Neutrino tomography: experiments

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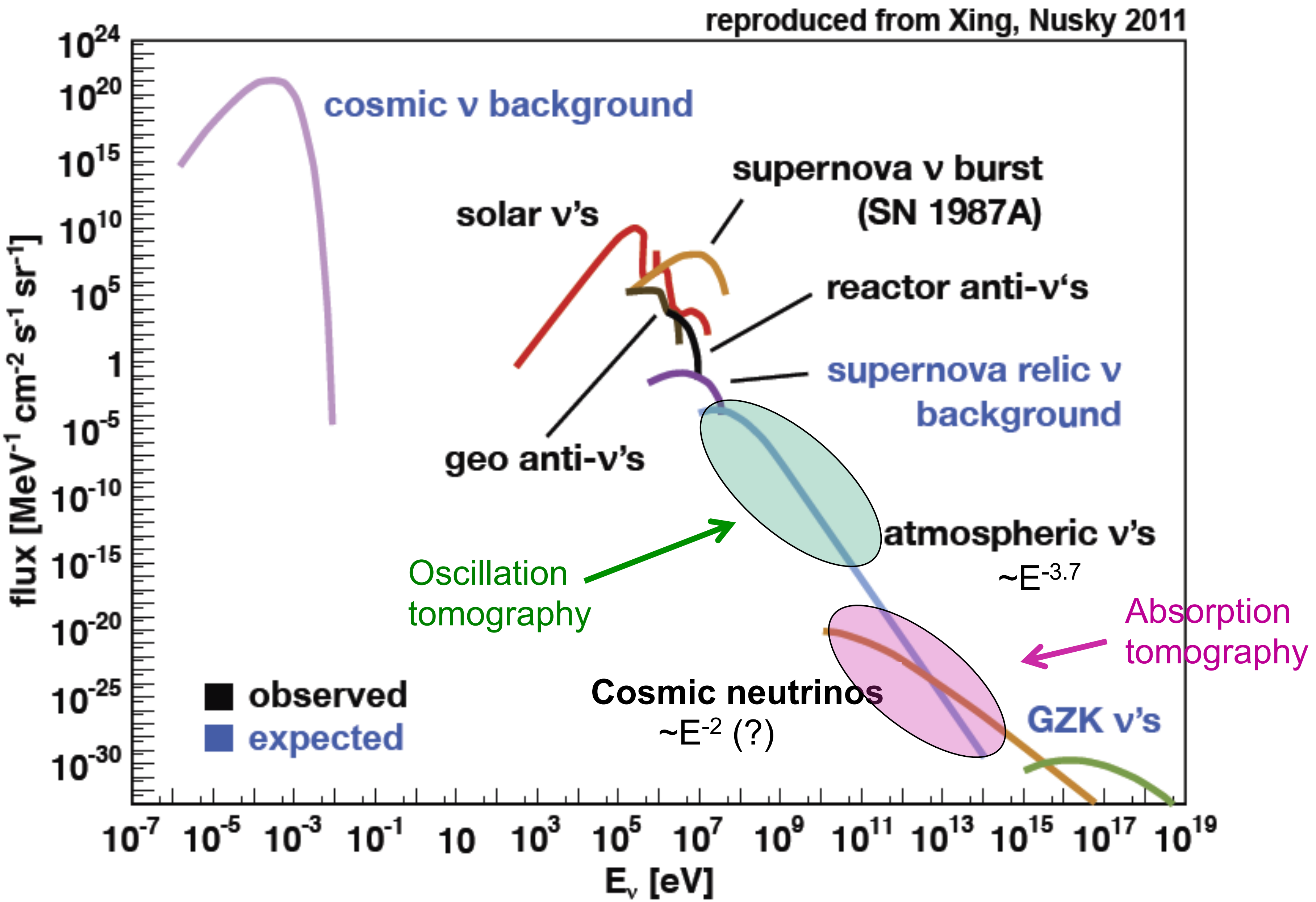
(APC & Université Paris Diderot)

… a review biased towards

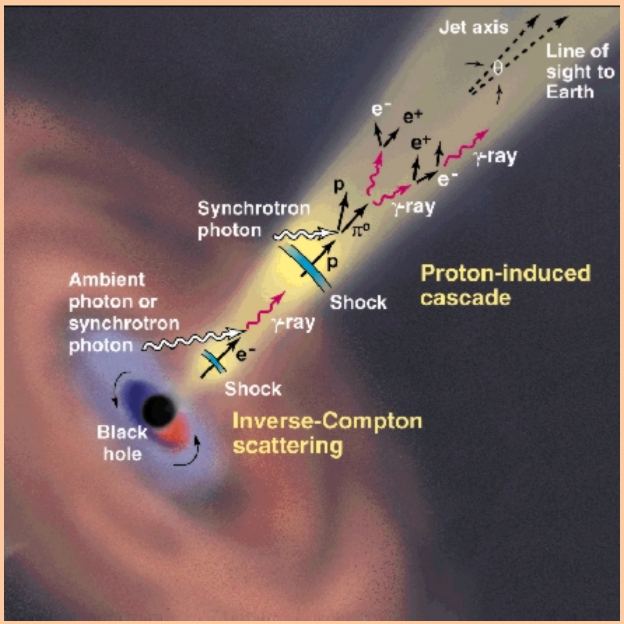
- Neutrino oscillation tomography
- Atmospheric neutrinos
- Water Cherenkov detectors

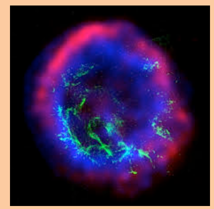
Which neutrino sources ?

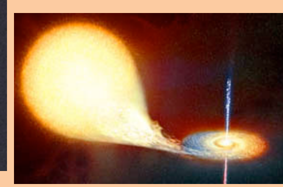


Which neutrino sources ?

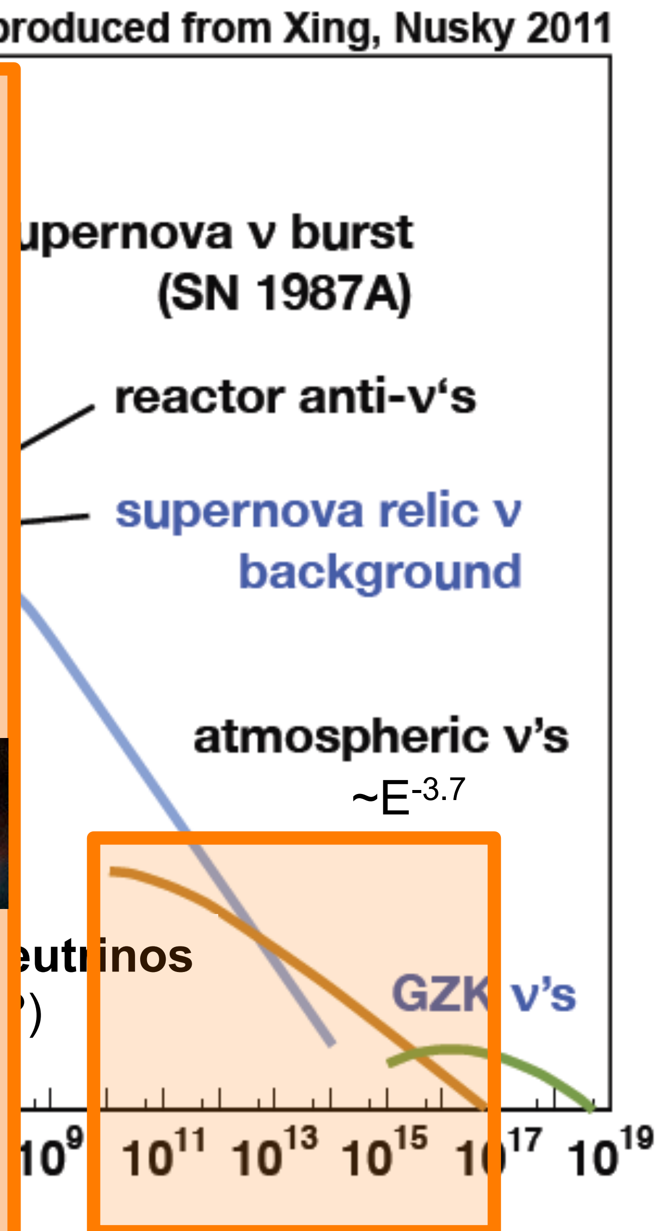
High-energy cosmic neutrinos: tracers of cosmic ray production sites in the Universe



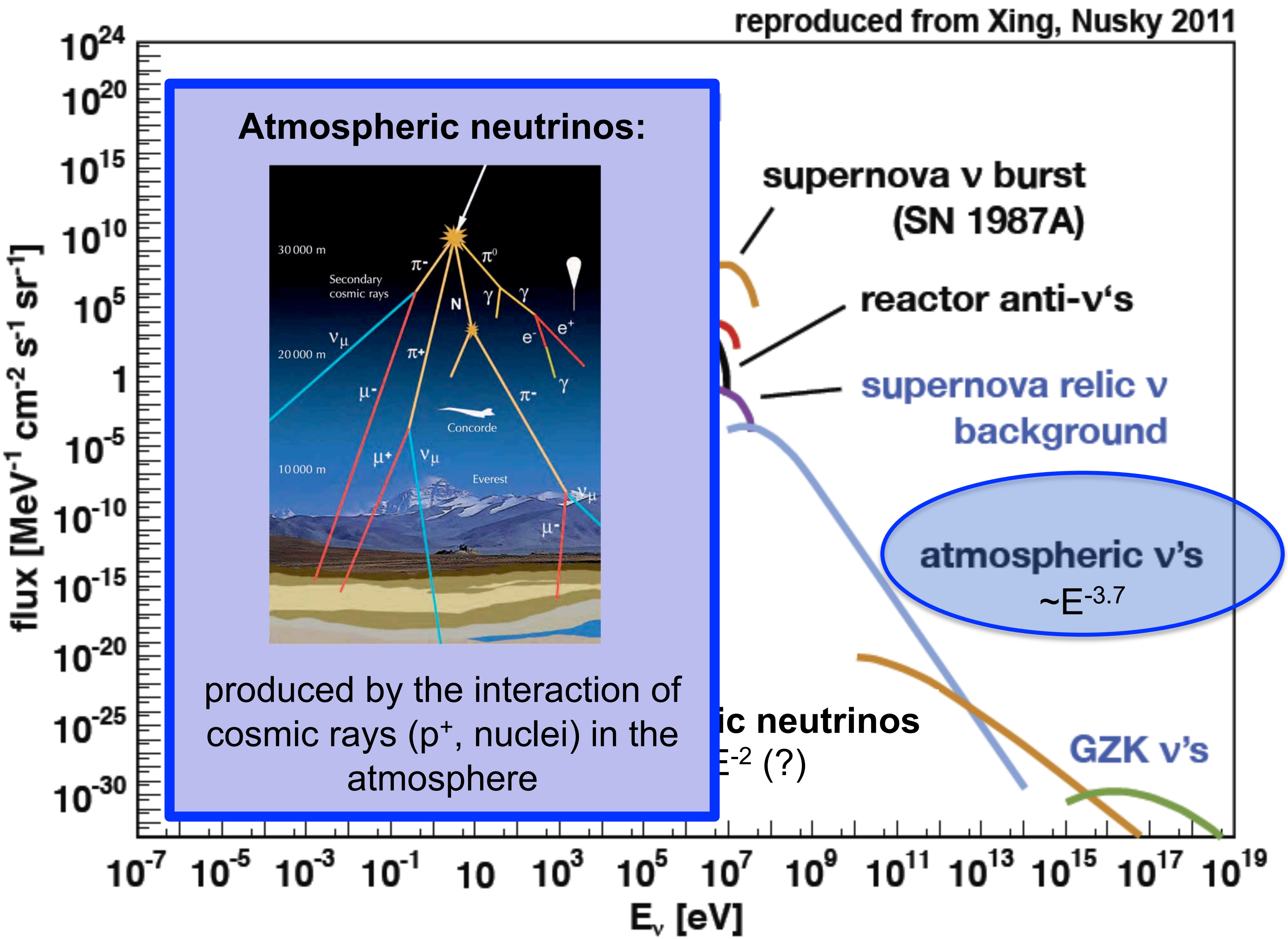




In the Galaxy: Supernovae remnants, microquasars, interstellar matter…
…and beyond: active galactic nuclei, Gamma-ray bursts,...

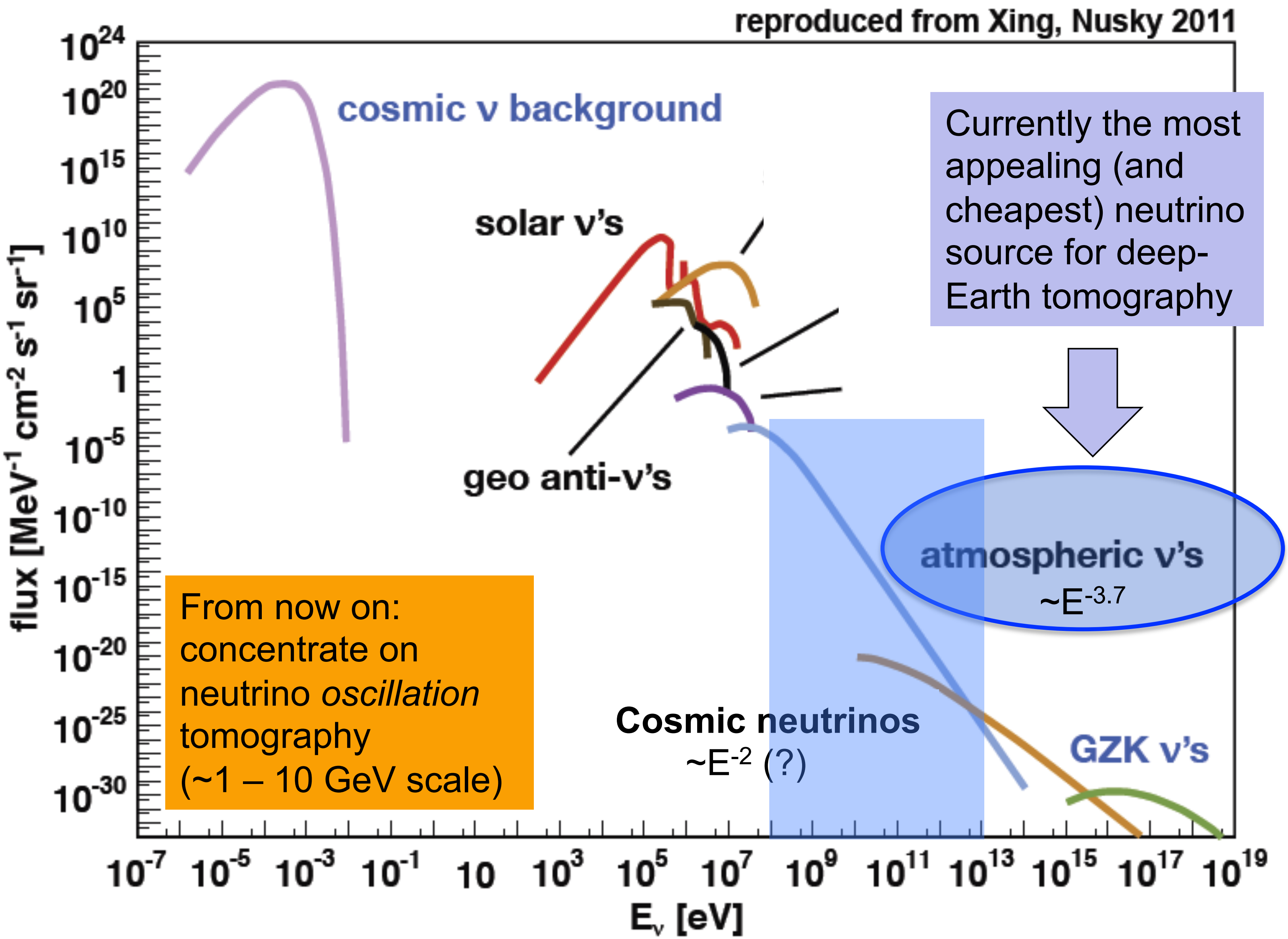


Which neutrino sources ?



produced by the interaction of cosmic rays (p^+, nuclei) in the atmosphere

Which neutrino sources ?



Currently the most appealing (and cheapest) neutrino source for deep-Earth tomography

From now on: concentrate on neutrino *oscillation* tomography (~1 – 10 GeV scale)

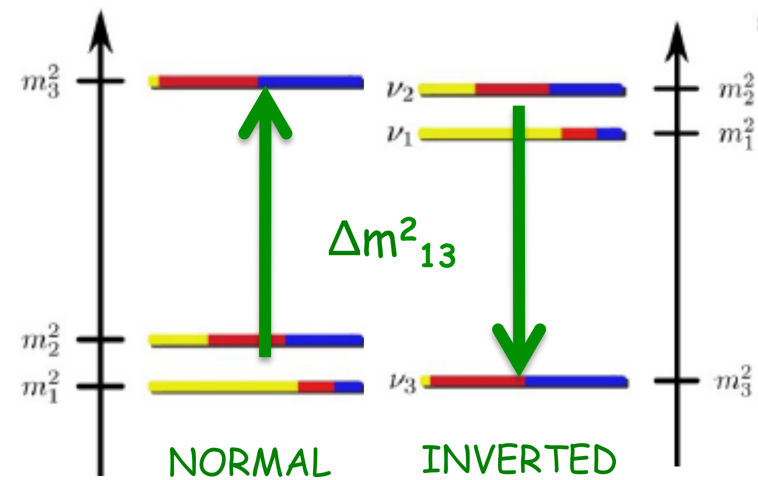
Matter effects and neutrino mass hierarchy

Strategy: probe ν_μ ←→ ν_e governed by Δm^2_{13}

+ need matter effects to resolve the sign of Δm^2_{13}

maximal enhancement at resonant energy

$$E_\nu^{\rm res} = \pm \frac{\Delta m^2_{13} \cos(2\theta_{13})}{2\sqrt{2} G_F N_e}$$ ≈ few GeV for Earth densities



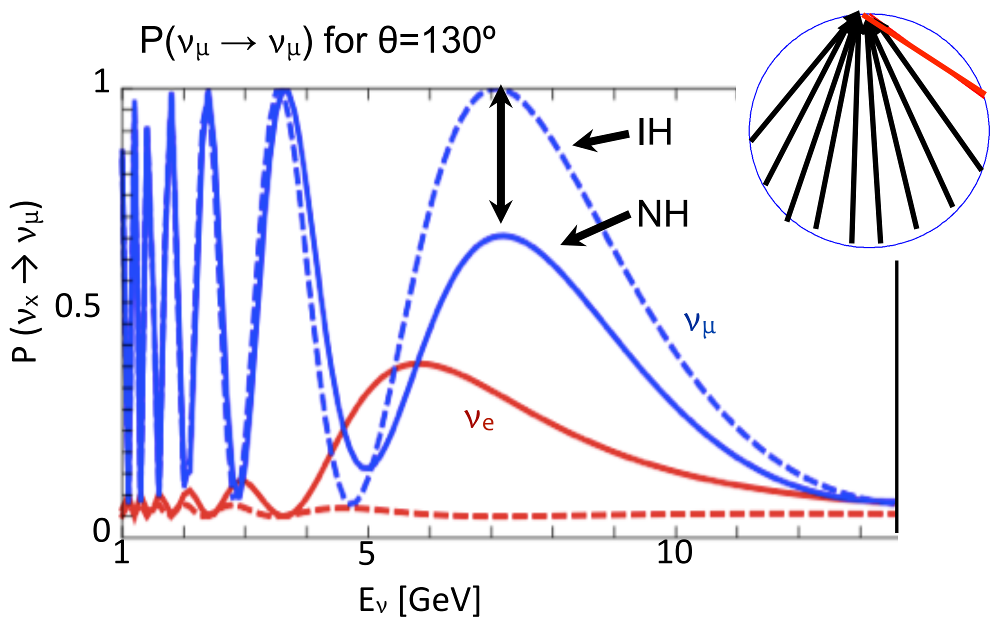
→ good prospects for atmospheric neutrino experiments !

