Neutrino Masses and Mixings: Theoretical Challenges

Joachim Kopp (CERN & JGU Mainz)

XIX Neutrino Telescopes Workshop | 19 February 2021

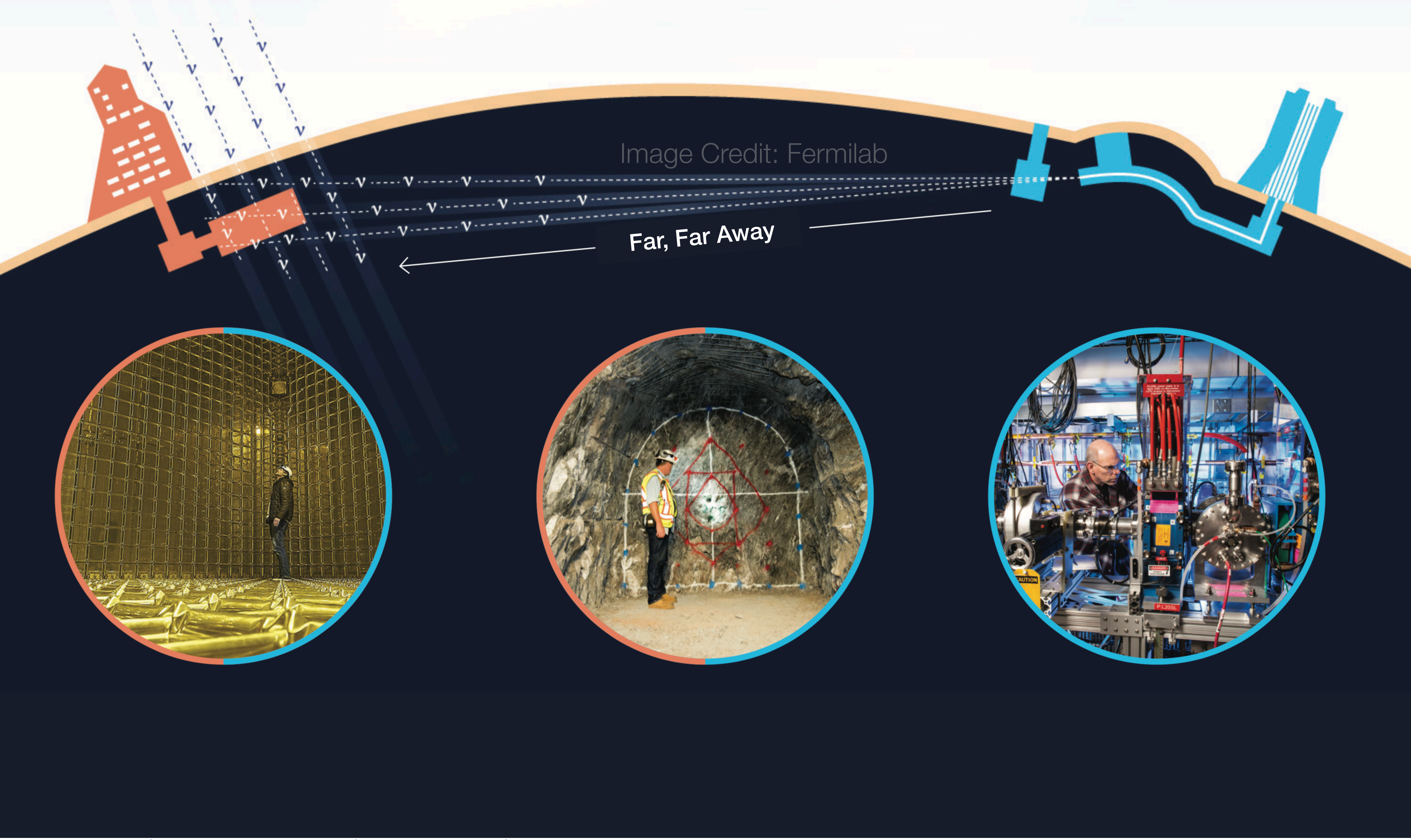
Outline

- ☑ Challenge 1: Understanding Neutrino Interactions
- ☑ Challenge 2: Oscillation Anomalies
- ☑ Challenge 3: Collective Oscillations
- ☑ Challenge 4: “New ν Physics”
- ☑ Summary

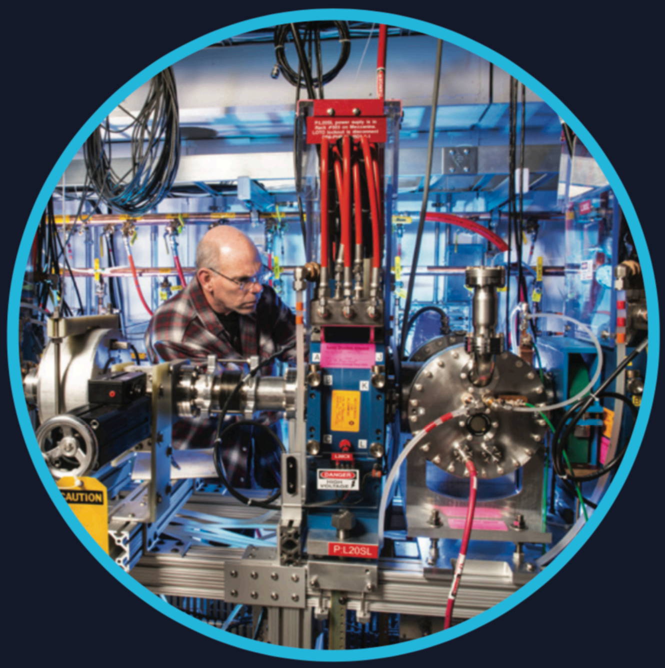
Challenge 1:

Understanding Neutrino Interactions

Next-Generation Long-Baseline Experiments

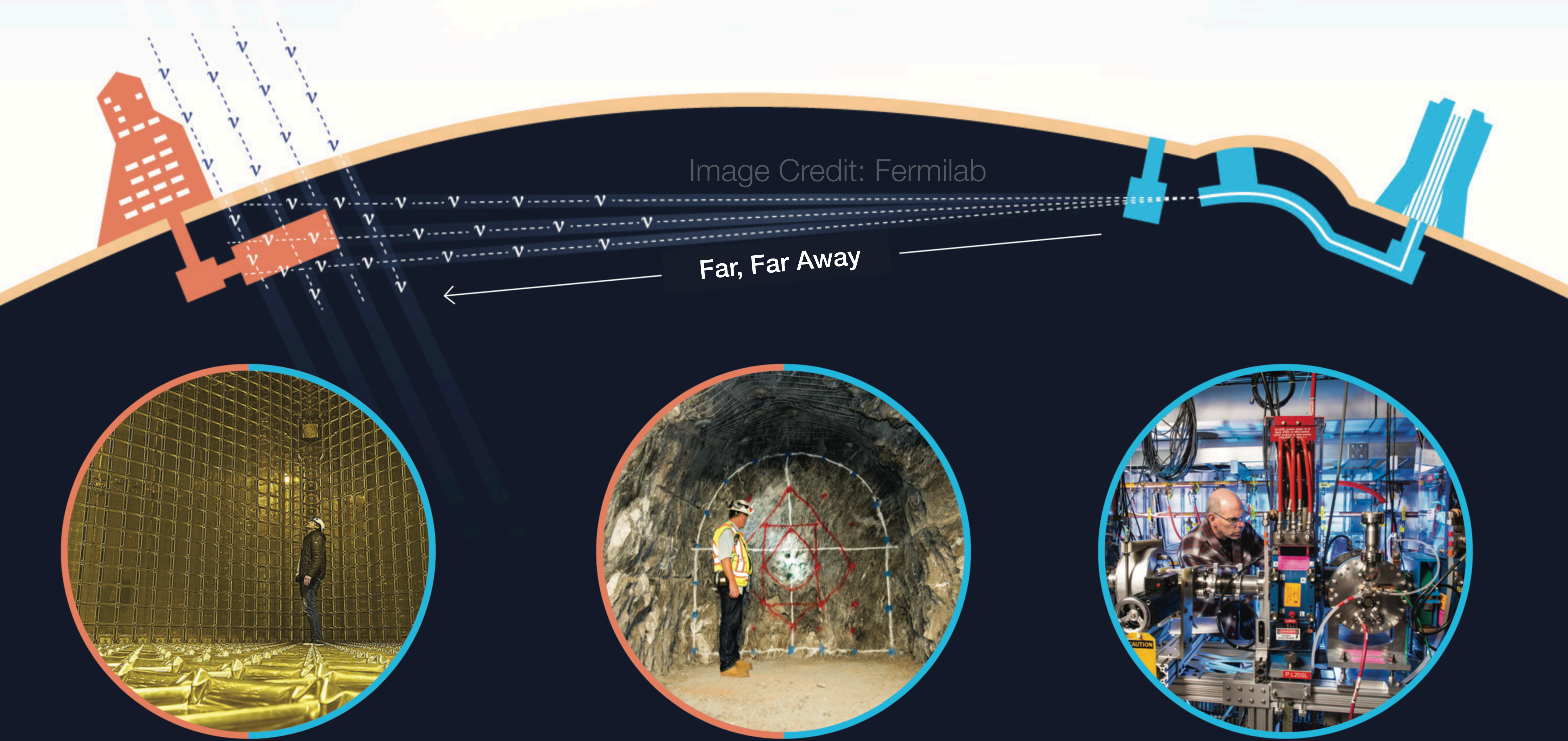


Next-Generation Long-Baseline Experiments



MACARONI
(**M**egawatt **A**ccelerator for **C**reating **A**bundant **R**adiation **O**f **N**eutrin**I**)

Next-Generation Long-Baseline Experiments



ENTRECOTE
(**E**xperiments **N**eeded for **T**ackling **R**eliably the **E**xtreme **C**onundrum **O**riginating from **T**heory **E**rrors)

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Next-Generation Long-Baseline Experiments

GELATO
(**G**inormous **E**xperiment at **L**ong-Baseline **A**iming to **T**est **O**scillations)

ENTRECOTE
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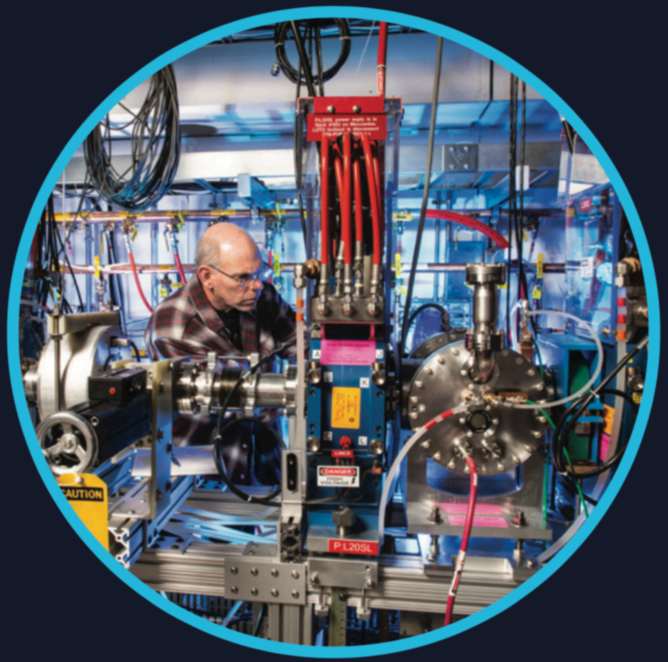

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Systematic Uncertainties

- Large systematic uncertainties in
  - Composition of neutrino beam
  - Neutrino interaction cross sections

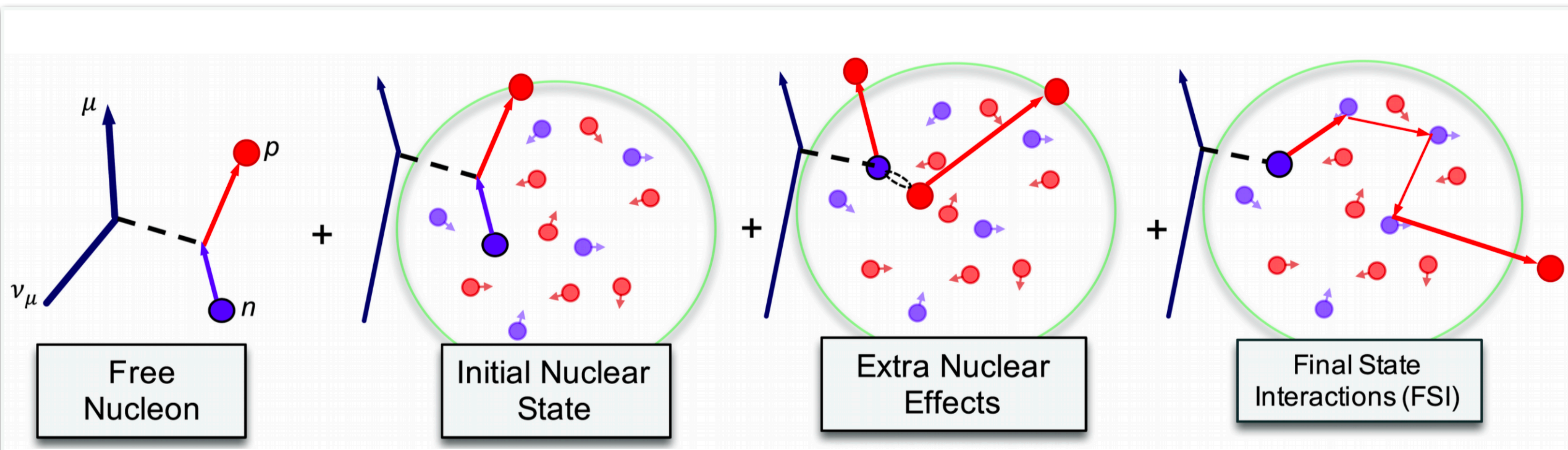


Image Credit: NA61/SHINE; Callum Wilkinson

Understanding Neutrino Interactions

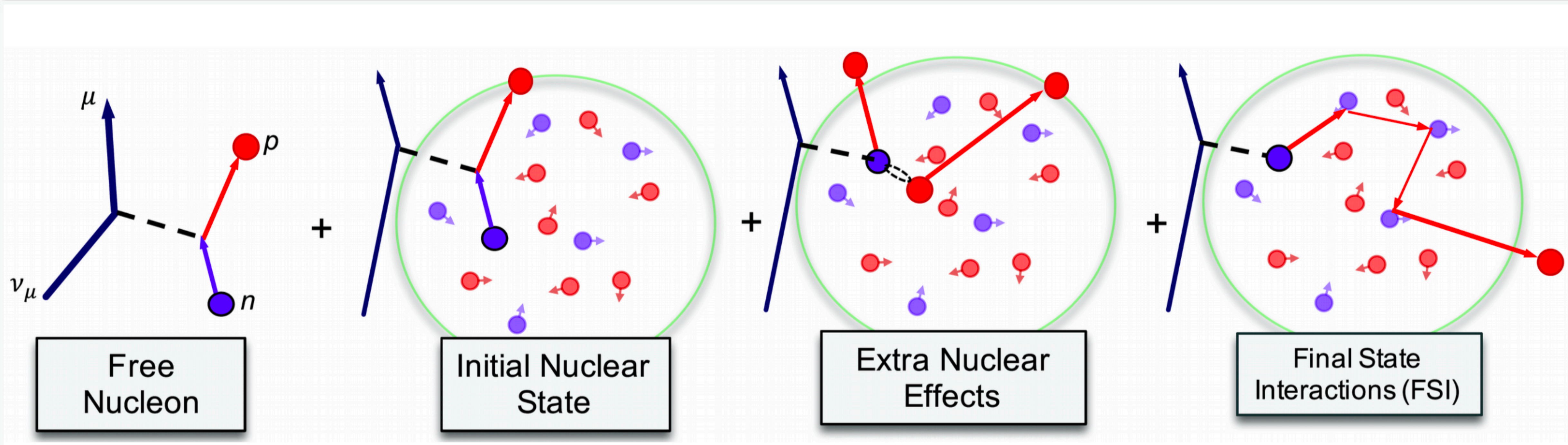
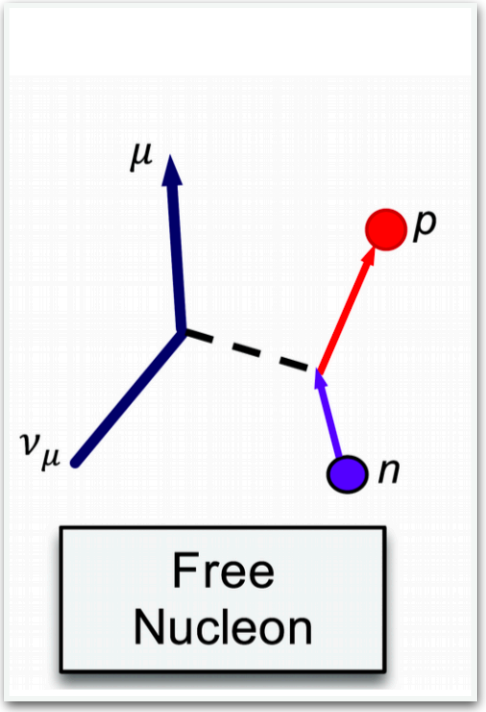


Image Credit: Callum Wilkinson

Understanding Neutrino Interactions



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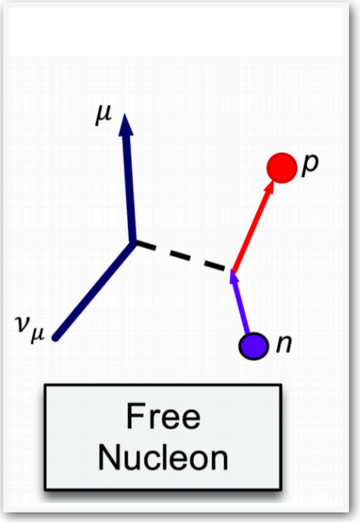
Understanding Neutrino Interactions



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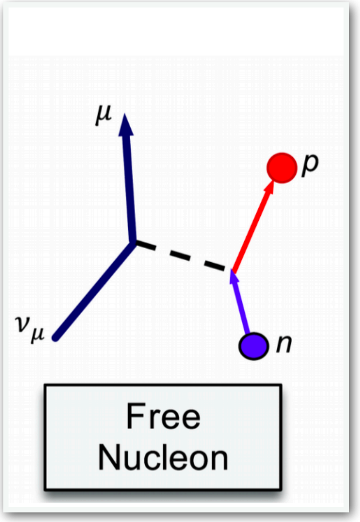
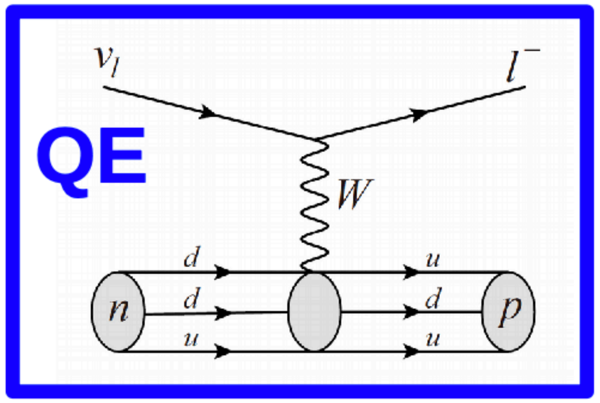
Understanding Neutrino Interactions





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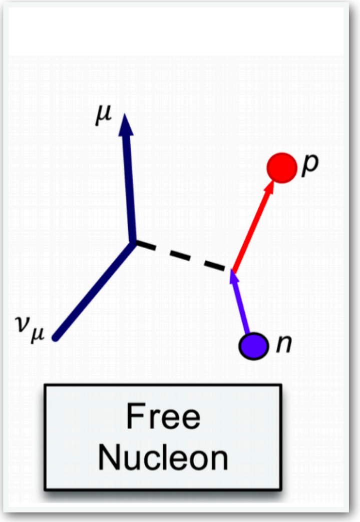

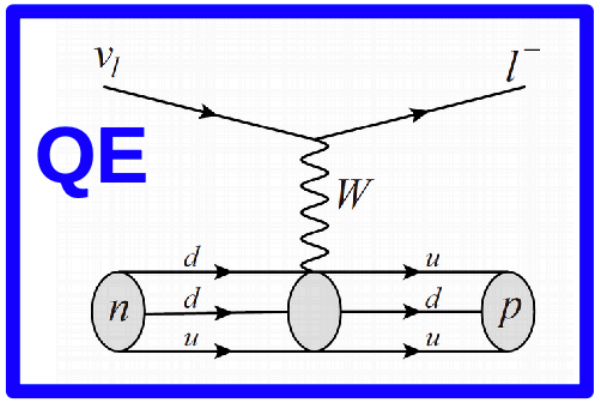

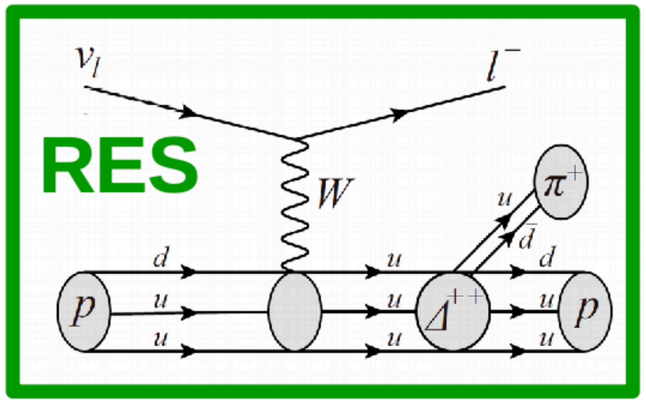

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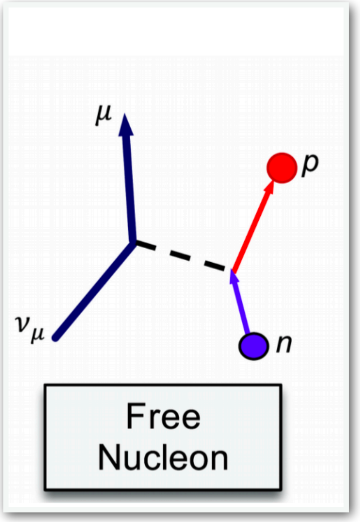
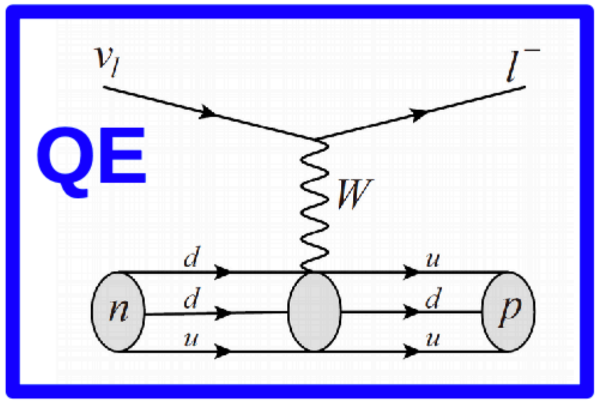
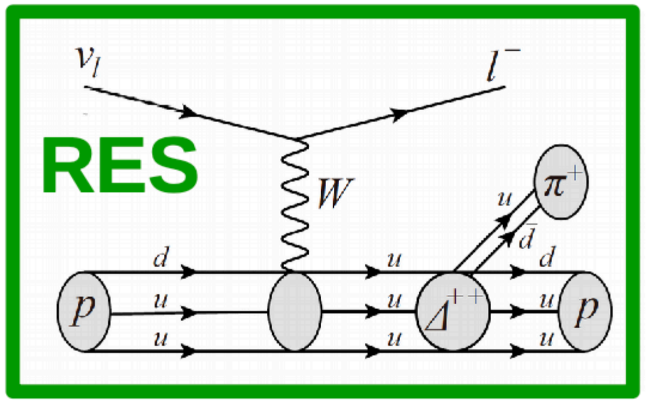
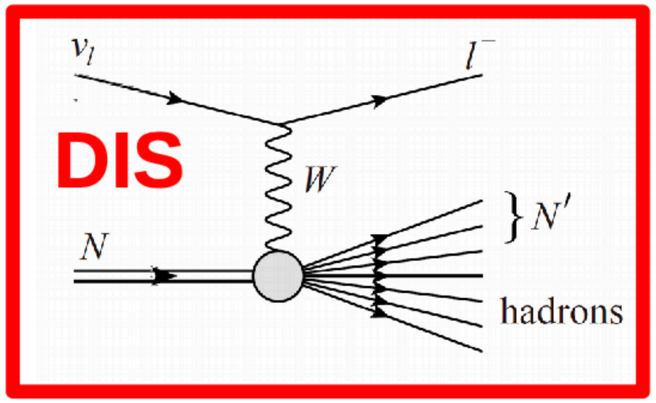
Understanding Neutrino Interactions









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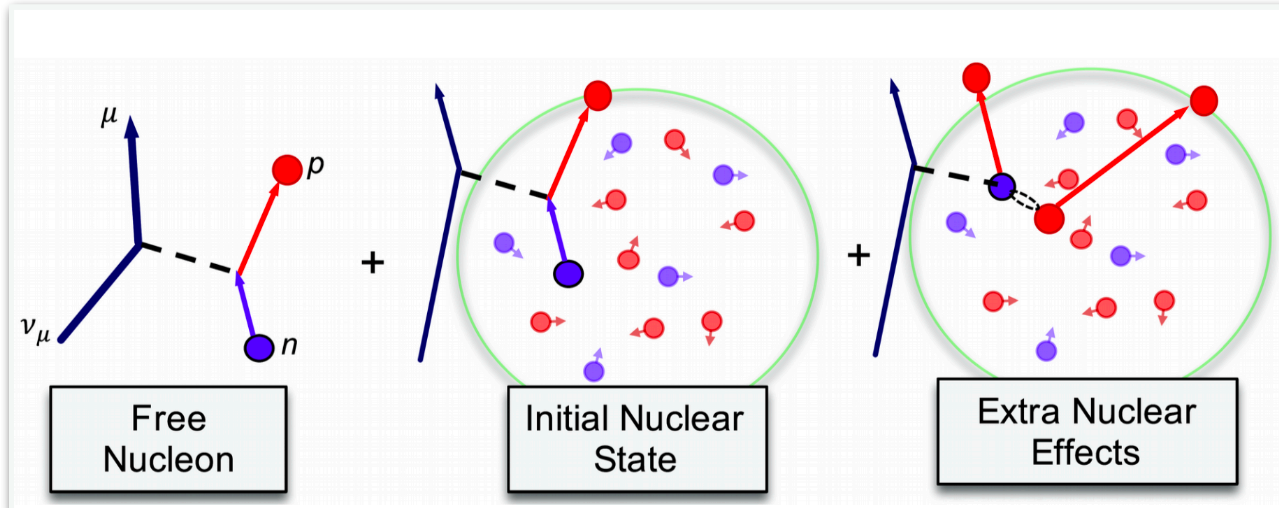

