Neutrino Theory

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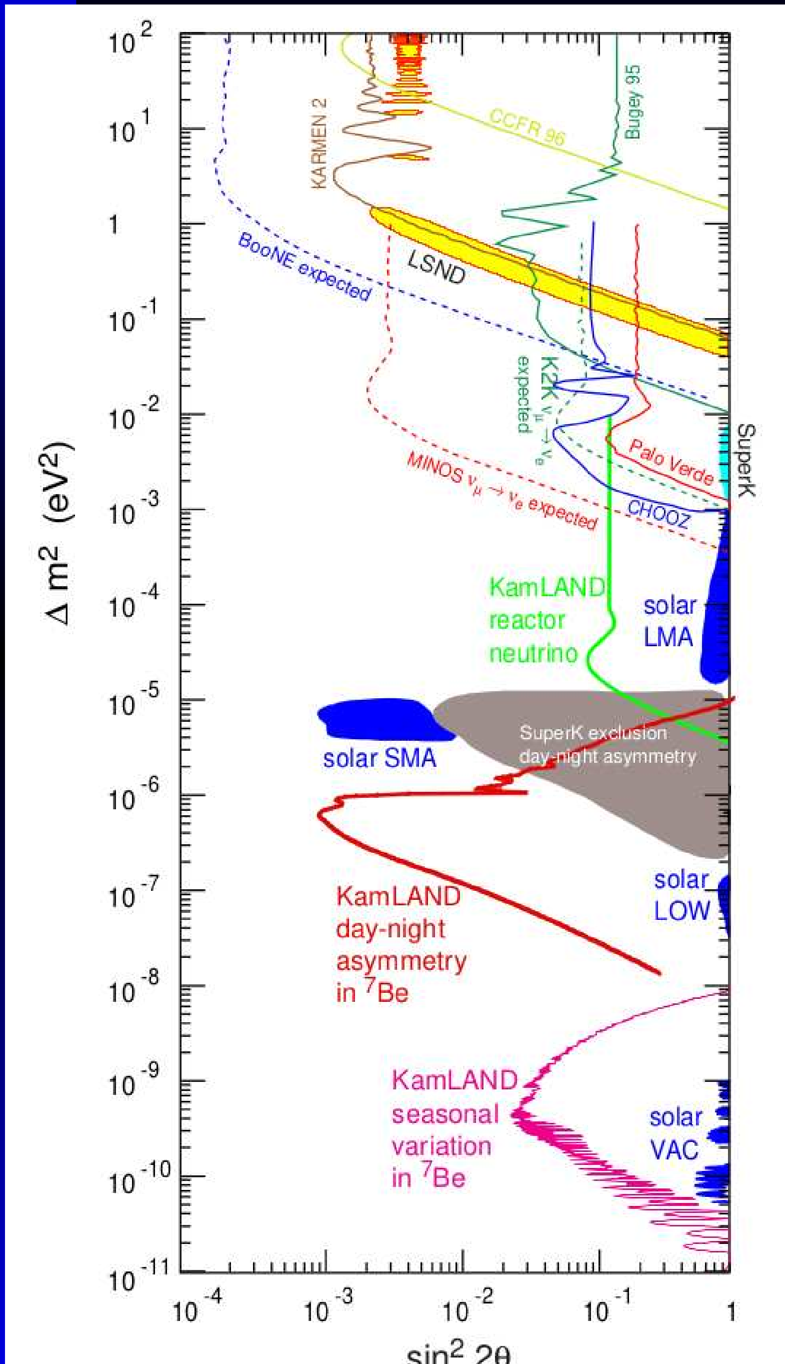
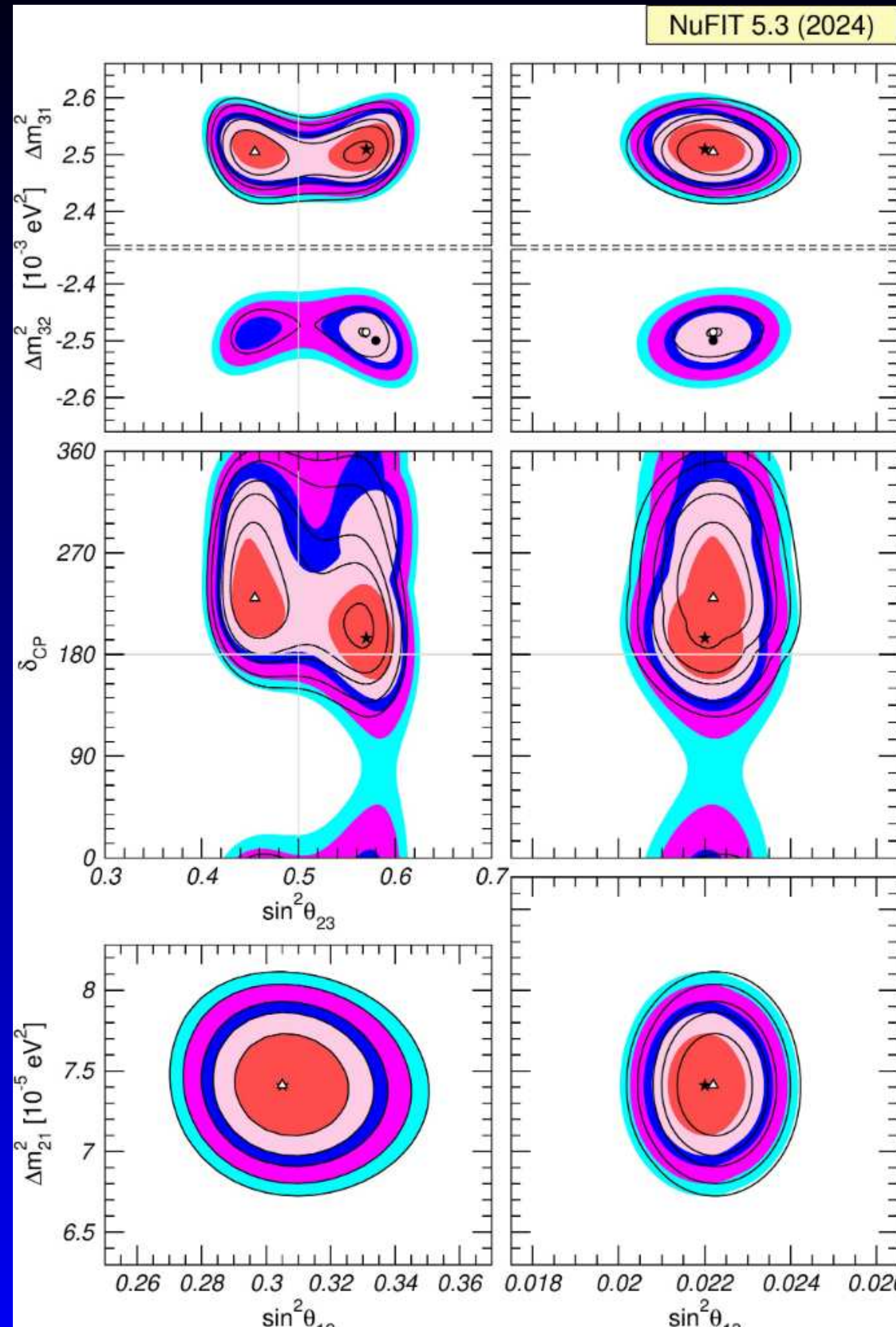




