Neutrino 2018, Heidelberg, 4-9 June 2018

# Future neutrino telescopes in water and ice

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6 June 2018

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

# The plan for the next 35 minutes

- Introduction – setting the scene
- Neutrino astronomy
- Neutrino physics
- Conclusion

Presentation by Ignacio Taboada

Presentation by Tyce DeYoung

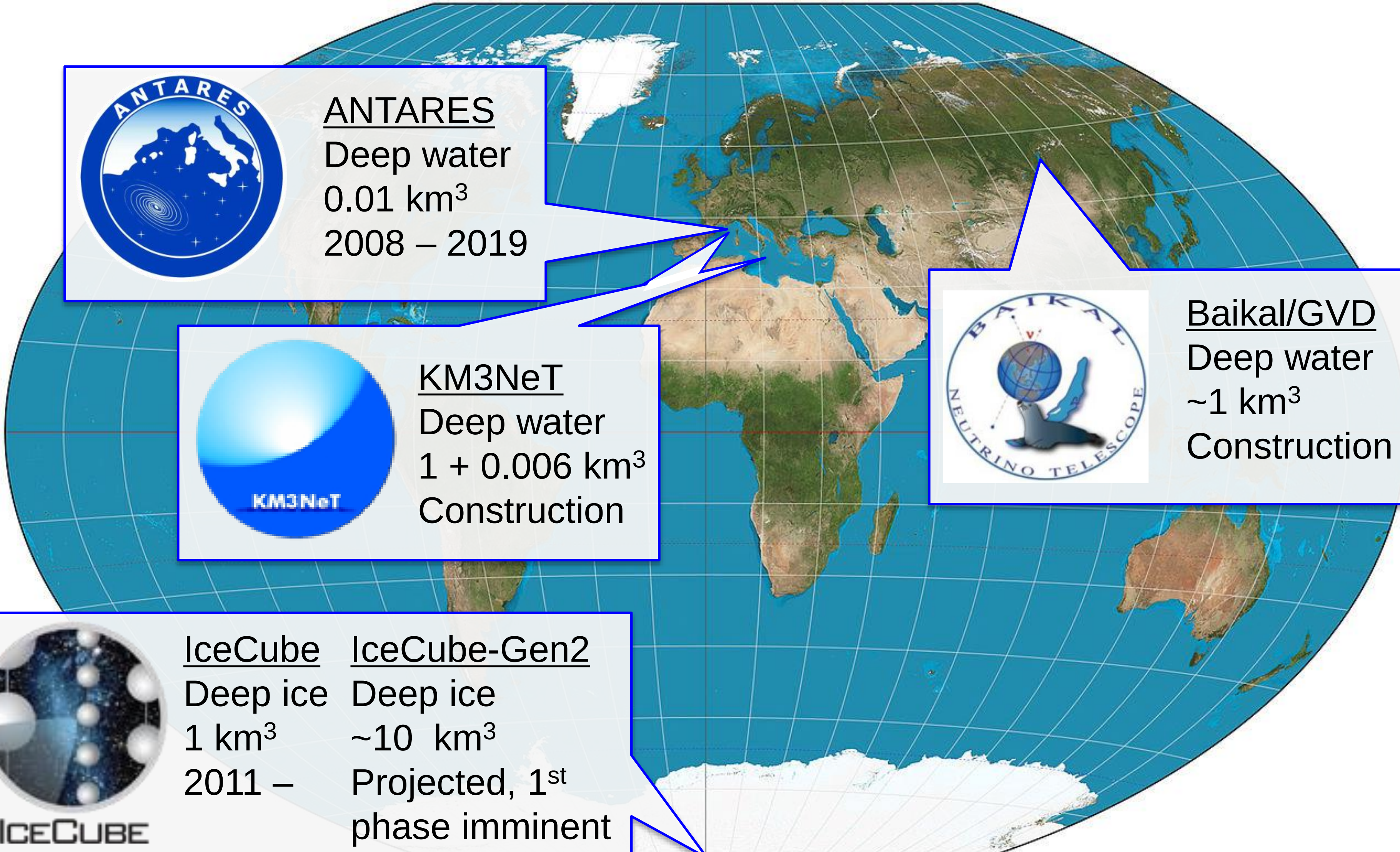
Note: P[k/nnn] points to poster #nnn in session #k

# Introduction – setting the scene

# The neutrino telescope world map 2018

Detecting GeV to PeV neutrinos
using Cherenkov detectors
in deep water or ice …

# The neutrino telescope world map 2018



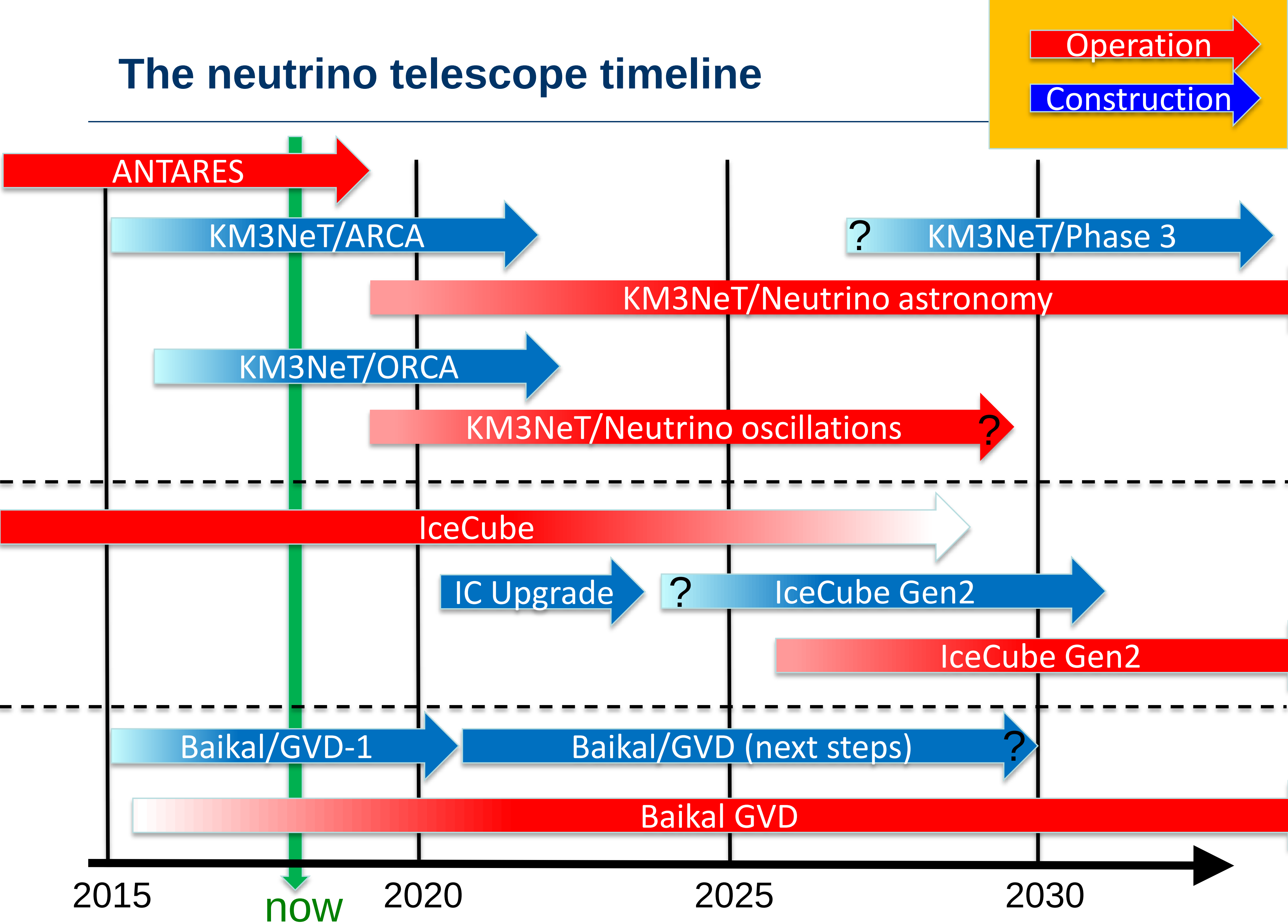
**ANTARES**
Deep water
0.01 km$^3$
2008 – 2019

**KM3NeT**
Deep water
1 + 0.006 km$^3$
Construction

**Baikal/GVD**
Deep water
~1 km$^3$
Construction

| IceCube | IceCube-Gen2 |
|---|---|
| Deep ice | Deep ice |
| 1 km$^3$ | ~10 km$^3$ |
| 2011 – | Projected, 1$^{st}$ phase imminent |

# The neutrino telescope timeline



# The Global Neutrino Network (GNN)

- Umbrella organisation of current & future neutrino telescope collaborations (ANTARES, Baikal/GVD, IceCube, KM3NeT)
- Objectives:
    - Forum for strategy development
    - Enhanced cooperation
    - Common analyses
    - Yearly common meetings (MANTS) & biannual conference (VLVnT)
- Can/will(?) be instrumental in providing global plan for the development of neutrino astronomy
- [www.globalneutrinonetwork.org](http://www.globalneutrinonetwork.org)
- Similar future role as GWIC is playing for gravitational waves?

# Neutrino astronomy

# Neutrino astronomy: where are we?

- ✓ High-energy cosmic neutrinos discovered by IceCube
- ✓ Recent neutrino/X-ray/gamma-ray coincidence (IceCube): First hint of a neutrino source?
- – Neutrinos from Galactic accelerators
- – "Real neutrino astronomy"

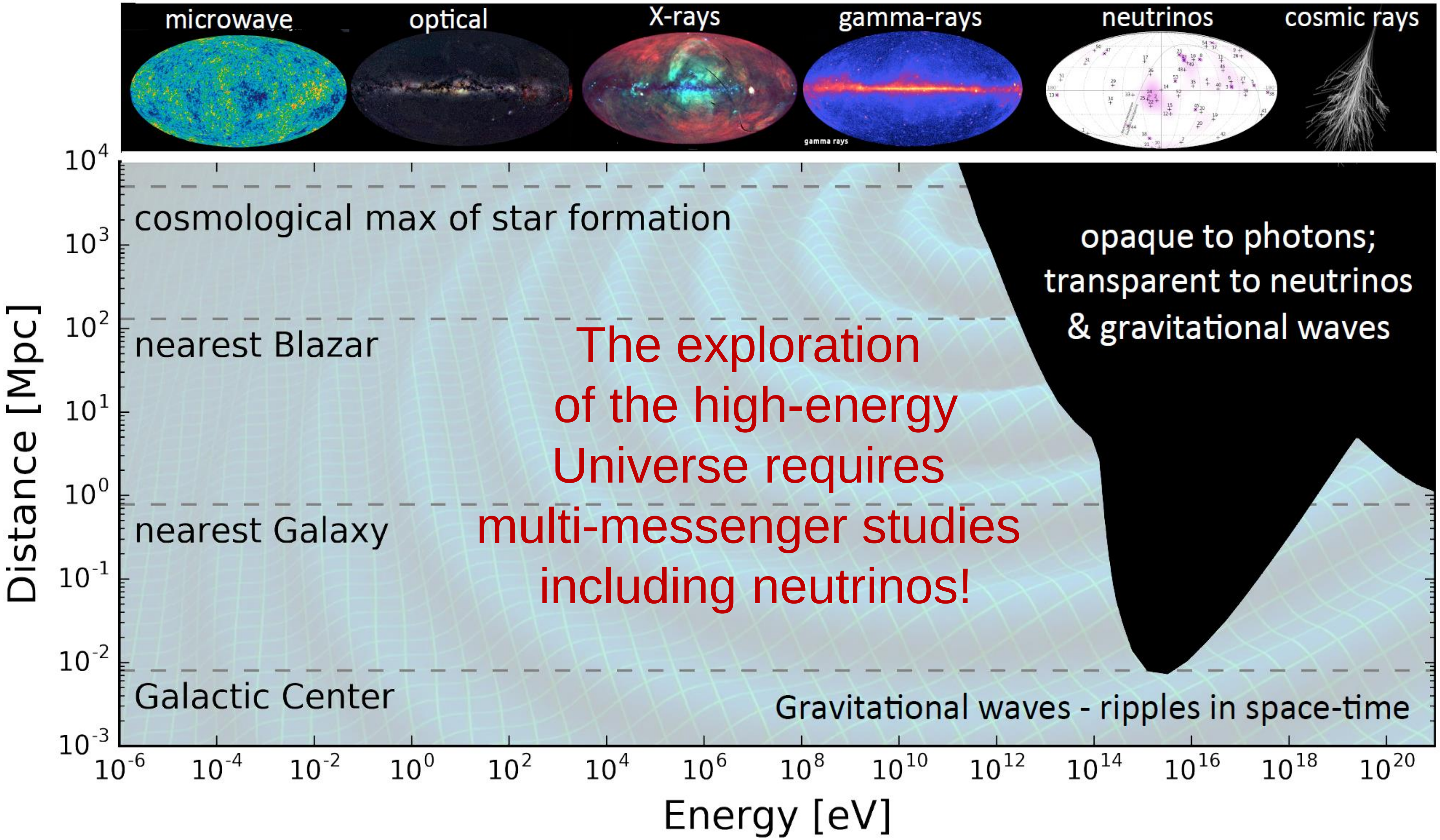
See talk by I. Taboada (We 14:00)

