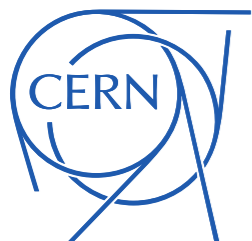
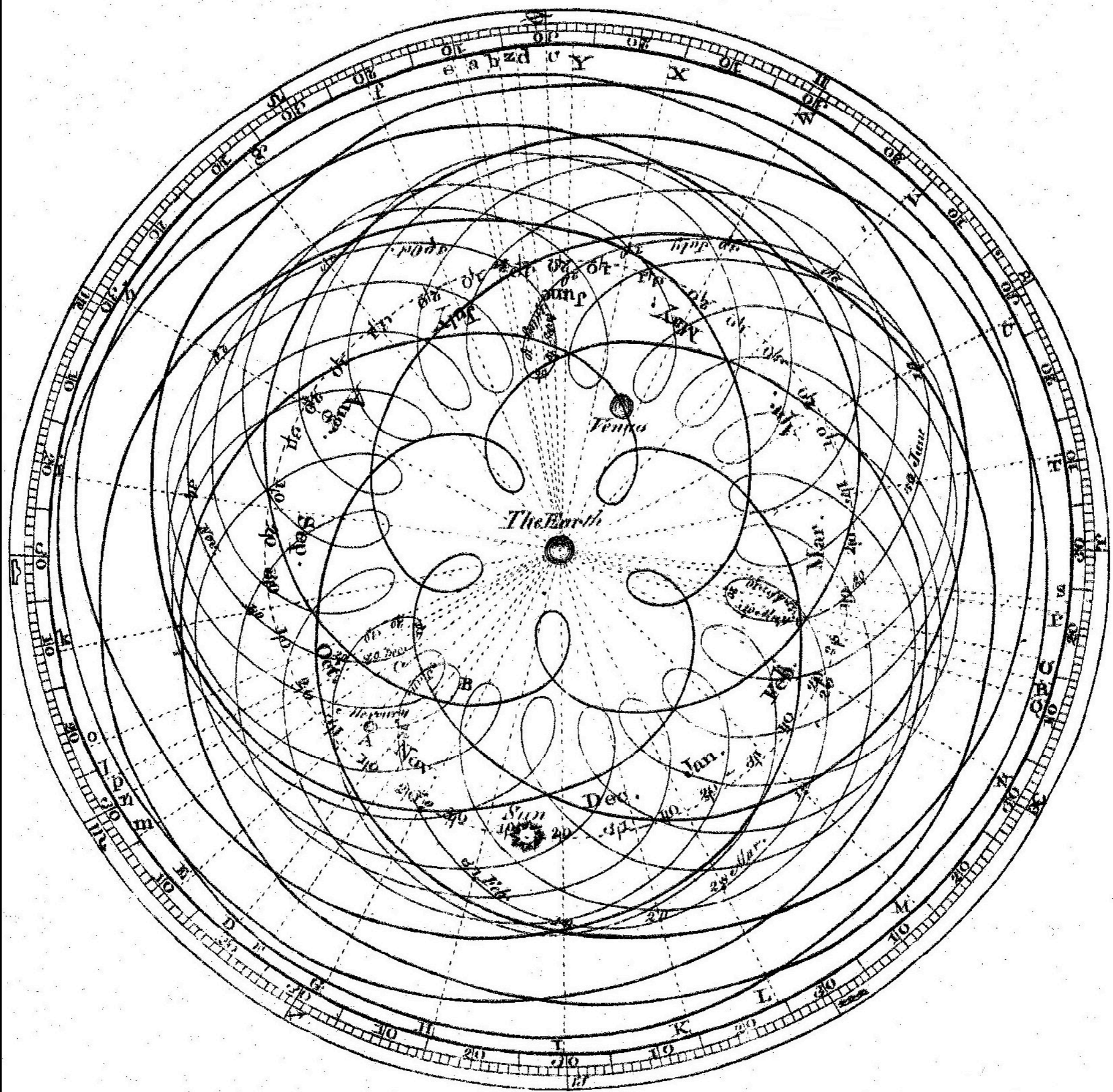


Neutrino Experiments as a Window to New Physics

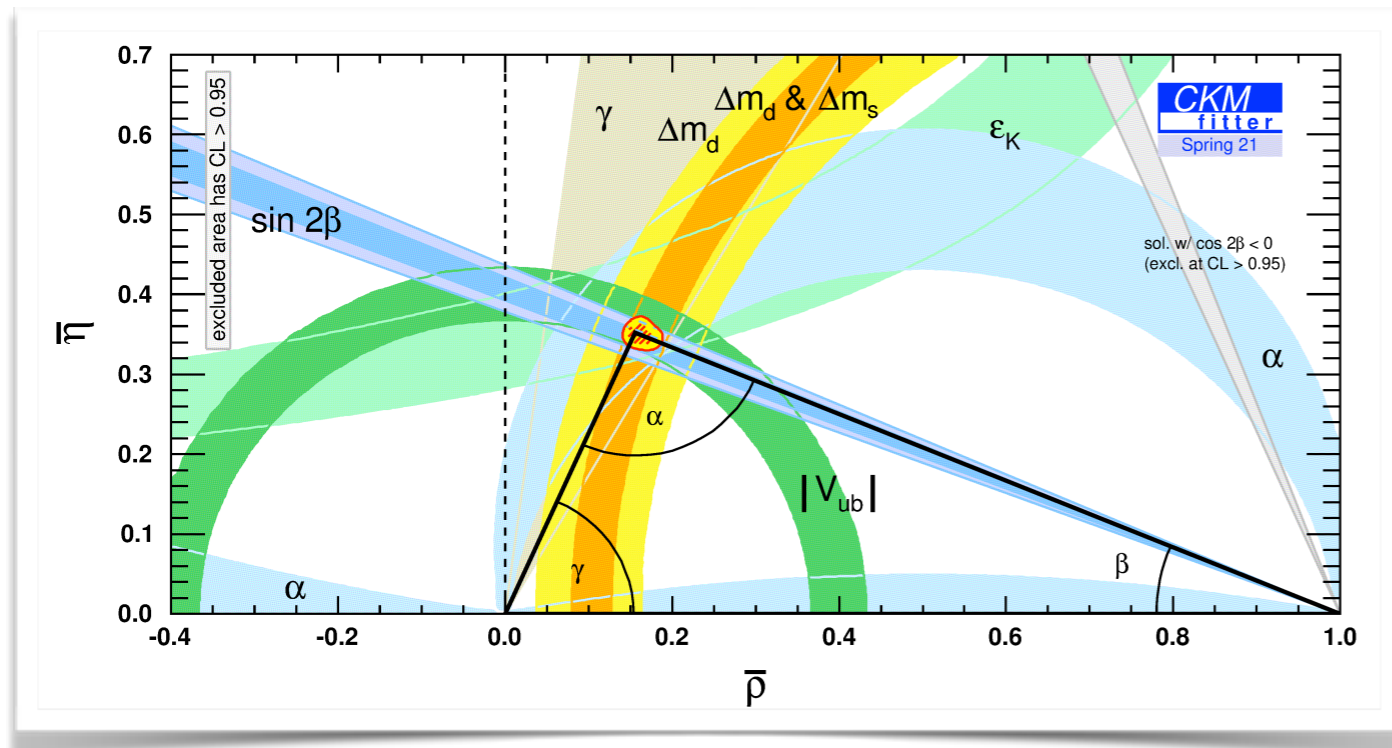
Joachim Kopp (CERN & JGU Mainz)
Snowmass Neutrino Colloquium | April 20, 2022



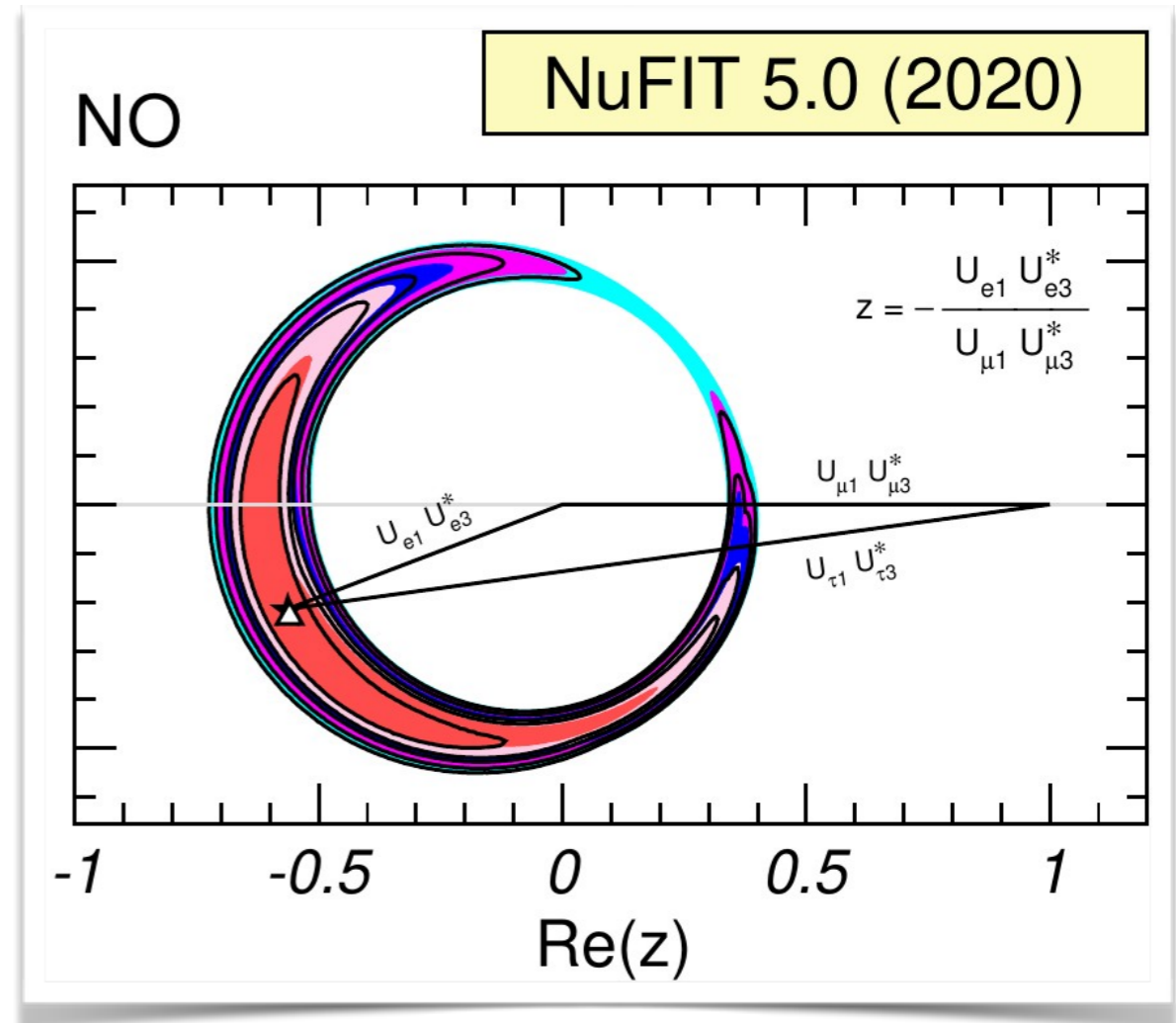


Unitarity Triangles

Quarks

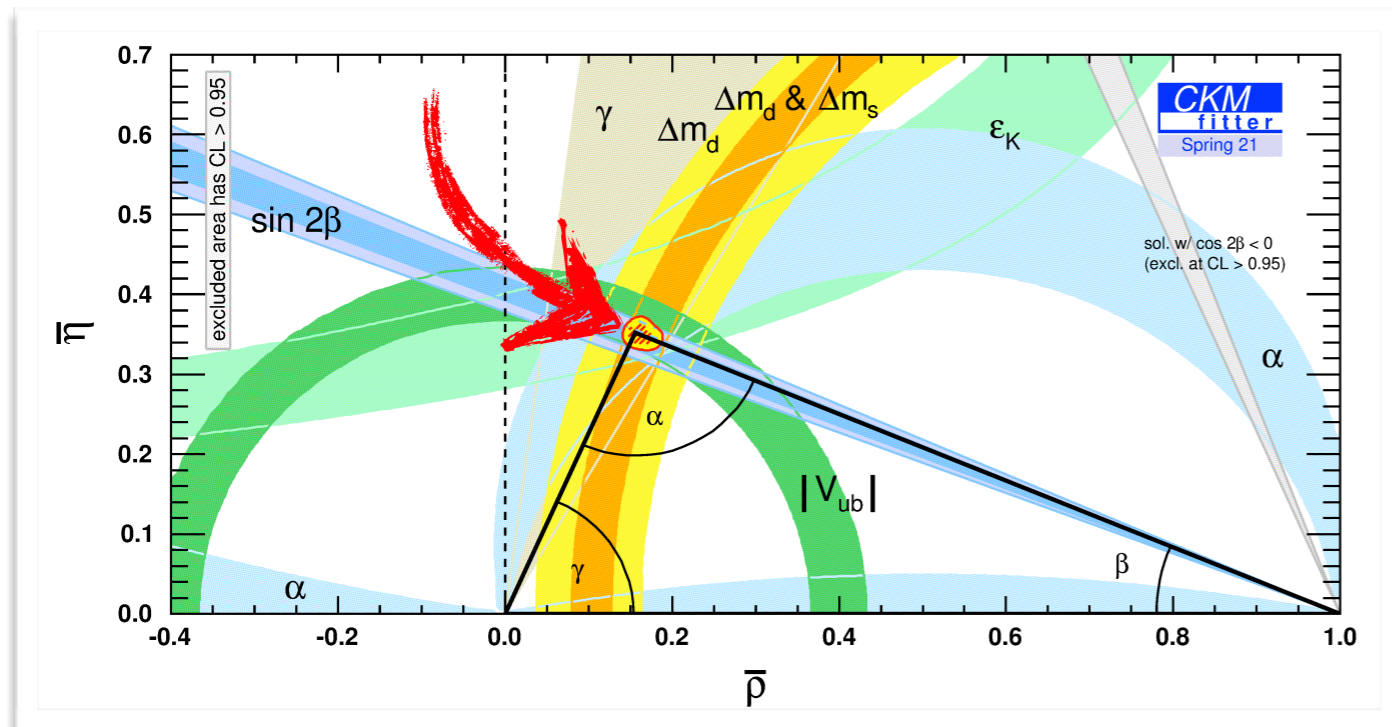


Leptons

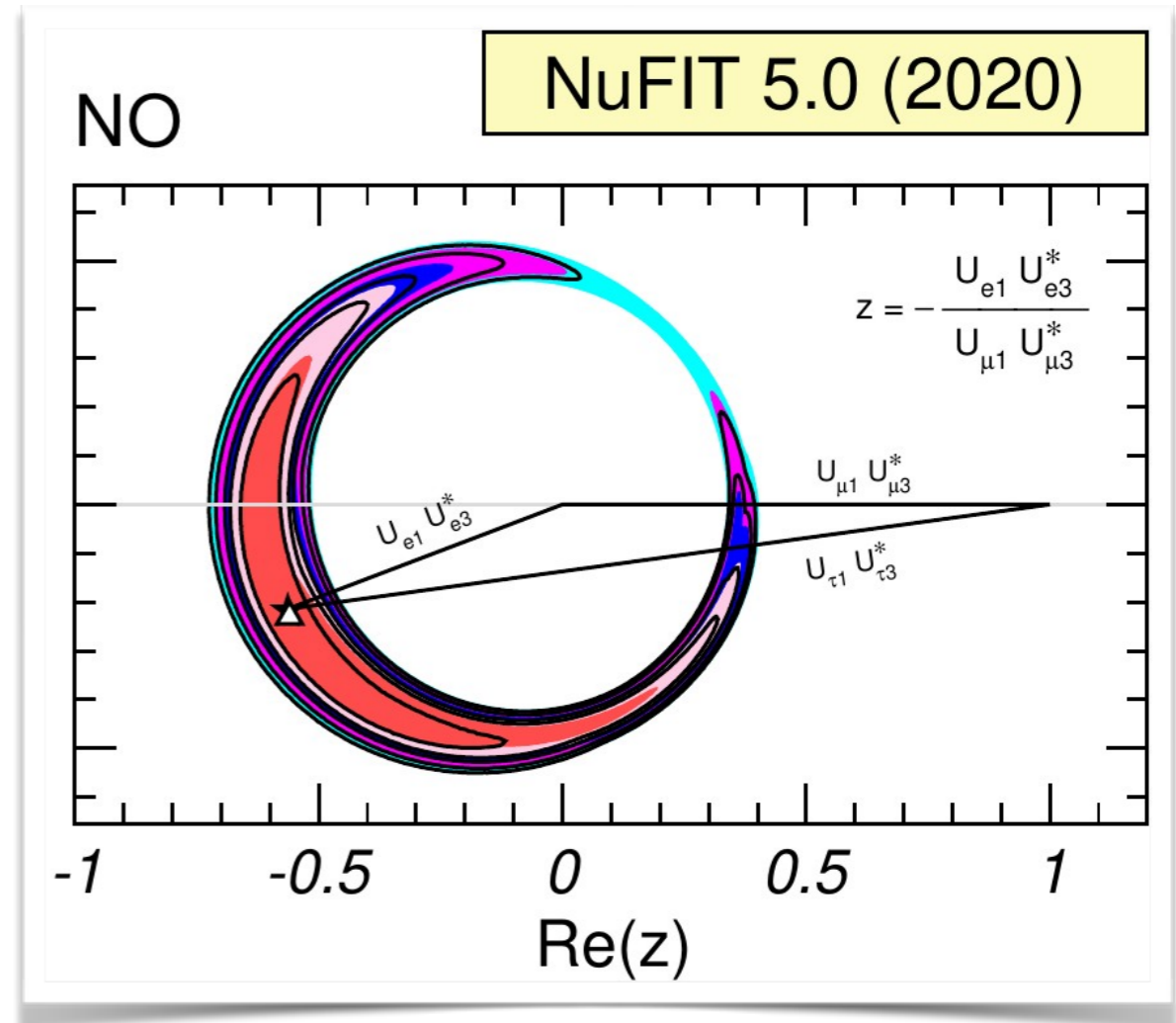


Unitarity Triangles

Quarks



Leptons



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

“With great precision comes great responsibility.”

