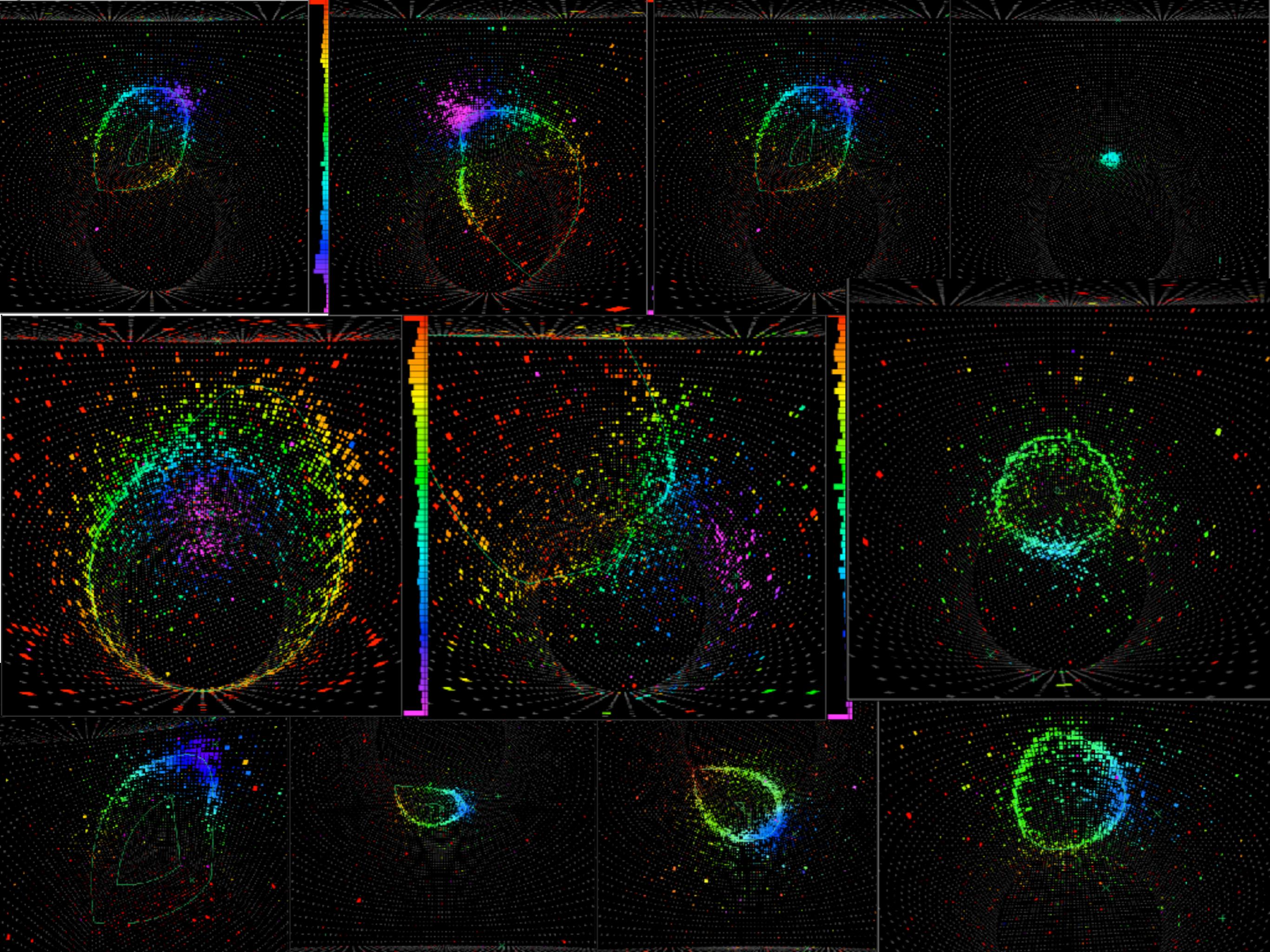




**EPS Conference on High Energy Physics**  
**Venice, Italy 5-12 July 2017**

# Neutrino Physics from Particle Beam and Decay Experiments

T. Nakaya (Kyoto University)



# Particle Physics Today!

- Success of the Standard Model.
  - Many presentations in this conference. No clear signal beyond SM except for neutrino mass
- **Challenge**
  - Dark Matter
  - Dark Energy
  - No anti-matter in our universe
  - Unification of force (unification of quark and lepton)
  - etc...
- Key particles in my mind are

Neutrino and Higgs!

# Discovery with Neutrinos



1998: Neutrino oscillations of atmospheric neutrinos ( $\Delta m_{32(1)}^2$ ,  $\theta_{23}$ ).

- The oscillations are confirmed by the accelerator experiment.



2001: Neutrino oscillations of solar neutrinos ( $\Delta m_{21}^2$ ,  $\theta_{12}$ ).

- The oscillations are confirmed by the reactor experiment.
- 2011-2013: Neutrino oscillations with  $\theta_{13}$  ( $\Delta m_{32(1)}^2$ ) by reactor and accelerator experiments
- **Today's key subjects**
  - CPV and the mass hierarchy
  - Majorana neutrino that causes neutrino-less double beta decay
  - Sterile neutrino anomaly including heavy neutrino decays

# Many experiments are on-going and planned!

Long-Baseline Acc.	Short-Baseline Acc.	$0\nu\beta\beta$	Others
* T2K * NOvA * OPERA MINOS * ICRARUS@CNGS * DUNE * Hyper-K ESSnuSB T2HKK	MiniBooNE * MicroBooNE * MINERvA * SBND J-PARC IWC nuSTORM ENUBET IsoDAR/ $\mu$ DAR * ICRARUS@FNAL * JSNS <sup>2</sup>	* GERDA * CUORE/Cuoricino * SuperNEMO CUPID SNO+ * NEXT * KamLAND-Zen * EXO/nEXO PANDAX-III AXEL LEGEND	* NA62 SHiP  On-going Planned * in this talk  Presentations in EPS

- In addition, there are more R&D and test experiments on-going (such as **CERN Neutrino Platform**, J-PARC  $\nu$  test experiments, Fermilab test experiment, etc..)

# One minute summary after EPS-HEP2015



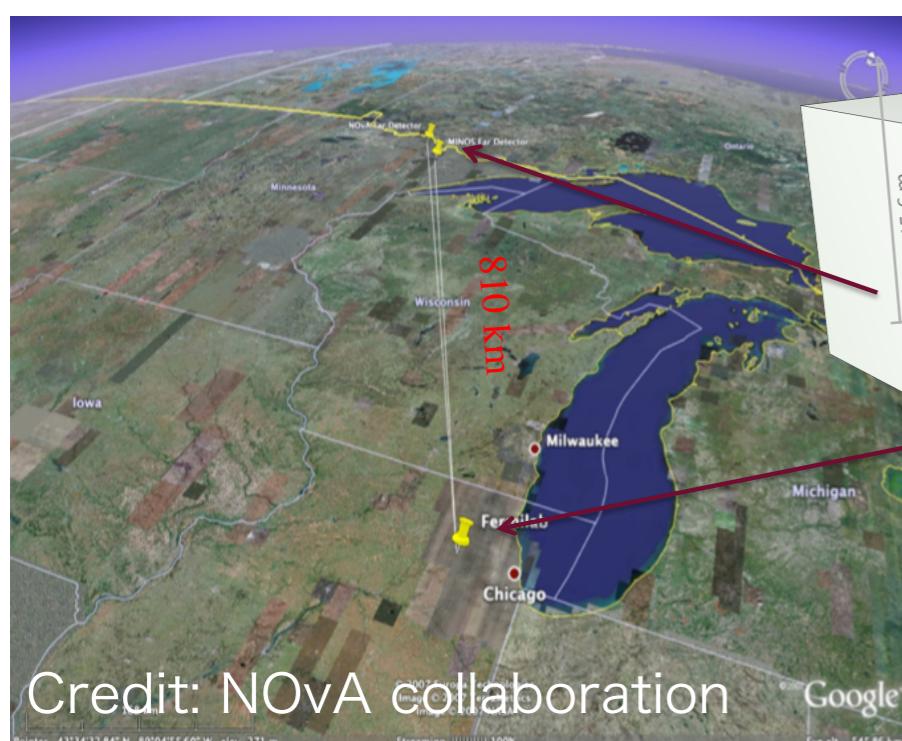
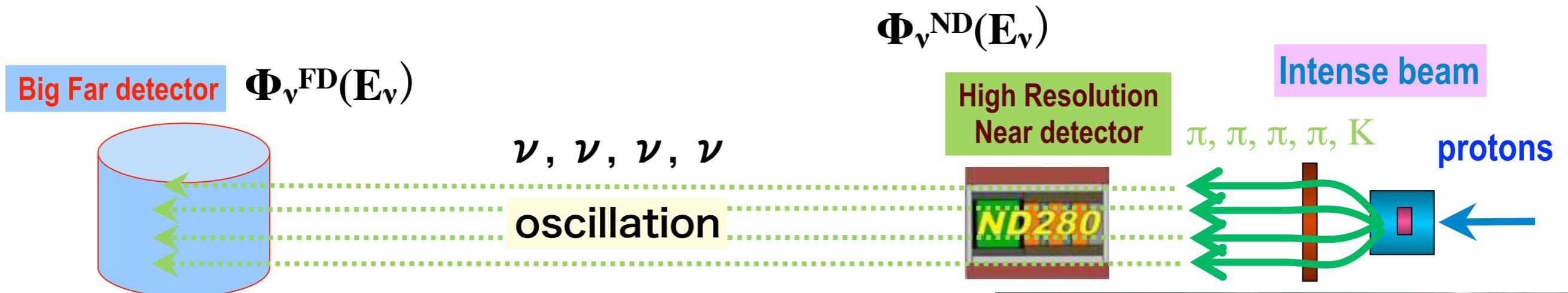
- A hint of Neutrino CPV is seen in accelerator neutrino experiments. Mass hierarchy is also seen?
  - Precision and sensitivity are being improved.
- Improved limit on the neutrino-less double beta decay.
  - No signal yet.
- Negative results on sterile neutrinos, but the existence is not excluded yet.
  - Many experiments and measurements are on-going.
- Future experiments with a lot of R&D are proposed and under preparation.

# Physics Motivation

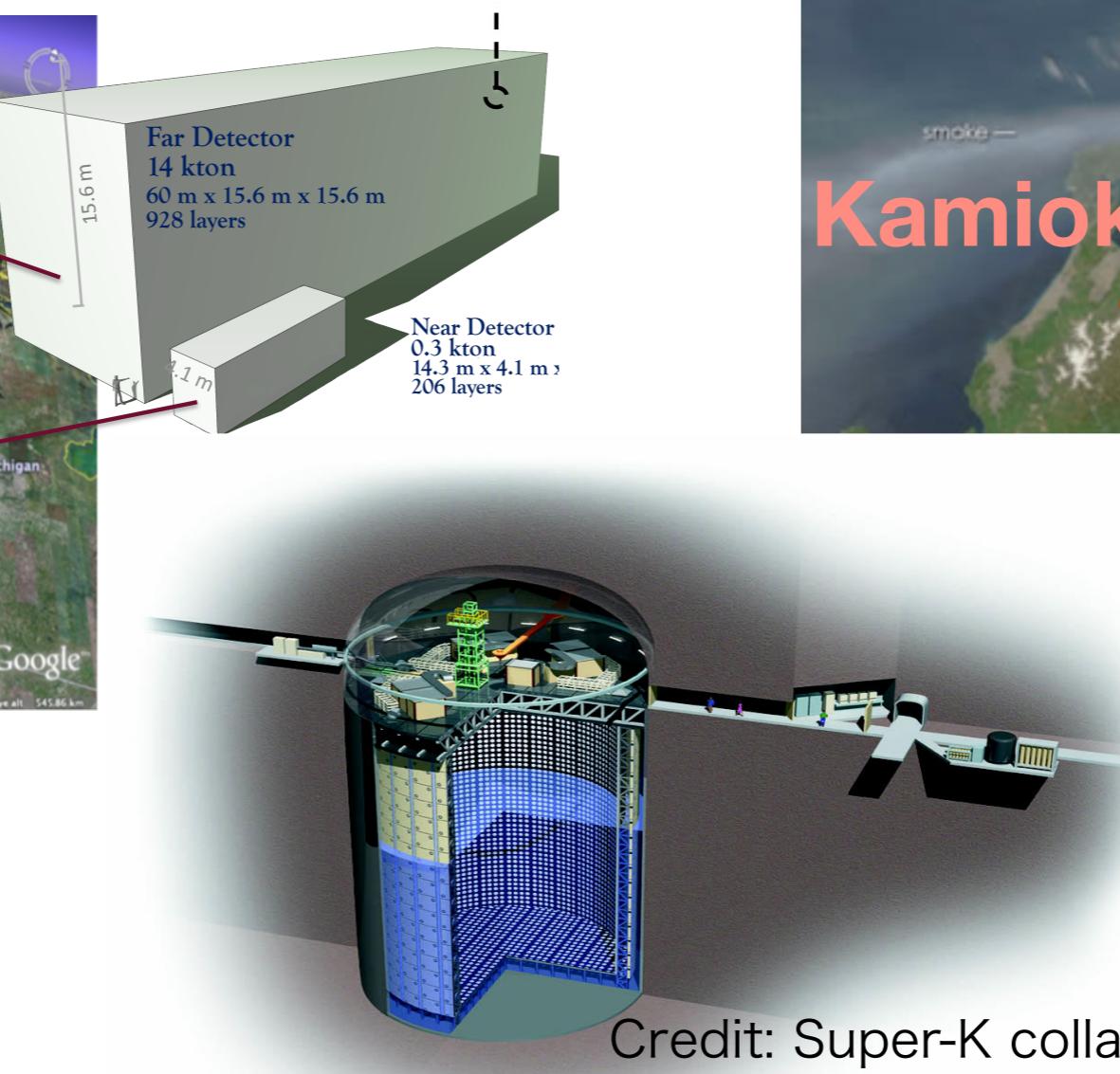
- Neutrino mass and mixing (right handed neutrinos) are physics beyond the standard model.
- Tiny Neutrino mass
  - What is the origin of the mass?
  - Majorana particle
- Flavor Symmetry
  - Between leptons and quarks
    - mass pattern
    - mixing pattern
    - the number of generations
- CP violation
  - the origin?
  - matter dominant universe with Leptogenesis

Three Generations of Matter (Fermions) spin $\frac{1}{2}$				Bosons (Forces) spin 1	Higgs boson
Quarks	I	II	III		
mass →	2.4 MeV	1.27 GeV	173.2 GeV		
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$		
name →	u up	c charm	t top		
	Left Right	Left Right	Left Right		
Quarks	d down	s strange	b bottom		
mass →	4.8 MeV	104 MeV	4.2 GeV		
charge →	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$		
name →	d down	s strange	b bottom		
	Left Right	Left Right	Left Right		
Leptons	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino		
mass →	0.511 MeV	105.7 MeV	1.777 GeV		
charge →	-1	-1	-1		
name →	e electron	$\mu$ muon	$\tau$ tau		
	Left Right	Left Right	Left Right		

# Accelerator Neutrino Beam



Credit: NOvA collaboration



Credit: Super-K collaboration

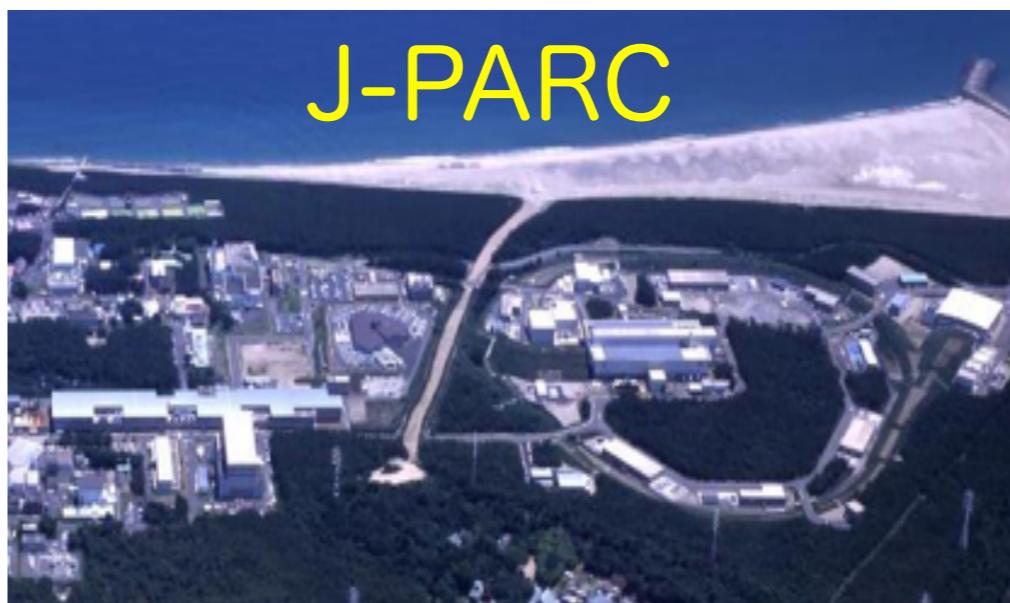
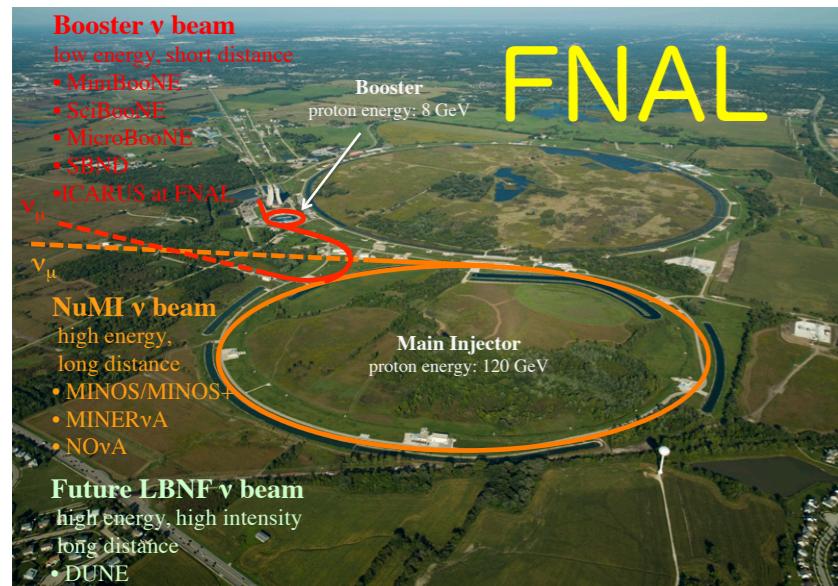


Credit:  
T2K collaboration

- T2K in Japan
- NOvA in USA

# Beam Performance

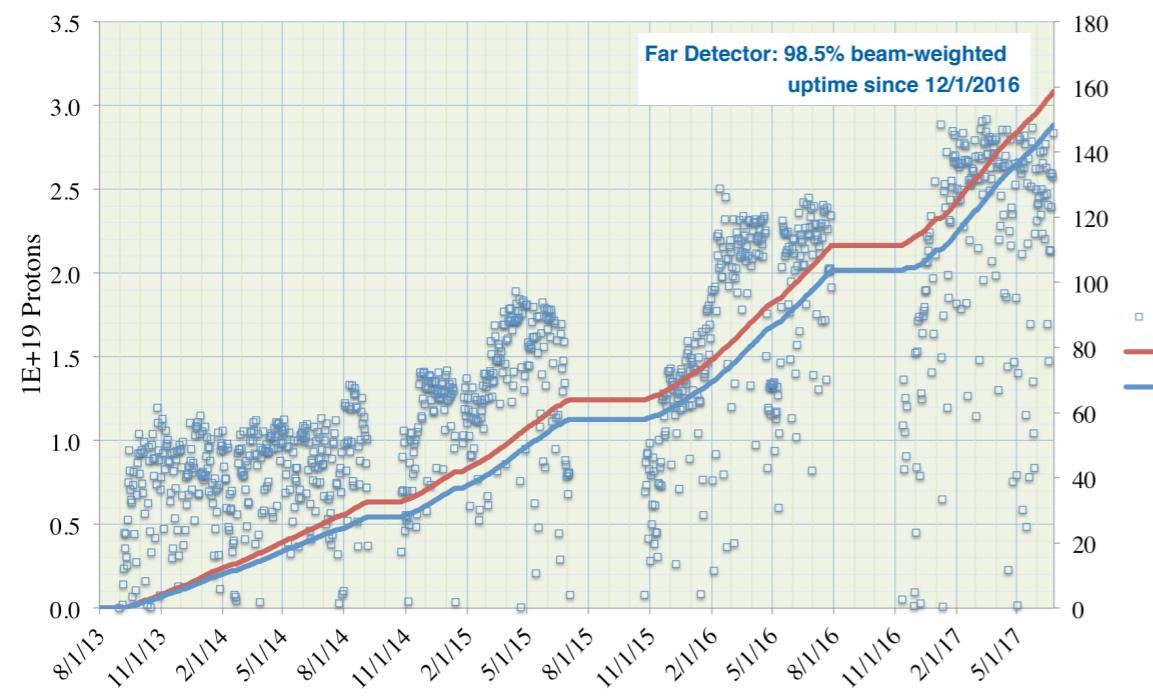
— Very intense proton beams at Fermilab and J-PARC —



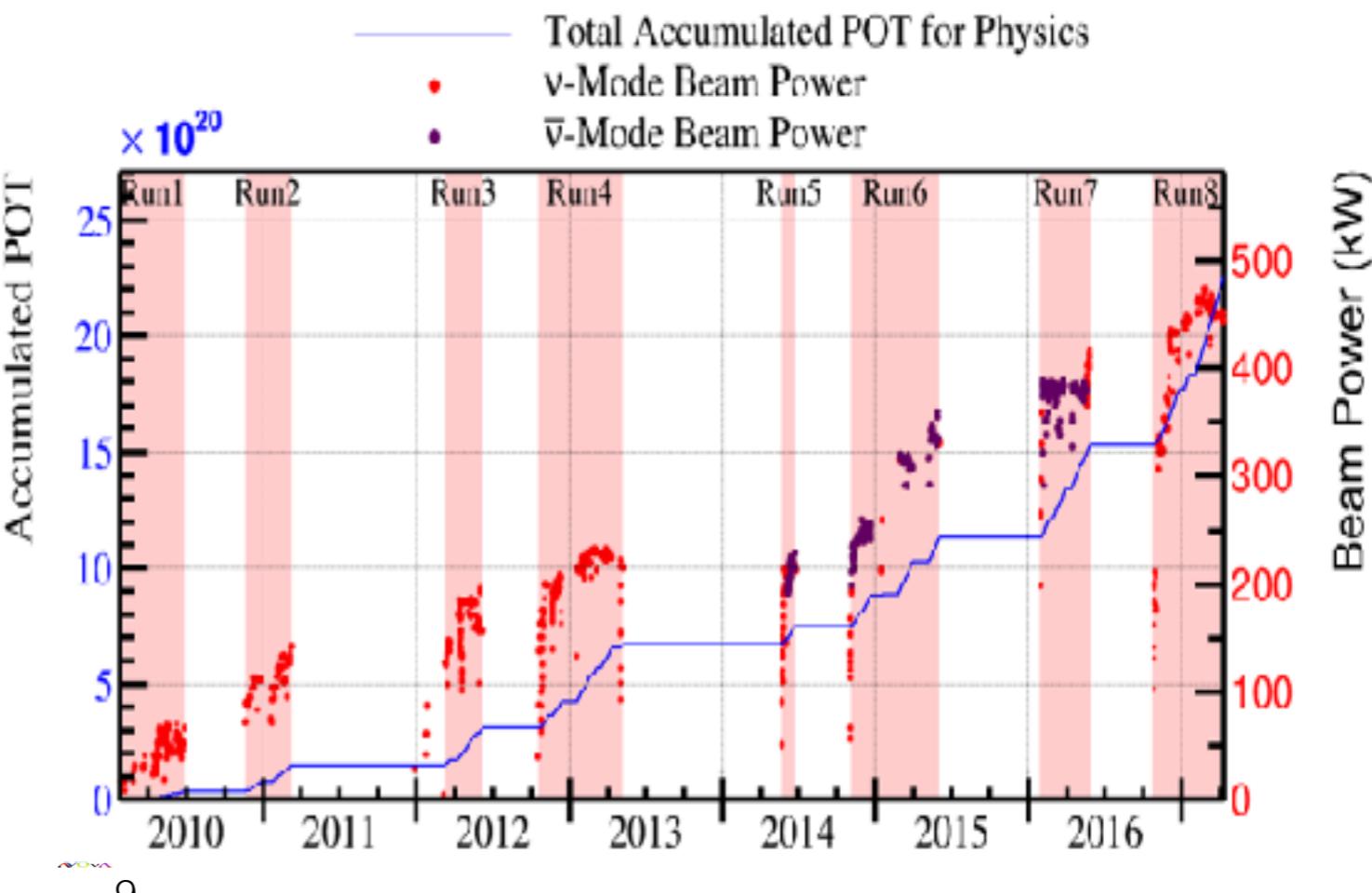
**FNAL NuMI: ~16E20 POT from 2013**

## NuMI Performance

- Protons delivered to the NuMI target (POT) recorded at Far Detector
- Routine 700 kW (NuMI-only-equivalent) running achieved in January



**J-PARC MR: ~22E20 POT from 2010**



# **LBL Accelerator Experiments**

# LBL Accelerator Experiments

	Baseline (km)	Energy (GeV)	Mass (ton)	Starting year	#Events
* T2K	295	0.6	32k	2010~	37 $\nu_e$ , 4 $\bar{\nu}_e$
* NOvA	810	2	14k	2013~	33 $\nu_e$
* OPERA	730	17	1.2k	2006~	5(+5) $\nu_\tau$
* ICARUS	730	17	0.6k	2010~	
MINOS(+)	730	2~10	5k	2005~	
* DUNE	1300	2~3	40k	2026~	$O(1000) \nu_e$
* Hyper-K	295	~0.6	190k	2026~	$O(1000) \nu_e$
ESSnuSB	360, 540	~0.3	500k	2030~	
T2HKK	295+1100	~1	190k+190k	TBA	$O(1000) \nu_e$

- $\nu_\mu \rightarrow \nu_e, \nu_\mu, \nu_\tau$  and the anti-neutrino oscillations
  - Note:  $P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$  in the case of two neutrinos in vacuum.