Albright *et al.*, 2000

Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless $\Leftrightarrow$ neutrino oscillation is BSM physics!

…yes, this is not SUSY, large extra dimensions or anyone's favorite BSM model, but it **IS the only** laboratory-based proof for the incompleteness of the SM.

Alas, it is indirect evidence: no energy scale, no symmetry, no new interaction, no new particles are seen in the laboratory.

Neutrinos in a nutshell

$m_\nu \lesssim 0.8\,\mathrm{eV}$, could be Dirac or Majorana

Quarks

Neutrinos

$$|U_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix} \quad |U_\nu| = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Majorana mass term allows for things like seesaw and could be simple explanation why mixings so different.

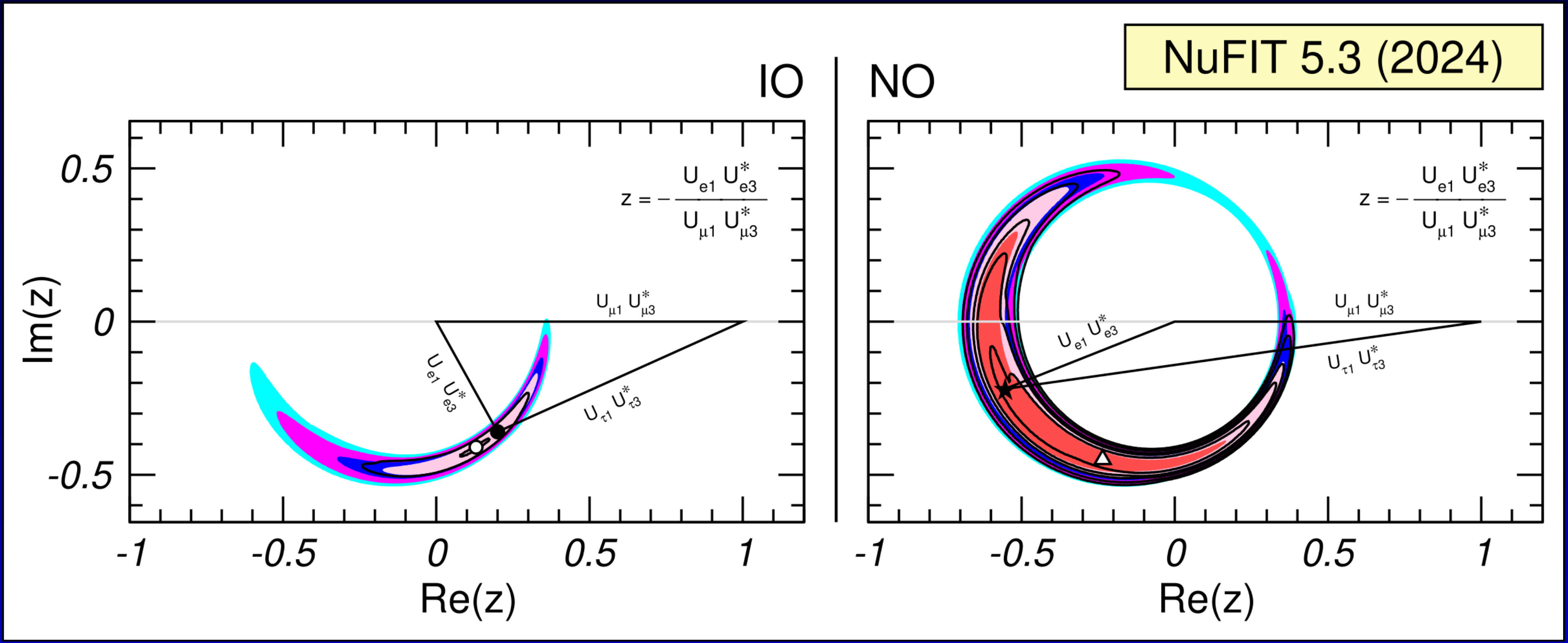
CP violation

There are only very few parameters in the νSM which can violate CP

- CKM phase – measured to be $\gamma \simeq 70^\circ$
- θ of the QCD vacuum – measured to be $< 10^{-10}$
- Dirac phase of neutrino mixing
- Possibly: 2 Majorana phases of neutrinos

At the same time we know that the EW phase transition is not responsible for the Baryon Asymmetry of the Universe…

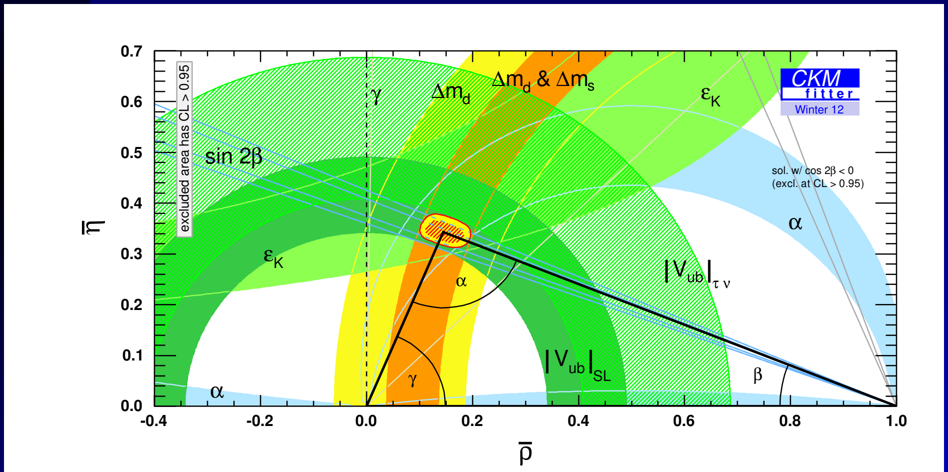
Unitarity triangles



We currently have no way to directly measure any of sides containing ν_τ.

