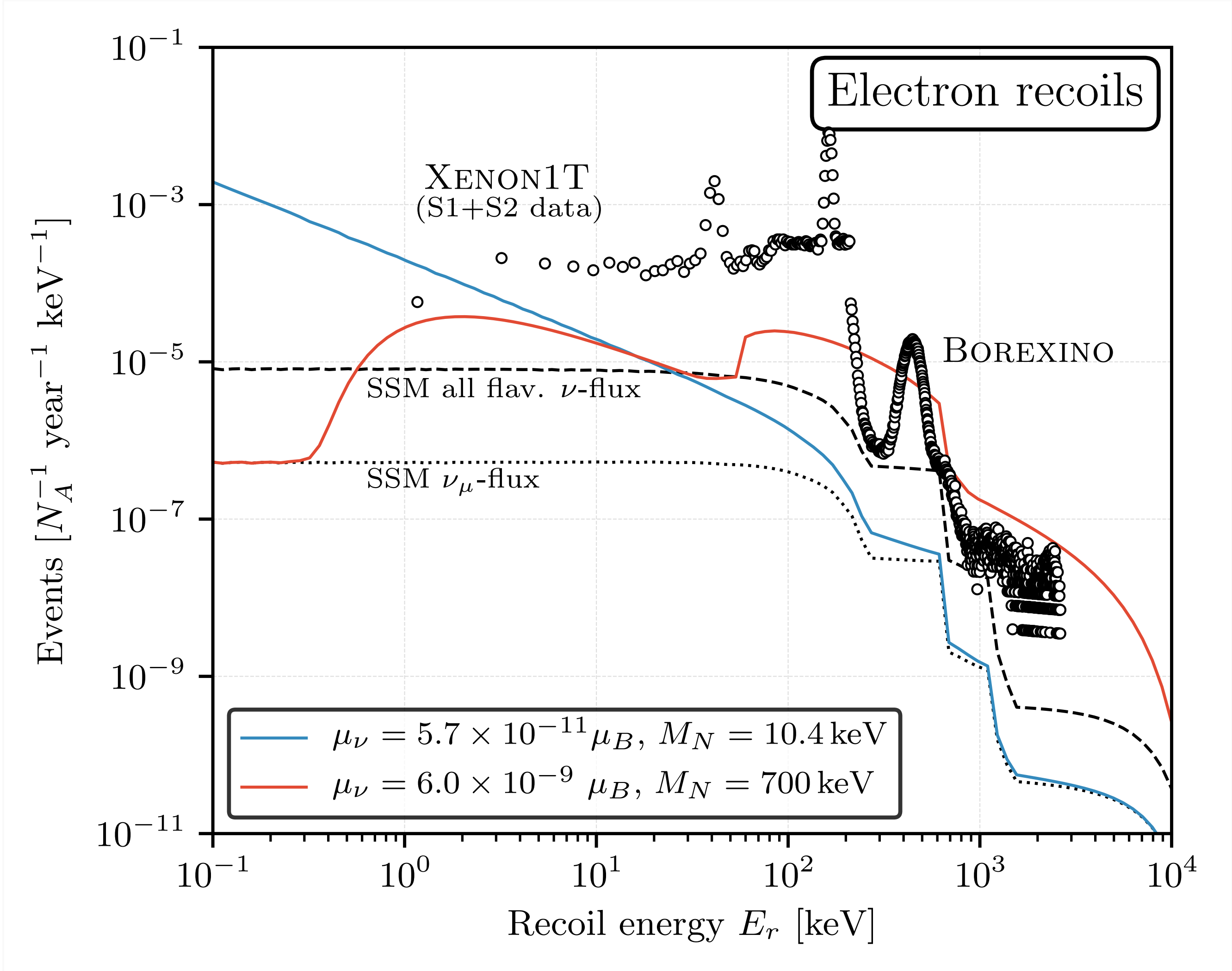
☑ solar ν always present in direct detection experiments

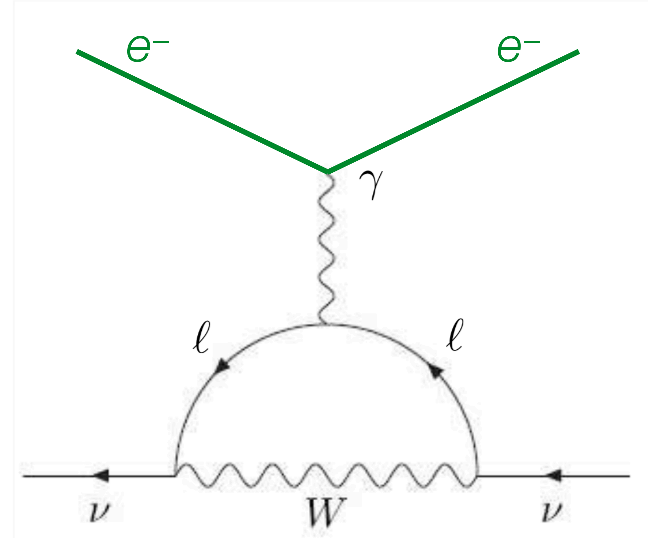


Gütlein et al. arXiv:1003.5530
Billard Strigari Figueroa-Feliciani arXiv:1307.5458

Signals in Direct Detection Experiments

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





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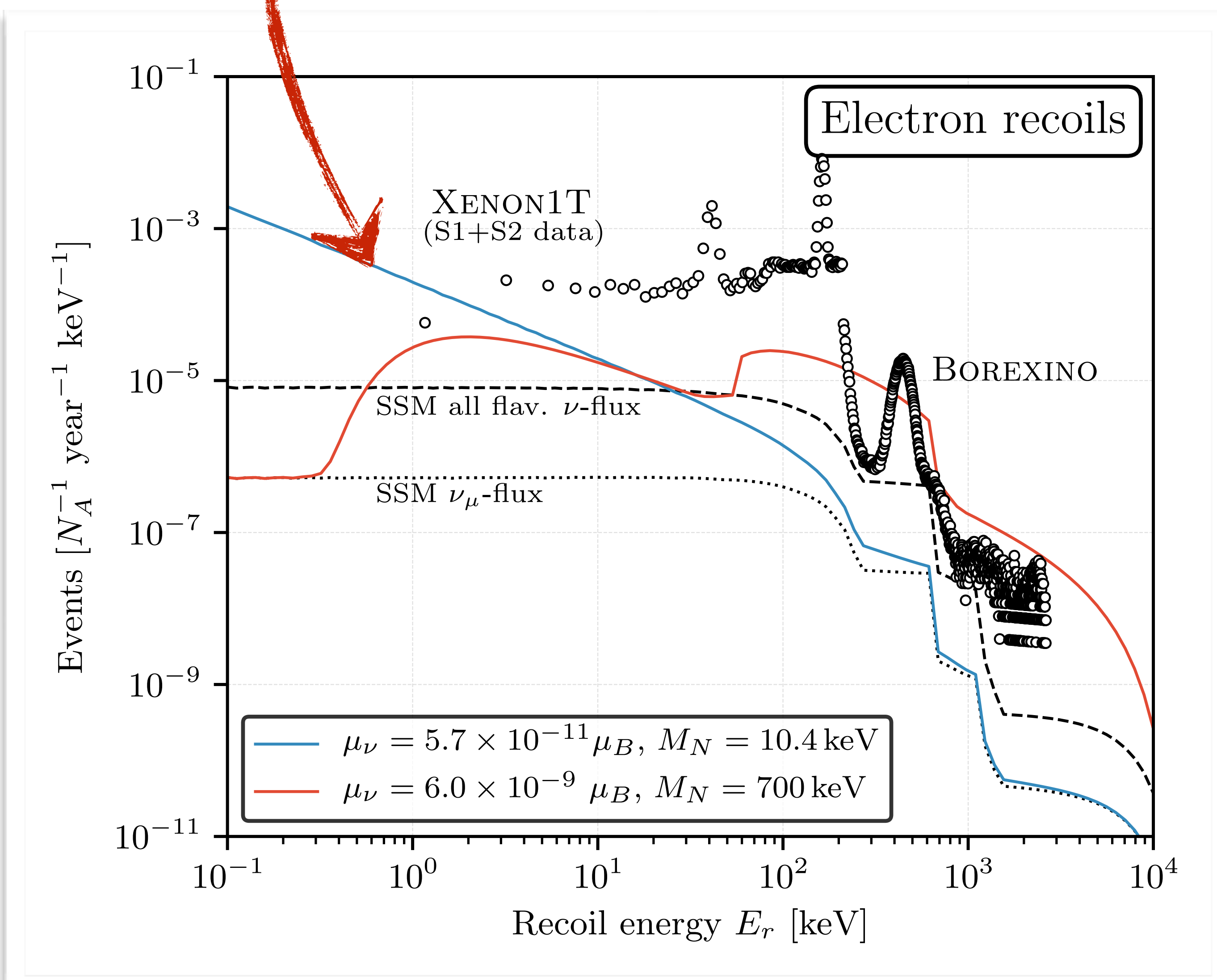
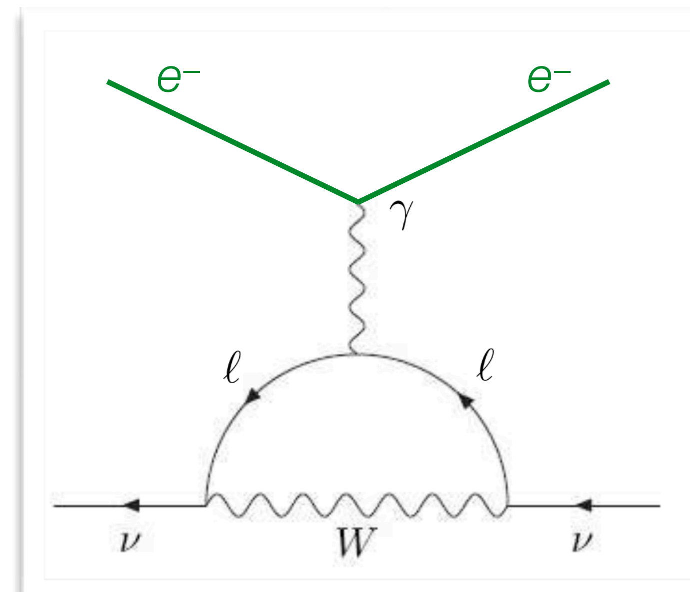
Signals in Direct Detection Experiments

- ☑ so... ct detection experiments
- ☑ en... 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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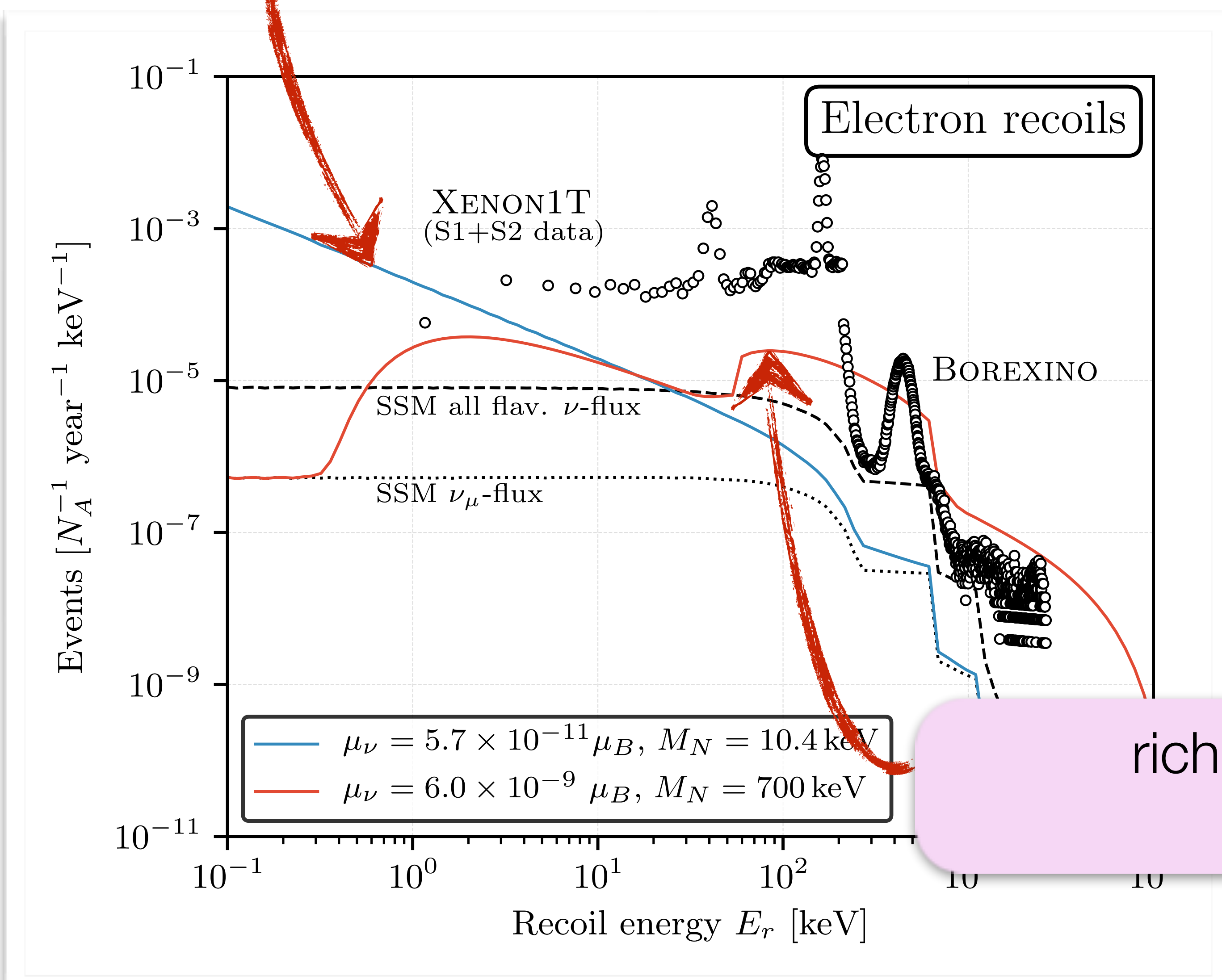
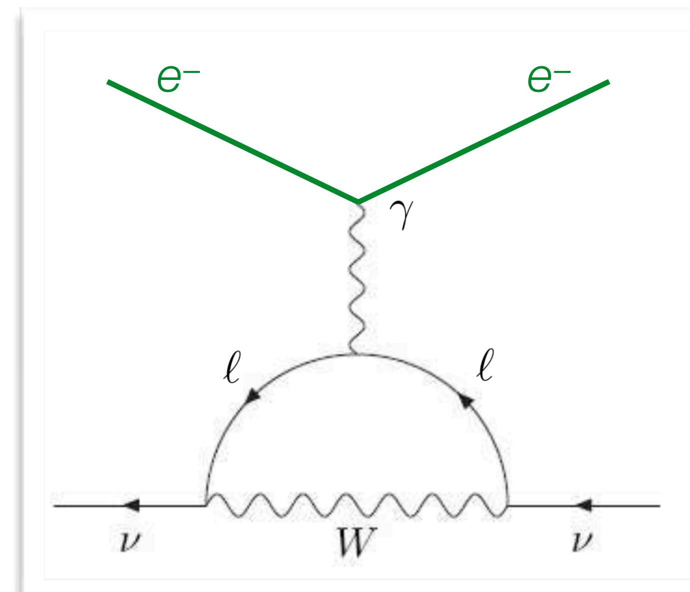
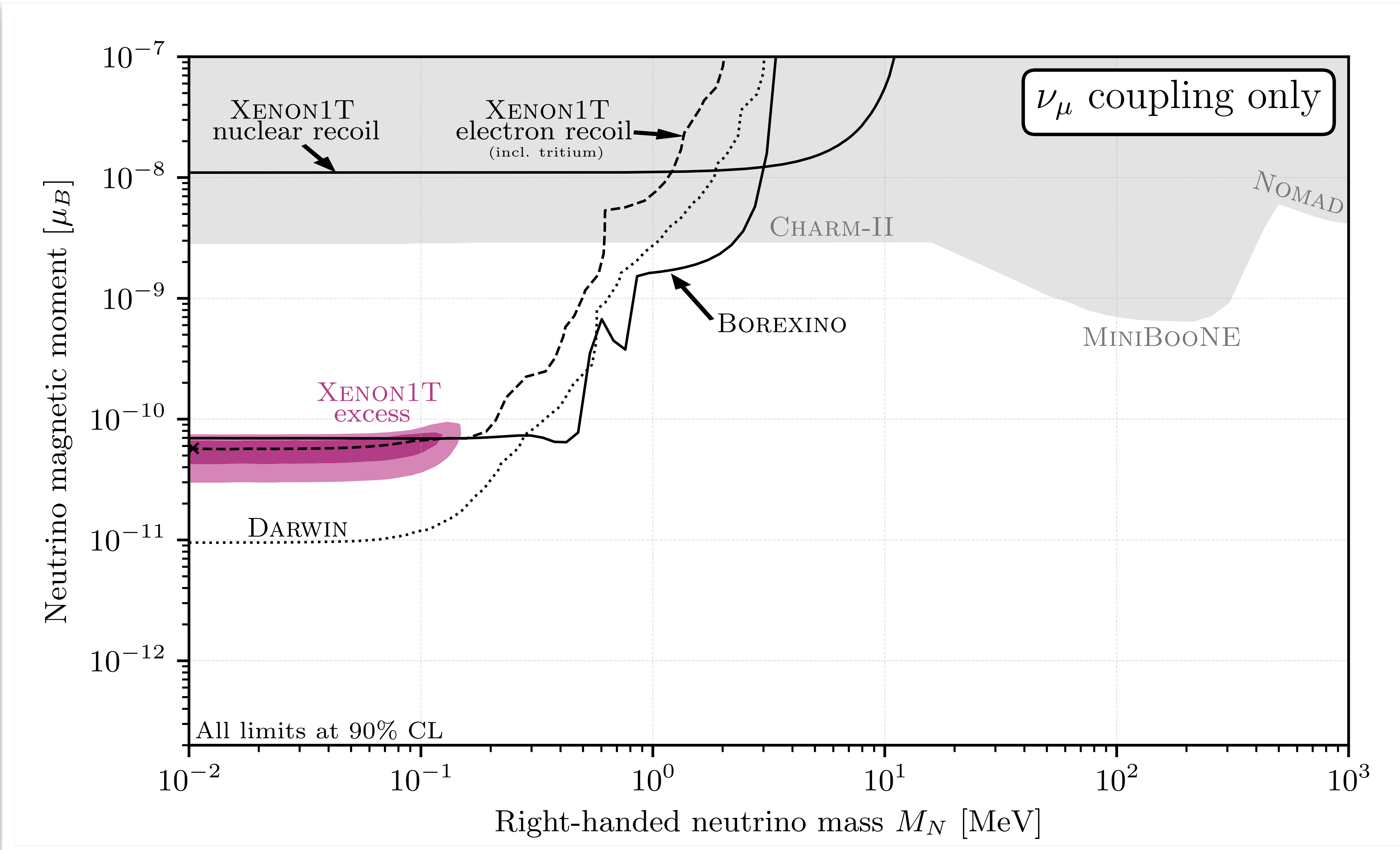


