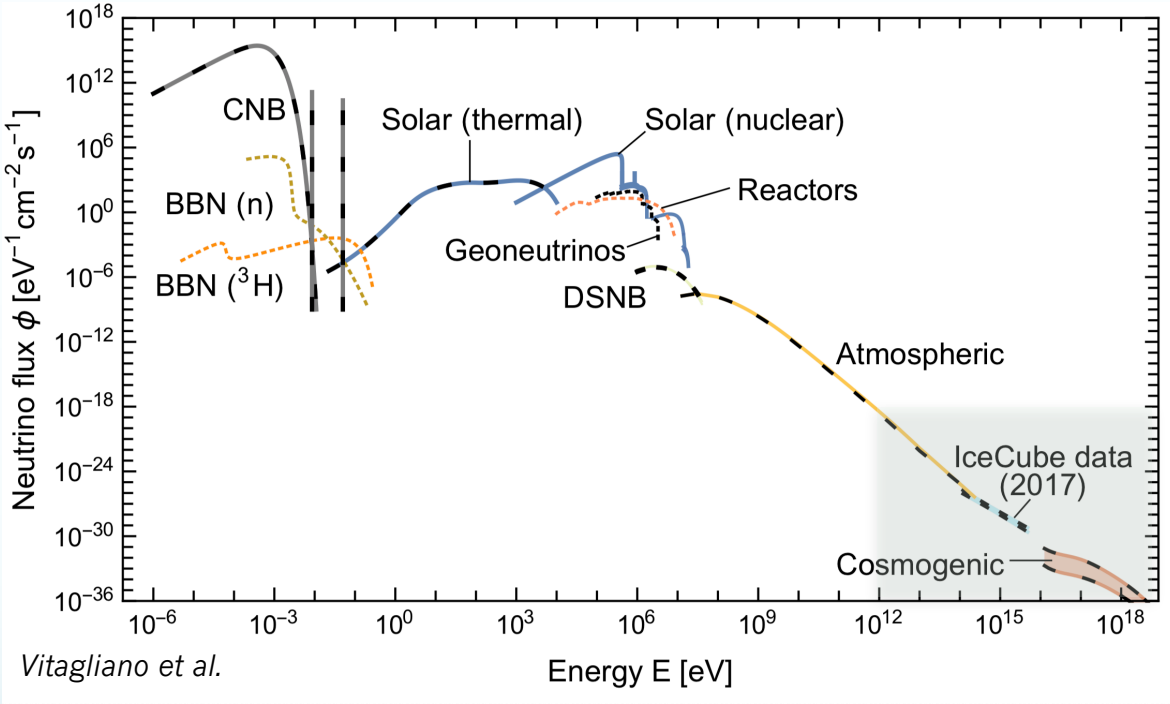
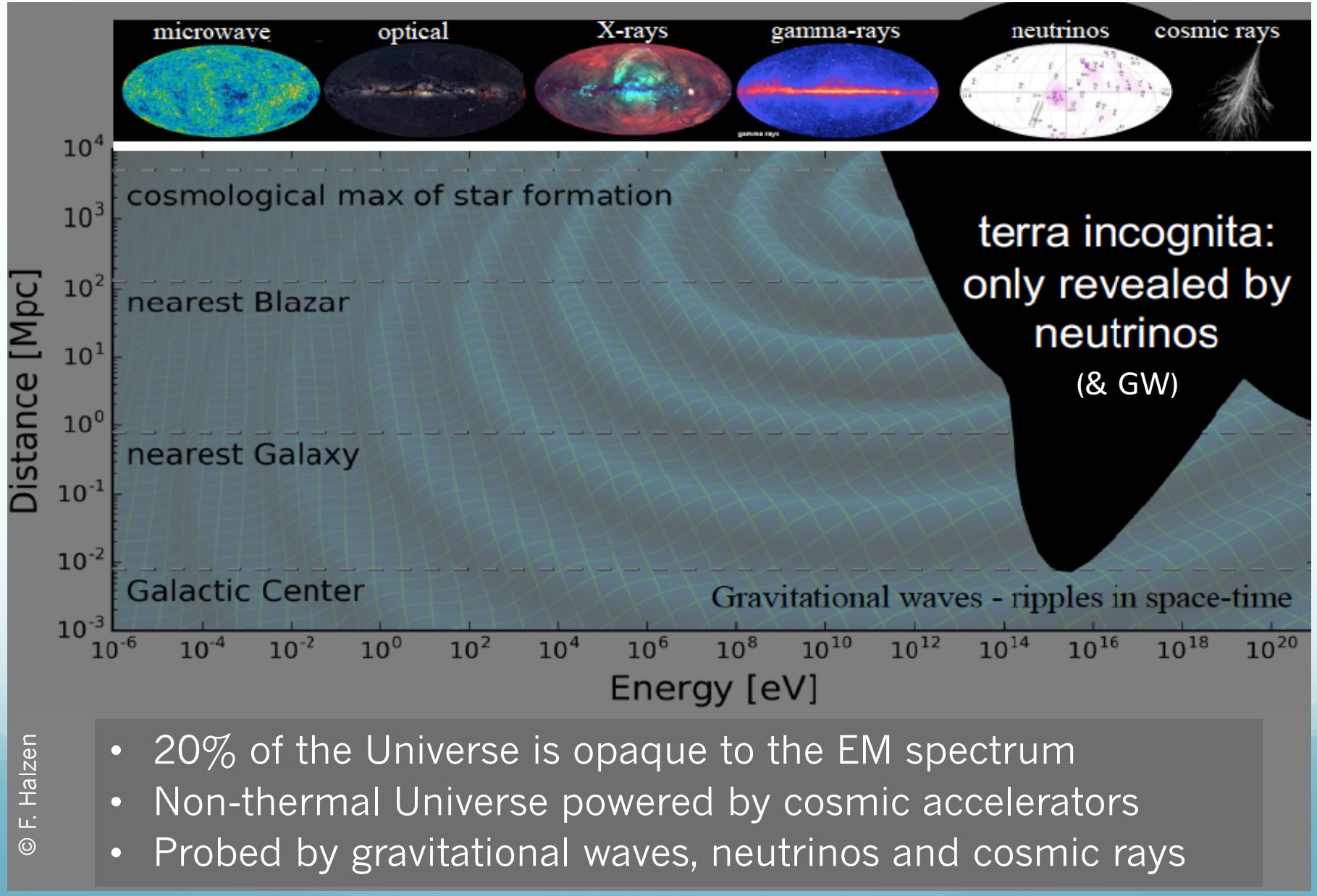
Neutrino landscape in next decade



- Rationale
- Cherenkov Detectors
- What to expect ?
- Radio Detectors
- Open Science

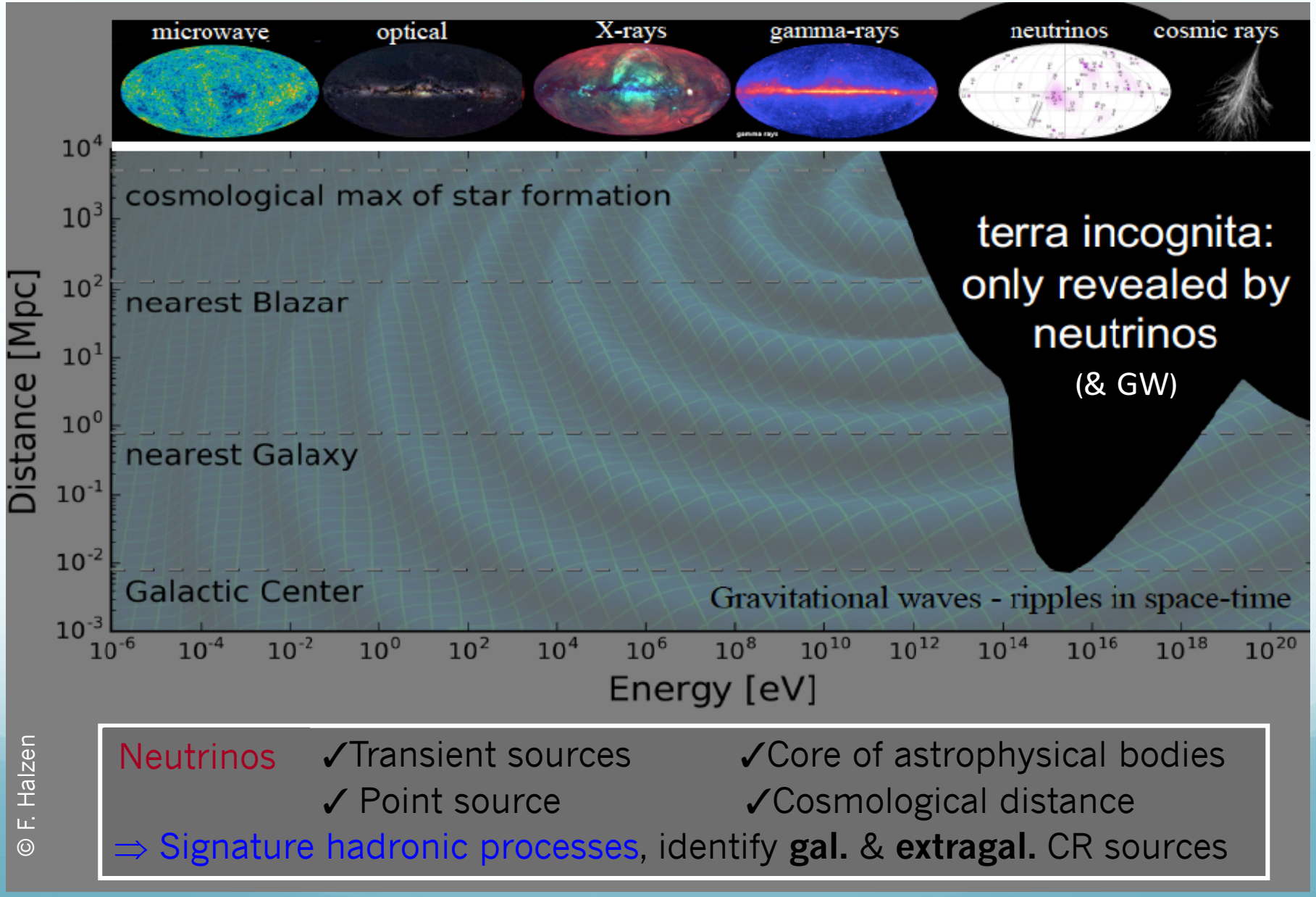
Antoine Kouchner

Multi-messenger astronomy



- 20% of the Universe is opaque to the EM spectrum
- Non-thermal Universe powered by cosmic accelerators
- Probed by gravitational waves, neutrinos and cosmic rays

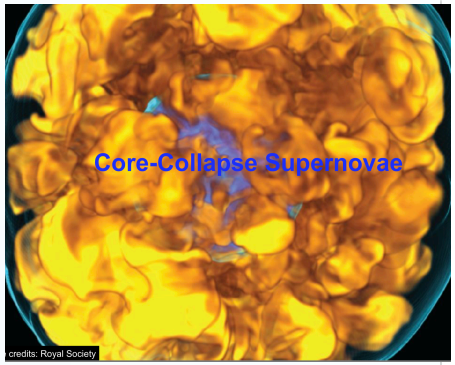
Multi-messenger astronomy

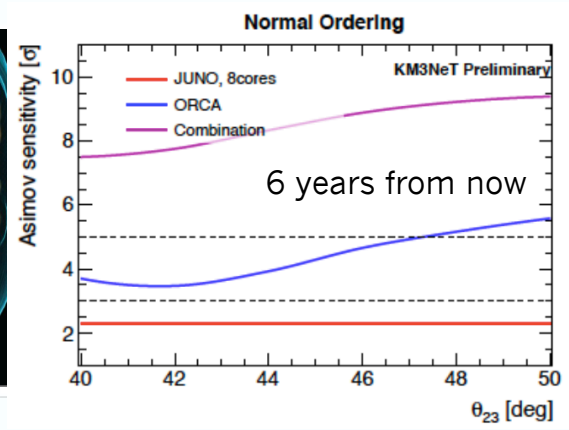


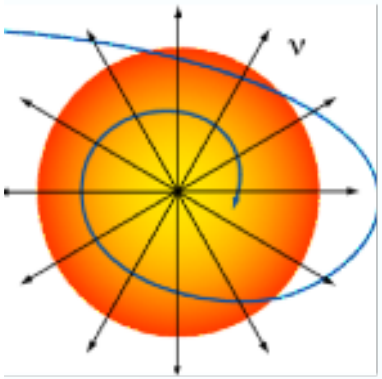
Neutrinos	✓Transient sources	✓Core of astrophysical bodies
	✓ Point source	✓Cosmological distance

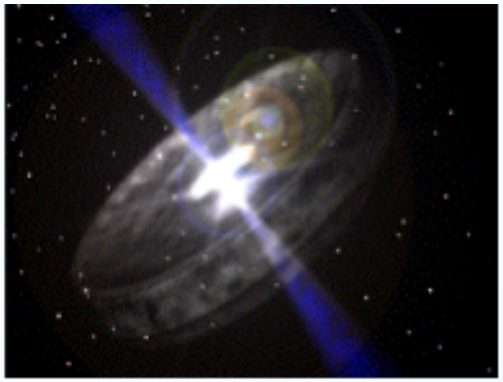
⇒ Signature hadronic processes, identify **gal.** & **extragal.** CR sources

The Physics Scope









MeV Energy
No reco. in HE NT

Low Energy
GeV < E < 50 GeV

Medium Energy
10GeV < E < 1 TeV

High Energy
E > 1 TeV

CCSNe

Full Galactic coverage
All mass progenitors
Triangulations

⇩

Localisation

Coleiro et al., Eur. Phys. J. C 80, 856 (2020)

Oscillation

PMNS Unitarity KM3NeT & IC
Neutrino Mass Ordering
with KM3NeT (ORCA ≥3σ 3yrs)

Dark Matter

Not covered
here

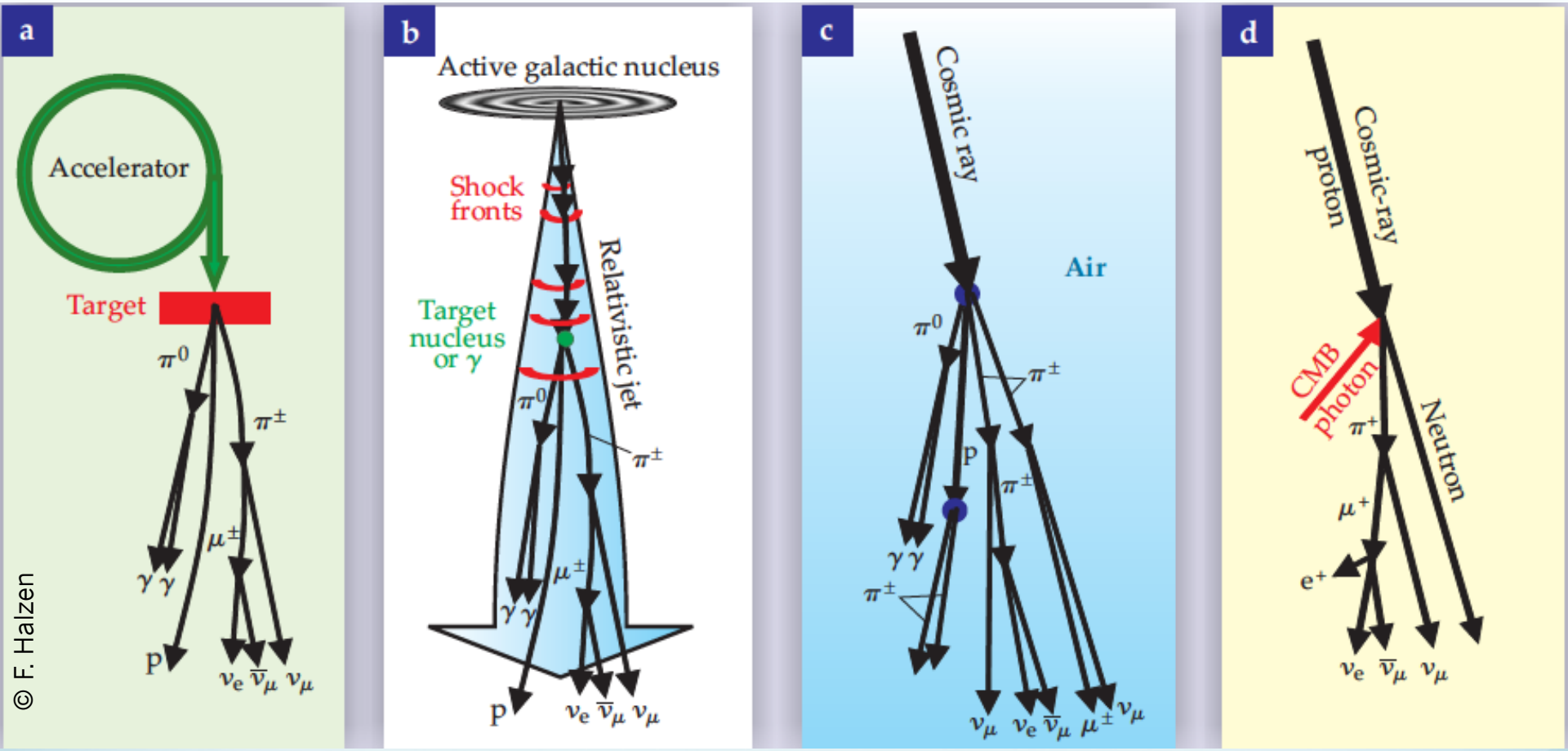
HE Astrophysics

Focus of this talk

+ Exotics (Monopoles, Nuclearites, etc.)

+ Environnemental Sciences

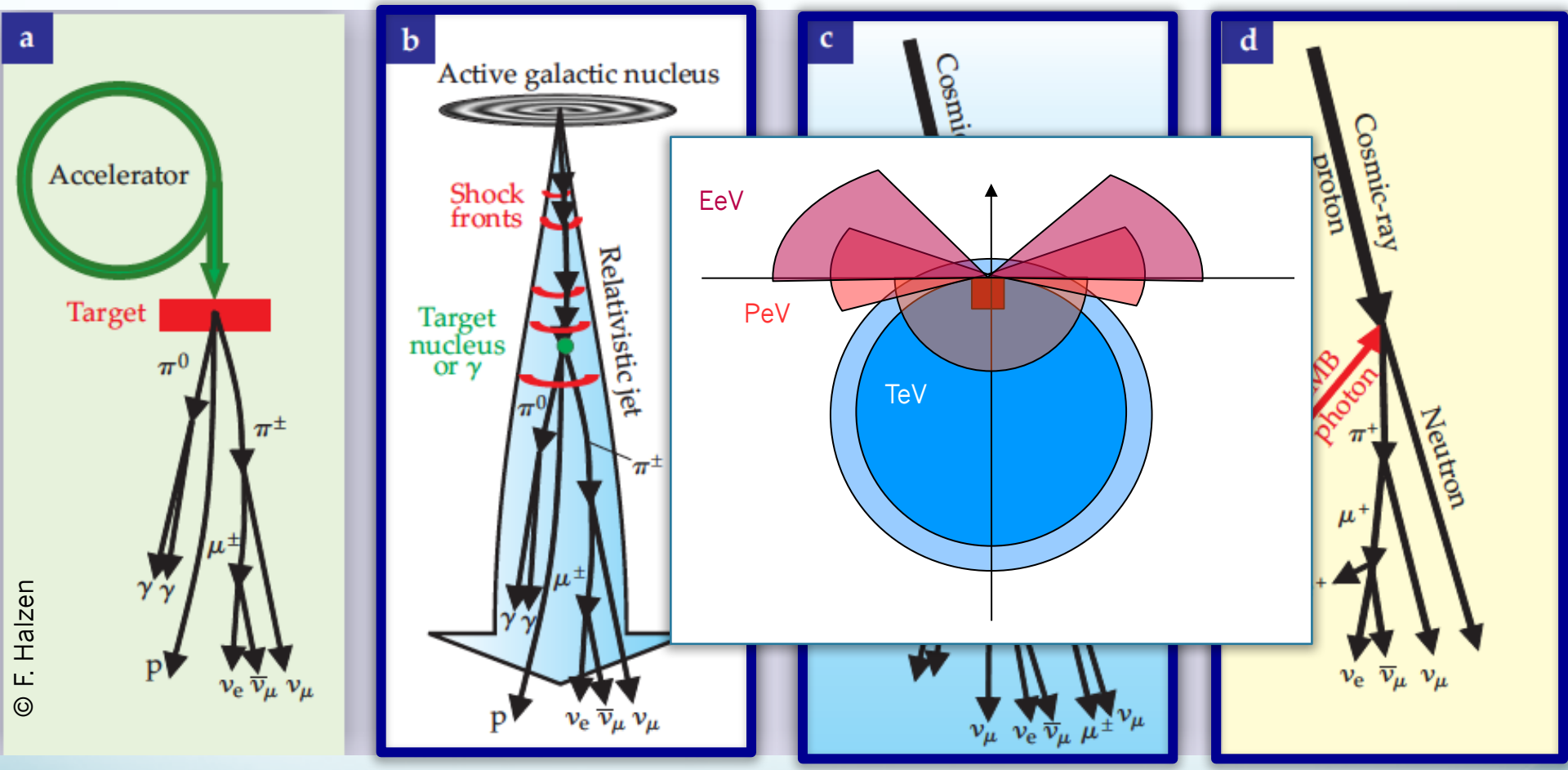
Which neutrinos for next decade detectors ?



Neutrino beam | Cosmic neutrinos | Atmospheric neutrinos | Cosmogenic ν (GZK)

→ Guaranteed source of >100 PeV neutrinos
→ Provide information on the composition of primaries
→ Alternative techniques (e.g Radio)

Which neutrinos for next decade detectors ?

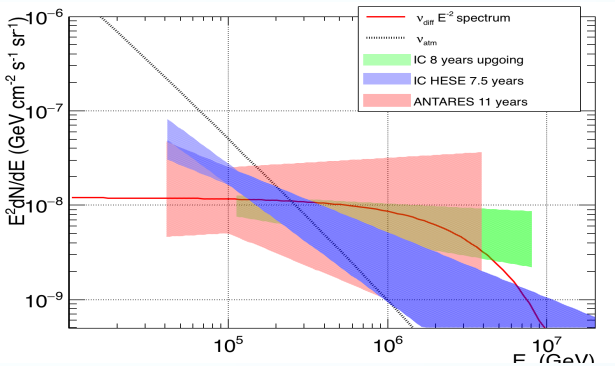


Neutrino beam | Cosmic neutrinos | Atmospheric neutrinos | Cosmogenic ν (GZK)

→ Guaranteed source of >100 PeV neutrinos
→ Provide information on the composition of primaries
→ Alternative techniques (e.g Radio)

Open questions addressed in workshop

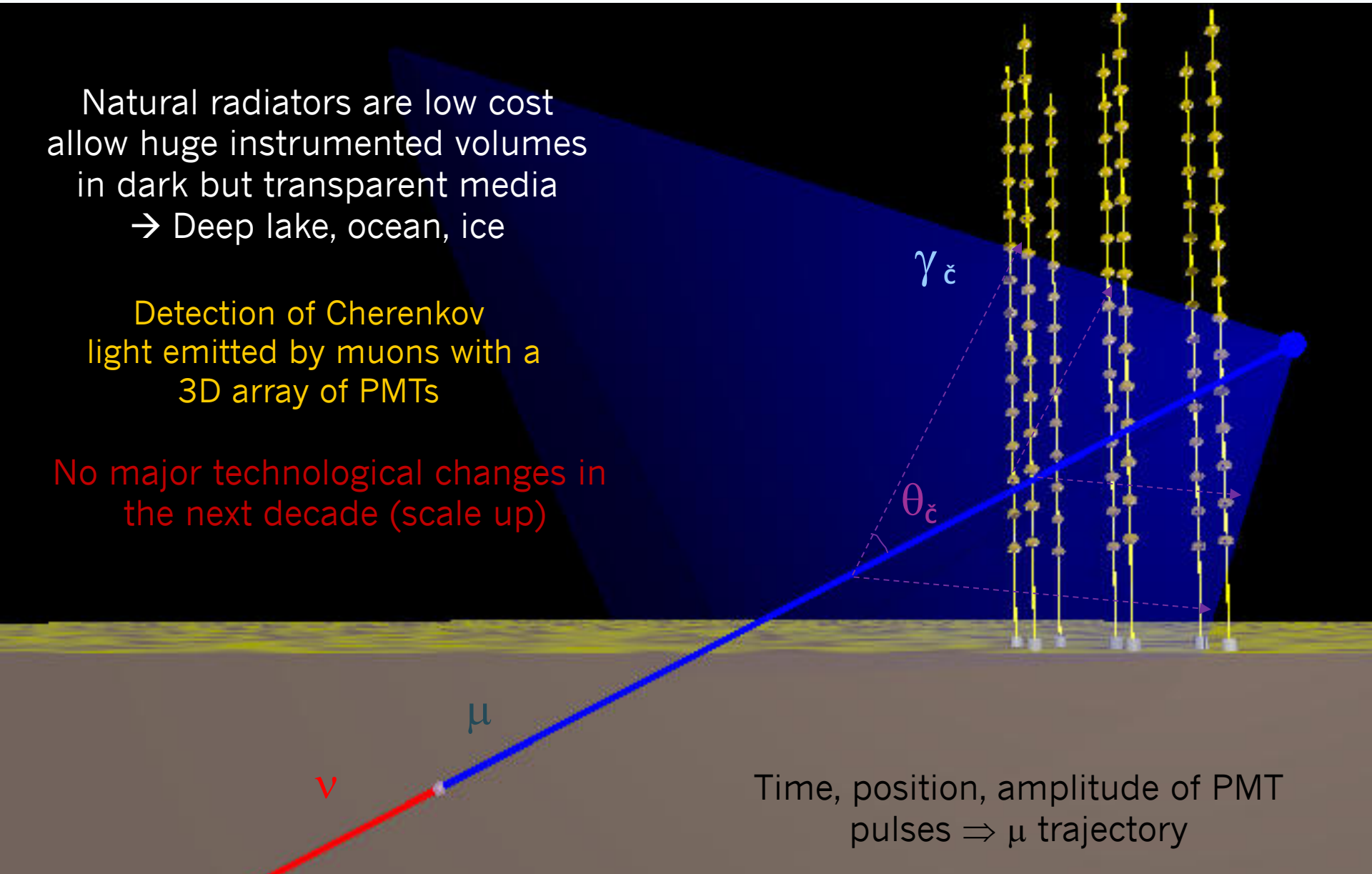
- Confirmation and Origin of IceCube HE astrophysical neutrinos
  - ANTARES:
    - No-signal hypothesis excluded at 90% C.L.
    - 1.8 σ only
  - Efforts undertaken to combine with GVD



- Production mechanisms HE CRs
- Disentangling leptons vs hadrons not assured with γ-rays alone
- Source identification. Gamma-ray / radio Blazars ?
- Disentangle astrophysical models with multi-messenger observations: i.e., GRBs with VHE gammas, GW, HEN and traditional EM band
- Study of galactic (and extra galactic?) propagation of CR with neutrinos as tracers → Northern Hemisphere NT
- Cosmogenic neutrinos: UHE CR composition
- Test the neutrino sector of the SM and BSM physics

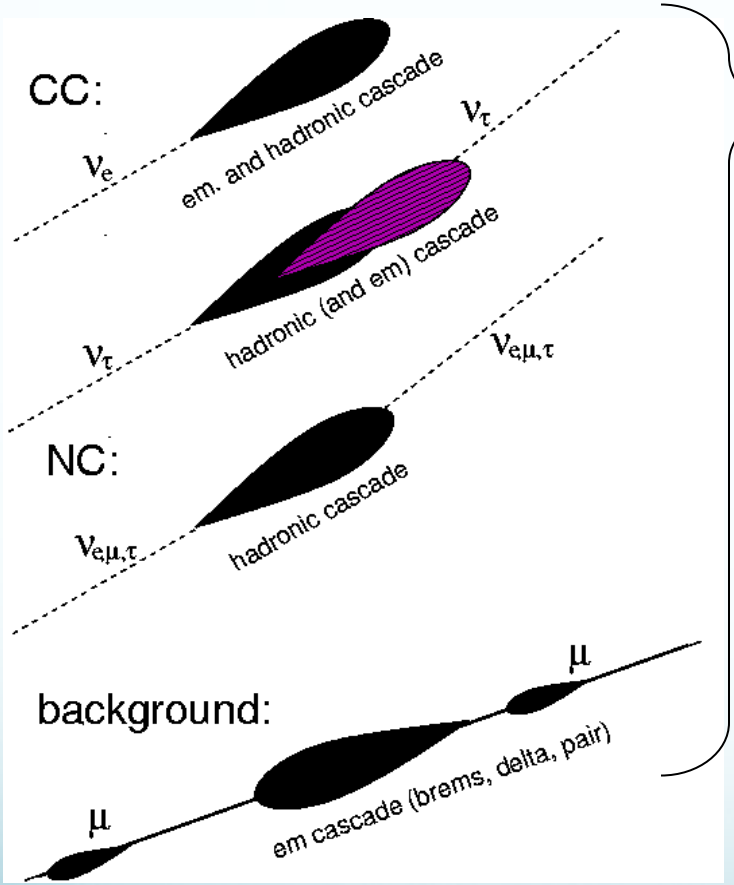
Adapted from M. Spurio

Detection Principles : Cherenkov

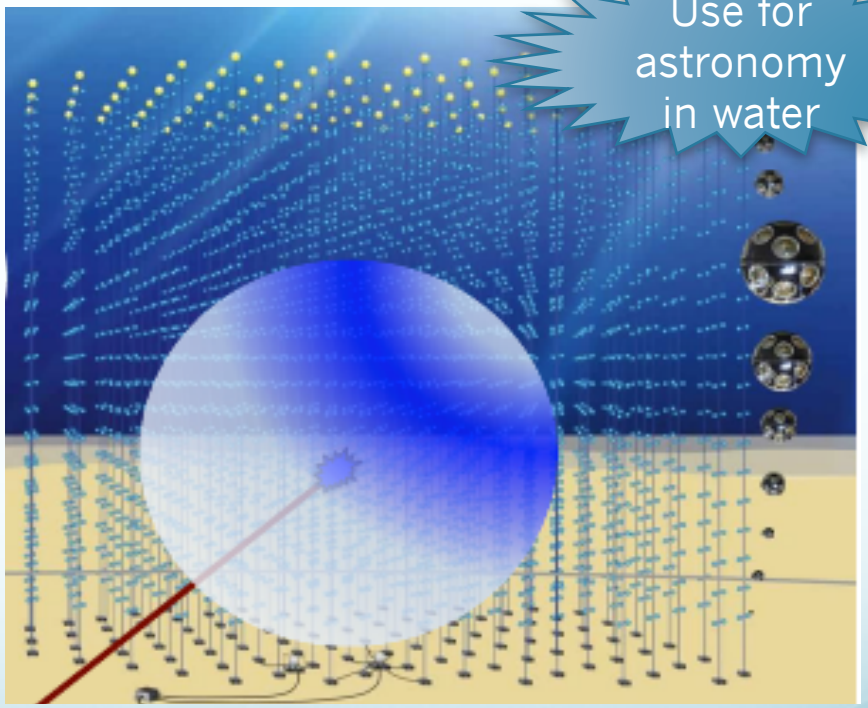


Cascade topology

$\nu_e:\nu_\mu:\nu_\tau$ =1:2:0 at source $\xrightarrow{oscillation}$ $\nu_e:\nu_\mu:\nu_\tau$ =1:1:1 at Earth !

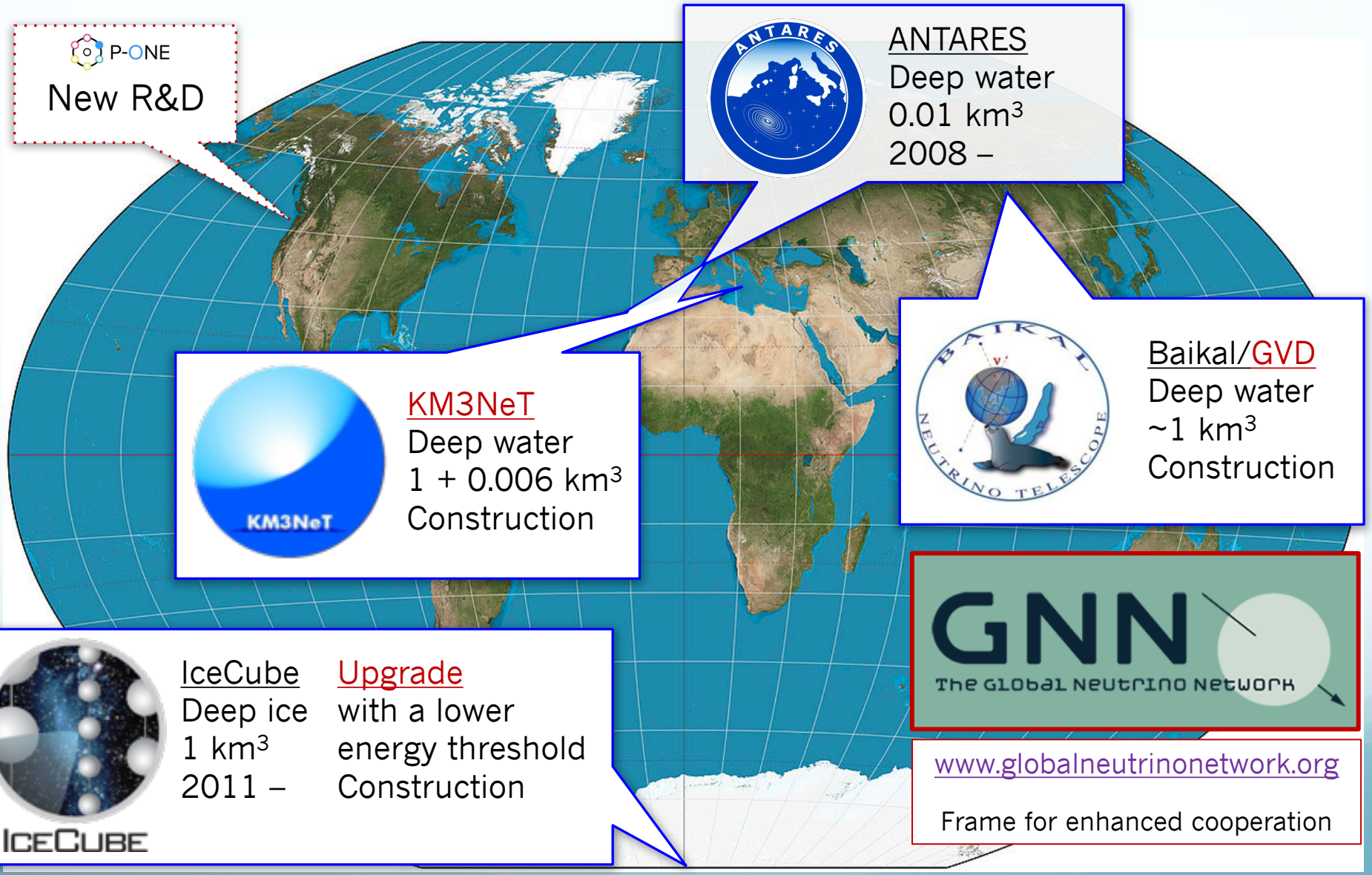


IceCube discovery channel

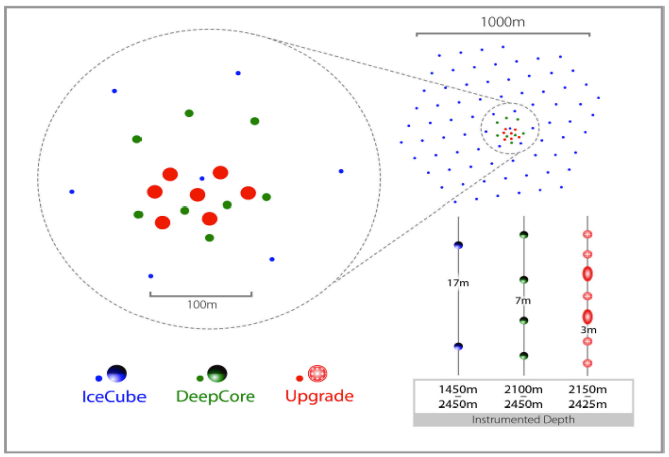


→ Provides sensitivity to all neutrino flavours – Increases overall sensitivity

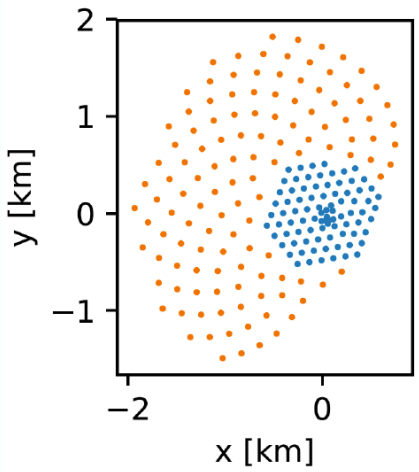
The neutrino telescope world map 2020



IceCube planned extensions



Approved by NSF, planned to deploy in 2022-23
7 new strings near the center of IceCube



- The origin of astrophysical neutrinos is largely unresolved
- IceCube-Gen2 is a proposed multi-cubic-kilometer neutrino detector designed to be sensitive to 5x fainter sources
- Wide-band neutrino observatory with optical and radio detectors, surface array

arXiv:2008.04323v1

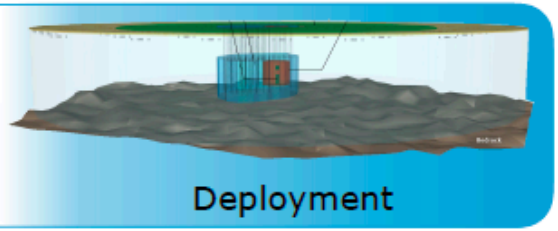
Planning before Covid crisis

2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | … | 2033

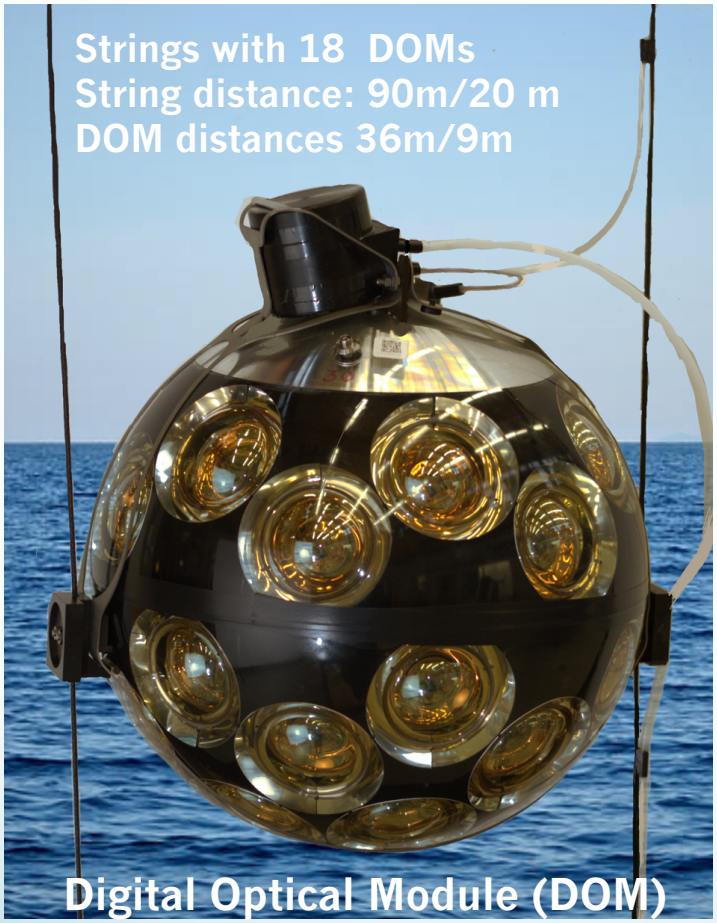
IceCube Upgrade
Design Production Deployment

- GeV neutrinos & τ appearance
- Improved understanding of ice properties

IceCube-Gen2
R&D Design & Approval Production Deployment



KM3NeT: Next gen. Med. detectors



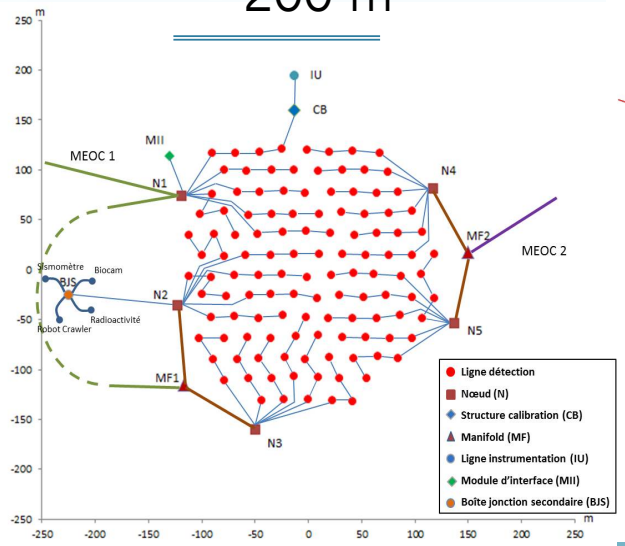
- 31 PMTs in one sphere
- 3 x cathode area wrt ANTARES OM
- Single photon counting
- Directional information
- Inspiring design for IceCube-Gen 2

KM3NeT ARCA/ORCA

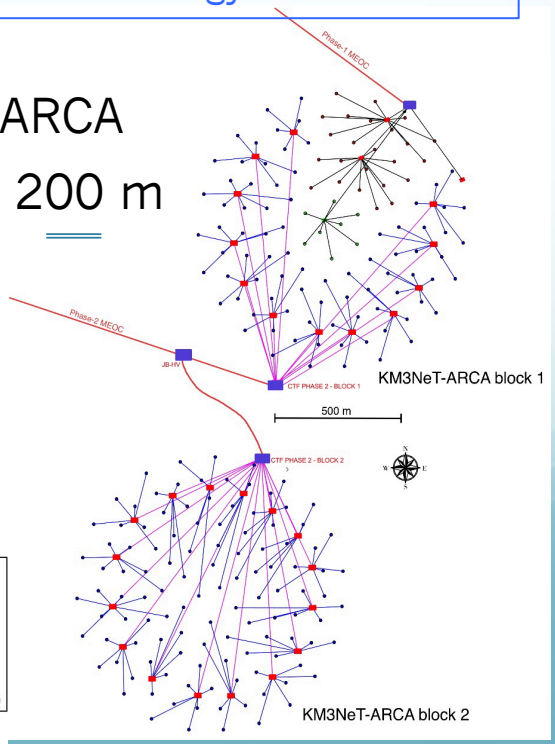
Astrophysics/**O**scillation **R**esearch
with **C**osmics in the **A**byss

ARCA: 3.5km depth, 100km from Capo Passero (Sicily)
Focus: Cosmic Neutrino Sources
large, sparse grid -> high energy
ORCA: 2.5 km depth, 40km from Toulon (France)
Focus: Atmospheric neutrino oscillations
small, dense grid -> low energy

ORCA
200 m



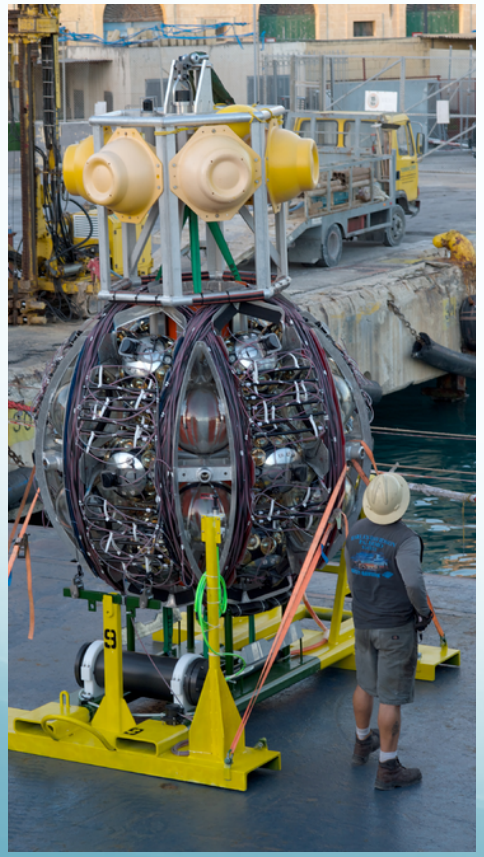
ARCA
200 m

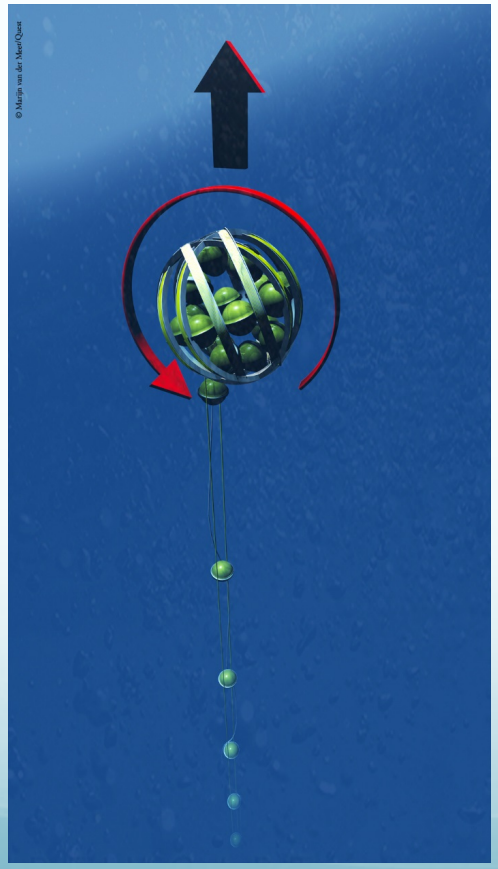


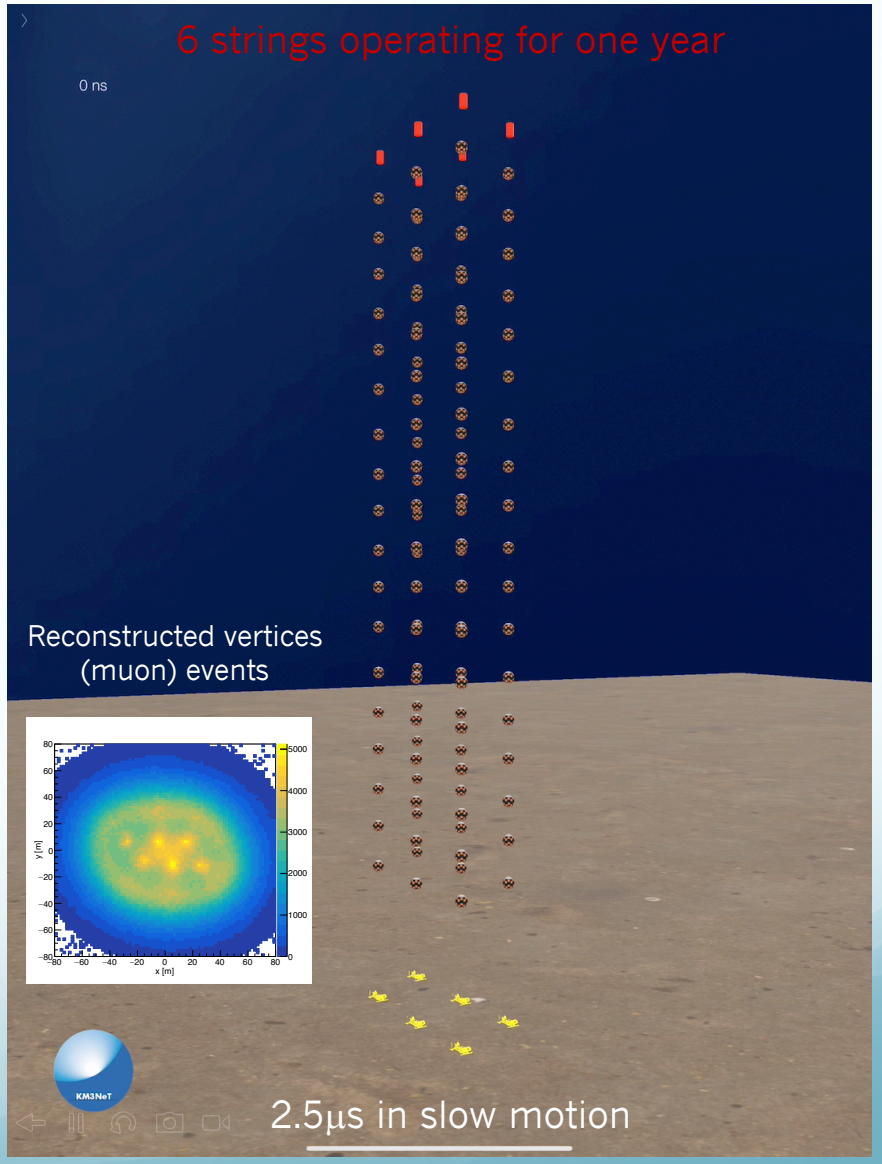
KM3NeT: Next gen. Med. detectors

First **ARCA** string deployed Dec 2015
1-2 strings operational till November 2019
-> Power refurbishment
Goal: 2x115 strings 2026

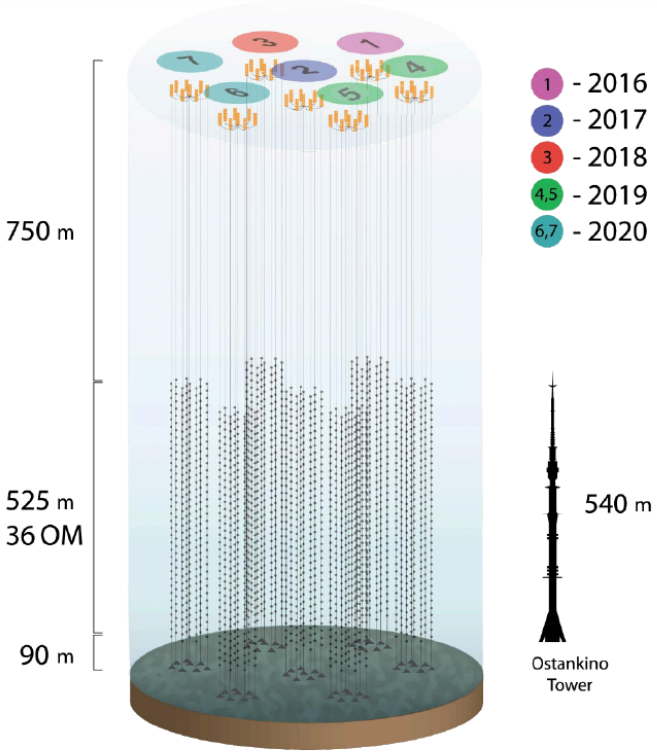
First **ORCA** string deployed Sep 2017
Goal: 115 strings 2024

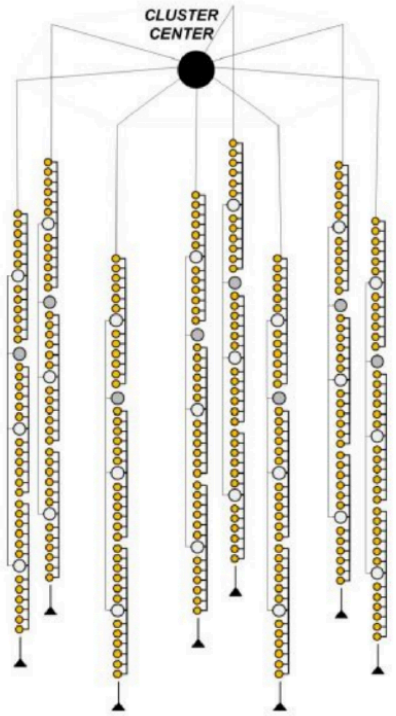


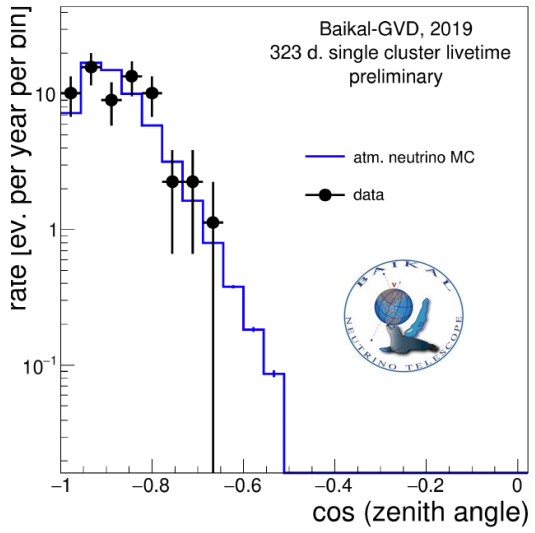




GVD: Next gen. Lake Baikal



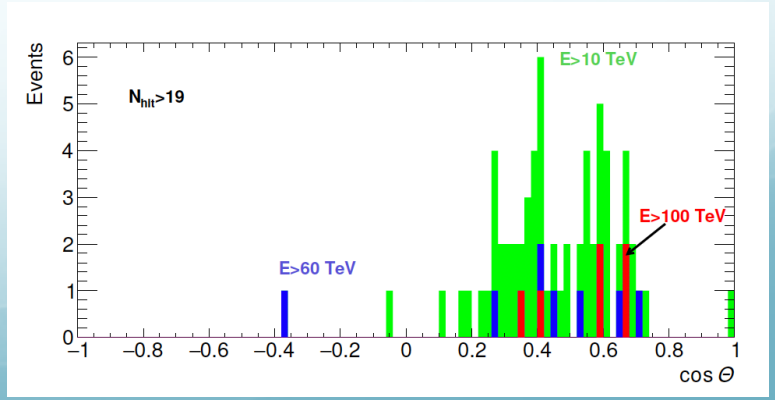




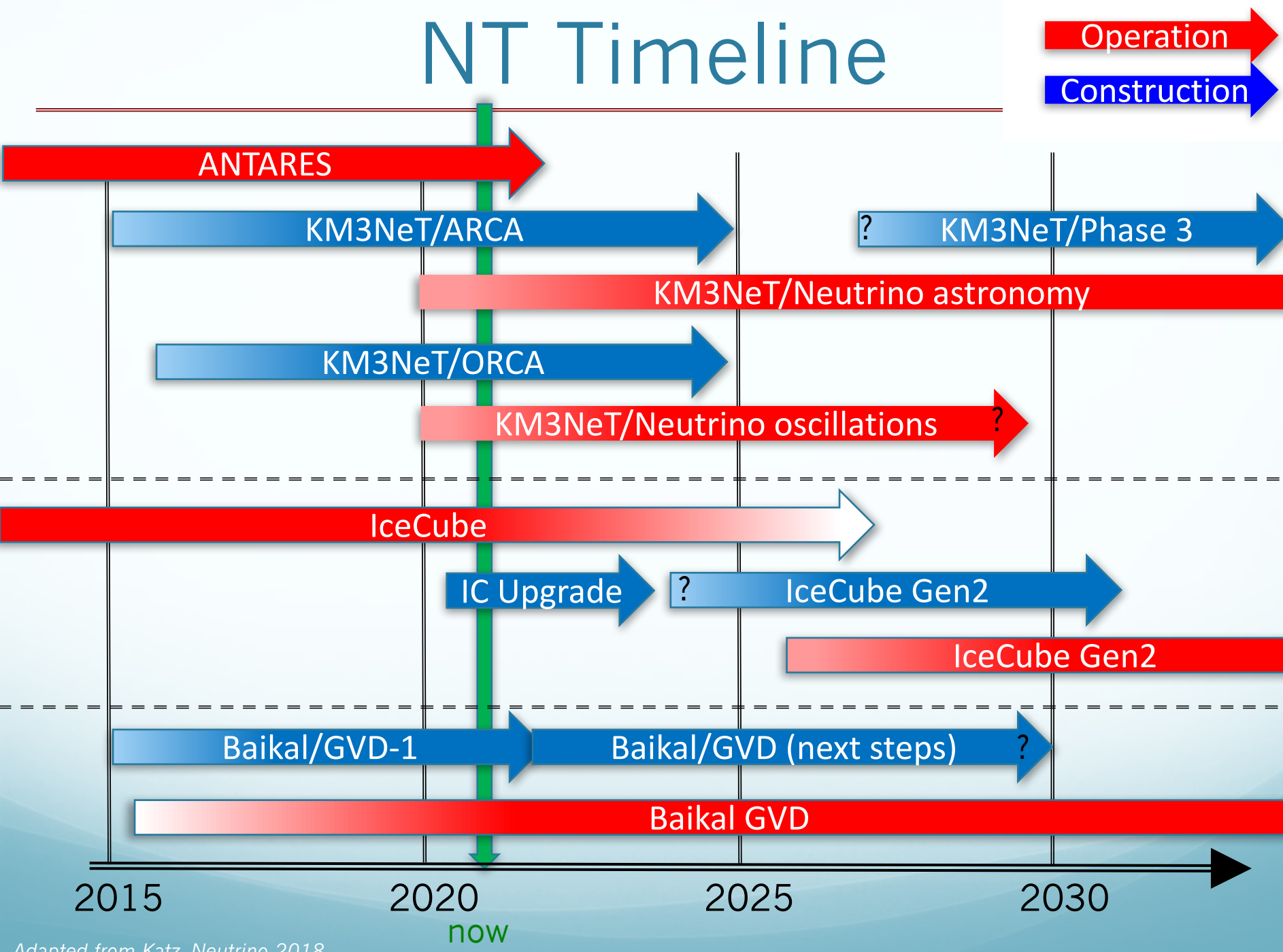
- 1366 m depth, light absorption length ~22 m.
- Project to construct a Gigaton (=km^3) detector
- Phase 1 (GVD-1): 8 clusters 0.4 km^3
  - 7 clusters operational: volume >> Antares !
  - Commissioning, calibration, sensitivity studies in progress
- 2 new clusters per year
- Final goal: 27 clusters, 1.5 km^3

Impressive progresses !

HE cascade-like with the 7-cluster detector



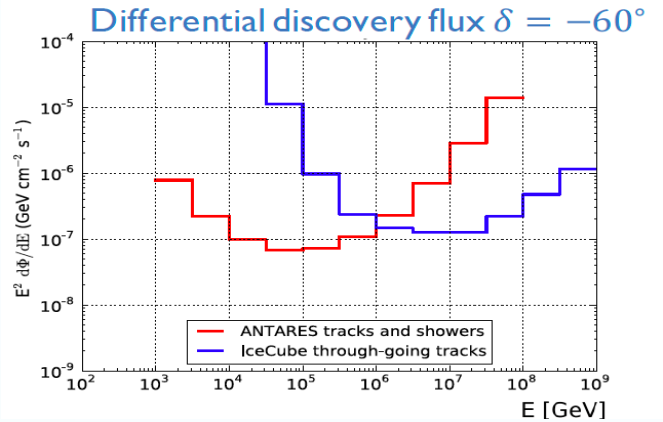
NT Timeline



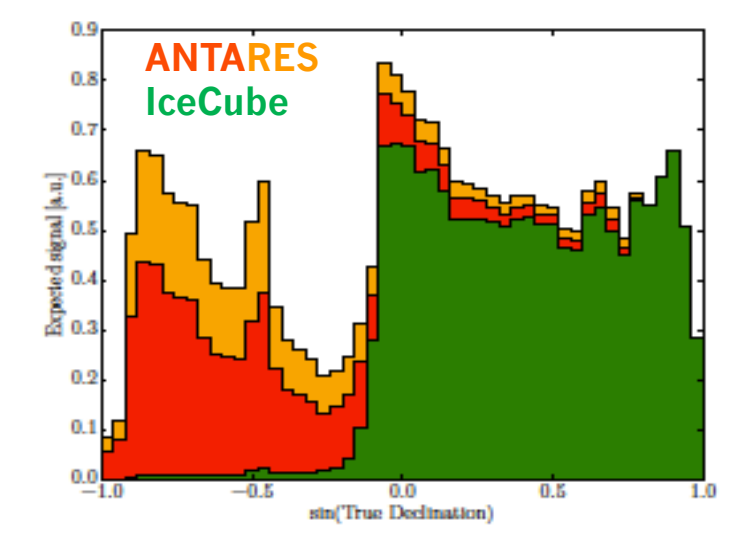
Adapted from Katz, Neutrino 2018

Some Complementarities

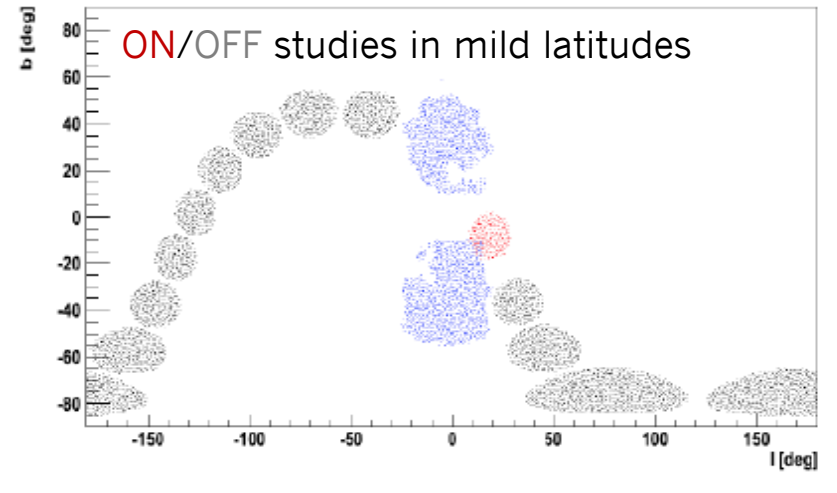
- **Field of view & Energy**

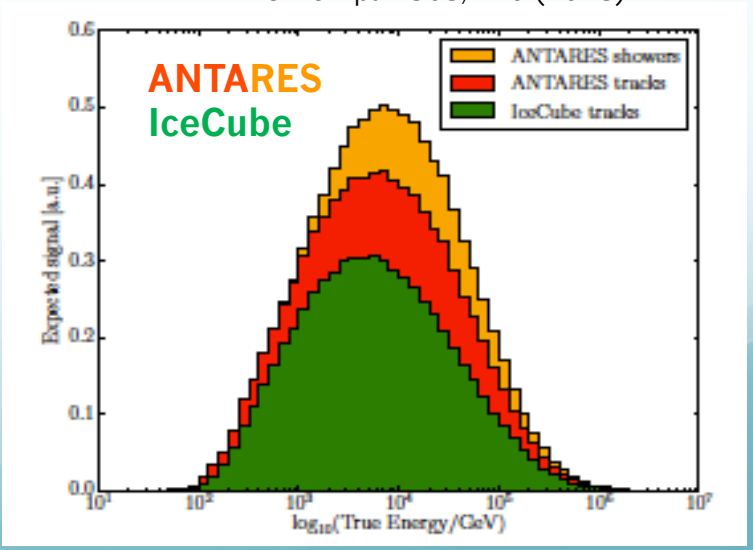


Stacked expected signal vs. δ (top) and energy (bottom). Colors relative contribution to the sensitivity



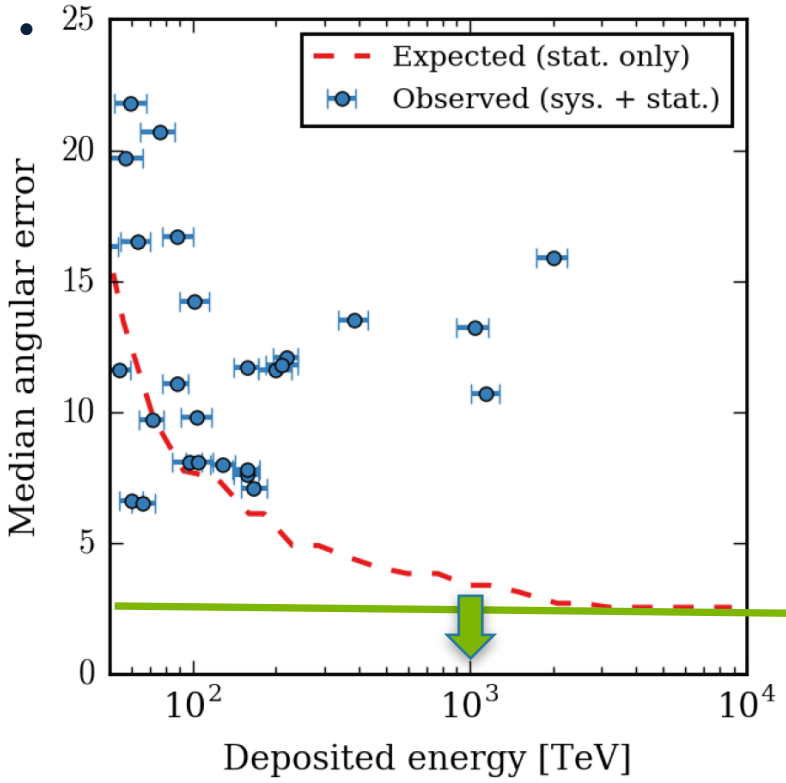
📖 ANTARES+IC ApJL 868, L20 (2018)

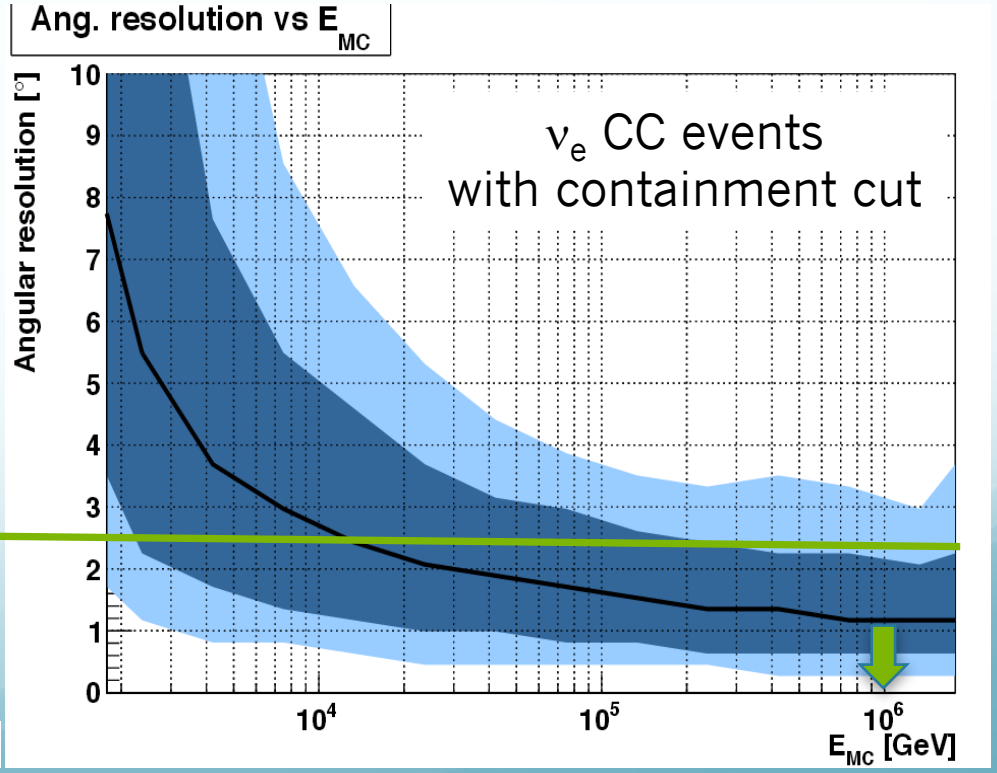




Some Complementarities

- **Distinct medium, distinct systematics**
- Ice properties is limiting factor for reconstruction precision and flavour id: Upgrade !
- Water is a much more homogenous medium than ice with long scattering length.
  - ARCA/Current IC tracks 0.2°/ 0.6* @10 TeV 0.05°/0.25° @10 PeV
- Angular resolution helps enormously in source association *Bartos et al. PRD* 96 (2017) 2, 023003

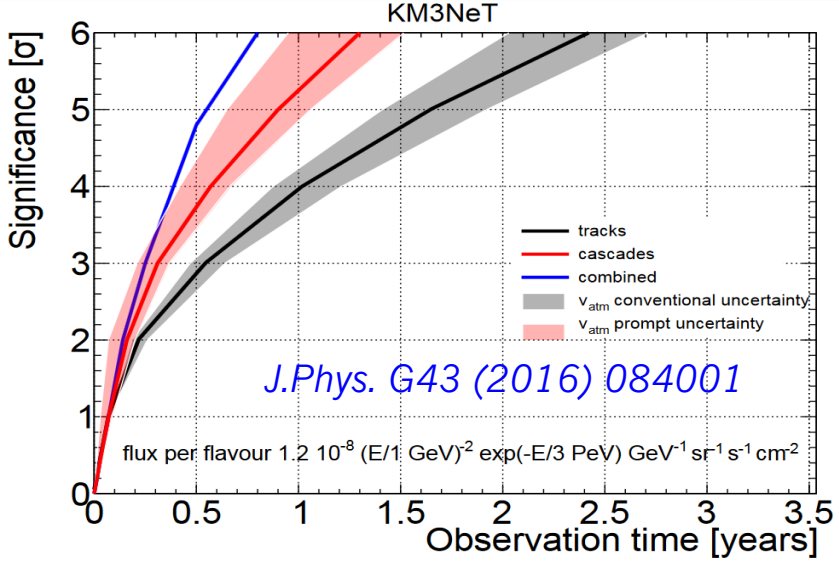


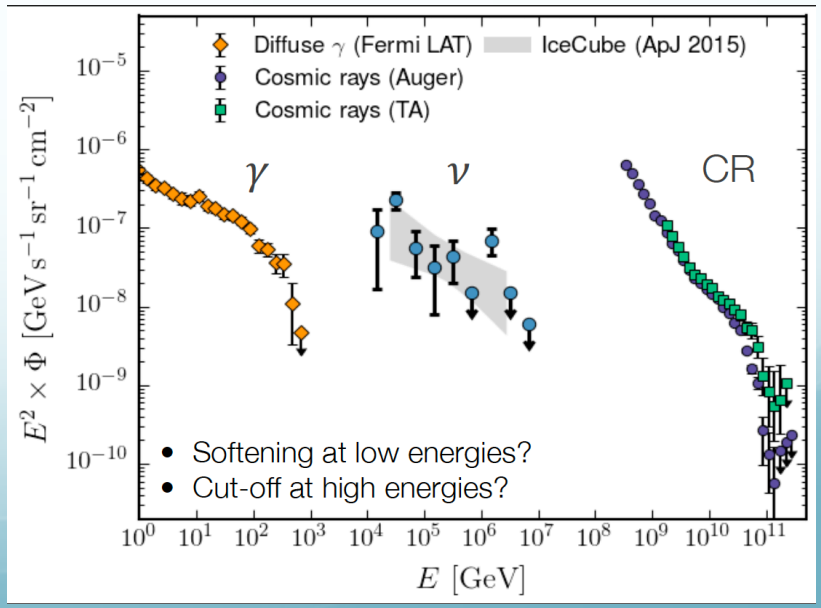


What can we hope to learn ?

- Higher statistics Diffuse
- Galactic
- Sources
- Multi-messengers
- Catalogues
- Flavor ID
- Neutrino Physics
- Supernovae

Spectral break ?
North/South difference ?
Galactic Contribution?
→ KM3NeT, GVD





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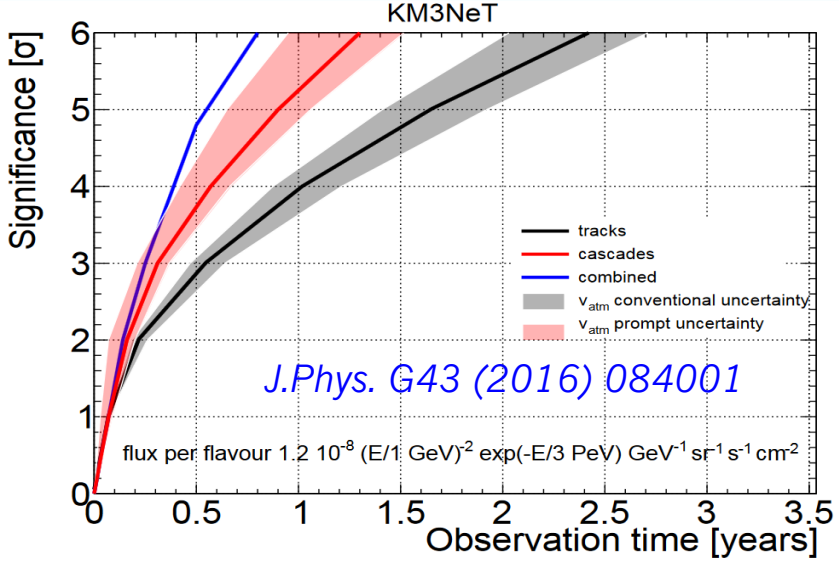

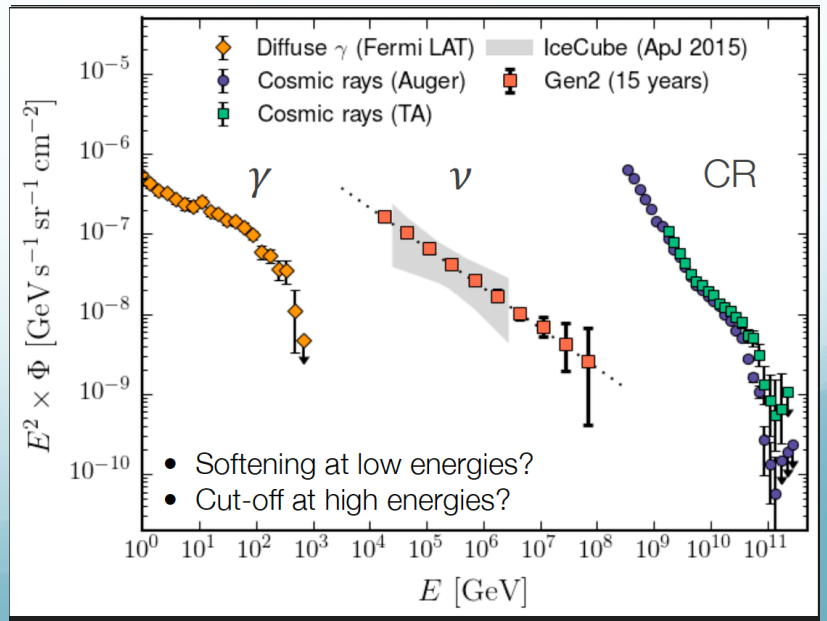

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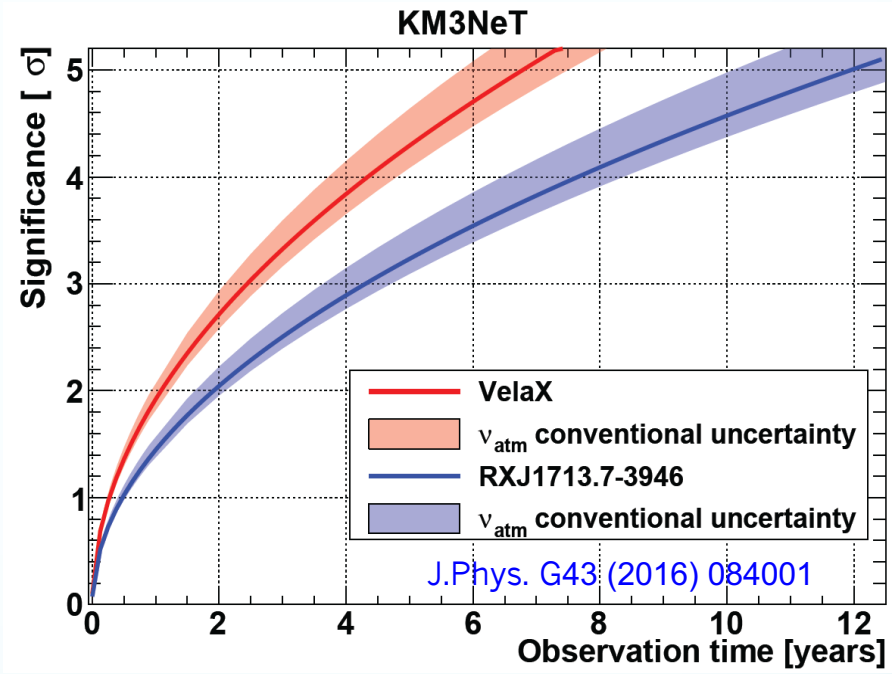
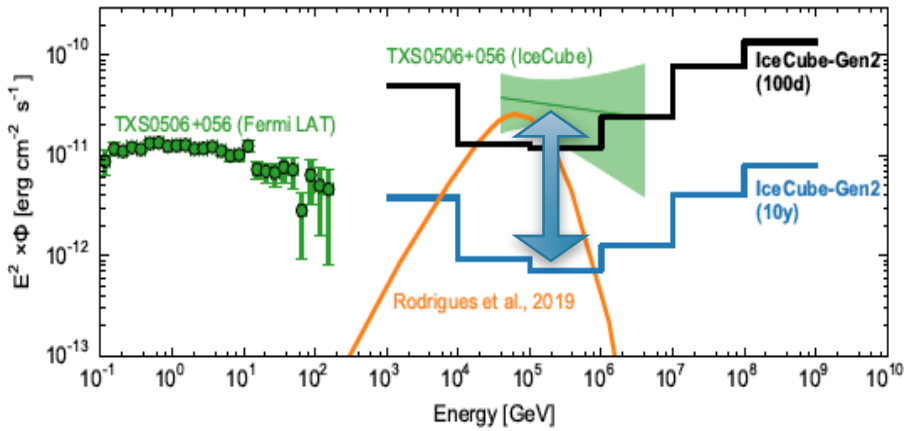
≥ order magnitude sensitivity @ any location

Constrain hadronic fraction





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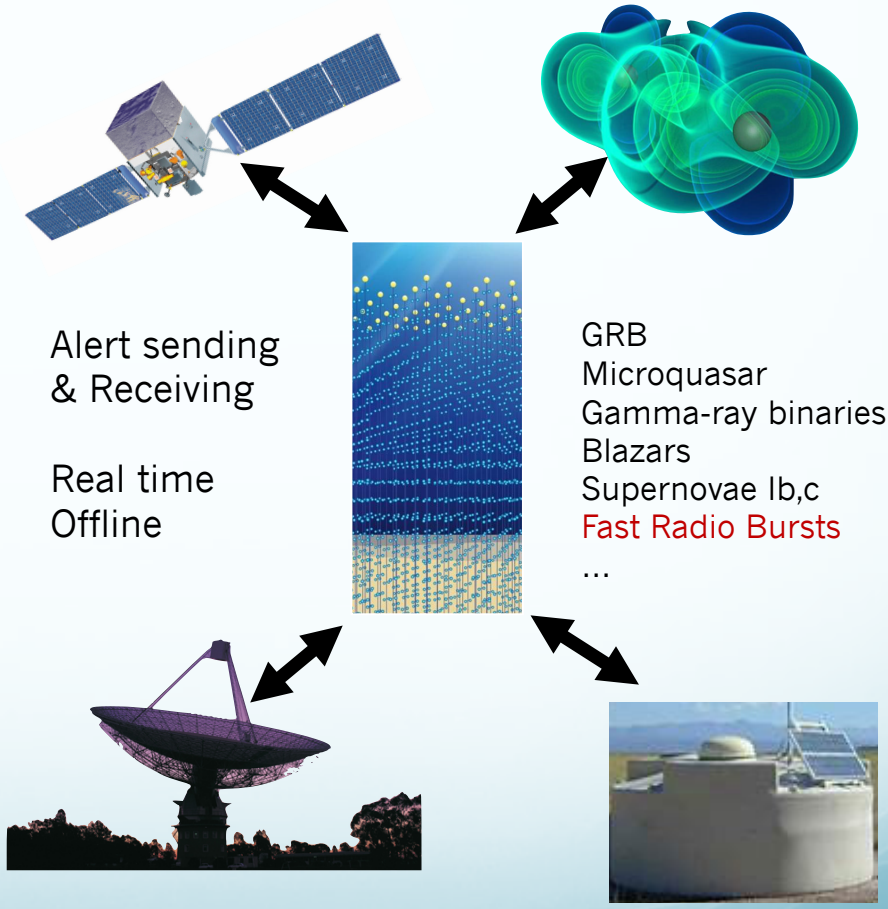

TXS 0506+056 found after MM coincidence !

What can we hope to learn ?

- Higher statistics Diffuse
- Galactic
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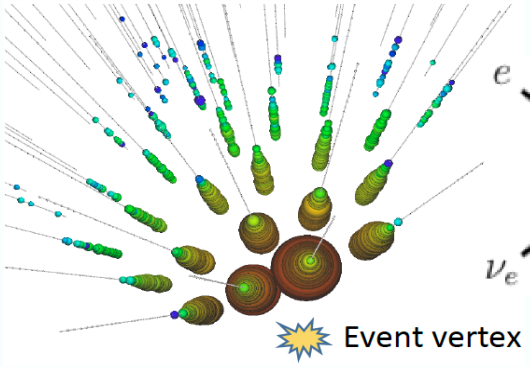
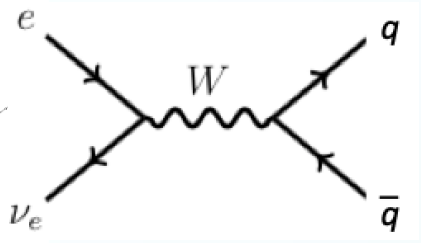
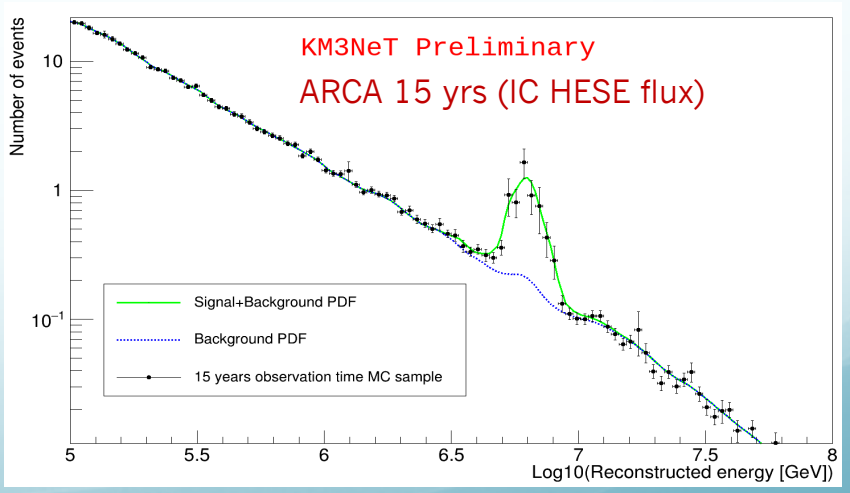
- Supernovae

First Glashow resonance
at 6.3 PeV seen by IC !

=







IC- Gen2 required for a large statistics sample

What can we hope to learn ?

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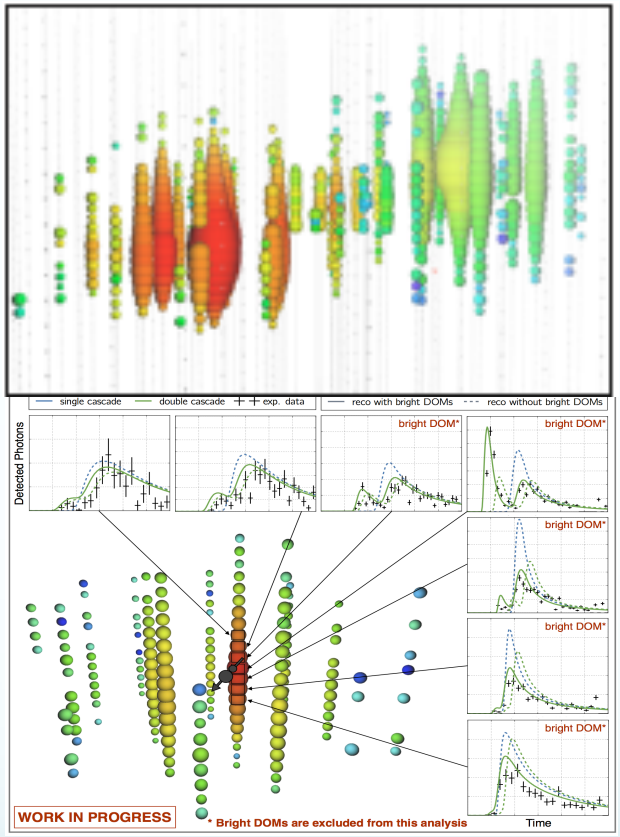
- Neutrino Physics
- Supernovae

Tau neutrinos : double bang



MC

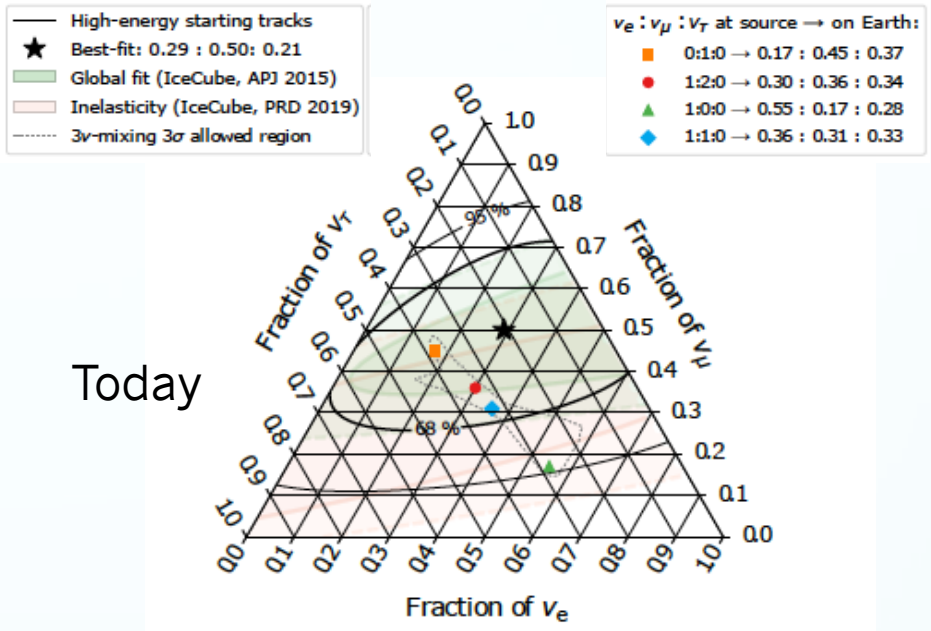
Data

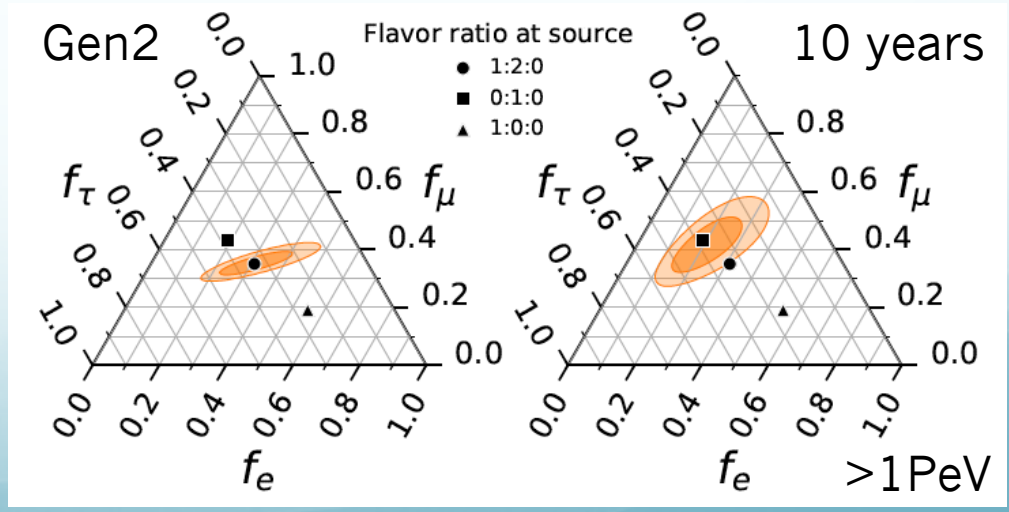
IC-Gen 2 >300 TeV : 1 event/year (optical)
Current IC 0.2 events/year

IC- Gen2 required for a large statistics sample

What can we hope to learn ?

- Higher statistics Diffuse
- Galactic
- Sources
- Multi-messengers
- Catalogues
- Flavor ID → New physics ?
- Neutrino Physics
- Supernovae





IGen2 Energy dependence of the flavor ratio (μ cooling)

The advent of neutrino radio astronomy

Below ~10 PeV, Cherenkov detectors dominate the landscape. No real alternative.

At higher energies, bigger acceptances are needed : e.g. radio techniques

→ Significant efforts in Antarctica

High altitude offers Large instantaneous Detection volume

Current best limit to the end of the spectrum

Two anomalous events with energy (~EeV) & zenith (~30°) hardly reconcilable

Stay tuned for PUEO, building on ANITA expertise 2023 on

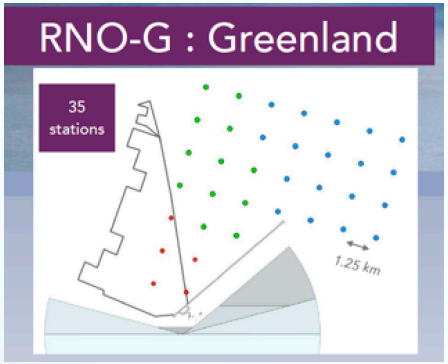
The advent of neutrino radio astronomy

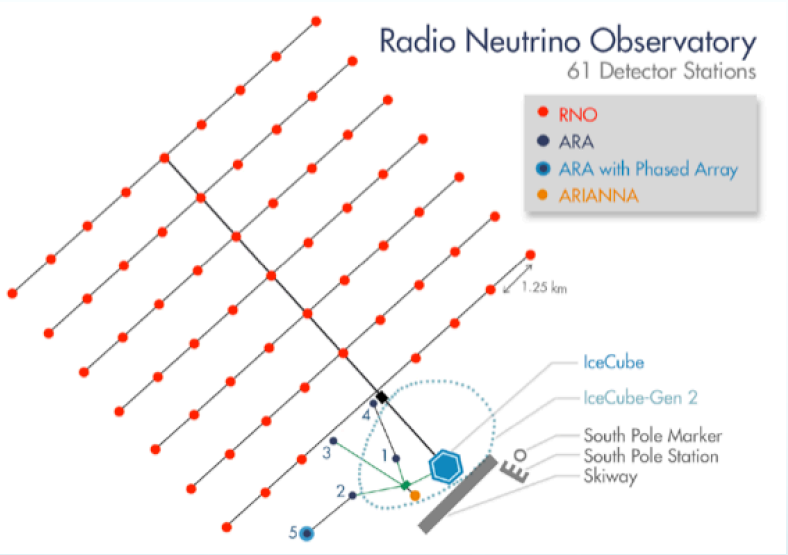
Below ~10 PeV, Cherenkov detectors dominate the landscape. No real alternative.

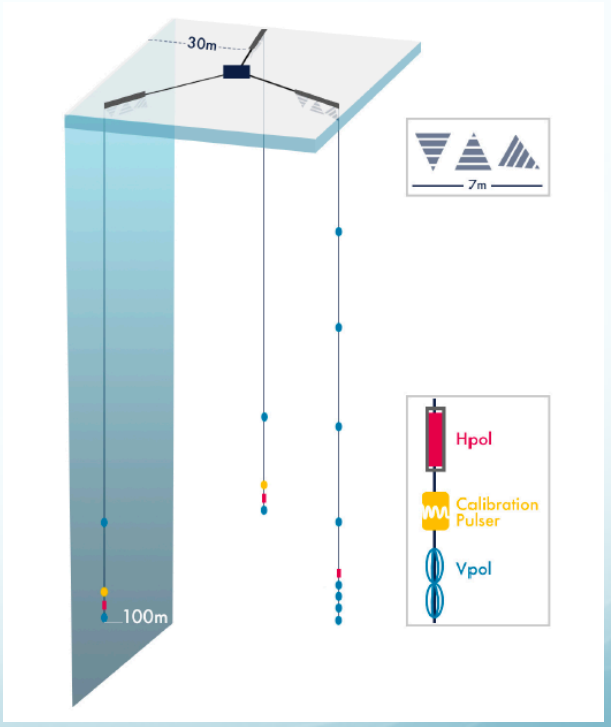
At higher energies, bigger acceptances are needed : e.g. radio techniques

→ Significant efforts in Antarctica

Preparatory R&D







- **Scalable to few 100 km²**
  Autonomous, low power, low cost, efficient & low threshold
- Hybrid Design builds on ARA & ARIANNA:
  - **Surface:**
    CRs, vetos, reconstruction
  - **Deep Phased Trigger:**
    Effective Volume

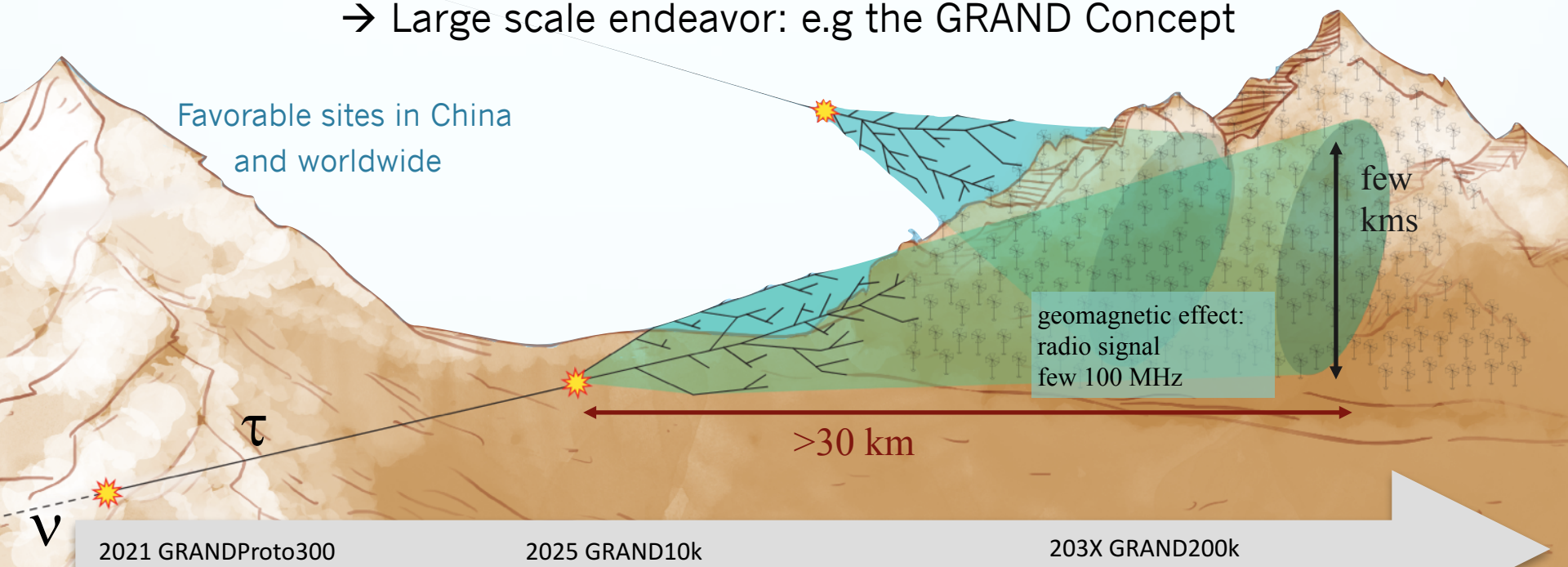
Talk by A. Nelles

The advent of neutrino radio astronomy

Below ~10 PeV, Cherenkov detectors dominate the landscape. No real alternative.

At higher energies, bigger acceptances are needed : e.g. radio techniques

→ Large scale endeavor: e.g the GRAND Concept



2021 GRANDProto300

- 300 antennas over 200 km²
- autonomous radio detection of very inclined air-showers
- cosmic rays $10^{16.5\text{-}18}$ eV
- 1.3 M€ (fully funded, China)

2025 GRAND10k

- 10^4 antennas over 10^4 km²
- 1st GRAND subarray
- discovery of EeV neutrinos for optimistic fluxes
- 13 M€ (mostly China)

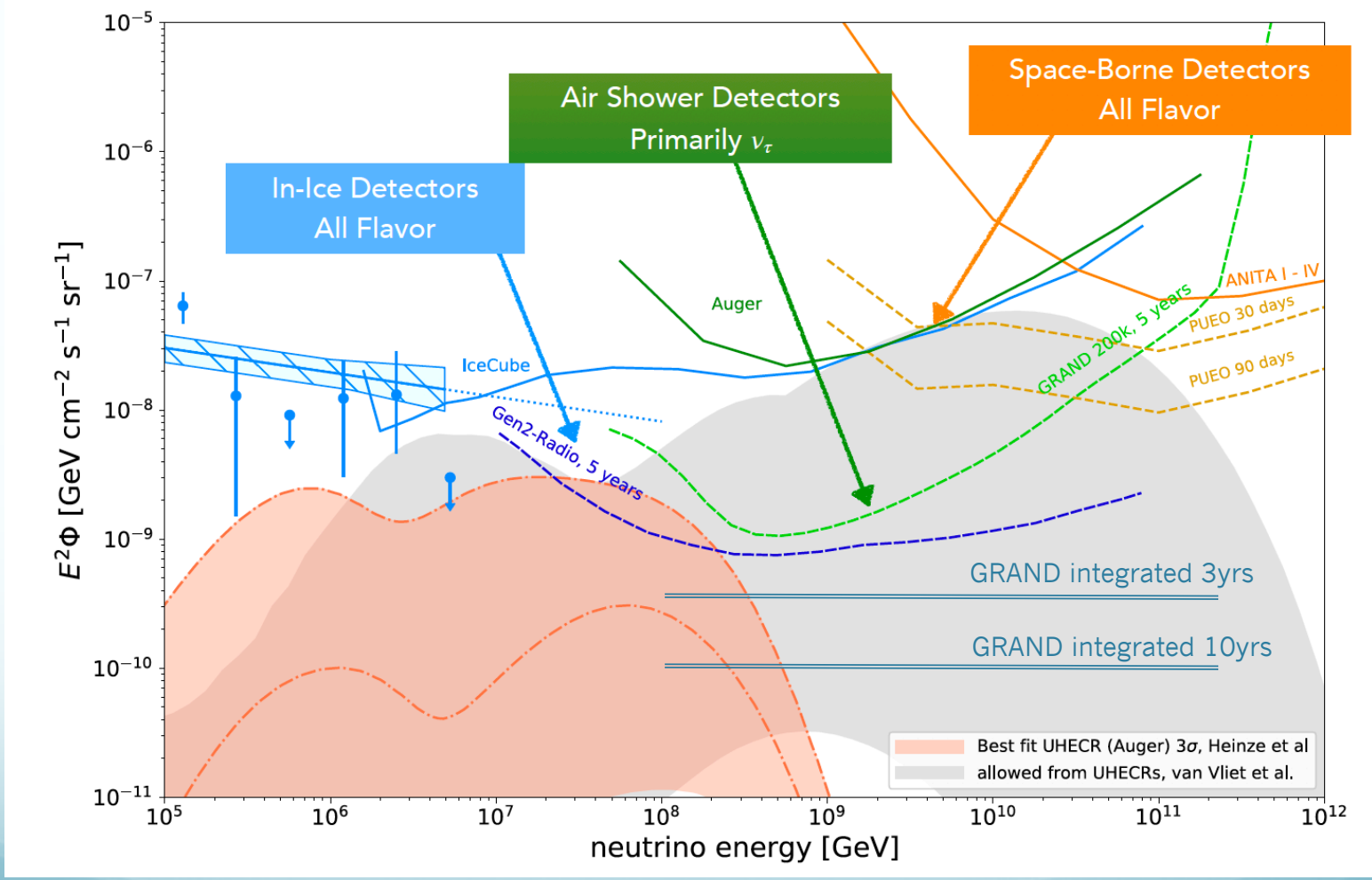
203X GRAND200k

- 200k antennas over 200k km²
- 20 sub-arrays of 10k antennas on different continents
- 1st EeV neutrino detection and/or neutrino astronomy!
- 150 M€

Talk by K. Kotera

Next Generation Radio Detectors

will probe the composition of UEHCRs and search for sources



Additional Challenges: open science

Meet the astrophysics standards (a cultural change requiring new resources)

GW community has taken the step:

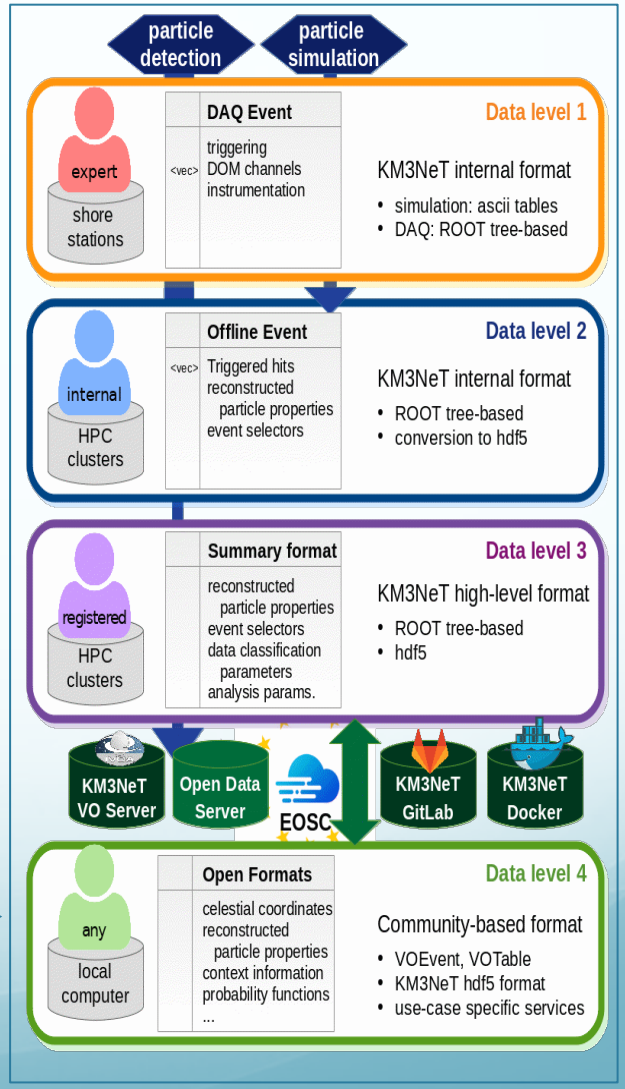
(e.g. 1.5 Virgo FTE)

Gravitational Wave Open Science Center

- Whole science-run data and GW event catalogs
  - Downloads: 60 TB/week peak
  - 80+ papers using open data
- Documentation, usage recommendation
- Online training: video tutorials and Jupyter notebooks

IceCube (and ANTARES) have released data but related to specific studies.
Additional efforts needed.

New generation detectors must improve → *KM3NeT scheme*



Additional Challenges: citizen science

Initiated by S. Katsanevas

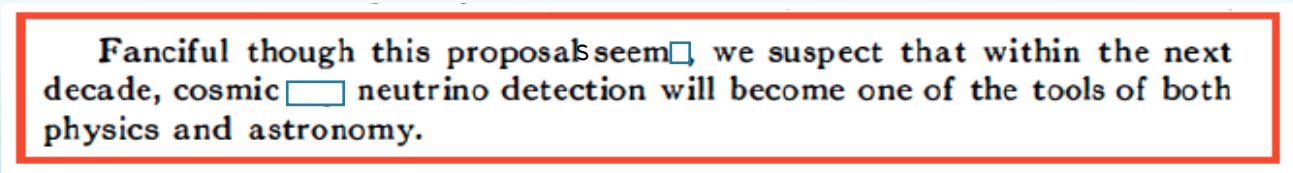
Summary

- IceCube has truly opened the field of neutrino astronomy
  - A first source identified (compelling evidence).
  - Plans for a MeV-EeV Observatory at South Pole – Order of magnitude more neutrinos !
- Deep Sea Cherenkov detectors
  - Excellent performances achieved by ANTARES, view of Southern sky
  - New generation detectors (KM3NeT) in construction.

GNN

- Lake Baikal on its way to host a km-scale detector
- End of 2020's: Hope to have >5 km^3 both in the North (GVD-2 and full ARCA) and in the South (IceCube Gen2)
- Promising Radio techniques to investigate the highest energy domain

Greisen 1960


Fanciful though this proposal seem[redacted], we suspect that within the next decade, cosmic [redacted] neutrino detection will become one of the tools of both physics and astronomy.

→ Exciting decade ahead with neutrinos as key players in MM era

Masatoshi Koshiba 1926-2020

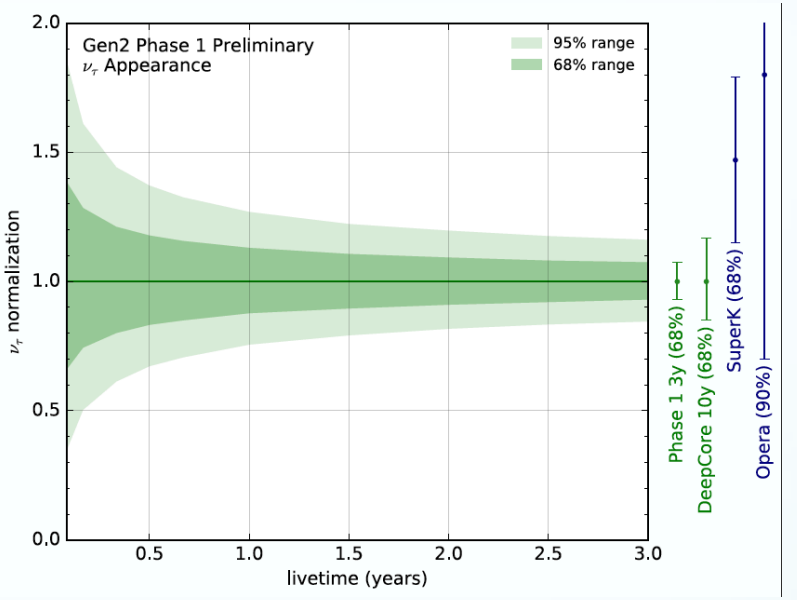
Nobel Prize in Physics in 2002

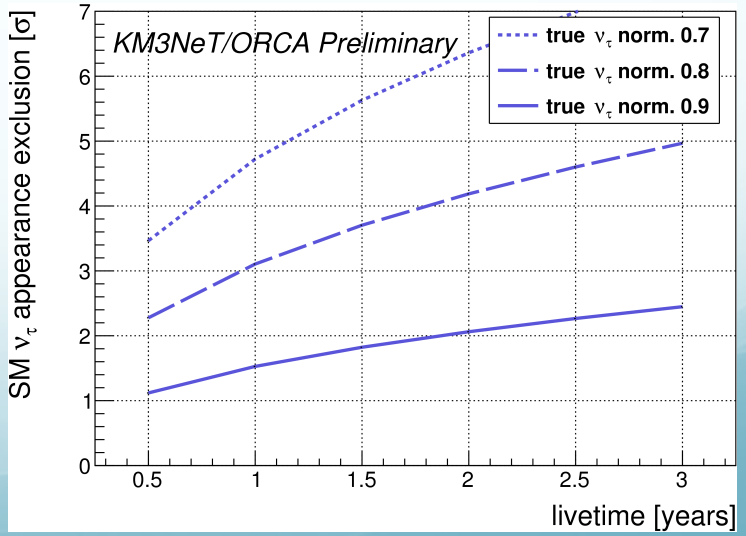
"for pioneering contributions to
astrophysics, in particular
for the detection of cosmic neutrinos."

What can we hope to learn ?

- Higher statistics Diffuse
- Galactic
- Sources
- Multi-messengers
- Catalogues
- Flavor ID → Probe New physics
- Neutrino Physics
- Supernovae

Probe PMNS matrix unitarity





What can we hope to learn ?

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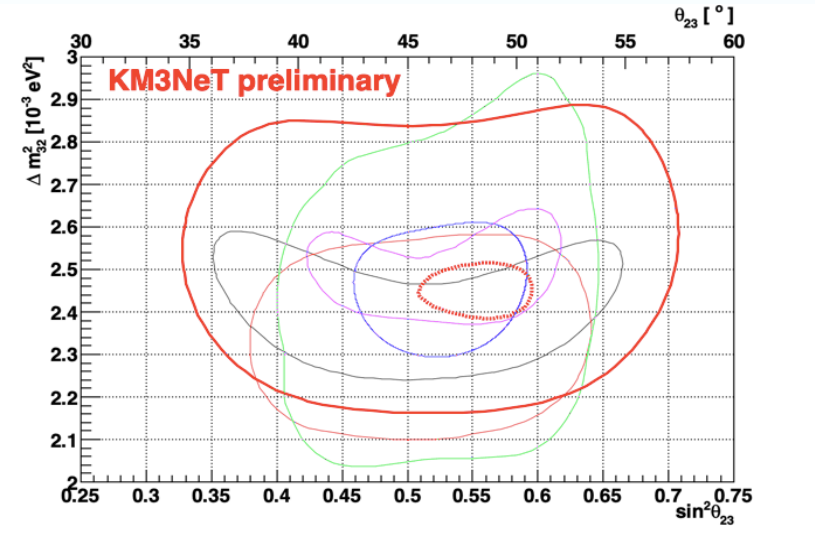
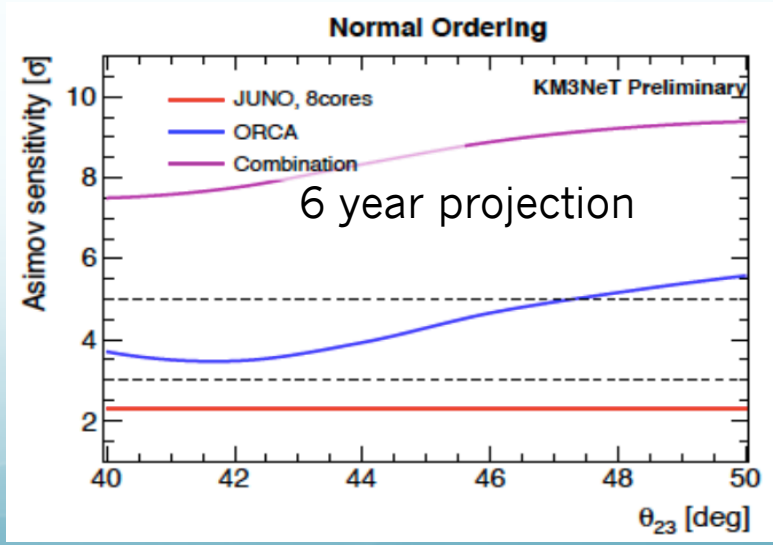
- Supernovae

90% CL contours for oscillation parameters
SuperKamiokande T2K NOvA IceCube MINOS
Sensitivity: ORCA-2019/20 ORCA115-3yr





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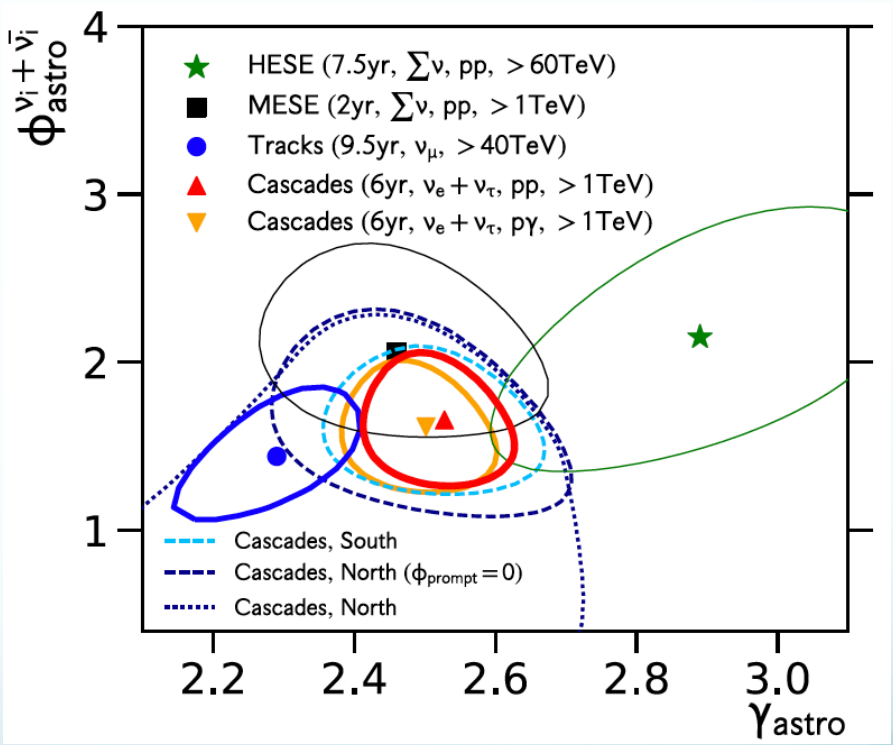
The single power-law paradigm

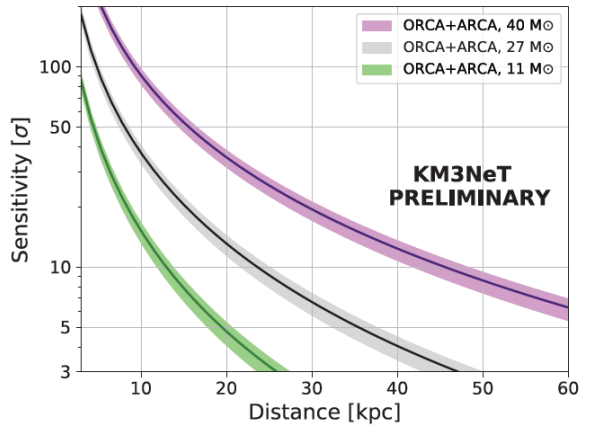


Is there a spectral break ?
Is there a North/South difference ?
Galactic Contribution? → KM3NeT, GVD

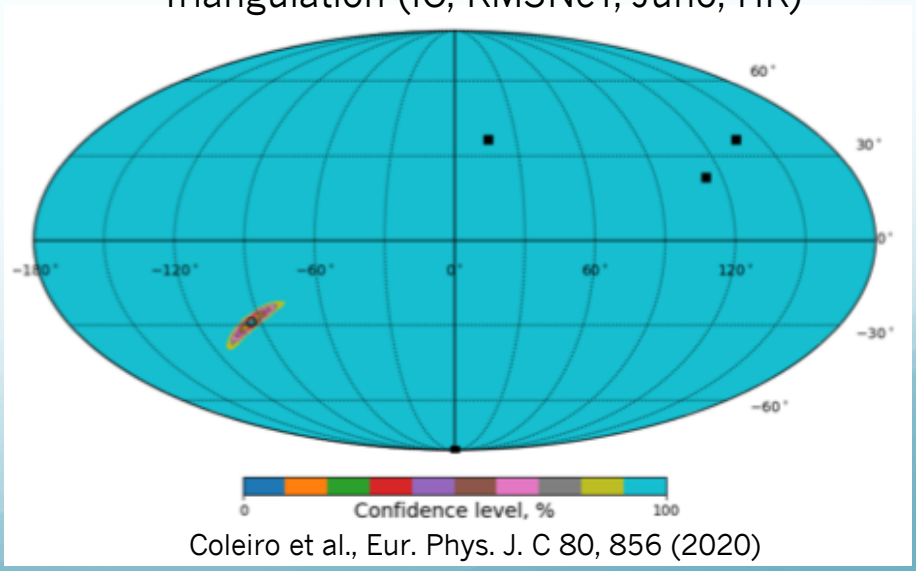
What can we hope to learn ?

- Higher statistics Diffuse
- Galactic
- Sources
- Multi-messengers
- Catalogues
- Flavor ID
- Neutrino Physics
- Supernovae

IC-Gen2 horizon @ 300 kpc, all progenitor masses



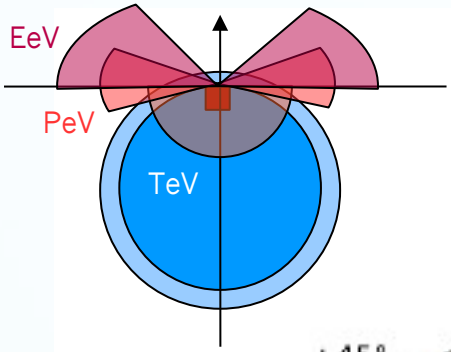
Triangulation (IC, KM3NeT, Juno, HK)



Coleiro et al., Eur. Phys. J. C 80, 856 (2020)

Towards a worldwide network

PeV ("background – free") coverage



"Neutrino telescopes, existing and under construction, around the globe with their horizontal coverage from which high energy neutrinos will not be affected by the Earth absorption. (Credit: M. Huber/TU)" -- https://www.pacific-neutrino.org

What can we hope to learn ?

- Higher statistics Diffuse
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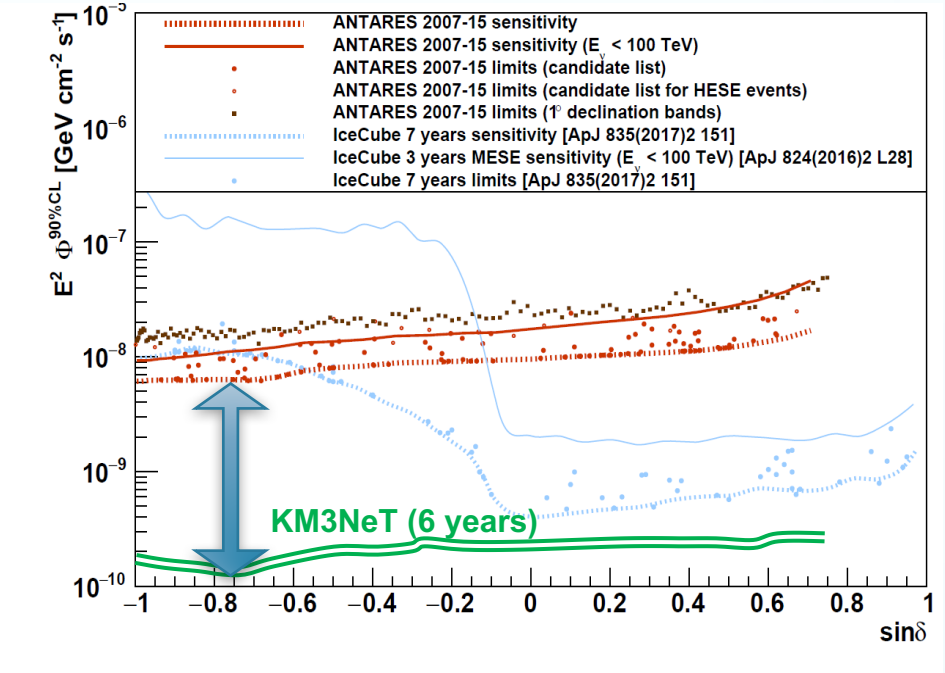
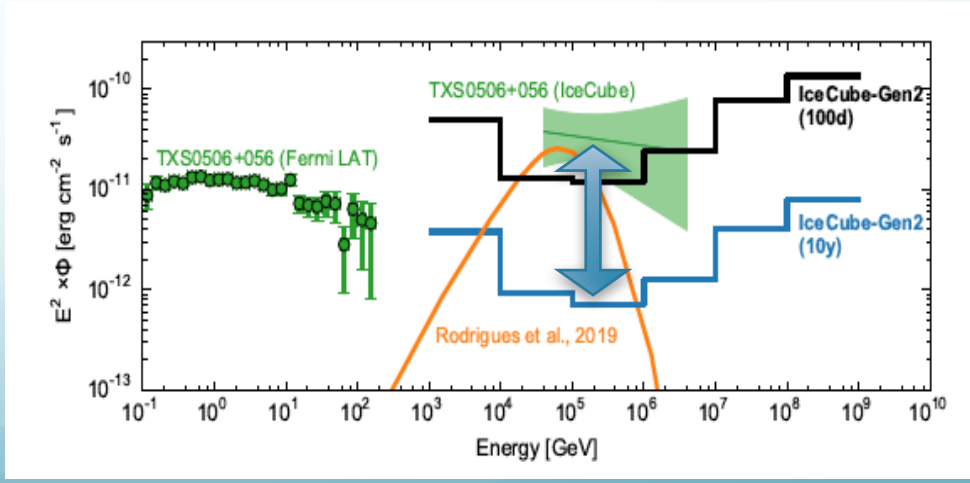
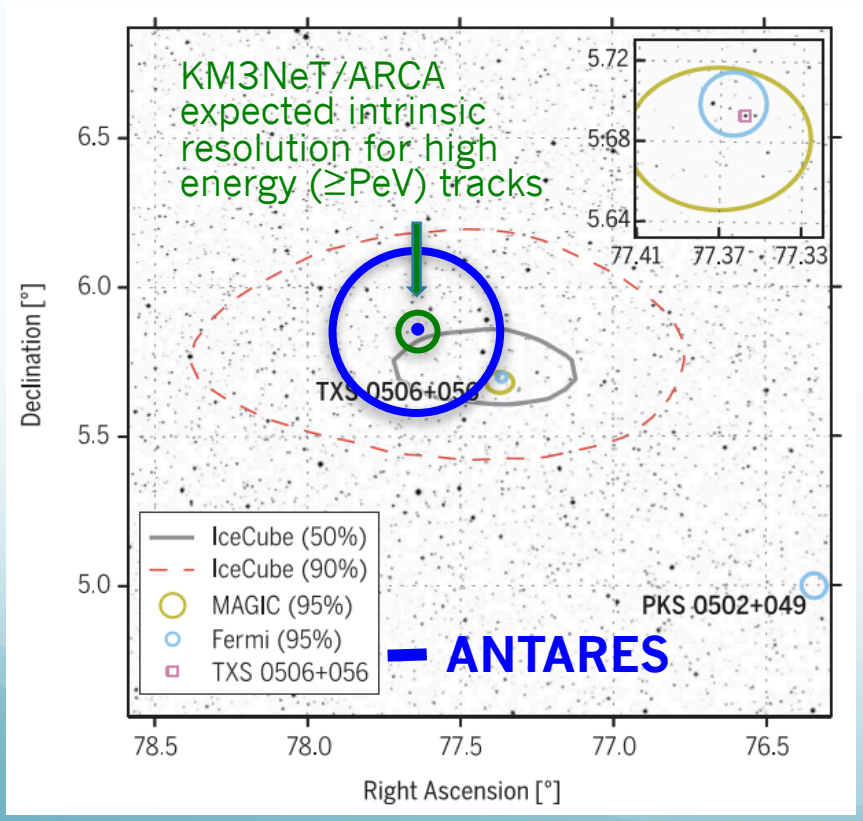




Some Complementarities

- **Distinct medium, distinct systematics**
  - Good angular resolution helps enormously in source association
  - Multi-messenger context.

Science 13 Jul 2018: Vol. 361, Issue 6398, 1378



Bartos et al. Phys.Rev.D 96 (2017) 2, 023003

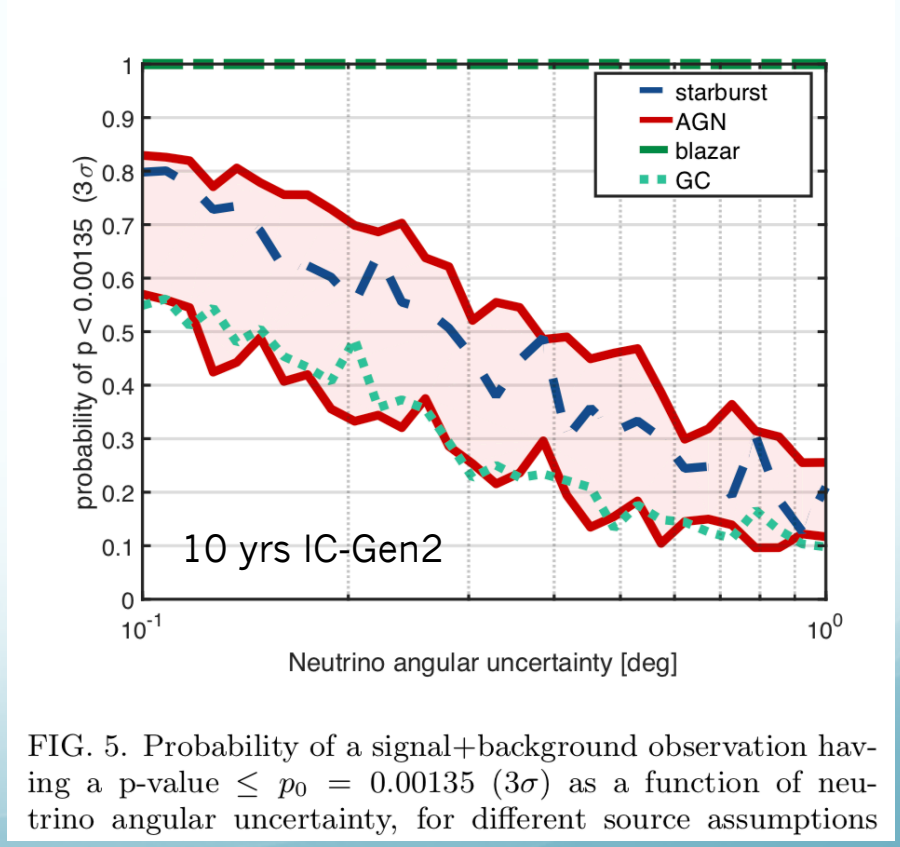
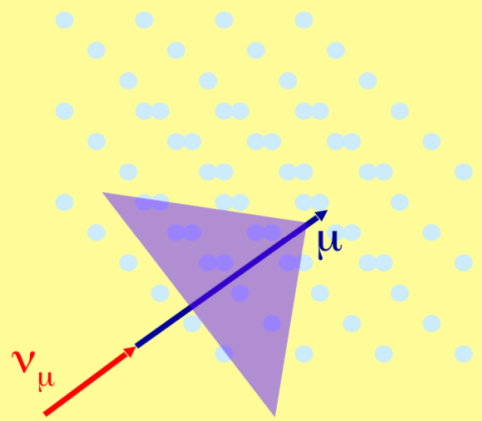


FIG. 5. Probability of a signal+background observation having a p-value $\leq p_0 = 0.00135$ (3σ) as a function of neutrino angular uncertainty, for different source assumptions

Detection techniques

1 TeV — 100 PeV — 1000 ZeV

Optical Detection (IceCube-KM3NeT)



Medium: Seawater, Polar Ice

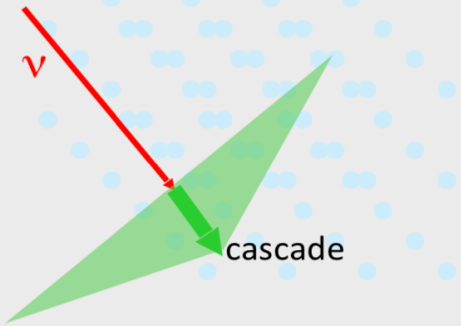
ν_μ (throughgoing and contained)

$\nu_{e,\tau}$ (contained cascades)

Carrier: Cherenkov Light (UV-visible)
Attenuation length: 100 m

Sensor: PMTs
Instrumented Volume: 1 km³

Radio Detection (Anita, Arianna, Ara, …)



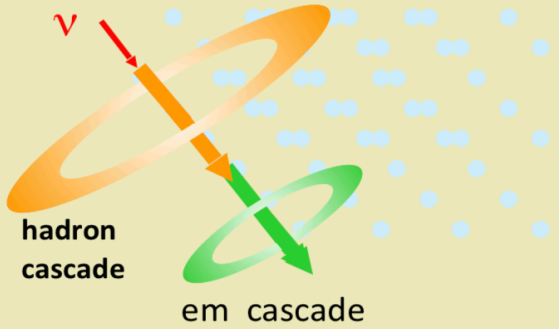
Medium: Polar ice, Salt domes

ν (cascades)

Carrier: Cherenkov Radio
Attenuation length: 1 km

Sensors: Antennas
Instrumented Volume: >1 km³

Acoustic Detection (prototypes)



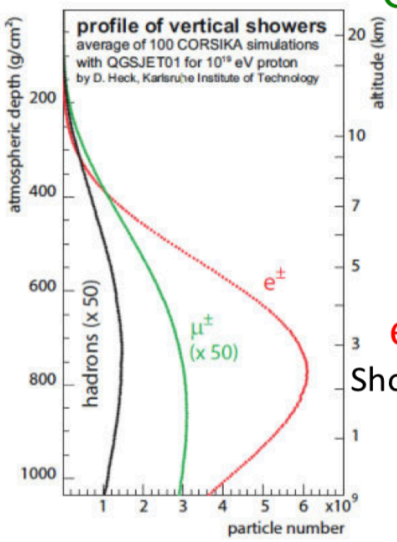
Medium: Seawater, Polar Ice

ν (cascades)

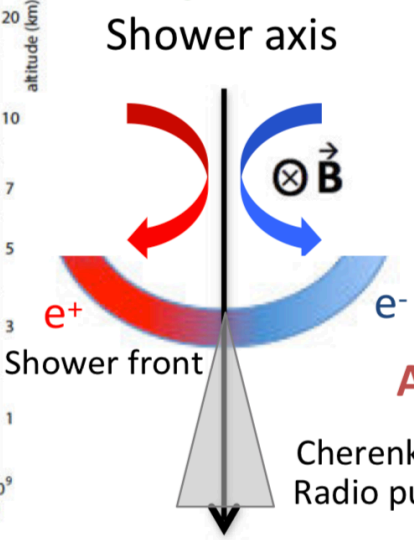
Carrier: Sound waves (tens kHz)
Attenuation length: few km

Hydro-phones
Instrumented Volume: >10 km³

Radio Arrays



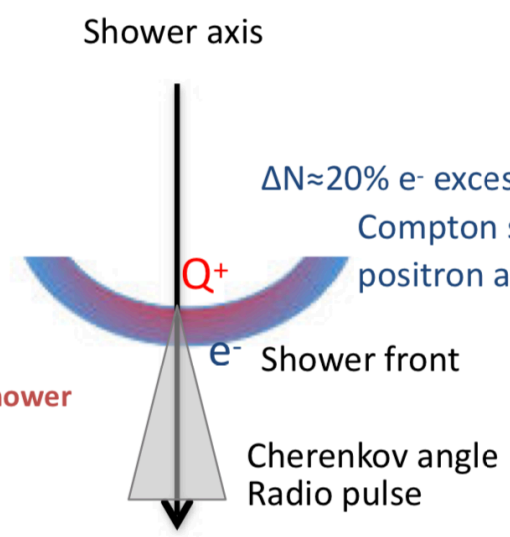
Geomagnetic radiation



Dielectric medium

$A_{radio\ pulse} \propto \Delta N \propto E_{shower}$

Askarian radiation



Air

extended cascades, large shower front

$R_{Moliere}$ ≈O(100 m), R_{core}≈O(10 m) →f ≈10 MHz: 100 MHz

L ≈ O(km)

Cherenkov angle≈ 1°

Geomagnetic effect dominates (≈80%)

large B → intense radio emission

Linear polarisation (direction of F_{Lorenz})

Radio absorption negligible