Neutrinos

Theory and Phenomenology

Joachim Kopp
EPS Conference on High Energy Physics | Venice, Italy | July 11th, 2017

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Apologies for not being here in person

The reason are these little fellows, born yesterday

In this Talk

- ☑ Phenomenoloy for Long Baseline Experiments
- ☑ Oscillation Anomalies and Sterile Neutrinos
- ☑ Neutrinos and Dark Matter
- ☑ Neutrinoless Double Beta Decay
- ☑ Understanding Neutrino Mass and Mixing

Not in this Talk

- ☑ Astrophysical Neutrinos
  ➣ talk by Maarten de Jong
- ☑ Supernova Neutrinos
  ➣ talk by Maarten de Jong
- ☑ Neutrino Cosmology
  ➣ talks by François Bouchet, Antonio Riotto
- ☑ Neutrinos as a probe for Dark Matter
  ➣ talks by Yonit Hochberg, Maarten de Jong
- ☑ Neutrino Physics with DM Detectors
  ➣ talk by Manfred Lindner

Phenomenology for Long Baseline Experiments

Theory Input for LBL Experiments

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LHC

- ☑ PDFs
- ☑ Matrix Elements
  - N^nLO calculation
  - MC simulations (Pythia, …)
- ☑ Model Building
- ☑ Global Fits

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- ☑ Beam Fluxes
- ☑ Cross Sections
- ☑ Oscillation Physics (SM + beyond)
  - Simulations (GENIE, GLoBES, …)
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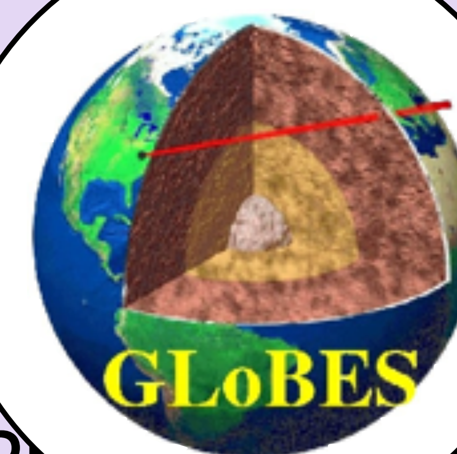

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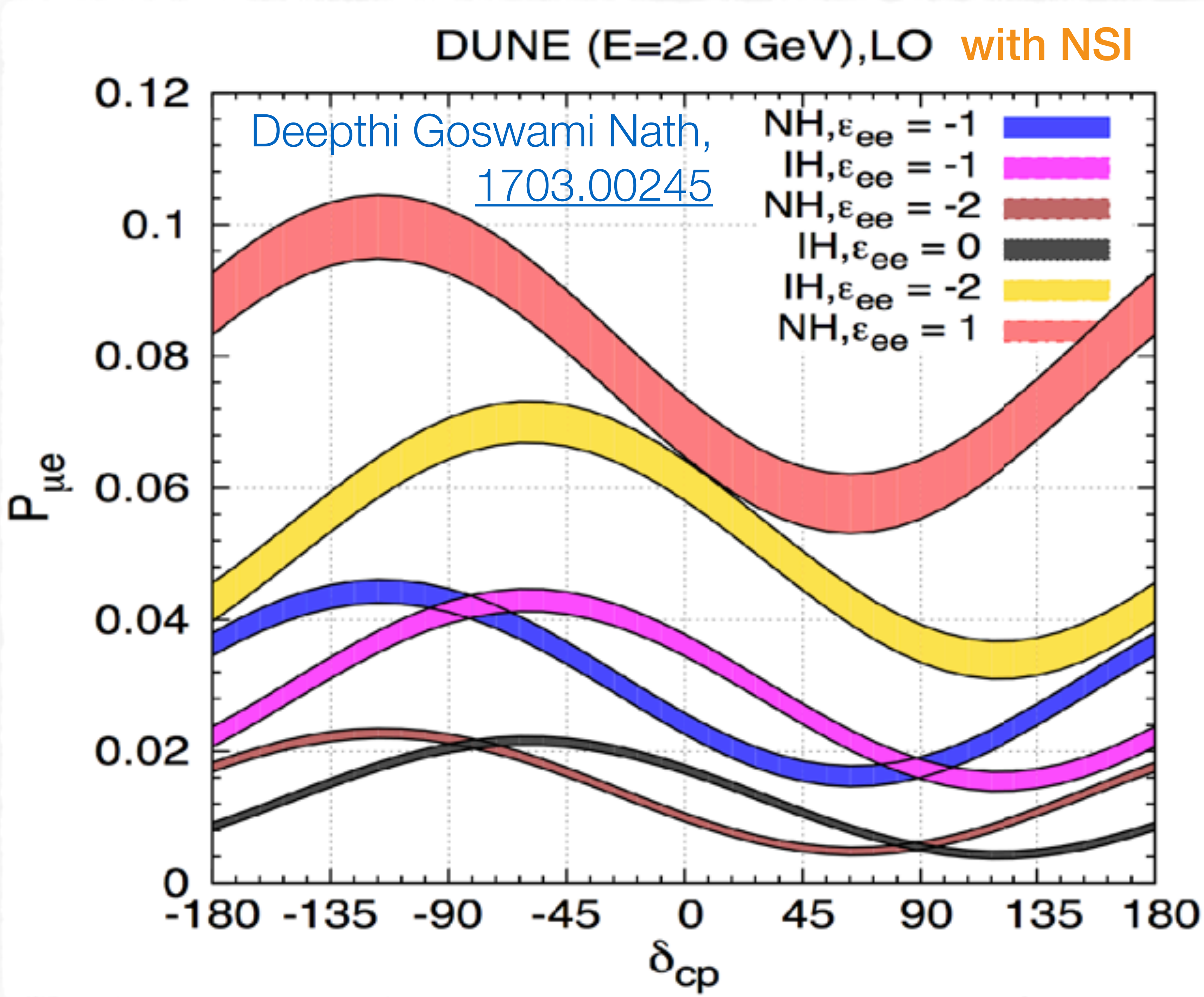
Long Baseline Phenomenology

- Optimization of Future Experiments
  - What are the most important physics goals?
  - SM precision measurements $\leftrightarrow$ BSM searches
  - Boundary conditions (available sites, budget, politics, …)
- How could BSM physics affect precision measurements?

Long Baseline Phenomenology

- Optim
  - Wh
  - SM
  - Bou
- How c ... ents?



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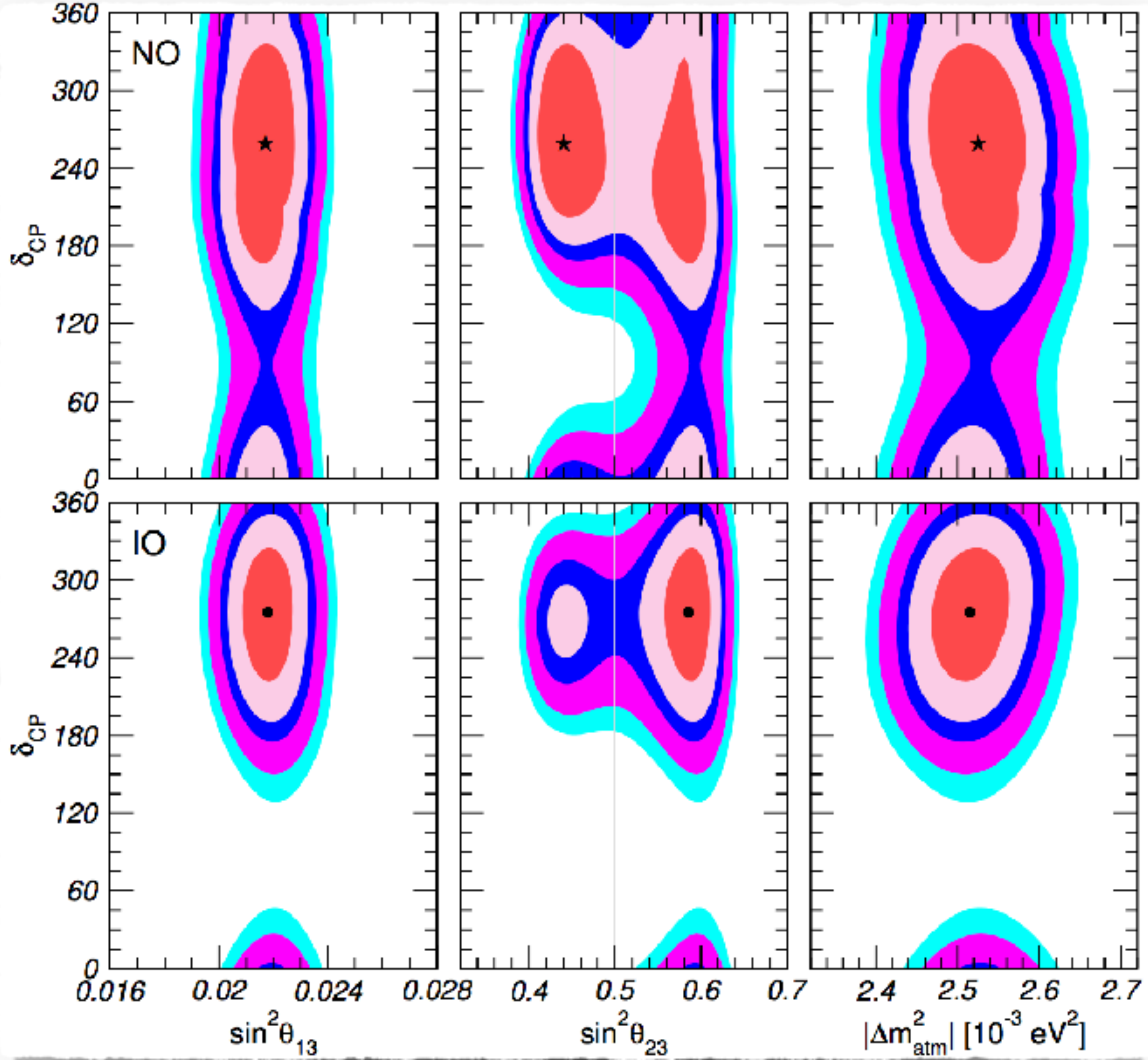
Global Fits

- Fits to oscillation data fraught with correlations and degeneracies
- Can often be resolved in global fits

NuFit 3.0 (Esteban Gonzalez-Garcia Maltoni Martinez Schwetz), 2016

Global Fits

- Fits to [partially obscured] ...generacies
- Can oft[partially obscured]



..., 2016

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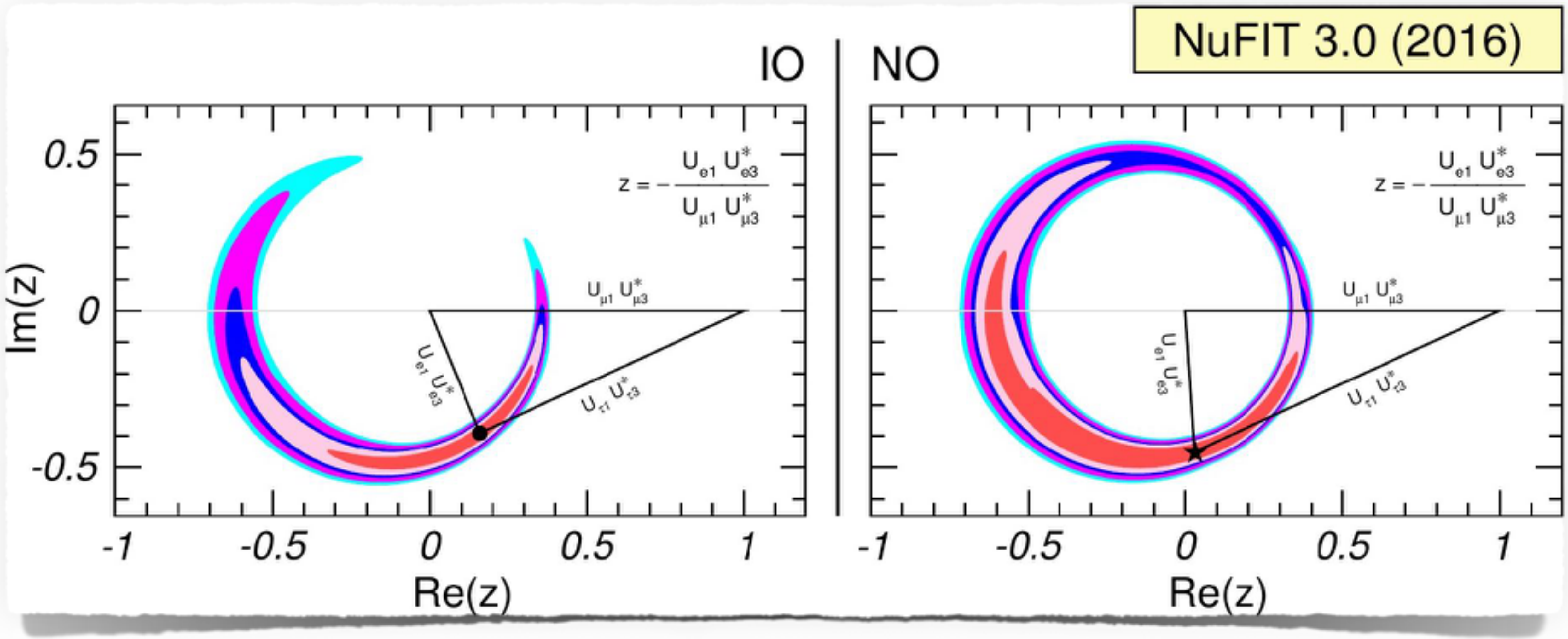

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Global Fits

- Fits to oscillation data fraught with correlations and degeneracies
- Can often be resolved in global fits

- ☆ $\mathcal{O}(\text{few } \%)$ precision
- ☆ no sensitivity to mass ordering, δ_{CP}, octant of θ_{23}
- ☆ … yet!
- ☆ First hints will probably emerge from global fits

