Neutrino theory = Neutrino physics viewed by a theoretician

Hisakazu Minakata IFT UAM/CSIC, Madrid → where??

My career in Latin America

- Since Feb 2013, Rio de Janeiro (6 meses), Sao Paulo (32 meses), Yachay Tech (Ecuador, 14 meses) ~ 4.5 años

Galapagos!! in 2006

Acknowledgements

- This is my 9th scientific visit to South America → great thanks for invitation
- My collaborators include:

Hiroshi Nunokawa at Universidade Cat'olica do Rio de Janeiro (PUC, Rio),

Renata Zukanovich Funchal & Walter Teves at Universidade de Sao Paulo (USP)

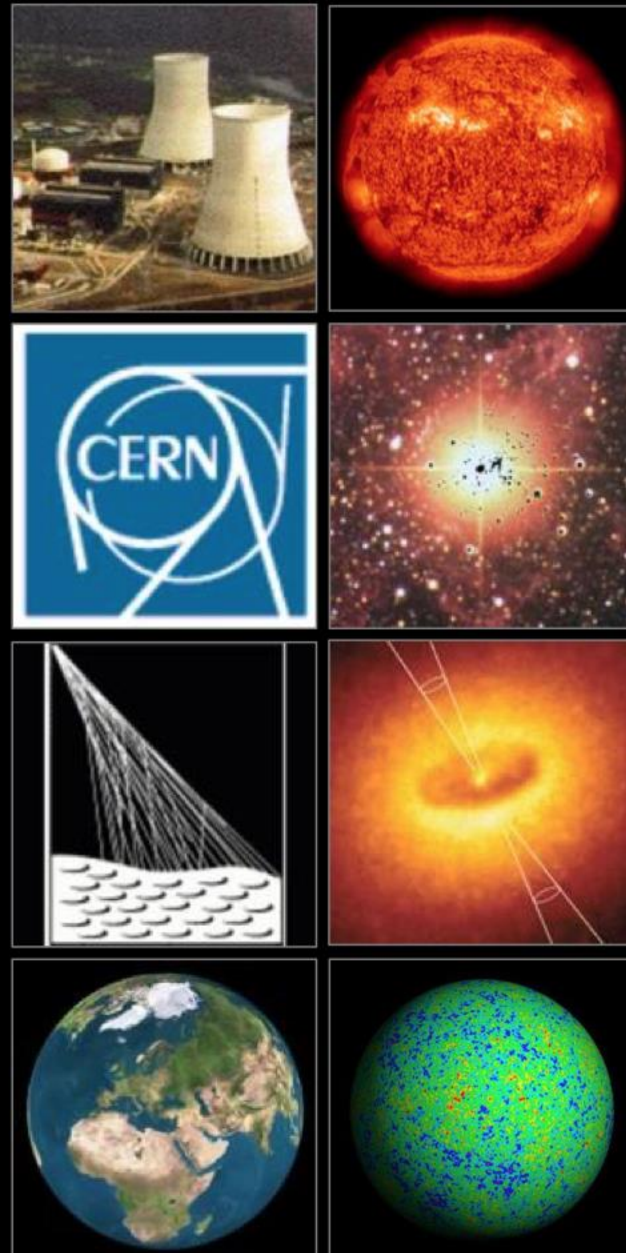
June 22-25, 2006 World Summit Physics

neutrino physics as interdiscipli nary field

Really enjoyable field!

Where do Neutrinos Appear in Nature?

Georg Raffelt, Physics Colloquium, Stockholm, 24 April 2014



✓ Nuclear Reactors

✓ Particle Accelerators

✓ Earth Atmosphere (Cosmic Rays)

✓ Earth Crust (Natural Radioactivity)

Sun ✓

Supernovae (Stellar Collapse)

SN 1987A ✓

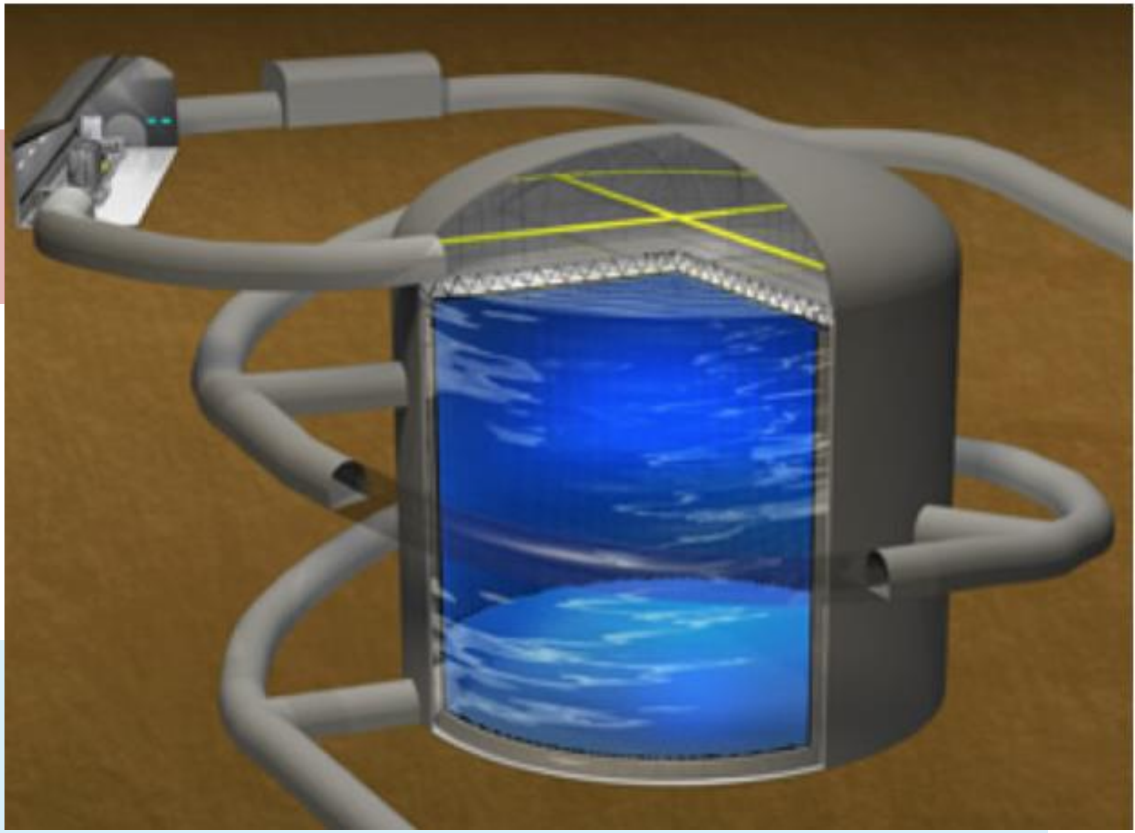
Astrophysical Accelerators ✓

Cosmic Big Bang (Today 330 ν/cm^3)

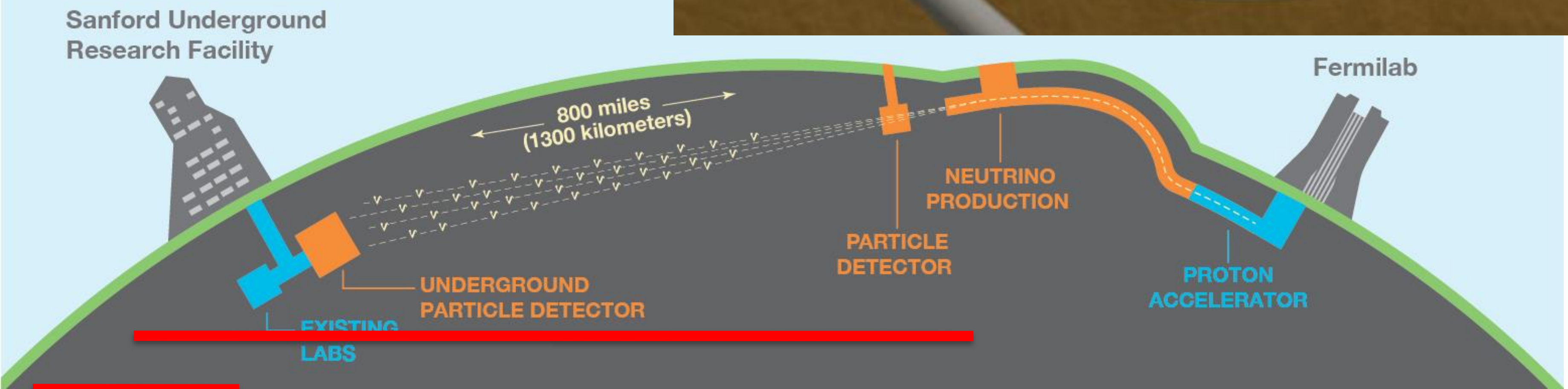
Indirect Evidence

Experimental nu is moving!!

Hyper-K → Start construction in 2020!



DUNE → DOE Stage 3 approval



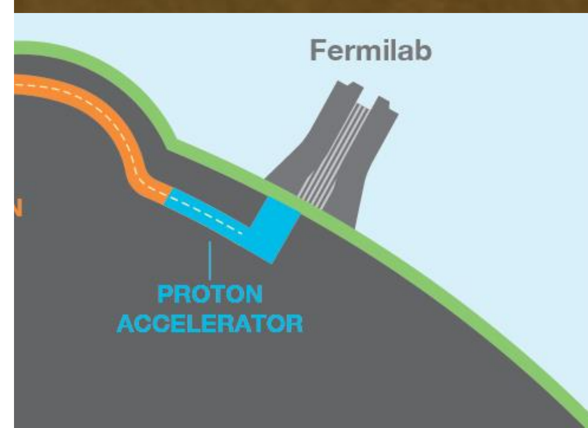
Experimental nu is moving!!

HYPER-KAMIOKANDE EXPERIMENT TO BEGIN CONSTRUCTION IN APRIL 2020

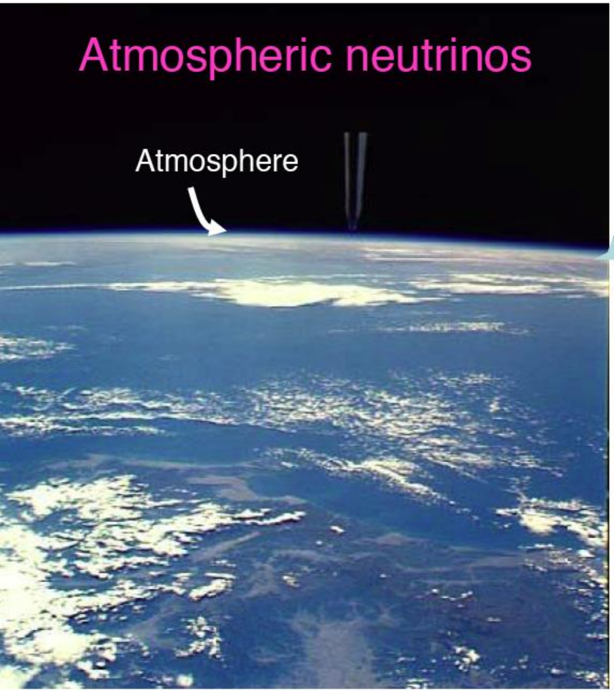
Posted on **SEPTEMBER 19, 2018 5:01 PM** by **ADMIN**

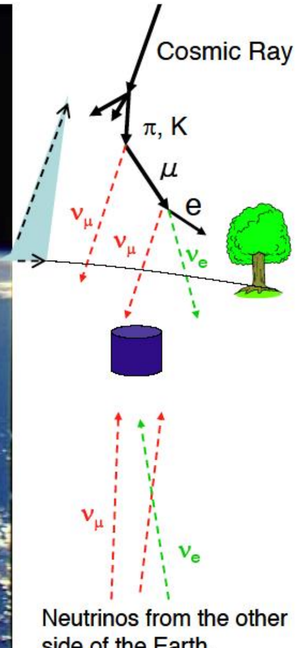
Last week at the 7th Hyper-Kamiokande proto-collaboration meeting, a statement was issued by the University of Tokyo recognizing the significant scientific discoveries which the planned Hyper-Kamiokande experiment would enable.

It states that, based on these exciting prospects, the University of Tokyo will ensure that construction of the experiment will begin in 2020. Hyper-Kamiokande now moves from planning to a real experiment.



Long discovery phase finally ended





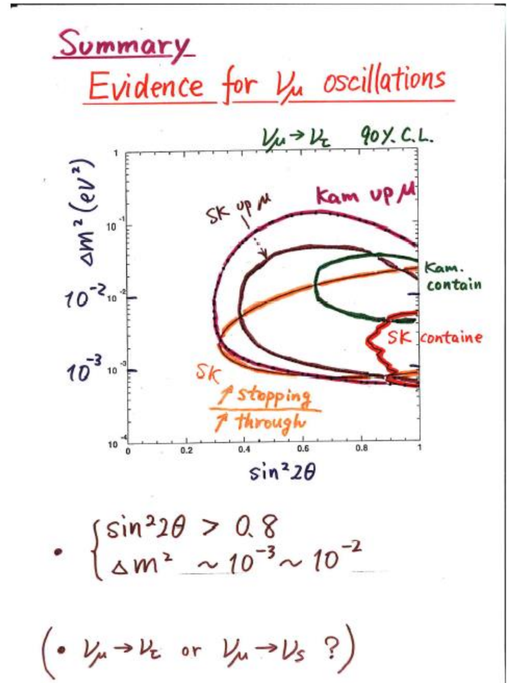
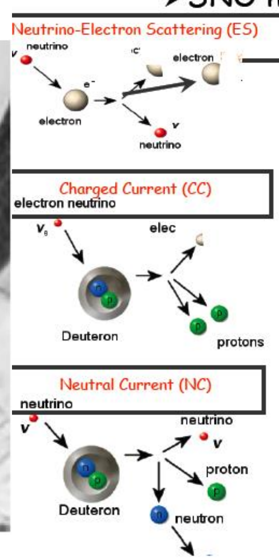


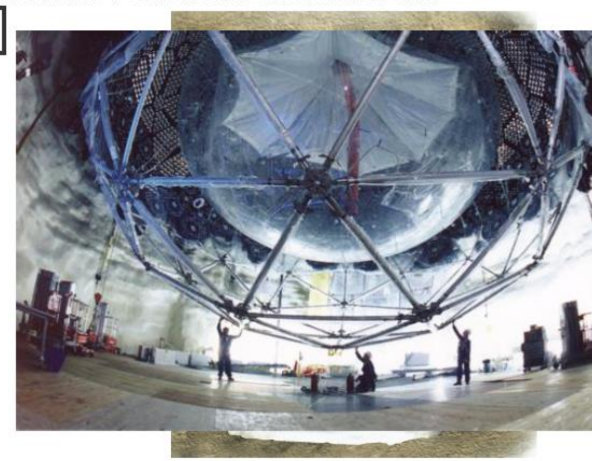
Photo: A. Mahmoud
Takaaki Kajita

Solar Neutrino Appearance

➢ SNO neutrino reactions on deuterons

Raymond David Jr. (left) and John Bahcall in miner's





National Geographic

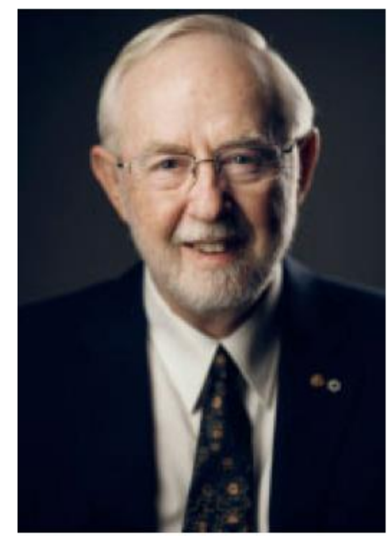


Photo: A. Mahmoud
Arthur B. McDonald

Signal rates determined by statistical fit

Physics 2015

3 flavor neutrino mixing established

All the angles are measured !
lepton CP phase δ left (1998-2012)

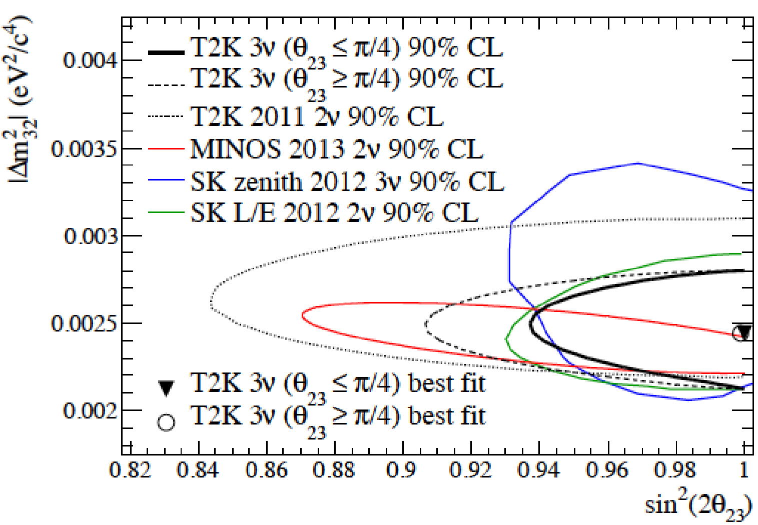
$\nu_\alpha = U_{\alpha i}\, \nu_i$

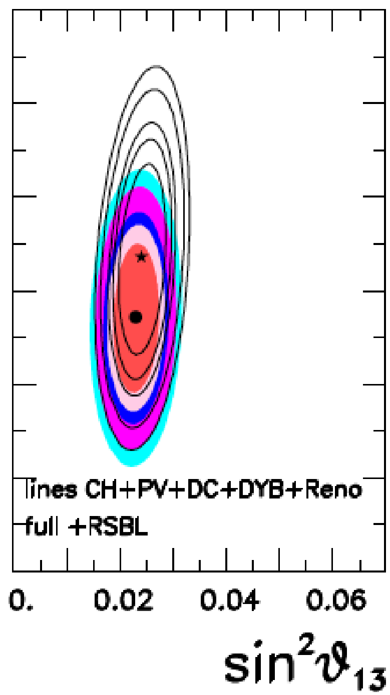
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

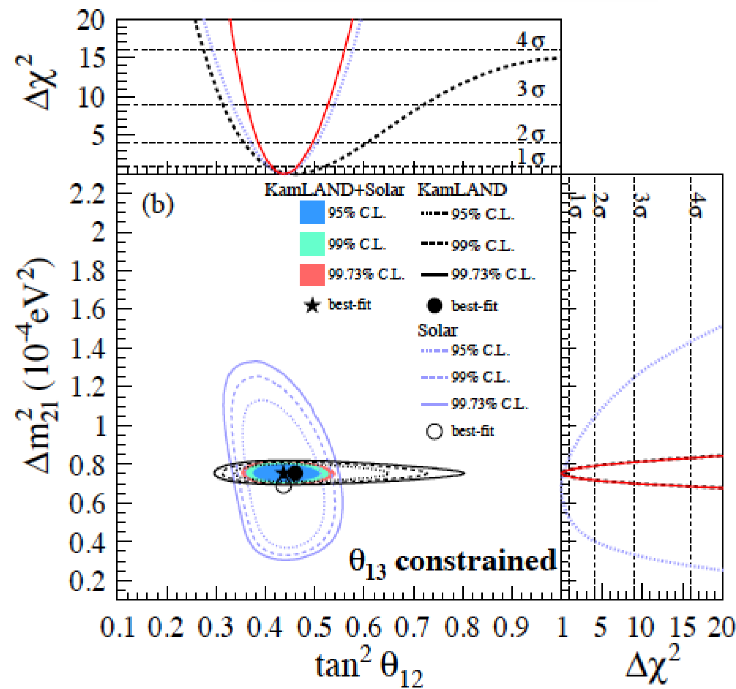
SK-atm+MINOS+T2K

T2K-MINOS-DC-DB-RENO

solar+KamLAND







All three angles are measured: Random angles?