What did we learn from that?

Our expectations where to find BSM physics are driven by models – but we should not confuse the number of models with the likelihood for discovery.



- CKM describes all flavor effects
- SM baryogenesis difficult
- New Physics at a TeV unlikely

and a vast number of parameter and model space excluded.

Non-standard interactions

NSI are the workhorse for BSM physics in the neutrino sector. They can be parameterized by terms like this

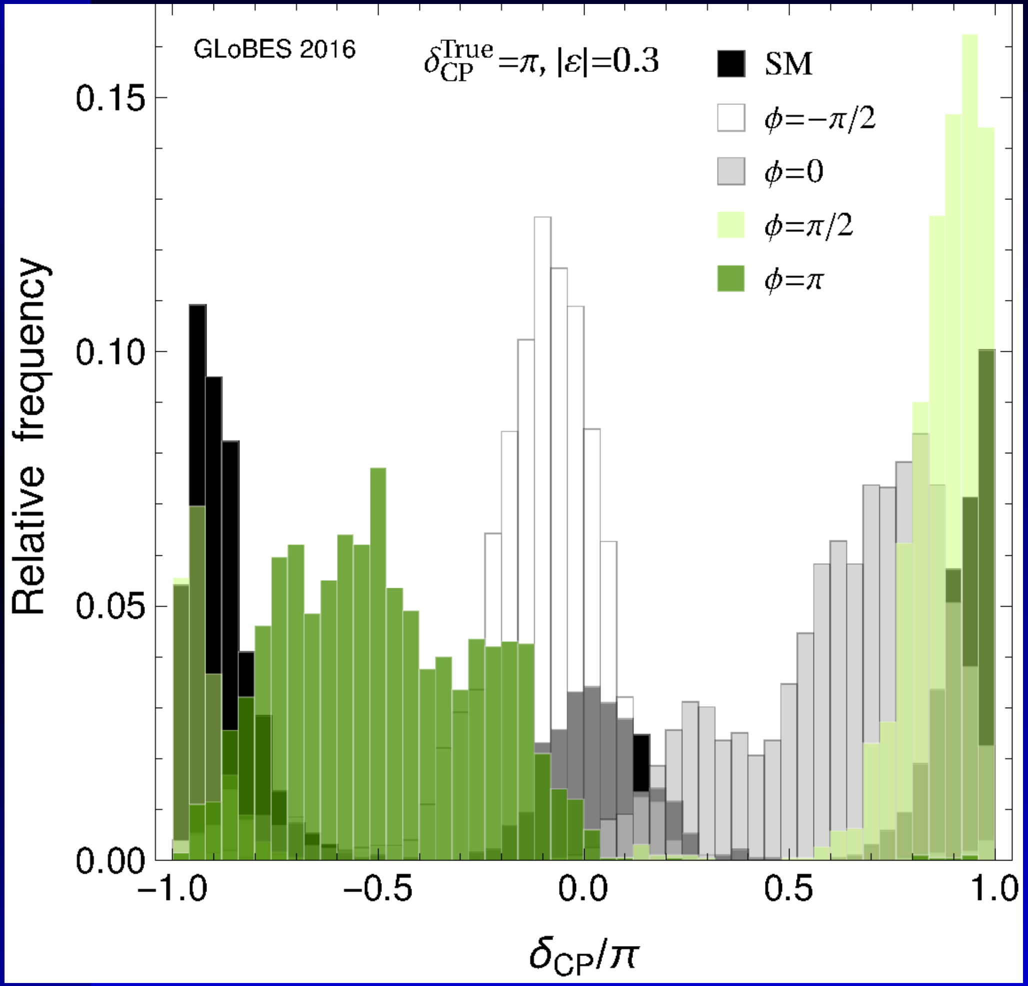
$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_f \epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\rho \nu_\beta)(\bar{f}\gamma_\rho P f)\,,$$

Wolfenstein, 1978

NB – difficult to build UV-complete models with large effects, e.g Farzan, 2015

Systematic matching to SM EFT also possible, resulting in relationships between the naive ϵ's.
Falkowski, Gonzaléz-Alonso, Tabrizi, 2019

Impact on three flavors

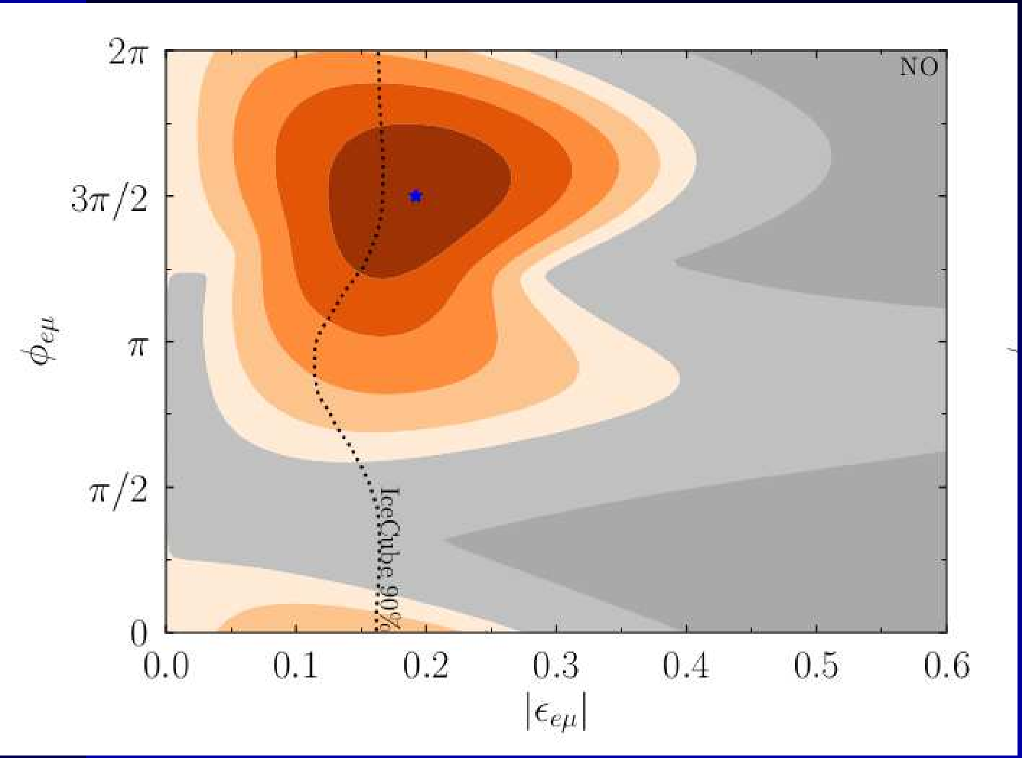


Three flavor analyses are not safe from these effects!