- a « free beam » of known composition (ν_e, ν_μ)
- wide range of baselines (50 → 12800 km) and energies (GeV → PeV)
- maximum difference IH ↔ NH at θ=130° (7645 km) and E_ν = 7 GeV
- opposite effect on anti-neutrinos: IH($\bar{\nu}$)≈NH(ν)

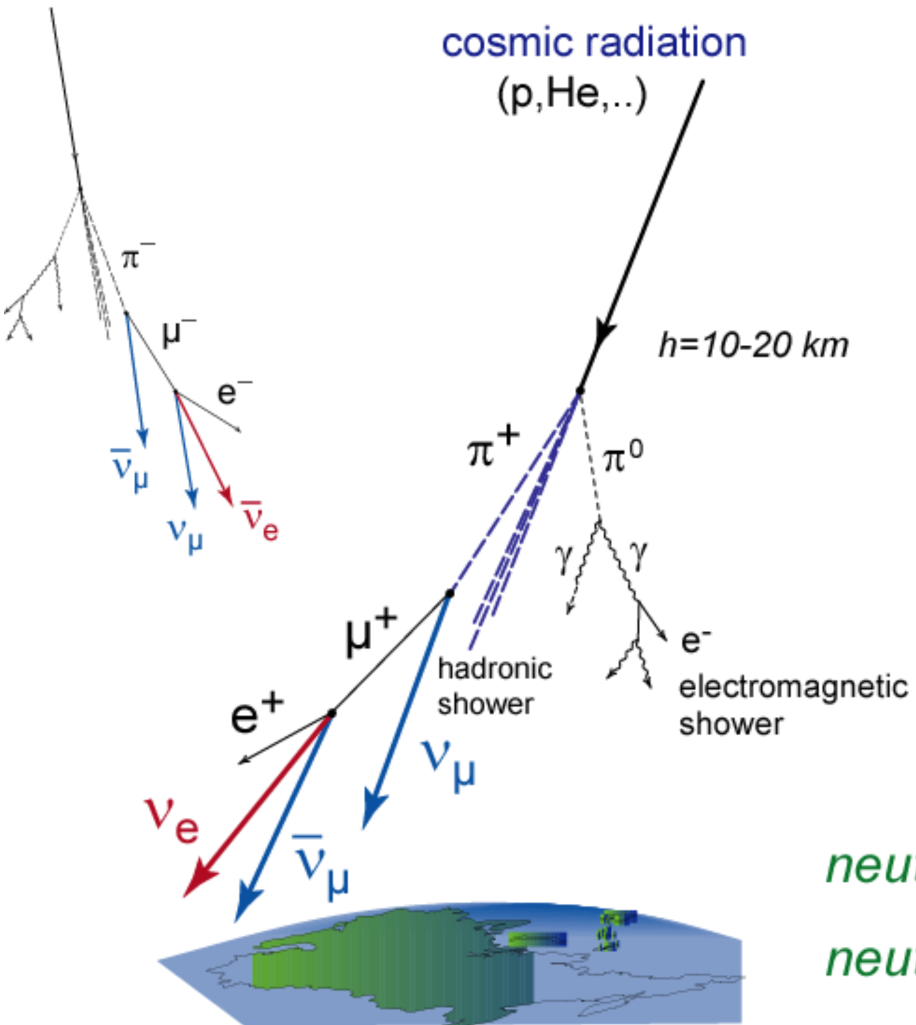
BUT differences in flux, cross-section:

$\Phi_{atm}(\nu) \approx 1.3 \times \Phi_{atm}(\nu)$

$\sigma(\nu) \approx 2\sigma(\nu)$ at low energies



Atmospheric neutrinos



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

also: π^- μ^- e^- decay chain
decays of kaons K^+, K^-

flavour ratio $\nu_\mu : \nu_e = 2 : 1$

for wide range of energies: E_ν = 1-20 GeV!

geomagnetic effects for E_ν < 2 GeV !

neutrino energies: E_ν = 0.5 - 500 GeV

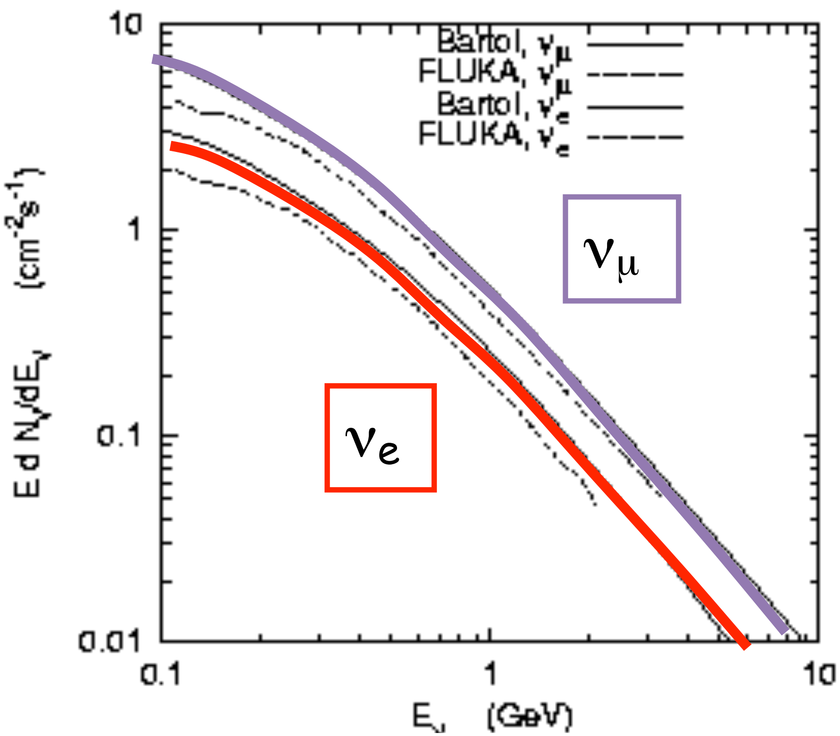
neutrino pathlength: L_ν = 12 - 12.000 km

large L/E variation, explore small Δm^2 - values

search for ν_μ - ν_e and ν_μ - ν_τ oscillations

Atmospheric neutrinos

Event rate inside a kton detector ?
("contained events")



1. Flux: $\Phi_\nu \sim 1\ cm^{-2}\ s^{-1}$
   (integrated over 4π sr)
2. Cross section: $\sigma_\nu \sim 0.5\ 10^{-38}\ cm^2$
3. Targets M= $6\ 10^{32}$ (nucleons/kton)
4. Time t= $3.1\ 10^7$ s/y

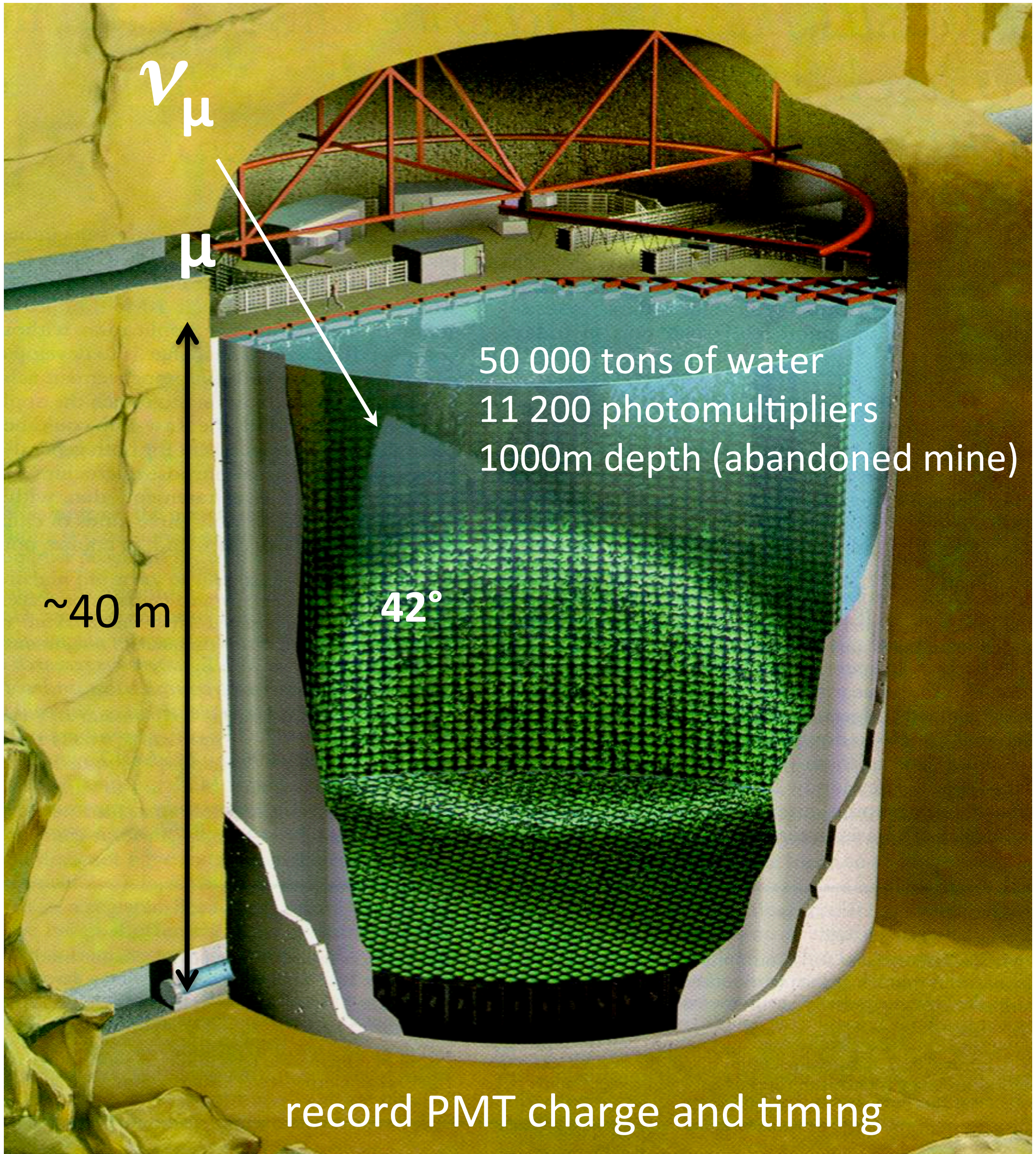
$N_{int} = \Phi_\nu\ (cm^{-2}\ s^{-1})\ x\ \sigma_\nu\ (cm^2)\ x\ M\ (nuc\ kton^{-1})\ x\ t\ (s)$

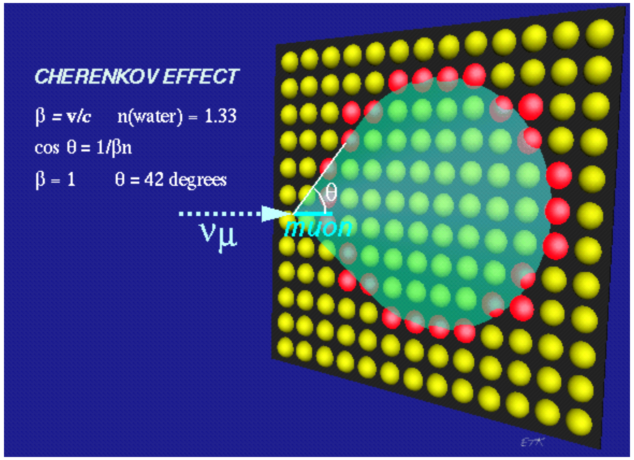
~ 100 interactions/ (kton y)

(to be folded with detector efficiencies, duty cycle,…)

SuperKamiokande

Water-Cherenkov detector:

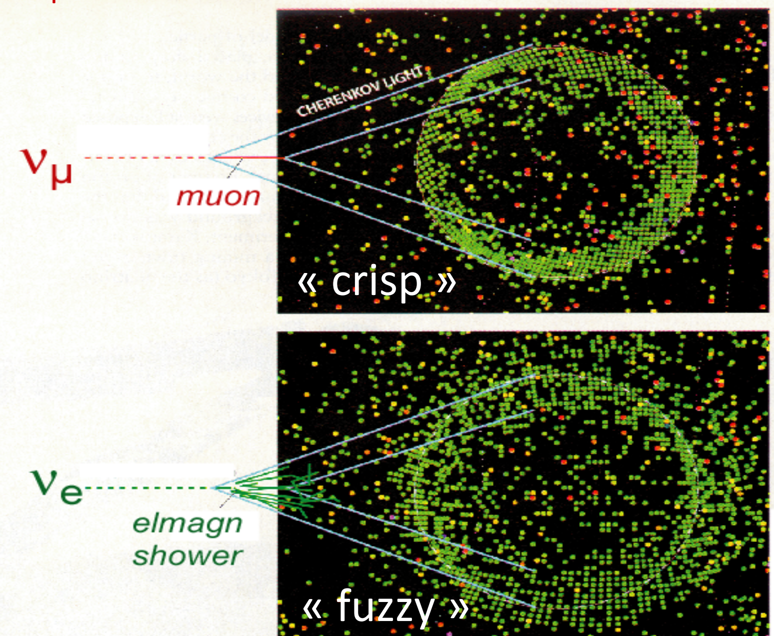




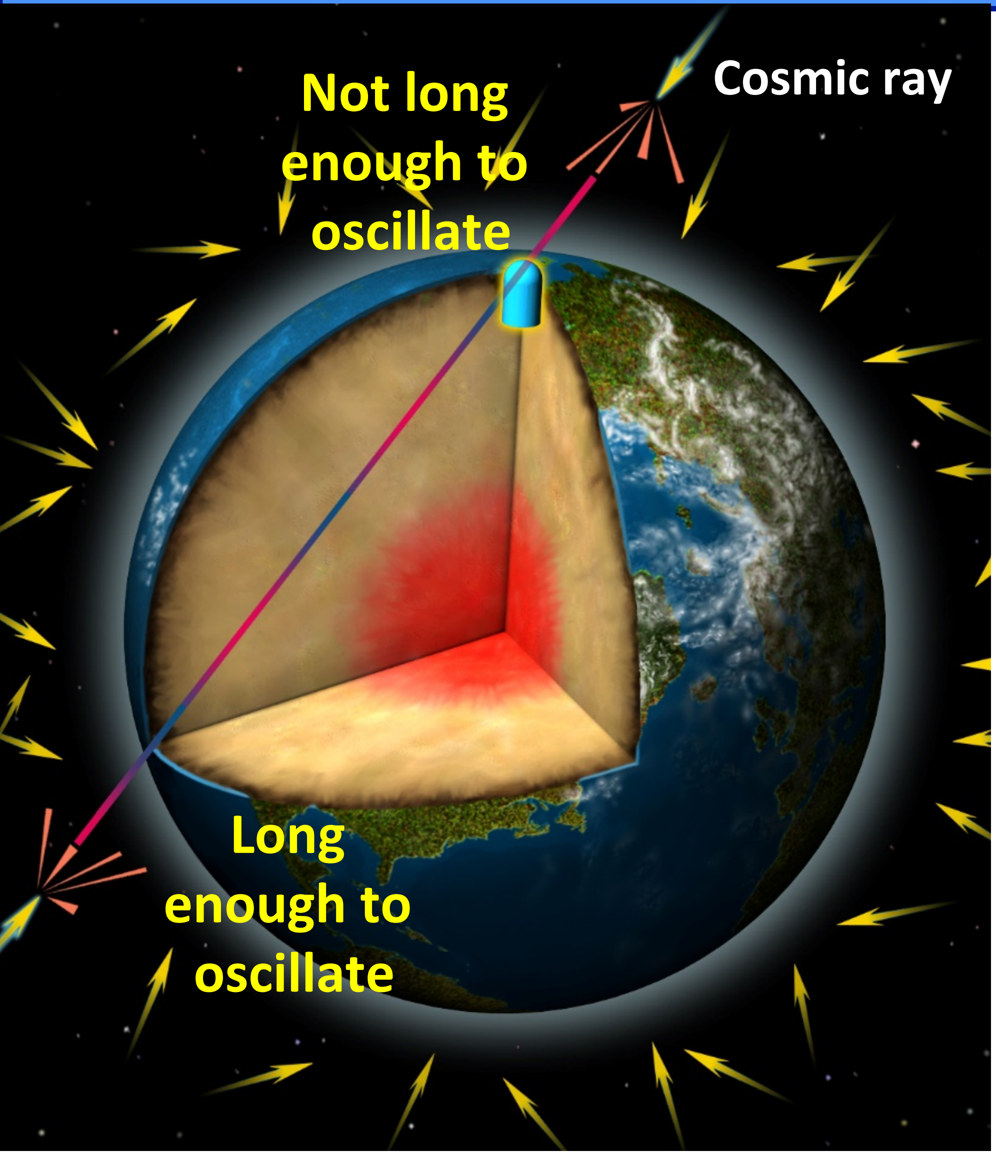
~3800 atmospheric neutrinos/year

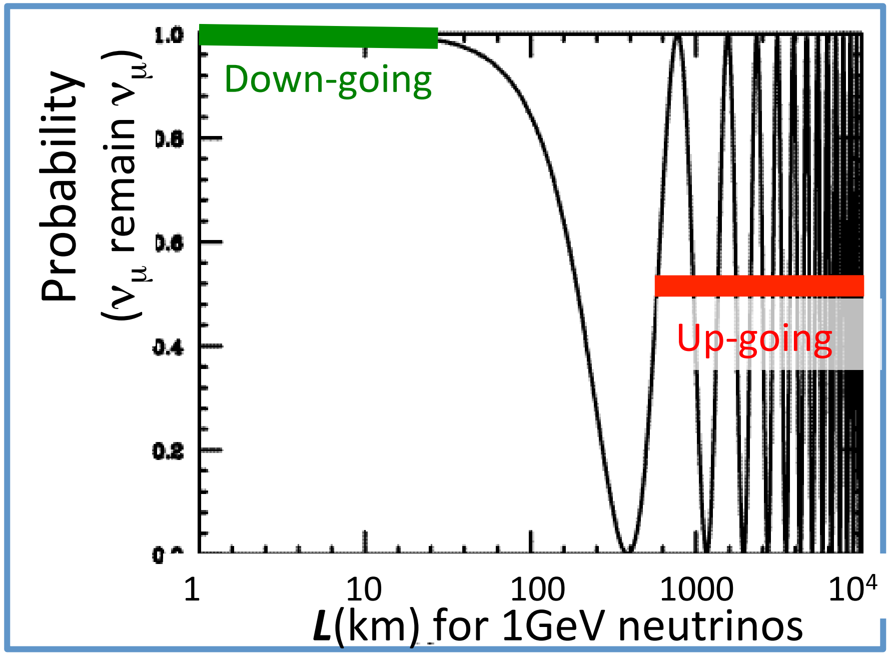
Position & angular reconstruction

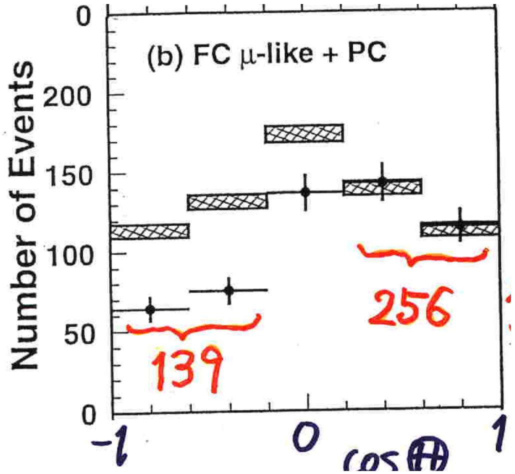
ν_μ / ν_e separation:



SuperKamiokande



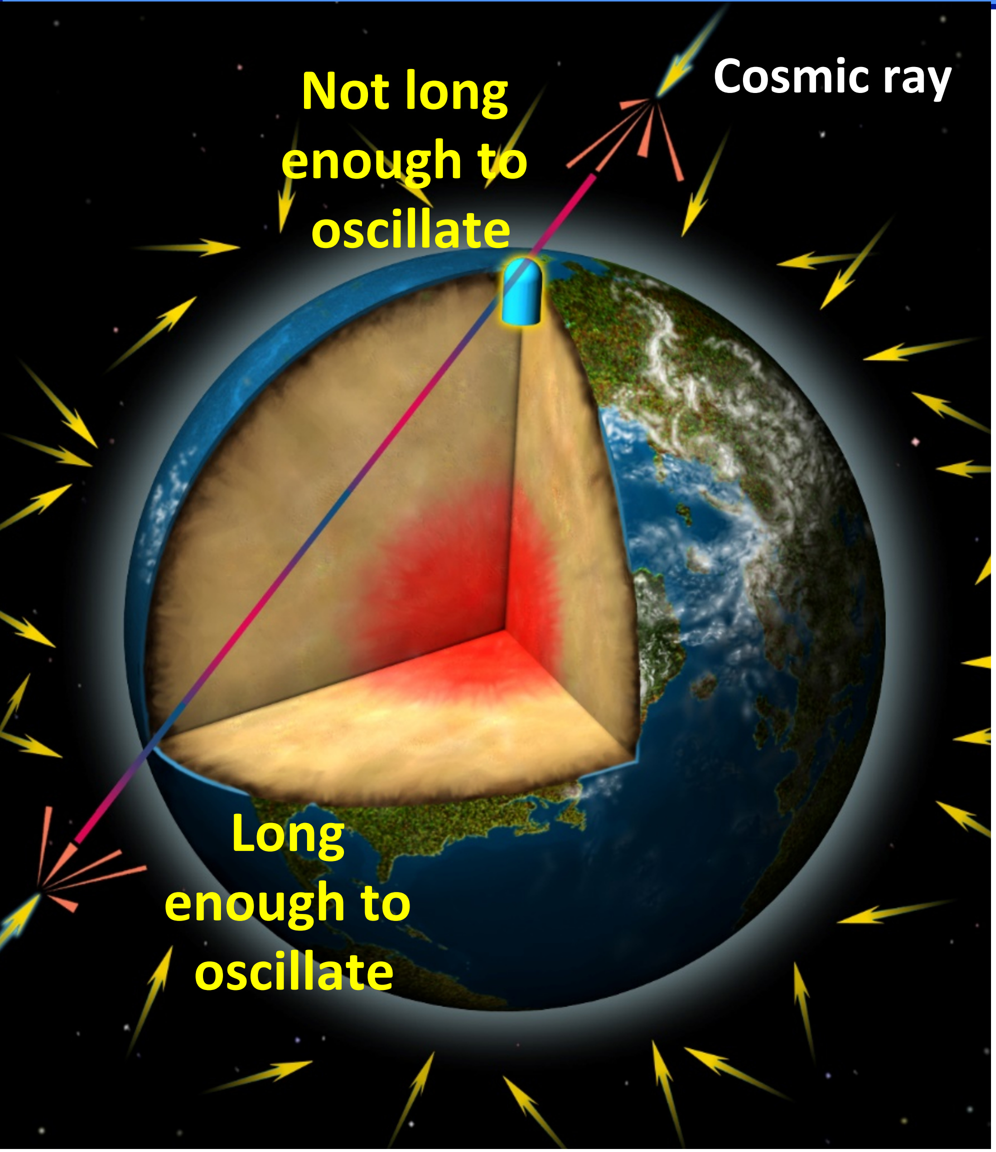




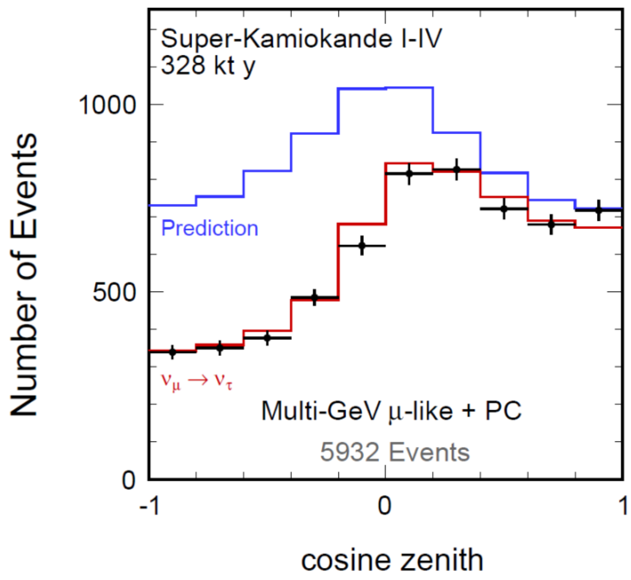
1998:
SK observes a deficit of upward-going ν_μ :

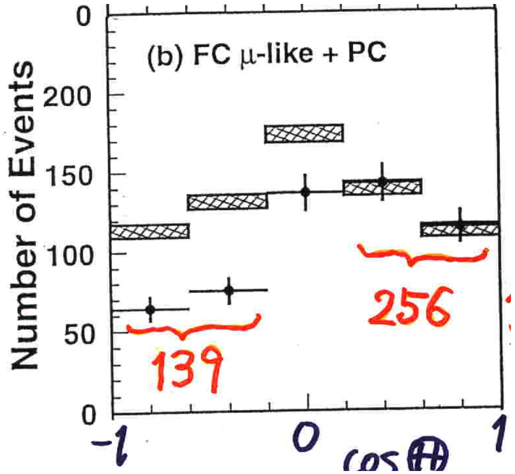
evidence for $\nu_\mu - \nu_\tau$ oscillation (~maximal mixing)

SuperKamiokande



…Today's results (2016):





