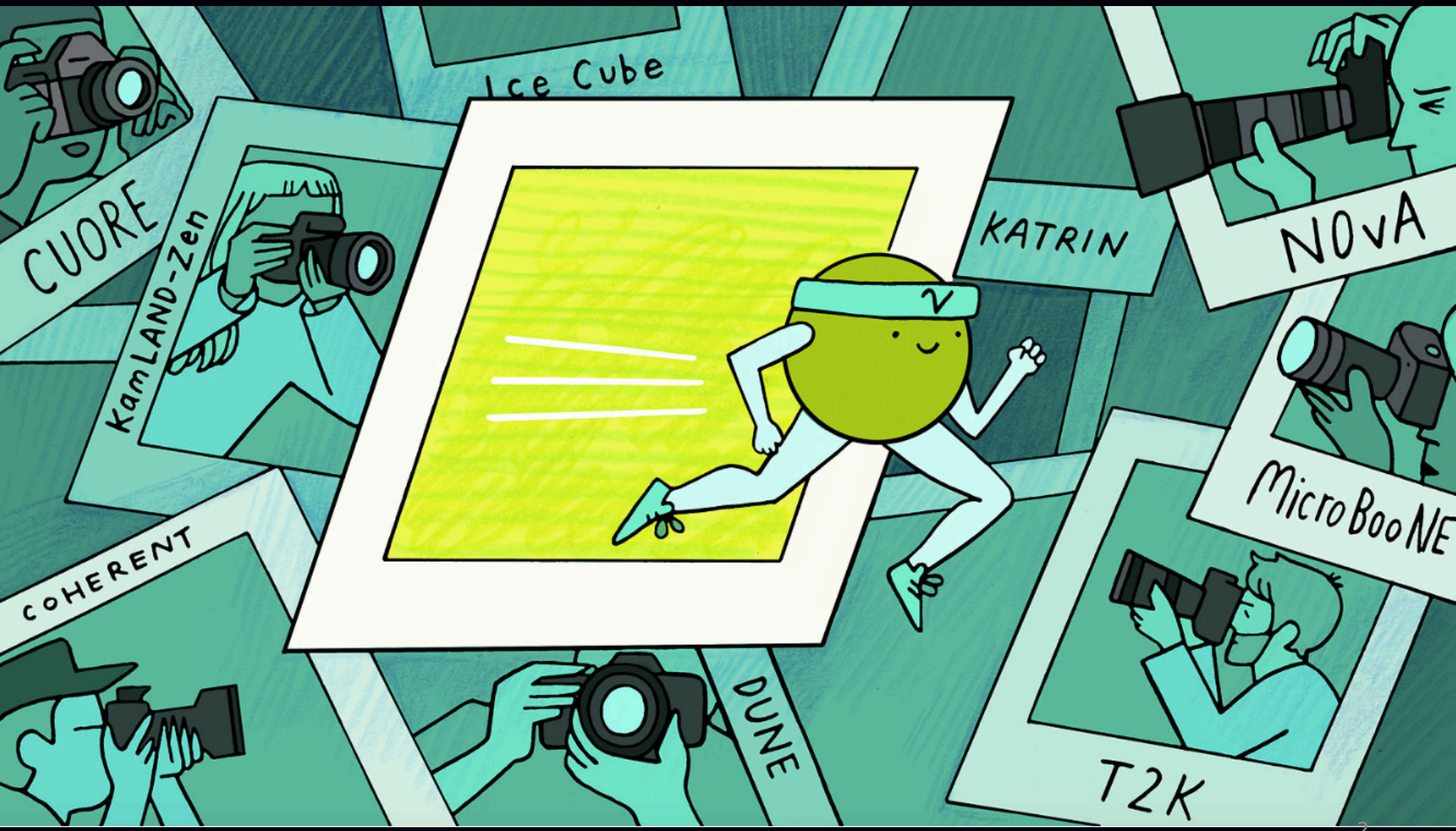
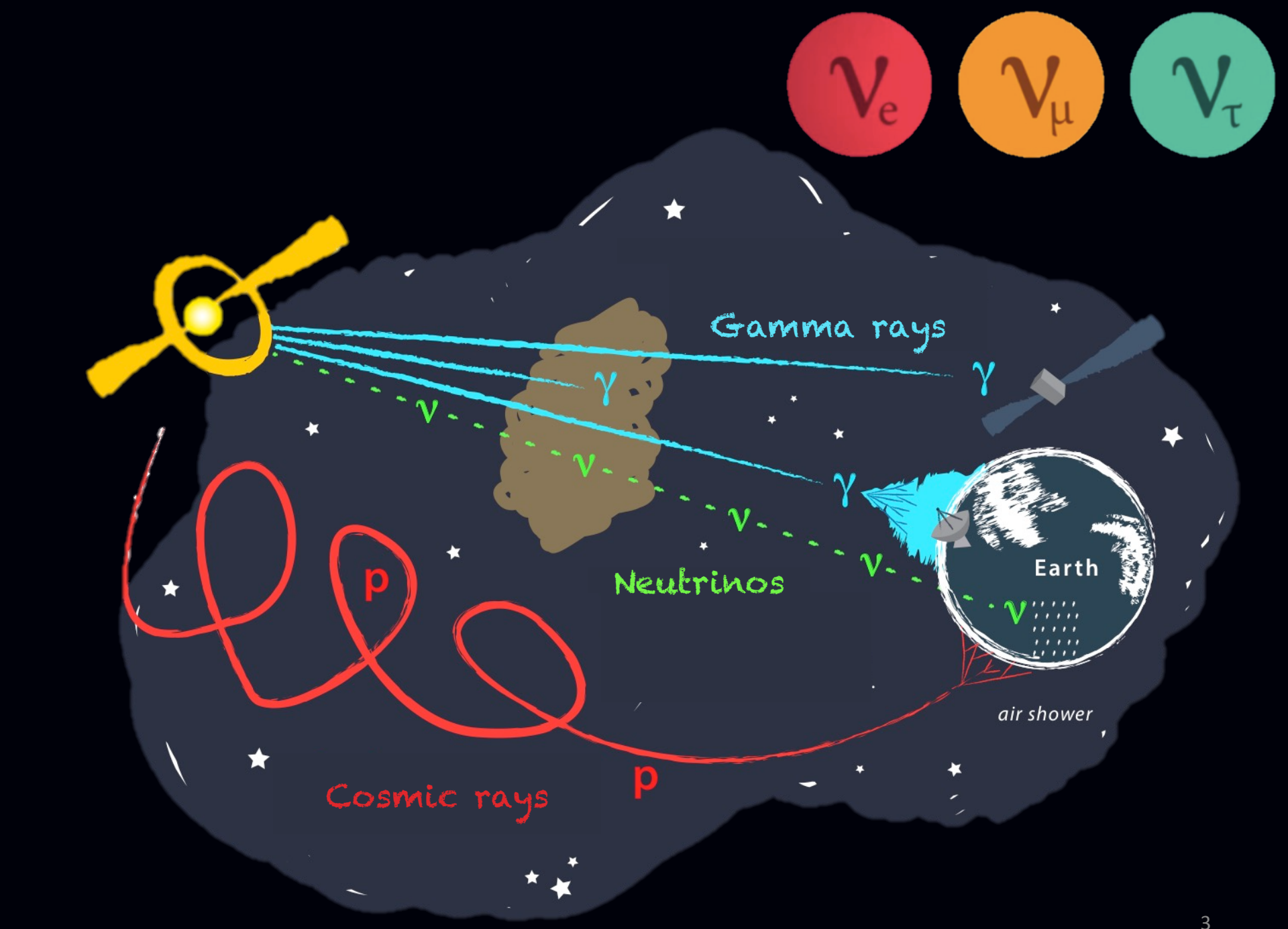
High-Energy Neutrino Astronomy: Current Status and Prospects

Gwenhaël de Wasseige

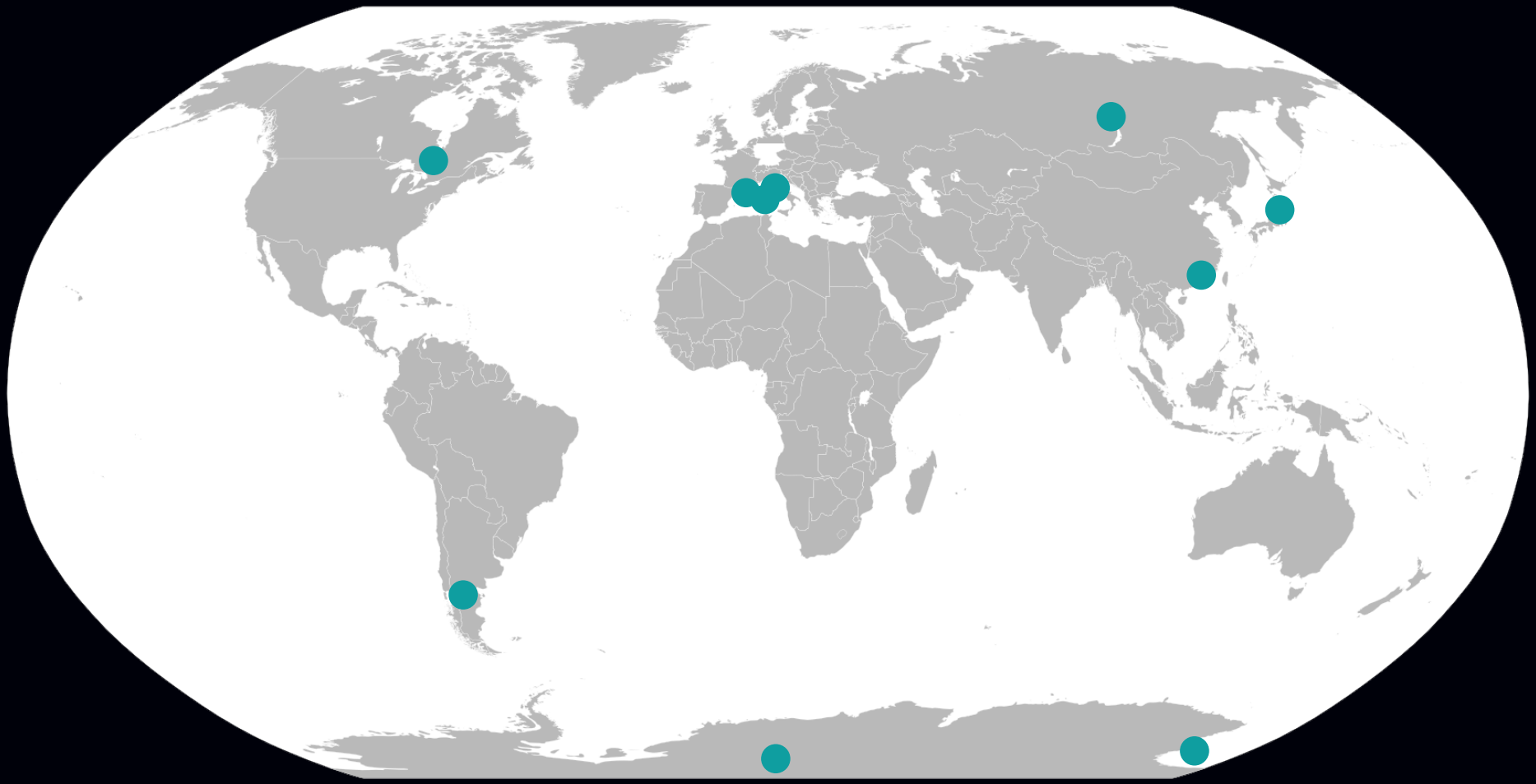
APC, CNRS, FRANCE



Symmetry magazine

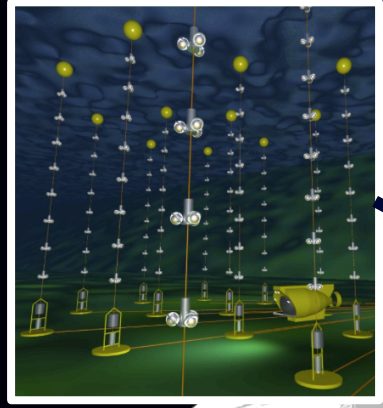

ν_e
ν_μ
ν_τ
Gamma rays
γ
γ
γ
ν
ν
ν
ν
ν
Neutrinos
Earth
p
p
Cosmic rays
air shower

