Neutrino oscillation with global data analysis

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Sampsa Vihonen, Tse-Chun Wang, Bing-Long Zhang

Ref: ***JHEP01(2021)124; JHEP03(2021)019;***
Phys.Rev.D 105 (2022) 7, 075022; Phys.Rev.D 105 (2022) 9, 096029;
Phys.Rev.D 108 (2023) 6, 062004; arXiv:2312.11704; arXiv: 2403.05819

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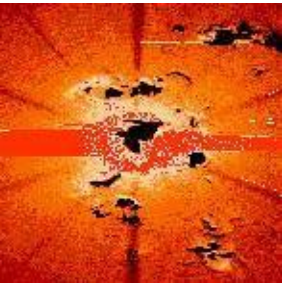
Where are neutrinos from?

Natural source



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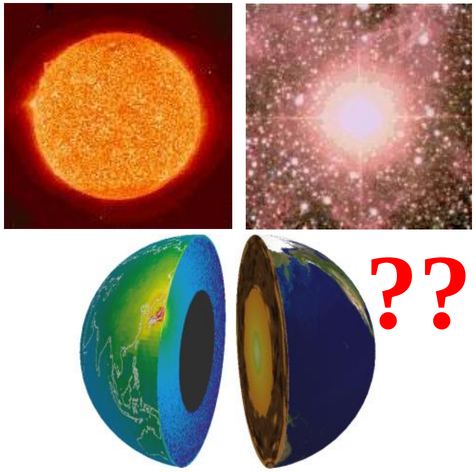

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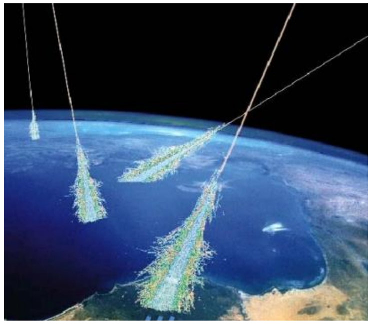

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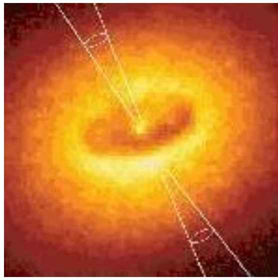
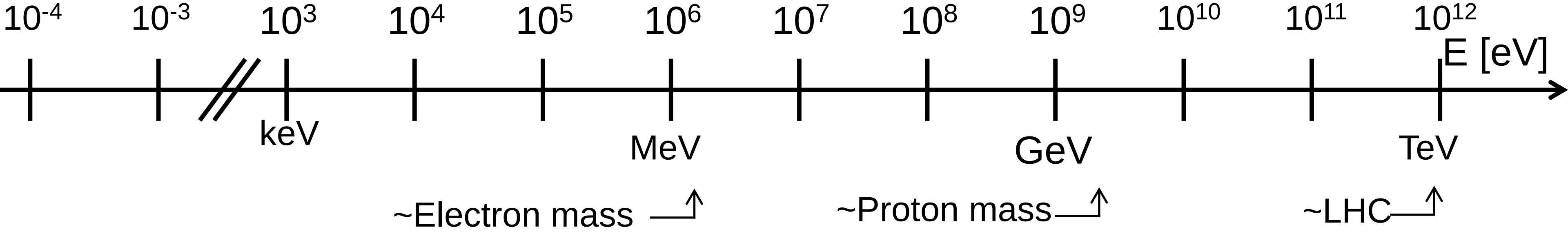




10^{-4} 10^{-3} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10} 10^{11} 10^{12}

E [eV]

keV MeV GeV TeV

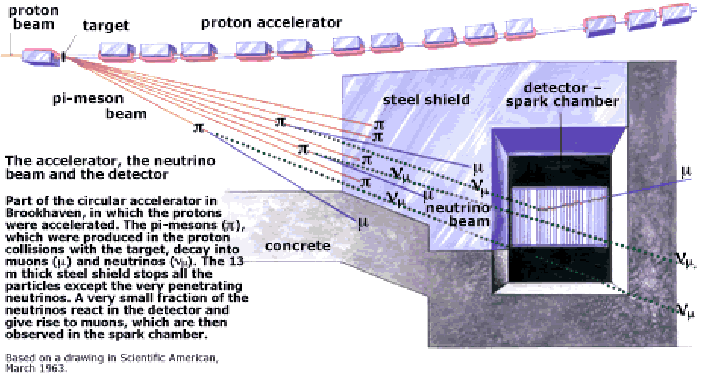
~Electron mass ↑

~Proton mass ↑

~LHC ↑

Artificial source

??

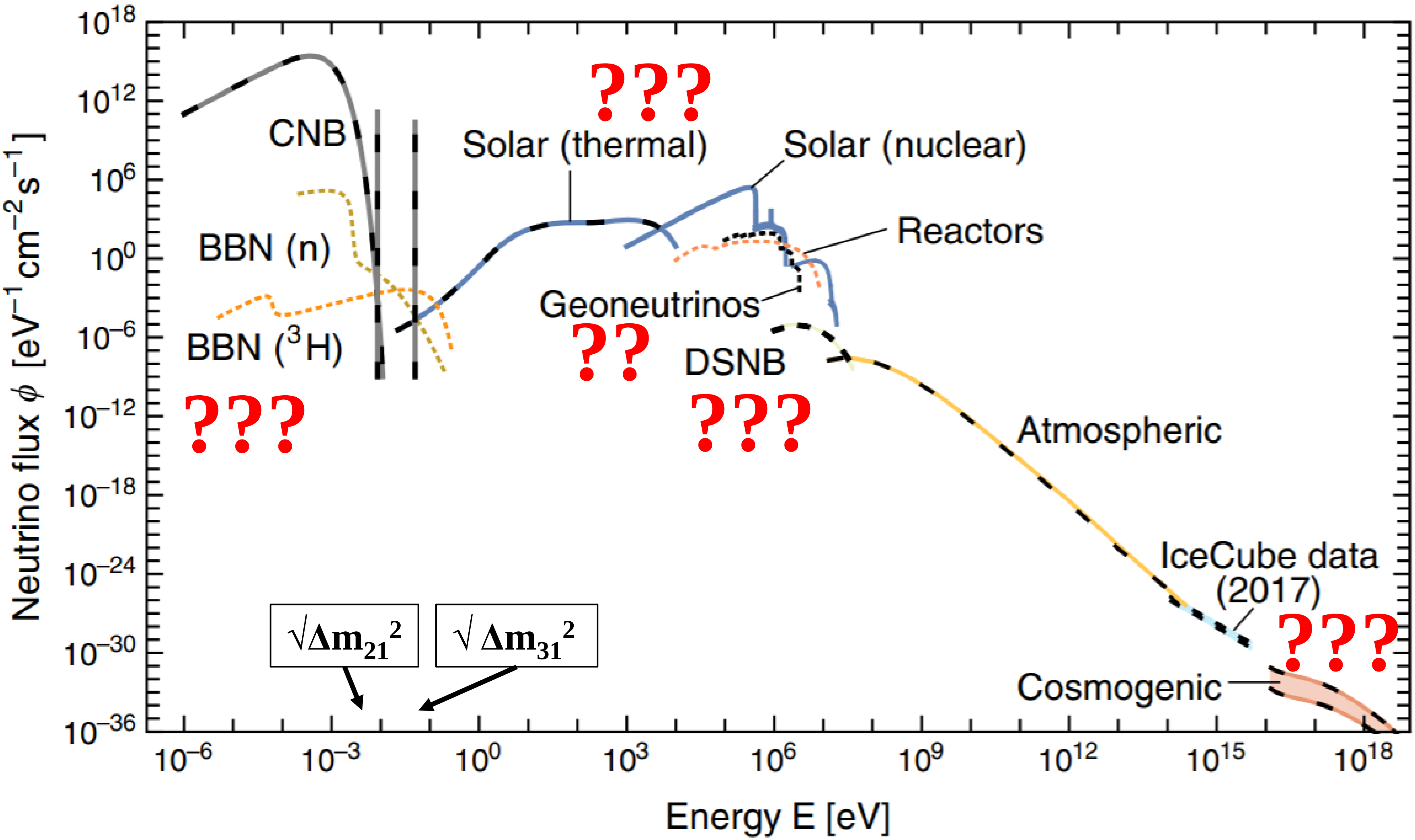


The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

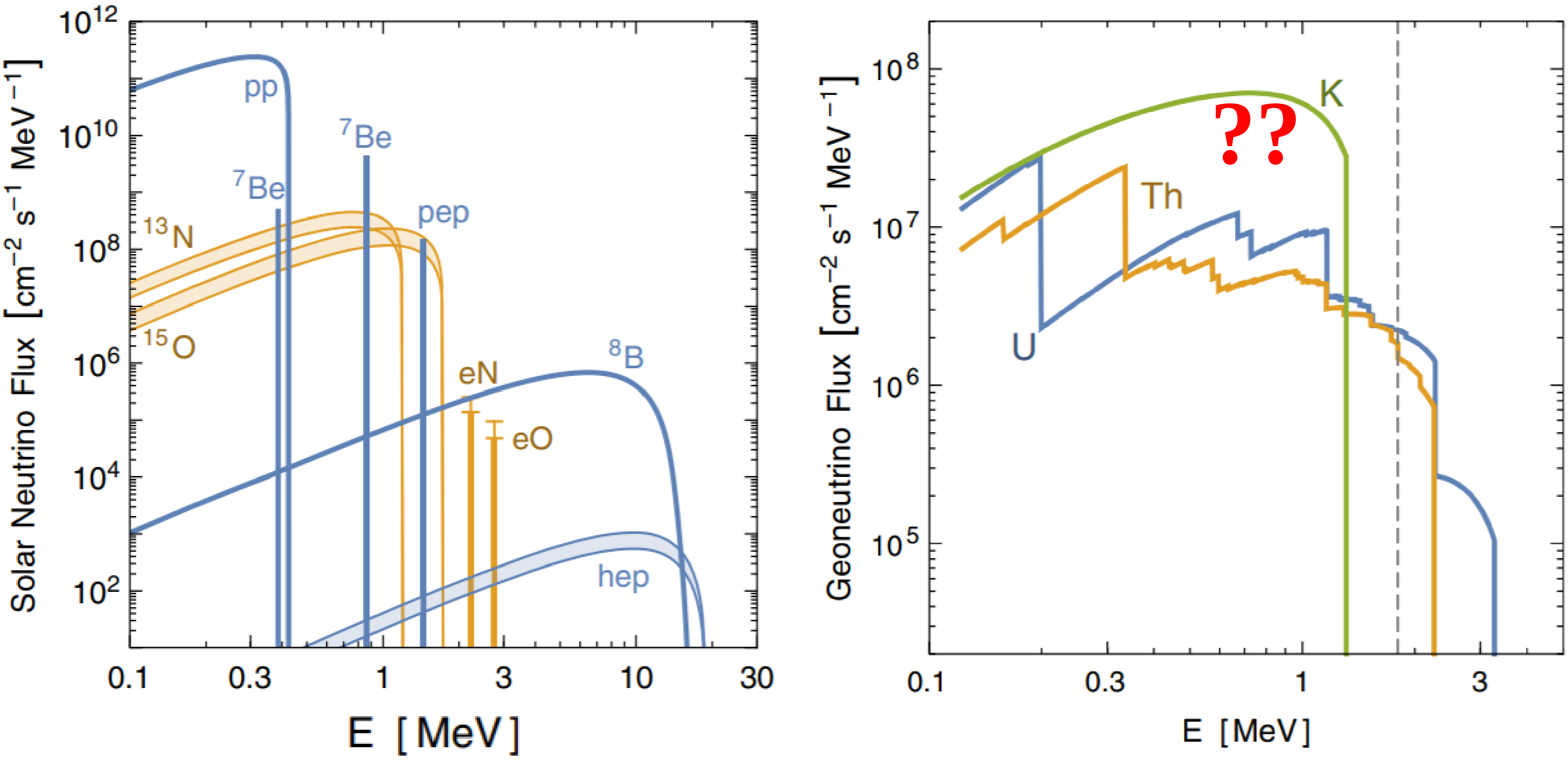
Based on a drawing in Scientific American, March 1963.

Energy spectra of various neutrino sources



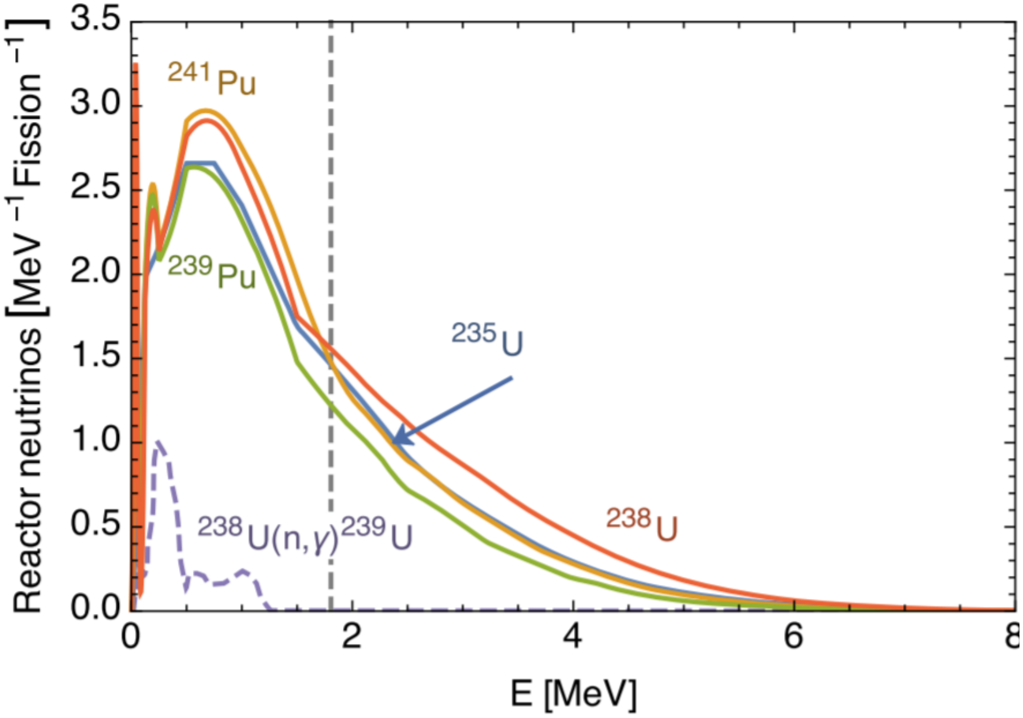
Ref: Edoardo Vitagliano, Irene Tamborra, and Georg Raffelt. Grand Unified Neutrino Spectrum at Earth: Sources and Spectral Components. Rev. Mod. Phys., 92:45006, 2020.

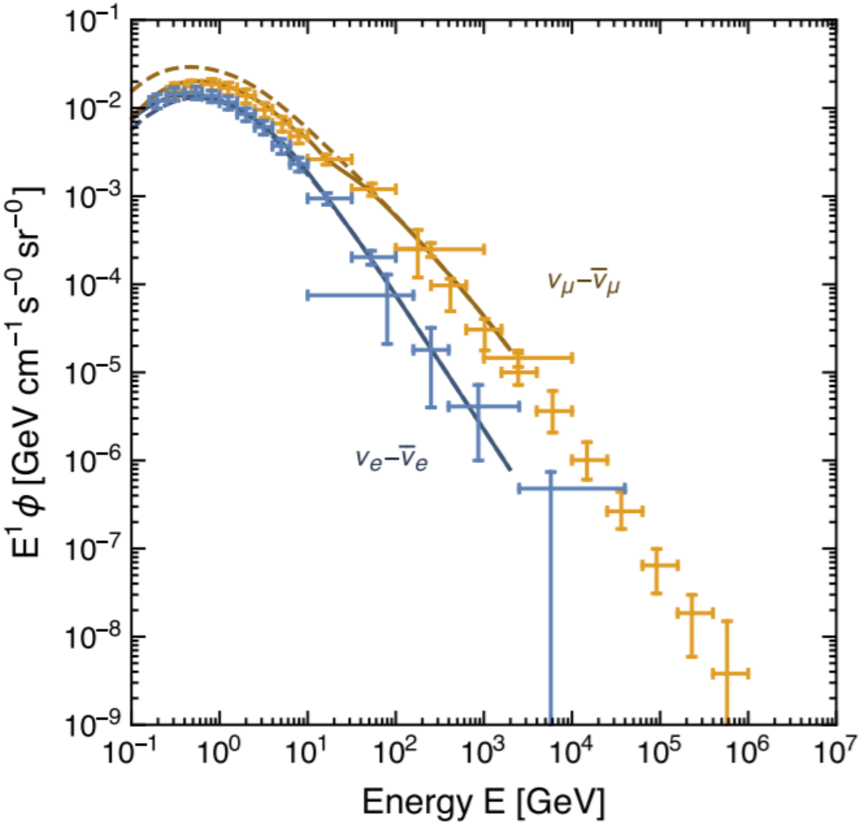
Energy spectra of solar&geo-neutrino sources



Ref: Edoardo Vitagliano, Irene Tamborra, and Georg Raffelt. Grand Unified Neutrino Spectrum at Earth: Sources and Spectral Components. Rev. Mod. Phys., 92:45006, 2020.