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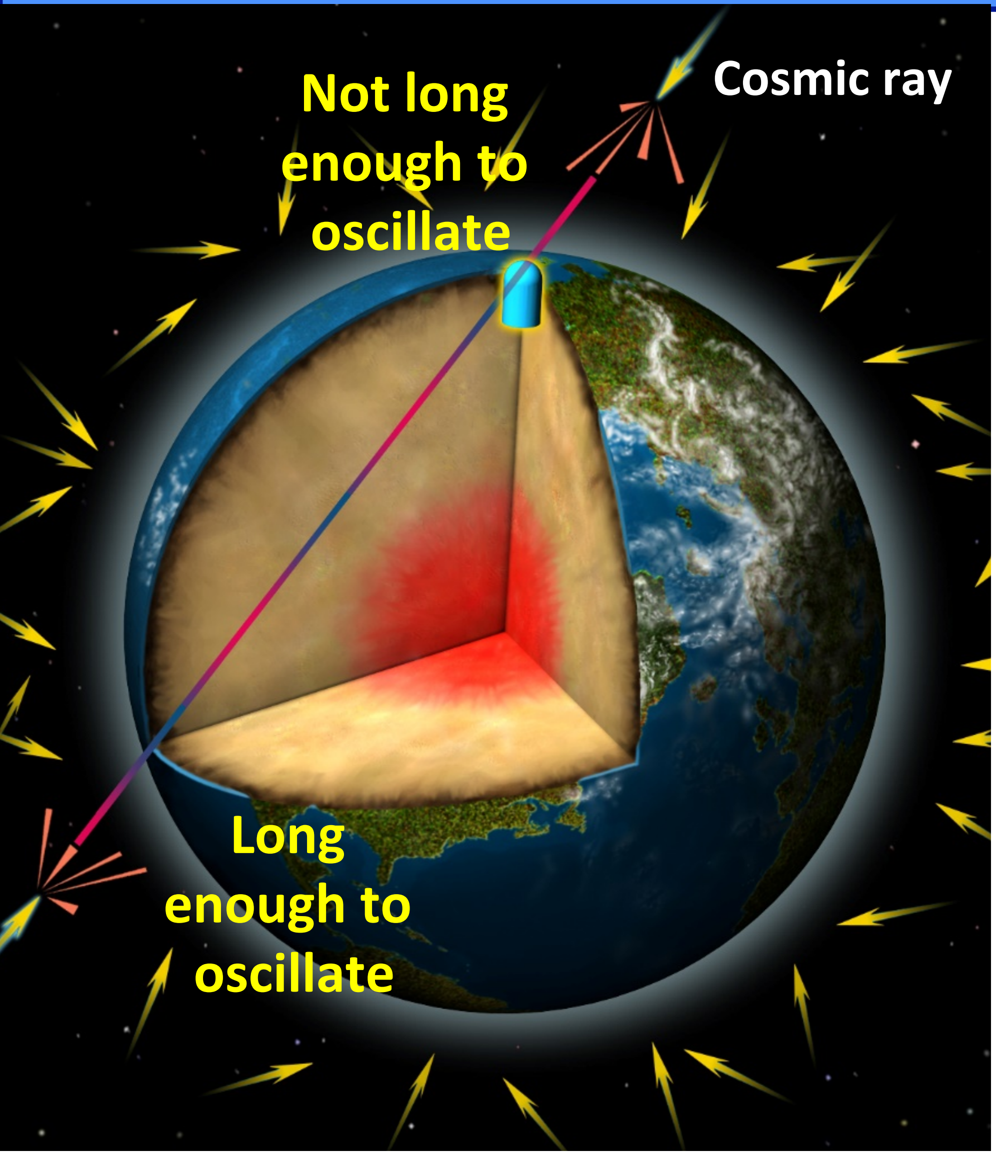

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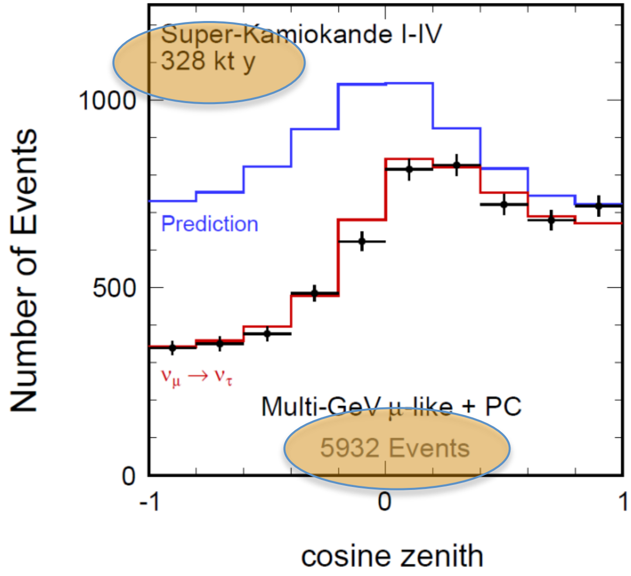
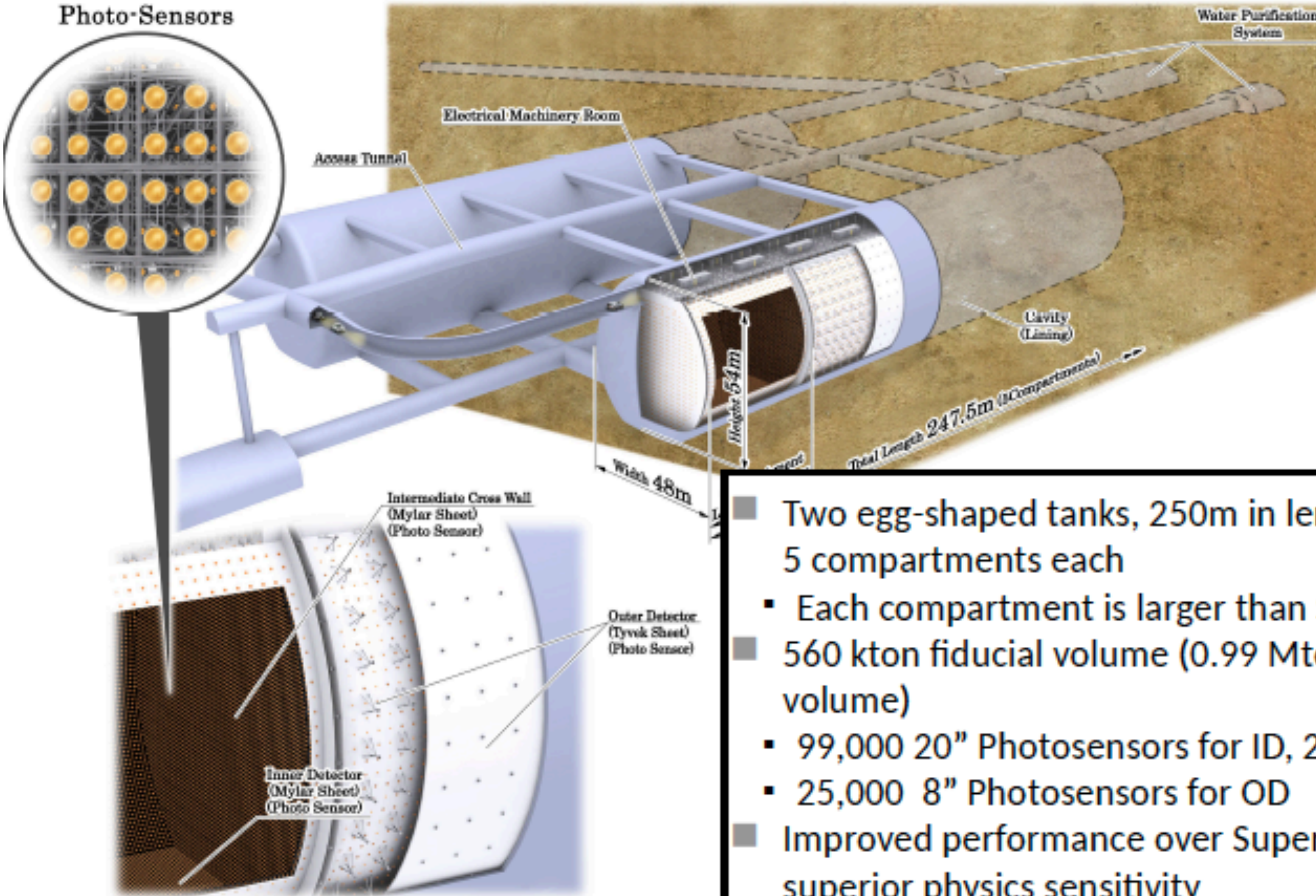


… too small statistics to perform tomography:

Need bigger detectors…

The next generation: HyperKamiokande

Hyper-Kamiokande: The Detector

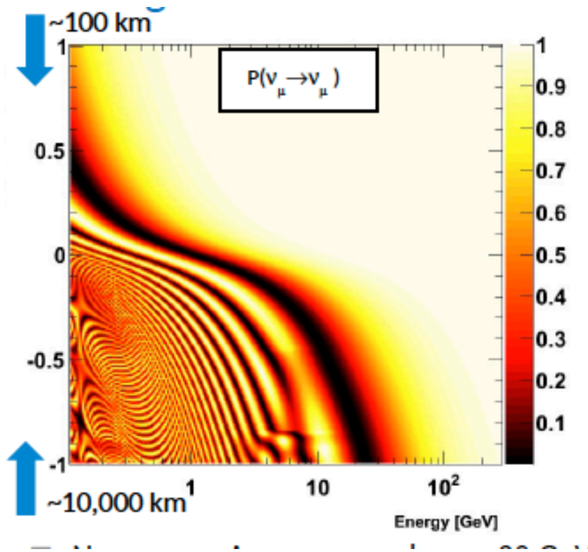


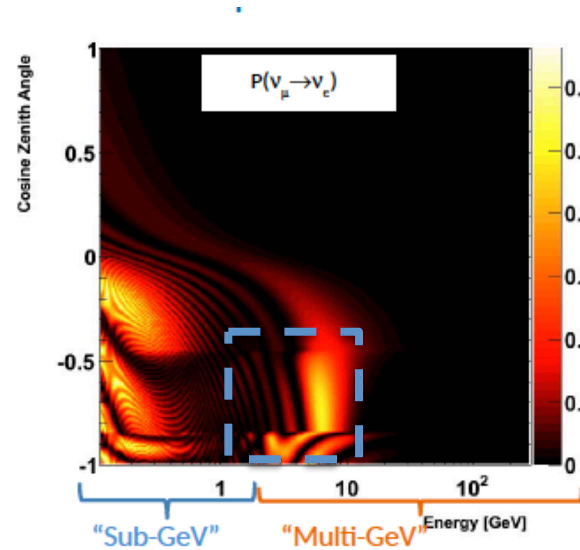
- Two egg-shaped tanks, 250m in length, with 5 compartments each
  - Each compartment is larger than Super-K
- 560 kton fiducial volume (0.99 Mton total volume)
  - 99,000 20" Photosensors for ID, 20%
  - 25,000 8" Photosensors for OD
- Improved performance over Super-K for superior physics sensitivity

Earth tomography with HyperKamiokande: core

Resolution	Hyper-K
σ_{mom} e / μ	5.6% /3.6%
σ_{dir} e / μ	3.0° / 1.8°
Atmospheric	ν CC Purity
FC e-like	94.2 %
FC μ-like	95.7 %
PC μ-like	98.7 %
MIS PID	<1%, 1 GeV

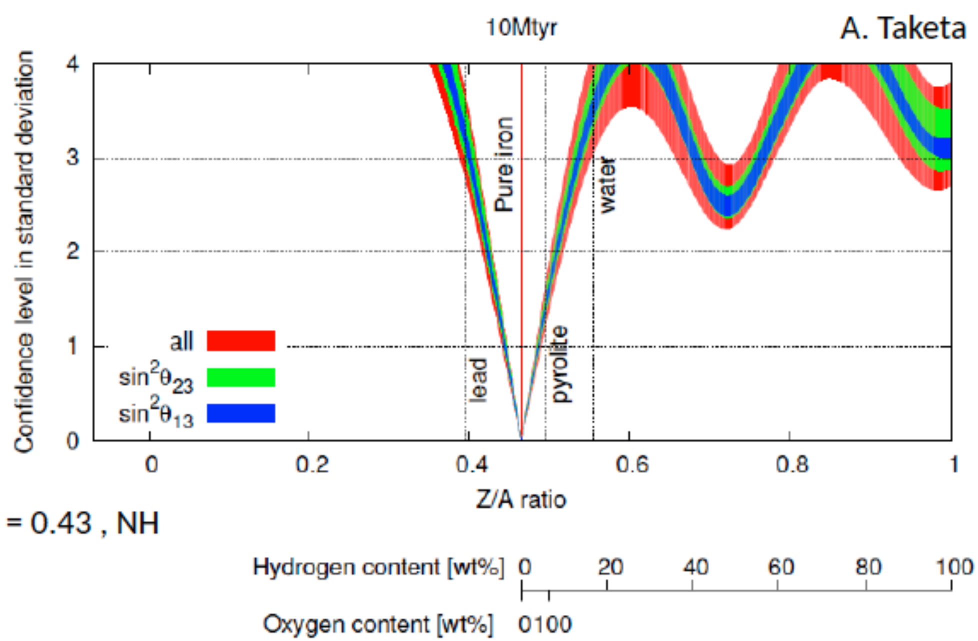
Good reconstruction/ particle identification performances





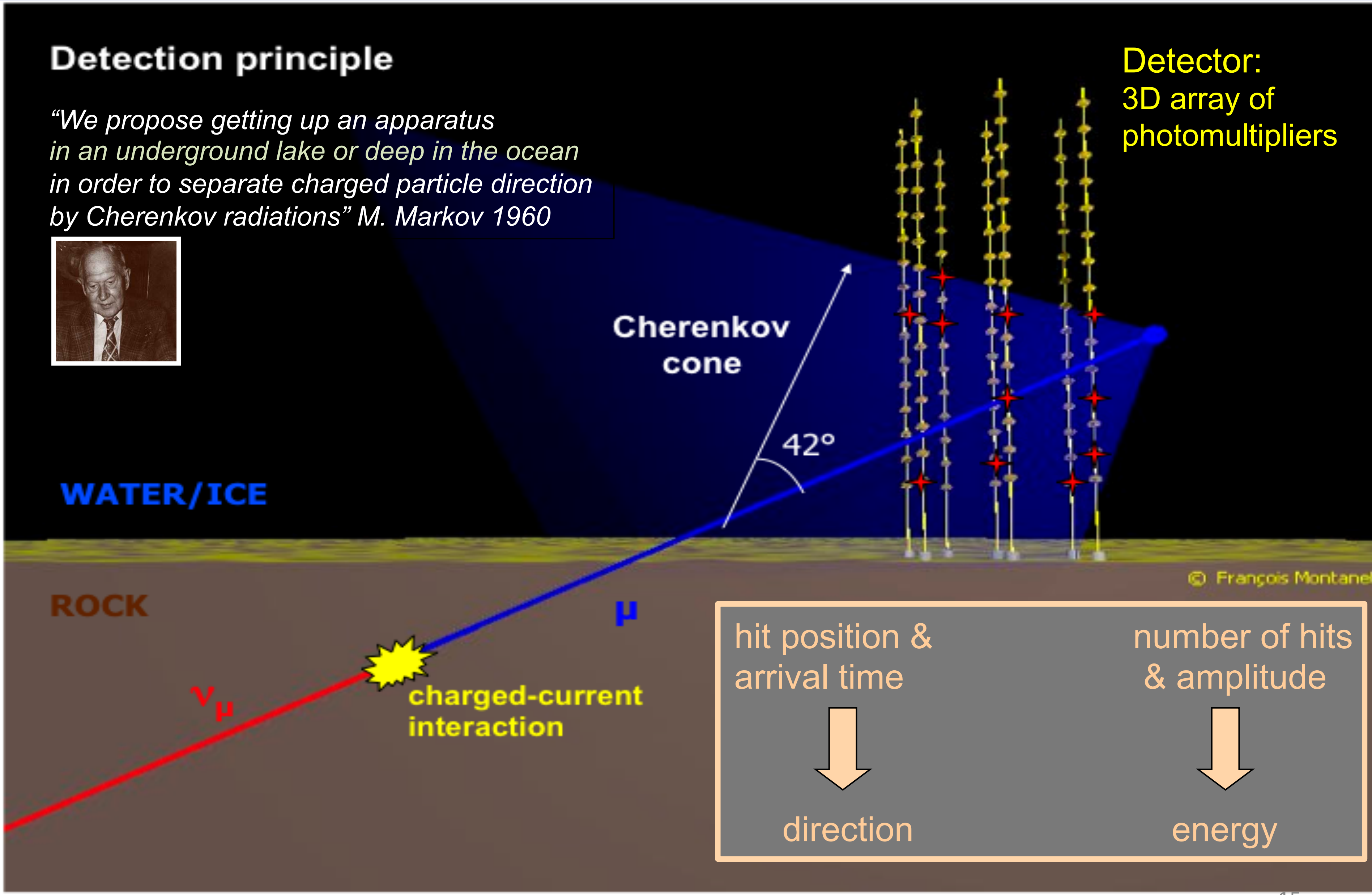
Preliminary study on outer core composition:
Normal hierarchy assumed
Most sensitivity from ν_e channel
Exclude extreme composition models after ~15 years ?

...need even bigger detectors ?

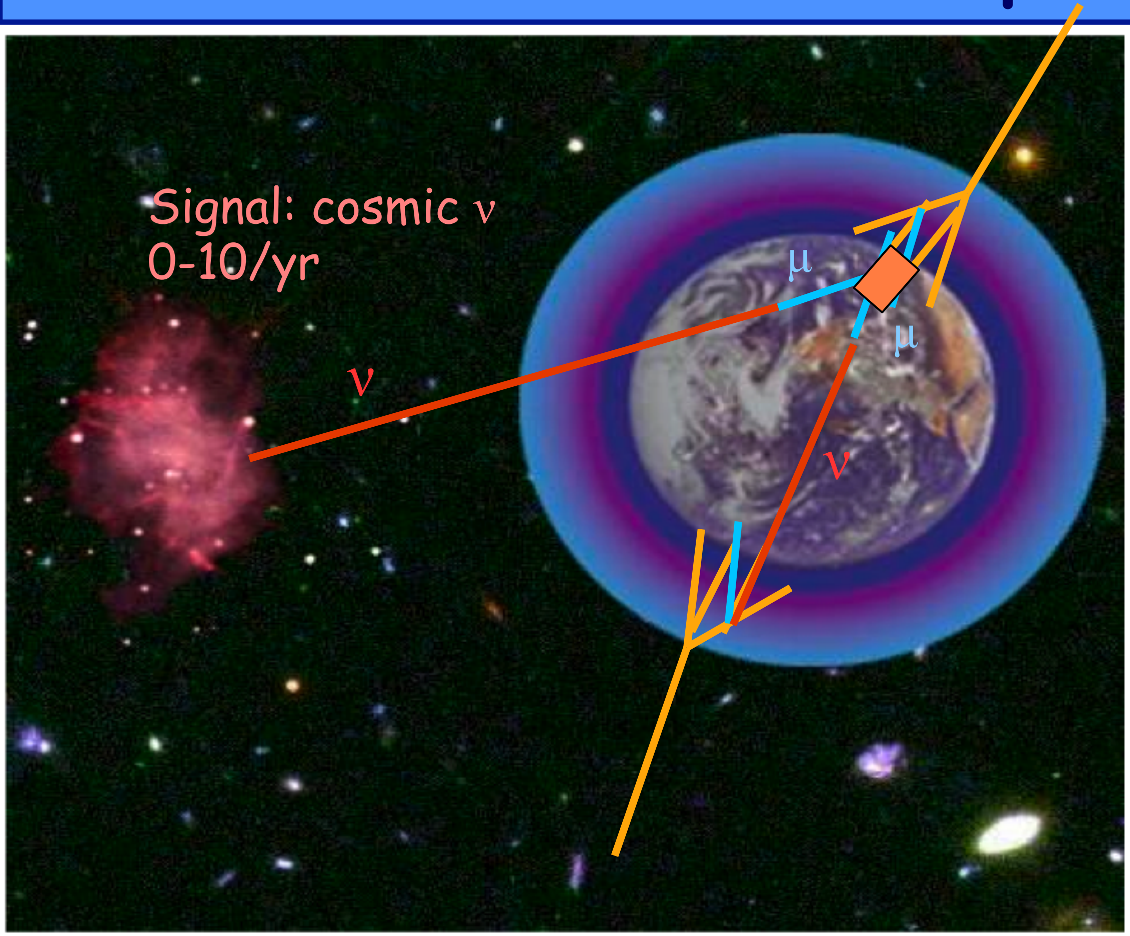


$\sin^2\theta_{23}$ = 0.43 , NH

A different technique: neutrino telescopes



Detection principle



Physical backgrounds

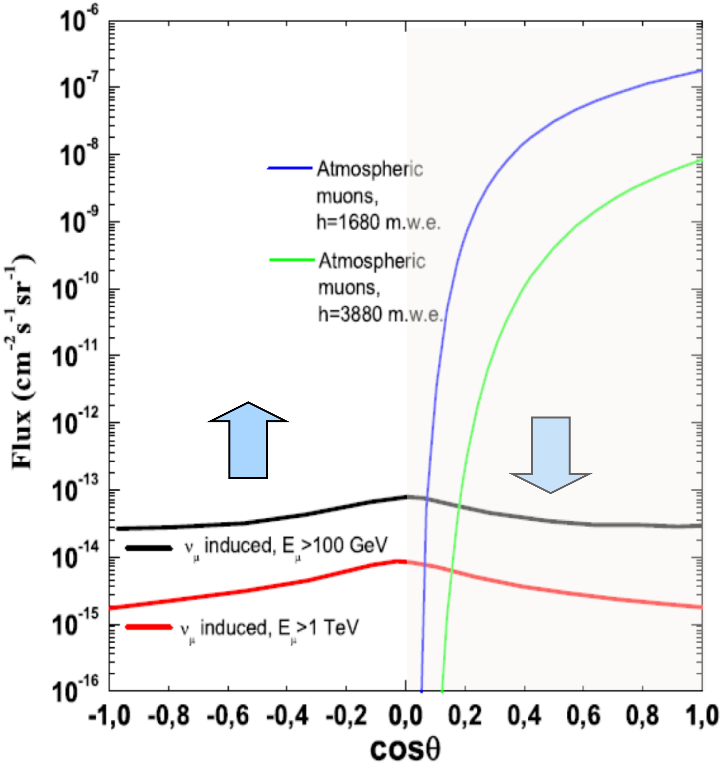
- Atmospheric muons:

~ 10^8/yr – 10^{10}/yr

- Atmospheric neutrinos

~10^3/yr – 10^5/yr

(depending on detector size)

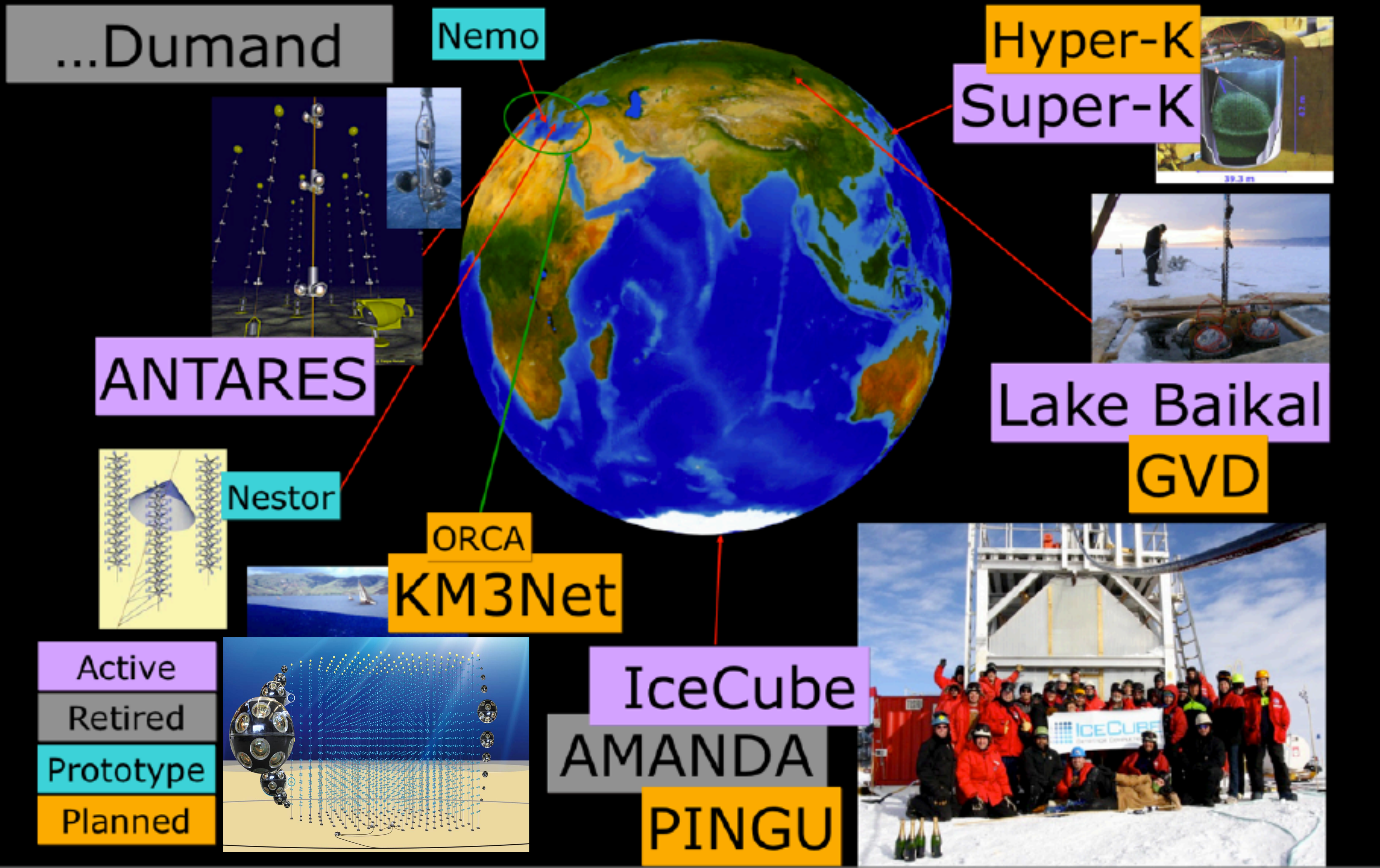


➡ Detectors buried deep

➡ Use veto against atmospheric muons

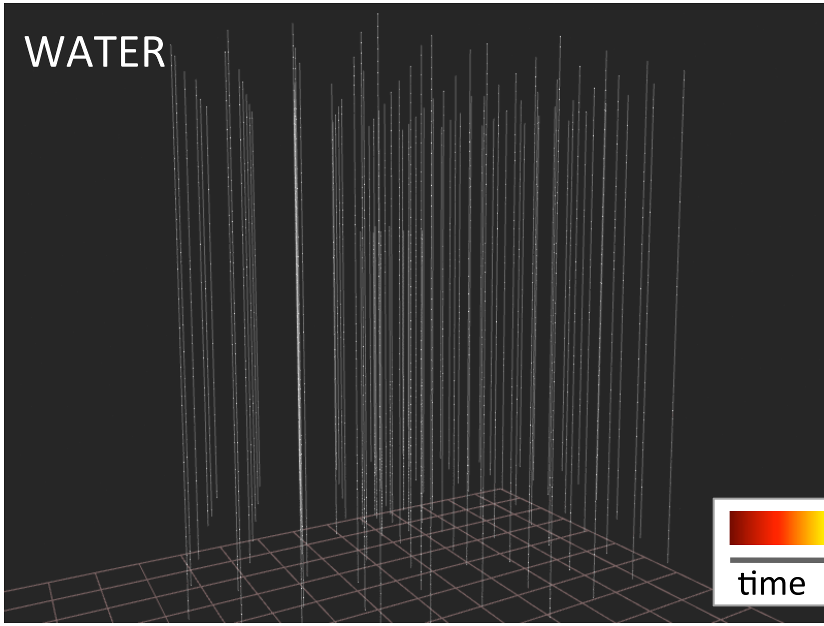
➡ Detectors optimised for upgoing neutrino detection

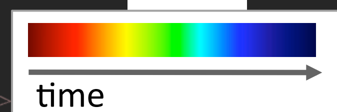
Neutrino Cherenkov telescopes worldwide

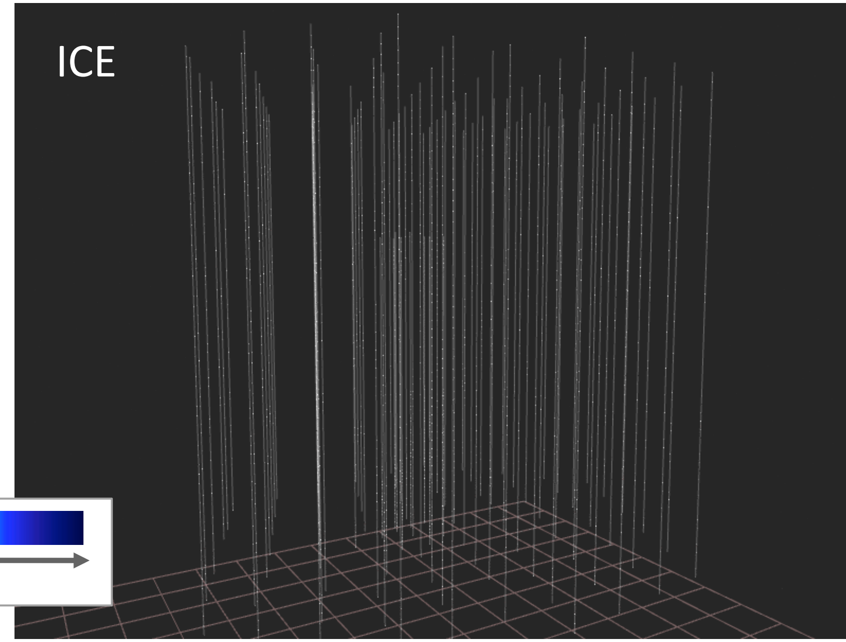


Adapted from C. Rott

Water vs. ice ?







(delay w.r.t. direct photons)

absorption length ≈ 55 m
scattering length ≈ 300m

absorption length ≈ 210 m
scattering length ≈ 20-40 m

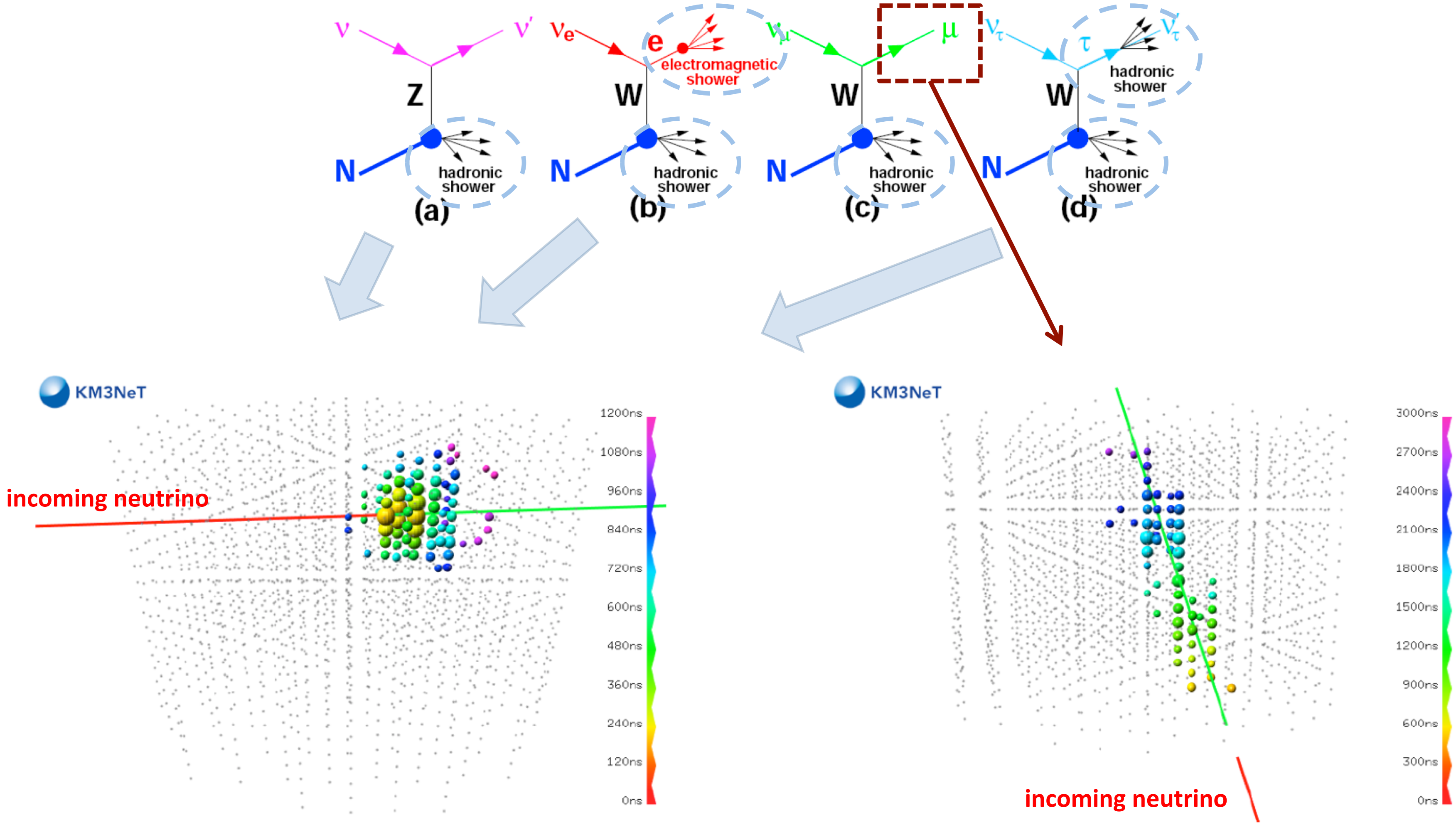
Water: better tracker

Optical activity:
- used for calibration
- opportunity for sea sciences

Ice: better calorimeter

Quiet environment,
long-term stability of detector,
almost 100% uptime

Experimental signatures



Cascade-like event

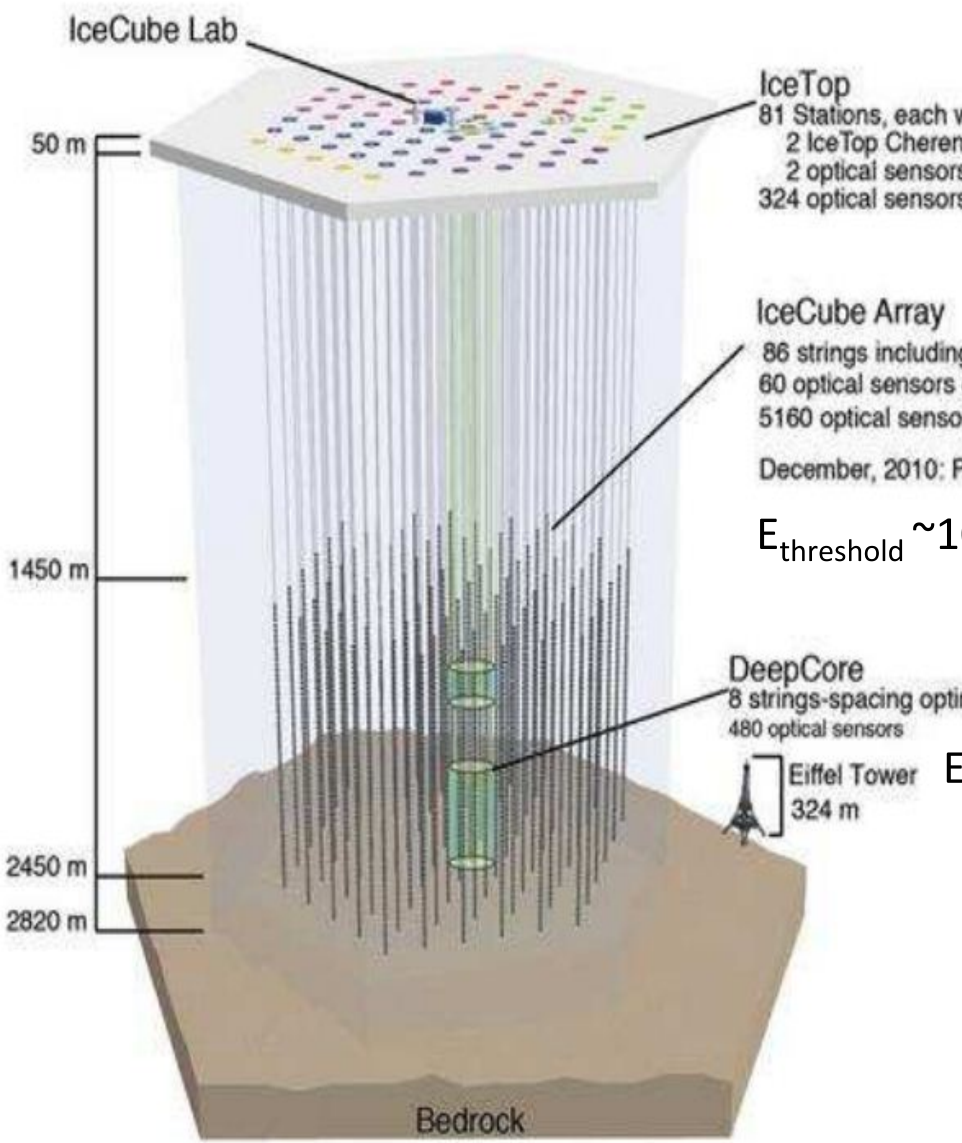
Track-like event

At the South Pole: IceCube

Completed end 2010

- 78 lines
- 60 DOMs/line
- ~1 Gton
  instrumented volume

+ Ice Top: surface array for cosmic ray studies
+ Deep Core: denser infill (8 strings)

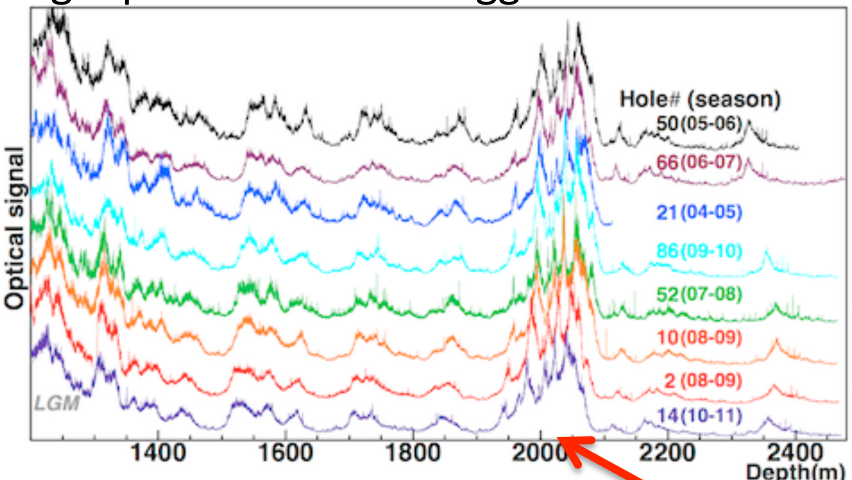


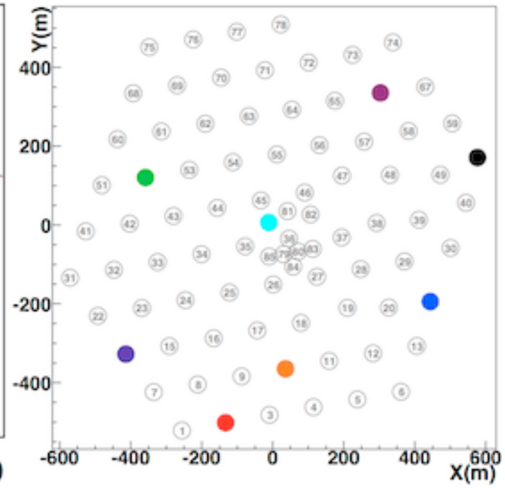
$E_{threshold}$ ~100 GeV

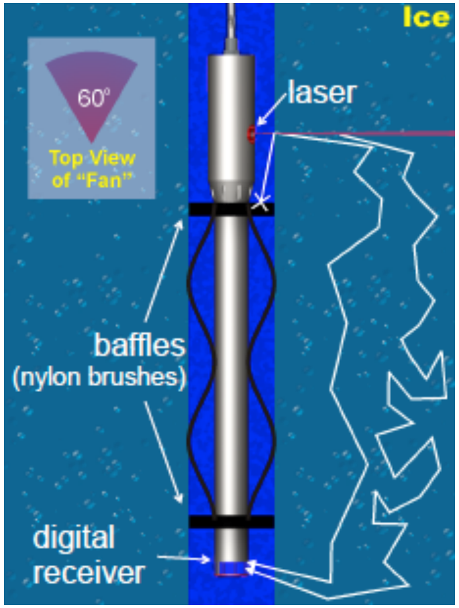
$E_{threshold}$ ~10 GeV

At the South Pole: IceCube

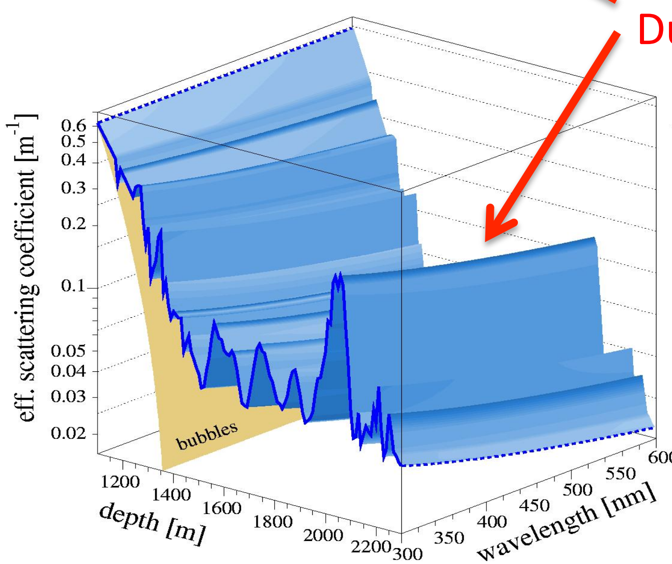
Major calibration efforts to precisely understand the ice properties around the detector:
e.g. optical laser dust logger

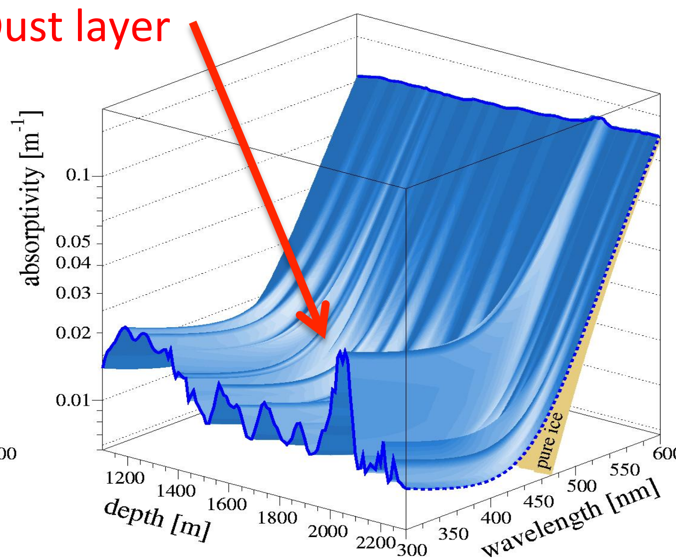






Dust layer



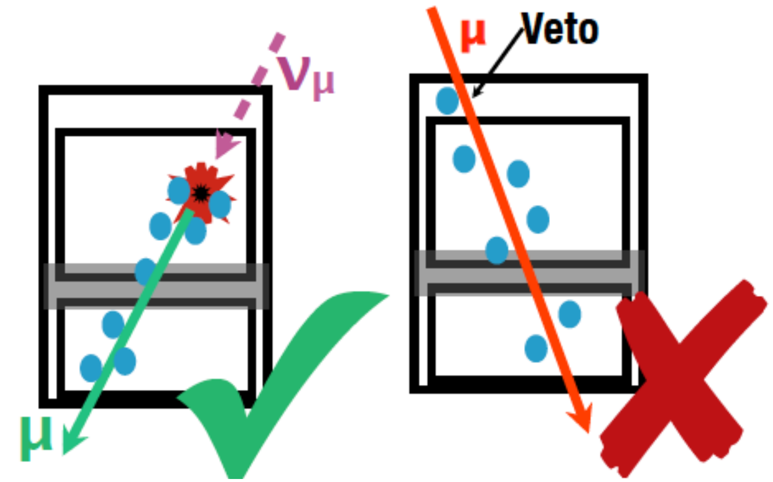


Ice Cube observes the first HE cosmic neutrinos!

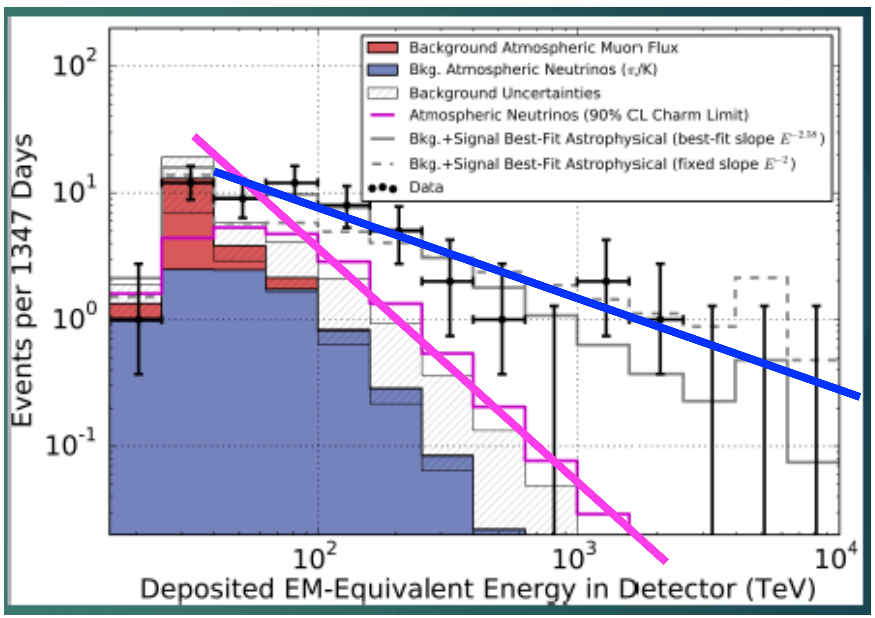
- Discovery channel:

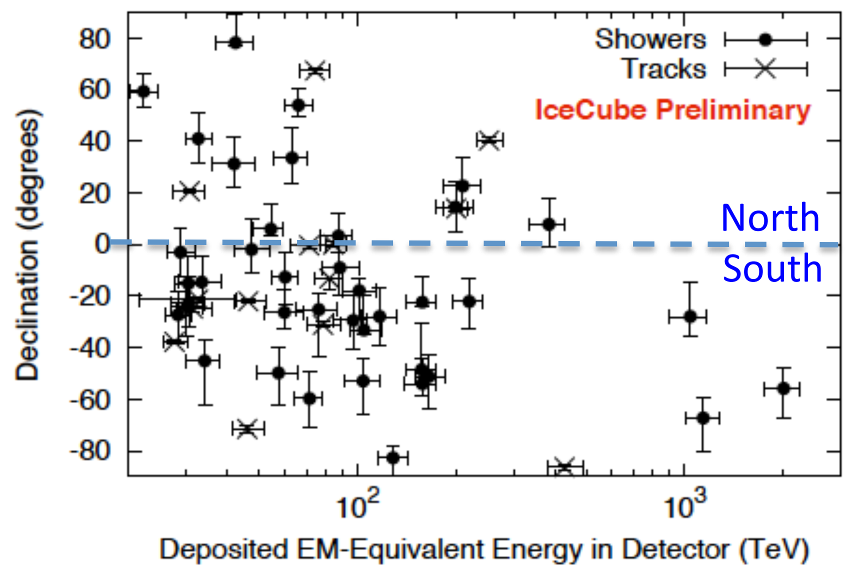
High-Energy Starting Events

both hemispheres,
$\nu_e + \nu_\mu + \nu_\tau$ (tracks+cascades)
energy > 60 TeV
outer layer used as veto against μ_{atm} & ν_{atm}



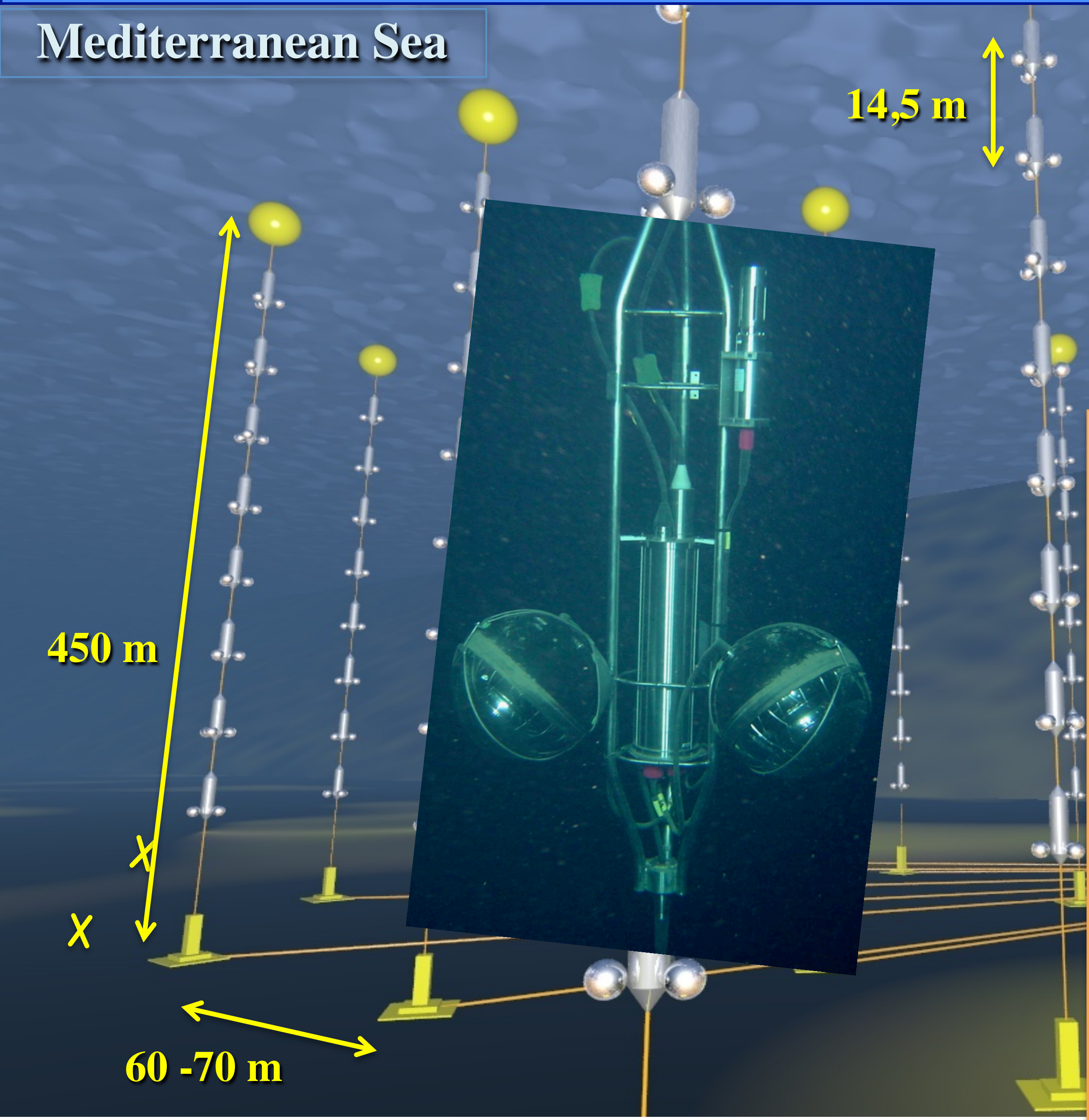
now 4-year data sample, 6.5 σ significance
observation of 3 over-PeV neutrinos





… no source identified so far
…too few events to perform absorption tomography !

In the Mediterranean: ANTARES



Completed 2008

- 12 lines
- 25 storeys/line
- 3 PMTs / storey
- 885 10” PMTs
- ~15 Mton instrumented volume
- $E_{threshold}$ ~20 GeV

+ instrumentation line
+ acoustic array AMADEUS
+ secondary junction box for Earth/marine science

In the Mediterranean: ANTARES

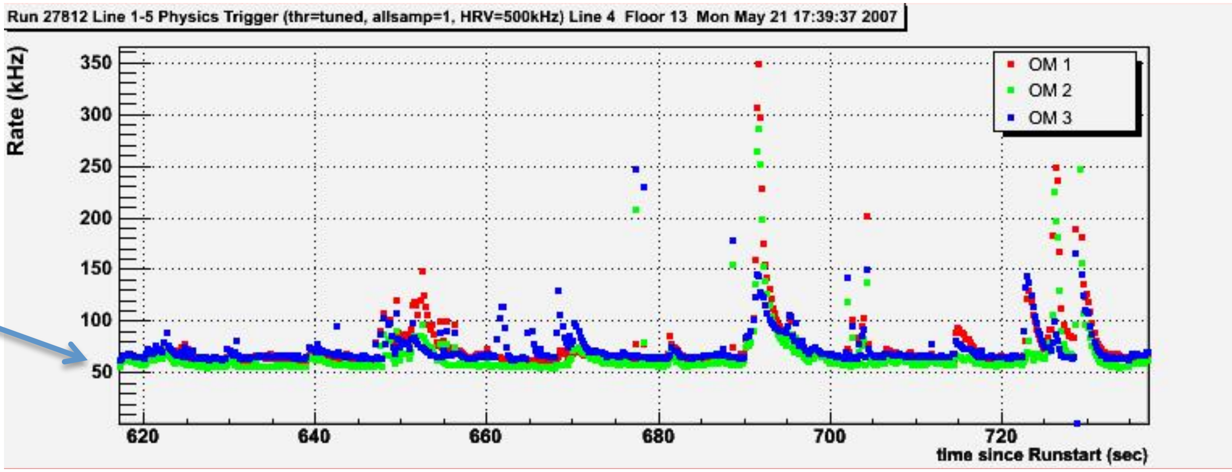
Optical backgrounds in sea water:

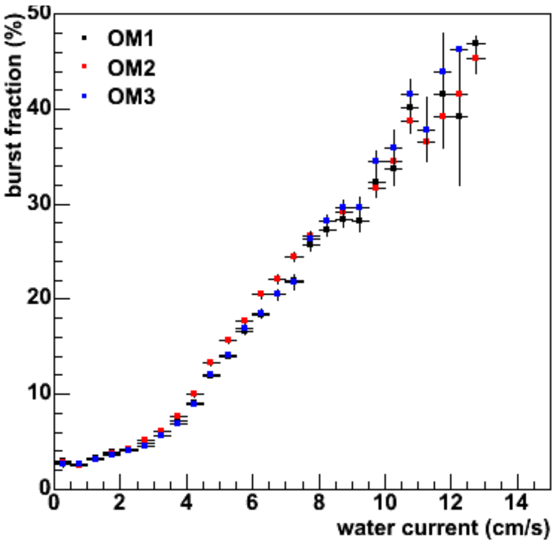
Baseline

^{40}K decay (~40 kHz)

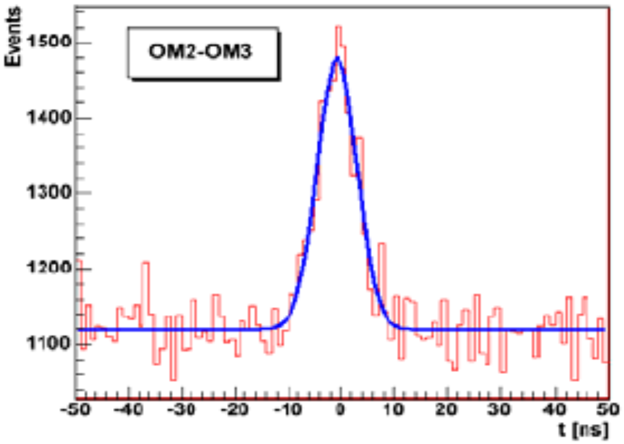
bioluminescence

+ bioluminescence bursts
(correlated with sea currents)

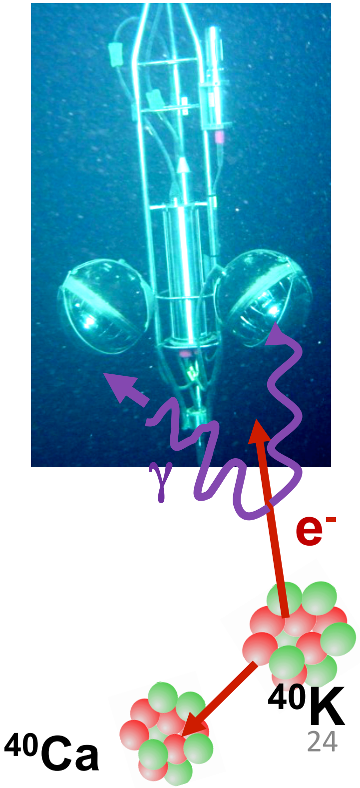




40K decay can be used for
time calibration and monitoring
of the efficiency of optical modules



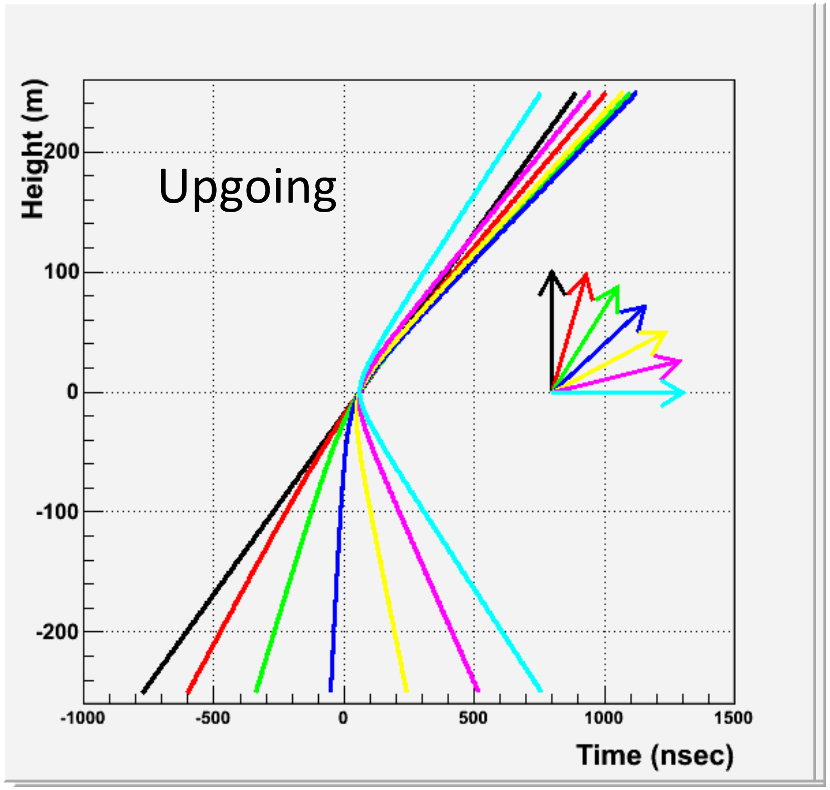
(stable concentration of 40K;
Up to 150 photons per decay)

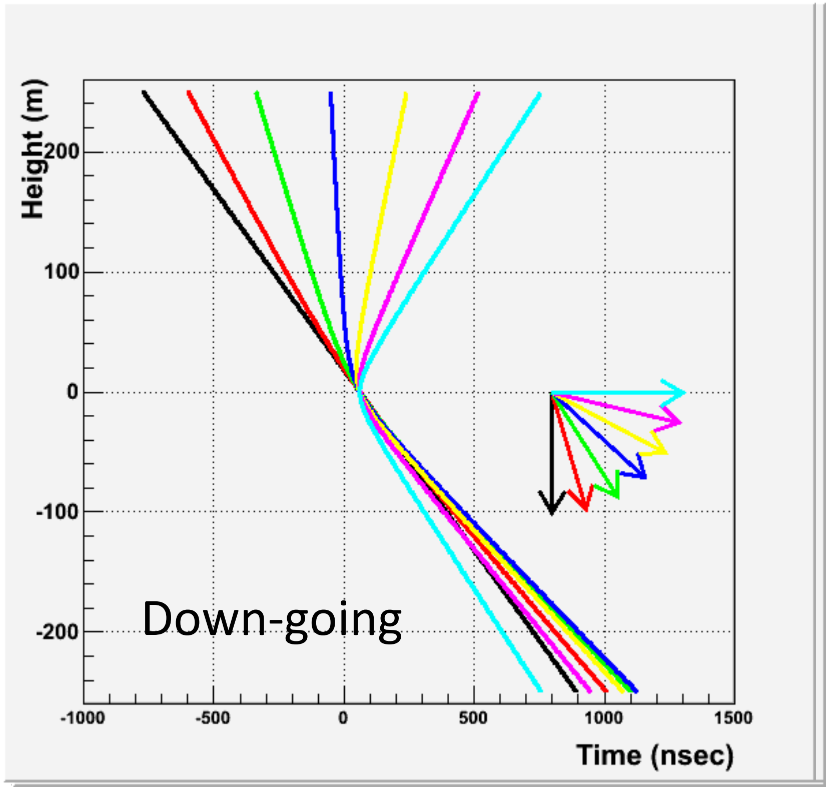


In the Mediterranean: ANTARES

Causality conditions on the time and position of hits allow to filter out the optical background

Track reconstruction: fitting algorithms based on PDFs for hit time residuals



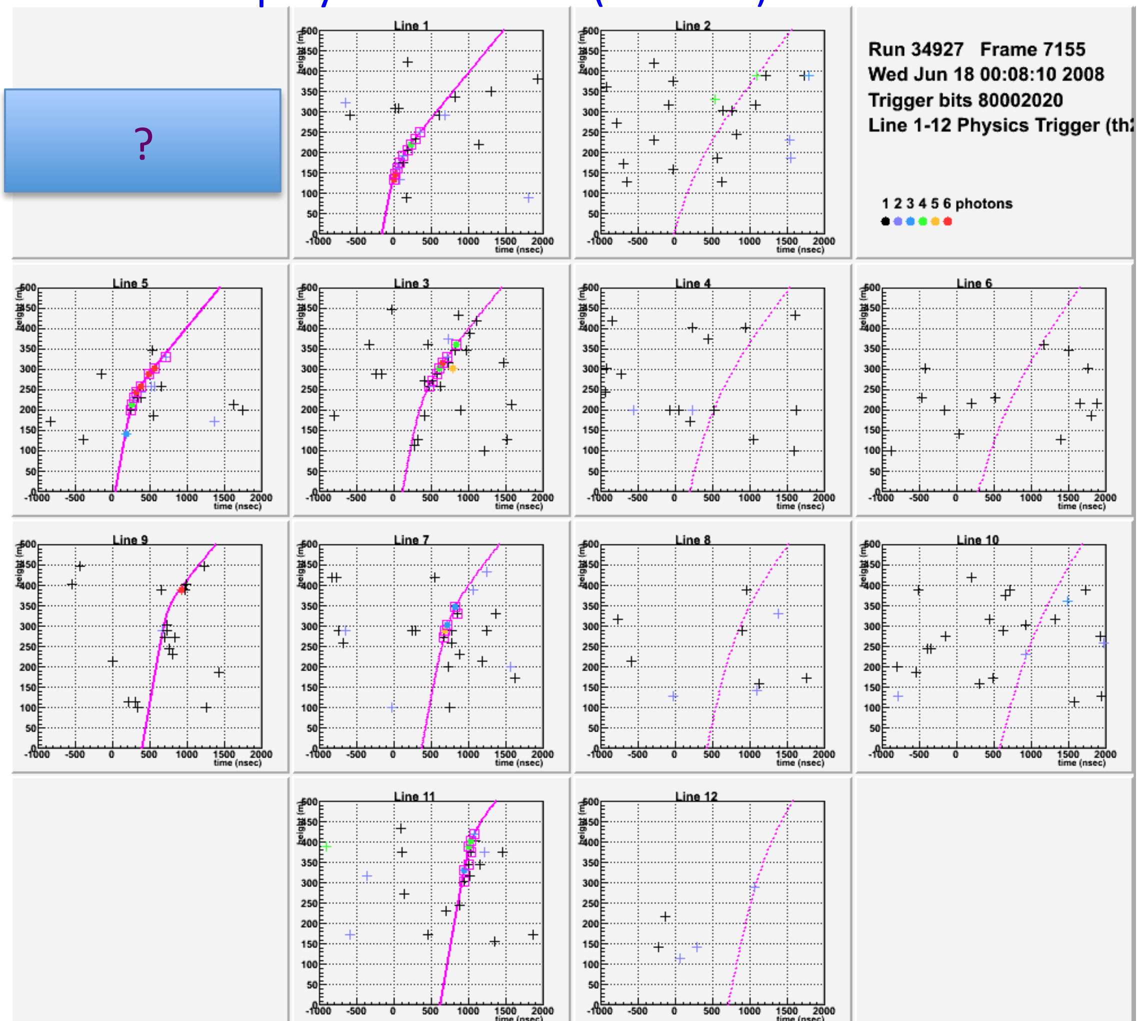


In the Mediterranean: ANTARES

Causality conditions on the time and position of hits allow to filter out the optical background

Track reconstruction: fitting algorithms based on PDFs for hit time residuals

An event display of ANTARES (12 lines):



What does this event display represent ?

In the Mediterranean: ANTARES

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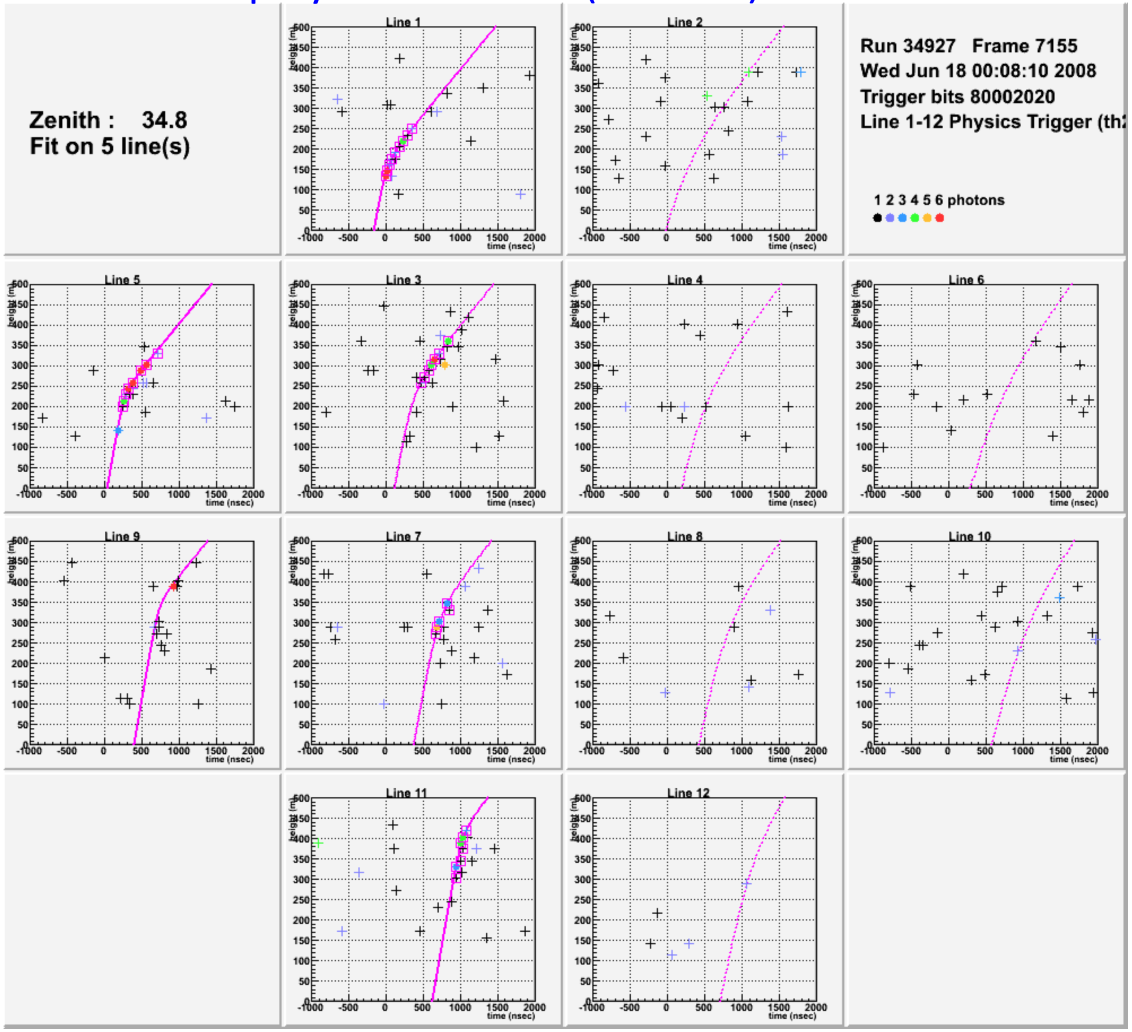
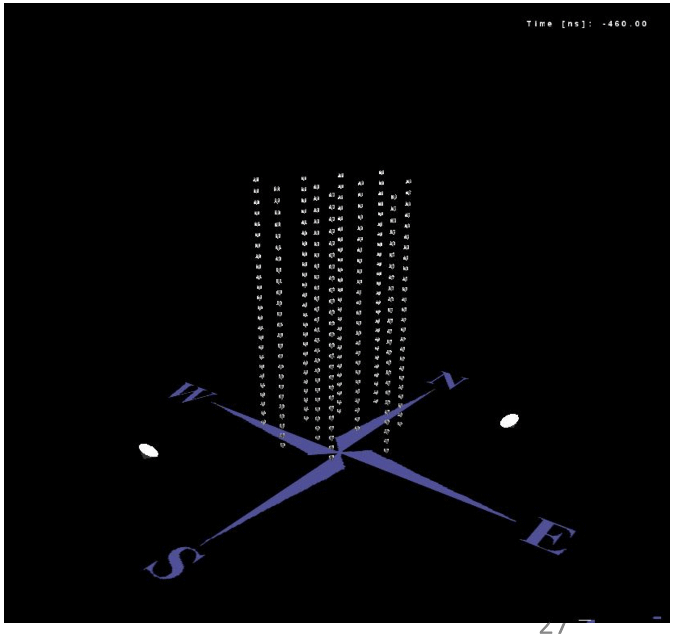


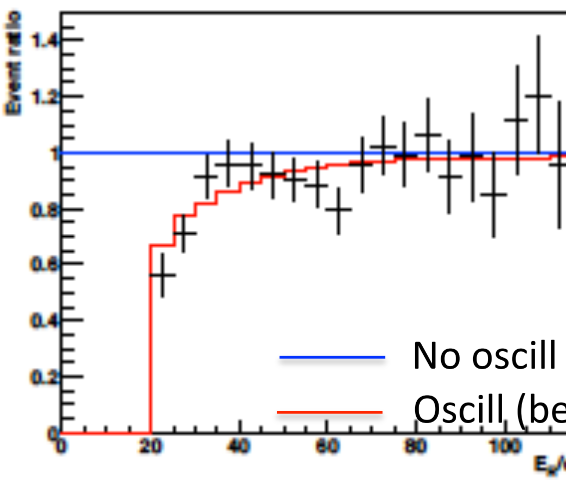
What does this event display represent ?

...a muon induced by an upgoing neutrino !

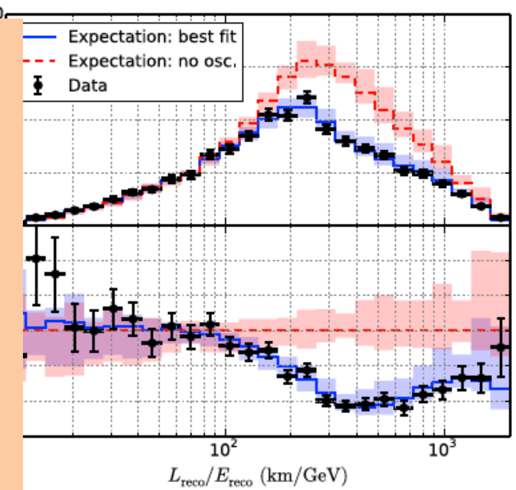


Oscillation measurements with neutrino telescopes

ANTARES 2008-2010 data
(863 days, ~2100 selected events)

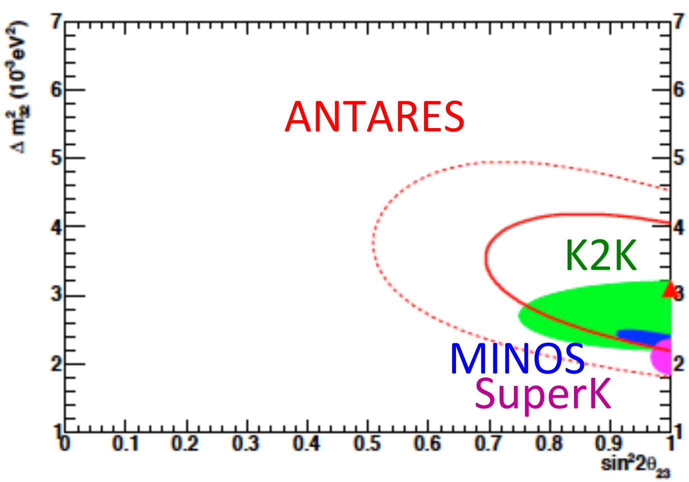


IceCube DeepCore 2008-2010 data
(953 days, ~5200 selected events)

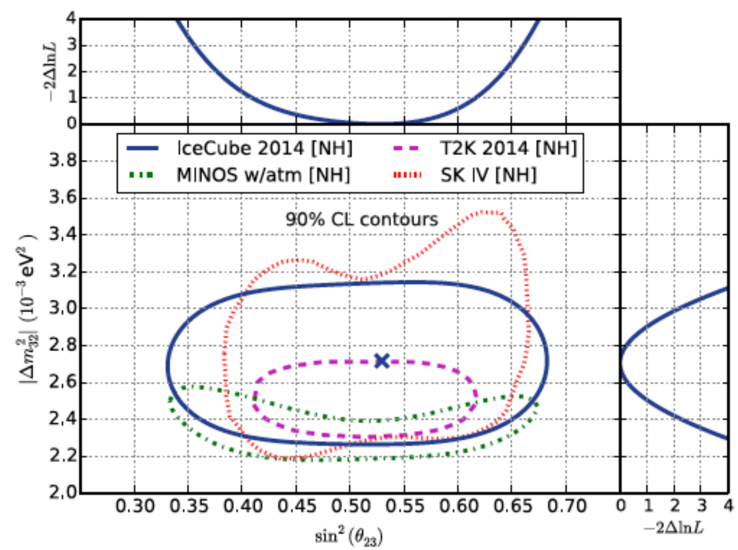


Earth tomography (and mass hierarchy) measurements require neutrino telescopes with a lower energy threshold !

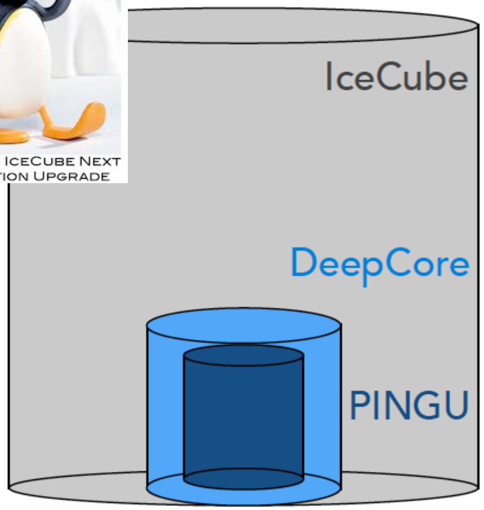
Energy threshold ~20 GeV



Energy threshold ~5 GeV



At the South Pole: PINGU



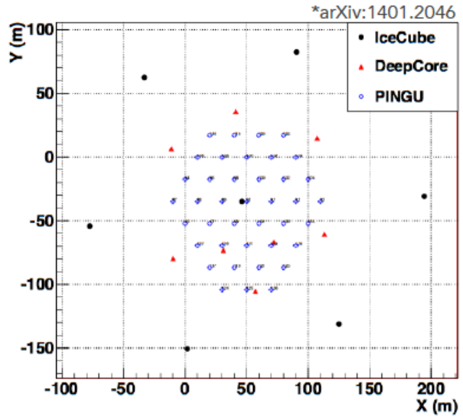
use IceCube/DeepCore as veto for atmospheric muons

Main goal: determination o
f the neutrino mass hierarchy

Funding request in preparation

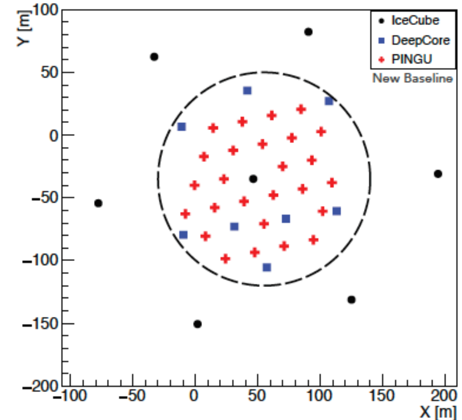
See PINGU Letter of Intent arXiv:1401.2046
Recent update: arXiv:1607.02671

Ongoing geometry optimisation…



Previous*

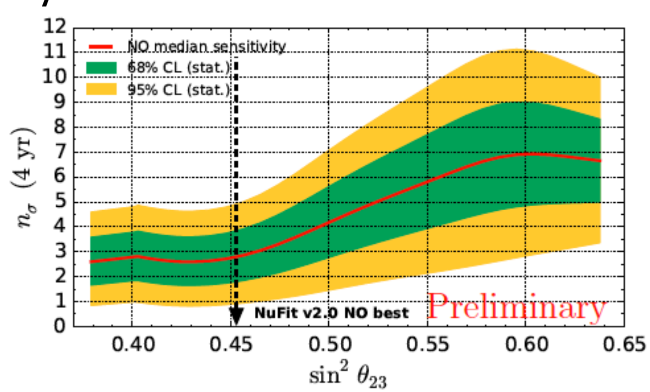
40 strings
60 DOMs/string
5 m DOM-DOM spacing



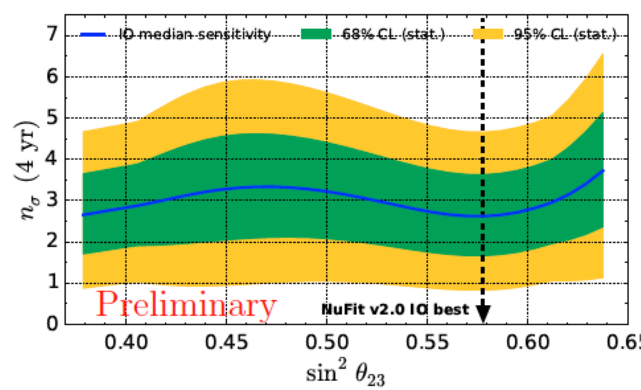
Current

26 strings
192 DOMs/string
1.5 m DOM-DOM spacing

6 Mton instrumented volume
~30 000 upgoing neutrinos/yr



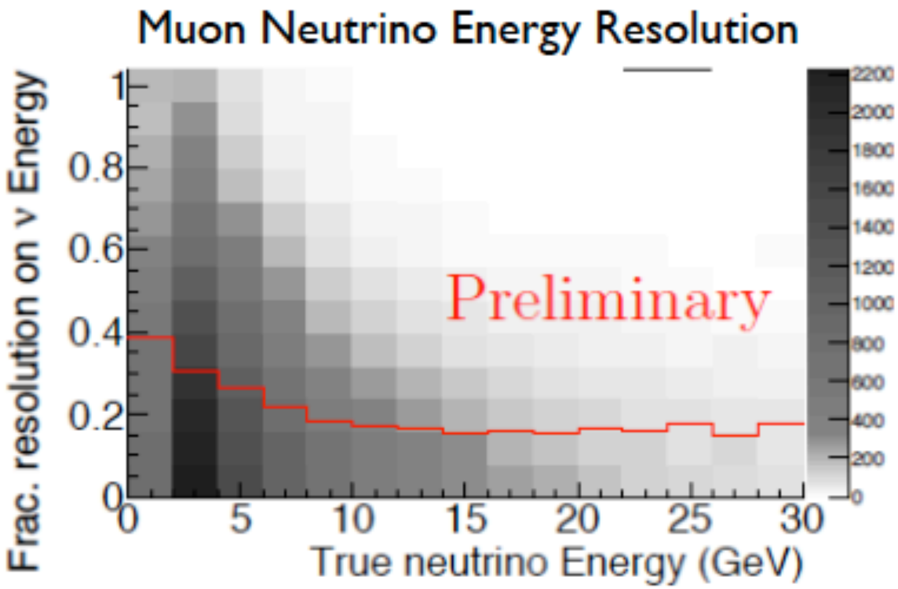
(a) Normal neutrino mass ordering assumed.



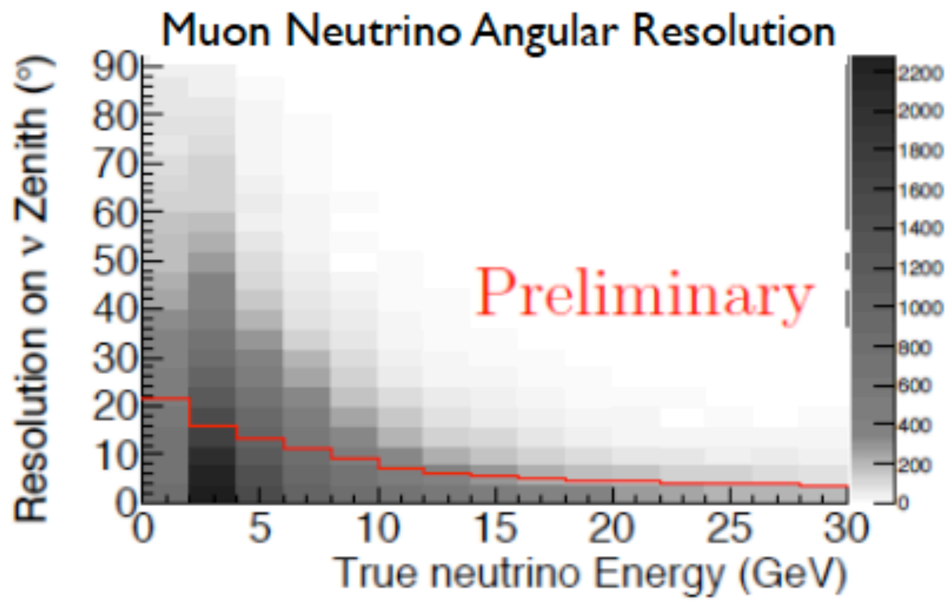
(b) Inverted neutrino mass ordering assumed.

Earth tomography with PINGU ?

Performances for track channel (ν_μ CC):



$|E_{\nu,\mathrm{reco}} - E_{\nu,\mathrm{true}}|/E_{\nu,\mathrm{true}}$ vs. $E_{\nu,\mathrm{true}}$.



$|\theta_{\nu,\mathrm{true}} - \theta_{\nu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.

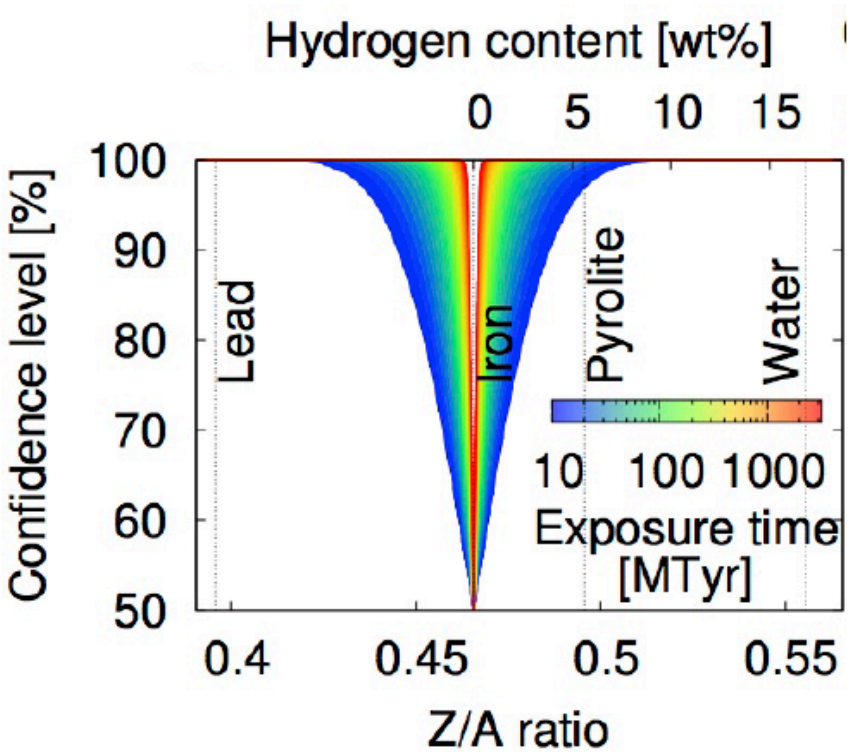
Energy resolution
$\alpha = \Delta E/E$

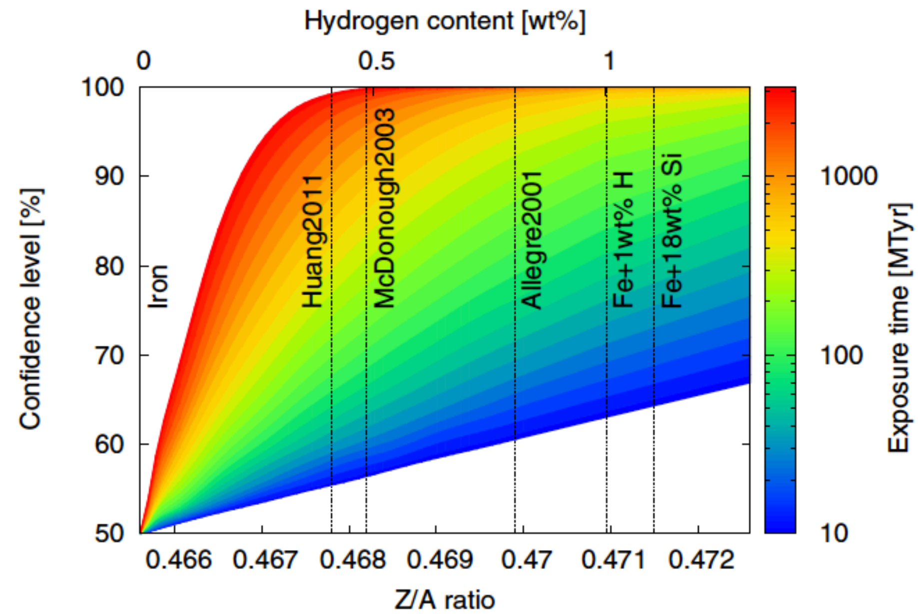
Zenith angle resolution
$\beta = \Delta\Theta \times (E[\mathrm{GeV}])^{0.5}$

We adopt a value of α=0.2 as benchmark

We adopt β =0.25 as benchmark

Earth tomography with PINGU: core composition





A few years of PINGU → ~30 Mton yr:

Exclude extreme composition models for the outer core ?
Probe the Hydrogen content ?

Model name	Z/A ratio	O(wt%)	C(wt%)	S(wt%)	H(wt%)	Si(wt%)
Single-light-element model (maximum abundance)						
Fe+11wt%O [32,34]	0.4693	11	-	-	-	-
Fe+12wt%C [5]	0.4697	-	12	-	-	-
Fe+13wt%S [5]	0.4699	-	-	13	-	-
Fe+1wt%H [5]	0.4709	-	-	-	1	-
Fe+18wt%Si [32]	0.4715	-	-	-	-	18
Multiple-light-element model						
Huang2011 [31]	0.4678	0.1	-	5.7	-	-
McDonough2003 [30]	0.4682	0	0.2	1.9	0.06	6
Allegre2001 [29]	0.4699	5	-	1.21	-	7

Rott, Taketa & Bose
Scientific Reports 5, 15225 (2015)

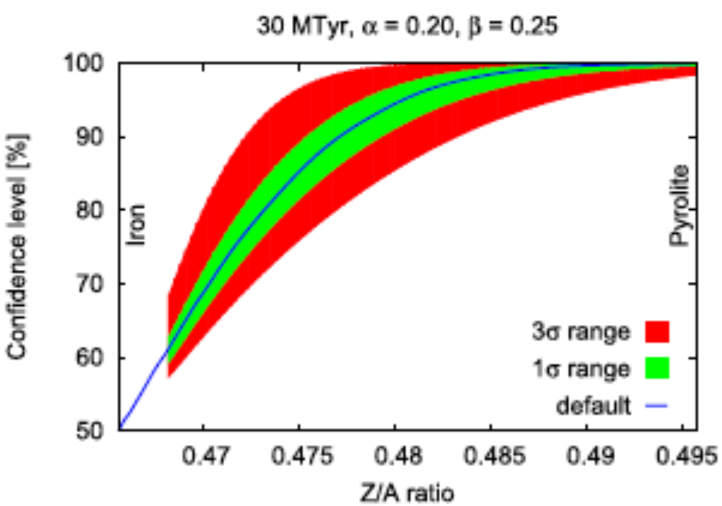
Earth tomography with PINGU: core composition

CAVEATS:
- Optimistic resolutions below 5 GeV
- Normal hierarchy assumed
- 100% detection efficiency down to 1 GeV
- Perfect particle identification (pure track channel)
- no muon background contamination
- No other systematics included

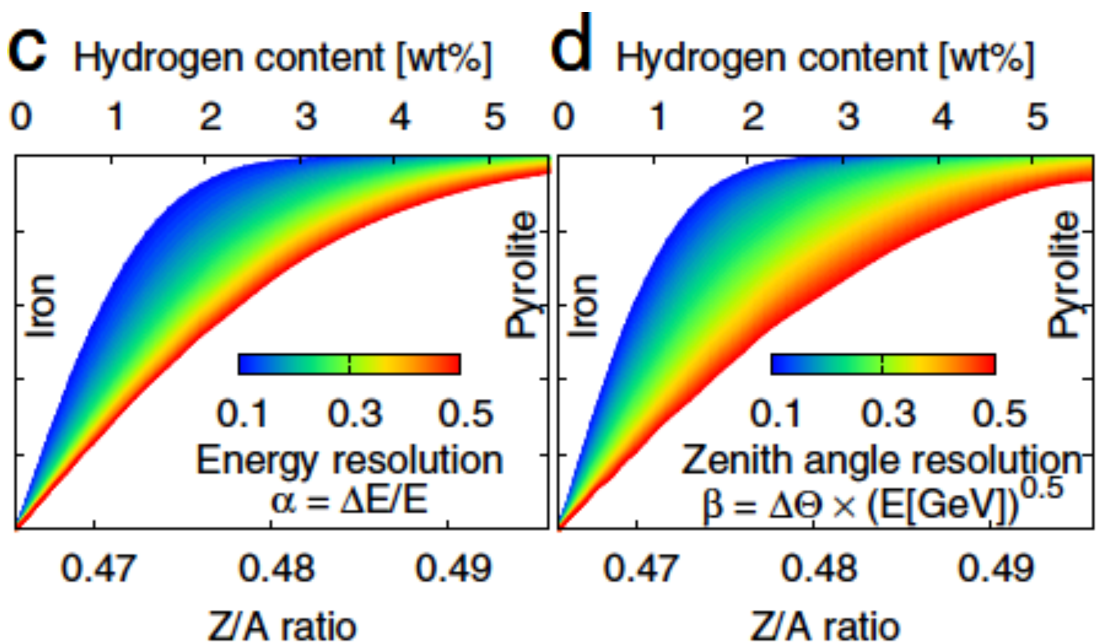
(atmospheric flux, oscillation parameters, neutrino cross-section,…)

Further studies ongoing with realistic PINGU simulations

Effect of uncertainties in oscilllation parameters:



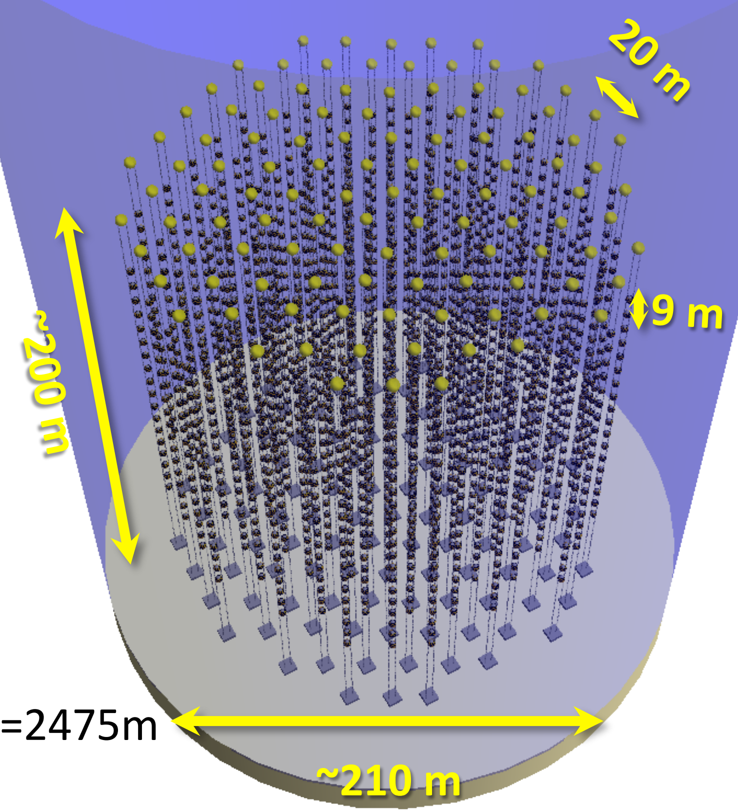
Effect of detector resolutions (30 Mt yr):



Rott, Taketa & Bose
Scientific Reports 5, 15225 (2015)

In the Mediterranean: KM3NeT/ORCA

- ~5.7 Mt instrumented
- **115** strings
- **18** DOMs / string (~50 kt ~ 2 × SK)
- **31** PMTs / DOM (~3 kt ~ MINOS)
- Total: **64k*3¨ PMTs**

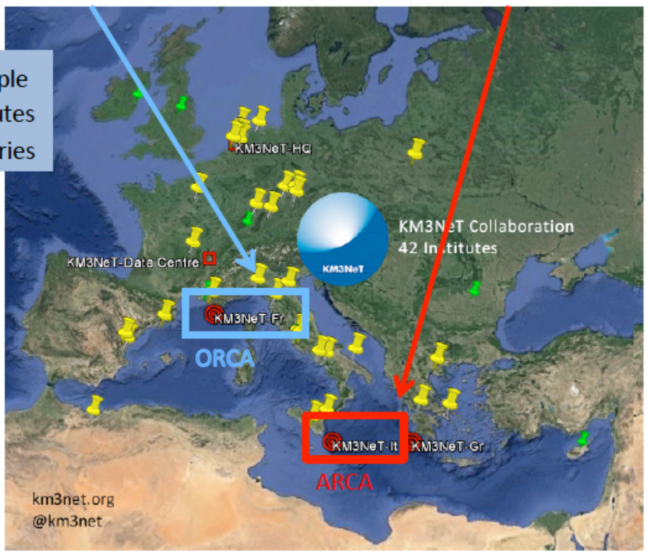


KM3NeT is a distributed research infrastructure with 2 main physics topics:

Oscillations and Astroparticle Research with Cosmics in the Abyss

Low-Energy studies of atmospheric neutrinos – High-Energy search for cosmic neutrinos

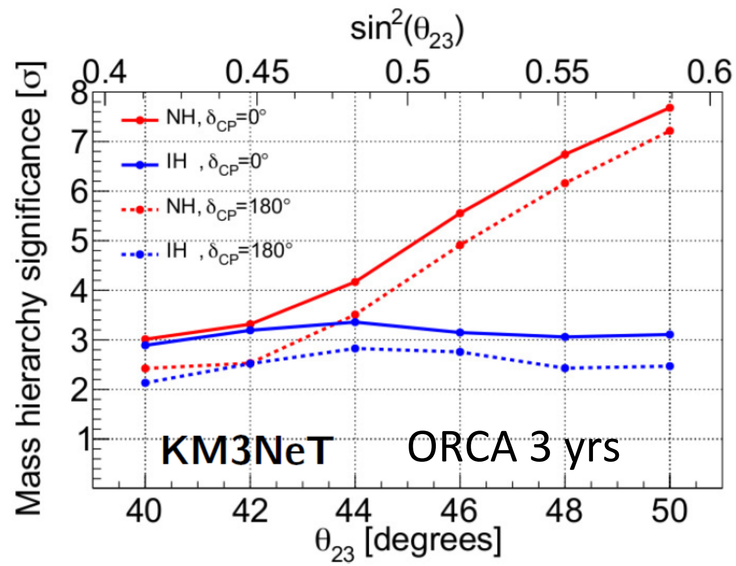
240 people
42 institutes
12 countries



2 sites currently under construction in France and Italy:

KM3NeT-Fr (Toulon, close to ANTARES)

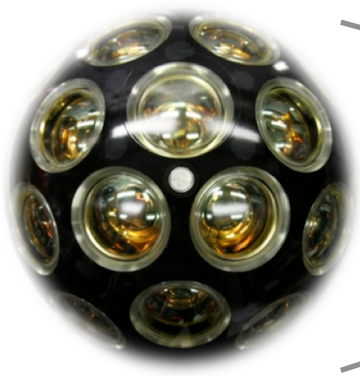
KM3NeT-It (Capo Passero, Sicily)



See KM3NeT 2.0 Letter of Intent, J.Phys. G43 (2016) 8, 084001 (arXiv:1601.07459)

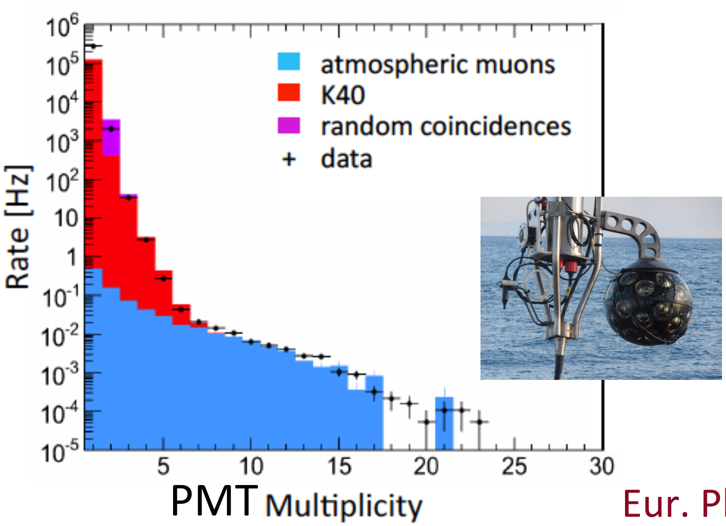
In the Mediterranean: KM3NeT/ORCA

Digital Optical module



17”

31 x 3” PMTs
~4 π sr coverage
Digital Photon counting
Directional information



(also under study for IceCube Gen2)

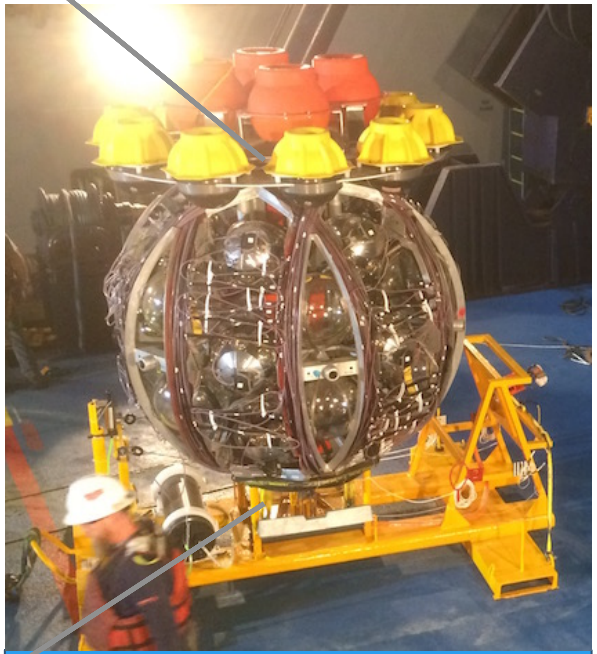
Eur. Phys. J. C (2014) 74:3056

String

~ 200 m (ORCA)

18 DOMs per line
inter-DOM spacing 9 m

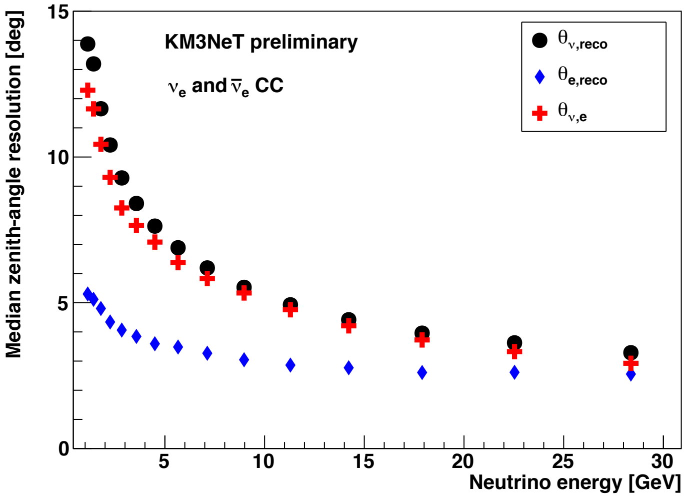
Launcher vehicle



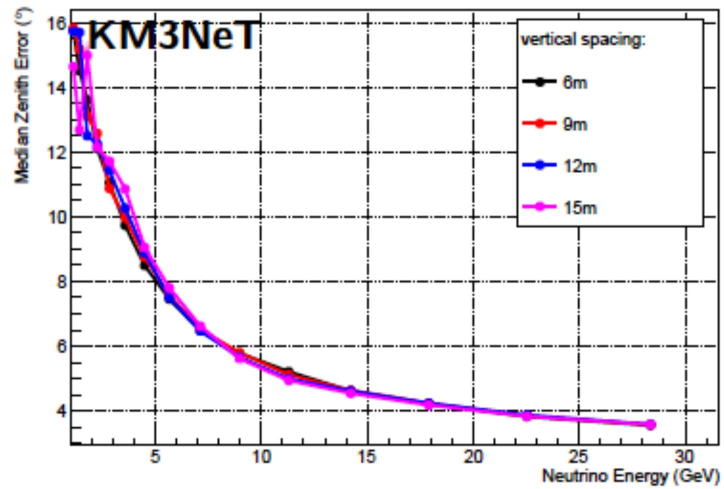
rapid deployment
autonomous unfurling
recoverable

ORCA performance: resolutions

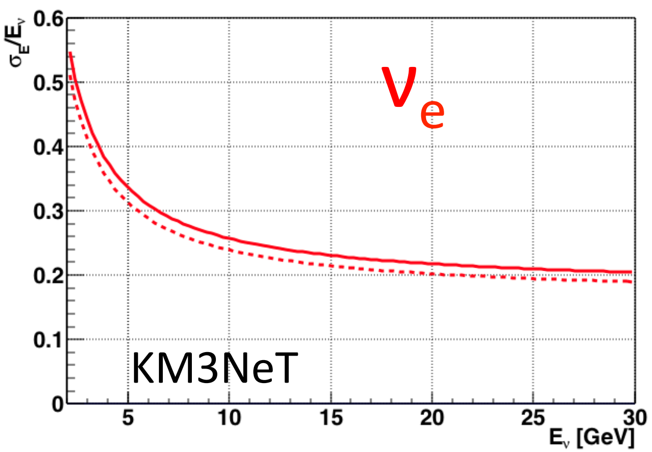
SHOWERS

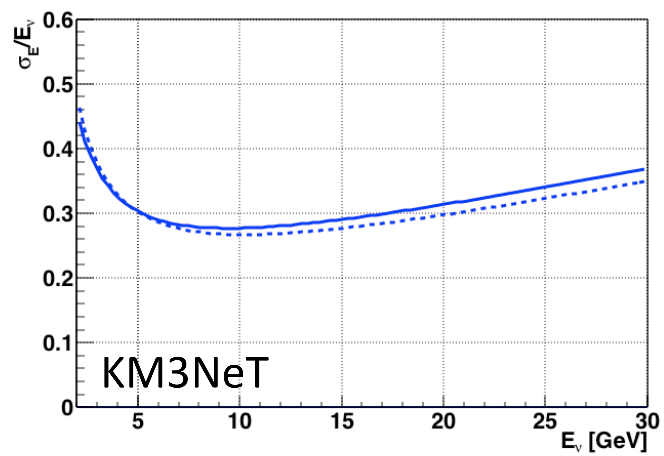


TRACKS



ANGULAR RESOLUTION:
7°(5°) at 5(10) GeV for both channels, dominated by kinematic smearing





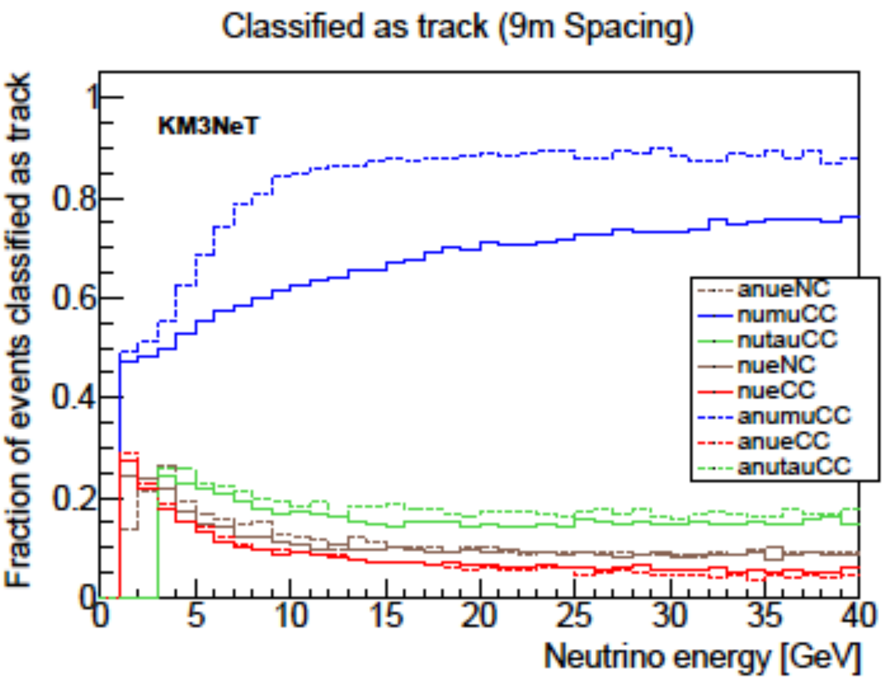
Solid : nu
Dashed: anti-nu

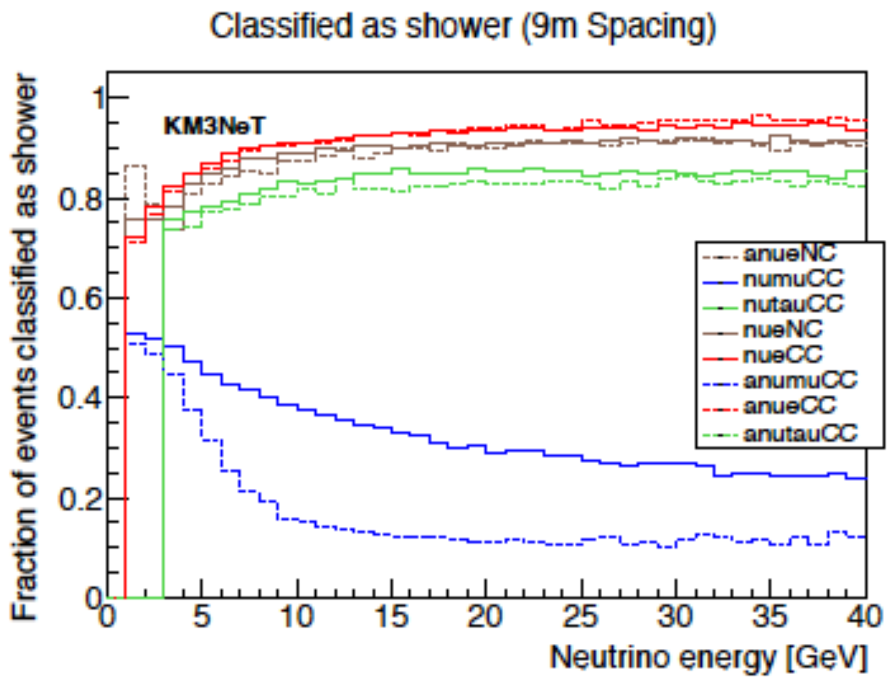
ENERGY RESOLUTION:
30% for both channels, in relevant energy range; worse at energies < 5 GeV

ORCA performance: particle identification

3 classes of events discriminated via Random Decision Forest:

- Tracks
- Cascades
- Atmospheric muons (= background)



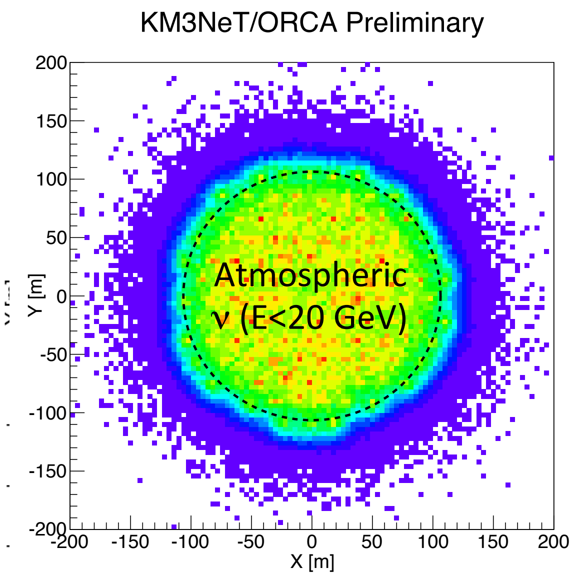


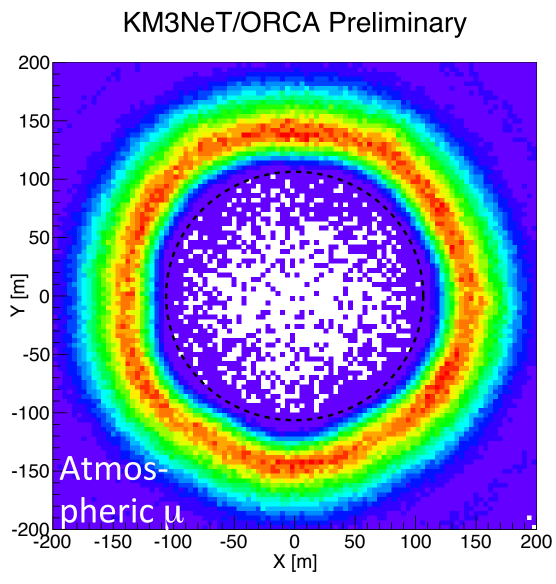
At 10 GeV:

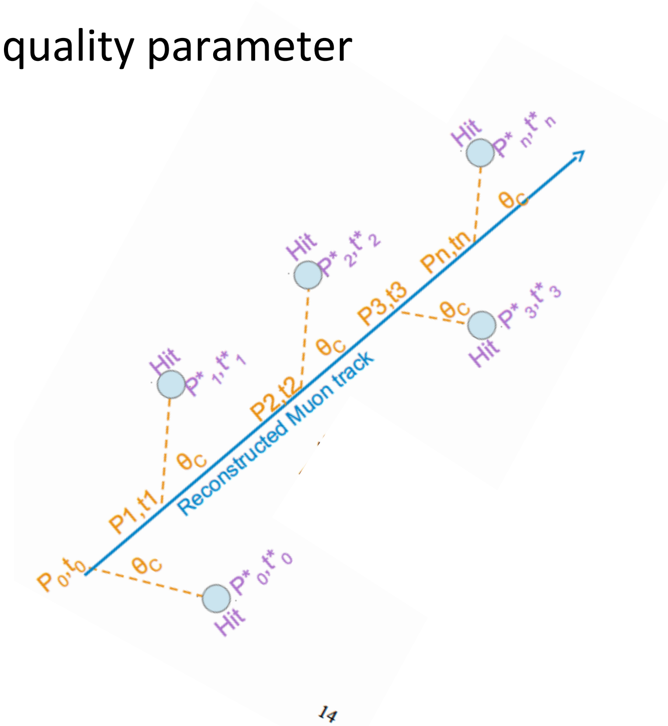
- 90% correct identification of ν_e^{CC}
- 60% (85%) correct identification of ν_μ^{CC} ($\bar{\nu}_\mu^{CC}$)

ORCA performance: background rejection

- ν_μ CC track reconstruction: cut on upgoing events + track fit quality parameter + reconstructed pseudo-vertex + BDT

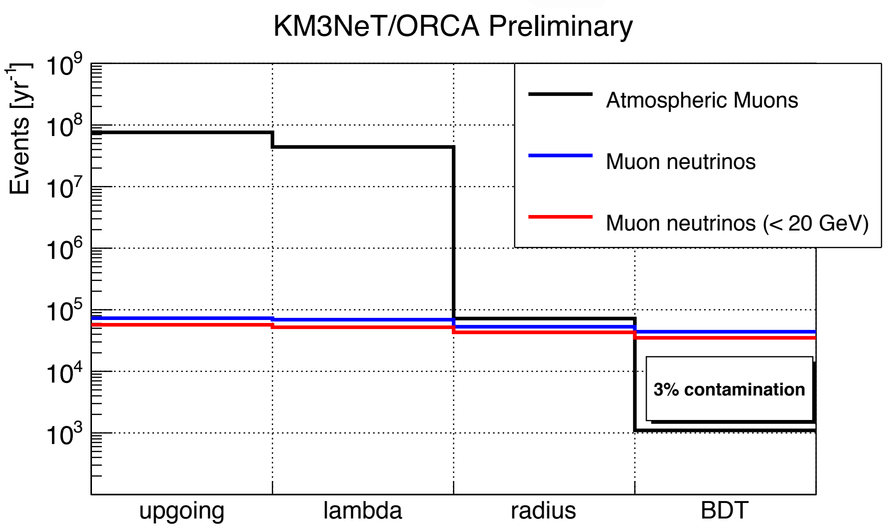




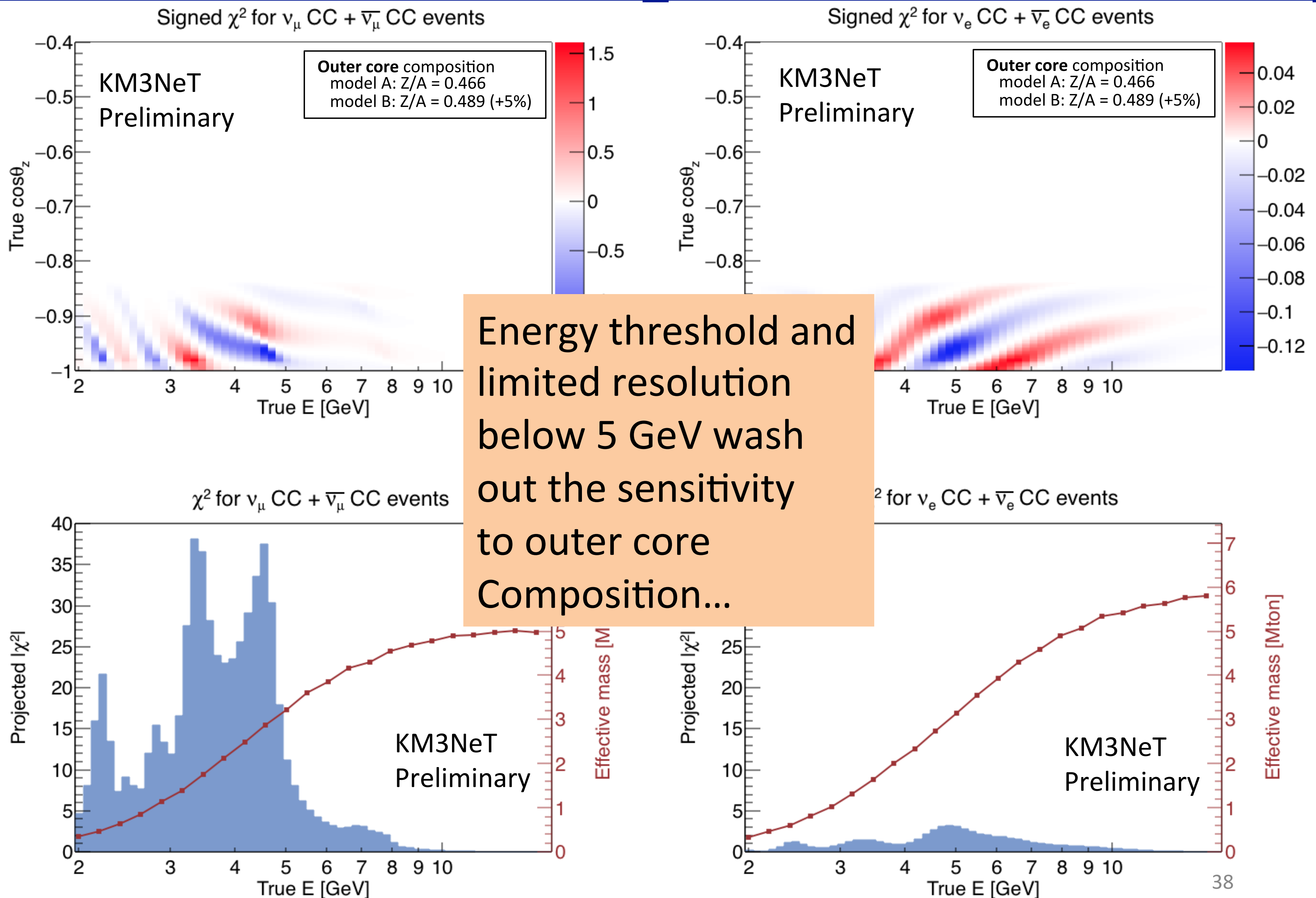


Tunable few % contamination achievable without too strong signal loss

Instrumental veto not mandatory

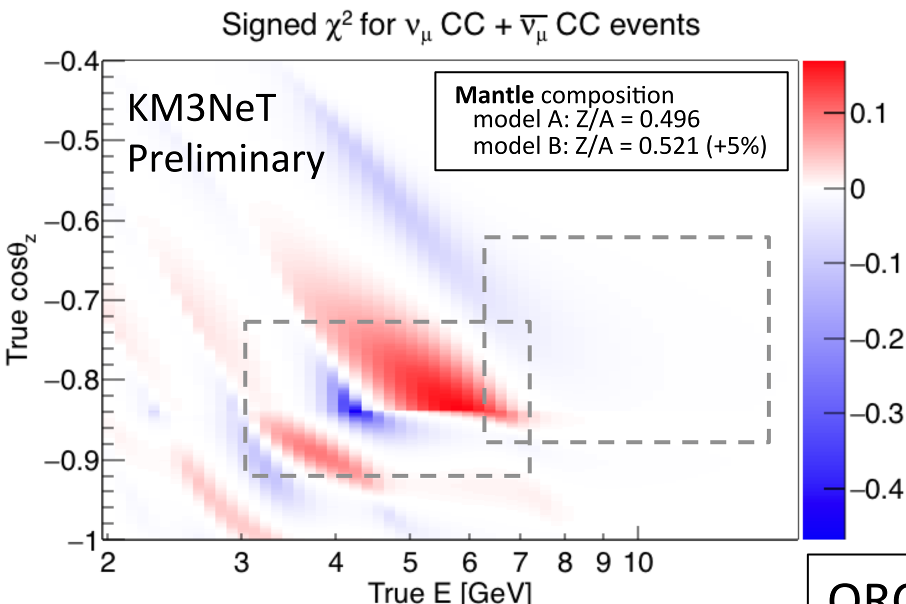


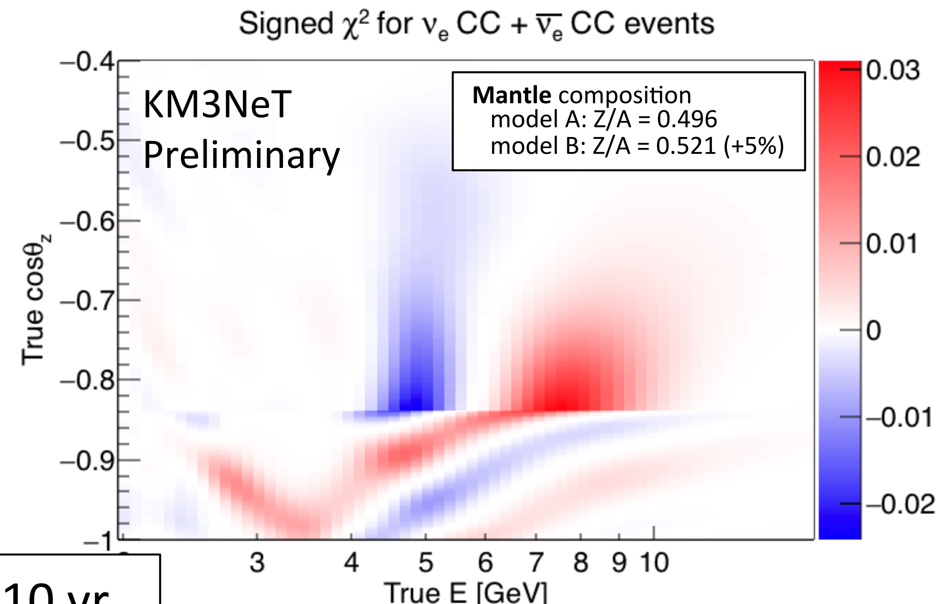
Earth tomography with ORCA: outer core



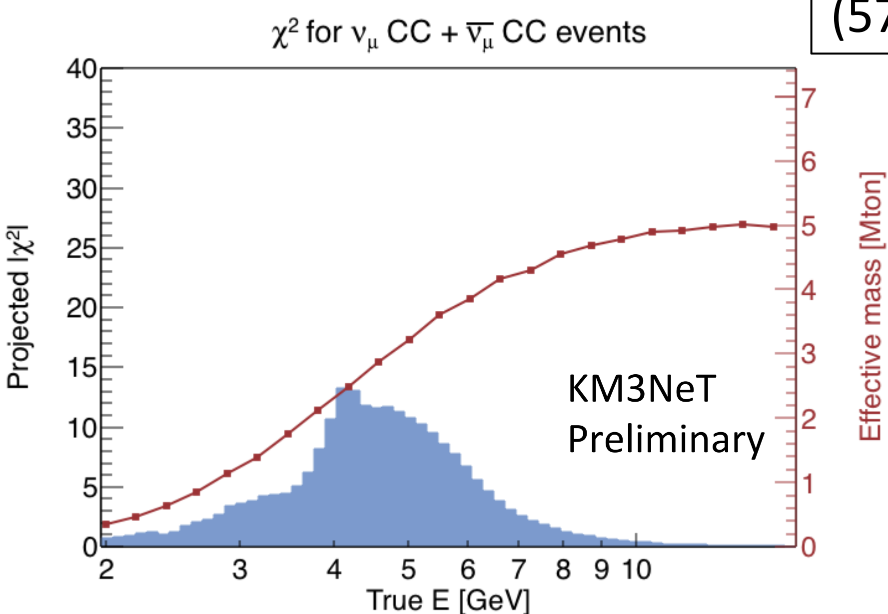
Energy threshold and limited resolution below 5 GeV wash out the sensitivity to outer core Composition…

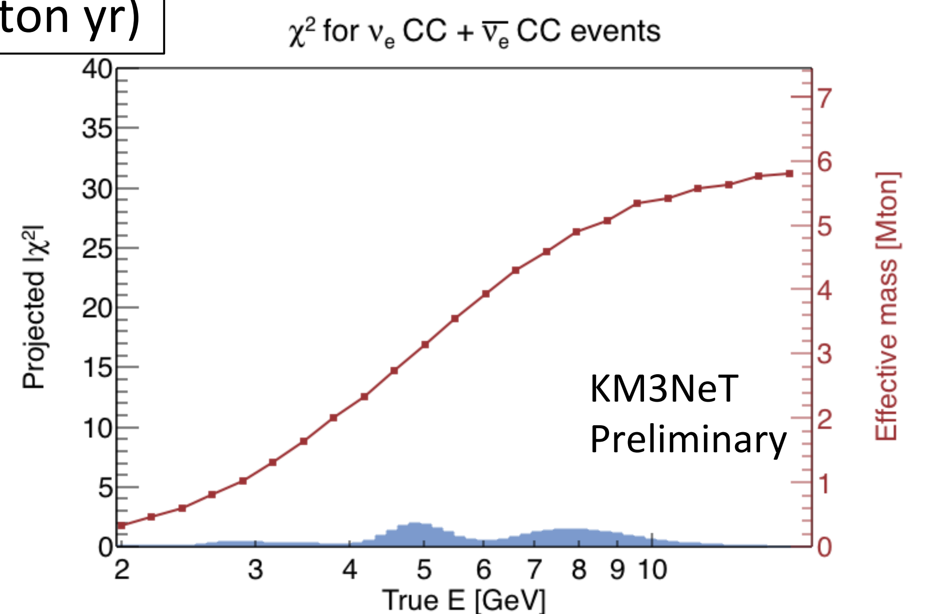
Earth tomography with ORCA: mantle



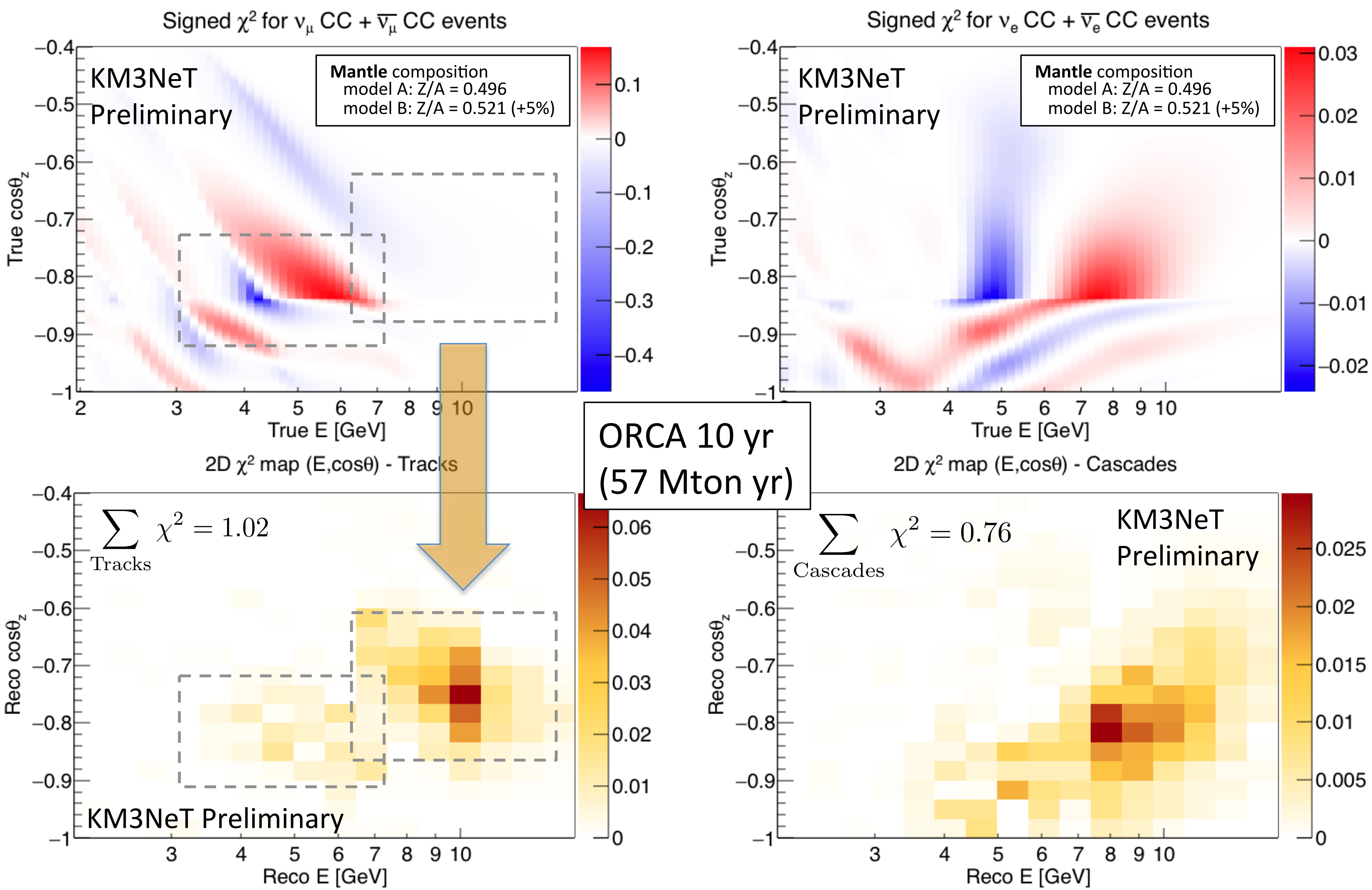


ORCA 10 yr
(57 Mton yr)





Earth tomography with ORCA: mantle

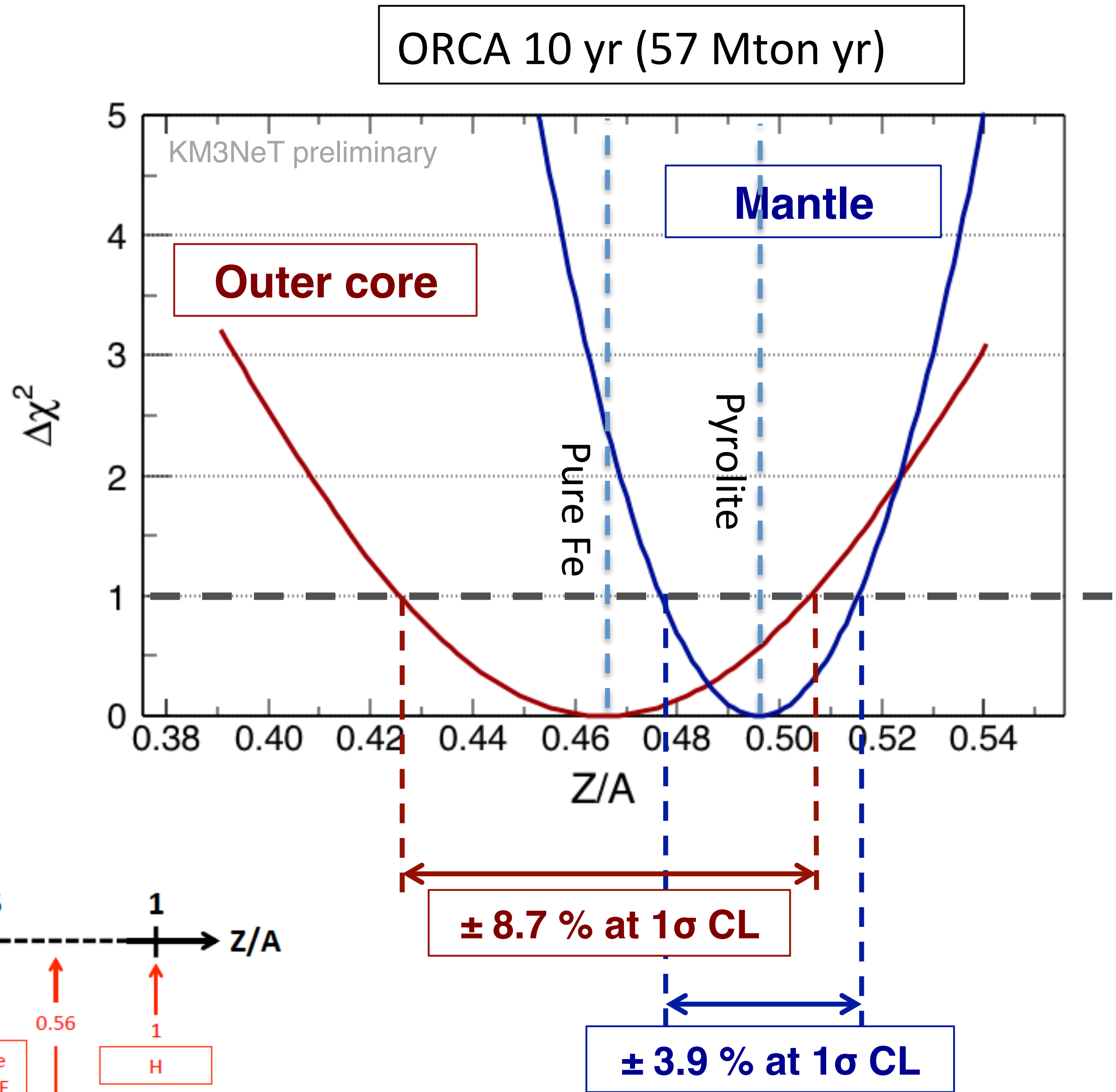


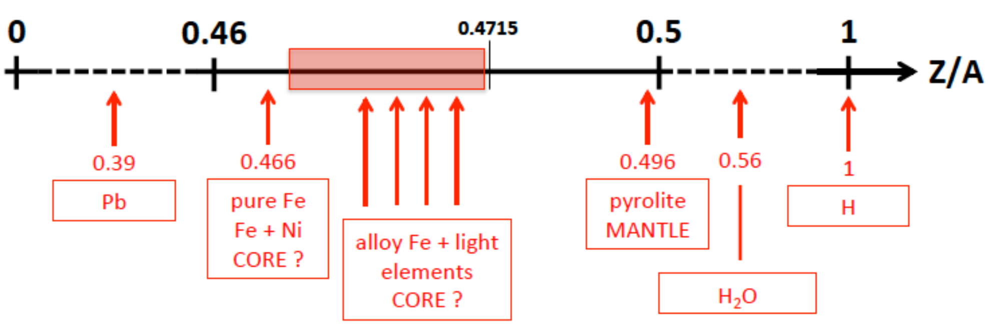
Earth tomography with ORCA

Including realistic detector Information:

- Resolutions
- Particle ID
- Detector efficiency (effective volume)

better sensitivity to mantle composition





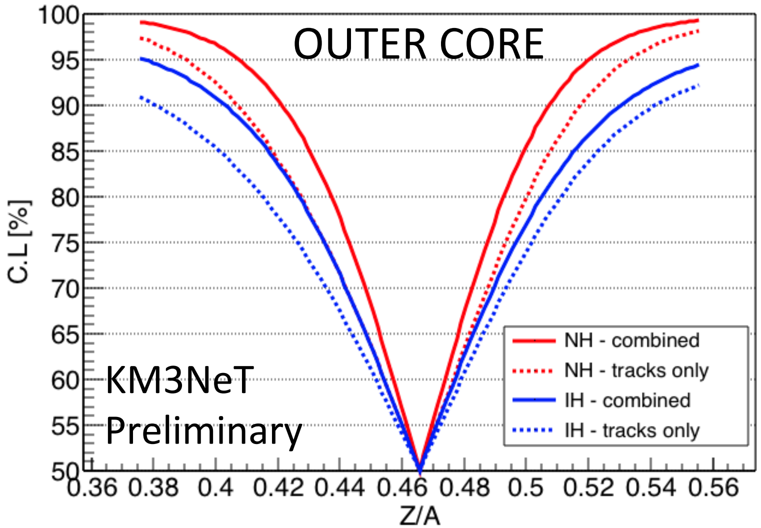
Earth tomography with ORCA

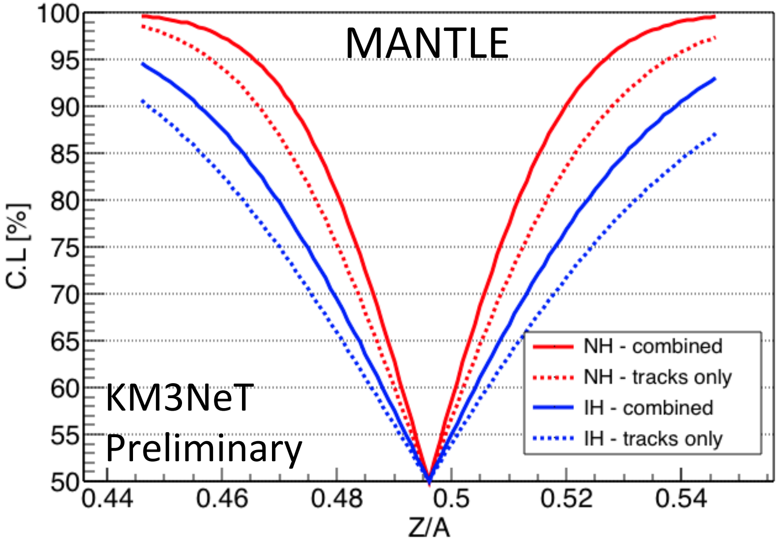
Performance on tomography depends
on neutrino mass hierarchy:
IH → resonance in anti-neutrino channel
→ smaller statistics

Cascade channel contribution is sizeable !

CAVEATS:
- No muon background contamination included
- No other systematics included

To be continued…





Conclusions and perspectives

Earth tomography with neutrinos (absorption/oscillation) is an « old » idea,
Various experimental setups are conceptually possible

→ see the review by W. Winter, *Earth Moon Planets 99 (2006) 285-307*

Measurement of a (relatively) large ϑ_{13} → possibility to study matter effects on oscillations in the atmospheric sector

⇒ determination of the neutrino mass hierarchy
⇒ neutrino oscillation tomography of the Earth

… a new generation of water/ice Cherenkov experiments in development/construction:
ORCA – PINGU – HyperKamiokande (+ beam)
(also other techniques – iron magnetized calorimeter: INO)

- constrain deep Earth composition through a completely independant method
- Ability to exclude extreme models after a few years operation

(performances still to be assessed by detailed studies)

…yet another generation of detectors needed for precise composition measurements & exploration of realistic models for mantle and core composition

- large volume (→ high statistics): ~10 Mton ?
- ~ 1-2 GeV threshold
- good energy/angular resolution

Remerciements

I am indebted with many colleagues for the preparation of these slides,
Special thanks are due to:
Simon Bourret, Joao Coelho, Paschal Coyle, Antoine. Kouchner,
Carsten Rott and Walter Winter

…as well as to the organizers of this School !