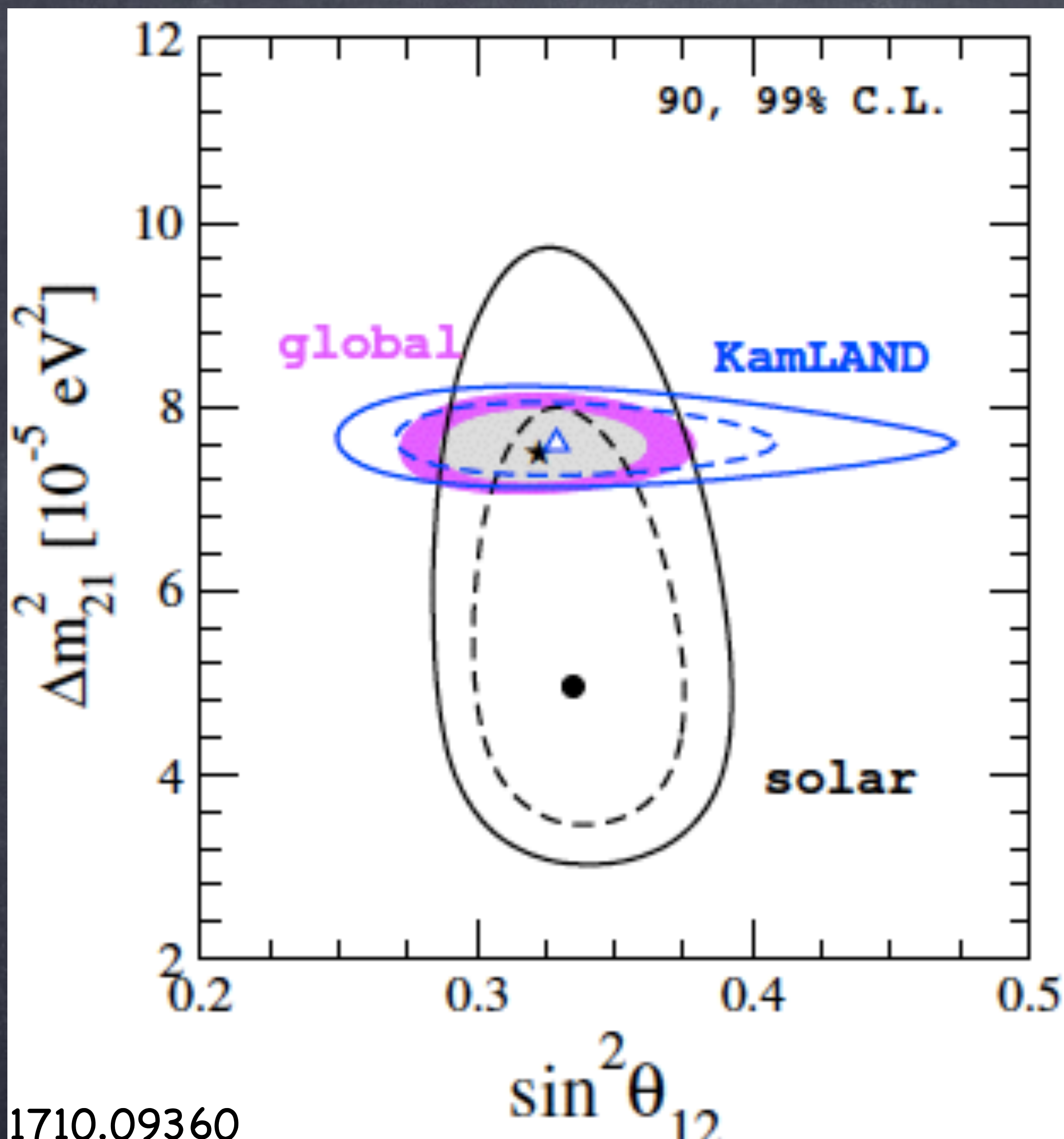
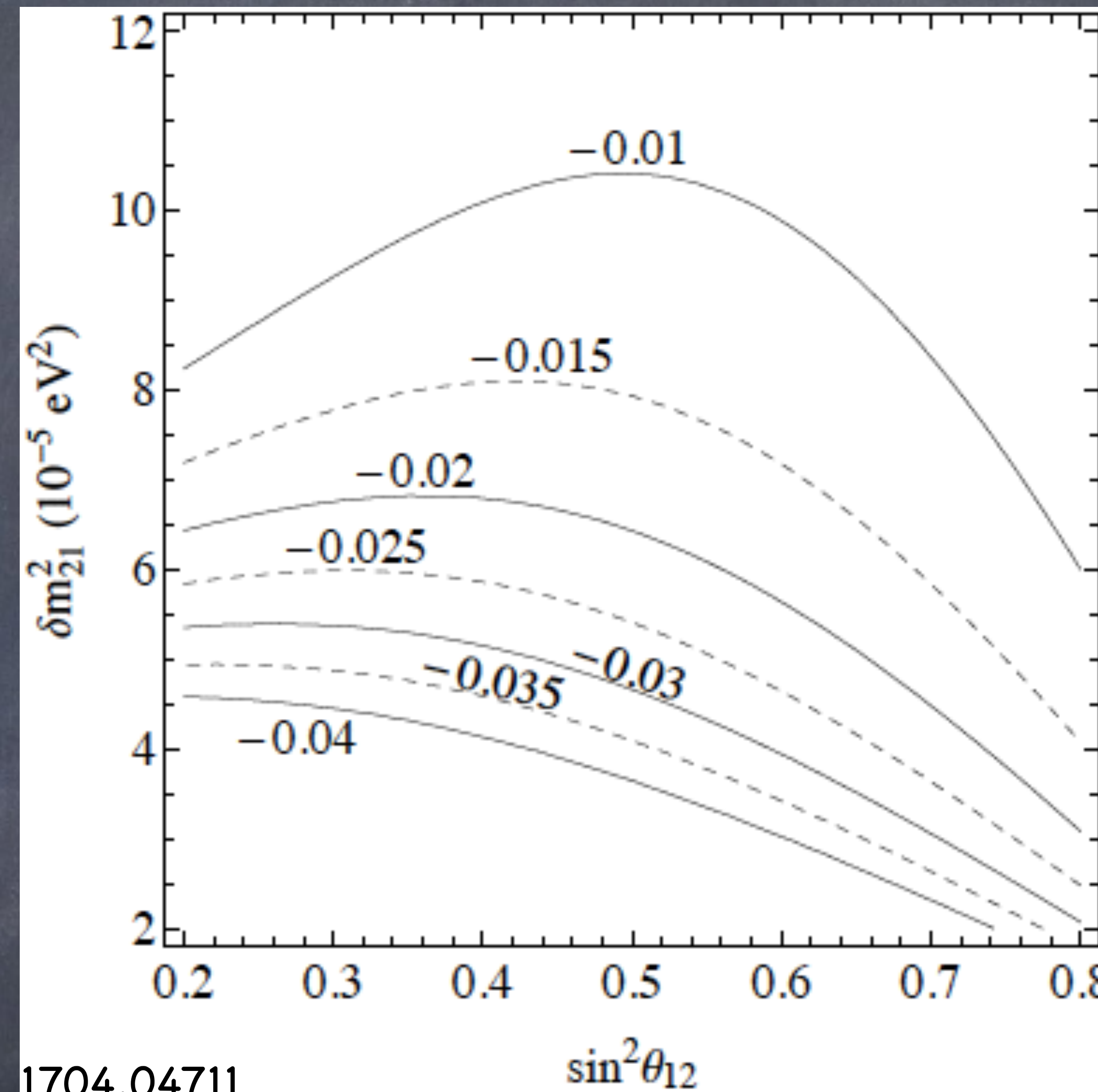
# New neutrino phenomena

Danny Marfatia

# New matter interactions

# Possible tension in standard oscillation picture




Discrepancy in mass-squared difference driven by Super-K's day-night asymmetry measurement:

$$-3.3 \pm 1.0 \pm 0.5\%$$

# Nonstandard interactions in matter

$$\mathcal{L}_{\text{NSI}} = 2\sqrt{2}G_F\epsilon_{\alpha\beta}^{\mathfrak{f}C}\left[\overline{\nu}_\alpha\gamma^\rho P_L\nu_\beta\right]\left[\bar{\mathfrak{f}}\gamma_\rho P_C\mathfrak{f}\right] + \text{h.c.}$$

where $\alpha, \beta = e, \mu, \tau,\ C = L, R,\ \mathfrak{f} = u, d, e$

$$V = A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}.$$

Here, $A \equiv 2\sqrt{2}G_F N_e E$ and $\epsilon_{\alpha\beta}e^{i\phi_{\alpha\beta}} \equiv \sum_{\mathfrak{f},C}\epsilon_{\alpha\beta}^{\mathfrak{f}C}\frac{N_{\mathfrak{f}}}{N_e}$

Vector interaction relevant for propagation:

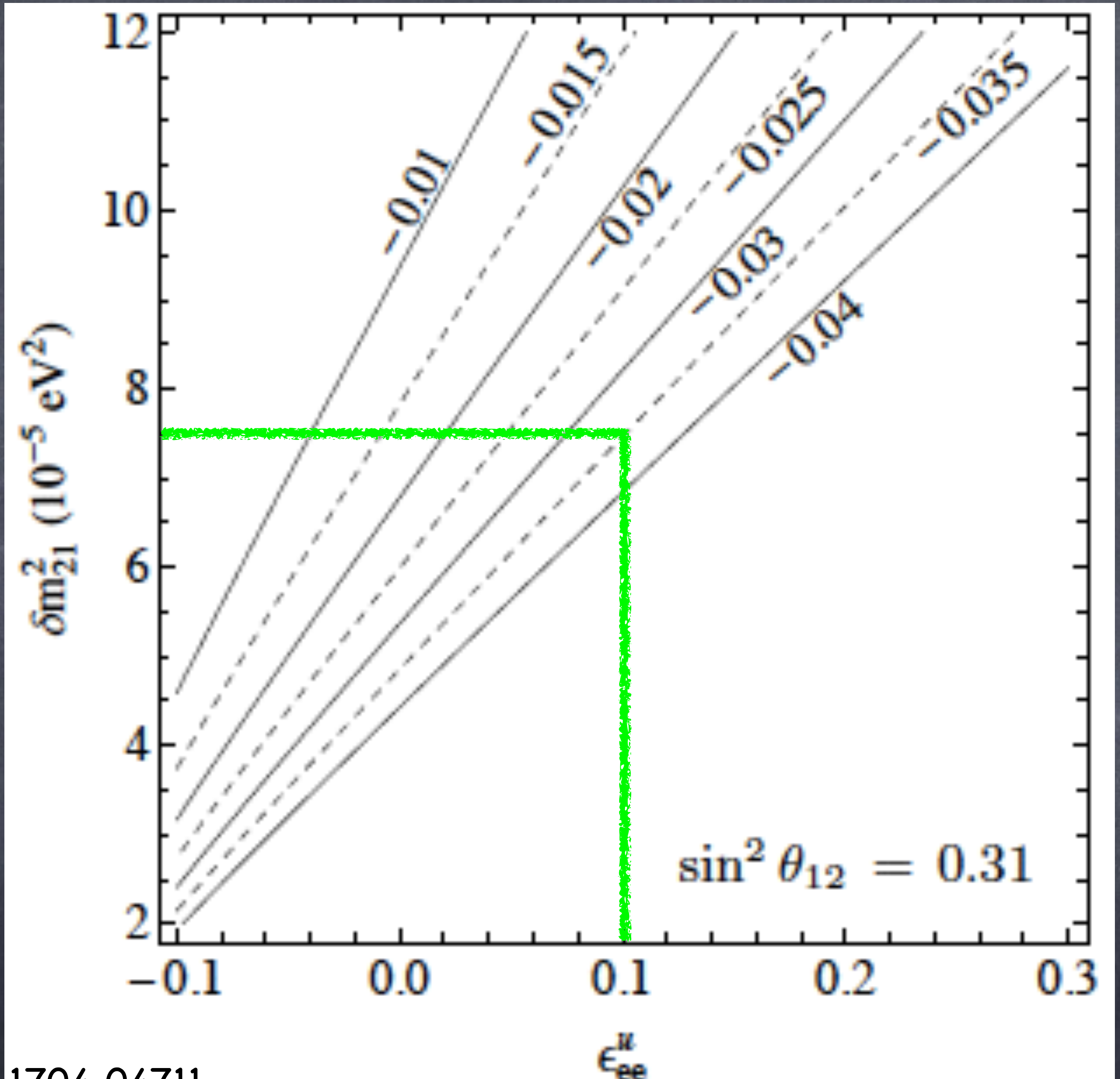
$$\epsilon_{\alpha\beta}^{\mathfrak{f}} \equiv \epsilon_{\alpha\beta}^{\mathfrak{f}L} + \epsilon_{\alpha\beta}^{\mathfrak{f}R} \implies \epsilon_{\alpha\beta}e^{i\phi_{\alpha\beta}} \equiv \sum_{\mathfrak{f}}\epsilon_{\alpha\beta}^{\mathfrak{f}}\frac{N_{\mathfrak{f}}}{N_e}$$

