Imaging the Deep Earth with neutrinos

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Université Paris Cité & Institut Universitaire de France

… Many thanks to my collaborators:

Lukas Maderer
Joao Coelho
Antoine Kouchner
Simon Bourret (2015-2018)

…& many other colleagues from

KM3NeT

Edouard Kaminski

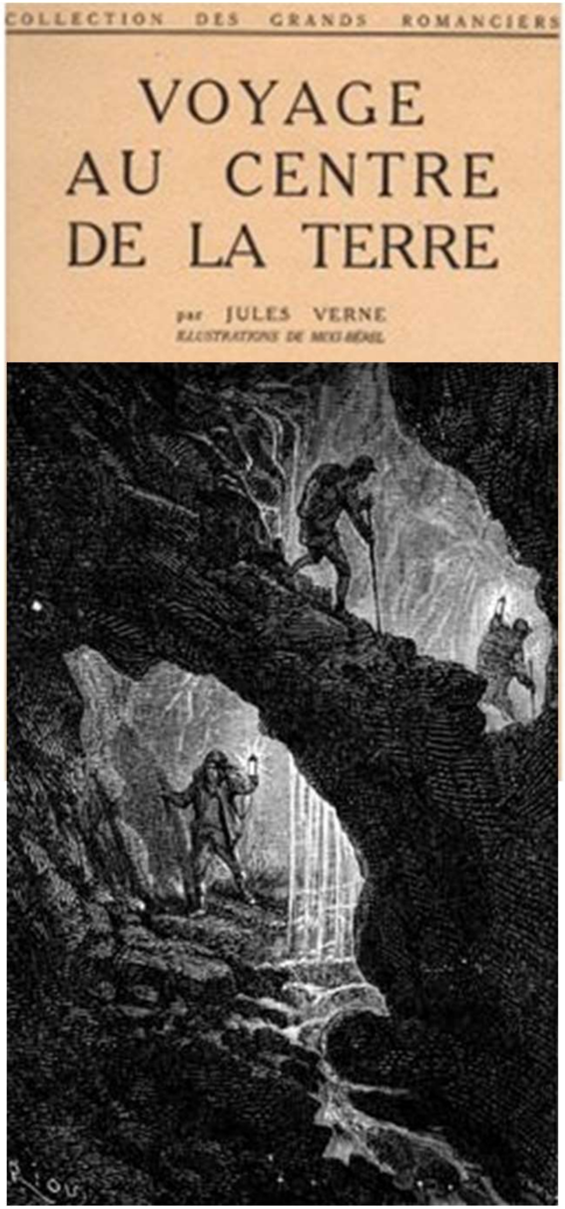
IPGP

Arwen Deuss
Rûna van Tent

Universiteit Utrecht

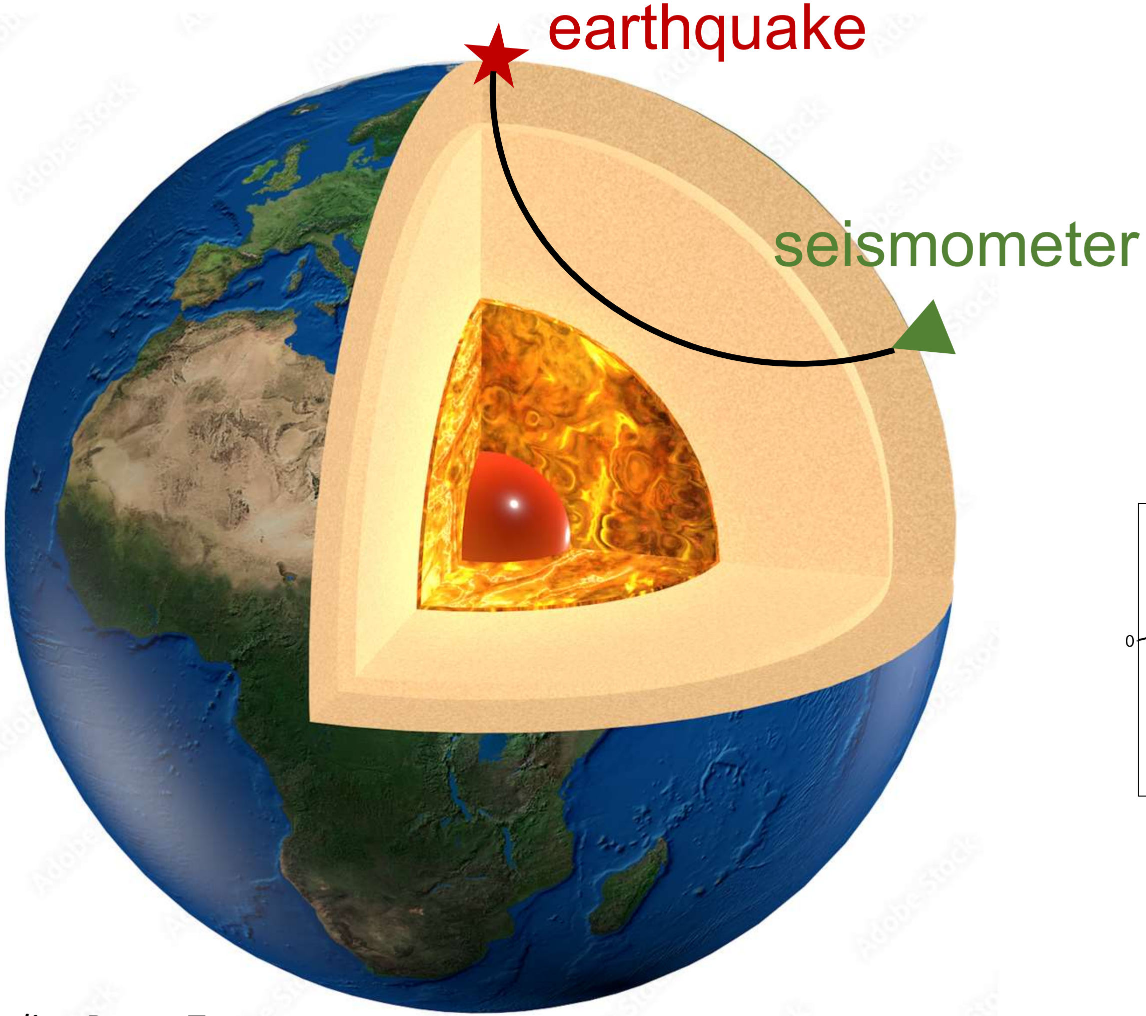
How can we probe the Earth's interior ?

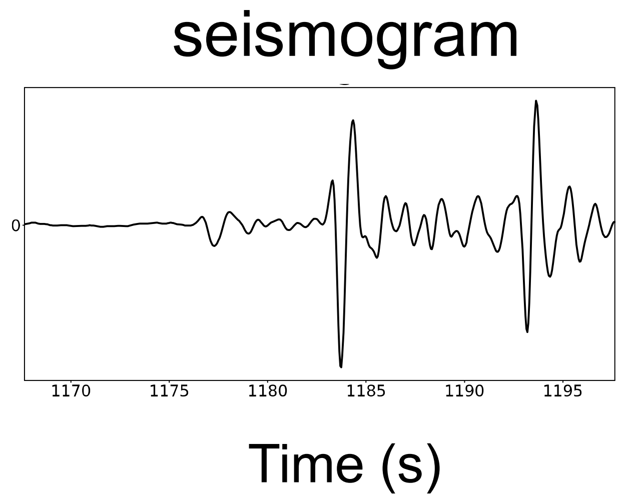
Jules Verne's way: a long journey…



How can we probe the Earth's interior ?

The geophysicist's way: studying seismic waves from earthquakes

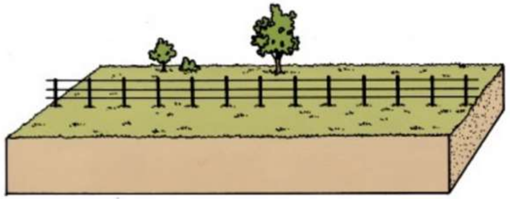


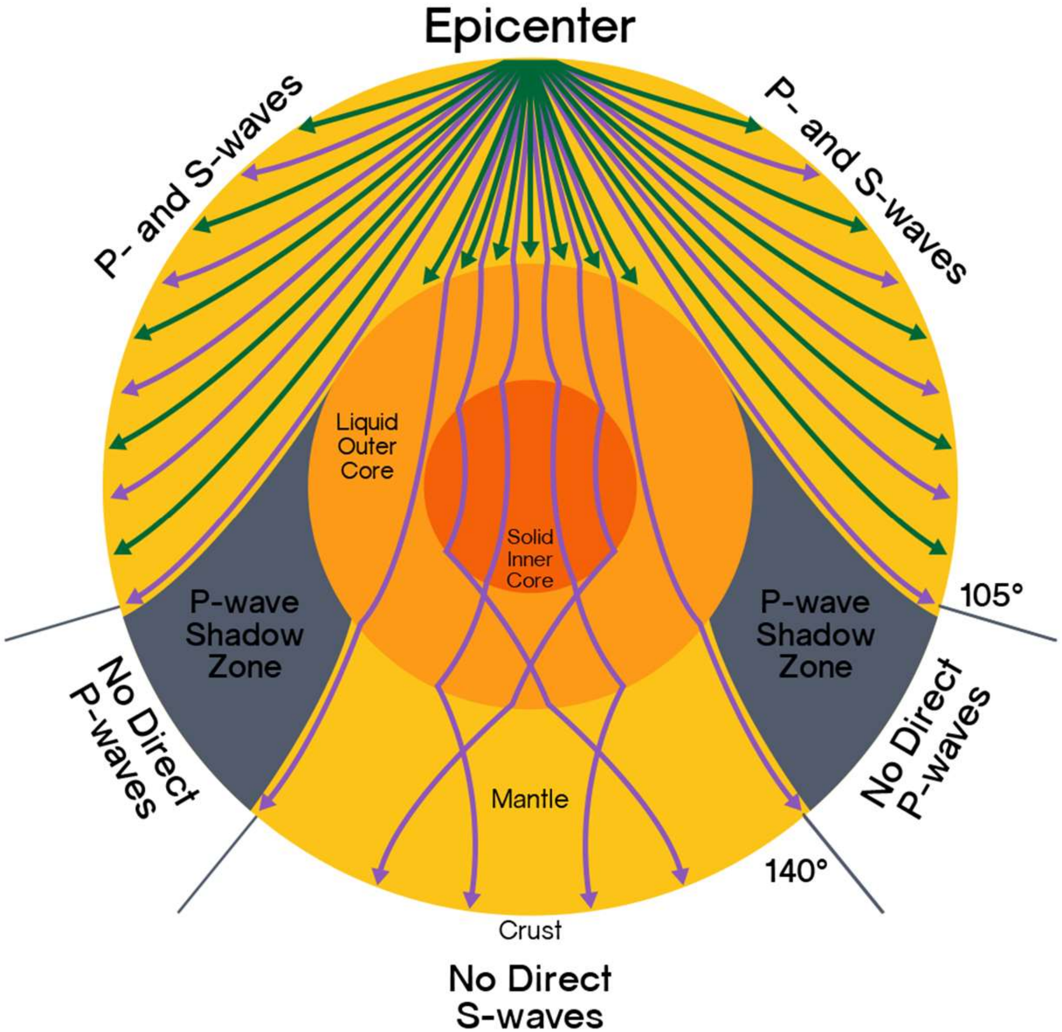


Credits: R. van Tent

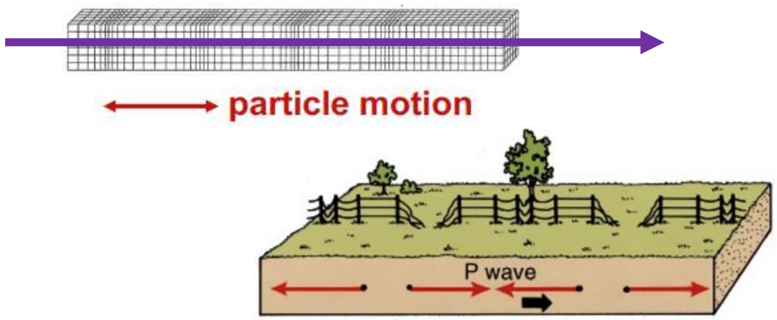
Looking at the Earth's interior…

The geophysicist's way: studying seismic waves

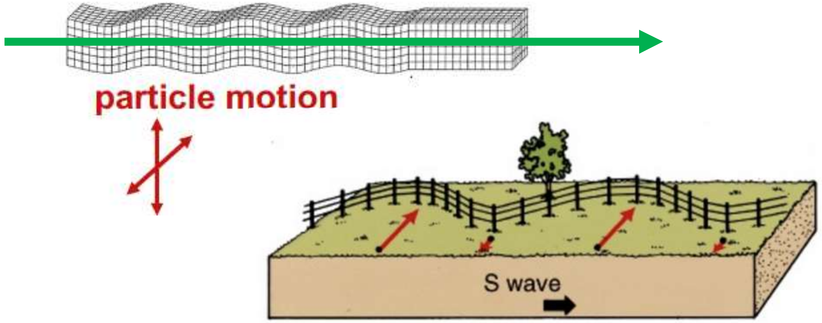




P waves (fastest) : pressure waves



S waves (slower): shear waves

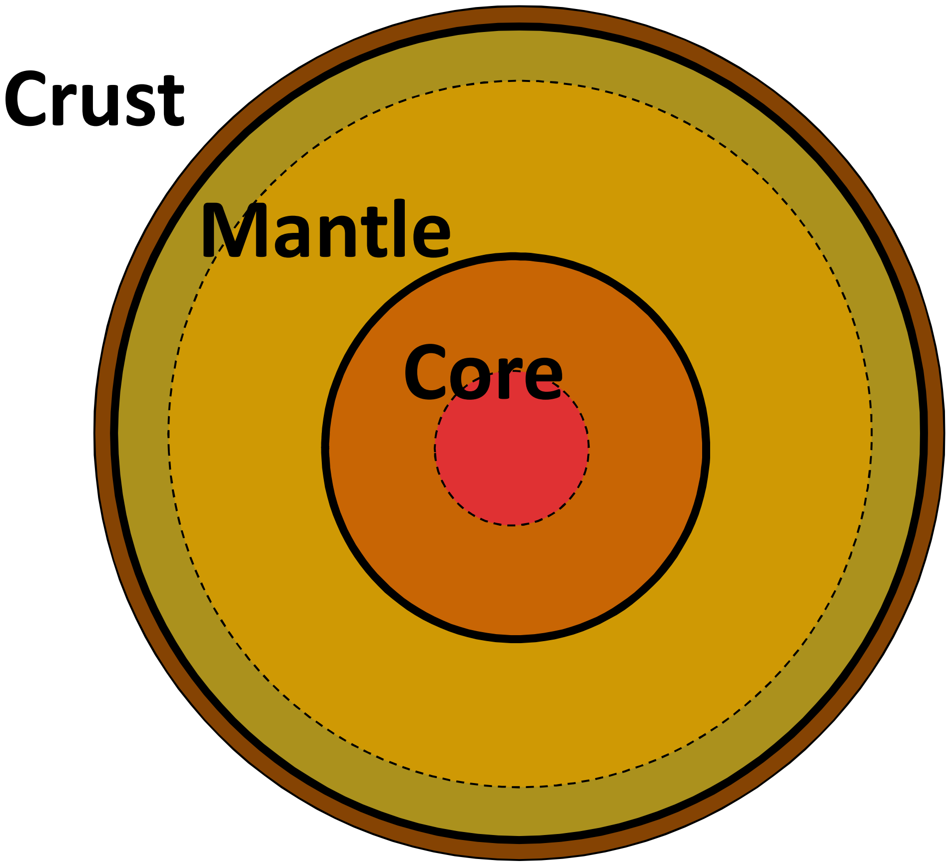


Looking at the Earth's interior…

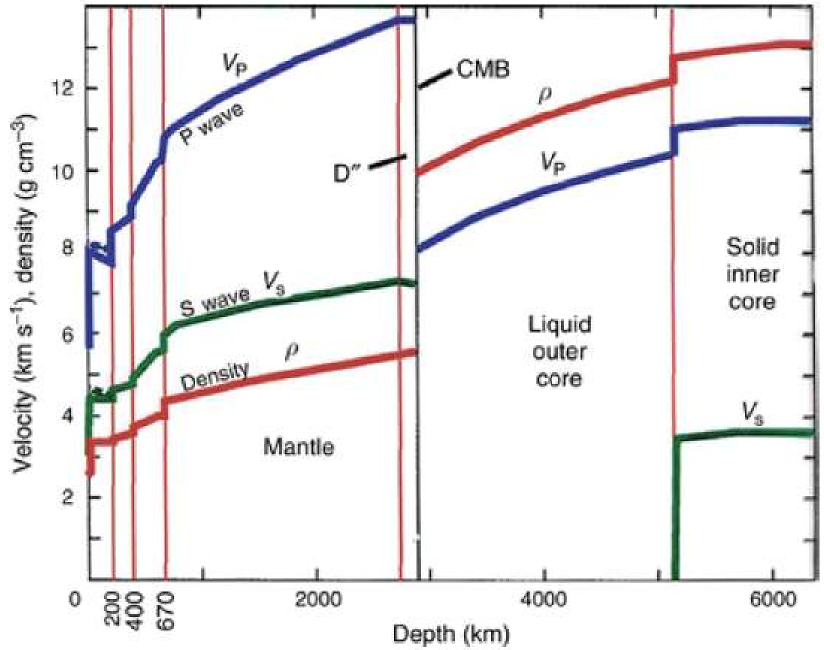
Inversion of seismic wave data

+ gravimetric constraints on Earth's total mass & moment of inertia:

→ **radial profile of Earth matter density inferred at ~1% precision**



Preliminary Reference Earth Model

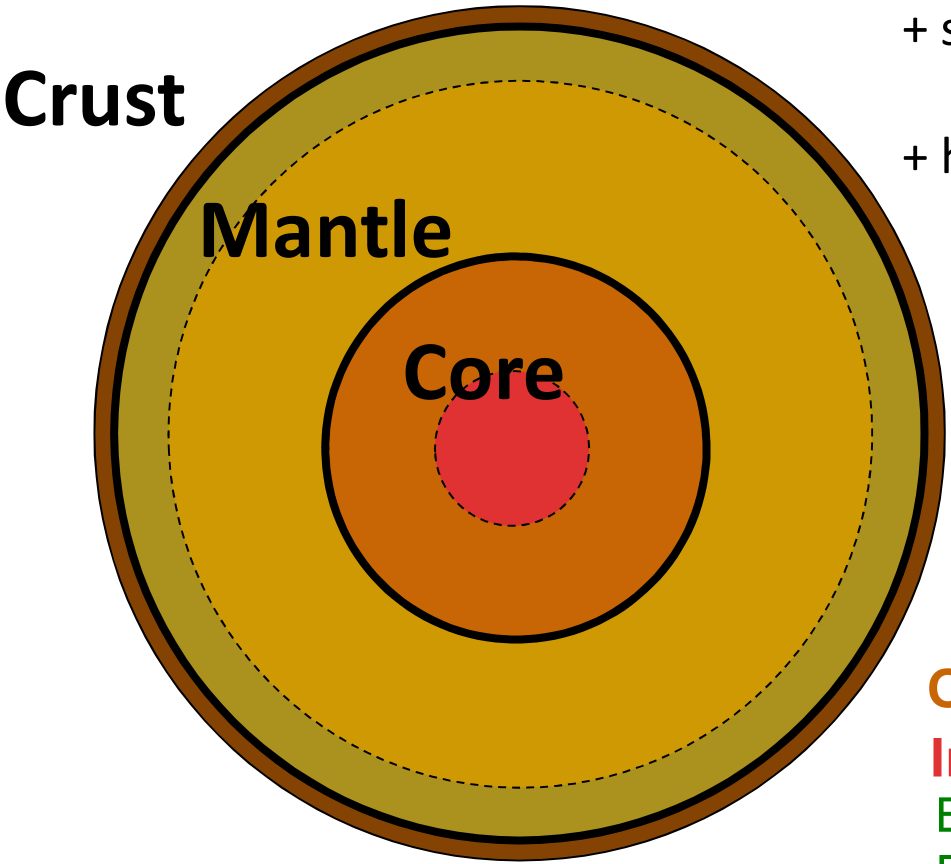


Dziewonski and Anderson, 1981

In a given layer: velocity of seismic waves increases with depth due to higher pressure/density

Looking at the Earth's interior…

Inversion of seismic wave data
+ gravimetric constraints on Earth's total mass & moment of inertia:
→ radial profile of Earth matter density inferred at ~1% precision



+ study of rock samples from crust & mantle, meteorites
+ high-pressure experiments
→ chemical composition of mantle/core:

