XXIV Workshop on Weak Interactions and Neutrinos

WIN 2013

Sep. 16 to 21, 2013 Natal, Brazil

Experimental status of Neutrino Physics

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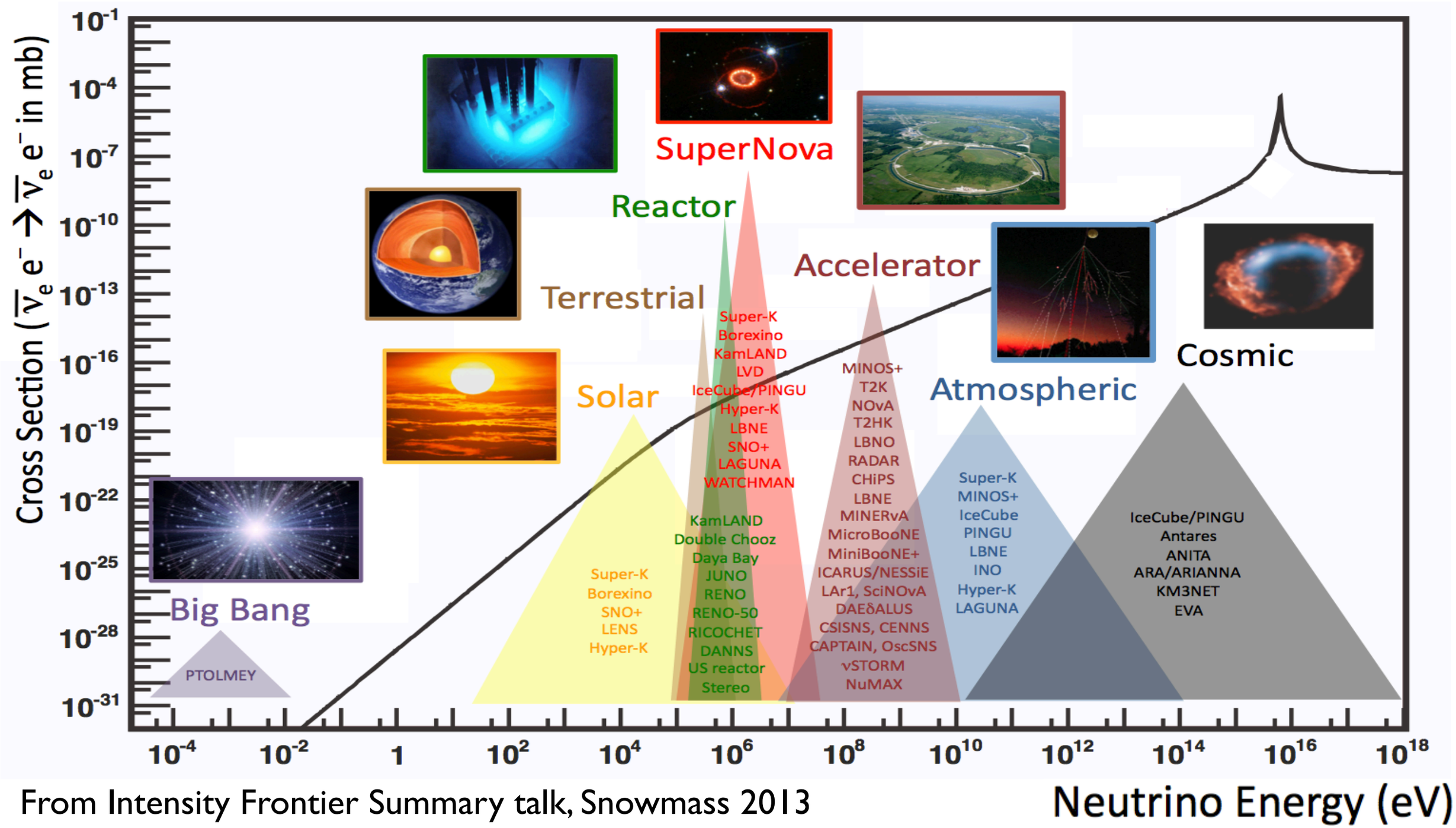
THE UNIVERSITY OF TOKYO

KAVLI IPMU

“Neutrino Phyiscs”

many sources ➔ many experimental opportunities



From Intensity Frontier Summary talk, Snowmass 2013

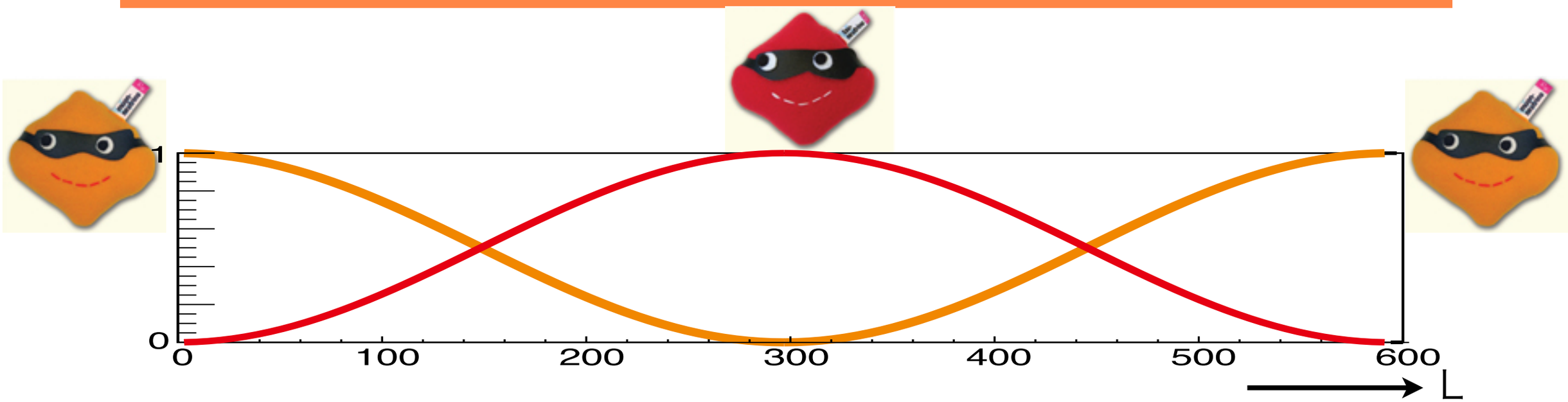
Contents

- Neutrino flavor mixing
  - Oscillation experiments, now and then
- Absolute neutrino mass
  - We know they're massive (at least two are).
- Neutrino as messenger from Nature
  - From Earth, Sun, Stars, and Universe

Apologies to topics not covered

Neutrino mixing

Neutrino oscillation



Flavor eigenstate Mass eigenstate

Two flavor case

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle+\sin\theta|\nu_2\rangle$$
$$|\nu_\beta\rangle = -\sin\theta|\nu_1\rangle+\cos\theta|\nu_2\rangle$$

θ:mixing angle
$\Delta m^2=m_1^2-m_2^2$

$$P(\nu_\alpha\rightarrow\nu_\alpha)=1-\sin^2 2\theta\cdot\sin^2(1.27\Delta m^2_{[eV^2]}\cdot L_{[km]}/E_{[GeV]})$$

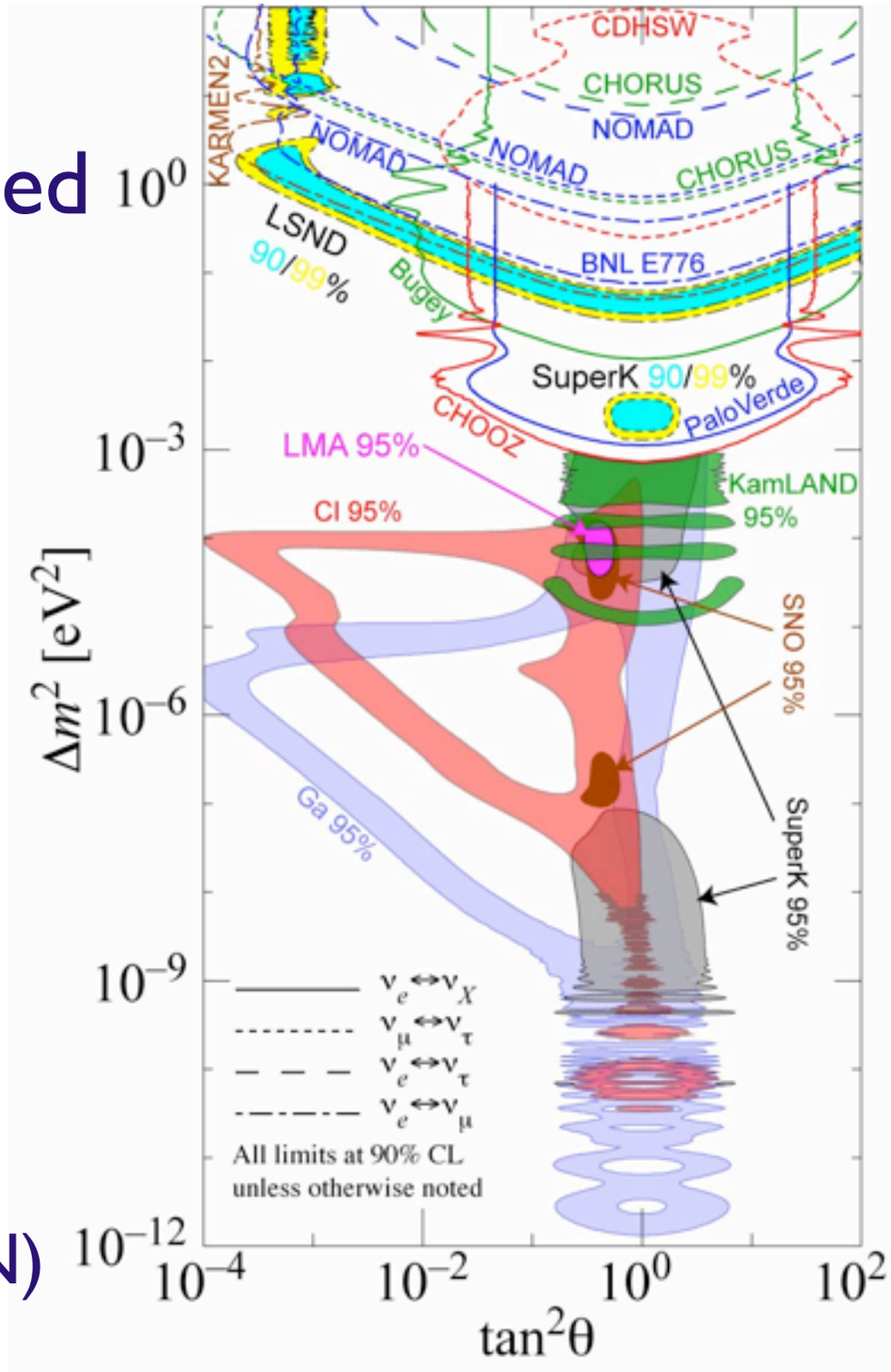
$$P(\nu_\alpha\rightarrow\nu_\beta)=\sin^2 2\theta\cdot\sin^2(1.27\Delta m^2\cdot L/E)$$

Three flavor: four parameters

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

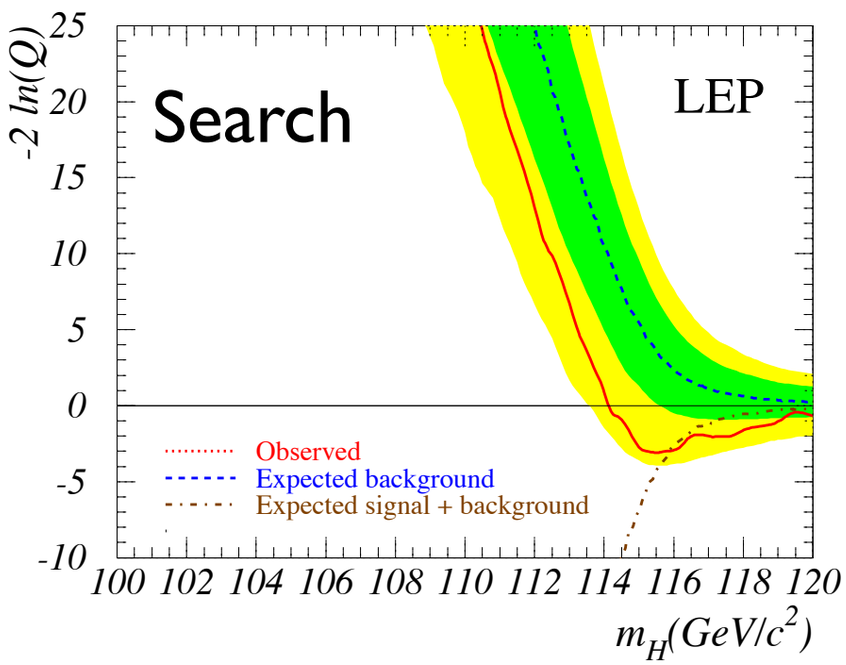
10 years ago (2003)

- When I started ν physics..
- Neutrino oscillation just established
  - *Atmospheric* mixing
    - Super-K, K2K
  - *Solar* mixing
    - Cl, Ga, SK, SNO, KamLAND
- Third mixing angle: only limit
  - $\bar{\nu}_e \rightarrow \bar{\nu}_x$ by Chooz & Palo Verde
  - $\nu_\mu \rightarrow \nu_e$ by K2K
- 4th ν? by LSND (but not by KARMEN)



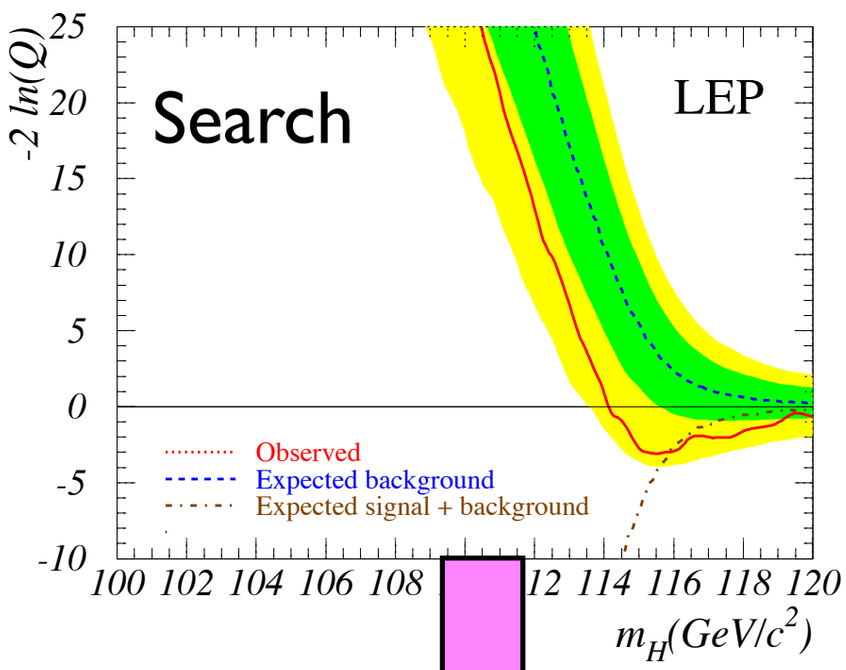
In 10 years..

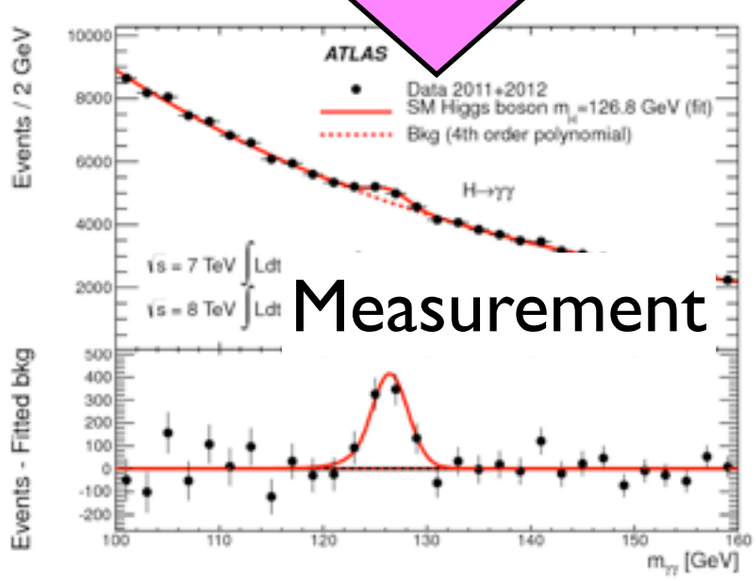
Higgs boson



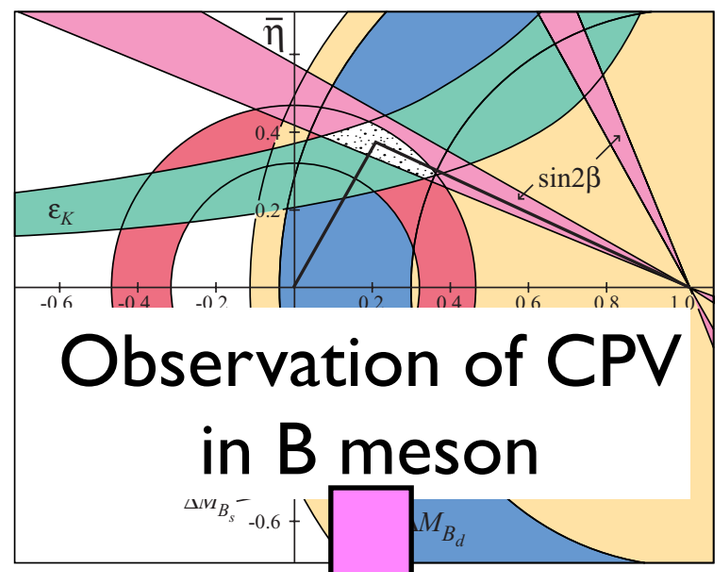
In 10 years..

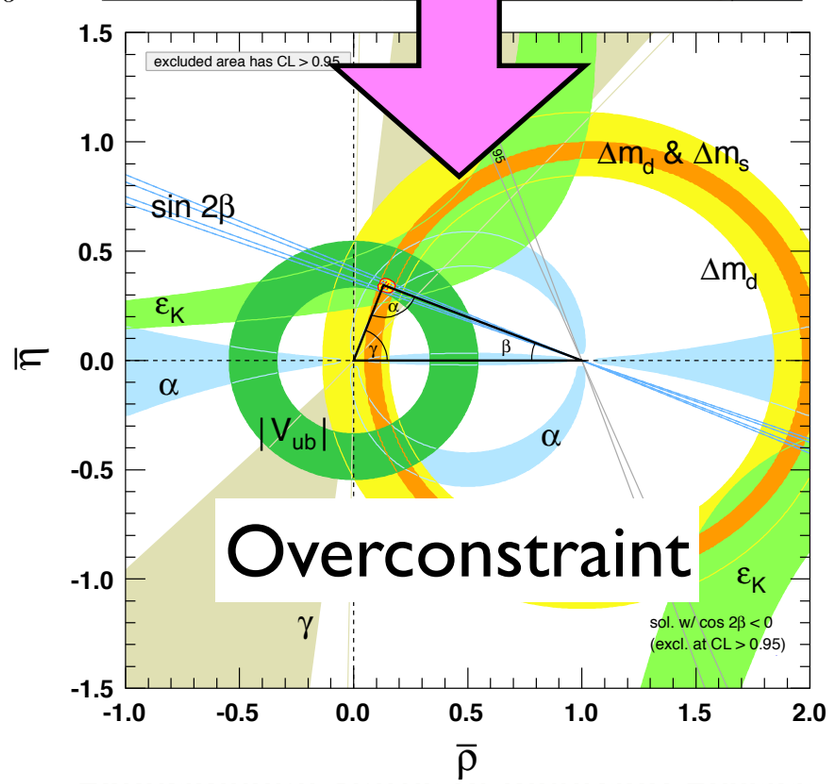
Higgs boson





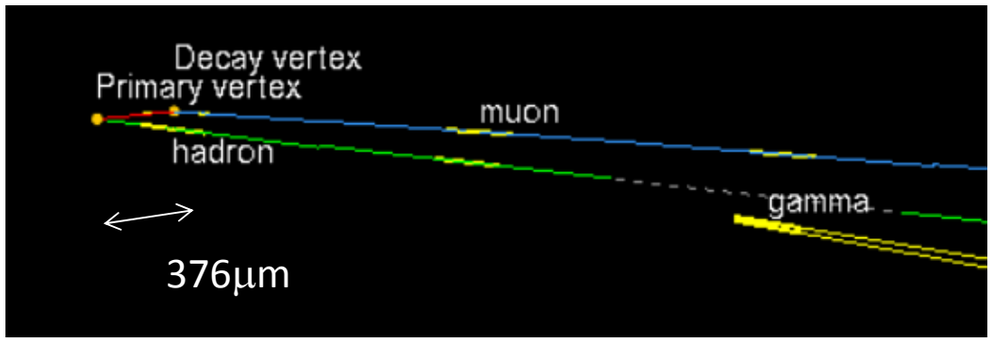
CKM angles

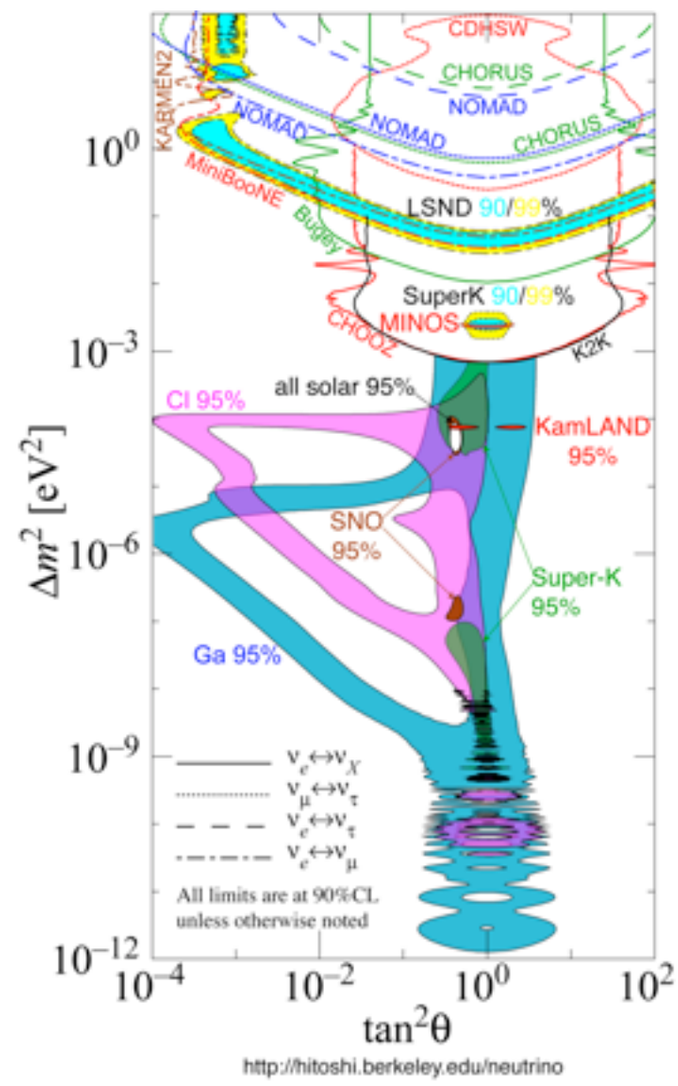




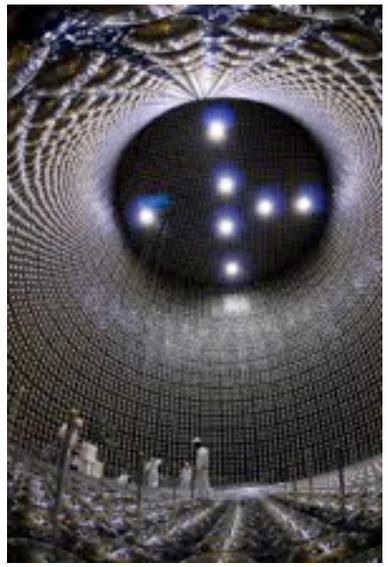
ν progress in 10 years

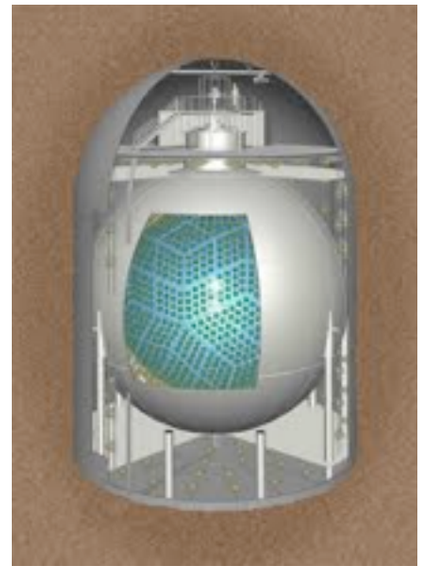
- Confirmation of ν_τ appearance by OPERA and Super-K
- Precise measurements of "atmospheric" and "solar" parameters
  - K2K, MINOS, SNO, KamLAND, Super-K, ..
- A few hints of sterile neutrinos?
  - MiniBooNE, reactor anomaly, Ga source, cosmology, ..
- Neutrino velocity..
- 2011-2012: θ_{13} revolution