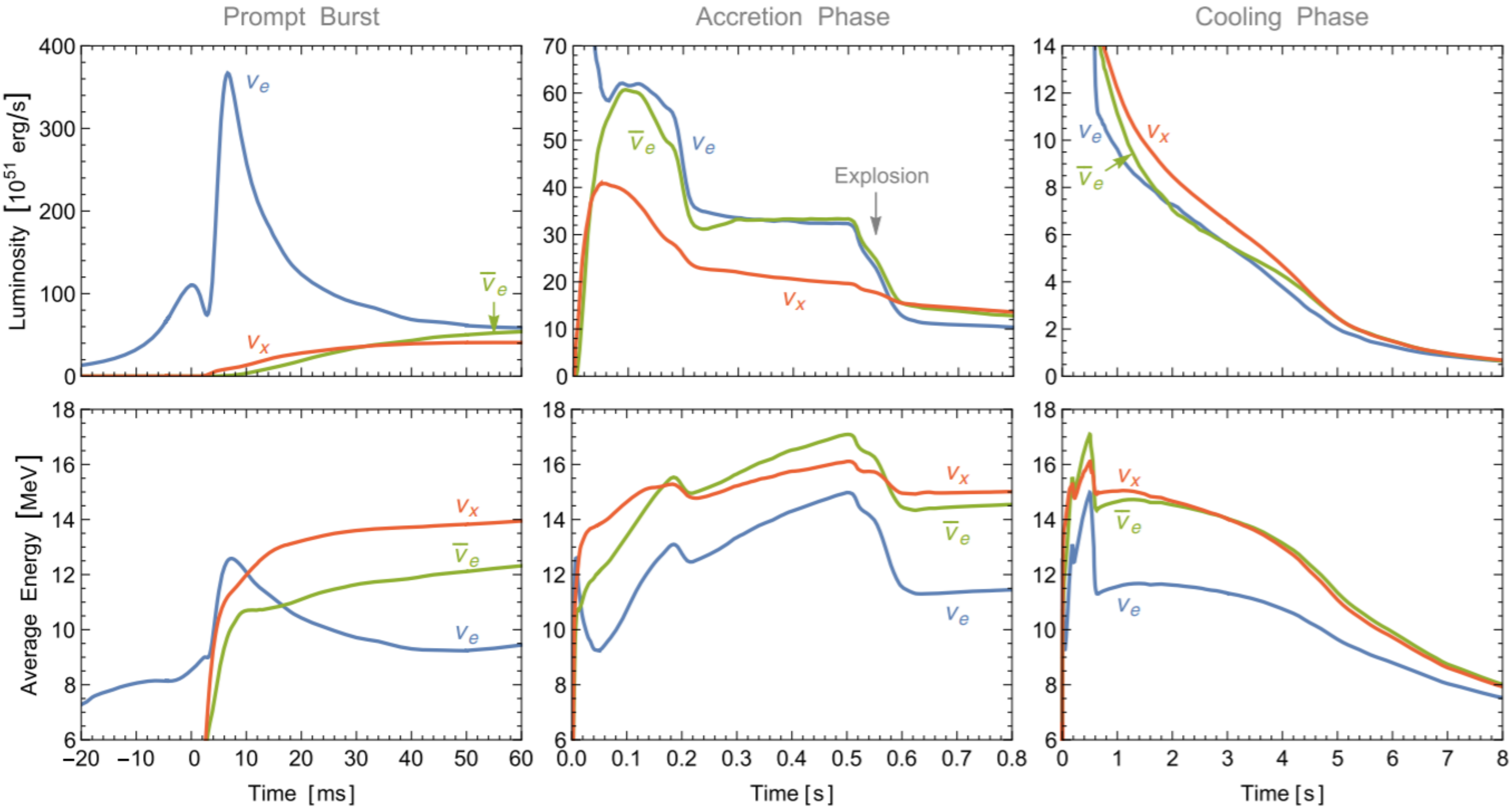
Energy spectra of reactor & atm. neutrinos





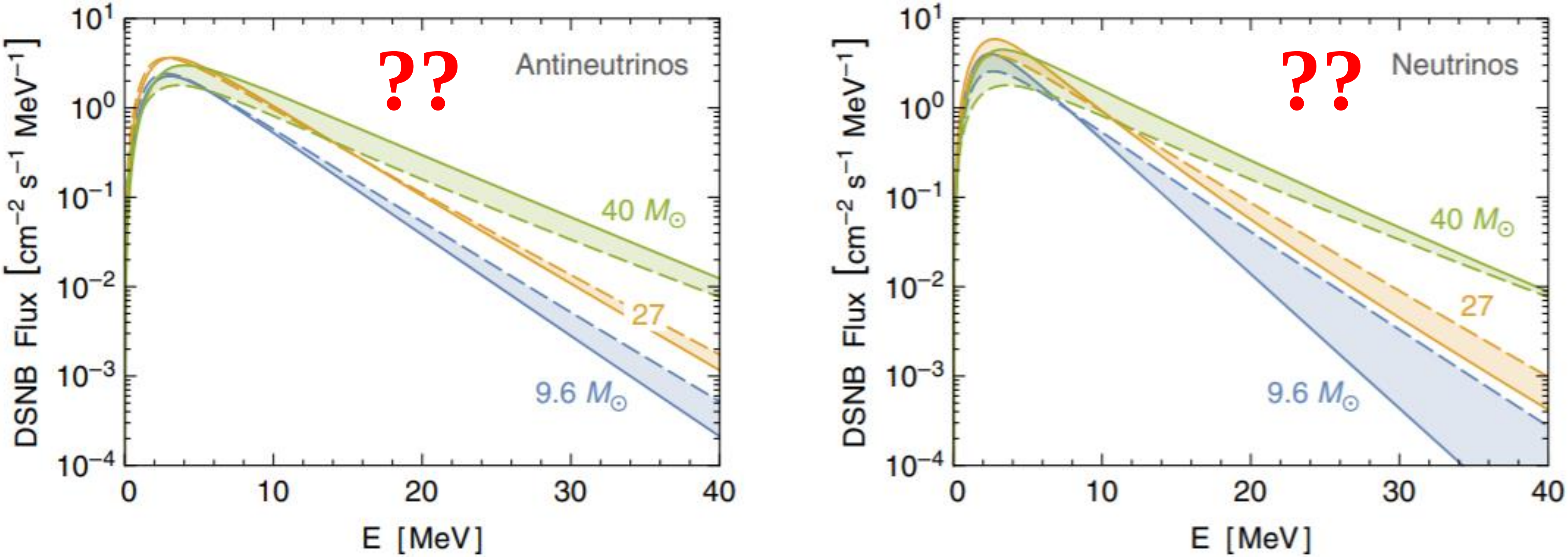
Ref: Edoardo Vitagliano, Irene Tamborra, and Georg Raffelt. Grand Unified Neutrino Spectrum at Earth: Sources and Spectral Components. Rev. Mod. Phys., 92:45006, 2020.

Energy spectra of SN neutrino sources



Ref: Edoardo Vitagliano, Irene Tamborra, and Georg Raffelt. Grand Unified Neutrino Spectrum at Earth: Sources and Spectral Components. Rev. Mod. Phys., 92:45006, 2020.

Energy spectra of DSNB neutrino sources



Ref: Edoardo Vitagliano, Irene Tamborra, and Georg Raffelt. Grand Unified Neutrino Spectrum at Earth: Sources and Spectral Components. Rev. Mod. Phys., 92:45006, 2020.

Three-generation neutrino oscillations

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} \mathrm{Re}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{i<j} \mathrm{Im}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin\left(\Delta_{ij}\right)$$

$$\boxed{U^\dagger U = 1}$$

$$\frac{\Delta_{ij}}{2} = 1.27 \frac{m_i^2 - m_j^2}{\mathrm{eV}^2} \frac{L/E}{\mathrm{Km/GeV}}$$

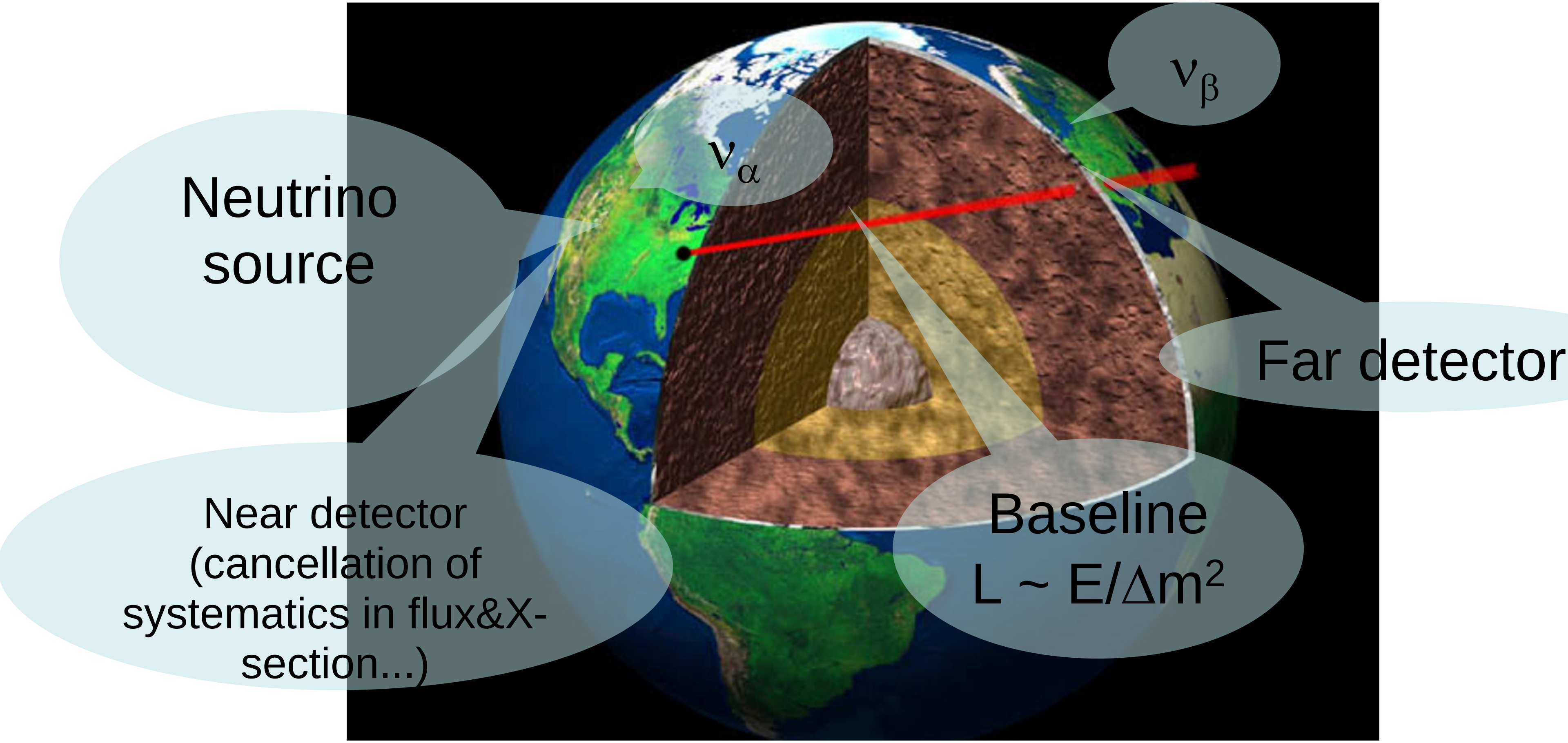
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$ The mass differences
- $U_{\alpha j}$ The mixing angles (and Dirac phases)
- E The neutrino energy
- L Distance ν source to detector

- For 3 ν framework , we have **6**+1 free parameters in neutrino oscillations:

P $(\theta_{12}, \theta_{13}, \theta_{23}, \delta, \Delta m_{21}^2, \Delta m_{31}^2)$ + ρ (in matter)

√ √ √ ? √ √?

Working principles of neutrino oscillation experiments



ν_β

ν_α

Neutrino source

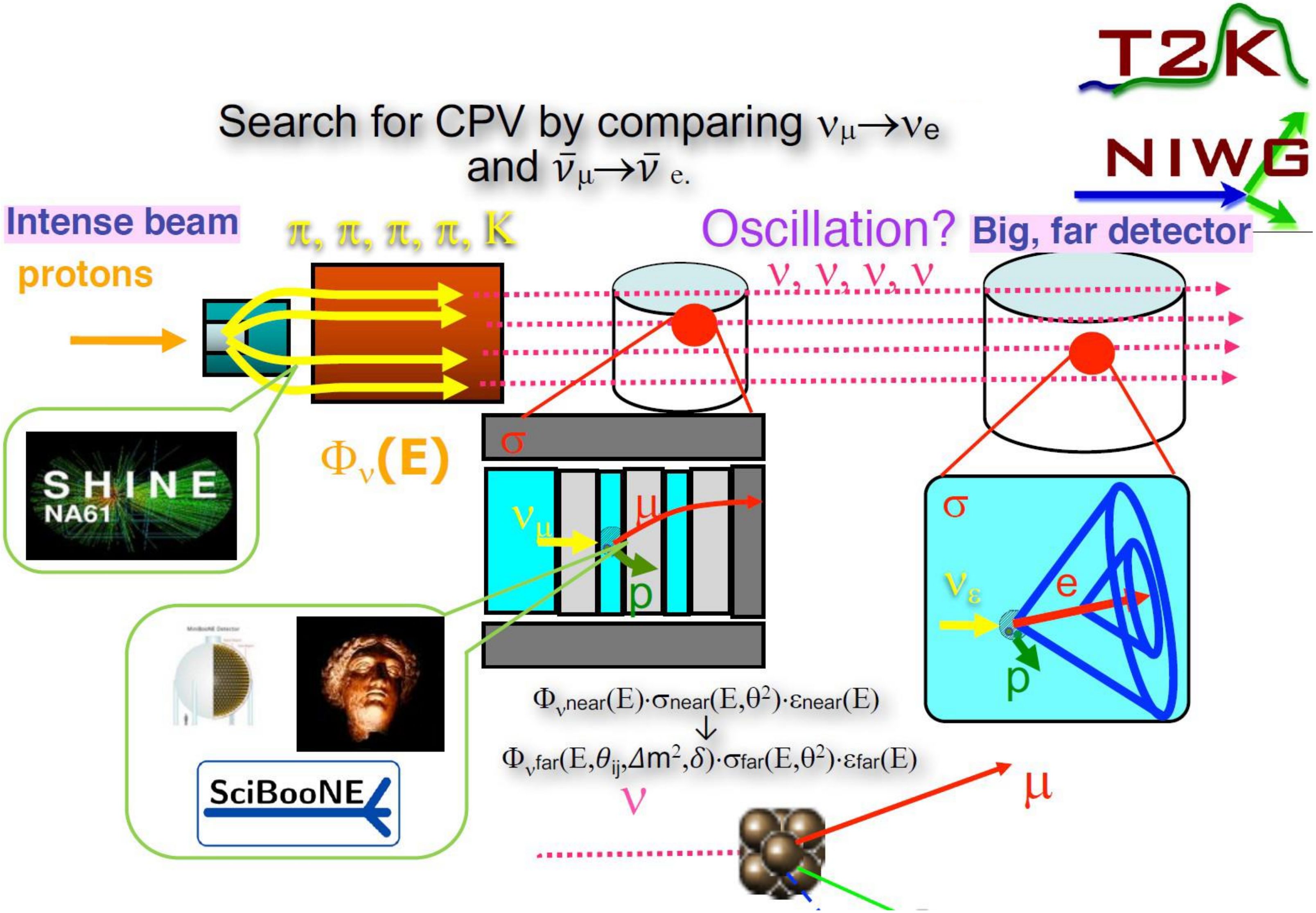
Far detector

Near detector (cancellation of systematics in flux&X-section...)

