भौतिक अनुसंधान प्रयोगशाला Physical Research Laboratory

Current Status of Neutrino Anomalies

Srubabati Goswami

Physical Research Laboratory, Ahmedabad, India

Anomalies 2020

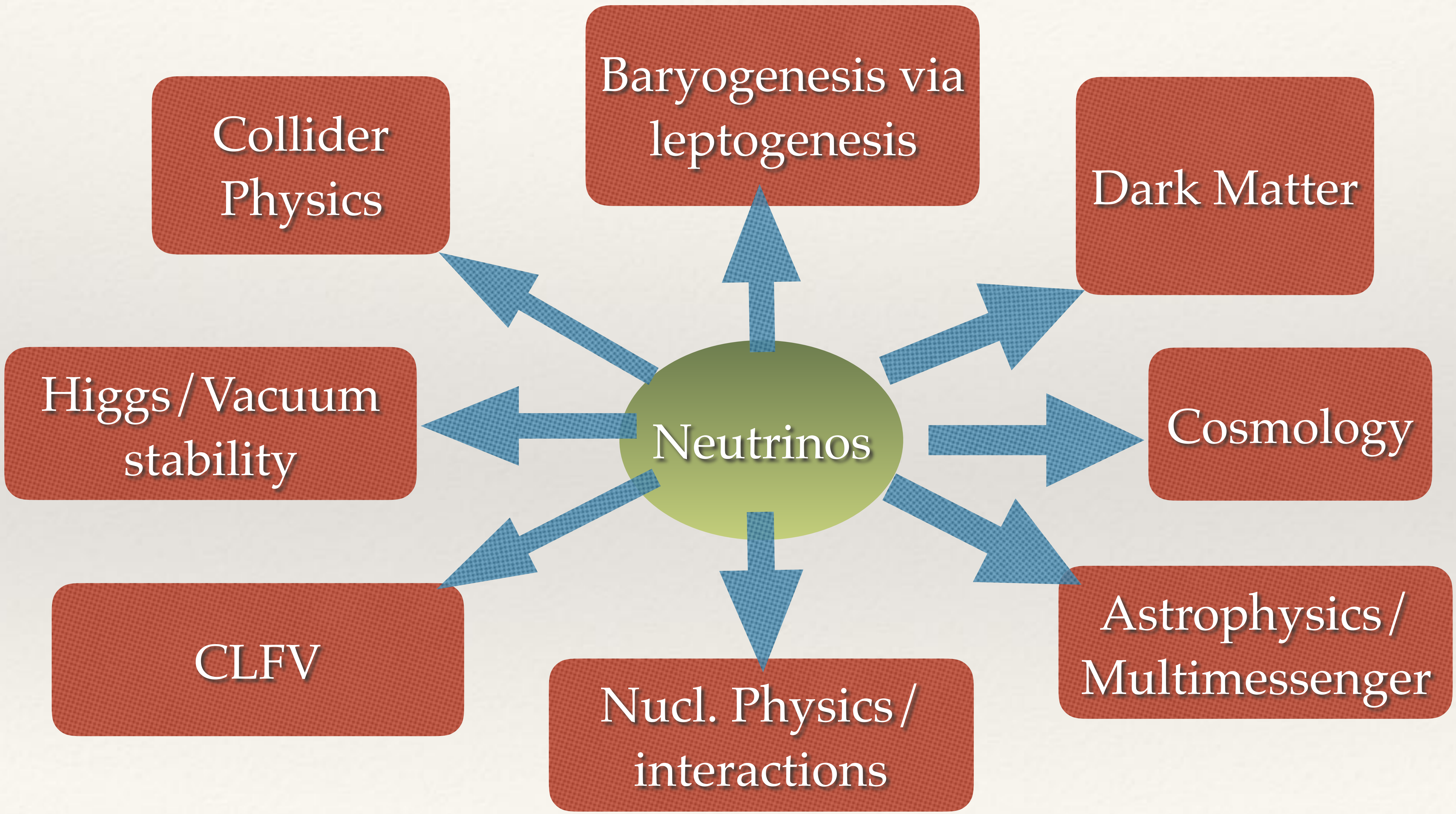
Is it a monument, a madrasa or a market square? Charminar holds many mysteries within its fold

https://www.thehindu.com/society/history-and-culture/the-very-many-mysteries-of-hyderabads-charminar/article24311906.ece

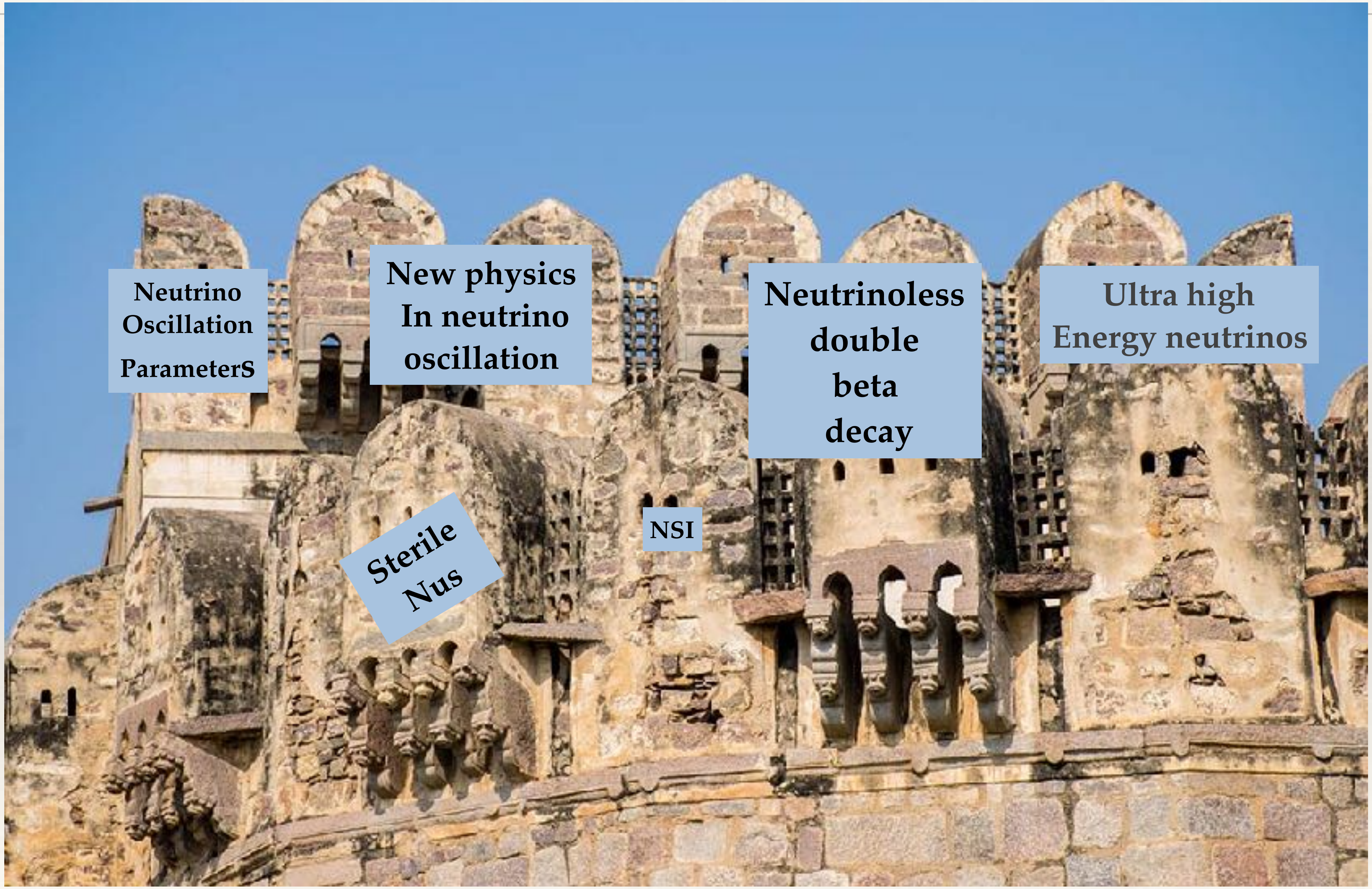
Neutrino: many questions

- What Unknown oscillation parameters - hierarchy, octant of 2-3 mixing angle and CP phase
- Absolute neutrino masses — beta decay, cosmology
- Nature of neutrinos - Dirac or Majorana — neutrino less double beta decay
- Are there more than three flavours — sterile neutrinos
- Origin of neutrino masses and mixing — seesaw , flavour symmetry — physics beyond Standard Model

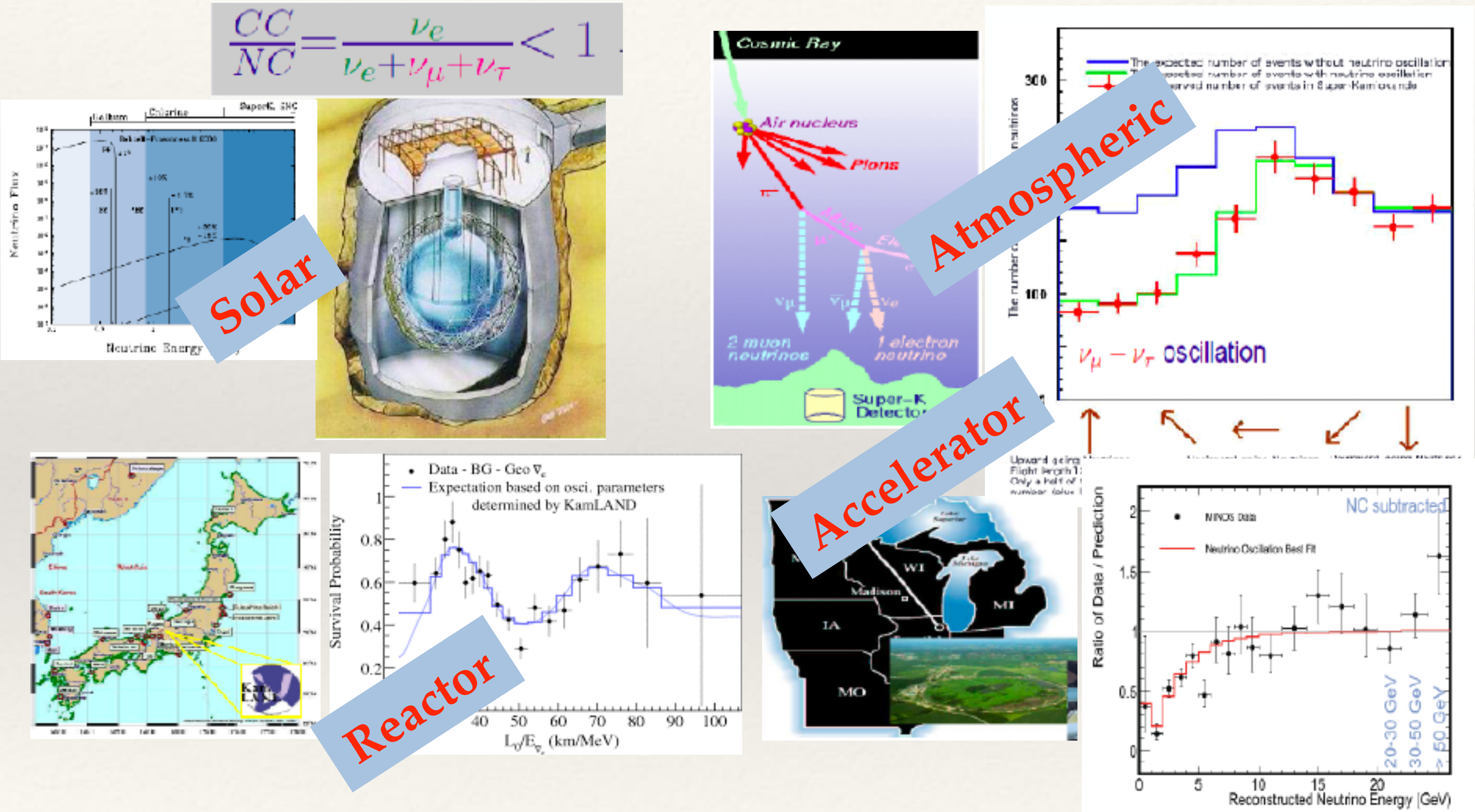
Neutrino Connections



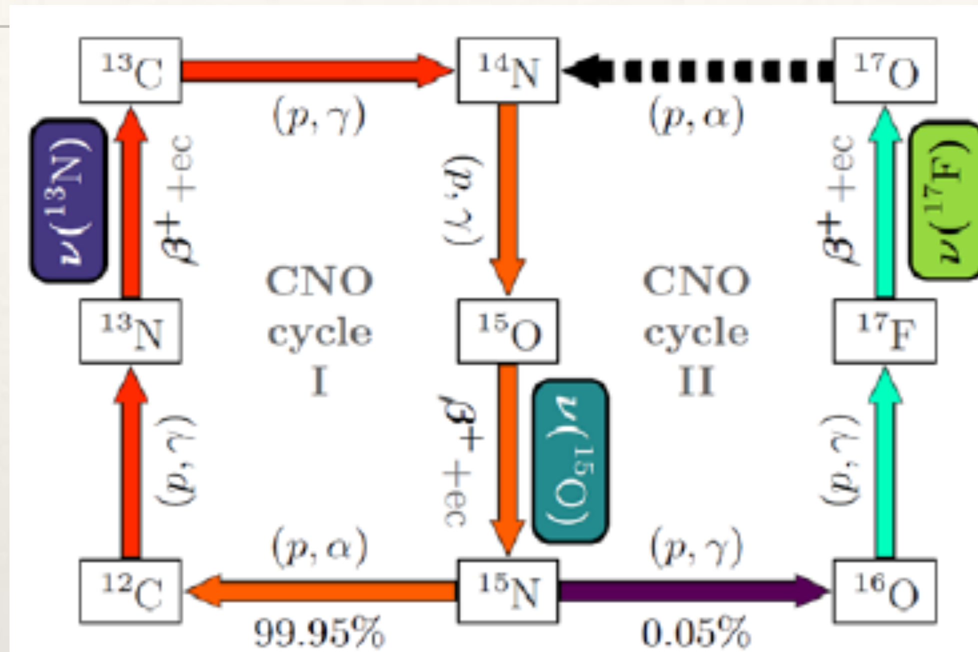
Plan of talk

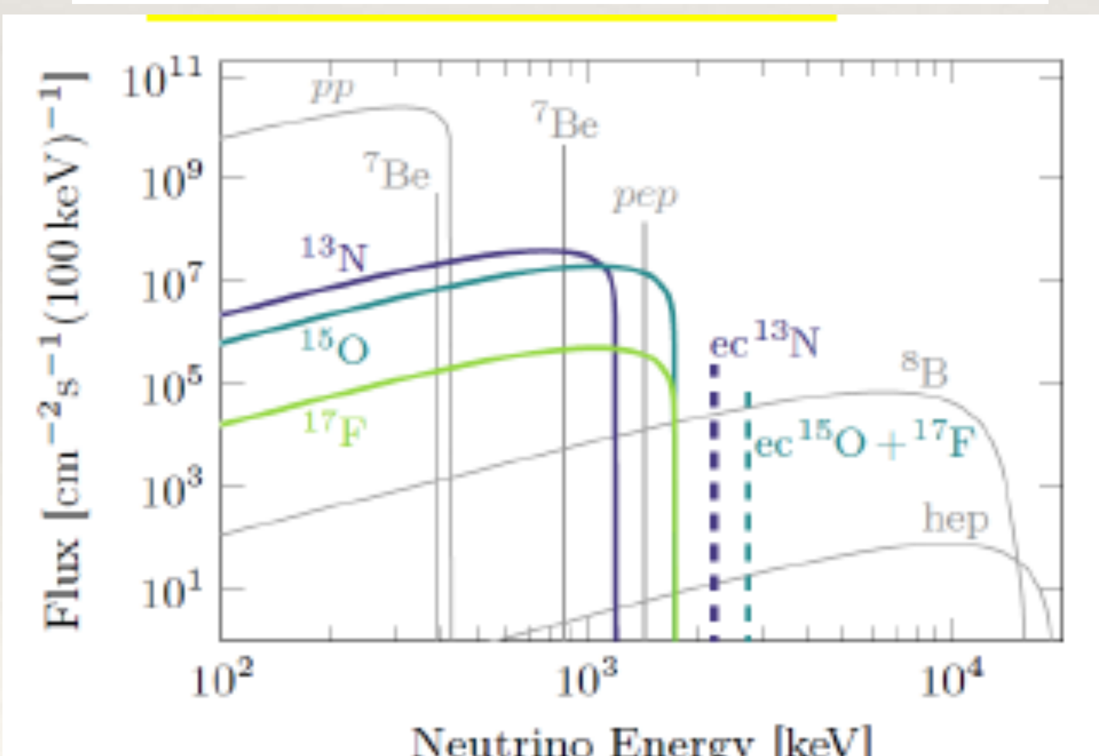

Neutrino
Oscillation
ParameterS
New physics
In neutrino
oscillation
Neutrinoless
double
beta
decay
Ultra high
Energy neutrinos
Sterile
Nus
NSI

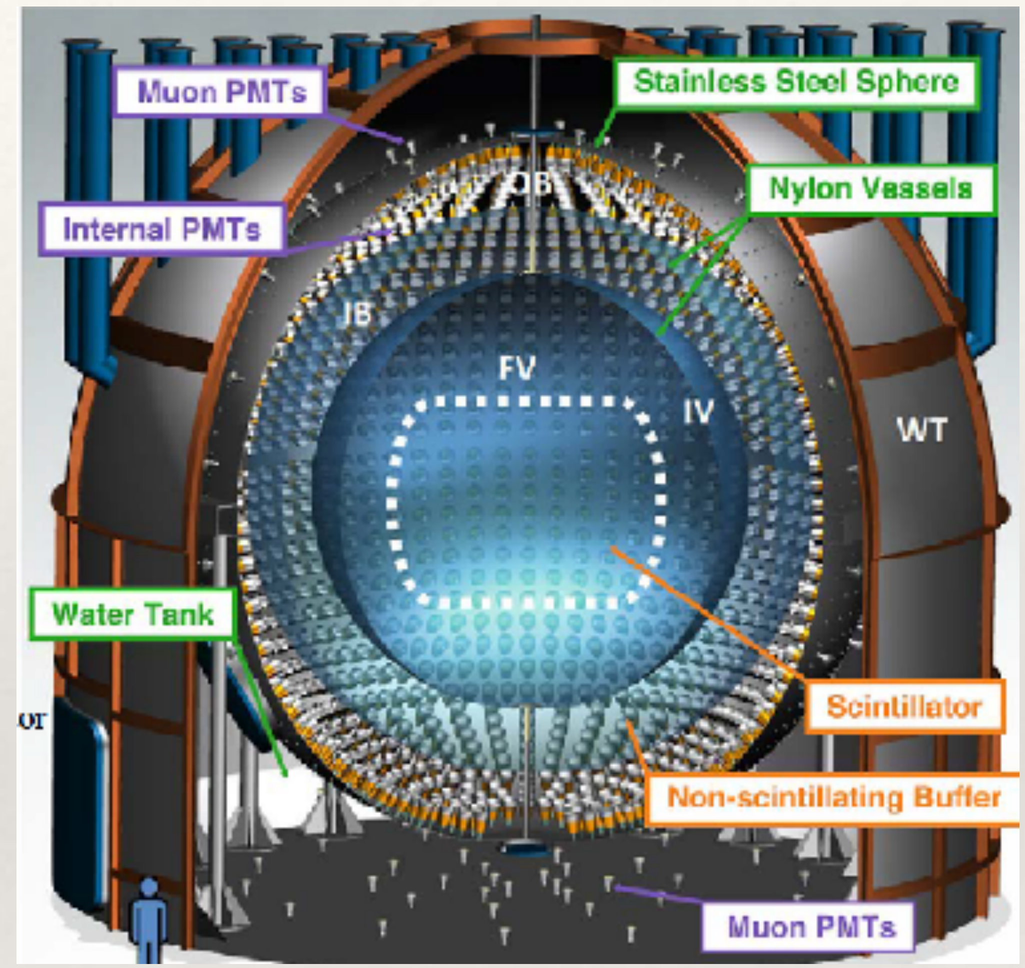
Neutrino Oscillations



New result from Borexino

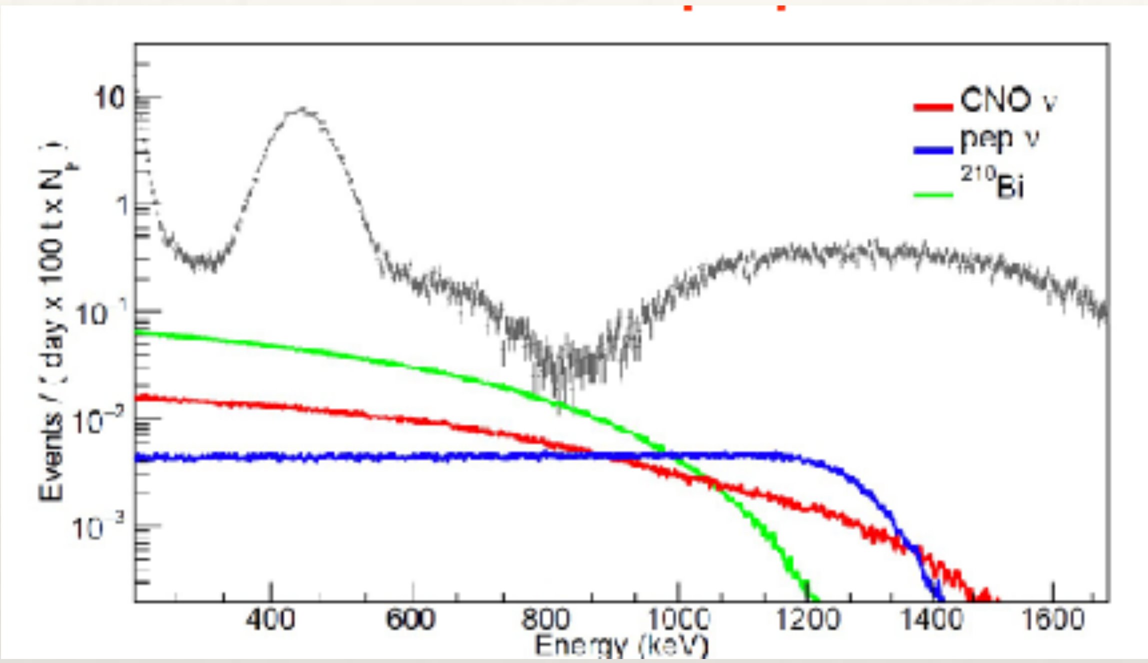




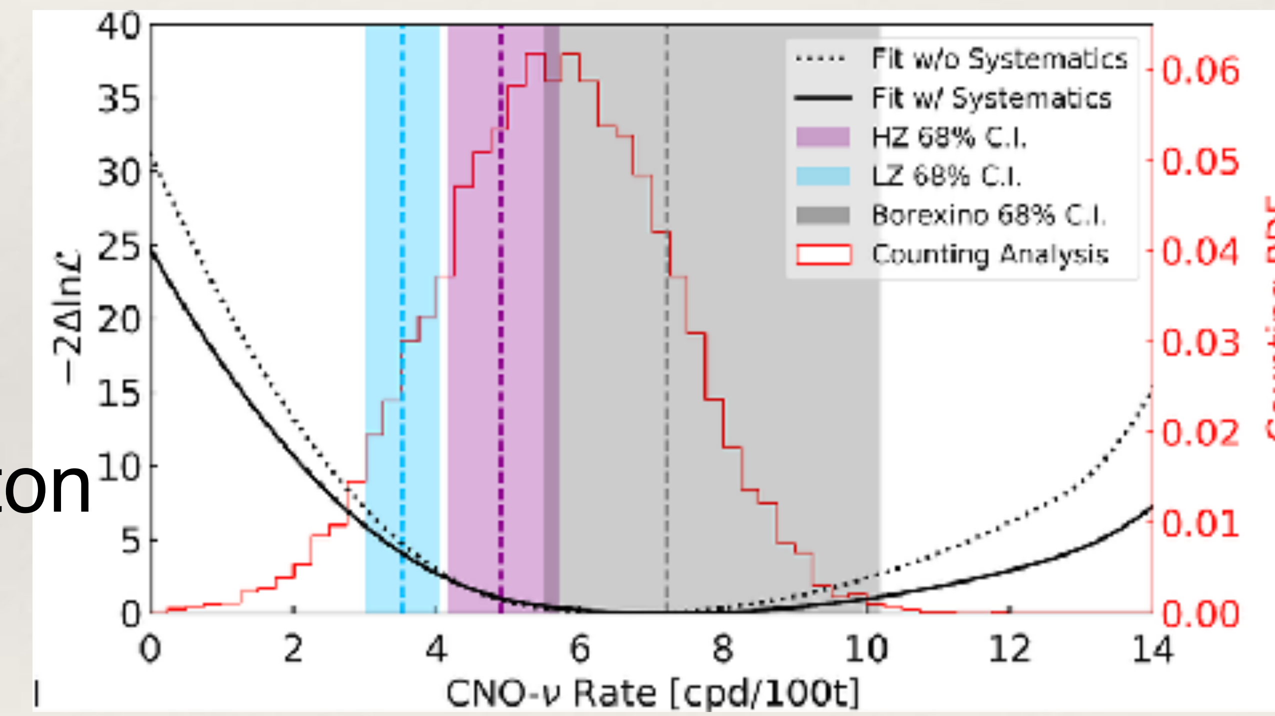


$$\nu_x + e \rightarrow \nu_x + e$$

First detection of CNO neutrinos



^{210}Bi-^{210}Po analysis:
Extract the ^{210}Bi decay rate in Borexino through the study of the ^{210}Po decay rate



R(CNO) = 7.2 +2.9 -1.7 cpd/100ton
Null hypothesis(CNO=0)
rejected at 5.1 sigma.

