# CP-Violating Neutrino Non-Standard Interactions in Long-Baseline-Accelerator Data

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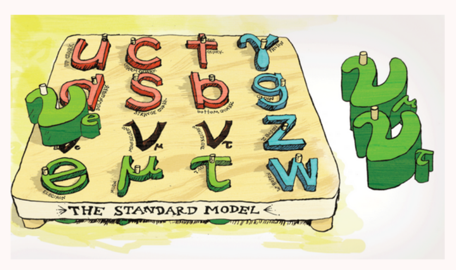
in collaboration with Peter B. Denton and Rebekah Pestes

- Neutrino oscillations: **strong** evidence for BSM physics



# Neutrino oscillations

- Neutrino oscillations: strong evidence for BSM physics
- flavor eigenstates (of weak interaction) and mass eigenstates (of free particle Hamiltonian) not aligned for neutrinos

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

$U_{PMNS}$: relates flavor and mass states

parametrized by 4 parameters (3 angles, at least 1 phase)

$\Rightarrow$ observation of neutrino oscillation introduced more parameters to the SM

# Neutrino oscillations

- standard parametrization for PMNS matrix as a series of three rotations

$$U_{PMNS} = U_{23}(\theta_{23})U_{13}(\theta_{13},\delta)U_{12}(\theta_{12})\text{diag}(e^{i\alpha_1/2},\ e^{i\alpha_2/2},\ 1)$$

- $\text{diag}(e^{i\alpha_1/2},\ e^{i\alpha_2/2},\ 1)$ only physical for Majorana neutrinos, oscillation experiments are not sensitive to these phases

  $\rightarrow$ not going to talk about them further

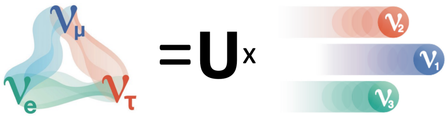
# Neutrino oscillations

standard parametrization for PMNS matrix as a series of three rotations

$$U_{PMNS} = U_{23}(\theta_{23})U_{13}(\theta_{13}, \delta)U_{12}(\theta_{12})$$

$\Rightarrow$ **want to measure these new parameters!**

# Neutrino oscillations

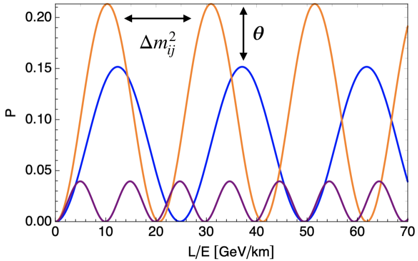



produce neutrino of flavor $\alpha$ with energy $E$

probability to detect neutrino with flavor $\beta$ at distance $L$ is

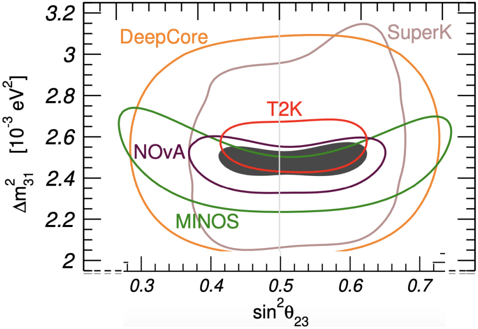
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2(\Delta m_{ij}^2 L/4E), \ \Delta m_{ij}^2 = m_i^2 - m_j^2$$

in a 2-flavor approximation



# Neutrino oscillations

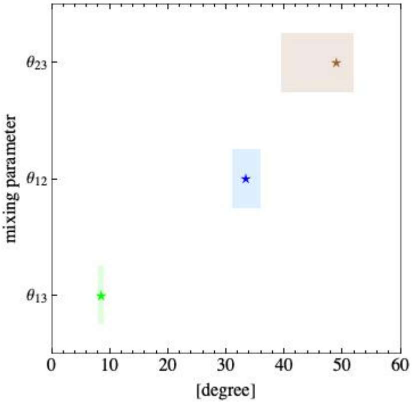
- many experiments have measured the angles and mass splittings $\rightarrow$ impressive agreement between experiments




[nuFit v5.0]

# Neutrino oscillations

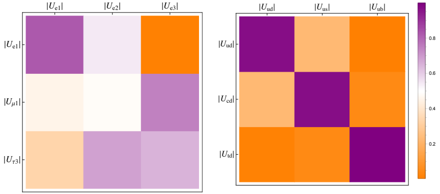
- all three angles non-zero
- mixing angles are large!