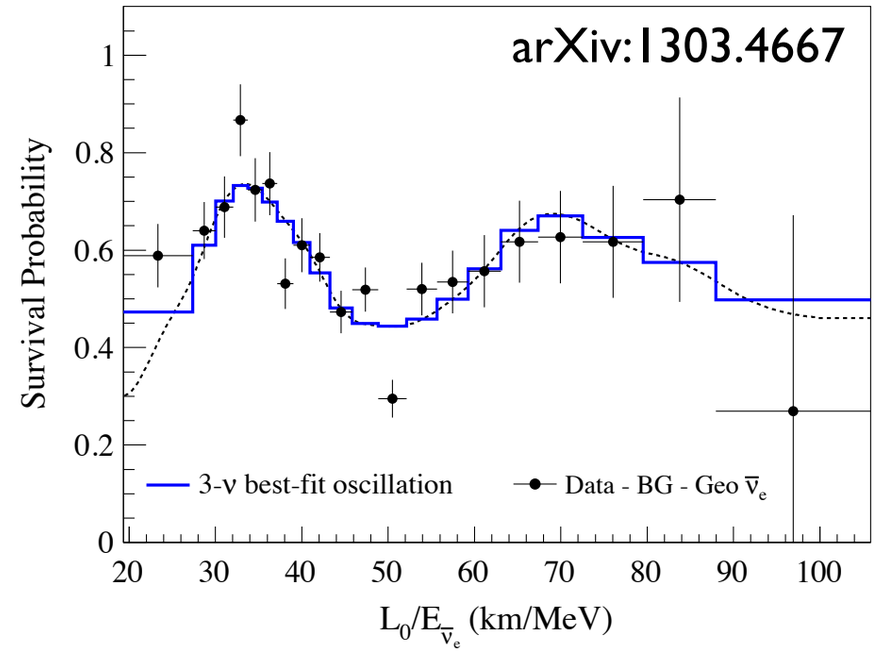




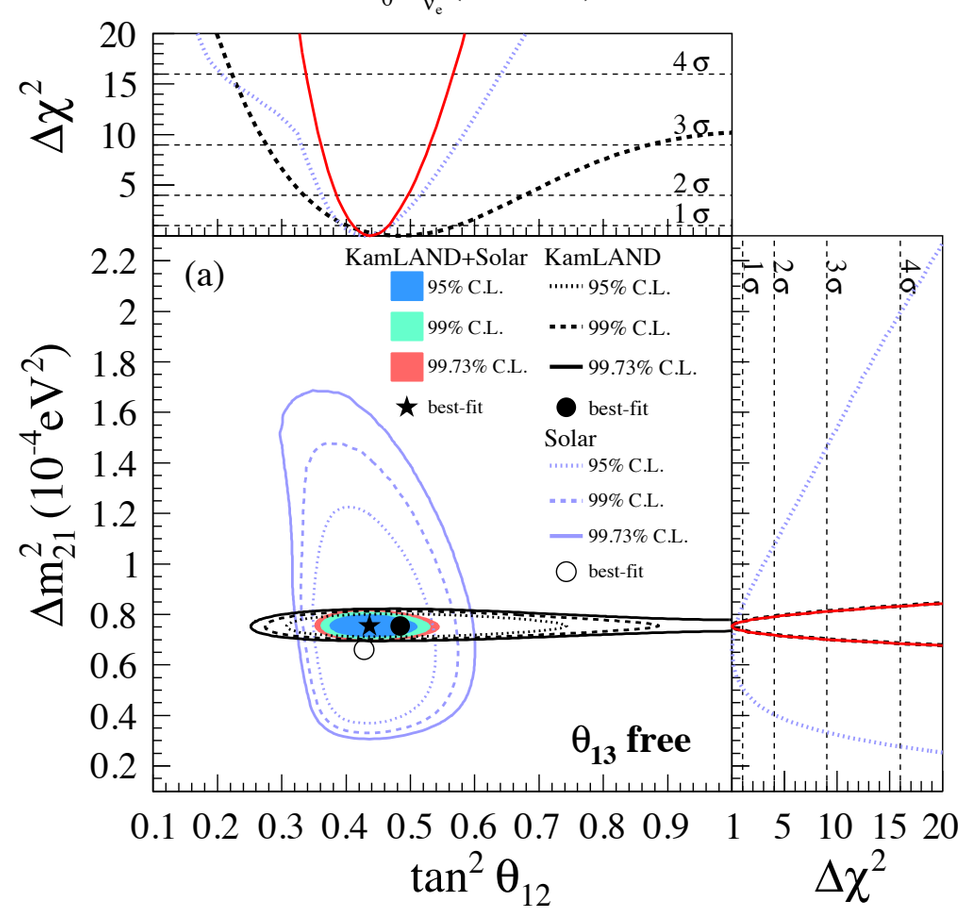
θ_{12}





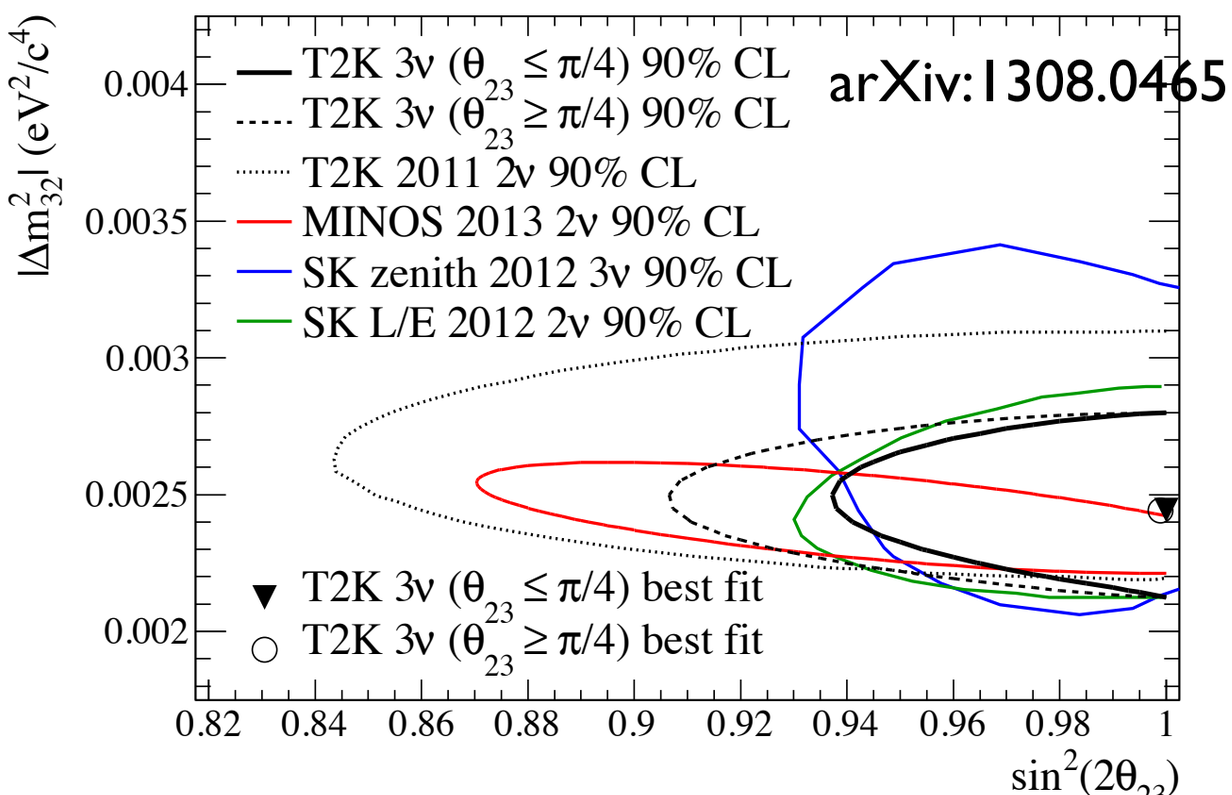


- Well determined by solar ν experiments + KamLAND
  - $\tan^2\theta_{12}=0.436^{+0.029}_{-0.025}$
- Next generation "middle-baseline" reactor ν experiments aims ≤1% level

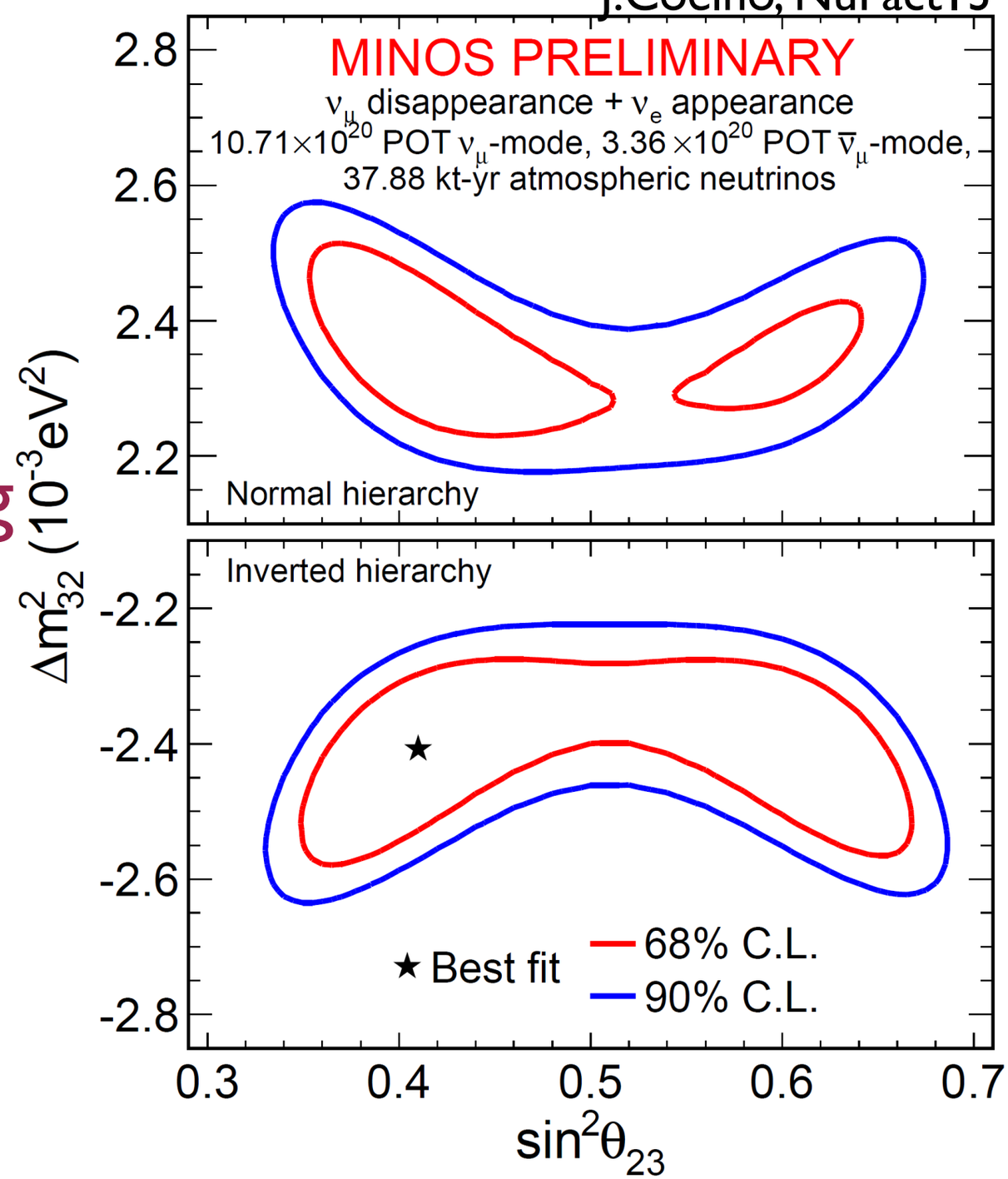


θ_{23}

- Super-K atm ν + accelerator (MINOS, T2K)
- Close to maximal mixing
  - MINOS: slight deviation?
  - More data from T2K (&NOνA) very interesting



J.Coelho, NuFact13



Motivation for θ_{13}

100th anniversary

δ: CP violationg complex phase

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

$s_{ij}=\sin\theta_{ij}$, $c_{ij}=\cos\theta_{ij}$

CP asymmetry depends on Jarlskog invariant

$$J_{CP} = \mathrm{Im}(U_{\mu 3}U_{e3}^{*}U_{e2}U_{\mu 2}^{*}) = \frac{1}{8}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta$$

- All θ_{ij} must be non-zero for CP violation in ν mixing
  - θ_{23}~45°
  - θ_{12}~34°
  - **θ_{13} was *the* key to open the door to the next stage**

(mass hierarchy too)

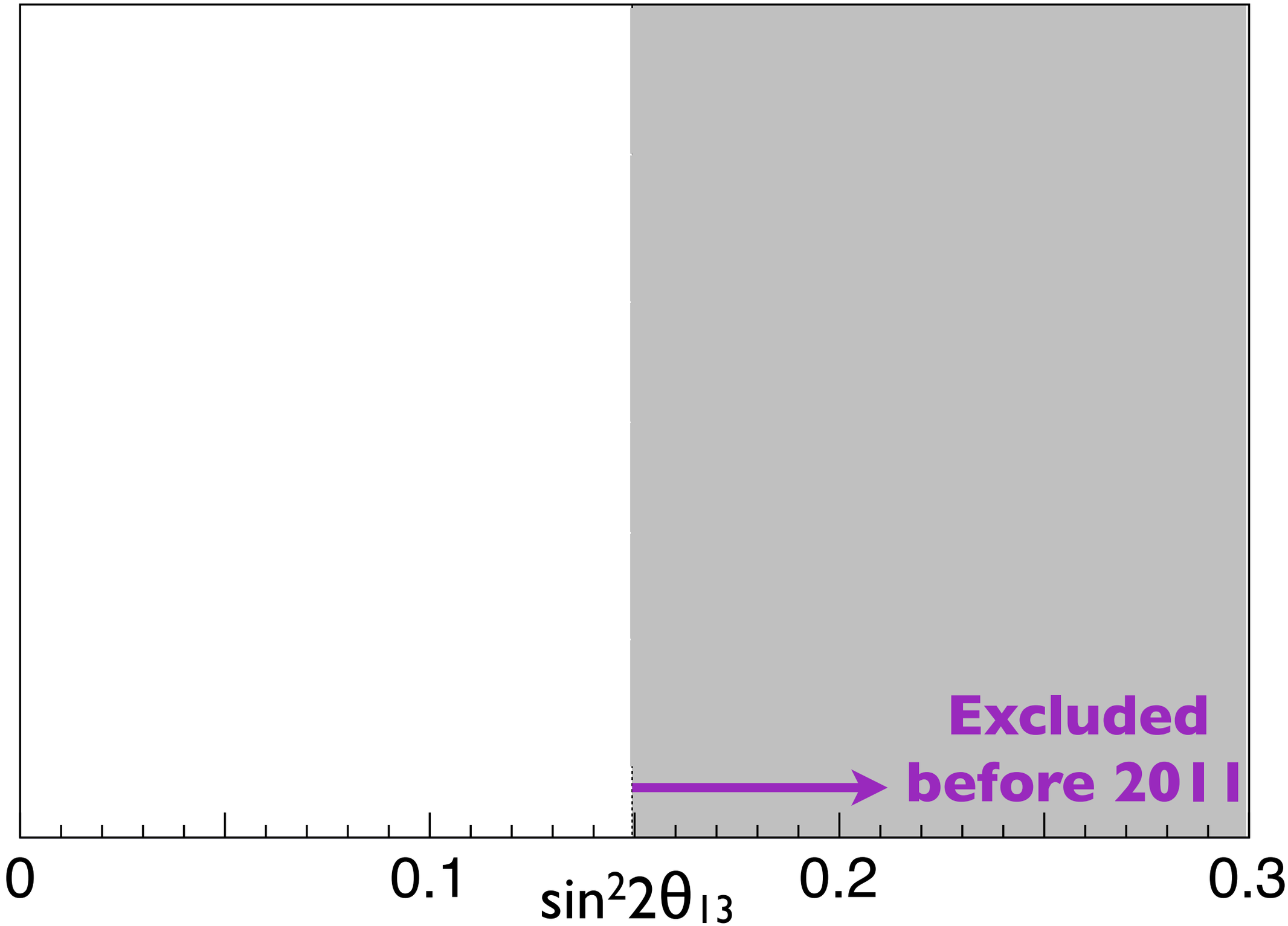
θ_{13}: International campaign

- Accelerator
  - T2K(2009-)
  - MINOS(2005-2012), NOνA(2013-)
- E_ν~GeV, **Search for $\nu_\mu \rightarrow \nu_e$** "Appearance" exp.

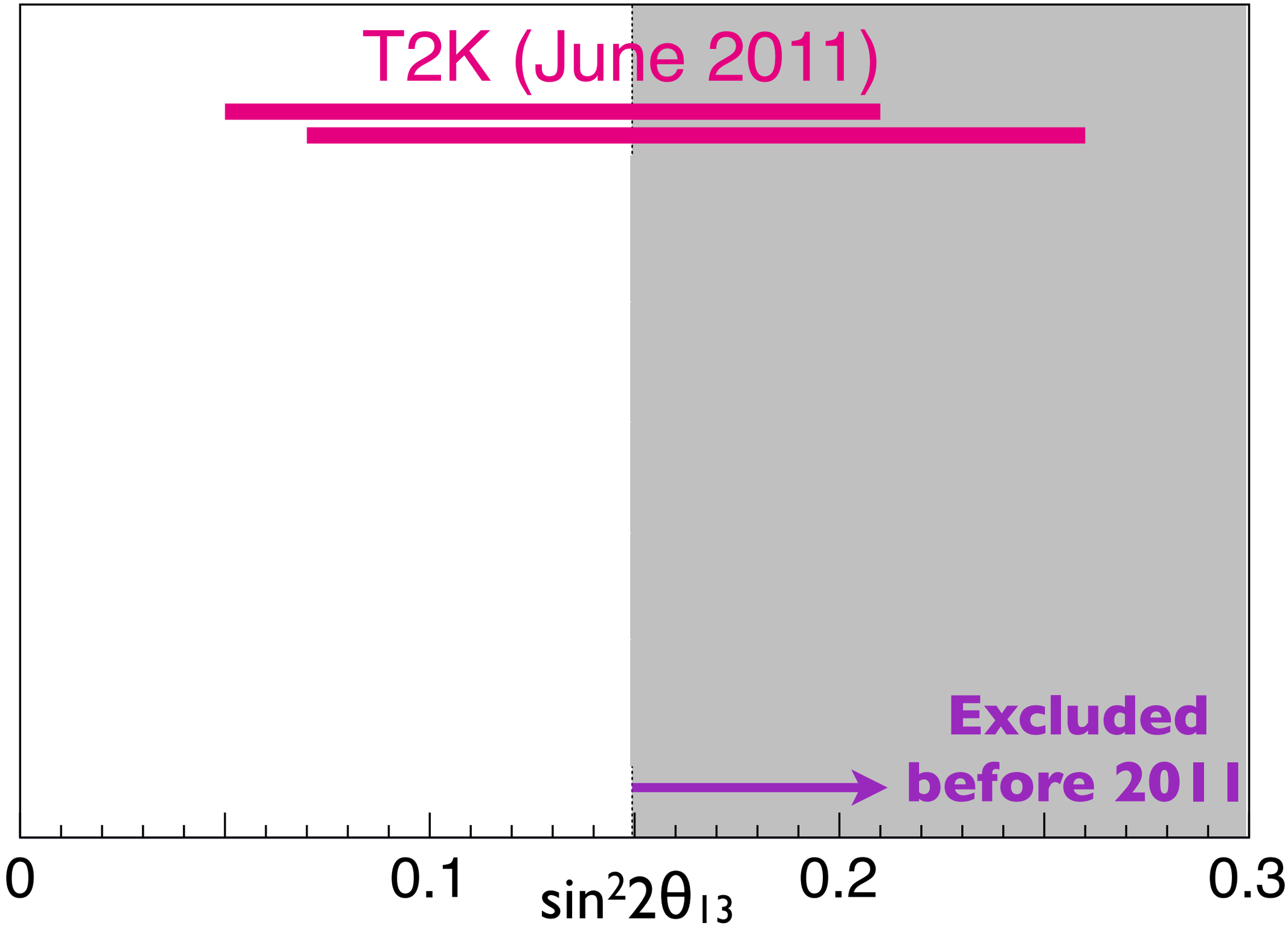
- Reactor
  - Double Chooz (2011-)
  - RENO (2011-)
  - Daya Bay(2012-)
- E~MeV, Search for $\bar{\nu}_e \rightarrow \bar{\nu}_{x(x \neq e)}$ "Disappearance" exp.