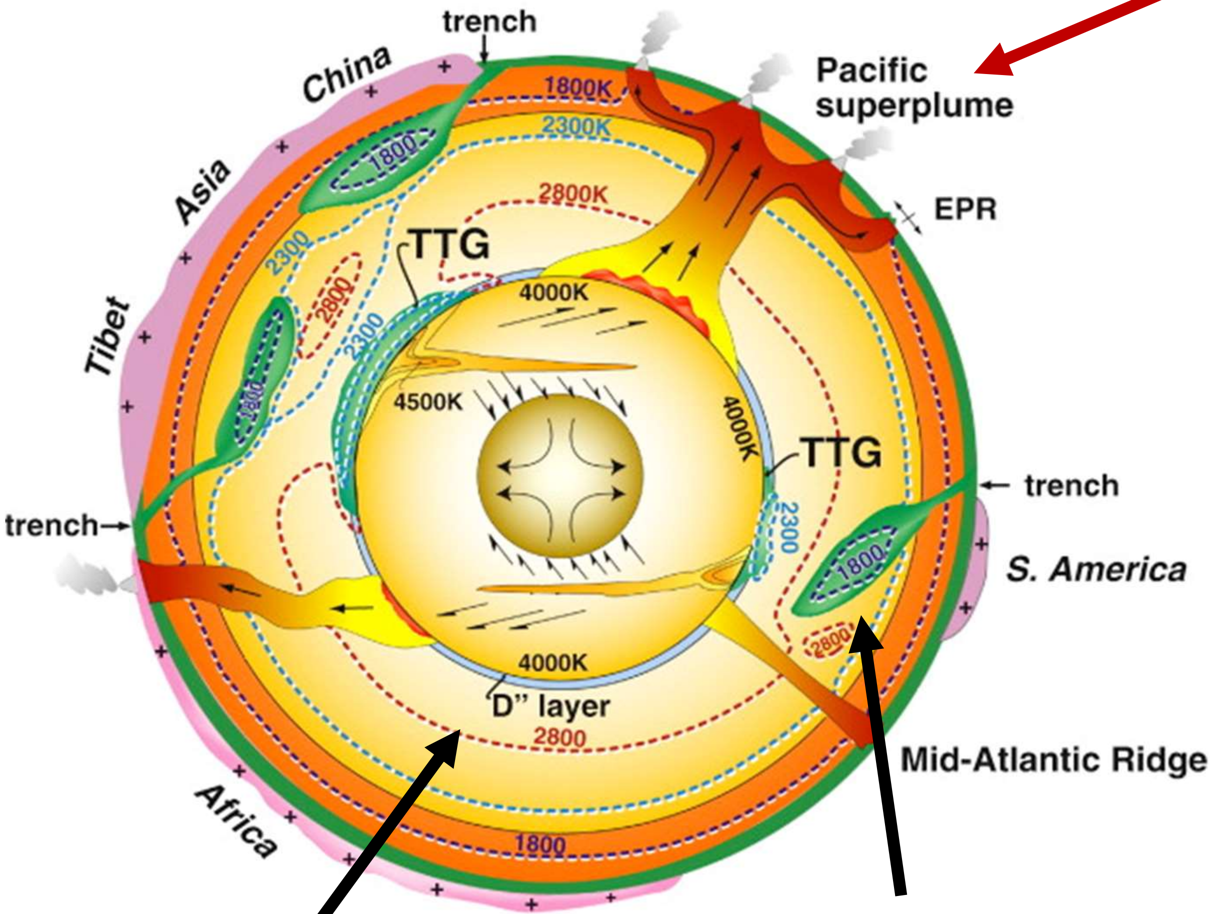
Upper mantle / Lower mantle:
Silicate minerals (SiO_4 + Fe, Mg, Mn…)
Benchmark composition: pyrolite (Z/A=0.496)

Outer core Liquid (no S-waves)
Inner core Solid
Benchmark composition: Fe-Ni alloy (Z/A=0.466)

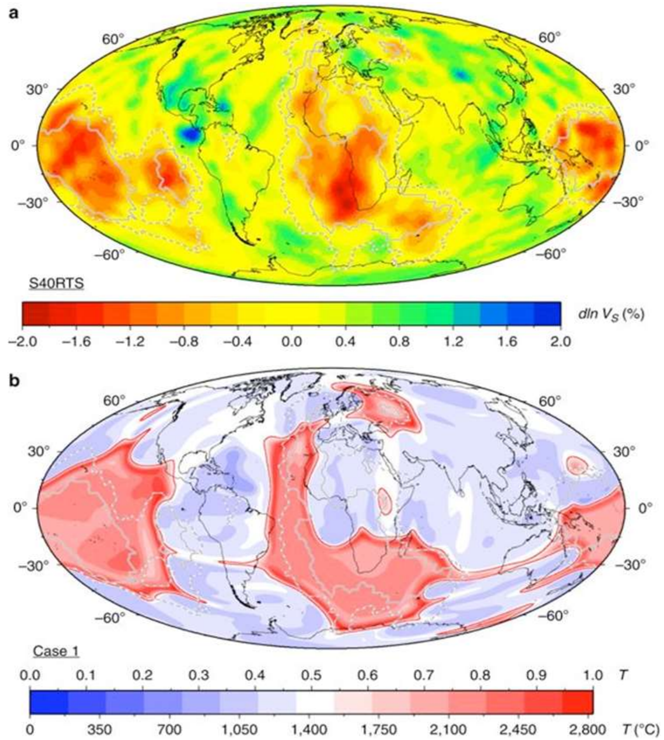
+ light elements in outer core ? (Si, O, S, C, H)

Looking at the Earth's interior…

CAVEAT: the radial model is only an approximation!



Large Low-Shear-Velocity Provinces (LLSVP)
extending over ~1000km
related to temperature/
density anomalies ?



potential water reservoir ?

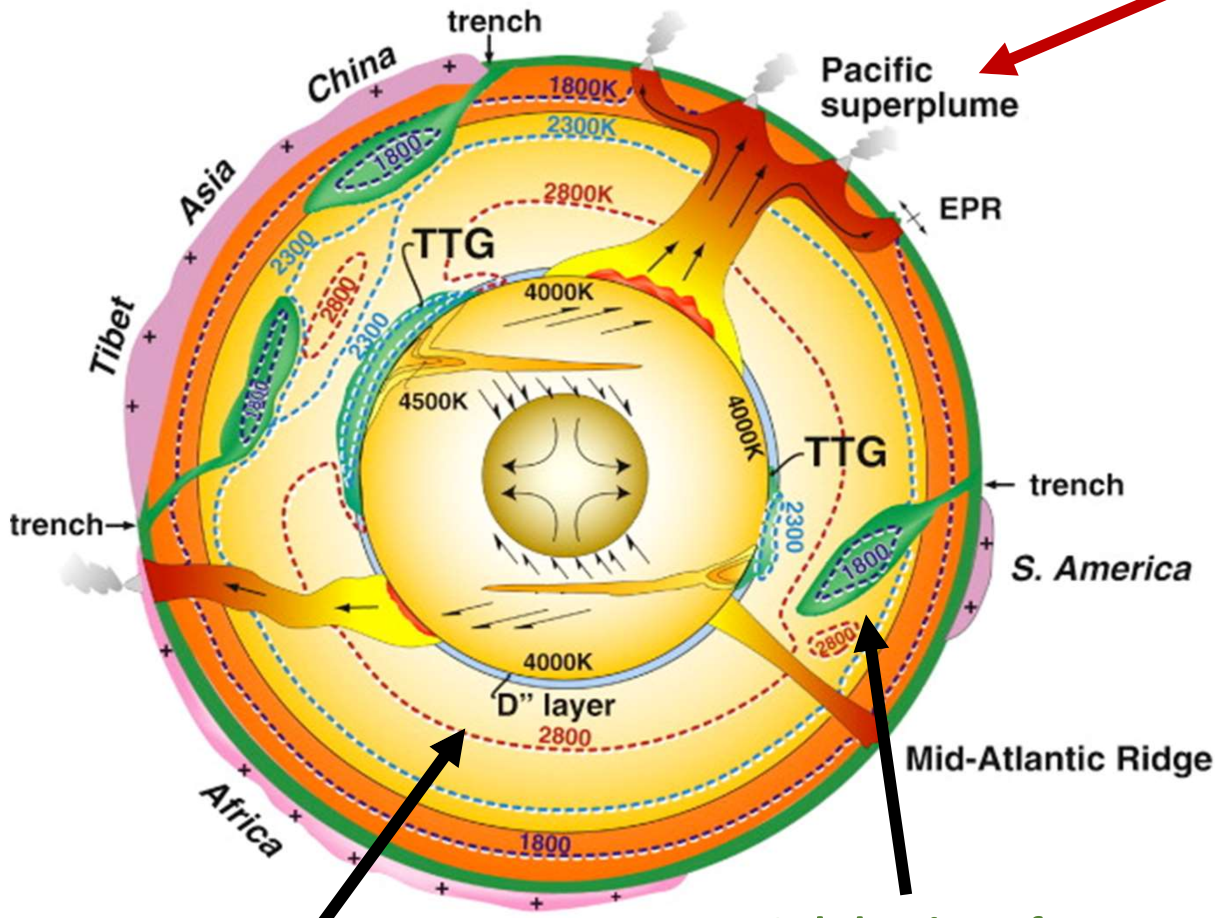
Subduction of cooler material

Nature ? Composition ?

Looking at the Earth's interior…

CAVEAT: the radial model is only an approximation!

→ Need for a reference 3D seismological model
… and complementary methods!



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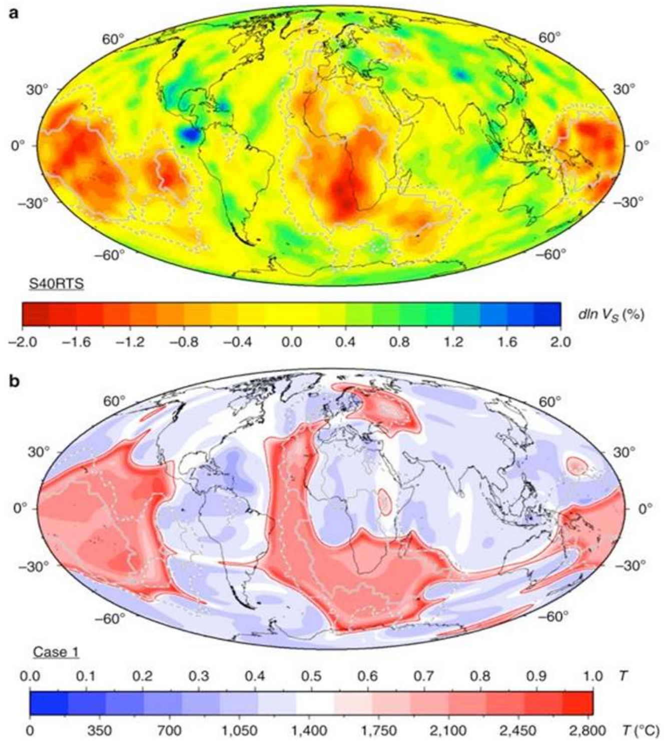

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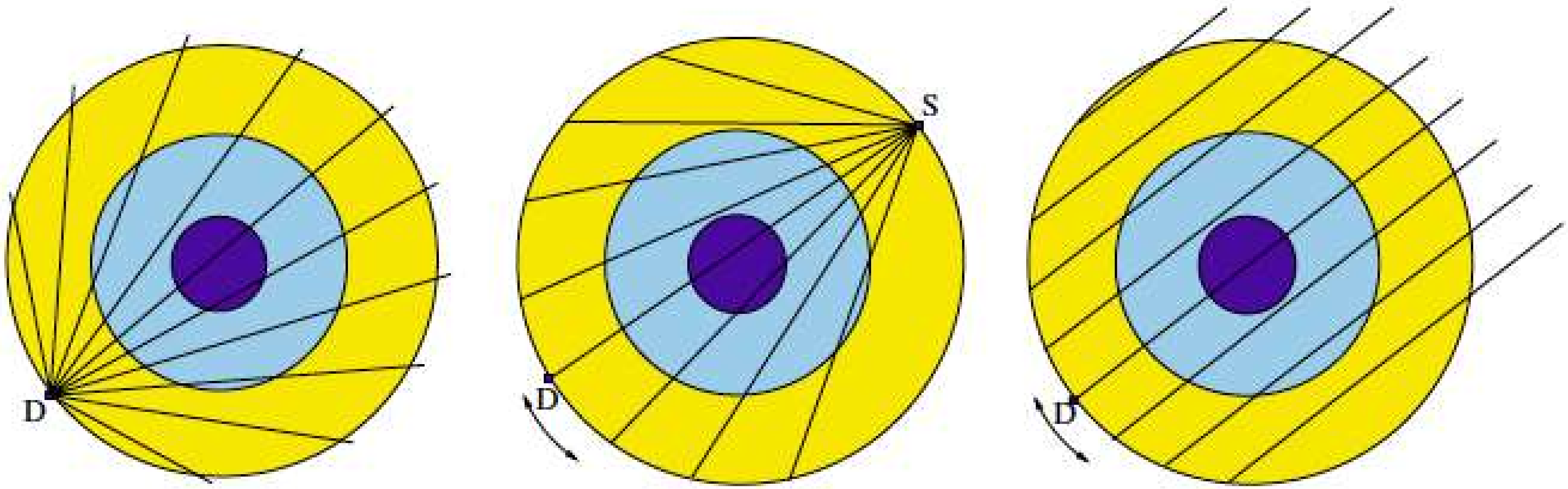
Looking at the Earth's interior…with neutrinos ?

Early (conceptual) attempts:

See review by W. Winter,
Earth Moon Planets 99 285 (2006)



a) Isotropic flux

b) High-energy neutrino beam

c) Cosmic point source

a) Isotropic flux	b) High-energy neutrino beam	c) Cosmic point source
Fixed detector, different baselines	Controlled source	Earth's rotation provides different baselines
Need distributed sources…	Needs steerable beam & moving detector…	Uncontrolled source, low fluxes

Looking at the Earth's interior…with neutrinos ?

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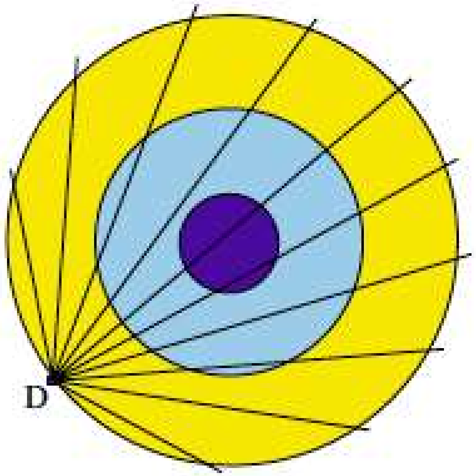
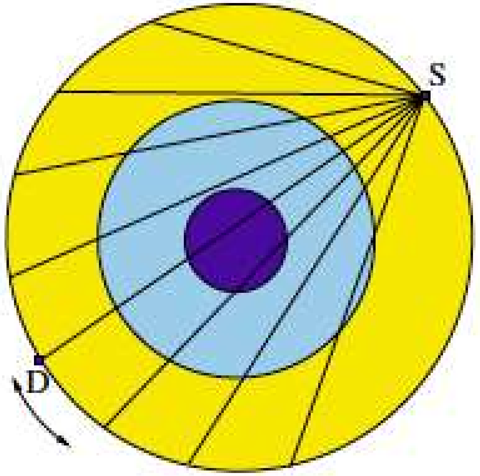


a) Isotropic flux

Fixed detector,
different baselines

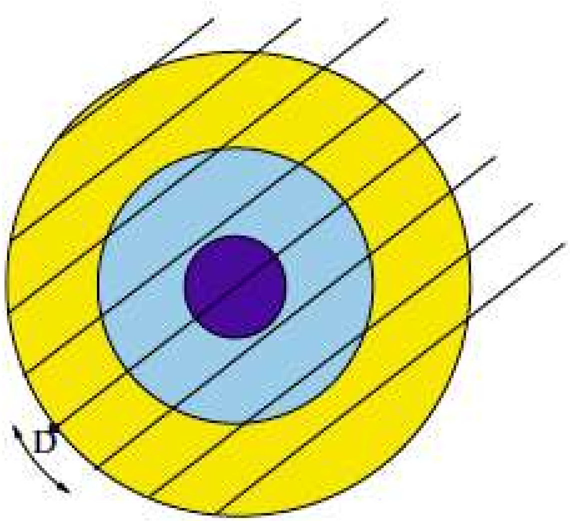
Need distributed
sources…



b) High-energy
neutrino beam

Controlled source

Needs steerable beam
& moving detector…



c) Cosmic point
source

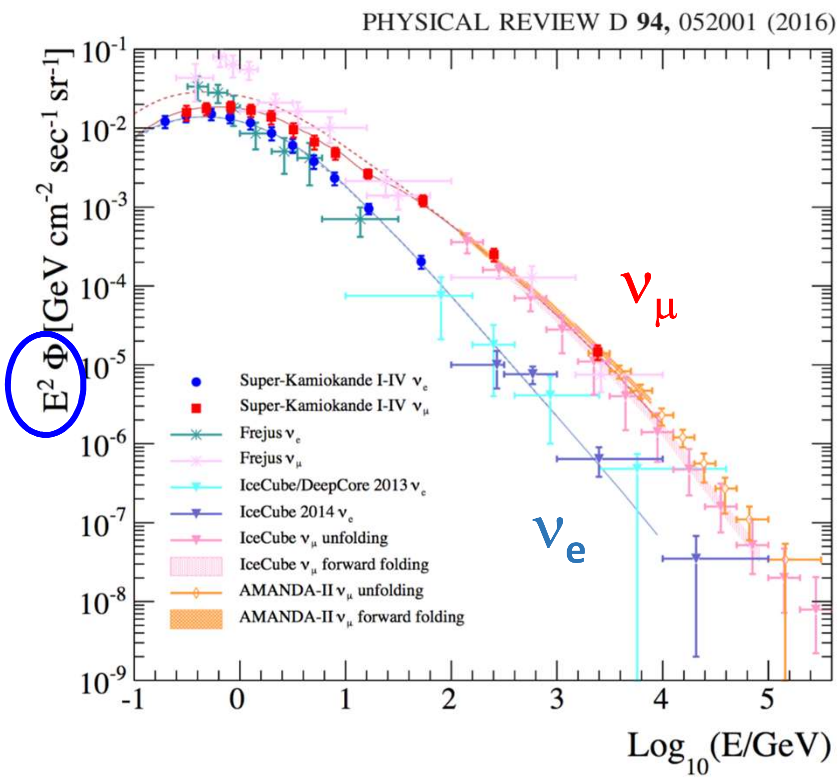
Earth's rotation provides
different baselines