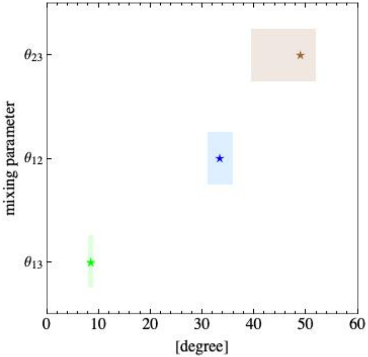


# Neutrino oscillations

- all three angles non-zero
- mixing angles are large!

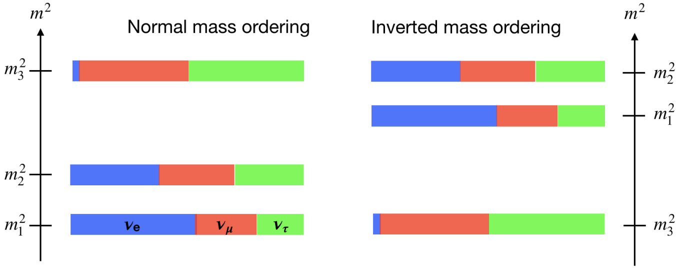
  surprising if compared to small quark mixing



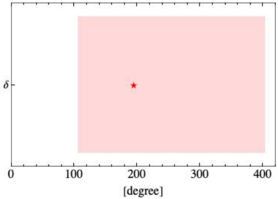
# Neutrino oscillations

- mass splittings: $|\Delta m^2_{32}| = 2.5 \cdot 10^{-3}\ \text{eV}^2$, $\Delta m^2_{21} = 7.4 \cdot 10^{-5}\ \text{eV}^2$
- mass ordering unknown



# CP violation

- all three mixing angles are non-zero $\rightarrow$ possibility for CPV
- currently least known parameter is $\delta$ which governs CPV in lepton sector
- want to measure $\delta$!



# CPV in the SM

- weak interaction: CP maximally violated [Cronin, Fitch '64]
- strong interaction: no observed EDM $\rightarrow$ CP conserved (?) ($\rightarrow$ strong CP problem)

# CPV in the SM

- CPV in mass matrices quantified via basis invariant

$$J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta$$

$J_{CP}^{max} = 1/(6\sqrt{3}) \approx 0.096$ [Jarlskog '85]

- quark mixing matrix: non-zero $\delta_{CKM}$ but CPV is small
  $|J_{CKM}|/J_{CP}^{max} = 3 \cdot 10^{-5}$

- **is CP violated in the lepton sector?** $|J_{PMNS}|/J_{CP}^{max} < 0.34$

# CPV in the lepton sector

How to measure delta?

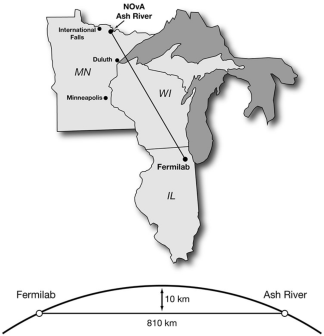
- CPV can only take place in appearance experiments $P(\nu_\alpha \to \nu_\beta)$
- need a channel where all three flavors play a role (need interference of two contributions to the oscillation probability given by the two mass splittings)
- compare neutrino with anti neutrino oscillation probability

use $P(\nu_\mu \to \nu_e)$ as oscillation channel!