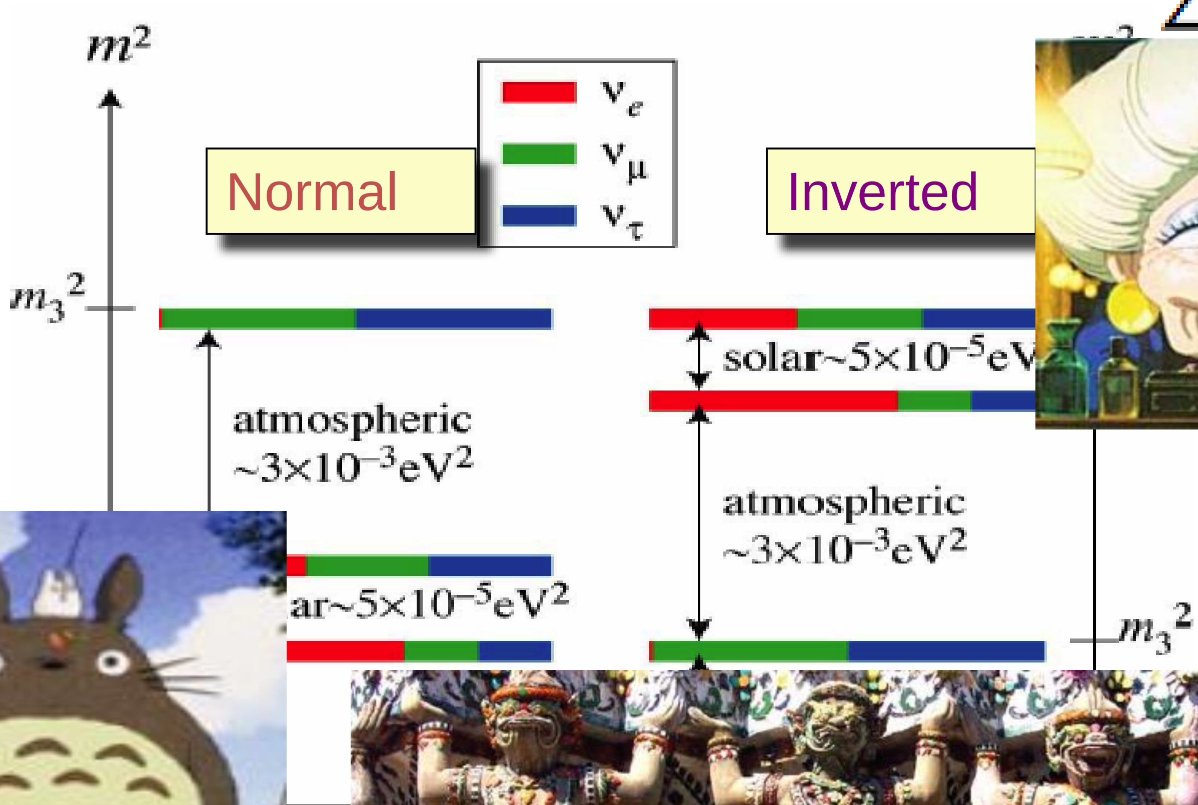
- θ_{23} ~ 45 degree
- θ_{12} ~ 33 degree
- θ_{13} ~ 8 degree
- What do they mean?

Quark mixing:
angles are tiny except for $\theta_{Cabibbo}$ = 13 deg.

Yet, we still don't know CP, ν mass pattern & absolute mass scale

← Cosmology helps
→ Planck 2018 !!

$\sum m_\nu < 0.12$ eV.



CP and mass ordering: Are we started to know the answer?

δ =~ $3\pi/2$ preferred (T2K)

~2 σ exclusion of CPC !

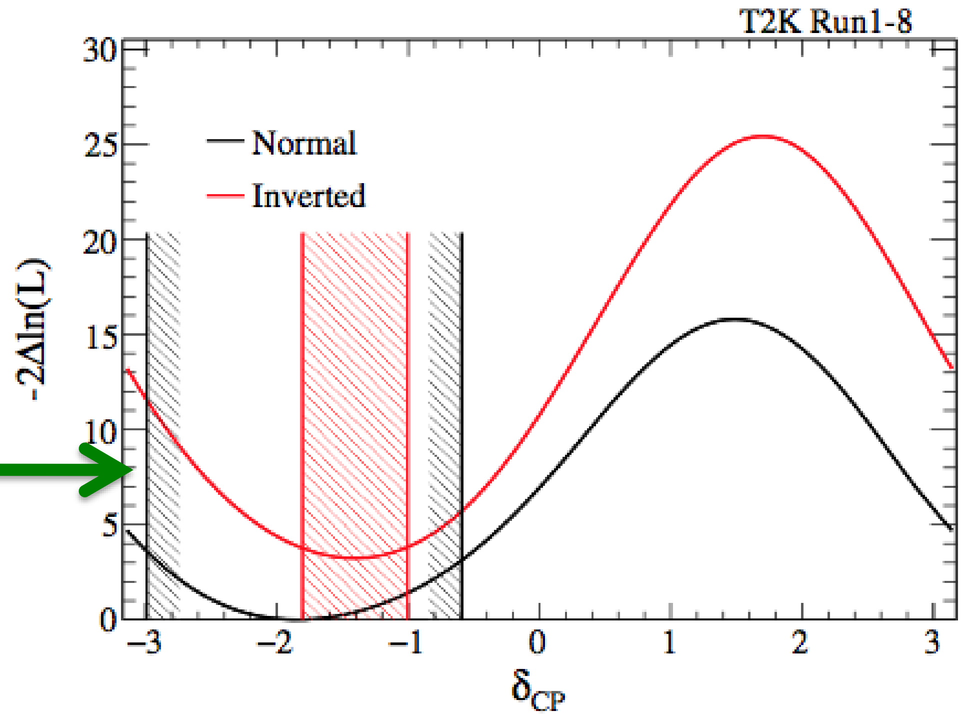


FIG. 6. 1D $-2\Delta\ln\mathcal{L}$ as a function of δ_{CP} for normal (black) and inverted (red) mass ordering using the reactor measurement prior on $\sin^2(2\theta_{13})$. The vertical lines show the corresponding allowed 2σ confidence intervals, calculated using the Feldman-Cousins method instead of the constant $-2\Delta\ln\mathcal{L}$ method.

T2K II (proposed, run until 2026) they could see CPV at ~3 σ (expected for ~15×10^{21} POT)

Apparently, normal ordering preferred !

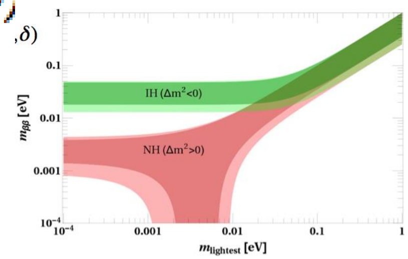
- A global analysis says normal ordering preferred at 3 σ level!

Bari group analysis: arXiv:1804.09678

$$\chi^2_{\rm min}({\rm IO}) - \chi^2_{\rm min}({\rm NO}) = 4.4 \quad ({\rm LBL\ acc.} + {\rm solar} + {\rm KL} + {\rm SBL\ reac.\ data})$$

Main additional contribution from Super-K atmospheric →

$$\chi^2_{\rm min}({\rm IO}) - \chi^2_{\rm min}({\rm NO}) = 9.5 \quad ({\rm all\ oscillation\ data})$$

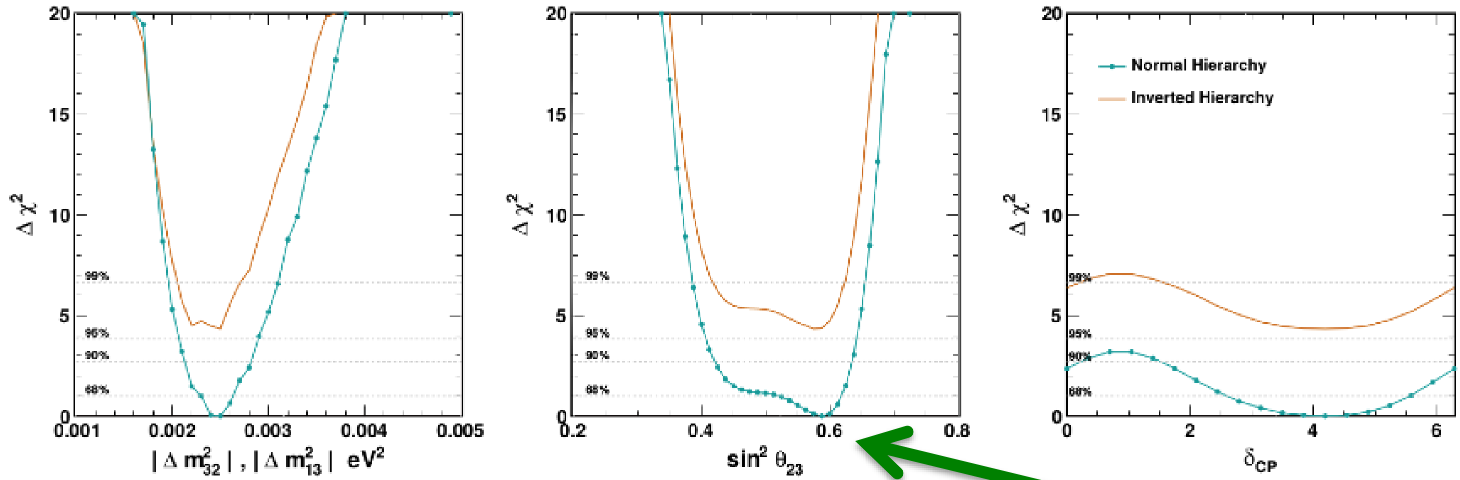


Immediate question: If normal, how we could attack ββ decay??

Super-K (+T2K, reactor)

Super-K latest atmospheric ν results Flor de María Blaszczyk

SK only



θ23 2nd octant!

Figure 4: Constraints when θ_{13} is fixed to the reactor experiments result.

T2K added

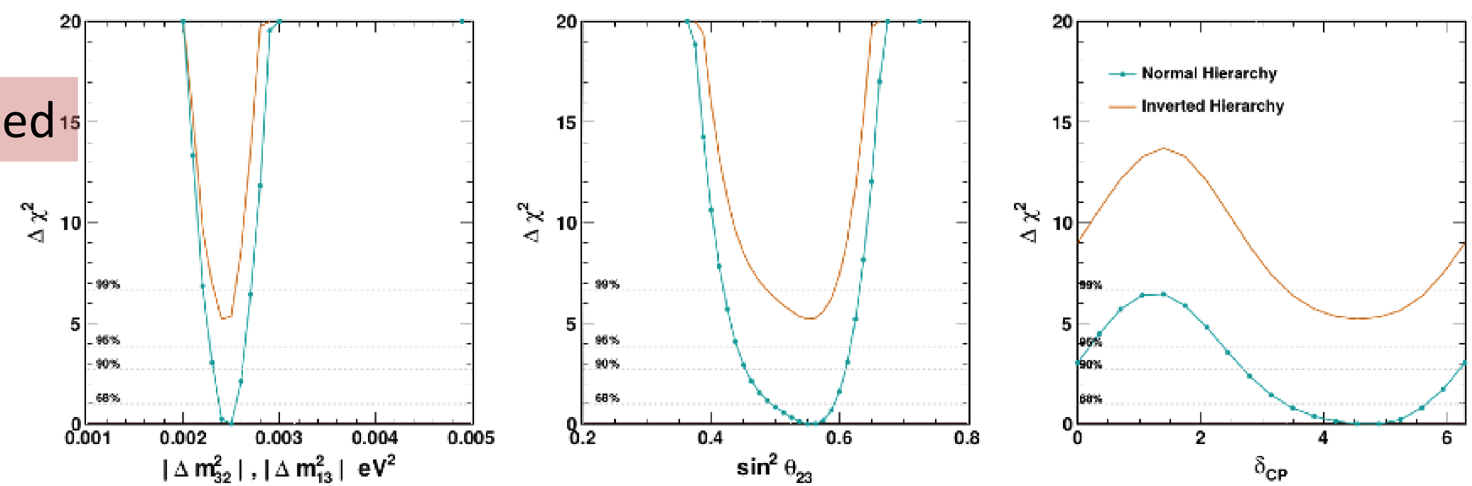


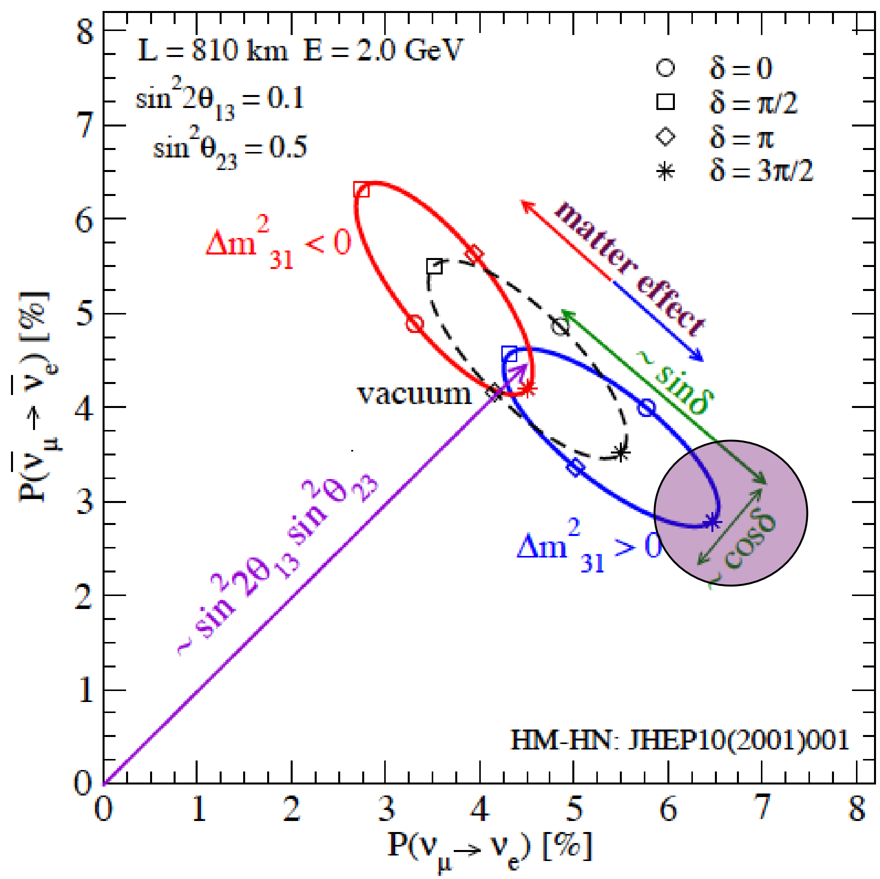
Figure 5: Constraints when θ_{13} is fixed and the T2K model is added.

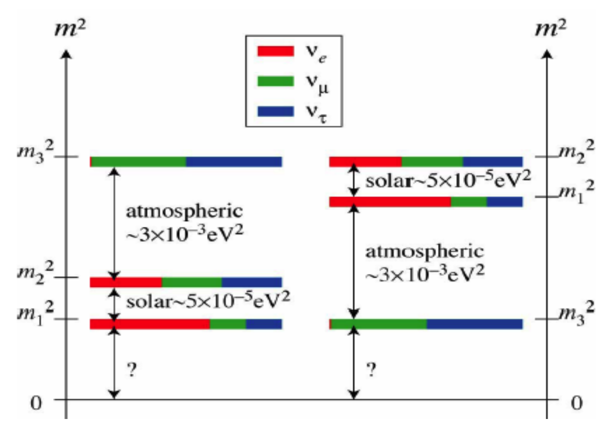
So, Things started to converge !!?

If so, it's
a great
news for
NOvA!

δ=3π/2 (or –π/2) implies that we are at the tip of the ellipse → the best case for NOvA

P-\bar{P} bi-probability diagram, proposed by HM-H.Nunokawa, JHEP 2001





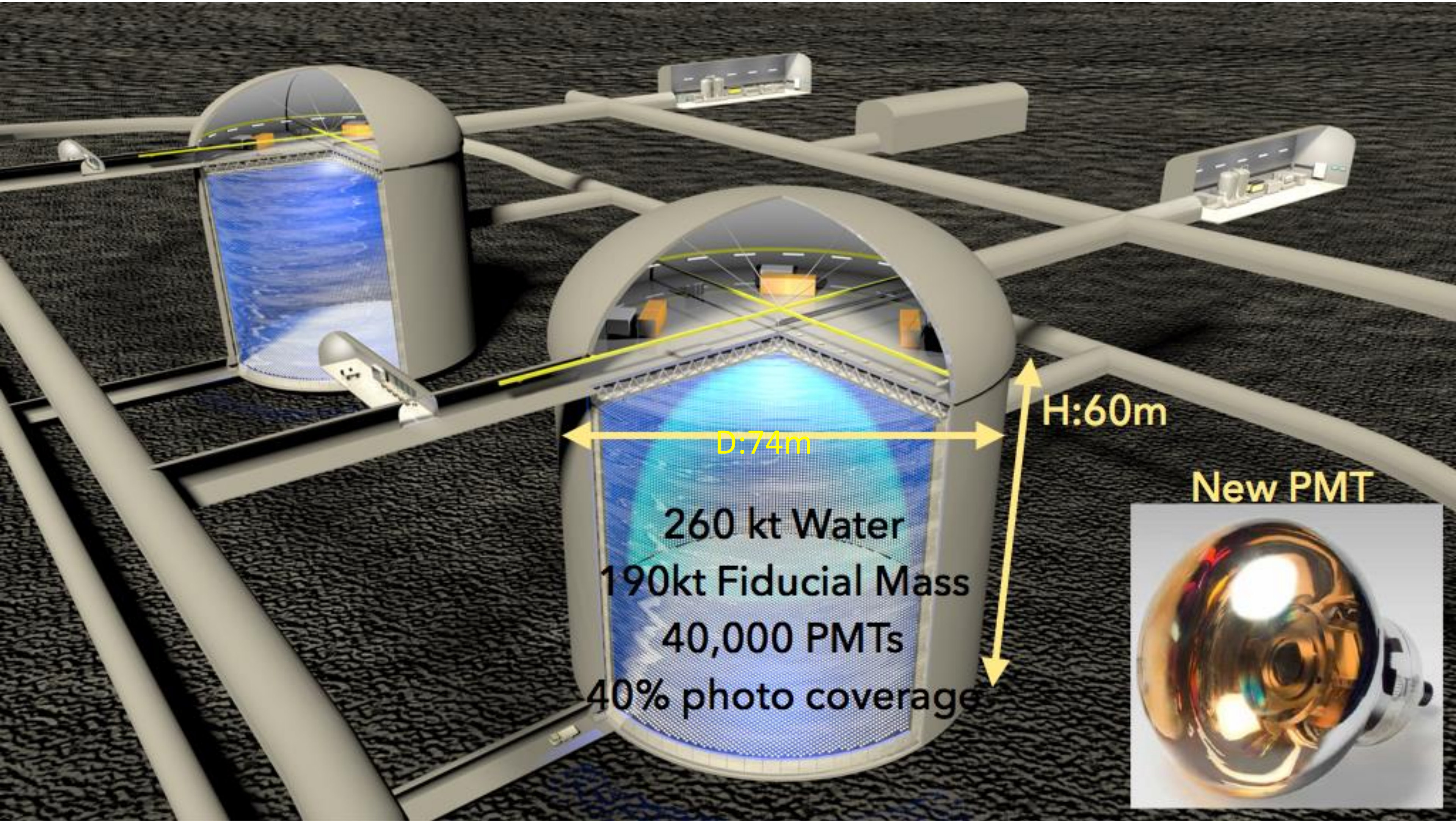
Sign of Δm^2_{31} distinguishes normal vs inverted mass ordering

δ and sign Δm^2_{31} couple because ($\Delta m^2_{31} \rightarrow -\Delta m^2_{31}$, $\delta \rightarrow \pi-\delta$) symmetry in vacuum (JHEP 2001)

