



# 2018 European Nuclear Physics Conference



September 2<sup>nd</sup>-7<sup>th</sup>, 2018: Bologna, Italy  
San Domenico Center



FEDERICO VERSARI



## ANTARES RESULTS AND KM3NET STATUS

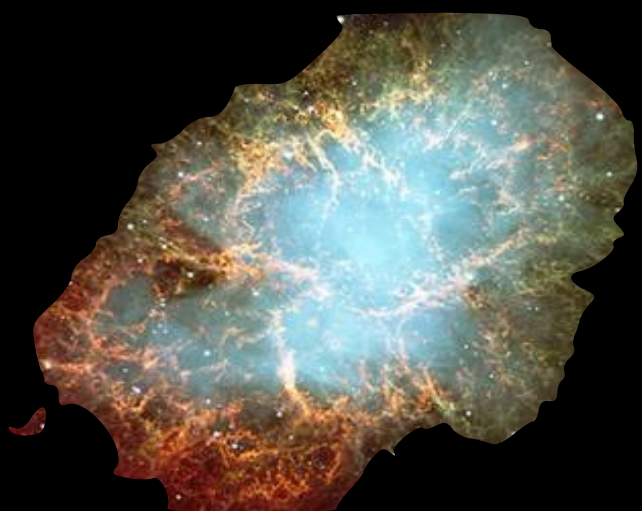


- ▶ **Why the neutrino astronomy:** The existence of Cosmic Ray (CR) sources seems to guarantee the existence of high-energy (HE) neutrino sources.
- ▶ **Neutrino astronomy goal:** Understand the sources mechanisms of Cosmic Rays acceleration.
- ▶ **Many candidate HE neutrino sources, Galactic or Extra Galactic**

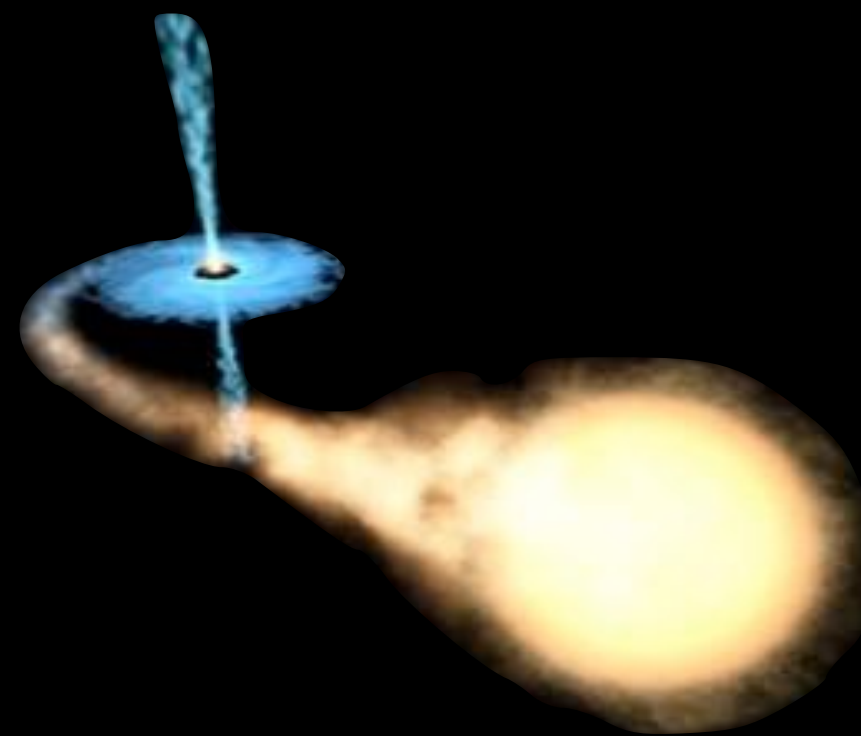
## *Examples of candidate neutrinos sources*