NuFit 3.0 (Esteban Gonzalez-Garcia Maltoni Martinez Schwetz), 2016

Oscillation Anomalies

Anomalies in Short Baseline Oscillations

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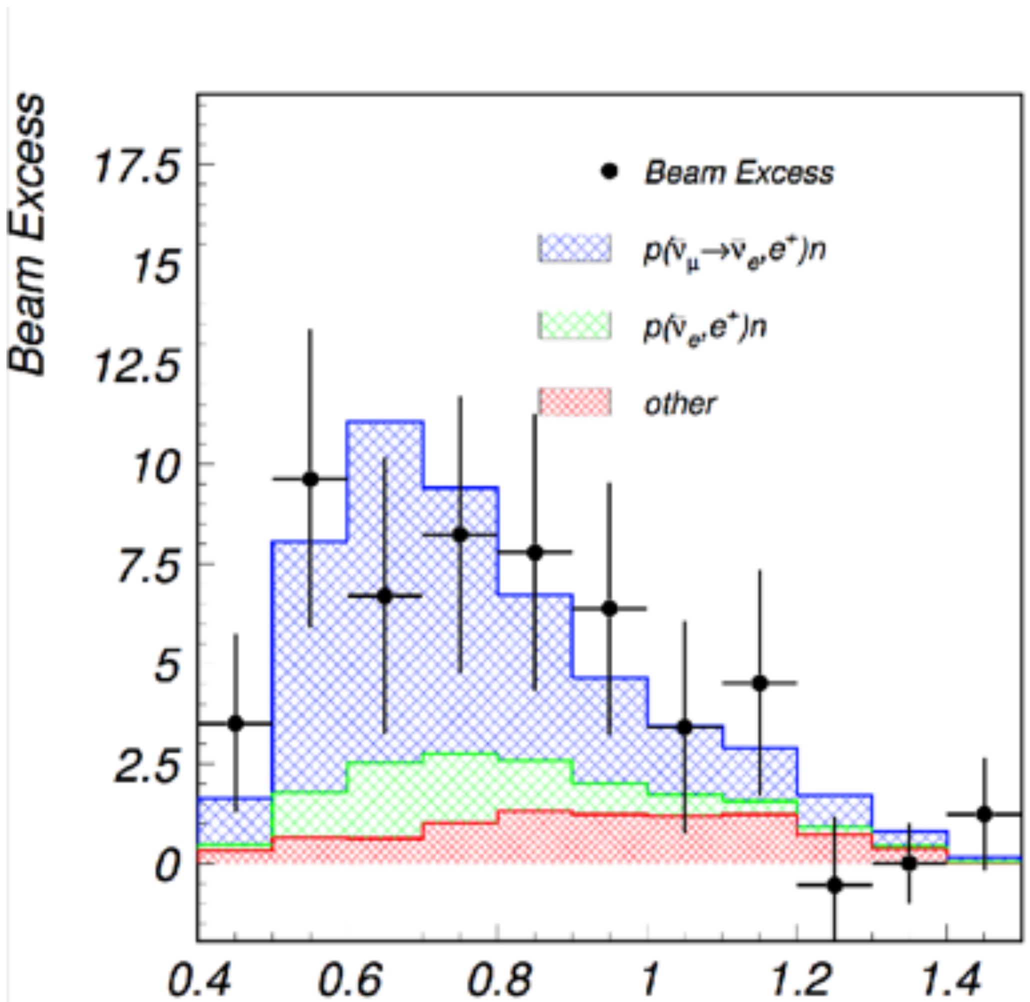
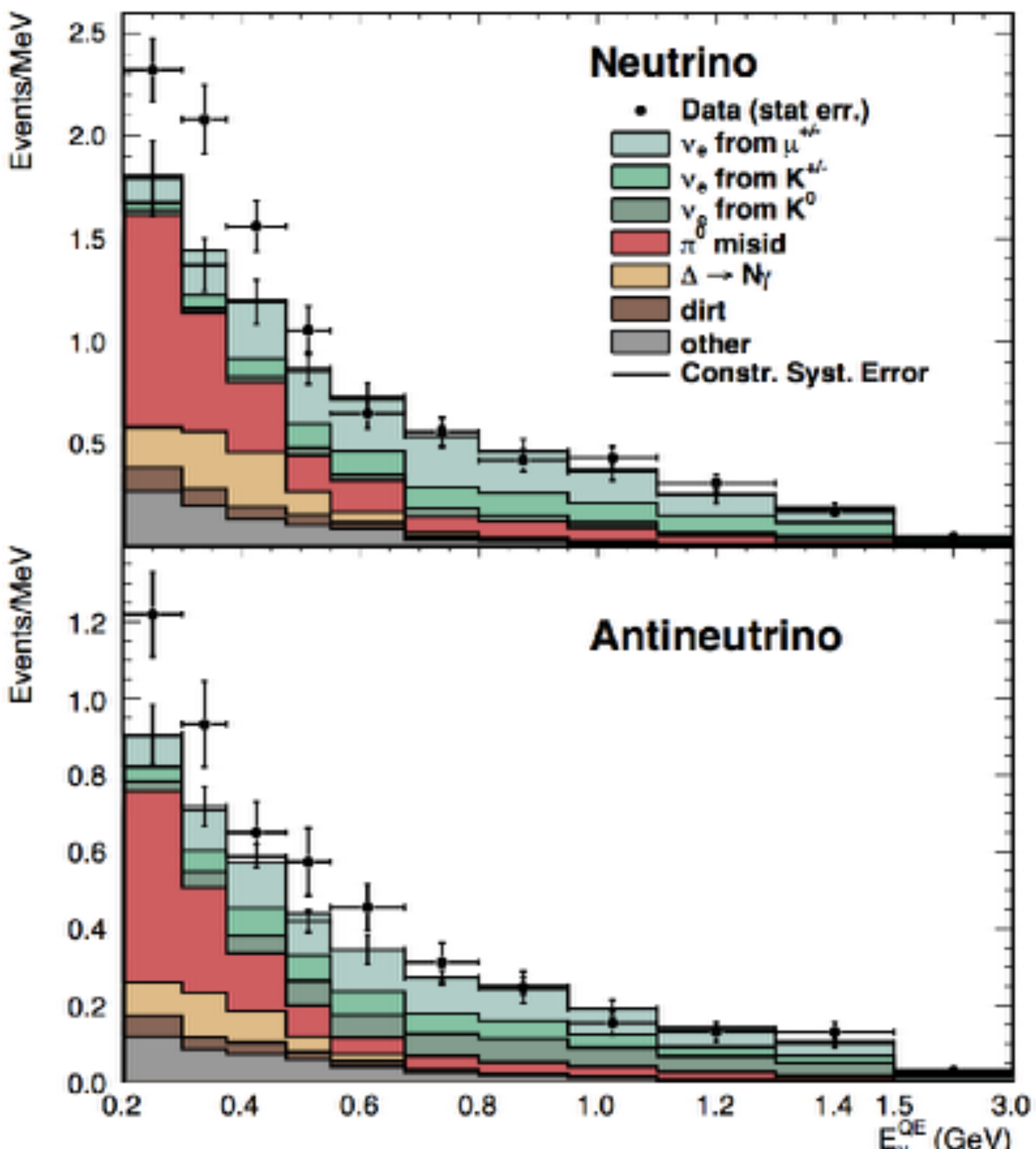
- LSND / MiniBooNE: anomalous $\nu_\mu \to \nu_e$ oscillations



LSND 2001



MiniBooNE 2001

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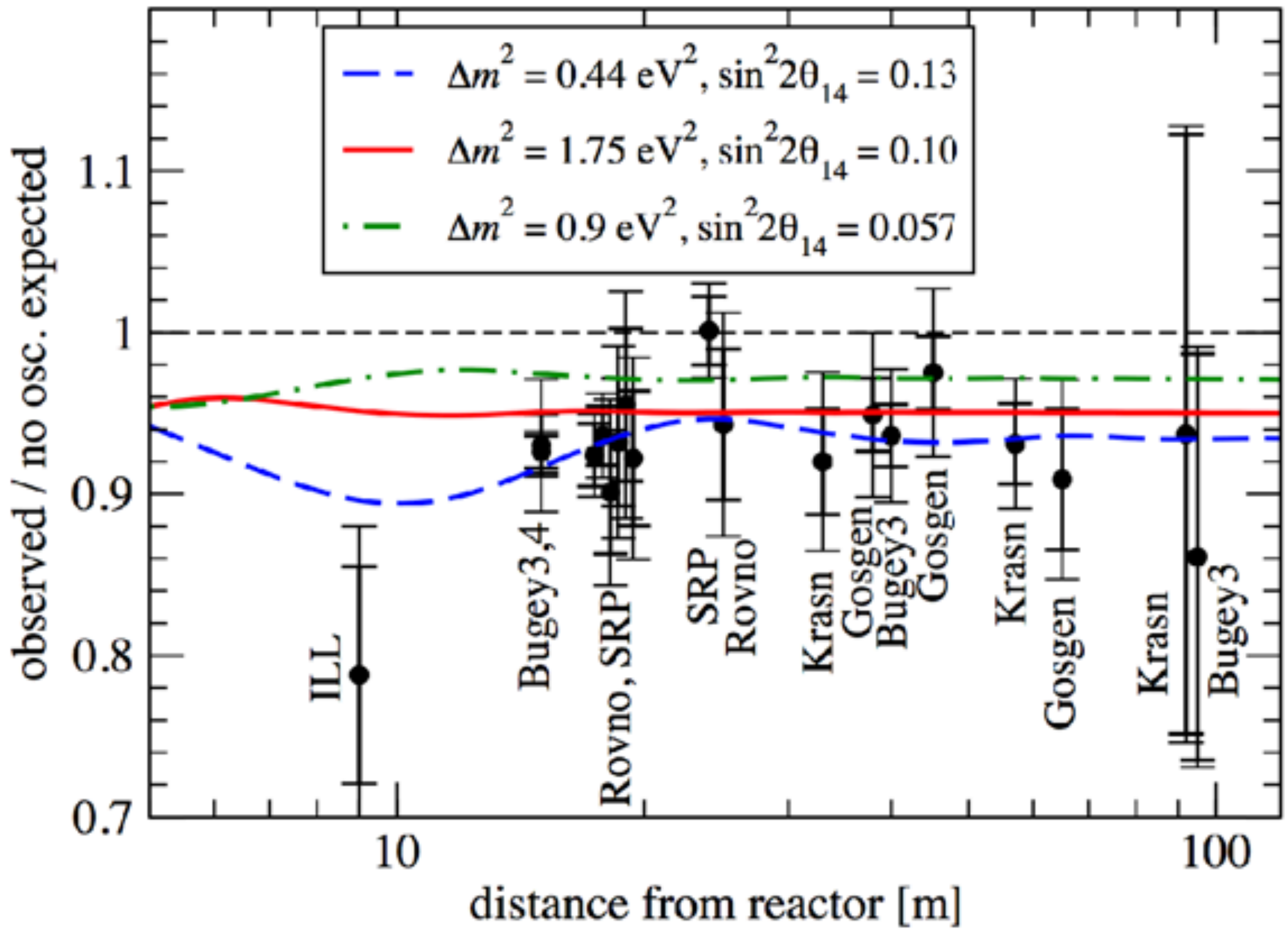
- Reactor & Gallium Experiments: anomalous ν_e disappearance



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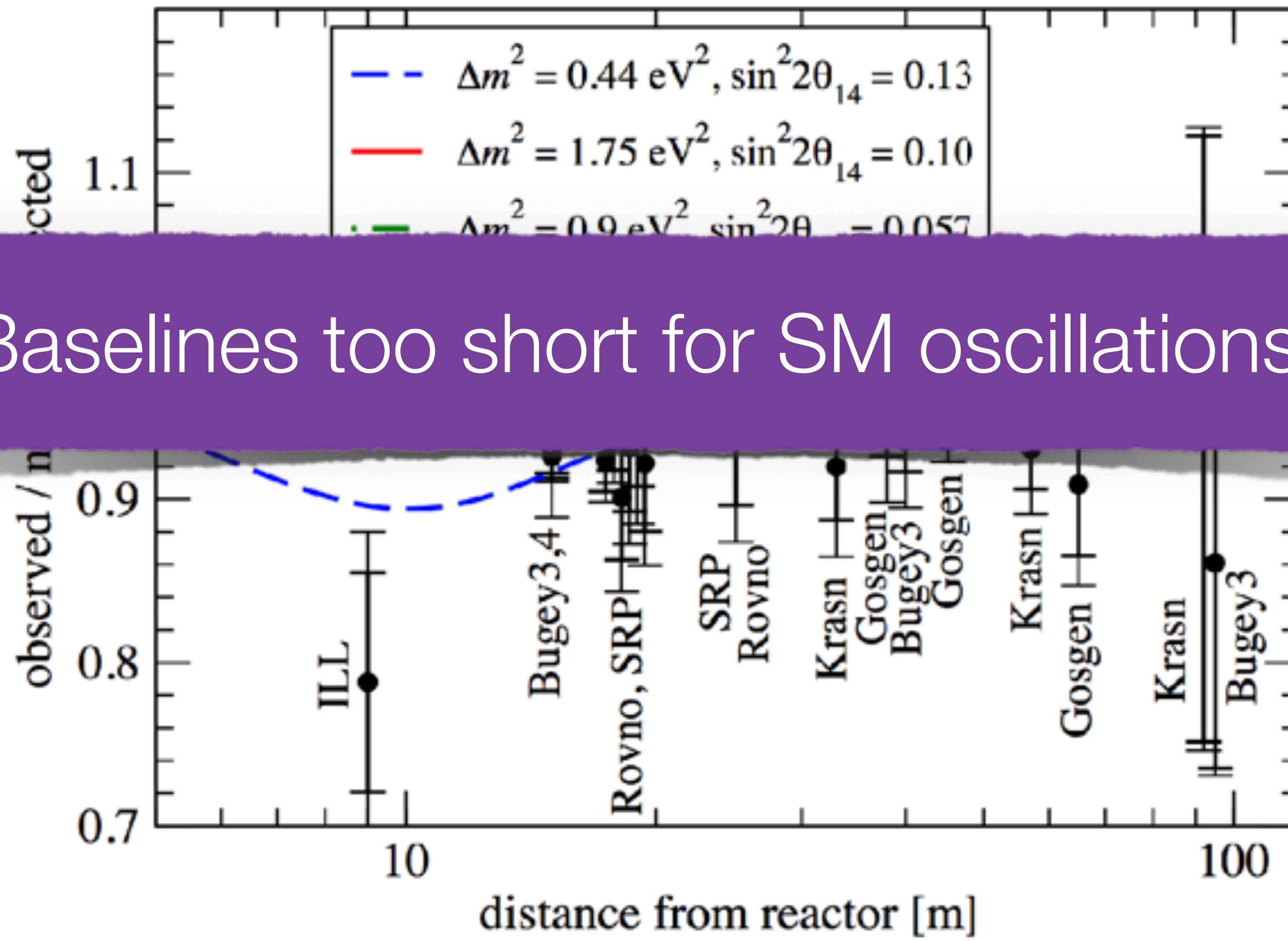


Baselines too short for SM oscillations!


“I felt a great disturbance in the force.”

Light Sterile Neutrinos?

- Promote mixing matrix to 4×4
- Oscillation channels are related:

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

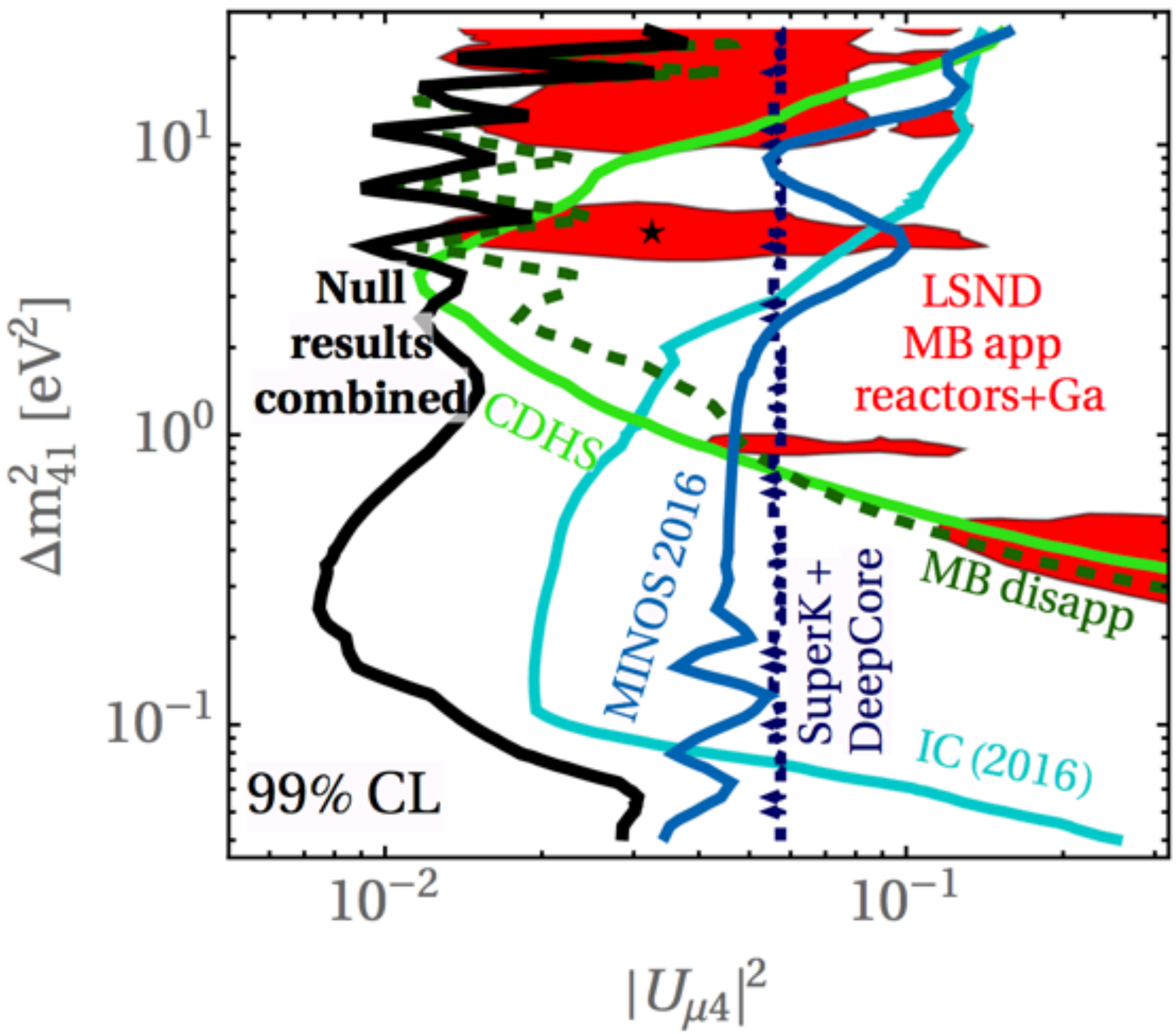
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

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

(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, in preparation
see also works by Collin Argüelles Conrad Shaevitz, 1607.00011,
Gariazzo Giunti Laveder Li, 1703.00860