Worldwide efforts for measuring θ_{13}

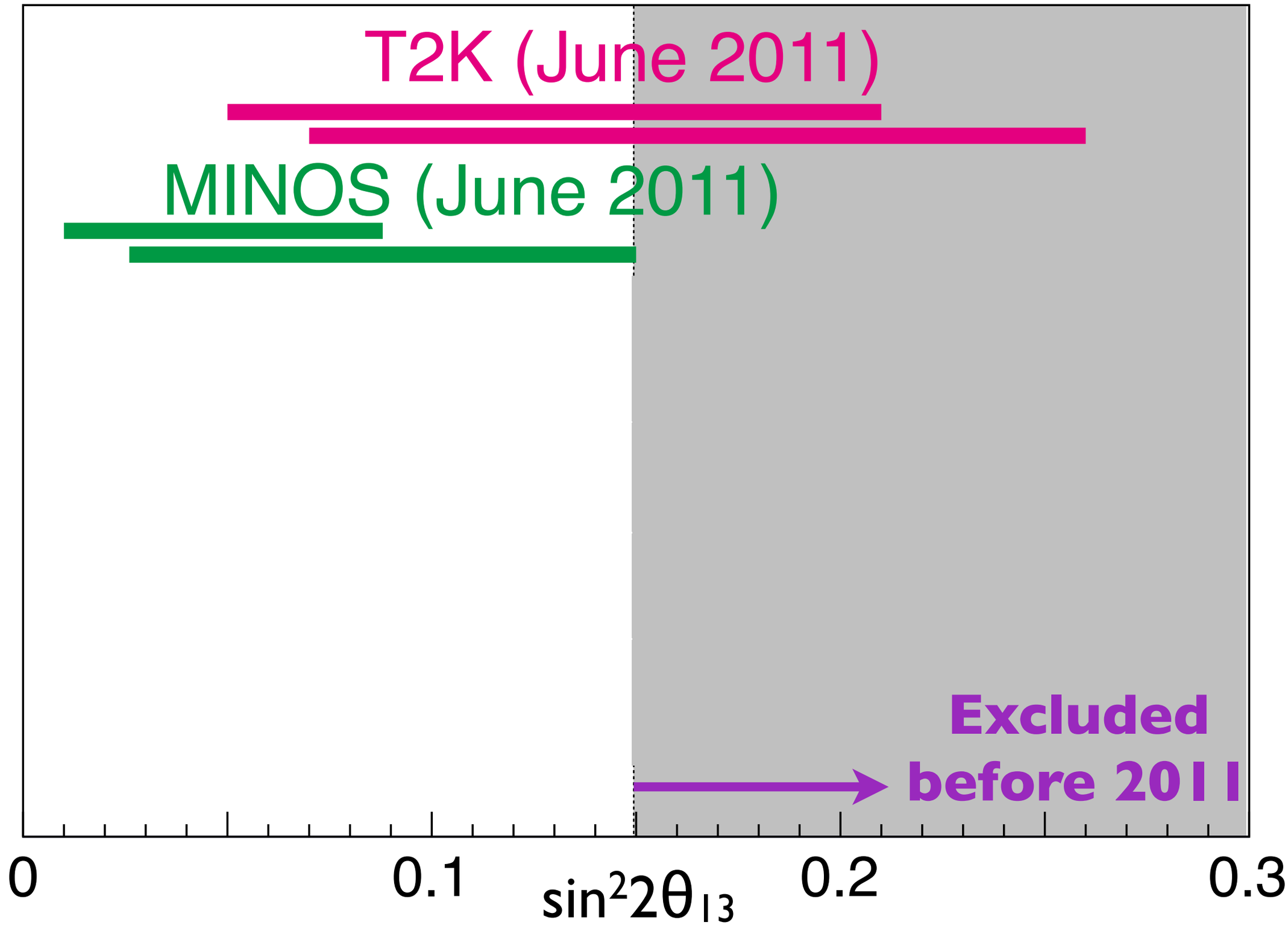
Revolution in 2011-2012



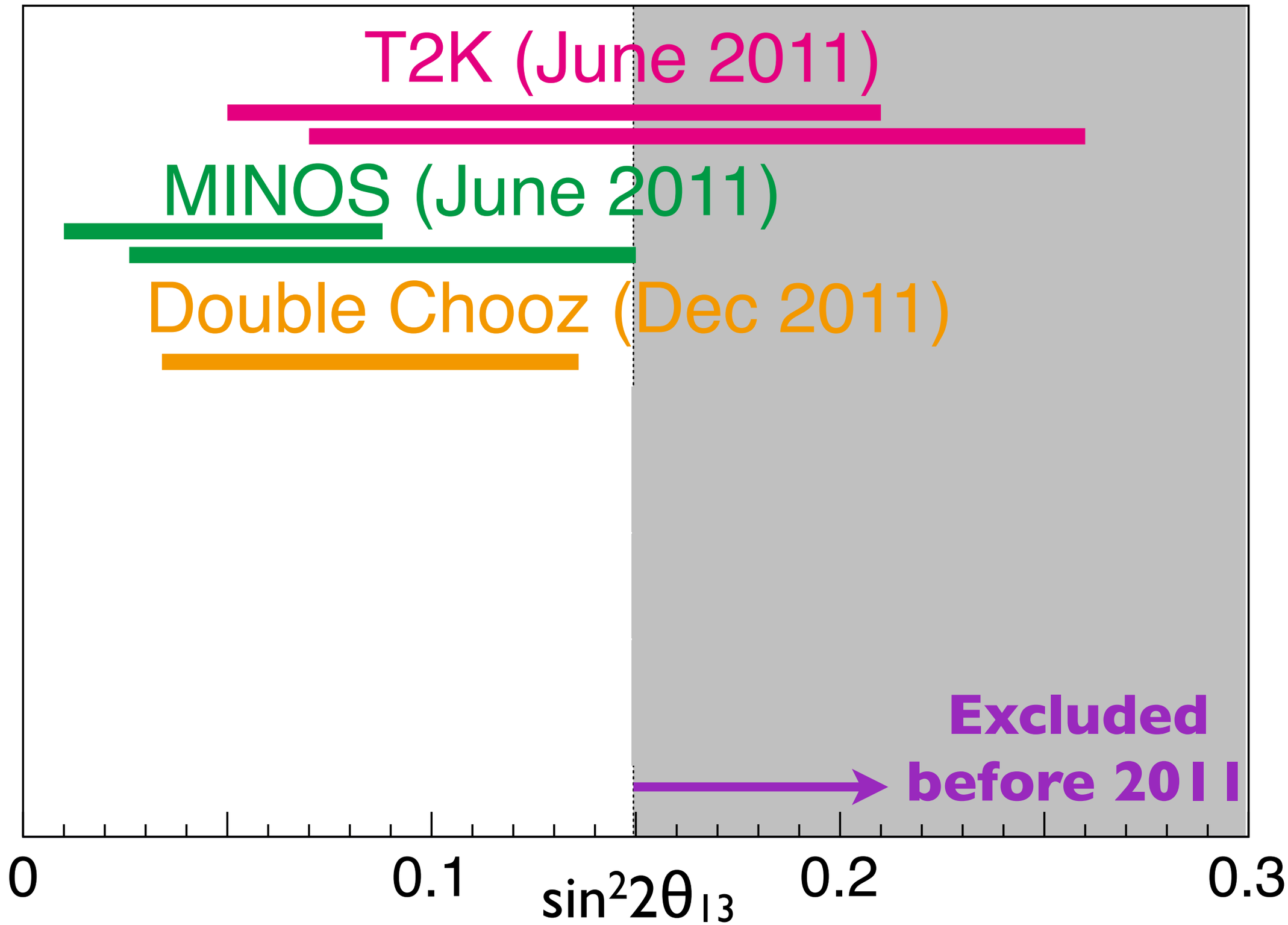
Revolution in 2011-2012



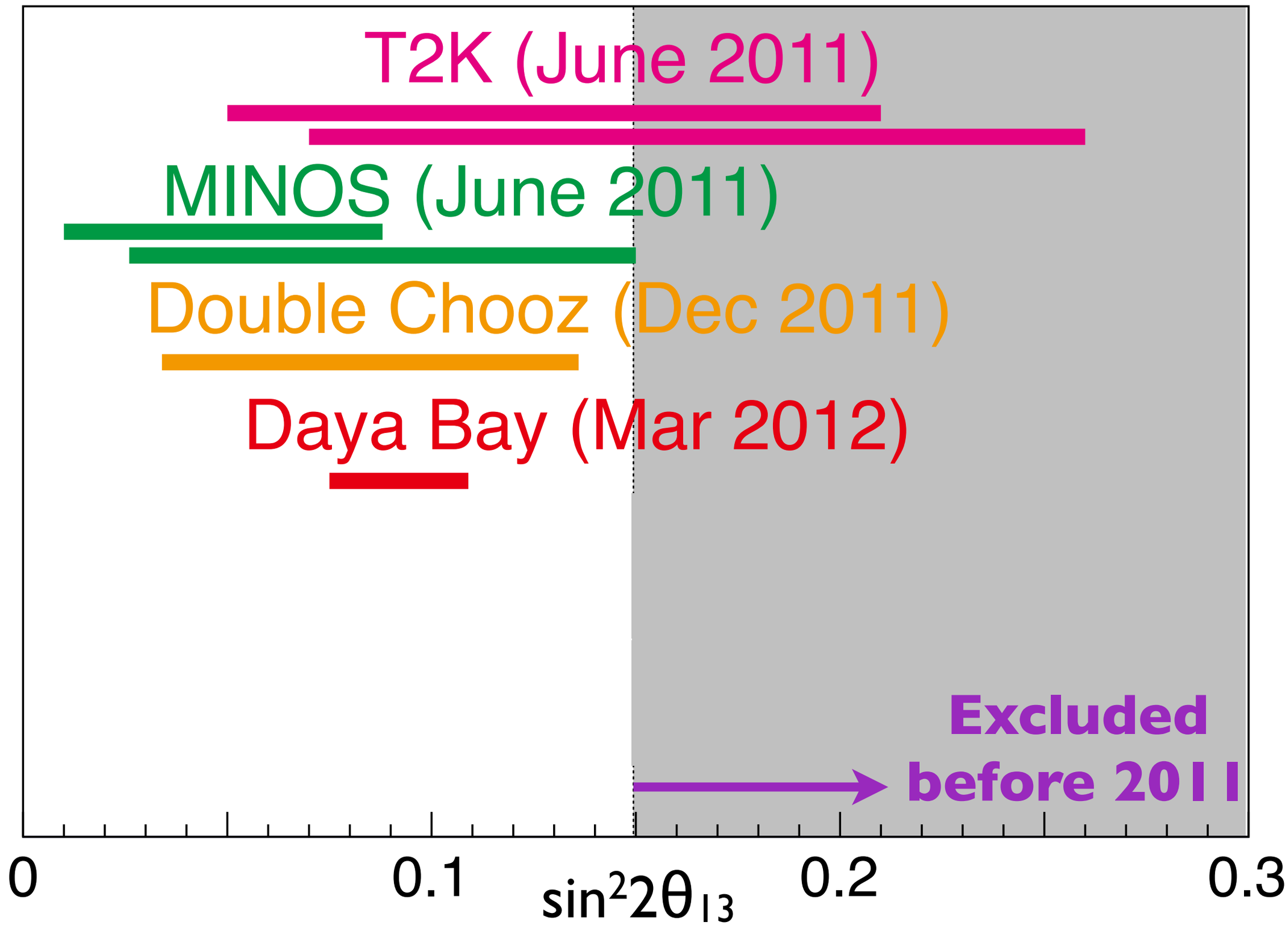
Revolution in 2011-2012



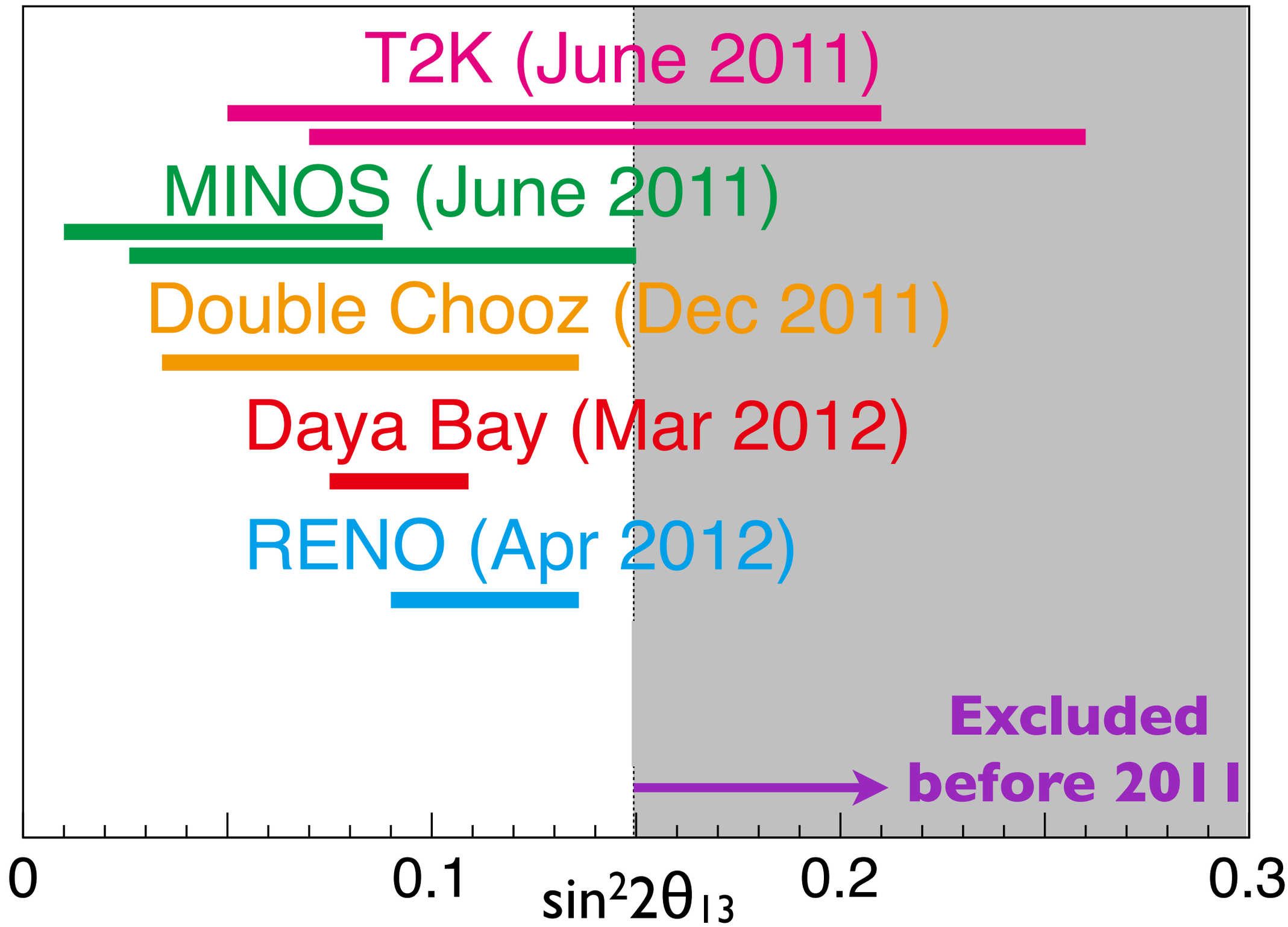
Revolution in 2011-2012



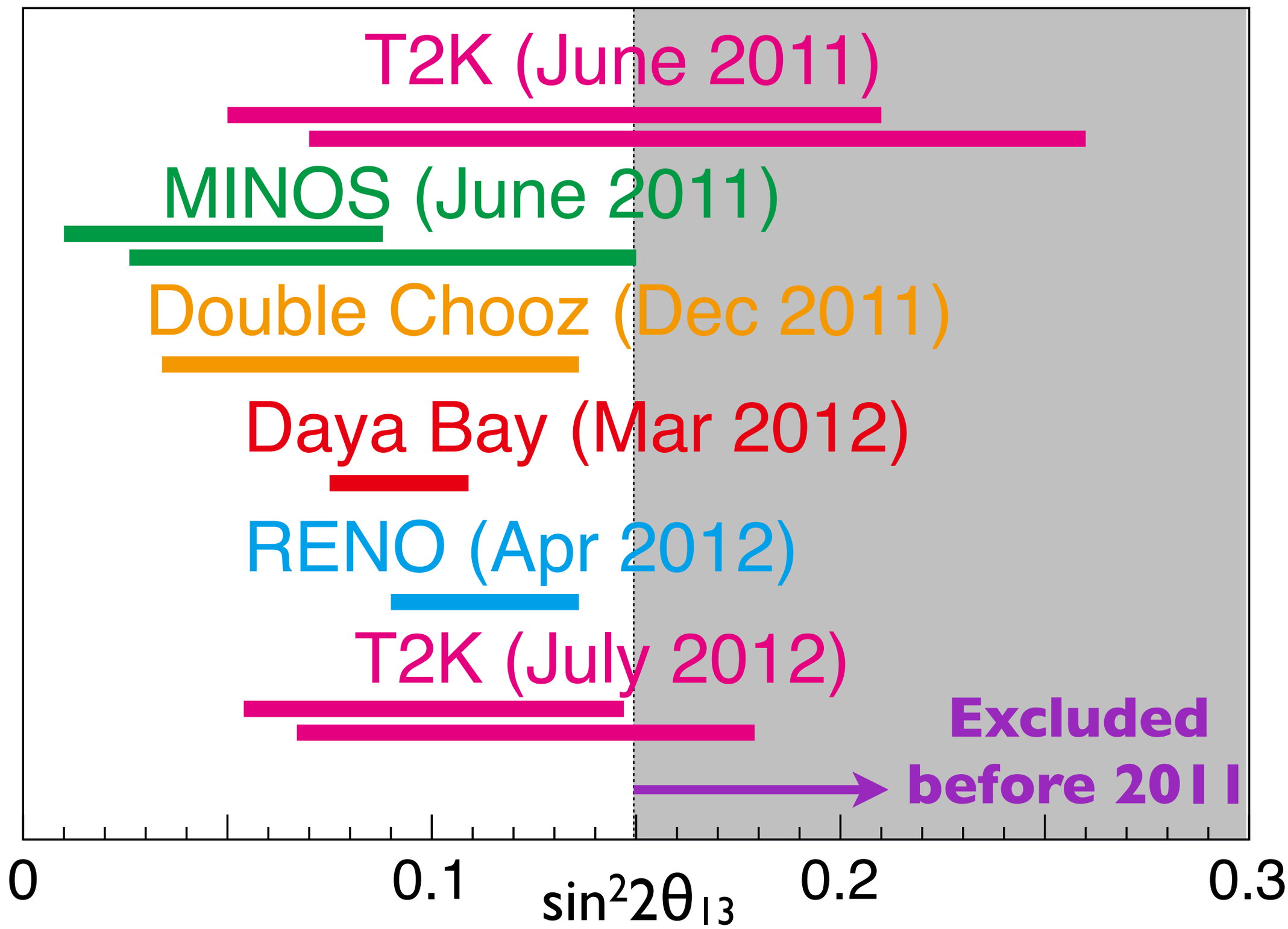
Revolution in 2011-2012



Revolution in 2011-2012



Revolution in 2011-2012

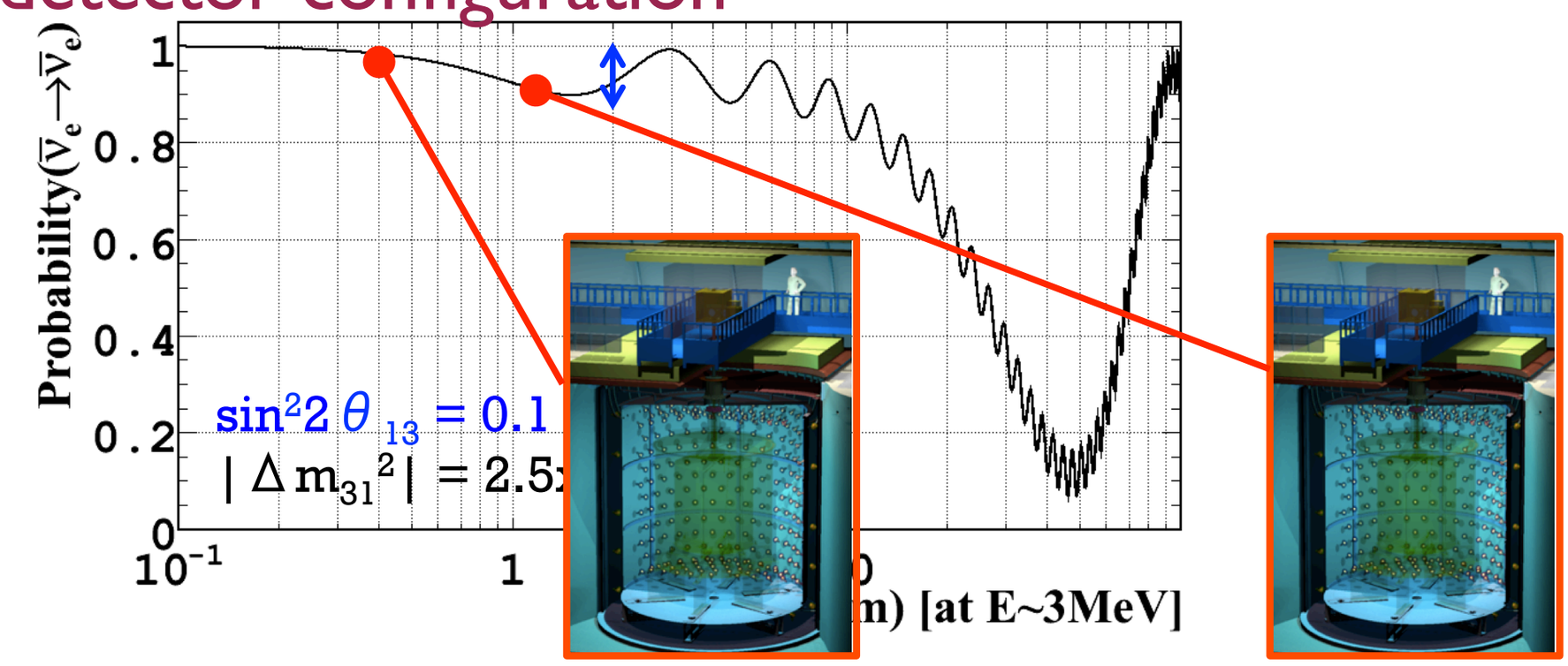


Reactor θ_{13} experiment

~pure θ_{13} measurement

$$P\left[\overline{\nu}_e \rightarrow \overline{\nu}_e\right] \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

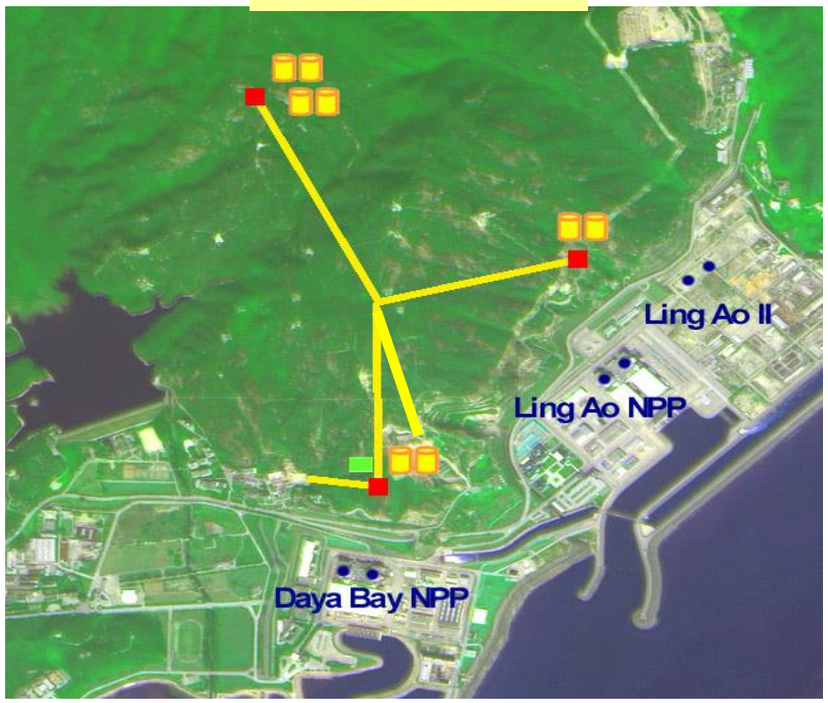
- Anti-neutrino signal by delayed coincidence
- Small disappearance effect:
  systematic uncertainties needs to be <1%
  - Improved detector design over past exp'ts
  - Two detector configuration



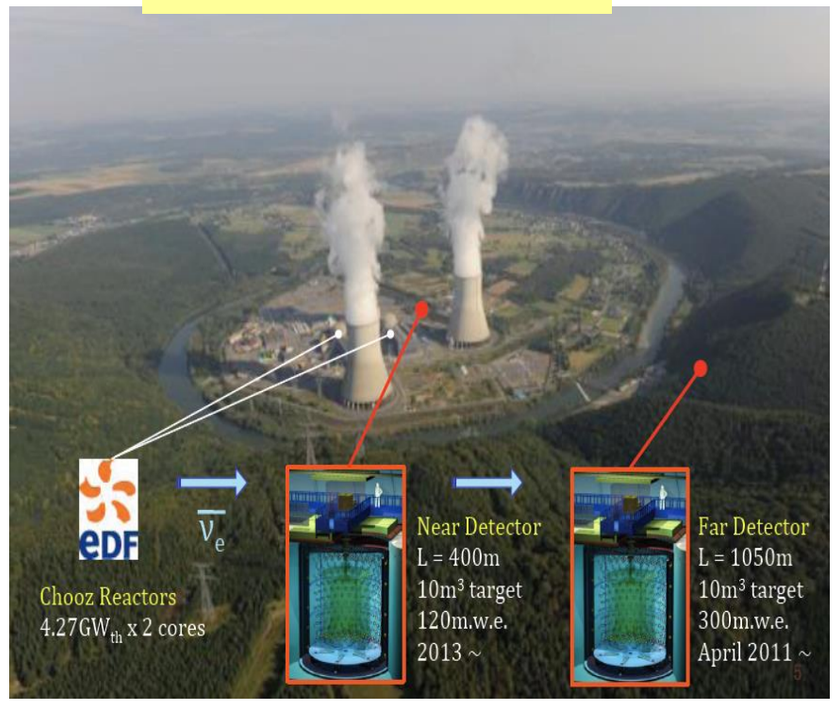
Reactor experiments

Experiment	Power (GW)	Baseline(m) Near/Far	Detector(t) Near/Far	Overburden (MWE) Near/Far	Designed Sensitivity (90%CL)
Daya Bay	17.4	470/576/1650	40//40/80	250/265/860	~0.008
Double Chooz	8.5	400/1050	8.2/8.2	120/300	~0.03
Reno	16.5	409/1444	16/16	120/450	~0.02

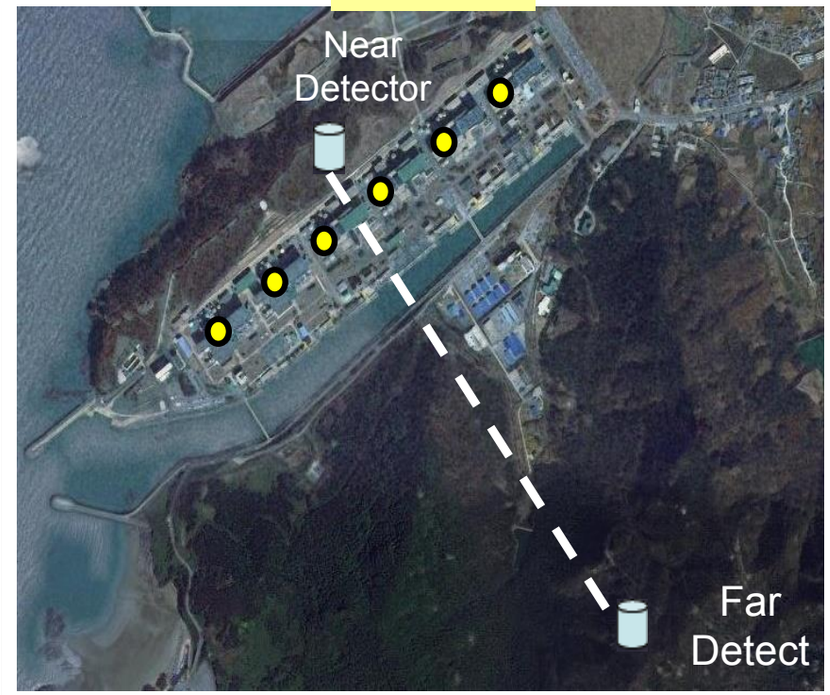
Daya Bay



Double Chooz



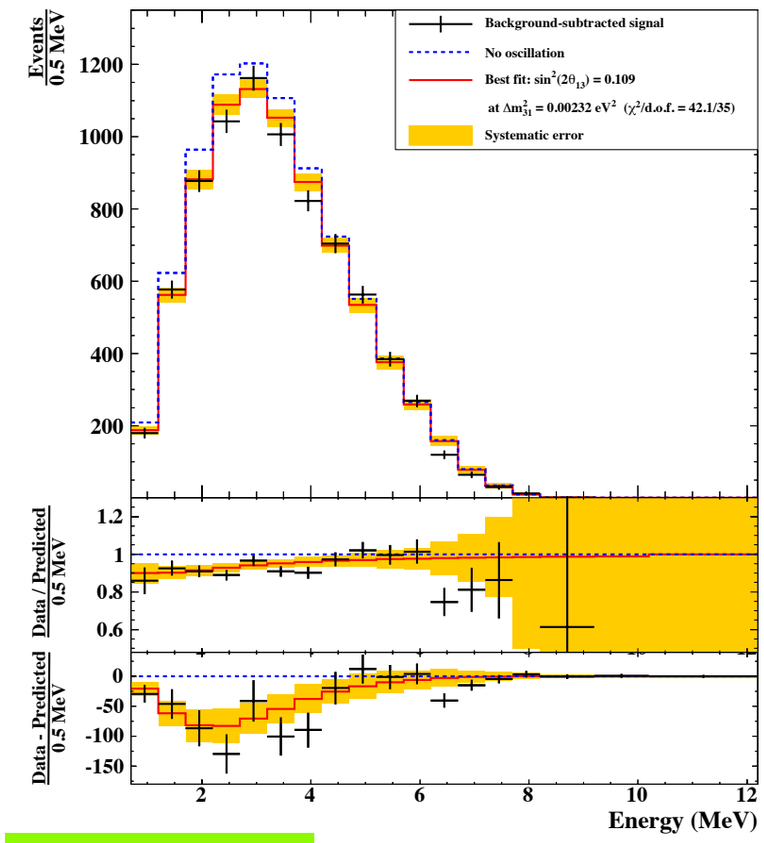
Reno



Reactor latest results

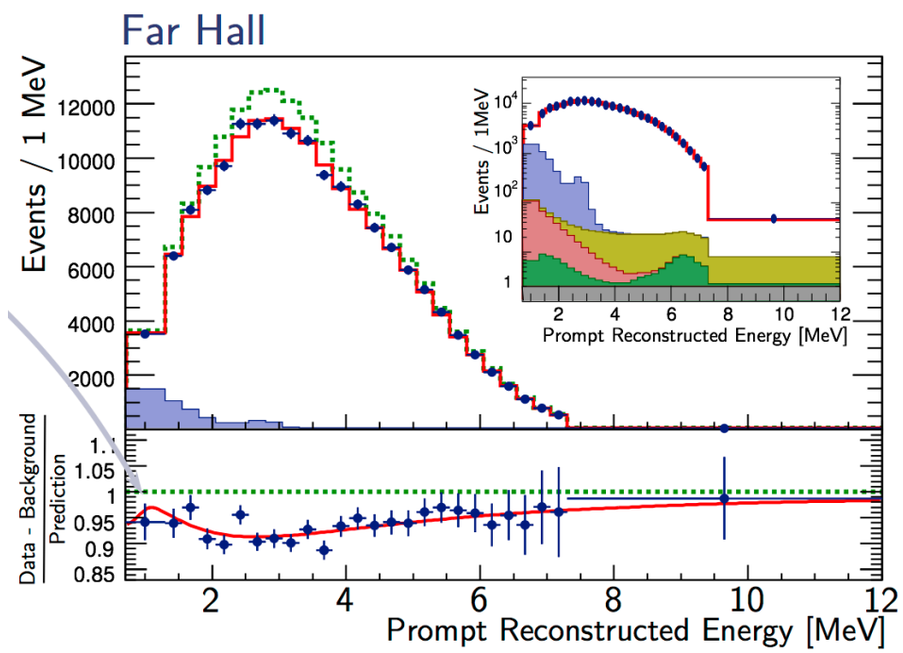
Double Chooz

(Gd+H combined, EPS 2013, July)



Daya Bay

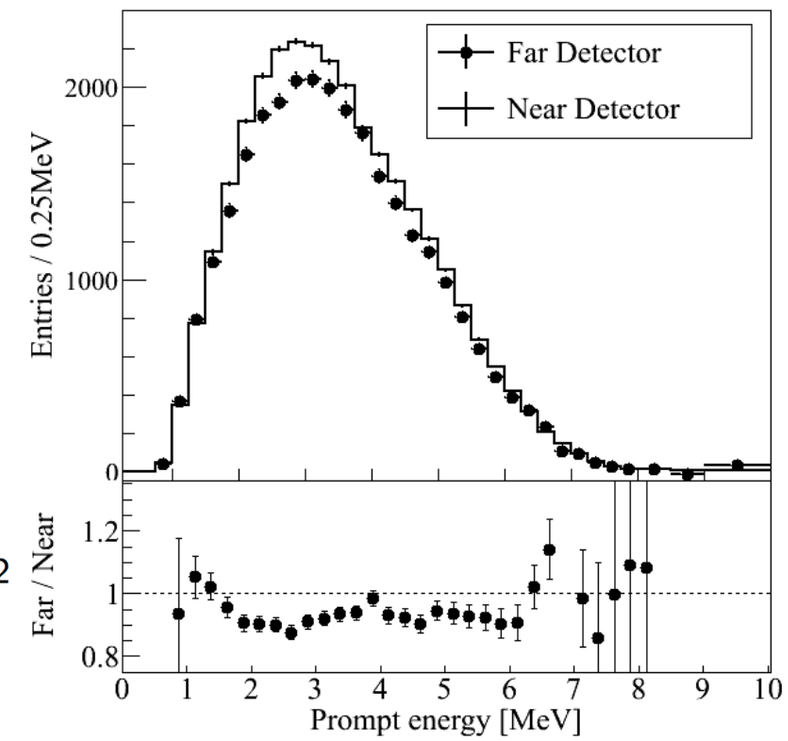
(NuFact 2013, August)



New results from Daya Bay
Rate+Shape fit just delivered

RENO

(NuTel 2013, March)



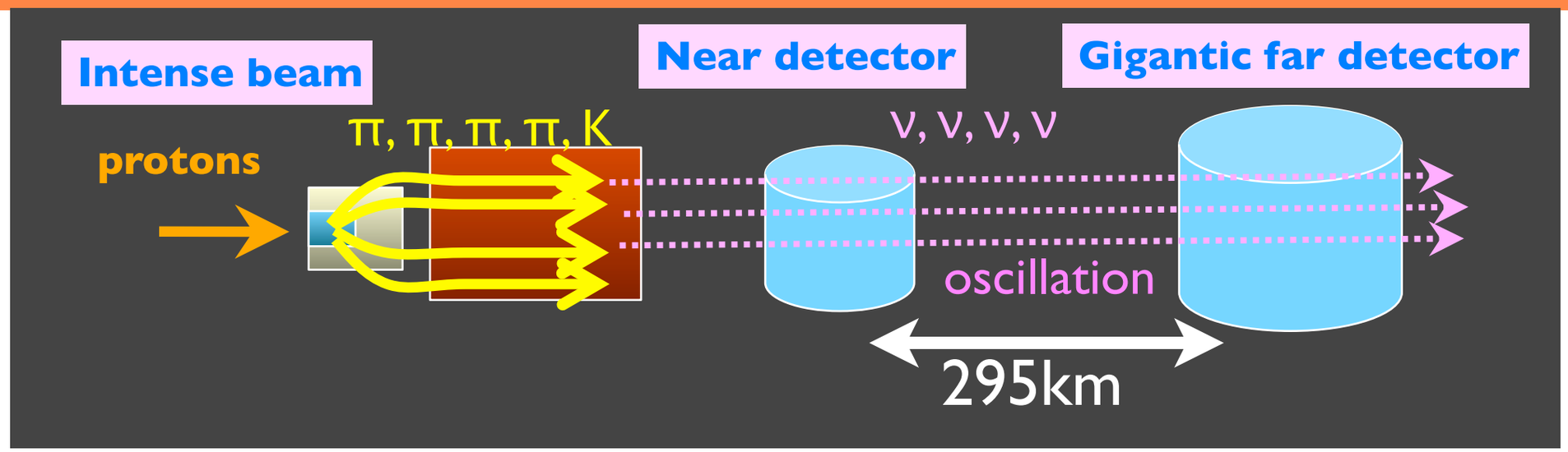
$\sin^2 2\theta_{13}$

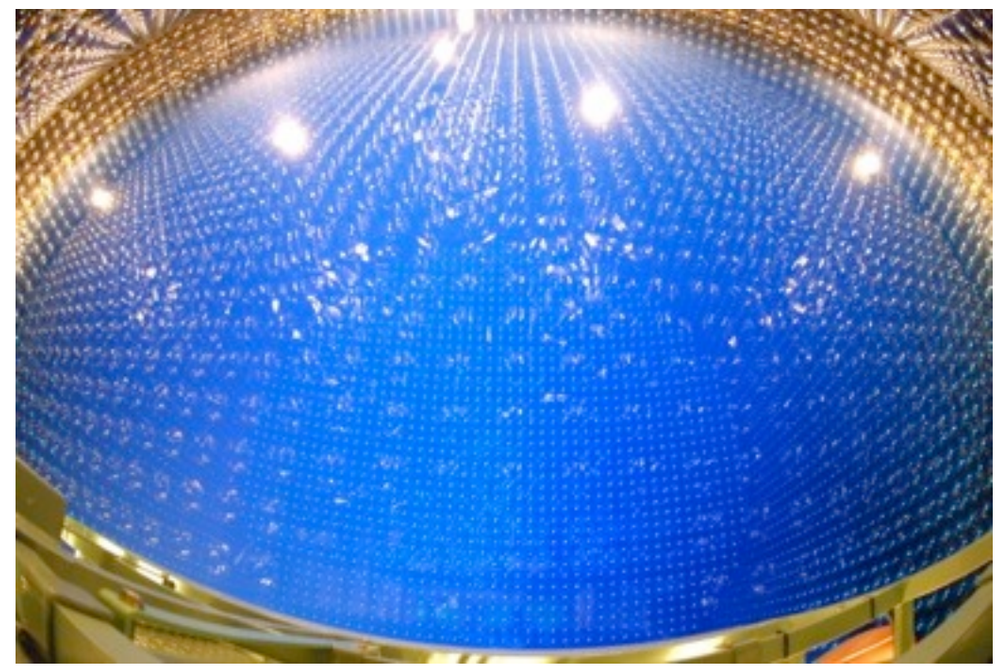
0.109±0.035	0.090+0.008-0.009	0.100±0.018

Precision already <10%!