→ We need more statistics, increasingly precise data, and full sky coverage

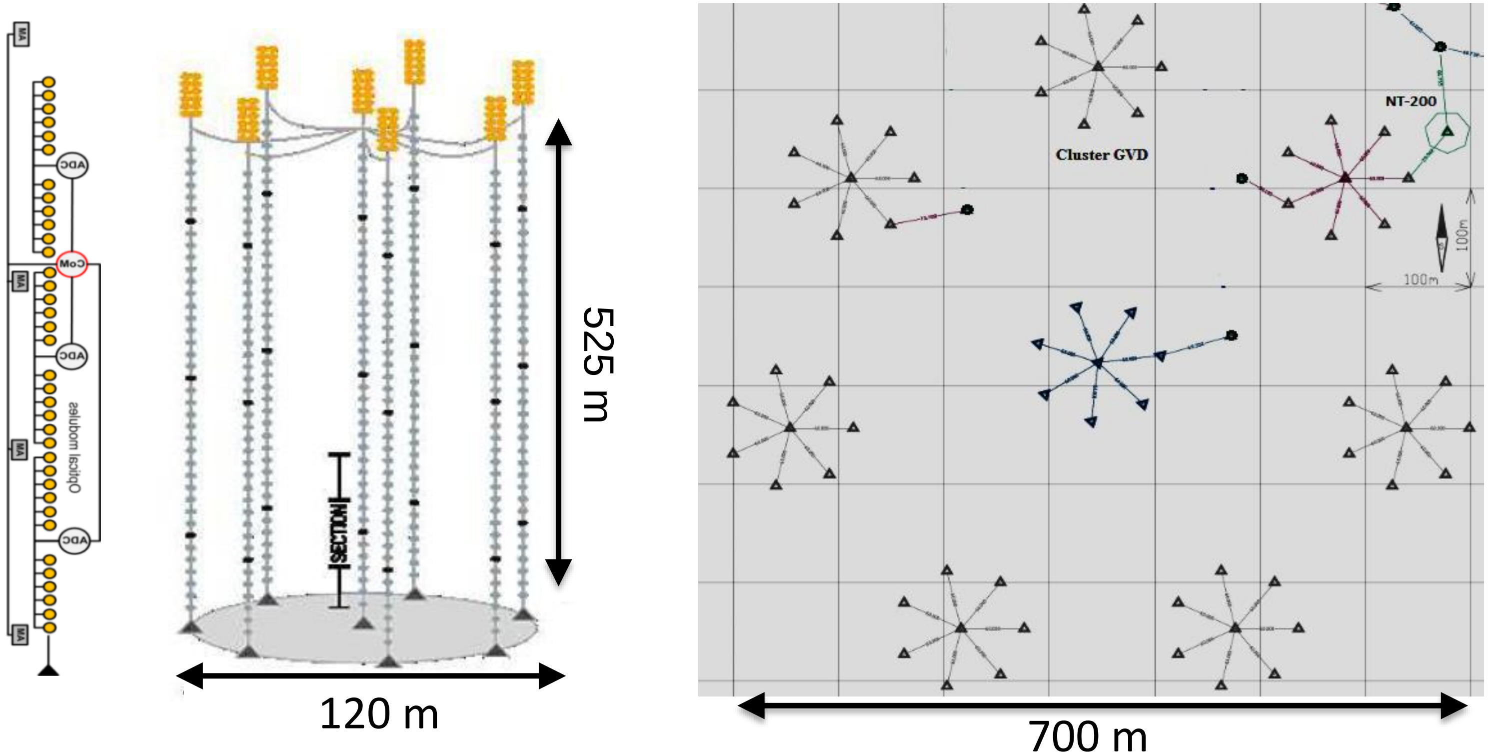
**Rich science program:**

- → Neutrino astronomy
- → Particle physics
- → Dark matter searches
- → Exotics
- → Earth and Sea sciences, glaciology, …

# Neutrino astronomy: where are we?



# The Baikal GVD




- Project to construct a Gigaton (=$km^3$) detector in Lake Baikal
- Phase 1 (GVD-1): 8 clusters (see figure), 0.4 $km^3$
- 3 clusters operational, 1-2 more clusters to be deployed per season
- Commissioning, calibration, sensitivity studies in progress
- Final goal: 27 clusters, 1.5 $km^3$

**P[2/192] Zh. Dzhilkibaev**

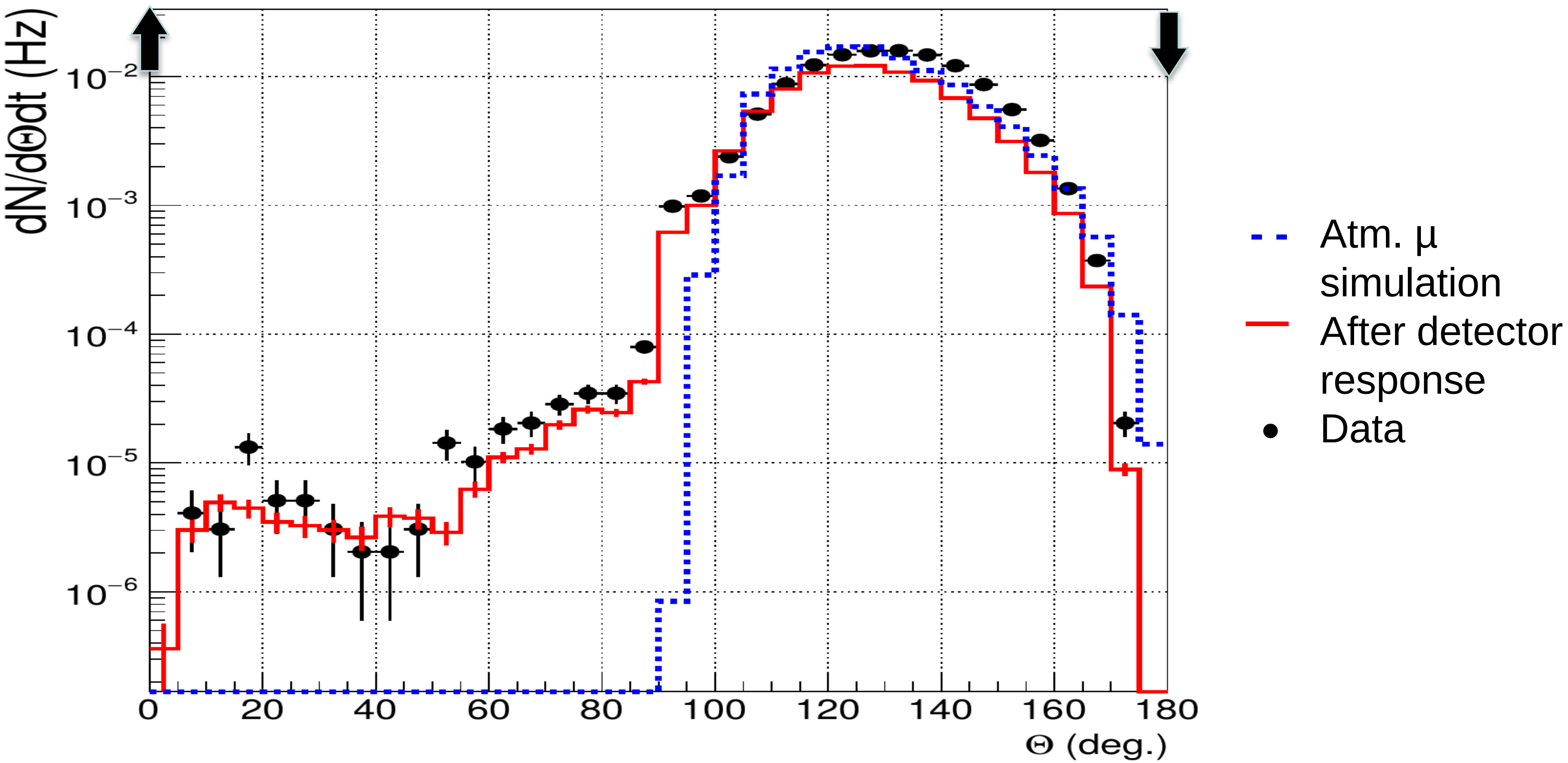
# GVD construction

P[1/106] L. Fajt

- Deployment in winter from frozen surface of Lake Baikal
- Maintenance & repair operations possible
- 10-inch Hamamatsu PMTs, in situ digitisation, data transfer via Ethernet

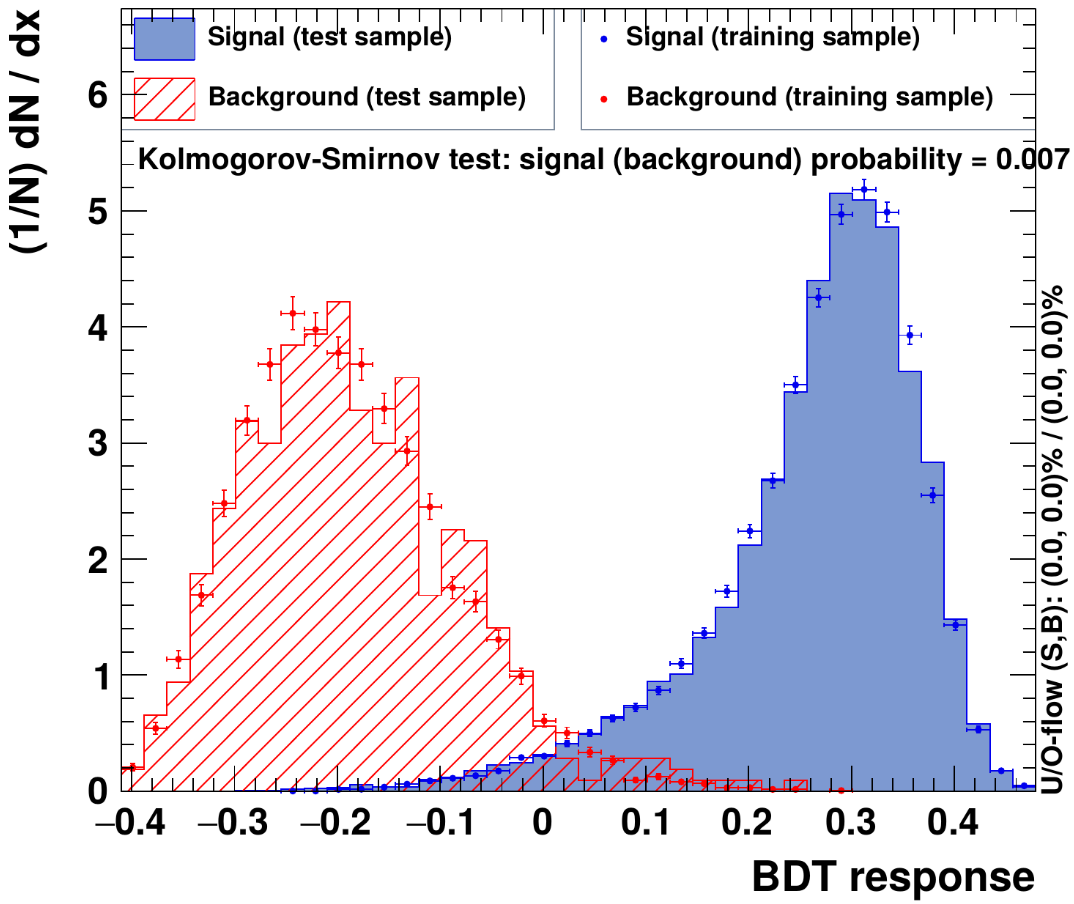
# GVD: first data analysed, first ν's …

- 2016 data: select atmospheric muons (≥6 OMs at ≥3 strings)



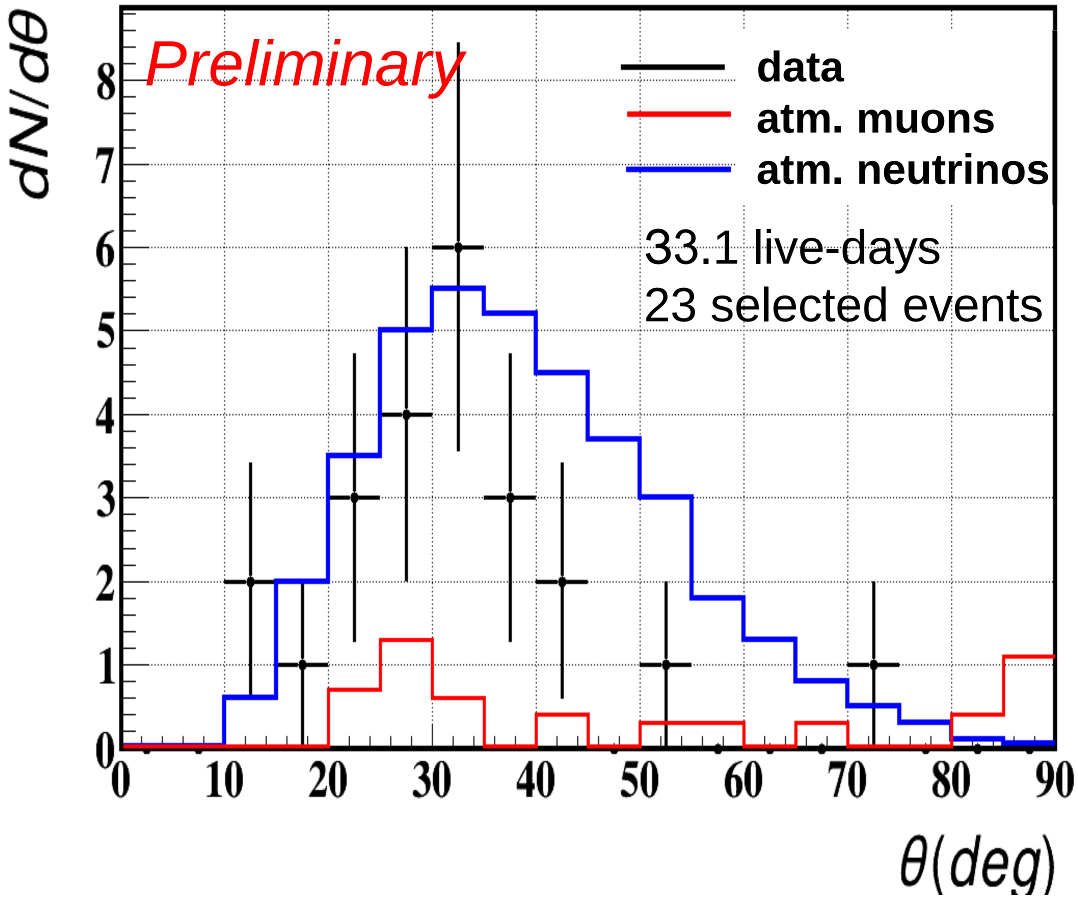
# GVD: first data analysed, first ν's …

- 2016 data: select atmospheric muons (≥6 OMs at ≥3 strings)
- Apply quality cuts and boosted decision tree for ν/μ separation



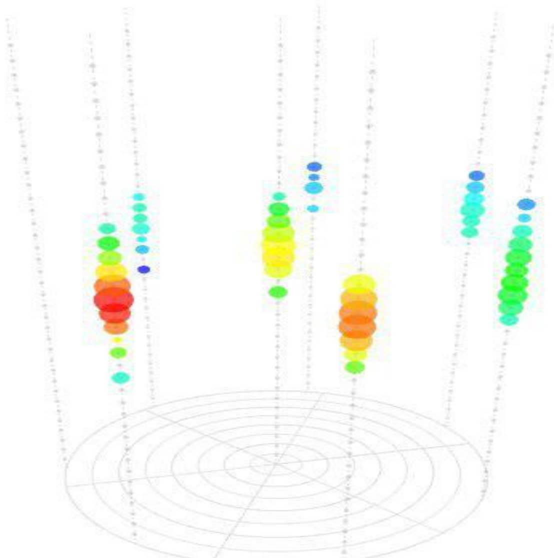
# GVD: first data analysed, first ν's …

- 2016 data: select atmospheric muons (≥6 OMs at ≥3 strings)
- Apply quality cuts and boosted decision tree for ν/μ separation
- … and observe first neutrinos!