On earth $N_u = N_d = 3N_e$

1805.04530

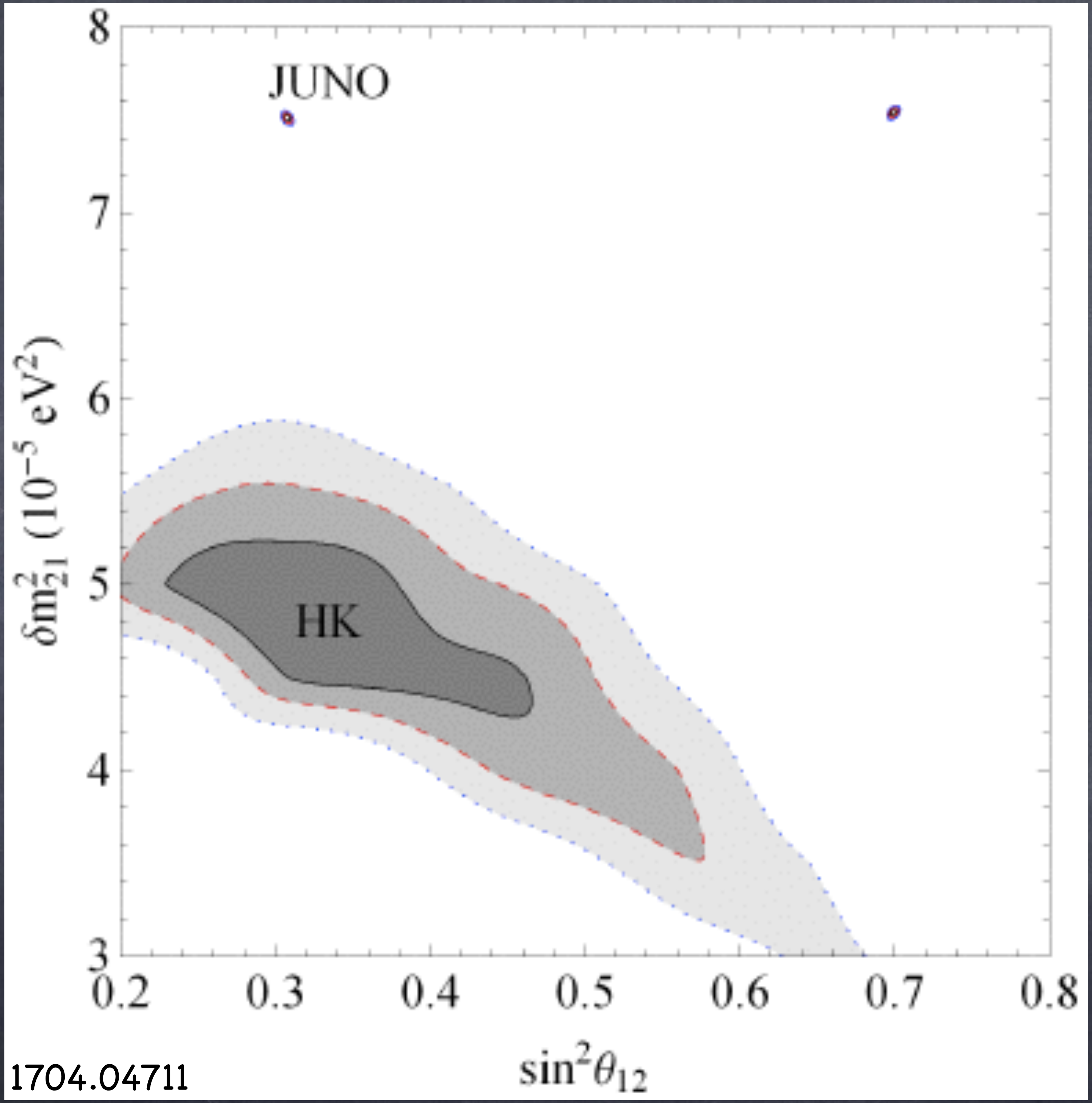
| | OSC | |
|---|---|---|
| | LMA | LMA $\oplus$ LMA-D |
| $\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$ | $[-0.020, +0.456]$ | $\oplus[-1.192, -0.802]$ |
| $\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$ | $[-0.005, +0.130]$ | $[-0.152, +0.130]$ |
| $\varepsilon^u_{e\mu}$ | $[-0.060, +0.049]$ | $[-0.060, +0.067]$ |
| $\varepsilon^u_{e\tau}$ | $[-0.292, +0.119]$ | $[-0.292, +0.336]$ |
| $\varepsilon^u_{\mu\tau}$ | $[-0.013, +0.010]$ | $[-0.013, +0.014]$ |
| $\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$ | $[-0.027, +0.474]$ | $\oplus[-1.232, -1.111]$ |
| $\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$ | $[-0.005, +0.095]$ | $[-0.013, +0.095]$ |
| $\varepsilon^d_{e\mu}$ | $[-0.061, +0.049]$ | $[-0.061, +0.073]$ |
| $\varepsilon^d_{e\tau}$ | $[-0.247, +0.119]$ | $[-0.247, +0.119]$ |
| $\varepsilon^d_{\mu\tau}$ | $[-0.012, +0.009]$ | $[-0.012, +0.009]$ |
| $\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$ | $[-0.041, +1.312]$ | $\oplus[-3.328, -1.958]$ |
| $\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$ | $[-0.015, +0.426]$ | $[-0.424, +0.426]$ |
| $\varepsilon^p_{e\mu}$ | $[-0.178, +0.147]$ | $[-0.178, +0.178]$ |
| $\varepsilon^p_{e\tau}$ | $[-0.954, +0.356]$ | $[-0.954, +0.949]$ |
| $\varepsilon^p_{\mu\tau}$ | $[-0.035, +0.027]$ | $[-0.035, +0.035]$ |

# Iso-day-night asymmetry contours




1704.04711

$$\epsilon^u_{ee} = \epsilon^d_{ee} \sim 0.1$$




Hyper-K and JUNO can detect NSI

# Future LBL experiments

| Experiment | $\frac{L(\text{km})}{E_{\text{peak}}(\text{GeV})}$ | $\nu + \bar{\nu}$ Exposure (kt·MW·$10^7$s) | Signal norm. uncertainty | Background norm. uncertainty |
|---|---|---|---|---|
| DUNE (LAr) | $\frac{1300}{3.0}$ | 264 + 264 (80 GeV protons, 1.07 MW power, $1.47 \times 10^{21}$ POT/yr, 40 kt fiducial mass, 3.5+3.5 yr) | app: 2.0%<br>dis: 5.0% | app: 5-20%<br>dis: 5-20% |
| T2HK (WC) | $\frac{295}{0.6}$ | 864.5 + 2593.5 (30 GeV protons, 1.3 MW power, $2.7 \times 10^{21}$ POT/yr, 0.19 Mt each tank, 1.5+4.5 yr with 1 tank, 1+3 yr with 2 tanks) | app: 2.5%<br>dis: 2.5% | app: 5%<br>dis: 20% |
| T2HKK-1.5 (WC) | $\frac{295}{0.6} + \frac{1100}{0.8}$ | 1235 + 3705 (30 GeV protons, 1.3 MW power, $2.7 \times 10^{21}$ POT/yr, 0.19 Mt each tank, 2.5+7.5 yr with 1 tank at KD and HK) | app: 2.5%<br>dis: 2.5% | app: 5%<br>dis: 20% |
| T2HKK-2.5 (WC) | $\frac{295}{0.6} + \frac{1100}{0.6}$ | | | |

For DUNE, 1 yr = $1.76 \times 10^7$s; for HyperK, 1 yr = $1.0 \times 10^7$s.

# Appearance channels

NH
$$P(\nu_\mu \to \nu_e) = x^2 f^2 + 2xyfg\cos(\Delta+\delta) + y^2 g^2$$
← Reduce to the SM when $\epsilon_{ee} = 0$

$$+\ 4\hat{A}\epsilon_{e\mu}\left\{xf[s_{23}^2 f\cos(\phi_{e\mu}+\delta) + c_{23}^2 g\cos(\Delta+\delta+\phi_{e\mu})]\right.$$
← 1st order due to $\epsilon_{e\mu}$

r suppressed → $$\left. +yg[c_{23}^2 g\cos\phi_{e\mu} + s_{23}^2 f\cos(\Delta-\phi_{e\mu})]\right\}$$

$$+\ 4\hat{A}\epsilon_{e\tau}s_{23}c_{23}\left\{xf[f\cos(\phi_{e\tau}+\delta) - g\cos(\Delta+\delta+\phi_{e\tau})]\right.$$
← 1st order due to $\epsilon_{e\tau}$

r suppressed → $$\left. -yg[g\cos\phi_{e\tau} - f\cos(\Delta-\phi_{e\tau})]\right\}$$

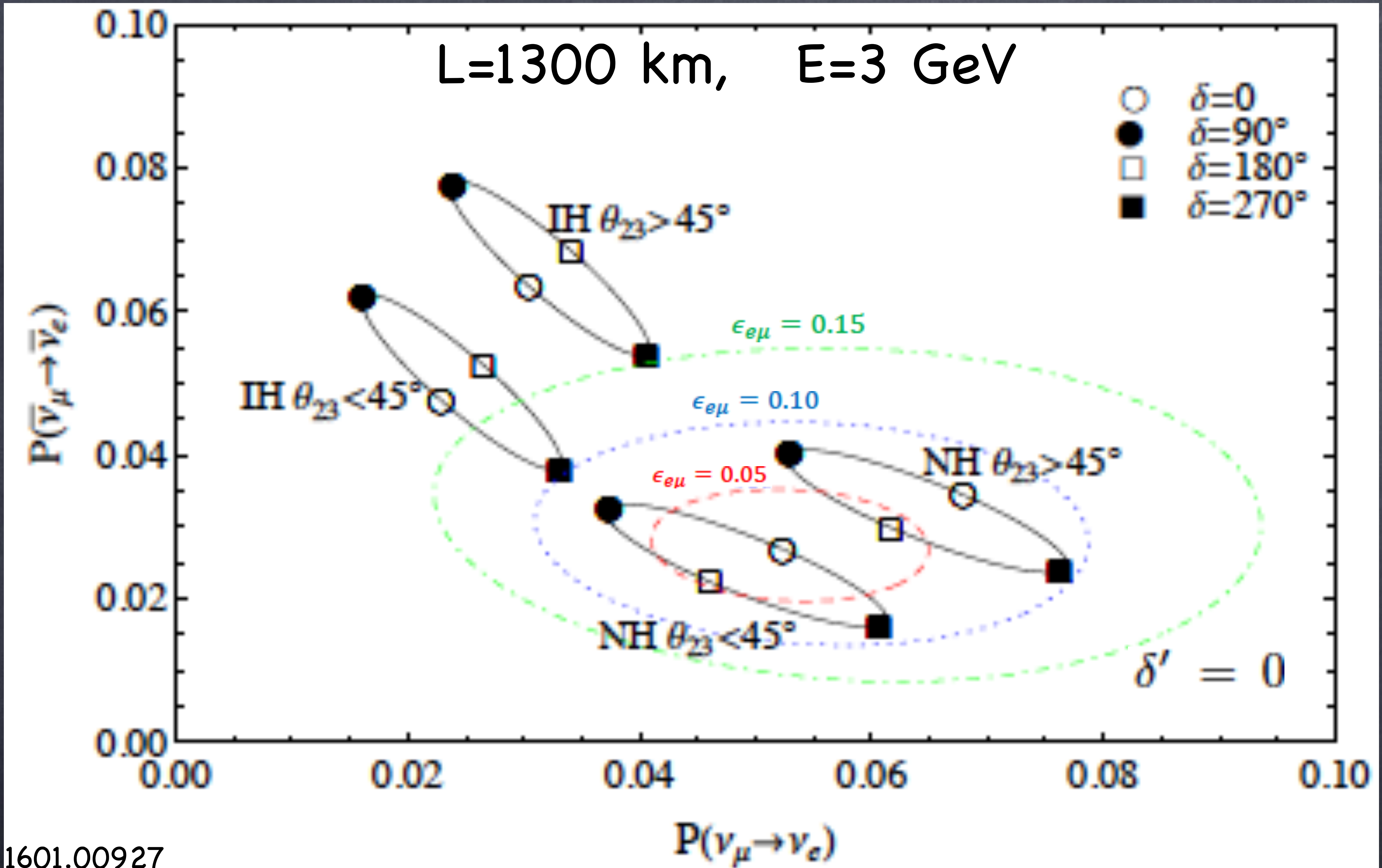
$$+\ 4\hat{A}^2\left(g^2 c_{23}^2|c_{23}\epsilon_{e\mu} - s_{23}\epsilon_{e\tau}|^2 + f^2 s_{23}^2|s_{23}\epsilon_{e\mu} + c_{23}\epsilon_{e\tau}|^2\right)$$
← 2nd order corrections

$$+\ 8\hat{A}^2 fg s_{23}c_{23}\left\{c_{23}\cos\Delta\left[s_{23}(\epsilon_{e\mu}^2 - \epsilon_{e\tau}^2) + 2c_{23}\epsilon_{e\mu}\epsilon_{e\tau}\cos(\phi_{e\mu}-\phi_{e\tau})\right]\right.$$
$$\left. -\epsilon_{e\mu}\epsilon_{e\tau}\cos(\Delta-\phi_{e\mu}+\phi_{e\tau})\right\} + \mathcal{O}(s_{13}^2\epsilon, s_{13}\epsilon^2, \epsilon^3)\,,$$

$$x \equiv 2s_{13}s_{23}\,,\quad y \equiv 2rs_{12}c_{12}c_{23}\,,\quad r = |\delta m_{21}^2/\delta m_{31}^2|\,,$$
$$f, \bar{f} \equiv \frac{\sin[\Delta(1\mp\hat{A}(1+\epsilon_{ee}))]}{(1\mp\hat{A}(1+\epsilon_{ee}))}\,,\quad g \equiv \frac{\sin(\hat{A}(1+\epsilon_{ee})\Delta)}{\hat{A}(1+\epsilon_{ee})}\,,$$
$$\Delta \equiv \left|\frac{\delta m_{31}^2 L}{4E}\right|\,,\quad \hat{A} \equiv \left|\frac{A}{\delta m_{31}^2}\right|$$

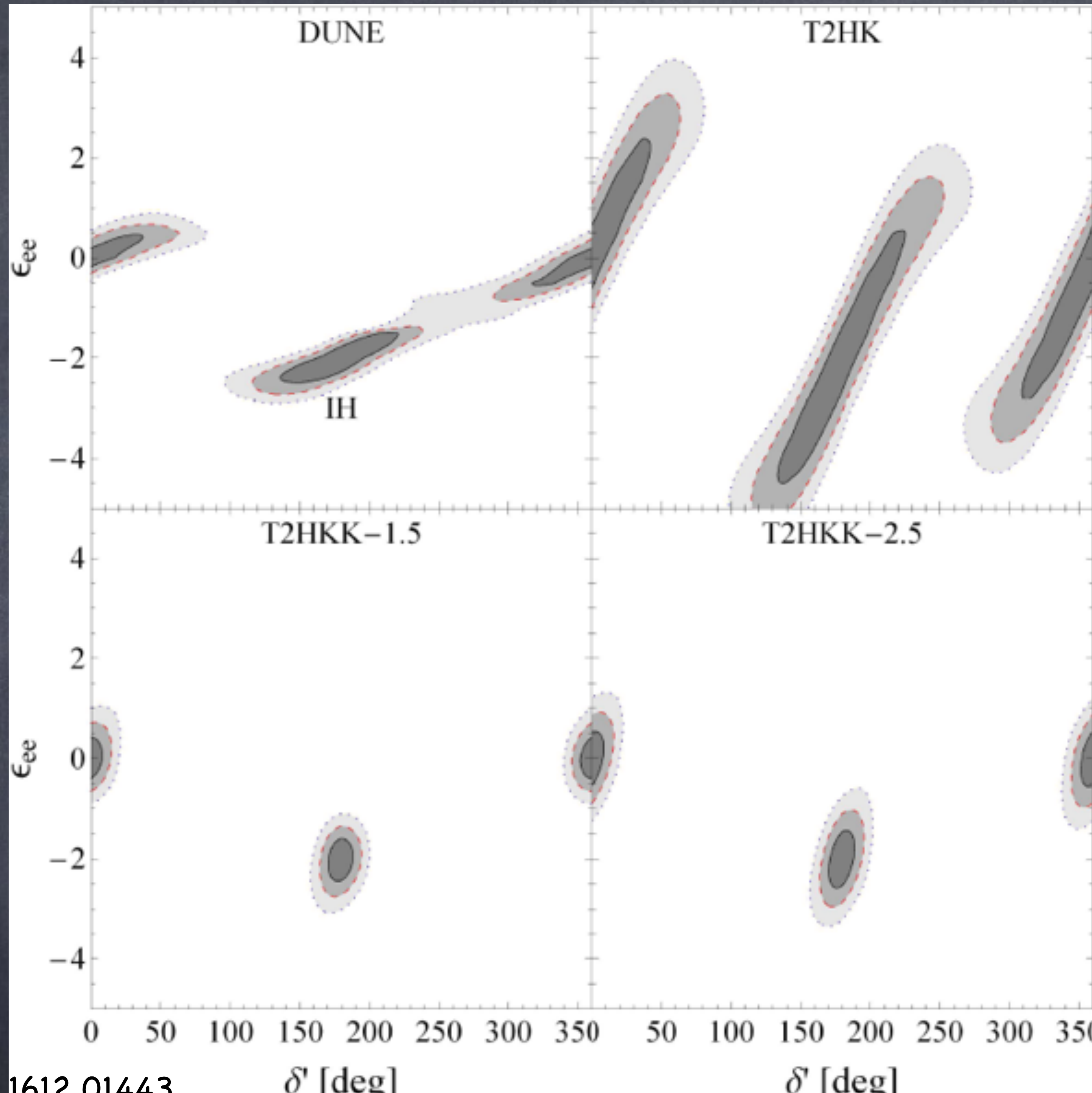
- $P_{\mu e} \to \bar{P}_{\mu e}$
  $\hat{A} \to -\hat{A}\ (f \to \bar{f})$,
  $\delta \to -\delta,\quad \phi_{\alpha\beta} \to -\phi_{\alpha\beta}$
- NH → IH
  $\Delta \to -\Delta,\ y \to -y$
  $\hat{A} \to -\hat{A}\ (f \leftrightarrow -\bar{f},\ \text{and}\ g \to -g)$