due to matter effects this channel is also sensitive to the MO

# Long baseline experiments: NOvA

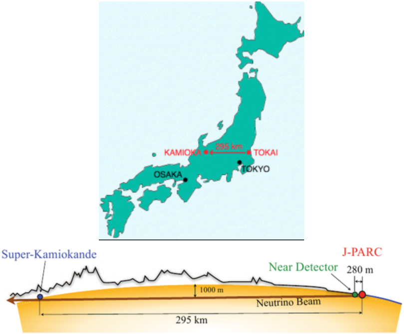
- neutrinos from NUMI beam at Fermilab
- $E \sim$ 1.9 GeV, L=810 km
- matter density $\rho =$ 2.84 g/cc
- Near (far) detector 0.3 (14) kT liquid scintillator



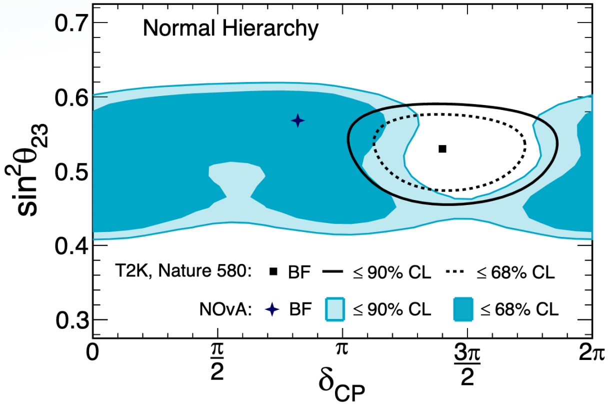
# Long baseline experiments: T2K

T2K

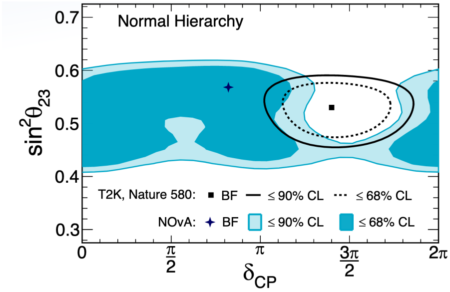
- neutrinos from JPARC beam
- $E \sim 0.6$ GeV, L=295 km
- matter density $\rho = 2.3$ g/cc
- near detector: plastic scintillator, far detector is SuperK



Excitement at Neutrino2020!




[Himmel '20]



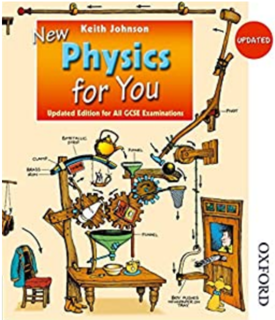

[Himmel '20]

- both experiments prefer NO
- no strong preference for NOvA, generally around $\delta \sim \pi$
- T2K prefers $\delta = 3\pi/2$

  $\Rightarrow$ slight disagreement at $\sim 2\sigma$

# New physics solutions

Can new physics alleviate this slight discrepancy?



# New physics

difference between NOvA and T2K is the baselines and the matter density

$\rightarrow$ neutrinos at NOvA experience stronger matter effects

new physics solution could be related to this difference

introduce new matter interactions for neutrinos

$\Rightarrow$ **neutrino non-standard interactions**

- framework

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f} \epsilon^f_{\alpha\beta}(\overline{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f}\gamma_\mu f)$$

- affect oscillations via new matter effect

$$H = \frac{1}{2E}\left[U^\dagger M^2 U + a \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}\right]$$

matter potential $a \propto G_F \rho E$

# Non-standard interactions

focus on vectorial NSI, flavor changing parameters

6 real parameters:

$$|\epsilon_{e\mu}|e^{i\phi_{e\mu}},\ |\epsilon_{e\tau}|e^{i\phi_{e\tau}},\ |\epsilon_{\mu\tau}|e^{i\phi_{\mu\tau}}$$

consider only one complex parameter at a time

# NSI: analytical results [Denton, JG, Pestes '20]

assumption: NSI only affects $\delta$, $\theta_{23}$&$\Delta m^2_{31}$ unaffected

$$P(\epsilon = 0, \delta_{\text{meas}}) = P(\epsilon, \delta_{\text{true}}) \,,$$
$$\bar{P}(\epsilon = 0, \delta_{\text{meas}}) = \bar{P}(\epsilon, \delta_{\text{true}}) \,,$$

using approximate expressions for NSI in LBL from [Kikuchi '09]