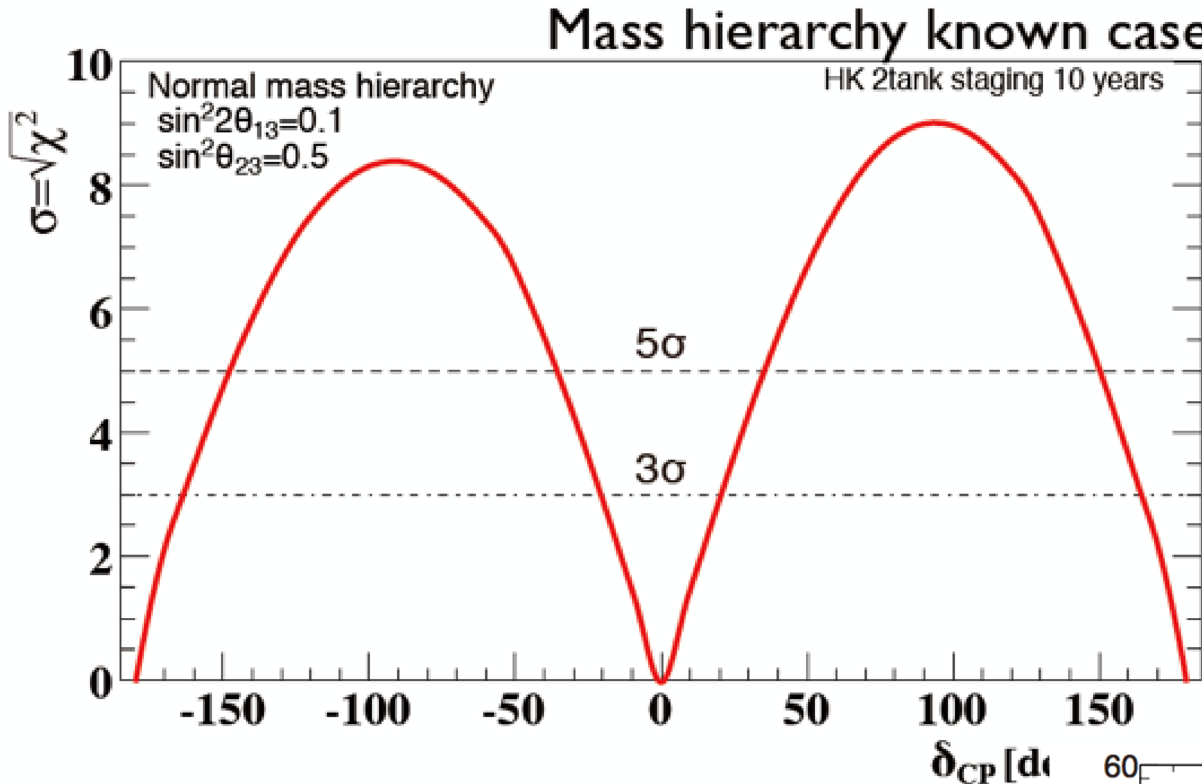
Next generation experiments

Hyper-Kamiokande

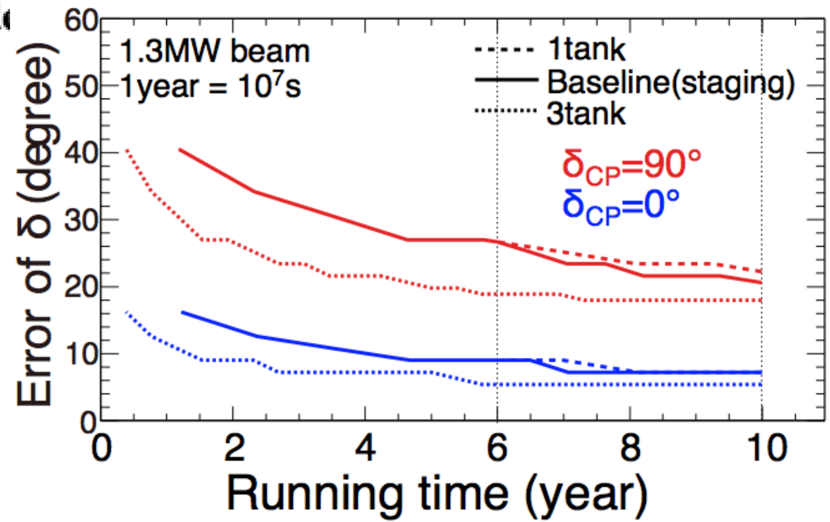
HK will start construction in 2020!



Sensitivity to CP phase

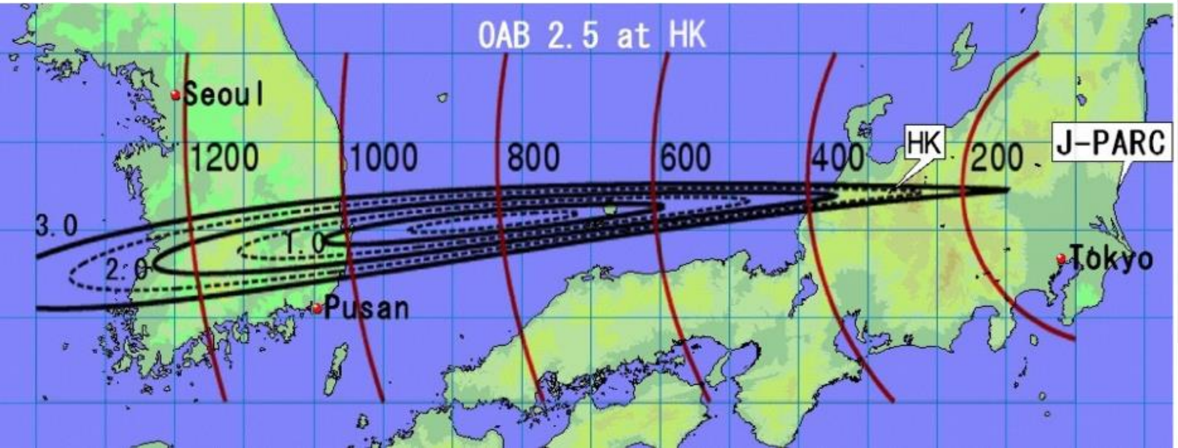


If CP is known to 3 σ, HK (or next generation machines) may have to have capability to measure something else → proton decay

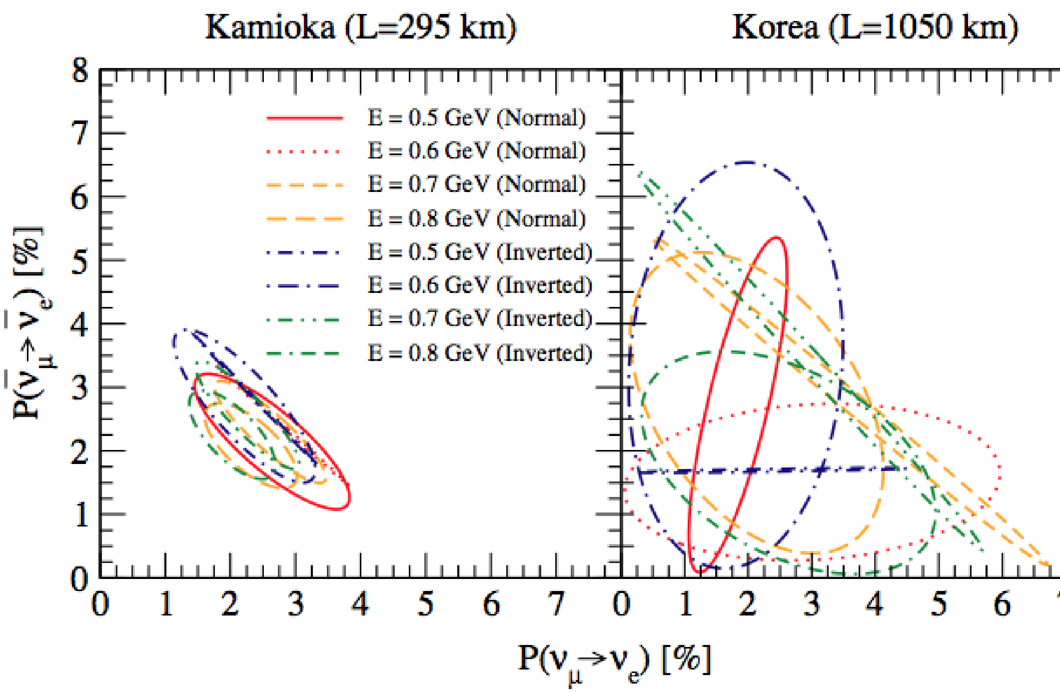


Ishitsuka-Kajita-HM-Nunokawa, PRD 2005, 2007

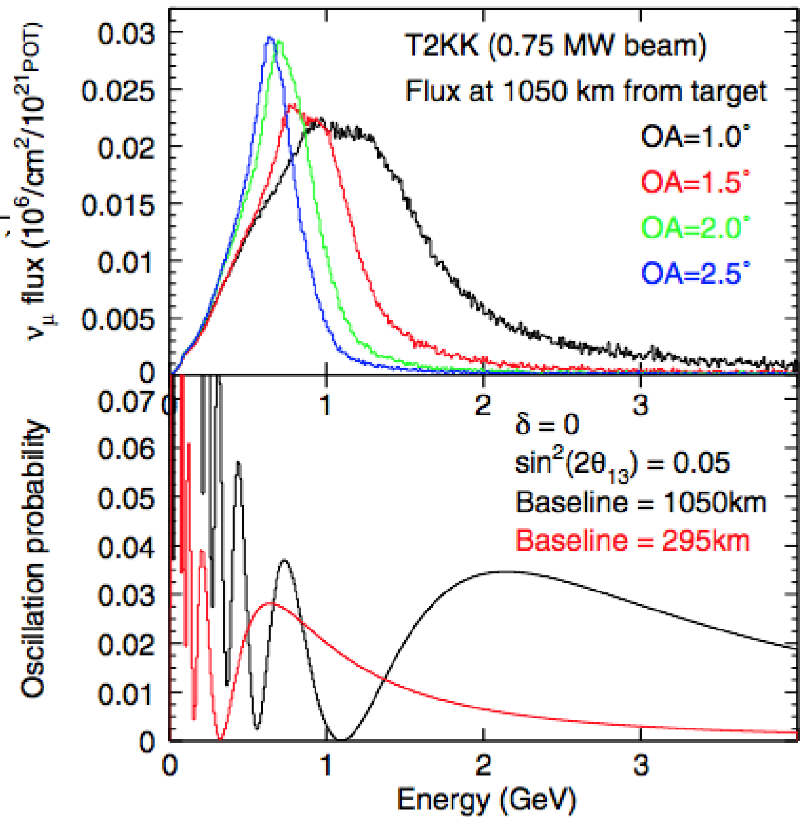
We discussed T2KK > 10 years ago, now revived as "T2HKK"



T2KK (or T2HKK)



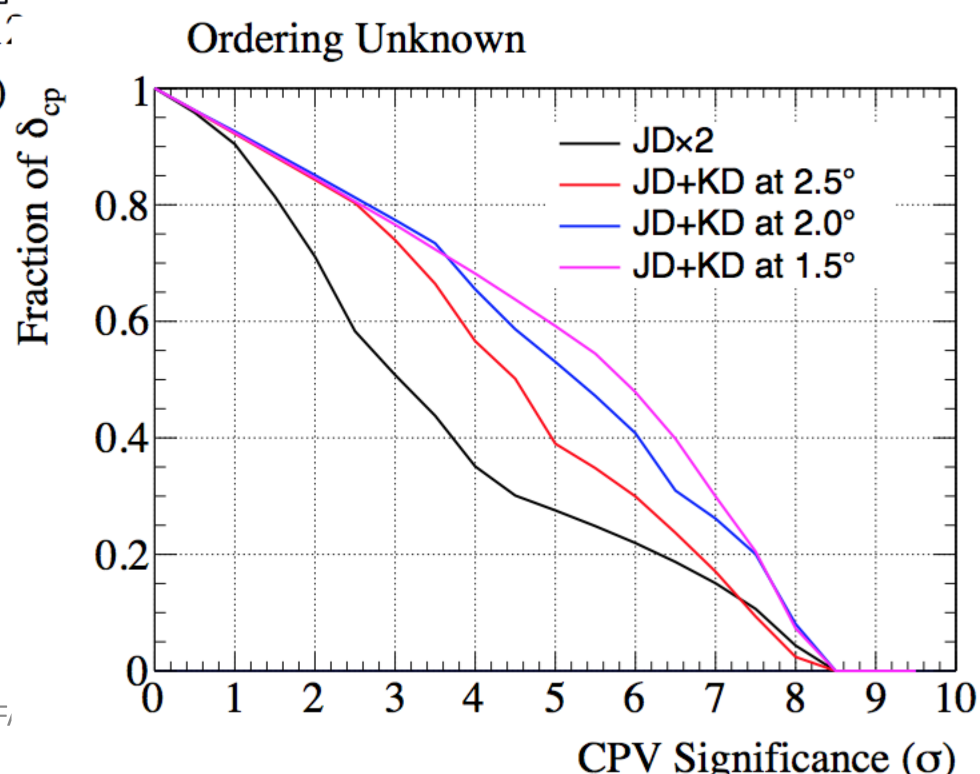
Dufour et al PRD 2010



E dependence far more dynamic at 2nd oscillation maximum

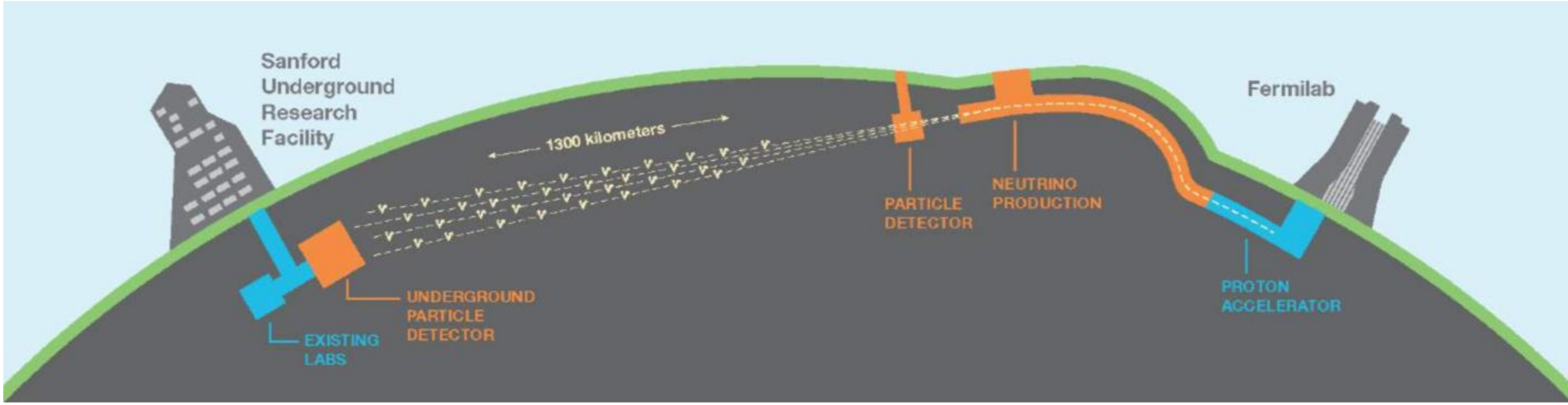
Ishitsuka-Kajita-HM-Nunokawa, PRD 2005, 2007

T2HKK: Mass ordering and CP sensitivities



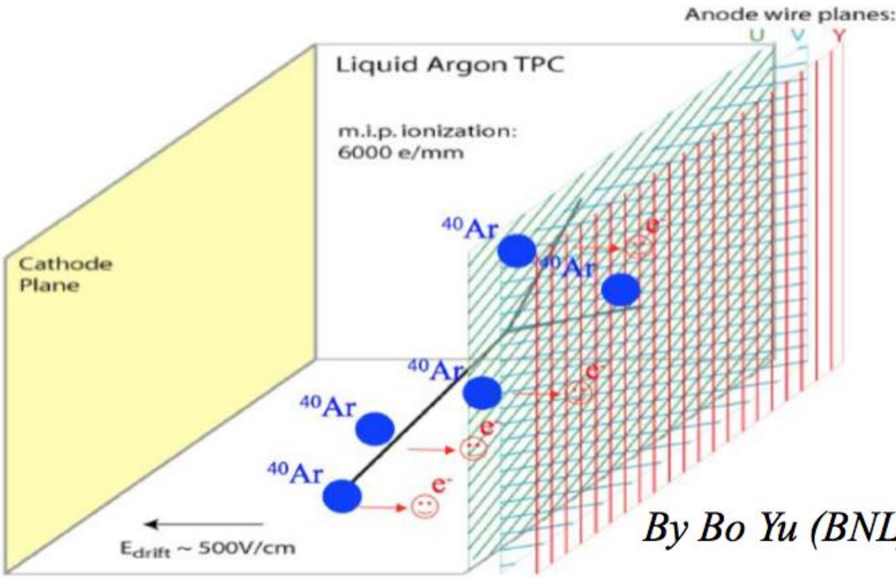
T2HKK White paper
arXiv 1611.06118

DEEP UNDERGROUND NEUTRINO EXPERIMENT

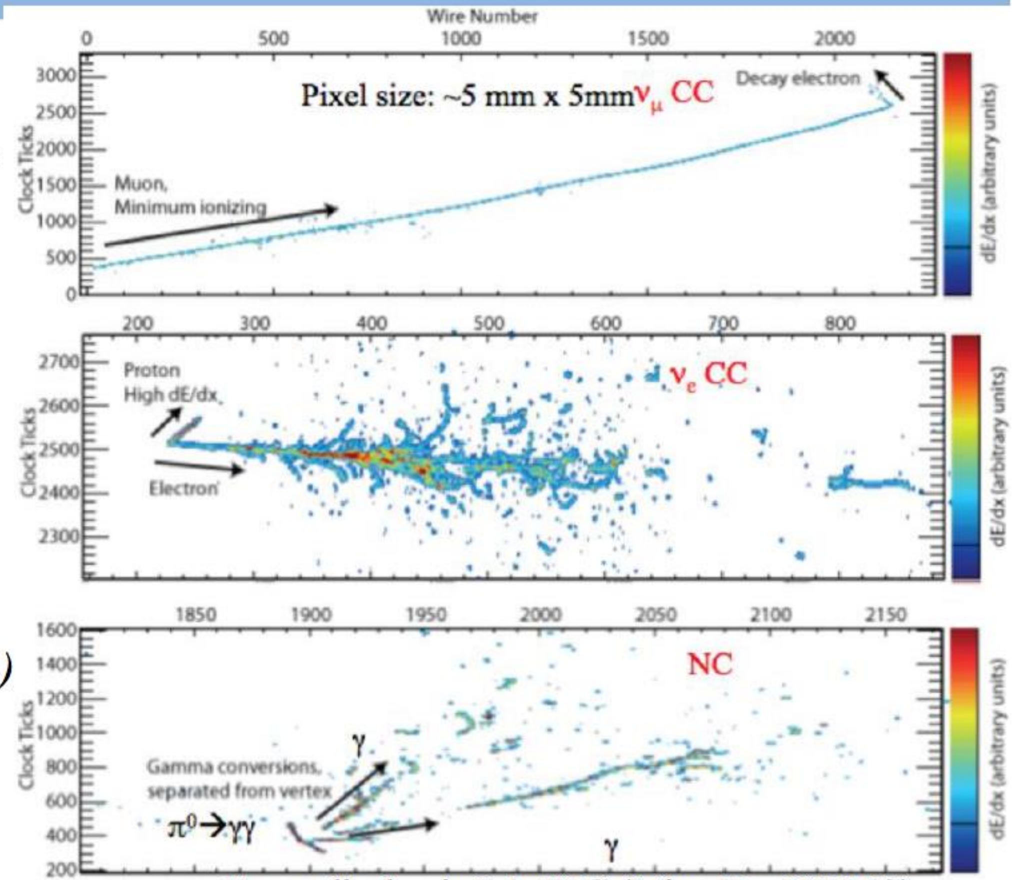


- New beam at Fermilab (1.2 MW@120 GeV protons, upgradeable to 2.4 MW), 1300 km baseline
- On-Axis 40 kton Liquid Argon Time Projection Chamber (LArTPC) Far Detector at Sanford Underground Research Facility, South Dakota, 1.5 km underground
- Highly-capable near detector at Fermilab
- ν_e appearance and ν_μ disappearance → Measure MH, CPV and mixing angles
- Large detector, deep underground → Nucleon decay, supernova burst neutrinos, atmospheric neutrinos, etc (Juergen Reichenbacher (SDSMT)'s talk, Wed.)