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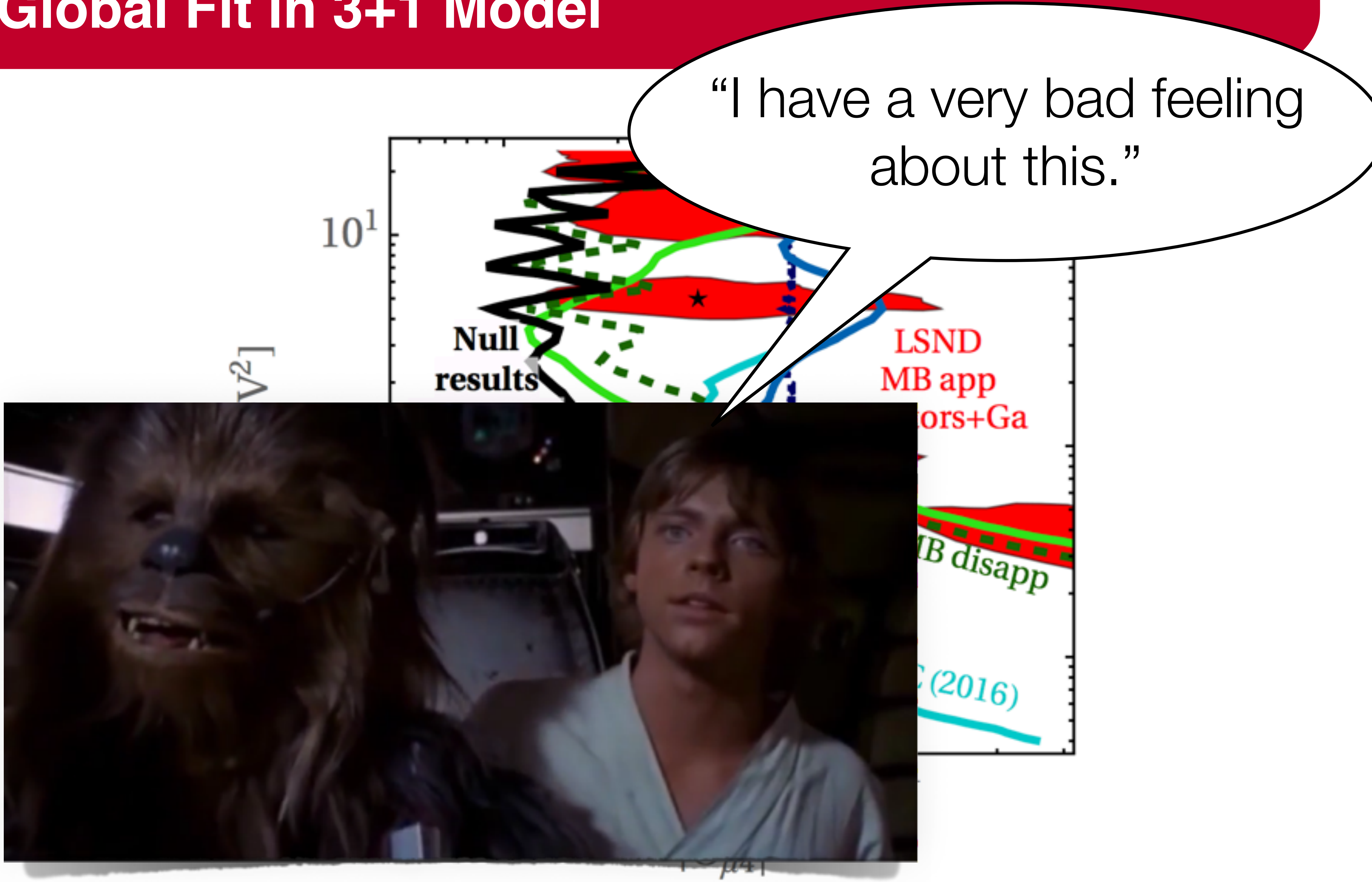

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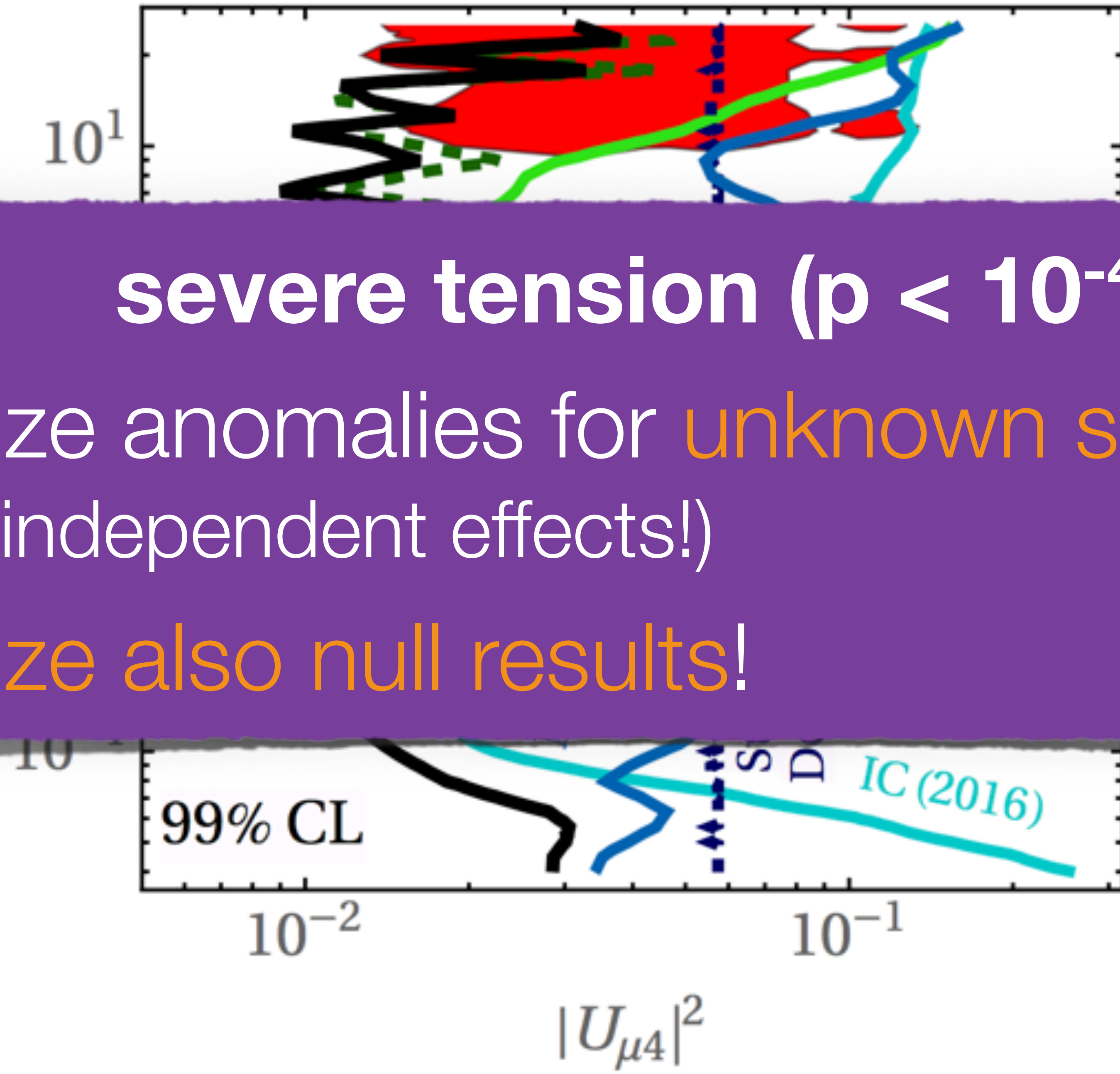

severe tension ($p < 10^{-4}$)

- ☆ scrutinize anomalies for unknown systematics (need 4 independent effects!)
- ☆ scrutinize also null results!

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Reconciling Sterile Neutrinos with Cosmology

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

Constrained by N_{eff} and Σm_ν

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Standard picture: ν_s production via oscillation at T ≳ MeV

Constrained by N_{eff} and Σm_ν

☑ Entropy production at T < MeV

- ν_s diluted — Fuller Kishimoto Kusenko, 1110.6479; Ho Scherrer, 1212.1689

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  - production suppressed by thermal potential

Hannestad et al. 1310.5926; Dasgupta JK, 1310.6337

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    Hannestad et al. 1310.5926; Dasgupta JK, 1310.6337
- ☑ ν_s properties change in late phase transition

  Bezrukov Chudaykin Gorbunov, 1705.02184

Flux Measurement by Daya Bay

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- Reactor fuel composition evolves with time ("burnup")

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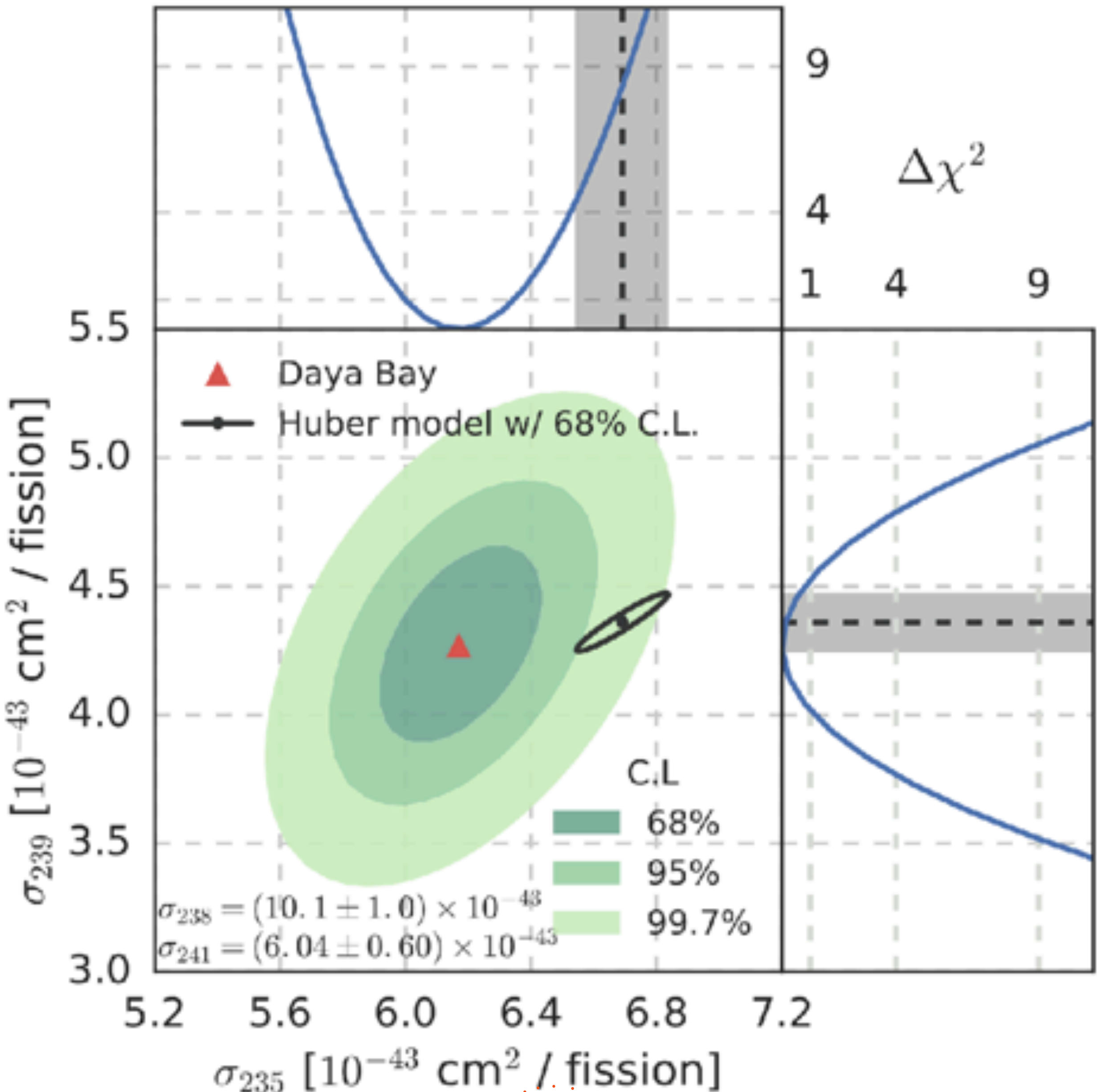

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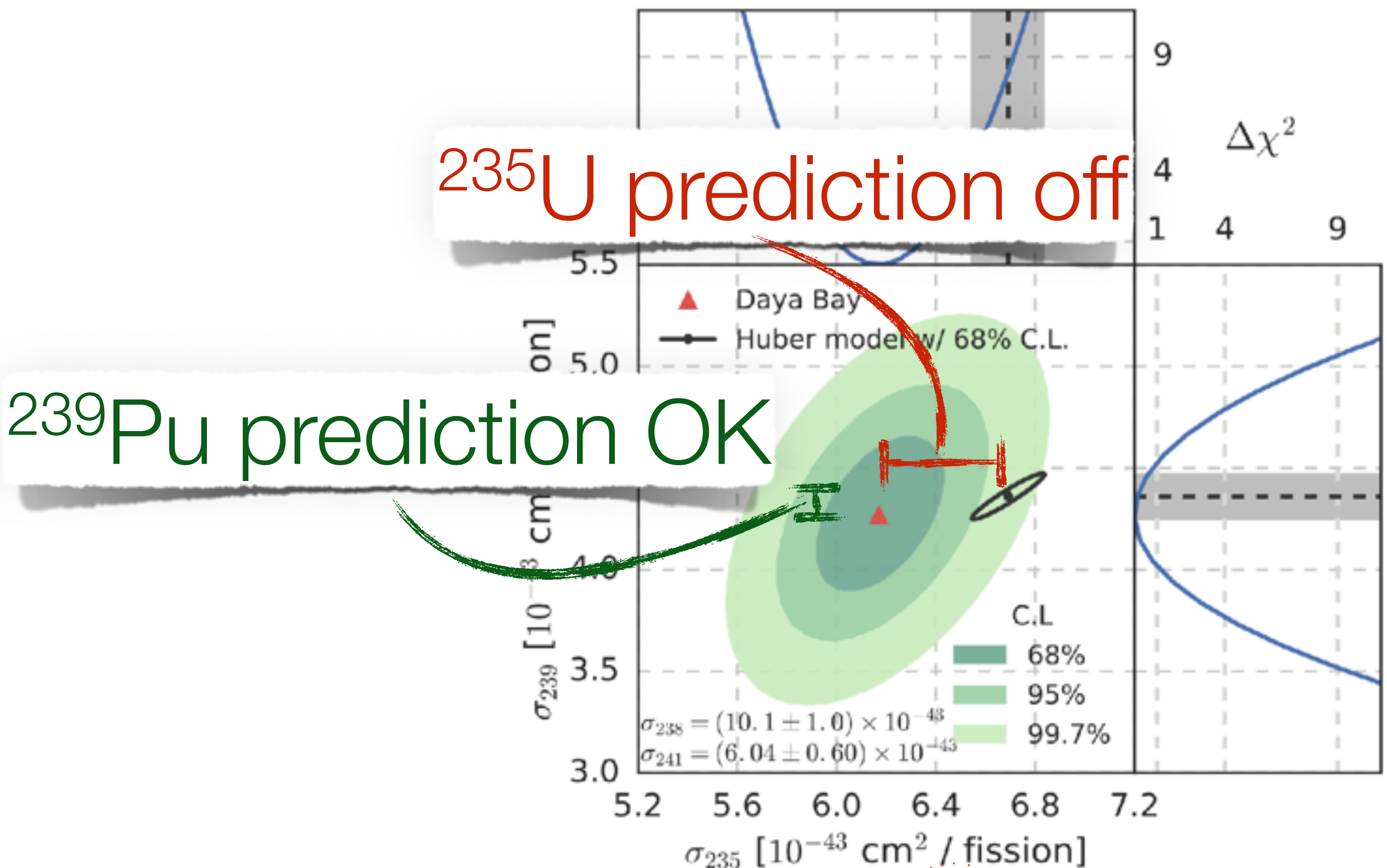

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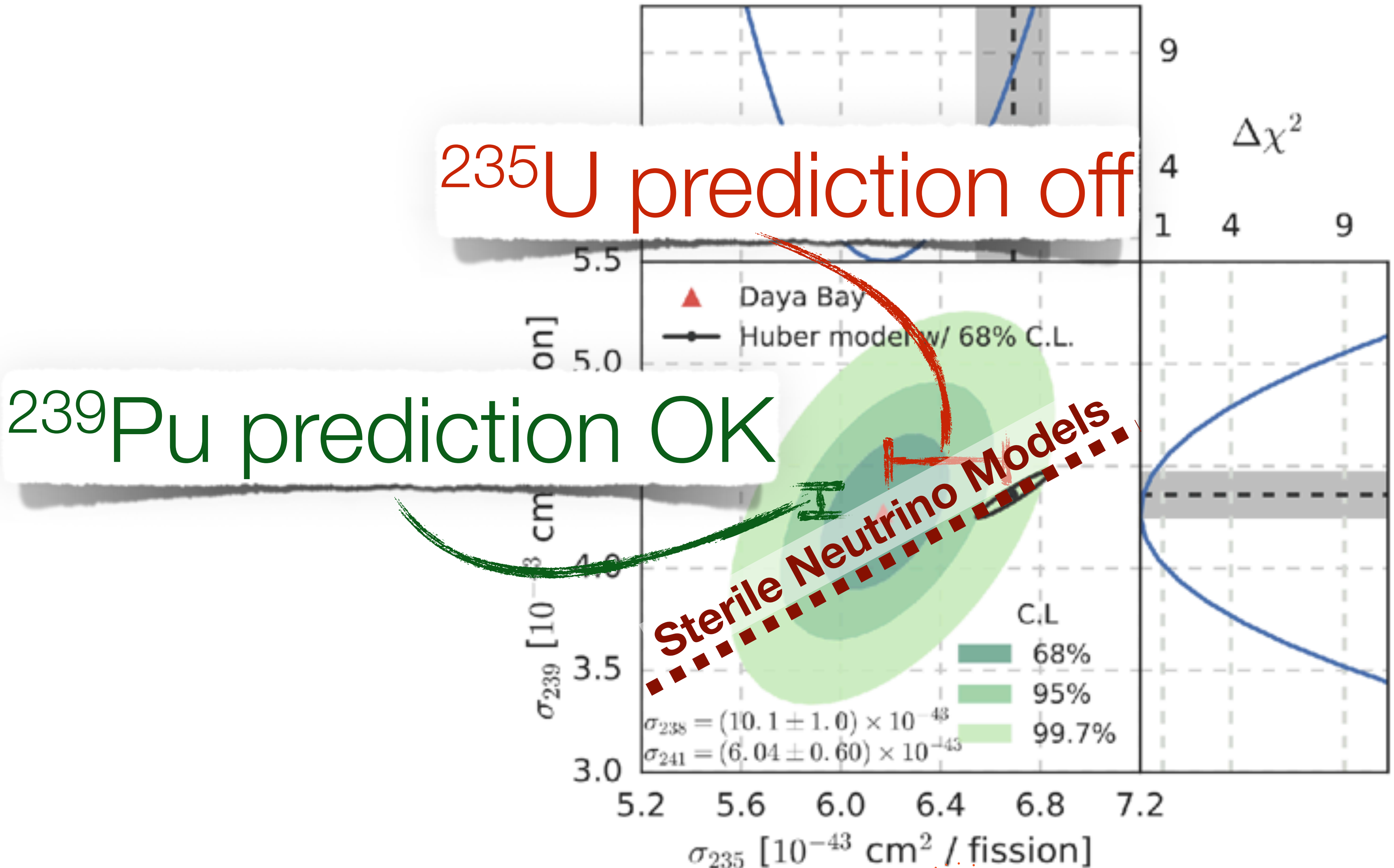