# Formula of Oscillation Probability with CP violation

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

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

Solar

**Leading**

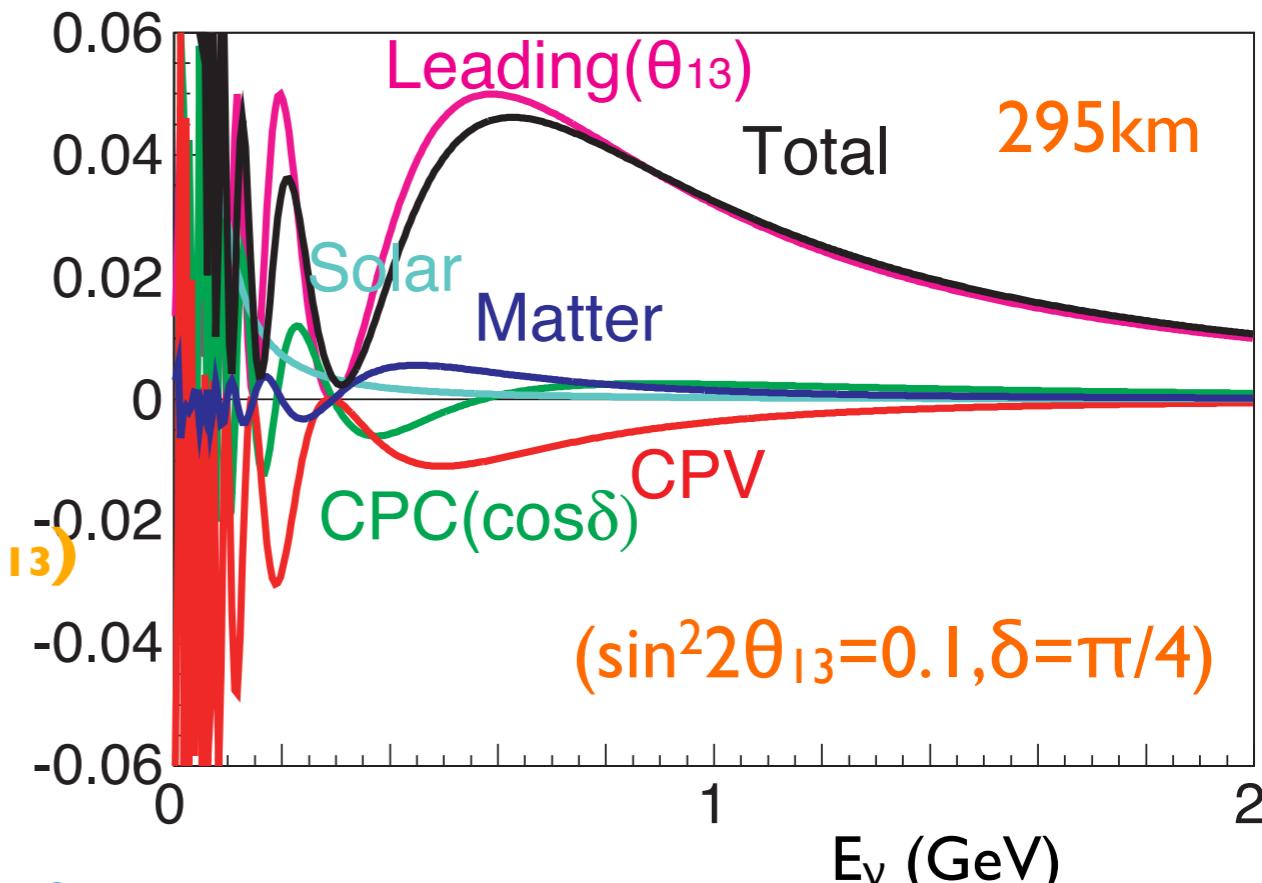
$$\sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right)$$

**CPV**

$$\begin{aligned}
 & \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \left[ \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \right] \sin \frac{\Delta m_{21}^2 L}{4E} \sin \delta \\
 & \sim 0.03 \\
 & \sim \frac{\pi}{4} \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{\sin^2 \theta_{23} \sin \theta_{13}} E_{1st \max} [\text{leading}] \sin \delta
 \end{aligned}$$

$$\sim 0.27 \times [\text{leading}] \times \frac{E_{1st \max}}{E} \times \sin \delta$$

27%



- No magic for the 2nd maximum.
- Energy dependence is important.

# OPERA and ICARUS

## Events selection with looser kinematical cuts

$\nu_\mu \rightarrow \nu_\tau$

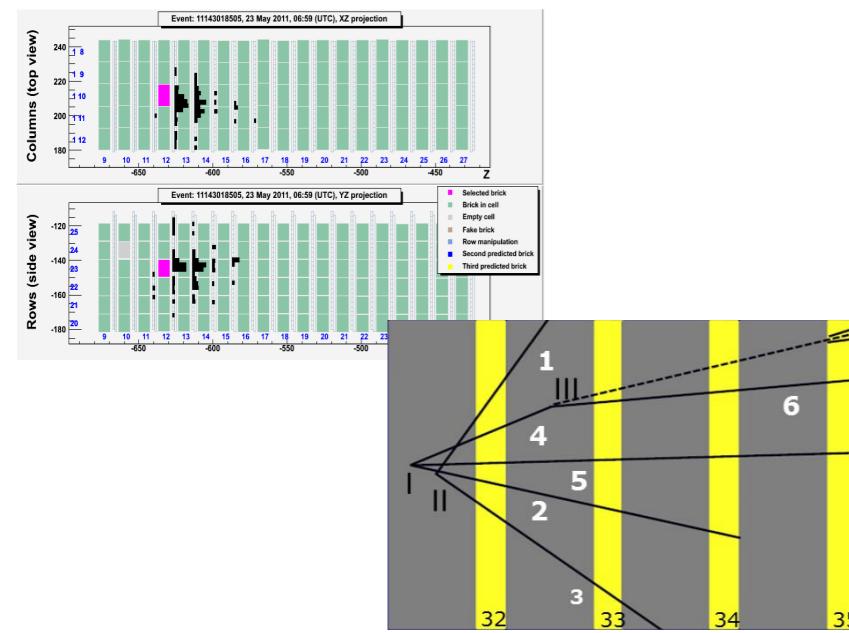
Expected Signal	Expected Background	Observed $\nu_\tau$	$\Delta m_{23}^2$ ( $10^{-3}$ eV $^2$ )
6.8	2.0	10	$2.7 \pm 0.6$ 68% C.L.

5.2  $\sigma$  significance

1 DIS  $\nu_\tau$  CC + charm candidate

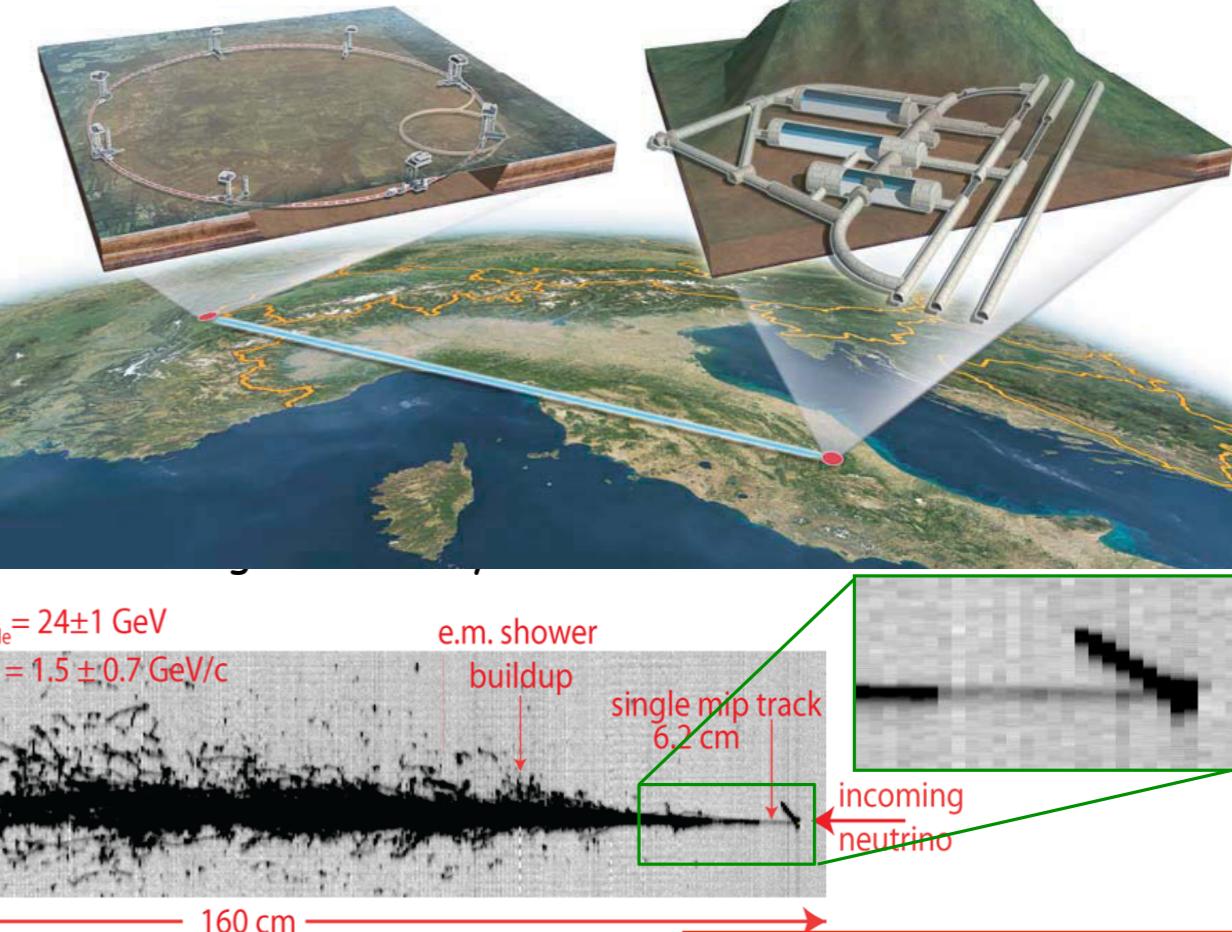
Muon-less event 114301850

Zoom of the interaction region : pink brick selected



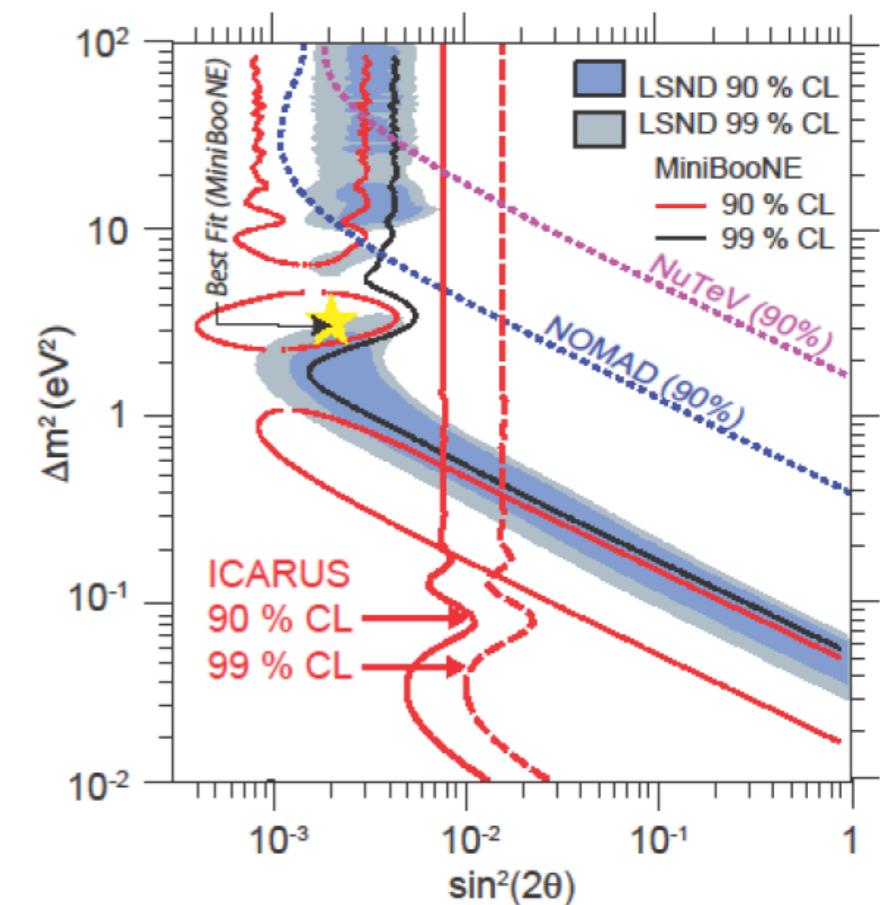
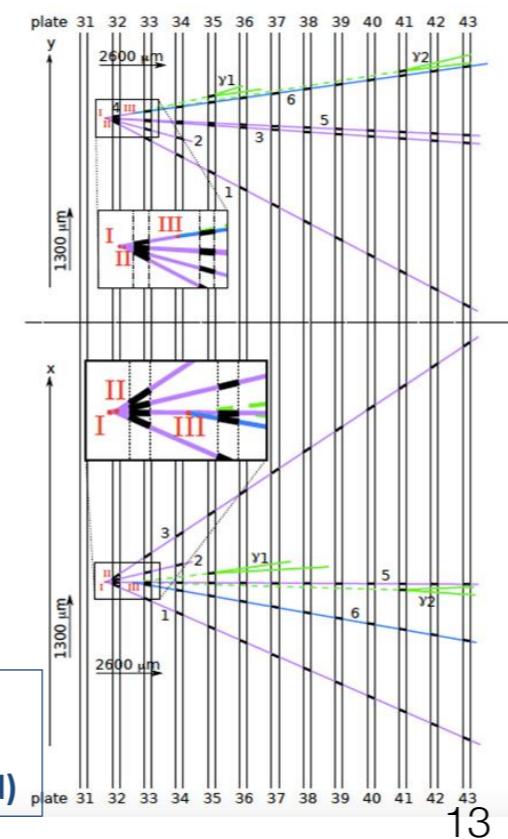
Two secondary vertices reconstructed in emulsion :

- short two prong (F.L. = 103  $\mu$ m)
- charged one prong (kink) (F.L.= 1174  $\mu$ m,  $\theta_k = 97$ mrad)



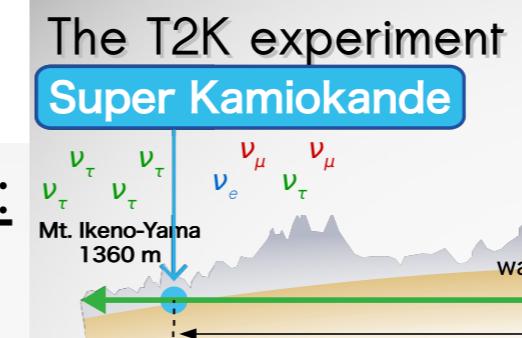
$$P(\nu_\mu \rightarrow \nu_e) \leq 3.85 \times 10^{-3} \text{ (90\% C.L.)}$$

$$P(\nu_\mu \rightarrow \nu_\tau) \leq 7.60 \times 10^{-3} \text{ (99\% C.L.)}$$



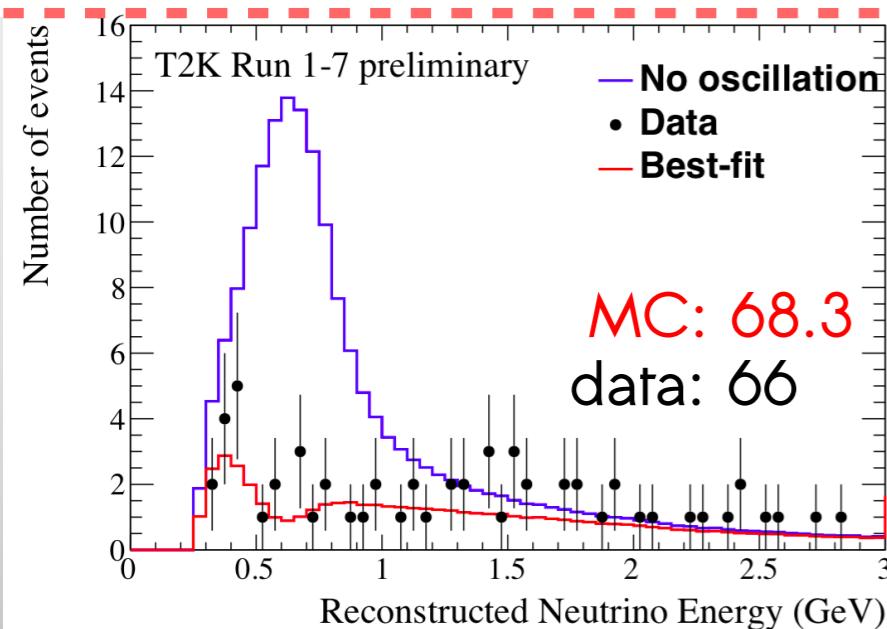
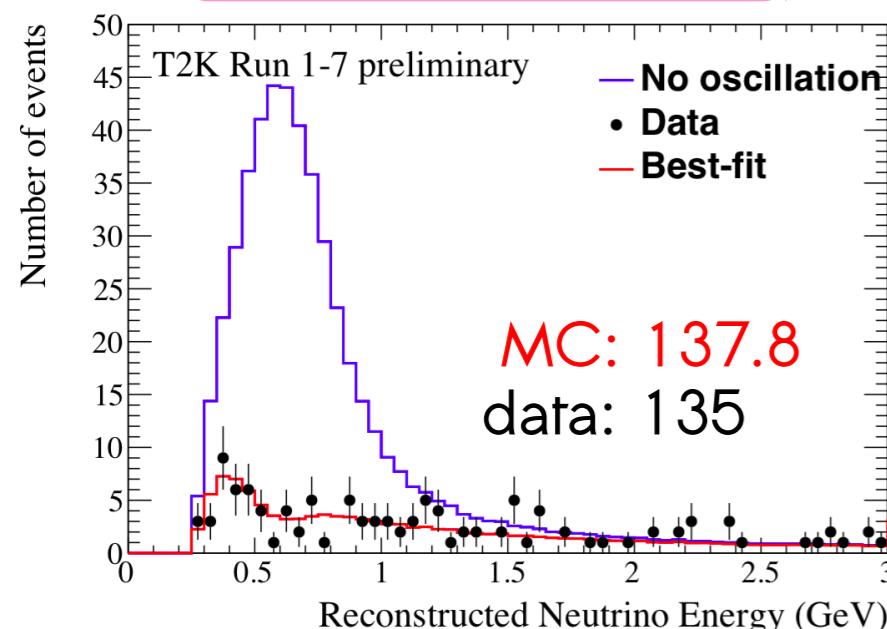
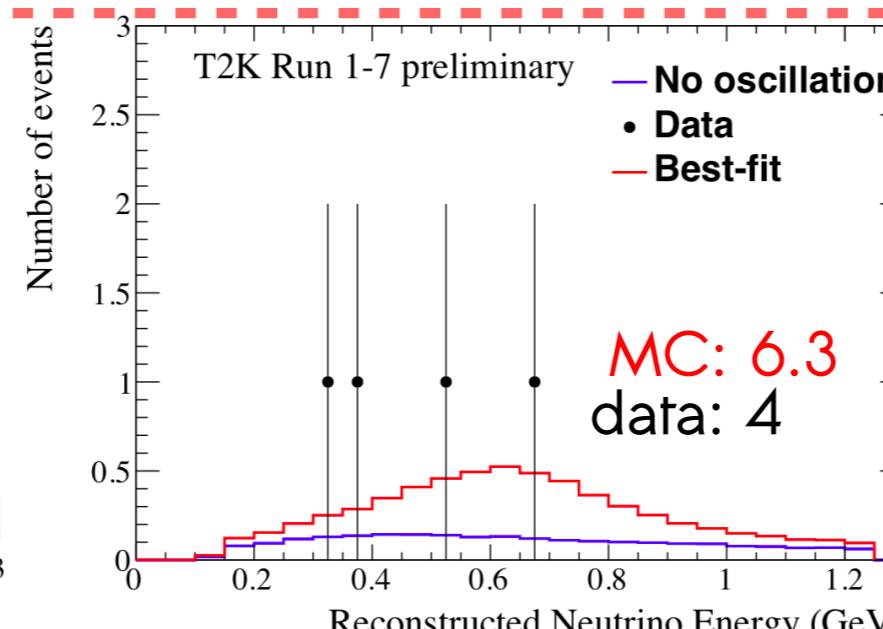
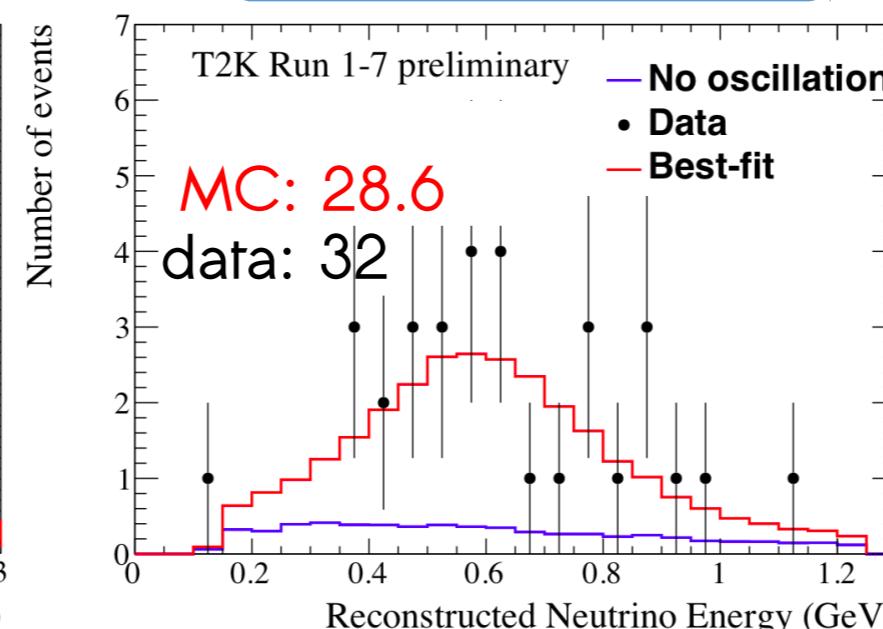
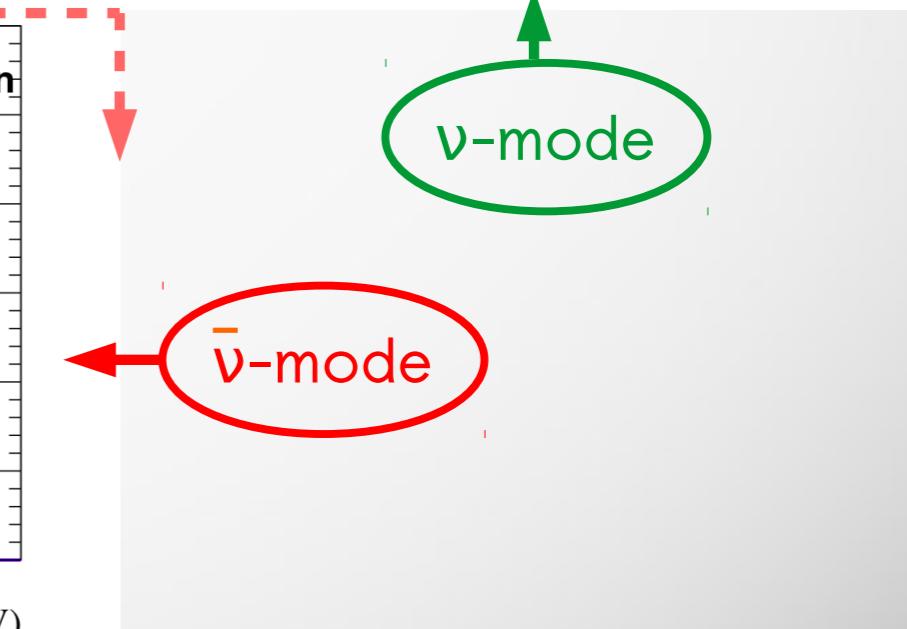
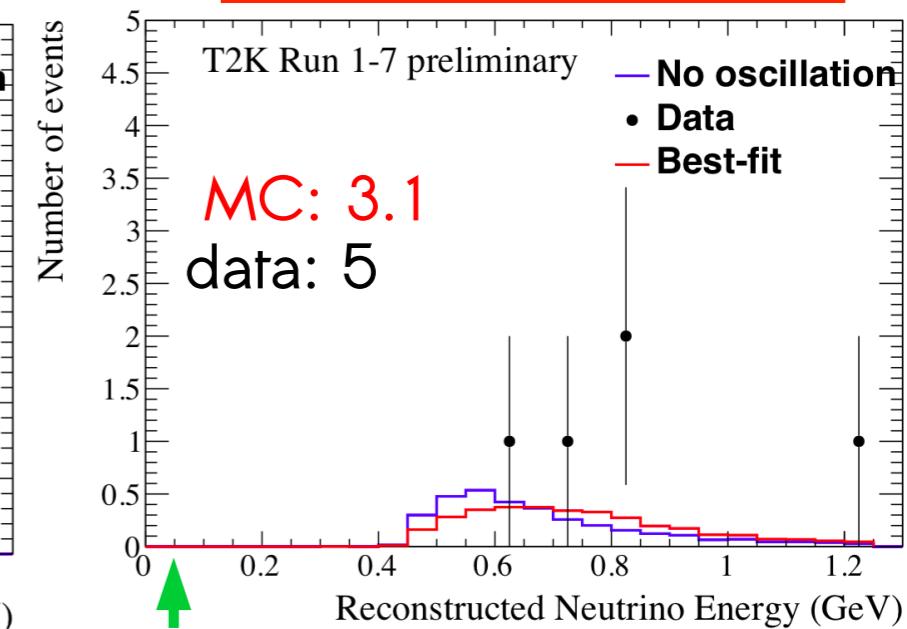
5 samples of charged-current (CC)  $\nu$  interactions:

determination of oscillation parameters

new  $e^-$  rings CC- $1\pi^+$  sample since ICHEP 2016

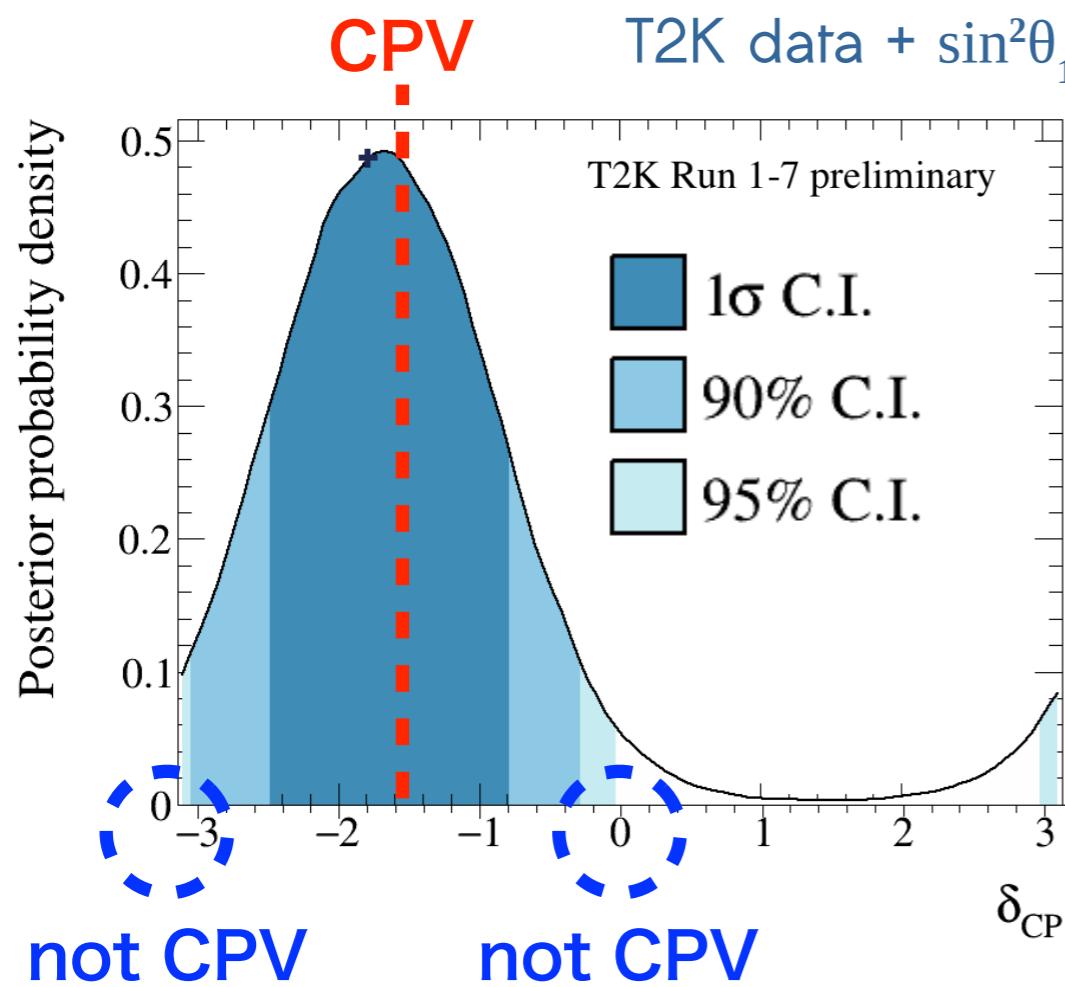
Near Detector

J-PARC

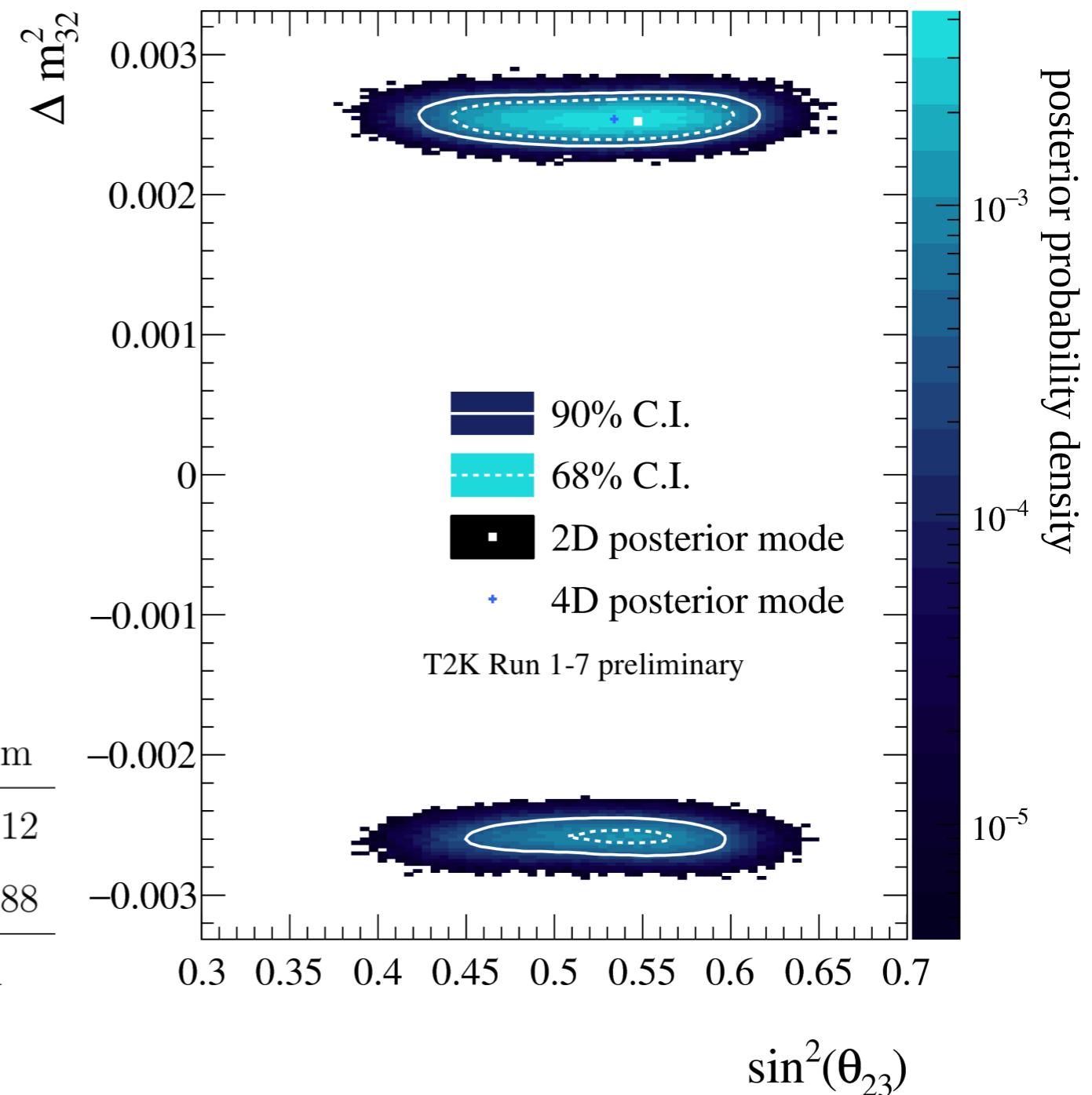
 $\mu^{+/-}$  rings CC- $0\pi$  $e^{+/-}$  rings CC- $0\pi$  $e^-$  rings CC- $1\pi^+$ 

# Results (Bayesian analysis)

by Dr. Leila Haegel



	$\sin^2 \theta_{23} < 0.5$	$\sin^2 \theta_{23} > 0.5$	Sum
IO ( $\Delta m_{32}^2 < 0$ )	0.060	0.152	0.212
NO ( $\Delta m_{32}^2 > 0$ )	0.233	0.555	0.788
Sum	0.293	0.707	1



The T2K result is submitted to PRD with arXiv:1707.01048 [hep-ex] 5 July 2017

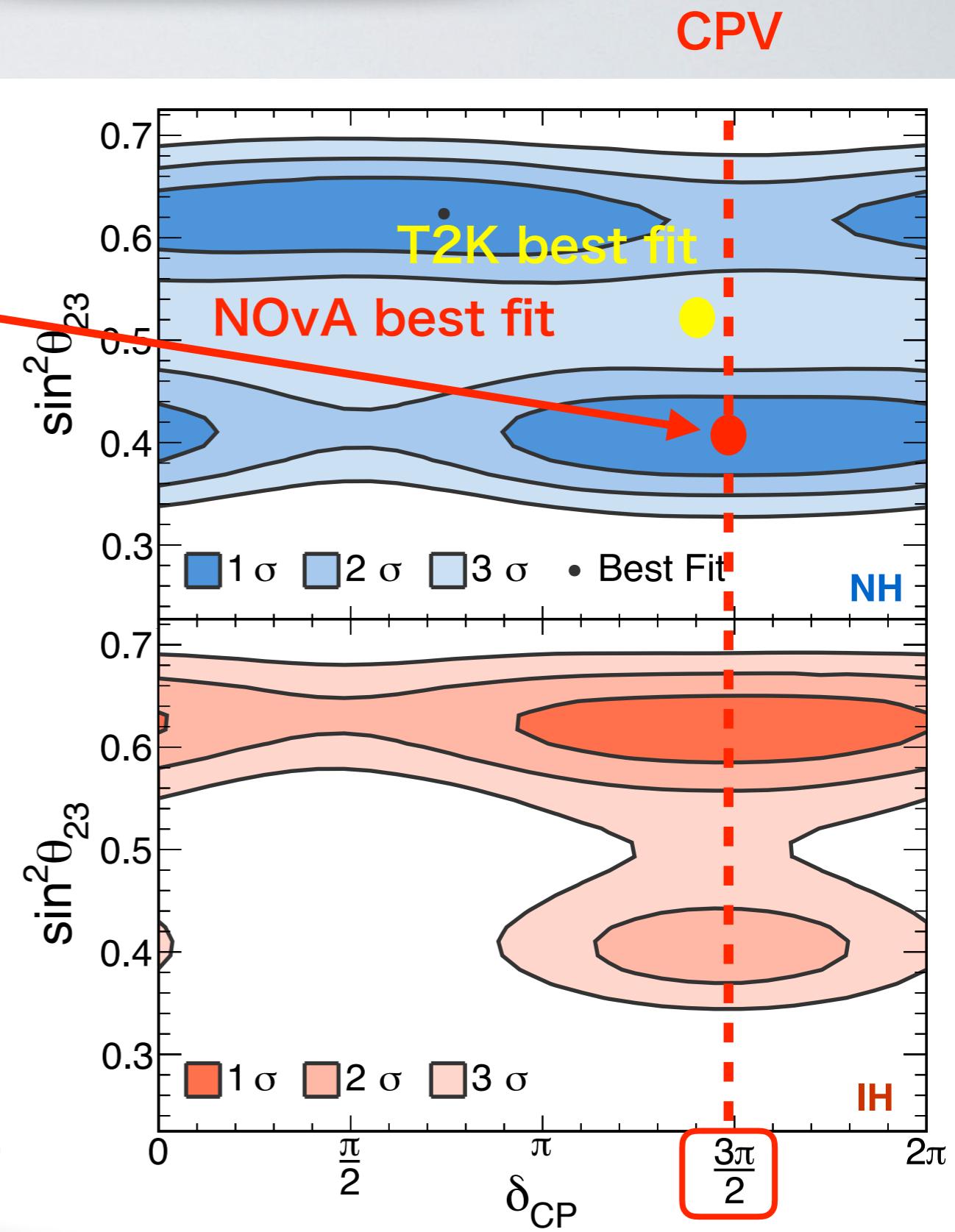
# NOvA $\nu_e$ appearance

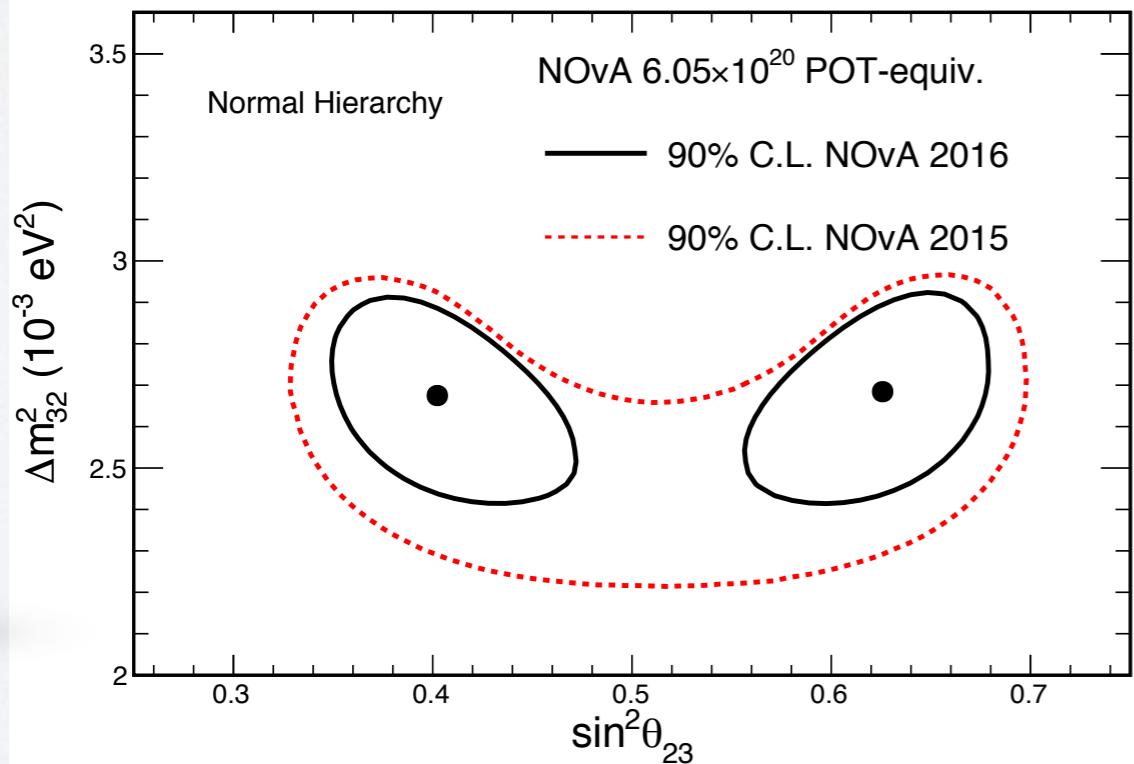
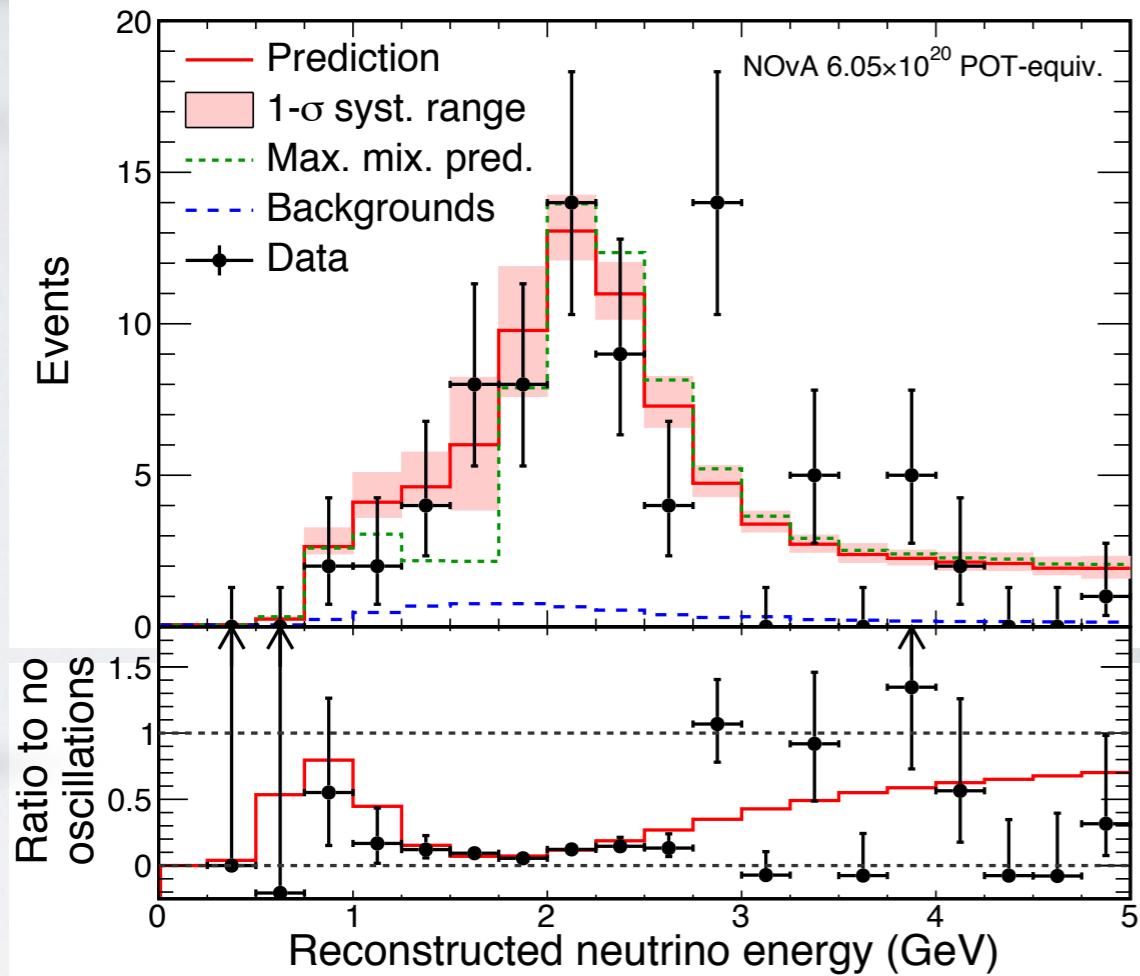
Electron neutrino  
appearance

by Dr. B. Zamorano

- Full joint-analysis including disappearance constraints
- Best fit to NH,  $\delta_{CP} = 1.49\pi$  and  $\sin^2(\theta_{23}) = 0.40$
- But best fit IH-NH has  $\Delta\chi^2 = 0.47$
- Both octants and hierarchies allowed at  $1\sigma$
- $3\sigma$  exclusion of IH, lower octant around  $\delta_{CP} = \pi/2$
- Antineutrino data will resolve degeneracies

Phys. Rev. Lett. 118, 231801 (2017)