### Galactic

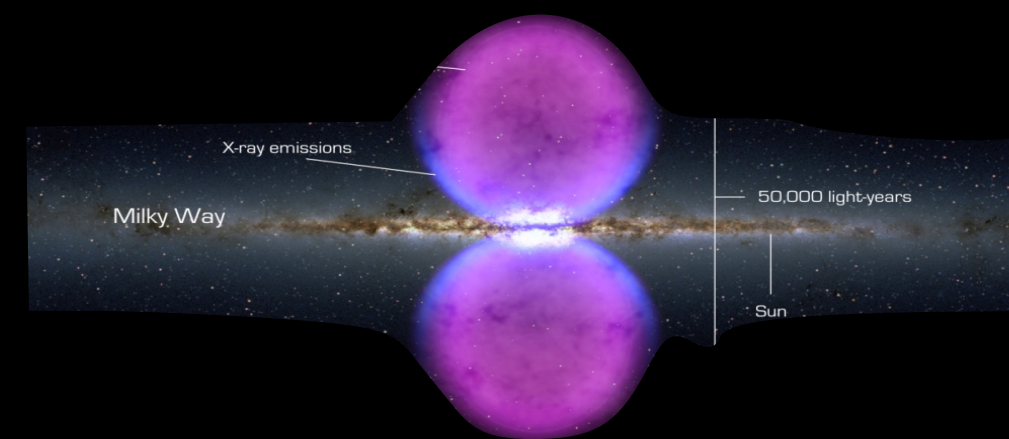
**Supernova  
remnant (SNR)**



**Micro-Quasars**



**Fermi-Bubbles**

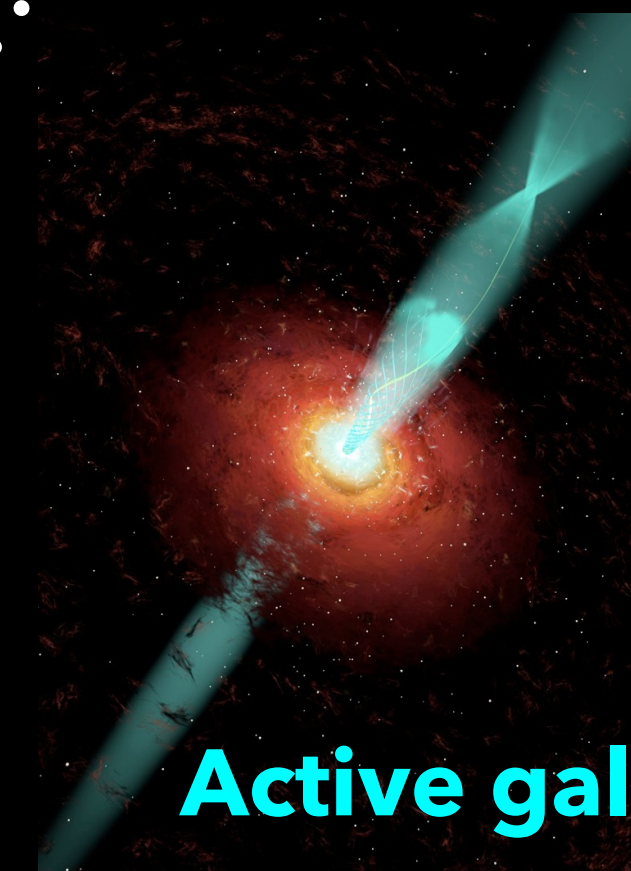


### Extra Galactic

**Gamma-ray  
burst (GRB)**



**Active galactic  
nucleus (AGN)**

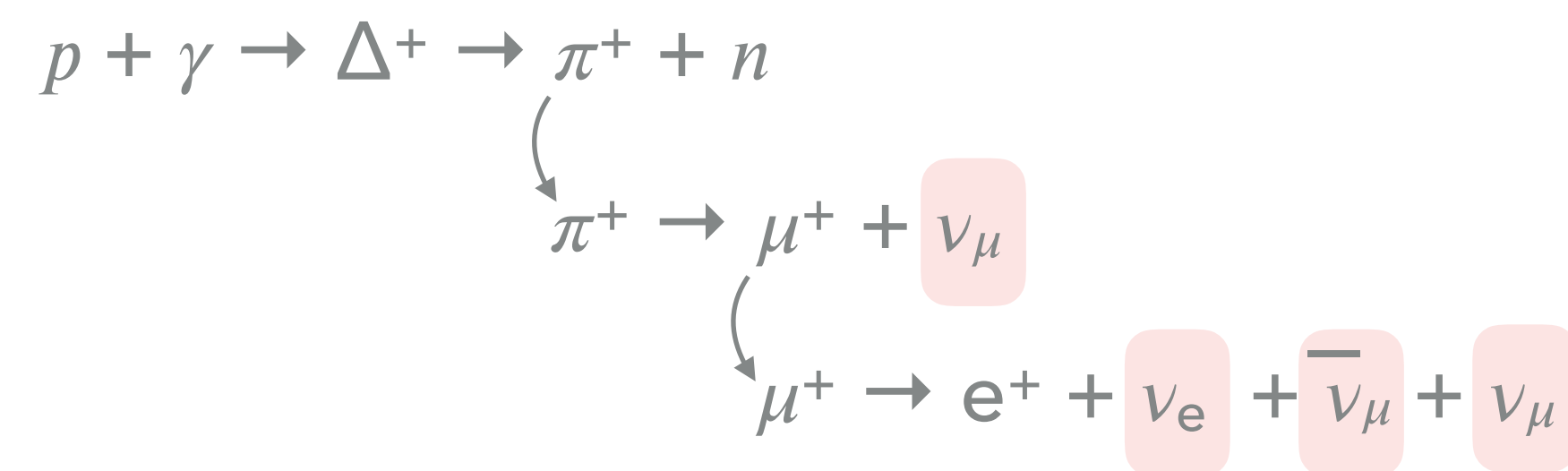


## NEUTRINO PROPERTIES:

- ▶ **ELECTRICALLY NEUTRAL** → trajectory