(cf. θ_{23} error ~13%)

Long baseline experiment

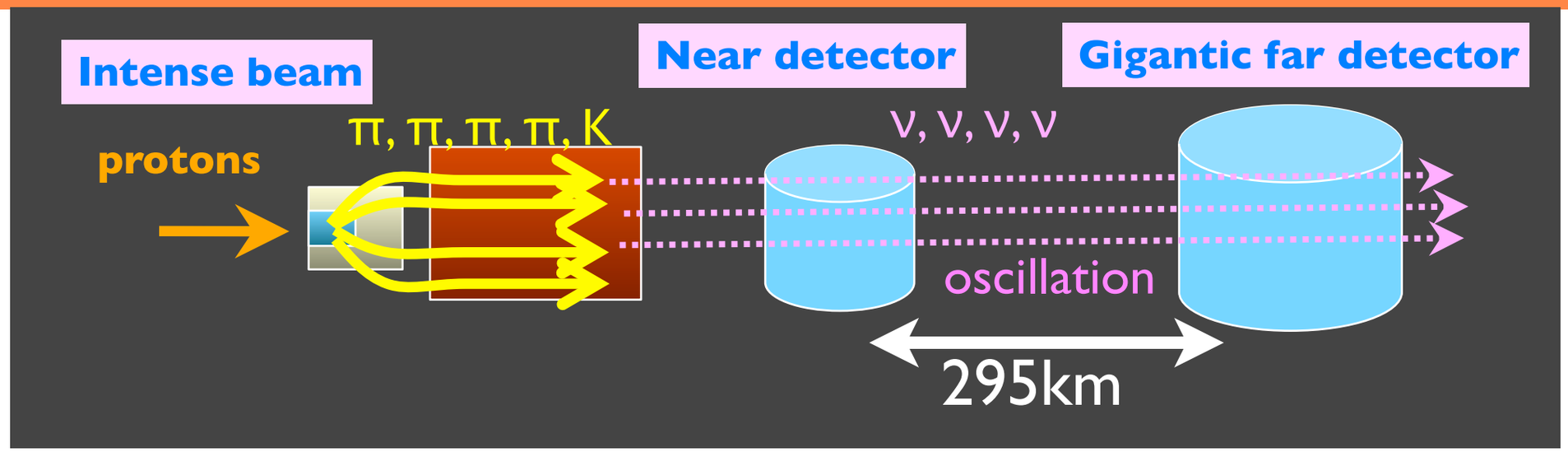


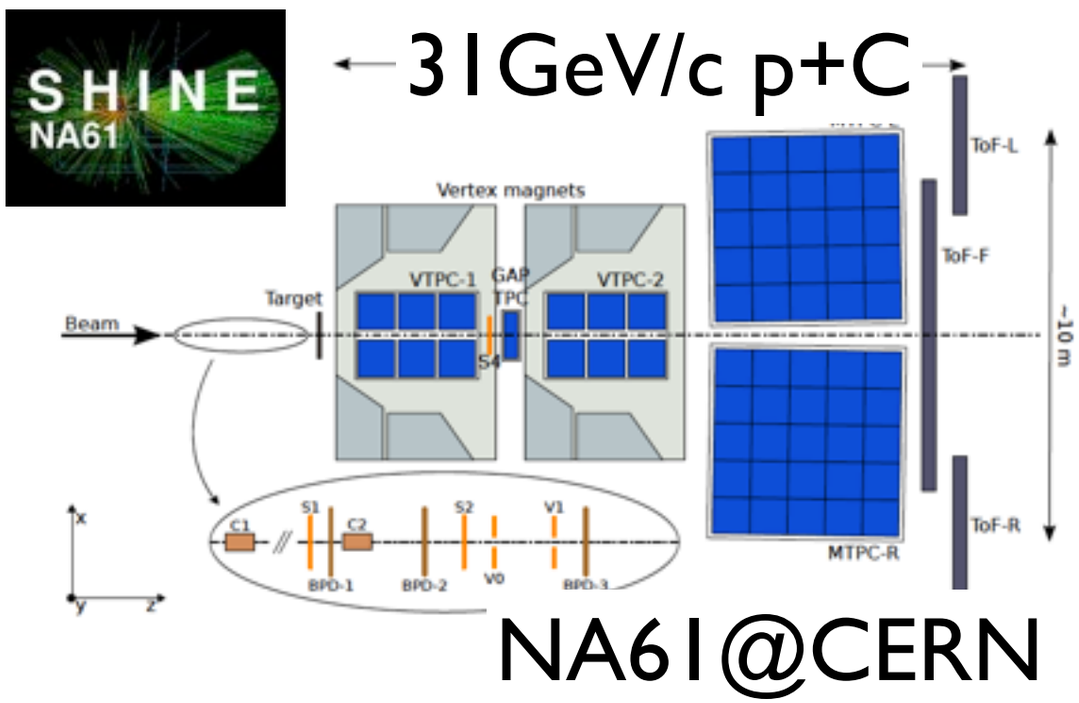


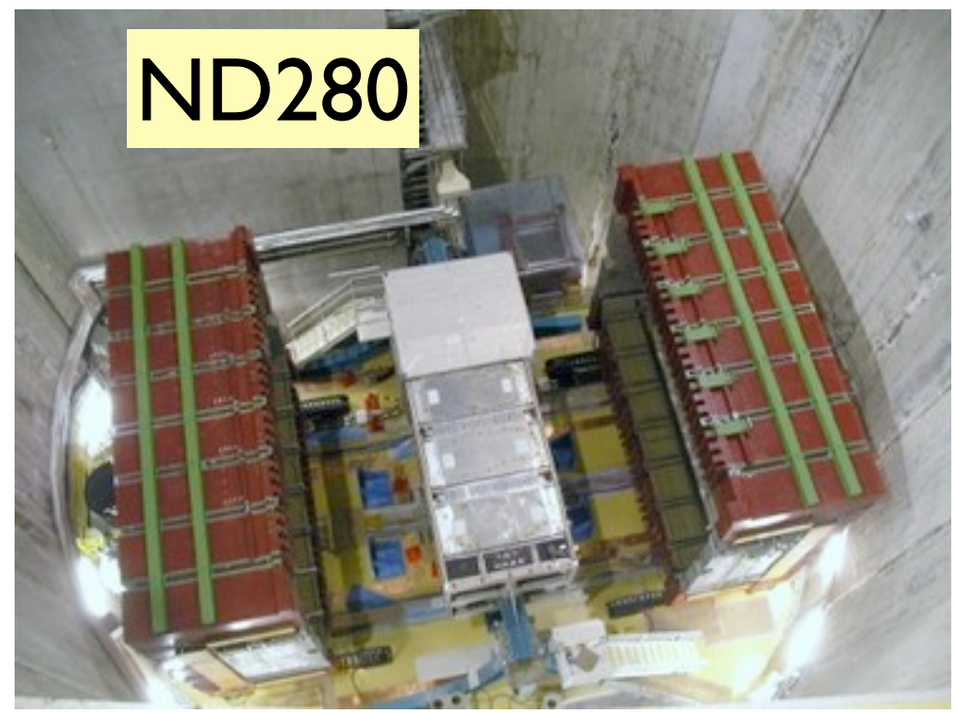
Statistics ↔ Intense beam & Gigantic detector

Systematics ↔ Off-axis beam, π production, Near Detectors

Long baseline experiment



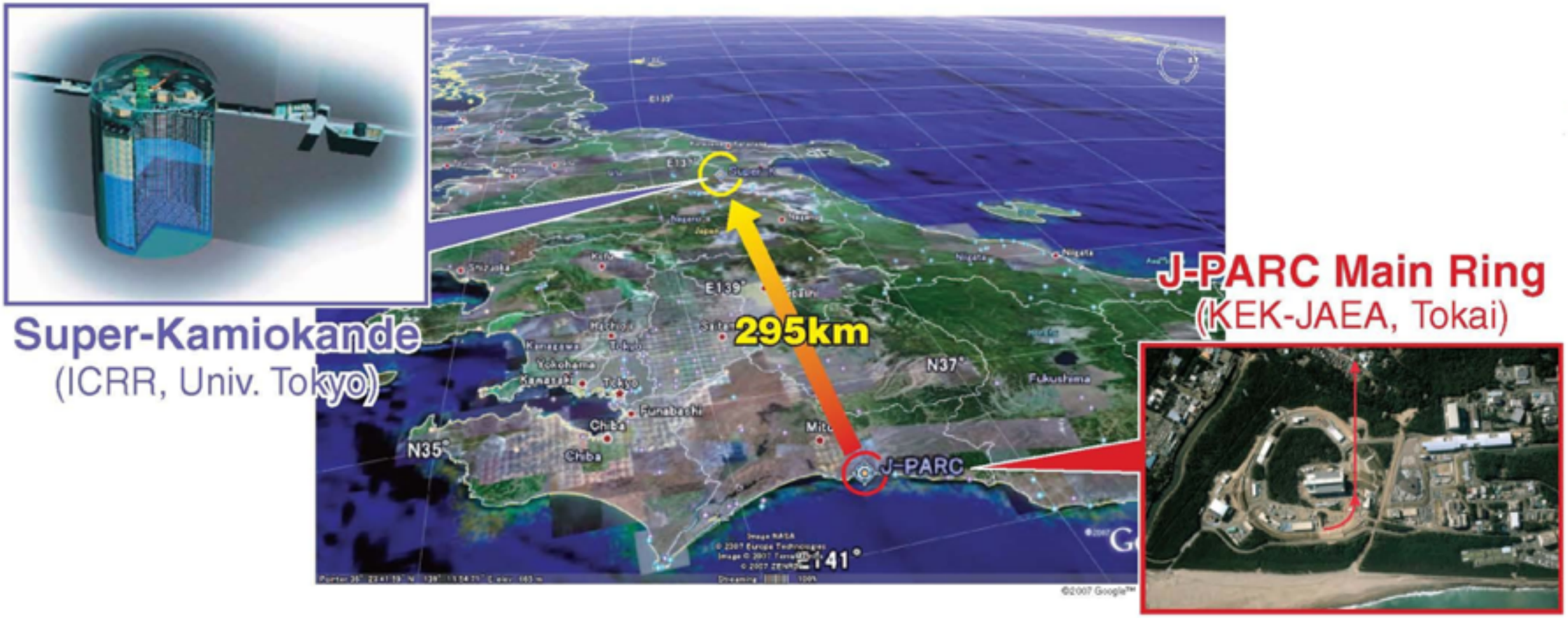




Statistics ↔ Intense beam & Gigantic detector

Systematics ↔ Off-axis beam, π production, Near Detectors

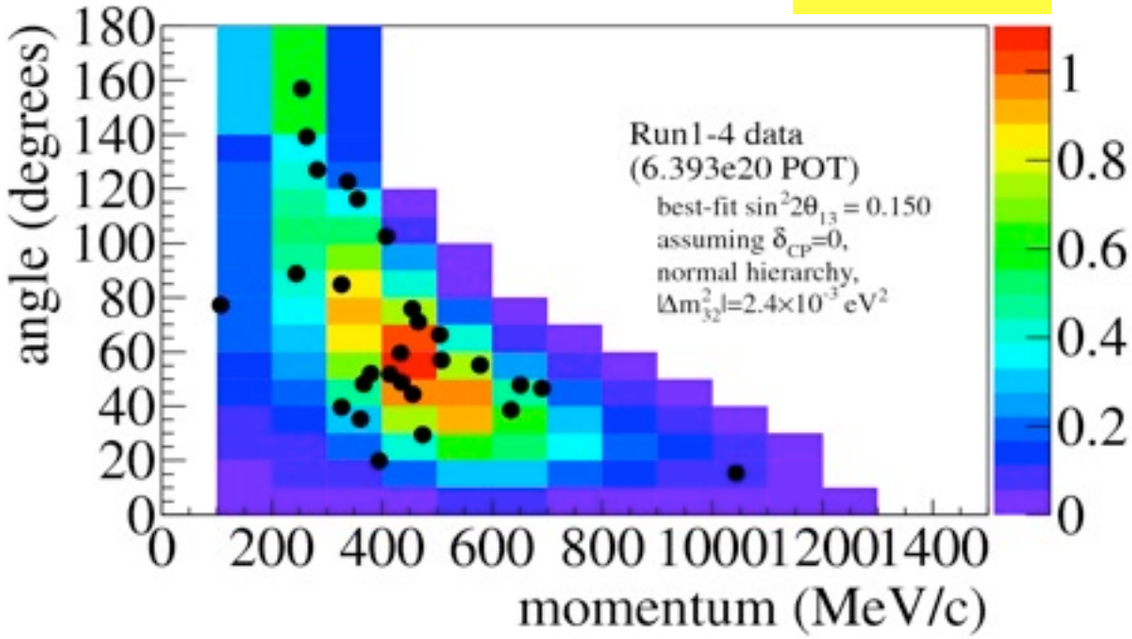
T2K

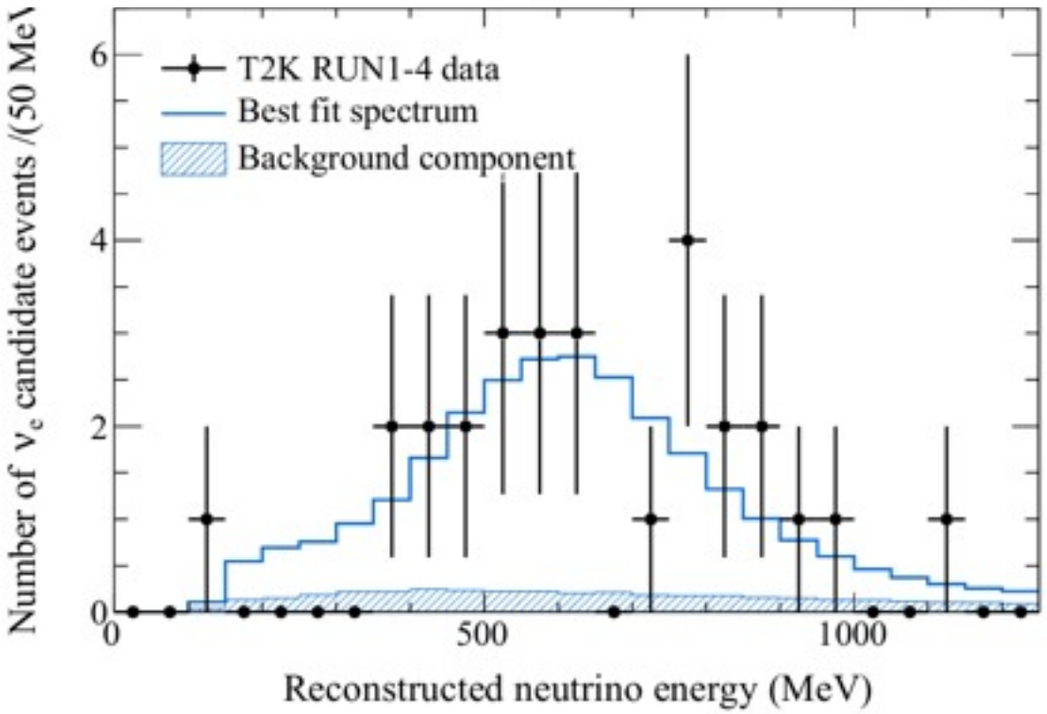


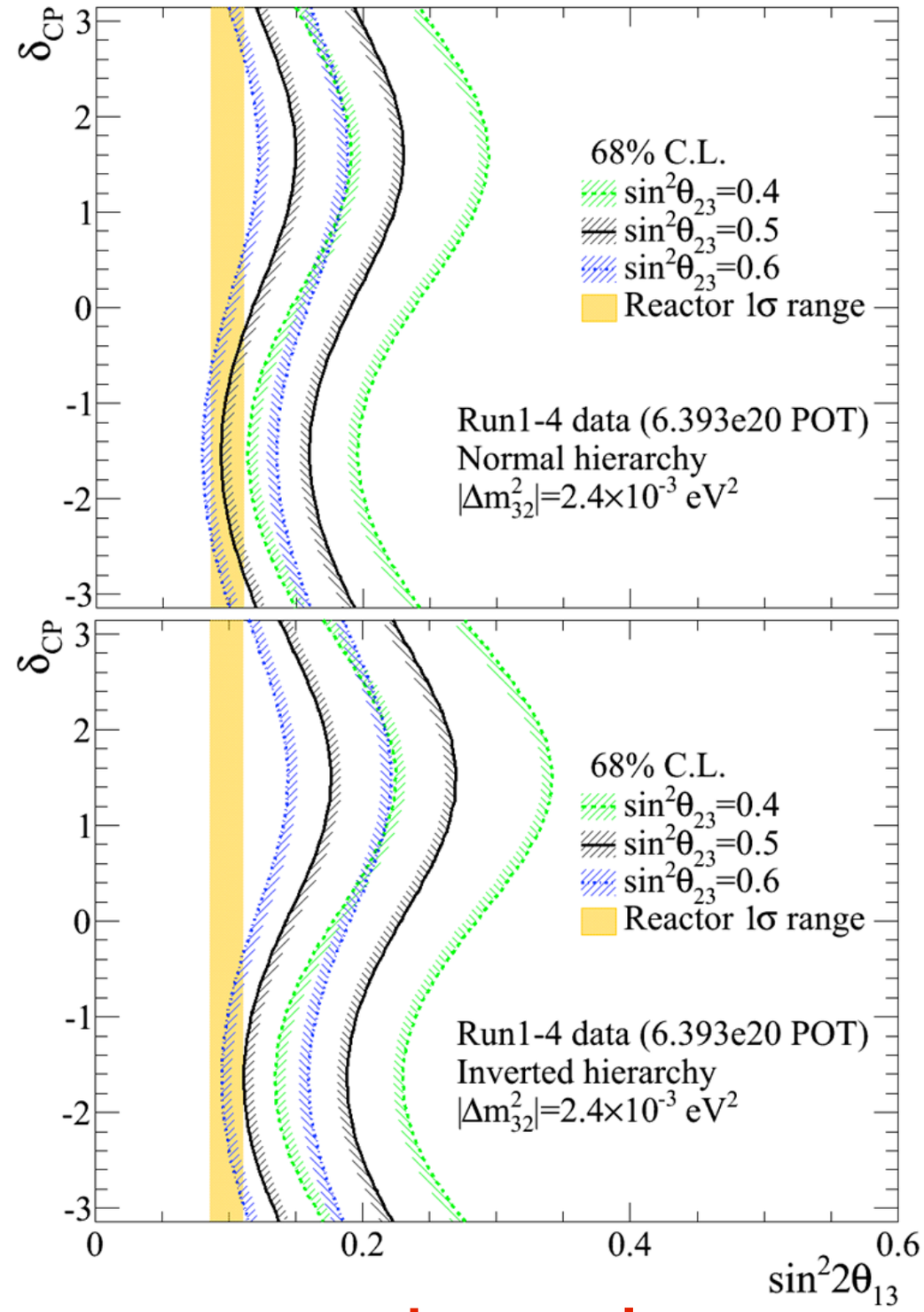
- 295km baseline, ~0.6GeV off-axis ν_μ beam
- Commissioning from April 2009, physics run from 2010
- One of main goals is $\nu_\mu \rightarrow \nu_e$ oscillation search
  - $P(\nu_\mu \rightarrow \nu_e) \sim \sin^2\theta_{23} \boxed{\sin^2 2\theta_{13}} \sin^2(\Delta m_{31} L/4E) + \ldots$
  - 2.5σ indication in June 2011, 3.1σ evidence in 2012

Definitive observation of $\nu_\mu \rightarrow \nu_e$

28 events (4.6±0.5BG) **7.5σ**

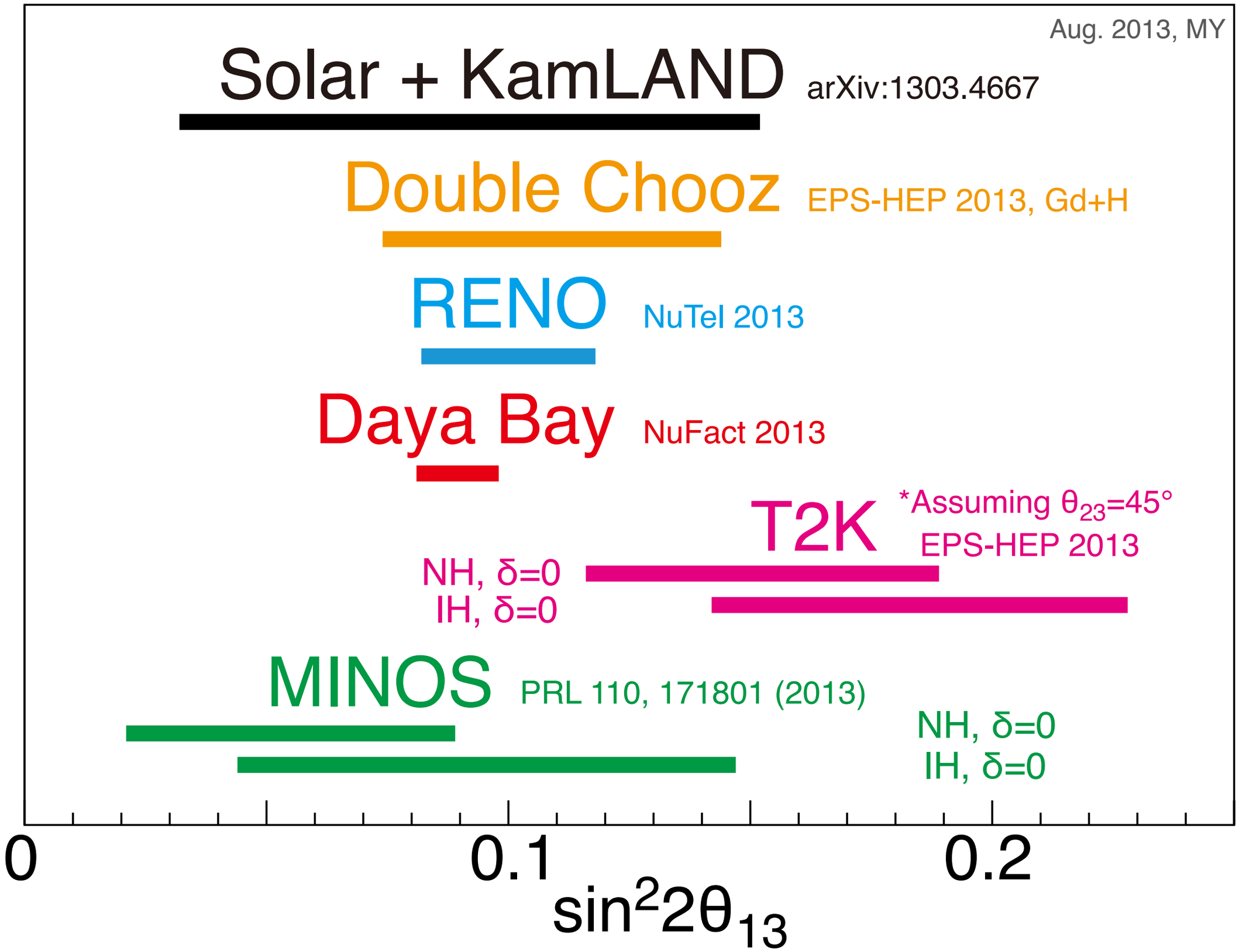






First >5σ observation of appearance channel

θ_{13} status



NOW, we have entered to "post-θ_{13}" era.

No more "Xσ" needed for θ_{13}. It's there.