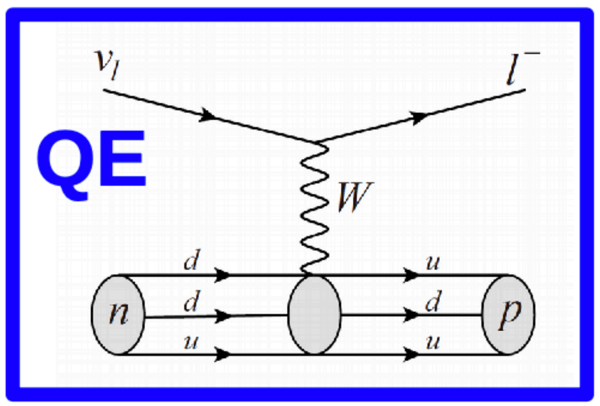

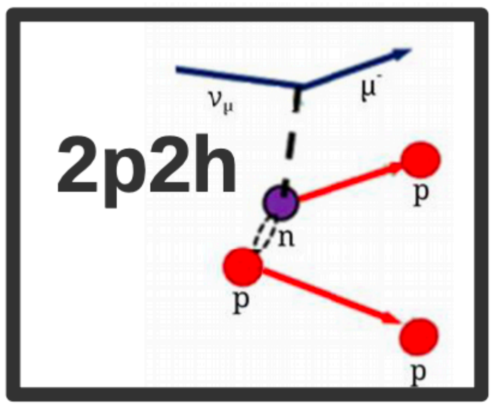

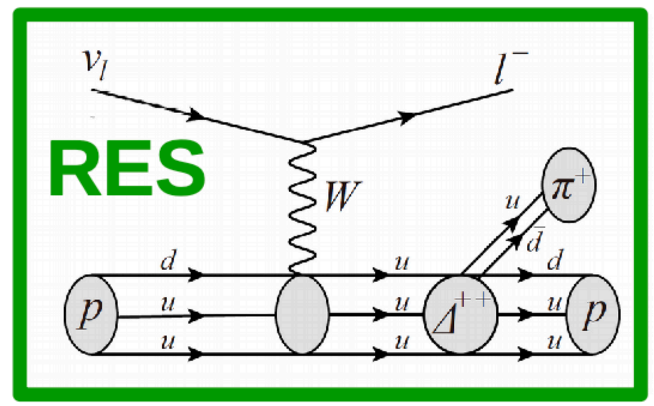

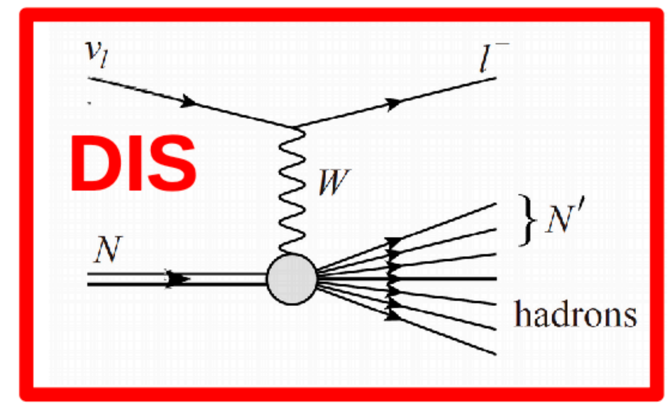

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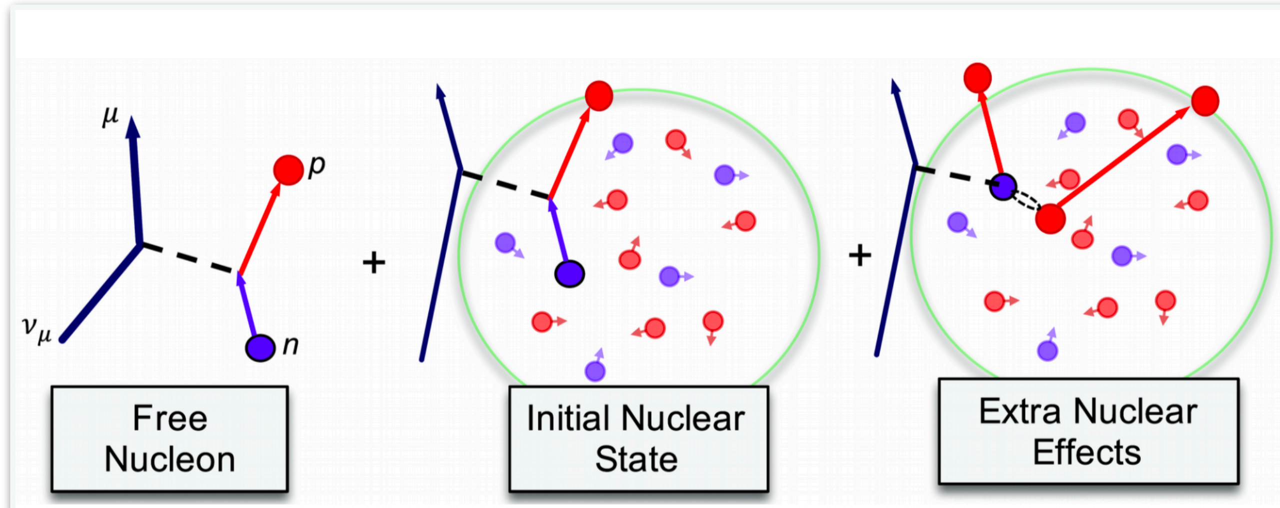
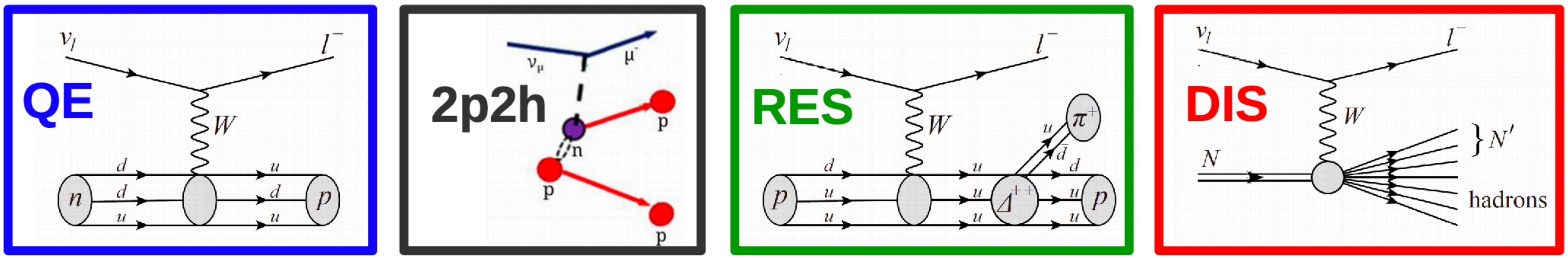
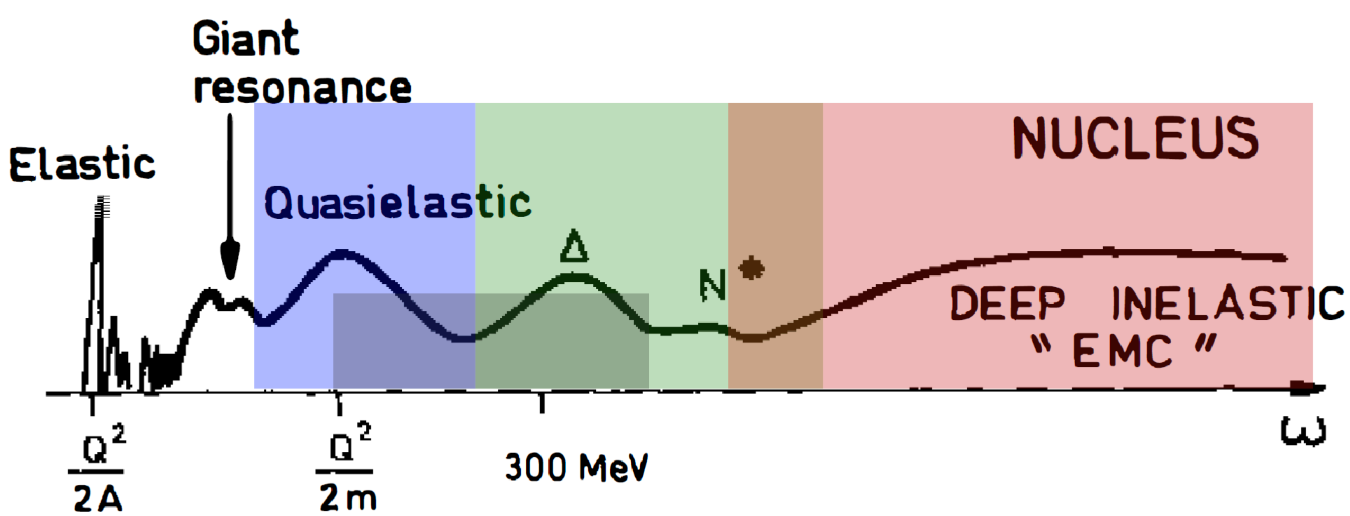






multi-nucleon effects are crucial

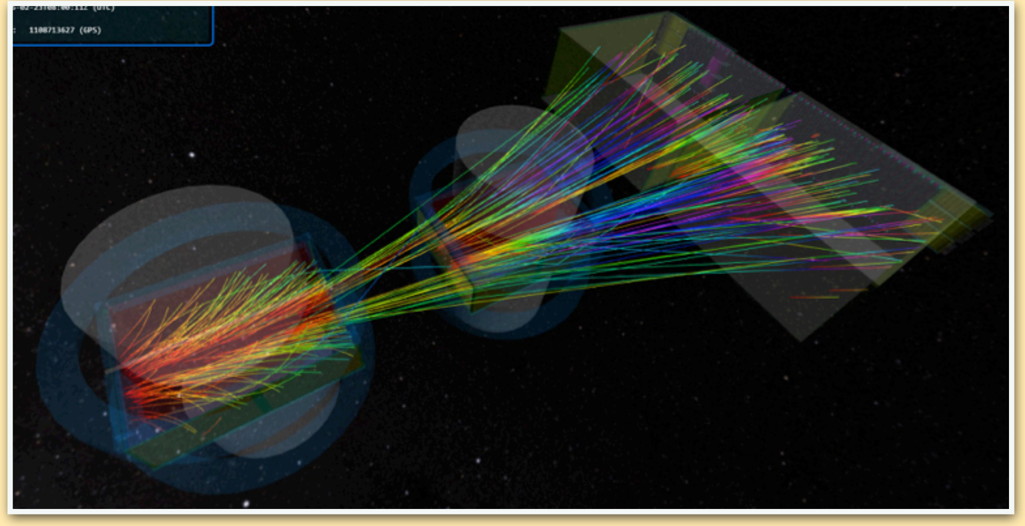
Image Credit: Callum Wilkinson

Systematic Uncertainties

- Large systematic uncertainties in
  - Composition of neutrino beam
  - Neutrino interaction cross sections

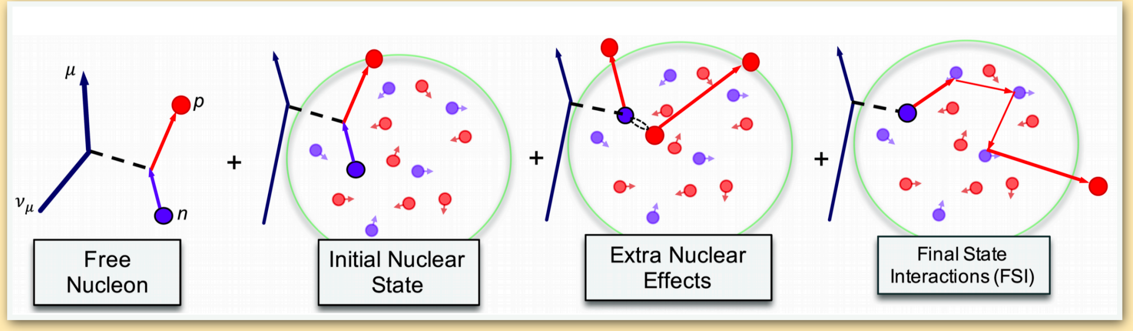
Experimental Mitigation

- near detectors (on-axis and off-axis)
- hadroproduction experiments (e.g. NA61/SHINE)



Theory Needs

- better modelling of neutrino interactions
- new strategies for optimally exploiting near detector data (in particular DUNE-PRISM)



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Challenge 2:
Oscillation Anomalies

Anomalies in Short Baseline Oscillations

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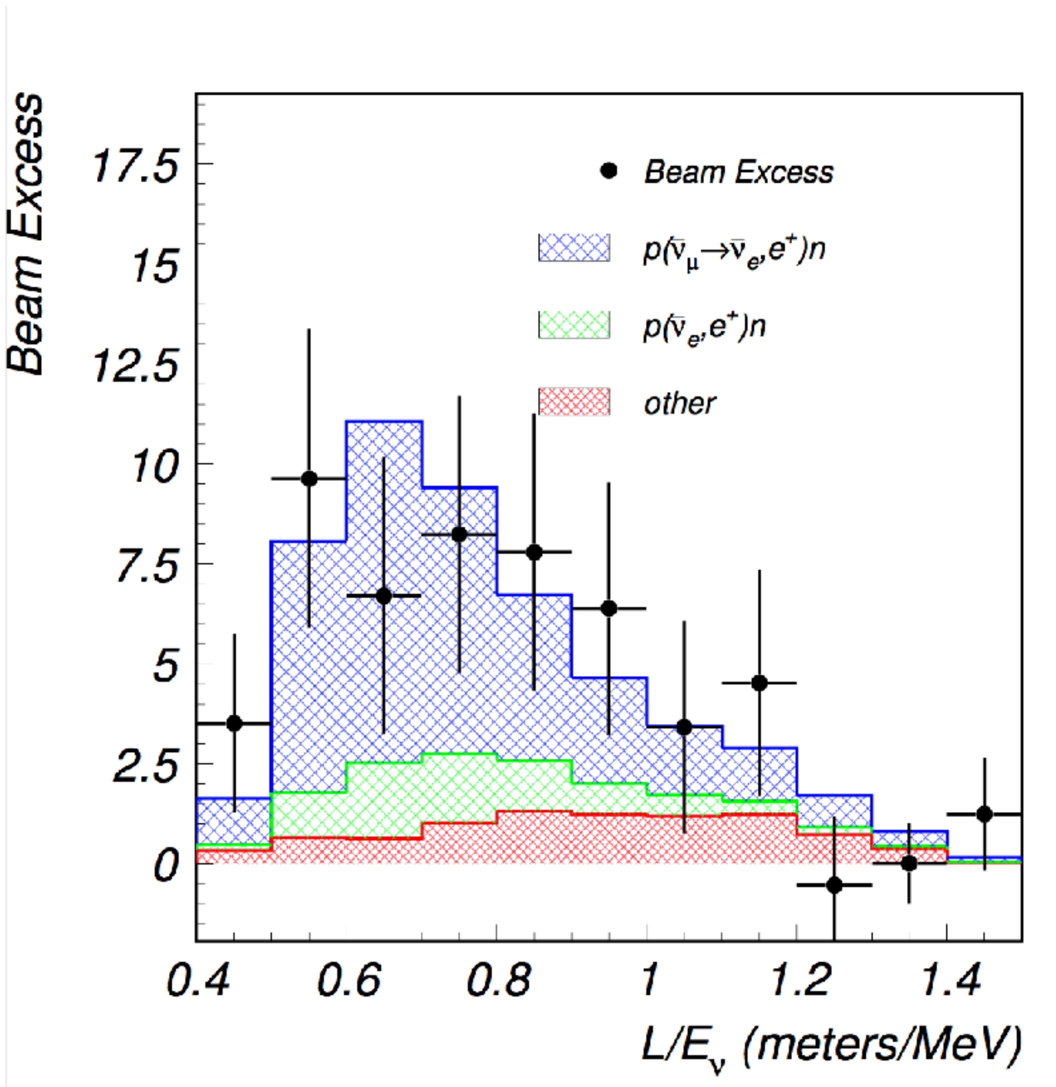
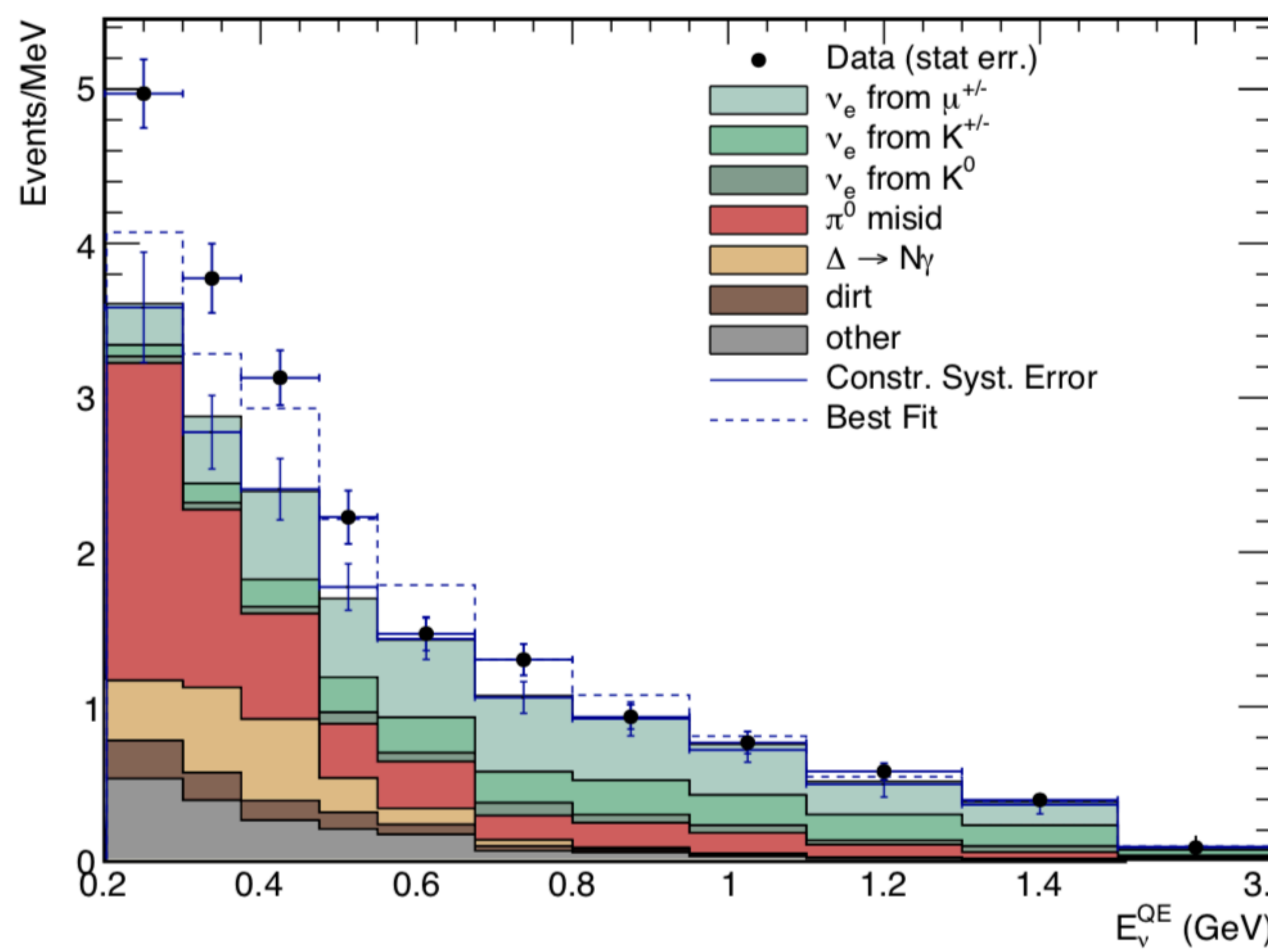
LSND / MiniBooNE: anomalous $\nu_\mu \to \nu_e$ oscillations



LSND 2001

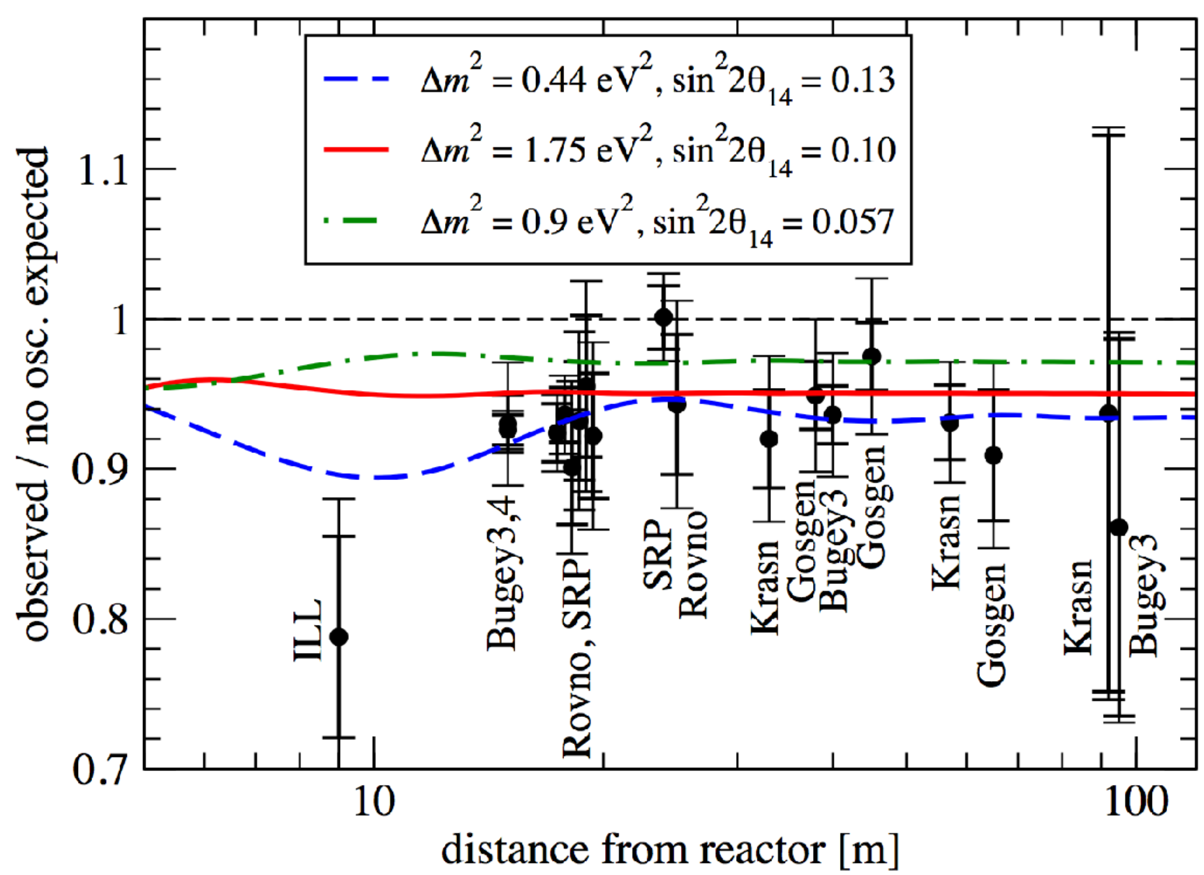


MiniBooNE 2018

Anomalies in Short Baseline Oscillations

- ☑ LSND / MiniBooNE: anomalous $\nu_\mu \to \nu_e$ oscillations
- ☑ Reactor & Gallium Experiments: anomalous ν_e disappearance
  (+ Neutrino-4 ➠ Carlo Rubbia yesterday & Anatolii Serebrov on 25.02.)

Mention et al., 1101.2755
Giunti Laveder, 1006.3244



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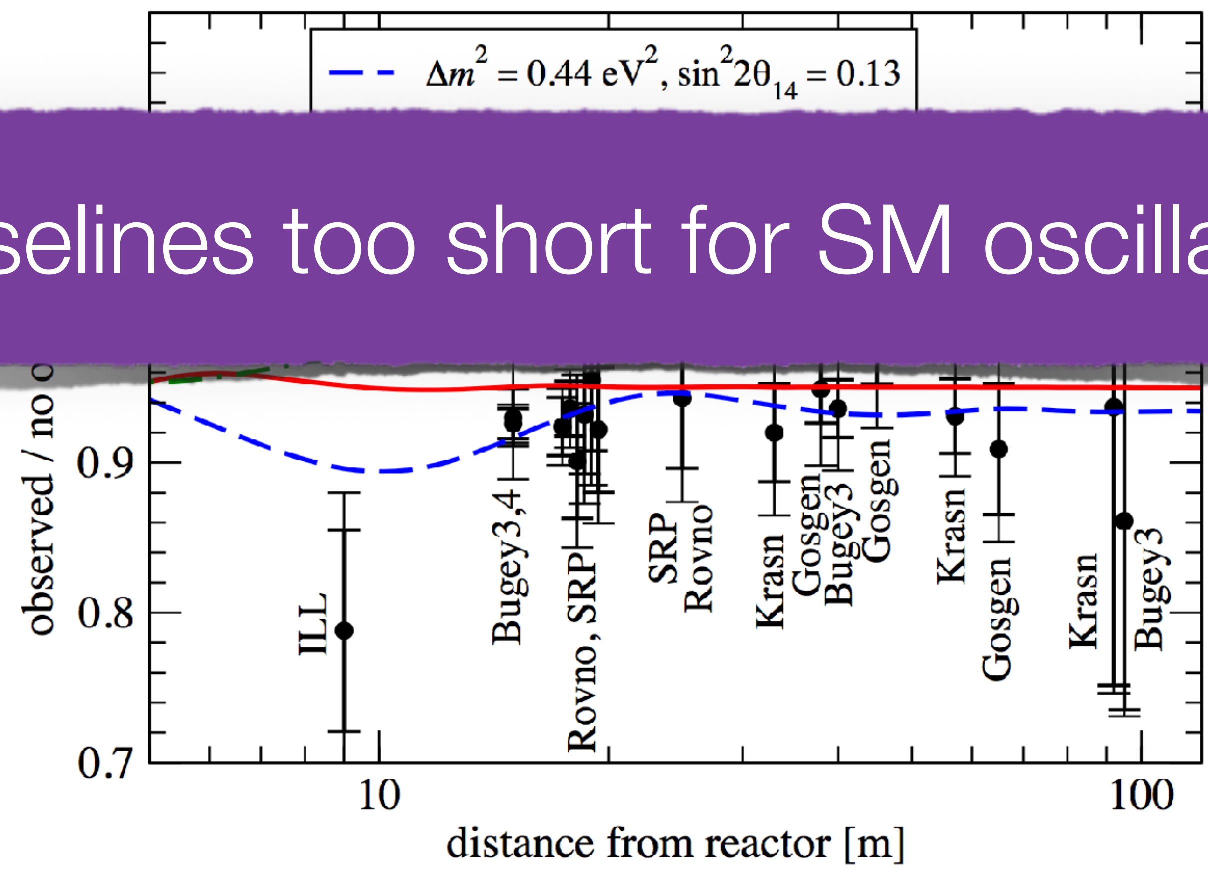


Baselines too short for SM oscillations

Light Sterile Neutrinos?

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

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

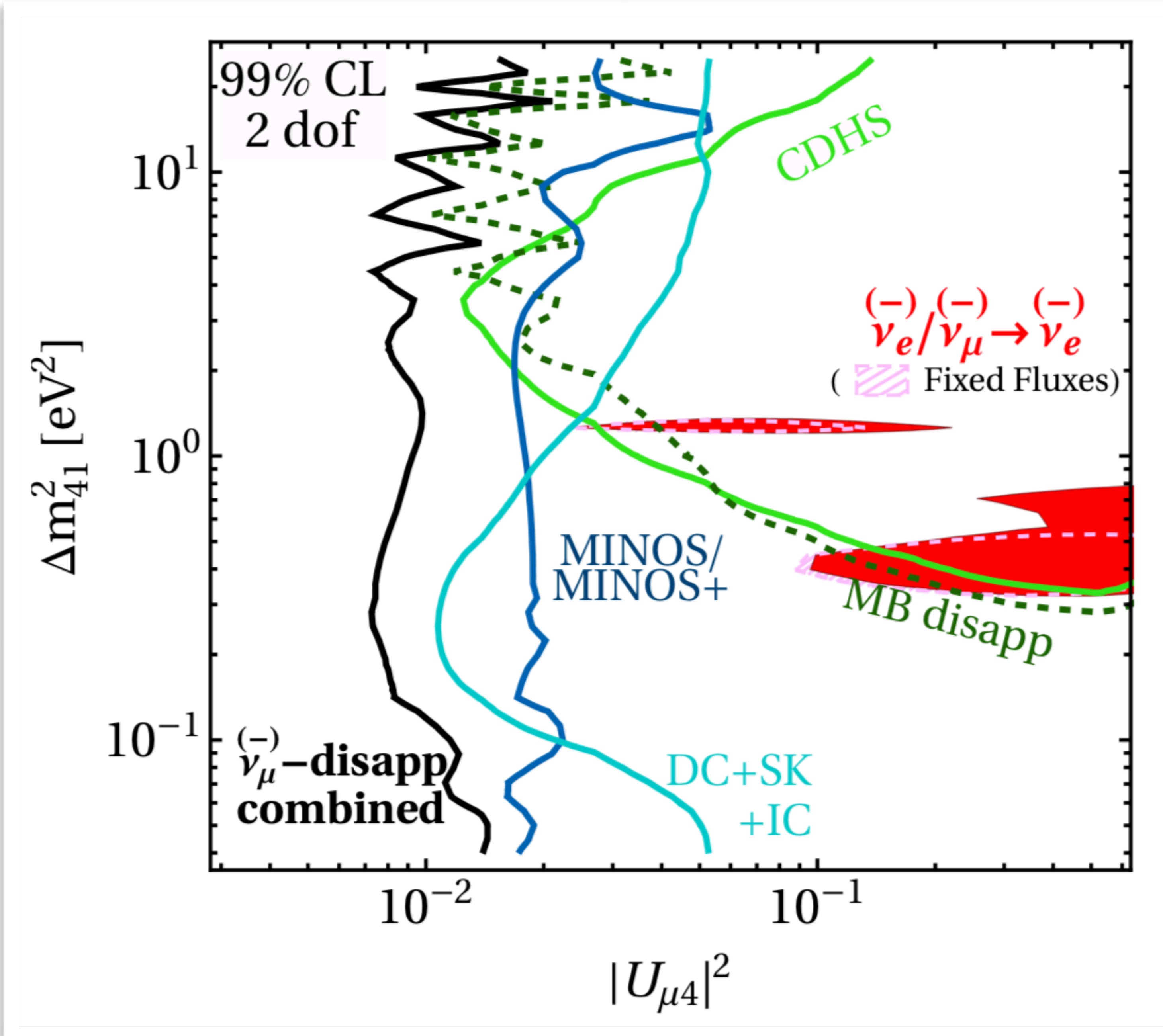
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)$$

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

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

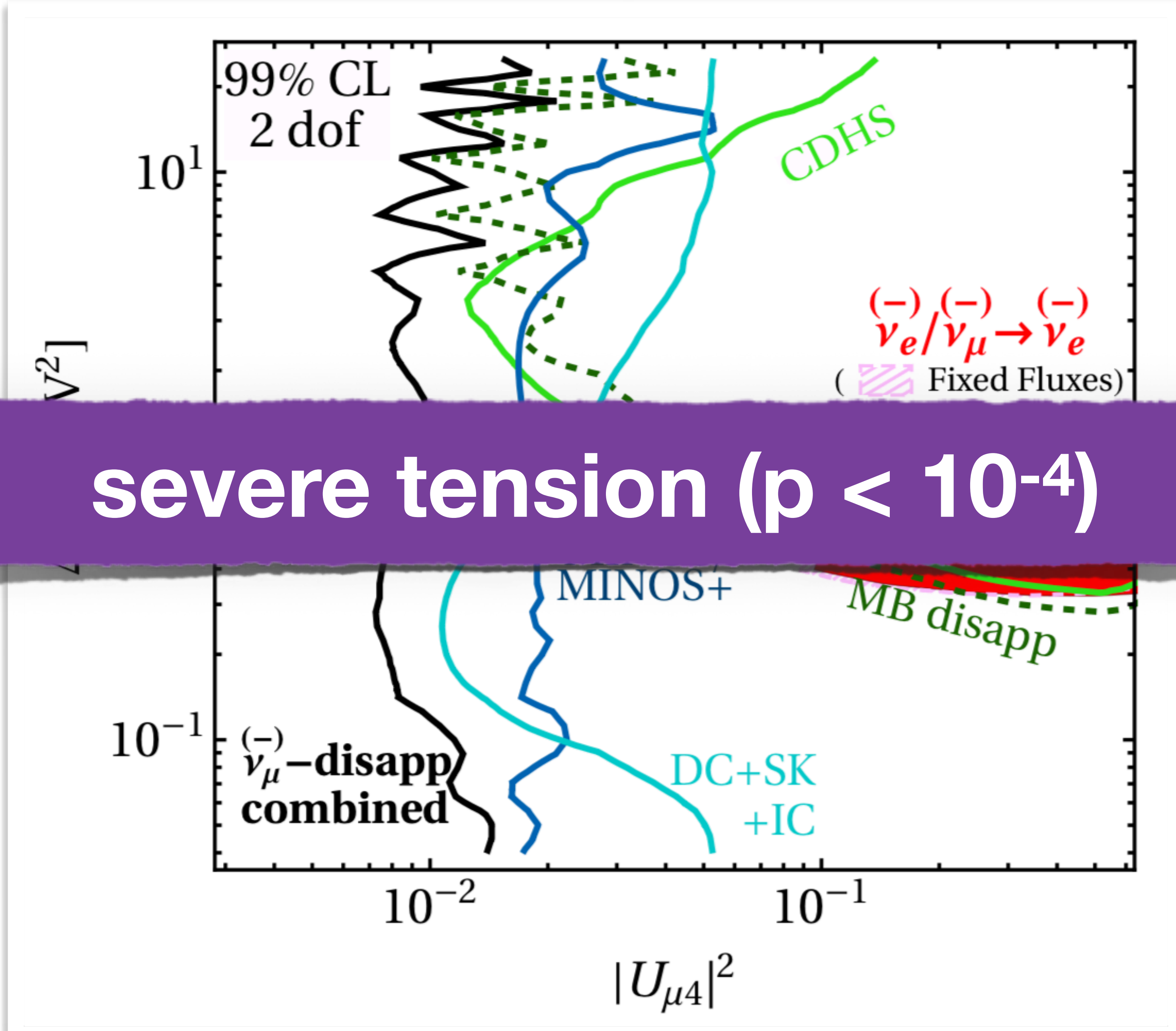
- ☑ Models can be over-constrained.