Far Detectors: Liquid Argon Time Projection Chamber (LArTPC)

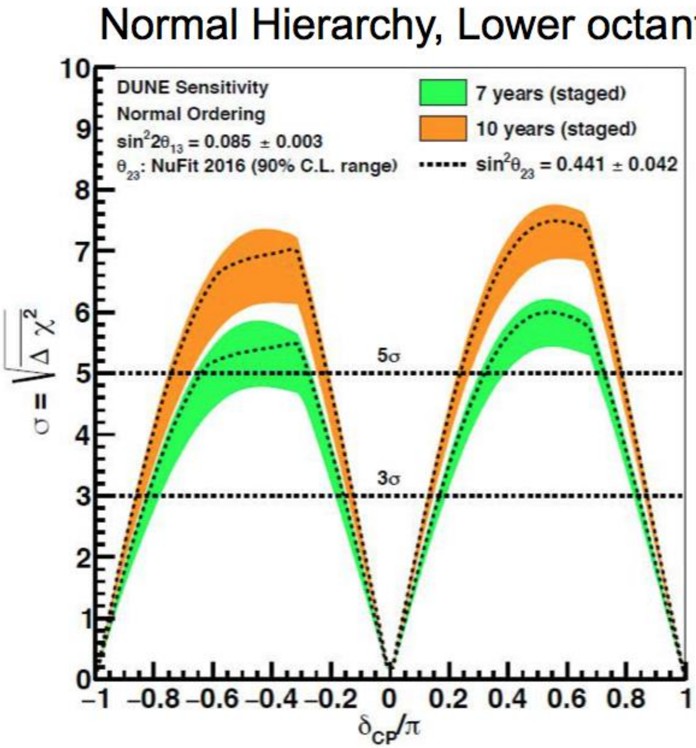


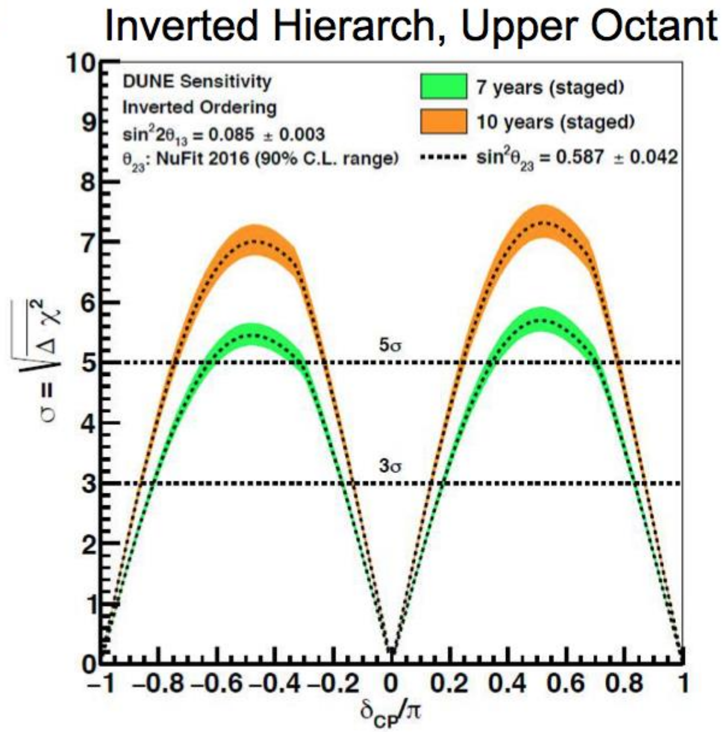
By Bo Yu (BNL)



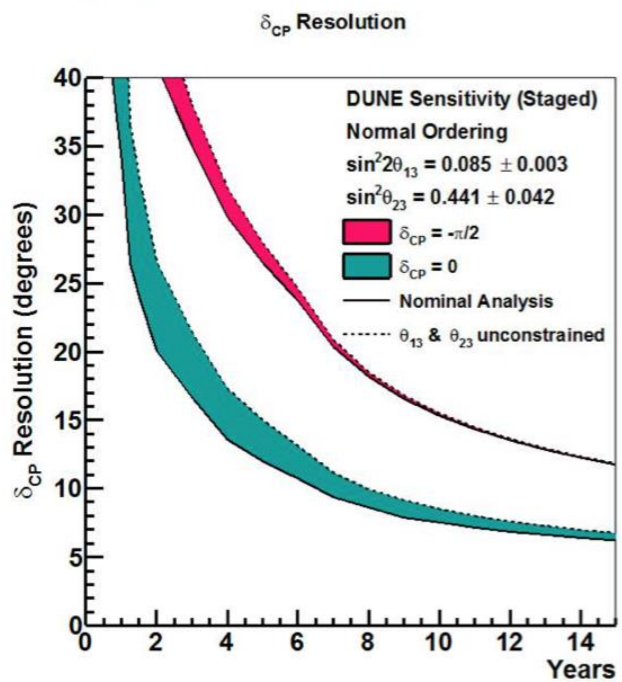
Event display in LArTPC (MicroBooNE MC)

- High resolution 3D track reconstruction
  - Charged particle tracks ionize argon atoms
  - Ionized electrons drift to anode wires (~ms) for XY-coordinate
  - Electron drift time projected for Z-coordinate
- Argon scintillation light (~ns) detected by photon detectors, providing t_0



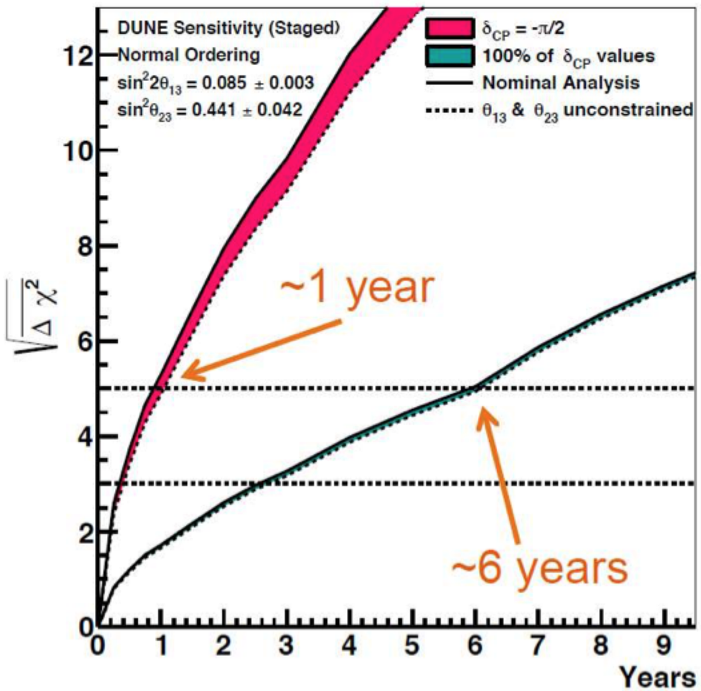


DUNE: CP sensitivity

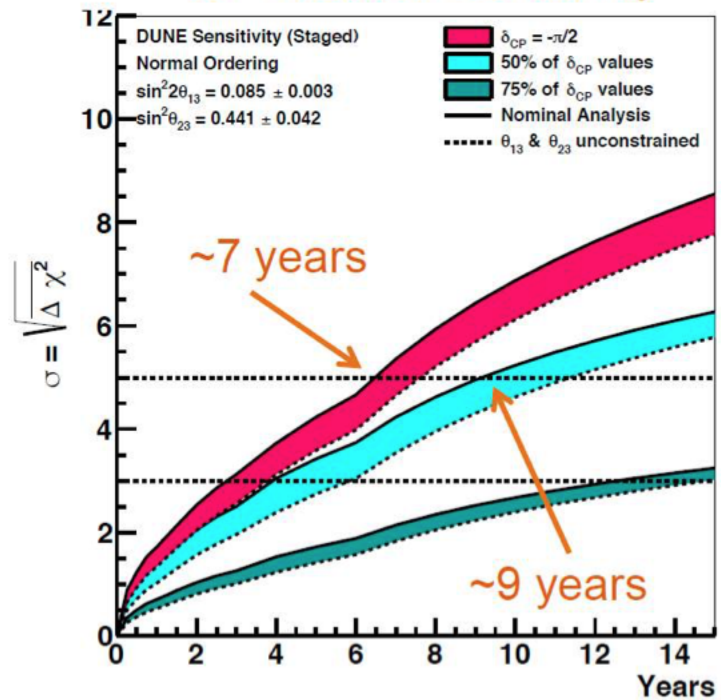


MH & CPV Sensitivity vs. Time

Mass Hierarchy Sensitivity



CP Violation Sensitivity



300 kt-MW-yrs

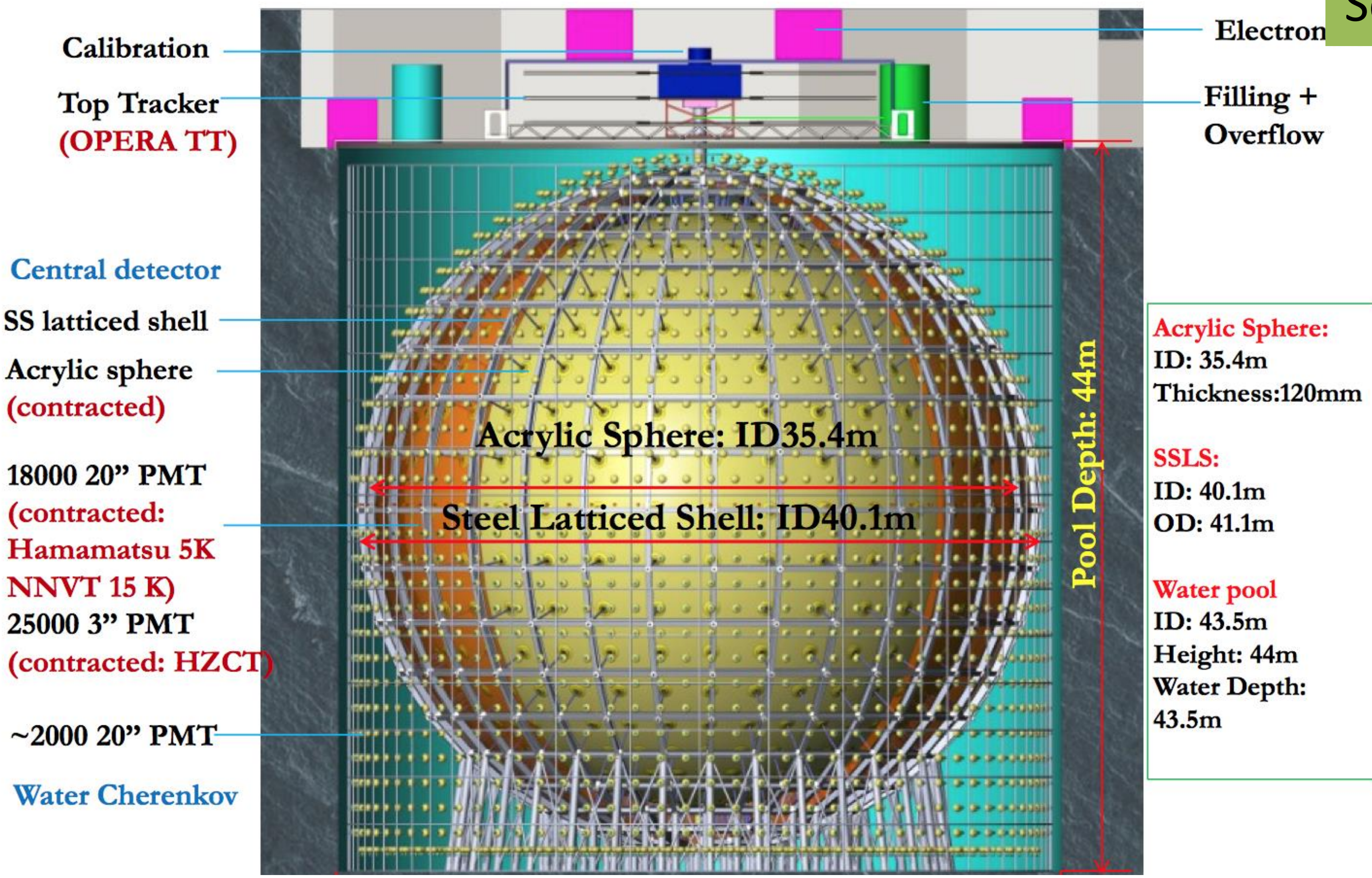
40kt @ 1.07 MW, 80GeV protons

Equal neutrino and anti-neutrino running

JUNO: exploring 12 sector & mass ordering

JUNO Detector

20 kt Liquid Scintillator Detector



Capozzi et al PRD2014

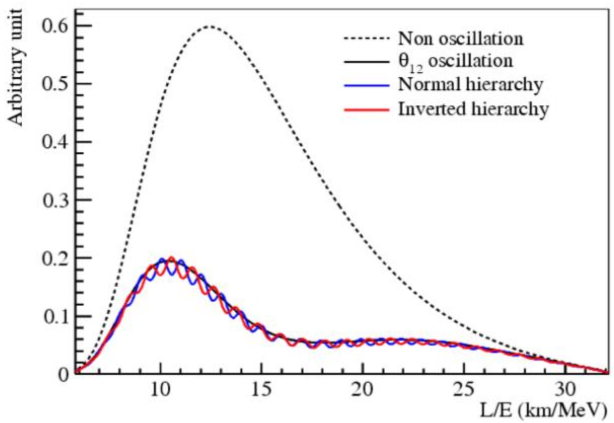
Parameter	% error (prior)	% error after fit (NH true)			% after fit (IH true)		
		All data	All – far	All – geo	All data	All – far	All – geo
α	∞	59.2	59.0	57.0	56.2	55.3	54.0
Δm^2_{ee}	2.0	0.26	0.25	0.26	0.26	0.25	0.25
δm^2	3.2	0.22	0.21	0.16	0.21	0.21	0.16
s^2_{12}	5.5	0.49	0.47	0.39	0.49	0.46	0.42
s^2_{13}	10.3	6.95	6.88	6.95	6.84	6.77	6.84
f_R	3.0	0.66	0.66	0.64	0.65	0.65	0.64
f_{Th}	20.0	15.3	14.6	...	15.5	15.4	...
f_{U}	20.0	13.3	13.3	...	13.3	13.3	...

Mass ordering in JUNO: highly debated subject

My slide in Neutrino 2012@Kyoto

Reactor ν at 60 km

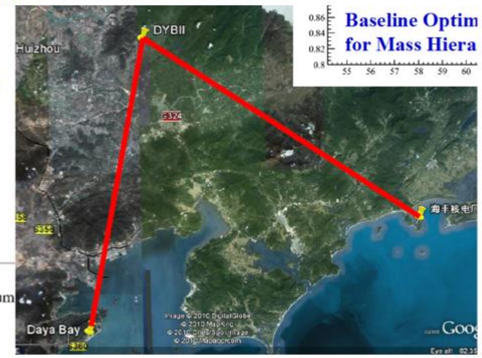
Daya Bay II, HanoHano



S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022

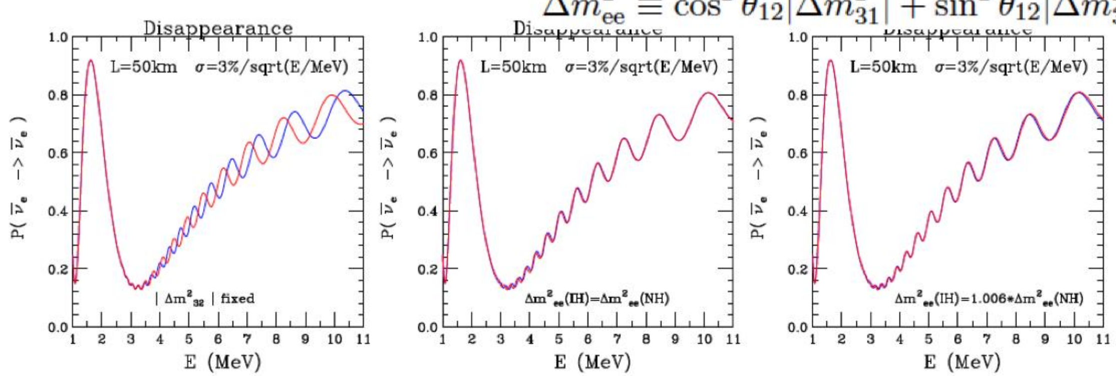
L. Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009

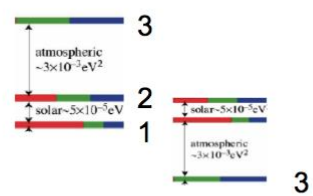
J.Cao@
NuTURN12



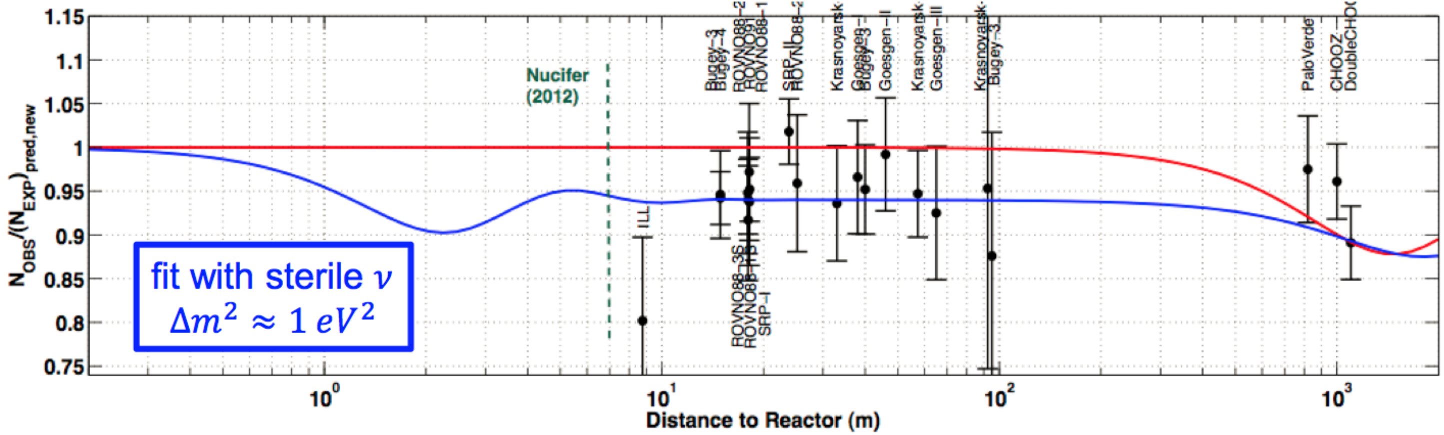
Sensitive to Δm^2 error and Δm^2 def: Parke et al. PRD07

$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$$



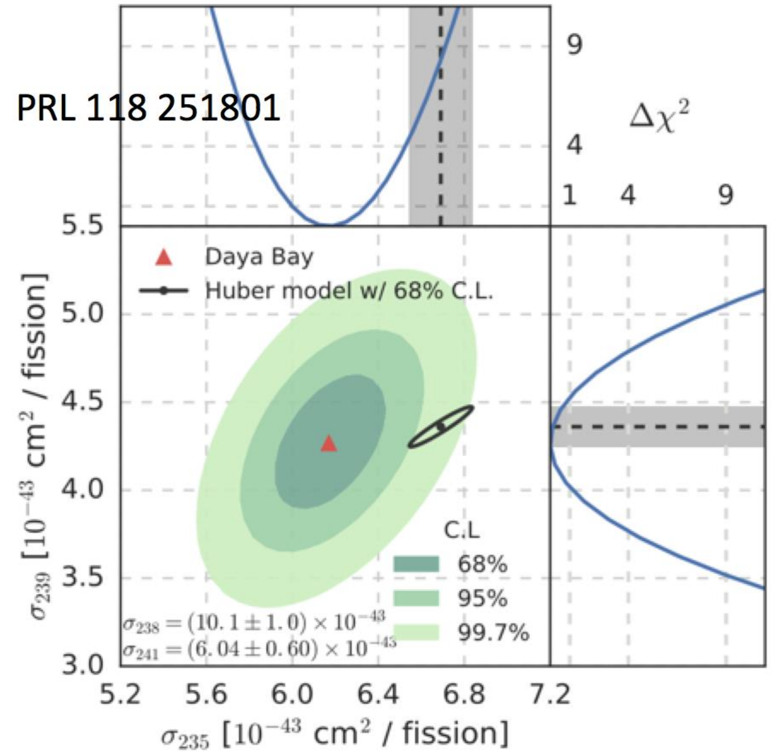


Anomaly?
Sterile ν?