Baseline
$L \sim E/\Delta m^2$

- Get the neutrino source as clean as possible. Muon decay v.s pion decay beams.
- Deploy the best detector to reconstruct the oscillated neutrino spectra: Gd-WC, LAr TPC, scintillator detector with flavour&charge identifications…
- Data mining: precision measurement & discovery of new physics…

An example: T2K



K. McFarland, Neutrino Interaction Uncertainties @ NNN2018

Lots of neutrino experiments to get a new horizon

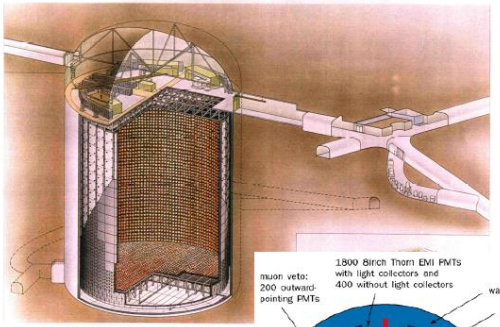
JUNO

Hyper-K

annie

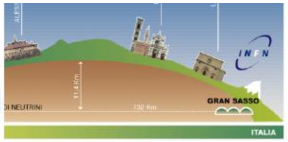
DUNE

BOREXINO GRAN SASSO



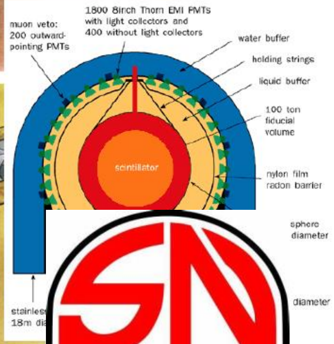
KamLAND

Kamioka Liquid scintillator Anti-Neutrino Detector

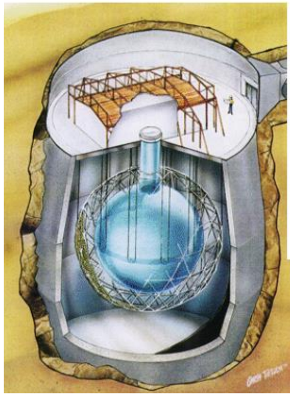


NOvA

T2K



ICECUBE SOUTH POLE NEUTRINO OBSERVATORY



SNO

DOUBLE CHOOZ

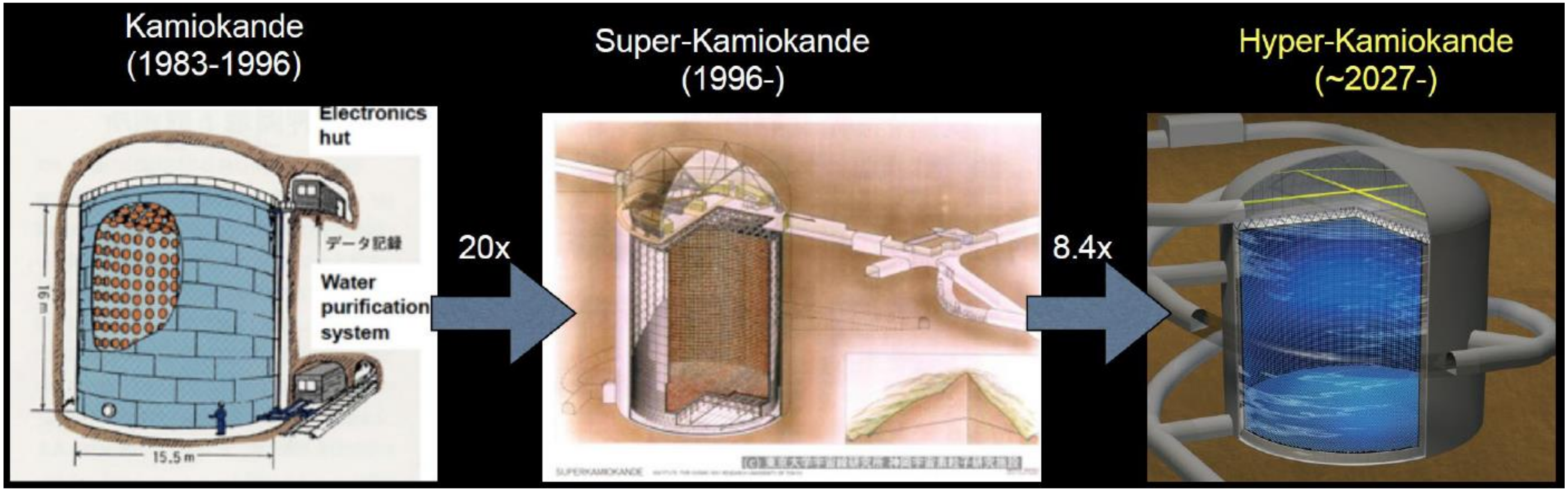
Daya Bay θ_{13}

RENO ν θ_{13}

More are coming…

WC detectors: Kamiokande→SK→HyperK

- Bigger than bigger! PMT technology revolutionized!



3 kton WC 20% coverage
with 20” PMT

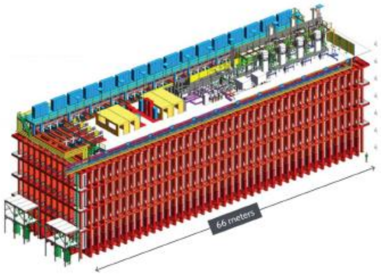
50 kton WC 40% coverage
with 20” PMT

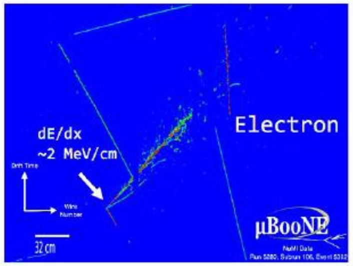
260 kton WC 40% coverage
with 20”+HQE PMT

- **Construction started in 2020.**
- **Data taking from 2027.**
- **J-PARC neutrino beam will be upgraded from 0.7 to 1.3 MW**

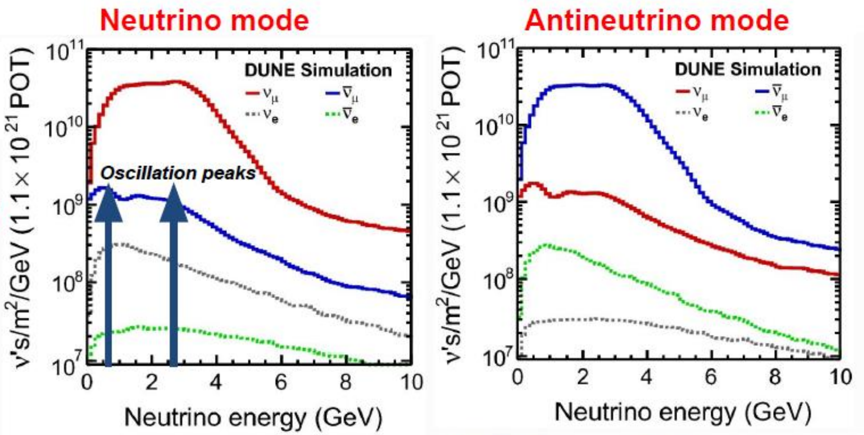
LAr TPC: DUNE

Courtesy: Guang Yang@NuFact2021

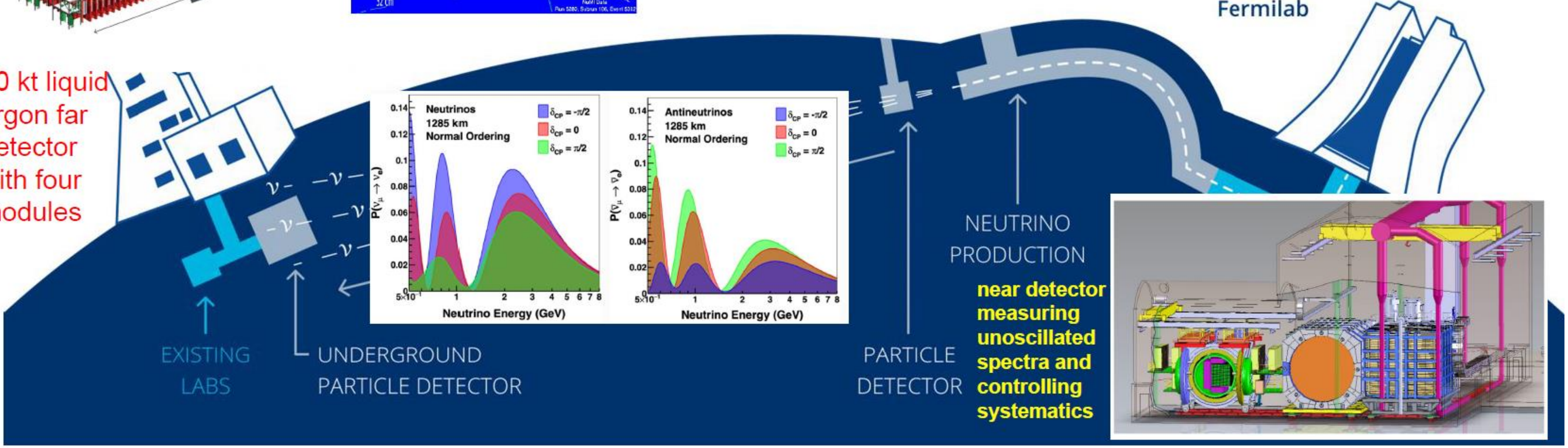




Broad band neutrino and antineutrino beam



70 kt liquid argon far detector with four modules



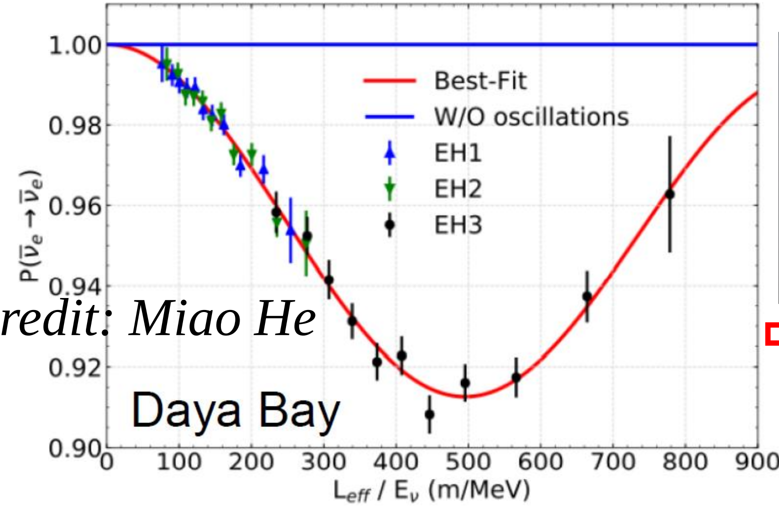
near detector measuring unoscillated spectra and controlling systematics

LSc: DYB (20 t*8) → JUNO (20 kt)

- Daya Bay neutrino experiment: mission completed!

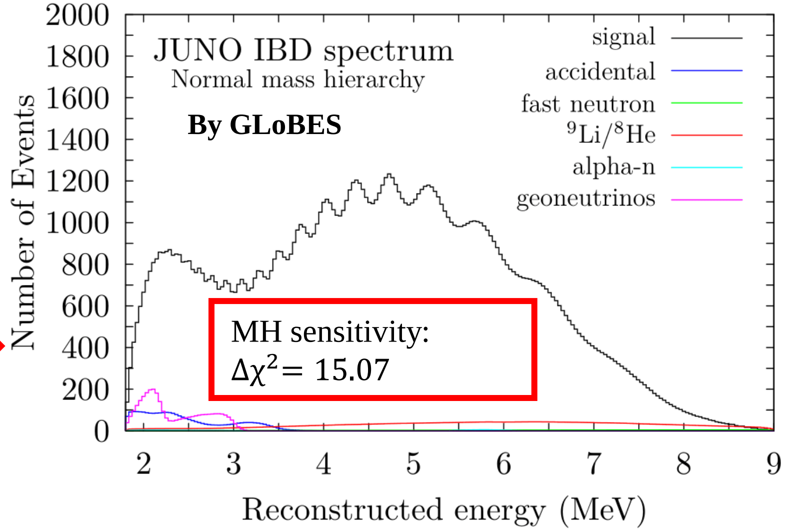
Dec. 12, 2020

Credit: Yuexiang Liu (IHEP)



Credit: Miao He

MCP-PMT
20”+HQE



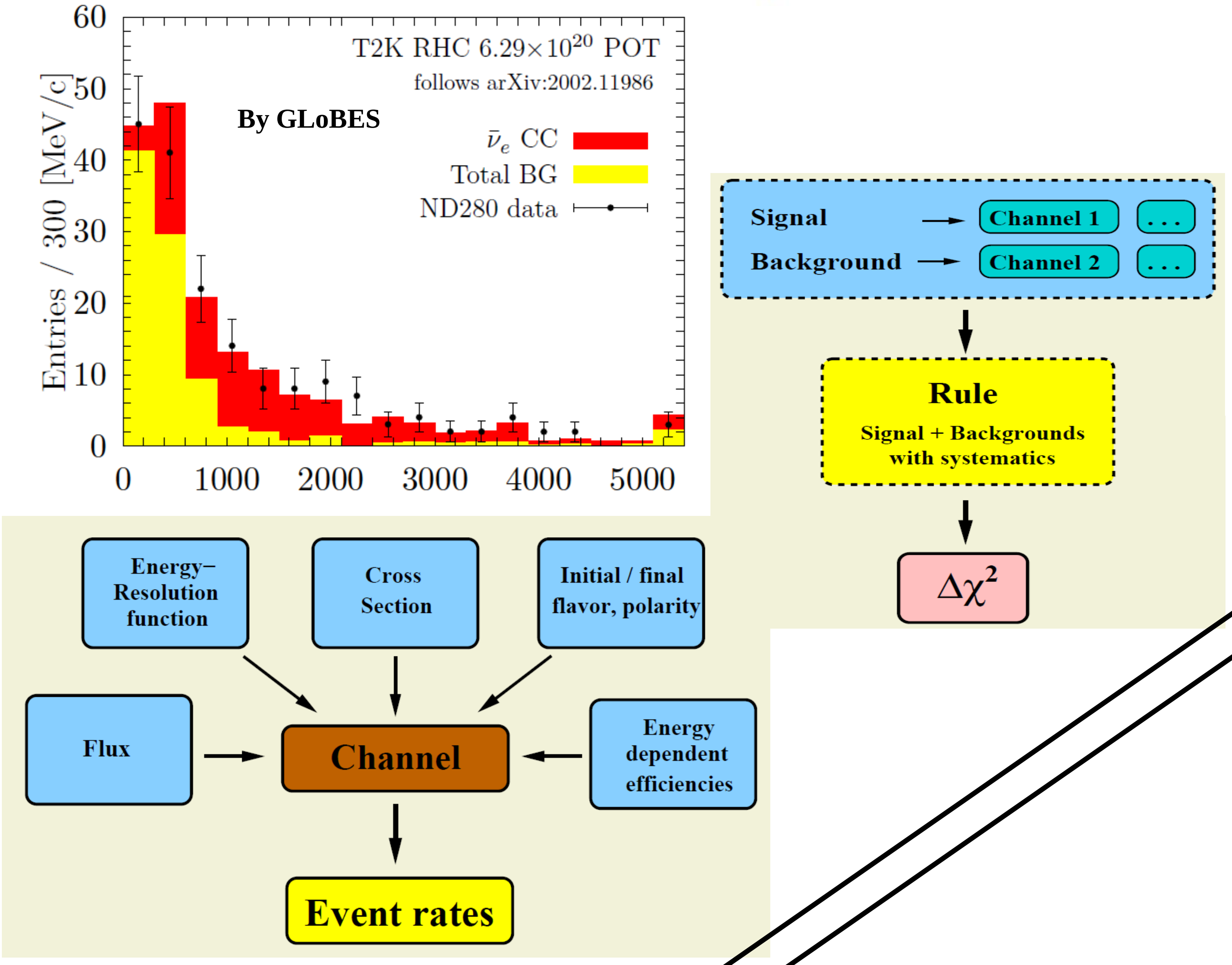
MH sensitivity:
$\Delta\chi^2 = 15.07$

Hot topics in neutrino oscillation physics

- What is the neutrino mass ordering?
- Are there CP violations in the lepton sector?
- How much precision shall we reach to tell new physics?
- What are the current and future systematic limitations on precision measurement and how to address them?
- Is the neutrino mixing matrix unitary?
- Are there non-standard neutrino interactions?
- Are there more than three-flavor neutrinos?
- Reactor antineutrino flux deficit seems resolved. How about Gallium anomaly?
- How consistent are results from NOvA and T2K?
- How to examine neutrino mass models based on flavor symmetries (A4, S4, Modular…)?
- What’s next even after neutrino mass ordering and Dirac CP phase?
- …