Global Fit in 3+1 Model



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

Global Fit in 3+1 Model



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

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

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

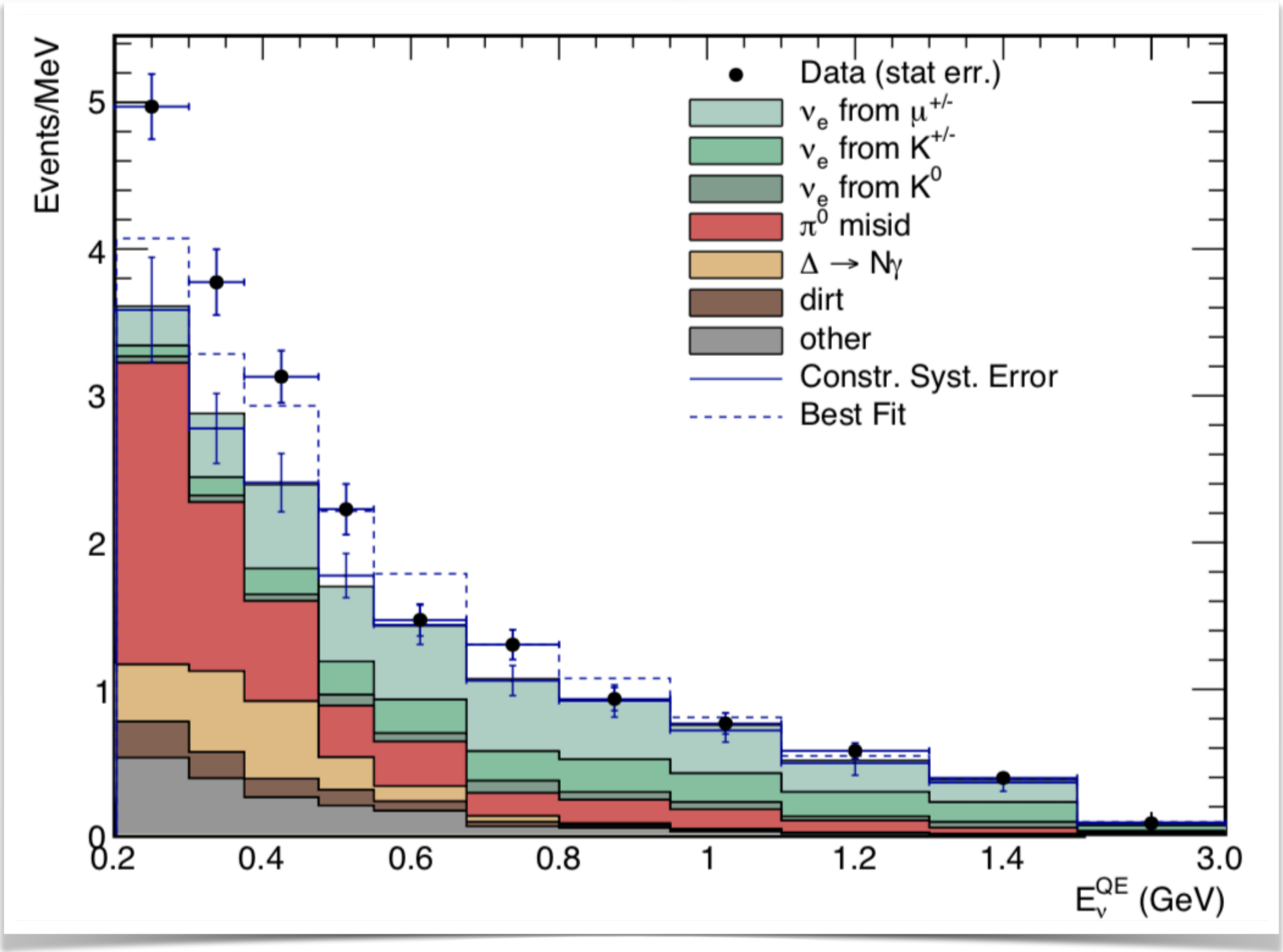
- ☑ Sterile Neutrino production in the detector, followed by
  $\nu_s \to \nu + (A' \to e^+e^-)$ decay (on-shell or off-shell)

  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

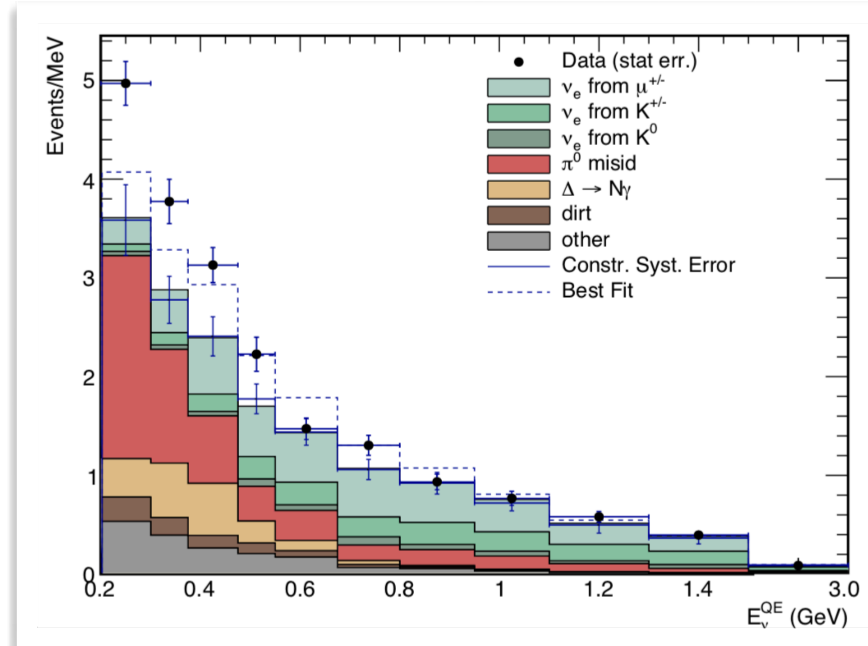
MiniBooNE Backgrounds



MiniBooNE 2018

Δ → γ N

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



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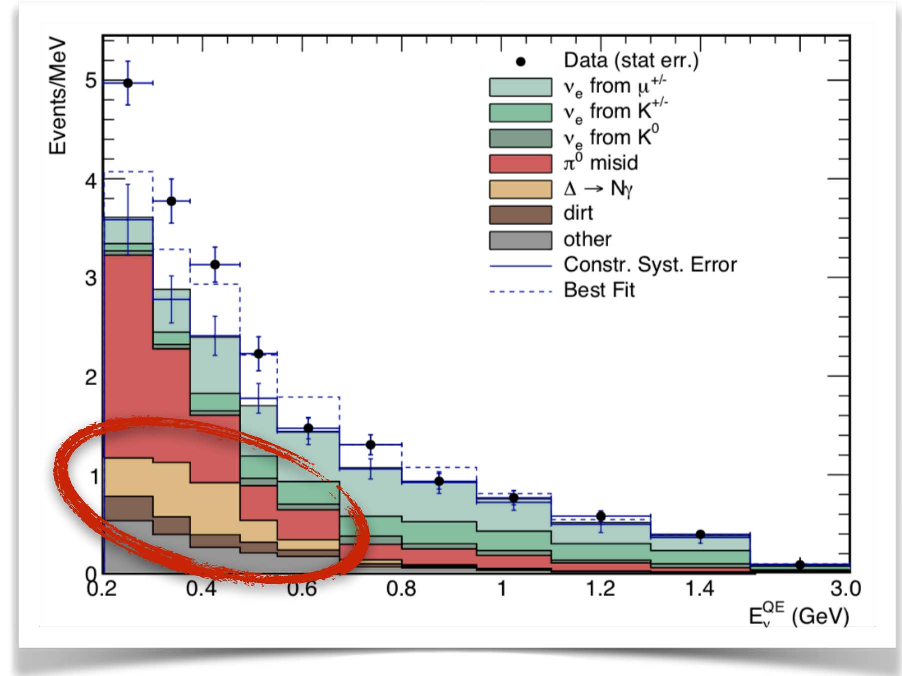
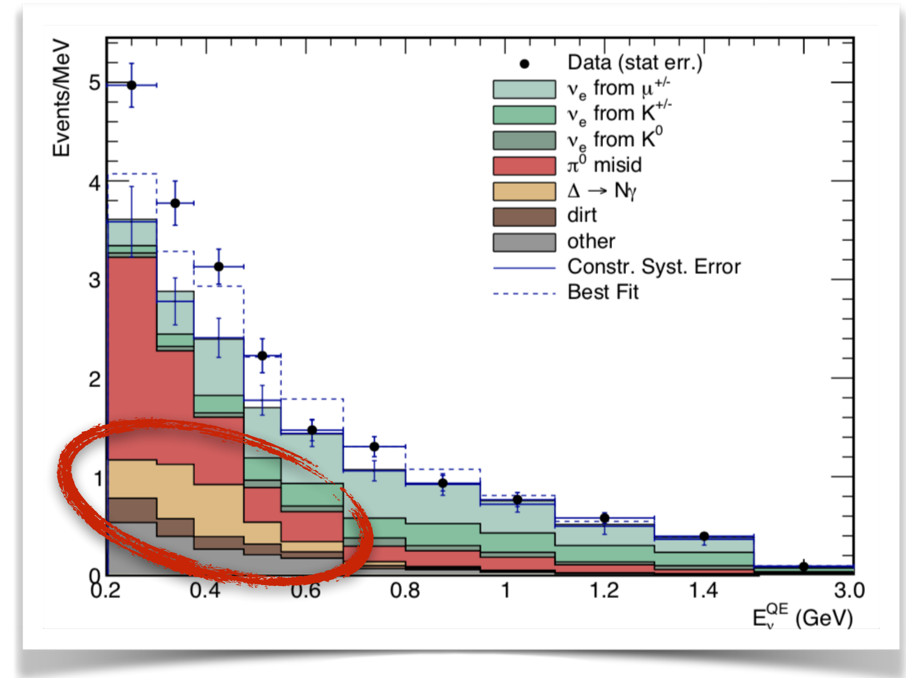


$\Delta \to \gamma N$

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



Ioannisian 1909.08571
Giunti Ioannisian Ranucci 1912.01524

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

To Do List for Neutrino Anomalies

To Do List for Neutrino Anomalies

- ★ scrutinize anomalies for unknown systematics
  (need 4 independent effects!)
- ★ scrutinize also null results!
- ★ extended models?

Challenge 3:
Collective Oscillations

Summa Janka Melson Marek
arXiv:1708.04154

Summa Janka Melson Marek
arXiv:1708.04154

Collective Neutrino Oscillations

- flavor evolution described by von Neumann equation

$$i(\partial_t + \vec{v} \cdot \vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\text{vac}} + H_{\text{MSW}} + H_{\nu\nu},\ \rho_{\vec{r},\vec{p}}]$$

Collective Neutrino Oscillations

- flavor evolution described … ann equation

density matrix
in flavour space

$$i(\partial_t + \vec{v}\cdot\vec{\nabla}_{\vec{r}})\rho_{\vec{r},\vec{p}} = [H_{\rm vac} + H_{\rm MSW} + H_{\nu\nu}, \rho_{\vec{r},\vec{p}}]$$

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vacuum oscillations

$$H_{\mathrm{vac}} = \frac{1}{2E} U_{\mathrm{PMNS}} M^2 U^{\dagger}_{\mathrm{PMNS}}$$

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Collective Neutrino Oscillations

- ☑ flavor evolution described … ann equation

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density matrix
in flavour space

vacuum oscillations

$$H_{\rm vac} = \frac{1}{2E} U_{\rm PMNS} M^2 U^\dagger_{\rm PMNS}$$

matter effects

$$H_{\rm MSW} = \sqrt{2} G_F n_e \begin{pmatrix} 1 & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

Collective Neutrino Oscillations

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density matrix
in flavour space

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self-interactions

$$H_{\nu\nu} = \sqrt{2} G_F \int \frac{d^3 q}{(2\pi)^3} (1 - \cos\theta_{\vec{p}\vec{q}})(\rho_{\vec{r},\vec{q}} - \bar{\rho}_{\vec{r},\vec{q}})$$

Collective Neutrino Oscillations

- flavor evolution described ... ann equation

density matrix
in flavour space

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vacuum oscillations

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- at large n_ν:
  - same equation for all energies ➠ synchronization
  - non-trivial angular dependence
- non-linear equation ➠ all kinds of instabilities

Collective Neutrino Oscillations

- pure Standard Model problem
- solution will be crucial for the next Galactic supernova
- **the neutrinos are already on their way**

Challenge 4:
New ν Physics

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

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

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

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New Neutrino Interaction

dim-6 operators

- EFT below the electroweak scale

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

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

☑ NC: non-standard matter effects

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

New Neutrino Interaction

dim-6 operators

☑ EFT below the electroweak scale

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

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

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

☑ NC: non-standard matter effects

☑ CC: anomalous production and detection

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$$\mathcal{L}_{\mathrm{NSI,CC}} = \sum_{f,f',\alpha,\beta} 2\sqrt{2} G_F \varepsilon^{ff',P}_{\alpha\beta} (\bar\nu_\alpha \gamma_\mu P_L \ell_\beta$$

not covered by EFT:

- ☑ light sterile neutrinos
- ☑ magnetic moments
- ☑ "secret" interactions
- ☑ neutrino–DM interactions
- ☑ …

see talks by Christina **Benso**, Sabya Sachi **Chatterjee**, Pilar **Coloma**, Matheus **Hostert**, Patrick **Huber**, Filipe **Joaquim**, Thierry **Lasserre**, Ninetta **Saviano**, Anatolii **Serebrov**, Jian **Tang**, Seok-Gyeong **Yoon**, Yiyu **Zhang**, …

- ☑ NC: non-standard matter effects
- ☑ CC: anomalous production and detection

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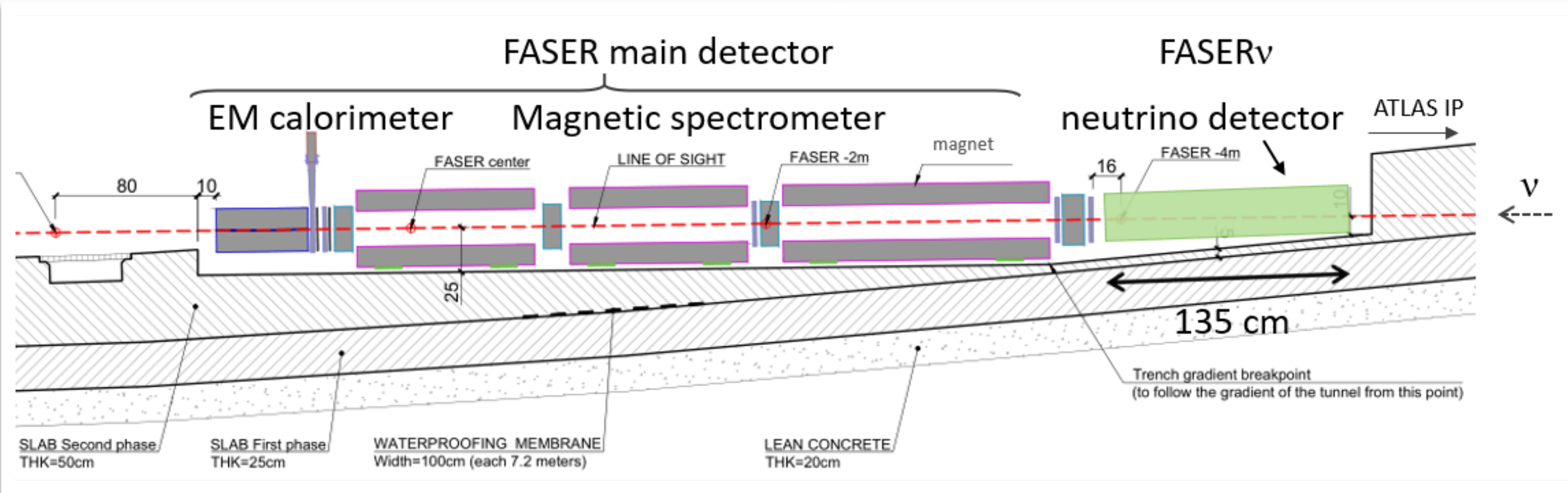
Anomalous Charged Currents

☑ Interesting new opportunity: FASERν at the LHC



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

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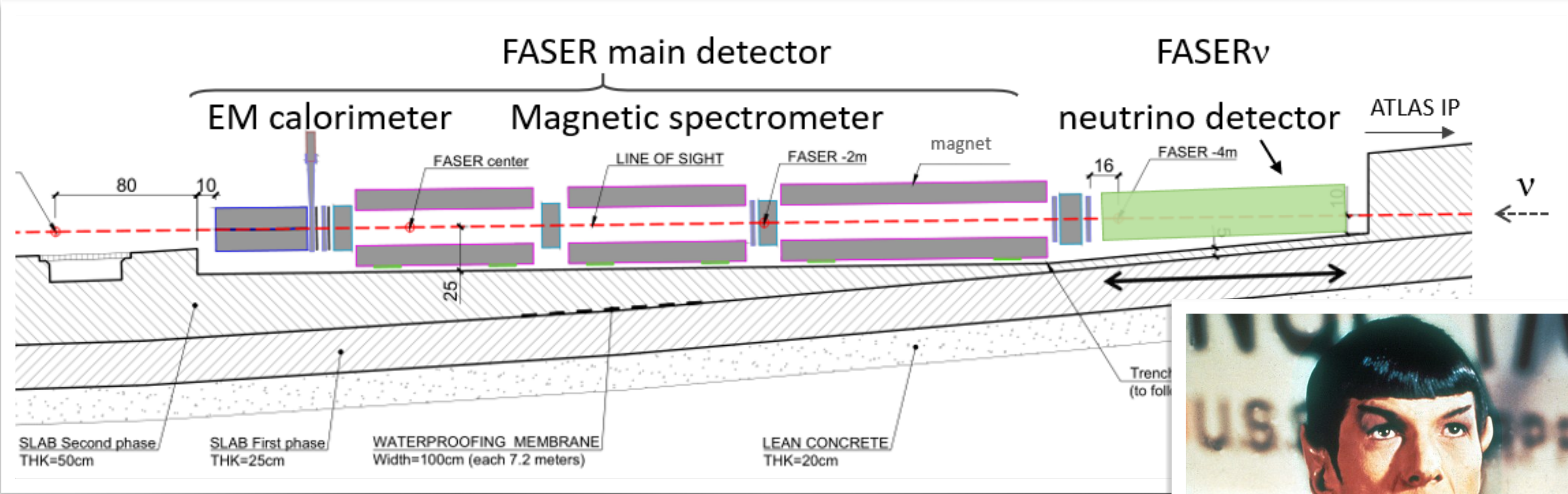

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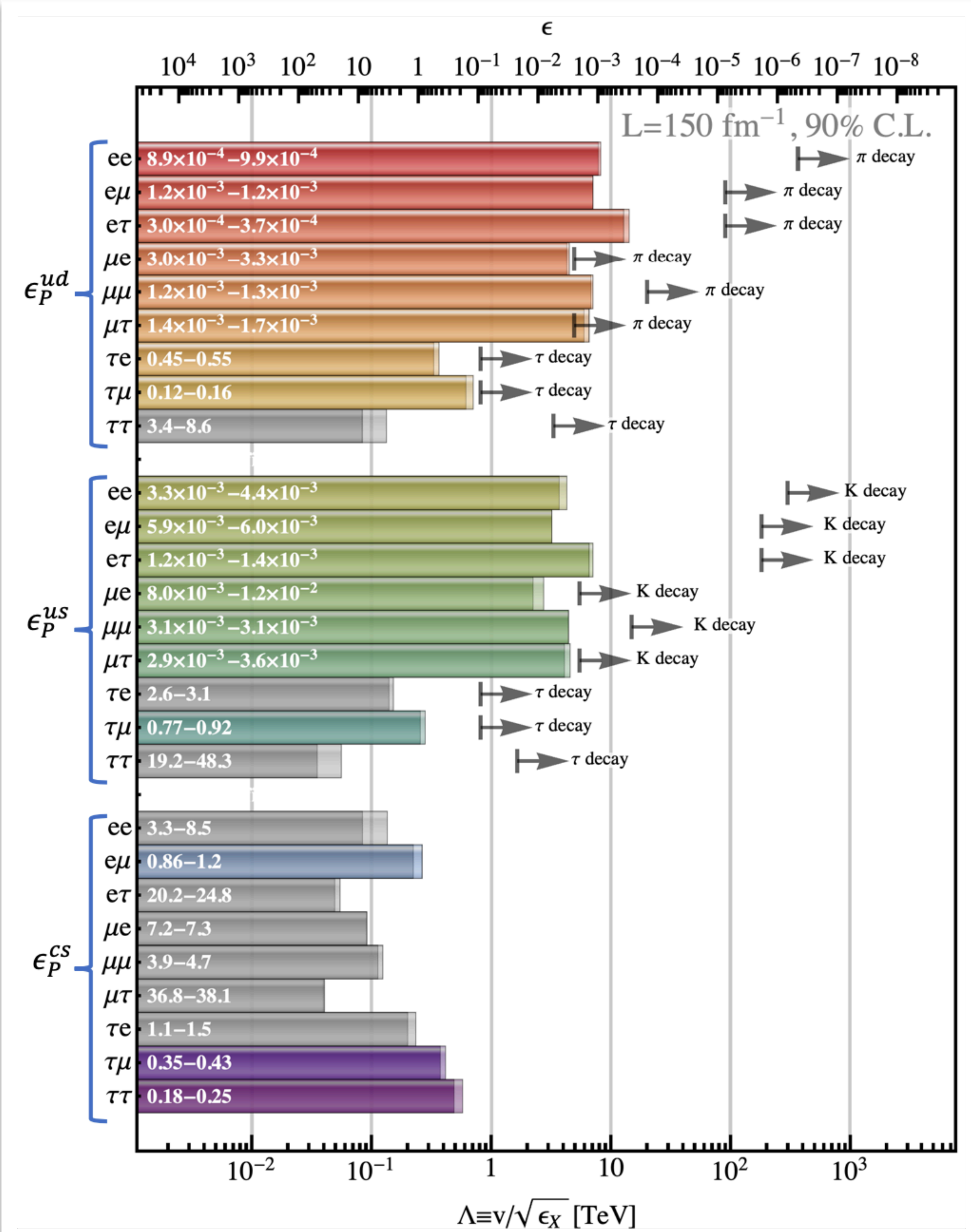
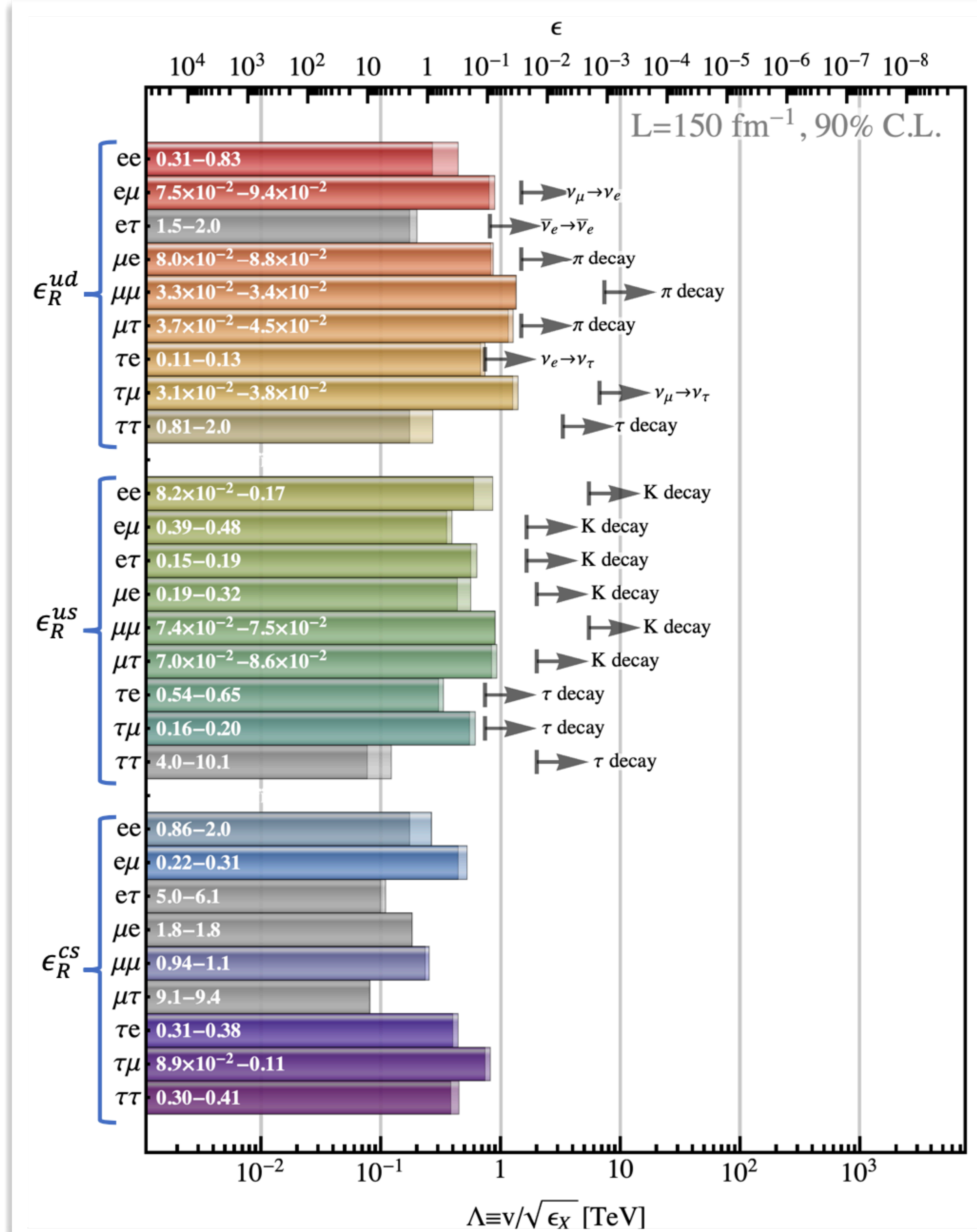