PH, D. Vanegas, 2016

In this example, CP conserving new physics fakes CP violation in oscillation!

NSI 2020



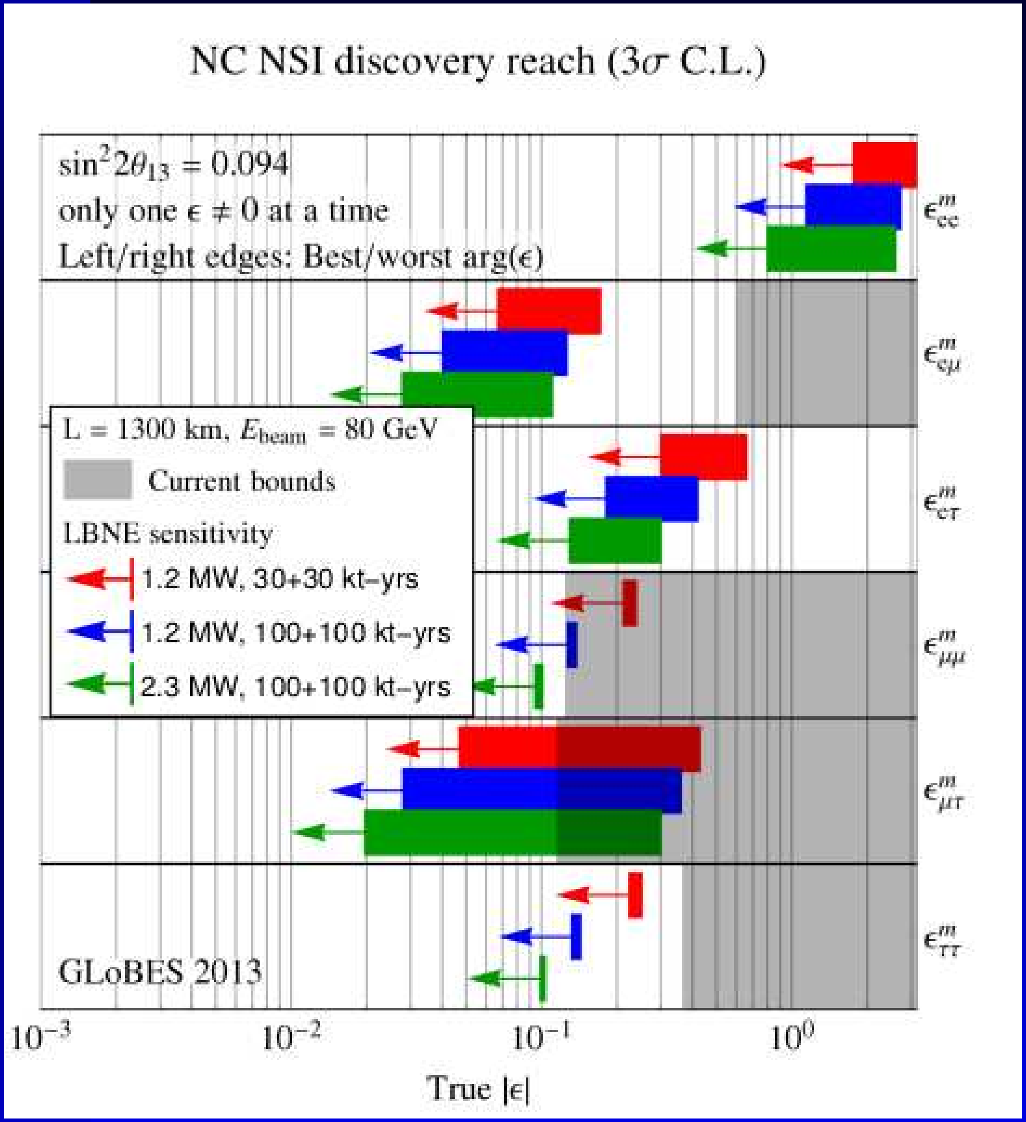
2020 NOvA and T2K data is in slight tension

CP violating NSI could be the explanation.

Gehrlein, Denton, Pestes, 2020

Every time T2HK & DUNE find different values for oscillation parameters the same game will be played and we'll never know if it's real or just systematics.

DUNE & NSI



Kopp for DUNE, 2013

NC NSI modifies matter effects

Only one NSI parameter at a time.

This is what a mass hierarchy measurement at $> 5\sigma$ really buys you.

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

$$dU = ds_{12}^2 \, dc_{13}^4 \, ds_{23}^2 \, d\delta_{CP} \, d\chi_1 \, d\chi_2$$