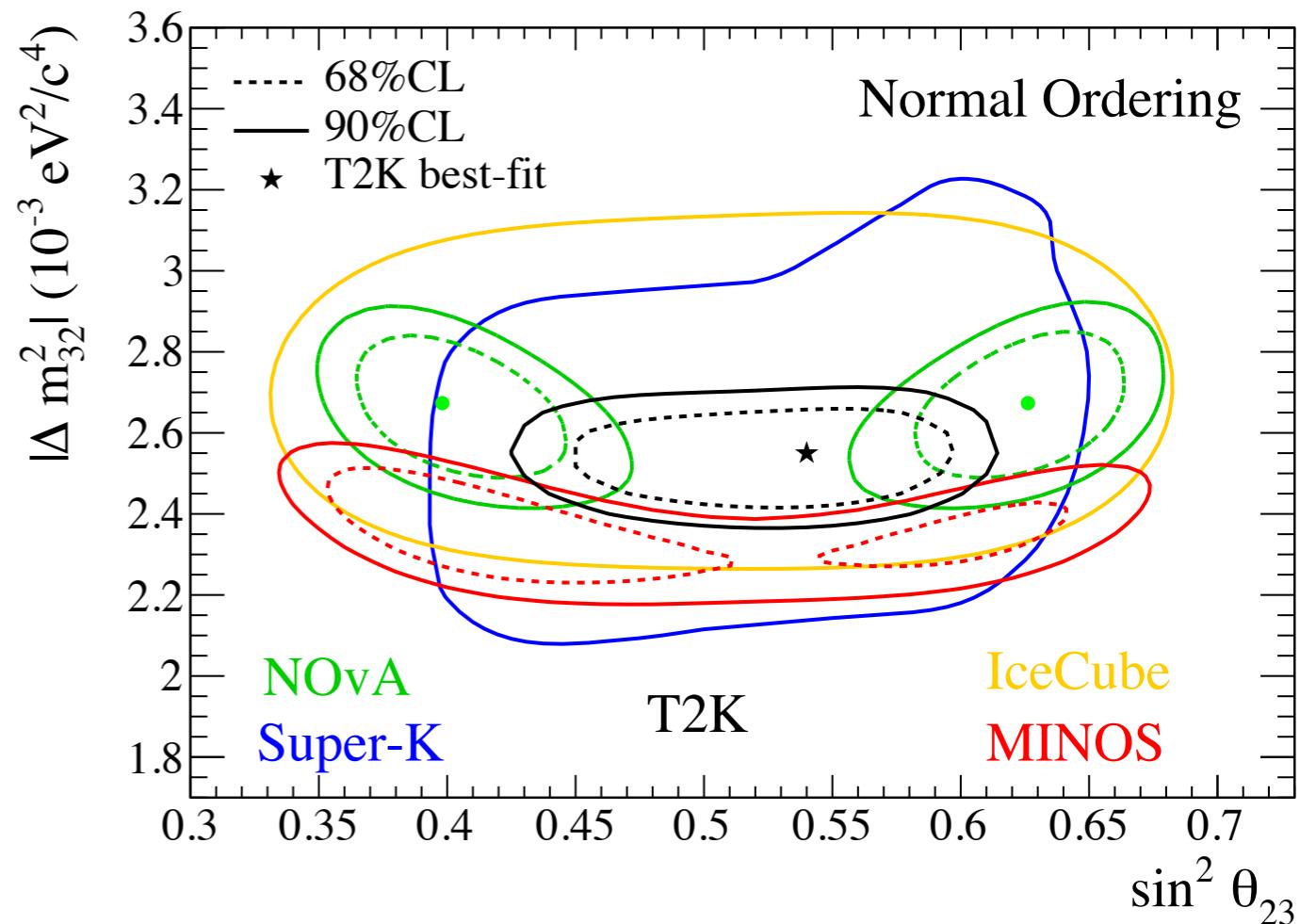




# NOvA $\nu_\mu$ disappearance

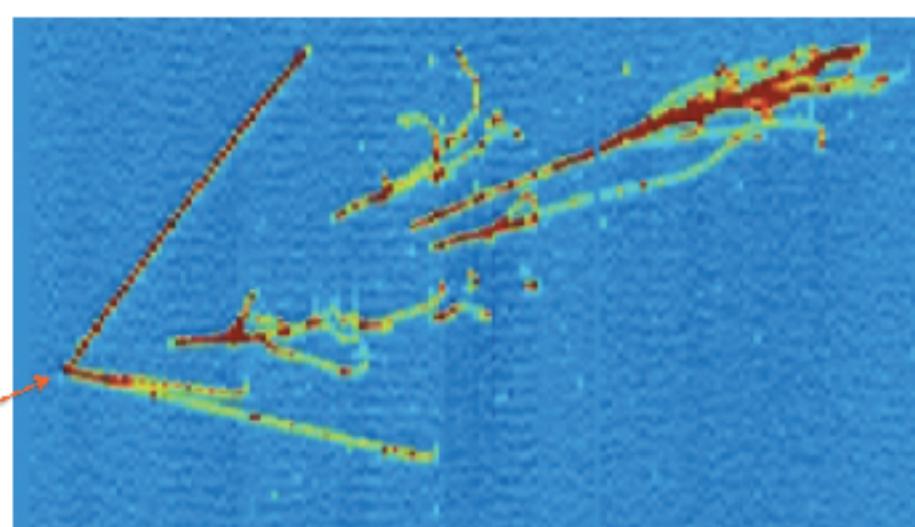
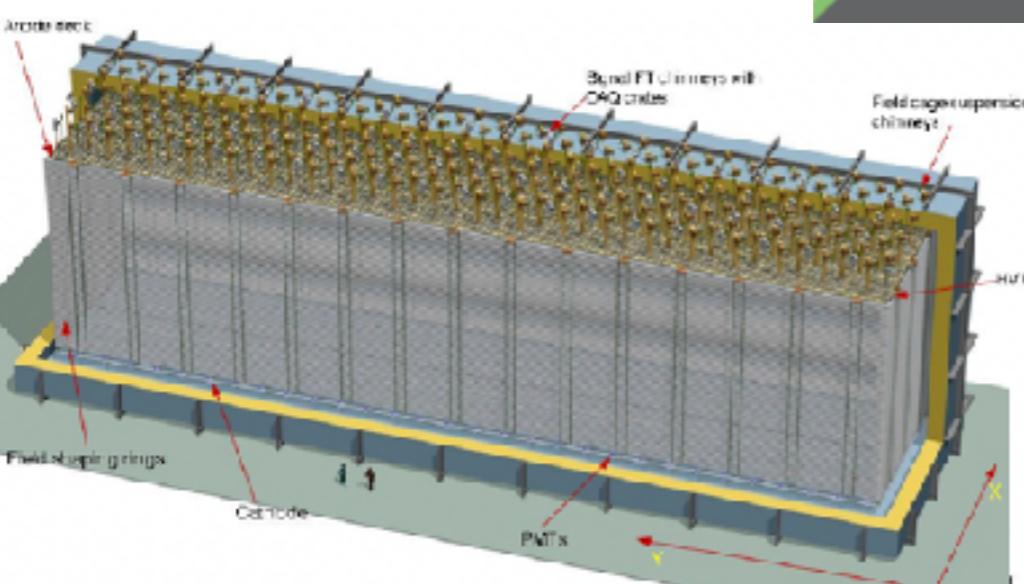
A tension between NOvA and T2K

- NOvA:  $\sin^2 \theta_{23} = 0.404^{+0.030}_{-0.022}$ , or  $0.624^{+0.022}_{-0.030}$
- T2K:  $\sin^2 \theta_{23} = 0.534^{+0.046}_{-0.044}$

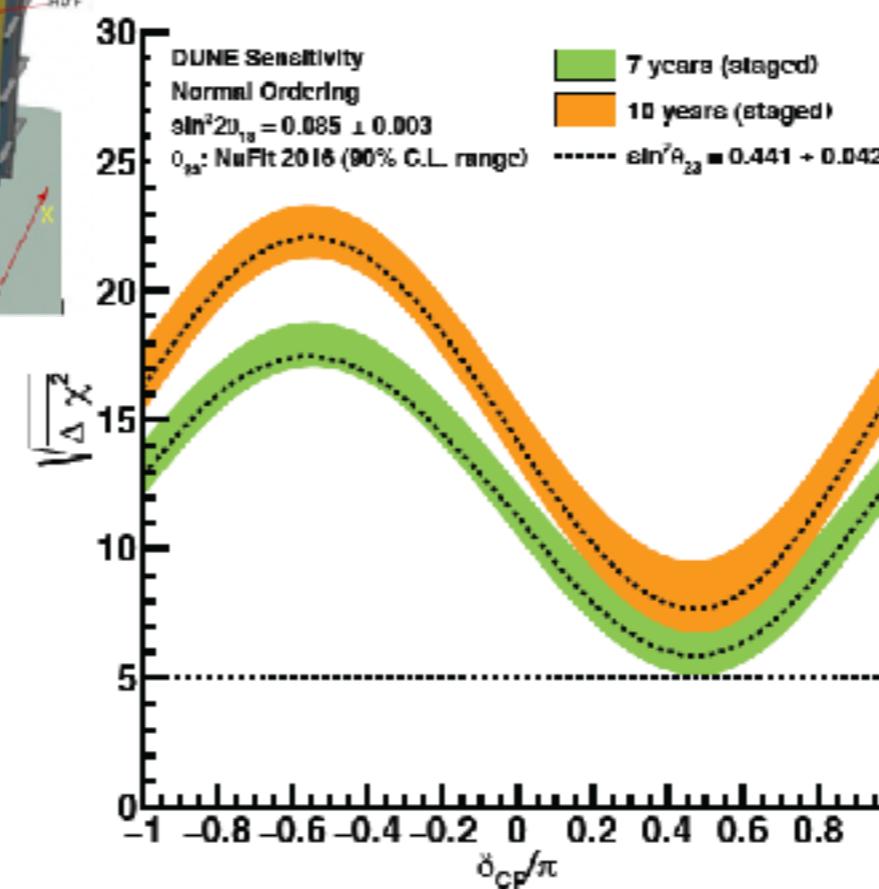


# DUNE

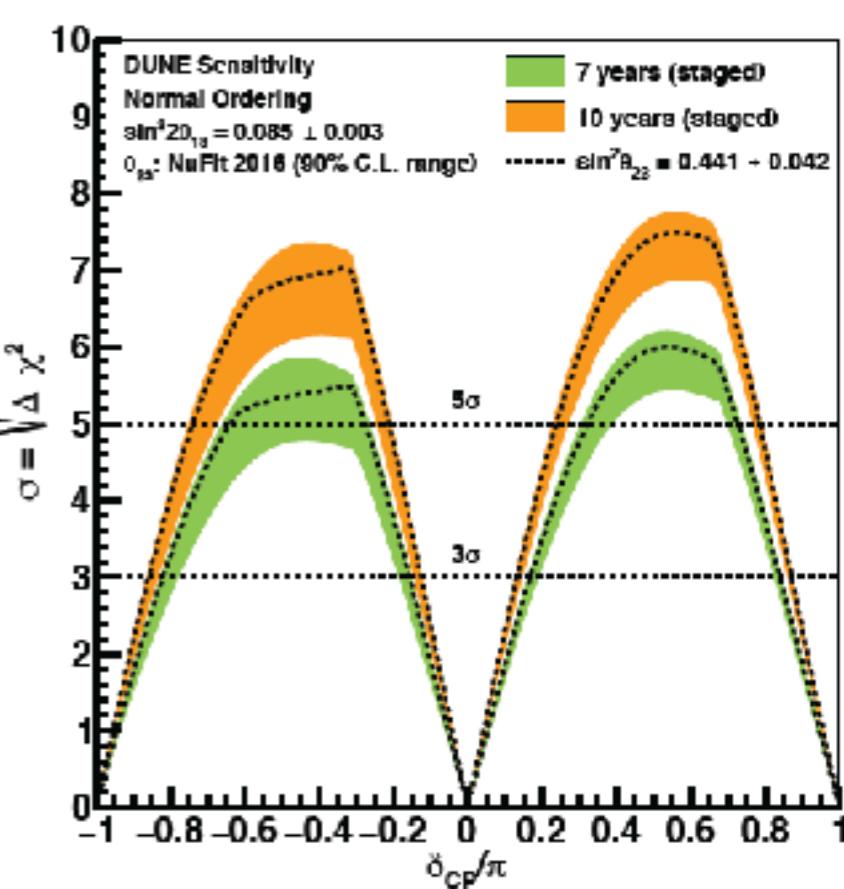
40 kton Lq. Ar TPC  
Starting around 2026



## Sensitivity Mass Hierarchy



## CP Violation

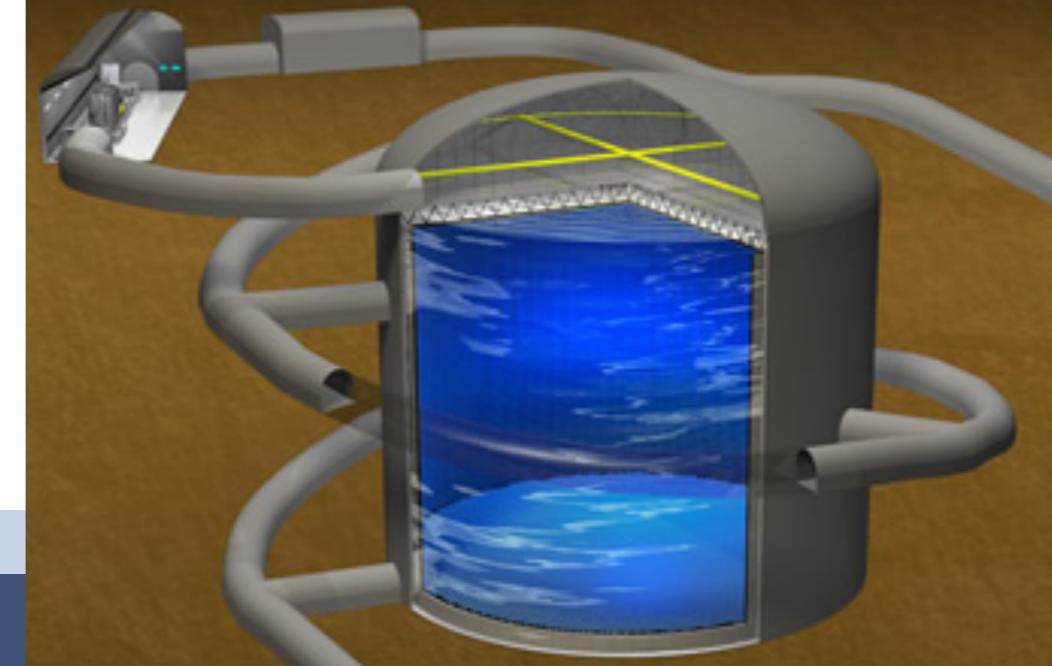


# Hyper-Kamiokande

190 kton Water Cherenkov

Starting around 2026

By Dr. Benjamin Richards



## $\delta_{\text{cp}}$ Comparison with DUNE

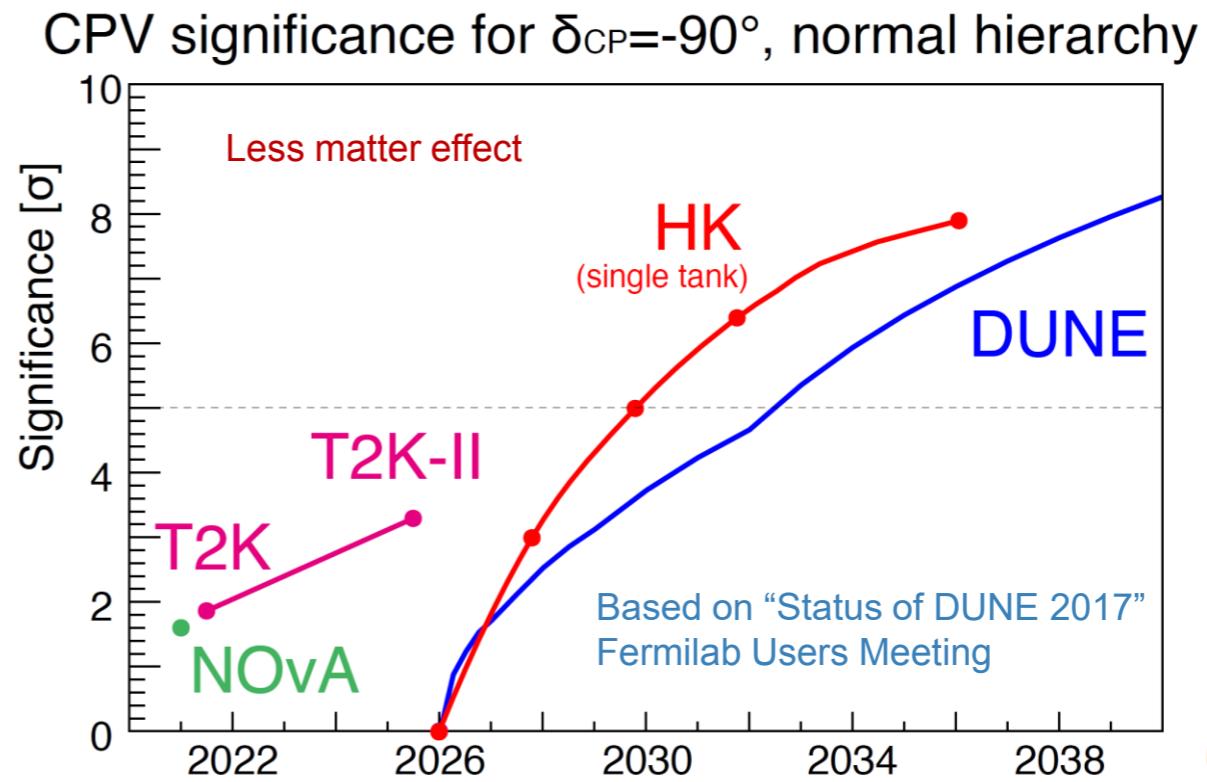
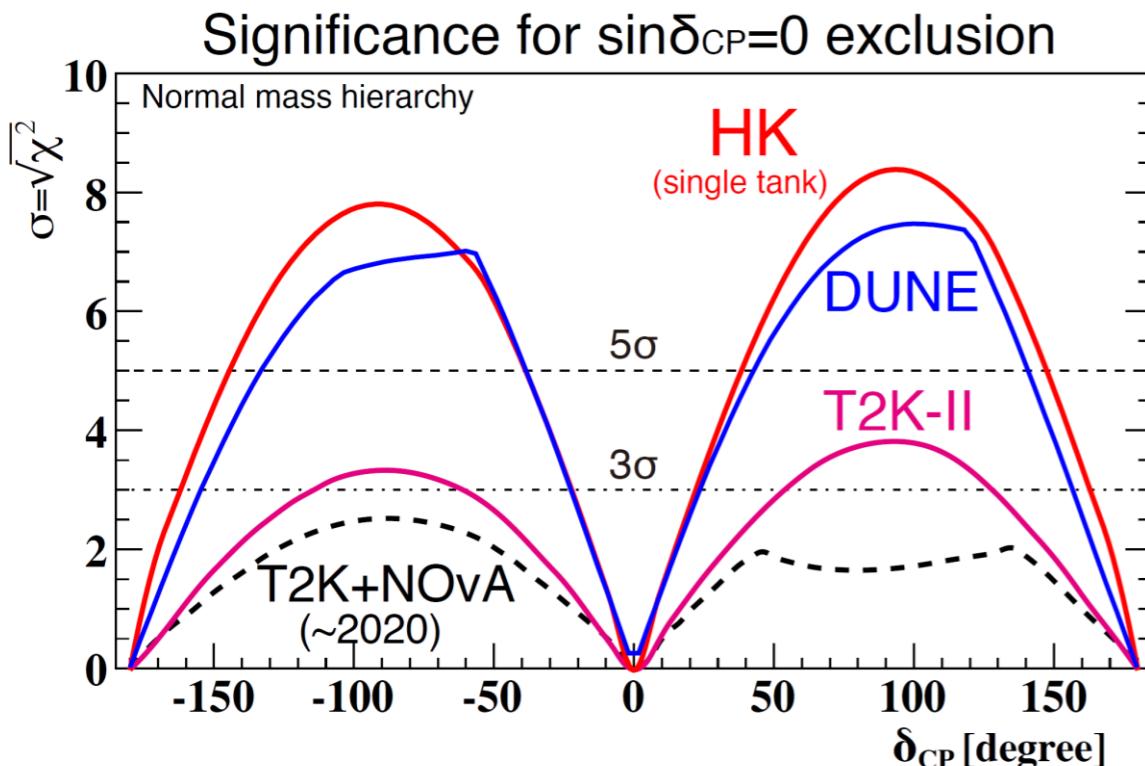
Exclusion of  $\sin\delta_{\text{cp}} = 0$

- $>8\sigma(6\sigma)$  for  $\delta_{\text{cp}} = -90^\circ(-45^\circ)$
- $\sim 80\%$  coverage of  $\delta_{\text{cp}}$  parameter space with  $>3\sigma$

## Sensitivity

$\sin\delta=0$  exclusion

$>3\sigma$	$>5\sigma$
78%	62%



A comparison strongly depends on the assumptions. Don't take it seriously!

# **SBL Accelerator Experiments**

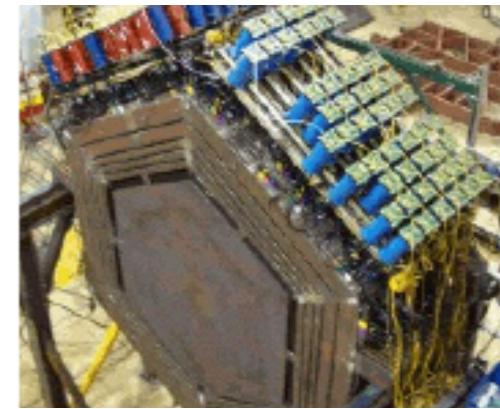
# SBL Accelerator Experiments

	Site	Energy (GeV)	Detector	Target
MiniBooNE	FNAL BNB	~1	Oil Cherenkov	LSND Anomaly
* MicroBooNE	FNAL BNB	~1	Lq. Ar TPC	MIniBooNE
* MINERvA	FNAL NuMI	2~10	Scinti. Tracker	$\nu$ Cross Section
* SBND	FNAL BNB	~1	Lq. Ar TPC	Steile $\nu$
J-PARC IWC	J-PARC MR	0.5~1	Water Cherenkov	$\nu$ Spectrum
nuSTORM	TBD	~1	TBD	$\nu$ Cross Section
ENUBET	TBD	~1	TBD	$\nu_e$ Cross Section
IsoDAR	TBD	~0.01	Lq. Sinti.	Steile $\nu$
$\mu$ DAR	TBD	~0.05	Water Cherenkov	CP violation
* ICRARUS@SBN	FNAL BNB	~1	Lq. Ar TPC	Sterile $\nu$
* JSNS <sup>2</sup>	J-PARC RCS	~0.05	Lq. Scinti.	Sterile $\nu$

- Main targets of the SBL experiments are the search for sterile neutrinos and the measurements of cross sections.

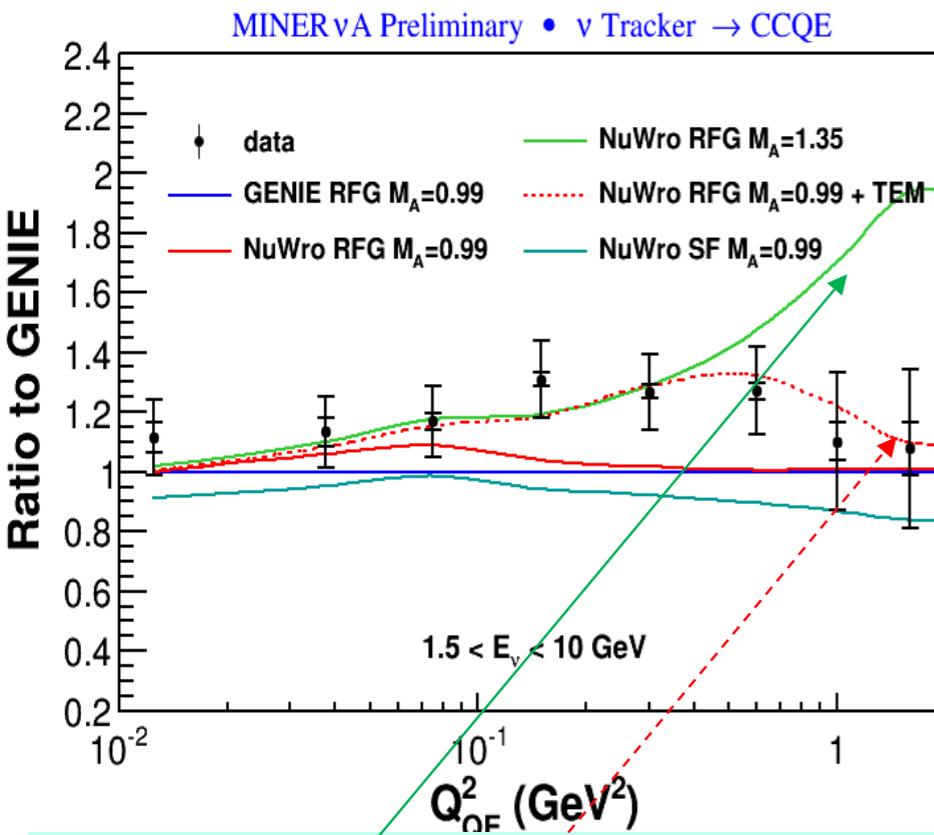
# MINERvA

by Dr. Arie Bodek

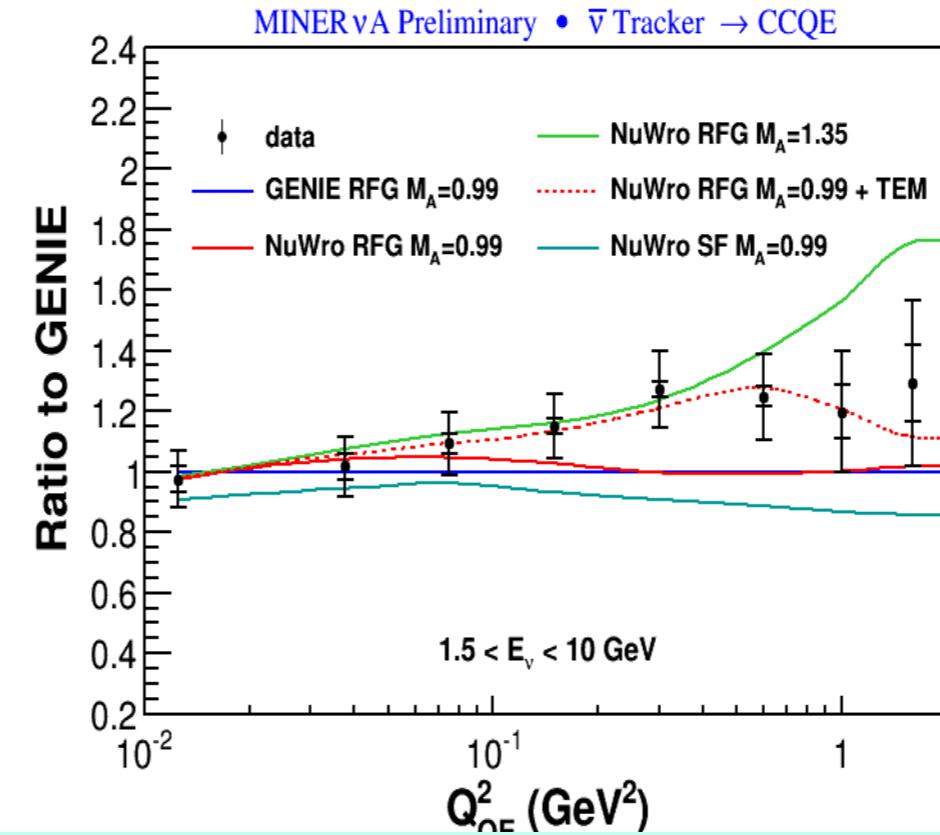


- Understanding of Neutrino Cross Section is important for Neutrino Oscillation measurements.
  - The neutrino energy reconstructed is not equal to the true energy.