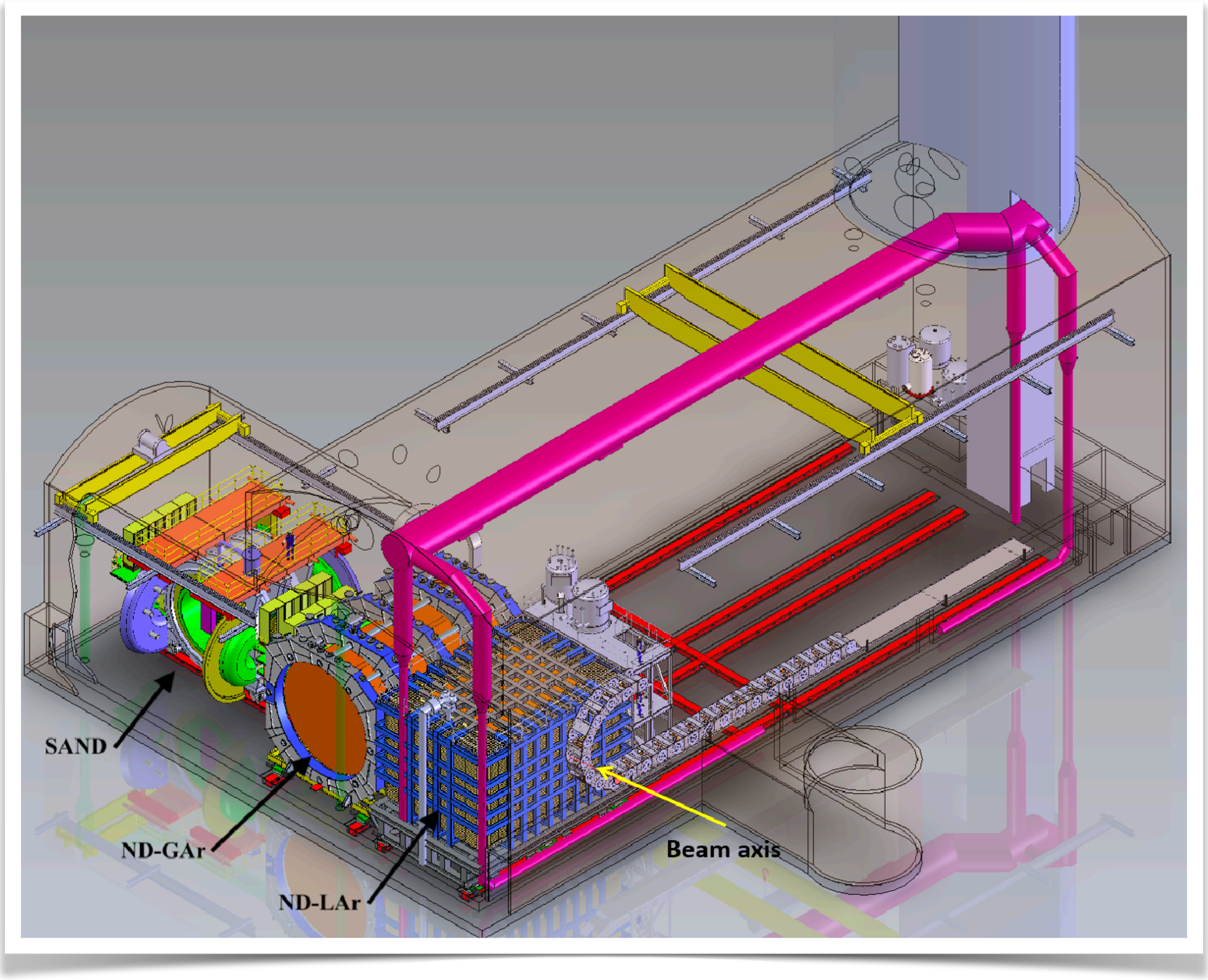


Falkowski Gonzalez-Alonso
JK Soreq Tabrizi, *in preparation*

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

☑ yes, in some cases ➠ see backup slides

New Physics at Near Detectors



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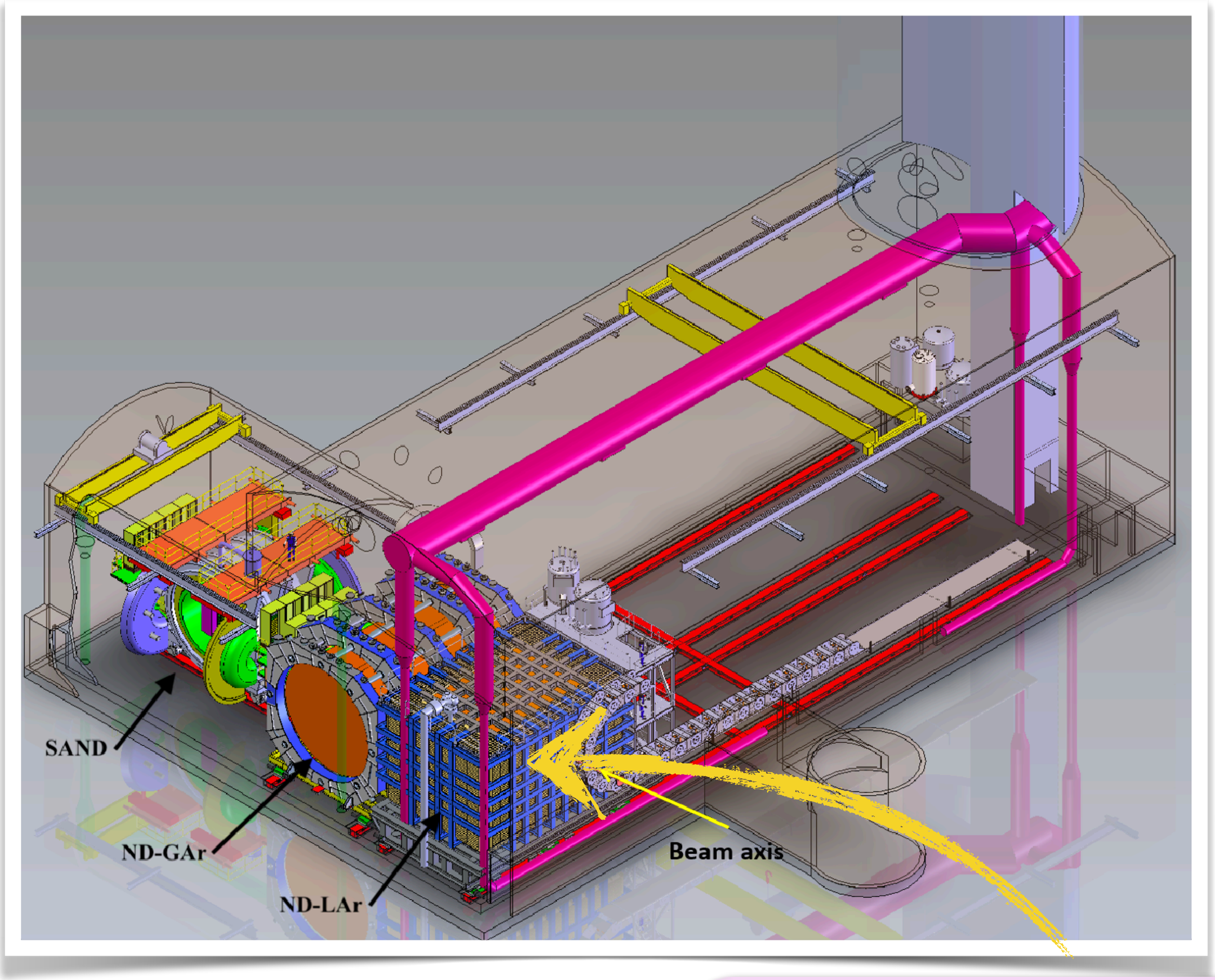
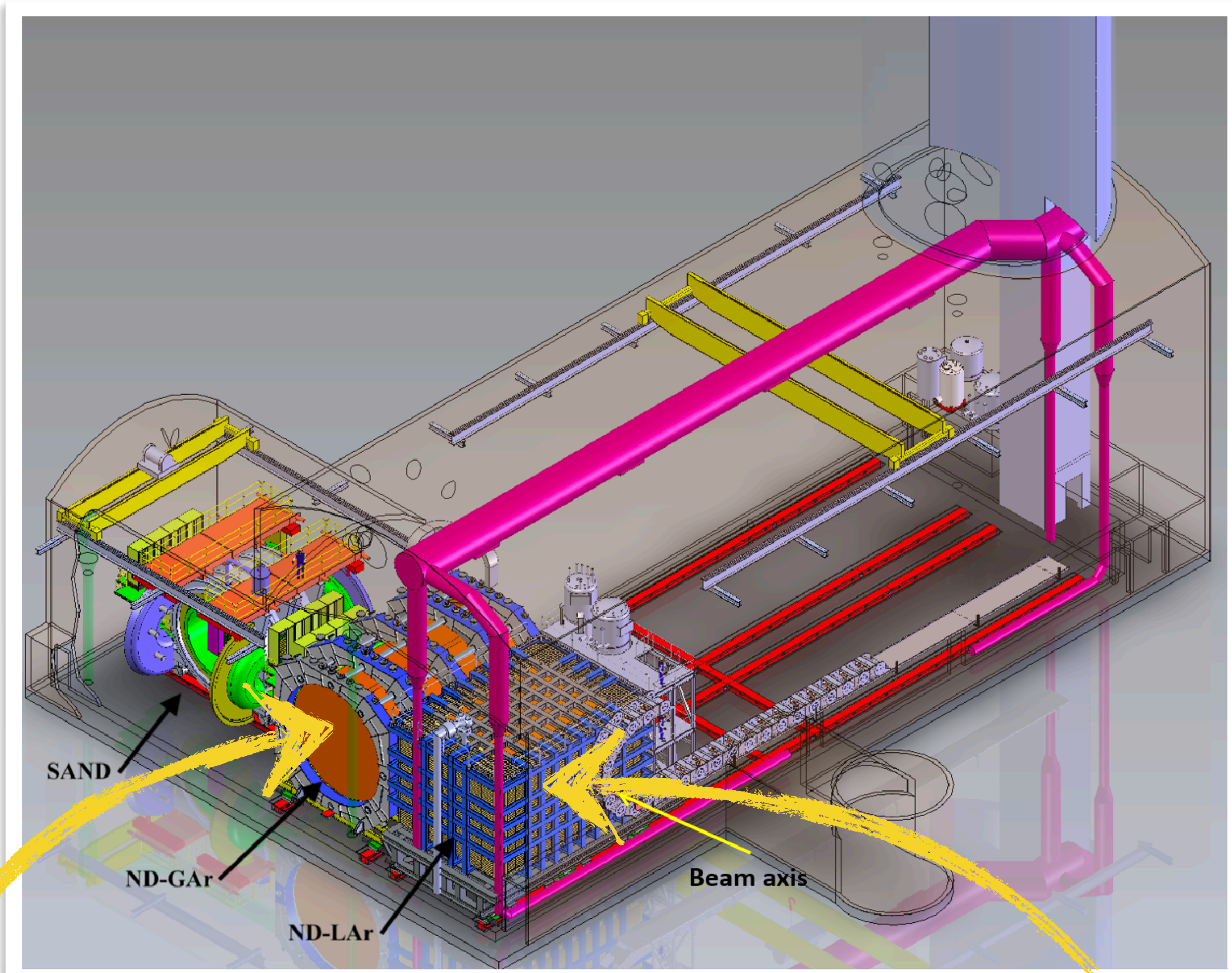


Liquid Argon TPC (“ND-LAr”)

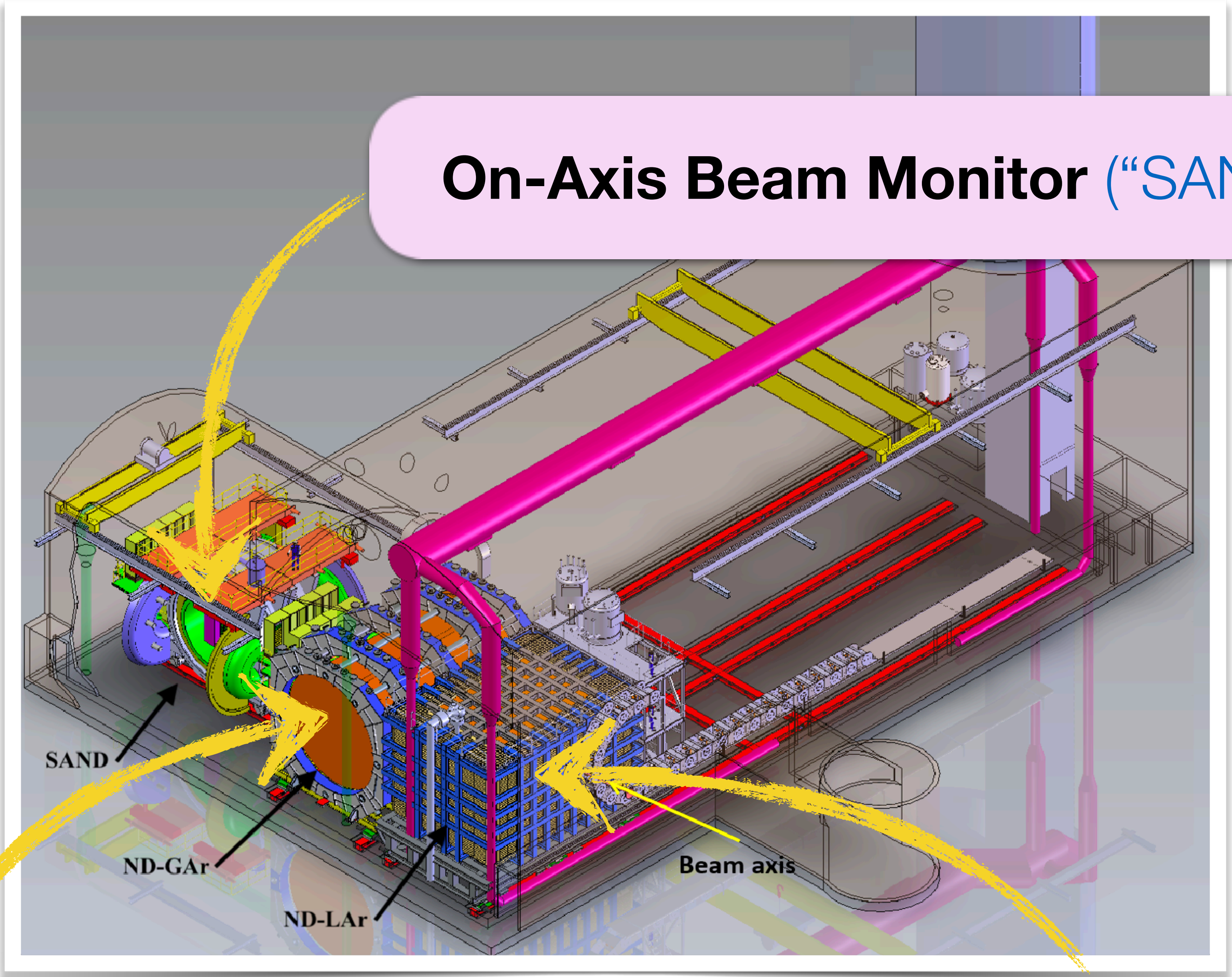
New Physics at Near Detectors



HP Gas TPC + ECal ("ND-GAr")

Liquid Argon TPC ("ND-LAr")

New Physics at Near Detectors



On-Axis Beam Monitor ("SAND")

HP Gas TPC + ECal ("ND-GAr")

Liquid Argon TPC ("ND-LAr")

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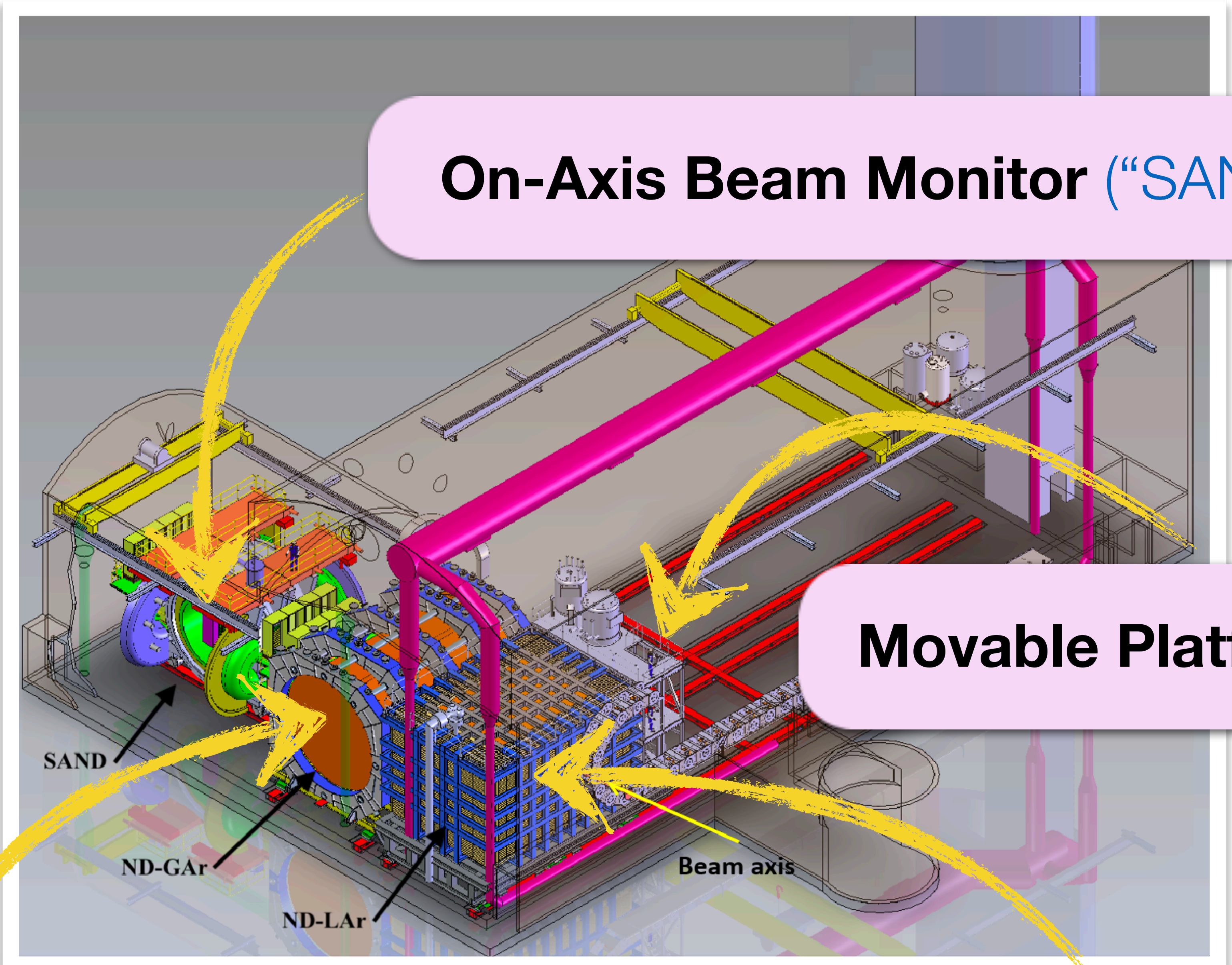
New Physics at Near Detectors



On-Axis Beam Monitor ("SAND")

Movable Platform ("PRISM")

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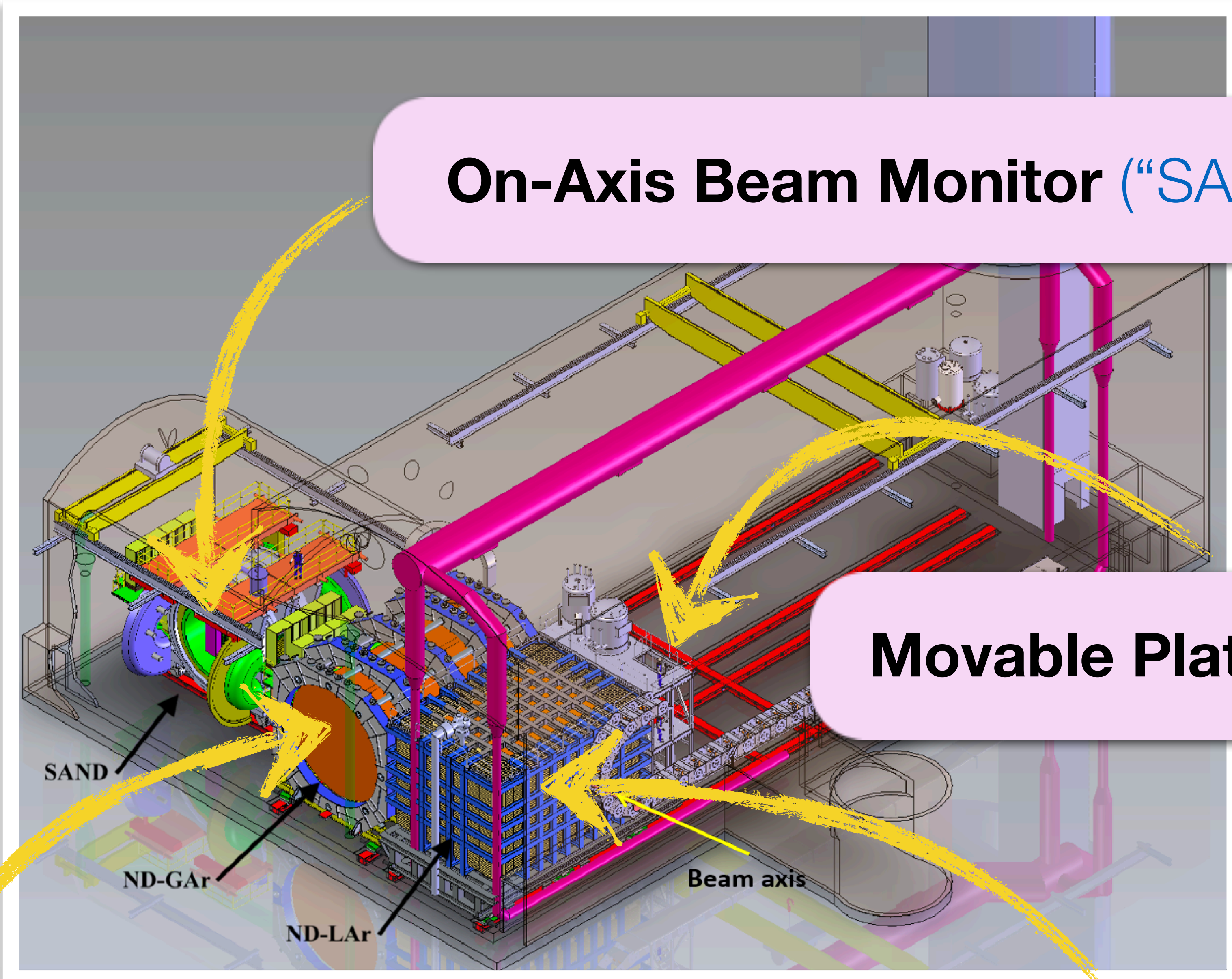


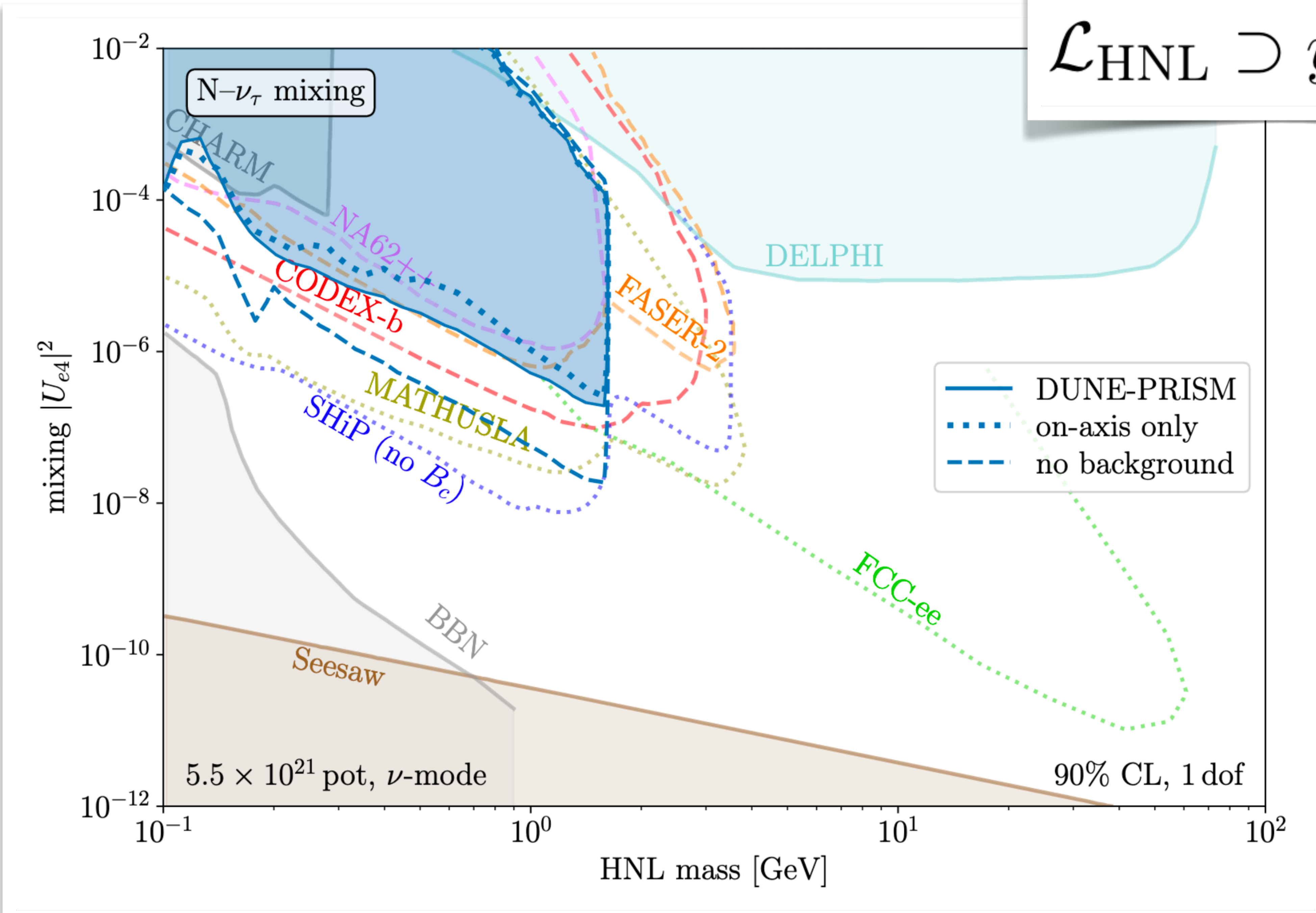
On-Axis Beam Monitor ("SAND")

Movable Platform ("PRISM")

HP Gas TPC + ECal ("SEASIDE")
(**S**ystem of **E**vaporated **A**rgon for **S**ystematics, **I**nteractions, and **D**etailed **E**vent Topologies)

Liquid Argon TPC ("LAGOON")
(**L**iquid **A**rgon **G**adget for **O**n-axis and **O**ff-axis **N**eutrinos

Example: Heavy Neutral Leptons



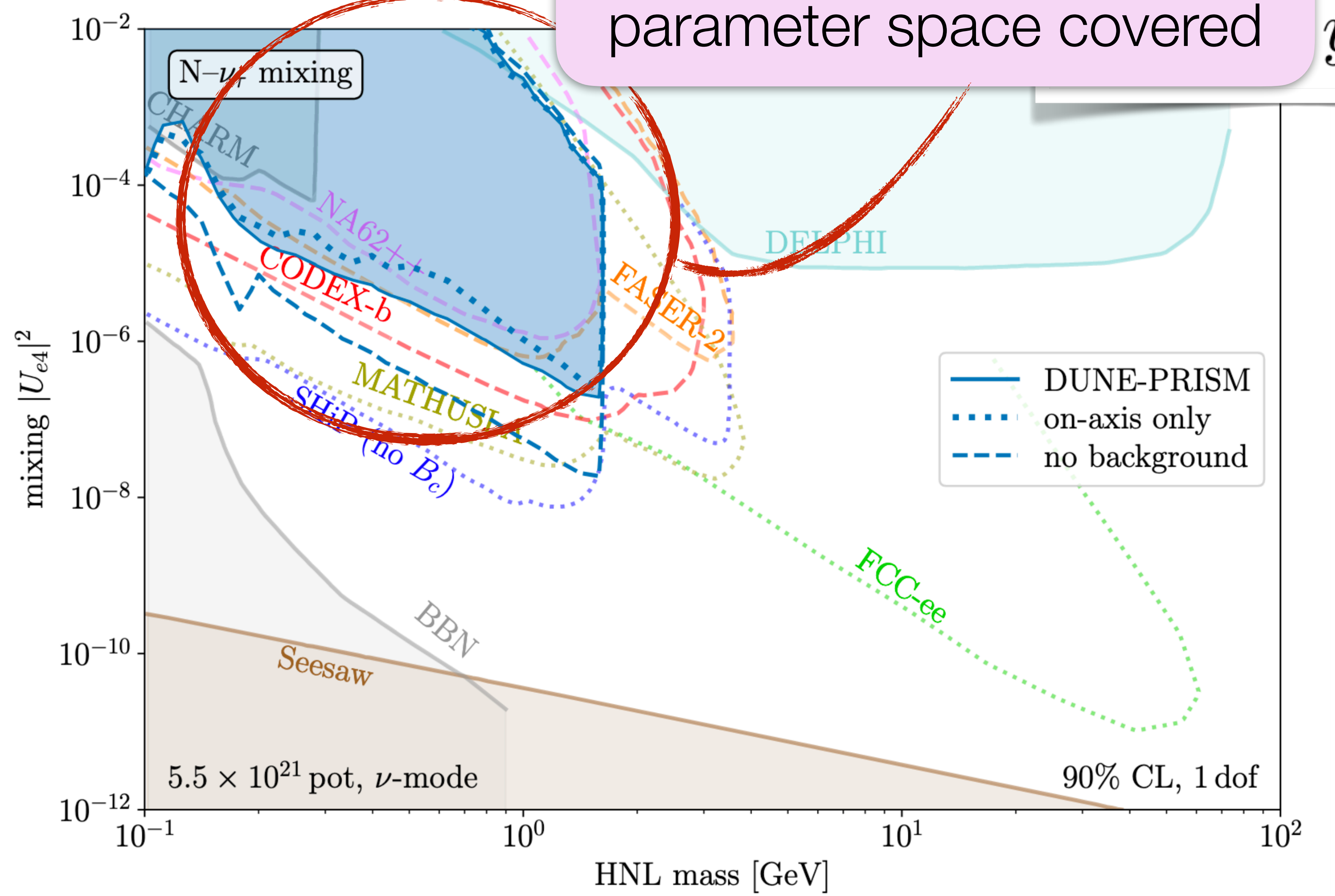
$$\mathcal{L}_{\text{HNL}} \supset y \bar{L} \tilde{H} N$$

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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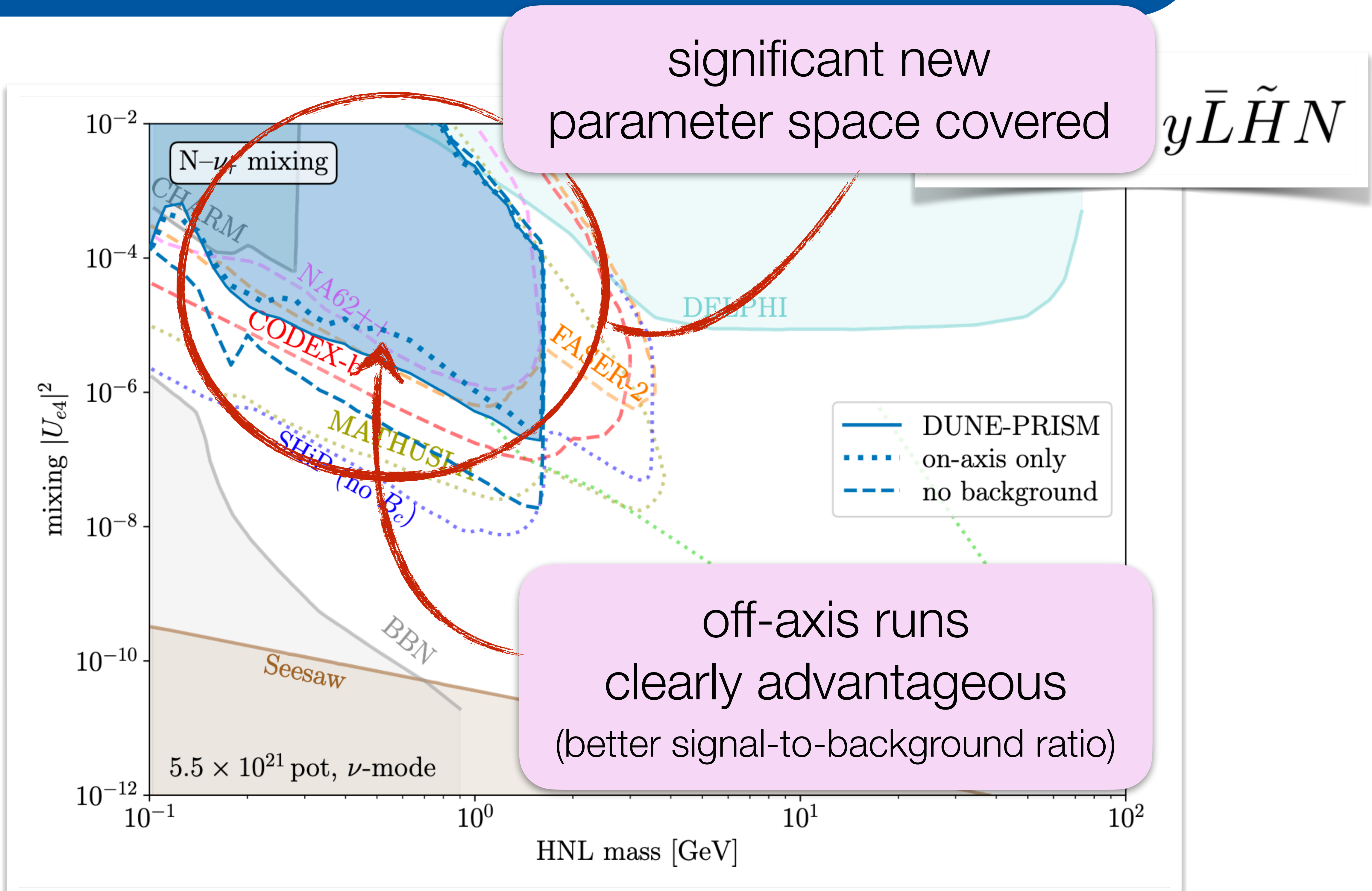