Simulations of neutrino oscillations w/o new physics

$$N = \text{time} \times \#\text{ of targets} \times \text{efficiency} \times \int_{E_i}^{E_f} dE_\nu \frac{d\phi(E_\nu)}{dE_\nu}\sigma(E_\nu)$$



Signal → **Channel 1** **. . .**

Background → **Channel 2** **. . .**

Rule

Signal + Backgrounds with systematics

$\Delta\chi^2$

Energy−Resolution function

Cross Section

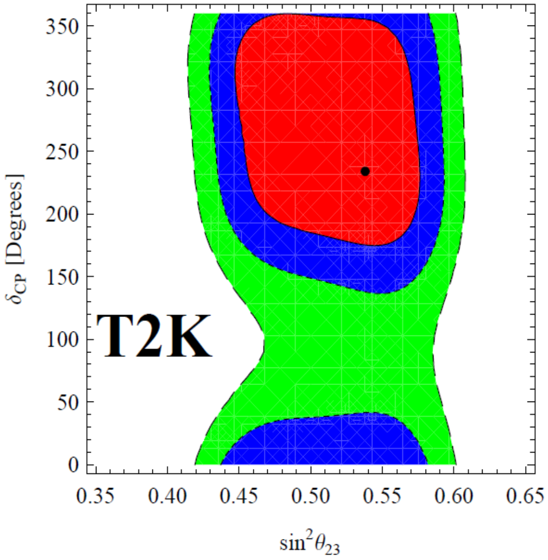
Initial / final flavor, polarity

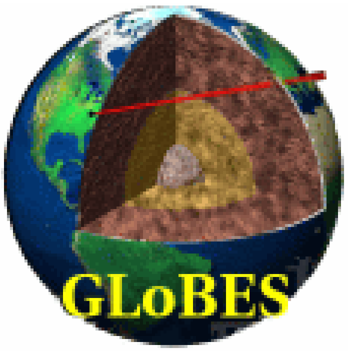
Flux

Channel

Energy dependent efficiencies

Event rates





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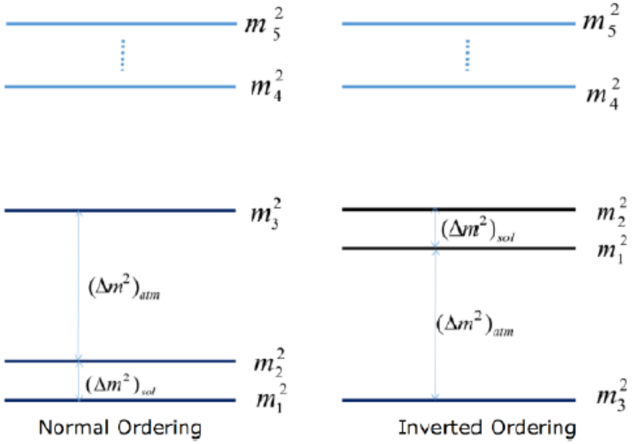
Non-unitary neutrino mixings (NU)

- Light sterile neutrino anomaly (eV scale)
- Heavy sterile neutrinos from see-saw model (GeV scale)
- Dark matter candidate (keV scale)
- IUV (indirect unitary violation) by heavy sterile neutrinos
- DUV (direct unitary violation) by light sterile neutrinos: oscillation with active ones



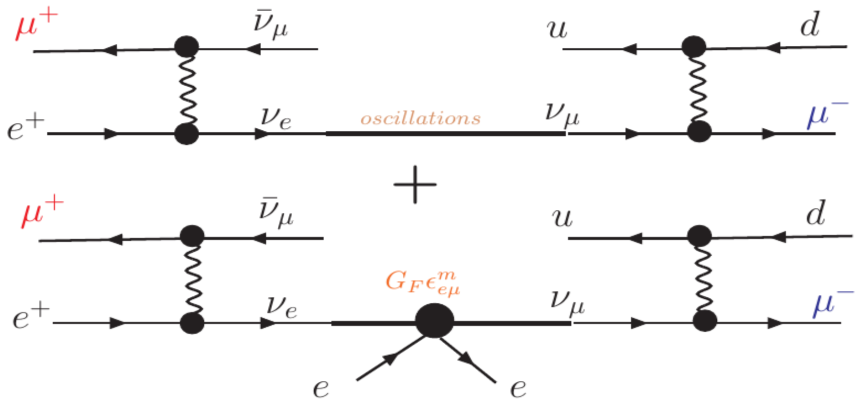
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

- Simplifying the mixing matrix to deal with DUV and IUV, Phys. Lett., B718:1447-1453, 2013
- Pertubation study of oscillation probabilities for DUV and IUV, Phys. Rev., D93(3):033008

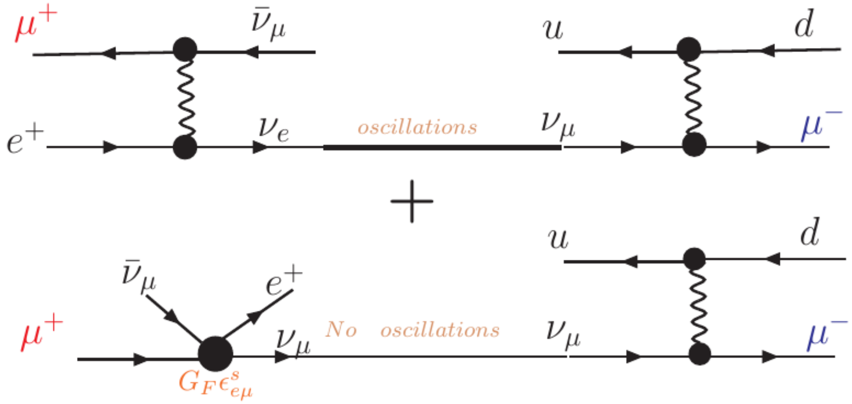
Non-Standard Interactions (NSIs)

- **New physics beyond SM: new particles, new couplings, new phenomenon...**

- Flavor violating interactions with neutrinos:
  $\nu_\alpha f \to \nu_\beta f, l_\alpha^- \to \nu_\beta e^- \bar{\nu}_e \cdots$
- 4-fermion vertices:
  $\mathrm{L}_{\mathrm{eff}} = 2\sqrt{2}\, G_F \, (\epsilon^{L/R})^{\alpha\gamma}_{\beta\delta} \, (\bar{\nu}^\beta \gamma^\rho \mathrm{P}_L \nu_\alpha) \, (\bar{\ell}^\delta \gamma^\rho \mathrm{P}_{L/R} \ell_\gamma)$



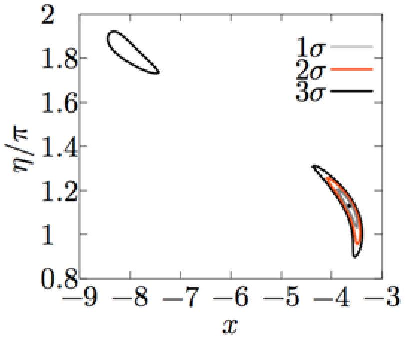
NSI happens to neutrino propagation in matter

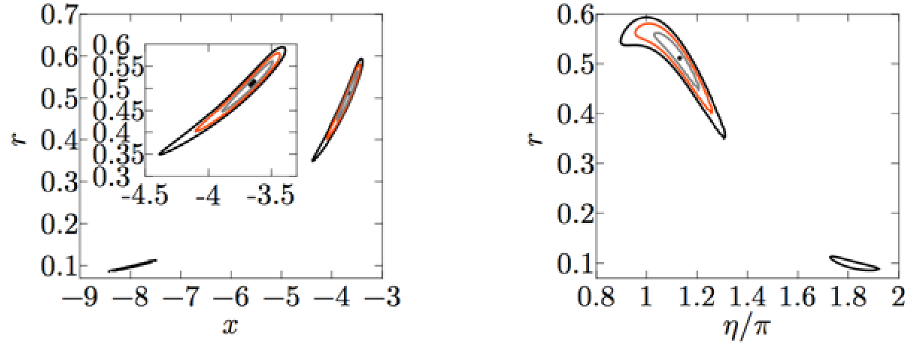


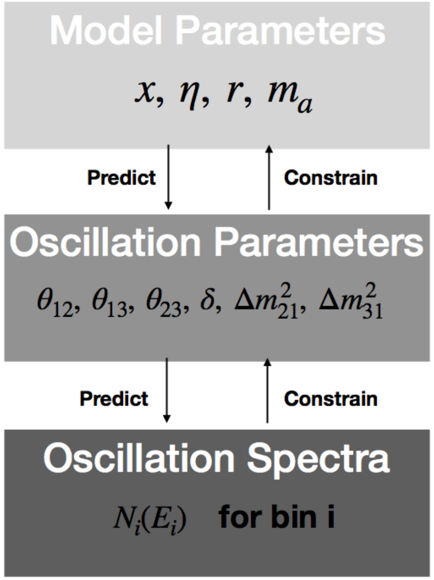
NSI at neutrino productions

Constraints on flavor-symmetry neutrino models

Flavour Symmetry Embedded -- GLoBES (FaSE-GLoBES) arXiv: [2006.14886](https://arxiv.org/abs/2006.14886)







Model Parameters

x, η, r, m_a

Predict ↓ ↑ **Constrain**

Oscillation Parameters

θ_{12}, θ_{13}, θ_{23}, δ, Δm^2_{21}, Δm^2_{31}

Predict ↓ ↑ **Constrain**

Oscillation Spectra

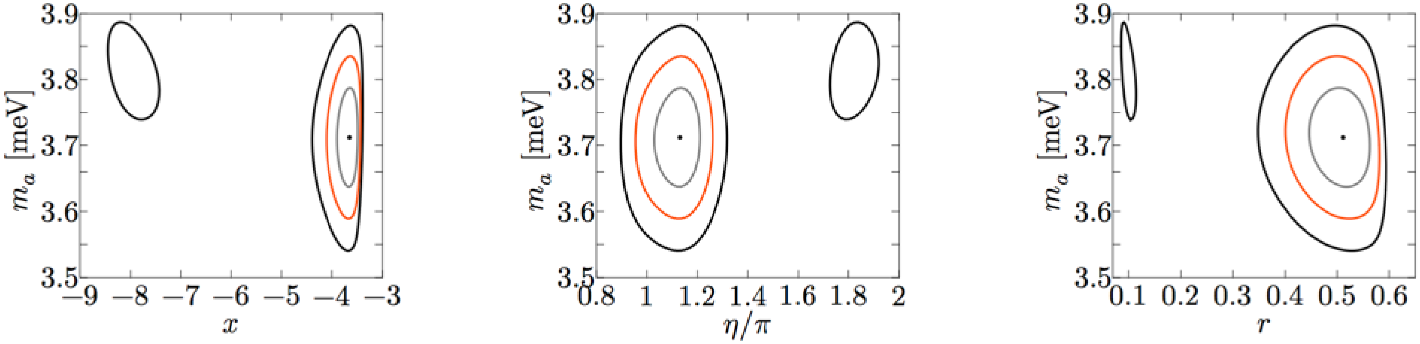
$N_i(E_i)$ **for bin i**

$$\overrightarrow{\mathcal{M}} = \{x\,,\eta\,,m_a\,,r\}$$

$$\chi^2(\overrightarrow{\mathcal{M}}) = \sum_{i=1}^{N} \frac{\left[\mu_i(\overrightarrow{\mathcal{O}}(\overrightarrow{\mathcal{M}})) - n_i\right]^2}{\sigma_i^2}$$

$$\overrightarrow{\mathcal{O}} = \{\theta_{12}\,,\theta_{13}\,,\theta_{23}\,,\delta_{\rm CP}\,,\Delta m^2_{21}\,,\Delta m^2_{31}\}$$

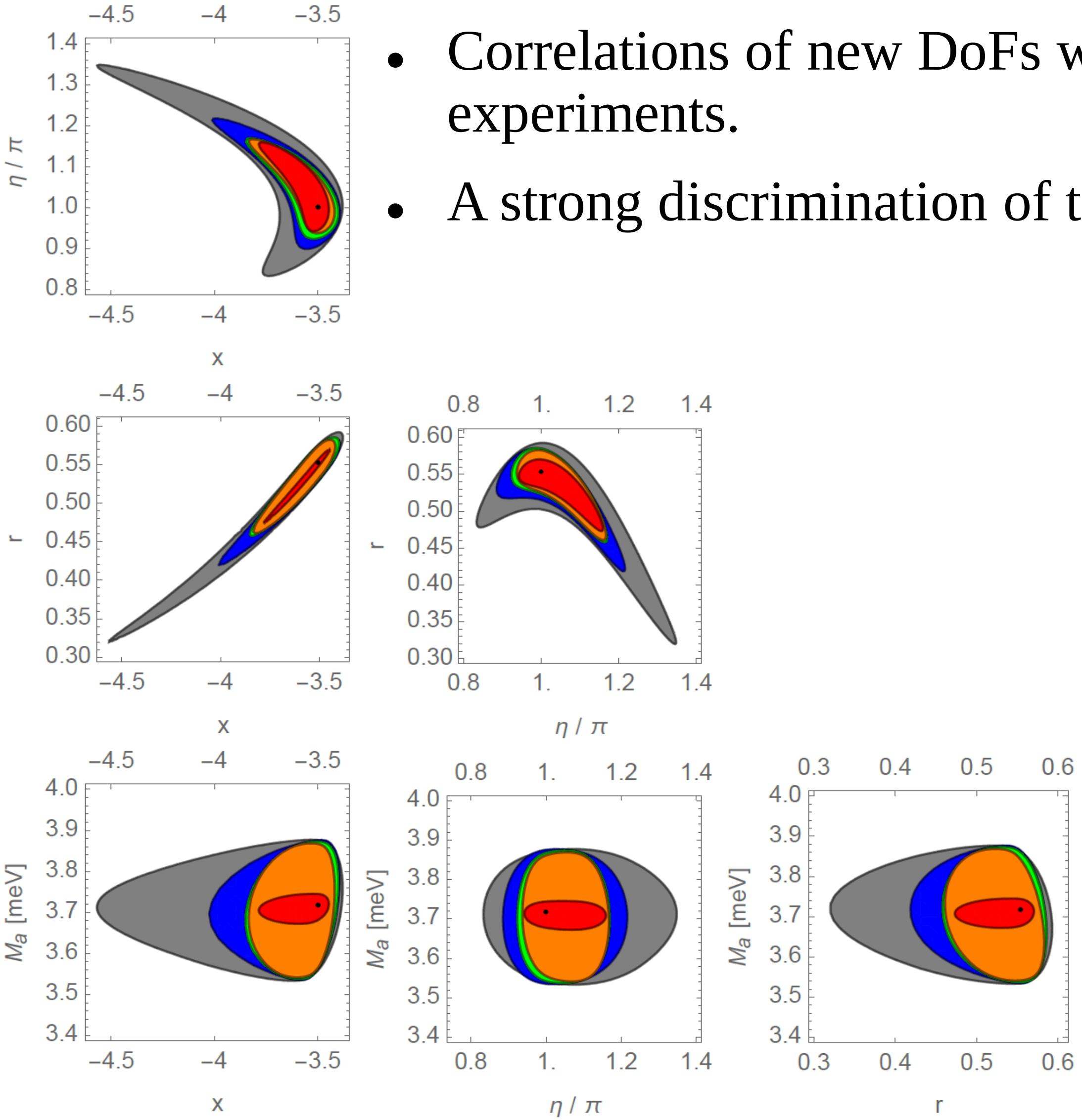
$$\chi^2(\overrightarrow{\mathcal{O}}) = \sum_{i=1}^{N} \frac{\left[\mu_i(\overrightarrow{\mathcal{O}}) - n_i\right]^2}{\sigma_i^2}$$

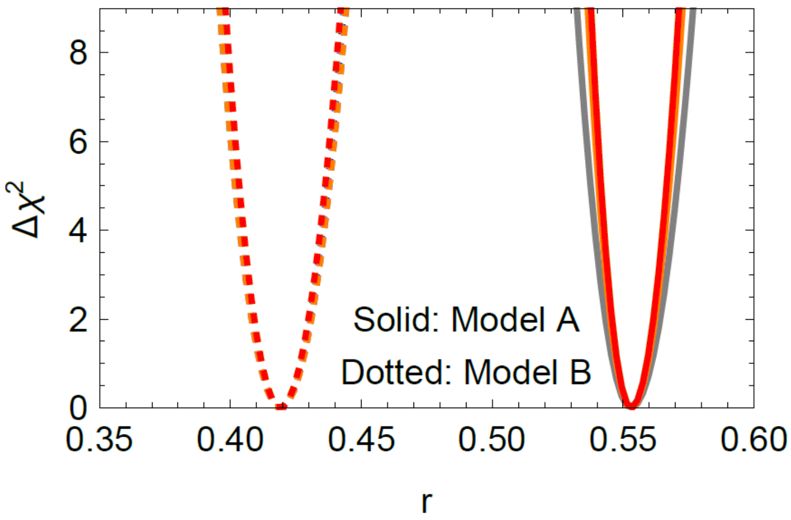


[Ref:1907.01371](https://arxiv.org/abs/1907.01371)

Test of neutrino models based on flavor symmetries

- Correlations of new DoFs well constrained by future neutrino experiments.
- A strong discrimination of tri-direct CP symmetry models.





