Particle Physics with Neutrino Telescopes

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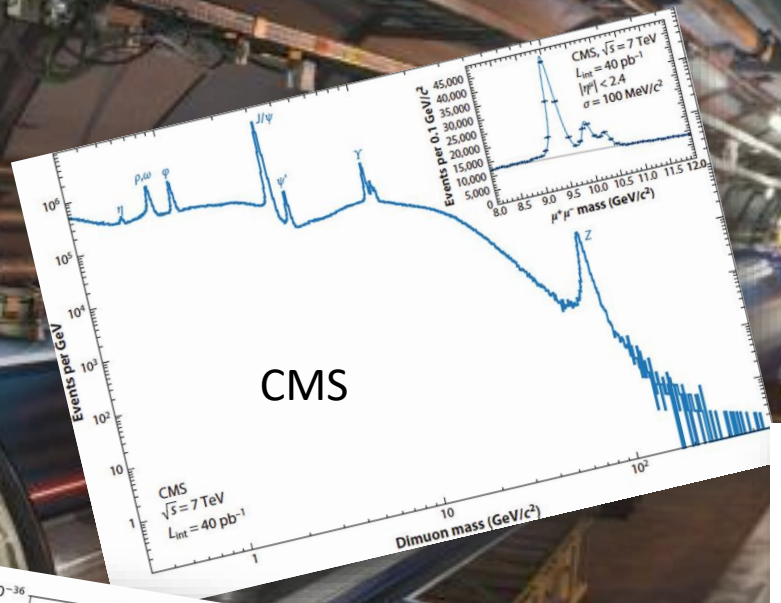
Technische Universität München

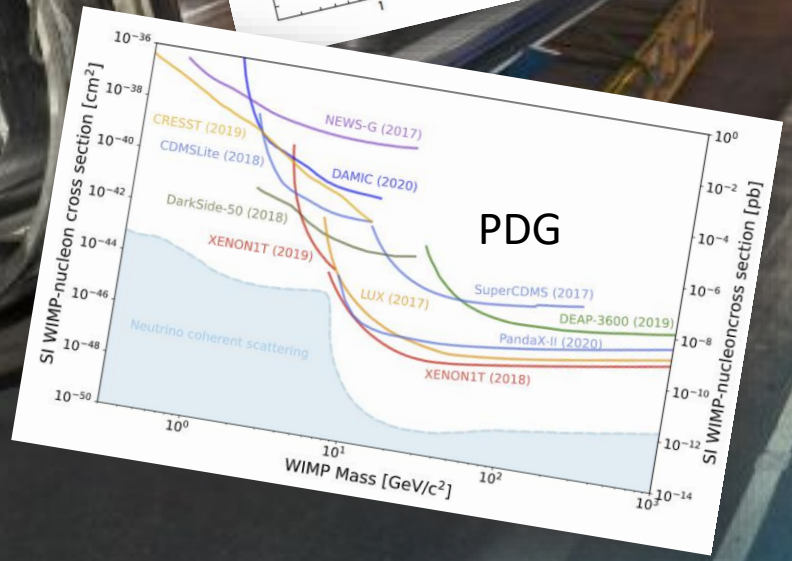
SFB 1258 Neutrinos Dark Matter Messengers

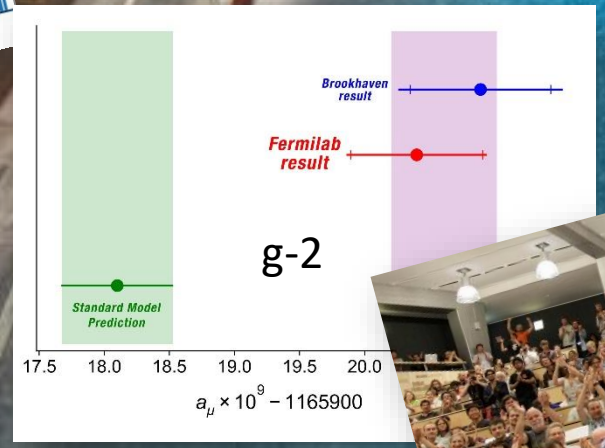
PUNCH 4 NFDI

ORIGINS Excellence Cluster

Particle Physics







Neutrino telescopes: Detection

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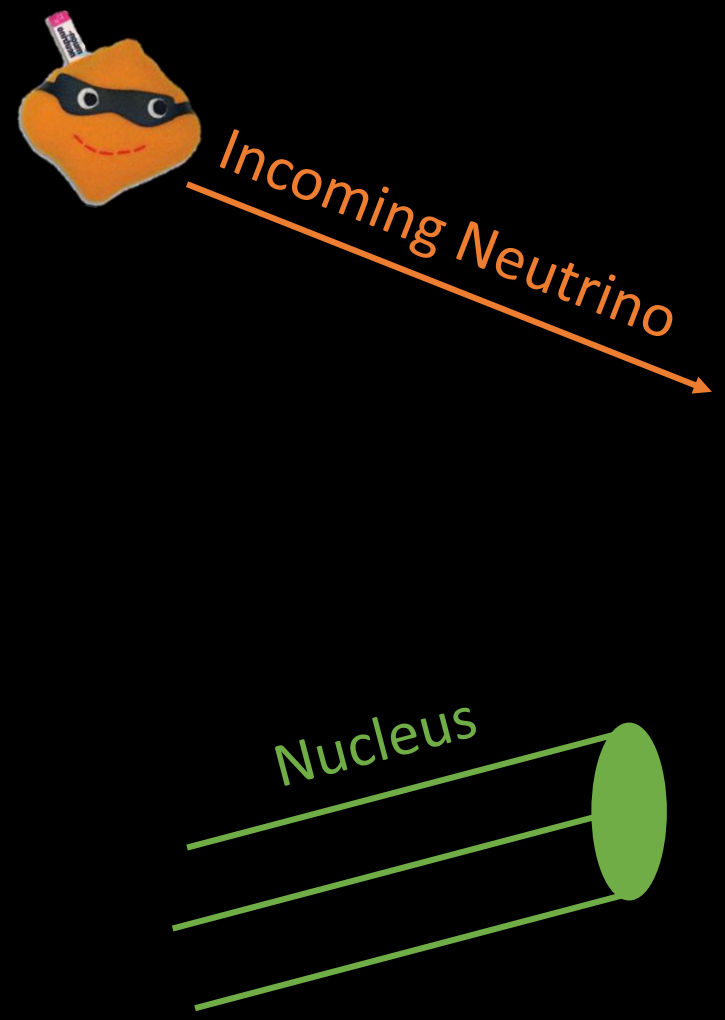
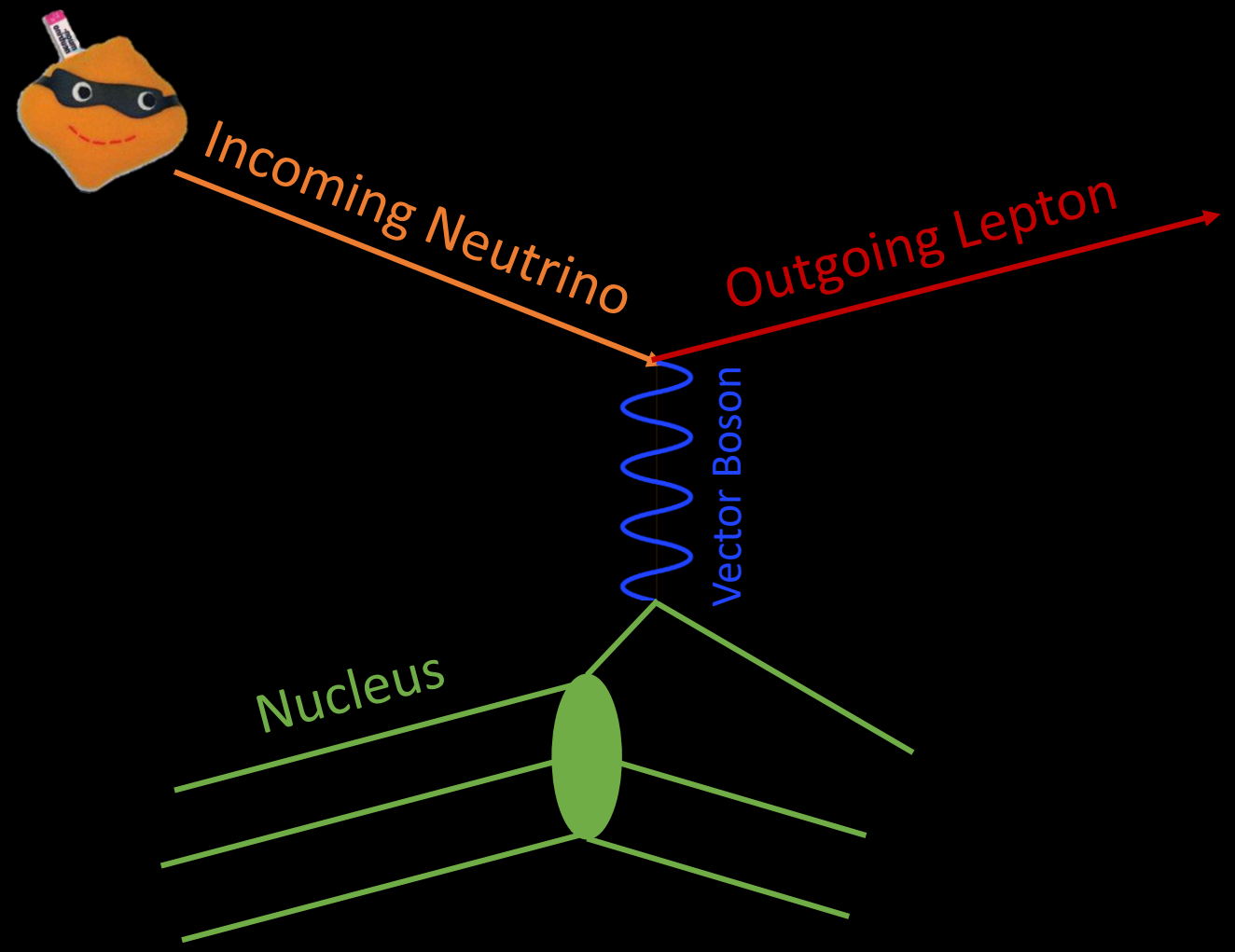


Neutrino telescopes: Detection



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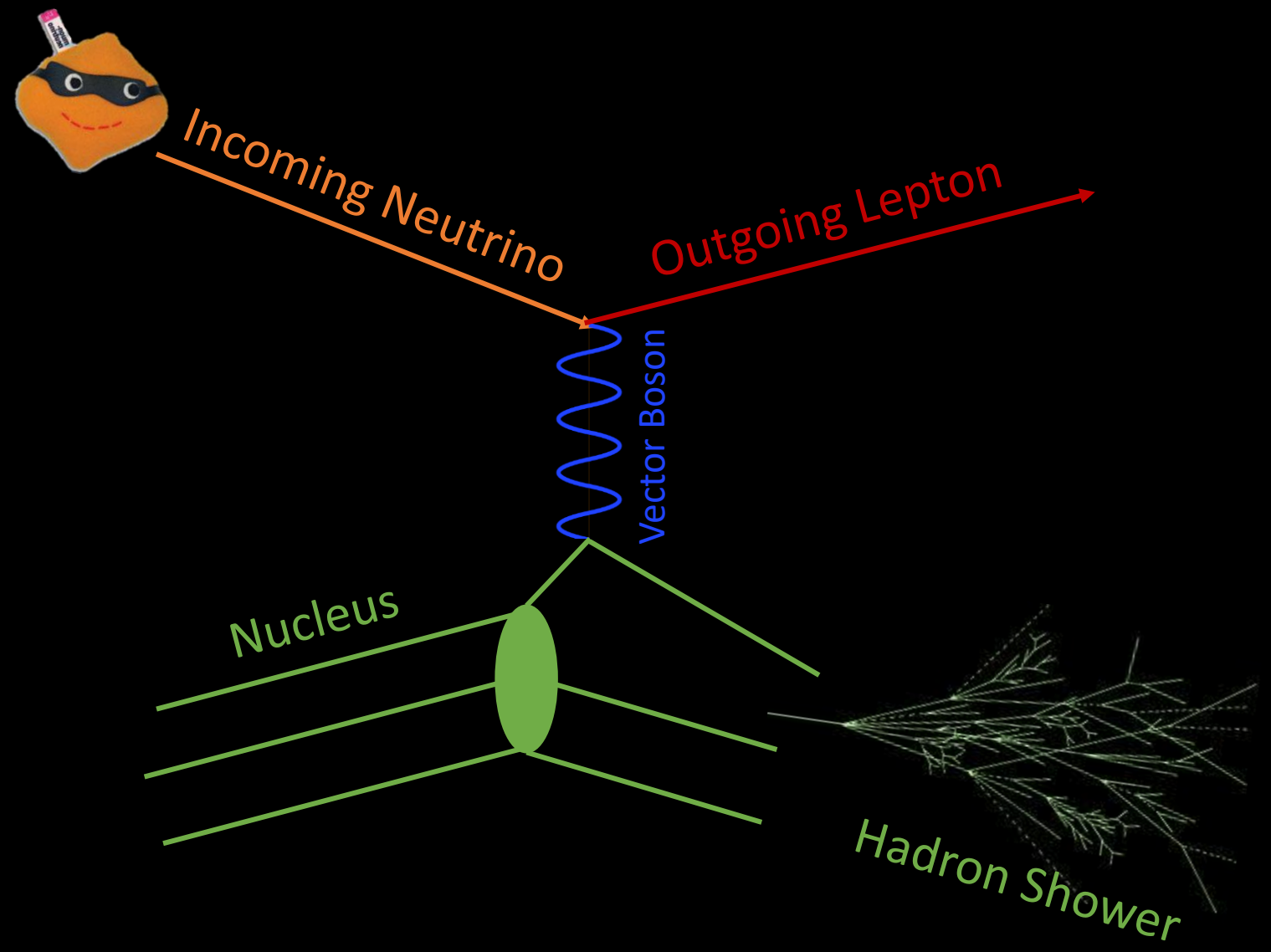
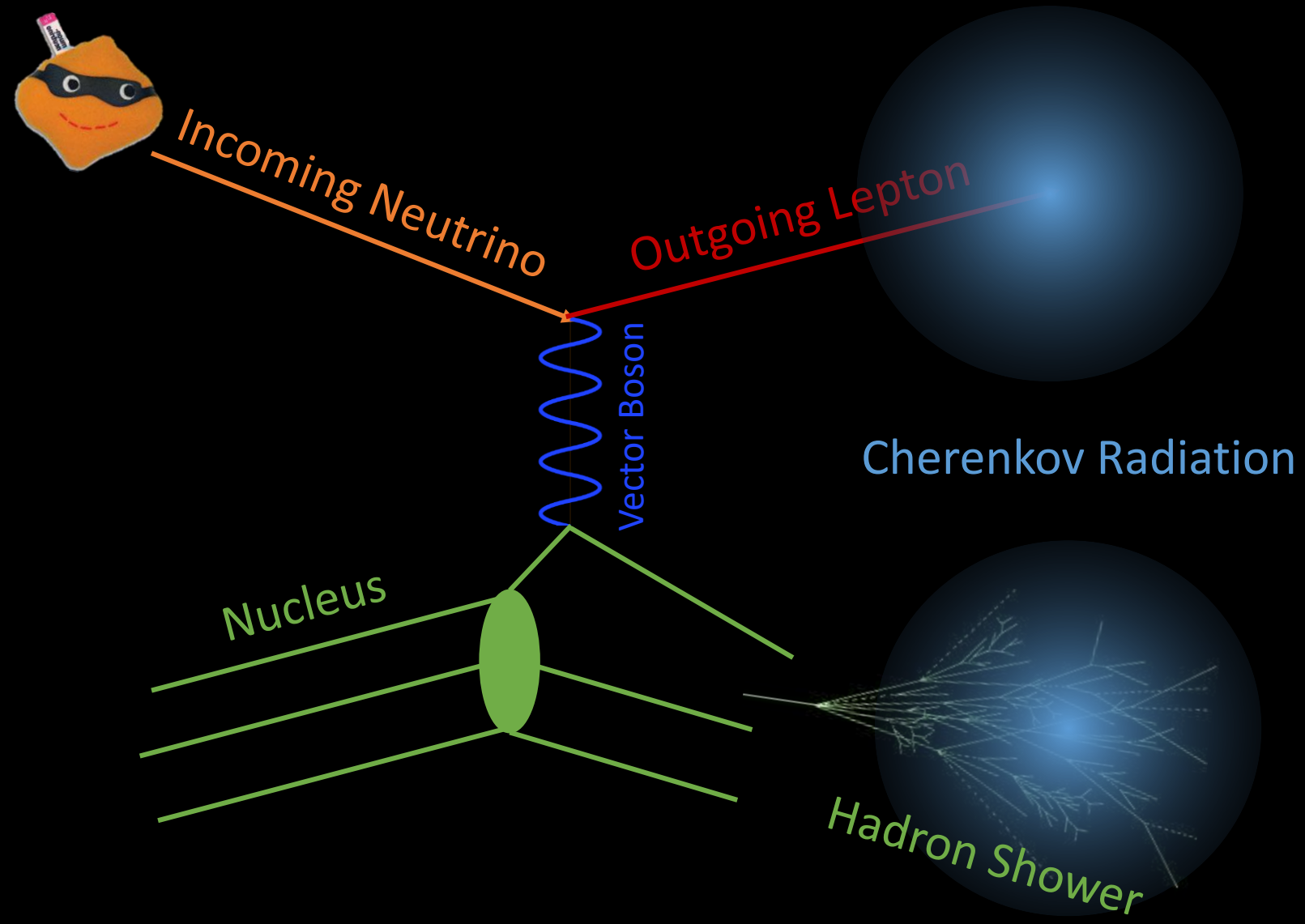
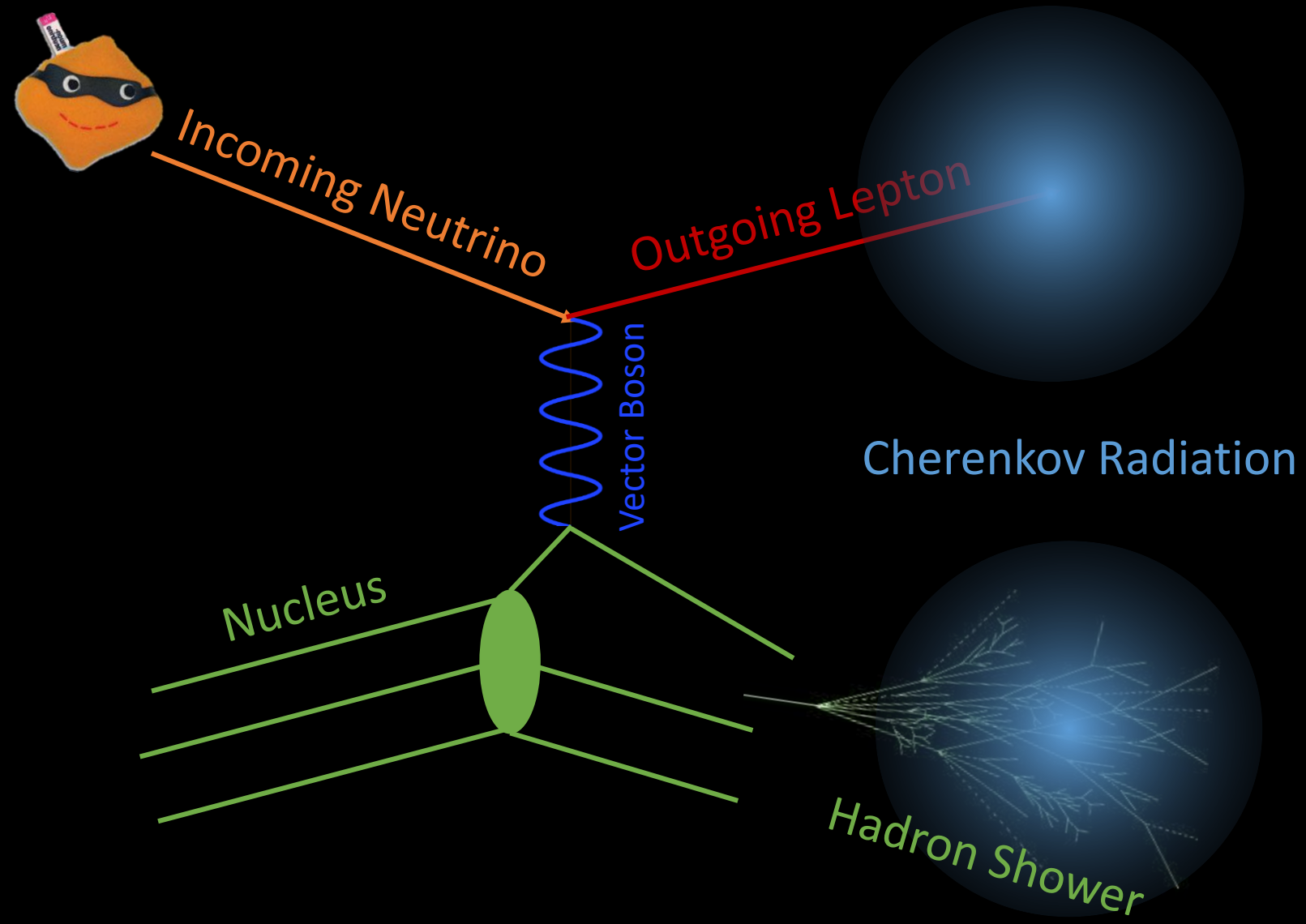