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$$\Delta\chi^2 = 7.9$$

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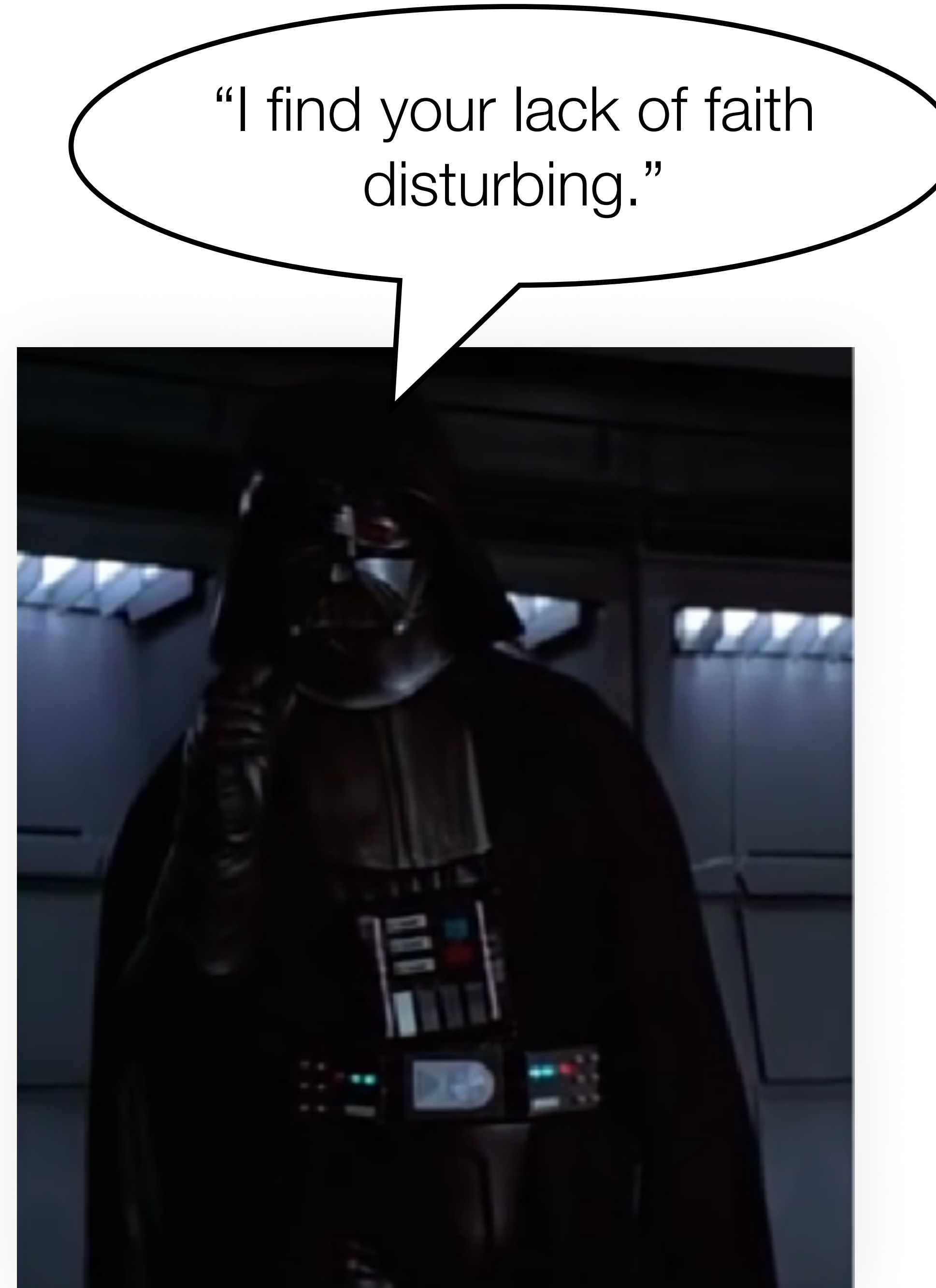
Fluxes within errors + $\sin^2 2\theta_{14}, \Delta m^2_{41}$	: p = 0.18
Fluxes free	: p = 0.73
$\Delta\chi^2$(sterile neutrino vs. free fluxes)	: p = 0.006

Hernandez Schwetz, in preparation

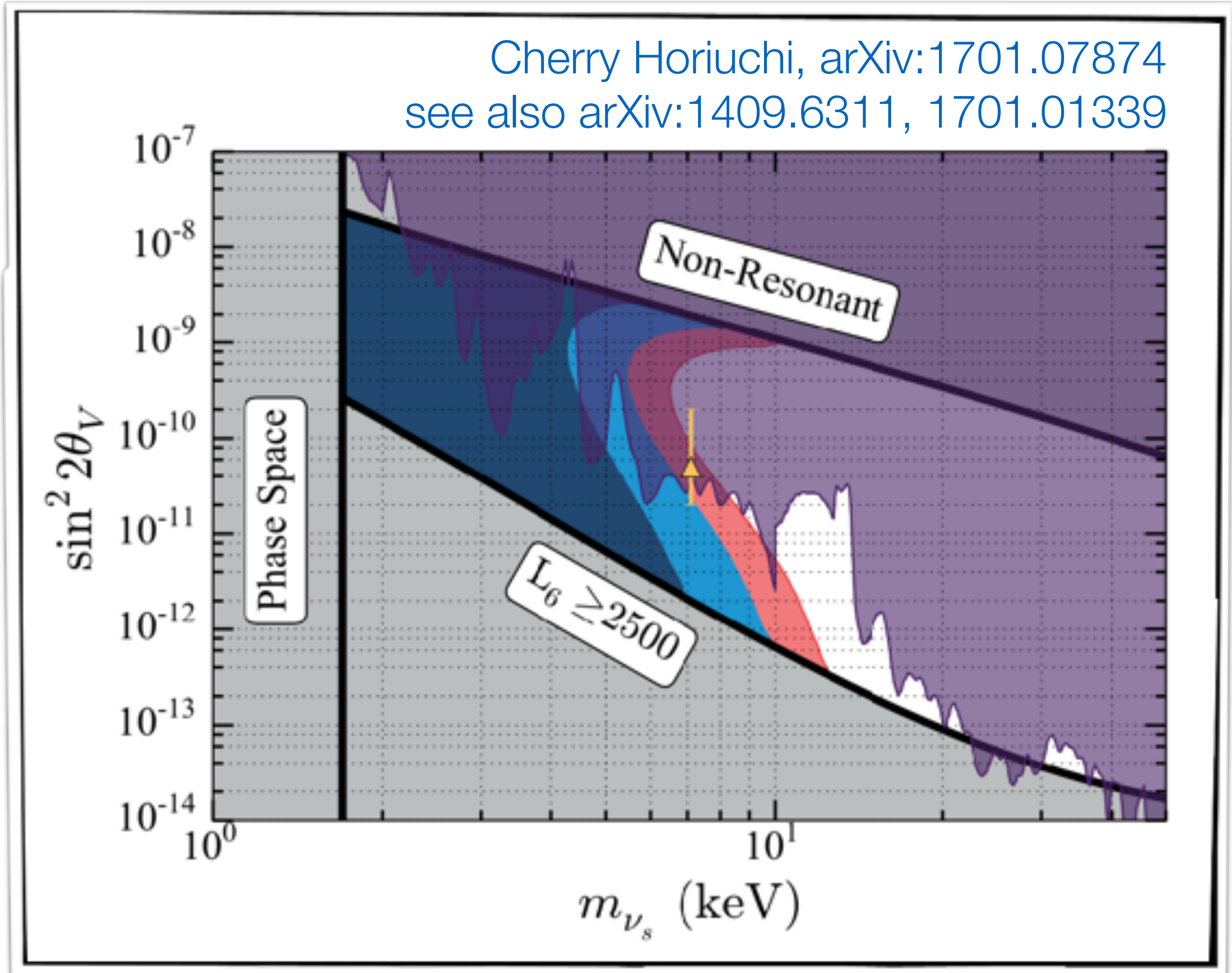

“Many of the truths we cling to depend greatly on our own point of view.”


“I find your lack of faith disturbing.”

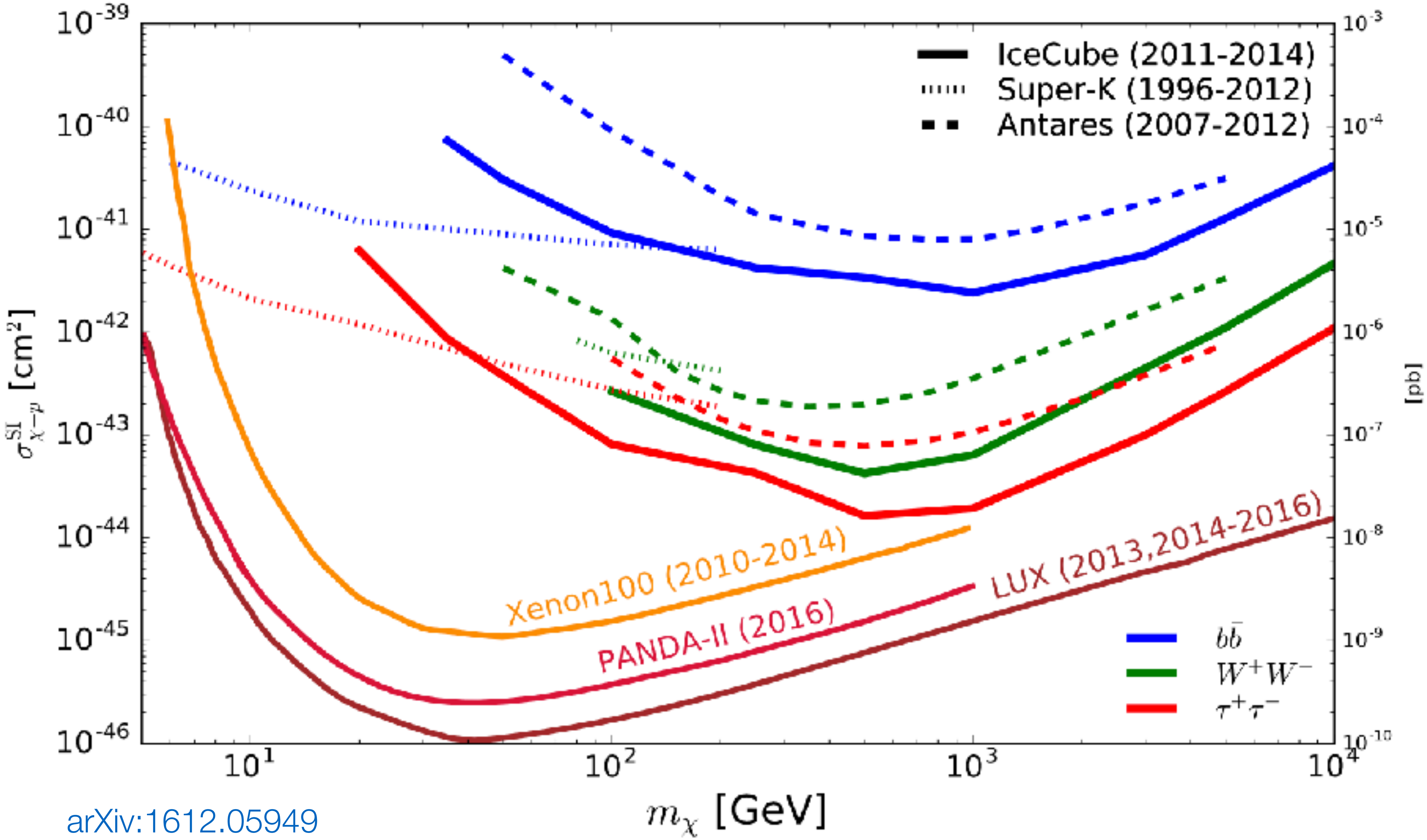
Neutrinos and Dark Matter

Sterile Neutrinos as Dark Matter

- Leading candidate for Warm Dark Matter
  - Improved small scale structure
  - x-ray line signature
- Production through oscillations challenged by e.g. Lyman-α data
- Promising alternative production mechanisms
  - Decays of heavy particles
  - High-T freeze-in



DM Annihilation in the Sun



arXiv:1612.05949

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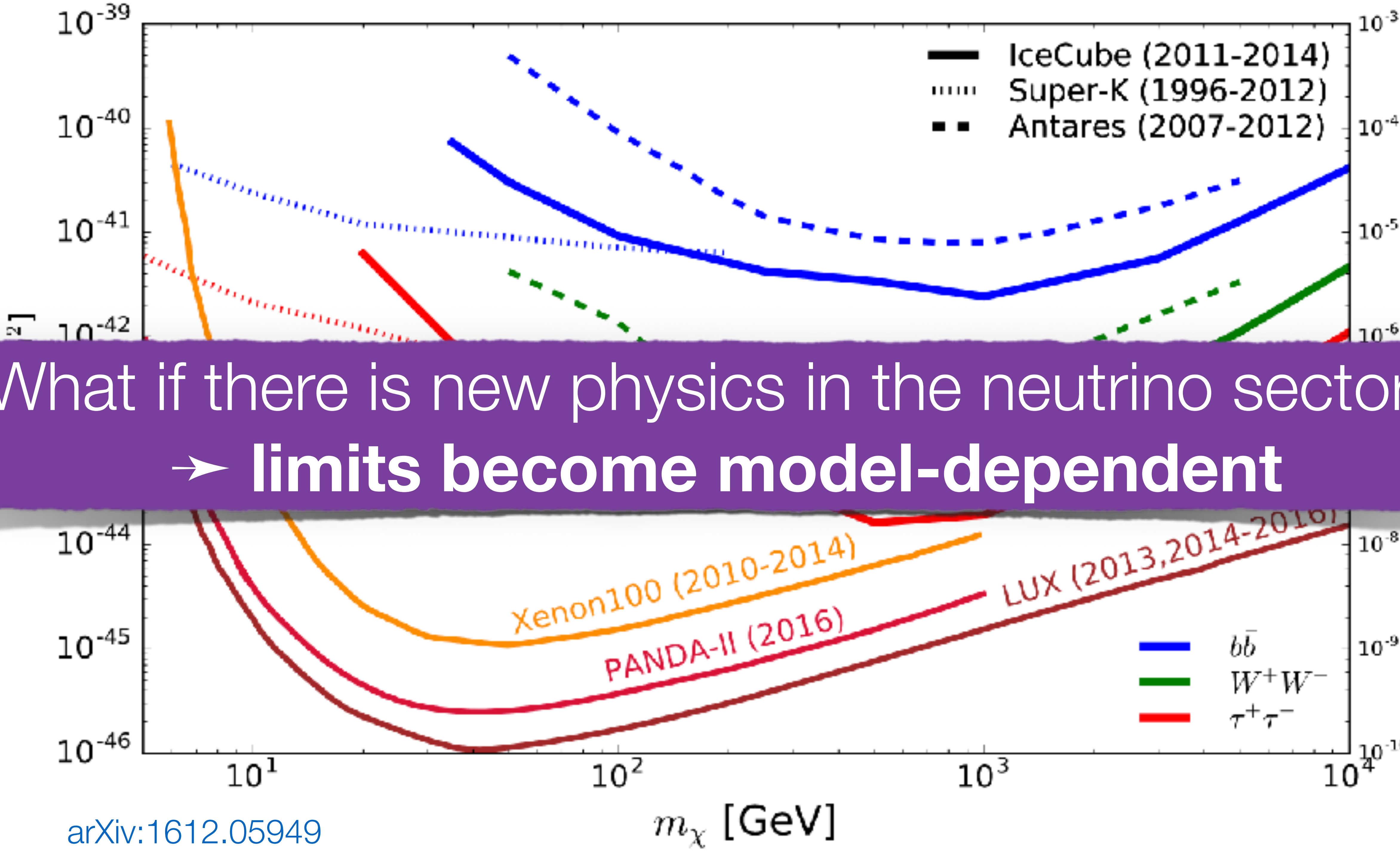


What if there is new physics in the neutrino sector?