Next goals

Yet unknown parameters (known unknown)

- Mass hierarchy (sign of Δm^2_{32})
- $(\theta_{23}-\pi/4) = 0?\ +?\ -?$ (octant)
- CP phase δ

Accessible via sub-leading terms in 3-flavor oscillation

Leading term (θ_{13})

CP violating (flips sign for $\bar{\nu}$)

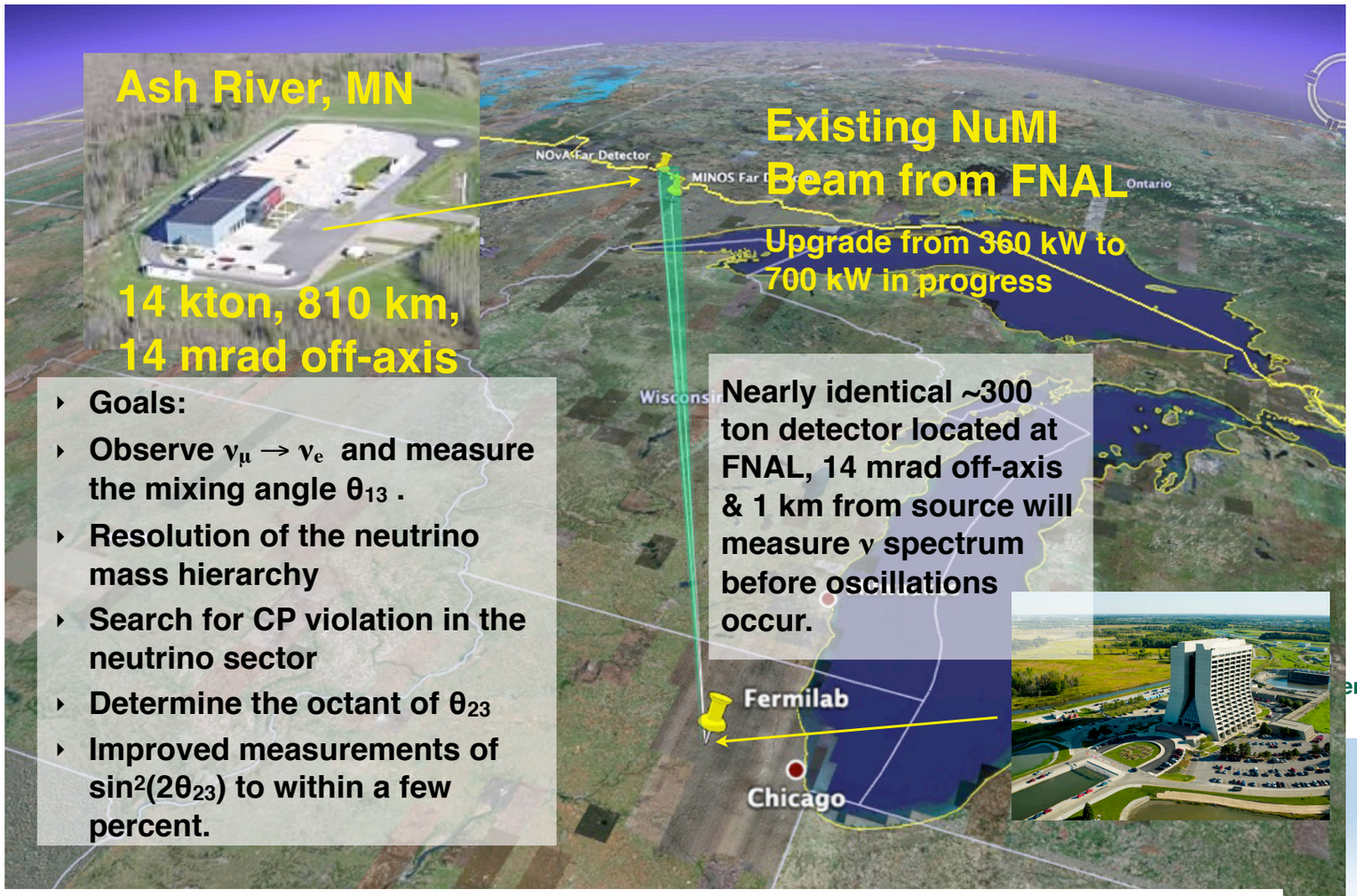
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = \; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
& + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& - 8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \\
& + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Solar

Matter effect

NOνA is starting up (&MINOS+)

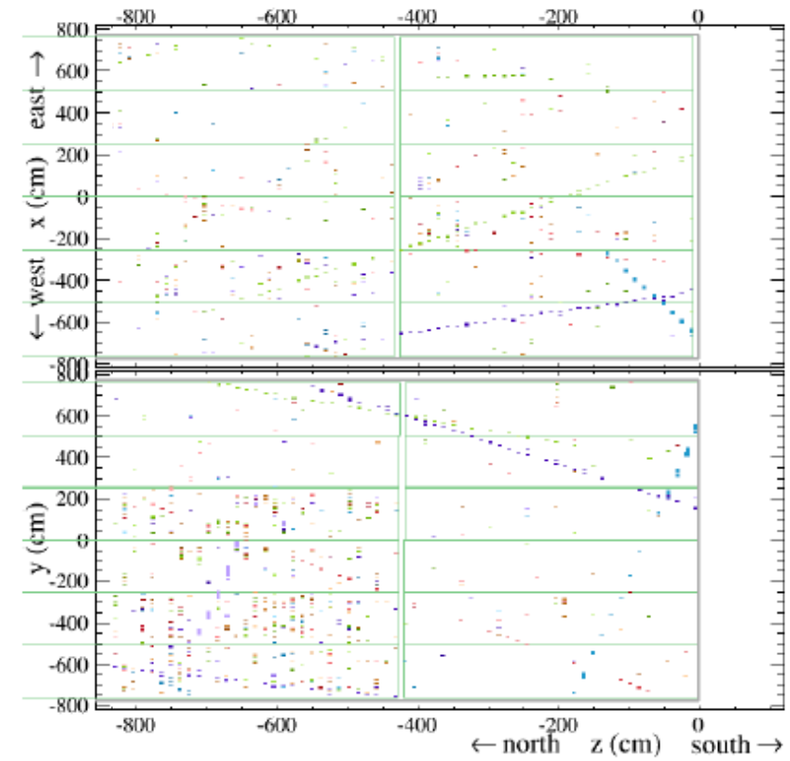
The NuMI Off-Axis ν_e Appearance (NOνA) Experiment



- Goals:
- Observe $\nu_\mu \rightarrow \nu_e$ and measure the mixing angle θ_{13} .
- Resolution of the neutrino mass hierarchy
- Search for CP violation in the neutrino sector
- Determine the octant of θ_{23}
- Improved measurements of $\sin^2(2\theta_{23})$ to within a few percent.

Nearly identical ~300 ton detector located at FNAL, 14 mrad off-axis & 1 km from source will measure ν spectrum before oscillations occur.

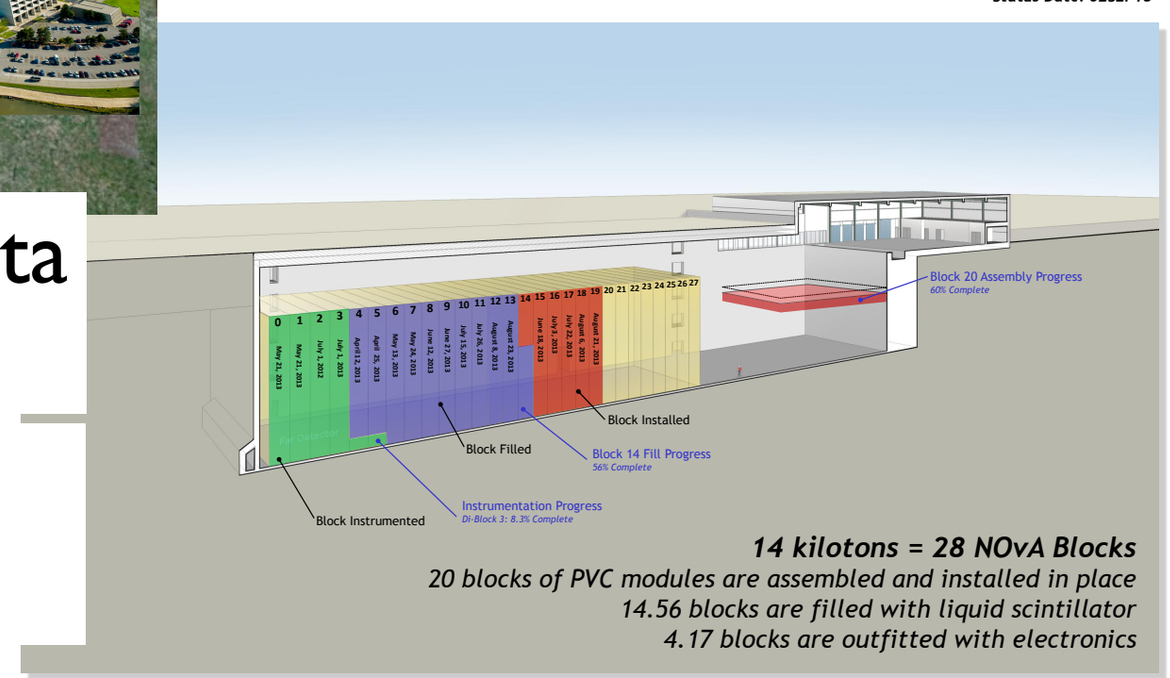
Cosmic data in NOνA far detector



ensity Frontier

NOvA Far Detector Assembly Progress

Status Date: 02SEP13



14 kilotons = 28 NOvA Blocks

20 blocks of PVC modules are assembled and installed in place

14.56 blocks are filled with liquid scintillator

4.17 blocks are outfitted with electronics

Partial far detector (2kton) taking data

Full detector in early 2014

NuMI beamline starting up after shutdown for acc. upgrade

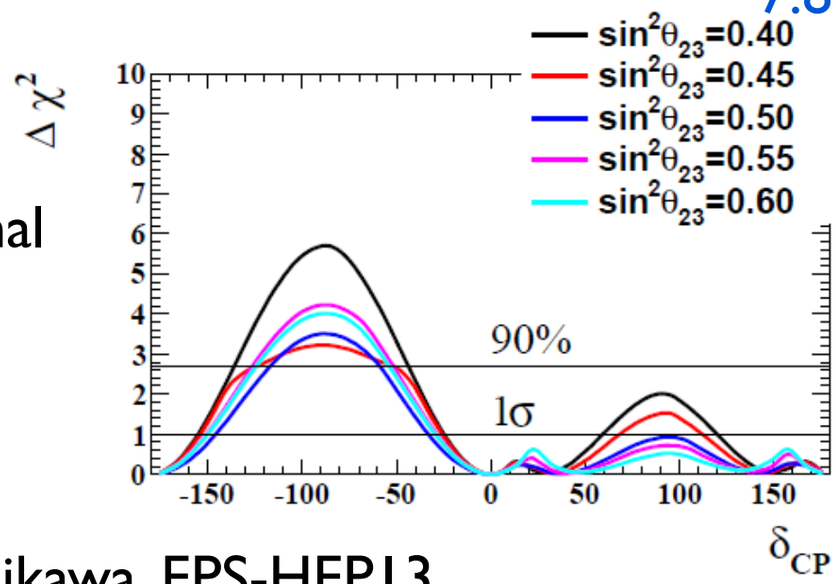
Near future: T2K and NOνA

T2K sensitivity to CP asymmetry

50%:50% ν-mode: ν̄-mode

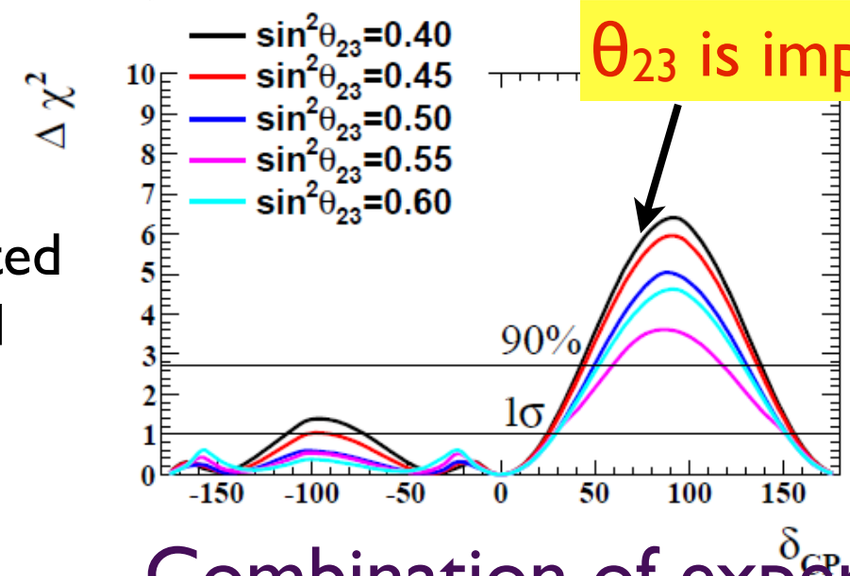
7.8×10^{21}POT total

Normal MH



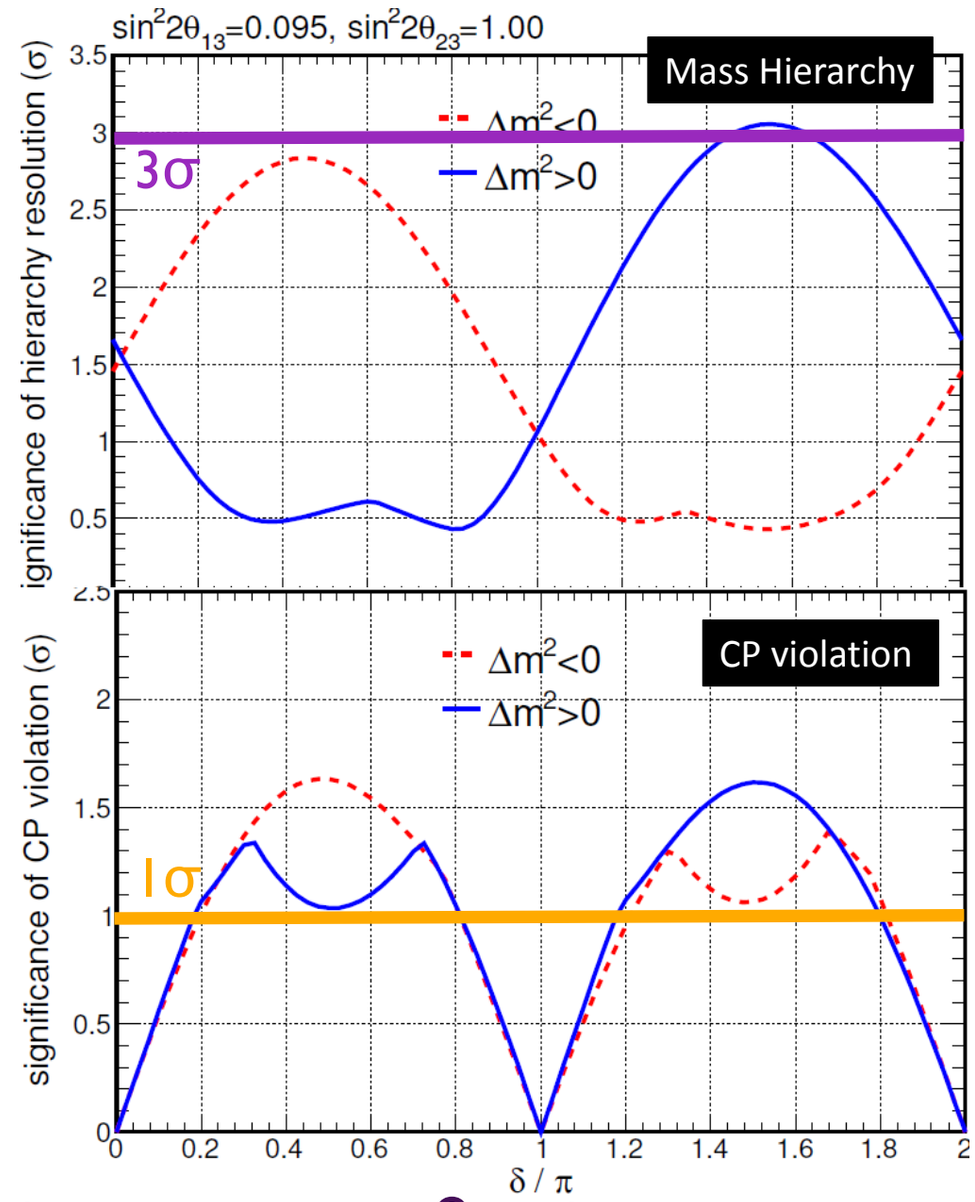
A.Ichikawa, EPS-HEP13

Inverted MH



θ_{23} is important!

NOνA sensitivity

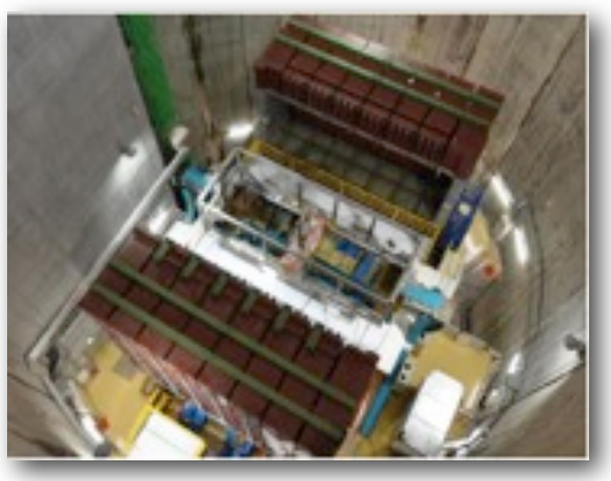


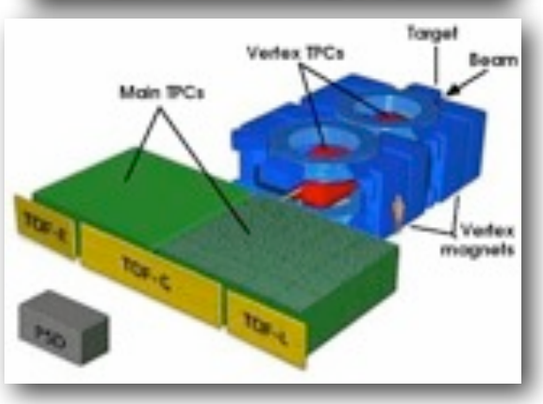
Combination of experiments (incl. precise θ_{13} from reactor) can enhance sensitivities

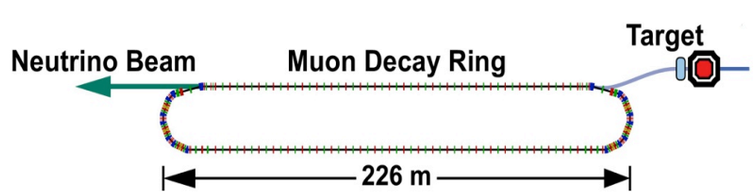
→ **Possibility to see hint of CP violation!**

Needs for precision

- Systematic uncertainties will be more important in precision measurements
  - Neutrino cross section, neutrino flux, ...
  - We learn a lot from ongoing program (real data) to make future projects better







Systematic uncertainties

Error source	$\sin^2 2\theta_{13}=0.0$	$\sin^2 2\theta_{13}=0.1$
Beam flux + ν int.	4.9 %	3.0 %
w/ND constraint		
ν int. (from other exp.)	6.7 %	7.5 %
Far detector (+FSI+SI+PN)	7.3 %	3.5 %
Total	11.1 %	8.8 %
Total (2012)	(13.0 %)	(9.9 %)

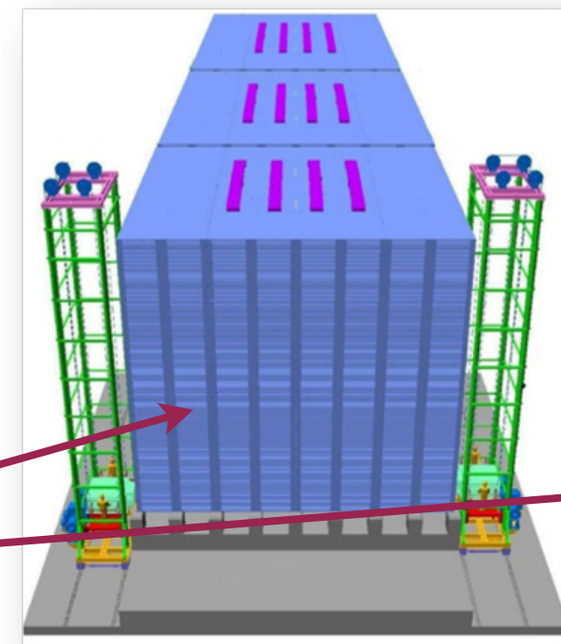
T2K systematics in 2013

Further improvement ongoing!

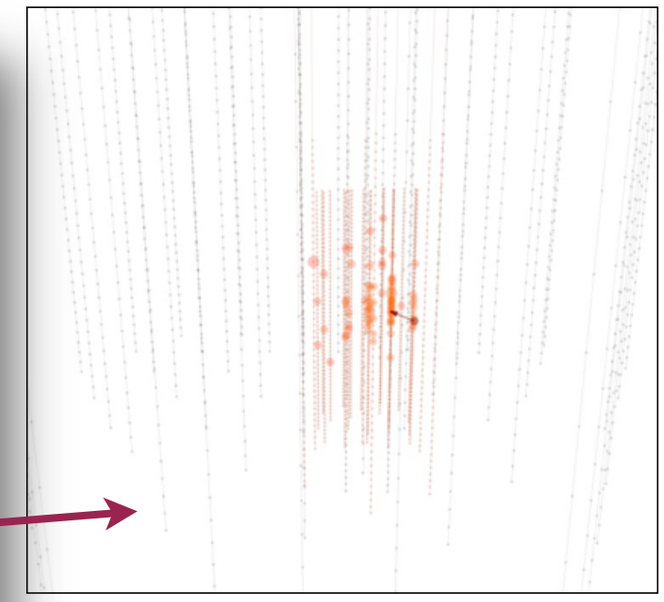
Future projects (I)

- Several approaches proposed for mass hierarchy determination
  - Atmospheric
  - Reactor
  - Supernovae
  - Double β decays (see later)

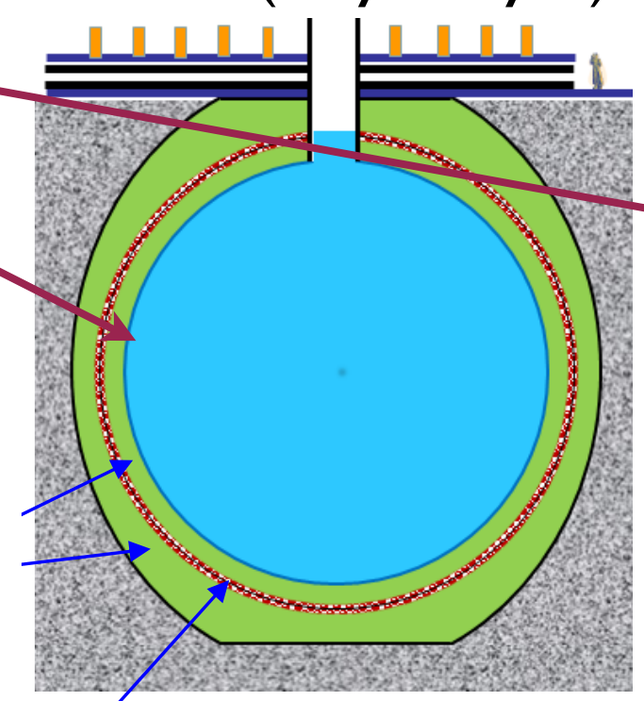
ICAL/INO



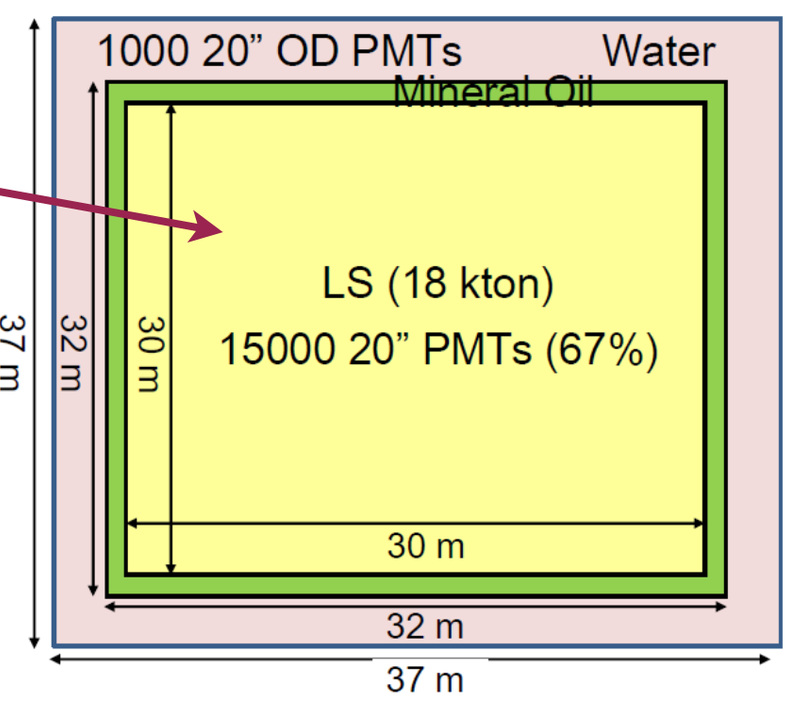
PINGU



JUNO (Daya Bay 2)

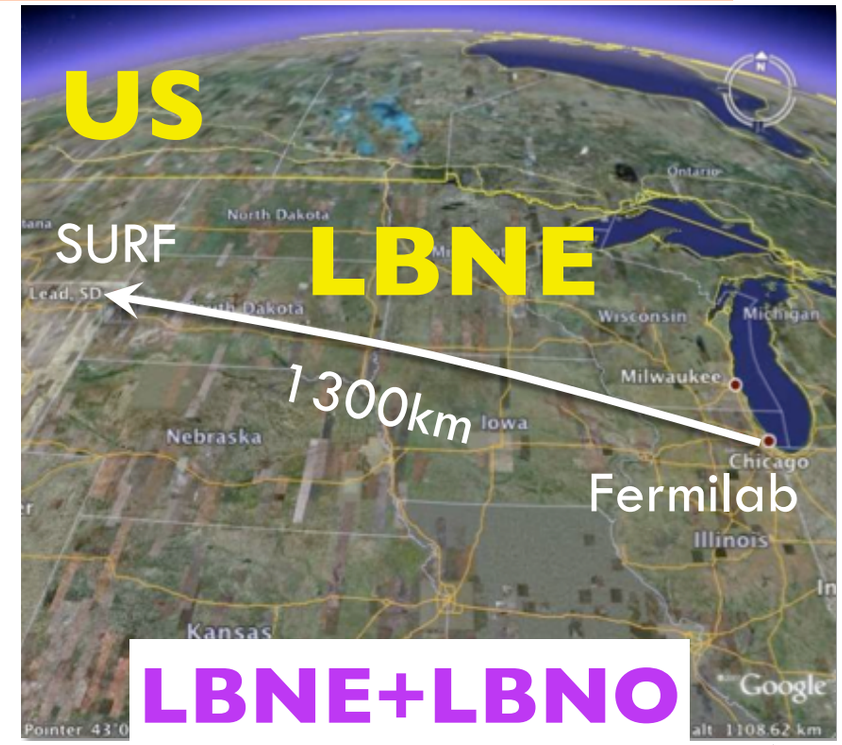


RENO-50

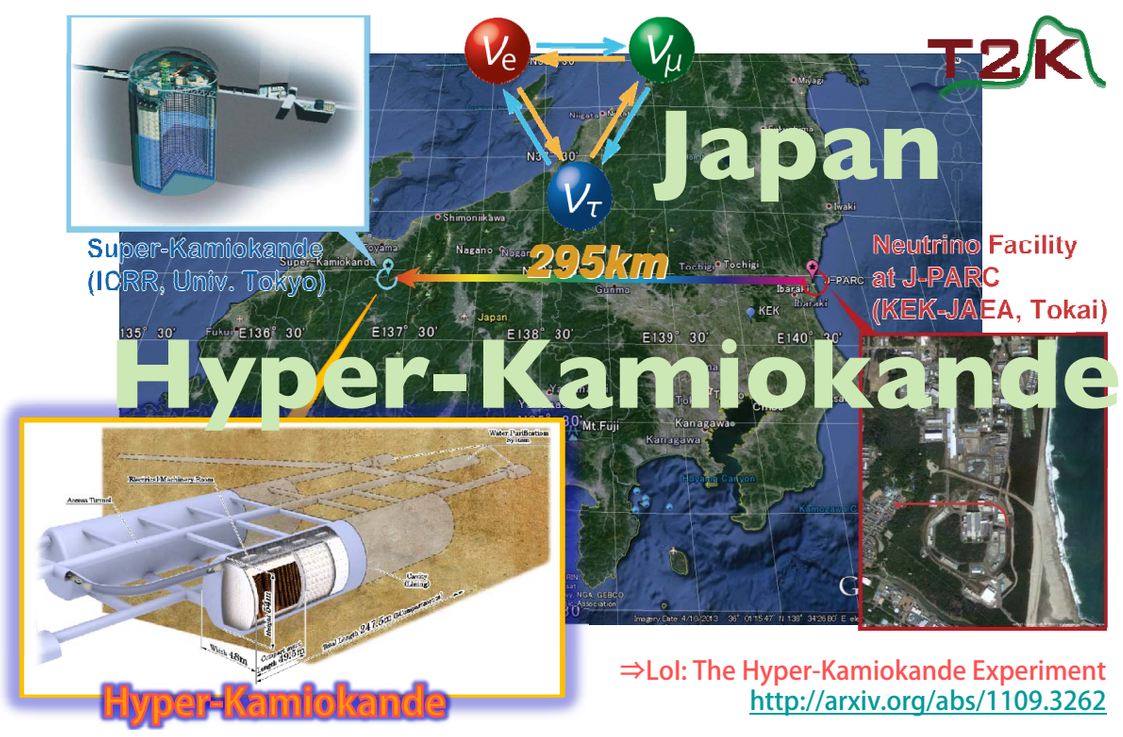


Future projects (2)

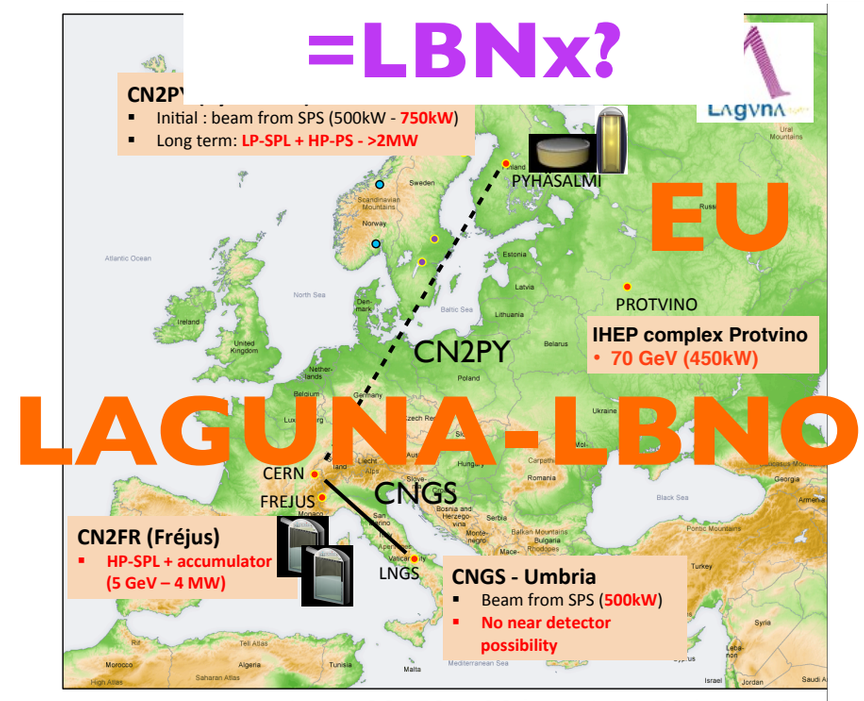
- Future long baseline experiments are major part of world wide HEP program
- Huge underground far detector enables additional, rich physics program
  - Proton decay, astrophysical ν, ..
- Intense R&D for new detectors
  - Two complementary technologies
    - Water Cherenkov & LAr TPC



LBNE+LBNO =LBNx?