Tim Linden, WIN 2021

dim-4: the Neutrino Portal

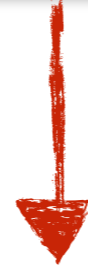


dim-5: Neutrino Magnetic Moments

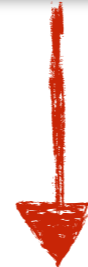


dim-6: Neutrinos in SMEFT

dim-4: the Neutrino Portal



dim-5: Neutrino Magnetic Moments



dim-6: Neutrinos in SMEFT

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

- ☑ the only **renormalizable** coupling of the SM to a **singlet fermion** (aka “sterile neutrino” or “heavy neutral lepton”)

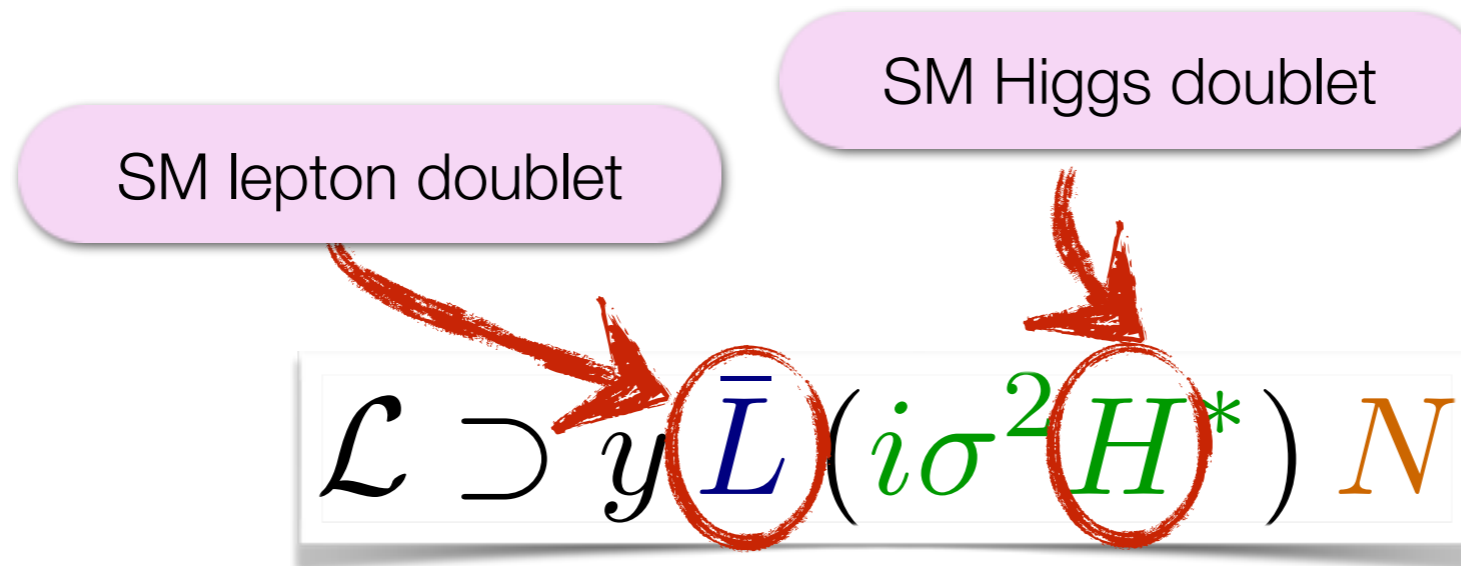
The Neutrino Portal

SM lepton doublet

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

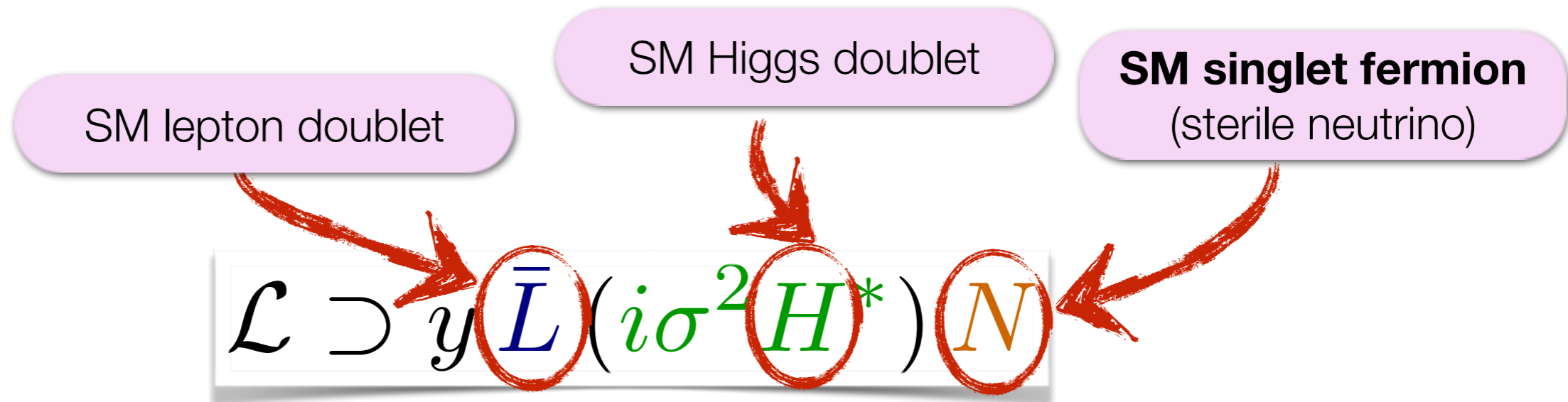
- ✓ the only **renormalizable** coupling of the SM to a **singlet fermion** (aka “sterile neutrino” or “heavy neutral lepton”)

The Neutrino Portal



- ✓ the only **renormalizable** coupling of the SM to a **singlet fermion** (aka “sterile neutrino” or “heavy neutral lepton”)

The Neutrino Portal



- the only **renormalizable** coupling of the SM to a **singlet fermion** (aka “sterile neutrino” or “heavy neutral lepton”)

Definition: sterile neutrino = SM singlet fermion

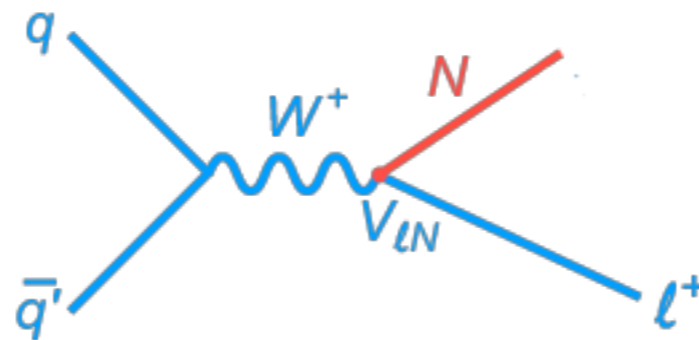
- ☑ Very generic extension of SM
 - can be leftover of extended gauge multiplet
- ☑ Useful phenomenological tool
 - can explain ν masses (seesaw mechanism, $m \sim \text{TeV} \dots M_{\text{Pl}}$)
 - can explain cosmic baryon asymmetry (thermal leptogenesis at $m \gg 100 \text{ GeV}$, ARS leptogenesis at $m < 100 \text{ GeV}$)
 - can explain dark matter ($m \sim \text{keV}$)
 - can act a mediator to a dark sector (any mass)
 - can explain oscillation anomalies ($m \sim \text{eV}$)
 - Georgia Karagiorgi's talk



Neutrino Portal Phenomenology

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

- ☑ leads to mass mixing between ν and N
 - ⇒ active–sterile neutrino **oscillations**
 - ⇒ N **production** in neutrino interactions



Neutrino Oscillations with 3 and 4 Flavours

$$|\nu_\alpha\rangle = \sum_j U_{\alpha j}^* |\nu_j\rangle$$

Neutrino Oscillations with 3 and 4 Flavours

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Mass Eigenstate
(well-defined energy)

Neutrino Oscillations with 3 and 4 Flavours

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Mixing Matrix
($n \times n$, unitary)

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☑ 3-flavor mixing matrix:

$$U = \begin{pmatrix} 1 & & \\ c_{23} & s_{23} & \\ -s_{23} & c_{23} & \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

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close to maximal

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Small
but non-negligible (~ 0.1)

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Neutrino Oscillations with 3 and 4 Flavours

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Small
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☑ generalization to 4 flavors straightforward

Oscillation Example: ν_μ Disappearance

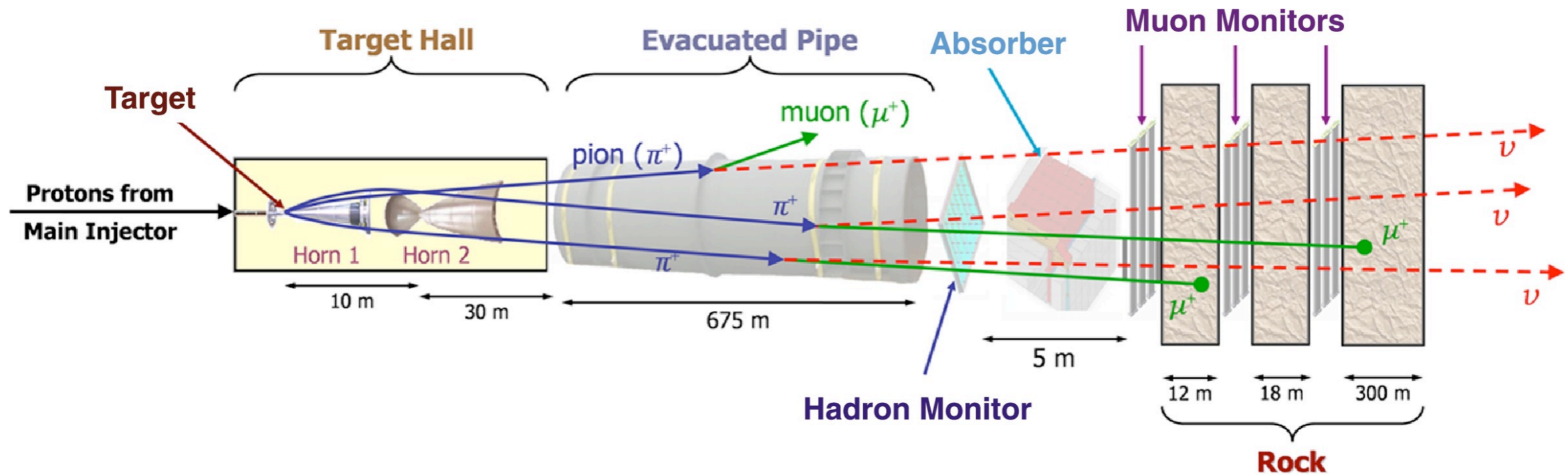


Oscillation Example: ν_μ Disappearance

- Use intense flux of ν_μ from pion decay
in **accelerator** experiment or in the **upper atmosphere**

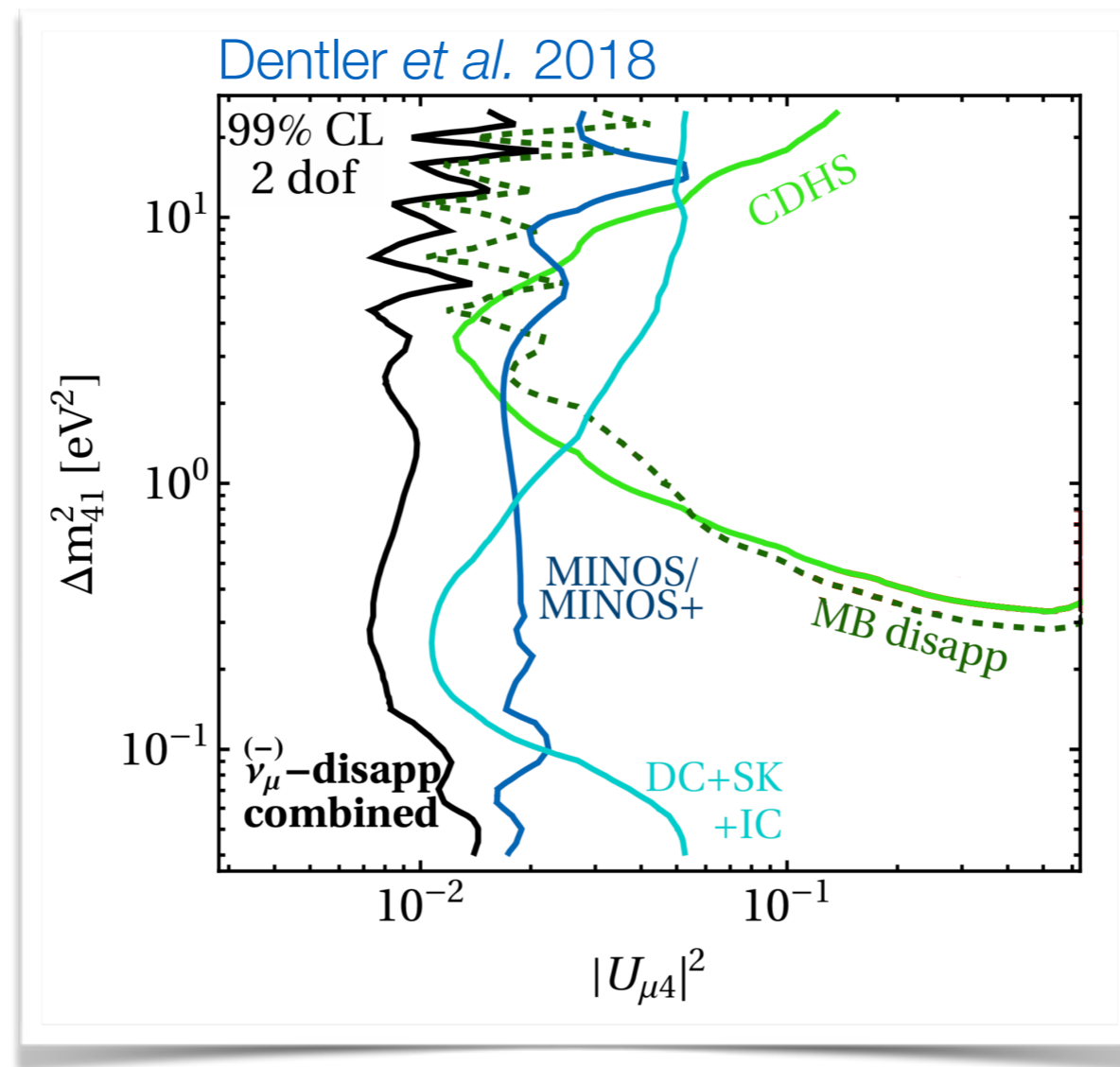
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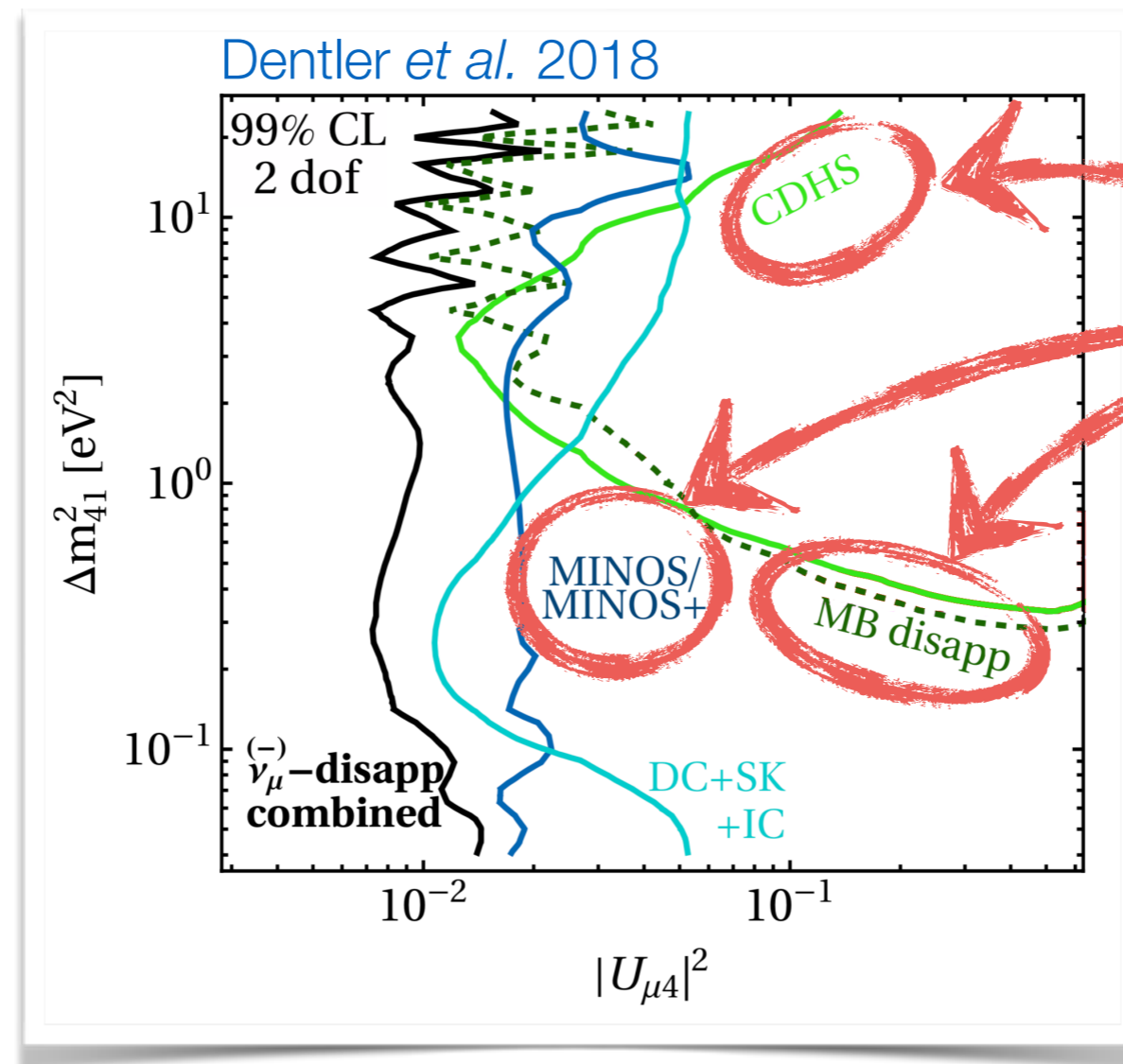
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- ☑ Look for “missing” ν_μ after propagation