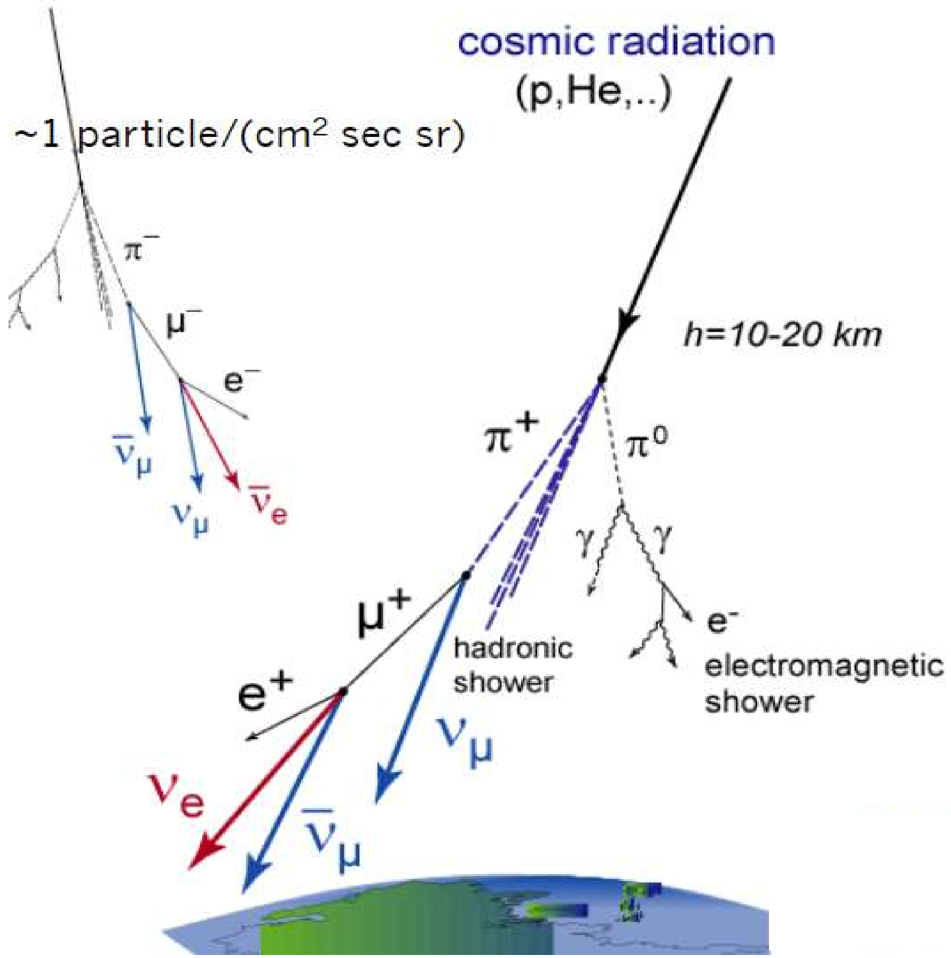
Uncontrolled source,
low fluxes

✓ **Atmospheric neutrinos !**

Atmospheric neutrinos

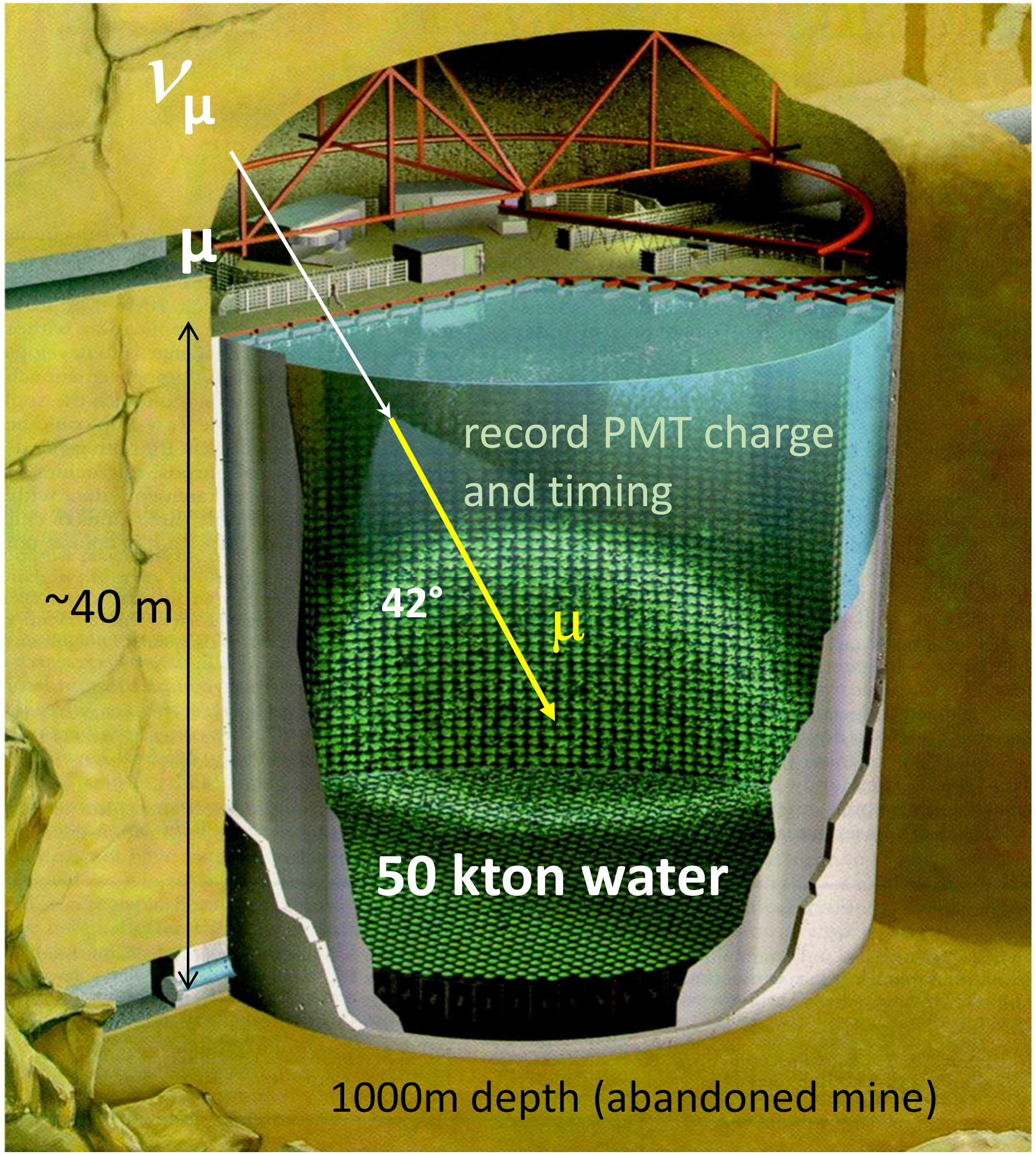
- (almost) isotropic flux
- known flavour composition (ν_e, ν_μ + antiparticles)
- Wide range of energies (GeV → PeV)
- steeply falling power-law spectrum:

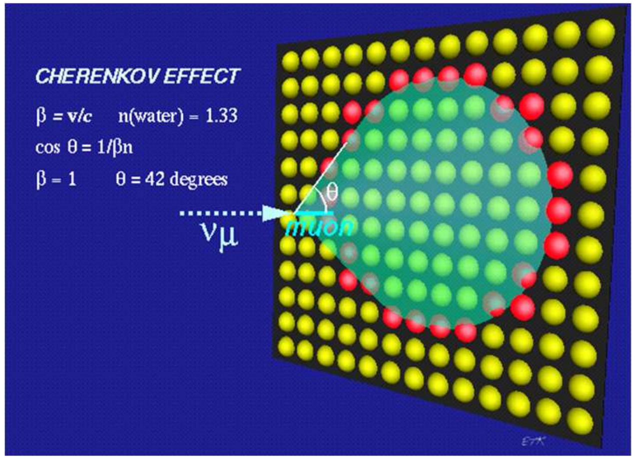




Atmospheric neutrino detectors: SuperKamiokande

Water-Cherenkov detector:

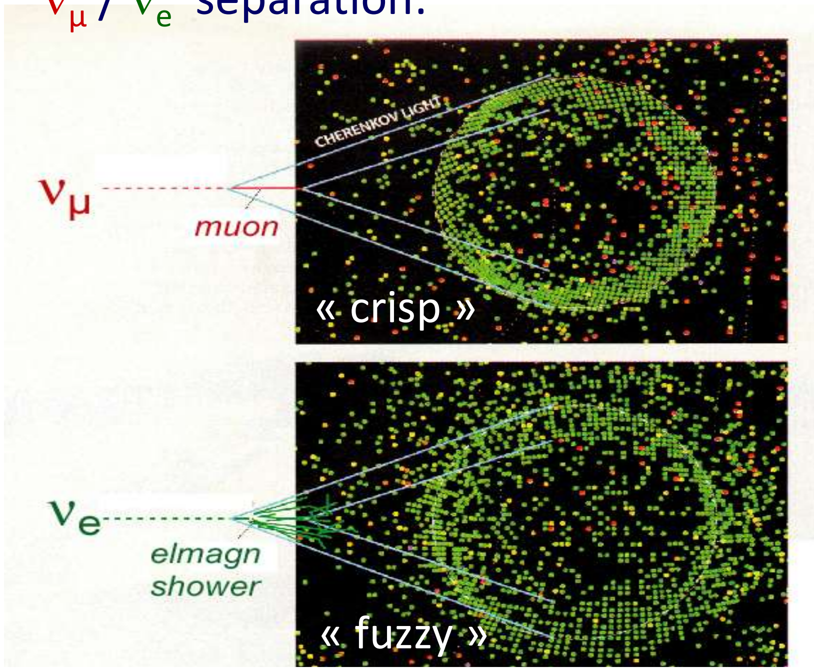




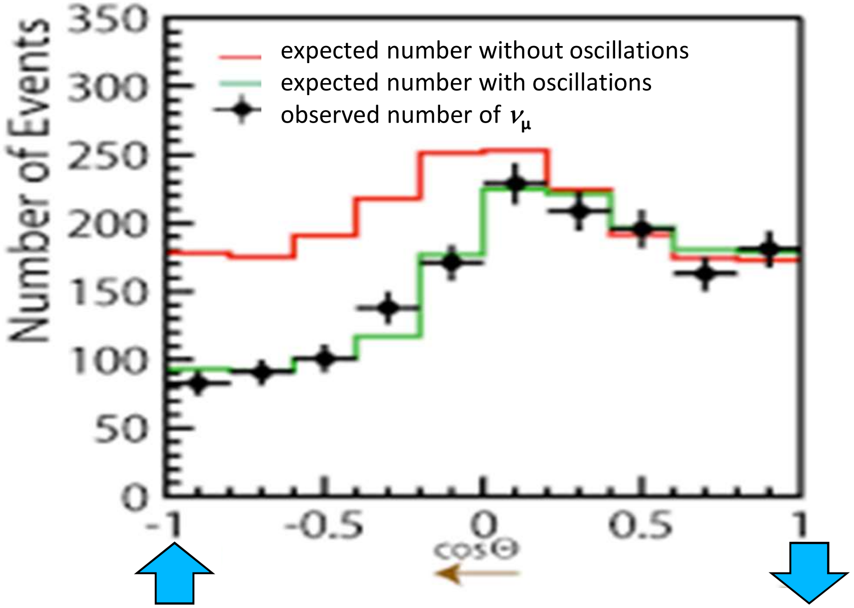
~3800 atmospheric neutrinos/year

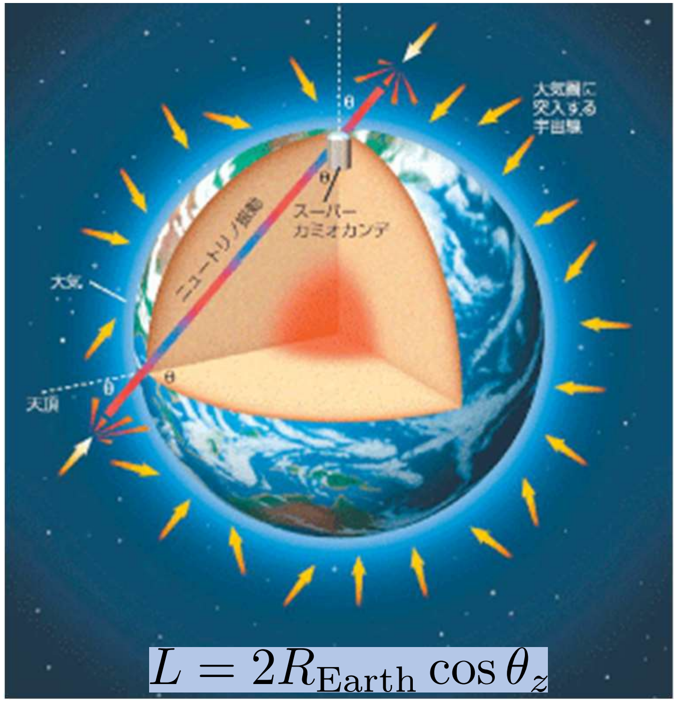
Position & angular reconstruction

ν_μ / ν_e separation:



Atmospheric neutrino detectors: SuperKamiokande

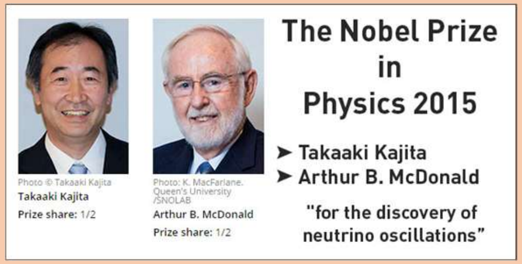




Up-going:
Baseline ~13 000 km

Down-going:
Baseline ~20 km

1998: discovery of neutrino oscillations



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{PMNS} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U_{PMNS} mixing matrix
3 angles (θ_{12}, θ_{23}, θ_{13})
+ 1 phase (δ)

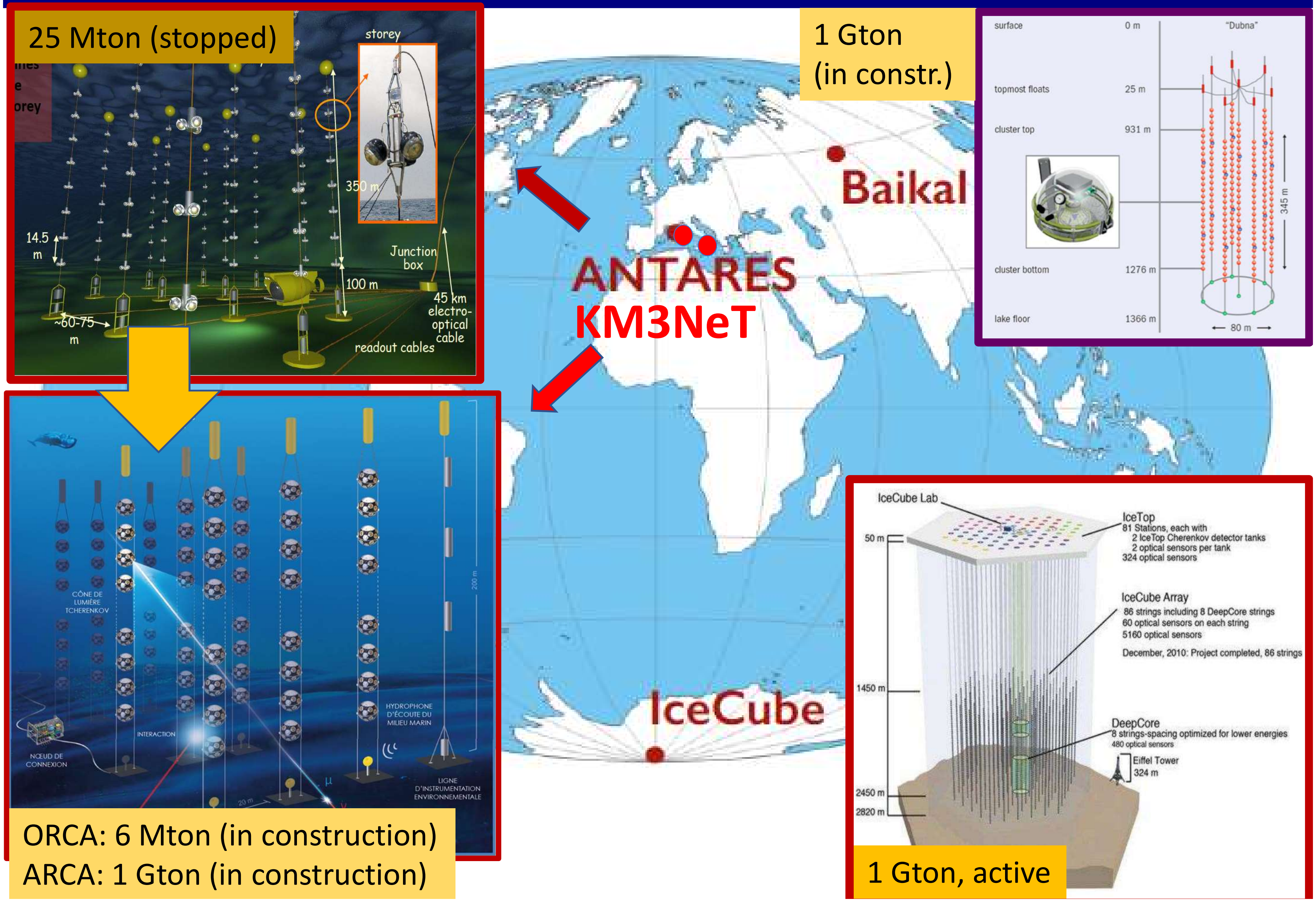
Δm^2_{12}

Δm^2_{23}

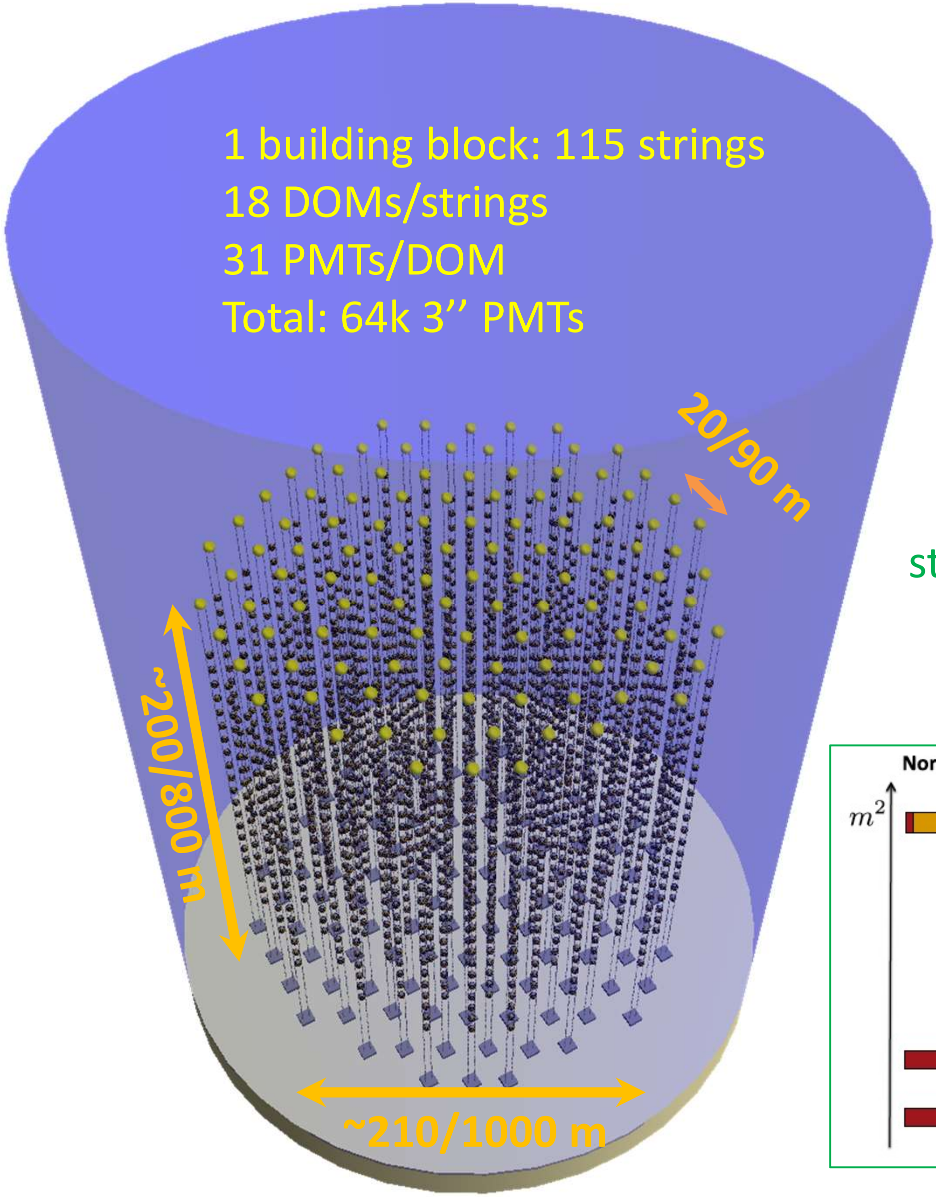
Flavour eigenstates

Mass eigenstates

Neutrino telescopes



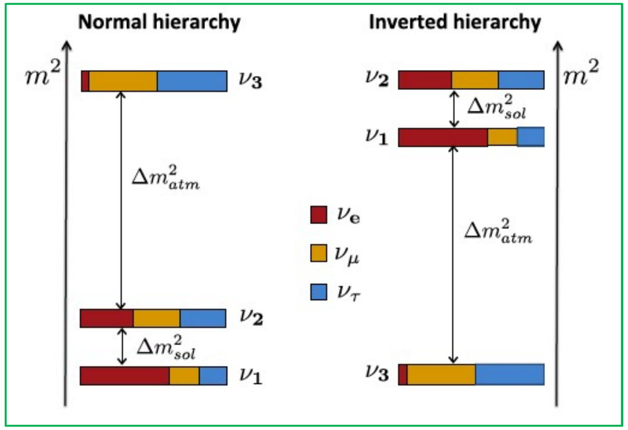
KM3NeT layout: ARCA vs ORCA



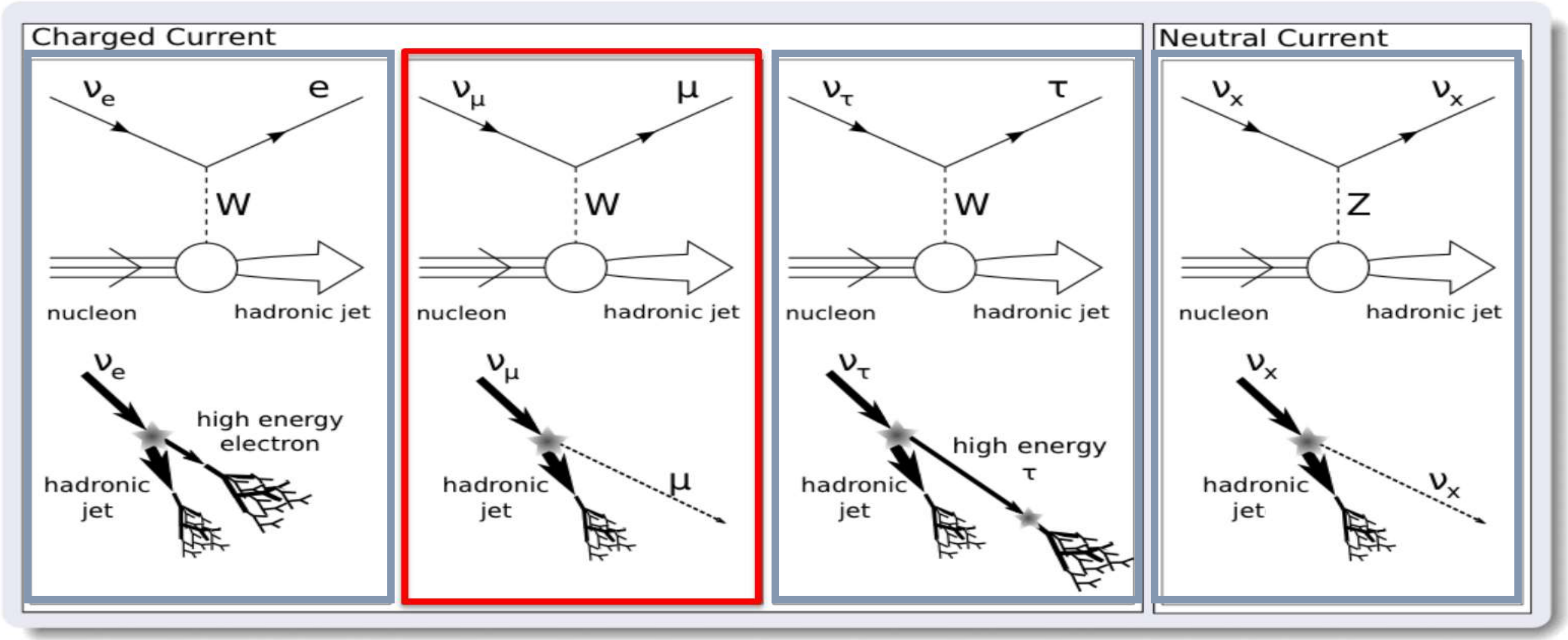
	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	~ 7 Mton	~ 2 × 0,5 Gton

ORCA:
optimised for
neutrino oscillation
studies & mass hierarchy
measurement
1 → 100 GeV energy

ARCA:
optimised for HE
neutrino astronomy
TeV → PeV energy



Neutrino telescopes: event topologies



credit: J. Tiffenberg, NUSKY11

TRACKS:

- Only for ν_μ – induced muons
- Good angular resolution
- interaction vertex can be outside of the detector:

→ increased effective volume

…but poor energy resolution

SHOWERS (or CASCADES):

- Sensitive to ν_e, ν_τ flavours

+ all-flavours NC interactions

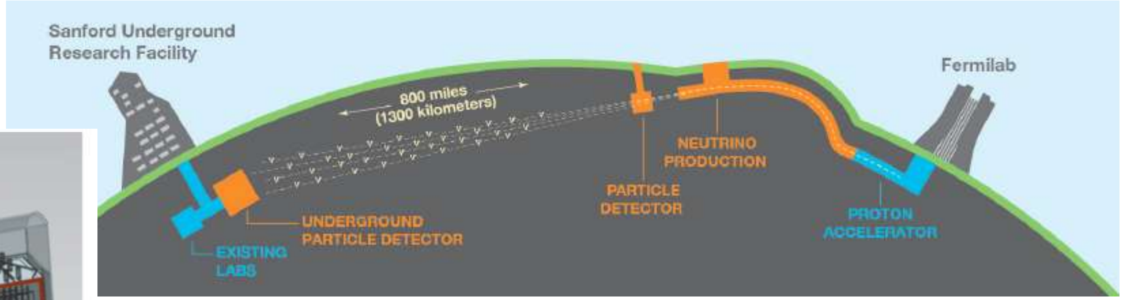
- Mostly contained events, quasi-spherical topology

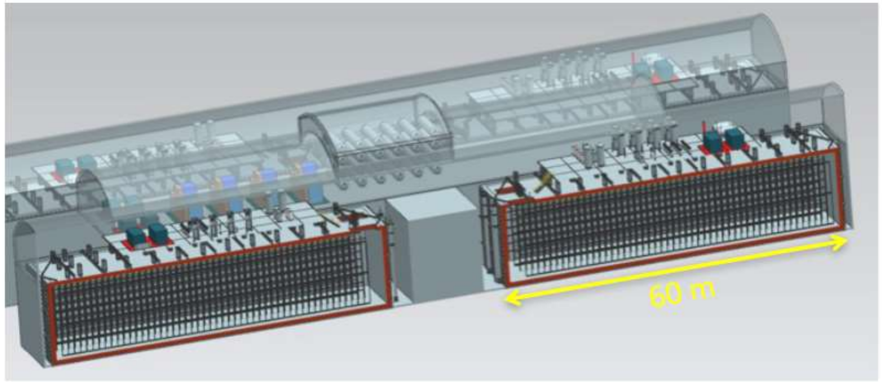
→ Limited angular resolution

→ Good energy resolution

DUNE also sees atmospheric neutrinos!

