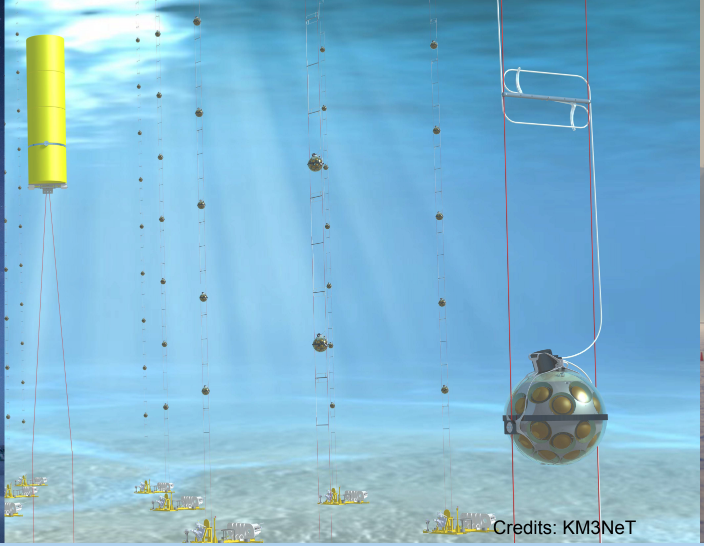
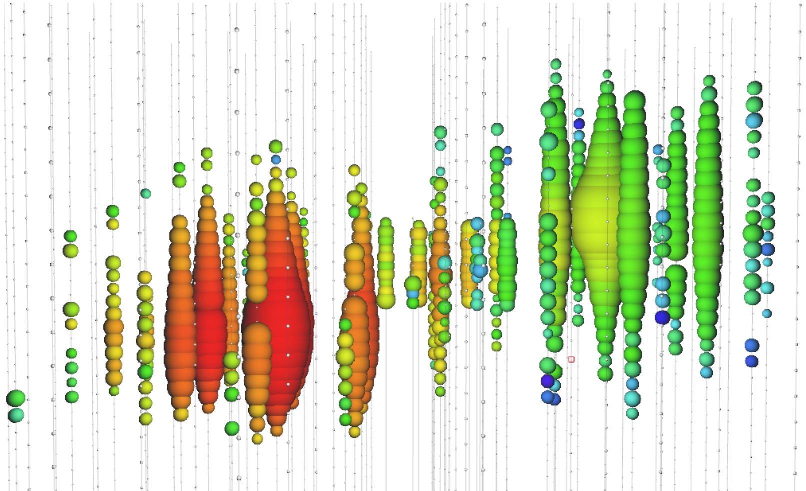


Tau Neutrino Detection at Neutrino Telescopes from GeV to PeV


SImulated tau-neutrino double-bang, Credits: IceCube

Steffen Hallmann
steffen.hallmann@desy.de

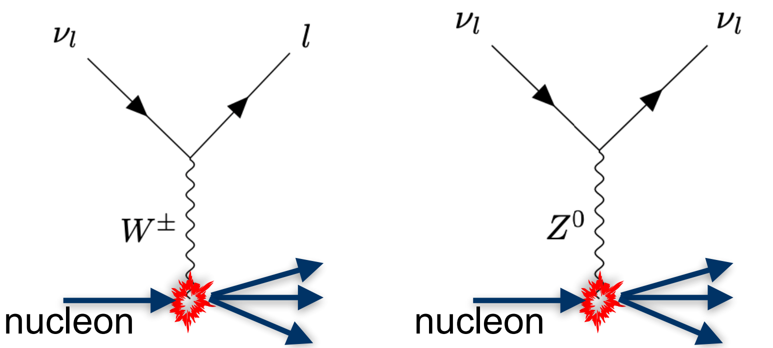
IRN Neutrino Meeting 2021
Paris, 02/12/2021

Neutrino detection in optical Cherenkov telescopes

- three known neutrino flavours: ν_e , ν_μ , ν_τ

- weak interactions
  produce relativistic + charged particles

charged current (CC) neutral current (NC)



- Cherenkov light induced

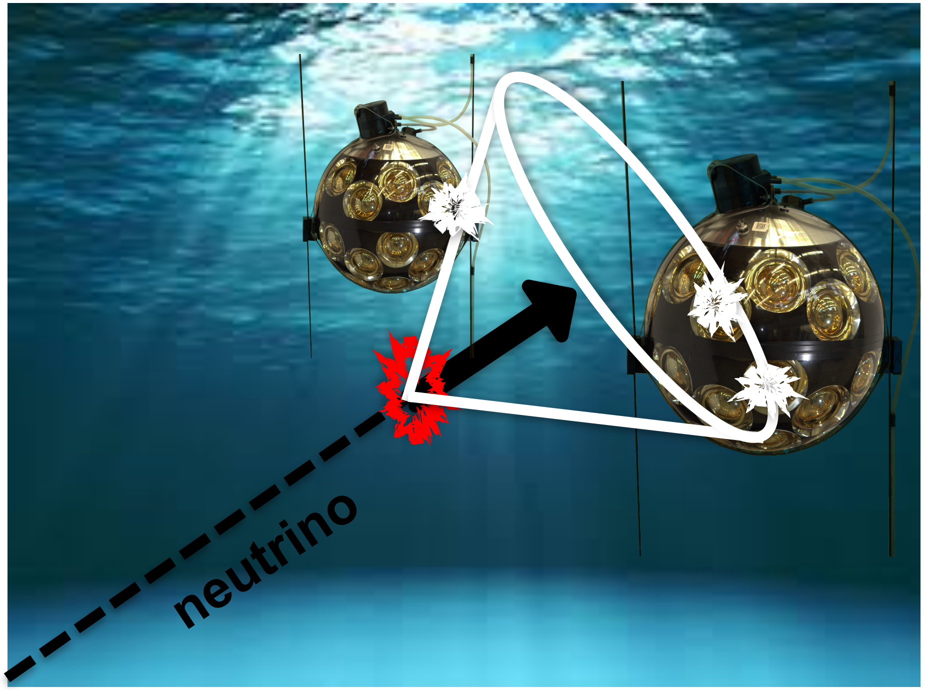
  characteristic angle: ~41˚/43˚ in ice/water

  ice (compared to water): less attenuation, but

  shorter scattering length, birefringence,…

- light collection
  3D array of photomultiplier tubes (PMTs)

  → reconstruct ν position/direction/energy



Neutrino telescopes

GeV TeV PeV EeV

complete

ANTARES
- instrumented volume ~0.01km^3
- 2008-2022

ICECUBE
- instrumented volume ~1km^3
- 10 years of data taken

construction

BAIKAL-GVD
- under construction, 8 clusters (à 8 strings) installed.
- instrumended volume ~0.4km^3

KM3NeT
- ARCA: km3-scale, astrophysical
  ORCA: ~GeV oscillations
- under construction, 8 (of 330) and 10 (of 115) Detection Units installed

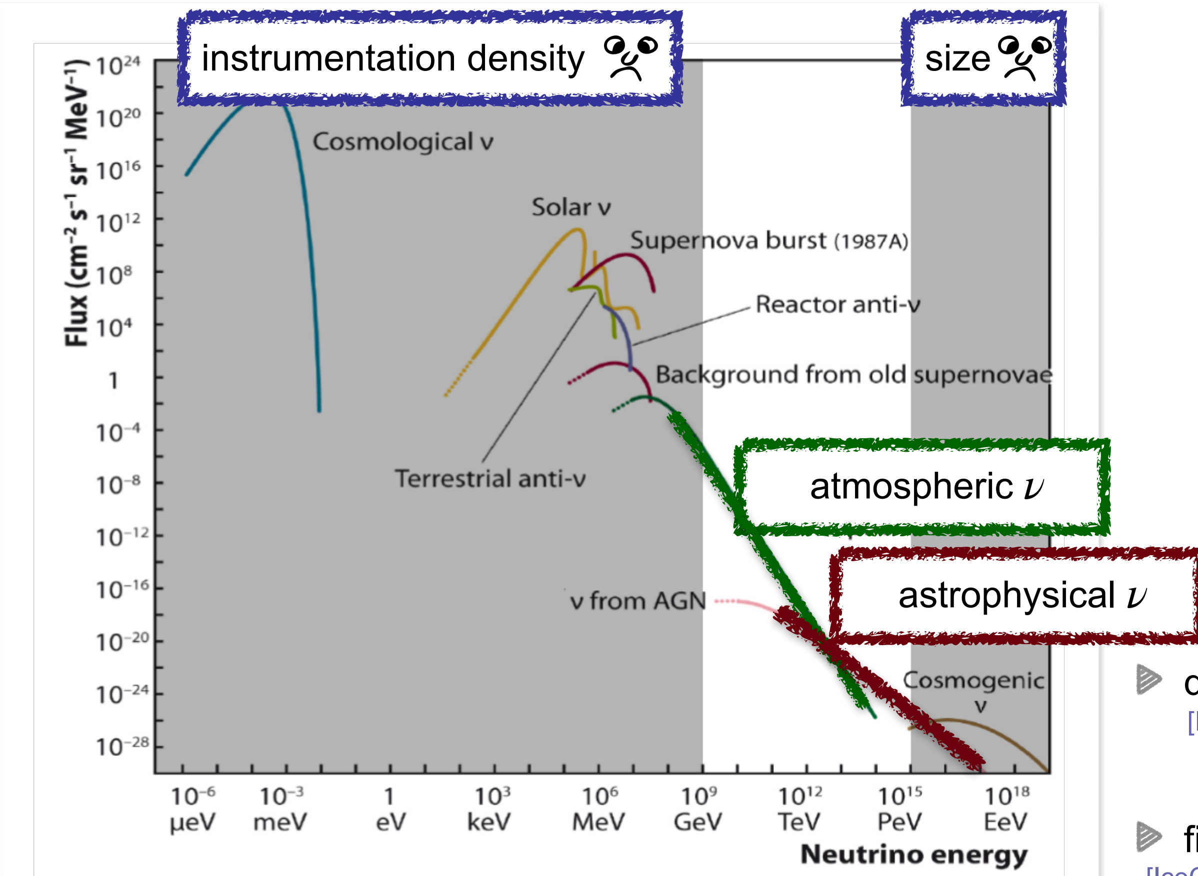
pathfinder/ planned

ICECUBE GEN2

P-ONE

Omitted here:
- underground (~GeV): Super-K / Hyper-K
- radio detection (~EeV): ARA, ARIANNA, Anita, RNO-G, GRAND, PUEO,…

Neutrino fluxes observed in optical Cherenkov telescopes



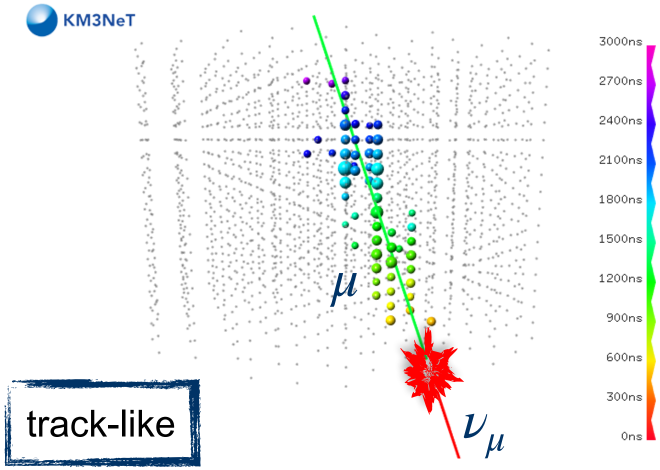
[Katz, Spiering, PPNP 67, 3:651-704 (2012)]

- diffuse astrophysical flux detected
  [IceCube Collab., Science 342, 1242:856 (2013)]

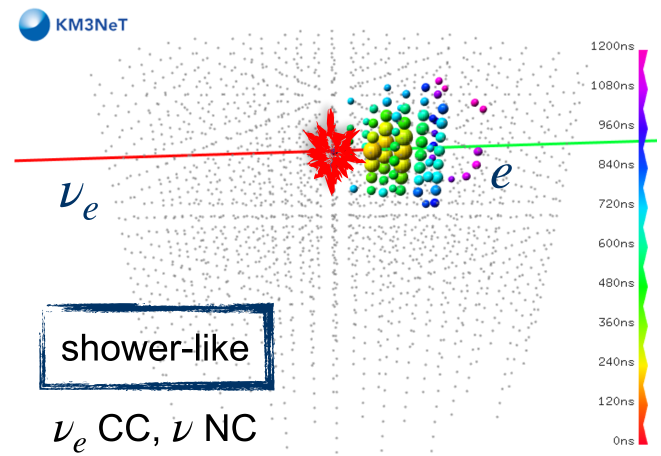
- first hints on individual contributors
  [IceCube Collab., GRB Coordinates Network, 25913, 1]
  [IceCube Collab., Science 361, 6398:147 (2017)]
  [IceCube Collab., Phys. Rev. Lett. **124**, 051103]

Neutrino signatures

- Each (may) produce unique event signatures in neutrino telescopes



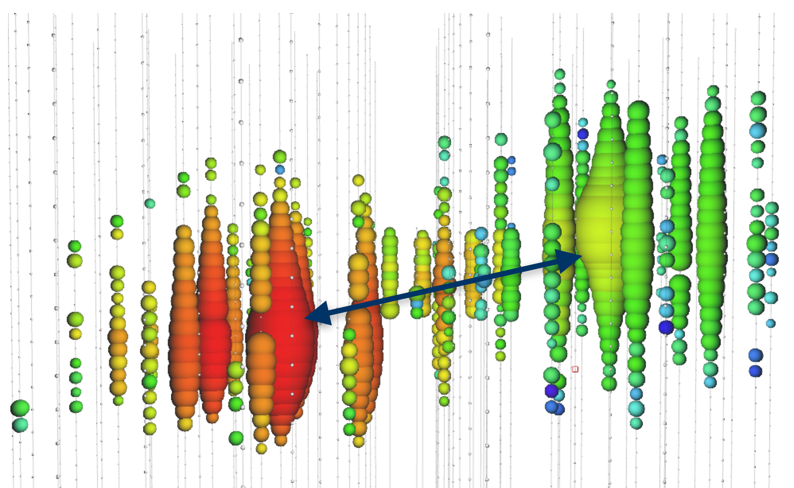
ν_μ CC



ν_e CC, ν NC

- “Smoking gun” double-bang event signature for ν_τ CC:

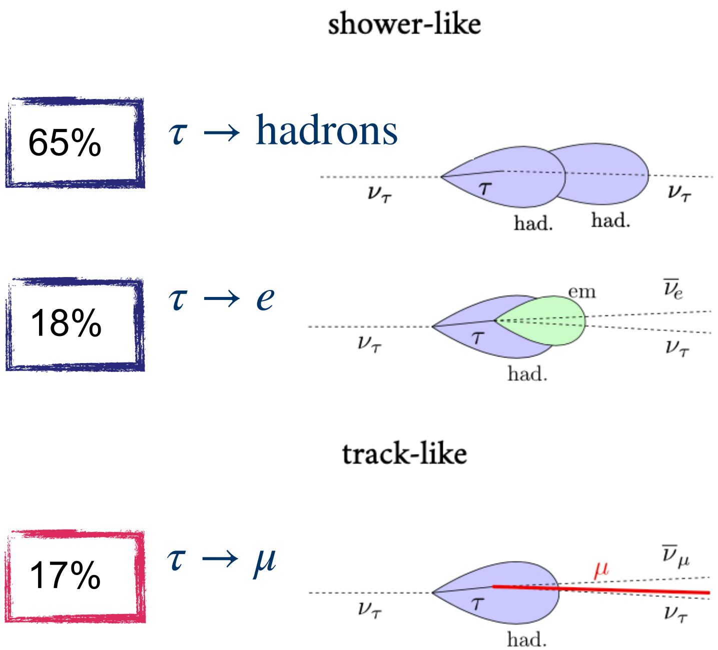
[Learned, Pakvasa: Astropart.Phys.3,267–274(1995)]



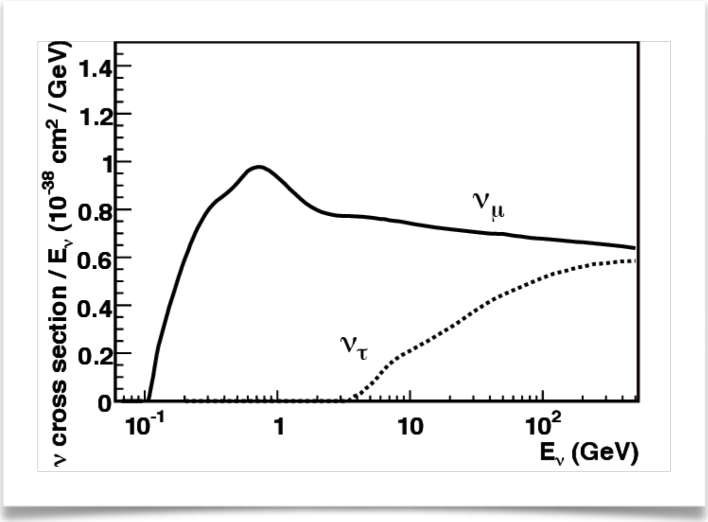
SImulated tau-neutrino double-bang, Credits: IceCube

ν_τ CC event signatures

- τ decay:



- τ mass $\approx 1.78\,\mathrm{GeV}/c^2$
  - cross section suppressed, threshold: 3.4 GeV



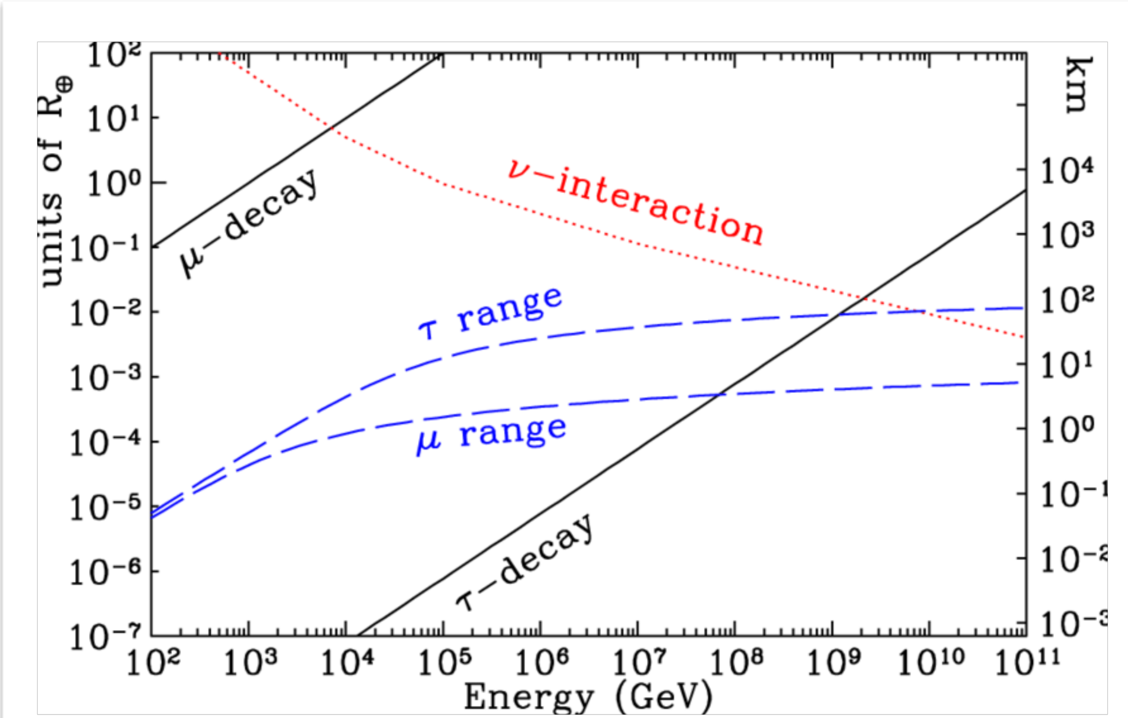
[Formaggio, Zeller, Rev. Mod. Phys. 84, 1307 (2012)]

- τ lifetime $\approx 2.9 \times 10^{-13}$ s

$$\gamma c \tau = \frac{E_\tau}{1.78\mathrm{GeV}} \times 87.03\mu\mathrm{m}$$

$49\,\mu\mathrm{m}/\mathrm{GeV}$ $49\,\mathrm{m}/\mathrm{PeV}$

Regimes of tau-neutrino detection:



[Beacom et al (2002)]

GeV
- atmospheric tau-neutrino appearance (statistical)

PeV
- flavour triangle / source composition (tau double-pulse/double-bang)

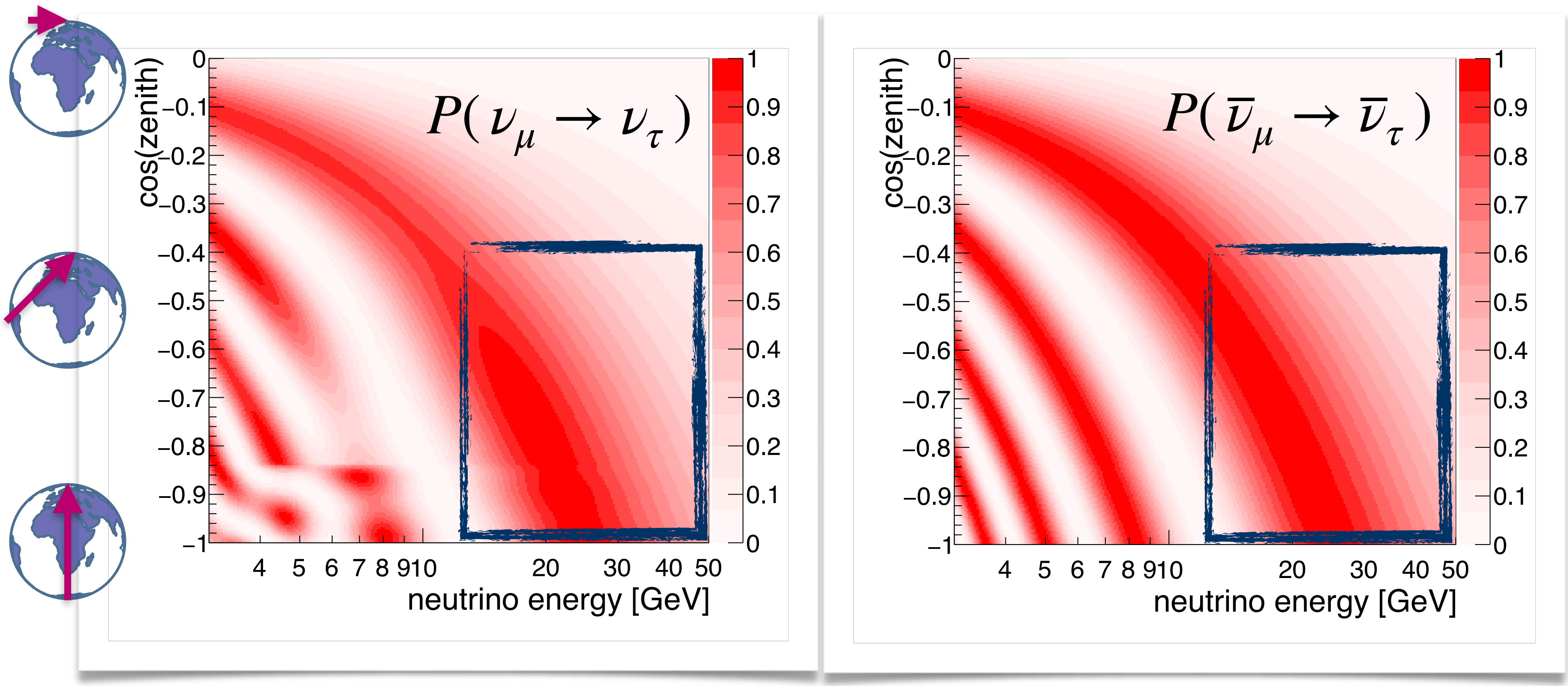
EeV
- radio regime (Earth skimming tau) (multiple in-ice showers)

[C. Glaser et al., Phys. Rev. D 102 083011 (2020) and PoS(ICRC2021)1231]

Atmospheric tau neutrino appearance

Atmospheric ν_τ appearance

[OscProb, https://github.com/joaoabcoelho/OscProb]



- oscillation from a pure ν_μ and ν_e atmospheric flux into ν_τ channel
- large oscillation maximum: complete $\nu_\mu \rightarrow \nu_\tau$ conversion at ~25 GeV and upward going

  O(mm) displaced vertex not observable in neutrino telescopes: measurement on statistical basis!
- significant distortion due to matter effects (mass ordering!) only < 10 GeV

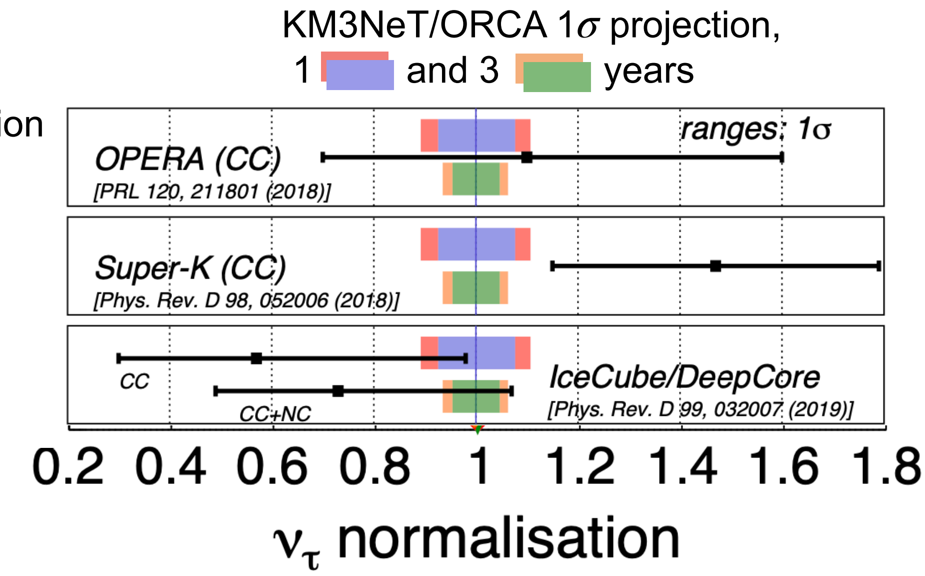
Sensitivity to ν_τ appearance

- compare measured signal strength of ν_τ contribution with physics model assumption

ν_τ normalisation measurement

- similar approaches used by Super-K, DeepCore (measurements) and KM3NeT (sensitivity)

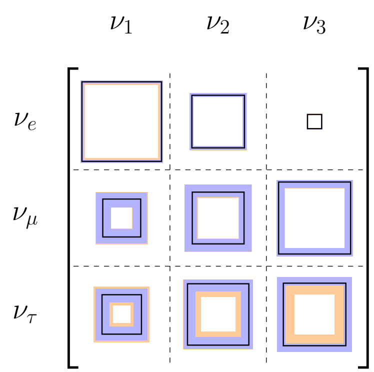
- current status: non-appearance excluded, **but**:
- **normalisation barely constrained**



[arXiv:2103.09885, EPJC accepted]

- **normalisation $\neq$ 1:**
  - **cross section off?** $\mathcal{O}(10\%)$? uncertainties in calculations due to τ mass
  - **additional interactions?**
  - **3 neutrino picture complete?** $\leftrightarrow$ unitarity: conserves normalisation

$$\left|\begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \mathcal{U}_{e3} & ? \\ \mathcal{U}_{\mu1} & \mathcal{U}_{\mu2} & \mathcal{U}_{\mu3} & ? \\ \mathcal{U}_{\tau1} & \mathcal{U}_{\tau2} & \mathcal{U}_{\tau3} & ? \\ ? & ? & ? & ? \end{pmatrix}\right| =$$



with unitarity:
%-level precision on most oscillation parameters from experiment

without unitarity:
$\leftarrow$ large uncertainties in ν_τ row !

Sensitivity to ν_τ appearance

- compare measured signal strength of ν_τ contribution with physics model assumption

ν_τ normalisation measurement

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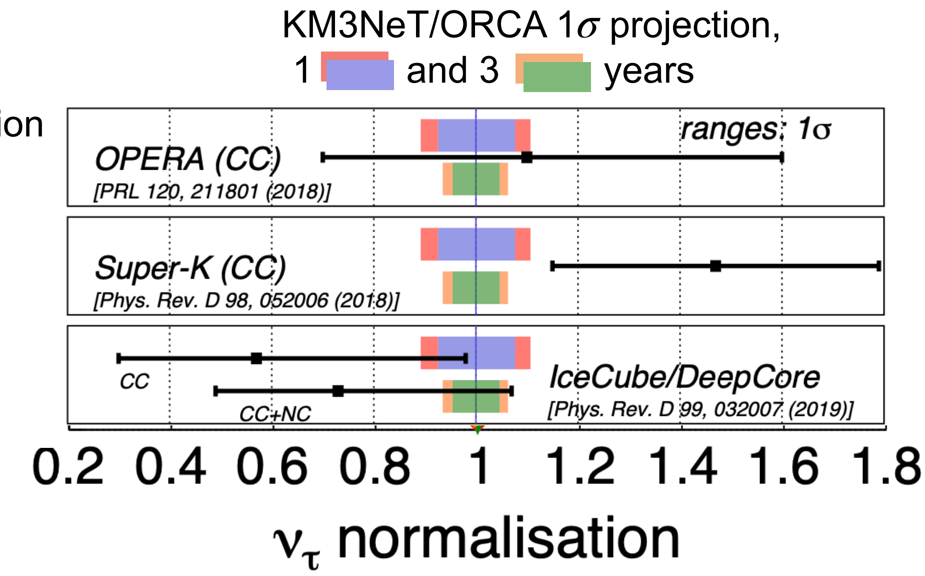


[arXiv:2103.09885, EPJC accepted]

- **normalisation $\neq$ 1:**
  - **cross section off?** $\mathcal{O}(1$ ... due to τ mass
  - **additional interactions**
  - **3 neutrino picture com** ... nalisation

$$\left|\begin{pmatrix} \mathcal{U}_{e1} & \mathcal{U}_{e2} & \mathcal{U}_{e3} & ? \\ \mathcal{U}_{\mu1} & \mathcal{U}_{\mu2} & \mathcal{U}_{\mu3} & ? \\ \mathcal{U}_{\tau1} & \mathcal{U}_{\tau2} & \mathcal{U}_{\tau3} & ? \\ ? & ? & ? & ? \end{pmatrix}\right.$$

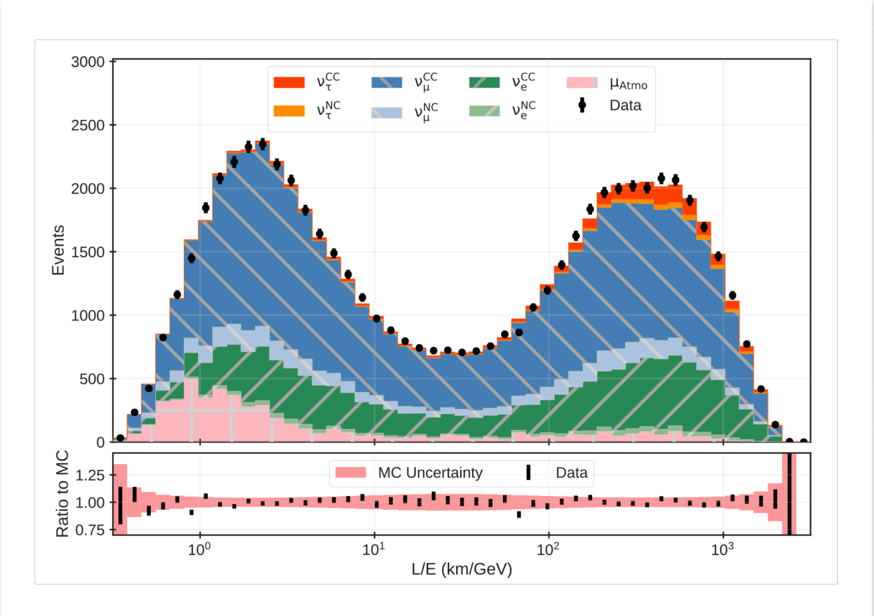
with unitarity:
%-level precision on most oscillation parameters from experiment

without unitarity:
$\leftarrow$ large uncertainties in ν_τ row !

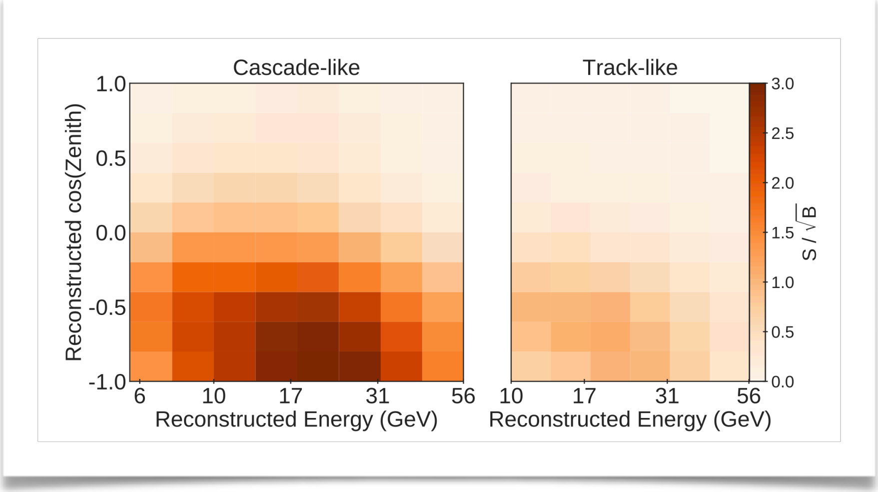
IceCube/DeepCore measurement

[IceCube, Phys. Rev. D 99, 032007 (2019)]

- performed two separate analyses with loose / strict event selection using 3 years of data (~1000 days livetime)
- significantly higher statistics compared to Super-K / OPERA:
  estimated 1804 CC, 556 NC (Analysis A)
  934 CC, 445 NC (Analysis B)
- ~3% contribution of ν_τ at analysis level in shower-channel

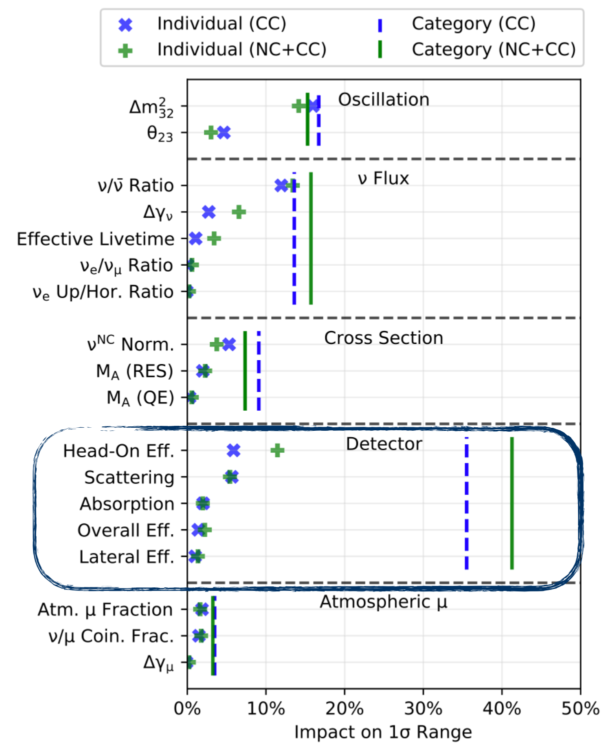


- Inclusive measurement in 3D-space of direction / energy / particle ID
- Fit overall normalisation of ν_τ (CC-only or combined CC+NC)



IceCube/DeepCore measurement

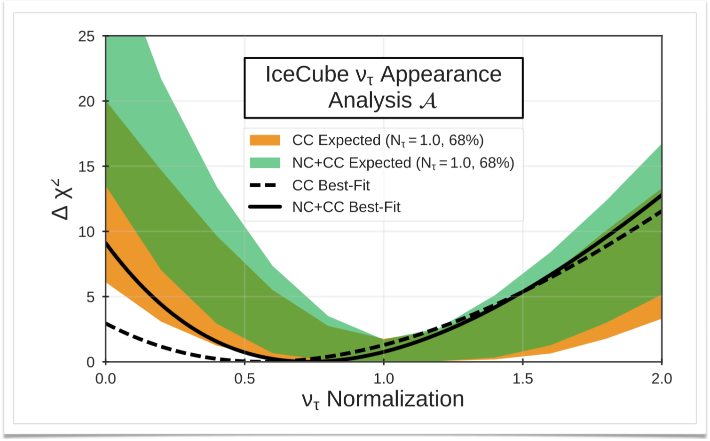
[IceCube, Phys. Rev. D 99, 032007 (2019)]



- systematics dominated by detector systematics
- these will be reduced by the IceCube Upgrade to be deployed

- best fit compatible with unitarity
- non-appearance excluded 3.2σ level

- Expected improvement from O(10) years data: ~15% precision on normalisation
- Expected improvement with IceCube Upgrade (dense in-fill to study ice-properties, oscillations): ~10% precision after one year



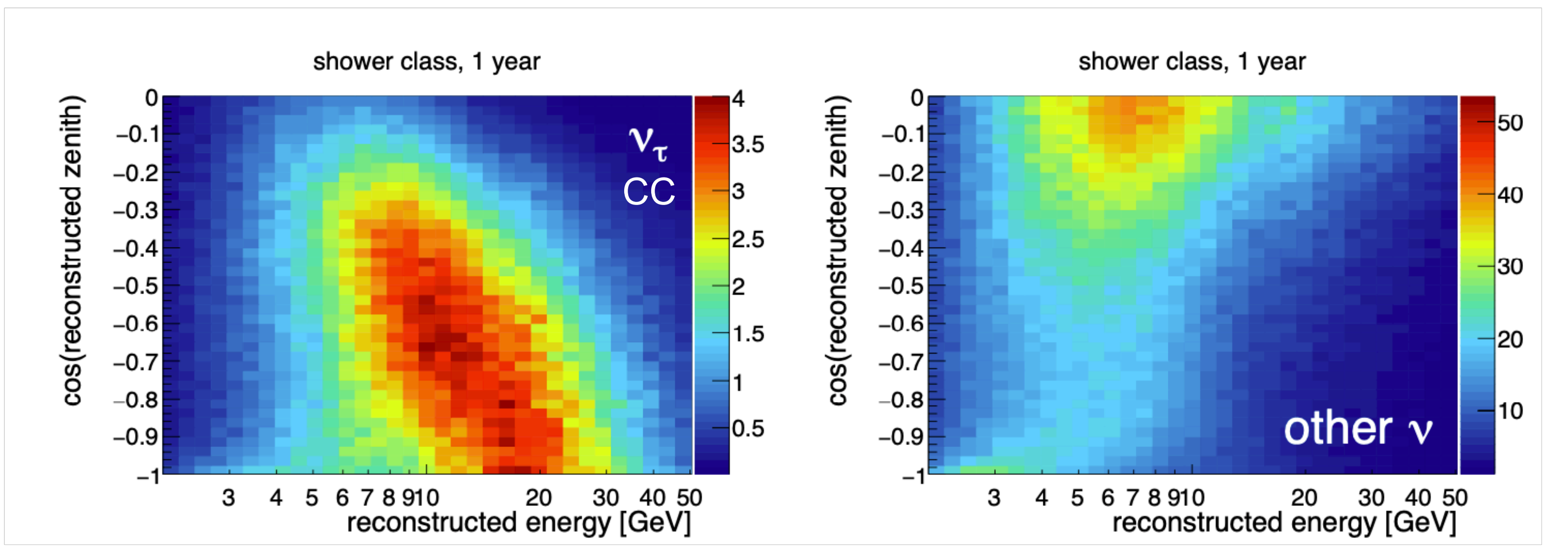
KM3NeT/ORCA sensitivity

KM3NeT/ORCA

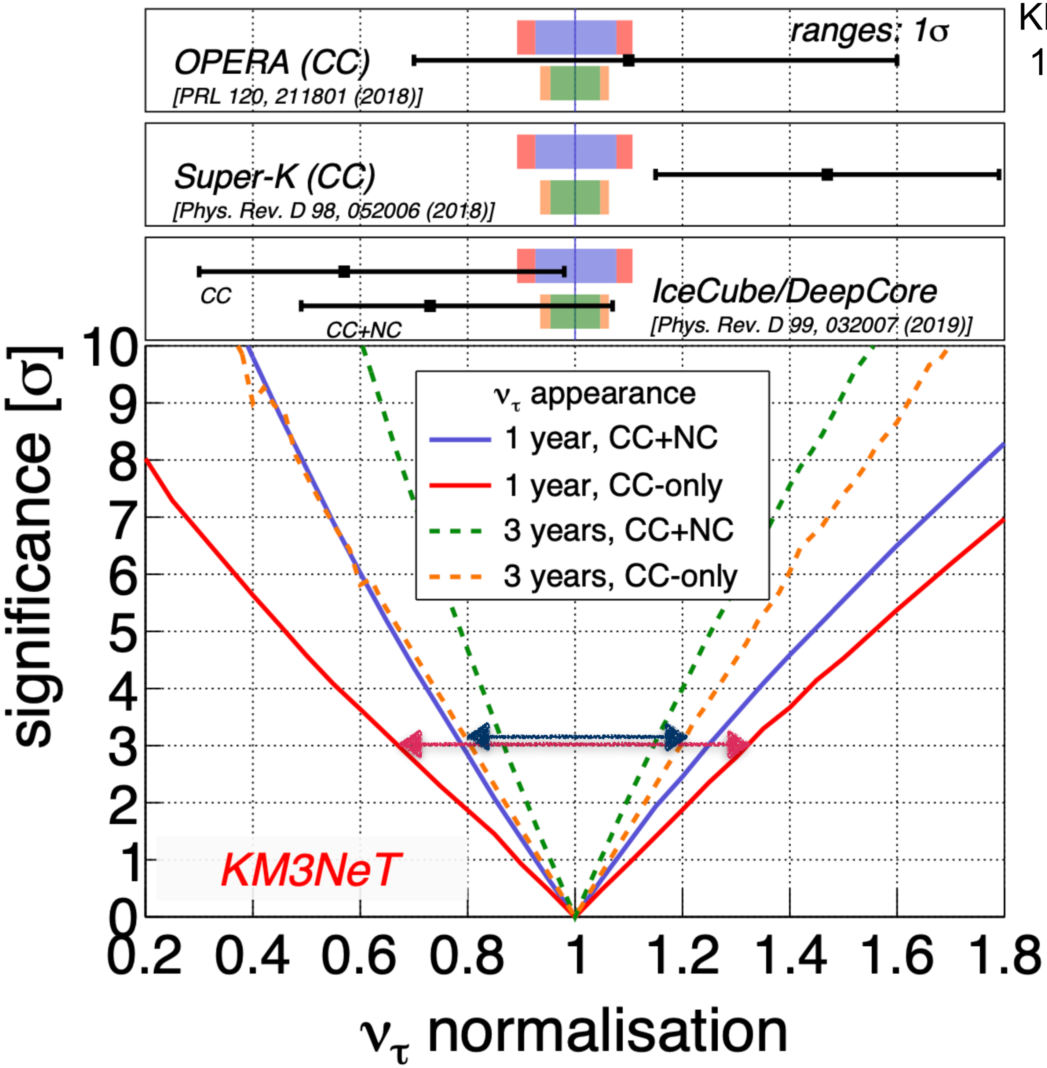
- dense detector with 20m horizontal / 9.3m vertical spacing between 2070 DOMs
- instrumented mass ~6.7 Mt
- currently: 10 out of 115 Detection Units deployed and taking data

- classification into three analysis classes
- >3000 ν_τ CC events per year in analysis sample:

	shower	middle	track
$\nu_\tau + \overline{\nu_\tau}$ CC	2.0×10^3	0.85×10^3	0.43×10^3
other ν	2.0×10^4	1.8×10^4	2.0×10^4



KM3NeT/ORCA sensitivity for 1 & 3 years of data taking



KM3NeT/ORCA 1σ projection, 1 and 3 years

- constraints at 3σ CL (CC-only case):

$\boxed{\pm 30\,\%}$ **after 1 year**

$\boxed{\pm 20\,\%}$ **after 3 years**

- after <2 months:
  5σ exclusion of ν_τ norm = 0

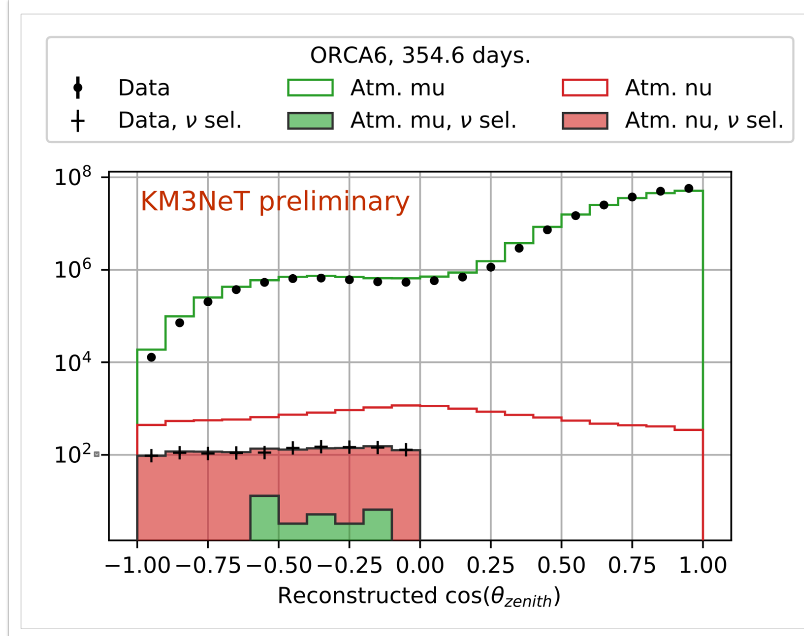
- KM3NeT/ORCA competitive already at early construction stage [PoS (ICRC2019) 1019]

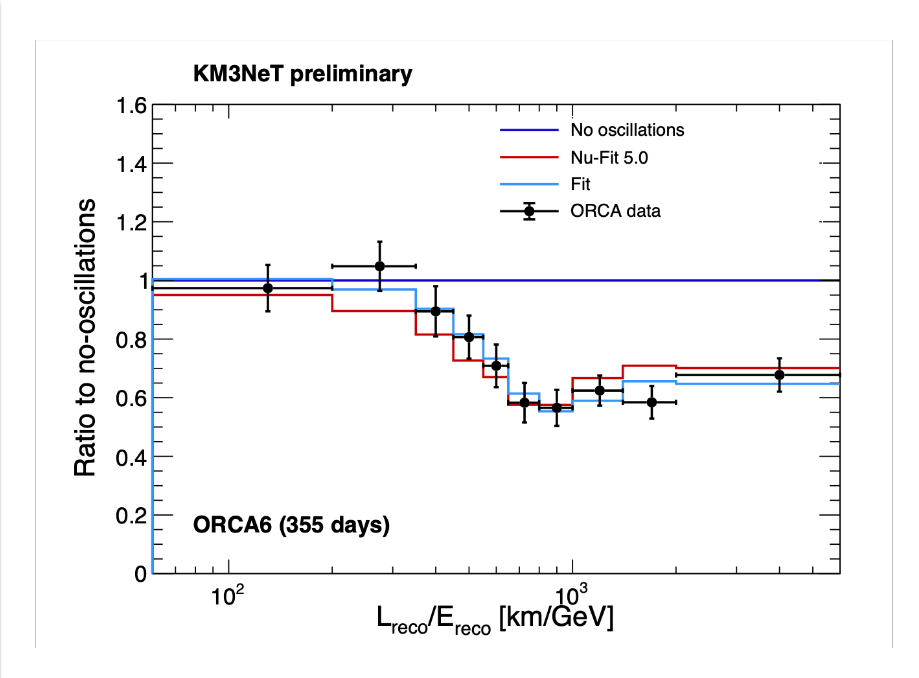
[arXiv:2103.09885, EPJC accepted]

First oscillation measurement with KM3NeT/ORCA

- first oscillation measurement: ν_μ disappearance mode
- analysed dataset: 355 out of 386 days taken with 6 DUs
- 'clean' neutrino sample

- atmospheric oscillation via **L/E** measurement
  - **L:** from reconstructed direction
  - **E:** from muon track length
- 5.9σ preference for oscillation



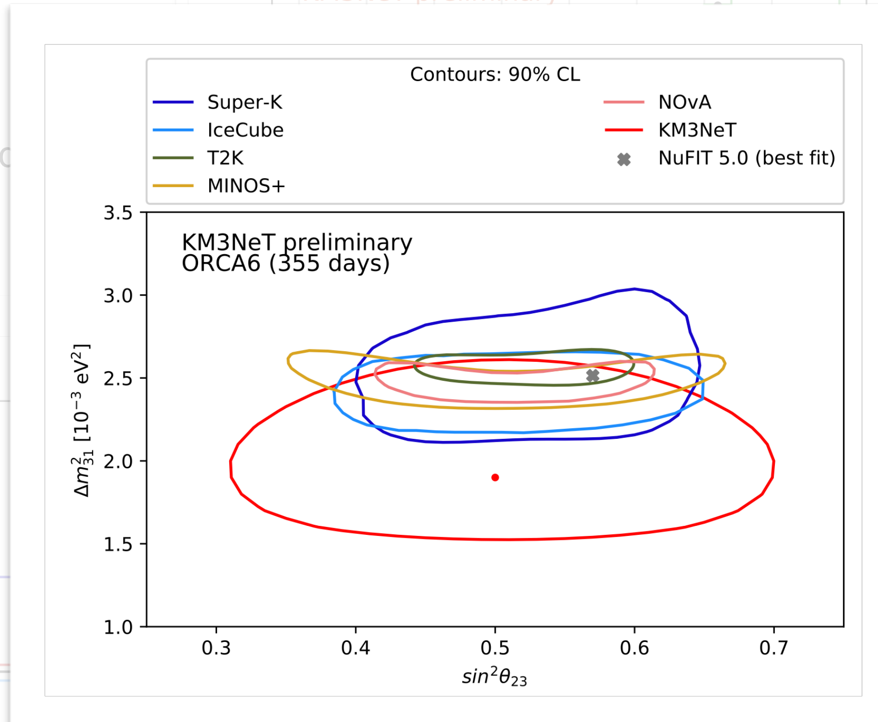


[PoS(ICRC2021)1123]

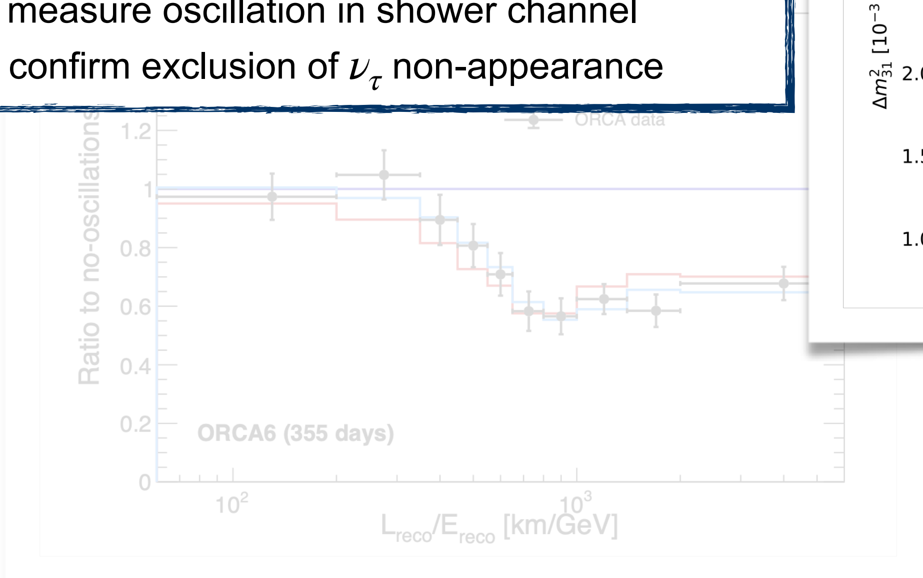
First oscillation measurement with KM3NeT/ORCA

- first oscillation measurement: ν_μ disappearance mode
- analysed dataset: 355 out of 386 days taken with 6 DUs
- ‘clean’ neutrino sample

- atmospheric oscillation via L/E measurement
  - traversed path length L from reconstructed d
  - energy E from muon track length



- KM3NeT/ORCA soon competitive in measuring atmospheric oscillation parameters
- next goals:
  measure oscillation in shower channel
  confirm exclusion of ν_τ non-appearance



[PoS(ICRC2021)1123]

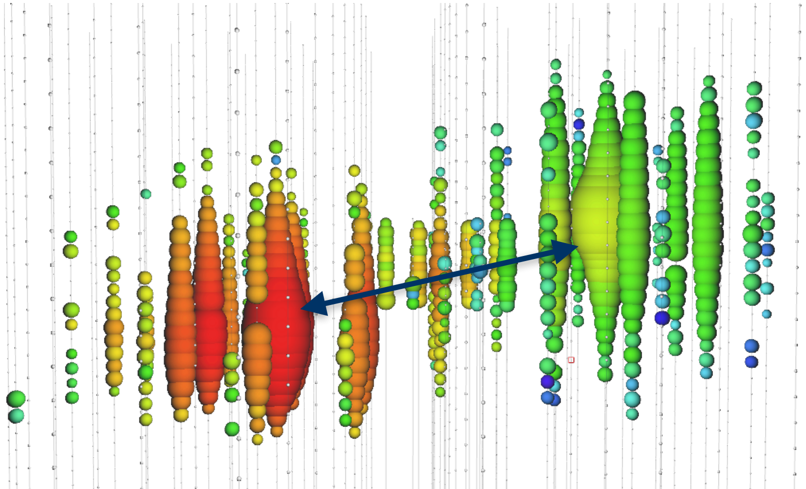
Double-bang and double-pulse signatures

Double-Cascades & Double-Pulses

- double-bangs almost*) background-free “smoking gun” signature but rarely large separation below ~PeV

- in reality: too rare to be currently observed (~O(100) astrophysical neutrinos in 7.5 years IceCube, steeply falling spectrum ~$E^{-2.87}$)

  [R. Abbasi et al., PRD 104 (2021)]



SImulated tau-neutrino double-bang, Credits: IceCube

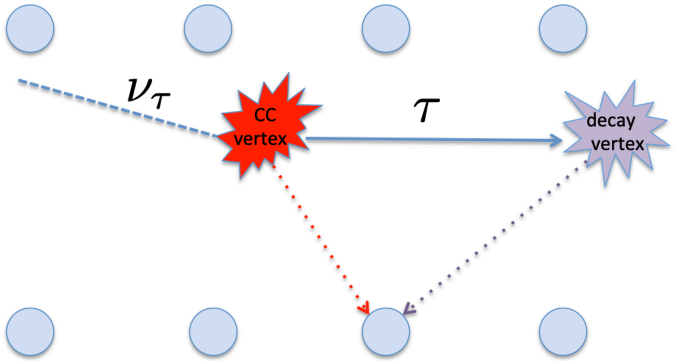
- **solution:** search for two cascades with smaller separation to lower the threshold

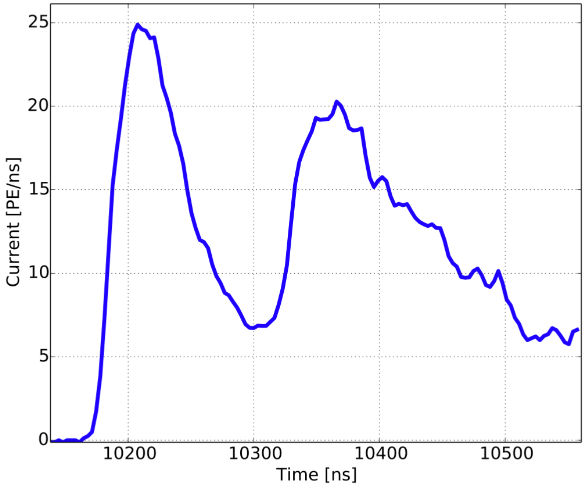
*) except: two coincident events or UHE muon tracks in sparse detectors

Double-Cascades & Double-Pulses

Options to lower energy threshold:

- direct maximum likelihood fit under hypothesis of two cascades [M.Usner,PoS(ICRC2017)974]
- double-pulse in PMT signals [IceCube, Phys. Rev. D 93, 022001 (2016)]





Note: need full waveform
(KM3NeT will need different approach, since record only
first hit + time-over-threshold; but: multi-PMTs and direct light)

- starting tracks [IceCube, PRD 99 (2019)]
- afterglows from muon decay / neutron capture [S. Li et al., PRL 123 (2019); A. Steuer, PoS(ICRC2017) 1008]

might be also an option,
but less “direct” & more affected by systematics

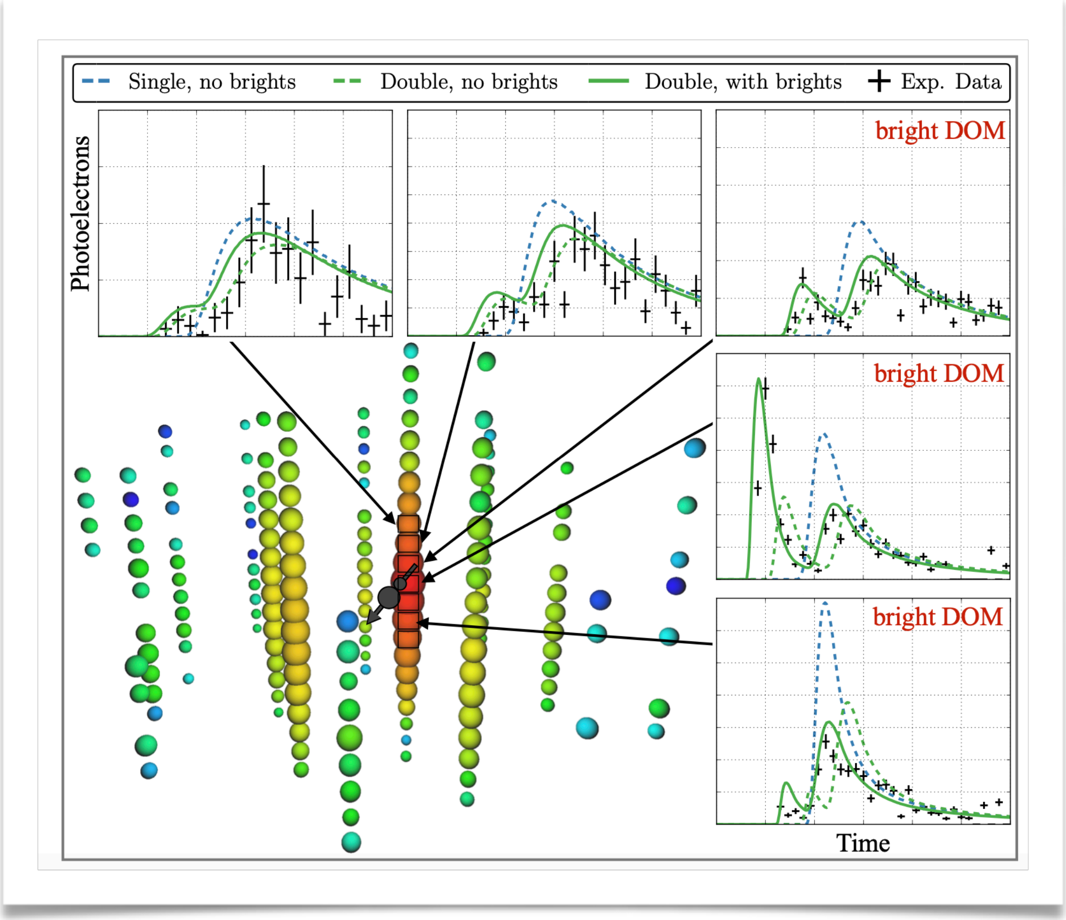
First detection of an astrophysical ν_τ:

$$\frac{E_1 - E_2}{E_1 + E_2} = -0.8$$

$$E_1 = 9 \text{ TeV} \;;\; E_2 = 80 \text{ TeV} \;; L = 17\text{m}$$

- event observed in 2014
- identified both in double-cascade and double-pulse analysis
- independent follow-up analyses with dedicated Monte Carlo:

- double-cascade: ~98% likely ν_τ
  [IceCube Collab., arXiv:2011.03561]
- double-pulse: >90% likely ν_τ
  [W. Tian et al., PoS(ICRC2021) 1146]

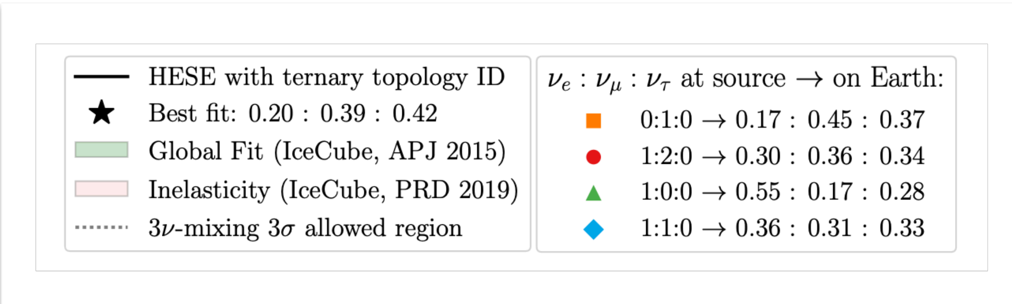


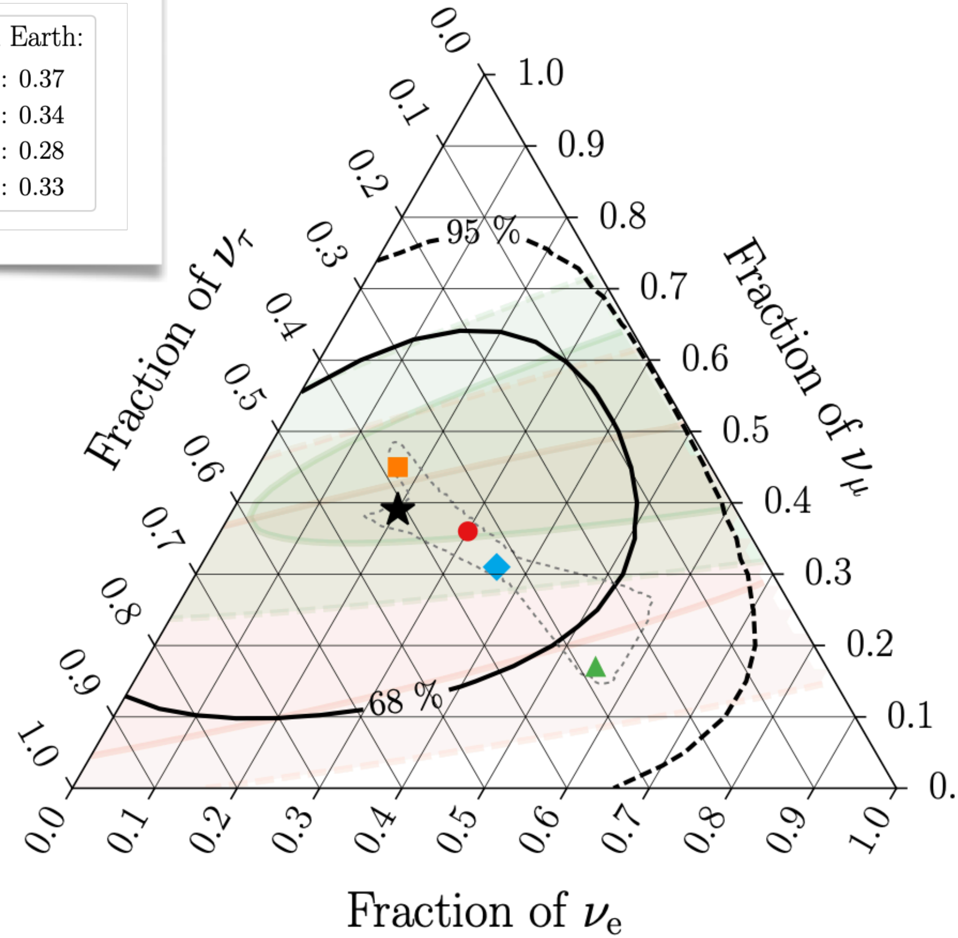
[IceCube Collab., arXiv:2011.03561]

Identified so far:

- 2 double-cascade candidates
  [J. Stachurska, PoS(ICRC2019) 1015]
- 2 double-pulse candidates
  [D. Xu, L. Wille, PoS(ICRC2019) 1036]
  [M. Meier, J. Soedingrekso, PoS(ICRC2019) 960]

Flavour composition measurement including ν_τ:





- 2.8σ preference for non-zero astrophysical ν_τ
- higher statistics needed!

[IceCube Collab., arXiv:2011.03561]

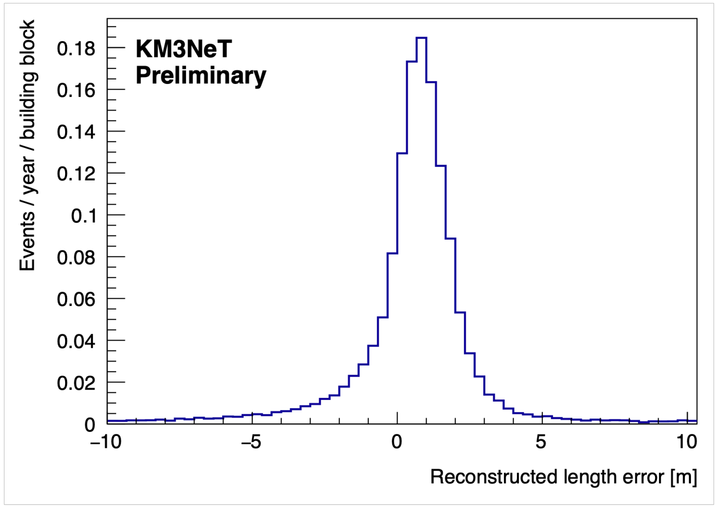
Flavour composition measurement future:

- Baikal-GVD has already identified one double cascade event: [E. Eckerova, PoS(ICRC2021) 1167]

  $E_1 = 8$ TeV, $E_2 = 4.7$ TeV, L = 330m, $P(\nu_\tau)$~0

- KM3NeT has presented double-cascade reconstruction technique based on simulations

  [T. van Eeden, J. Seneca et al., PoS(ICRC2021) 1089]

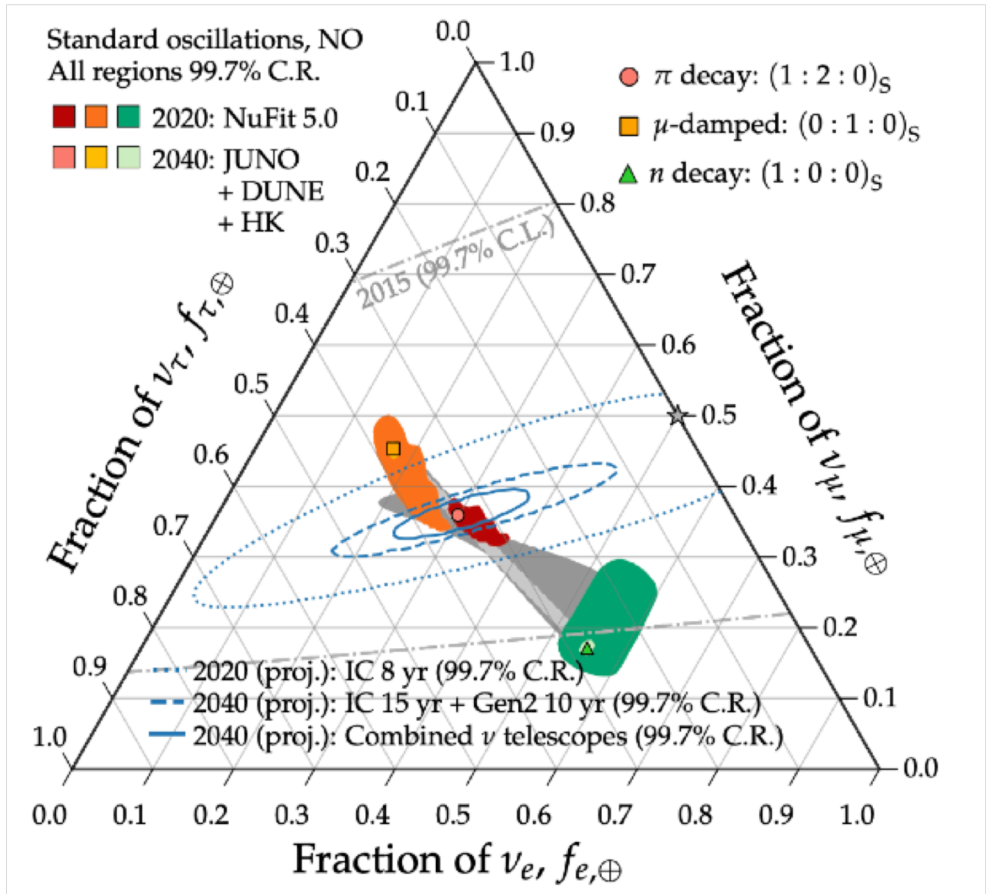


- Longer term: P-One, IceCube-Gen2

  →energy-dependent flavour composition measurement

Flavour composition measurement future:

- Baikal-GVD has a
  double cascade e
  E_1 = 8 TeV, E_2 =
- KM3NeT has pres
  reconstruction tec
  [T. van Eeden, J. Seneca



[Song et al., arXiv:2012.12893]

- Longer term: P-On
  →energy-dep

Summary

- ν_τ signatures depend on energy regime:
  - GeV: shower-like, only statistical measurement in energy / zenith / event ID - space
  - TeV-PeV: double-pulse / double-cascades (double-bangs are rare)
  - EeV: Earth skimming taus, or multiple in-ice showers using radio detection
- atmospheric tau-neutrino appearance:
  - only neutrino telescopes achieve high statistics in ν_τ
  - IceCube/DeepCore: >3σ exclusion of non-appearance, normalisation weakly constrained
  - O(15%) and O(10%) precision possible with more livetime; IceCube/Upgrade
  - further improvement by KM3NeT/ORCA (20% at 3σ and CC-only)
- flavour composition:
  - IceCube has identified first astrophysical ν_τ and measured composition with all 3 flavours
  - Baikal-GVD and KM3NeT are developing reconstruction methods
  - More statistics and future detectors needed to constrain source models