not affected by magnetic fields, point back to the source
- ▶ **STABLE** → travel long distances without decaying
- ▶ **WEAKLY INTERACTING** → penetrate regions which are opaque to photons

## NEUTRINO PRODUCTION:

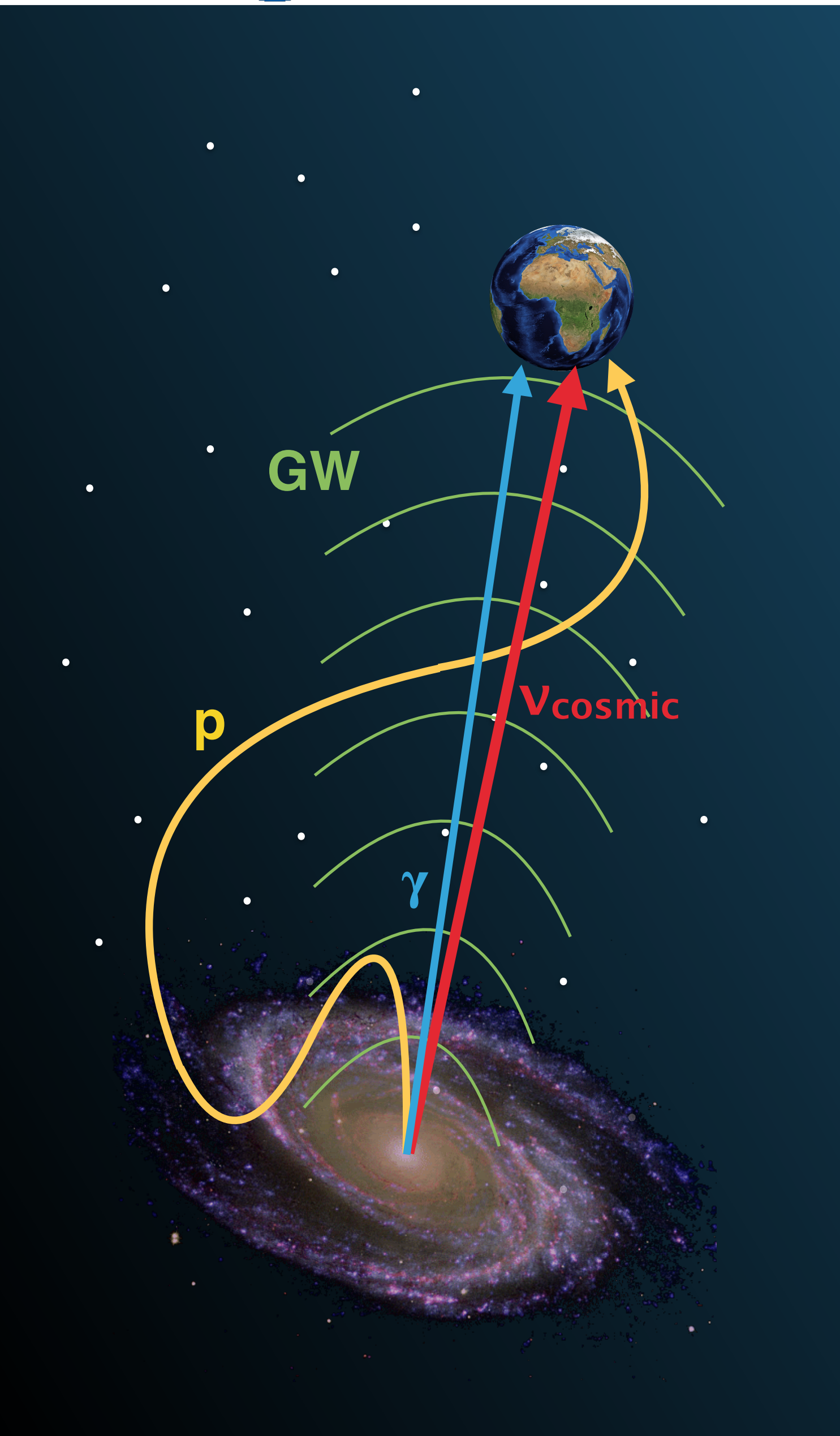
- ▶ Neutrino detection provides strong indication of hadronic acceleration in astrophysical sources:



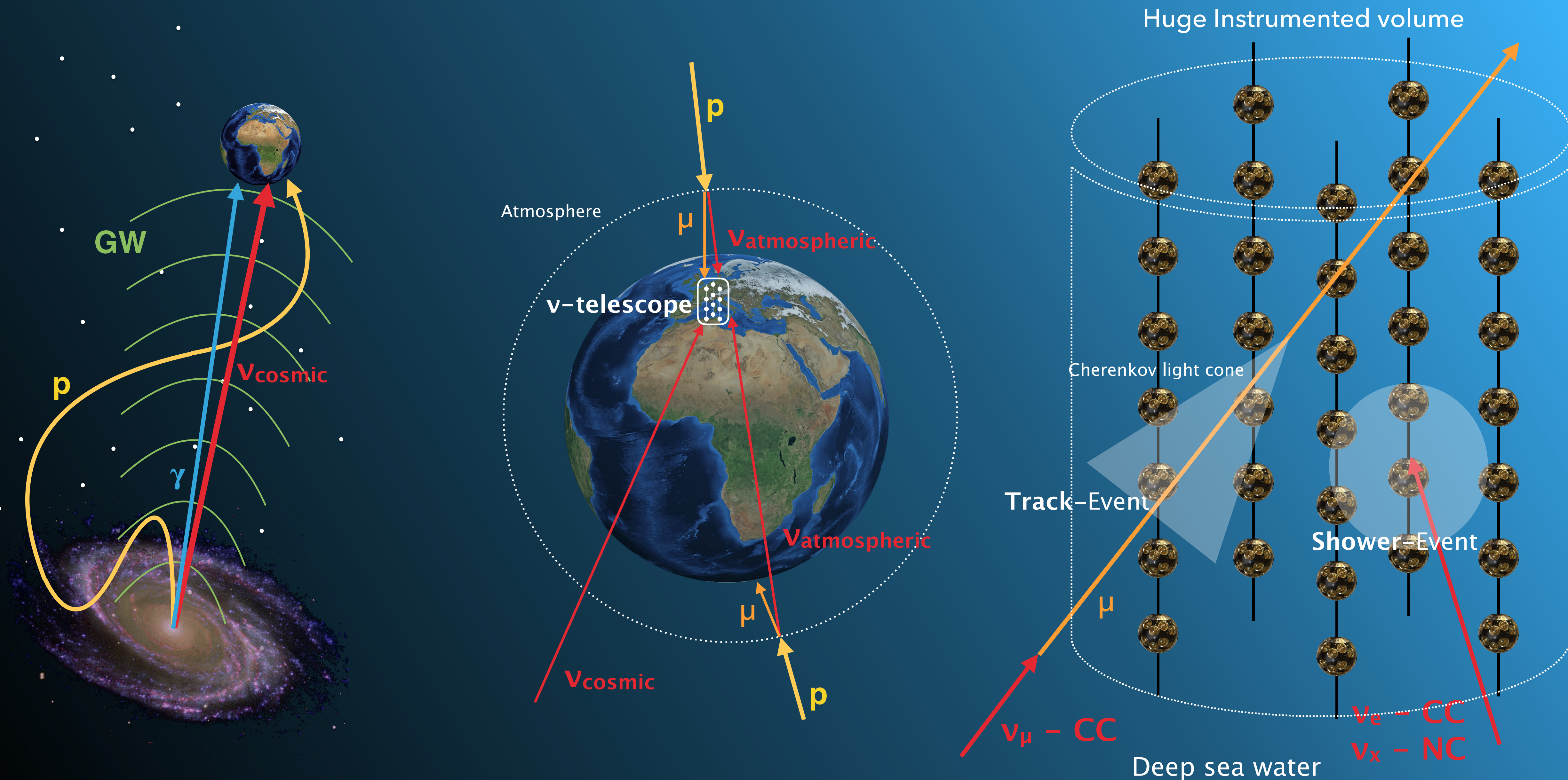
- ▶ Neutrino flavours composition:

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0 \quad \text{at the source}$$

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1 \quad \text{at the Earth}$$











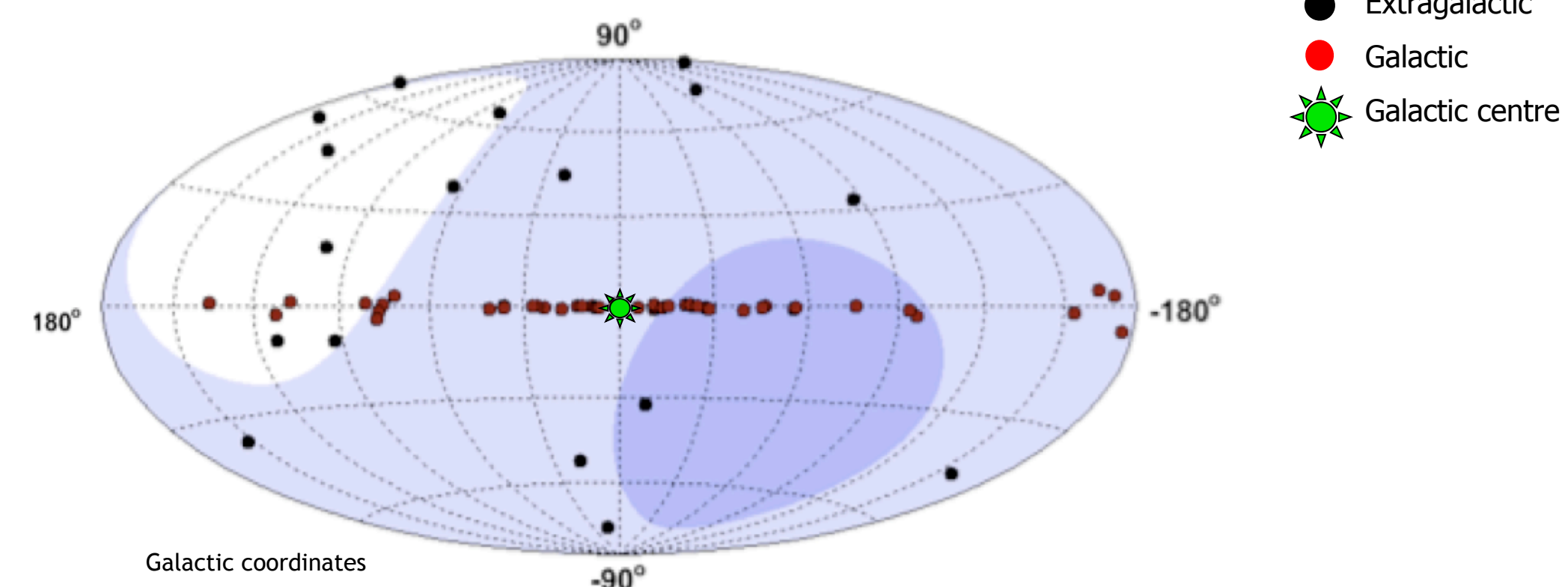
**ANTARES:** data taking since 2007, at about 2500 m under the sea level, off shore Southern French coast

**KM3NeT:**

- ▶ **ARCA (HE neutrino telescope)** in construction at 3500 m under the sea at about 100 km off shore Sicily
- ▶ **ORCA (neutrino mass hierarchy)** in construction near the ANTARES site