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New ν Physics

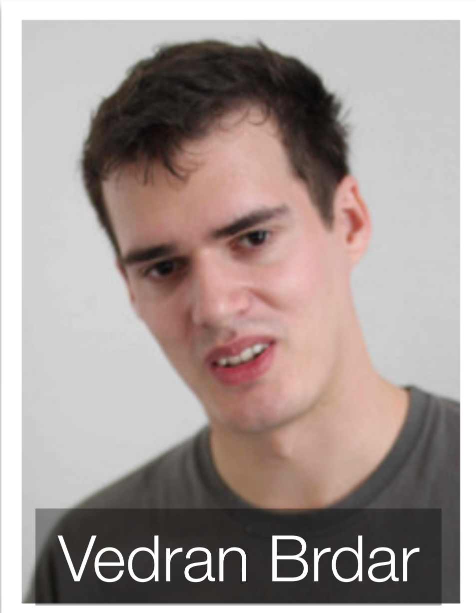
- ★ Need to fully explore the potential of upcoming experiments for BSM Physics
- ★ These are not single-purpose detectors any more, but **multi-purpose facilities** — much like the LHC

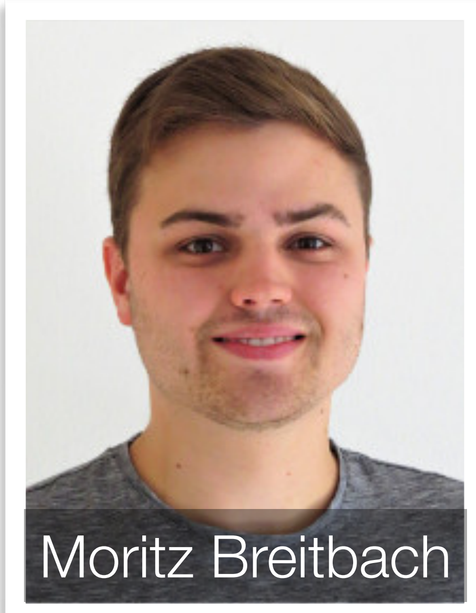
Summary

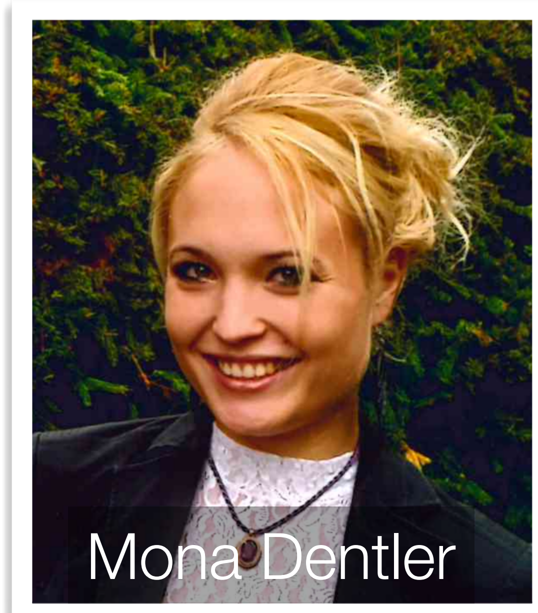
Summary

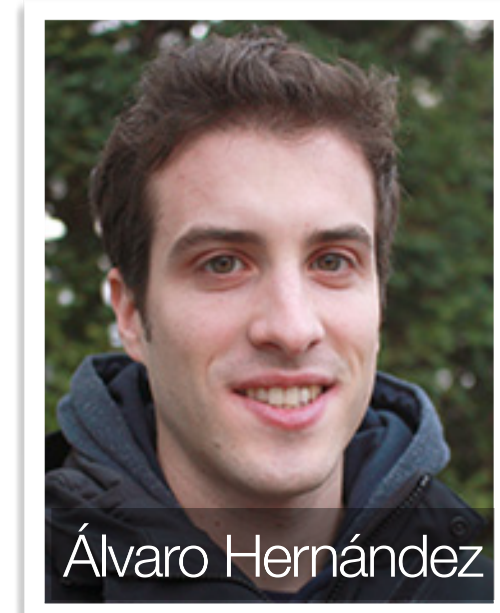
- ☑ Challenge 1: Understanding Neutrino Interactions
- ☑ Challenge 2: Oscillation Anomalies
- ☑ Challenge 3: Collective Oscillations
- ☑ Challenge 4: “New ν Physics”
- ☑ Summary

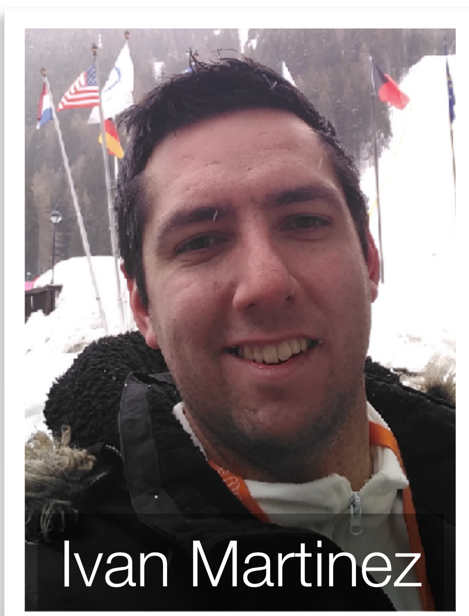
Thank You!

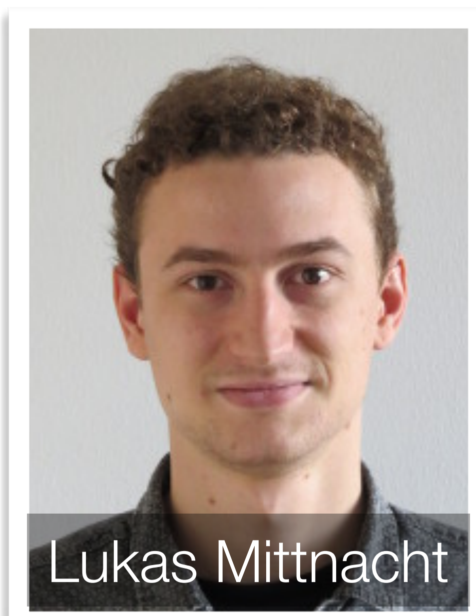












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Bonus Slides

Neutrino Interactions

Neutrino Event Generators

Phenomenological

- different physics models for different kinematic regimes (smooth transitions in between)
- separation between ν-nucleon interaction, final state interactions, etc.
- tuneable to data
- but theoretically inconsistent
- e.g. GENIE, NuWro

First Principles

- unified theoretical framework (quantum transport equations for baryons & mesons)
- theoretically consistent
- not easily unable to data
- e.g. GiBUU

Image Credit: NA61/SHINE; Callum Wilkinson

Neutrino Event Generators

Phenomenological

- different physics models for different kinematic regimes (smooth transitions in between)
- separat
  interact
  interact
- tuneab
- but theoretically inconsistent
- e.g. GENIE, NuWro

First Principles

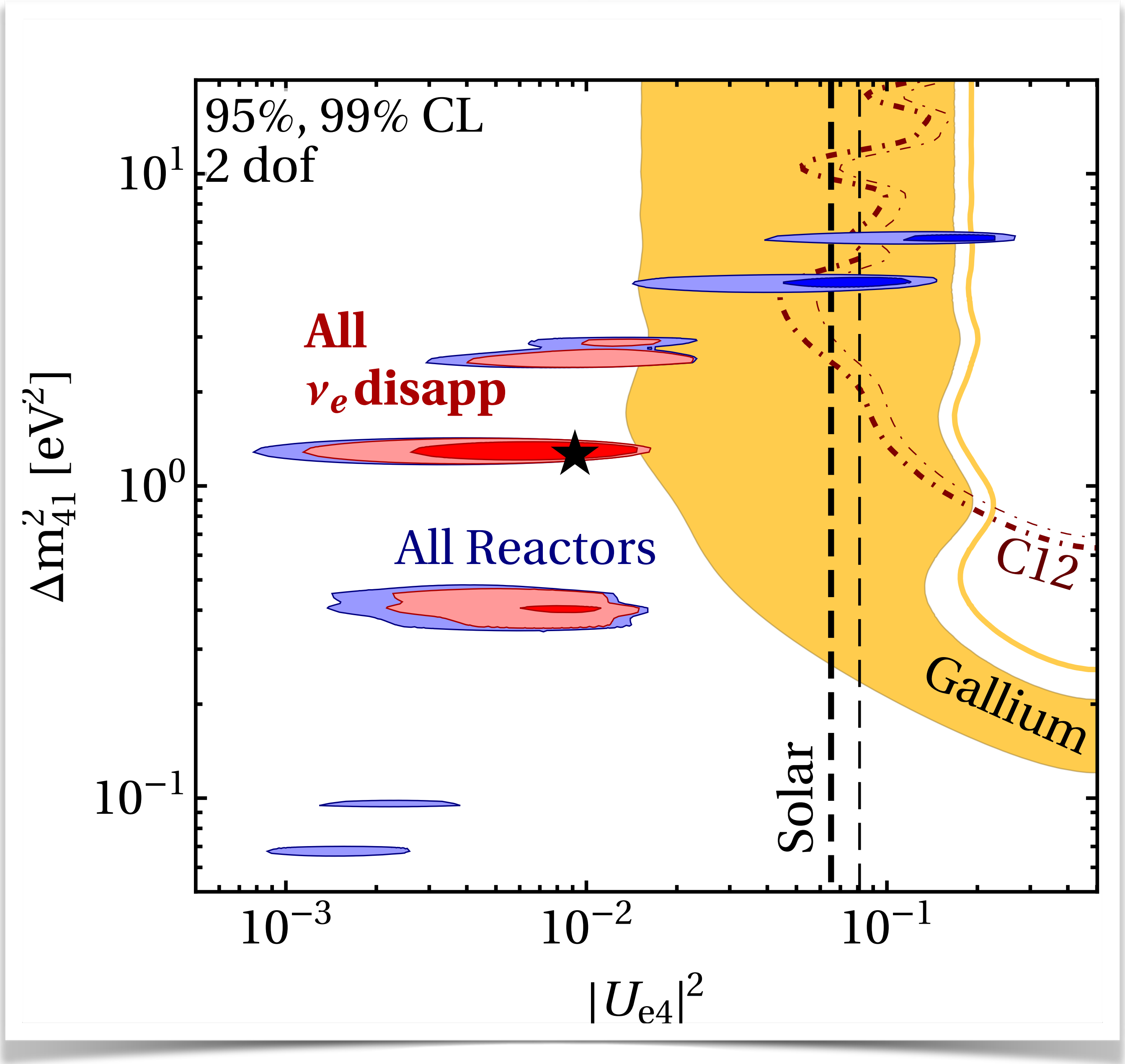
- unified theoretical framework (quantum transport equations for baryons & mesons)
- nt
  data

both approaches need to be pursued further and improved

Image Credit: NA61/SHINE; Callum Wilkinson

Oscillation Anomalies

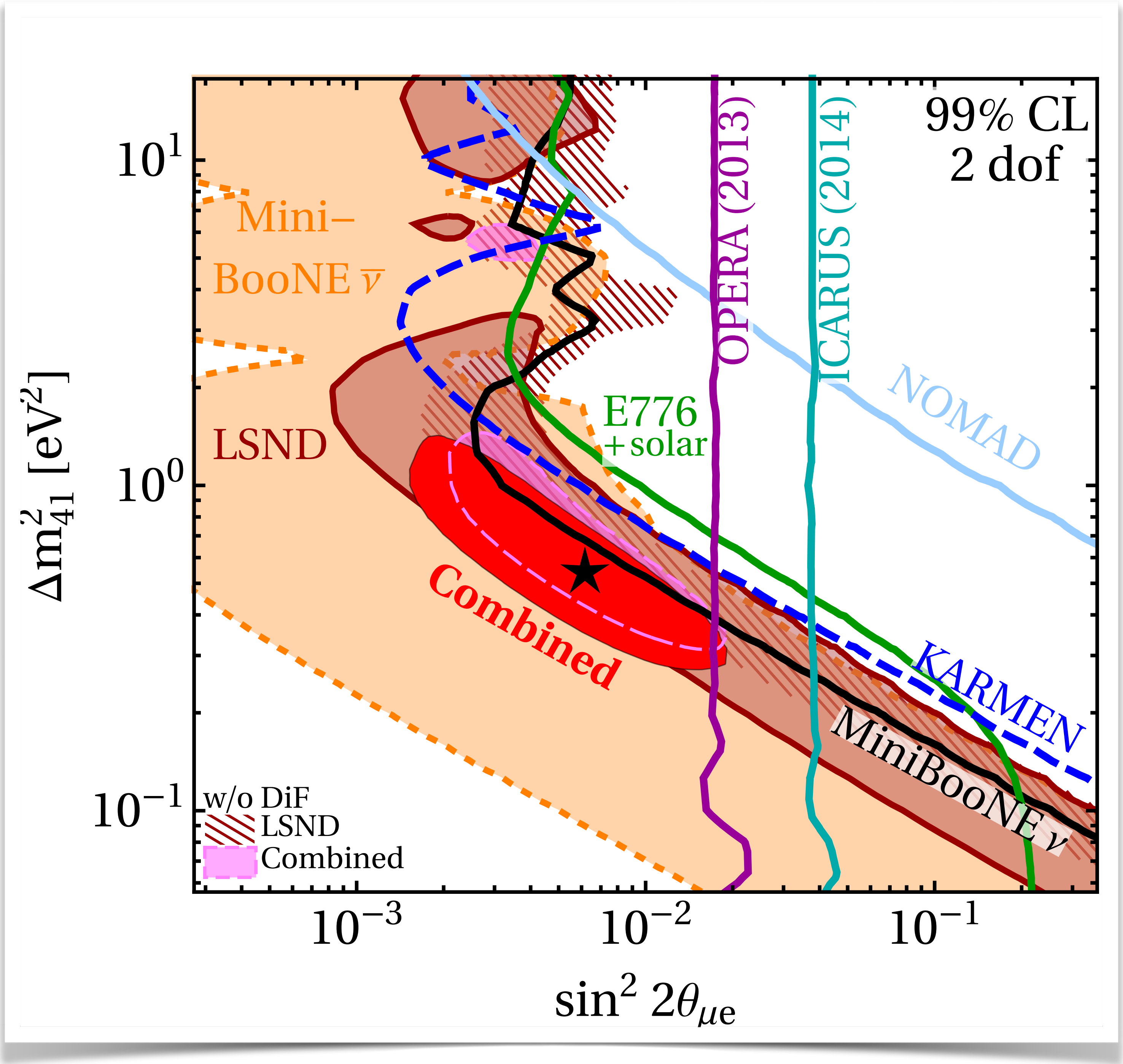
Global Fit to ν_e and $\bar{\nu}_e$ Disappearance



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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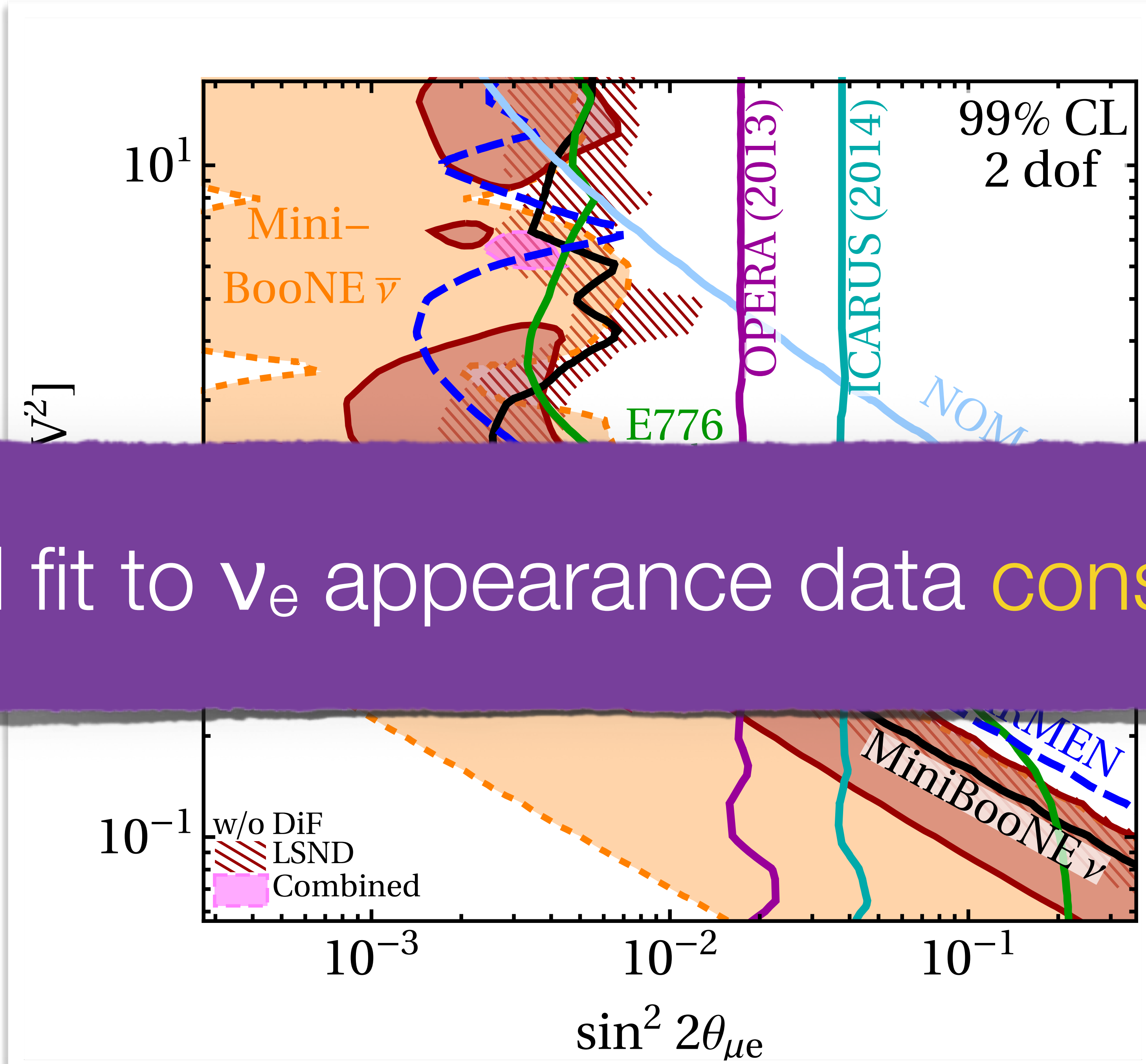
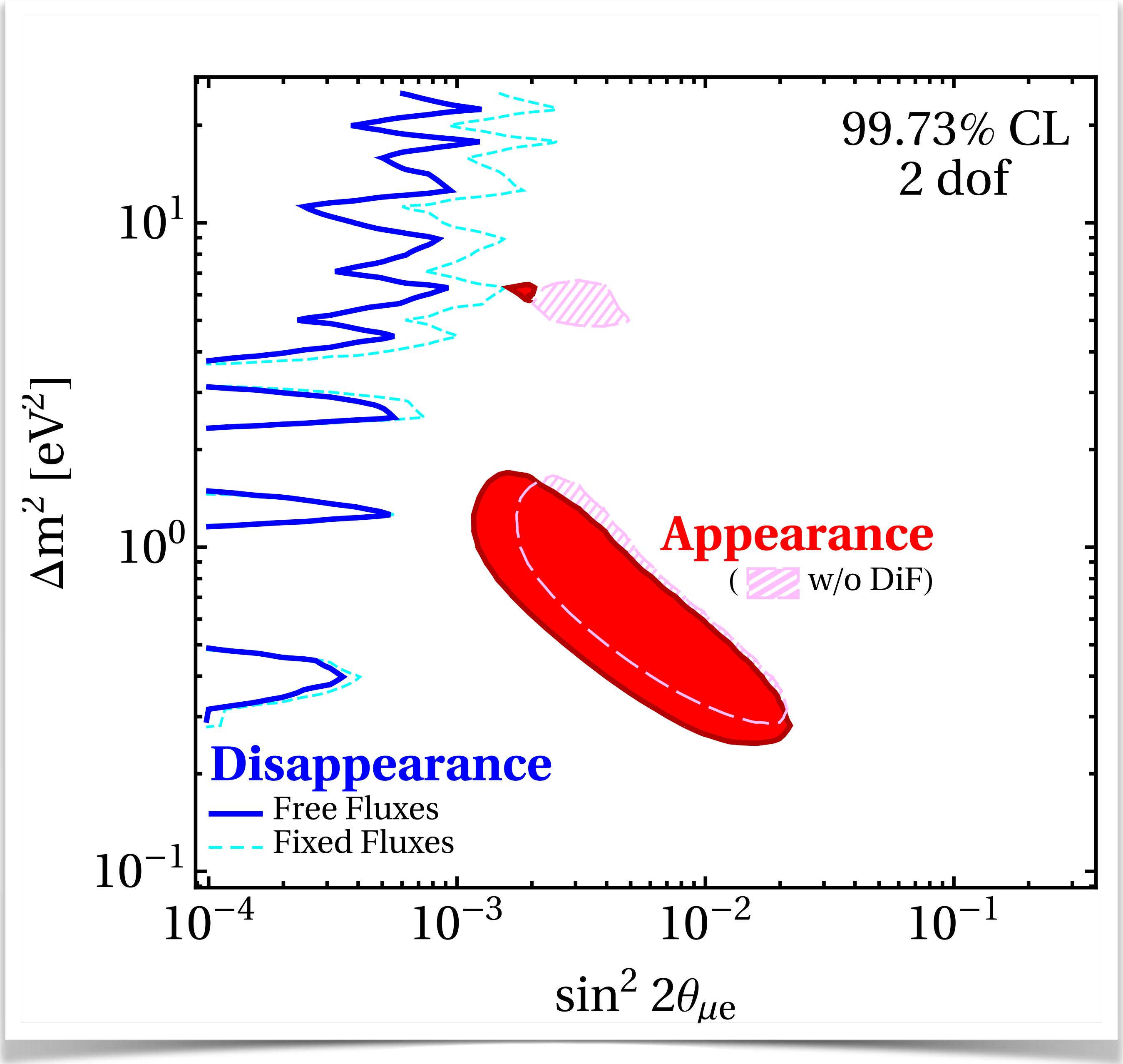


Global fit to ν_e appearance data consistent.

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

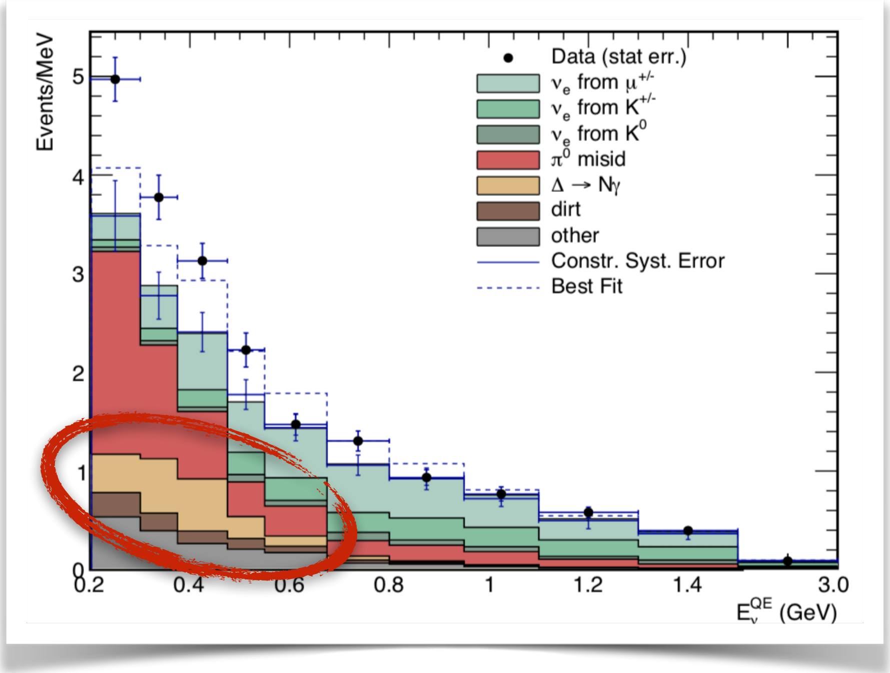
Appearance vs. Disappearance



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

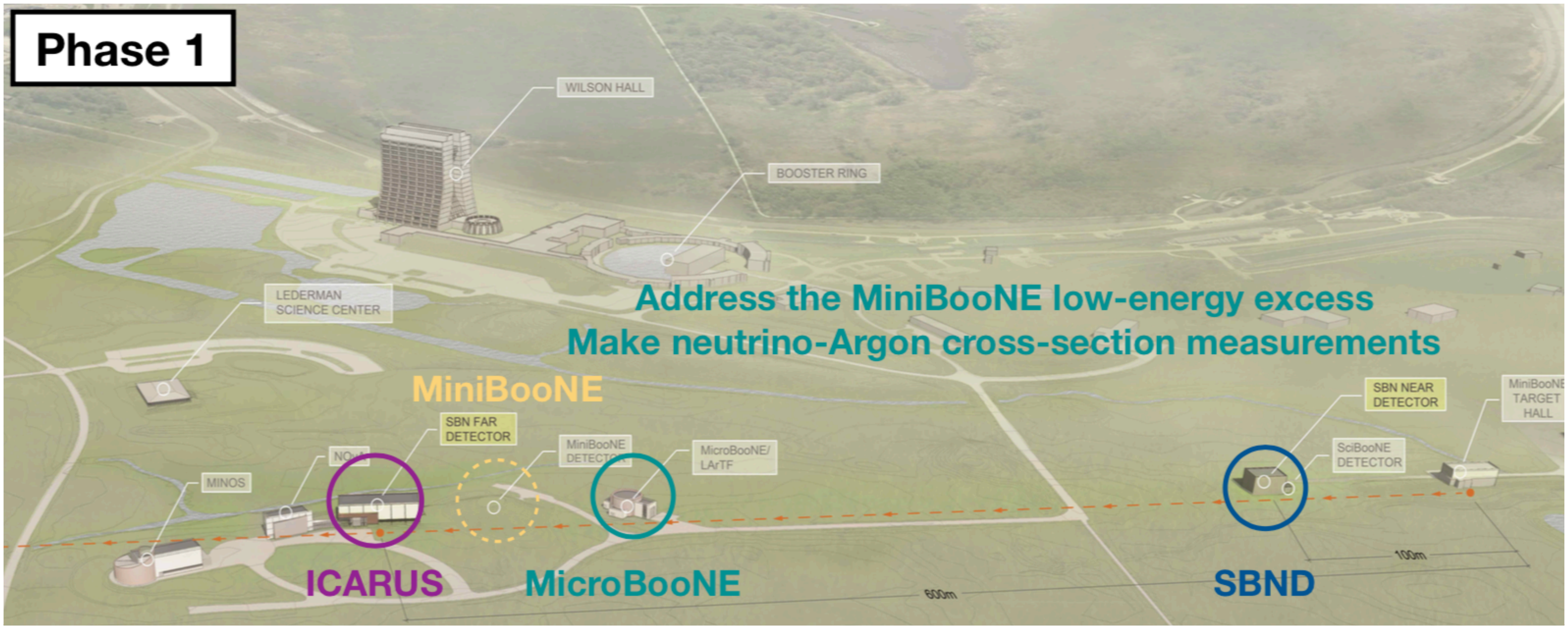
$\Delta \to \gamma N$

- Uncertainty in BR($\Delta \to \gamma N$)
  - PDG: 0.55–0.65%
  - no measurements
- Even larger uncertainties for heavier resonances
- How reliable is the background estimate?