Liao




$$P^{SM}(\delta) = P^{NSI}(\delta', \epsilon, \phi)$$
$$\overline{P}^{SM}(\delta) = \overline{P}^{NSI}(\delta', \epsilon, \phi)$$

# One NSI parameter



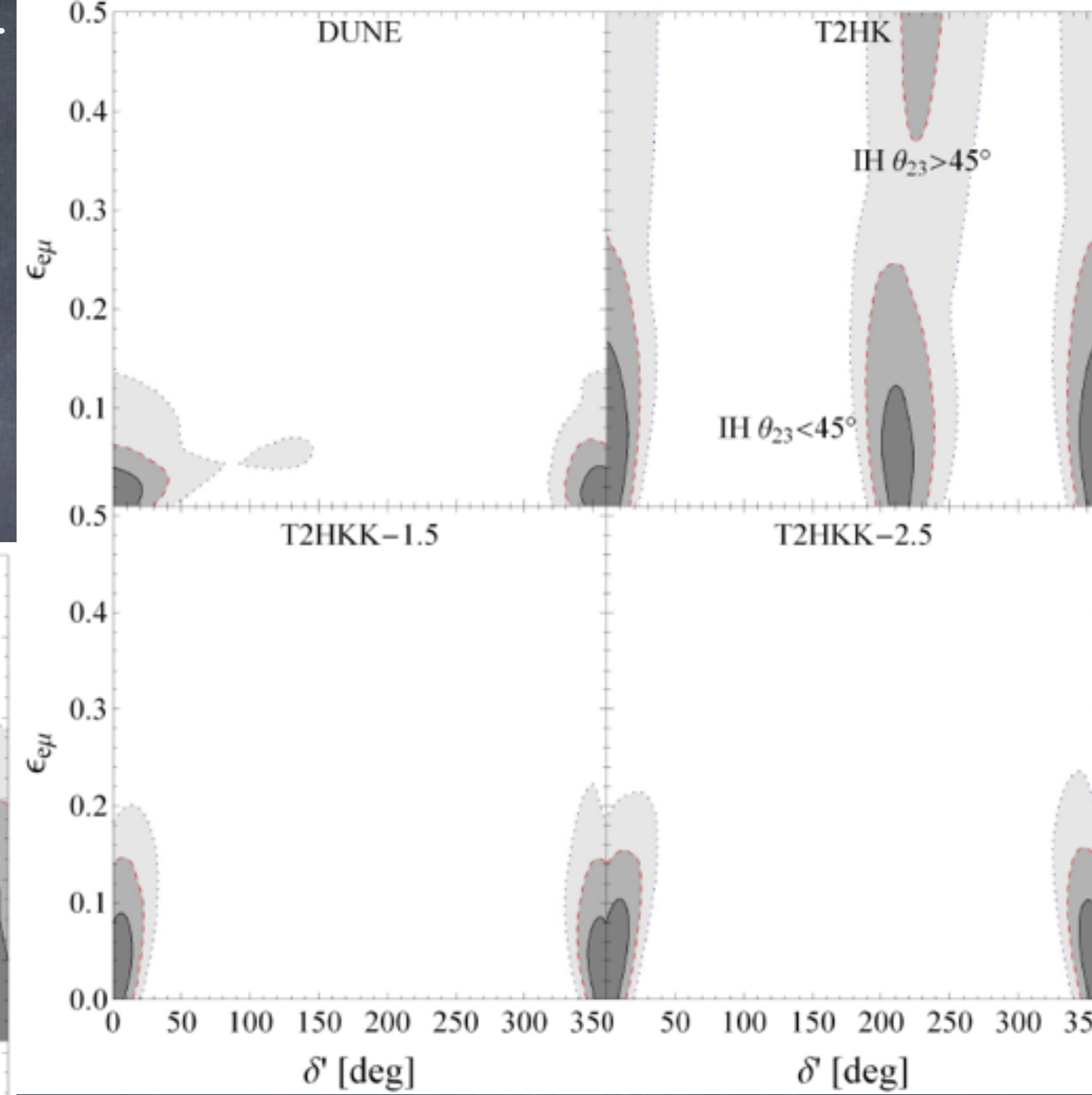

1612.01443

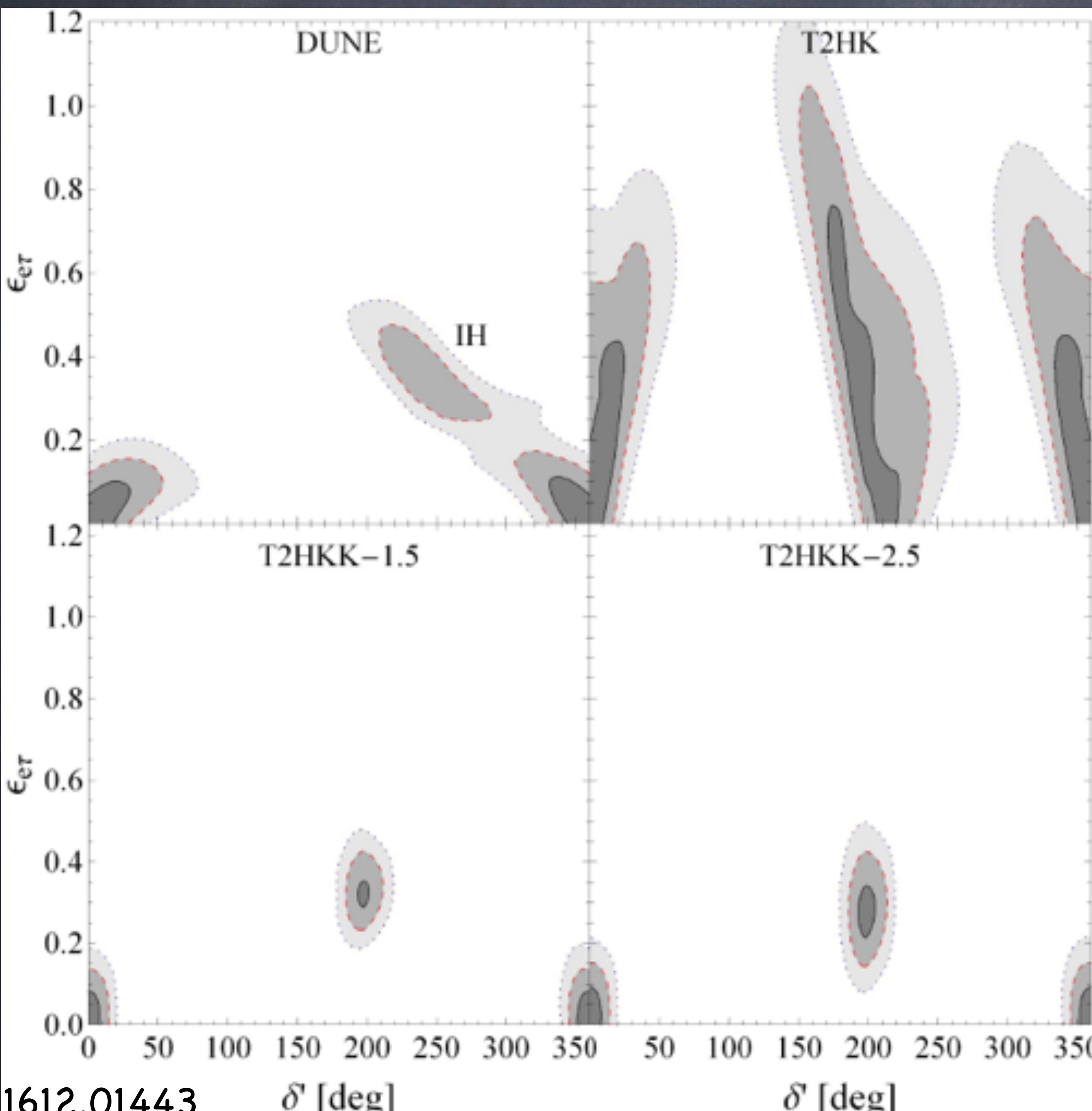
$$\delta m^2_{31} \to -\delta m^2_{32}, \quad \theta_{12} \to 90^\circ - \theta_{12}, \quad \delta \to 180^\circ - \delta$$

$$\epsilon_{ee} \to -\epsilon_{ee} - 2, \quad \epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \to -\epsilon_{\alpha\beta} e^{-i\phi_{\alpha\beta}} (\alpha\beta \neq ee)$$