Oscillation Example: ν_μ Disappearance

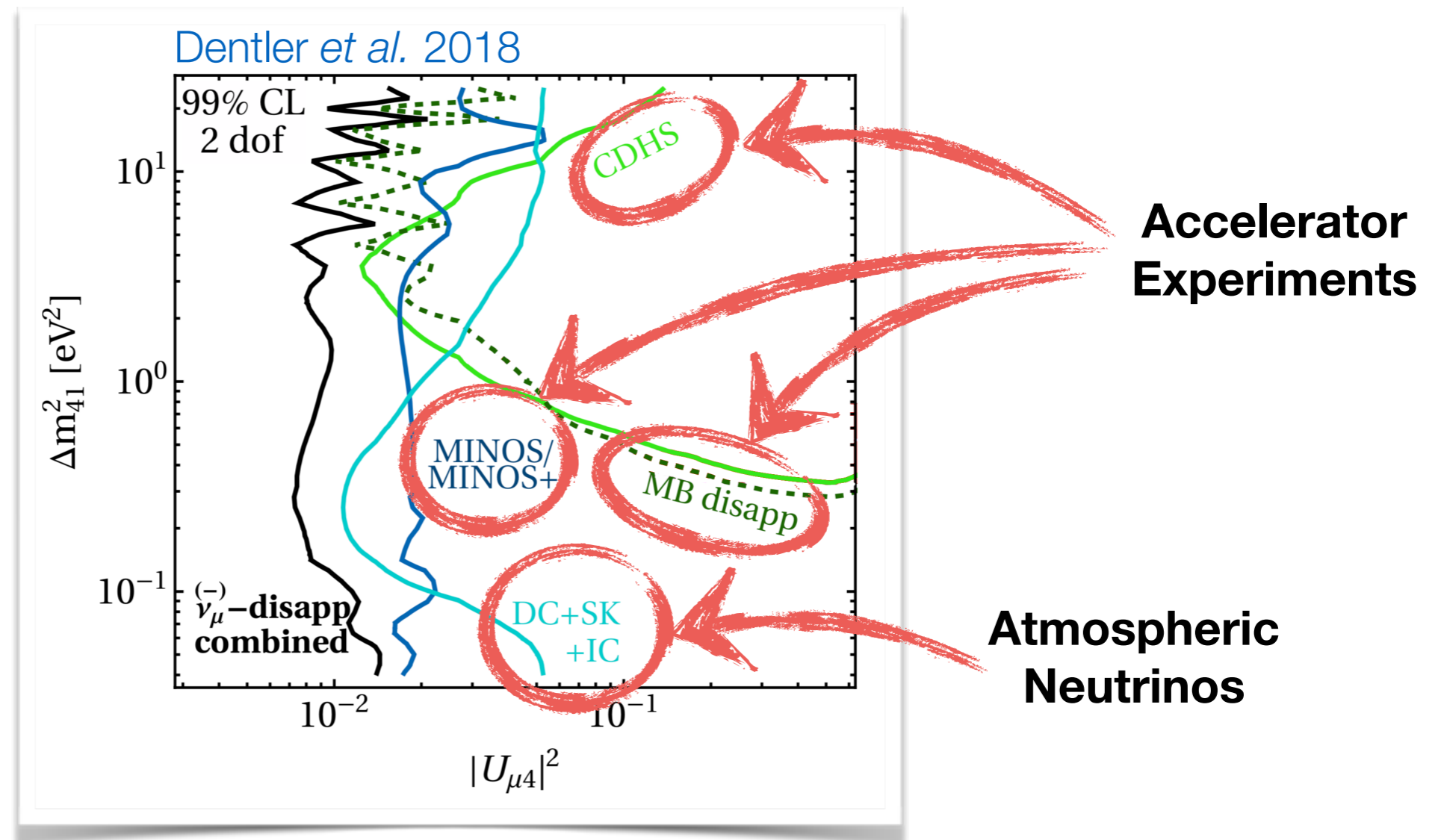
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**Accelerator
Experiments**

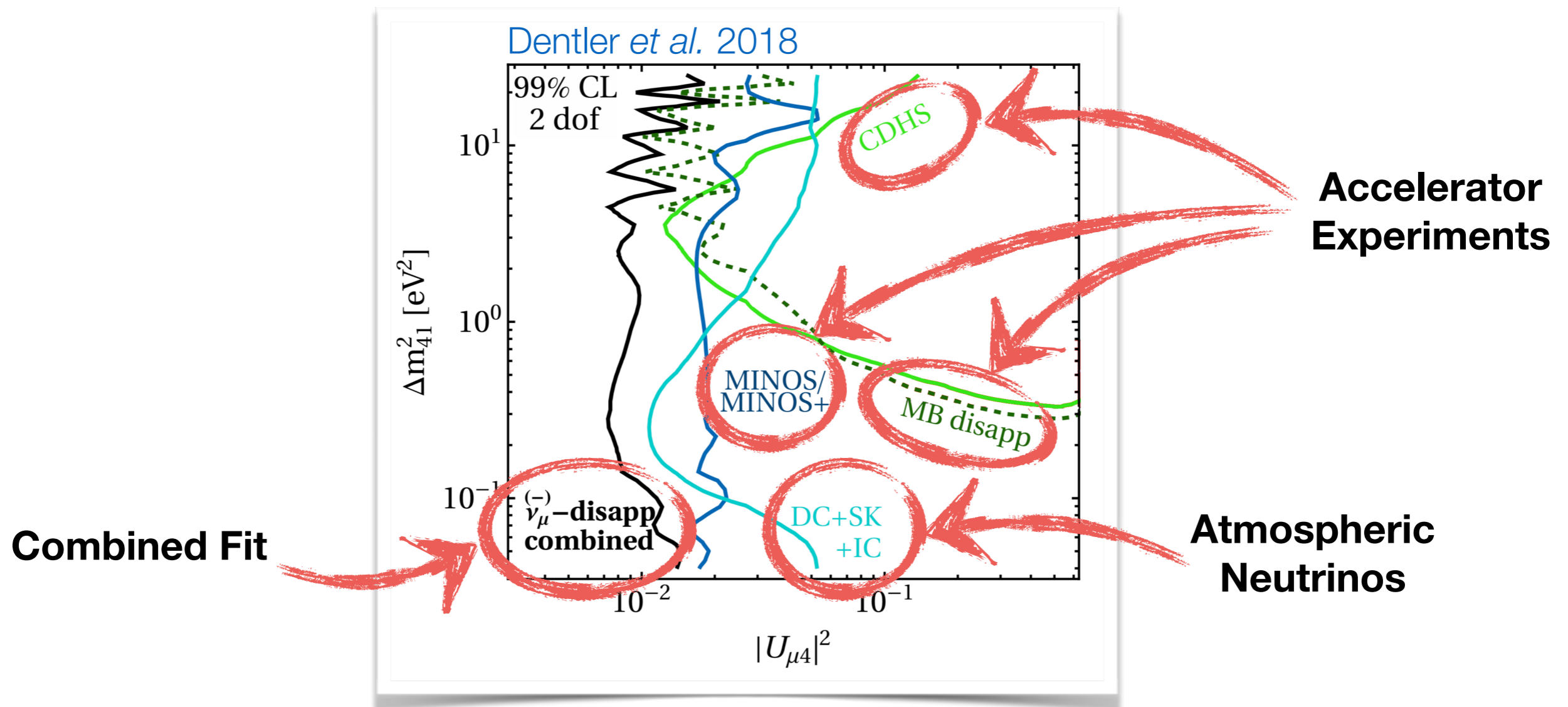
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Dentler *et al.* 2018

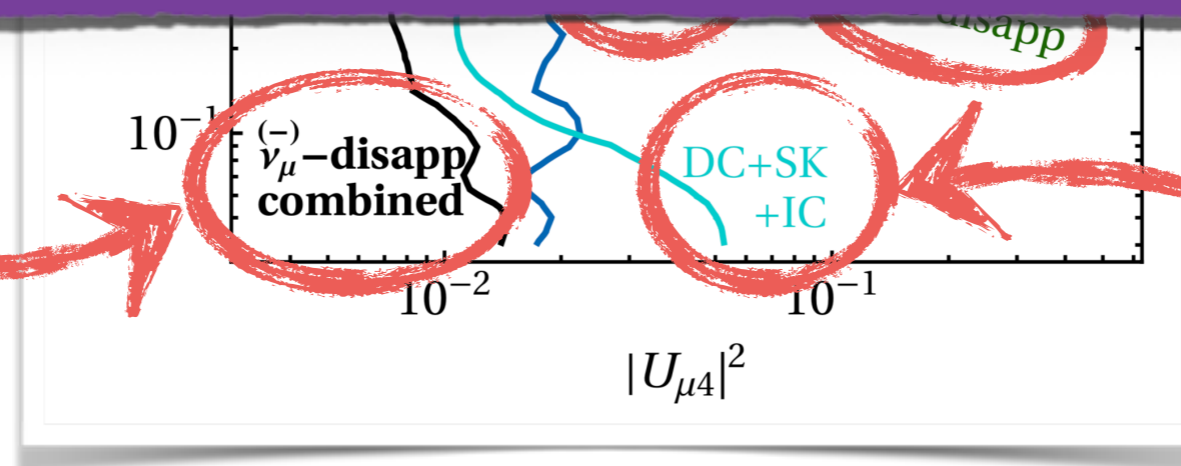
99% CI

not shown here:

short-baseline oscillation anomalies

➡ see Georgia Karagiorgi's talk

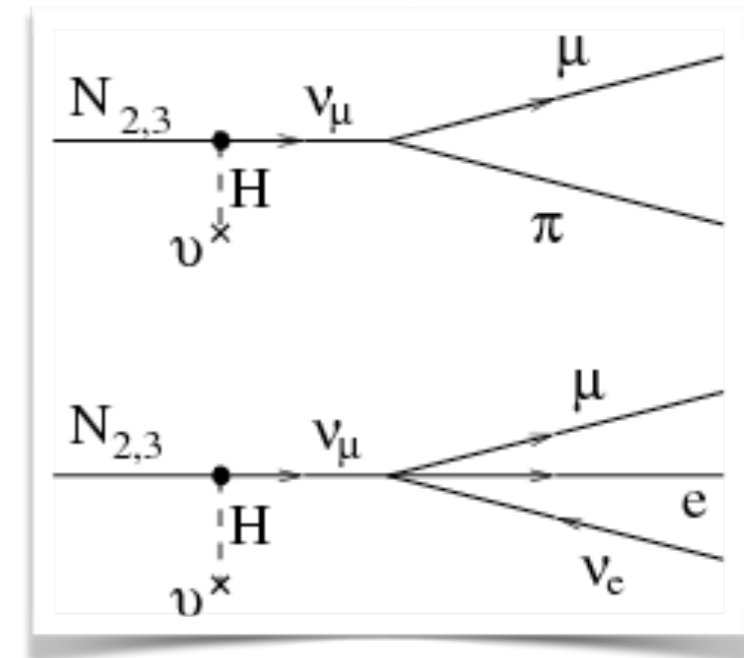
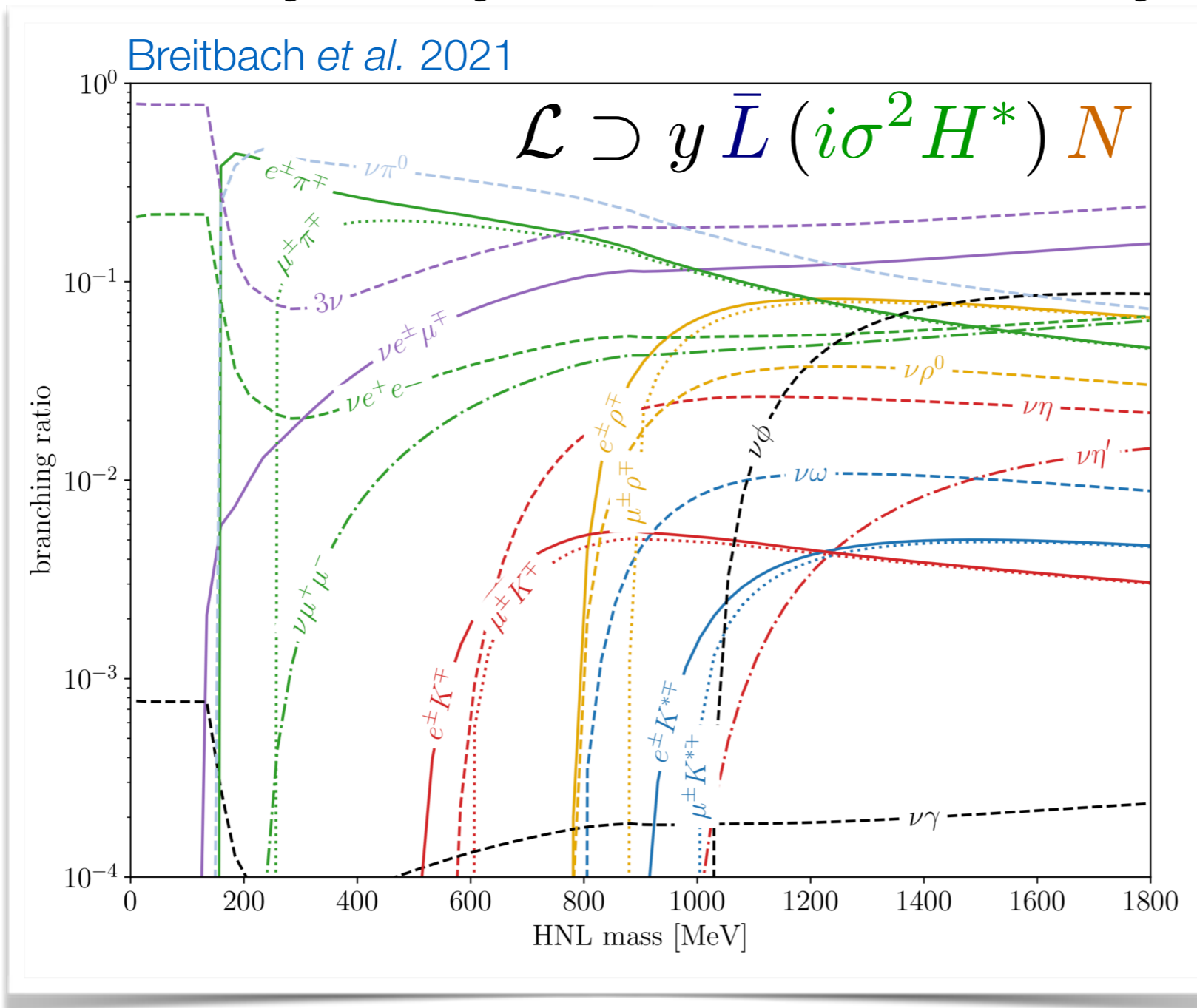
Combined Fit