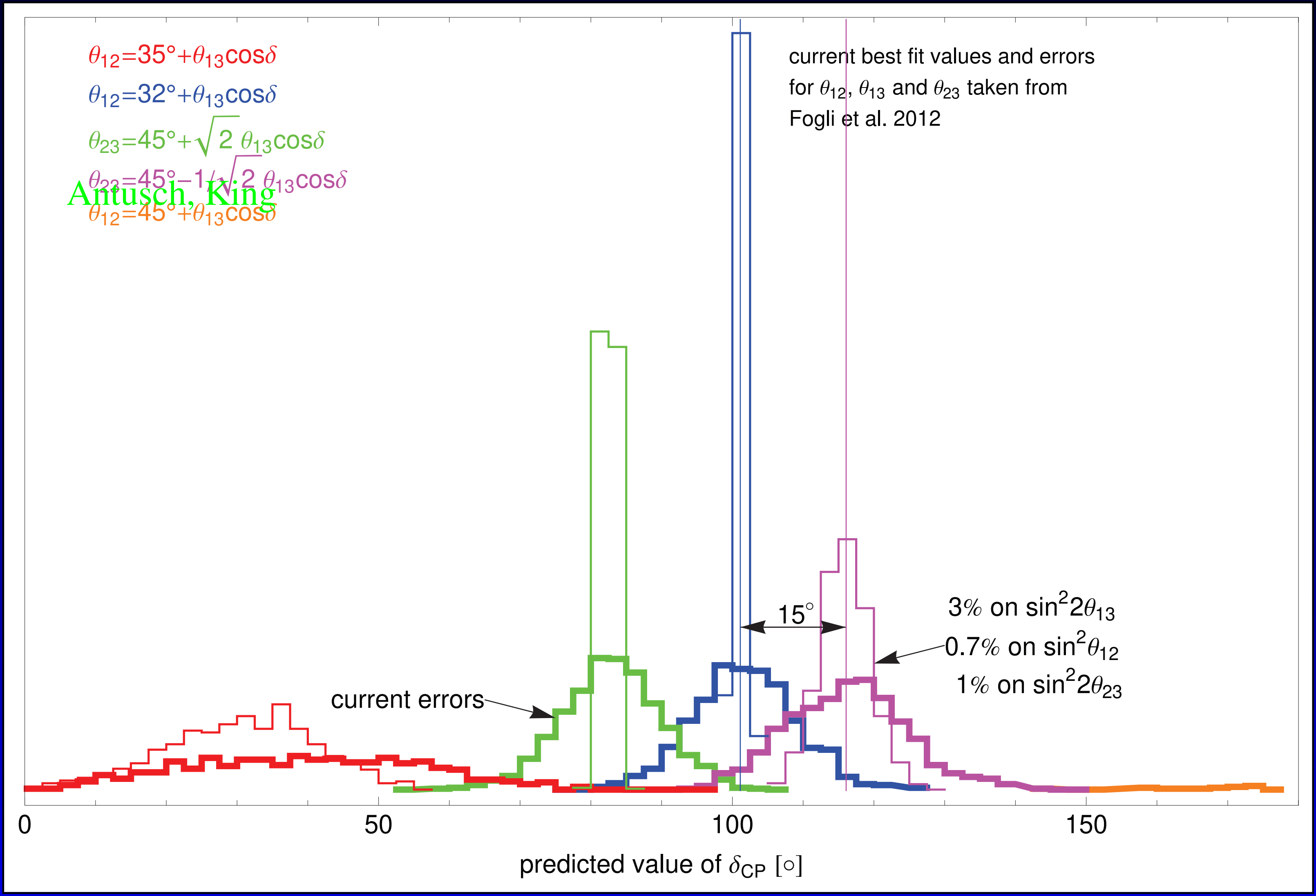
predicts flat distribution in δ_{CP}

Simplest model – Tri-bimaximal mixing Harrison, Perkins, Scott

$$\begin{pmatrix} \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

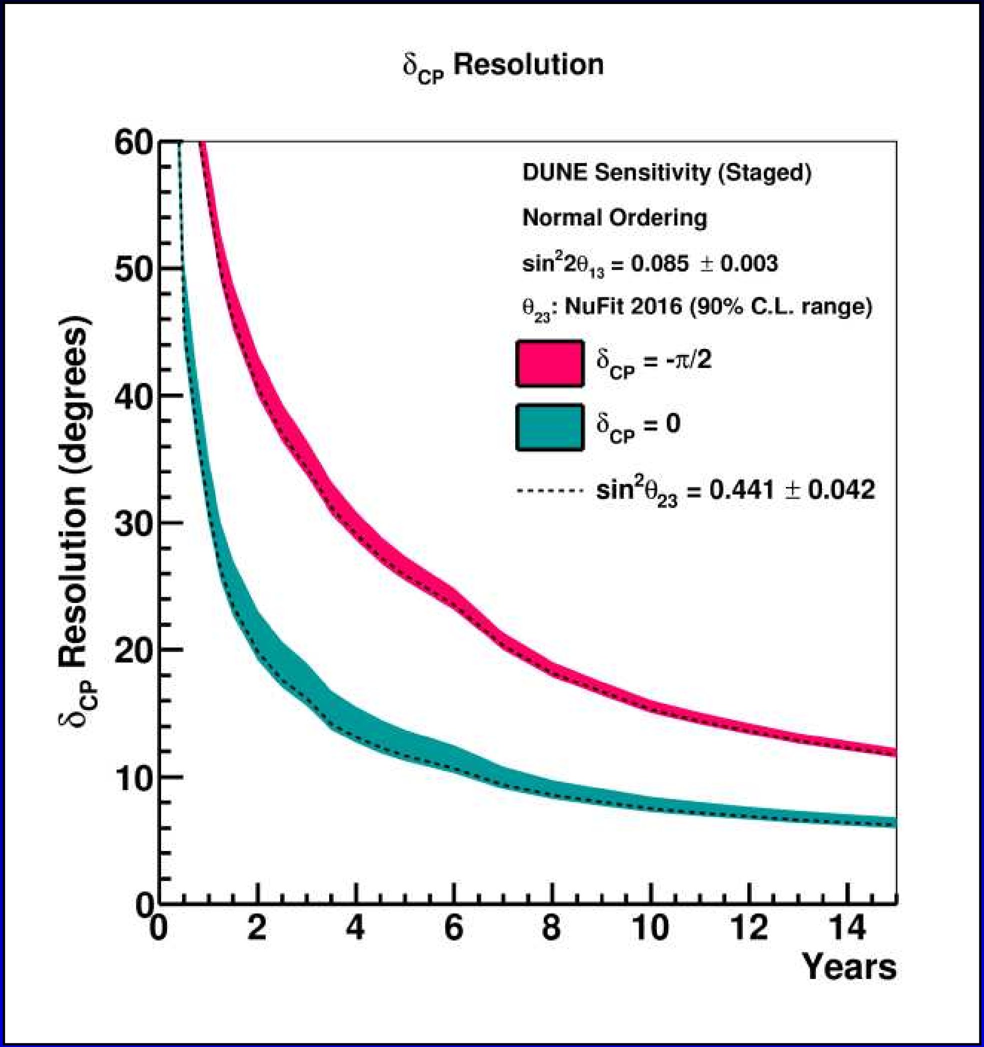
obviously corrections are needed – predictivity?

Sum rules



NB – smaller error on θ_{12} requires dedicated experiment like JUNO

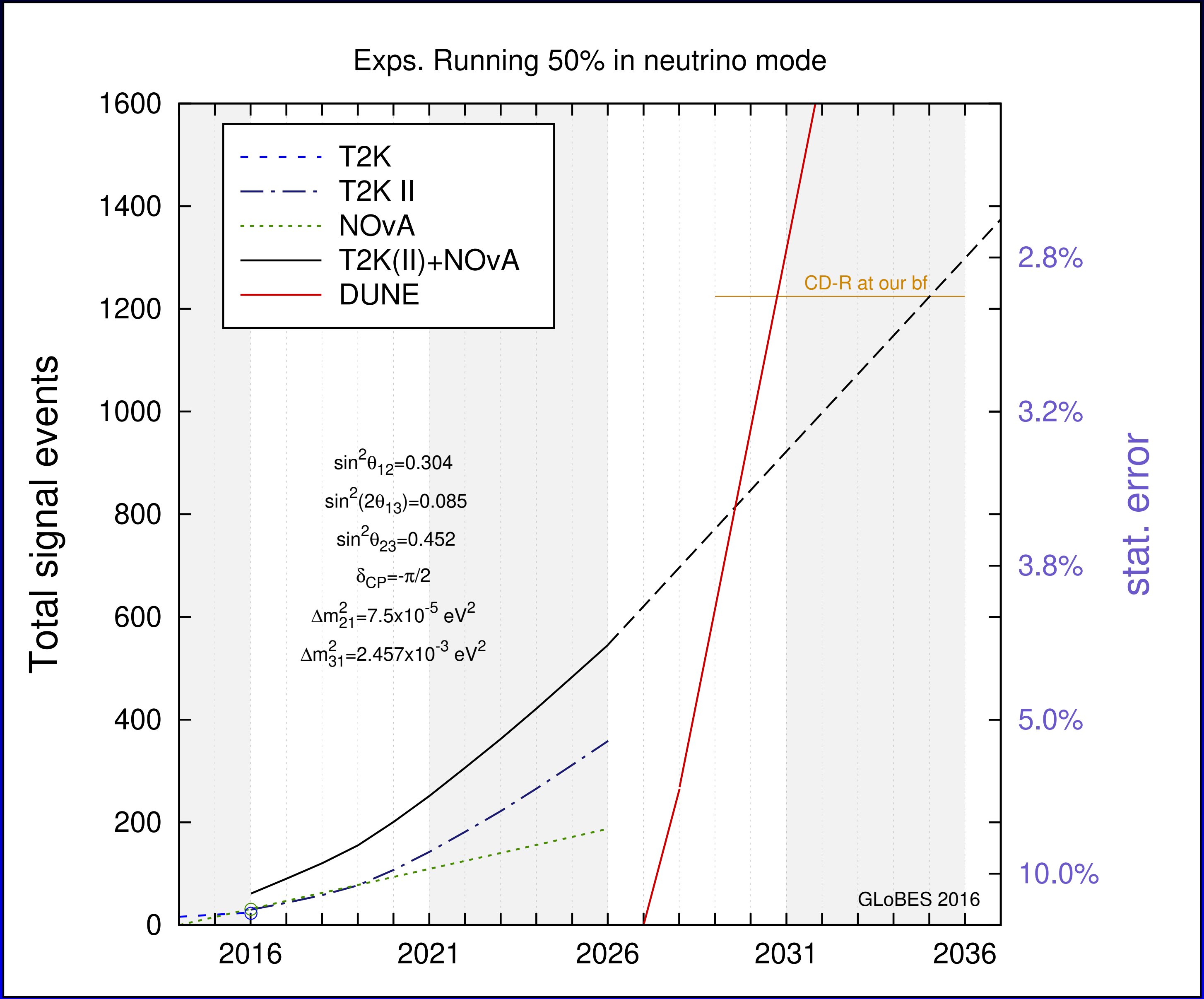
How well can we measure δ?



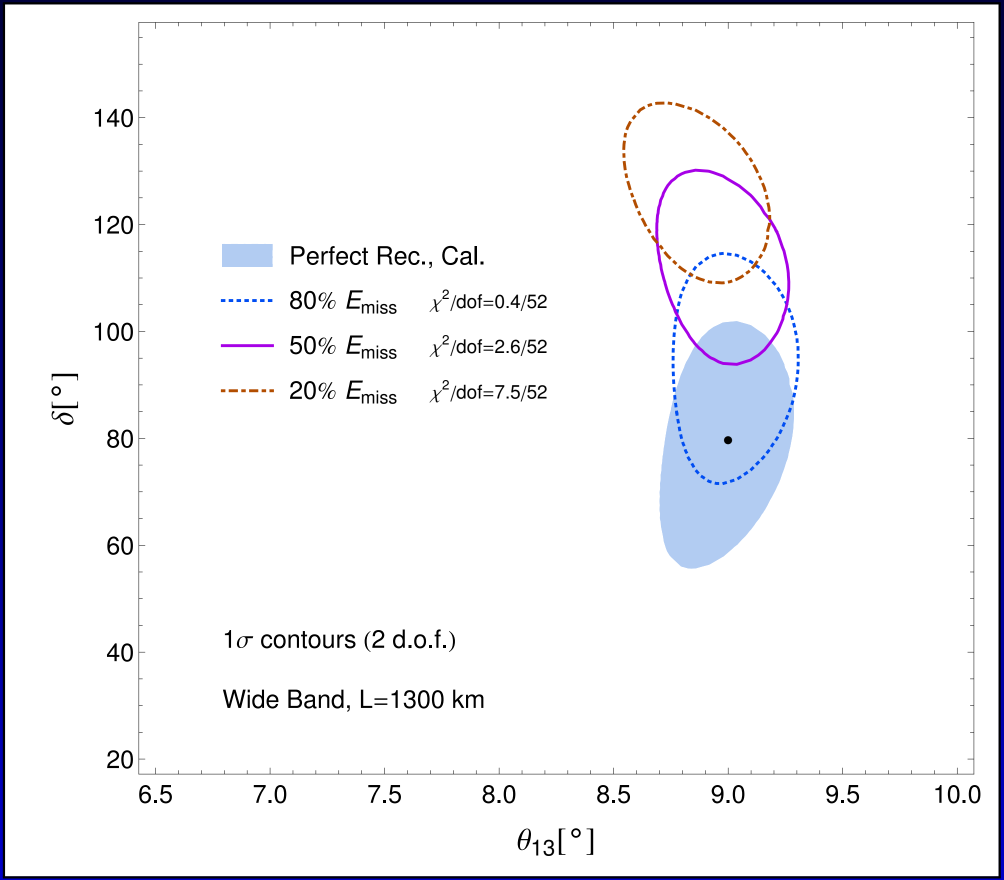
DUNE TDR

This corresponds approximately to phase II.

The way forward



Nuclear effects – example



In elastic scattering a certain number of neutrons is made

Neutrons will be largely invisible even in a liquid argon TPC

$\Rightarrow$ missing energy

Ankowski *et al.*, 2015

In general, **neutrino** energy reconstruction is a difficult problem.

Theory and cross sections

Theory is cheap, but multi-nucleon systems and their dynamic response are a hard problem and there is not a huge number of people working on this. . .

LQCD right now starts to be able to derive nucleon (!) level information.

Without being anchored by data, any result will be based on assumptions and uncontrolled approximations.

Requires a novel precision, high-luminosity neutrino source ⇒ nuSTORM & ENUBET

The big question

Things the Standard Model does NOT explain

- Neutrino mass
- Dark matter
- Baryon asymmetry
- Dark energy
- Gravity

50 years of ideas, most have been retired by flavor physics and LHC results

Is there anything within our means we can find?

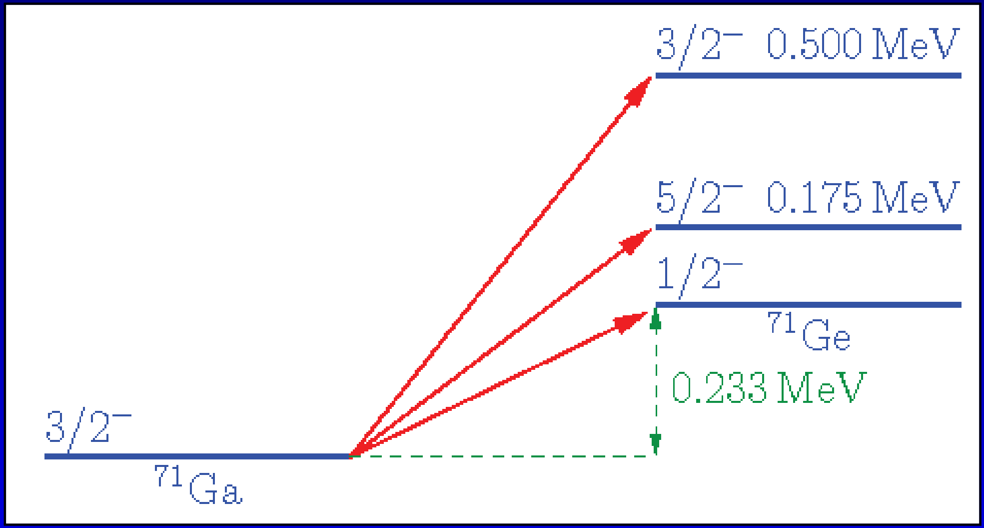
NB: None of the neutrino properties & discoveries was anticipated by theory.

Gallium anomaly

Radioactive source experiments

GALLEX	GALLEX	SAGE	SAGE	BEST (inner)	BEST (outer)
0.953 ± 0.11	0.812 ± 0.10	0.95 ± 0.12	0.791 ± 0.084	0.791 ± 0.044	0.766 ± 0.045

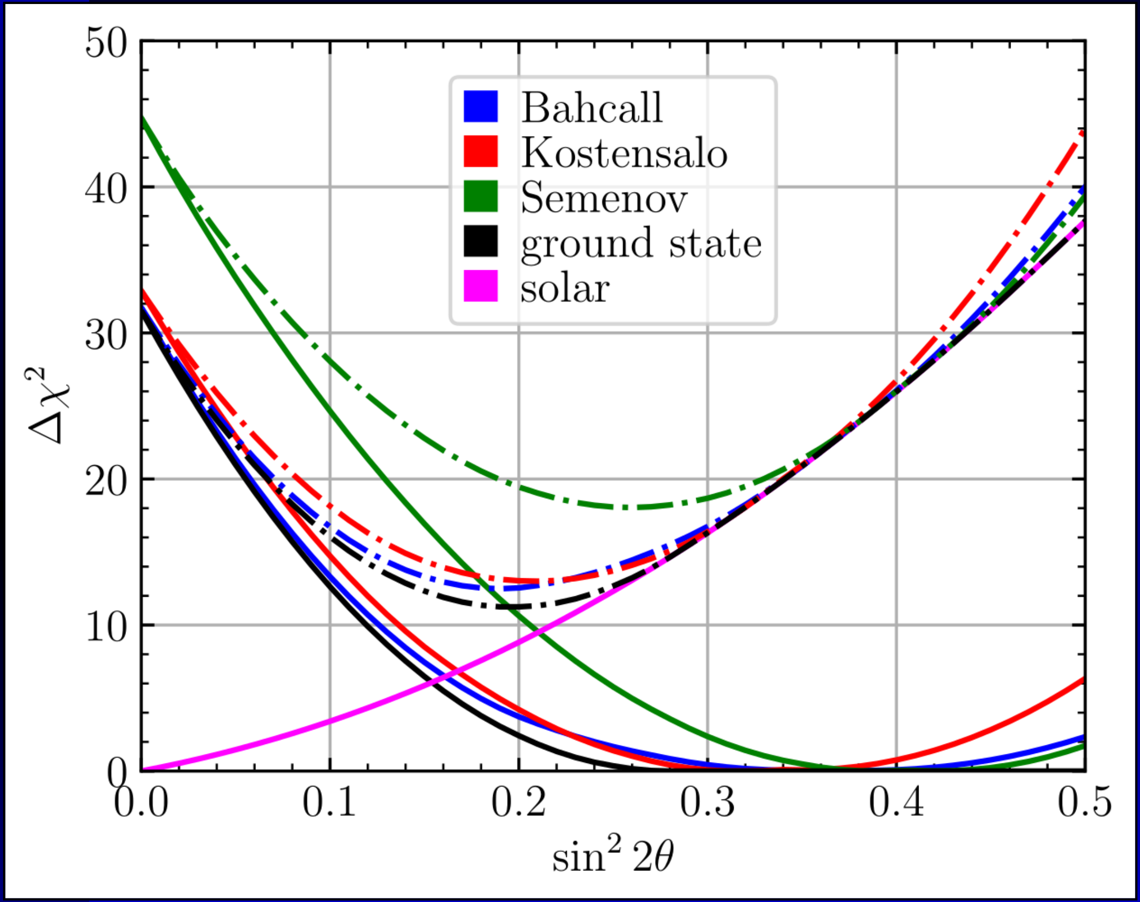
Nuclear matrix elements



ground state follows from beta decay of ^{71}Ge

excited states?

Gallium and solar



BCHSZ 2021

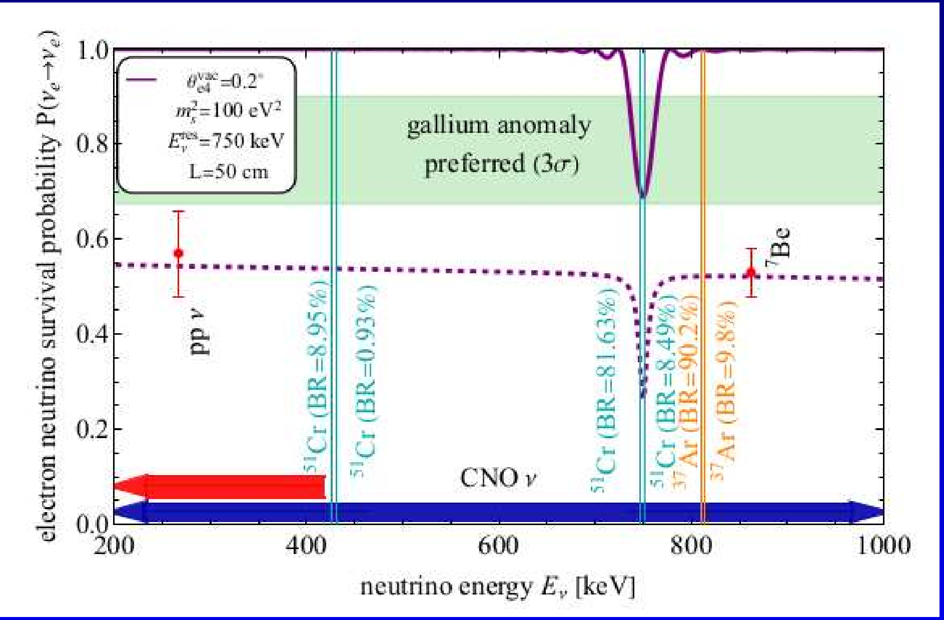
Any model for the matrix element yields more than 5σ for the gallium anomaly, even the ground state contribution by itself.

BUT, there is a more than 3σ tension with solar data.

Explanations?

Experimental reasons (all disfavored)

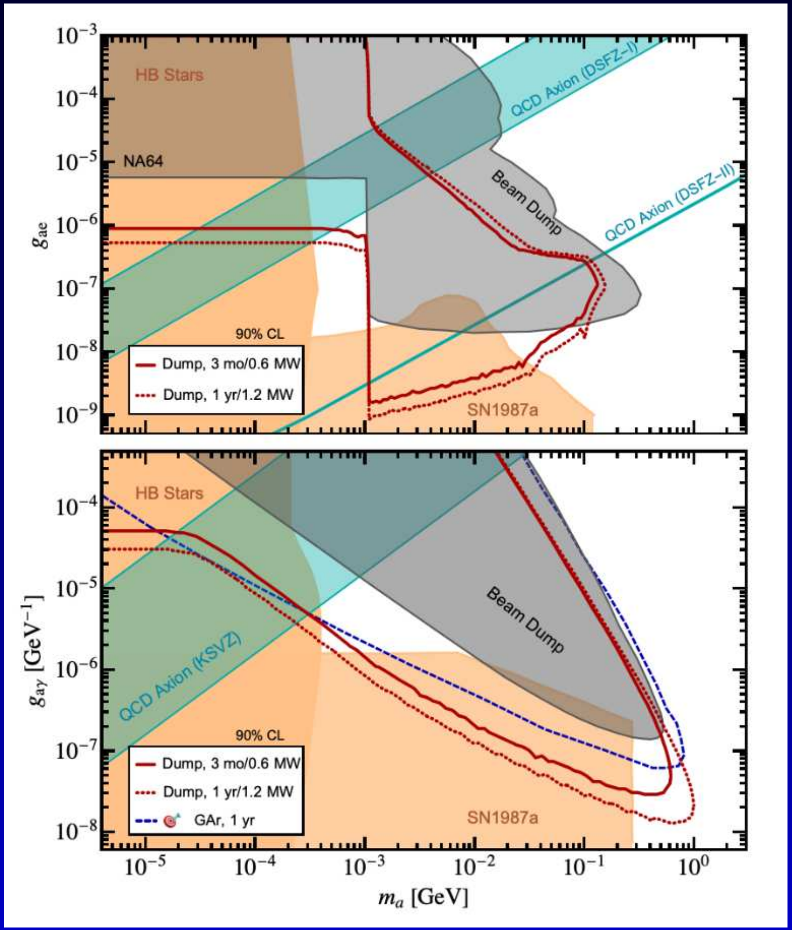
longer ^{71}Ge halflife	smaller matrix element, smaller cross section see also Giunti 2023
new excited state in ^{71}Ga	would change the matrix element
larger BR(^{51}Cr $\to$ ^{51}V*)	changes relation between decay heat and source strength
^{71}Ge extraction efficiency	some ^{71}Ge does not get extracted



Engineer a MSW resonance at the ^{51}Cr neutrino energy.

Brdar, Gehrlein, Kopp, 2023

Non-neutrino BSM



Brdar *et al.*, 2023

Running DUNE w/o a target to reduce neutrino background (!)

Relies on the MCND

Also sensitive to scalar light dark matter

Outlook

- Neutrino physics has a lot of room for surprises.
- DUNE and T2HK are highly synergistic.
- Having both experiments is a crucial cross check on cross section systematics.
- It makes sense to push sensitivities even after DUNE/T2HK with neutrino factories.
- Neutrino factories have strong synergies with muon collider R&D.

What to do with the gallium results?