1403.0744, 1604.05772

Mass hierarchy resolved at DUNE and T2HKK

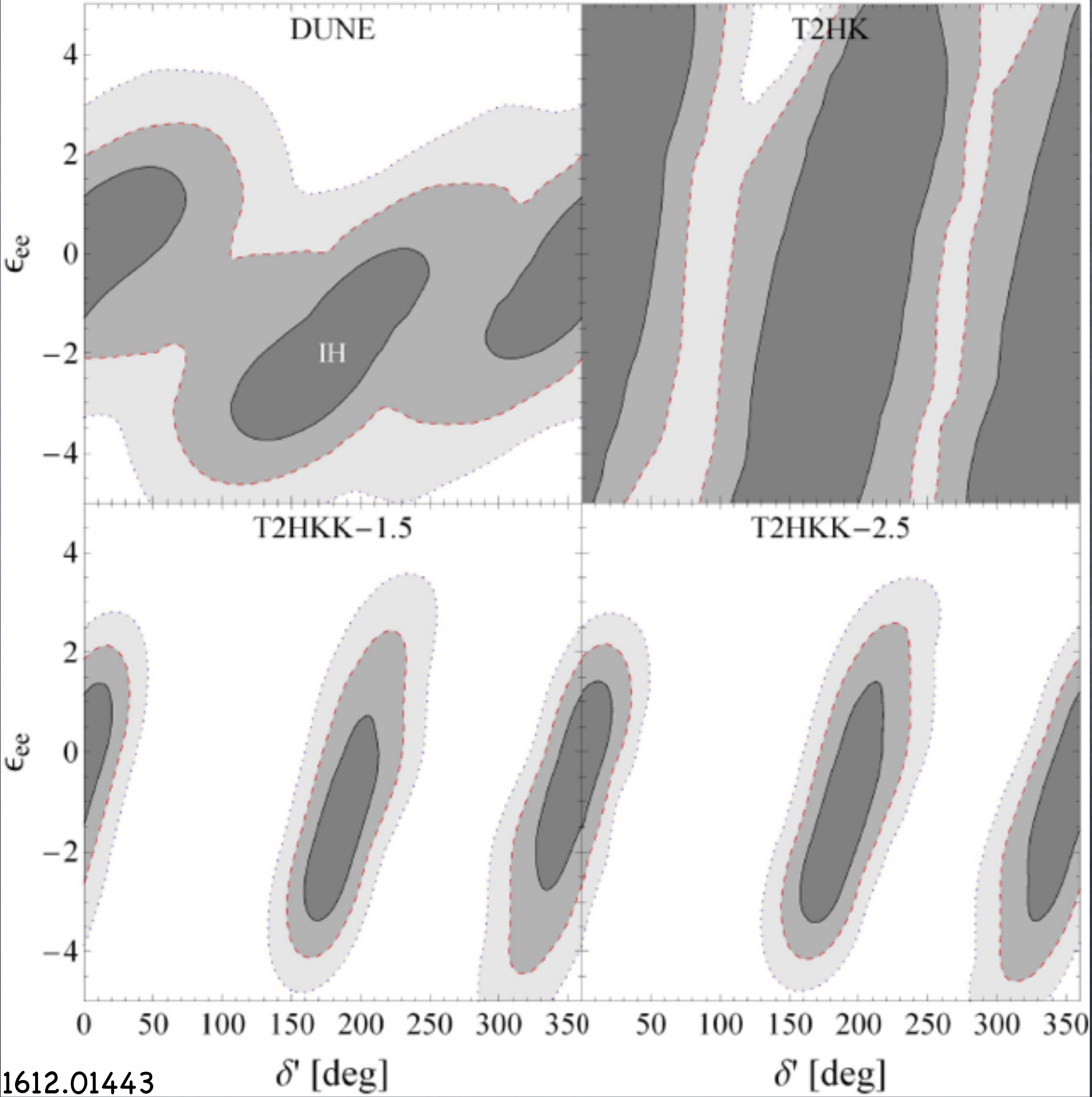



1612.01443

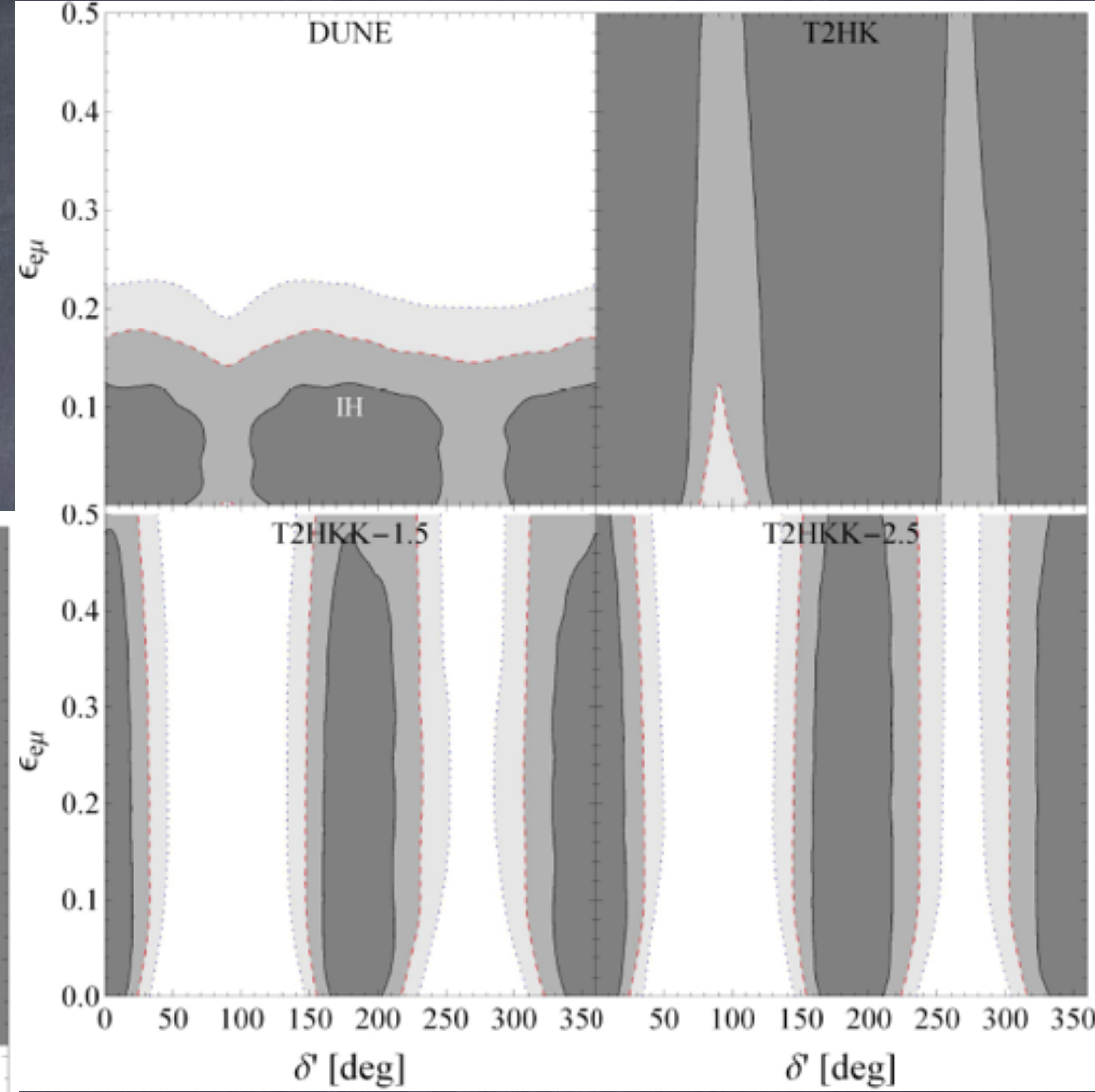
Hierarchy not resolved
Wrong determination of the CP phase possible

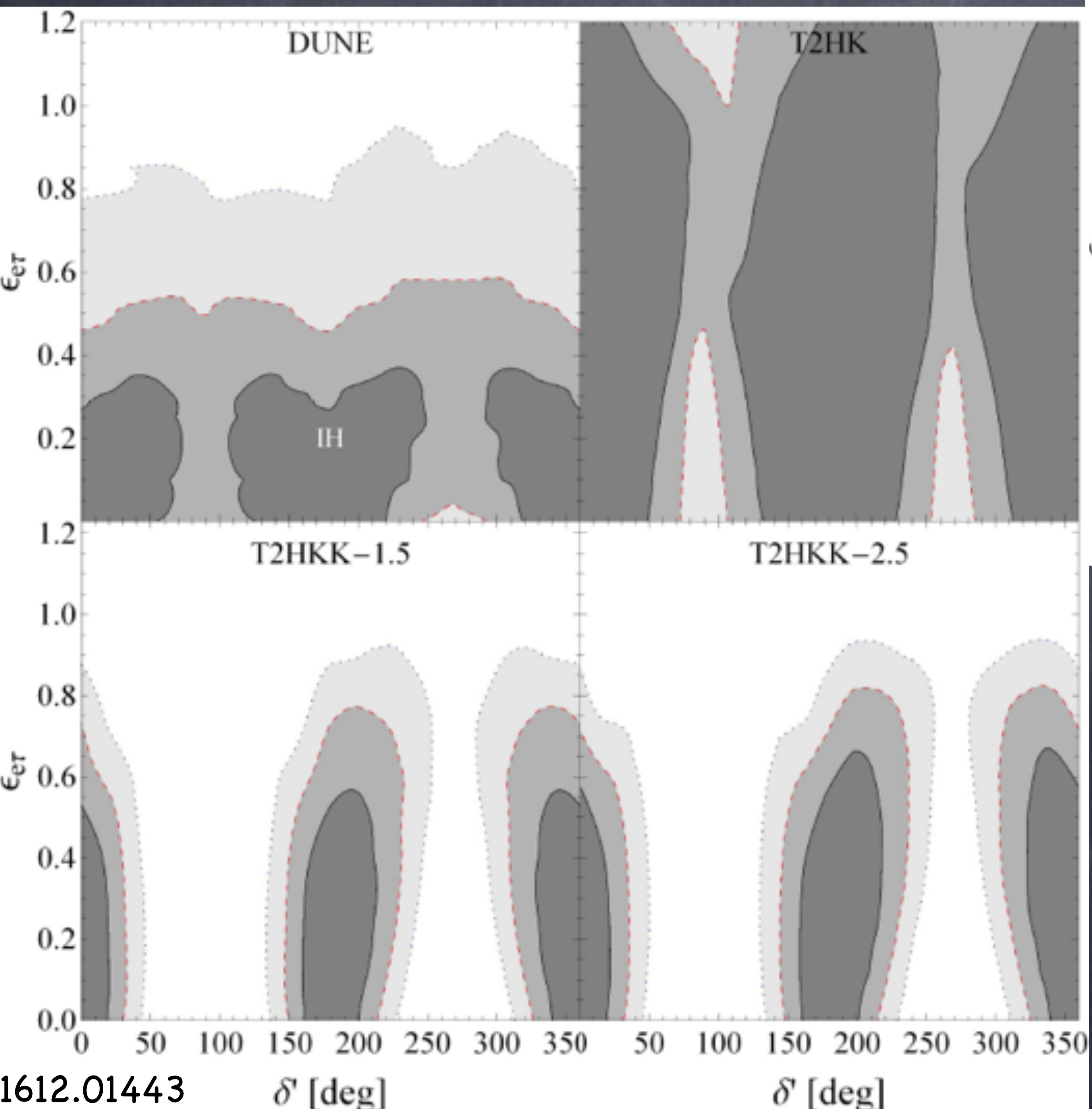
# 3 NSI parameters




1612.01443

Constraint on $\epsilon_{e\mu}$ much weaker at T2HK and T2HKK




1612.01443

$$\epsilon_{e\mu} = \tan\theta_{23}\epsilon_{e\tau}$$

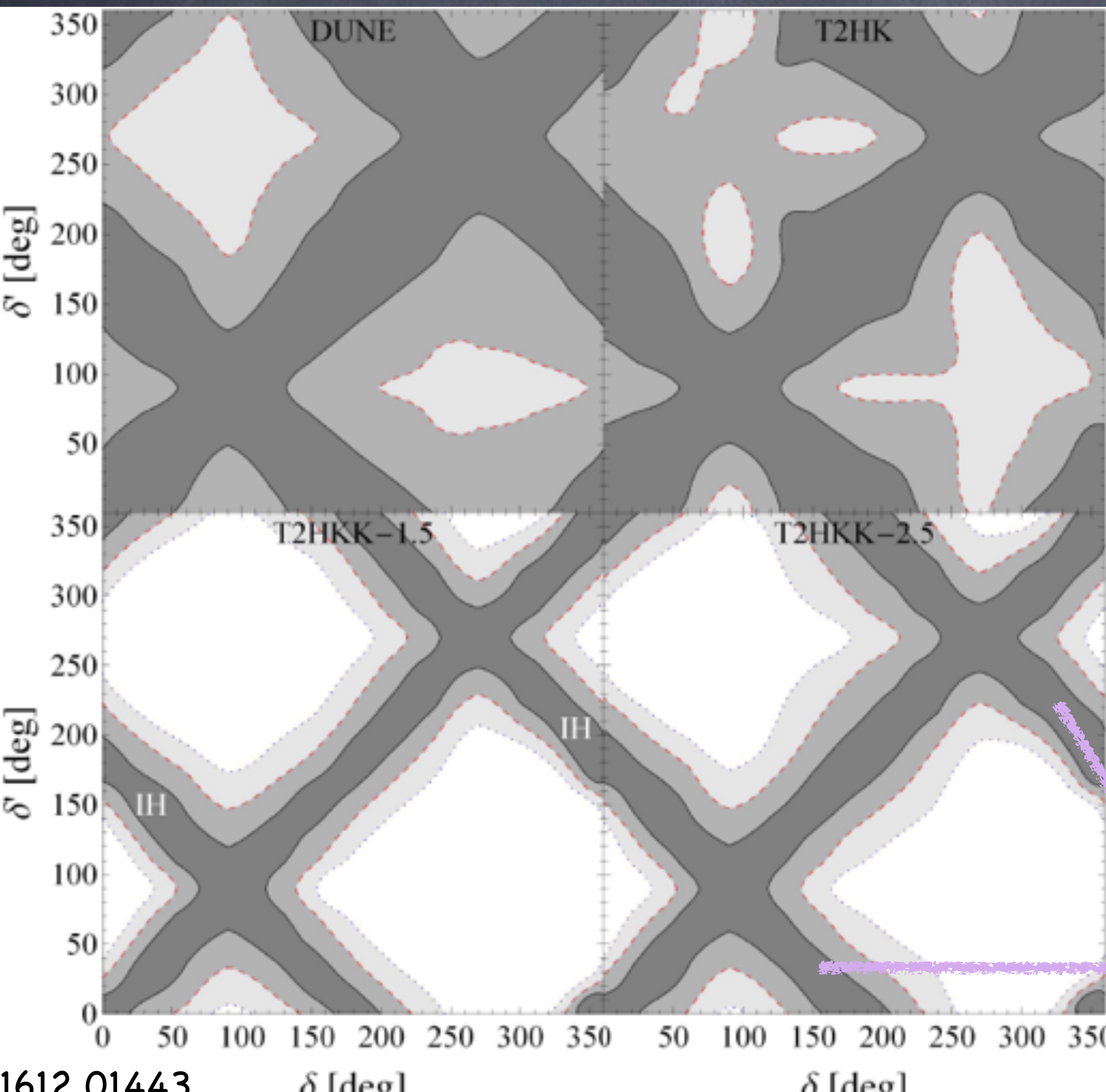
Degeneracy between NSI parameters unbroken at T2HK and T2HKK because of the lower energy J-PARC beam

# CP sensitivity

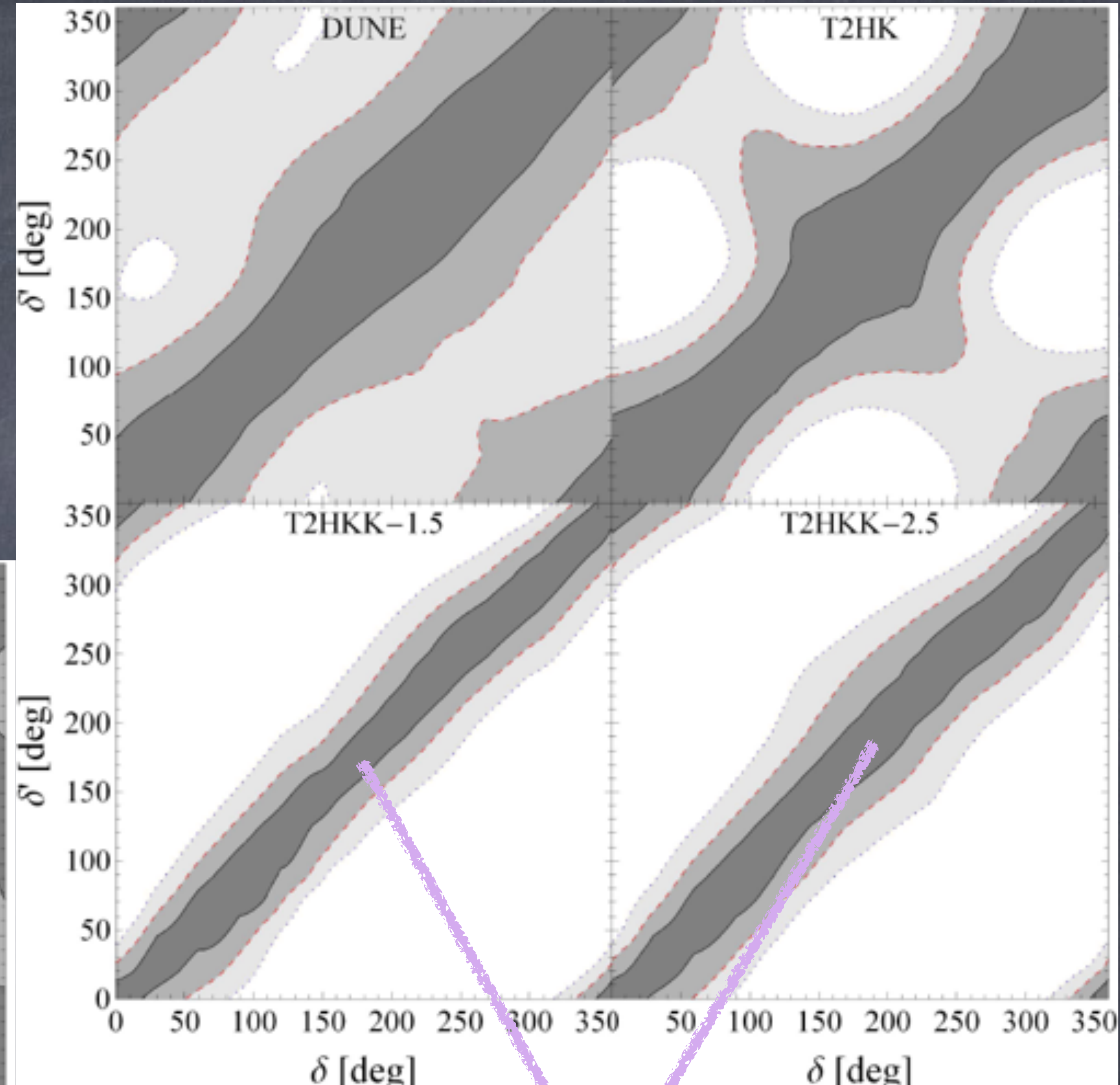
MH known

T2HKK better than DUNE for CP; is the only expt. that can measure the CP phase if MH is unknown

