

Current Status and Future Prospects of Neutrino Physics

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Neutrino summer school, June 21, 2023

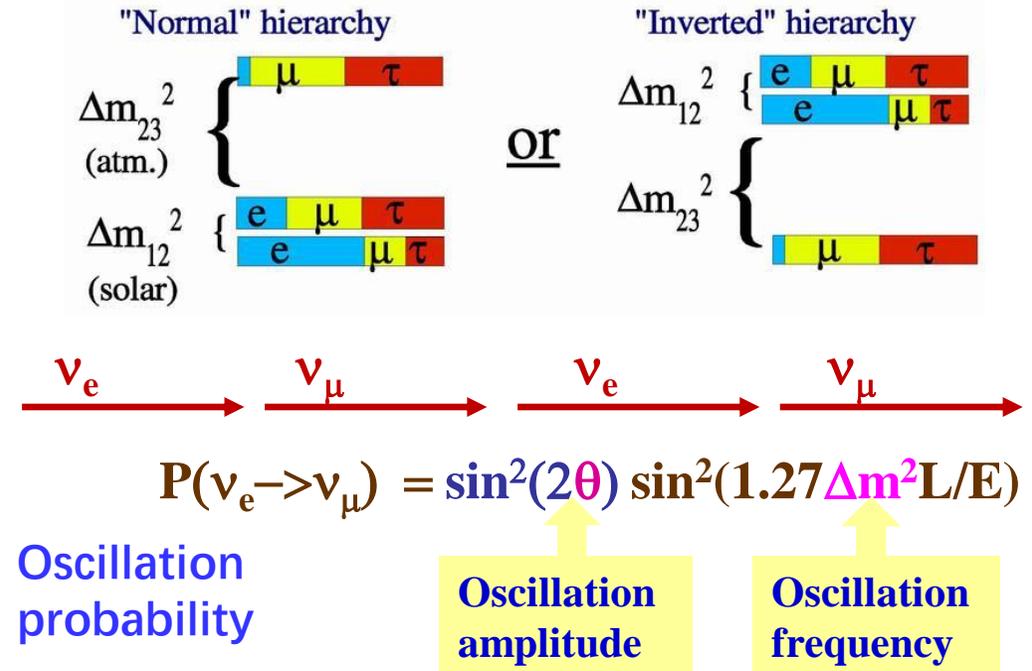
Outline

- Relative neutrino masses & neutrino oscillations
- Absolute neutrino masses, β & $\beta\beta$ decays
- CEvNS
- New physics searches and Sterile Neutrinos
- Neutrinos for astrophysics
- Tools, Methods, Technologies & Projects
 - Flux, cross sections, Monte Carlo packages
 - New technologies
 - New projects
- Summary

Based on my summary talk at neutrino 2022
<https://neutrino2022.org>
<https://indico.kps.or.kr/event/30/>

Relative Neutrino Masses & Neutrino oscillations

- A major achievement of particle physics
 - It is important by itself, as a macroscopic manifestation of quantum effects
 - It proved that neutrinos have non-zero masses → huge impact to particle physics & cosmology
 - Neutrinos are the possible source of CP violation which could explain the matter-antimatter asymmetry in the Universe
- After 24 years of its discovery, we still miss:
 - Mass ordering ($|\Delta m^2_{23}| \rightarrow \Delta m^2_{23}$)
 - CP phase (δ)
 - θ_{23} octant
 - Very precise knowledge of oscillation parameters



$\theta_{23} \ \& \ \Delta M^2_{32}$ CP phase δ & θ_{13} $\theta_{12} \ \& \ \Delta M^2_{21}$ Majorana phase

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

Atmospheric accelerator reactor accelerator solar reactor Double beta decays

θ_{13} and Δm^2_{32}

- New results from **Daya Bay** nGd capture:

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024} \quad (2.8\% \text{ precision})$$

Normal hierarchy: $\Delta m^2_{32} = + (2.454^{+0.057}_{-0.057}) \times 10^{-3} \text{ eV}^2$ (2.3% precision)

Inverted hierarchy: $\Delta m^2_{32} = - (2.559^{+0.057}_{-0.057}) \times 10^{-3} \text{ eV}^2$

- Expect final results from **Daya Bay** on combined nGd+nH analysis: $\sim 2.6\%$ for $\sin^2 2\theta_{13}$?

- RENO** reported new results(up to 2019)

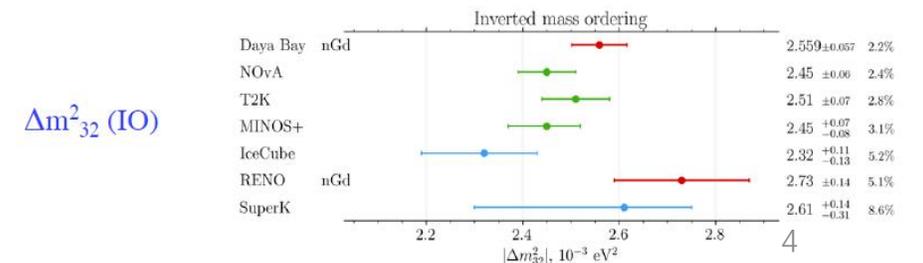
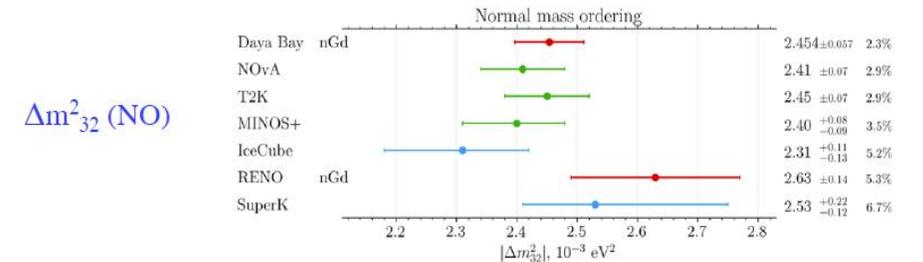
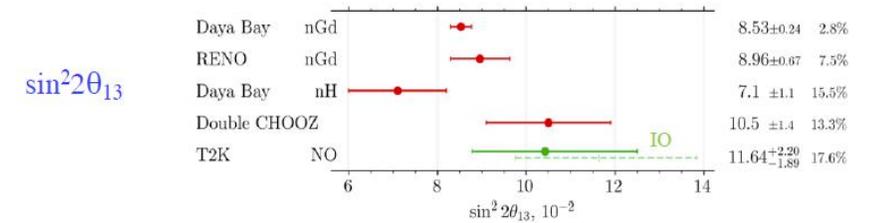
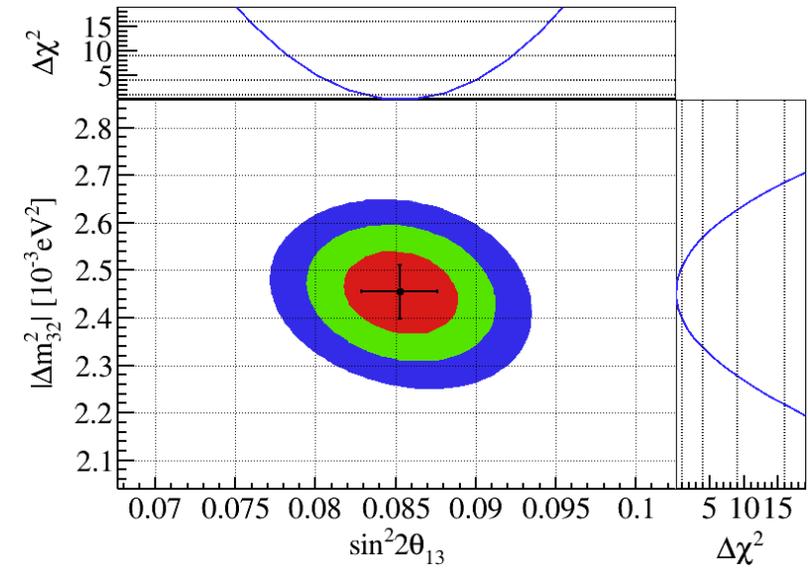
$$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(\text{stat.}) \pm 0.0045(\text{sys.}) \quad (\pm 7.0 \%)$$

$$|\Delta m^2_{ee}| = 2.74 \pm 0.10(\text{stat.}) \pm 0.06(\text{sys.})(\times 10^{-3} \text{ eV}^2) \quad (\pm 4.4 \%)$$

- RENO** will continue for another ~ 3 years(up to 4400 d)

$$\sin^2 2\theta_{13}: 6.4\%; \quad \Delta m^2_{ee}: 4.1\%$$

- DUNE** can measure $\sin^2 2\theta_{13}$ in appearance channel, to a precision of $\sim 5\%$



θ_{23} and $|\Delta m_{32}^2|$

- New results from T2K and Nova

Nova best fit: Normal hierarchy

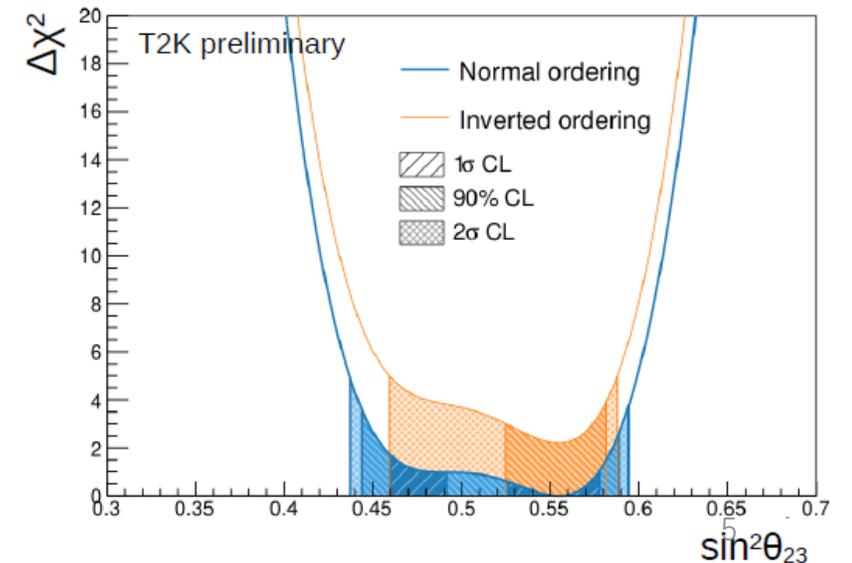
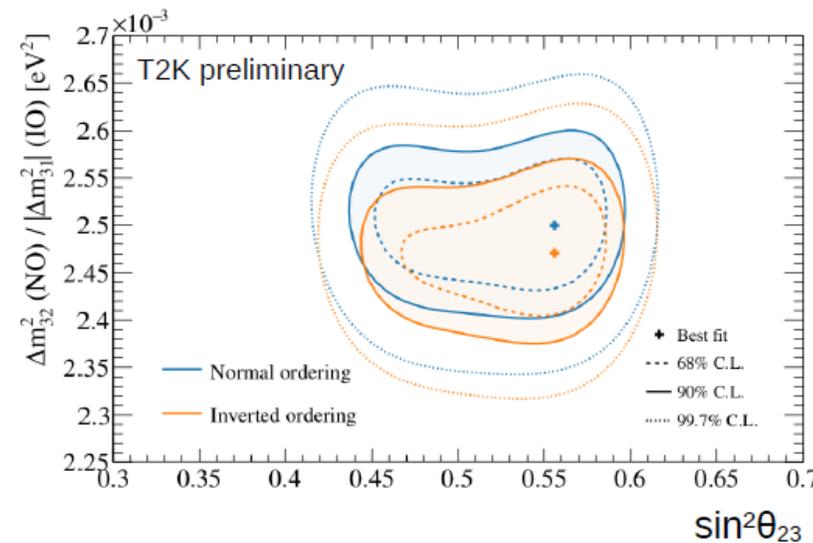
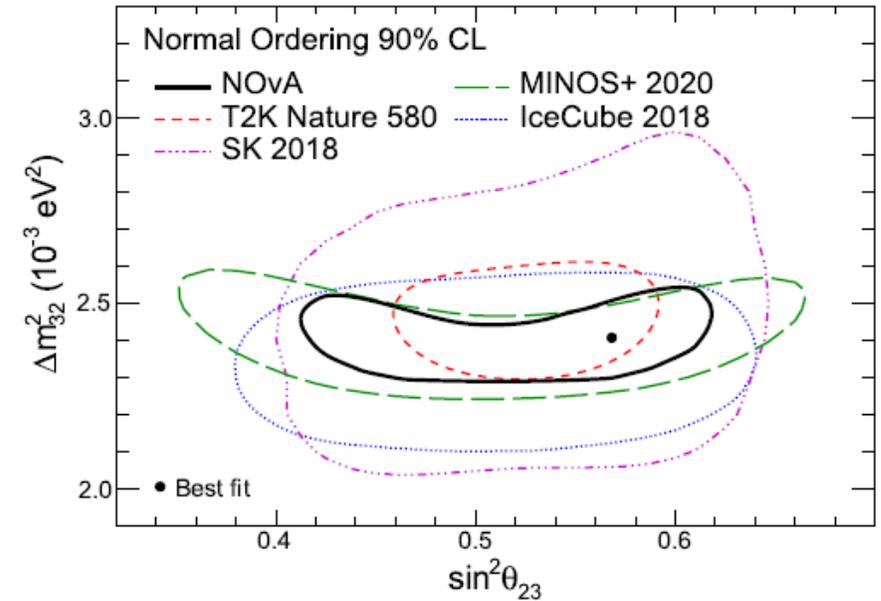
$$\Delta m_{32}^2 = (2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2 \quad 2.9\%$$

$$\sin^2 \vartheta_{23} = 0.57^{+0.04}_{-0.03} \quad \sim 6\%$$

$$\delta = 0.82\pi$$

- SuperK and Icecube also reported new results from atmospheric neutrinos

- Various combined analysis on the way



θ_{12} and Δm_{21}^2

- Tension between solar & reactor result reduced to 1.5σ .
- **JUNO** can simultaneously measure Δm_{21}^2 and θ_{12} using reactor antineutrinos and solar neutrinos with a great precision.
- **HyperK** will improve the solar neutrino result

$$\sin^2(\theta_{12}) = 0.316_{-0.026}^{+0.034}$$

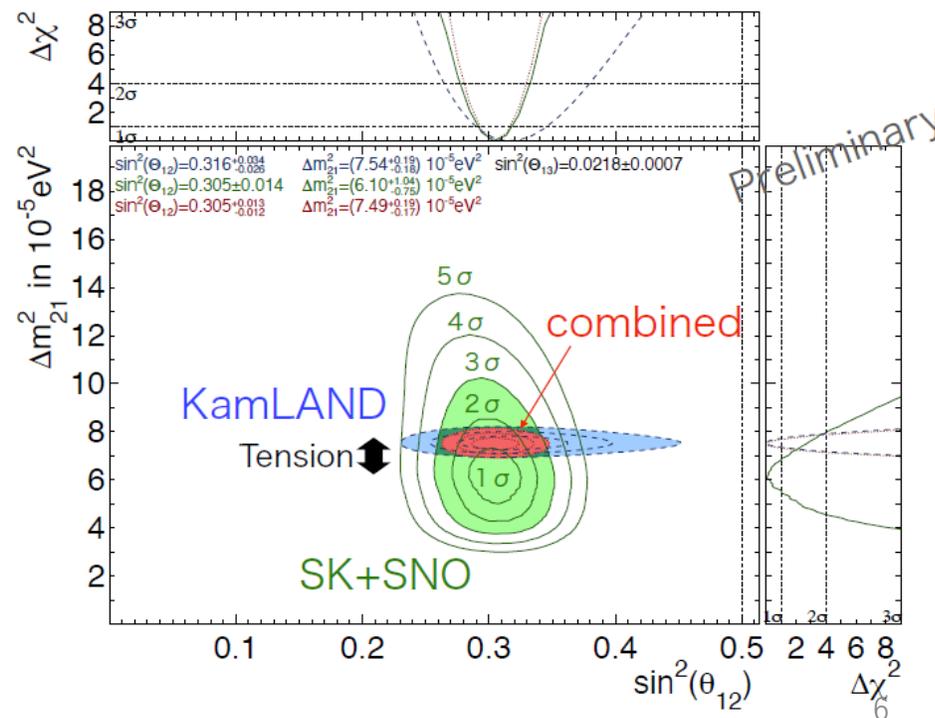
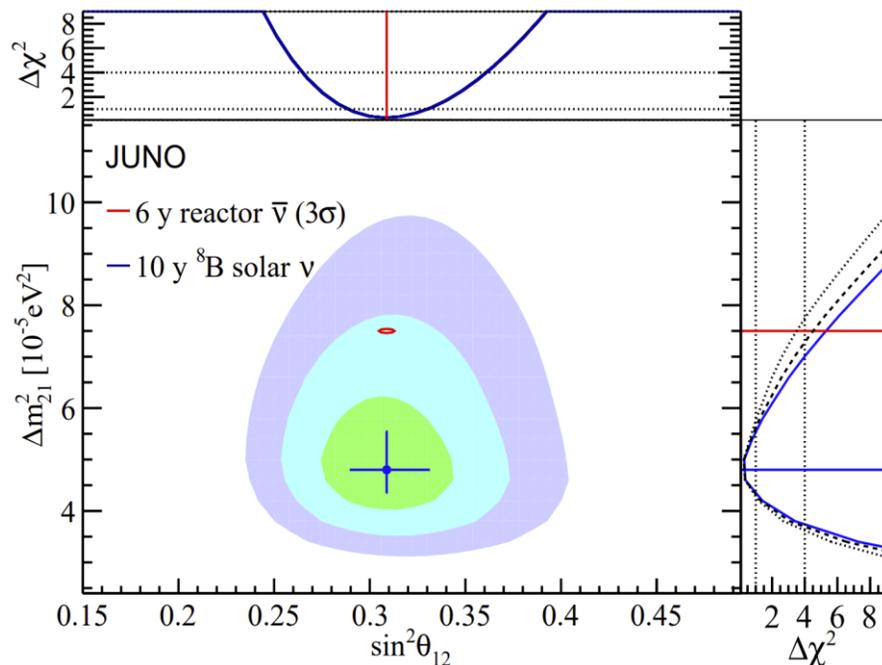
$$| \Delta m_{21}^2 = 7.54_{-0.18}^{+0.19} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305 \pm 0.014$$

$$\Delta m_{21}^2 = 6.10_{-0.75}^{+1.04} \times 10^{-5} eV^2$$

$$\sin^2(\theta_{12}) = 0.305_{-0.012}^{+0.013}$$

$$\Delta m_{21}^2 = 7.49_{-0.17}^{+0.19} \times 10^{-5} eV^2$$



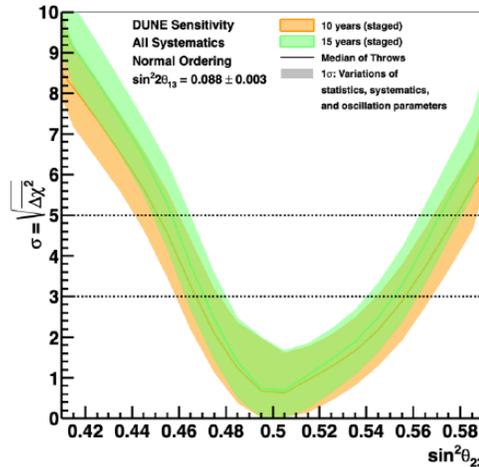
Future: Significant Improvement Expected