⇒LoI: The Hyper-Kamiokande Experiment
http://arxiv.org/abs/1109.3262



- **Detector options:** 20, 50, 100 kton LAr; 50 kton LSc and 540 kton WCD

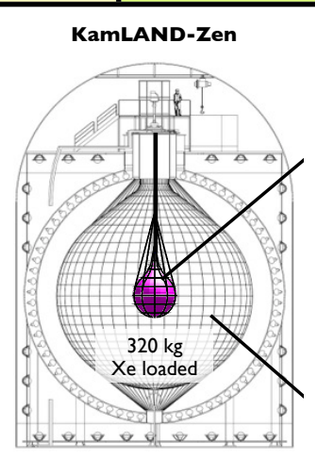
Outlook: ν mixing&CP

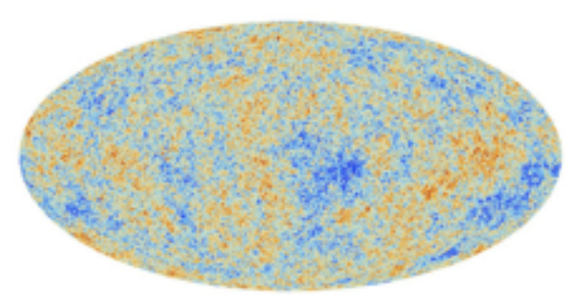
- We have clear goals and exciting programs for future
  - Yet be open to new, unexpected discovery!
- There is still plenty of room for "unexpected" in neutrino
  - It took decades to identify the source of CP violation in quark sector after CPV discovery in neutral kaon.
  - Almost no information on CPV in lepton sector, so far!
  - History tells us "common belief" can be *completely wrong* (almost always with neutrino!?)
- It is important (essential) to have more than one experiments/techniques for definite discovery
- More idea may emerge in future, as we go on

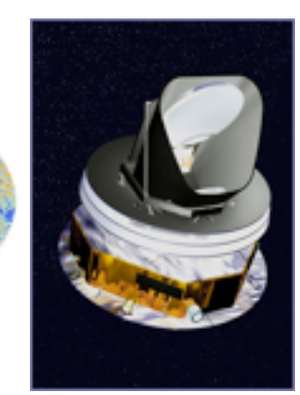
Neutrino mass

Approaches to absolute ν mass

	β decay end point	ν-less double β decay	Cosmology
Observable	$(\sum m_{\nu i}\lvert U_{ei}\rvert^2)^{1/2}$	$\lvert\sum m_{\nu i} U_{ei}^2\rvert$	$\sum m_{\nu i}$
Present limit	~2 eV	~0.2eV	<1eV
Future sensitivity	0.2 eV	≲0.02 eV	≲0.1 eV
Model dependence	No☺	Yes☹	Yes☹

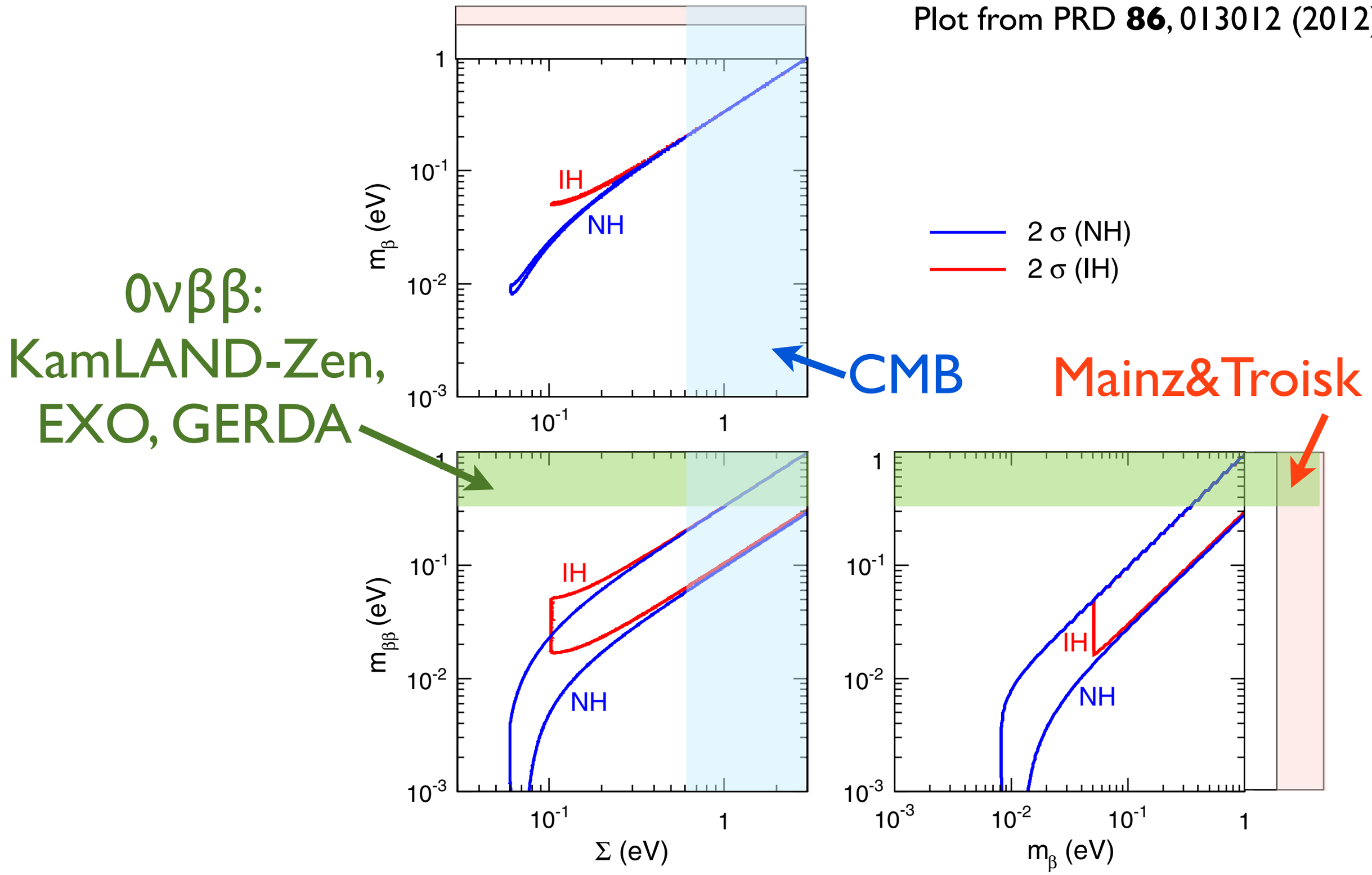






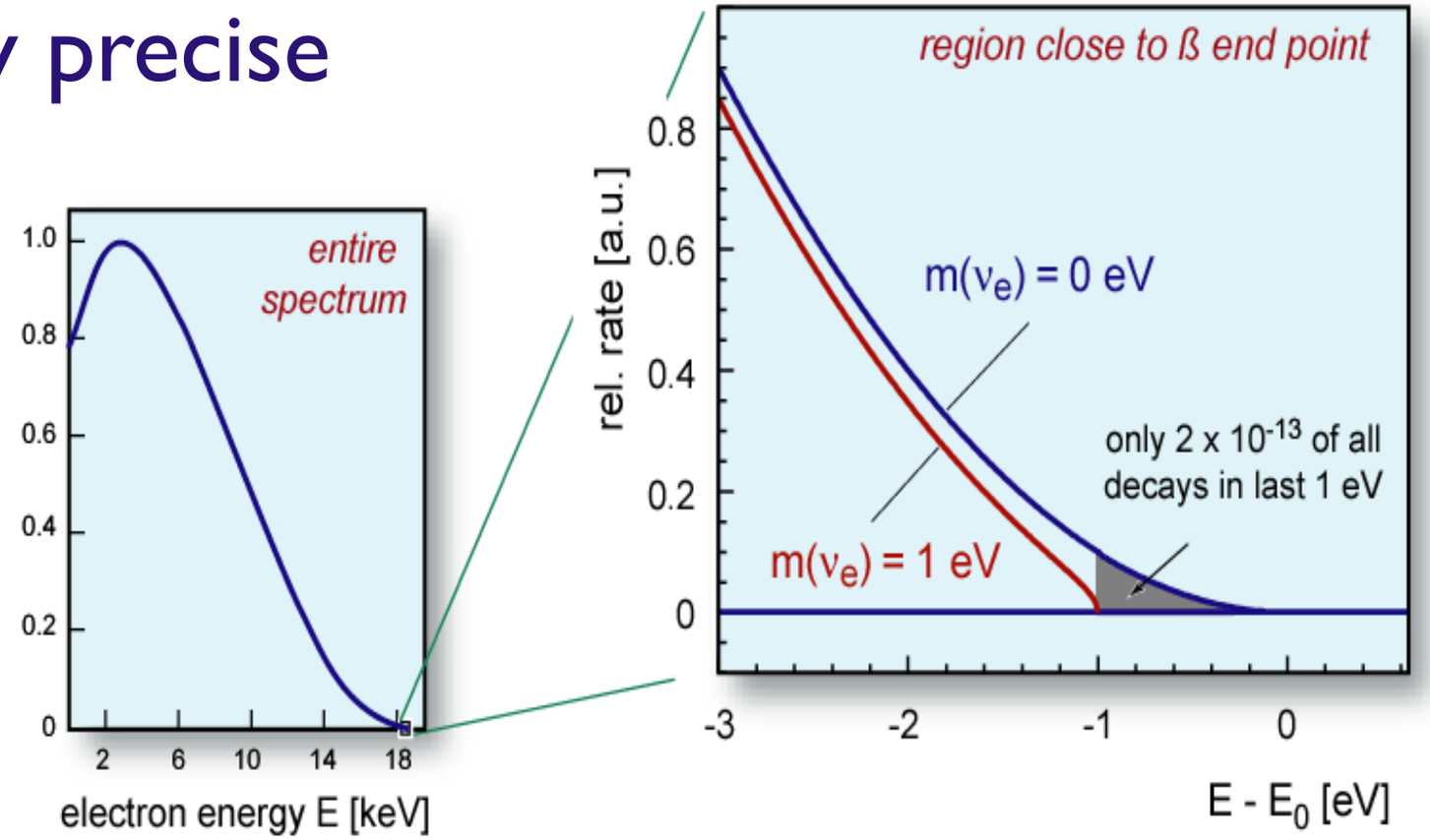
Neutrino mass limit

Plot from PRD **86**, 013012 (2012)



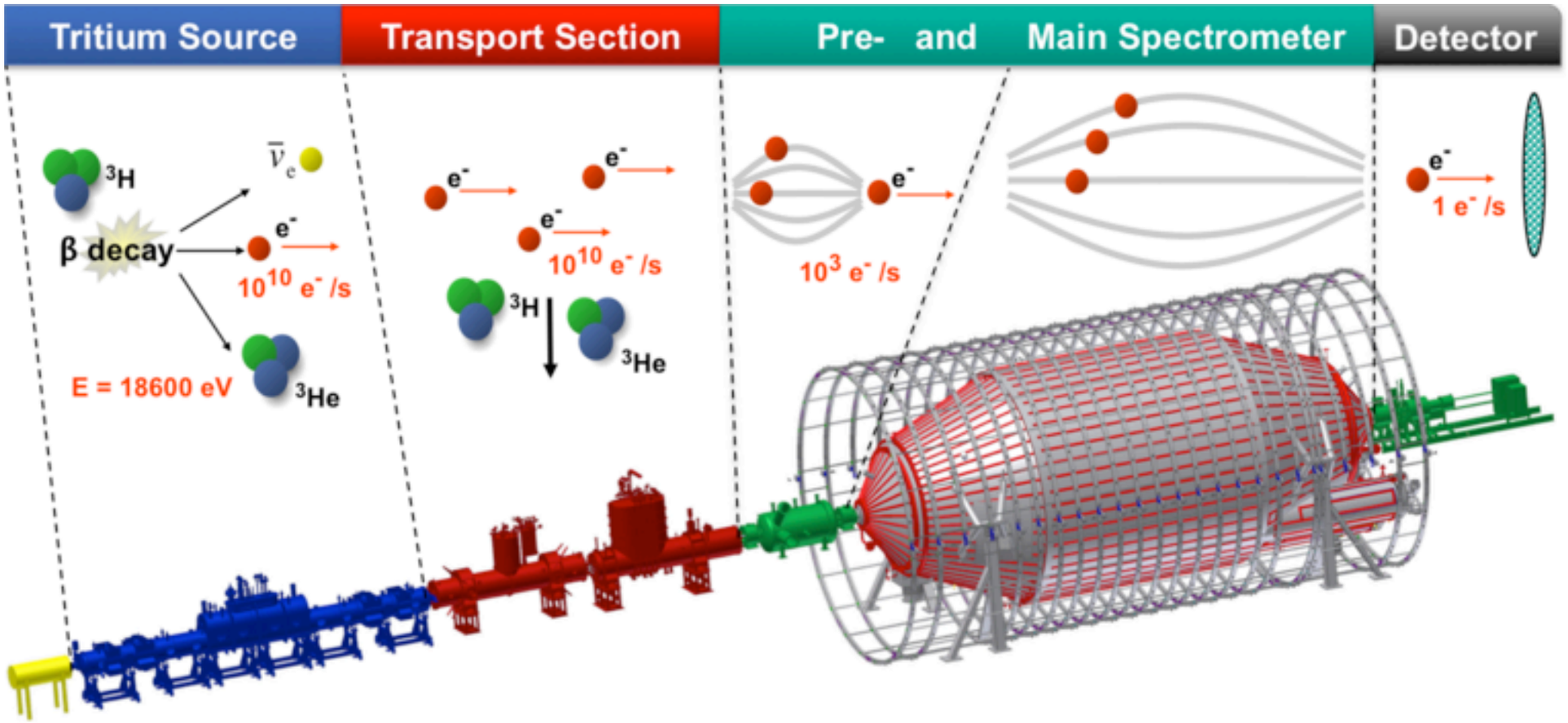
Direct ν mass measurement

- Weak decay kinematics
  - Single β decay (^{3}H, ^{187}Re,)
  - Electron capture (^{163}Ho,)
- Assume only energy/momentum conservation
- Large statistics + very precise energy measurement required to go beyond current limit



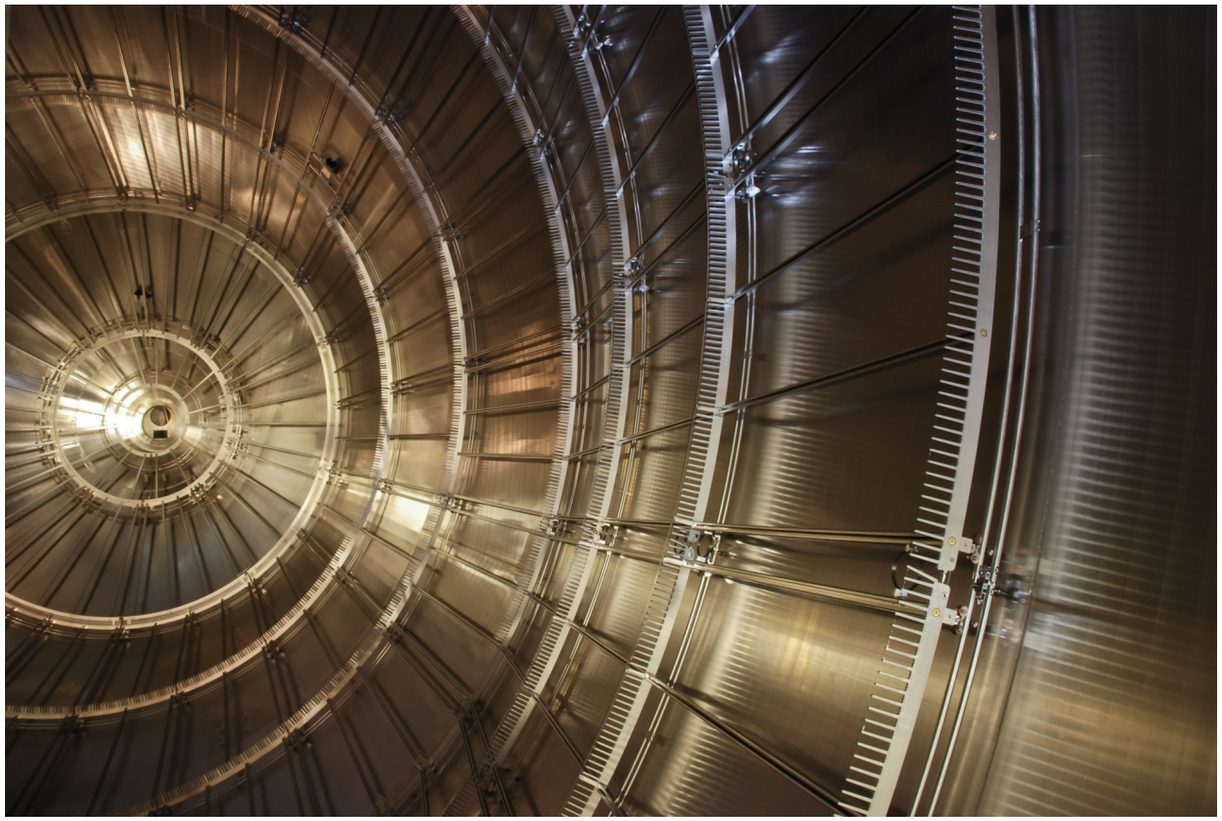
KATRIN

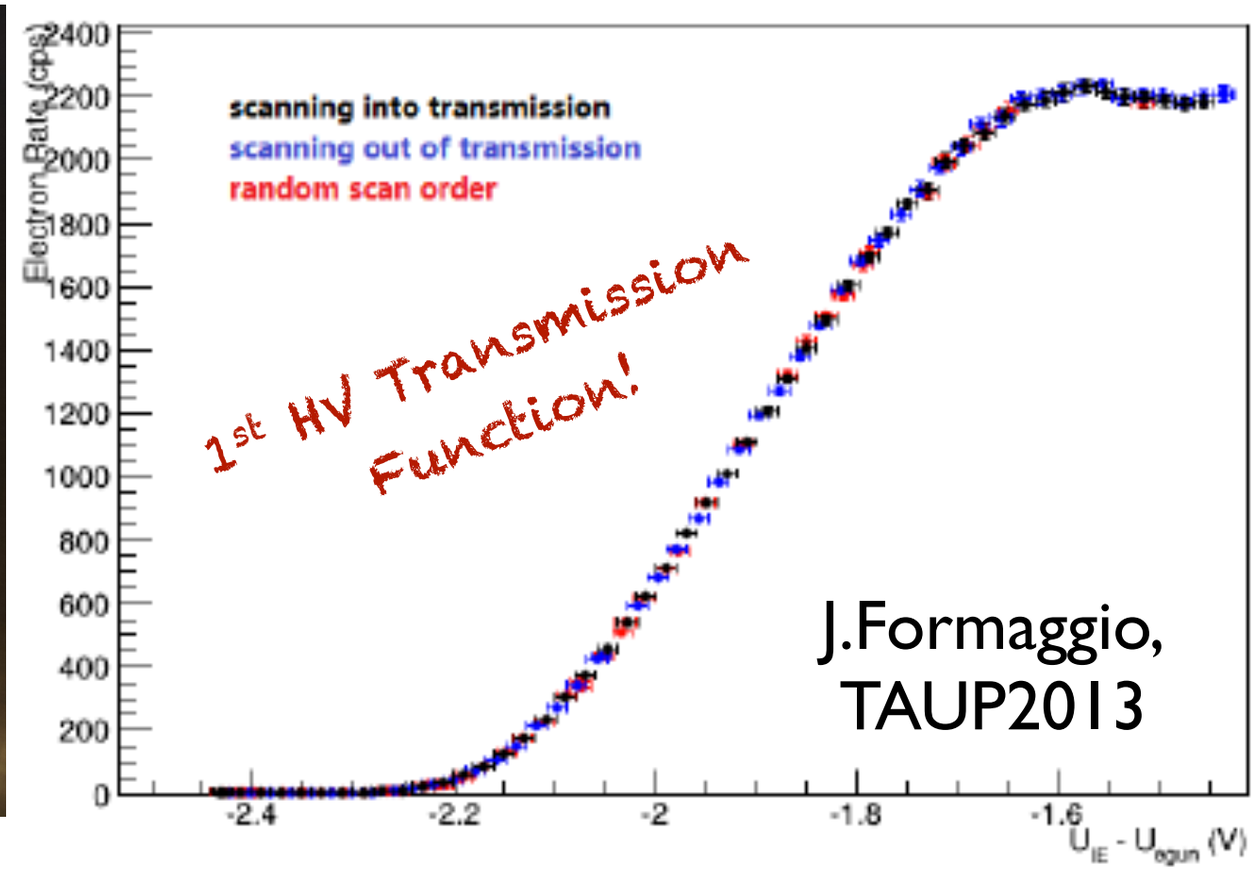
KArlsruhe TRItium Neutrino experiment



- Large electrostatic spectrometer with gaseous ^{3}H source (Q=18.6keV)
- Expected sensitivity
  - m_ν < 0.2 eV @ 90%CL, 0.3 eV @ 3σ

KATRIN status





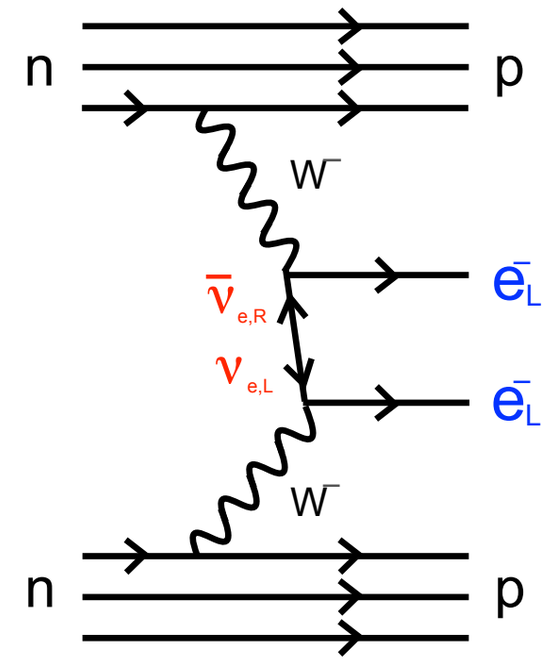
- Spectrometer commissioning started this year
  - BG suppression techniques to be tested
- Tritium source and transport being built
- Start data taking 2014/2015

Double β decays

- 2νββ: allowed in Standard Model

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

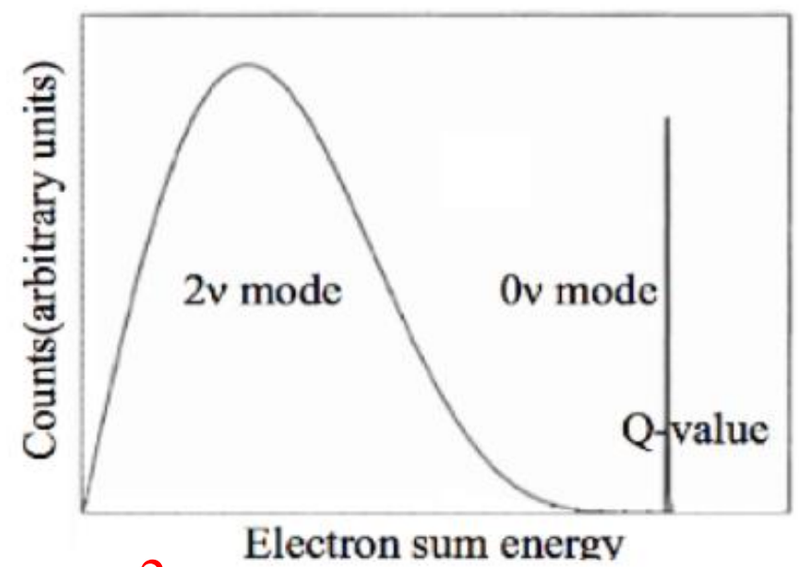
  - Second order weak interaction



- 0νββ: clear sign of BSM, if observed

$$(Z,A) \rightarrow (Z+2,A)+2e^{-}$$

  - Violates lepton number ΔL=2
  - Evidence for Majorana nature of neutrino



$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q_{\beta\beta},Z)\left|M^{0\nu}\right|^2 \left\langle m_{\beta\beta}\right\rangle^2$$

Phase space factor

Nuclear Matrix Element

Effective neutrino mass

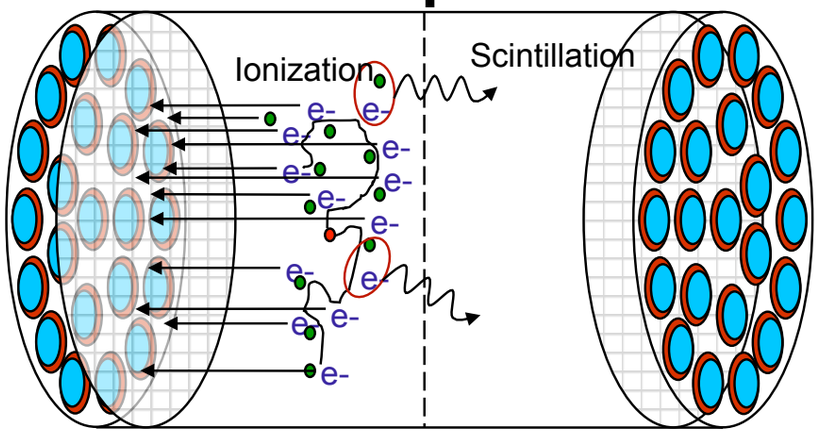
0νββ limits

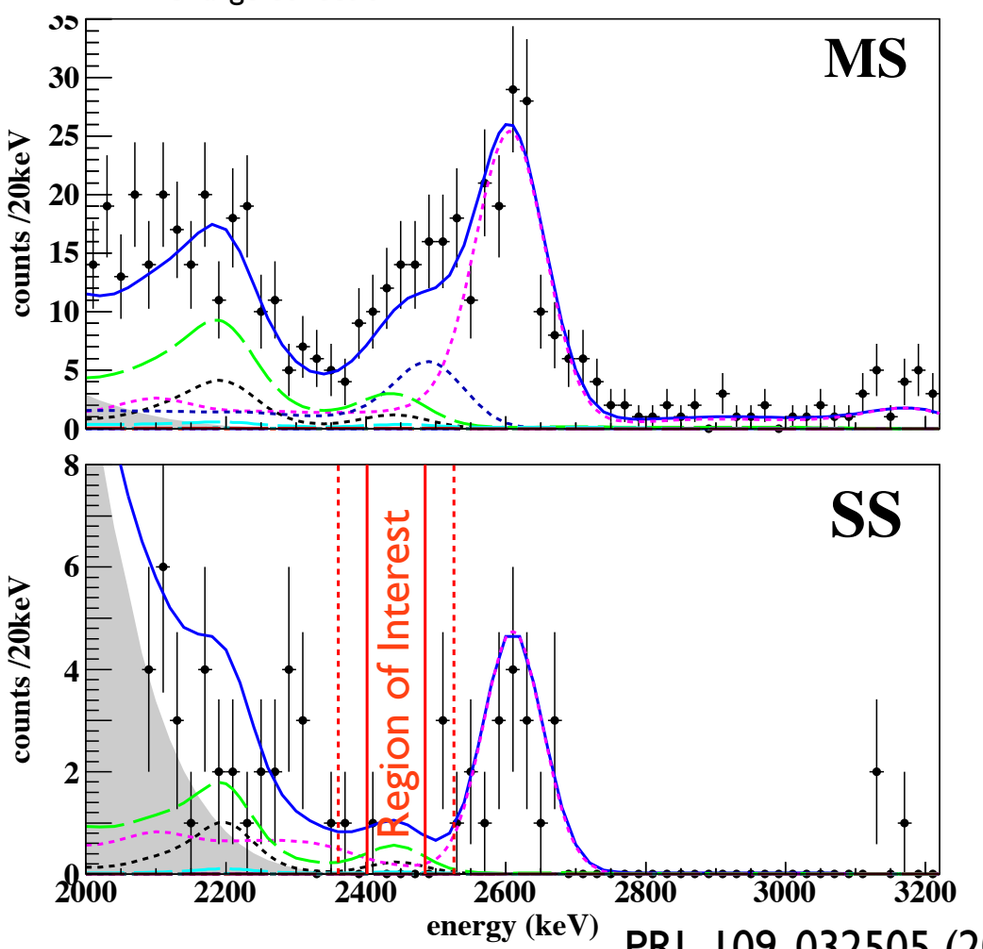
Nucleus	Experiment	Exposure (kg · year)	$T^{0\nu}_{1/2}$ limit (yr) 90%CL	$\langle m_{\beta\beta} \rangle$ (eV)
^{48}Ca	ELEGANT VI	0.025	$>5.8\times10^{22}$	<3.5-22
^{76}Ge	Heidelberg-Moscow	35.5	$>1.9\times10^{25}$	<0.2-0.32*
	GERDA	21.6	$>3.0\times10^{25}$	<0.2-0.4
^{82}Se	NEMO-3	4.2	$>3.2\times10^{23}$	<0.8-1.4
^{96}Zr	NEMO-3	0.031	$>9.2\times10^{21}$	<9.3-13.7
^{100}Mo	NEMO-3	31.2	$>1.0\times10^{24}$	<0.4-0.7
^{116}Cd	Solotvina	0.14	$>1.7\times10^{23}$	<1.2-2.2
^{128}Te	Geochemical	–	$>7.7\times10^{24}$	<0.7-1.2
^{130}Te	CUORICINO	19.75	$>2.8\times10^{24}$	<0.44-0.81
^{136}Xe	KamLAND-Zen	89.5	$>1.9\times10^{25}$	<0.16-0.33
	EXO-200	32.5	$>1.6\times10^{25}$	<0.16-0.33
^{150}Nd	NEMO-3	0.093	$>1.8\times10^{22}$	<4.0-6.3

*part of the group claims a finite value

Recent progress: Xe

EXO-200: Liquid Xe TPC

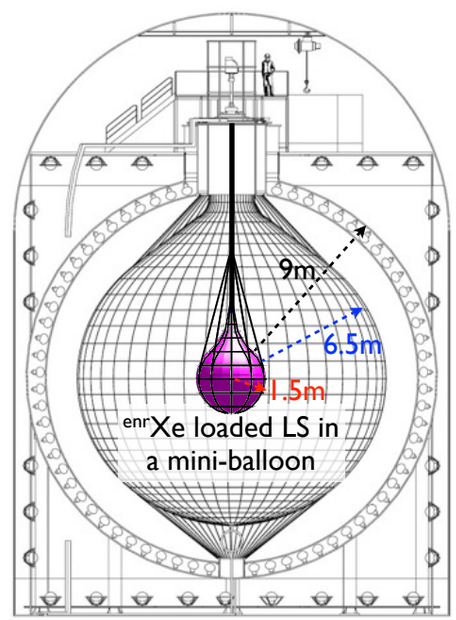


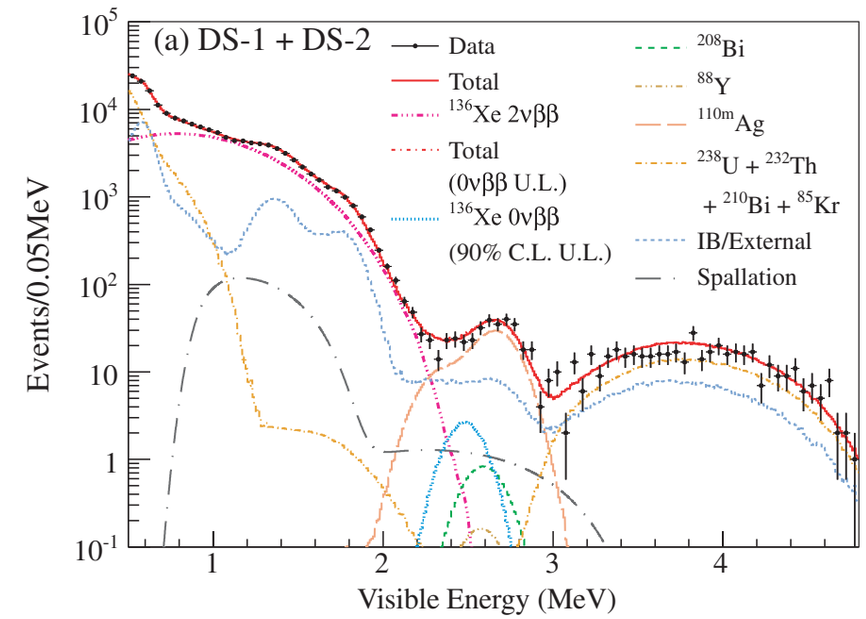


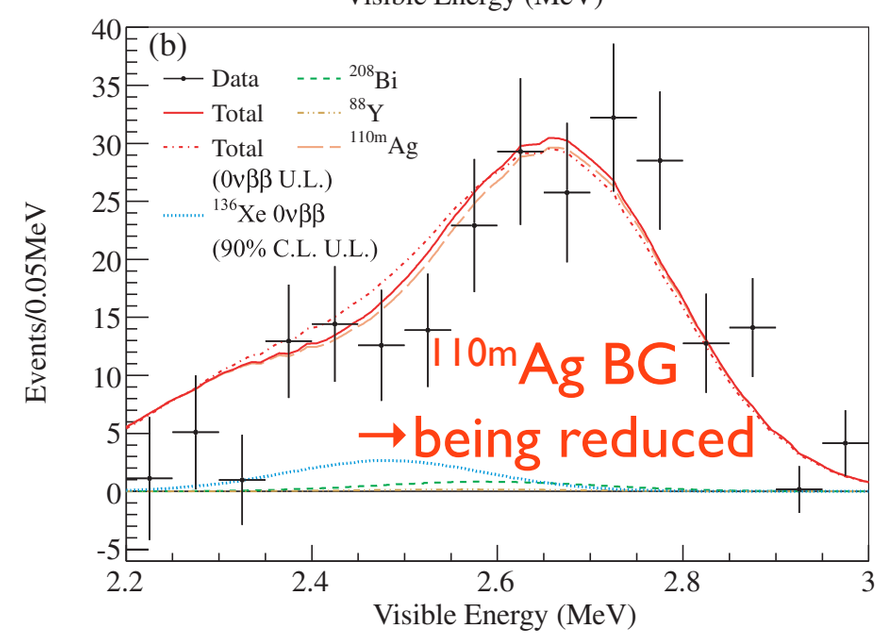
PRL 109, 032505 (2012)

KamLAND-Zen

^{136}Xe loaded LS in a mini-baloon inside ultra-low BG KamLAND



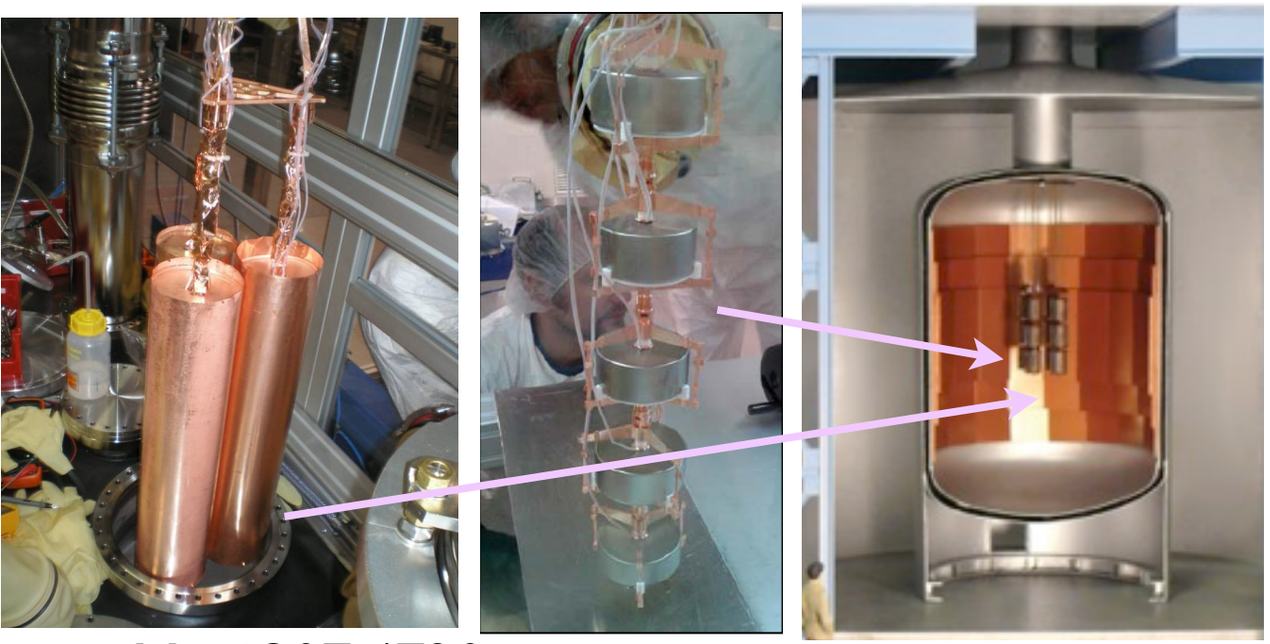




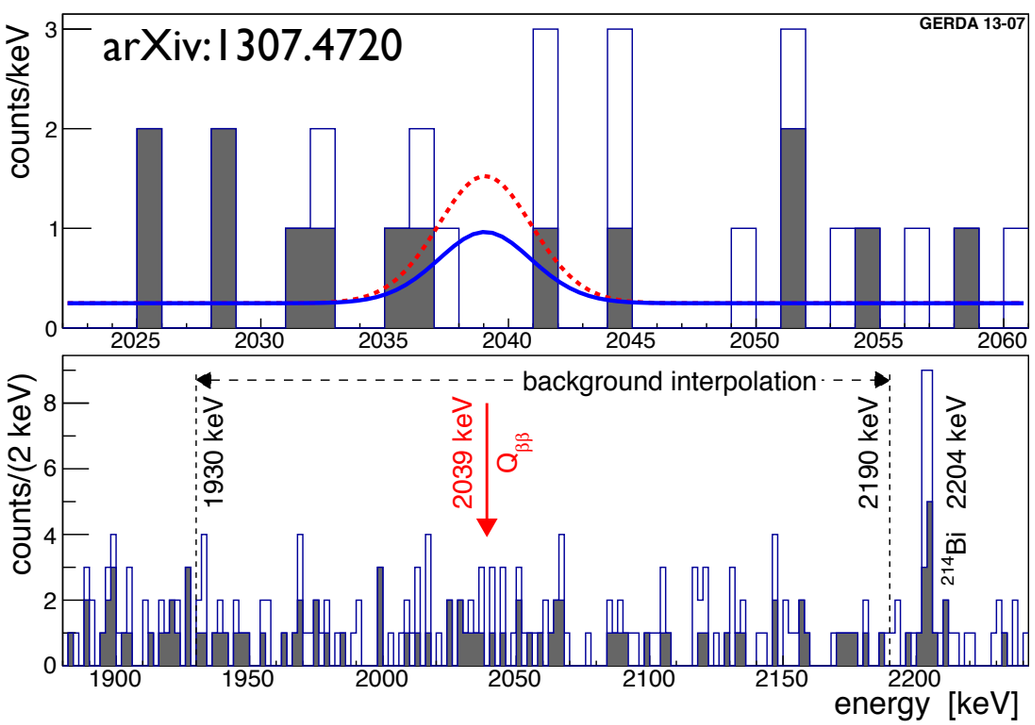
PRL 100, 062502 (2013)

Recent progress: Ge

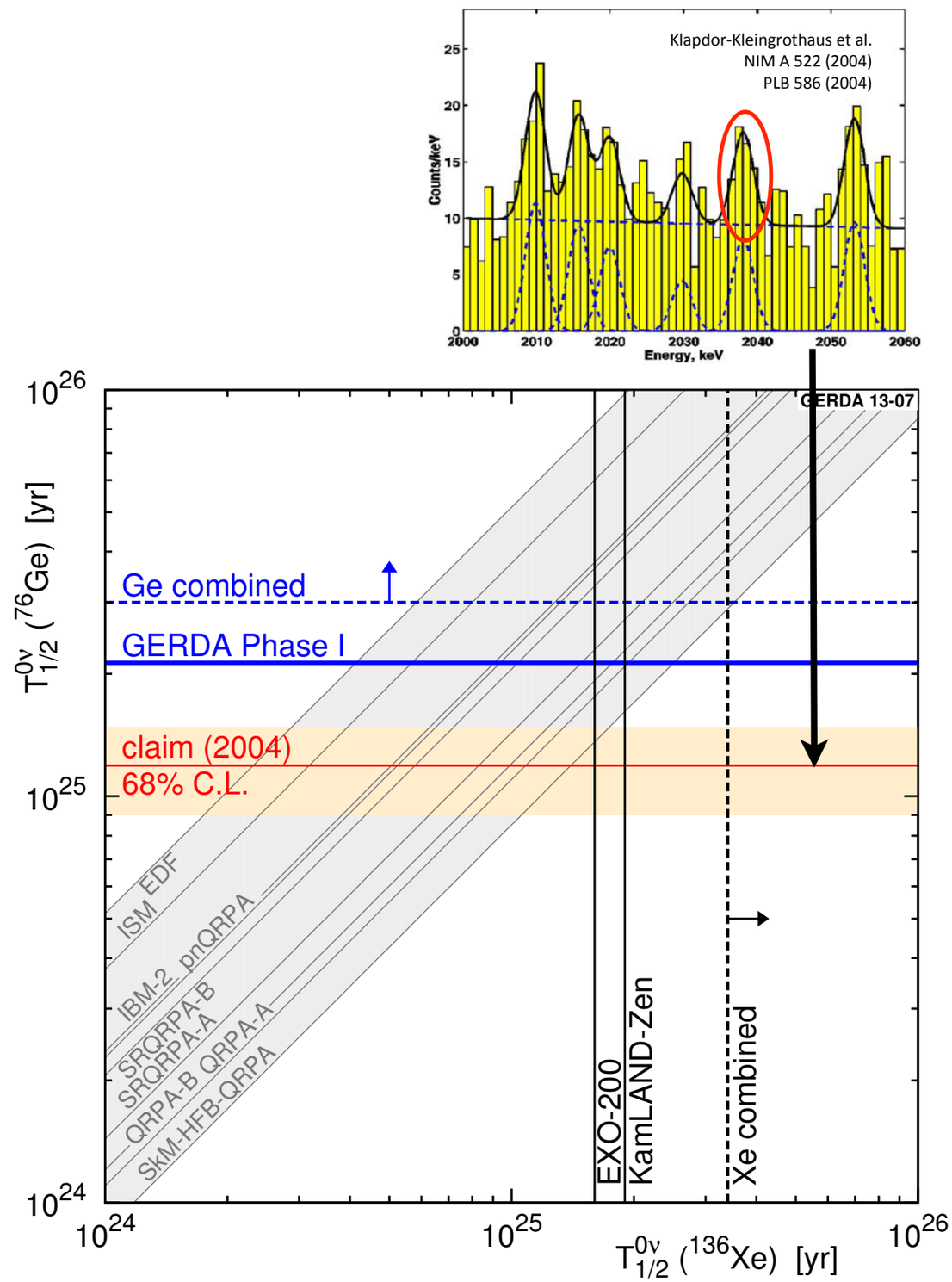
Result from GERDA phase I



arXiv:1307.4720



KK claim is strongly disfavored

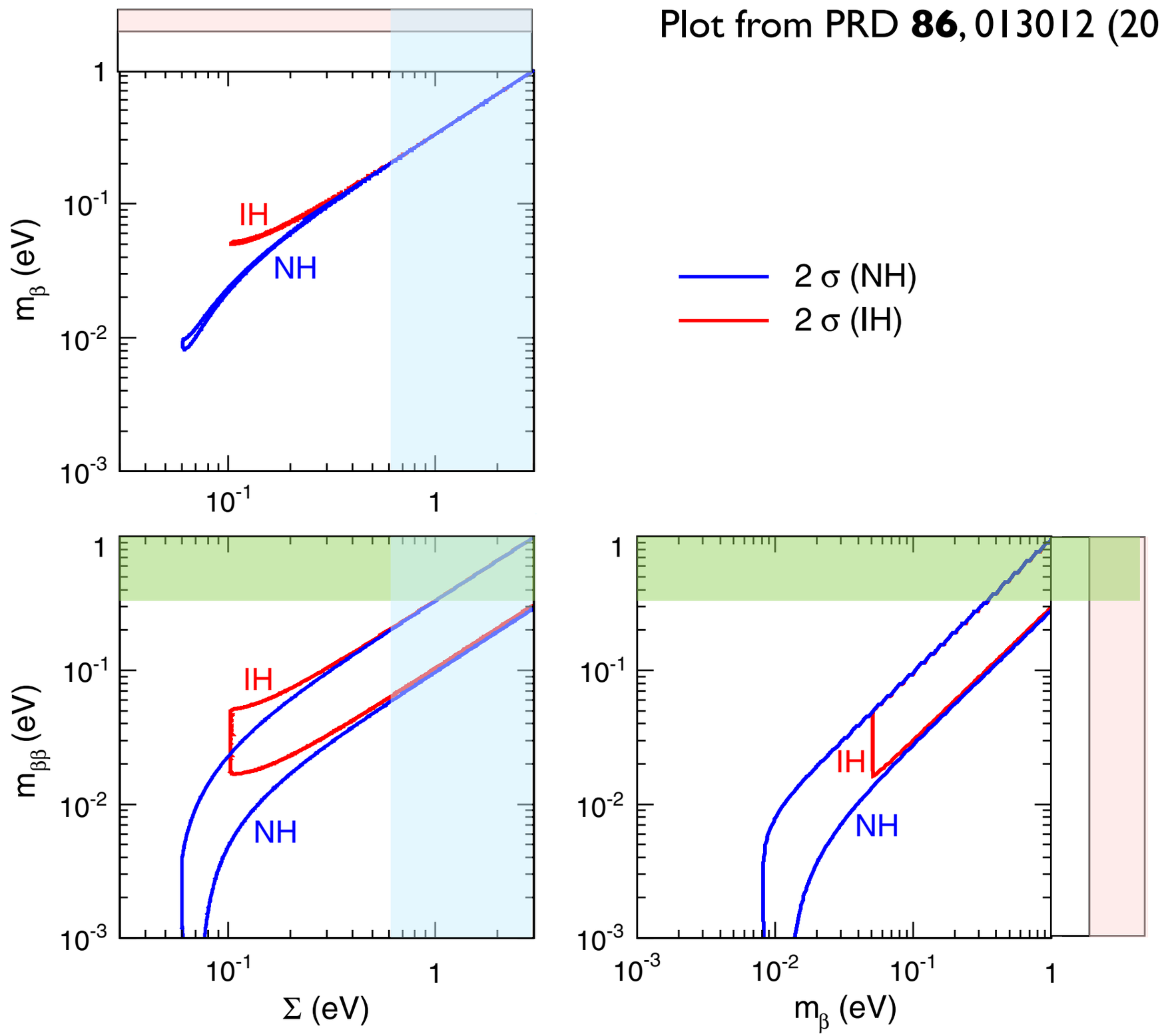


DBD experiments summary

Experiment	Isotope	Technique	Mass ββ(0v) isotope	Status
CANDLES	48Ca	305 kg of CaF2 crystals - liq. scint	0.3 kg	Construction
CARVEL	48Ca	48CaWO4 crystal scint.	~ tonne	R&D
GERDA I	76Ge	Ge diodes in LAr	18 kg	Operating
GERDA II	76Ge	Point contact Ge in LAr	18+21 kg	Construction
Majorana D	76Ge	Point contact Ge	30 kg	Construction
1TGe (GERDA +MJ)	76Ge	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	100Mo/ 82Se	Foils with tracking	6.9/0.9 kg	Complete
SuperNEMO D	82Se	Foils with tracking	7 kg	Construction
SuperNEMO	82Se	Foils with tracking	100 kg	R&D
LUCIFER	82Se	ZnSe scint. bolometer	18 kg	R&D
AMoRE	100Mo	CaMoO4 scint. bolometer	50 kg	R&D
MOON	100Mo	Mo sheets	200 kg	R&D
COBRA	116Cd	CdZnTe detectors	10 kg/183 kg	R&D
CUORICINO	130Te	TeO2 Bolometer	10 kg	Complete
CUORE-0	130Te	TeO2 Bolometer	11 kg	Operating
CUORE	130Te	TeO2 Bolometer	206 kg	Construction
SNO+	130Te	0.1% natNd suspended in Scint	55 kg	Construction
KamLAND-ZEN	136Xe	2.7% in liquid scint.	380 kg	Operating
NEXT-100	136Xe	High pressure Xe TPC	80 kg	Construction
EXO200	136Xe	Xe liquid TPC	160 kg	Operating
nEXO	136Xe	Xe liquid TPC	~ tonne	R&D
DCBA	150Nd	Nd foils & tracking chambers	20 kg	R&D

Neutrino mass: prospects

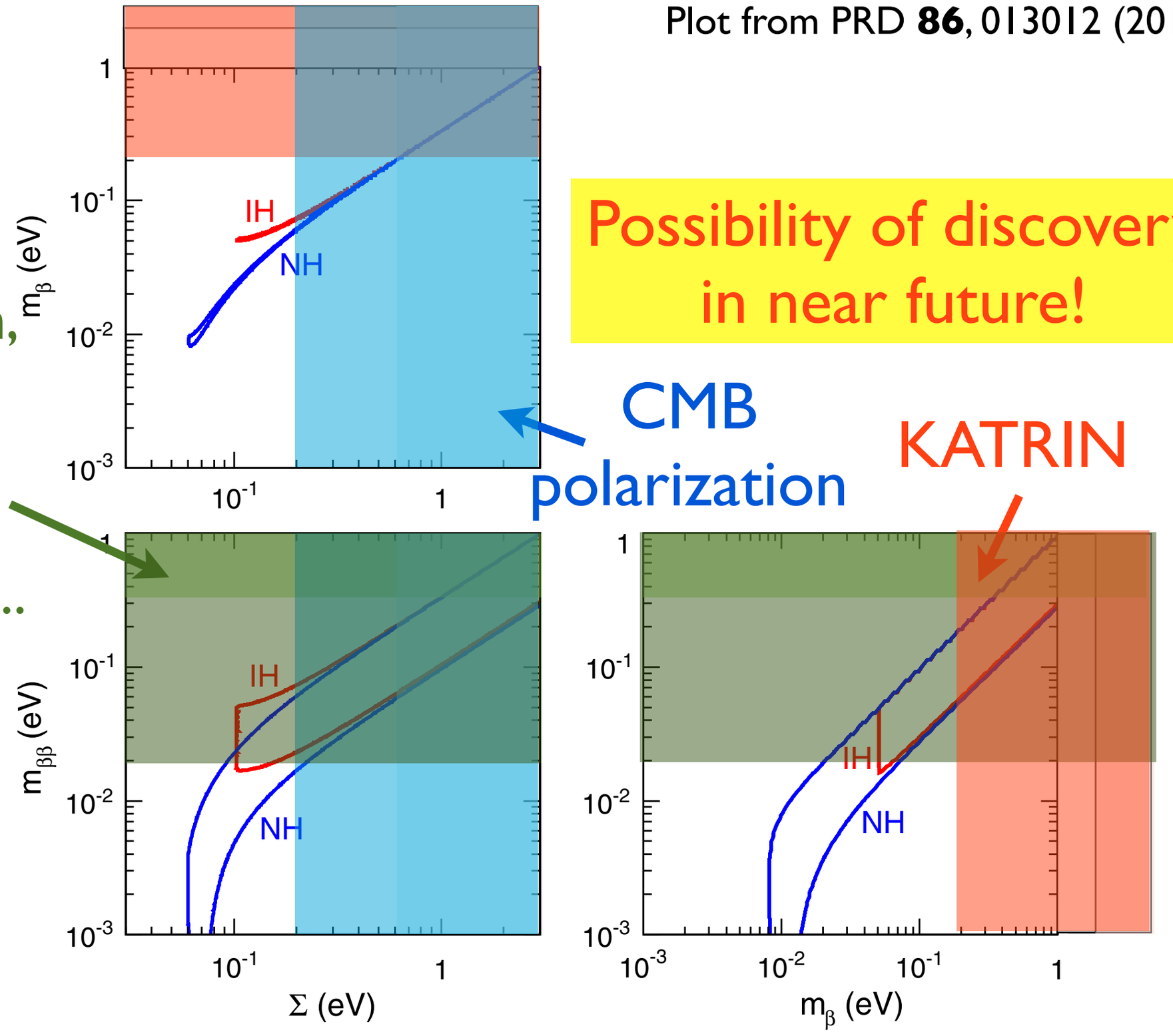
Plot from PRD **86**, 013012 (2012)



Neutrino mass: prospects

Plot from PRD **86**, 013012 (2012)

0νββ:
KamLAND-Zen,
EXO, GERDA,
CUORE, MJD,
SNO+,
SuperNEMO D....



Possibility of discovery in near future!

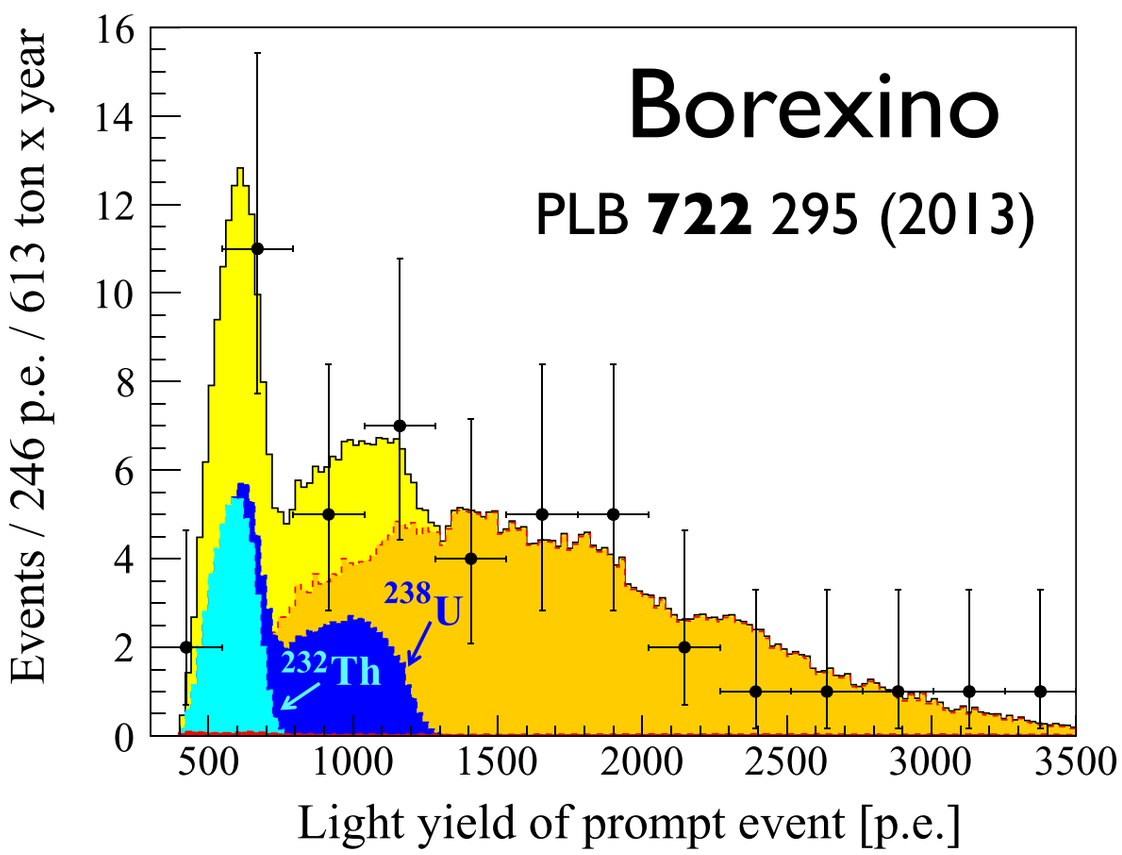
CMB polarization

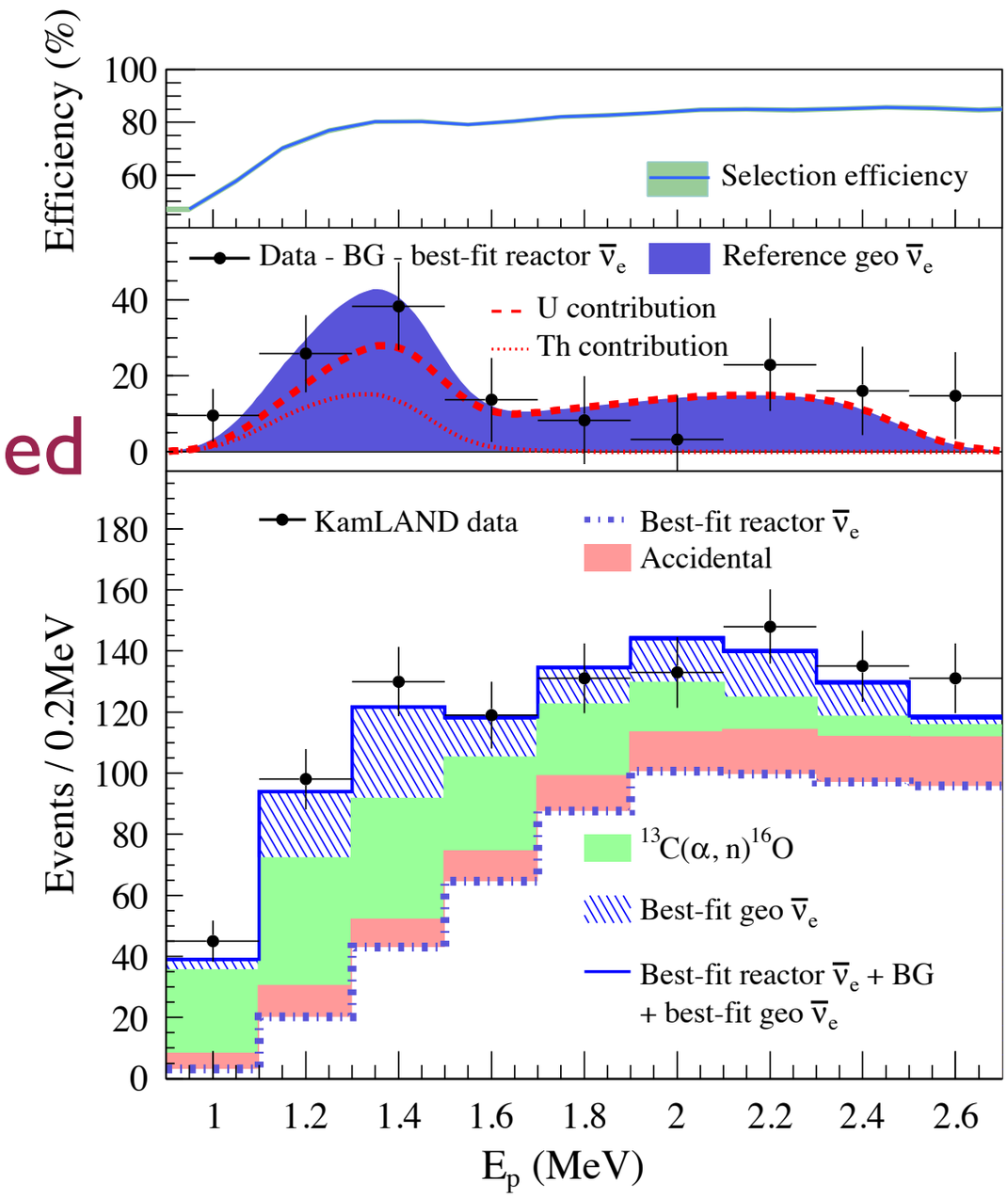
KATRIN

Neutrino as a messenger from Nature

Geo-neutrio

- Observation by KamLAND and Borexino
  - Start of ν geophysics
- Future experiments
  - SNO+: under construction
  - LENA, HANOHANO,... : proposed

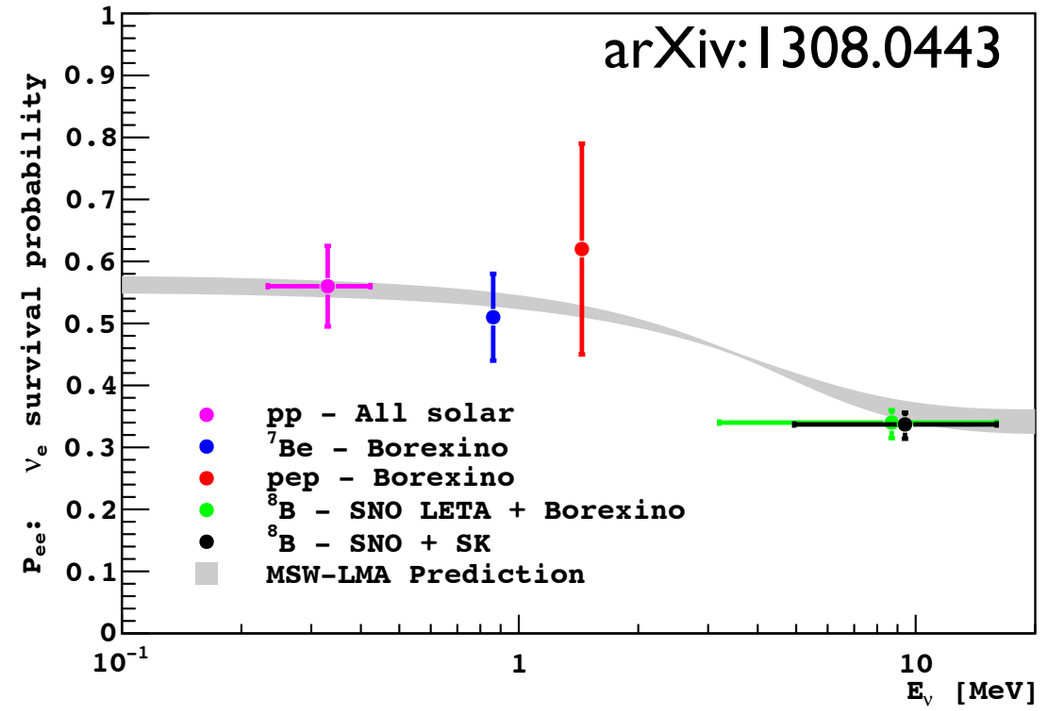


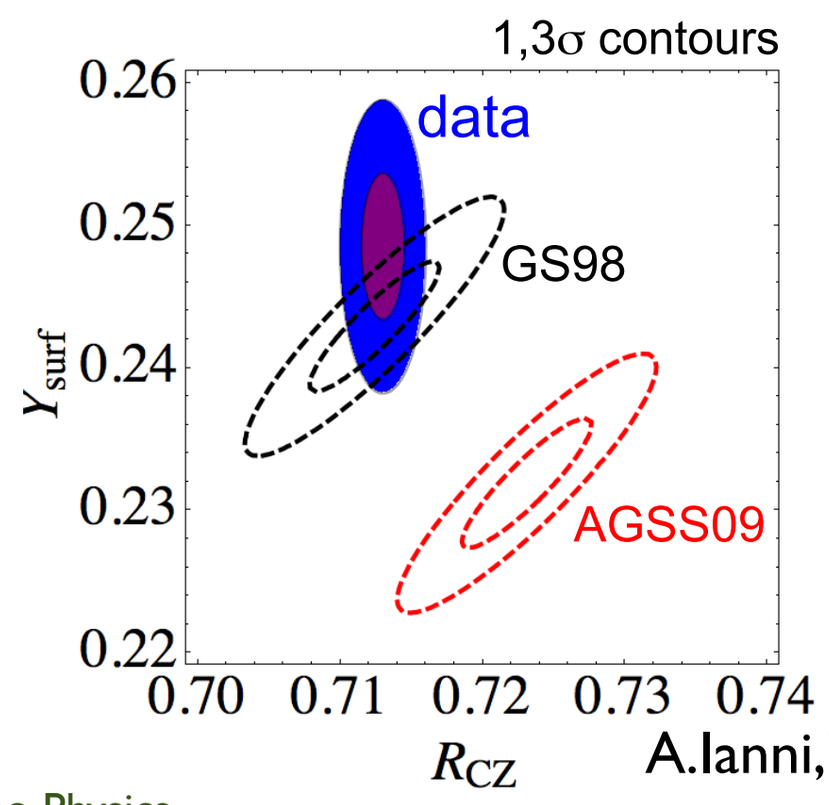


KamLAND arXiv:1303.4667

Solar neutrino

- Many recent progress
  - Precise measurement of θ_{12}
  - ^{7}Be and pep ν observation by Borexino
  - Day-Night effect by Super-K
- Future goals
  - Confirmation of upturn (MSW effect, or new physics?)
  - More precise flux meas.
  - CNO neutrino detection
  - Solar abundance problem



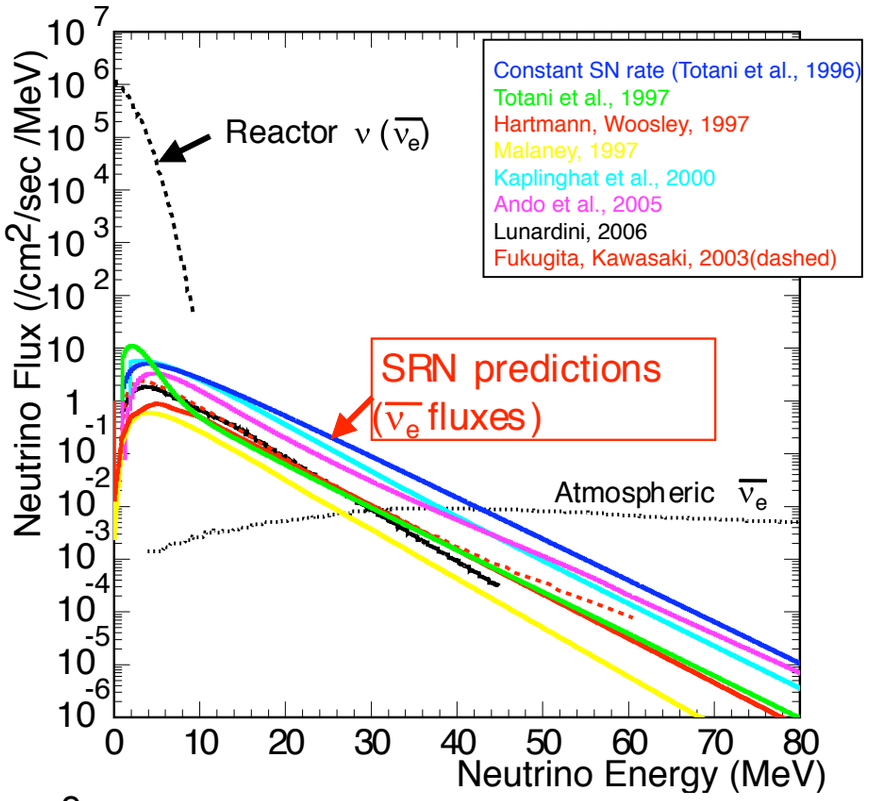


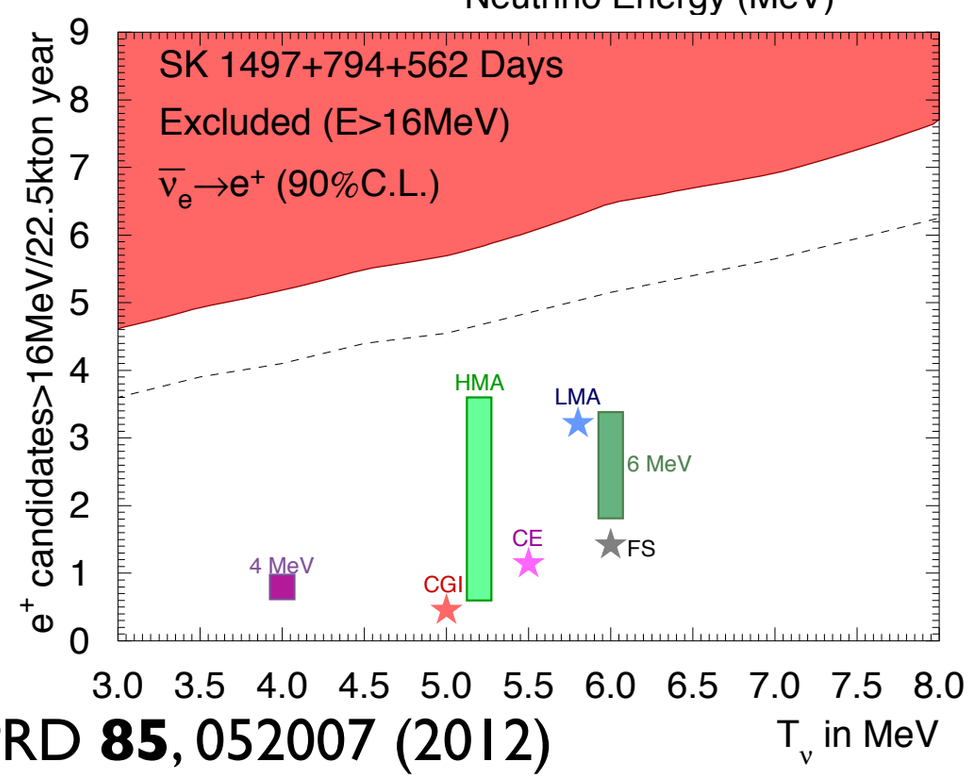
A.Ianni, TAUP13

Burst ν from core-collapse SN

- Large number of events if happens nearby
  - ~8000 events expected for Super-K for SN at 10kpc (cf. 24 events for SN1987a)
- Lots of physics/astrophysics
  - Comparison to SN models (time, flavor, energy)
  - Sensitivity to mass hierarchy
- SN Early Warning System (SNEWS) online
  - Network of SN sensitive ν detectors to send alert to astronomers
- Keep prepared, and wait and see... (Betelgeuse?)

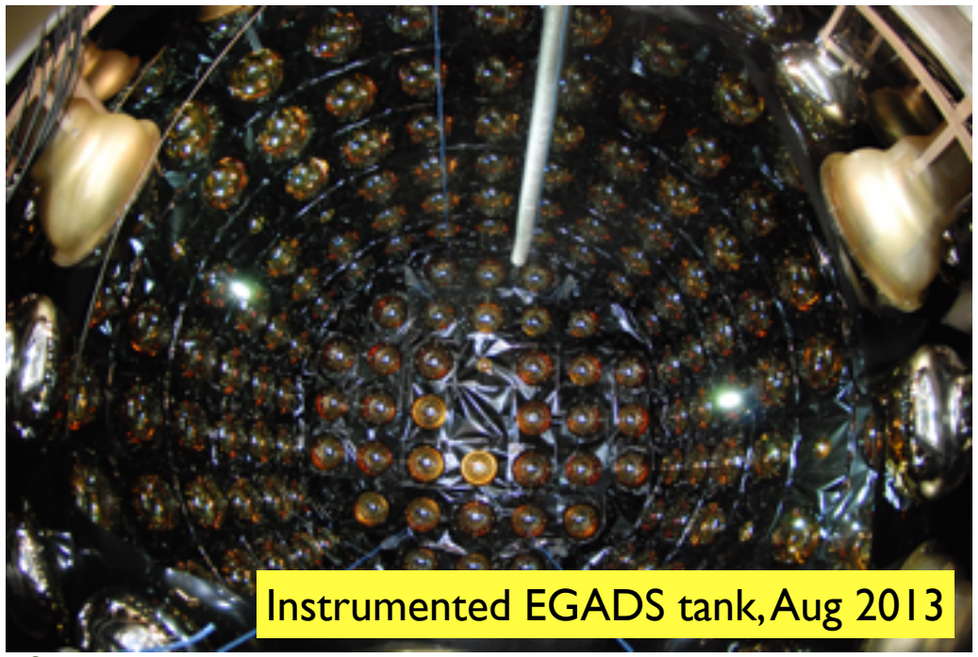
Diffuse supernova neutrino background (DSNB, SN relic ν)





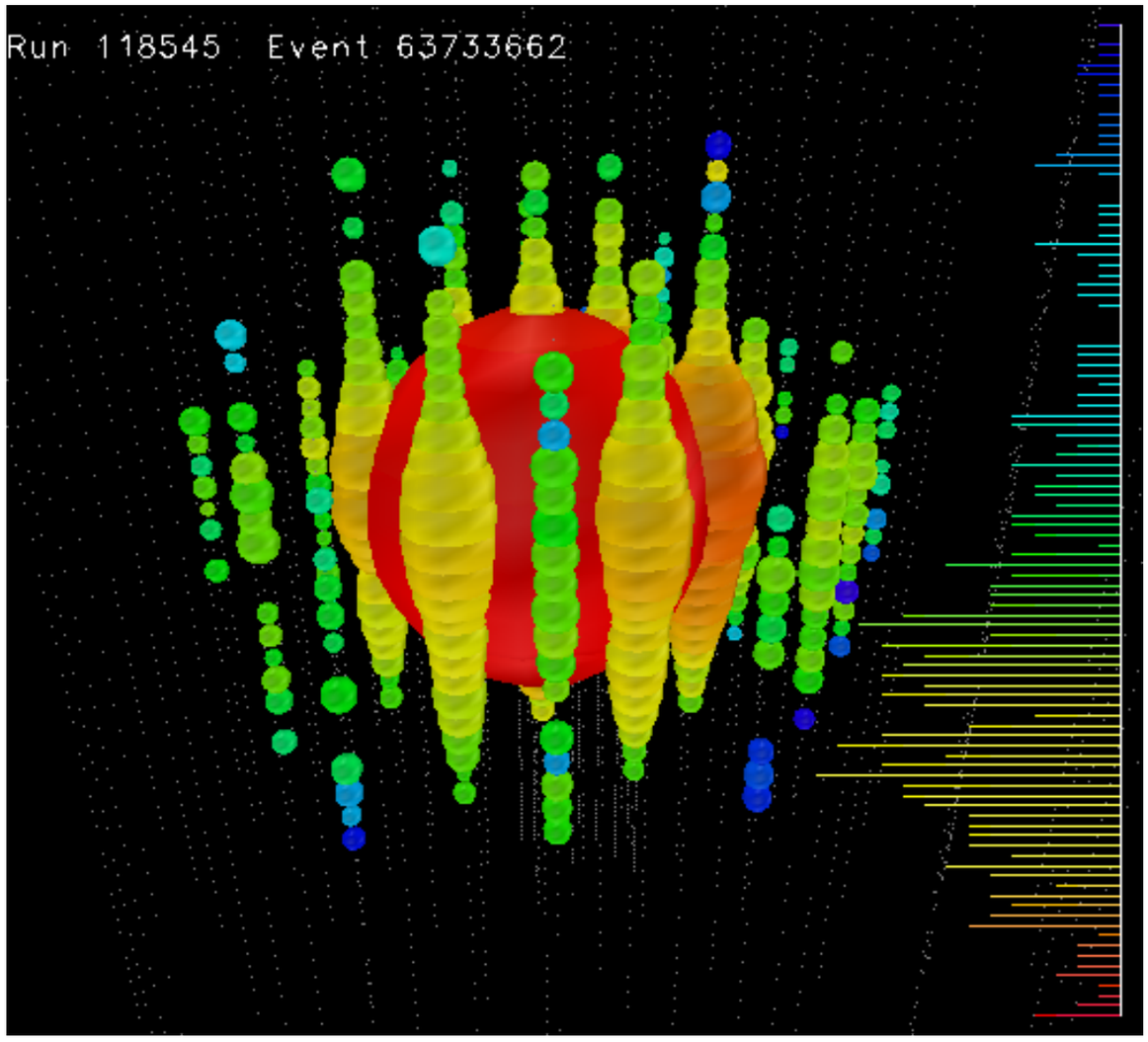
PRD **85**, 052007 (2012)

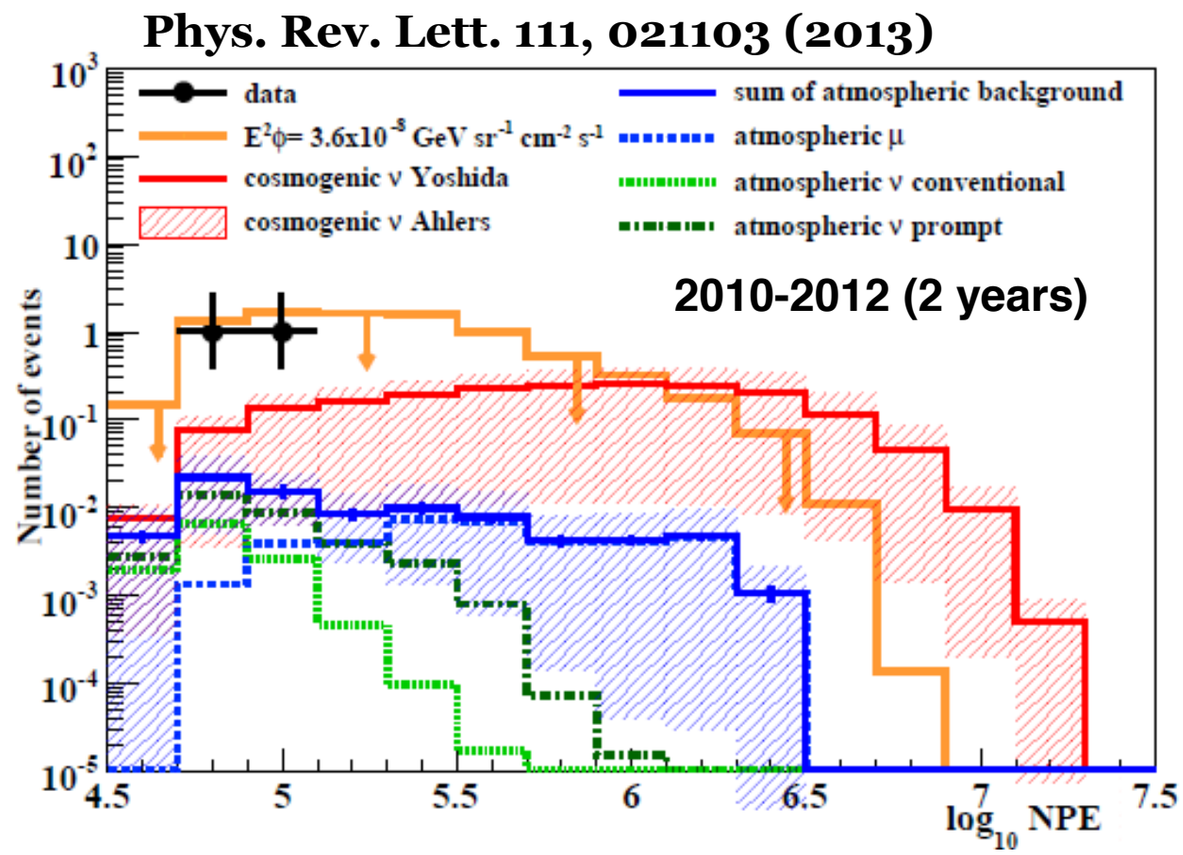
- Star formation history embedded
- Current limit by Super-K approaching to model predictions
- Enhance sensitivity by neutron tagging with Gd added to water
  - Gadzooks! (M.Vagins and J. Beacom)
  - R&D well in progress, prototype test (EGADS) ongoing


Instrumented EGADS tank, Aug 2013

High energy neutrino astrophysics

- PeV neutrino observed at IceCube





The 'First Light' of the high energy neutrino astronomy

Summary

- Lots of progress in neutrino physics in the past years.
  - Discovery of $\sin\theta_{13}$~0.1 → future opportunities
- Still lots to learn
  - about properties of neutrino
  - about Nature using neutrino as a probe
- Rich, diverse experimental programs and proposals exist over the world
  - New era of neutrino physics
- More ideas will emerge in future
- Expect more surprises in future!!!