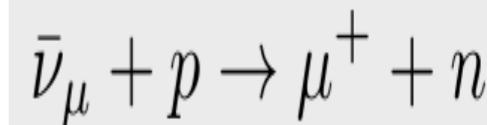
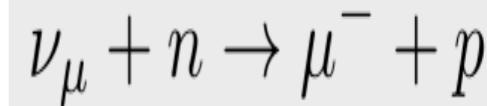
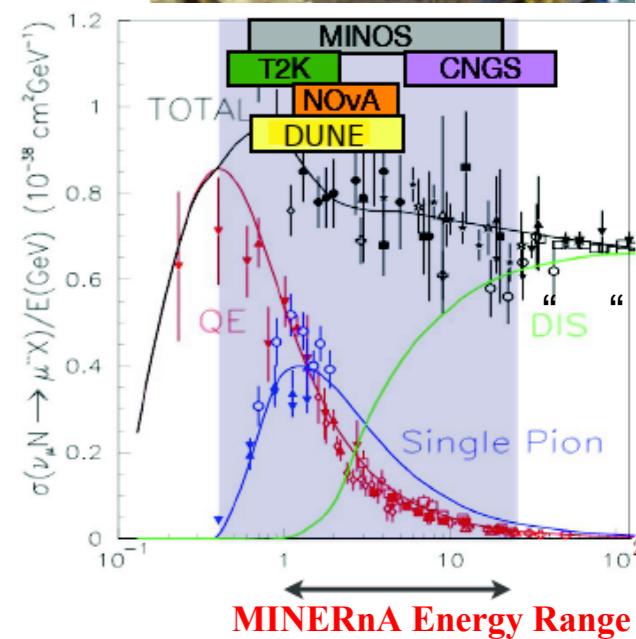
## CCQE neutrinos



## CCQE antineutrinos



Both results prefer models with additional interactions involving multi-nucleons → More later



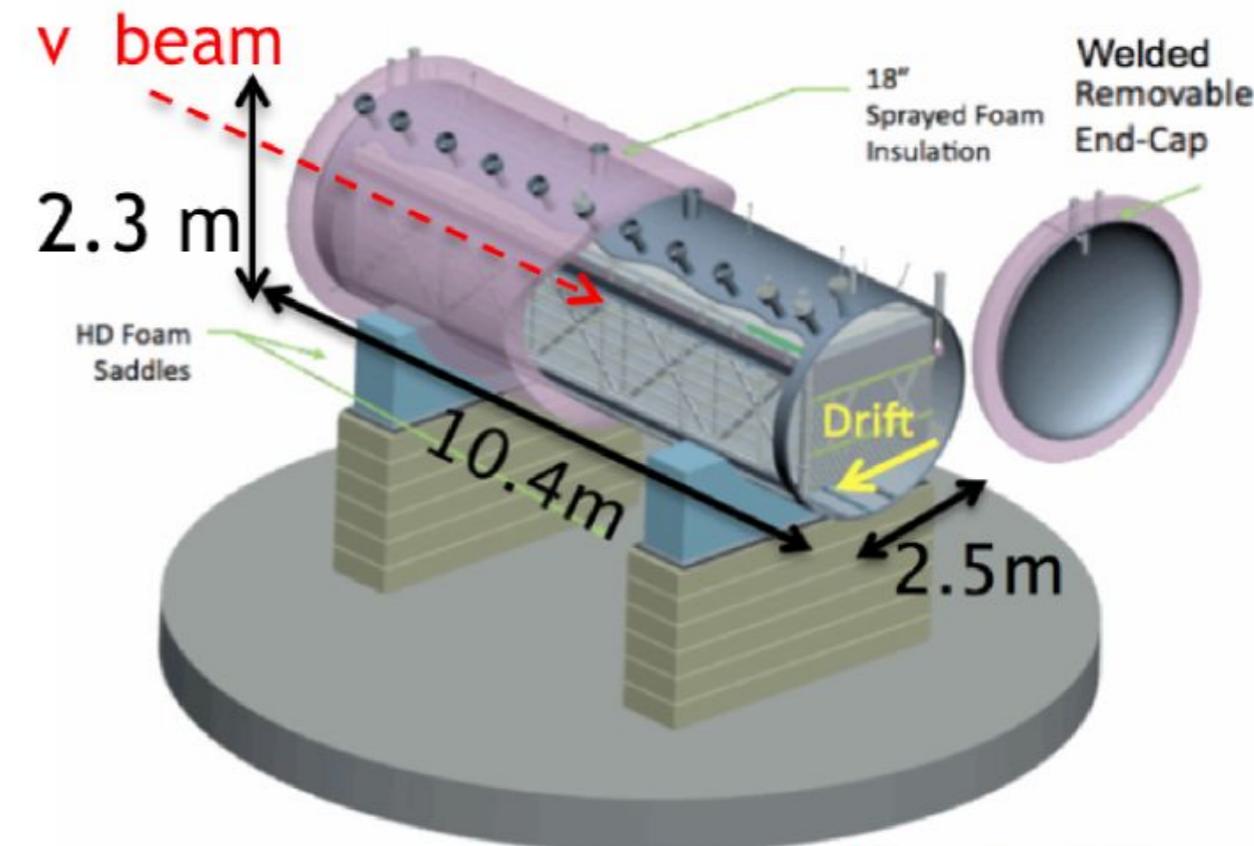
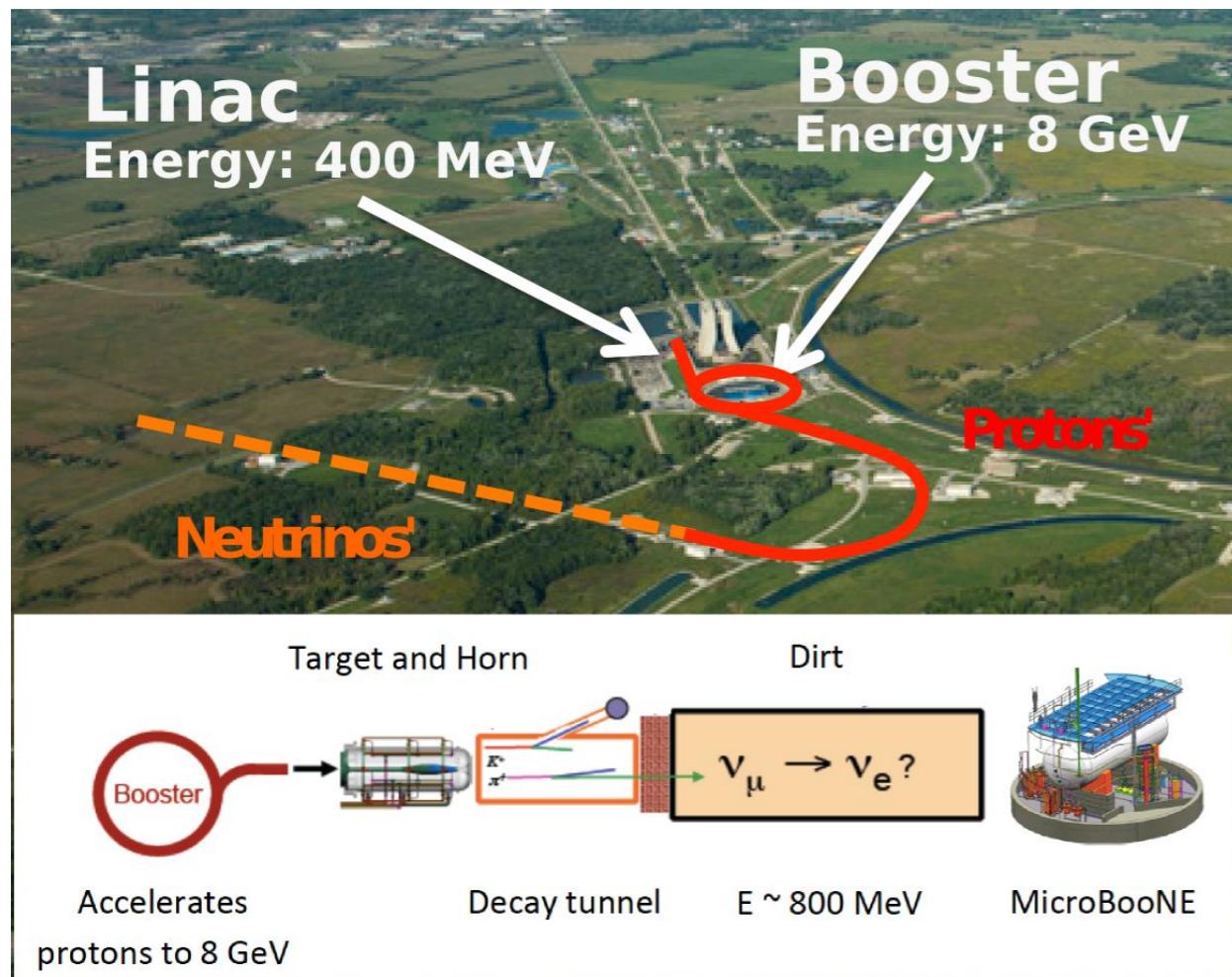
Used as the “Standard Candle” disappearance signal channel in oscillations experiments:

# MicroBooNE

## @ FNAL BNB

by Dr. Martin Auger

### The Booster Neutrino Beam

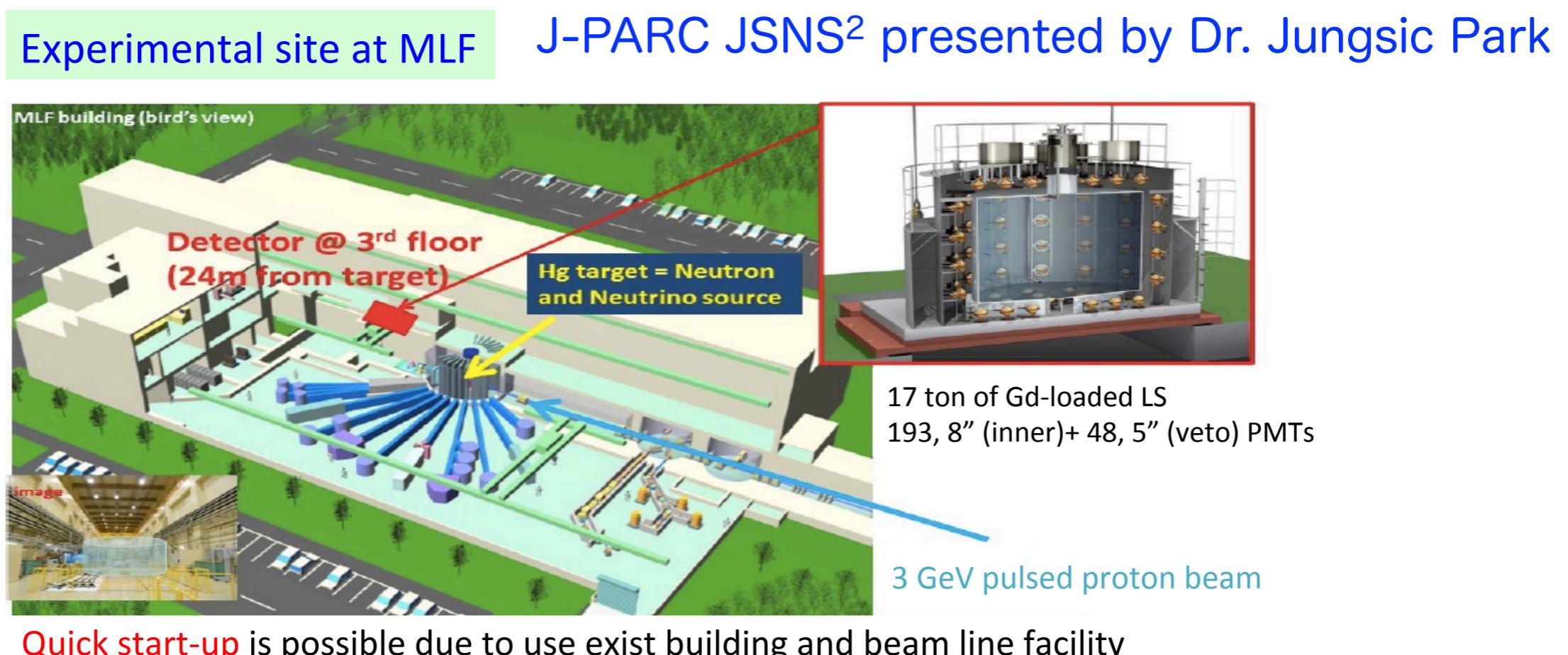


Proton bunches reach the target at a rate of up to 5Hz. This beam will also be the crux of the complete SBN program:

- **SBND (2019):**
  - 110m from target
  - 112 tons liquid argon
- **MicroBooNE (since Oct. 2015):**
  - 470m from target
  - 87 tons liquid argon
- **ICARUS T-600 (2018):**
  - 600m from target
  - 476 tons liquid argon

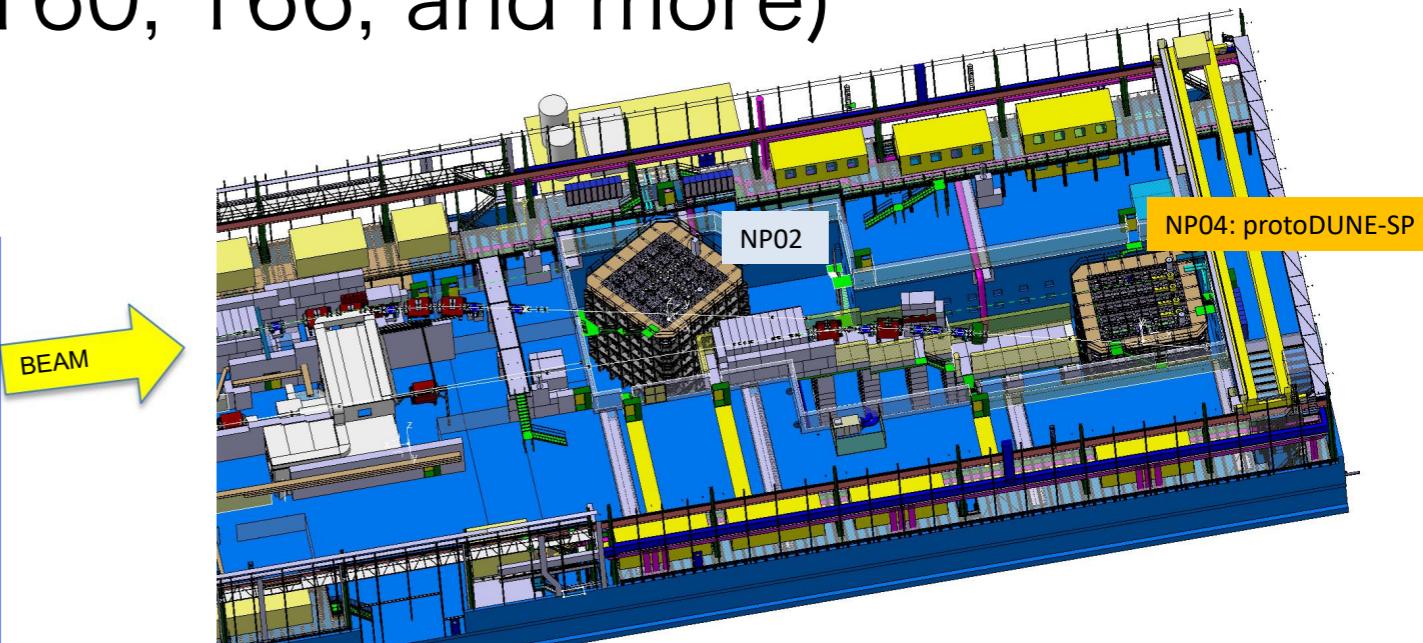
# Sterile $\nu$ experiments

- Several SBL accelerator experiments are hunting sterile neutrinos. So far, there is no positive result except for original LSND and MiniBooNE. The situation will be more clear in a couple of years.



# Detector developments for the future

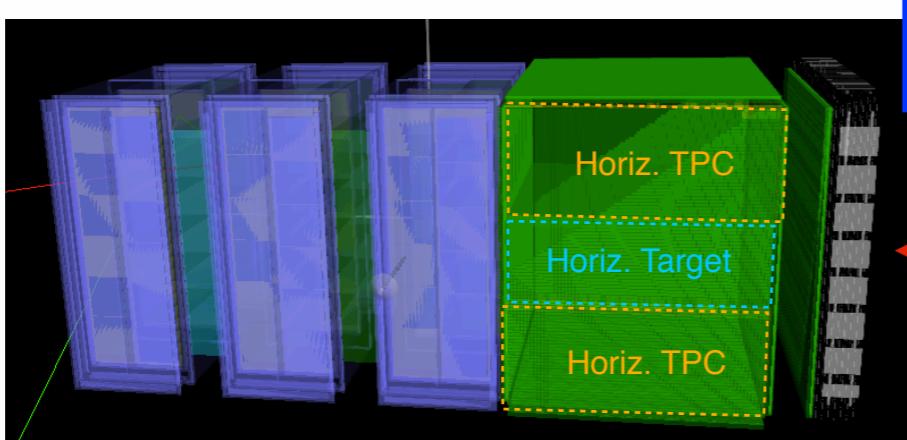
- CERN Neutrino Platform (NP01, ⋯, NP05, and more)
- J-PARC  $\nu$  test beam (T59, T60, T66, and more)
- FNAL test beam



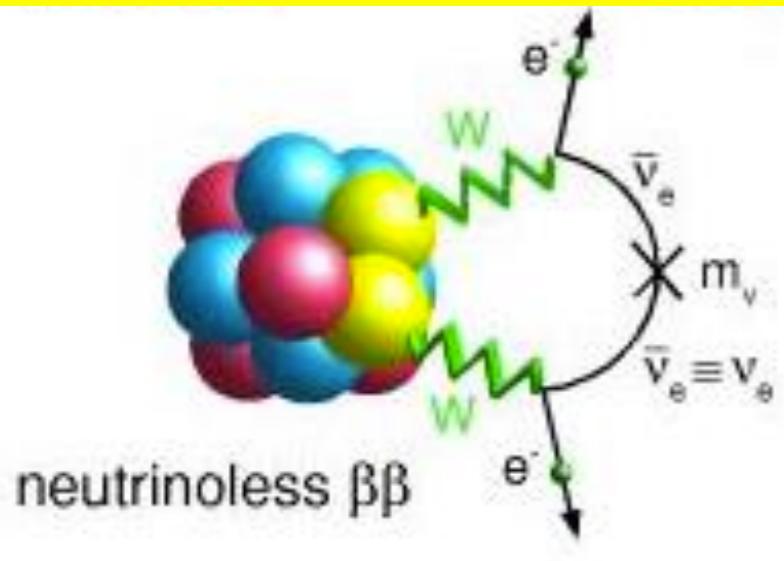
- 6 Projects presented to the SPSC and approved:

- ✓ NP01: WA104, ICARUS as far detector for the US SBN
- ✓ NP02: protoDUNE WA105, demonstrator + engineering prototype for a double ph. TPC
- ✓ NP03: PLAFOND, an generic R&D framework
- ✓ NP04: ProtoDUNE, engineering prototype for a single phase TPC
- ✓ NP05: Baby Mind, a muon spectrometer for the WAGASCI experiment at T2K
- ✓ Argon Cube : a modular TPC R&D

- A few Projects in the pipeline : T2K near detector, DUNE near detector, HPgas TPC, ENUBET, ....



T2K Near Detector Upgrade@CERN NP  
CERN SPSC-EOI-015  
for T2K-II presented by Dr. Davide Sgalaberna



# 0νββ Experiments

$M_\nu \neq 0$

$\nu = \bar{\nu} ?$

2 mass eigenstates

N Seesaw

GUT

Big Bang

Matter dominance

Afterglow Light Pattern 375,000 yrs.

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy Accelerated Expansion

Inflation

Quantum Fluctuations

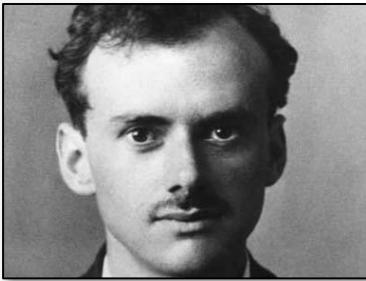
1st Stars about 400 million yrs.

WMAP

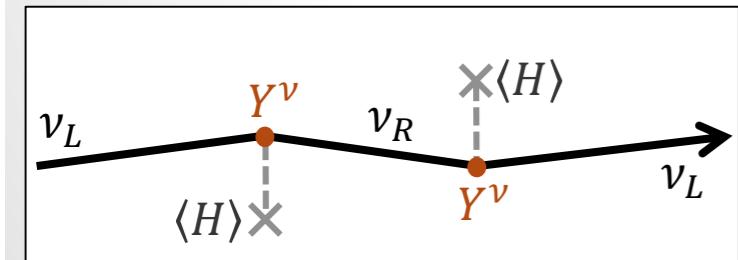
Big Bang Expansion 13.77 billion years

by J. Shirai @ NEUTRINO2016

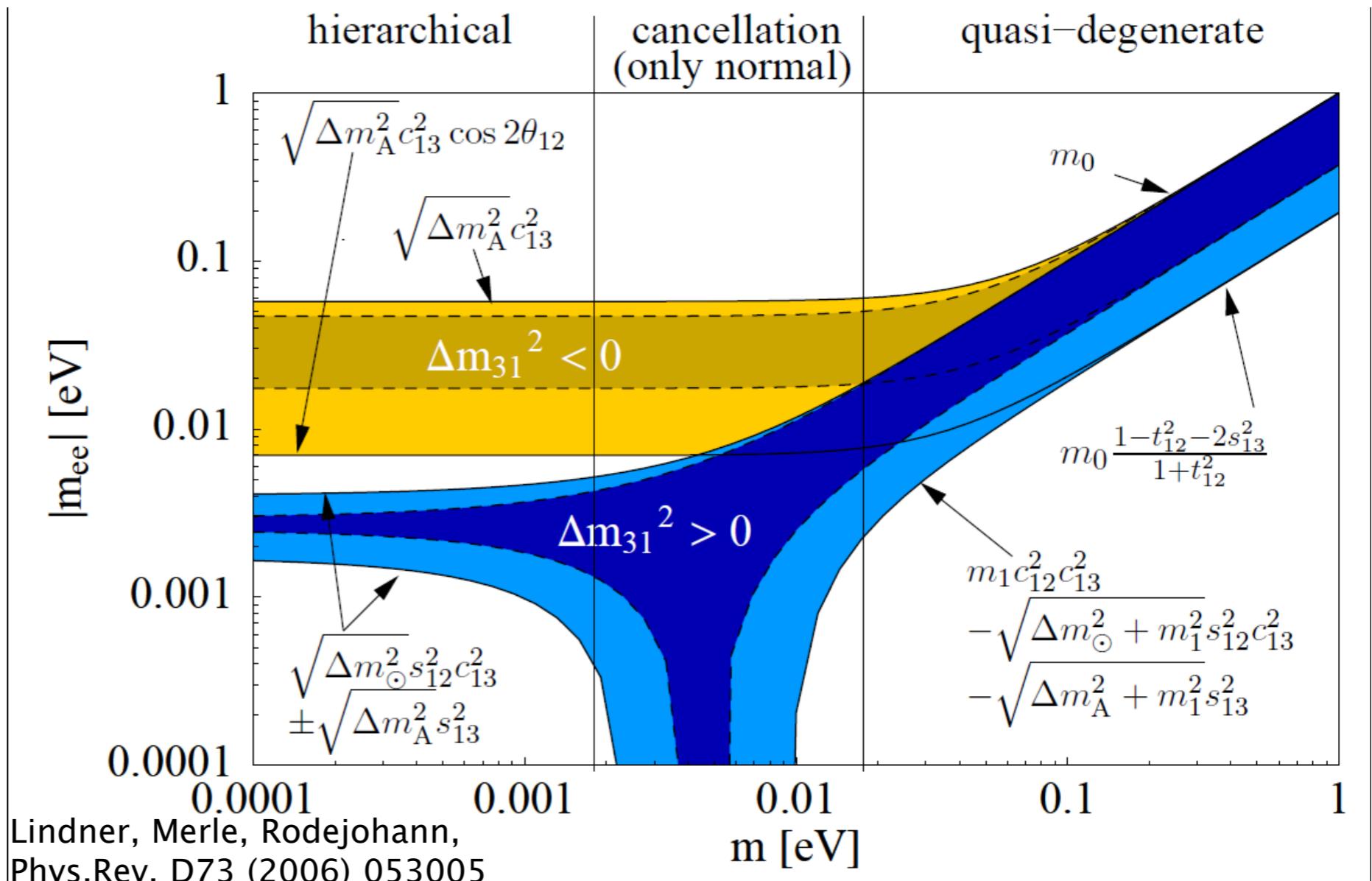
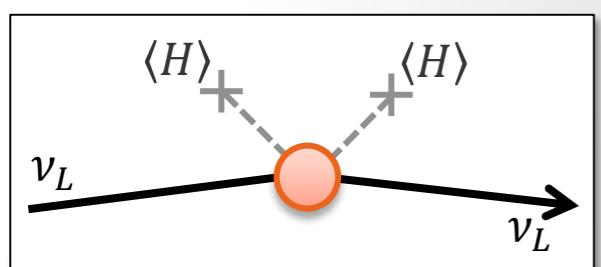
# $\nu$ mass with Dirac?, Majorana?