Atmospheric Neutrinos

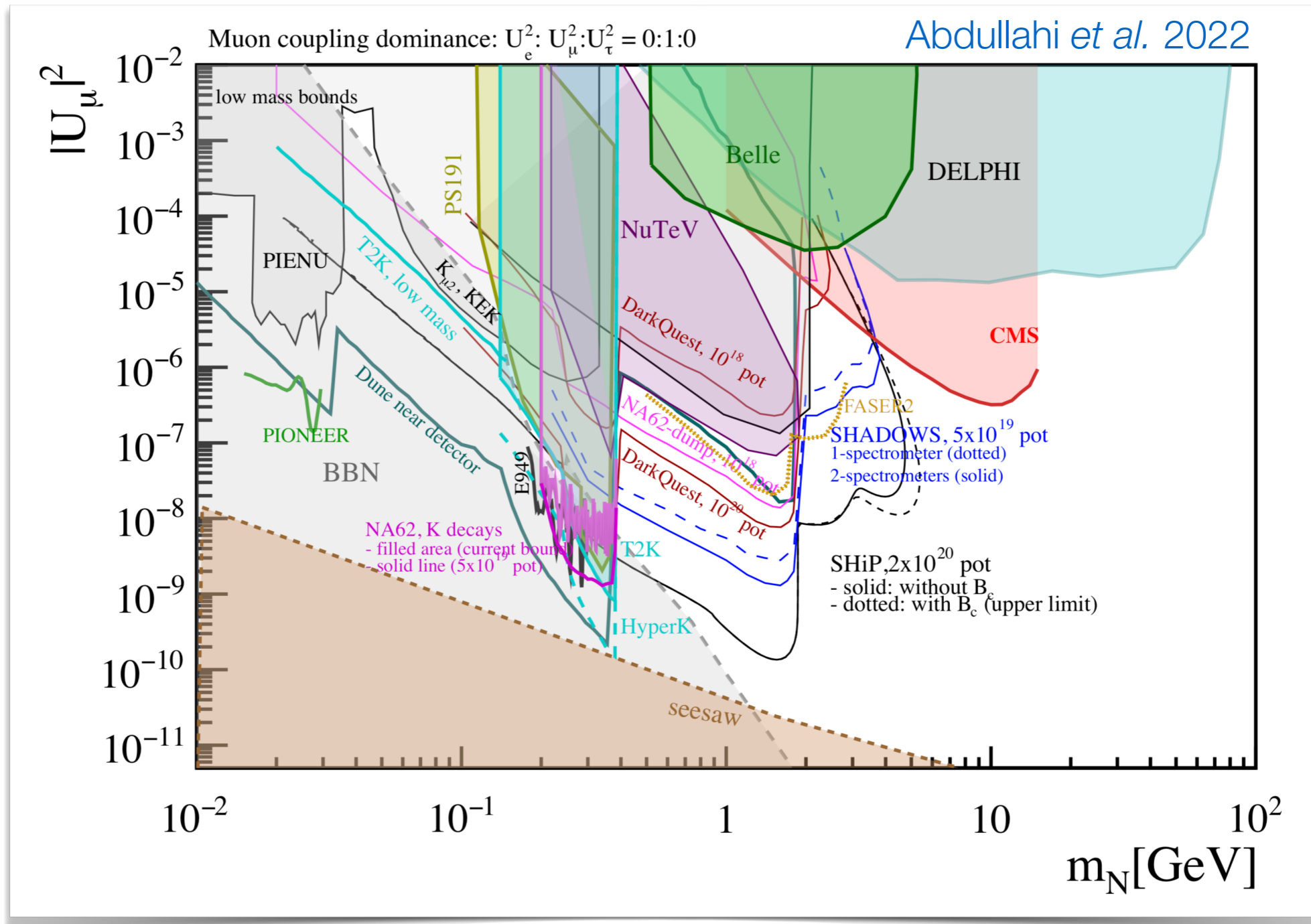
Sterile Neutrino Decay Example

for sufficiently heavy N : multitude of decay modes



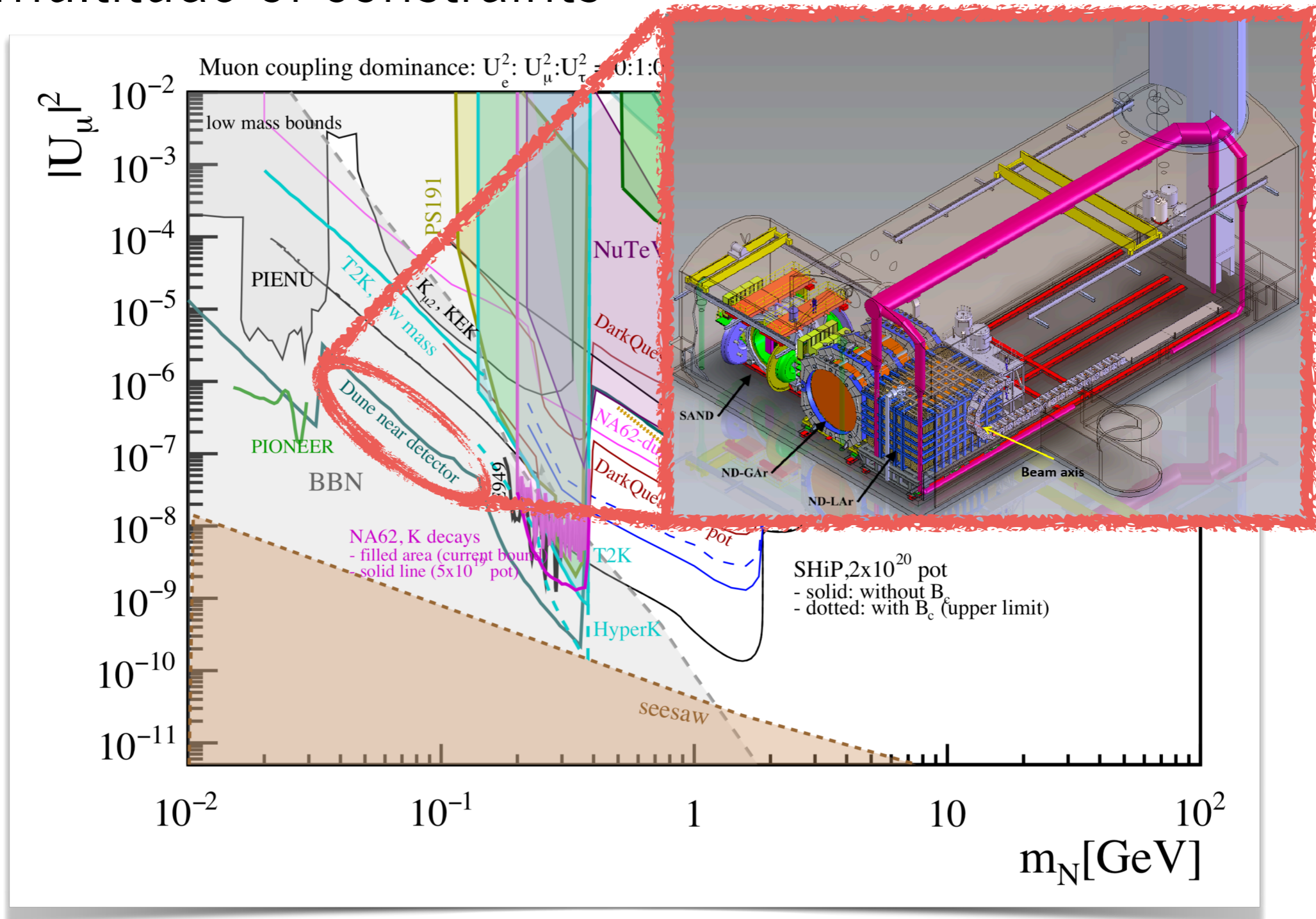
Sterile Neutrino Decay Example

... and multitude of constraints



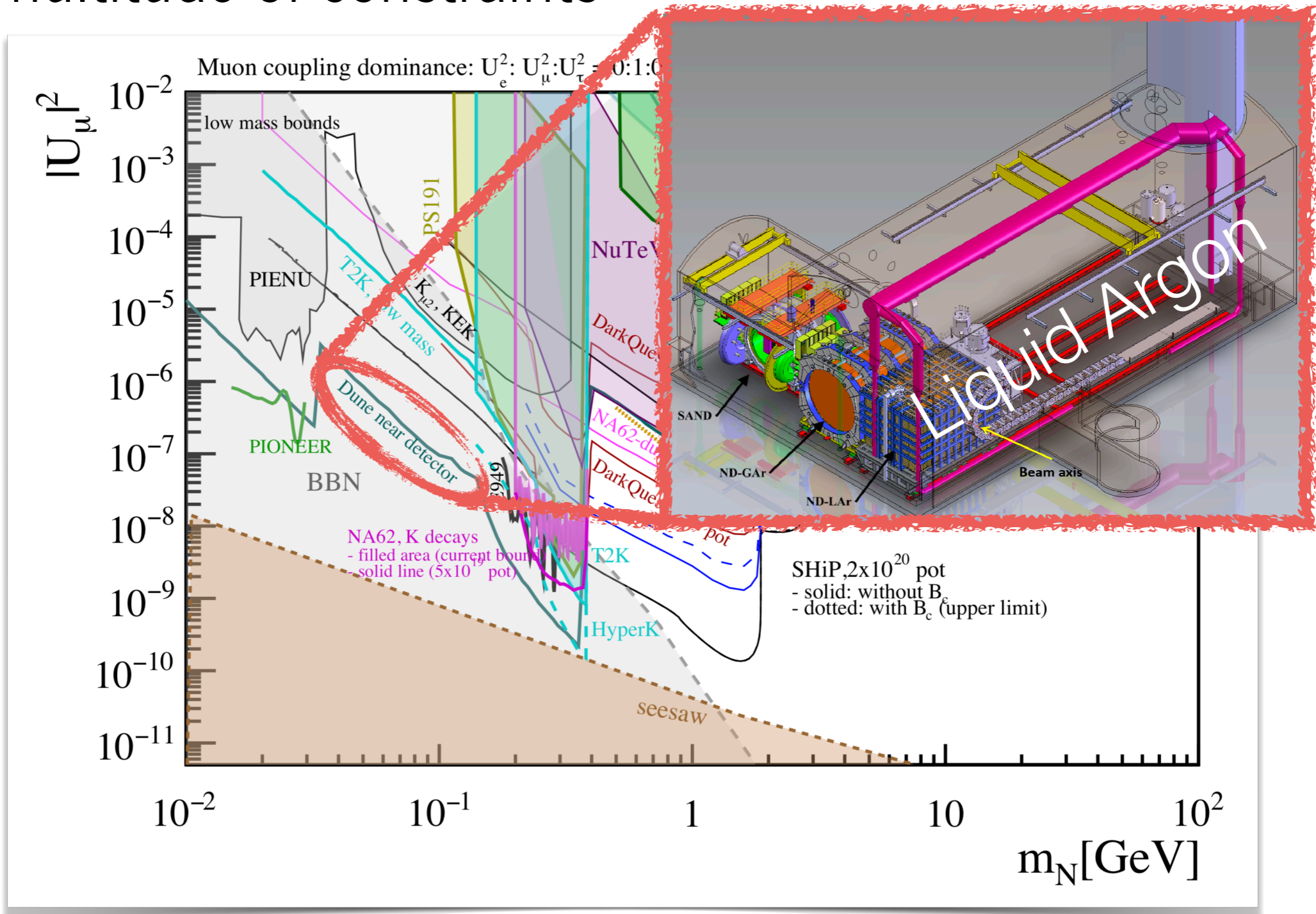
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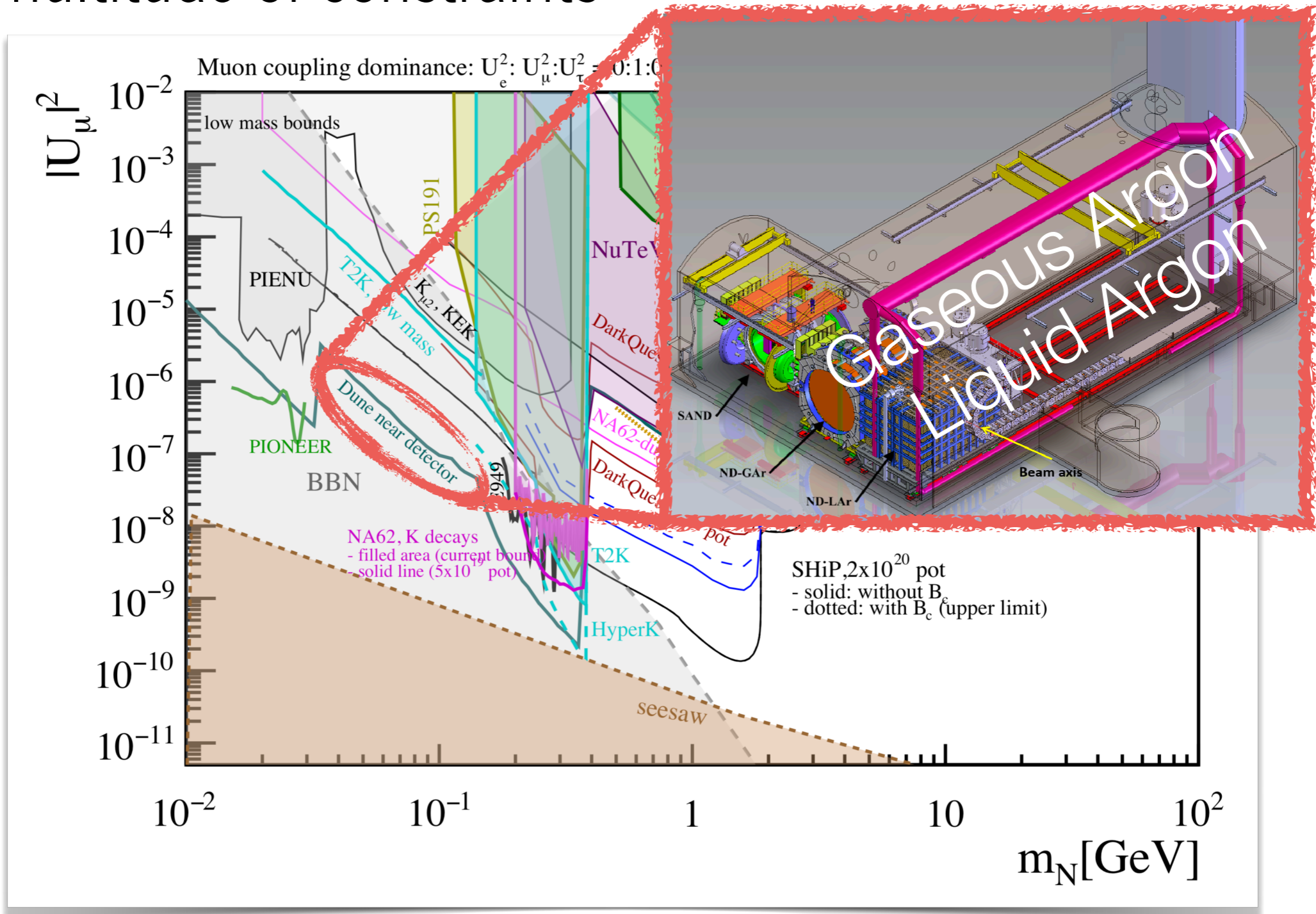
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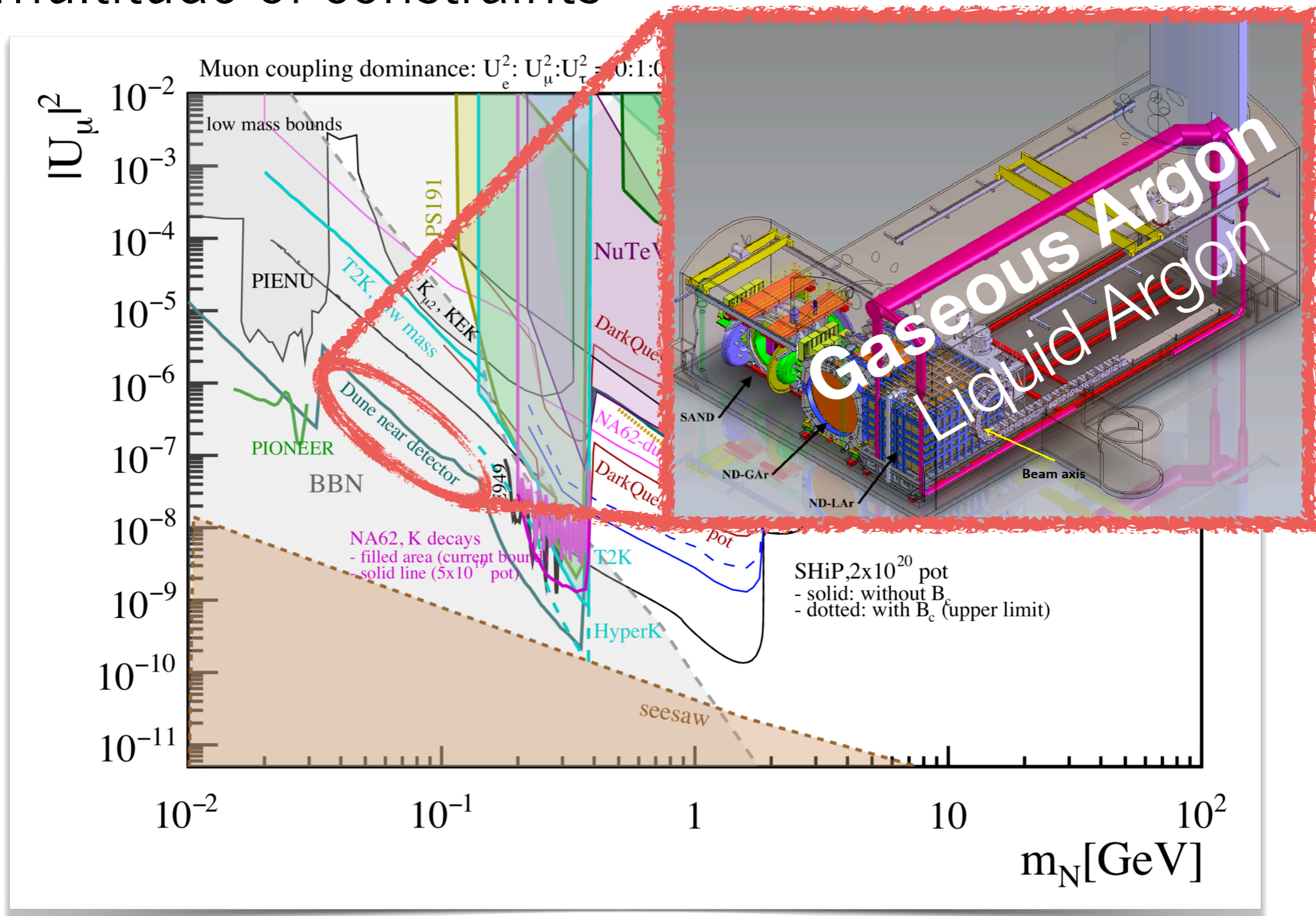
Sterile Neutrino Decay Example

... and multitude of constraints



Sterile Neutrino Decay Example

... and multitude of constraints



Long-baseline oscillation experiments are
multi-purpose intensity frontier observatories





Advanced Sterile Neutrino Models

$$\begin{aligned}
 \mathcal{L} \supset \mathcal{L}_{\text{SM}} &- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin \chi}{2} X_{\mu\nu} B^{\mu\nu} \\
 &+ (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi) - \lambda_{\Phi H} |H|^2 |\Phi|^2 \\
 &+ \overline{\hat{\nu}}_N i \not{\partial} \hat{\nu}_N + \overline{\hat{\nu}}_D i \not{D}_X \hat{\nu}_D - \left[(\overline{L} \tilde{H}) Y \hat{\nu}_N^c + \frac{1}{2} \overline{\hat{\nu}}_N M_N \hat{\nu}_N^c \right. \\
 &\left. + \overline{\hat{\nu}}_N (Y_L \hat{\nu}_{D_L}^c \Phi + Y_R \hat{\nu}_{D_R} \Phi^*) + \overline{\hat{\nu}}_D M_X \hat{\nu}_D + \text{h.c.} \right]
 \end{aligned}$$

Abdullahi Hostert Pascoli 2020

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Vector Portal

(kinetic mixing with
“dark photon”)

Abdullahi Hostert Pascoli 2020

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 \end{aligned}$$

Vector Portal
 (kinetic mixing with
 “dark photon”)

Higgs Portal
 (scalar mixing)

Abdullahi Hostert Pascoli 2020

Advanced Sterile Neutrino Models

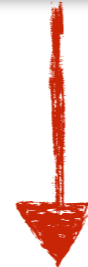
$$\begin{aligned}
 \mathcal{L} \supset \mathcal{L}_{\text{SM}} &- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin \chi}{2} X_{\mu\nu} B^{\mu\nu} && \text{Vector Portal} \\
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 &+ \left. \overline{\hat{\nu}}_N (Y_L \hat{\nu}_{D_L}^c \Phi + Y_R \hat{\nu}_{D_R} \Phi^*) + \overline{\hat{\nu}}_D M_X \hat{\nu}_D + \text{h.c.} \right] && \text{(fermion mixing)}
 \end{aligned}$$

Abdullahi Hostert Pascoli 2020

dim-4: the Neutrino Portal



dim-5: Neutrino Magnetic Moments



dim-6: Neutrinos in SMEFT

dim-4: the Neutrino Portal

- one of the main [portals to the dark sector](#)
- superior sensitivity at future experiments (near & far detectors!)

dim-5: Neutrino Magnetic Moments



dim-6: Neutrinos in SMEFT

dim-4: the Neutrino Portal



dim-5: Neutrino Magnetic Moments



dim-6: Neutrinos in SMEFT

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

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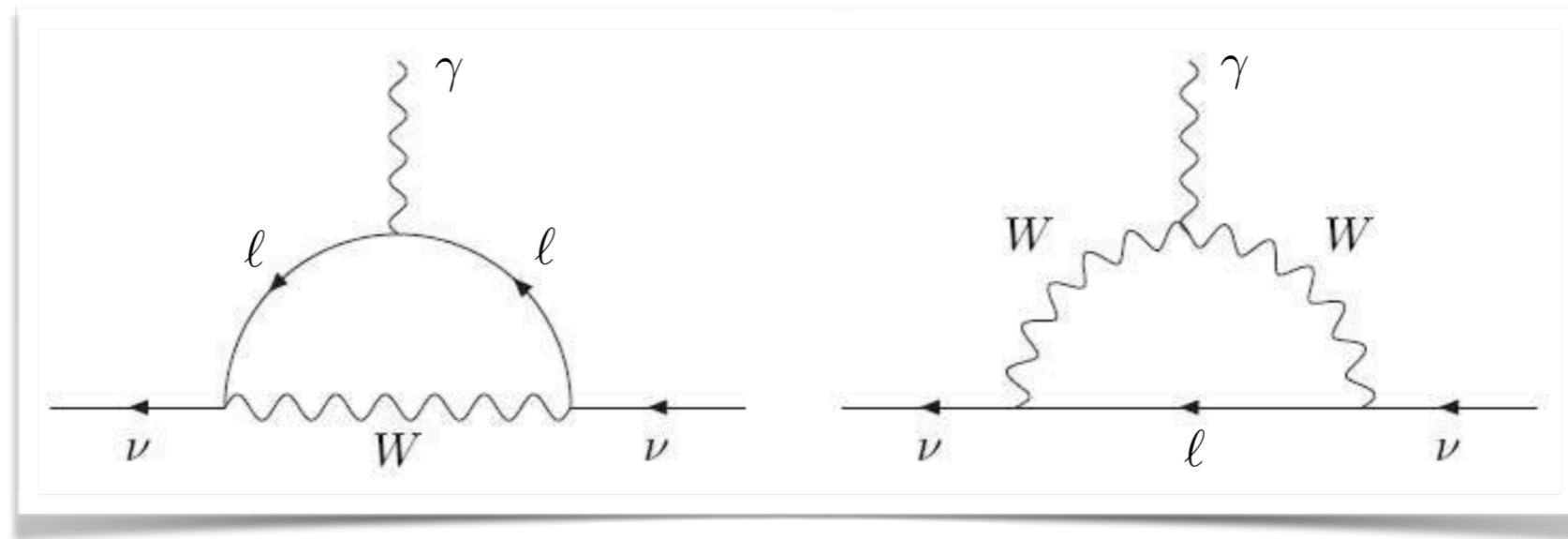
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☑ In the SM: generated by loop diagrams