- JUNO will determine most oscillation parameters to a sub-percent level
- T2K and Nova will improve $\sin^2\theta_{23}$ slightly
- ORCA, Icecube, DUNE and HyperK can improve $\sin^2\theta_{23}$ significantly:

	Current (PDG2020)	JUNO (100 d)	JUNO (6 y)
Δm^2_{31} Δm^2_{32}	1.3%	0.8%	0.2%
Δm^2_{21}	2.4%	1.0%	0.3%
$\sin^2\theta_{12}$	4.2%	1.9%	0.5
$\sin^2\theta_{13}$	3.2%	47.9%	12.1%

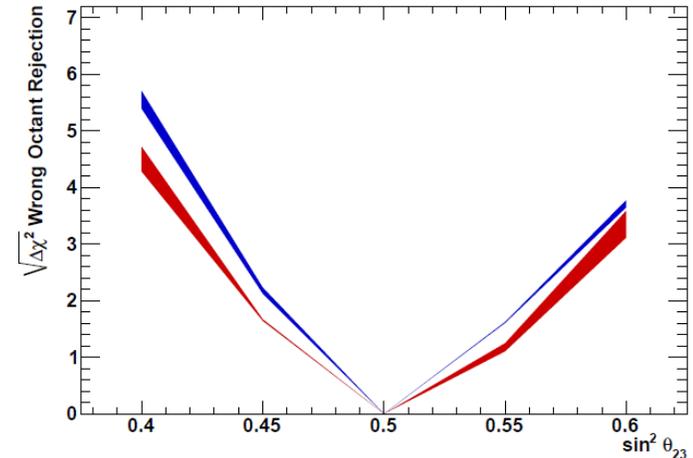
~4%(PDG2020) → ~1.8%(1 exp.)

- Combined analysis may reach ~ 1% for $\sin^2\theta_{23}$
- θ_{23} octant can be probed with a good sensitivity



~ 3 - 5σ

DUNE 2002.03005

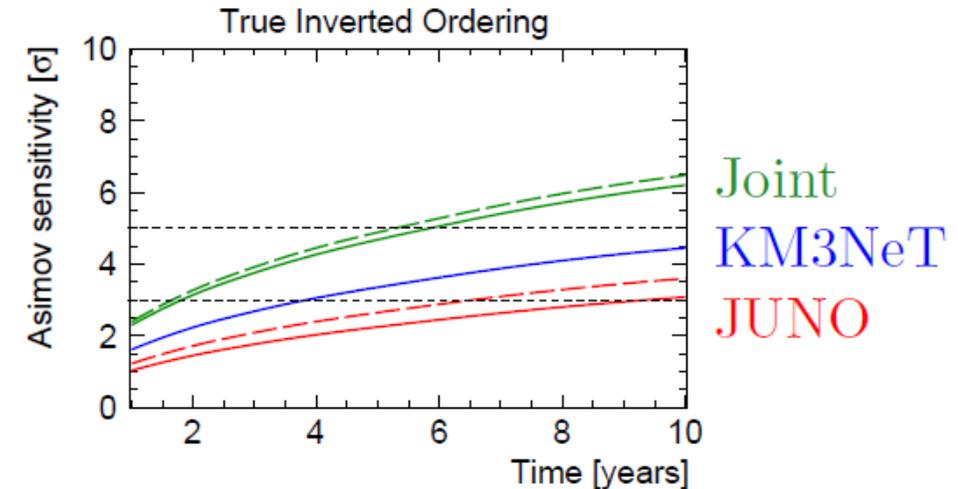
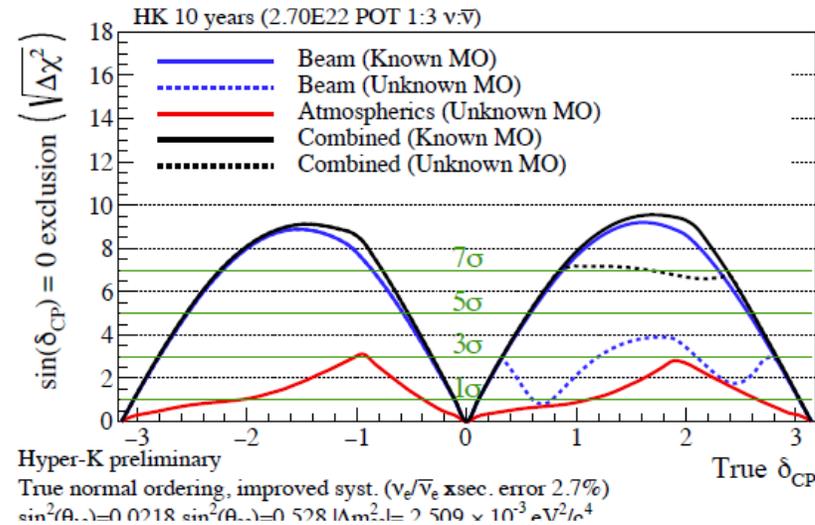
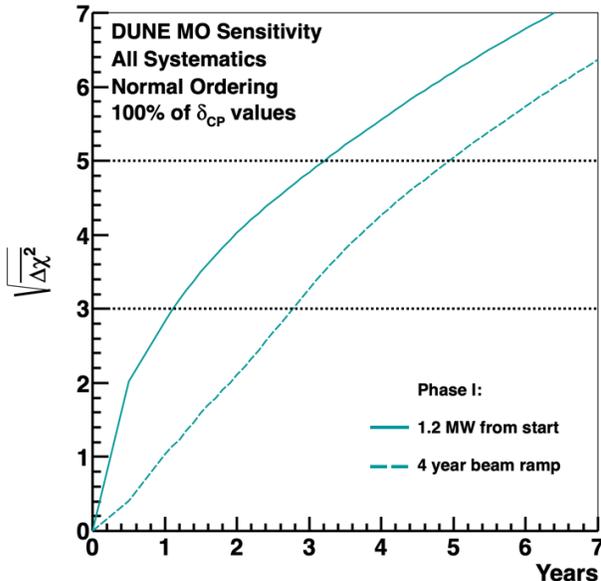
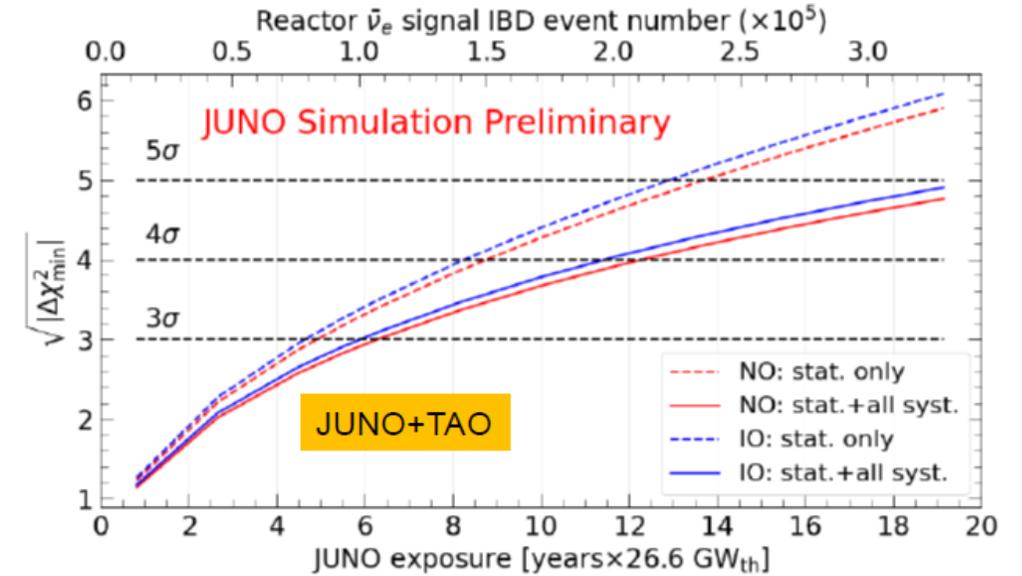


Beam+Atm ⇒ ~ 3 - 6σ₇

HK 1805.04163

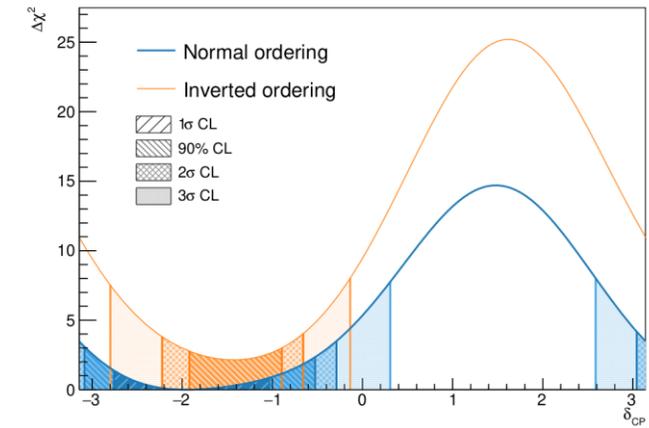
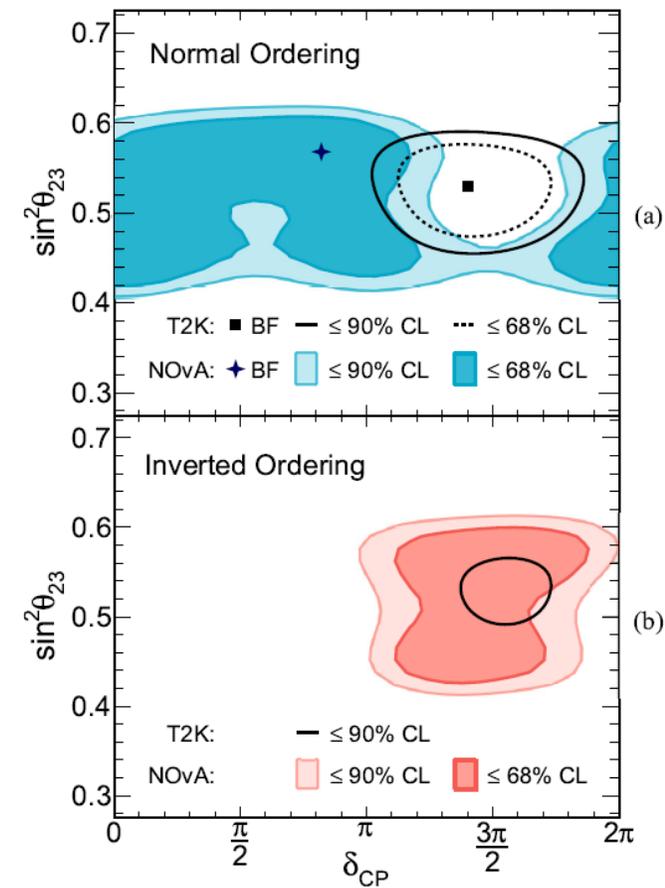
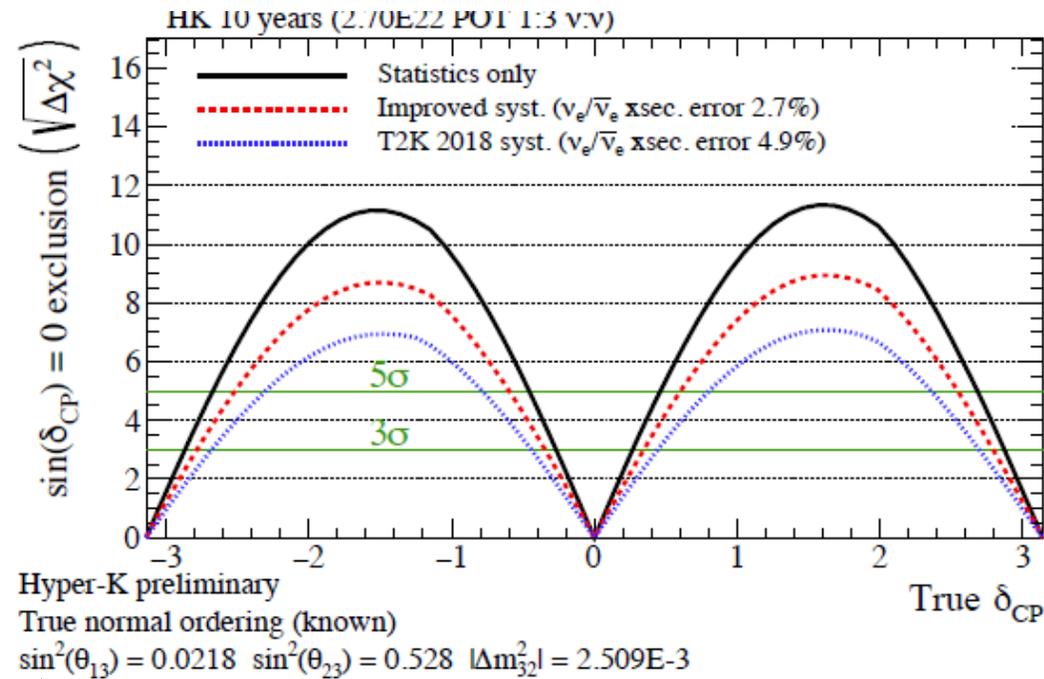
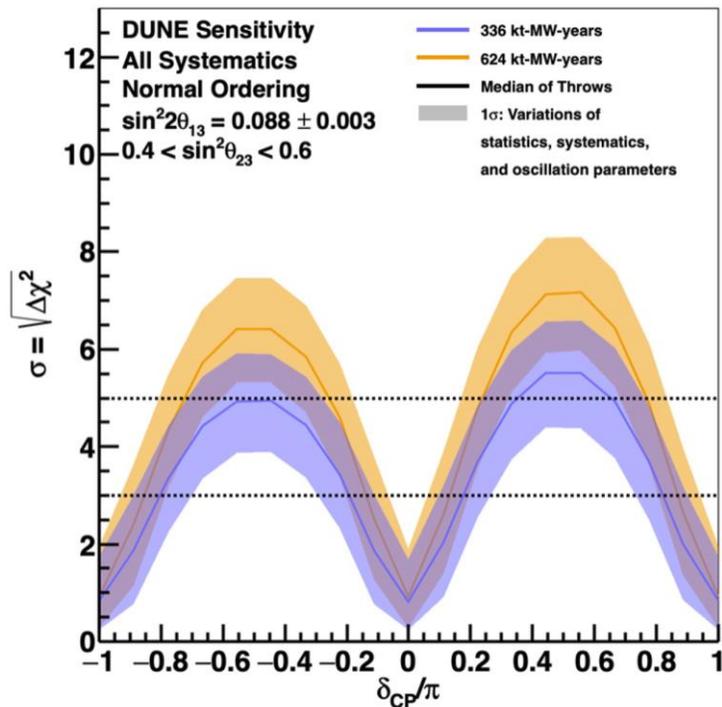
Mass Ordering

- No concrete evidence of MO from individual experiment (T2K, Nova and SuperK)
- Global fit seems slightly prefer NO(<3 σ)
- Definite answer will come from JUNO, HyperK, DUNE, ORCA and Icecube.