Testing the MiniBooNE Anomaly

Roxanne Guenette, Neutrino 2018



Testing the Reactor Anomaly

- ☑ Do we understand reactor neutrino fluxes?
- ☑ New short-baseline experiments
  - looking for spectral wiggles (smoking-gun oscillation signature)
- ☑ Analyze isotope-dependence of the anomaly
  - $\nu_e \to \nu_s$ oscillation are isotope-independent
  - Problems with flux prediction are typically different for different fissible isotopes

Isotope-Dependence of the Reactor Anomaly

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- ☑ Reactor fuel composition evolves with time ("burnup")
  ➛ time dependence = isotope dependence

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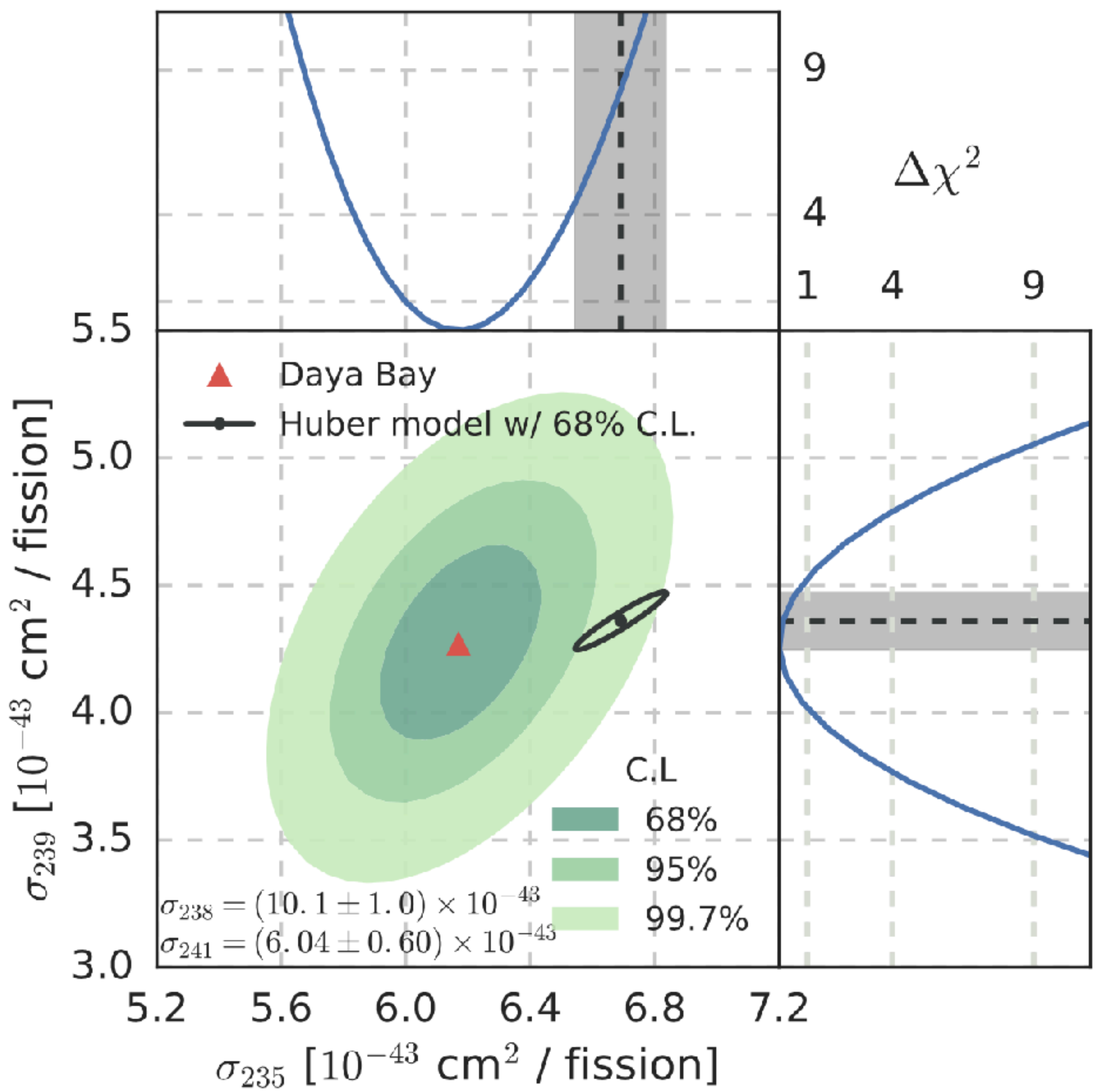

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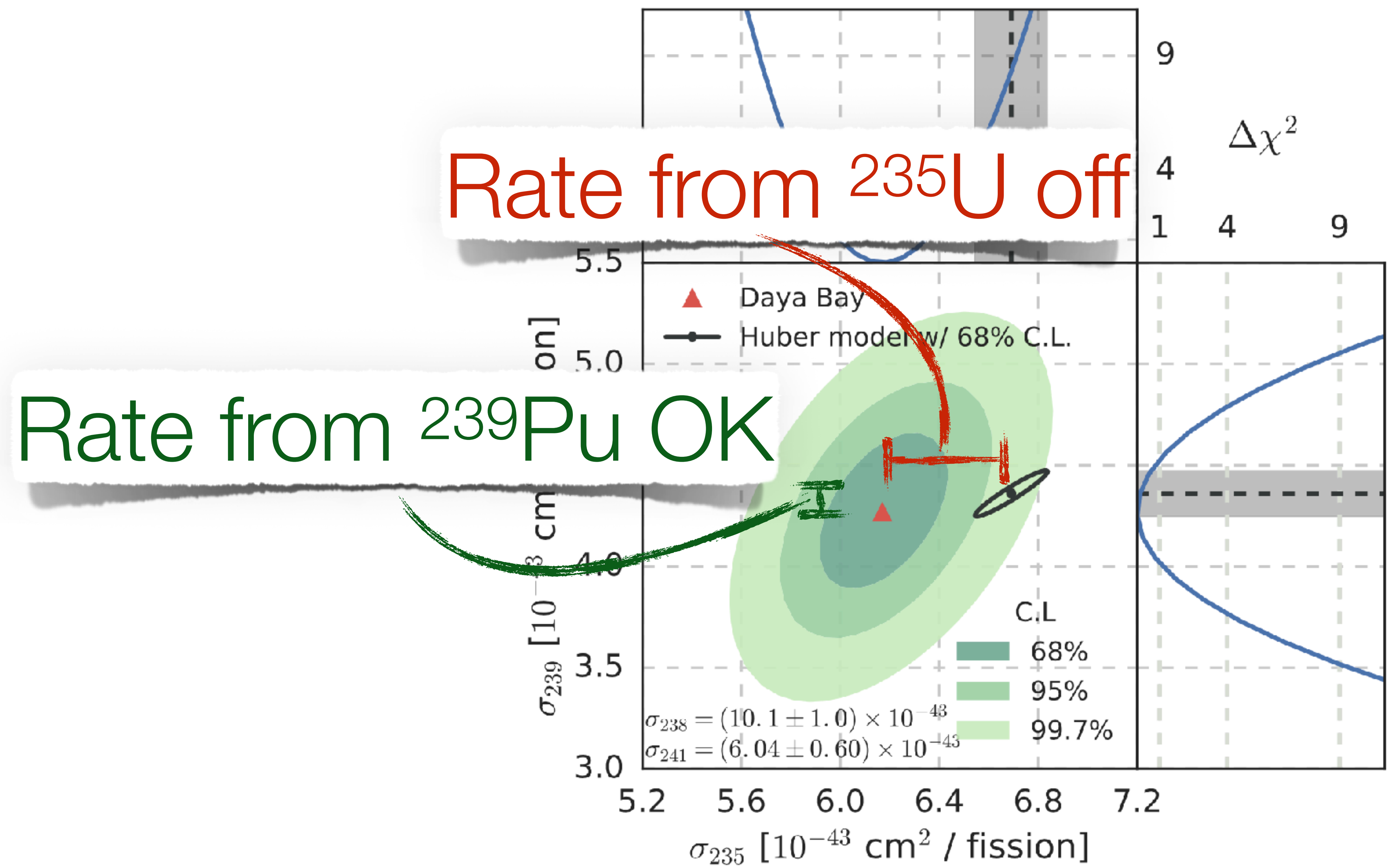

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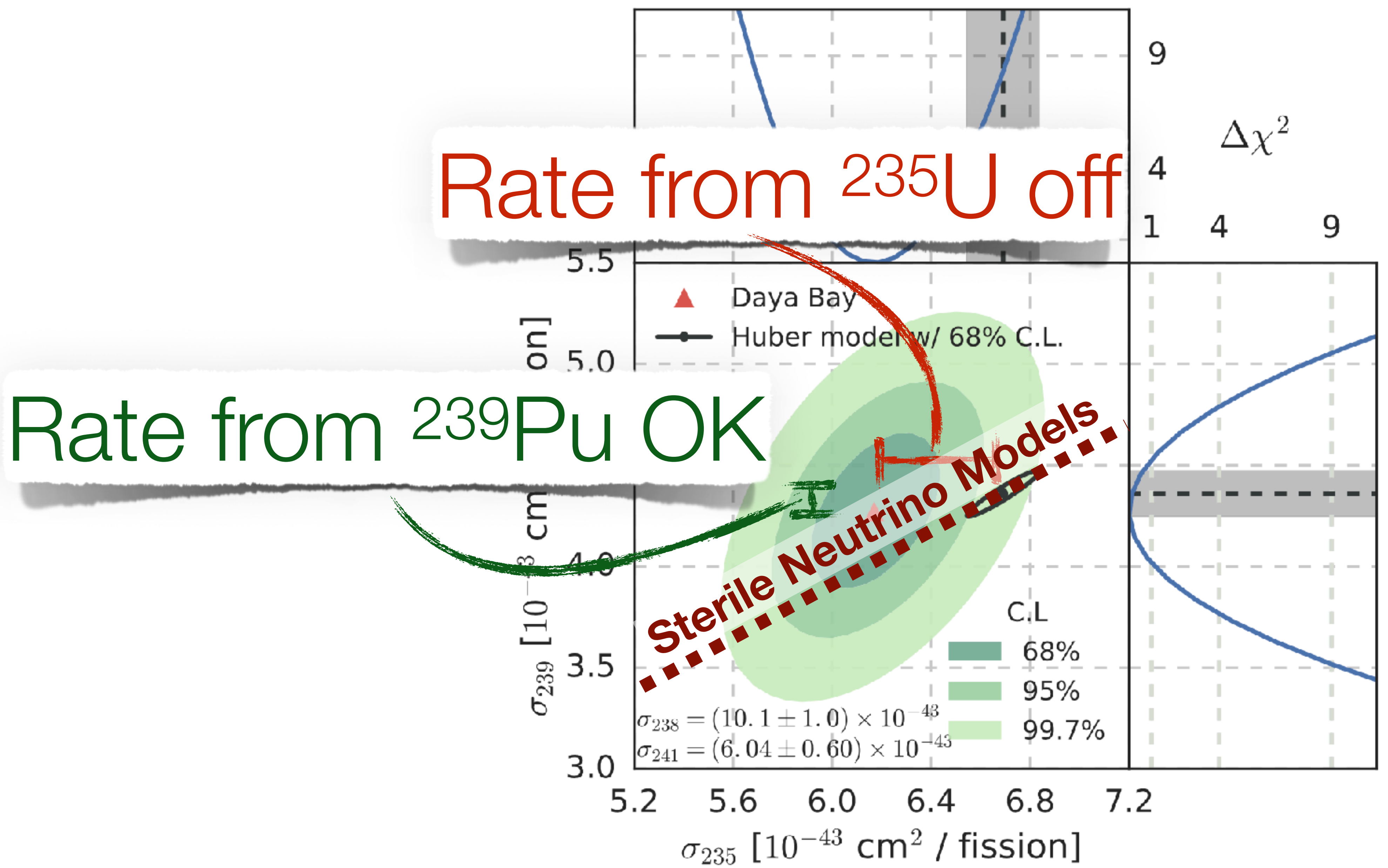

Decaying Sterile Neutrinos?

Dentler Esteban JK Machado, 1911.01427

Decaying Sterile Neutrinos?

- Idea: production of sterile neutrinos that quickly decay back into active neutrinos (+ light new scalar): $\nu_s \to \nu_a + \Phi$

$$\mathcal{L} \supset -g\,\bar{\nu}_s \nu_s \phi - \sum_{a=e,\mu,\tau,s} m_{\alpha\beta}\,\bar{\nu}_\alpha \nu_\beta$$

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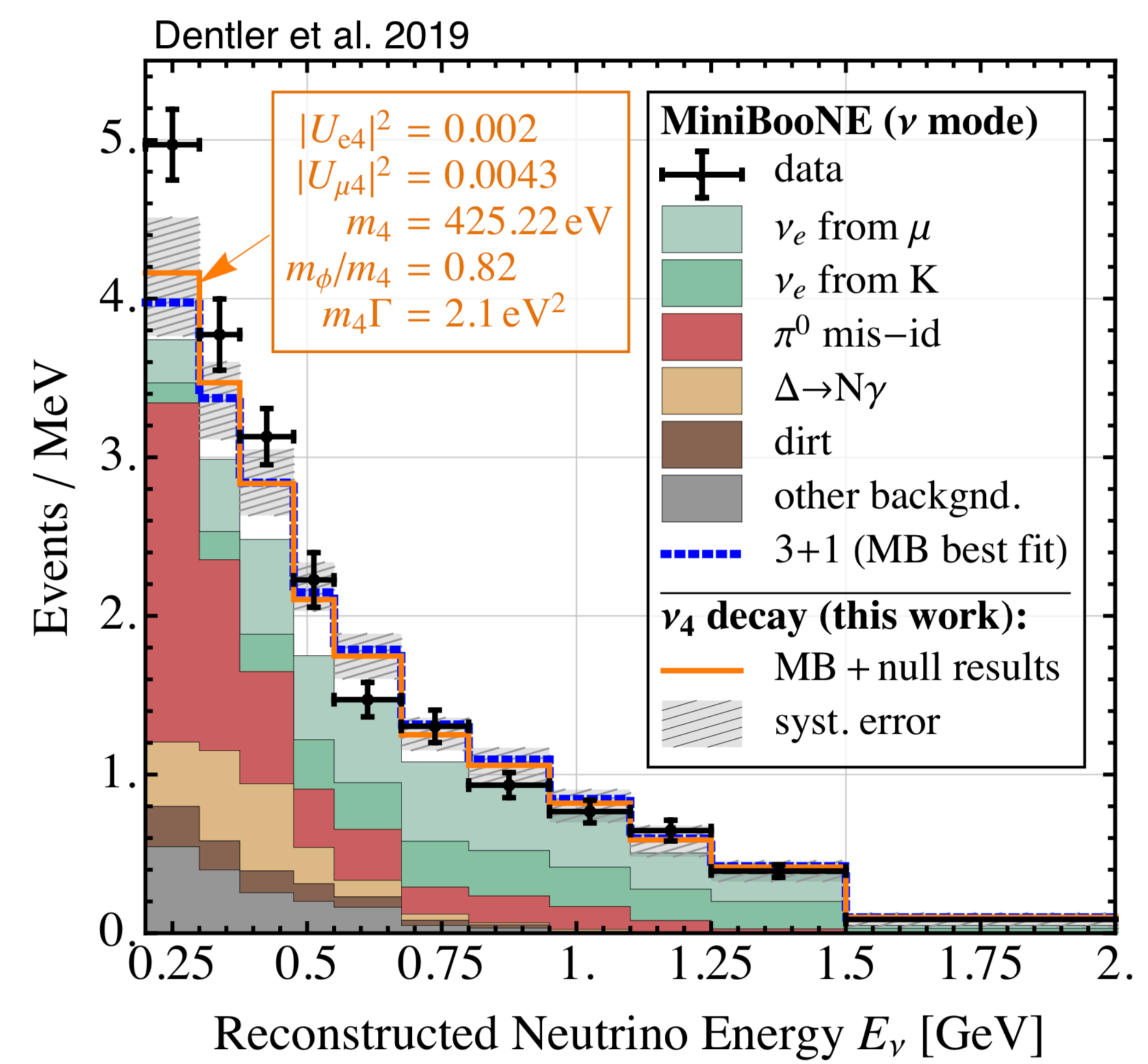

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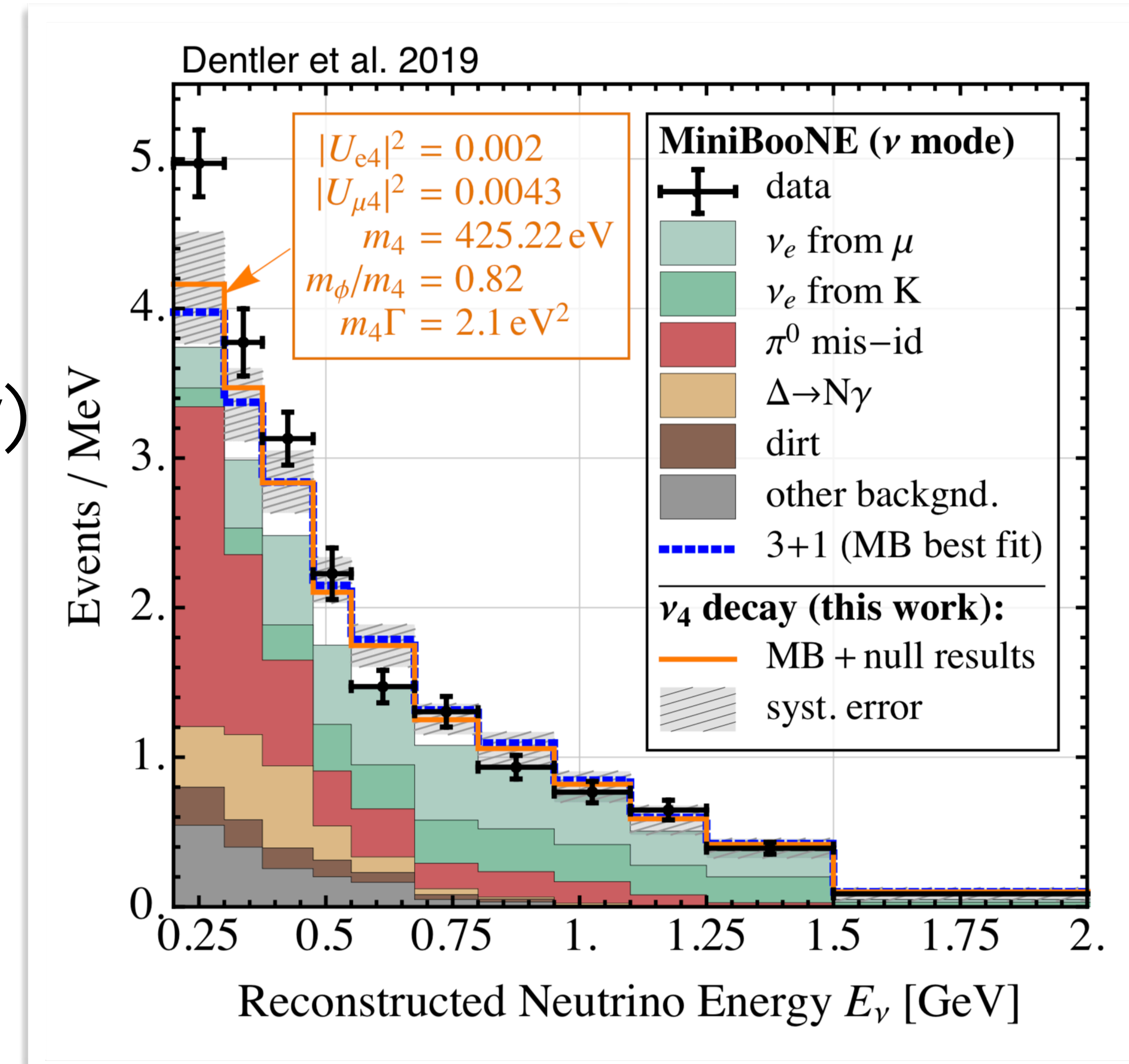

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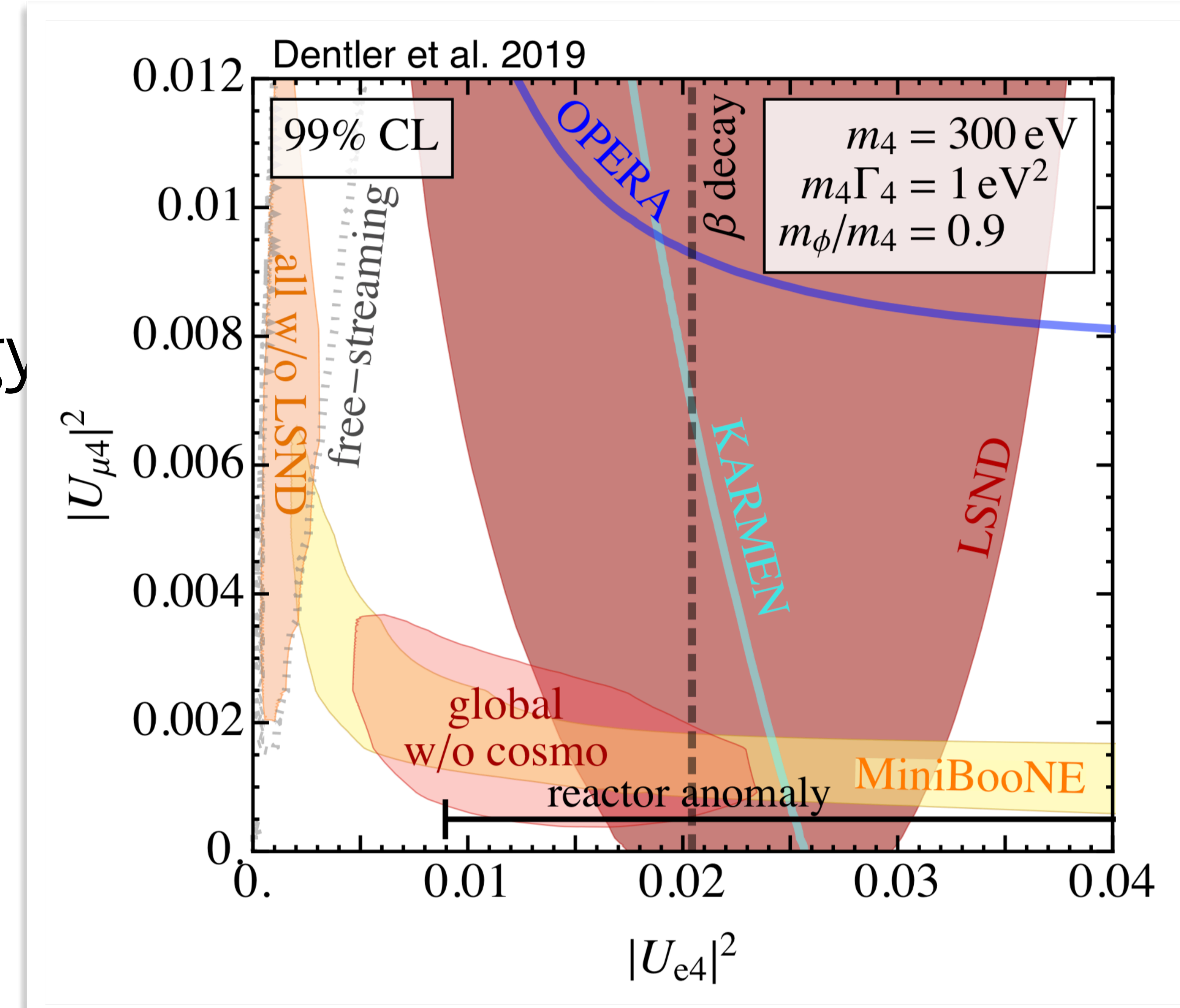
- Excellent fit to MiniBooNE data
- Consistent with all null results (incl. cosmology)
- with small extensions: consistent also with LSND + reactors + gallium



Dentler Esteban JK Machado, 1911.01427

Reconciling Sterile Neutrinos with Cosmology

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Standard picture: ν_s production via oscillation at $T \gtrsim$ MeV

$\Sigma m_\nu \lesssim 0.12$ eV ⚡

$N_{eff} \lesssim 3.16$ ⚡

- ☑ New interactions in the ν_s sector
  - production suppressed by thermal potential
  - avoids N_{eff} constraint, weakens or avoids Σm_ν constraint

Hannestad et al. 1310.5926
Dasgupta JK, 1310.6337

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- ☑ ν_s properties change in late phase transition

Bezrukov Chudaykin Gorbunov, 1705.02184
Chu et al., 1806.10629

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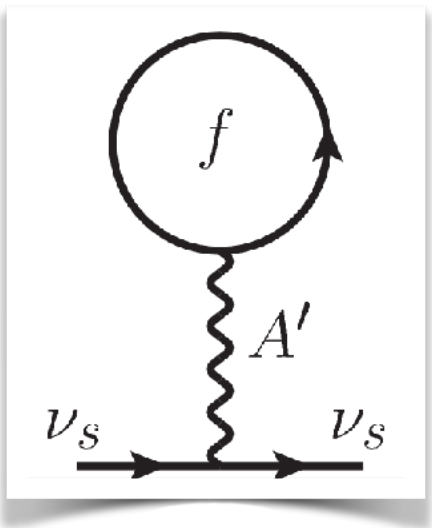
Bezrukov Chudaykin Gorbunov, 1705.02184
Chu et al., 1806.10629

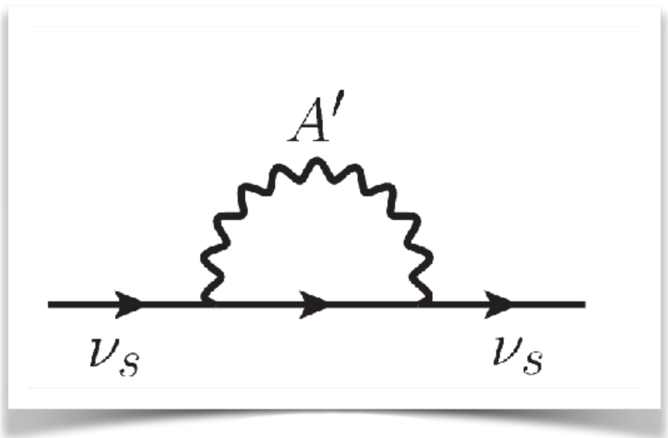
- ☑ Coupling to slow-rolling scalar field

Fardon Nelson Weiner, astro-ph/0309800
Bezrukov Chudaykin Gorbunov, 1705.02184

New Interaction in the Sterile Sector

- Assume ν_s coupled to new force mediator
- Neutrino self-energy contributes to effective potential V^{eff}





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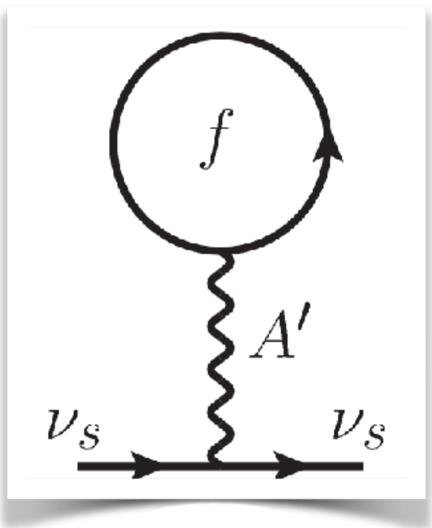

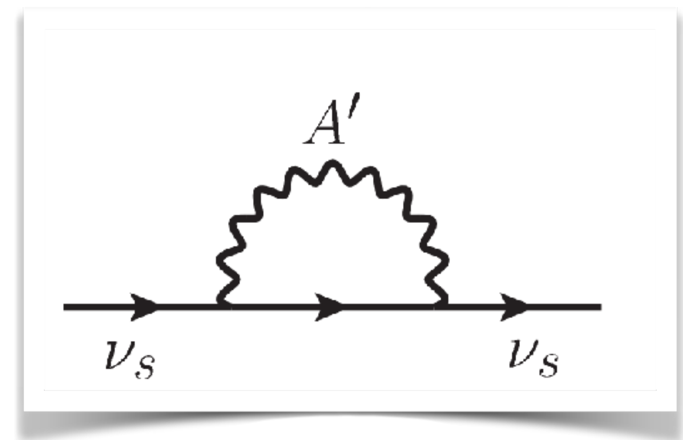

- Thermal propagators

$$S(p) = (\not{p} + m)\left[\frac{1}{p^2 - m^2} + i\Gamma_f(p)\right]$$

$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2)\left[\frac{1}{p^2 - M^2} + i\Gamma_b(p)\right]$$

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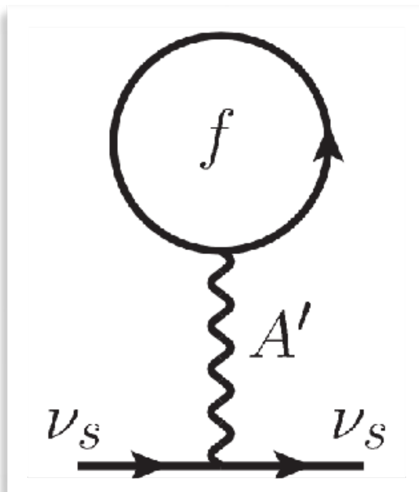

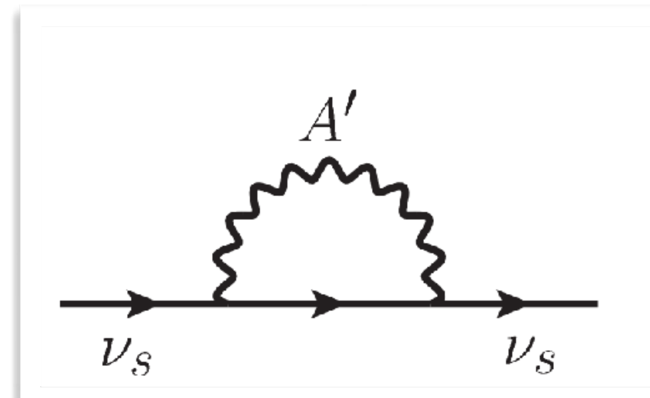

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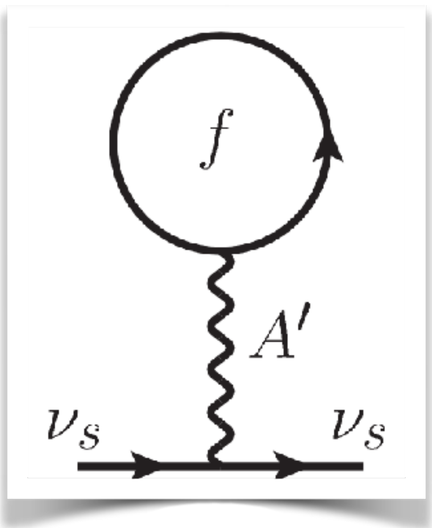

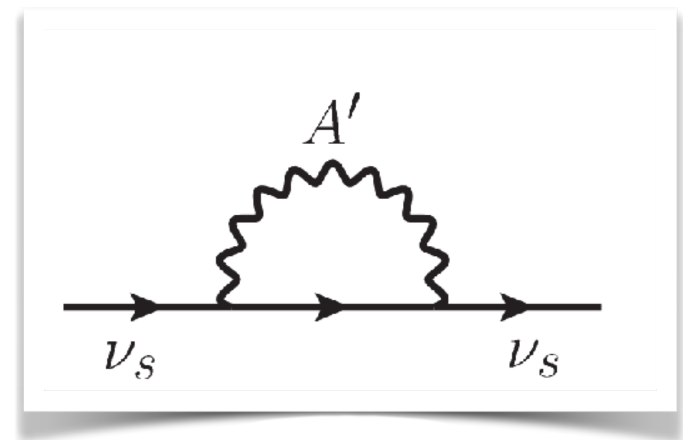

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$$\Gamma_{f,b}(p) = 2\pi\delta(p^2 - m^2)\, n_{f,b}(p)$$

$$n_{f,b}(p) = [e^{|p\cdot u|/T_s} \pm 1]^{-1}$$

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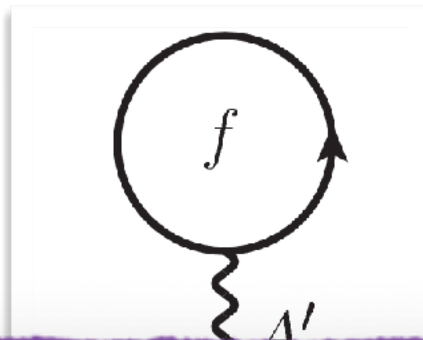
- ☑ Neutrino self-energy contributes to effective potential V^{eff}