Ref: 1905.12939

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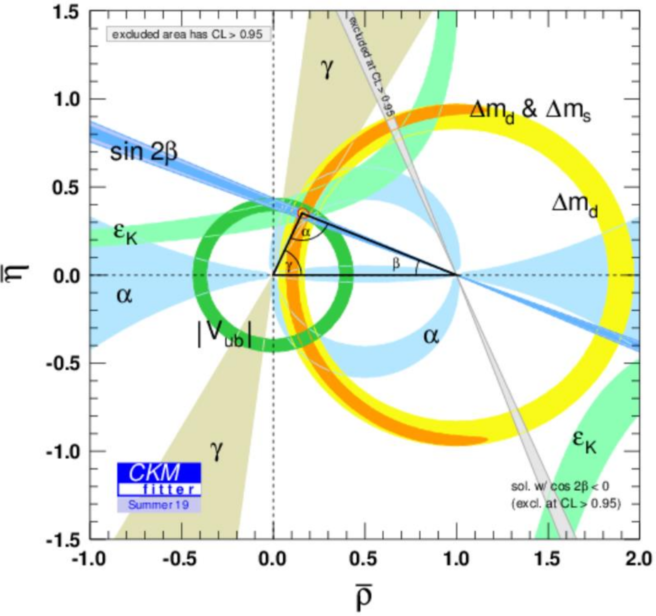
- Motivations
- Non-unitarity(NU) v.s non-standard interactions(NSIs)
- Global fits of mixing parameters without unitarity
- Constraints of NSIs based on SMEFT
- Future prospects

What if there is non-unitary mixing?

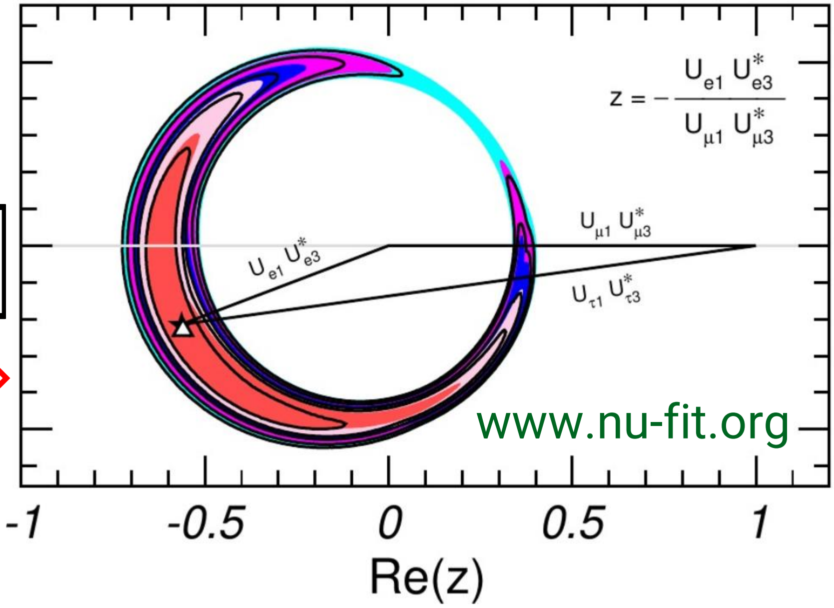
Quark mixing



No unitarity assumption here!

$$\boxed{U^\dagger U \stackrel{?}{=} 1}$$

Lepton mixing



$$U_{e1}U_{\mu 2}{}^* + U_{e2}U_{\mu 2}{}^* + U_{e3}U_{\mu 3}{}^* = 0$$

- Reduced constraints without the unitary assumption in the quark mixing.
- Let’s keep the democratic way in quark and lepton mixing?

Simple mathematics w/o unitarity assumption

Unitarity

ROWS: $\alpha = (e, \mu, \tau)$ $\quad j = (1, 2, 3)$ COLUMNS:

$$UU^\dagger = 1 \qquad\qquad U^\dagger U = 1$$

$$\sum_j |U_{\alpha j}|^2 = 1$$ row normalizations

$$\sum_\alpha |U_{\alpha j}|^2 = 1$$ column normalizations

$$\sum_j U_{\alpha j} U^*_{\beta j} = 0 \quad \alpha \neq \beta$$ row orthogonality

$$\sum_\alpha U_{\alpha j} U^*_{\alpha k} = 0 \quad j \neq k$$ column orthogonality

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Non-unitarity(NU)

18 real parameters in linear algebra

→ **-5** by rephrasing fields in physics

$$U^{\mathrm{NU}} = \begin{pmatrix} |U_{e1}|e^{i\phi_{e1}} & |U_{e2}|e^{i\phi_{e2}} & |U_{e3}| \\ |U_{\mu 1}|e^{i\phi_{\mu 1}} & |U_{\mu 2}|e^{i\phi_{\mu 2}} & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix}$$

- Only 4 real parameters with unitarity.
- Now we have 13 real parameters after rephrasing fields for NU!

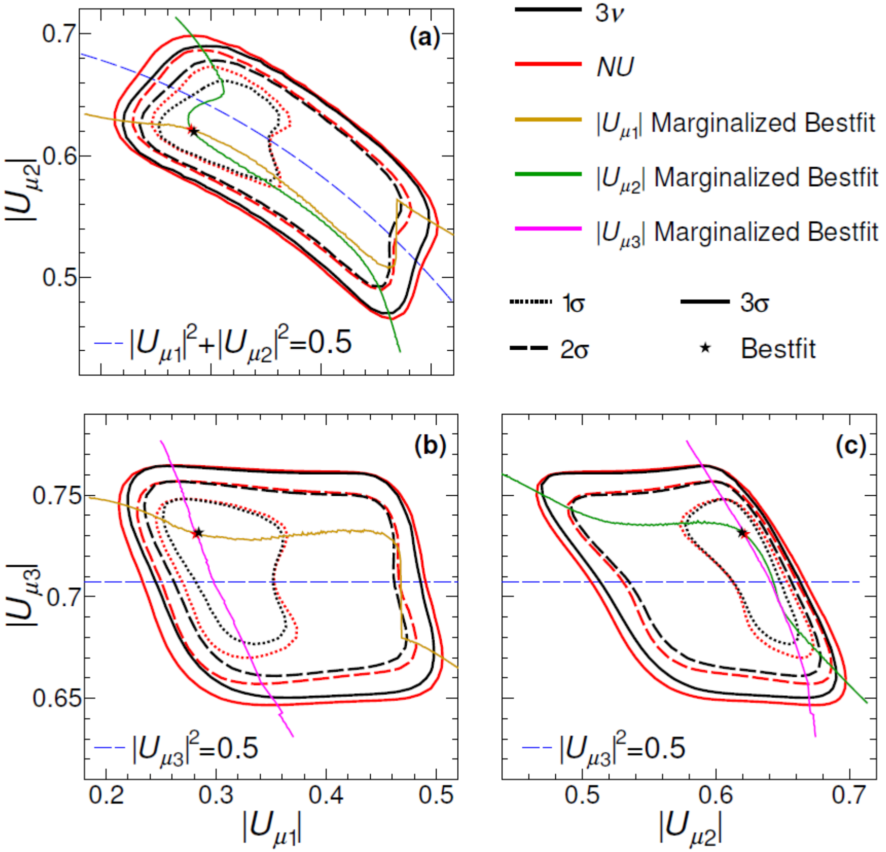
What if there is non-unitary mixing?

$$U^{\mathrm{NU}} = \begin{pmatrix} |U_{e1}|e^{i\phi_{e1}} & |U_{e2}|e^{i\phi_{e2}} & |U_{e3}| \\ |U_{\mu 1}|e^{i\phi_{\mu 1}} & |U_{\mu 2}|e^{i\phi_{\mu 2}} & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{pmatrix}$$

$$P^{\mathrm{NU}}_{\nu_\alpha \to \nu_\beta} = \left| \sum_{i=1} U^*_{\beta i} U_{\alpha i} \right|^2 - 4 \sum_{i<j} \Re\left(U_{\alpha i} U_{\beta j} U^*_{\alpha j} U^*_{\beta i} \right) \sin^2\left(\frac{\Delta m^2_{ji} L}{4E_\nu} \right)$$

$$\pm 2 \sum_{i<j} \Im \left(U_{\alpha i} U_{\beta j} U^*_{\alpha j} U^*_{\beta i} \right) \sin\left(\frac{\Delta m^2_{ji} L}{2E_\nu} \right),$$

Type	Exps	Measurement
MBL Reactor	RENO, Daya Bay Double Chooz	$4\lvert U_{e3}\rvert^2(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2)$
LBL Reactor	KamLAND	$4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2$
Solar	SNO	$\lvert U_{e2}\rvert^2$
LBL Accelerator ($\nu_\mu \to \nu_\mu$)	NOvA, T2K	$4\lvert U_{\mu 3}\rvert^2(\lvert U_{\mu 1}\rvert^2 + \lvert U_{\mu 2}\rvert^2)$
LBL Accelerator ($\nu_\mu \to \nu_e$)	NOvA, T2K	$4\Re[U_{e3}U^*_{\mu 3}(U_{e1}U^*_{\mu 1} + U_{e2}U^*_{\mu 2})]$
LBL Accelerator ($\nu_\mu \to \nu_\tau$)	OPERA	$4\Re[U_{\tau 3}U^*_{\mu 3}(U_{\tau 1}U^*_{\mu 1} + U_{\tau 2}U^*_{\mu 2})]$



- Correlations between 3nu mixing matrix elements without unitarity assumption.
- Octant degeneracies get worse for NU.

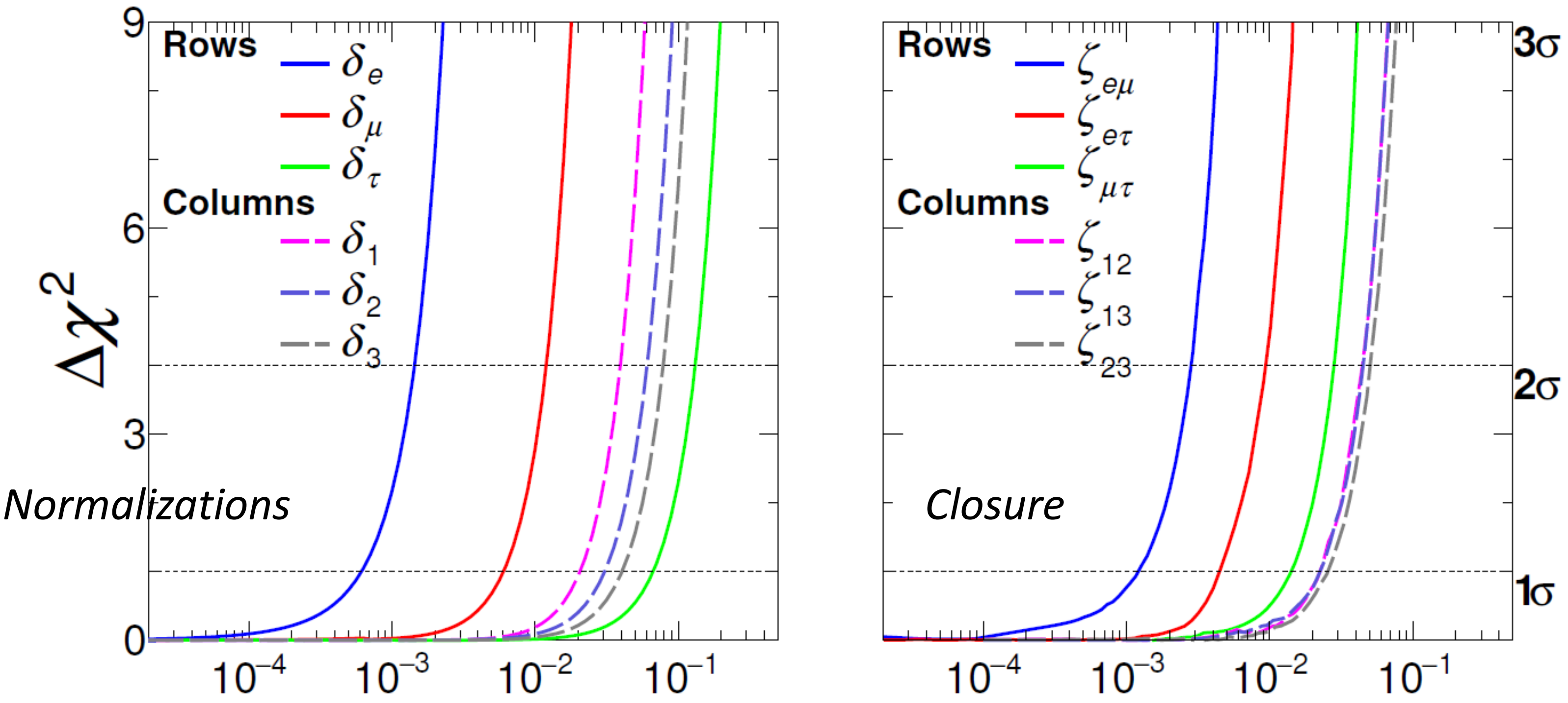
What if there is non-unitary mixing?

$$U^{\rm NU} = \begin{pmatrix} |U_{e1}|e^{i\phi_{e1}} & |U_{e2}|e^{i\phi_{e2}} & |U_{e3}| \\ |U_{\mu1}|e^{i\phi_{\mu1}} & |U_{\mu2}|e^{i\phi_{\mu2}} & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{pmatrix}$$

$$P^{\rm NU}_{\nu_\alpha\to\nu_\beta} = \left|\sum_{i=1} U^*_{\beta i}U_{\alpha i}\right|^2 - 4\sum_{i<j}\Re\left(U_{\alpha i}U_{\beta j}U^*_{\alpha j}U^*_{\beta i}\right)\sin^2\left(\frac{\Delta m^2_{ji}L}{4E_\nu}\right) \pm 2\sum_{i<j}\Im\left(U_{\alpha i}U_{\beta j}U^*_{\alpha j}U^*_{\beta i}\right)\sin\left(\frac{\Delta m^2_{ji}L}{2E_\nu}\right),$$

$\delta_\alpha=1-|U_{\alpha1}|^2-|U_{\alpha2}|^2-|U_{\alpha3}|^2$ $\delta_i=1-|U_{ei}|^2-|U_{\mu i}|^2-|U_{\tau i}|^2$

$\zeta_{\alpha\beta}=U_{\alpha1}U^*_{\beta1}+U_{\alpha2}U^*_{\beta2}+U_{\alpha3}U^*_{\beta3}$ $\zeta_{ij}=U_{ei}U^*_{ej}+U_{\mu i}U^*_{\mu j}+U_{\tau i}U^*_{\tau j}$



- Nice precision in the first and second row/column.
- Tau neutrino physics are to be improved for better constraints on 3rd row/column!