Reactor neutrino anomaly?

- Calculated nu flux ~3-5% higher than measured
- Sterile nu?
- But the discrepancy is in ^{235}U, not in ^{239}Pu (Daya Bay)

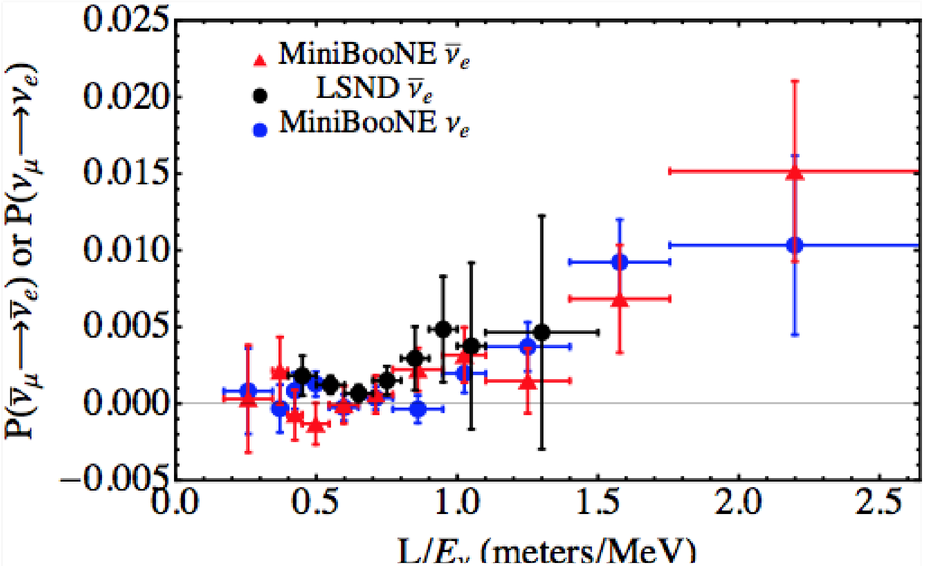


Sterile neutrino oscillation requires equal deficit for ^{235}U and ^{239}Pu

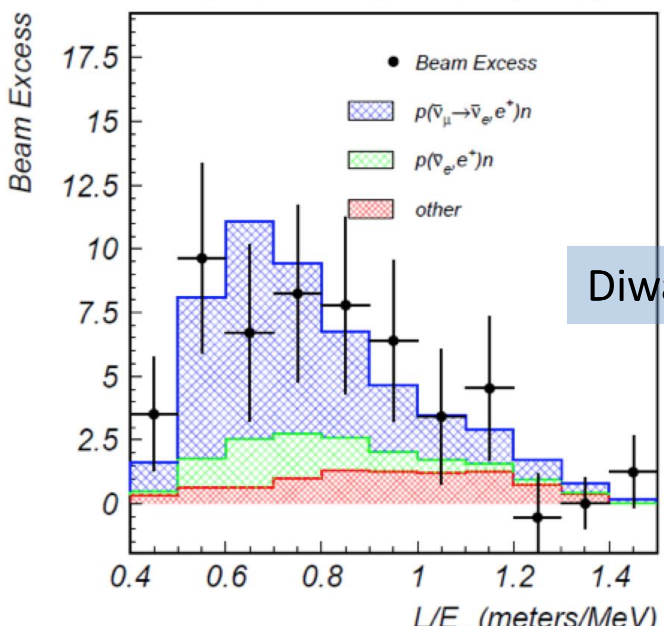
Daya Bay data prefer ^{235}U to be mainly responsible for the reactor anomaly

talk from David Martinez Caicedo

LSND-MiniBooNE anomaly



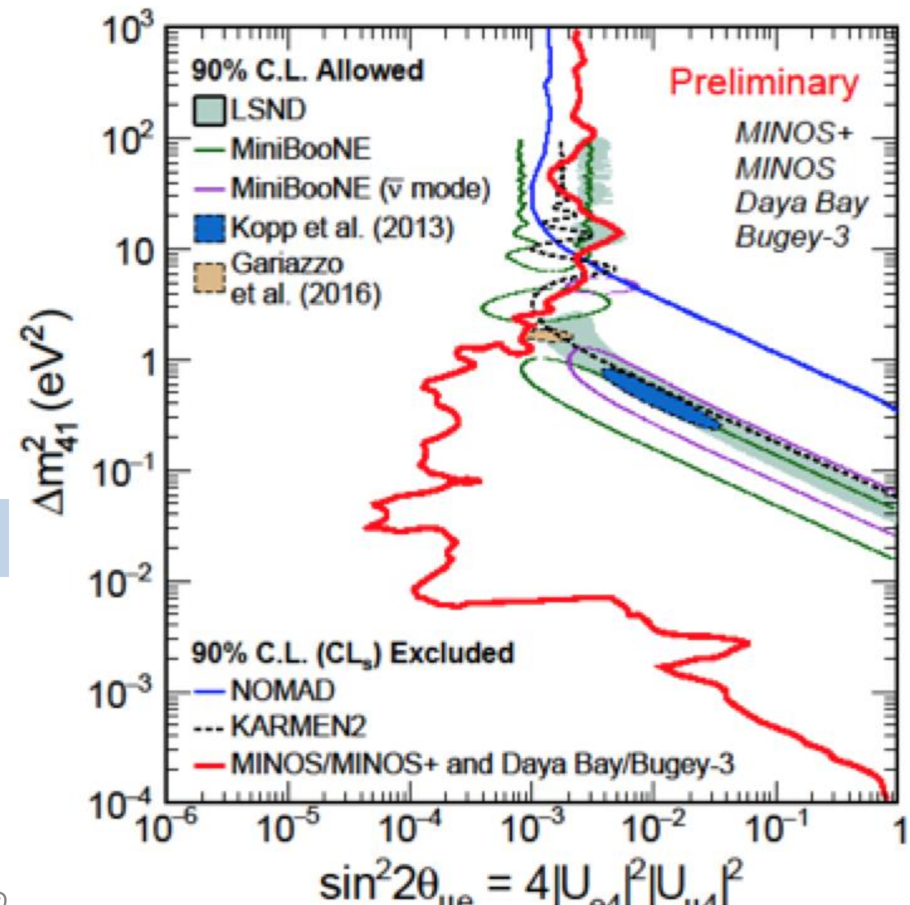
Phys. Rev. D64, 112007 (2001)



plot of a subset of data with good n-tag

Diwan@WIN2017

PRL 117, 151801 (2016)+MINOS+ results



Tension between appearance and disappearance

M. Dentler et al 1803.10661

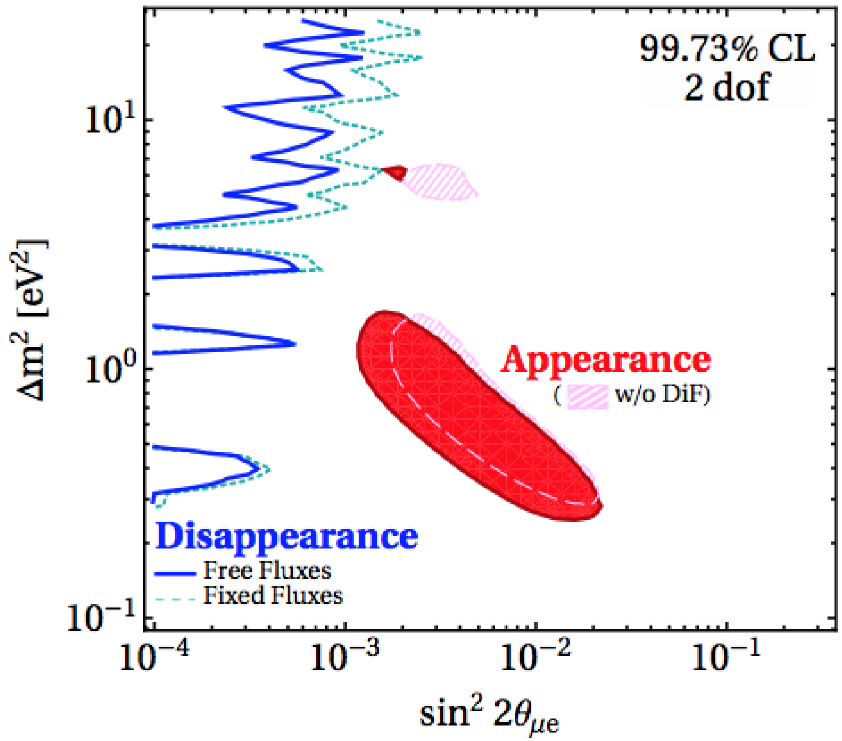


FIG. 7. Appearance versus disappearance data in the plane spanned by the effective mixing angle $\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}U_{\mu 4}|^2$ and the mass squared difference Δm^2_{41}. The blue curves show limits from the disappearance data sets using free reactor fluxes (solid) or fixed reactor fluxes (dashed), while the shaded contours are based on the appearance data sets using LSND DaR+DiF (red) and LSND DaR (pink hatched). All contours are at 99.73% CL for 2 dof.

N

SBL experiments ongoing

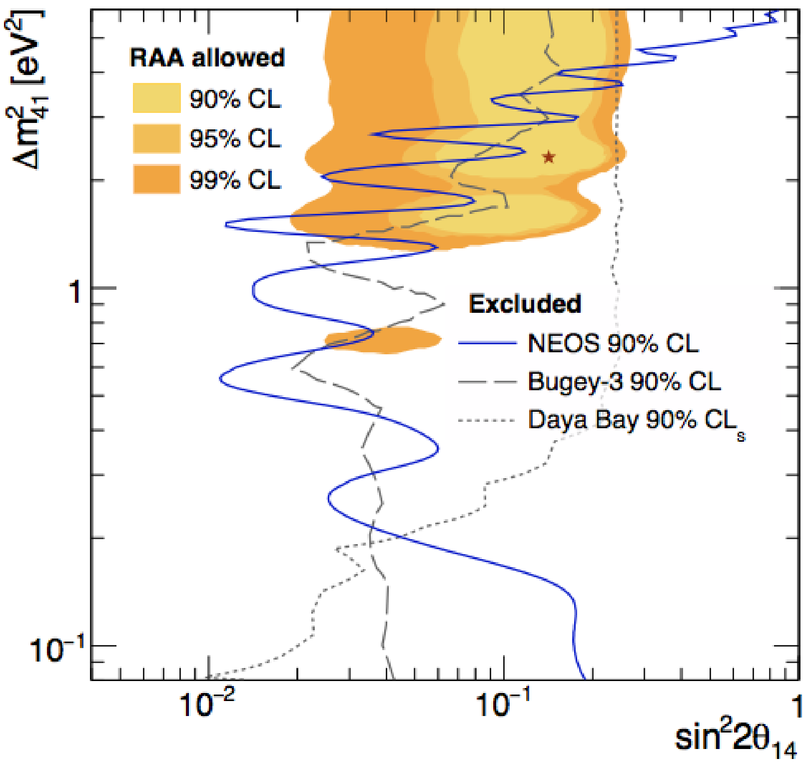
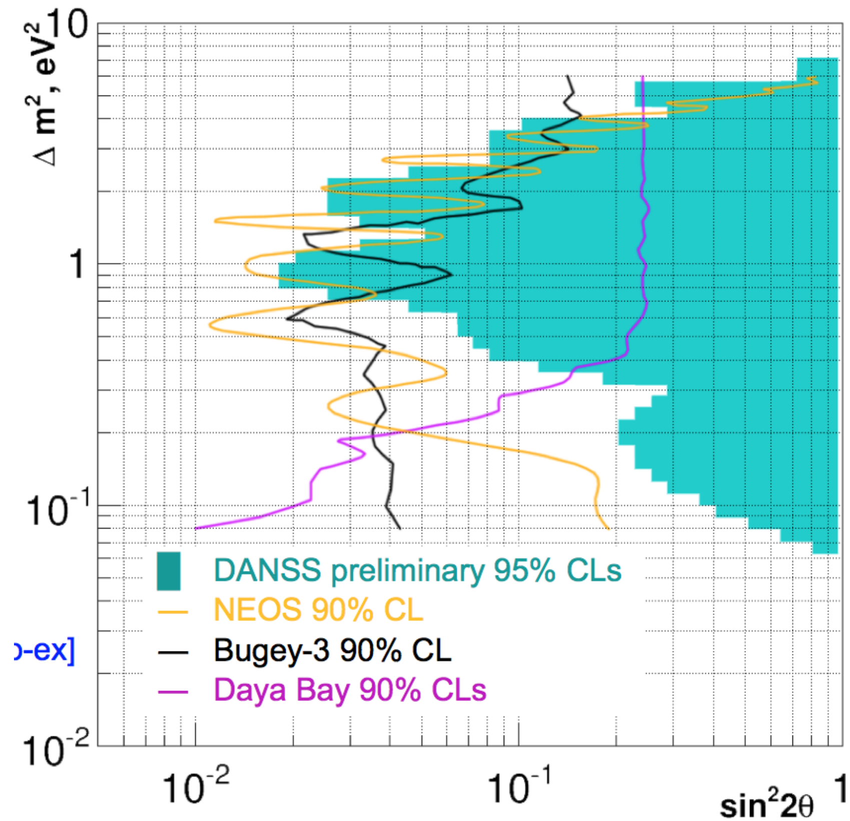


FIG. 4. Exclusion curves for 3+1 neutrino oscillations in the $\sin^2 2\theta_{14} - \Delta m^2_{41}$ parameter space. The solid blue curve is 90% C.L. exclusion contours based on the comparison with the Daya Bay spectrum, and the dashed gray curve is the Bugey-3 90% C.L. result [10]. The dotted curve shows the Daya Bay 90% CL$_s$ result [34]. The shaded area is the allowed region from the reactor antineutrino anomaly fit, and the star is its optimum point [12].

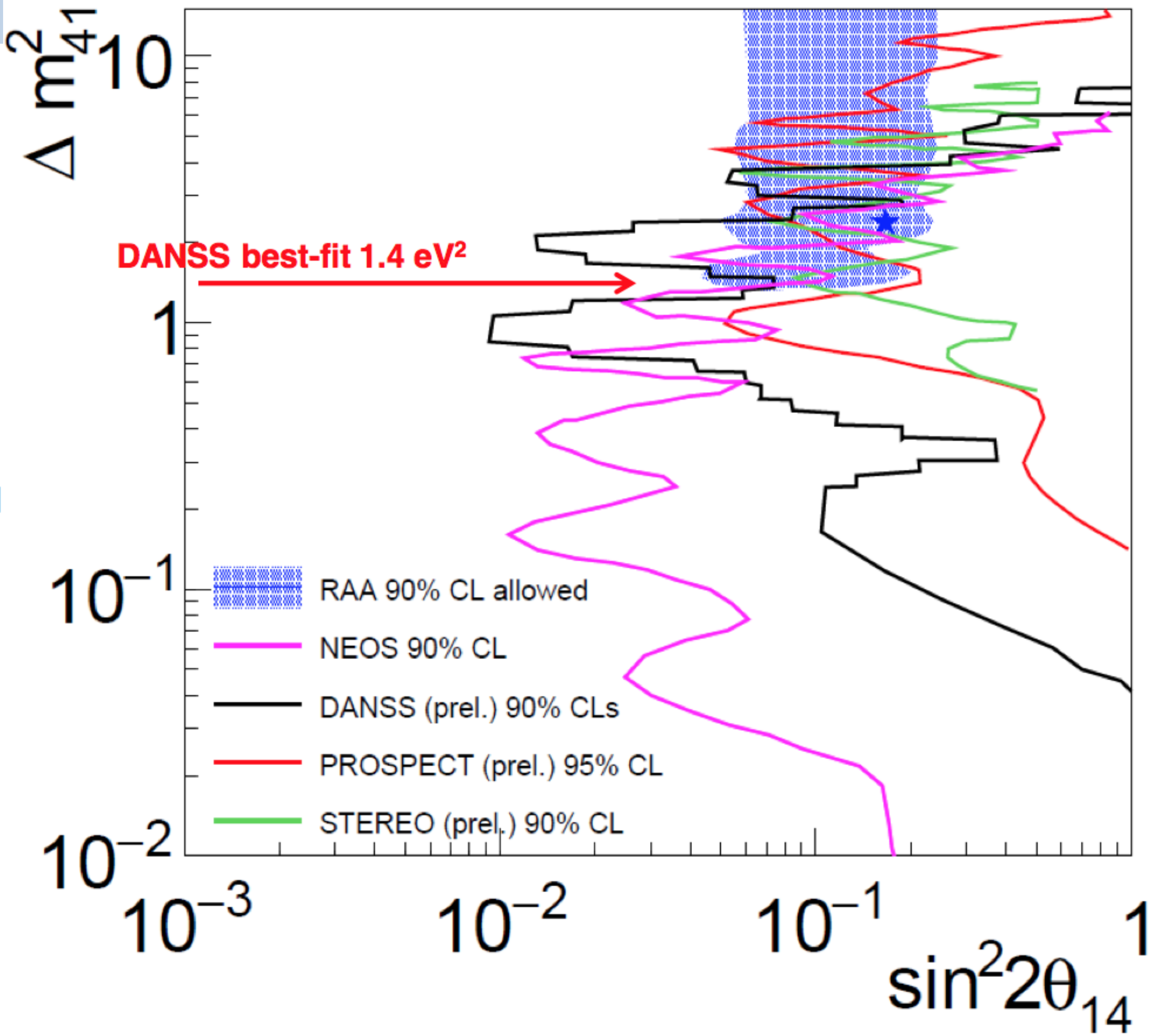
NEOS (Korea)



DANSS (Russia)

Chao Zhang Nufact2018

- Data fluctuation due to statistics and systematic uncertainties
- At 1.4 eV²
  - DANSS, NEOS, PROSPECT all show downward fluctuation
  - STEREO shows upward fluctuation
- More statistics and better understanding of systematics is necessary
- Statistical analysis best practice:
  - Use Feldman-Cousins approach with full MC uncertainty fluctuation for correct C.L.
  - Use Gaussian CLs method for cross-checking exclusion regions



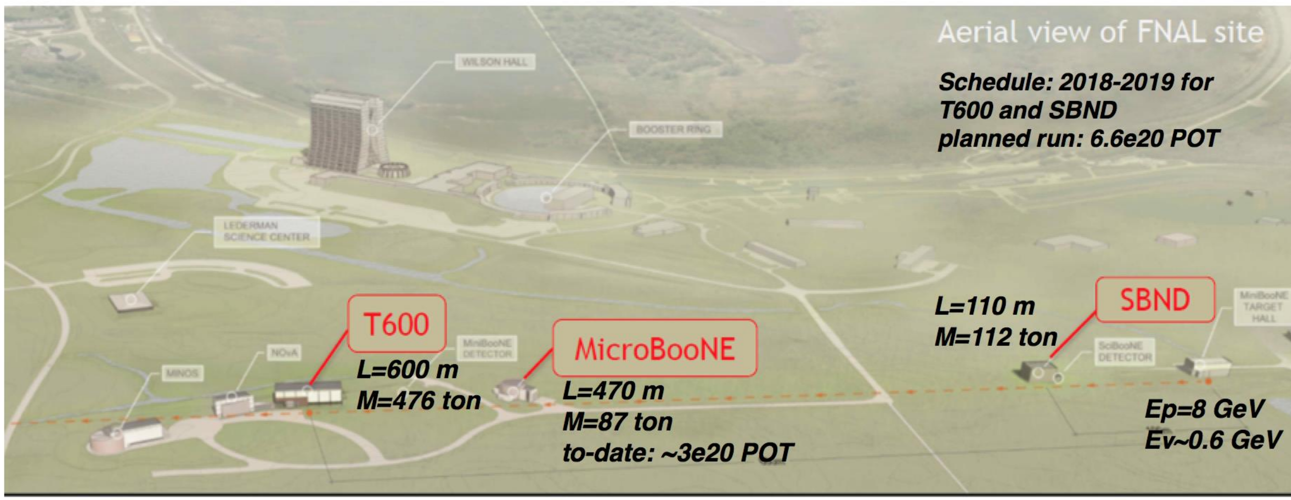
X. Qian and J-C Peng, arXiv:1801.05386

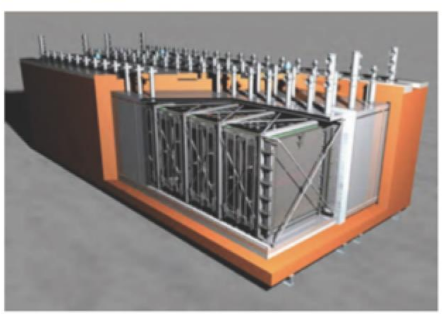
We want to hear definitive result!