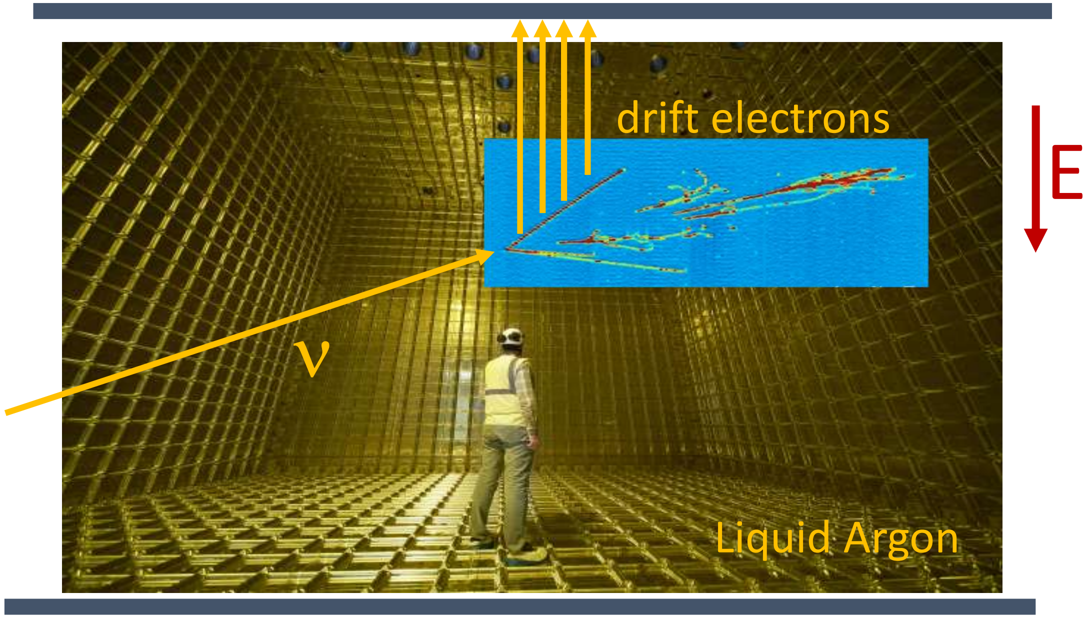
Future neutrino beam experiment
Fermilab → Sanford





- Towards the largest LAr TPCs in existence (4 x 17 kT modules)

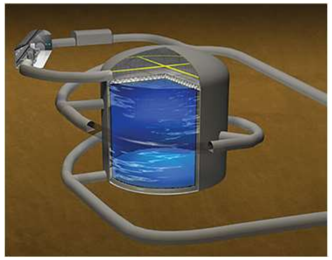
Liquid Argon Time Projection Chambers:
ionization of liquid Argon by charged secondary particles from neutrino interactions



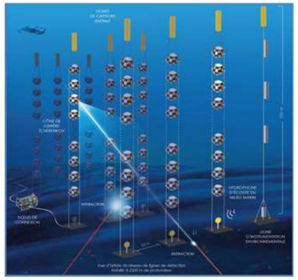
Detection of drift electrons
→ reconstruction of neutrino energy, flavor,direction

Precise reconstruction of events:
High resolution in energy, angle
Low threshold (~0.1 GeV)

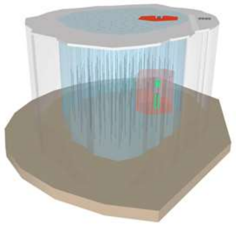
Earth tomography with atmospheric neutrinos



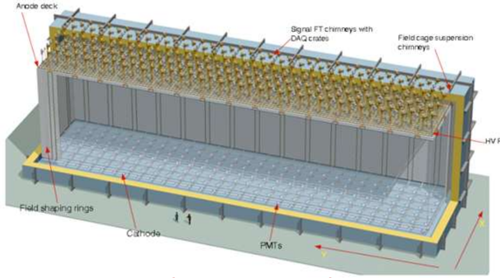
SuperKamiokande (50 kton)
HyperKamiokande (260 kton)



KM3NeT/ORCA
(7 Mton)



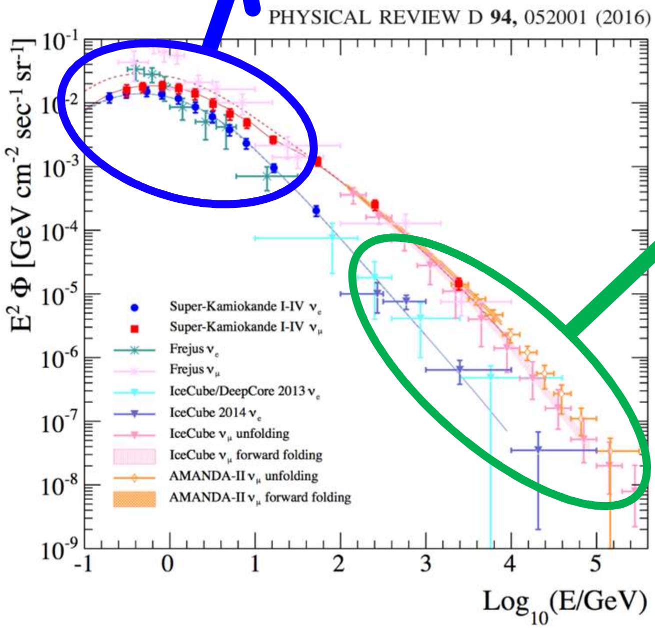
PINGU (IceCube)
(1-5 Mton)



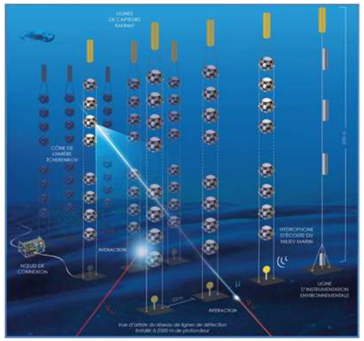
DUNE (40 kton)

active
in construction
proposed/prototyping

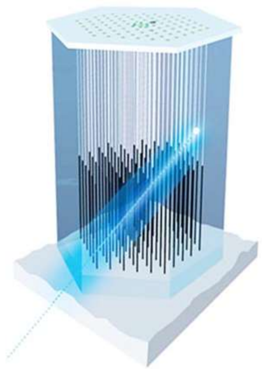
At low (GeV) energies:
Neutrino oscillation tomography
(sub- or multi-)Megaton-scale detectors



At high (TeV-PeV) energies:
Neutrino absorption tomography
~ Gigaton-scale detectors



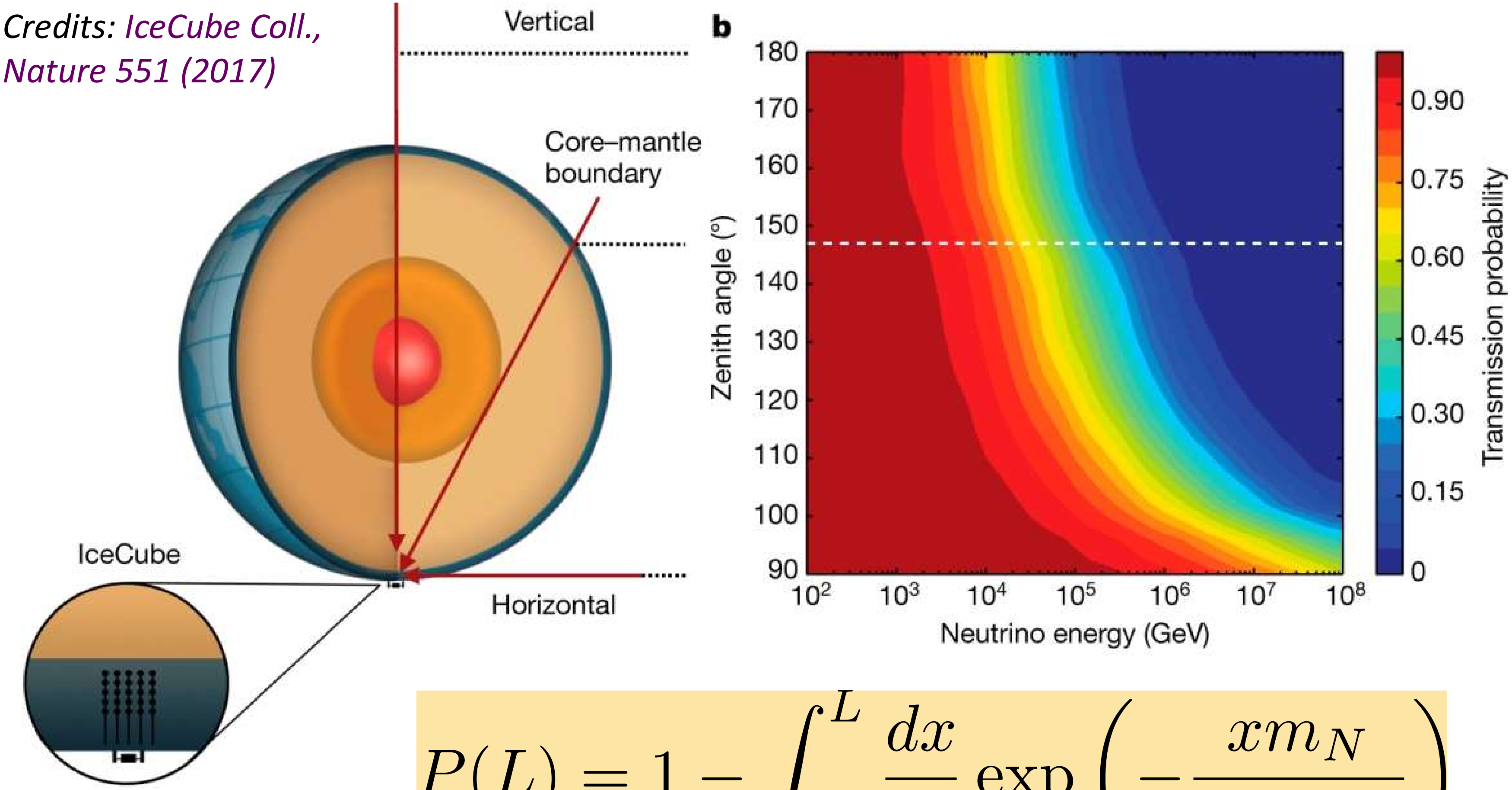
KM3NeT/ARCA (1 Gton)



IceCube/Gen2 (1+ Gton)

At high energies: absorption tomography

Credits: IceCube Coll., Nature 551 (2017)

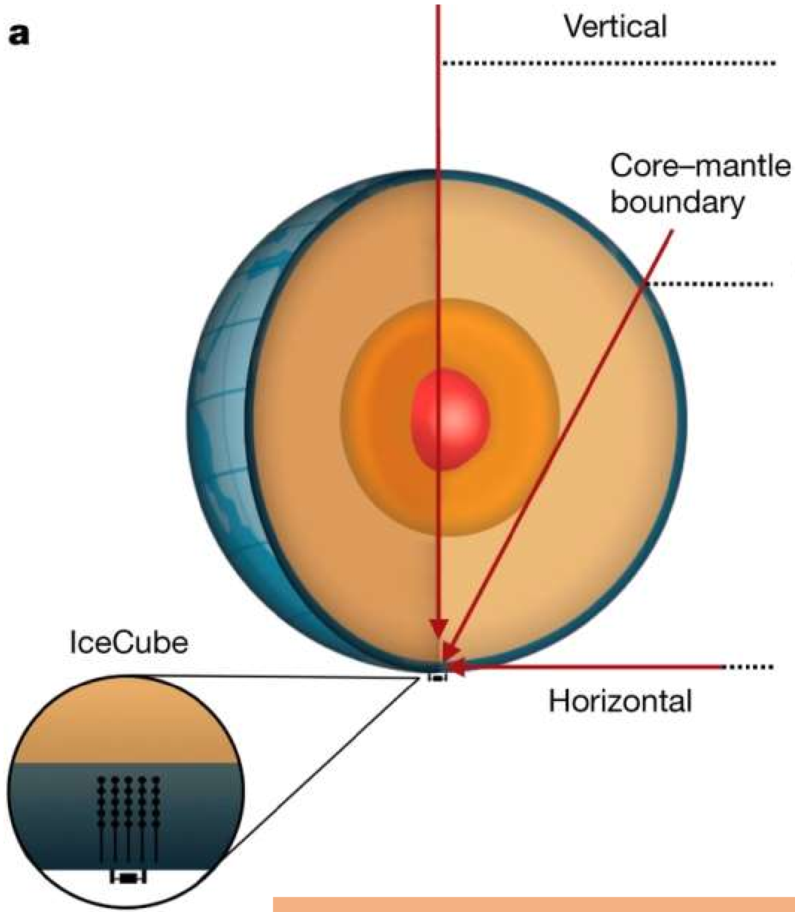


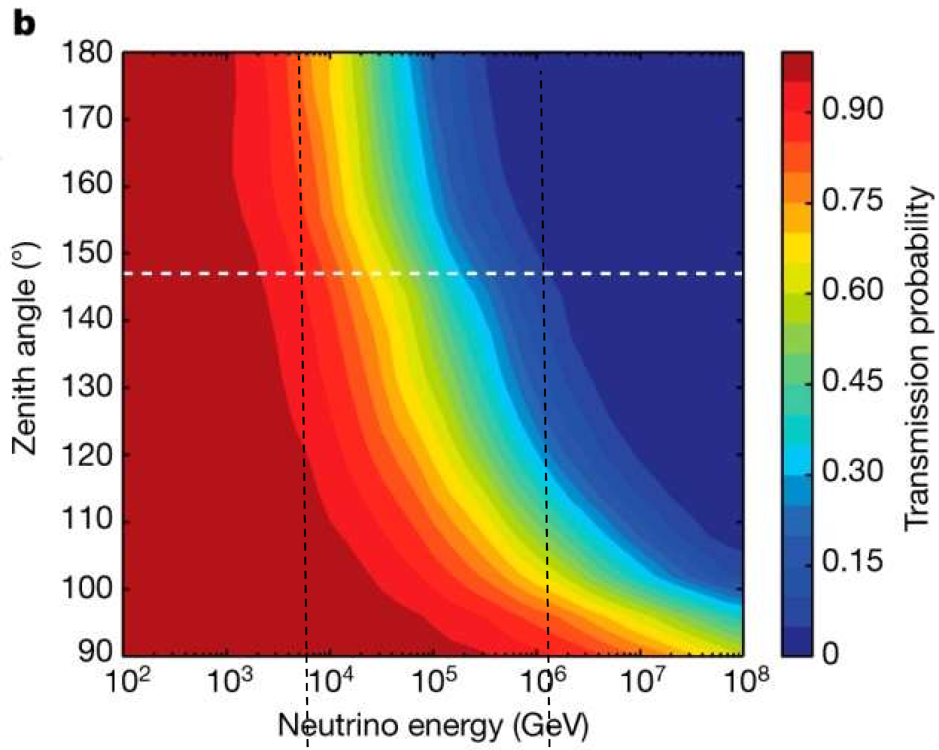
$$P(L) = 1 - \int_0^L \frac{dx}{L} \exp\left(-\frac{x m_N}{\sigma_{\nu N}\, \rho_m}\right)$$

The neutrino transmission probability depends on the amount of matter traversed, hence on the neutrino baseline

Absorption tomography is directly sensitive to Earth matter density ρ_m

At high energies: absorption tomography





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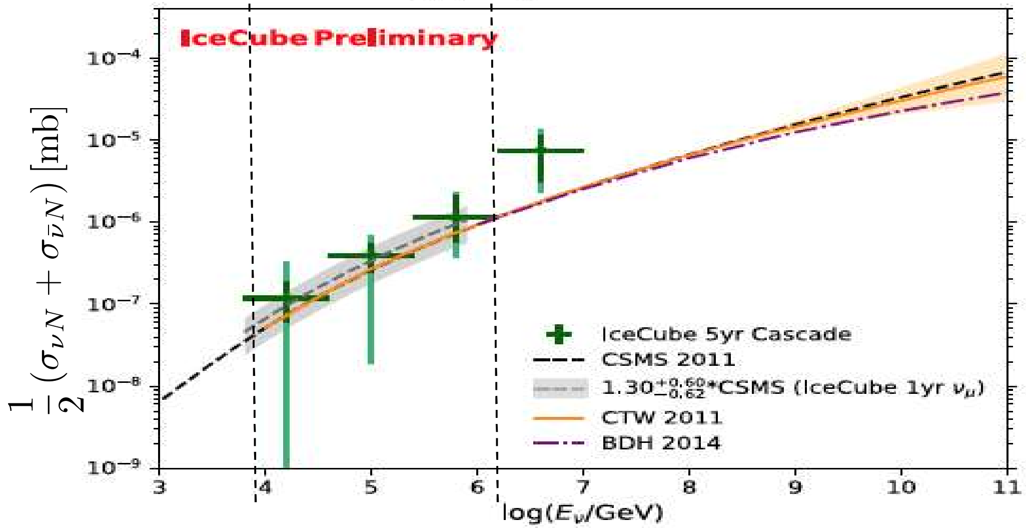
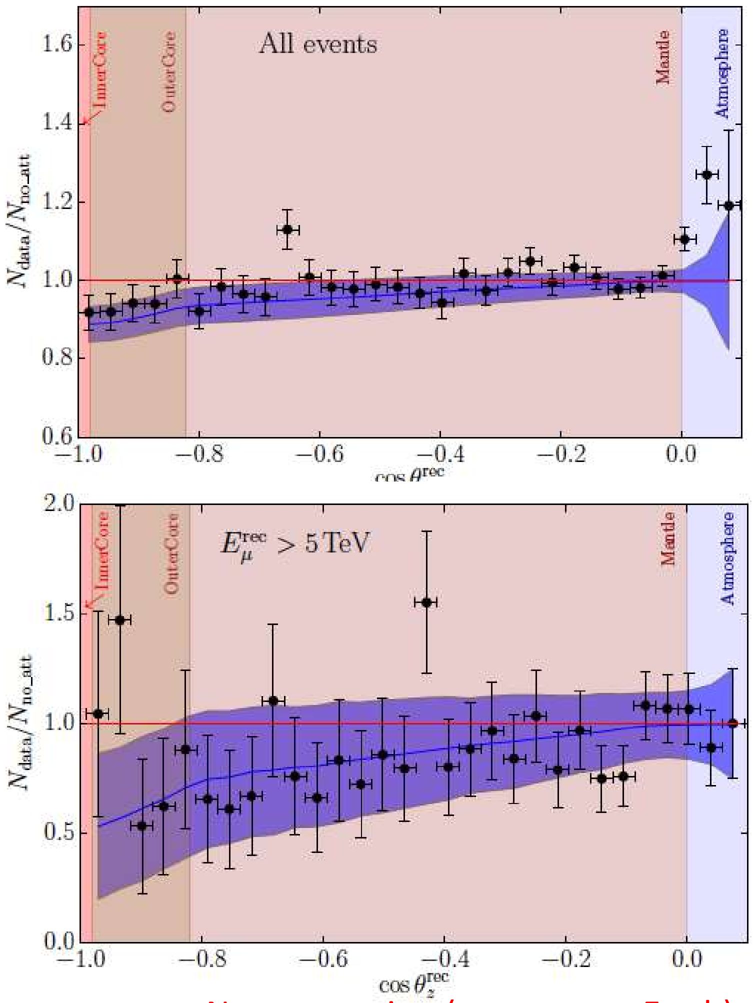


driven by the increase
of neutrino-nucleon
cross-section
at high energies

IceCube Coll., Nature 551 (2017)
& arXiv:1809.06782v1

At high energies: absorption tomography



No attenuation (transparent Earth)