MH unknown




1612.01443




$\delta' = \delta$ holds when $\epsilon = 0$

IH and $\delta' = 180 - \delta$

# Sterile neutrino NSI

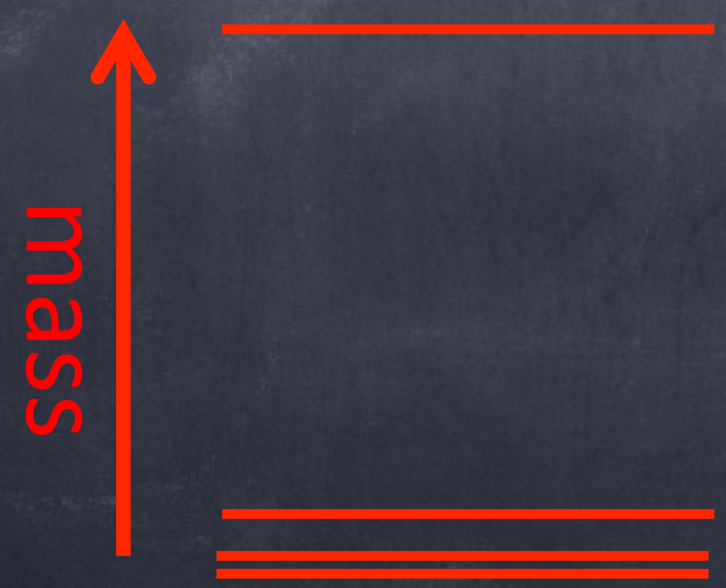
# LSND

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

Baseline: 30 m

Maximum energy: 53 MeV

$$L/E \sim 1 \text{ km/GeV} \implies \Delta m^2 \sim 1 \text{ eV}^2$$



# MiniBooNE

$$\nu_\mu \to \nu_e \qquad \bar{\nu}_\mu \to \bar{\nu}_e$$

Baseline: 500 m

Average energy: 800 MeV

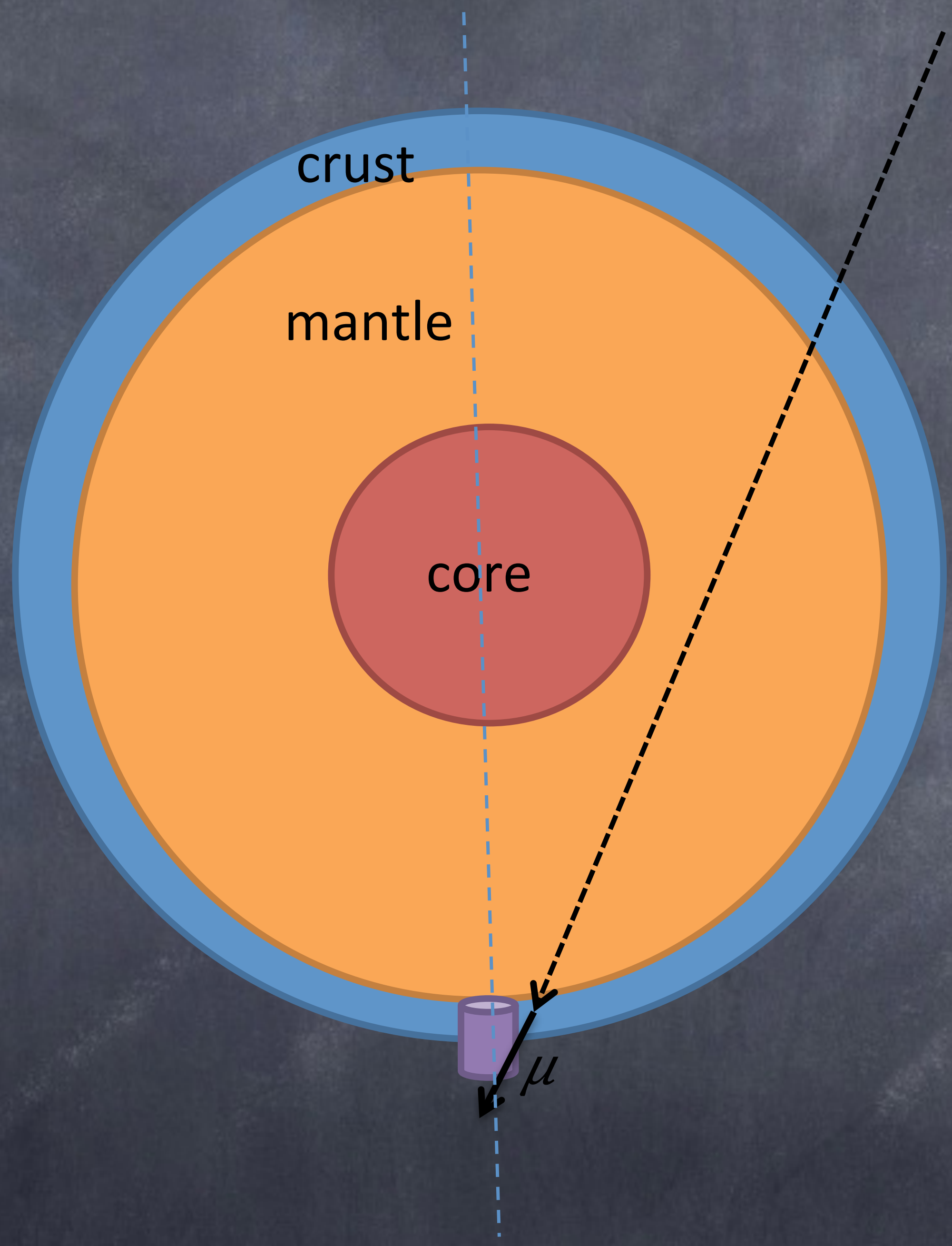
$$L/E \sim 1 \text{ km/GeV} \implies \Delta m^2 \sim 1 \text{ eV}^2$$

**LSND+MiniBooNE anomaly has 6.1 sigma significance**

Oscillation amplitude from global analysis:

$$\sin^2 2\theta_{14} \sin^2 \theta_{24} \sim 0.04 \sin^2 \theta_{24}$$

# IceCube




Focus on (anti)muon neutrino survival probabilities

# Resonant 3+1 atmospheric neutrino oscillations

Oscillation maximum in vacuum: $\frac{\Delta m^2}{\mathrm{eV}^2} \frac{L}{10^3\ \mathrm{km}} \frac{\mathrm{TeV}}{E} \sim 1$

Resonance condition in earth matter:

$$\Delta m^2_{41} \cos 2\theta_{24} \simeq \mp 1\ \mathrm{eV}^2\ \frac{E}{5\ \mathrm{TeV}}$$

Resonance occurs in antineutrino channel

# NSI in matter to the rescue?

- Model independent bounds from neutrino oscillation data allow large diagonal NSI parameters with O(1) differences between them

- COHERENT bounds obtained using contact approx don't apply for mediators lighter than 50 MeV

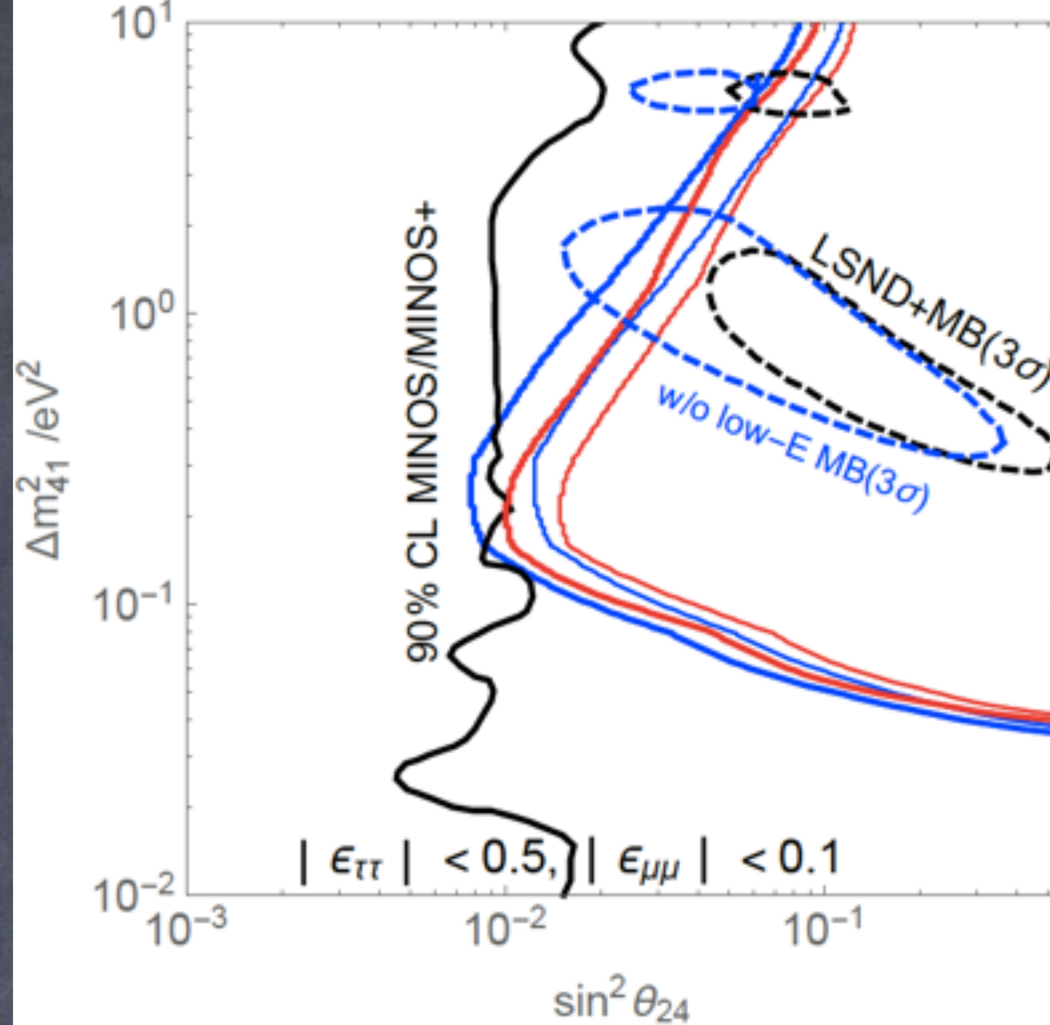
# 3+1 oscillations with NSI

$$H = \frac{\Delta m_{41}^2}{2E_\nu}\left[\begin{pmatrix} 0 & s_{24}s_{34} & s_{24}c_{34} \\ s_{24}s_{34} & s_{34}^2 & s_{34}c_{34} \\ s_{24}c_{34} & s_{34}c_{34} & c_{34}^2 \end{pmatrix} + \hat{A}\begin{pmatrix} \epsilon_{\mu\mu} & \epsilon_{\mu\tau} & 0 \\ \epsilon_{\mu\tau} & \epsilon_{\tau\tau} & 0 \\ 0 & 0 & \kappa \end{pmatrix}\right] + \mathcal{O}(s_{14}^2, s_{24}^2)$$

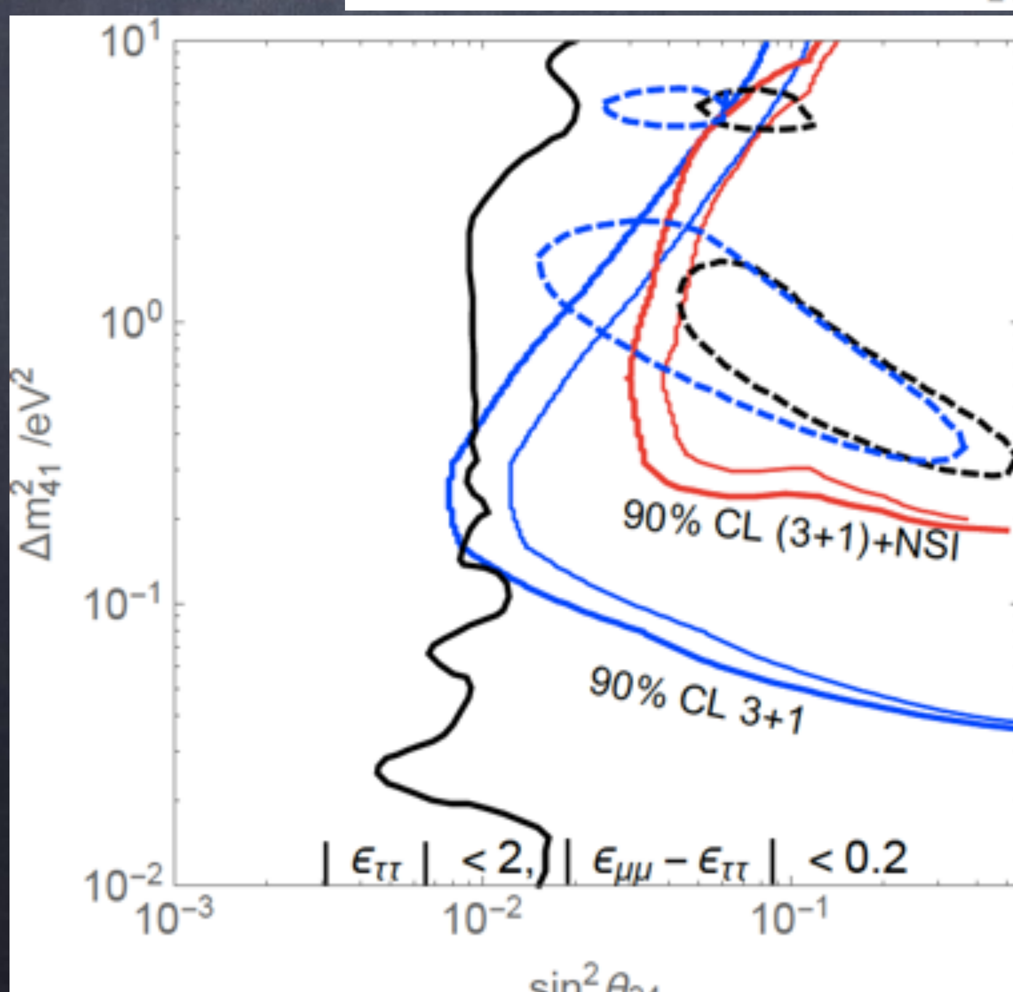
$$\hat{A} = \frac{2\sqrt{2}G_F N_e E_\nu}{\Delta m_{41}^2} \qquad \kappa = \frac{N_n}{2N_e} \simeq 0.5$$