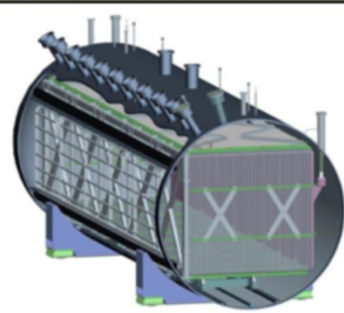
Puzzle lasted for ~20 years!

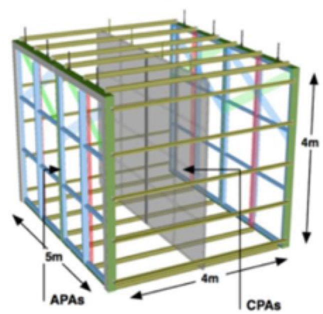
- LSND paper → 2001
- LIGO started observation in 2002 !!

Fermilab Short Baseline program

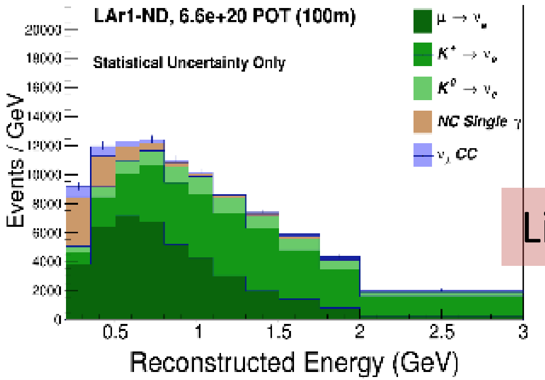


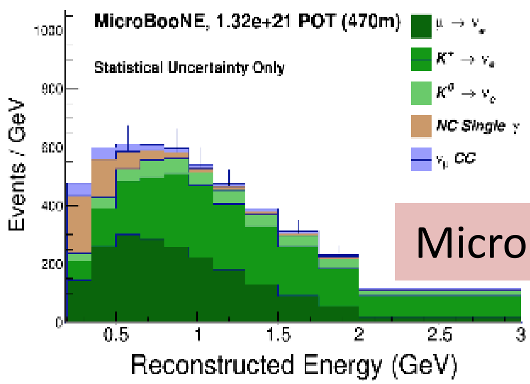


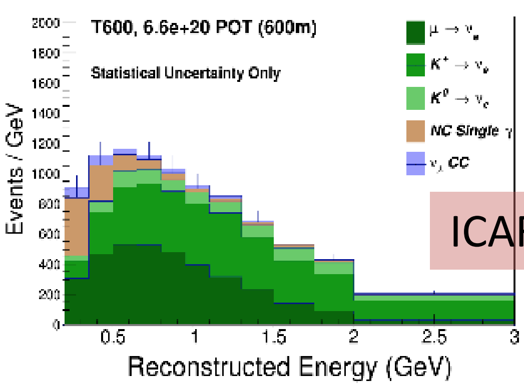


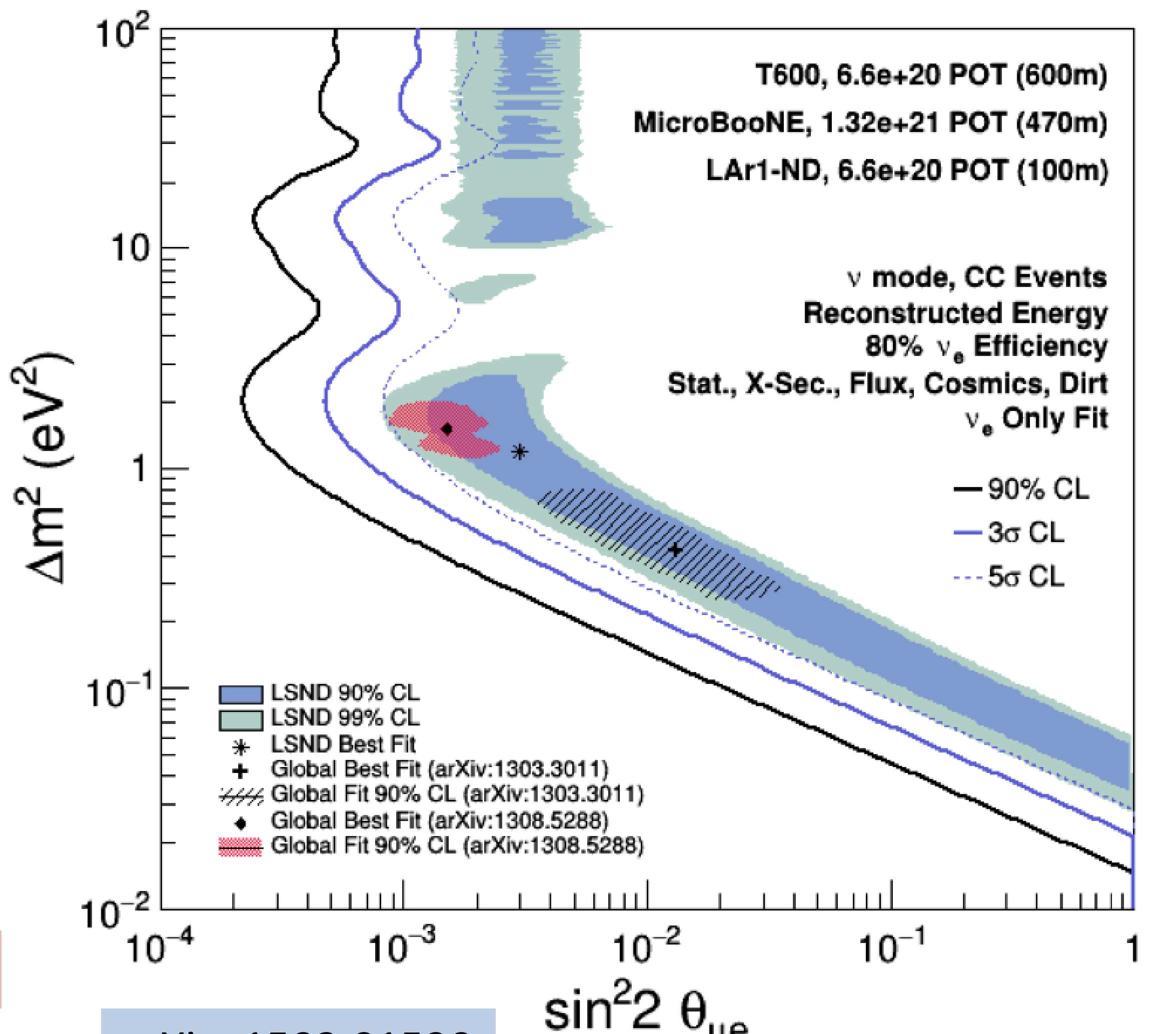


Fermilab SBL program: 5σ coverage!







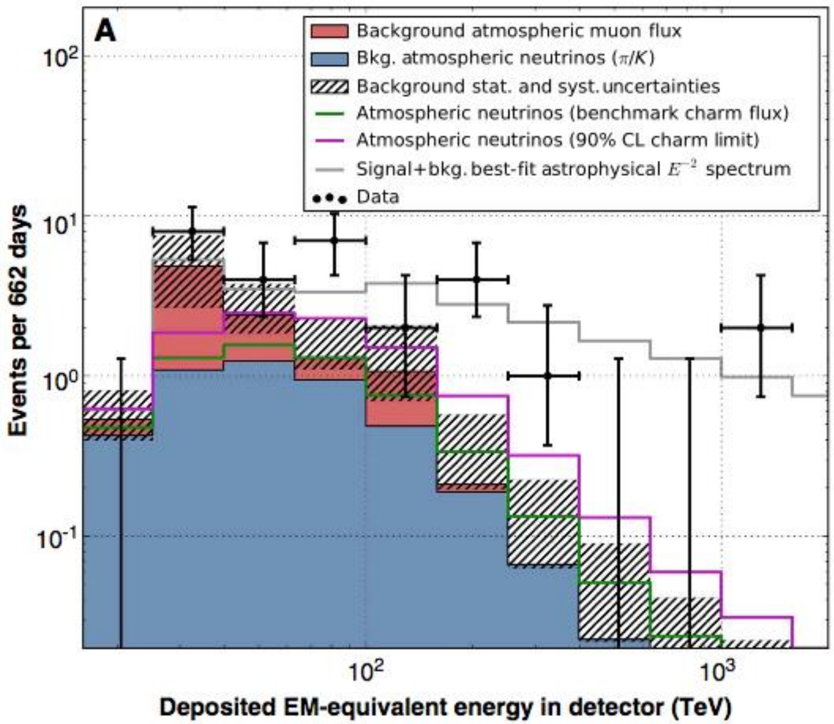


arXiv: 1503.01520

Astrophysical neutrinos

Neutrino is moving !!

IceCube discovered astrophysical neutrinos!



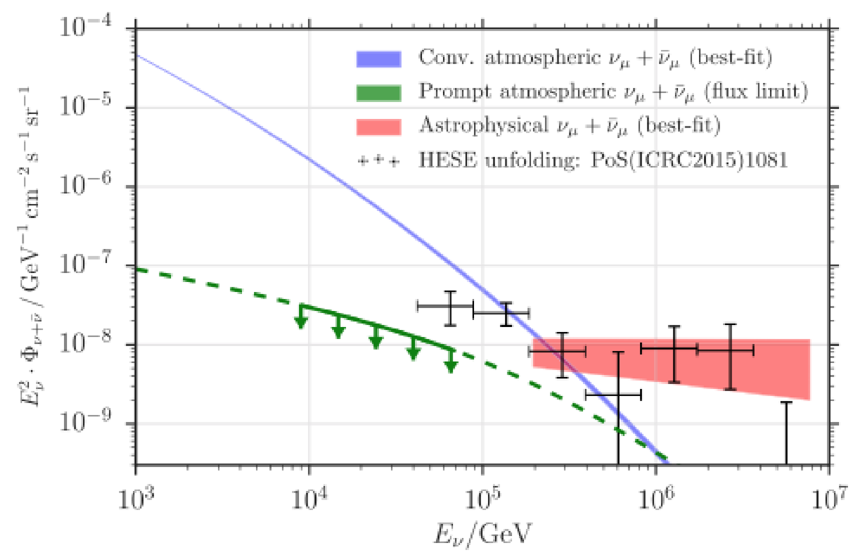
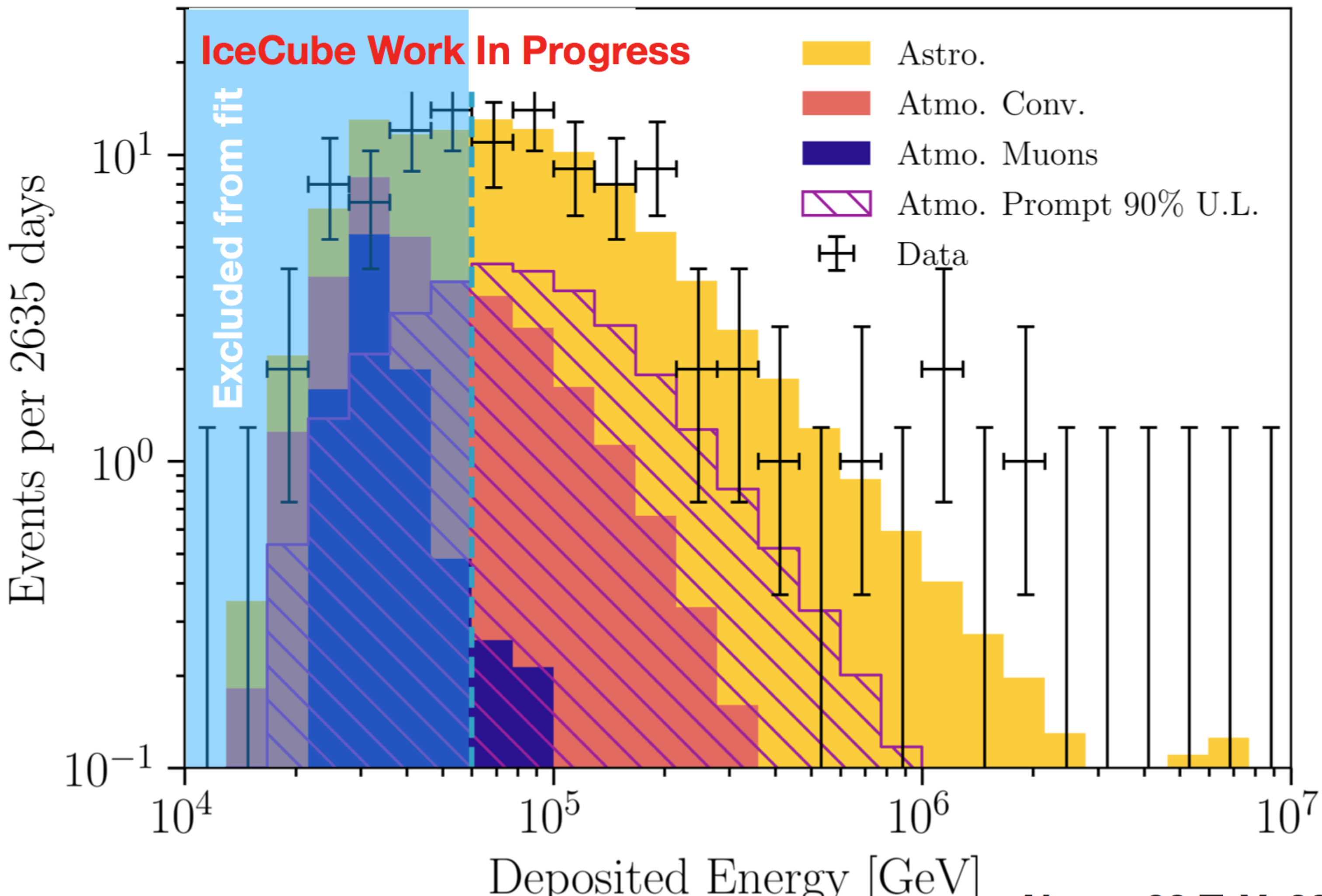


Figure 5. Best-fit neutrino spectra for the unbroken power-law model. The width of the line corresponding to conventional atmospheric neutrinos (blue) represents the one-sigma error on the measured spectrum. The width of the line corresponding to astrophysical neutrinos (red) shows the effect of varying both of the astrophysical parameters within one-sigma of the best fit values, without accounting for correlation. The green line represents the upper limit on the prompt model (Enberg et al. 2008). The horizontal width of the red band denotes the energy range of neutrino energies which contribute 90% to the total likelihood ratio between the best-fit and the conventional atmospheric-only hypothesis. The black crosses show the unfolded spectrum published in Kopper et al. (2015).

New **7.5 years high-energy starting events data!**

***HESE = high-energy starting events**

Carlos Argüelles @ Nufact 2018



All energies: 103 events
22 new events in 2016
9 new events in 2017

Above 60 TeV: 60 events
12 new events in 2016
4 new events in 2017

IceCube discovered the source!

IceCube-170922A from blazar TXS 0506+056

E~290 TeV

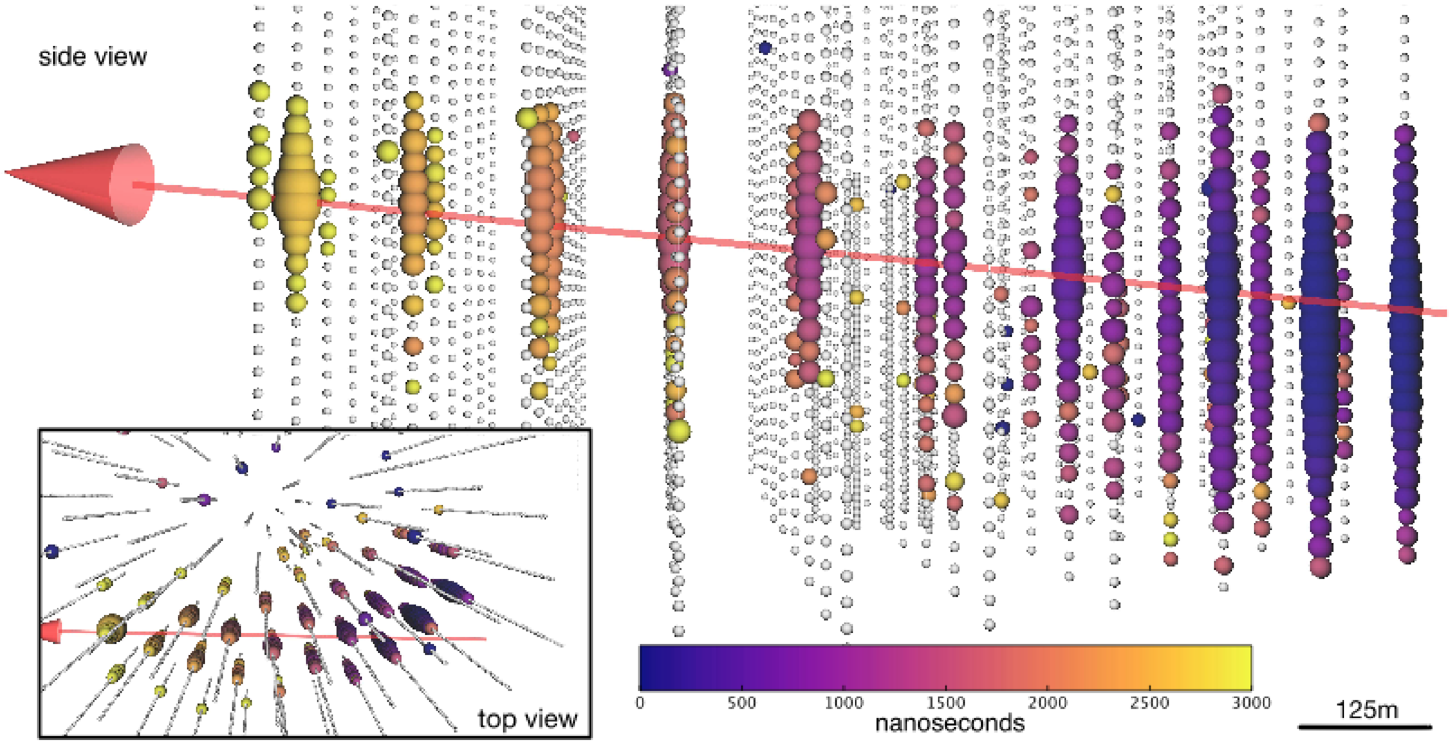
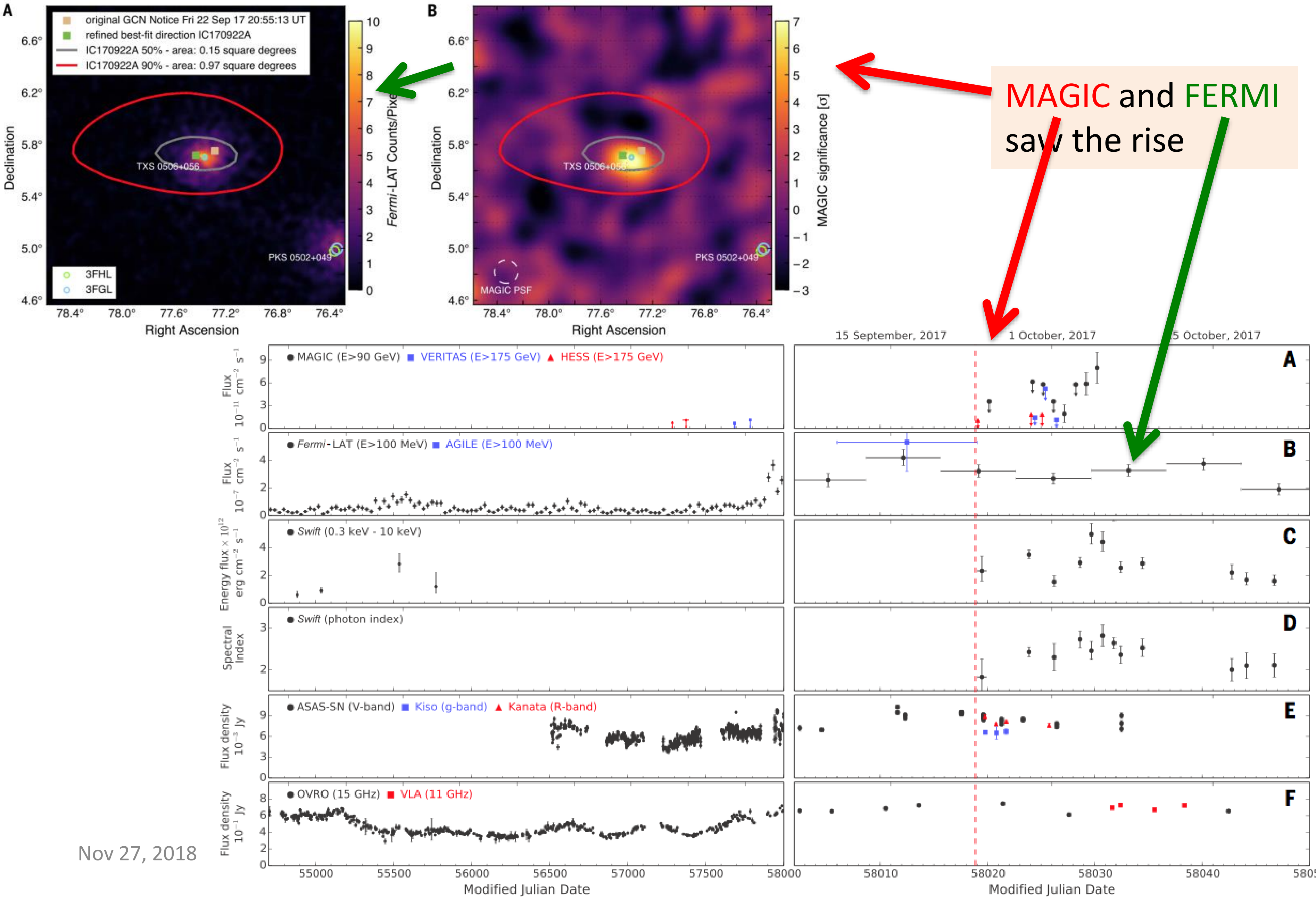