rich kinematic features for heavy N_R



Summary of Terrestrial Constraints



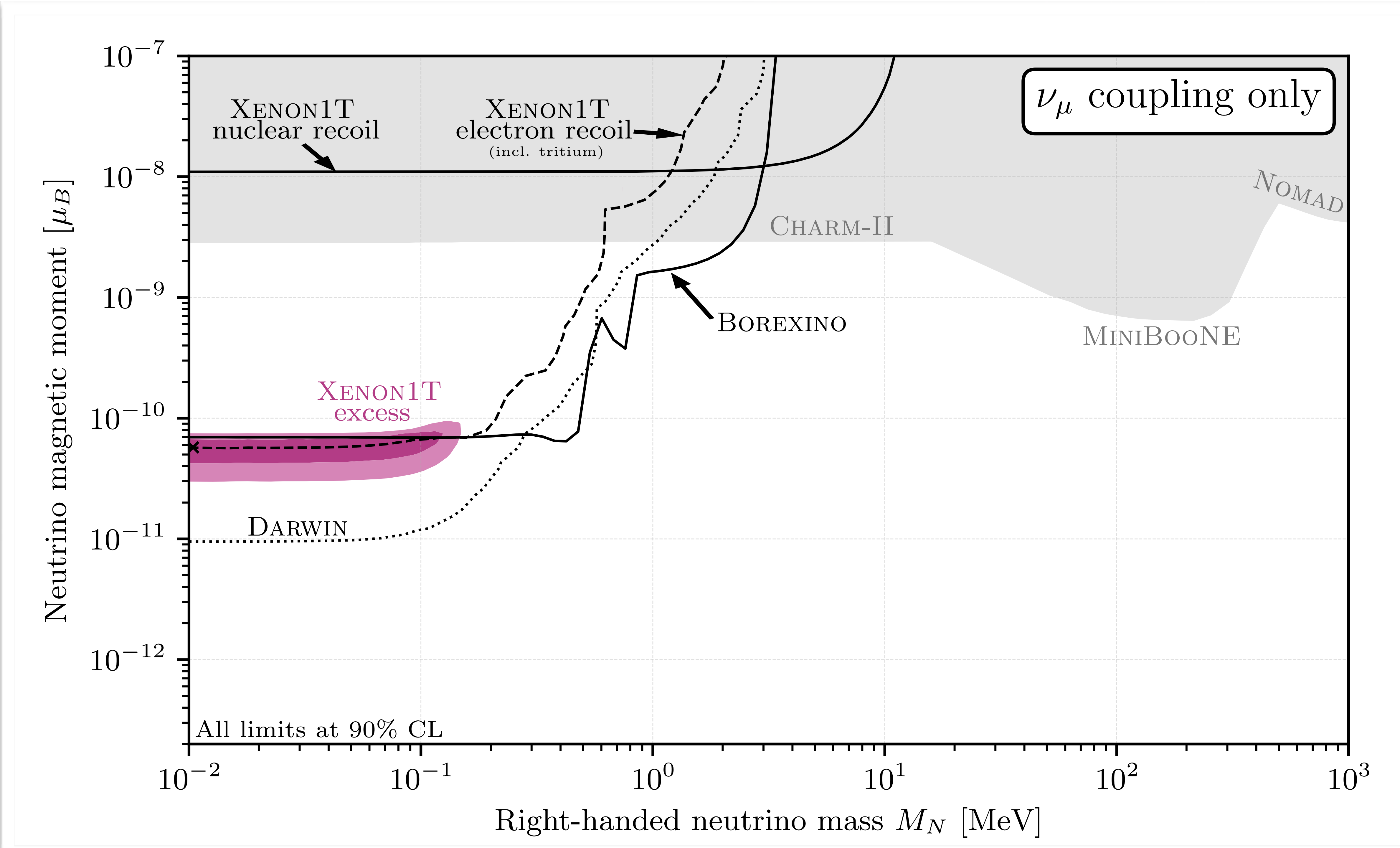
Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

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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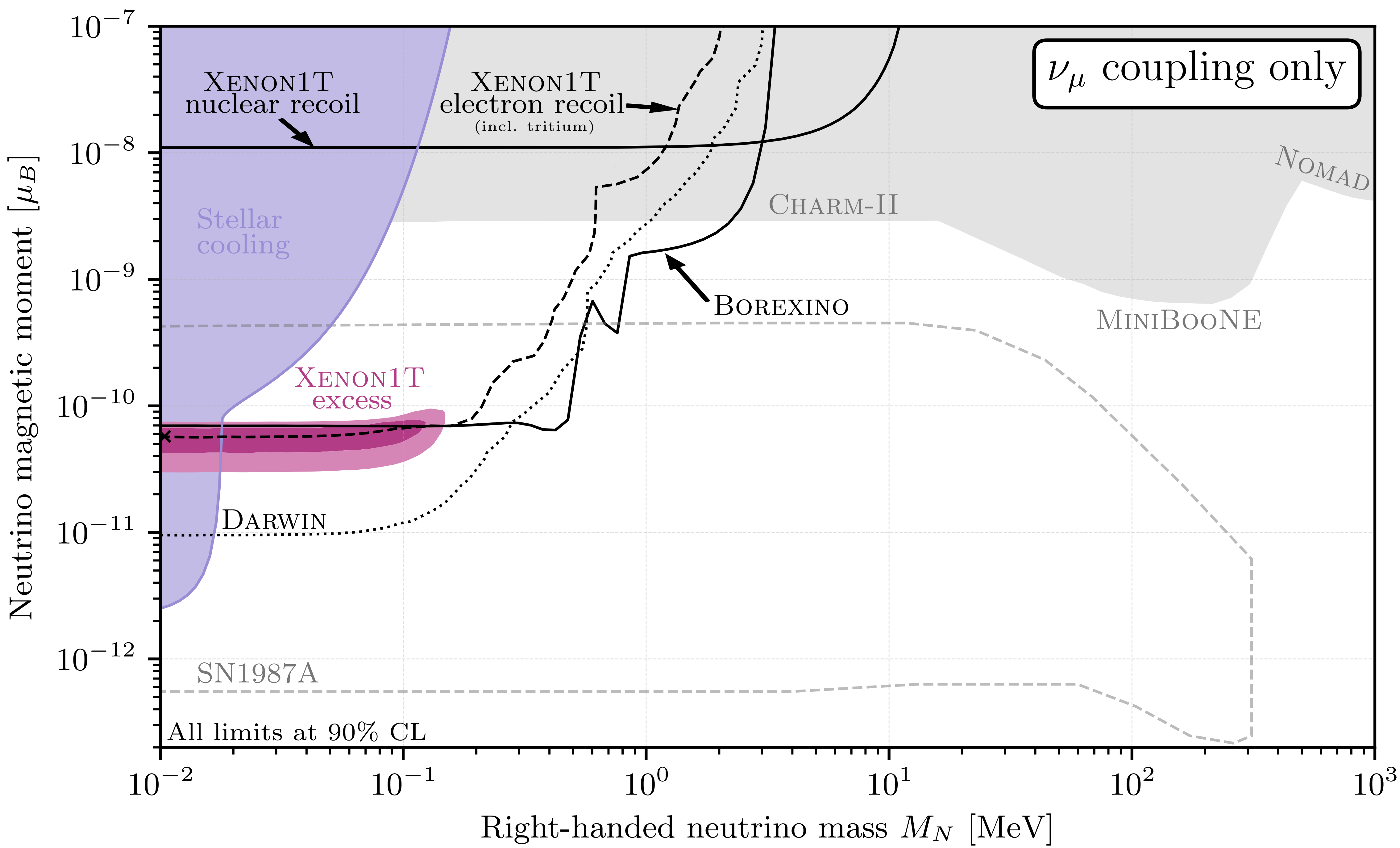

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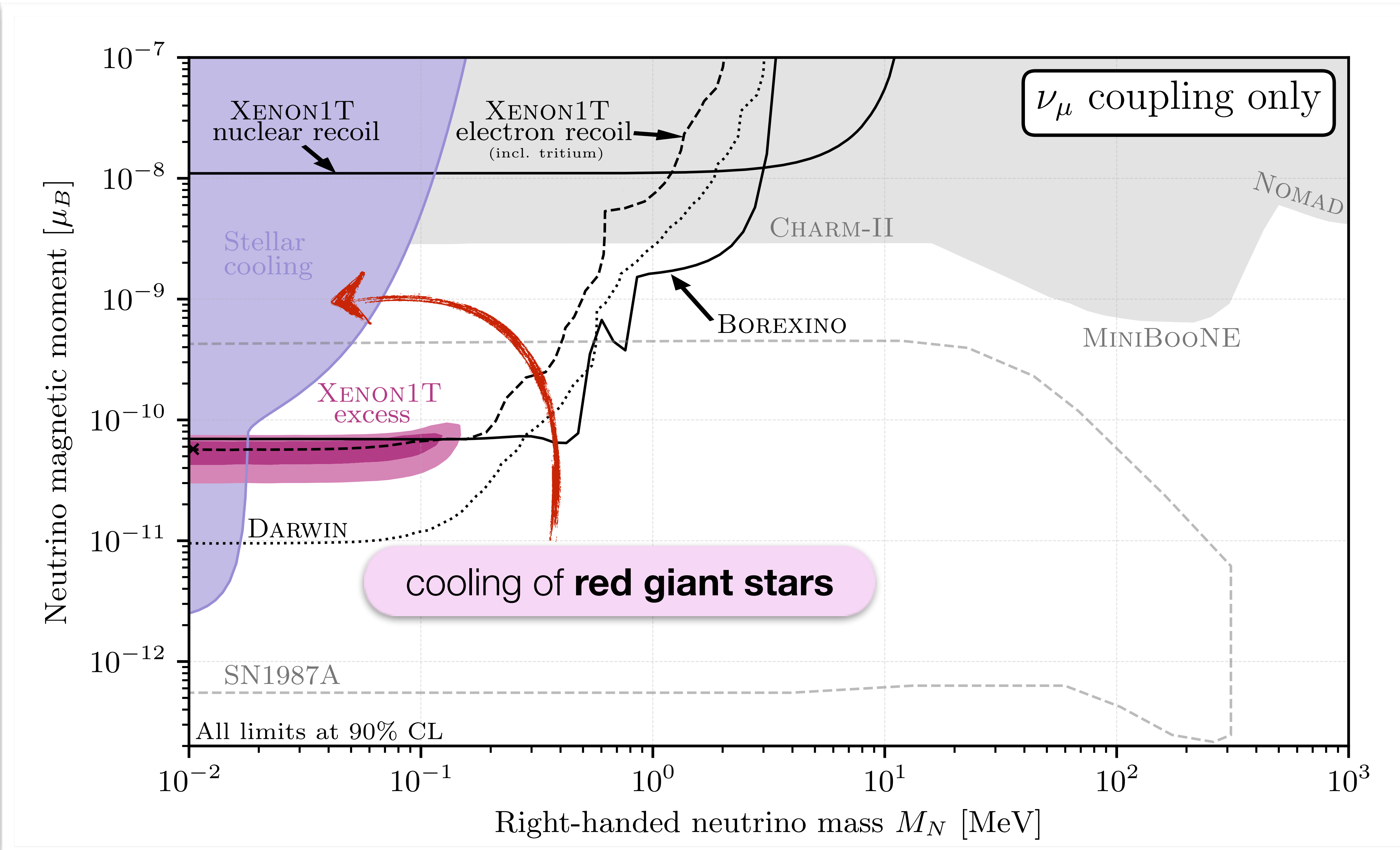
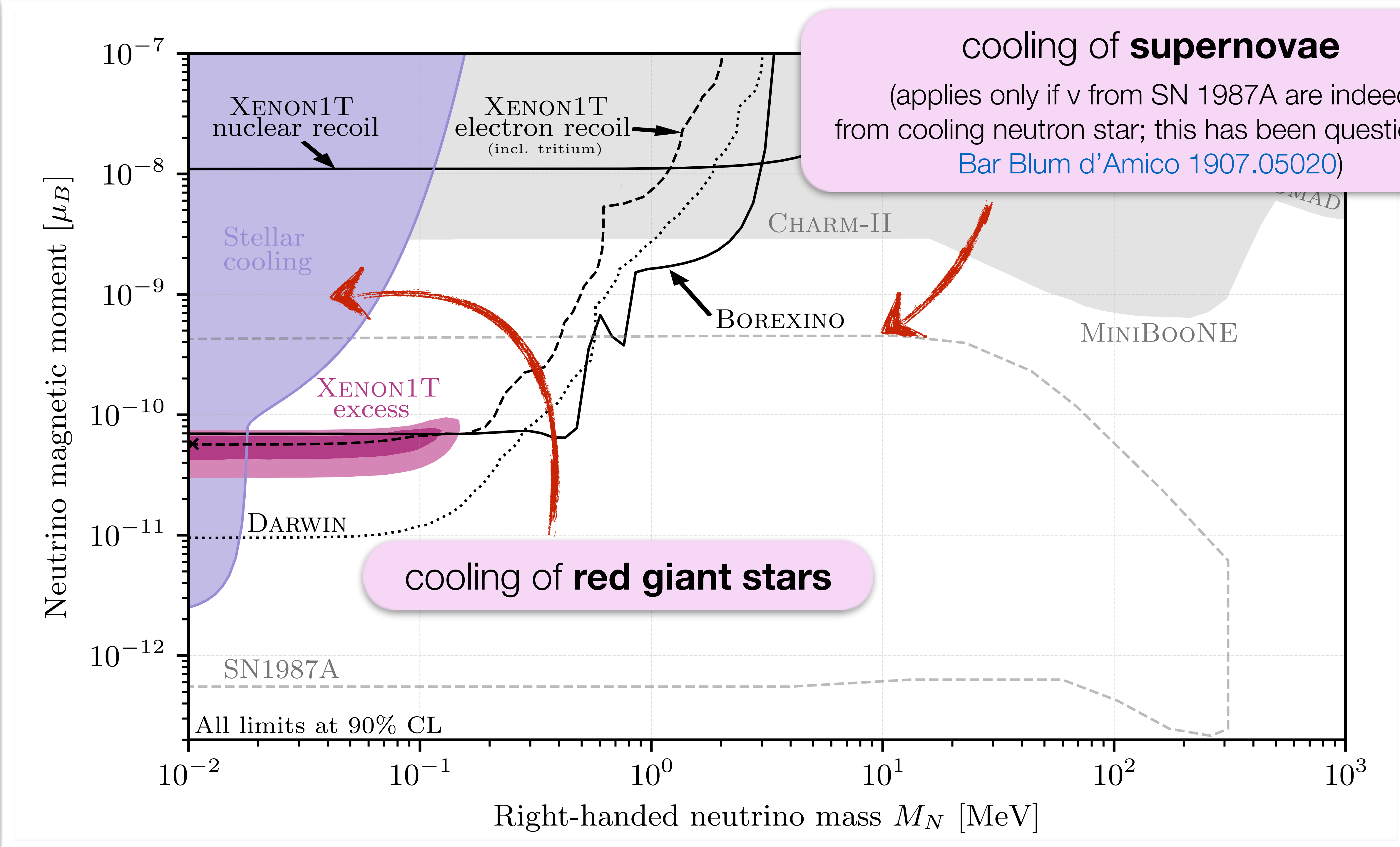
Stellar Cooling