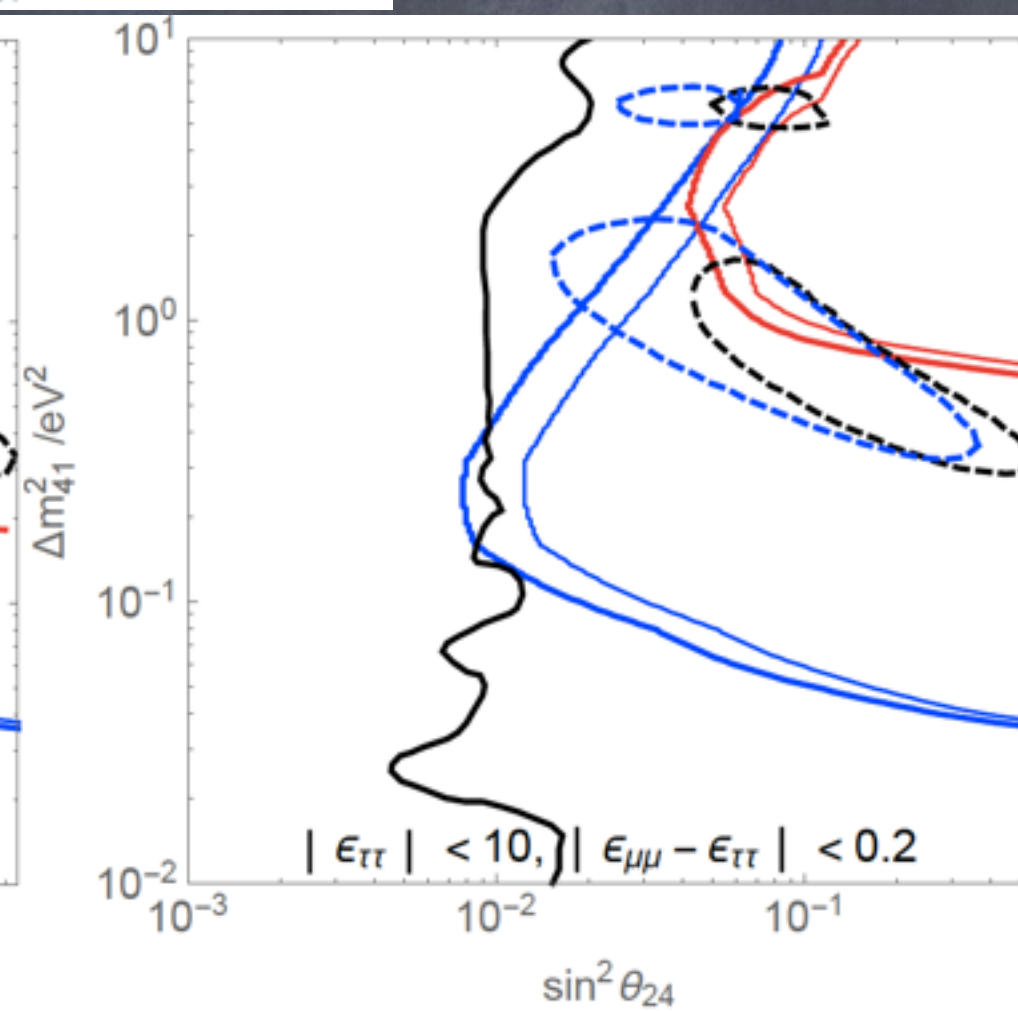
Special case: If the submatrix of NSI parameters is proportional to the identity, the NSI interaction can be attributed entirely to the sterile neutrino