CP phase

- $\sim 270^\circ$ (-90°) seems slightly favored by many exp.s ($< 3\sigma$)
- Combined analysis may give more preference, but not stable yet
- **DUNE** & **HyperK** can give a more definite answer
- Further improvement may come from **KNO**, **ESSnuSB**, and **THEIA**



Absolute Neutrino Masses, β & $\beta\beta$ decays

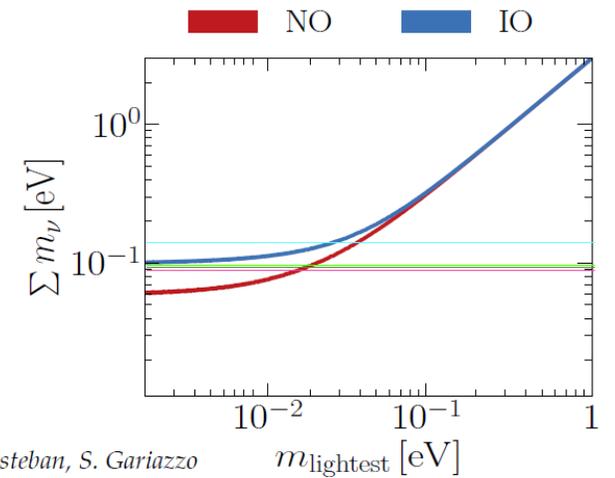
- From cosmology: $\Sigma m_i < \sim 0.1$ eV@95%CL
 - Future experiments may determine the mass (4σ) in ~ 10 years
- β decays can probe $m_\beta \sim 0.2$ eV (future 0.02 eV ?)

$$m_\beta = [\Sigma_i |U_{ei}|^2 m_{\nu_i}^2]^{1/2}$$

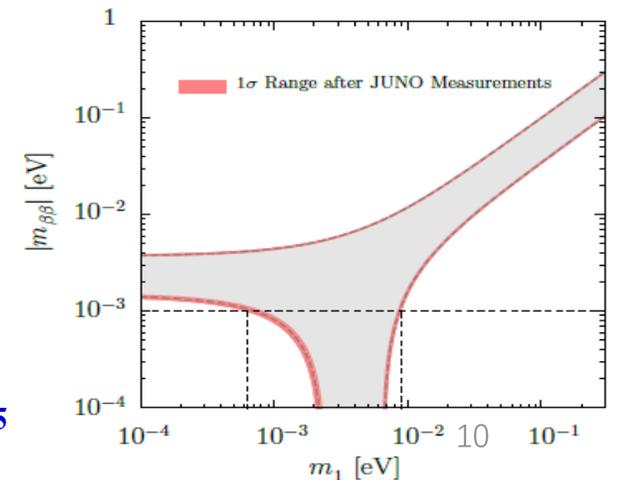
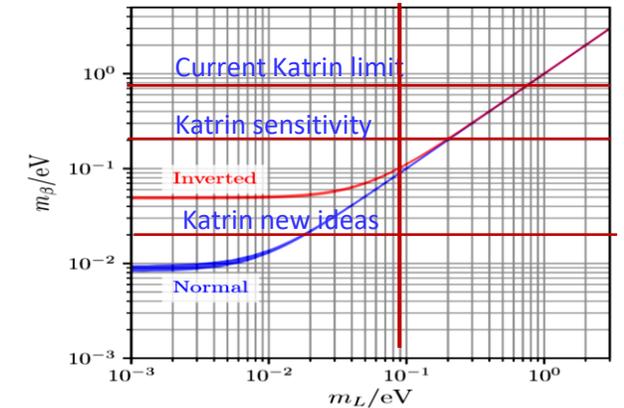
- $0\nu\beta\beta$ decays can probe $M_{\beta\beta} \sim 0.01$ eV

$$|M_{\beta\beta}| = |\Sigma_i (U_{ei})^2 m_{\nu_i}|$$

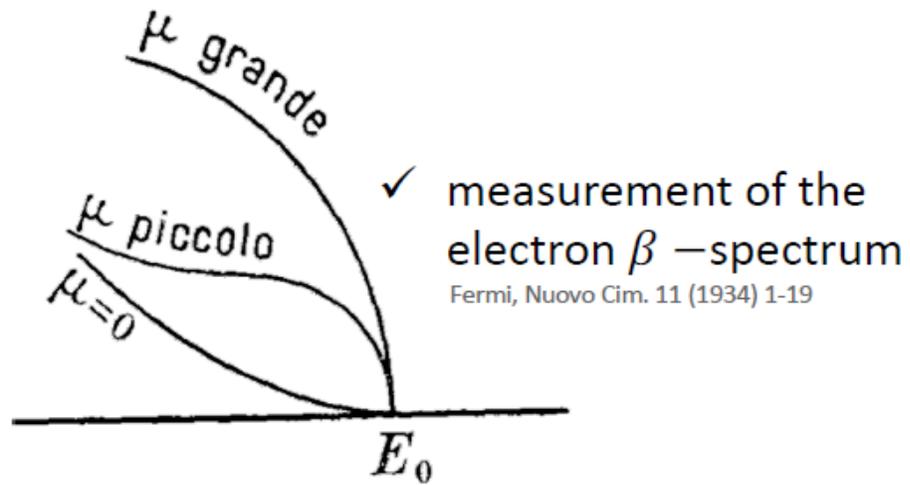
- Search for $0\nu\beta\beta$ decays is a no loss game:
 - If $0\nu\beta\beta$ decays seen \rightarrow Majorana neutrinos, lepton number violation
 - if no $0\nu\beta\beta$ decays up to $|M_{\beta\beta}| \sim 0.001$ eV \rightarrow lightest neutrino mass can be determined to be ~ 5 meV



I. Esteban, S. Gariazzo



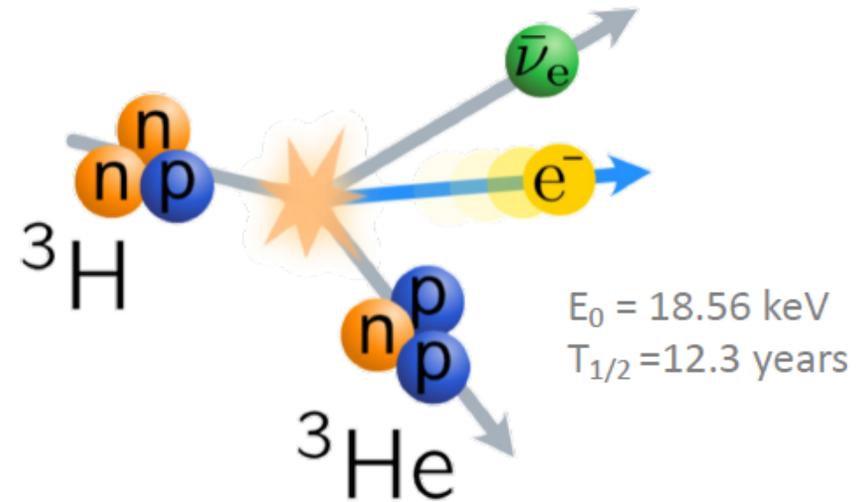
β decays: Katrin for m_β



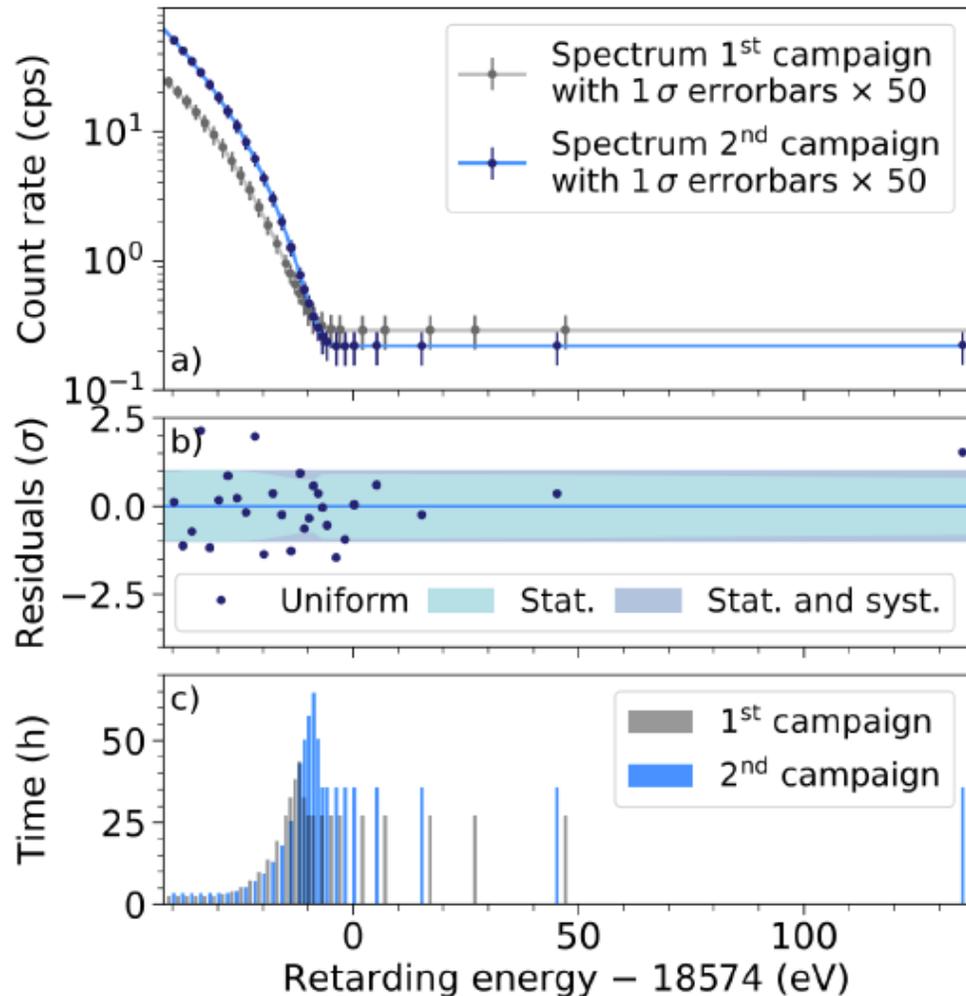
- ✓ based on kinematics and energy conservation
- ✓ m_ν^2 spectral distortion, maximal at endpoint energy E_0

- ✓ incoherent neutrino mass: $m_\nu^2 = \sum_i |U_{ei}|^2 \cdot m_i^2$

- ✓ independent of cosmology
- ✓ independent of neutrino nature



β decays: Katrin for m_β



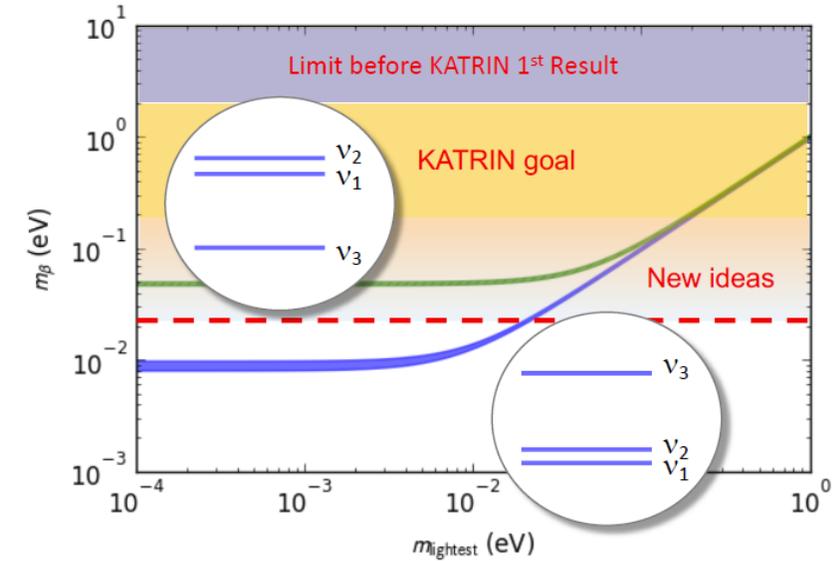
First campaign (spring)

- ✓ total statistics: 2 mil
- ✓ best fit: m_ν^2
- ✓ limit: m_ν

Second campaign (aut)

- ✓ total statistics: 4.3 million events
- ✓ best fit: $m_\nu^2 = (0.26^{+0.34}_{-0.34}) \text{ eV}^2$ (stat. dom.)
- ✓ limit: $m_\nu < 0.9 \text{ eV}$ (90% CL)

- Combined result: $m_\nu < 0.8 \text{ eV}$ (90% CL)



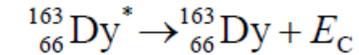
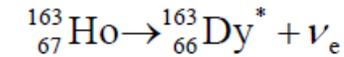
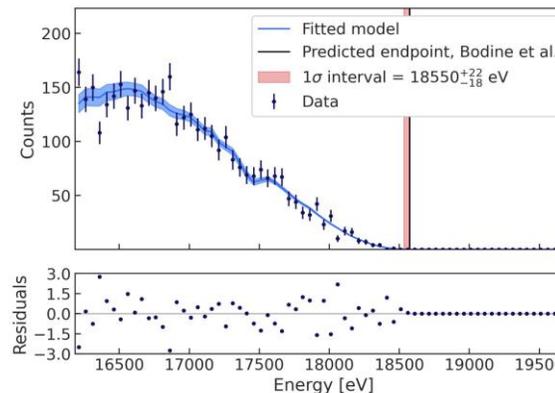
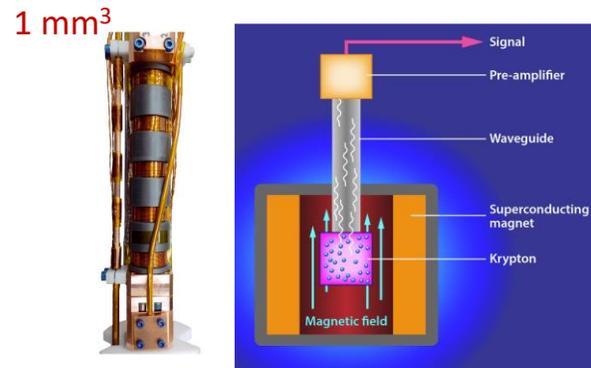
β decays: New Projects

- ECHO & HOLMS: calorimetric sensors coupled to ^{163}Ho implanted sources

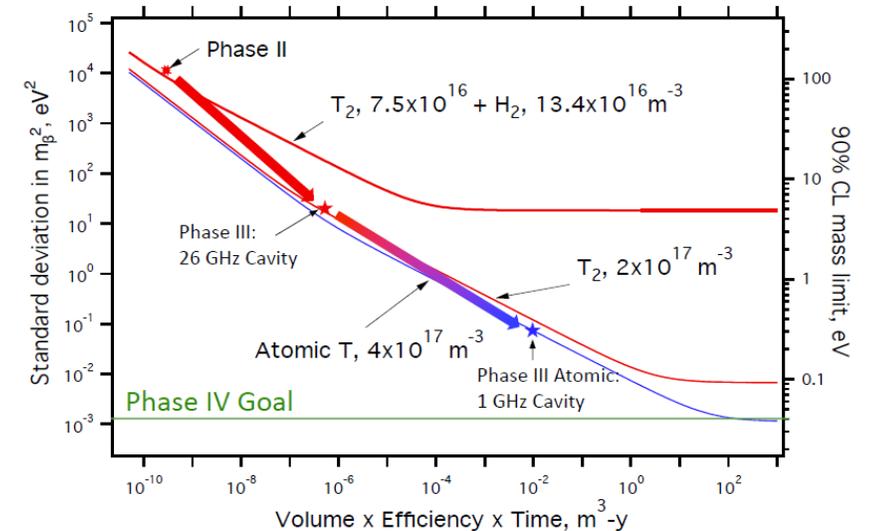
- Obtained neutrino mass limit: ~ 150 eV
- Promise: ~ 1 eV

- Project 8: Cyclotron Radiation Emission Spectroscopy (CRES)

- Phase I: prove of principle
- Phase II successful
 - Uncertainties understood
 - $m_\beta < 178$ eV @90% C.L.
- Phase III:
 - Atomic T system & Larger cavity
 - Goal in 5 years: $m_\beta < 0.4$ eV
- Phase IV: 5 years ?
 - Goal: $m_\beta < 0.04$ eV



- $\tau_{1/2} \cong 4570$ years ($2 \cdot 10^{11}$ atoms for 1 Bq)
 - $Q_{EC} = (2.833 \pm 0.030^{\text{stat}} \pm 0.015^{\text{syst}})$ keV
- S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501



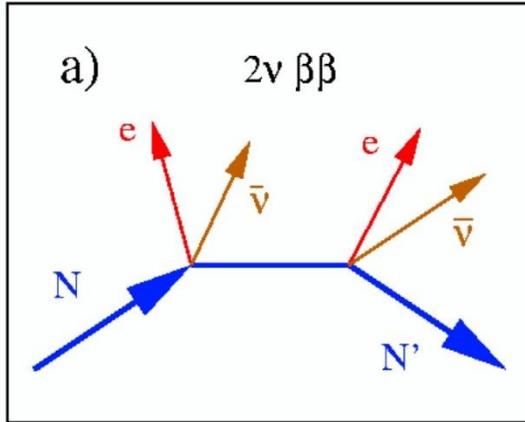
$\beta\beta$ -decays: two modes

2ν mode: a conventional
2nd order process
in nuclear physics

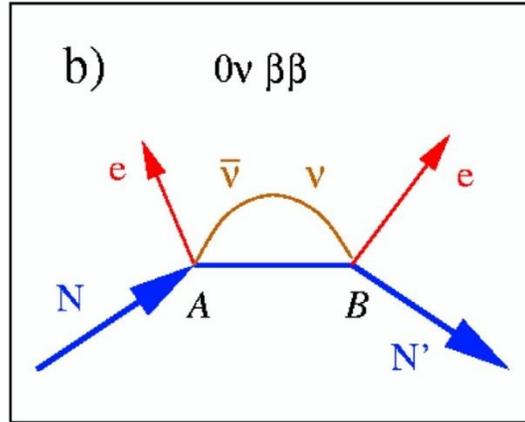
0ν mode: a hypothetical
process can happen

- only if:
- $M_\nu \neq 0$
 - $\bar{\nu} = \nu$

Since helicity
has to "flip"



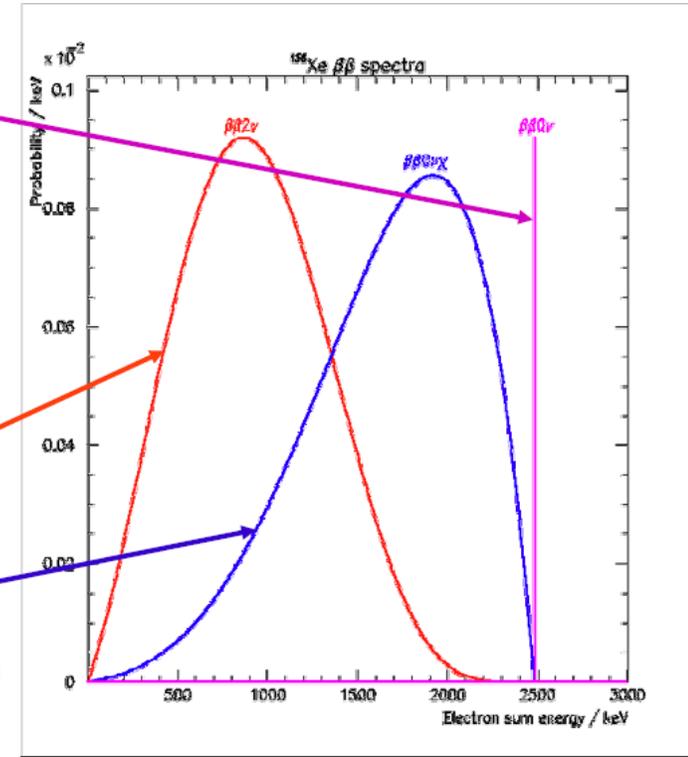
Continuous
 β spectrum



Monochromatic
 β spectrum

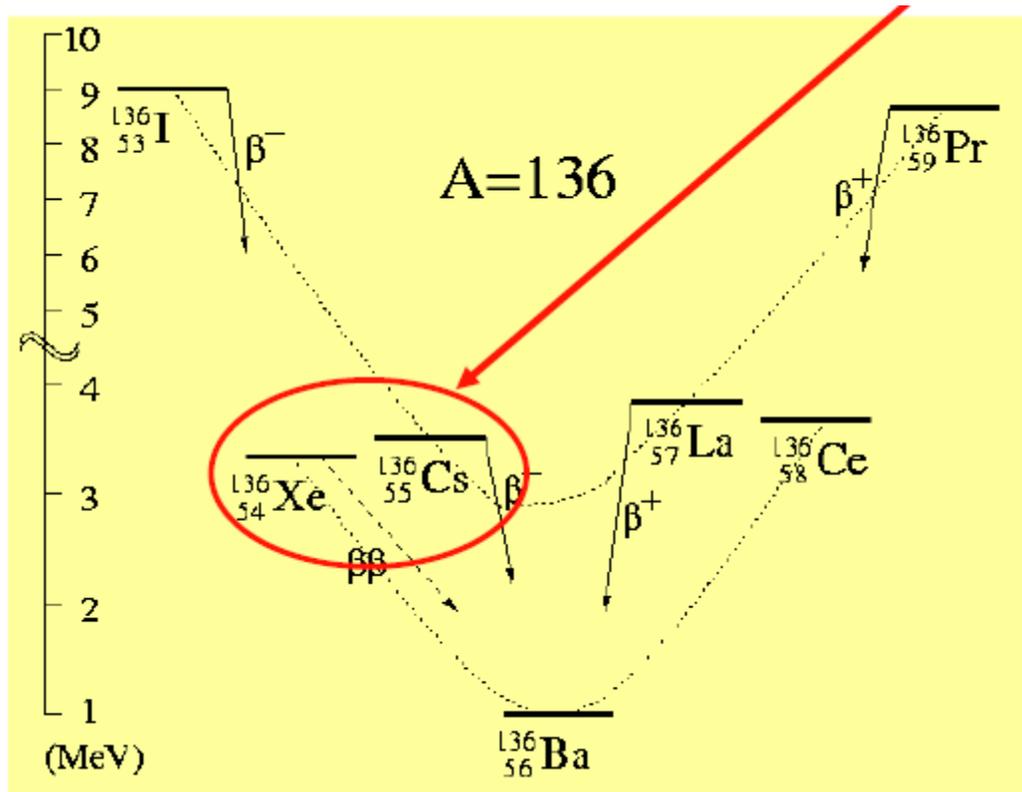
$0\nu\beta\beta$ decay can
be separated
from other modes
using kinematics

$\chi\beta\beta$
 χ Majoron, the Goldstone
boson of lepton symm
breaking



2ν ββ–decay mode

- 2ν mode ββ decays would have a half lives in excess of 10^{20} years
 - M. Goeppert-Mayer, Physics. Rev. 48 (1935) 512

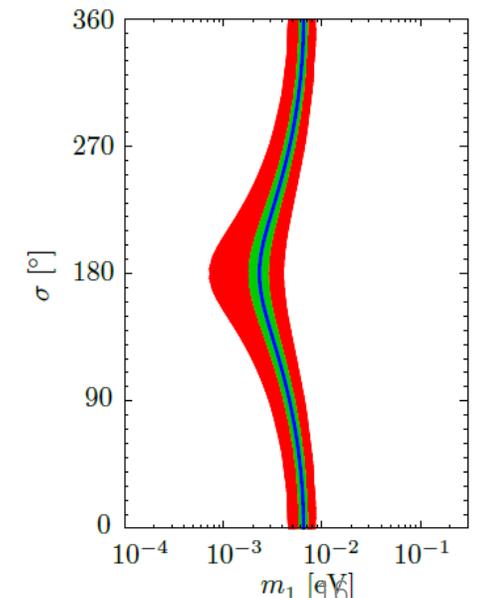
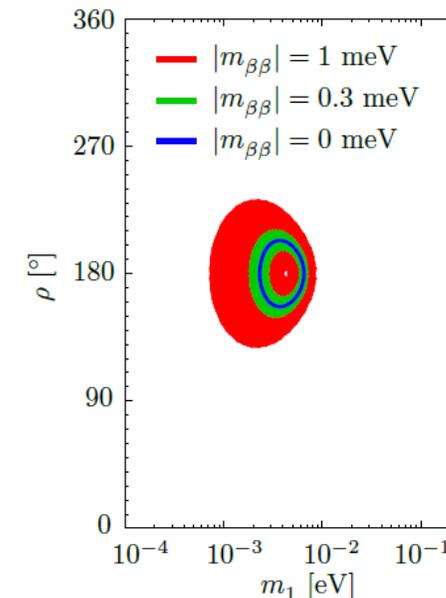
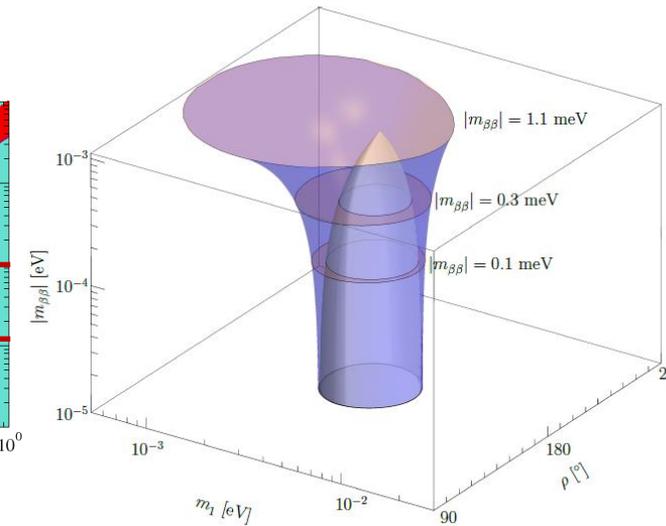
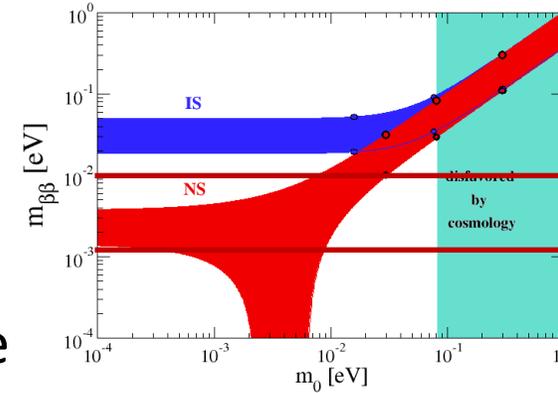


A second order process
Only if the first order
beta decay is
energetically forbidden

Experimental observation of
2ν ββ–decays in 1980's →
(left hand) neutrinos are
Dirac

Goals of $0\nu\beta\beta$ Sensitivities

- **Goal 1:** $|M_{\beta\beta}| \sim 0.01$ eV covering IO region, achievable in 10 years
 - Target mass ~ 1 T
- **Goal 2:** $|M_{\beta\beta}| \sim 0.001$ eV to determine the absolute mass of the lightest neutrino and the Majorana phase ρ , achievable in 20 years ?
 - Increase the target mass by a factor of 10 to 100 \rightarrow 10-100 t target mass
- **Goal 3:** $|M_{\beta\beta}| \sim 0.0001$ eV to cover (almost) all possible parameters space of Majorana neutrinos to prove or dis-prove Majorana neutrinos, achievable ?
 - Increase the target mass by another factor of 10 to 100 \rightarrow 100-10000 t target mass



$\beta\beta$ decays: Summary of Current Results

Experiment	Isotope	Exposure [kg yr]	$T_{1/2}^{0\nu} [10^{25} \text{ yr}]$	$m_{\beta\beta} [\text{meV}]$
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

$$\langle m_{ee} \rangle = \sum_{i=1}^3 |U_{e,i}|^2 m_i \epsilon_i \quad \nu \text{ mass from } \beta\beta 0\nu \text{ decay}$$

($\epsilon = \pm 1$ if CP is conserved)

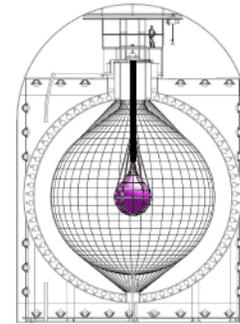
$\beta\beta$ decays: KamLAND-Zen

- Load 3% ^{136}Xe (91% enriched) into LS
- Fill LS into a balloon at the center of KamLAND
- Improvement of KamLAND-Zen 800 over KamLAND-Zen 400:
 - ^{136}Xe amount doubled
 - Balloon produced in class-1 cleanroom: 10 times less ^{232}Th background
 - New rejection method for C & Xe spallation products
- Reached the IO region for the first time

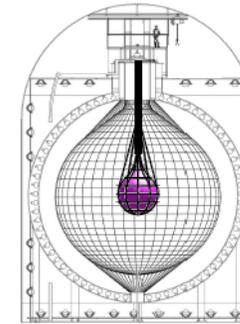
$T_{1/2} > 2.3 \times 10^{26}$ yr

$\langle m_{\beta\beta} \rangle < 36-156$ meV

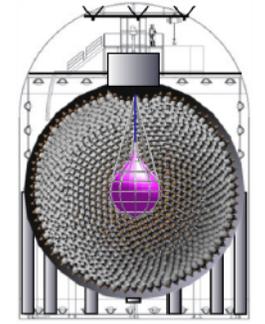
Past
KamLAND-Zen 400
320-380 kg of Xenon
Data taking in 2011 - 2015



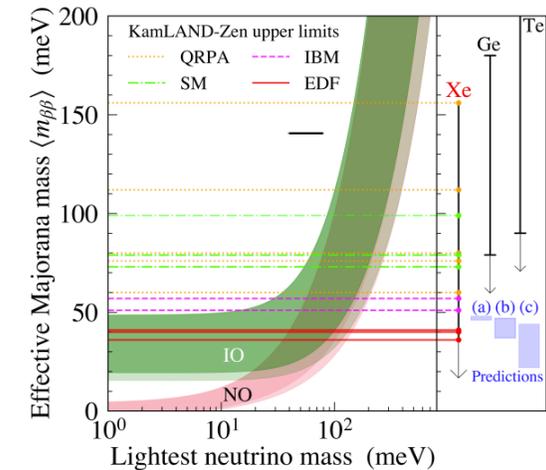
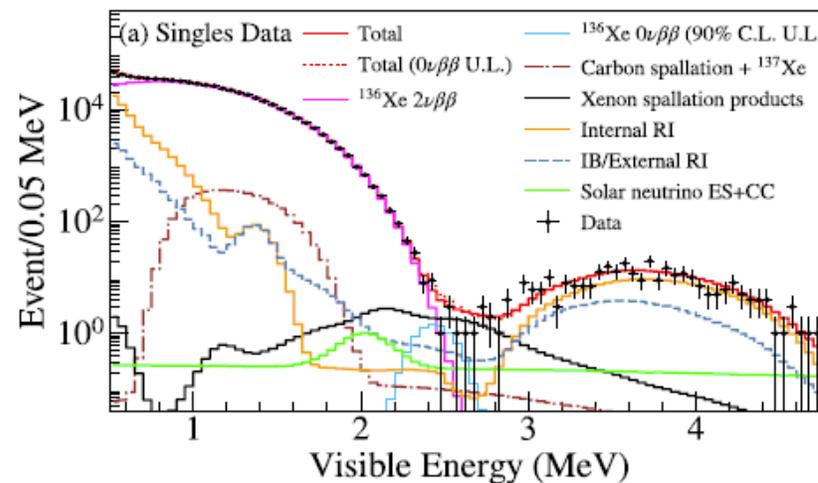
Present
KamLAND-Zen 800
~750 kg of Xenon
DAQ started in 2019



Future
KamLAND2-Zen
~1 ton of ^{136}Xe
Better energy resolution

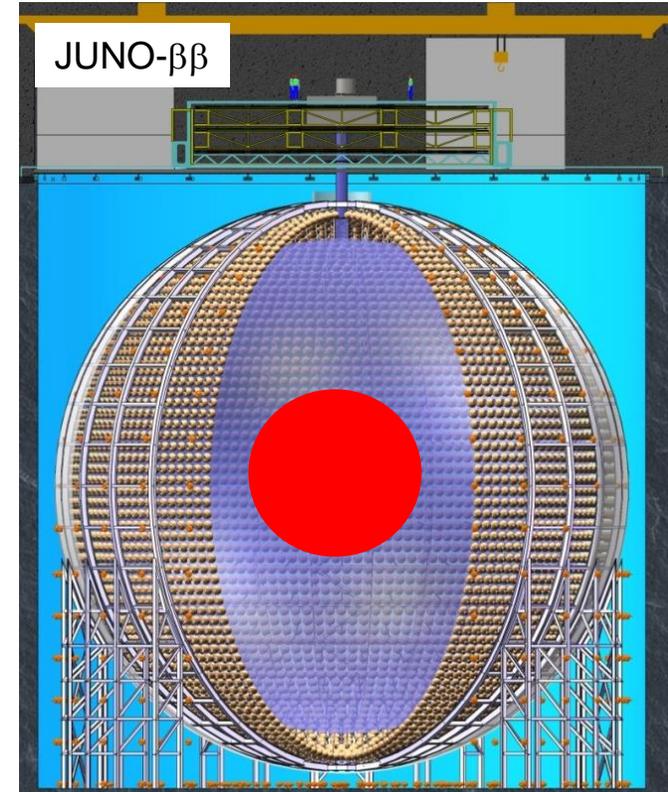


Reanalysis $\xrightarrow{\text{combined}}$ **1st result** [arXiv:2203.02139v1 \[hep-ex\]](https://arxiv.org/abs/2203.02139v1)
& Long paper in preparation



$\beta\beta$ decays: Future Prospects

	Isotope	Mass(t)	$\langle m_{\beta\beta} \rangle, \text{meV}$
SNO+	^{130}Te	8	19-46
KamLAND2-Zen	^{136}Xe	1	~20
NEXT-HD	^{136}Xe	1	14-40
nEXO	^{136}Xe	5	7-22
LEGEND-1000	^{76}Ge	1	10-40
AMoRE-II	^{100}Mo	0.1	12-22
CUPID	^{100}Mo	0.24	12-20
CUPID-1T	^{100}Mo	1	4-7
JUNO- $\beta\beta$	^{136}Xe	50	4-10
	^{130}Te	100	3-14

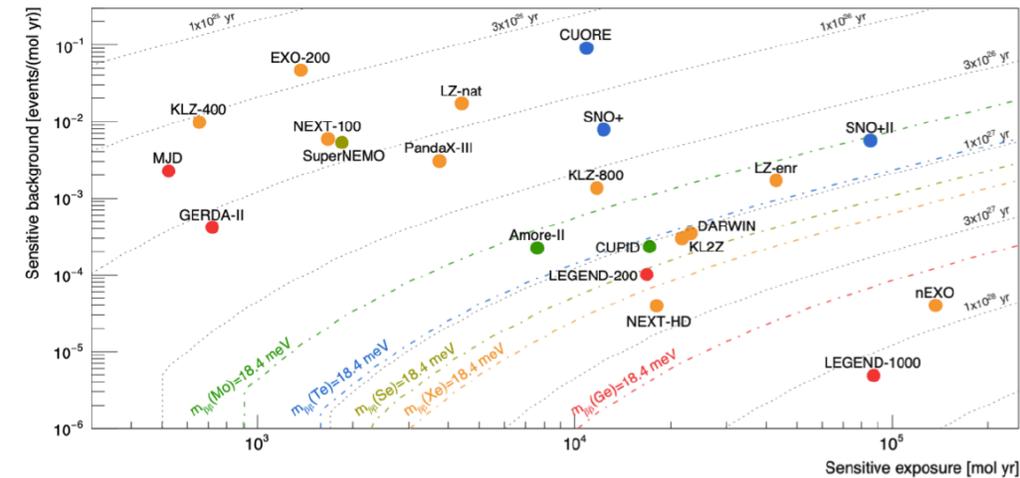


Zhao et al., arXiv: 1610.07143,
CPC 41 (2017) 5

We may be very close to 1 meV

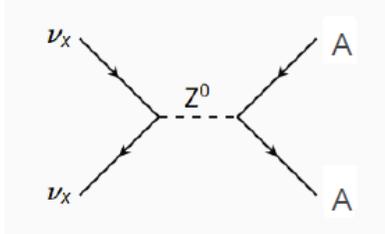
How to Reach $|m_{\beta\beta}| \sim < 1 \text{ meV}$

- Increase the target mass while reducing backgrounds:
 - Internal backgrounds by purification and/or tagging
 - External backgrounds by tagging, (self-)shielding and/or reduction of the surface-volume ratio
 - ^8B solar ν background reduction by directionality
- Technology choices
 - Gas & sampling detectors seems hard
 - Liquid scintillator detectors need to improve loading:
 - ^{136}Xe : reduce the cost by 1 order
 - ^{130}Te : increase the loading, reduce internal backgrounds
 - Crystal detectors need to improve shielding(in LAr ?) and reduce the cost
- International efforts for cope with the escalated cost:
 - Enrichment, R&D, site, shielding detector(HyperK, THEIA ?)
 - New ideas(resolution ?): LiquidO, THEIA, ...



Coherent Elastic Neutrino-Nucleus Scattering

What is
CE ν NS?

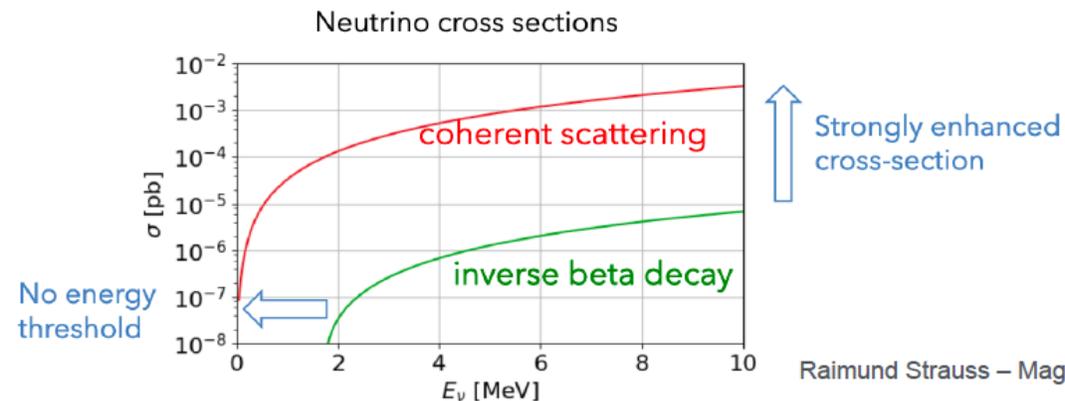


Coherent Elastic
Neutrino-Nucleus Scattering

is a process in which neutrinos scatter off a nucleus acting as a single particle

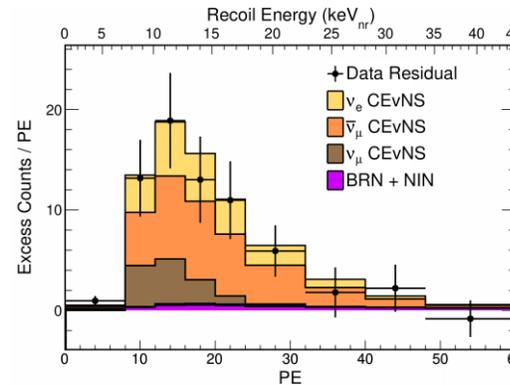
- ◆ Predicted in 1974 by Freedman
[D. Freedman, Phys.Rev. D 9 1389 \(1974\)](#)
- ◆ Measured for the first time in 2017 by COHERENT
[D. Akimov et al, Science 357 \(2017\)](#)
- ◆ Dominant process for $E_\nu \lesssim 50$ MeV

- ◆ Cross section increases as N^2 $\sigma_{SM} \sim \frac{G_F^2}{4\pi} N^2 E_\nu^2$



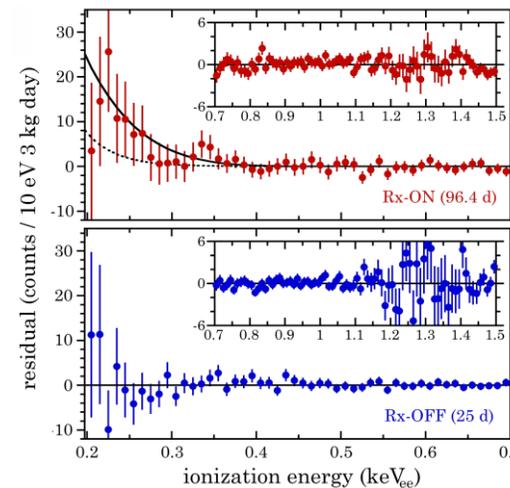
Coherent Elastic Neutrino-Nucleus Scattering

- New results from COHERENT
 - full-exposure CsI[Na] data: 11.6σ , shape and rate agrees well with SM
 - Ar data: 3σ
 - NSI and dark matter searches
- Dresden-II found a strong preference for CEvNS signals at reactors using Ge detector ($<3\sigma$)
- Tens other experiments at beams and reactors: no signals yet
- Upgrades and new experiments on the way
- Powerful for searches: DM, NSI, Magnetic Moments...



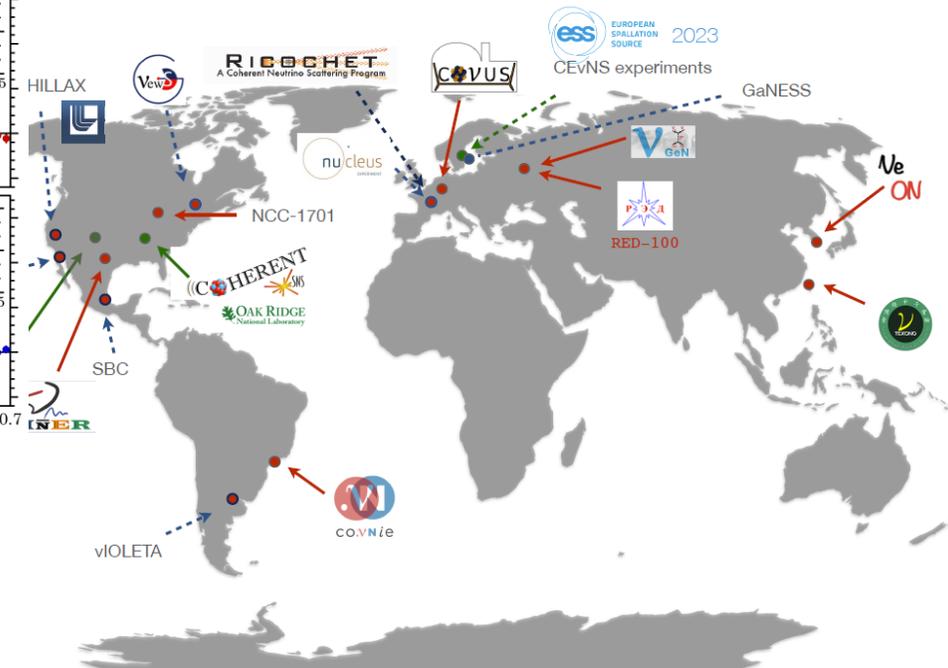
COHERENT CEvNS detectors

Target	Technology	Fid. Mass	Threshold	Deployment
CsI[Na]	Scintillation	14.6	6.5 keV _{nr}	2015
Liquid Ar	Scintillation	24.4/610 kg	20 keV _{nr}	2017/≈2023
Ge	Ionization	18 kg	0.4 keV _{ee}	2022
NaI[Tl]	Scintillation	3500 kg	13 keV _{nr}	2022



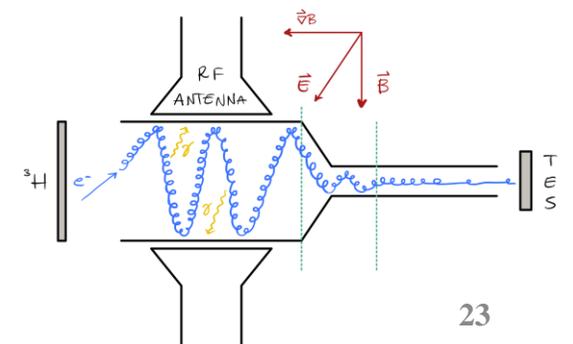
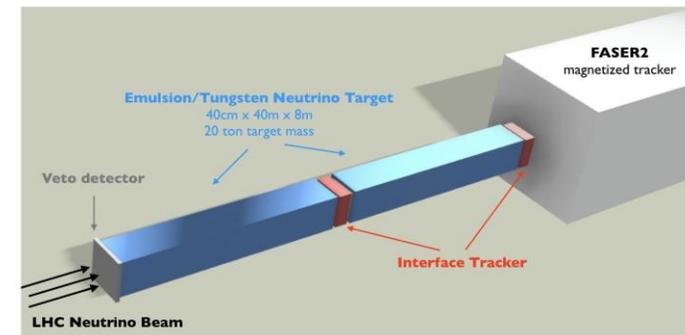
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● Future/Planned



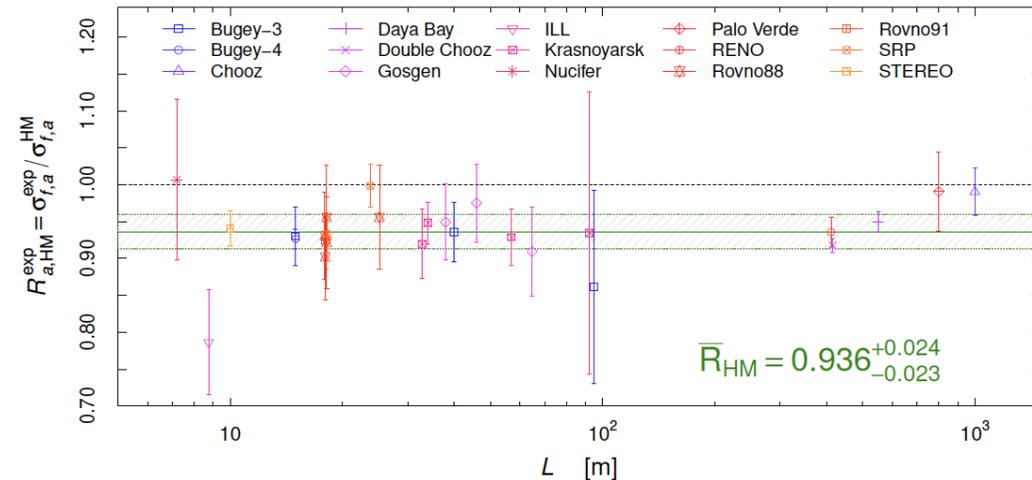
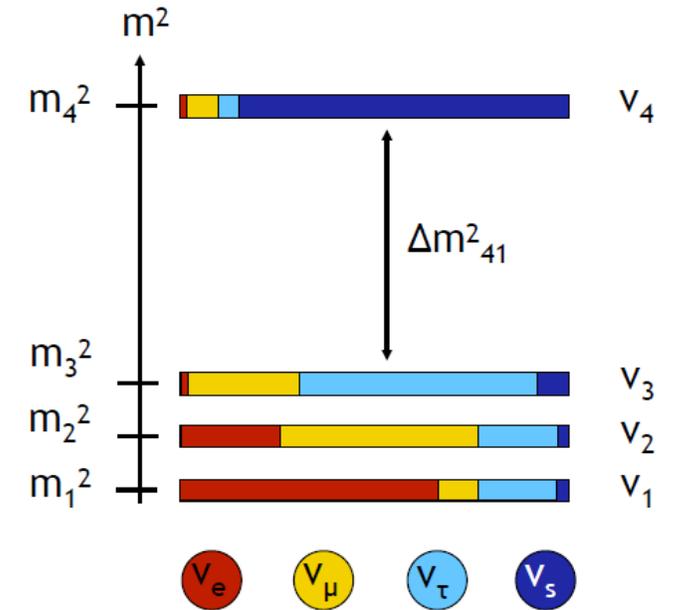
Search for New Physics

- A long list: **sterile neutrinos**, proton decays, NSI, Unitarity test, dark sector, heavy neutrinos, neutrino decays, decoherence, ...
 - Very high energies:
 - At LHC exp.s, FPF, SHiP, SND, ...
 - At medium energies:
 - HyperK, DUNE, SuperK, Icecube, ICARUS, SBND, ...
 - At low energies
 - JUNO, JUNO-TAO, PROSPECT-II, BEST, ISODAR, ...
 - keV neutrino searches:
 - Katrin, Project 8, Magneto- ν , BeEST, HUNTER, etc.
- Cosmic neutrino searches: Katrin, Ptolemy, ...
- In 5 years from now, several new experiments will be operational, new results are expected



Sterile Neutrinos and Anomalies

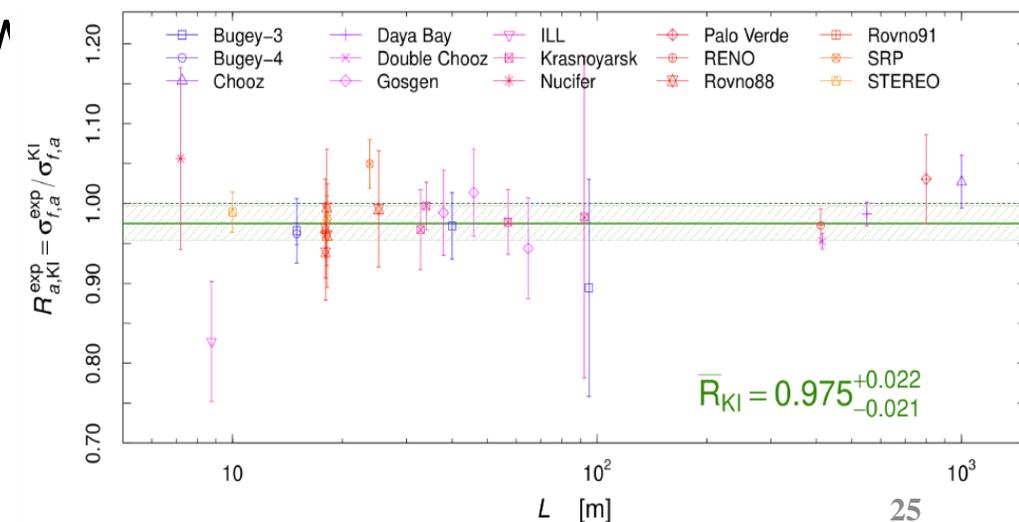
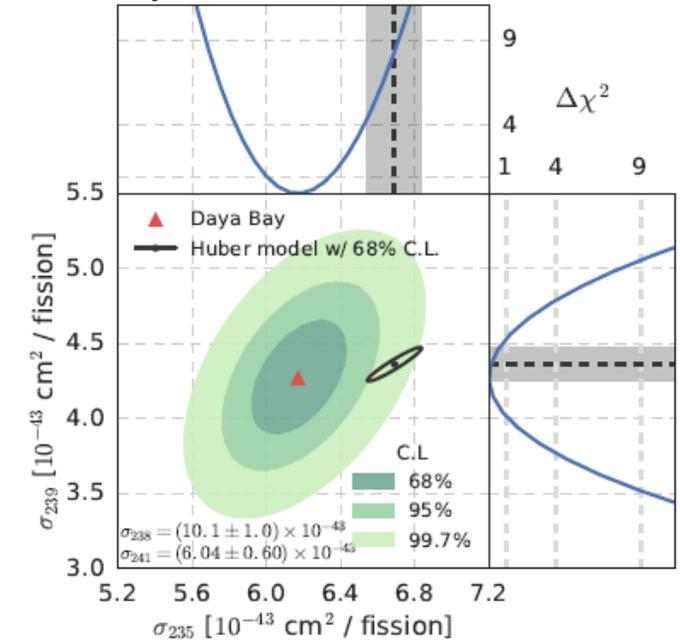
- An active area with a lot of experiments and anomalies
 - Most anomalies at $\sim 3\text{-}4\sigma$ level
 - Simplest 3+1 model seems in tension to cover all anomalies
 - Some anomalies seems real, but maybe not related to sterile neutrinos
- Three main classes of “evidence”
 - Reactor anomaly
 - Neutrino-4 anomaly
 - Ga anomaly
 - LSND anomaly



Reactor Anomaly

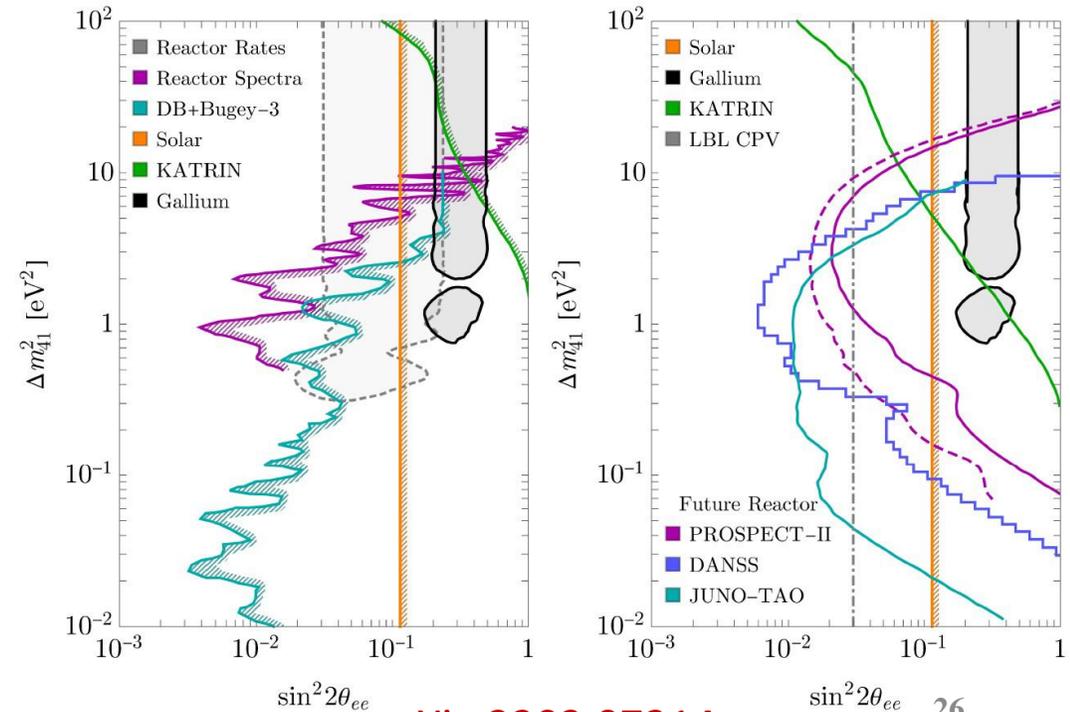
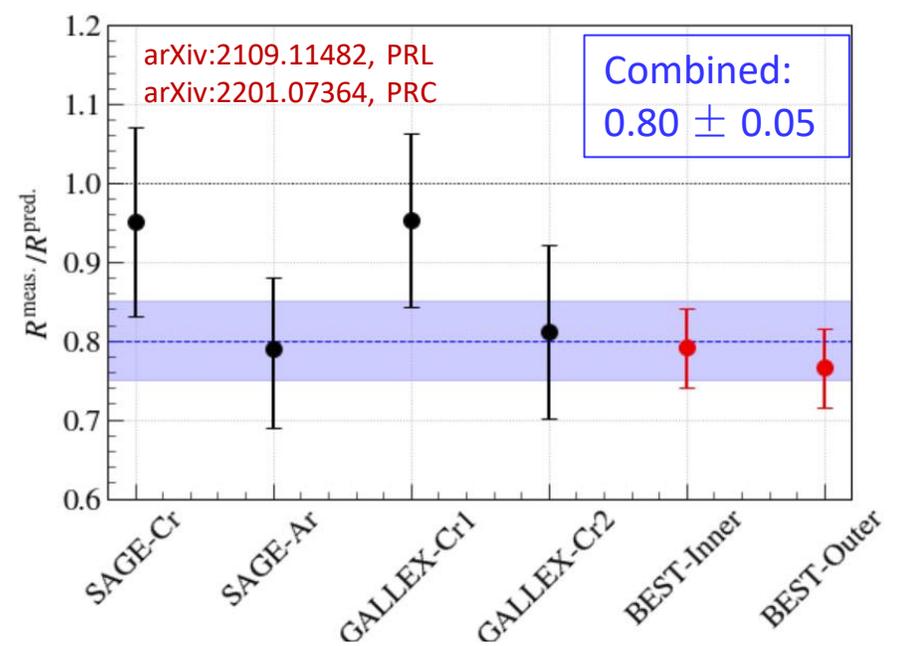
- Flux deficit can be explained as sterile neutrino
- Many experiments reported new results, no oscillation signals beyond 2σ , except
 - Neutrino-4 sees a 2.7σ oscillation signal, but rejected by STEREO at 3.1σ
- Daya Bay reported that the flux deficit is mostly from ^{235}U
- Other reactor and dedicated ^{235}U spectrum measurement confirmed the Daya Bay result
- Current flux calculations using these new data show no deficit, but the 5 MeV bump is still there
- Further improvement by JUNO-TAO and PROSPECT-II for reference nuclear data
 - Neutrino physics: CEvNS, searches, ...
 - Non-proliferation application
 - Precision input for nuclear data

Phys. Rev. Lett. 118, 251801 (2017)



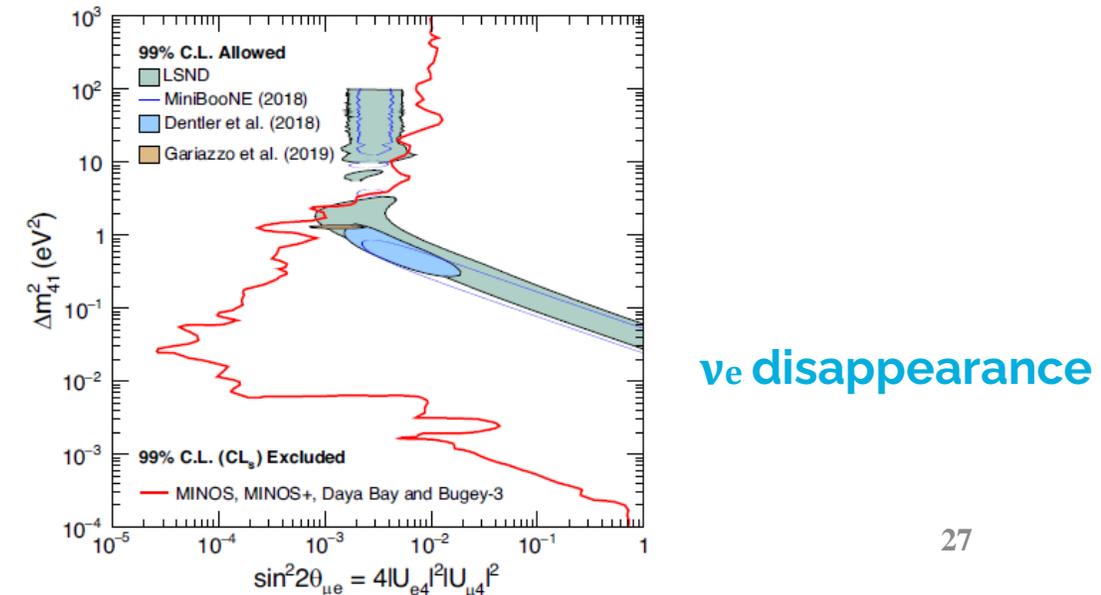
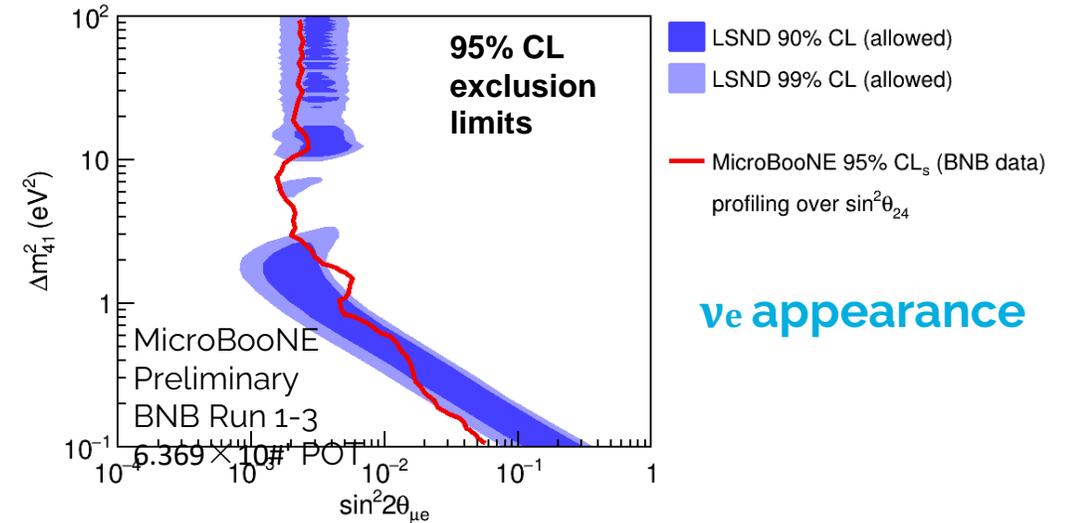
Ga Anomaly

- BEST confirmed GALLEX & SAGE deficit, but no dependence on the oscillation baseline
- Katrin+Reactor experiments excluded most regions of the Ga anomaly
- Seems not due to sterile neutrinos but other explanations should be looked for.
- Future:
 - ^{65}Zn by BEST
 - New data from PROSPECTII, DANSS
 - New experiments: JUNO-TAO and IsoDAR



LSND Anomaly

- MiniBooNE largely confirmed LSND anomaly
- MicroBooNE did not rule out the MiniBooNE allowed region, and confirmed its background estimation, at least partially.
- Daya Bay+Minos exclude part of the MiniBooNE allowed region
- The LSND+MiniBooNE anomaly still exist
 - Other backgrounds ?
 - Sterile neutrinos ?
 - new physics ?
 - More complicated models: Sterile + (NSI, Decay, Decoherence)
- Future: SBND, ICARUS, JSNS²/JSNS²-II, DUNE...



Solar Neutrinos and Solar Physics

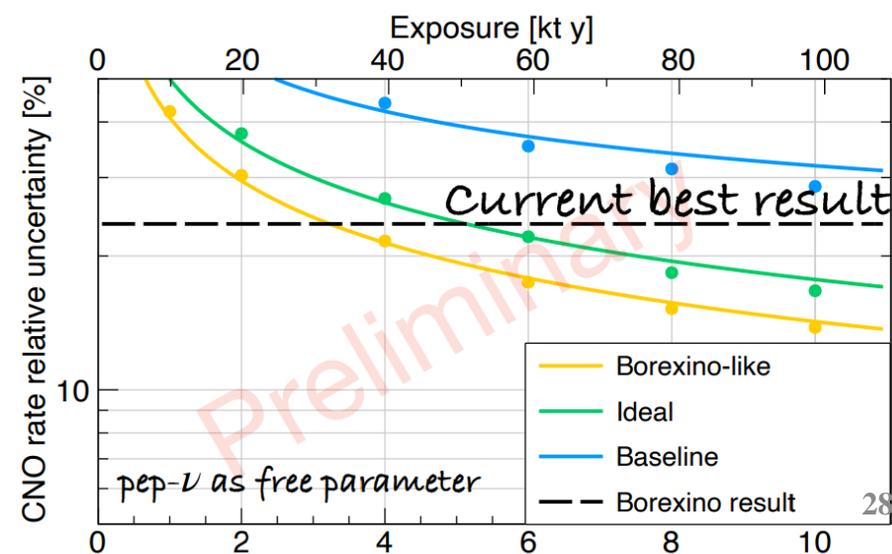
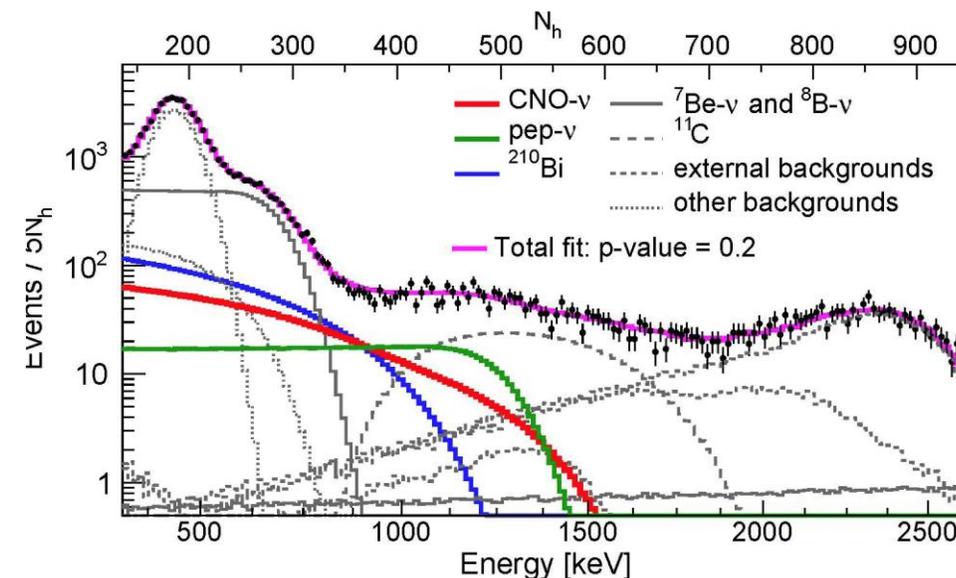
- Borexino reported new CNO results:

Results (including sys errors)

$$\text{Rate(CNO)} = 6.7^{+2.0}_{-0.8} \text{ cpd/100t}$$

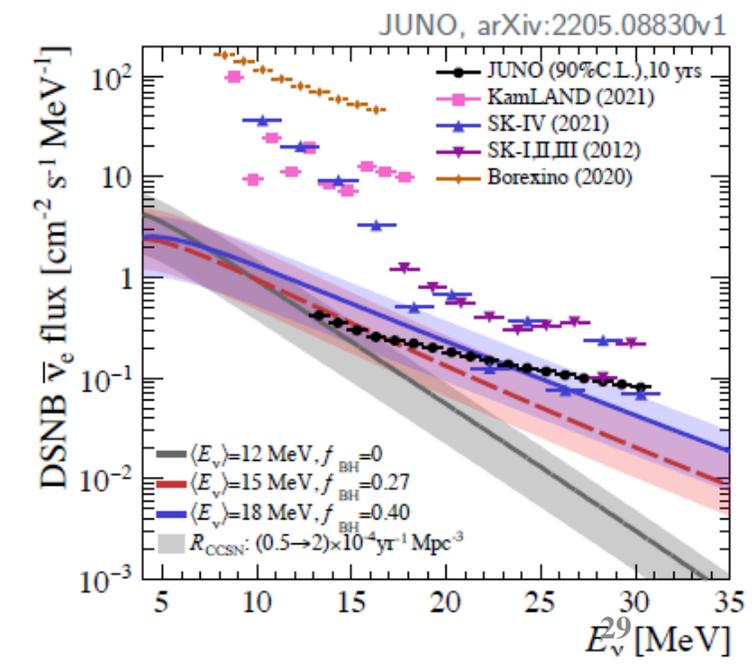
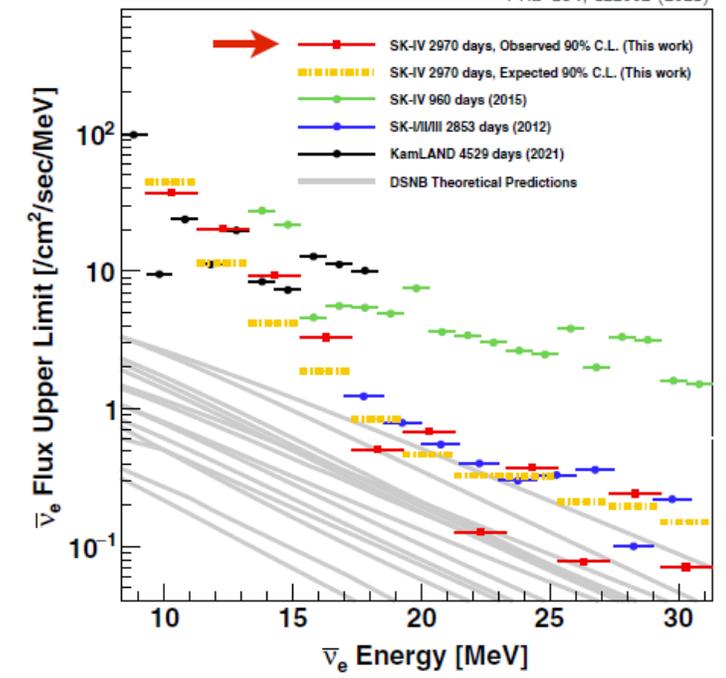
$$\phi(\text{CNO}) = 6.6^{+2.0}_{-0.9} \times 10^8 \text{ v cm}^{-2} \text{ s}^{-1}$$

- CNO-null hypothesis excluded at $\sim 7\sigma$
- Energy spectrum(shape) compatible with electrons scattered by CNO neutrinos
- C and N abundance determined
- CNO+7Be+8B disfavor SSM-LZ at 3.1σ
- Improvement from JUNO expected if background can be controlled to 10^{-17} g/g



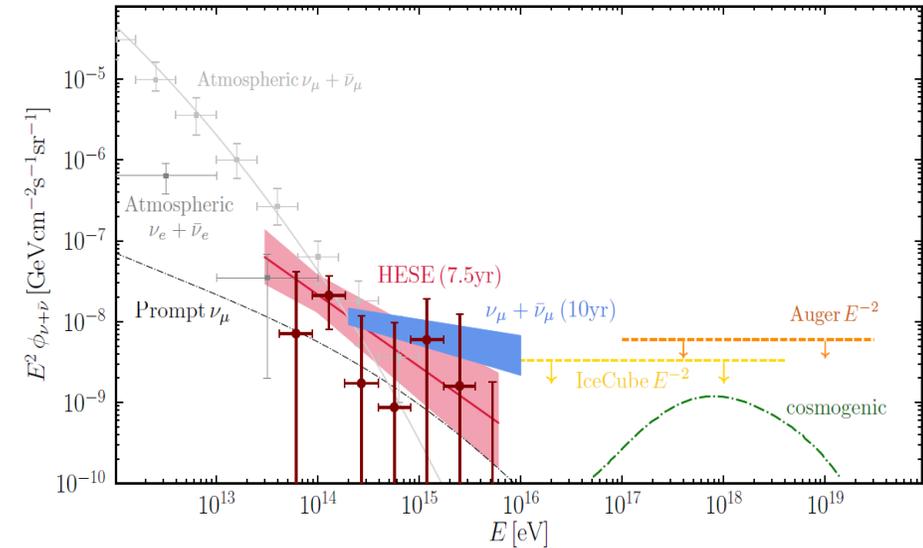
Diffused Supernova Neutrinos

- Latest results from SuperK
 - Sensitive to $1.5 \bar{\nu}_e/\text{cm}^2/\text{s}$, Horiuchi+09 model is 1.9
 - Combined upper limit of $2.6 \bar{\nu}_e/\text{cm}^2/\text{s}$
 - Most optimistic signals are excluded
 - Best fit is $1.3^{+0.90}_{-0.85} \bar{\nu}_e/\text{cm}^2/\text{s}$
 - 1.5σ excess over background expectation
- Signal right at the corner ?
- SuperK-Gd successfully operated for 2 years with 0.01% loading. Phase 2 with 0.03% loading just started
- JUNO can significantly improve the sensitivity
- Future experiments: HyperK, DUNE, THEIA, ...
- Shall be discovered in ~ 15 years from now !



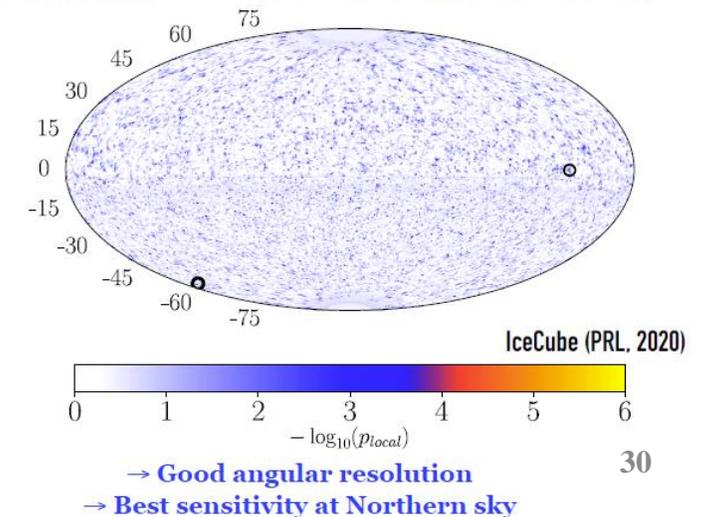
Cosmic-Neutrinos and Multi-messengers

- Astrophysical neutrinos firstly observed by Icecube
 - Diffused flux and sources “identified”
- Baikai-GVD confirmed the flux result, KM3NET is joining the force
- In association with Multi-messengers
 - neutrino detectors: JUNO, HyperK, DUNE, ...
 - GW detectors: LIGO, Virgo, Kagra, Cosmic-Explorer, LISA, ...
 - Cosmic-rays and HE γ s: HWAC, HESS, Magic, LHAASO, CTA, ...
 - γ -rays and X-rays in space: Swift, Fermi, GECAM, eXTP, ...
- A bright new era for astrophysics:
 - Quantitative understanding of AGN, Blazars, Quasar, GRB, SuperNova burst, binary mergers, ...
 - Origin and acceleration mechanism of Cosmic-rays
 - Neutrino oscillation and new physics searches



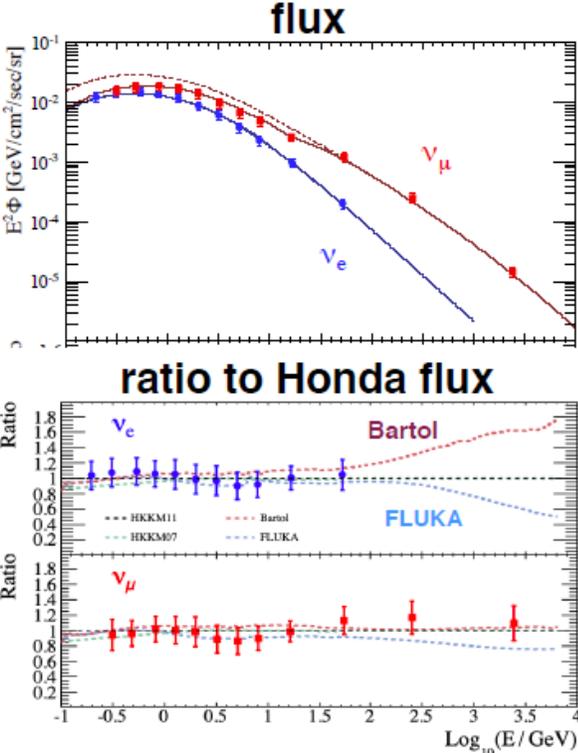
10 Year track-like events ($E > 10$ TeV, $\mu + \nu_\mu$)

(<https://icecube.wisc.edu/data-releases/2021/01/all-sky-point-source-icecube-data-years-2008-2018/>)

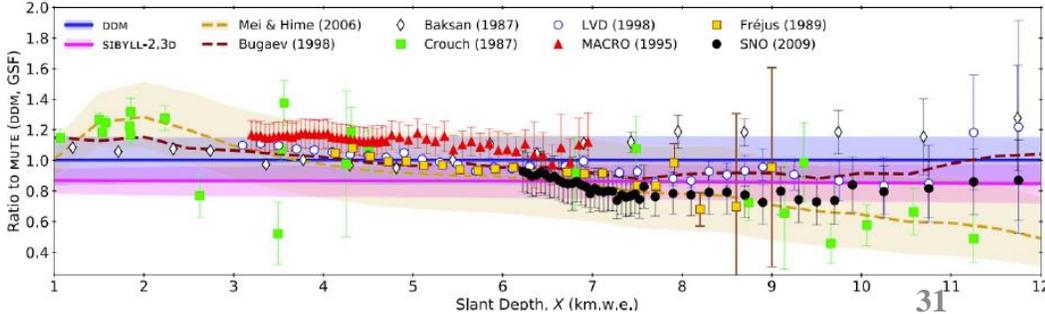


Flux

- Increased precision of experiment requires better understanding of sources(Flux), final states, and interaction cross sections
- Each type of experiments have specific issues
 - Solar: flux: ~1-5%, interactions ~1%
 - With Near detector, flux errors < 1%
 - Reactor: flux: 2%, interactions <1%
 - With Near detector, flux errors < 1%
 - Atmospheric, flux: ~5-10%
 - Off the energy peak, flux uncertainty can be much higher
 - Main flux uncertainty is hadron production cross section
 - With near detector, flux errors ~3%
 - Accelerator, flux: ~5-10%
 - Off the energy peak, flux uncertainty can be much higher
 - Main flux uncertainty is hadron production cross section
 - With near detector, flux errors ~3%
 - Cosmic
- A long time development of Monte Carlo packages for atmospheric ν flux

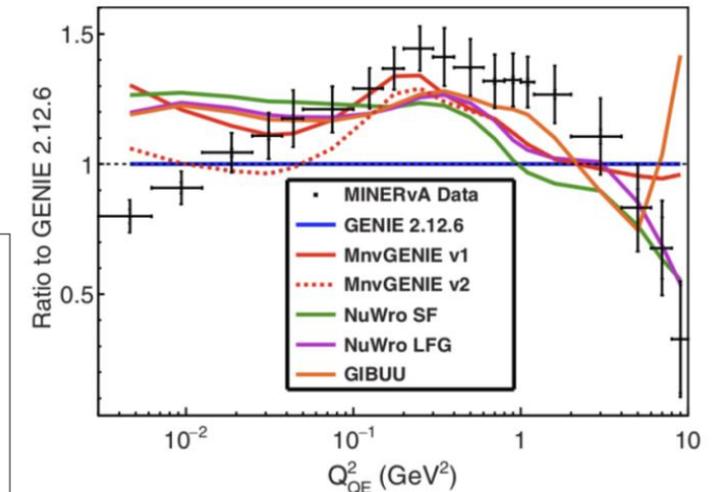
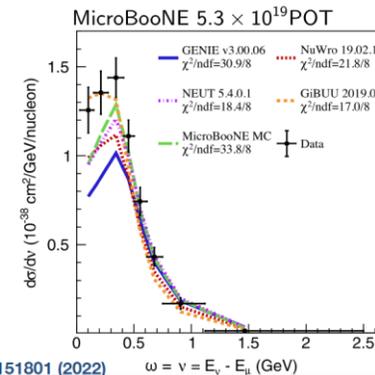
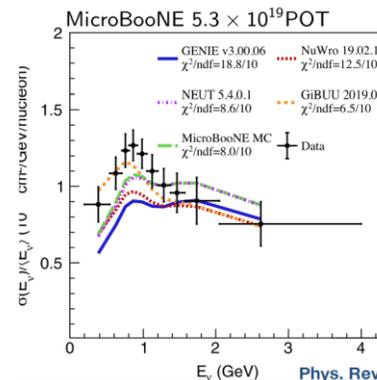


AF, W. Woodley, M.-C. Piro, *ApJ* **928** 27 (2022)



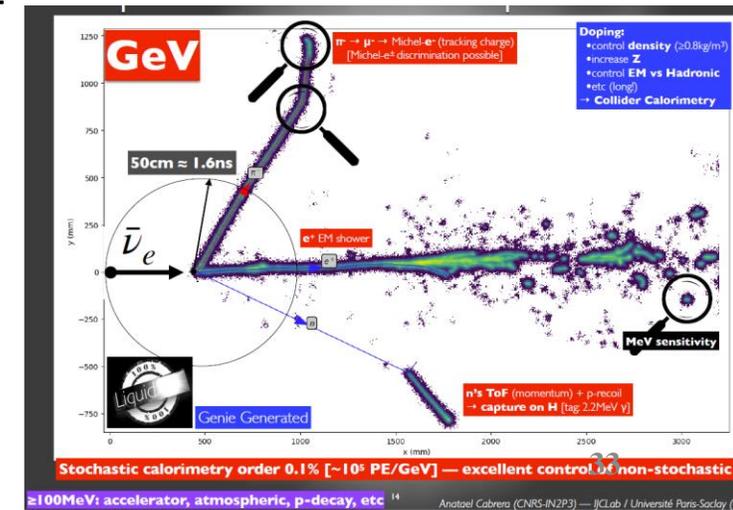
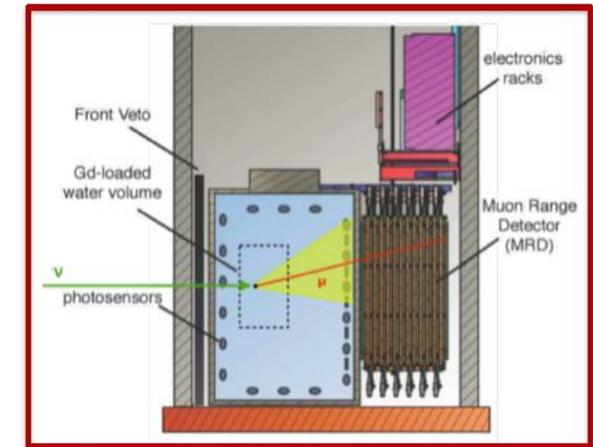
Interaction Cross Sections

- Progresses of theoretic understanding and calculations
- A lot of measurement of cross sections by experiments and their prototypes
 - Many experiments: T2K, NOVA, MicroBooNE, MiniBooNE, MINERvA ...
- Dedicated experiments
 - High energy neutrinos: FASERn, SND, and FPF at LHC
 - Medium energy neutrinos: CLAS, e4v...
- Great effort of Monte Carlo Modelling and improvement
 - GENIE, NEUT, NuWro, GiBUU
- Still a lot to do, in particular for new experiments (new nucleus)



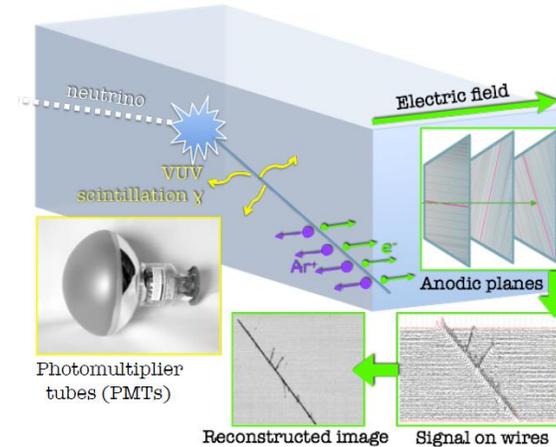
New Technologies: LS

- Approach 1: Hybrid of Cerenkov and Scintillation detector for Directionality
 - Method: Water-based LS, slow scintillation light, fast PMT or LAPPD readout
 - Several prototypes at tons scale: ANNIE, SANDI, EOS, Jinping 1T, ...
 - Direction capability using normal LS: Borexino solar neutrino data
 - Future:
 - Jinping: 500t \rightarrow 4kt
 - THEIA: 100 kt: for neutrino oscillations and $0\nu\beta\beta$ decays
- Approach 2: loading for neutron tagging or $0\nu\beta\beta$ decays
 - Successful Gd-loading up to $\sim 0.1-0.3\%$, Daya Bay, RENO, Double Chooz
 - Te loading: 0.5 – 4.0%, SNO+, JUNO- $\beta\beta$
- Approach 3: Opaque LS detector with a fiber array
 - 3D Imaging + timing: TPC-like
 - Good PID: e^+ , e^- , γ , n , p , ...
 - Fiber array in a uniform media(liquid/solid): Cerenkov, Scintillations, ...



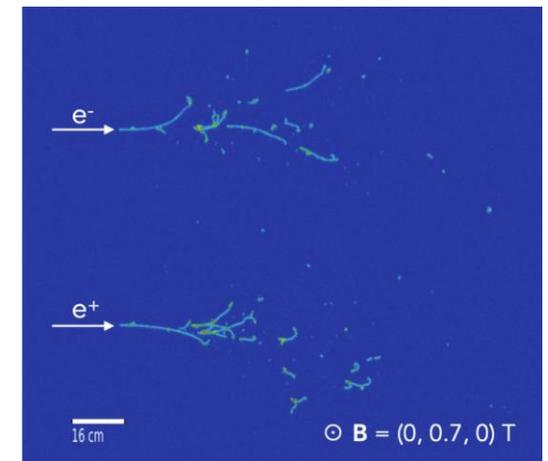
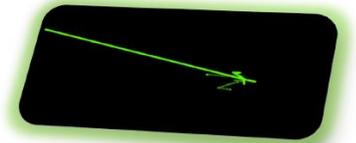
New Technologies: LArTPC

- New ideas to for a large detector, easy operation and more applications:
 - Low power, low noise readout
 - SiPM at HV(300 KV) surfaces,
 - Analog signal, HV and power over fiber
 - Large area reflective coating with WLS to collect light
 - Flat optical metalenses as light concentrators coupled with small area SiPMs
 - Magnet to discriminate particle charges
 - Electron multiplication in liquid to low the threshold to <100 keV \rightarrow DM, CEvNS
 - Proportional scintillation light in LAr
 - Dopants to convert scintillation light into charge for lowing the threshold and improve resolution $\rightarrow 0\nu\beta\beta$
 - Integrated charge and light (L) sensor
 - Dual readout TPCs



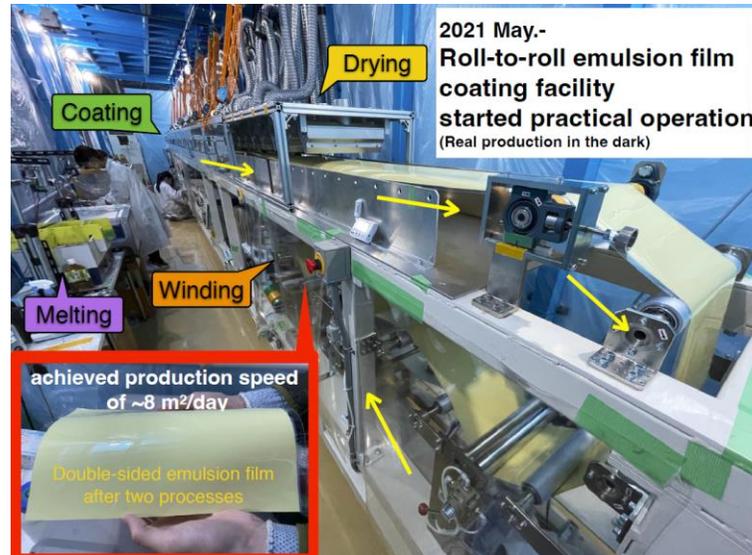
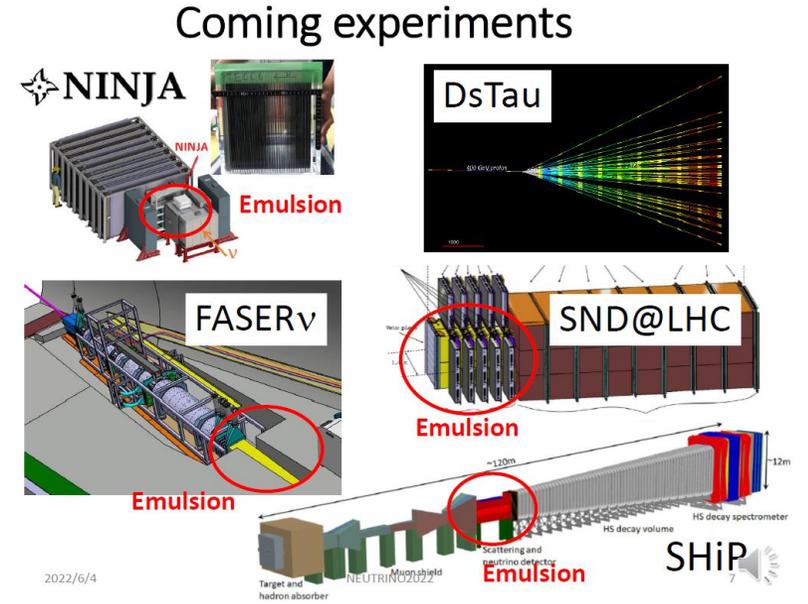
$\lambda = 128$ nm scintillation light:
 40000 γ /MeV wo electric field.
 Response time ~ 6 ns \div 1.6 μ S.

Ionisation electrons:
 42000 e⁻/MeV.
 Drifted (E) toward planes of wires on which they induce a signal. Response time = drift time (ms).



New Technologies: Emulsion Detector

- Nuclear emulsion film: optical resolution <math>< 0.5 \mu\text{m}</math>
- Scanning system(GPU): $0.5 \rightarrow 2.5\text{--}10 \text{ m}^2/\text{h}$
 - Large field of view
 - Mosaic imager with beam splitter to eliminate the dead zone
- The decline of the photographic film Industry lead to the development of emulsion films at Nagoya U.
 - Stable and consistent large scale gel production
 - New automatic roll-to-roll facility for coating and drying to supply films $\sim 8 \text{ m}^2/\text{d}$
- Track efficiency: 80->97%
- Start to supply for exp.
- a new stage for neutrino physics using emulsion films



Projects: JUNO

- Installation in smooth progress, after civil issues resolved
- Key components production in good shape, technical and engineering problems solved.
- Ambitious requirements, such as the energy resolution (3%@1MeV), cleanness(10^{-17} g/g), etc. seems realizable
- LS Filling will start next year



Liquid scintillator (20 kton)



Poster: #265

NIM.A 908 (2021) 164823

Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm.

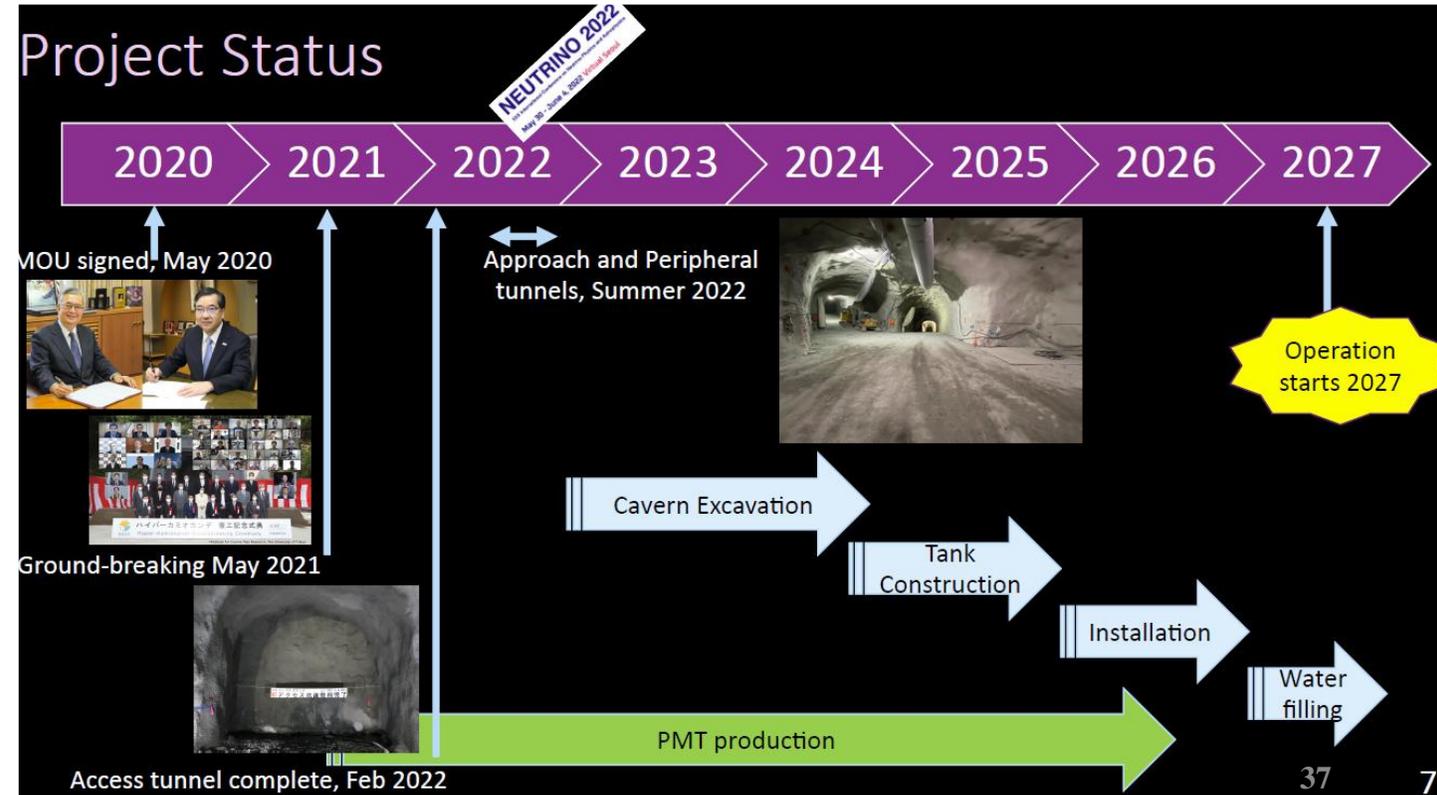
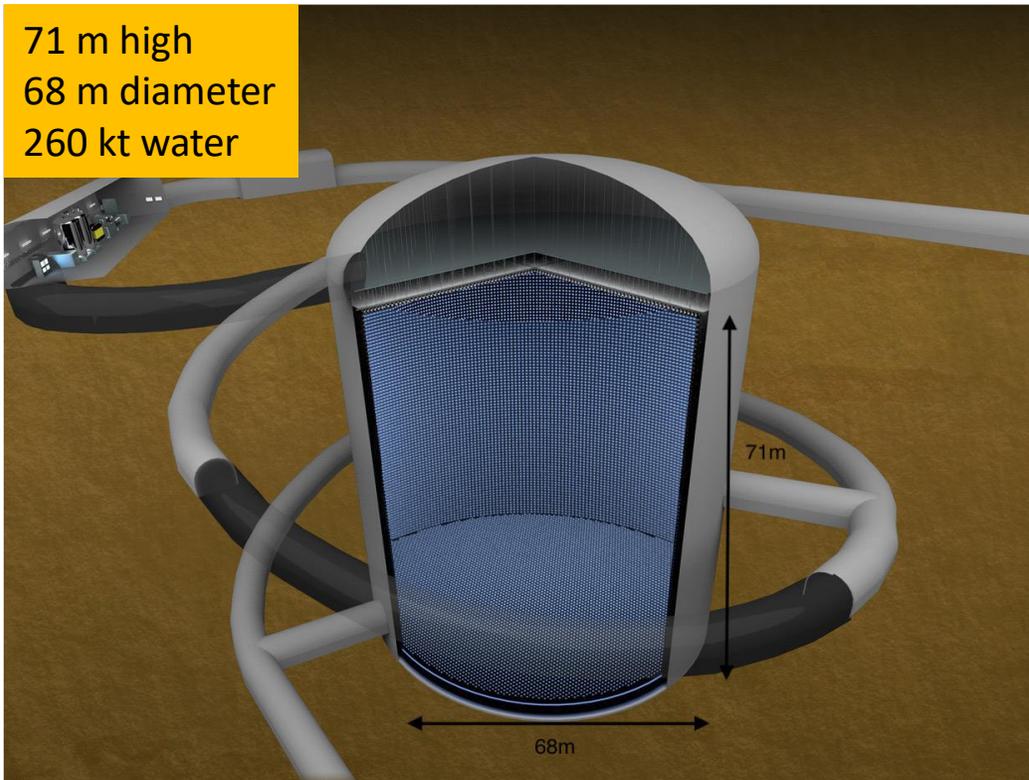


All the LS related systems will finish assembly in summer.