Neutrino telescopes: Detection

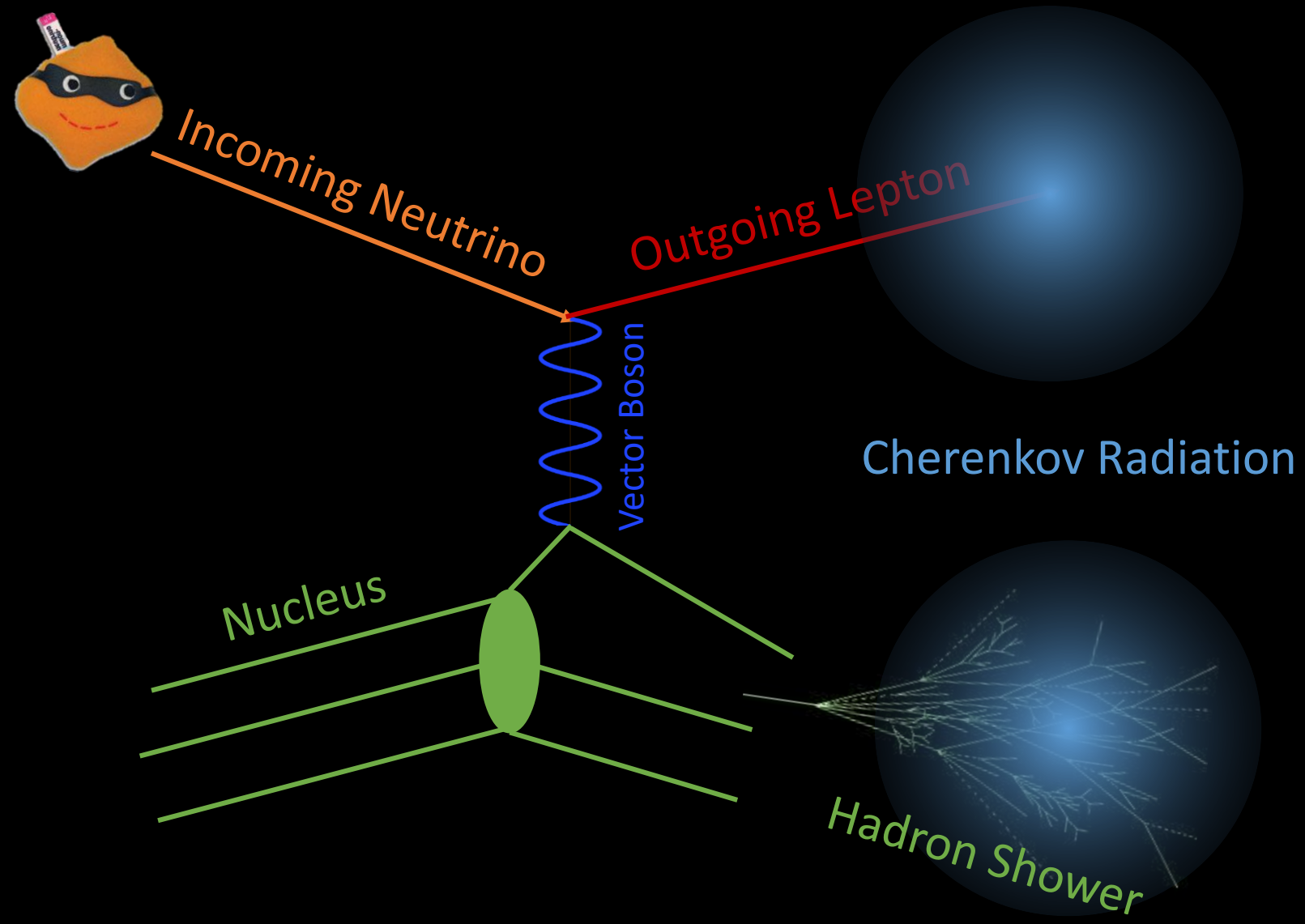


Neutrino telescopes: Detection



Detector properties:

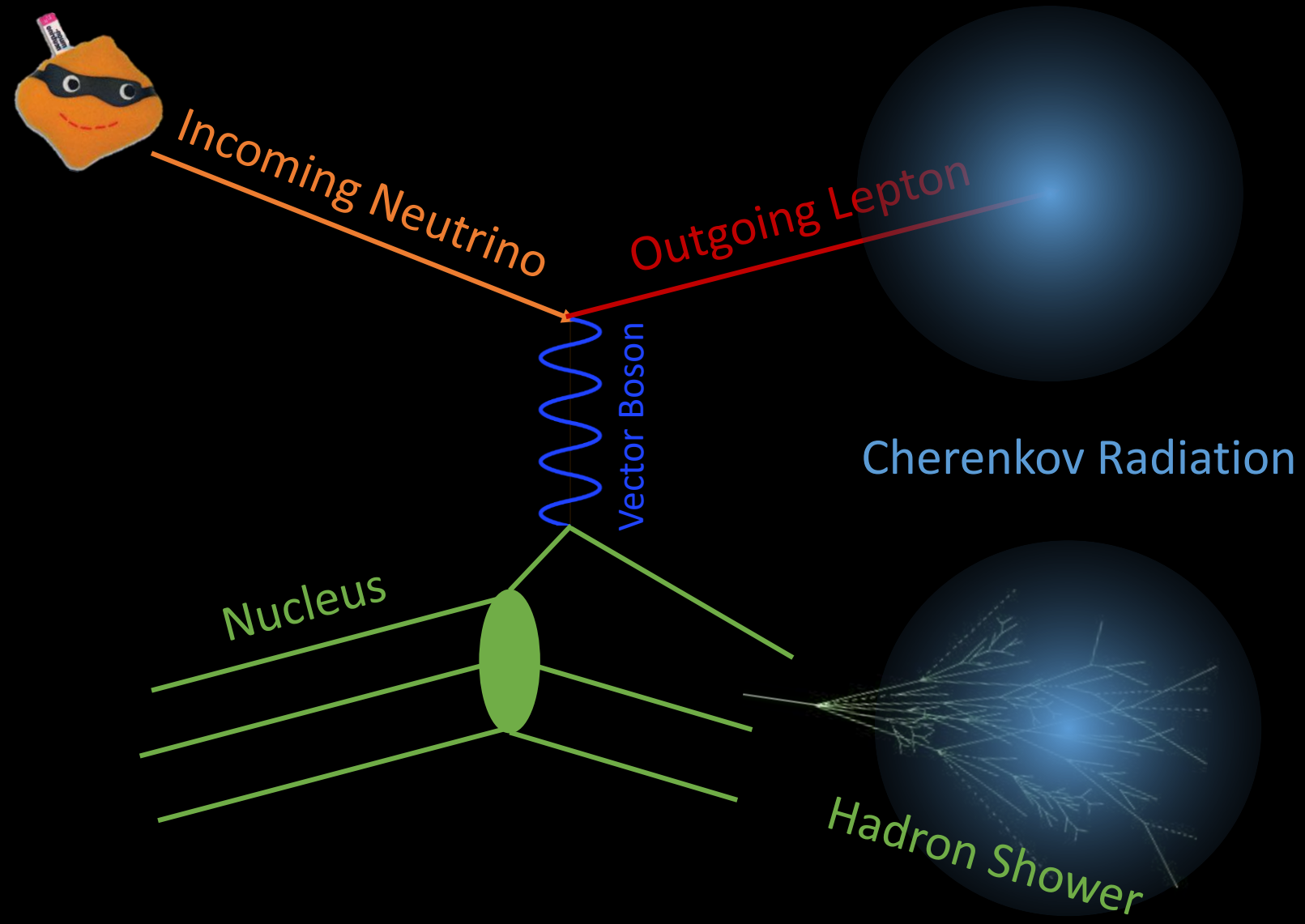
Neutrino telescopes: Detection



Detector properties:

- Transparent Medium

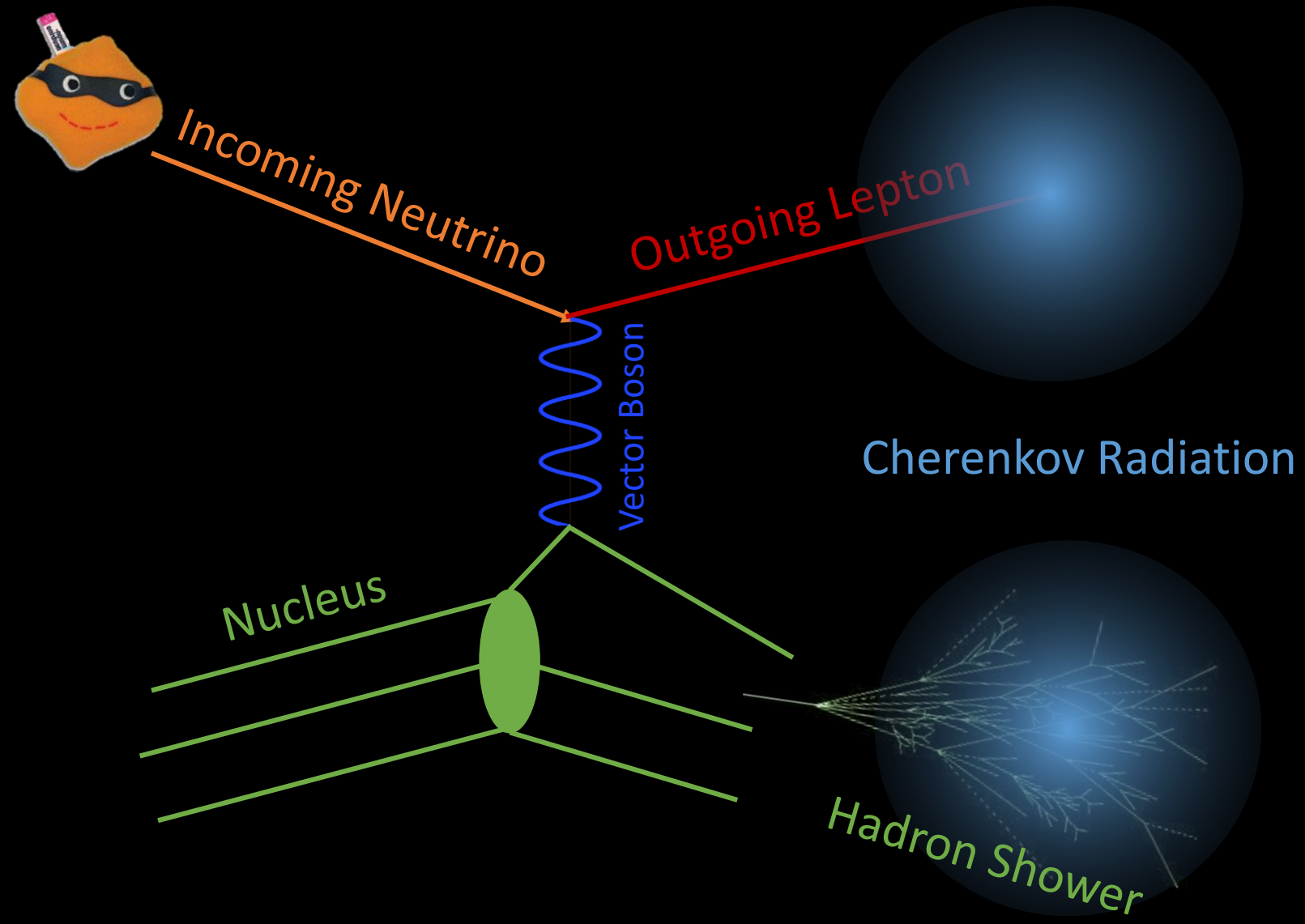
Neutrino telescopes: Detection



Detector properties:

- Transparent Medium
- Deep underground to shield backgrounds

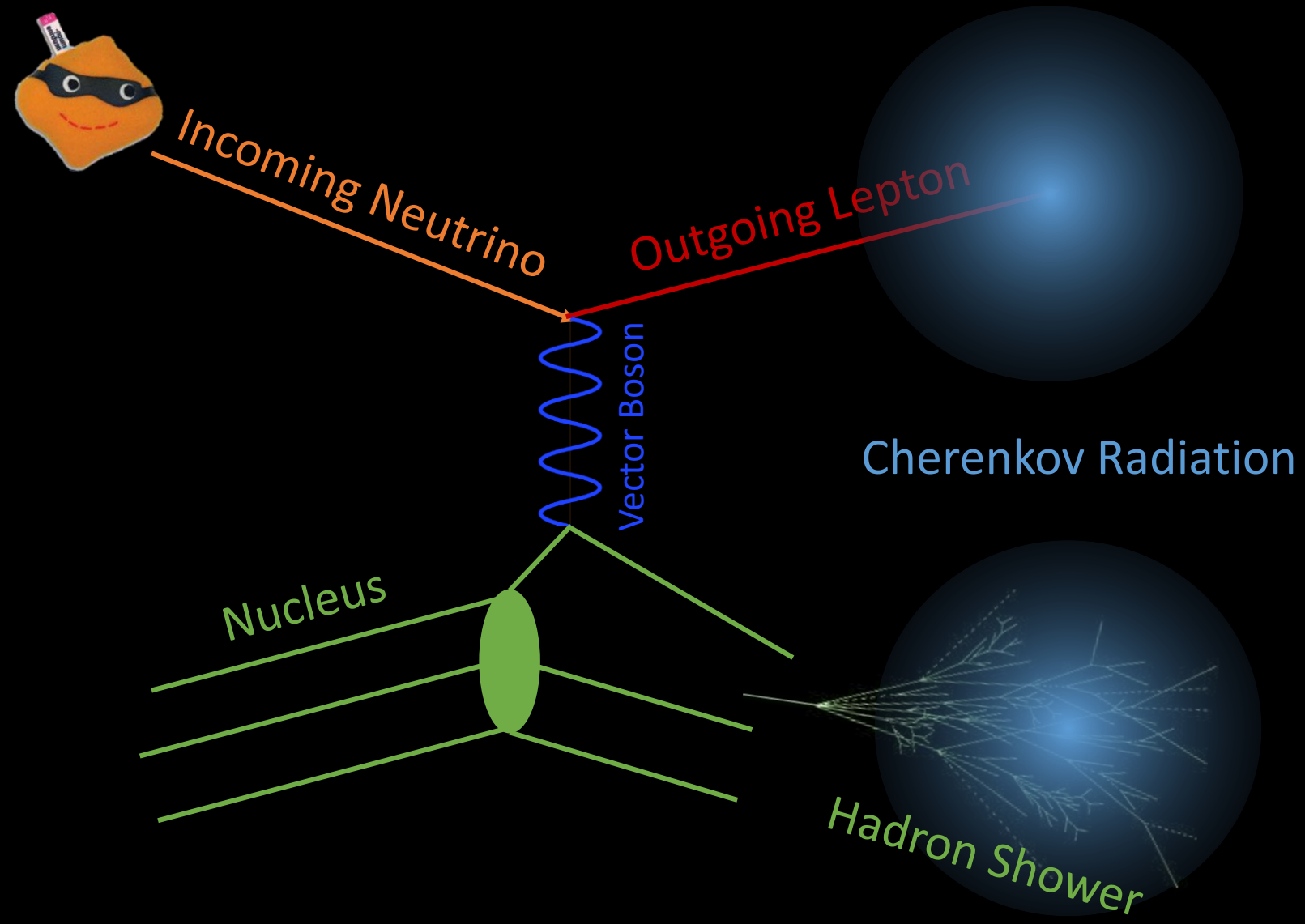
Neutrino telescopes: Detection



Detector properties:

- Transparent Medium
- Deep underground to shield backgrounds
- HUGE Volume
  - Interactions are rare
    Events can spread over hundrets of meters

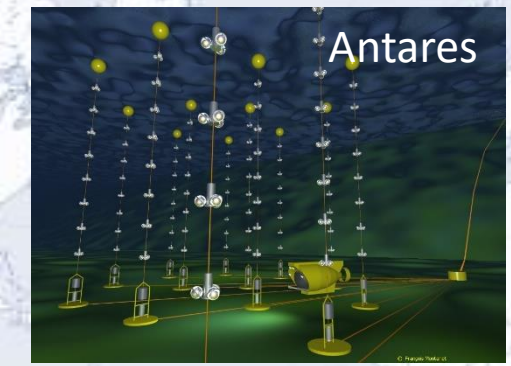
Neutrino telescopes: Detection



Detector properties:

- Transparent Medium
- Deep underground to shield backgrounds
- HUGE Volume
  - Interactions are rare
    Events can spread over hundrets of meters

→ Deep Water / Ice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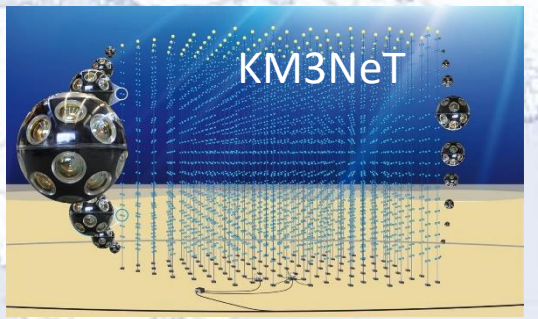
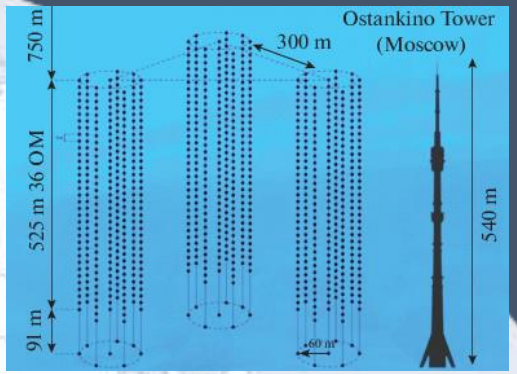
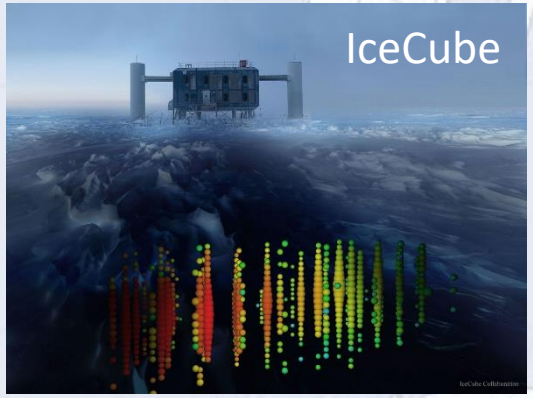
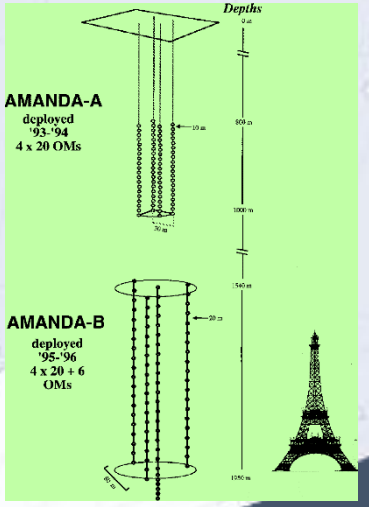