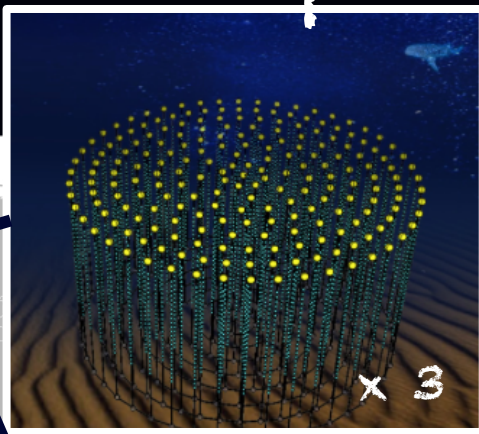
Neutrino telescopes

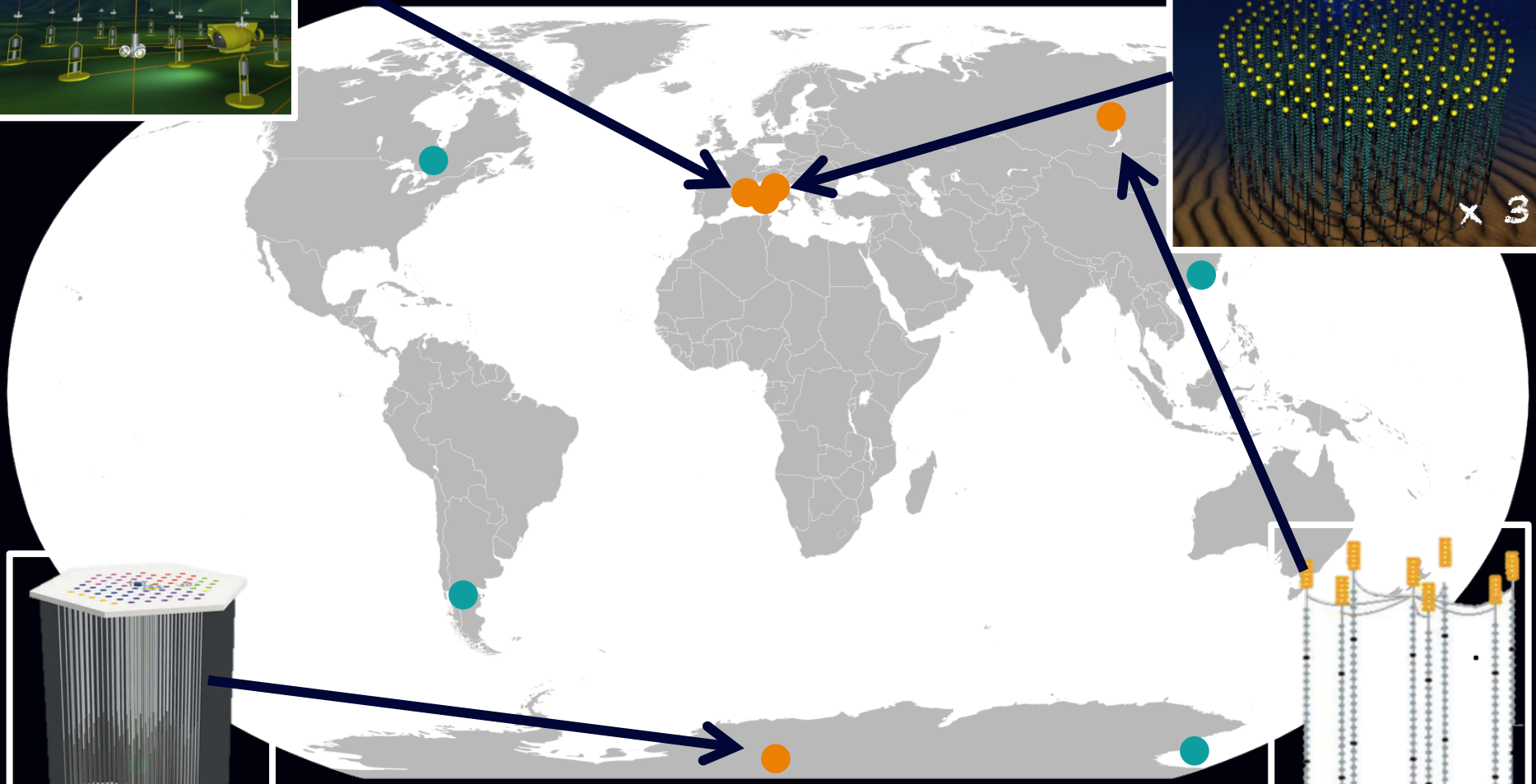


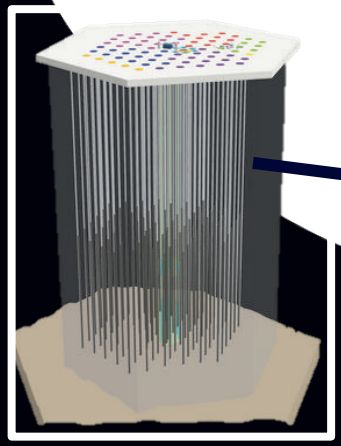
Non-exhaustive list

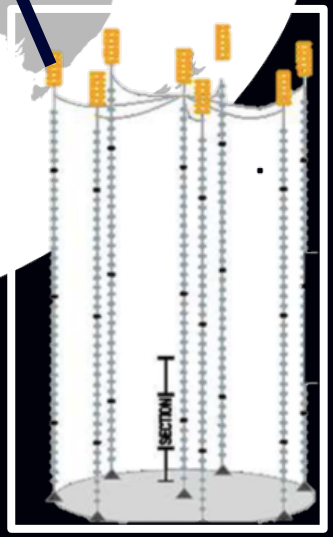
Neutrino telescopes







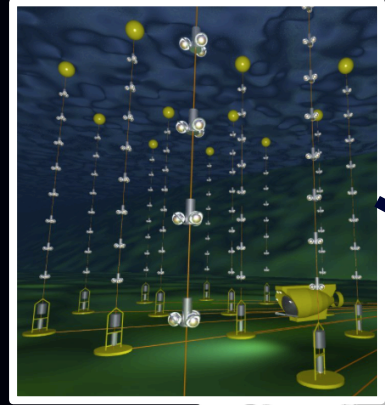




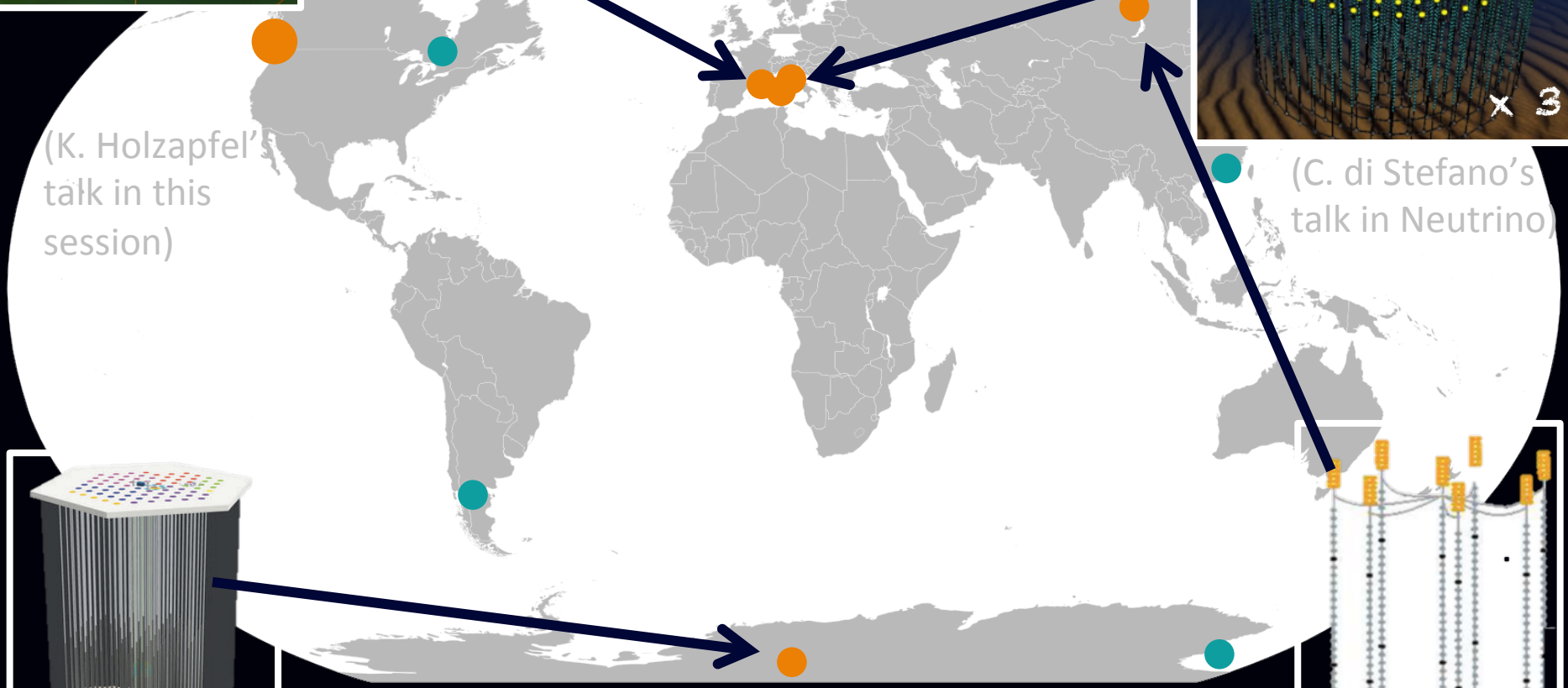
GNN
The Global Neutrino Network

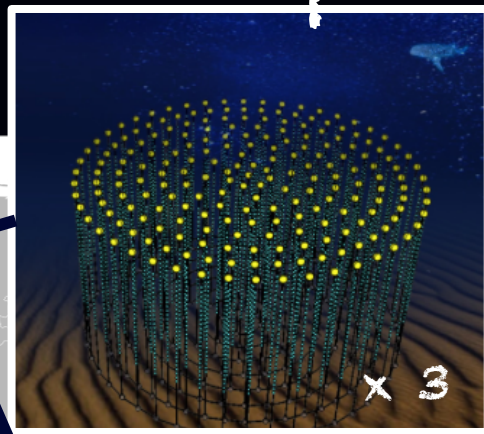
Non-exhaustive list

Neutrino telescopes



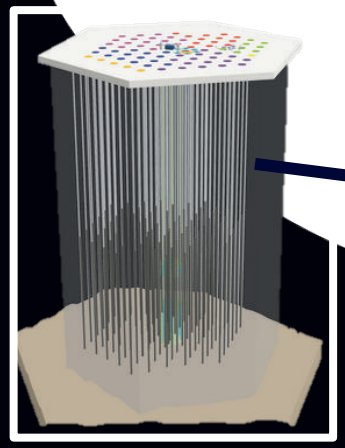
(T. Chiarusi's talk on Saturday)

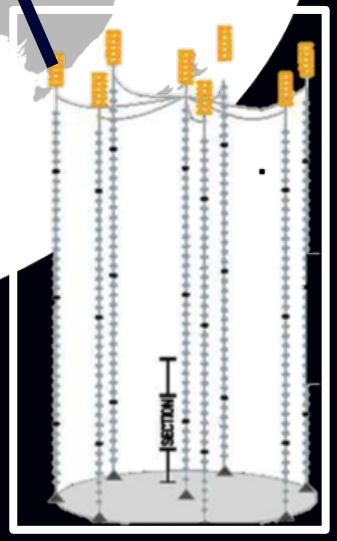




(C. di Stefano's talk in Neutrino)

(K. Holzapfel's talk in this session)

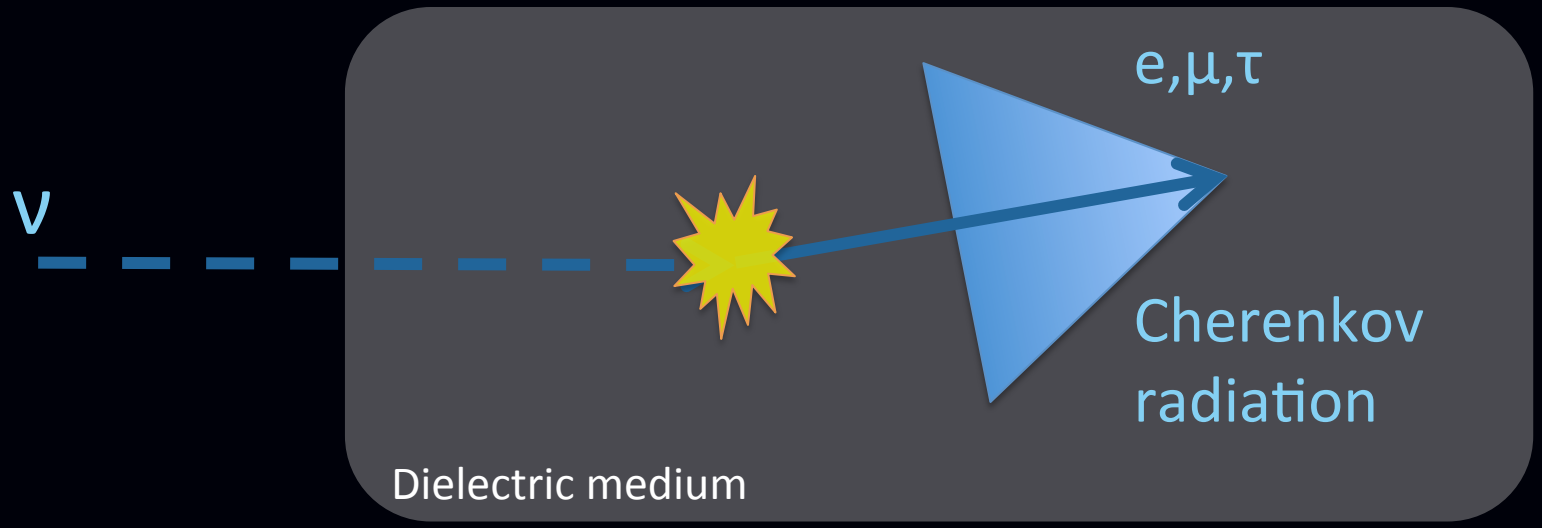


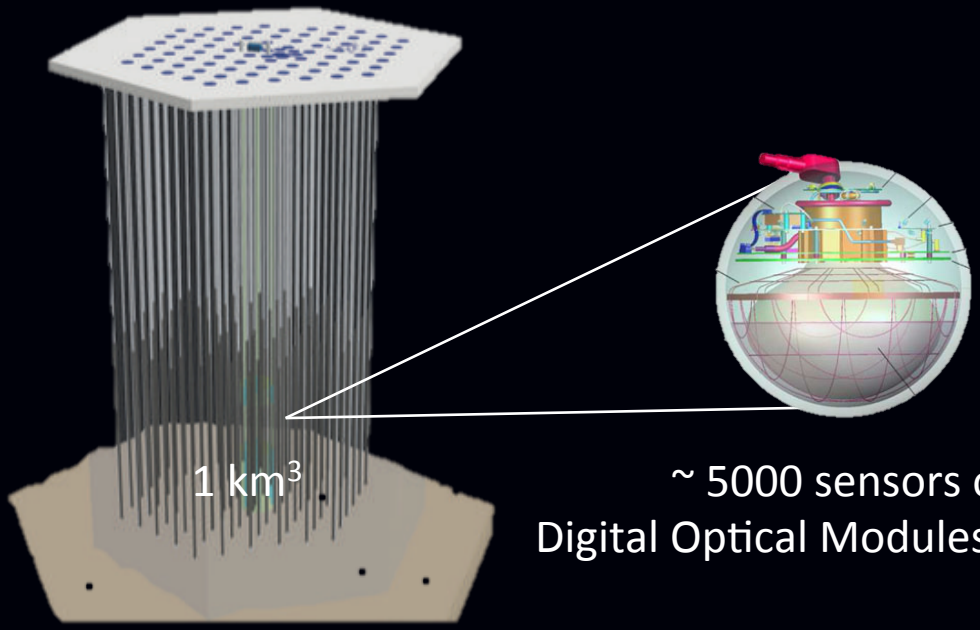


(O. Suvorova's talk in this session) x 8

Non-exhaustive list

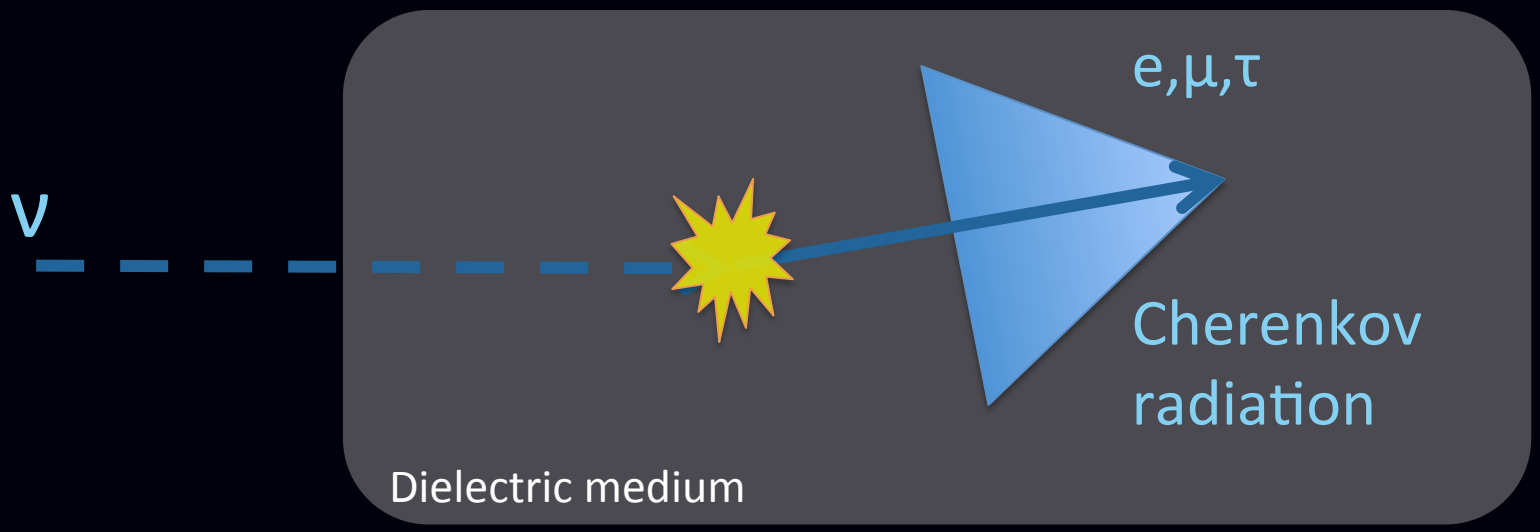
How to detect high-energy neutrinos?

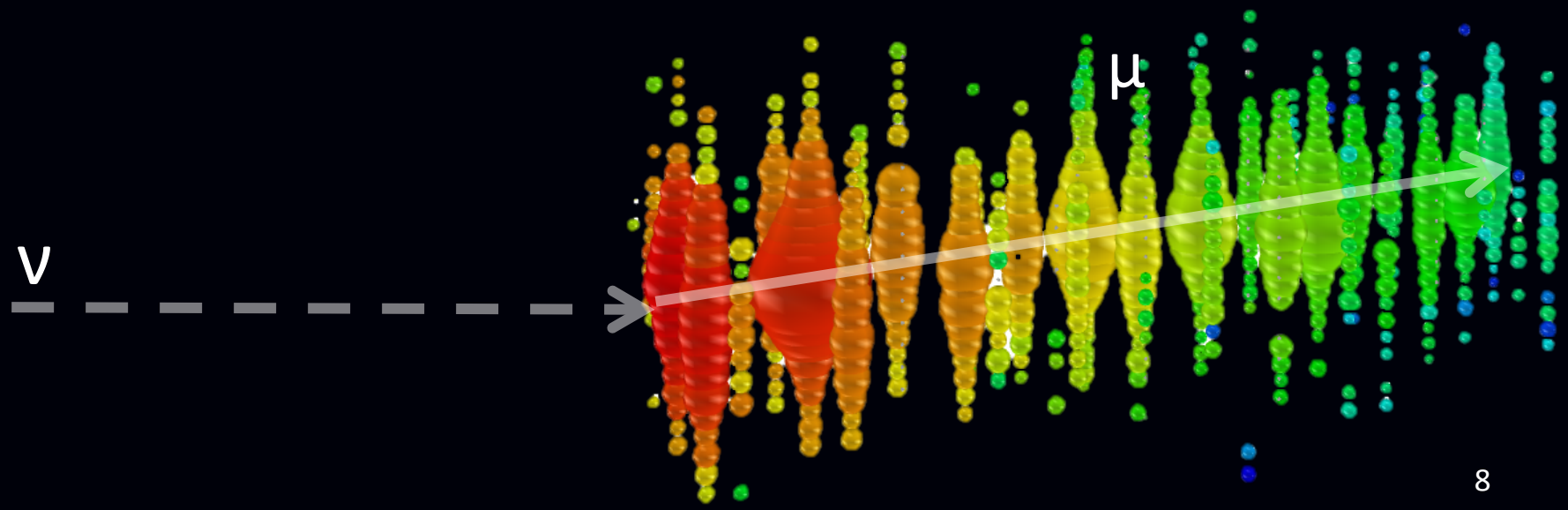




~ 5000 sensors or
Digital Optical Modules (DOMs)

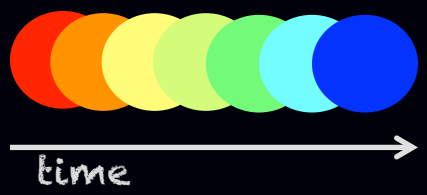
How to detect high-energy neutrinos?