- ★ ν_s production strongly suppressed at high T
- ★ cosmological constraints avoided

$$S(p) = (\not{p} + m)\left[\frac{1}{p^2 - m^2} + i\Gamma_f(p)\right]$$

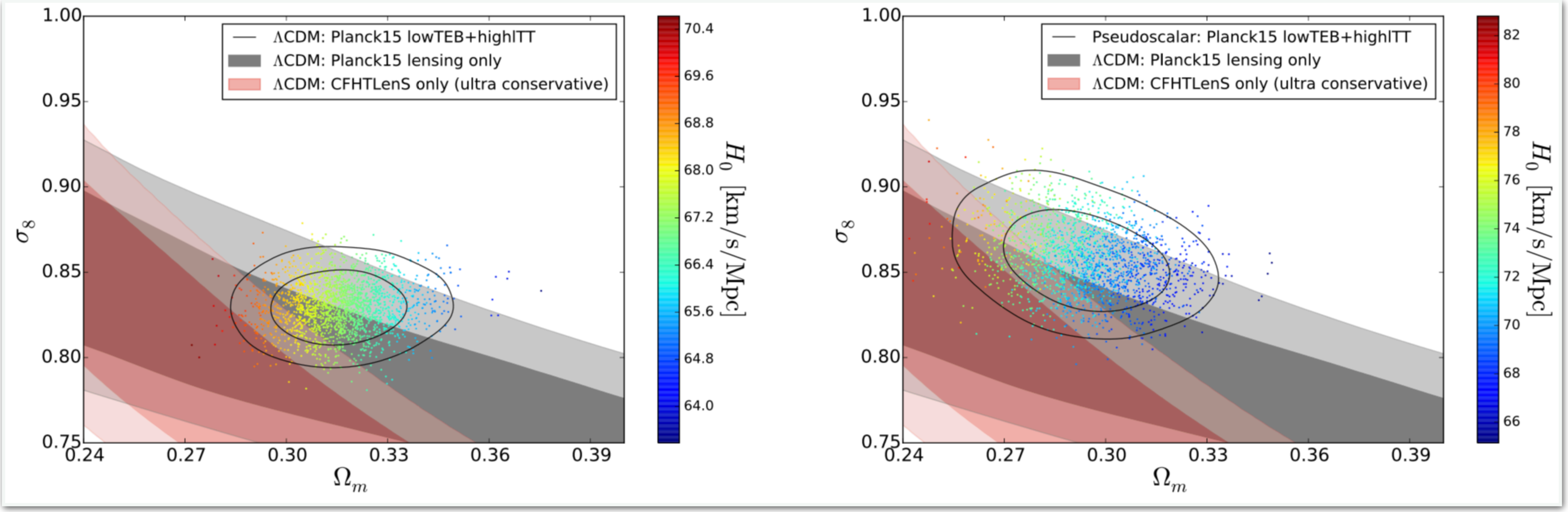
$$D^{\mu\nu}(p) = (-g^{\mu\nu} + p^\mu p^\nu / M^2)\left[\frac{1}{p^2 - M^2} + i\Gamma_b(p)\right]$$

$$n_{f,b}(p) = [e^{|p\cdot u|/T_s} \pm 1]^{-1}$$

New Interaction in the Sterile Sector

- ☑ Effective potential $V^{eff} \gg \Delta m^2/(2T)$: suppresses ν_s production
- ☑ Later: equilibration between $\nu_{e,\mu,\tau}$ and ν_s (N_{eff} is fixed by then)

Archidiacono *et al.* 1606.07673

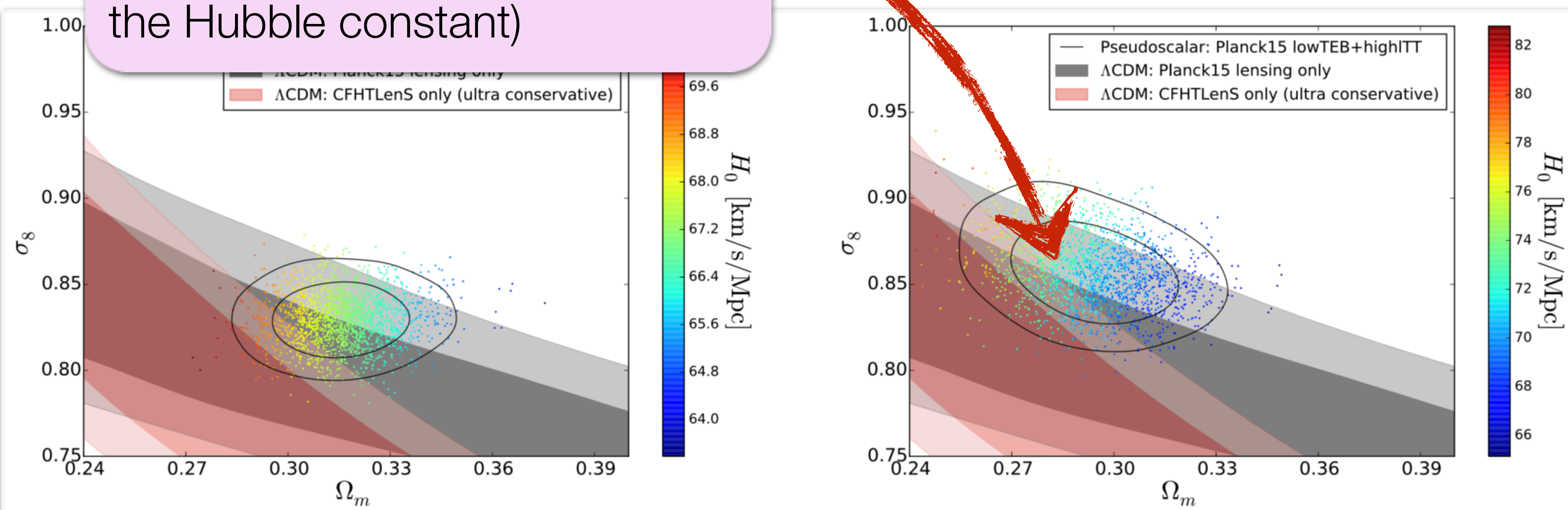


New Interaction in the Sterile Sector

- ☑ Effective potential $V^{eff} \gg \Delta m^2 / (2\,T)$: suppresses ν_s production
- ☑ … n $\nu_{e,\mu,\tau}$ and ν_s

May easy H_0 tension
(discrepancy between local and cosmological measurements of the Hubble constant)

Archidiacono *et al.* 1606.07673



New ν Physics

Neutrino—DM Interactions

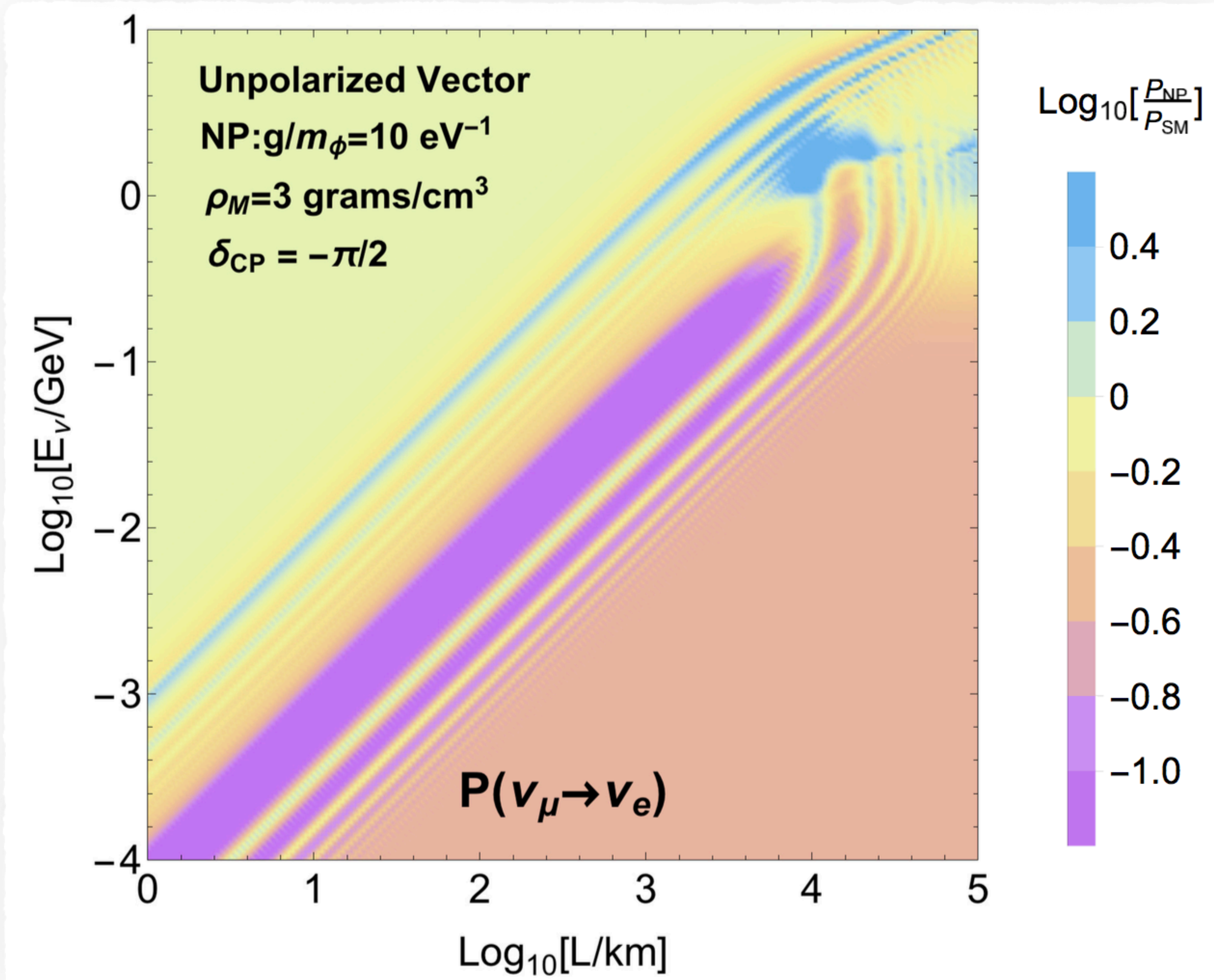
- Coherent forward scattering of neutrinos on DM
  - analogous to SM matter effects (“MSW effect”)
  - Requires huge DM number density
- Fuzzy Dark Matter
  - scalar or vector, $m < 10^{-20}$ eV
  - Compton wave length ~ pc
  - Interesting for small scale structure

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…

Modified Oscillation Probabilities



….06740
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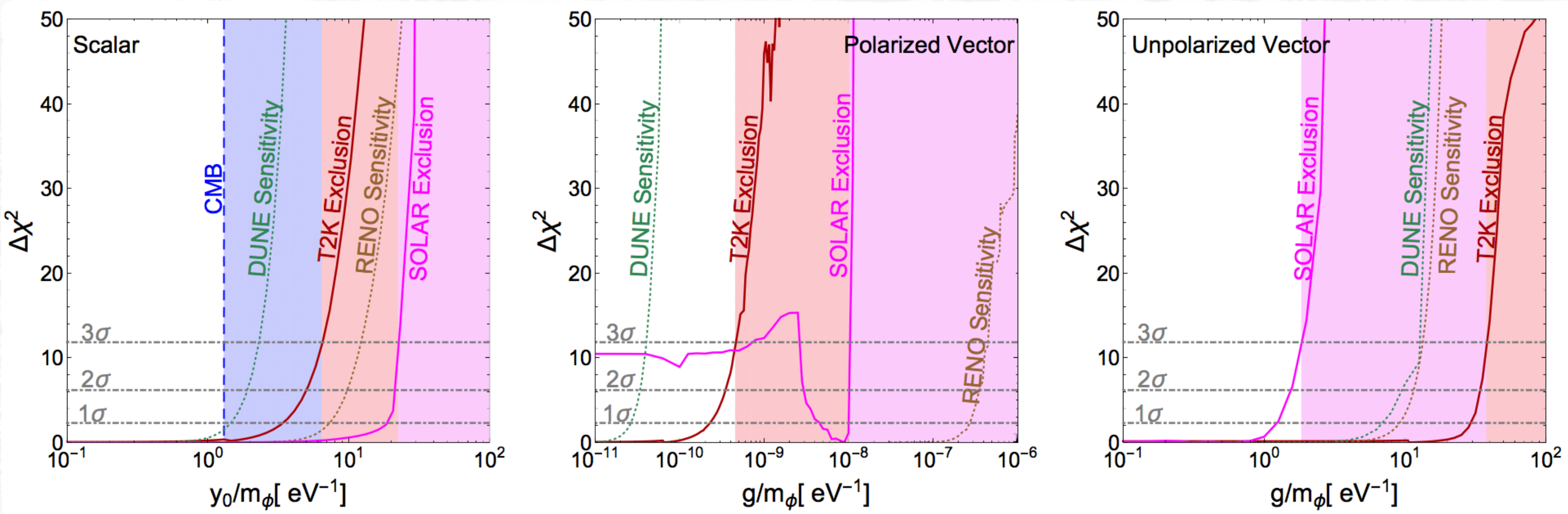
Neutrino—DM Interactions

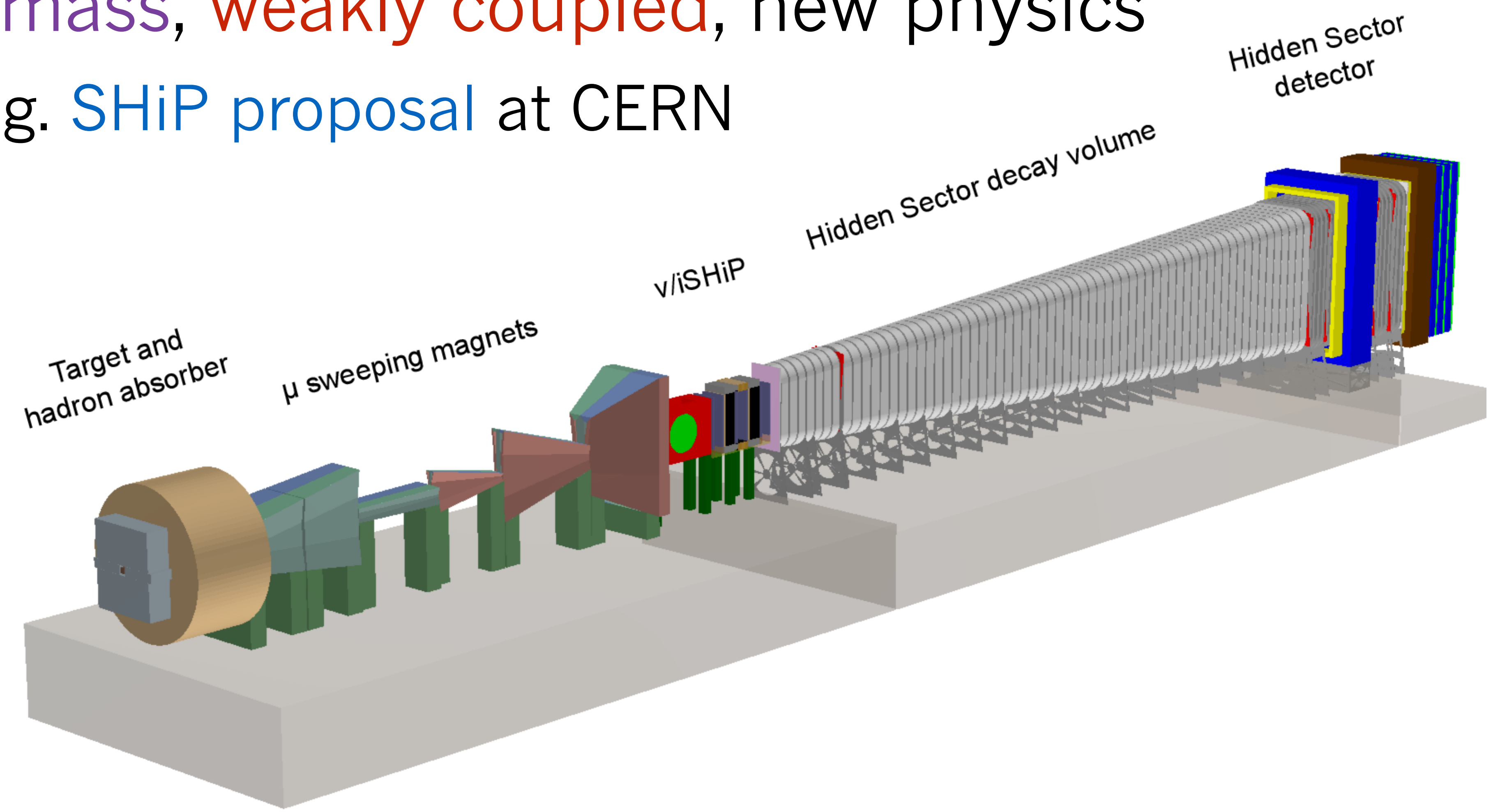
- ☑ Coherent forward scattering of neutrinos on DM
  - an
  - Requires huge DM number density

Limits from Long-Baseline Experiments



New Physics at Near Detectors

- Rich worldwide program searching for low-mass, weakly coupled, new physics
  - E.g. SHiP proposal at CERN

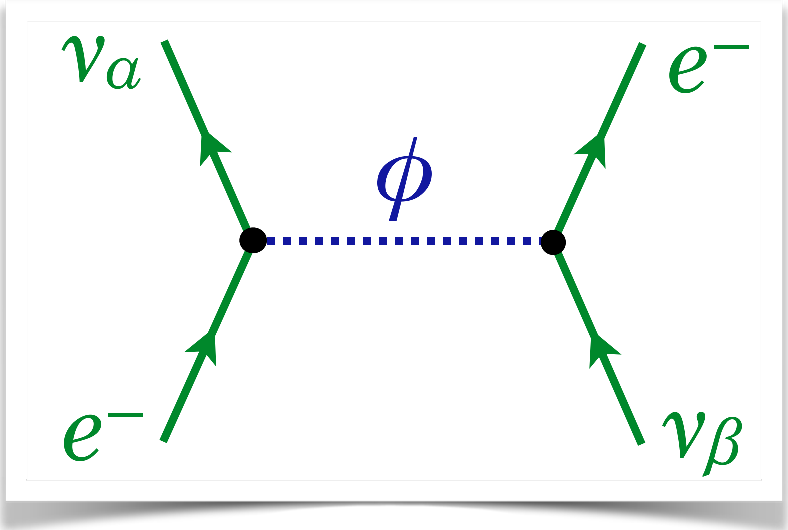


  - Search for displaced decays of new particles
- DUNE / T2HK Near Detectors have similar configuration

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^+

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



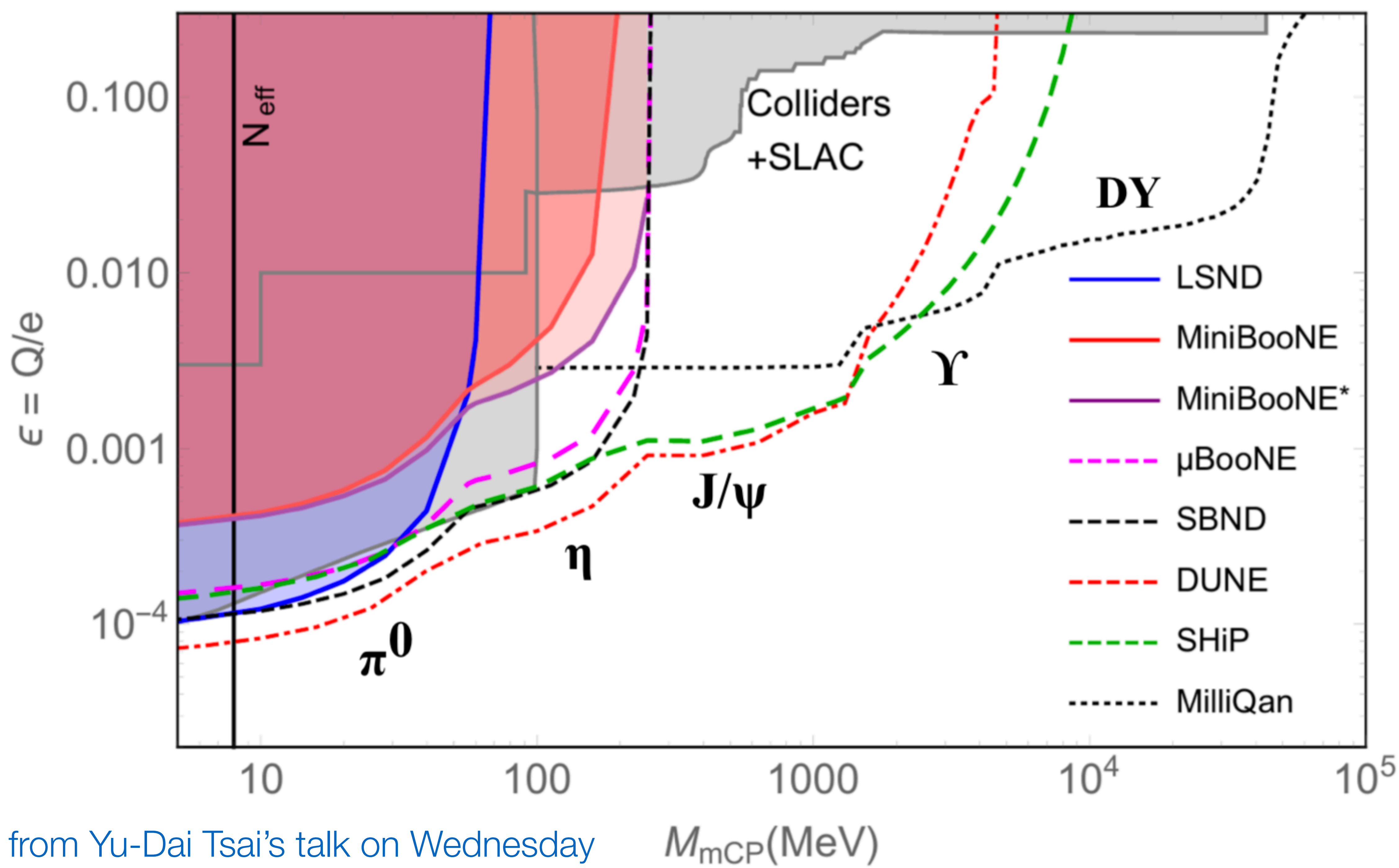
$$\mathcal{L}_{\rm EFT} \supset \frac{\xi^{\alpha\beta}\xi^{\gamma\delta*}}{4m_\phi^2} \left[\bar{L}_a^{c,\alpha} \epsilon_{ab} L_b^{\beta}\right] \left[\bar{L}_a^{c,\delta} \epsilon_{ab} L_b^{\gamma}\right]$$

- coupling can arise naturally from TeV scale new physics

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

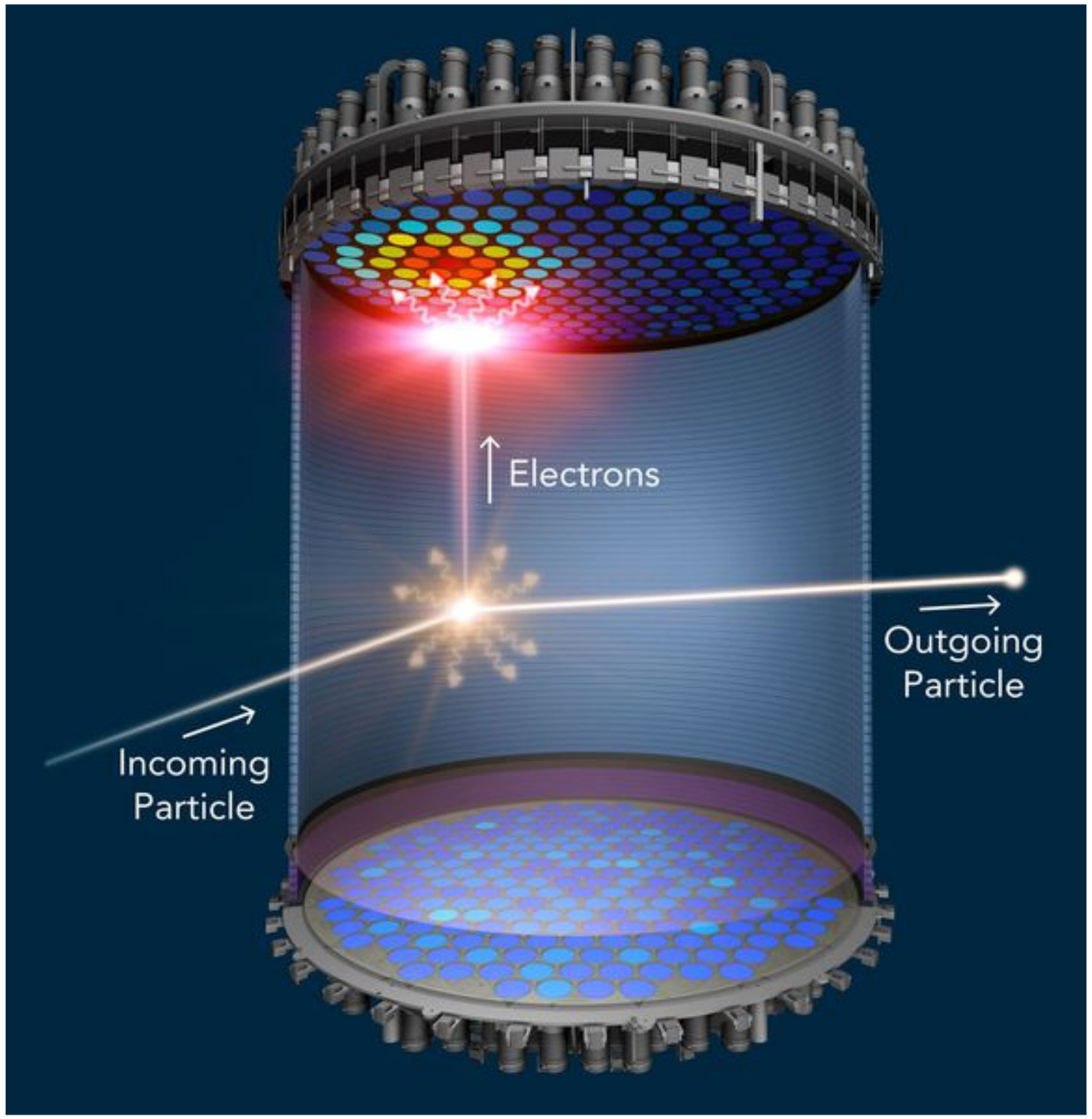
CERN | Neutrino PLATFORM | erc | JG|U

Example: Millicharged Particles



from Yu-Dai Tsai's talk on Wednesday

Electron Recoil Excess in Xenon1T



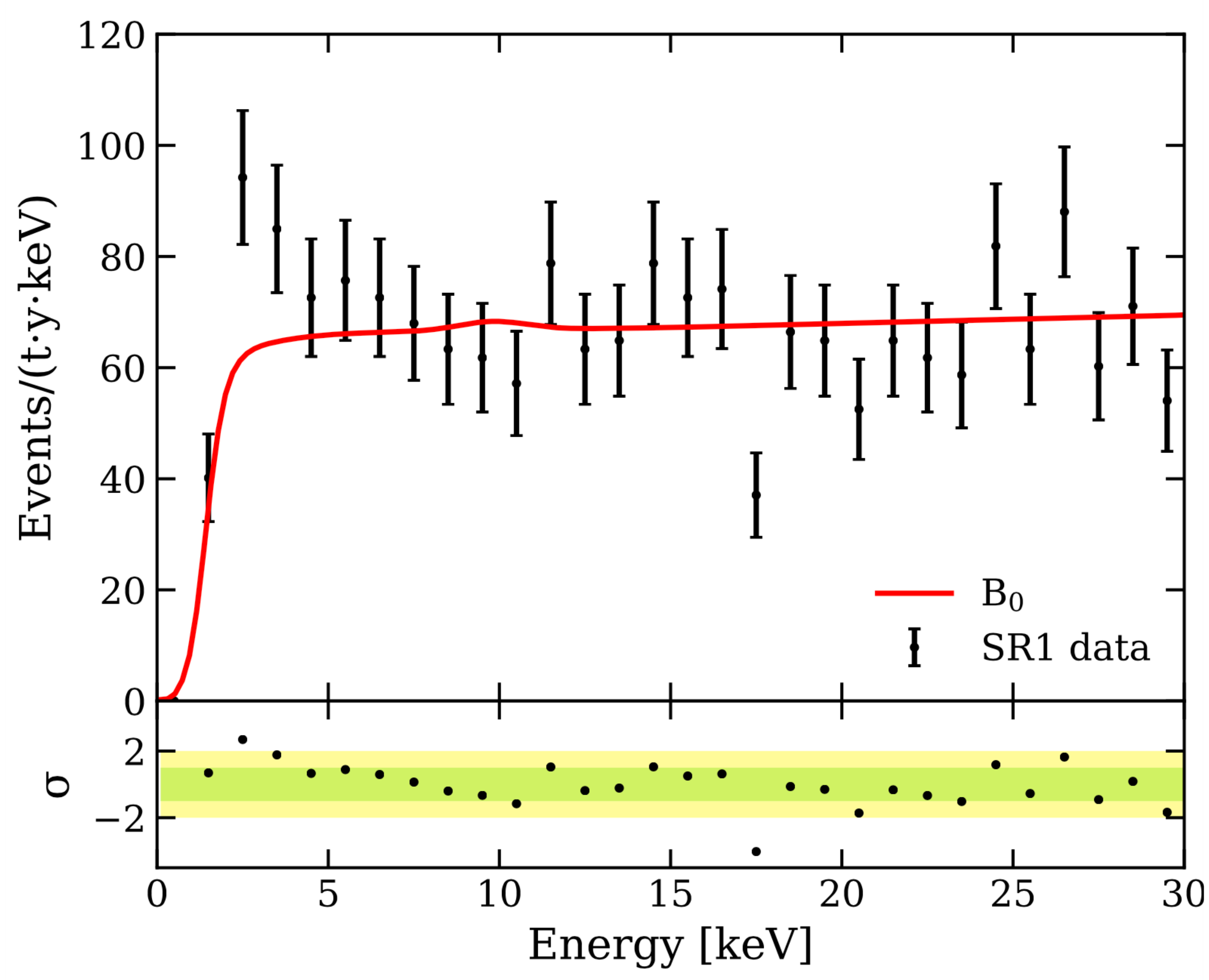
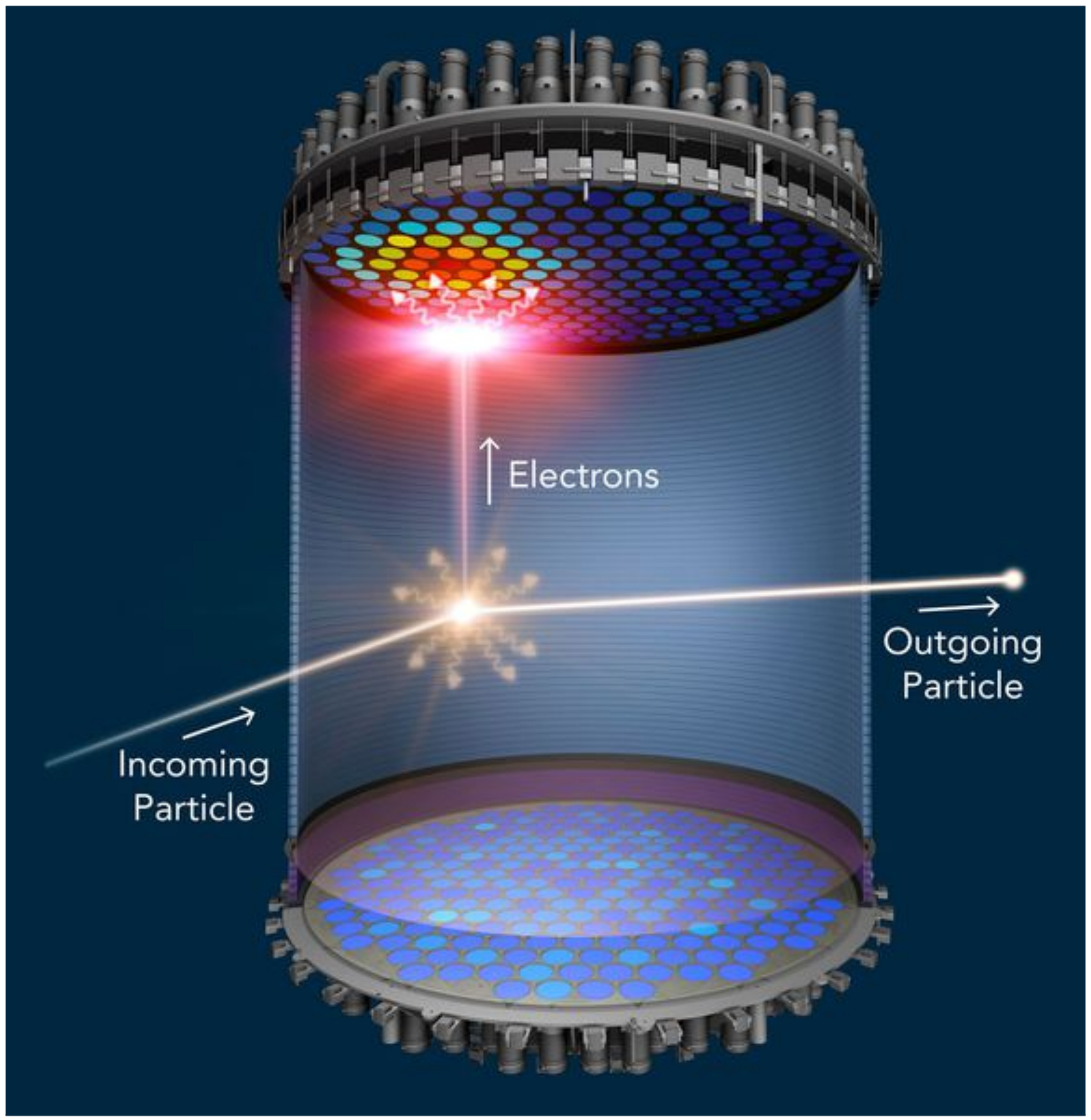