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



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**

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

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 ($N_R \to \nu_L + \gamma$) after BBN alters baryon-to-photon ratio η.

Brdar Greljo JK Opferkuch 2007.15563
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Cosmology

- BBN
  - presence of light N_R during BBN alters N_{eff}
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- CMB
  - N_R decay ($N_R \rightarrow \nu_L + \gamma$) after ν decoupling changes N_{eff}

Brdar Greljo JK Opferkuch 2007.15563
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- ☑ BBN
  - presence of light N_R during BBN alters N_{eff}
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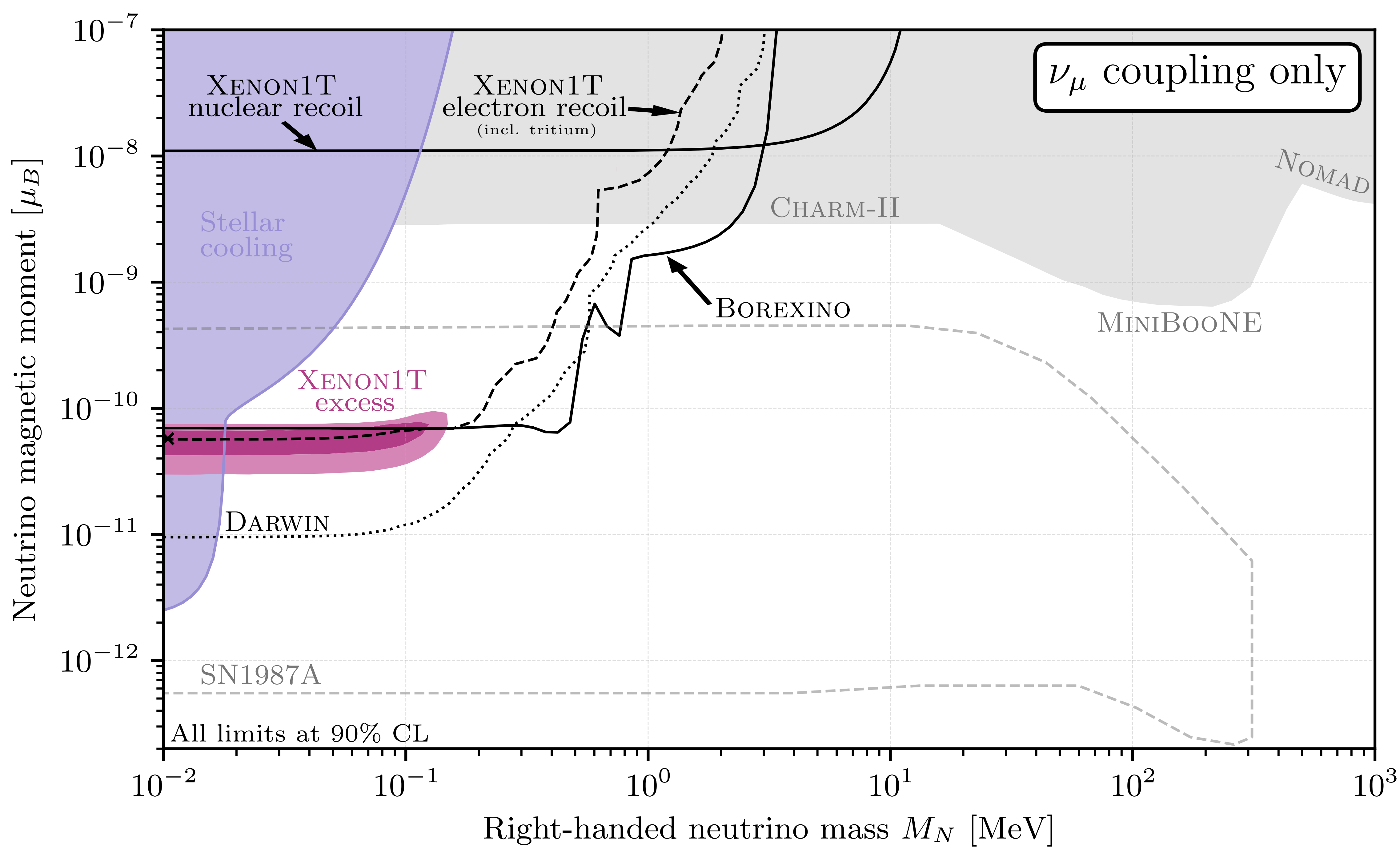
- ☑ CMB
  - N_R decay ($N_R \Rightarrow \nu_L + \gamma$) after ν decoupling changes N_{eff}
- ☑ technical details ➟ backup slides

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

Summary of Constraints



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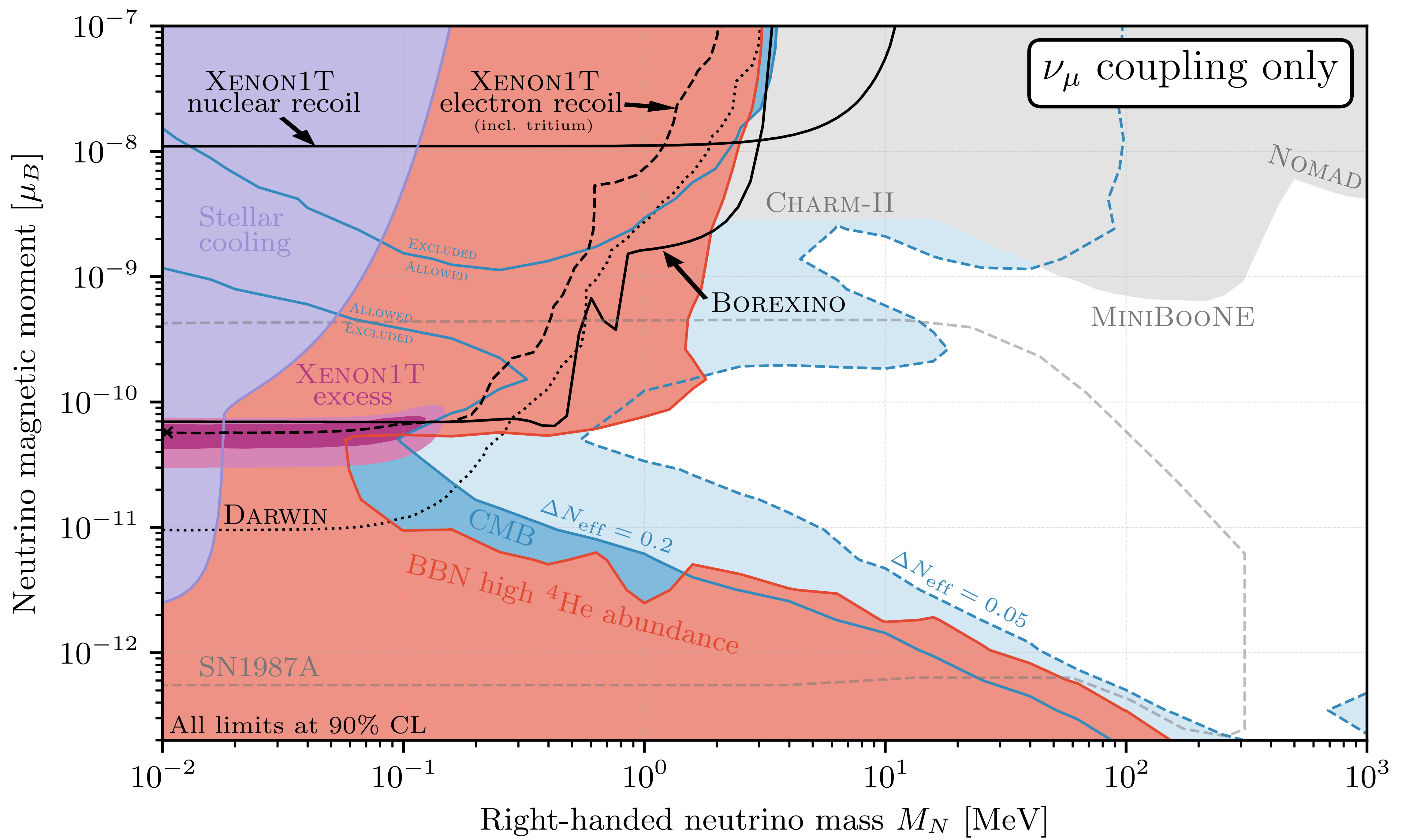

Coloma Machado Martinez-Soler Shoemaker 1707.08573, Magill Plestid Pospelov Tsai 1803.03262
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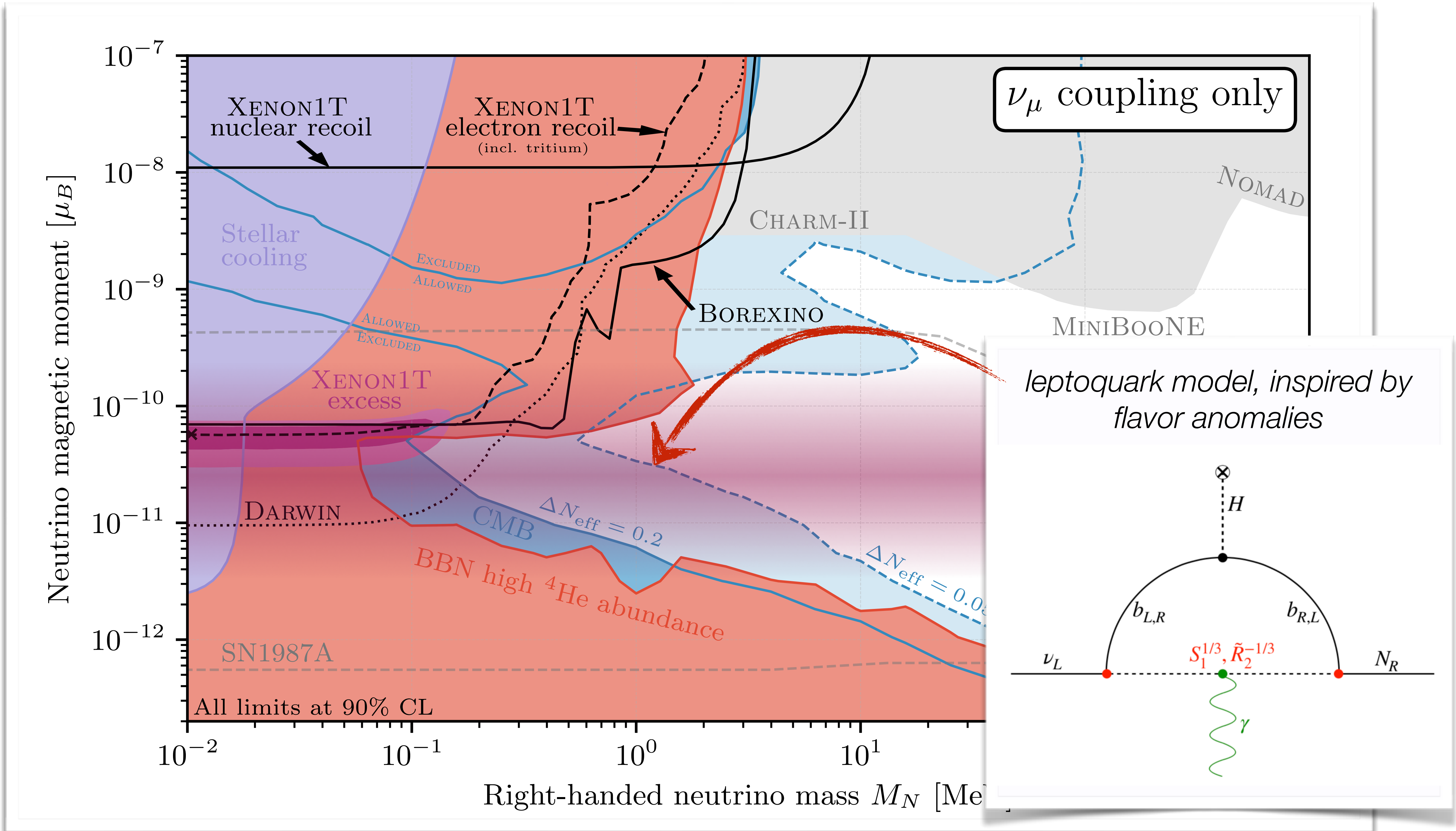

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Shoemaker Wyenberg 1811.12435, Brdar Greljo JK Opferkuch arXiv:2007.15563, Greljo Stangl Thomsen 2103.13991

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

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

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

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New Neutrino Interaction

dim-6 operators

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

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New Neutrino Interaction

dim-6 operators

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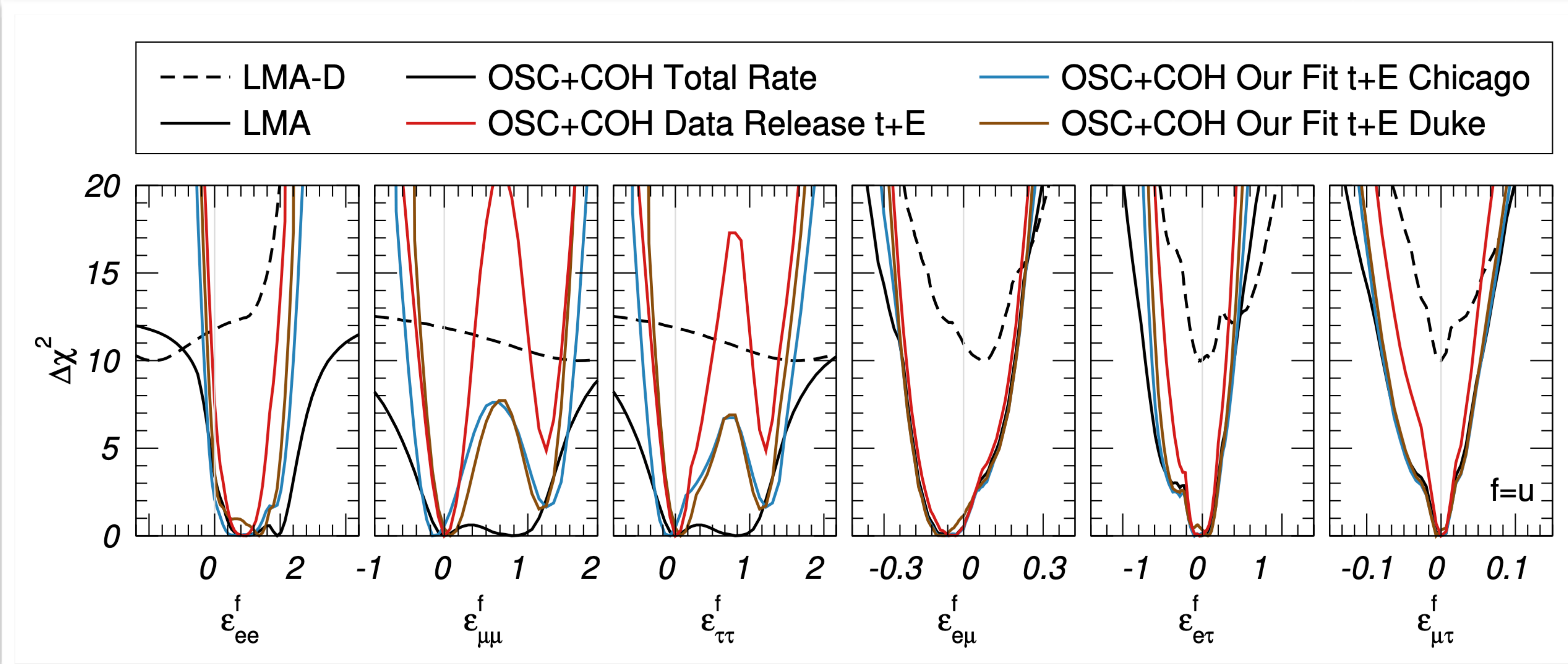
dimensionless coefficients
(strength of new interactions
relative to SM weak interactions)

- 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



Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109

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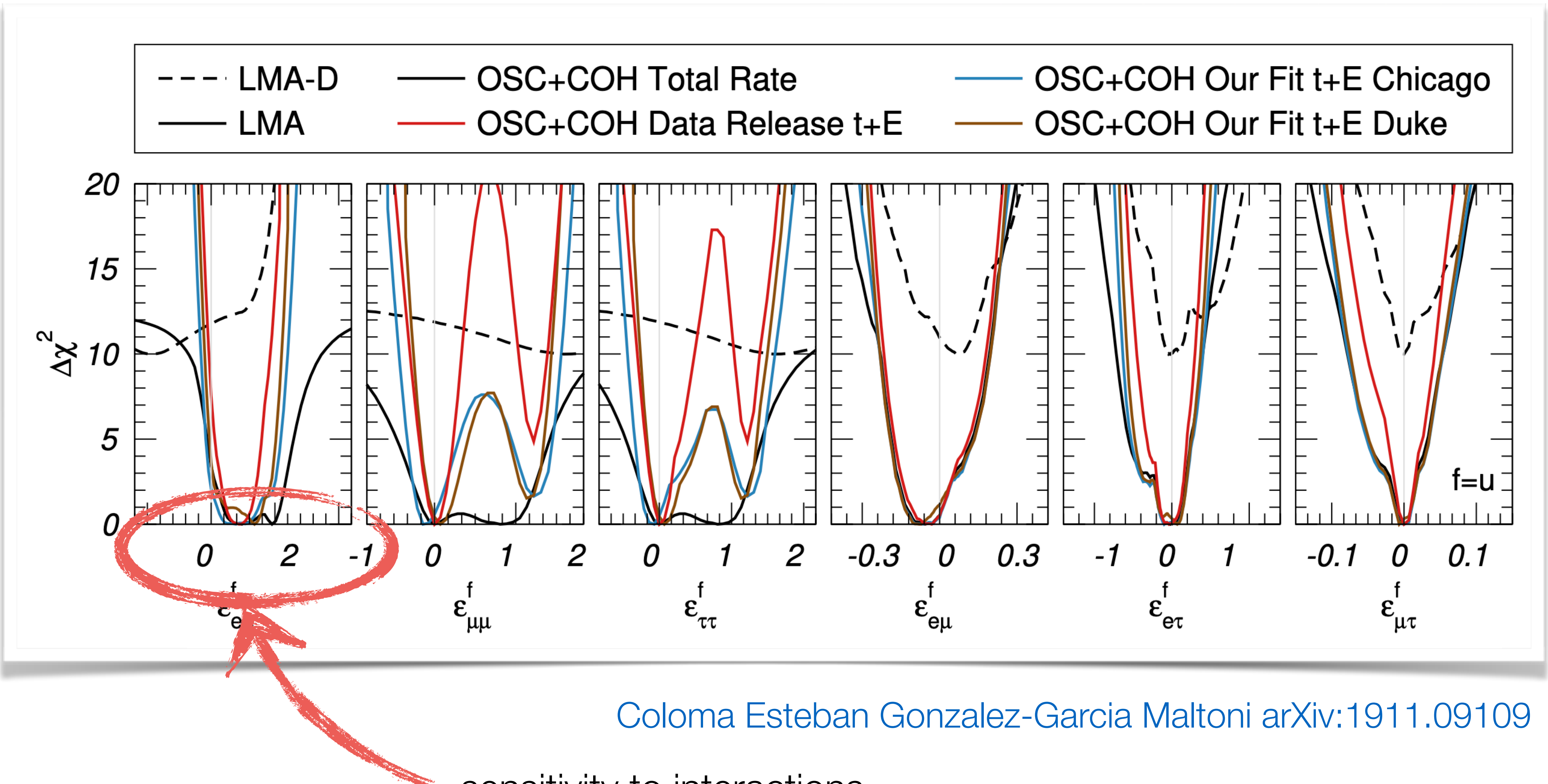
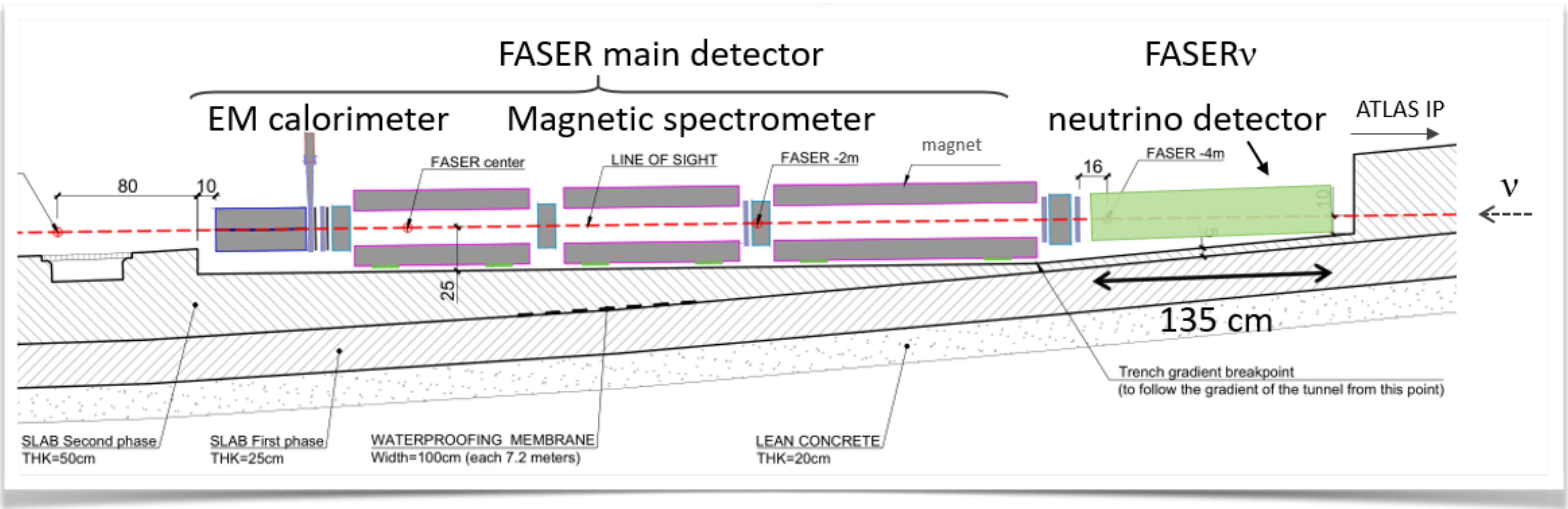


Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109

sensitivity to interactions
similar in strength to
SM weak interactions

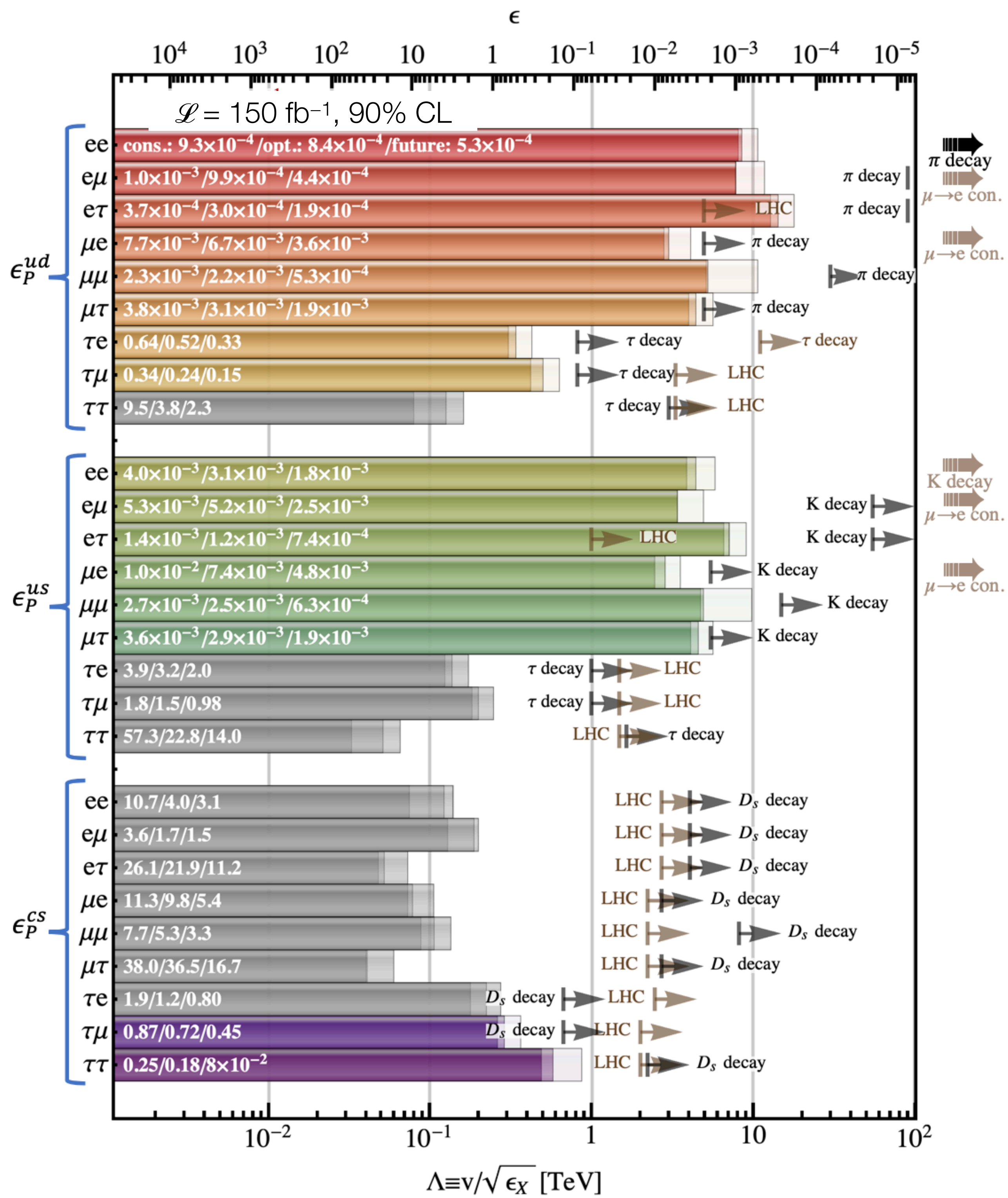
Anomalous Charged Currents

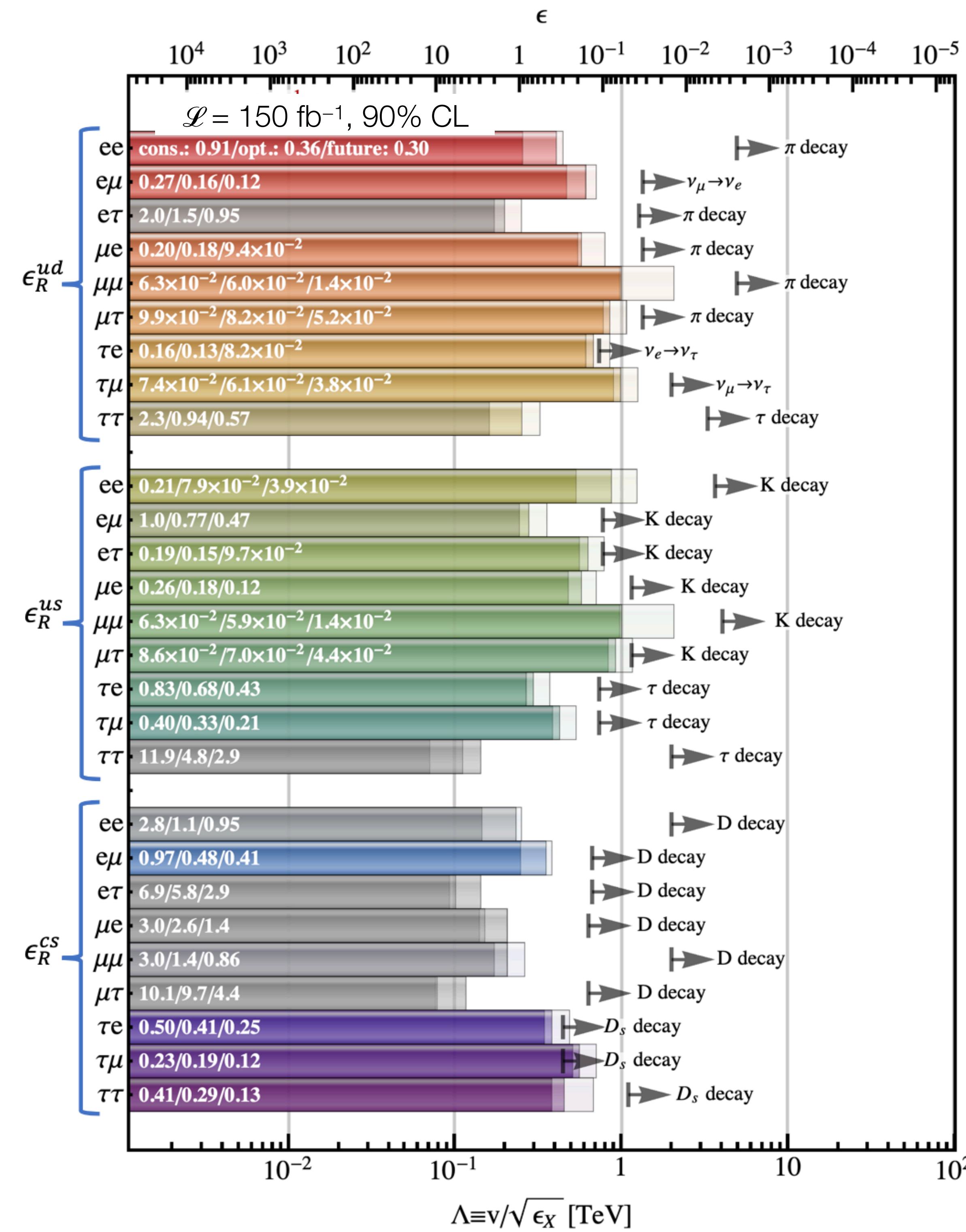
☑ Interesting new opportunity: FASERν at the LHC



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

Anomalous Charged Currents





Falkowski González-Alonso JK
Soreq Tabrizi, arXiv:2105.12136

Outlook

dim-4: the Neutrino Portal

↓

dim-5: Neutrino Magnetic Moments

↓

dim-6: Neutrinos in SMEFT

Outlook

dim-4: the Neutrino Portal

↓

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↓

dim-6: Neutrinos in SMEFT

- ☑ 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

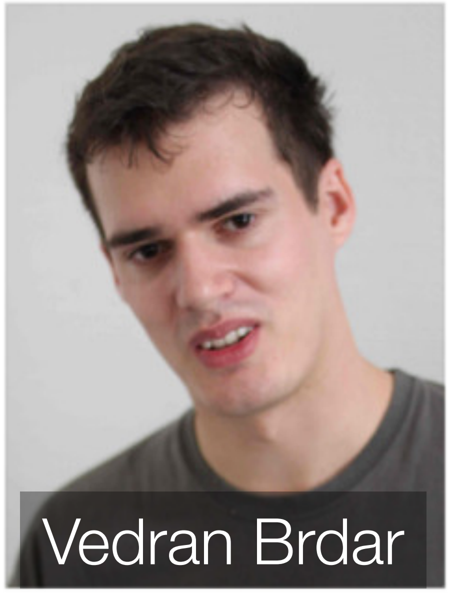
dim-5: Neutrino Magnetic Moments

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

dim-6: Neutrinos in SMEFT

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

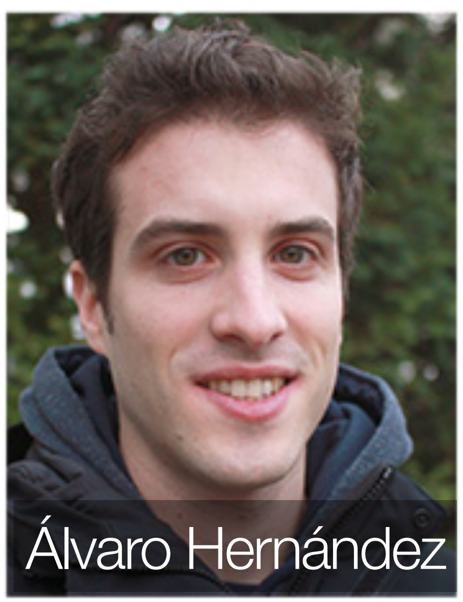
Thank You!


Vedran Brdar


Toby Opferkuch


Mona Dentler


Ivan Esteban


Álvaro Hernández


Ivan Martinez


Ninetta Saviano


Zahra Tabrizi

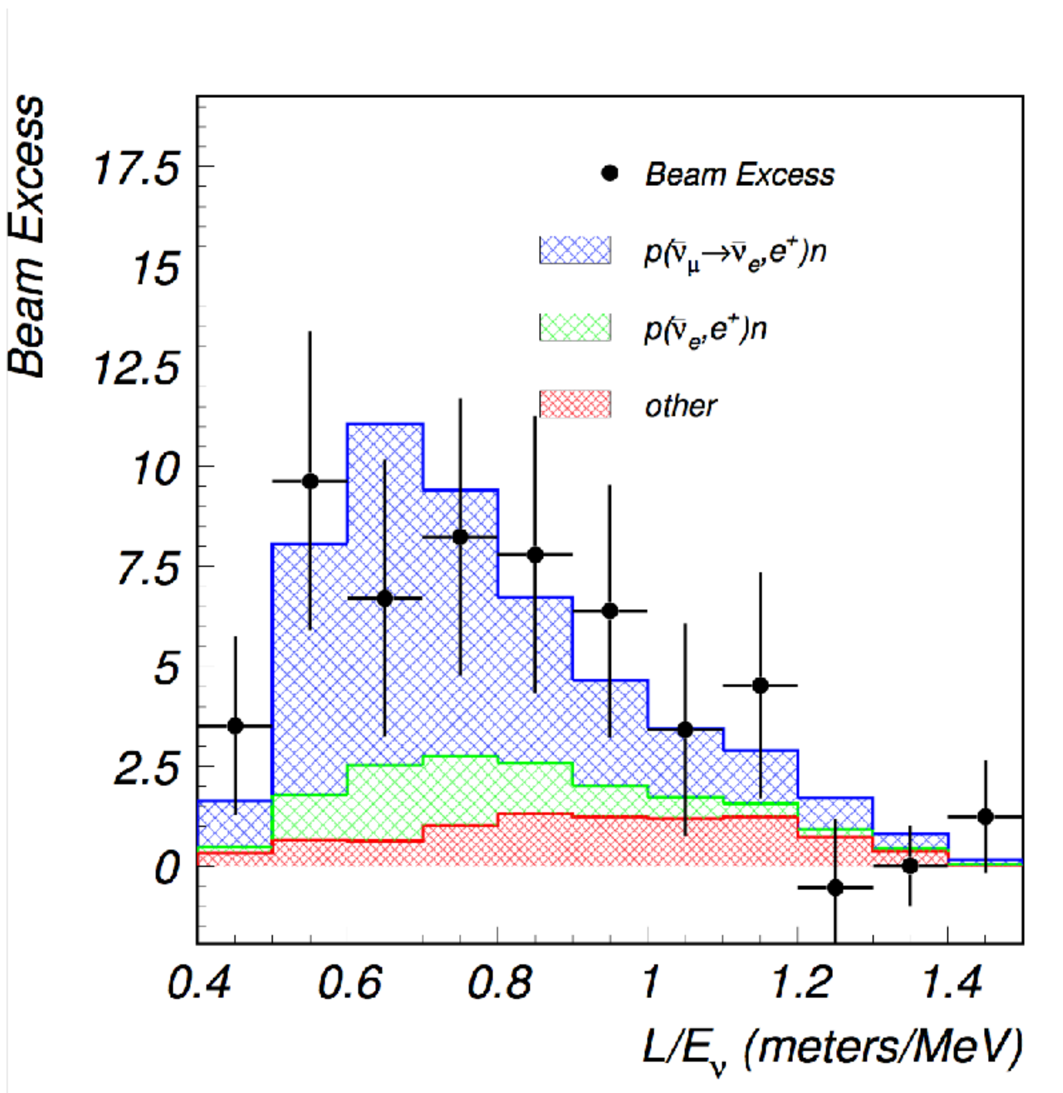
Bonus Slides

Oscillation Anomalies

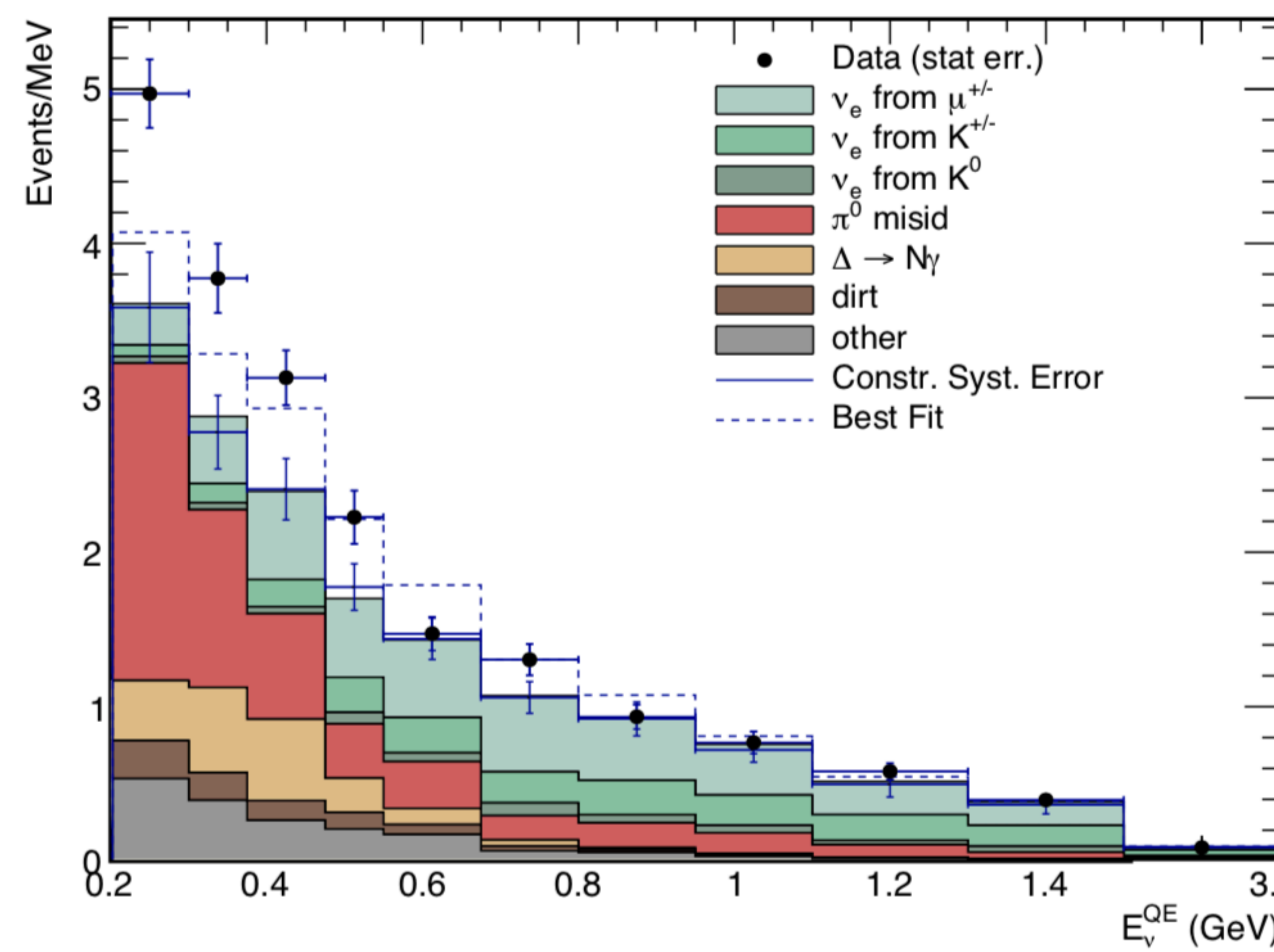
Anomalies in Short Baseline Oscillations

Anomalies in Short Baseline Oscillations

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



LSND 2001

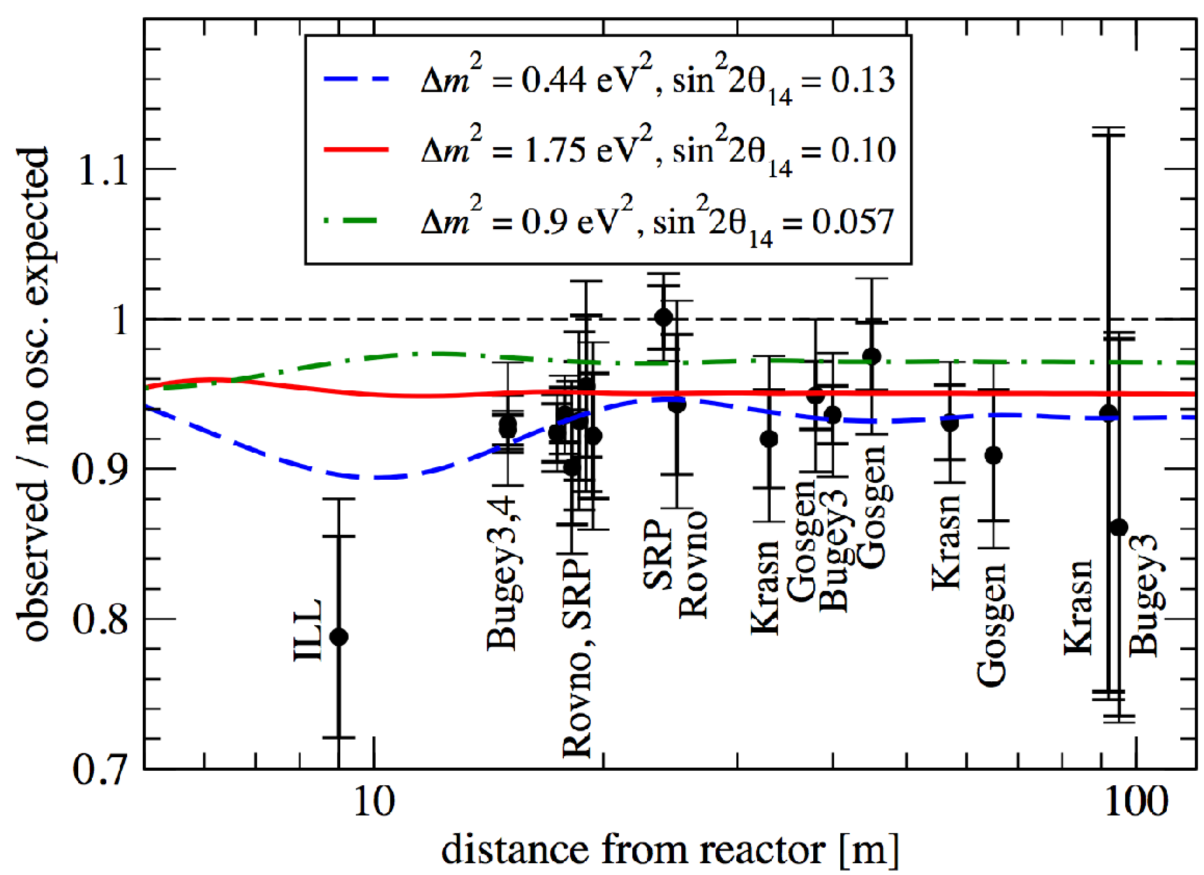


MiniBooNE 2018

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



Anomalies in Short Baseline Oscillations

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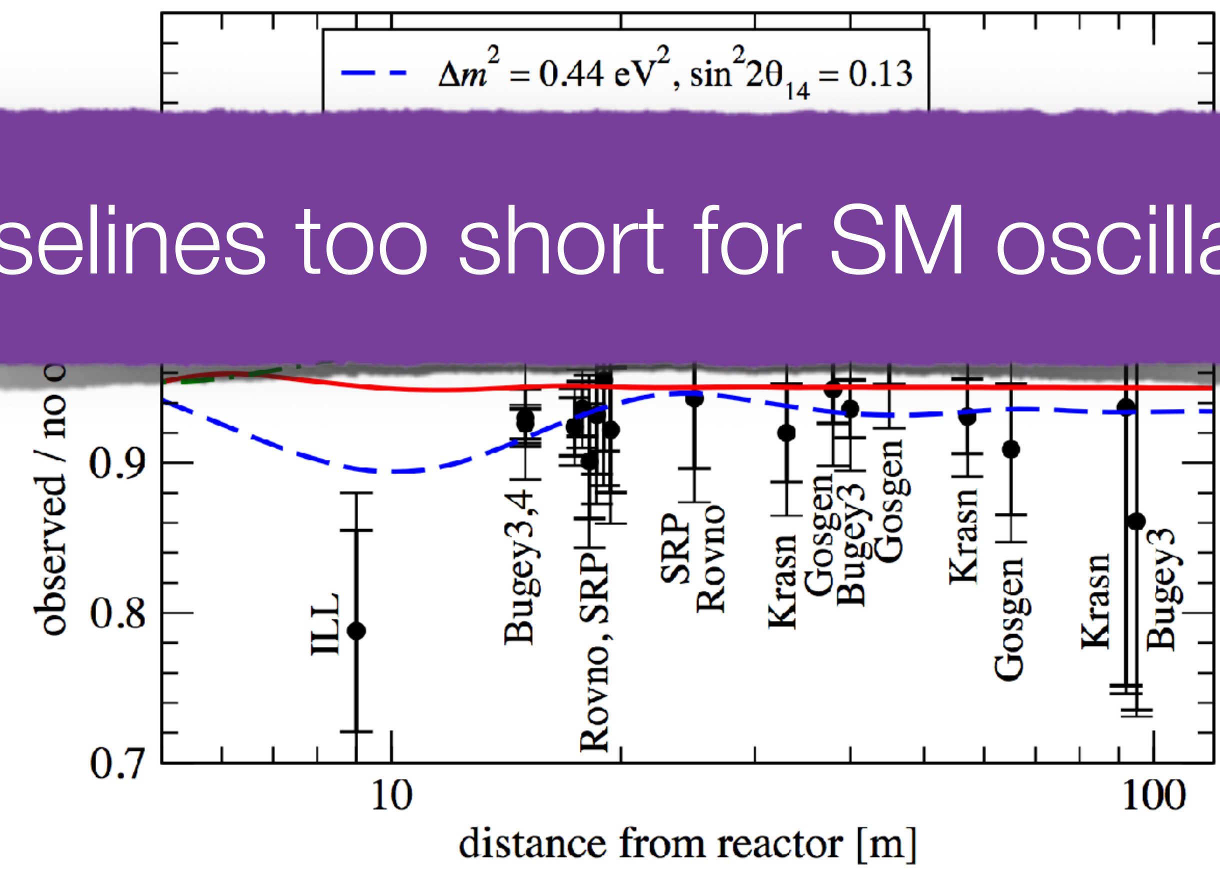
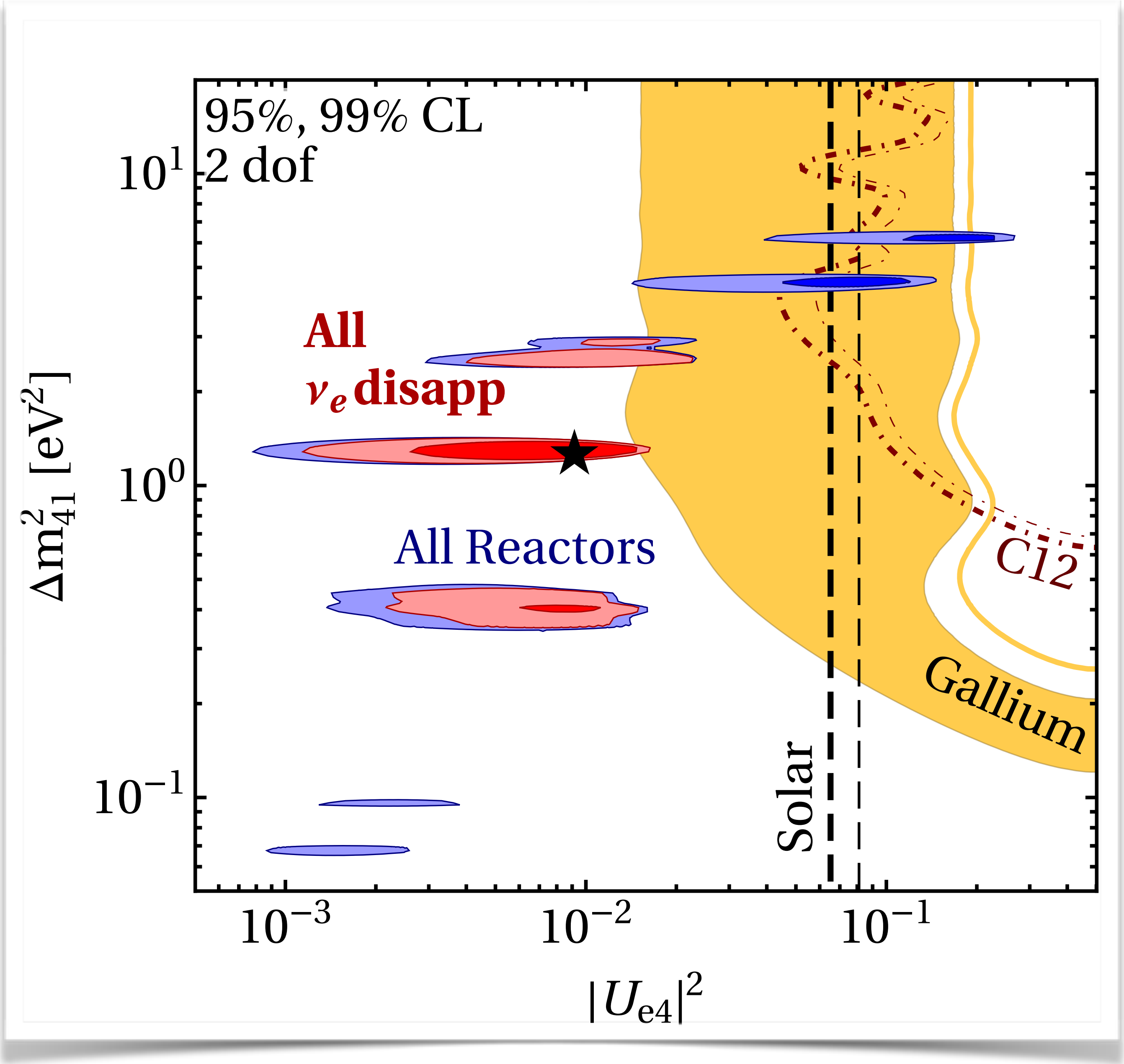


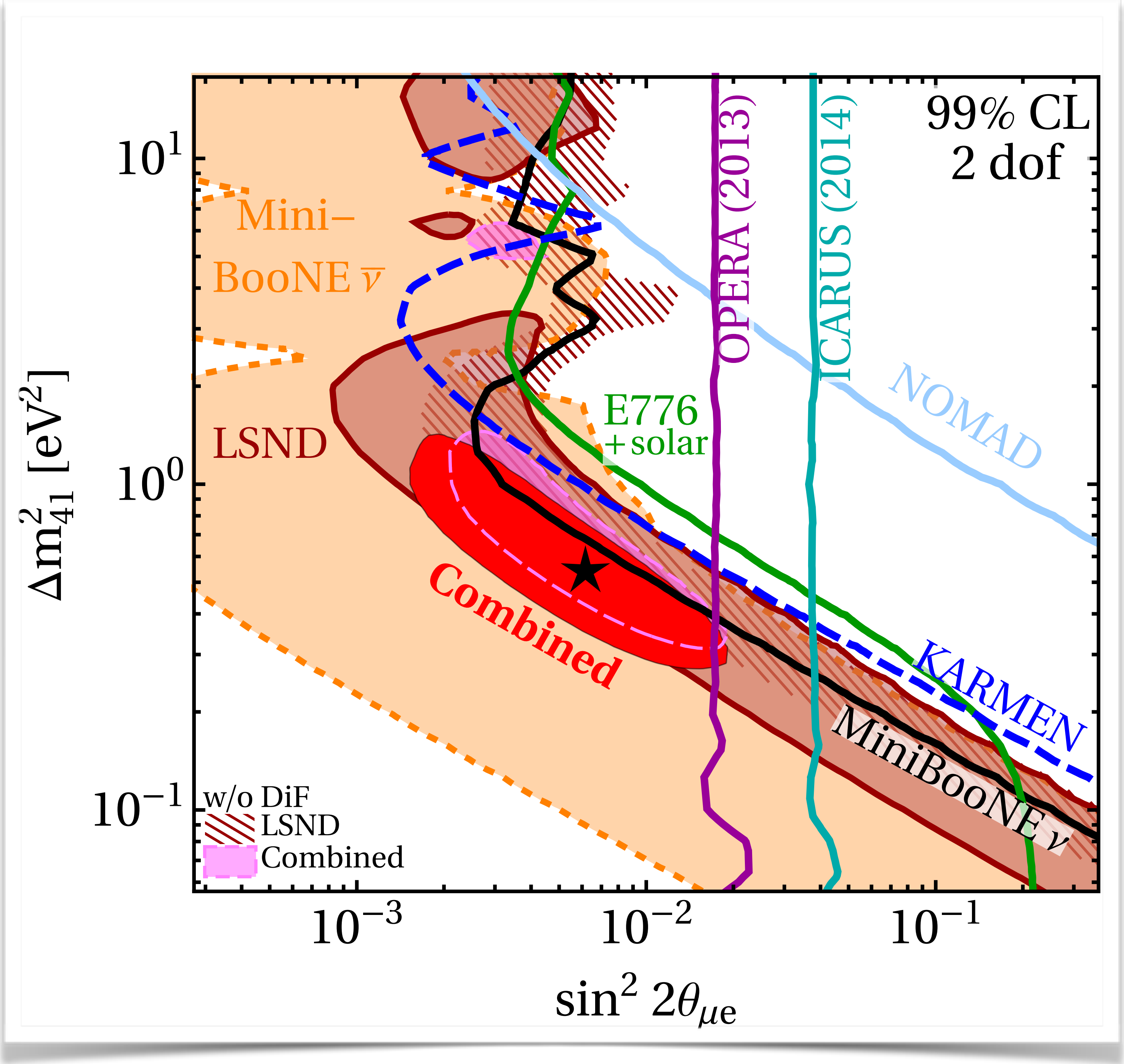
Baselines too short for SM oscillations

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*

$\nu_\mu \to \nu_e$ appearance



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

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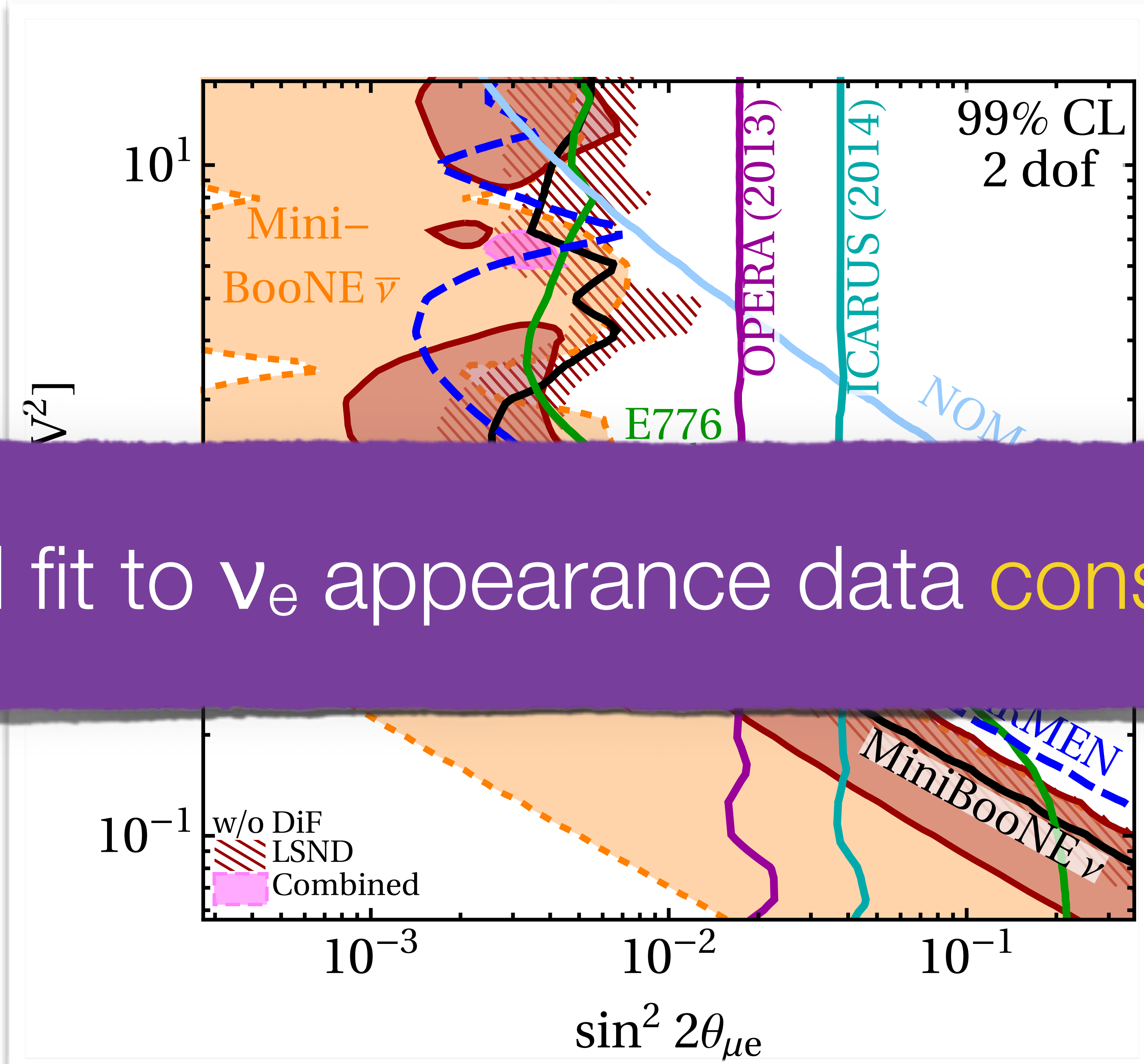
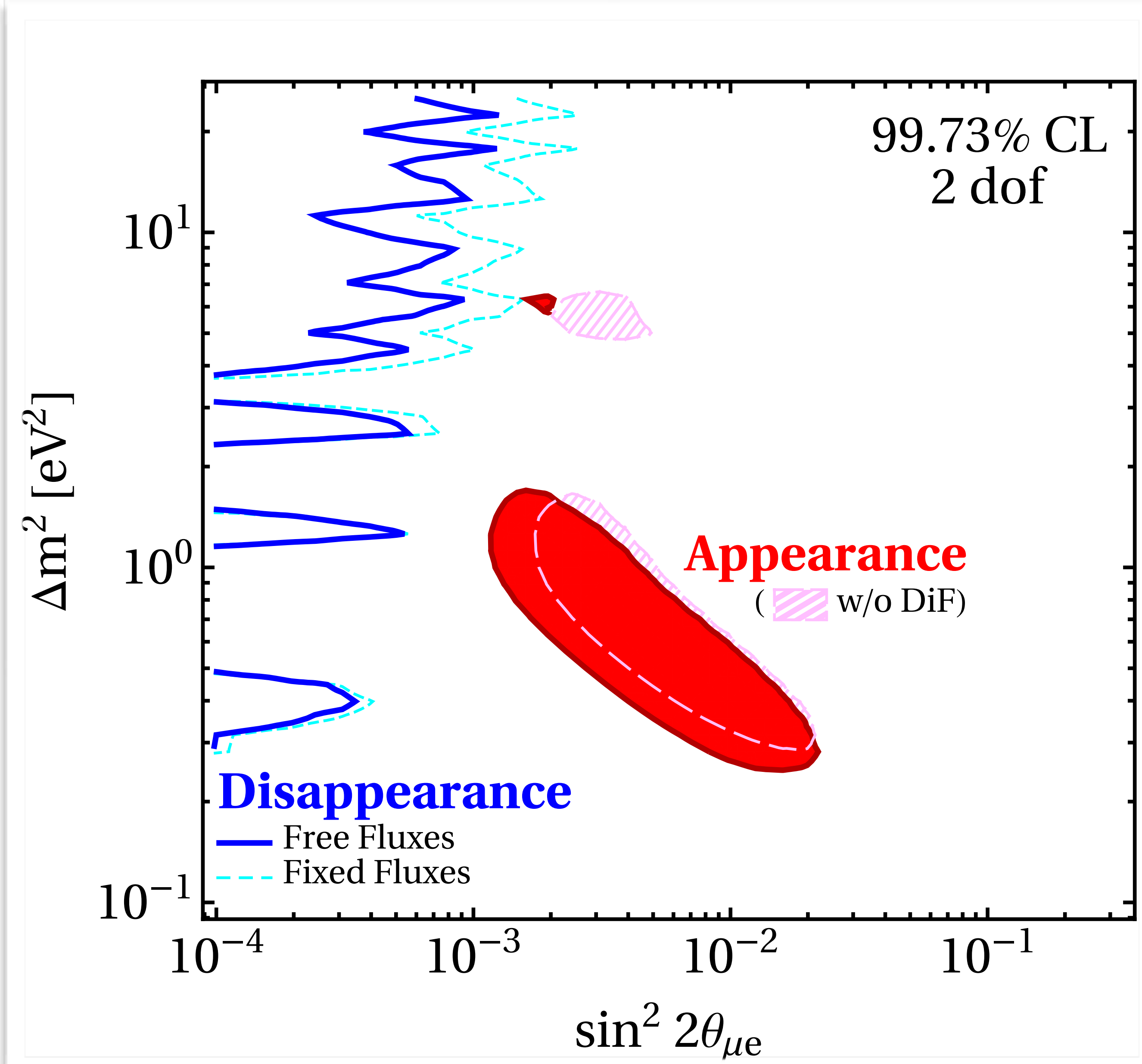