# Bottomline:



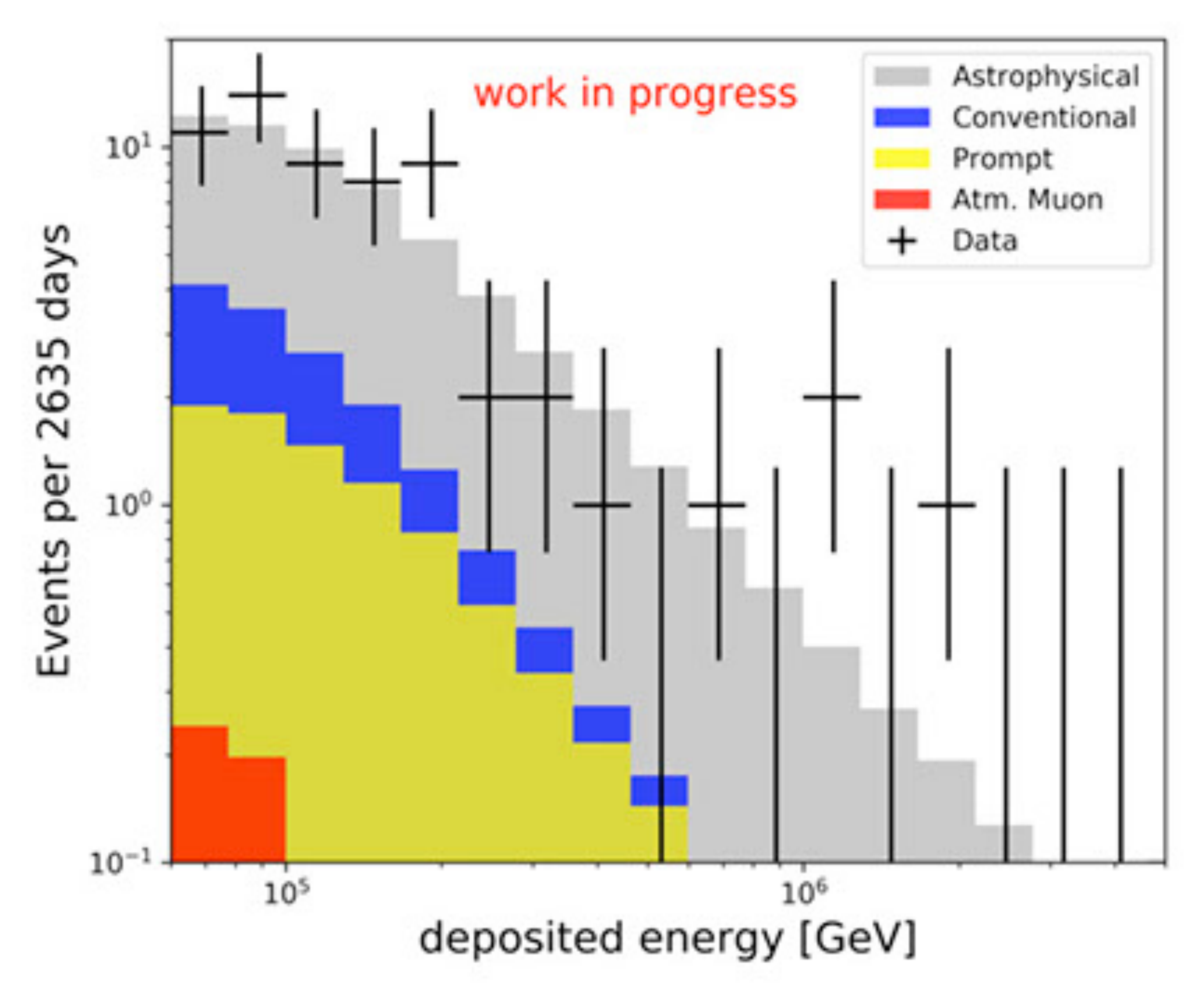

Adapted from 1602.08766, 1703.00860, 1710.06488, 1803.10661



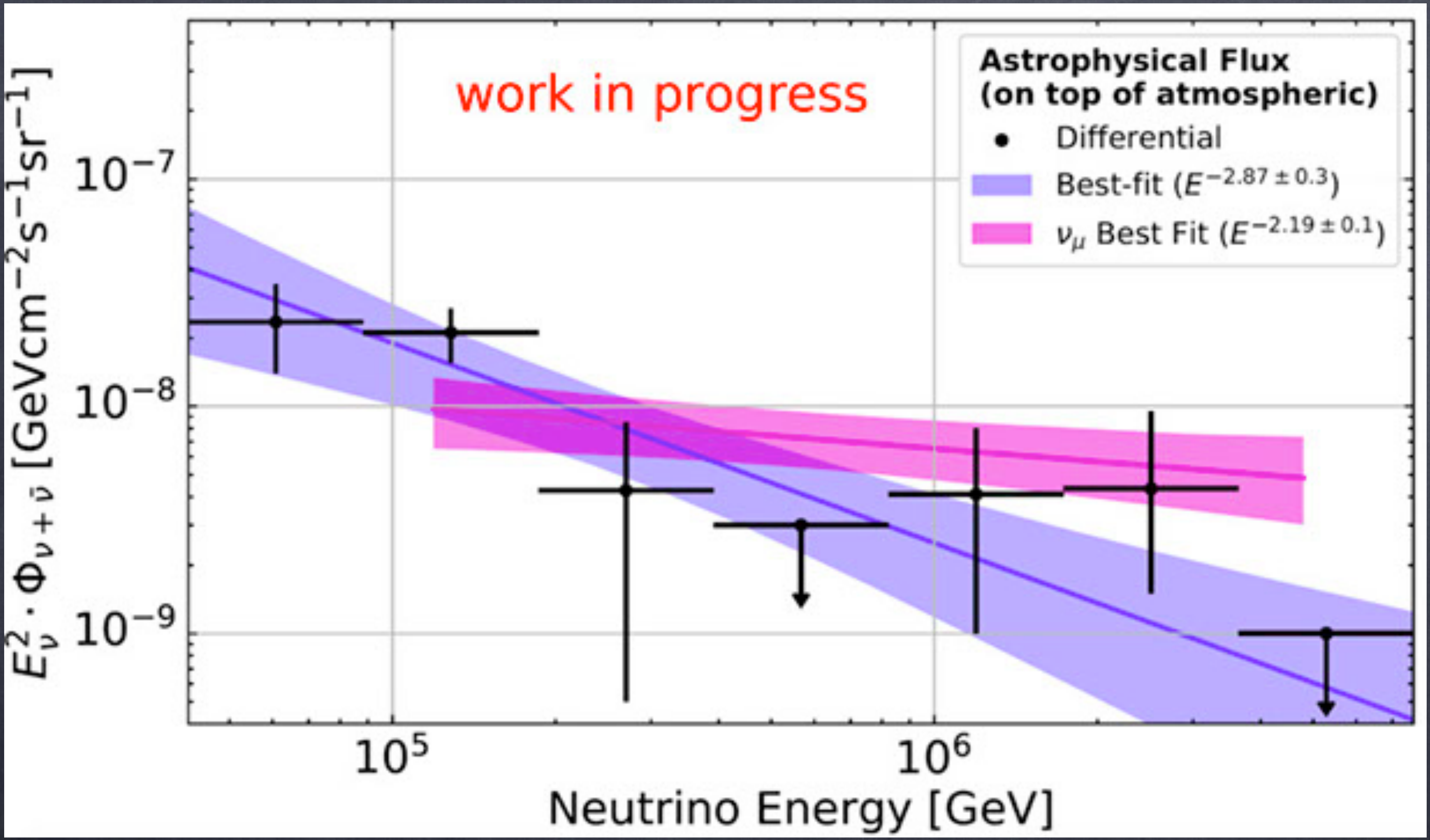



# LIV/CPTV interactions

# Cosmic neutrinos at IceCube




- 60 events with dep. energy > 60 TeV
- 3 cascade events between 1-2 PeV



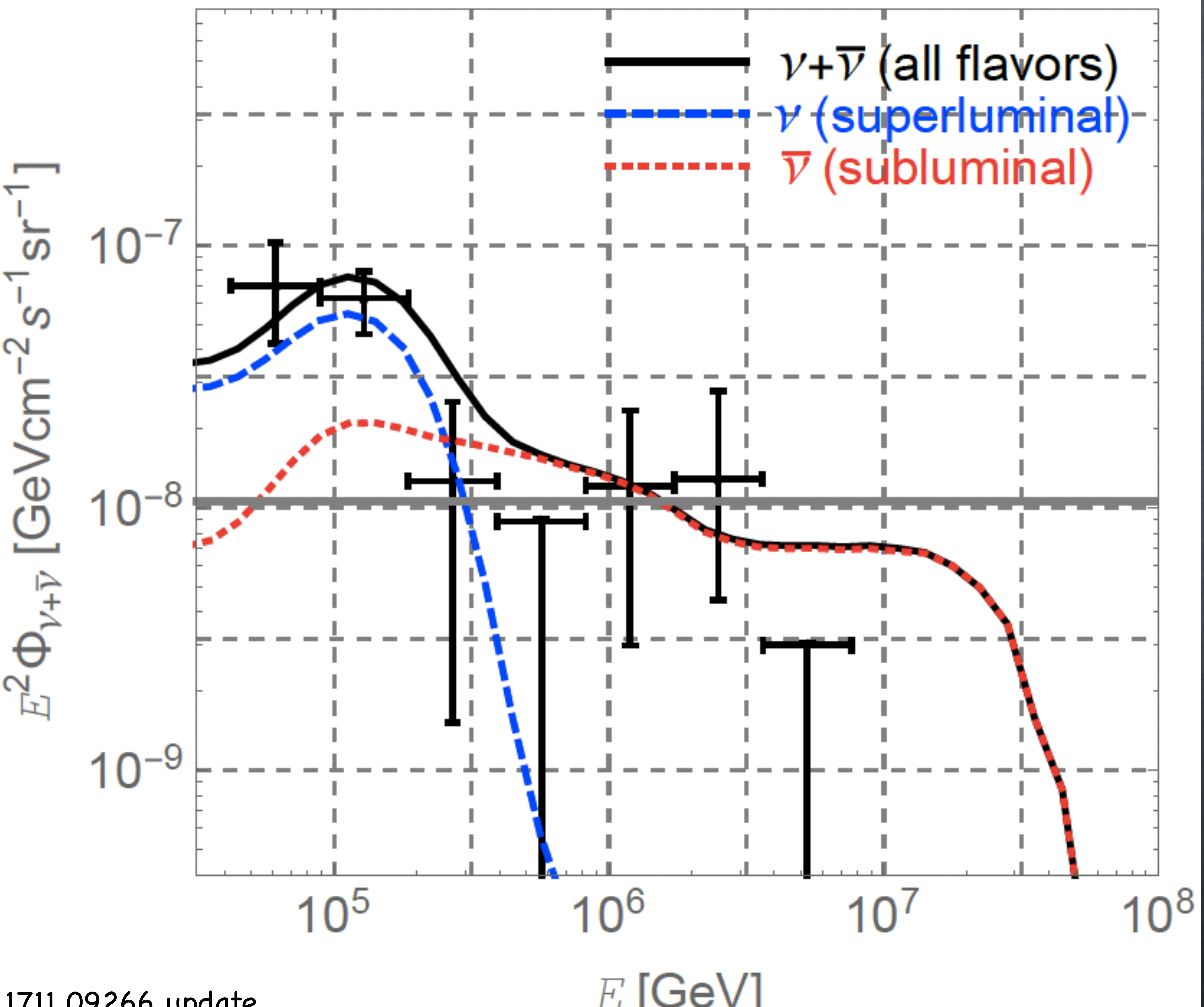

Upgoing muon neutrino spectrum (E > 120 TeV) harder than HESE spectrum

# One Glashow resonance event observed

$\bar{\nu}_e$ is unique because of resonant scattering at

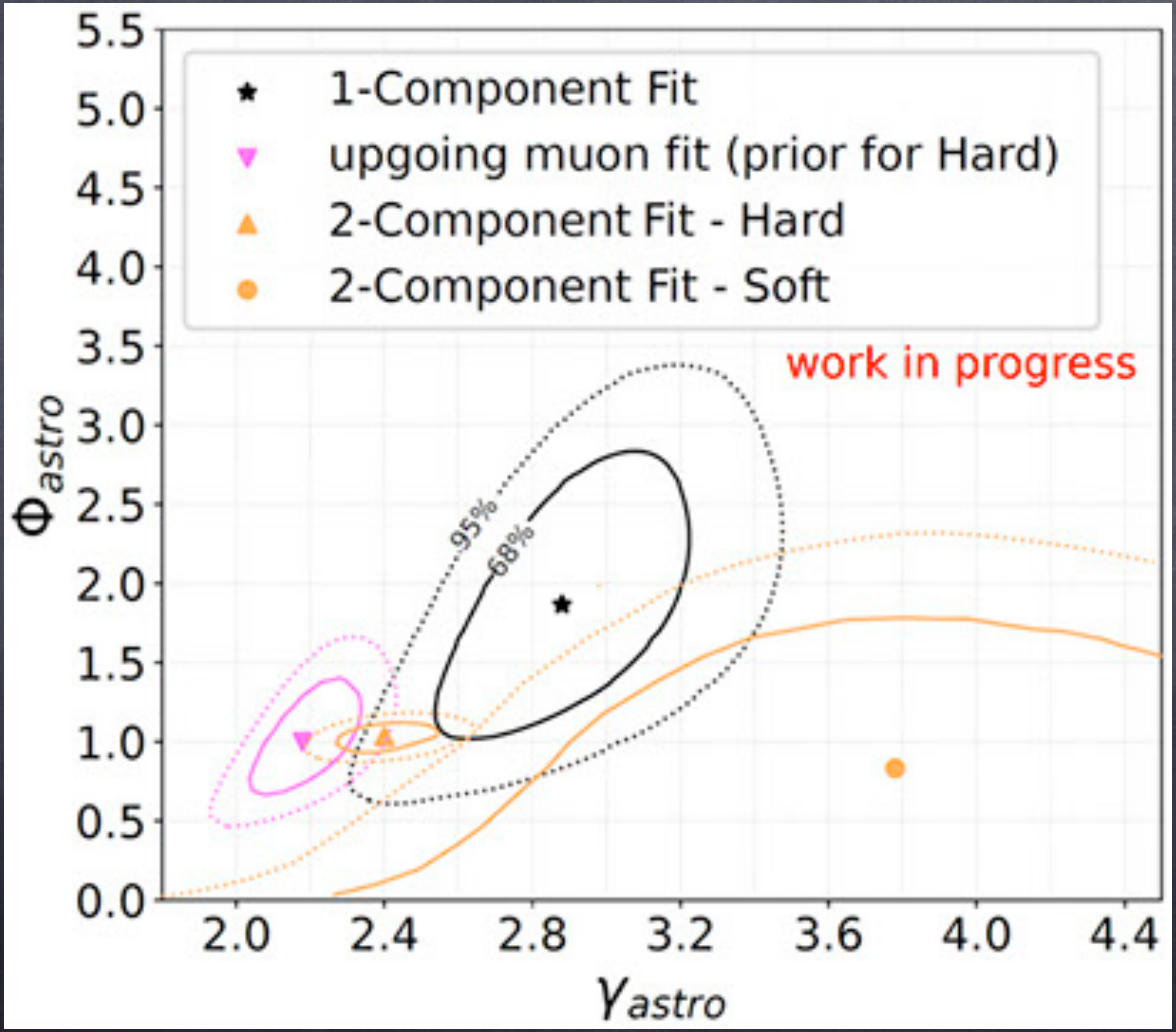
$$E_\nu = \frac{M_W^2}{2m_e} = 6.3 \text{ PeV}$$

$$\bar{\nu}_e e^- \to W^- \to \text{anything}$$




1711.09266 update

# Multicomponent flux?



# Lorentz and CPT violation?

- Suppose LIV and CPTV only occur in neutrino sector
- Only consider effects that change the kinematics of particle interactions
- Postulate that CPTV arises from Planck-suppressed terms in the Lagrangian

- Modified dispersion relation

$$E^2 - p^2 = m^2 + 2\delta E^2$$

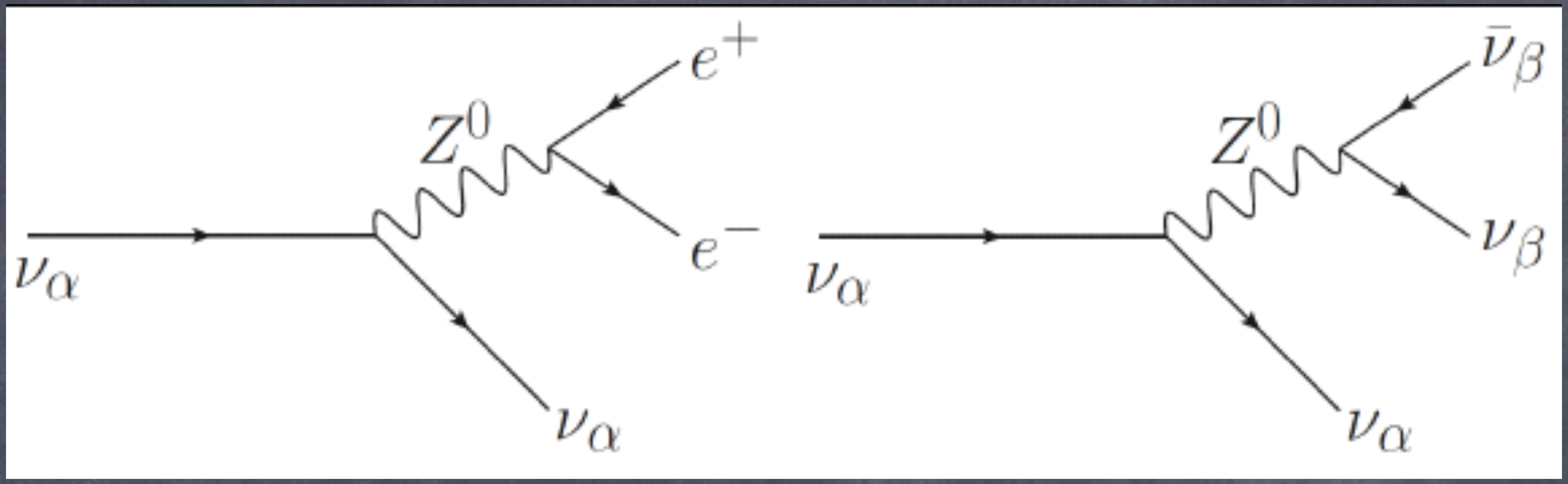
$$\delta = \kappa \frac{E}{M_{Pl}}$$

- Assume all neutrino flavors have same LIV parameter to be consistent with neutrino oscillation data

- Dispersion relation for antineutrinos: $\delta \to -\delta$

- Our choice $\delta > 0 \implies$ neutrinos are superluminal and antineutrinos are subluminal

- Dominant energy loss processes for superluminal neutrinos are vacuum pair emission (VPE) and neutrino splitting




- Event pile-up caused by neutrino splitting is larger than for VPE because splitting produces 2 additional lower energy neutrinos

$$\Gamma \propto \kappa^3 \frac{G_F^2 E^8}{M_{Pl}^3}$$

## Effect on neutrino sources?

$\pi^+ \rightarrow \mu^+ \nu_\mu$ imposes an upper bound on the energy of superluminal neutrinos:

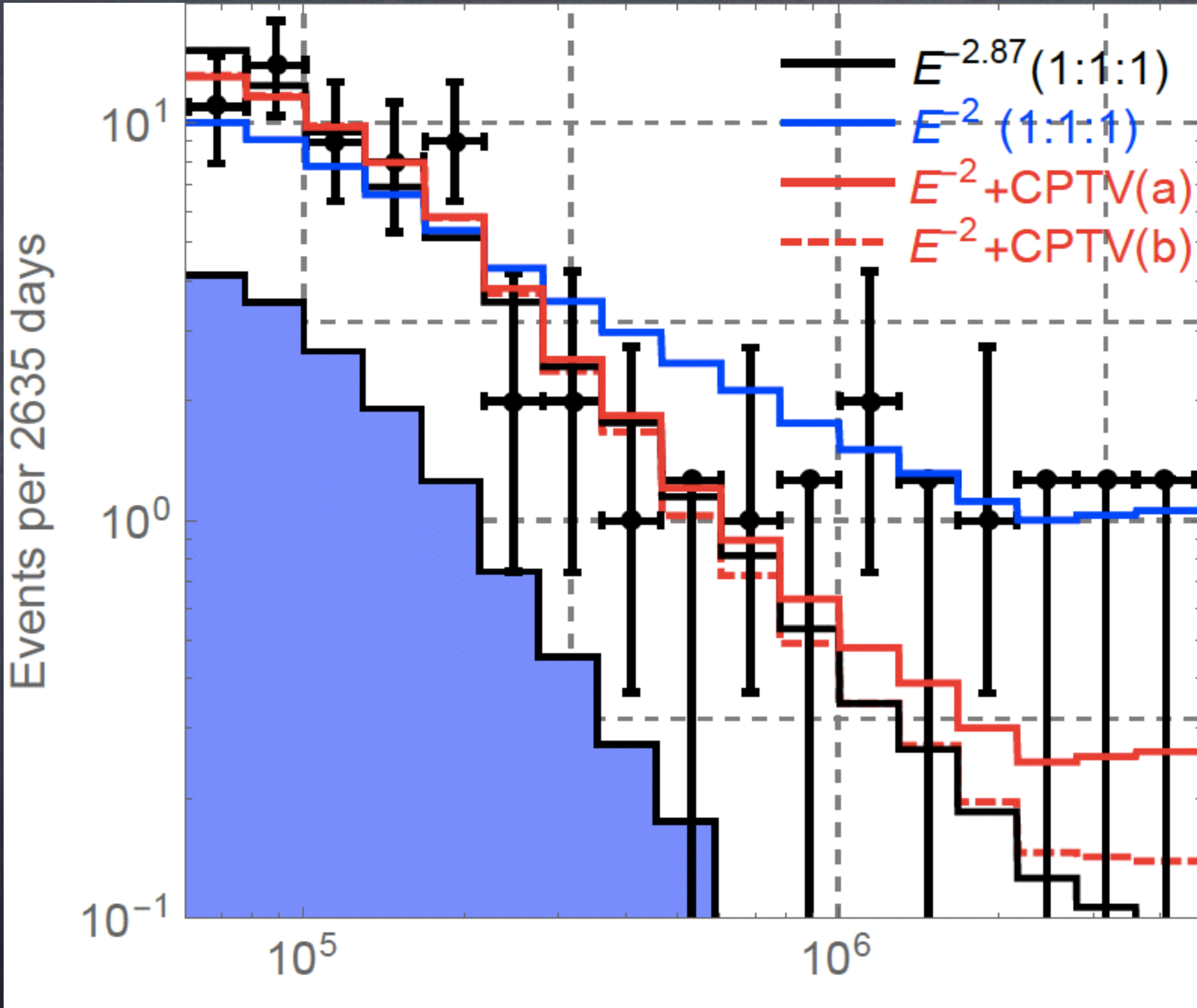
$$E^3 \leq \frac{(m_\pi - m_\mu)^2 M_{Pl}}{2\kappa}$$

VPE occurs above an energy threshold given by

$$E_{th}^3 = \frac{2m_e^2 M_{Pl}}{\kappa}$$

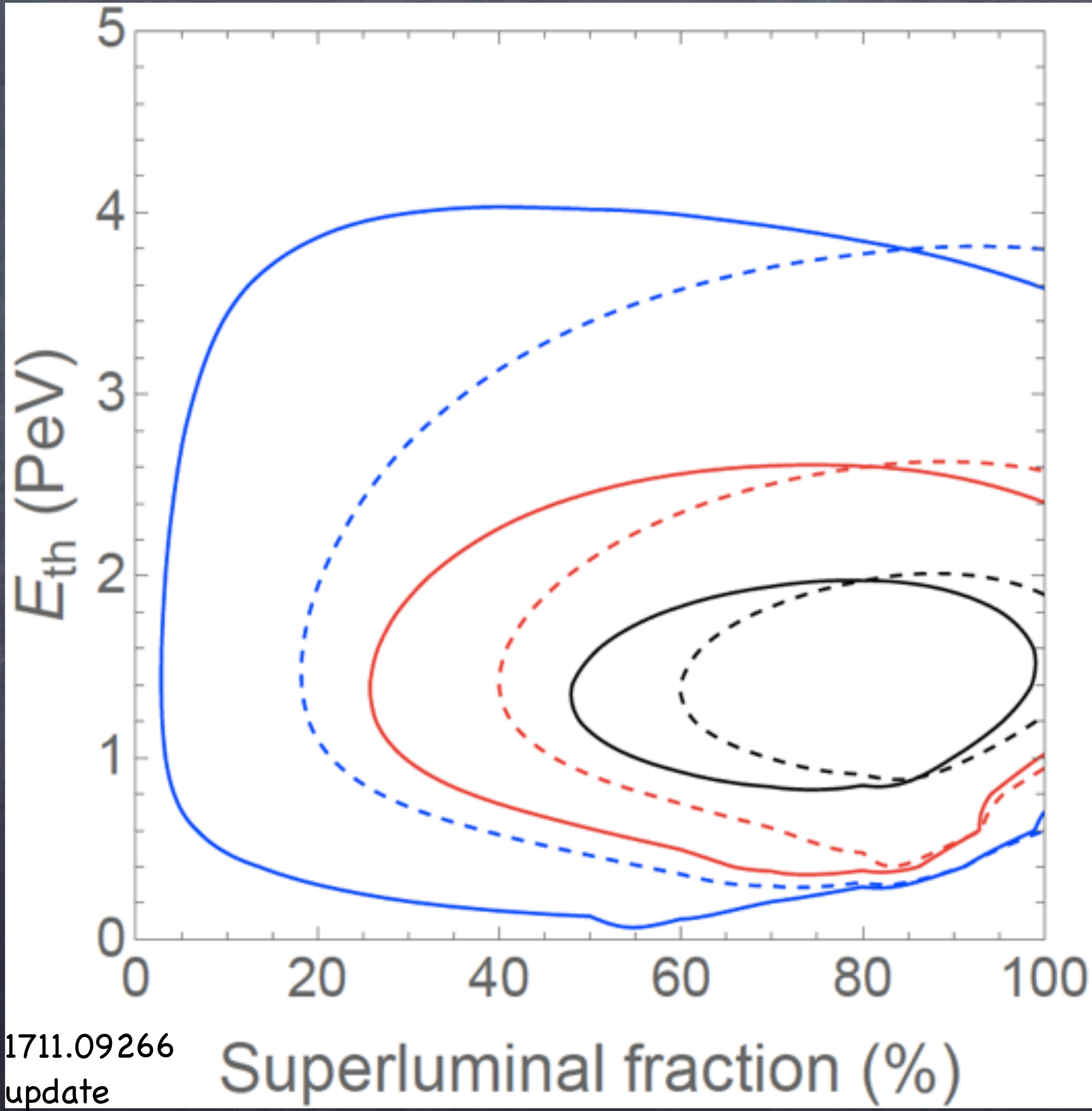
For a given VPE threshold energy, the upper bound on the superluminal neutrino energy is

