KM3NeT: studying atmospheric and astrophysical neutrinos in the Mediterranean

International Centre for Radio Astronomy Research

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Thanks to KM3NeT Collaboration

KM3NeT

Curtin University

THE UNIVERSITY OF WESTERN AUSTRALIA

Government of Western Australia
Department of the Premier and Cabinet
Office of Science

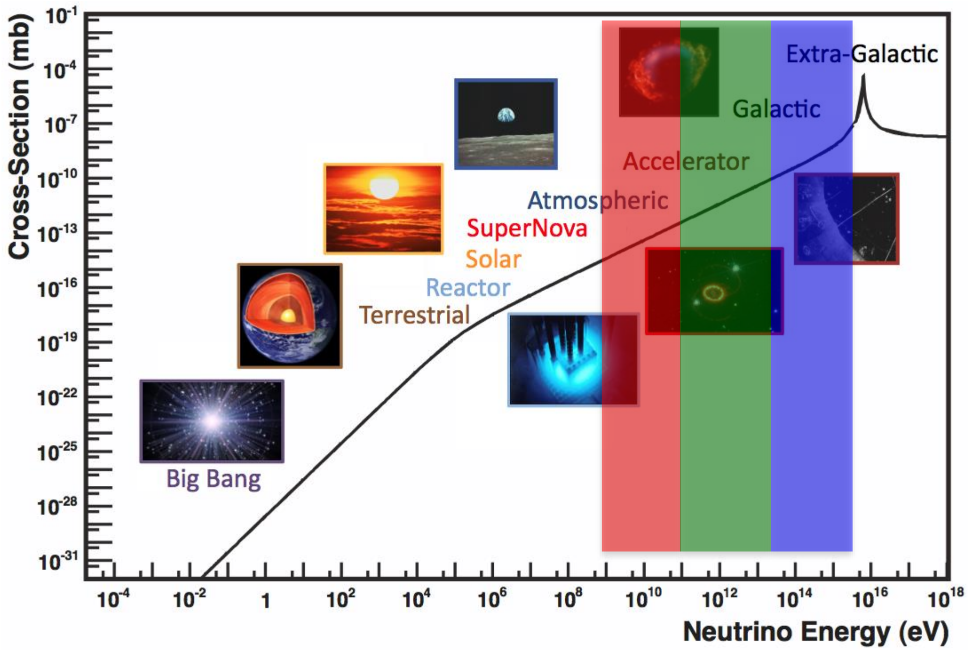
Neutrino physics

Neutrino science

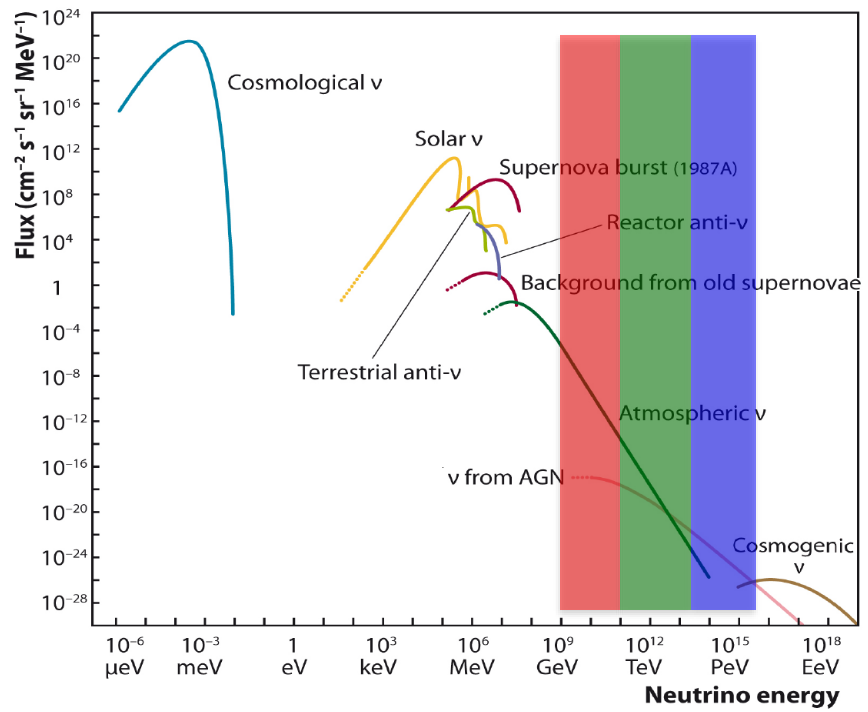
1 – 100 GeV: neutrino mass hierarchy w. atmospheric flux

100 GeV - 100 TeV: various galactic (TeV gamma) sources

100 TeV – 10 PeV: extragalactic sources



Formaggio & Zeller, RevModPhys 84 (2012) 1307

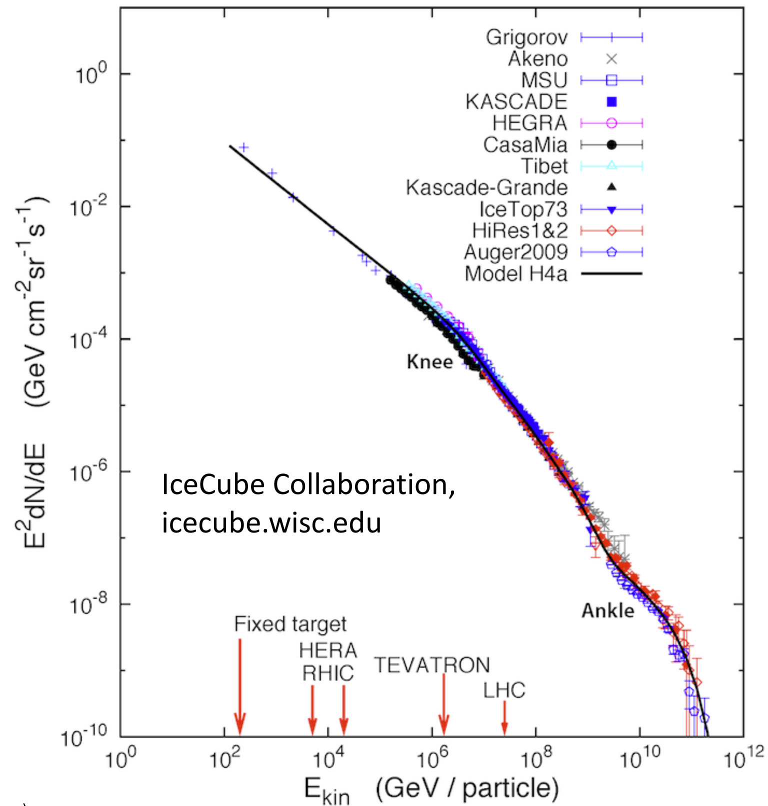


Multimessenger paradigm

Cosmic ray interactions:

$$\left.\begin{array}{l} p_{CR} + p \\ p_{CR} + g \end{array}\right\rangle p_{CR} / n + p^{\pm}, p^{0}$$

Secondaries: only neutrinos provide unambiguous signal



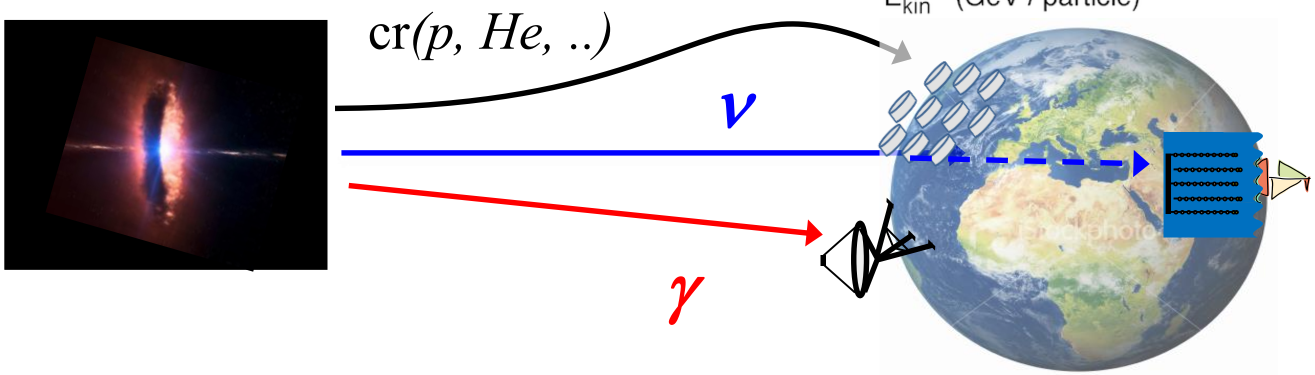
$$p^{+} \rightarrow m^{+} + n_{m}$$

$$m^{+} \rightarrow e^{+} + n_{e} + \bar{n}_{m}$$

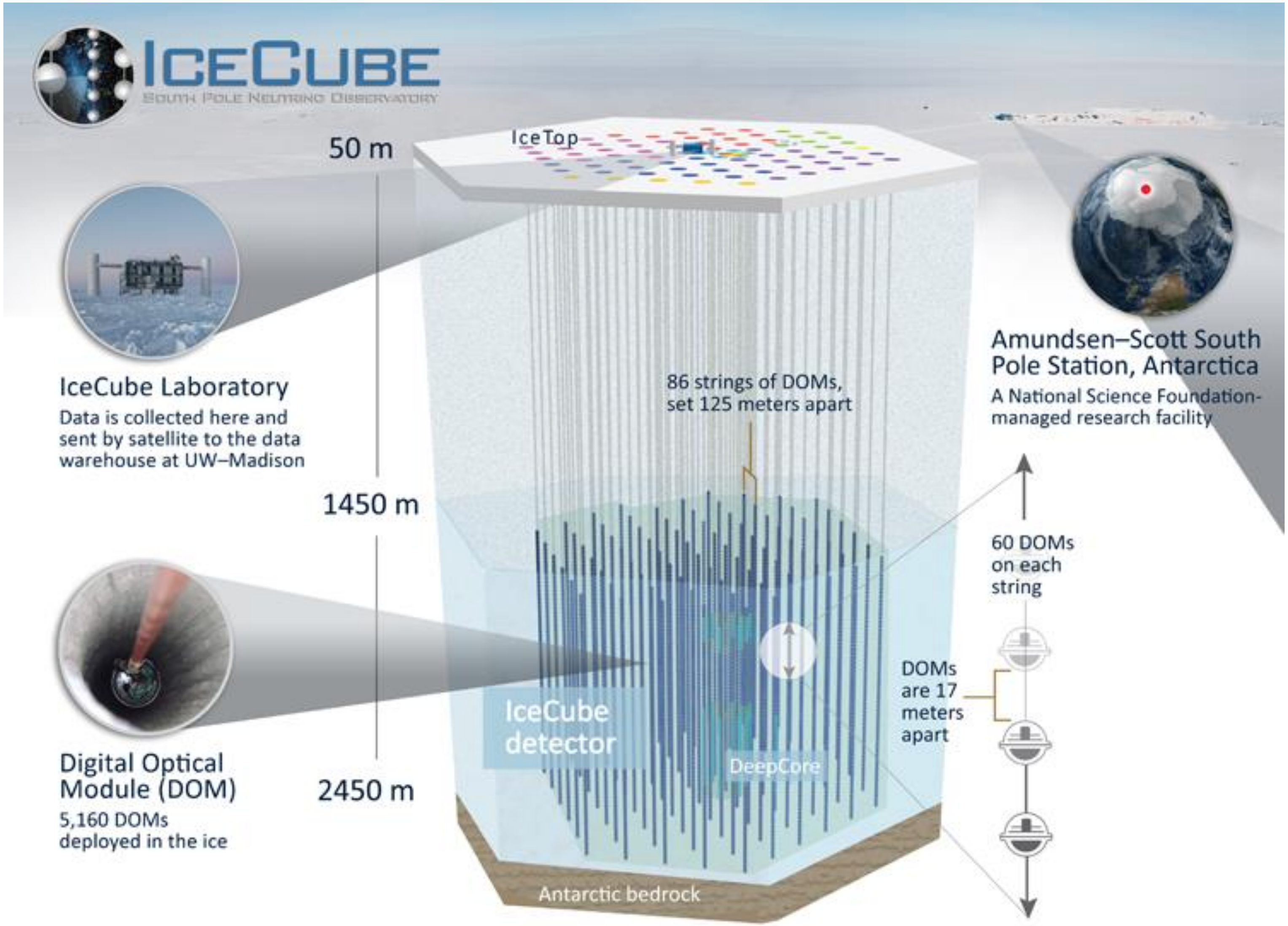
$$n \rightarrow p_{CR} + e^{-} + \bar{n}_{e}$$

$$p^{0} \rightarrow 2g$$

$$e^{-} \rightarrow g_{synch}, g_{IC,bremms}$$



IceCube neutrino observatory



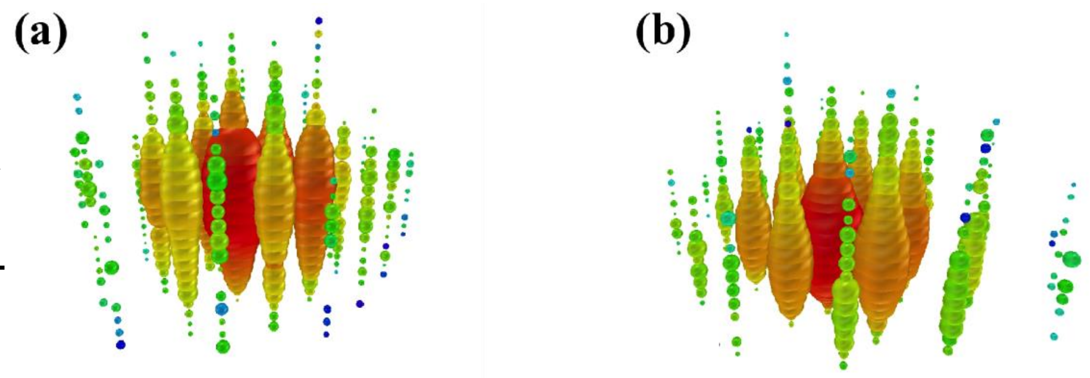
Courtesy: IceCube Collaboration

Astrophysical neutrino flux

IceCube: Physical Review Letters, vol. 111, Issue 2, id. 021103 (2013)

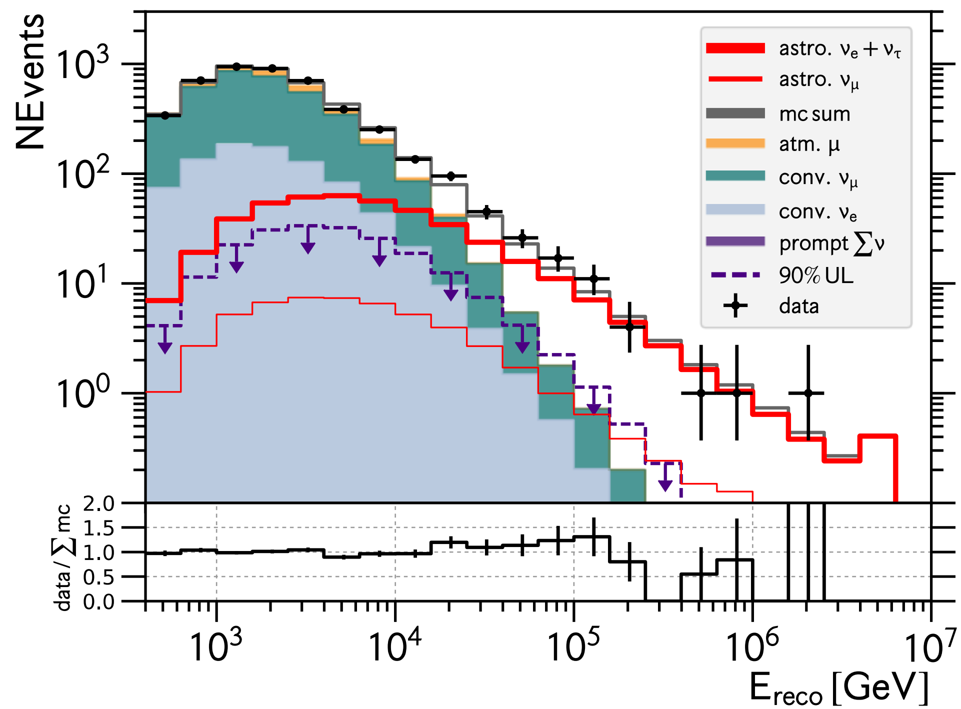
IceCube

- Bert (a) & Ernie (b) (2011, 2012). E~1 PeV
- Astrophysical flux: PRL 113, 101101 (2014)
- Many updates since



Current knowledge

- Inconsistent with single power-law, flavour-uniform, isotropic flux
- Source unknown



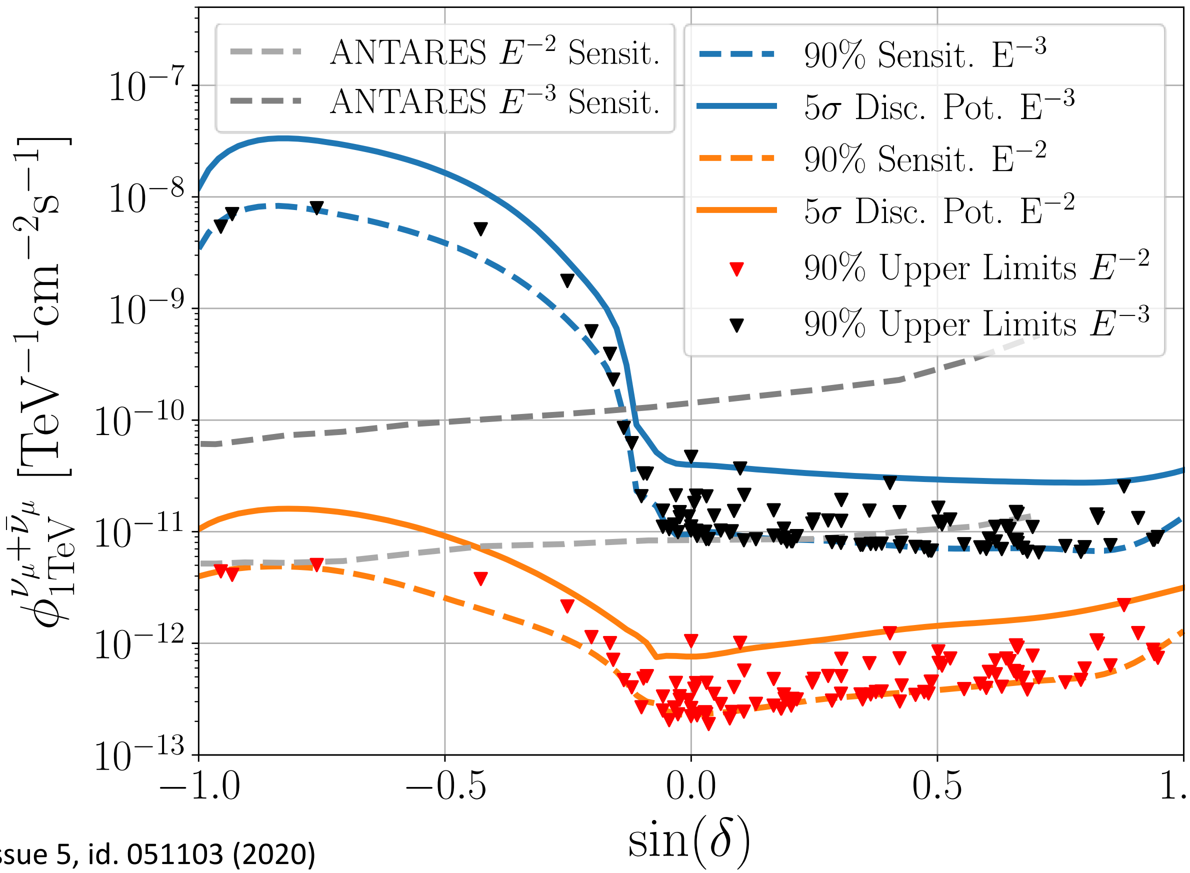
Sources? Time-integrated search

IceCube

- Assume constant point-like source with power-law index
- Search for excess of events in data
- None found!

  (stacked searches also fail)

$$F(E) = f\left(\frac{E}{1\ \mathrm{TeV}}\right)^{-g}$$



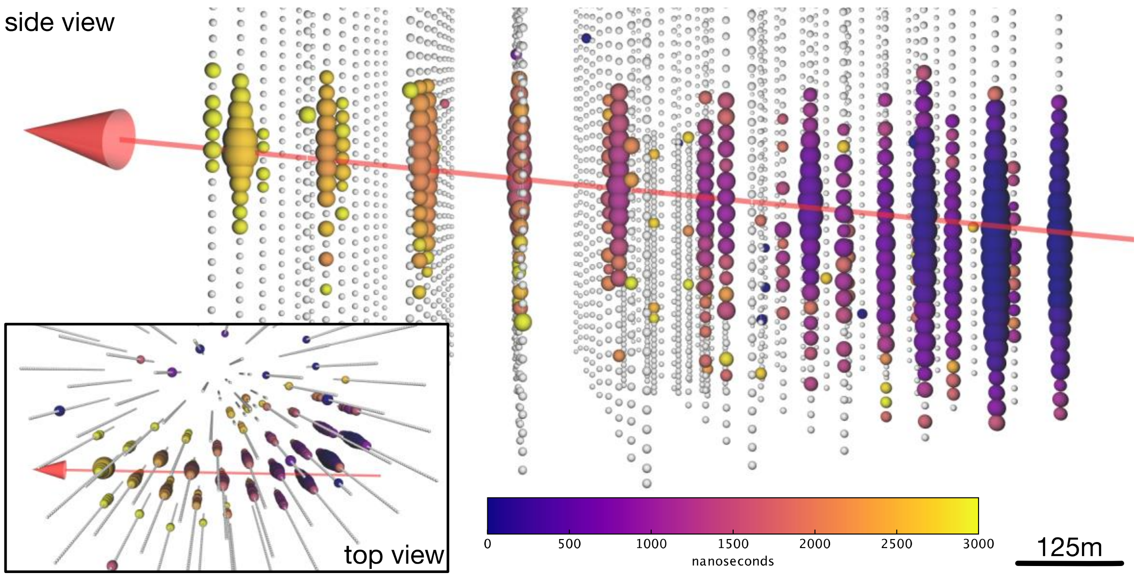
IceCube: Physical Review Letters, vol. 124, Issue 5, id. 051103 (2020)

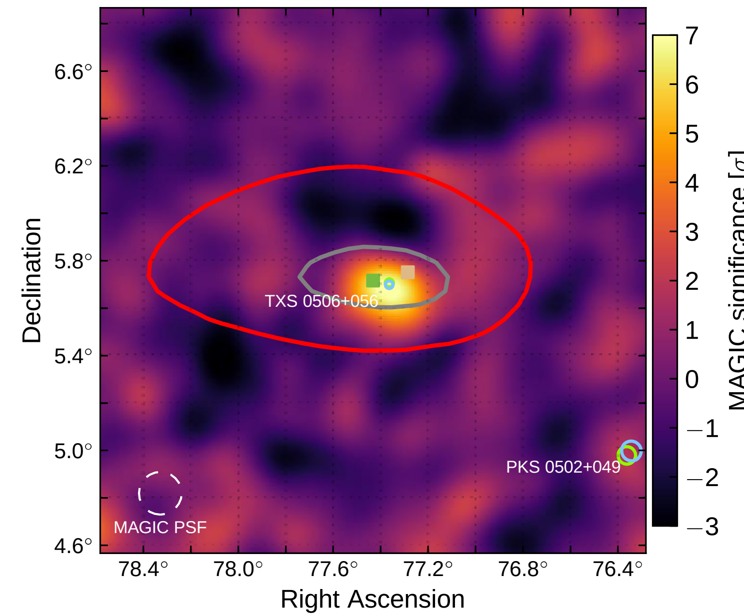
TXS 0506+056

IceCube

- IC170922A: high-energy track event
- Points back to blazar TXS 0506+056

IceCube et al: Science, Volume 361, Issue 6398, id. eaat1378 (2018).





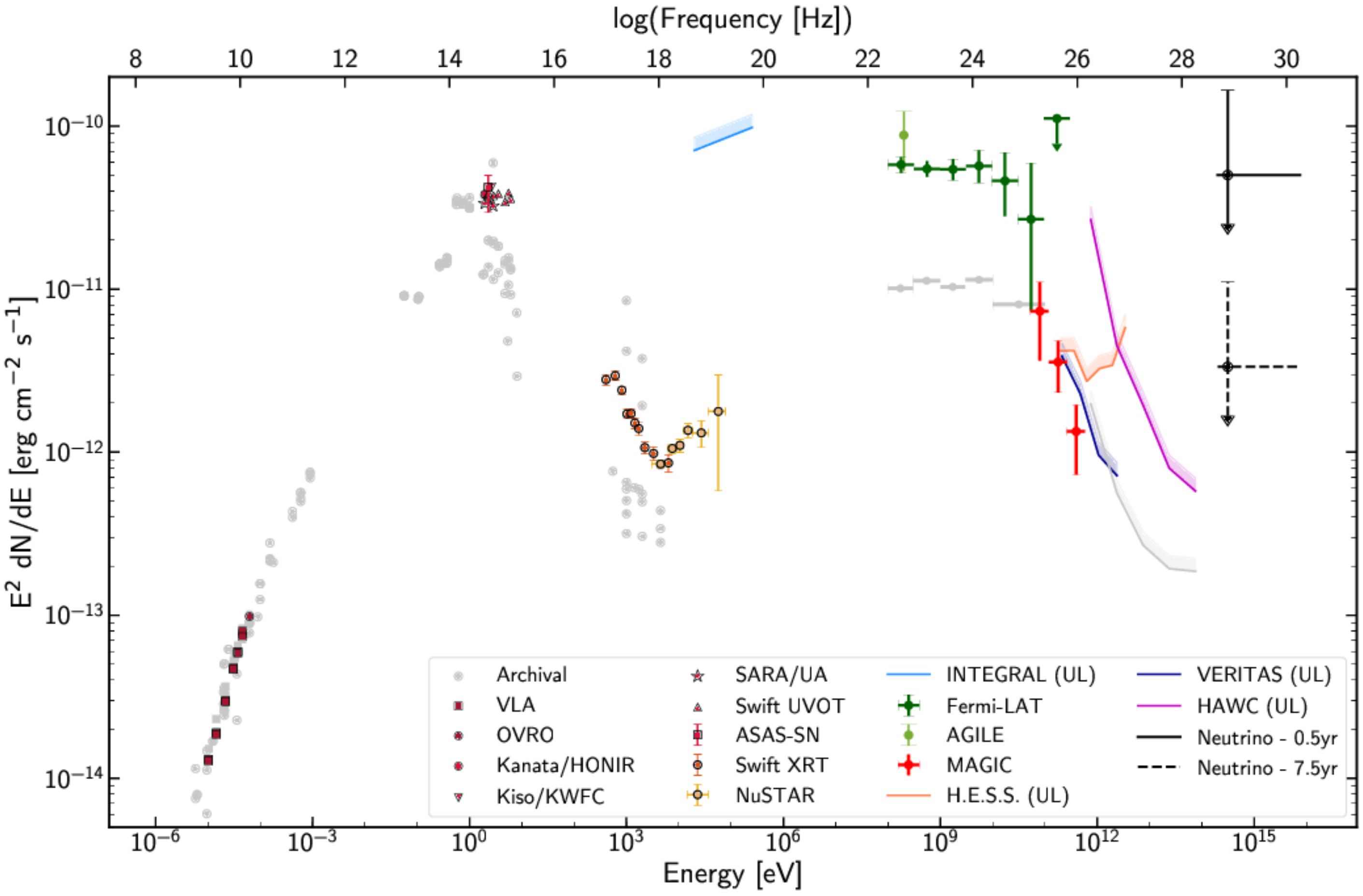
- O~3.5 sigma significance
- BUT: at most one other HE event can be associated with a blazar…

TXS 0506+056

Fermi: this blazar is flaring!

- Multiwavelength campaign

IceCube et al: Science, Volume 361, Issue 6398, id. eaat1378 (2018).

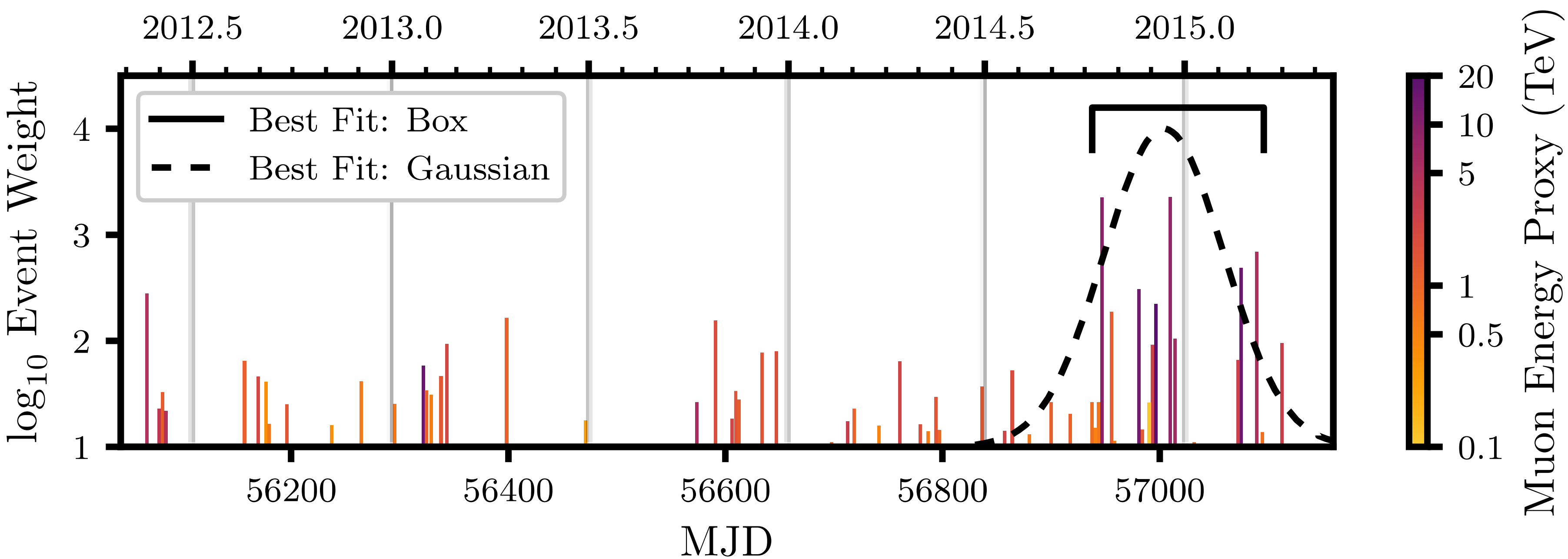


TXS 0506+056

Further evidence: lookback analysis

- Neutrino flare: ~6 months in 2014-2015

IceCube, Science, Volume 361, Issue 6398, pp. 147-151 (2018).



- Another 3.5 sigma
- Combined: strong evidence that TXS 0506+056 is first astrophysical source of high-energy neutrinos (second overall after SN 1987a)

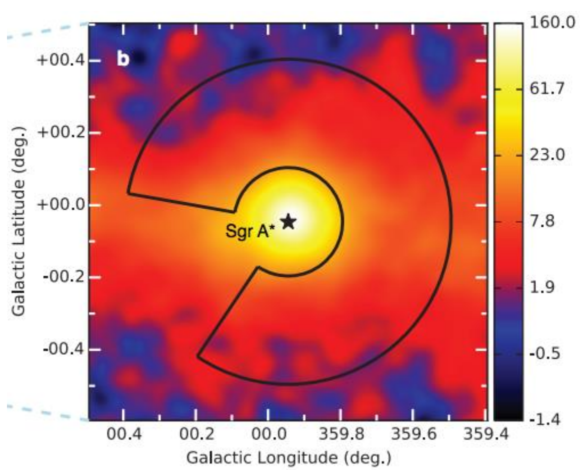
Remaining questions: 1 TeV-10 PeV

Where do IceCube's high-energy neutrinos come from?

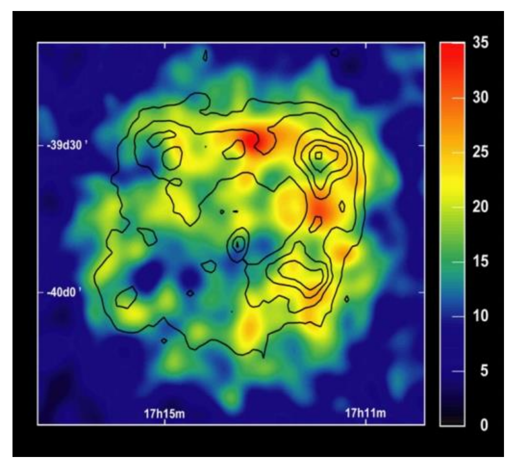
- One blazar source – but how did it produce its neutrinos?
- Why not other blazars?
- What other sources are there (blazar stacking: ~ <20% contribution)?

What about our Galaxy?

- Galactic cosmic rays exist to at least PeV –Pevatrons!
- HESS, Fermi, HAWK, etc: evidence for Galactic sources
- Photon signals always ambiguous (can be produced leptonically)



GC Pevatron: H.E.S.S., Abramowski et al. Nature 531, 476-479 (2016)



RX J1713: Credit: H.E.S.S. Collaboration

Neutrino mixing

$$\begin{bmatrix} n_e \\ n_m \\ n_t \end{bmatrix} = \mathbf{U} \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix}$$

Neutrino mixing

- Flavour states mix into mass states
- PMNS matrix U describes mixing (4 parameters)

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

Neutrino oscillations

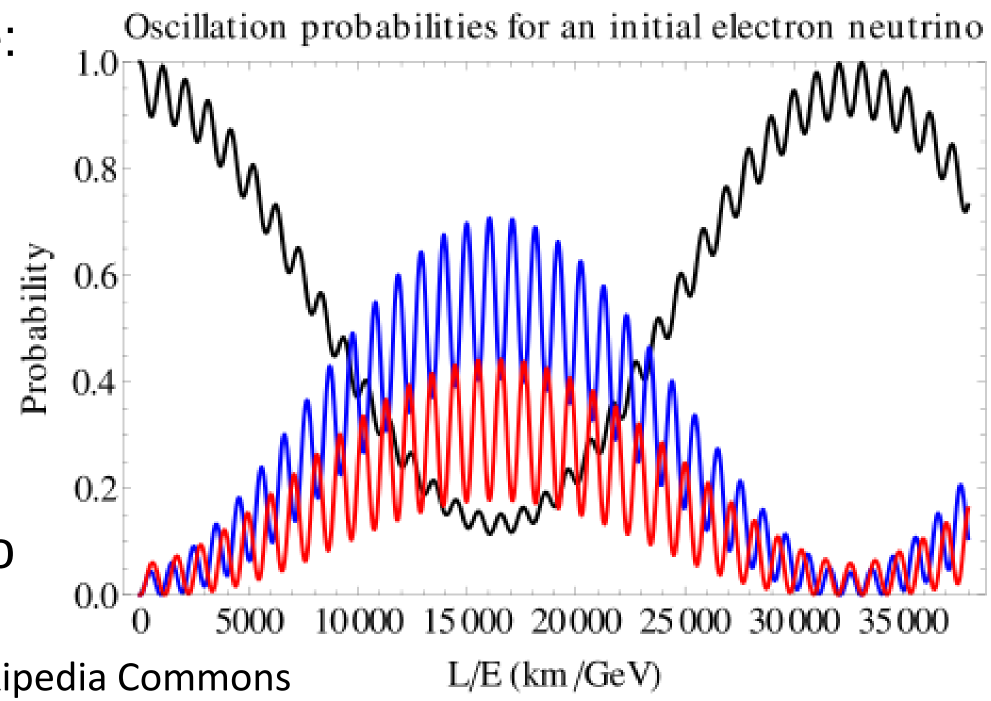
- Propagator of mass eigenstate:

$$|\nu_i(t)\rangle = e^{-i\left(E_i t - \vec{p}_i \cdot \vec{x}\right)} \, |\nu_i(0)\rangle$$

- Ultra-relativistic limit (low m_i):

$$|\nu_i(L)\rangle = e^{-i\frac{m_i^2 L}{2E}} \, |\nu_i(0)\rangle$$

- Phase difference: different ratio of mass states => changed flavour state!



From Wikipedia Commons

Mass hierarchy problem

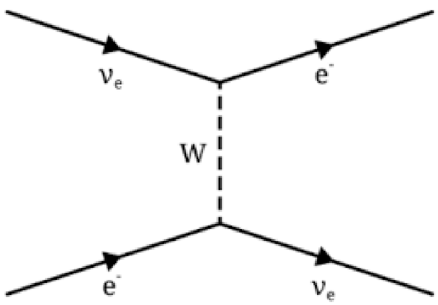
Neutrino oscillations

- Vaccuum oscillations: depends on squared mass differences only
- No way to tell absolute values!

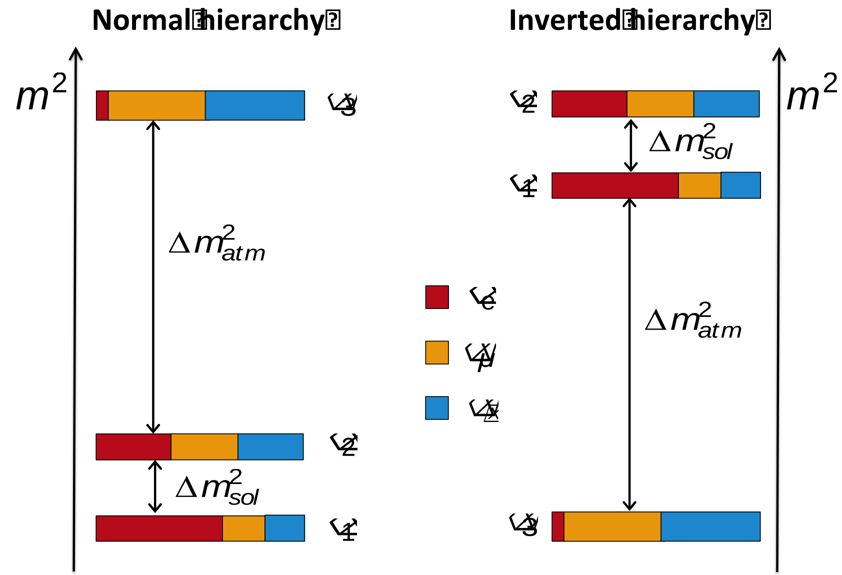
$$|\nu_i(L)\rangle = e^{-i\frac{m_i^2 L}{2E}} |\nu_i(0)\rangle$$

Matter effects

- In a medium…



- Effective mass changes
- Hierarchy dependent effects!
- Solar neutrino oscillations: $v_2 > v_1$
- What about v_3?



KM3NeT LoI, J.Phys G, 43, 084001, 2016

Solution!

KM3NeT LoI, J.Phys G, 43, 084001, 2016

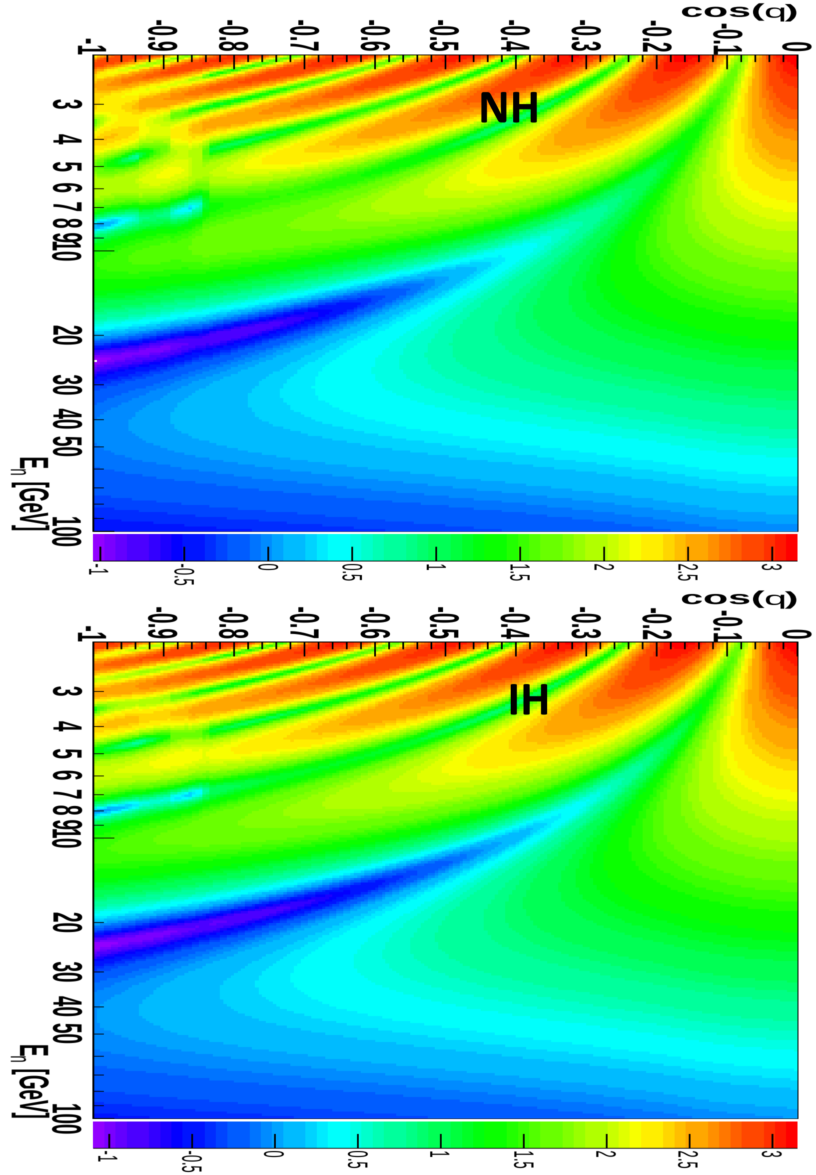
Earth oscillations

- Cosmic rays: muon neutrino flux
- Daya Bay et al: $\sin^2 q_{13} \sim 0.022$

- Oscillations on Earth baselines: hierarchy-dependent effects!
- Energy

Oscillograms

- Direction (baseline) – energy rate distributions
- Measure this, compare to predictions
- Required detector size: ~megatons!



Signature

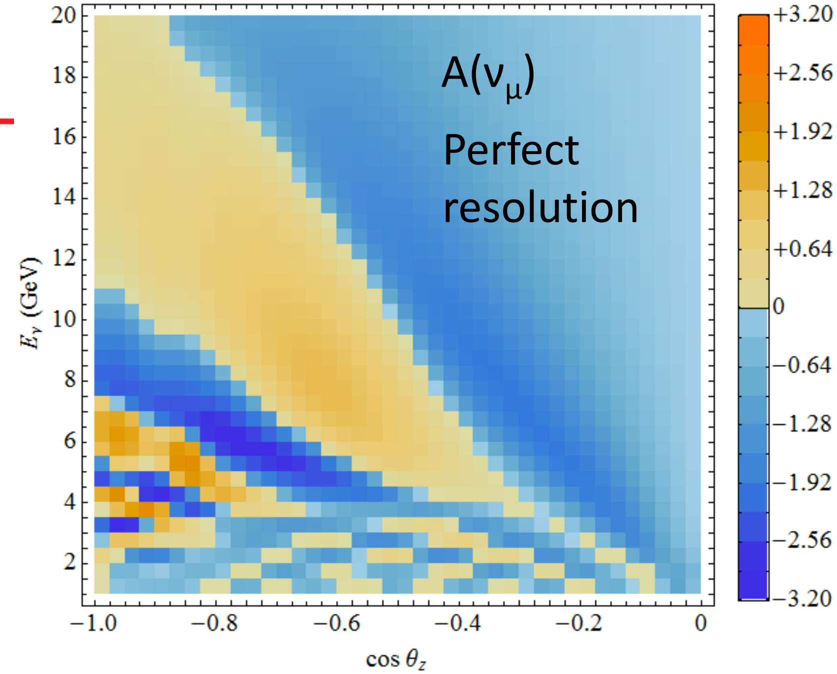
Experimental signature

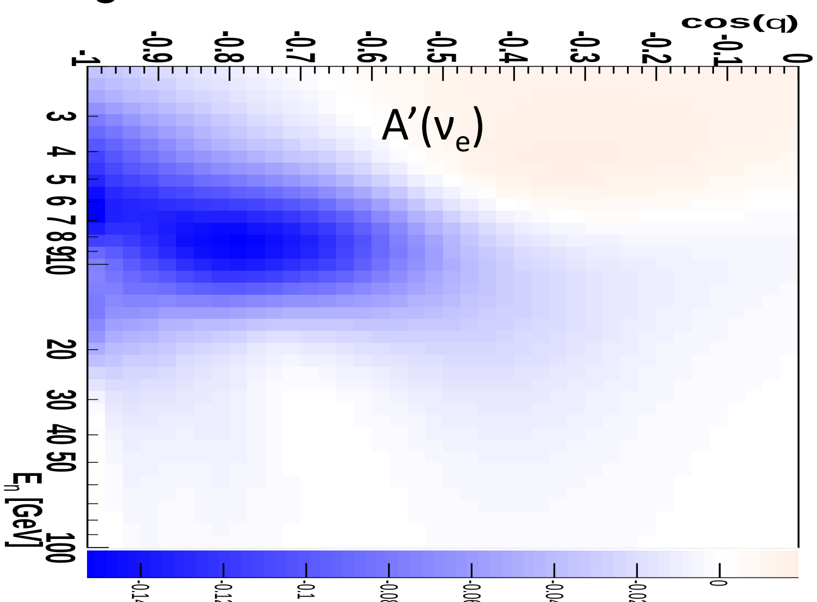
- Relative surplus/deficit of electron and muon neutrinos

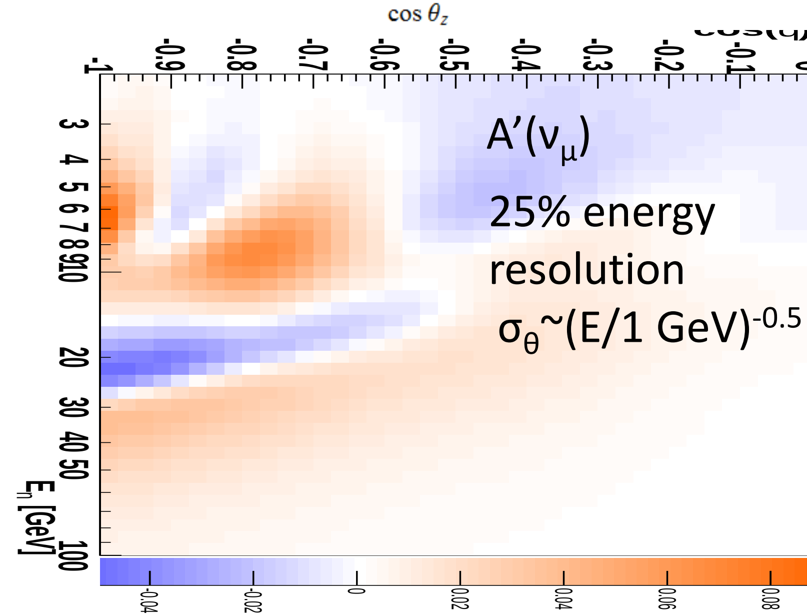
$$A' = \frac{N_{IH} - N_{NH}}{N_{NH}}$$

- Need O~1 MT detector and good resolution at 1-20 GeV

Akhmedov et al., JHEP 02 (2013) 082







KM3NeT LoI, J.Phys G, 43, 084001, 2016

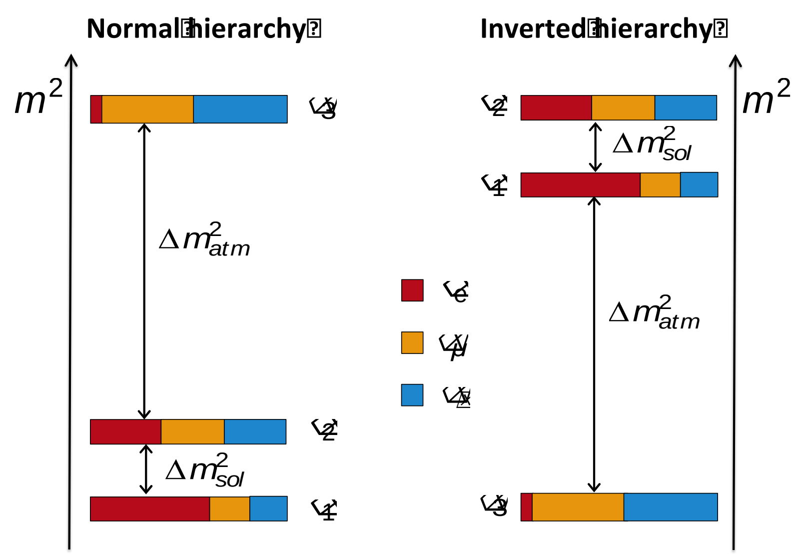
Remaining questions: 1 GeV-100 GeV

What is the neutrino mass hierarchy?

- Normal or inverted?
- What is the CP-violating phase?
- Can we further pin down the mixing angles

Beyond the standard model physics

- Neutrino masses unexplained in SM – good place to look for new physics!
- E.g. a 4th neutrino flavour?
- Sterile neutrinos?

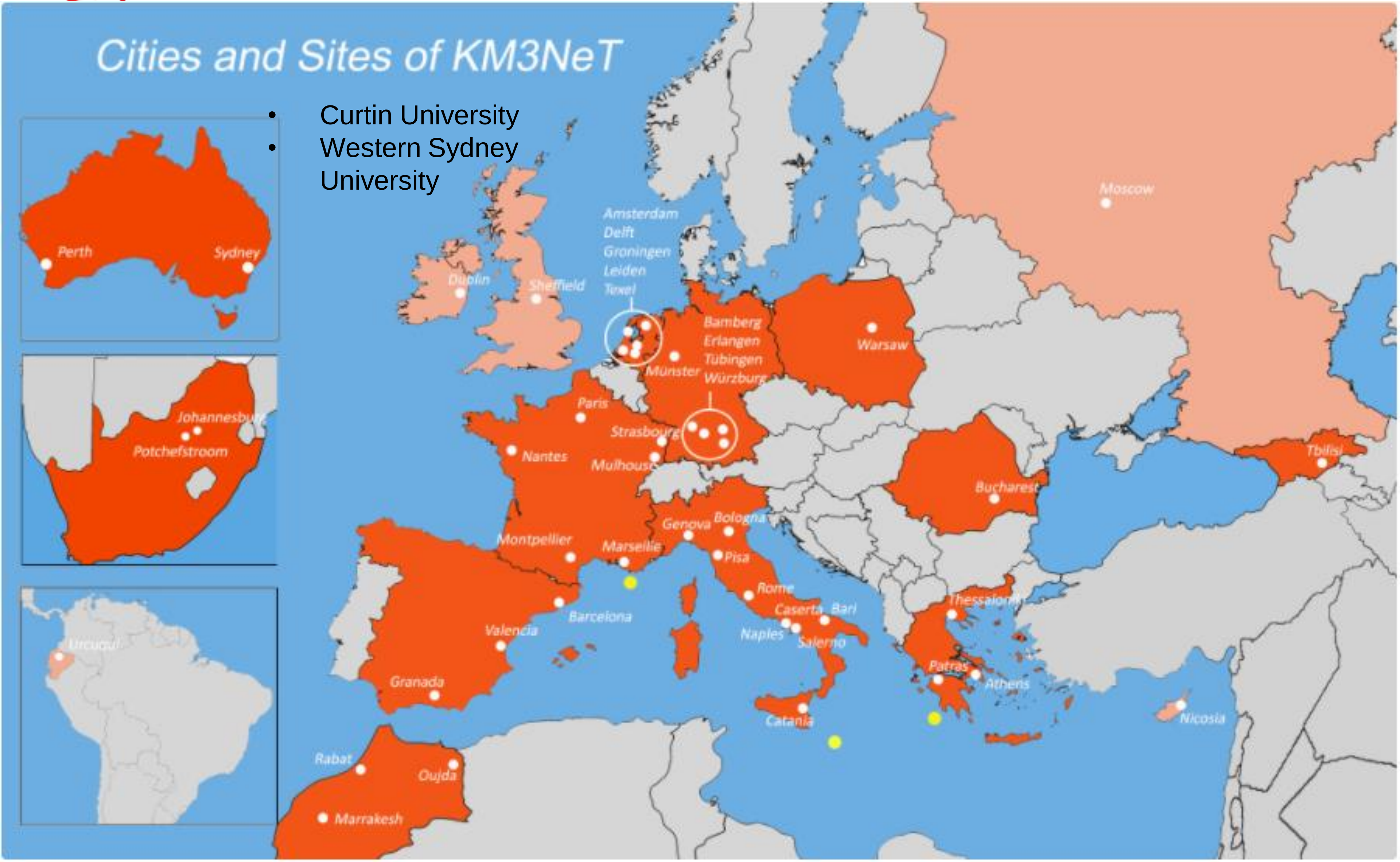


+???

KM3NeT

Solve these problems! KM3NeT

- Curtin University
- Western Sydney University



KM3NeT: ARCA + ORCA

ARCA

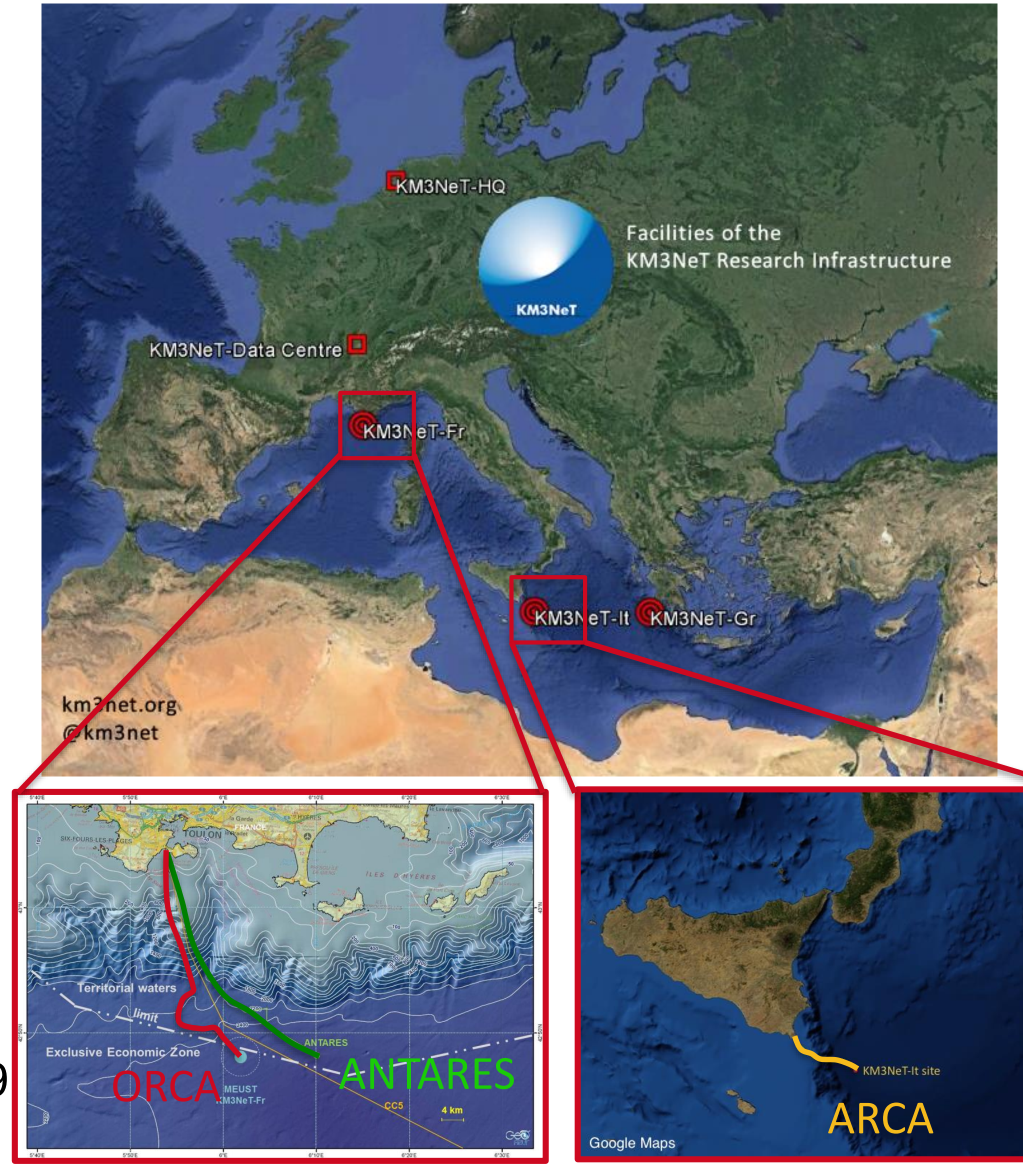
Astrophysical Research with Cosmics in the Abyss

- E_ν 1 TeV -10 PeV
- KM3NeT-It (3.5 km depth)
- Astrophysical neutrino sources

ORCA

Oscillation Research with Cosmics in the Abyss

- E_ν 1 GeV - 100 GeV
- KM3NeT-Fr (2.5 km)
- Neutrino mass hierarchy

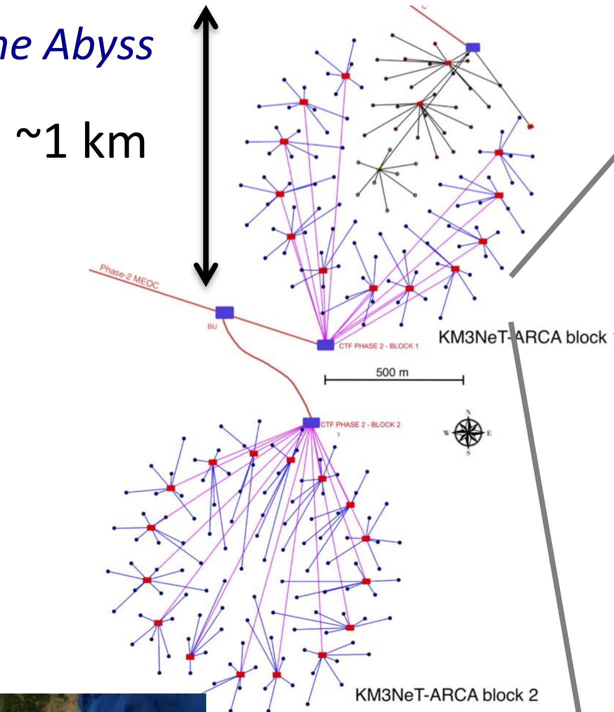


KM3NeT Letter of Intent

- *J. Phys. G*, **43** (2016) 084001
- https://arxiv.org/abs/1601.07459

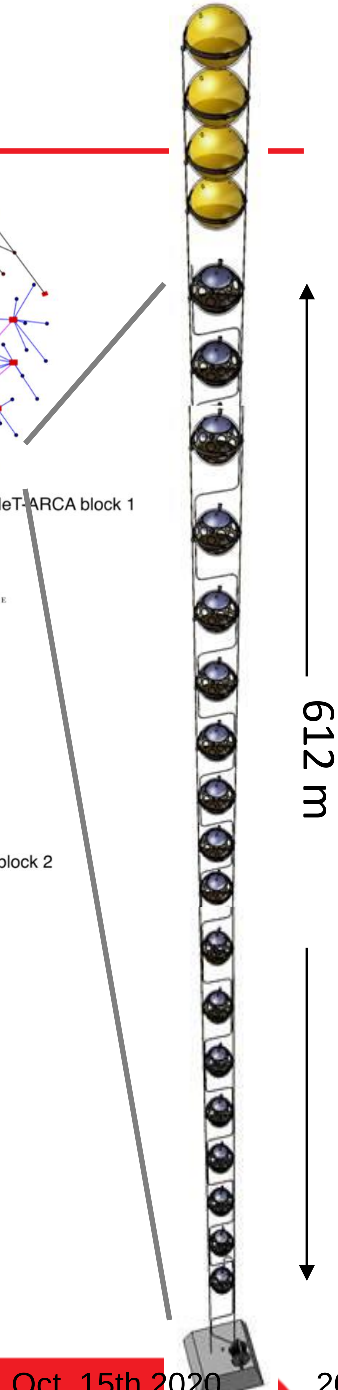
ARCA: TeV-PeV

ARCA: Astroparticle Research with Cosmics in the Abyss



ARCA: 2 blocks:
- 115 ‘detection units’ per block
- 90m horizontal spacing

Detection unit:
- Line anchored to the sea floor
- 18 optical modules
- 36m spacing



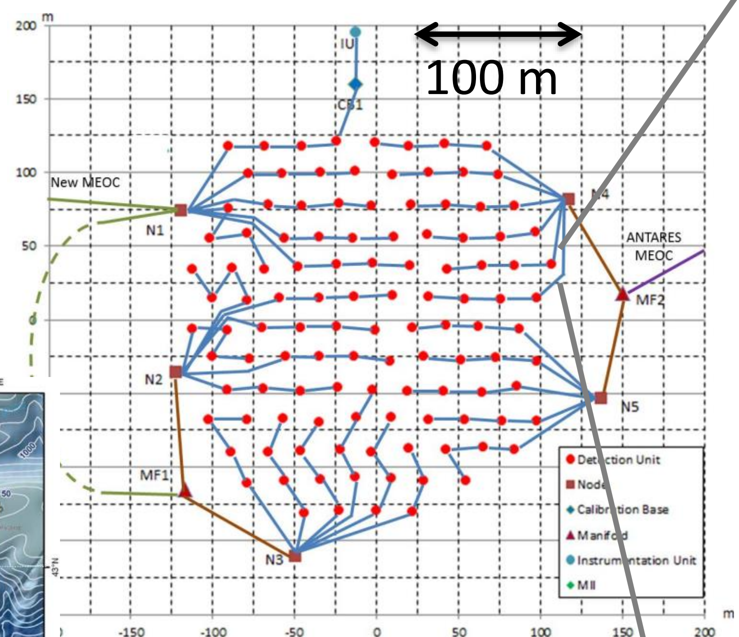
Total volume: 1.2 km^3
- Site: 3.5 km depth
- Shore station:
  Capo Passero
  (Sicily)

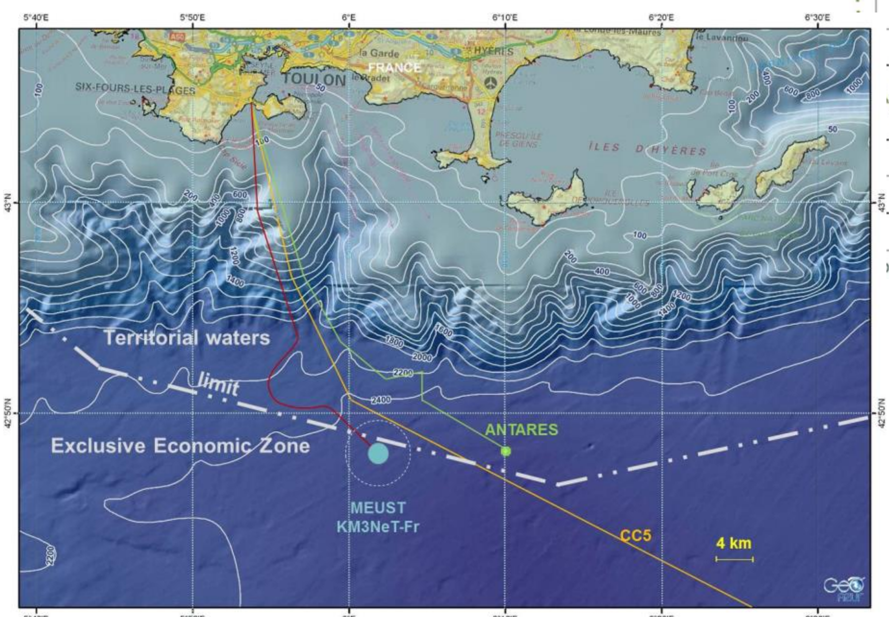
ORCA: 3-100 GeV

ORCA: Oscillation Research with Cosmics in the Abyss

1 ORCA block:

- 115 lines
- 20 m horizontal spacing
- 9 m vertical DOM spacing

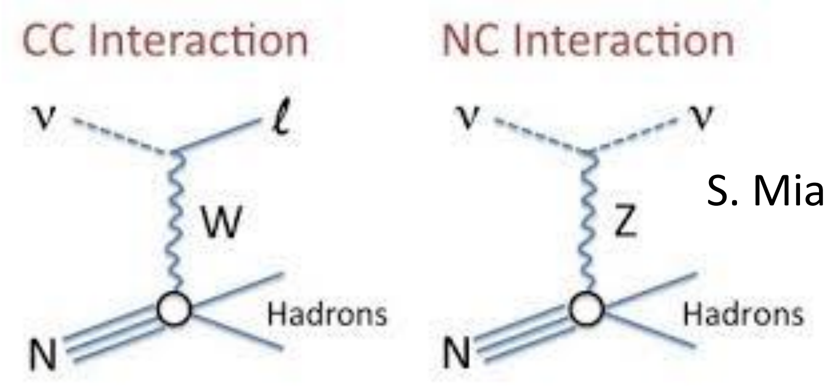




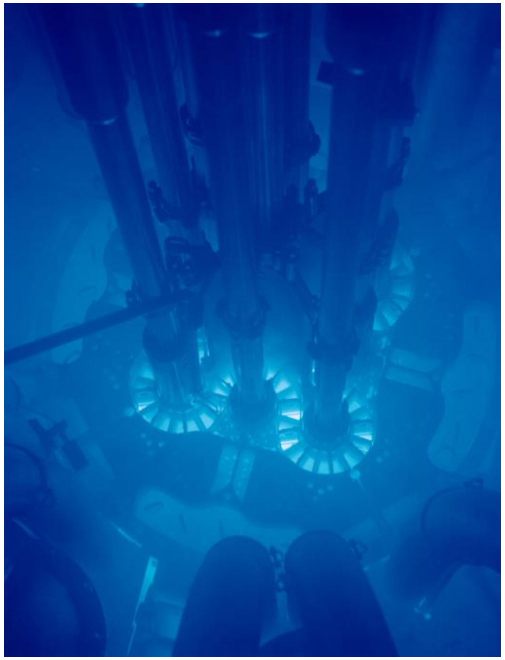
Basic detection method

Neutrino interactions

- Deep inelastic scattering
- Charged current (CC)
- Neutral current (NC)
- Relativistic secondaries produced
- Charged particles: Cherenkov radiation (~EM sonic boom)



S. Miarecki 2016



Argonne National Labs

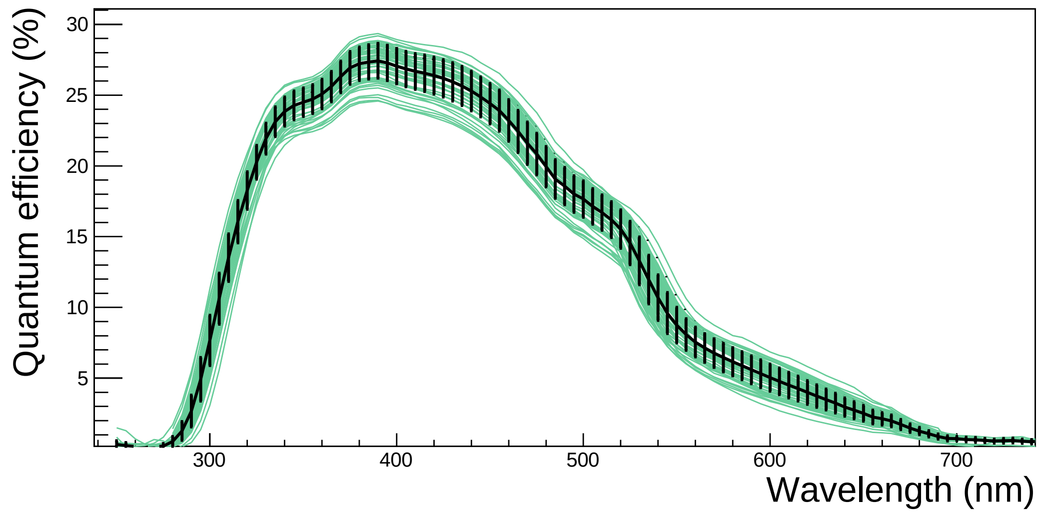
Technology

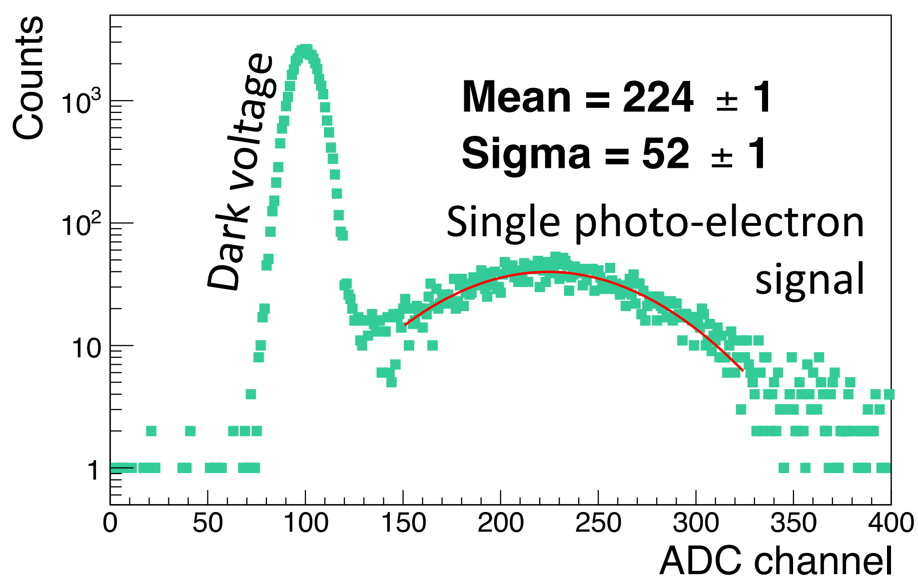
PMTs

KM3NeT Collaboration (S. Aiello et al.), JINST 13 P05035 (2018)

Optical module:

- Hammamatsu R12199-02 PMTs
- Nominal 3” diameter
- Sensitive to blue-near UV (Cherenkov) light
- KM3NeT will use nearly 200,000 of them!

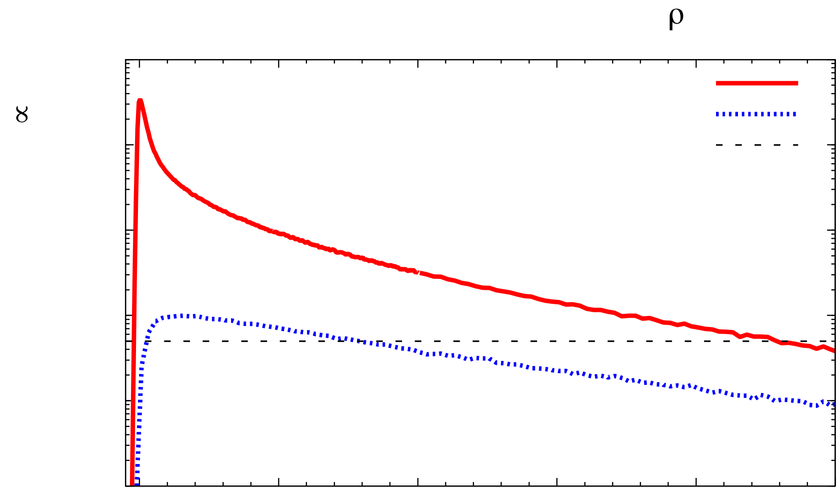




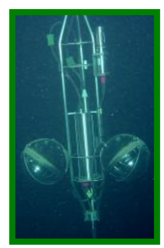
KM3NeT: digital optical module

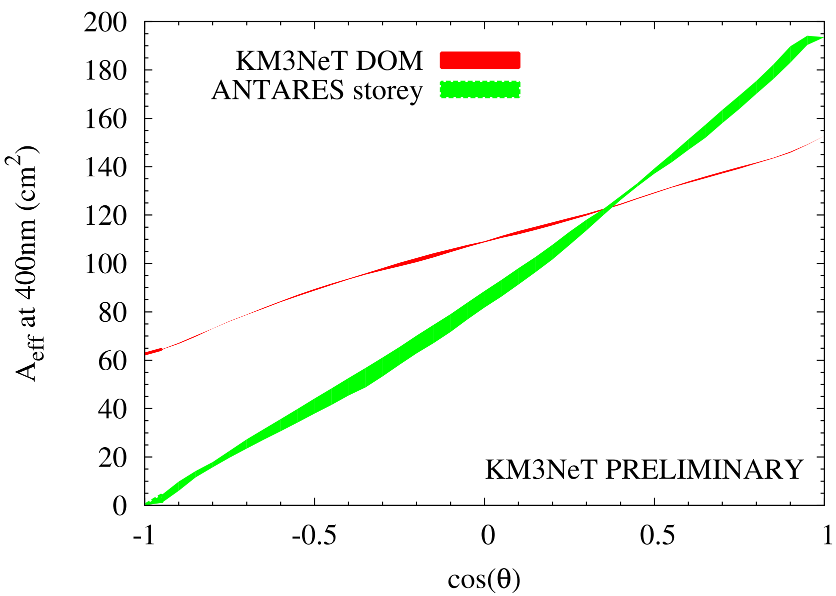
Optical module:

- 31 x 3” PMTs
- 4π sr coverage
- directional resolution
- dynamic range



17”





Construction: pictures

DOM assembly
- Test PMTs
- Assemble in bench
- 3D printed mounting
- Connect hemispheres

Current capacity
- 7 sites
- 3 DOMs/day
- 60 DU/yr

DOM integration into DU

Five sites

- Initial time calibration performed
- Check all connections pre-deployment

Deployment

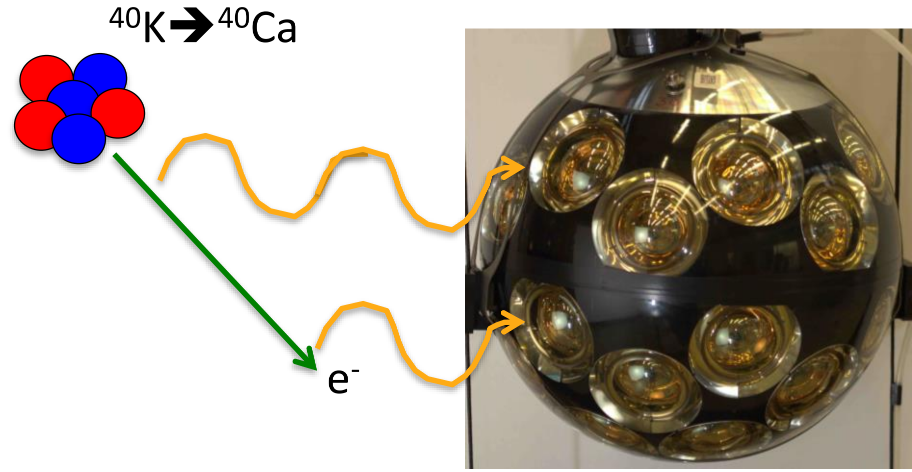
Drop it off a ship

- Gravity-guided
- Acoustic release
- Deployment vehicle recovered
- ROV connects cables

Self-calibration: ^{40}K

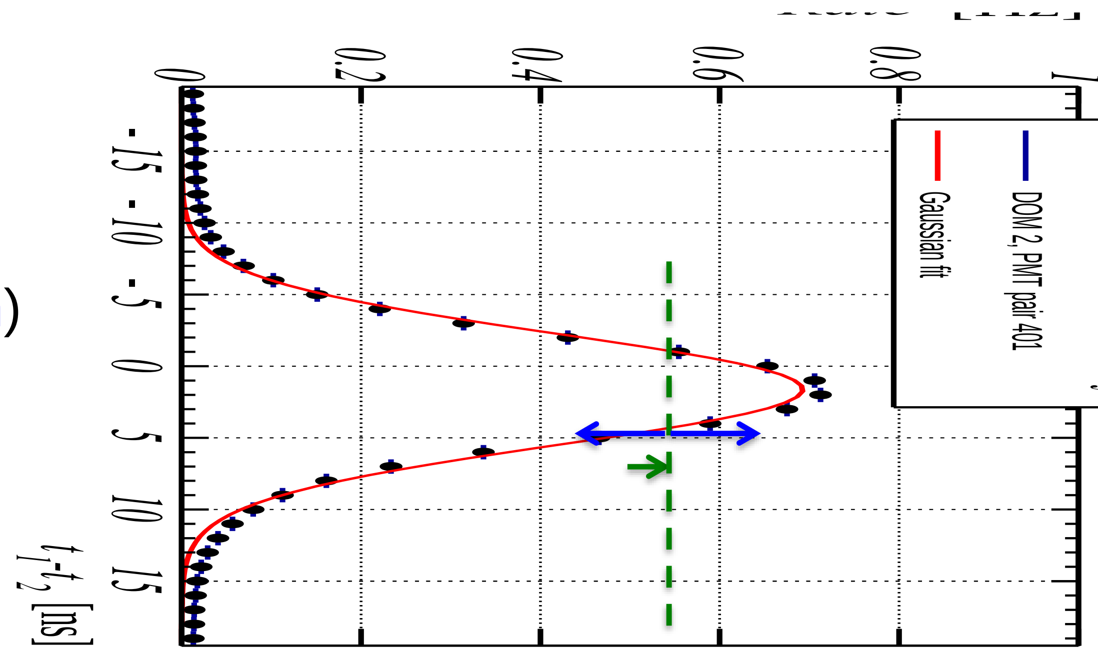
Natural radioactive decays from ^{40}K

- Cherenkov light
- ~5 kHz rate in PMTs
- Filtered by CPUs at on-shore DAQ
- Self-calibration mechanism!



Calibration tells us:

- Time offset (centre)
- Efficiency (area)
- Single-photon spread (width)

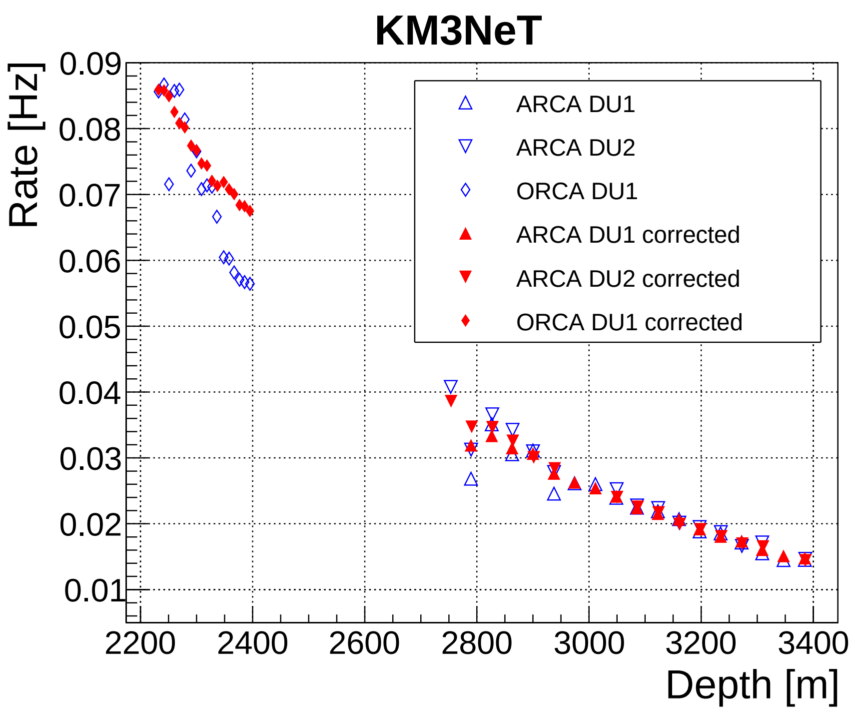


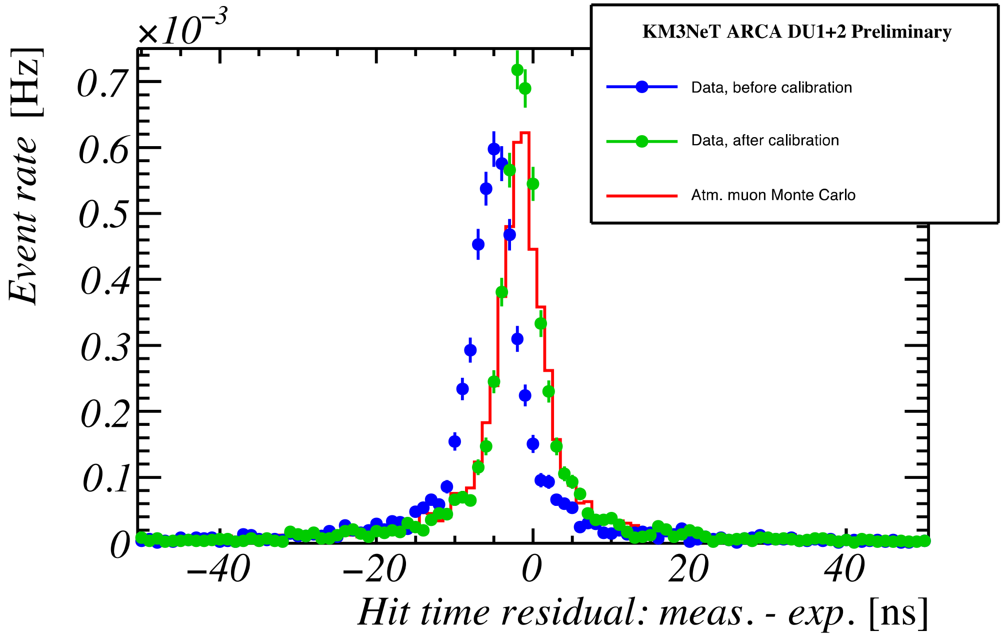
Long-term stability observed

Calibration – does it work?

Compare with MC

- Good agreement!





Correct data

- Much smoother distribution!

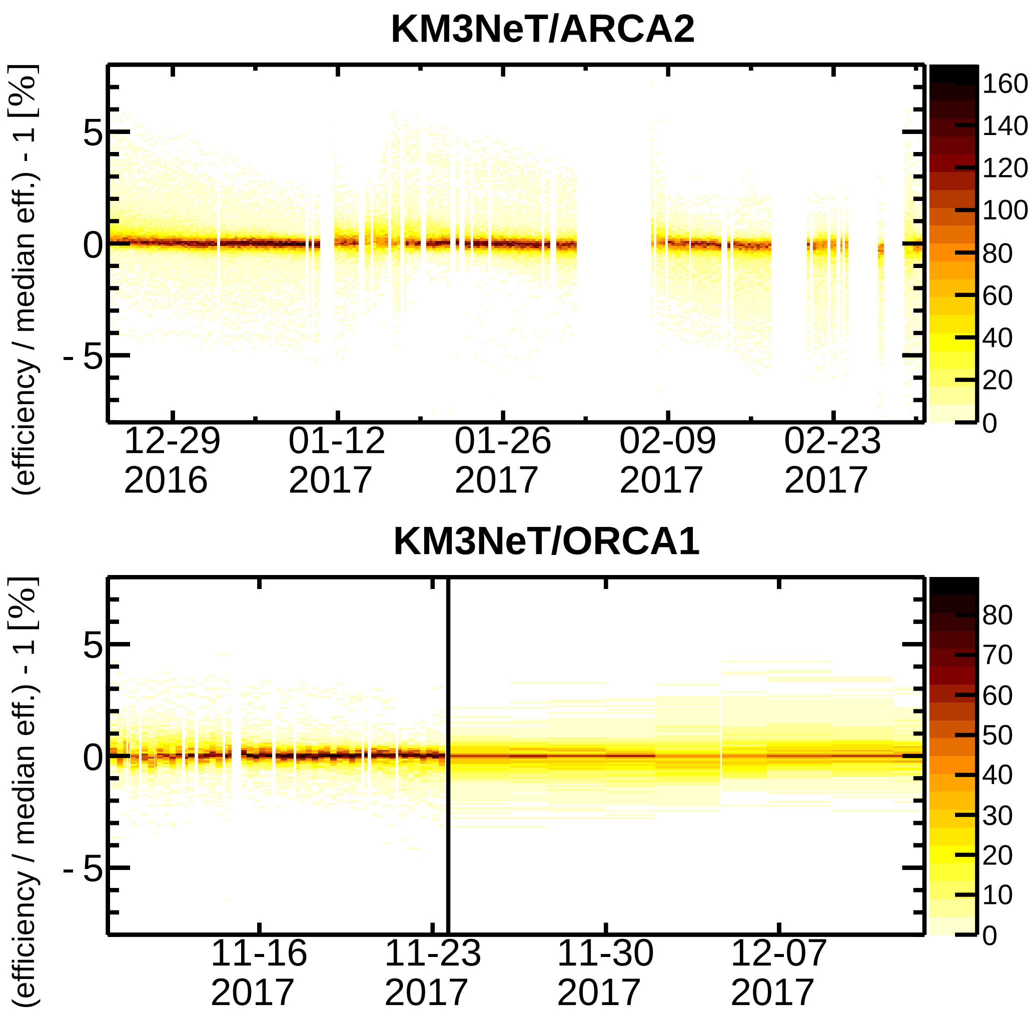
M. Lincetto et al, for KM3NeT,
Presented at Neutrino 2020

Long-term stability

M. Lincetto et al, for KM3NeT,
Presented at Neutrino 2020

Fluctuations?

- Sediment build-up
- Washed by currents
- PMT settling in
- On/off recovery
- ~0.1%!



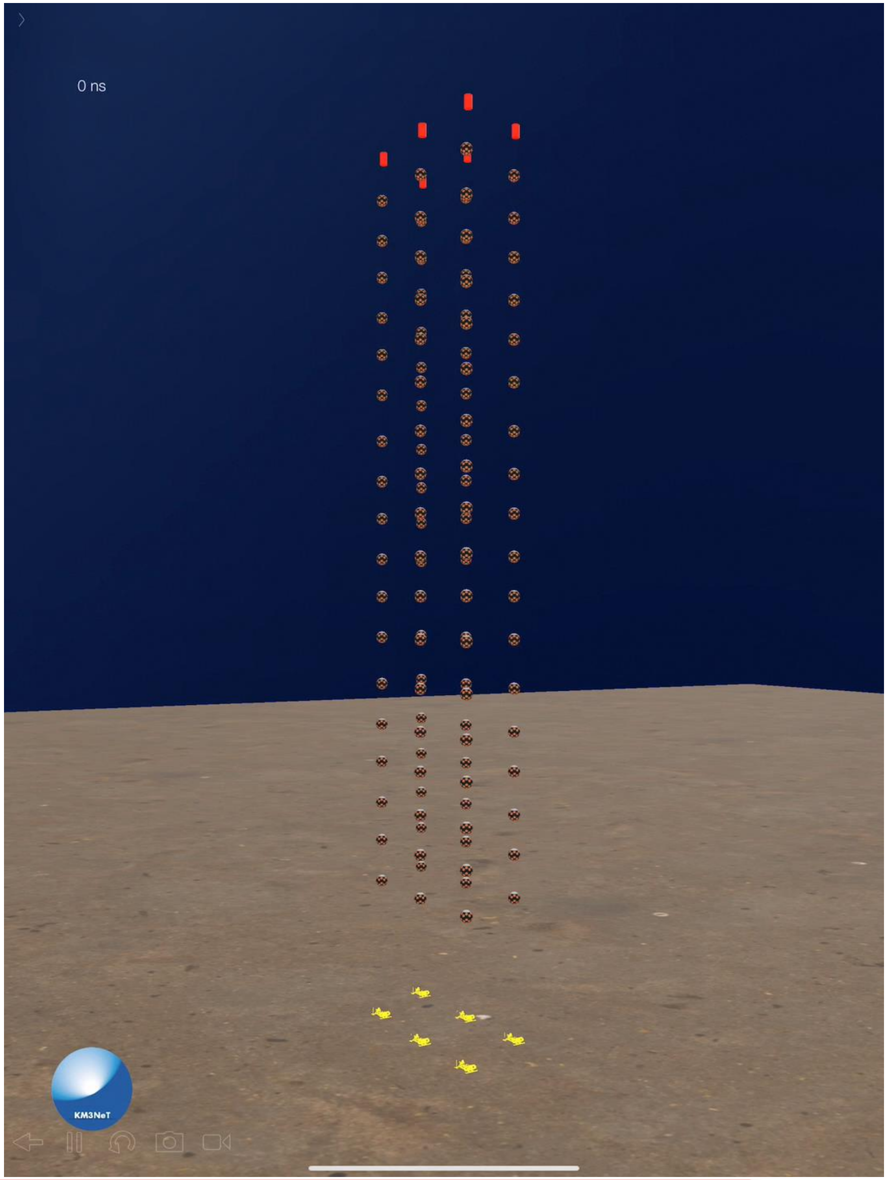
Status – operating!

ARCA

- 1st string 2015
- 2 strings operational to 2019
- Refurbishment of seafloor systems
- Just restarting!
- Goal: 2x115 2026

ORCA

- 1st string 2017
- Now six (Jan 2020)
- Goal: 115 string 2024

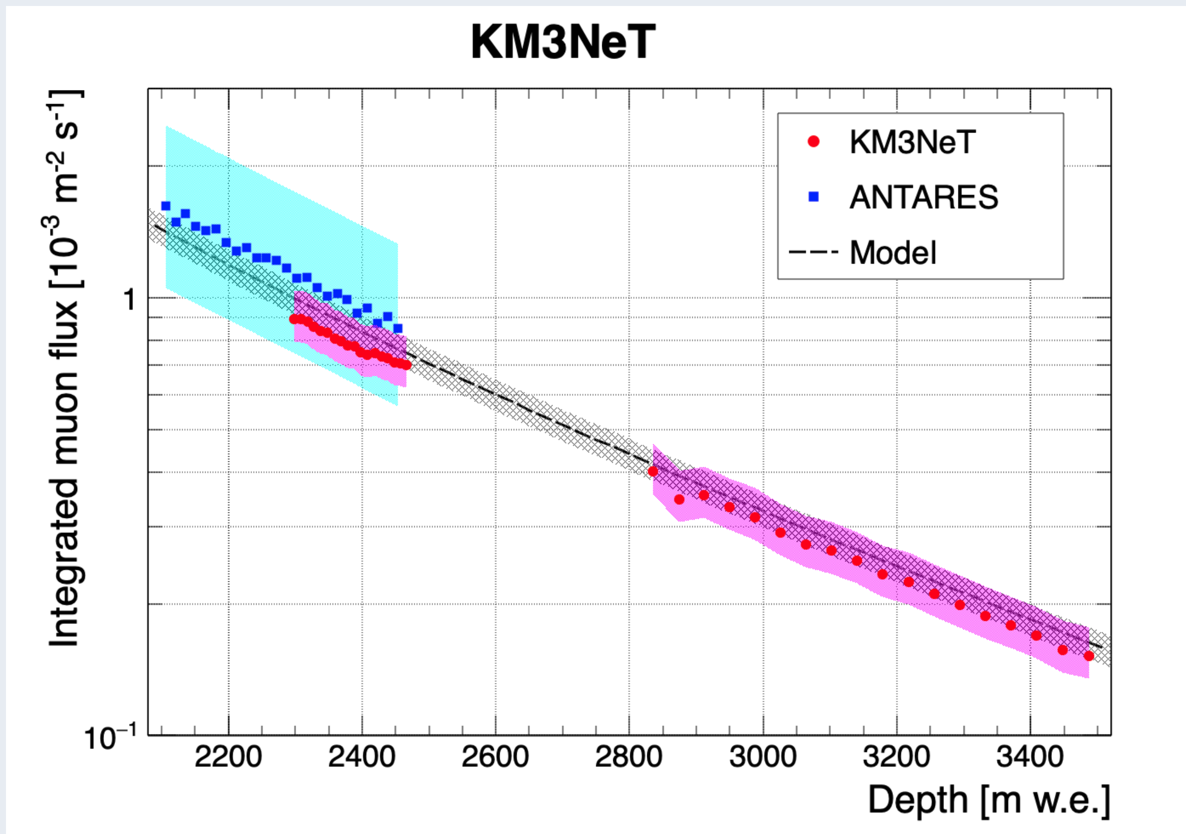


First results

Absolute muon flux measurement

- KM3NeT (systematics)
- ANTARES (systematics)
- Prediction (systematics) E. Bugaev *et al.*, Phys. Rev. D **58** (1998), 054001)

M. Lincetto et al, for KM3NeT, Presented at Neutrino 2020



ARCA: estimated performance

The ‘track’ channel

Track channel

$n_m \xrightarrow[CC]{} m + \text{shower}$ ~90%

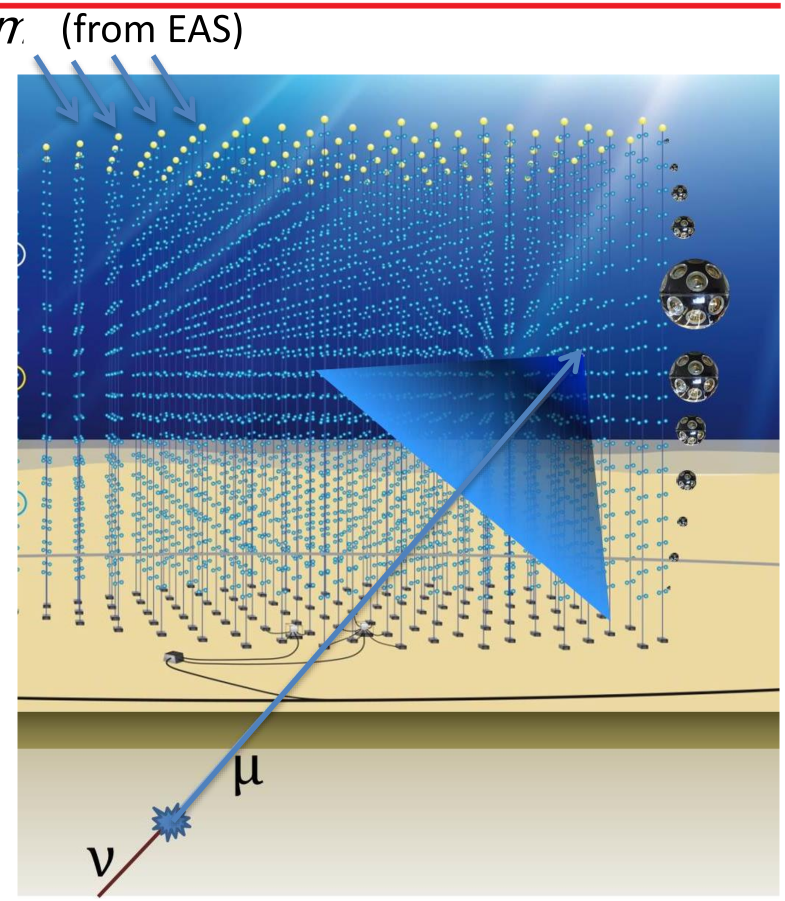
$n_t \xrightarrow[CC]{} t + \text{shower}$

$t \xrightarrow[\sim 17\%]{} n_t + m + \bar{n}_m$ ~9%

$n_\ell \xrightarrow[NC/CC]{} \text{shower w. D}$

$D \xrightarrow[\sim 17.6\%\ (D^+)]{} m + \ldots$ ~1%

$\bar{n}_e \xrightarrow[Glashow]{} W \xrightarrow[decay]{} m + \bar{n}_m$



- Mostly sensitive to muon neutrinos
- High effective area, good angular resolution
- High atmospheric background: look at events from below only

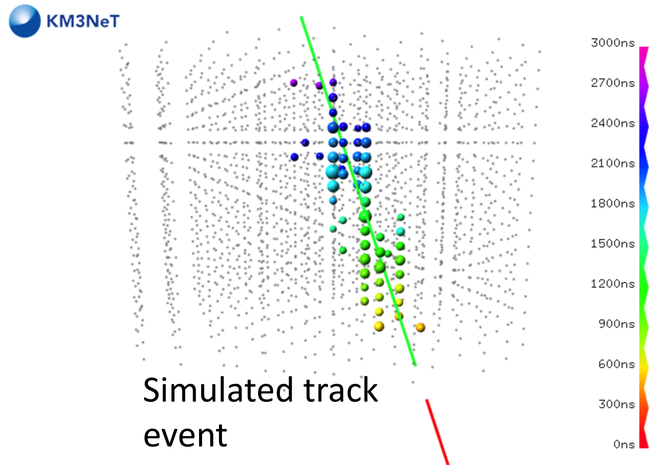
Direction resolution: tracks

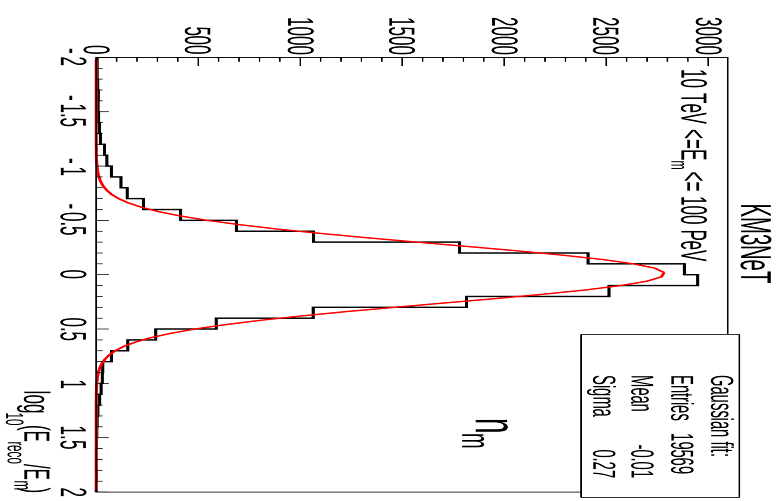
Step 1: use timing for position/direction

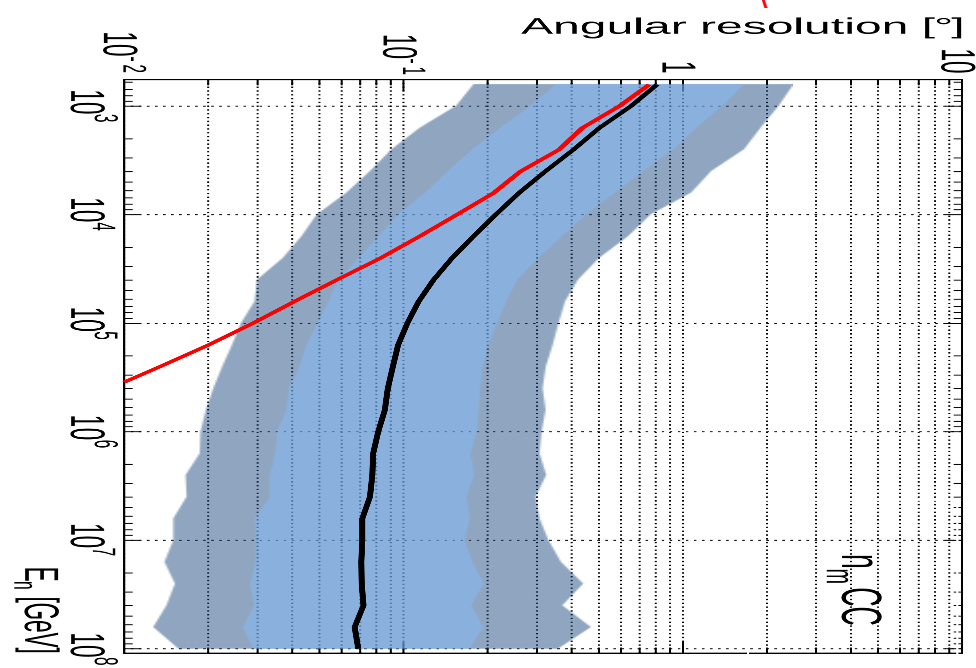
- Limit from interaction kinematics
- **Median**, 68%, 90% quantiles
- < 0.1^{o} at > 100 TeV (~astro flux)
- 0.2^{o} at 10 TeV (~Galactic)

Step 2: fit hits to determine energy

- 0.27 in $\log_{10}$ E







Cascade/shower events

Paths

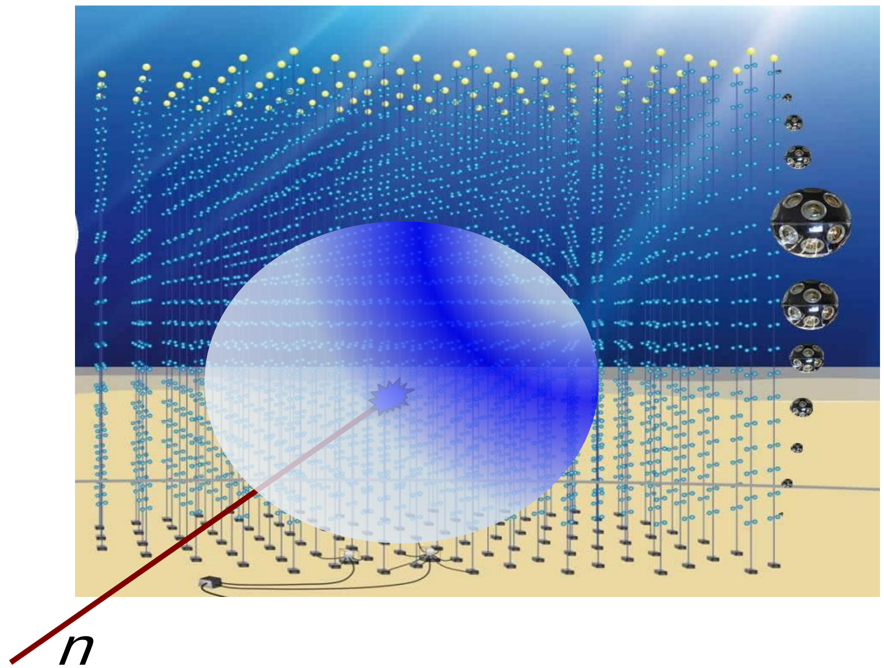
$$n_m \xrightarrow[CC]{} m + \text{shower}$$

$$n_\ell \xrightarrow[NC]{} n'_\ell + \text{shower}$$

$$n_e \xrightarrow[CC]{} \text{shower}$$

$$n_t \xrightarrow[CC]{} t + \text{shower}$$

$$t \xrightarrow[\sim 83\%]{} n_t + \text{shower}$$

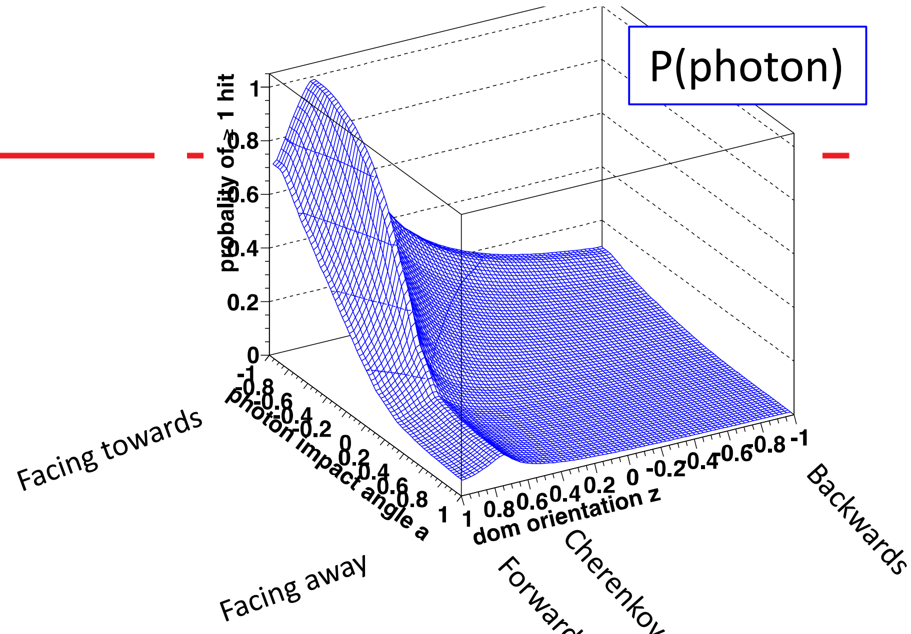


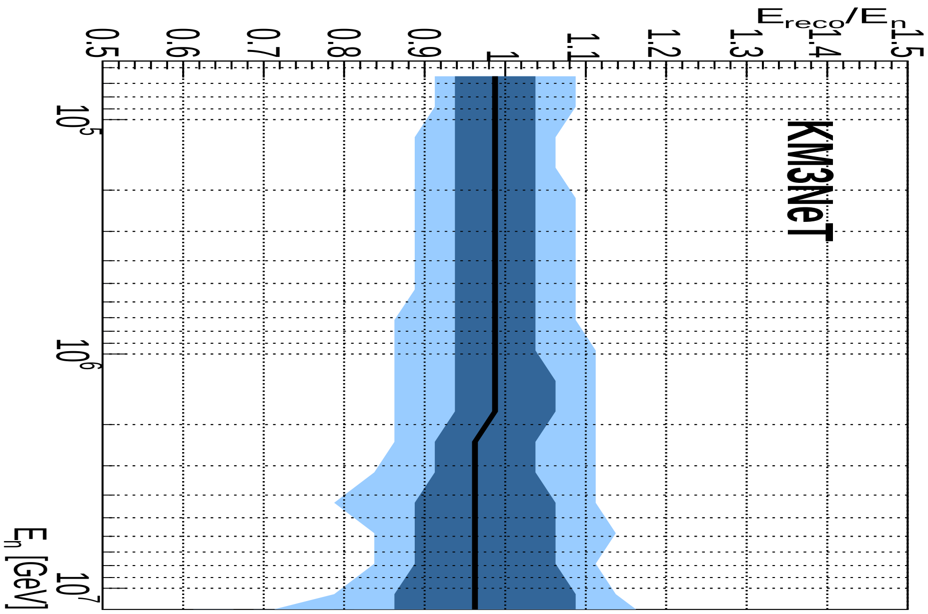
- Mostly sensitive to electron neutrinos
- Clean neutrino signature: signals over 4 π
- ‘Good’ energy resolution, worse directional resolution: diffuse flux!

Resolution

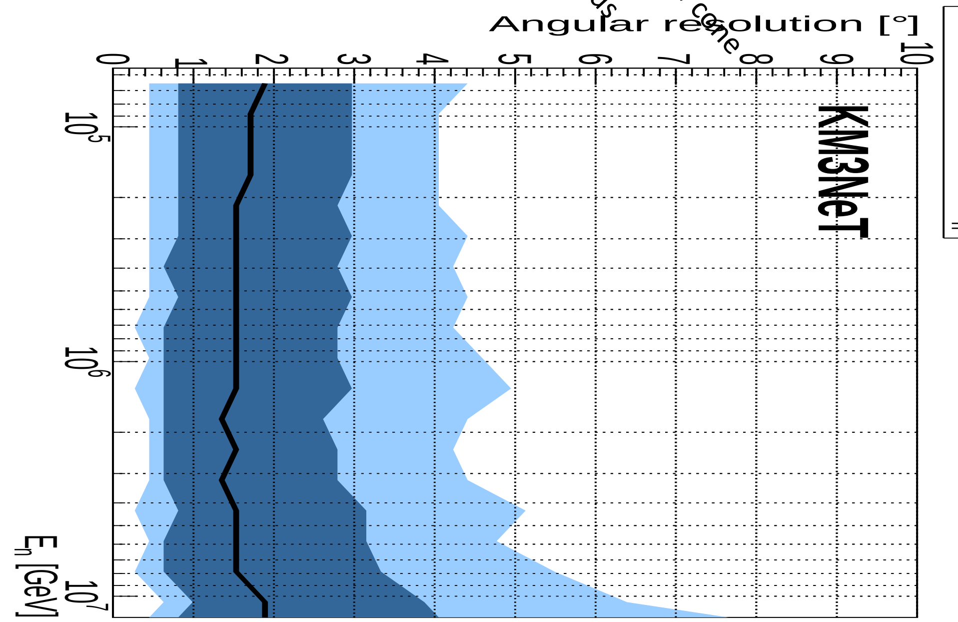
Energy / direction

- 5% energy reconstruction error (sensitive to systematics)
- 1.5 degree resolution on cascade events (insensitive to systematics)





KM3NeT LoI, J.Phys G, 43, 084001, 2016



KM3NeT LoI, J.Phys G, 43, 084001, 2016

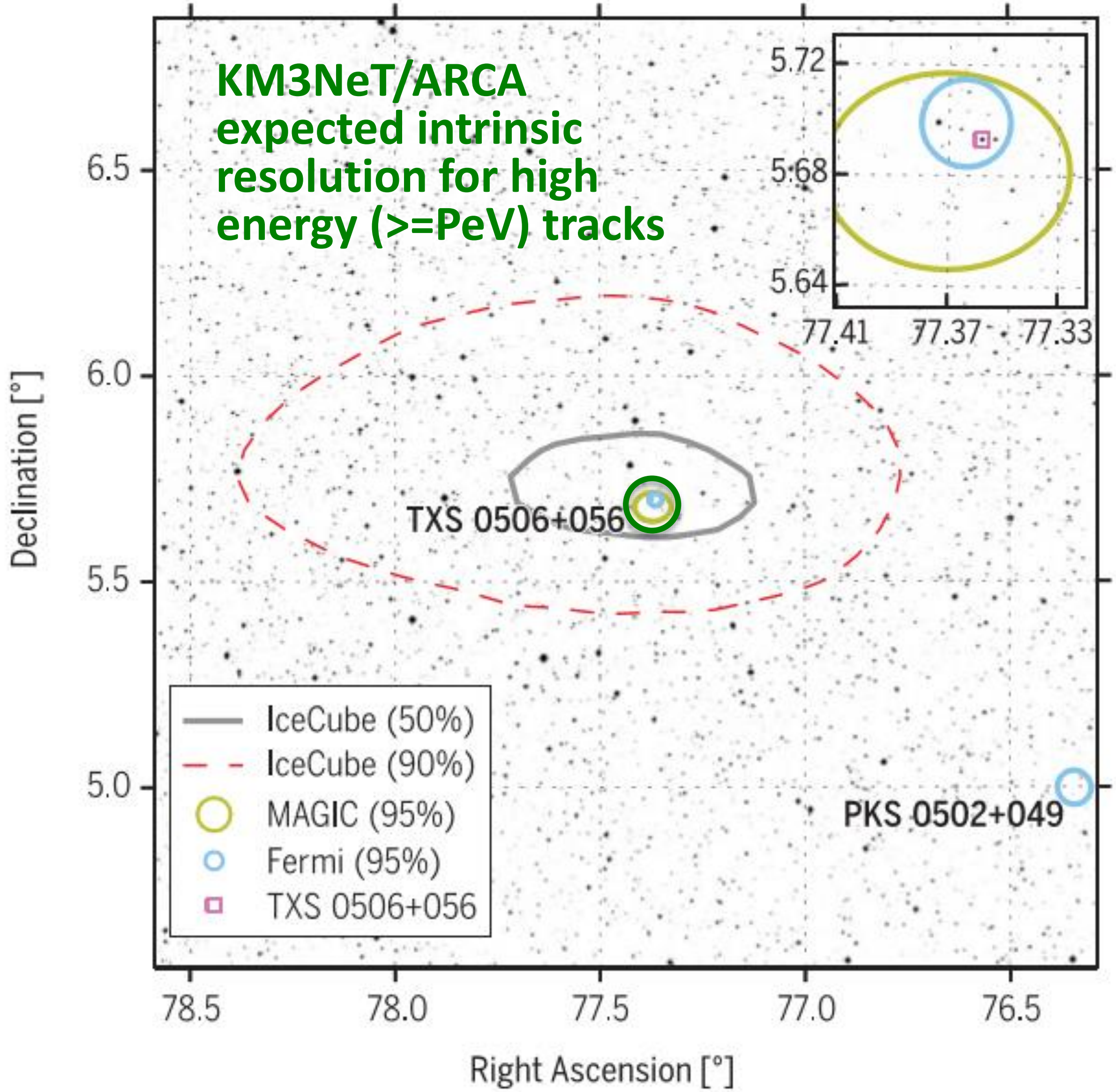
Why angular resolution?

Because there are lots of things in the sky!

e.g. TXS 0506+056

Neutrino flare:

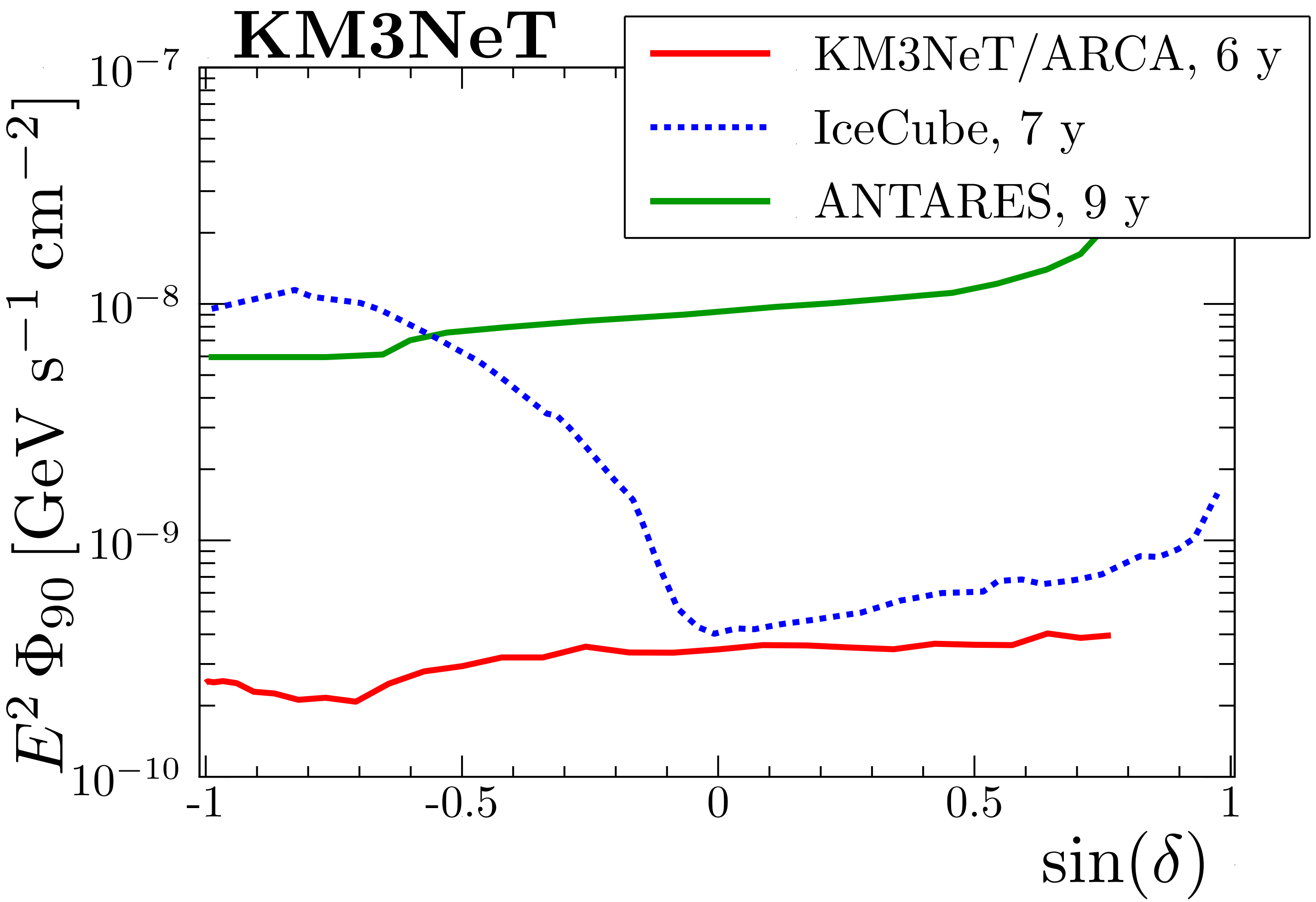
- IceCube:
  13 +- 5 events
- KM3NeT/ARCA:
  13 +- 1



Performance – generic sources

(~extragalactic)

$$F(E_n) = F_0 \left(\frac{E_n}{1\,\mathrm{GeV}} \right)^{-2}$$

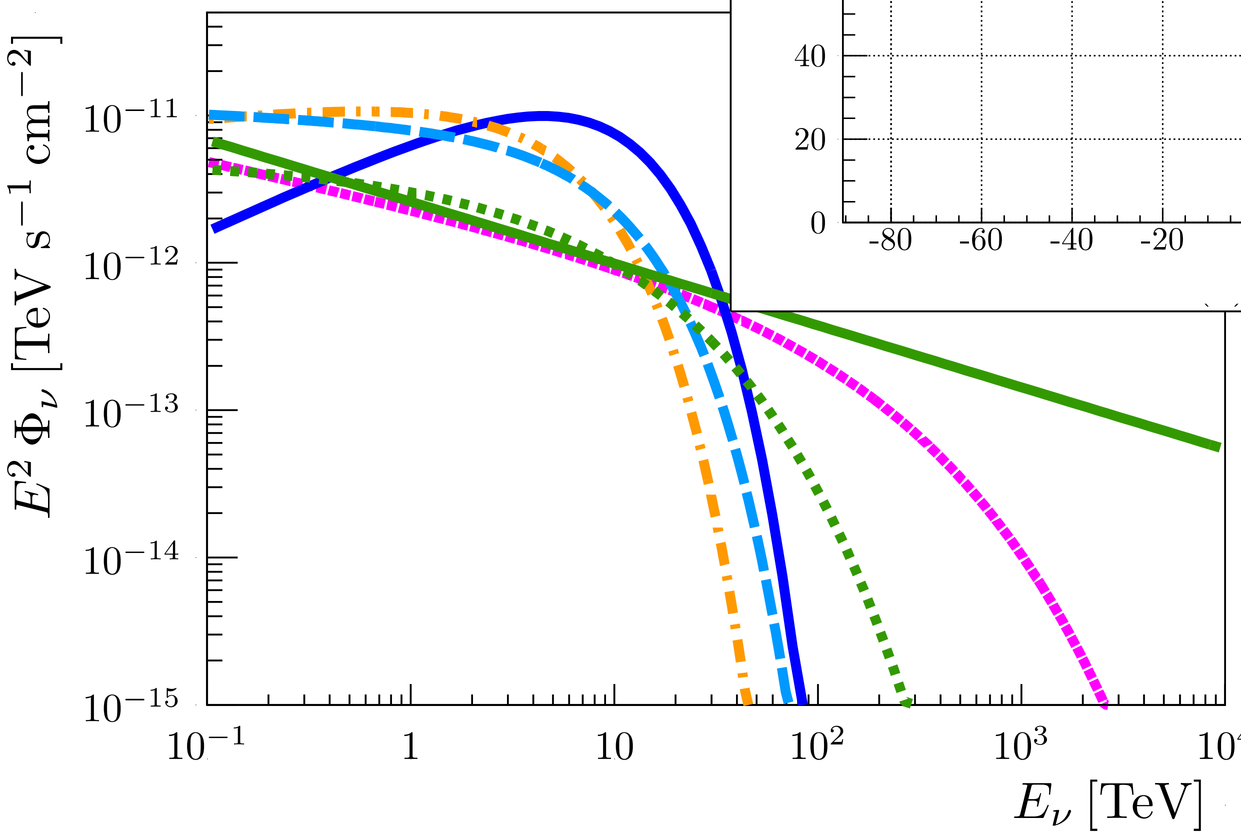


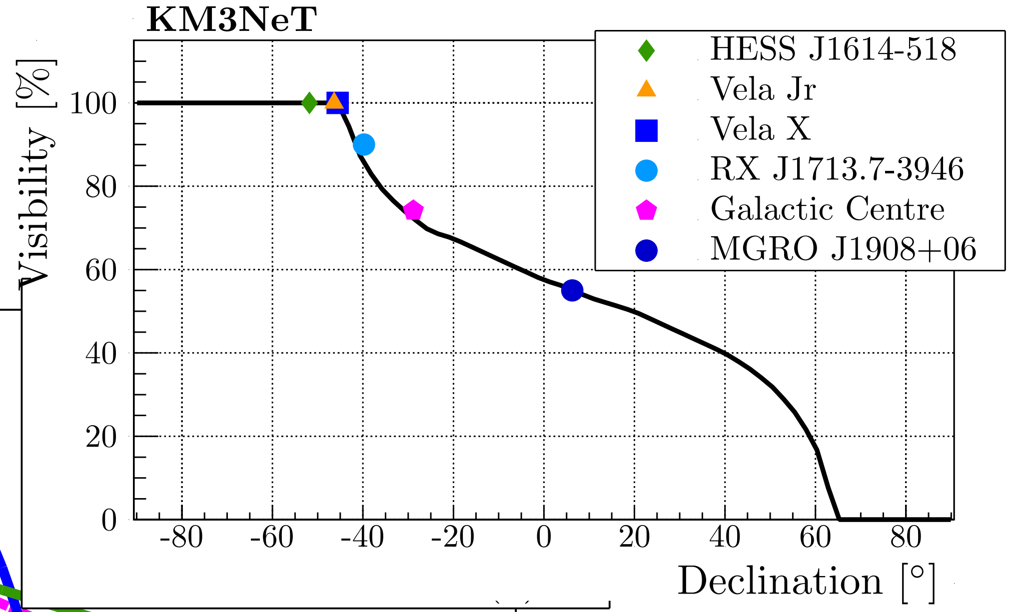
Performance – Galactic sources

KM3NeT Collaboration: Astroparticle Physics 111 (2019) 100

Northern Hemisphere

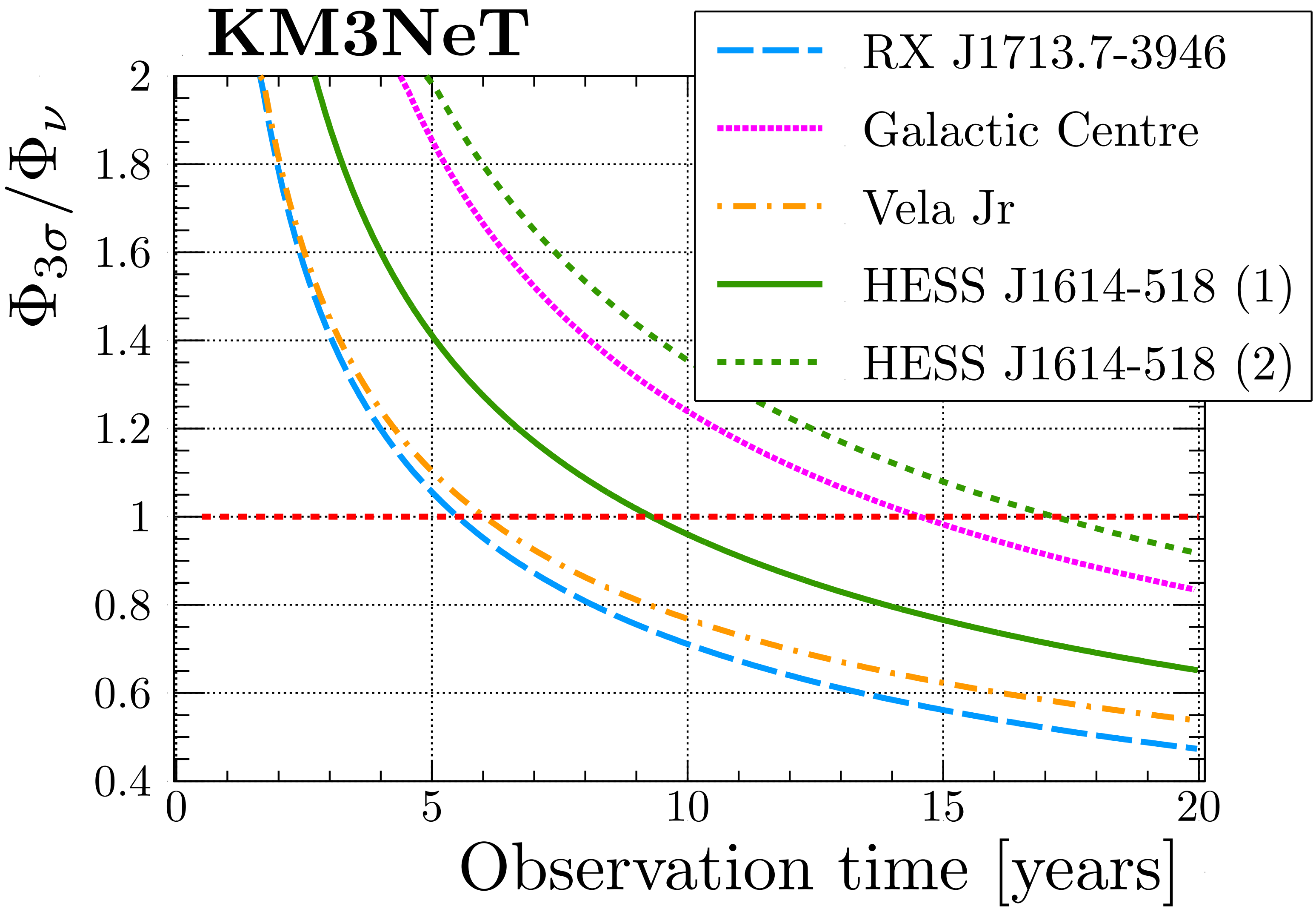
- Sees Galactic sources
- Cut-offs near 10 TeV expected (Pevatrons)





Clearly model-dependent

Sensitivity (mean time to 3 sigma excess)



KM3NeT Collaboration: Astroparticle Physics 111 (2019) 100

Clancy's unsolicited comment #1

Wtf is the deal with blazars?

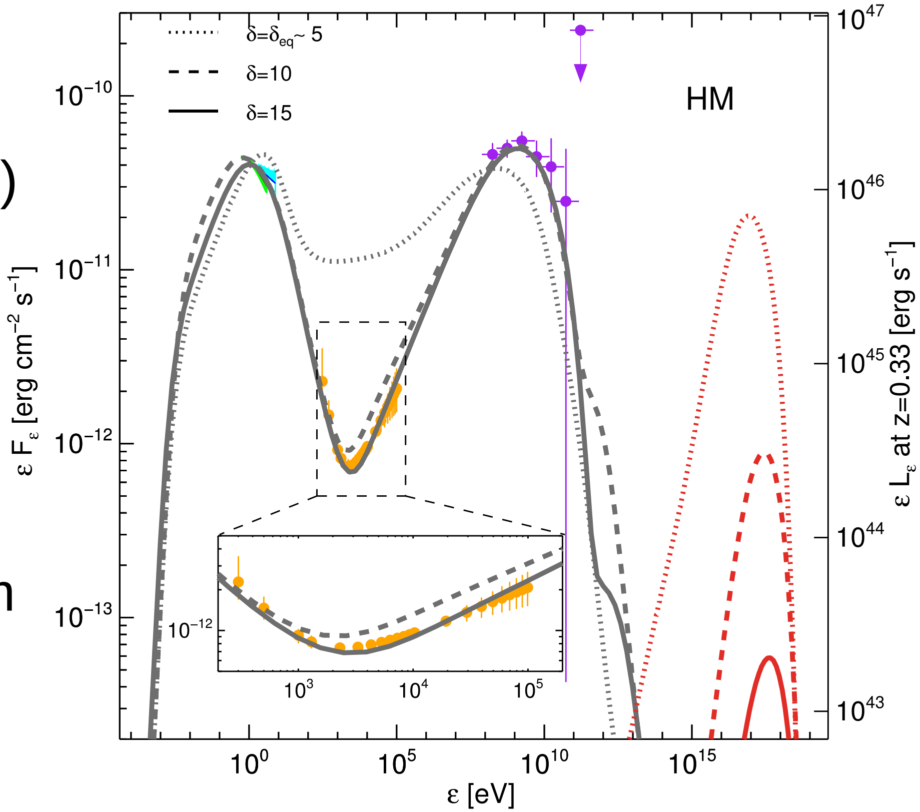
- TXS 0506+056 unexpected (~50th brightest blazar!)
- SED inconsistent with significant neutrino production (Keivani et al)
- We do not understand this

Searches?

- Stacking: we will never get the correct weights
- Individual searches: the spectrum will NOT be a power-law!

Critical to be guided by astrophysics

The Astrophysical Journal, Volume 864, Issue 1, article id. 84, 16 pp. (2018)

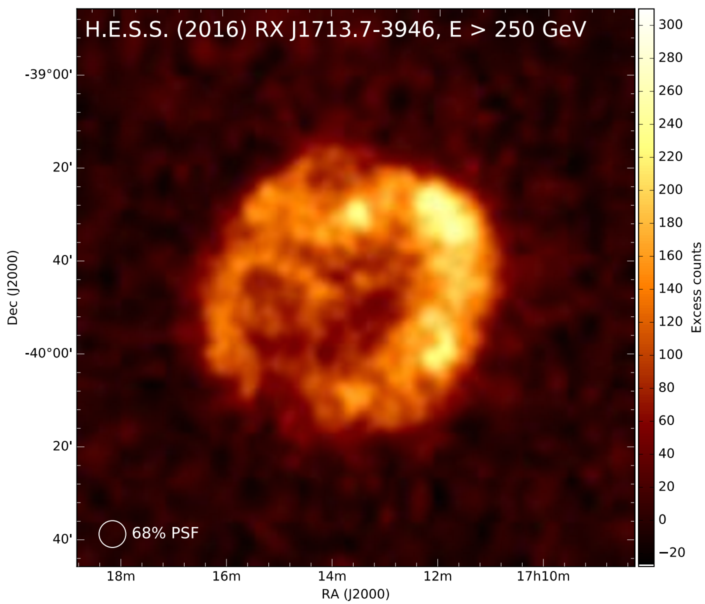


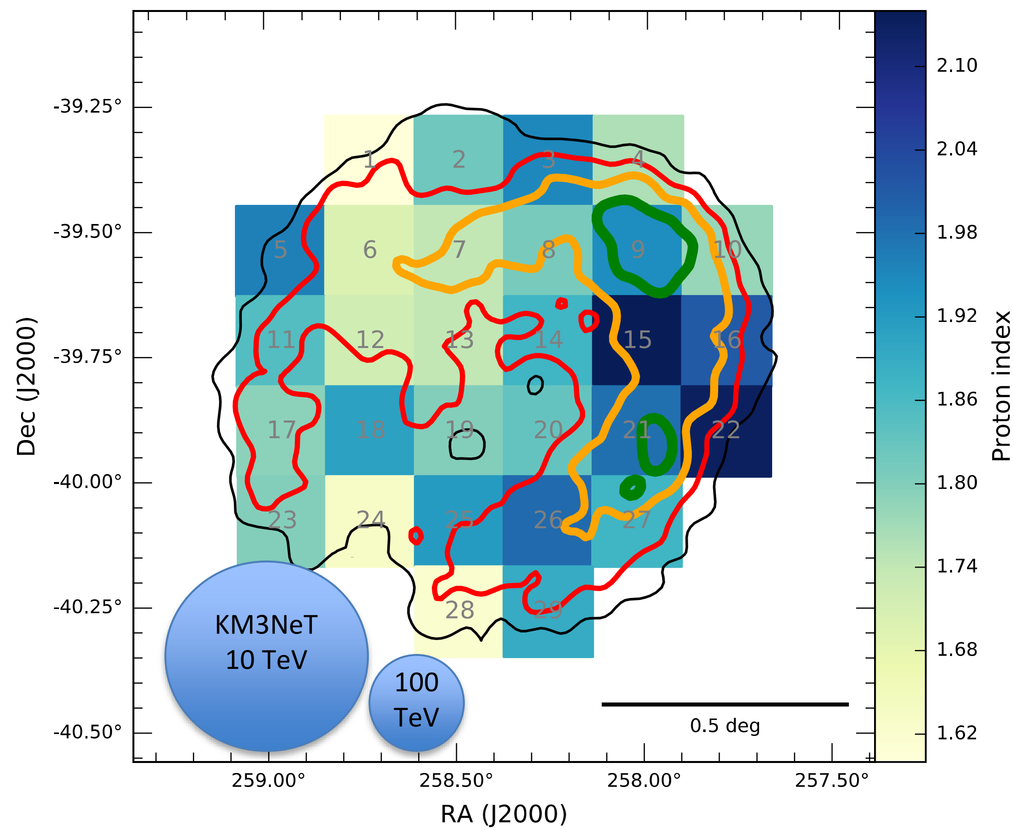
Clancy’s unsolicited comment #2

Astrophysics is complicated!

- E.g. RX J1713
- KM3NeT analysis: assumes a uniform disc
- H.E.S.S. observations: complicated structure

H.E.S.S. Collaboration, Astronomy & Astrophysics, Volume 612, id.A6





CTA + KM3NeT + multiwavelength (X-ray, radio) studies of Galactic SNR are important!

Not discussed

Tau identification & double-bang events

Diffuse sources: Galactic plane

Transients and MM (inc MWA) campaign: GRBs, SN, GW

Indirect dark matter searches (GC, Sun,…)

Exotic physics (nuclearites, monopoles, LIV)

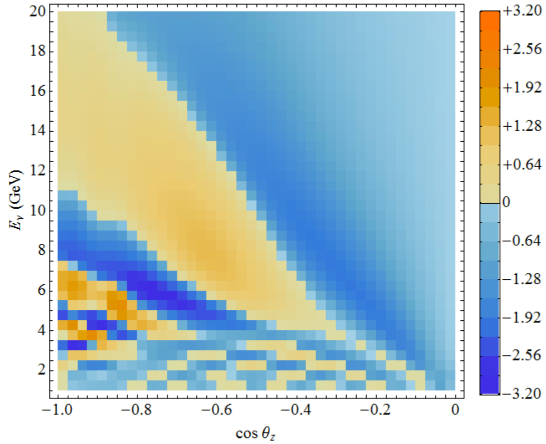
Earth & sea science (whales, deep water formation)

ORCA: estimated performance

How to measure the neutrino mass hierarchy?

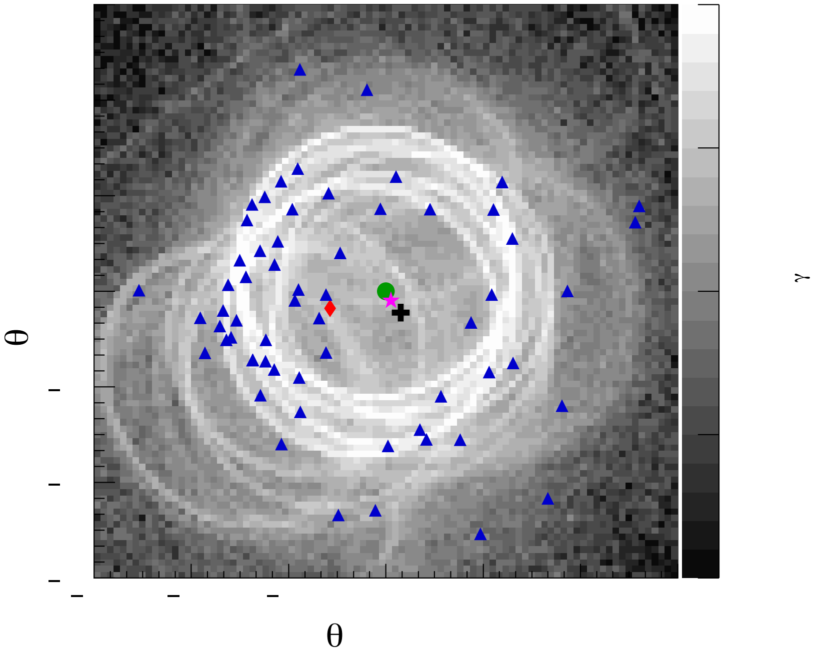
Reconstruction at low energies

- Energy
- Zenith angle (do not care about azimuthal angle!)
- Interaction type (with muon or without muon)
- "Raw" oscillograms useless!



Intrinsic fluctuations

- Large fluctuations in light yield
- Fluctuations in light pattern
- Even "perfect" reconstruction limited



Tracks vs cascades

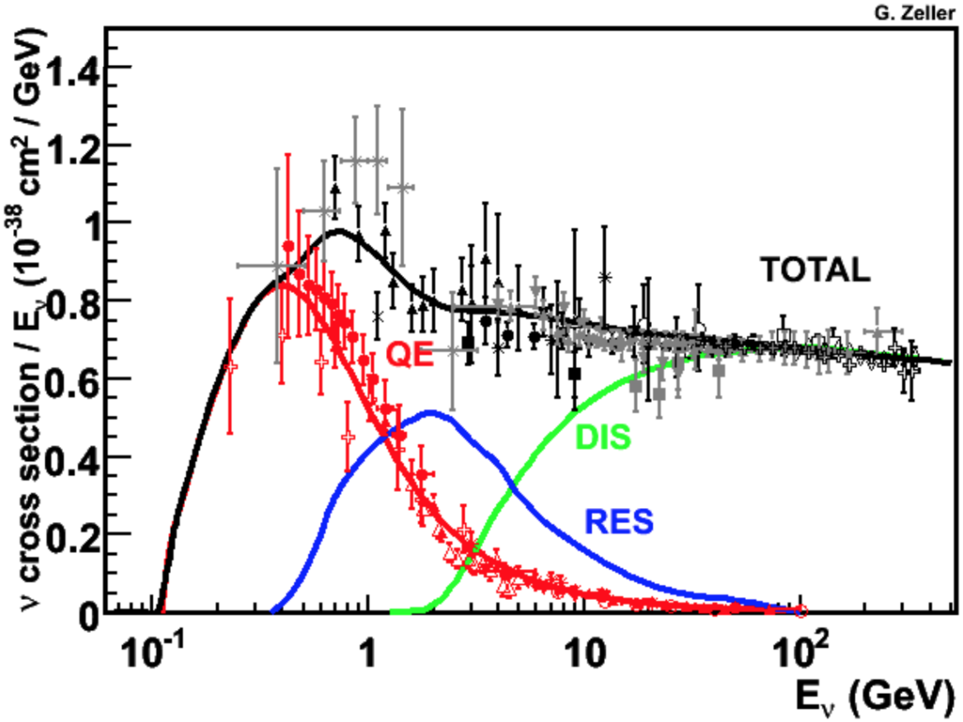
- Muons: 4m/GeV
- Radiation length: 36cm
- Critical energy 80 MeV
- Hard to distinguish!

Systematics!

GeV-scale physics is *hard*!

- Quasi-eleastic and resonant interactions important
- Very difficult to model "shallow inelastic scattering" in 1-10 GeV range
  - Standard code: GENIE, implemented in gSeaGen
  - GIBUU
- Low-energy hadronic propagators:
  - FLUKA: incorrect multiplicity
  - GEISHA: energy not conserved
- Sensitive to systematics…
- Need to fit several systematics in sensitivity estimates
- This is why I talked so much about calibration!

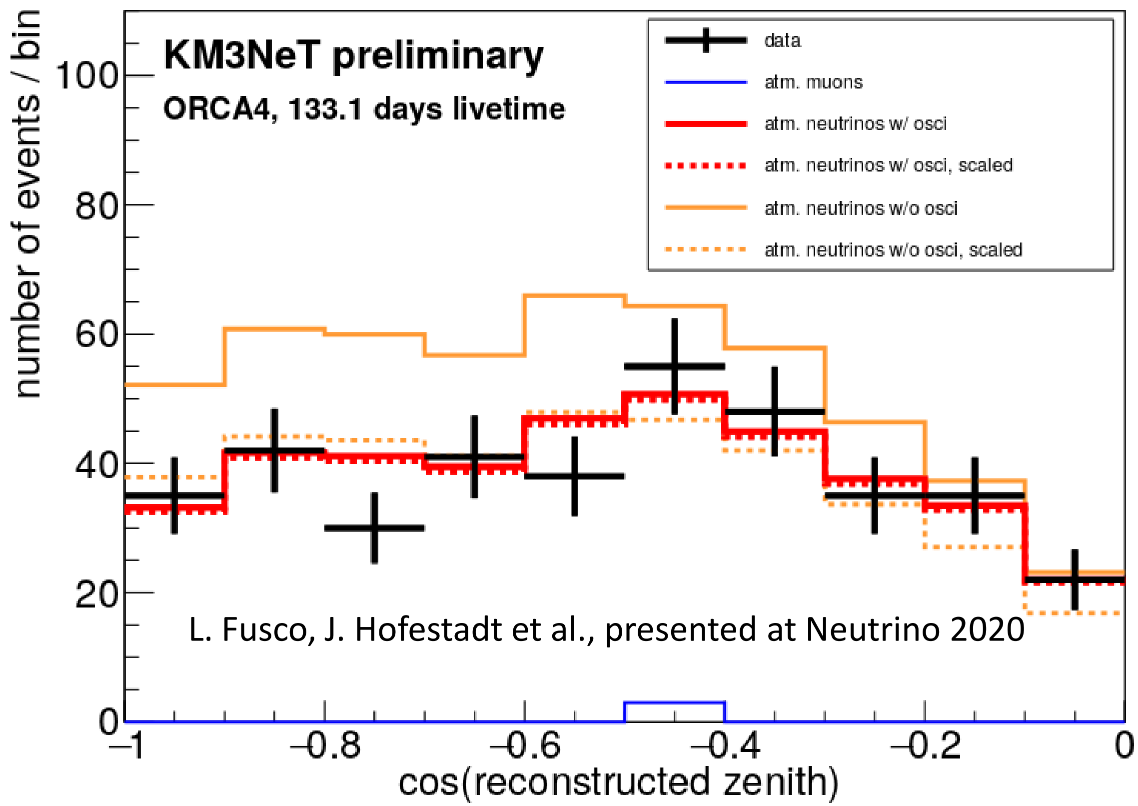
✓



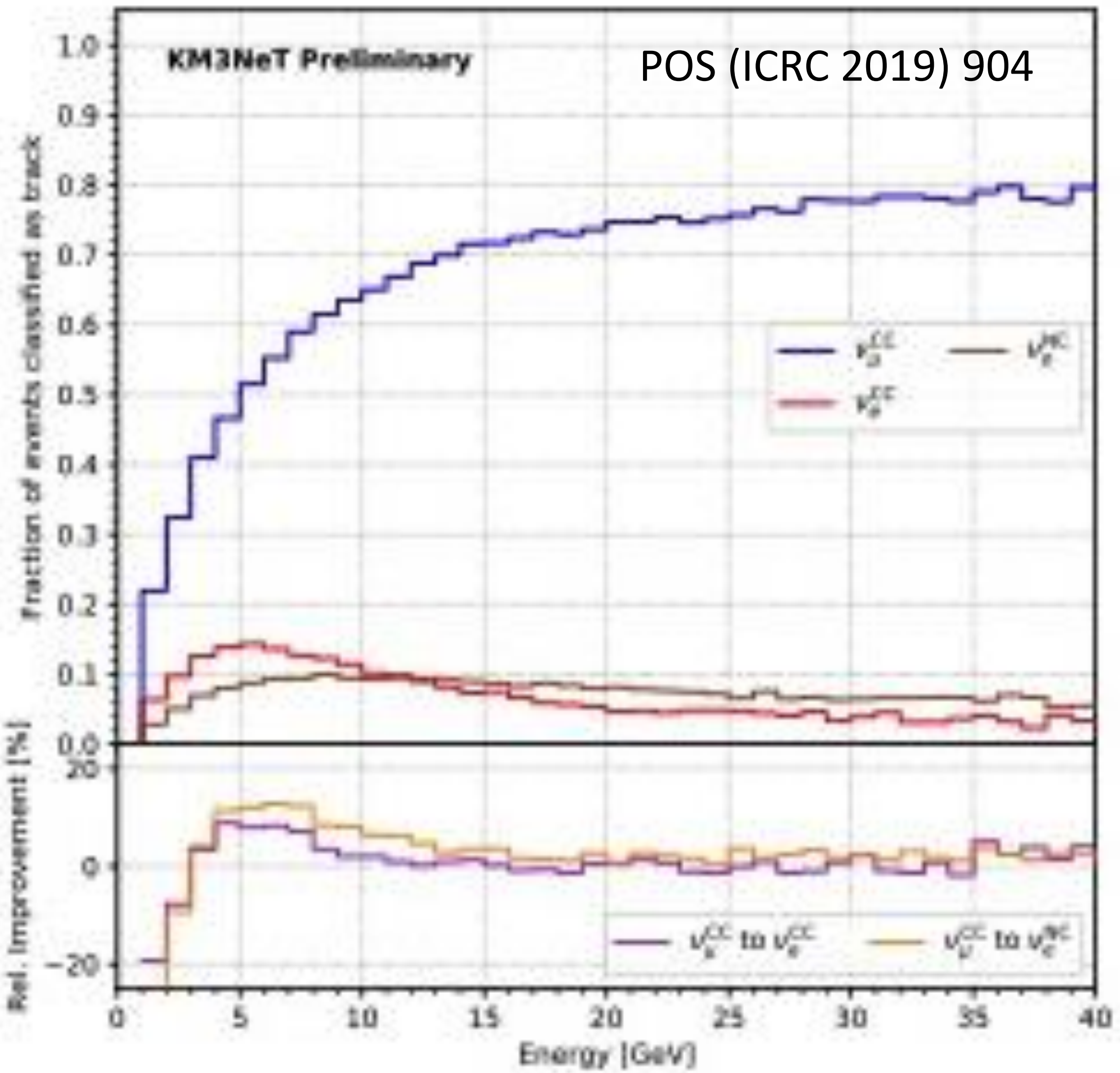
Some first results

We detect neutrino oscillations! (duh…)

- 1/3rd of a year
- 5% of ORCA
- Seeing something is good!



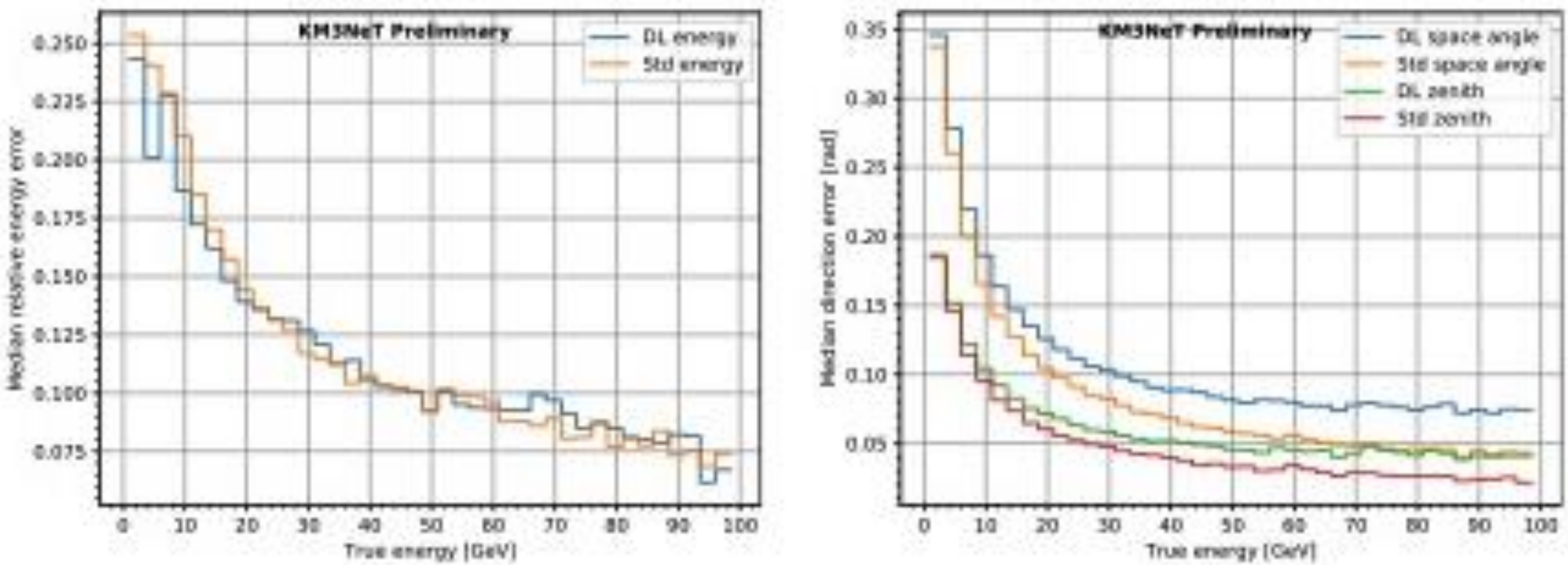
Classification – machine learning



One of several methods being tested

Resolution (ν_e CC)

Deep learning (DL) vs standard (Std)

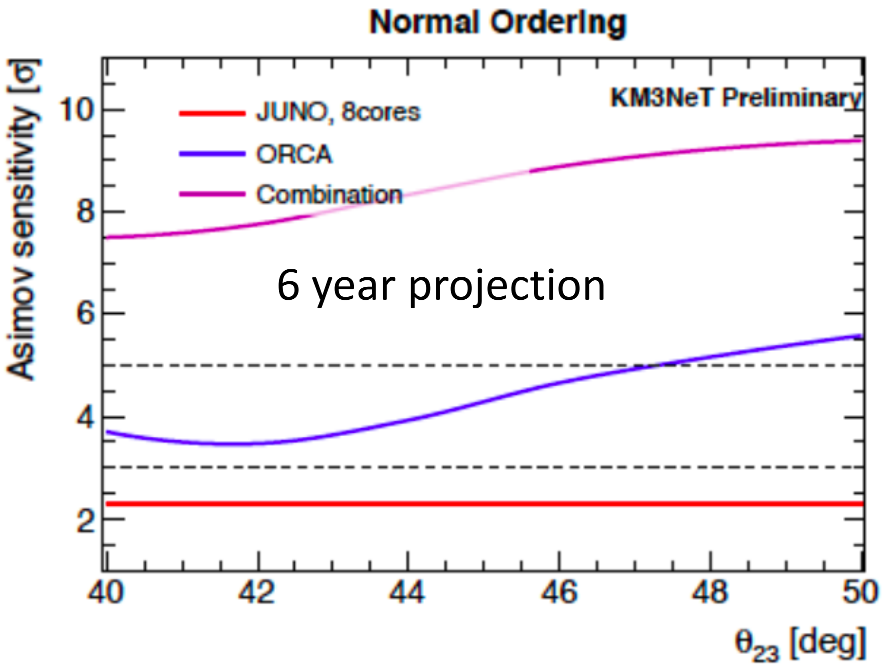


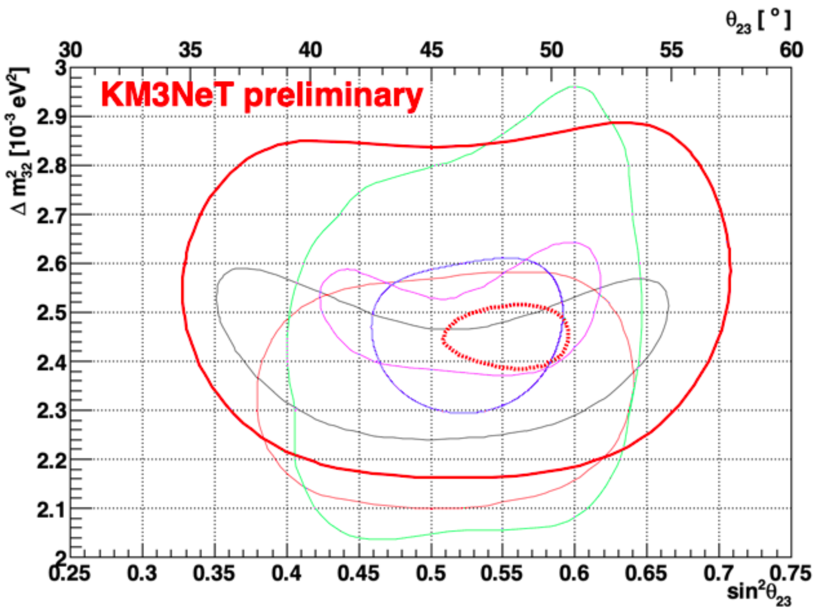
POS (ICRC 2019) 904

KM3NeT/ORCA Sensitivity for Neutrino Mass Ordering

Sensitivity to Neutrino Mass Ordering
- including systematics
- statistics bands shown

90% CL contours for oscillation parameters
SuperKamiokande T2K NOνA IceCube MINOS
Sensitivity: ORCA-2019/20 ORCA115-3y

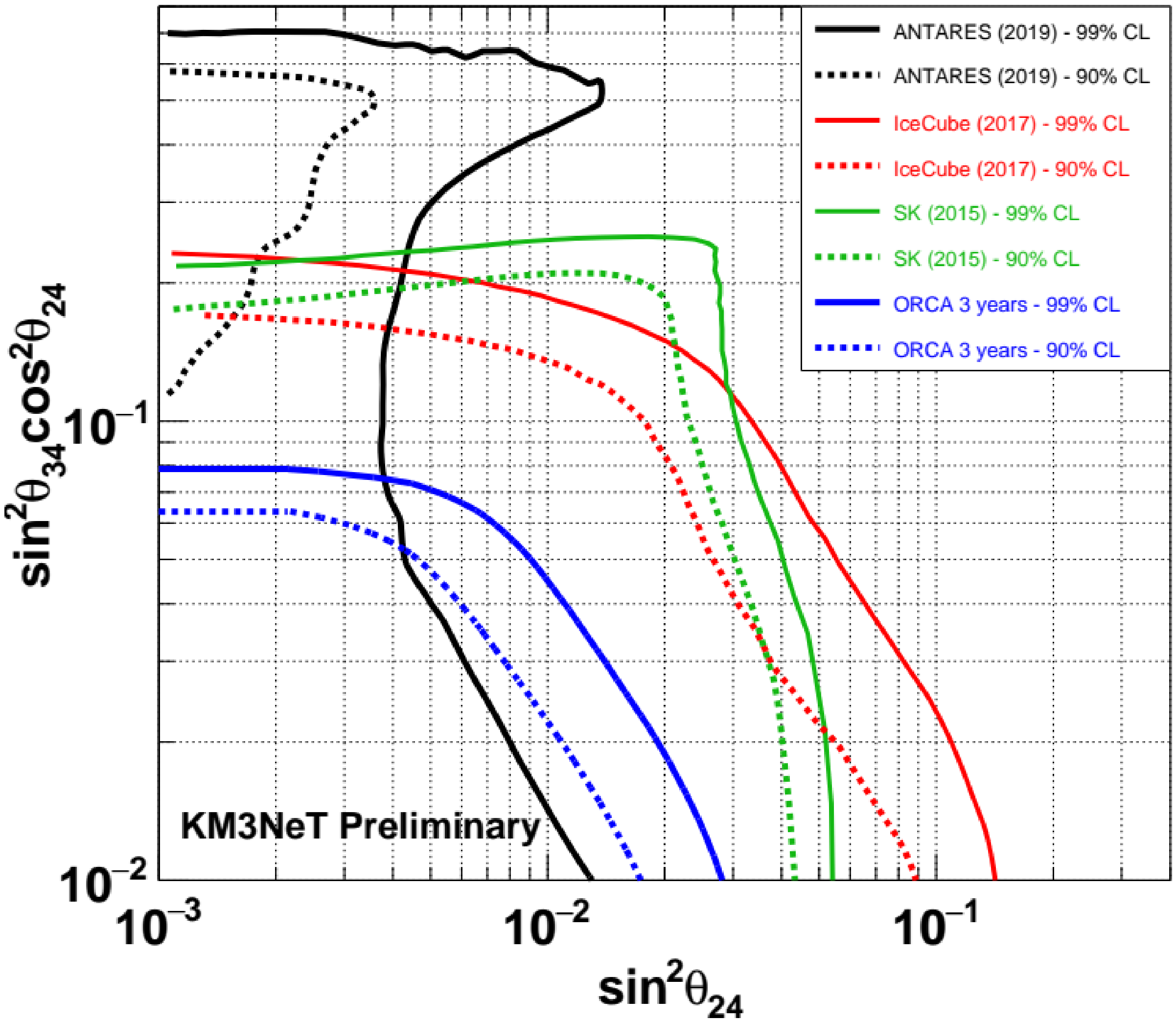




- 2.5-5σ determination of Neutrino Mass Ordering possible in 3 years
- Combination with JUNO results can significantly enhance the sensitivity
- Competitive oscillation parameter measurement possible

Slide courtesy D. Samtleben, ANTARES/KM3NeT NEUTRINO 2020

What about a 4th neutrino flavour?



Unsure of limits from beamline and reactor experiments (DUNE?)

T. Thakore et al, Chowdhury et al, Neutrino 2020

Australia's role

Theoretical neutrino physics

- Specific expectations for BSM oscillations much more useful than searching for "something unusual"
- Statistical methods: currently computationally intense!

Astrophysics

- Studying Galactic accelerators (MWA, Mopra)
- Multi-messenger links (CTA, IceCube, radio, optical, x-ray.. GW?)
- Blazar VLBI: what about Southern blazars?

Diversity

- These initiatives are now becoming mandatory for EU funding
- Australia has quite a bit of experience at this (e.g. Pleiades)
- Environment?
- We have a strong incentive to encourage online meetings!

Conclusion

KM3NeT

- ARCA: high-energy astrophysics astrophysics
- ORCA: neutrino oscillations and mass hierarchy
- Common (beautiful!) technology

Status

- Under construction: ~2026 completion
- Some initial setbacks
- Preliminary results show that everything is under control

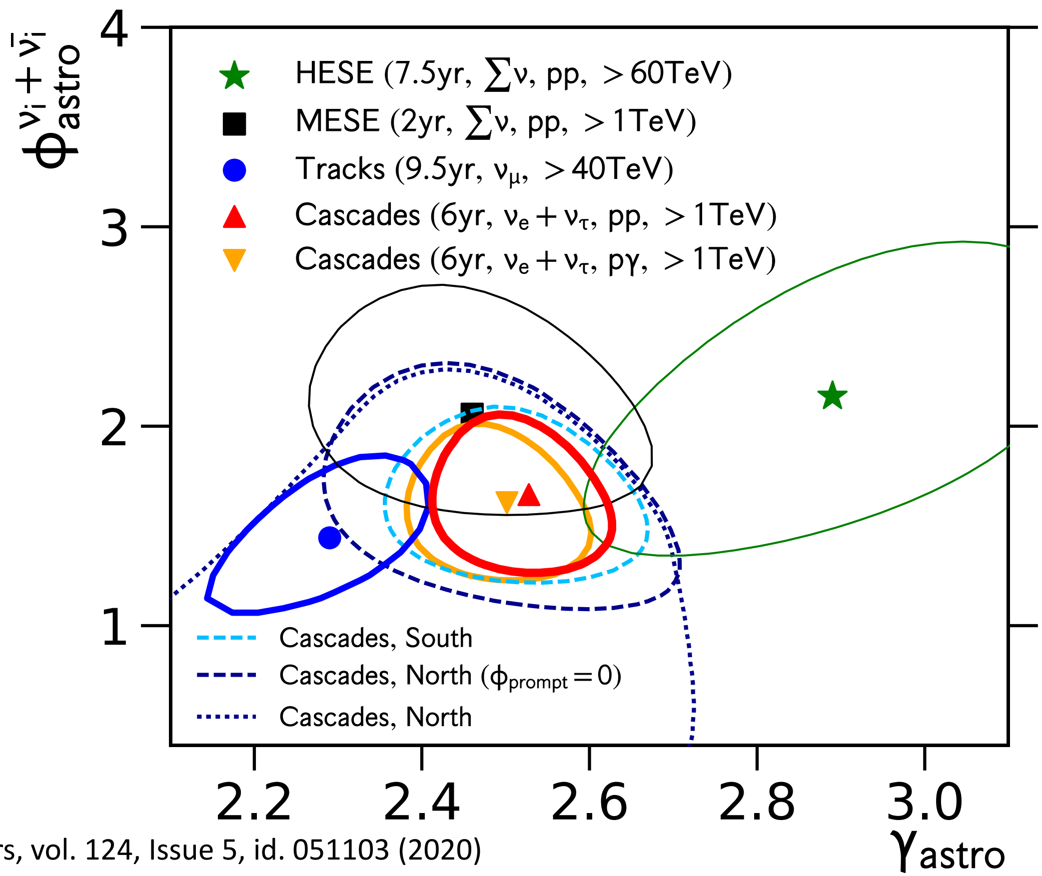
My motivation

- Build up participation in KM3NeT now
- Prepare for neutrino astronomy in the near future.
- Thank you!

IceCube: astrophysical flux

Single power-law fits

- Different event types
- Different flavour/energy/direction sensitivities



IceCube: Physical Review Letters, vol. 124, Issue 5, id. 051103 (2020)