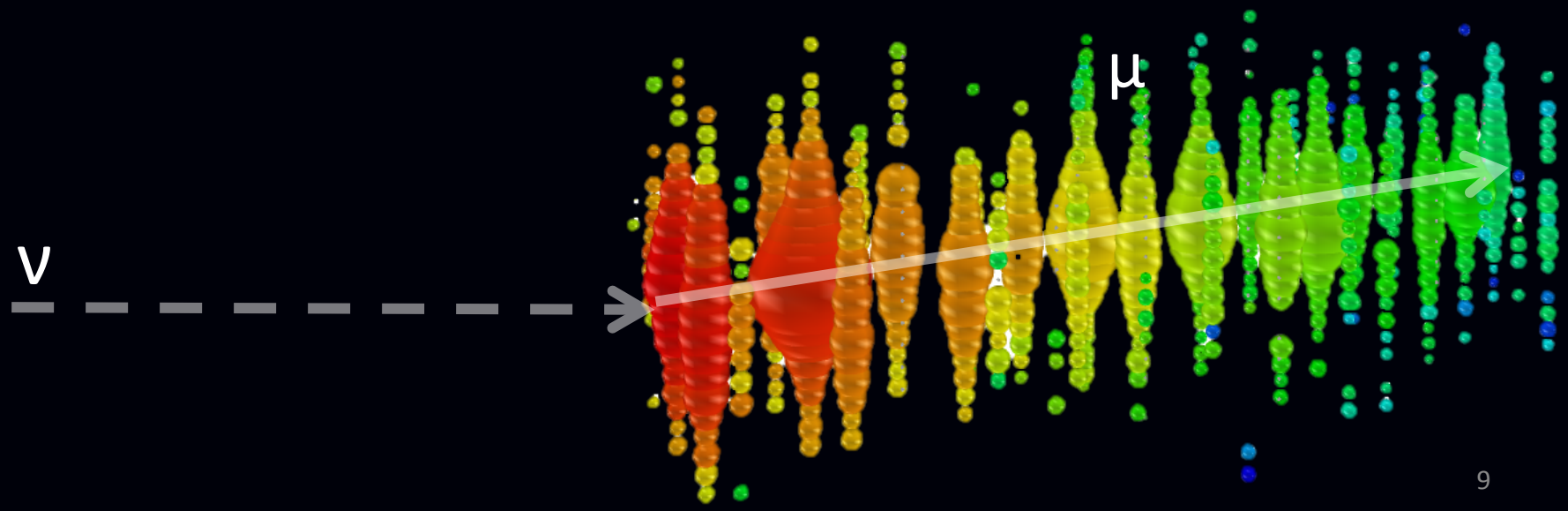


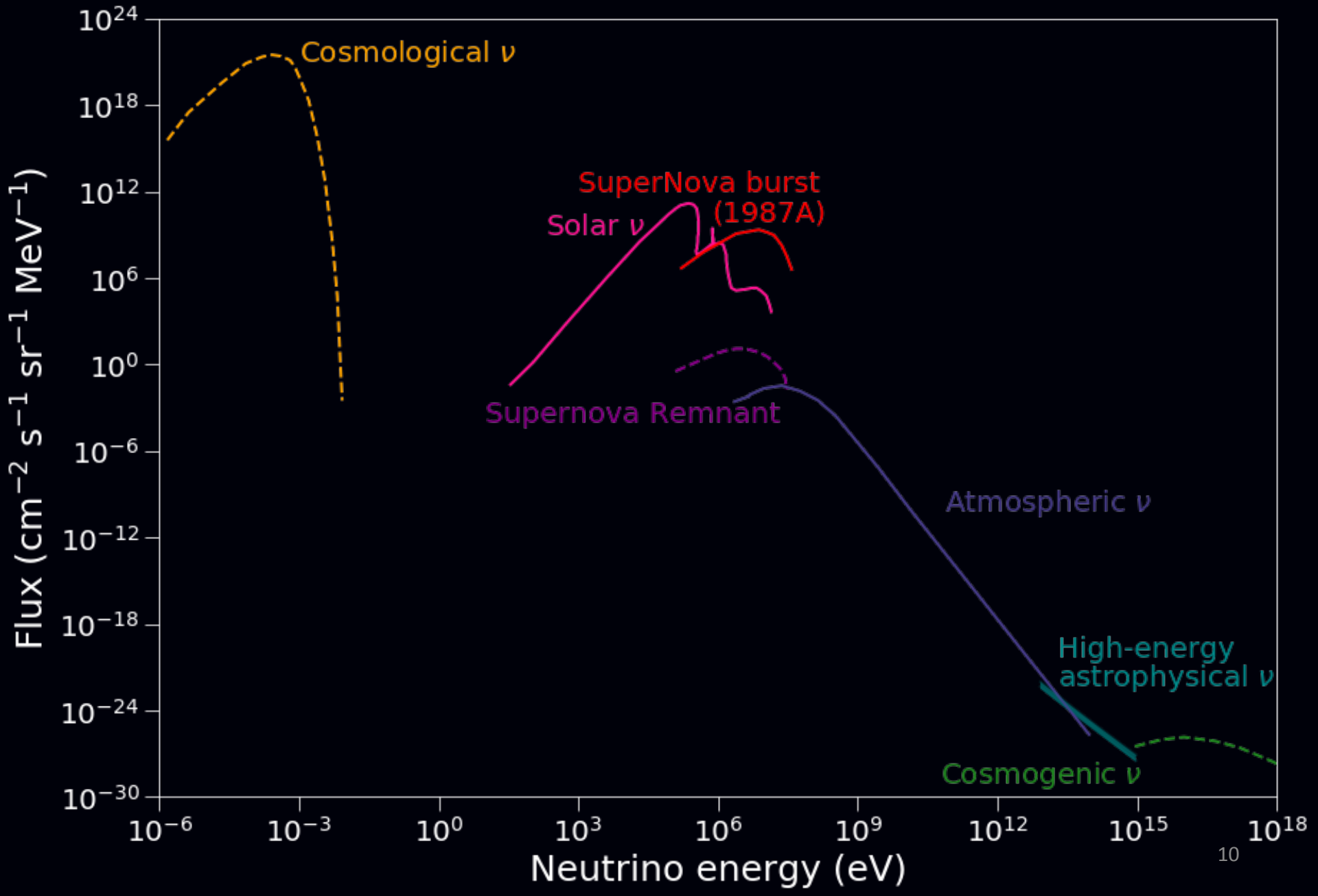


Which information can we get?

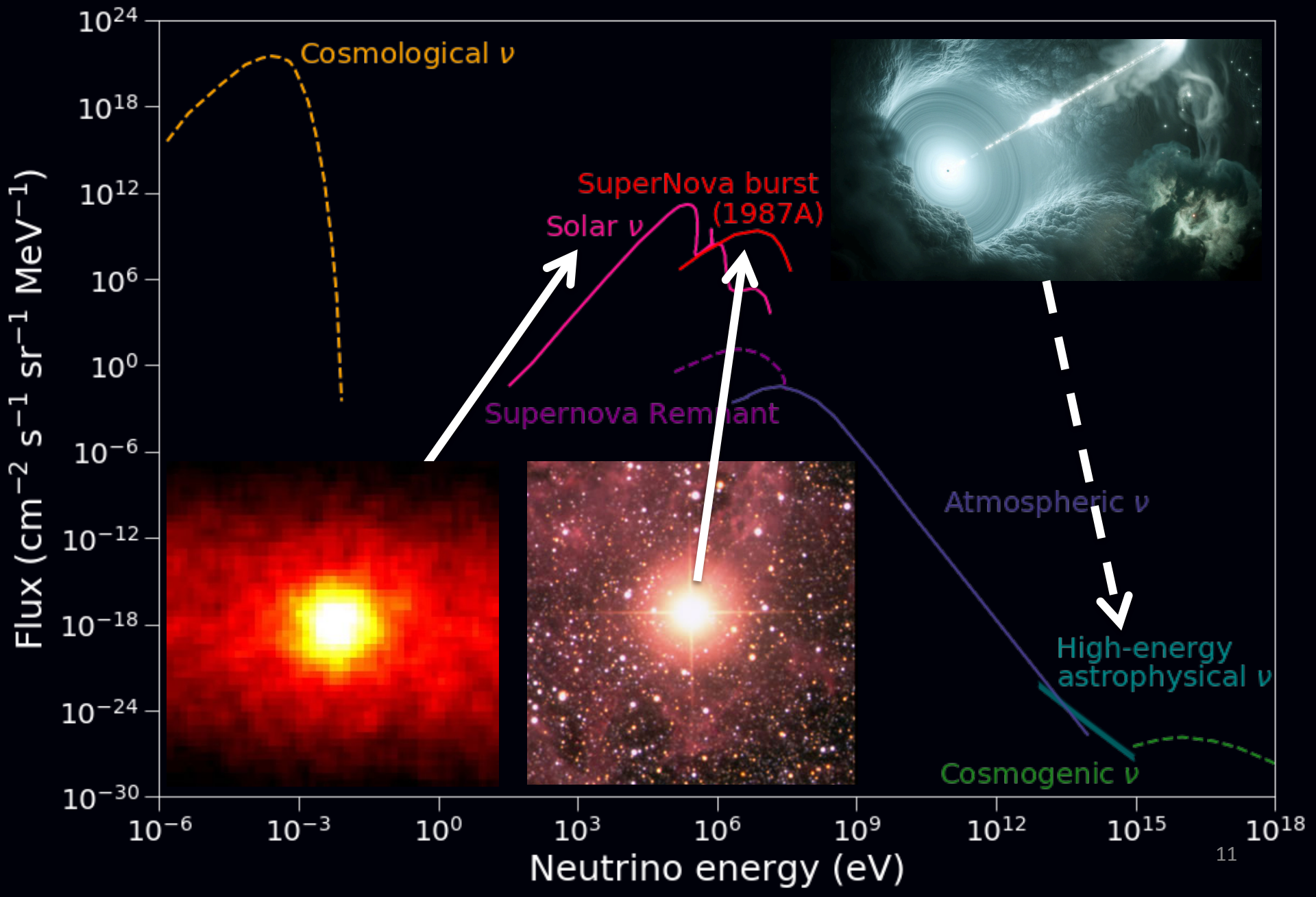
- Amount of light -> Energy
- Timing -> Direction
- Topology -> Flavour



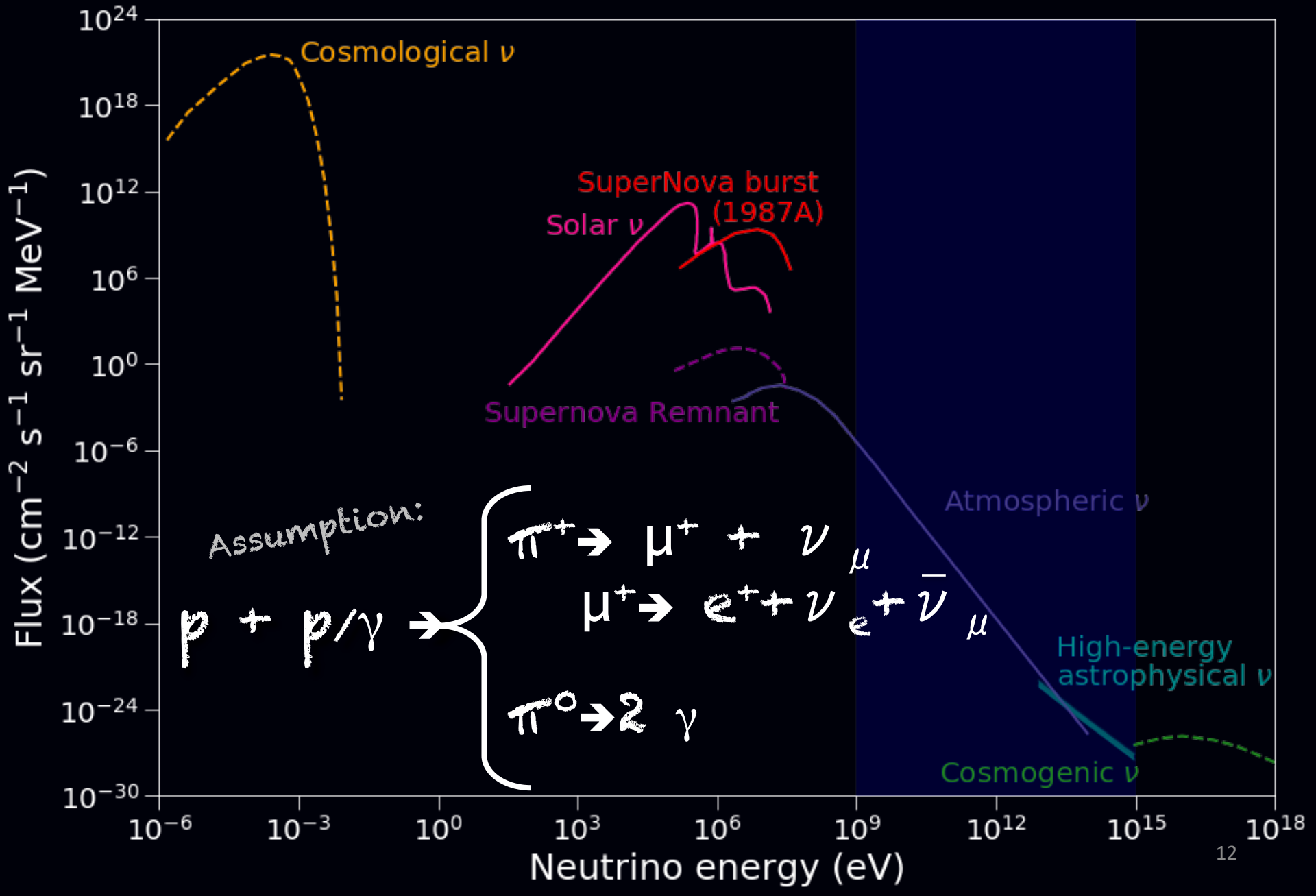



Cosmological ν
SuperNova burst
(1987A)
Solar ν
Supernova Remnant
Atmospheric ν
High-energy
astrophysical ν
Cosmogenic ν
Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
Neutrino energy (eV)
10^{24}
10^{18}
10^{12}
10^{6}
10^{0}
10^{-6}
10^{-12}
10^{-18}
10^{-24}
10^{-30}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}

Figures not to scale



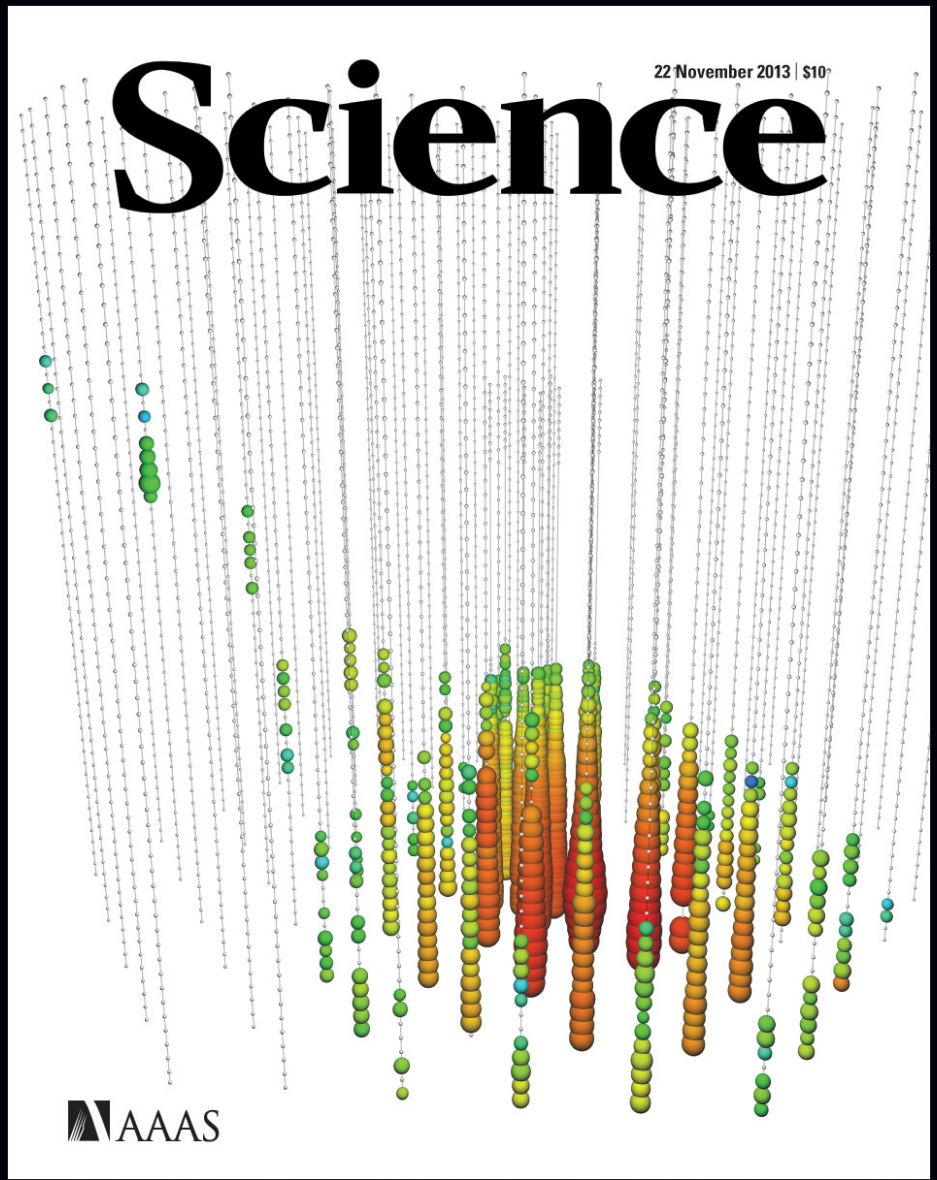
What do we learn from HE neutrinos?