KM3NeT

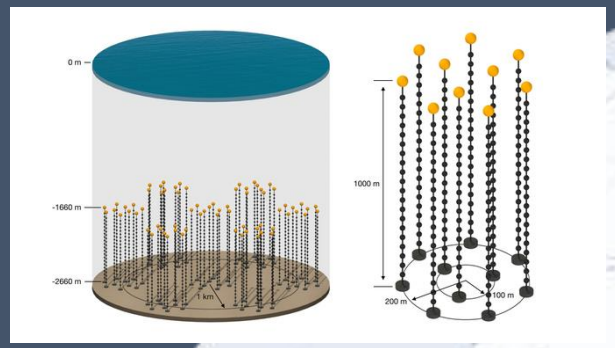

750 m
525 m 36 OM
91 m
300 m
Ostankino Tower
(Moscow)
540 m
60 m

GVD

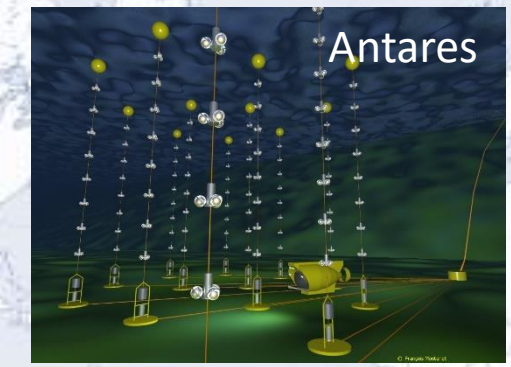

IceCube

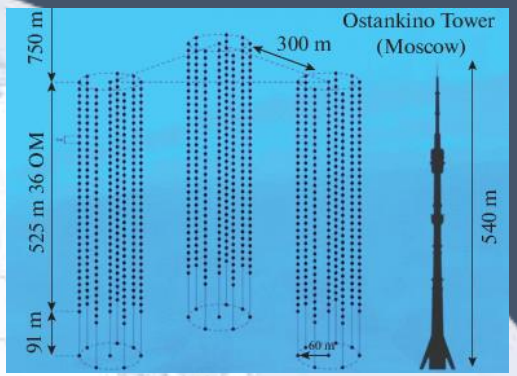
AMANDA


Depths
AMANDA-A
deployed
'93-'94
4 x 20 OMs
AMANDA-B
deployed
'95-'96
4 x 20 + 6
OMs

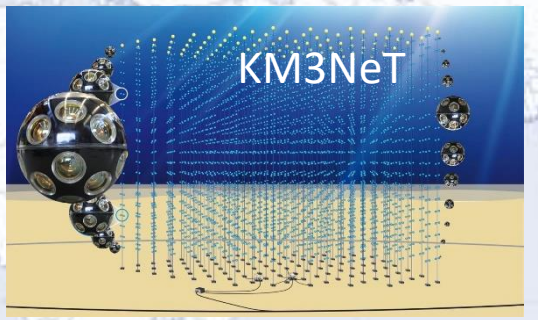


P-ONE

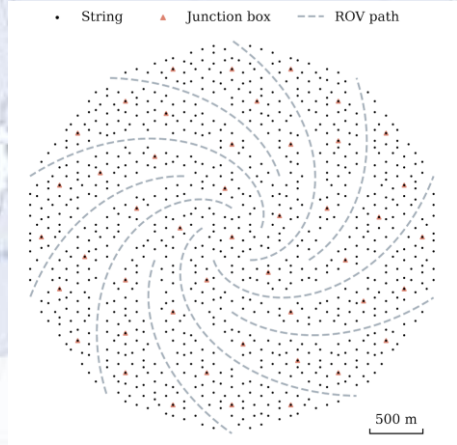




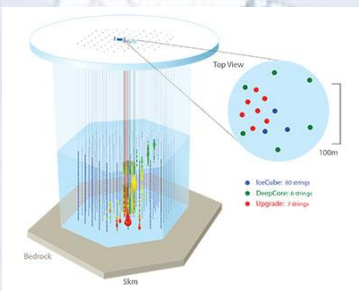
GVD

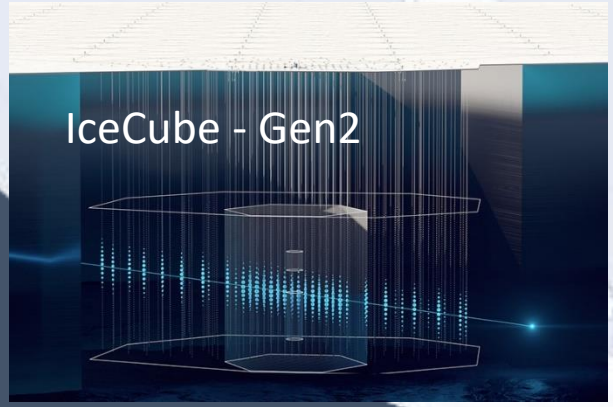


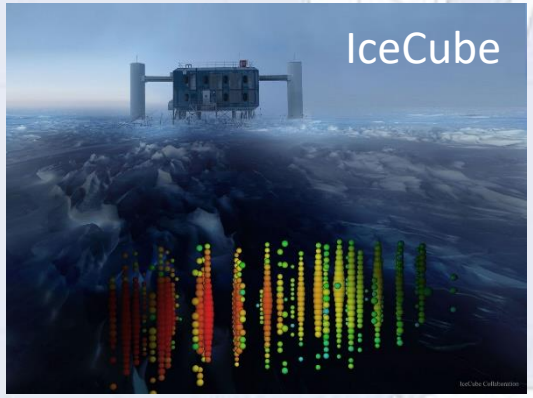
Trident?



IceCube Upgrade







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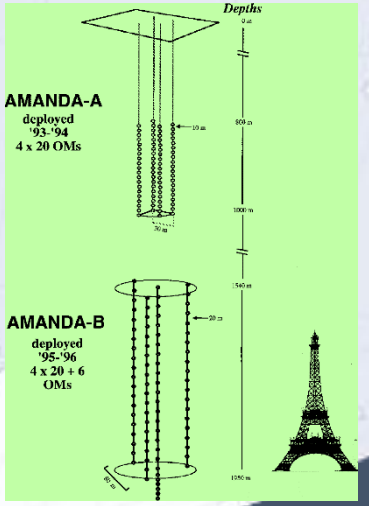
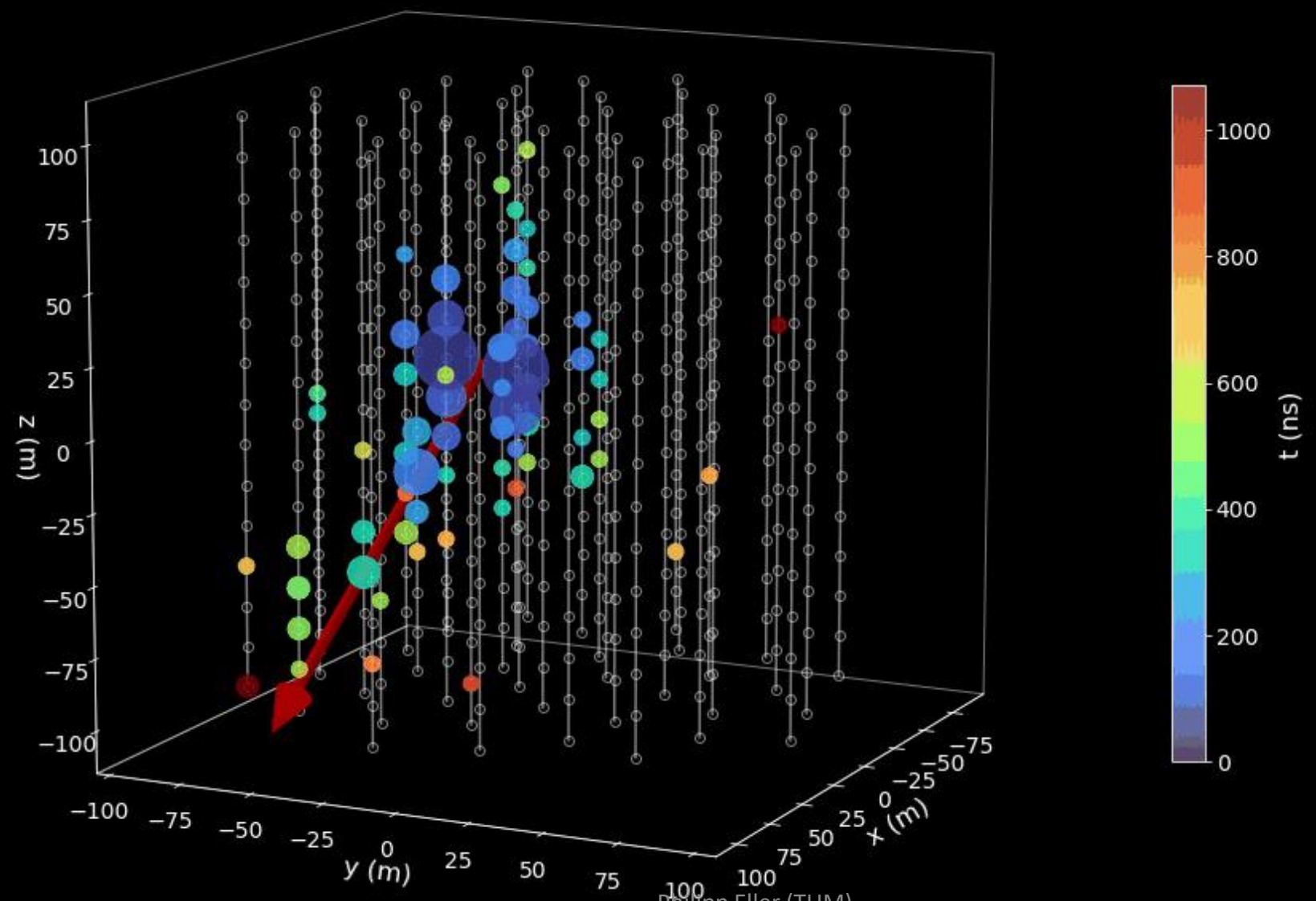


Example Event

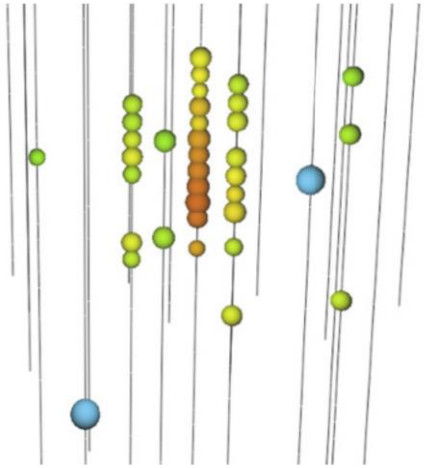


Energy of Interaction

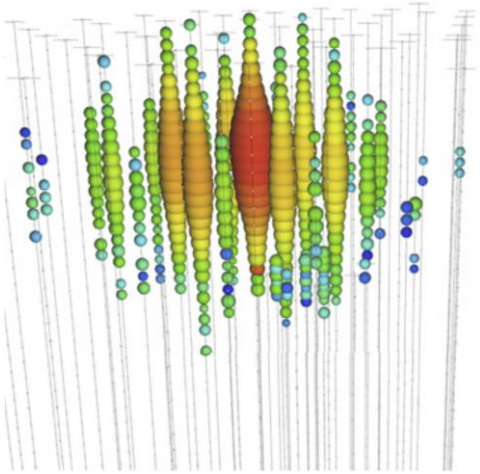
- From the amount* of observed Cherenkov light

  (*) and the timing, vertex position, geometry, optical properties, …

  → We can estimate the **deposited energy**



GeV



PeV

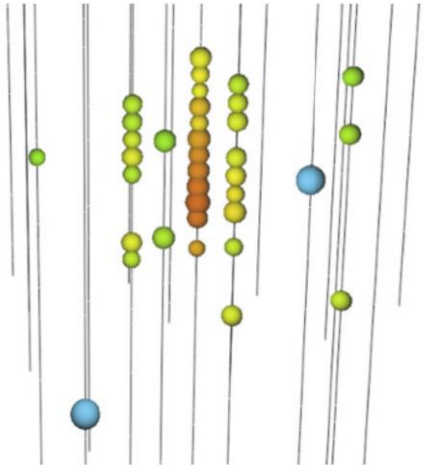
Energy

Energy of Interaction

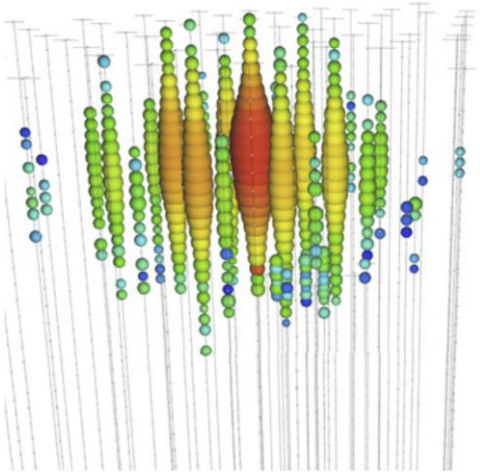
- From the amount* of observed Cherenkov light

  (*) and the timing, vertex position, geometry, optical properties, …

  → We can estimate the **deposited energy**



GeV

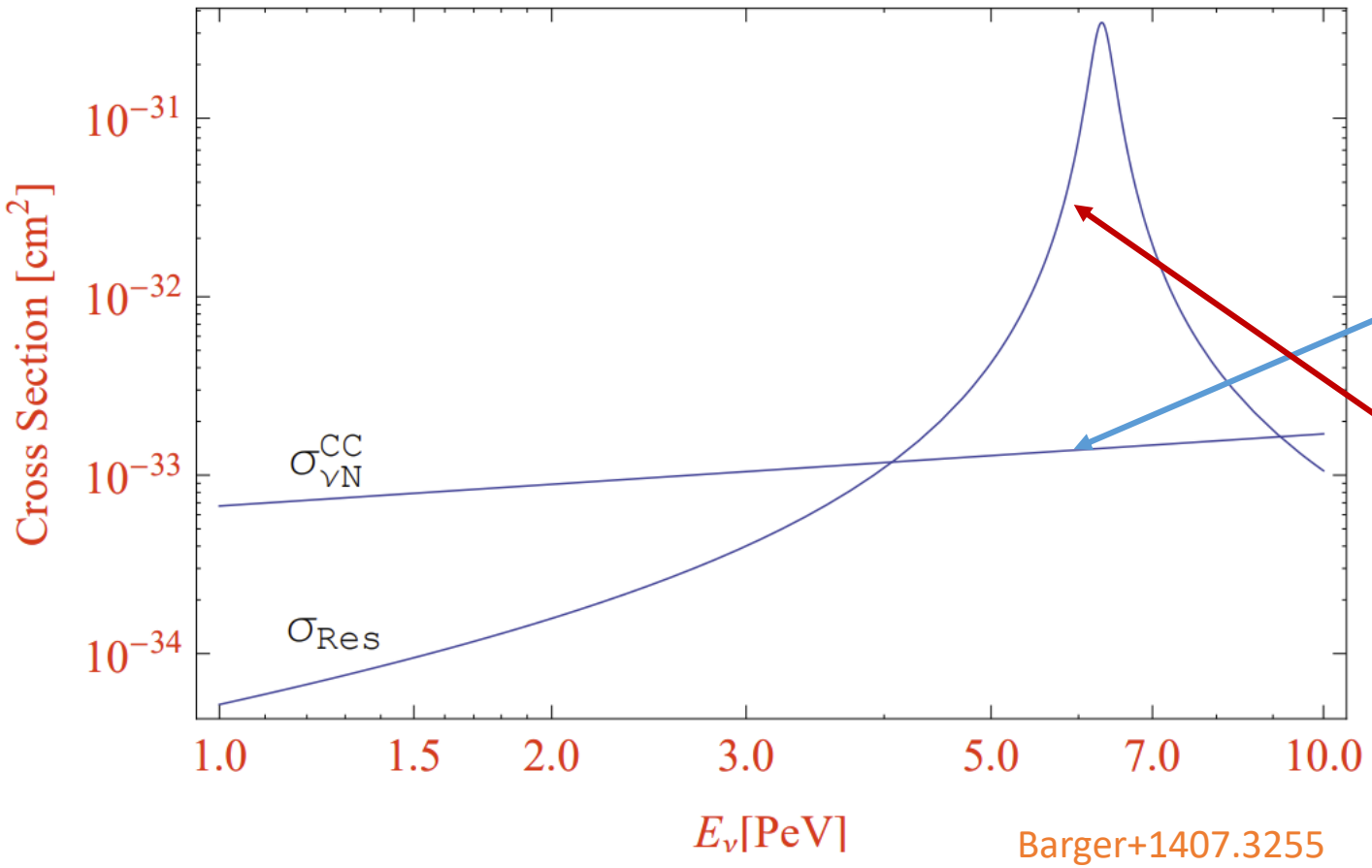


PeV

Energy

Event "**Reconstruction**": Statistically infer energy of neutrino interaction based on observed light
see e.g. IC 1311.4767

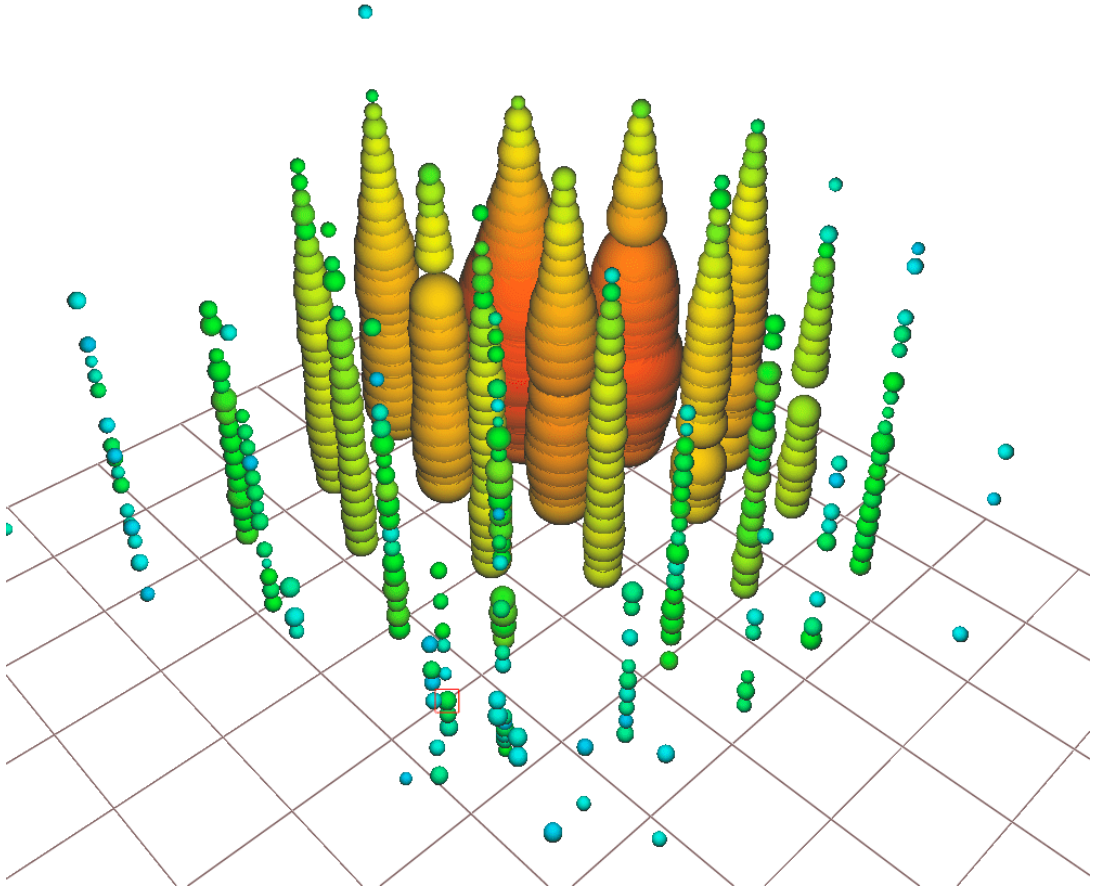
Cross section



Barger+1407.3255

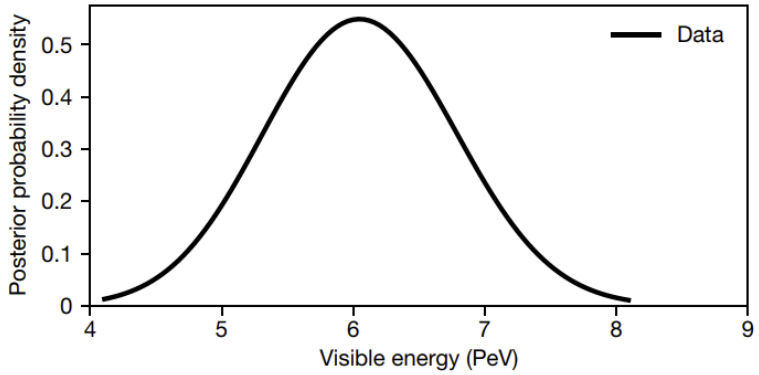
- Deep inelastic scattering
  - Neutrino-nucleon
- Slowly rising cross section for CC and NC
- Glashow resonance
  - $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ decay
  - On-shell W resonance
  - 6.3 PeV

