Non-standard neutrino interaction

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High-energy astrophysics in the multi-messenger era
Erlangen - Germany

M82, a nearby galaxy, is home to a type Ia supernova. nature.com/articles/nature.2014.14579

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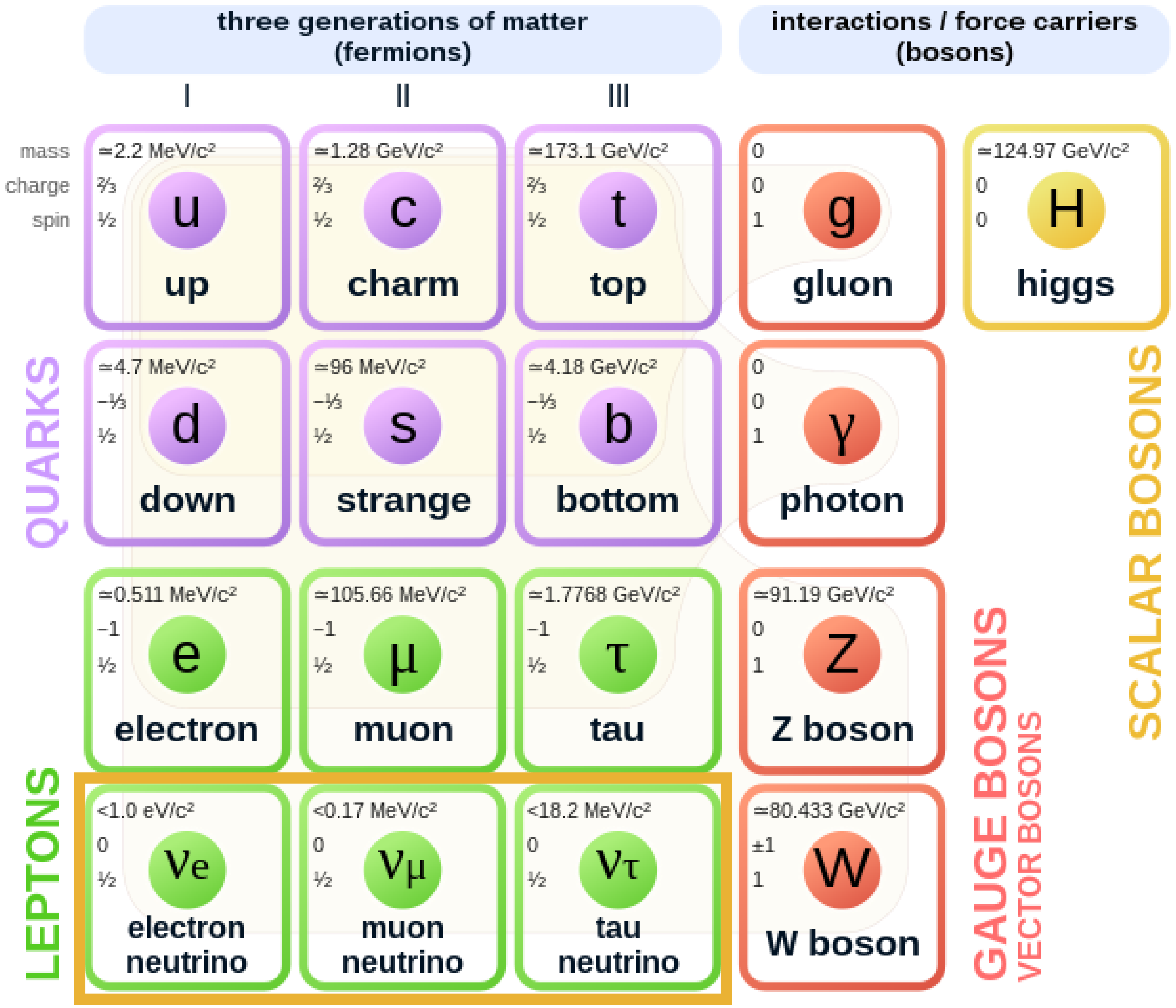
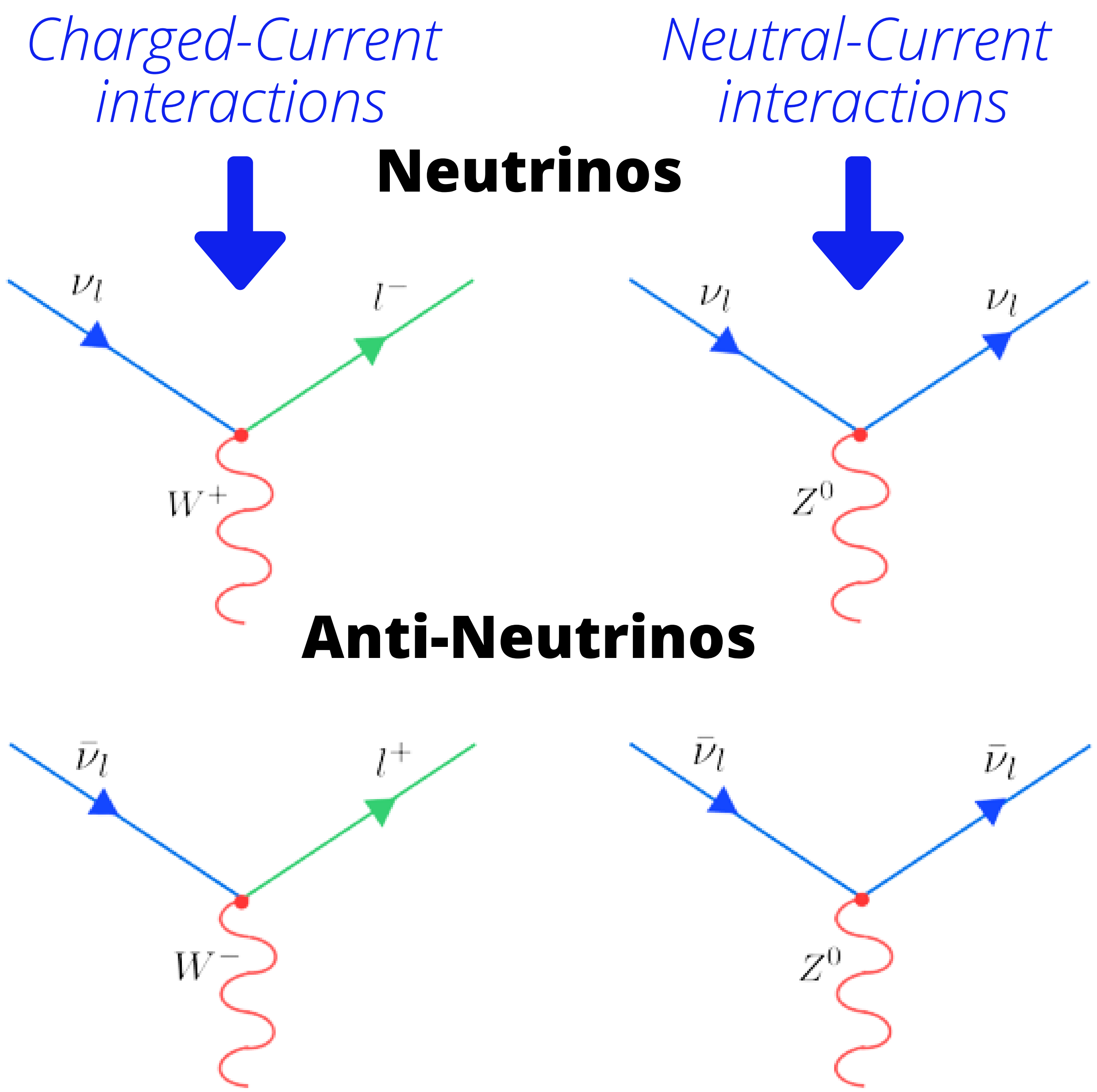
Standard model (SM)



Standard Model (SM) of Elementary Particles.
pt.wikipedia.org/wiki/Standard_Model