G. Ranucci , Neutrino 2020

Three Neutrino Paradigm

- Measurement of non-zero θ_{13} in reactor experiments → three neutrino picture

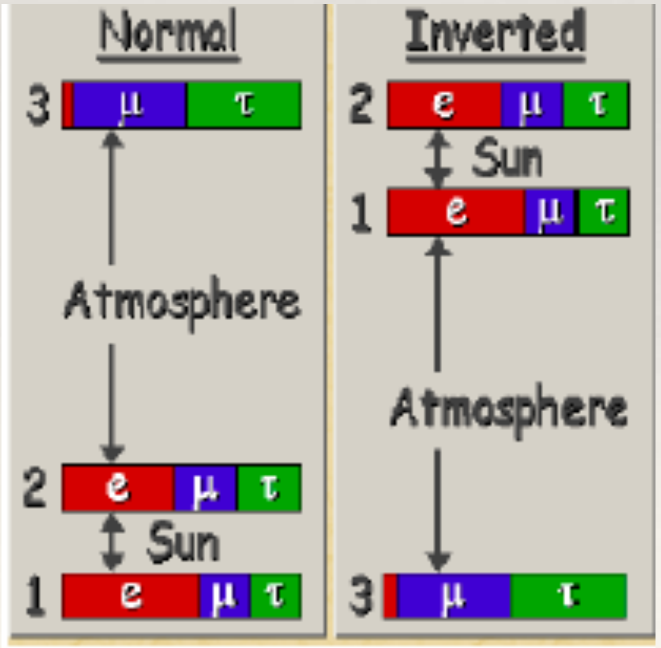
Atm +LBL — Sol+KL

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&&\\ &c_{23}&s_{23}\\ &-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&&e^{-i\delta}s_{13}\\ &1&\\ -e^{i\delta}s_{13}&&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&\\ -s_{12}&c_{12}&\\ &&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

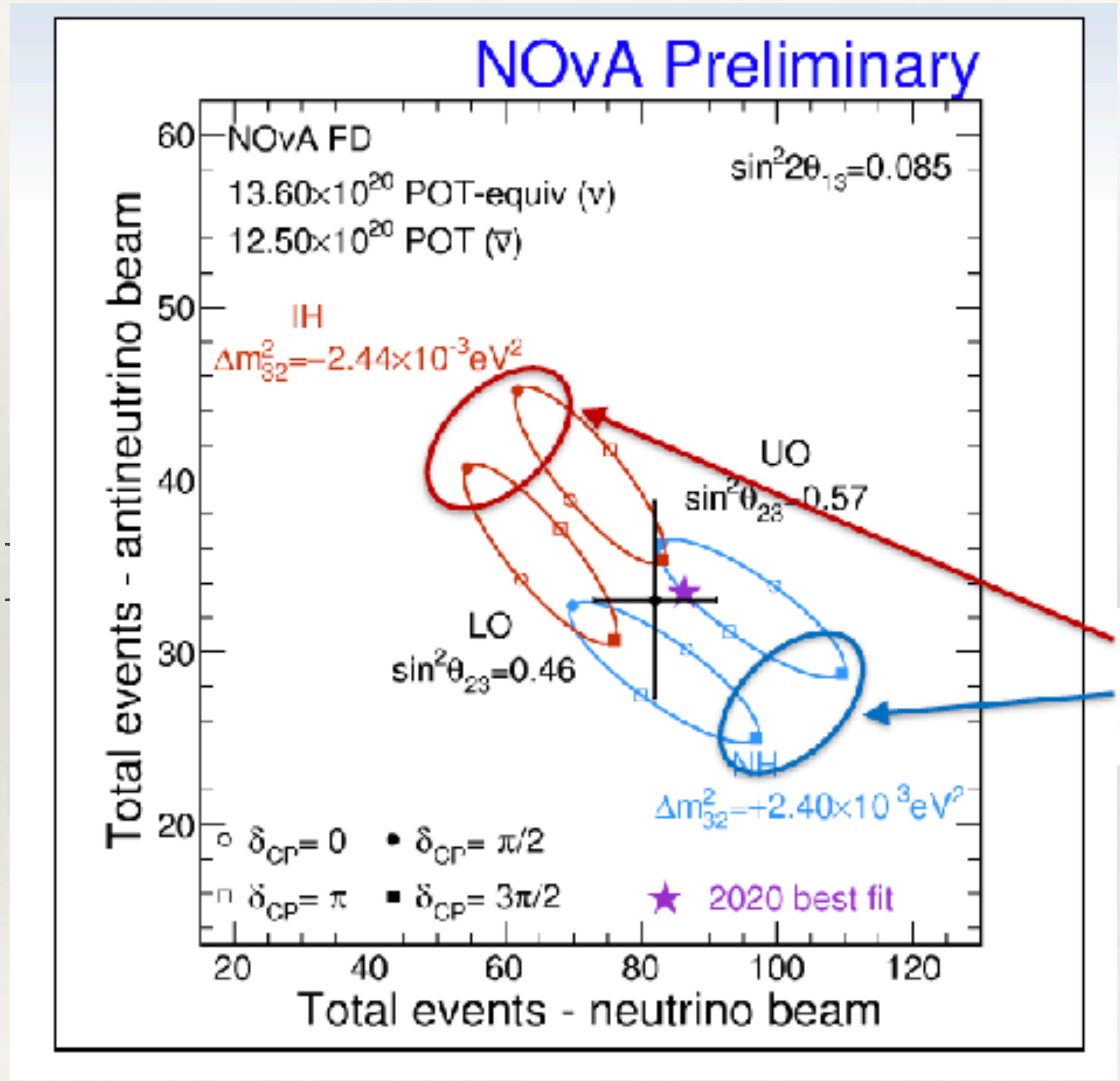
$c_{12} = \cos\theta_{12}$ etc., δ CP-violating phase

- Δm^2_{21}, θ_{12}, θ_{13} Solar + KamLND
- Δm^2_{31}, θ_{13} Reactor
- Δm^2_{31}, θ_{23}, θ_{13}, δ_{CP} Atm + LBL

Interplay among different sectors because of θ_{13}



NOvA Results



Joint analysis of disappearance and Appearance data in both neutrino and antineutrino channel

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ eV^2$

$\sin^2(\theta_{23}) = 0.57\ ^{+0.04}_{-0.03}$ (49°)

B.F. for $\delta_{CP} = 0.83\pi$

Exclude IH $\delta_{CP} = \pi/2$ at > 3 σ

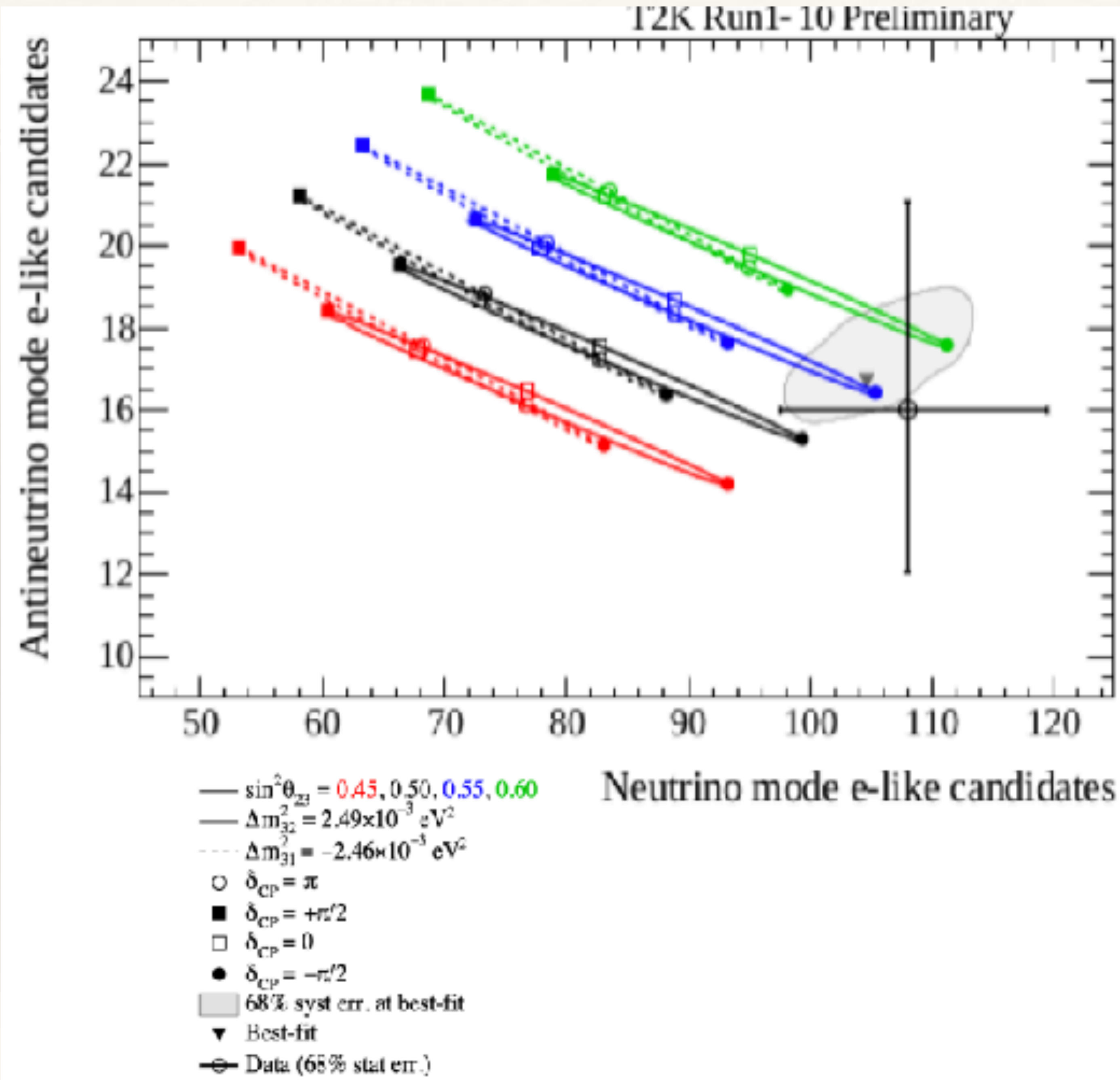
Disfavor NH $\delta_{CP} = 3\pi/2$ at ~2 σ

Preference for

Normal Hierarchy at	1.0 σ
Upper Octant at	1.2 σ

Neutrino 2020

T2K Results



Appearance channel

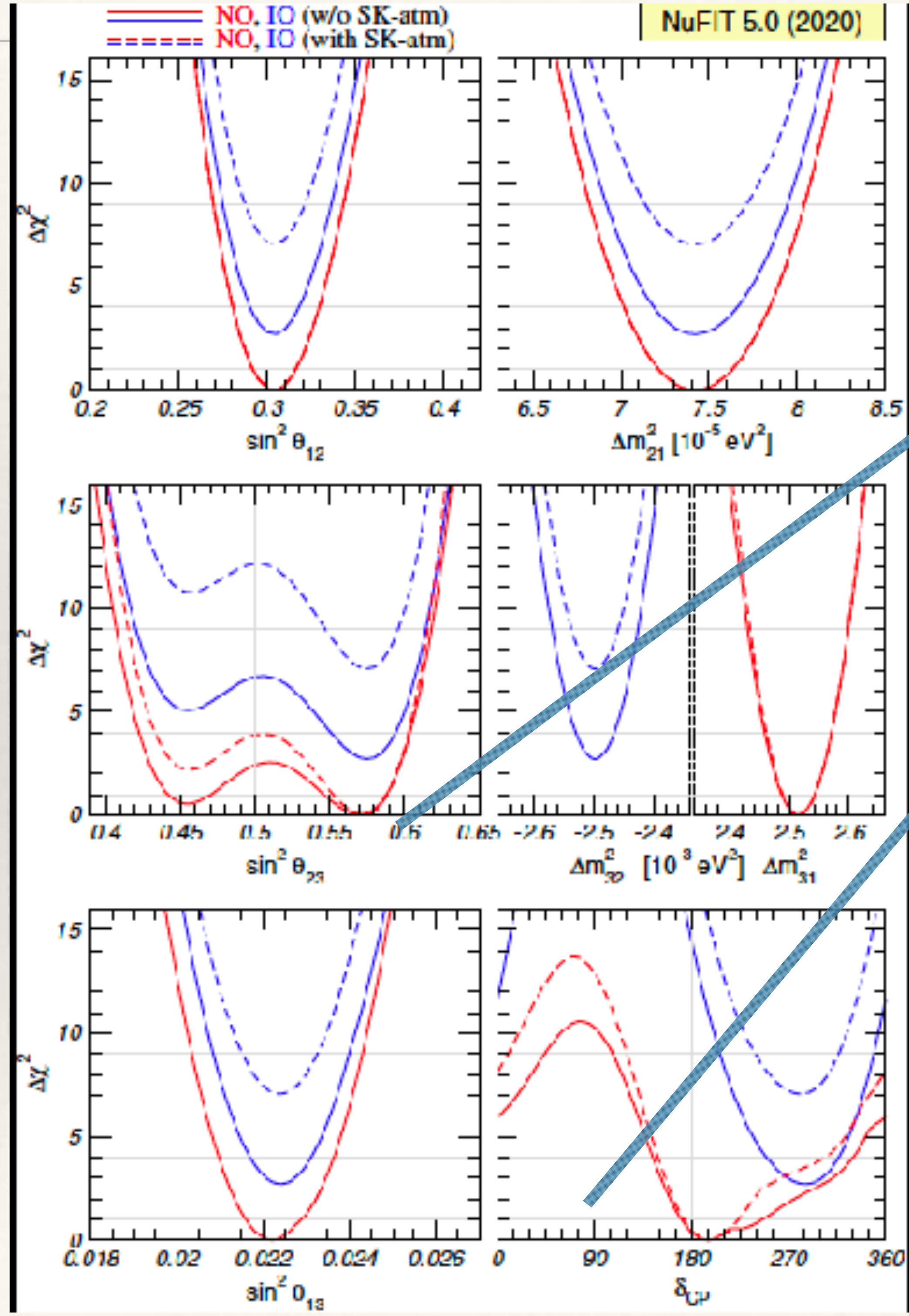
Preference for NH

CP phase close to $-\pi/2$

CP conserving values disfavoured

L. Muntaneu, Neutrino 2020

Current Status



- Best-fit θ_{23} in second octant
- Preference for NO
- $\delta_{CP} = +90^\circ$ disfavoured at more than 3σ irrespective of mass ordering
- Oscillation experiments not sensitive to Majorana phases

Degeneracy problem

- The main problem in determination of hierarchy, octant and δ_{CP} in LBL experiments is due to presence of degeneracies
- Degeneracy ➡ different set of parameters giving the same probability ➡ equally good fit to the data
-

Hierarchy - δ_{CP} degeneracy

$$P_{\mu e}(\Delta, \delta_{CP}) = P_{\mu e}(-\Delta, \delta'_{CP})$$

Minakata, NunoKawa, 2001

Intrinsic octant degeneracy

$$P_{\mu\mu}(\theta_{23}) = P_{\mu\mu}(\theta_{23} - \pi/2 - \theta_{23})$$

Fogli and Lisi, 1996

Octant - δ_{CP} degeneracy

$$P_{\mu e}(\theta_{23}, \delta_{CP}) = P_{\mu e}(\theta'_{23}, \delta'_{CP})$$

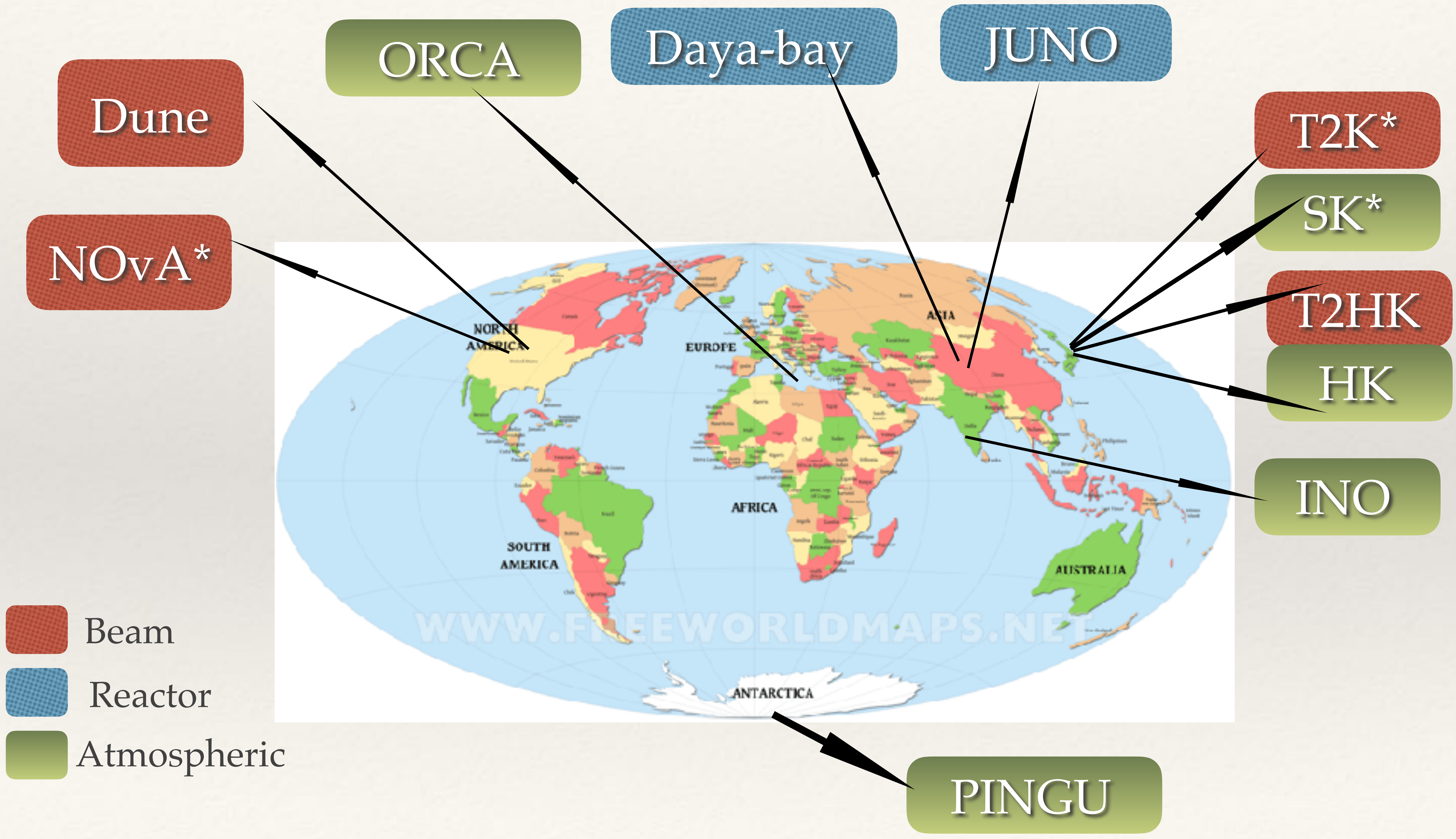
Gandhi, Ghosal, Goswami, Shankar 2005

Comprehensive Approach

$$P_{\mu e}(\theta_{23}, \Delta, \delta_{CP}) = P_{\mu e}(\theta'_{23}, -\Delta', \delta'_{CP}) \Rightarrow \text{generalized}\,(\text{hierarchy} - \theta_{23} - \delta_{CP})\,\text{degeneracy}.$$