➛ **limits become model-dependent**

arXiv:1612.05949

Neutrino—DM Interactions

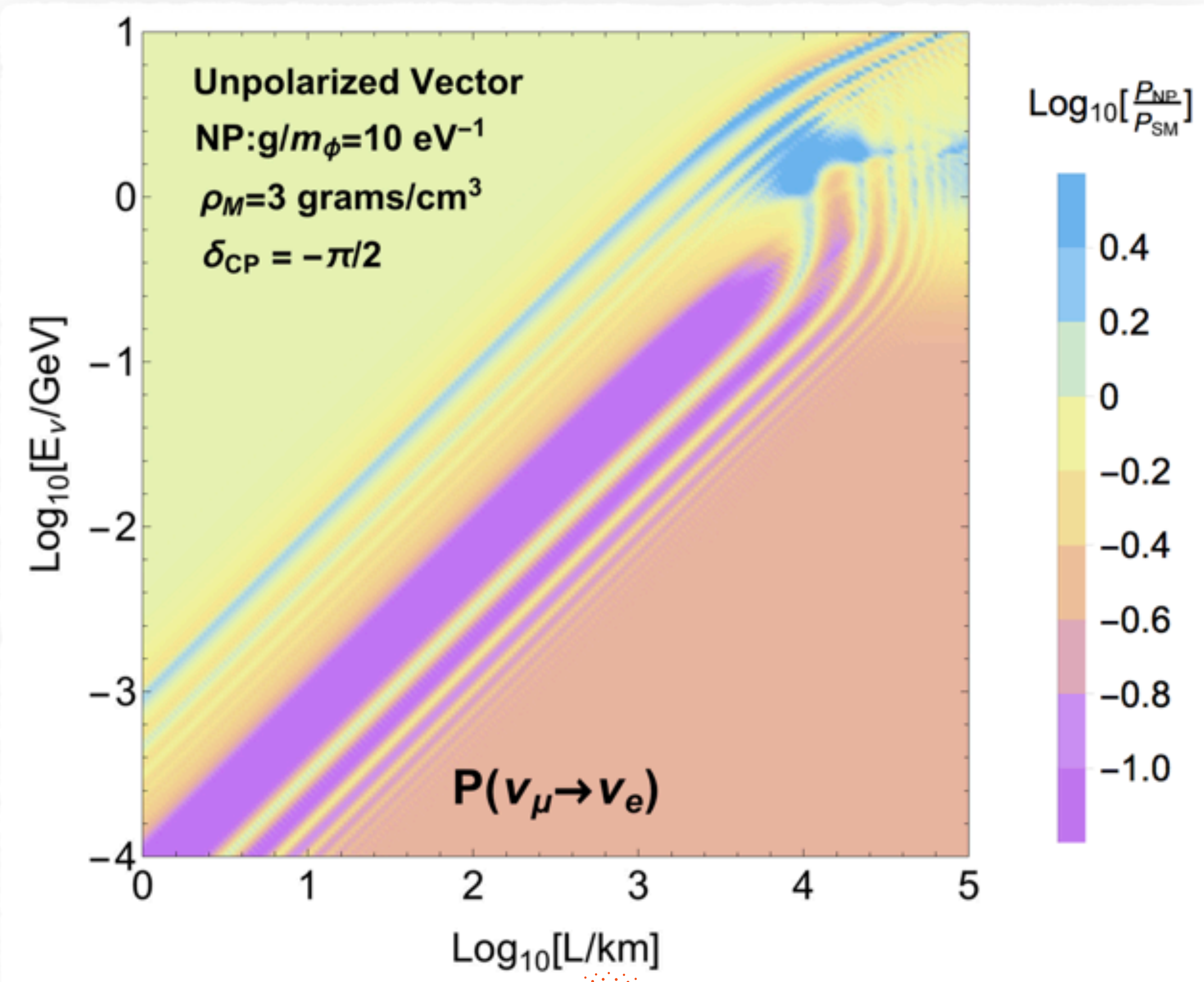
- ☑ Coherent forward scattering of neutrinos on DM
  - analogous to SM matter effects (“MSW effect”)
  - Requires huge DM number density
- ☑ Fuzzy Dark Matter
  - scalar or vector, $m < 10^{-20}\,\mathrm{eV}$
  - Compton wave length $\sim \mathrm{pc}$
  - Interesting for small scale structure

Krnjaic Machado Necib, 1705.06740
Brdar JK Liu Prass Wang, 1705.09455

Neutrino—DM Interactions

- Coherent
  - anal
  - Req
- Fuzzy
  - scal
  - Con
  - Inte

Modified Oscillation Probabilities



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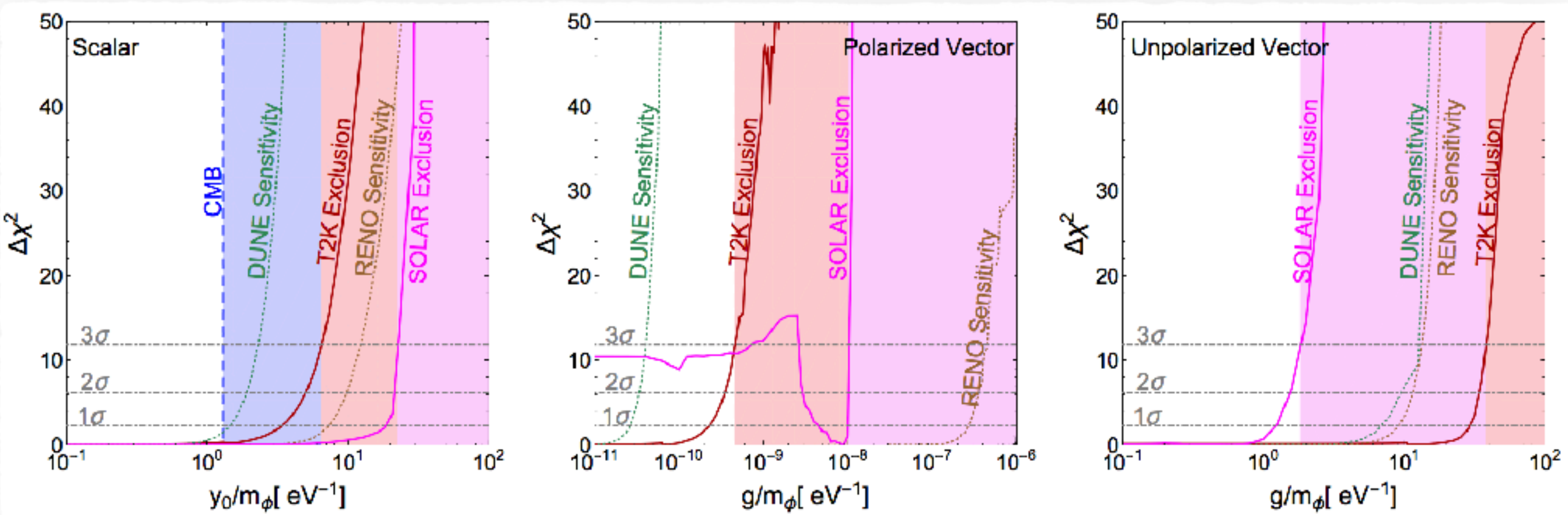
  - an
  - Re

Limits from Long-Baseline Experiments




“You underestimate the power of the dark side.”

Matrix Elements for Neutrinoless Double Beta Decay

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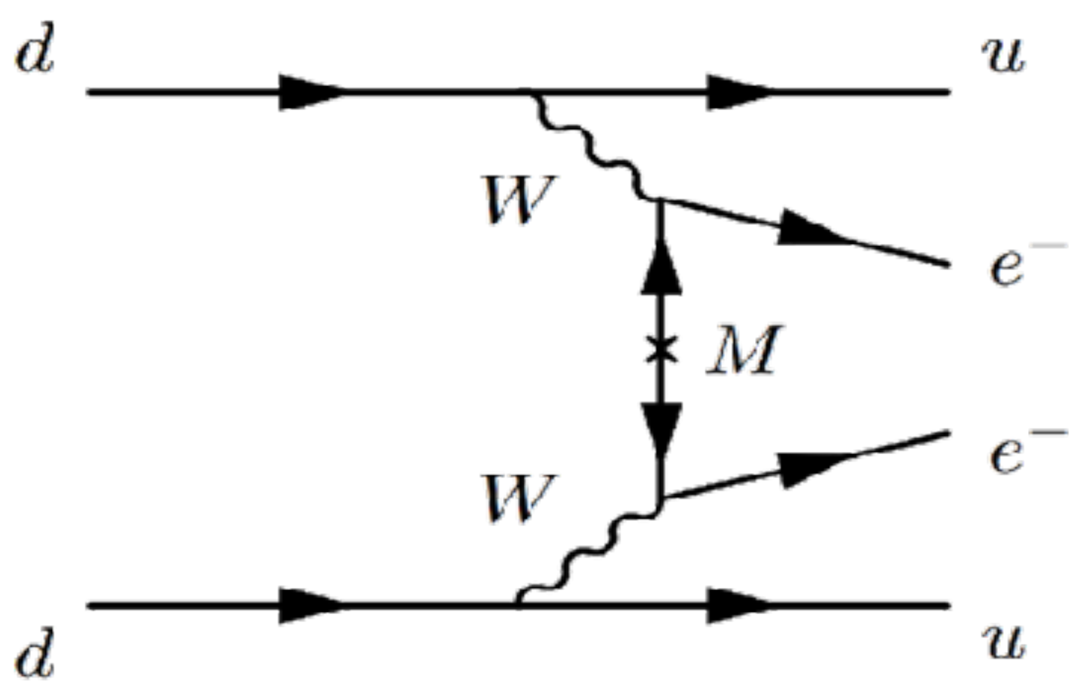
“Never tell me the odds.”

Neutrinoless Double Beta Decay

$$\Gamma \propto G_F^4 \, |\mathcal{M}|^2 \left| \sum U_{ej}^2 m_j \right|^2 p_e^2$$



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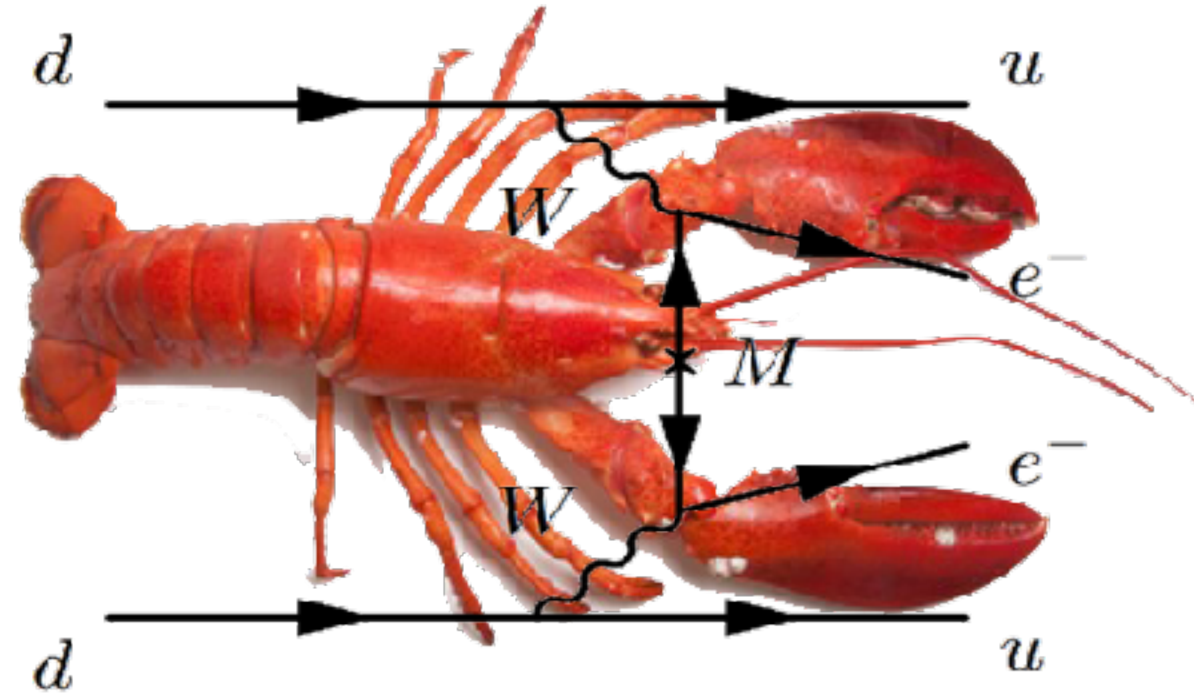

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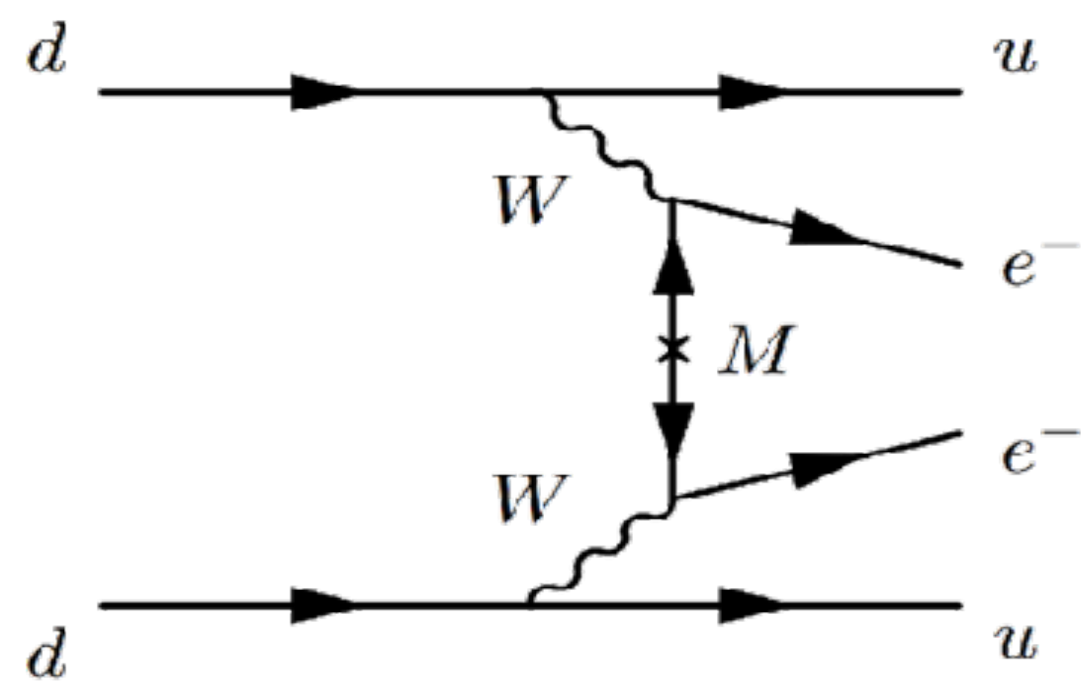

Neutrinoless Double Beta Decay

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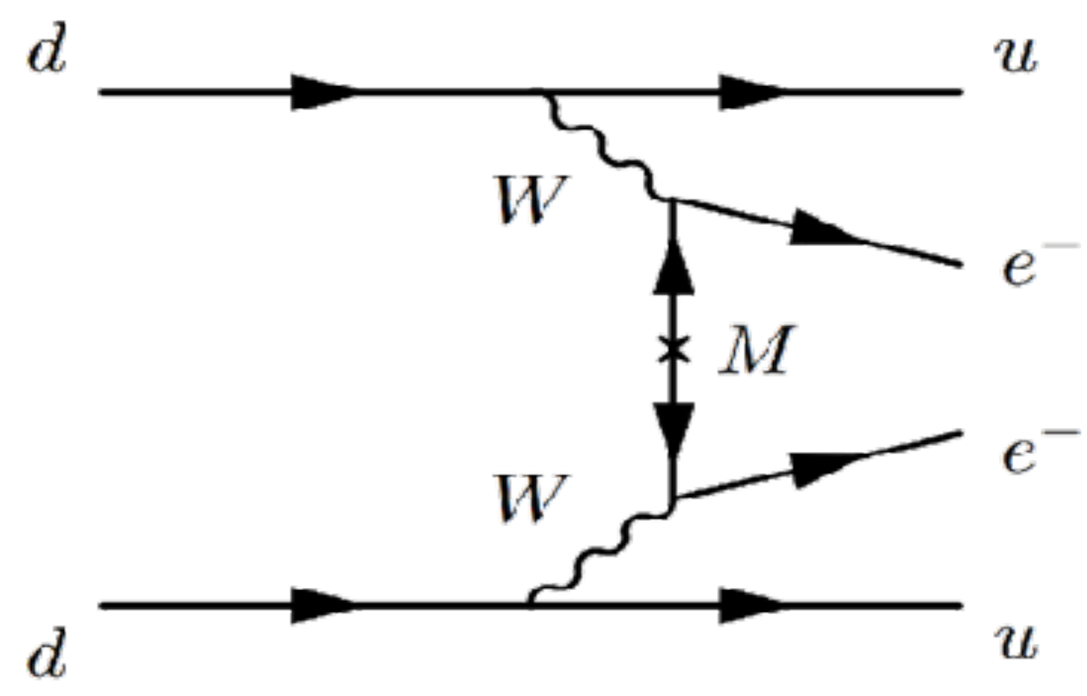
well understood