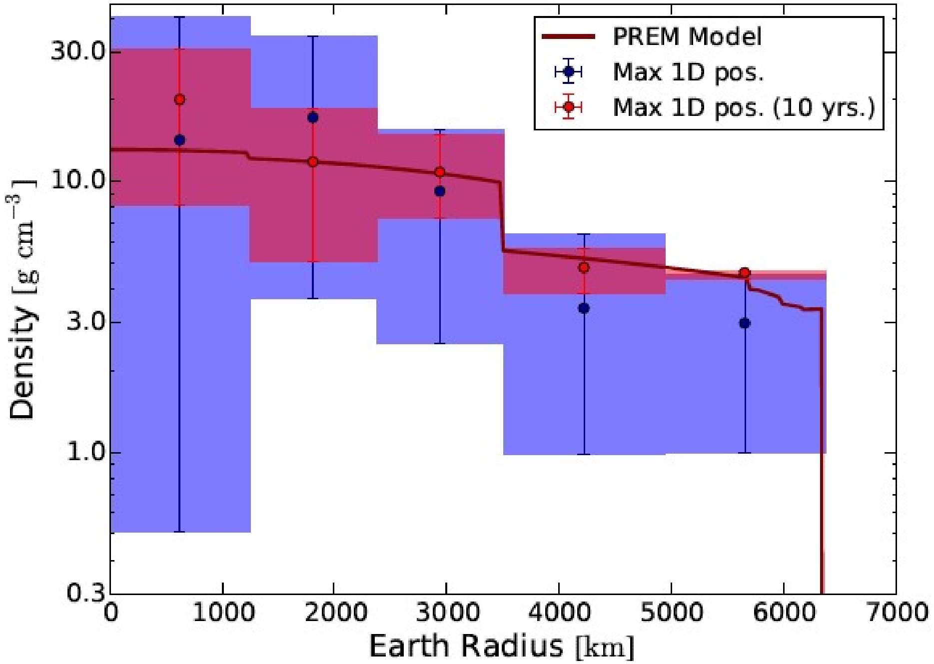
PREM expectation

2018: first study with real IceCube data

1 yr sample (2011-2012) – upgoing ν_μ

Radial model with 5 layers of constant density

A. Donini et al., *Nature Phys.* 15 (2019) 1, 37-40



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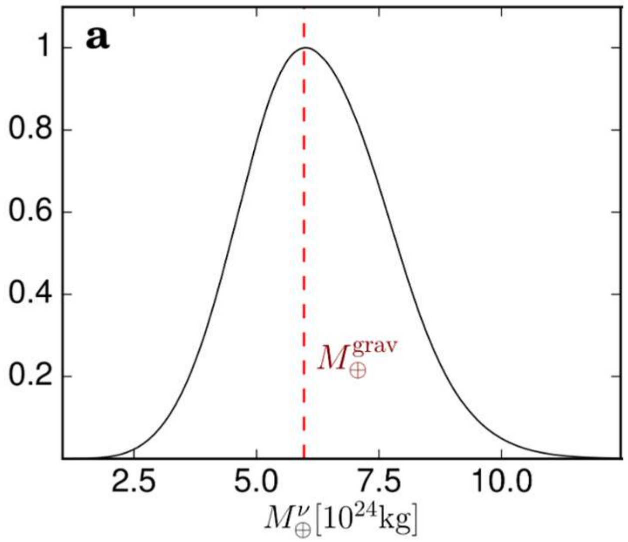
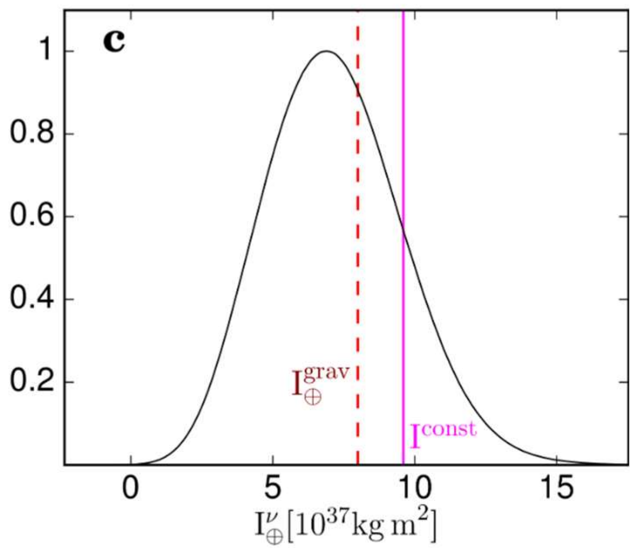


Earth mass



Earth moment of inertia

2018: first study with real IceCube data

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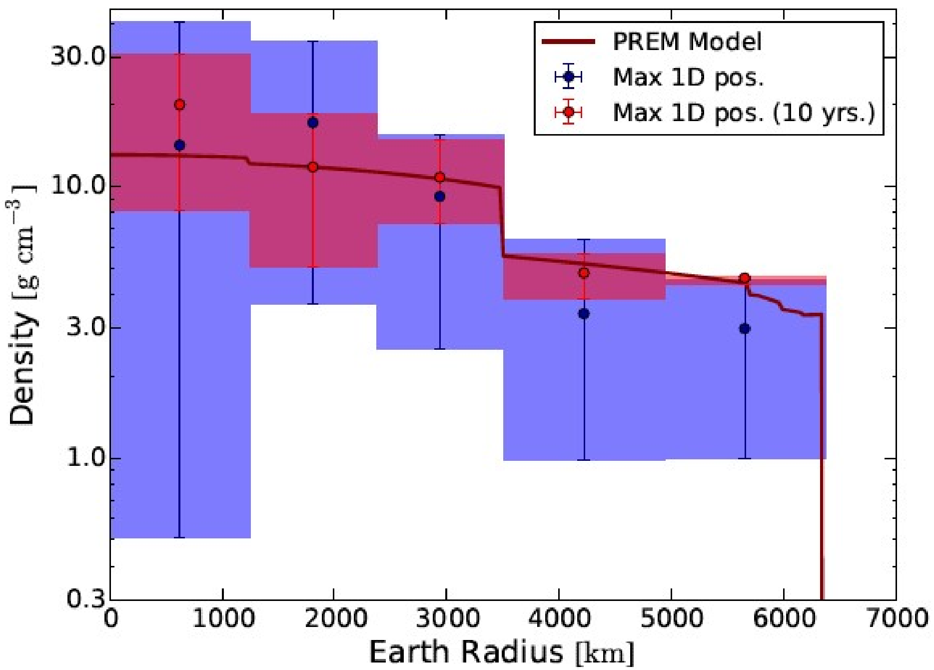
A. Donini et al., *Nature Phys.* 15 (2019) 1, 37-40



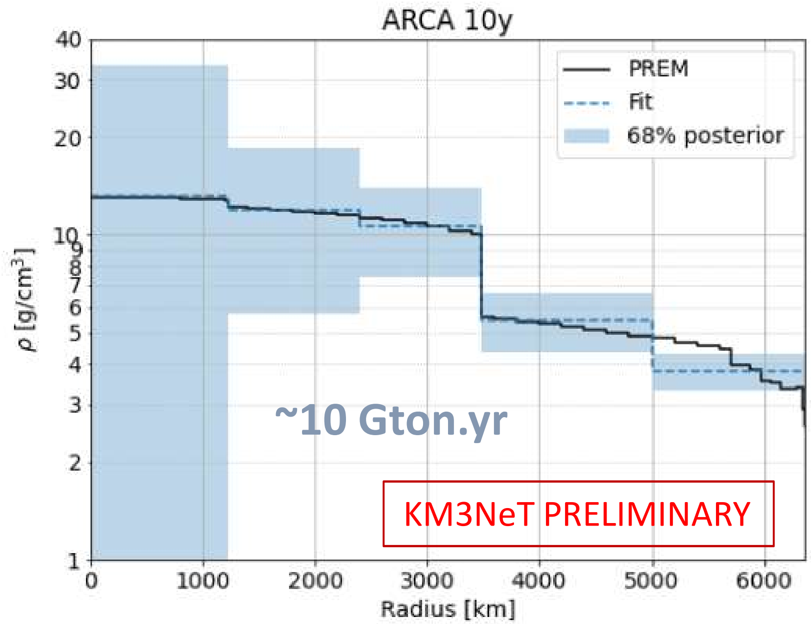
Global quantities inferred from neutrino data are in agreement with gravimetric measurements (but large uncertainties!)

At high energies: absorption tomography

Similar projections for ARCA

(preliminary study:

- no NC regeneration included
- only atmospheric flux
- no systematics
- Low MC statistics)



L. Maderer et al. [KM3NeT Coll.], *PoS(ICRC 2021) 1172*

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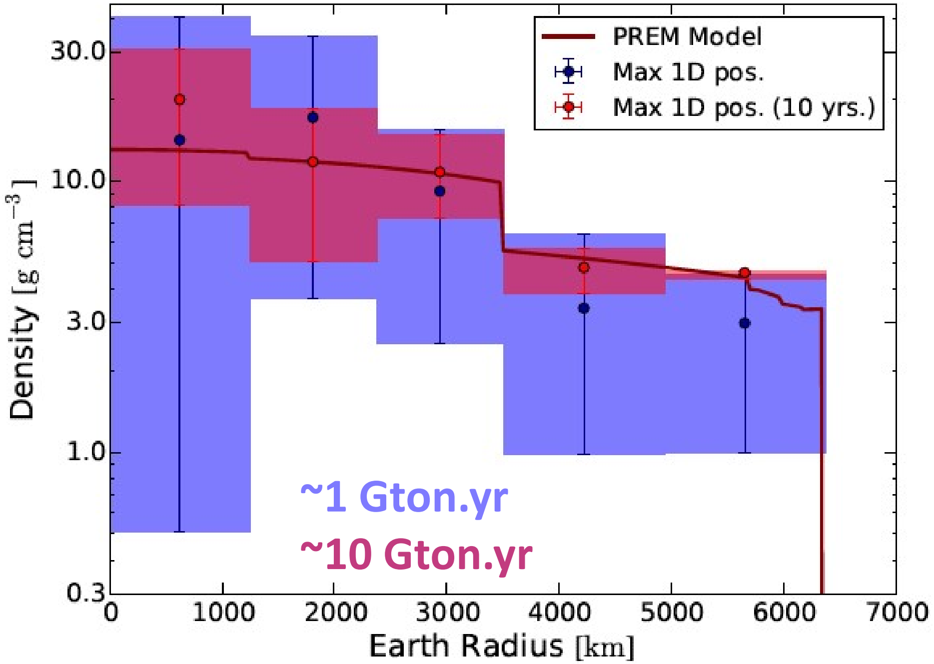
A. Donini et al., *Nature Phys.* 15 (2019) 1, 37-40

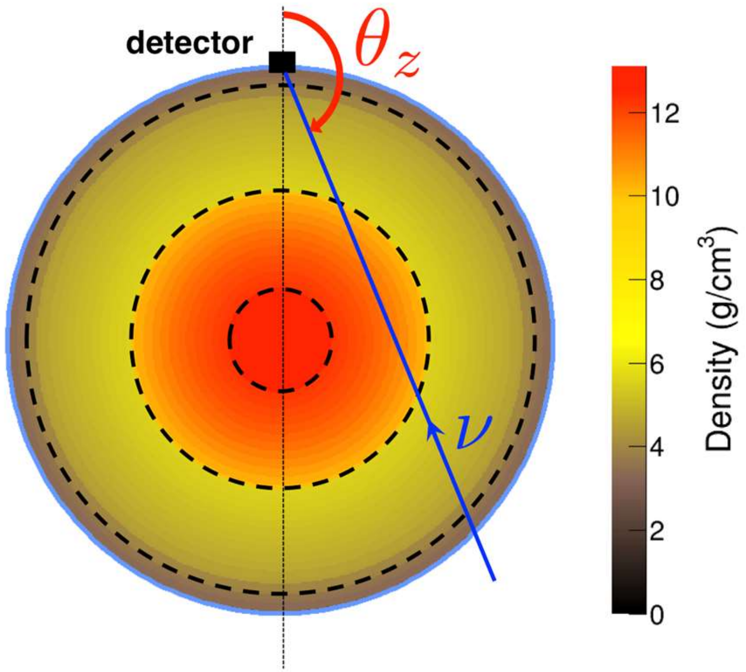


→ (much) more statistics needed to reach < few % uncertainty level

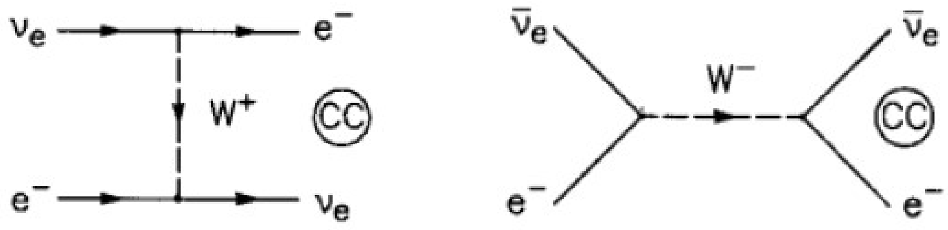
→ main systematics: neutrino flux & cross-section, detector effects

At low energies: oscillation tomography

Neutrino oscillations are affected by the presence of matter:



ordinary matter contains e's but no μ's or τ's
→ extra interaction channels for ν_e / $\bar{\nu}_e$



→ extra potential in propagation Hamiltonian,
proportional to electron density in medium

$$A \equiv \pm\sqrt{2} G_F N_e$$

→ Resonance energy for enhanced neutrino oscillations due to matter effects:

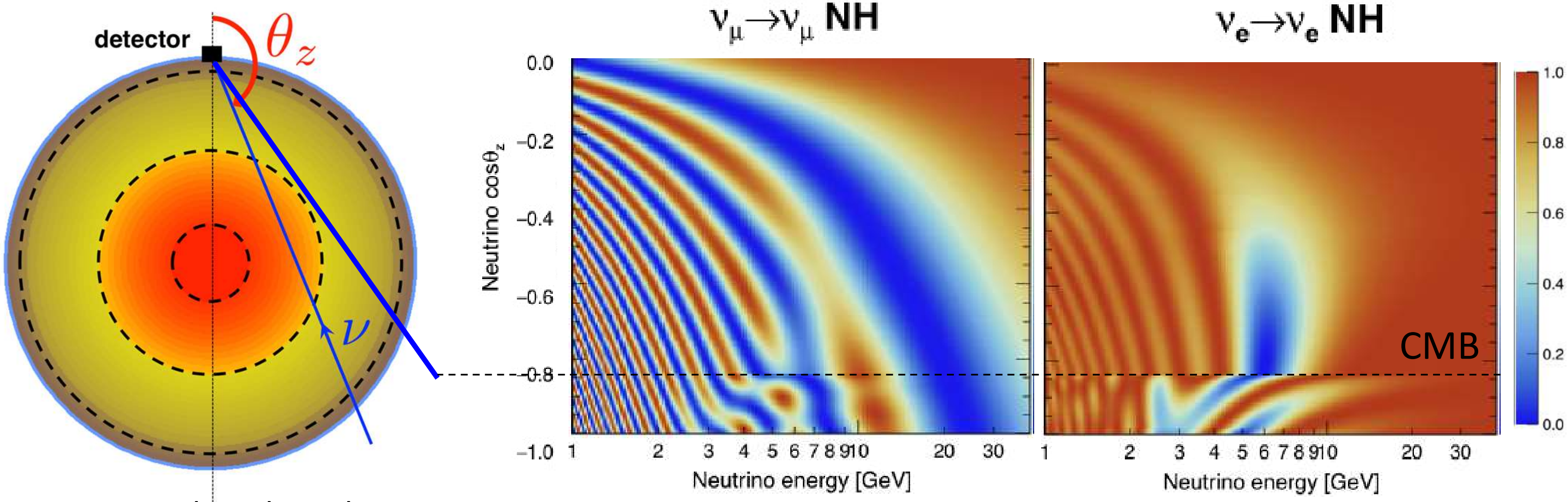
$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\,\cos 2\theta_{13}}{2\sqrt{2}\,G_F\,N_e} \simeq 7\,{\rm GeV}\left(\frac{4.5\,{\rm g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times10^{-3}\,{\rm eV^2}}\right)\cos 2\theta_{13}$$

≅ 3 GeV (core)
≅ 7 GeV (mantle)

for neutrinos if $\Delta m^2_{13} > 0$ / antineutrinos if $\Delta m^2_{13} < 0$
→ **depends on the neutrino mass hierarchy** – not yet measured…

At low energies: oscillation tomography

Oscillation (survival) probabilities for ν_e and ν_μ crossing the Earth:



PREM + benchmark composition

At low energies: oscillation tomography

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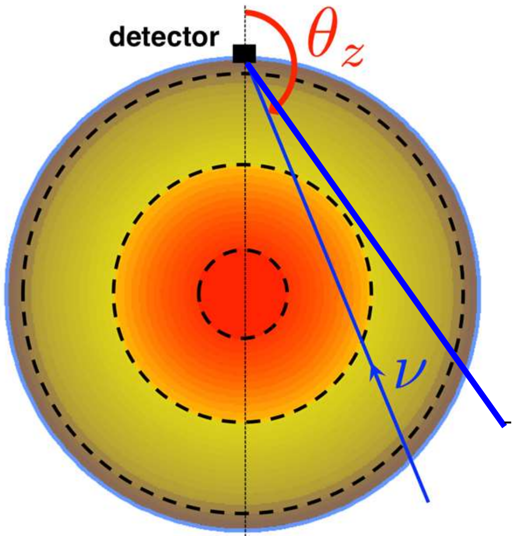
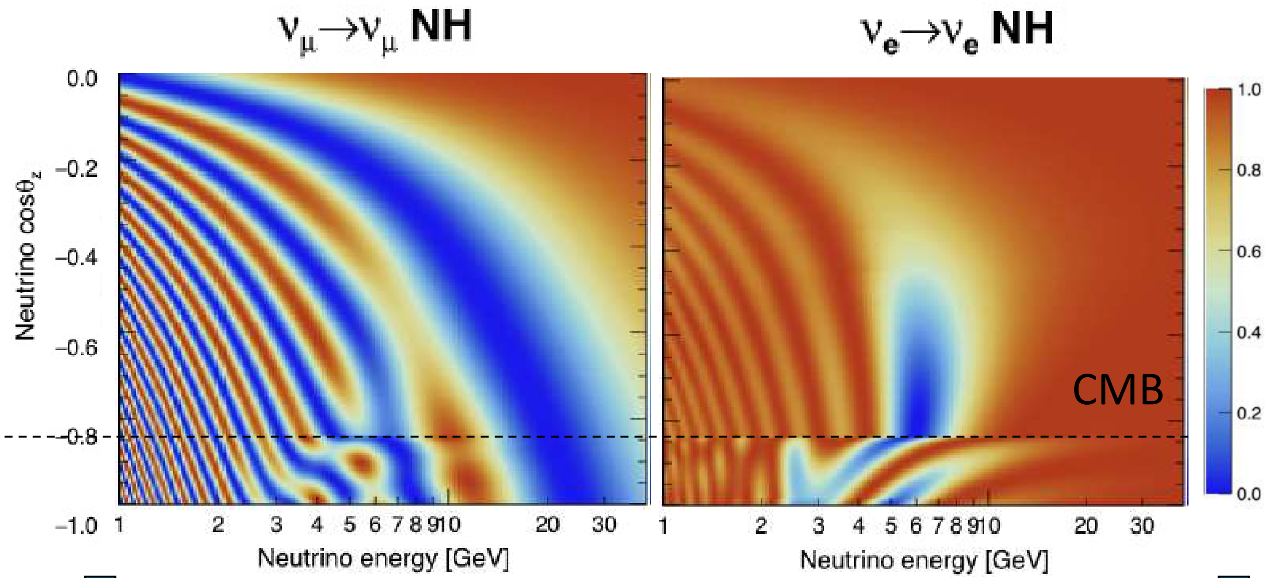
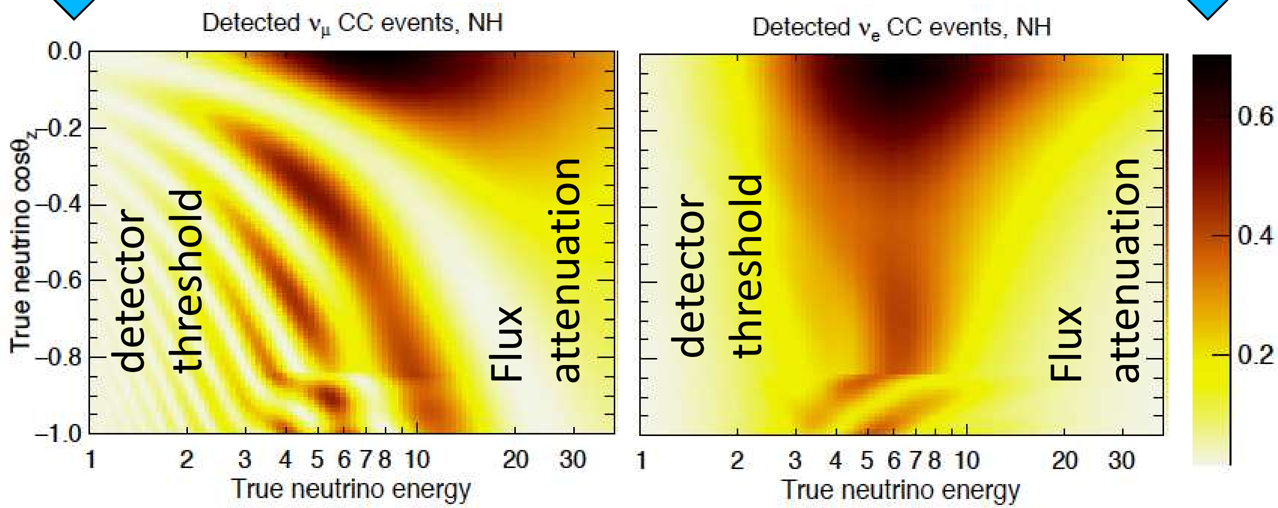