Global fit to ν_e appearance data consistent.

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

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 ($N_R \to \nu_L + \gamma$) 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:

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

Brdar Greljo JK Opferkuch 2007.15563

Big Bang Nucleosynthesis — Implementation

☑ Solve (integrated) Boltzmann equations:

Hubble expansion

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

Brdar Greljo JK Opferkuch 2007.15563

Big Bang Nucleosynthesis — Implementation

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$$\dot\rho_N = -s_N H\rho_N - \Gamma_N(\rho_N - \rho_N^{\rm eq}) - \Gamma_{eN}(\rho_N - \rho_N^{\rm eq})\,.$$

e^+e^- annihilation

Brdar Greljo JK Opferkuch 2007.15563

Big Bang Nucleosynthesis — Implementation

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Hubble expansion

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\begin{aligned}
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\end{aligned}
$$

e^+e^- annihilation

N_R decay

Brdar Greljo JK Opferkuch 2007.15563

Big Bang Nucleosynthesis — Implementation

☑ Solve (integrated) Boltzmann equations:

Hubble expansion

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$$\dot\rho_\nu = -4H\rho_\nu + \tfrac{1}{2}\Gamma_N(\rho_N - \rho_N^{\rm eq}) + \Gamma_{eN}(\rho_N - \rho_N^{\rm eq})\,,$$
$$\dot\rho_N = -s_N H\rho_N - \Gamma_N(\rho_N - \rho_N^{\rm eq}) - \Gamma_{eN}(\rho_N - \rho_N^{\rm eq})\,.$$

e^+e^- annihilation

e^+N_R scattering

N_R decay

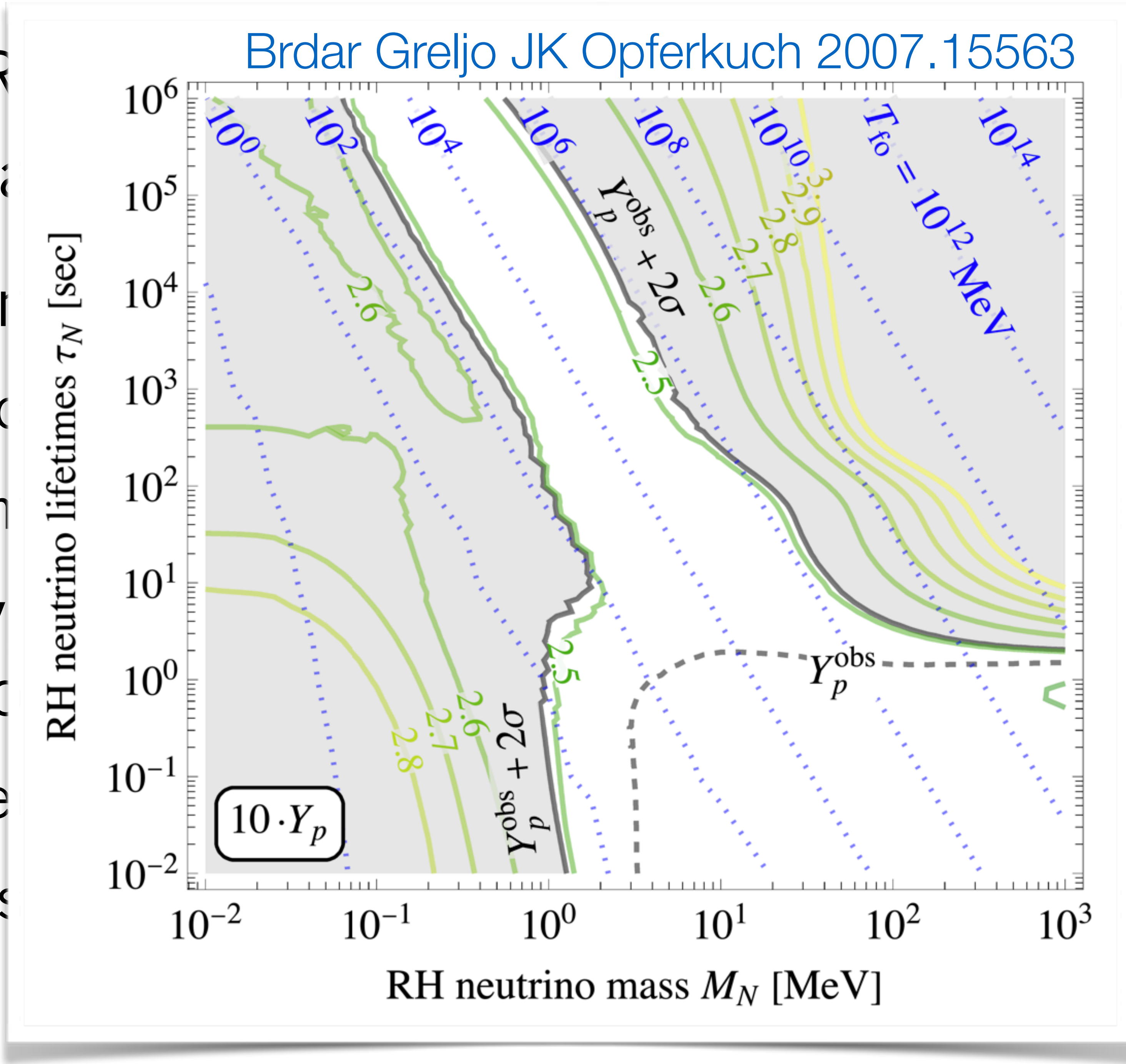
Brdar Greljo JK Opferkuch 2007.15563

Big Bang Nucleosynthesis — Results

Consider a R... ...nt μ_R.

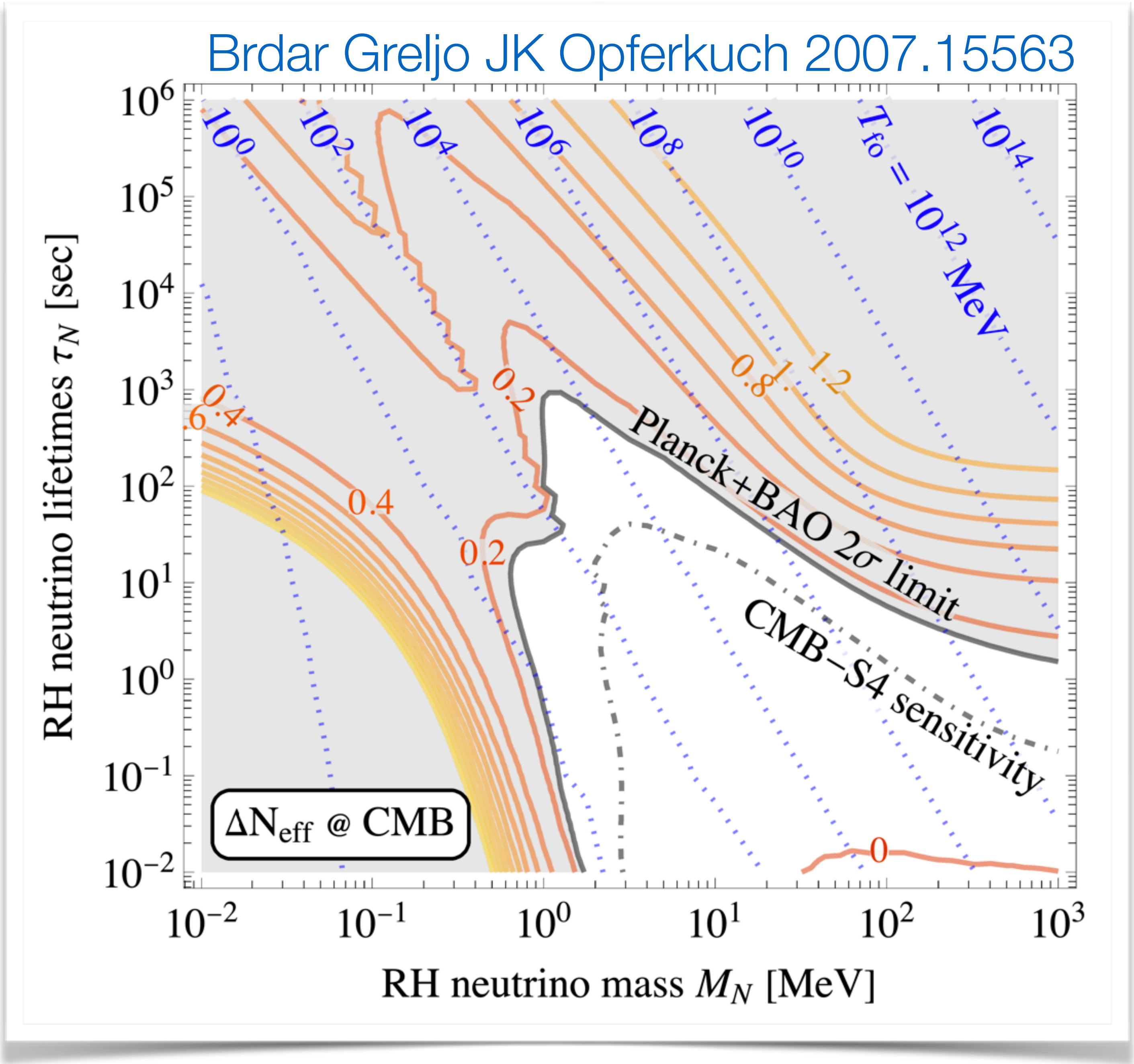
Assume deca...

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

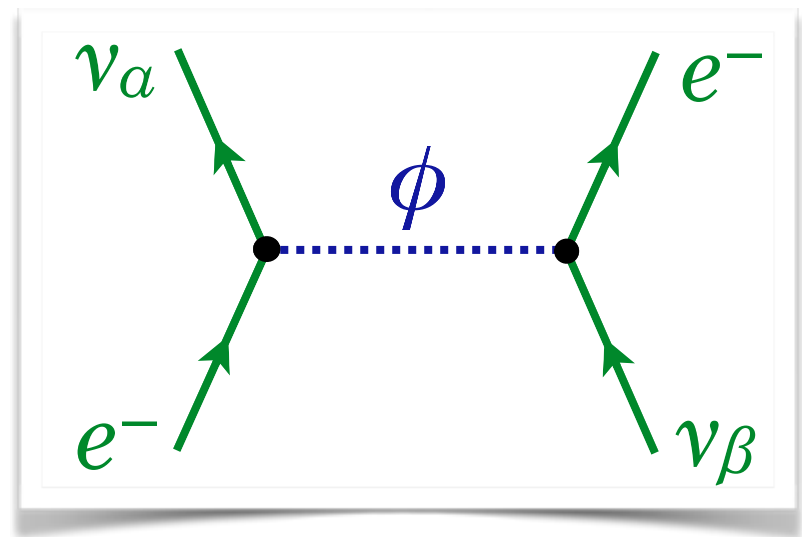


New ν Physics

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^+

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



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

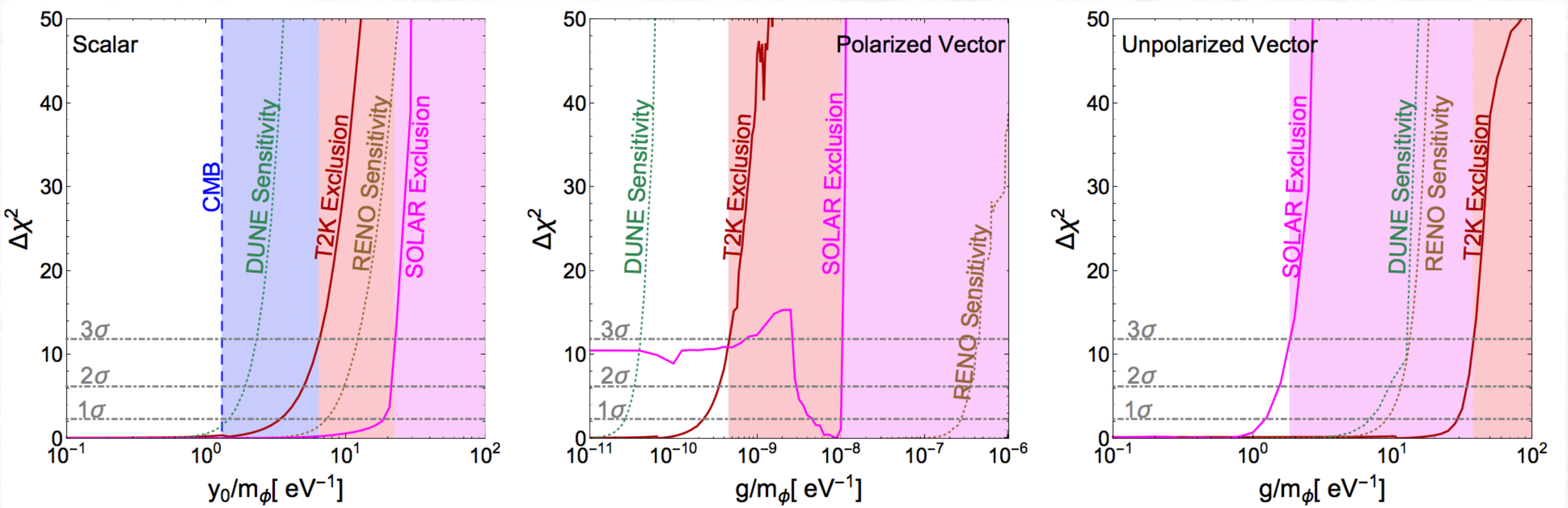
- coupling can arise naturally from TeV scale new physics