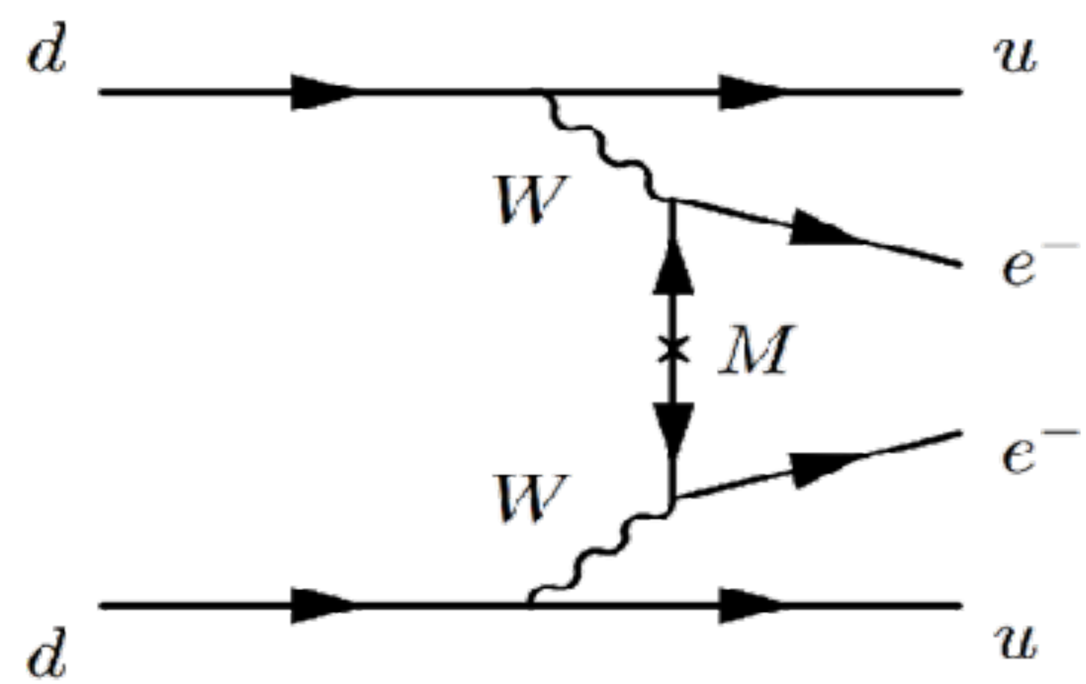


Neutrinoless Double Beta Decay

$$\Gamma \propto G_F^4 |\mathcal{M}|^2 \left| \sum U_{ej}^2 m_j \right|^2 p_e^2$$

black magic

well understood



Nuclear Theory for 0ν2β Decay

- Nuclear Matrix Elements cannot be measured independently
- Nuclear Shell Model
  - good for small nuclei
  - fails for heavy nuclei, does not capture multiparticle excitation
- Quasiparticle Random Phase Approximation (QRPA)
  - quasiparticle state = linear combination of single nucleon states
  - large set of states
  - but less accurate description of nucleon—nucleon correlations
- Currently $\mathcal{O}(1)$ uncertainties
- Future:
  - Improvements to Shell Model, QRPA
  - Ab Initio method (e.g. in χPT)

Engel Menéndez, 1610.06548

Nuclear Theory for 0ν2β Decay

- Nuclear Ma ... ependently
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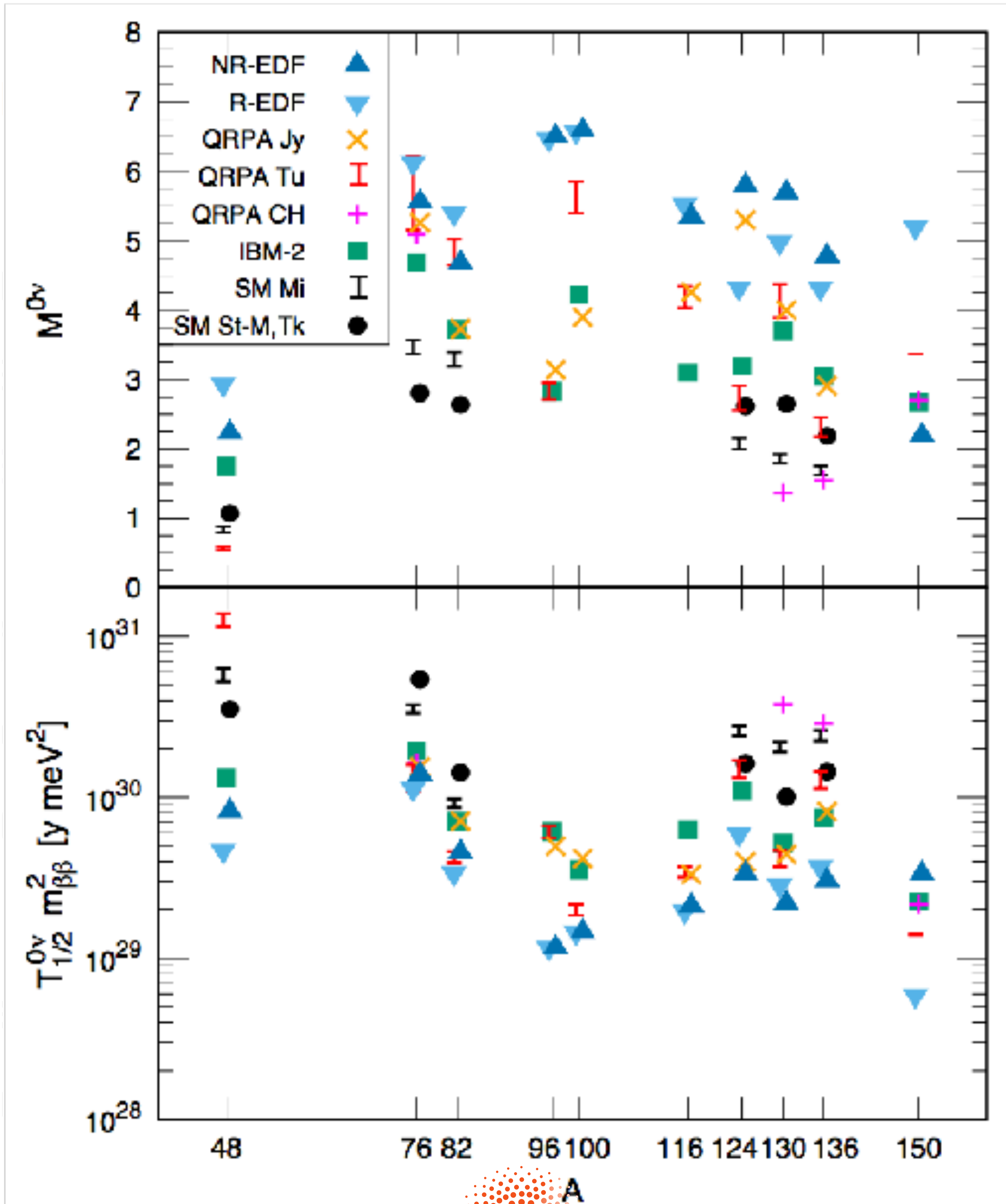

... dez, 1610.06548

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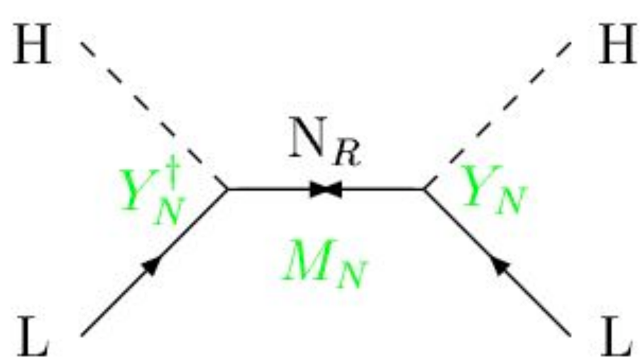
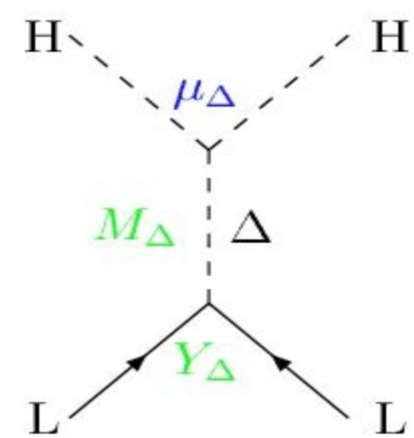
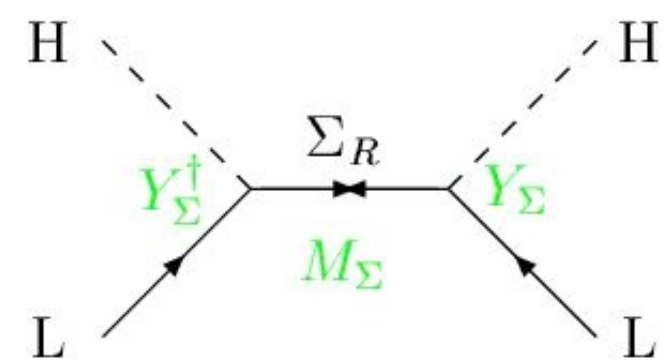
Understanding Neutrino Mass and Mixing

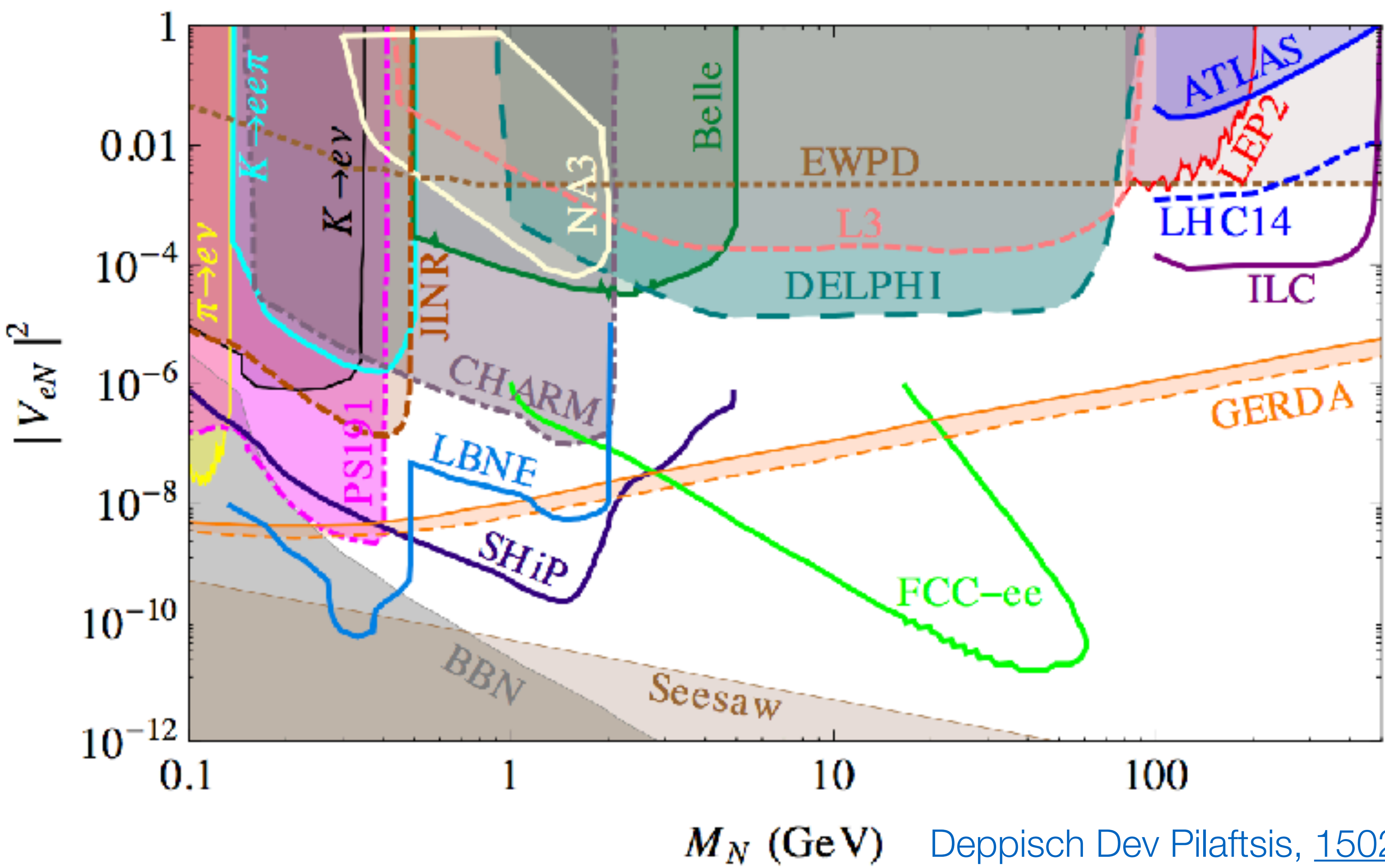
Seesaw Models

Right-handed singlet: (type-I seesaw)	Scalar triplet: (type-II seesaw)	Fermion triplet: (type-III seesaw)
		
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$	$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$	$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$
Minkowski; Gellman, Ramon, Slansky; Yanagida;Glashow; Mohapatra, Senjanovic	Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle	Foot, Lew, He, Joshi; Ma; Ma, Roy;T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

slide by Thomas Hambye

Direct Production of RH Neutrinos

- ☑ Generic seesaw scale (10^{14} GeV) out of reach
- ☑ Opportunities in low-scale seesaw, LR symmetry, B-L models.



Deppisch Dev Pilaftsis, 1502.06541
Alekhin et al., 1504.04855

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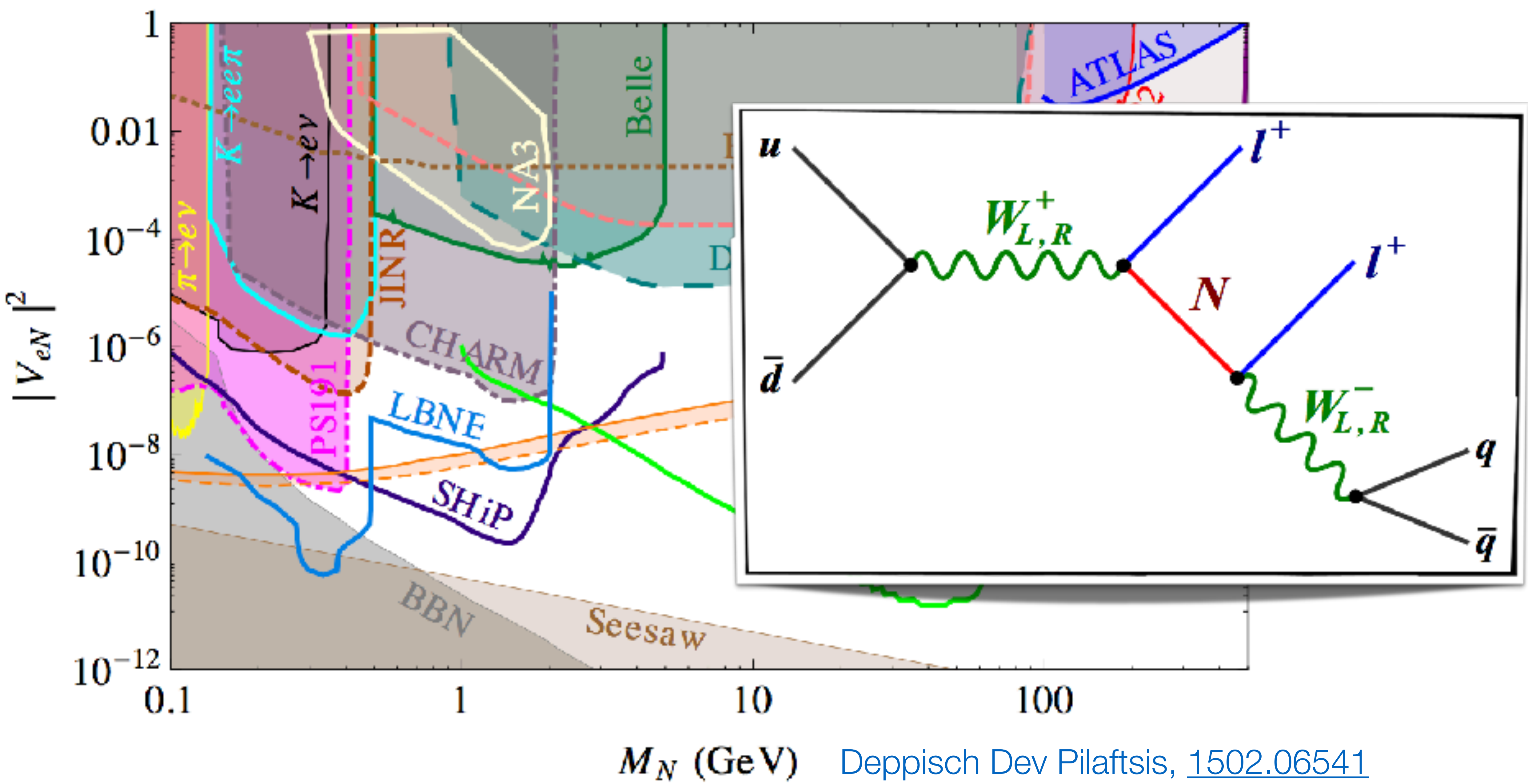