Image: SLAC

Xenon1T arXiv:2006.09721

Electron Recoil Excess in Xenon1T



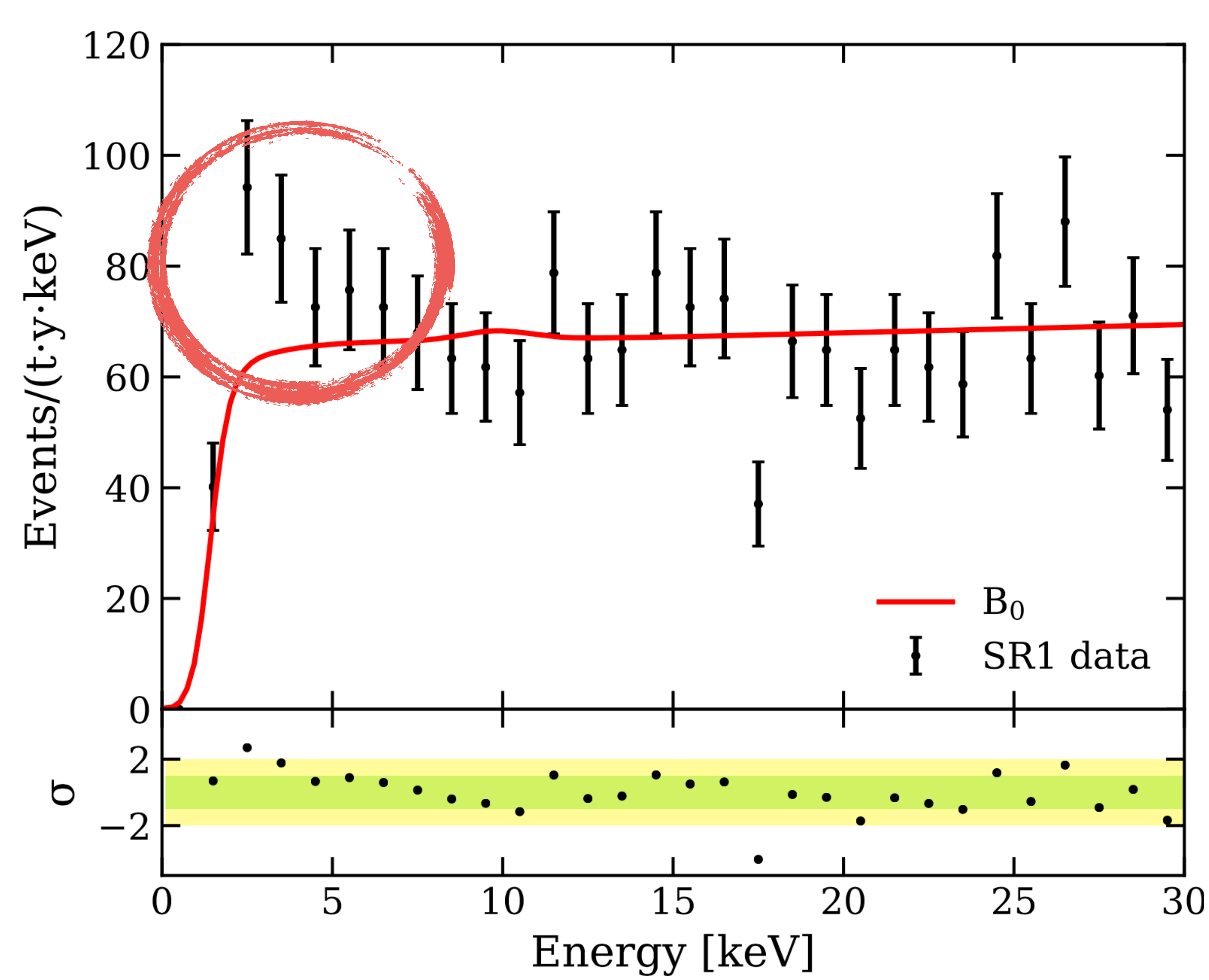


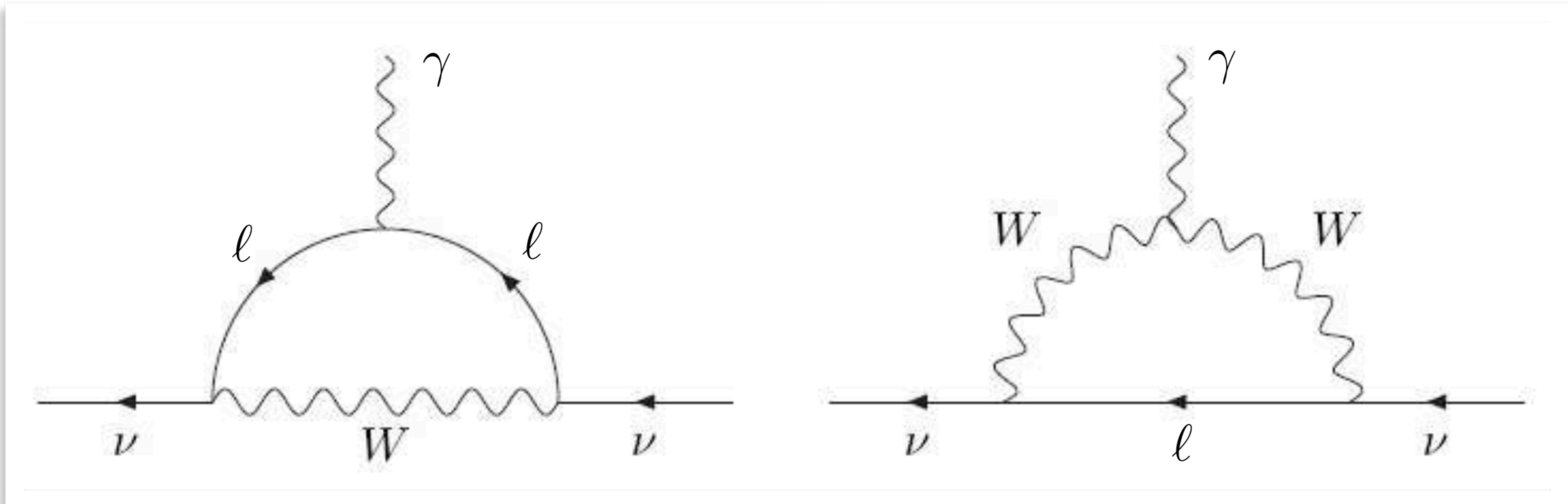
Image: SLAC

Xenon1T arXiv:2006.09721

Neutrino Magnetic Moments

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

☑ Tiny in the SM



☑ can be significantly enhanced in BSM theories

Beyond the SM

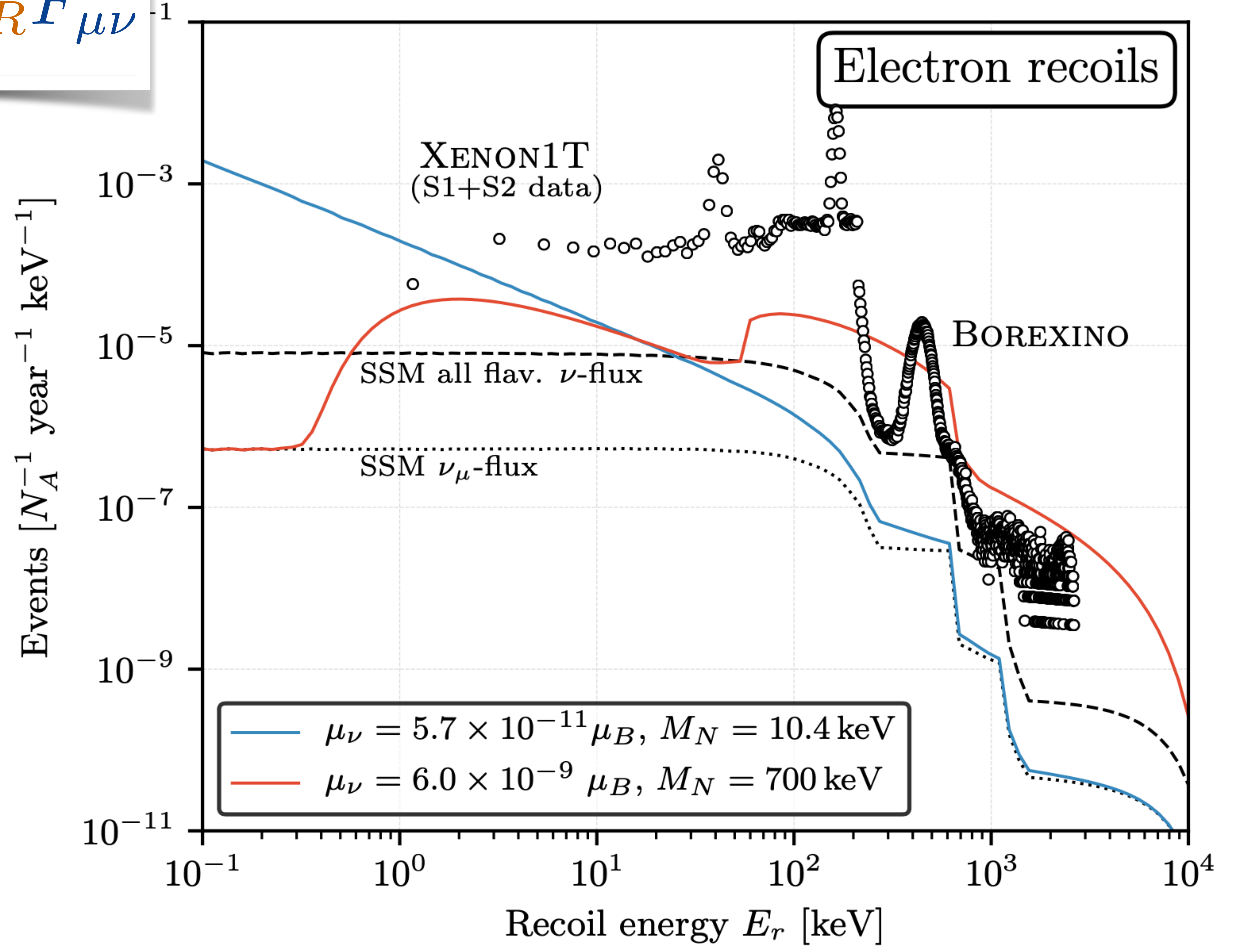
- ☑ Simplest option: a singlet fermion N (sterile neutrino)
- ☑ New transition magnetic moment operator

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

- ☑ Leads to ν_L ➟ N conversion

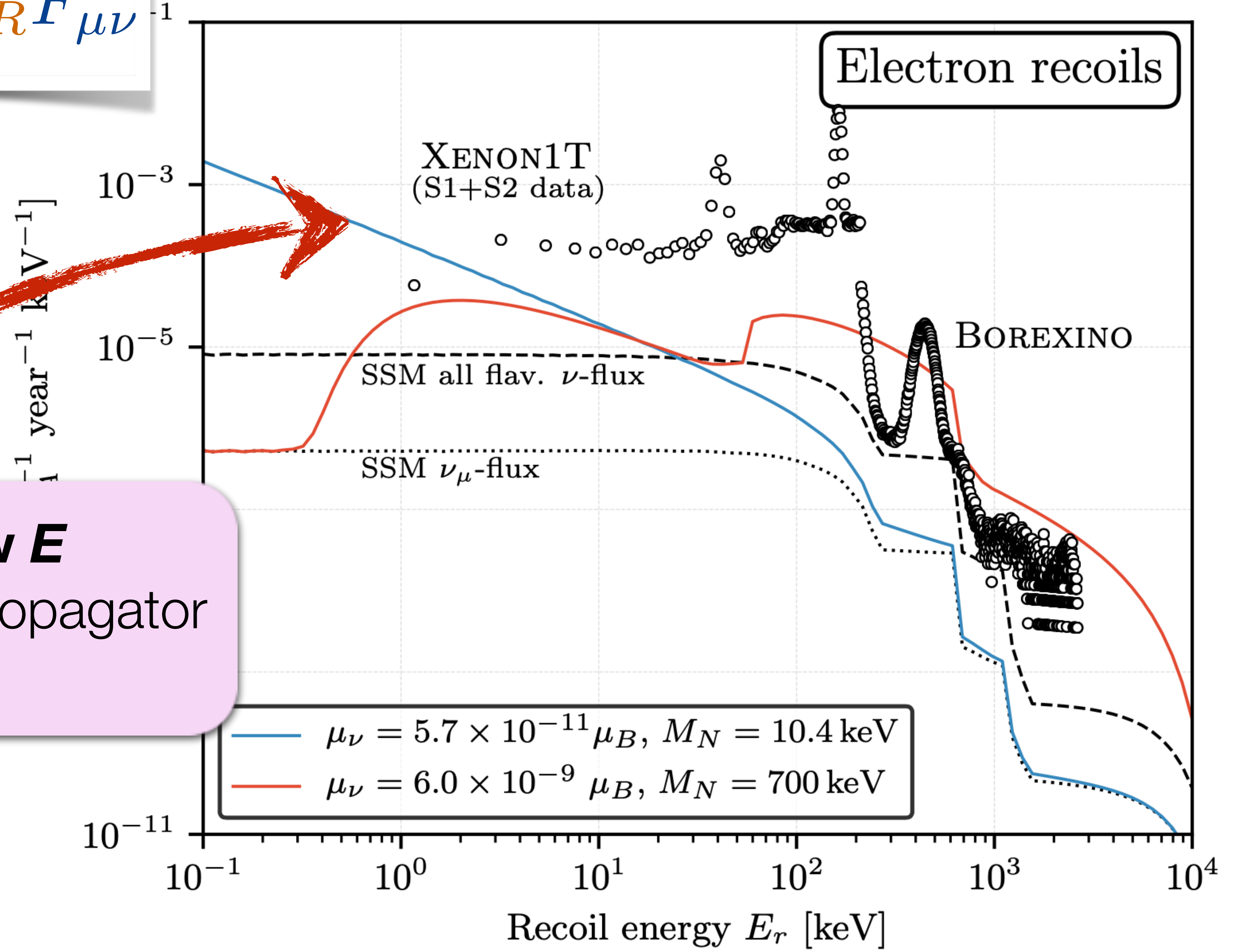
Neutrino Magnetic Moments

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



Neutrino Magnetic Moments

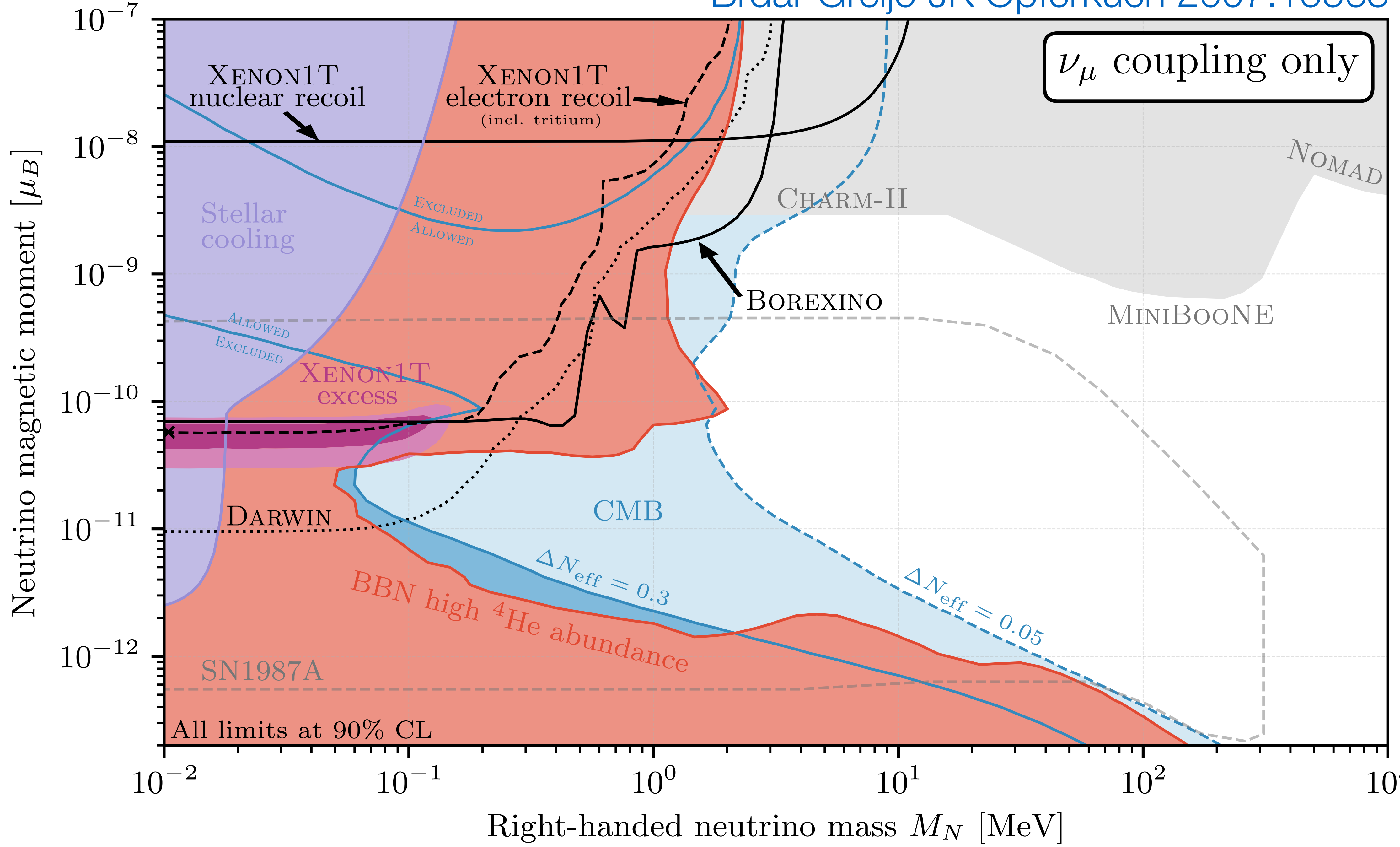
$$\mathcal{L} \supset \frac{1}{2} \mu_N \, \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R F_{\mu\nu}$$



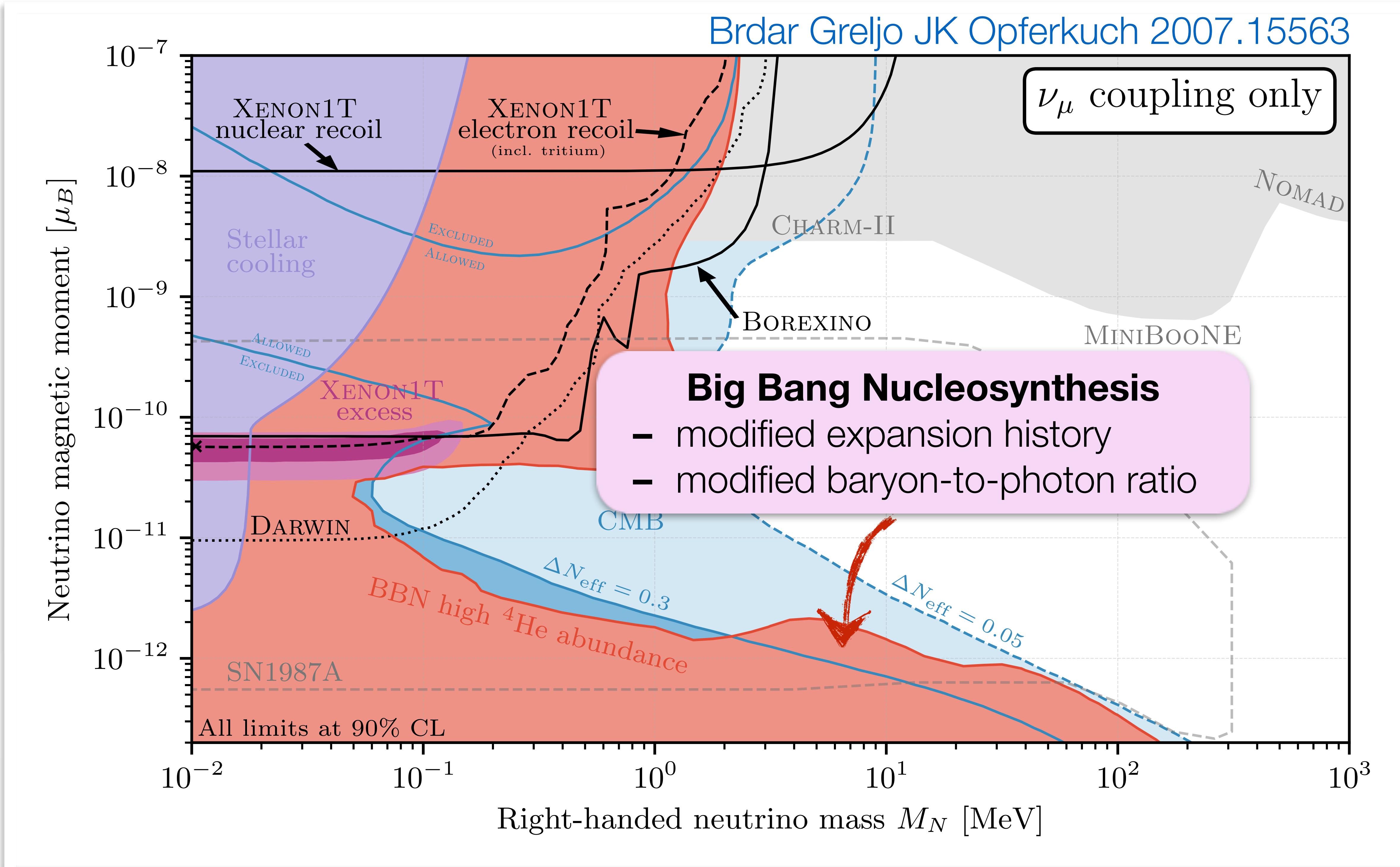
Enhancement at low *E*
thanks to massless propagator
in *t*-channel process

Neutrino Magnetic Moments

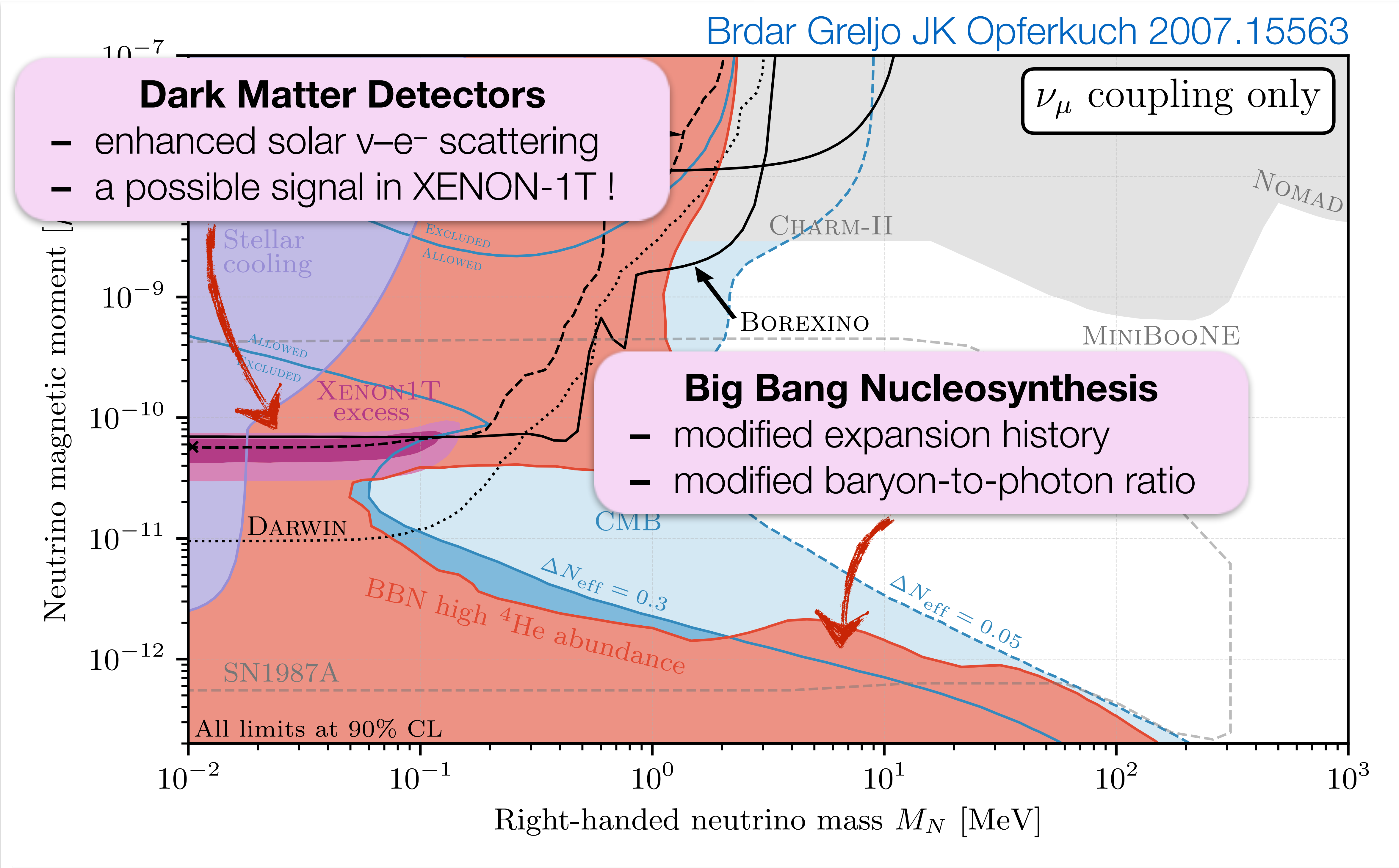
Brdar Greljo JK Opferkuch 2007.15563



Neutrino Magnetic Moments



Neutrino Magnetic Moments



Dark Matter Detectors

- enhanced solar ν–e⁻ scattering
- a possible signal in XENON-1T !

Big Bang Nucleosynthesis

- modified expansion history
- modified baryon-to-photon ratio