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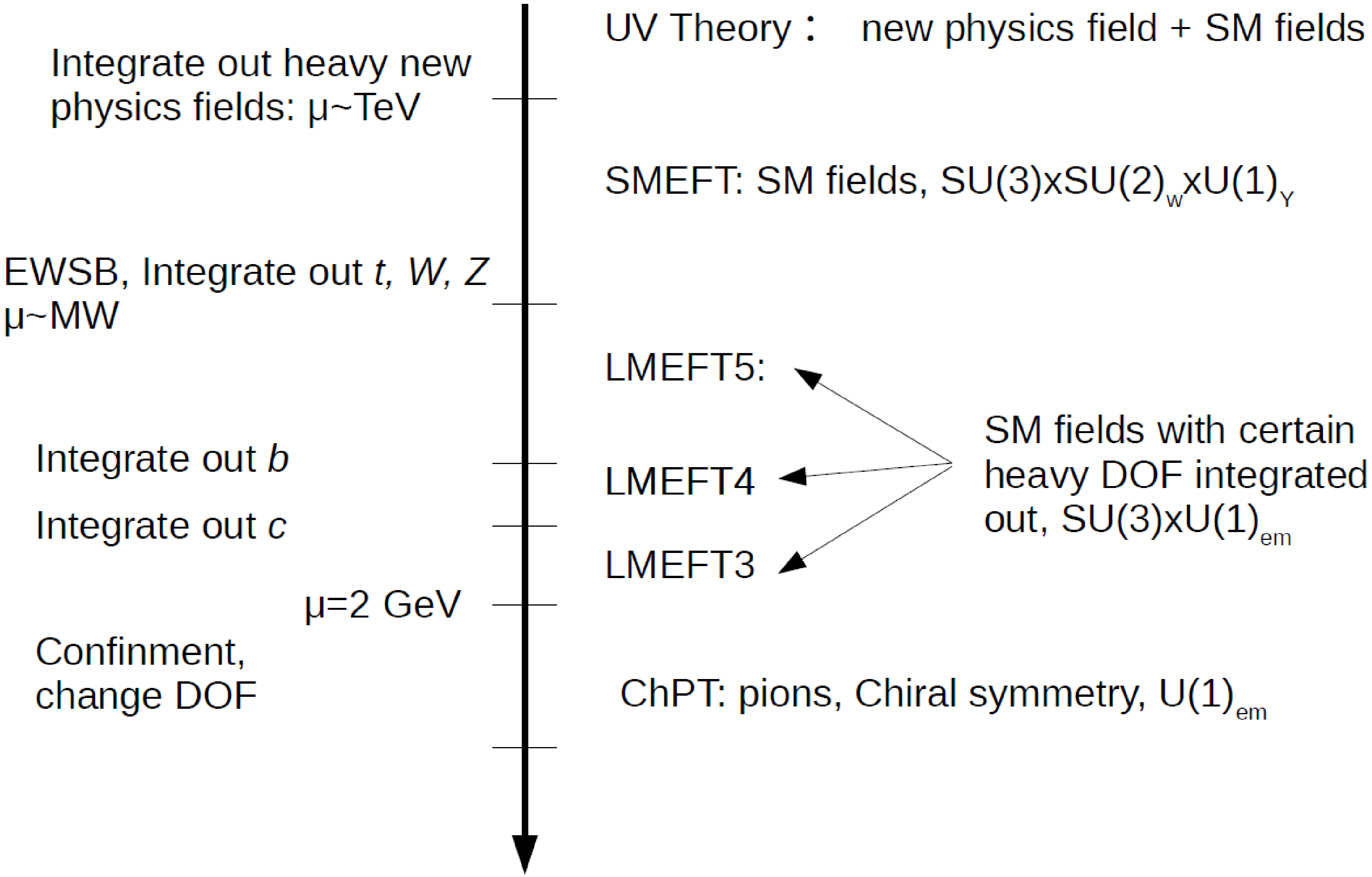
Working principle of effective field theory (EFT)



UV Theory： new physics field + SM fields

Integrate out heavy new physics fields: μ~TeV

SMEFT: SM fields, $SU(3)xSU(2)_{W}xU(1)_{Y}$

EWSB, Integrate out *t, W, Z* μ~MW

LMEFT5:

Integrate out *b*

LMEFT4

Integrate out *c*

LMEFT3

SM fields with certain heavy DOF integrated out, $SU(3)xU(1)_{em}$

μ=2 GeV

Confinment, change DOF

ChPT: pions, Chiral symmetry, $U(1)_{em}$

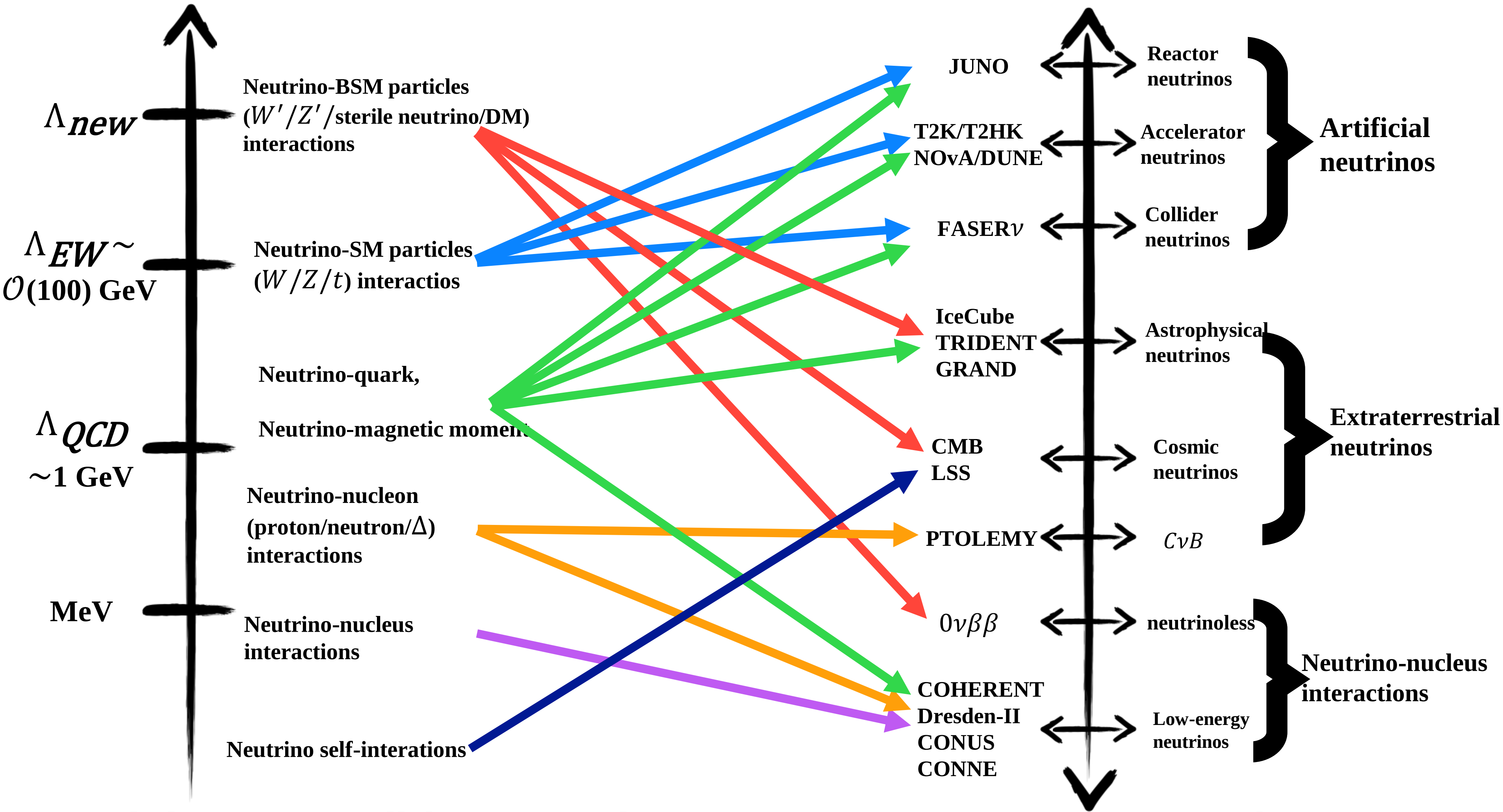
EFT: connecting low-energy phenomenon to high-energy scale

EFT ladder

Energy Scale	Theory	Particles	Expansion Parameter
Λ = ???	New Physics		?
1 TeV	SMEFT		$\frac{E}{\Lambda}$
100 GeV 10 GeV	WEFT (aka Fermi theory, LEFT, WET)	γ,g,ν,e,μ,τ + N_f q	$\frac{E}{m_W}$
1 GeV 100 MeV	χPT	γ,ν,e,μ,π,K	$\frac{E}{4\pi f_\pi}$
10 MeV 1 MeV	Lee-Yang	p,n,e,ν,γ	$\frac{E_k}{m_p}$

Credit: Adam Falkowski

EFT: connecting low-energy phenomenon to high-energy scale



Λ_{new}

$\Lambda_{EW}\sim$ $\mathcal{O}(100)$ GeV

Λ_{QCD} ~1 GeV

MeV

Neutrino-BSM particles ($W'/Z'/$sterile neutrino/DM) interactions

Neutrino-SM particles ($W/Z/t$) interactios

Neutrino-quark,

Neutrino-magnetic moment

Neutrino-nucleon (proton/neutron/Δ) interactions

Neutrino-nucleus interactions

Neutrino self-interations

JUNO

T2K/T2HK NOvA/DUNE

FASERν

IceCube TRIDENT GRAND

CMB LSS

PTOLEMY

$0\nu\beta\beta$

COHERENT Dresden-II CONUS CONNE

Reactor neutrinos

Accelerator neutrinos

Collider neutrinos

Artificial neutrinos

Astrophysical neutrinos

Cosmic neutrinos

$C\nu B$

Extraterrestrial neutrinos

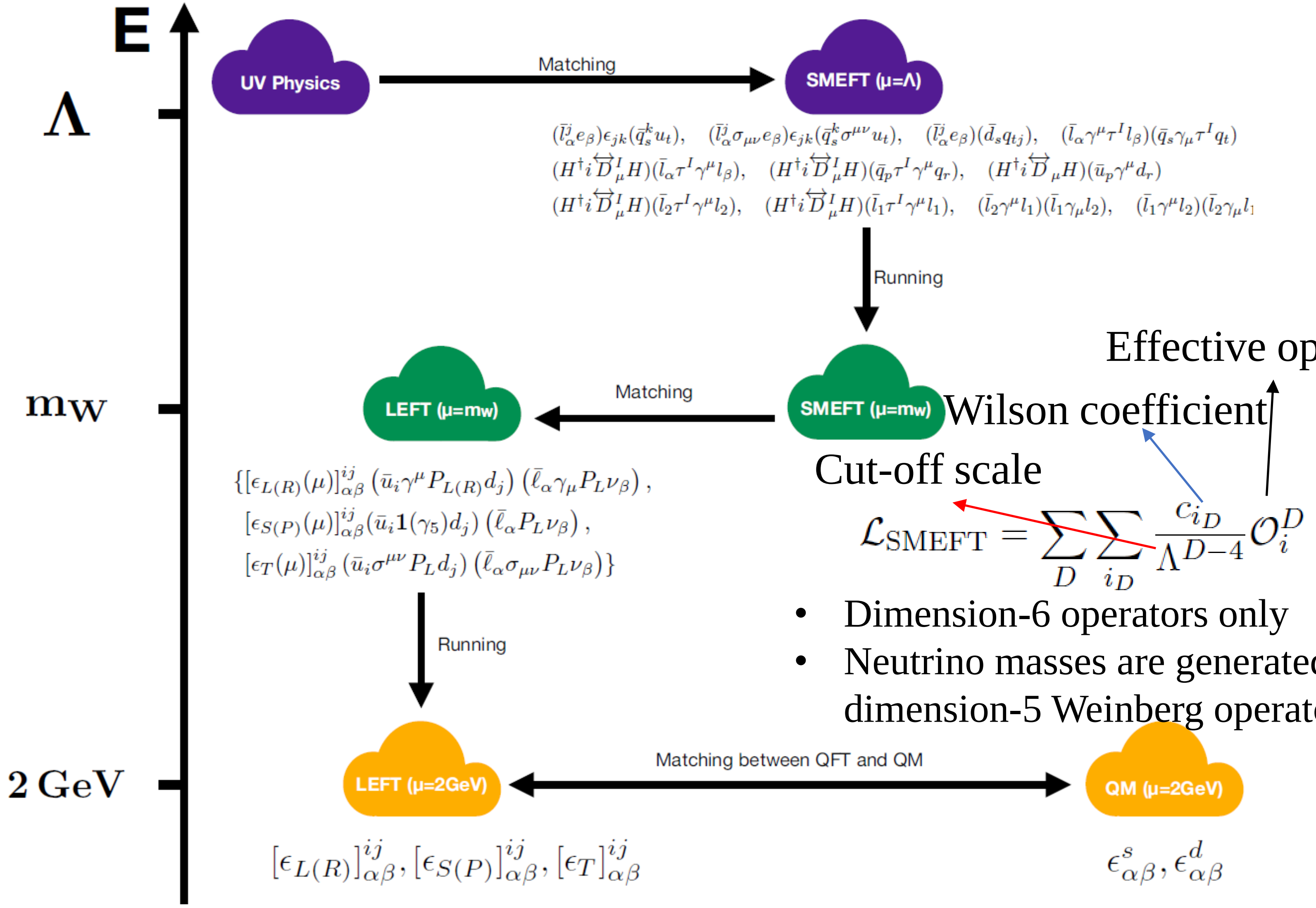
neutrinoless

Low-energy neutrinos

Neutrino-nucleus interactions

Funded project in collaboration with **Jiang-Hao Yu**, **Ning-Qiang Song** and **Guang Li**!

EFT: connecting low-energy phenomenon to high-energy scale



$(\bar{l}^j_\alpha e_\beta)\epsilon_{jk}(\bar{q}^k_s u_t)$, $(\bar{l}^j_\alpha \sigma_{\mu\nu} e_\beta)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$, $(\bar{l}^j_\alpha e_\beta)(\bar{d}_s q_{tj})$, $(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(\bar{q}_s \gamma_\mu \tau^I q_t)$

$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_\alpha \tau^I \gamma^\mu l_\beta)$, $(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$, $(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_2 \tau^I \gamma^\mu l_2)$, $(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_1 \tau^I \gamma^\mu l_1)$, $(\bar{l}_2 \gamma^\mu l_1)(\bar{l}_1 \gamma_\mu l_2)$, $(\bar{l}_1 \gamma^\mu l_2)(\bar{l}_2 \gamma_\mu l_1$

$$\{[\epsilon_{L(R)}(\mu)]^{ij}_{\alpha\beta}\,(\bar{u}_i \gamma^\mu P_{L(R)} d_j)\,(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta)\,,$$
$$[\epsilon_{S(P)}(\mu)]^{ij}_{\alpha\beta}(\bar{u}_i \mathbf{1}(\gamma_5) d_j)\,(\bar{\ell}_\alpha P_L \nu_\beta)\,,$$
$$[\epsilon_T(\mu)]^{ij}_{\alpha\beta}\,(\bar{u}_i \sigma^{\mu\nu} P_L d_j)\,(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta)\}$$

$$[\epsilon_{L(R)}]^{ij}_{\alpha\beta}, [\epsilon_{S(P)}]^{ij}_{\alpha\beta}, [\epsilon_T]^{ij}_{\alpha\beta}$$