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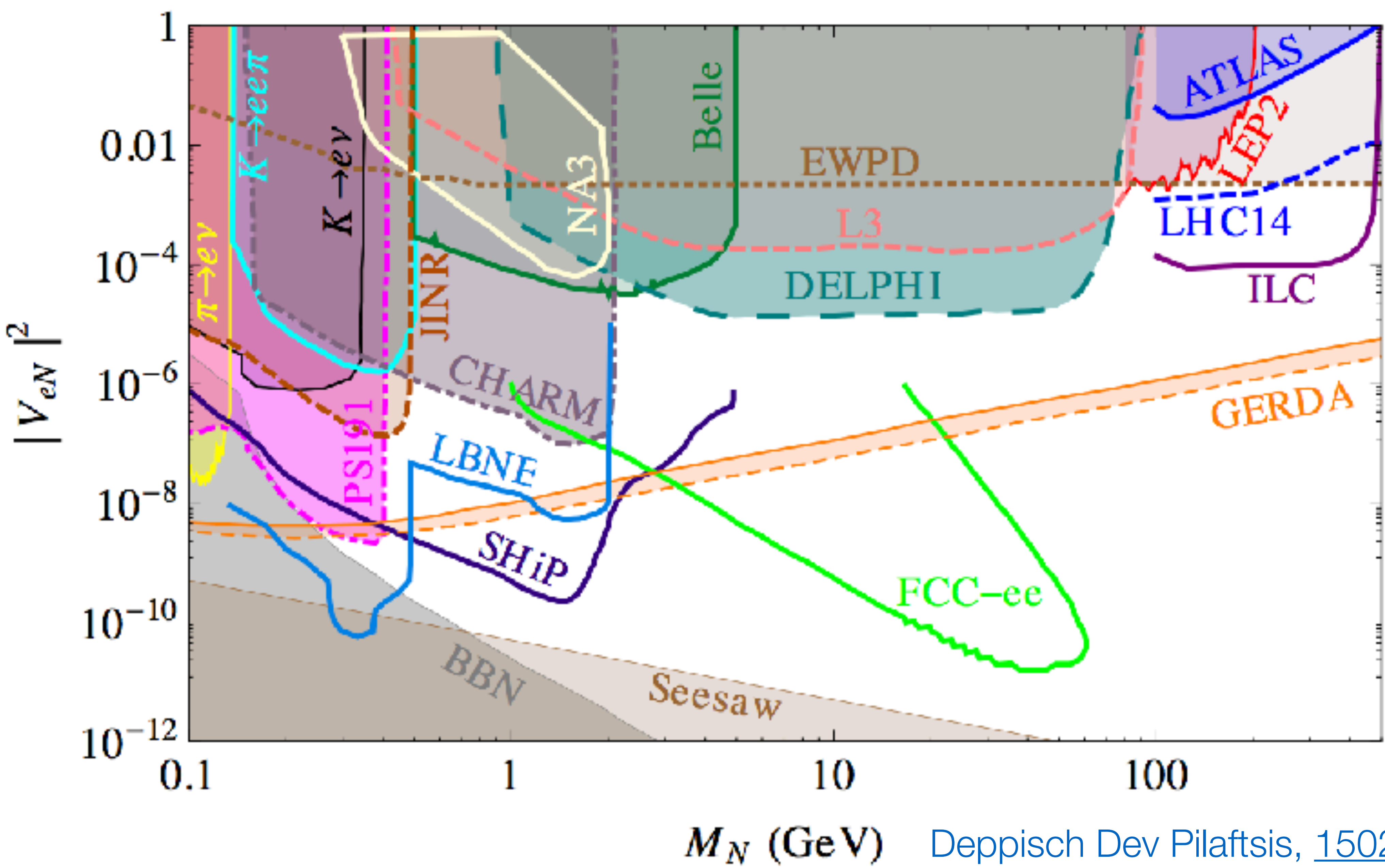

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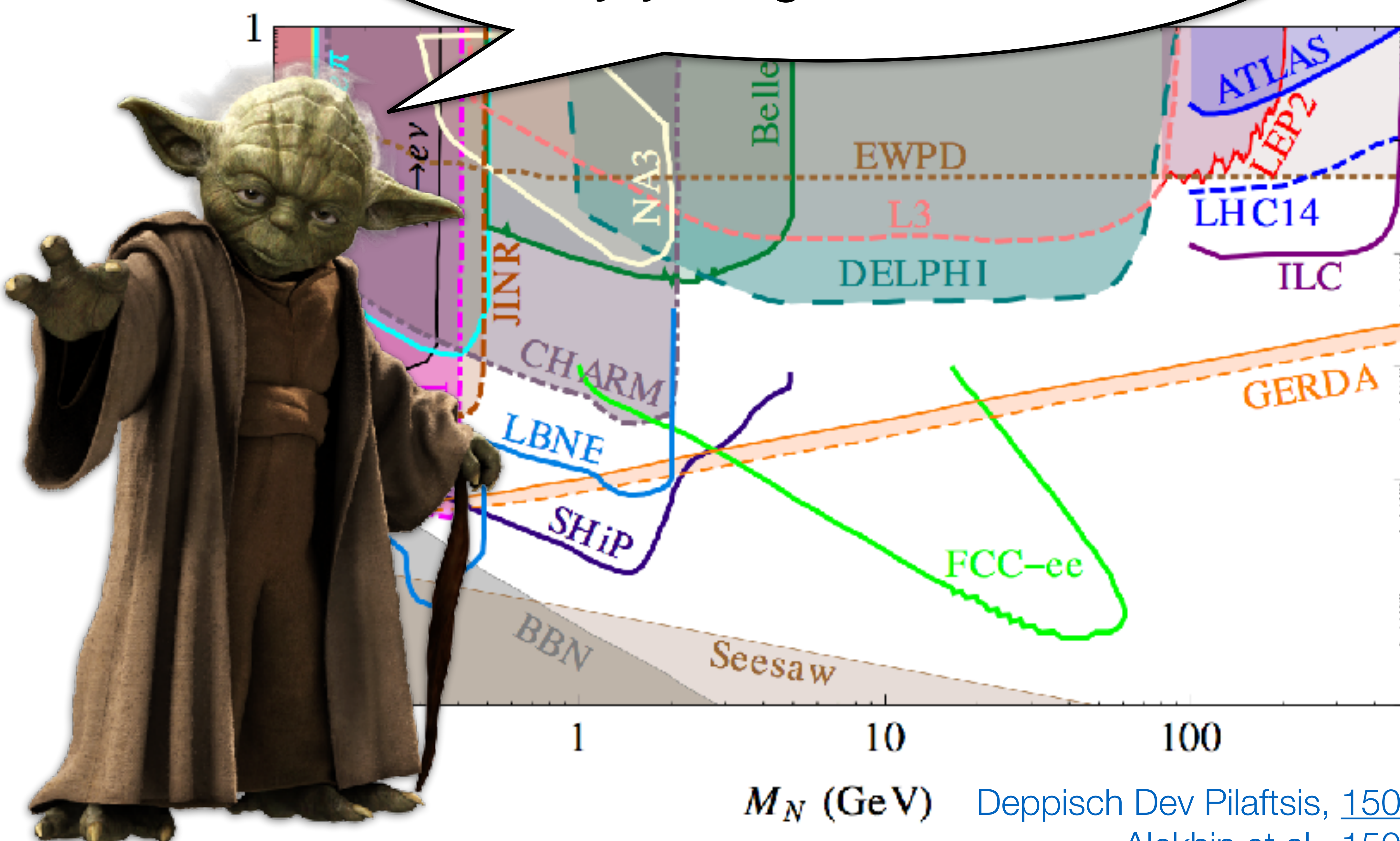

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Radiative Neutrino Mass Models

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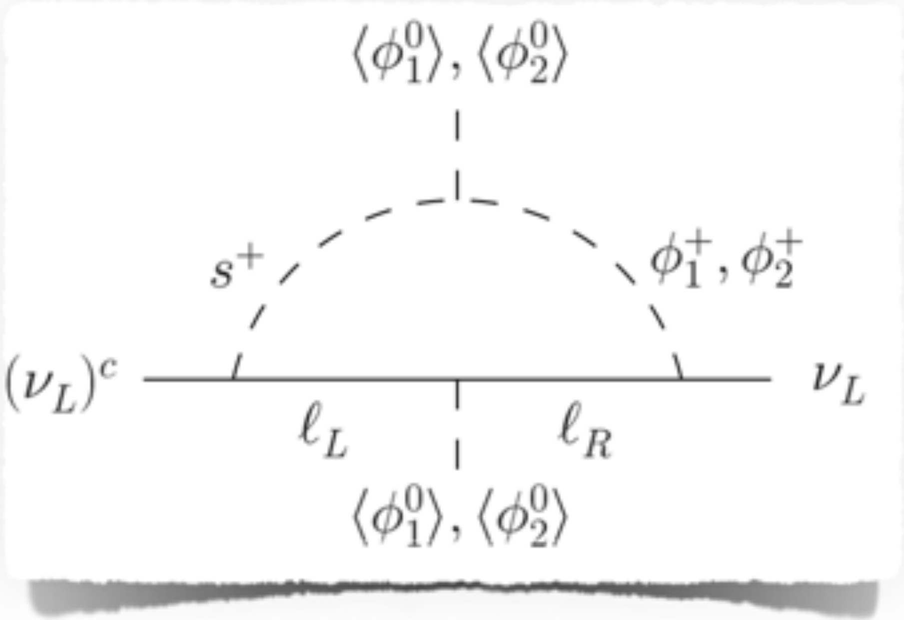

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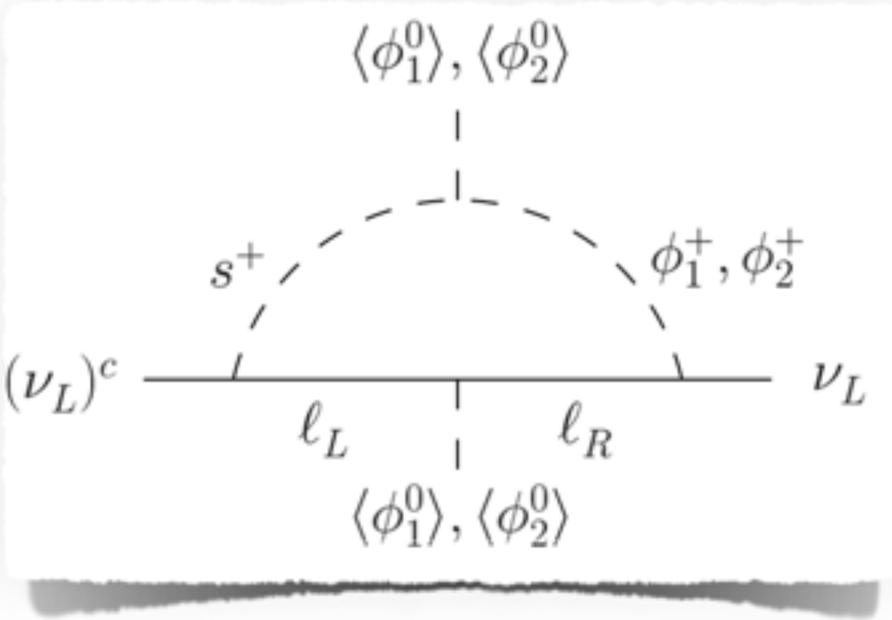

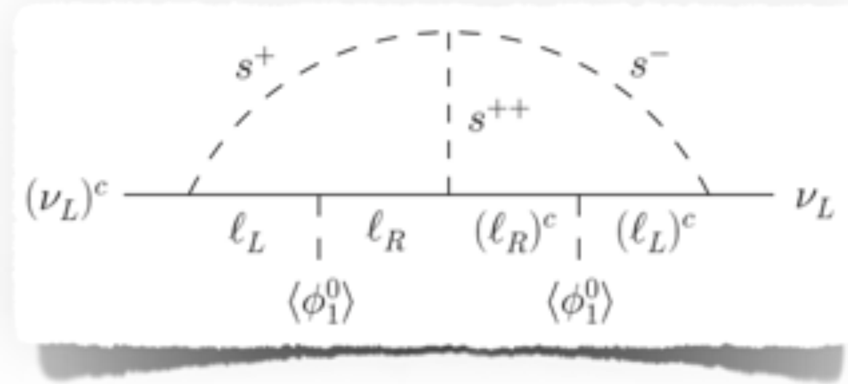

diagrams from Sugiyama, 1505.01738

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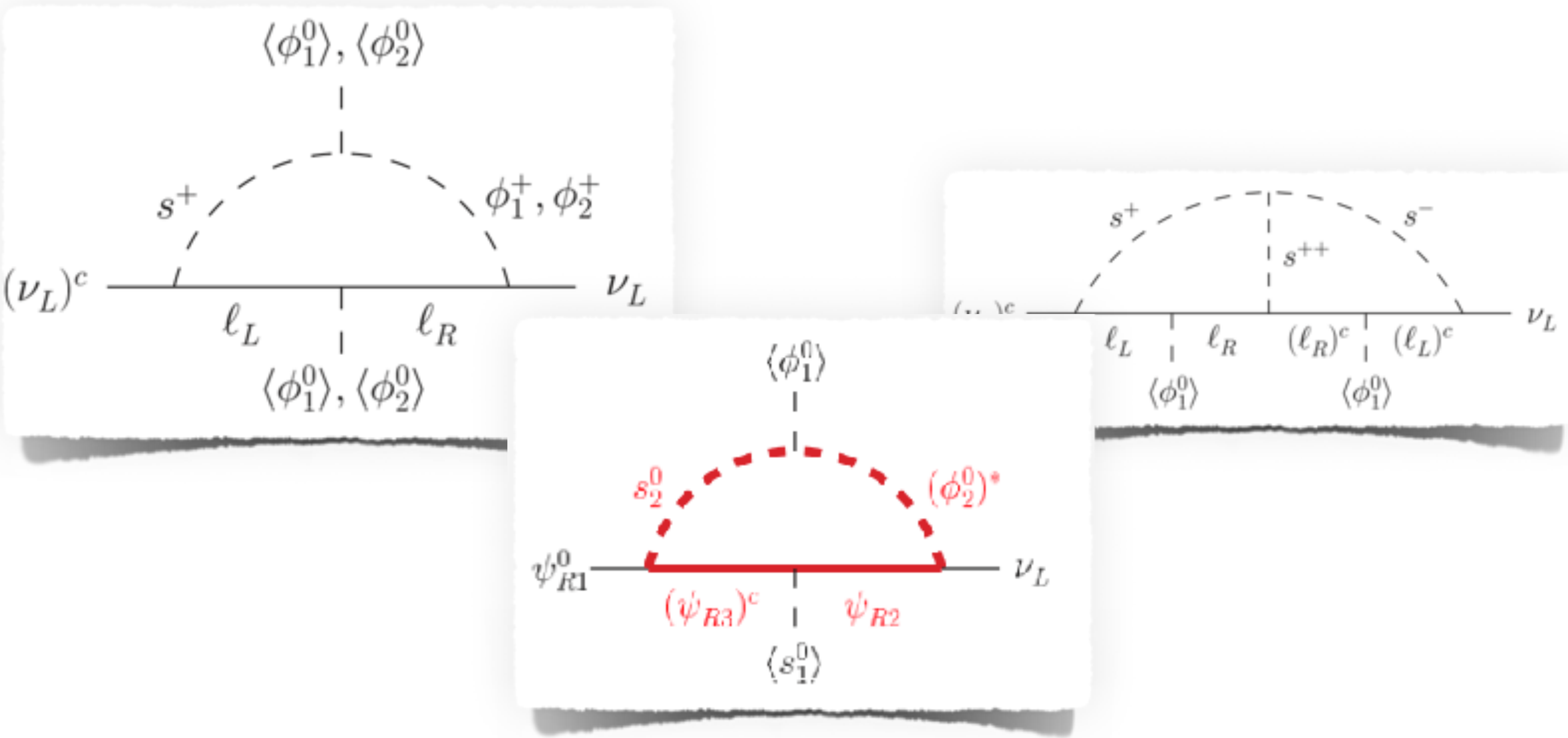

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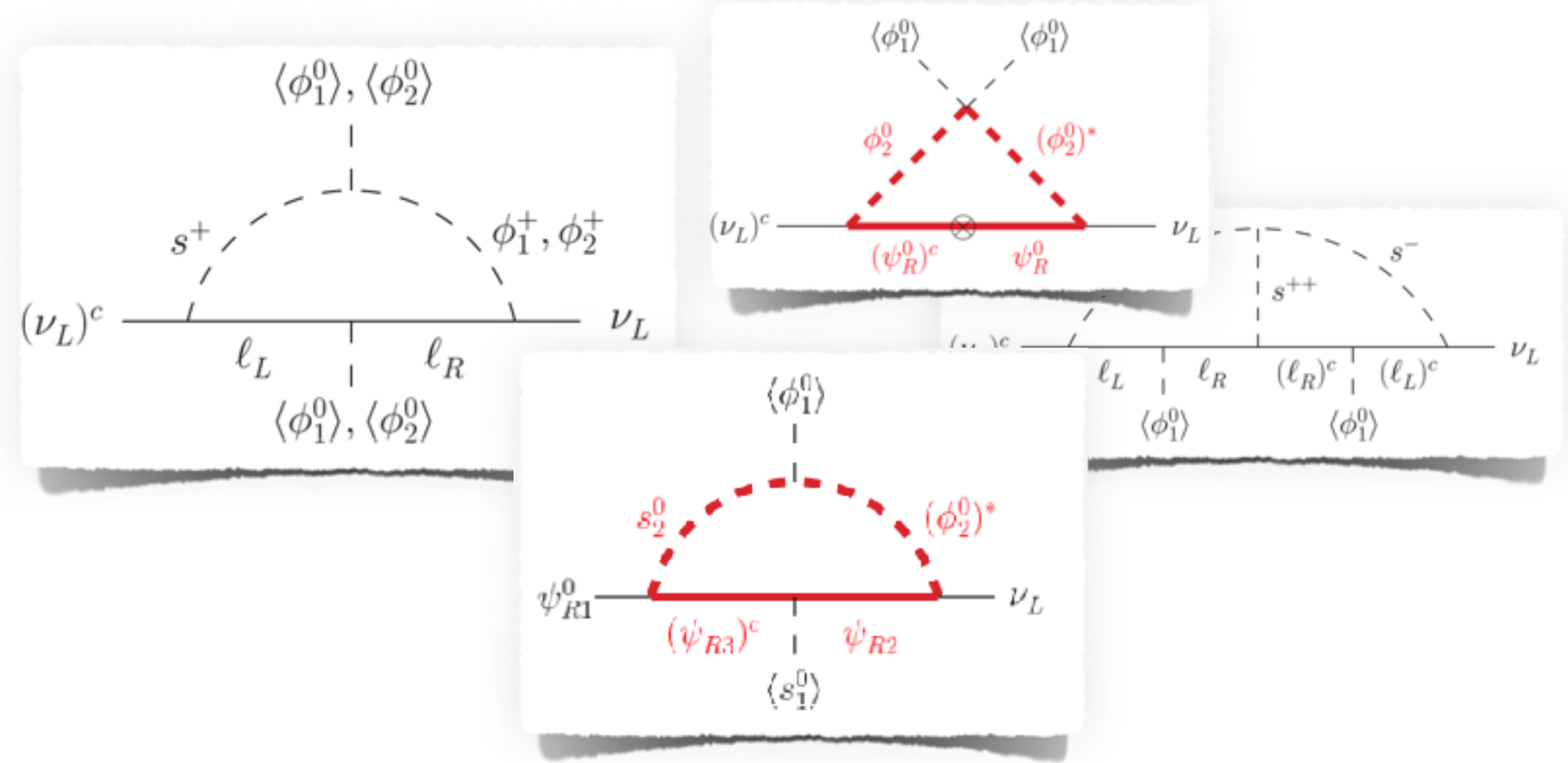