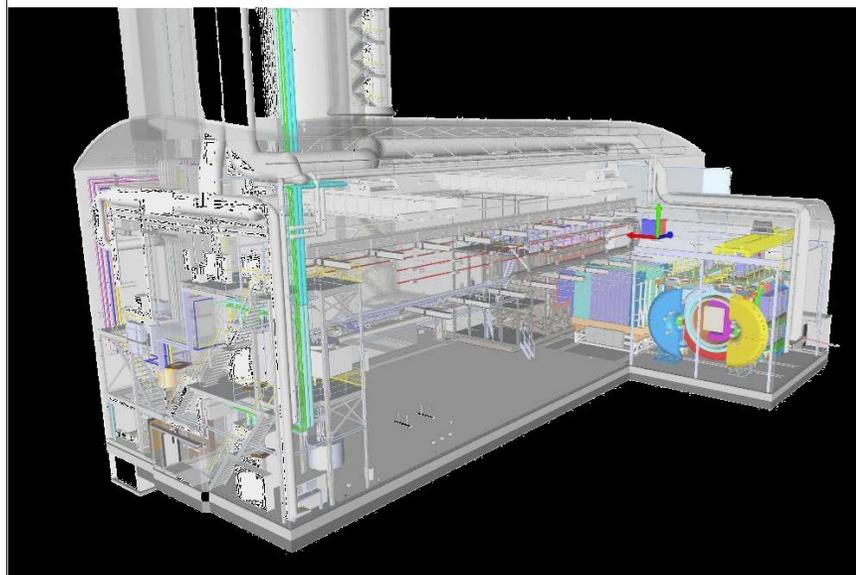
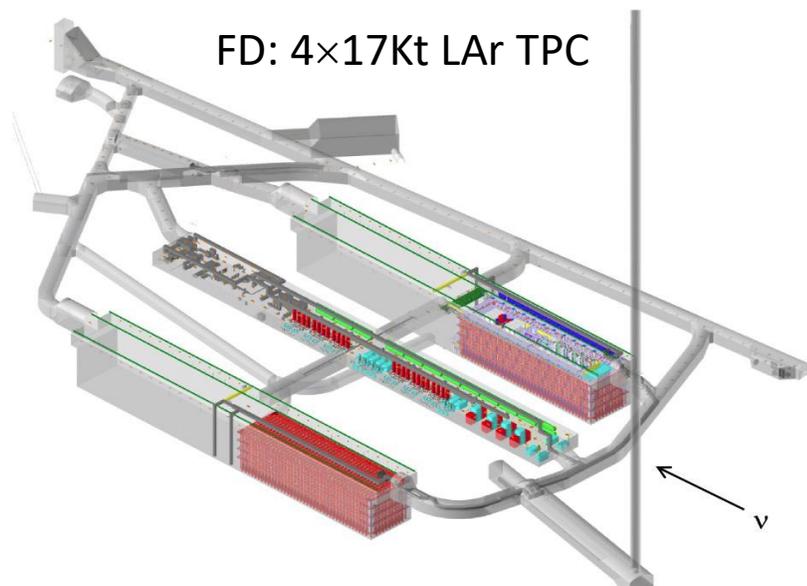
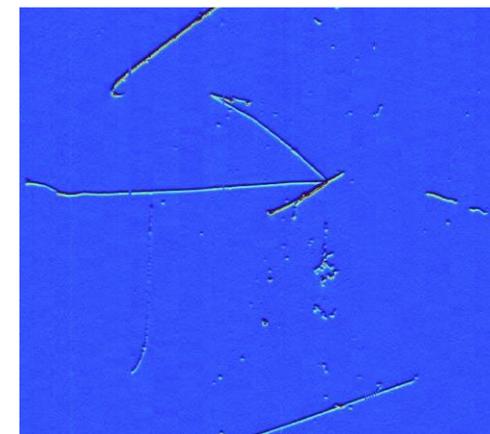
Project: HyperK & T2HK

- Beam upgrade in progress, now: 0.5 MW, goal: 1.3 MW
- Civil construction went on smoothly
- Near detector(T2K) upgrade, and the intermediate detector in progress
- PMTs production started: 20K pieces, 20", HQE, Box and Line Dynode



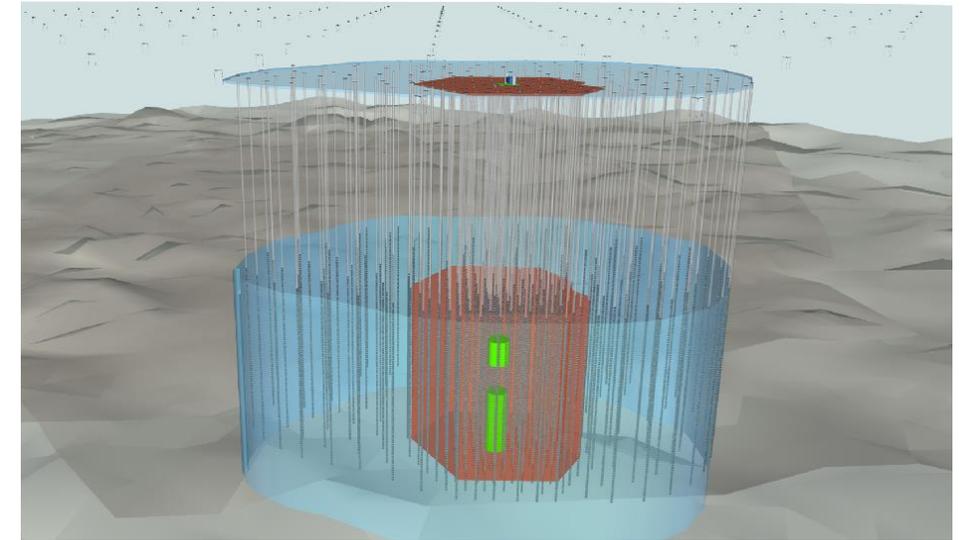
Projects: DUNE & PIP-II

- Beam upgrade in progress, now:0.9MW, goal:1.2MW, future:2.4MW
- Far site: Excavation in progress, on schedule and on budget
- Near detector and beamline design completed
- ProtoDUNE successful and scalable. Preparations underway to install and operate the first FD1 production components



Projects: Icecube

- Near term upgrade:
 - Prototype for Gen2
 - Oscillation measurement
 - Start drilling in 2024-25, deployment in 2025-2026
- Icecube-Gen2: $\times 5$ sensitivity
 - $\times 8$ active volume
 - Improved optical module
 - Surface air shower array, $\times 40$ coincidence
 - Radio array: 500 km² area for EeV neutrinos

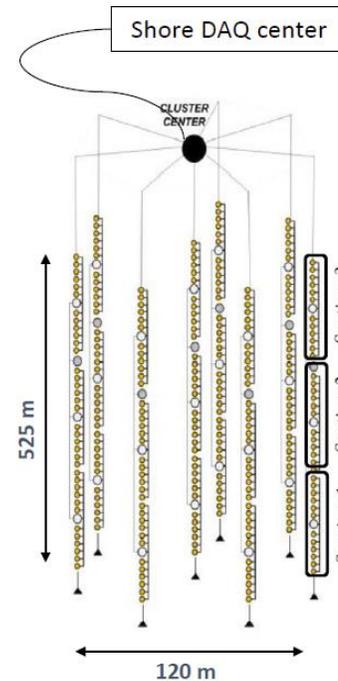
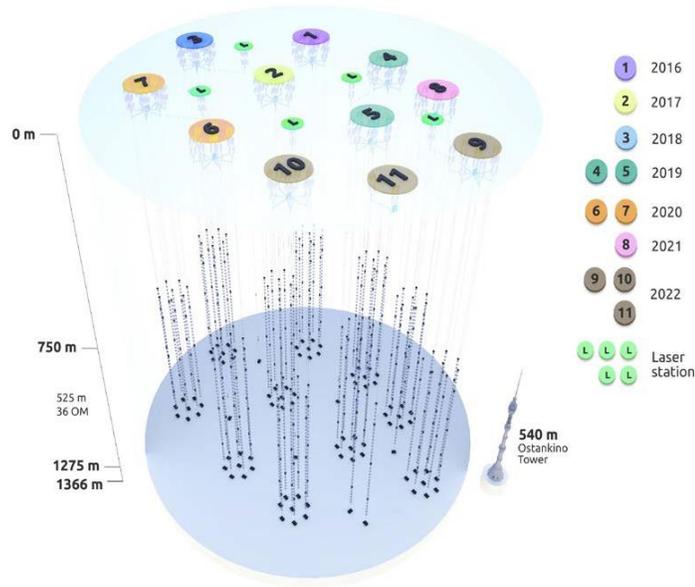


Projects: Baikai-GVD

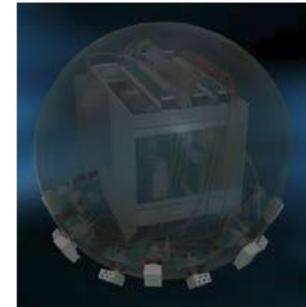
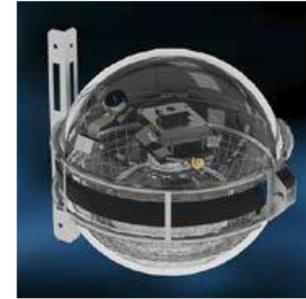
- Largest neutrino telescope in the Northern Hemisphere and still growing
- Outlook:
 - 2025/2026 – $\sim 1\text{km}^3$ GVD with total of 16-18 clusters
 - 2022-2024 – “Conceptual Design Report” for next generation neutrino telescope in Lake Baikal

Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032
2025	16	4608
2026	18	5184



Optical module



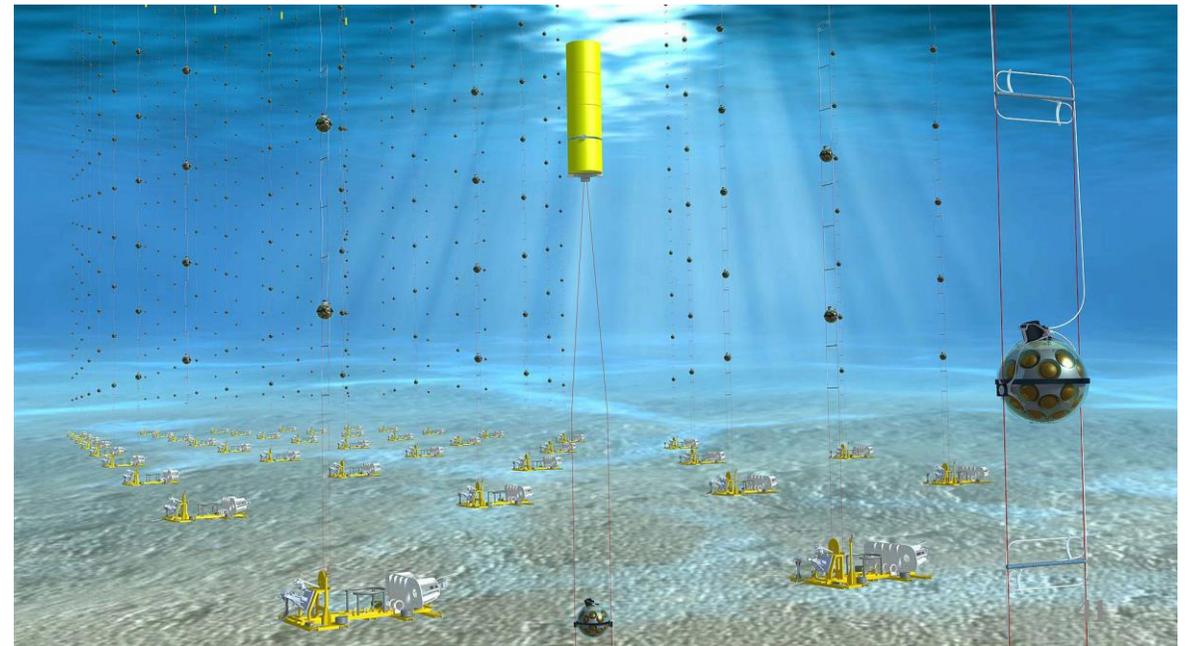
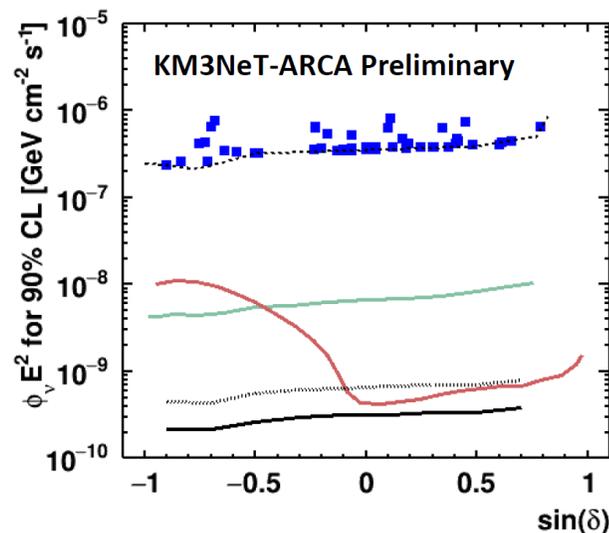
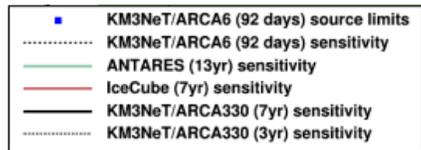
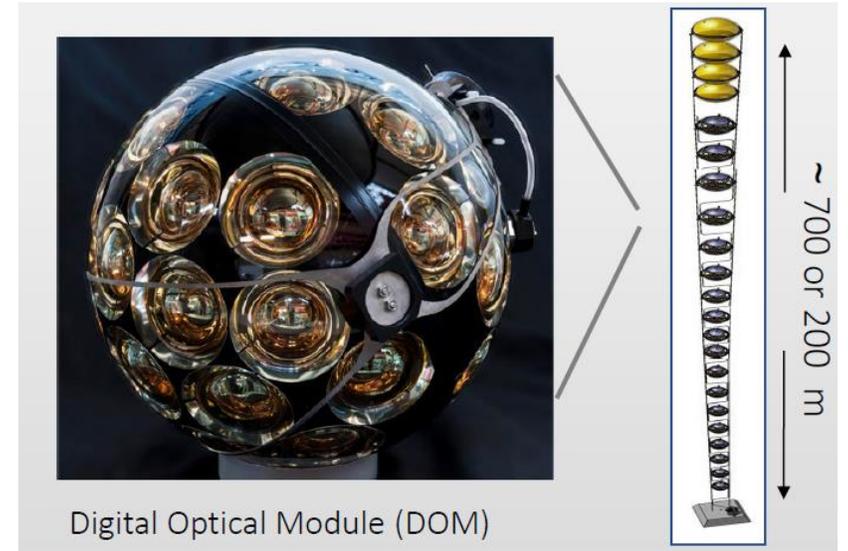
Section control module



Projects: KM3NET

- First deployment successful, calibration OK
 - 16 DU for ORCA
 - 9 for ARCA
- Data quality is good
- Next milestone:
 - 8 More DUs this year in ORCA.
 - 11 DUs + 2 Junction boxes in ARCA.

	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Instrumented mass	7 Mton	500*2 Mton



Summary

- In ~ 10 years from now, oscillation will mostly be understood: mass hierarchy and CP phase will be known
- Neutrino absolute masses may be measured in ~ 20 years, through cosmology, beta decays and double beta decays
- Majorana neutrino nature maybe determined in ~ 30 years
- Sterile neutrinos are unlikely the cause of reactor and Ga anomalies, but still possible for the LSND anomaly
- A new era of astrophysics with multi-messengers, including neutrinos
- Many new projects will start within 10 years
- **A bright future**