Dirac mass analogous to other fermions but with  $m_\nu/\Lambda_{EW} \approx 10^{-12}$  couplings to Higgs



Majorana mass, using only a left-handed neutrino  
 $\rightarrow$  Lepton Number Violation

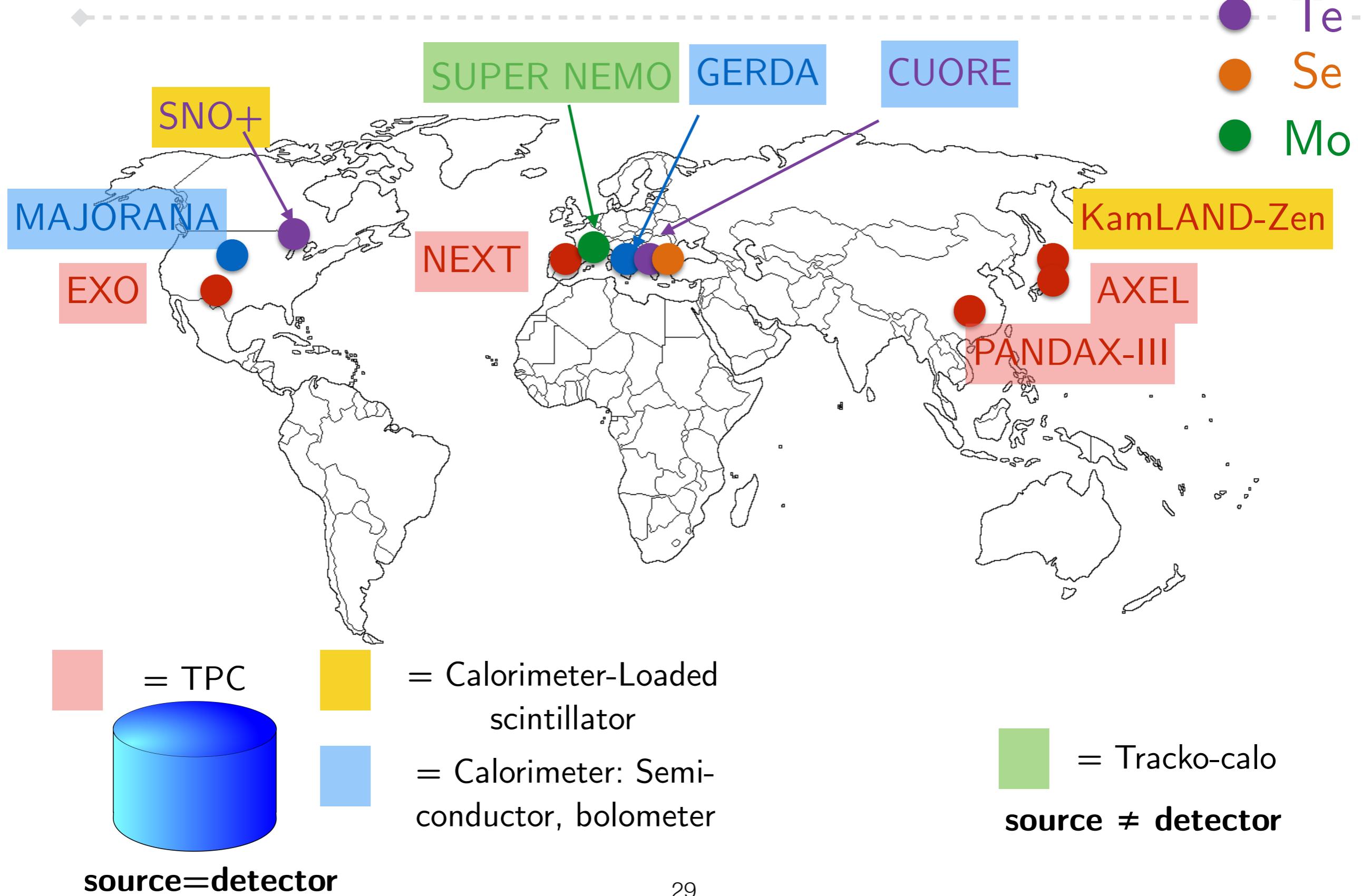


# $0\nu\beta\beta$ Experiments

	Source	Mass (kg)	Detector	Sensitivity $\tau_{1/2}$ (yr)	Sensitivity $m_{\beta\beta}$ (meV)	Background (/kev/kg/yr)
* GERDA	$^{76}\text{Ge}$	43.4	HPGe	$5.3 \times 10^{25}$	150-330	$10^{-3}$
* CUORE/Cuoricino	$^{130}\text{Te}$	206	Bolometers	$9 \times 10^{25}$	50-130	0.01
* NEXT	$^{136}\text{Xe}$	100	HP-TPC	$6 \times 10^{25}$	200	$4 \times 10^{-4}$
CUPID	$^{82}\text{Se}$	5.2	Bolometers			$\sim 0$
SNO+	$^{130}\text{Te}$	1300	Lq. Scinti	$2 \times 10^{25}$	40	$5 \times 10^{-5}$
* SuperNEMO	$^{82}\text{Se}$	100	Tracker	$10^{26}$	40-110	
* KamLAND-Zen	$^{136}\text{Xe}$	383	Lq. Scinti	$1 \times 10^{26}$	61-165	$1.6 \times 10^{-4}$
AXEL	$^{136}\text{Xe}$	100	HP-TPC			
PANDAX-III	$^{136}\text{Xe}$	200	HP-TPC	$5 \times 10^{25}$	90-230	$1 \times 10^{-4}$
* EXO	$^{136}\text{Xe}$	76.5	Lq-TPC	$1.1 \times 10^{25}$	190-450	$1.7 \times 10^{-3}$
LEGEND	$^{76}\text{Ge}$	1000	HPGe			

- The target of new results sounds like TAUP2017 this month.  
Stay tuned!

# Current $0\nu\beta\beta$ experiments

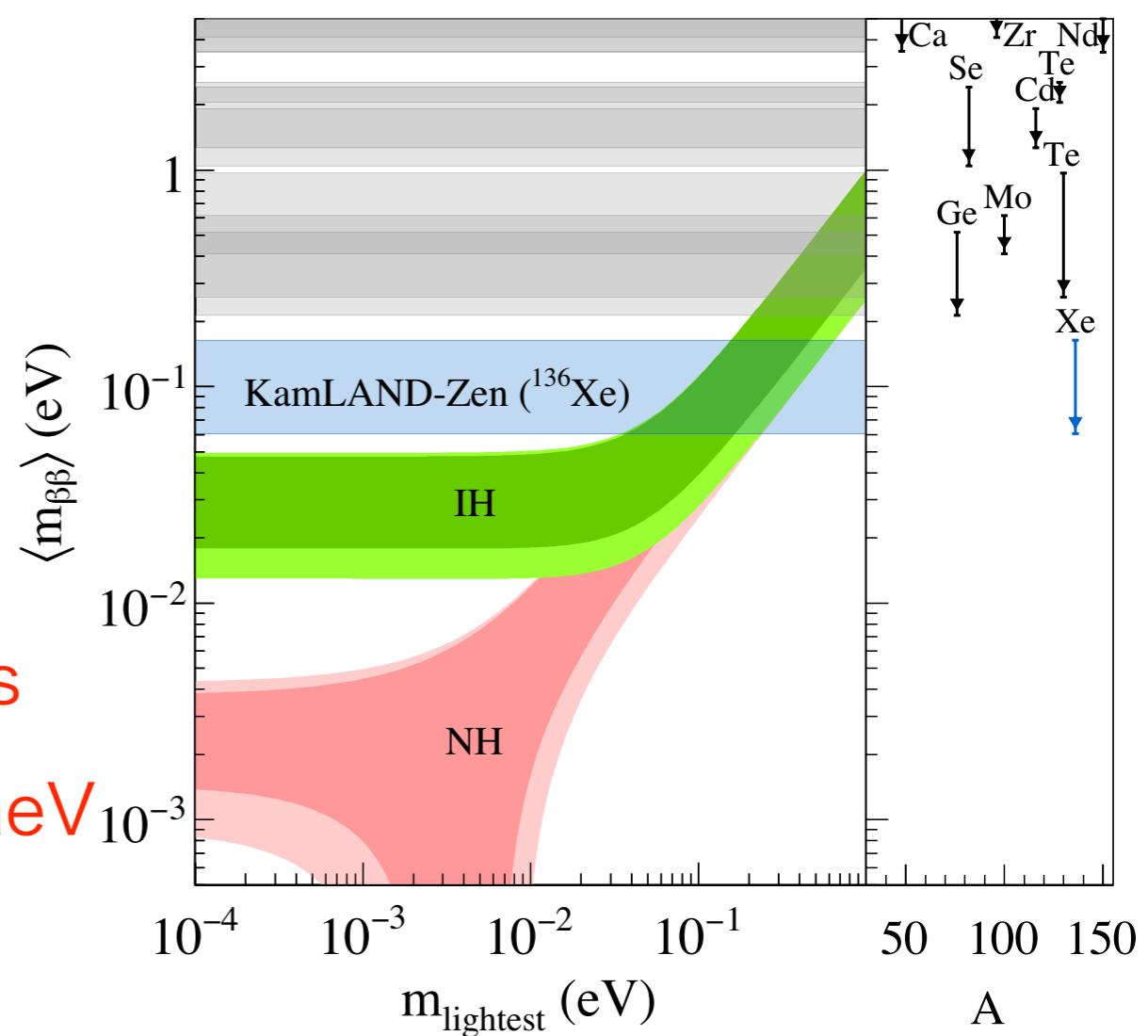
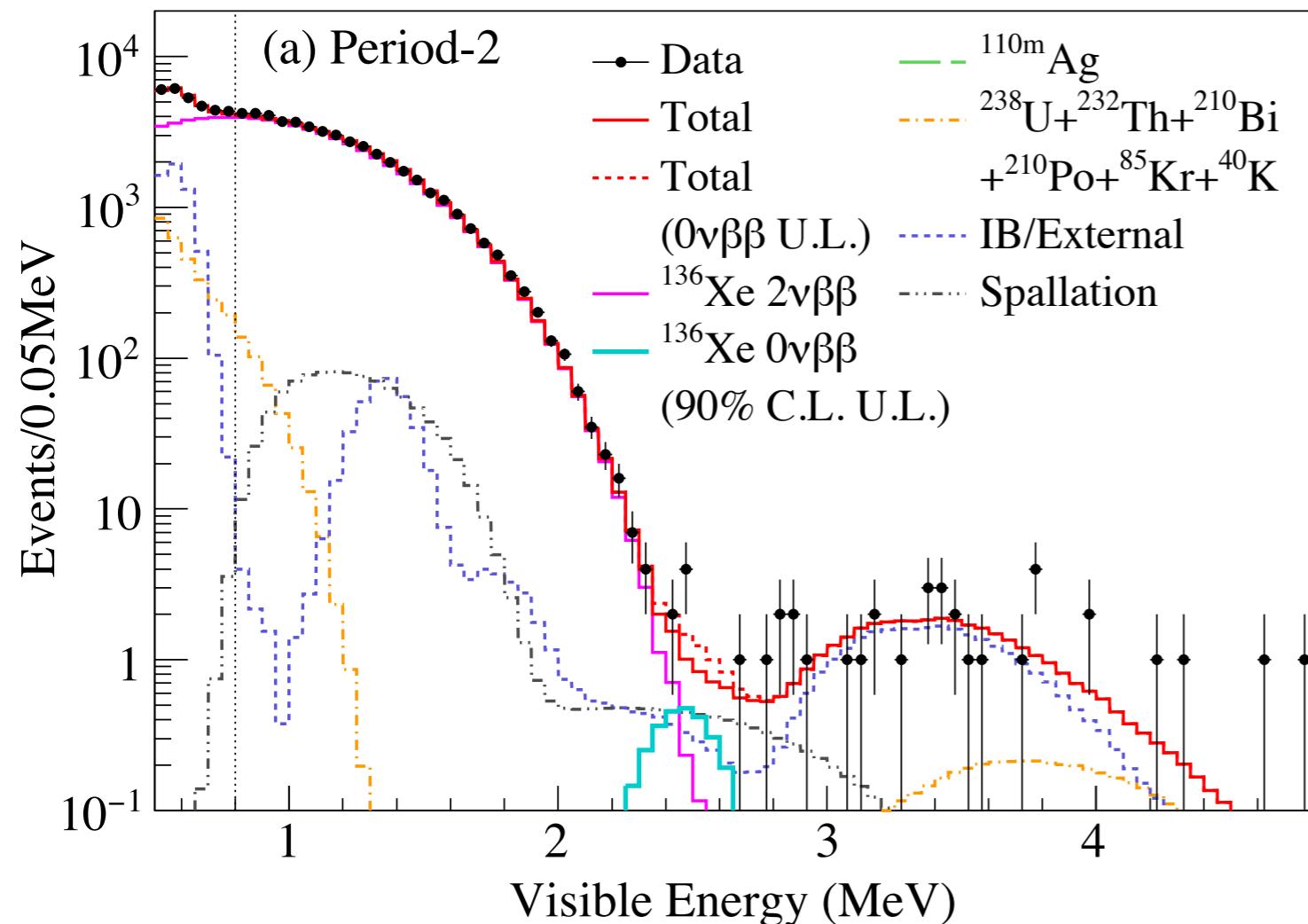




Zero Neutrino  
double beta decay search

# KamLAND-Zen

— Phys. Rev. Lett. 117, 082503 (2016) —

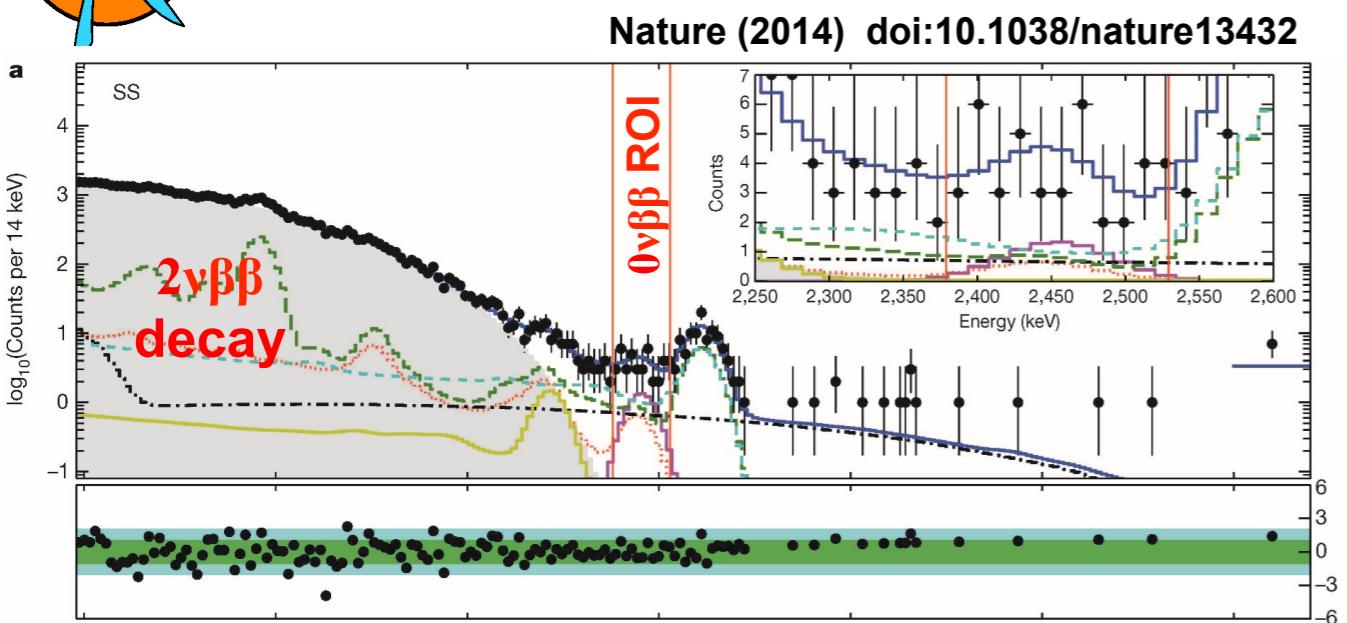


- Lifetime limit:  $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$  years
- $2\beta$  ν mass:  $\langle m_{\beta\beta} \rangle < (61 - 165)$  meV

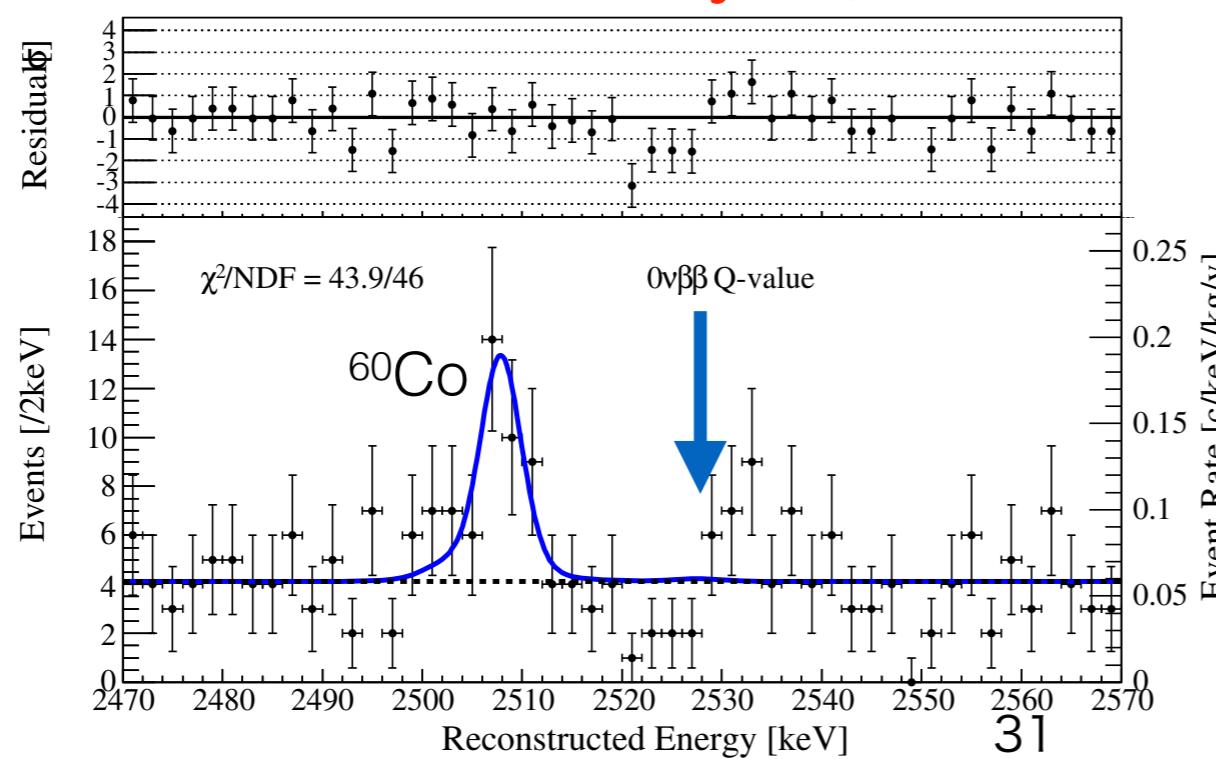
# Many results



- $T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}$  yr w/ Xe
- $\langle m_{\beta\beta} \rangle < (190-450)$  meV



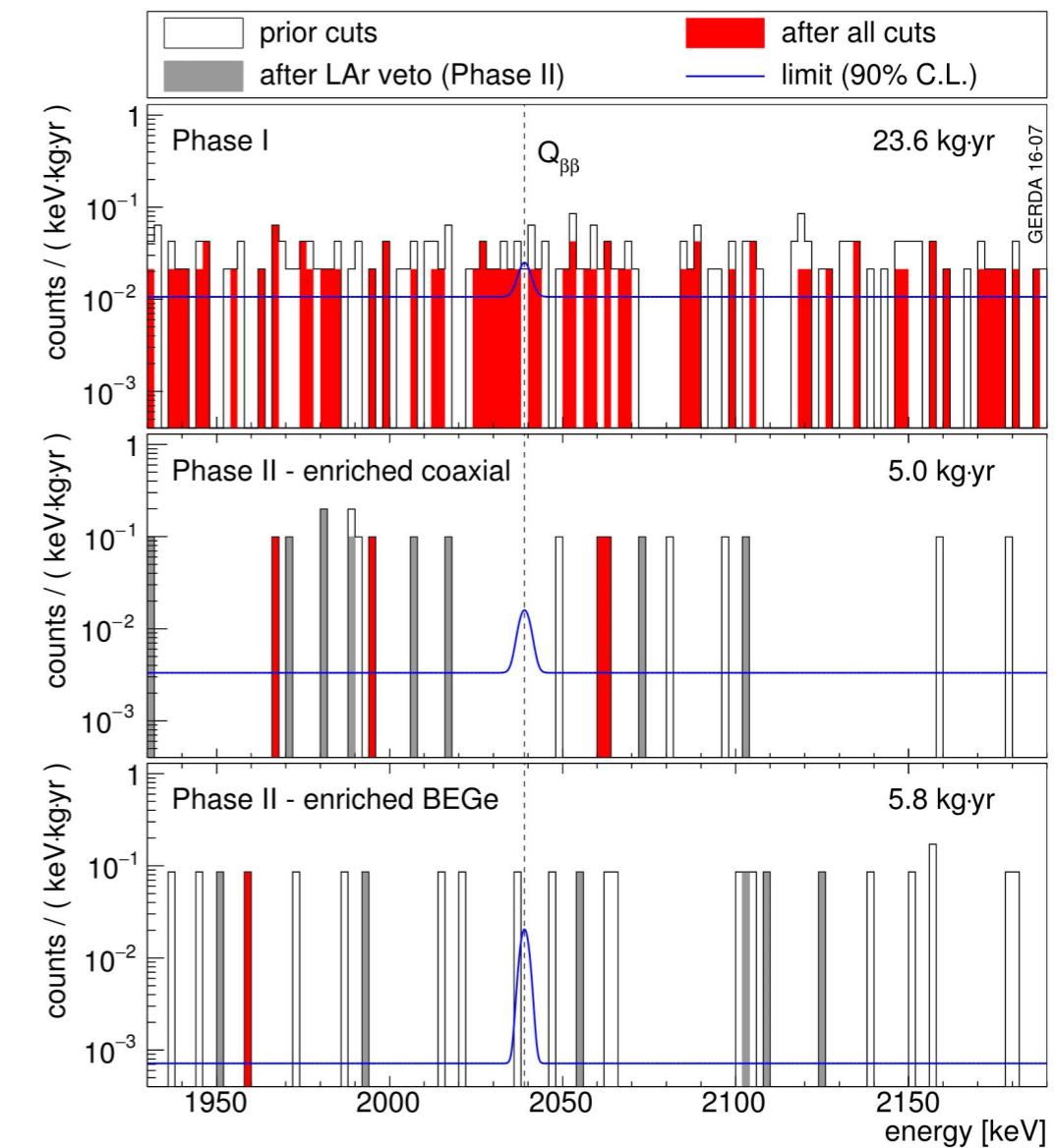
- $T_{1/2}^{0\nu\beta\beta} > 4 \times 10^{24}$  yr w/ Te