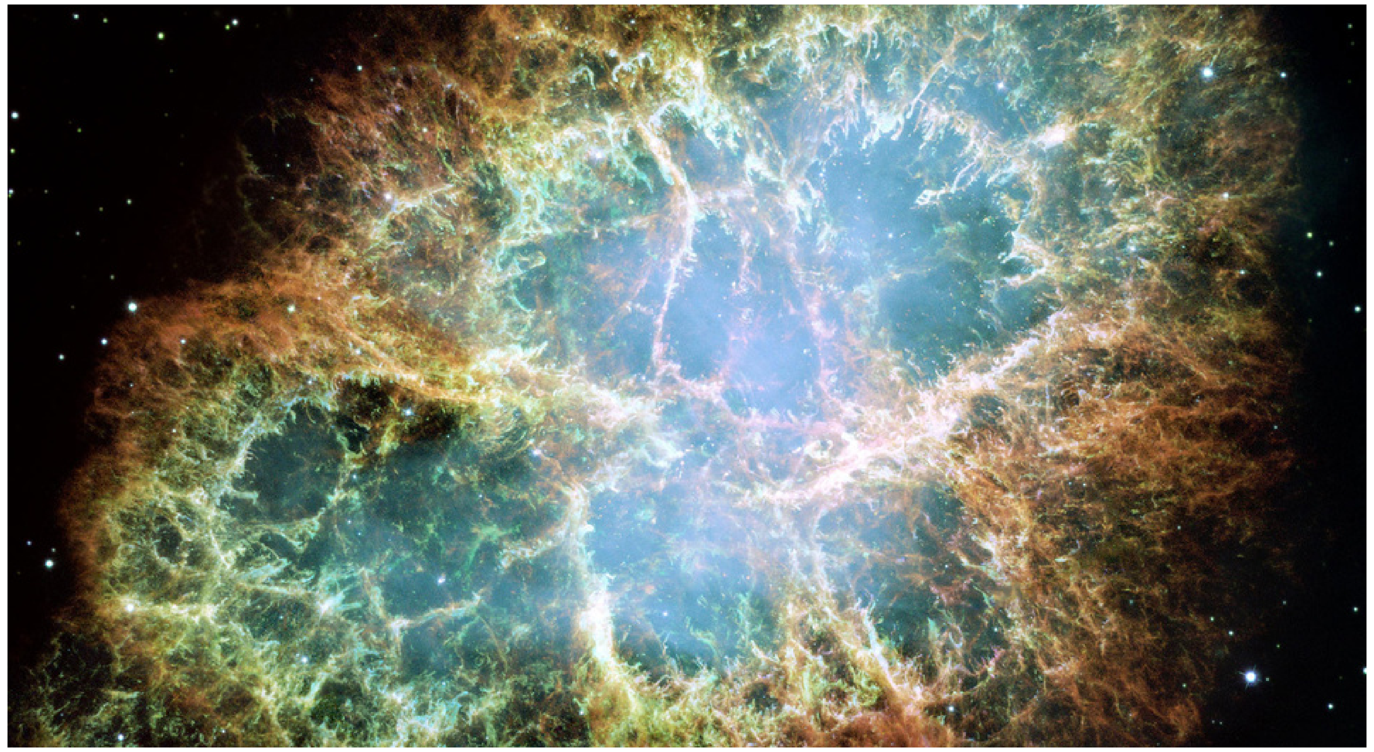
Neutrinos

- Neutrinos are electrically neutral and come in three flavors;
- Reacts to gravity and the weak force.