$\rightarrow$ estimates for needed magnitude and phase of NSI parameter

# NSI: analytical results [Denton, JG, Pestes '20]

estimate for magnitude of NSI parameter

$$|\epsilon_{e\beta}| \approx \frac{s_{12}c_{12}c_{23}\pi\Delta m^2_{21}}{2s_{23}w_\beta}\left|\frac{\sin\delta_{\text{T2K}} - \sin\delta_{\text{NOvA}}}{a_{\text{NOvA}} - a_{\text{T2K}}}\right| \approx \begin{cases} 0.22 & \text{for } \beta = \mu \\ 0.24 & \text{for } \beta = \tau \end{cases},$$

with $w_\beta = \sin\theta_{23}(\cos\theta_{23})$

- if $\sin\delta_{\text{T2K}} = \sin\delta_{\text{NOvA}} \rightarrow |\epsilon| = 0$
- if $a_{\text{T2K}} = a_{\text{NOvA}} \rightarrow |\epsilon| \rightarrow \infty$

# NSI: analytical results [Denton, JG, Pestes '20]

estimate for phase of NSI parameter

with $\delta_{\text{NOvA}} \neq \delta_{\text{T2K}}$

we find that $\sin(\delta_{\text{true}} + \phi_{e\beta}) \approx 0$

with $a_{\text{NOvA}} > a_{\text{T2K}}$ and $\sin\delta_{\text{T2K}} < \sin\delta_{\text{NOvA}}$:

$$\cos(\delta_{\text{true}} + \phi_{e\beta}) \approx = -1$$

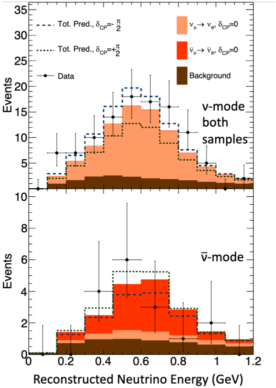
$$\delta_{\text{true}} \approx \delta_{\text{T2K}} \rightarrow \phi_{e\beta} \approx \frac{3}{2}\pi$$

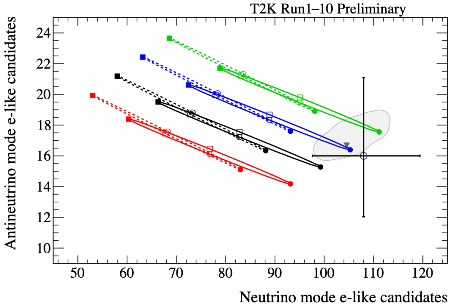
# NSI: numerical results [Denton, JG, Pestes '20]

- Appearance data:

$$n(\nu_e) = xP(\nu_\mu \to \nu_e) + yP(\bar{\nu}_\mu \to \bar{\nu}_e) + z\,,$$

include wrong sign leptons, fit to points on biprobability plot



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include wrong sign leptons, fit to points on biprobability plot

- Disappearance data:

NOvA: use fit results from [Kelly et al '20]

T2K: use provided likelihoods

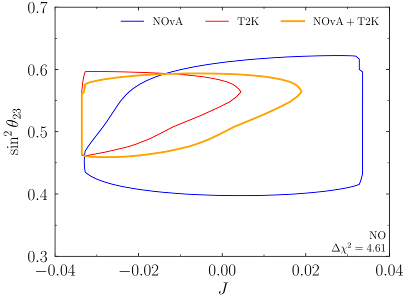
# NSI: numerical results [Denton, JG, Pestes '20]

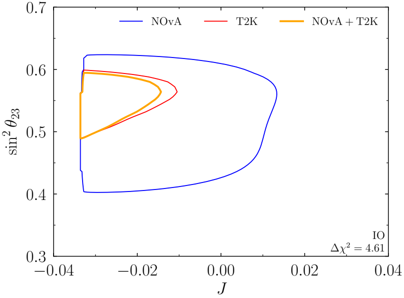
use information from vacuum experiments for remaining parameters