Fig. 1. Event display for neutrino event IceCube-170922A. The time at which a DOM observed a signal is reflected in the color of the hit, with dark blues for earliest hits and yellow for latest. Times shown are relative to the first DOM hit according to the track reconstruction, and earlier and later times are shown with the same colors as the first and last times, respectively. The total time the event took to cross the detector is ~3000 ns. The size of a colored sphere is proportional to the logarithm of the amount of light observed at the DOM, with larger spheres corresponding to larger signals. The total charge recorded is ~5800 photoelectrons. Inset is an overhead perspective view of the event. The best-fitting track direction is shown as an arrow, consistent with a zenith angle $5.7^{+0.50}_{-0.30}$ degrees below the horizon.

blazar TXS 0506+056



Multi-wavelength observations of TXS 0506+056

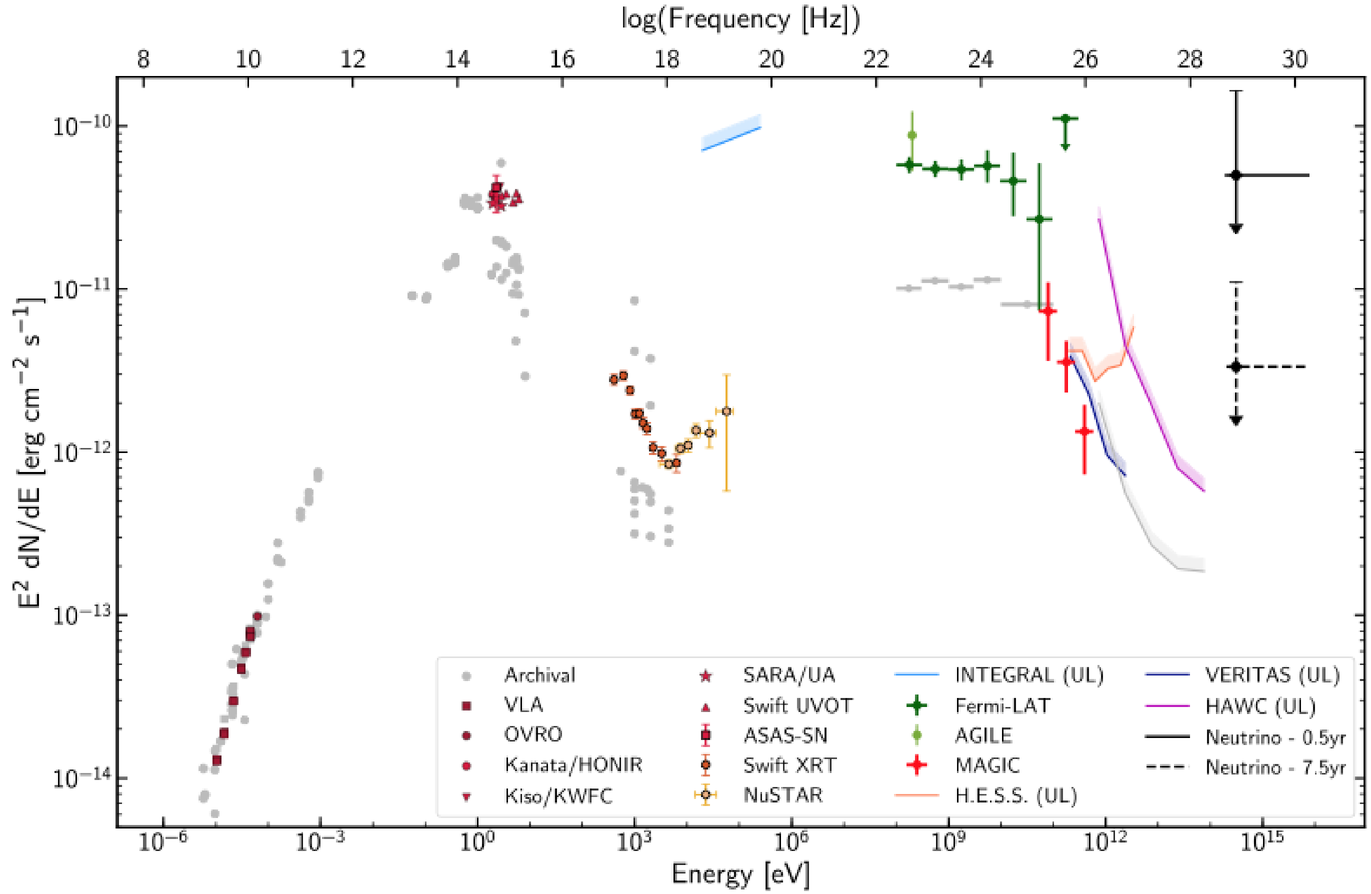
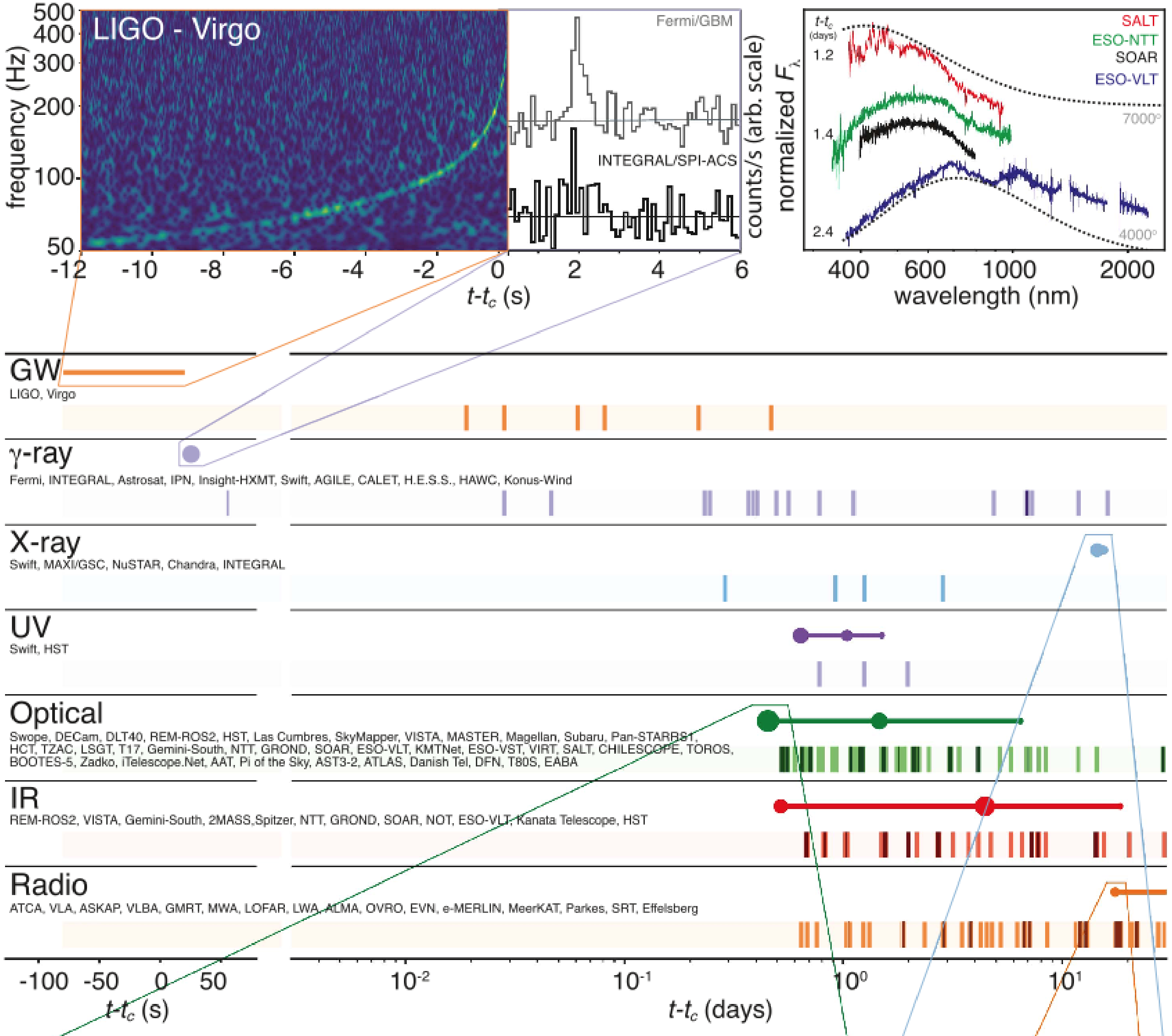


Fig. 4. Broadband spectral energy distribution for the blazar TXS 0506+056. The SED is based on observations obtained within 14 days of the detection of the IceCube-170922A event. The $E^2 dN/dE$ vertical axis is equivalent to a νF_ν scale. Contributions are provided by the following instruments: VLA (38), OVRO (39), Kanata Hiroshima Optical and Near-InfraRed camera (HONIR) (52), Kiso, and the Kiso Wide Field Camera (KWFC) (43), Southeastern Association for Research in Astronomy Observatory (SARA/UA) (53), ASAS-SN (54), *Swift* Ultraviolet and Optical Telescope (UVOT) and XRT (55), *NuSTAR* (56), *INTEGRAL* (57), *AGILE* (58), *Fermi*-LAT (16), MAGIC (35), VERITAS (59), H.E.S.S. (60), and HAWC (61). Specific observation dates and times are provided in (25). Differential flux upper limits (shown as colored bands and indicated as "UL" in the legend) are quoted at the 95% CL, while markers indicate significant detections. Archival observations are shown in gray to illustrate the historical flux level of the blazar in the radio-to-keV range as retrieved from the ASDC SED Builder (62), and in the γ-ray band as listed in the *Fermi*-LAT 3FGL catalog (23) and from an analysis of 2.5 years of HAWC data. The γ-ray observations have not been corrected for absorption owing to the EBL. SARA/UA, ASAS-SN, and Kiso/KWFC observations have not been corrected for Galactic attenuation. The electromagnetic SED displays a double-bump structure, one peaking in the optical-ultraviolet range and the second one in the GeV range, which is characteristic of the nonthermal emission from blazars. Even within this 14-day period, there is variability observed in several of the energy bands shown (see Fig. 3), and the data are not all obtained simultaneously. Representative $\nu_\mu + \bar{\nu}_\mu$ neutrino flux upper limits that produce on average one detection like IceCube-170922A over a period of 0.5 (solid black line) and 7.5 years (dashed black line) are shown, assuming a spectrum of $dN/dE \propto E^{-2}$ at the most probable neutrino energy (311 TeV).

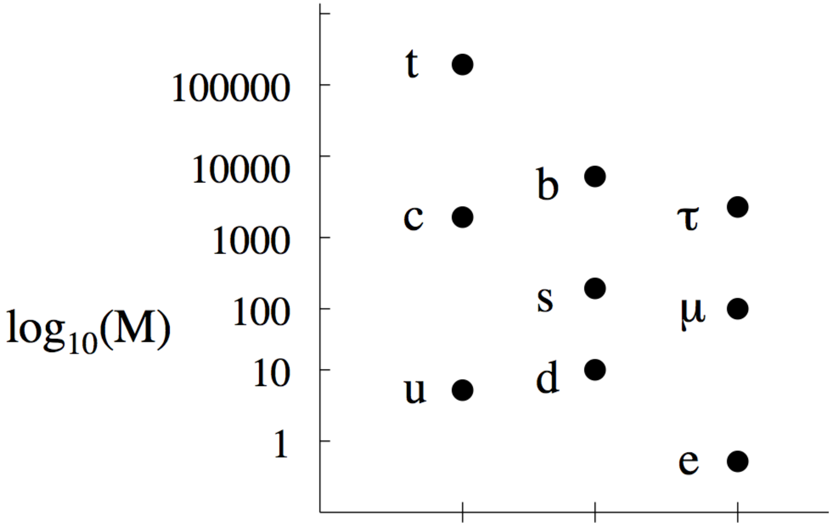
neutrino follows gravitational wave in multi-messenger astronomy



We live in the new era of astronomy !!

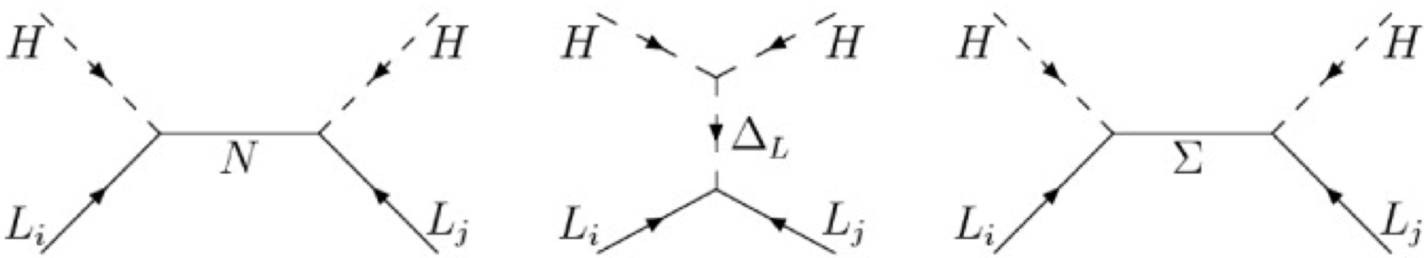
Physics of neutrino mass

If I ask the question "what is the origin of nu mass?"



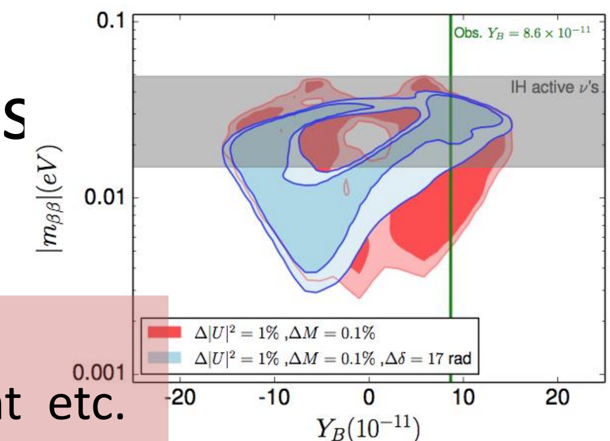
- Varying mechanisms proposed
- Majority would agree with Weinberg's dimension 5 operator $(1/M_{NP})\ \phi\phi\nu\nu$
- But what is inside??

Seesaw scenarios



“multi-messenger approach” in nu theory?

- TeV scale seesaw + small nu mass → radiative nu masses → Z_2 symmetry (no tree mass) → stability of dark matter
- Ma, Krauss etal, Aoki etal, Kanemura etal, many references..
- Low mass minimal seesaw model, testable by SHiP, leptogenesis, ββ decay etc
- P. Hernandez et al, (using Pilaftsis Underwood) + ...



→ generically leads to testable models in collider, ββ decay, leptogenesis, lepton flavor violation, precision measurement etc.

νMSM by Asaka, Shaposhnikov et al

- Sterile neutrino DM populated through mixing with active nu
- Successful leptogenesis etc
- Constrained by NuSTAR

Kenny Ng, IPMU seminar Nov 2018

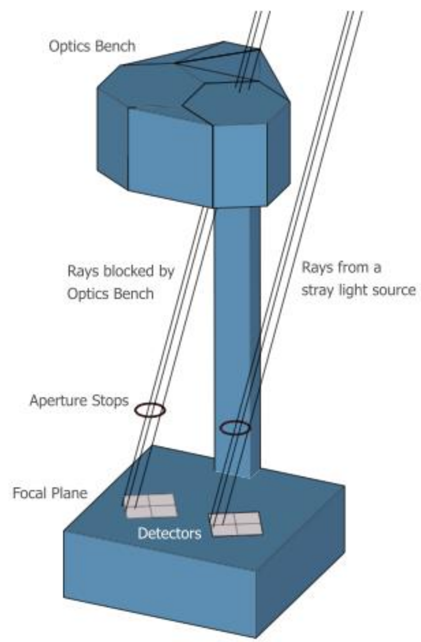
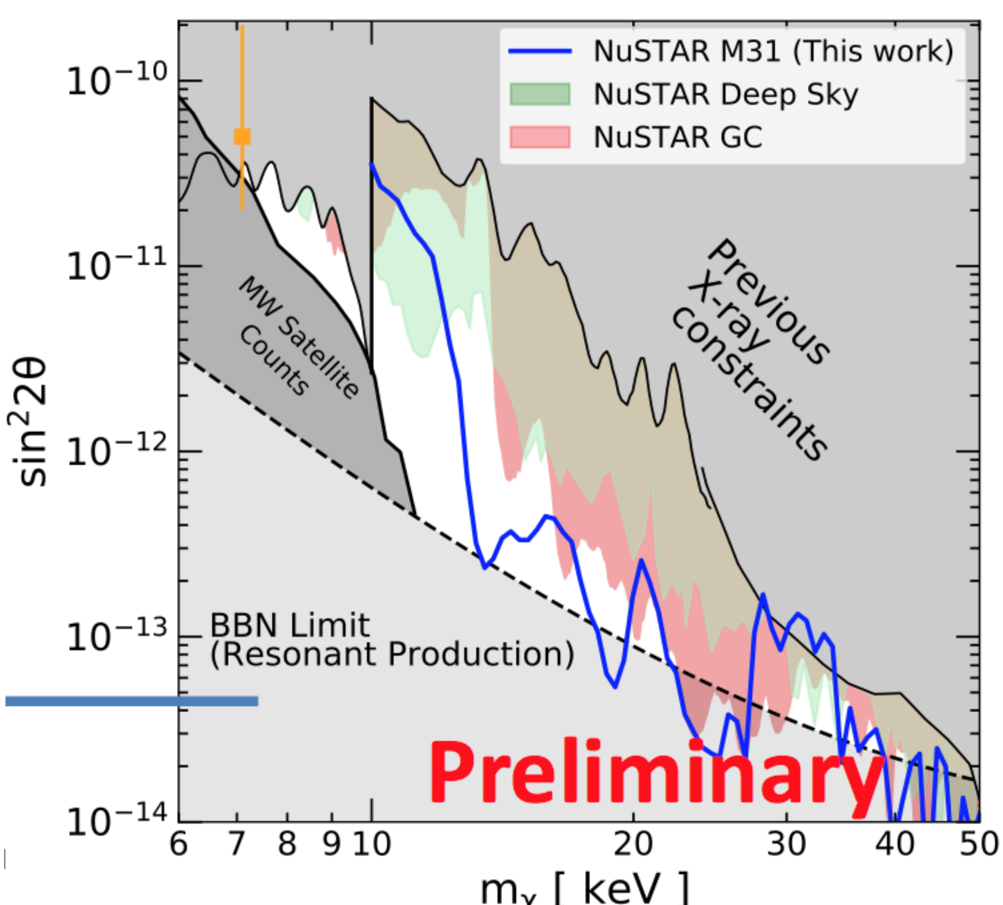


FIG. 2. Illustration, adopted from Ref. [16], of the NuSTAR observatory geometry. 0-bounce photons from far off-axis sources can bypass the aperture stops and shine directly on



What is next? (or toward the end?)