PREM + benchmark composition



$$\times \Phi_{\nu_X}(E,\theta) \times \sigma_{\nu N}(E) \times M^{eff}_{\nu_X}(E,\theta) \times t$$

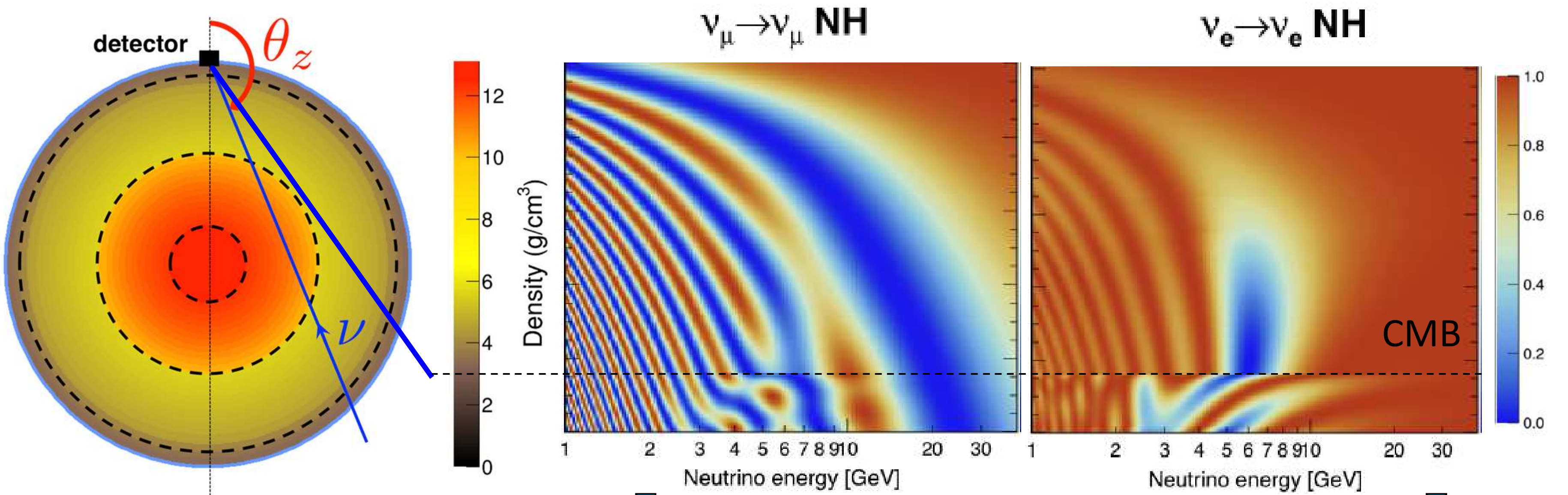


→infer the electron density by measuring the ν_e / ν_μ event rates at the detector

(here:
1 Mton yr exposure)

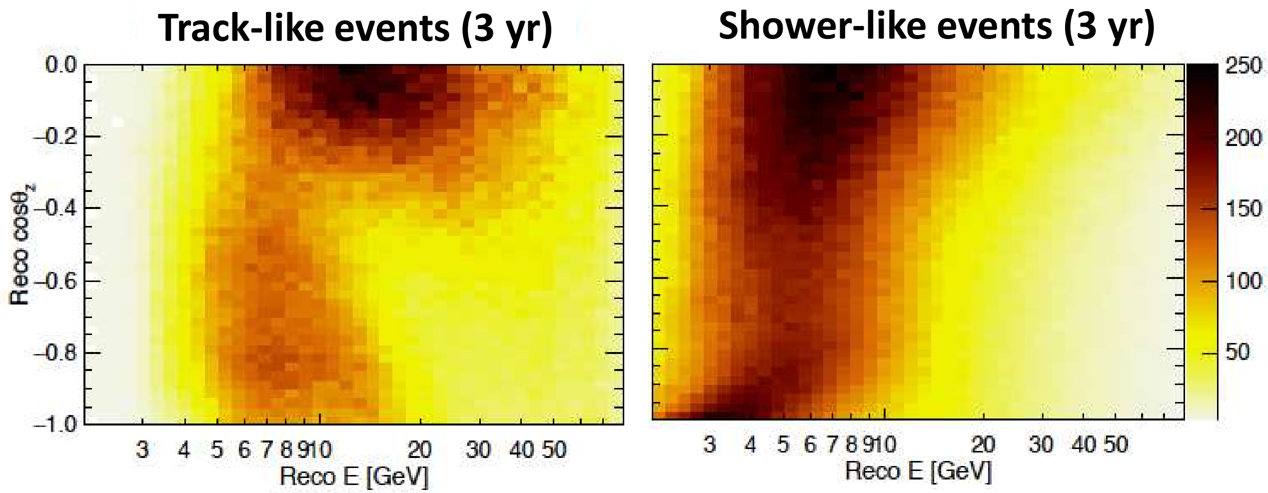
At low energies: oscillation tomography

Oscillation (survival) probabilities for ν_e and ν_μ crossing the Earth



PREM + benchmark composition

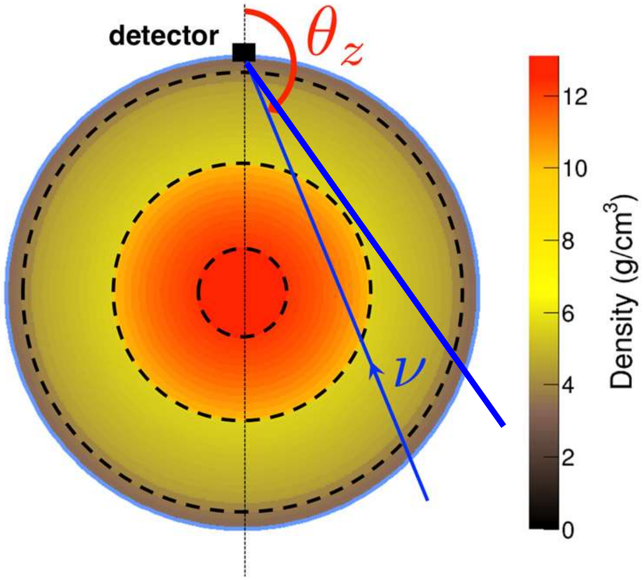
All detector effects included



CHALLENGE:
Achieve sufficient Reconstruction/ID performances in the detector !!

(here: ORCA 3 years)

Constraining the deep Earth composition ?

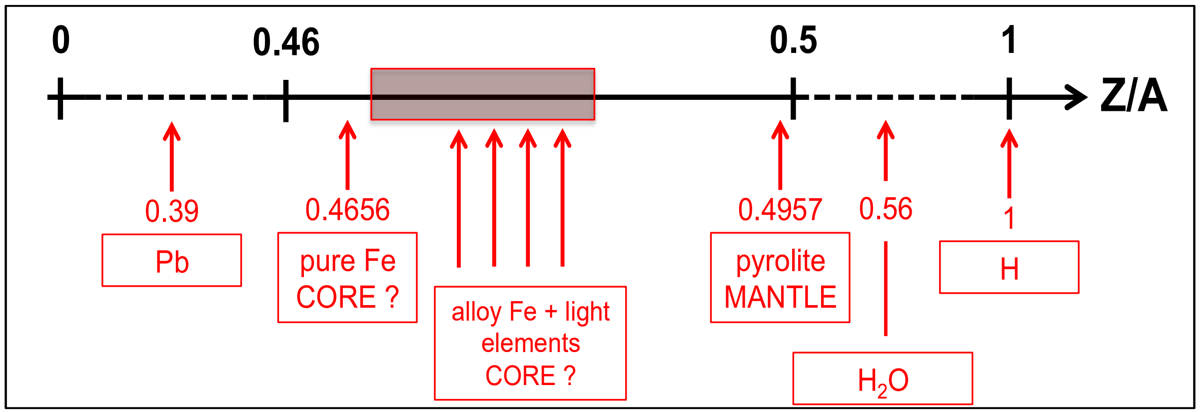


Measured in neutrino oscillation patterns

$$N_e = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{matter}$$

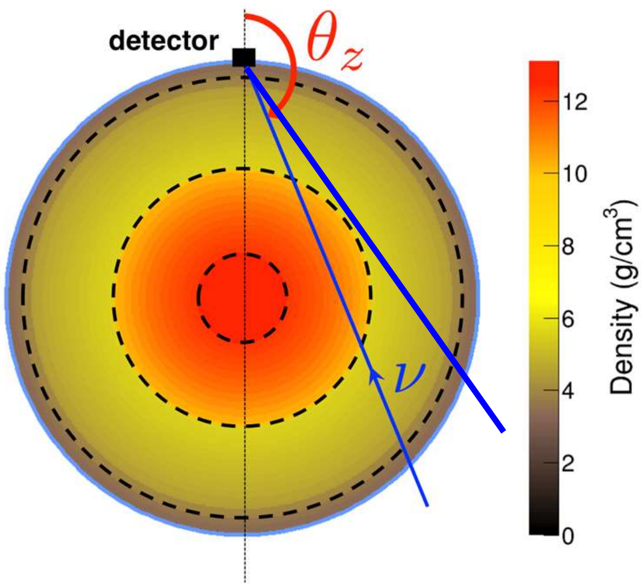
probes composition

probes matter density



Typical values of Z/A for chemical elements or alloys present in the Earth

Constraining the deep Earth composition ?



Measured in neutrino oscillation patterns

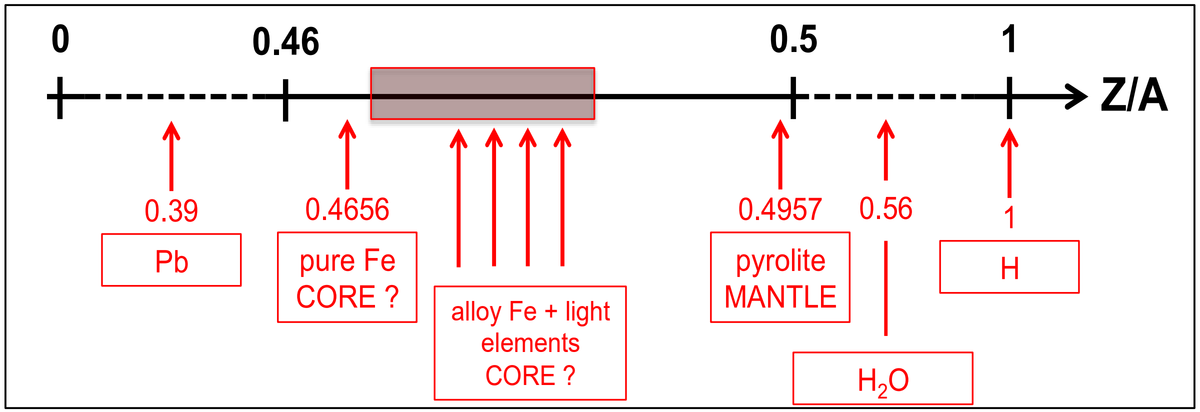
$$N_e = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{matter}$$

assume known matter density profile (PREM)

Constrain Z/A in core/mantle

Assuming known density profile, oscillation tomography is sensitive to Earth composition !

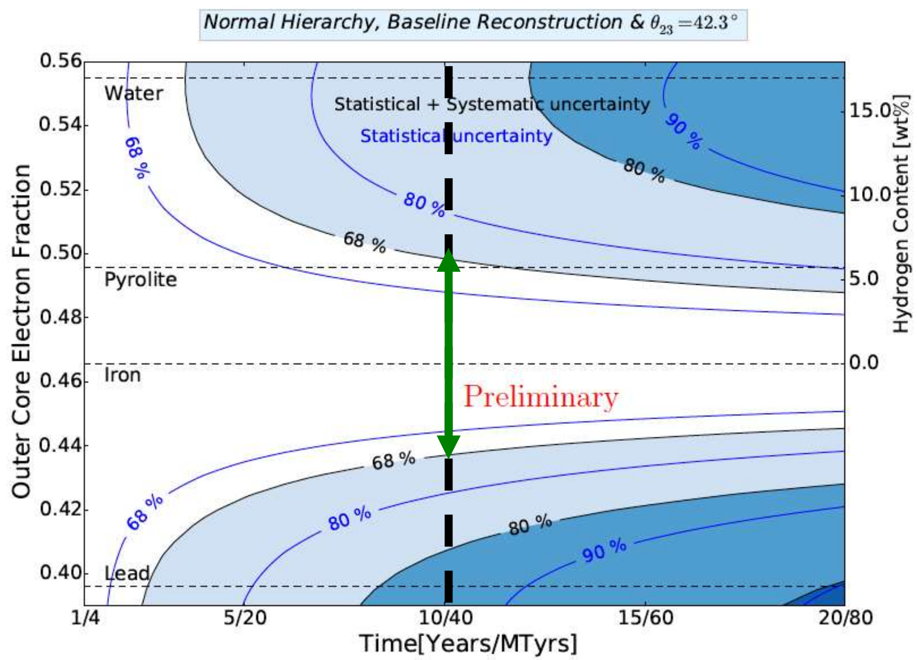
See also W. Winter, Nucl. Phys. B 908 (2016)



Typical values of Z/A for chemical elements or alloys present in the Earth

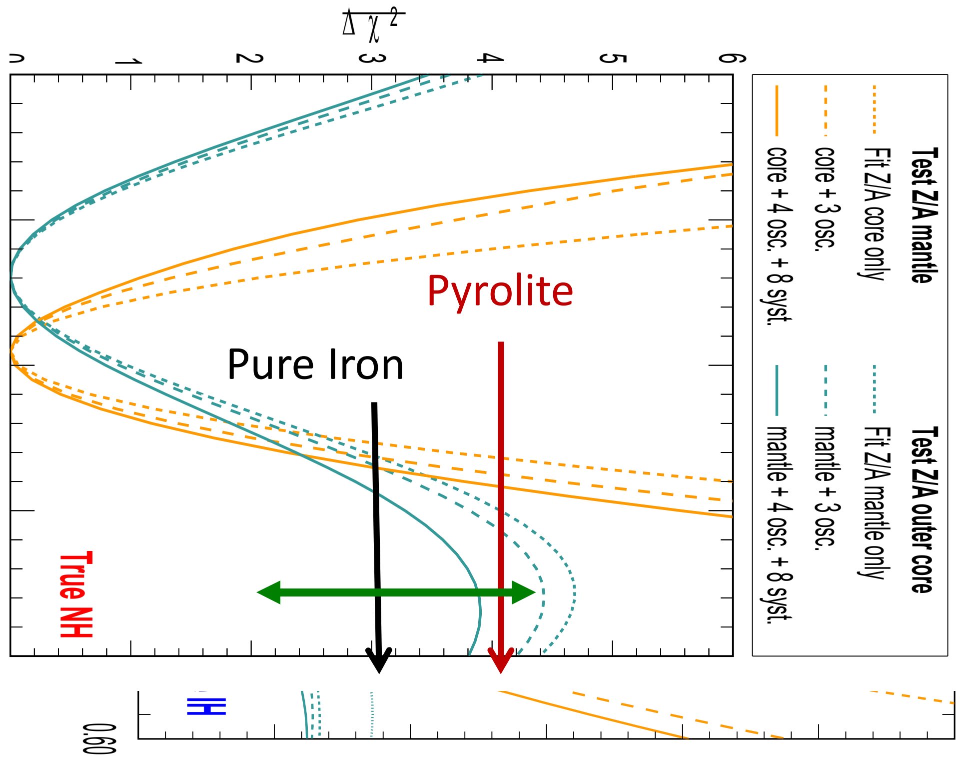
Constraining the deep Earth composition ?

PINGU outer core, normal neutrino hierarchy



PINGU LoI, arXiv:1401.2046

ORCA 10 years, normal neutrino hierarchy



Bourret et al.[KM3NeT Coll.], *EPJ Web Conf.* 207 (2019) 04008

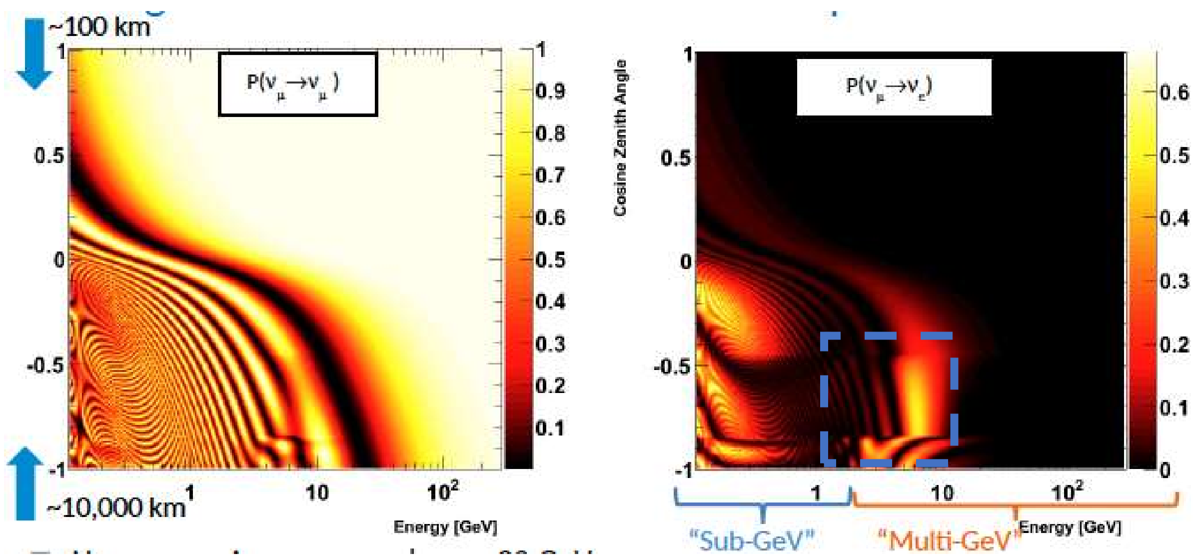
→ A few % sensitivity on Z/A in outer core and inner mantle within reach of the upcoming generation of Cherenkov detectors (10 years timescale)

Needs measurement of neutrino mass hierarchy first! (aka sign of Δm^2_{13})

Core composition with Hyperkamiokande

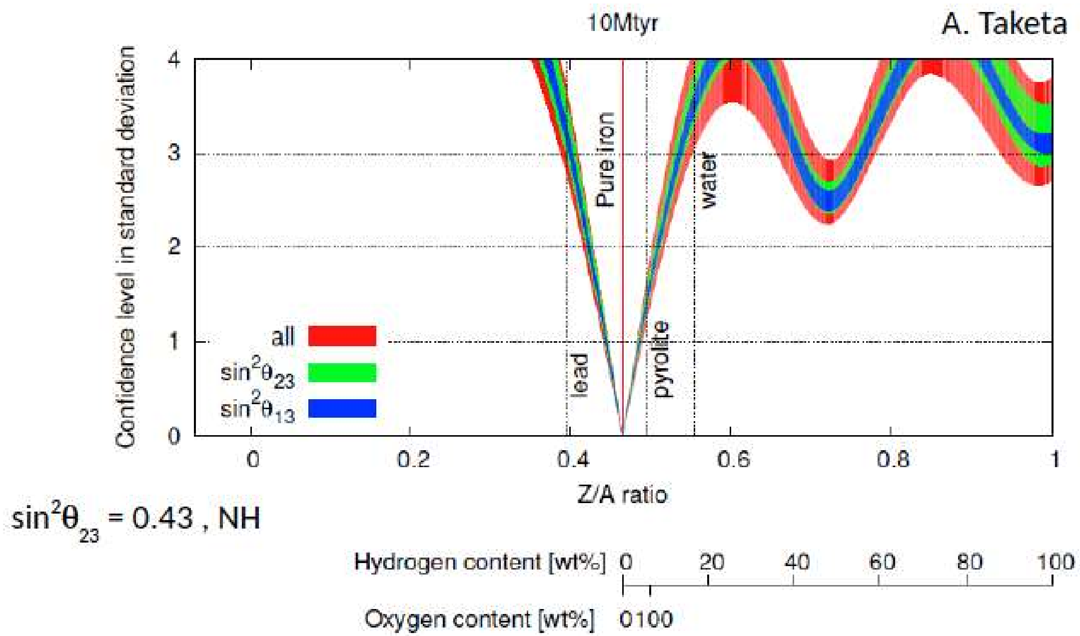
Resolution	Hyper-K
σ_{mom} e / μ	5.6% /3.6%
σ_{dir} e / μ	3.0° / 1.8°
Atmospheric	ν CC Purity
FC e-like	94.2 %
FC μ-like	95.7 %
PC μ-like	98.7 %
MIS PID	<1%, 1 GeV