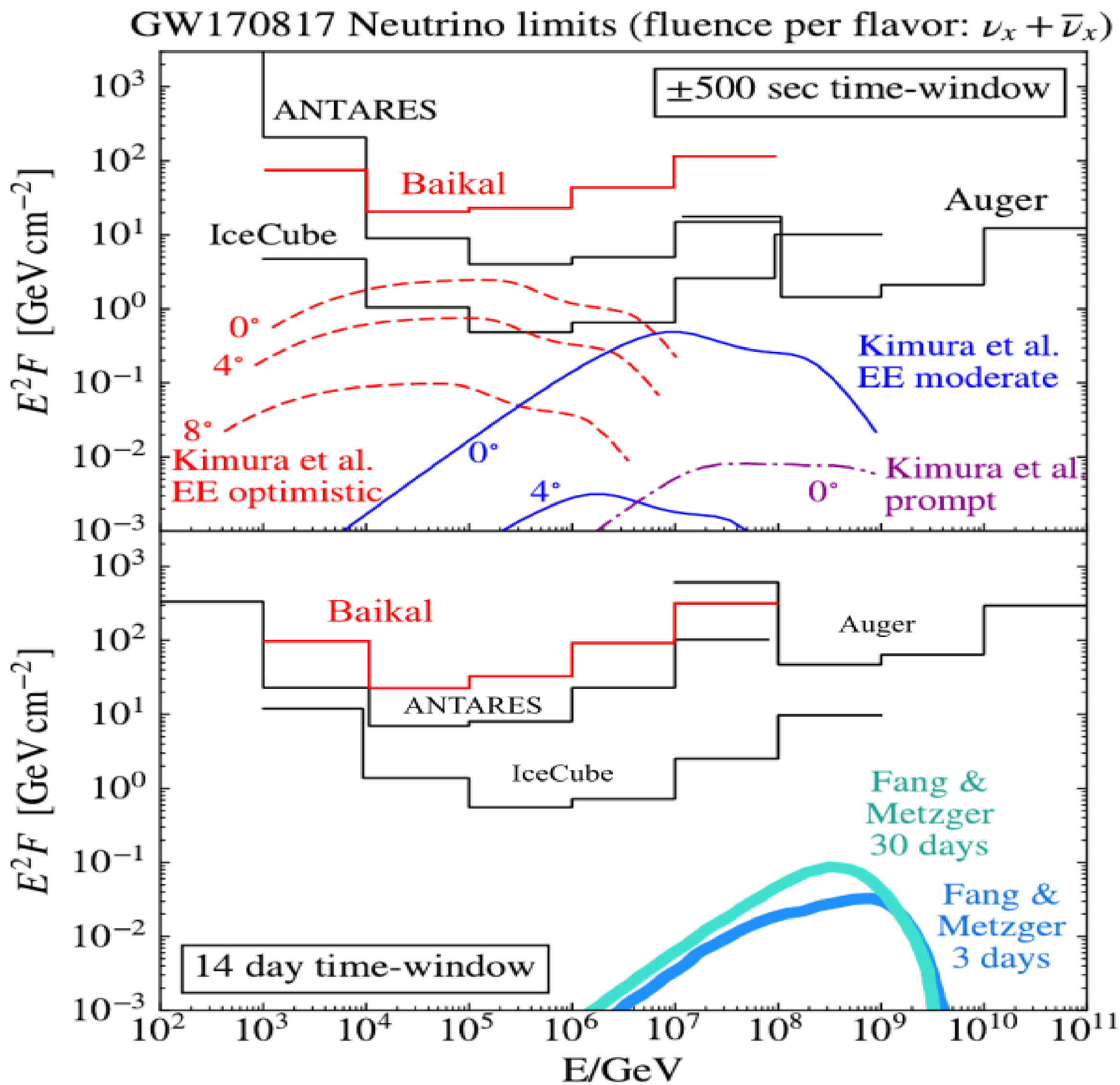


## … and first results from 2016+2017 data

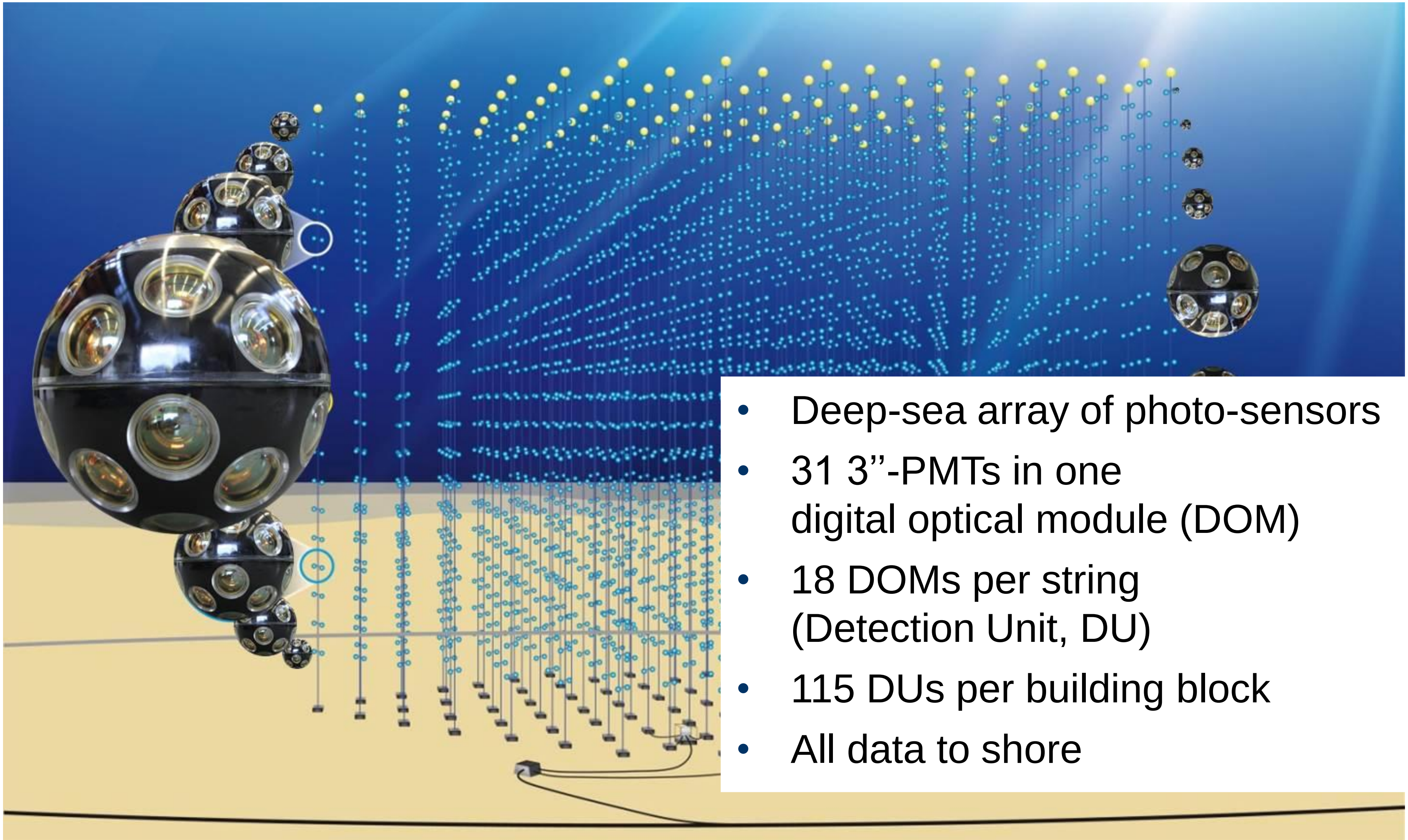
- One high-energy cascade event (157 TeV [reconstr.])



- Search for events coincident with GW170817 in time windows of ±500 s and 14 days after NS-NS merger
  → no signal found
  → upper ν flux limits for each decade of energy



# KM3NeT: the concept

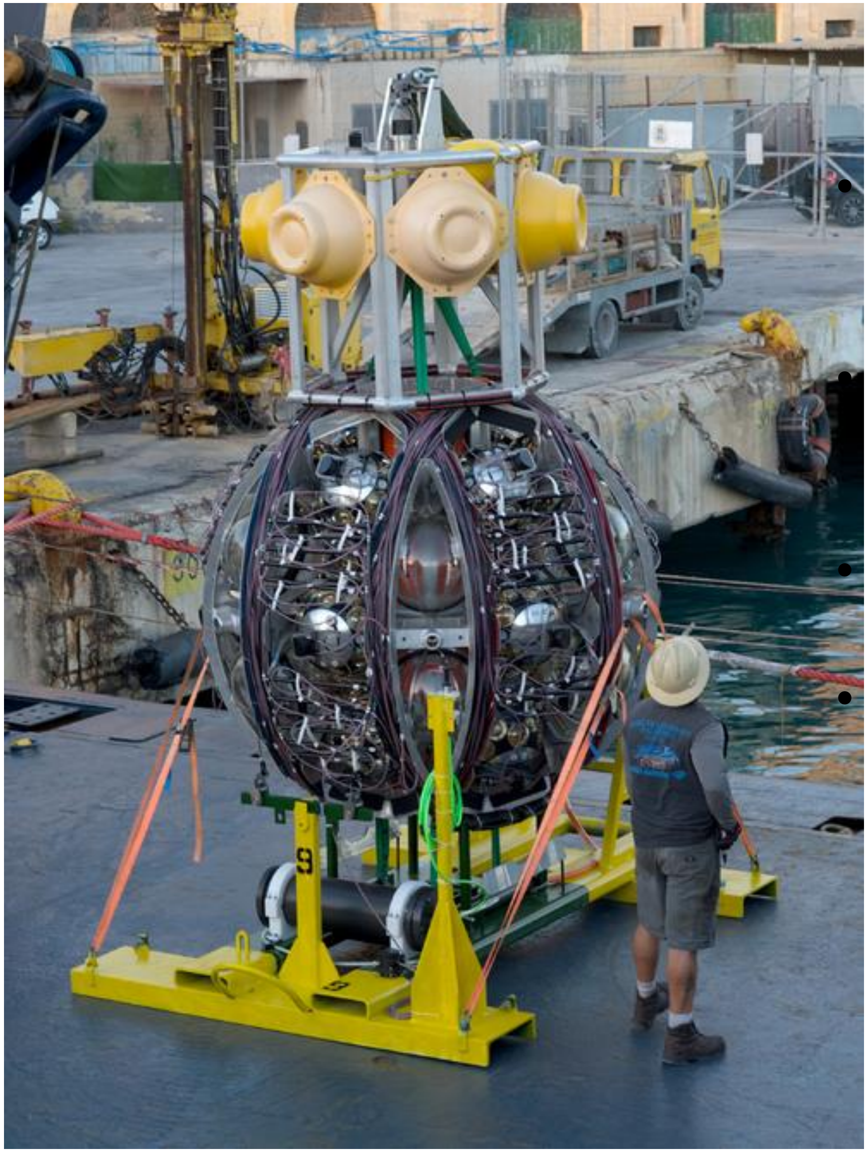


- Deep-sea array of photo-sensors
- 31 3''-PMTs in one digital optical module (DOM)
- 18 DOMs per string (Detection Unit, DU)
- 115 DUs per building block
- All data to shore

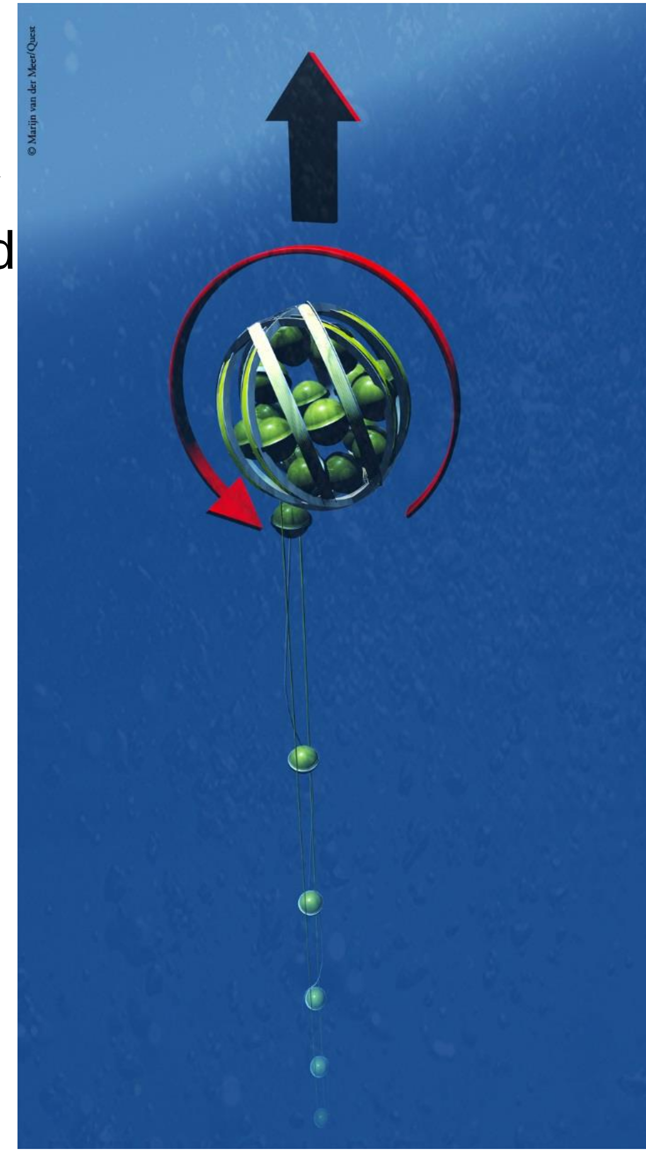
# The KM3NeT Digital Optical Module

- 31 3-inch PMTs  in 17-inch glass sphere (cathode area ~3x10-inch PMTs)
- Front-end electronics, digitisation, optical signal → glass fibre
- Single penetrator
- Advantages:
  - Increased photocathode area
  - 1-vs-2 photo-electron separation → better detection of coincidences
  - Directionality
  - Cost / photocathode area
  - Minimal number of penetrations → reduced risk

# KM3NeT Deployment



- ← Deploy to sea bed
- Release by ROV
- Unfurl →
- Collect frame

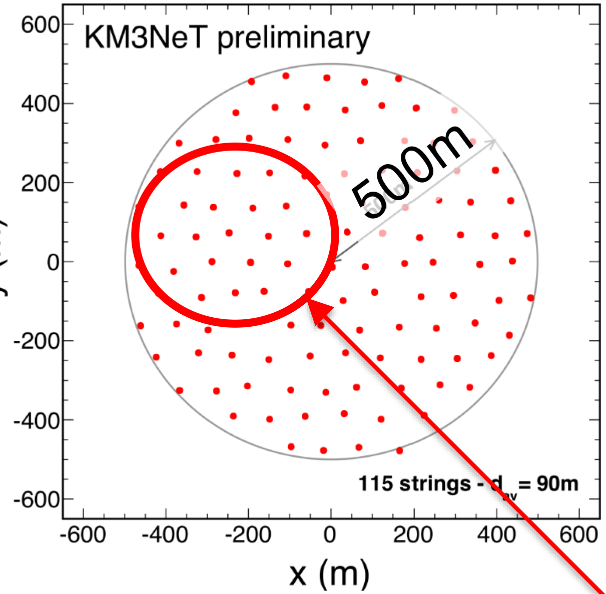


# KM3NeT 2.0 = ARCA and ORCA

ARCA =

Astroparticle Research with Cosmics in the Abyss

Vertical DOM distance = 36 m

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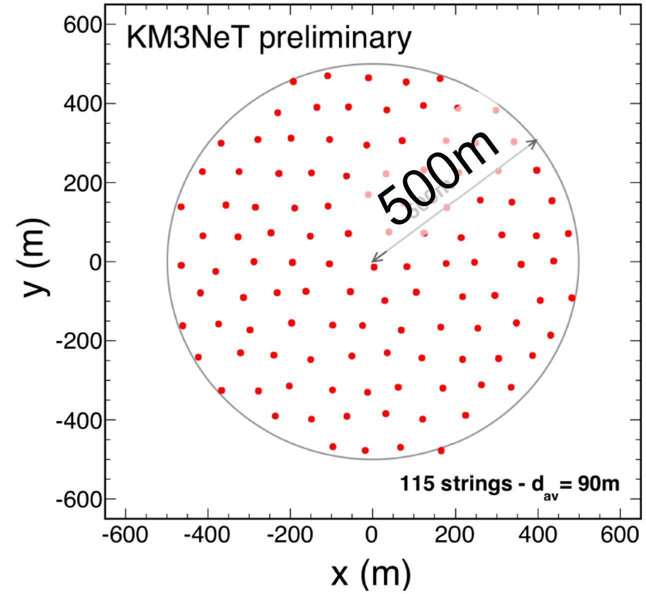
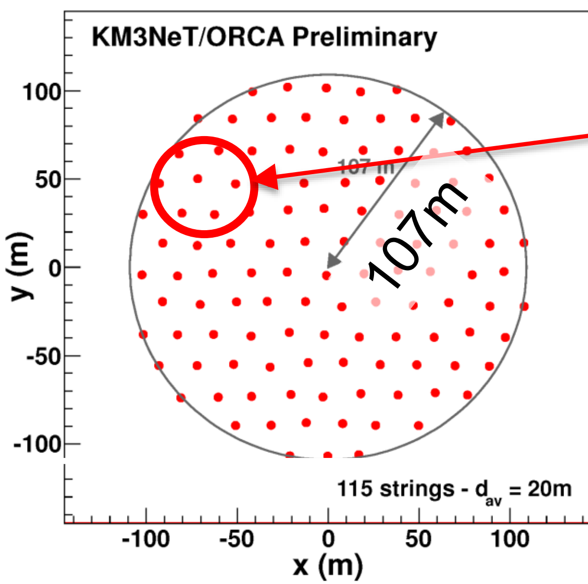



ORCA =

Oscillation Research with Cosmics in the Abyss

Vertical DOM distance = 9 m

**See below**




Phase 1 (fully funded)

Phase 2 partially funded

KM3NeT 2.0 Letter of Intent: arXiv:1601.07459 and J.Phys. G43 (2016) 084001

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ARCA =

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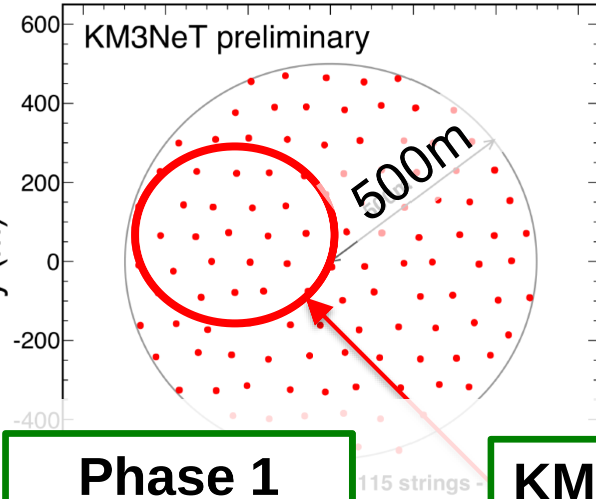


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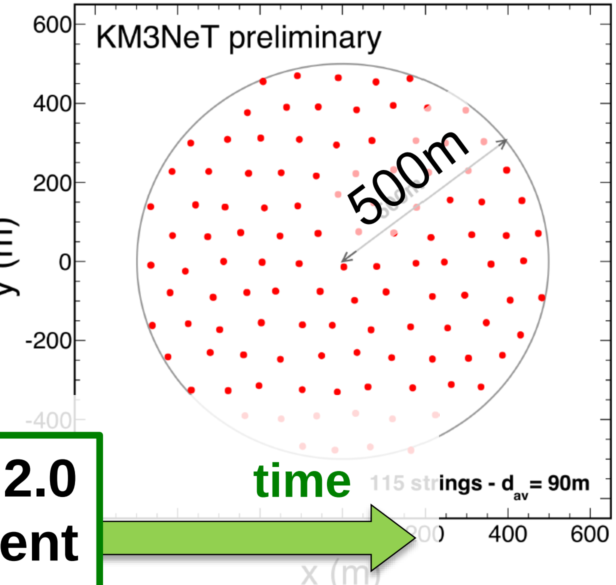



**Phase 1 Deployment 2018-19**

**KM3NeT 2.0 Deployment 2019-21**

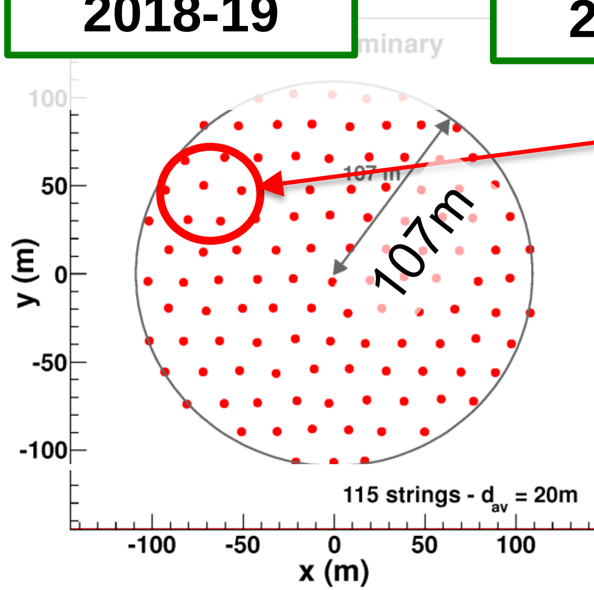
**time**

ORCA =

Oscillation Research with Cosmics in the Abyss

Vertical DOM distance = 9 m

**See below**




Phase 1 (fully funded)

Phase 2 partially funded

KM3NeT 2.0 Letter of Intent: arXiv:1601.07459 and J.Phys. G43 (2016) 084001

# KM3NeT status

**P[2/193] I. di Palma**

### ARCA

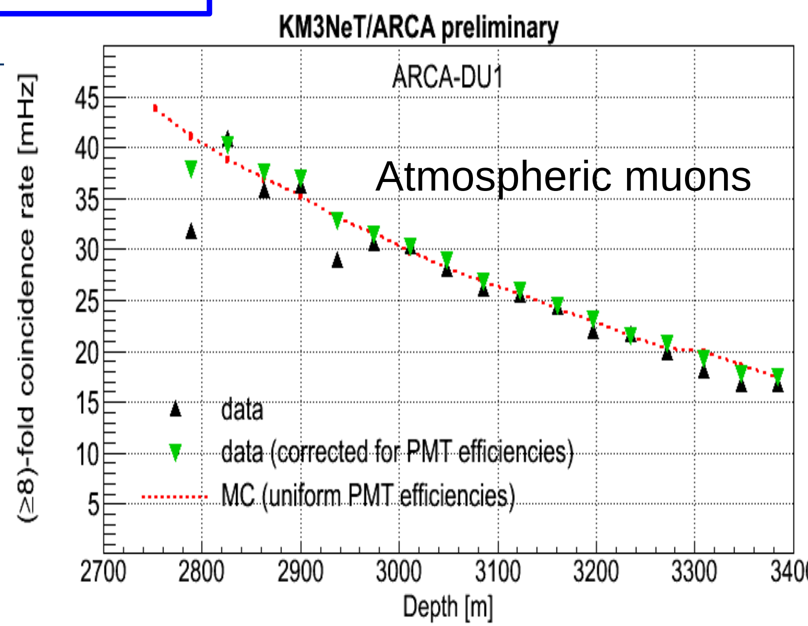
- 3 strings deployed Dec 2015 & May 2016
- 2 out of 3 operated, string #3 with short in power system, recovered
- Attempt to power the 2 deployed strings later this year
- Full restoration of sea-bed network by mid-2019

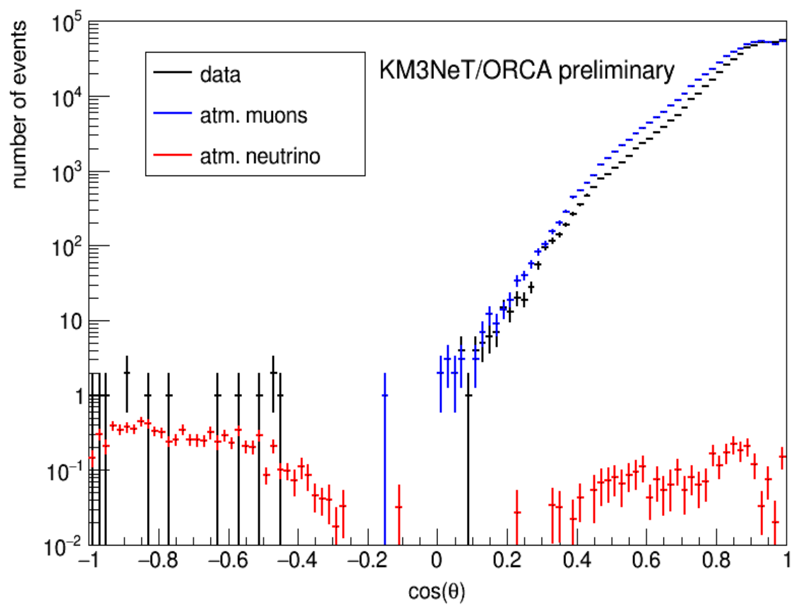
### ORCA

- Successful deployment & operation of first string (Sept 2017)
- Cable problem, replacement in summer 2018, resume operations thereafter

### Construction

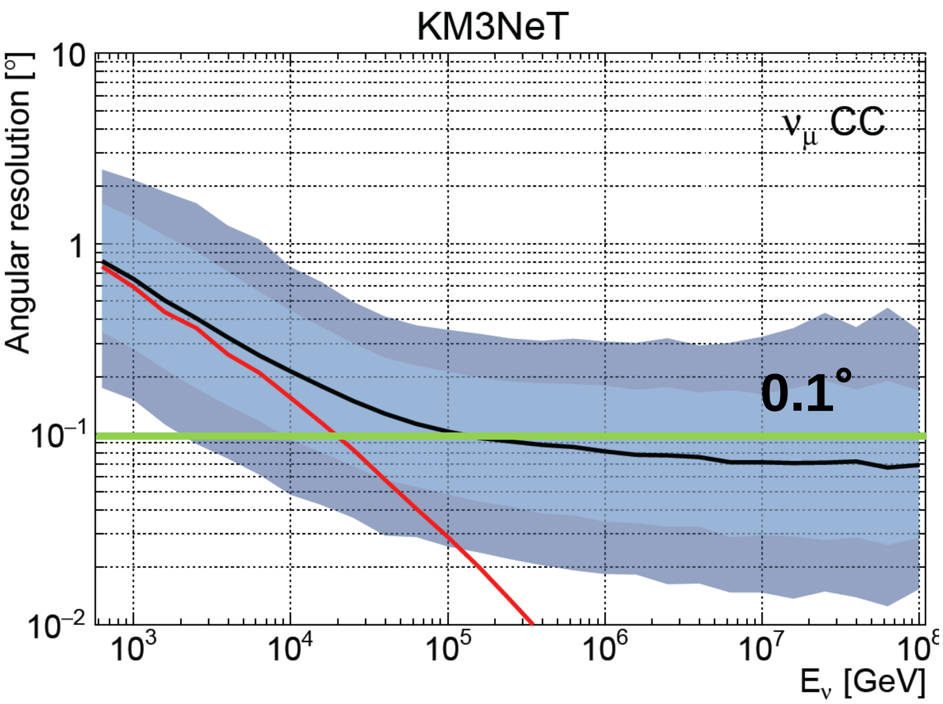
- DOM and DU assembly proceeding
- Deployment after repairs, consistent with schedule on previous slide



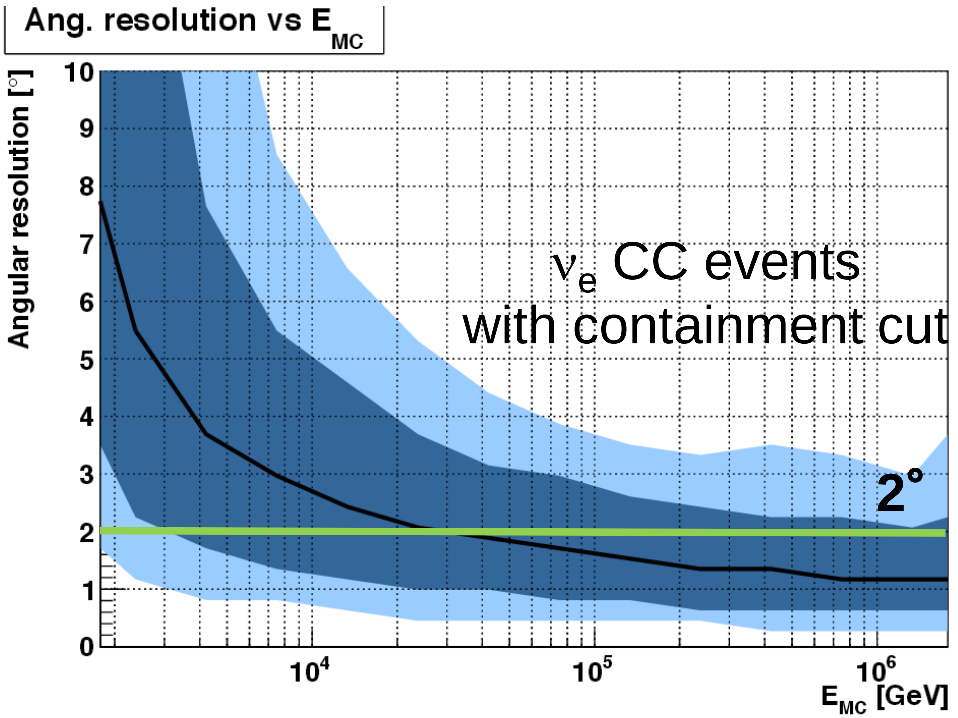



# KM3NeT/ARCA angular resolutions

Track-like events:




Cascades:



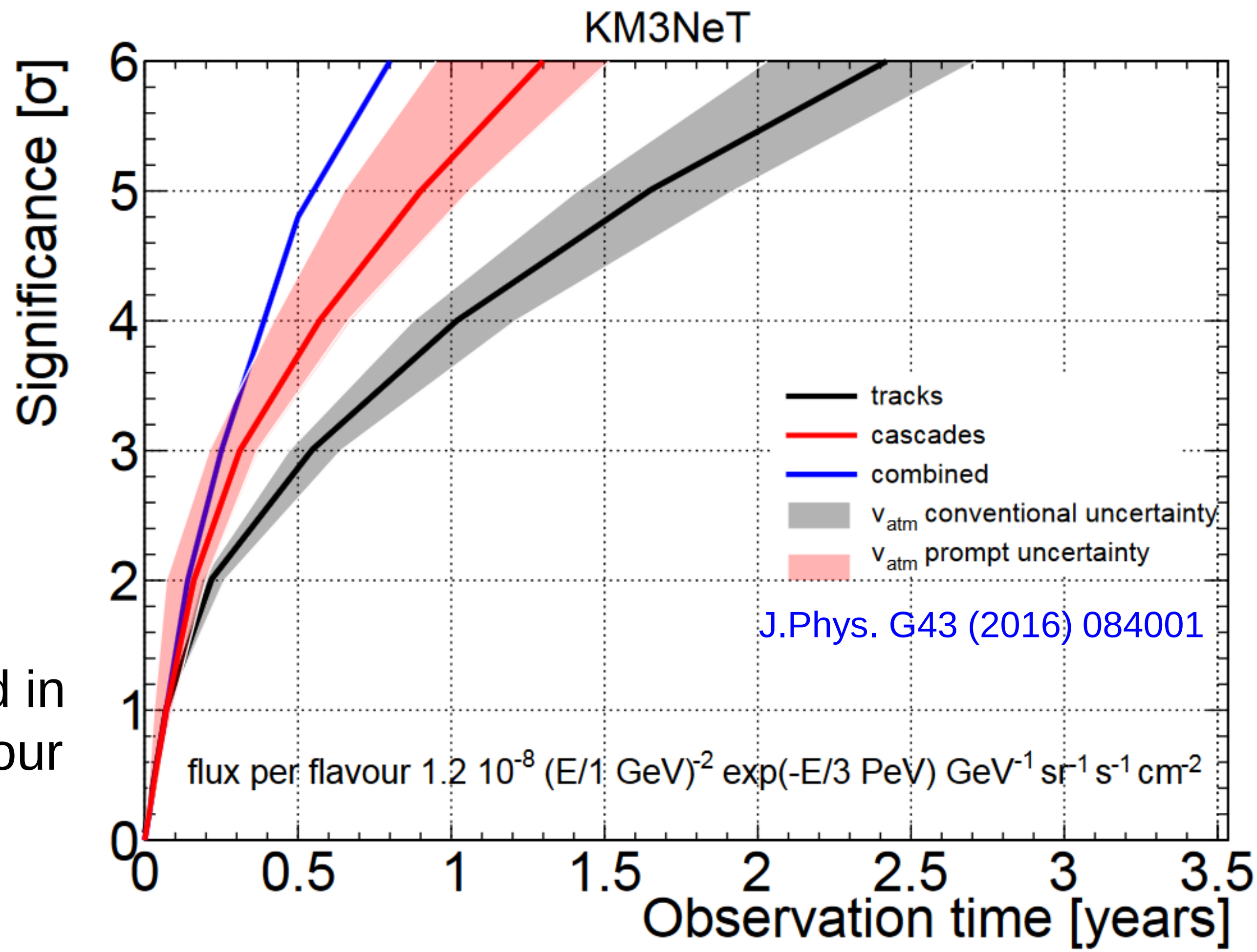

- Muon energy: d(log10 E)=0.25-0.3 at E > 10 TeV
- Cascade energy: 5-10% at E > some 10 TeV
- Good angular resolution helps enormously in source associations

# Diffuse flux sensitivity

- Event numbers (cut&count):

  16/9 cascades
  6.5/4.4 track-like
  (signal/background)
  per ARCA year

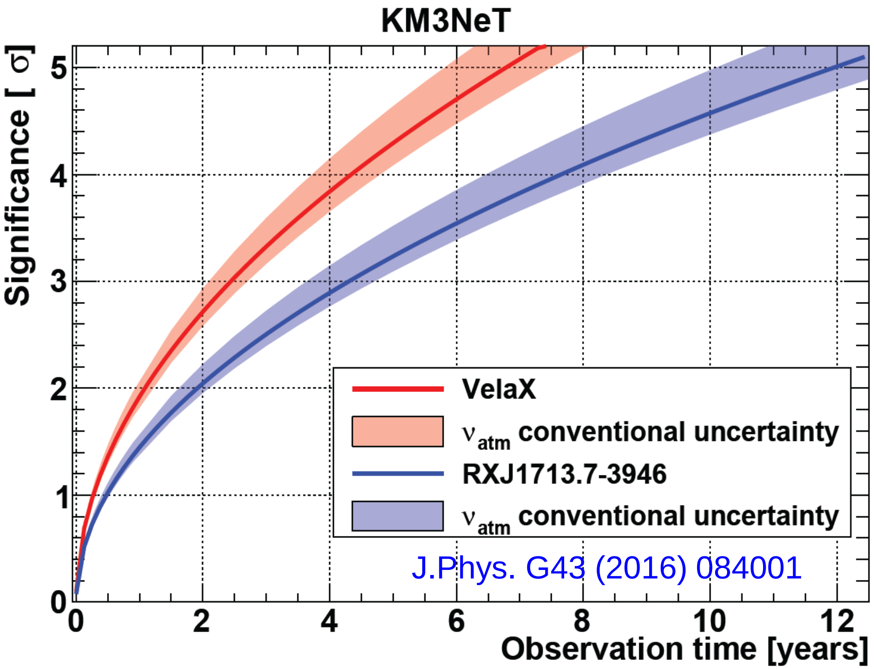
- Note:
  KM3NeT and IceCube are complementary in their fields of view, and in energy range and flavour coverage for a given source direction



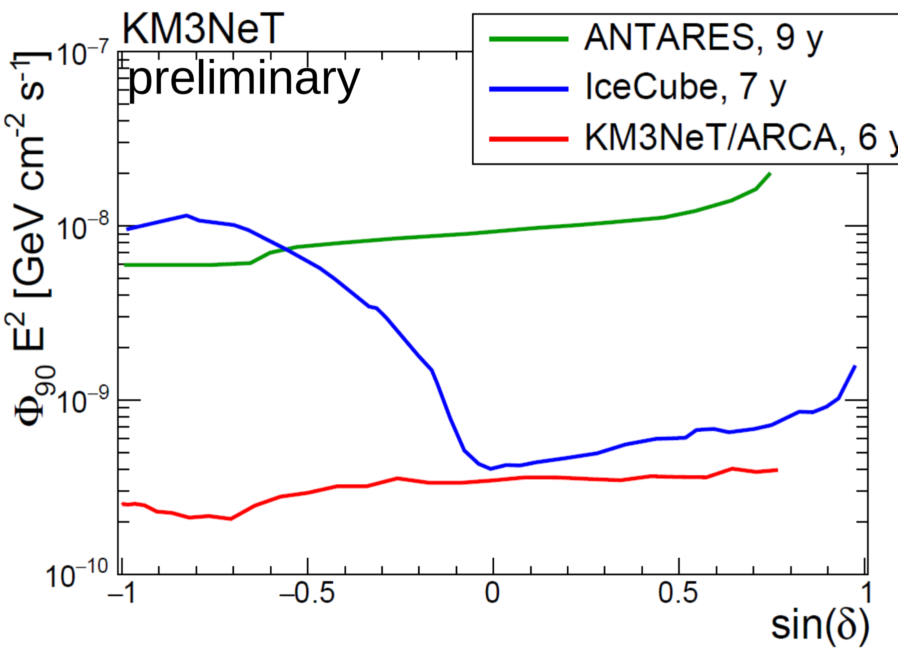

Other flux assumptions yield
10-30% improvement in discovery time.

# Point-source results

→see also talk by Ignacio Taboada (We 14:00)




- Refined analysis and starting-event study in the pipeline
  **P[2/182] K. Pikounis**
- Galactic sources in reach




- Significant discovery potential for extragalactic sources, complementing IceCube field of view
- Note: We compare detector sensitivities, not discovery potential at a given time – IceCube will have ~10 years of data when KM3NeT will start operation

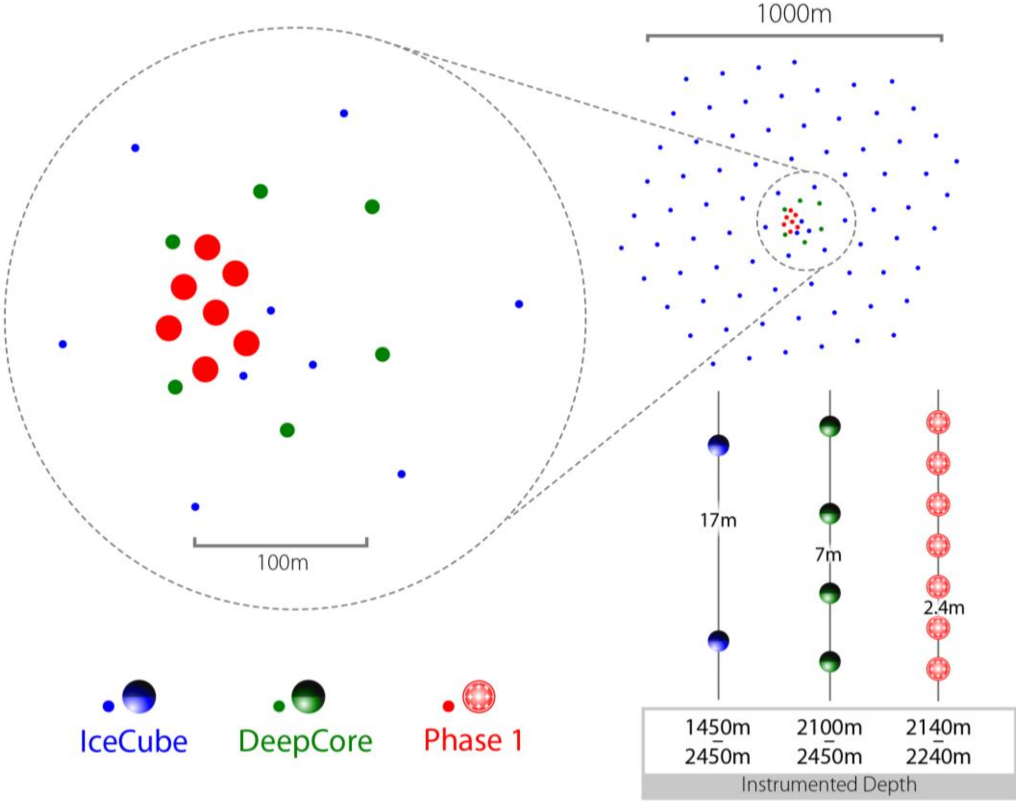
# IceCube: next step = Upgrade

### IceCube-Upgrade

- 7 additional strings in Deep Core domain, densely instrumented
- Objectives:
  - GeV neutrinos: τ appearance, Dark Matter, …
  - Improved understanding of ice properties → better precision, reduced systematic uncertainties
  - Opportunity to test new hardware developments
- Funding commitment expected very soon

**Deployment 2022/23**

time

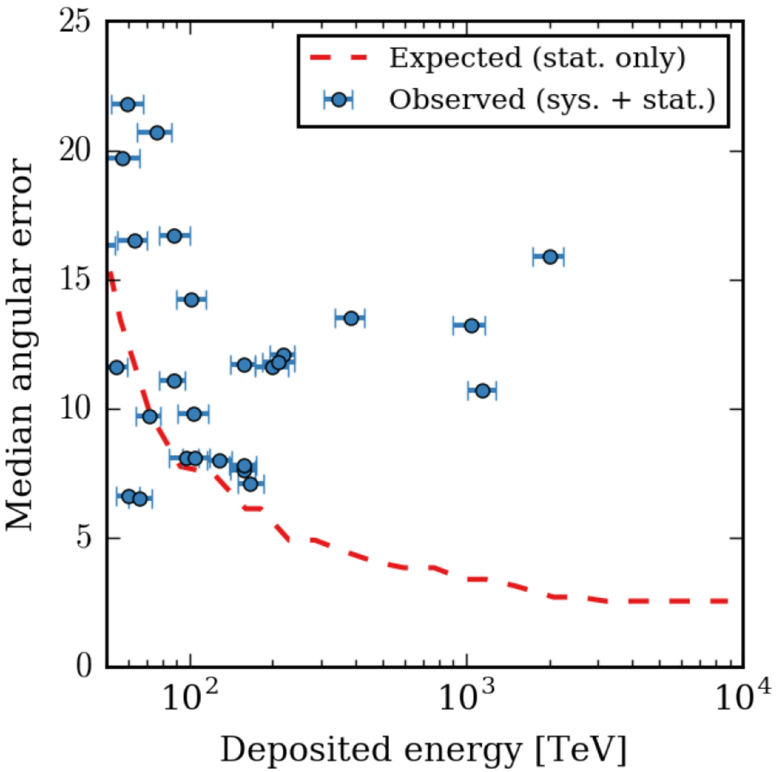


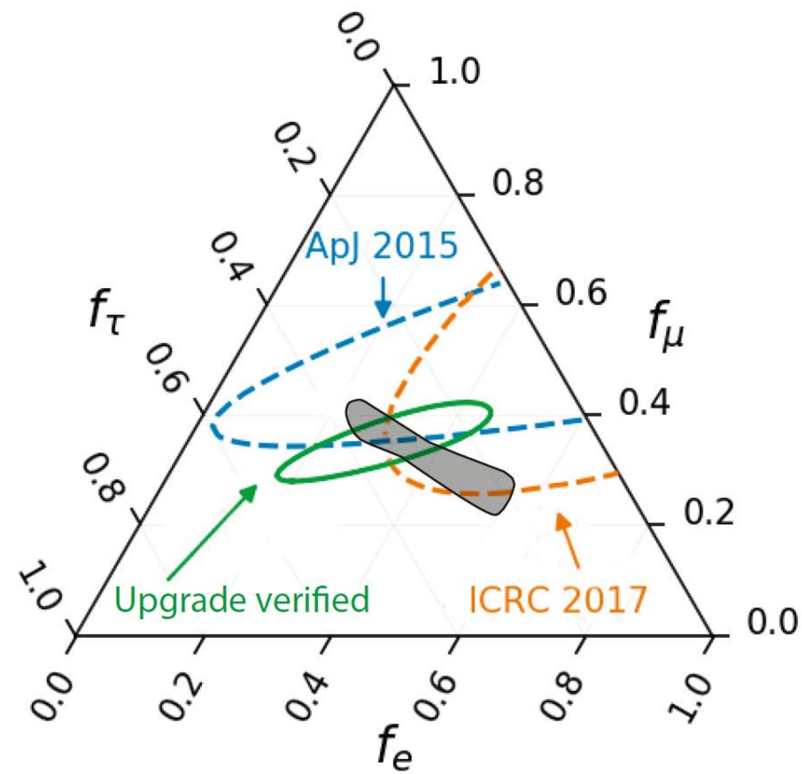

| Array | String Spacing | Module Spacing | Modules / String |
|---|---|---|---|
| IceCube | 125 m | 17 m | 60 |
| DeepCore | 75 m | 7 m | 60 |
| Upgrade | 20 m | 2 m | 125 |

P[2/163] J. Evans

# IceCube Upgrade: improve data quality

- Limiting factor for reconstruction precision and flavour id: Ice properties
- Precision calibration with Upgrade (dense instrumentation, additional devices)
- Better angular resolution. W/o ice systematics: Cascades 3-5$^{o}$; tracks 0.1-0.2$^{o}$
- Yields improved multi-messenger capabilities, improved tau identification



# IceCube: Sensor developments

## Multi-PMT optical module (mDOM)

- 24 × 3” PMTs (e.g. Hamamatsu 12199-02)
- 14” borosilicate glass vessel rated @ 700 bar
- Based on proven KM3NeT design
- Baseline design for Upgrade

P[1/154] M. Unland

## “D-Egg”

- 2 x 8” PMTs
- UV-transparent glass and gel
- R&D and production by Japanese groups

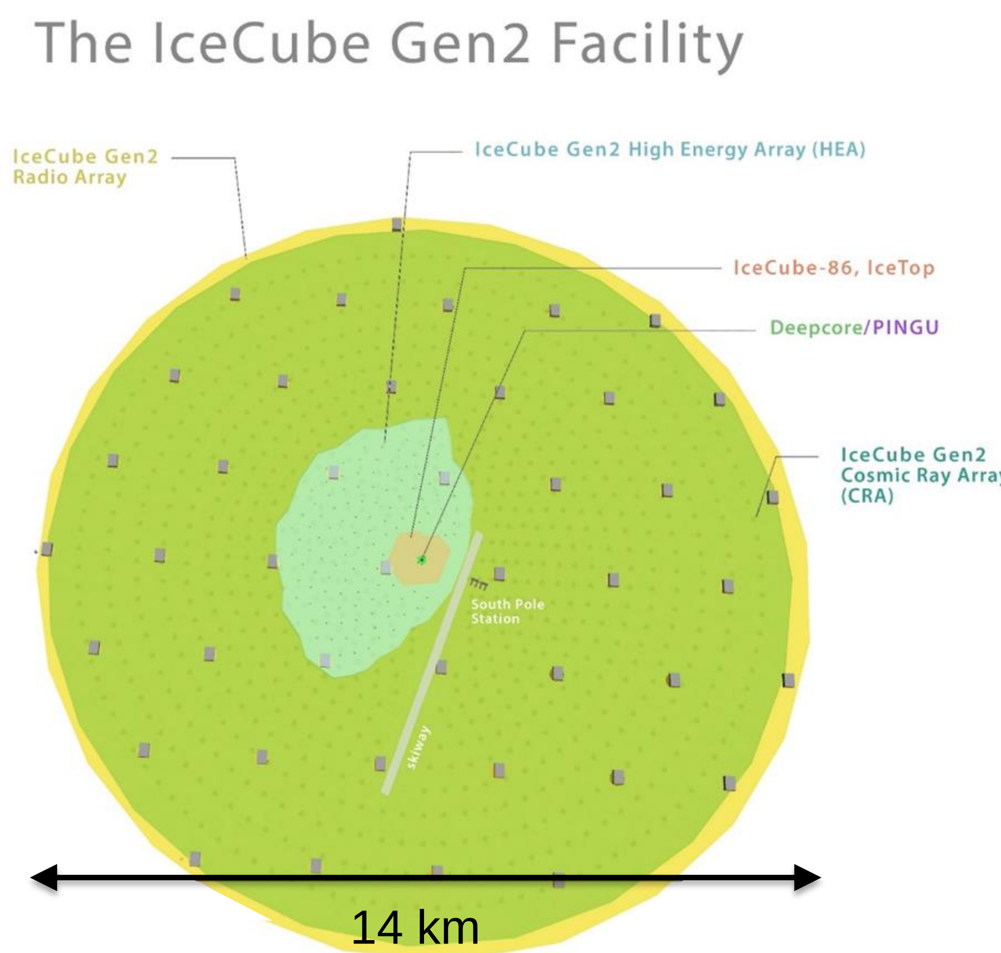
Further light sensor technologies under study

# IceCube Gen2

- Next-generation neutrino observatory at South Pole, with
  - High-energy deep-ice detector (High-energy array, HEA)
  - Cosmic-ray and veto surface array (CRA)
  - Radio array (RA)
  - High-density core for low-energy neutrinos (PINGU)
- Funding application expected in NSF MREFC scheme (~2020)

**Deployment 2025-31**

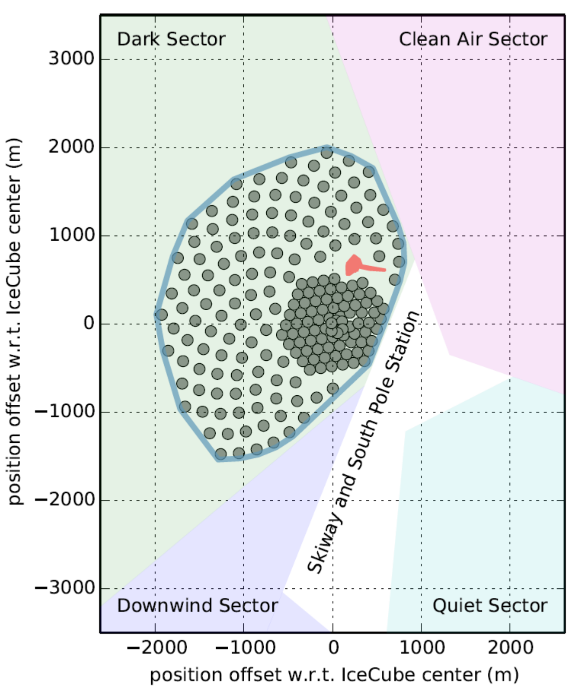
**time**

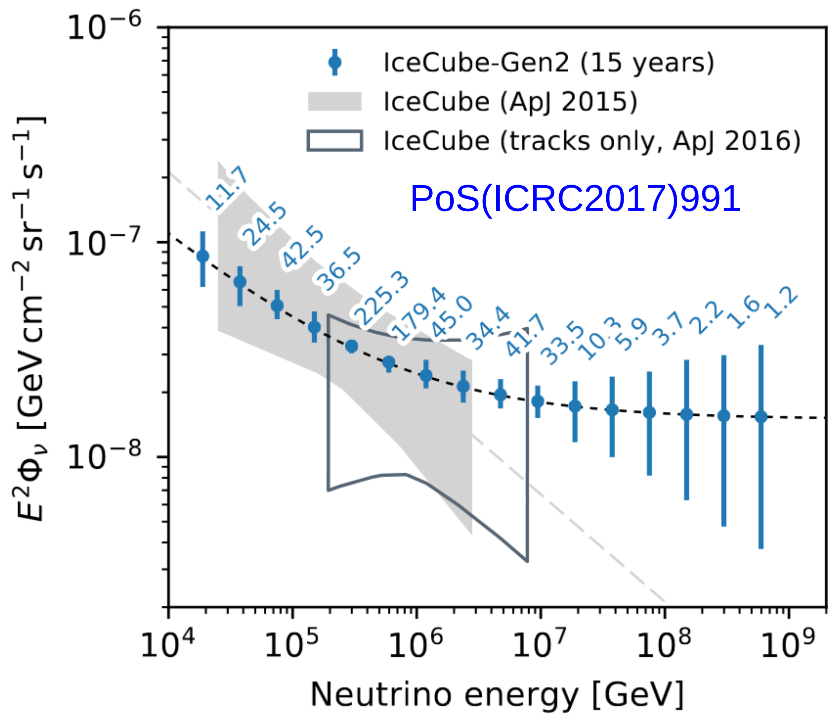


# IceCube Gen2: high-energy array

**Following up IceCube's PeV ν's: Detection of neutrinos with 100+ TeV**

- Events are huge and produce a vast amount of Cherenkov light
- Sparse instrumentation suffices:
  String distance 240-300 m, 80 DOMs/string, 1.3 km string length
- Test with real IceCube PeV shower event, masking strings:
  Resolution 30$^o$ in direction, 10% in energy, 12m in vertex position



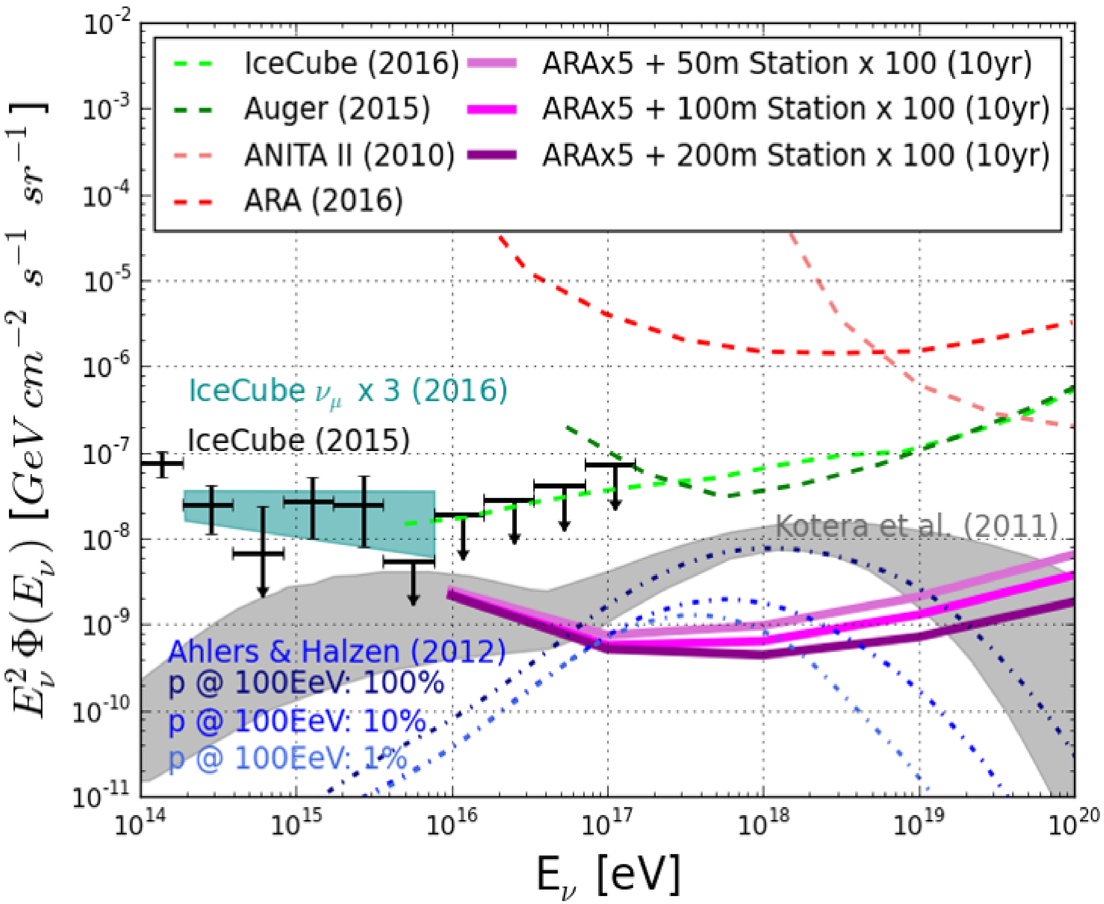




O(10)
PeV events
per year

# IceCube Gen2: Radio array

### Detection of neutrinos with 100+ PeV

- Radio technique by far more cost-effective at these energies
- Important input/experience from ARA and ARIANNA projects **P[2/172] C. Glaser**
- Many open questions on technology and design
- Target: Cosmogenic neutrinos from GZK effect




**See presentation by Amy Connolly (We 14:40)**

# Neutrino physics with neutrino telescopes

# ν physics with ν telescopes: where are we?

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- ✓ IceCube and ANTARES have proven sensitivity to neutrino oscillations
- ✓ IceCube/Deep Core has demonstrated precision competitive to leading experiments
- ✓ New opportunities studied in much detail: Neutrino mass ordering, tau appearance
- – Need suitable instrument(s) for these measurements
- – CP violation not yet in reach, but might be in future

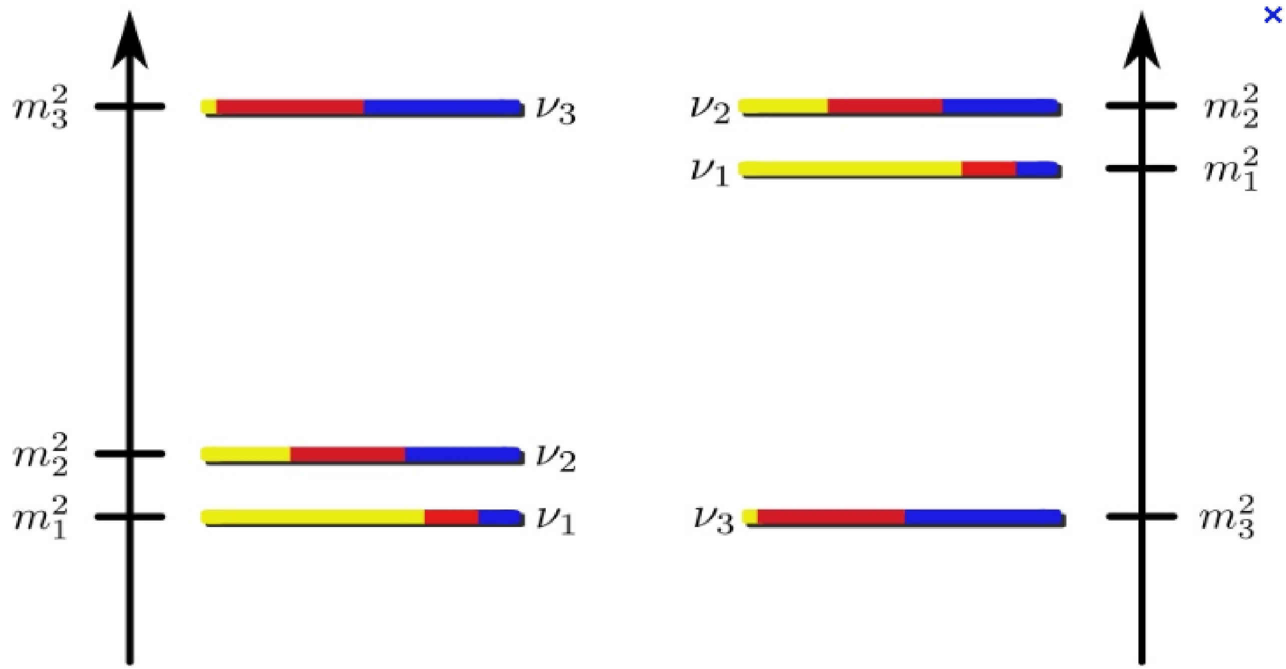
see talk by Tyce DeYoung (Tu 11:55)

**Rich science program:**

→ Neutrino physics
→ Dark matter searches
→ Non-standard ν interactions
→ …

# Example 1: Neutrino mass ordering (NMO)

“normal ordering” (NO) or “inverted ordering” ? (IO)

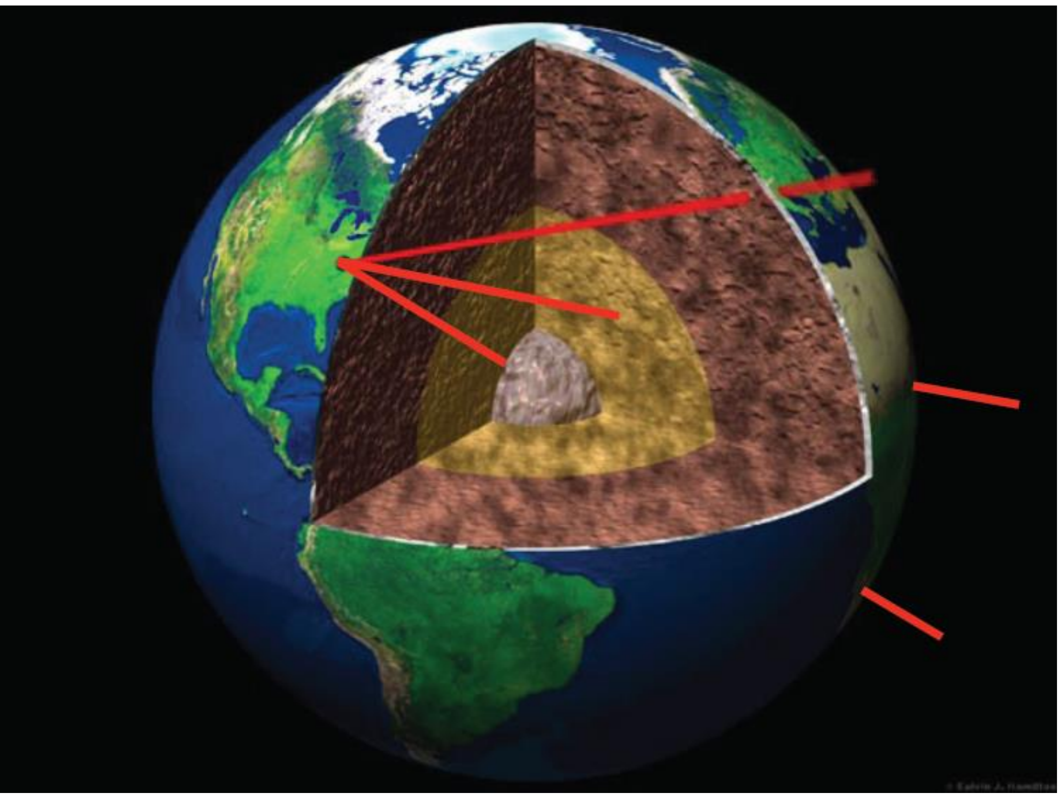


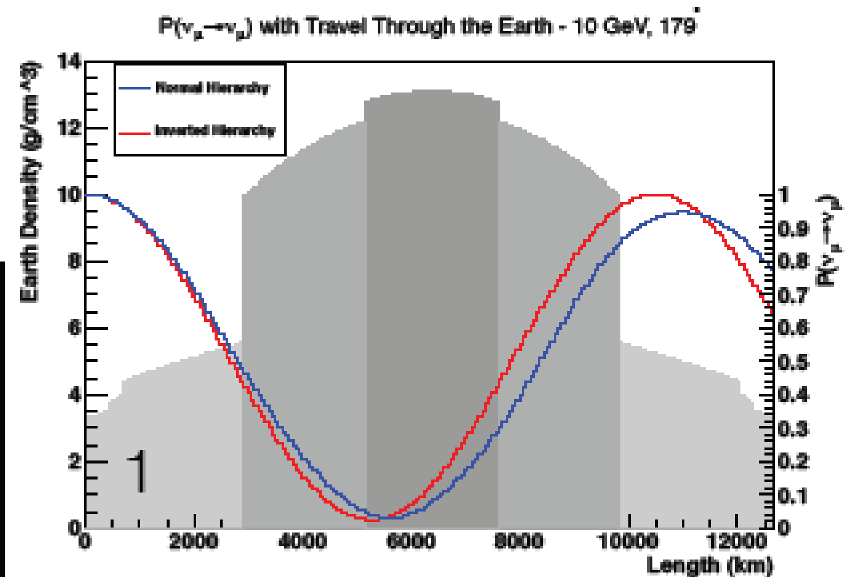

Fundamental parameter of particle physics.
→ Knowledge required to investigate neutrino CP violation
→ Important also for cosmology

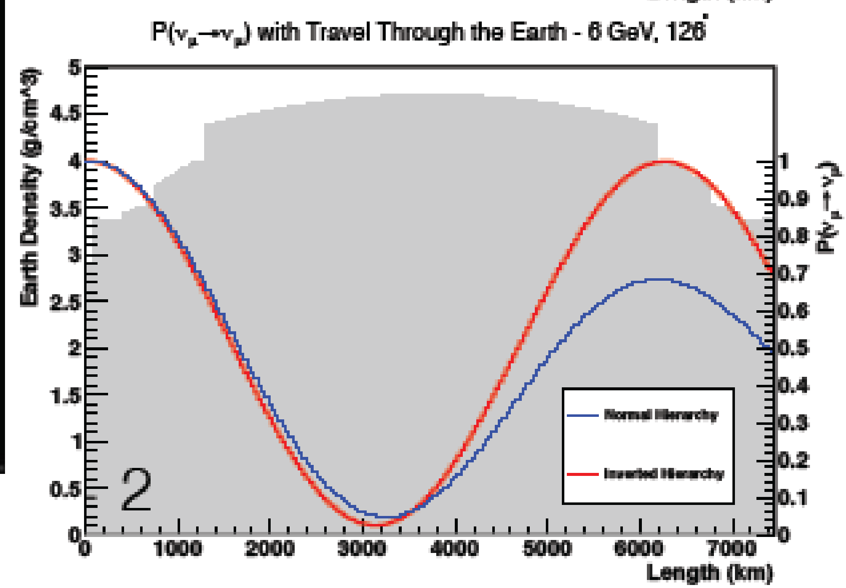
# NMO from ν oscillations in Earth

Earth density 4-13 g/cm³ →

Relevant: $E_\nu \sim 3\text{–}10$ GeV






**Method complementary to reactor ν's !**

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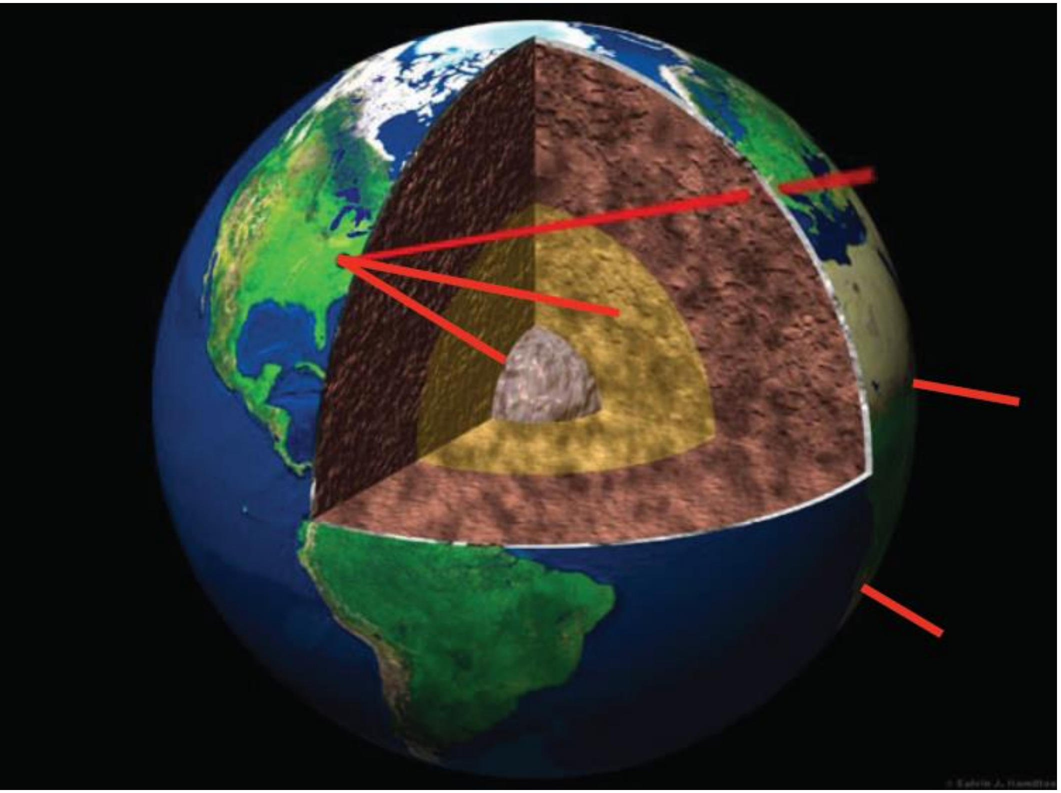
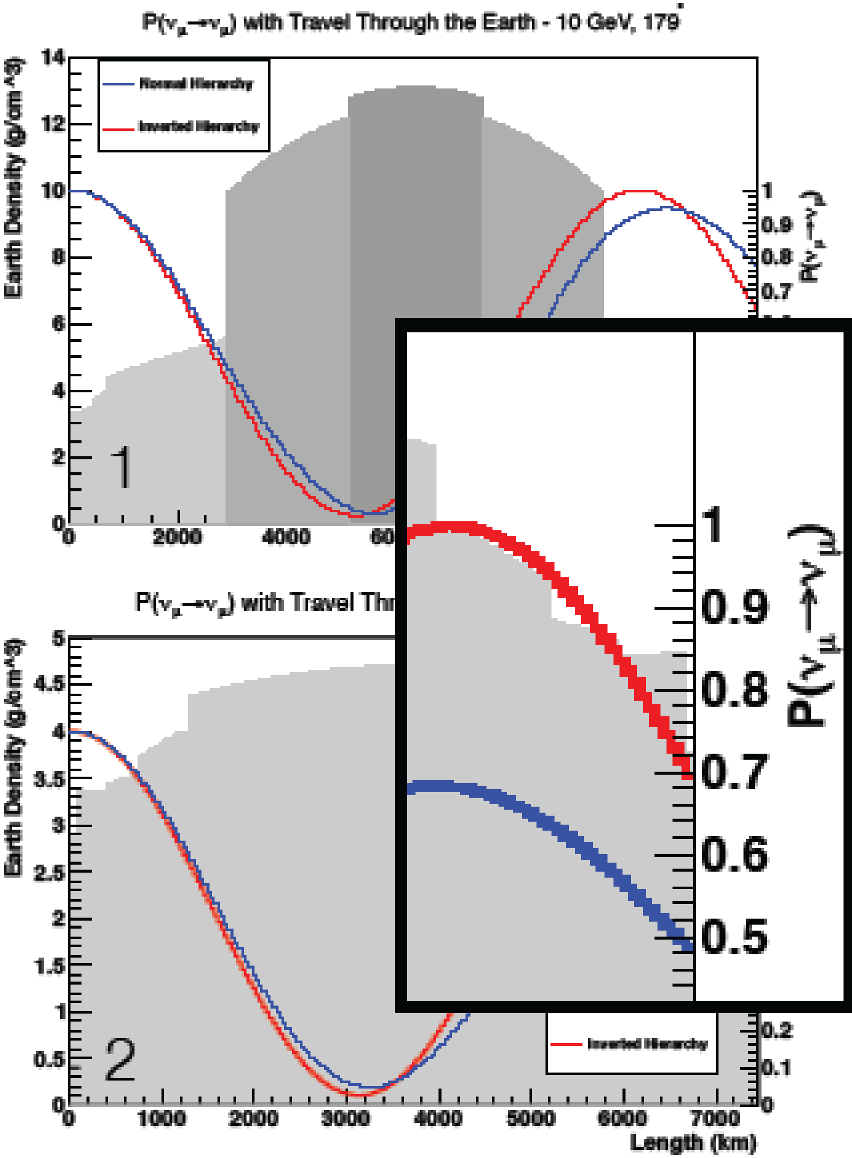




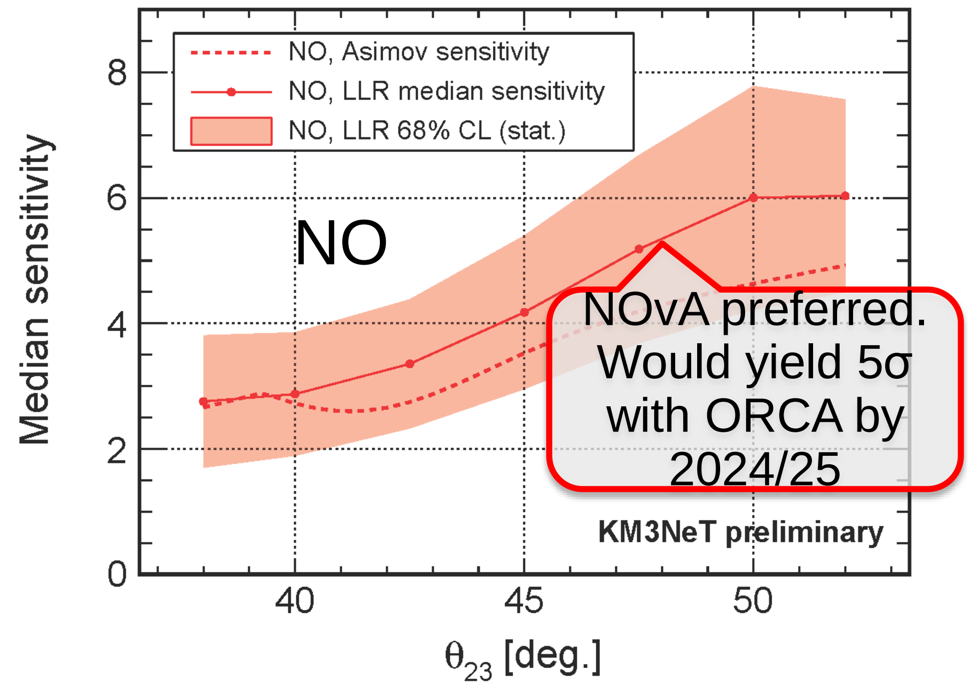

**Method complementary to reactor ν's !**

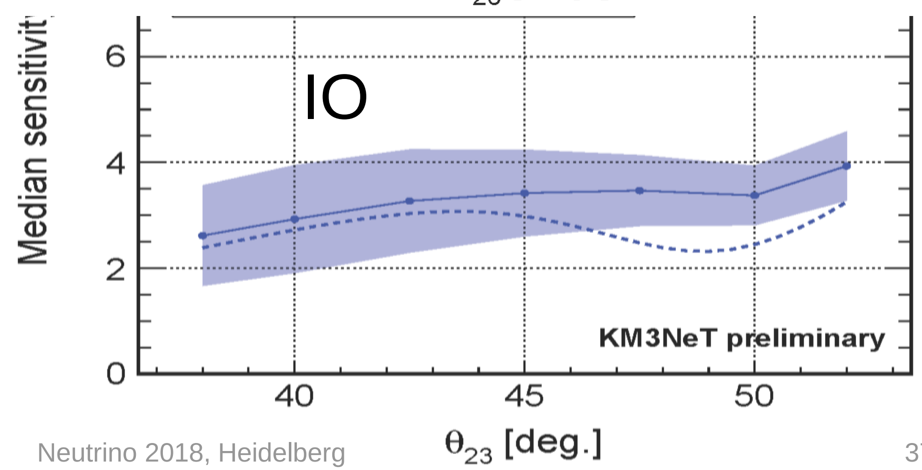
# NMO measurement

- Primary signature:
  Energy-zenith distribution
- Inverse signatures for $\nu$ and $\bar{\nu}$, but signal measurable since $\sigma(\nu) \approx 2\,\sigma(\bar{\nu})$ and $\Phi(\nu) > \Phi(\bar{\nu})$
- Measurement requires
  - best possible resolution in energy and zenith
  - separation $\nu_e/\nu_\mu$
  - detailed understanding of systematics
- In-depth studies by KM3NeT and IceCube, extensive cooperation
- Results very similar

**P[2/161] S. Bourret**

Asimov and LLR median sensitivity after 3 years, $\delta_{CP} = 0$

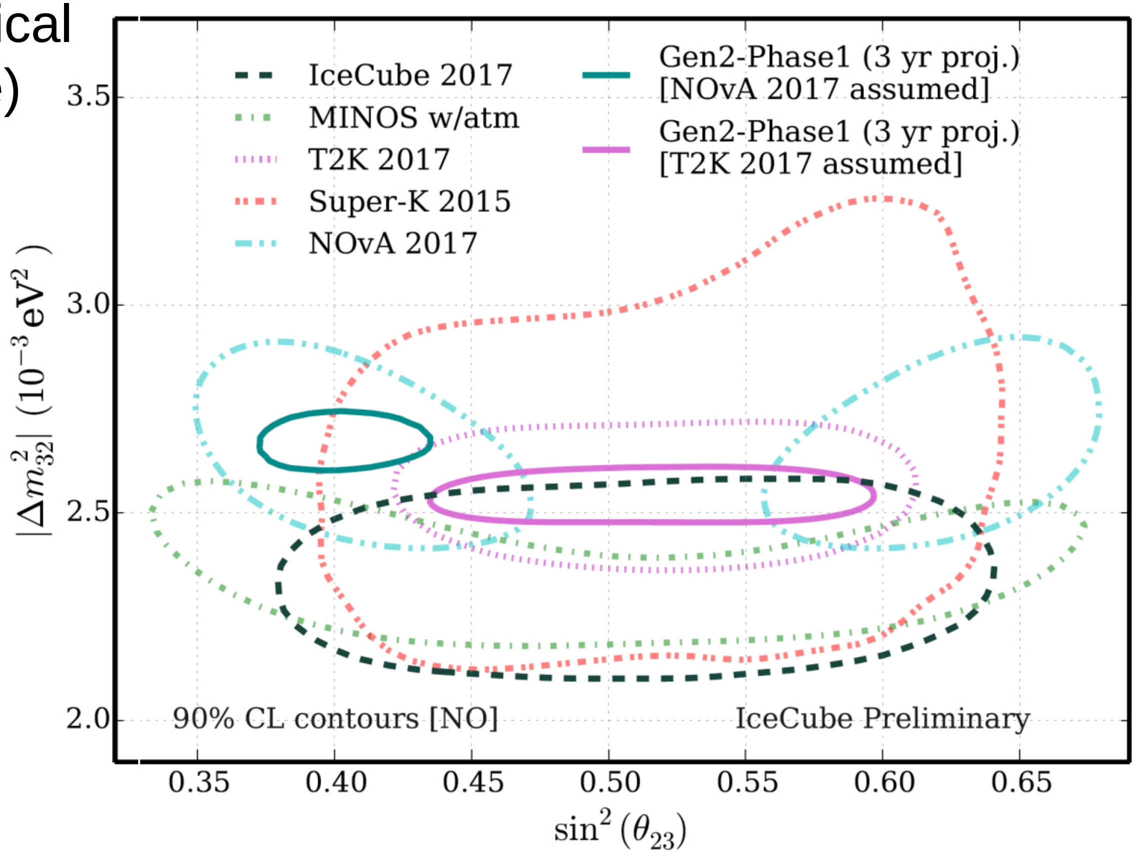


# Example 2: Neutrino mixing

- Target $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Detect $\nu_\tau$ events on a statistical basis (up-going, shower-like)
- Case study for IceCube Upgrade:
  - ~2500 $\nu_\tau$ events / year
  - Drastically improve measurement of atmospheric mixing parameters
  - Chance to determine octant of $\theta_{23}$
- Also possible with ORCA

**P[2/159] T. Eberl**



# Future visions

- Neutrino beam Protvino-ORCA (P2O)
  - Target: measure CP-violating phase
  - Requires substantial effort in Russia
  - Currently under investigation
  - See D. Zaborov et al., arXiv:1803.08017

**P[2/186] J. Brunner**

- Extended ORCA and/or PINGU (Super-ORCA, Super-PINGU)
  - Target: measure CP-violating phase with atmospheric neutrinos
  - See S. Razzaque, arXiv:1406.1407
  - Requires ~5-10 Mton eff. volume with energy threshold 0.5-1 GeV
  - Being investigated for ORCA

**P[2/158] J. Hofestädt**

# Conclusions

- Neutrino astronomy is on its way to increased sensitivity and full sky coverage
- Neutrinos are an indispensable ingredient of multi-messenger astronomy
- Neutrino telescopes also offer opportunities for precision measurements in neutrino physics
- Timelines for next decade(s) synchronised with funding scenarios
- Personal remark: global coordination to be strengthened