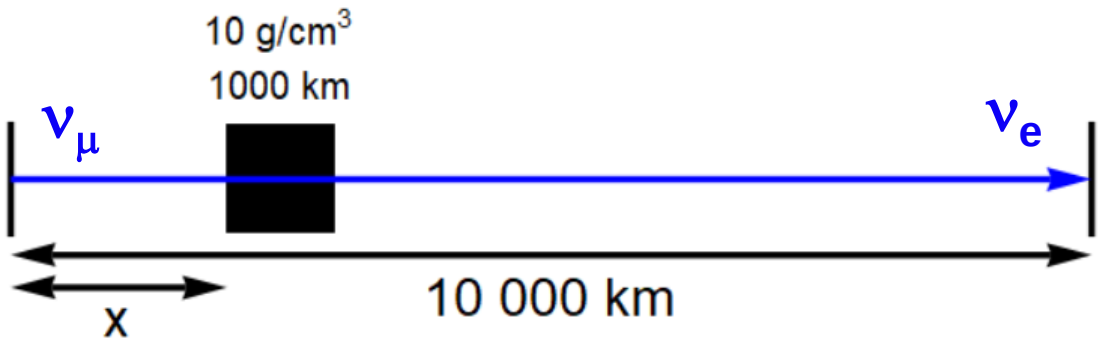
Measuring the Earth's outer core composition using neutrino oscillations

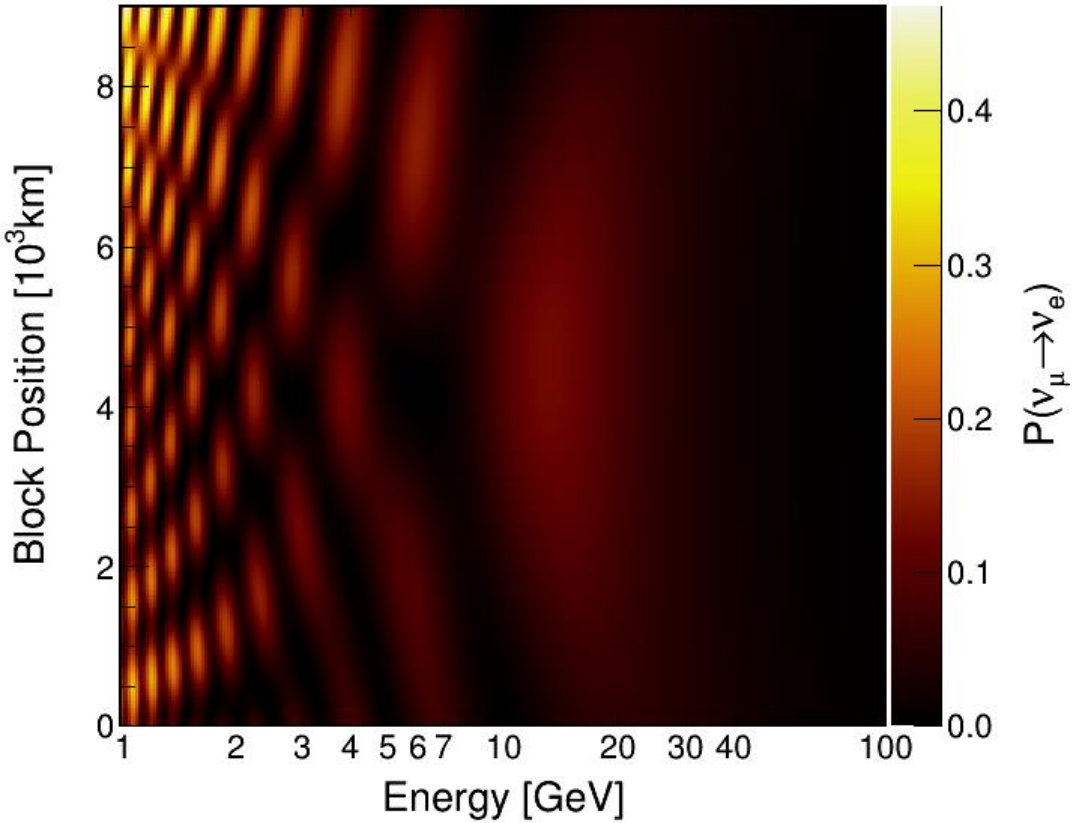
João Coelho

APC Laboratory

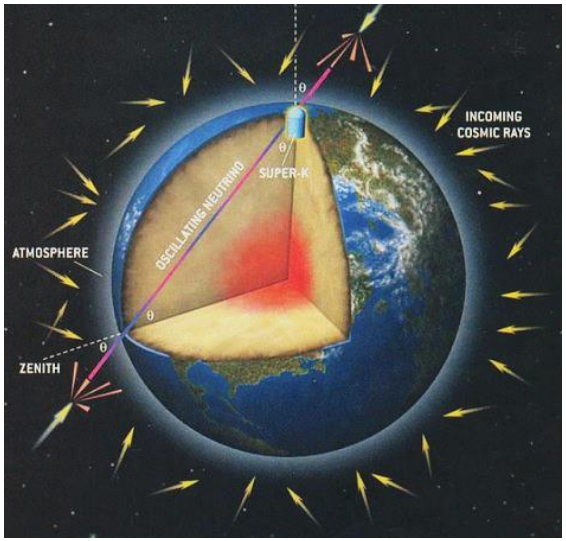
31 July 2022

Why Oscillation?

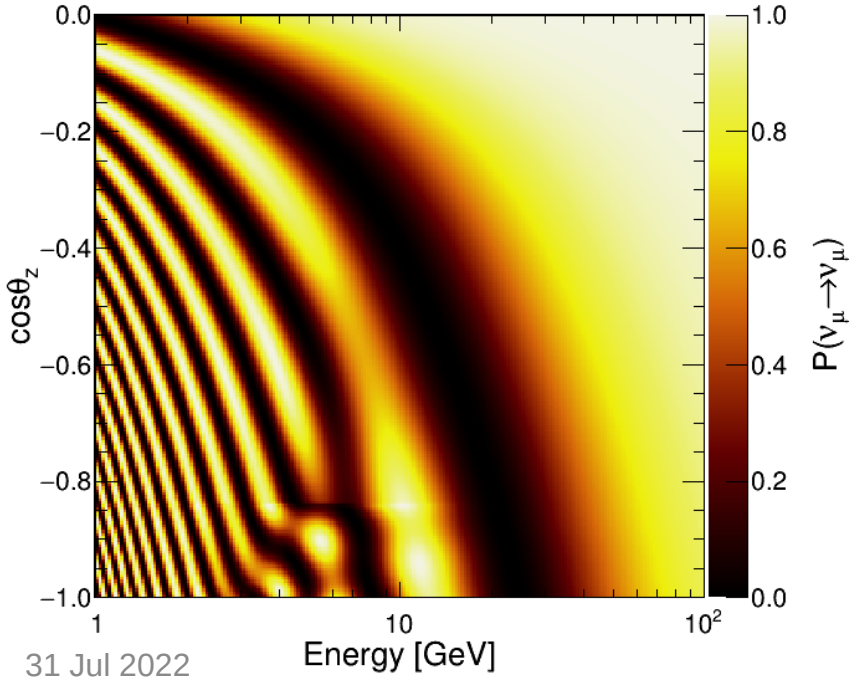


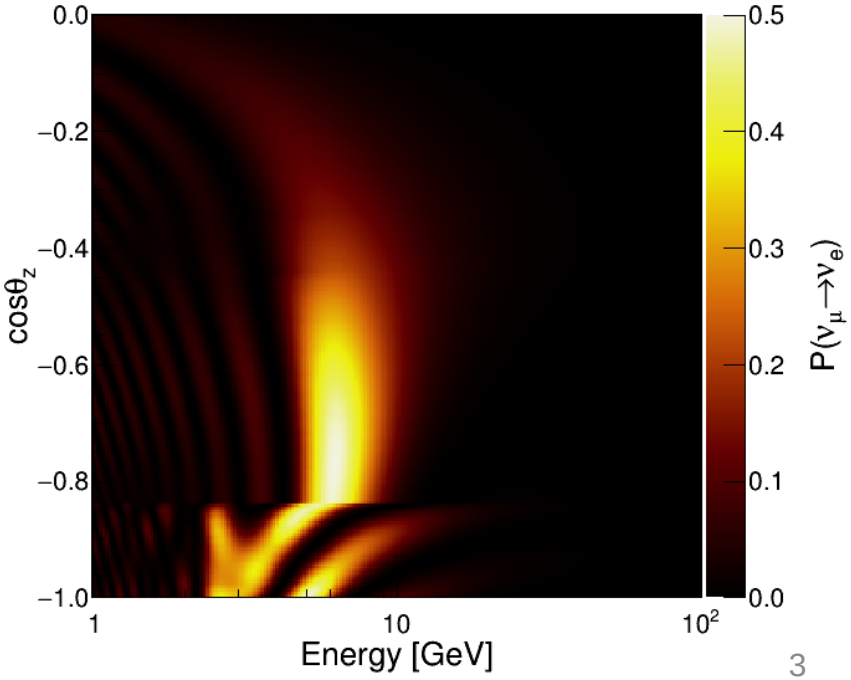


Atmospheric Neutrinos



- Very long baselines available
- Strong matter effects give sensitivity to electron density
- Resonances occur at a few GeV

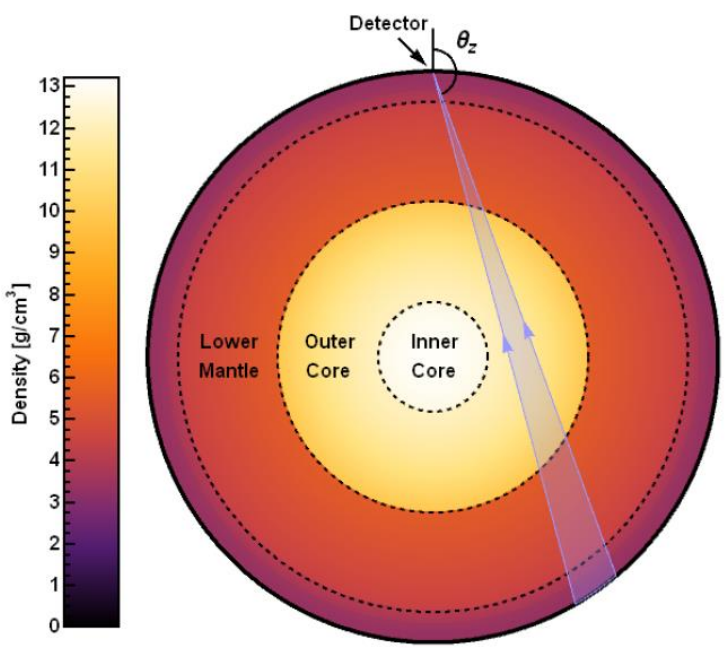


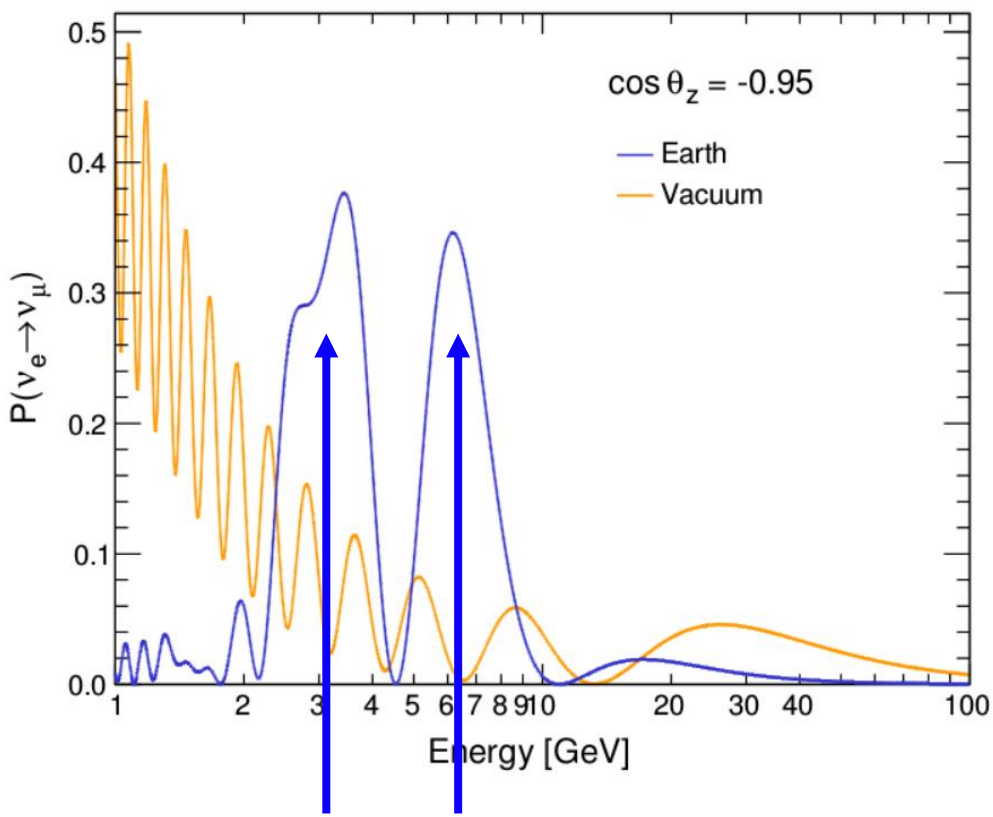


Resonances

- Very large deviations from vacuum oscillations at resonance energies

$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F N_e} \simeq 7\,{\rm GeV}\left(\frac{4.5\,{\rm g/cm^3}}{\rho}\right)$$

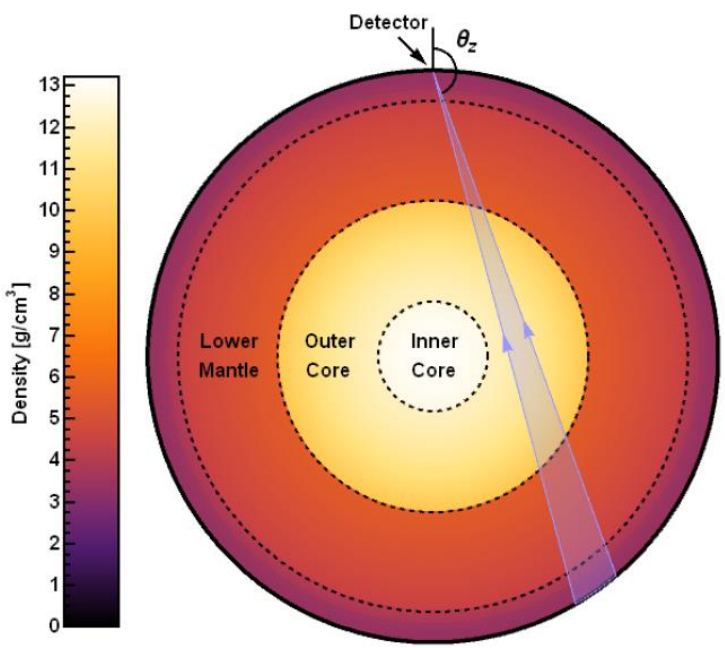


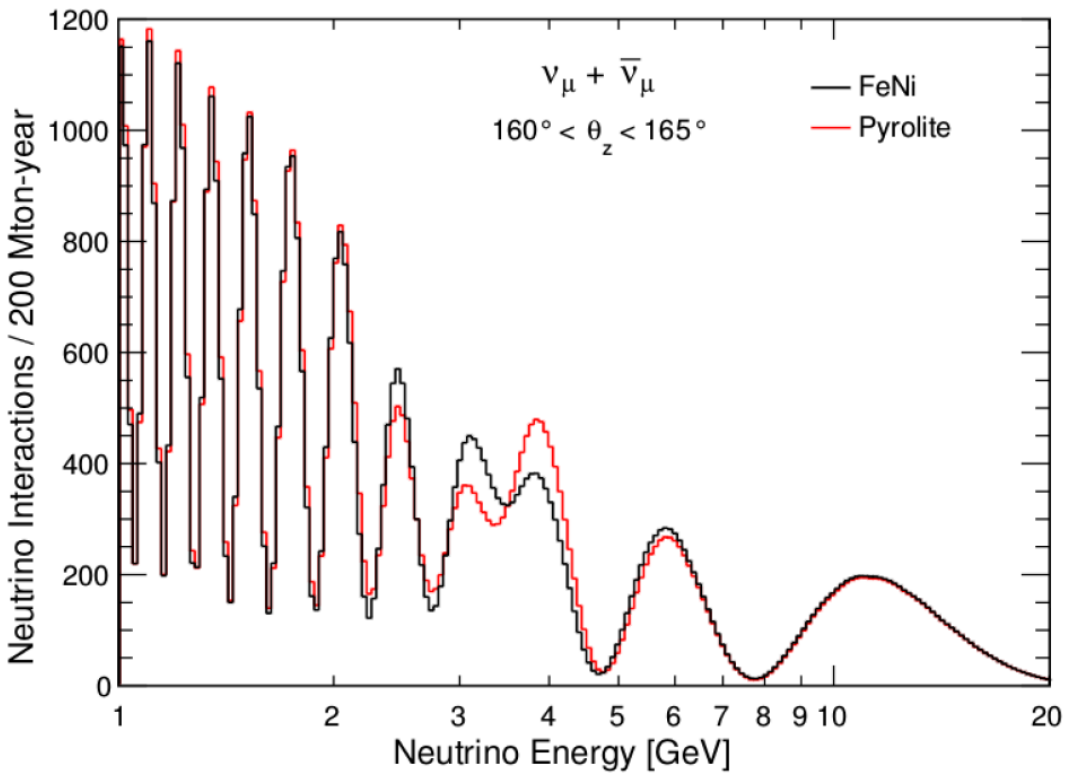


Core Mantle

Observables

- In reality we observe:
- $\Phi_e * P(\nu_e \rightarrow \nu_\mu) + \Phi_\mu * P(\nu_\mu \rightarrow \nu_\mu)$ + antineutrinos
- Extreme example:
  - Pyrolite outer core with a 10 Mton detector after 20 years (perfect resolution)

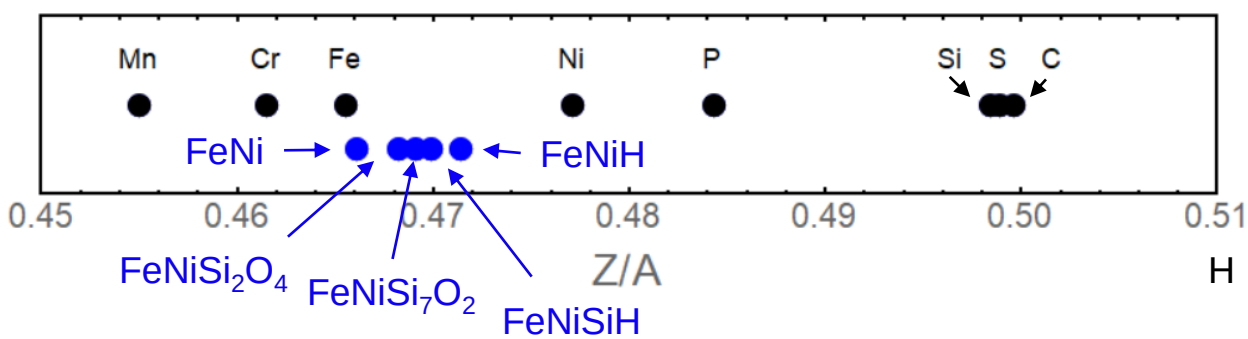




Outer Core Models

- Focus on a few reasonably motivated models
  - FeNiSi2O4 (Badro et al., 2015)
  - FeNiSi7O2 (Kaminski and Javoy, 2013),
  - FeNiSiH (Tagawa et al., 2016)
  - FeNiH (Sakamaki et al., 2016)
- Ranging from 0.4661 to 0.4714 in Z/A

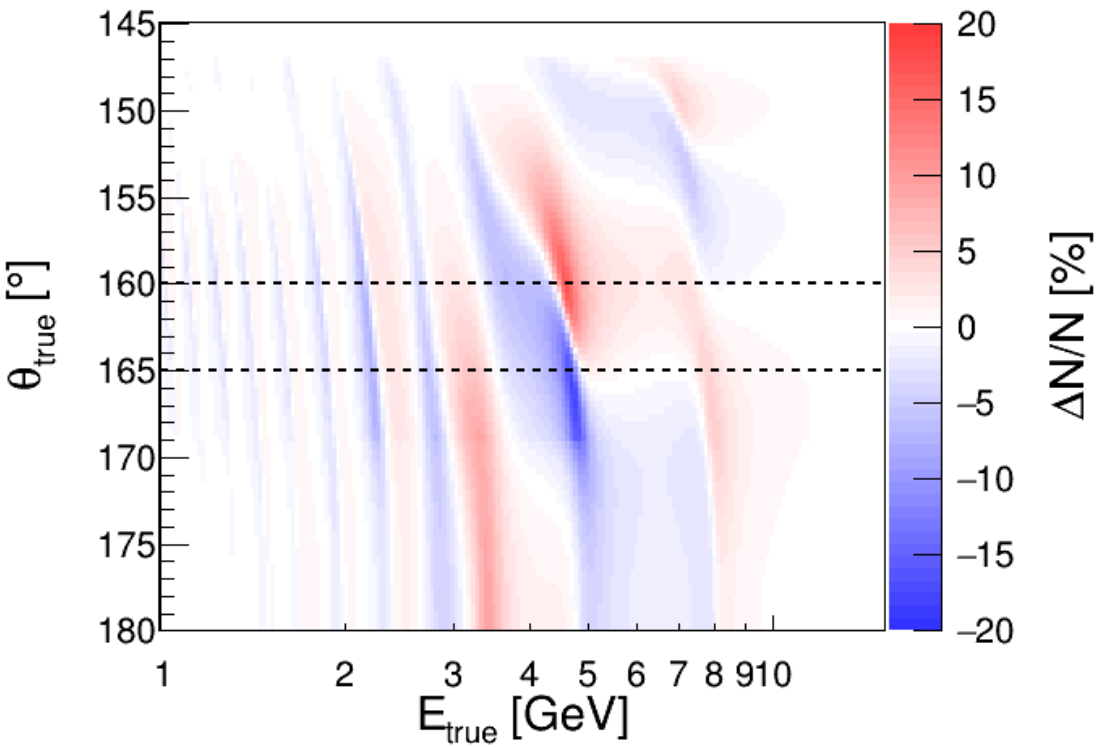
Label	FeNi	$FeNiSi_2O_4$	$FeNiSi_7O_2$	FeNiSiH	FeNiH
Composition	95 wt% Fe 5 wt% Ni - -	94 wt% Fe 5 wt% Ni 2 wt% Si 4 wt% O	91 wt% Fe 5 wt% Ni 7 wt% Si 2 wt% O	93.2 wt% Fe 5 wt% Ni 6.5 wt% Si 0.3 wt% H	94 wt% Fe 5 wt% Ni 1 wt% H -
Z/A	0.4661	0.4682	0.4691	0.4699	0.4714

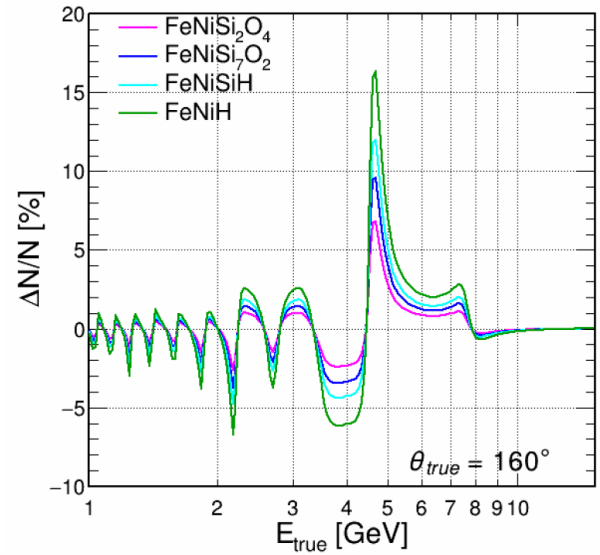


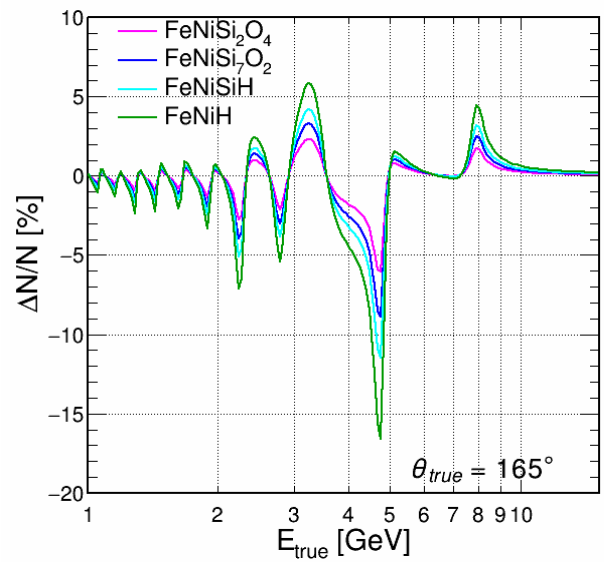
H

Signal Maps

- Signal is very sensitive to neutrino direction
- Need to work in 2D





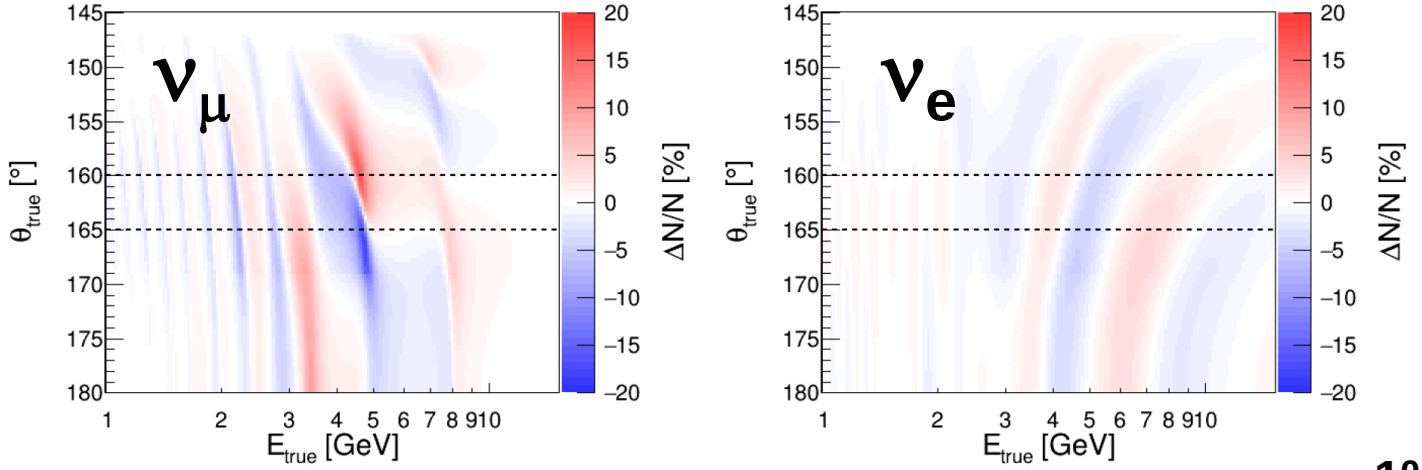


Detector Blurring

- Energy and direction measurements are imperfect
- Detector is less efficient at lower energies

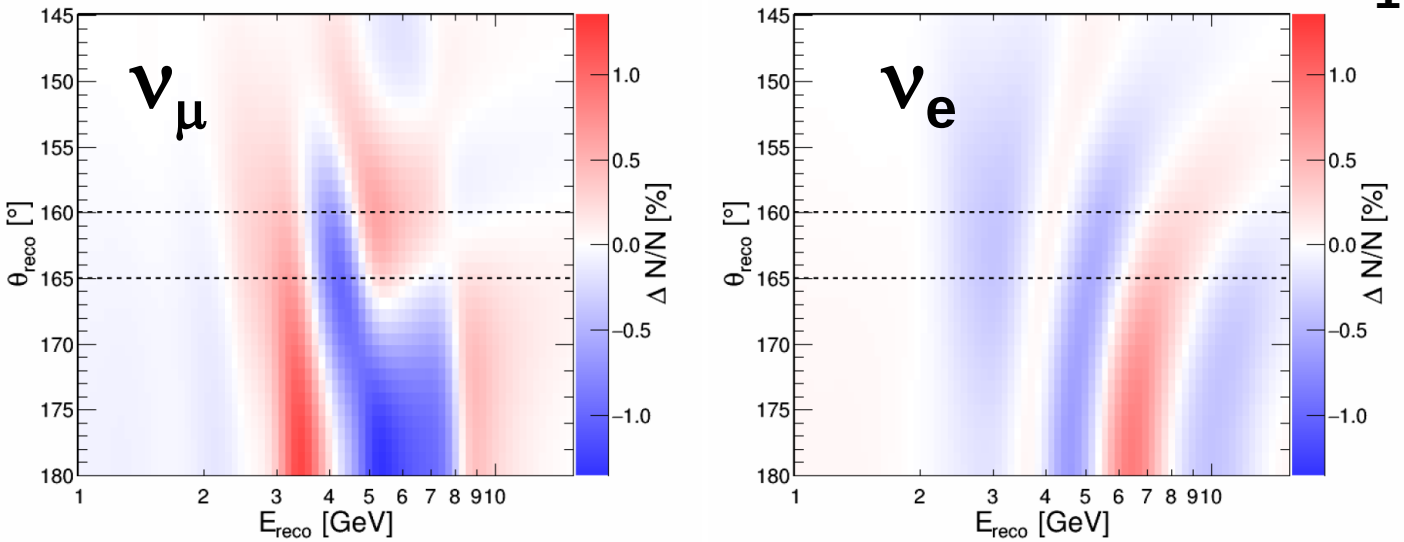
20%

Perfect Detector

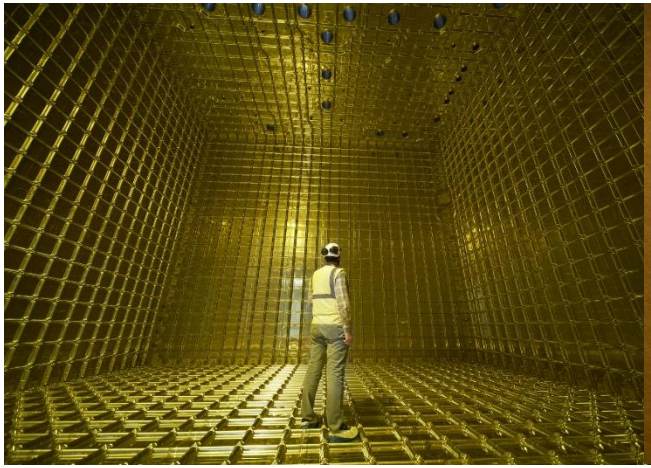


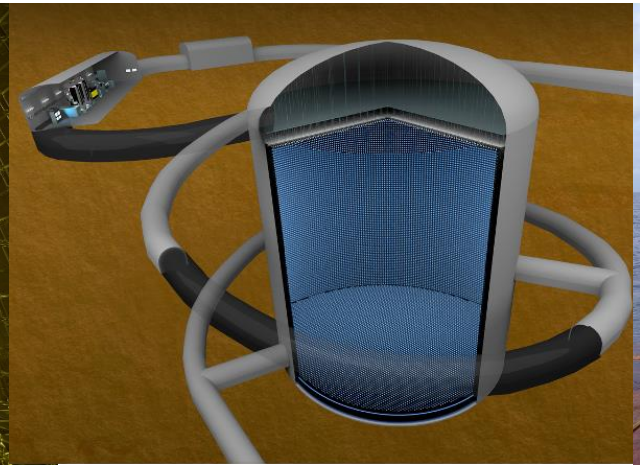
1%

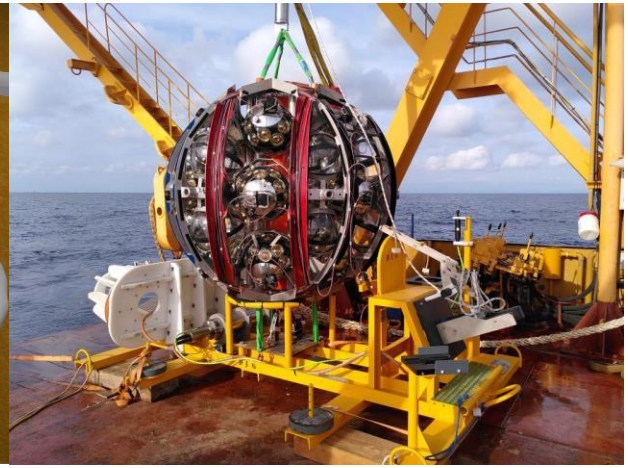
Realistic Detector

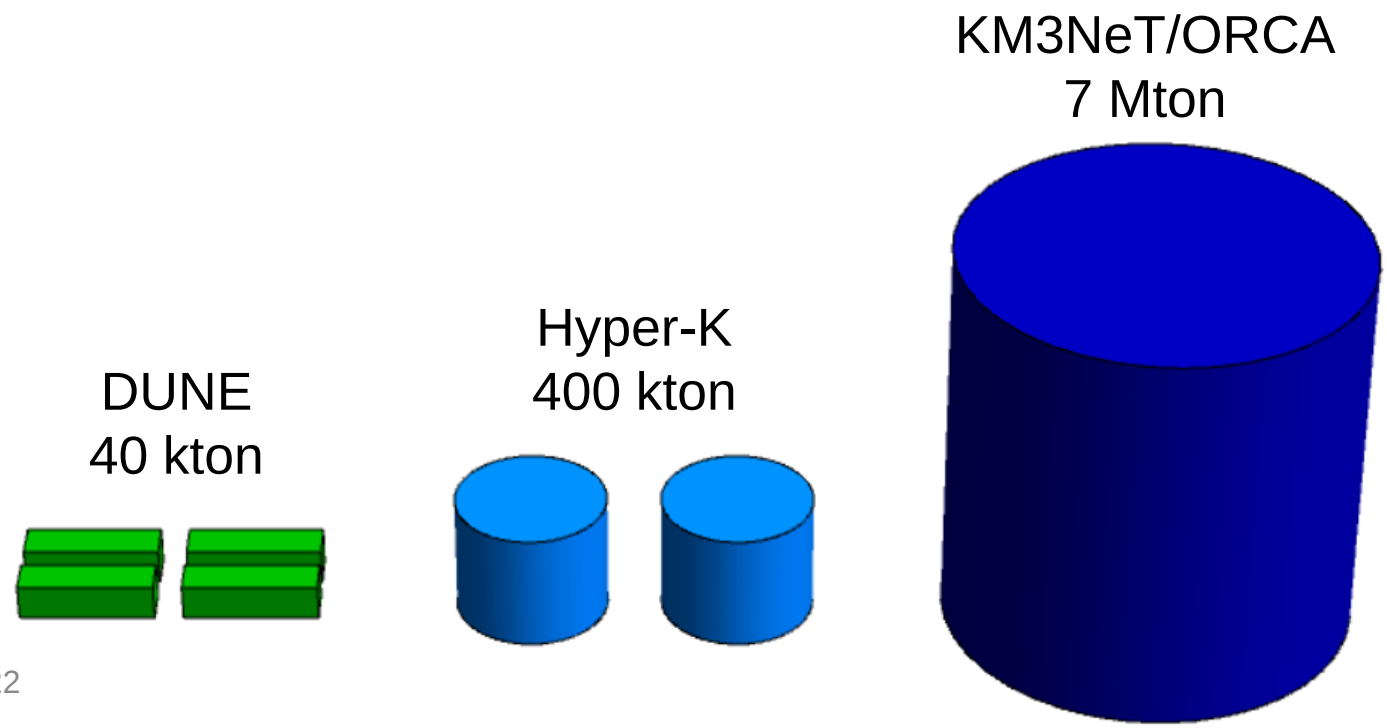


3 Detector Examples



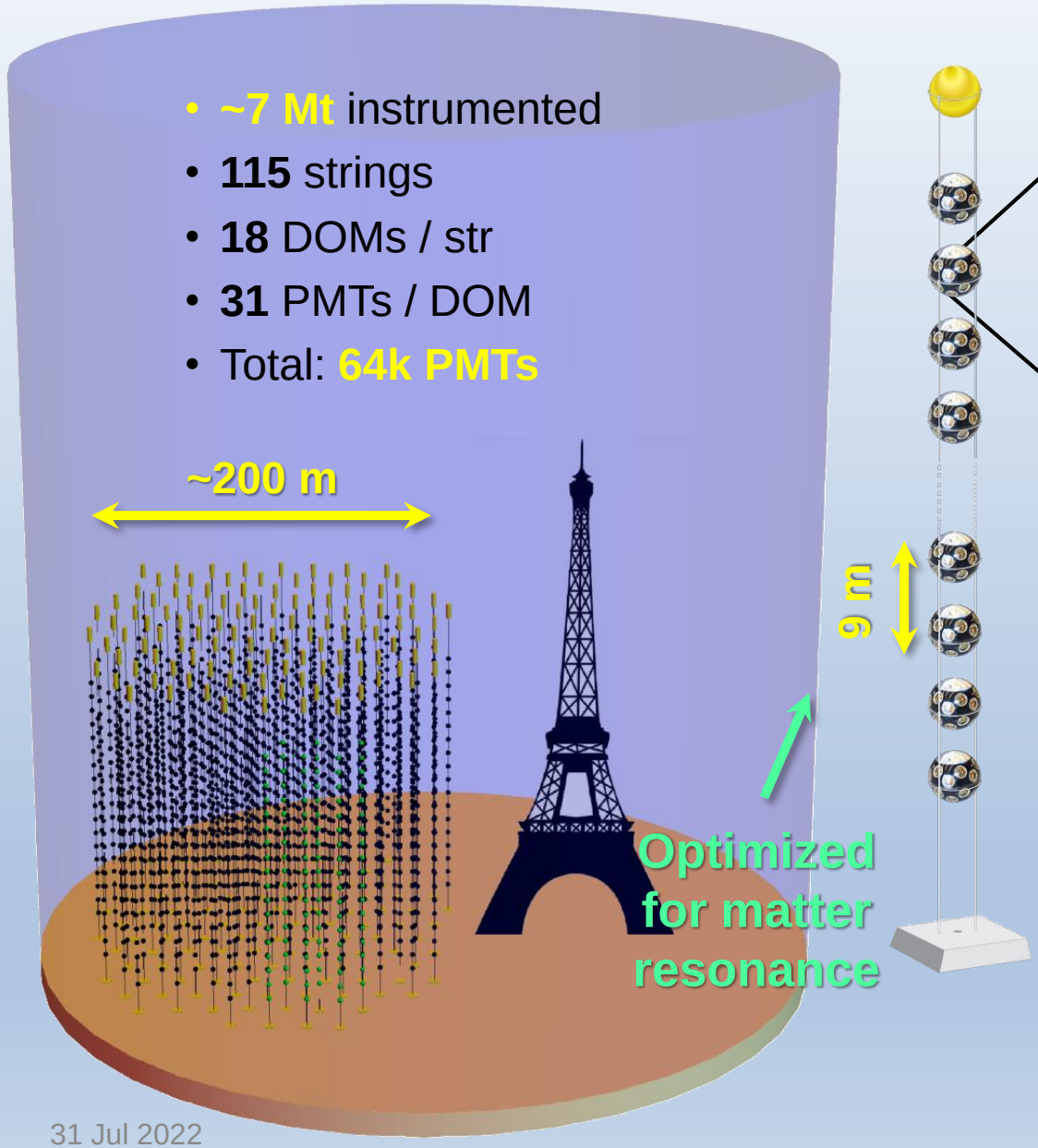


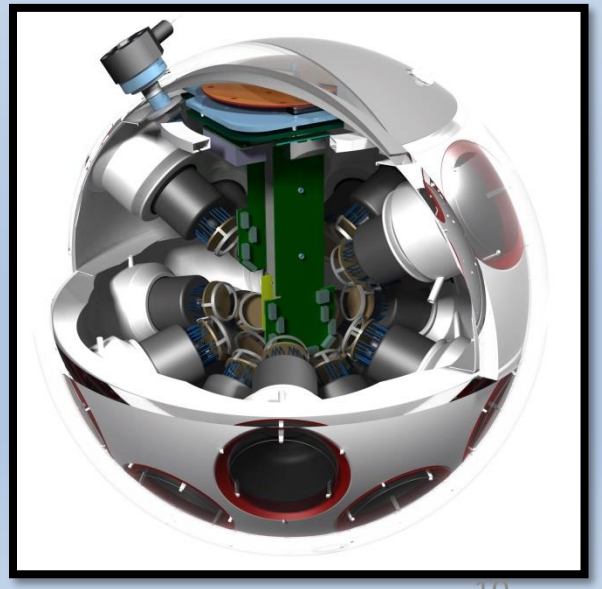




The ORCA Detector

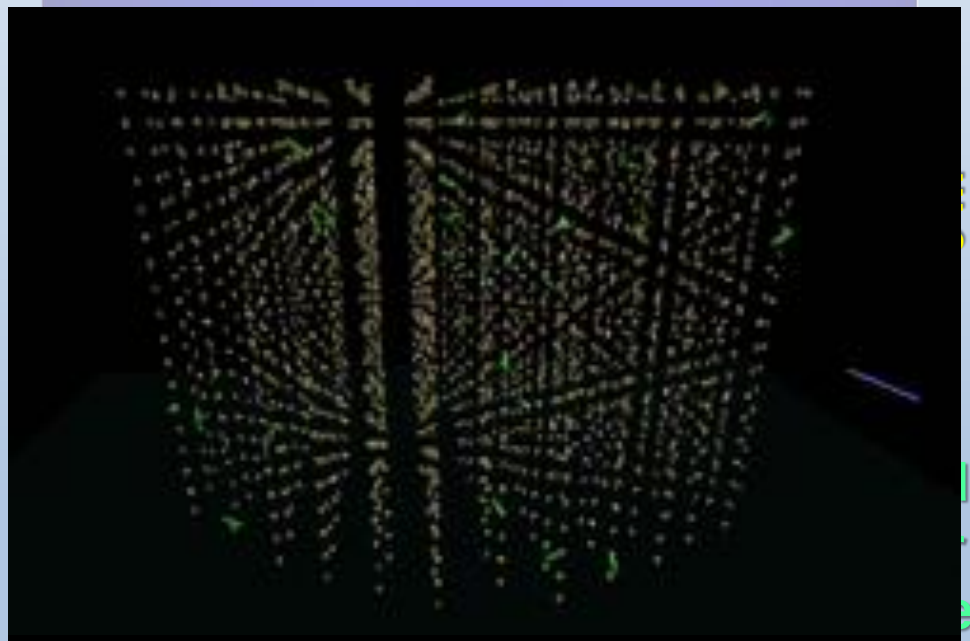
- **~7 Mt** instrumented
- **115** strings
- **18** DOMs / str
- **31** PMTs / DOM
- Total: **64k PMTs**



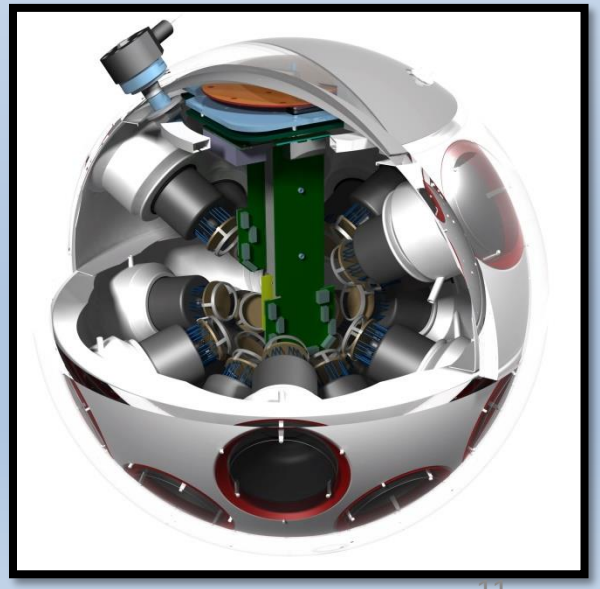


The ORCA Detector

- ~7 Mt instrumented
- **115** strings
- **18** DOMs / str
- **31** PMTs / DOM
- Total: **64k PMTs**

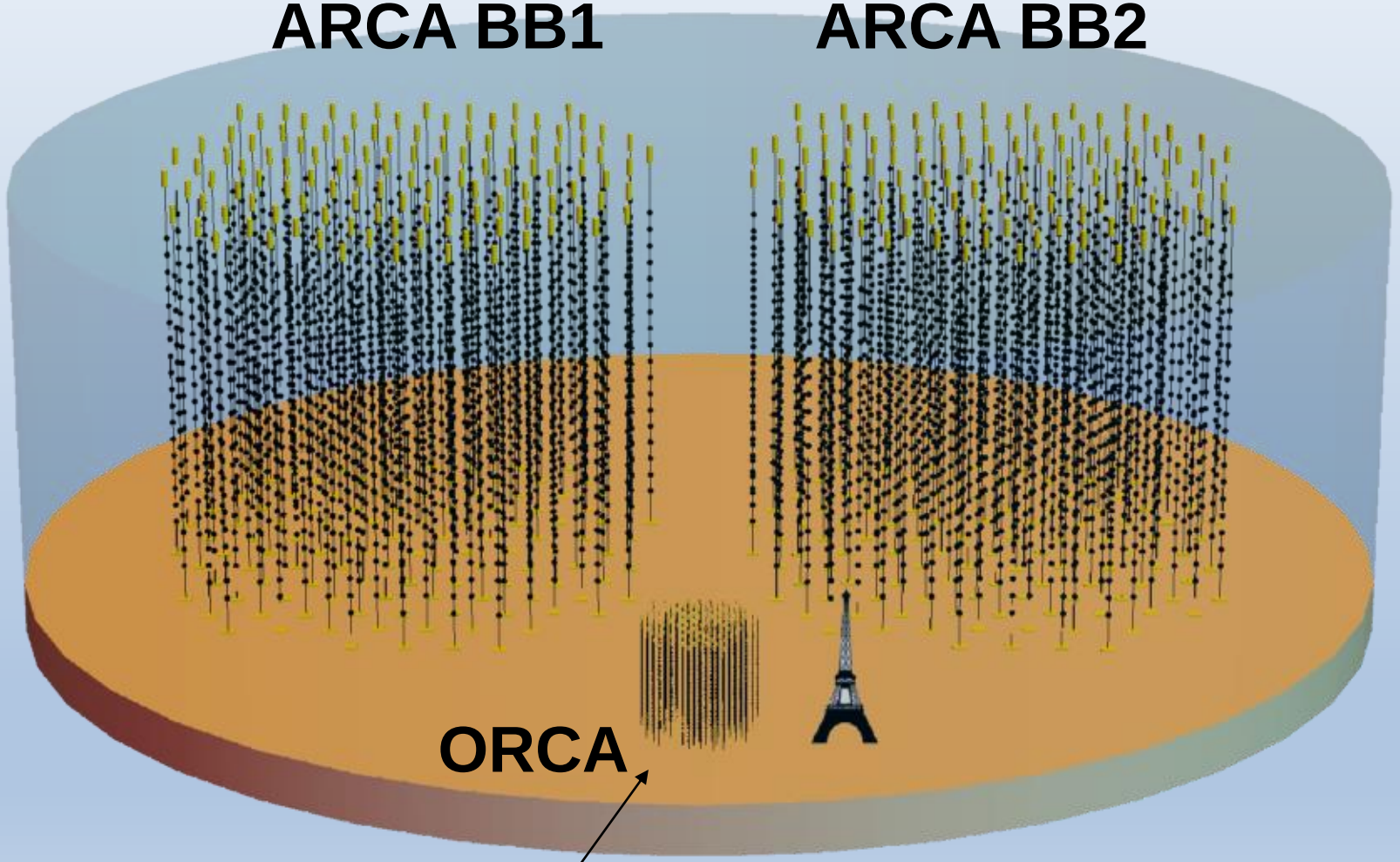


http://www.cherenkov.nl/



Two Detector Scales

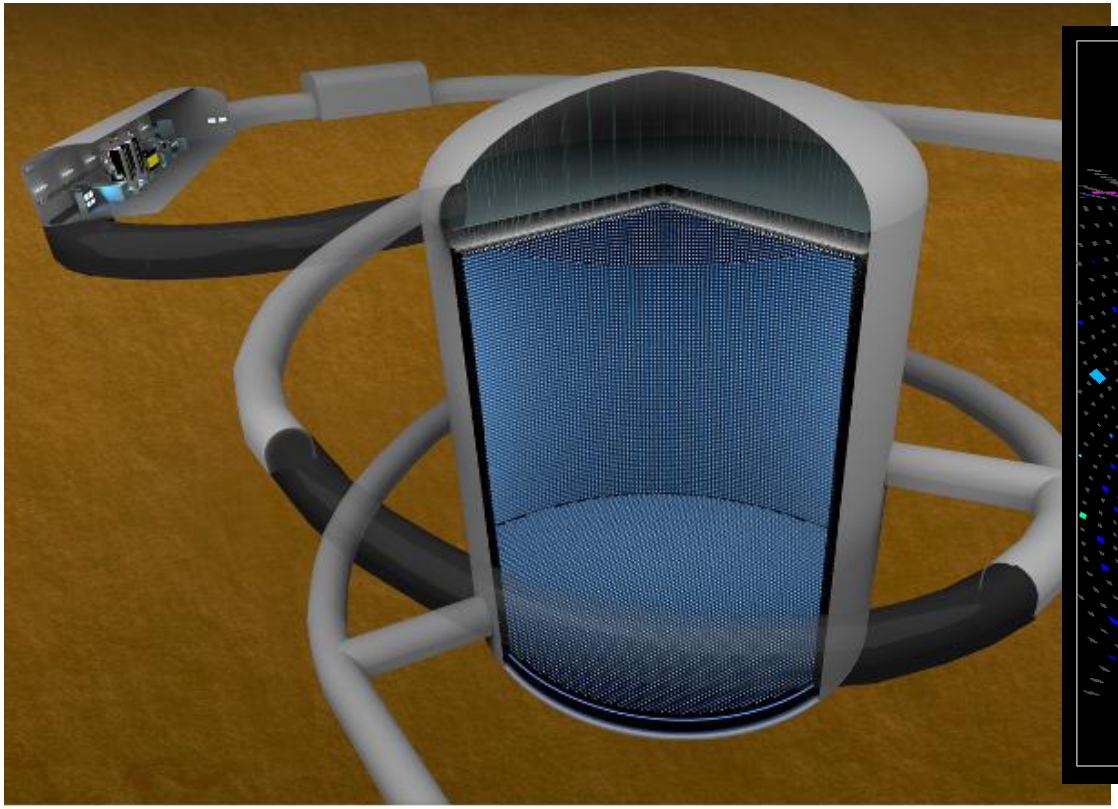
36m vert. x 90m horiz. spacing TeV - PeV

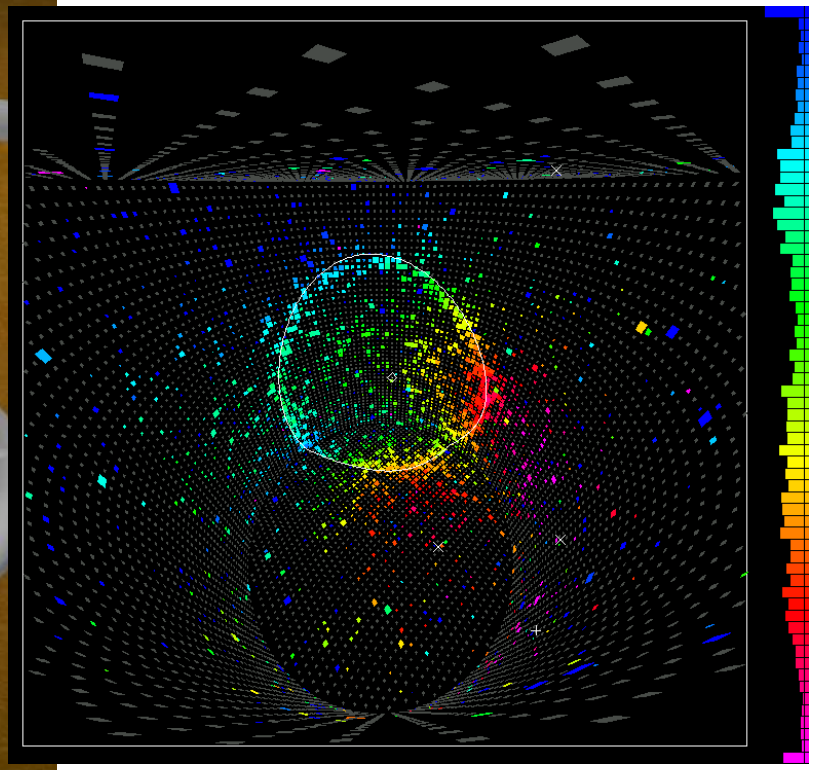


9m vert. x 20m horiz. spacing
GeV - TeV

Hyper-Kamiokande

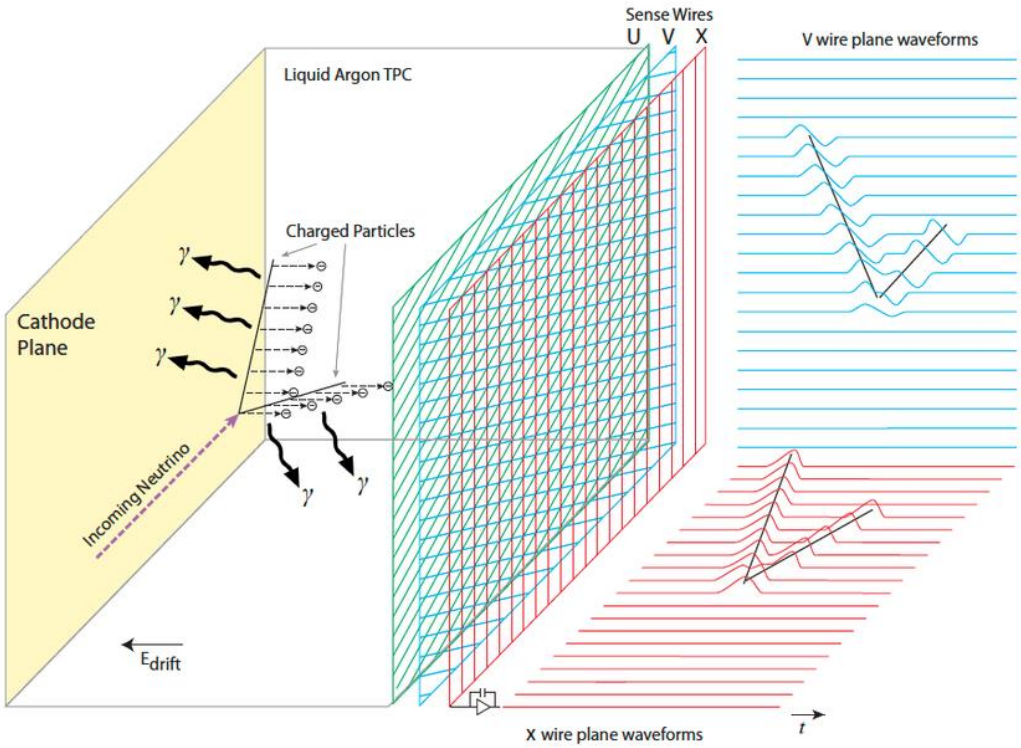
- 400 kton Water-Cherenkov detector
- Good energy resolution but 10x smaller than ORCA

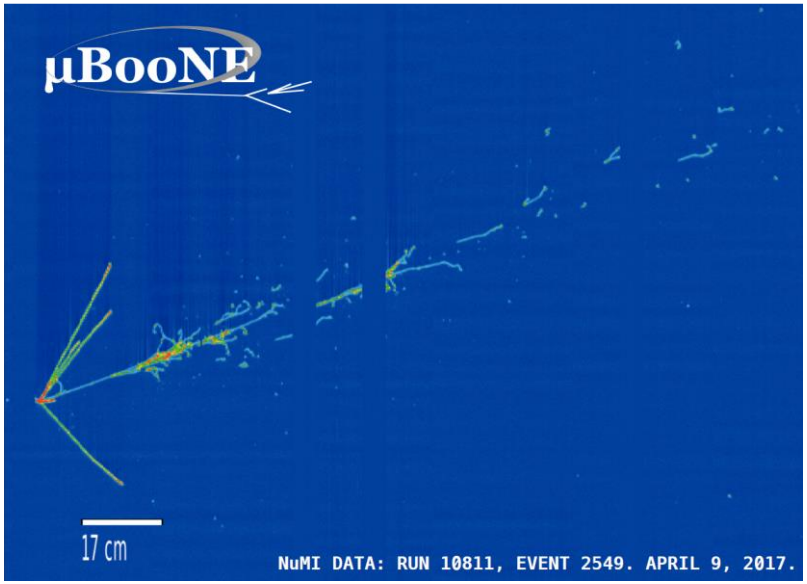




DUNE

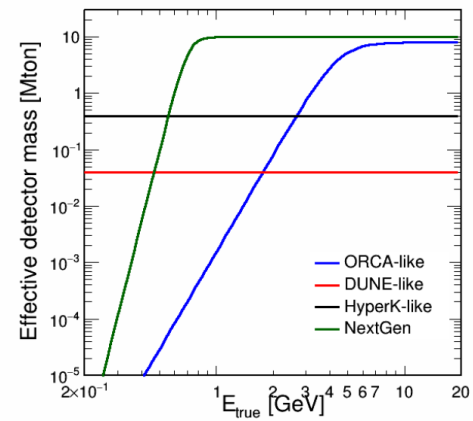
- 40kton Liquid Argon TPC
- Excellent resolution, but 10x smaller than HK

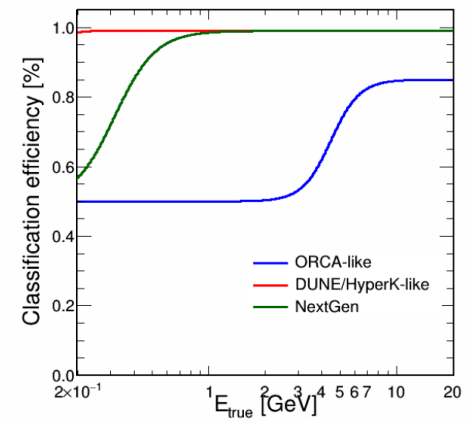


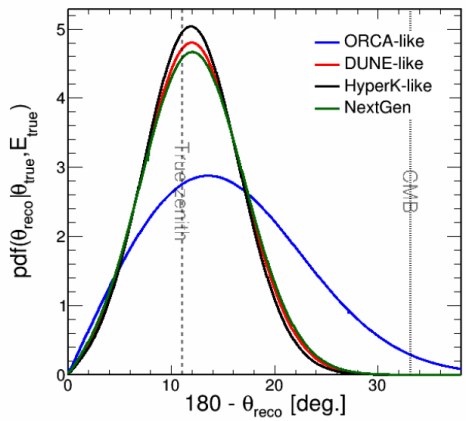


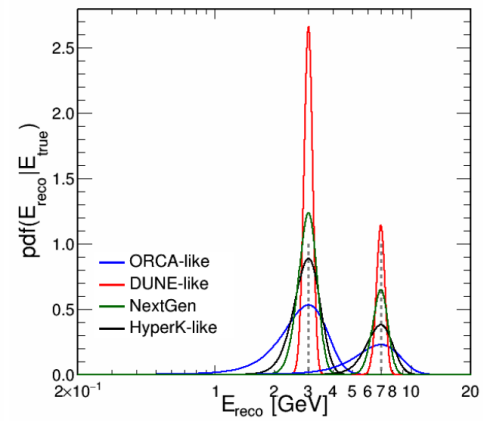
Detector Modelling

- Parametrized detector responses
- Energy/direction resolution
- Detection efficiency
- Nu flavour identification



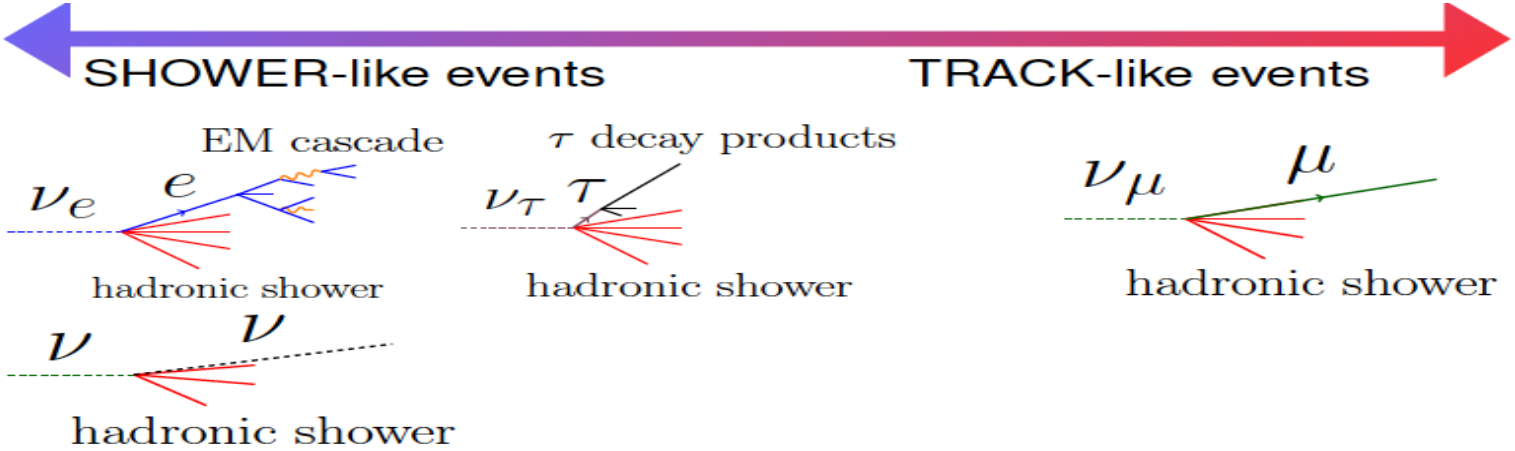


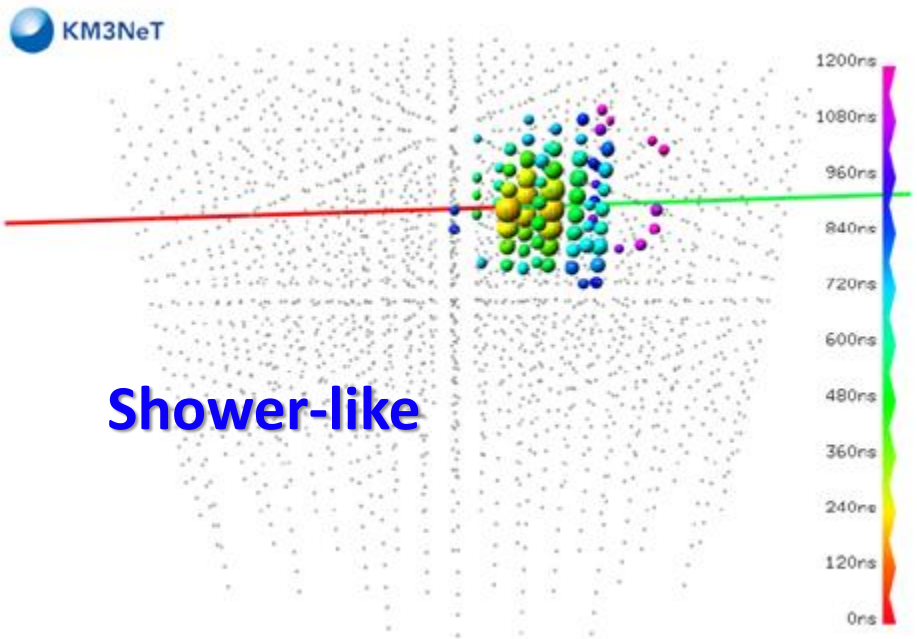


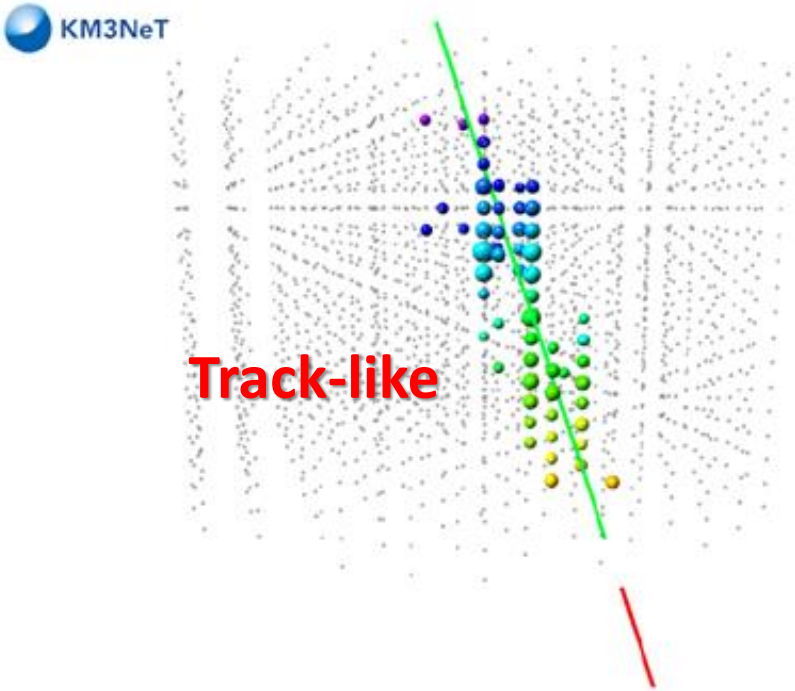


Detector	M (Mton)	E_{th} (GeV)	E_{pl} (GeV)	$\sigma(E)/E$	σ_θ (deg)	E_{th}^{class} (GeV)	E_{pl}^{class} (GeV)	P_{max}^{class}
ORCA-like	8	2	10	25%	$30/\sqrt{E}$	2	10	85%
HyperKamiokande-like	0.40	0.1	0.2	15%	$15/\sqrt{E}$	0.1	0.2	99%
DUNE-like	0.04	0.1	0.2	5%	5	0.1	0.2	99%
Next-Generation	10	0.5	1.0	$5\% + 10\%/\sqrt{E}$	$2 + 10/\sqrt{E}$	0.5	1	99%

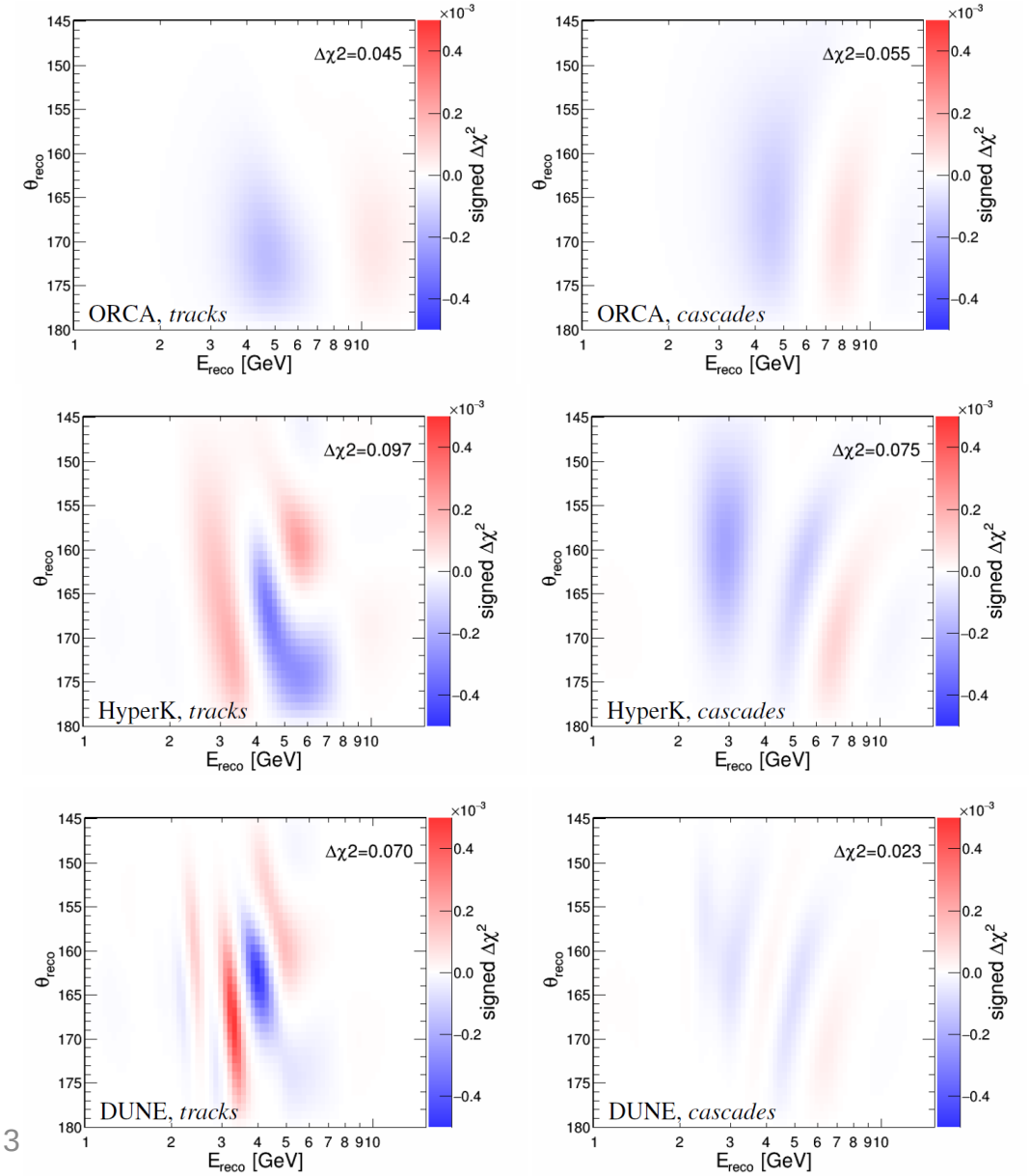
Simplified Particle ID







Statistical Significance Maps

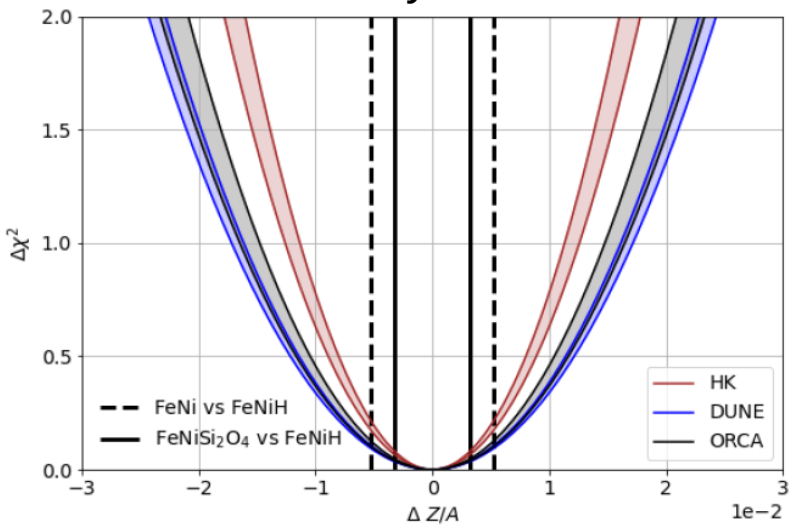


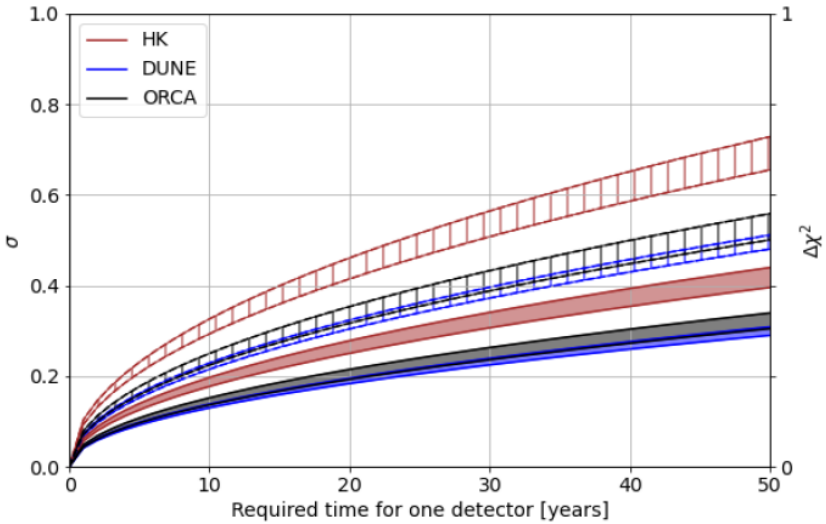
- Separation between two extreme models:
  - FeNi (Z/A = 0.4661)
  - FeNiH (Z/A = 0.4714)
- Similar significance from all 3 detectors
  - ~0.1 units of $\Delta\chi^2$
- Balance between size and detector performance

Sensitivity Results

- Upcoming generation of experiments will measure the outer core Z/A with precision between 0.01 and 0.02
- Hyper-K has the strongest power
- ORCA and DUNE achieve similar sensitivity
- This will be shy of resolving even most extreme models

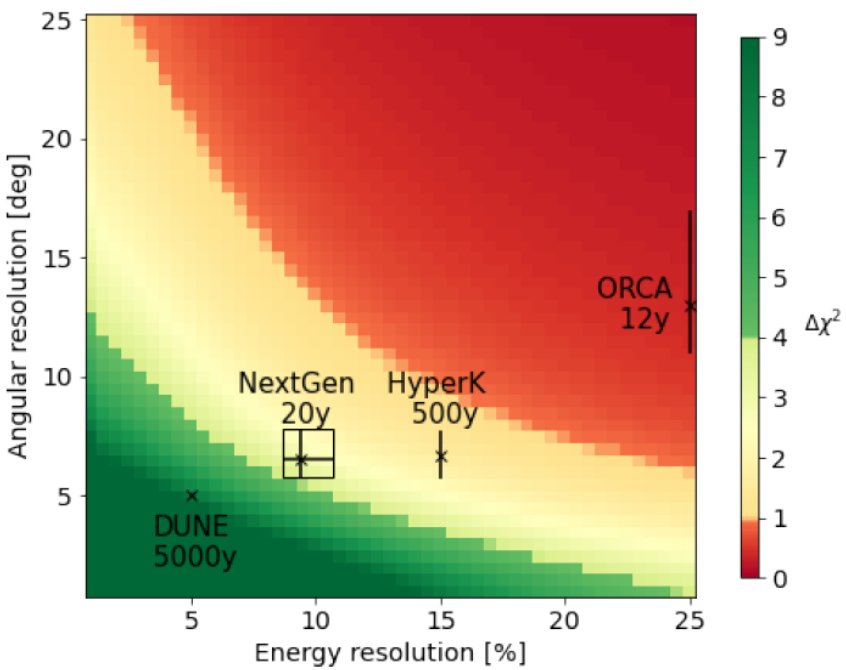
20 years

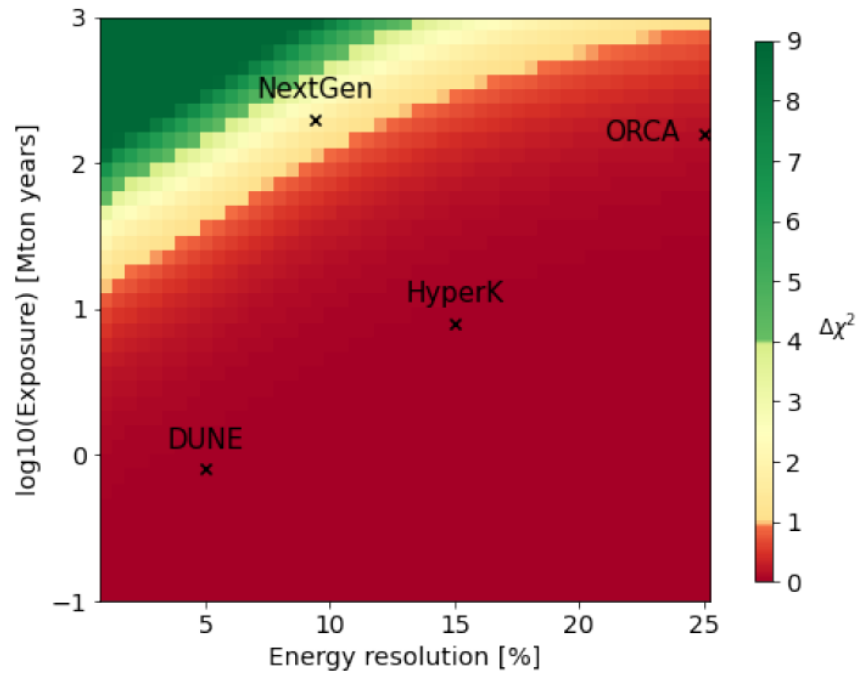




What would be required?

- What are the requirements on a detector to improve on upcoming generation
- NextGen detector needs Mton scale and HK resolution



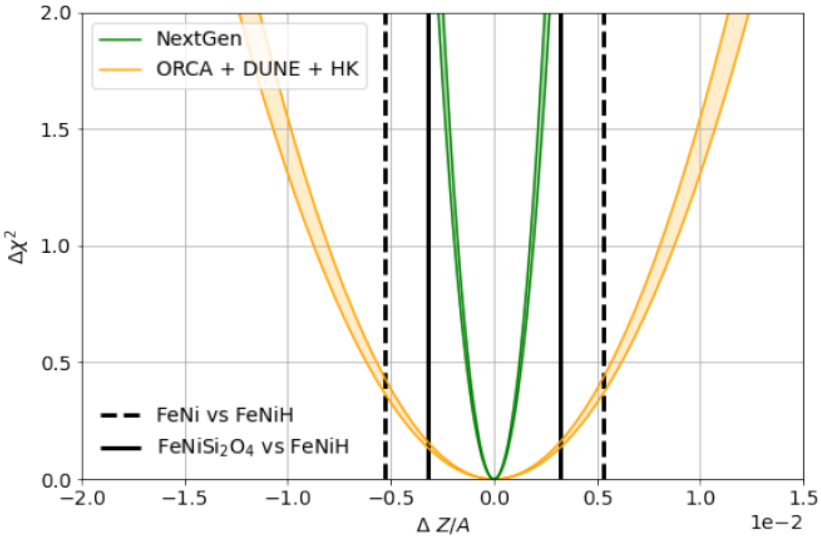


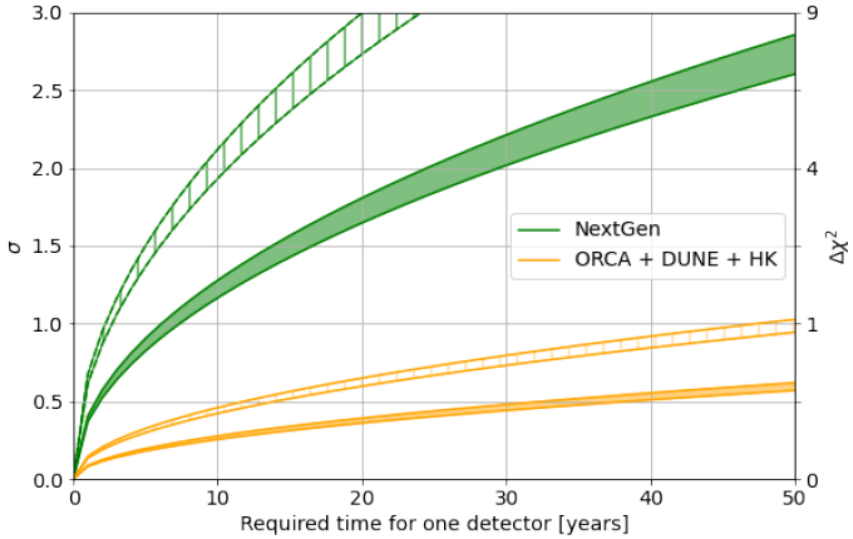
$FeNiSi_2O_4$ vs FeNiH

Prospects for NextGen

- The combination ORCA+DUNE+HK would take 50 years to resolve 1wt% H vs pure FeNi at 1σ level
- A NextGen detector may reach this level in 2-3 years
- Even a more realistic $FeNiSi_2O_4$ model could be separated from FeNiH within 10 years

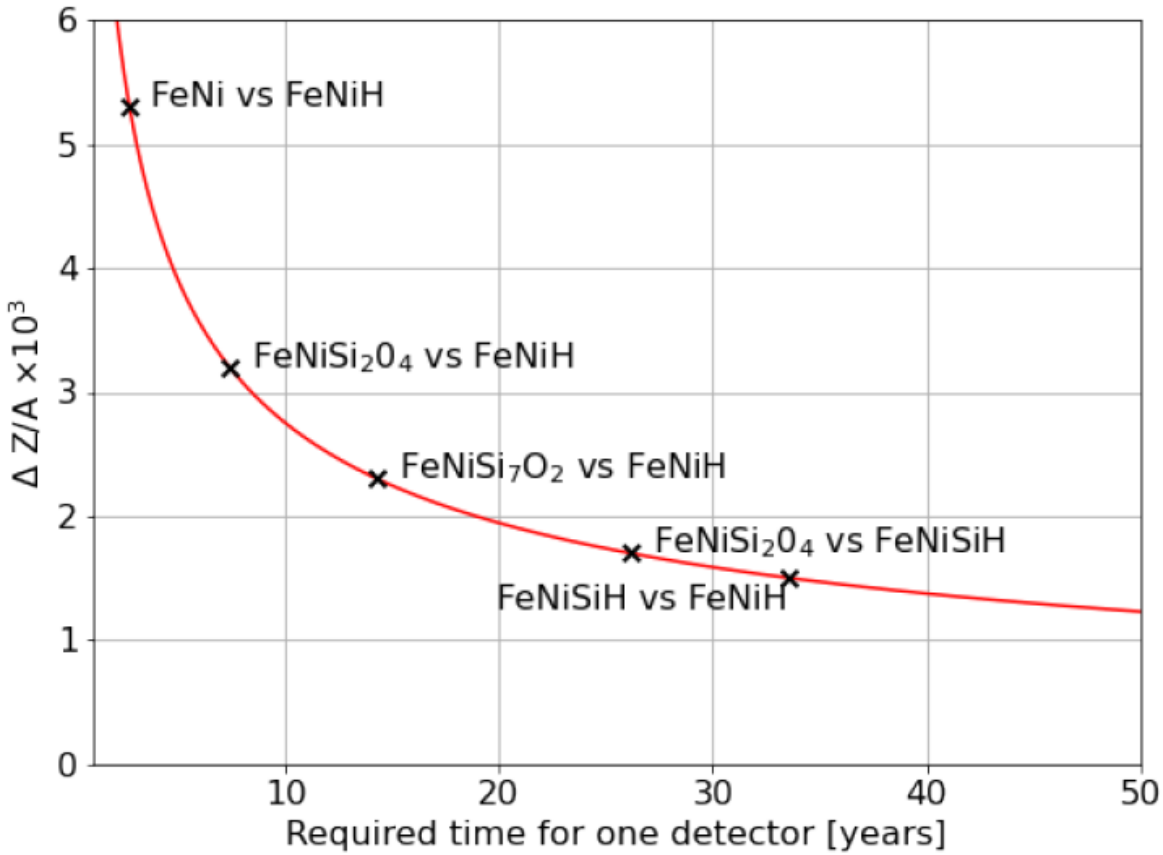
20 years





Potential Z/A Resolution

- Within a span of 50 years, a NextGen detector would be able to probe meaningful outer core models
- The most challenging models ($FeNiSi_7O_2$ vs FeNiSiH) would require 1200 Mton-years to resolve at 1σ



Summary

- The upcoming generation of neutrino detectors will start to probe the composition of the Earth's outer core

- Discriminating realistic models will likely require a detector beyond the capability of the existing projects

- A 10 Mton detector with HK-like resolution would be able to measure Z/A to the per mille level and provide the first direct information on the outer core composition

- CAVEAT: We have not yet considered systematic uncertainties in detail. These will have some impact, but initial checks indicate no show-stoppers

Some Advertisement

- Our paper will appear on arXiv this week. Stay tuned!

- The software used to reproduce these results will also be freely available alongside our paper. Hopefully it can be useful to this community for additional studies.

- We are looking for a post-doc to further develop this project. Let me know if you or someone you know may be interested

Thank you!

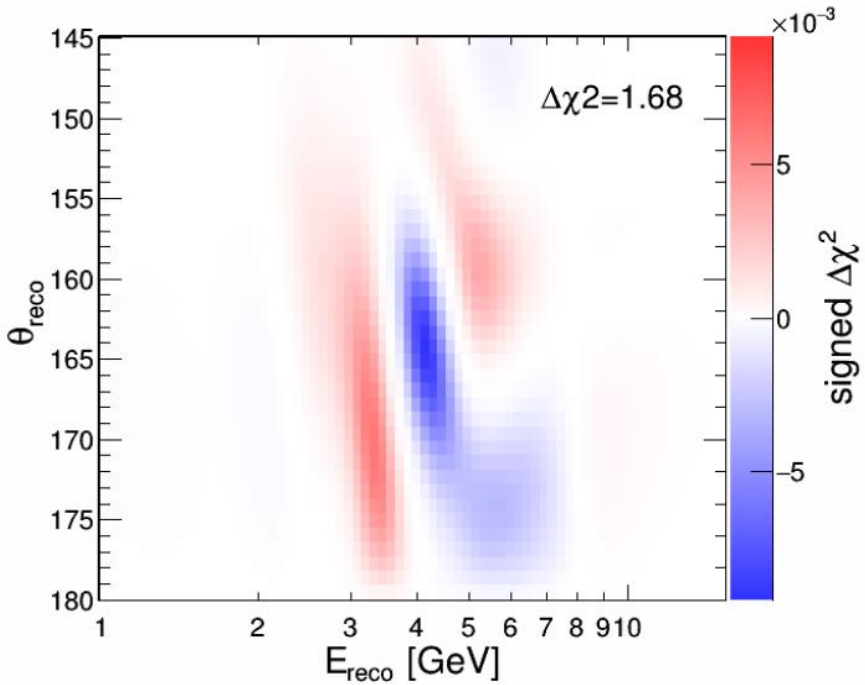
Lukas Maderer

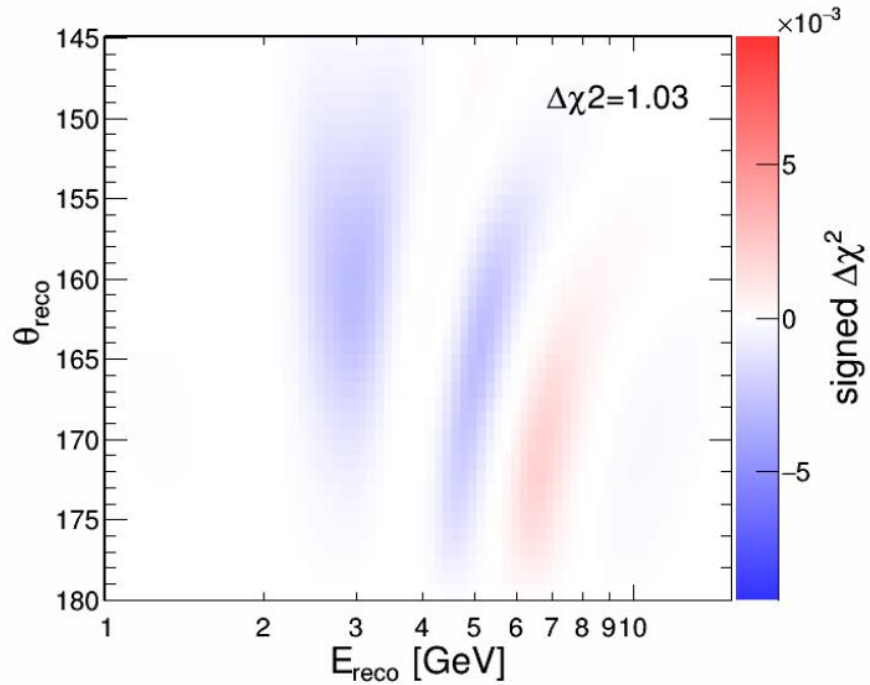
Edouard Kaminsky

Veronique Van Elewyck

Simon Bourret

NextGen $\Delta\chi^2$ Maps





$FeNiSi_2O_4$ vs FeNiH

ORCA Systematic Studies