Good reconstruction/ particle identification performances

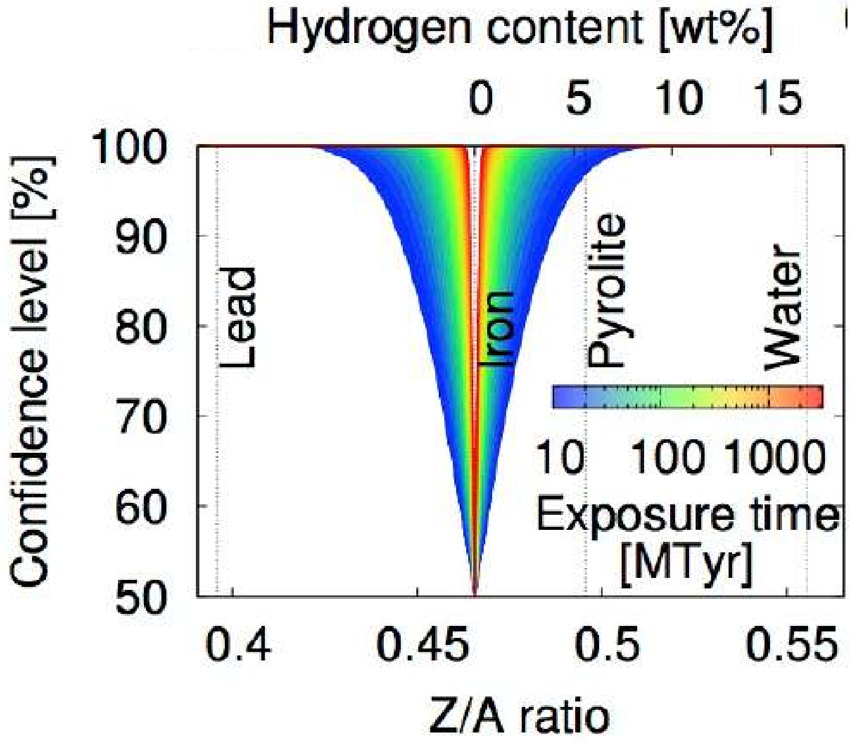


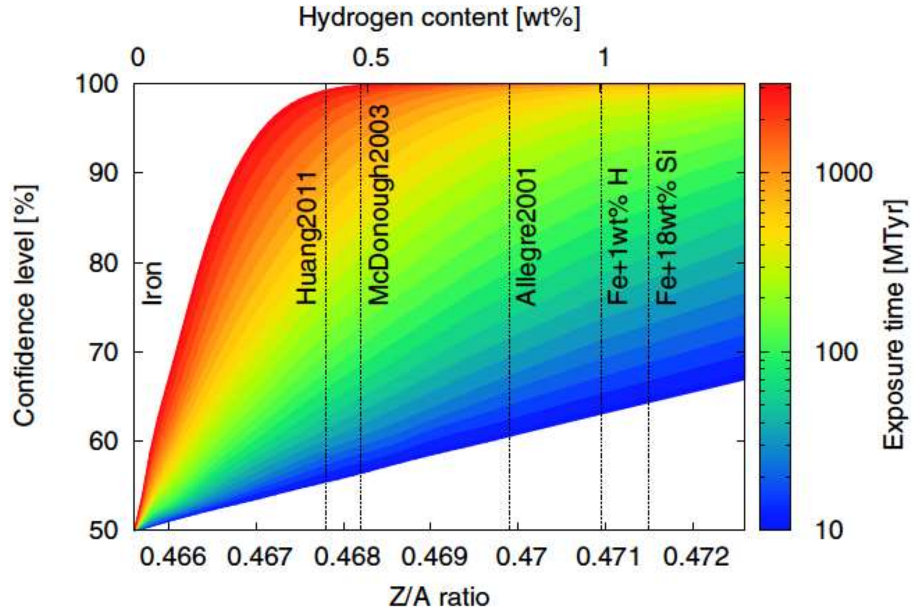
Preliminary study on outer core composition:
Normal hierarchy assumed
Most sensitivity from ν_e channel
Exclude extreme composition models after ~15 years ?

…need even bigger detectors ?



Core composition with "enhanced PINGU"





A few years of PINGU → ~30 Mton yr:

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

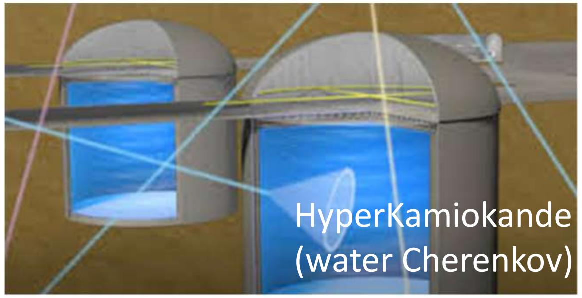
Rott, Taketa & Bose
Scientific Reports 5, 15225 (2015)

CAVEATS:
- Normal hierarchy assumed
- Optimistic resolutions below 5 GeV
- 100% detection efficiency down to 1 GeV
- Perfect PID (pure track channel)
- No systematics included

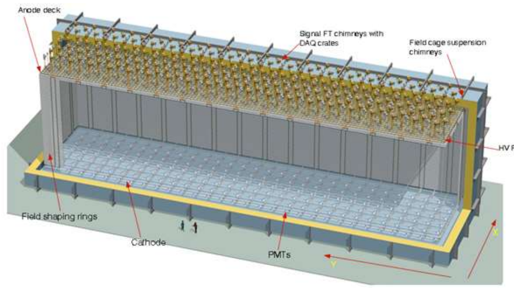
(atmospheric flux, oscillation parameters, neutrino cross-section,…)

Core composition: which neutrino detector ?

L. Maderer, J. Coelho, E. Kaminski, V. Van Elewyck, in preparation for J. Geophys. Res.



DUNE (liquid Argon)



BENCHMARK DETECTOR SPECIFICATIONS

Effective mass
Energy threshold
Track/shower (PID) identification

Energy resolution
Angular resolution

PERFORMANCE ON REALISTIC CORE COMPOSITION MODELS

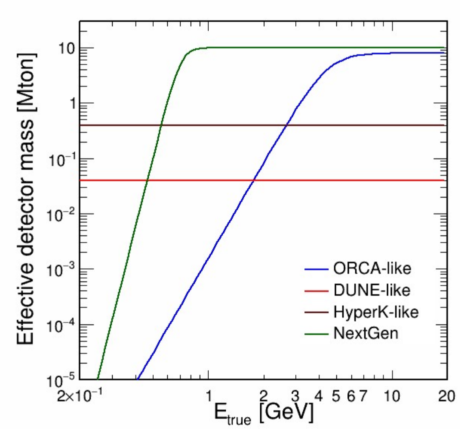
Model Label	FeNi	$FeNiSi_2O_4$	$FeNiSi_7O_2$	FeNiSiH	FeNiH
	-	Kaminski & Javoy[6]	Badro[5]	Tagawa[19]	Sakamaki[8]
Composition	95 wt% Fe	94 wt% Fe	91 wt% Fe	93.2 wt% Fe	94 wt% Fe
	5 wt% Ni	5 wt% Ni	5 wt% Ni	5 wt% Ni	5 wt% Ni
	-	2 wt% Si	7 wt% Si	6.5 wt% Si	1 wt% H
		4 wt% O	2 wt% O	0.3 wt% H	
Z/A	0.4661	0.4682	0.4691	0.4699	0.4714

small differences
in Z/A!

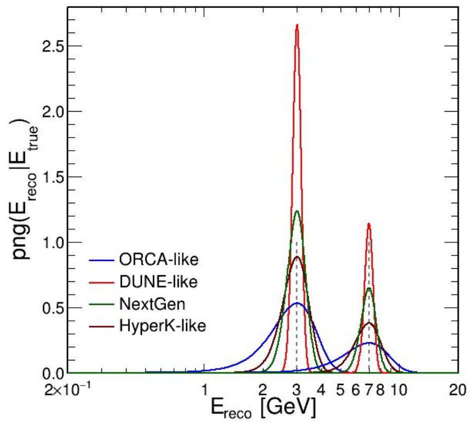
Core composition: which neutrino detector ?

…Use parametrized detector response function:

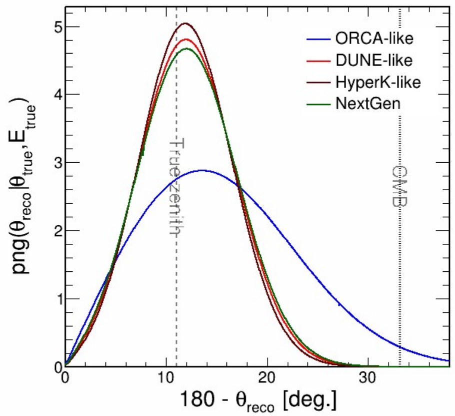
effective mass



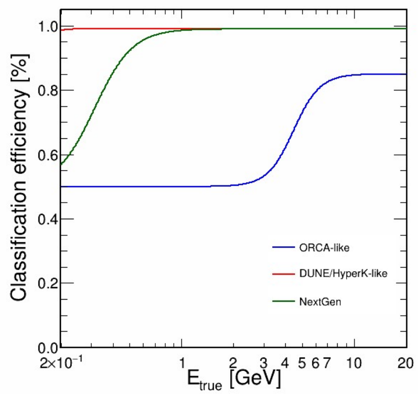
energy resolution



angular resolution



classification (PID) efficiency



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%

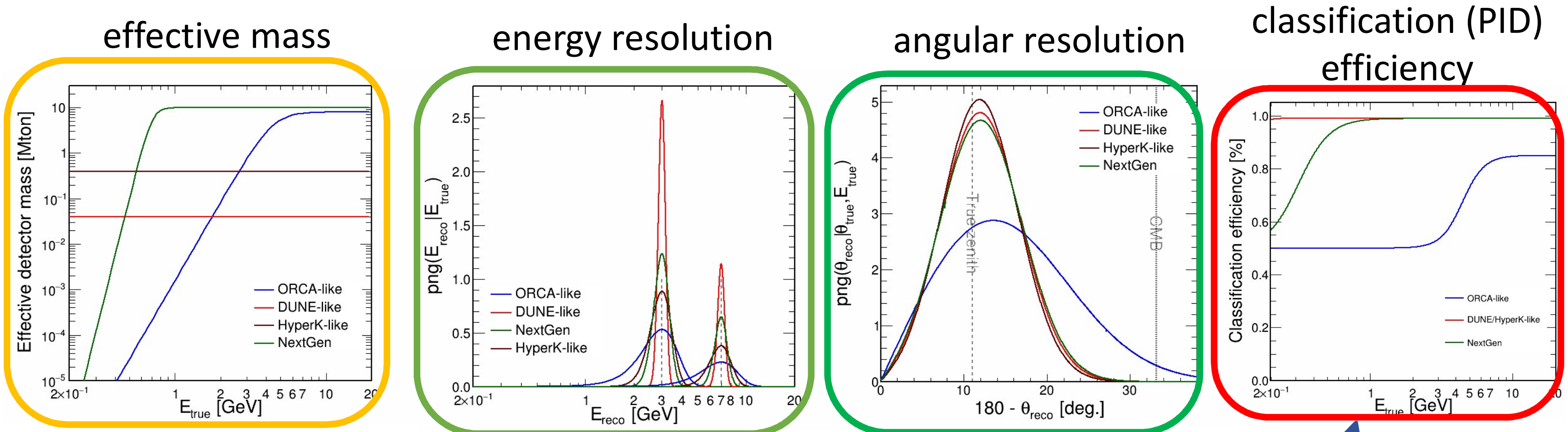
hypothetical detector with desirable performances (see later)

Core composition: which neutrino detector ?

…Use parametrized detector response function:

correctly classified / wrongly classified

$$R_{\text{tracks}}(E_{reco},\Theta_{reco}) = \sum_{E,\theta} \Big(\underbrace{R^{\text{int}}_{tracks}(E_{\text{true}},\theta_{\text{true}}) \times \rho_{class}(E_{\text{true}})}_{\text{correctly classified}} + \underbrace{R^{\text{int}}_{casc}(E_{\text{true}},\Theta_{\text{true}}) \times (1-\rho_{class}(E_{\text{true}}))}_{\text{wrongly classified}} \Big)$$
$$\times \varepsilon_{det}(E_{\text{true}}) \times PDF_{angle}(\theta_{reco};E_{\text{true}},\theta_{\text{true}}) \times PDF_{energy}(E_{reco};E_{\text{true}})$$



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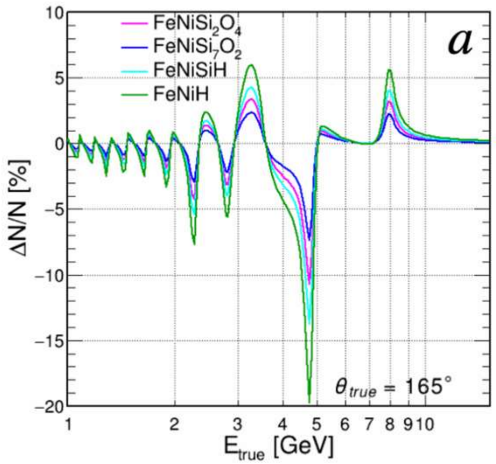
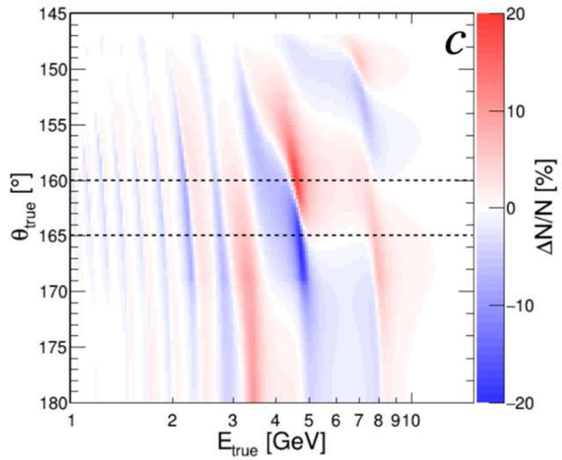
Core composition: which neutrino detector ?

Start from distributions of interacting events…





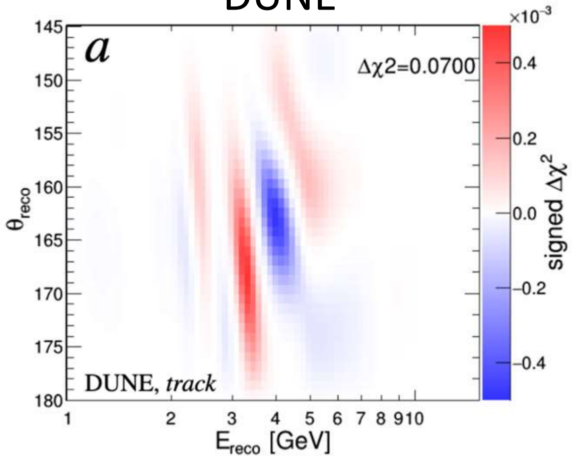
Relative difference in ν_μ interacting events

FeNi vs FeNiH

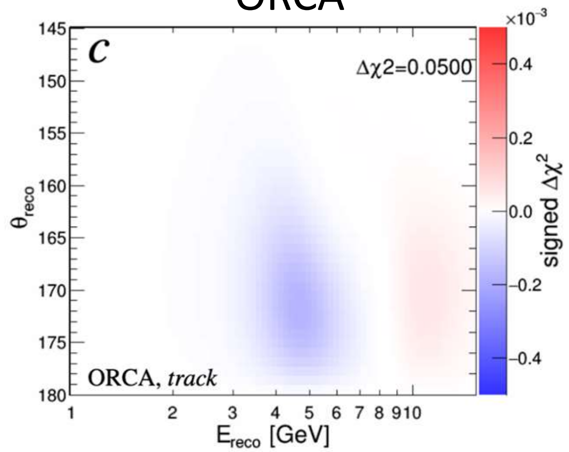
…then apply detector response and compute statistical significance (signed chi2)

for 20 years detector lifetime:

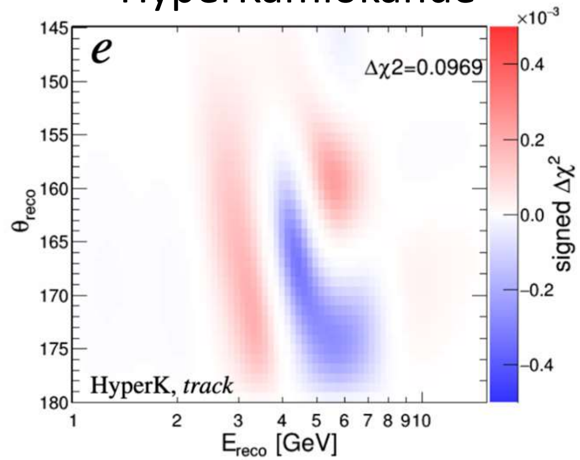
DUNE



ORCA



HyperKamiokande

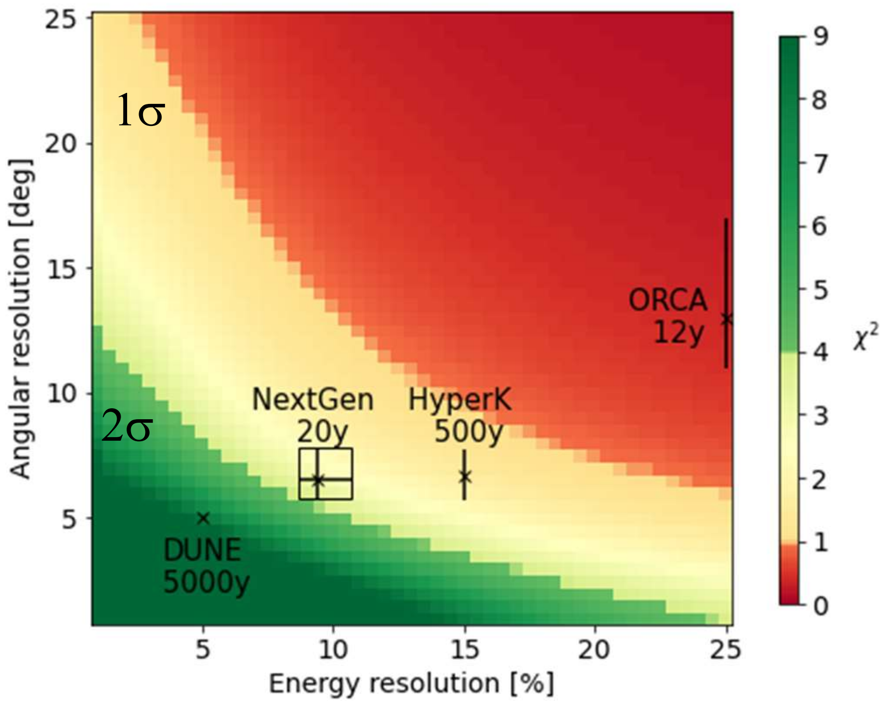


Comparable (and low) significance → need a better detector!

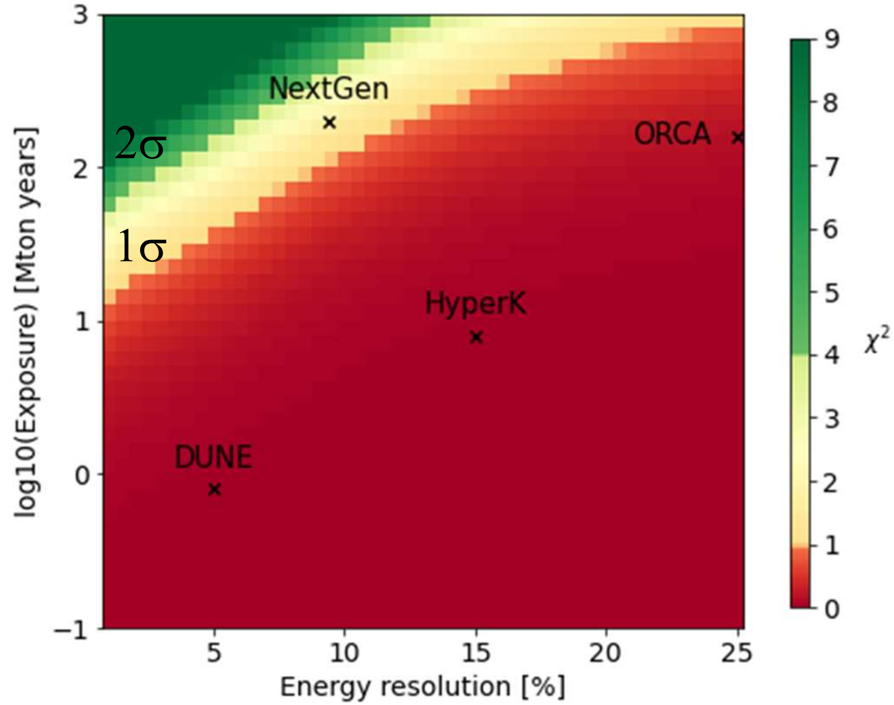
Core composition: which neutrino detector ?