Coloma, Minakata, Parke, 2014
Ghosh, Ghoshal, Goswami, Nath, Raut, 2015

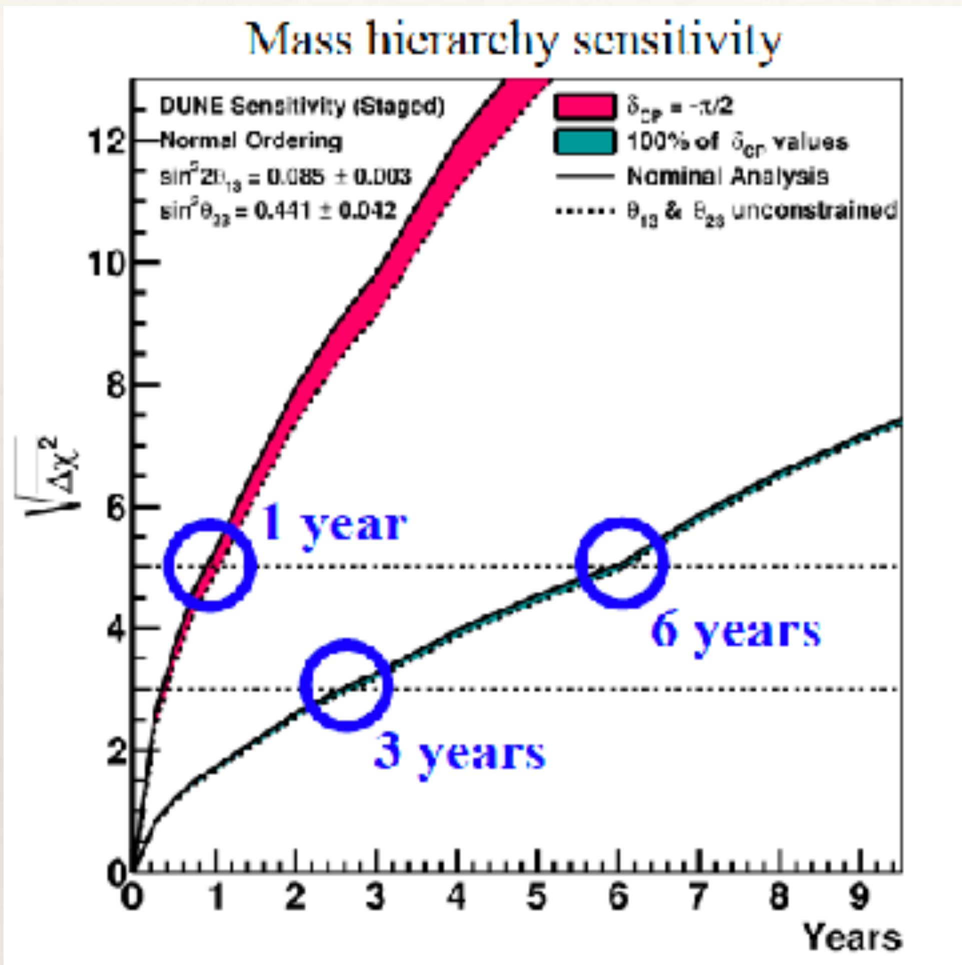
Ongoing and planned experiments



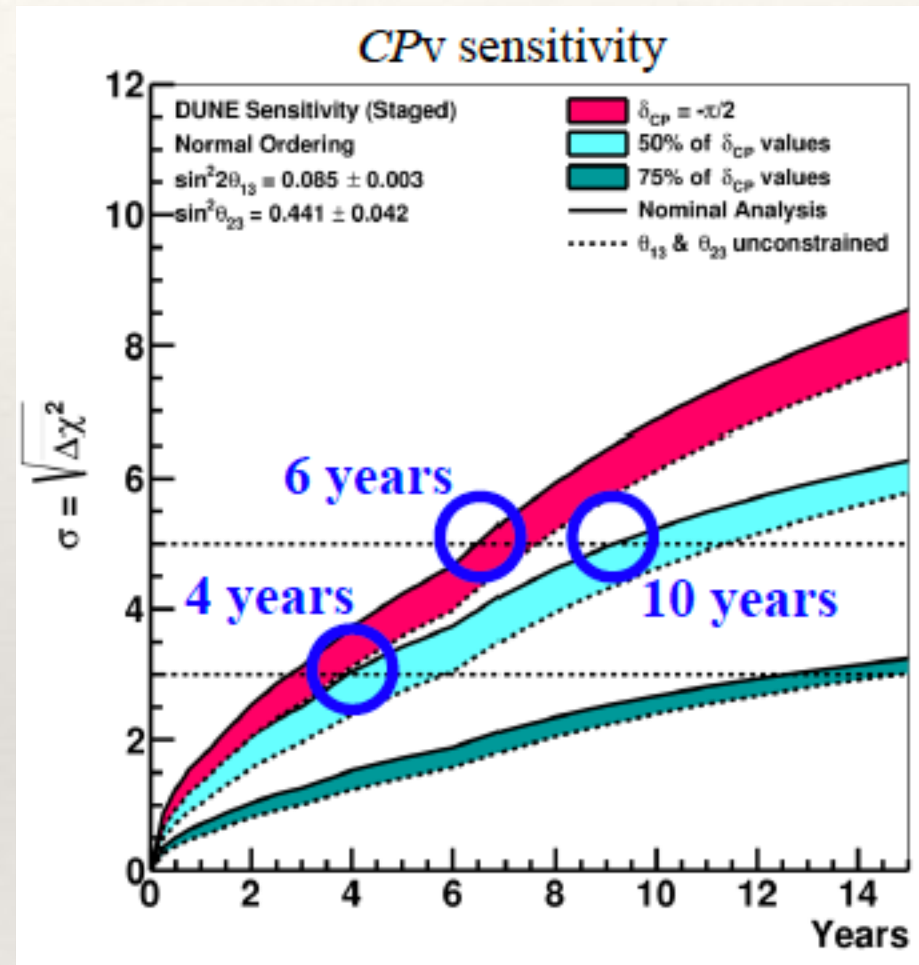
Future Goals

- Determination of hierarchy, octant and CP phase
- Probing new physics in oscillation experiments
- Testing models of flavour symmetry
- Synergy between different experiments

Mass hierarchy and CP with DUNE



Hierarchy sensitivity due to enhanced matter effects

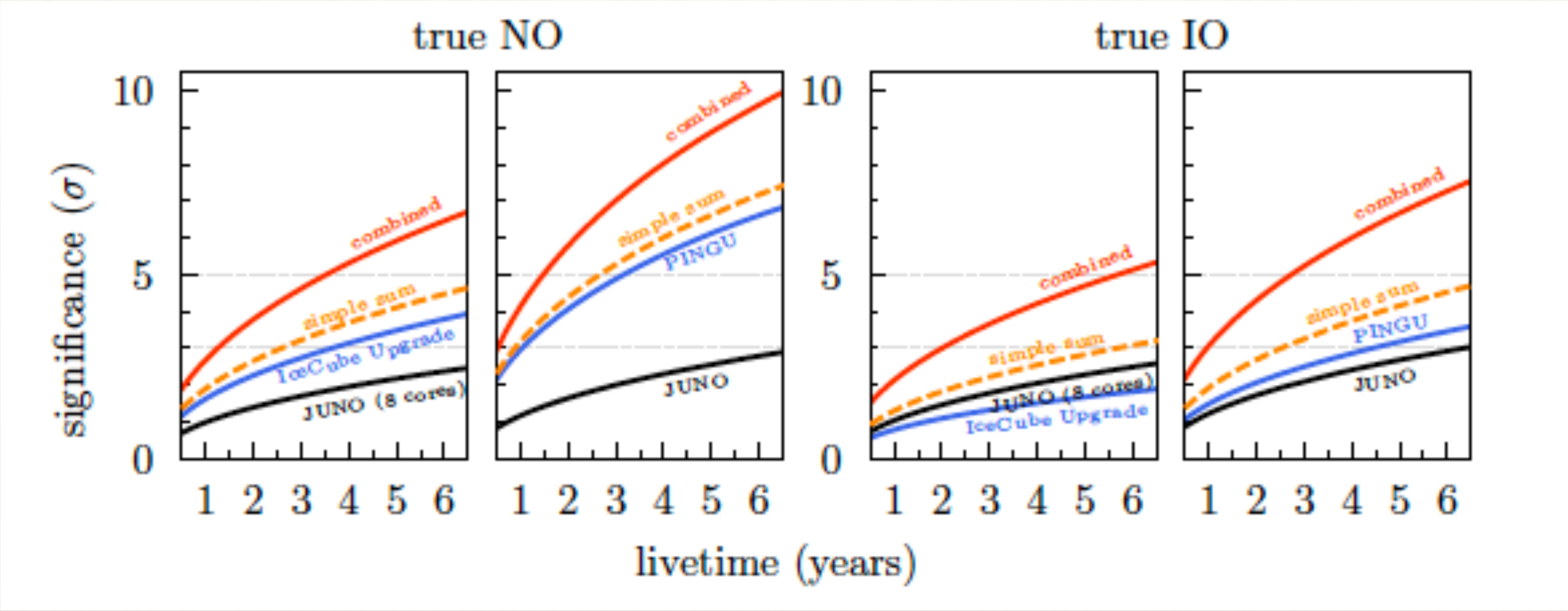


Matter effects help in removing wrong hierarchy-wrong CP solutions

From: R. Patterson's slides

Hierarchy: Juno+IceCube upgrade

8 core JUNO + IceCube upgrade/PINGU / (better efficiency for lower energy neutrinos)



5σ sensitivity in 4(6) years NO (IO)

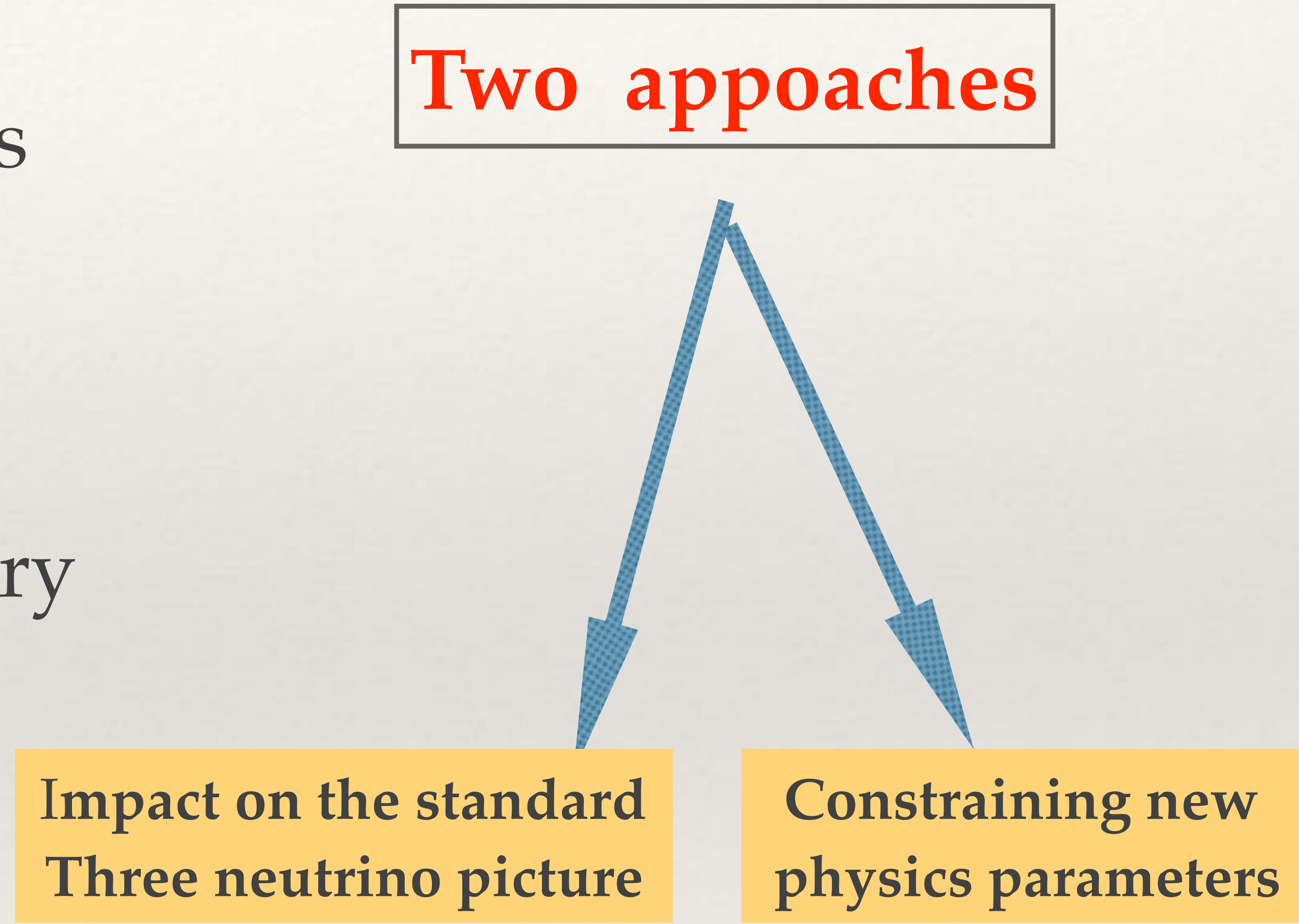
IceCube : earth matter effect of atmospheric neutrinos
JUNO: interference effect in vacuum oscillation

} **Synergy**

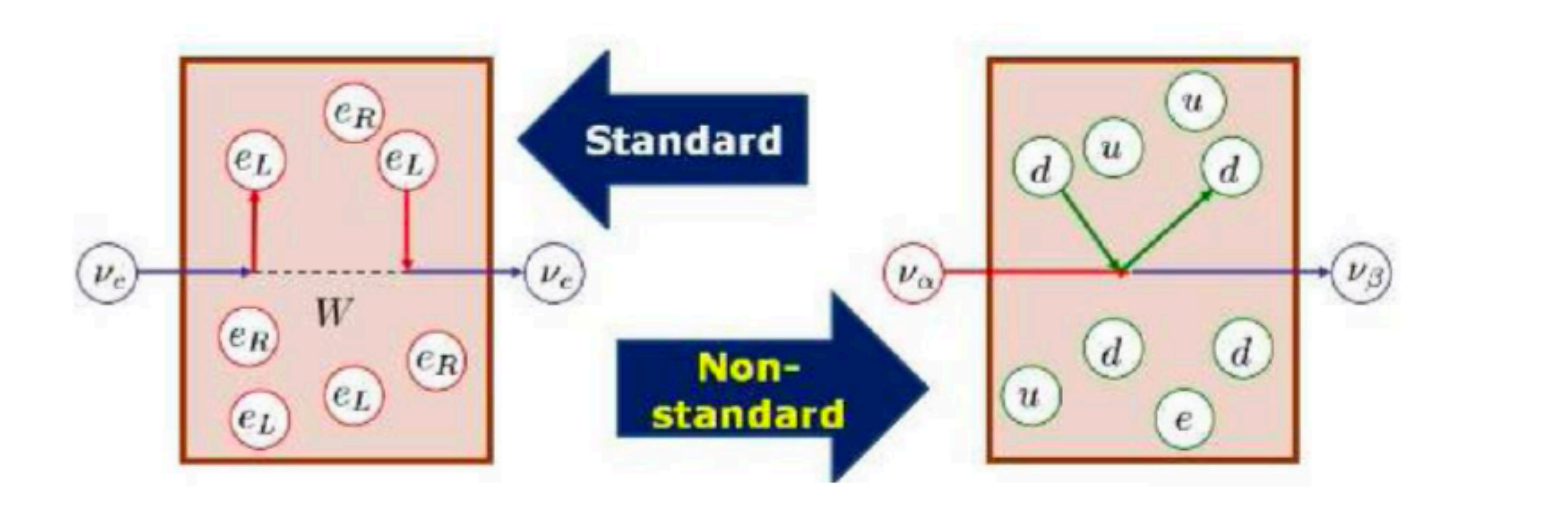
hep-ex 1911.06745

New Physics

- Sterile Neutrinos
- Non-standard Interactions (NSI)
- Non-unitary mixing
- CPT and Lorentz symmetry violation
- Long range forces
- Neutrino decay



Non-standard interactions



$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{ff'C}\left(\overline{\nu_\alpha}\gamma^\mu P_L\nu_\beta\right)\left(\bar{f}\gamma_\mu P_C f'\right)$$

$\varepsilon_{\alpha\beta}^{ff'C}$ are NSI parameters, $\alpha, \beta = e, \mu, \tau,\ f, f' = e, u, d$ and $C = L, R.$

$f \neq f'$ → Charged Current NSI

$f = f'$ → Neutral Current NSI

Non-standard interactions

Standard-NC interaction

$$\nu_\alpha + f \to \nu_\alpha + f$$

Non-Standard NC interaction

$$\nu_\alpha + f \to \nu_\beta + f$$

$$\mathcal{L} = -G^{\alpha\beta}\epsilon^f_{\alpha\beta}\bar{\nu}_\alpha\gamma^\mu\nu_\beta\bar{f}\gamma_\mu f$$

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d}\frac{N_f}{N_e}\epsilon^f_{\alpha\beta}$$

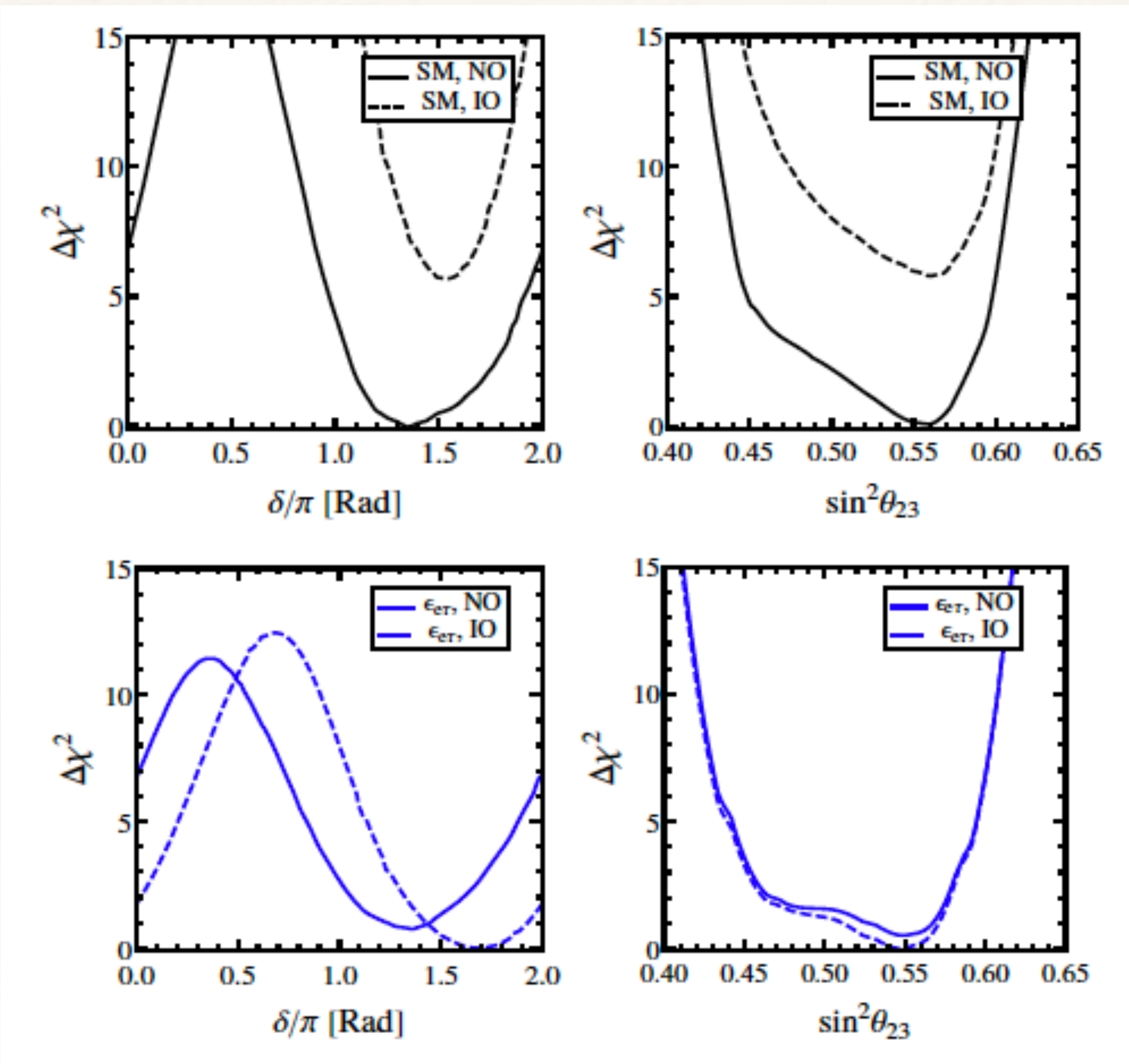
$$H = \frac{1}{2E}\left[U\mathrm{diag}(0,\Delta m^2_{21},\Delta m^2_{31})U^\dagger + V\right],$$

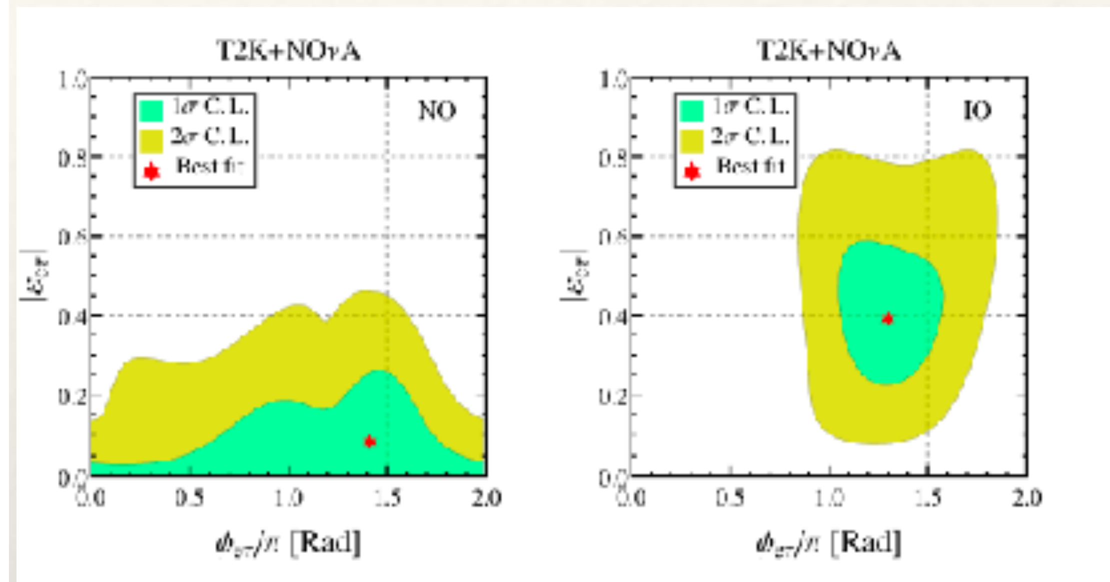
$V \Rightarrow$ matter potential in presence of NSI,