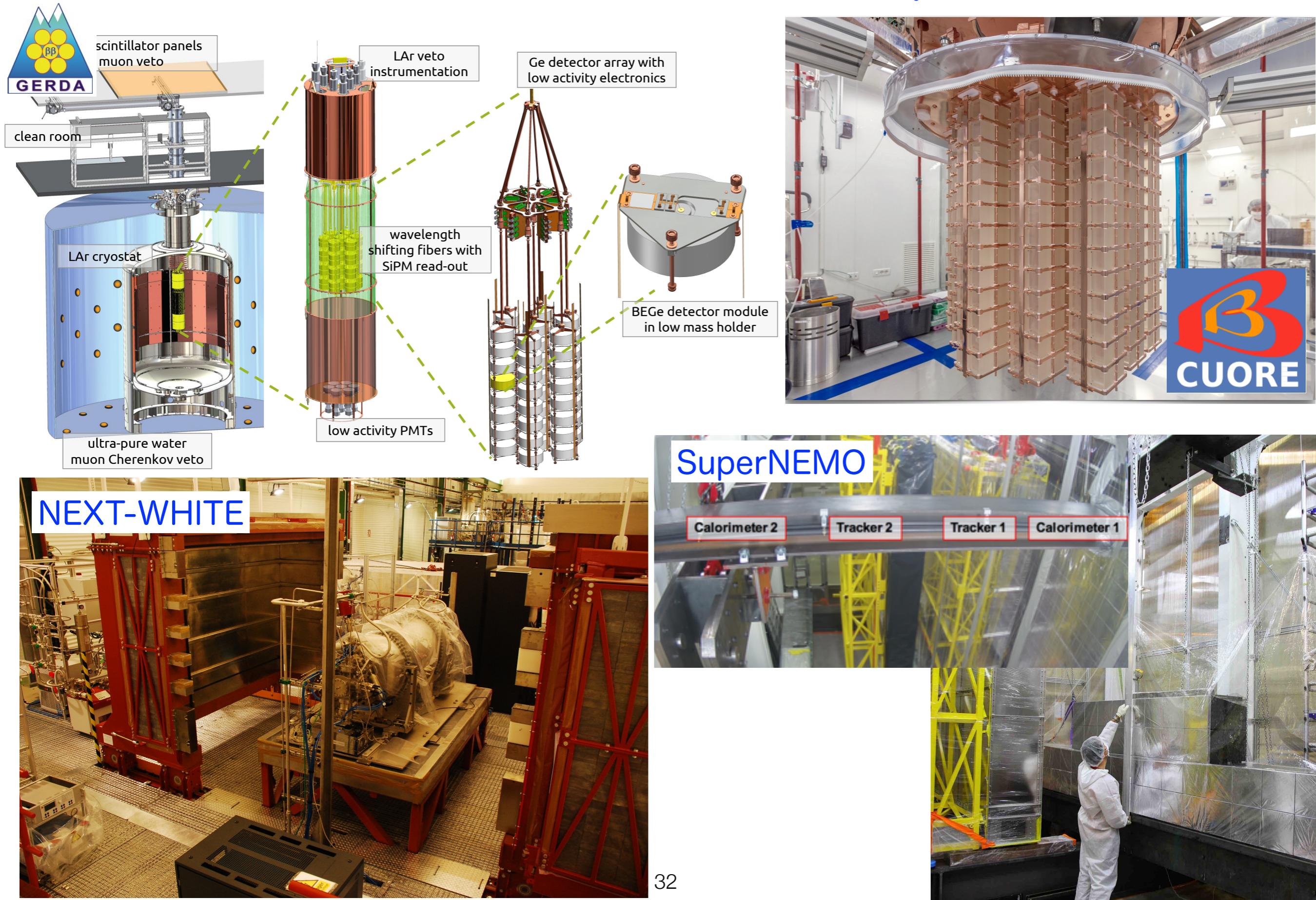
More and more experiments are running and being developed.



- $T_{1/2}^{0\nu\beta\beta} > 5.3 \times 10^{25}$  yr w/ Ge
- $\langle m_{\beta\beta} \rangle < (160-260)$  meV



# GERDA, CUORE, NEXT, Super-NEMO



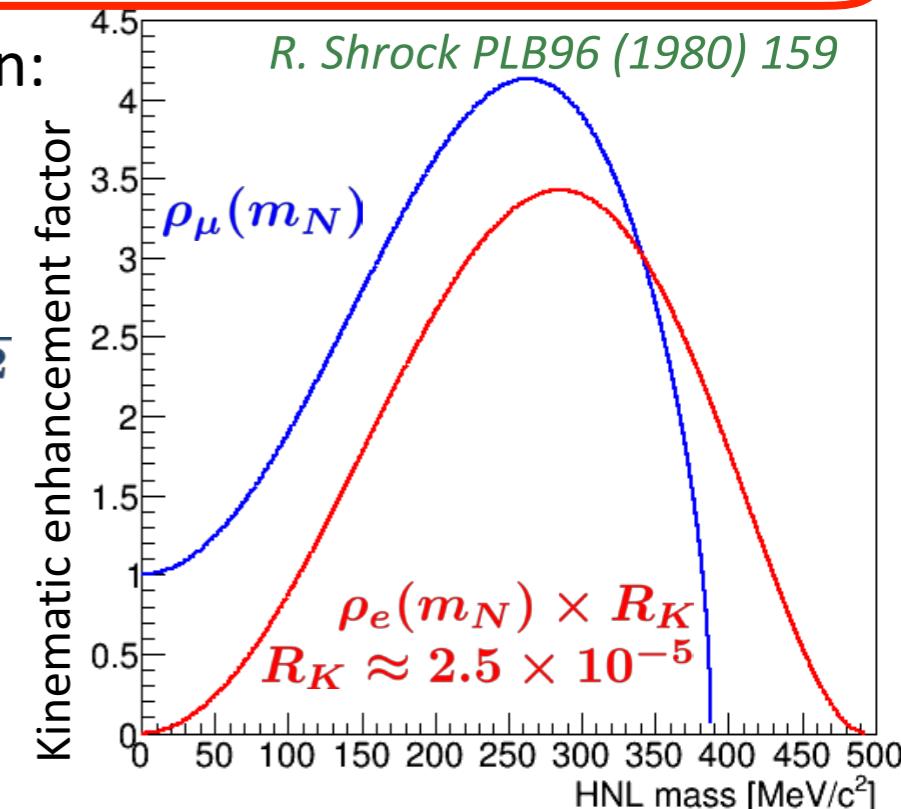
# **Exotic Search**



# Heavy Neutrino (Decay)

## Heavy Neutrino: Motivation

- Observation of neutrino oscillations → massive neutrinos need to be accommodated in SM
- Example of a SM extension: Neutrino Minimal SM ( $\nu$ MSM) [*Asaka et al., PLB 620 (2005) 17*]
  - 3 right-handed neutrinos  $N_i$  added to SM, masses:  $m_1 \sim 10 \text{ keV}$ ,  $m_{2,3} \sim 1 \text{ GeV}$
  - $N_1$ : dark matter candidate
  - $N_{2,3}$ : extra CPV-phases to account for Baryon Asymmetry, produce SM masses via see-saw mech
- If  $m_N < m_{K^+}$ , heavy neutrinos observable via production in:
 
$$\Gamma(K^+ \rightarrow l^+ N) = \Gamma(K^+ \rightarrow l^+ \nu_l) \rho_l(m_N) |U_{l4}|^2$$
- This talk: search for peaks in  $m_{miss}(K_{l2}) = \sqrt{(P_K - P_l)^2}$ 
  - NA62 2007 data sample:  $l = \mu$
  - NA62 2015 data sample:  $l = e$
- Other searches look for decays of heavy neutrinos (HN), e.g.
 
$$N \rightarrow \pi^\pm l^\mp, N \rightarrow \pi^0 \nu, \dots$$

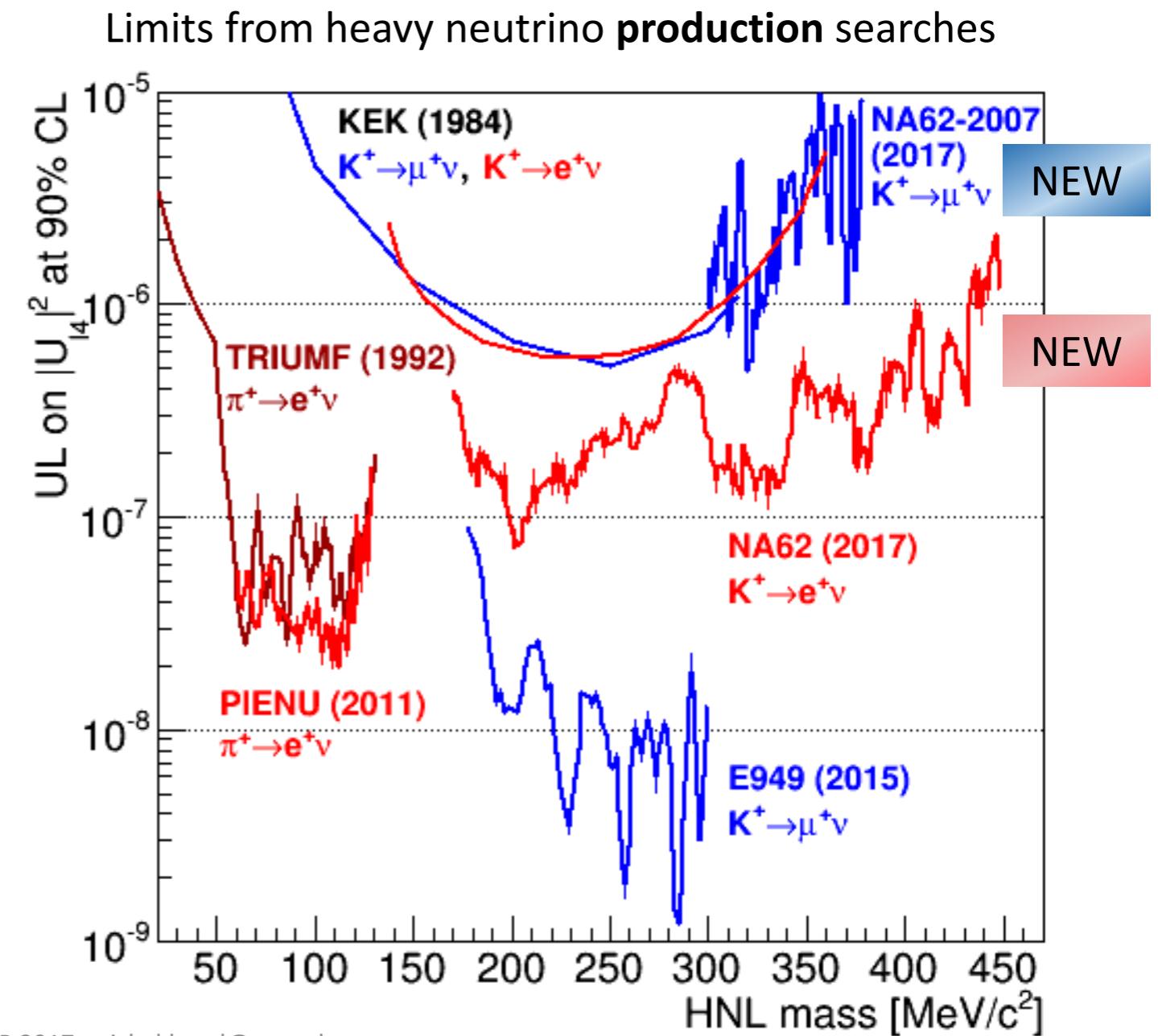




## Upper Limits on $|U_{l4}|^2$

$$|U_{l4}|^2 = \frac{\mathcal{B}(K^+ \rightarrow l^+ N)}{\mathcal{B}(K^+ \rightarrow l^+ \nu_l) \rho_l(m_N)}$$

- NA62 2007 data analysis:
  - Extends the mass range for upper limits on  $|U_{\mu 4}|^2$
  - Most stringent limit in  $m_N \in (300, 375) \text{ MeV}/c^2$
- NA62 2015 data analysis:
  - Reaches  $10^{-6} - 10^{-7}$  limits on  $|U_{e4}|^2$  in the range  $m_N \in (170, 448) \text{ MeV}/c^2$

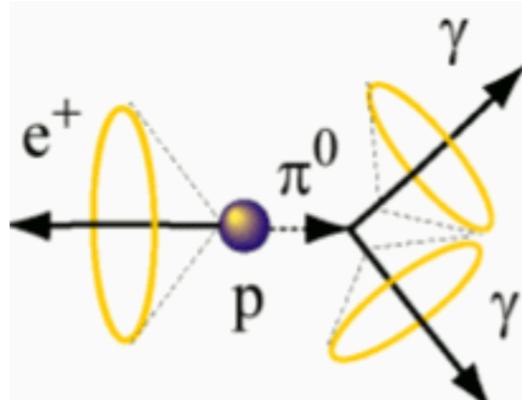


# Don't forget proton decay

By Dr. Luis Labarga

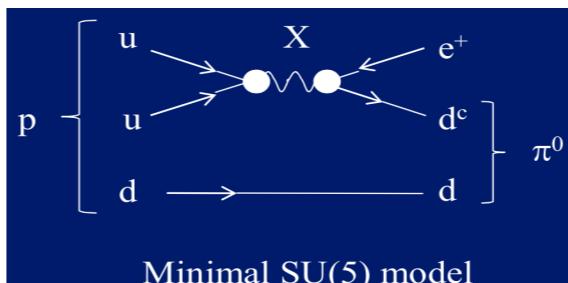
$$p \rightarrow e^+ \pi^0$$

- favored by non supersymmetric GUTs
- nearly model independent reaction

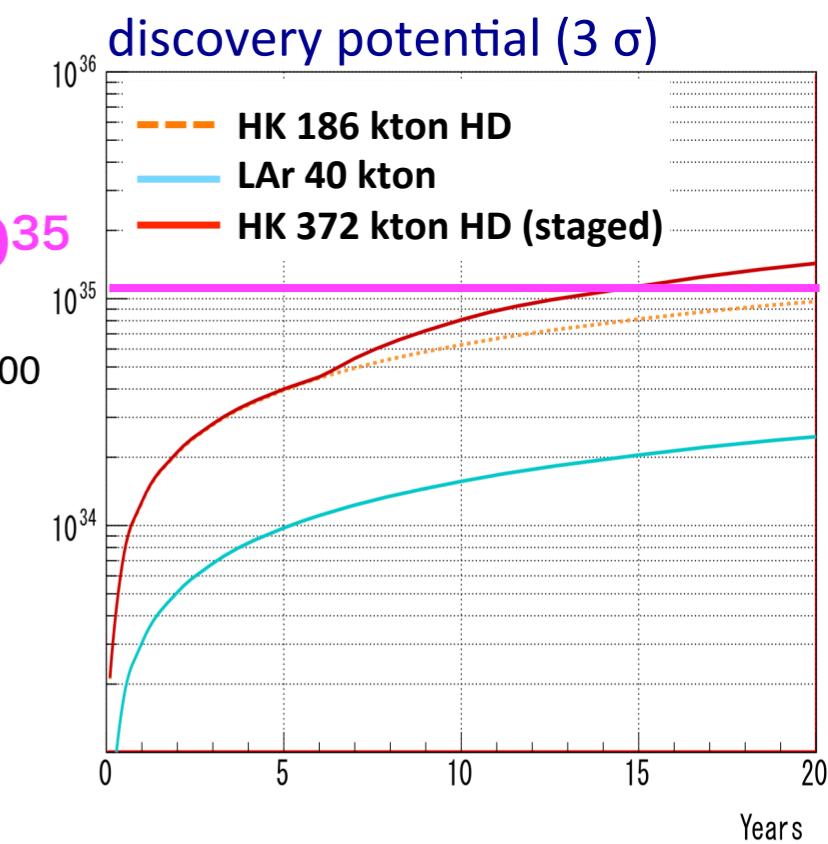
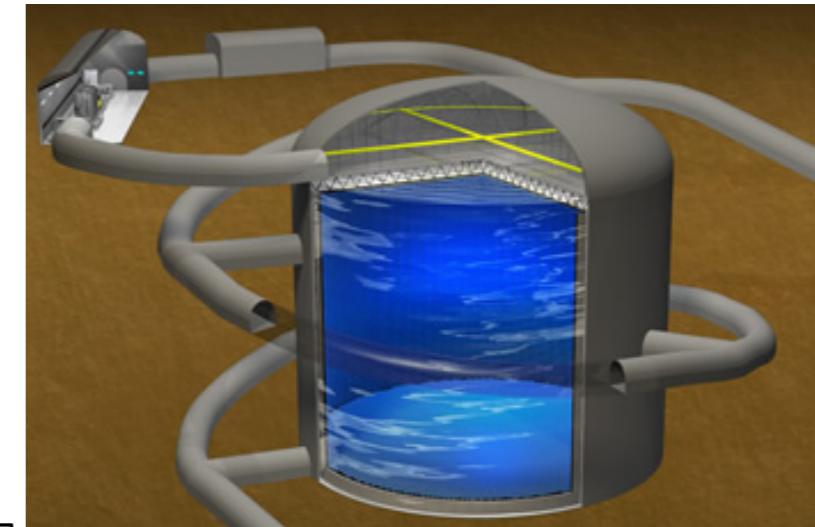
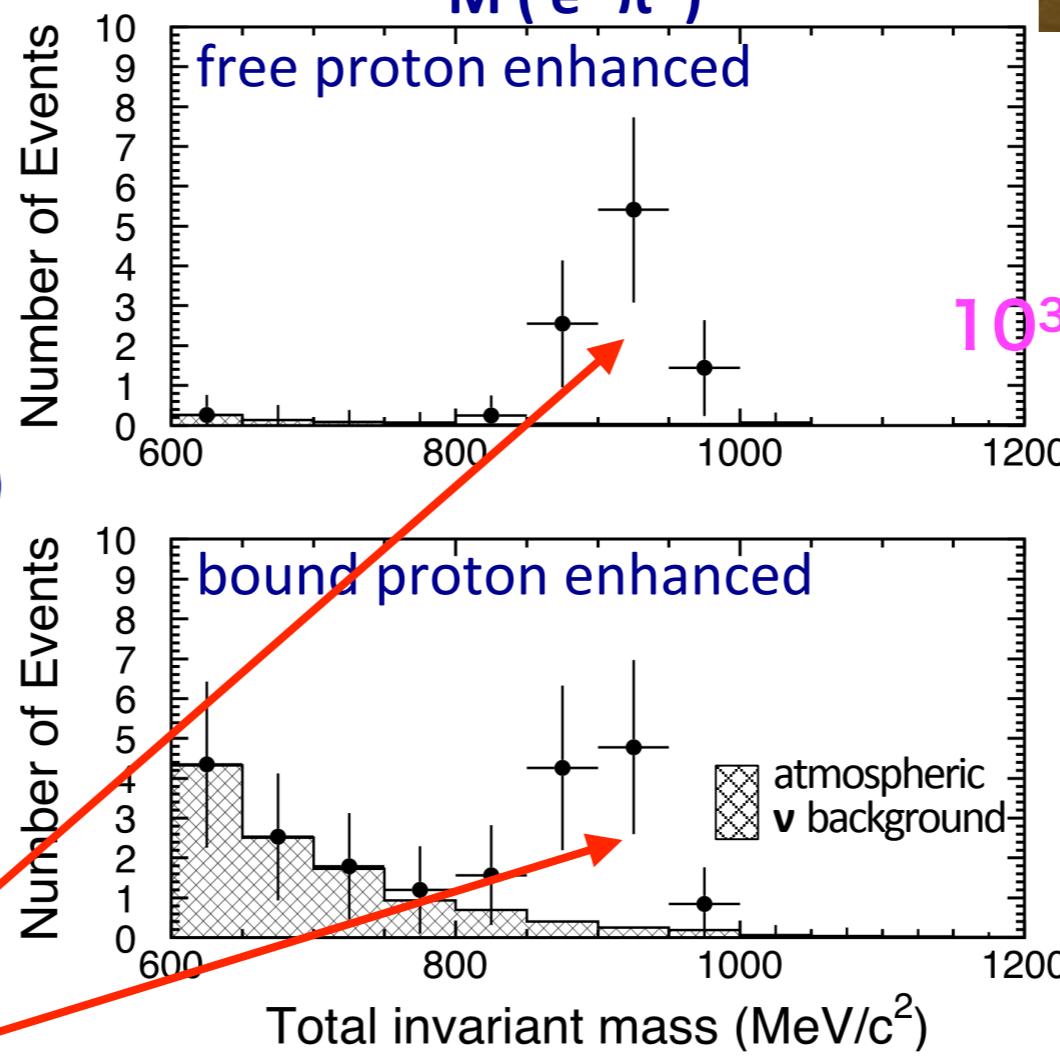


- back-to-back  $e^+$ ,  $\pi^0$  (459 MeV)
- $e^+$ ,  $\pi^0$  ( $\rightarrow \gamma\gamma$ ) are detected
- final state fully reconstructed in Water Cherenkov detectors

used  $\tau_p = 1.7 \cdot 10^{34}$  (SK limit), 10 years exposure



Minimal SU(5) model



# Conclusion and Prospect

*Let's join to explore the quest of neutrinos.*

- Neutrino CP violation
- Majorana neutrino by observing the neutrino less double beta decay
- Neutrino mixing patters including mass hierarchy shedding light on GUT
- Proton decay as an evinced of GUT
- Sterile Neutrinos

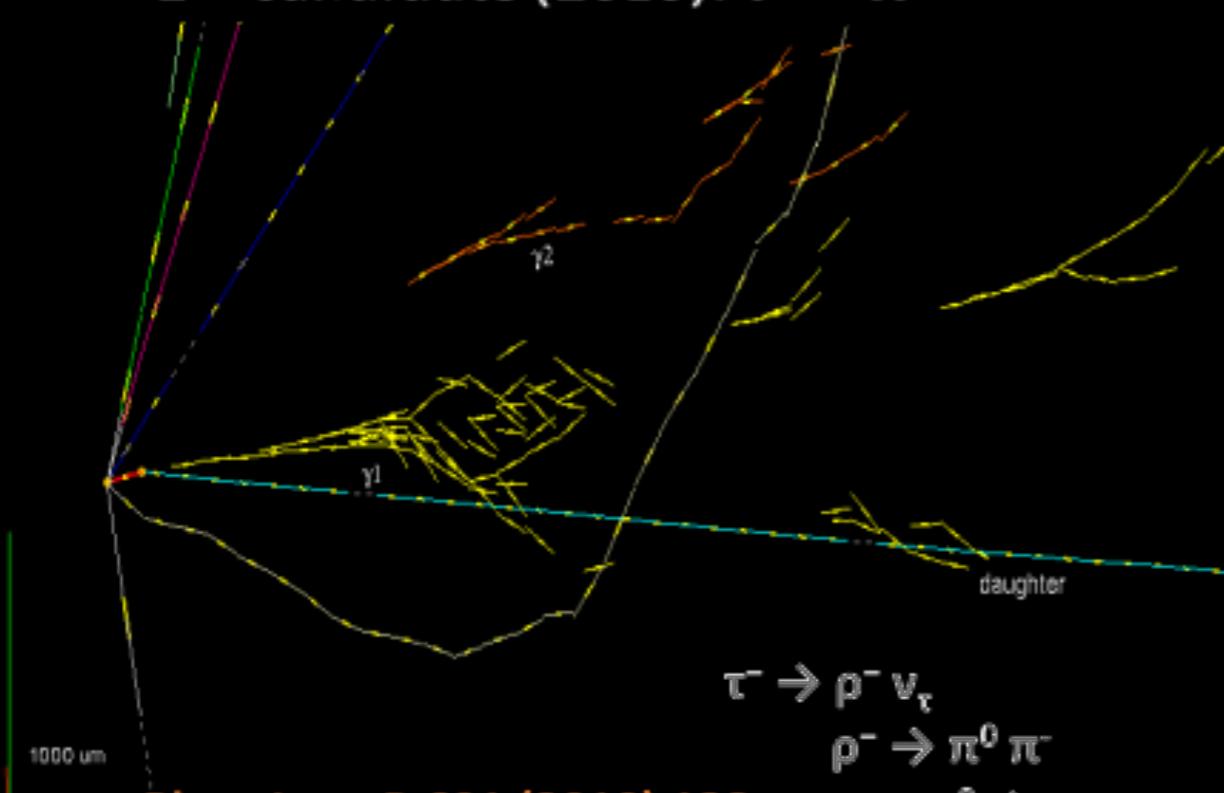
Many measurements from  $\nu$  XSEC and many detector R&D with your idea!