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

☑ Coherent … M

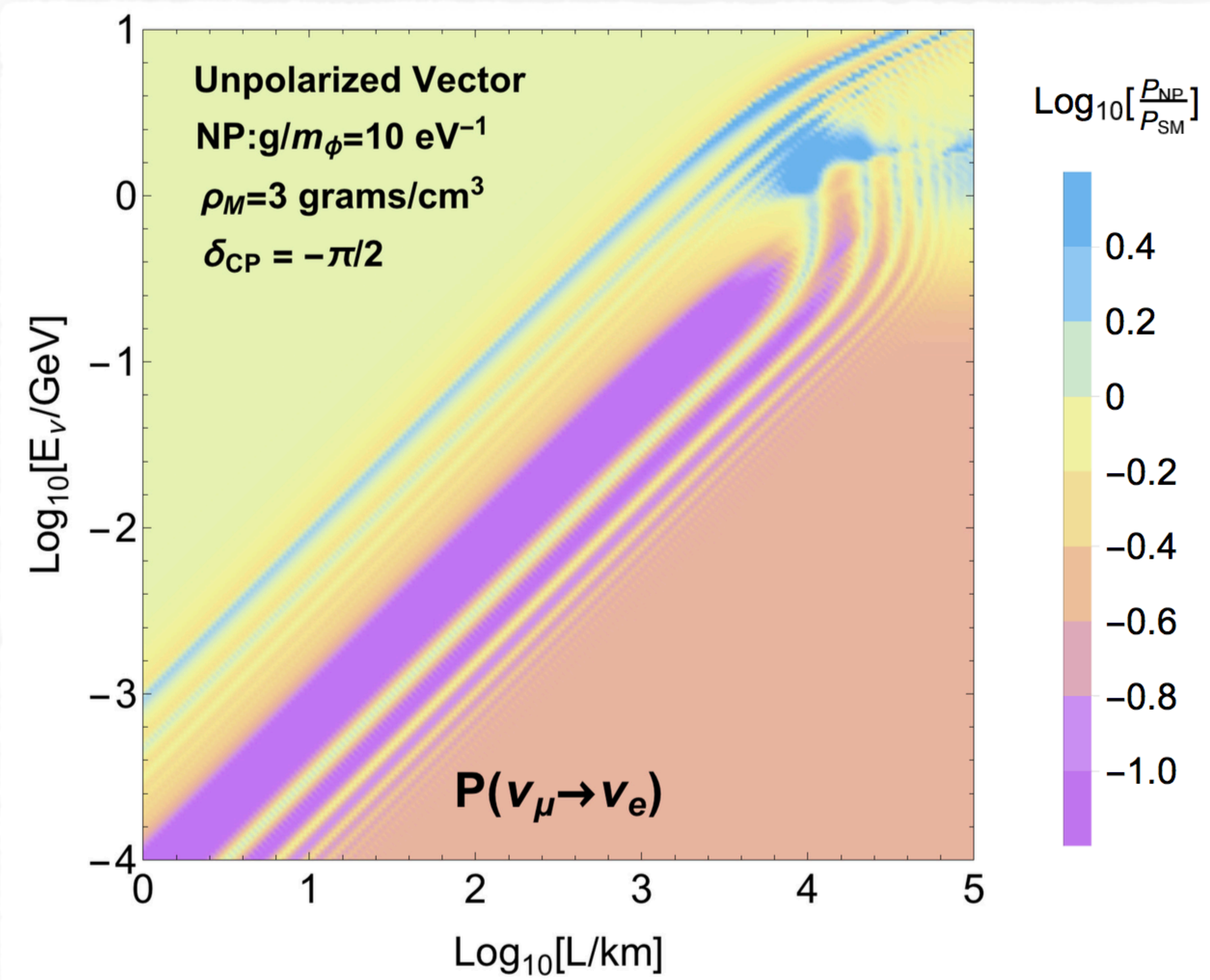
- ana
- Req

☑ Fuzzy

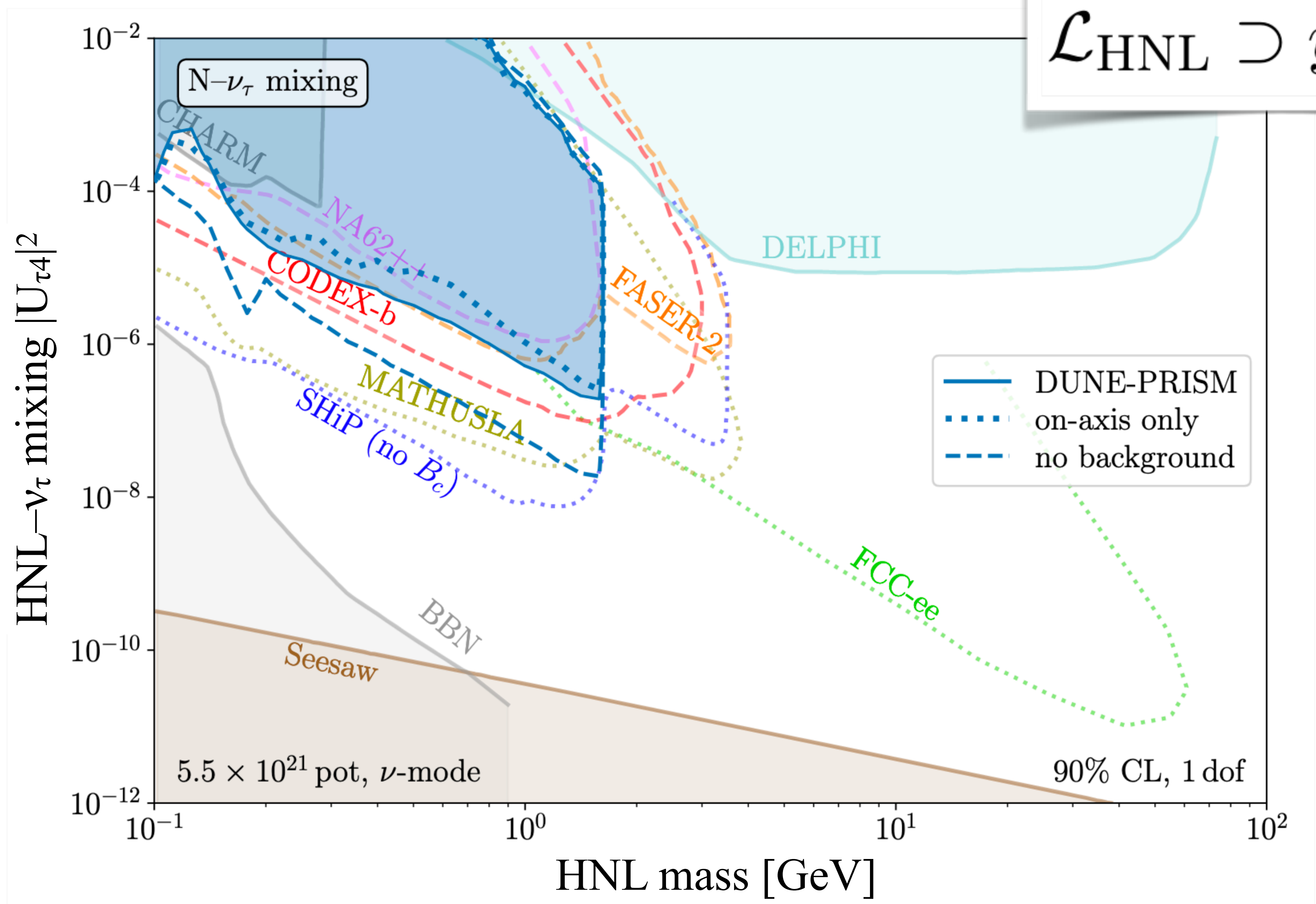
- scal
- Con
- Inte

…06740
…09455
…05117

Modified Oscillation Probabilities



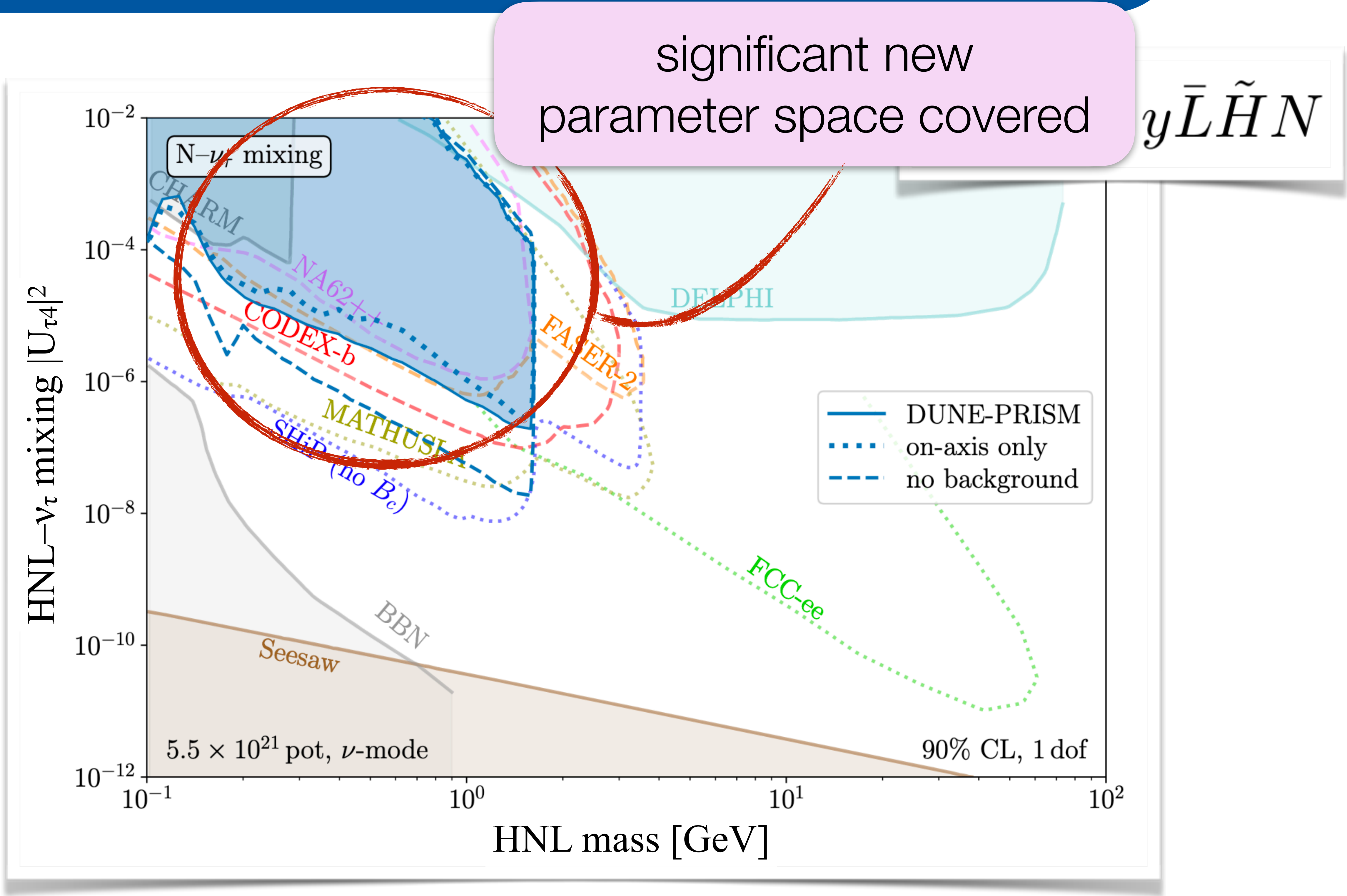
Example: Heavy Neutral Leptons



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

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



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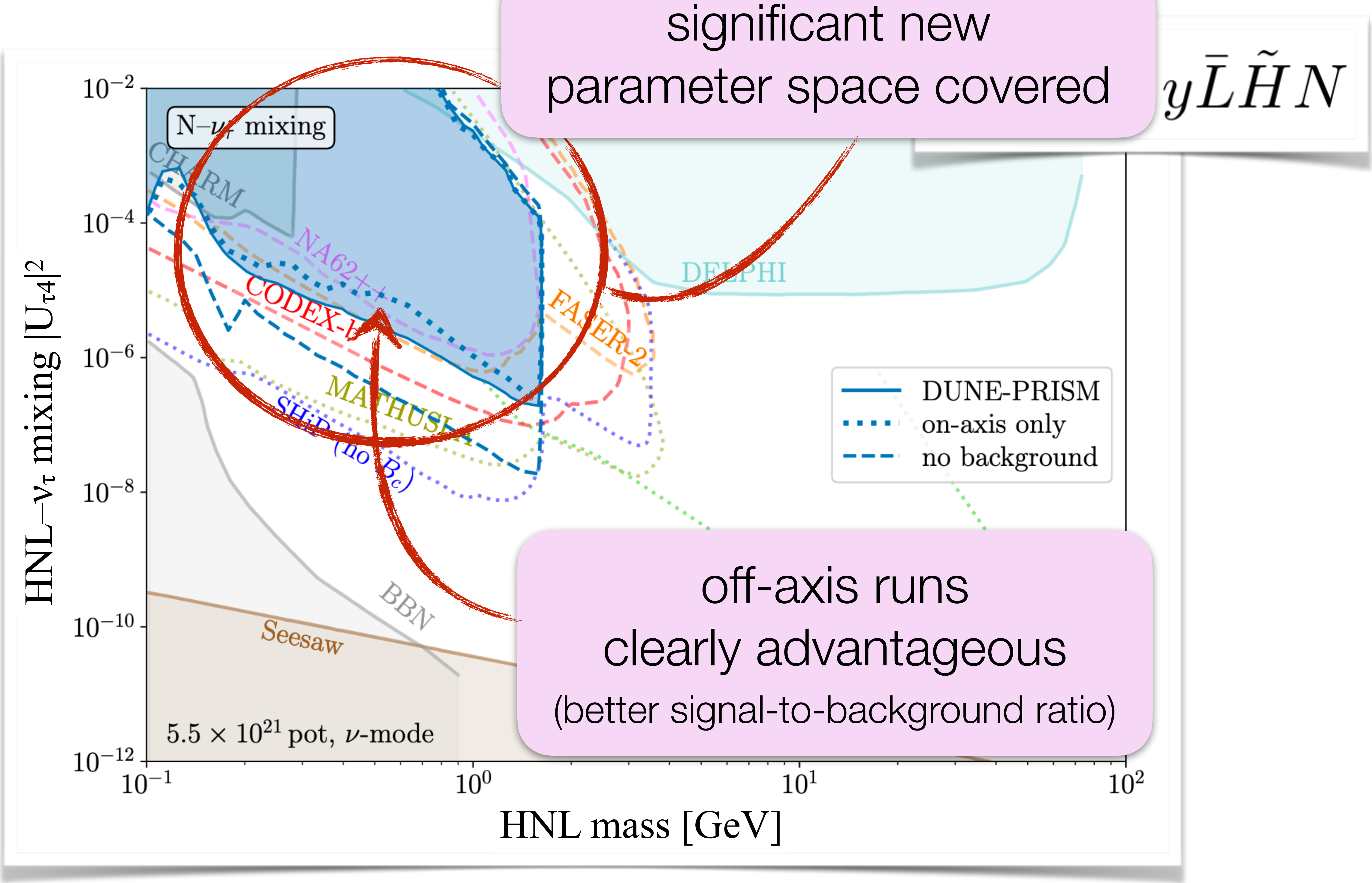
Example: Heavy Neutral Leptons



significant new parameter space covered

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

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