Outline

1. What did we discover?
2. What's new? / What else?
3. What's next?

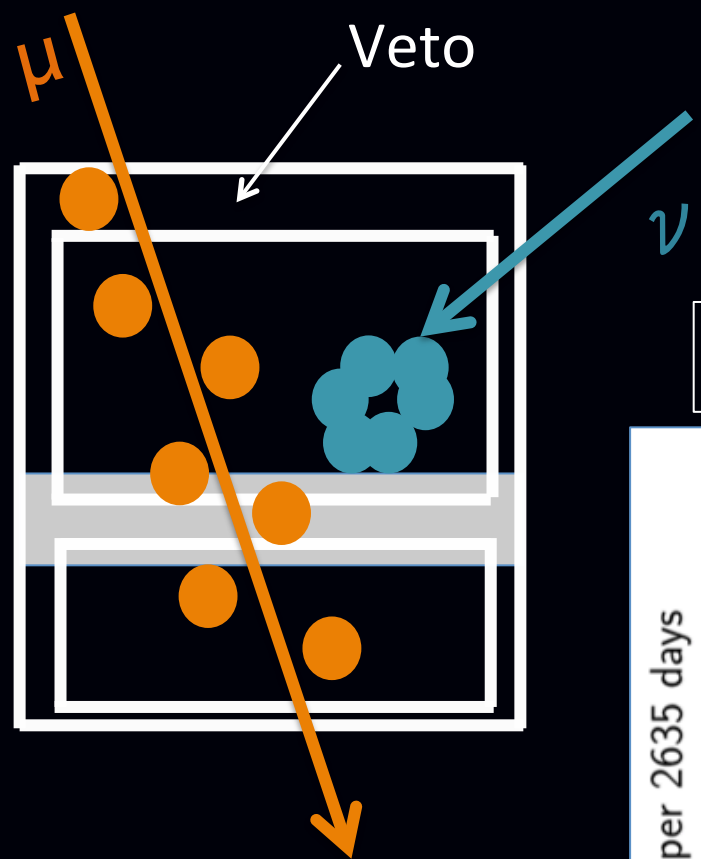
1. What did we discover?



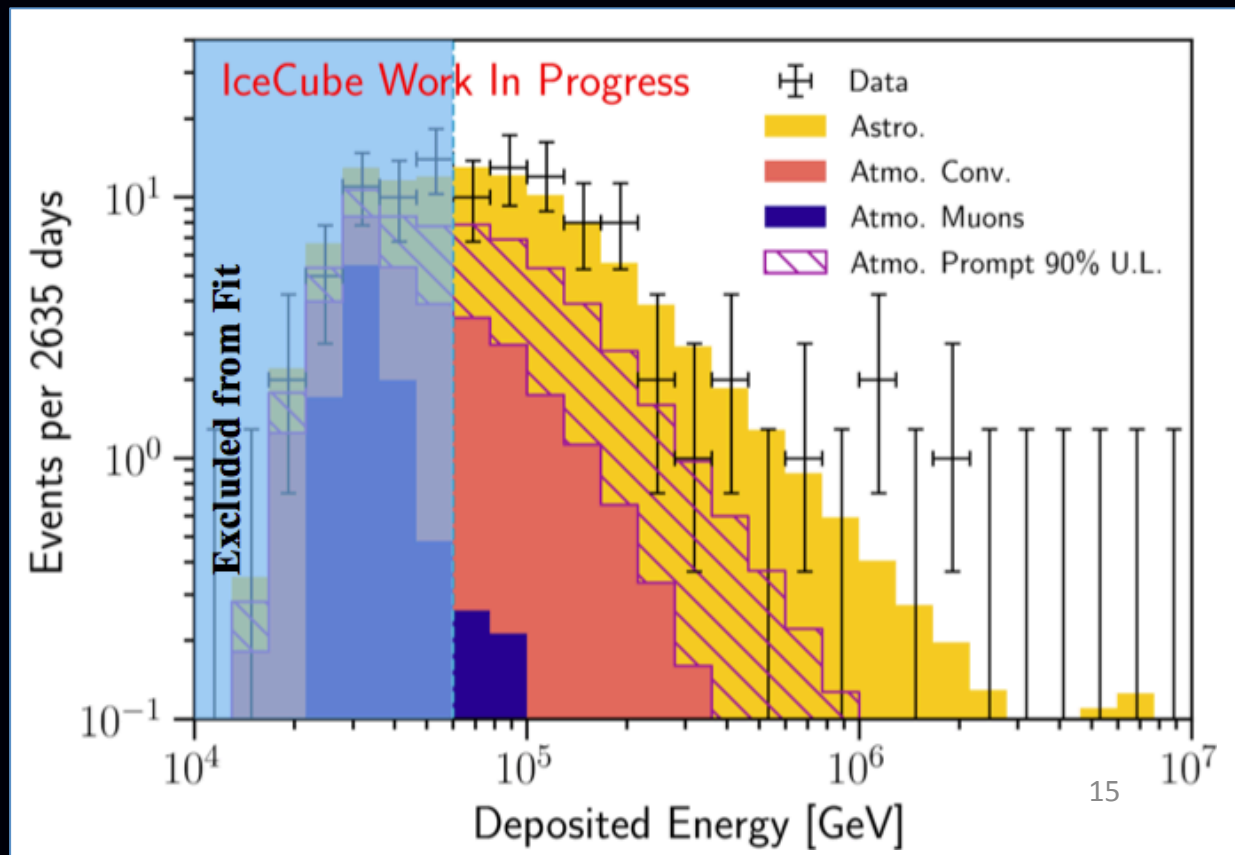
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

22 Nov. 2013

Diffuse neutrino flux 7.5 year

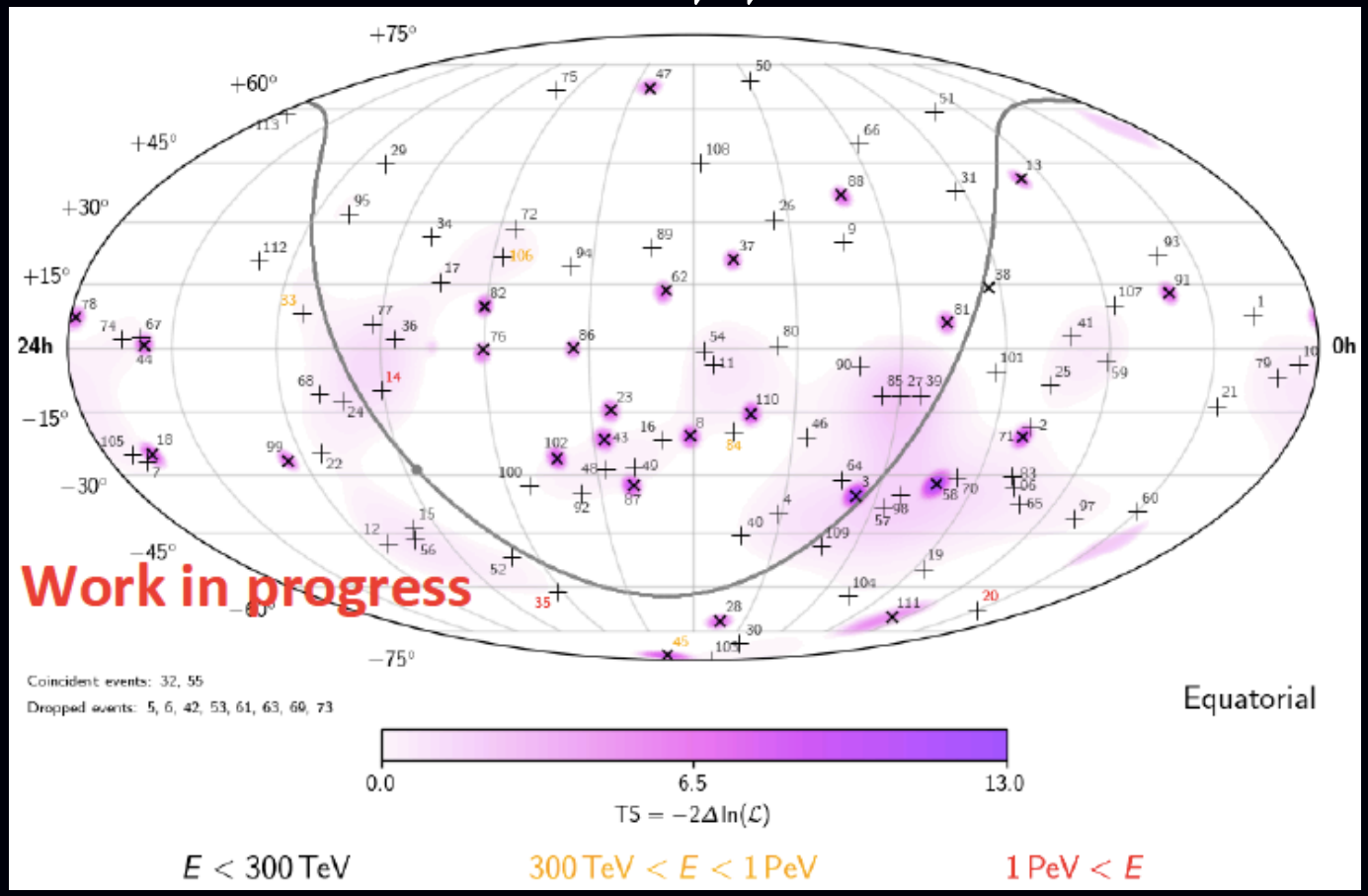


103 events, with 60 events > 60 TeV



- Updated calibration and ice model
- Changes to RA, Dec, energy

Diffuse neutrino flux 7.5 year



- No evidence for point sources
- No correlation with the galactic plane
- <u>Best fit</u>: Single power law with spectral index $\gamma = 2.89^{+0.20}_{-0.19}$
  all-flavor flux normalization $\Phi = 6.45^{+1.46}_{-0.46}$
- Data does not prefer a broken power law model

1. What did we discover?

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

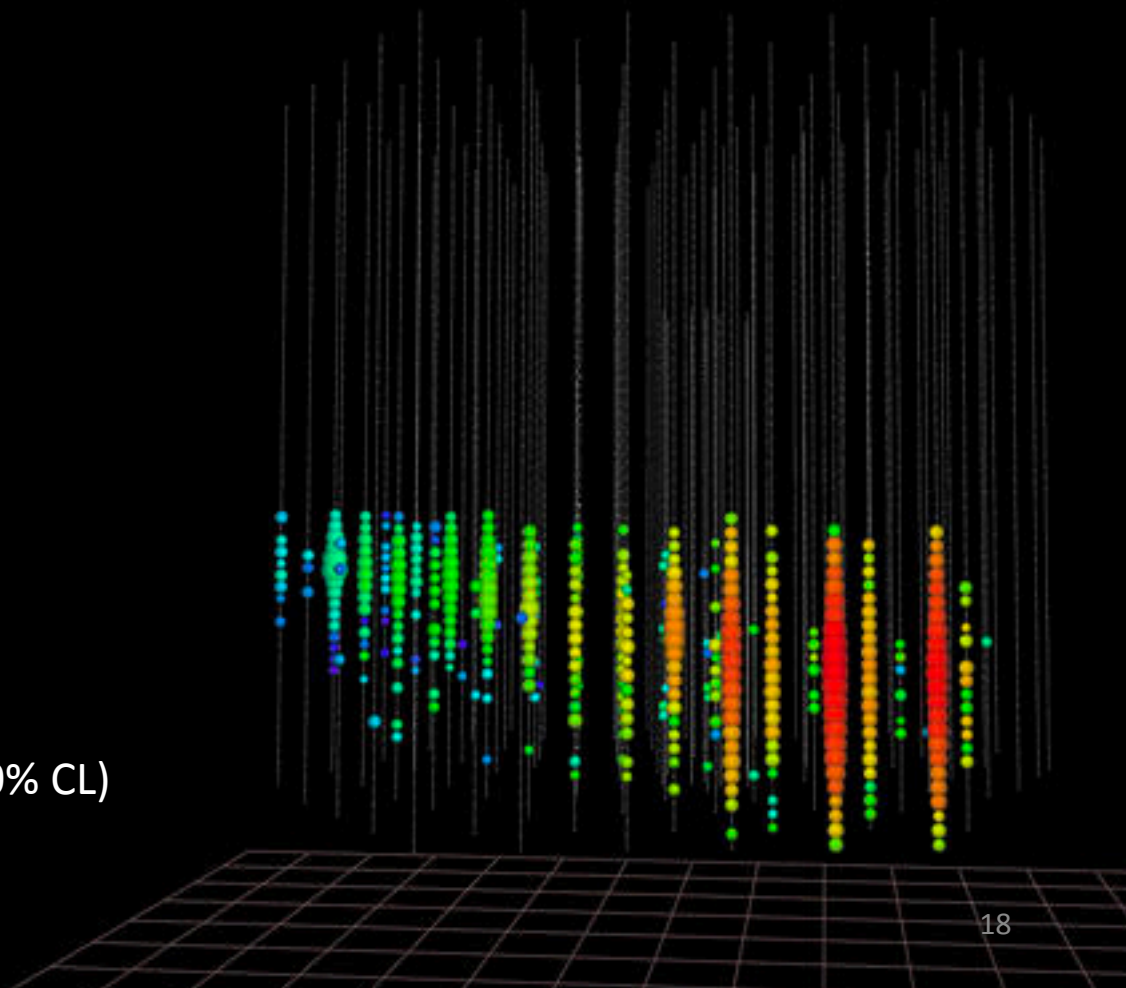
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert

13 Jul. 2018

F. Oikonomou's talk

22 September 2017

IceCube-170922A

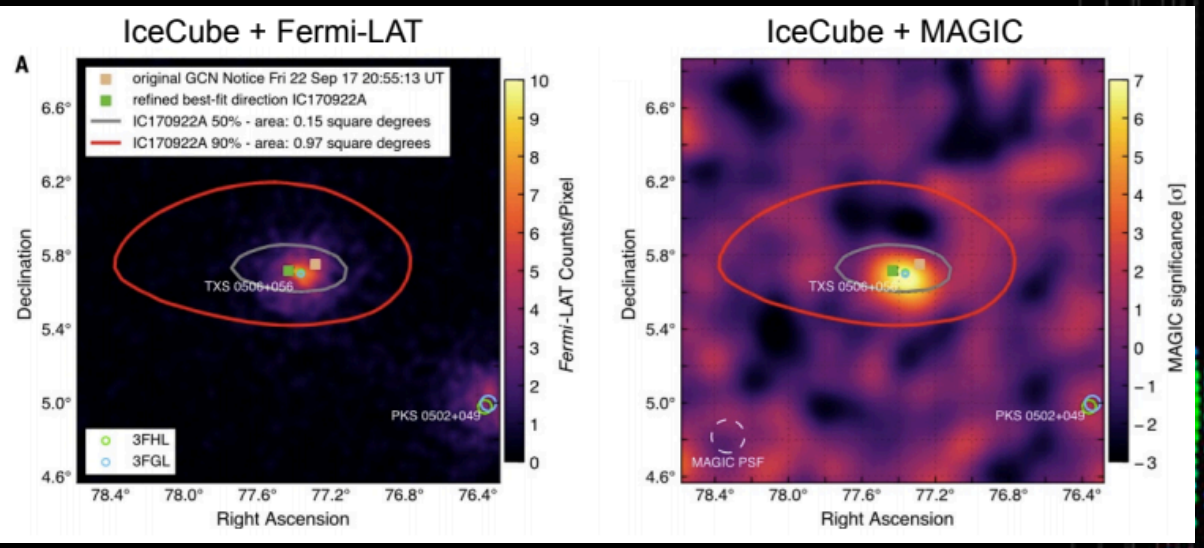


Neutrino Energy: 290 TeV (>180 TeV, 90% CL)
RA: 77.43° (-0.65°/+0.95° 90% CL)
Dec: 5.72° (-0.30°/+0.50° 90% CL)

22 September 2017
IceCube-170922A

- Fermi observations of a known blazar TXS 0506+056, in a state of enhanced gamma-ray emission

- MAGIC detection of > 400 GeV gamma rays from the blazar



Significance for the overlap: 3σ

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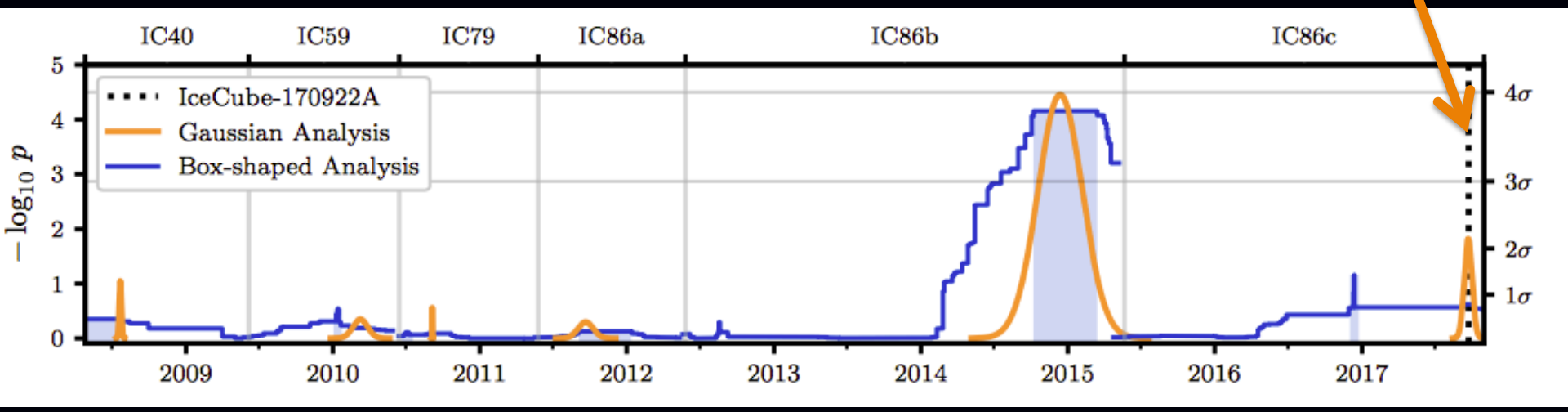
Dec: 5.72° (-0.30°/+0.50° 90% CL)

Archival data search



- Time-dependent point source search at location of TXS blazar
- 13 ± 5 neutrino excess in 2014-2015 over 110 days
- Significance defined using identical searches using randomized event directions: 3.5σ

2. What's new? What else?

- Astrophysical neutrino search using through-going ν_μ events Just a selection
- First Glashow resonance candidate observed by IceCube 10-y update @ ICRC

  (C. Haack's talk in the session)
- Neutrino point source searches with 10 years of IceCube data
- Search for correlations of high-energy neutrinos and ultra-high-energy cosmic rays @ ICRC
- Study of the high-energy neutrino diffuse flux with the ANTARES neutrino telescope @ ICRC
- ANTARES search for point sources of neutrinos with 9 yr of data @ ICRC
- ANTARES-IceCube Combined Search for Neutrino Point Sources @ ICRC
- Combined ANTARES and IceCube search for neutrinos from dark matter annihilation in the GC @ ICRC

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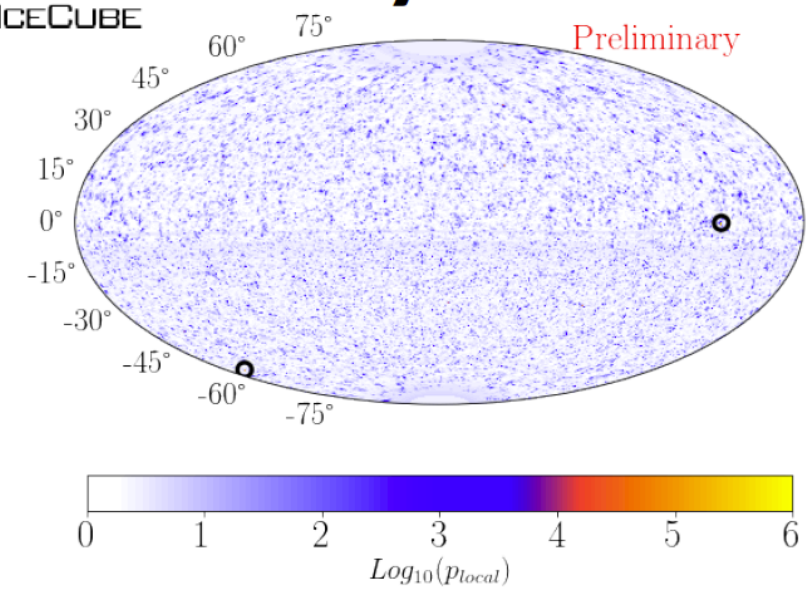
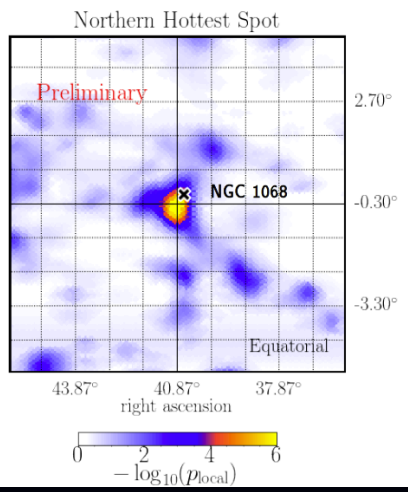
2. What's new? What else?

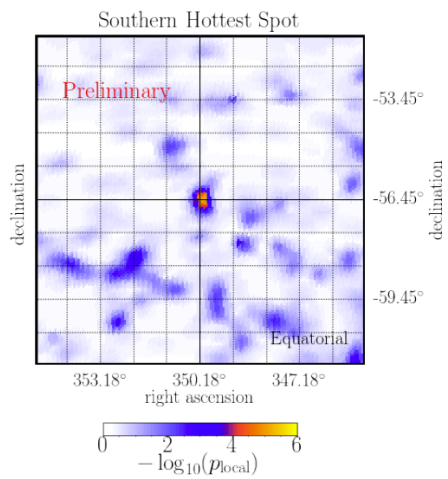
T. Carver and T. Montaruli, NuTel 2019

ICECUBE

10 year All-Sky Scan Results







- Scan the entire sky and evaluate the likelihood of signal over background.
- The position with the smallest p-value in each hemisphere is taken as the hottest spot.
- The post-trial pvalue is calculated by comparing this p-value with many background hotspots.

Hottest Point in Northern Hemisphere : $\delta \geq -5^{o}$

RA = 40.87° , Dec = -0.30°

n_{signal} = 61.45 , γ= 3.411

Pval = 6.45, TS = 25.34 ⇒ 9.9 % post-trial

Hottest Point in Southern Hemisphere : $\delta < -5^{o}$

Ra = 350.18° , dec -56.45°

n_{signal} =17.75, γ = 3.34

Pval =5.37, TS= 19.95 ⇒ 75 % post-trial

2. What's new? / What else?

- Neutrinos in the multi-messenger era

- Flavor ratio and tau neutrinos

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- Neutrinos in the multi-messenger era

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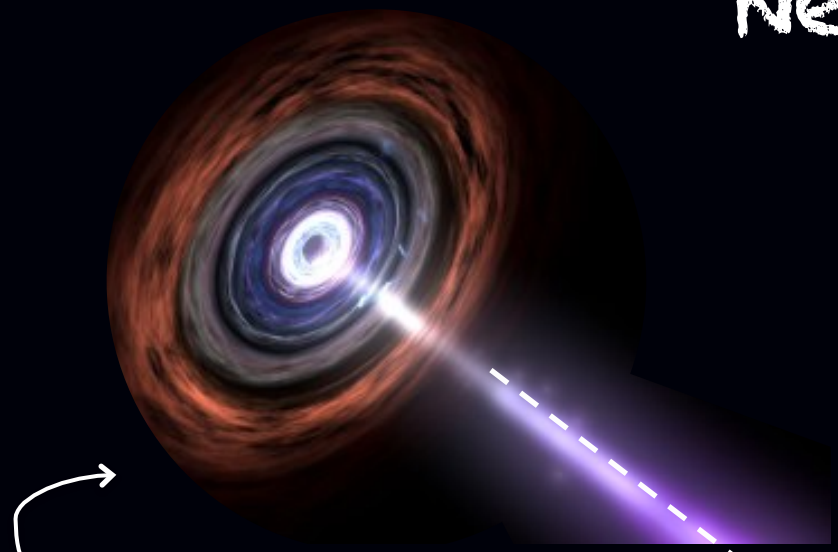
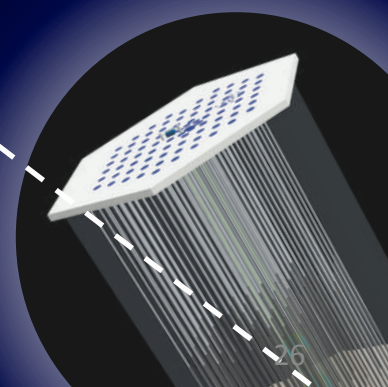
Neutrino search from known sources



Potential high-energy ν emitter

ν

Neutrino telescope



<u>Goal</u>: Identifying hadronic accelerators in the Universe

Neutrino search from known sources

	Contribution to the HE ν flux
Blazars (Fermi 2LAC catalog)	< 27%
Gamma-ray burst	< 1%
Galactic plane	< 14%

What can we do to find sources?

Real-time multi-messenger astronomy

Multi-messenger partners

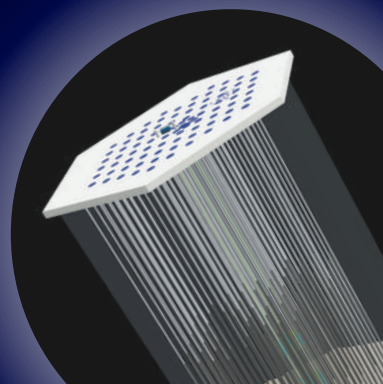
IACTs
Gamma-ray satellites

Ground based observatories
Satellites

Neutrino telescopes -> See also ANTARES program in T. Chiarusi's talk

Interferometers

IceCube



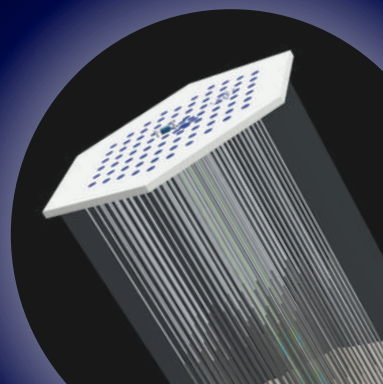
Real-time multi-messenger astronomy

Multi-messenger partners

IceCube170922A!

IceCube

- New alert categories since June 17th 2019
  - Gold = 50% signal probability 1/month
  - Bronze = 30% signal probability 1.3/month
- Alert contains:
  - data and time
  - right ascension + declination
  - angular radii of the 50% and 90% containment circles
  - the signal probability



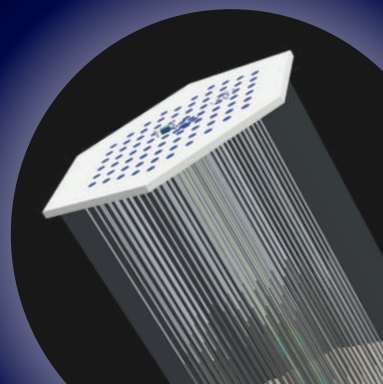
Real-time multi-messenger astronomy

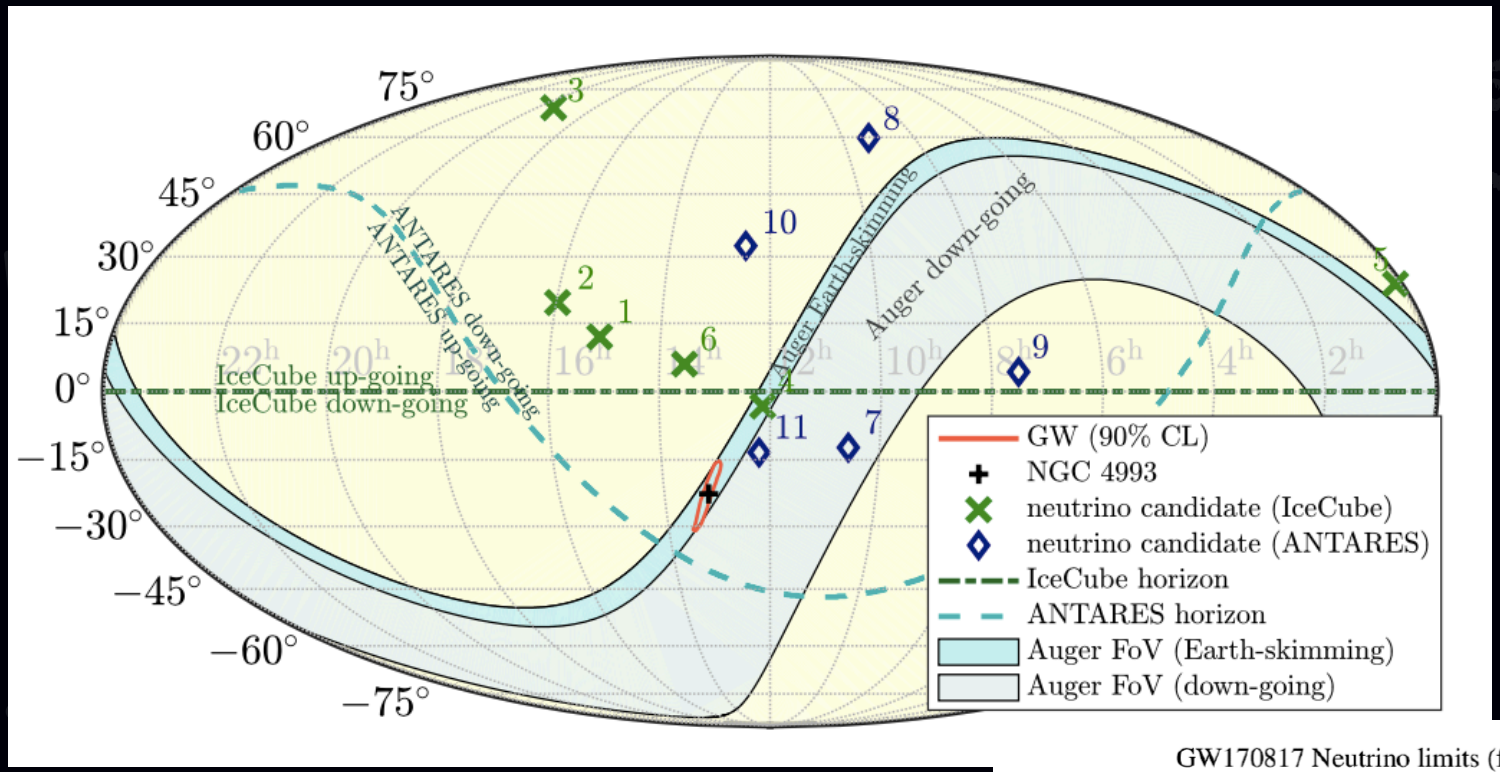
Multi-messenger partners

- Fast-response analysis for interesting events, such as flares from the Crab Nebula or unknown bright transients

IceCube

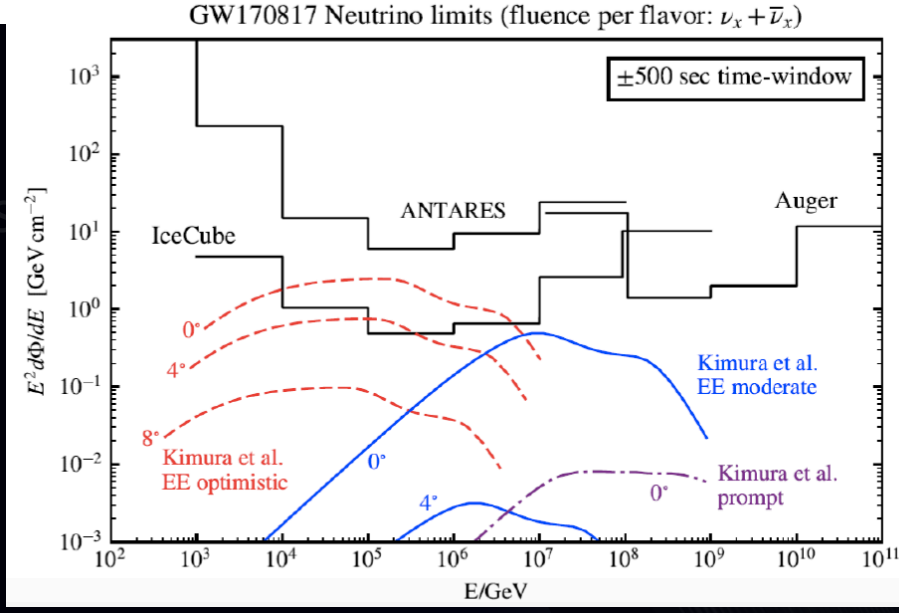
- Systematic follow-up of GW events





GW170817
[-500s , +500s]

- So far in O3:
  - > 10 BBH candidates
  - 2 (1) BNS candidates
  - 1 NS-BH candidate
- No coincident neutrino detection reported
- Followup in the GeV energy range



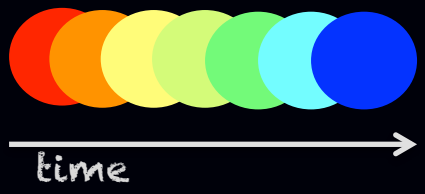
@ ICRC

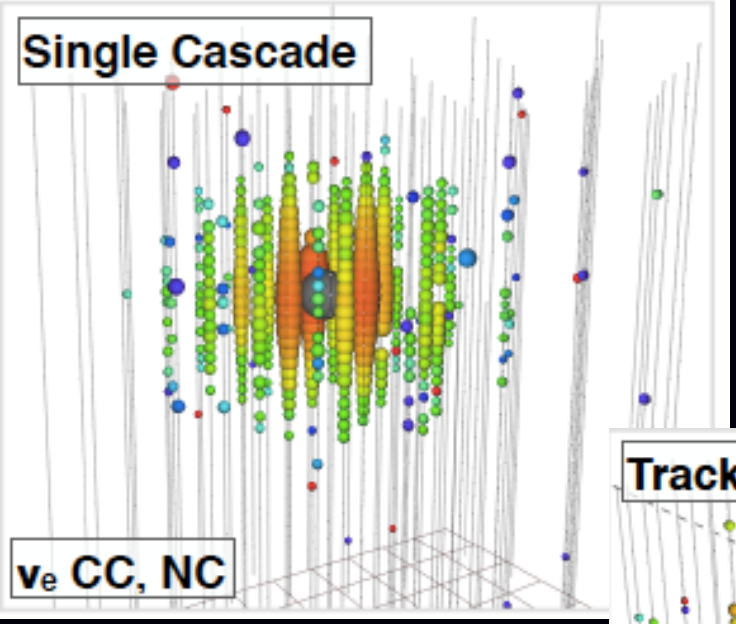
2. What's new? / What else?

- Neutrinos in the multi-messenger era

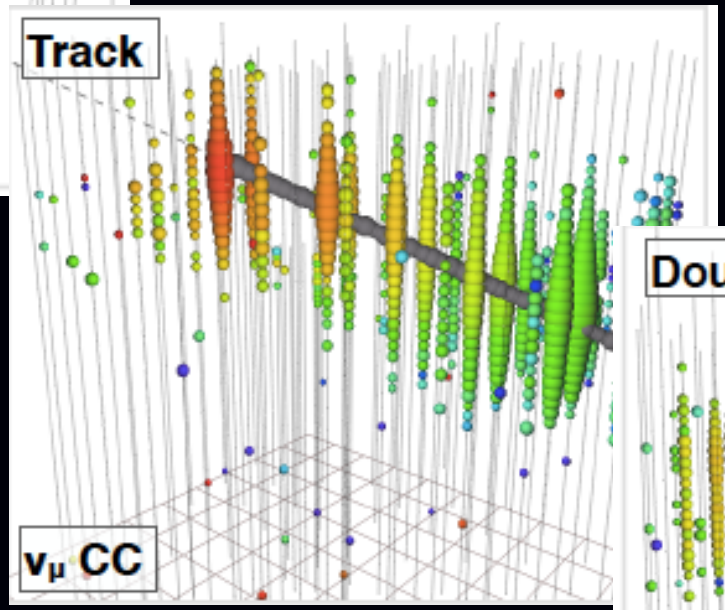
- Flavor ratio and tau neutrinos

Event topology



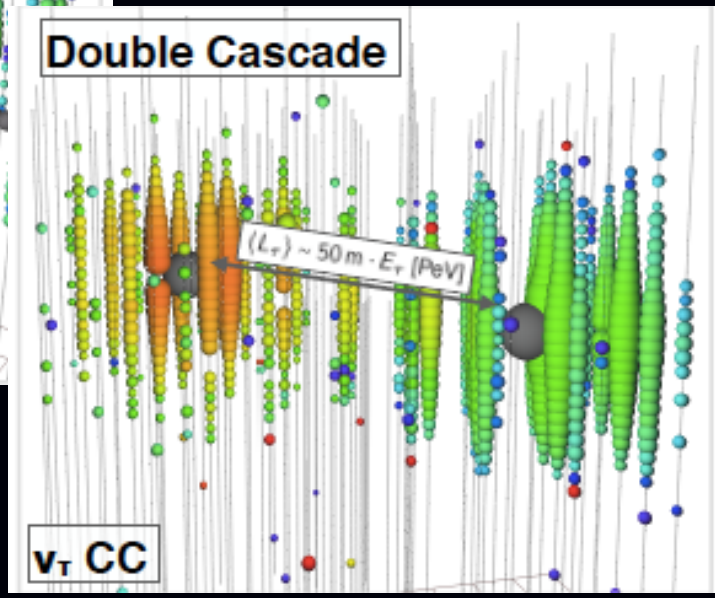


- Good E resolution
- Bad angular resolution



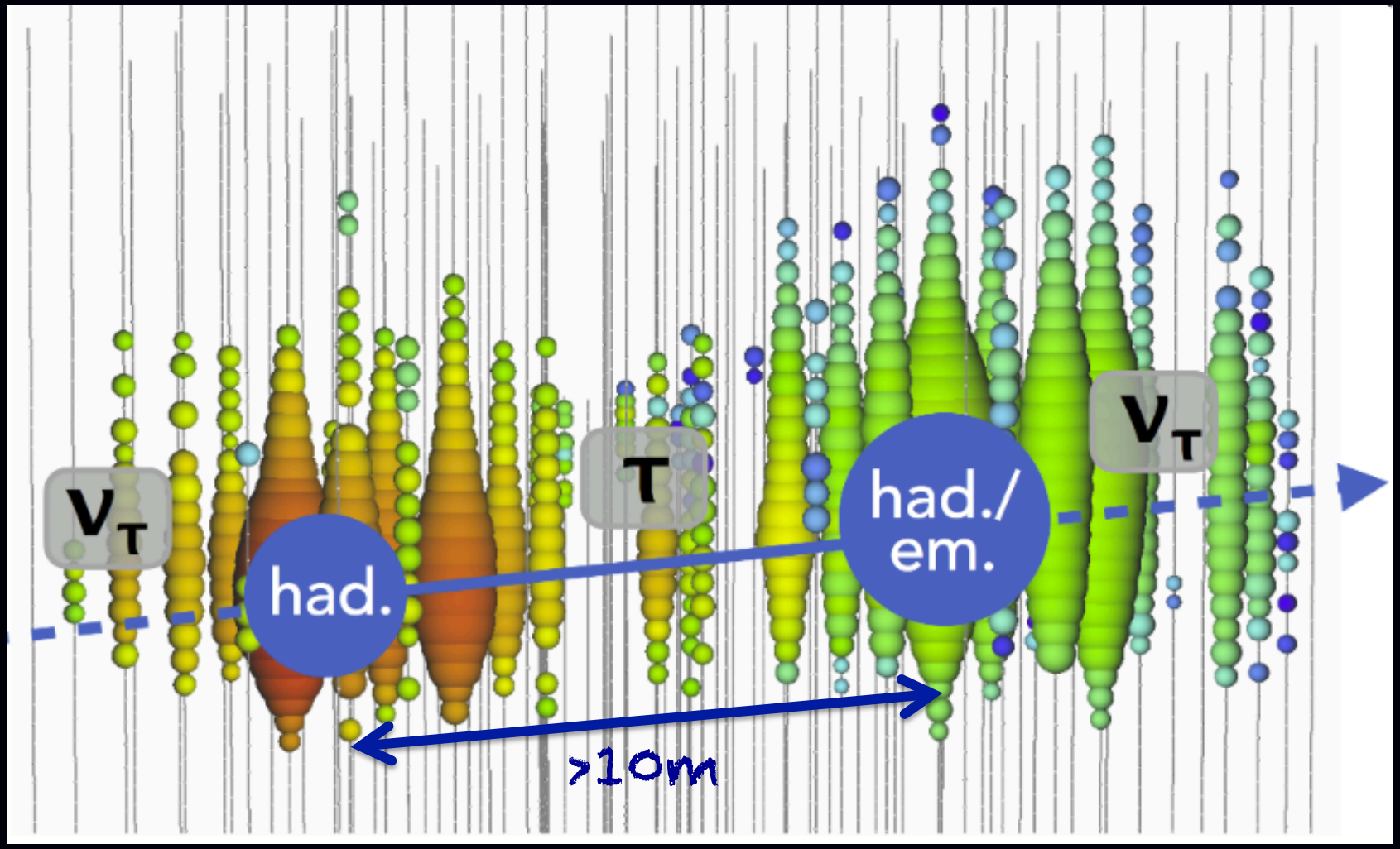
- Bad energy resolution
- Good angular resolution

+ Starting track!



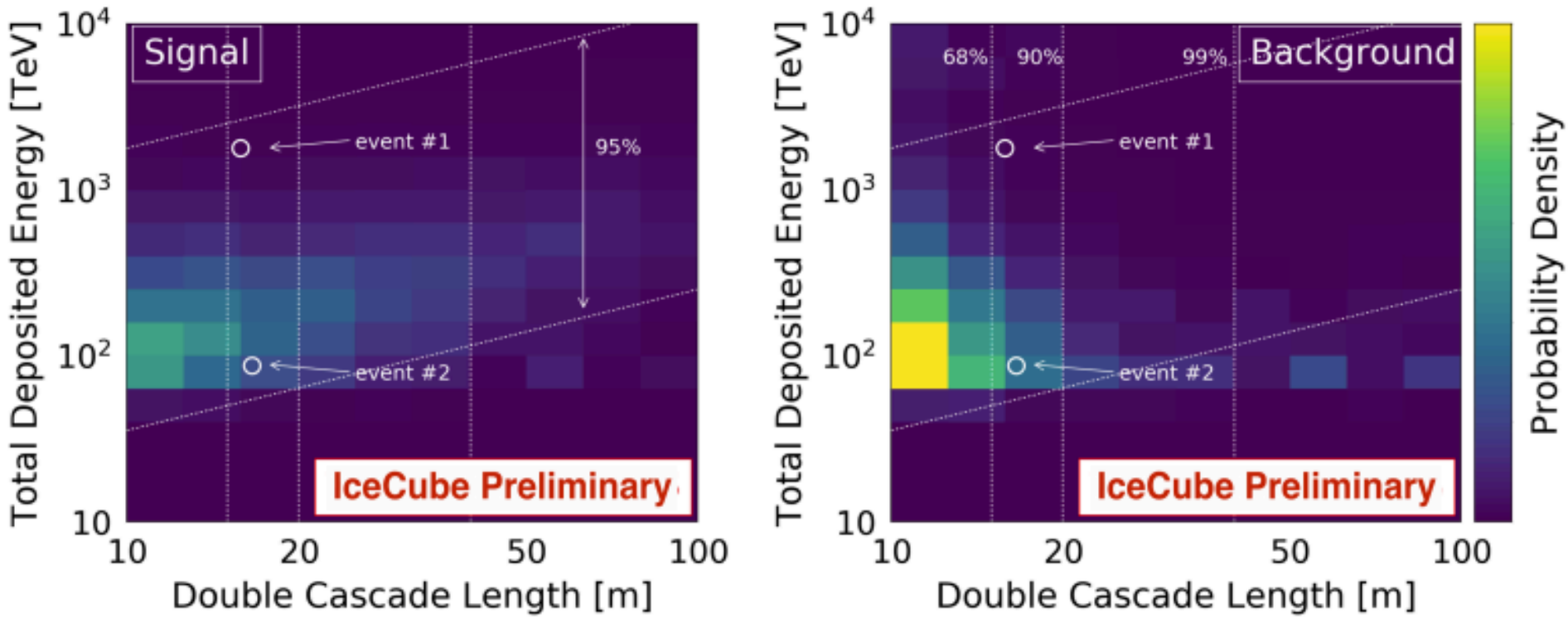
- Good E resolution
- Better angular resolution than single cascade

Double cascade



- Both cascades with E > 1 TeV
- Separation distance > 10 m

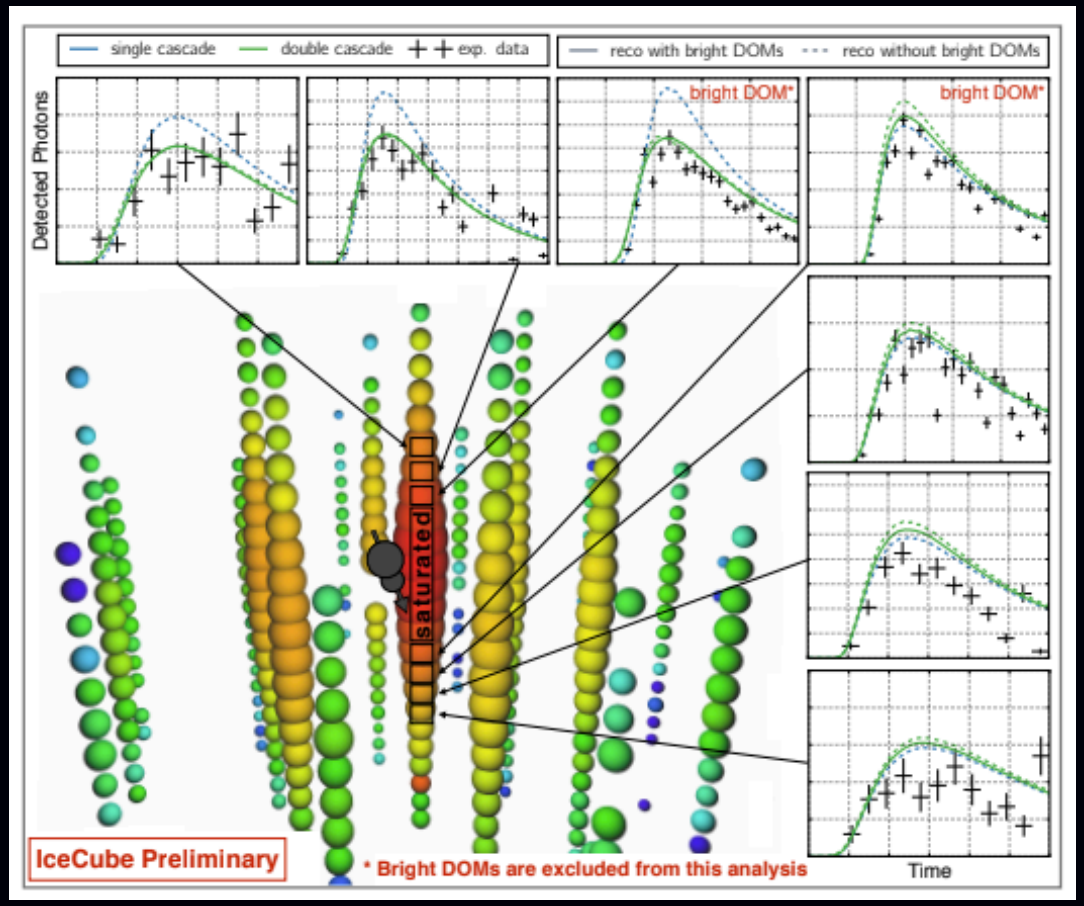
Double cascade



- Ternary-PID of cascades, tracks and double-cascades
- 2 double-cascade candidates
- ν_τ or mis-identified background

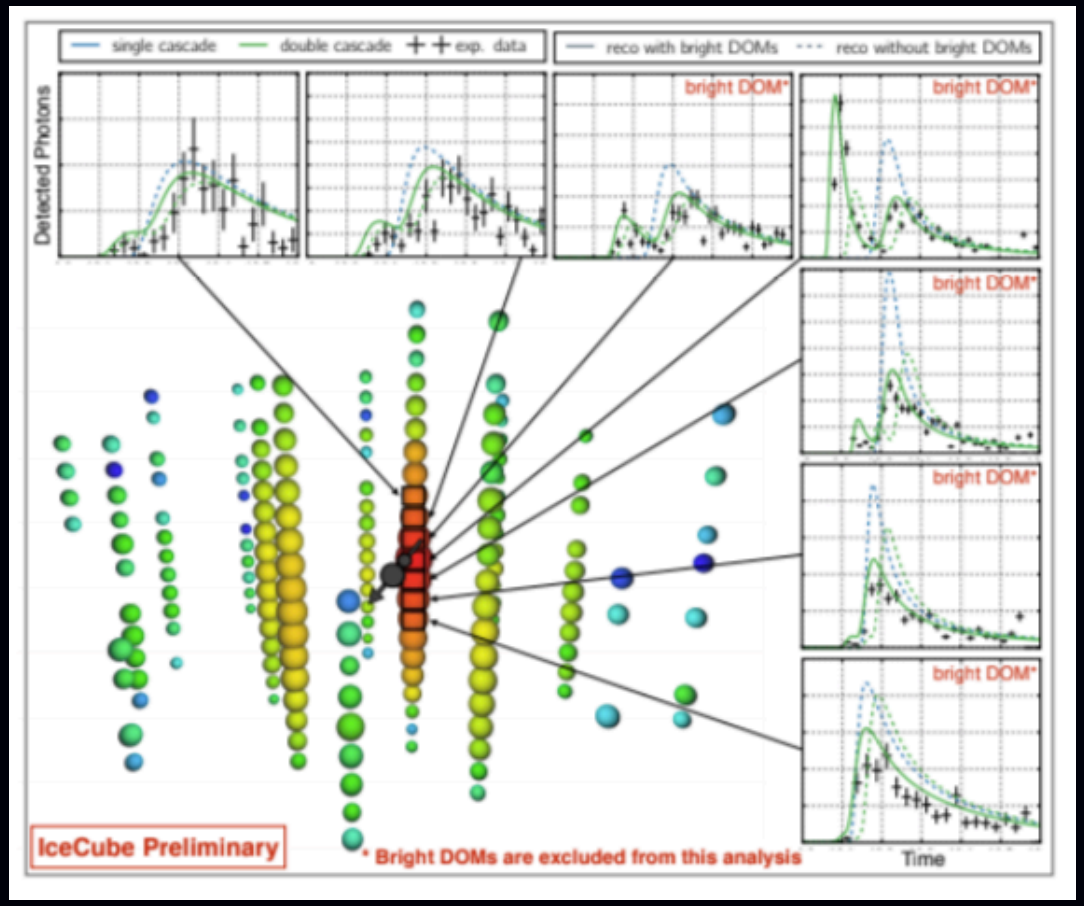
@ ICRC

Event 1: Big Bird



- Energy of the cascades = 1.2 PeV and 0.6 PeV
- Separation = 16m
- Observed in 2012
- No clear preference between a single cascade and double-cascade

Event 2: Double Double



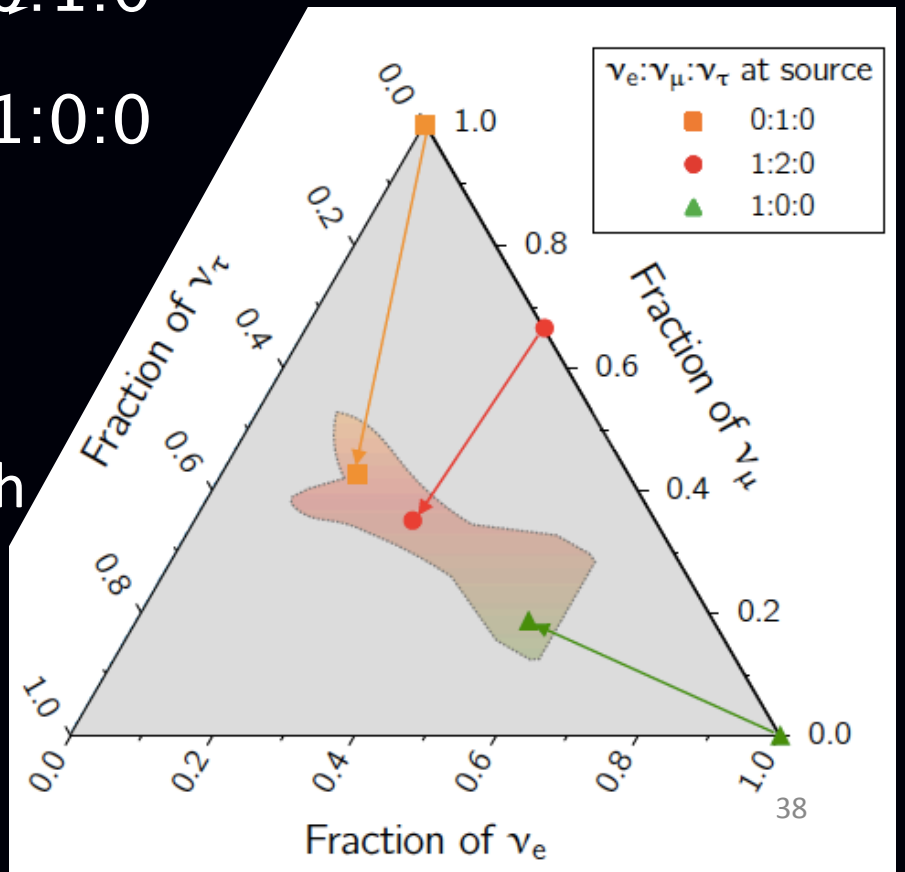
- Energy of the cascades = 9 TeV and 80 TeV
- Separation = 17m
- Observed in 2014
- Observed light arrival pattern clearly favors double cascade

Flavor composition

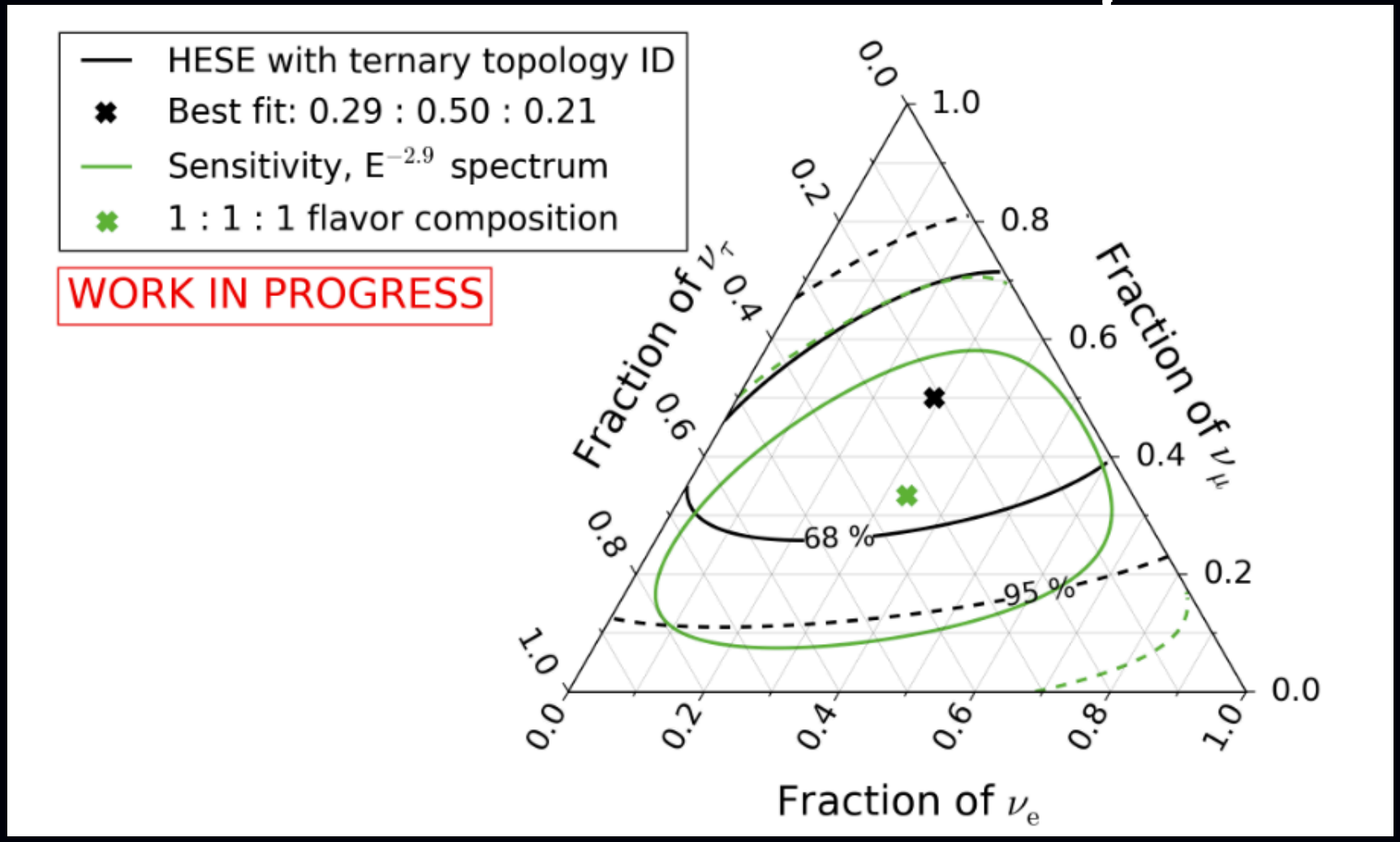
Cosmic particle accelerator	$\nu_e:\nu_\mu:\nu_\tau$
Pion decay	1:2:0
Muon- damped	0:1:0
Neutron decay	1:0:0

+ others

- Study of the composition at Earth
- Oscillation back to the source
- Information on the emission mechanism

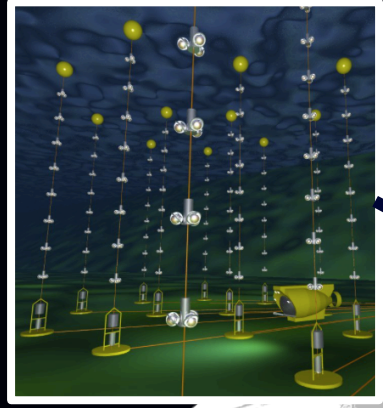


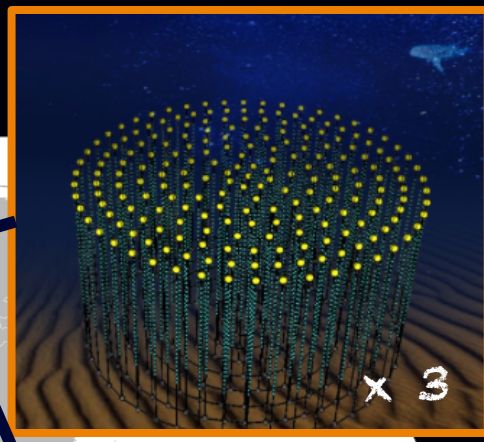
Flavor composition

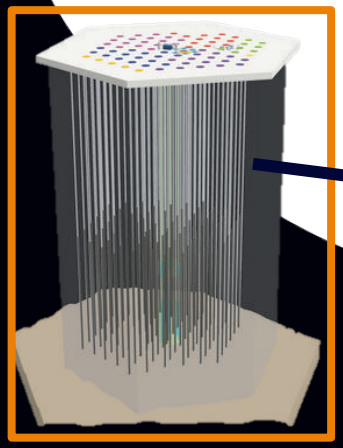


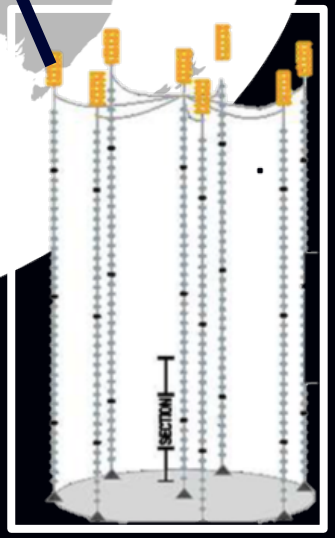
- Non-zero best-fit for ν_τ
- Zero ν_τ flux not excluded

3. What's next?







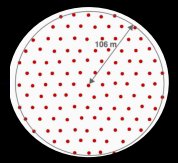


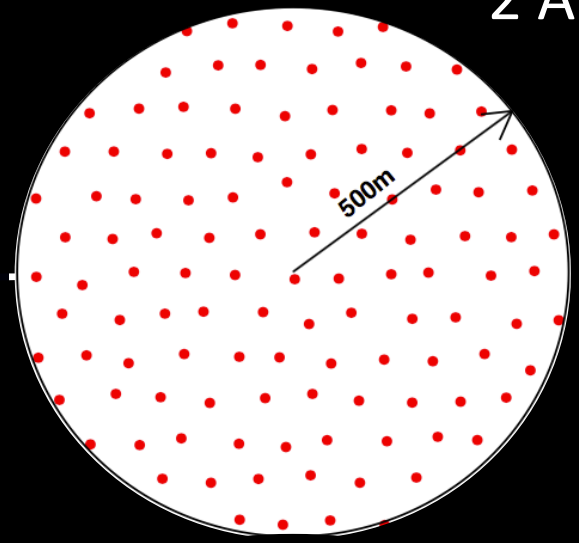
GNN
The Global Neutrino Network

Non-exhaustive list

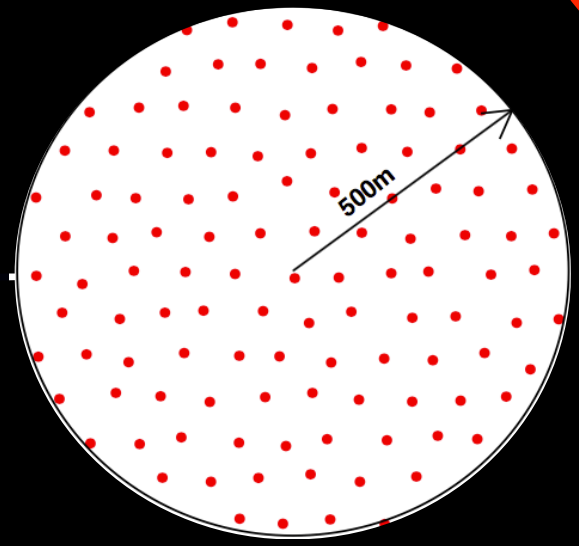
KM3NeT

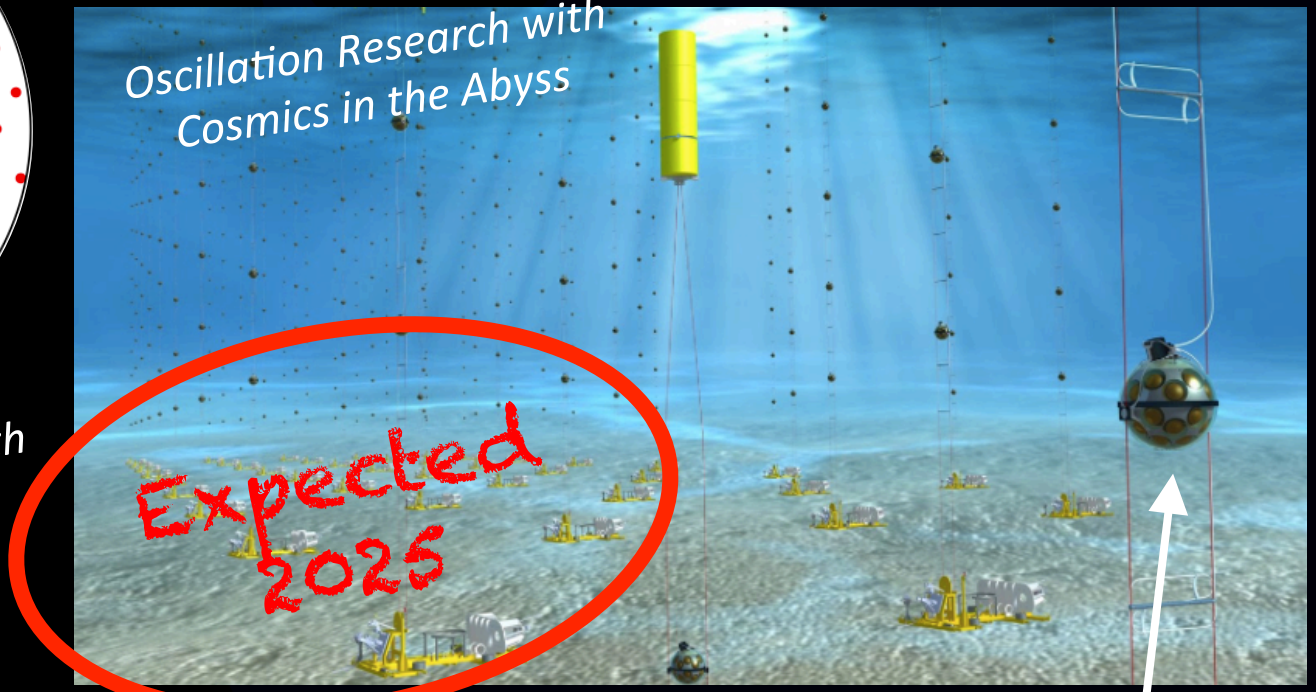
2 ARCA blocks
+ ORCA





Astroparticle Research with
Cosmics in the Abyss

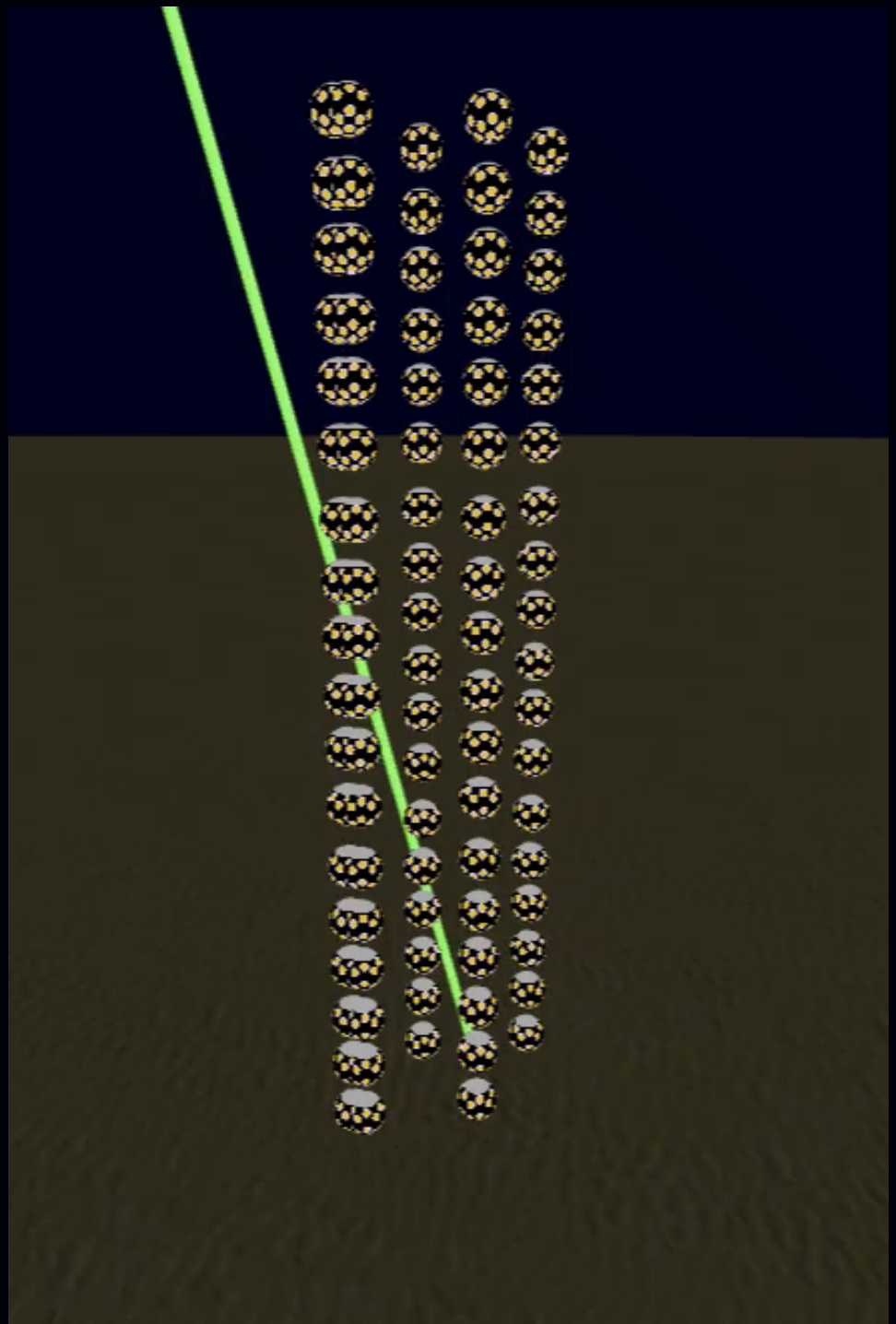




31 PMTs

- 3 x 115 Detector Units
  InterDU spacing: 20m or 90m
- 18 DOMs
  Interdom spacing: 9m or 36m

Currently 1 ARCA + 4 ORCA DUs taking data



KM3NeT

ORCA - 4 Dus

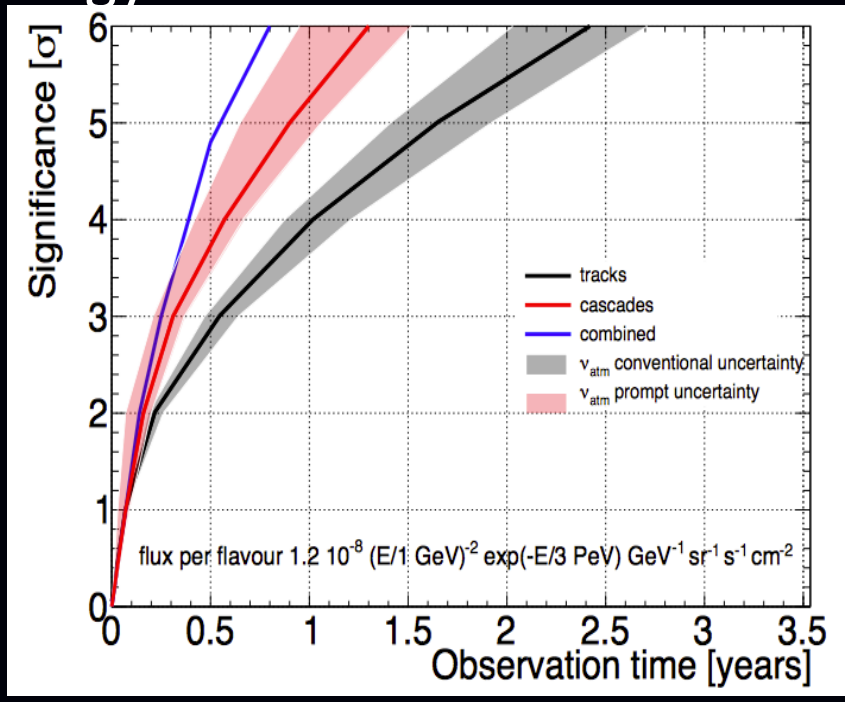
Downgoing muon event

Real data!

KM3NeT

ARCA:

- ν_μ angular resolution < 0.1° for E_ν> 100 TeV
- ν_e angular resolution < 2° and energy resolution ~ 5%



- Diffuse flux combining tracks and cascades

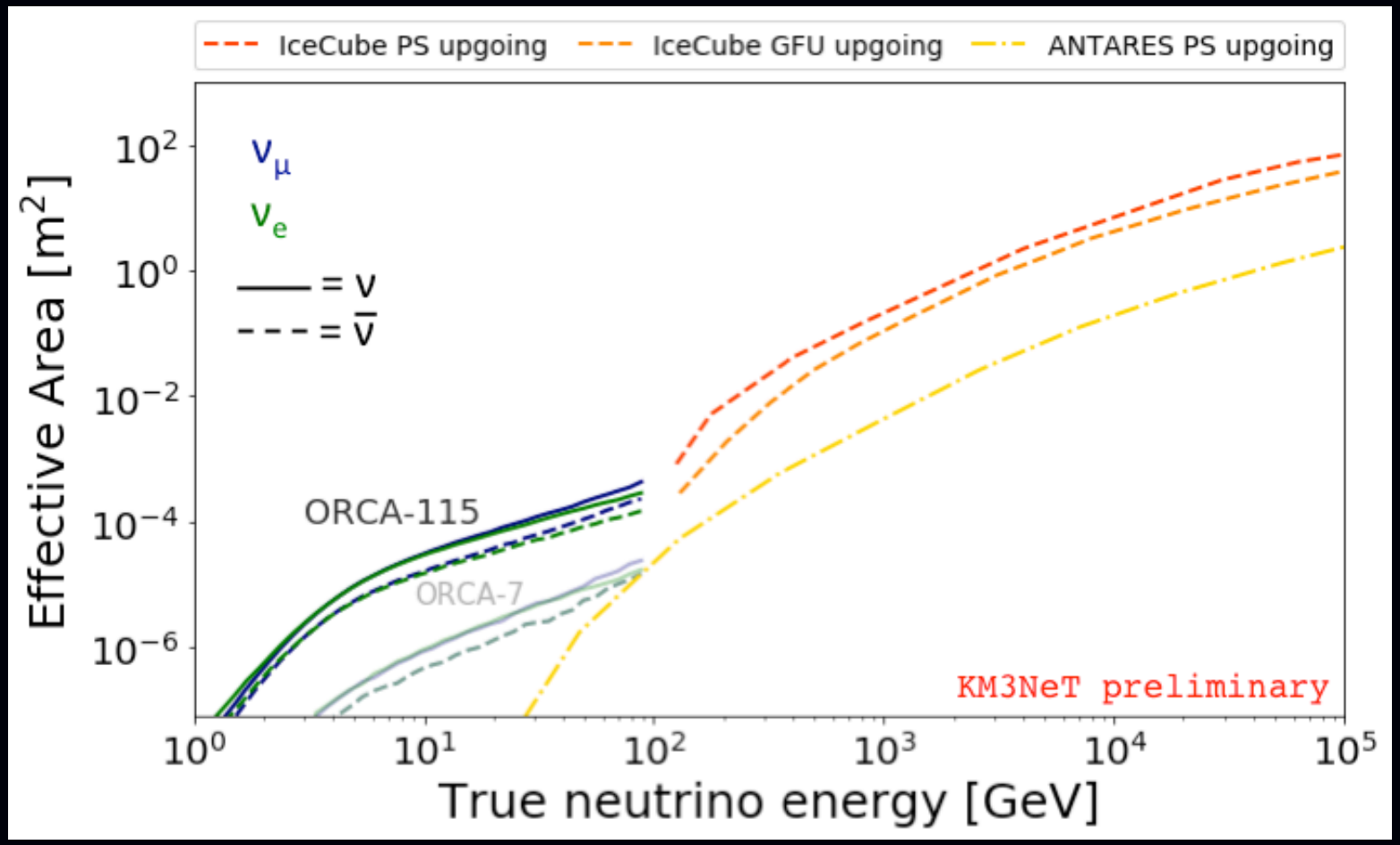
-> IceCube flux equivalent at 5σ in 6 months

ORCA:

- Multi-messenger astronomy down to 1 GeV @ ICRC
- Neutrino physics with ORCA

See C. Distefano's talk!

KM3NeT



ORCA:

- Multi-messenger astronomy down to 1 GeV @ ICRC
- Opportunity of e.g., GW follow-up with reduced configuration

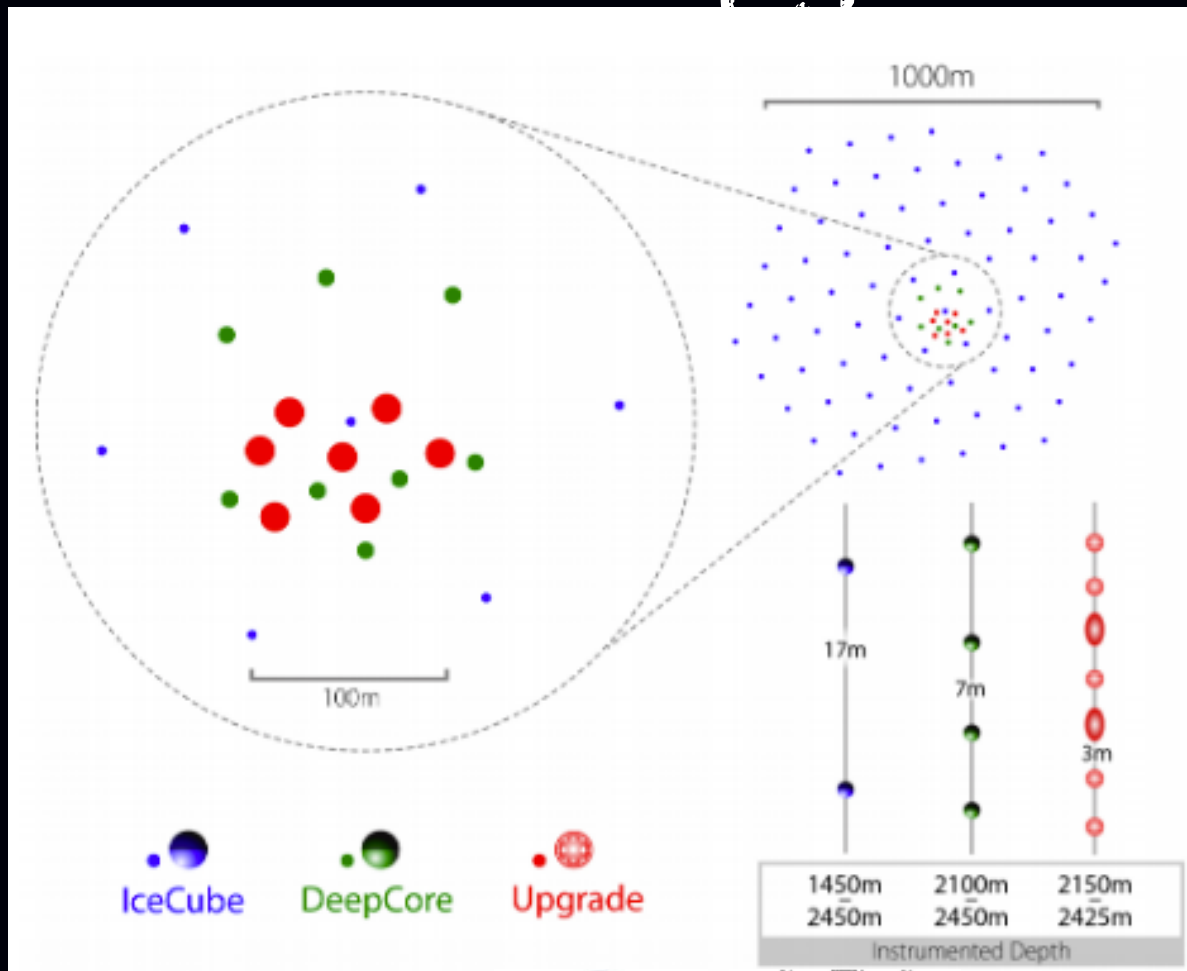
The Upgrade

- 7 new strings of modules
  - Interstring spacing 20m (DC 70m)
  - InterDOM spacing 2.4m (DC 7m)

- Neutrino physics:
  - oscillations
  - atmospheric tau neutrino
  - appearance, test of unitarity of PMNS mixing matrix

- Astrophysics:

precise calibration of ice optical properties and DOM response -> apply to 10-years of existing data



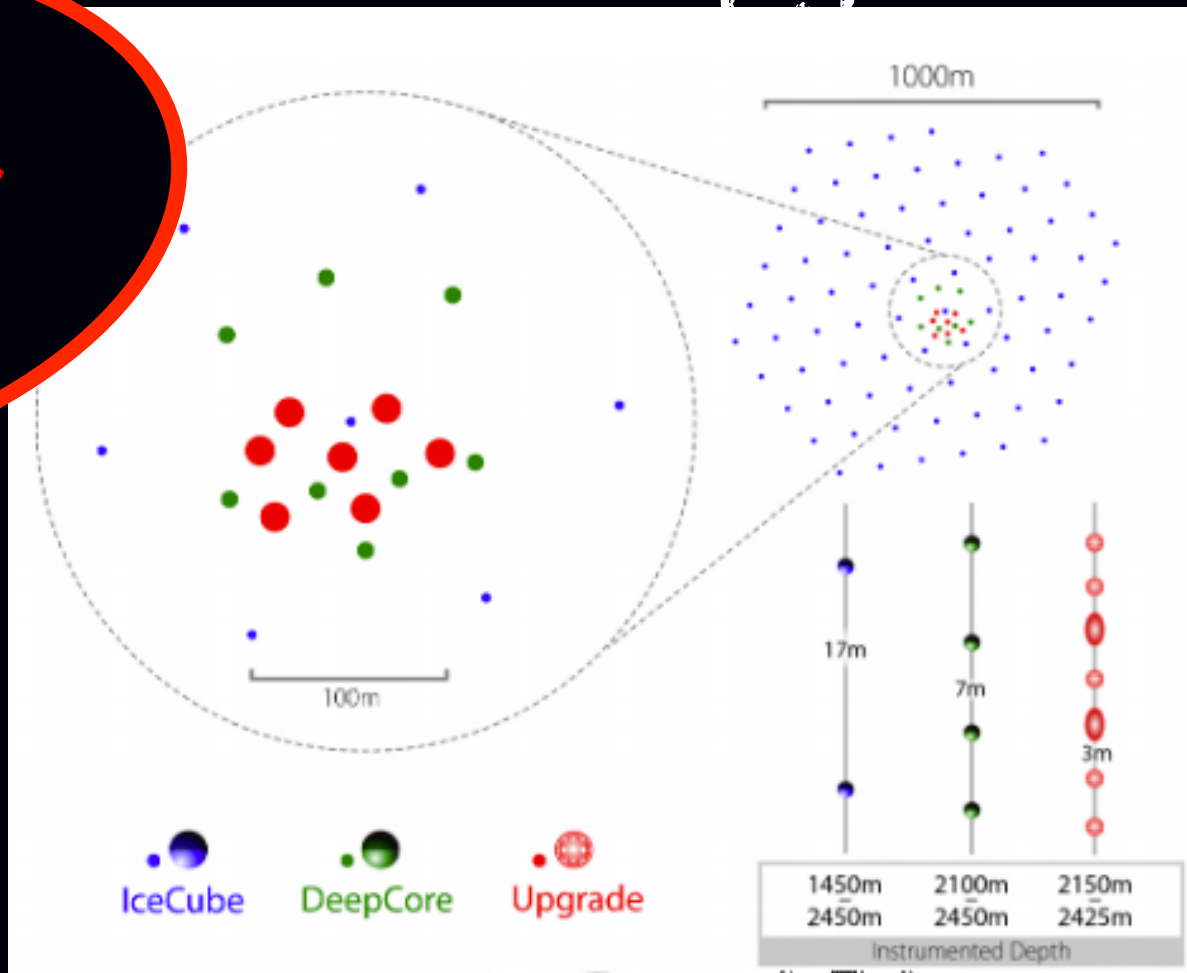
The Upgrade

- Deployment planned for 2022- 2023

- Neutrino physics:
  - oscillations
  - atmospheric tau neutrino
  - appearance, test of unitarity of PMNS mixing matrix

- Astrophysics:

precise calibration of ice optical properties and DOM response -> apply to 10-years of existing data

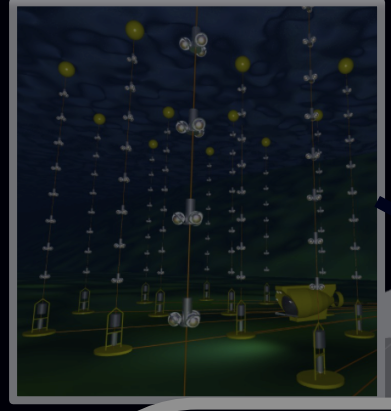


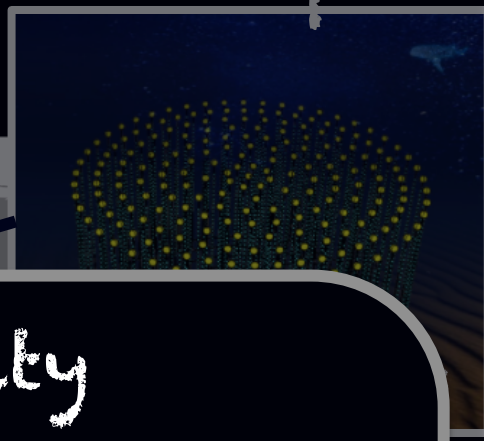
Take-home message

- High-energy neutrino astronomy is a young field of research but already…
- Several breakthroughs
- Many new results coming
- Promising future with the next generation being deployed

Thanks!

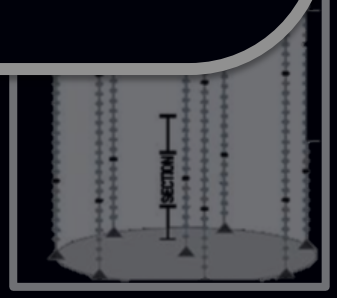
Neutrino telescopes





Instrumentation density

Particle detectors (e.g., pixel detector in CMS)	~ 1k modules/m^2
HE neutrino detectors (e.g., IceCube)	~ 5k sensors/km^3



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