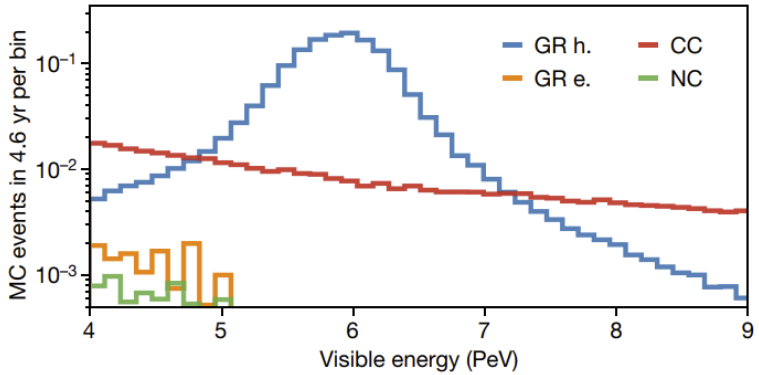
Glashow resonance in IceCube



IceCube 2110.15051

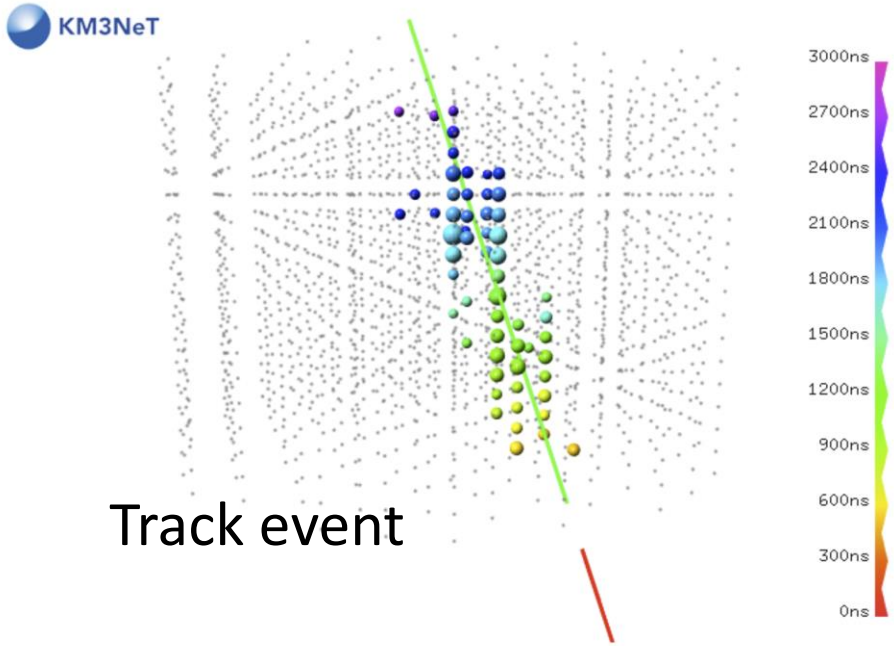
- 6.05 ± 0.72 PeV event observed
  - Muons observed in particle showers → smoking gun for hadronic decay of W
  - Clear evidence for anti-electron neutrino



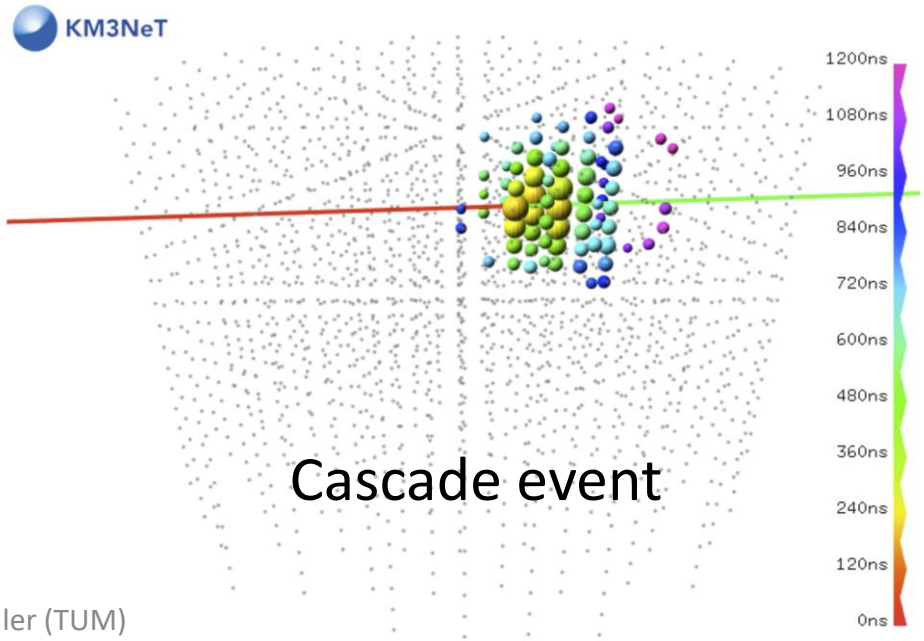


Adding Event Topology

- Some interactions deposit large fractions of the energy into muons
  - Numu CC interactions, and some nutau CC interactions
  - Muons can travel appreciable distances emitting Cherenkov light → “Track”



Track event



Cascade event

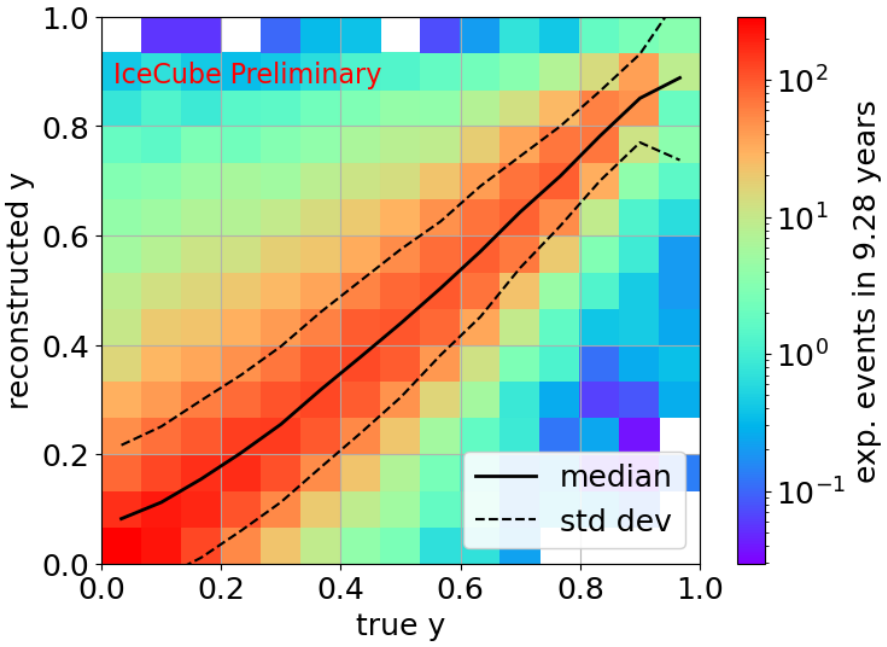
Inelasticity

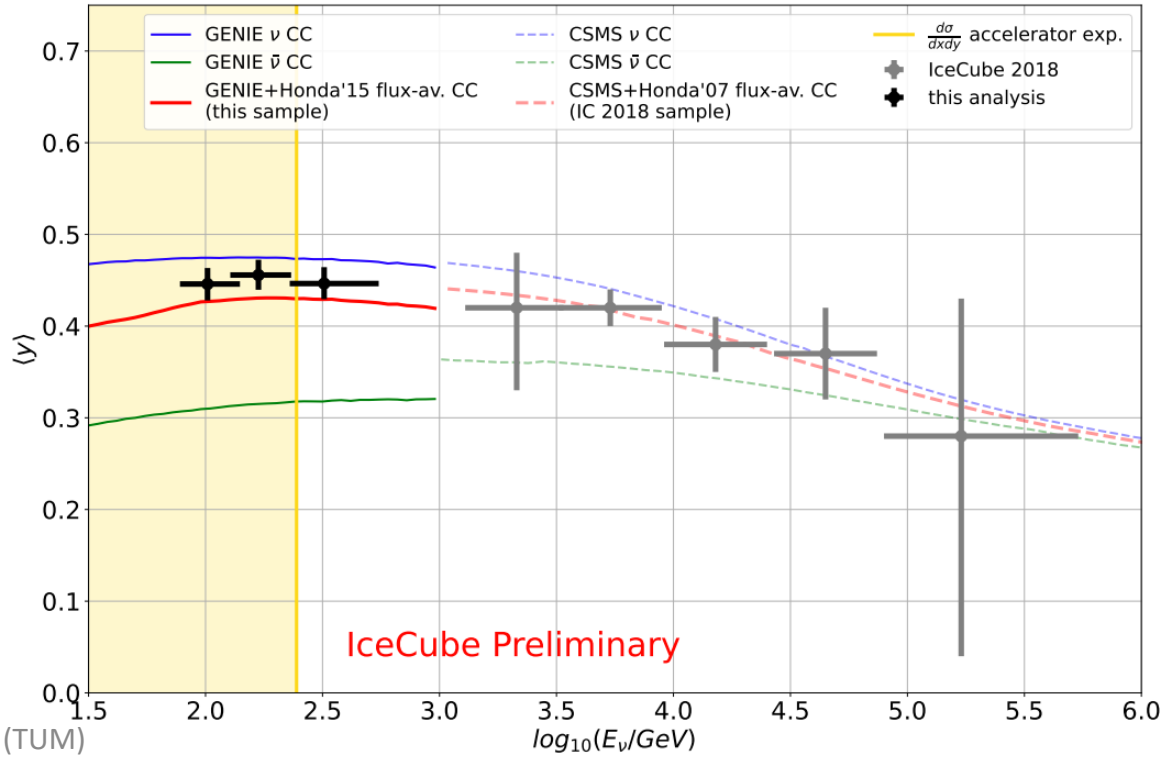
Separately estimate the energy of the cascade and the track

→ Bjorken y of deep inelastic scattering "Inelasticity"

For numu CC interactions:

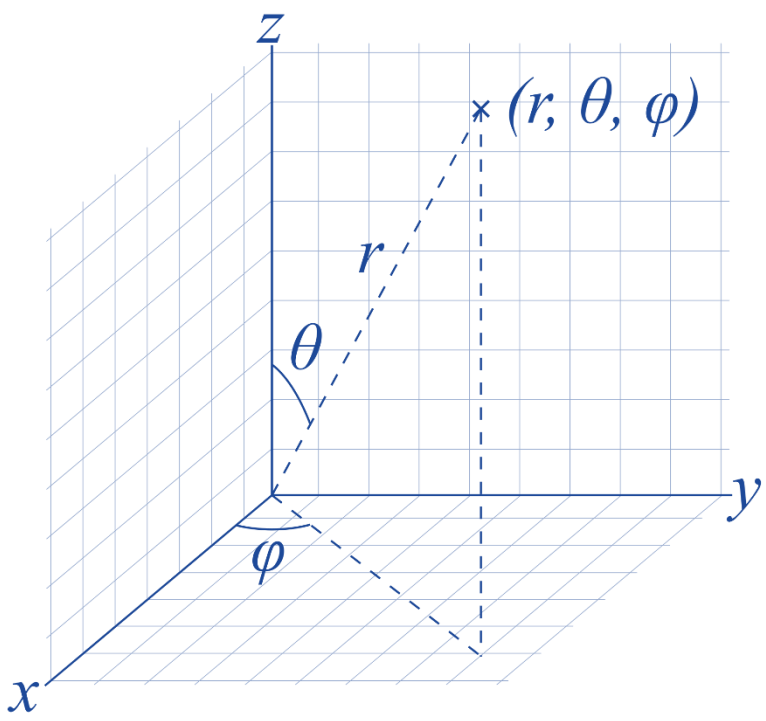
$1 - y$ = track energy / total energy





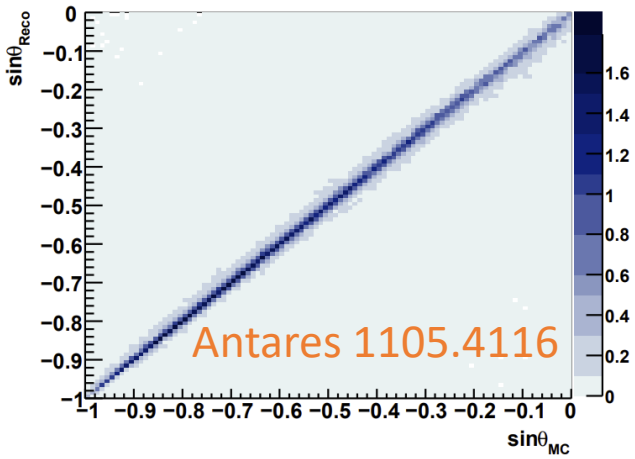
Adding Angular Information

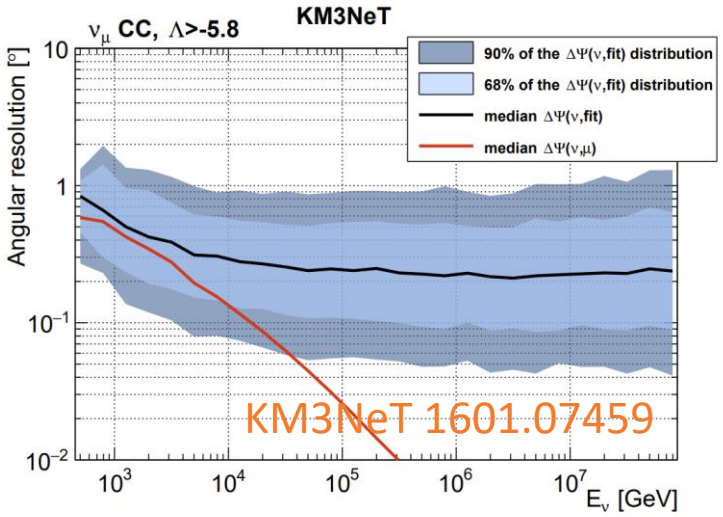
- So far we only used an interaction's:
  - Energy
  - Topology
- We can also try to estimate the direction:
  - Azimuth
  - Zenith

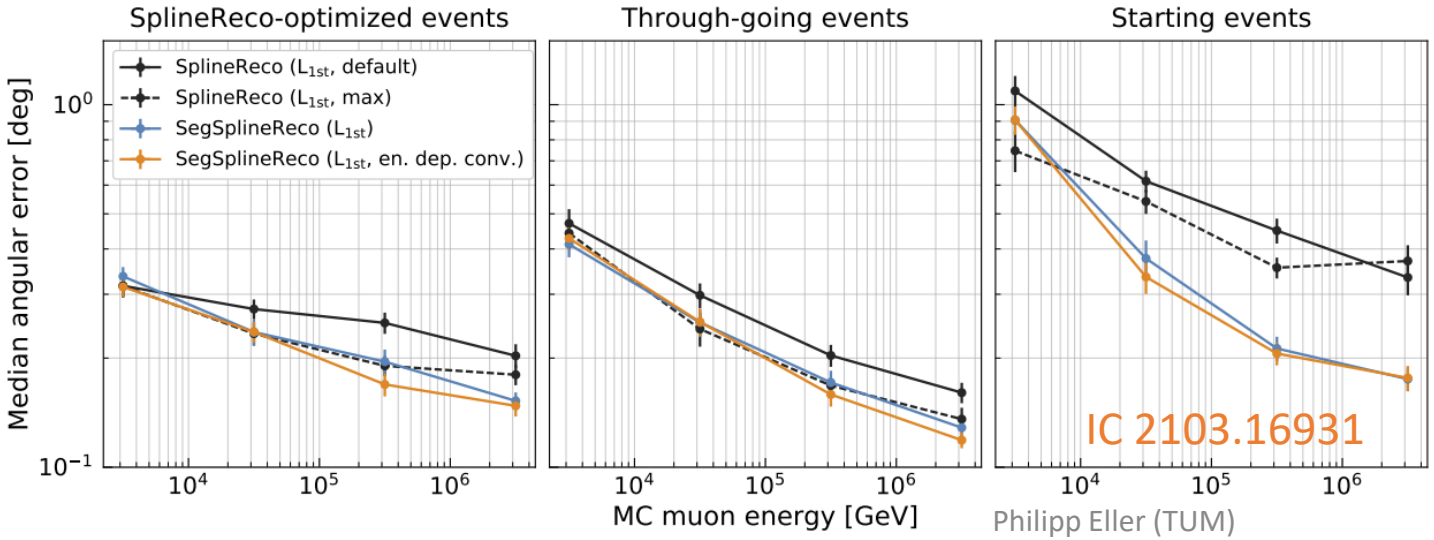


- Different approaches exist:
  - Likelihood based reconstructions, see e.g. Antares 1105.4116, KM3NeT 1601.07459, IC 2103.16931
  - Machine learning (CNNs, GNNs, …), see KM3NeT 2004.08254, or IC 2101.11589

Angular Reconstruction Performance

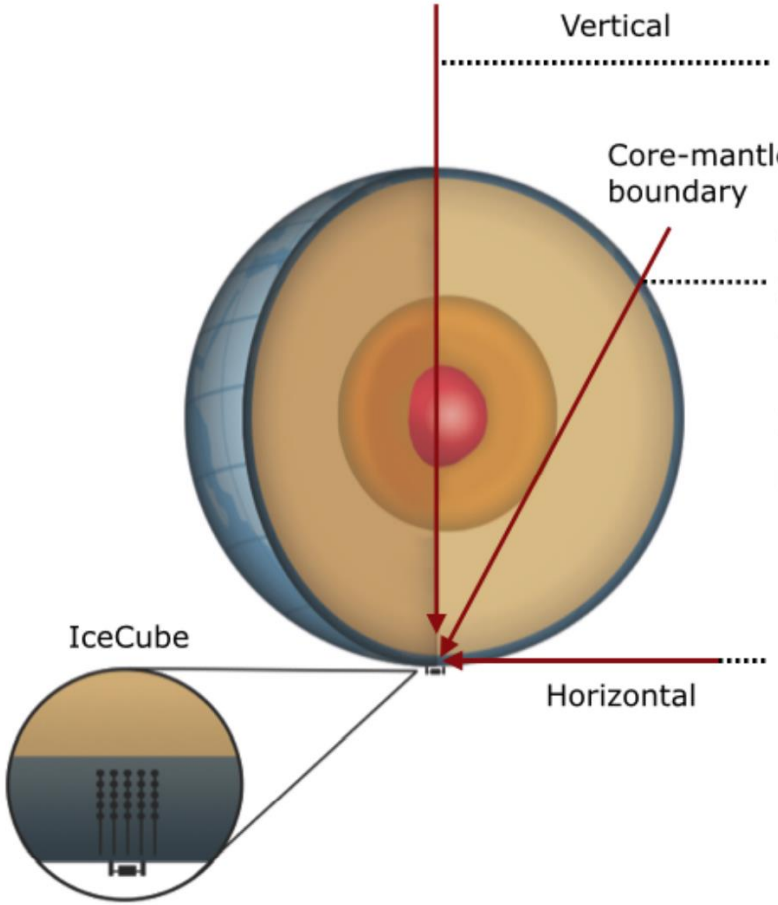


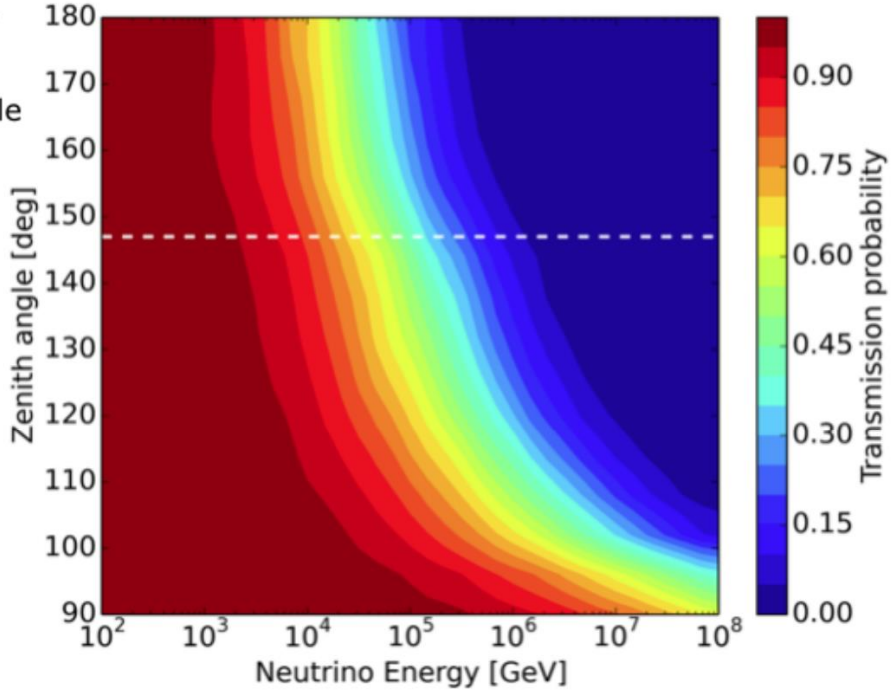




- Sub-degree angular resolution achieved for high energy tracks
- For cascade events, directional reconstruction more difficult
  → ~order of magnitude lower resolution