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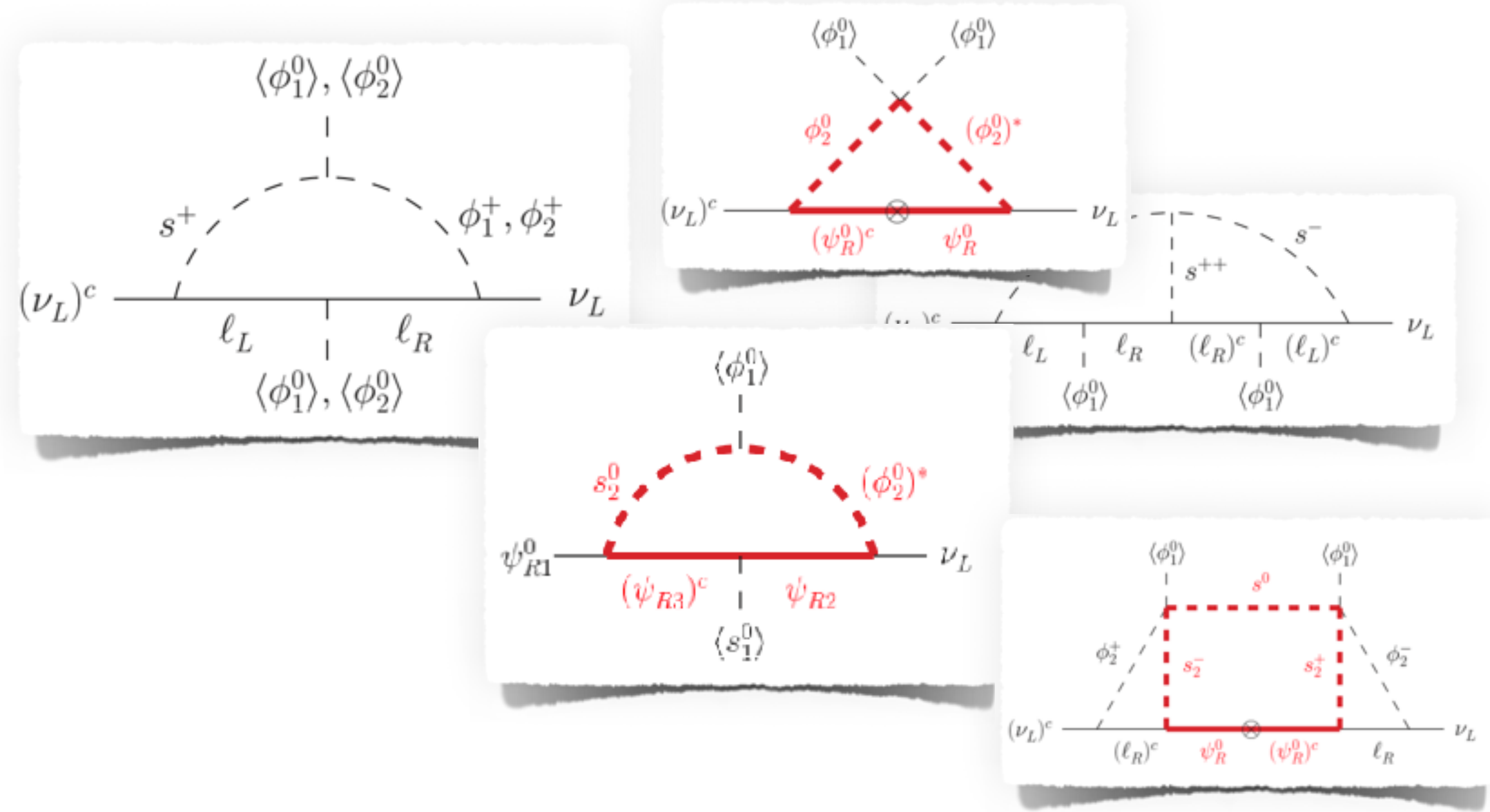

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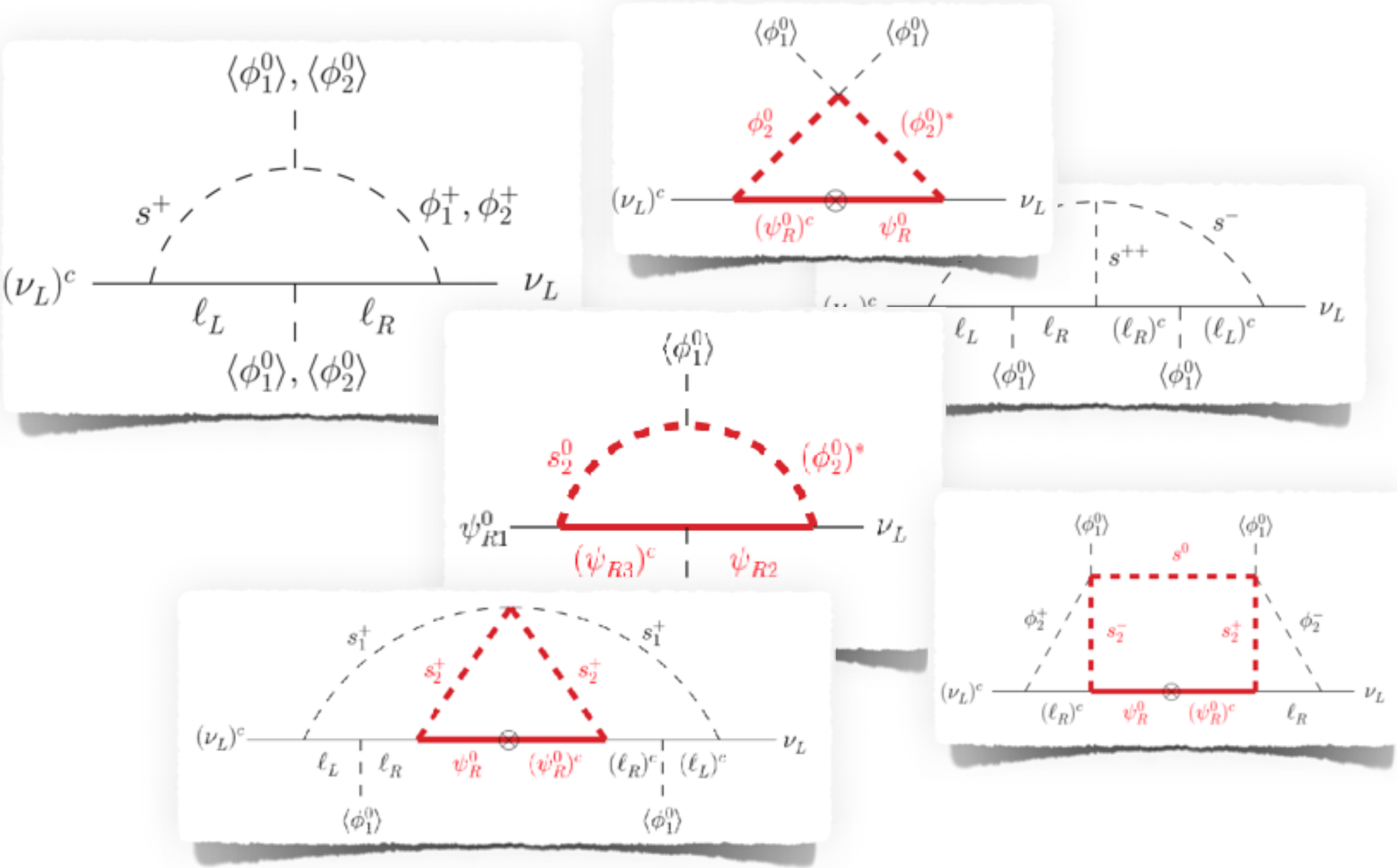

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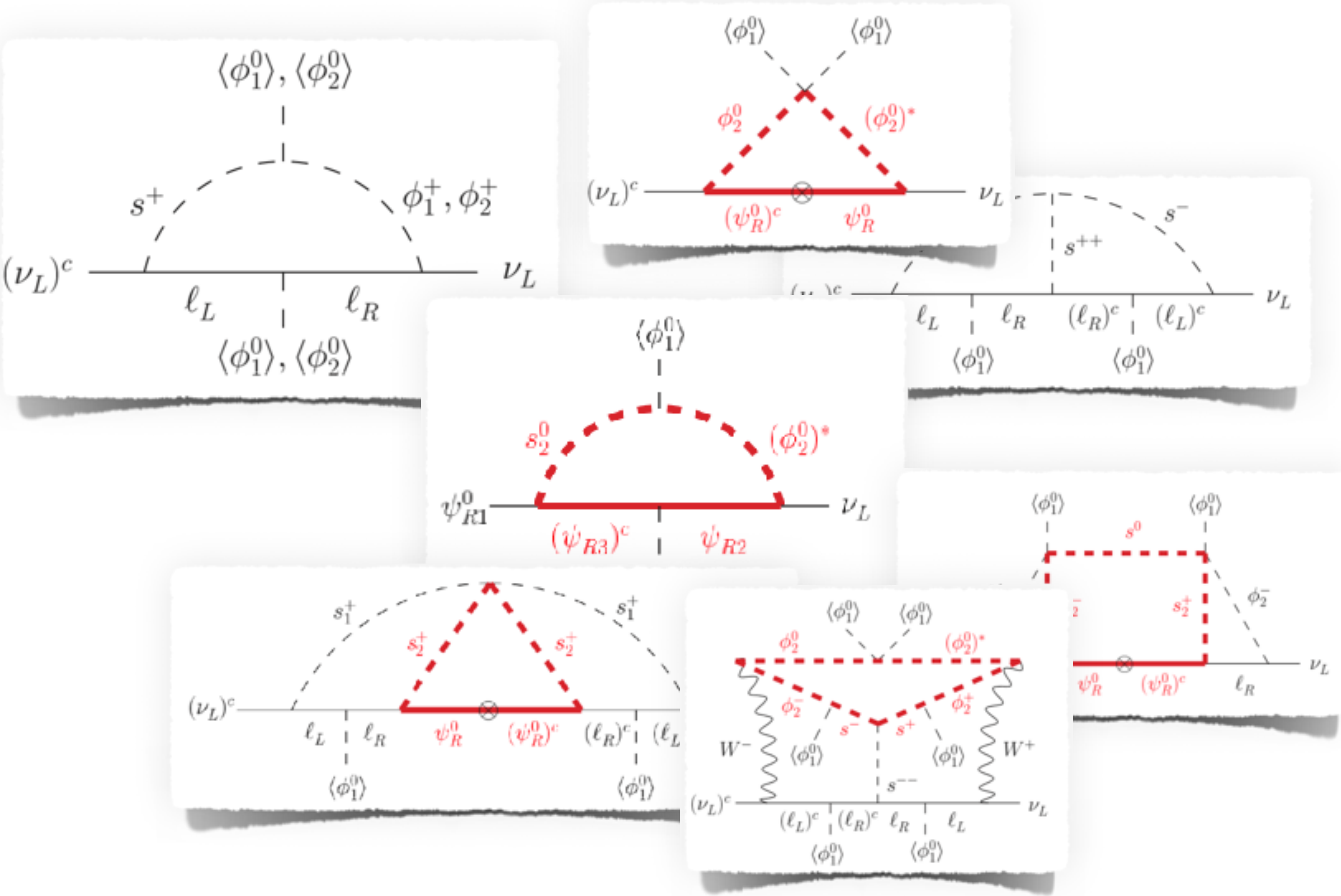

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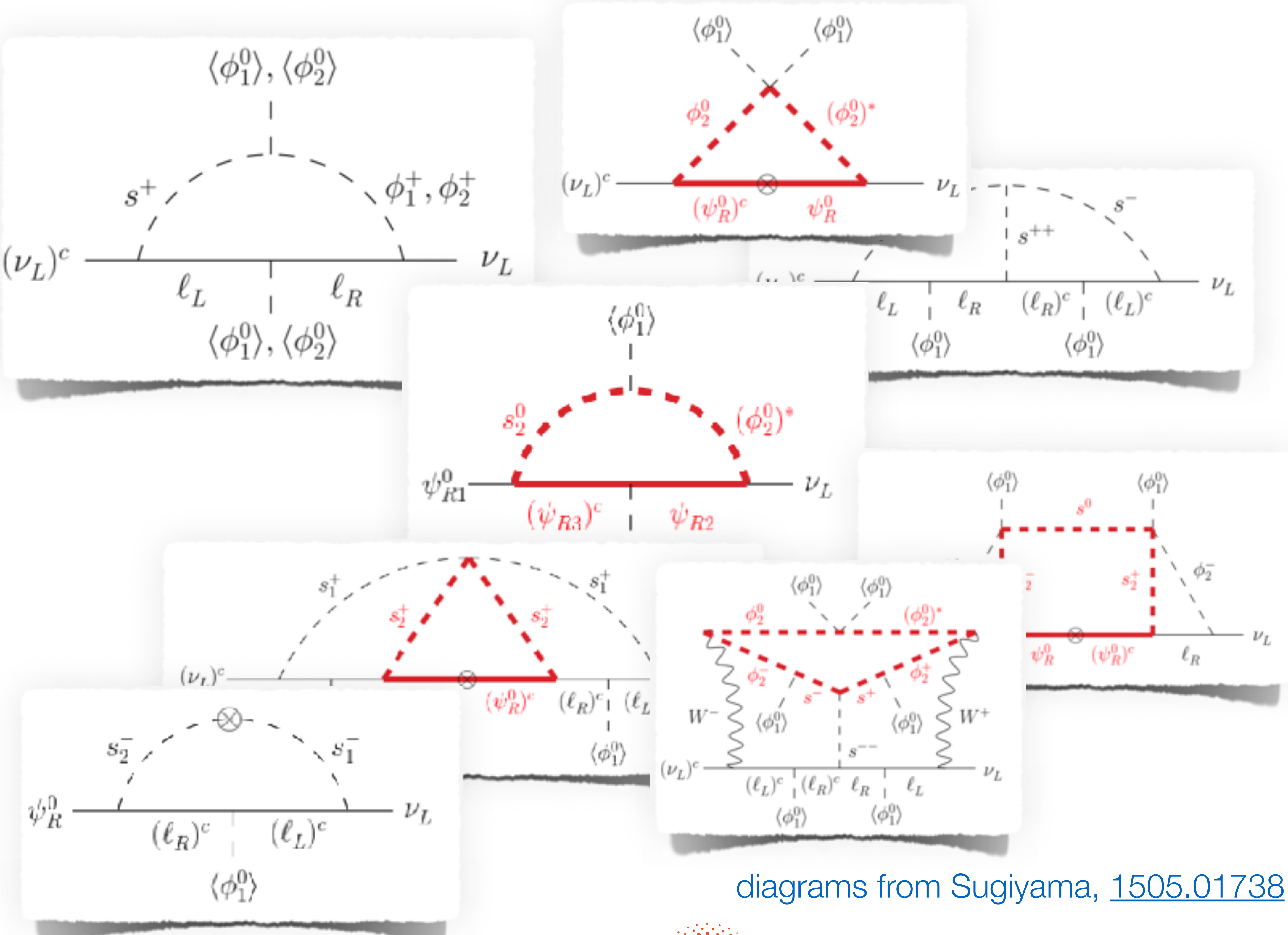

diagrams from Sugiyama, 1505.01738

Models of Flavor

- Based on symmetries
  - continuous ↔ discrete
  - Abelian ↔ non-Abelian
  - with/without CP symmetry
- Can reproduce observed masses / mixing angles
- Predictive power in specific models

Hagedorn, 1705.00684

Summary

Summary

- ☑ Theory & Phenomenology essential for future experiments
- ☑ Need to get to the bottom of oscillation anomalies
- ☑ Neutrino physics and DM physics closely intertwined
- ☑ $0\nu 2\beta$ decay needs accurate matrix elements
- ☑ Neutrino mass & flavor models need experimental input


“Always in motion is the future”

Thank you!