Petcov 1977

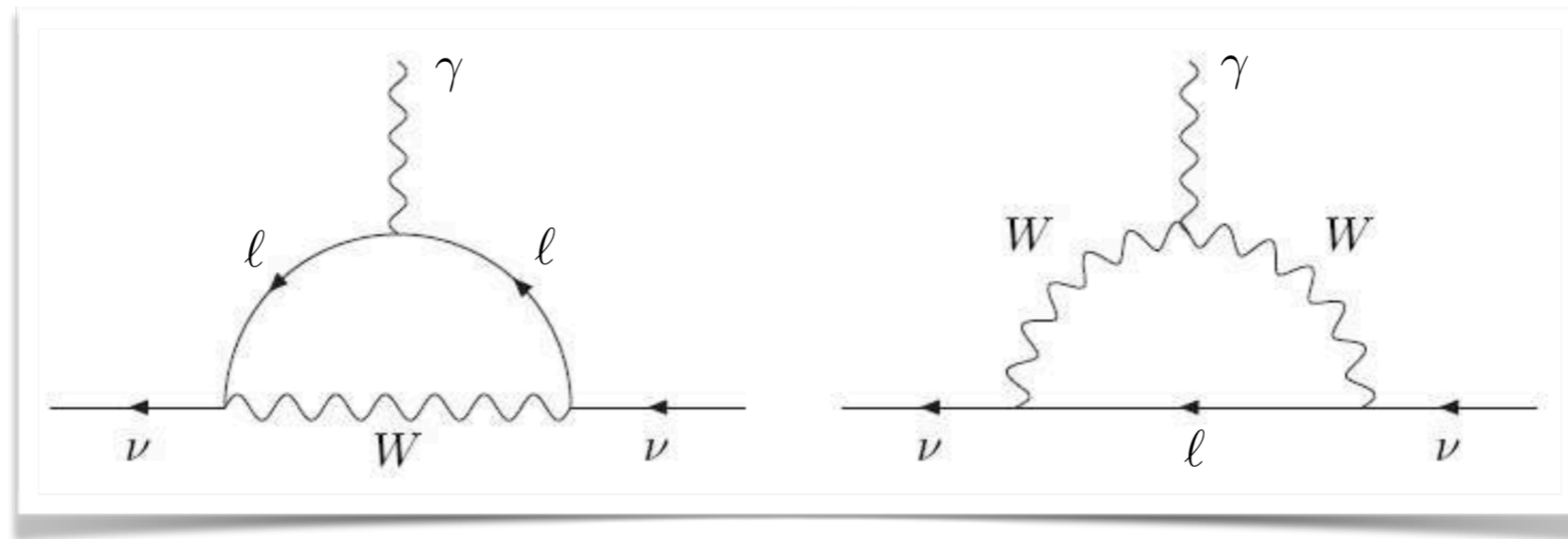
Fujikawa Shrock 1980

Neutrino Magnetic Moments in the SM

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☑ In the SM: generated by loop diagrams



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

Petcov 1977

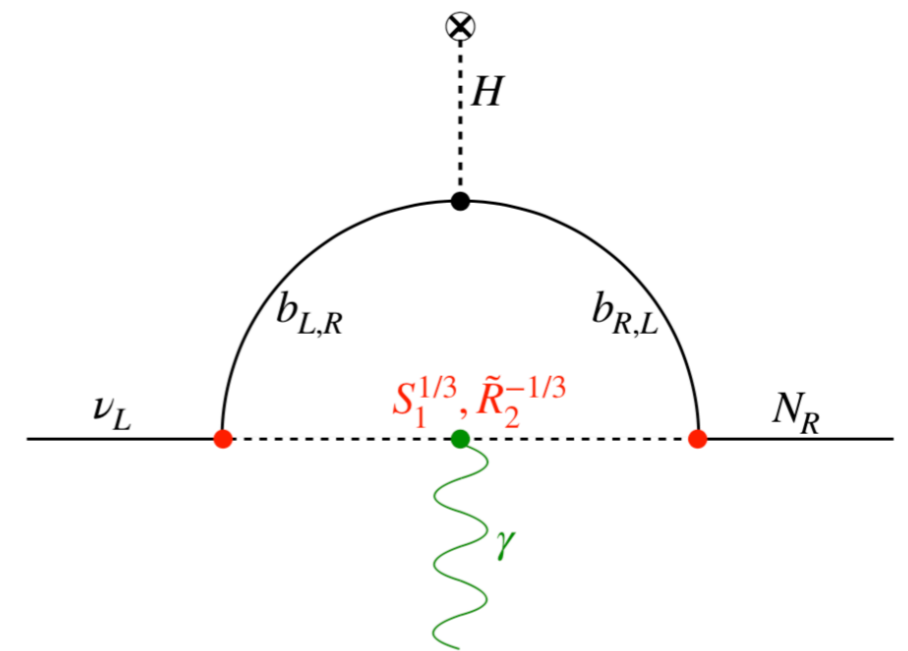
Fujikawa Shrock 1980

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*



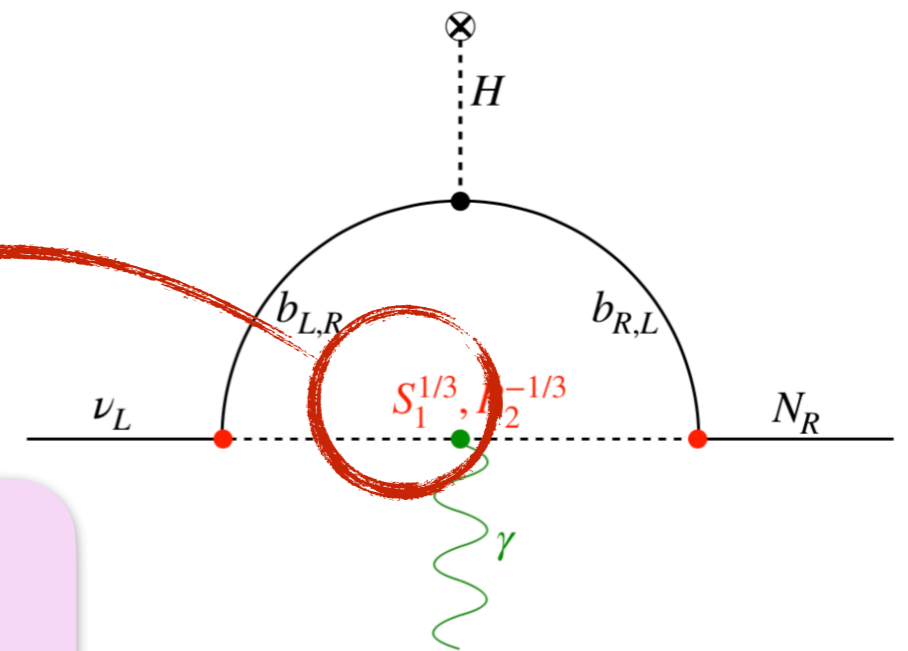
Brdar Greljo JK Opferkuch
2007.15563

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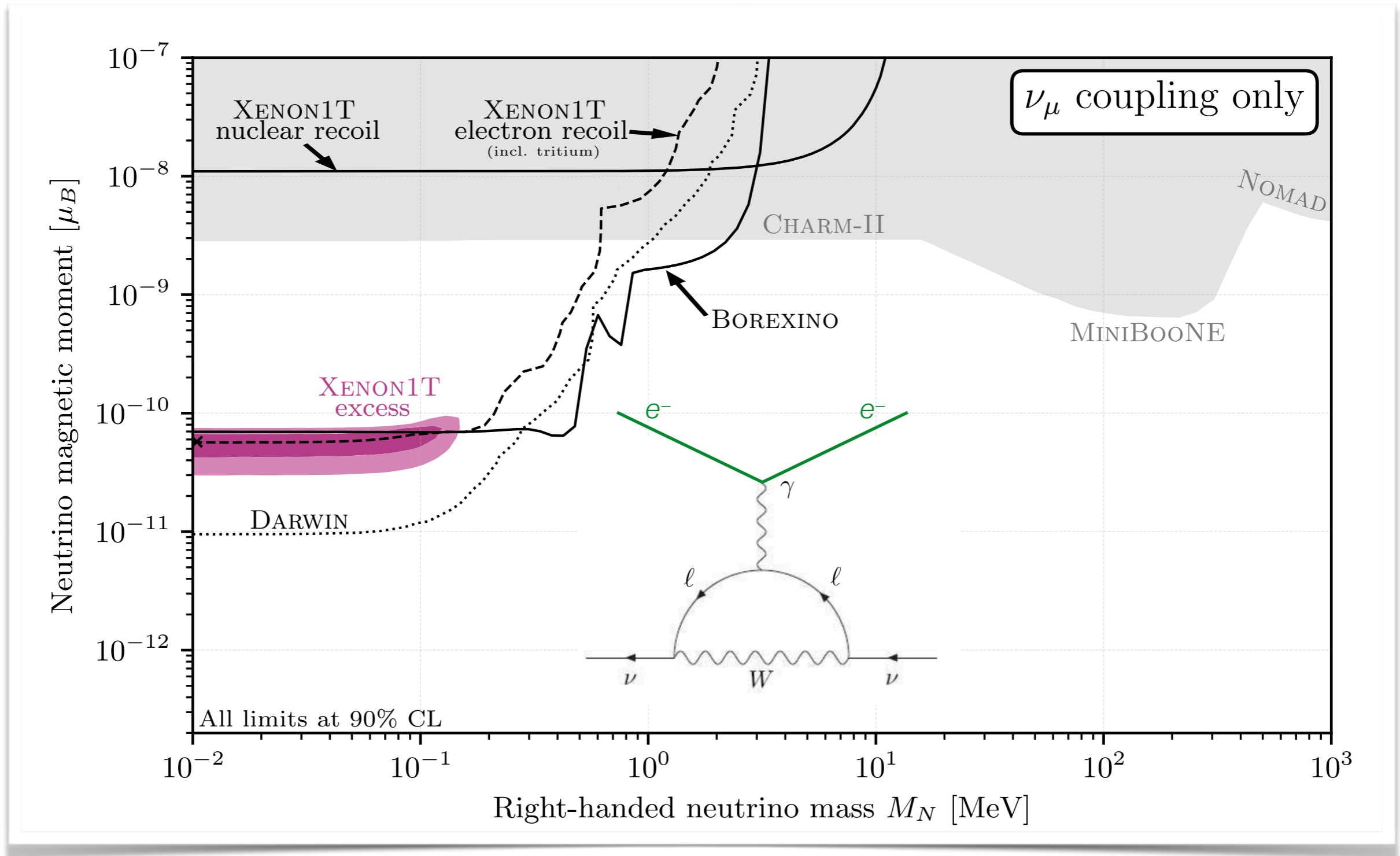
*leptoquark model, inspired by
B physics anomalies*



can explain
 $R(D^*)$ and $(g-2)_\mu$ anomalies.
(but constrained by ν masses)

Brdar Grejko JK Opferkuch
2007.15563

Summary of Terrestrial Constraints

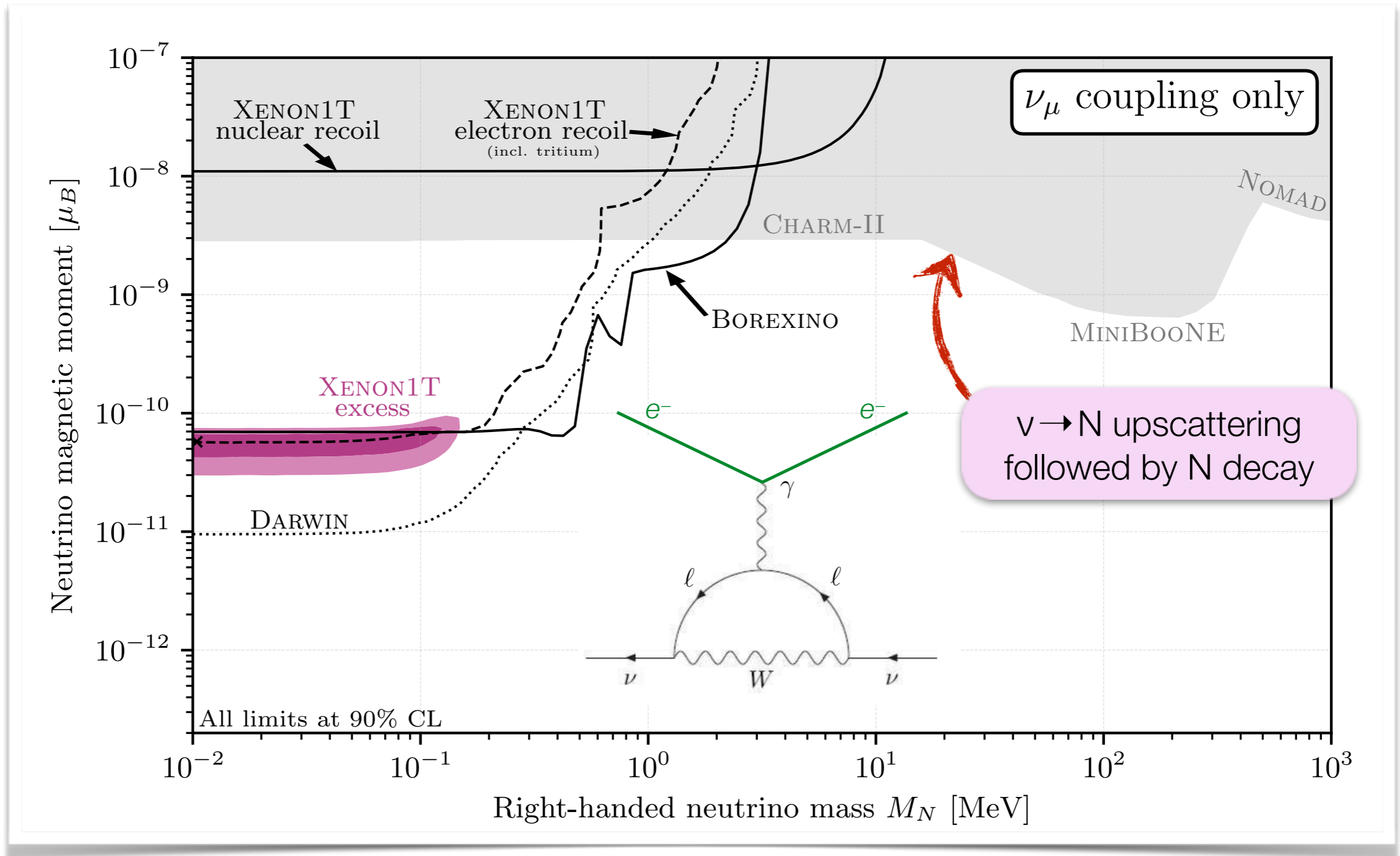


Coloma Machado Martinez-Soler Shoemaker [1707.08573](#), Magill Plestid Pospelov Tsai [1803.03262](#)

Shoemaker Wyenberg [1811.12435](#), Brdar Greljo JK Opferkuch [arXiv:2007.15563](#), Greljo Stangl Thomsen [2103.13991](#)



Summary of Terrestrial Constraints

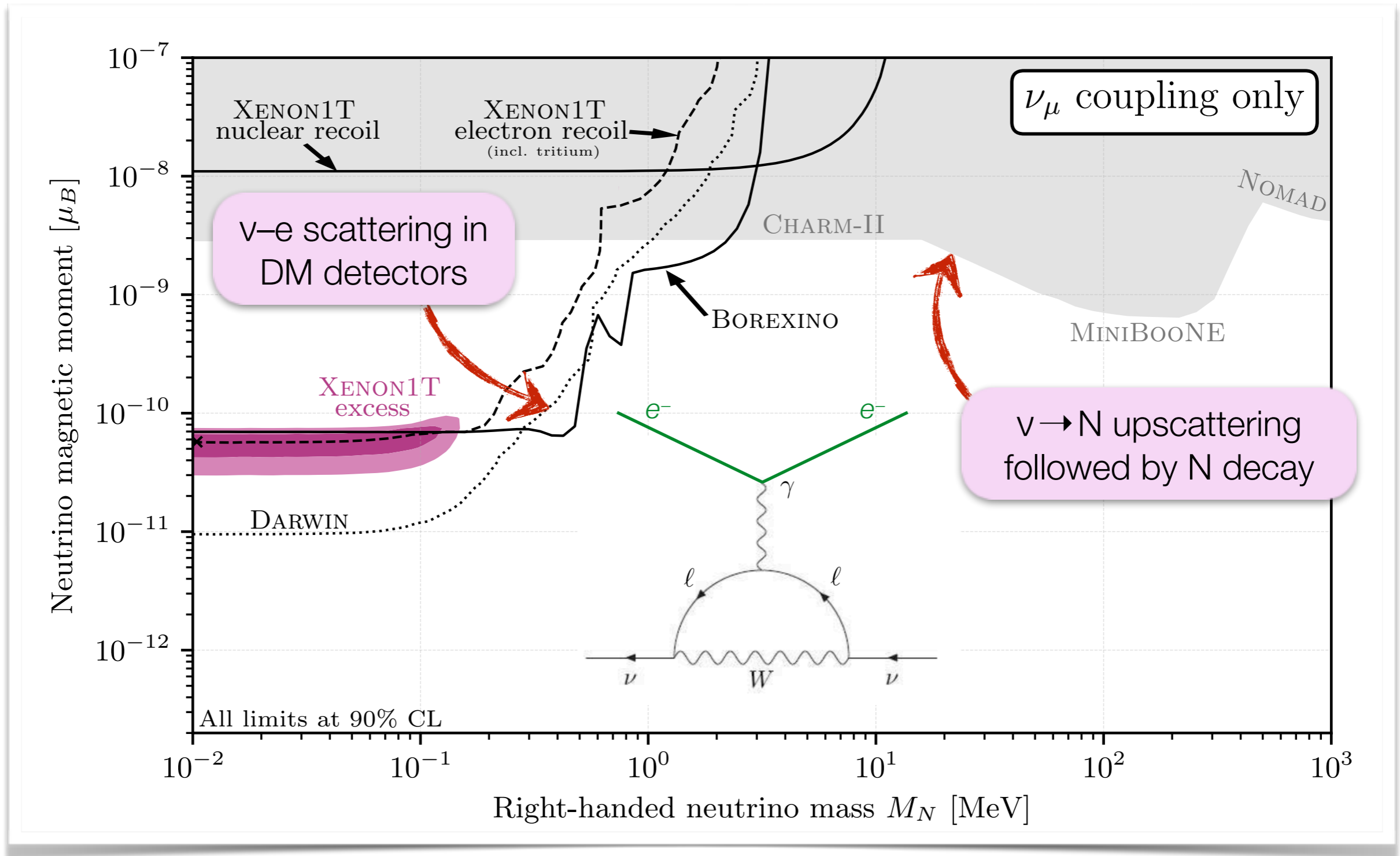


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Shoemaker Wyenberg [1811.12435](#), Brdar Greljo JK Opferkuch [arXiv:2007.15563](#), Greljo Stangl Thomsen [2103.13991](#)



Summary of Terrestrial Constraints

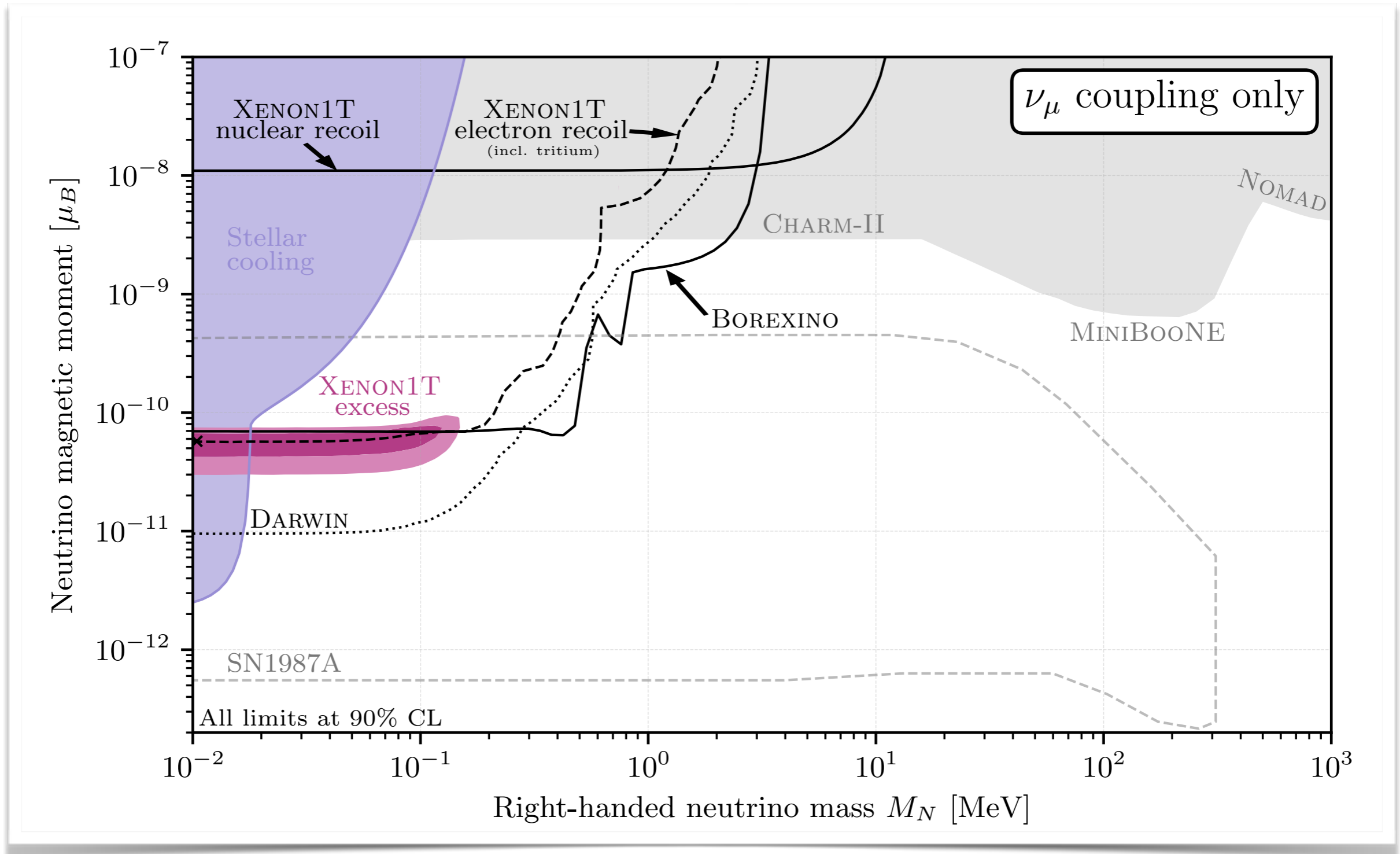


Coloma Machado Martinez-Soler Shoemaker [1707.08573](#), Magill Plestid Pospelov Tsai [1803.03262](#)

Shoemaker Wyenberg [1811.12435](#), Brdar Greljo JK Opferkuch [arXiv:2007.15563](#), Greljo Stangl Thomsen [2103.13991](#)



Stellar Cooling

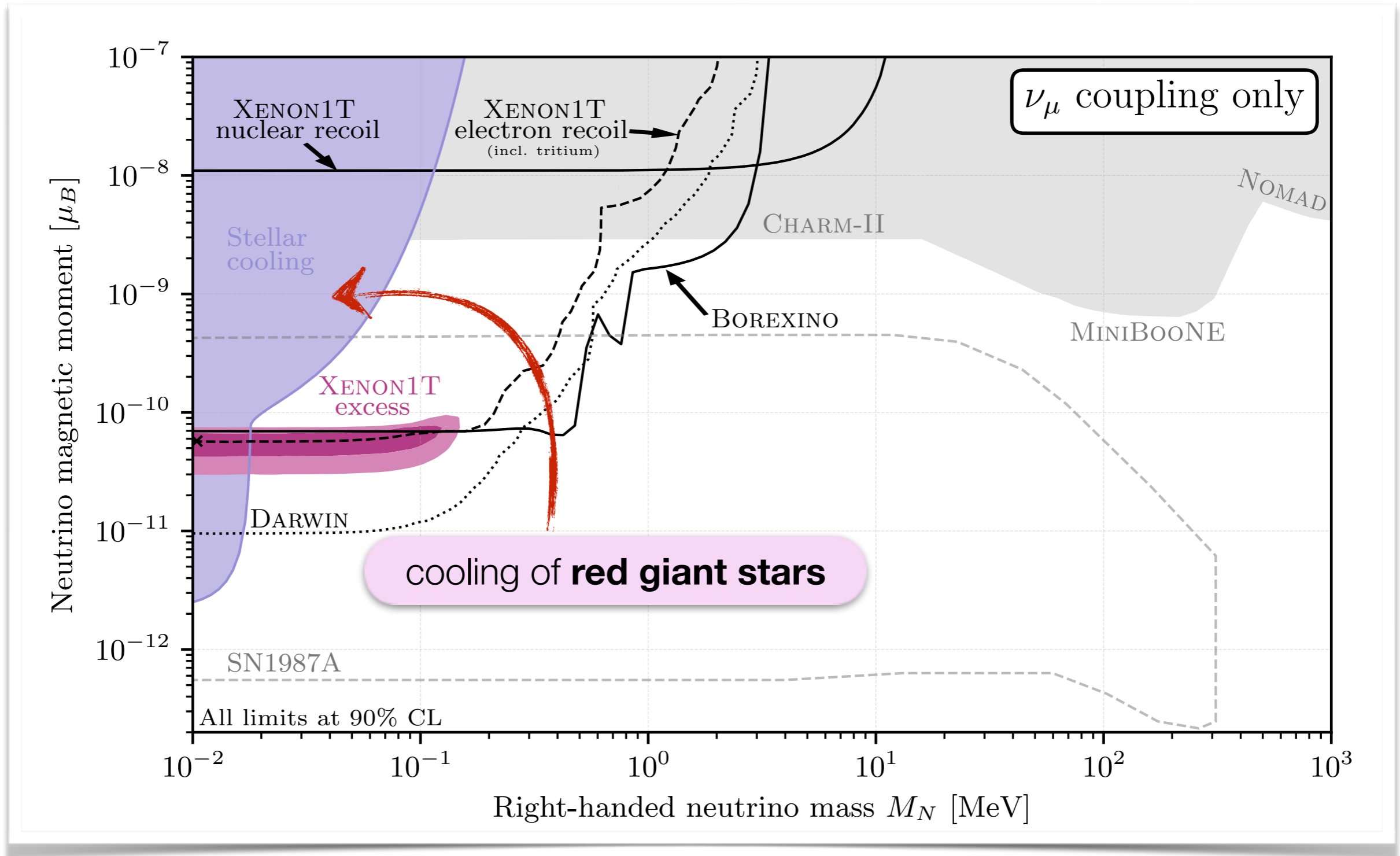


Coloma Machado Martinez-Soler Shoemaker [1707.08573](#), Magill Plestid Pospelov Tsai [1803.03262](#)

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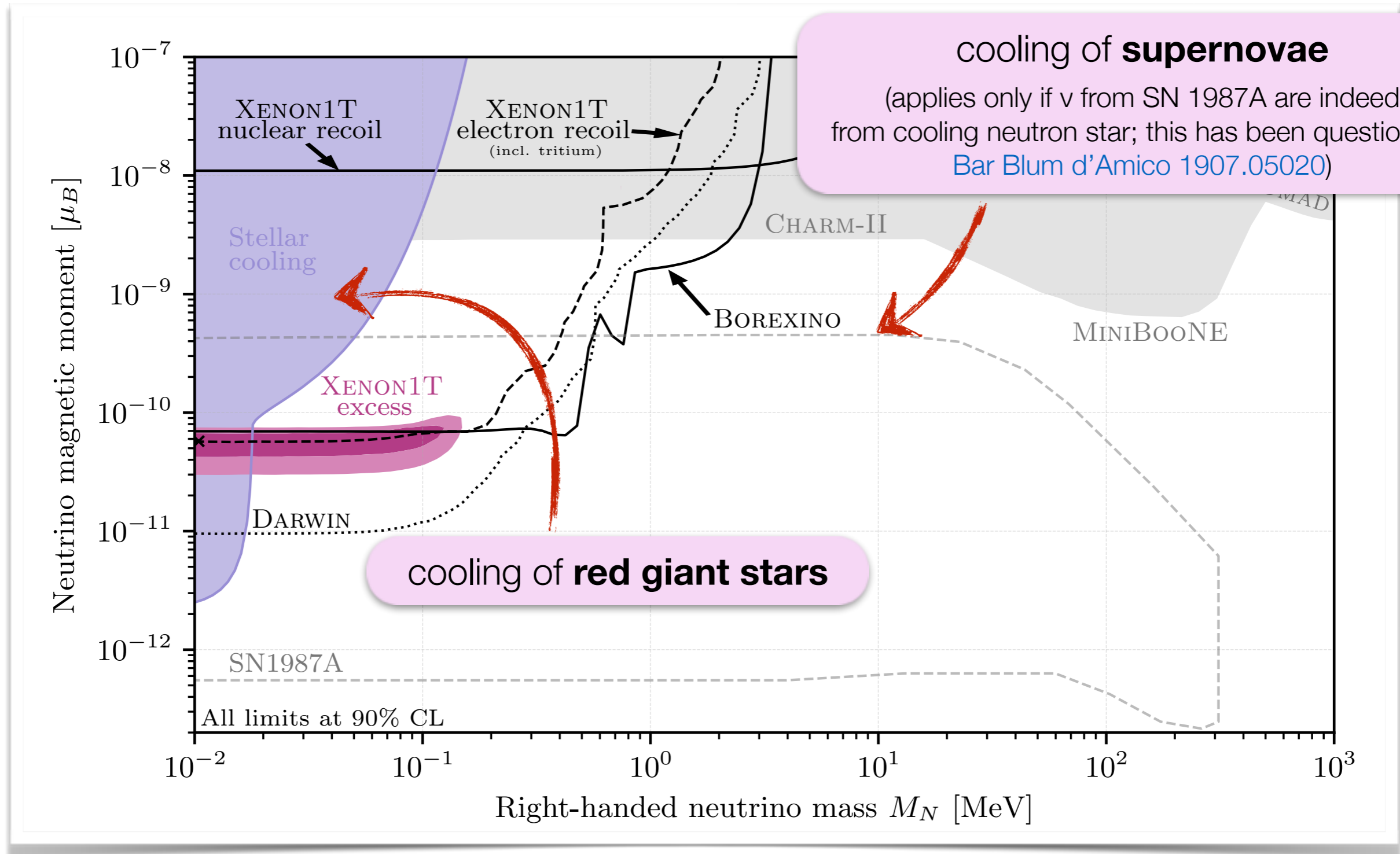


Coloma Machado Martinez-Soler Shoemaker [1707.08573](#), Magill Plestid Pospelov Tsai [1803.03262](#)

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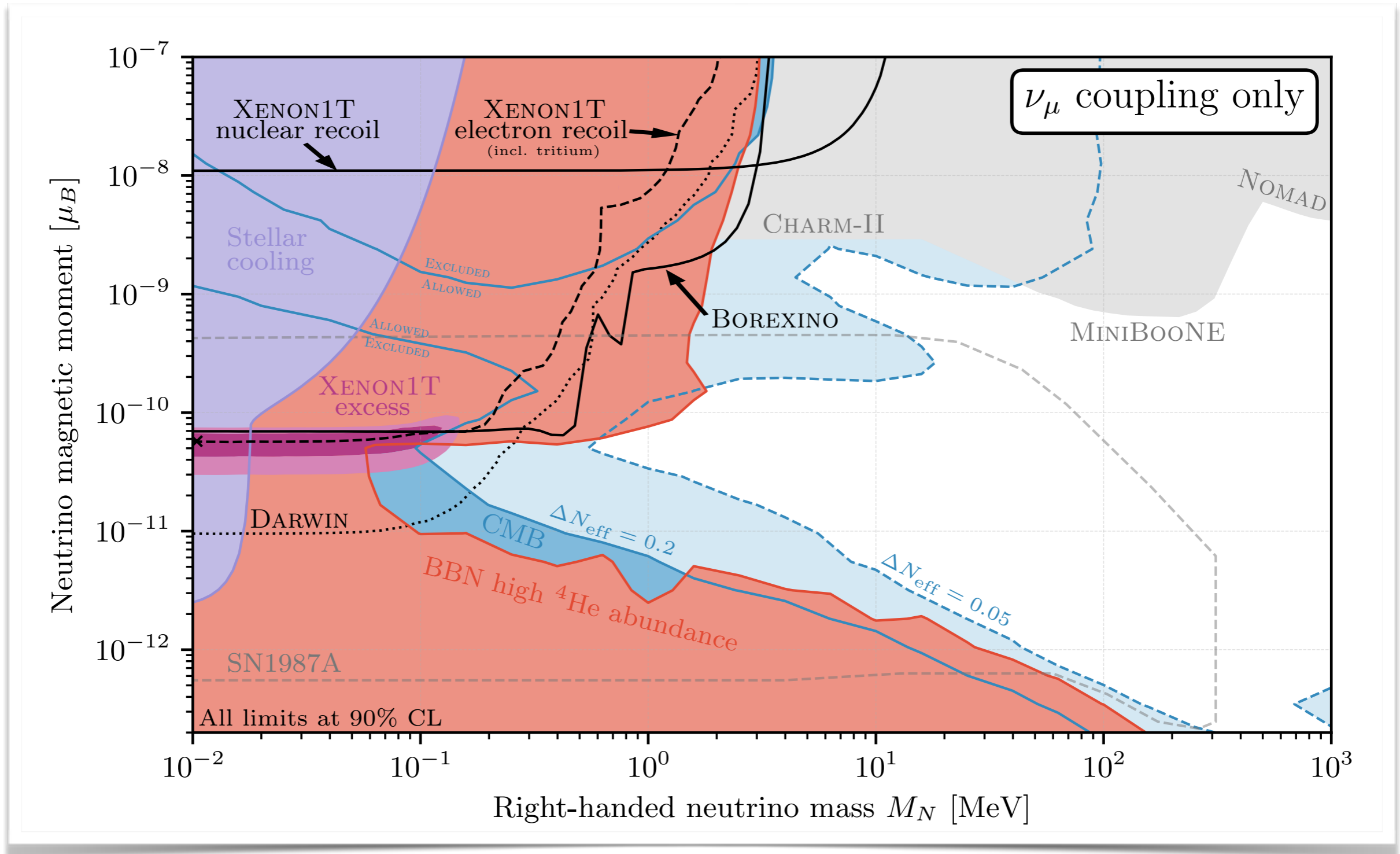
Stellar Cooling



Coloma Machado Martinez-Soler Shoemaker [1707.08573](#), Magill Plestid Pospelov Tsai [1803.03262](#)
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Summary of Constraints

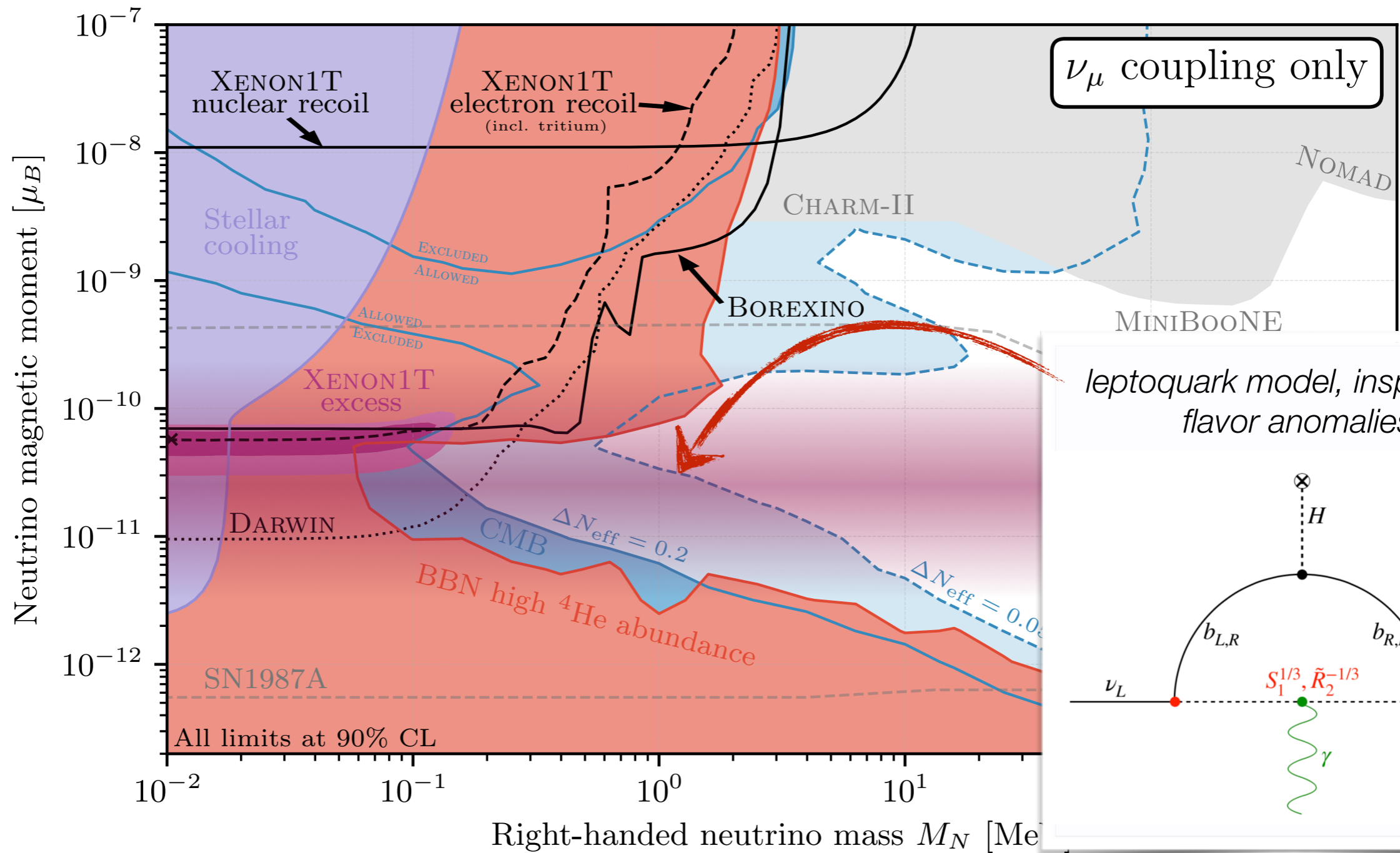


Coloma Machado Martinez-Soler Shoemaker [1707.08573](#), Magill Plestid Pospelov Tsai [1803.03262](#)

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Summary of Constraints

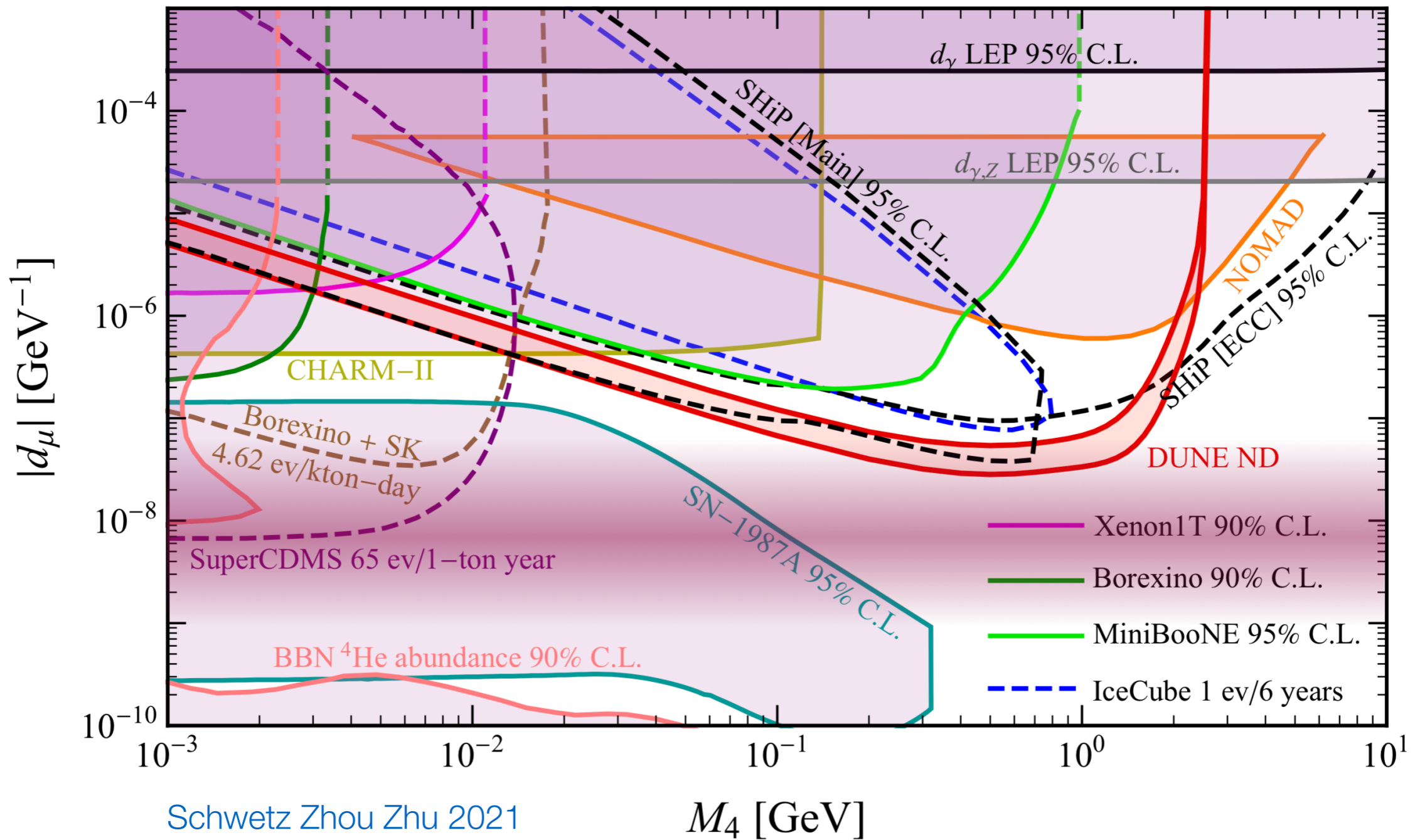


Coloma Machado Martinez-Soler Shoemaker [1707.08573](#), Magill Plestid Pospelov Tsai [1803.03262](#)

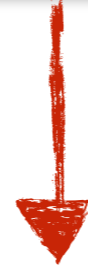
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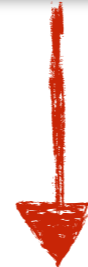
Future Constraints



dim-4: the Neutrino Portal



dim-5: Neutrino Magnetic Moments



dim-6: Neutrinos in SMEFT

dim-4: the Neutrino Portal



dim-5: Neutrino Magnetic Moments

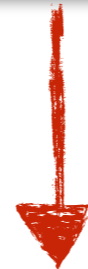
- starting probe **TeV-scale** new physics
- strong **synergies** between different searches

dim-6: Neutrinos in SMEFT

dim-4: the Neutrino Portal



dim-5: Neutrino Magnetic Moments



dim-6: Neutrinos in SMEFT

New Neutrino Interaction



New Neutrino Interaction

- ☑ SMEFT (**S**tandard **M**odel **E**ffective **T**heory)
= most general parameterization of UV-scale new physics
⇒ Zahra Tabrizi's talk

New Neutrino Interaction

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- ☑ For neutrino experiments:
map onto EFT below the electroweak scale

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

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dim-6 operators

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dimensionless coefficients

(strength of new interactions
relative to SM weak interactions)

New Neutrino Interaction

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- ☑ Replaces partially inconsistent “non-standard neutrino interactions” formalism with modern EFT

New Neutrino Interaction

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

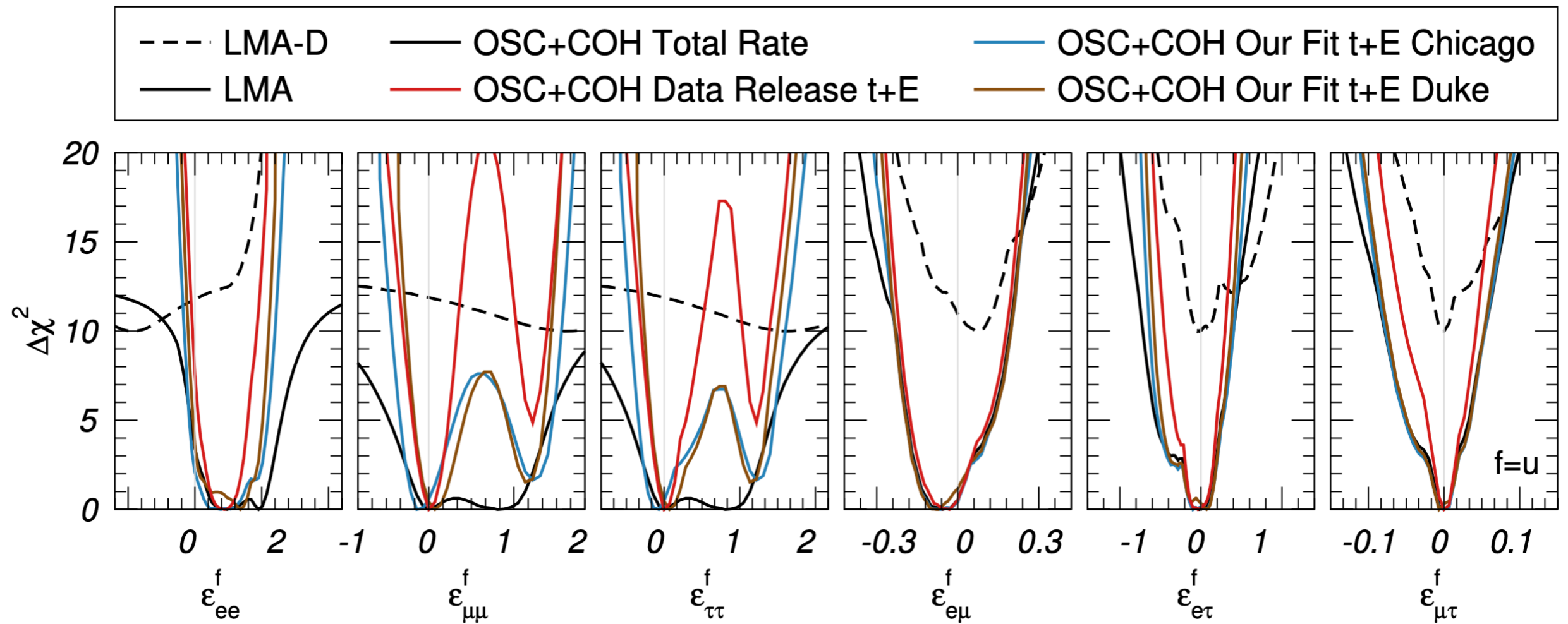
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- ☑ Neutral Current (NC): new matter effects in oscillations
- ☑ Charged Current (CC): modified ν production & detection

Coloma Esteban Gonzalez-Garcia Maltoni [arXiv:1911.09109](https://arxiv.org/abs/1911.09109)

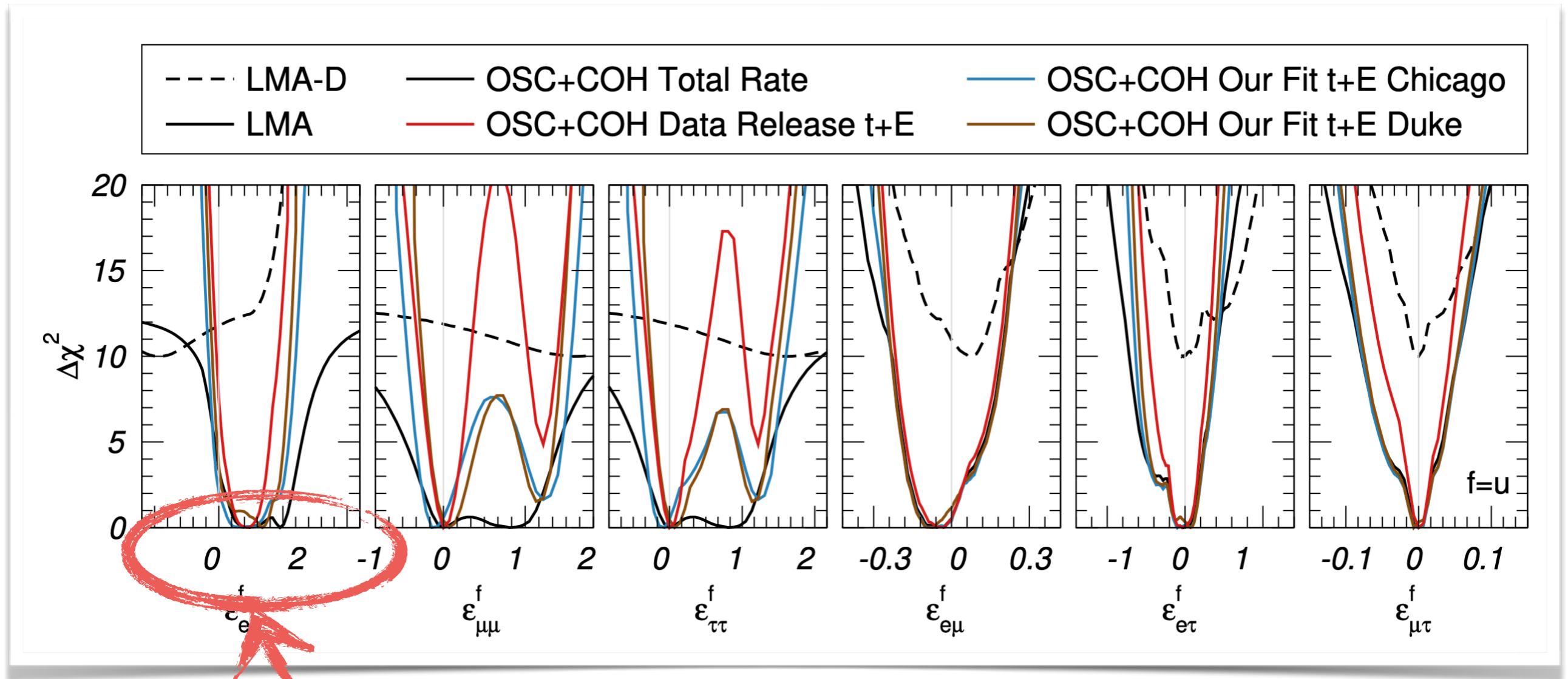
Biggio Blennow Fernandez-Martinez [arXiv:0907.0097](https://arxiv.org/abs/0907.0097)

Anomalous Neutral Currents in Oscillations



Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109

Anomalous Neutral Currents in Oscillations



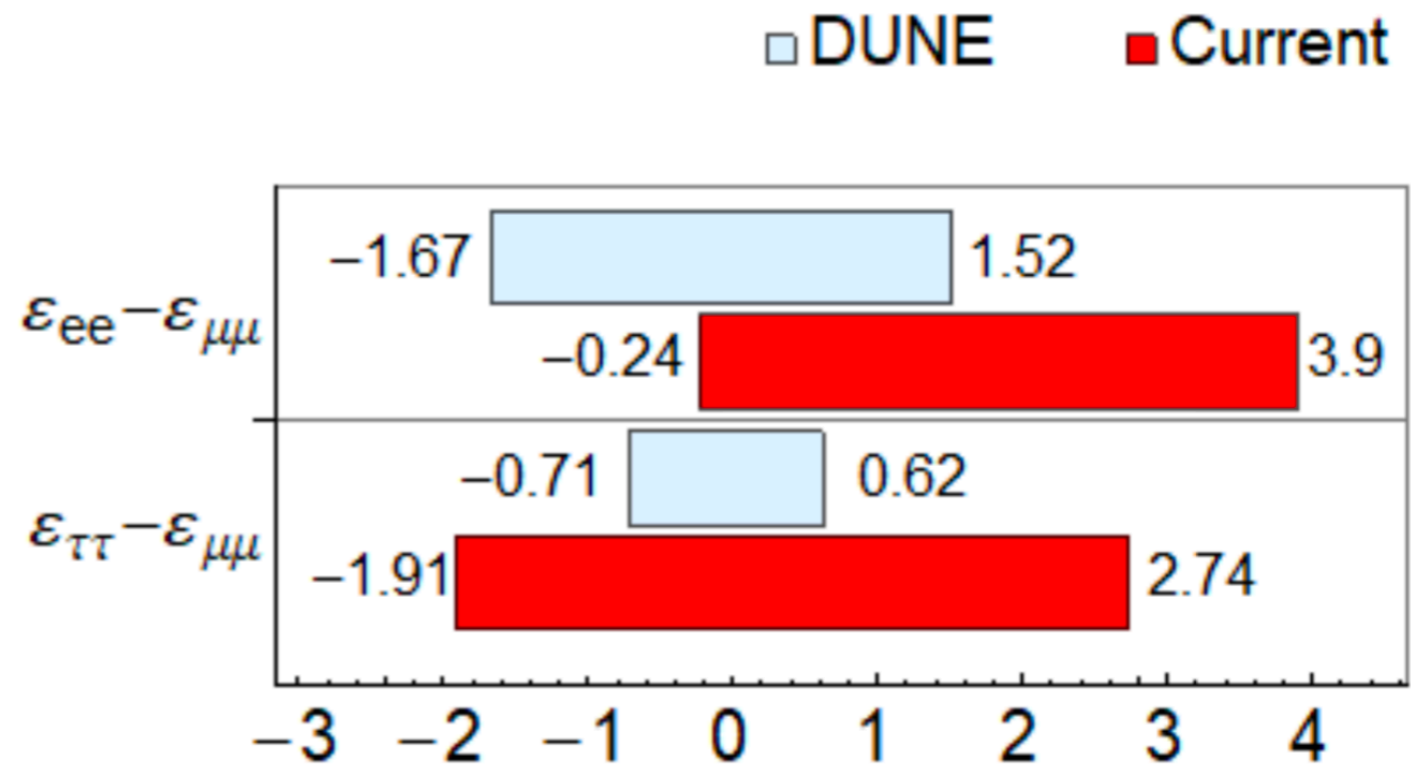
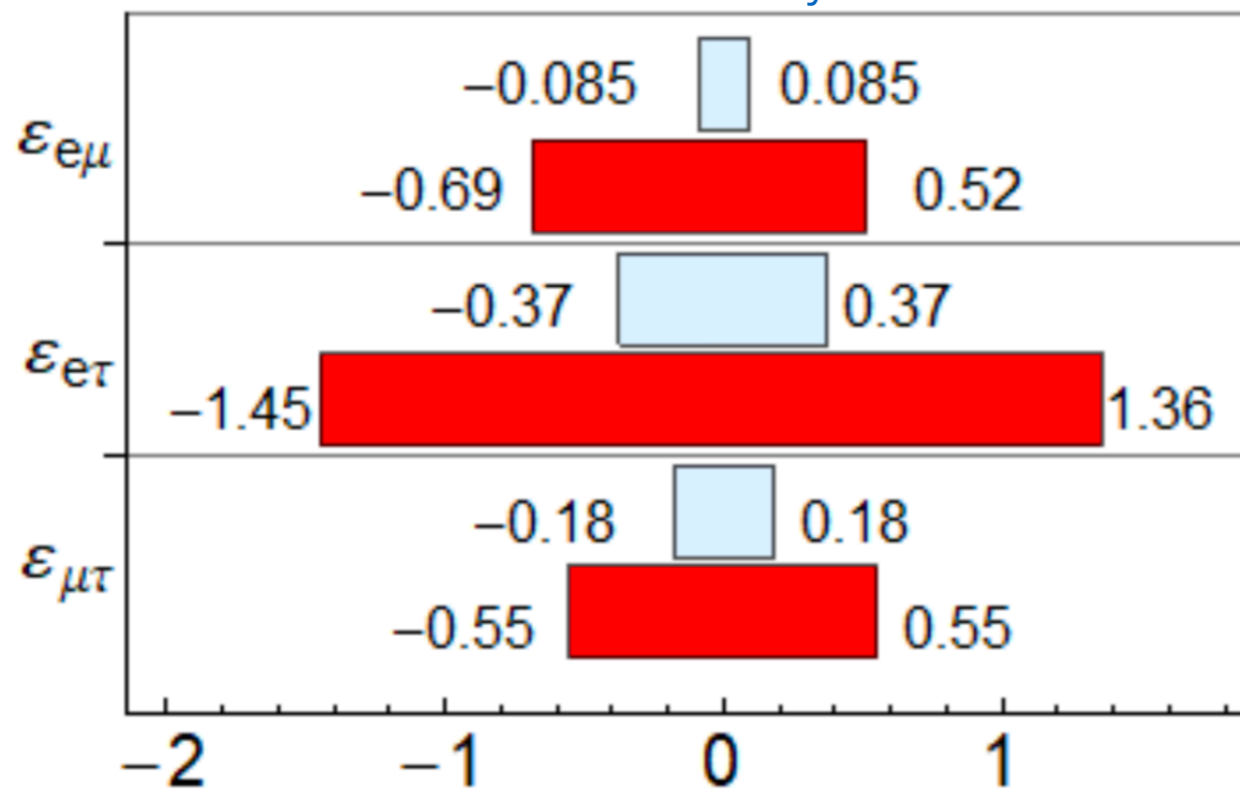
Coloma Esteban Gonzalez-Garcia Maltoni arXiv:1911.09109

sensitivity to interactions
similar in strength to
SM weak interactions

Anomalous Neutral Currents in Oscillations

- ☑ Significant improvement with DUNE
 - ➡ probing new physics at the **few 100 GeV** scale

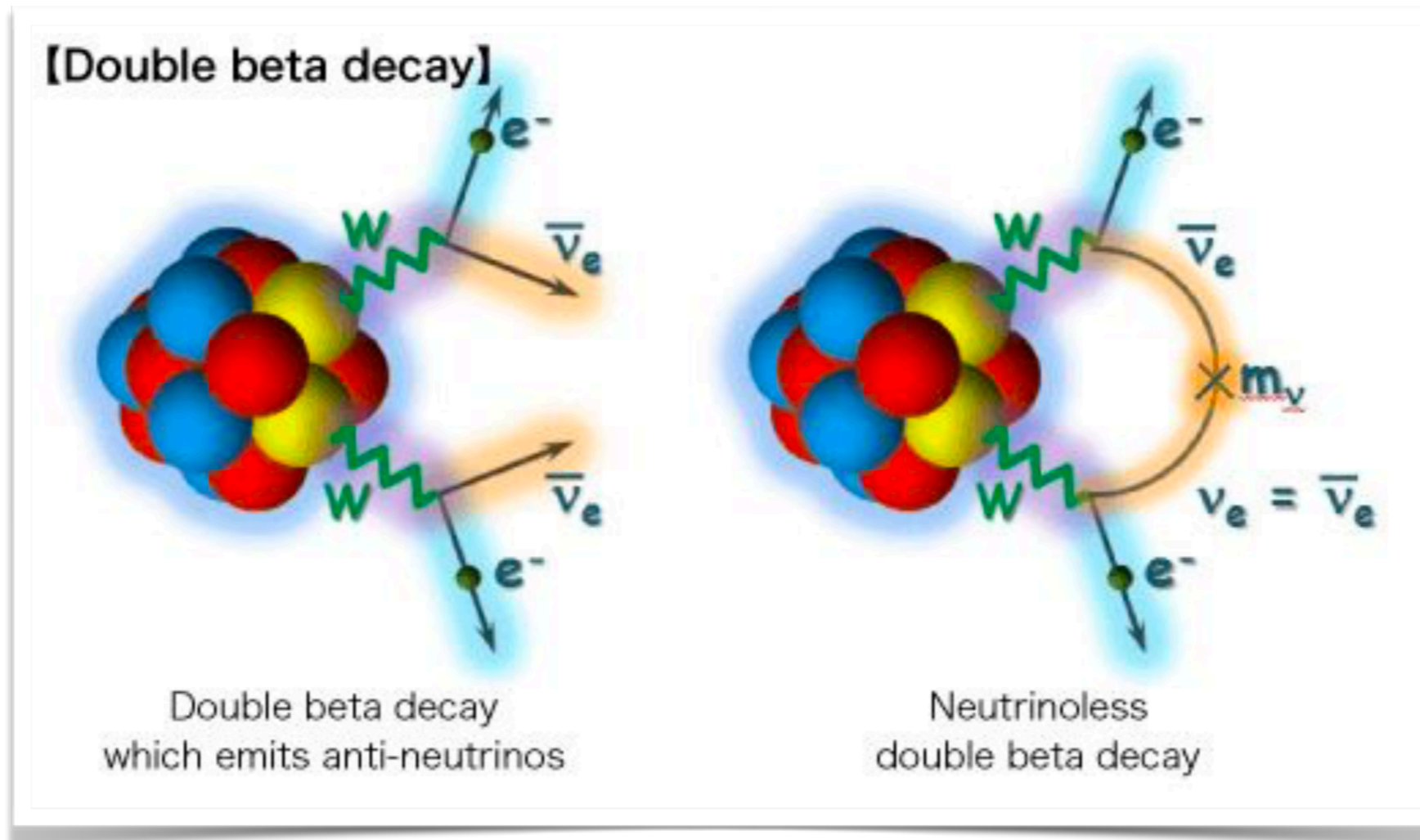
DUNE FD TDR – Vol II – Physics



Anomalous Charged Currents

- ☑ Modified [neutrino production and detection](#) processes
- ☑ not independent of NC operators
 - ▣ consistent EFT essential
- ☑ Interesting new opportunities at [FASER \$\nu\$](#) , [SND@LHC](#), etc.
- ☑ see [Zahra Tabrizi's](#) talk

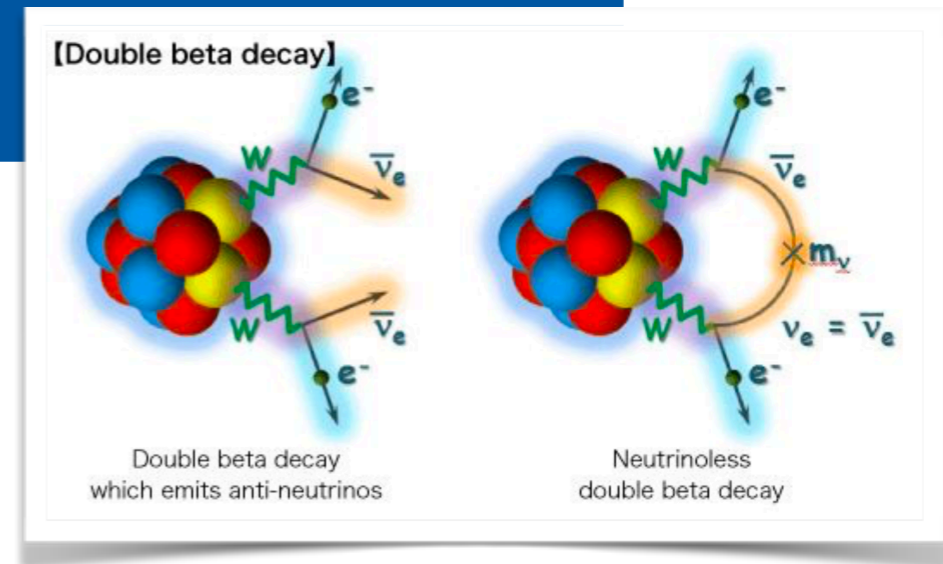
New Physics in Double Beta Decay



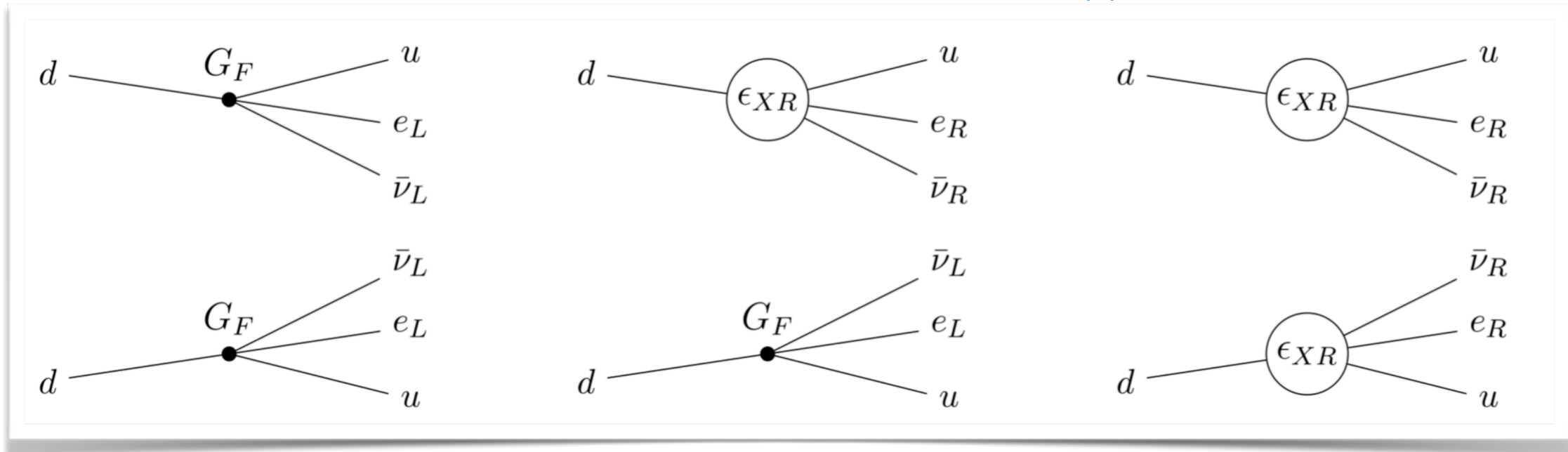
New Physics in Double Beta Decay

☑ BSM contributions possible in both cases

○ for $2\nu 2\beta$:



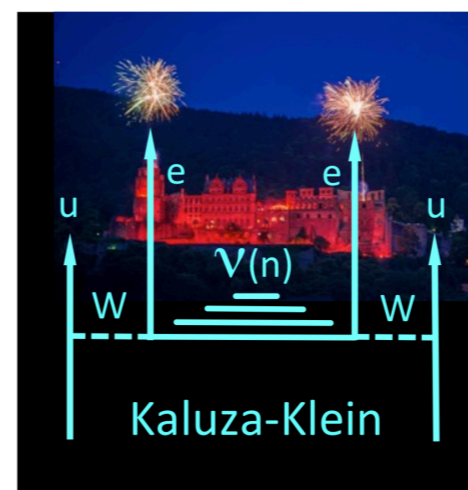
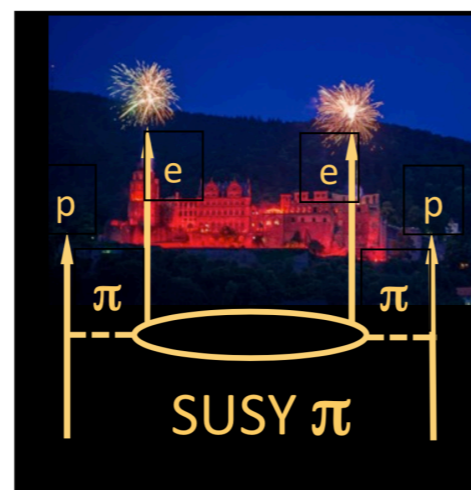
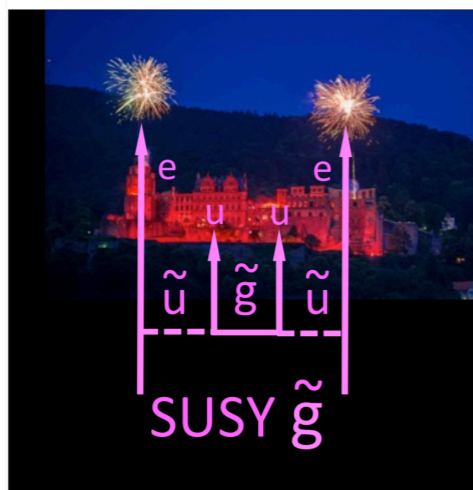
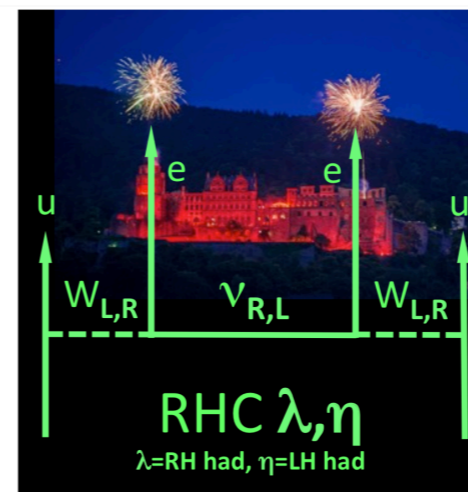
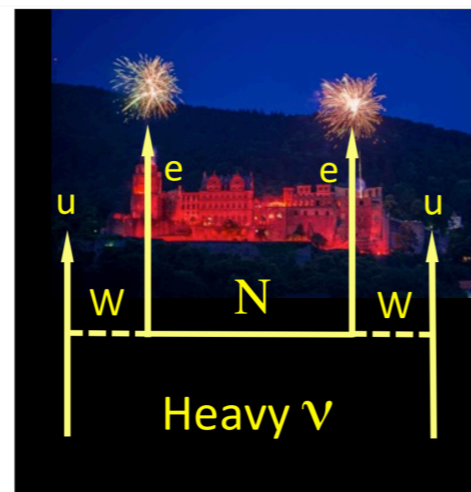
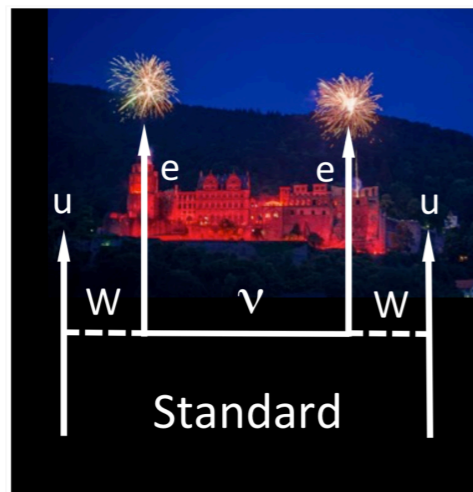
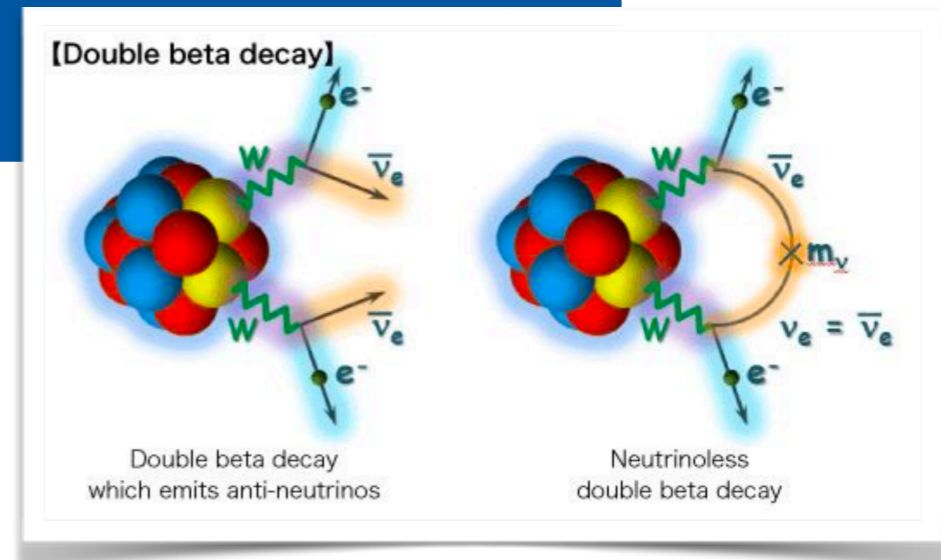
Deppisch Graf Simkovic 2020



New Physics in Double Beta Decay

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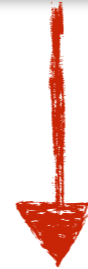


slide by Eligio Lisi (Nu2018)
Schechter Valle 1982
Duerr Lindner Merle 2011

dim-4: the Neutrino Portal



dim-5: Neutrino Magnetic Moments



dim-6: Neutrinos in SMEFT

dim-4: the Neutrino Portal



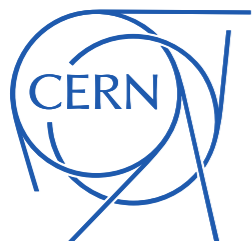
dim-5: Neutrino Magnetic Moments



dim-6: Neutrinos in SMEFT

- model-independent formalism for high-scale new physics
- easy comparison between experiments

Summary



dim-4: the Neutrino Portal

- ☑ one of the main [portals to the dark sector](#)
- ☑ superior sensitivity at future experiments (near & far detectors!)

dim-5: Neutrino Magnetic Moments

- ☑ starting probe [TeV-scale](#) new physics
- ☑ strong [synergies](#) between different searches

dim-6: Neutrinos in SMEFT

- ☑ model-independent formalism for high-scale new physics
- ☑ easy comparison between experiments