Adding angular information

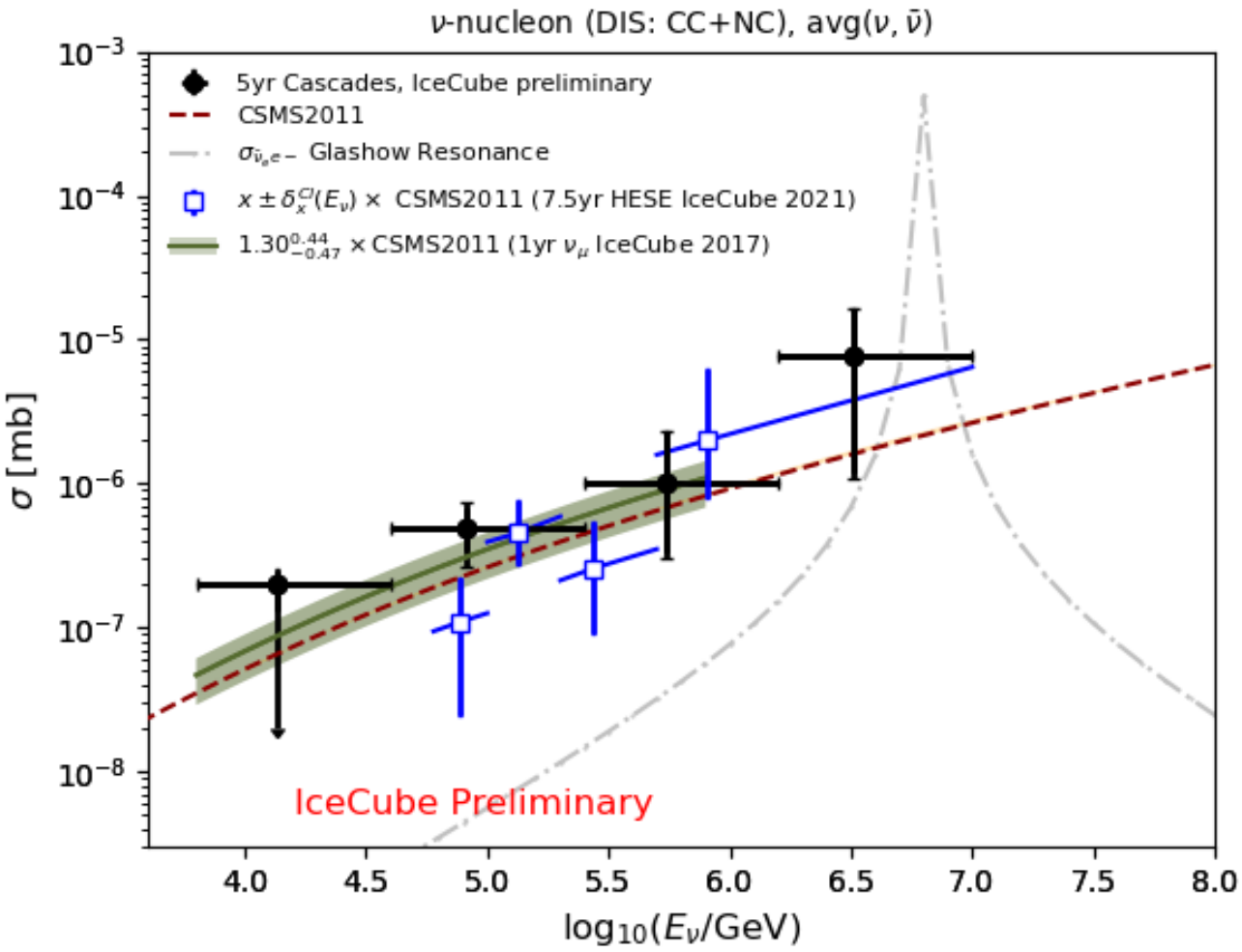




- Neutrino-nucleon cross section is very low, but rises with energy
  - For > 40 TeV, Earth causes appreciable absorption (~1 absorption length)

Earth Absorption

- Can measure the cross section (neutrino absorption) by comparing events of different zenith angles → different trajectories trough Earth
- Data consistent with SM expectations
- Measurements of DIS cross section at energies inaccessible for accelerators

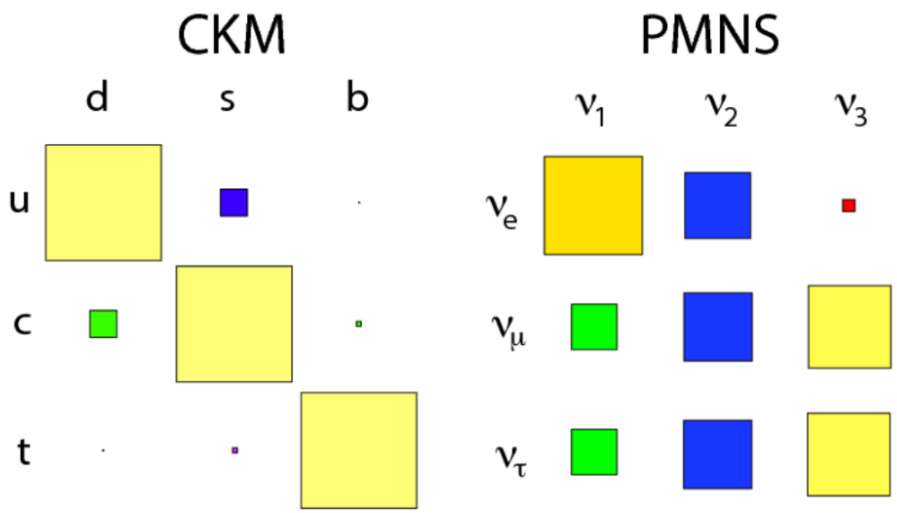


IceCube 1711.08119

IceCube 1908.07027

Neutrino oscillations

Neutrino Flavour Oscillations



- Neutrinos oscillate their flavor while travelling
  (Due to the flavor and mass eigenstates not being aligned)

- Example: simplest 2-flavor, vacuum oscillation probability:

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E_\nu} L$$

Mass eigenstates

Length

From mixing matrix

Energy

Atmospheric oscillations

- Atmospheric mass splitting is around $2.4\ 10^{-3}\ \mathrm{eV}^2$
- Earth diameter is around 12700 km
- $\sin^2 \frac{\Delta m^2}{4E} L$

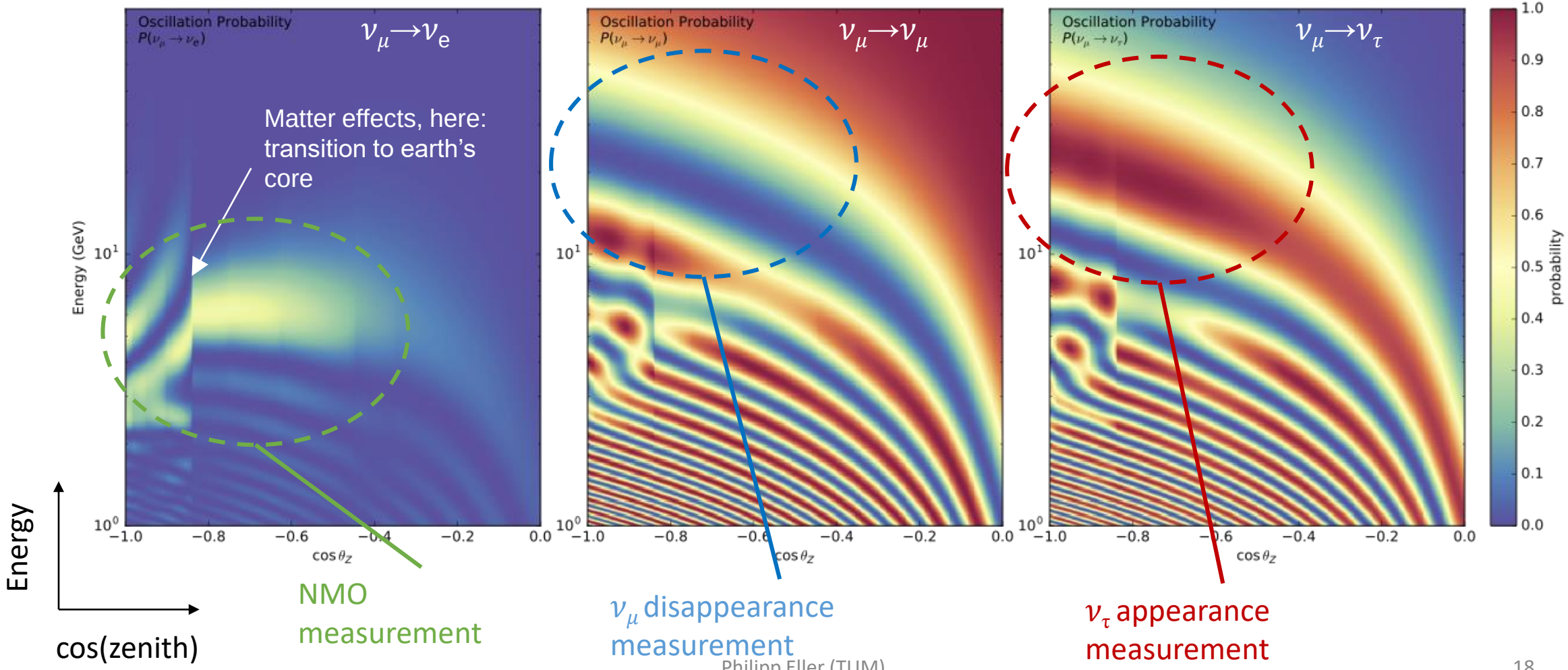
$$= \sin^2 1.27 \frac{2.4\ 10^{-3}\ \mathrm{eV}^2}{E(\mathrm{GeV})} 12700\ km$$

$$\approx \sin^2 \frac{38.7}{E(\mathrm{GeV})} \overset{!}{\Leftrightarrow} \sin^2\left(\frac{\pi}{2}\right)$$

→ Energy E should be ~ **25 GeV** for maximal mixing
(or odd numbered division thereof)

Atmospheric oscillations

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E_\nu} L$$



Accessing lower energies

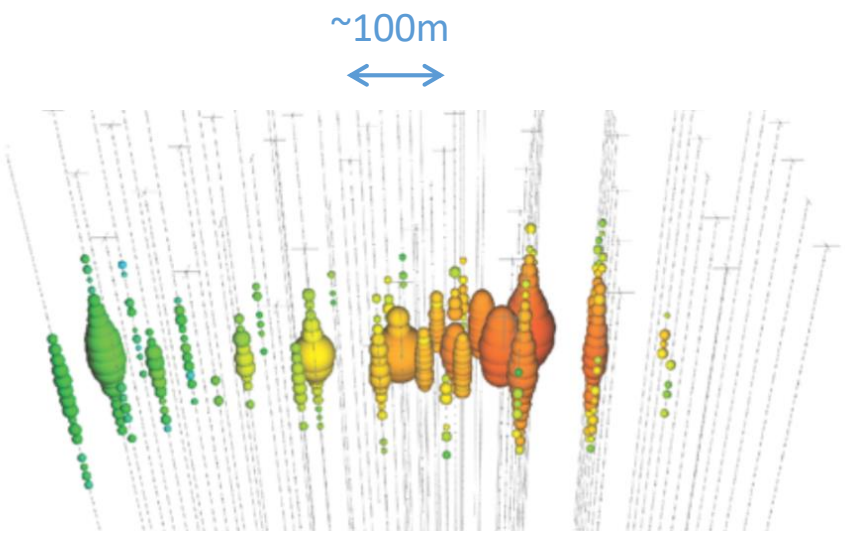
Typical TeV-PeV event:

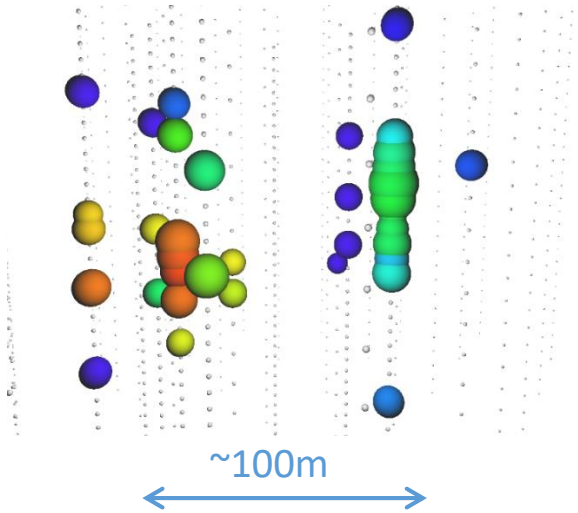
- Photons from secondary particles arriving in many strings and modules
- Very clear, extended signature

Lower energy

Typical GeV event:

- Photons from secondary particles arriving in few strings, tens of sensors
- Almost impossible to see the signature “by eye”

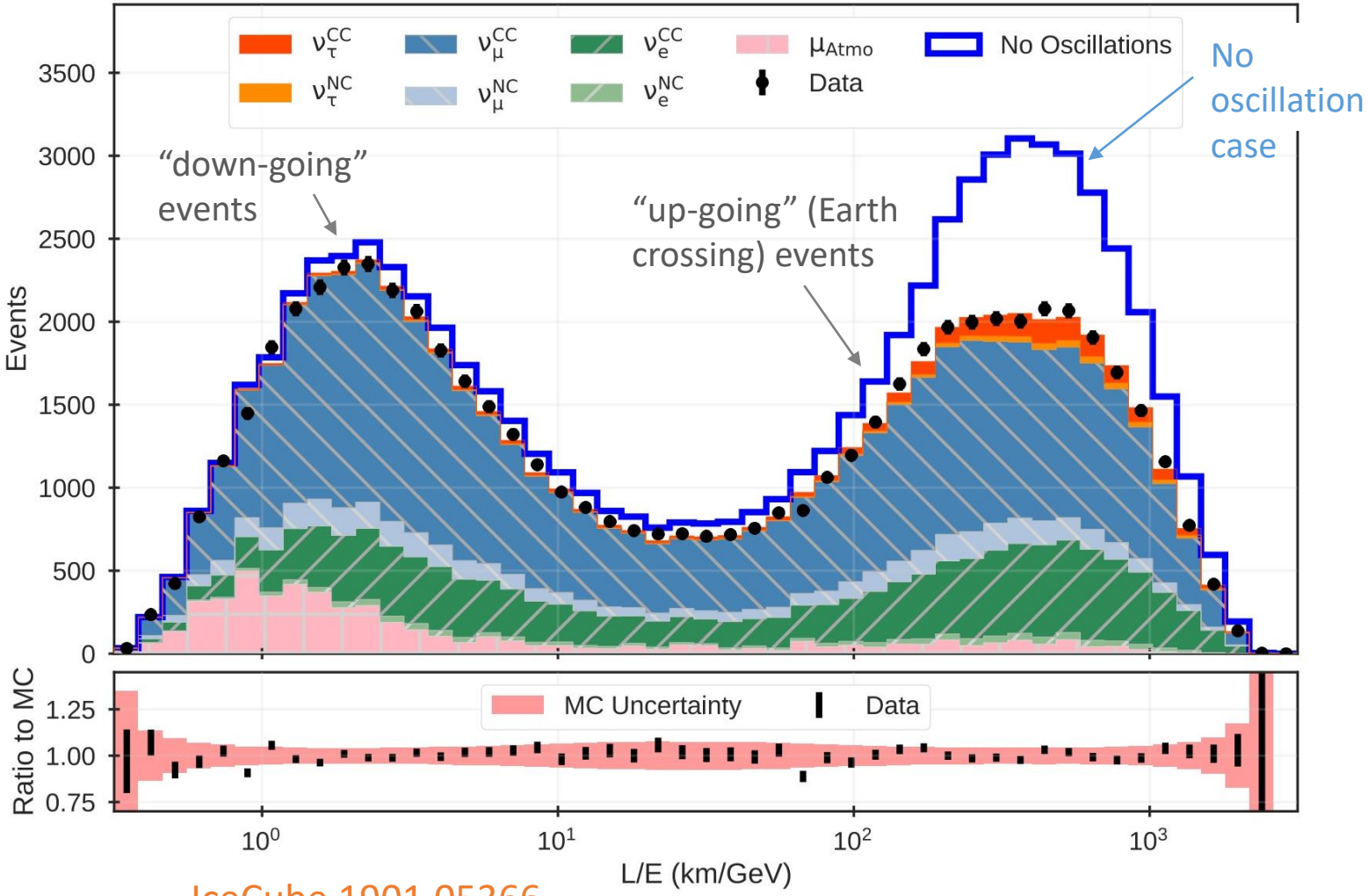




→ We need detectors able to access those energies: DeepCore, ORCA, IC Upgrade, (Antares)

Atmospheric Oscillations

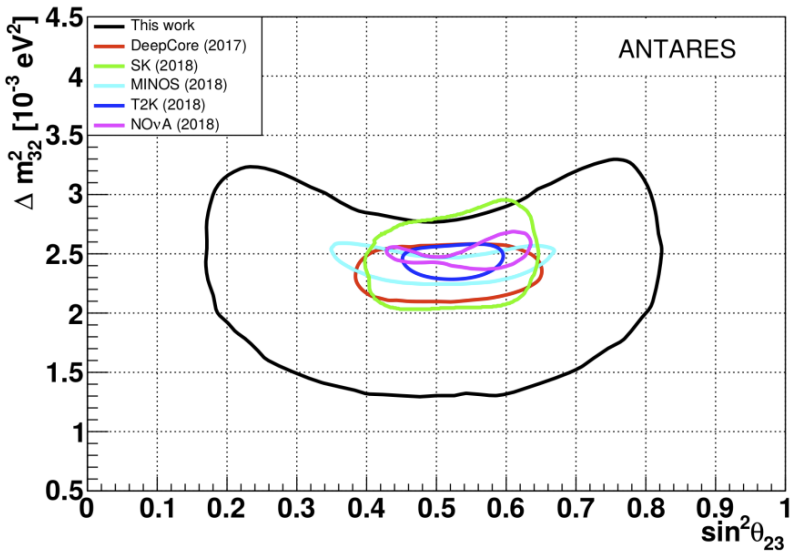
- Measure the numu → numu disappearance channel
- Oscillation manifesting itself as deficit of track-like events, compared to flux prediction
- Independent of overall flux, just measuring shape differences in E-zenith



IceCube 1901.05366

Oscillation Results

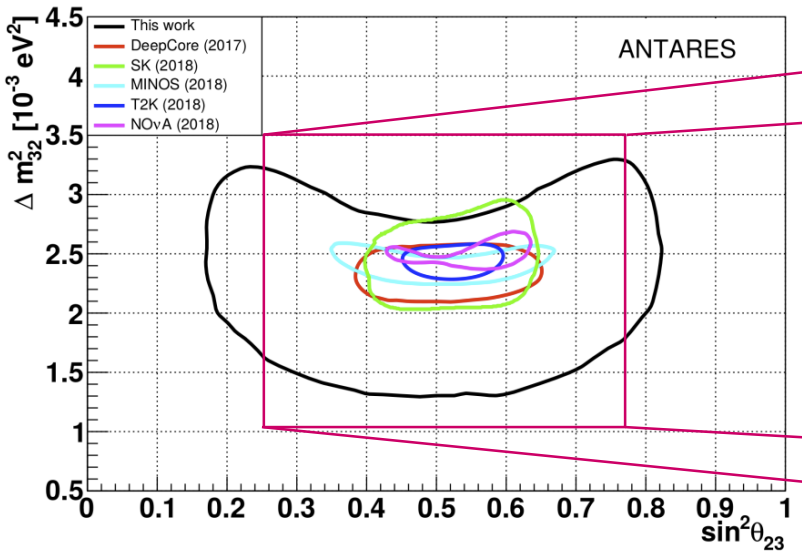
Antares 10 year



Antares 1812.08650

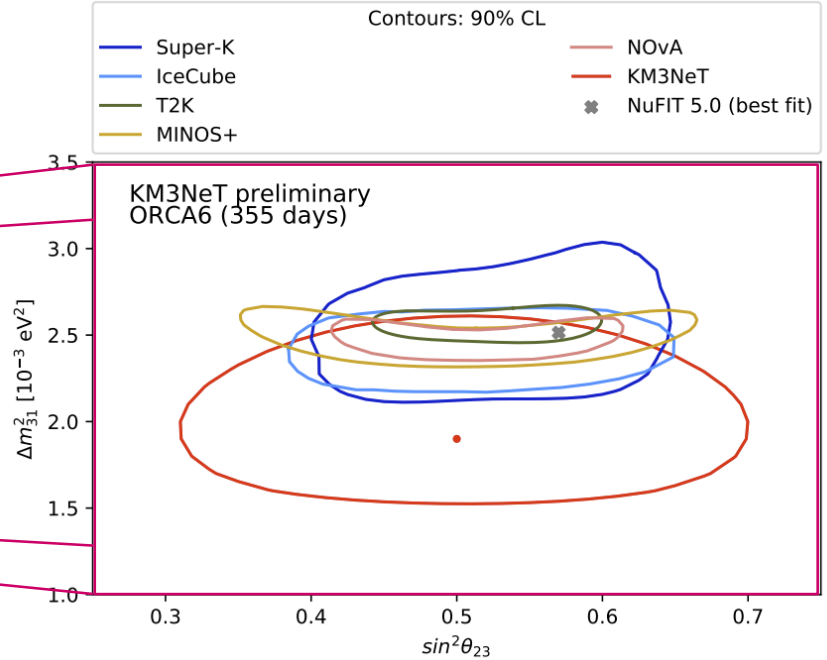
Oscillation Results

Antares 10 year



Antares 1812.08650

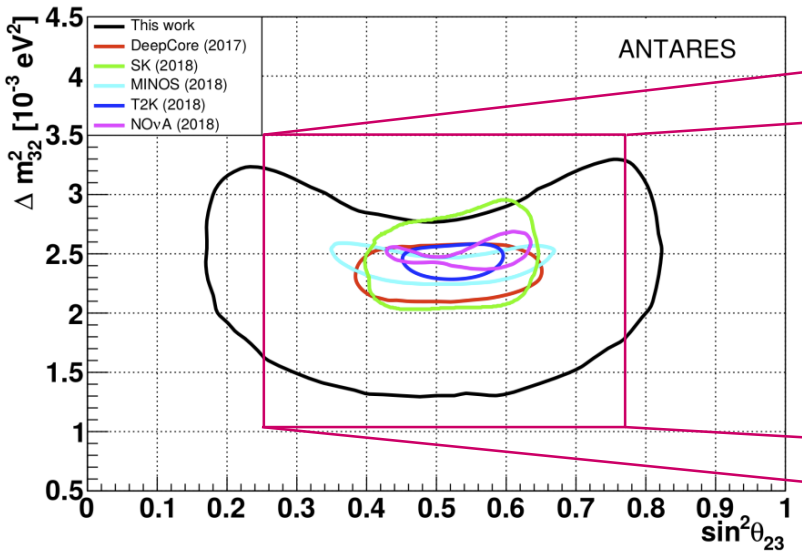
KM3NeT ORCA6 1 year



KM3NeT 10.22323/1.395.1123

Oscillation Results

Antares 10 year



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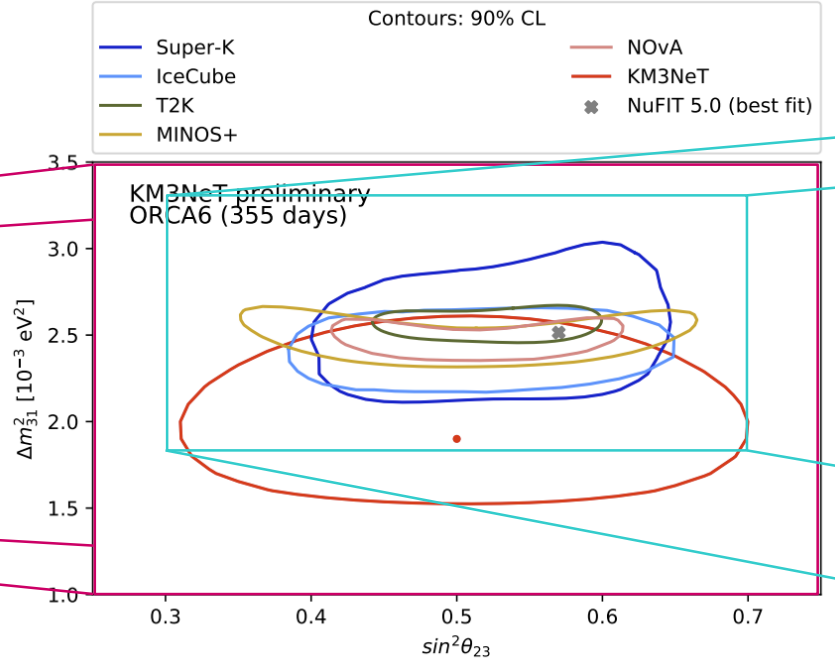
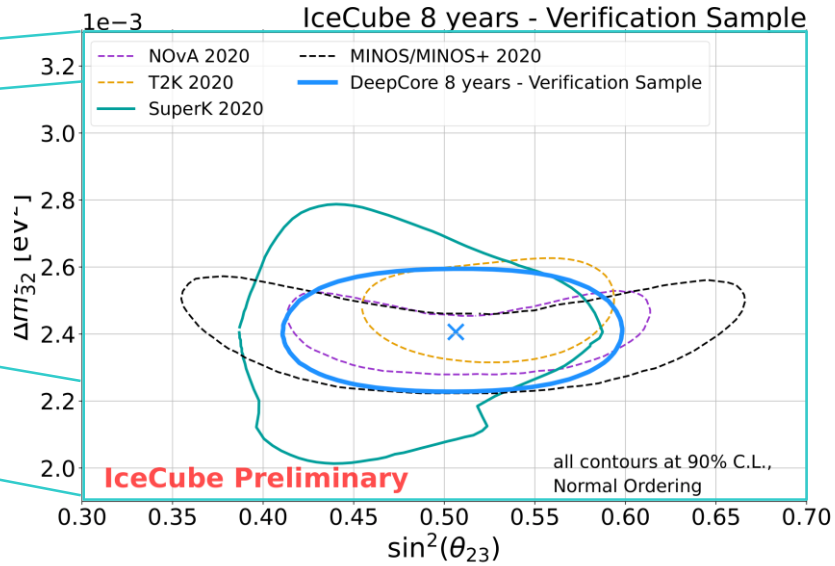
KM3NeT ORCA6 1 year



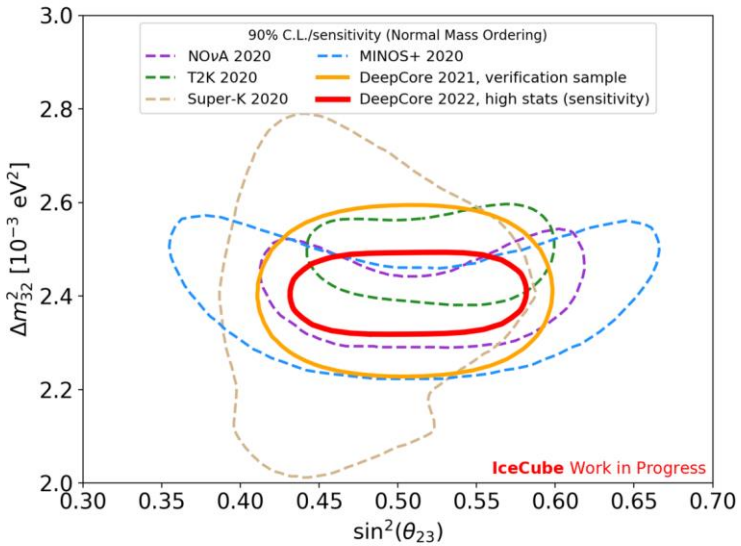
KM3NeT 10.22323/1.395.1123

IceCube DeepCore 8 year

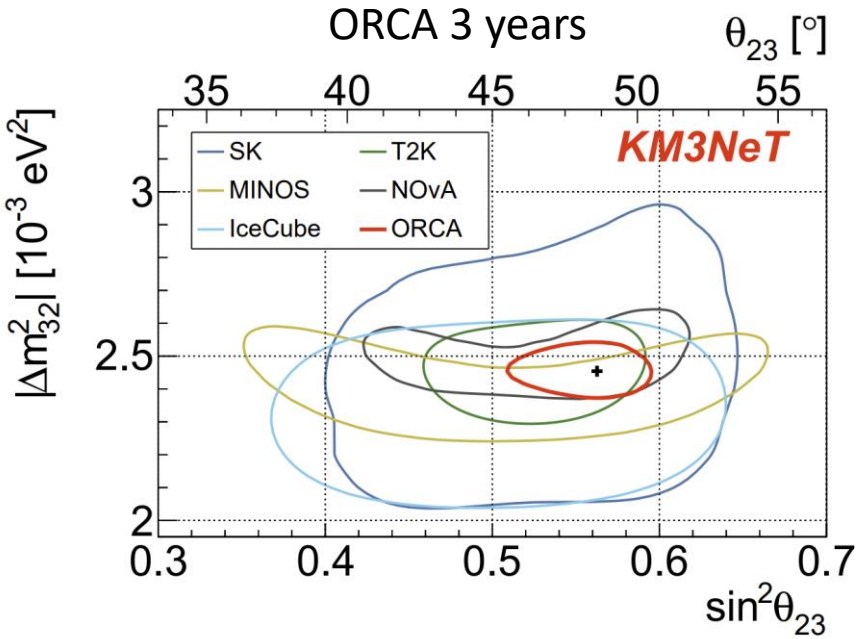


Future Oscillation Sensitivities

DeepCore 8 years
(improved methods)

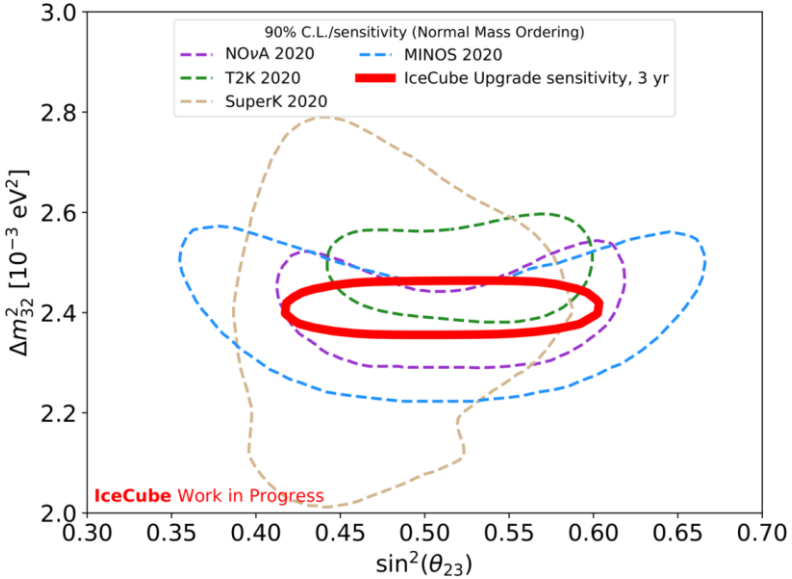


ORCA 3 years



KM3NeT 2103.09885

IC Upgrade 3 years (NO)



(Assuming normal ordering)

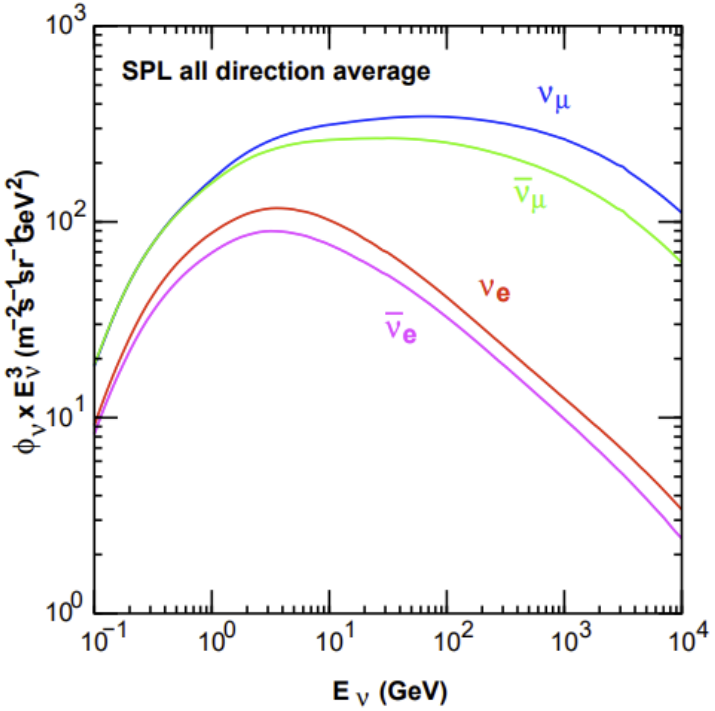
Neutrino Mass Ordering (NMO)

- Neutrino mass ordering:
  - is m_1 or m_3 the lightest mass eigenstate?

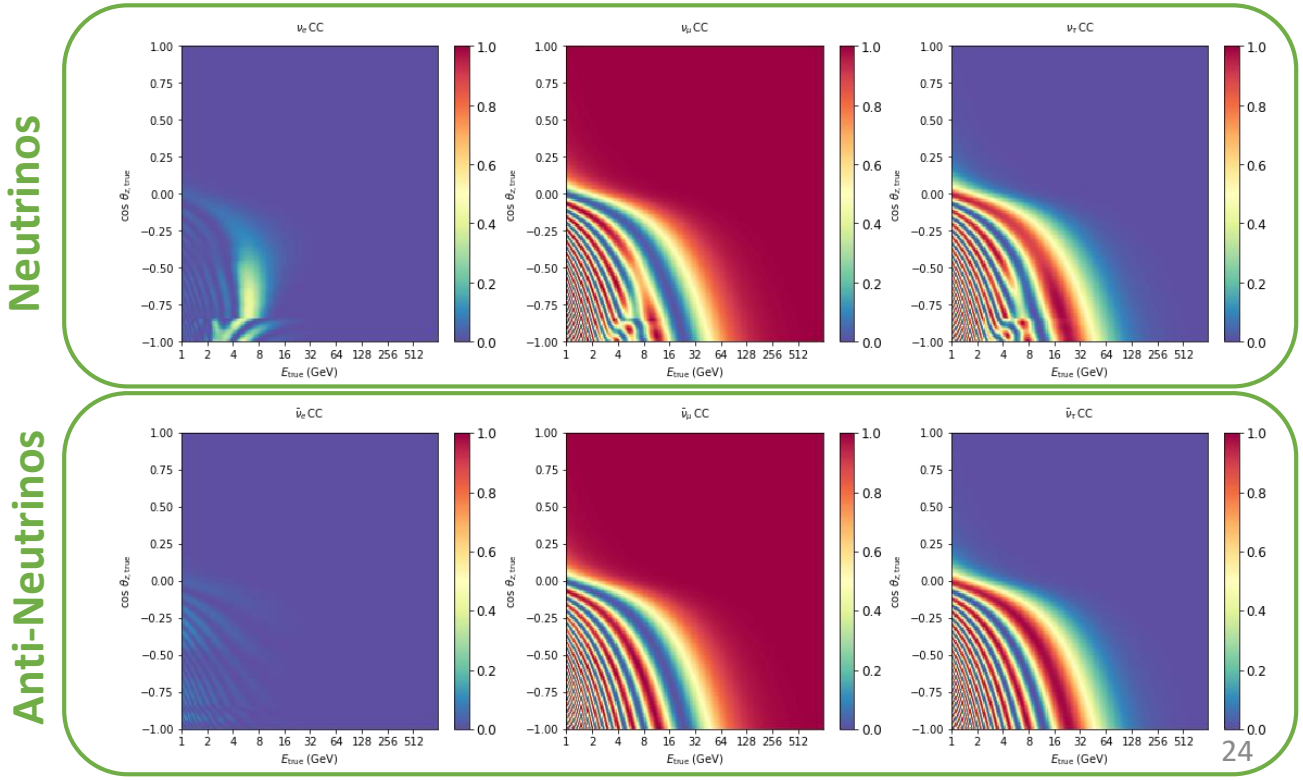
- Important consequences for the establishment of absolute neutrino mass scale and particle nature
  - Cosmology (sum of masses), beta decay (mb), neutrino-less double beta decay (mbb)

NMO Measurement

- Difference in atmospheric flux:
  - more neutrinos than anti-neutrinos



- Difference in oscillations (matter effects)
- Depending on mass ordering
  - **NO**: enhanced mixing for neutrinos



NMO Measurement

- Difference in atmospheric flux:
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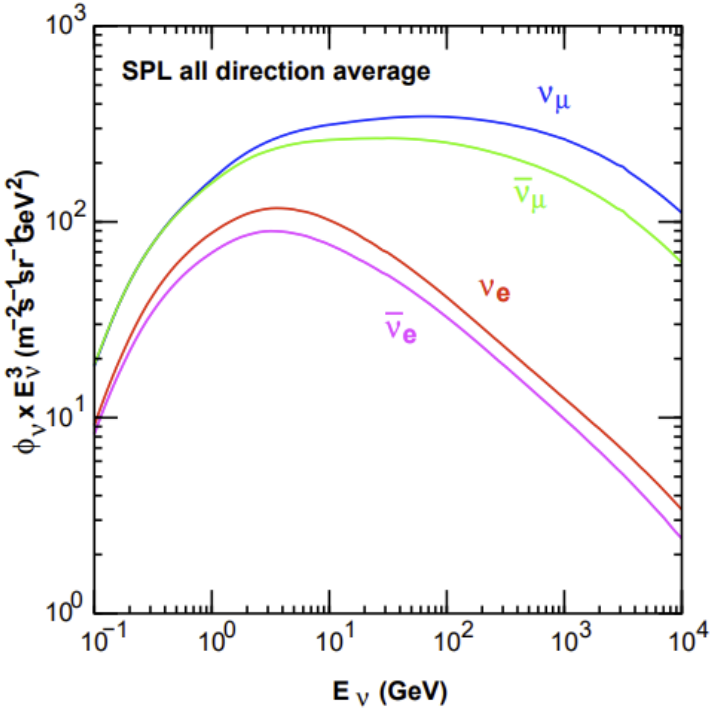
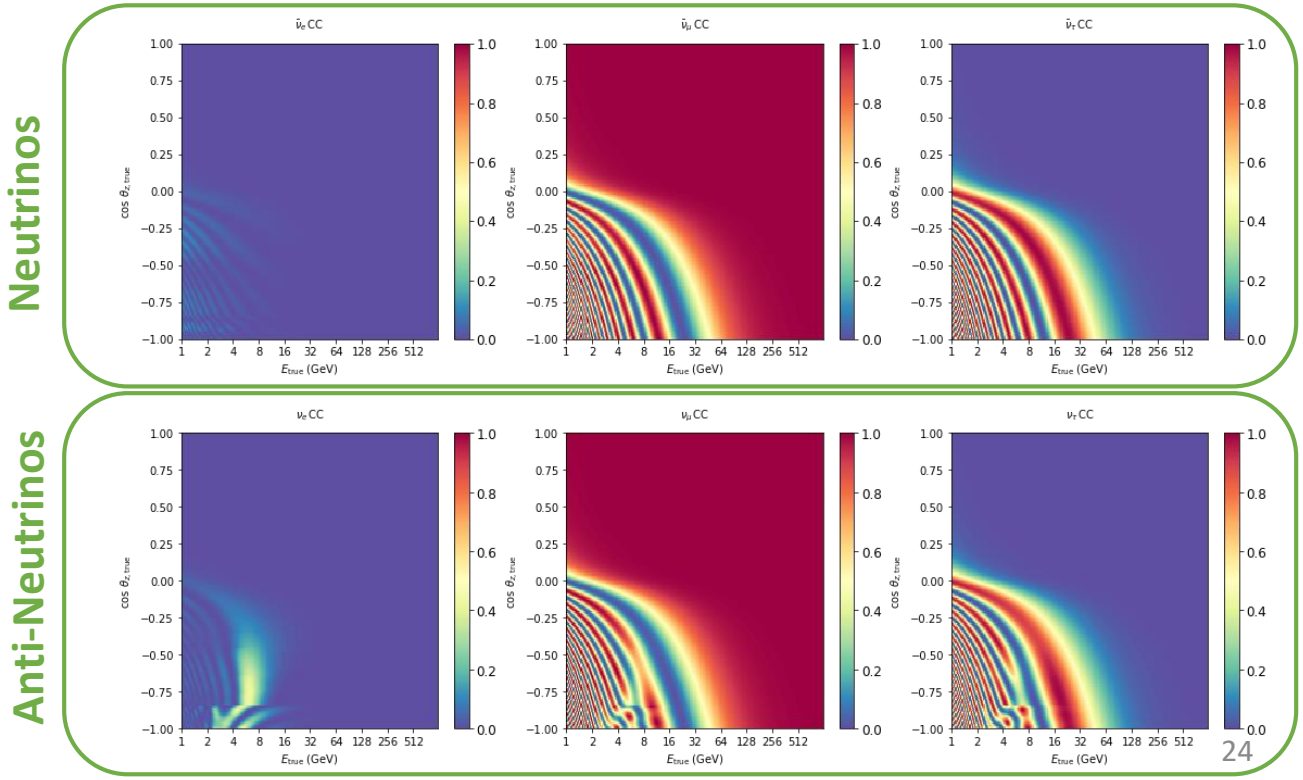
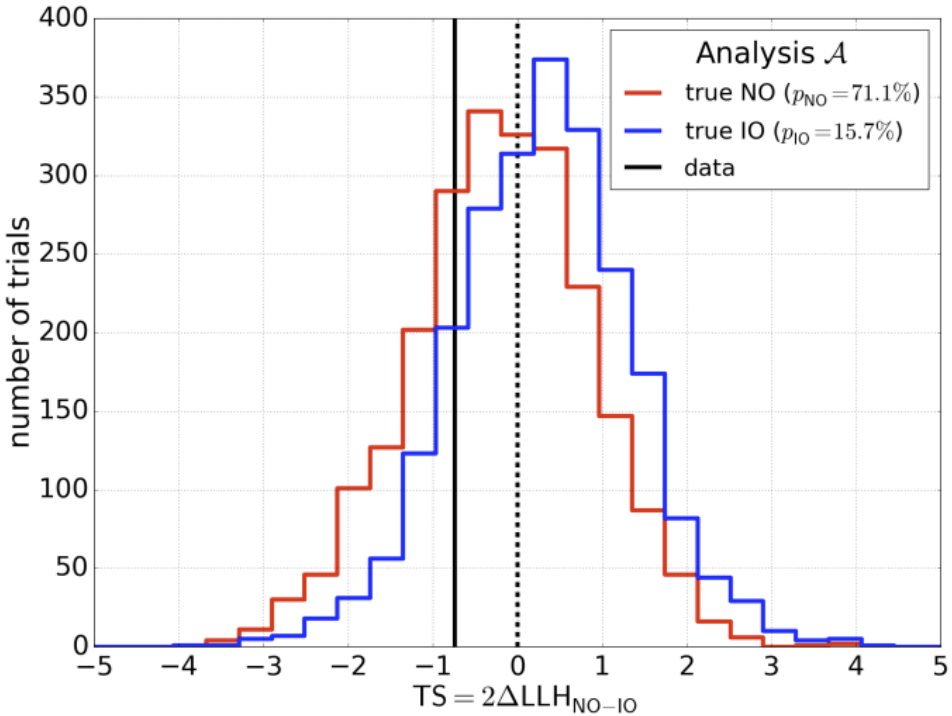


- Difference in oscillations (matter effects)
- Depending on mass ordering
  - **NO**: enhanced mixing for neutrinos
  - **IO**: enhanced mixing for anti-neutrinos

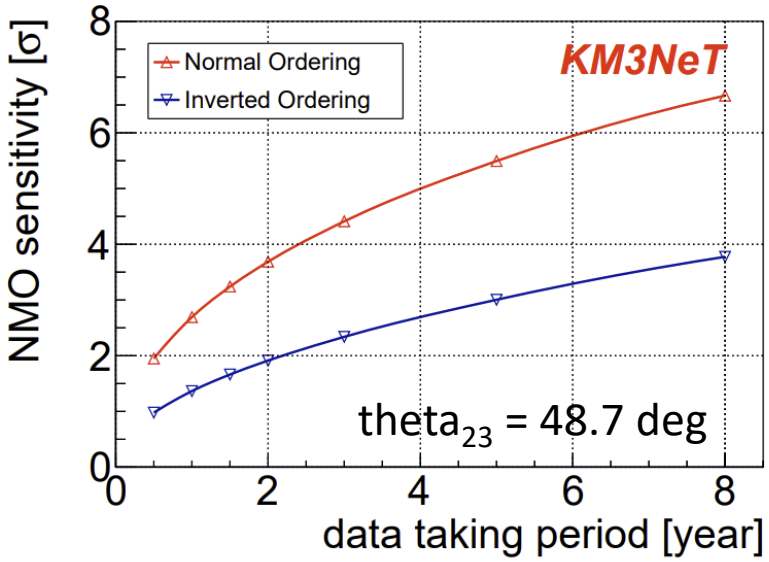


NMO Results & Sensitivities

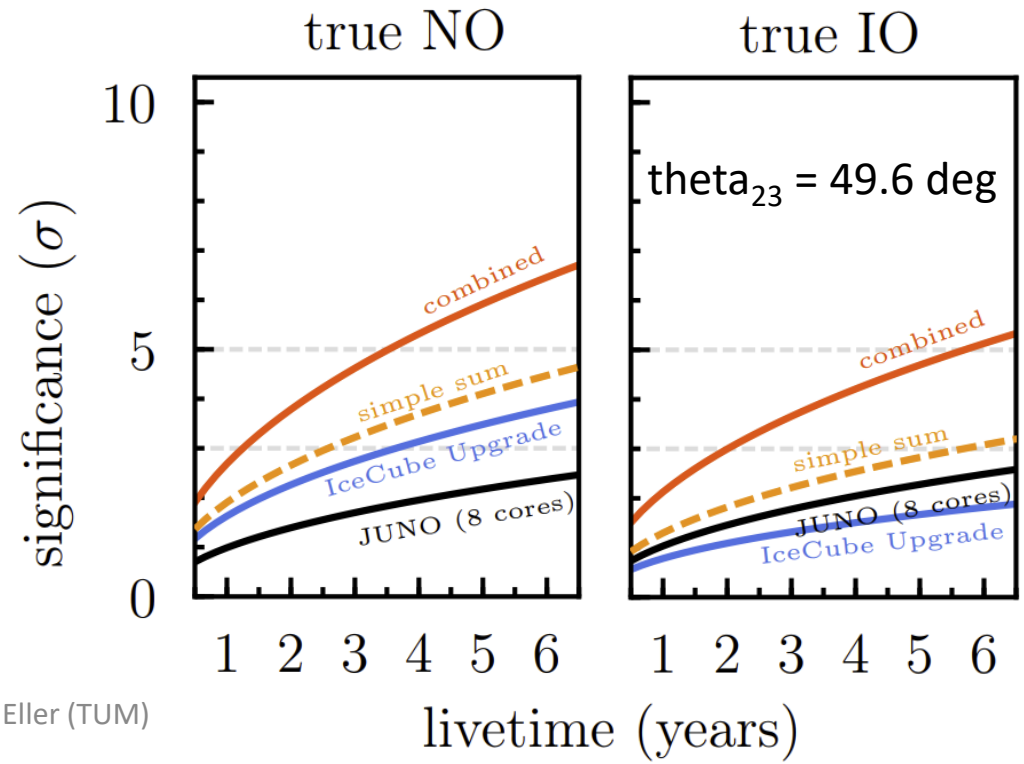
DeepCore 3 years



IceCube 1902.07771



KM3NeT 2103.09885



IceCube/JUNO 1911.06745

Beyond standard oscillations

Unitarity of the mixing

- Search for beyond standard oscillations
  - Additional components could violate the 3x3 unitarity condition of the PMNS mixing matrix
  - Model independent test

PMNS (sub?) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \\ & & \vdots & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix}$$

BSM? (steriles)

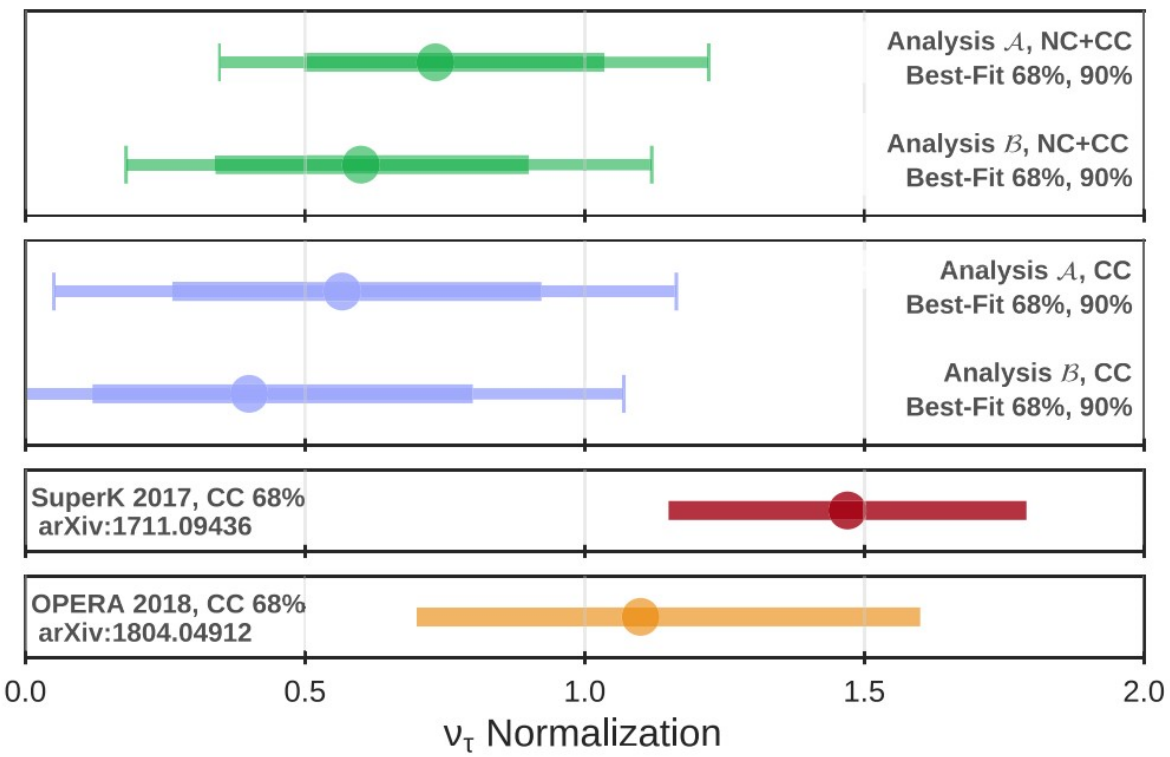
- Include a unitarity breaking parameter: nutau normalization
  - Scaling the appearing numu→nutau component up/down with additional scalefactor
  - Nutau norm = 0 : absence of tau neutrinos
  - Nutau norm = 1 : standard 3-flavor expectation

Tau neutrino Measurement

- Nutau CC threshold energy ~3.5 GeV
  → Out of reach for most LBL experiments! (e.g. T2K, NOvA)
- Suppressed cross section
- Appearance in cascade channel (more difficult to reconstruct)

- So far consistent with expectations

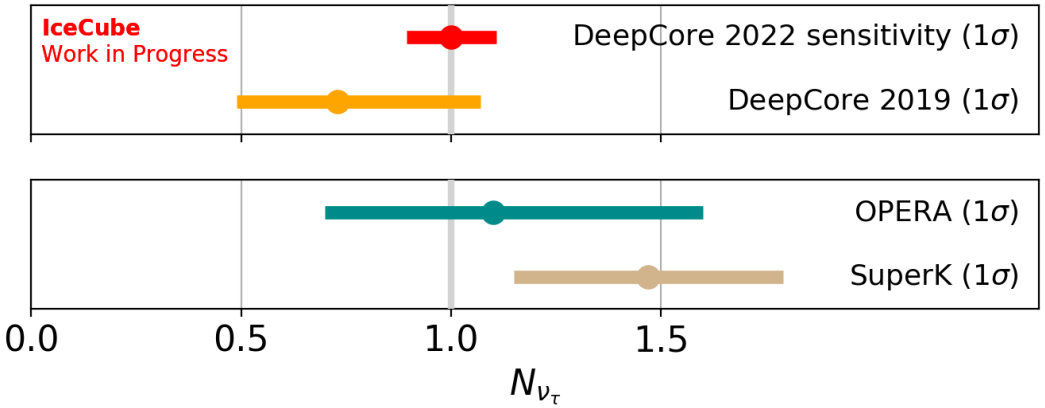
DeepCore 3 years



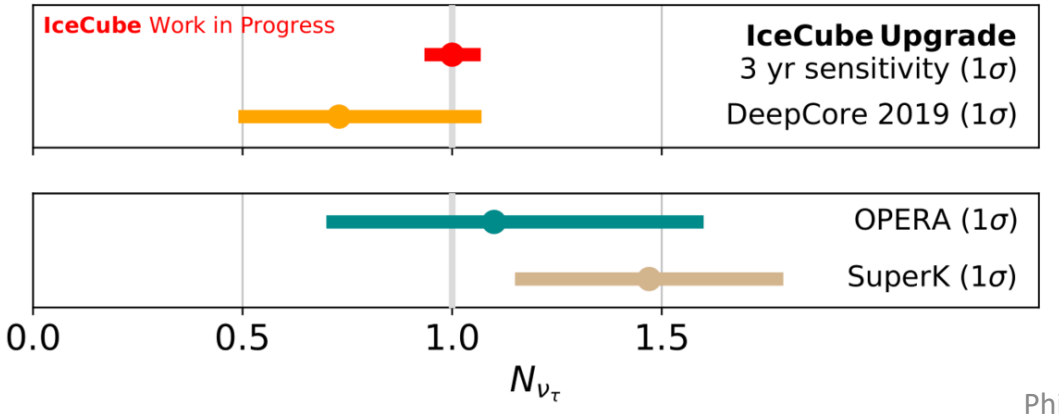
IceCube 1901.05366

Tau neutrino sensitivities

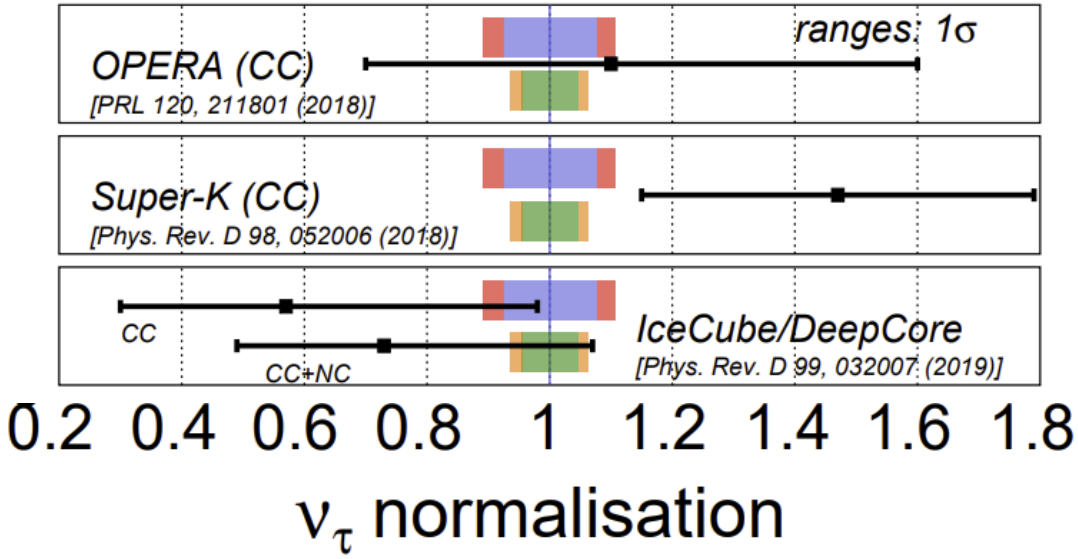
DeepCore 8 years



IceCube Upgrade 3 years



Orca 1 year and 3 years



KM3NeT 2103.09885

Sterile Neutrino Models

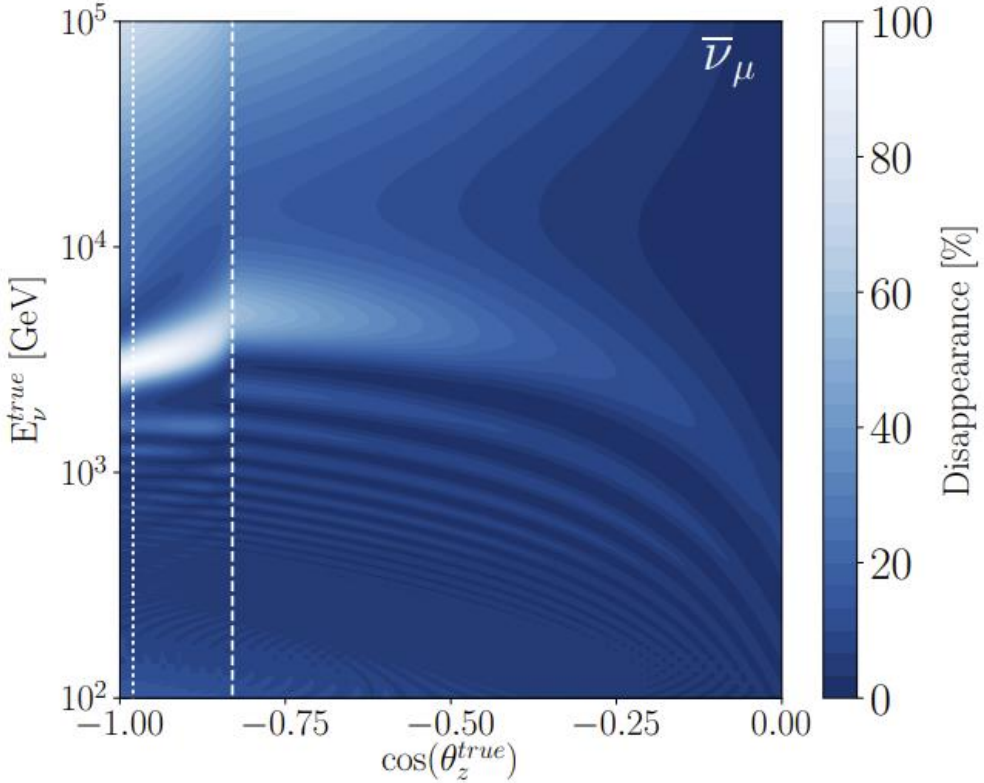
- For specific BSM models, we know what oscillation modes to expect
- If extra states are light enough, observable oscillations
- → 3+1 eV-scale steriles
  - Motivated by some anomalies (Reactor, Gallium, SBL)

- $\sin^2 \frac{\Delta m^2}{4E} L = \sin^2 1.27 \frac{1\ \mathrm{eV}^2}{E(\mathrm{GeV})} 12700\ km$

$$\approx \sin^2 \frac{16129}{E(\mathrm{GeV})} \overset{!}{\Leftrightarrow} \sin^2\left(\frac{\pi}{2}\right)$$

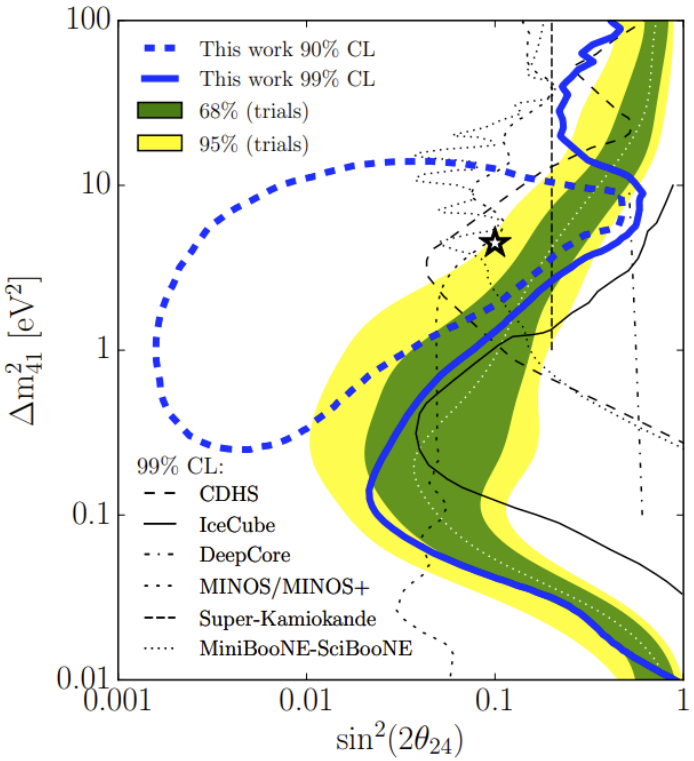
- → Energy E should be ~ 10 TeV for maximal mixing
- Oscillations enhanced by matter effects around 1 TeV
  - (anti-neutrinos)

- At lower energies, oscillations become too fast to resolve measure averaged-out effect



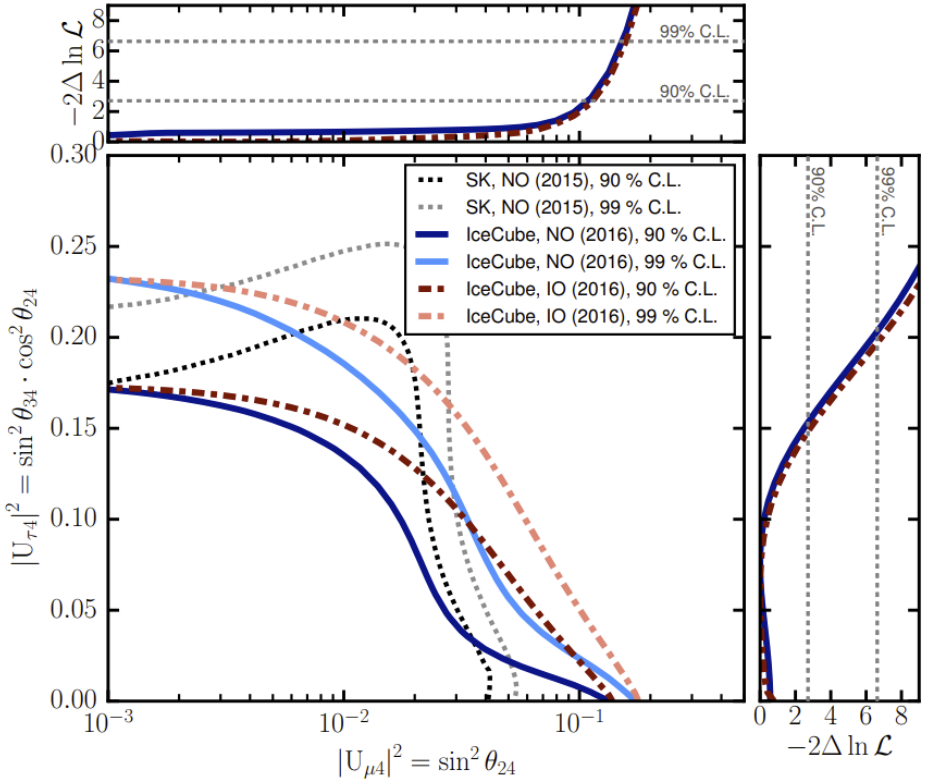
3+1 eV Sterile results

IceCube 8 years



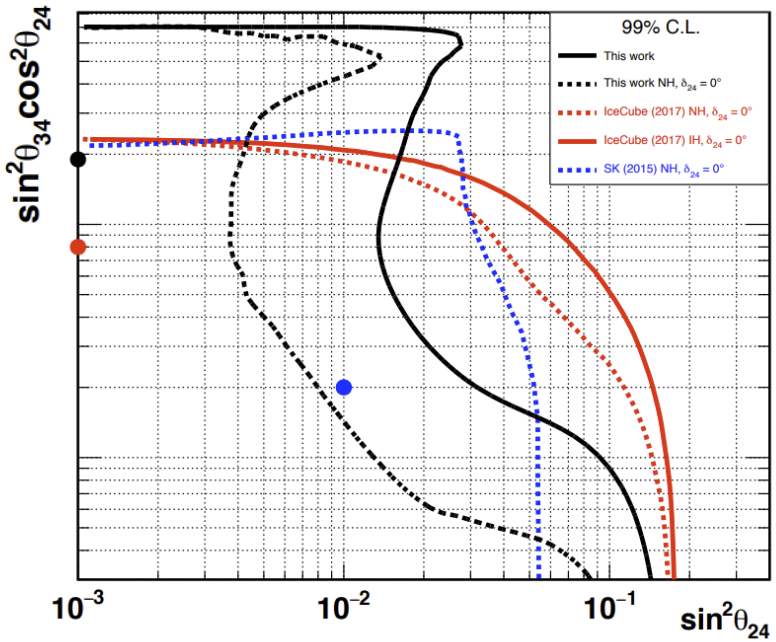
IceCube 2005.12942

DeepCore 3 years



IceCube 1702.05160

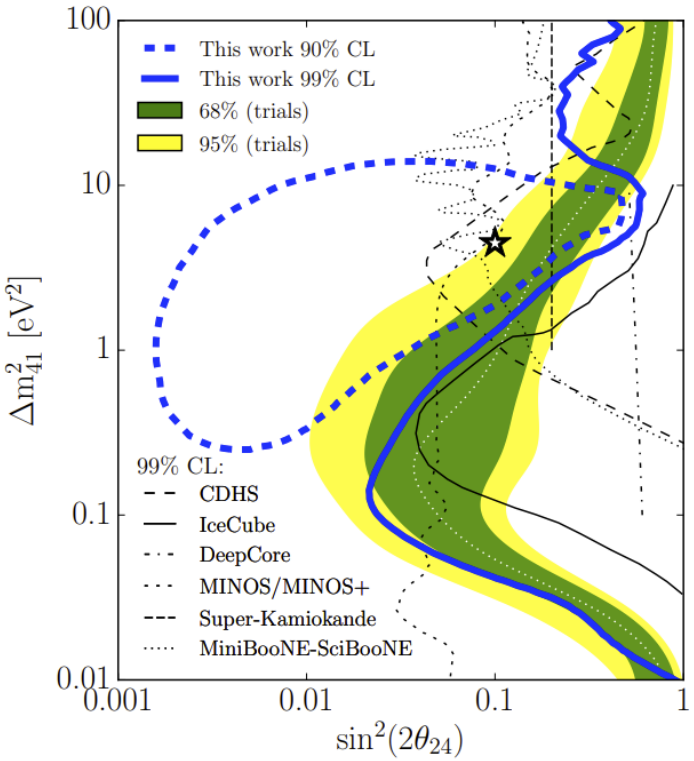
Antares 10 years



Antares 1812.08650

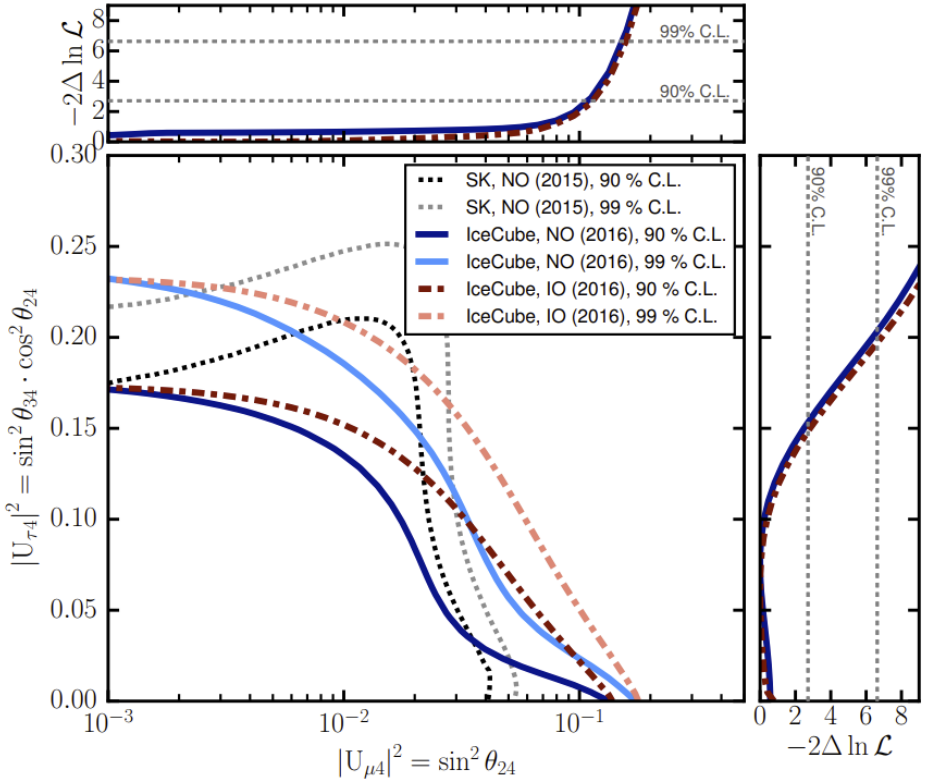
3+1 eV Sterile results

IceCube 8 years



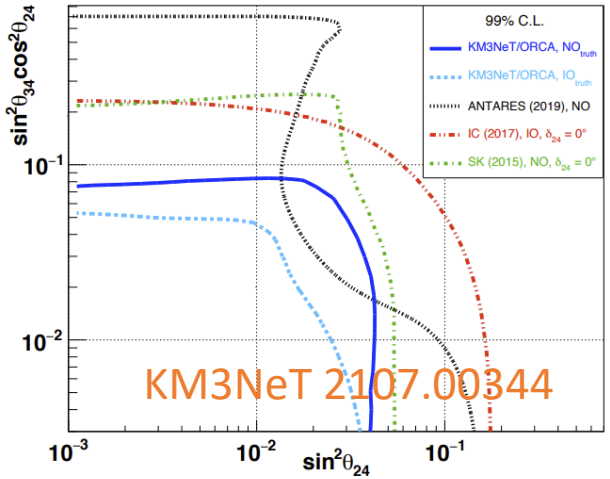
IceCube 2005.12942

DeepCore 3 years



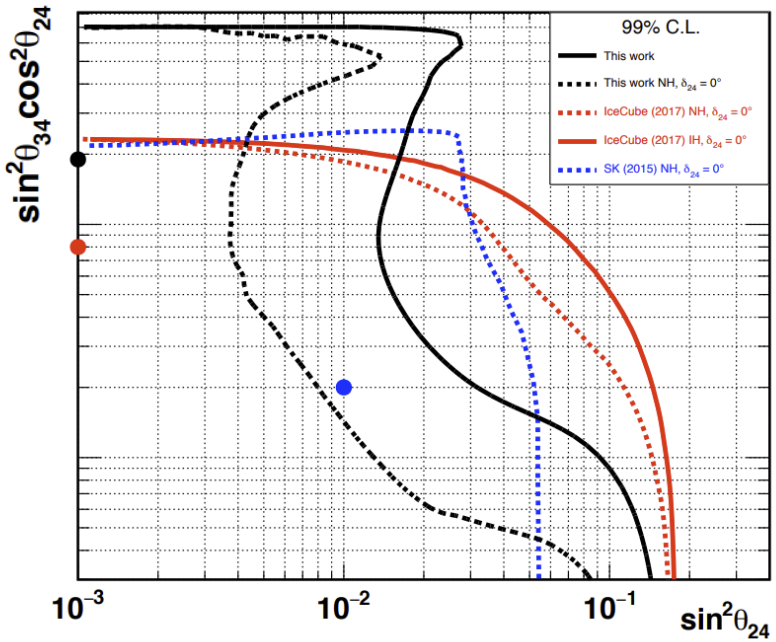
IceCube 1702.05160

ORCA 3 years sensitivity



KM3NeT 2107.00344

Antares 10 years



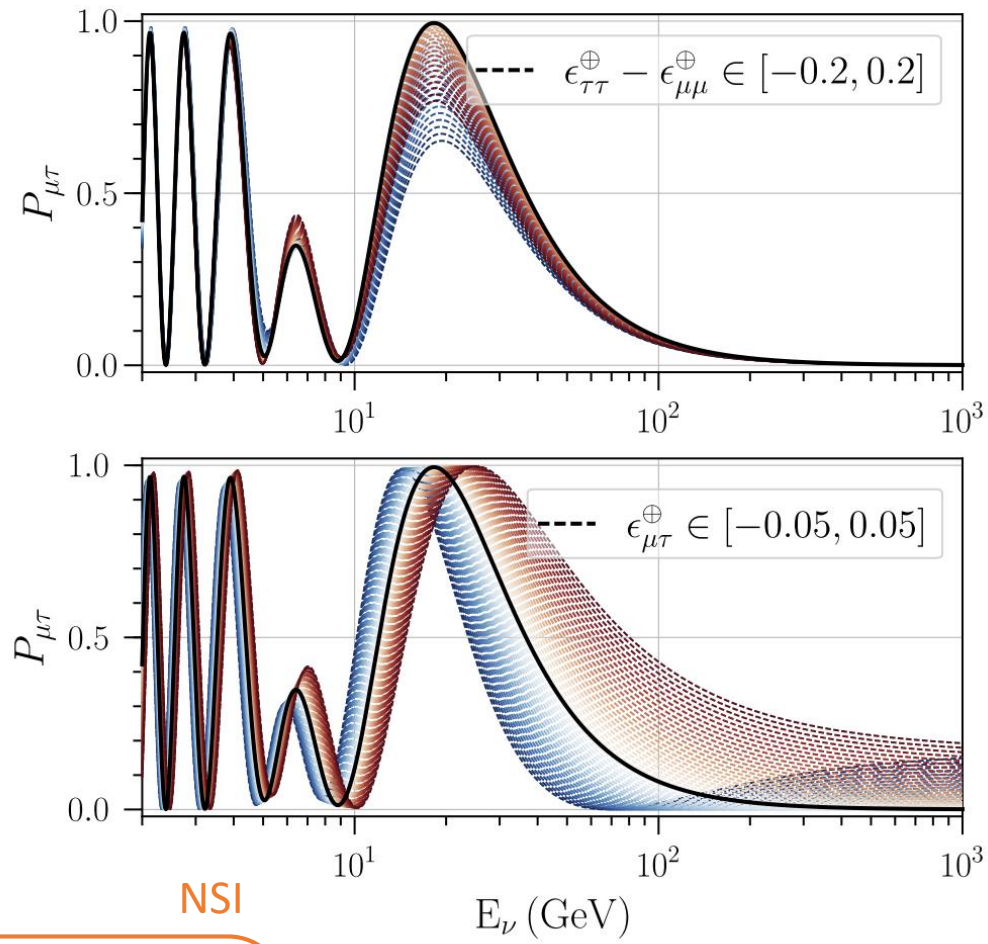
Antares 1812.08650

Non-standard Interactions

- Looking for new (non-standard) interactions

→Additional non-zero terms in Hamiltonian

→Measurable effect/distortion of matter oscillations



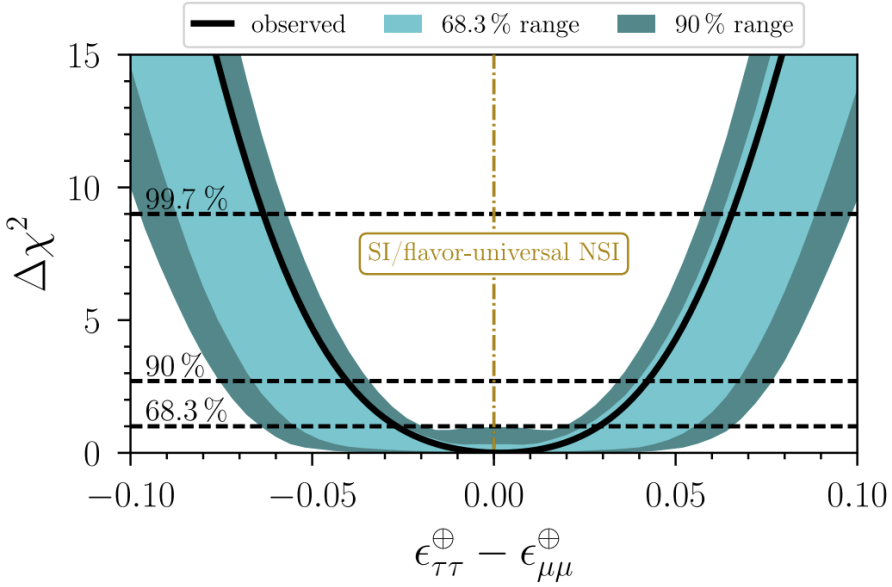
SM interaction (nue CC)

NSI

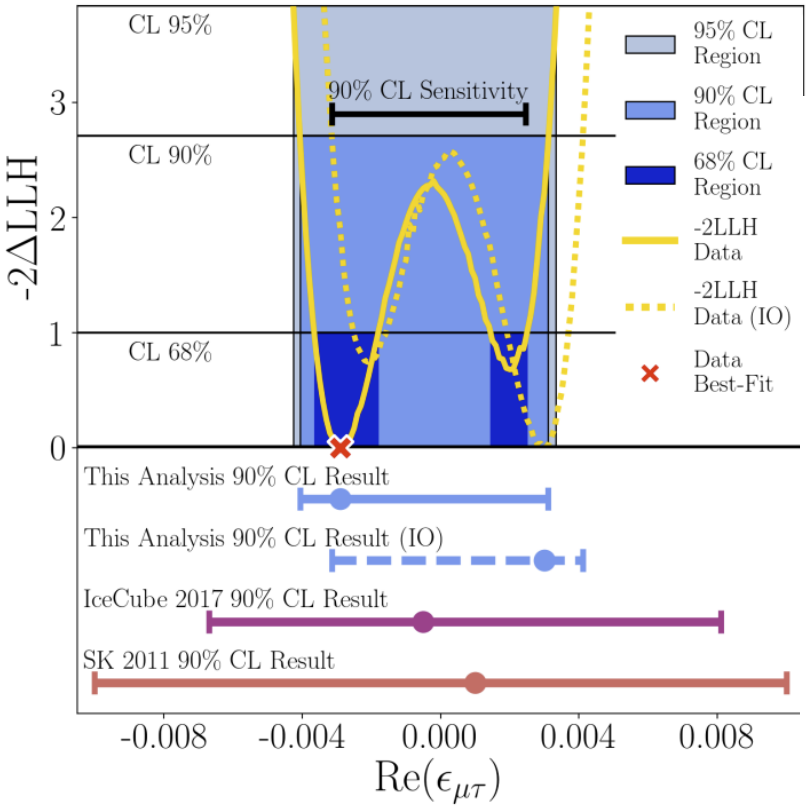
$$H_{\mathrm{mat}}(x) = V_{\mathrm{CC}}(x) \begin{pmatrix} 1 + \epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & 0 & \epsilon^{\oplus}_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & \epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu} \end{pmatrix}$$

NSI Results

DeepCore 3 years

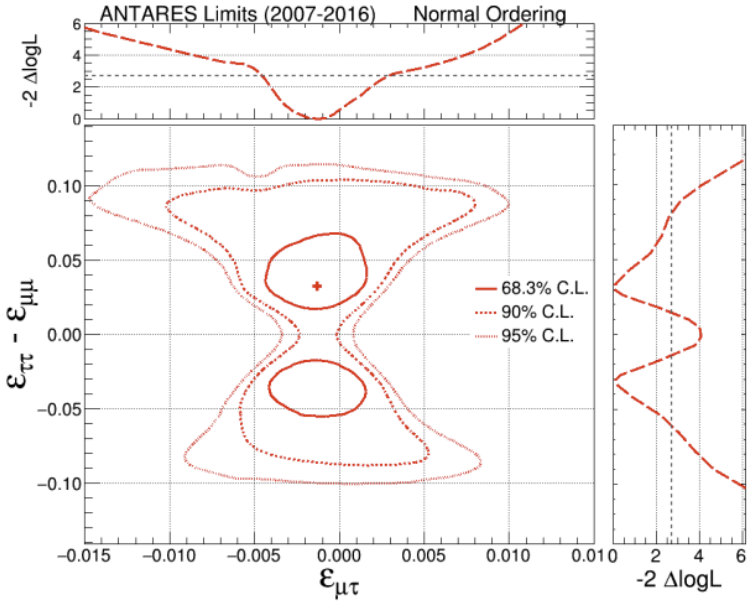


IceCube 8 years



IceCube 2201.03566

Antares 10 years



Antares 2112.14517

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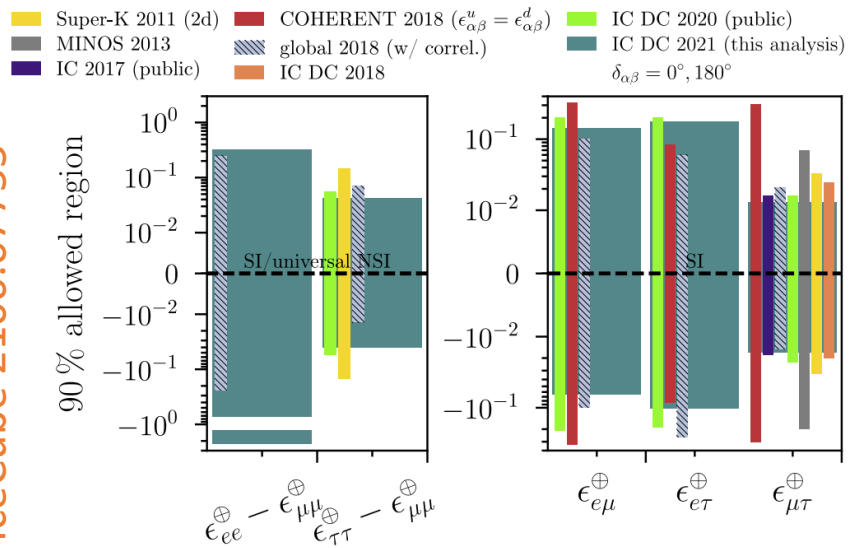

Many more things…

There are many more particle physics measurements that neutrino telescopes can do!

- Dark matter:
  → See also session from Monday & Wednesday

- Other BSM theories:
  - (large) extra dimensions, neutrino decay, …

- Beyond pure particle physics:
  - Fundamental physics questions: Lorentz violation, Quantum decoherence, …

Summary

- Neutrino telescopes provide a **unique** kind of particle physics laboratory
  - Study cross sections, oscillations, search for BSM physics
- Energies and baselines accessible that are **out of reach** for lab-based experiments
  - Cross sections in the TeV – PeV range
  - Oscillations above tau threshold, resonances of light steriles, …
- **Competitive**
  - Atmospheric oscillation parameters: rivaling LBL experiments
  - Tau neutrinos: world leading
  - Light steriles: competitive with SBL expriments
  - NSI: world leading in mu-tau parameters

Additional Material