Scan the next-generation (NextGen) detector parameter space:
Here, **$FeNiSi_2O_4$ vs FeNiH**

- Fixed exposure: 200 Mton yr



- Fixed lifetime: 20 yr



→ Combination of high exposure (thus, mass) and very good resolution needed

Core composition: which neutrino detector ?

Start from distributions of interacting events…

Detector				$\sigma(E)/E$	σ_θ (deg)	E_{th}^{class} (GeV)	E_{pl}^{class} (GeV)	P_{max}^{class}
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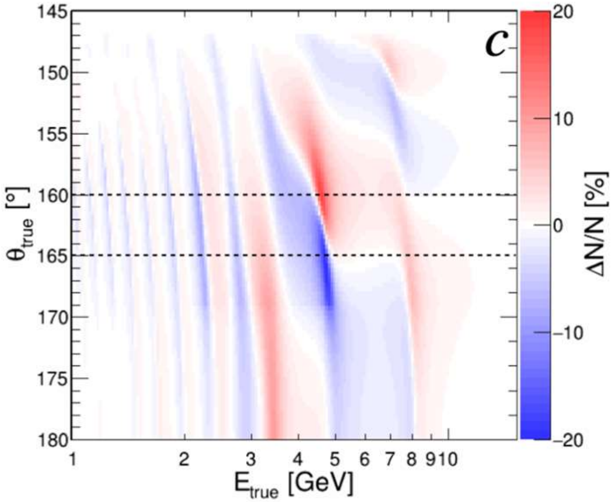
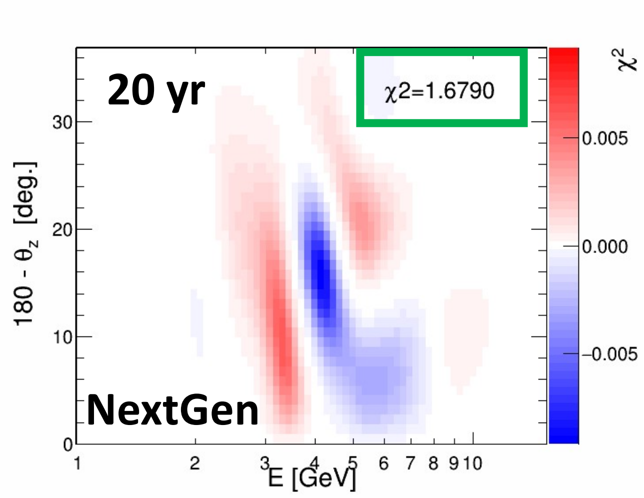
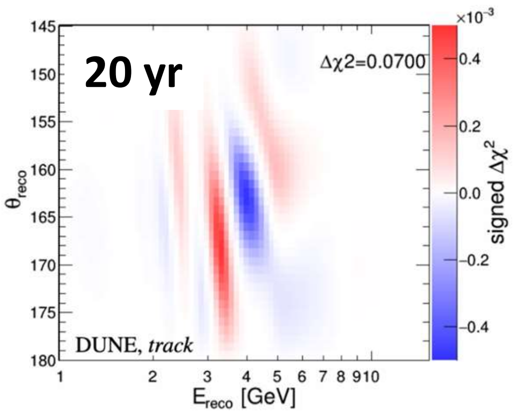
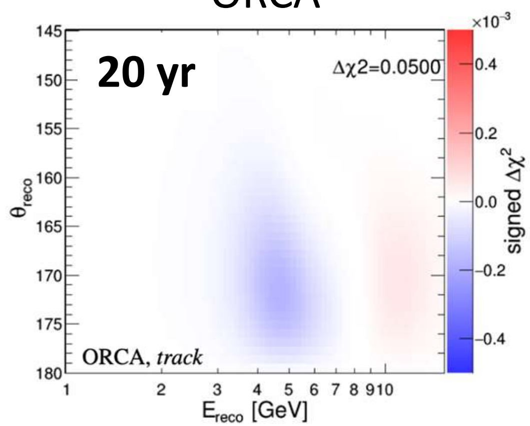




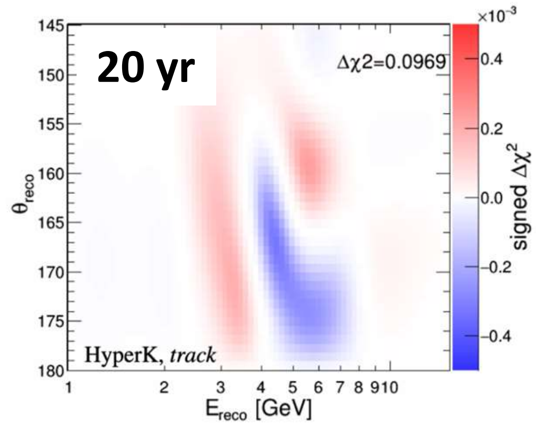
DUNE



ORCA

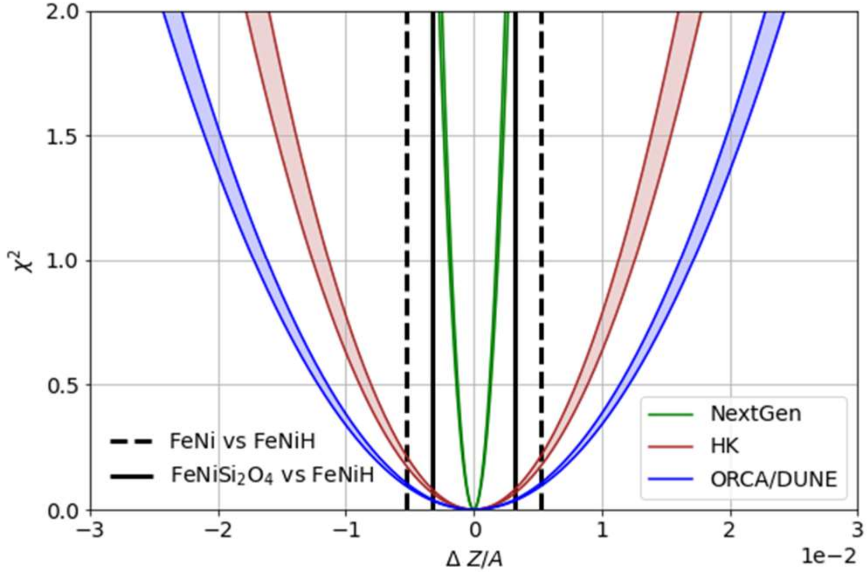


HyperKamiokande

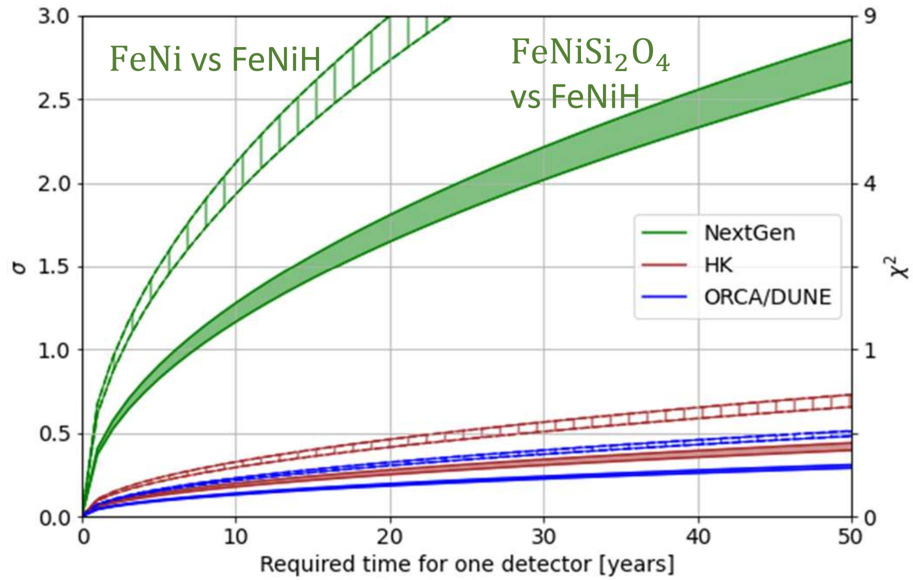


Core composition: which neutrino detector ?

chi2 for model discrimination
in 20 yr detector lifetime



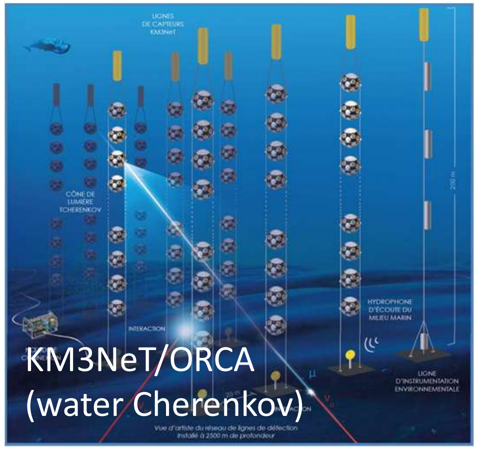
chi2 for model discrimination
as a function of time

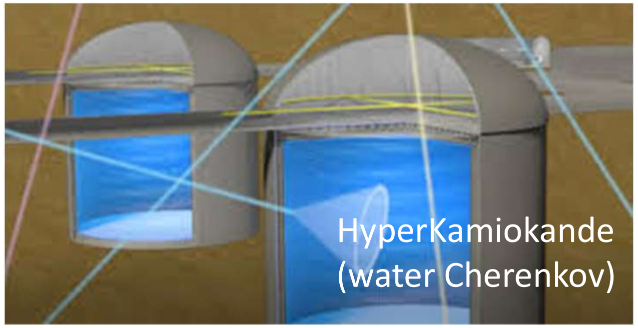


The bands indicate potential of CC/NC separation (→ background reduction)

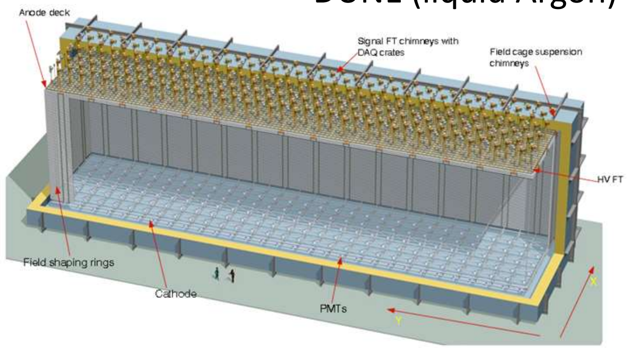
→ ORCA and DUNE show similar performance, despite different detection techniques
→ HyperKamiokande outperforms the other upcoming detectors, but resolution/size still not sufficient to distinguish between different realistic core composition models
→ NextGen detector achieves > 1σ discrimination for FeNi AND $FeNiSi_2O_4$ vs FeNiH in less than 10 years

Core composition: which neutrino detector ?





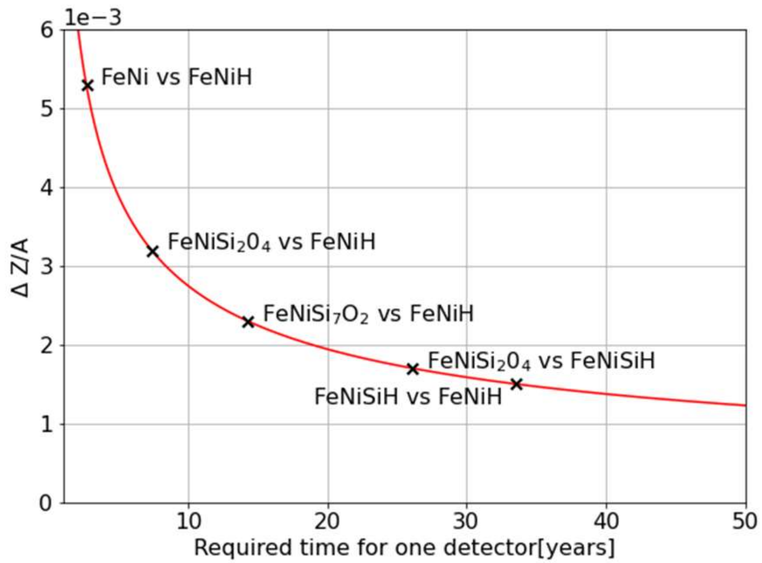
DUNE (liquid Argon)



A NEXT-GENERATION NEUTRINO DETECTOR OPTIMISED FOR TOMOGRAPHY ?

Effective mass → need > 10 Mton
Energy threshold → need < 1 GeV
Track/shower (PID) → need > 95%
Energy resolution → need < 15%
Angular resolution → need < 10°

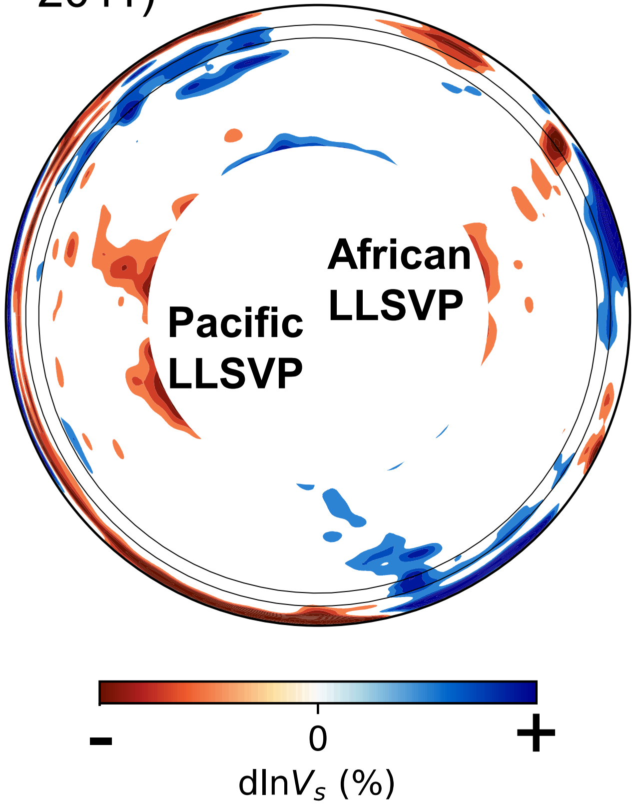
..and normal mass hierarchy of neutrinos
(to be measured by ORCA, JUNO, DUNE,…)



(for 1σ discrimination)

Outlook: composition anisotropies in the mantle ?

S40RTS (Ritsema et al. 2011)



LLSVP =
'Large Low Shear Velocity Province'

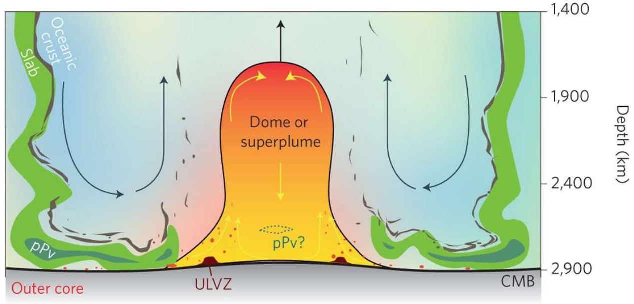
Low seismic velocity $\stackrel{?}{=}$ hot $\stackrel{?}{=}$ upgoing

High seismic velocity $\stackrel{?}{=}$ cold $\stackrel{?}{=}$ downgoing

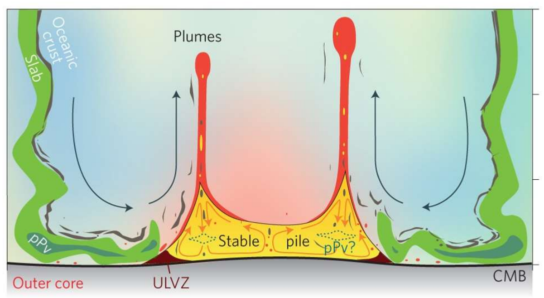
→ This interpretation does not hold for changes in chemical composition

→ Need to know the density!

Rising superplumes?



Stable piles?

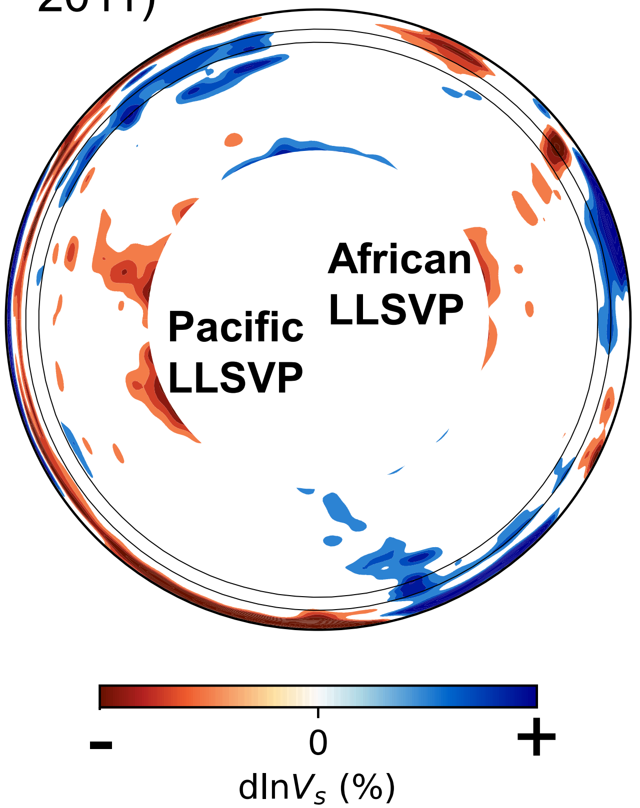


Credits: R. van Tent

From Garnero et al. (2016)

Outlook: composition anisotropies in the mantle ?

S40RTS (Ritsema et al. 2011)



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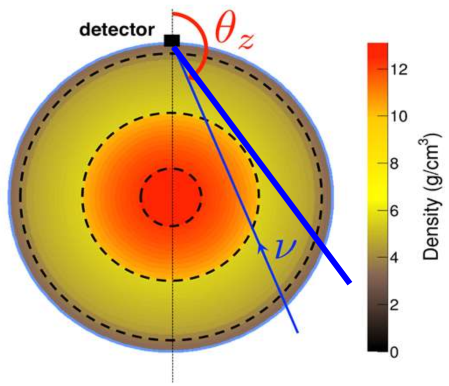
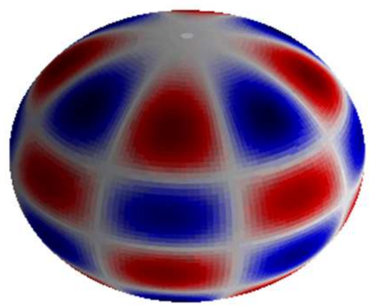
High seismic velocity $\overset{?}{=}$ cold $\overset{?}{=}$ downgoing

→ This interpretation does not hold for changes in chemical composition

→ Need to know the density!

→ **Combine neutrino data with seismic normal modes measurements: whole-Earth oscillations, directly sensitive to matter density**





Universiteit Utrecht

Collaboration with
A. Deuss
R. Van Tent

Conclusions and Perspectives

Neutrinos offer novel methods to probe the Earth's interior:

◆ Absorption tomography (TeV-PeV neutrinos)

can inform on **Earth matter density in D" and LLSVP**

→ needs large statistics of events at >10 TeV energies (IceCube/ARCA)

◆ Oscillation tomography (~GeV neutrinos)

can inform on **core/lower mantle composition**

→ needs large statistics of events at ~GeV energies (ORCA/PINGU)

→ needs improved detector performances (lower threshold/better reco)

→ needs to resolve first the neutrino mass hierarchy

Upcoming detectors → benchmark sensitivity ~ few % after 10 years
…not enough to constrain realistic models

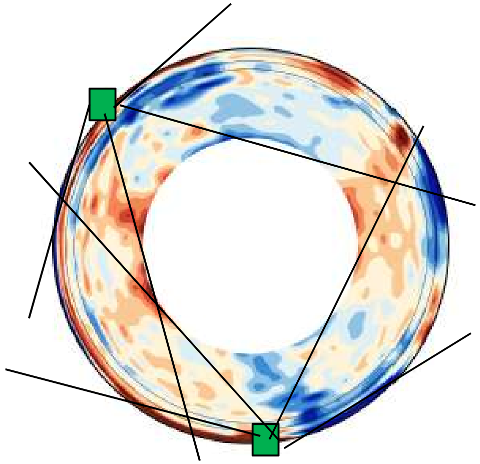
→ A case for next-generation detectors optimised for neutrino tomography

… reach 1% sensitivity level

(H in outer core, H_2O in mantle…)

… **detector network** for combined measurements

(3D profiles and large-scale inhomogeneities)




obrigado
Dank U
Merci
mahalo
Köszi
спасибо
Grazie
Thank you
mauruuru
Takk
Gracias
Dziękuję
Děkuju
danke
Kiitos

ORCA sensitivity to Z/A

- ❖ Oscillation parameters from NUFIT 3.2
  $\sin^2\theta_{23} = 0.5$; $\delta_{CP} = 0$
- ❖ Systematics treatment improved:
  - includes MC sparseness effect
  - flavour and polarity skews
  - channel-by-channel normalization
- ❖ Simultaneous fit of other layer

Combined measurement: