Neutrino Oscillations

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Disclaimer:

This is a theorist point of view

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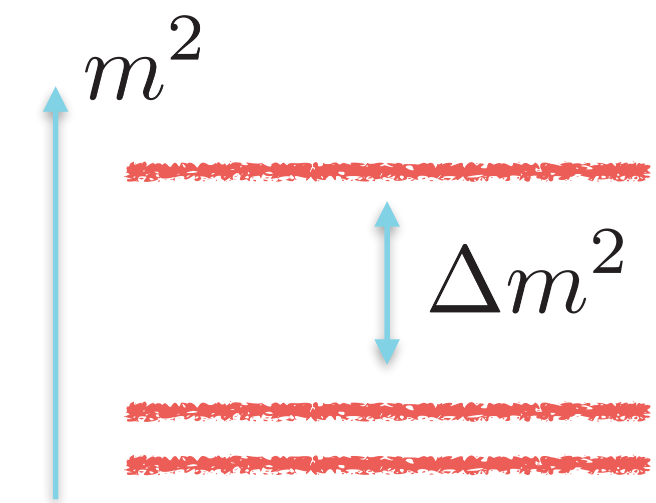
Neutrino oscillations in a nutshell

$$P(\nu_e \to \nu_e) \simeq 1 - \sin^2(2\theta_{13}) \sin^2 \left[1.27 \frac{(\Delta m^2/\mathrm{eV}^2)(L/\mathrm{km})}{(E/\mathrm{GeV})} \right]$$

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



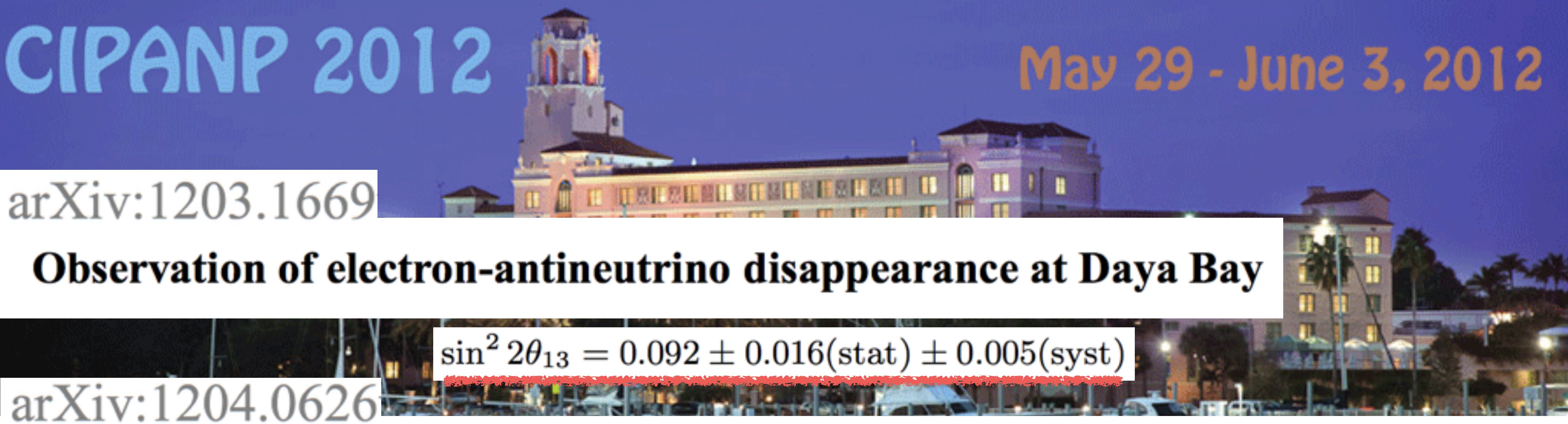
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

16:30 The first result from RENO experiment for θ_{13} (30') (Slides) — June Ho Choi (*Dongshin University*)

The RENO (Reactor Experiment for Neutrino Oscillation) experiment is to measure the smallest neutrino mixing angle $\theta_{13} using anti-neutrinos emitted from the Yonggwang nuclear power plant in Korea. It has been taking data with both near and far detectors since August 2011. The data-taking has been quite successful, and analysis is in progress to obtain inverse beta decay candidate events from reactor neutrinos. In this talk, we will present the status of data taking, the performance of the two detectors, and a preliminary result from the RENO experiment.

17:00 Results from the Daya Bay Reactor Neutrino Experiment (30') (Paper; Slides) — Jiajie Ling (*Brookhaven National Laboratory*)

The phenomenon of neutrino oscillation is well established, however an important neutrino mixing angle θ_{13} is still unknown. Among other things, this parameter is a key to determine CP violation in the leptonic sector. The Daya Bay Reactor Neutrino Experiment measures electron antineutrino disappearance, and is designed to determine $\sin^2(2\theta_{13})$ with sensitivity better than 0.01 at 90\% C.L. Multiple ``identical" antineutrino detectors are placed underground at different distances from the reactor cores to minimize the systematic errors and suppress cosmogenic backgrounds. The experiment has been taking data since August 15, 2011. The current status, including the most recent results, and future plans of the experiment will be presented.



arXiv:1203.1669

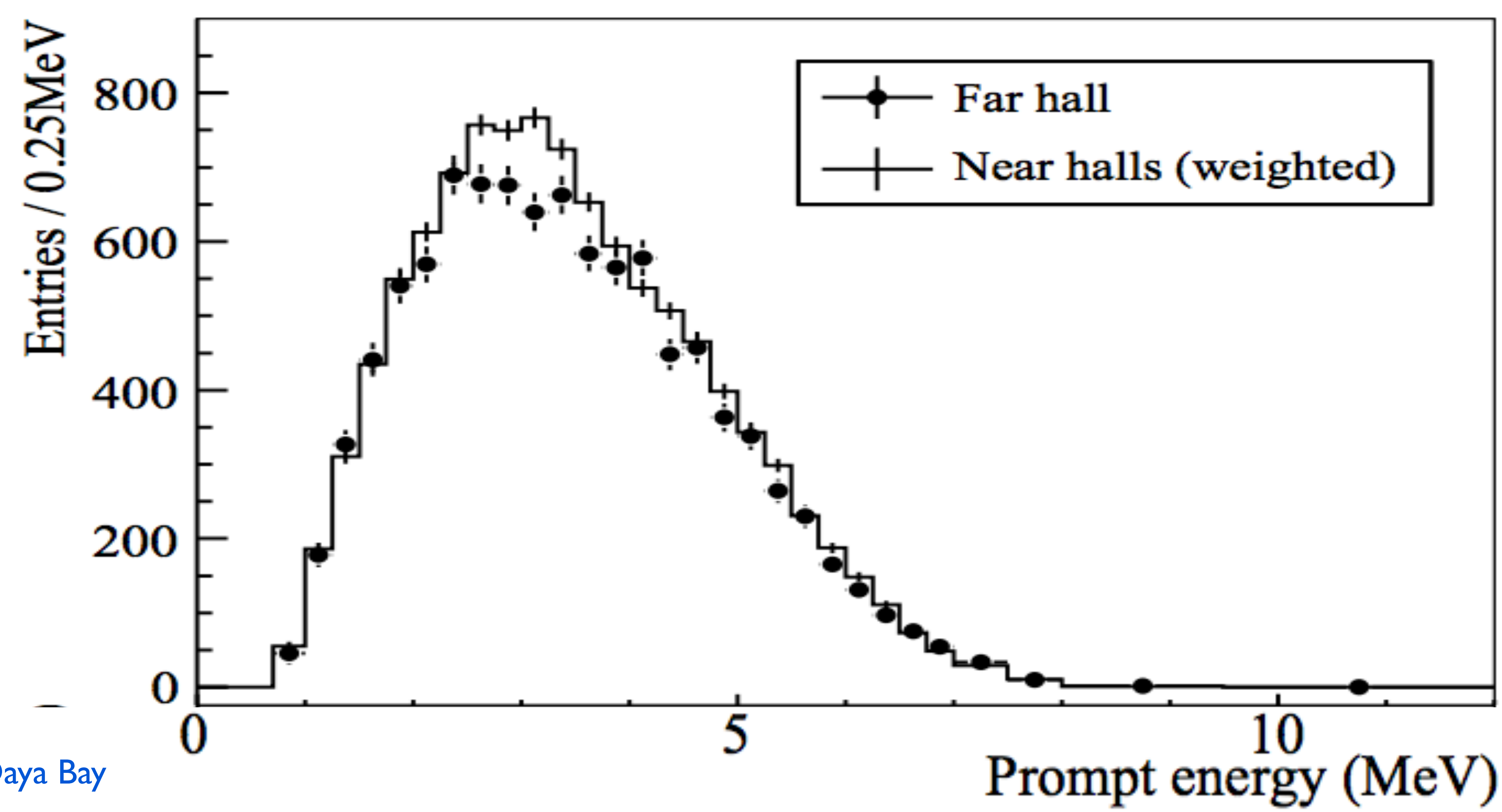
Observation of electron-antineutrino disappearance at Daya Bay

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$

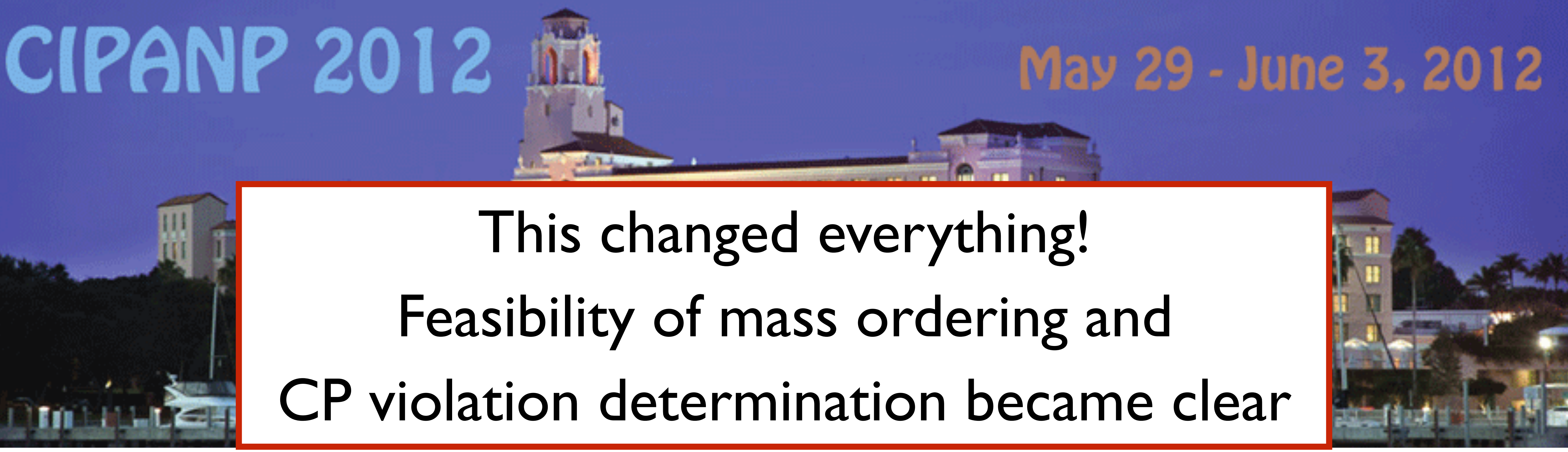
arXiv:1204.0626

Observation of Reactor Electron Antineutrino Disappearance in the RENO Experiment

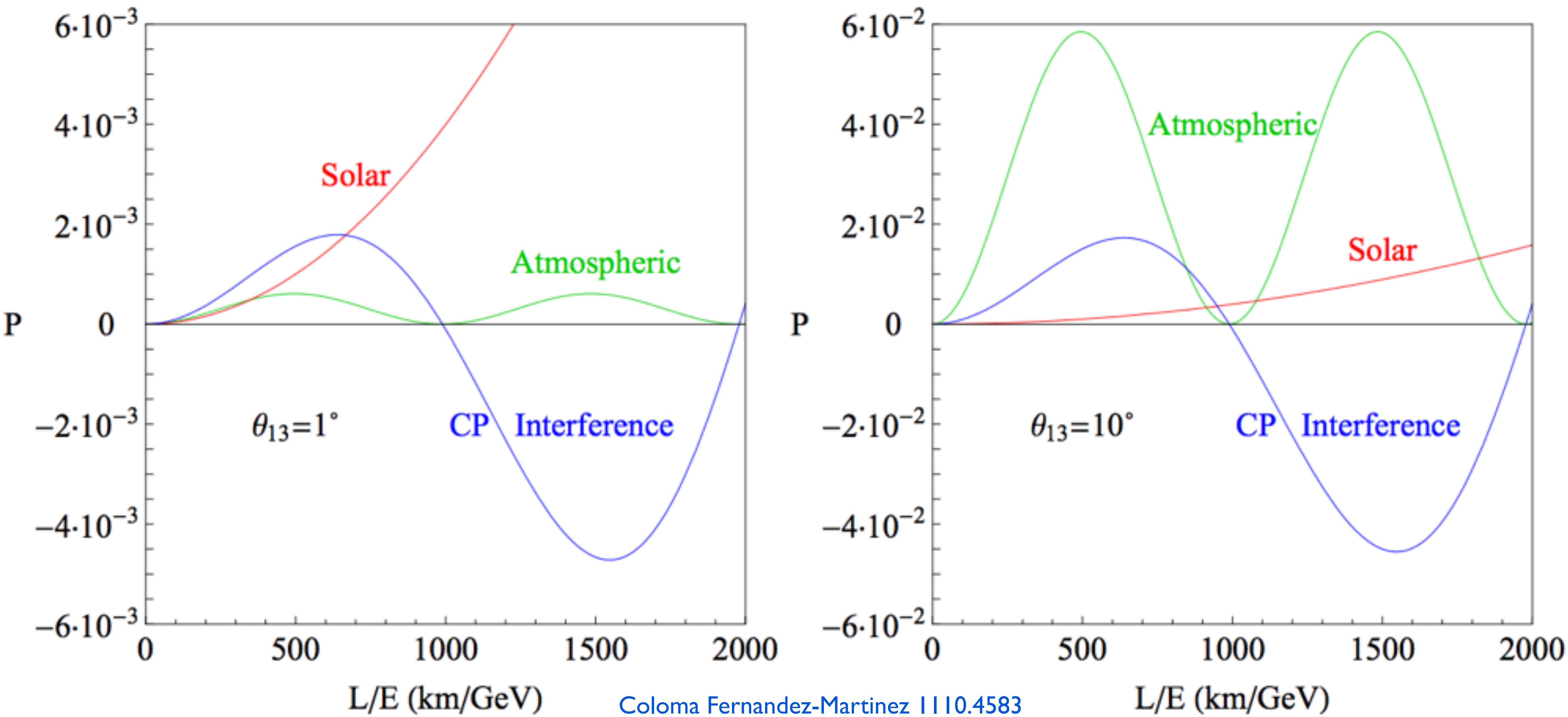
$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$$



Daya Bay



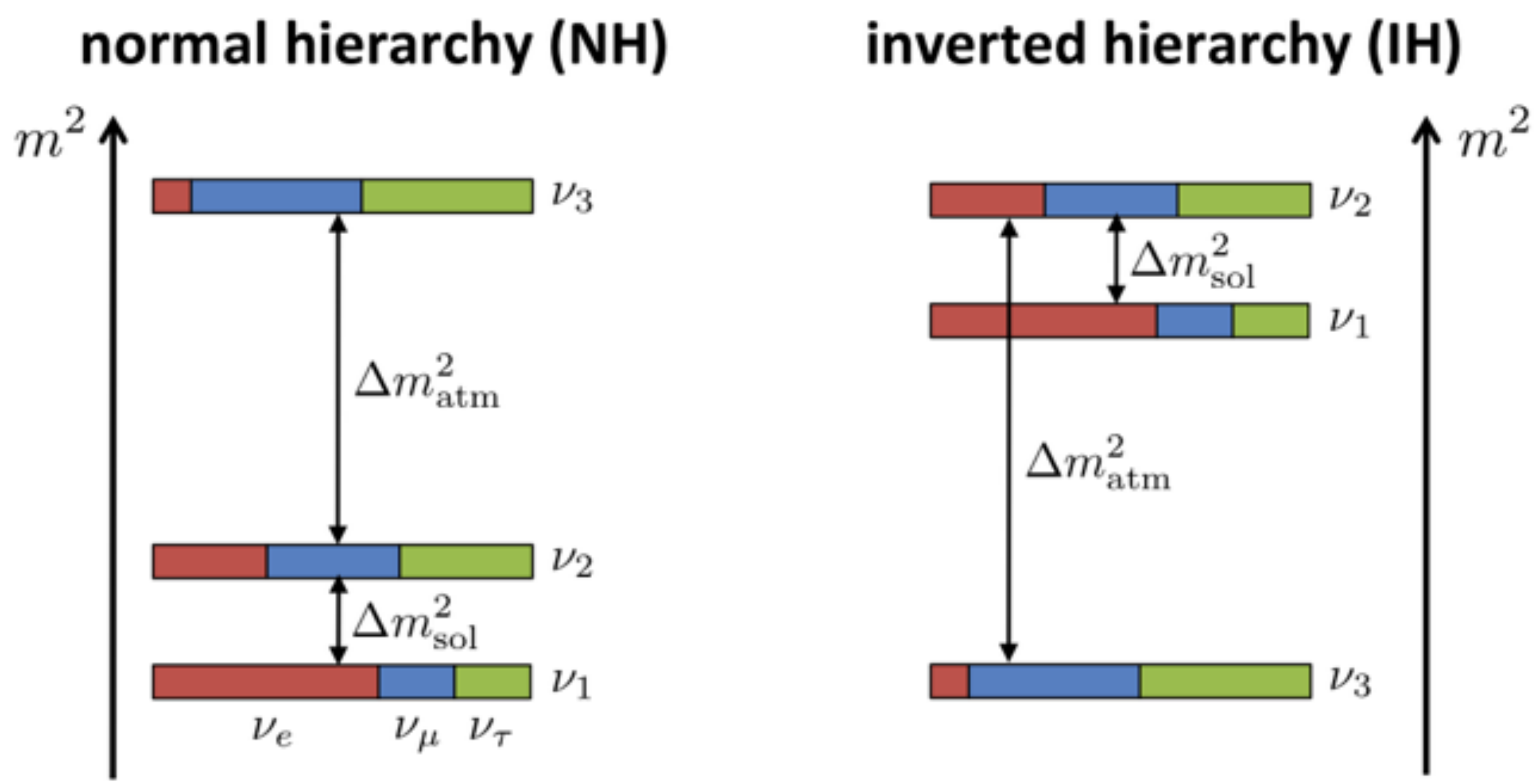
This changed everything!
Feasibility of mass ordering and CP violation determination became clear



Coloma Fernandez-Martinez 1110.4583

Neutrino oscillations

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



Neutrino oscillations

Δm^2_{21}: LBL reactor (KamLAND), Solar (Borexino, SK, SNO)

θ_{12}: LBL reactor (KamLAND), Solar (Borexino, SK, SNO)

θ_{13}: SBL reactor (Daya Bay, RENO, DChooz)

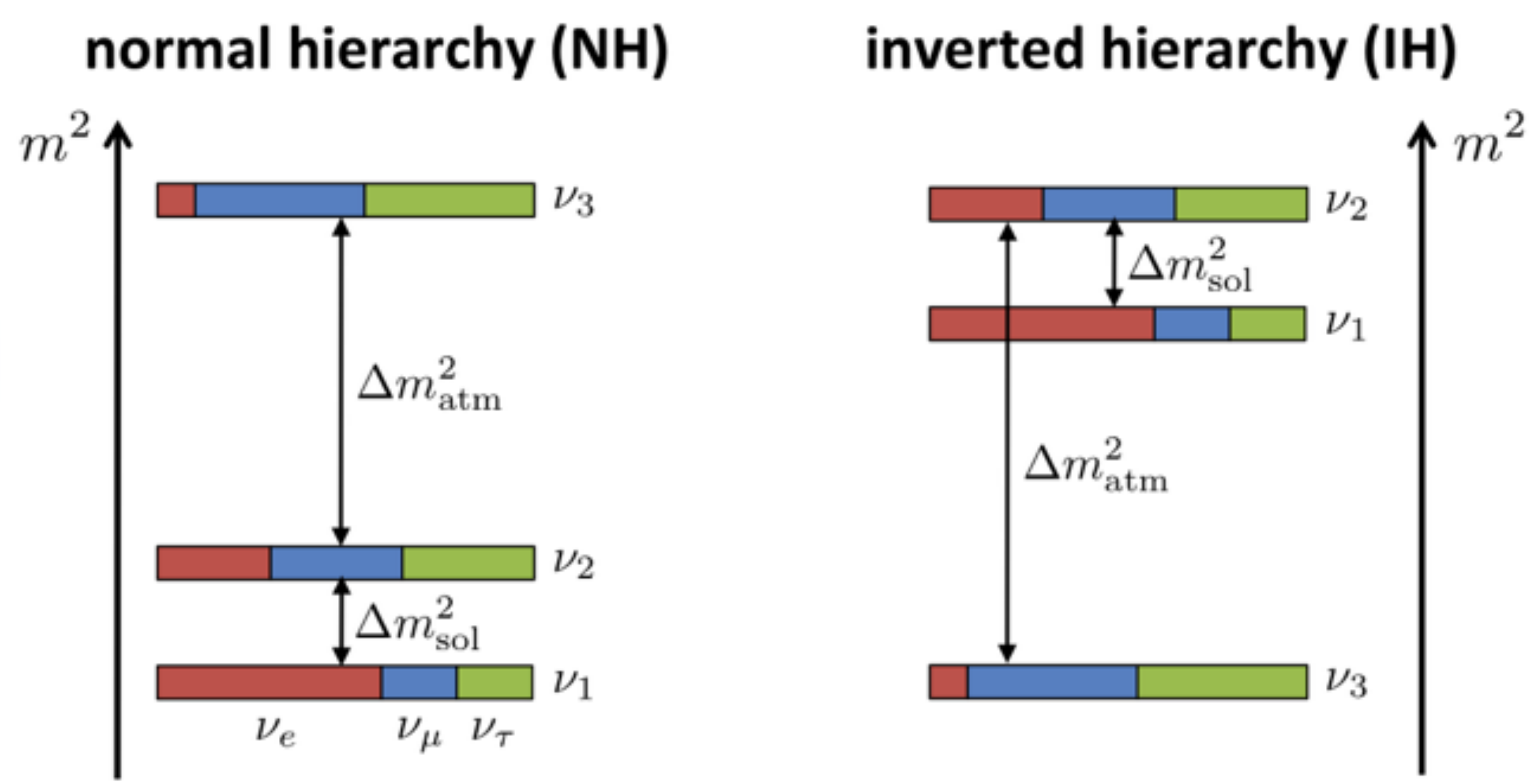
Δm^2_{31}: Accel. (NOvA, T2K), SBL reactor (Daya Bay, RENO)

θ_{23}: Accel. (NOvA, T2K), atmospherics (SK)

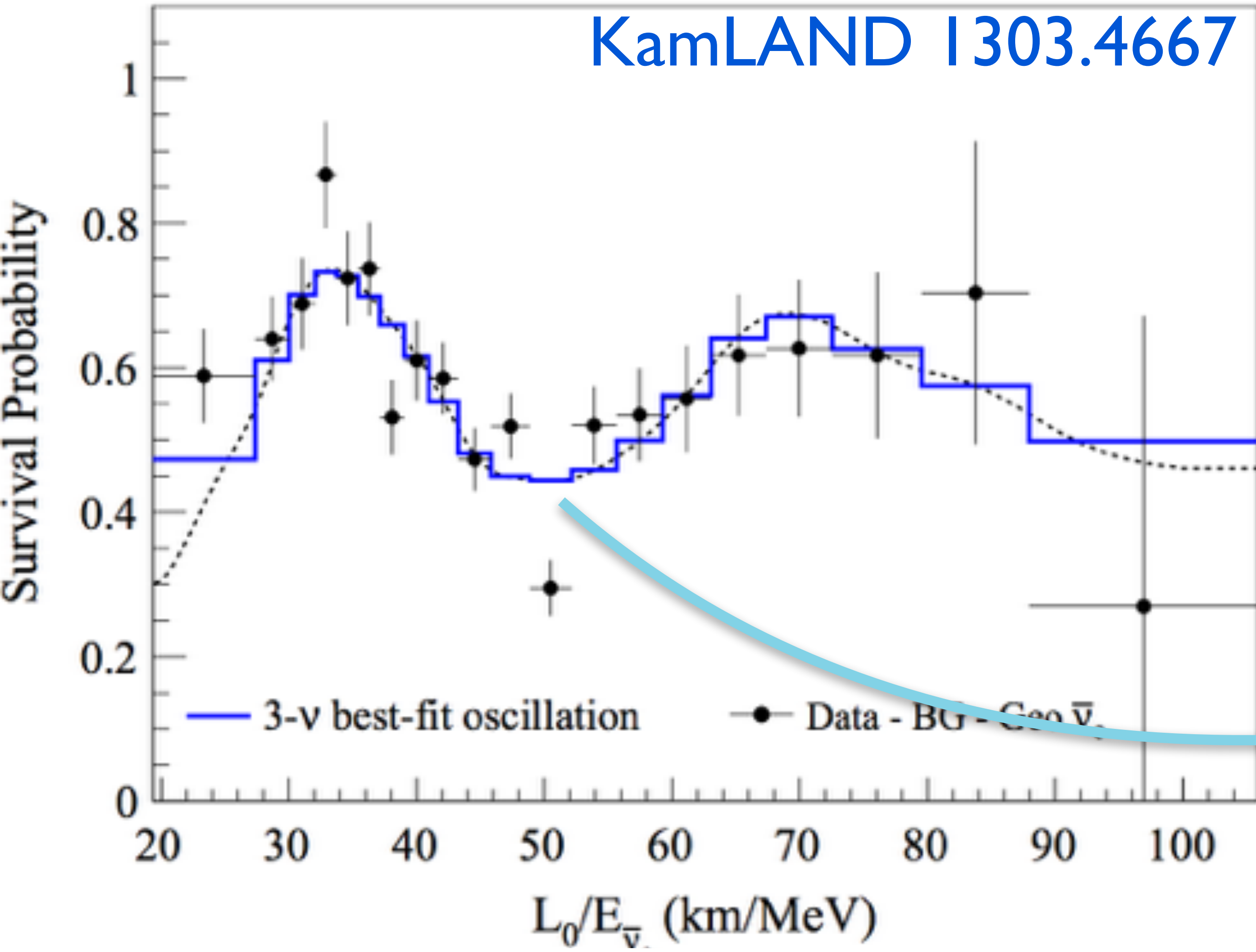
δ_{CP}: Accel. (NOvA, T2K)

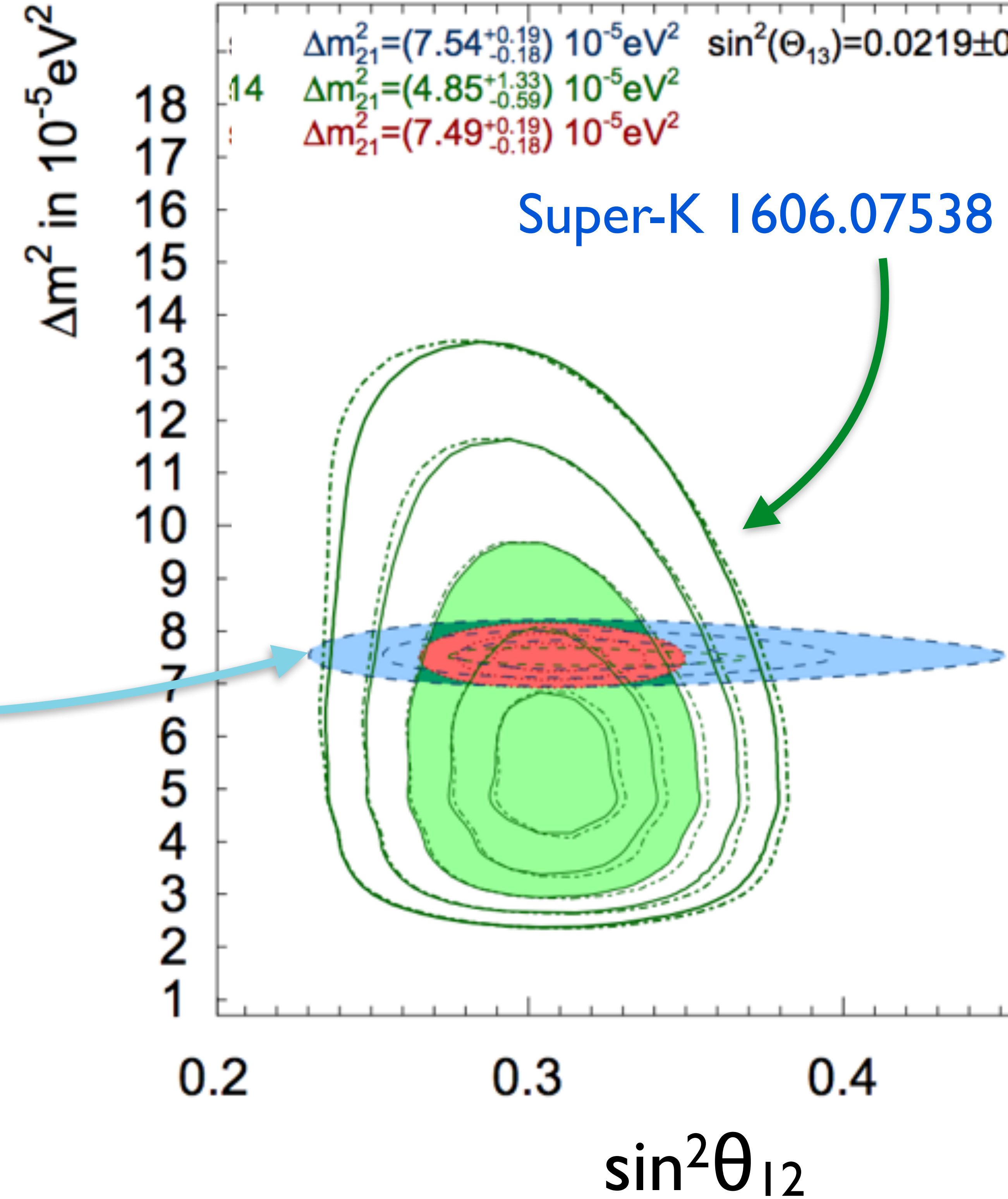
Mass ordering: Accel. (NOvA, T2K), atmospherics (SK)

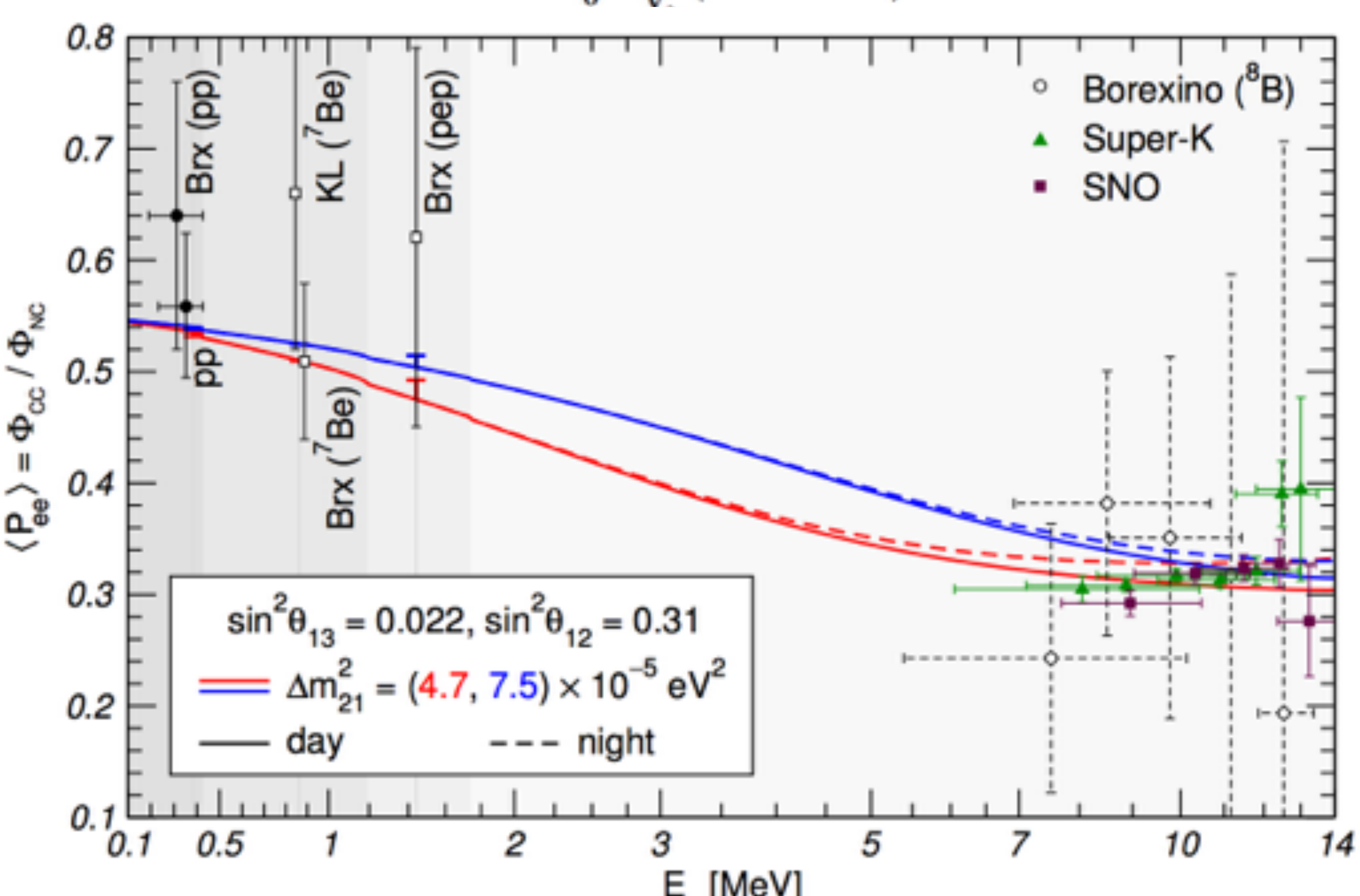
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



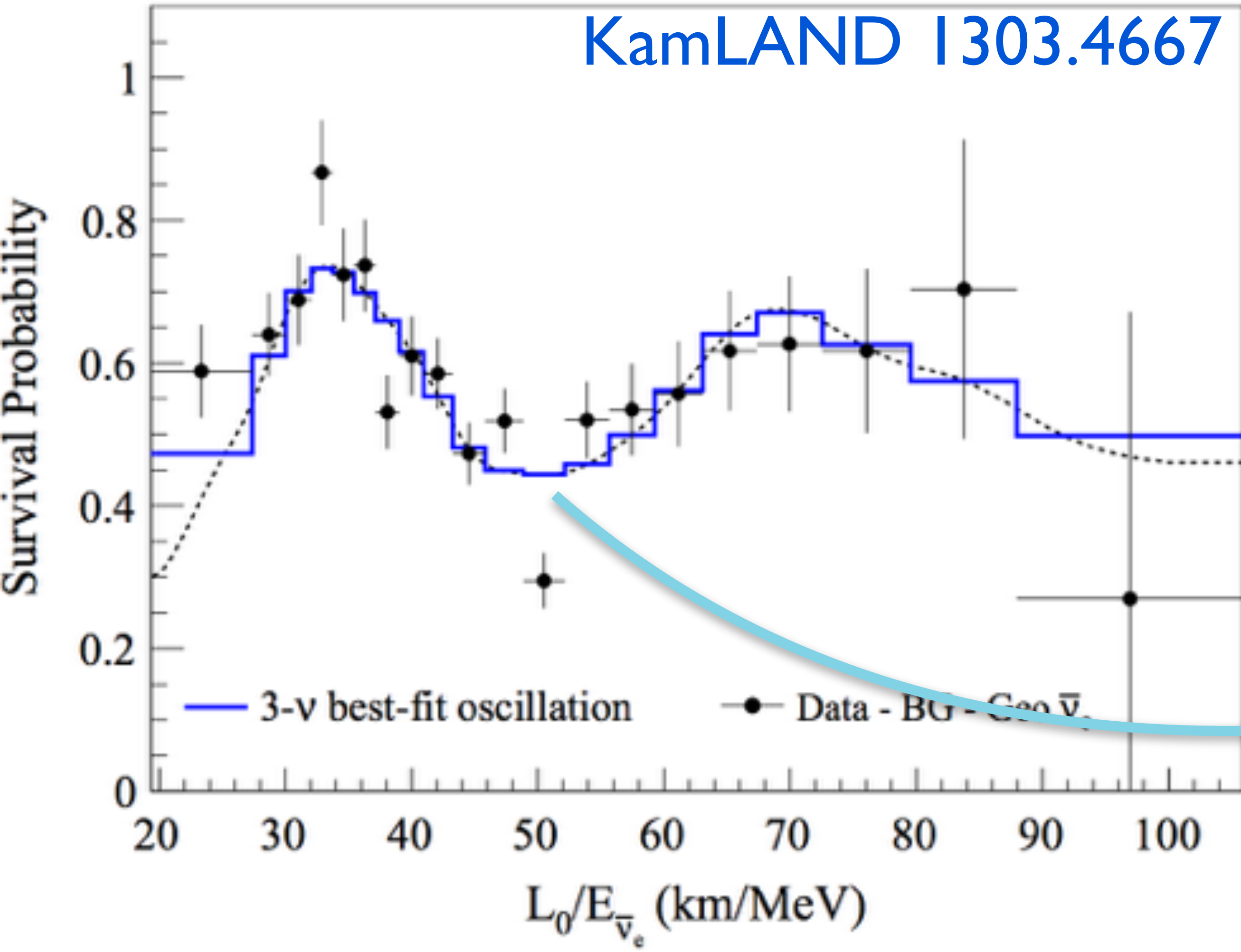
Δm^2_{21} and θ_{12}

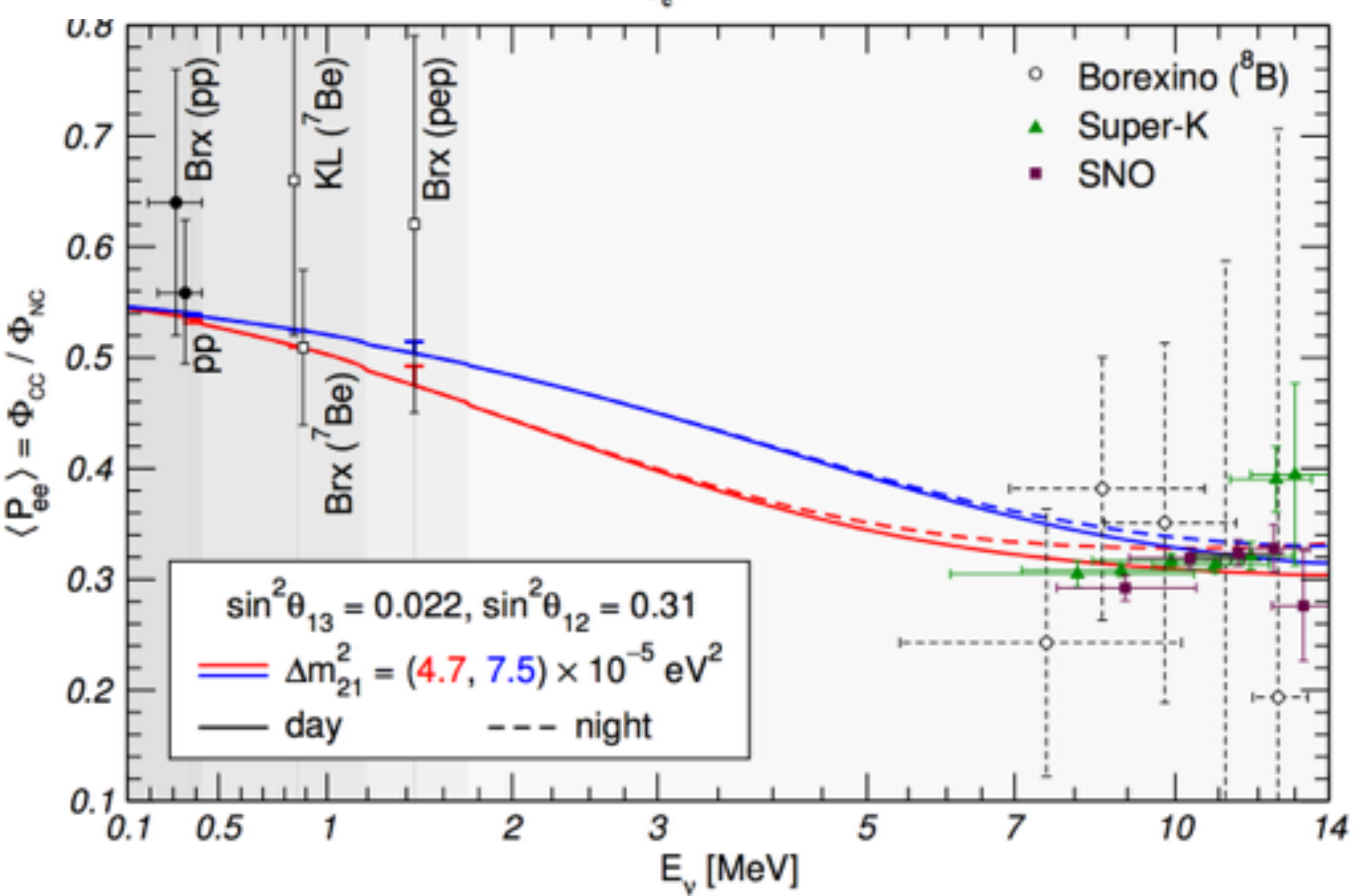


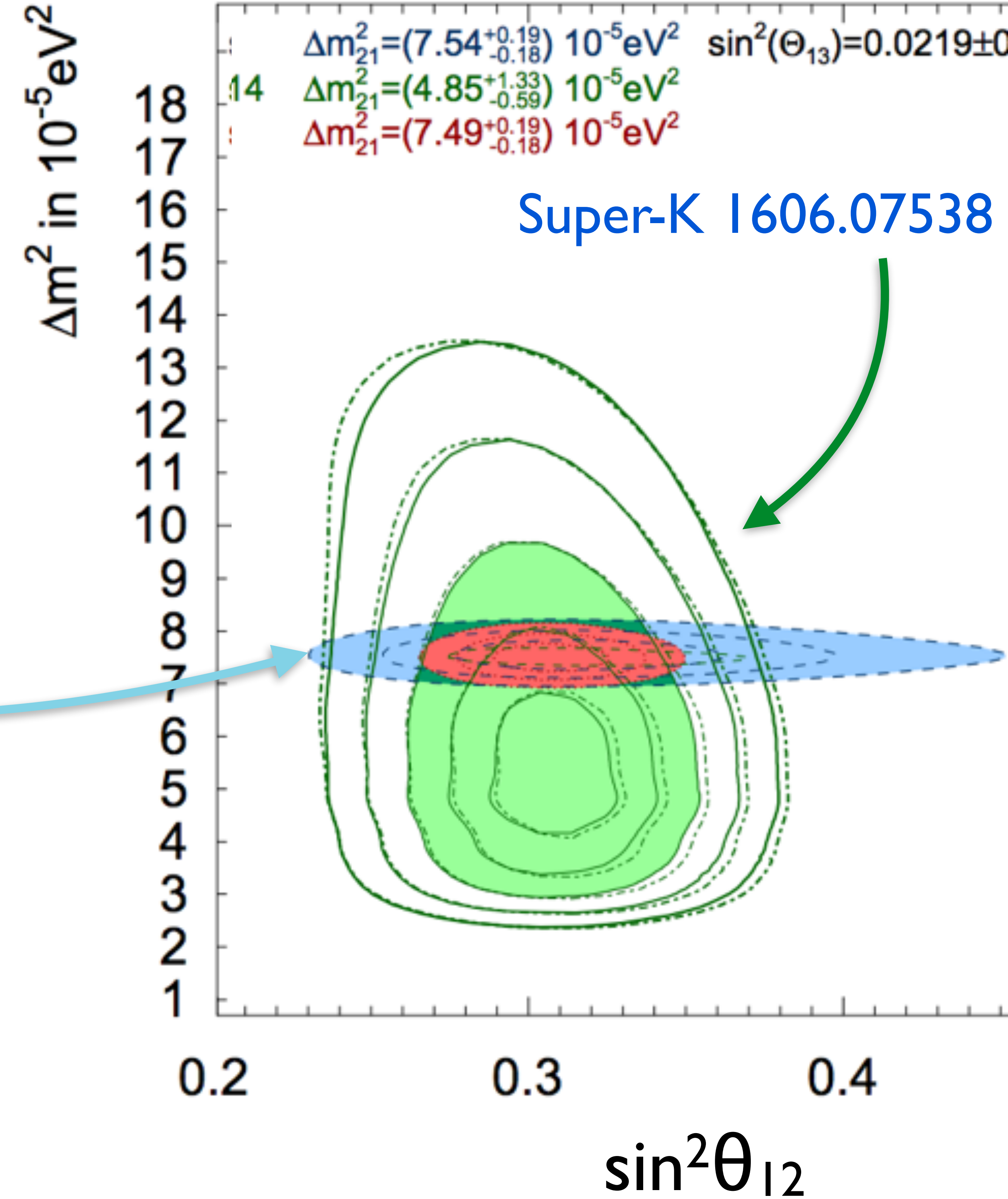




Δm^2_{21} and θ_{12}







Solar neutrino data prefer lower Δm^2_{21}, but all is compatible within 2σ

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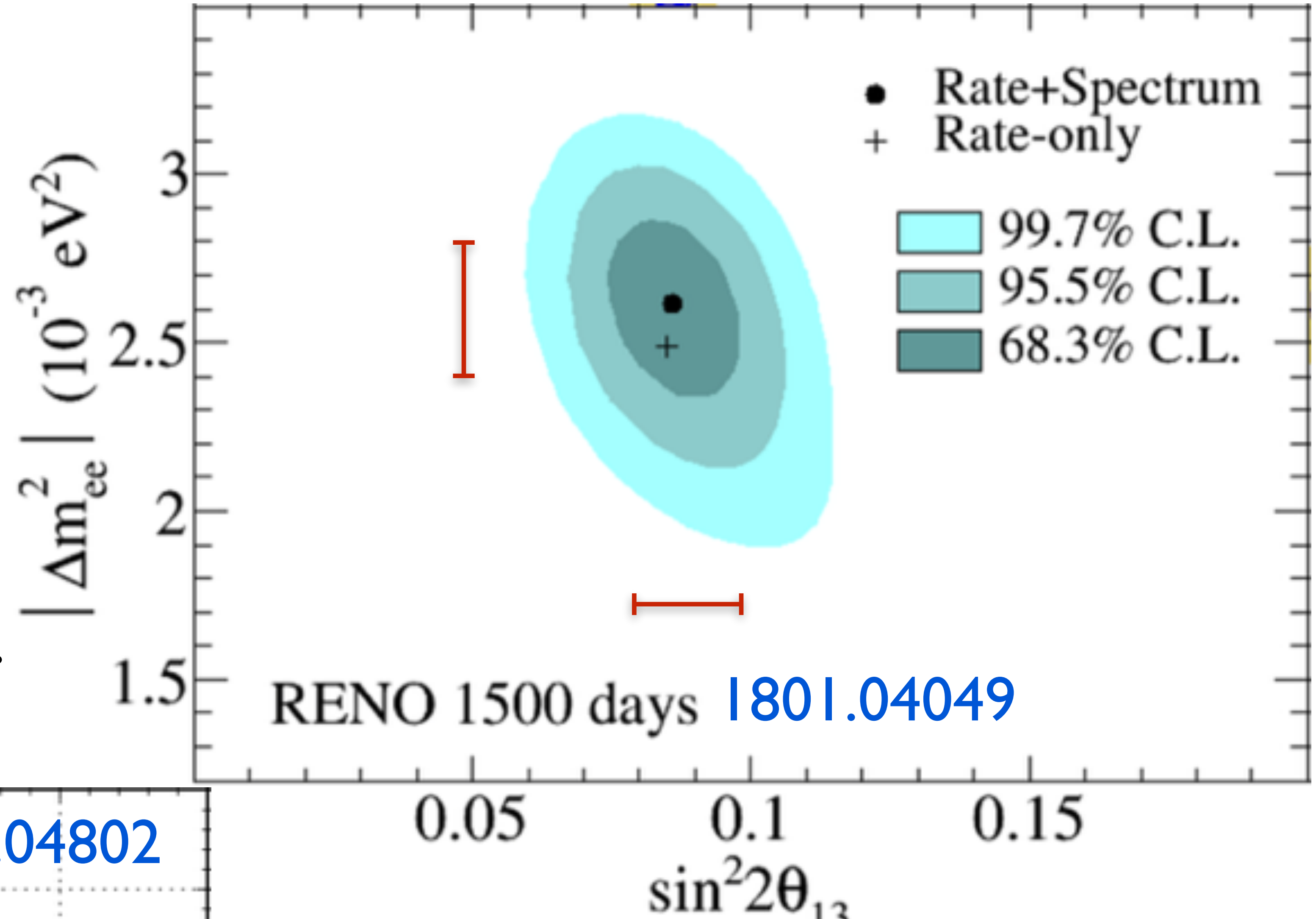
θ_{13} and Δm^2_{ee}