$$\epsilon^s_{\alpha\beta}, \epsilon^d_{\alpha\beta}$$

Effective operators

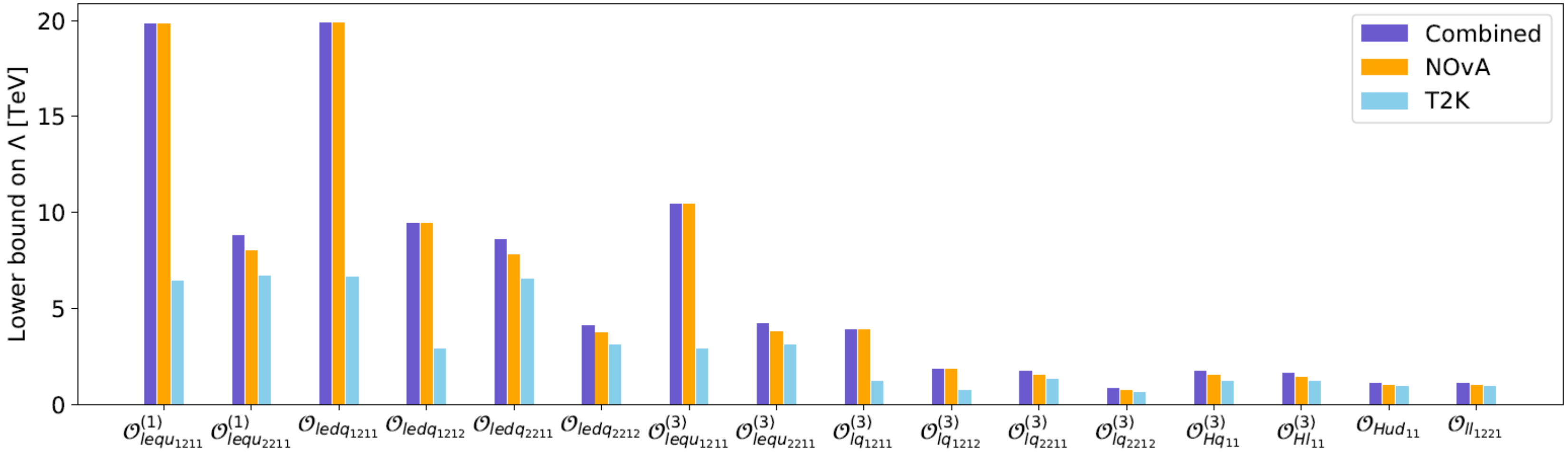
Wilson coefficient

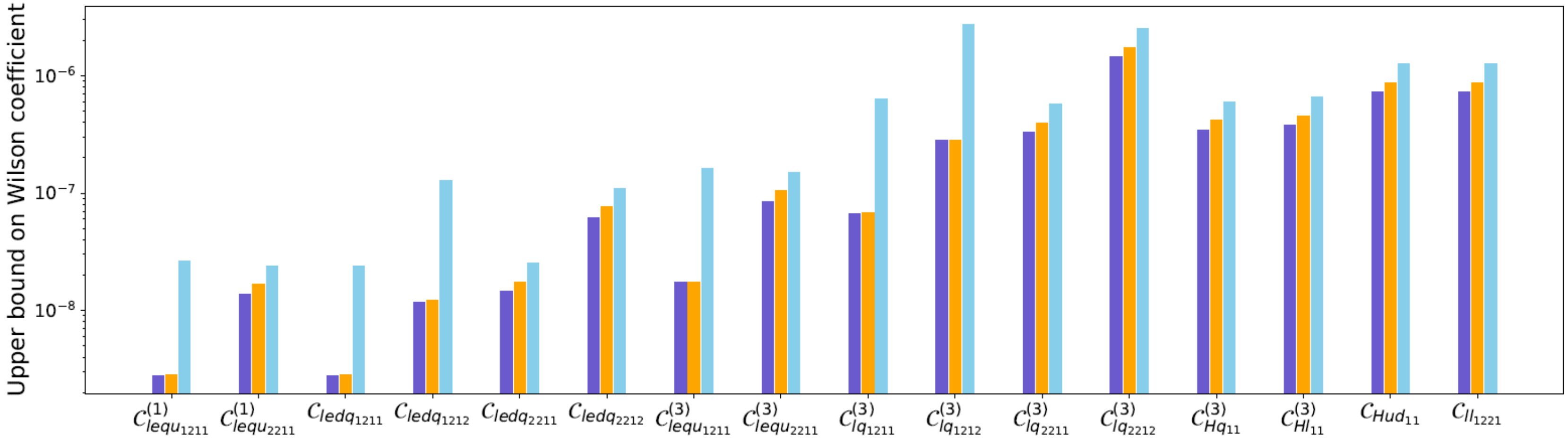
Cut-off scale

$$\mathcal{L}_{\rm SMEFT} = \sum_D \sum_{i_D} \frac{c_{i_D}}{\Lambda^{D-4}} \mathcal{O}^D_i$$

- Dimension-6 operators only
- Neutrino masses are generated by dimension-5 Weinberg operators

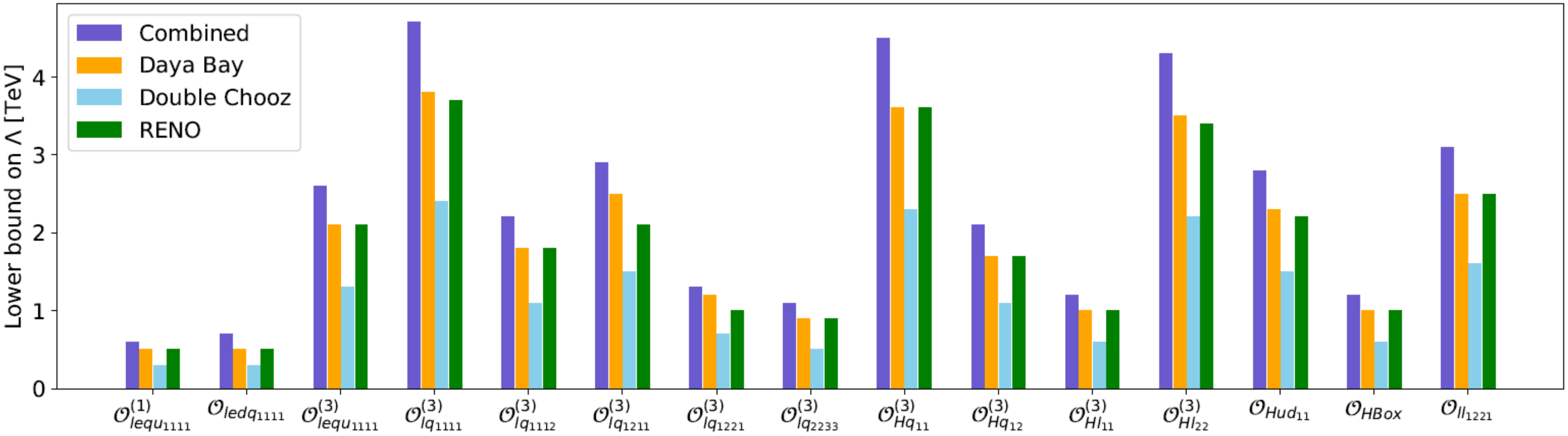
SMEFT-NSIs by T2K and NOvA

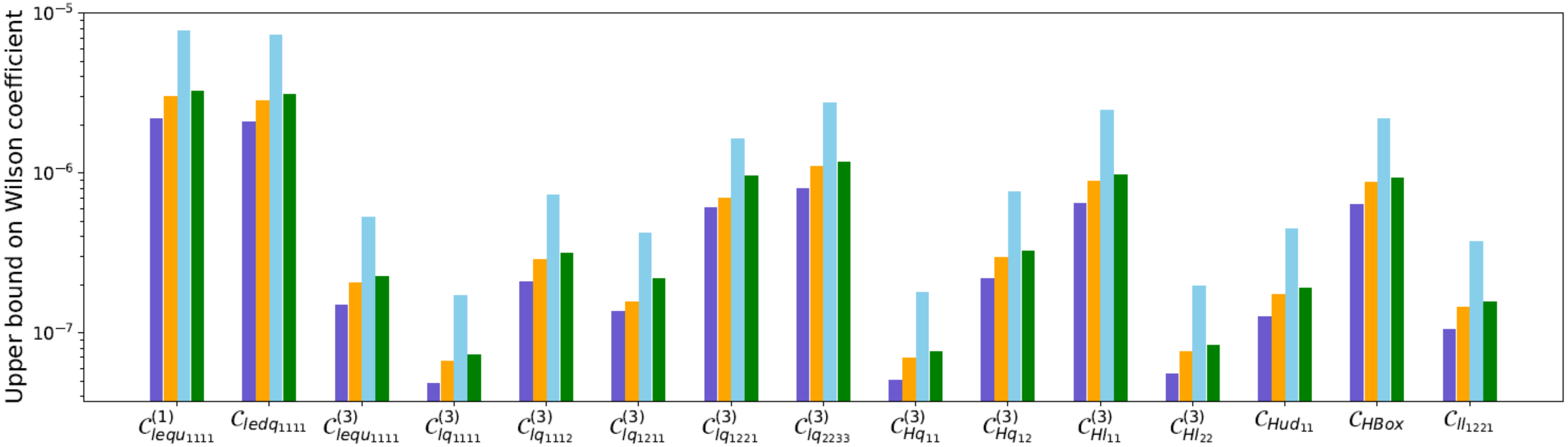




- T2K and NOvA are already sensitive to new physics around 20 TeV.
- Correlations among different dimension-6 operators play important roles.

SMEFT-NSIs by reactor neutrino experiments





- Reactor neutrino experiments are sensitive to new physics around 5 TeV.
- Complementarity between LBL and reactor expts due to different sets of operators

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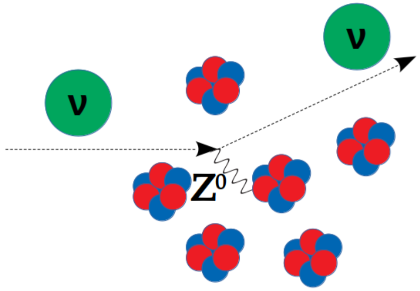
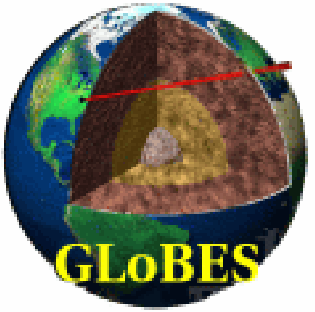
Democratic treatment of CKM and PMNS mixing

flavio

Smelli



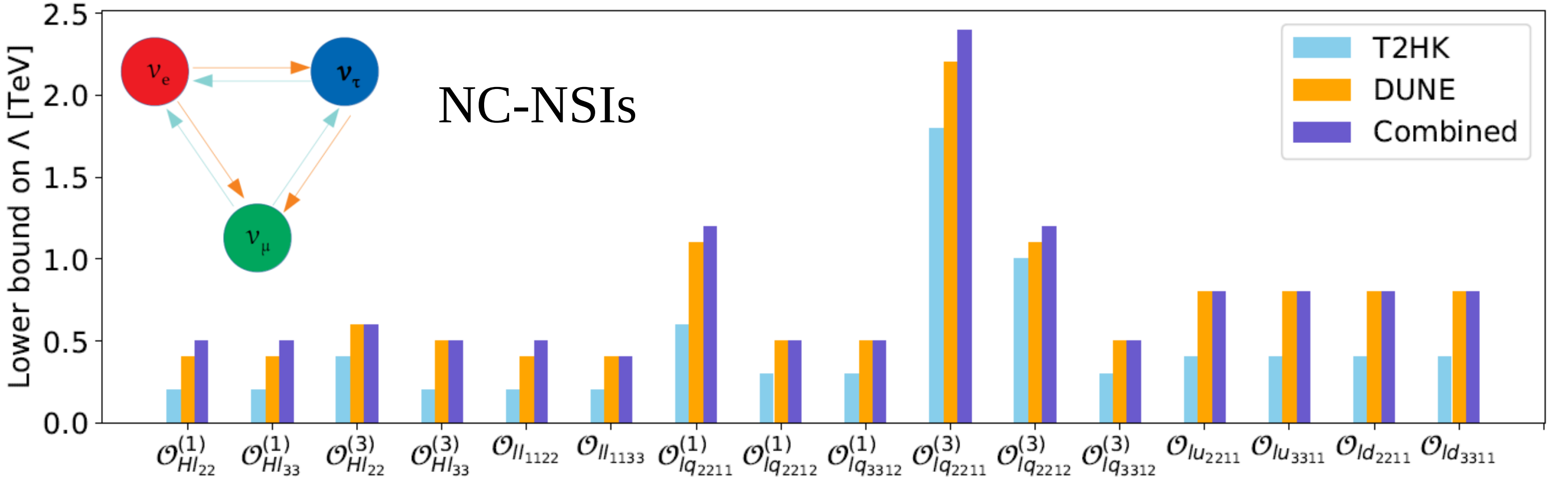


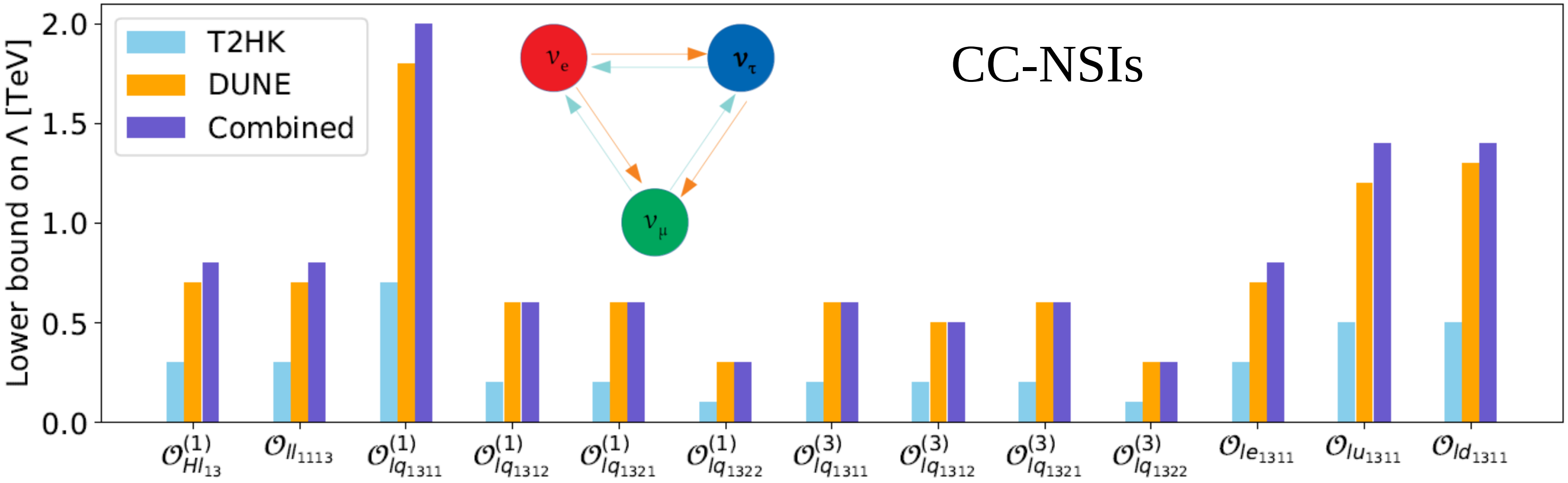
Quark mixing v.s neutrino mixing/scattering

$$\mathcal{O}^{\mathrm{CKM}}_{1,2,3,4} = \Gamma\left(K \to \mu\nu_\mu\right)/\Gamma\left(\pi \to \mu\nu_\mu\right),\ \mathrm{Br}(B \to X_c e\nu),\ \mathrm{Br}(B^+ \to \tau\nu),\ \Delta M_d/\Delta M_s$$

Operator	$\mathcal{O}^{(1)}_{qq1313}$	$\mathcal{O}^{(1)}_{qq2323}$	$\mathcal{O}^{(3)}_{qq1313}$	$\mathcal{O}^{(3)}_{qq2323}$	$\mathcal{O}_{dd1313}$	$\mathcal{O}_{dd2323}$
Λ valid (TeV)	> 365	> 51	> 365	> 51	> 383	> 53
Operator	$\mathcal{O}^{(1)}_{qd1213}$	$\mathcal{O}^{(1)}_{qd1313}$	$\mathcal{O}^{(1)}_{qd2323}$	$\mathcal{O}^{(8)}_{qd1213}$	$\mathcal{O}^{(8)}_{qd1313}$	$\mathcal{O}^{(8)}_{dd2323}$
Λ valid (TeV)	> 23	> 1383	> 178	> 25	> 1466	> 188

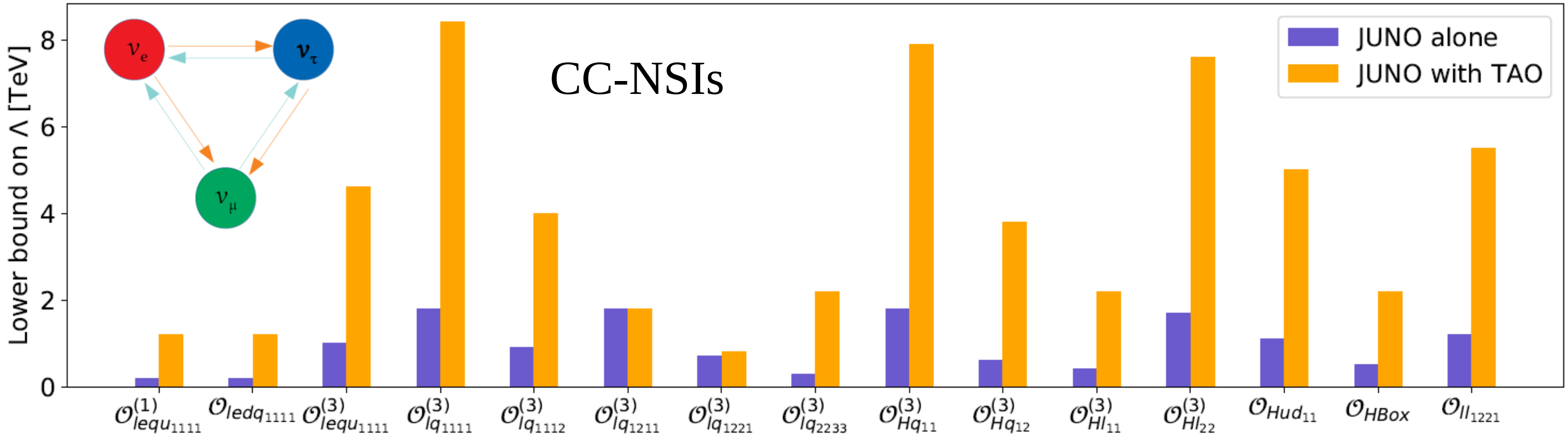
SMEFT-NSIs by T2HK and DUNE

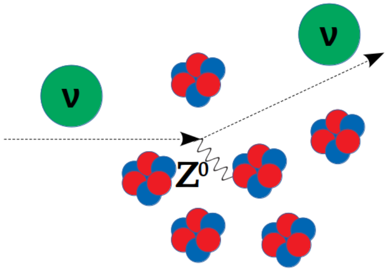


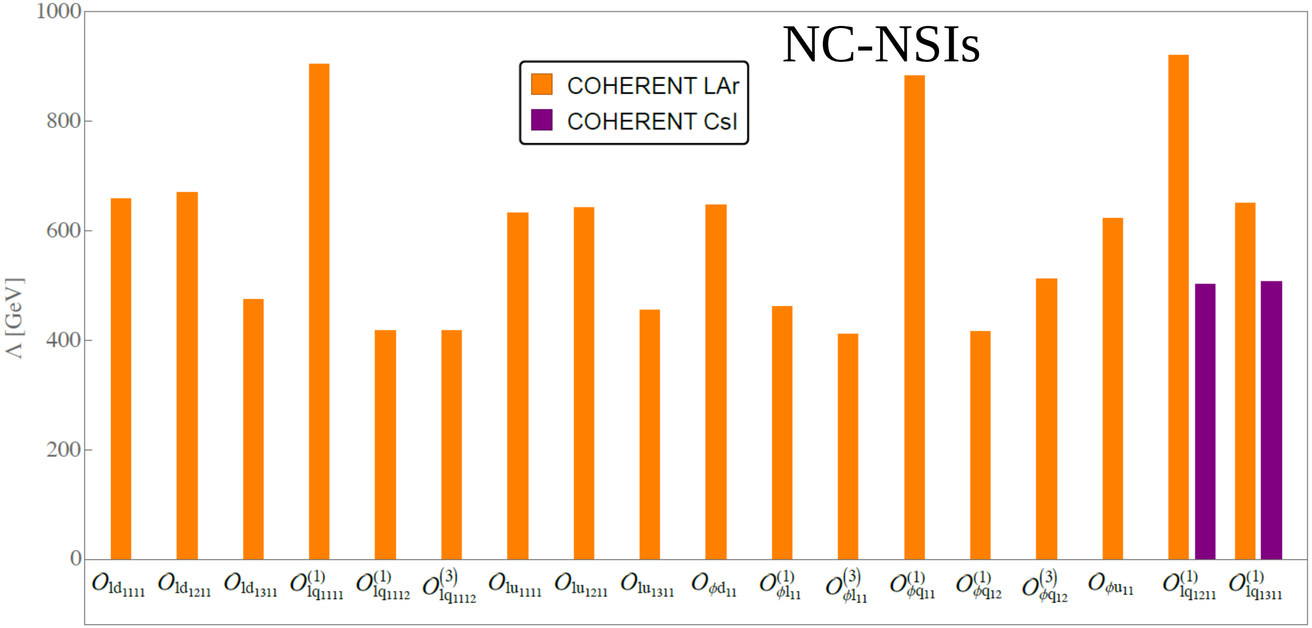


- Cover 1635 SMEFT operators in dimention-6. ND is important to constraint SMEFT-NSIs.
- DUNE has better sensitivity than T2HK due to the longer baseline.

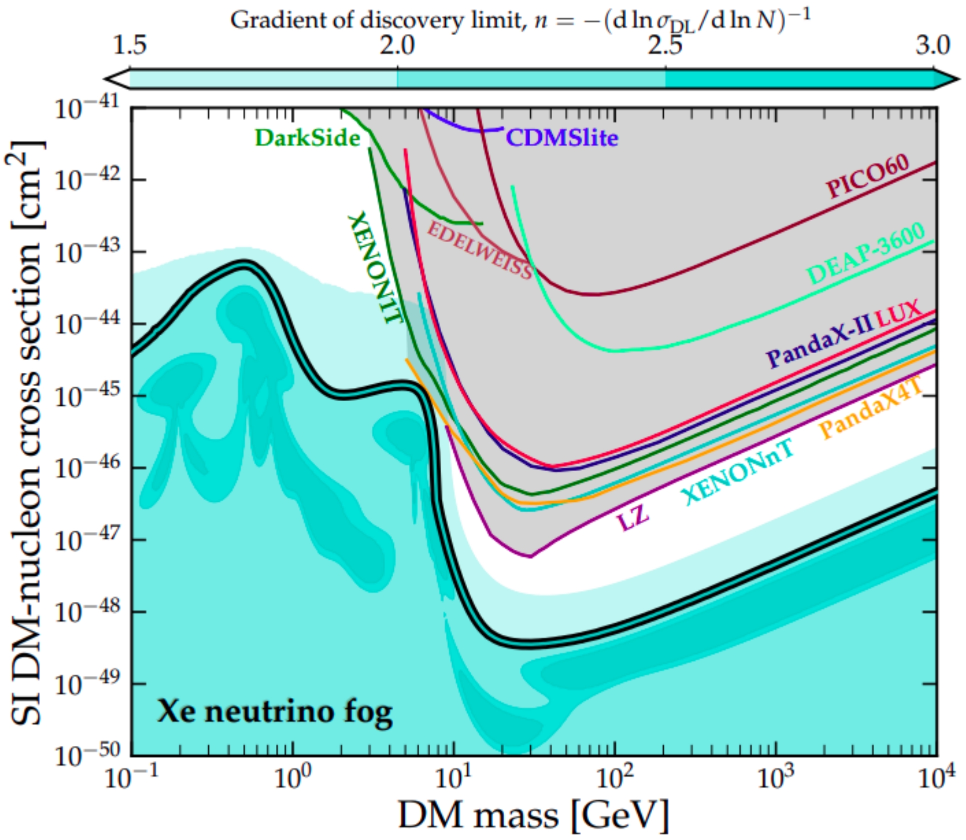
SMEFT-NSIs by JUNO w/o TAO and COHERENT



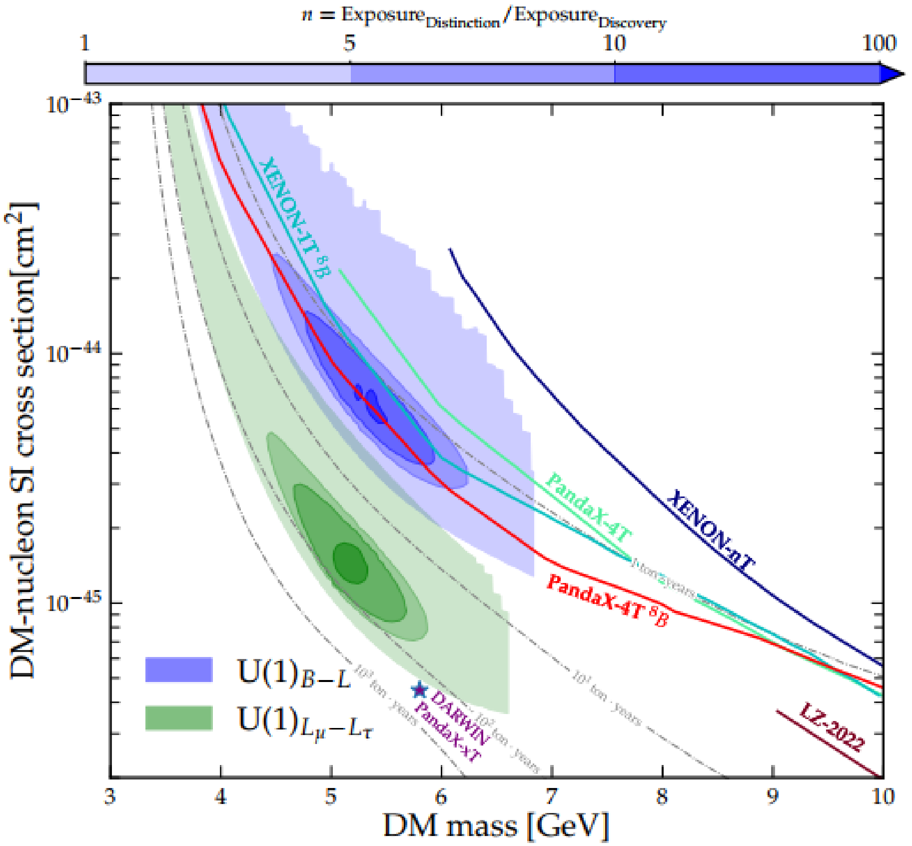




One stone, two birds: DM & neutrino NSIs



J. Tang, *B. L. Zhang, Phys.Rev.D 108 (2023) 6, 062004*



J. Tang, *B. L. Zhang, arXiv: [2403.05819](https://arxiv.org/abs/2403.05819),*

https://github.com/zhangblong/DistinctionLimit

Summary

- Neutrino oscillation is the first direct evidence BSM.
- Discovery of CPV & determination of MH is around the corner. Neutrino will be used for new physics searches.
- New physics might be hidden in the uncertainties.
- Unitary mixing should not be taken by default, as tau neutrino-related part is yet to be improved.
- We can have better knowledge of underlying theory by RGE running and matching in different scales to connect the low-energy neutrino oscillation experiments and the UV completion model in SMEFT.
- Let's work together to discover new physics with neutrinos…

News—Two Postdoc positions opening in SYSU

1. One to work on neutrino physics, such as neutrino scattering or data analysis for JUNO OSIRIS with German colleagues.
2. The other to work on muon physics and its applications

◆Salary: ~50 k Euros/year + bonus + on-campus apartment.

◆Application packages: CV, publication list, research statement, two reference letters to email: tangjian5@mail.sysu.edu.cn

◆Remote interview might happen soon after a complete application package is received.

◆Deadline: June 30, 2024.

THANK YOU

An example for demonstration

- Start from a UV theory

$$\Delta\mathcal{L} = (D_\mu H_2^\dagger)(D^\mu H_2) - M^2|H_2|^2 - Y\overline{L}_i H_{2i} e_R - Y^*\overline{e_R} H_{2i}^\dagger L_i$$

- Matching by covariant derivative expansion, EoM

$$(D^2 H_2^\dagger)_i + M^2 H_{2i}^\dagger = -Y\overline{L}_i e_R$$

$$(D_{ij}^2 + M^2\delta_{ij})H_{2j}^\dagger = -Y\overline{L}_i e_R$$

$$(D^2 H_2)_i + M^2 H_{2i} = -Y^*\overline{e_R} L_i$$

$$(D_{ij}^2 + M^2\delta_{ij})H_{2j} = -Y^*\overline{e_R} L_i$$

- Solve for classical solution

$$\begin{aligned} H_{c,2i} &= -(D_{ij}^2 + M^2\delta_{ij})^{-1} Y^*\overline{e_R} L_j \\ &= -\frac{1}{M^2}\left(1 + \frac{D^2}{M^2}\right)_{ij}^{-1} Y^*\overline{e_R} L_j \\ &= -\frac{1}{M^2} Y^*\overline{e_R} L_i + \mathcal{O}(\frac{1}{M^4}) \end{aligned}$$

$$H_{c,2i}^\dagger = -\frac{1}{M^2} Y\overline{L}_i e_R + \mathcal{O}(\frac{1}{M^4})$$

An example for demonstration

- Put the classical solution back to Lagrangian density

$$(D_\mu H_{2,c}^\dagger)(D^\mu H_{2,c}) = -H_{2,c}^\dagger D^2 H_{2,c} \sim \mathcal{O}(\frac{1}{M^4})$$

$$-M^2|H_{2,c}|^2 = -\frac{|Y|^2}{M^2}\overline{L}_i e_R \overline{e_R} L_i$$

$$-Y\overline{L}_i H_{2i,c} e_R - Y^*\overline{e_R} H_{2i,c}^\dagger L_i = \frac{2|Y|^2}{M^2}\overline{L}_i e_R \overline{e_R} L_i$$

$$\mathcal{L}_{eff}^{dim-6} = \frac{|Y|^2}{M^2}\overline{L}_i e_R \overline{e_R} L_i$$

Not in Warsaw Basis

- Fierz transformation to Warsaw basis

$$\frac{|Y|^2}{M^2}\overline{L}_i e_R \overline{e_R} L_i = \frac{|Y|^2}{2M^2}\boxed{(\overline{L}_i \gamma^\mu L_i)(\overline{e_R}\gamma^\mu e_R)}$$

$$C_{le} = \frac{|Y|^2}{2M^2} \qquad Q_{le}$$

SMEFT at scale M

An example for demonstration

- Run down from scale M to electroweak scale v

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}C_i = \sum_j \gamma_{ij}C_j$$

- Probably generate non-zero Wilson coefficients other than C_{le}
- Matching at electroweak scale to LEFT

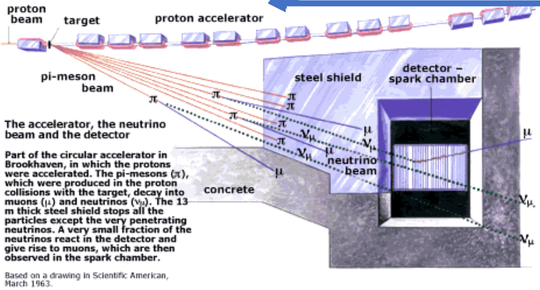
$$L_p = \begin{bmatrix} \nu_p \\ e_p \end{bmatrix}$$

$$\begin{aligned}
\frac{Y_{ps}Y_{tr}^{\dagger}}{2M^2}(\overline{L_i^p}\gamma^\mu L_i^r)(\overline{e_R^s}\gamma^\mu e_R^t) &= \frac{Y_{ps}Y_{tr}^{\dagger}}{2M^2}(\overline{\nu_L}^p\gamma^\mu \nu_L^r + \overline{e_L}^p\gamma^\mu e_L^r)(\overline{e_R^s}\gamma^\mu e_R^t) \\
&= \boxed{\frac{Y_{ps}Y_{tr}^{\dagger}}{2M^2}}\left[\underbrace{\boxed{(\overline{\nu_L}^p\gamma^\mu \nu_L^r)(\overline{e_R^s}\gamma^\mu e_R^t)}}_{\mathcal{O}_{\nu e}^{V,LR}} + \underbrace{\boxed{(\overline{e_L}^p\gamma^\mu e_L^r)(\overline{e_R^s}\gamma^\mu e_R^t)}}_{\mathcal{O}_{ee}^{V,LR}}\right]
\end{aligned}$$

Matching between QM and QFT NSIs

$$H = \frac{1}{2E_\nu}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee}^m & \epsilon_{e\mu}^m & \epsilon_{e\tau}^m\\ \epsilon_{e\mu}^{m*} & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m\\ \epsilon_{e\tau}^{m*} & \epsilon_{\mu\tau}^{m*} & \epsilon_{\tau\tau}^m\end{pmatrix}\right]$$

QM NSIs	Relations to QFT NSIs
$\epsilon^s_{e\beta}$ (β decay)	$\left[\epsilon_L - \epsilon_R - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}\epsilon_T\right]^*_{e\beta}$
$\epsilon^d_{\beta e}$ (inverse β decay)	$\left[\epsilon_L + \frac{1-3g_A^2}{1+3g_A^2}\epsilon_R - \frac{m_e}{E_\nu-\Delta}\left(\frac{g_S}{1+3g_A^2}\epsilon_S - \frac{3g_A g_T}{1+3g_A^2}\epsilon_T\right)\right]_{e\beta}$
$\epsilon^s_{\mu\beta}$ (pion decay)	$\left[\epsilon_L - \epsilon_R - \frac{m_\pi^2}{m_\mu(m_u+m_d)}\epsilon_P\right]^*_{\mu\beta}$
$\epsilon^s_{\mu\beta}$(muon decay)	$\left[g_{22} + \frac{3m_e m_\mu(m_\mu-2E_\nu)}{16m_\mu E_\nu^2+6m_\mu(m_\mu^2+m_e^2)-4E_\nu(5m_\mu^2+m_e^2)}h_{21}\right]^*_{\mu\beta}$
$\epsilon^s_{e\beta}$ (muon decay)	$\left[g_{22} + \frac{m_e}{4(m_\mu-2E_{\bar\nu})}h_{21}\right]^*_{e\beta}$



The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.

- QM NSIs are fully independent without much info about the underlying theory.
- QFT NSIs allow their correlations.