- Daya Bay: $\theta_{13},\ |\Delta m^2_{32}|$ [1809.02261]
- KamLAND: $\theta_{12},\ |\Delta m^2_{21}|$ [1303.4667]
- SNO: $\Delta m^2_{21} > 0$

conduct combined analysis of NOvA and T2K using a log likelihood ratio with Poisson statistics

# Standard oscillation parameters [Denton, JG, Pestes '20]




combination is more compatible with IO, IO preferred over NO at $\Delta\chi^2 = 2.3$

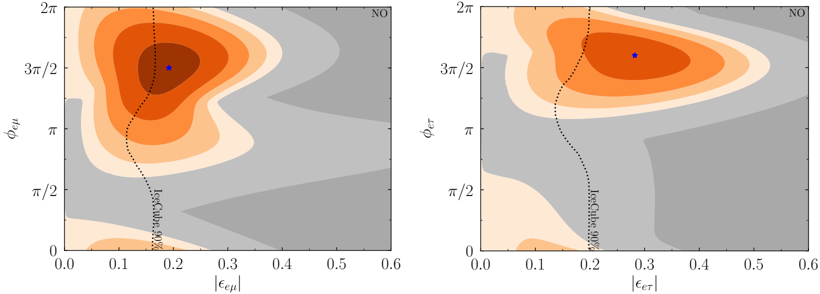
# Swap mass ordering

discrepancy slightly resolved by swapping the mass ordering

1. NOvA and T2K both prefer NO over IO
2. NOvA+T2K prefers IO over NO
3. SK still prefers NO over IO
4. NOvA+T2K+SK still prefers NO over IO
5. near future reactor experiments provide information in the future

[Kelly et al ’20; Esteban et al ’20; Denton, JG, Pestes ’20]

# NSI parameters [Denton, JG, Pestes '20]




orange preferred over SM at integer values of $\Delta\chi^2$, dark gray disfavored at $\Delta\chi^2 = 4.61$

[see also Chatterjee, Palazzo '20]

# NSI parameters [Denton, JG, Pestes '20]

analytical estimates: $|\epsilon_{\alpha\beta}| \approx 0.2,\ \phi_{\alpha\beta} \approx 3\pi/2,\ \delta_{\text{true}} \approx 3\pi/2$

| MO | NSI | $\lvert\epsilon_{\alpha\beta}\rvert$ | $\phi_{\alpha\beta}/\pi$ | $\delta/\pi$ | $\Delta\chi^2$ |
|---|---|---|---|---|---|
| NO | $\epsilon_{e\mu}$ | 0.19 | 1.50 | 1.46 | 4.44 |
| | $\epsilon_{e\tau}$ | 0.28 | 1.60 | 1.46 | 3.65 |
| | $\epsilon_{\mu\tau}$ | 0.35 | 0.60 | 1.83 | 0.90 |
| IO | $\epsilon_{e\mu}$ | 0.04 | 1.50 | 1.52 | 0.23 |
| | $\epsilon_{e\tau}$ | 0.15 | 1.46 | 1.59 | 0.69 |
| | $\epsilon_{\mu\tau}$ | 0.17 | 0.14 | 1.51 | 1.03 |

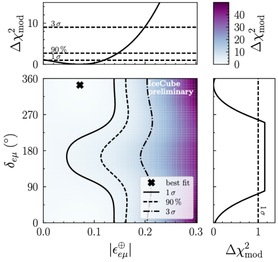
$\Delta\chi^2 = \chi^2_{\text{SM}} - \chi^2_{\text{NSI}}$ for a fixed MO, $\chi^2_{\text{NO}} - \chi^2_{\text{IO}} = 2.3$

# Oscillation constraints on NSI parameters

NSI effects grow with energy, distance and matter density

- $\epsilon_{\mu\tau}$ best probed with atmospheric neutrinos
- $\epsilon_{e\mu}$, $\epsilon_{e\tau}$ best probed with LBL appearance, atmospheric neutrinos

- IceCube: slightly disfavors LBL best fit points, prefers non-zero $|\epsilon_{e\mu}|$ at $1\sigma$
- SuperK: only considered real NSI, comparable sensitivity to IceCube




[IceCube '21]

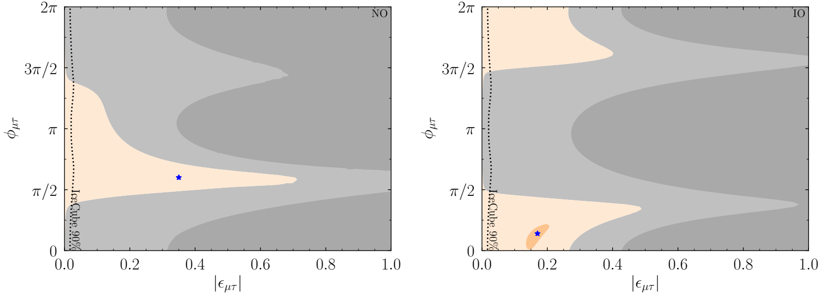
- CEvNS at COHERENT: applies to $M_{Z'} > 10$ MeV, comparable constraints [Denton, JG '20]

# Summary & Conclusions

- open question of CPV in lepton sector
- slight tension between NOvA and T2K
- swap in mass ordering NO$\rightarrow$ IO can resolve this partially
- tension fully resolved with NSI!
- predict maximal CP violation in PMNS matrix and for new physics
- hint for NSI can be further probed with near-future experiments like T2HK and DUNE

# Thank you for your attention!

in general no preference for IO with NSI parameters




orange preferred over SM at integer values of $\Delta\chi^2$, dark gray disfavored at $\Delta\chi^2 = 4.61$

$$P(\epsilon = 0, \delta_{\text{meas}}) = P(\epsilon, \delta_{\text{true}}) \, ,$$
$$\bar{P}(\epsilon = 0, \delta_{\text{meas}}) = \bar{P}(\epsilon, \delta_{\text{true}}) \, ,$$

$$-s_{12}c_{12}c_{23}\frac{\pi}{2}\Delta m^2_{21}\sin\delta + a_{\text{NOvA}}|\epsilon_{e\beta}|\left[w_\beta s_{23}\cos(\delta+\phi_{e\beta}) - v_\beta c_{23}\frac{\pi}{2}\sin(\delta+\phi_{e\beta})\right] \approx -s_{12}c_{12}c_{23}\frac{\pi}{2}\Delta m^2_{21}\sin\delta_{\text{NOvA}} \, , \tag{A3}$$

$$s_{12}c_{12}c_{23}\frac{\pi}{2}\Delta m^2_{21}\sin\delta - a_{\text{NOvA}}|\epsilon_{e\beta}|\left[w_\beta s_{23}\cos(\delta+\phi_{e\beta}) + v_\beta c_{23}\frac{\pi}{2}\sin(\delta+\phi_{e\beta})\right] \approx s_{12}c_{12}c_{23}\frac{\pi}{2}\Delta m^2_{21}\sin\delta_{\text{NOvA}} \, , \tag{A4}$$

# Scattering constraints on NSI parameters

- NSI framework [Dev et al '19]

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f} \epsilon^f_{\alpha\beta}(\overline{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f}\gamma_\mu f)$$

$\rightarrow$ NSI affect neutrino-SM scattering experiments like CEvNS

- NSI effect on weak charge

$$Q^2_{w\alpha} \propto \left[N(g^V_n + \epsilon^V_{\alpha\alpha})\right]^2 + \sum_{\beta\neq\alpha}\left[\epsilon^V_{\alpha\beta}(Z+N)\right]^2$$

$\rightarrow$ no sensitivity to complex NSI phase

# Backup: Scattering constraints on NSI parameters

- CEvNS detected for the first time in 2016 by COHERENT
- NSI constraints apply to mediators $M_{Z'} > 10$ MeV
- constraints derived in [Denton, JG '20] using Feldman-Cousins framework