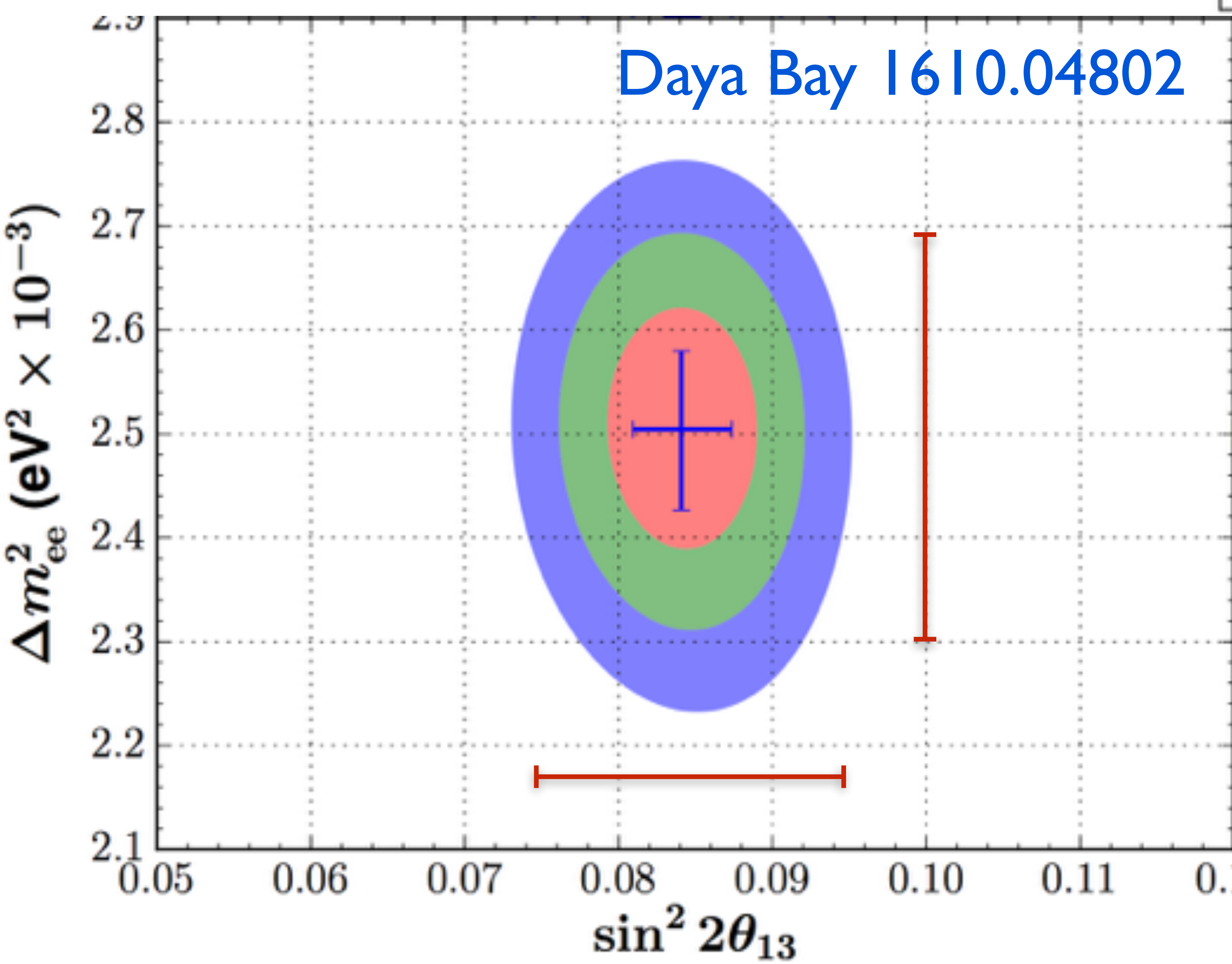
Best measured mixing angle

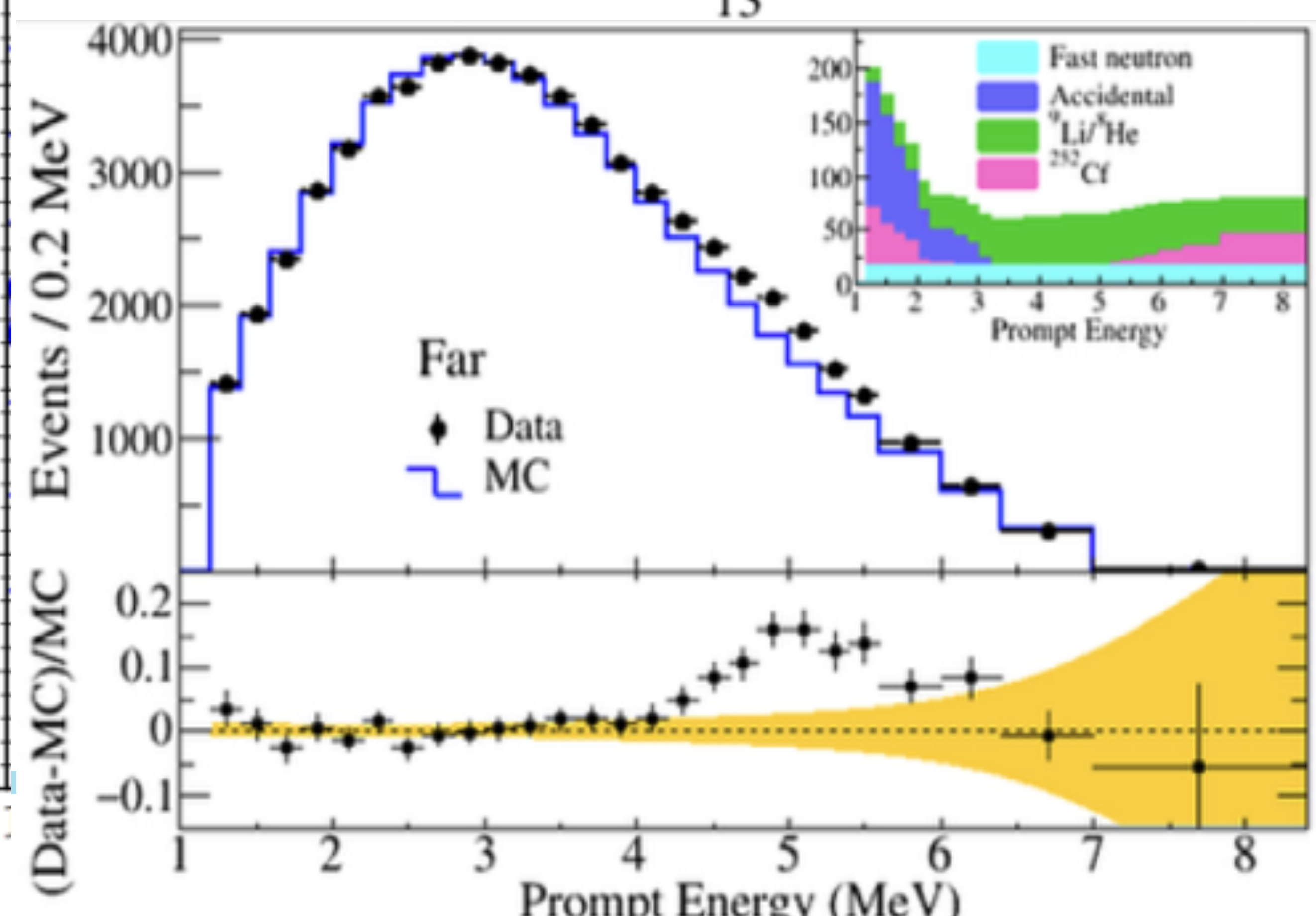
Δm^2 precision improving

Important measurement of Δm^2_{ee}

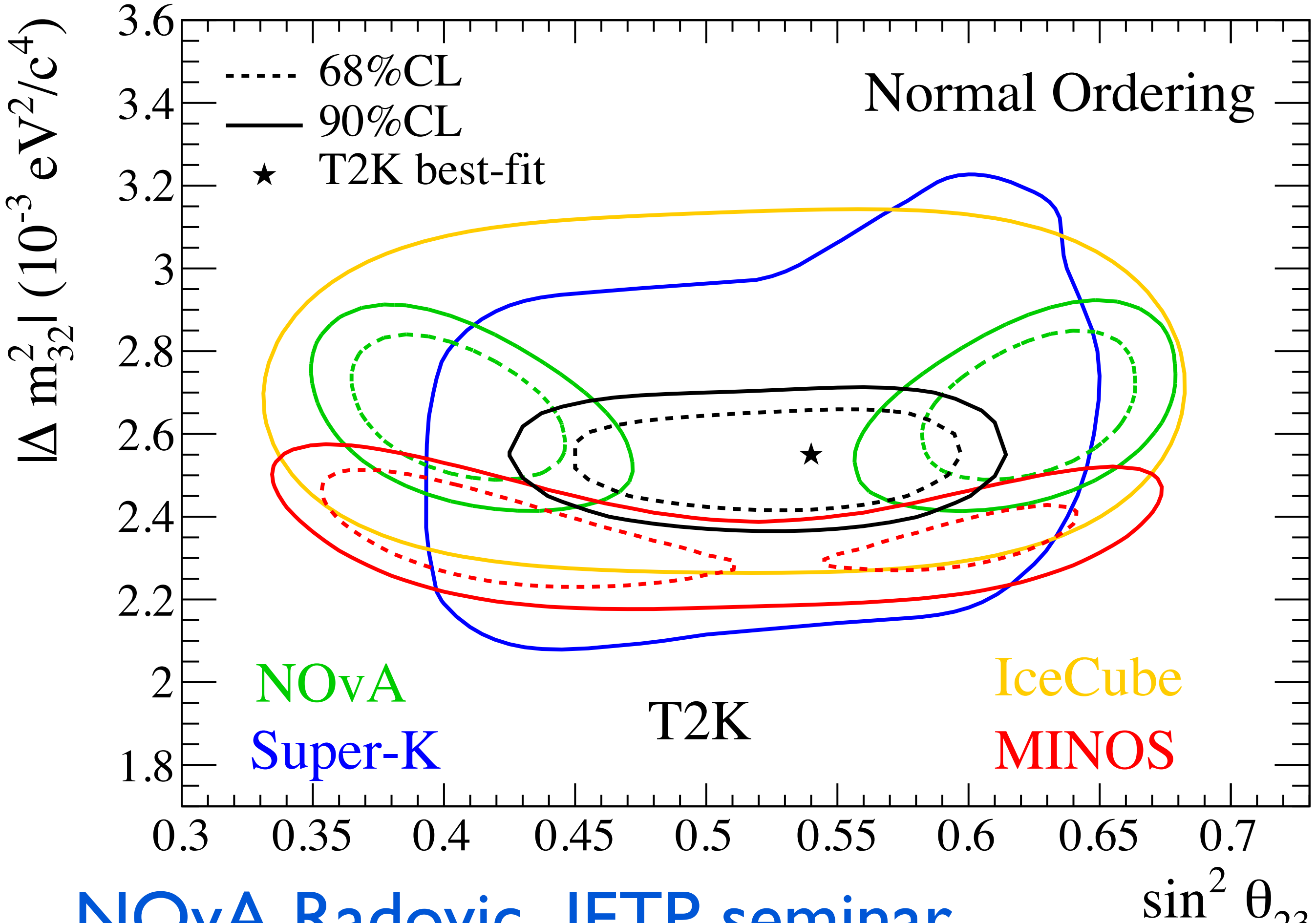
5 MeV shoulder still unexplained…



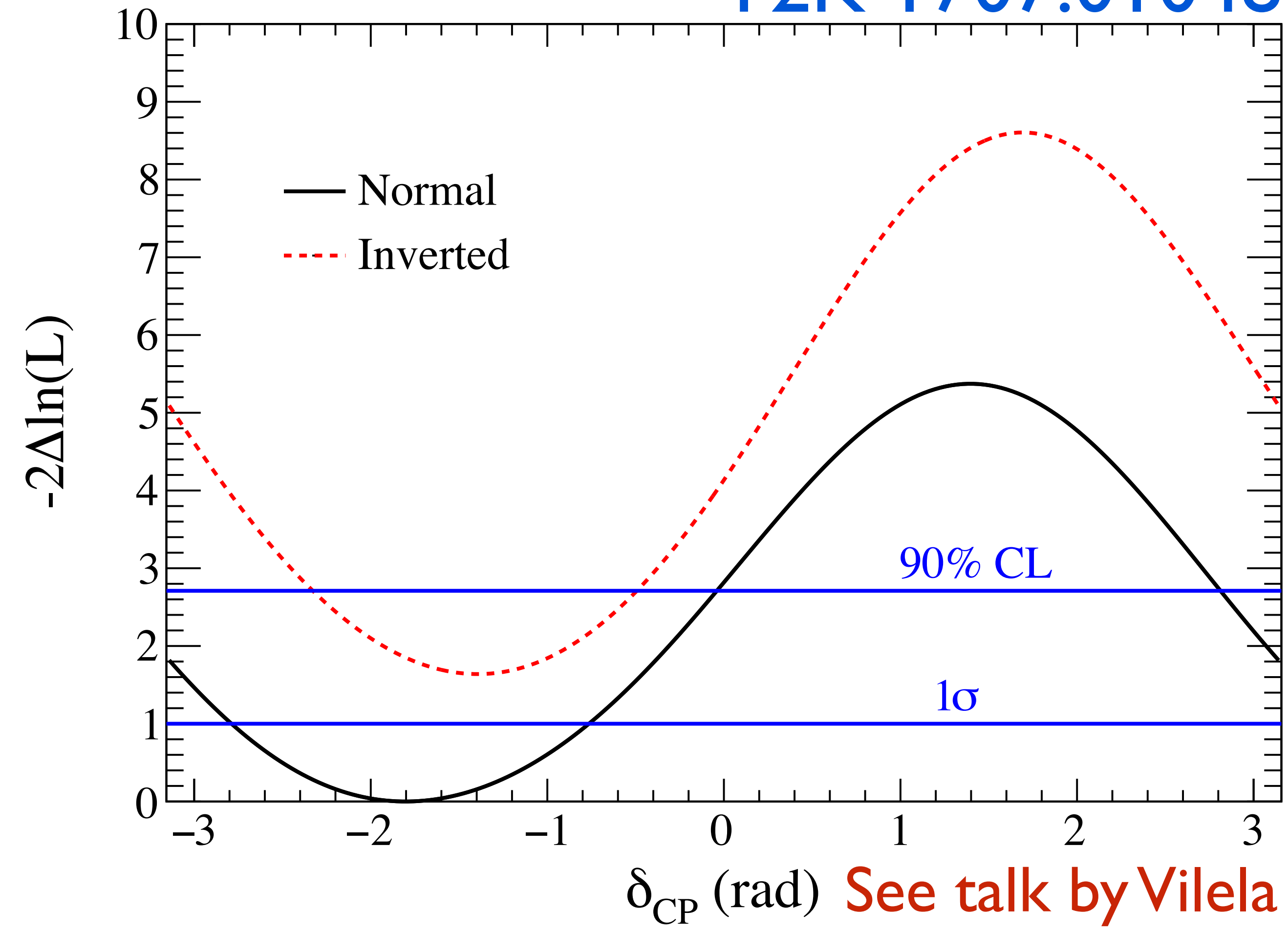




θ_{23}, Δm^2_{atm}, and δ_{CP}

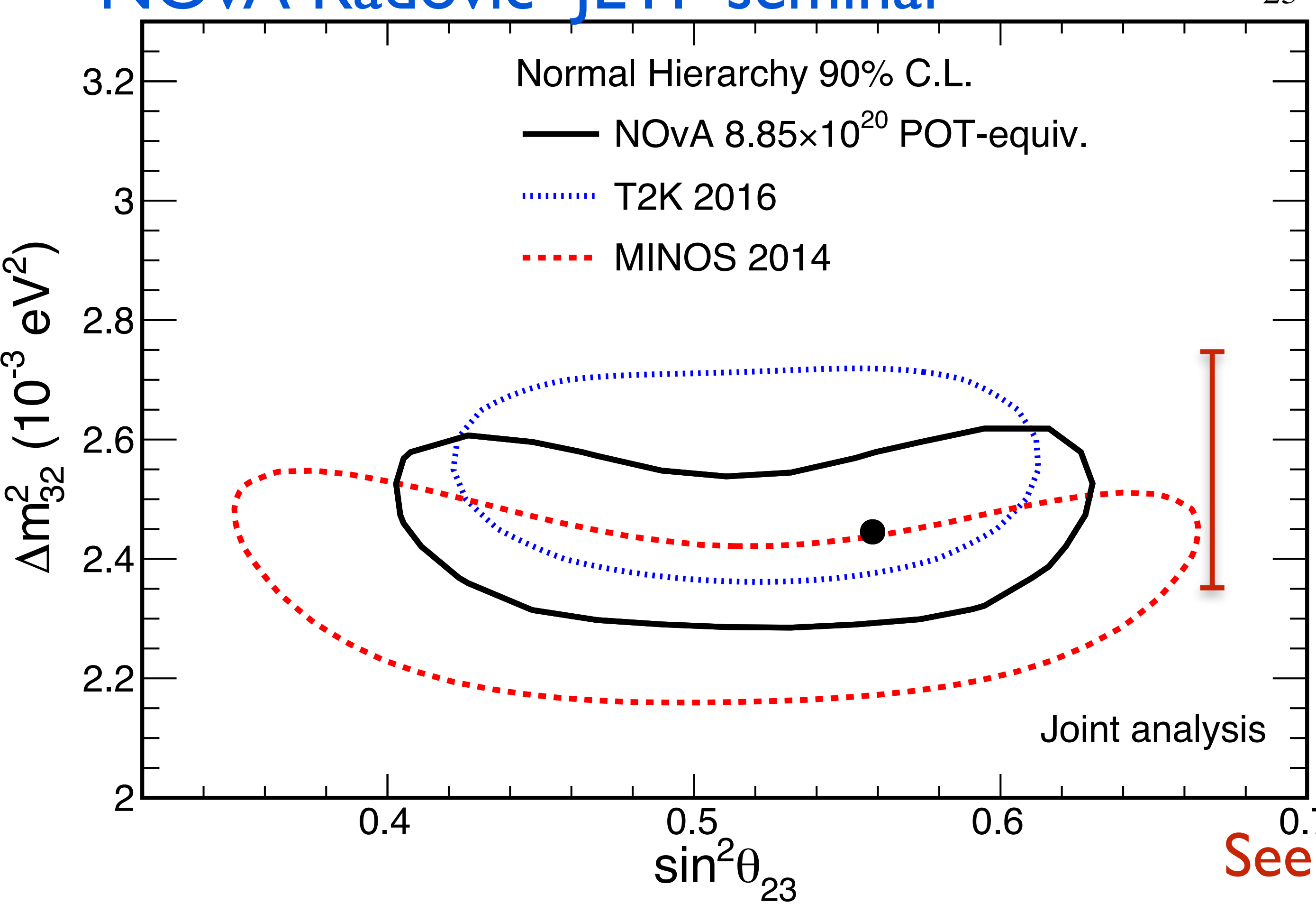


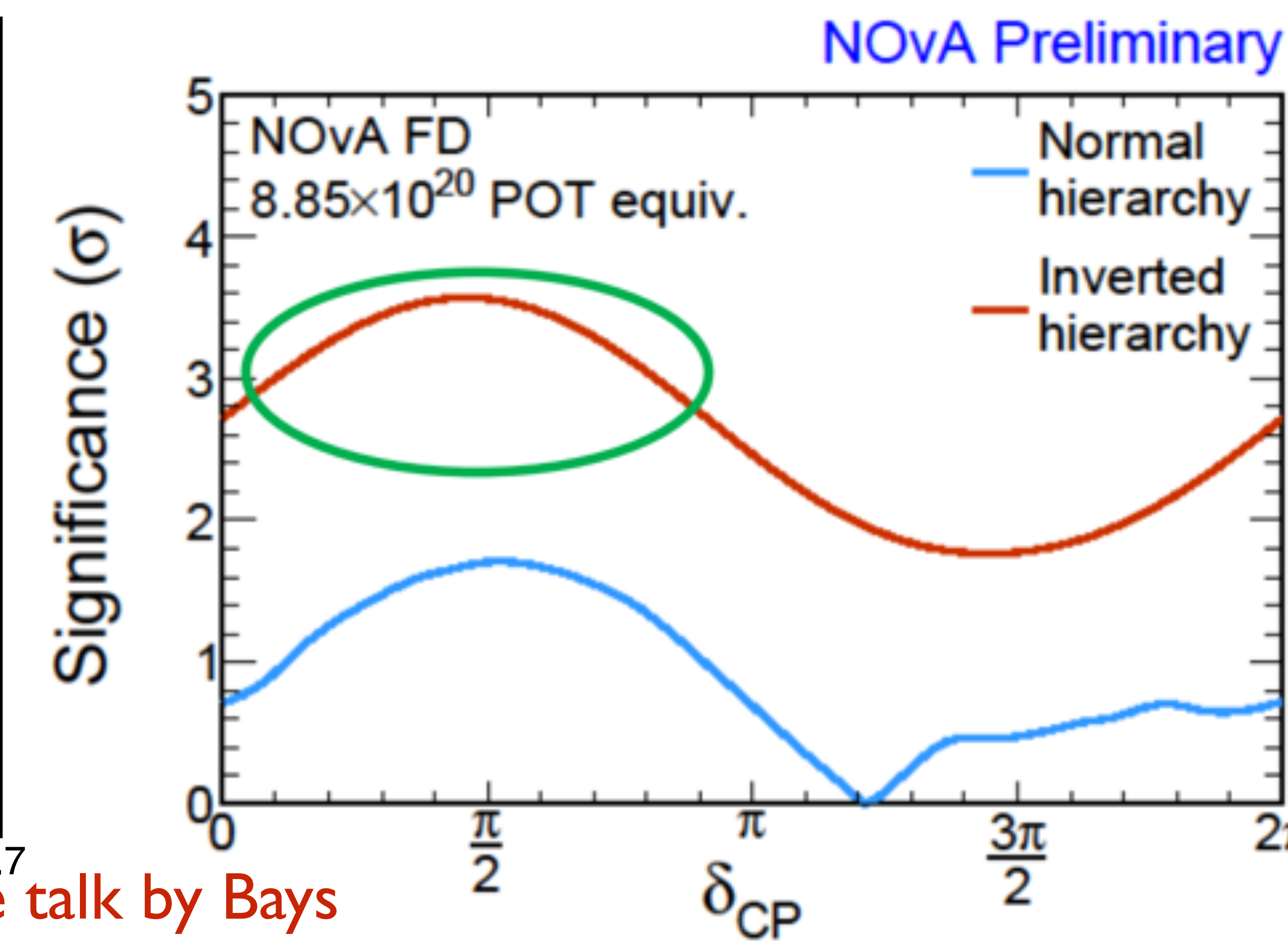
T2K 1707.01048



See talk by Vilela

NOvA Radovic JETP seminar





See talk by Bays

Global fit

NuFIT 3.2 (2018)

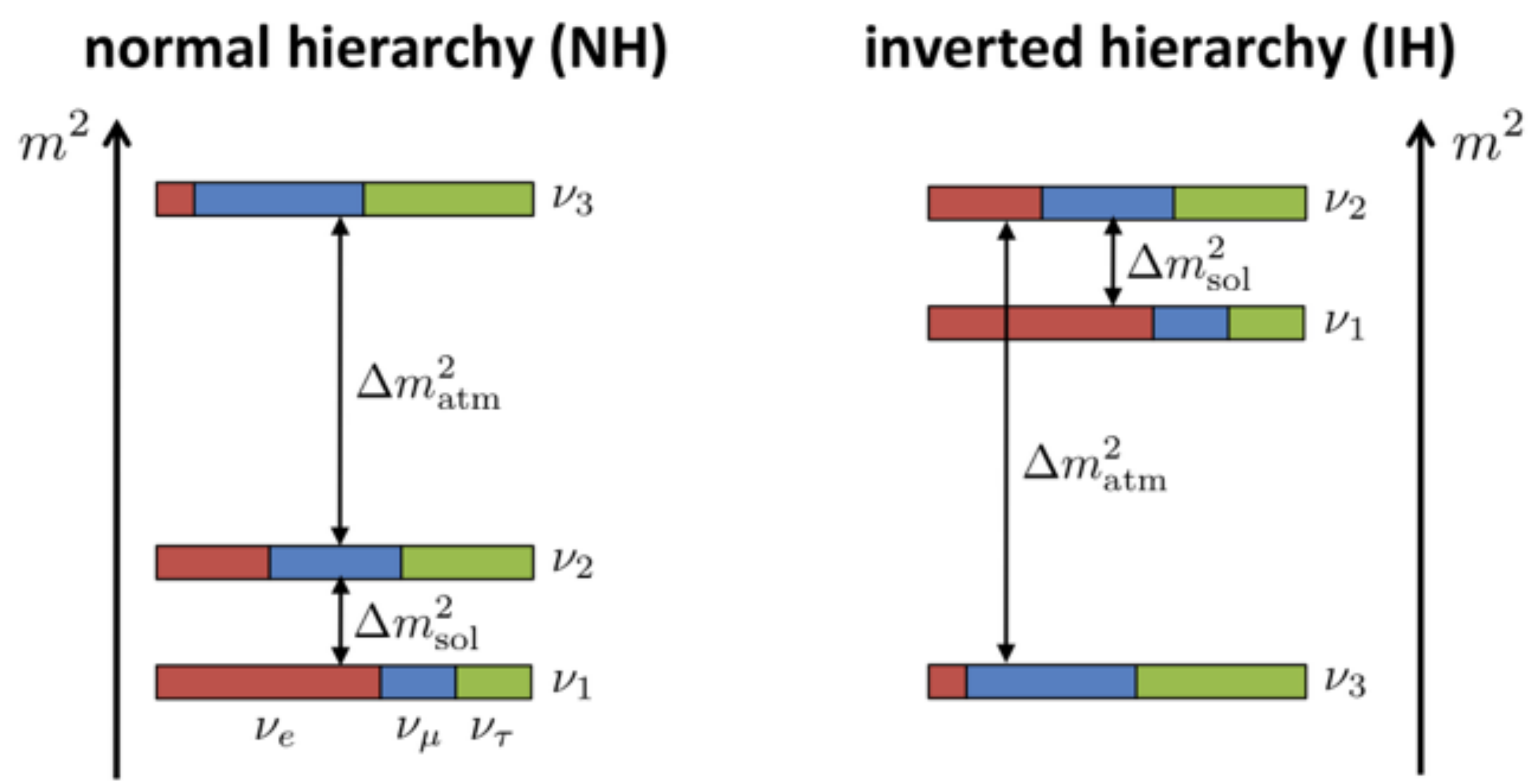
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

Status of standard three neutrino oscillations

NuFIT 3.2 (2018)

Δm^2_{sol} quite well measured (7.4×10^{-5} eV^2, 3%, reactor)
$|\Delta m^2_{atm}|$ quite well measured (2.5×10^{-3} eV^2, 2%, reactor)
θ_{13} quite well measured (8.5°, 3.5%, reactor)
θ_{12} quite well measured from (33°, 4%, solar)

θ_{23} is compatible with 45° (40°-51°, 3σ, accelerator/atm)
Hint (~ 90%CL) for δ_{CP} between $-\pi$ and 0
Hint (almost 2σ) for normal mass ordering



See talks by Kramer, Soldin, Bays, Vilela

Is that the whole story?

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What do we really know…

$$|U|_{3\sigma}^{\substack{\textbf{w/o Unitarity} \\ \text{(with Unitarity)}}} = \begin{pmatrix} \begin{matrix}0.76 \rightarrow 0.85 \\ (0.79 \rightarrow 0.85)\end{matrix} & \begin{matrix}0.50 \rightarrow 0.60 \\ (0.50 \rightarrow 0.59)\end{matrix} & \begin{matrix}0.13 \rightarrow 0.16 \\ (0.14 \rightarrow 0.16)\end{matrix} \\ \begin{matrix}0.21 \rightarrow 0.54 \\ (0.22 \rightarrow 0.52)\end{matrix} & \begin{matrix}0.42 \rightarrow 0.70 \\ (0.43 \rightarrow 0.70)\end{matrix} & \begin{matrix}0.61 \rightarrow 0.79 \\ (0.62 \rightarrow 0.79)\end{matrix} \\ \begin{matrix}0.18 \rightarrow 0.58 \\ (0.24 \rightarrow 0.54)\end{matrix} & \begin{matrix}0.38 \rightarrow 0.72 \\ (0.47 \rightarrow 0.72)\end{matrix} & \begin{matrix}0.40 \rightarrow 0.78 \\ (0.60 \rightarrow 0.77)\end{matrix} \end{pmatrix}$$

Parke Ross-Lonergan 1508.05095

The future

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DUNE

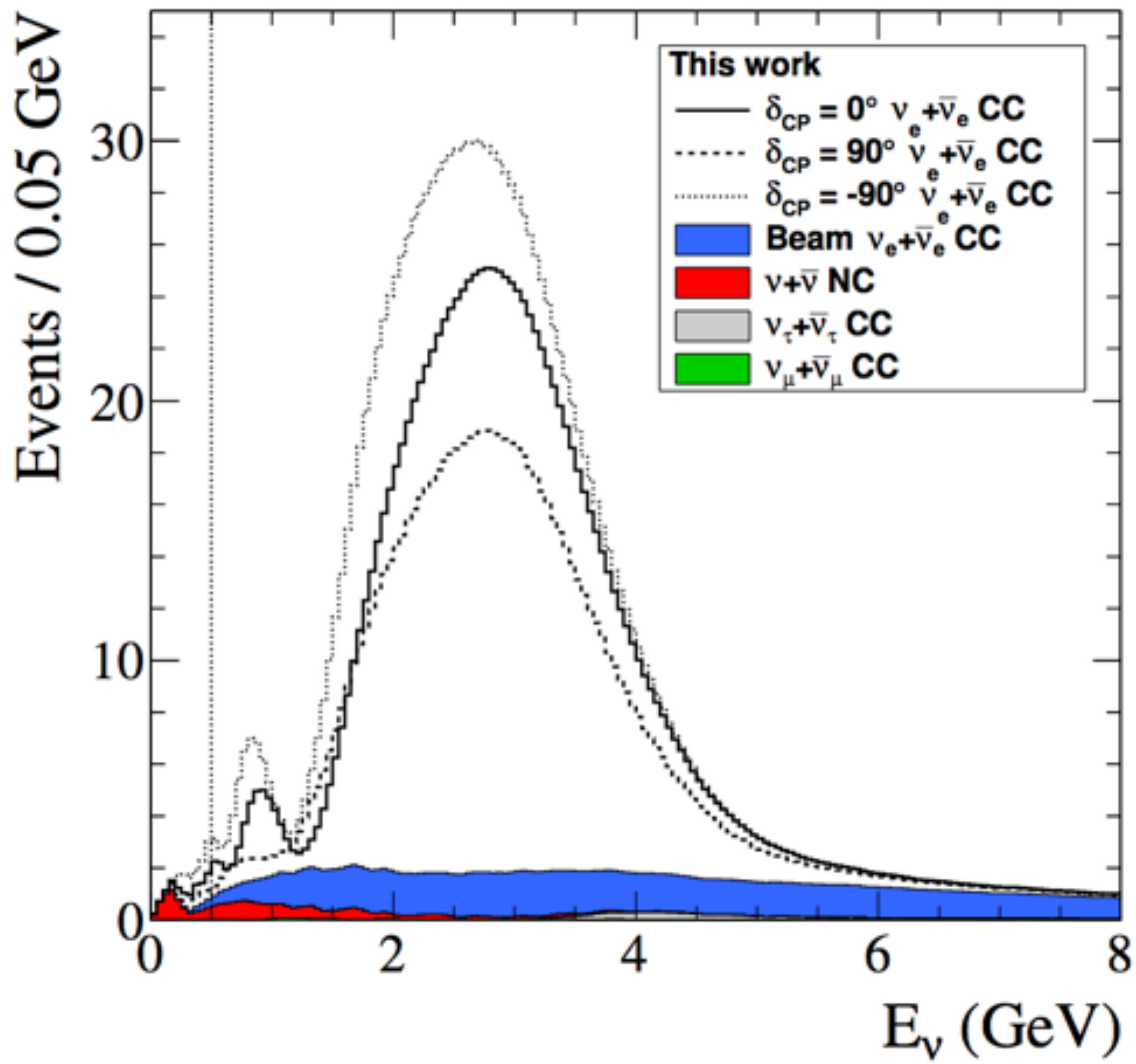
Goals:

See talk by Bian

- Mass ordering
- δ_{CP}
- θ_{23} precision measurement
- Supernova and solar neutrinos
- Proton decay
- neutron-antineutron oscillations

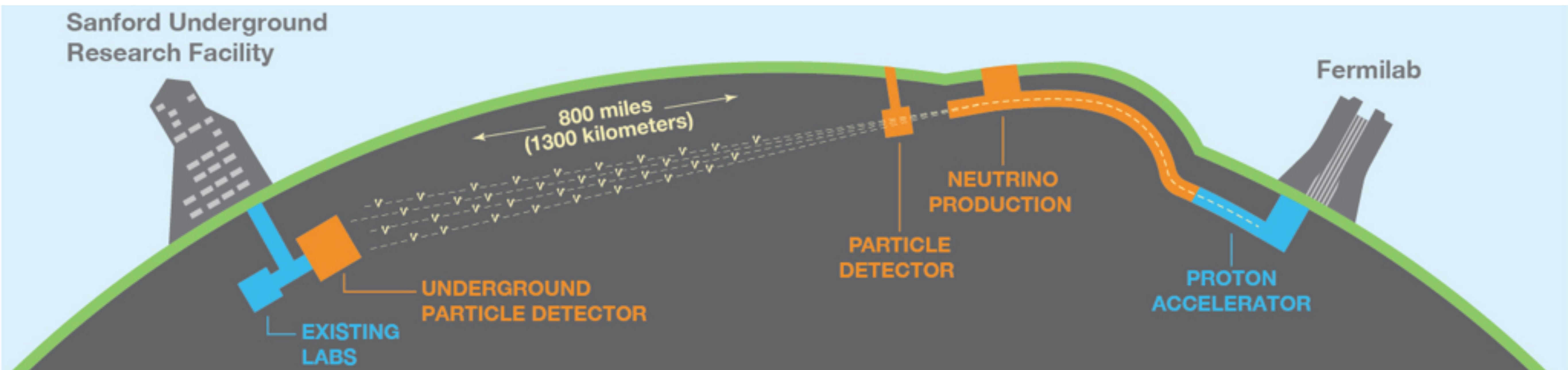
Beacom et al, in prep.

De Romeri et al 1607.00293



Status and plans:

- July 21st: SURF groundbreaking
- ND: to be defined
- FD: Four 10kton LAr-TPCs
- Lots of neutrinos



T2HK

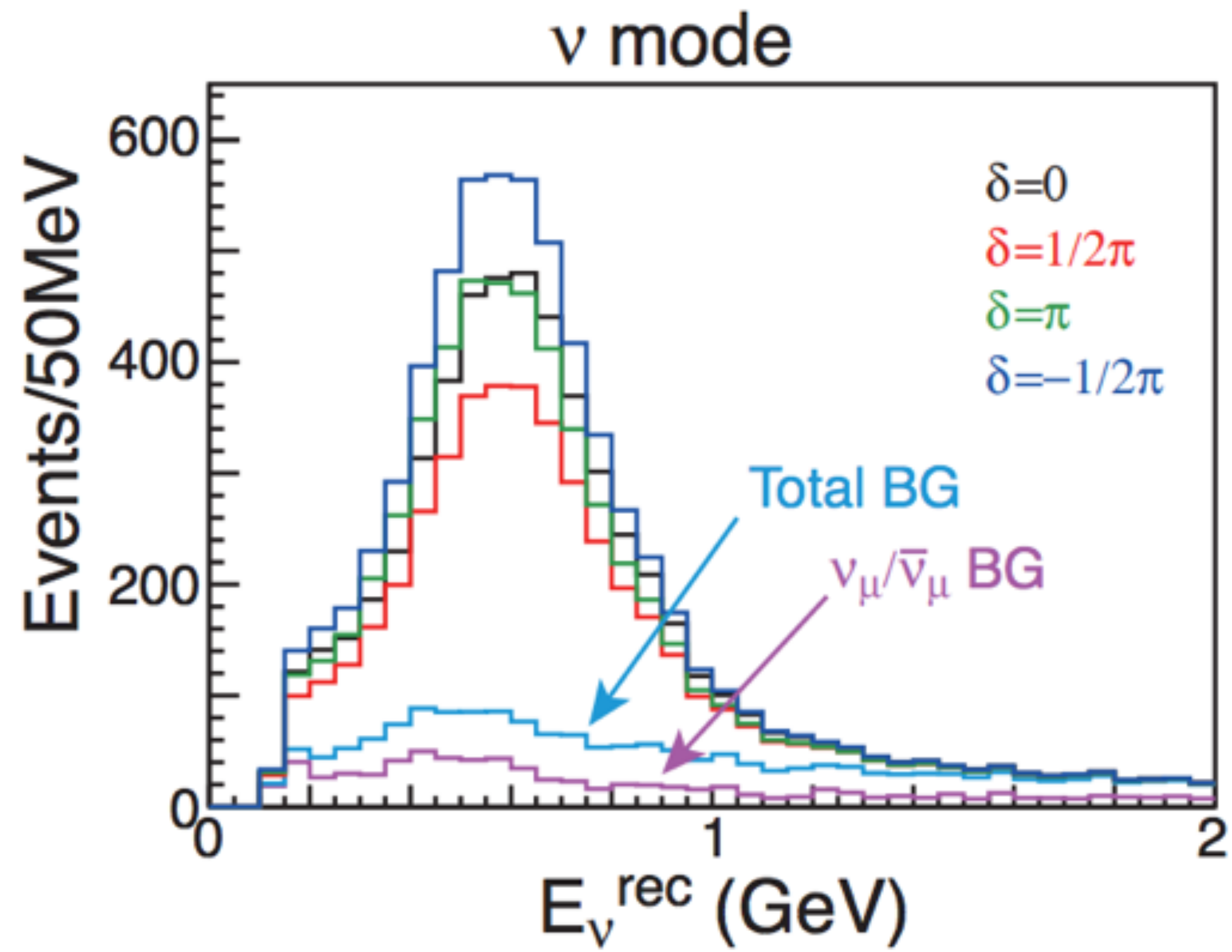
Goals:

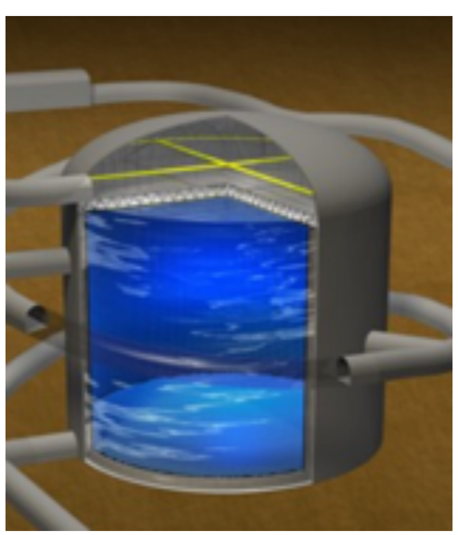
- Mass ordering
- δ_{CP}
- θ_{23} precision measurement
- Supernova and solar neutrinos
- Proton decay
- neutron-antineutron oscillations

Status and plans:

- ND: WC, NUPRISM ?
- FD: two 260kton WC
- Lots of neutrinos

T2HK LoI 1109.3262





Hyper-Kamiokande

JUNO

Goals:

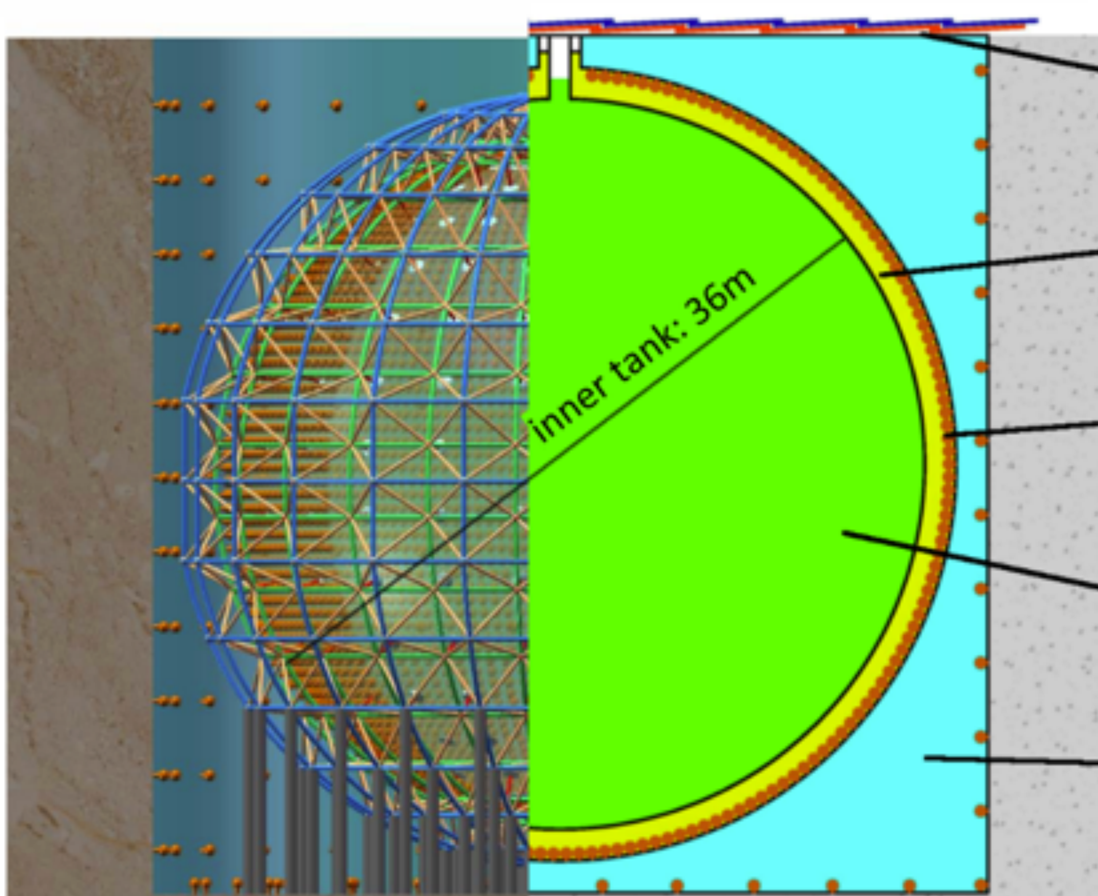
- Mass ordering
- θ_{12} and Δm^2 precision measurements
- Supernova and solar neutrinos

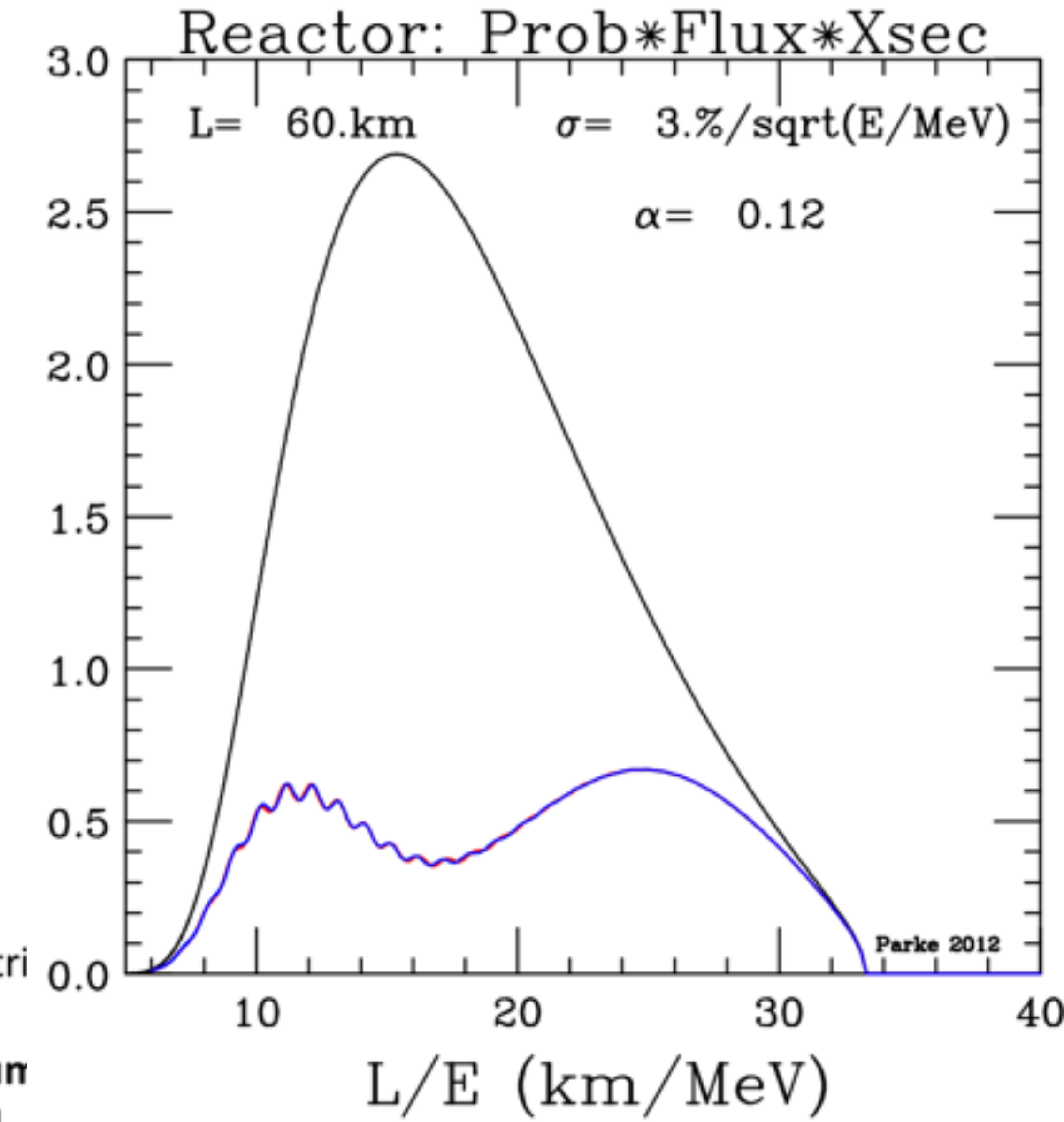
Status and plans:

- Under construction
- ND? Forero et al 1710.07378

FD: 20kton liquid scintillator

Lots of neutrinos





Parke 1310.5992
Qian et al 1208.1551
Parke et al 0812.1879

arXiv:1805.12028v1 [hep-ex] 30 May 2018

The MiniBooNE Collaboration

Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

arXiv:1805.12028v1 [hep-ex] 30 May 2018

The MiniBooNE Collaboration

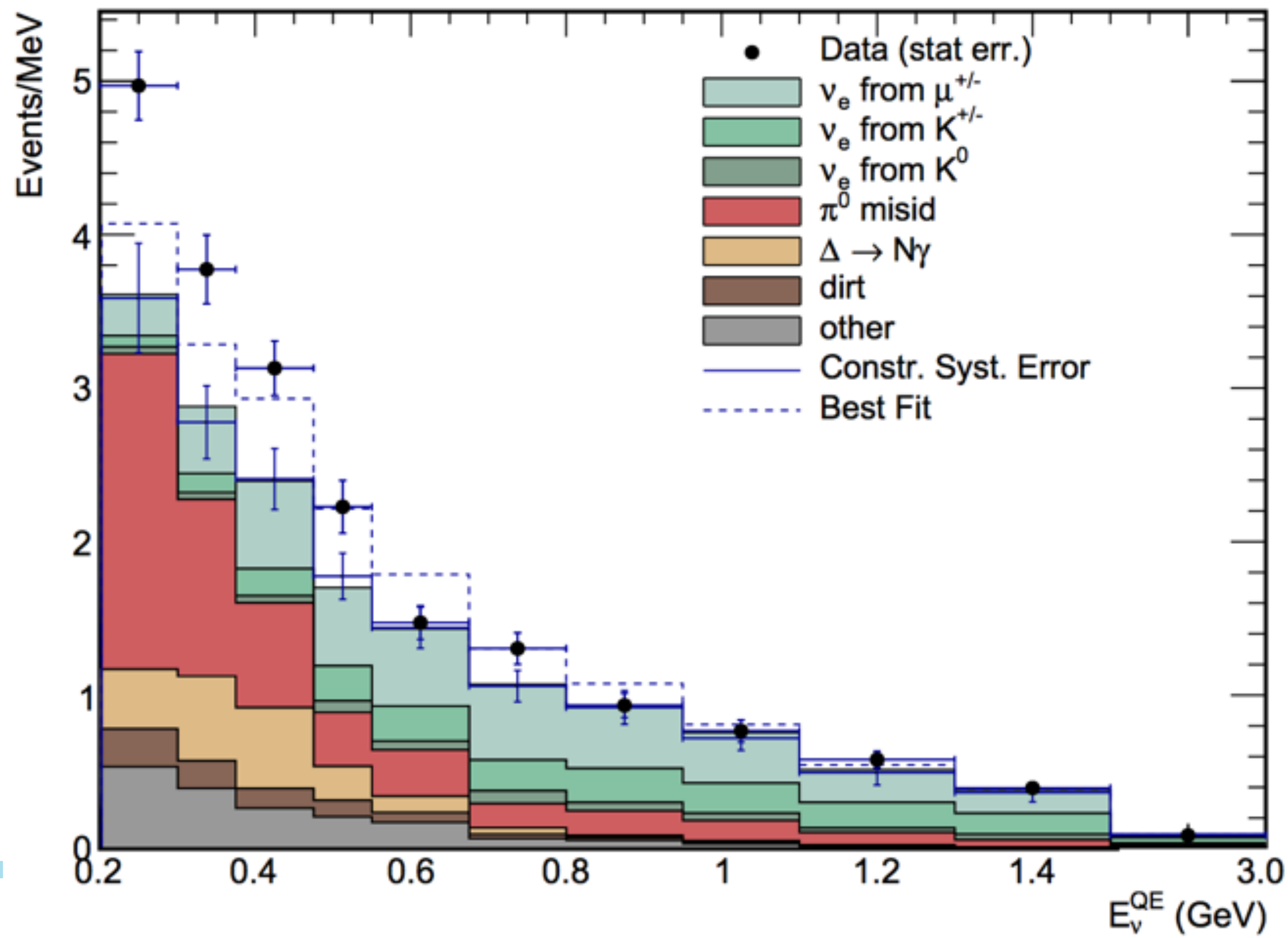
Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

Double neutrino-mode data in 2016-2017

(6.46×10^{20} + 6.38×10^{20} POT)

Event excess: 381.2 ± 85.2 (4.5σ)

LSND + MiniBooNE: 6.1σ



arXiv:1805.12028v1 [hep-ex] 30 May 2018

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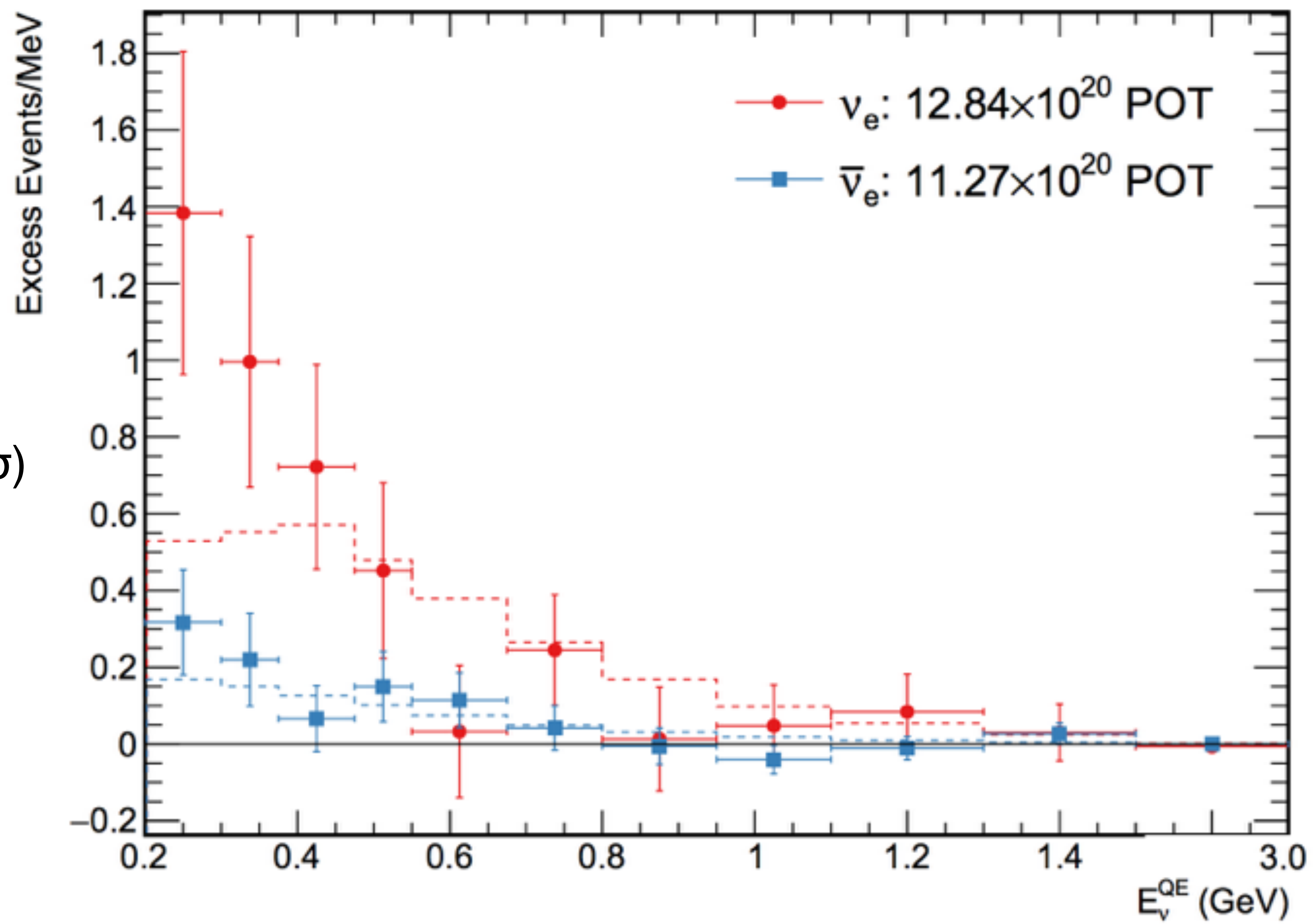


What does that mean for sterile neutrinos?

What does that mean for sterile neutrinos?

1) There are anomalies in ν_e disappearance and ν_μ to ν_e appearance data

Reactor anomaly

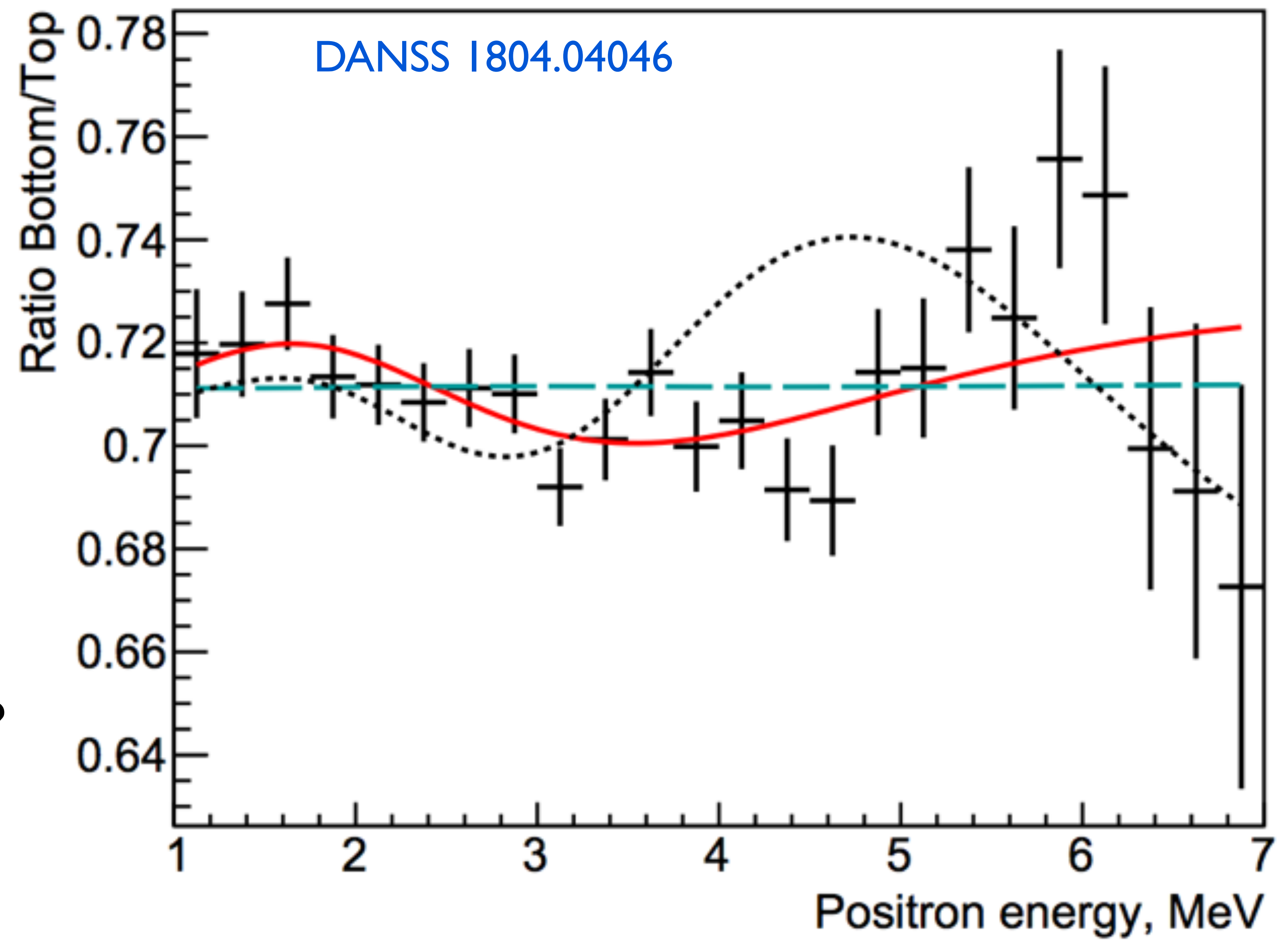
$\bar{\nu}_e$ to $\bar{\nu}_e$

TH-data discrepancy (obs/TH = 0.94±0.02)

Mention et al 1101.2755
Mueller et al 1101.2663
Huber 1106.0687
Hayes et al 1309.4146
Dwyer Langford 1407.1281
...

Now some wiggles observed by both DANSS and NEOS???

see also NEOS 1610.05134



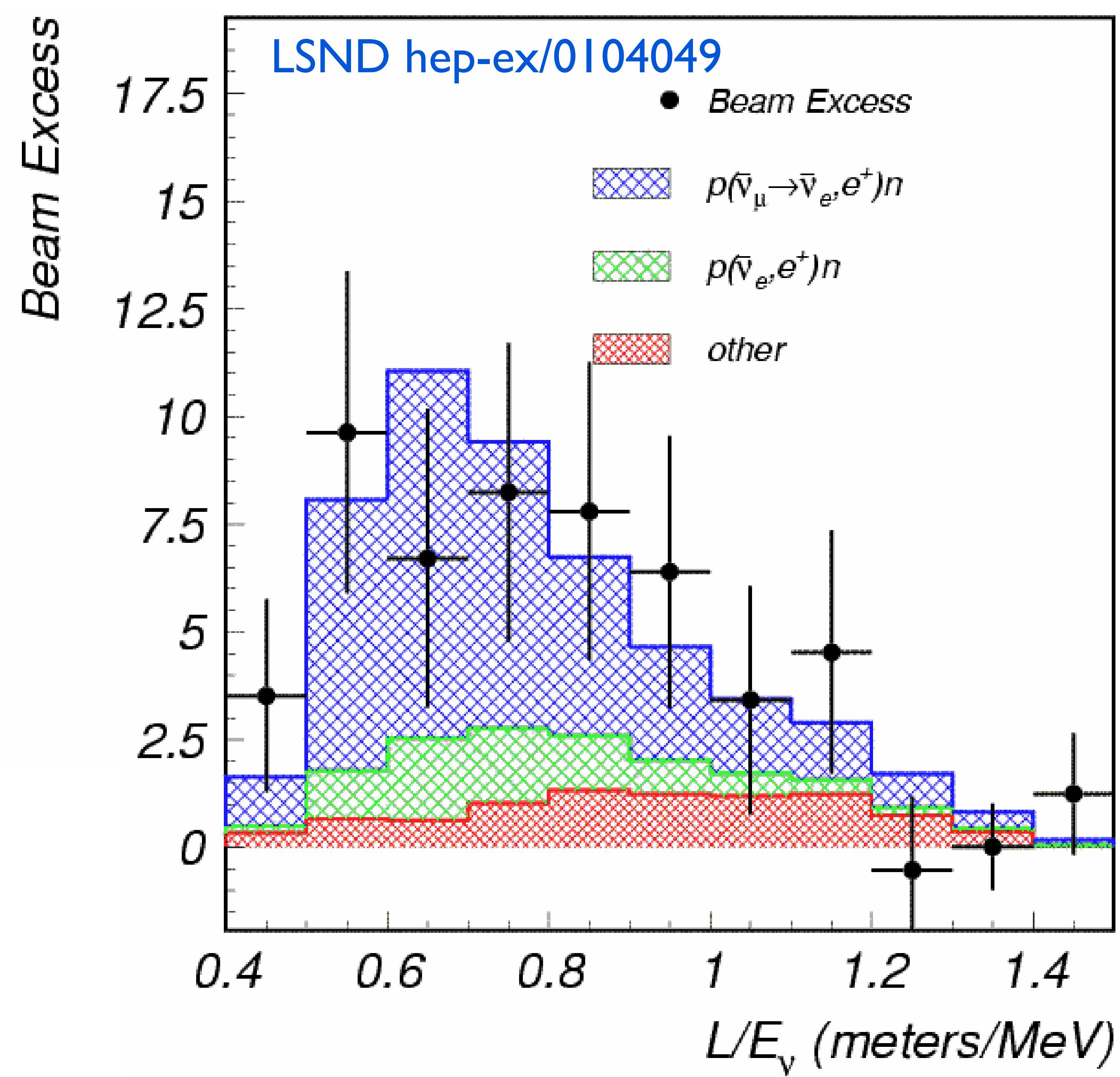
What does that mean for sterile neutrinos?

1) There are anomalies in ν_e disappearance and ν_μ to ν_e appearance data

LSND/MiniBooNE

Excess of ν_e in ν_μ beam
(Both in neutrinos and antinus)

Long-standing problem
LSND: 3.8σ
MiniBooNE: ~~3.8σ~~ 4.5σ



What does that mean for sterile neutrinos?

2) Strong tension between different data sets (sterile neutrino scenario)

$P(\nu_e \text{ to } \nu_e) \sim 1 - 4|U_{e4}|^2 \sin^2(\text{phase})$

$P(\nu_\mu \text{ to } \nu_\mu) \sim 1 - 4|U_{\mu 4}|^2 \sin^2(\text{phase})$

$P(\nu_\mu \text{ to } \nu_e) \sim 1 - 4|U_{e4}U_{\mu 4}|^2 \sin^2(\text{phase})$

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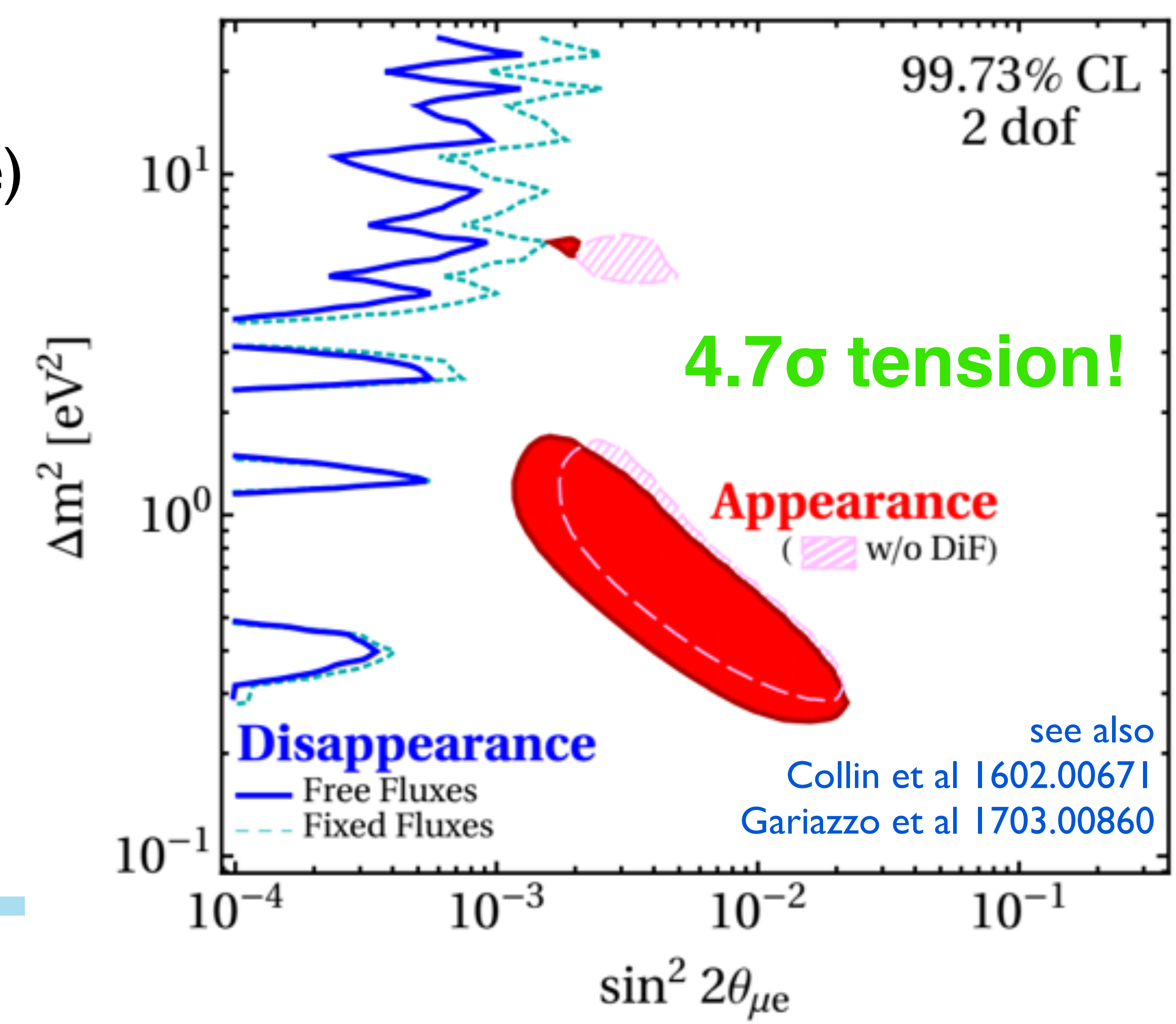
$P(\nu_\mu \text{ to } \nu_e) \sim 1 - 4|U_{e4}U_{\mu 4}|^2 \sin^2(\text{phase})$

$4|U_{e4}U_{\mu 4}|^2 = \sin^2(2\theta_{\mu e})$

Dentler et al 1803.10661



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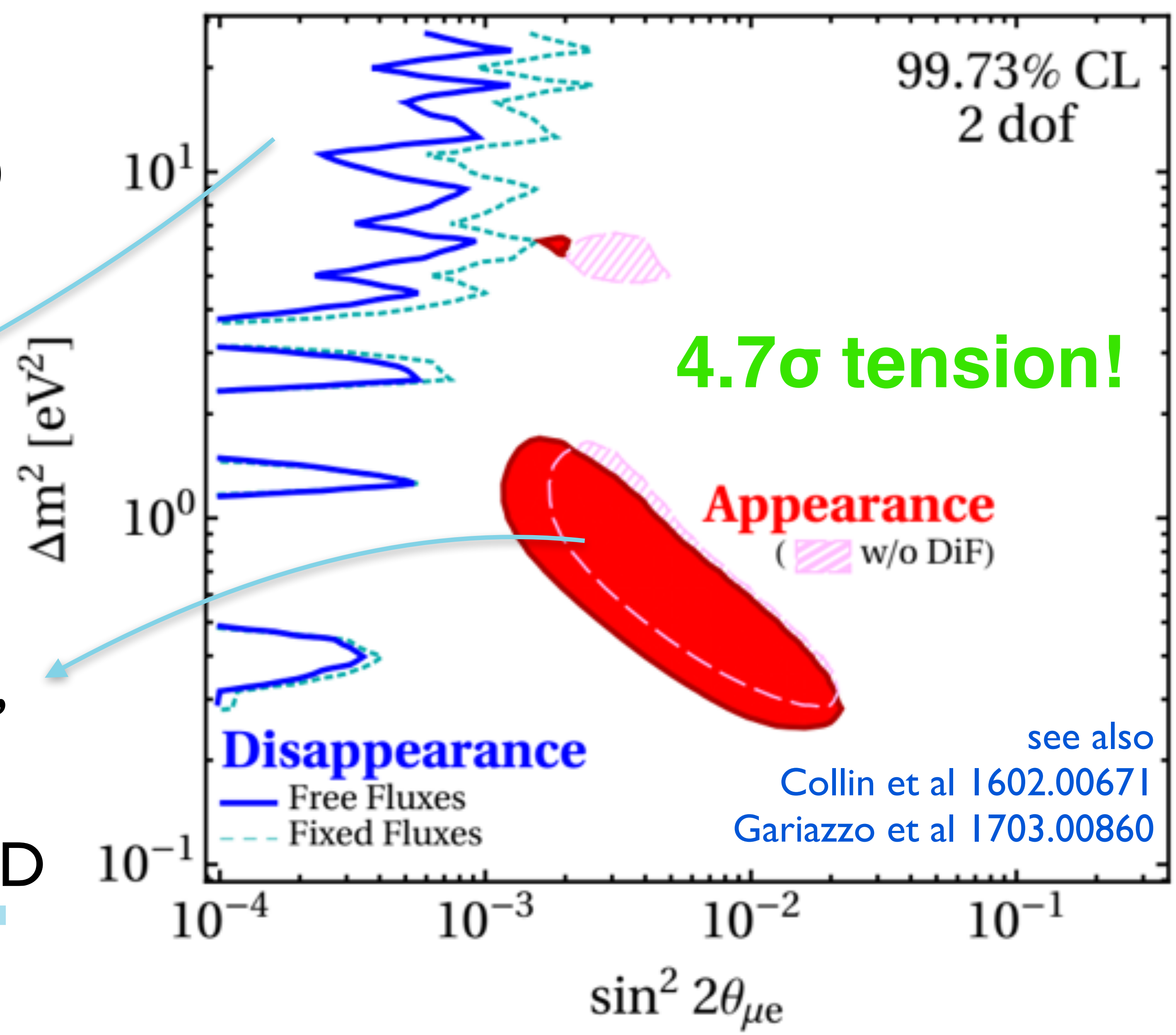
$P(\nu_\mu \text{ to } \nu_e) \sim 1 - \underbrace{4|U_{e4}U_{\mu 4}|^2}_{\sin^2(2\theta_{\mu e})} \sin^2(\text{phase})$

Dentler et al 1803.10661



MINOS, IceCube, MiniBooNE dis, reactors, solar, CDHS

MiniBooNE app, LSND, KARMEN, OPERA, E776, ICARUS, NOMAD

see also
Collin et al 1602.00671
Gariazzo et al 1703.00860

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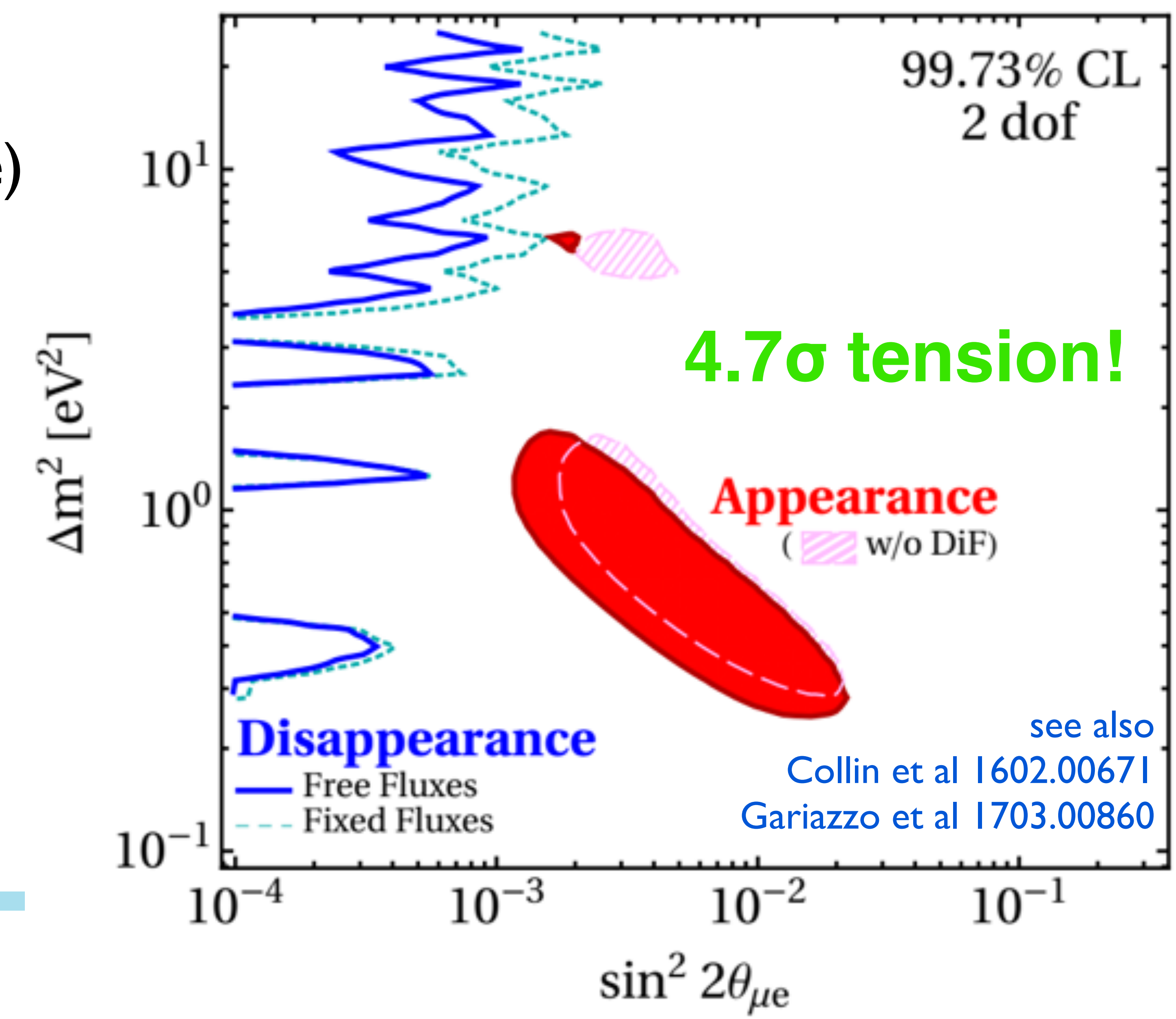
$P(\nu_\mu \text{ to } \nu_e) \sim 1 - \underbrace{4|U_{e4}U_{\mu4}|^2}_{\sin^2(2\theta_{\mu e})} \sin^2(\text{phase})$

Other explanations, each with their own advantages and drawbacks:
New interactions with CνB (Asaadi et al 1712.08019)
Lorentz violation (Katori et al hep-ph/0606154)
Heavy sterile neutrino decay (Gninenko 0902.3802)
Steriles+NSI (Liao Marfatia 1602.08766)
Large extra dimensions (Carena et al 1708.09548)
…

Dentler et al 1803.10661



What does that mean for sterile neutrinos?

Tension will get worse — the plot thickens

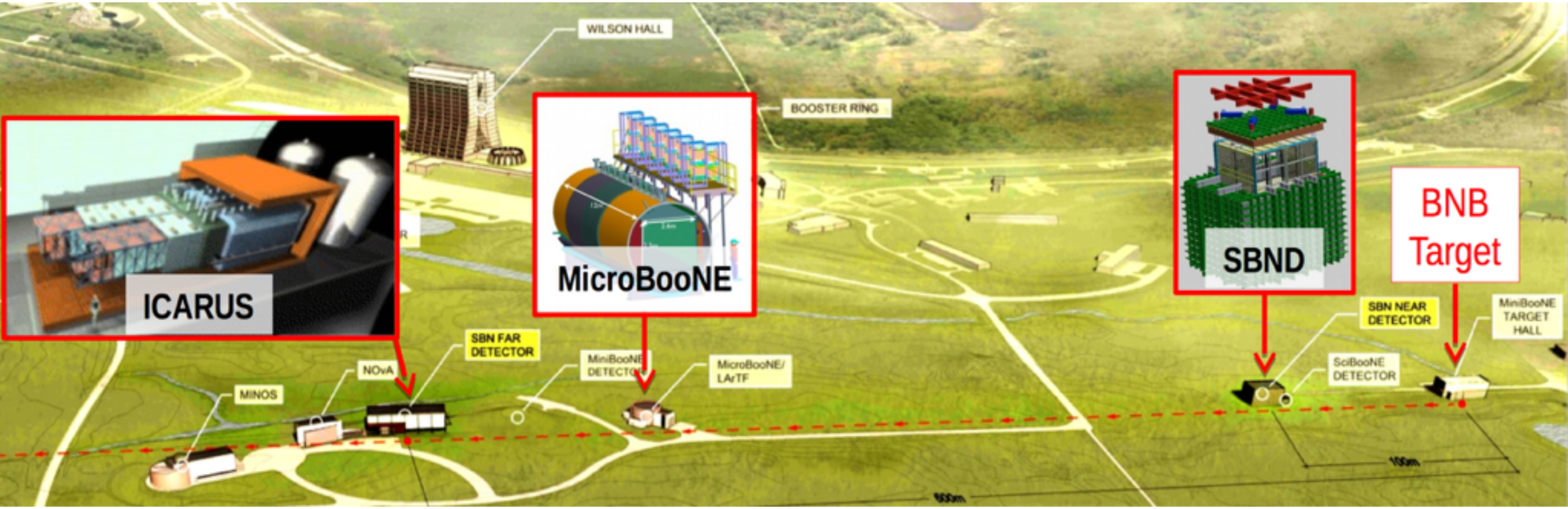
What is this low energy excess???

What does that mean for sterile neutrinos?

Tension will get worse — the plot thickens

What is this low energy excess???

Short Baseline Neutrino Program

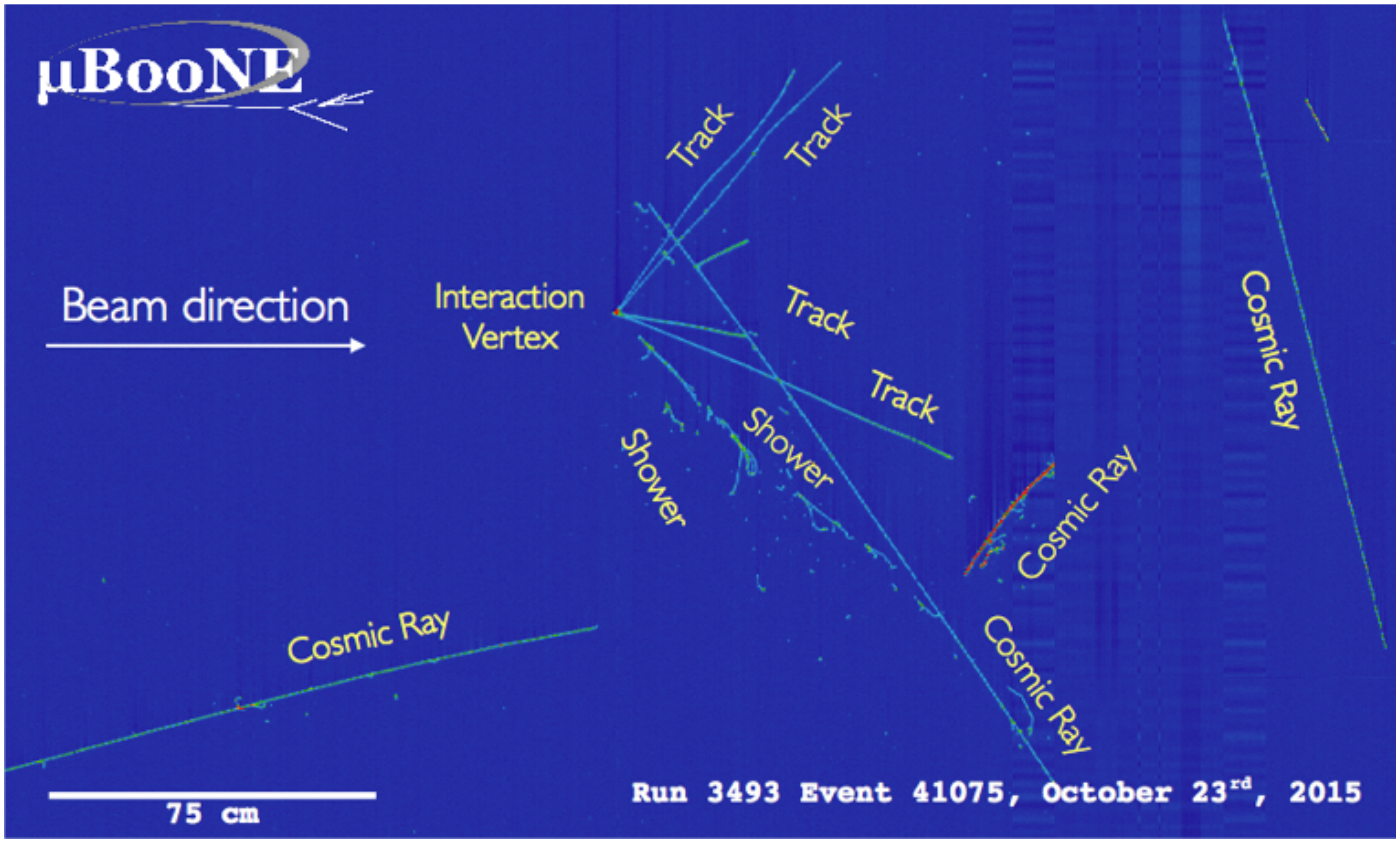


See talk by Joshi

The MicroBooNE
Technical Design Report

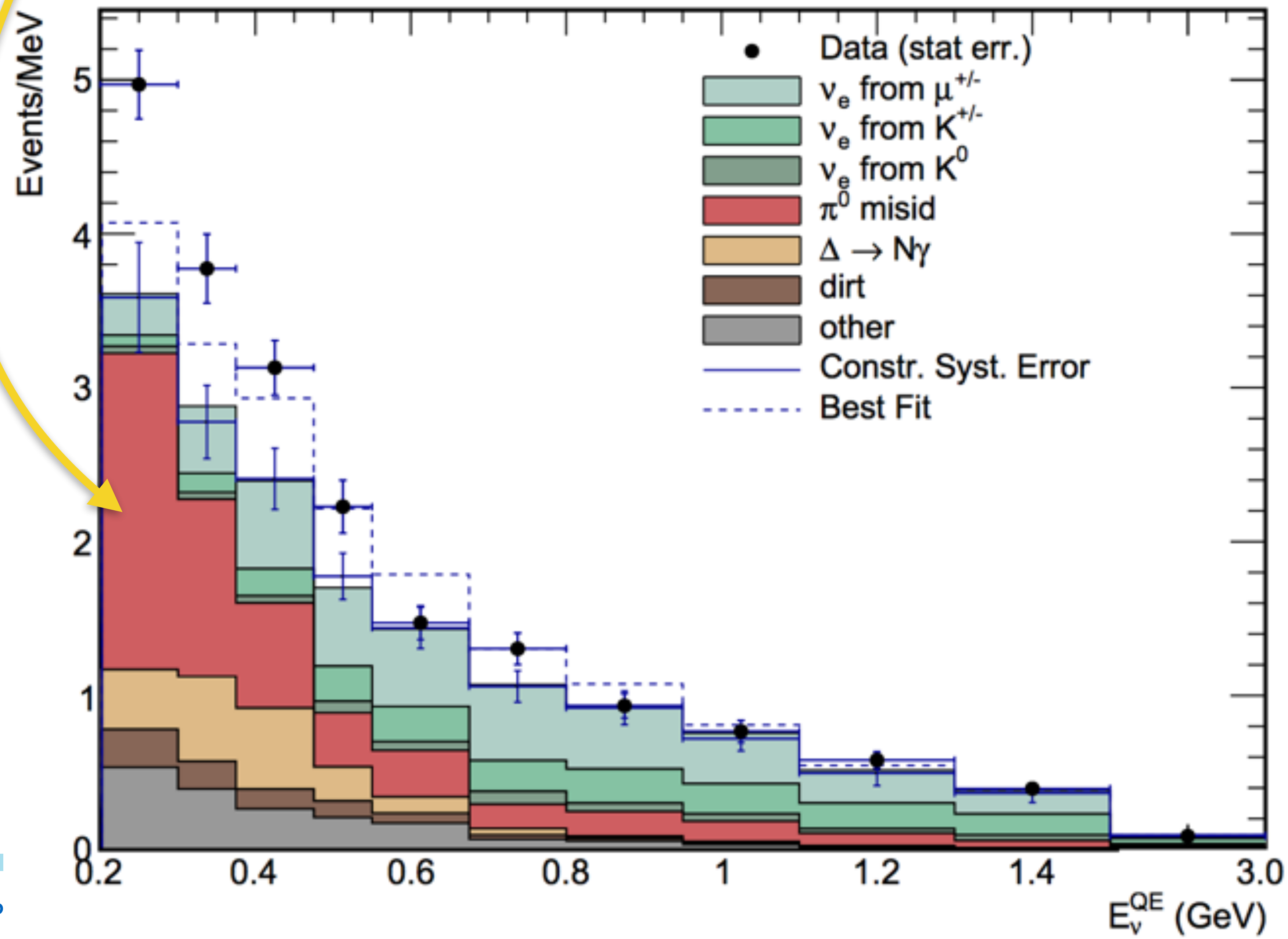
See talks by Chang, Gupta, Marshal, Mauger, Meyer, Nagai, Nicholson, Papavassiliou, …

Important milestone for the liquid argon technology and **neutrino cross sections**



The MicroBooNE
Technical Design Report

The unique electron-photon discrimination power offered by the LArTPC will allow MicroBooNE to either confirm or rule out the low energy excess of electron-like interactions observed by MiniBooNE, and, if confirmation occurs, to test many models that have developed



Fermilab
pmachado@fnal.gov

Roxanne Guenette <guenette@g.harvard.edu>
4 recipients
Resent-From: pmachado <pmachado@fnal.gov>
Re: Potential talks from MicroBooNE at NuFACT?

May 10, 2018 at 11:29 AM
Archive - Google (All Mail)

New contact info found in this email: Roxanne Guenette guenette@g.harvard.edu add...

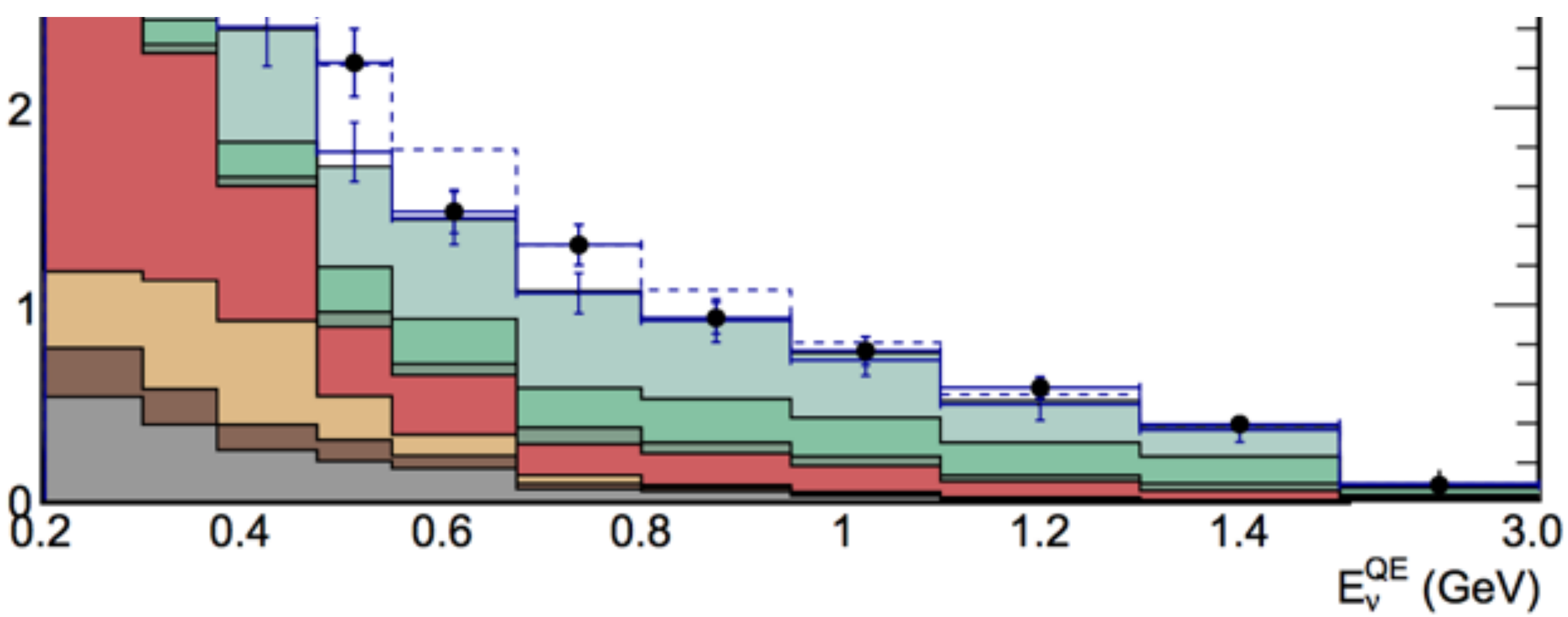
Dear Walter, Sanjib and Pedro,

I removed the Scattering conveners here, as we started a separate thread. We are still finalizing the exact results, but Microboone will present the recent updates on our low-energy search. These will be our first results towards our final analysis. I imagine there also could be a possibility to present this in the larger context of SBN.

Thank you for considering this request as a possibility for your session.

Best Regards,

Roxanne



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New ideas?

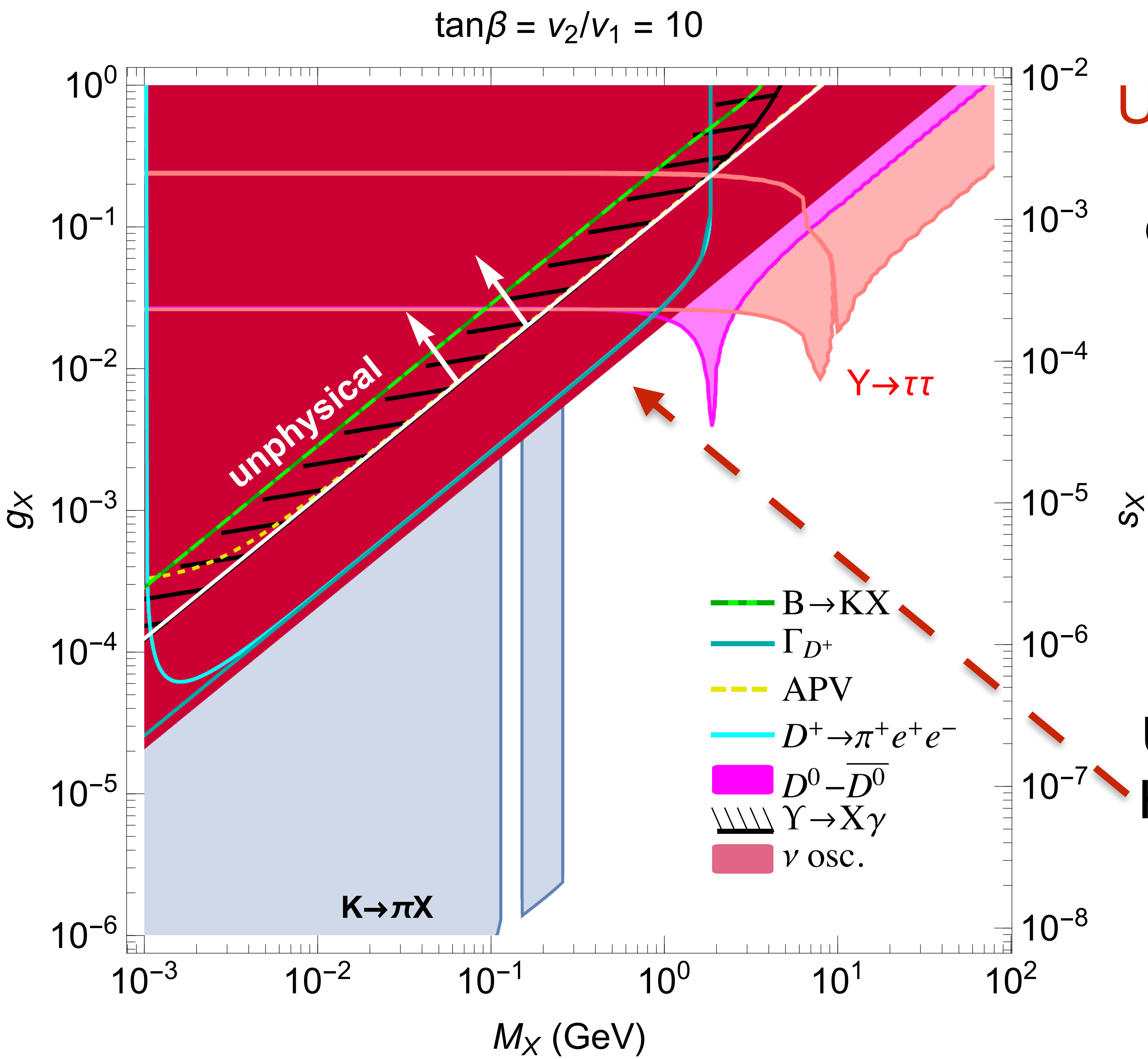
New approaches?

Neutrinos and low scale new Physics

Can there be a flavor mediators at low scale???

Neutrinos and low scale new Physics

Can there be a flavor mediators at low scale???



U(1) B – L of the third family

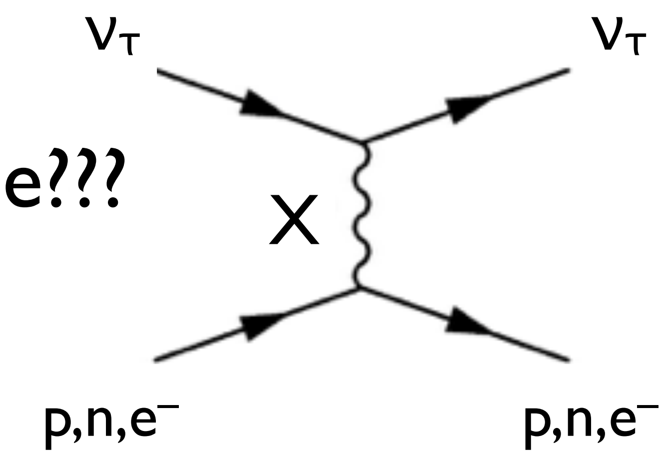
Complete model, including scalar sector and CKM generation

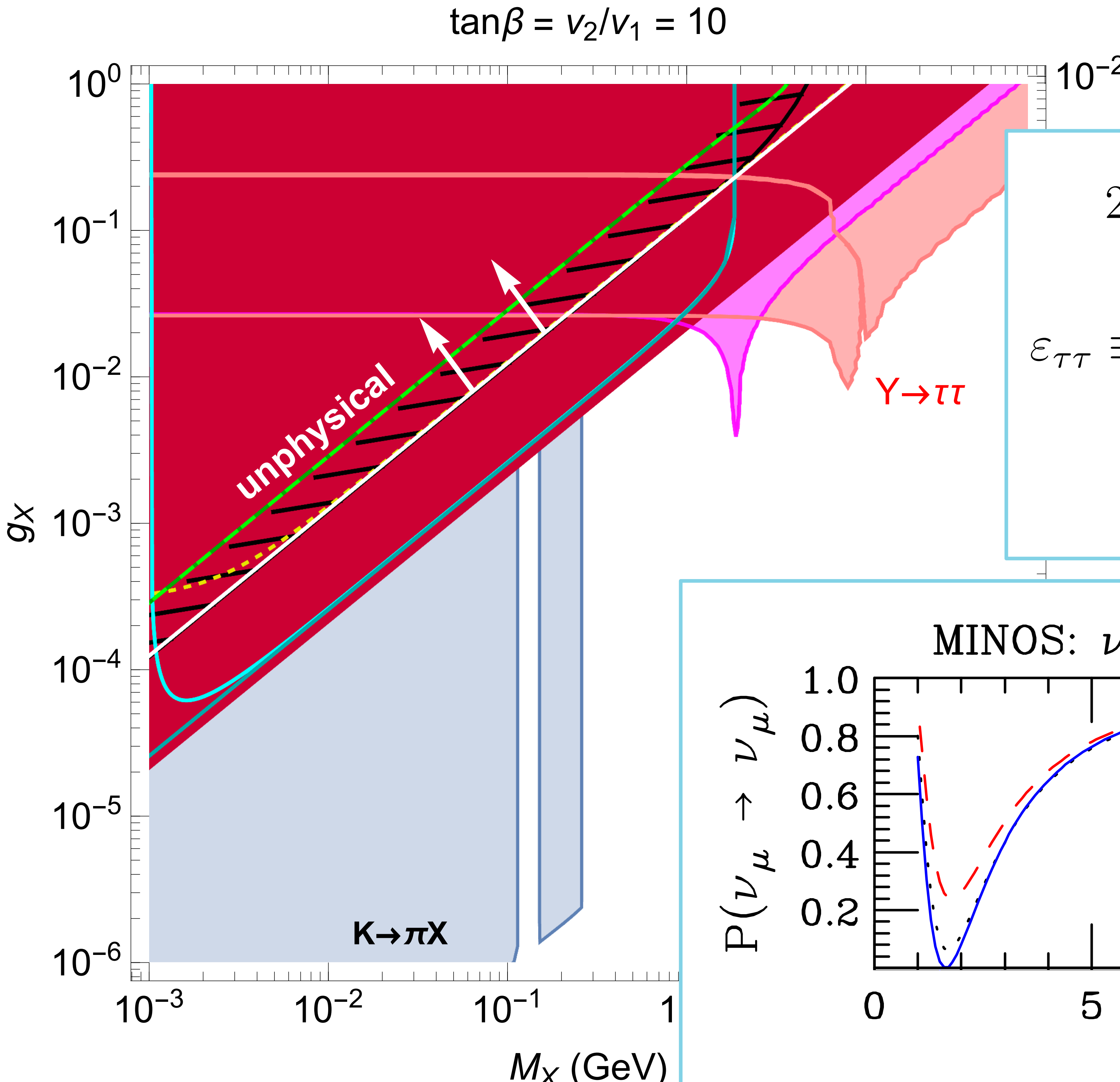
Vast phenomenology:
Z-X mixing (s_X)
D oscillations
Atomic Parity Violation
Upsilon, B, D, and K decays
Higgs, top, Z, and W decays
Neutrino oscillations
…

Babu Friedland Machado Mocioiu 1705.01822

Neutrinos and low scale new Physics

Can there be a flavor mediators at low scale???



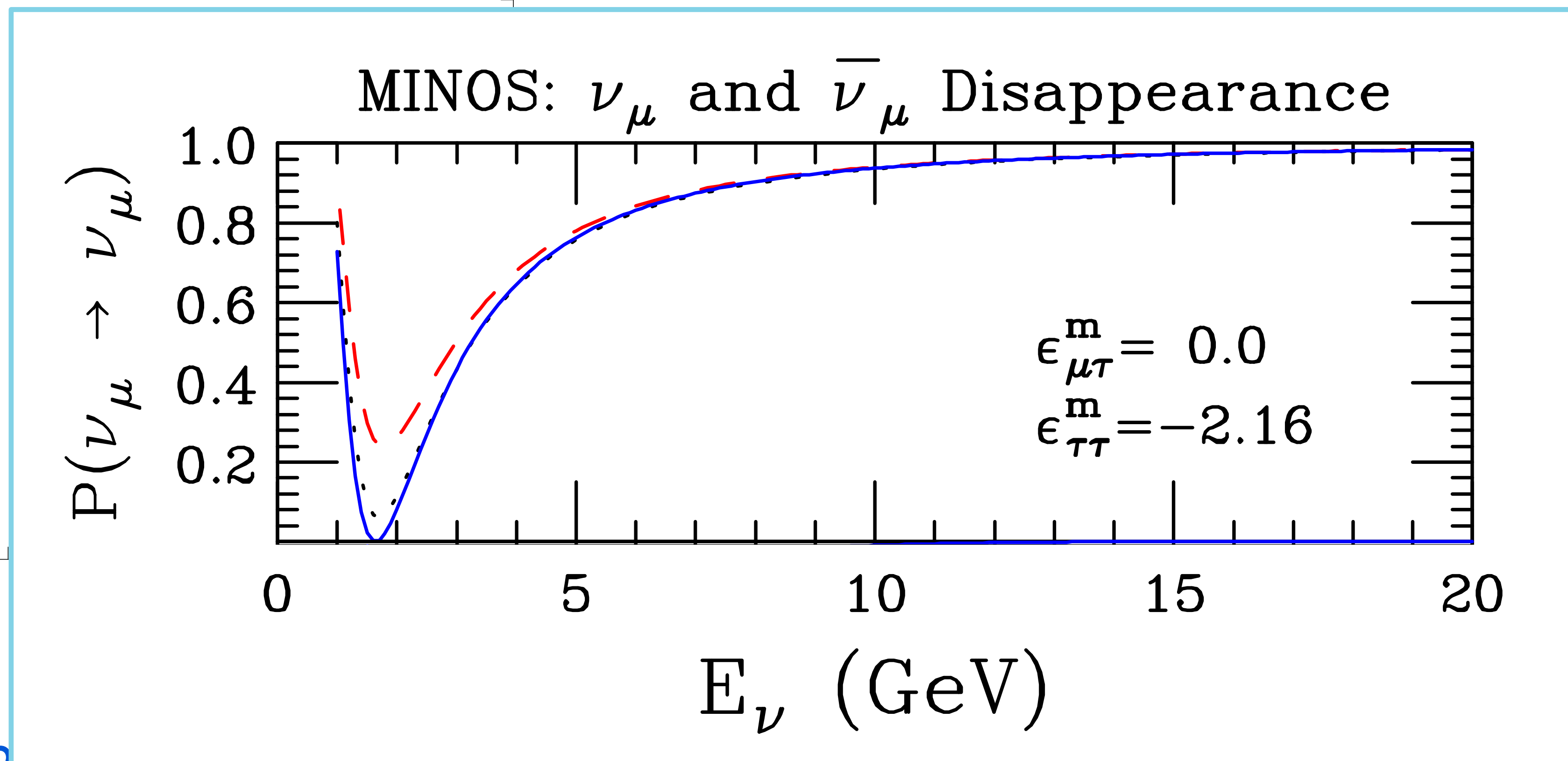


$$2\sqrt{2}G_F\varepsilon^f_{\alpha\alpha}\,(\bar{\nu}_{\alpha L}\gamma_\mu\nu_{\alpha L})\,(\bar{f}\gamma^\mu f)$$

$$\varepsilon_{\tau\tau} \equiv \varepsilon^p_{\tau\tau} + \varepsilon^n_{\tau\tau} + \varepsilon^e_{\tau\tau} = 3\frac{v_1^2 v^2}{v_1^2 v_2^2 + v_s^2 v^2}$$

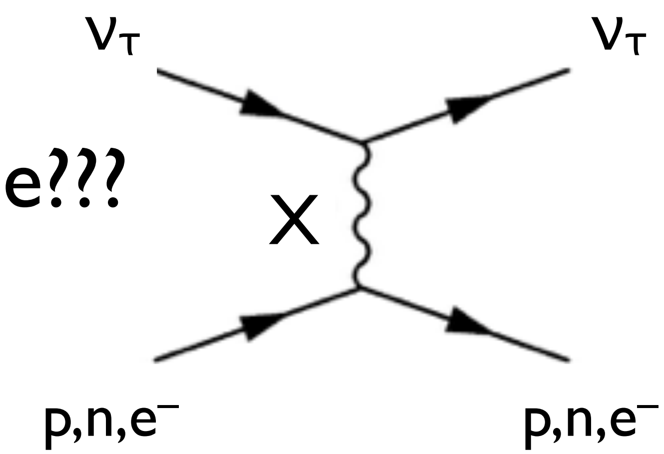
$$|\varepsilon_{\tau\tau}| < 0.09$$

NSI bounds: Esteban et al 1805.04530

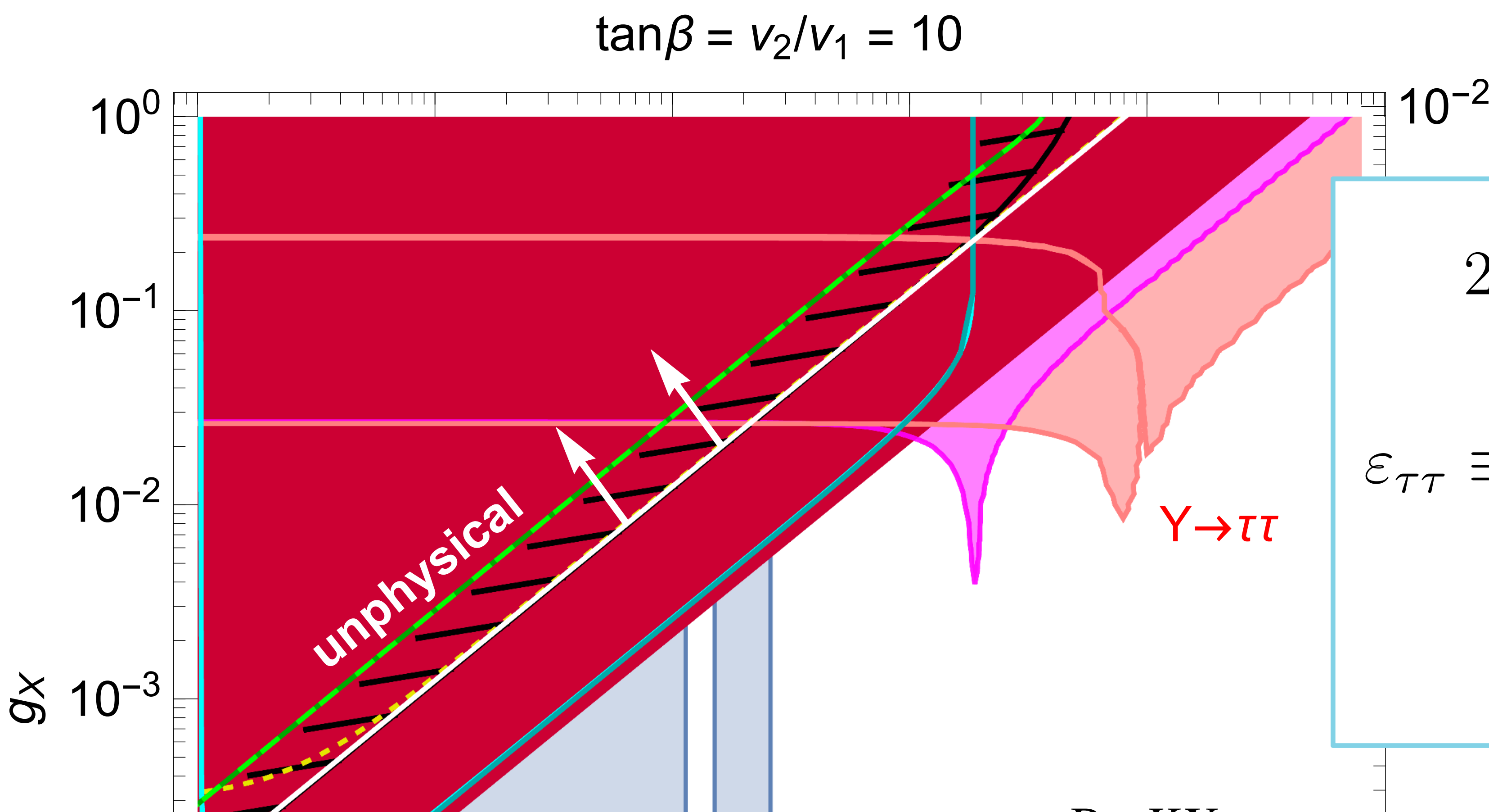


Babu Friedland Machado Mocioiu 1705.0182

Neutrinos and low scale new Physics



Can there be a flavor mediators at low scale???



$$2\sqrt{2}G_F\varepsilon^f_{\alpha\alpha}\left(\bar{\nu}_{\alpha L}\gamma_\mu\nu_{\alpha L}\right)\left(\bar{f}\gamma^\mu f\right)$$

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Neutrinos could probe low scale flavor physics

The third family is special: not so much for neutrinos!

Neutrino matter potential actually probes the symmetry breaking scale

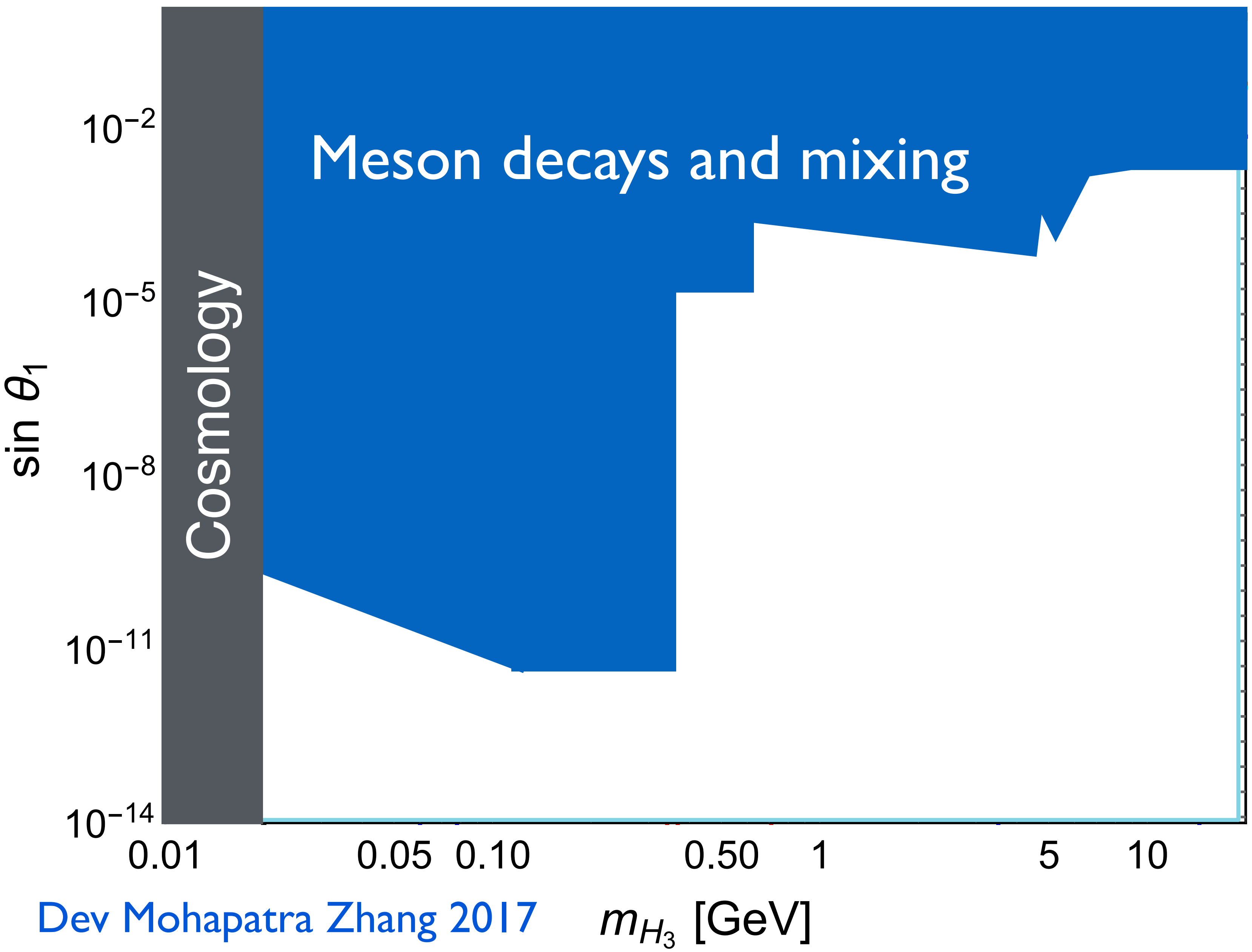
$$V_{CC} = \sqrt{2}G_F N_e, \quad G_F = \frac{1}{\sqrt{2}v^2}$$

NSI: $2\sqrt{2}G_F\varepsilon^f_{\alpha\alpha}\left(\bar{\nu}_{\alpha L}\gamma_\mu\nu_{\alpha L}\right)\left(\bar{f}\gamma^\mu f\right)$ → 1% NSI translate into v' ~ 10v

Babu Friedland Machado Mocioiu 1705.01822

Neutrinos and low scale new Physics

TeV scale seesaw with local $U(1)_{B-L}$ can yield a GeV scalar!



Dev Mohapatra Zhang 2017

Vast phenomenology:
B and K decays
B mixing
Cosmology
LHC displaced vertices
...

Neutrinos and low scale new Physics

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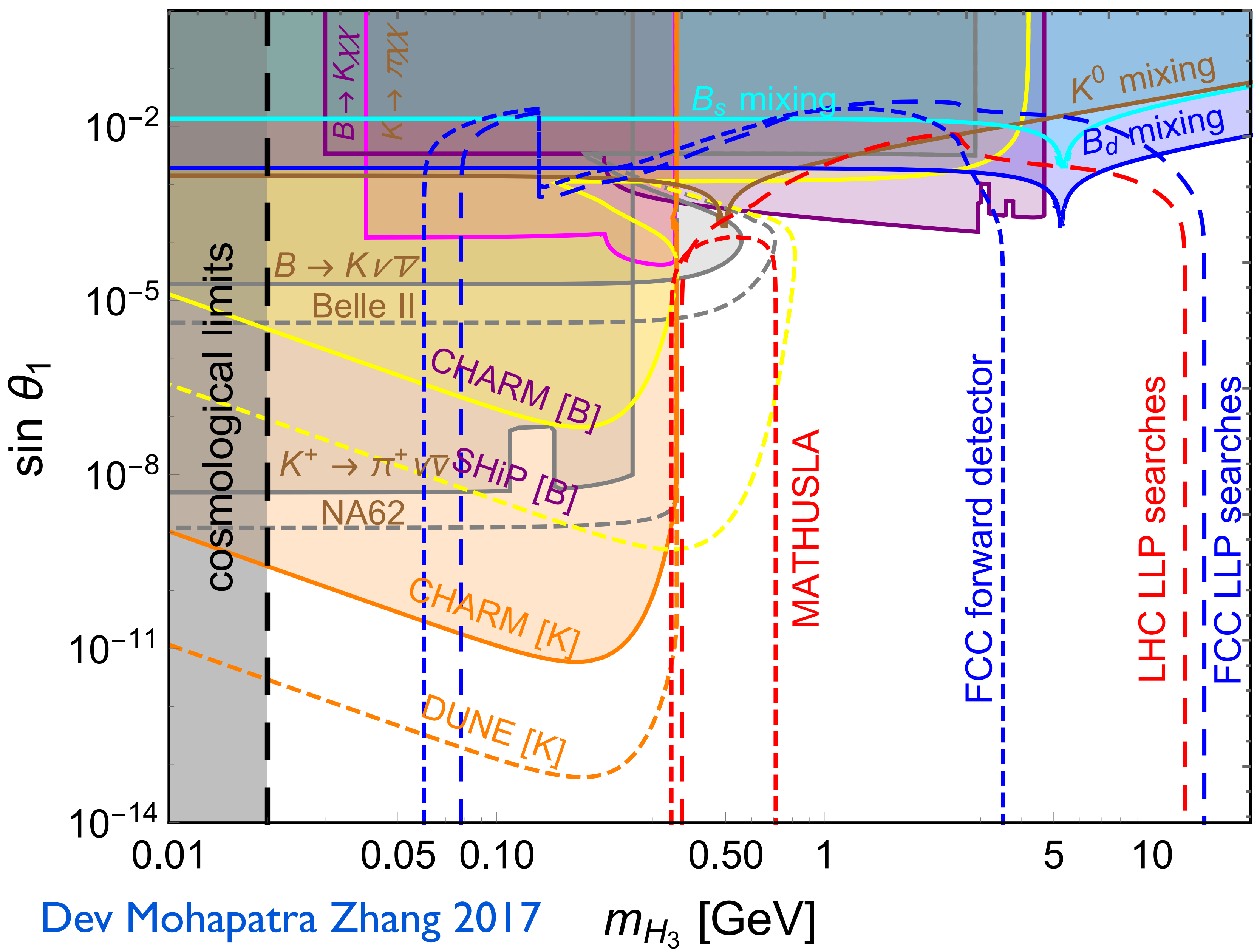

Dev Mohapatra Zhang 2017

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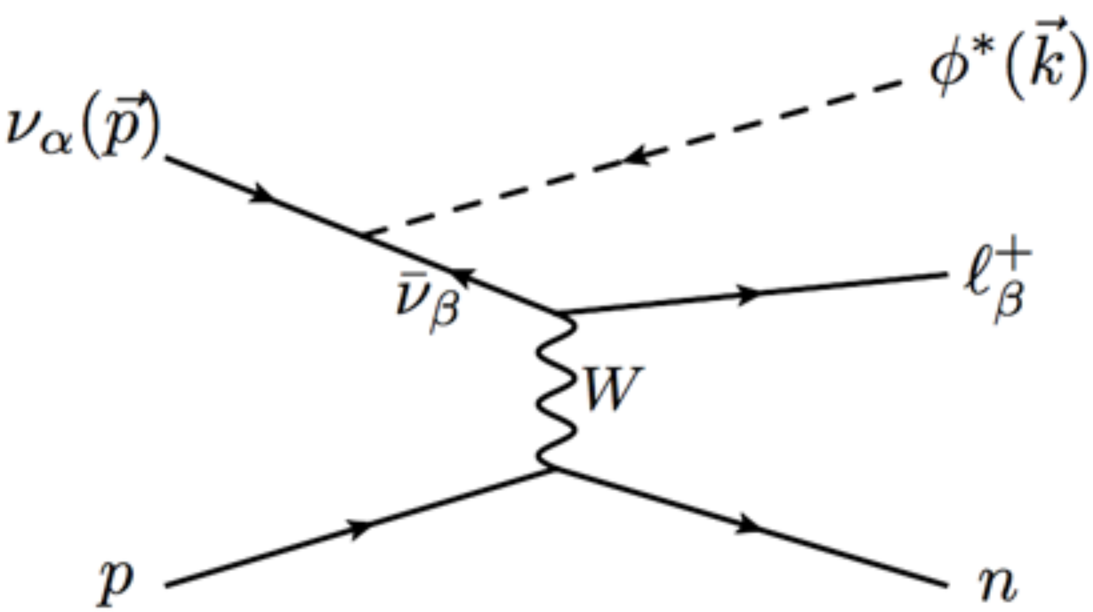
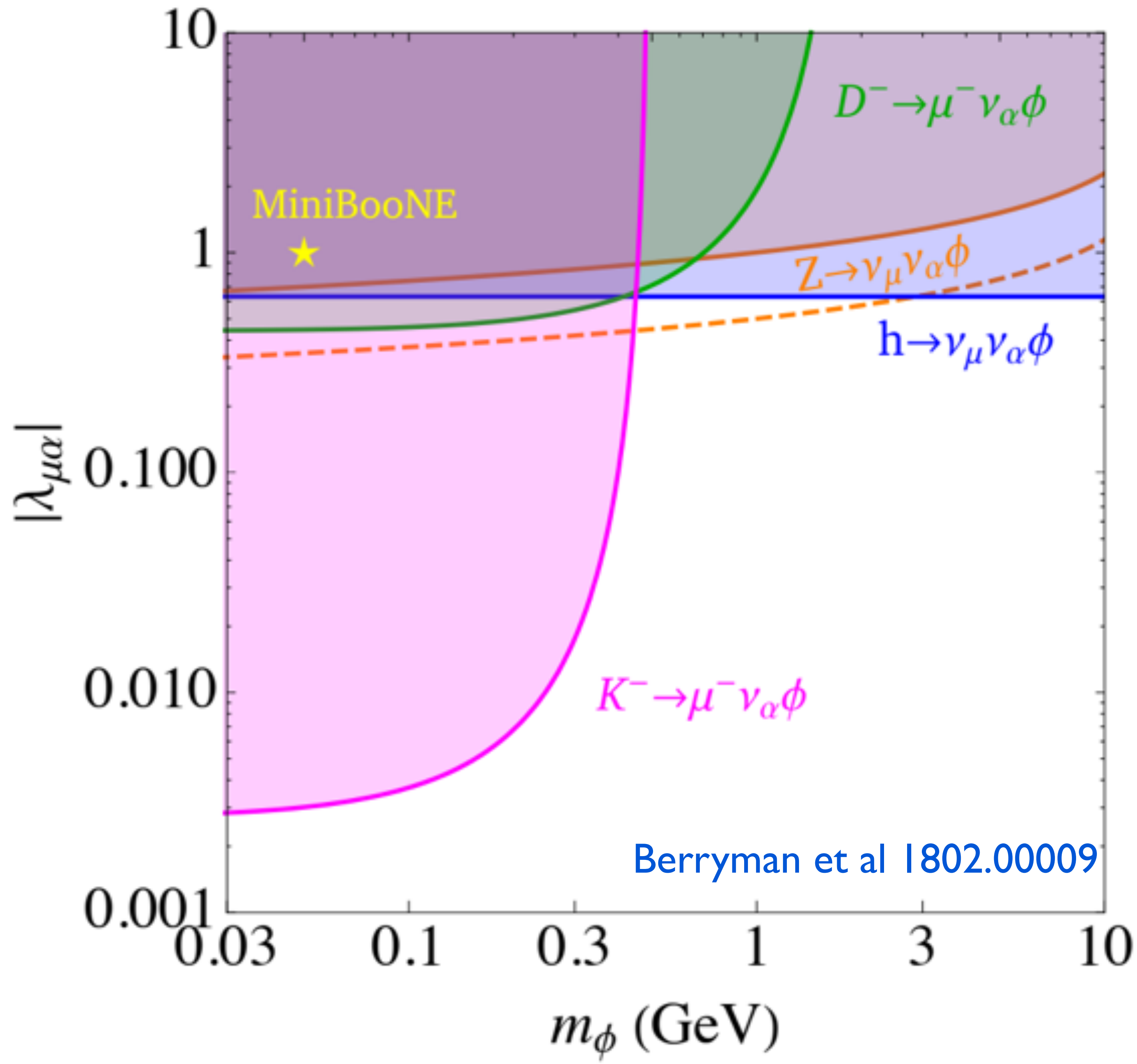
Neutrinos and low scale new Physics

Light scalar mediators (carrying lepton number) coupled to neutrinos

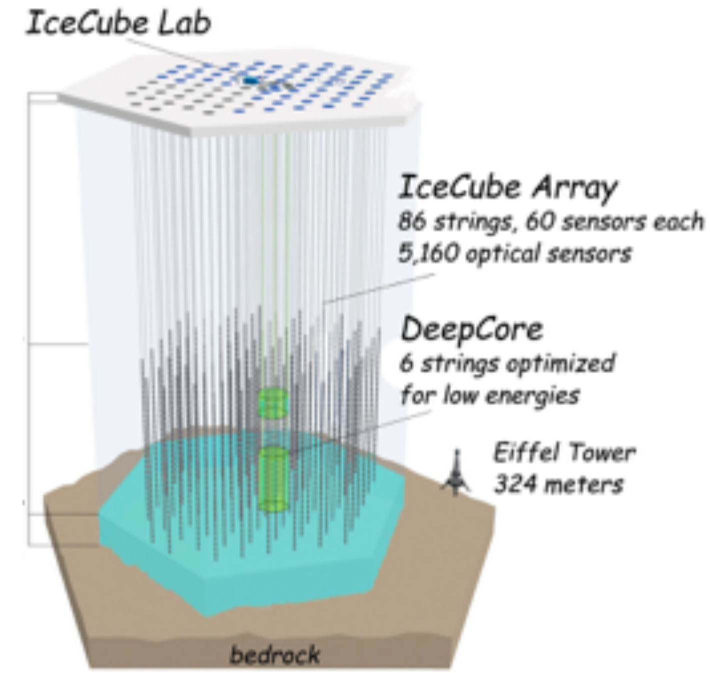
$$\frac{\lambda_{\alpha\beta}}{2}\nu_\alpha\nu_\beta\phi$$





Neutrinos and new Physics

Revolution in Neutrino Astrophysics



Flavor composition of IceCube high energy neutrinos can probe new Physics unambiguously

Palomarez-Ruiz Mena Vincent 2014, Bustamante Beacom Winter 2015, Arguelles Katori Salvado 2015, Nunokawa Panes Zukanovich-Funchal 2016, Bustamante Beacom Murase 2016, Brdar Kopp Wang 2016

Neutrinos and new Physics

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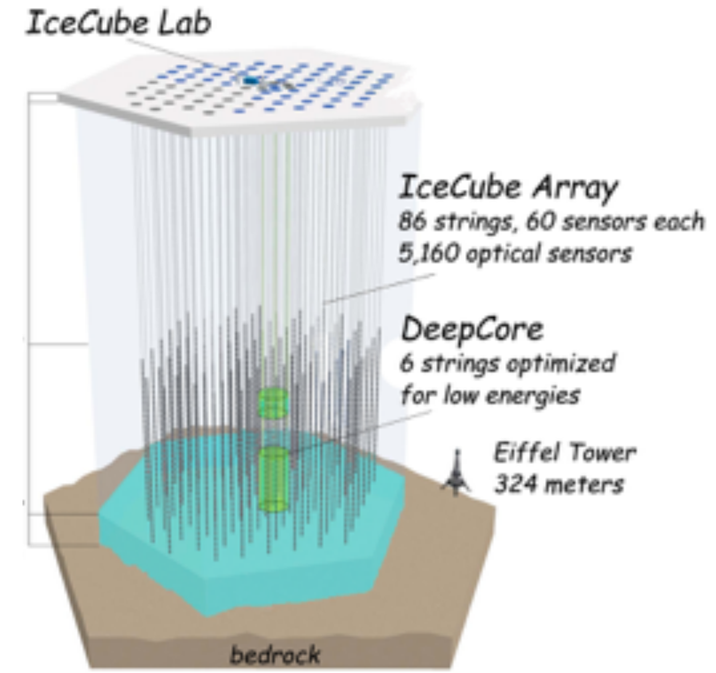

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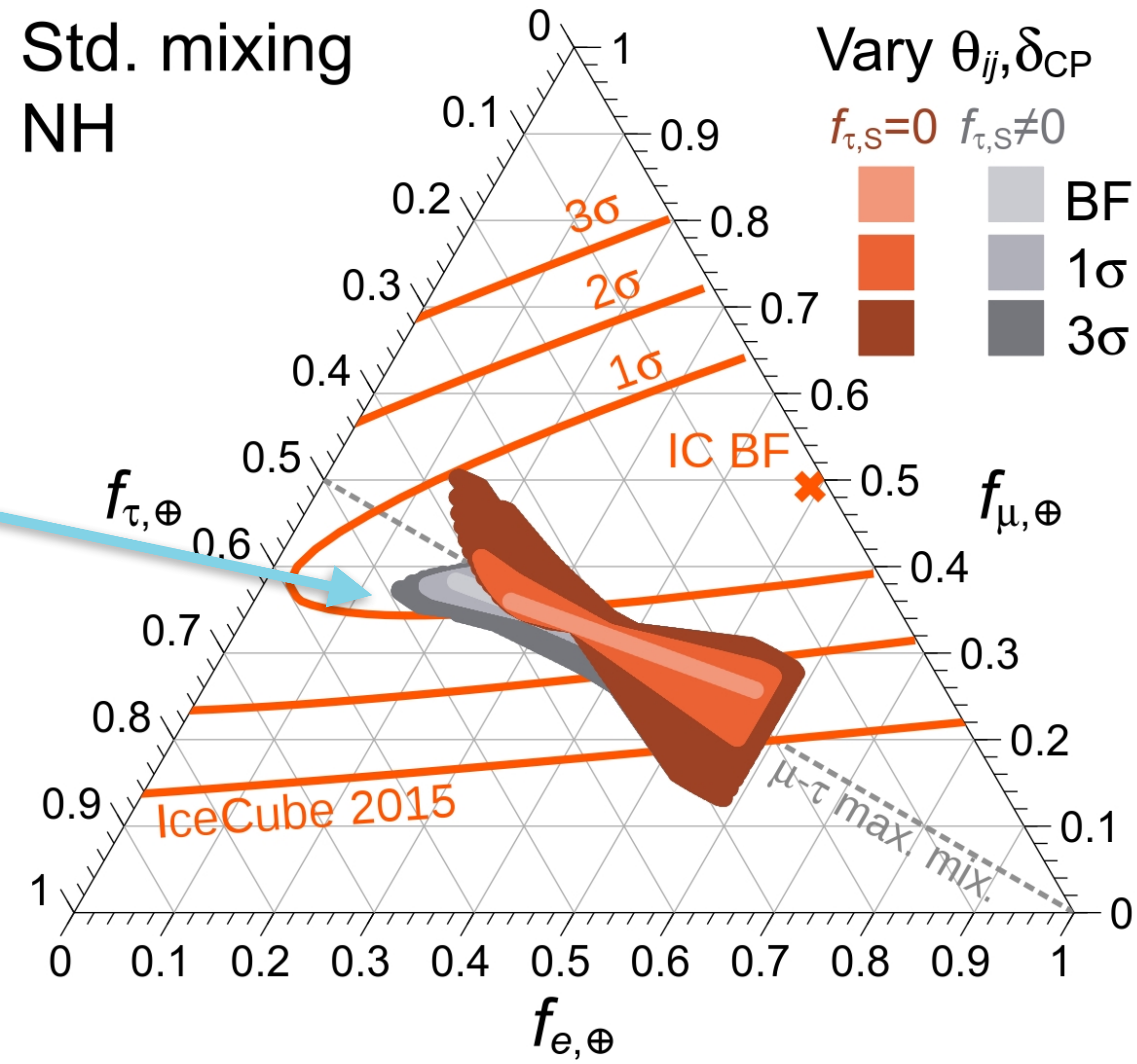
$$\bar{P}_{\nu_\alpha \to \nu_\beta}(E) = \sum_i |V_{\alpha i}(E)|^2 \, |V_{\beta i}(E)|^2$$

For any flavor composition at the source, the flavor ratio at detection is constrained by the PMNS matrix uncertainty

New experimental technique to separate EM from hadronic showers can improve the flavor ratio determination considerably

Li Bustamante Beacom 2016



pmachado@fnal.gov

Few things I coundn't talk about…

Neutrino cross sections (NuSTEC effort)

Neutrinos in cosmology
Early universe - BBN

Abazajian, Barbieri, Cirelli, Chizov, Di Bari, Dodelson, Dolgov, Foot, Holanda, Iocco, Kirilova, Kusenko, Mangano, Lesgourges, Pastor, Smirnov, Steigman, Volkas

Secret neutrino interactions

Dasgupta Kopp 2013, Chu Dasgupta Kopp 2015, Lundkvist Archidiacono Hannestad Tram 2016, Ghalsasi McKeen Nelson 2016, Archidiacono Gariazzo Giunti Hannestad Hansen Laveder Tram 2016, Forastieri Lattanzi Mangano Mirizzi Natoli Saviano 2017

Supernova evolution: non-linear effects from collective oscillations

Friedland 2010, Cherry Carlson Friedland Fuller Vlaesnko 2012, Chakraborty Hansen Izaguirre Raffeelt 2016, Capozzi Basudeb Dasgupta 2016, Izaguirre Raffelt Tamborra 2016, Capozzi Dasgupta Lisi Marrone Mirizzi 2017

Chen Ratz Trautner 2015

Cosmic neutrino background: ideas to measure it? Non-thermal component?

Type II, type III and radiative seesaw

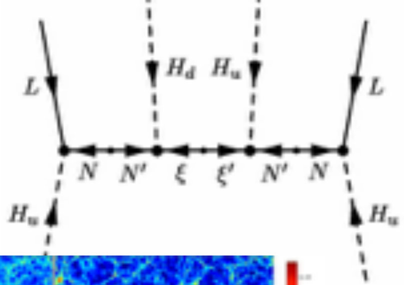
Akhmedov, Bonnet, Babu, Barbieri, Barger, Berezhiani, Ellis, Gaillard, Glashow, Hirsch, Keung, Ma, Mohapatra, Ota, Pakvasa, Schechter, Senjanovic, Valle, Yanagida, Winter, Wolfenstein, Zee, and many others

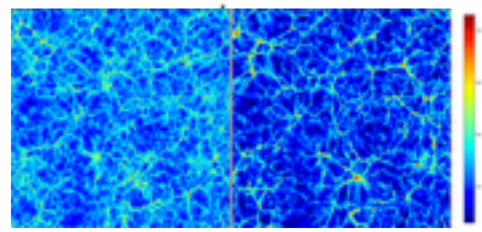
Flat extra dimensions: light sterile neutrinos

Antoniadis, Arkani-Hamed, Barbieri, Berryman, Davoudiasl, Dimopoulos, Dvali, de Gouvea, Langacker, Machado, Mohapatra, Nandi, Nunokawa, Perelstein, Peres, Perez-Lorenzana, Smirnov, Strumia, Tabrizi, Zukanovich-Funchal, …

Leptogenesis

Barenboim, Davidson, Di Bari, Dolgov, Fukugita, Kuzmin, Rubakov, Servant, Shaposhnikov, Yanagida, Zeldovich, …



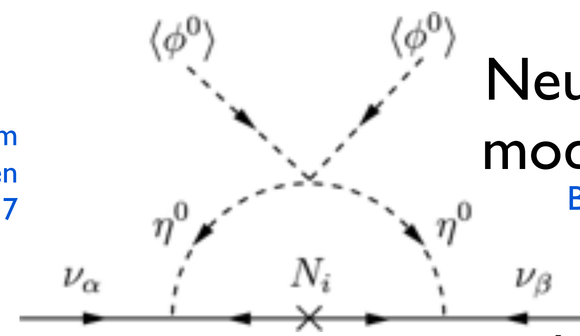


Sterile neutrino in long baseline oscillation experiments

Agarwalla, Bhattacharya, Chaterjee, Dasgupta, Dighe, Donini, Fuki, Klop, Lopez-Pavon, Meloni, Migliozzi, Palazzo, Ray, Tang, Terranova, Thalapillil, Wagner, Yasuda, Winter, …

Dark matter in neutrino detectors: light DM and light mediators

Ballett, Batell, Chen, Coloma, deNiverville, Dobrescu, Frugiuele, Harnik, McKeen, Pascoli, Pospelov, Ritz, Ross-Lonergan

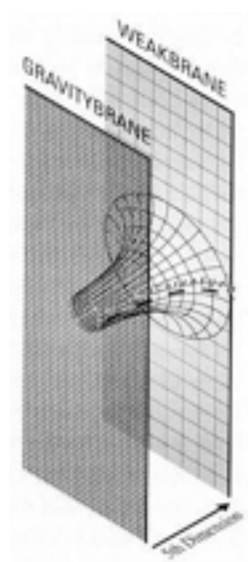


Neutrinos and the standard solar model: CNO cycle and metallicity

Bailey, Busoni, Christensen-Dalsgaard, Krief, Simone, Serenelli, Scott, Vincent, Vilante, Vissani, Vynioli, …

Neutrino magnetic moment

see e.g. Salam 1957, Barbieri Fiorentini 1988, Barbieri Mohapatra 1989, Babu Chang Keung Phillips 1992, Tarazona Diaz Morales Castillo 2015 Cañas Miranda Parada Tortola Valle 2015, Barranco Delepine Napsuciale Yebra 2017 Coloma Machado Martinez-Soler Shoemaker 2017

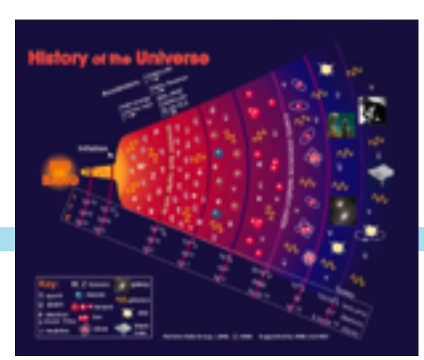


Discrete symmetries with non-zero θ_{13}

Feruglio Hagedorn Toroop 2011, Lam 2012, Lam 2013, Holthausen Lim Lindner2012, Neder King Stuart 2013, Hagedorn Meroni Vitale 2013 King Neder 2014, Ishimori King Okada Tanimoto 2014, Yao Ding 2015, …

Effective operator approach to neutrino masses and collider/low scale pheno

de Gouvea Jenkins 2007, Boucenna Morisi Valle 2014, Nath Syed 2015, Geng Tsai Wang 2015, Chiang Huo 2015, Bhattacharya Wudka 2015, Geng Huang 2016, Quintero 2016, Mohapatra 2016, Kobach 2016



New physics in neutrinoless double beta decay, lepton number violation at the LHC, left-right models, RS models and neutrino masses, neutrinos as dark matter, and much more!

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The future of neutrino physics is bright

Precision era in neutrino physics

Better tests of the three neutrino paradigm

Standard and BSM neutrino programs

LSND/MiniBooNE anomalies clarified soon (hopefully)

Reactor anomaly clarified soon (hopefully)