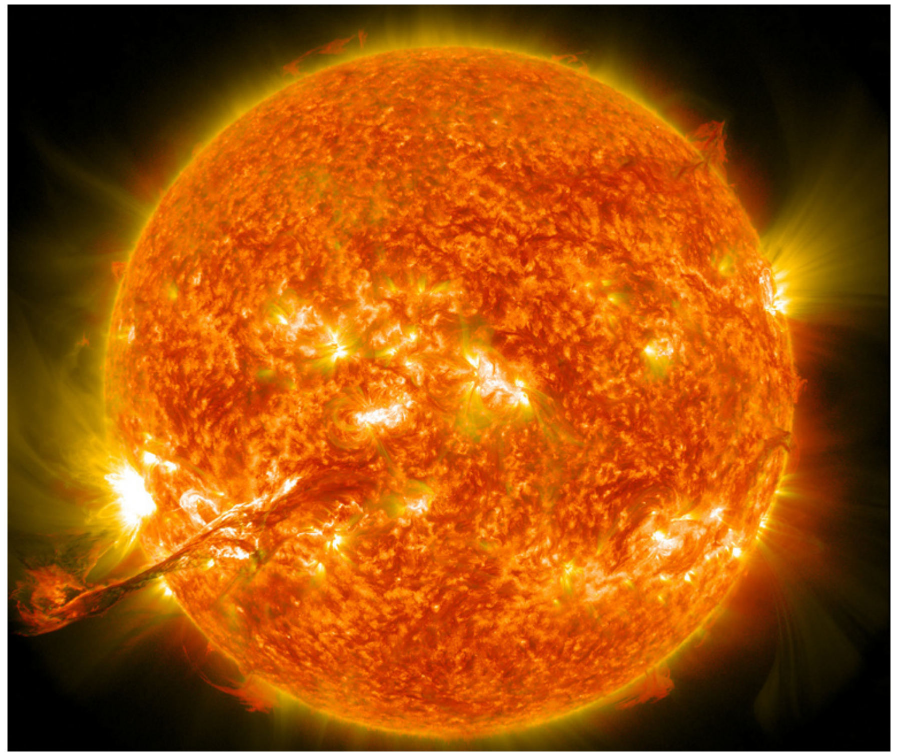


Neutrino sources

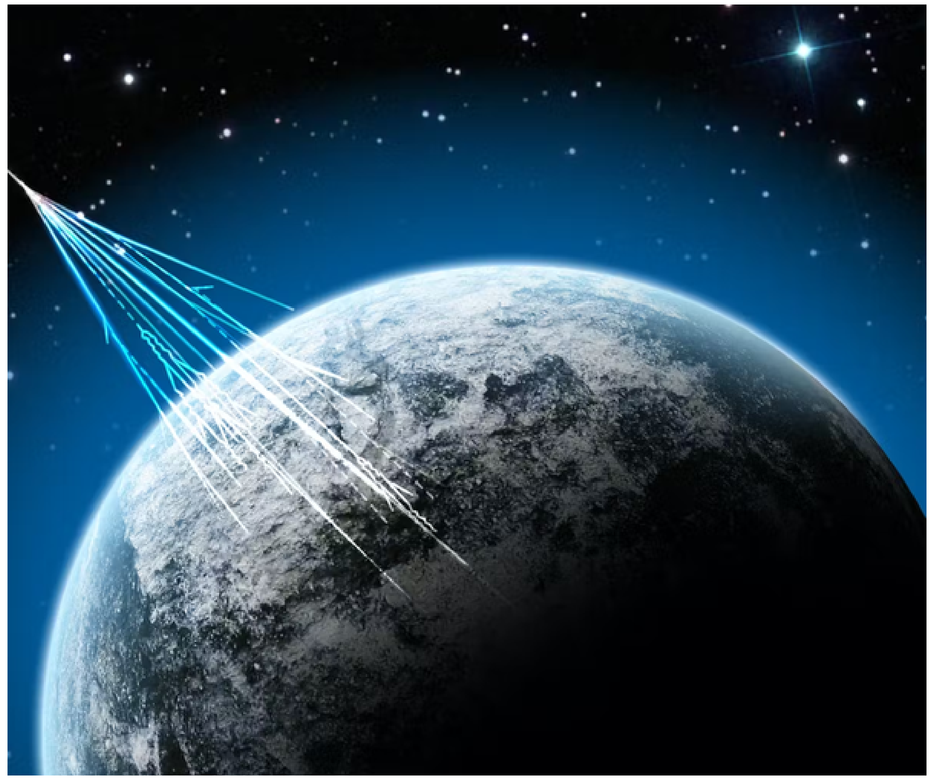
Accelerator



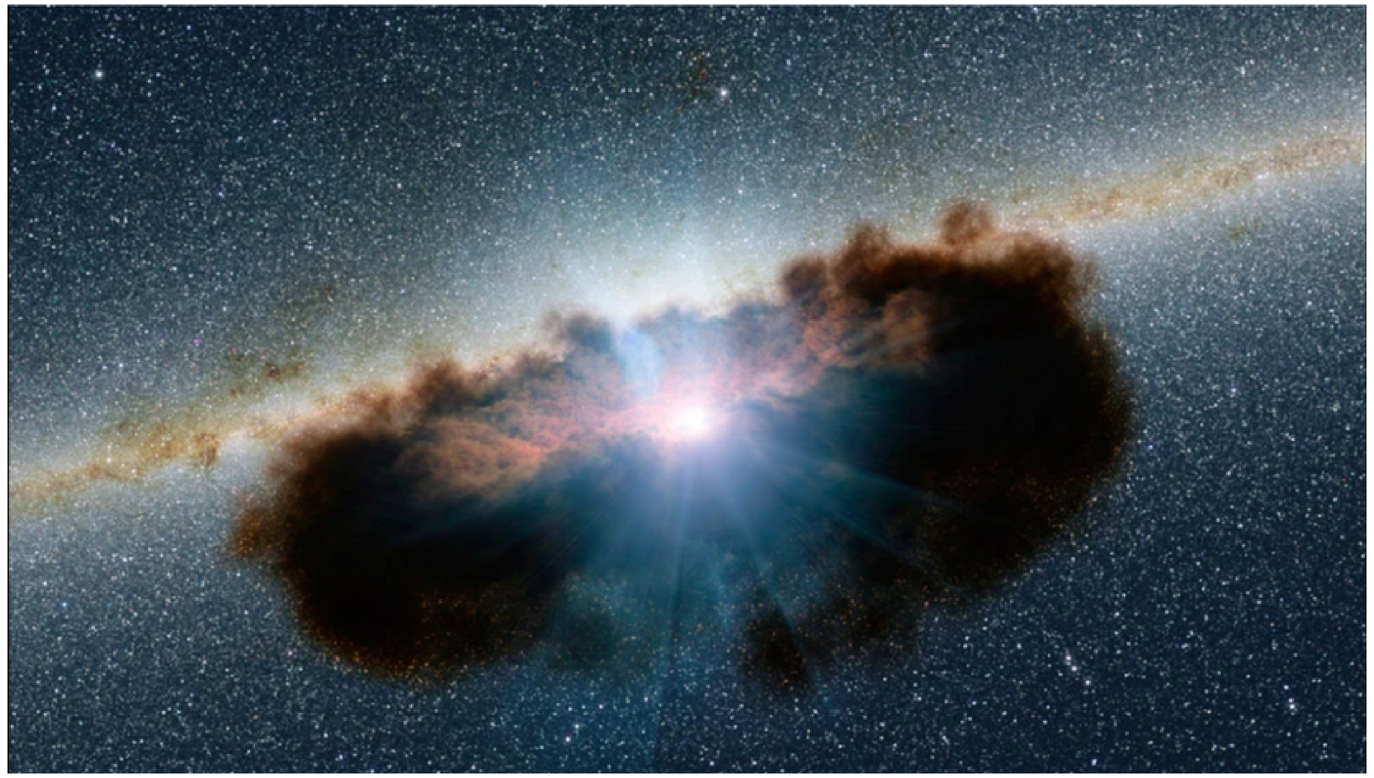
Supernova



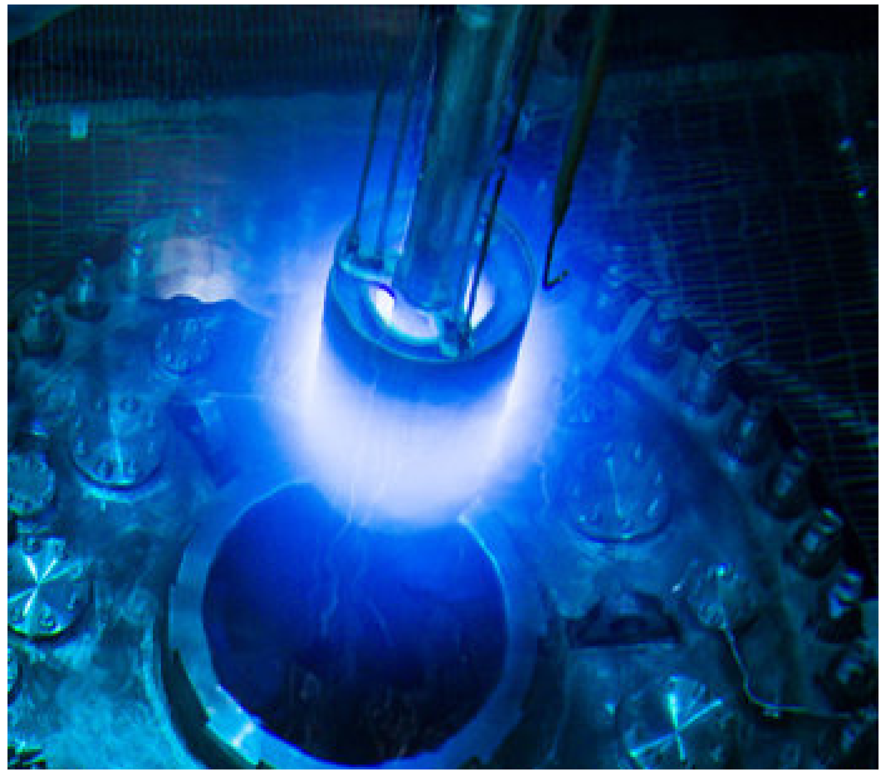
Solar



Atmospheric

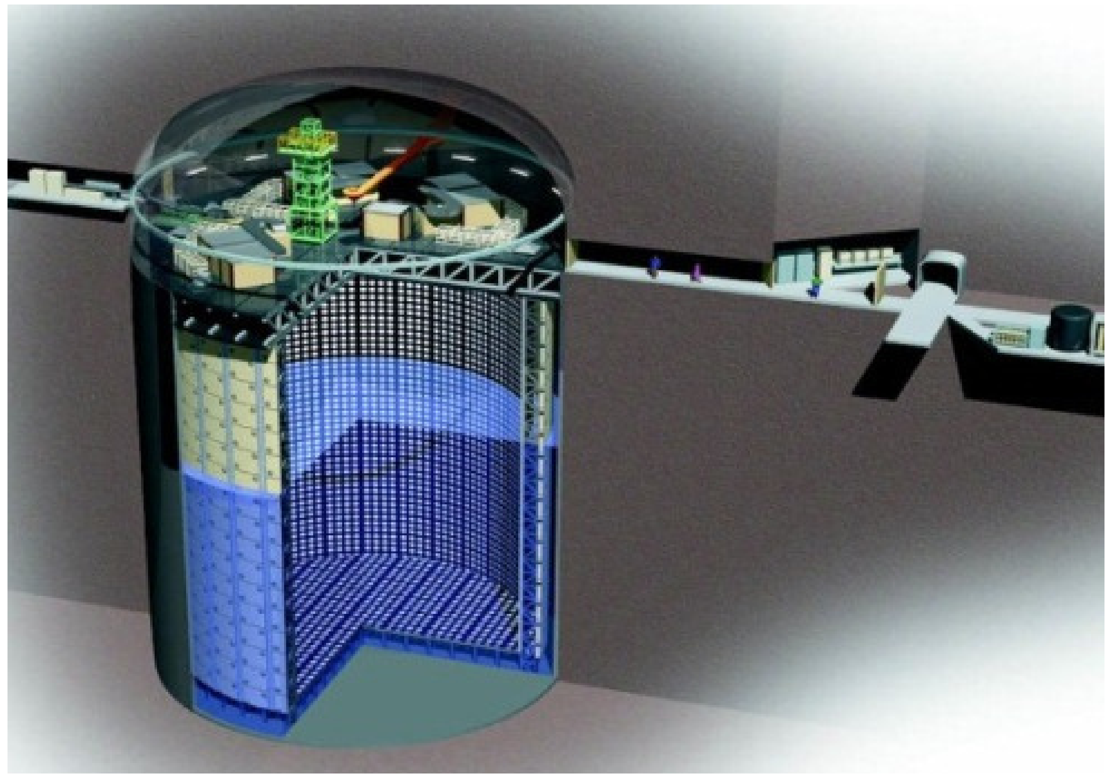


Cosmic



Reactor

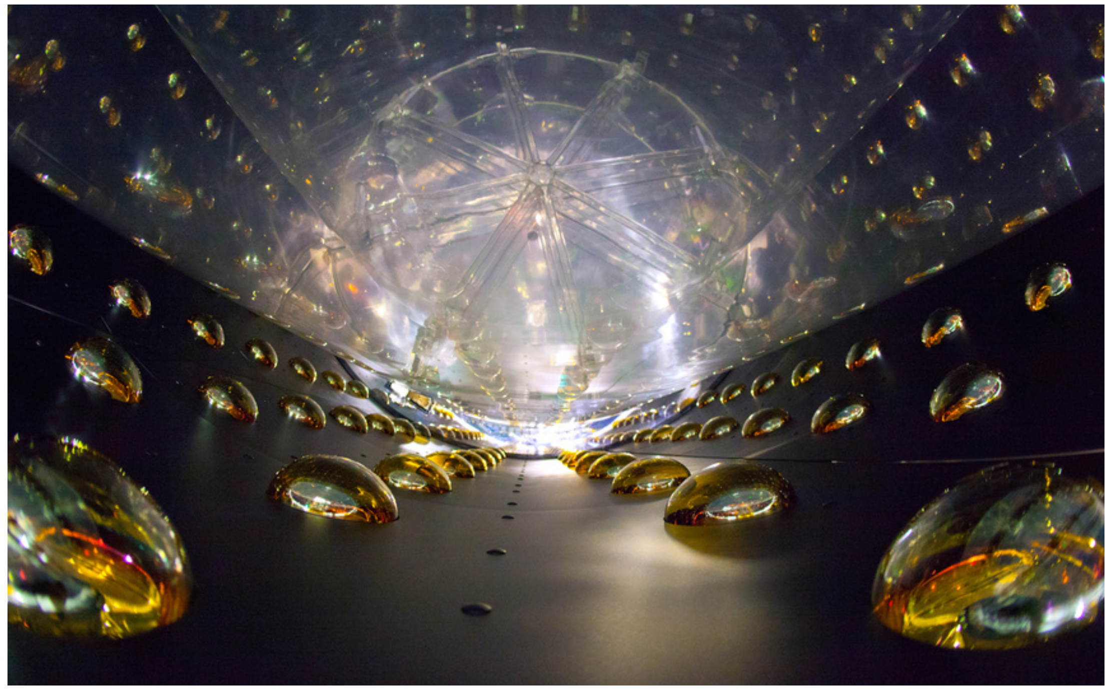
Neutrinos experiments



T2K experiment. t2k-experiment.org

Icecube experiment. icecube.wisc.edu

NOvA far detector. novaexperiment.fnal.gov



Daya Bay detector. dayawane.ihep.ac.cn/twiki/bin/view/Public/

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do".

Wolfgang Pauli

Neutrino oscillations

- The flavor eigenstates of a neutrino are the states in which a neutrino is produced or detected as an electron, muon, or tau neutrino;

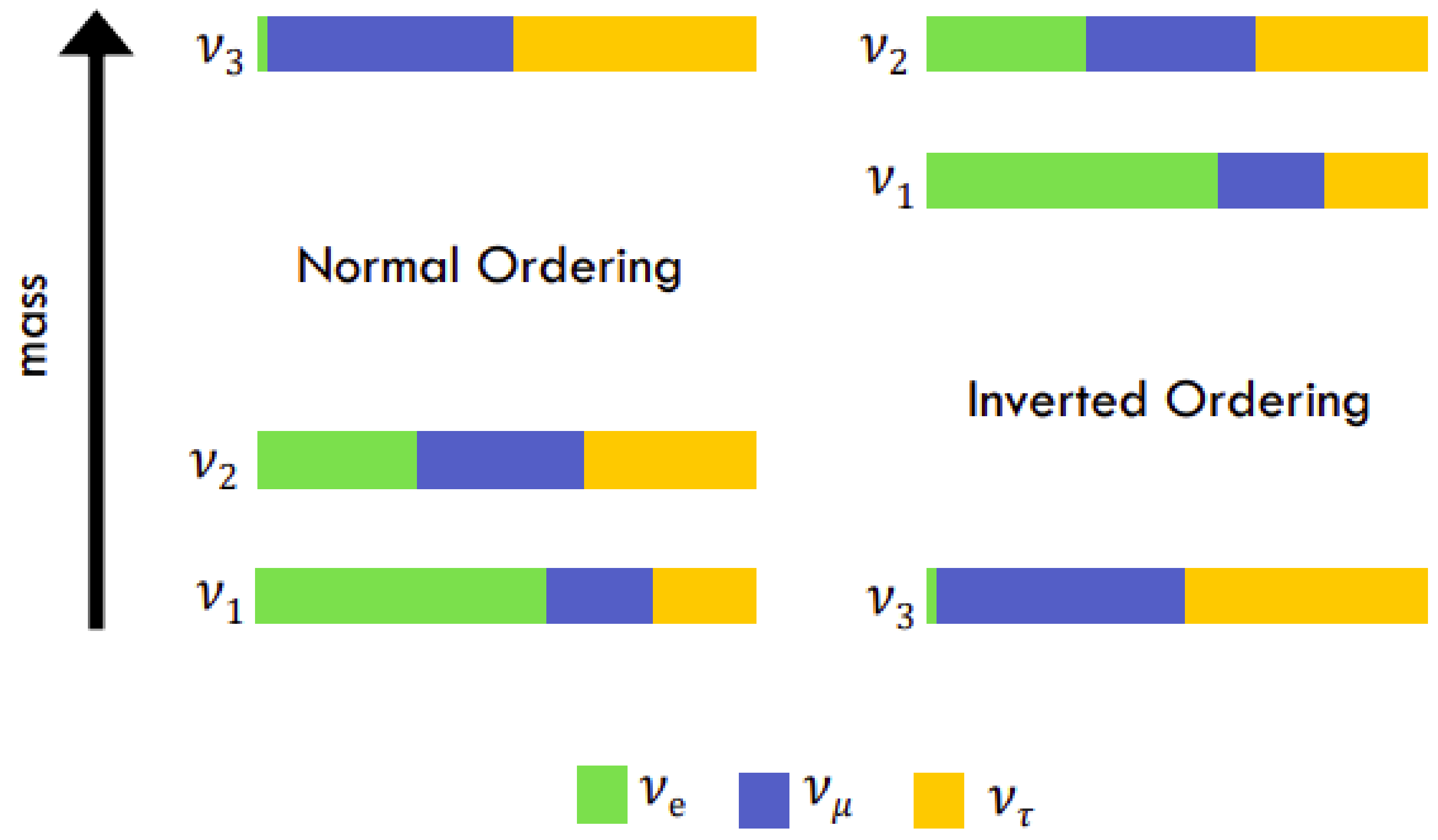
- These flavor eigenstates are not the same as the mass eigenstates, which are the states in which a neutrino propagates through space and time.

Neutrino oscillation is a consequence of the difference between the flavor and mass eigenstates.

MASS EIGENSTATES

$$P_{\nu_\mu \to \nu_e} = sin^2(2\theta) sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E_\nu}\right)$$

FROM MIXING MATRIX



Open questions

Extra dimensions

Non-standard interaction

Generation of mass ?

Steriles ?

Absolute masses ?

Majorana / Dirac ?

Mass ordering ?

CP violation ?

Dark matter ?

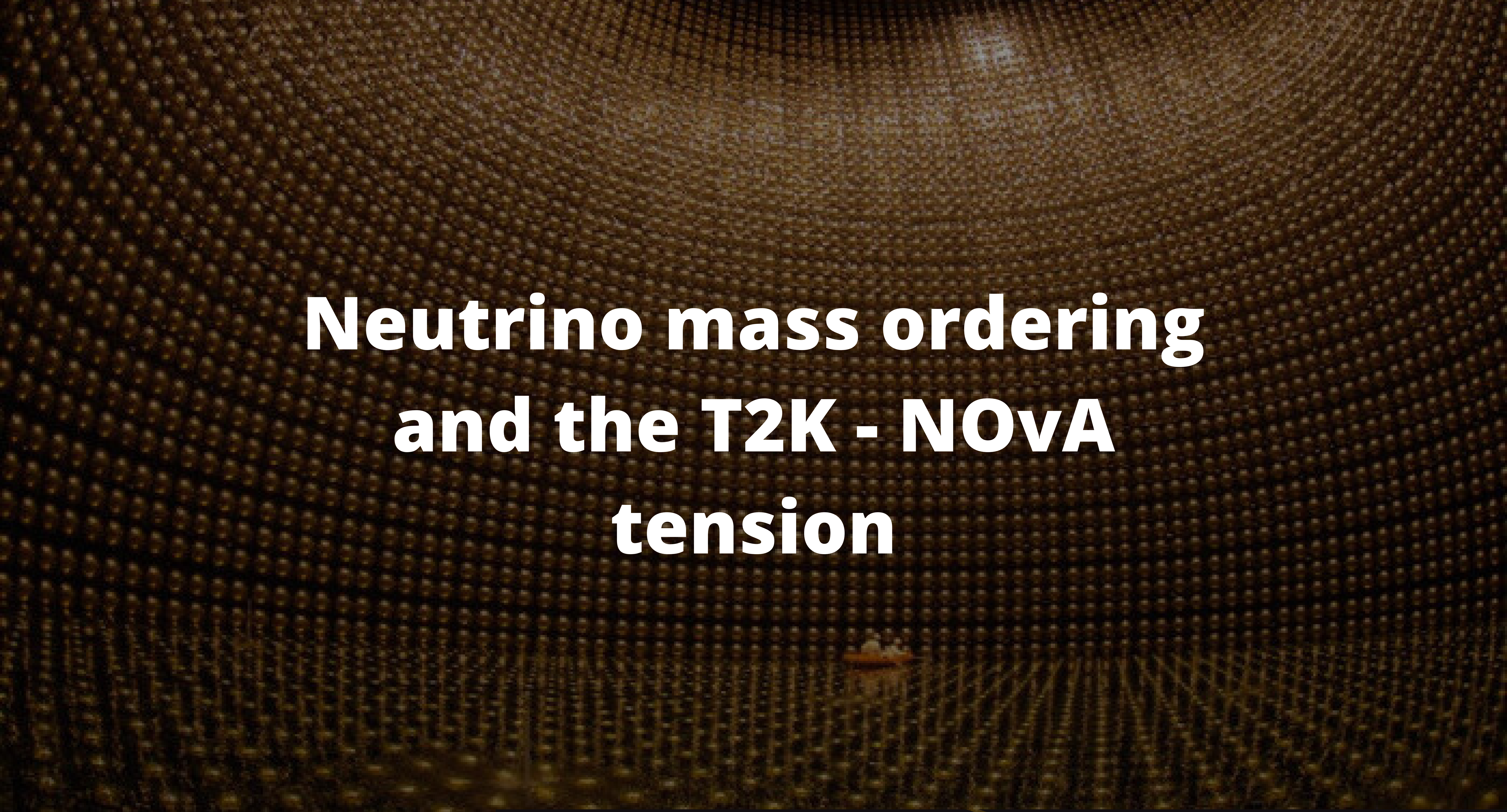
Angles ?

Multi-messenger

Supernova

Credit to Richard Thompsom. www.nytimes.coml

Neutrino mass ordering and the T2K - NOvA tension



The inside of Super-Kamiokande. http://t2k-experiment.org

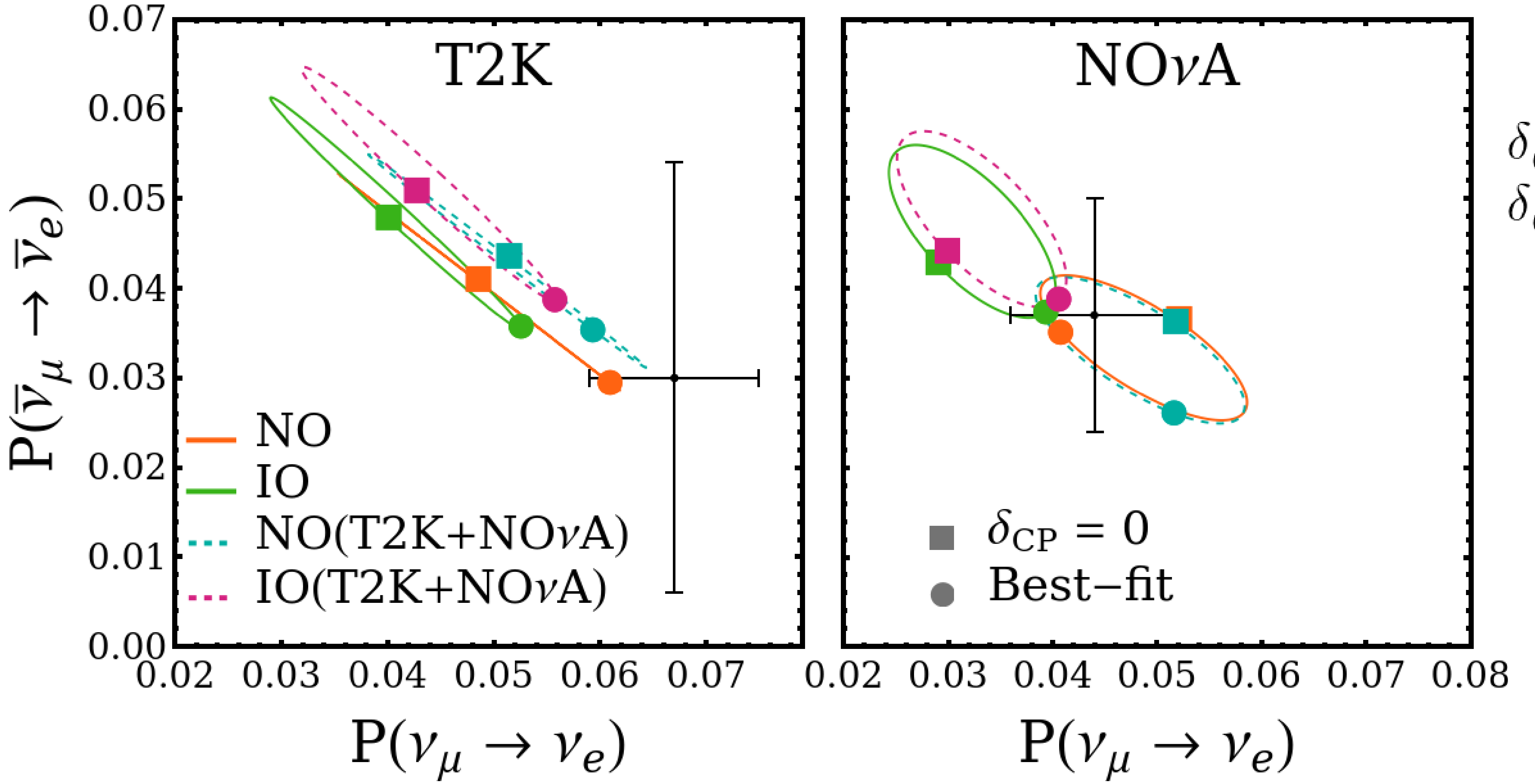
Bi-probability plots of oscillation for neutrinos (x axes) and antineutrinos (y axes) while varying δ_{CP}

T2K

$\delta_{CP} = -0.60\pi$ for NO
$\delta_{CP} = -0.44\pi$ for IO

NOvA

$\delta_{CP} = 0.82\pi$ for NO
$\delta_{CP} = 1.52\pi$ for IO



Combined

$\delta_{CP} = 1.22\pi$ for NO
$\delta_{CP} = 1.50\pi$ for IO

Figure 1: Solid (dashed) ellipses correspond to best-fit points according to T2K and NOvA separated (combined). χ^2_{min}combined for NO (IO) are 140.79 (139.45)

The parameters for experiment T2K (NOvA) were taken from the article: PRD 103 (2021) 112008 (PRD 106 (2022) 032004)

Allowed region for 90% C.L. curve in the parameter space of $\sin^2(\theta_{23}) \times \delta_{CP}$ for the usual neutrino oscillation.

$\delta_{CP} = -0.60\pi$ for NO
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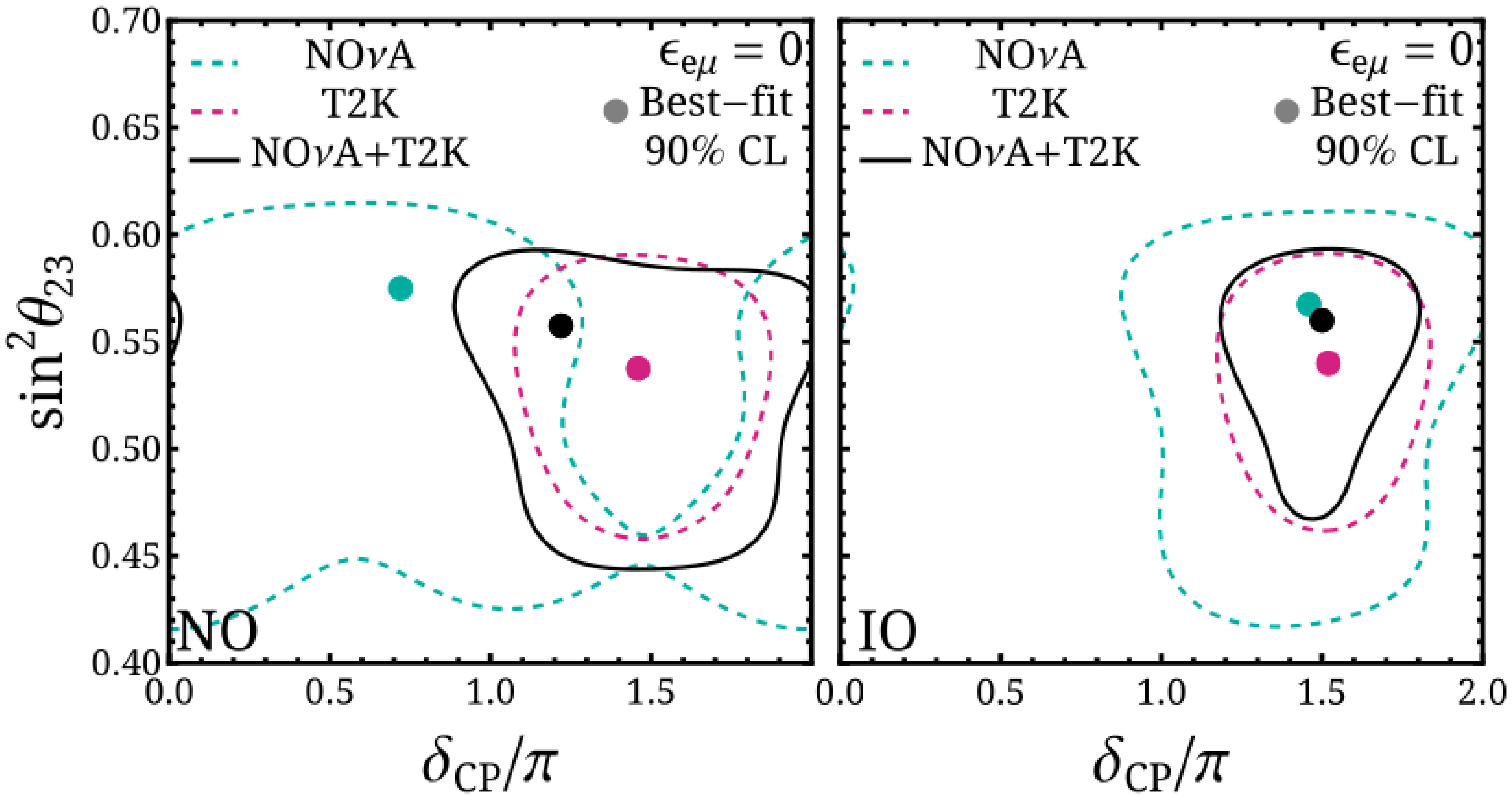

Figure 2: Dashed (solid) lines correspond to the results according to T2K and NOvA separated (combined). χ^2_{min} combined for NO (IO) are 140.79 (139.45)

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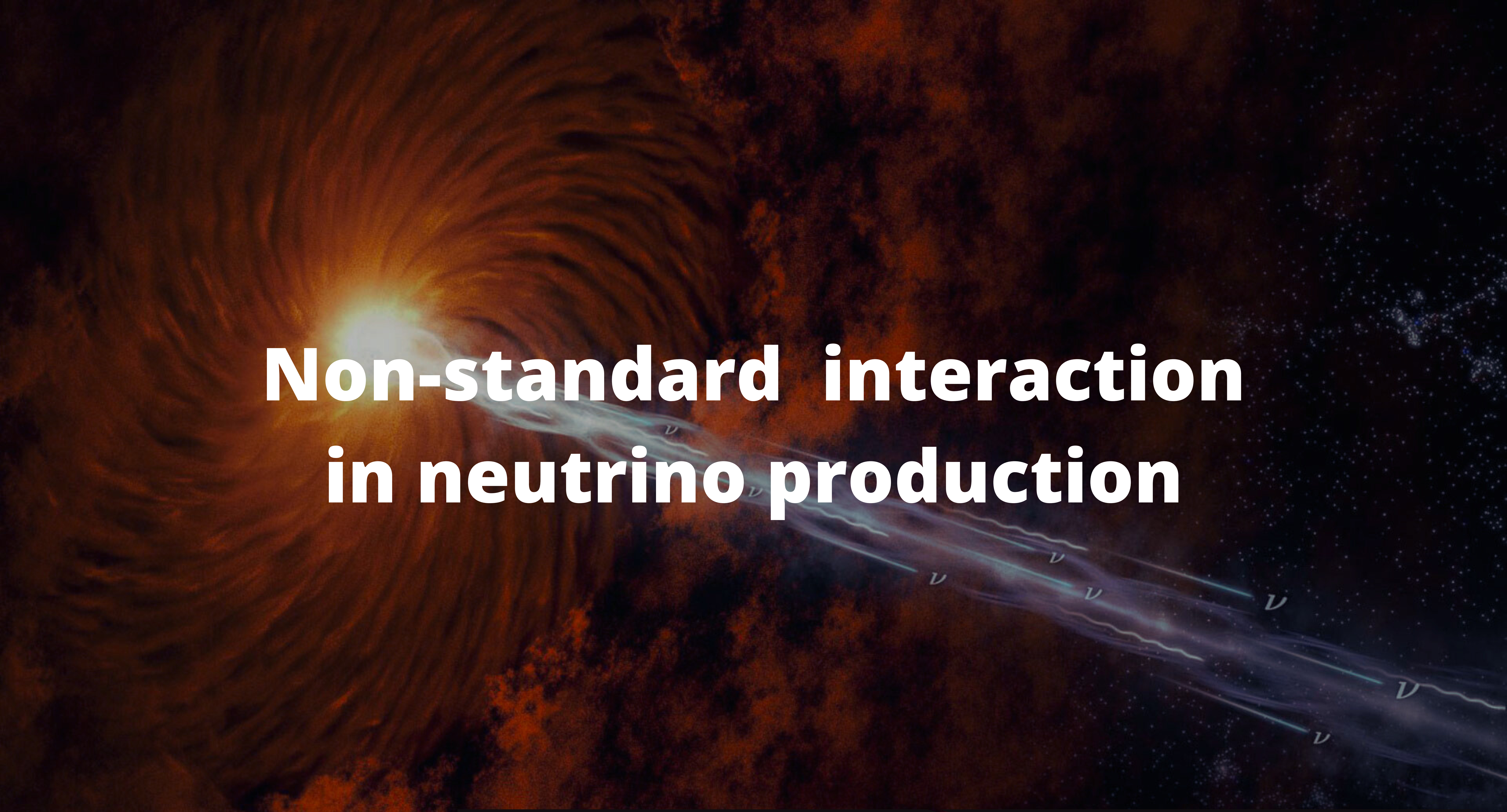

Non-standard interaction in neutrino production

Illustration by Benjamin Amend (ben.amend@gmail.com)

New physics

- Non-standard neutrino interactions (NSIs) are hypothetical interactions between neutrinos and new heavy particles that are not described by the SM [1, 2];

- NSIs can arise from an effective field theory (EFT) approach, which provides a framework for describing new physics beyond the SM ;

- The new physics is encoded in coefficients of EFT which modifies the strength of interactions between neutrinos and other particles;

- An NSI in neutrino production affects the neutrino production amplitude;

- NSIs could have a range of consequences for neutrino physics and astrophysics. For example, they could affect the propagation of neutrinos through matter, leading to changes in their oscillation patterns.

Falkowski, González-Alonso, Tabrini [1] JHEP05(2019)173. [2] JHEP11(2020)048.

We investigate a non-standard interaction in neutrino production

$$P_{(\nu_\alpha \to \nu_\beta)} = \sum_{k,l} e^{-\frac{i\Delta m^2_{kl} L}{2E_\nu}} \left[U^*_{\alpha k} + p_{XL,\alpha}(\epsilon_X U)_{\alpha k})^*\right] \left[U_{\alpha l} + p_{YL,\alpha}(\epsilon_Y U)_{\alpha l}\right] U_{\beta k} U^*_{\beta l}$$

The neutrino production process: a muon neutrino produced in a pion decay.

The transition probability from a muon neutrino to a electron neutrino is

$$P(\nu_\mu \to \nu_e) = +\frac{4s^2_{23}s^2_{13}}{(1-r_A)^2}\sin^2\left(\frac{(1-r_A)\Delta L}{2}\right) + \frac{8J_r r_\Delta}{r_A(1-r_A)}\cos\left(\frac{\Delta L}{2}+\delta_{CP}\right)\sin\left(\frac{r_A \Delta L}{2}\right)\sin\left(\frac{(1-r_A)\Delta L}{2}\right)$$

$$-\frac{4p_\mu|\epsilon_{e\mu}|s_{13}s_{23}}{(1-r_A)}\sin\left(\frac{(1-r_A)\Delta L}{2}\right)\sin\left(\delta_{CP}-\phi_{e\mu}+\frac{(1-r_A)\Delta L}{2}\right)$$

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = P\left((\nu_\mu \to \nu_e), \delta_{CP} \to -\delta_{CP}, r_A \to -r_A, \phi_{e\mu} \to -\phi_{e\mu}\right)$$

where

$$s_{13} = sin(\theta_{13}), \quad s_{23} = sin(\theta_{23}), \quad J_r = cos(\theta_{12})sin(\theta_{12})cos(\theta_{23})sin(\theta_{23})sin(\theta_{13}),$$

$$\Delta L = \frac{\Delta m^2_{31} L}{2E}, \quad r_\Delta = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}, \quad r_A = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}},$$

Cherchiglia, Pasquini, Peres, Rodrigues, Rossi and Souza

Alleviating the tension between T2K and NOvA

Bi-probability plots of oscillation for neutrinos (x axes) and antineutrinos (y axes) while varying δ_{CP} in a NSI scenario

T2K

$\delta_{CP} = 1.93\pi$ for NO
$|\epsilon_{e\mu}| = 0.60 \times 10^{-3}$
$\phi_{e\mu} = 0.55\pi$

$\delta_{CP} = 1.45\pi$ for IO
$|\epsilon_{e\mu}| = 0.34 \times 10^{-3}$
$\phi_{e\mu} = 0.14\pi$

Combined

$\delta_{CP} = 1.51\pi$ for NO
$|\epsilon_{e\mu}| = 0.82 \times 10^{-3}$
$\phi_{e\mu} = 0.96\pi$

$\delta_{CP} = 1.53\pi$ for IO
$|\epsilon_{e\mu}| = 0.42 \times 10^{-3}$
$\phi_{e\mu} = 1.95\pi$

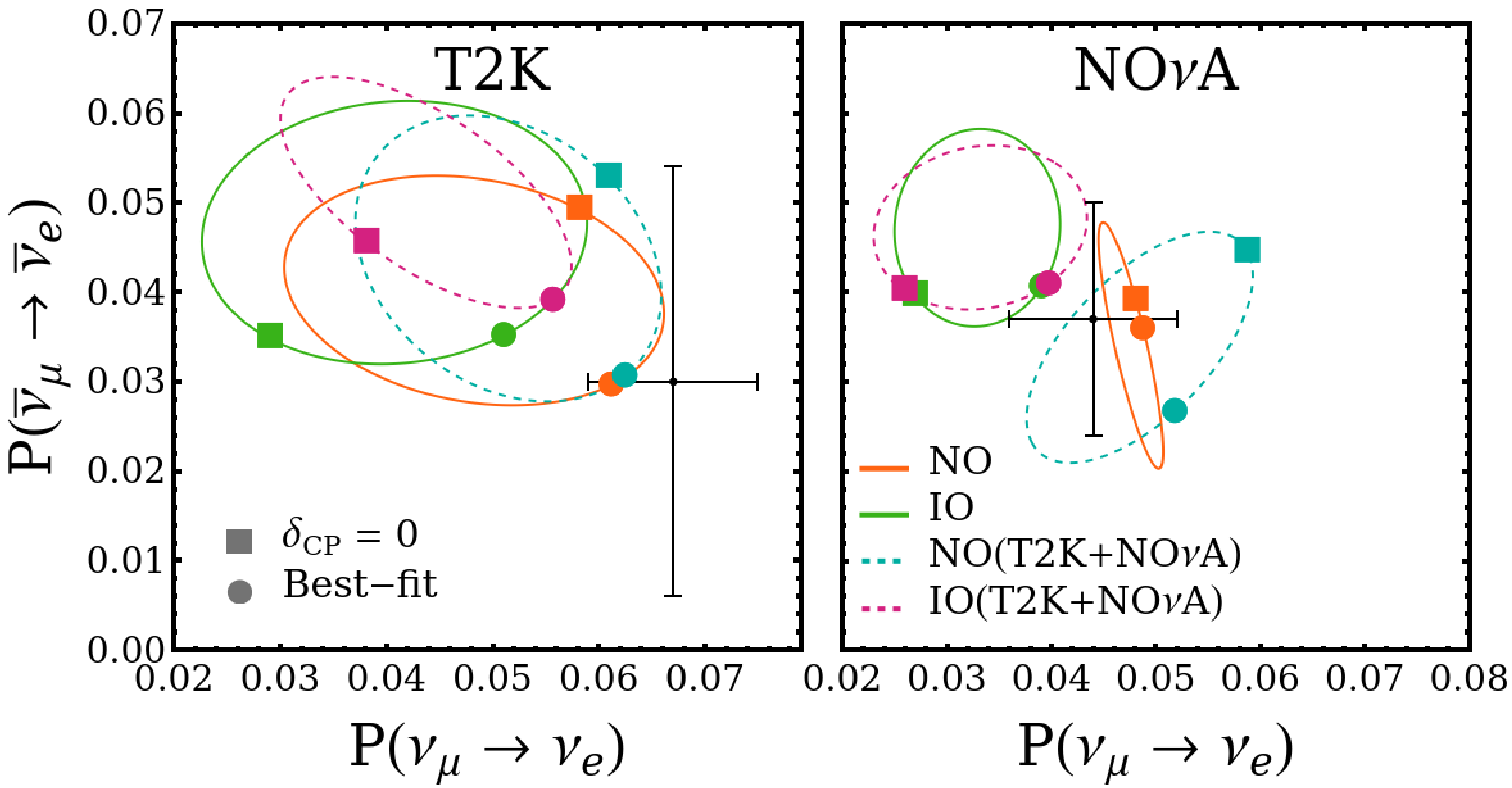

Figure 3: Solid (dashed) ellipses correspond to best-fit points according to T2K and NOvA separated (combined). χ^2_{min} combined for NO (IO) are 132.09 (137.01)

NOvA

$\delta_{CP} = 1.45\pi$ for NO
$|\epsilon_{e\mu}| = 0.86 \times 10^{-3}$
$\phi_{e\mu} = 1.10\pi$

$\delta_{CP} = 1.59\pi$ for IO
$|\epsilon_{e\mu}| = 1.03 \times 10^{-3}$
$\phi_{e\mu} = 1.93\pi$

Cherchiglia, Pasquini, Peres, Rodrigues, Rossi and Souza

Alleviating the tension between T2K and NOvA

Allowed region for 90% C.L. curve in the parameter space of $\sin^2(\theta_{23}) \times \delta_{CP}$ for the usual neutrino oscillation in a NSI scenario

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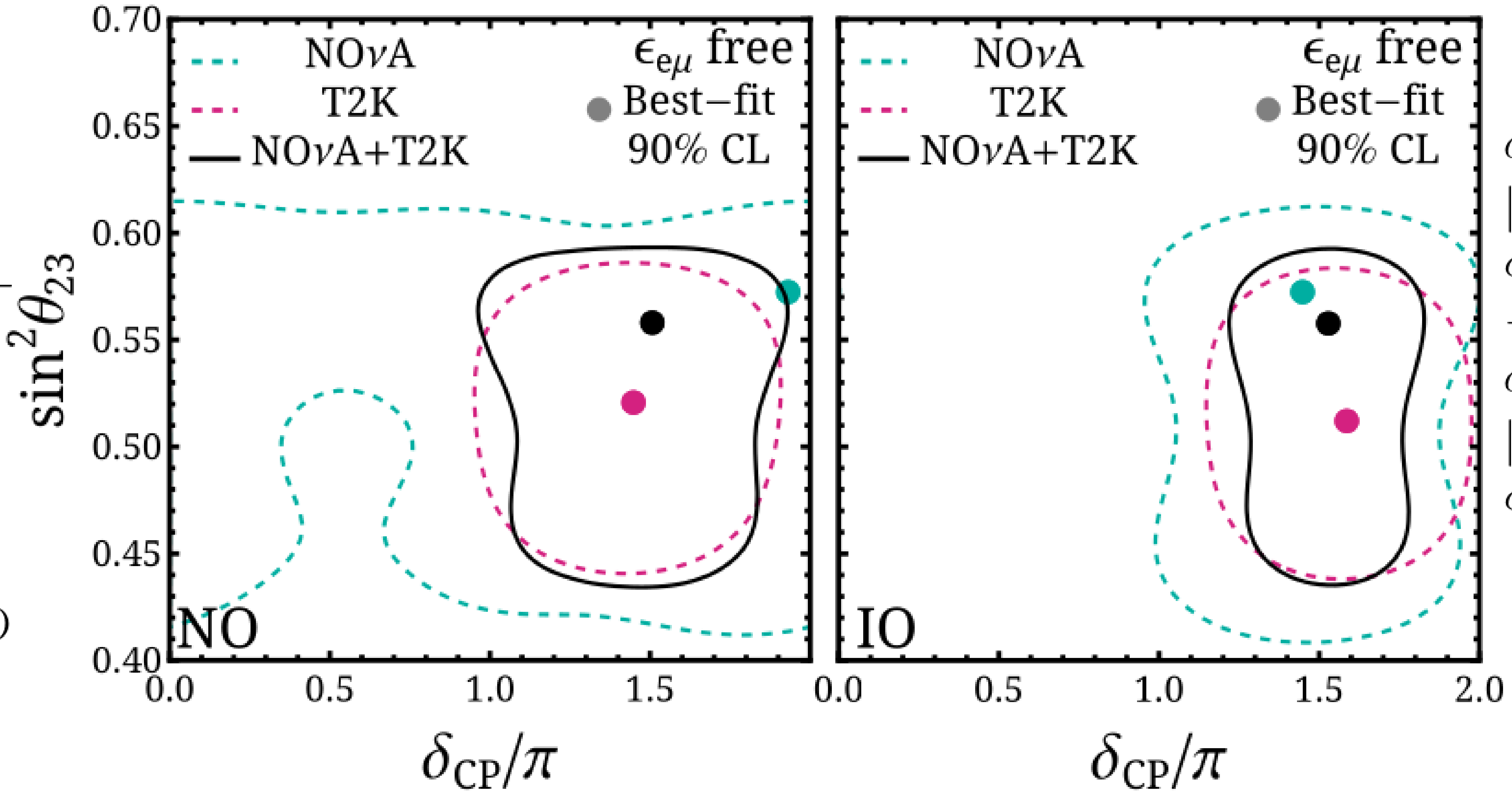

Figure 4: Dashed (solid) lines correspond to the results according to T2K and NOvA separated (combined). χ^2_{min}combined for NO (IO) are 132.09 (137.01)

NOνA

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Combined

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$|\epsilon_{e\mu}| = 0.42 \times 10^{-3}$
$\phi_{e\mu} = 1.95\pi$

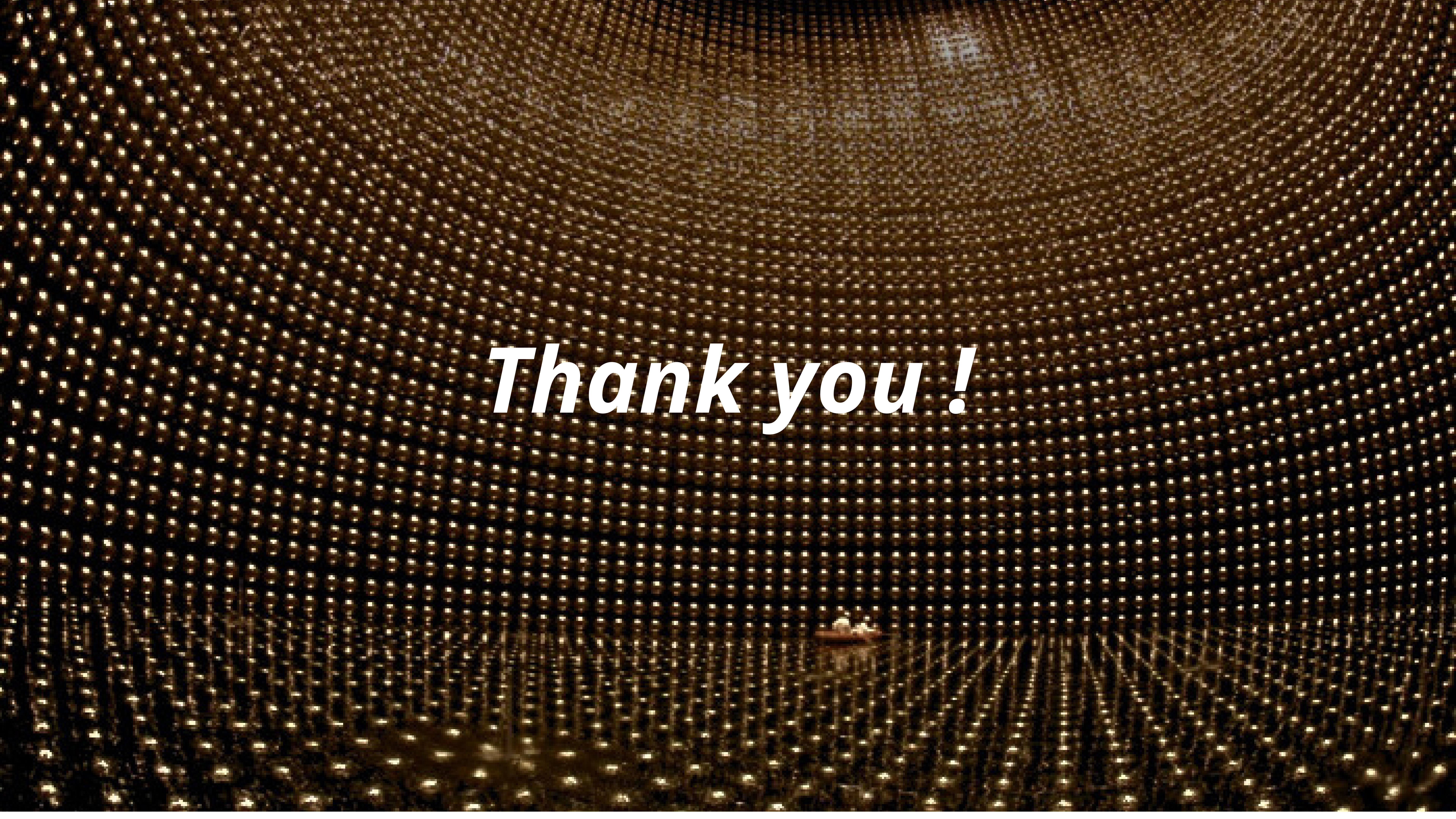
Cherchiglia, Pasquini, Peres, Rodrigues, Rossi and Souza

Conclusion

- Neutrino physics has a interdisciplinary nature: intersects other fields, such as particle physics, astrophysics, and cosmology. It is very important an interdisciplinary collaboration in order to address some of the open problems in neutrino physics.

- Neutrinos are an important topic in physics beyond the Standard Model, as open problems such as neutrino mass suggest the existence of new physics.

- Non-standard neutrino interaction could have implications in neutrino oscillation probability. It could change constrains, have consequences in matter effect, alleviate tensions between experiments as a consequences of new physics.


Thank you !