$$E < 10.3 E_{th}$$

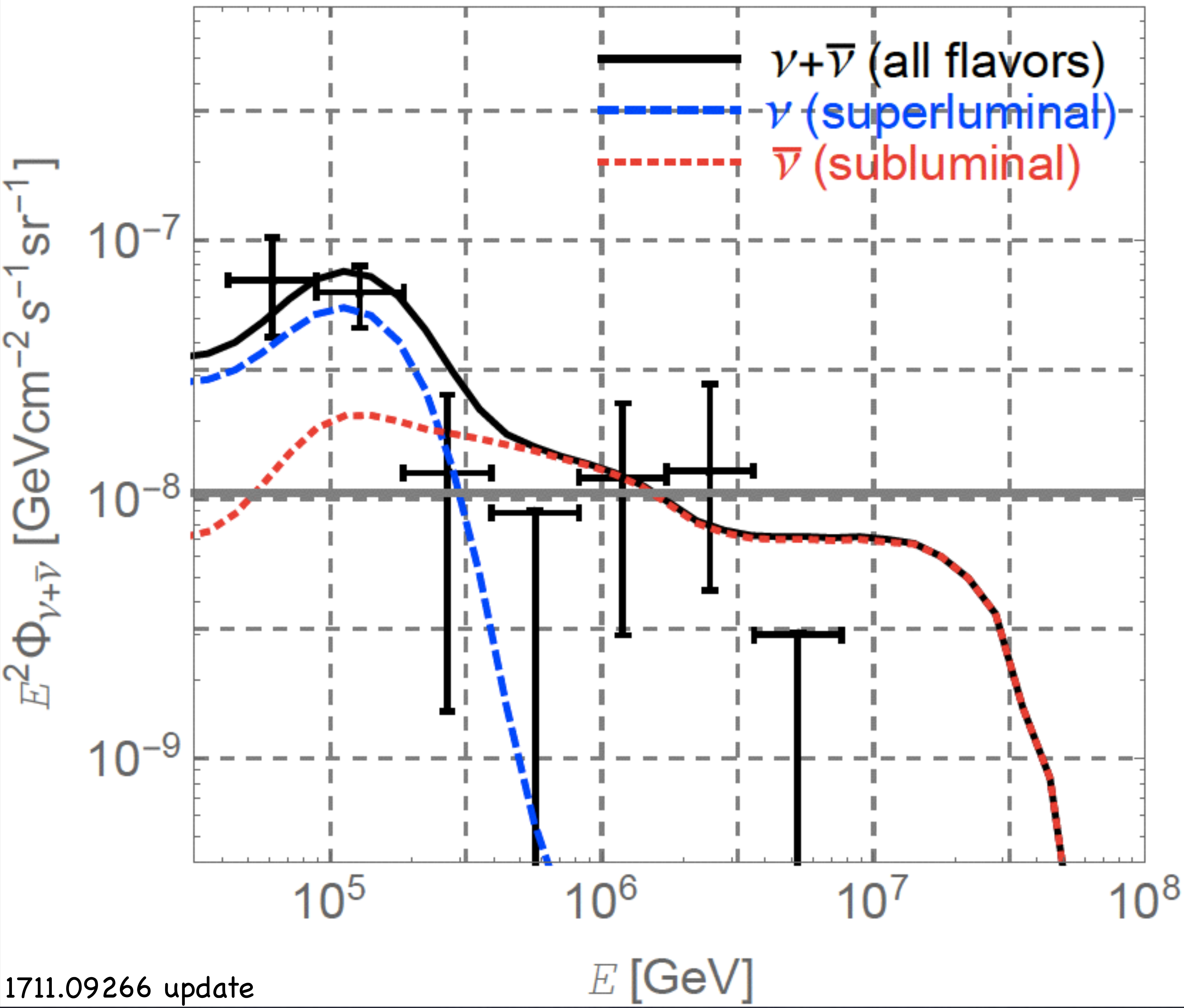



1711.09266 update

| | $E^{-2.87}(1:1:1)$ | | $E^{-2}(1:1:1)$ | | $E^{-2}$ with CPTV | |
|---|---|---|---|---|---|---|
| Case | (a) | (b) | (a) | (b) | (a) | (b) |
| $\chi^2$ | 16.0 | 16.6 | 24.9 | 30.7 | 13.0 | 14.5 |
| GR events | 0.20 | 0.20 | 3.2 | 2.8 | 0.95 | 0.48 |



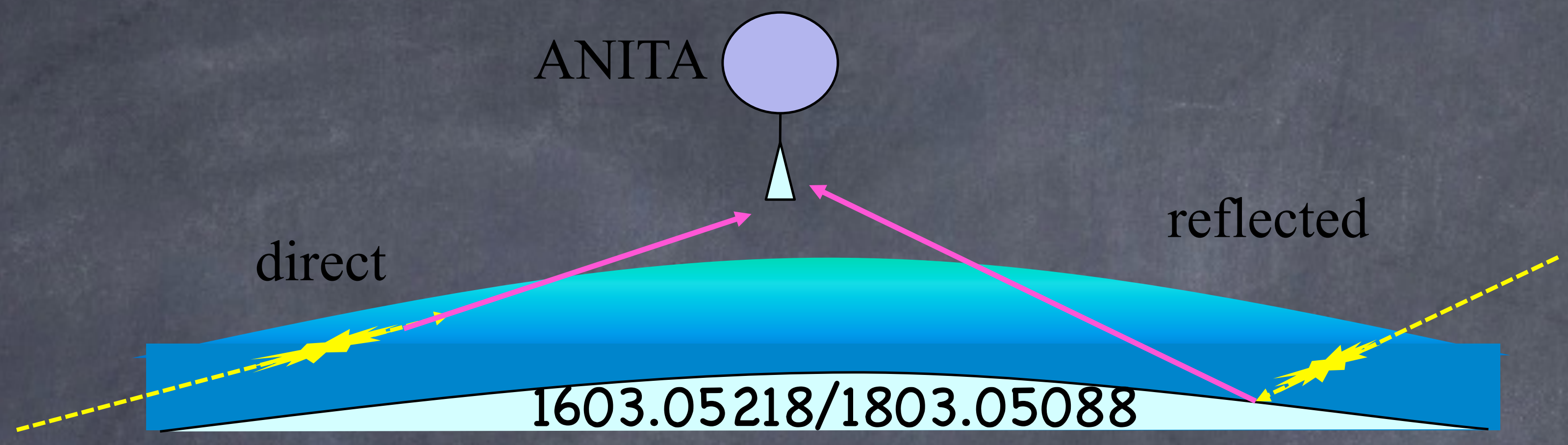

Superluminal fraction compatible with $\pi^-$ contamination




1711.09266 update

# Interactions with dark matter

# Has ANITA seen two 600 PeV tau events?



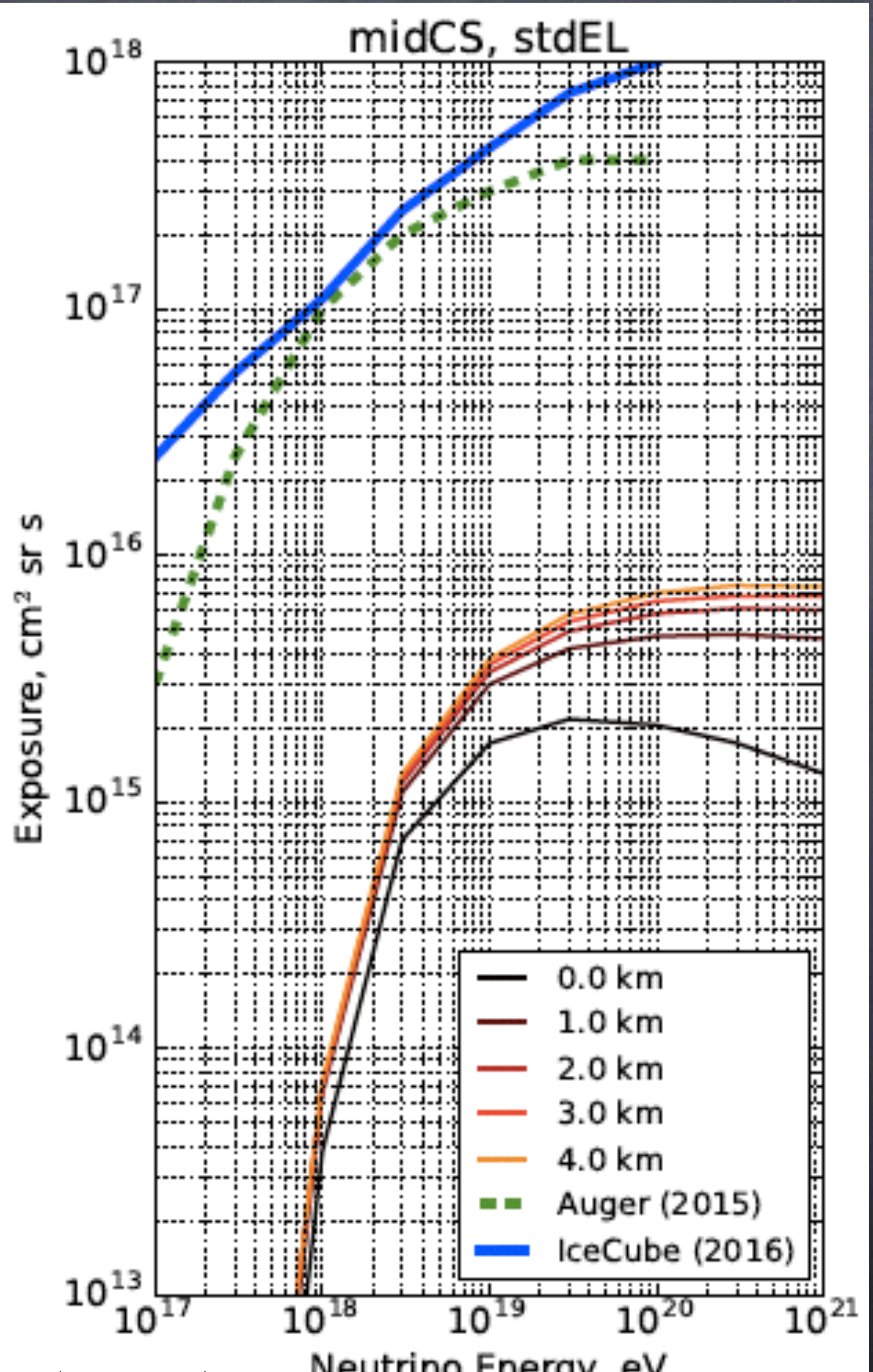

- 0.6 EeV events arrived at ~ 30 degs. above the horizon

- Polarity and plane of polarization consistent with air showers seen directly w/o the reflection phase inversion

- Could be tau lepton initiated air showers

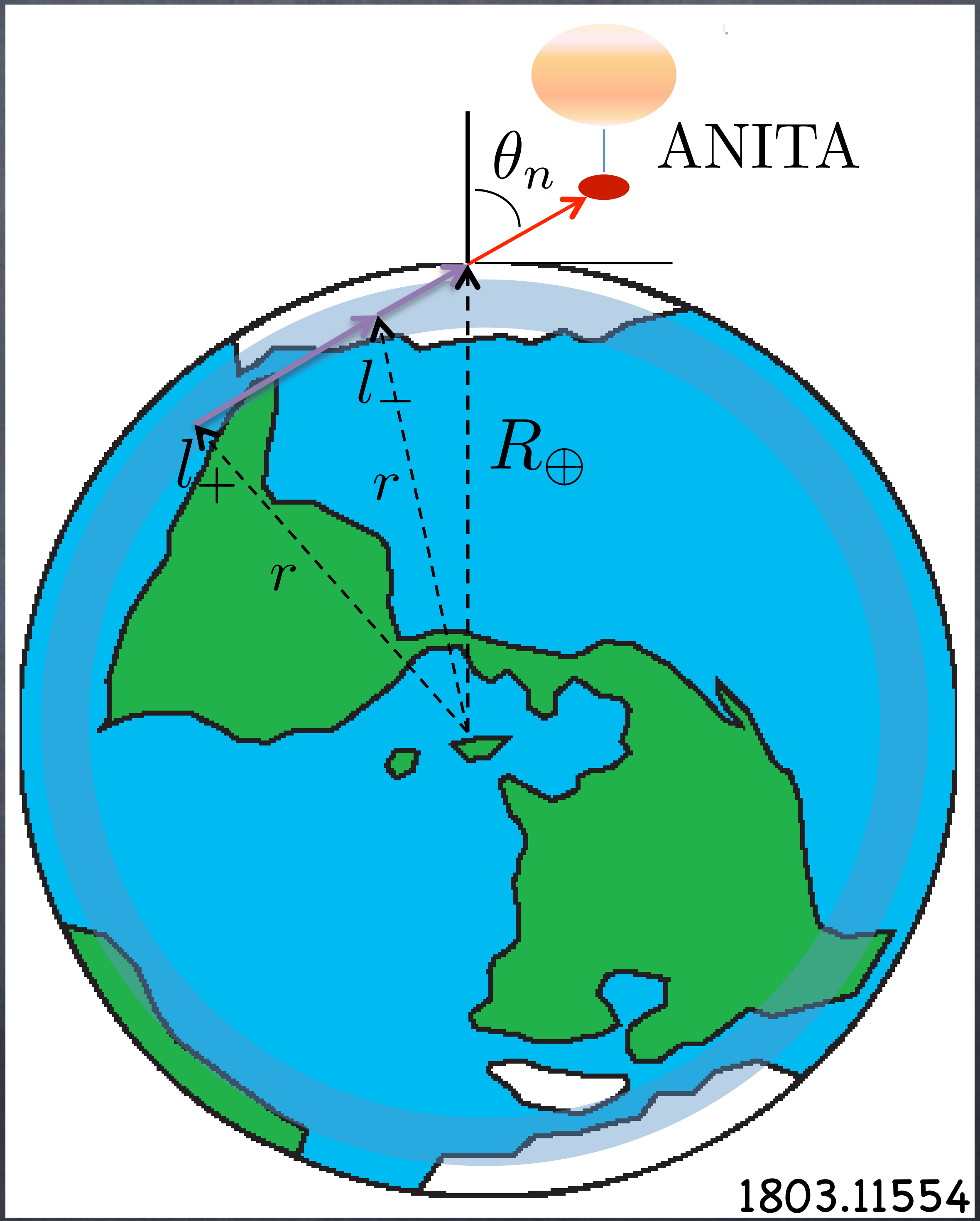
- But, propagating chord distance is 10-12 interaction lengths at 0.6 EeV

- ANITA (solid angle integrated) exposure is 60 times smaller than Auger/IceCube exposure
- Problems solved if source is inside the Earth
- Heavy right-handed neutrino (dark matter) decays to Higgs and light neutrino
- Lifetime > 10^(29.5) s




PoS(ICRC2017)935

- Event distribution maximized at 60 deg nadir angle by combination of ANITA's efficiency and DM distribution in Earth
- Atypical DM distribution required
- CPT symmetric universe has 480 PeV right-handed neutrino as DM candidate



# Summary

- At LBL expts, degeneracies between SM and NSI parameters, and between NSI parameters strongly affect sensitivities
- If $\epsilon_{ee} - \epsilon_{\mu\mu}$ is O(1), impossible to determine hierarchy at oscillation experiments
- DUNE has best sensitivity to NSI
- T2HKK has best sensitivity to CP phase in the presence of NSI

- LSND/MiniBooNE is consistent with IceCube in a (3+1)+NSI model if the NSI parameters only obey model-independent bounds; NSI can be attributed entirely to sterile neutrino

- Can survive MINOS/MINOS+ bound only if systematics underestimated a la 1803.11488

- Features in IceCube's cosmic neutrino spectrum may be hint of new physics

- If ANITA's events are initiated by neutrinos, radical explanations may be needed