Massenordnung (Massenhierarchie) der Neutrinos

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Neutrino Mass & Mixing

Basic features of 3 Neutrino Mixing confirmed in numerous experiments

- 2 independent mass differences: Δm^2_{12}, Δm^2_{23} **(measured)**

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

- 3 mixing angles: θ_{12}, θ_{23}, θ_{13} **(measured)**
- 1 Dirac-phase (CP violating): δ **(measurement in next decade)**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Really maximal?
Octant?

$\Theta_{23} \approx 45°$

atmospheric neutrinos,
neutrino beams

$\Theta_{13} \approx 9°$, δ ?

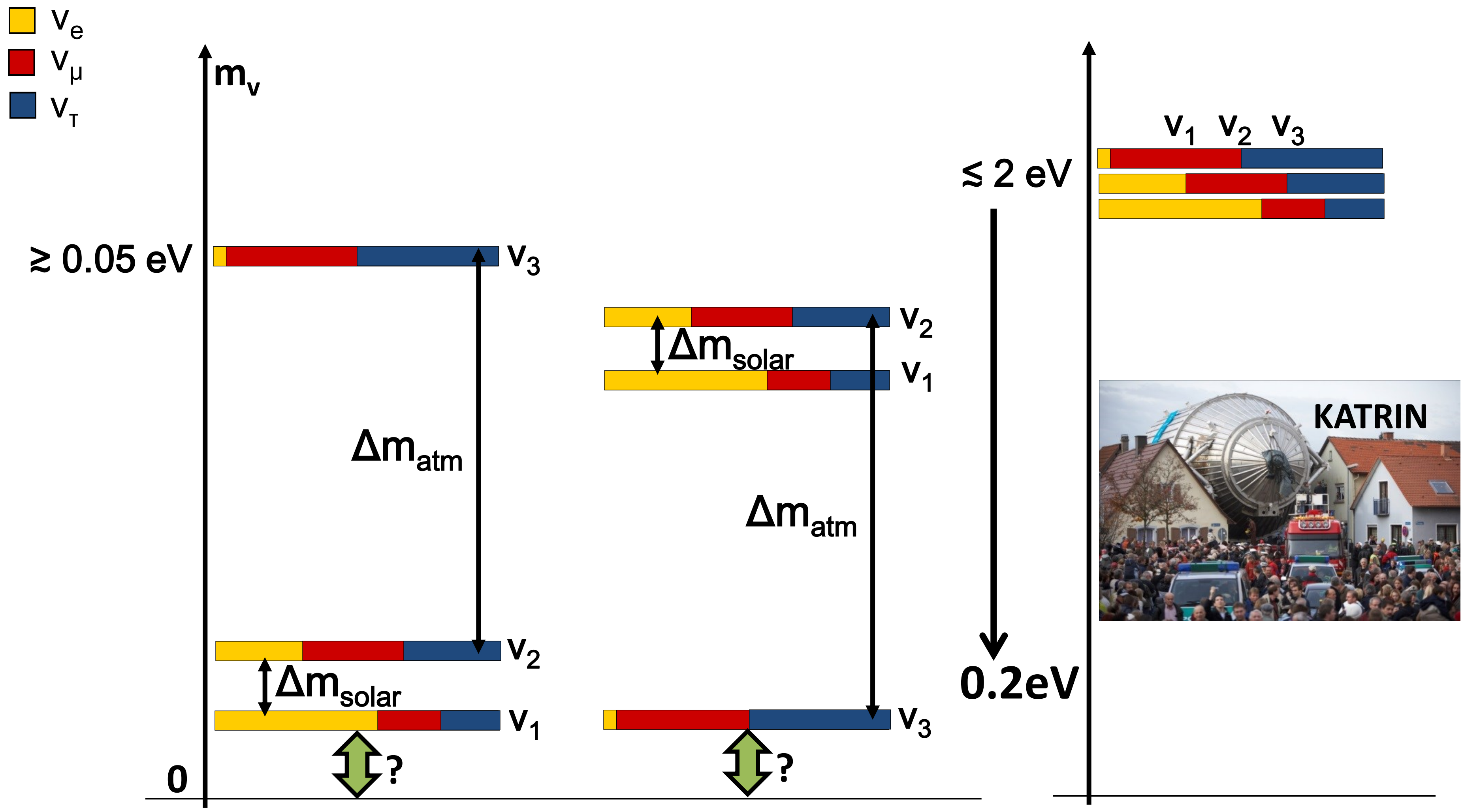
reactor neutrinos,
neutrino beams,
atm. neutrinos

$\Theta_{12} \approx 33°$

solar neutrinos,
reactor neutrinos

What do we know about neutrino masses?

$\Delta m^2_{solar} \approx 7.4 \cdot 10^{-5} eV^2$, $\Delta m^2_{atm} \approx 2.5 \cdot 10^{-3} eV^2$



🟨 ν_e
🟥 ν_μ
🟦 ν_τ

m_ν

$\gtrsim 0.05$ eV

ν_3 ν_2 ν_1

Δm_{atm}

Δm_{solar}

?

0

ν_2 ν_1 ν_3

Δm_{solar}

Δm_{atm}

?

$\lesssim 2$ eV

0.2eV

ν_1 ν_2 ν_3

KATRIN

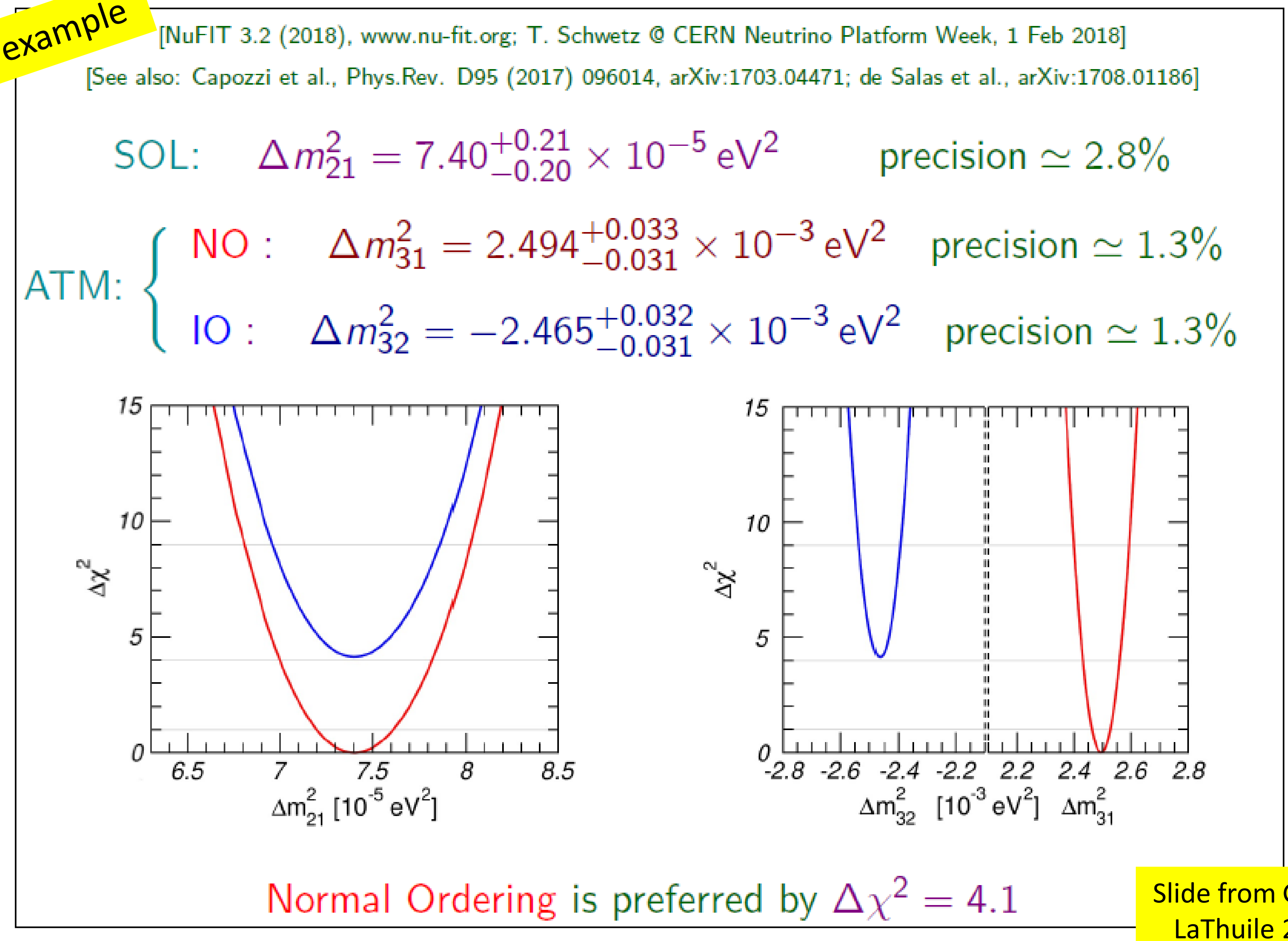
normal hierarchy

inverted hierarchy

quasi - degenerate

Status of Global Fits of Oscillation Parameters

one example



[NuFIT 3.2 (2018), www.nu-fit.org; T. Schwetz @ CERN Neutrino Platform Week, 1 Feb 2018]

[See also: Capozzi et al., Phys.Rev. D95 (2017) 096014, arXiv:1703.04471; de Salas et al., arXiv:1708.01186]

SOL: $\Delta m^2_{21} = 7.40^{+0.21}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$ precision $\simeq$ 2.8%

ATM:

- NO : $\Delta m^2_{31} = 2.494^{+0.033}_{-0.031} \times 10^{-3}\,\mathrm{eV}^2$ precision $\simeq$ 1.3%
- IO : $\Delta m^2_{32} = -2.465^{+0.032}_{-0.031} \times 10^{-3}\,\mathrm{eV}^2$ precision $\simeq$ 1.3%

Normal Ordering is preferred by $\Delta\chi^2 = 4.1$

Slide from Giunti LaThuile 2018

Open Questions

Oscillation Experiments:

- Is Θ_{23} maximal (45°) ?
  If not, which octant (e.g. 41° or 49°)?

- **What is the mass ordering (hierarchy)?**

- **What is the value of δ_{CP} ?**

- Are there additional light (eV) sterile neutrinos?
  (LSND result, reactor neutrino anomaly)

- Unitarity of mixing matrix?

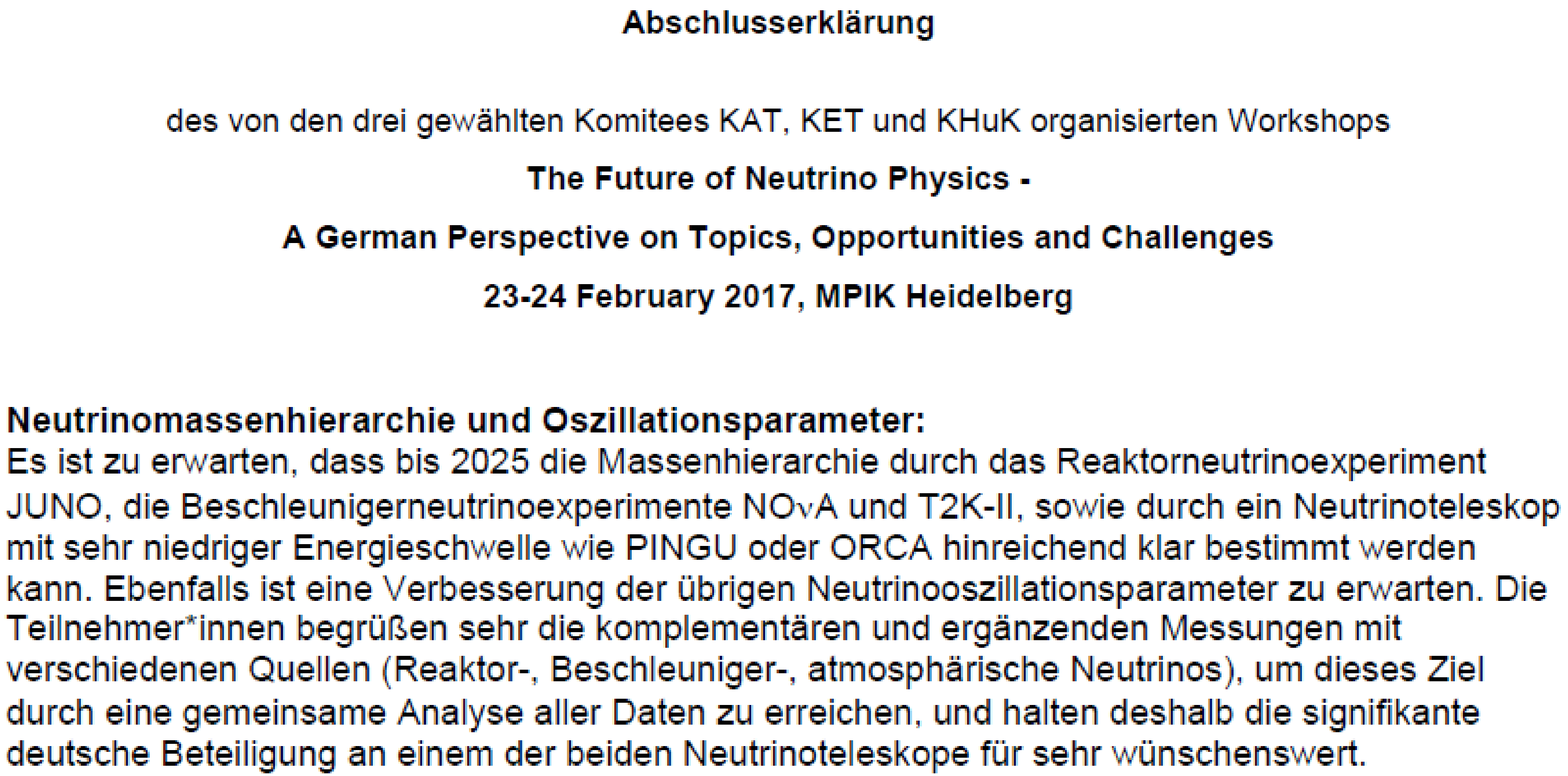
- Are there sum rules?

Other:

- **Mass of lightest neutrino?**
  (KATRIN, cosmology)

- **Majorana Neutrinos?**
  (Double Beta Decay)
- …

Ergebnis Neutrino Strategie Workshop



Abschlusserklärung

des von den drei gewählten Komitees KAT, KET und KHuK organisierten Workshops

The Future of Neutrino Physics -

A German Perspective on Topics, Opportunities and Challenges

23-24 February 2017, MPIK Heidelberg

Neutrinomassenhierarchie und Oszillationsparameter:
Es ist zu erwarten, dass bis 2025 die Massenhierarchie durch das Reaktorneutrinoexperiment JUNO, die Beschleunigerneutrinoexperimente NOνA und T2K-II, sowie durch ein Neutrinoteleskop mit sehr niedriger Energieschwelle wie PINGU oder ORCA hinreichend klar bestimmt werden kann. Ebenfalls ist eine Verbesserung der übrigen Neutrinooszillationsparameter zu erwarten. Die Teilnehmer*innen begrüßen sehr die komplementären und ergänzenden Messungen mit verschiedenen Quellen (Reaktor-, Beschleuniger-, atmosphärische Neutrinos), um dieses Ziel durch eine gemeinsame Analyse aller Daten zu erreichen, und halten deshalb die signifikante deutsche Beteiligung an einem der beiden Neutrinoteleskope für sehr wünschenswert.

How to determine the mass hierarchy:

1. Disappearance of anti-ν_e from nuclear reactor (vacuum oscill.)
China: JUNO @53km with 20kt Liquid Scintillator

2. Appearance of ν_e in beam of ν_μ (matter effects)

Atmospheric Neutrinos
Ice: PINGU
Water: ORCA

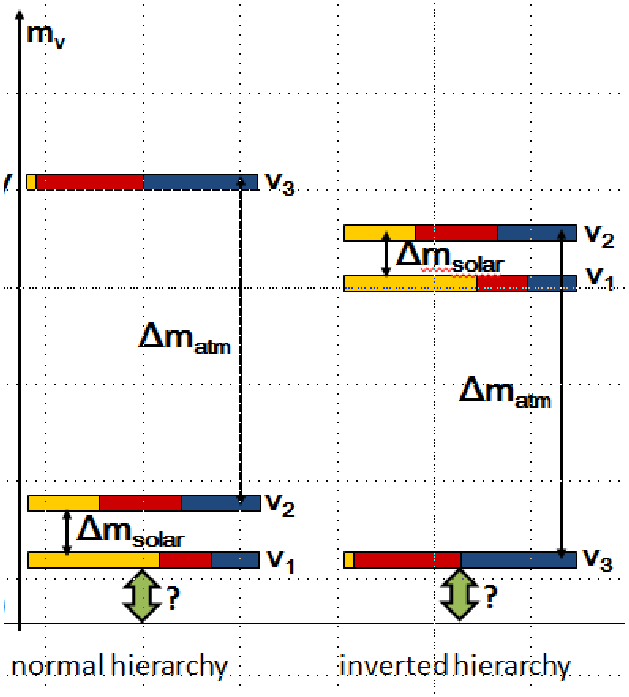
Long Baseline Oscillations
Detectors: Liquid Argon, Water Cerenkov, Liquid Scintillator
USA: NOvA, LBNF/DUNE, Japan: T2K, HyperK

Determination of Mass Hierarchy in a Reactor Neutrino Experiment

$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

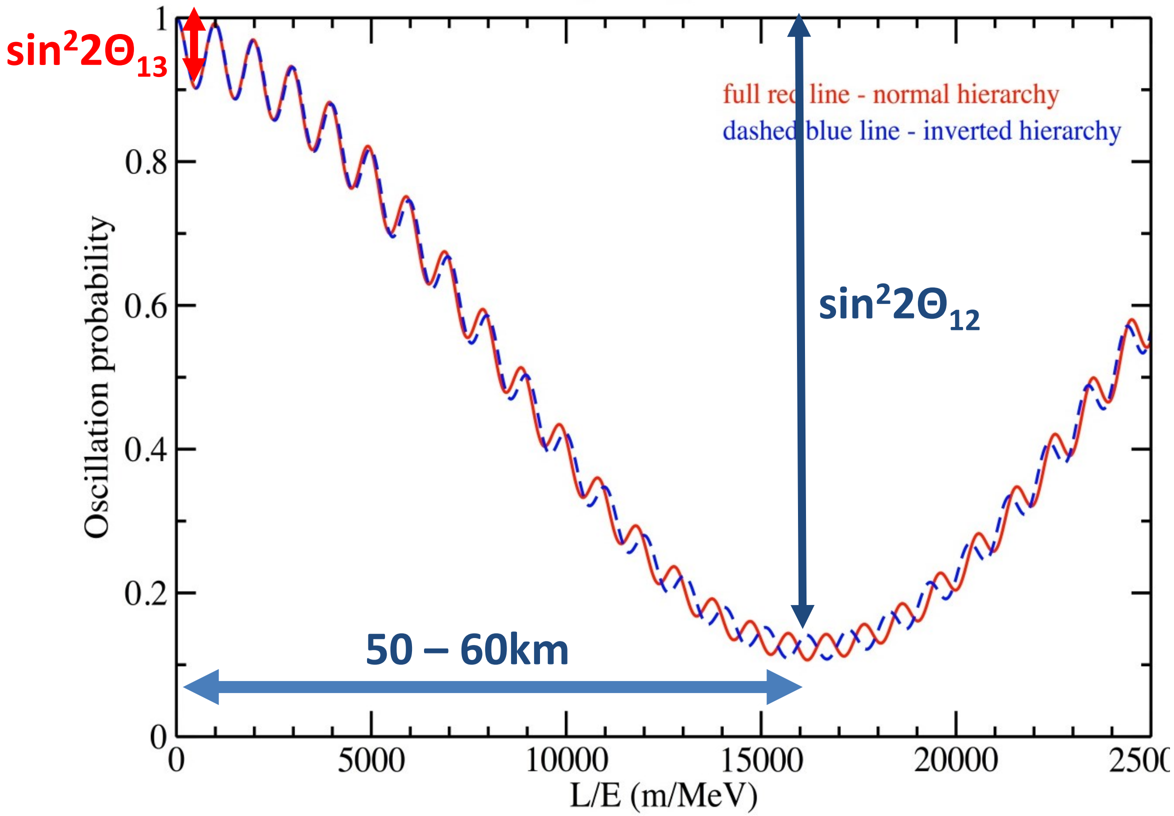
$$\boxed{\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}}$$

With $\Delta_{ij} = 1.27\ |\Delta m^2_{ji}\,(\mathrm{eV}^2)|\ L(\mathrm{m})/E(\mathrm{MeV})$

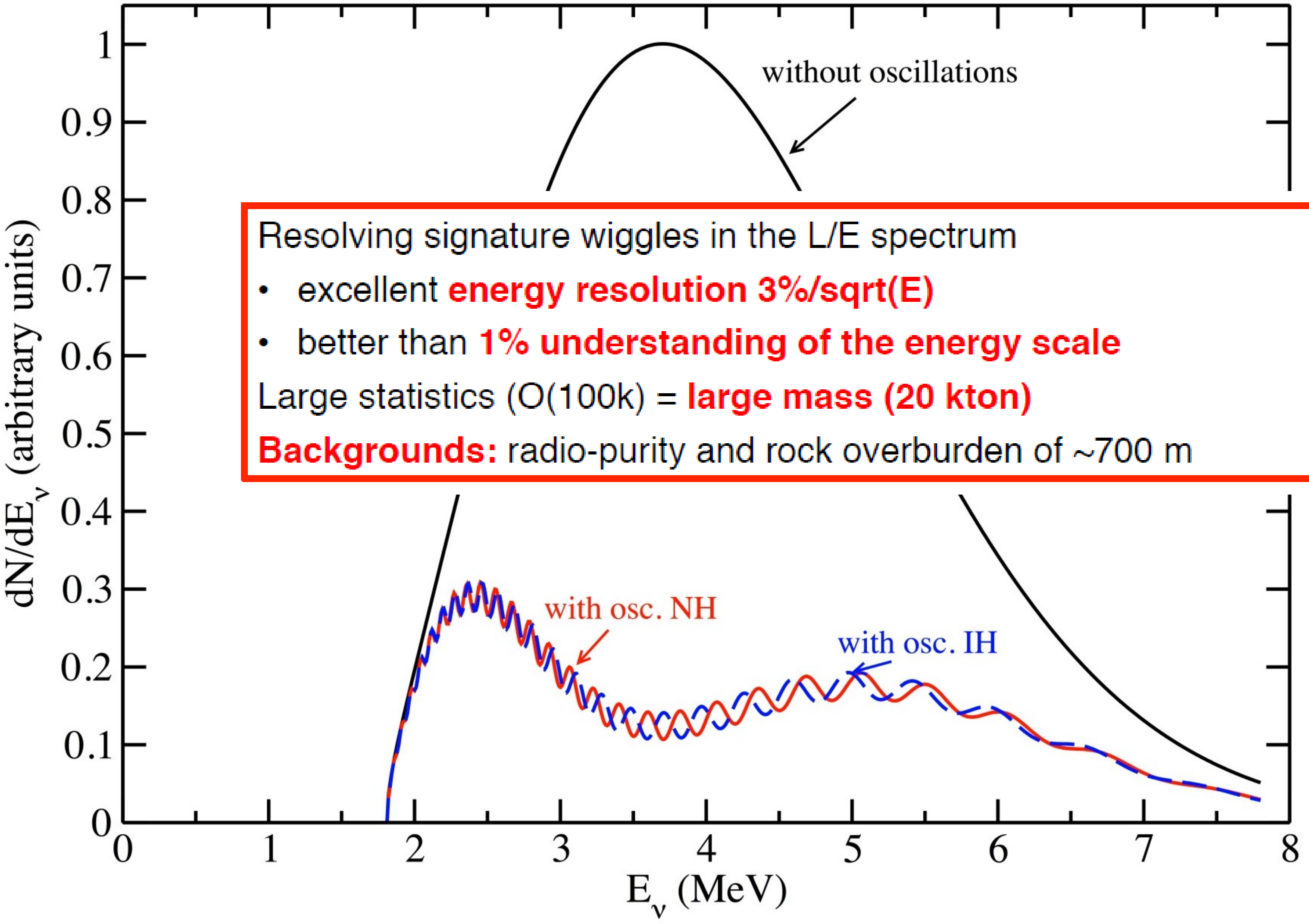


Vacuum oscillation probability $P(\nu_e \to \nu_e)$

Here for $\Delta m^2_{31} + \Delta m^2_{32} = 2\times2.49\times10^{-3}\ \mathrm{eV}^2$



Expected Reactor Antineutrino Spectrum



Resolving signature wiggles in the L/E spectrum

- excellent **energy resolution 3%/sqrt(E)**
- better than **1% understanding of the energy scale**

Large statistics (O(100k) = **large mass (20 kton)**

Backgrounds: radio-purity and rock overburden of ~700 m

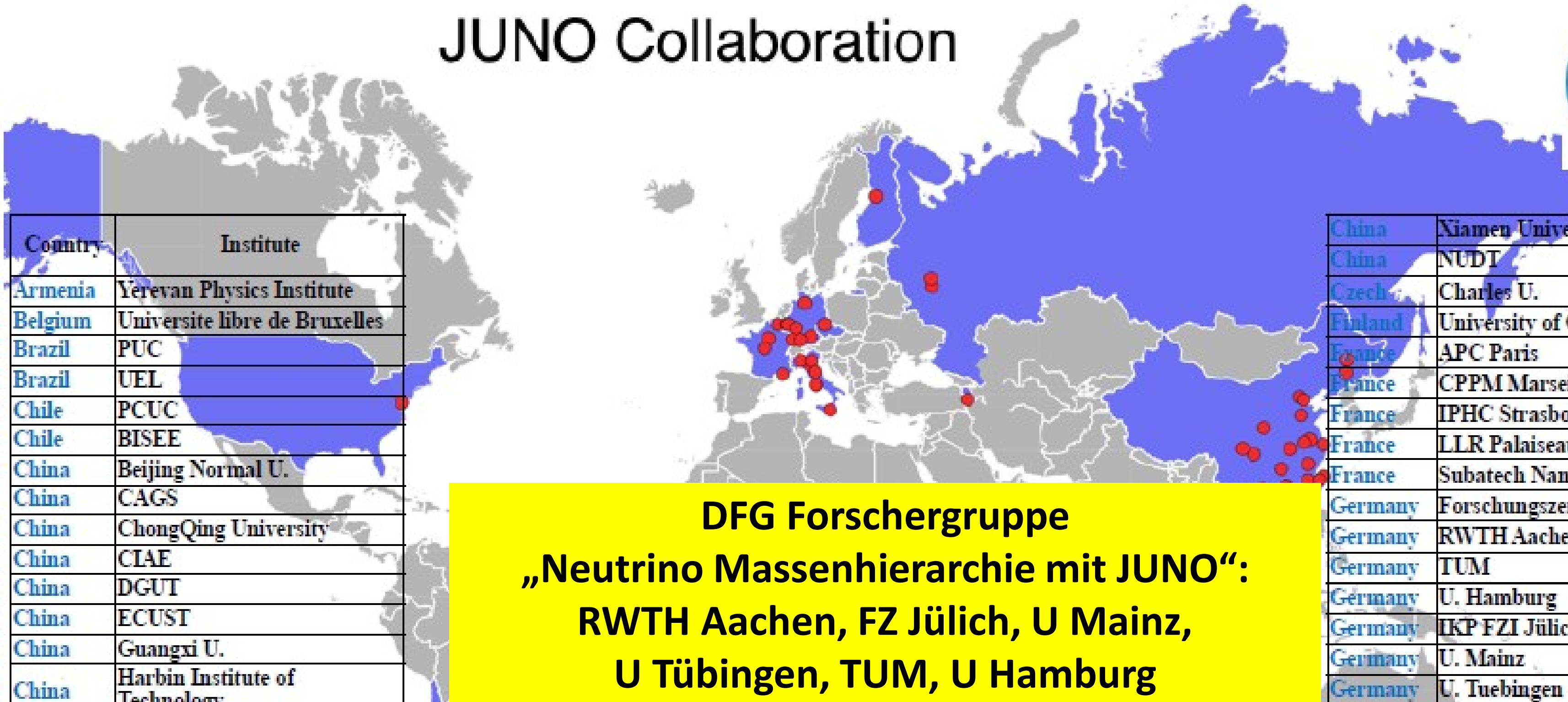
Jiangmen Underground Neutrino Observatory

the first multi-kton liquid scintillator detector ever

Start Data Taking in 2021

mass hierarchy to 3-4 sigma in 6 years

JUNO Collaboration

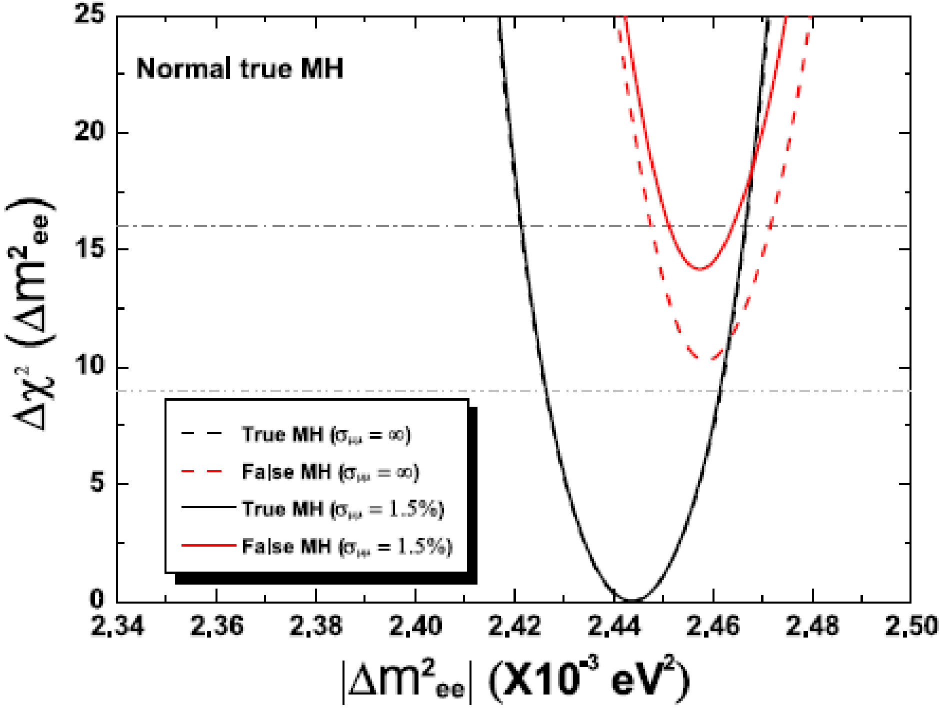


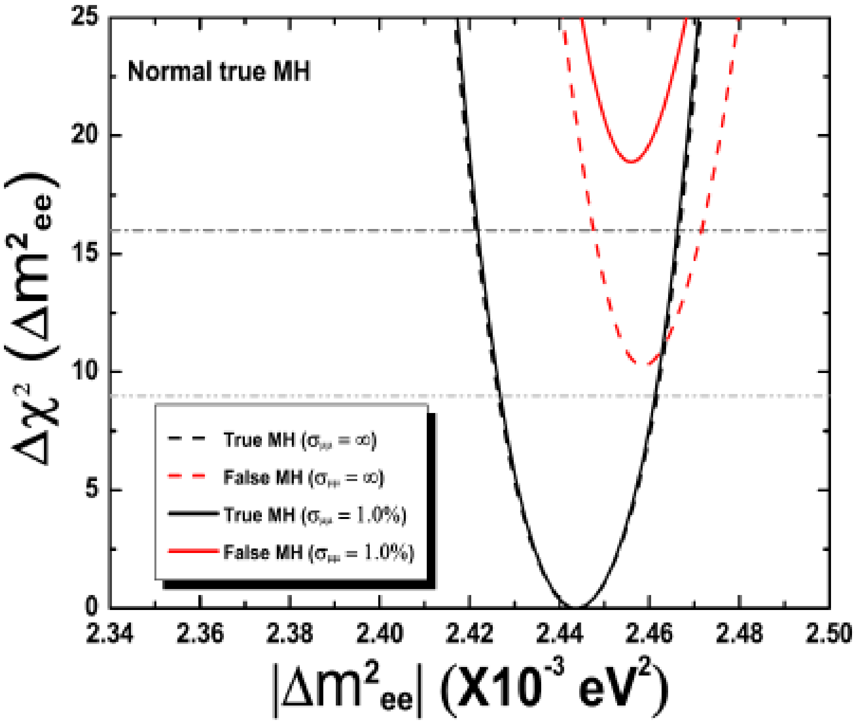
Country	Institute
Armenia	Yerevan Physics Institute
Belgium	Universite libre de Bruxelles
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	DGUT
China	ECUST
China	Guangxi U.
China	Harbin Institute of Technology
China	IHEP
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NCEPU
China	Pekin U.
China	Shandong U.
China	Shanghai JT U.
China	IMP-CAS
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
China	Wu Yi U.
China	Wuhan U.
China	Xi'an JT U.
China	Xiamen University
China	NUDT
Czech	Charles U.
Finland	University of Oulu
France	APC Paris
France	CPPM Marseille
France	IPHC Strasbourg
France	LLR Palaiseau
France	Subatech Nantes
Germany	Forschungszentrum Julich
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg
Germany	IKP FZI Jülich
Germany	U. Mainz
Germany	U. Tuebingen
Italy	INFN Catania
Italy	INFN di Frascati
Italy	INFN-Ferrara
Italy	INFN-Milano
Italy	INFN-Milano Bicocca
Italy	INFN-Padova
Italy	INFN-Perugia
Italy	INFN-Roma 3
Pakistan	PINSTECH
Russia	INR Moscow
Russia	JINR
Russia	MSU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	SUT
USA	UMD1
USA	UMD2

DFG Forschergruppe
„Neutrino Massenhierarchie mit JUNO“:
RWTH Aachen, FZ Jülich, U Mainz,
U Tübingen, TUM, U Hamburg

Collaboration established in July 2015
ca. 70 Institutions
ca. 500 Collaborators

Mass Hierarchy with JUNO





- Reactor neutrino survival spectrum can tell MH to **~3σ**
- JUNO can use help: If T2K+NOvA tells $\Delta m^2_{\mu\mu}$ ~1%, **~4σ**
  - *T2K+NOvA $\Delta m^2_{\mu\mu}$ ~1%, S.K. Agarwalla, S. Prakash, WW, arXiv:1312.1477*

Precision Physics with JUNO

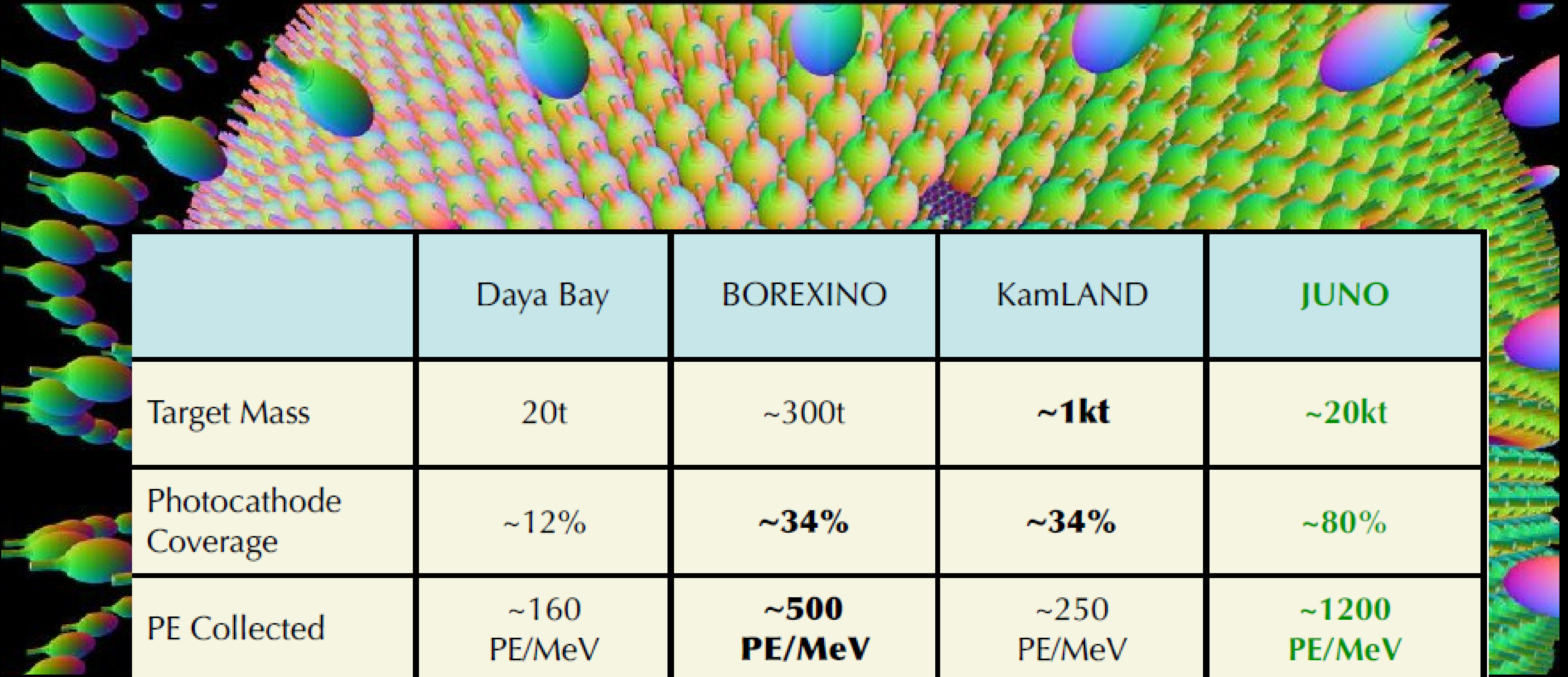
	Δm^2_{21}	$\lvert\Delta m^2_{31}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
Dominant Exps.	KamLAND	MINOS	SNO	Daya Bay	SK/T2K
Individual 1σ	2.7% [121]	4.1% [123]	6.7% [109]	6% [122]	14% [124, 125]
Global 1σ	2.6%	2.7%	4.1%	5.0%	11%

Probing the unitarity of U_{PMNS} to ~1%

	Statistics	**+BG** **+1% b2b** **+1% EScale** **+1% EnonL**
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%

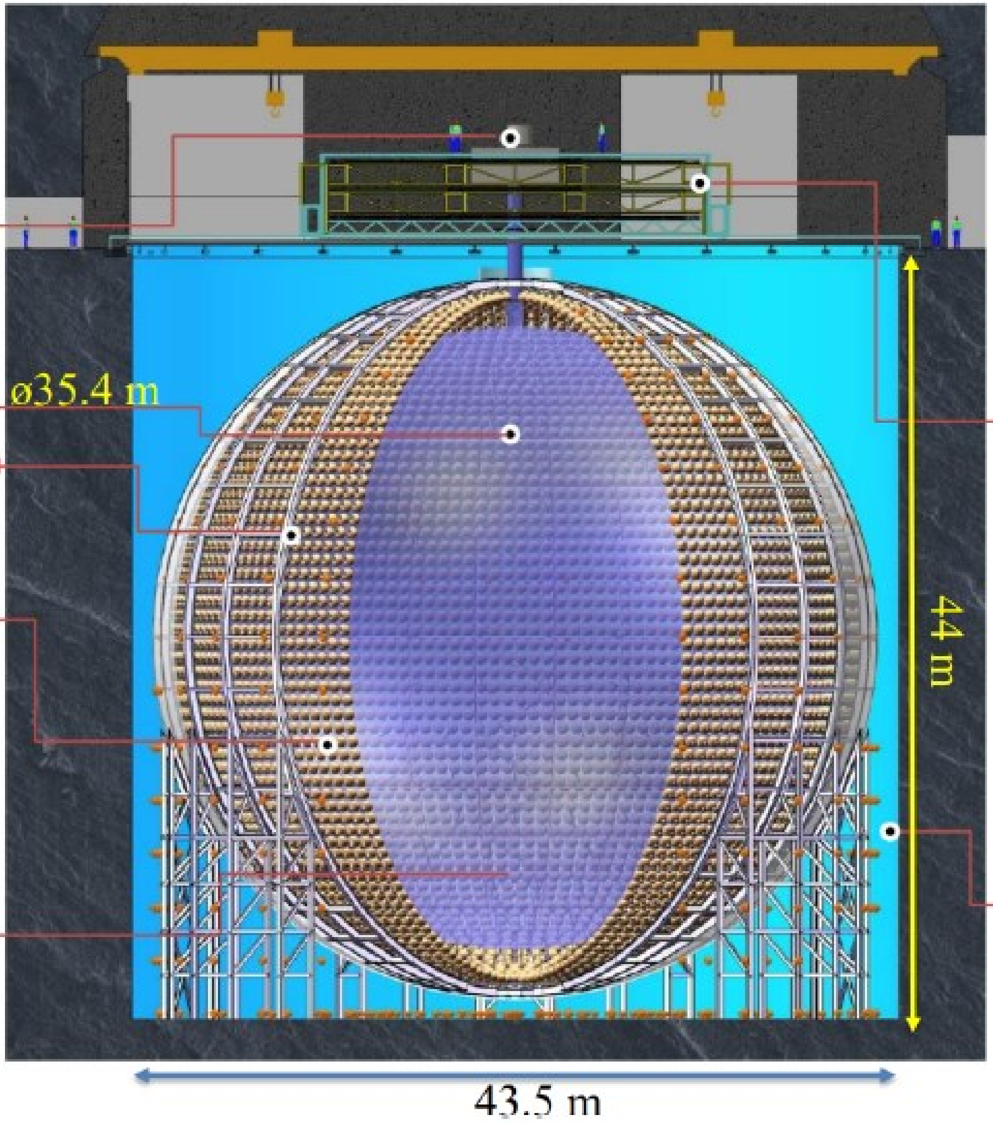
JUNO: 100k evts, arXiv:1507.05613

Detector Requirements
(Development of Large Liquid Scintillator Detectors)



	Daya Bay	BOREXINO	KamLAND	JUNO
Target Mass	20t	~300t	**~1kt**	~20kt
Photocathode Coverage	~12%	**~34%**	**~34%**	~80%
PE Collected	~160 PE/MeV	**~500 PE/MeV**	~250 PE/MeV	~1200 PE/MeV
Energy Resolution	~7.5%/√E	**~5%/√E**	~6%/√E	3%/√E
Energy Calibration	~1.5%	**~1%**	~2%	<1%

JUNO: Detector Concept



Central detector

Calibration
-ACU, ROV, etc.

Acrylic sphere

Stainless-steel truss

PMT
-18,000 20” PMTs
-25,000 3” PMTs

Liquid scintillator
-20 kton LS

VETO detector

Top Tracker
-62 Plastic scintillator walls

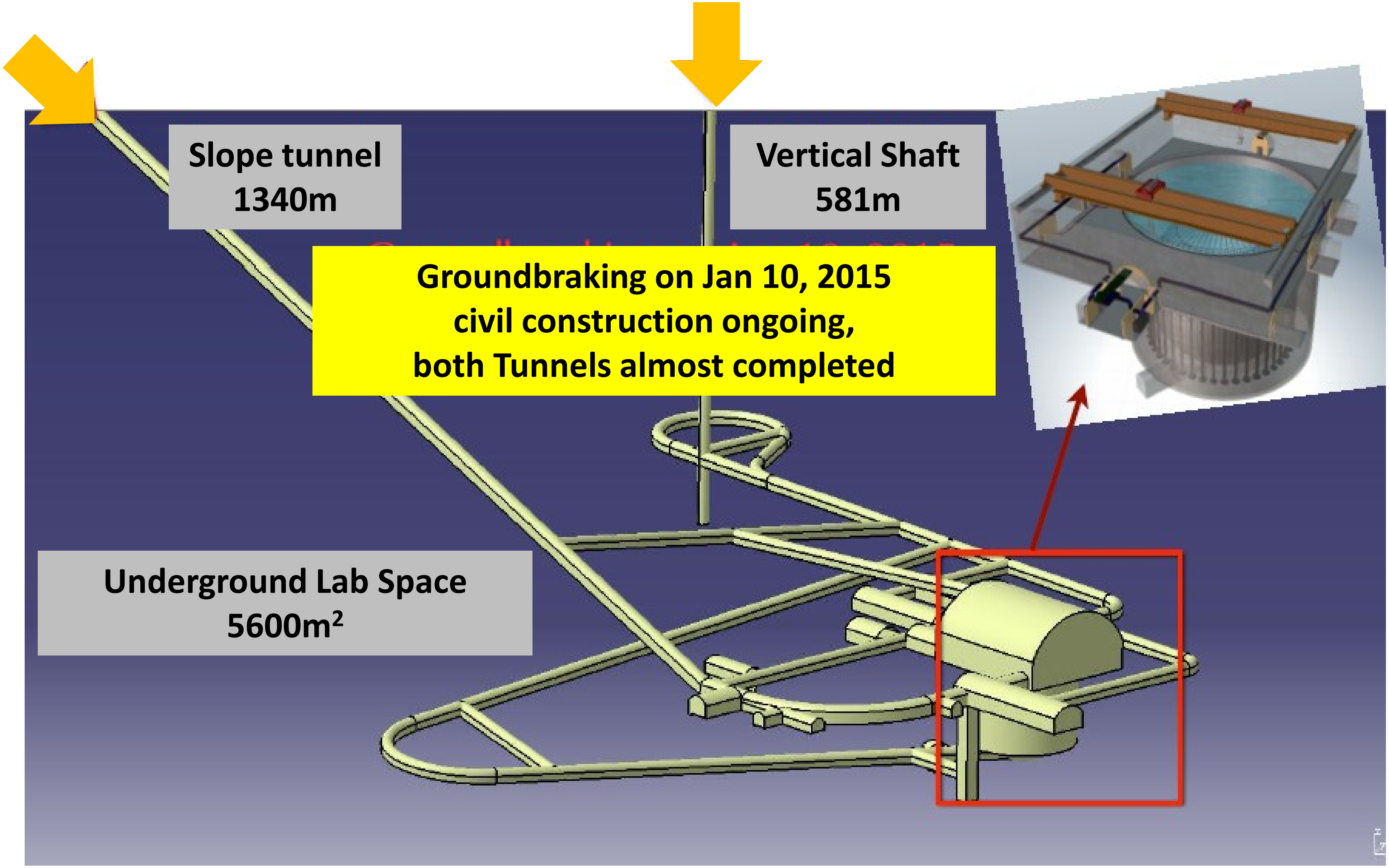
Water Cherenkov
-35 kt high-purity water
-2000 20” PMTs

JUNO Site

by 2020: 26.6 GW

both reactors have same distance (within 0.5km)

JUNO Lab @700m Underground



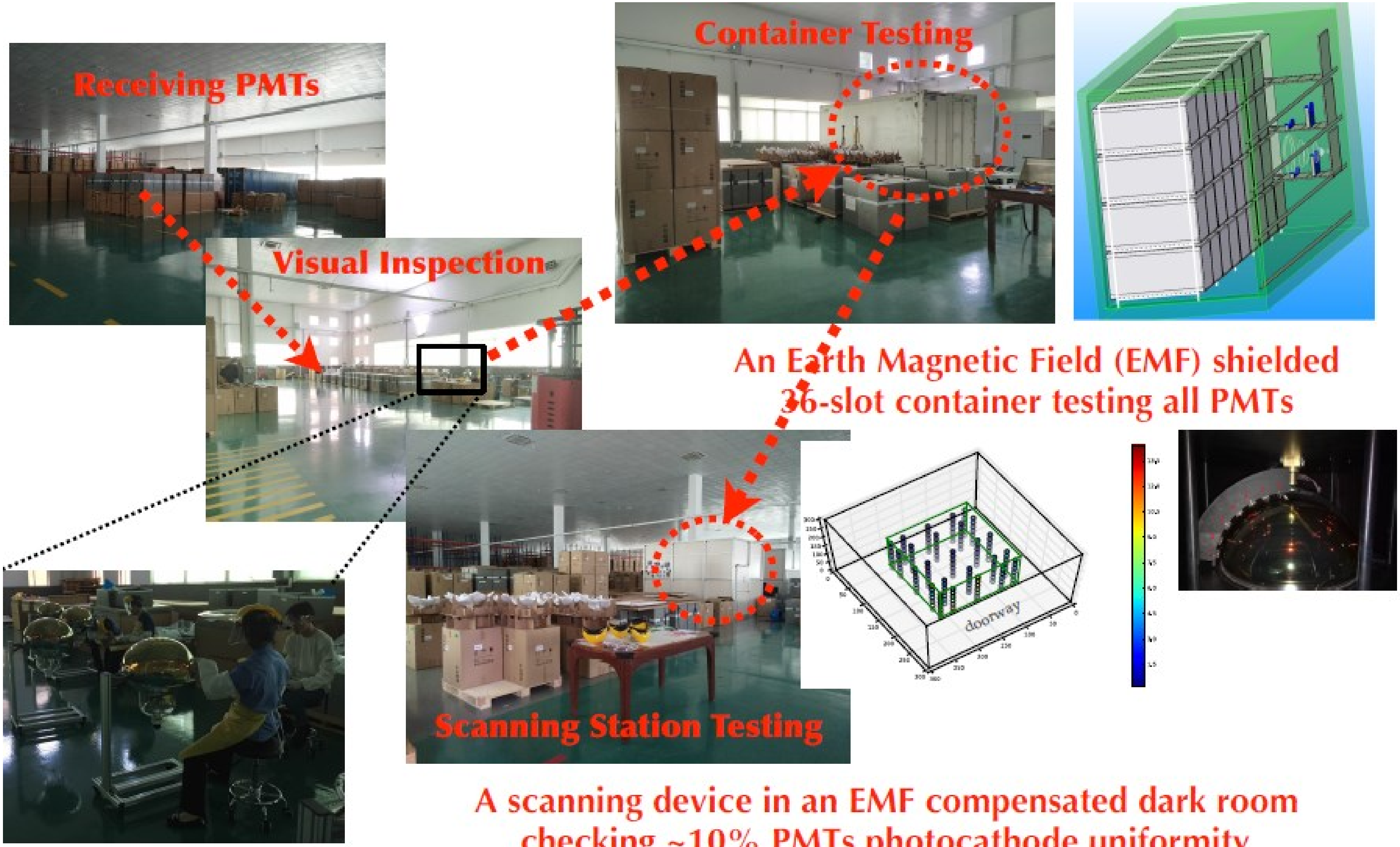
Slope tunnel
1340m

Vertical Shaft
581m

Groundbraking on Jan 10, 2015
civil construction ongoing,
both Tunnels almost completed

Underground Lab Space
5600m^2

JUNO PMTs:
Quality Control and Characterization ongoing

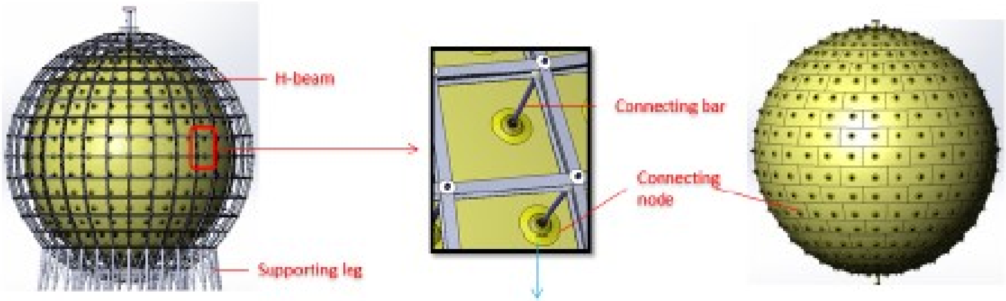


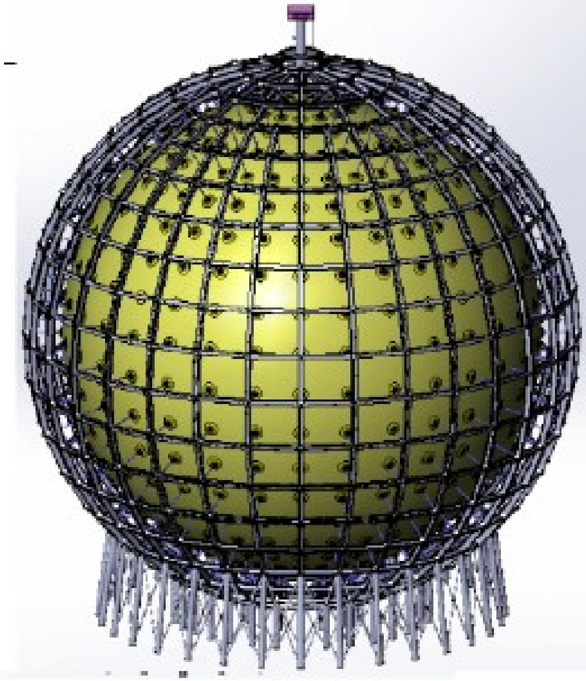
An Earth Magnetic Field (EMF) shielded 36-slot container testing all PMTs

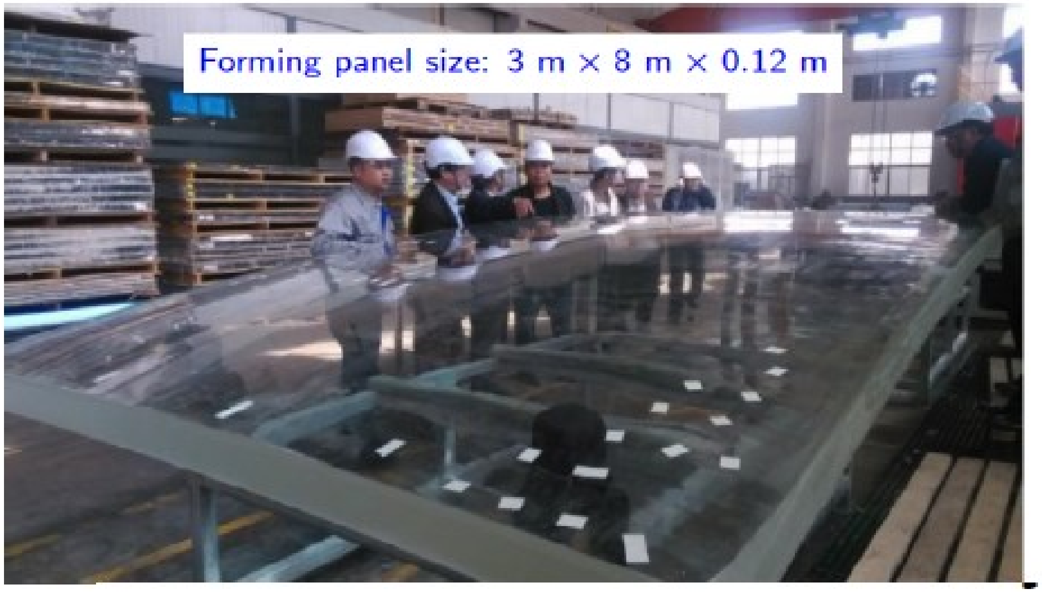
A scanning device in an EMF compensated dark room checking ~10% PMTs photocathode uniformity

Acrylic Sphere and Stainless Steel truss

- ✓ safety was given a priority
- ✓ 260 acrylic panels of 120 mm thickness
- ✓ Total weight: ~600 t of acrylic and ~600 t of steel






Forming panel size: 3 m × 8 m × 0.12 m

Liquid Scintillator Pilot Plant

Use Pilot Plant @ Daya Bay to test purification system:
Purification of 20ton LAB (replacement of target LS in one Daya Bay Detector)

Distillation system

Steam stripping system

Water extraction

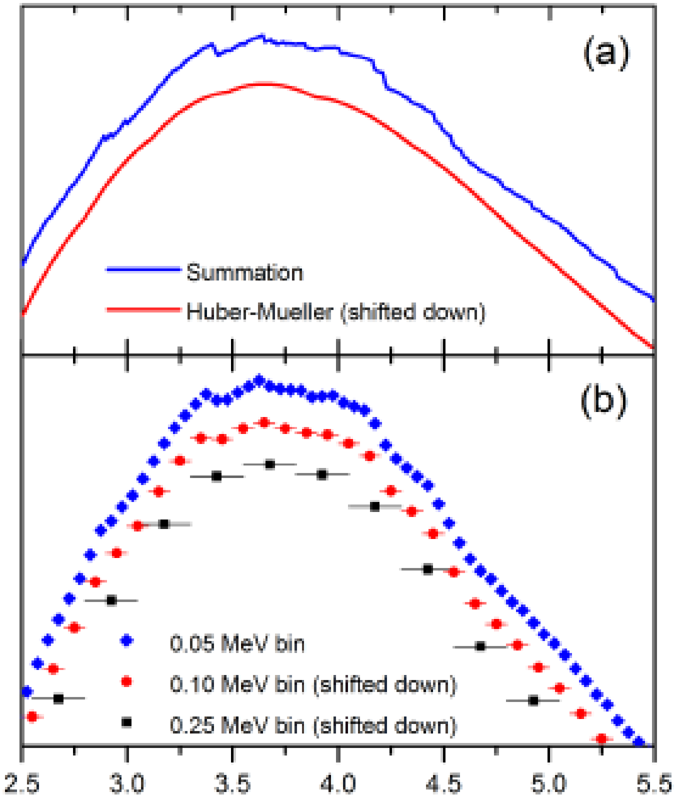
Ultra-pure nitrogen

LAB storage tank

Al_2O_3 column

Do we need a Near Detector for JUNO?

Recent discussion whether (unknown) fine structure of reactor neutrino spectrum could worsen systematics.



Szongoni, Nino, McCutchan, arxiv:1710.00092

If necessary build **Near Detector:**

Basic parameters of a Gd-LS near detector:

- Fiducial Volume: 1 ton
  - Event rate 400k/year @ 50m
  - 3 years data taking yields 10x JUNO 6-year data

JUNO Milestones & Schedule

2014:-2015 International collaboration established

- start civil construction

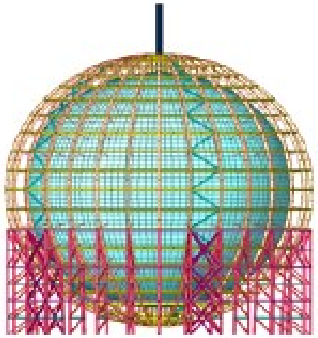
2015: PMT production line setup; CD parts R&D

2016: Start PMT and CD parts production

2017: Start PMT testing; TT arrived

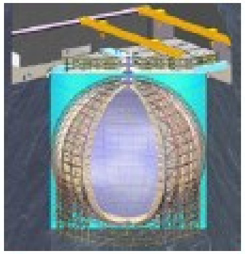
2018: PMT potting starts; Electronics production starts

2019 - 2020: Civil work and lab preparation completed; Detector Constructing

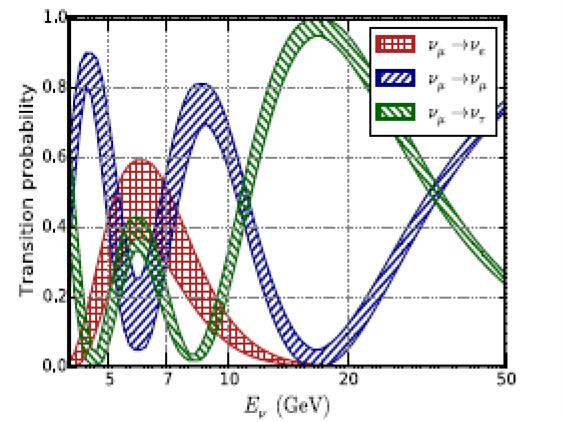


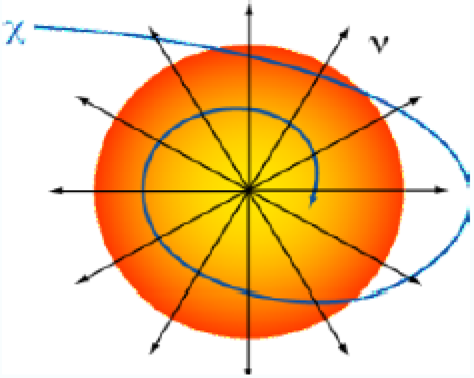
2021:

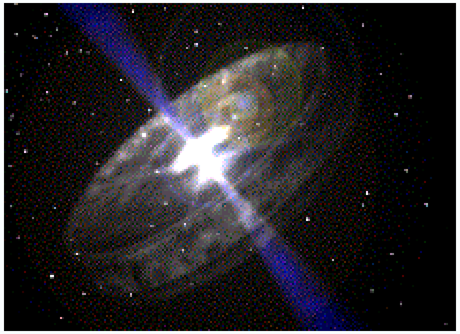
Detector Ready; DATA!



Neutrino Telescopes: Physics Overview

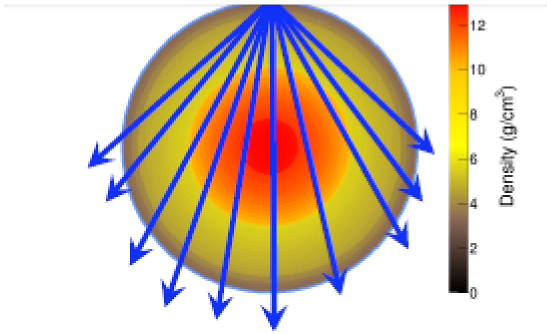






Low Energy	Medium Energy	High Energy
3 GeV < E_ν < 50 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV
ν Oscillations ν Mass Hierarchy	Dark Matter search	ν from extra-terrestrial sources Origin and production mechanism of HE CR
KM3NeT-ORCA, PINGU	Antares, Deep Core	KM3NeT-ARCA, IceCube

Mass Hierarchy with Atmospheric Neutrinos



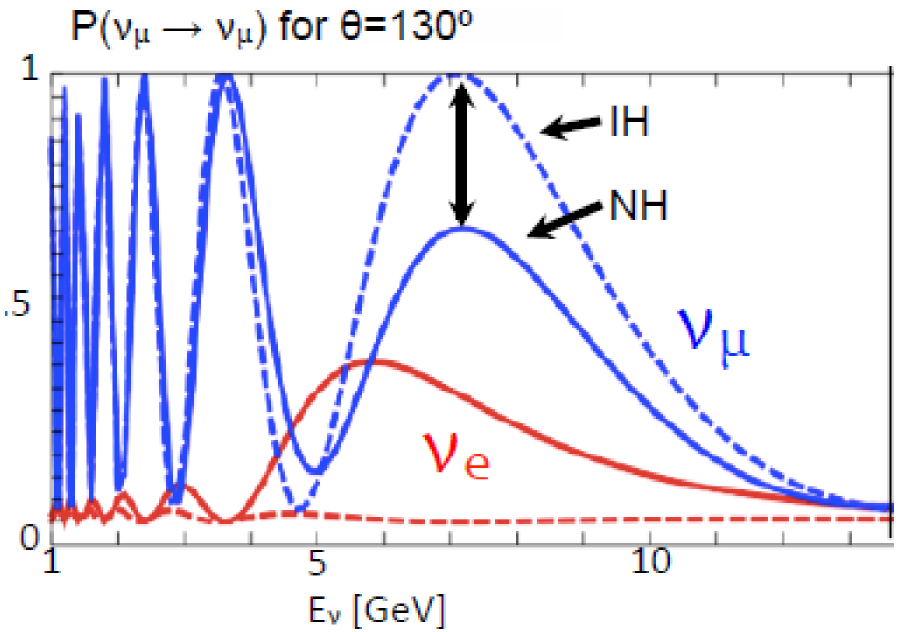
- Oscillation pattern distorted by Earth matter effects (hierarchy-dependent):

  maximum difference IH ↔ NH at
  $\theta=130°$ (7645 km) and E_ν = 7 GeV

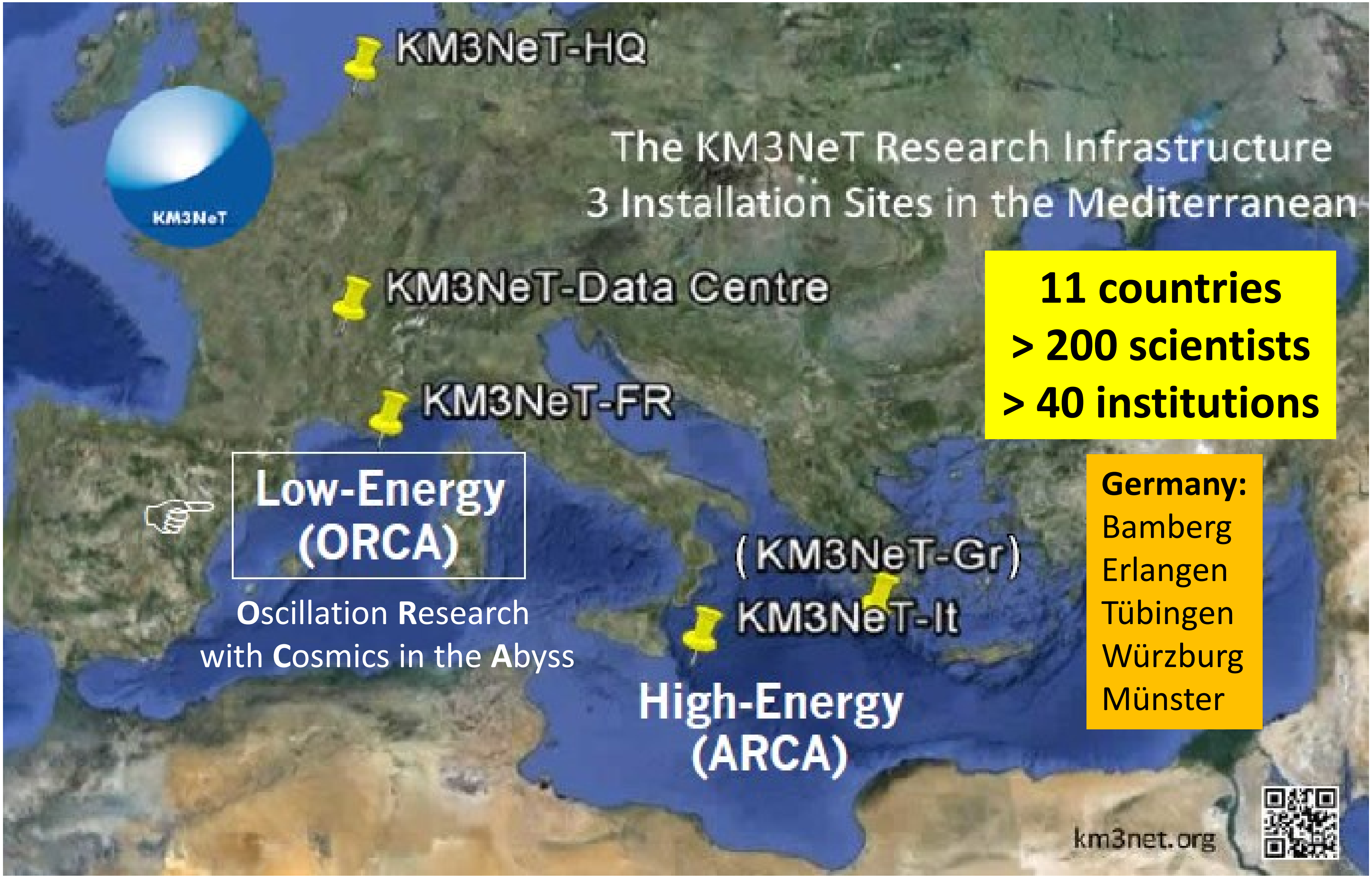
- Opposite effect on anti-neutrinos: IH(ν)≈NH(anti-ν) BUT differences in flux and cross-section:

  $\Phi_{atm}(\nu) \approx 1.3 \times \Phi_{atm}(\text{anti-}\nu)$
  $\sigma(\nu) \approx 2\sigma(\text{anti-}\nu)$ at low energies

- Measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos, identify and count muon and electron channel events



KM3NeT



The KM3NeT Research Infrastructure
3 Installation Sites in the Mediterranean

11 countries
> 200 scientists
> 40 institutions

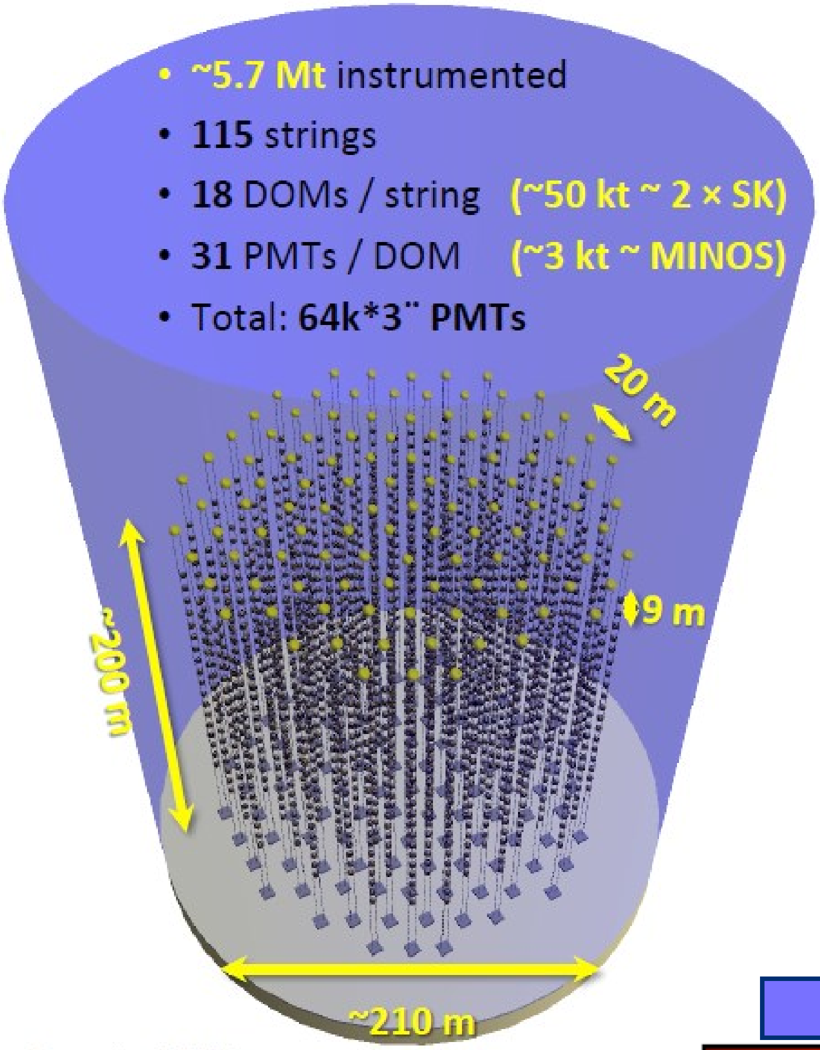
Germany:
Bamberg
Erlangen
Tübingen
Würzburg
Münster

☞ **Low-Energy (ORCA)**

Oscillation **R**esearch
with **C**osmics in the **A**byss

High-Energy (ARCA)

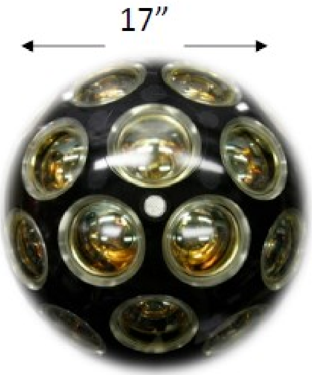
ORCA detector



- ~5.7 Mt instrumented
- **115** strings
- **18** DOMs / string (~50 kt ~ 2 × SK)
- **31** PMTs / DOM (~3 kt ~ MINOS)
- Total: **64k*3¨ PMTs**

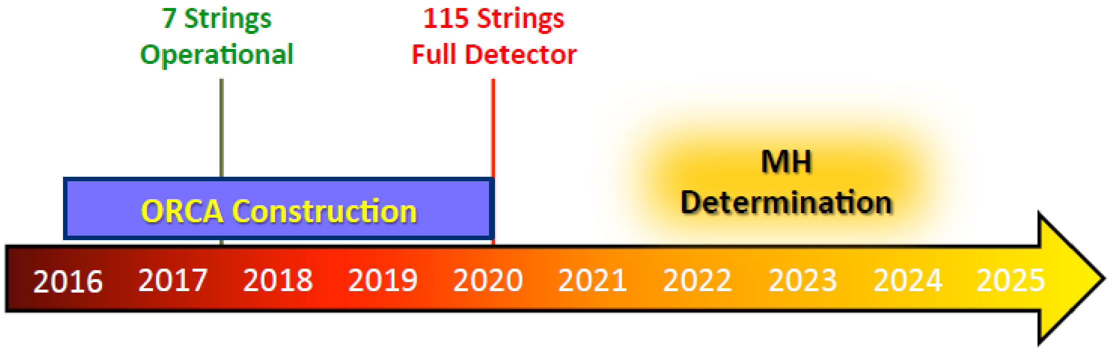
Depth=2475m

Digital Optical Module



– 31 x 3" PMTs

1st ORCA string: Autumn 2016



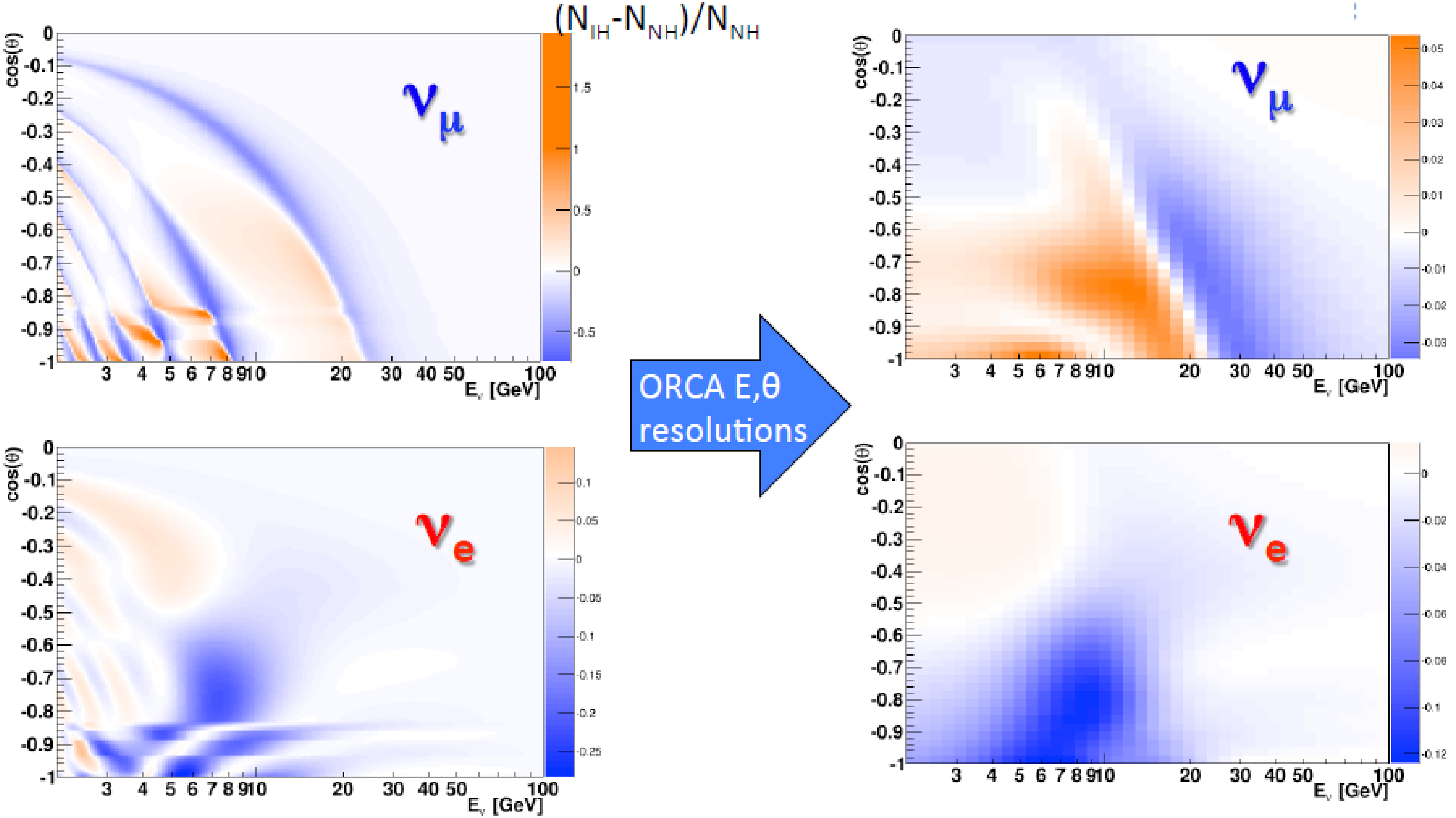
7 Strings Operational

115 Strings Full Detector

ORCA Construction

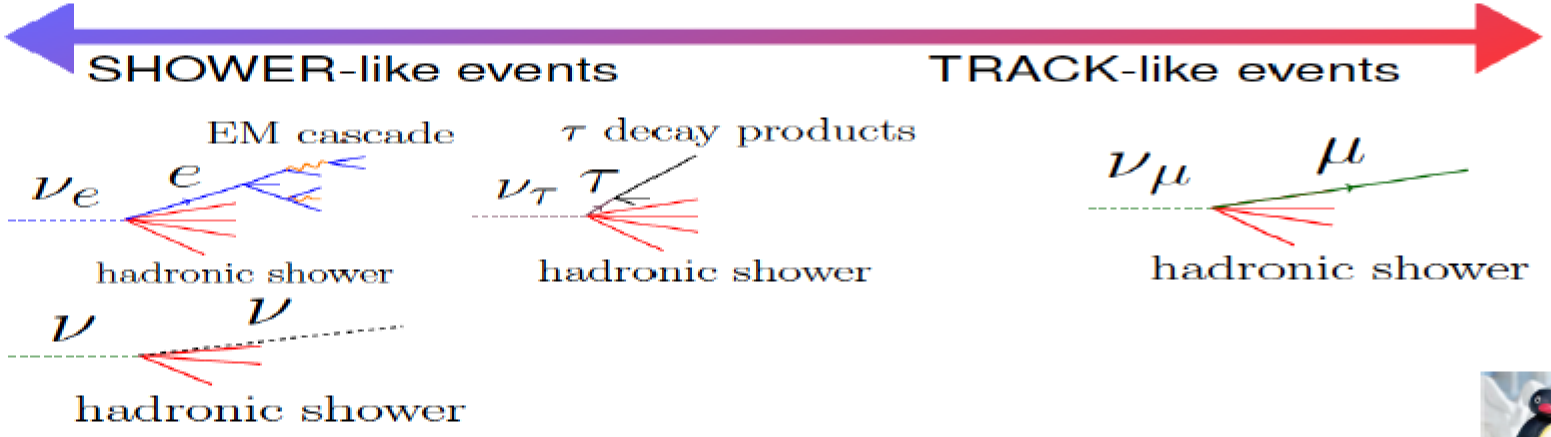
MH Determination

Mass Hierarchy @ ORCA



ORCA E,θ resolutions

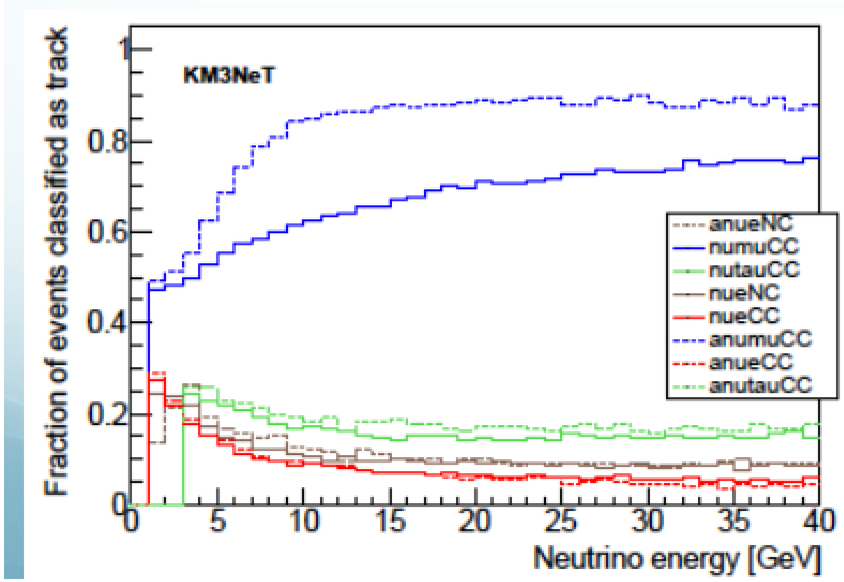
Crucial: Flavor Identification in ORCA and PINGU

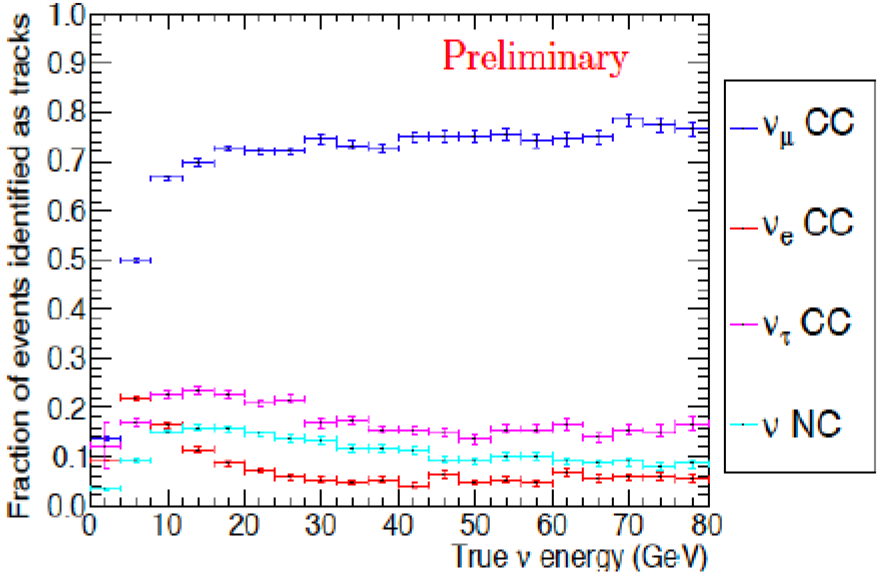


KM3NeT Collaboration

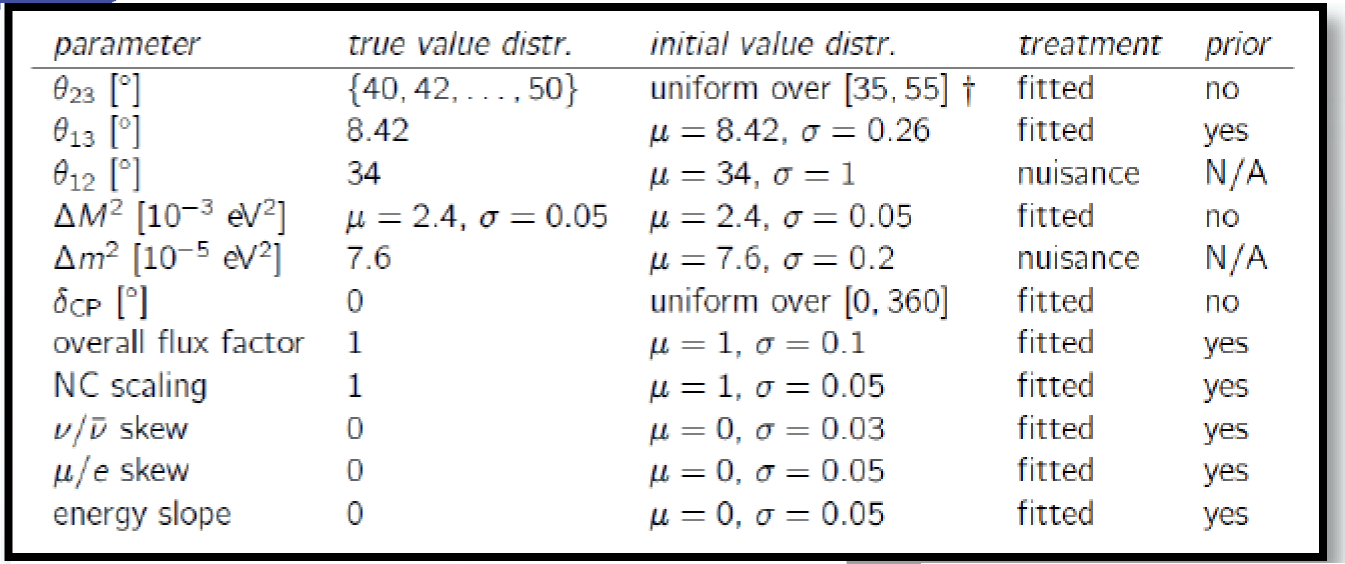
very similar results for both experiments

PRECISION ICECUBE NEXT GENERATION UPGRADE





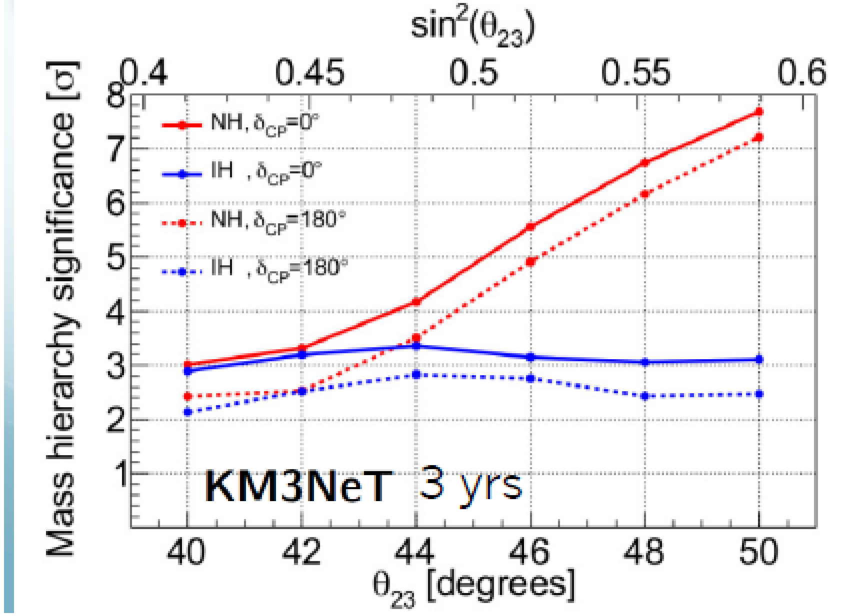
ORCA Sensitivity

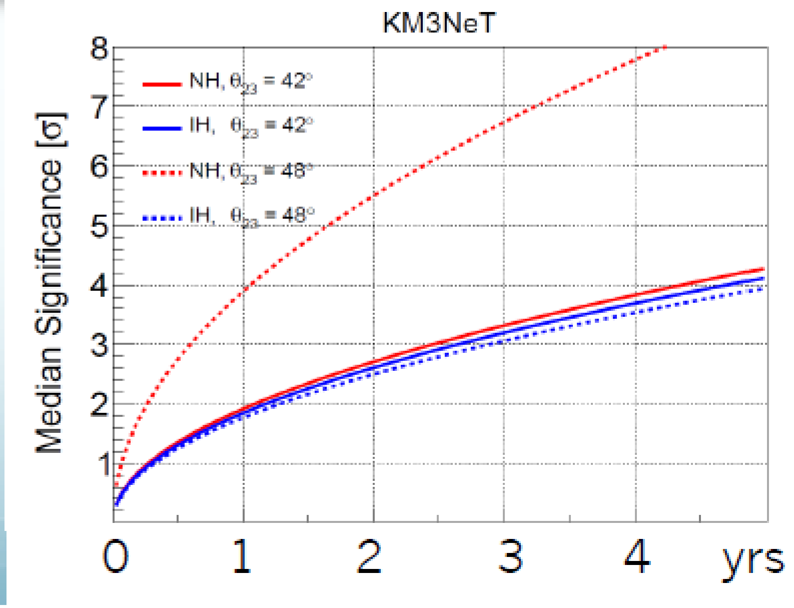


parameter	*true value distr.*	*initial value distr.*	*treatment*	*prior*
θ_{23} [°]	$\{40, 42, \ldots, 50\}$	uniform over [35, 55] †	fitted	no
θ_{13} [°]	8.42	$\mu = 8.42,\ \sigma = 0.26$	fitted	yes
θ_{12} [°]	34	$\mu = 34,\ \sigma = 1$	nuisance	N/A
ΔM^2 [10^{-3} eV^2]	$\mu = 2.4,\ \sigma = 0.05$	$\mu = 2.4,\ \sigma = 0.05$	fitted	no
Δm^2 [10^{-5} eV^2]	7.6	$\mu = 7.6,\ \sigma = 0.2$	nuisance	N/A
δ_{CP} [°]	0	uniform over [0, 360]	fitted	no
overall flux factor	1	$\mu = 1,\ \sigma = 0.1$	fitted	yes
NC scaling	1	$\mu = 1,\ \sigma = 0.05$	fitted	yes
$\nu/\bar{\nu}$ skew	0	$\mu = 0,\ \sigma = 0.03$	fitted	yes
μ/e skew	0	$\mu = 0,\ \sigma = 0.05$	fitted	yes
energy slope	0	$\mu = 0,\ \sigma = 0.05$	fitted	yes

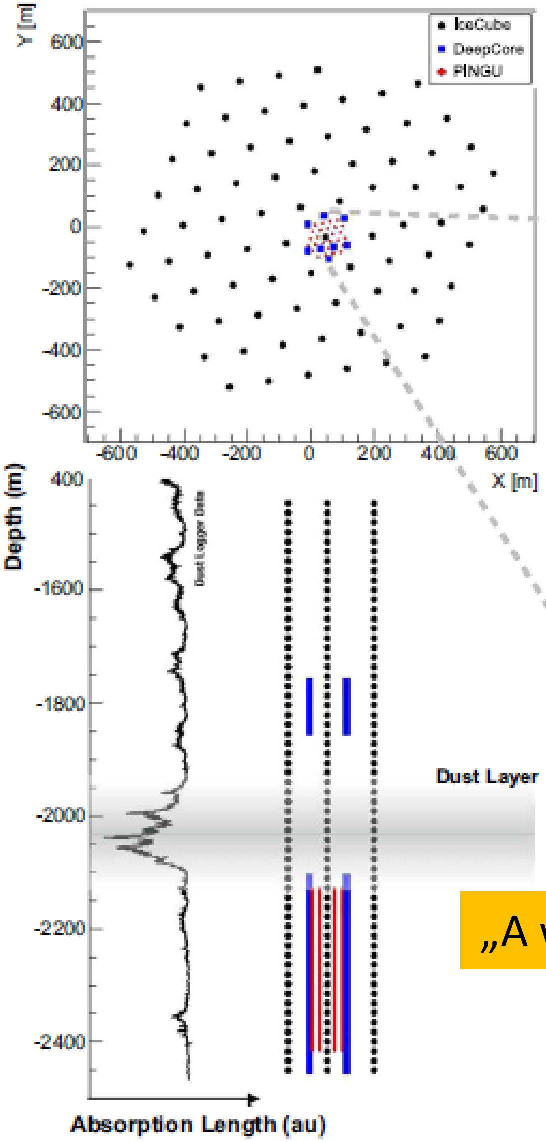
Worst case 3σ in 4 years

δ_{cp} small but non-negligible ~0.5 σ impact on sensitivity





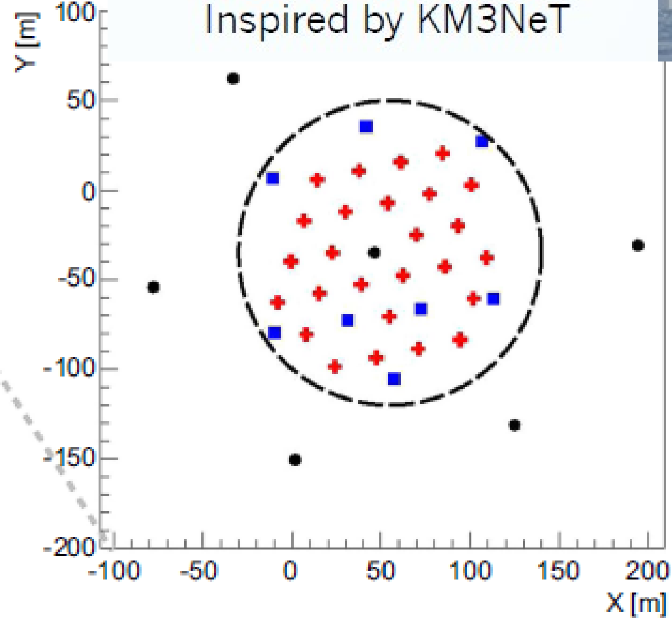
PINGU: Precision IceCube Next Generation Upgrade



mDOM: multi-PMT module
24 3" PMTs

mDOM is focus of IceCube-Upgrade and PINGU

Inspired by KM3NeT



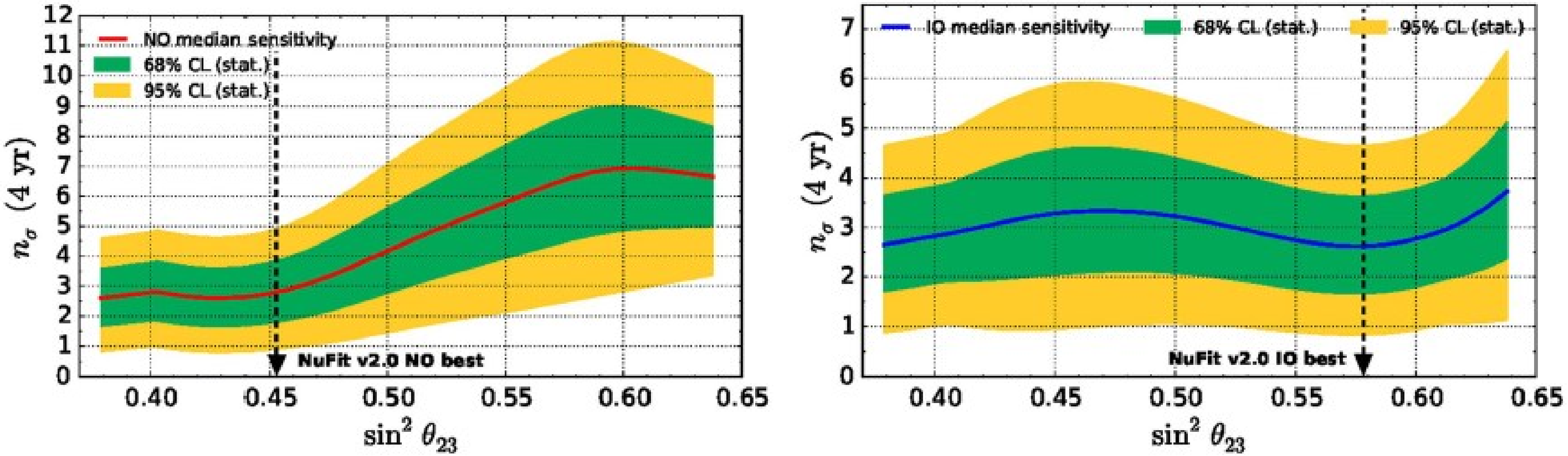
Original proposal:
40 strings,
each 96 optical modules

New Design:
26 strings,
each 192 optical modules

„A world-class 6 Mton water Cherenkov detector for < 100M US$“

energy resolution $\Delta E/E \approx 20\%$, angular resolution $\approx 15°$

PINGU Sensitivity on Mass Hierarchy



from M.G.Aartsen et al., J. Phys. G. Nucl. Part. Phys. 44 (2017) 054008

Conclusion

Status 2018: Global fits favor normal hierarchy @ 2σ

JUNO construction ongoing.
Some delays → start data taking in 2021.
Potential to reach 3 – 4 σ on mass hierarchy

ORCA construction (deployment of strings) started.
Start data taking in 2021
Potential to reach 3 - 5σ on mass hierarchy

PINGU has similar potential for mass hierarchy.
More than 3σ after 5 years of measurement.

Vacuum oscillation:
Interference of Δm^2_{32}, Δm^2_{21}

highly complementary methods

Matter effects:
Interference of Δm^2_{32}, $\sqrt{2}\, G_F N_e$

German groups have made significant contributions (expertise in key technologies) to all 3 experiments.