The image shows the EPS HEP2017 conference logo on the left, featuring a globe icon with 'EPS' and 'HEP2017' text. To the right is a dark blue header bar with white text: 'Home', 'Scientific programme', 'Registration', 'Practical Information', 'Events', and 'Committees'. Below the header is a night scene of a city skyline with a prominent church tower and a fireworks display in the sky.

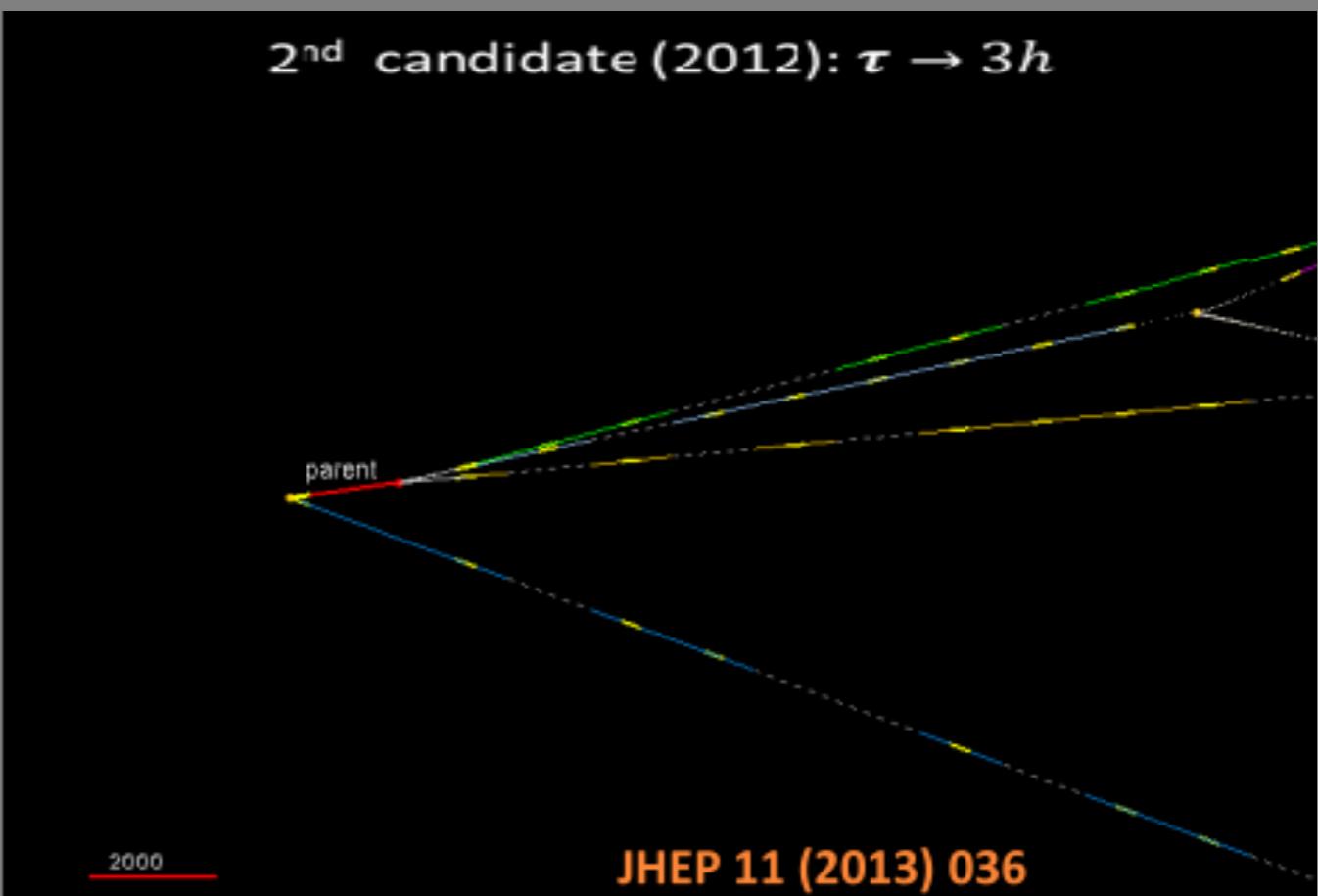
**EPS Conference on High Energy Physics**  
Venice, Italy 5-12 July 2017

# Backup

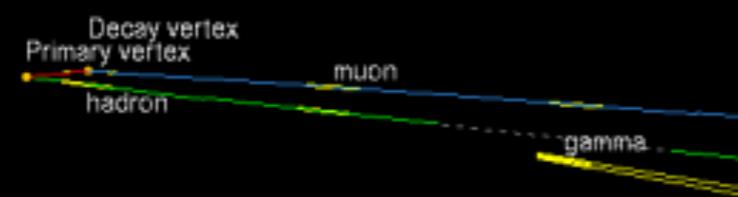
1<sup>st</sup> candidate (2010):  $\tau \rightarrow h$ 

Phys. Lett. B 691 (2010) 138

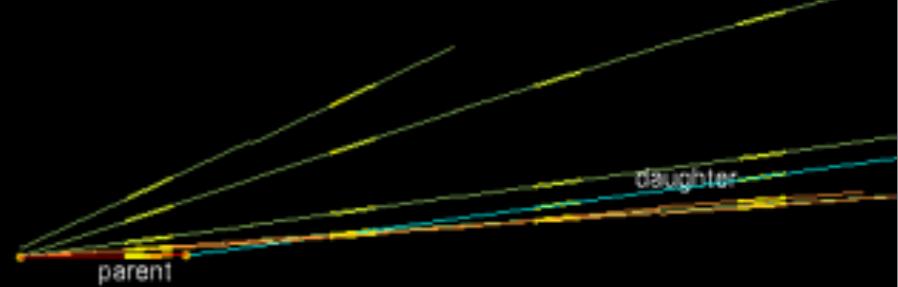
$$\begin{aligned}\tau^- &\rightarrow \rho^- \bar{\nu}_\tau \\ \rho^- &\rightarrow \pi^0 \pi^- \\ \pi^0 &\rightarrow \gamma\gamma\end{aligned}$$

2<sup>nd</sup> candidate (2012):  $\tau \rightarrow 3h$ 

JHEP 11 (2013) 036

3<sup>rd</sup> candidate (2013):  $\tau \rightarrow \mu$ 

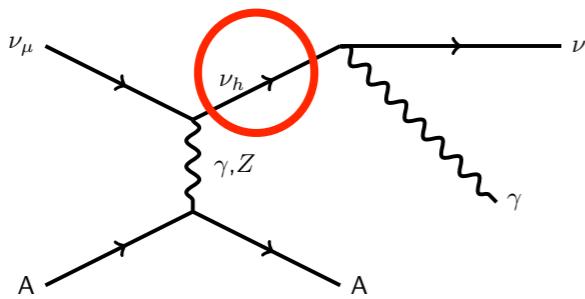
Phys. Rev. D 89 (2013) 051102

4<sup>th</sup> candidate (2014):  $\tau \rightarrow h$ 

PTEP (2014) 101C01

# MinBooNE

- Heavy neutrinos Gninenco, PRL 103 (2009), Masip et al., JHEP01(2013)106
- We have analyzed this scenario in order to compare with MiniBooNE measurements. Also we have predicted the signal due to this kind of processes for SBN.

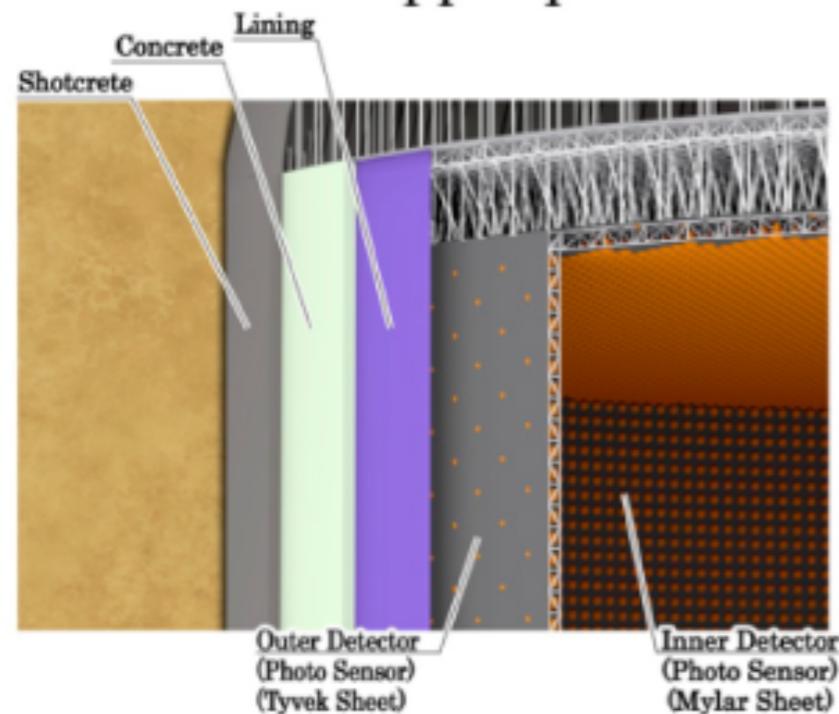


- On nucleons  $\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \nu_h(\bar{\nu}_h) + N$
- On nuclei
  - $\nu_\mu(\bar{\nu}_\mu) + A \rightarrow \nu_h(\bar{\nu}_h) + A$  ← coherent
  - $\nu_\mu(\bar{\nu}_\mu) + A \rightarrow \nu_h(\bar{\nu}_h) + X$  ← incoherent
- $\nu_h$  = Dirac  $\nu$  with  $m \approx 50$  MeV, slightly mixed with  $\nu_\mu$
- $A = {}^{12}\text{C}$  (MiniBooNE, CH<sub>2</sub>),  ${}^{40}\text{Ar}$  (SBN program: SBND, MicroBooNE, Icarus)

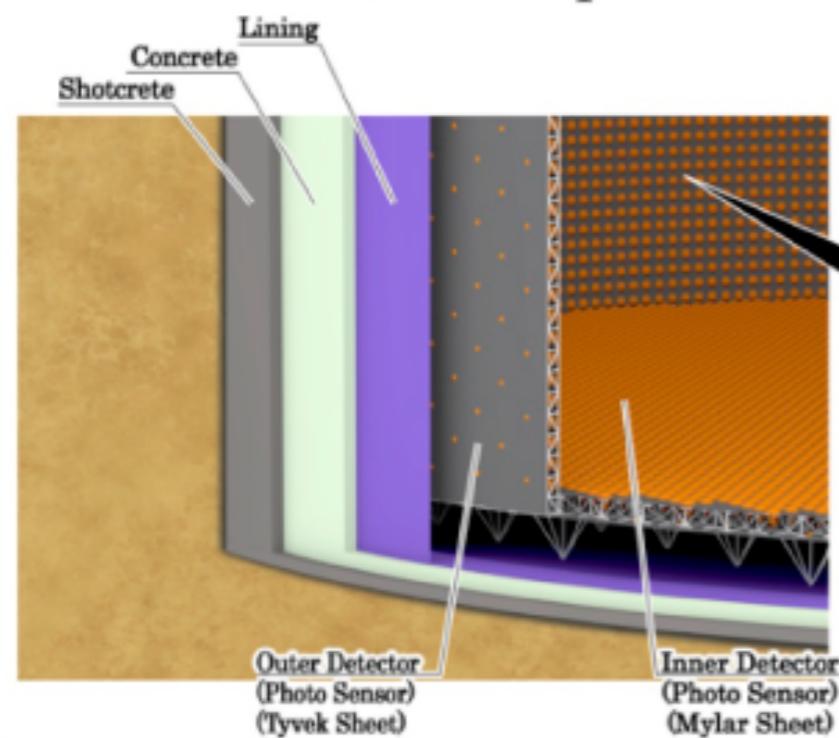
## Conclusions

- The origin of MiniBooNE anomaly is still not understood.
- Production and radiative decay of heavy sterile neutrino could be a solution.
- We have made an analysis of this scenario using our understanding about neutrino interactions with matter.
- In the range of parameter values consistent with LSND anomaly this scenario does not fully describe MiniBooNE anomaly, but could be sizable contribution.
- We can predict the impact in SBN measurements (SBND, MicroBooNE and ICARUS) and test the model.

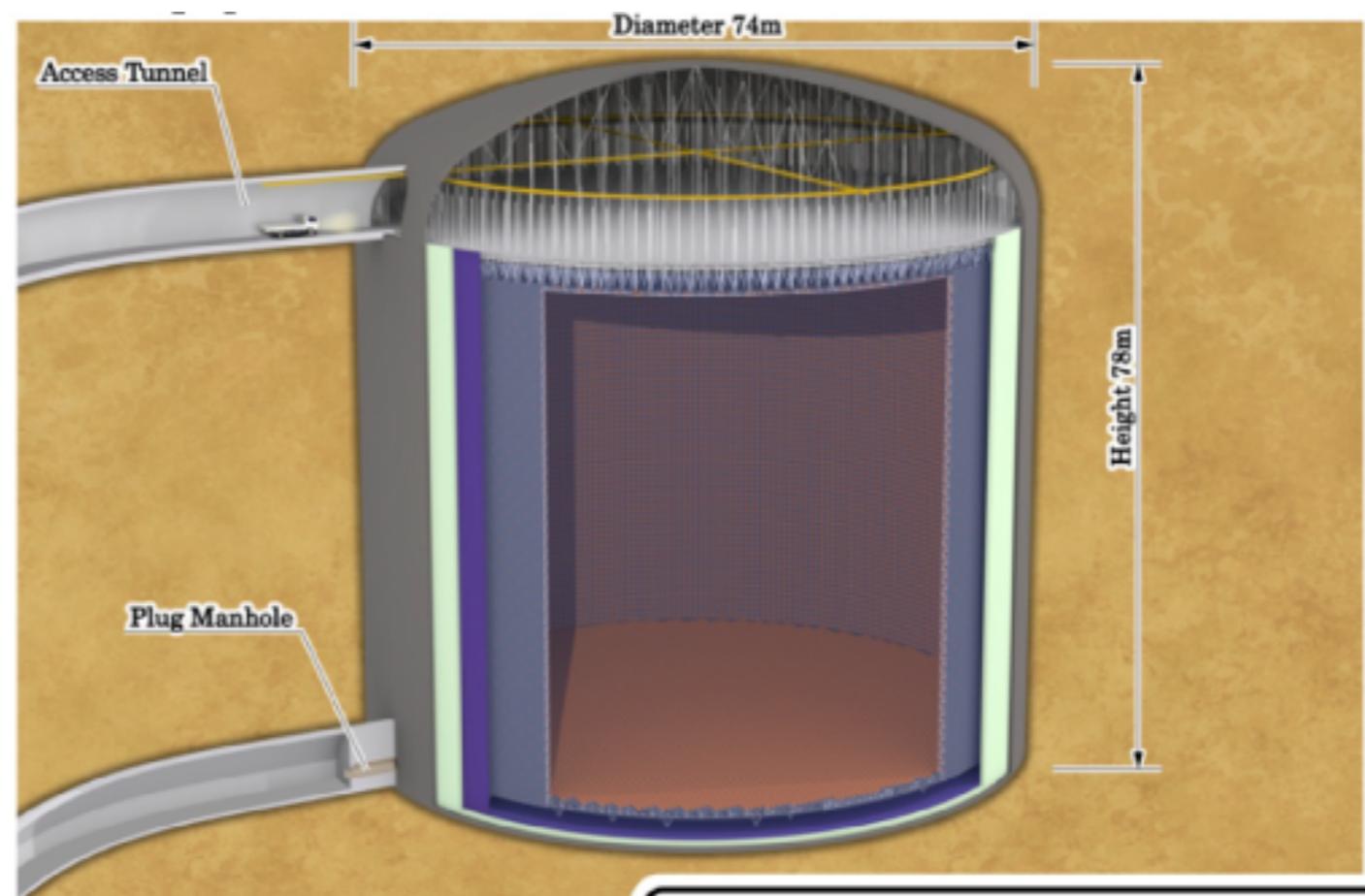
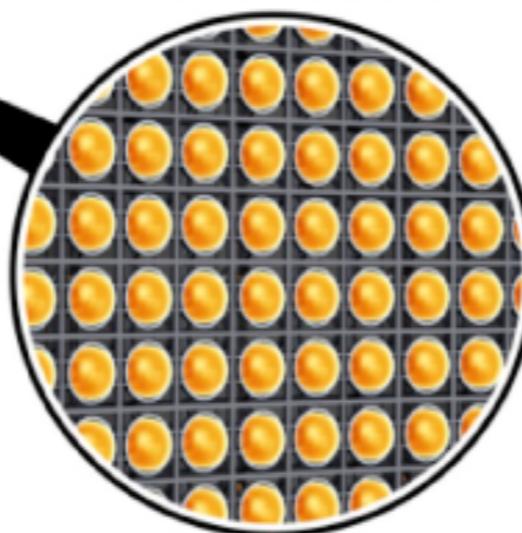
## Structure of upper part



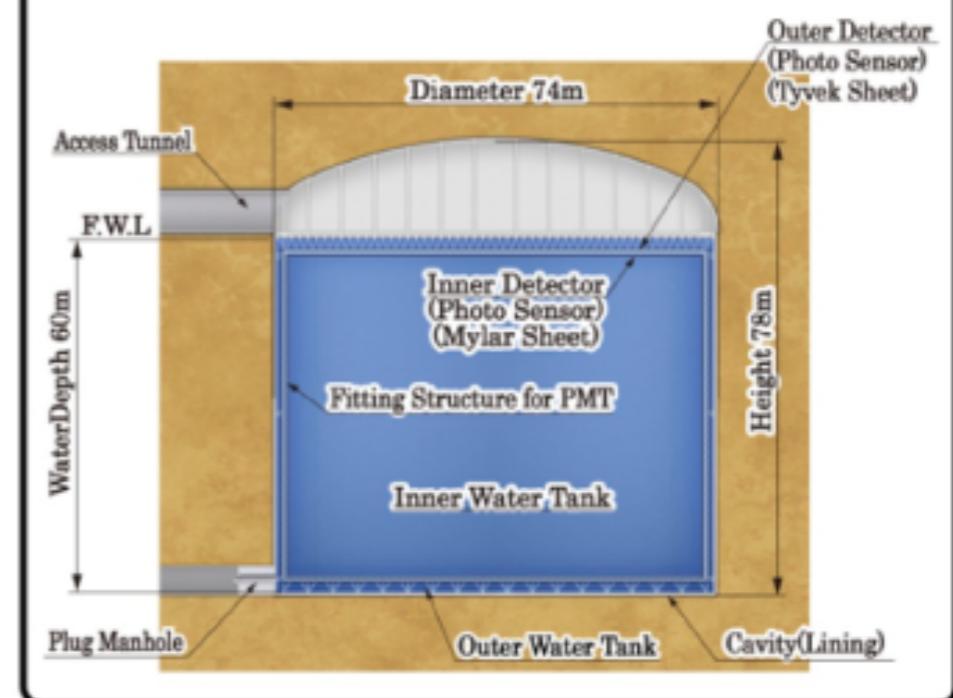
## Structure of bottom part



**Photo-Sensors**

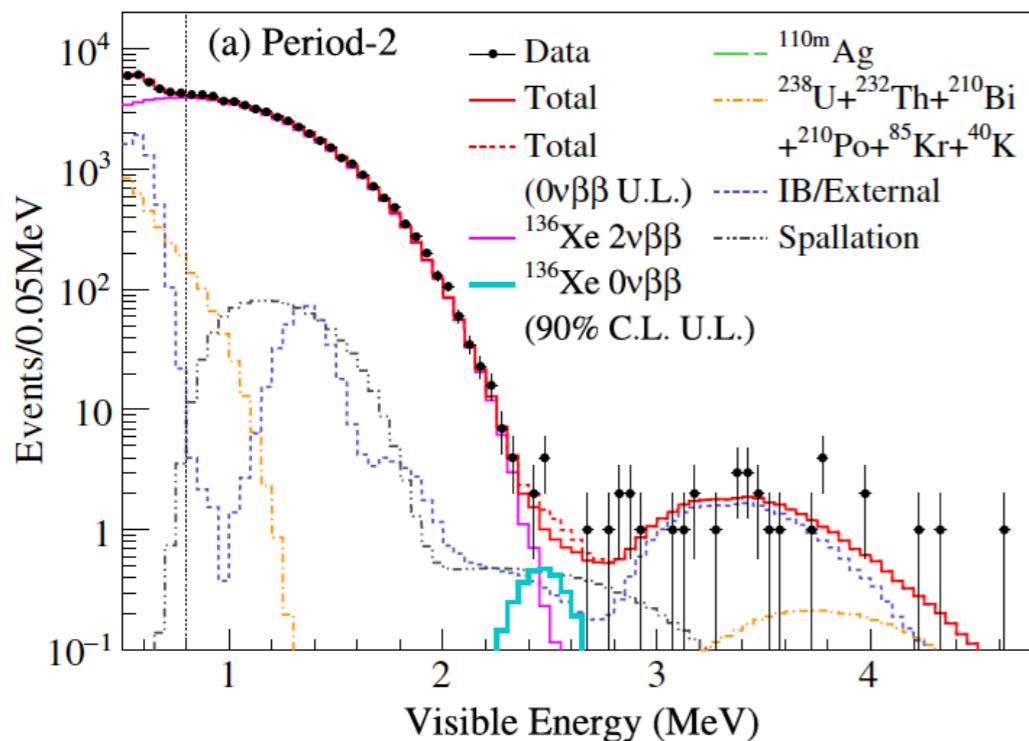
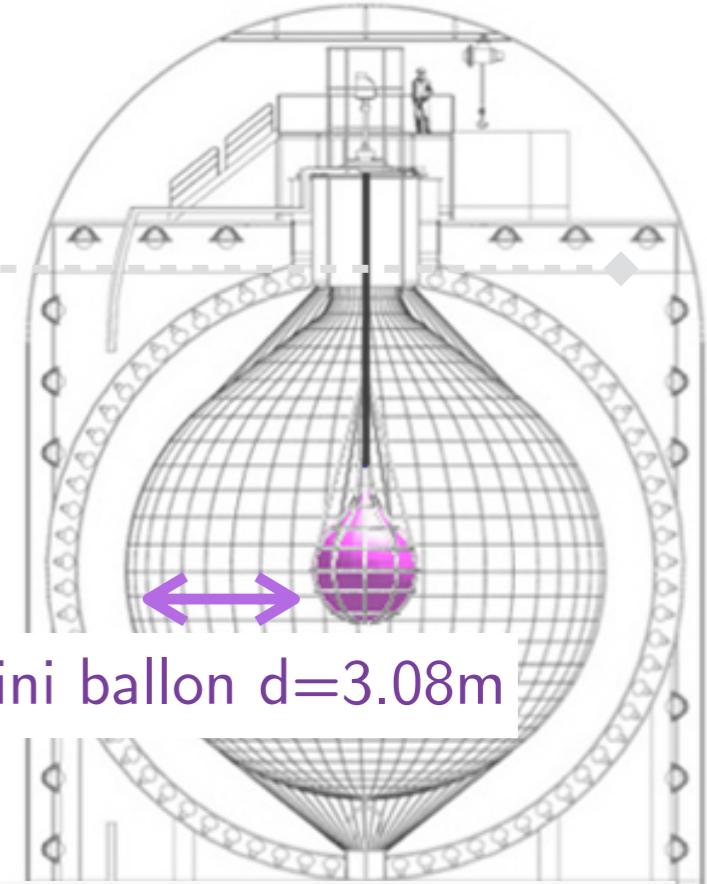


## CROSS SECTION



# KamLAND-Zero neutrino $\beta\beta$ decay

- Isotope: 383kg of  $^{136}\text{Xe}$  dissolved in liquid scintillator,
- Poor energy resolution:** 11% FWHM at the Q-value
- Shielding:** low background rate  $1.6\text{e}^{-4} \text{ c/(kev/kg/yr)}$
- Easy to scale up**



Combining phaseI and phaseII:  
**(best limit!)**

$T_{1/2} > 1.07 \times 10^{26} \text{ yr}$  at 90% C.L.  
(sensitivity:  $5.6 \times 10^{25}$ )  $(m_{\beta\beta} \sim 61-165 \text{ meV})$

Phys. Rev. Lett. 117, 082503

- **Future plan:** 1) install a bigger MB of 800kg of  $^{136}\text{Xe}$  (2018) to explore down to  $m_{\beta\beta} = 40 \text{ meV}$ ; 2) install (2020?) the 1tonne MB covering most of the IH region!