What is next?

- Suppose in some day we come to know lepton CP phase and the neutrino mass ordering
- Then, the question is “what is next?”, or could be “what is the last?”
- Certainly we will definitely have high precision measurement of the mixing parameters

e.g. by JUNO!

- Paradigm Test ! → Prove that 3 nu mixing is our world

In what circumstance, do we have unitarity test ?

- We don’t know what is NP that causes UV
- Yet, we want to test unitarity
- If we know what is NP, we don’t need “unitarity test”. We can just go to the model of NP to confront it to experiments!
- The only way we could pursue is to prepare (as much as) model-independent framework for unitarity test ← “CKM triangle” difficult..

High-energy vs. Low-energy unitarity violation

- Feature of unitarity violation different for
- High-energy ($E \gg M_W$) unitarity violation vs.
- Low-energy ($E \ll M_W$) unitarity violation
- For Low-E UV: probability leakage to “sterile” sector → small but observable effect
- High-E UV: “model-independent” framework by integrated out NP sector, but no systematic way for Low-E UV →

New trial by C-S. Fong, HM, H. Nunokawa, arXiv: 1609.08623, 1712.02798

High- vs low-scale unitarity violation: more generic differences

High-scale UV >> m_W	Low-scale UV << m_W
lepton flavor universality: NO	lepton flavor universality: YES
zero distance neutrino flavor transition: YES	zero distance neutrino flavor transition: NO
Kinematical effect of sterile nu emission: YES (if kinematically allowed)	Kinematical effect of sterile nu emission: YES

Parametrizing non-unitarity: alpha parametrization → Escrihuela etal PRD2015 (Valencia group)

$$N = (1-\alpha)U = \left\{ 1 - \begin{bmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{bmatrix} \right\} U$$

Then, NP parameter α is universally correlated with SM parameter δ !!

$$e^{-i\delta}\alpha_{\mu e},\ \alpha_{\tau e},\ \text{and}\ e^{i\delta}\alpha_{\tau\mu},$$

Ivan Martinez-Soler, HM, arXiv:1806.10152

- Framework of UV itself knows how NP is related with SM
- UV is better defined framework than "NSI put in by hand" approach

Conclusion

- Tried to review neutrinos in interdisciplinary field
- We started to see convergence: CP phase ~ $3\pi/2$, normal mass ordering (2^{nd} octant of θ_{23}?)
- Nu is moving #1: 2 big projects, T2HK (Japan) and DUNE (US) are going to happen
- Nu is moving #2: birth of multi-messenger neutrino astronomy
- Theoretical "multi-messenger" approach described
- How to close the neutrino story? → 3 ν paradigm test

Conclusion continued

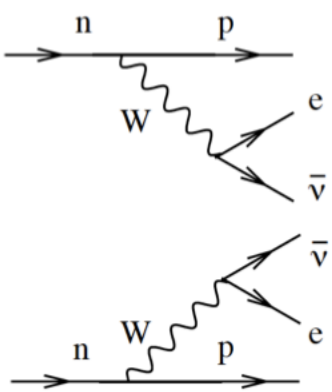
- LSND-MiniBooNE anomaly + reactor neutrino anomaly → hints for sterile neutrinos?
- Waiting for the definitive answer (anomaly ~20 years old..) →
- Fermilab short baseline program
- 0ν double beta decay must be discussed (important subject but not discussed).....as a mean to determine Majorana vs Dirac neutrinos
- Absolute nu mass (KATRIN+Planck) too....

Backup slides

Majorana vs. Dirac neutrinos

Double beta decay (DBD)

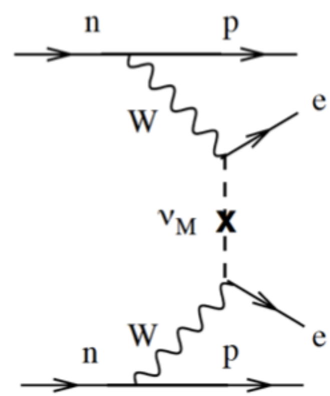
2ν DBD: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$



- proposed in 1935 by Maria Goeppert-Mayer;
- 2[nd] order process allowed in the Standard Model;

$$\tau \sim 10^{19-21}\, yr$$

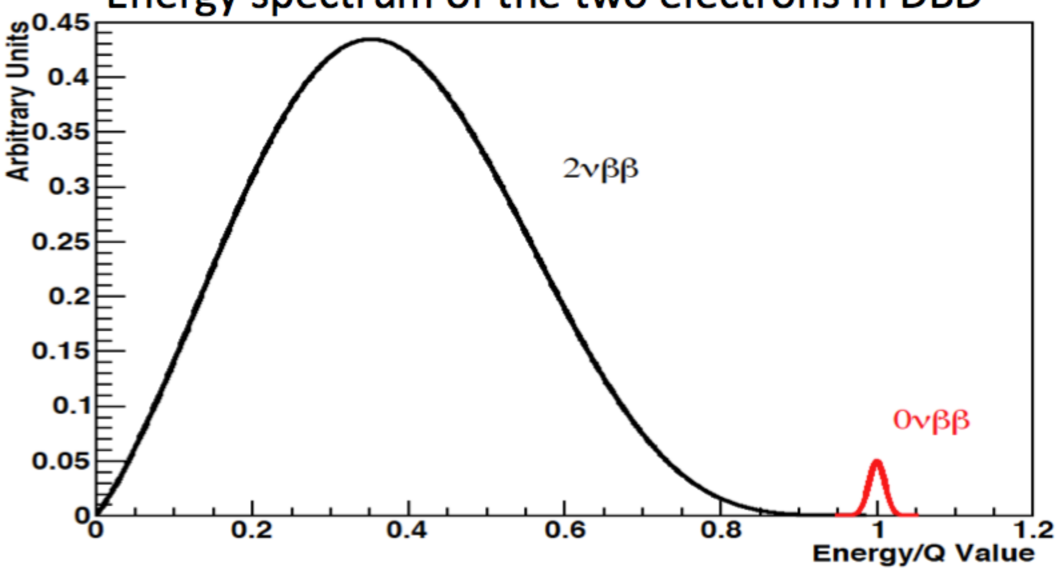
0ν DBD: $(A,Z) \rightarrow (A,Z+2) + 2e^-$



- proposed in 1937 by Ettore Majorana;
- requires physics beyond Standard Model;

$$\tau > 10^{24-25}\, yr$$

Energy spectrum of the two electrons in DBD

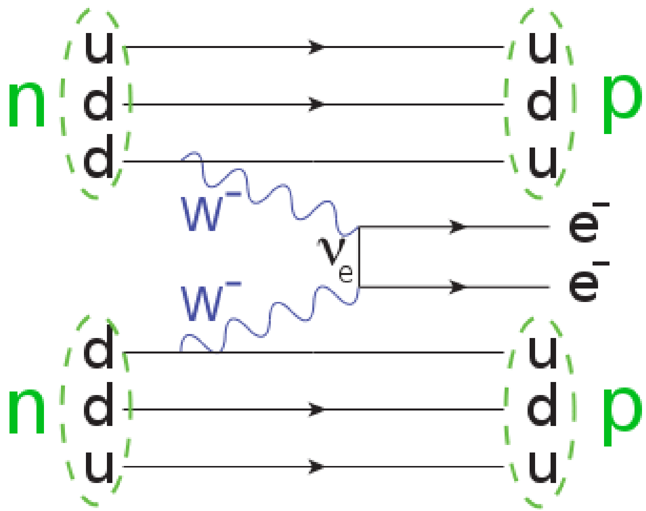


0ν DBD Signature: monochromatic line in the energy spectrum at the energy value

$$Q_{\beta\beta} = M_p - (M_d + 2\, m_e)$$

smeared by detector resolution!

Observable: 0ν DBD half life



The 0ν DBD half-life:

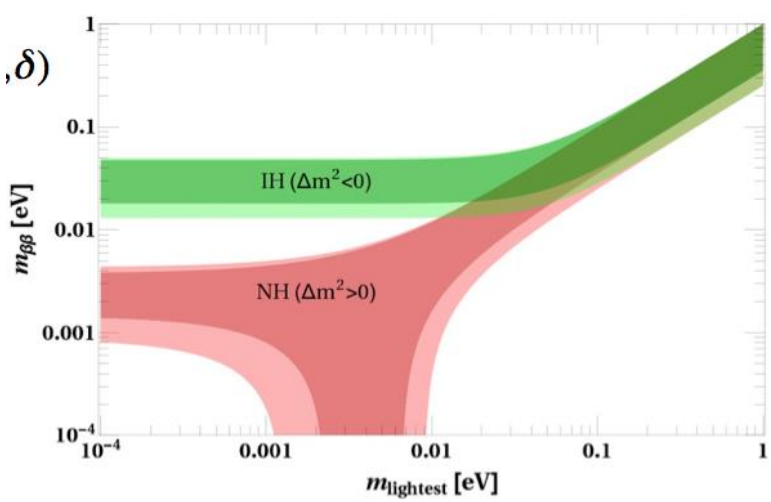
Effective Majorana mass

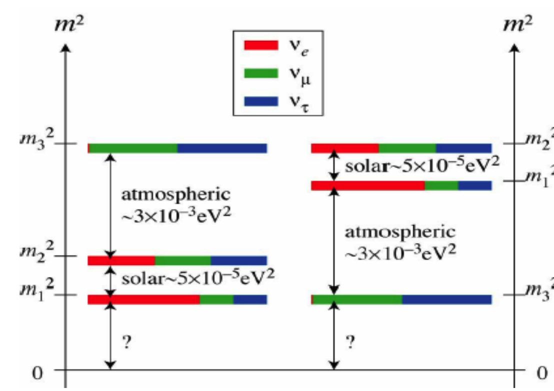
$$m_{\beta\beta} = f(\Delta m_{1,2}, \Delta m_{2,3}, m_1, \alpha_1, \alpha_2, \delta)$$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor ~$Q^5_{\beta\beta}$ (accurately calculable)

Nuclear Matrix Element (theoretical uncertainty ~2-3)





$$m_{0\nu\beta\beta} = \left| m_1 c_{13}^2 c_{12}^2 + m_2 c_{13}^2 s_{12}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i\alpha_{31}} \right|,$$

Currently, Xe constraint seems the strongest

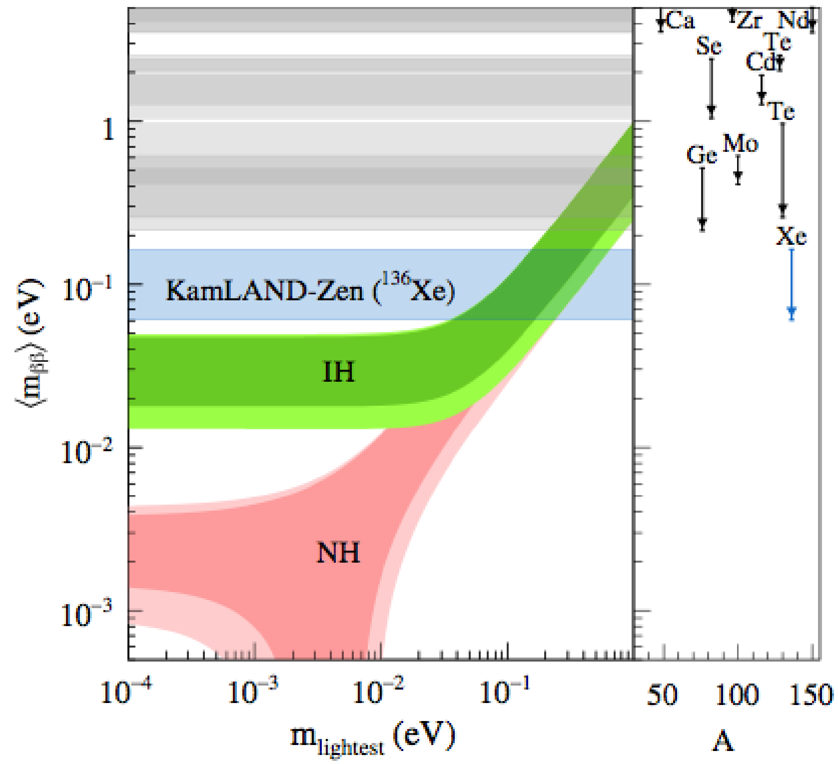
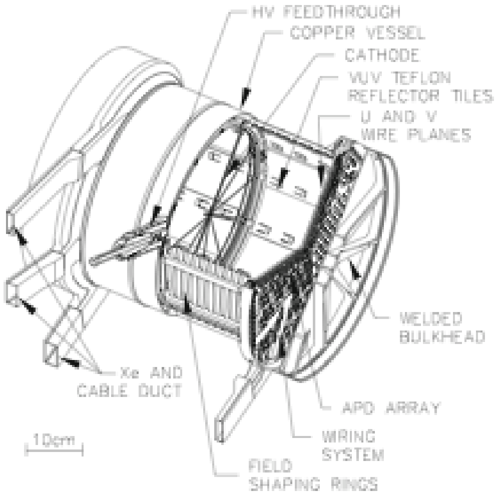
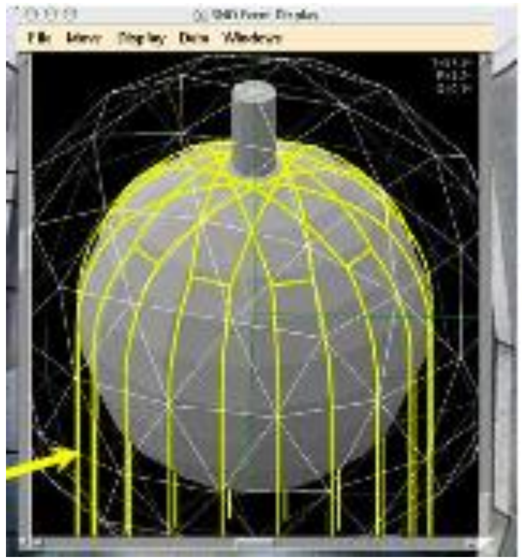
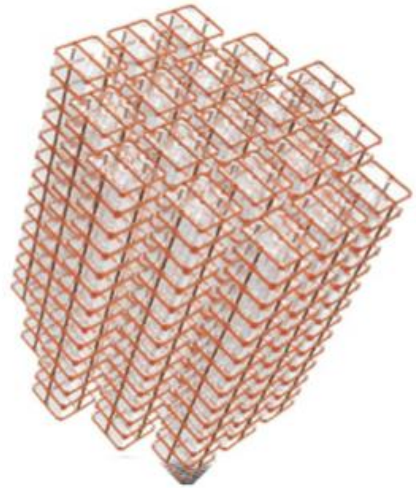


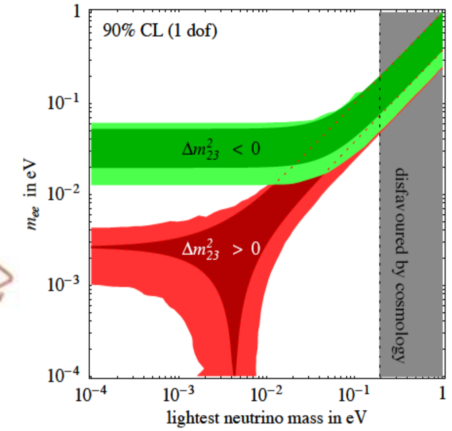
FIG. 3. Effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle$ as a function of the lightest neutrino mass m_{lightest}. The dark shaded regions are the predictions based on best-fit values of neutrino oscillation parameters for the normal hierarchy (NH) and the inverted hierarchy (IH), and the light shaded regions indicate the 3σ ranges calculated from the oscillation parameter uncertainties [29,30]. The horizontal bands indicate 90% C.L. upper limits on $\langle m_{\beta\beta} \rangle$ with ^{136}Xe from KamLAND-Zen (this work), and with other nuclei from Refs. [2,26–28], considering an improved phase space factor calculation [17,18] and commonly used NME calculations [19–25]. The side panel shows the corresponding limits for each nucleus as a function of the mass number.

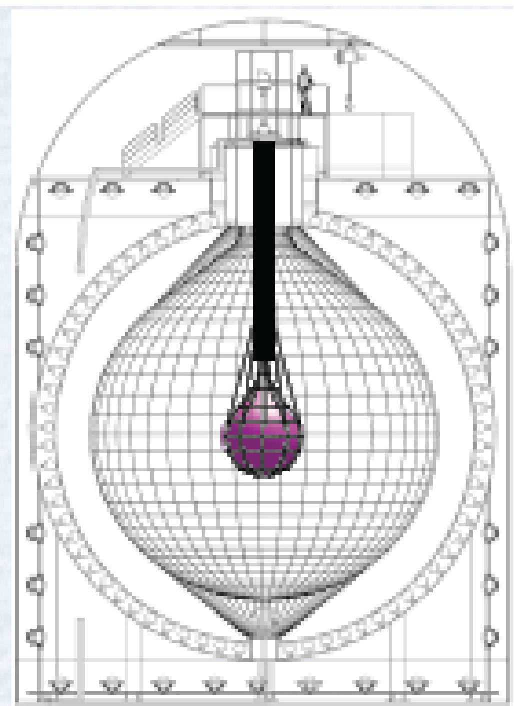
Many double beta decay experiments are either ongoing or coming

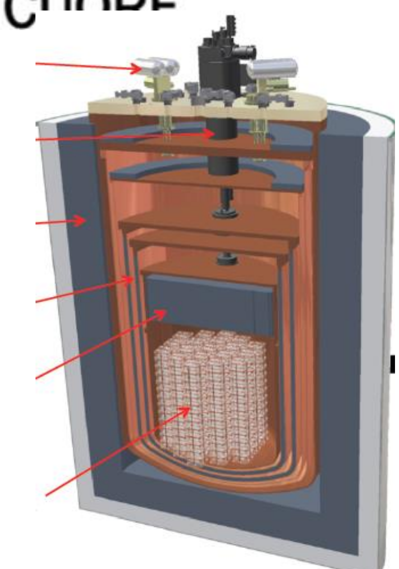












If 0ν DBD is discovered ..

- If 0ν DBD is discovered what that means?
- Neutrinos are Majorana particle
- Lepton number is violated by 2 units
- $(1/M_{NP})\ \phi\phi\nu\nu$ (=Majorana mass) favored but not proven