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

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

NSI and mass hierarchy





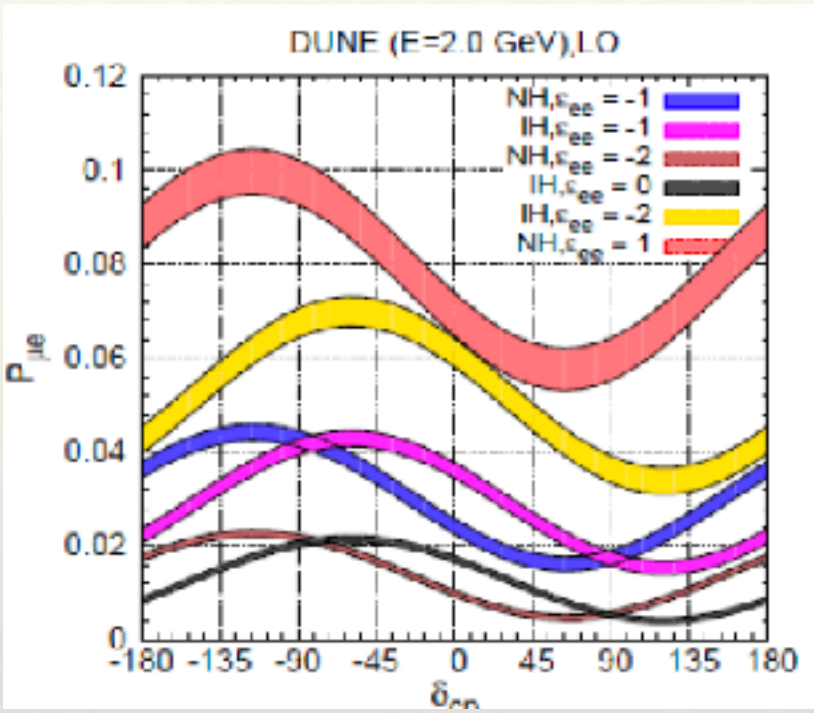
Fit to T2K and NOvA data assuming NSI

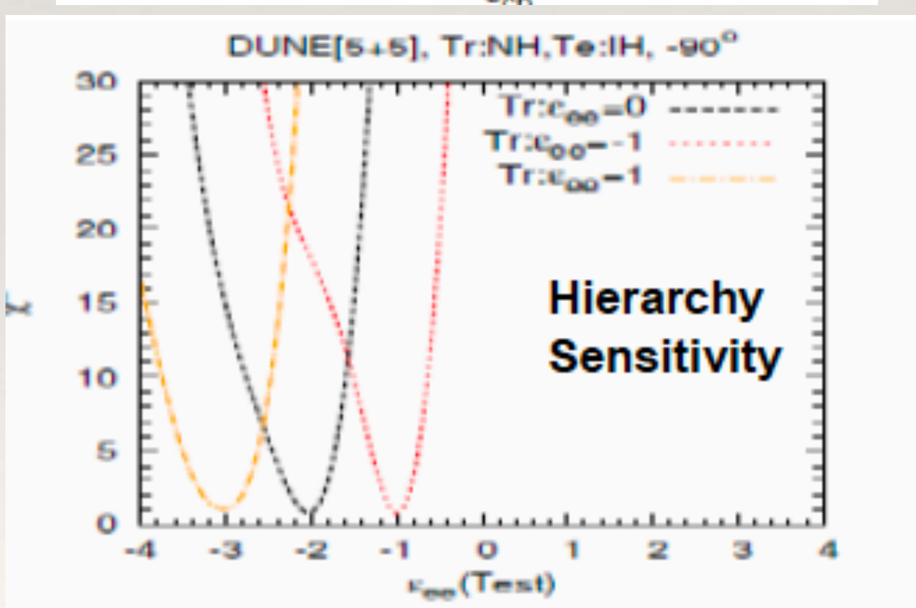
IO prefers non-zero NSI

IO no longer disfavoured

Capozzi, Chatterjee, Palazzo 1908.06992

Degeneracies due to diagonal NSI





K.N. Deepthi, S.Goswami, N. Nath, PRD 2016

$$V = 2\sqrt{2}G_F N_e(r) E \begin{pmatrix} 1+\epsilon_{ee} & 0 & 0 \\ 0 & \epsilon_{\mu\mu} & 0 \\ 0 & 0 & \epsilon_{\tau\tau} \end{pmatrix},$$

- **New degeneracies with NSI**
- $P(\epsilon_{ee}, \delta_{CP}) = P(\epsilon'_{ee}, \delta'_{CP})$

$$P(\epsilon_{ee}, \delta_{CP}) = P(-\epsilon_{ee} - 2, \delta'_{CP})$$

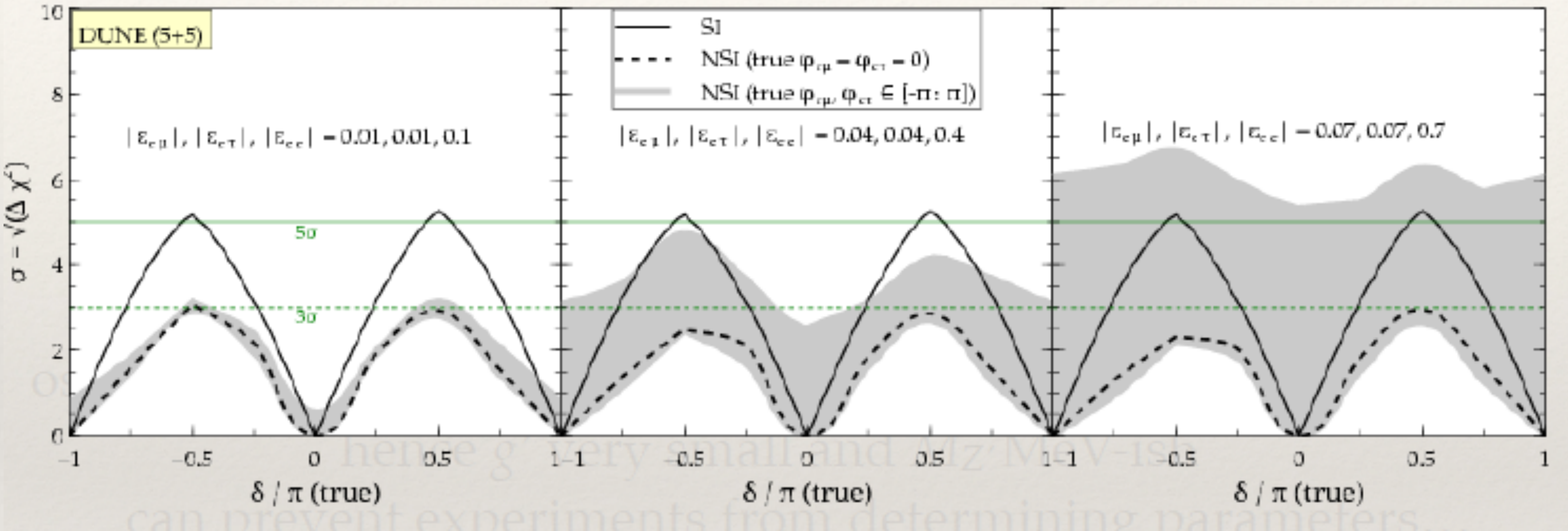
Coloma, Schwetz, PRD 2016

$$(1+\epsilon_{ee}) \rightarrow -(1+\epsilon_{ee})$$

In matter potential

Spoils the hierarchy sensitivity of Dune

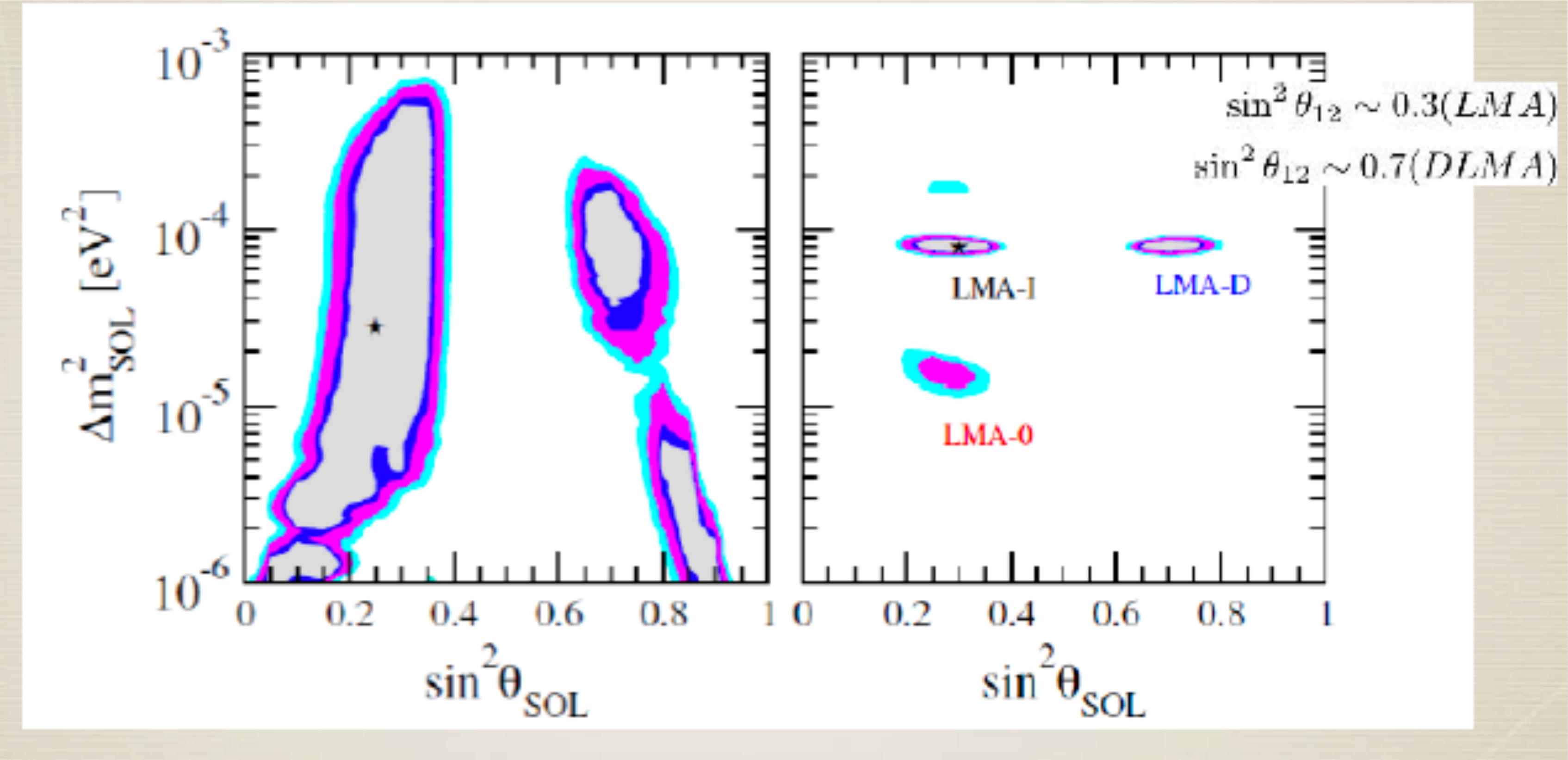
NSI and CP sensitivity



Mehta, Masood, 1603.01380

NSI can spoil CP sensitivity

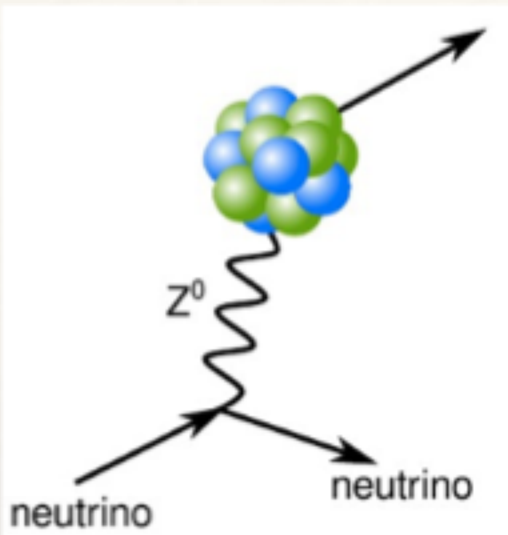
Dark-LMA solution



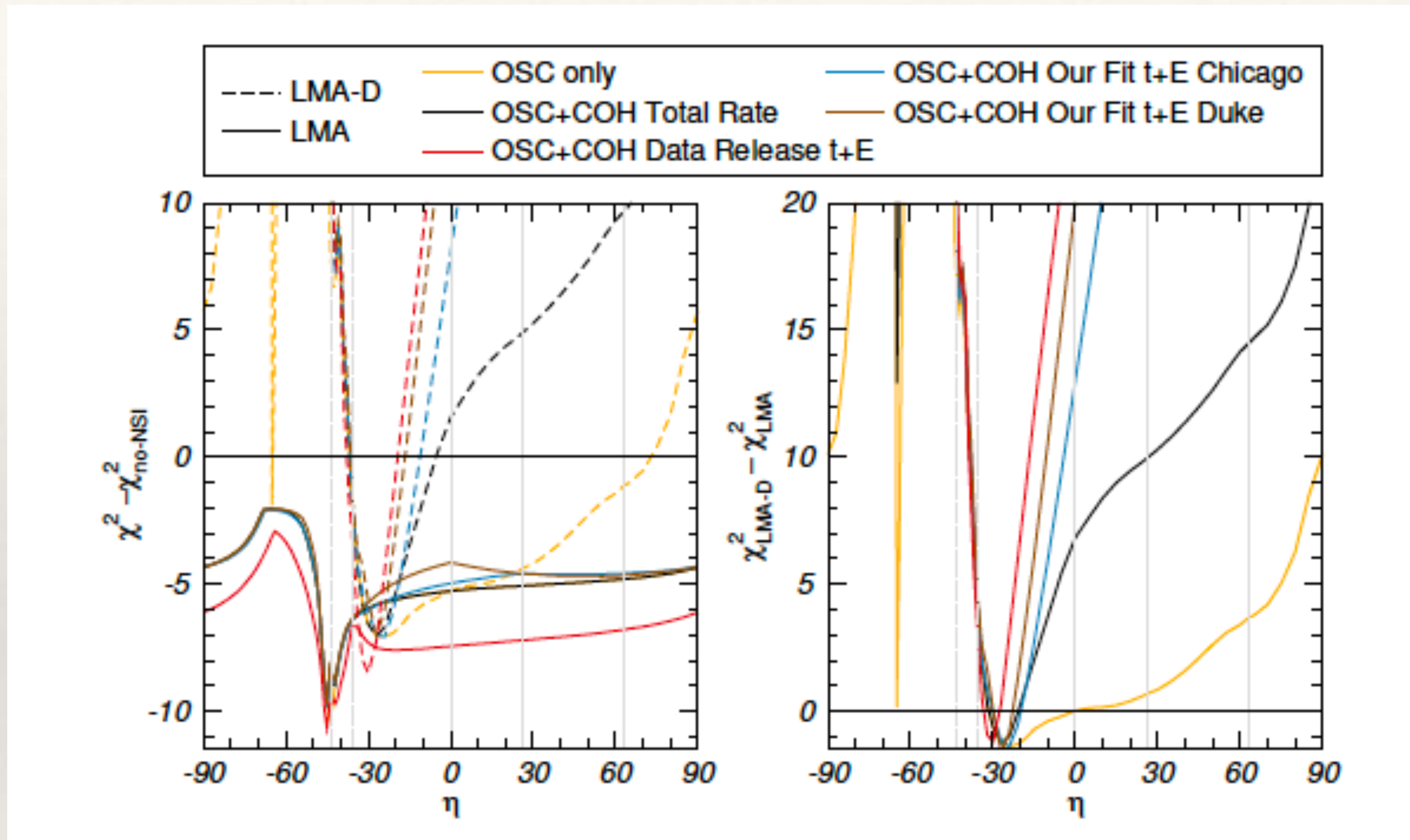
- Degenerate solution to the solar neutrinos problem
- $\sin^2\theta_{12} > 45^o$

Miranda, Tortola, Valle ,JHEP. 10 (2006) 008.

COHERENT constraints



Nucleus recoils as a whole
Coherent upto 50 MeV

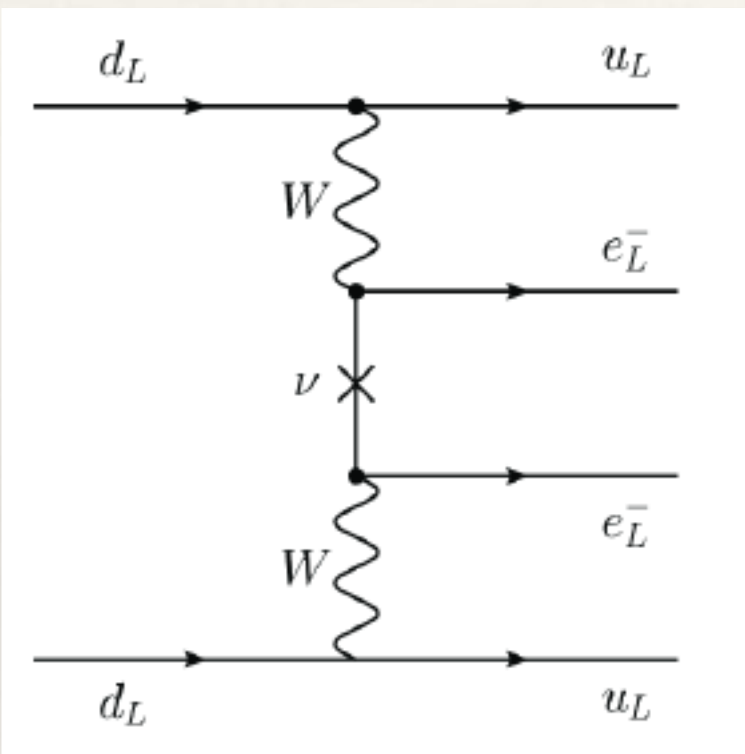


- Highly constrained by COHERENT using energy spectrum information

Coloma, Esteban,Gonzalez-Garcia, Maltoni 1911.09109

Neutrinoless double beta decay

$$(A, Z) \rightarrow (A, Z+2) + 2\,e^- \quad (0\nu\beta\beta)$$



- Standard picture $0\nu\beta\beta$ mediated by light neutrinos
- The half-life for $0\nu\beta\beta$,

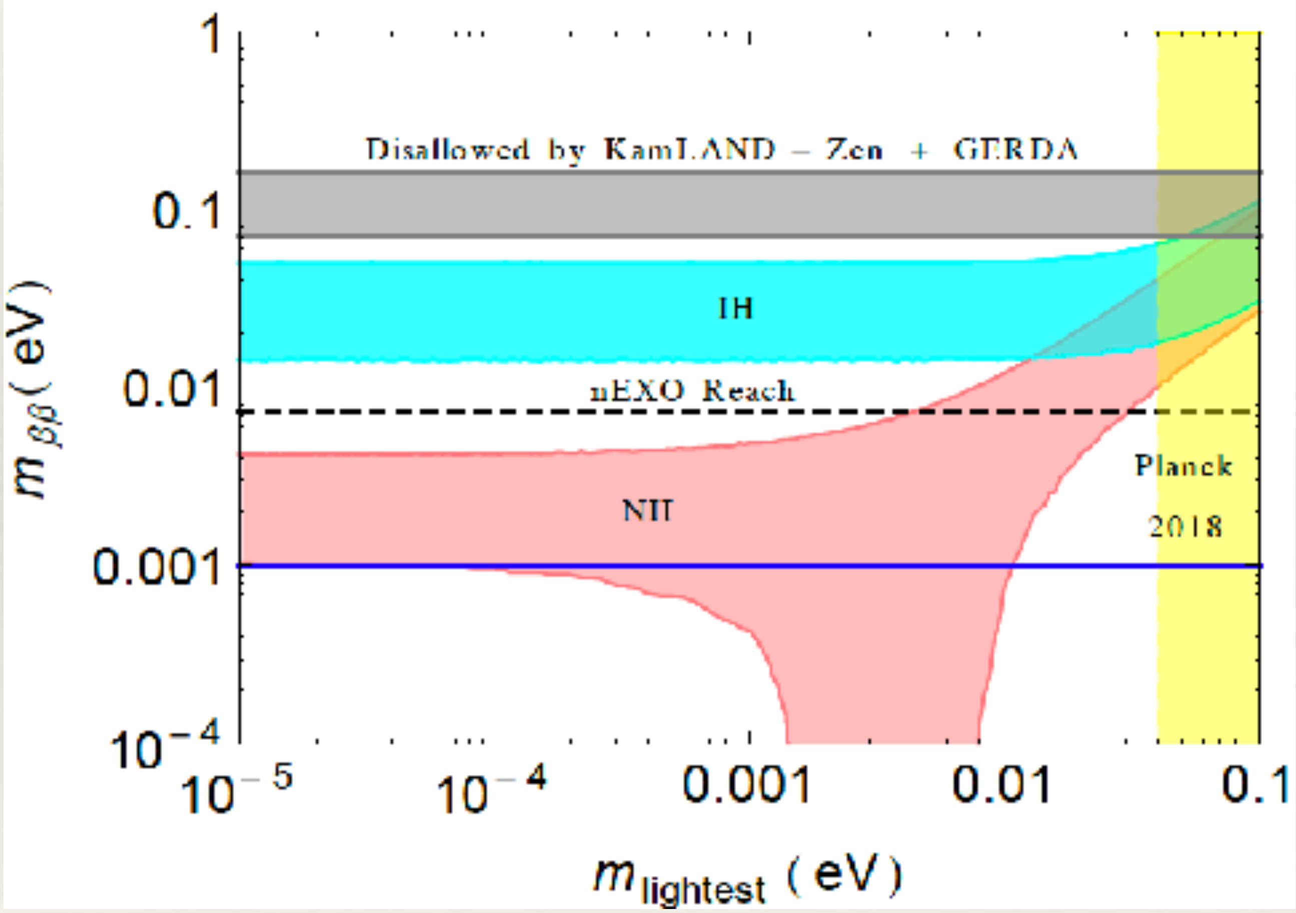
$$\frac{1}{T_{1/2}^{0\nu}} = G|\mathcal{M}_\nu|^2 \left|\frac{m_{ee}^\nu}{m_e}\right|^2 ,$$

G contains the phase space factor
M_ν is the nuclear matrix elements

- $|m_\nu^{ee}| = |U_{ei}^2\, m_i| \rightarrow$ the effective mass

Current and future sensitivity

$$|m_\nu^{ee}| = |m_1 U_{e1}^2 + m_2 U_{e2}^2 e^{2i\alpha_1} + m_3 U_{e3}^2 e^{2i\alpha_2}$$



Current Sensitivity

KamLAND-ZEN : 61-165 meV
EXO 200 : 93-286 meV
GERDA : 110-260 meV
CUORE : 110-520 meV

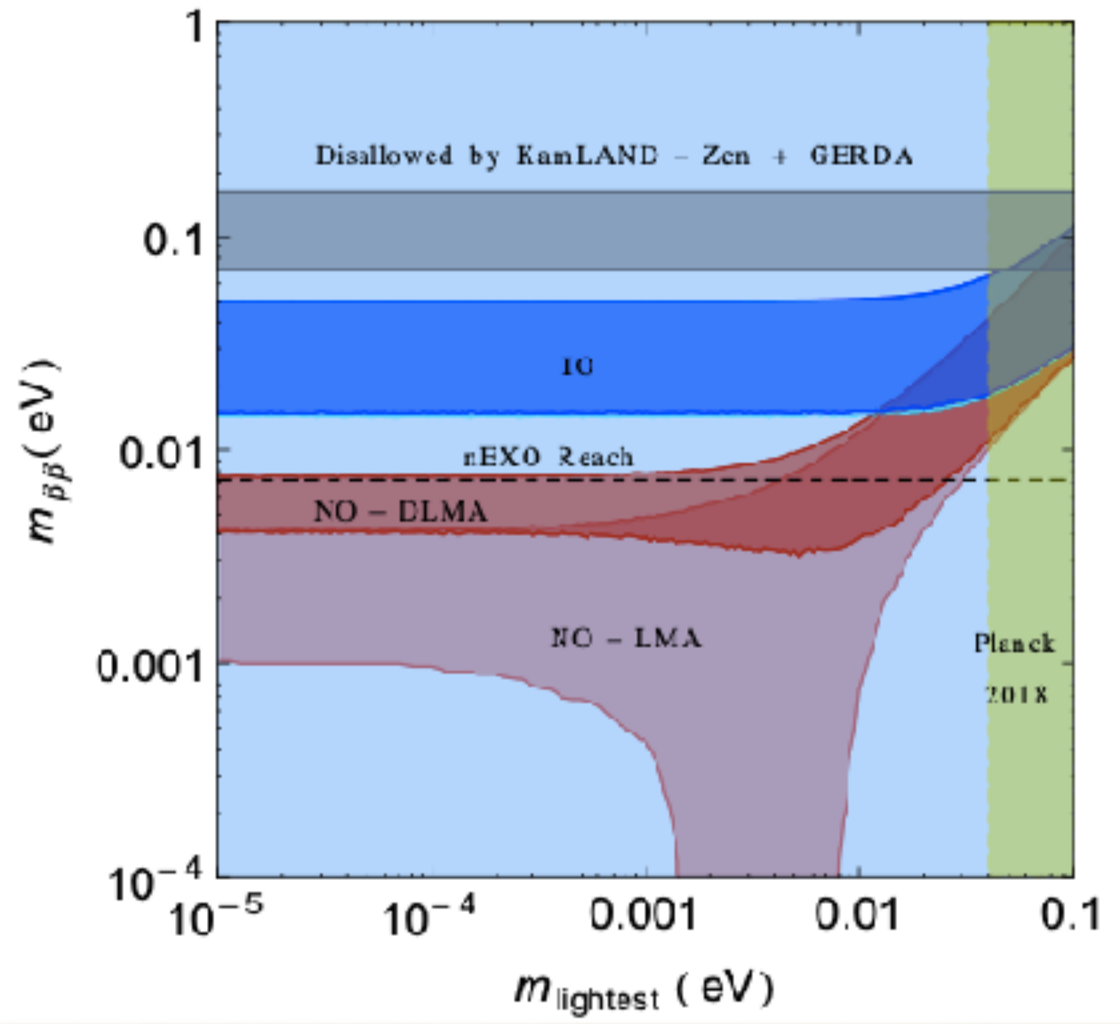
Future sensitivity

0.008 - 0.3 eV : IH can be confirmed
0.003 - .008 eV : 1-10 ton detector
0.001 - .003 eV : 10-100 ton detector
ultimate sensitivity

Barabash, 1901.11342

NSI and Neutrinoless double beta decay

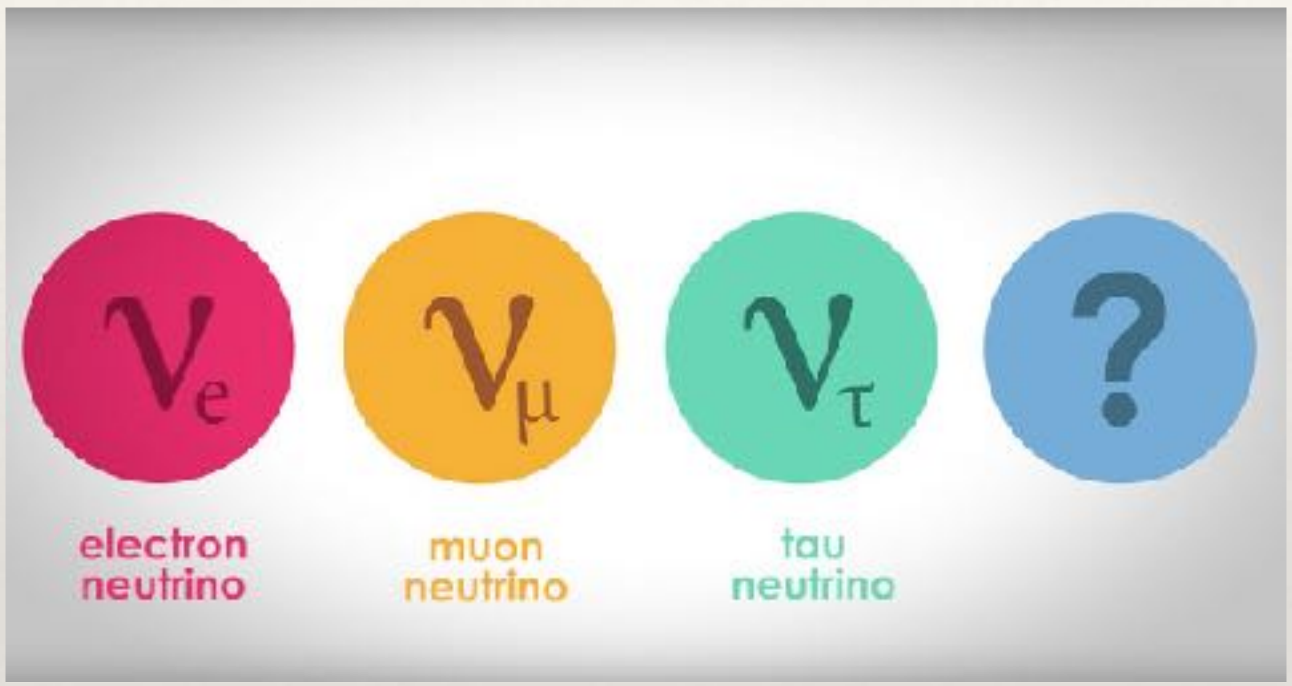
$$m_{\beta\beta} = |m_1\, c_{12}^2 c_{13}^2 + m_2\, s_{12}^2 c_{13}^2 e^{2i\alpha_2} + m_3\, s_{13}^2 e^{2i\alpha_3}|$$



- New predictions in presence of NSI for NH
- Within reach of 10 kt detectors
- New sensitivity goal
- For NH degeneracy between LMA and DLMA can be broken for lower values of lightest neutrino mass
- Model independent

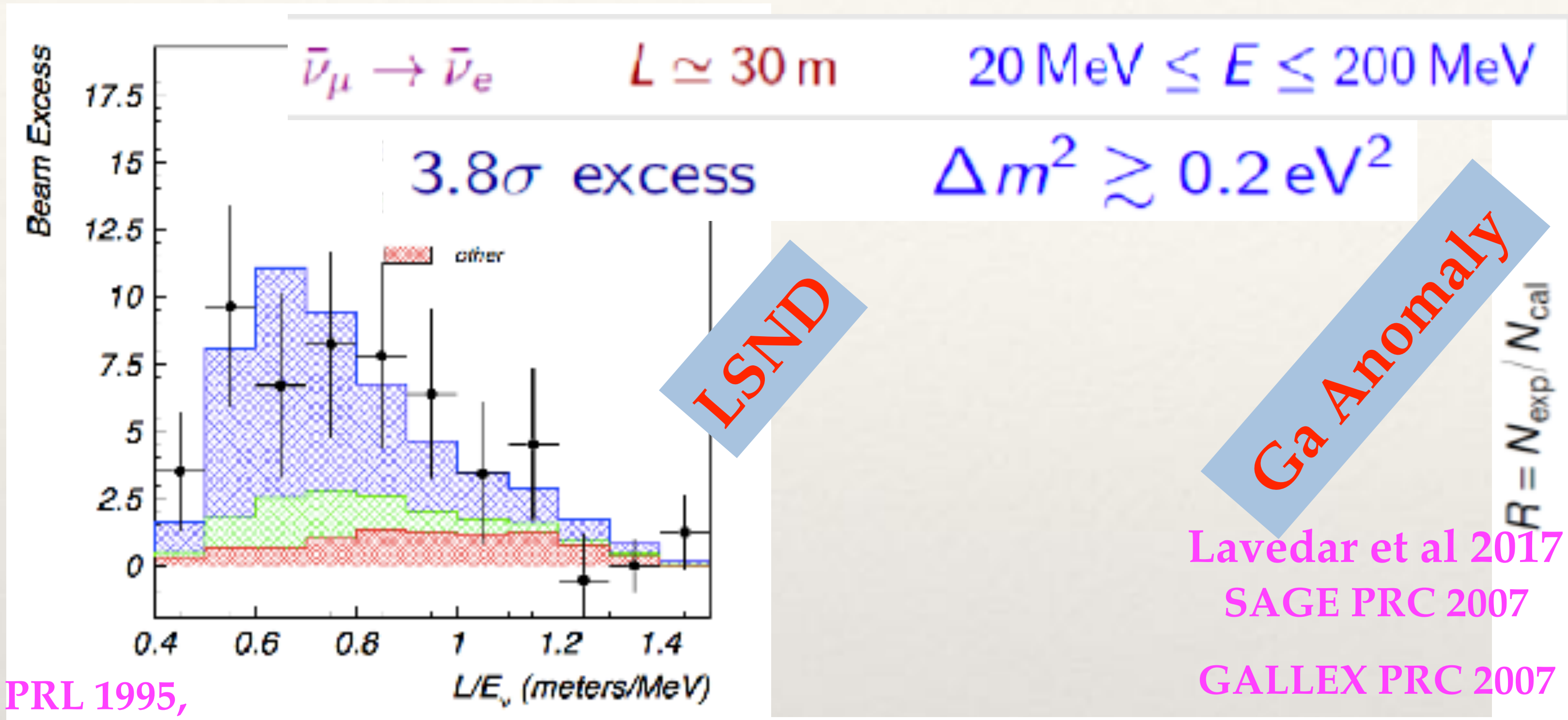
Vishnudath, Choubey, Goswami, Phys, Rev. D. (2019)

Are there more than 3 neutrinos ?



Extra sterile neutrino ?
Light or heavy or both ?

Sterile Neutrinos : indications

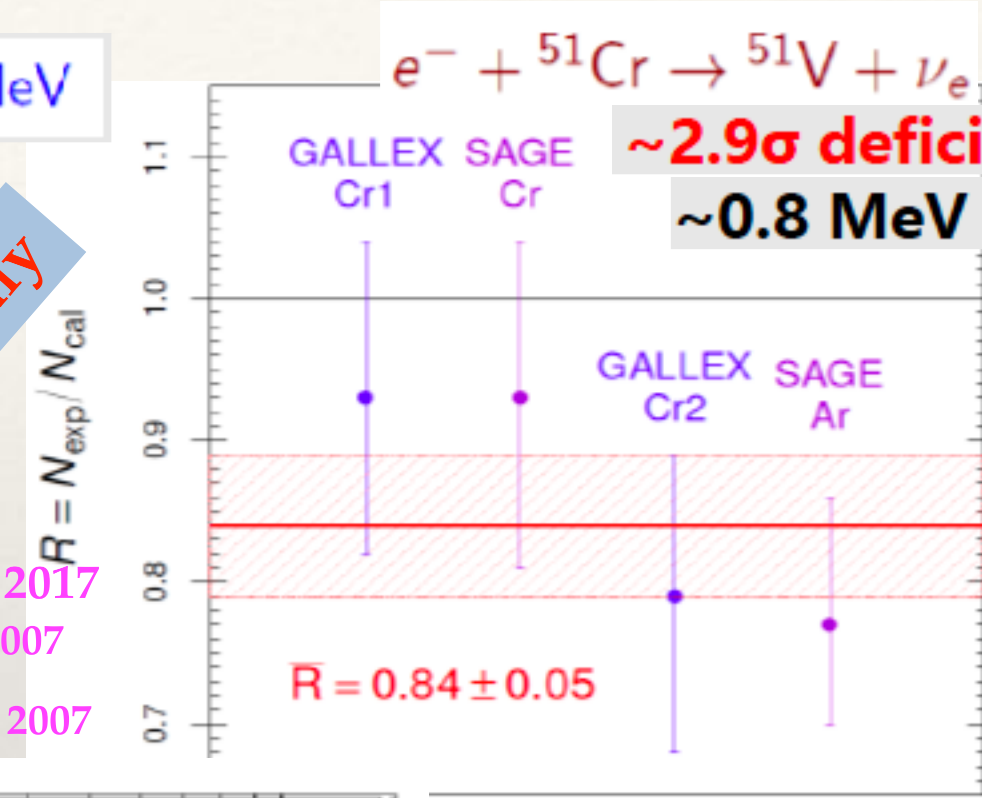


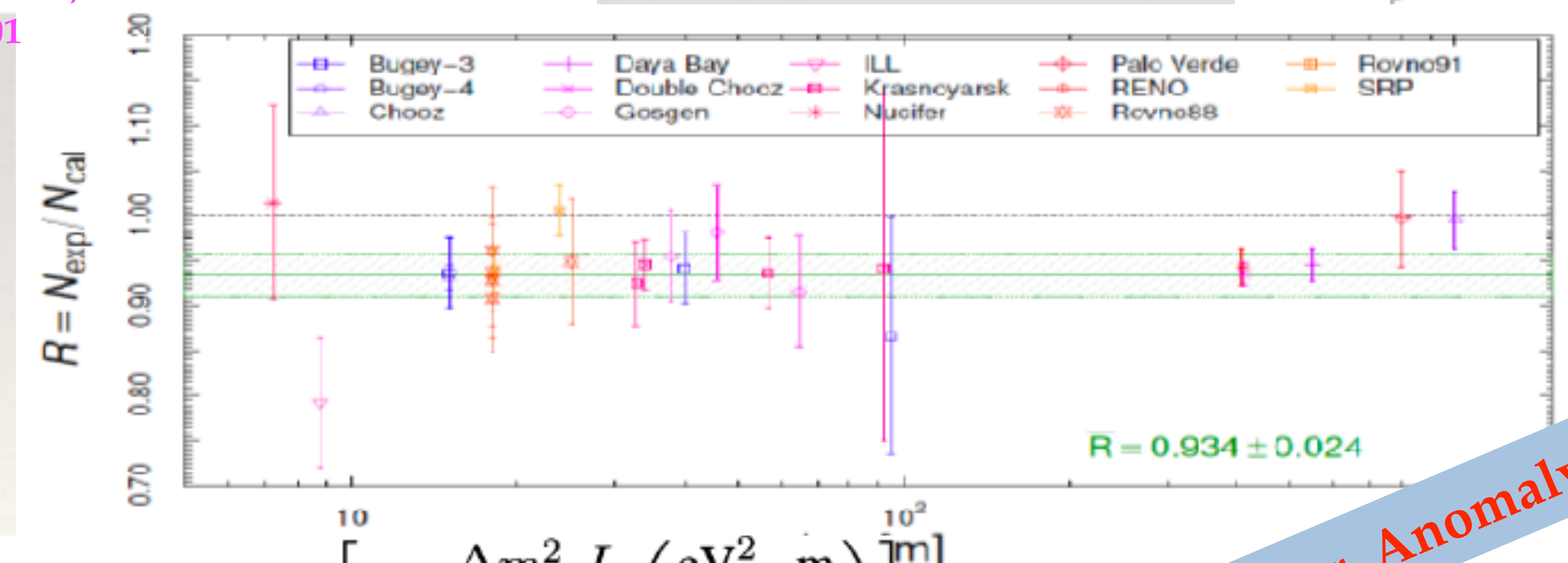
LSND

LSND PRL 1995, PRD 2001

Ga Anomaly

Lavedar et al 2017
SAGE PRC 2007
GALLEX PRC 2007





Mueller et al PRC 2011
Huber PRC 2011
Mention et al PRD 2011

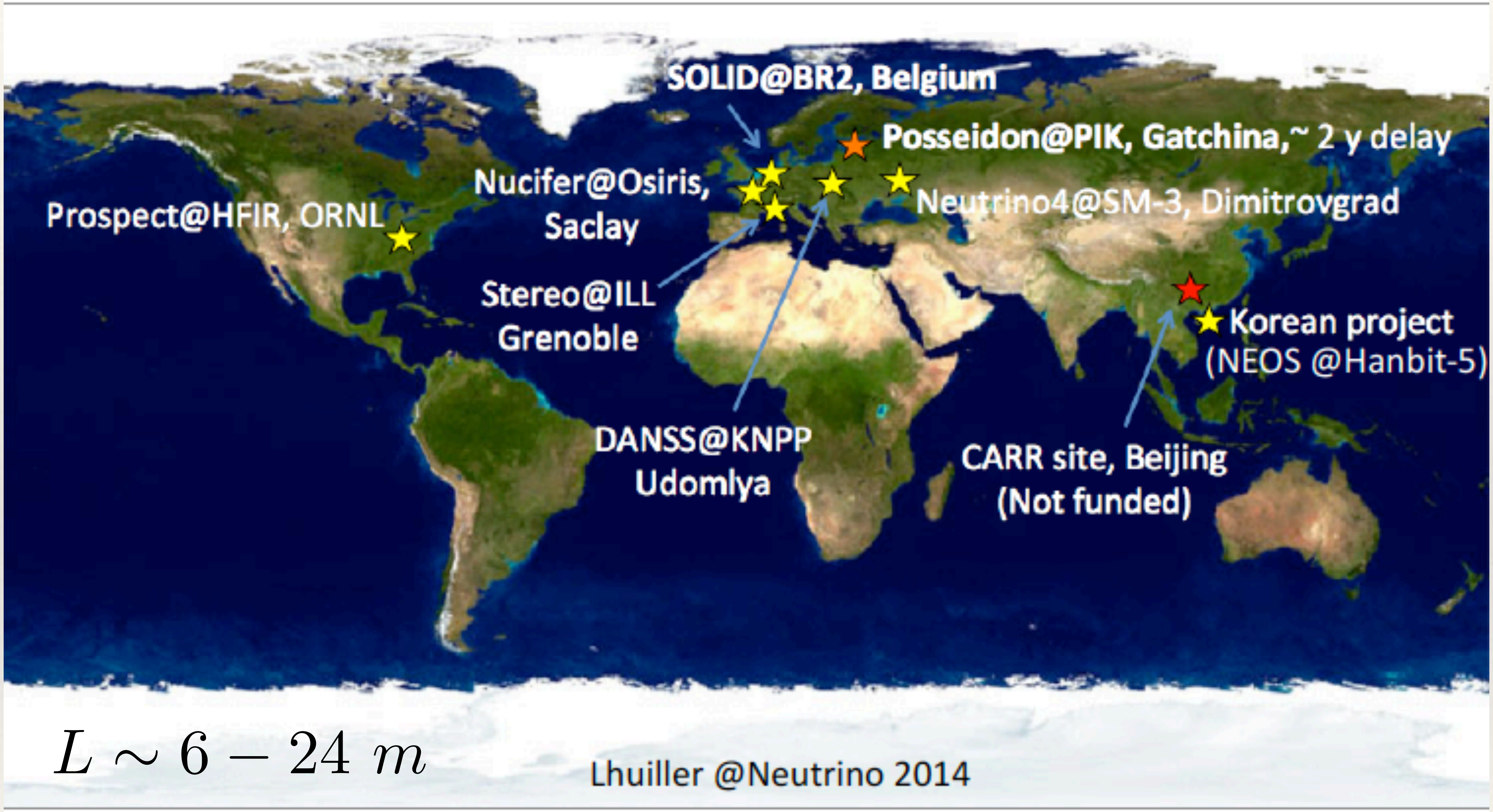
$\Delta m^2_{41} = 2.4\,\text{eV}^2$

$\sin^2(2\theta_{14}) = 0.14$

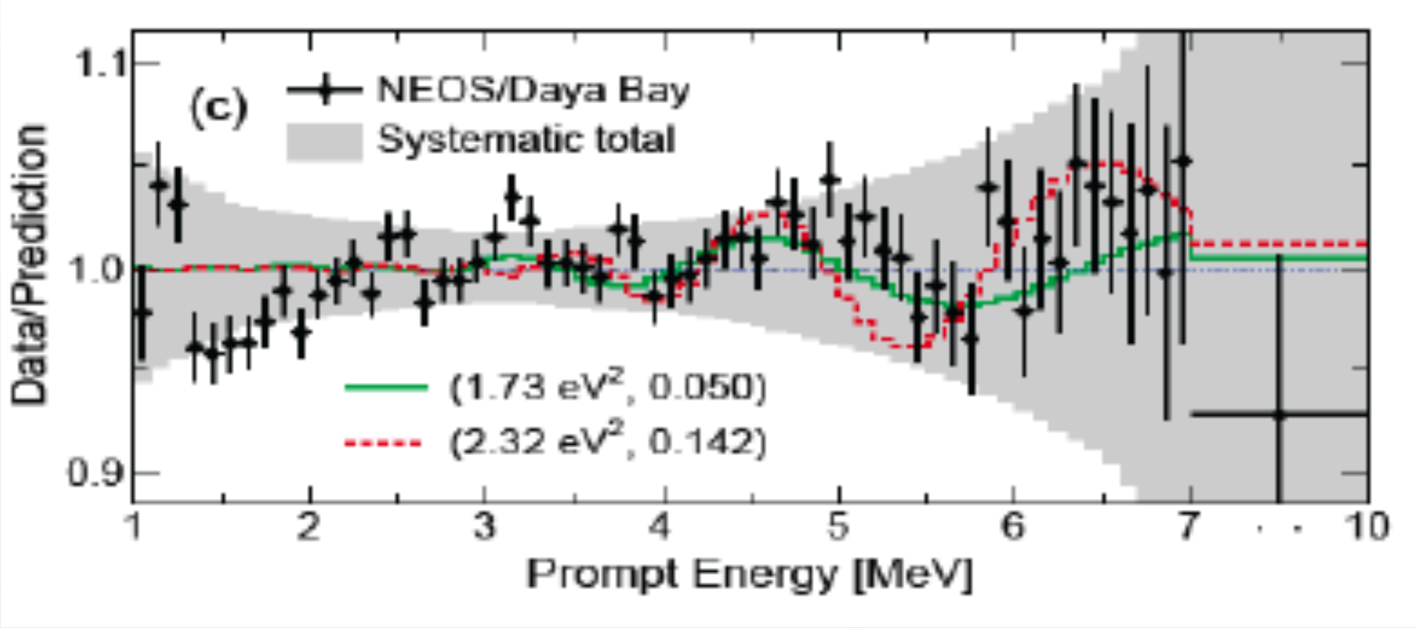
$$P \simeq 1 - \sin^2 2\theta_{14} \sin^2\left[1.27 \frac{\Delta m^2_{41} L}{E_\nu}\left(\frac{\text{eV}^2 \cdot \text{m}}{\text{MeV}}\right)\right]$$

Reactor Anomaly

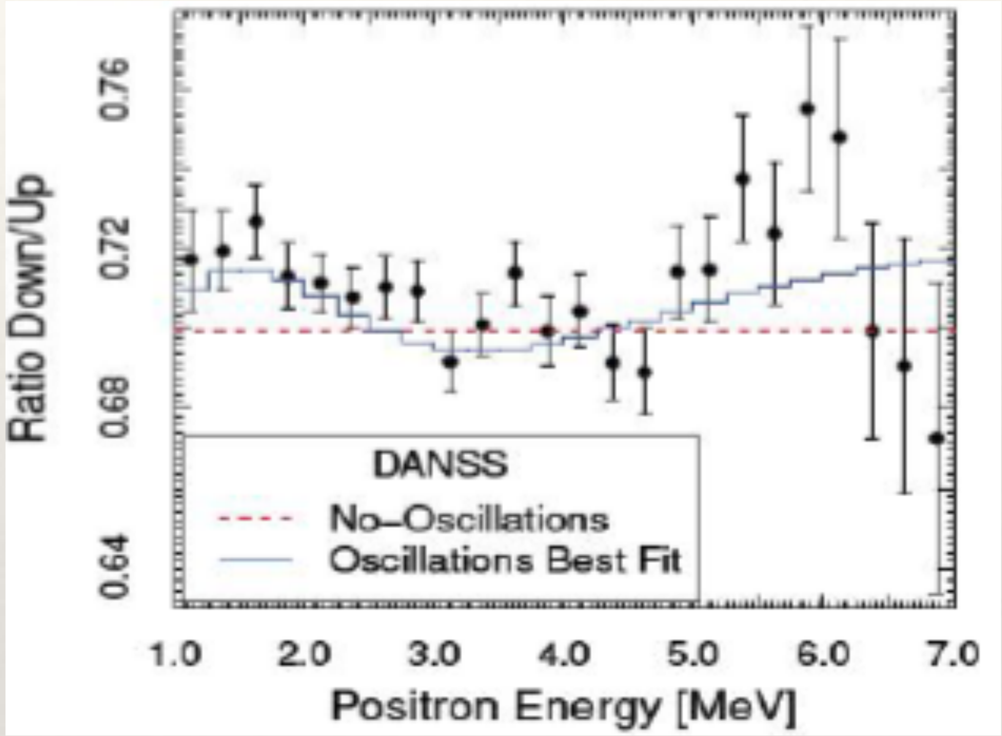
Very short baseline reactor experiments



NEOS and DANSS



Neos Collaboration PRL 2016



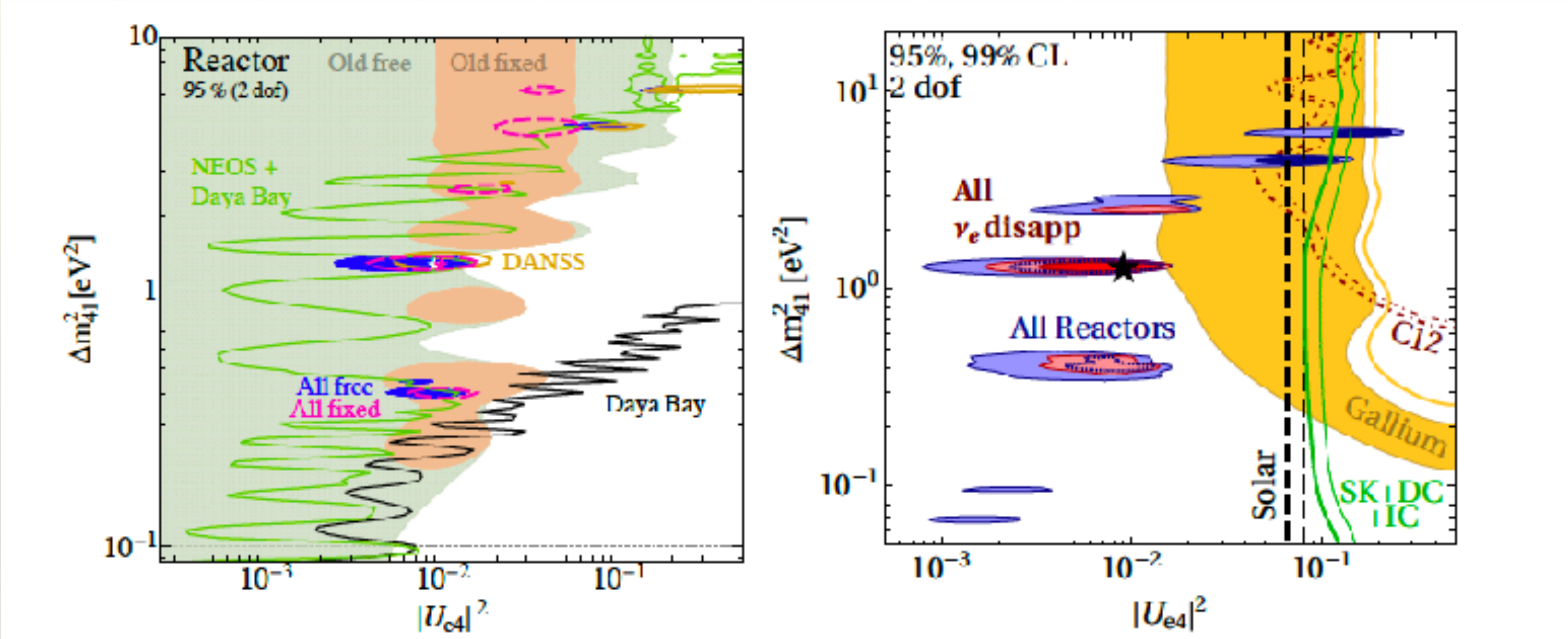
Danss collaboration, PLB 2018

Comparison of measured spectra at different baselines

Insensitive to flux calculation uncertainty

Bounds from reactor searches

$$P_{\alpha\alpha}^{\rm SBL} = 1 - 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)\,\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$



(a) (b)

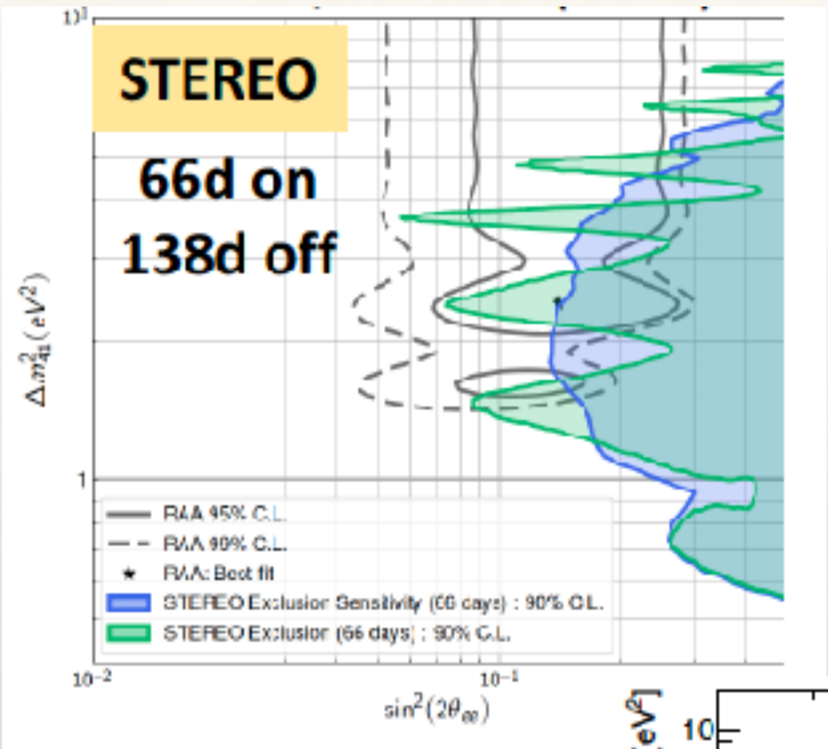
Dentler et al. JHEP 2018

Blue shaded regions allowed by fitting all reactor data with free fluxes

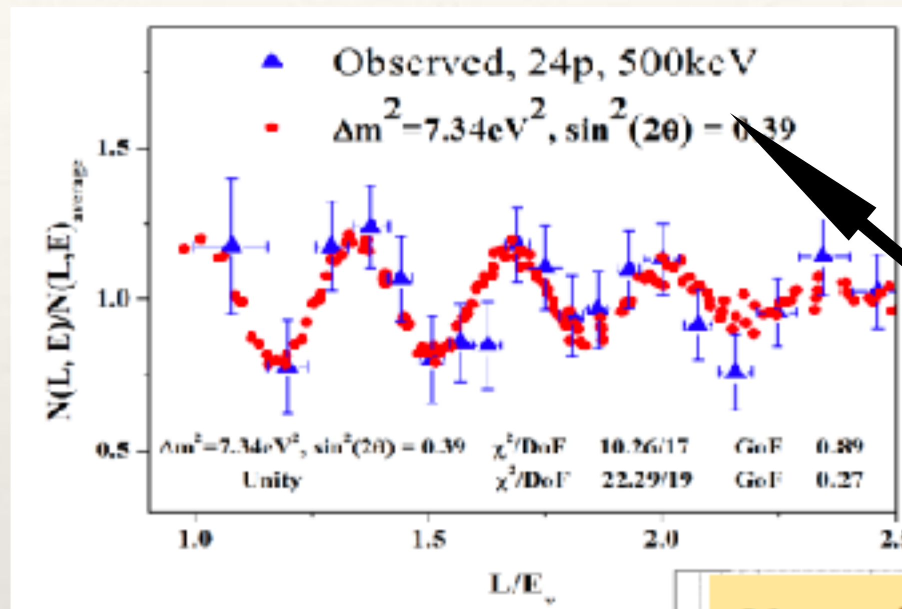
DANSS 2019 results give a lower Δm_{41}^2

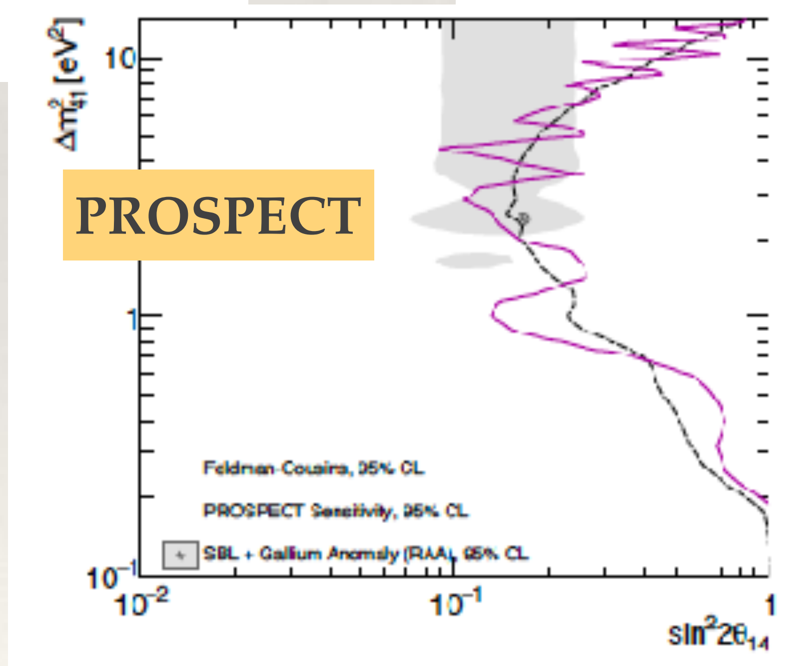
Danilov, talk at EPSHEP 2019
Ternes talk at CERN 2019

New results from reactor experiments

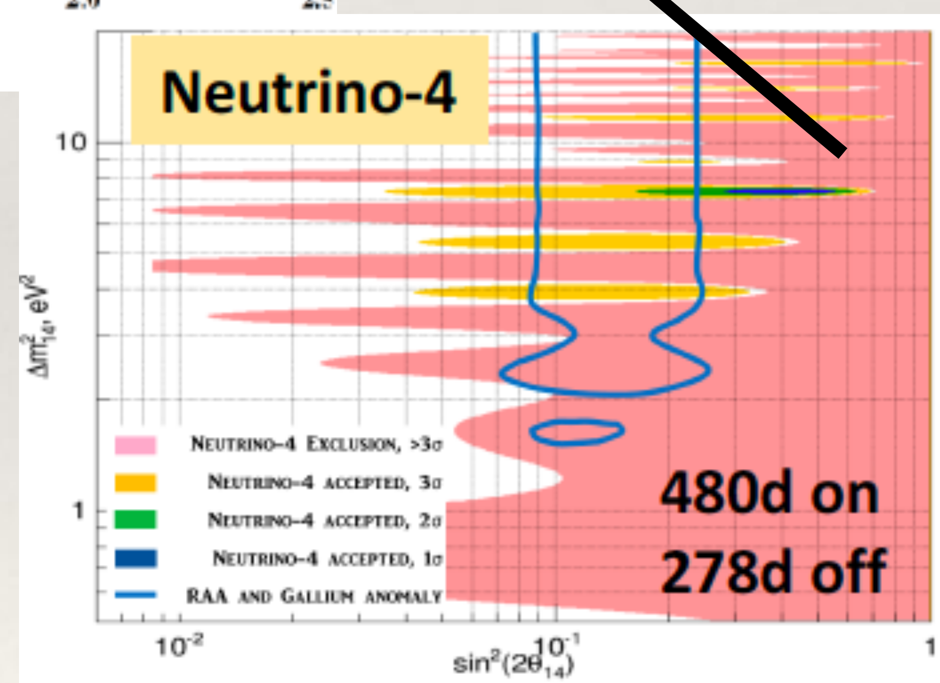


PRL 121 160821 2018





PRL 12 251802, 2018

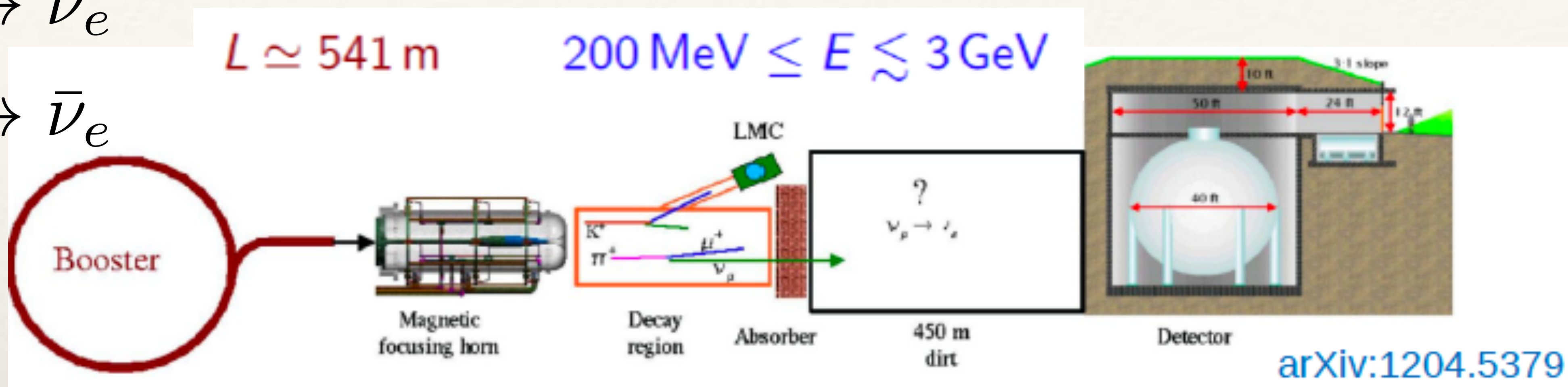


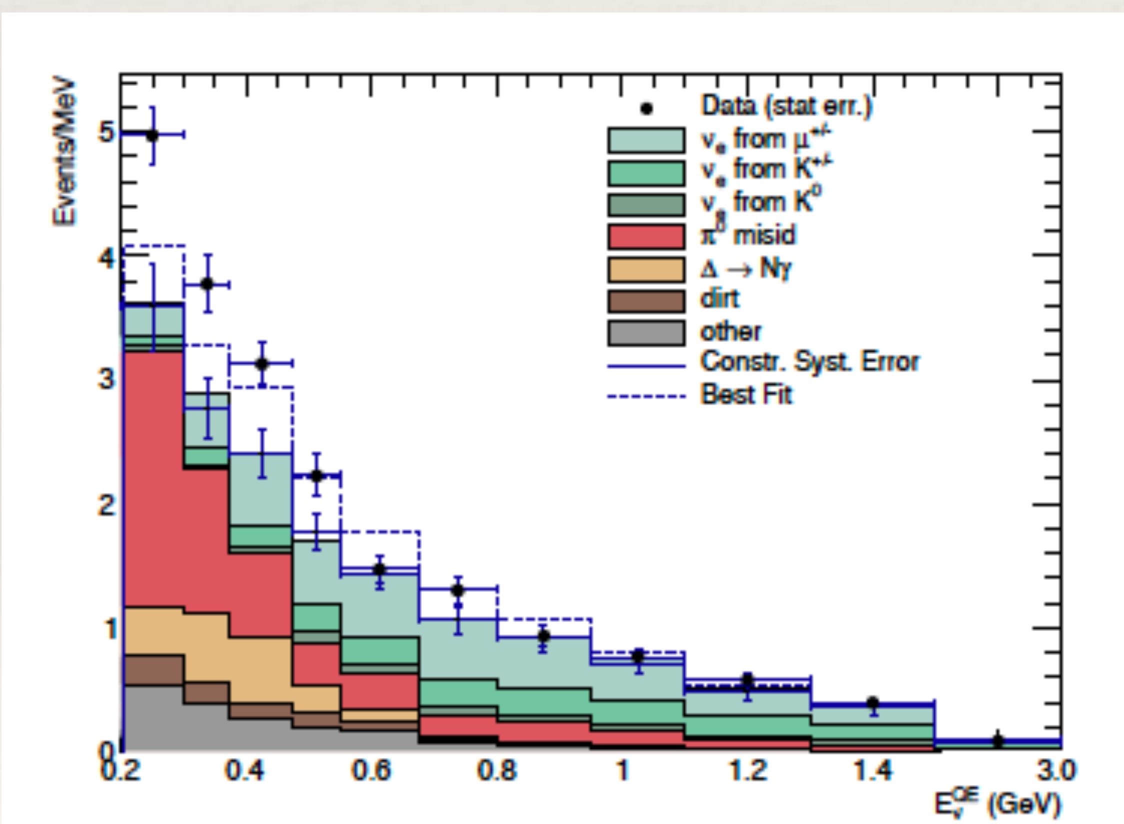
JETP letters 109, 213 2019

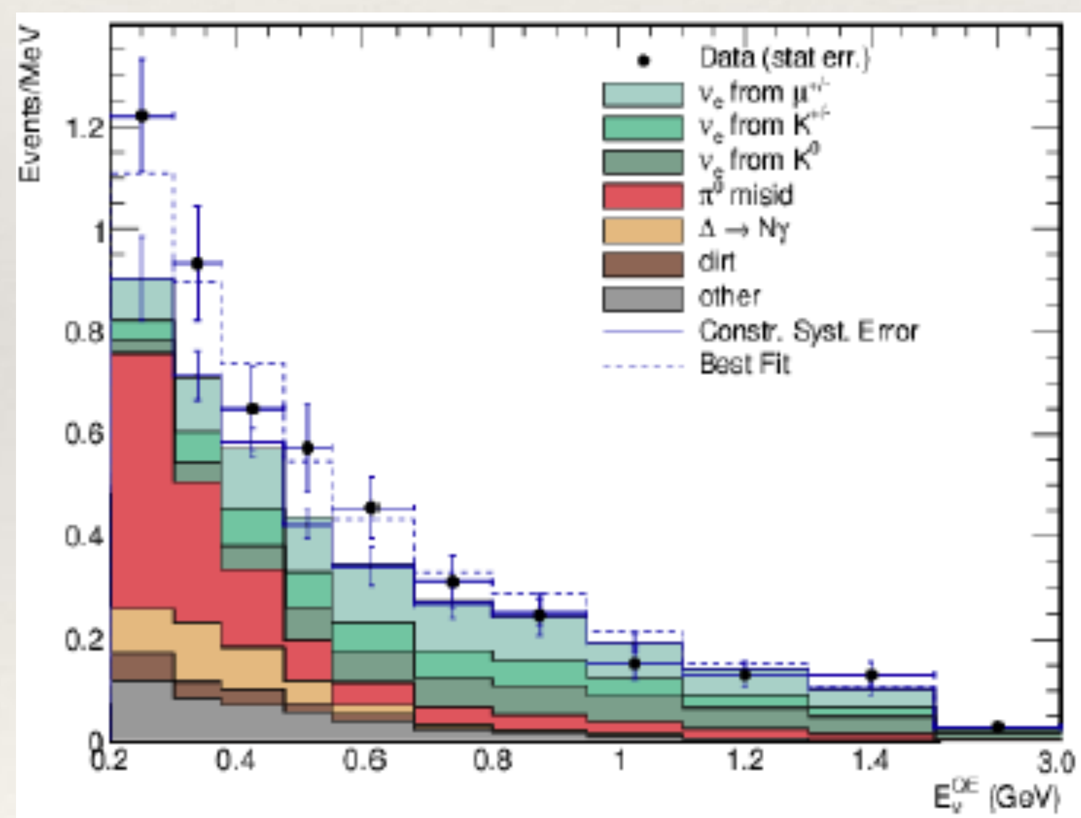
MiniBoone

$\nu_\mu \to \nu_e$

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

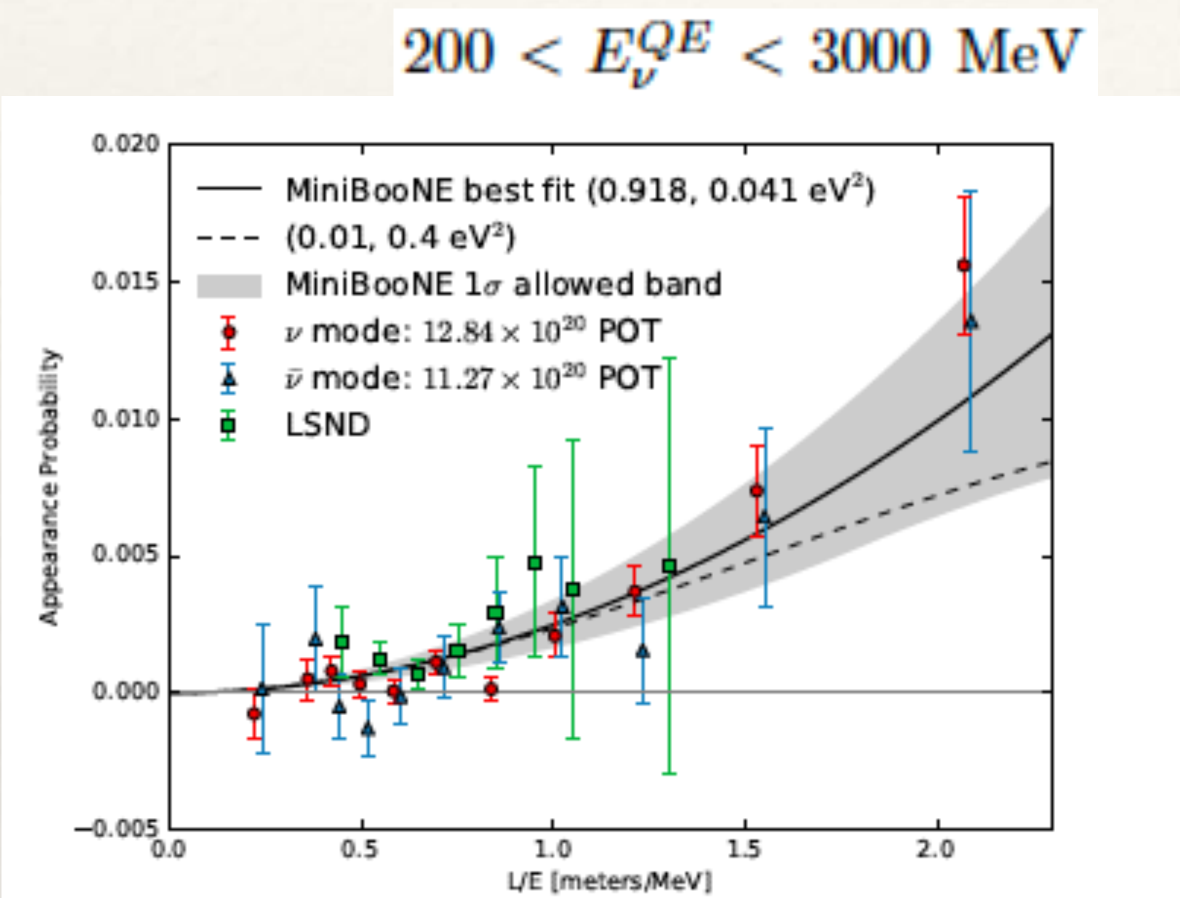






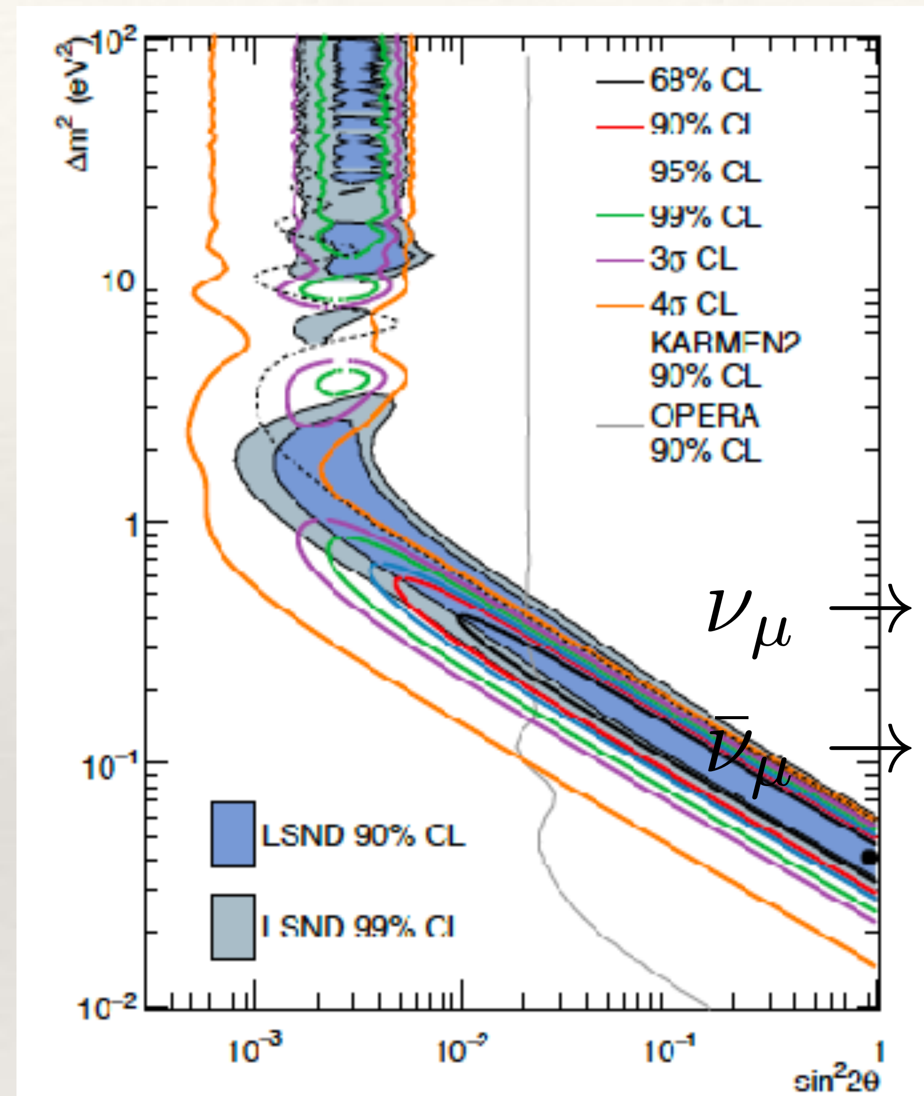
A.A. Aguilar Arevalo, PRL 121, 221801, 2018.

LSND and MiniBoone



Combined significance $\sim 6\sigma$

A.A. Aguilar Arevalo, PRL 121, 221801, 2018.



$\nu_\mu \to \nu_e$

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

Two neutrino fit

MiniBoone : neutrino + antineutrino

Disappearance and appearance tension

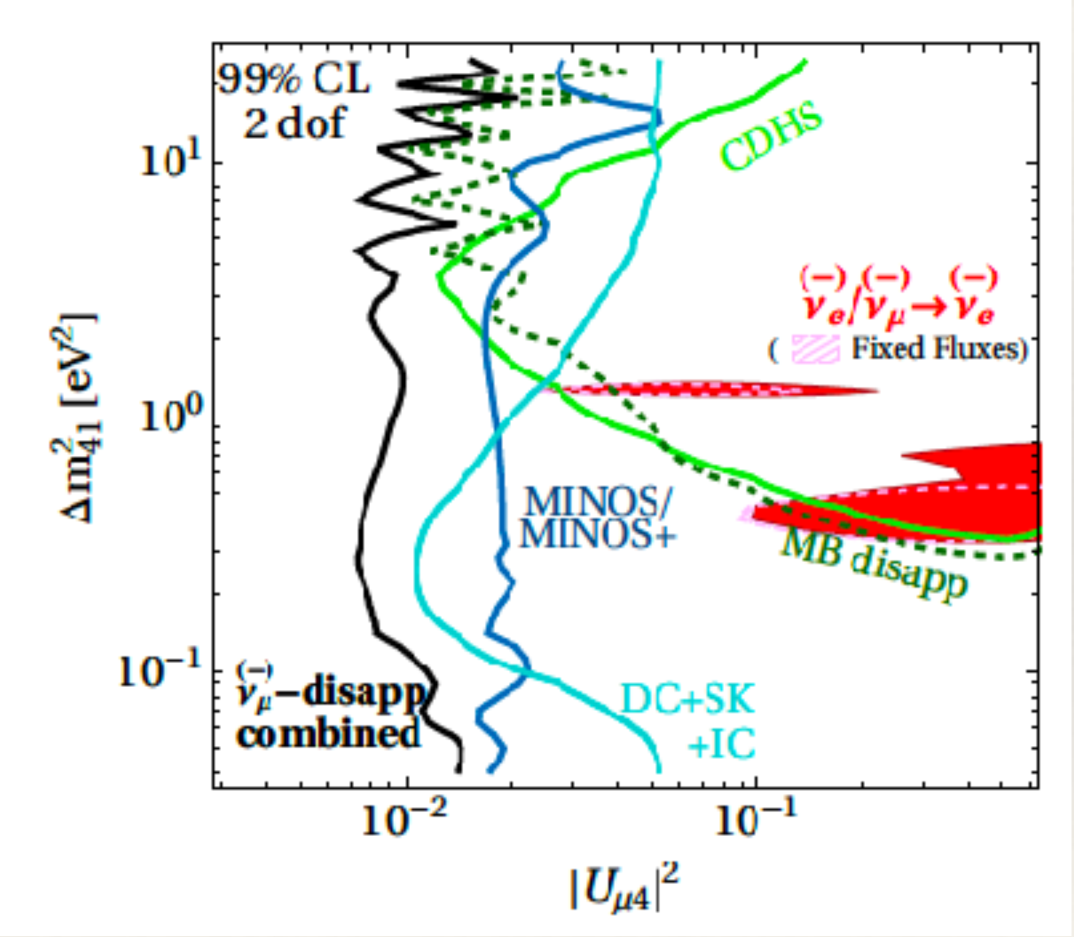
$$P_{\alpha\alpha}^{\rm SBL} = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P_{\alpha\beta}^{\rm SBL} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2\sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right).$$

P_{ee} depends on $|U_{e4}|^2$

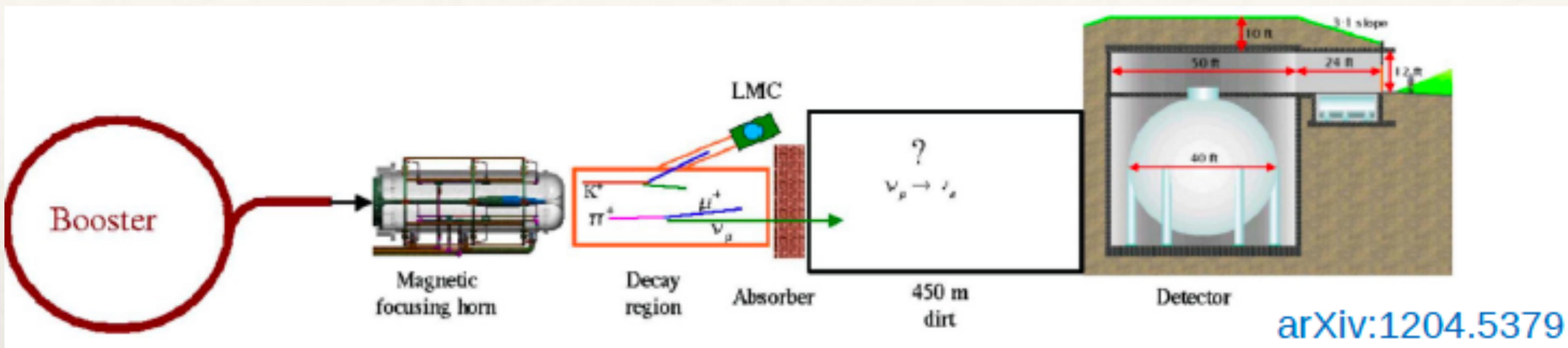
$P_{\mu\mu}$ depends on $|U_{\mu 4}|^2$

$P_{\mu e}$ depends on $|U_{\mu 4}|^2 |U_{e4}|^2$

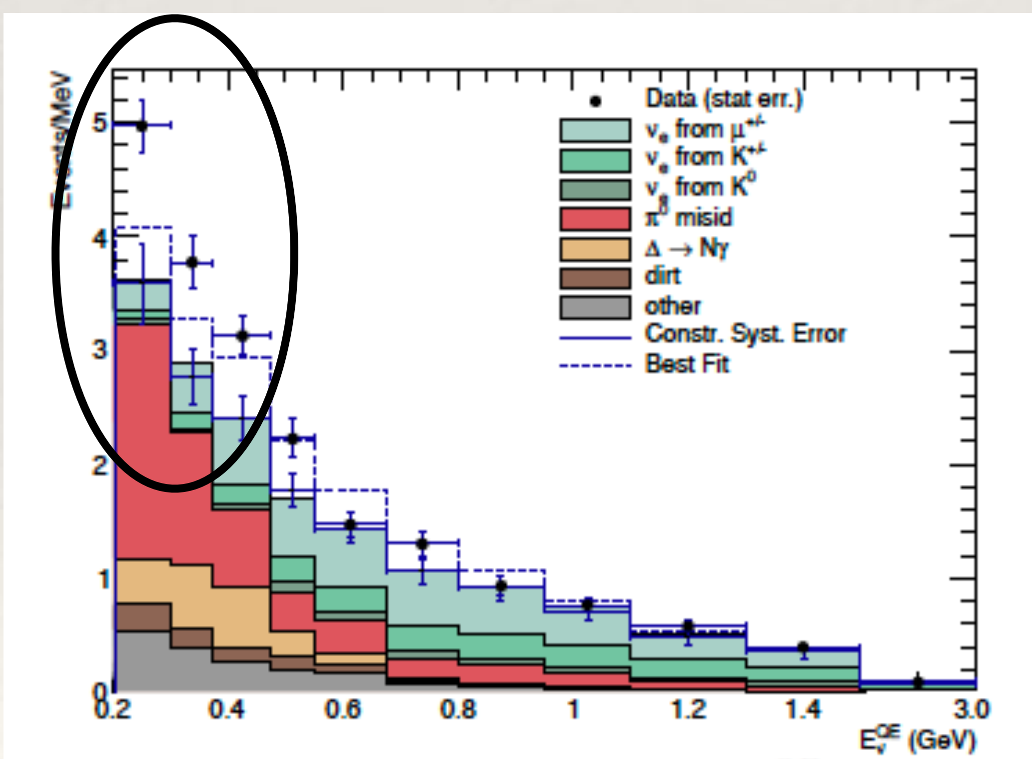


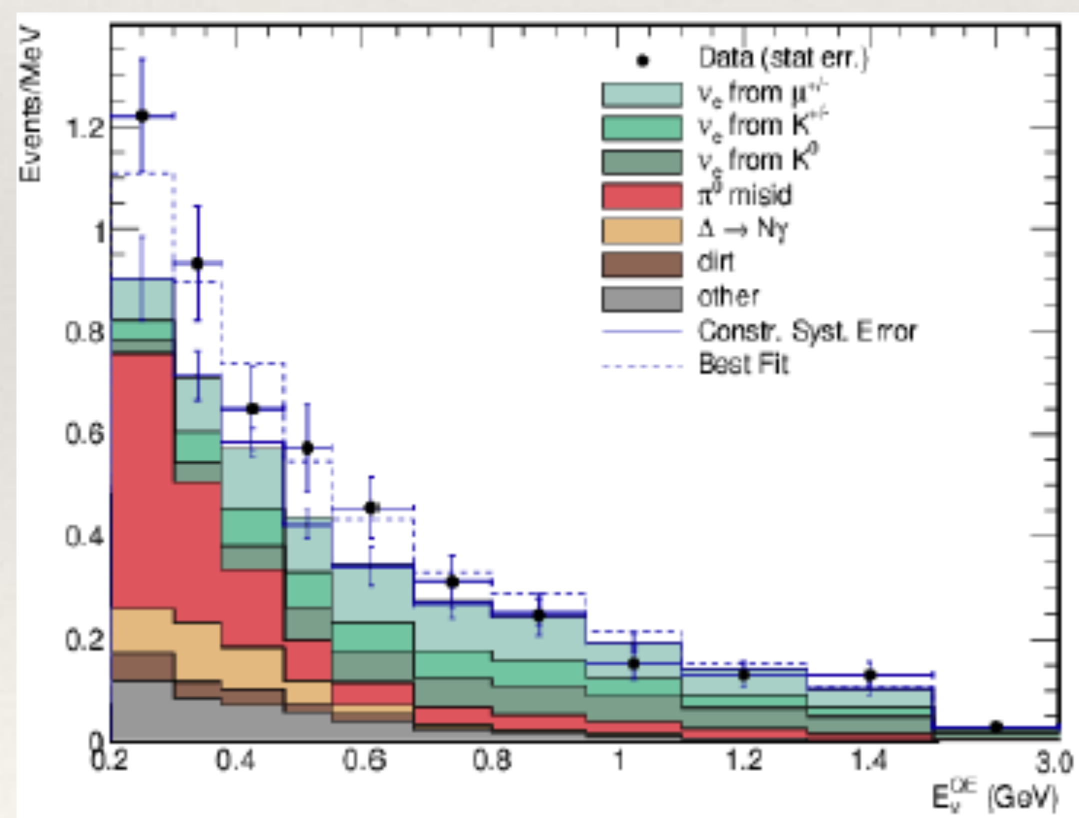
Dentler, Hernandez-Cabezudo,Kopp, Maltoni, Schwetz,JHEP 2017

Low Energy Excess in MiniBoone

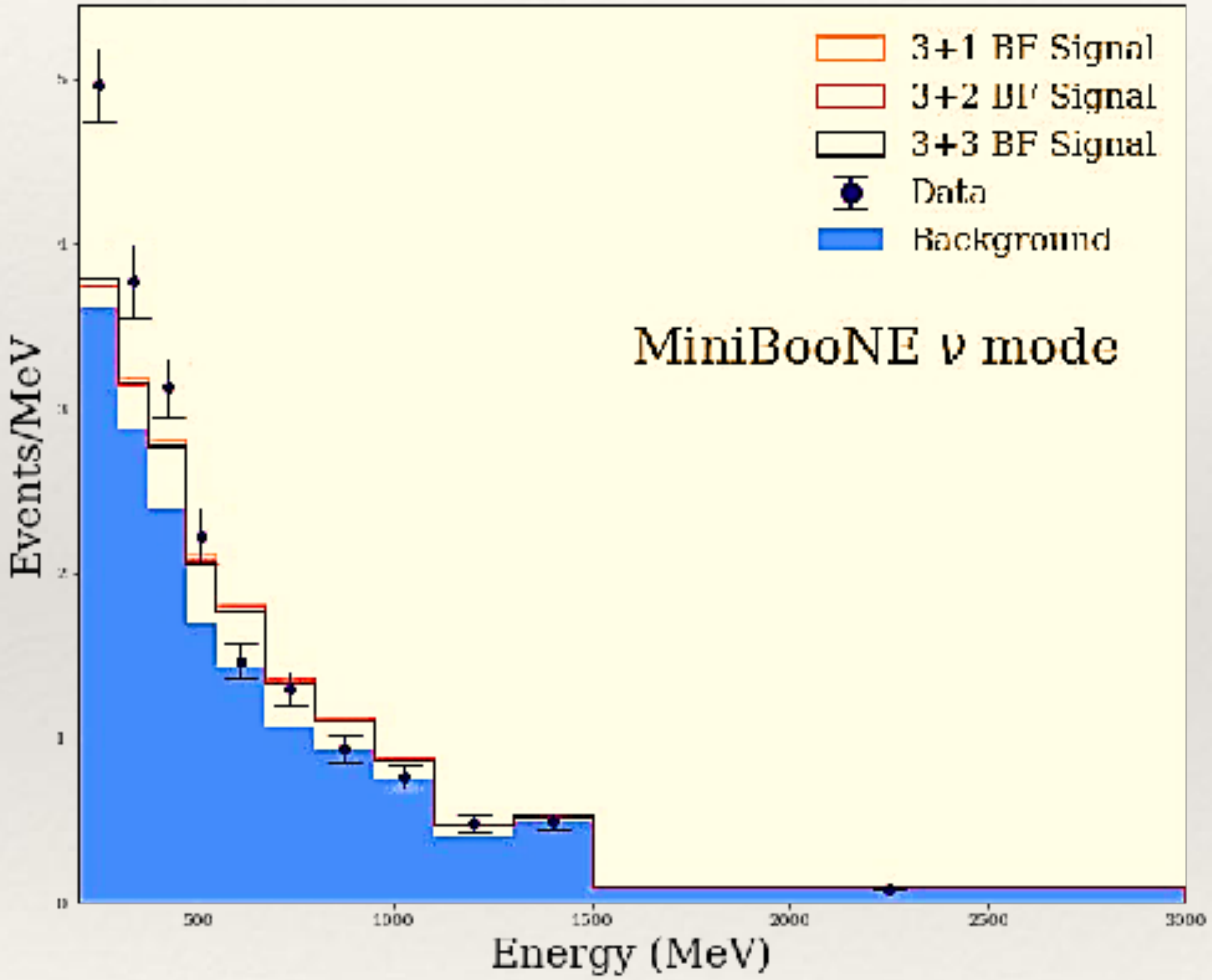


4.5σ
Excess





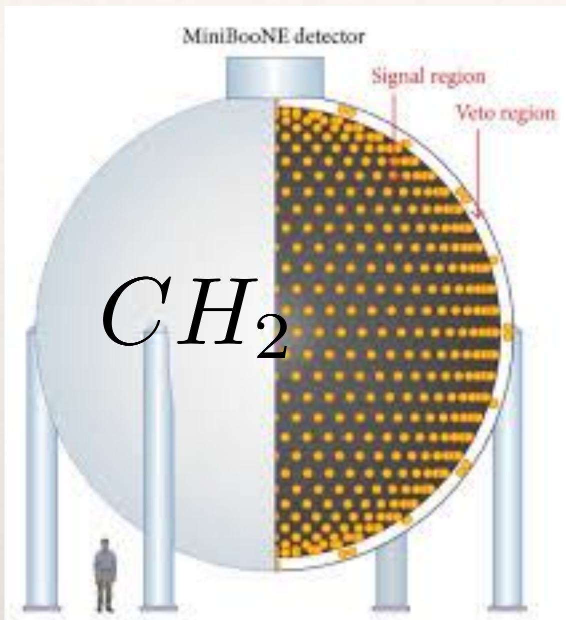
Can sterile neutrinos explain this ?

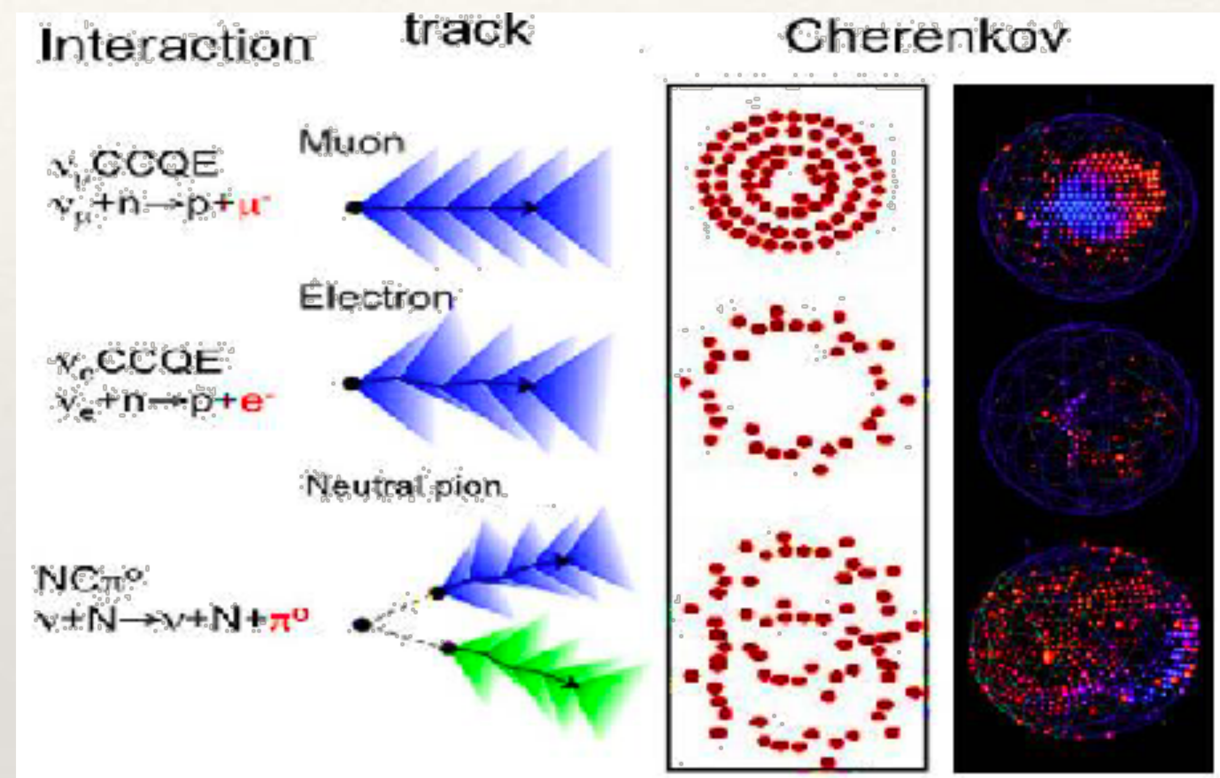


3+N sterile neutrino scenario cannot explain the MiniBoone low energy excess

D. Cianci , talk at Applied Antineutrino Physics Workshop 2018

Is it due to background effect ?





From : S. Jana , Pheno 2019

Cannot distinguish between Cherenkov cone of electrons and single photon

The single photons coming from NC background cannot explain the excess

Alternative explanations

Dark Neutrino Portal to Explain MiniBooNE excess
Enrico Bertuzzo (Sao Paulo U.), Sudip Jana (Oklahoma Ctr. High Energy Phys. & Oklahoma State
Published in **Phys.Rev.Lett. 121 (2018) no.24, 241801**

Explaining the MiniBooNE excess by a decaying sterile neutrino with mass in the 250 MeV range
Oliver Fischer, Álvaro Hernández-Cabezudo, Thomas Schwetz (KIT, Karlsruhe, IKP). Sep 20, 2019. 26 pp.
e-Print: **arXiv:1909.09561 [hep-ph]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service

U(1)' mediated decays of heavy sterile neutrinos in MiniBooNE
Peter Ballett, Silvia Pascoli (Durham U., IPPP), Mark Ross-Lonergan (Nevis Labs, Columbia U.). Aug 8, 2018. 8 pp.
Published in **Phys.Rev. D99 (2019) 071701**
IPPP/18/70

Testing New Physics Explanations of MiniBooNE Anomaly at Neutrino Scattering Experiments
Carlos A. Argüelles (MIT, Cambridge, Dept. Phys.), Matheus Hostert (Durham U., IPPP), Yu-Dai Tsai (Fermilab). Dec 20, 2018. 7 pp.
IPPP/18/113, FERMILAB-PUB-18-686-A-ND-PPD-T
e-Print: **arXiv:1812.08768 [hep-ph]** | **PDF**

Severe Constraints on New Physics Explanations of the MiniBooNE Excess
Johnathon R. Jordan (Michigan U.), Yonatan Kahn (Princeton U. & Chicago U., KICP & Illinois U., Urbana (main))
2018. 7 pp.
Published in **Phys.Rev.Lett. 122 (2019) no.8, 081801**

Many more, apologies if your paper is not listed

Slide: D. Pramanik, Whepp 2019

Alternative Explanations

N. Gninenko,
The MiniBooNE anomaly and heavy neutrino decay,   Phys. Rev. Lett.103(2009)241802.

Abdullahi, M. Hostert, and S. Pascoli,
A Dark Seesaw Solution to Low Energy Anomalies:MiniBooNE, the muon(g−2 and BaBar, arXiv:2007.11813

O. Fischer, A. Hern´andez-Cabezudo, and T. Schwetz
Explaining the MiniBooNE excess by a decaying sterile neutrino with mass in the 250 MeV range, arXiv 1909.09561.

A. de Gouvêa, O. L.G. Peres, S. Prakash and G.V. Stenico,`
On The Decaying-Sterile Neutrino Solution to the Electron (Anti)Neutrino Appearance Anomalies,"
JHEP {07}, 141 (2020)

A. Datta, Kamali, and. Marfatia,
Dark sector origin of the KOTO and MiniBooNE anomalies, Phys. Lett. B807(2020) 135579,

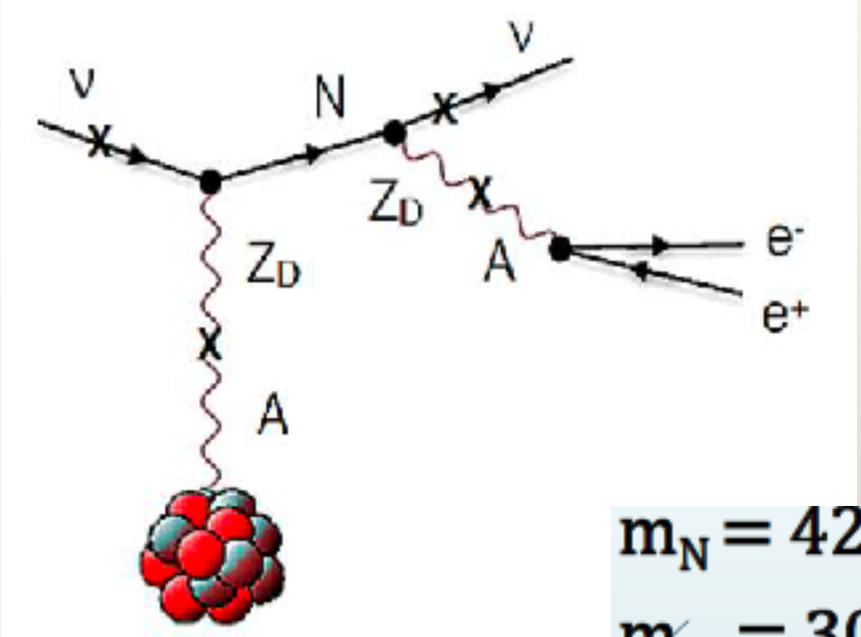
B. Dutta, S. Ghosh, and T. Li,
Explaining$(g-2)_{\mu,e}$, KOTO anomaly and MiniBooNE excess in an extended Higgs model with sterile neutrinos,
arXiv:2006.01319

W. Abdallah, R. Gandhi, and S. Roy,
Understanding the MiniBooNE and the muong−2 anomalies with a light$Z'$and a second Higgs doublet,
arXiv:2006.01948.

V. Brdar, O. Fischer and A. Y. Smirnov,
Model Independent Bounds on the Non-Oscillatory Explanations of the MiniBooNE Excess,"
[arXiv:2007.14411

Dark neutrino portal

$$\mathcal{L}_D \supset \frac{m^2_{Z_D}}{2} Z_{D\mu} Z^\mu_D + g_D Z^\mu_D\, J_{D\mu} + e\epsilon\, Z^\mu_D\, J^{\rm em}_\mu + \frac{g}{c_W}\epsilon'\, Z^\mu_D\, J^Z_\mu$$

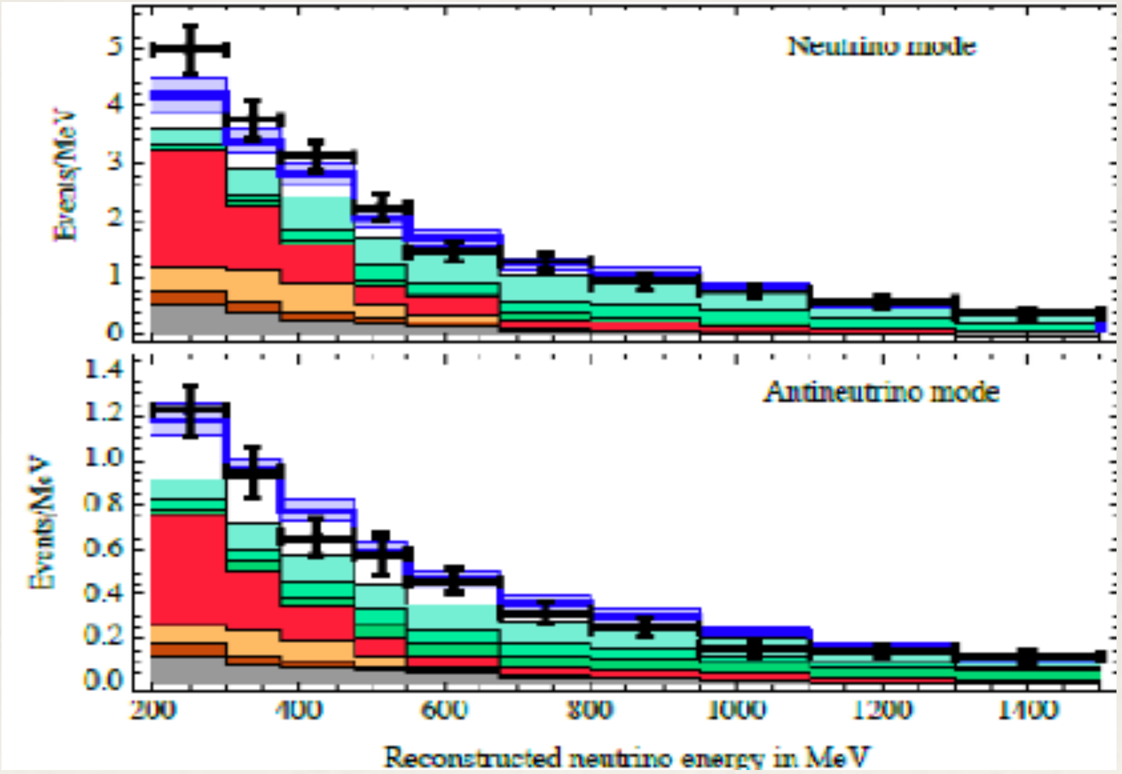


$m_N = 420$ MeV
$m_{Z_D} = 30$ MeV
$|U_{\mu 4}|^2 = 9\times10^{-7}$

$\alpha_D = 0.25$
$\alpha\varepsilon^2 = 2 \times 10^{-10}$
$\chi^2/\mathrm{dof} = 33.2/36$

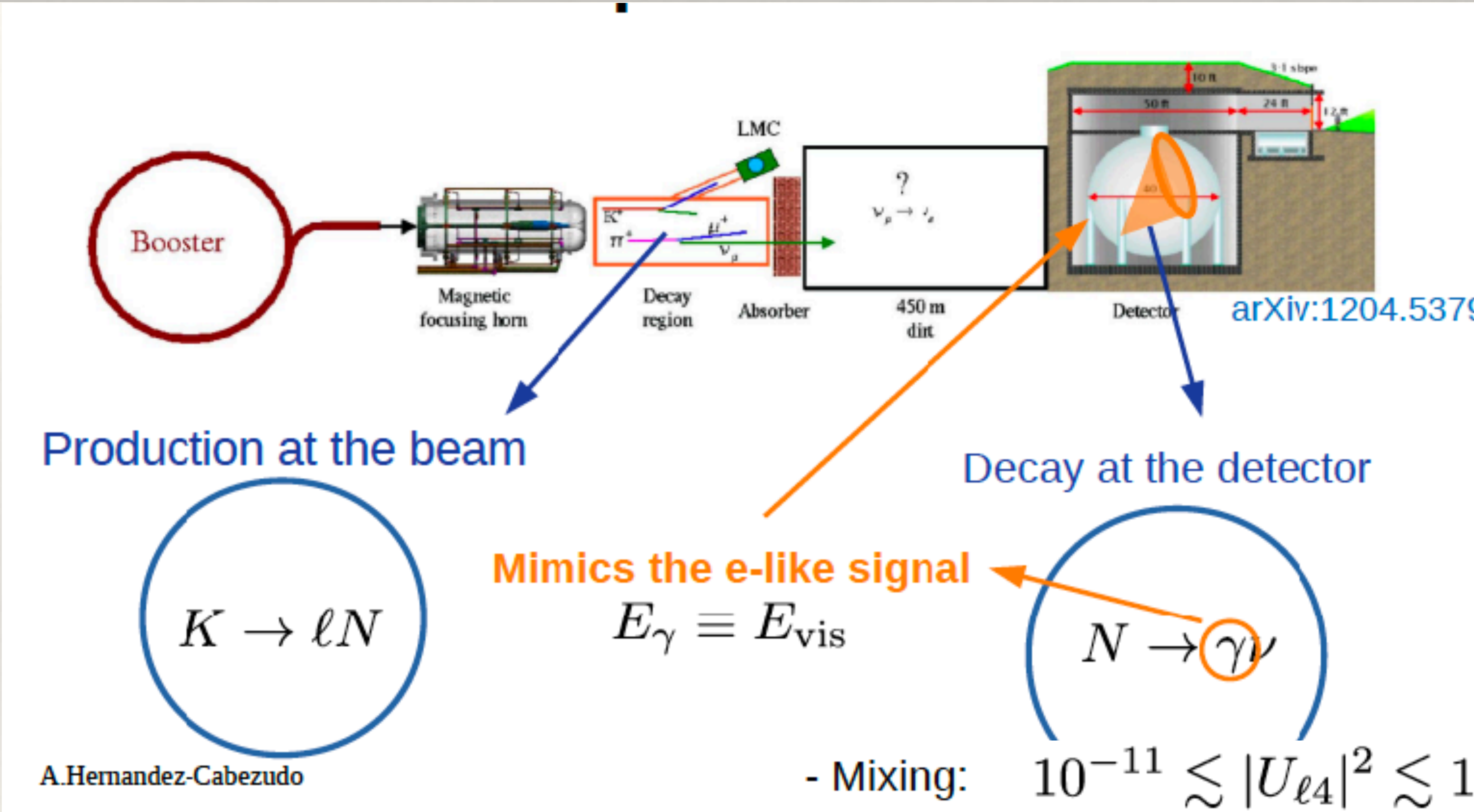
Explains the observed distribution

Right handed neutrinos part of dark sector



Bartuzzo, Jana, Machado, Zukanovich-Funchal, PRL 2018

Sterile neutrino decay



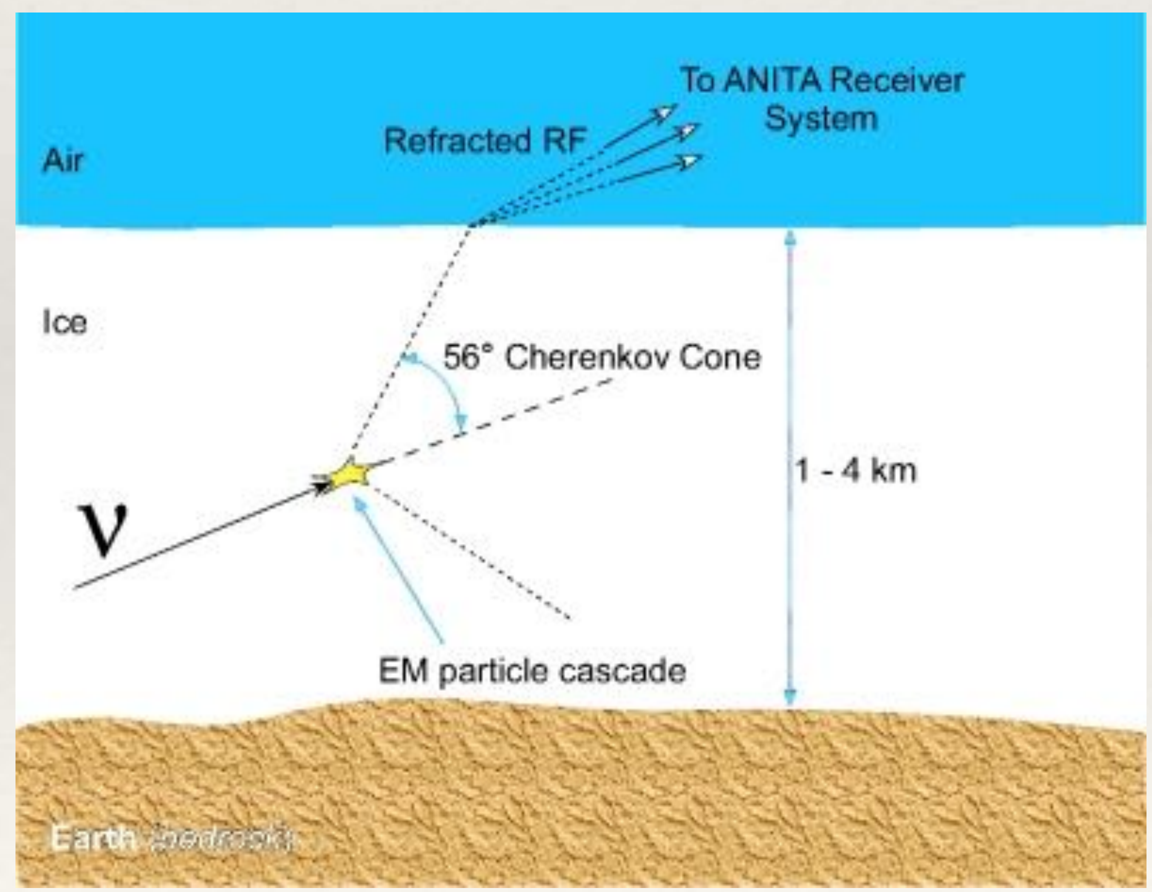
Fischer, Hernandez-Cabezudo, Schwetz, .1909 09501

- Mixing: $10^{-11} \lesssim |U_{\ell 4}|^2 \lesssim 10^{-7}$
- Mass: $\sim 250\,\mathrm{MeV}$
- New physics scale: $10^4\,\mathrm{TeV} \lesssim \Lambda \lesssim 10^7\,\mathrm{TeV}$

Antarctic Impulsive Transient Antenna

An array of radio antennas attached to a helium balloon which flies over the Antarctic ice sheet at 37,000 meters.

Aim to detect ultra high energy cosmic neutrinos



Anomalous events at ANITA

ANITA has detected two anomalous events coming from below

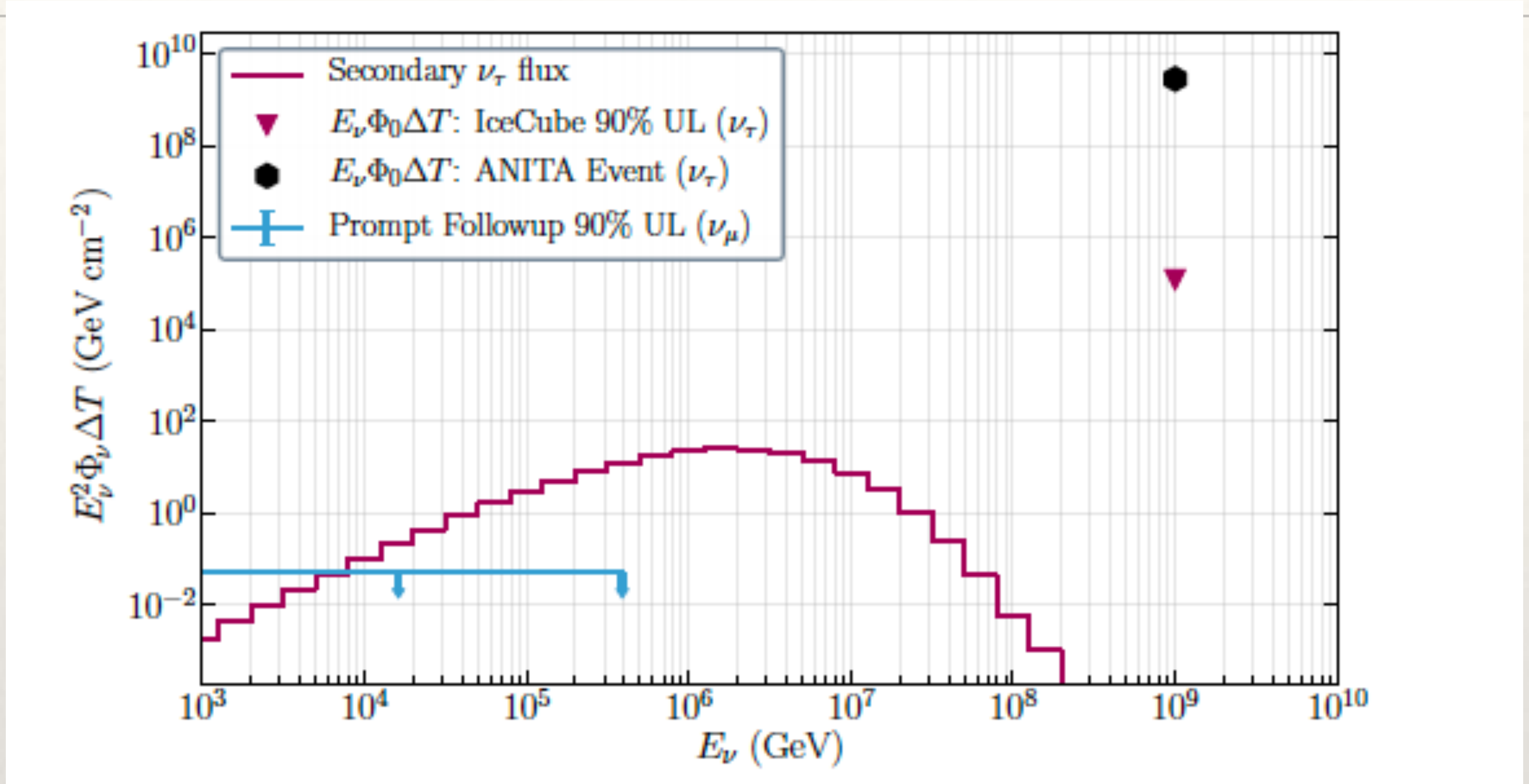
Characteristics closely matching an extensive air shower — can it be a τ-lepton decay-driven air shower ?

Difficult in SM framework , MFP much shorter at these energies, **New Physics ?**

	AAE-061228	AAE-141220	AC-150108
Detection Channel	Geomagnetic	Geomagnetic	Askaryan
Date (UTC)	2006-12-28	2014-12-20	2015-01-08
Time (UTC)	00:33:20.0	08:33:22.5	19:04:24.2
RA, Dec (J2000)	$282^\circ.14, +20^\circ.33$	$50^\circ.78, +38^\circ.65$	$171^\circ.45, +16^\circ.30$
Localization Uncertainty	$1^\circ.5 \times 1^\circ.5, 0^\circ.0$	$1^\circ.5 \times 1^\circ.5, 0^\circ.0$	$5^\circ.0 \times 1^\circ.0, +73^\circ.7$
Reconstructed Energy (EeV)	0.6 ± 0.4	$0.56^{+0.30}_{-0.20}$	≥ 10
Earth Chord Length (km)	5740 ± 60	7210 ± 55	-

Cherry andShoemaker,2019; Anchordoqui and others,2018; Huang,2018; Dudas and others,2018;Collins et al. ,2019; Chauhan and Mohanty,2019; Anchordoqui and Antoniadis,2019; Heurtier and others,2019; Hooper et al. 2019; Cline et al. ,2019, Borah et al. 2019

IceCube Search in the direction of Anita Candidates



Considered eight years of IceCube data and looked for correlations between the ocations of the ANITA events and the locations of the IceCube events.

No evidence for a neutrino source in the direction of the strange ANITA events

New Physics beyond SM ?

Aarsten et al. arXiv 2001.01737

Concluding Remarks

- Three neutrino oscillation paradigm well established
- Future experiments expected to determine hierarchy, octant and CP
- Can new physics be probed in these experiments — extra parameters giving rise to additional degeneracies
- Complementary information
- Sterile neutrino — oscillation explanation is trouble
- MiniBoone low energy excess — many ideas
- Future neutrinoless double beta decay experiments can test IO —new physics can give different predictions
- Interesting anomalies in Ultra high energy neutrino experiments

Concluding Remarks

- There are many issues in neutrino physics — still under mist.


Thank
you!!


BACKUP

Neutrinoless double beta decay experiments

Experiment	Isotope	Techinique	Total mass [kg]	Exposure [kg yr]	FWHM @ $Q_{\beta\beta}$ [keV]	Background [counts/keV/kg/yr]	$S^{0\nu}$ (90% C.L.) [10^{25} yr]
Past							
Cuoricino, [177]	^{130}Te	bolometers	40.7 (TeO_2)	19.75	5.8 ± 2.1	0.153 ± 0.006	0.24
CUORE-0, [178]	^{130}Te	bolometers	39 (TeO_2)	9.8	5.1 ± 0.3	0.058 ± 0.006	0.29
Heidelberg-Moscow, [179]	^{76}Ge	Ge diodes	11 (^{enr}Ge)	35.5	4.23 ± 0.14	0.06 ± 0.01	1.9
IGEX, [180, 181]	^{76}Ge	Ge diodes	8.1 (^{enr}Ge)	8.9	~ 4	$\lesssim 0.06$	1.57
GERDA-I, [165, 182]	^{76}Ge	Ge diodes	17.7 (^{enr}Ge)	21.64	3.2 ± 0.2	~ 0.01	2.1
NEMO-3, [183]	^{100}Mo	tracker + calorimeter	6.9 (^{100}Mo)	34.7	350	0.013	0.11
Present							
EXO-200, [184]	^{136}Xe	LXe TPC	175 (^{enr}Xe)	100	89 ± 3	$(1.7 \pm 0.2) \cdot 10^{-3}$	1.1
KamLAND-Zen, [185, 186]	^{136}Xe	loaded liquid scintillator	348 (^{enr}Xe)	89.5	244 ± 11	~ 0.01	1.9
Future							
CUORE, [187]	^{130}Te	bolometers	741 (TeO_2)	1030	5	0.01	9.5
GERDA-II, [172]	^{76}Ge	Ge diodes	37.8 (^{enr}Ge)	100	3	0.001	15
LUCIFER, [188]	^{82}Se	bolometers	17 (Zn^{82}Se)	18	10	0.001	1.8
MAJORANA D., [189]	^{76}Ge	Ge diodes	44.8 ($^{enr/nat}$Ge)	100 [a]	4	0.003	12
NEXT, [190, 191]	^{136}Xe	Xe TPC	100 (^{enr}Xe)	300	$12.3 - 17.2$	$5 \cdot 10^{-4}$	5
AMoRE, [192]	^{100}Mo	bolometers	200 (Ca^{enr}MoO_4)	295	9	$1 \cdot 10^{-4}$	5
nEXO, [193]	^{136}Xe	LXe TPC	4780 (^{enr}Xe)	12150 [b]	58	$1.7 \cdot 10^{-5}$ [b]	66
PandaX-III, [194]	^{136}Xe	Xe TPC	1000 (^{enr}Xe)	3000 [c]	$12 - 76$	0.001	11 [c]
SNO+, [195]	^{130}Te	loaded liquid scintillator	2340 (^{nat}Te)	3980	270	$2 \cdot 10^{-4}$	9
SuperNEMO, [196, 197]	^{82}Se	tracker + calorimeter	100 (^{82}Se)	500	120	0.01	10

[a] our assumption (corresponding sensitivity from Fig. 14 of Ref. [189]).
[b] we assume 3 tons fiducial volume.
[c] our assumption by rescaling NEXT.

Dell'Oro , Marcocci, Viel, Vissani, 2016