ANTARES, KM3NeT (Mediterranean) VISIBILITY

□ < 25%    □ 25% – 75%    □ > 75%



**A neutrino telescope in the Mediterranean (North Hemisphere) means:**

- ▶ full sky coverage
- ▶ **visibility of Galactic Plane + Galactic Center**



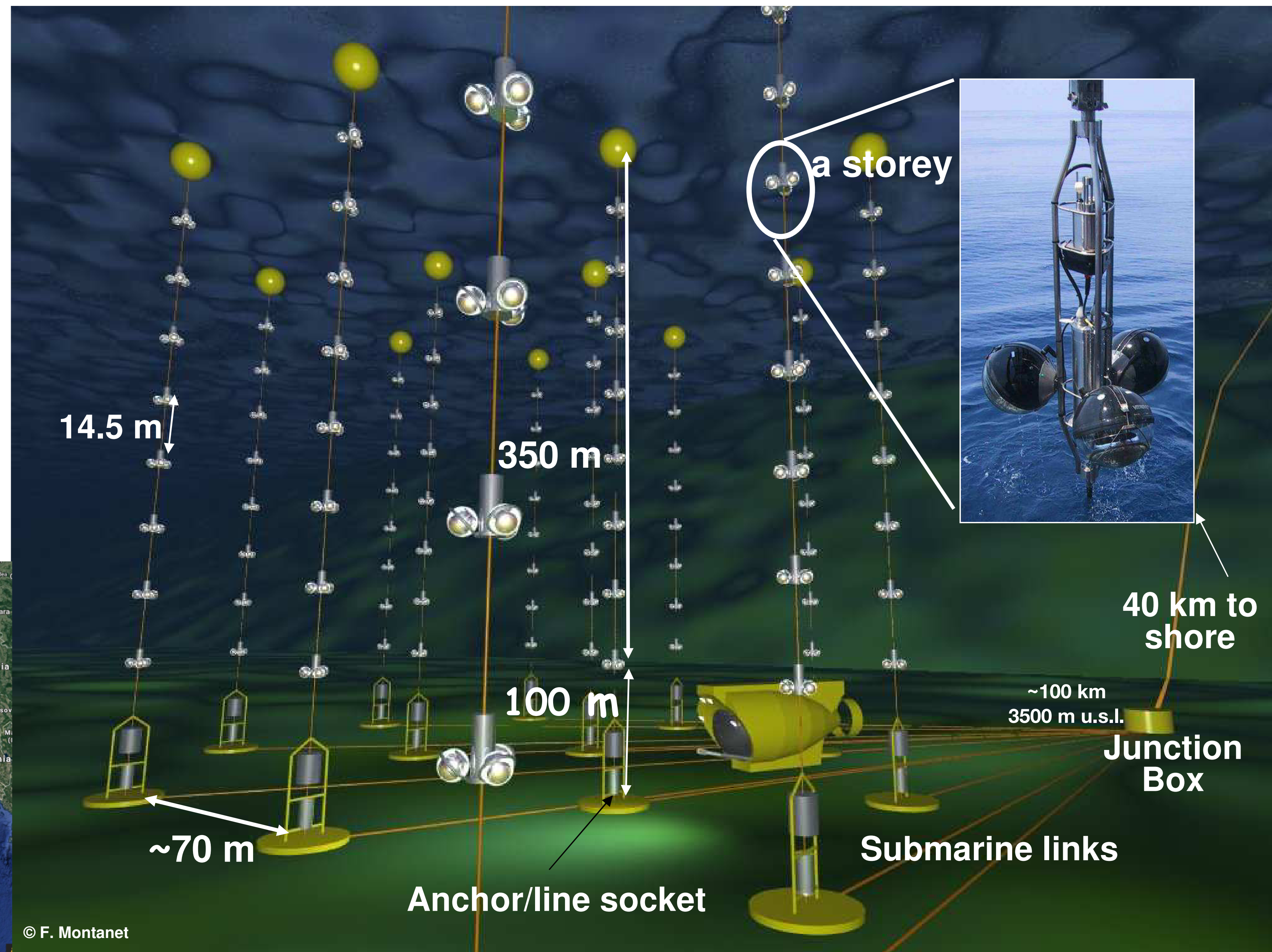


# ANTARES

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- ▶ Running since 2007
- ▶ 885 10" PMTs
- ▶ 12 lines
- ▶ 25/storeys/line
- ▶ 3 PMTs/storey
- ▶ 0.05 km<sup>3</sup> instr. Vol.

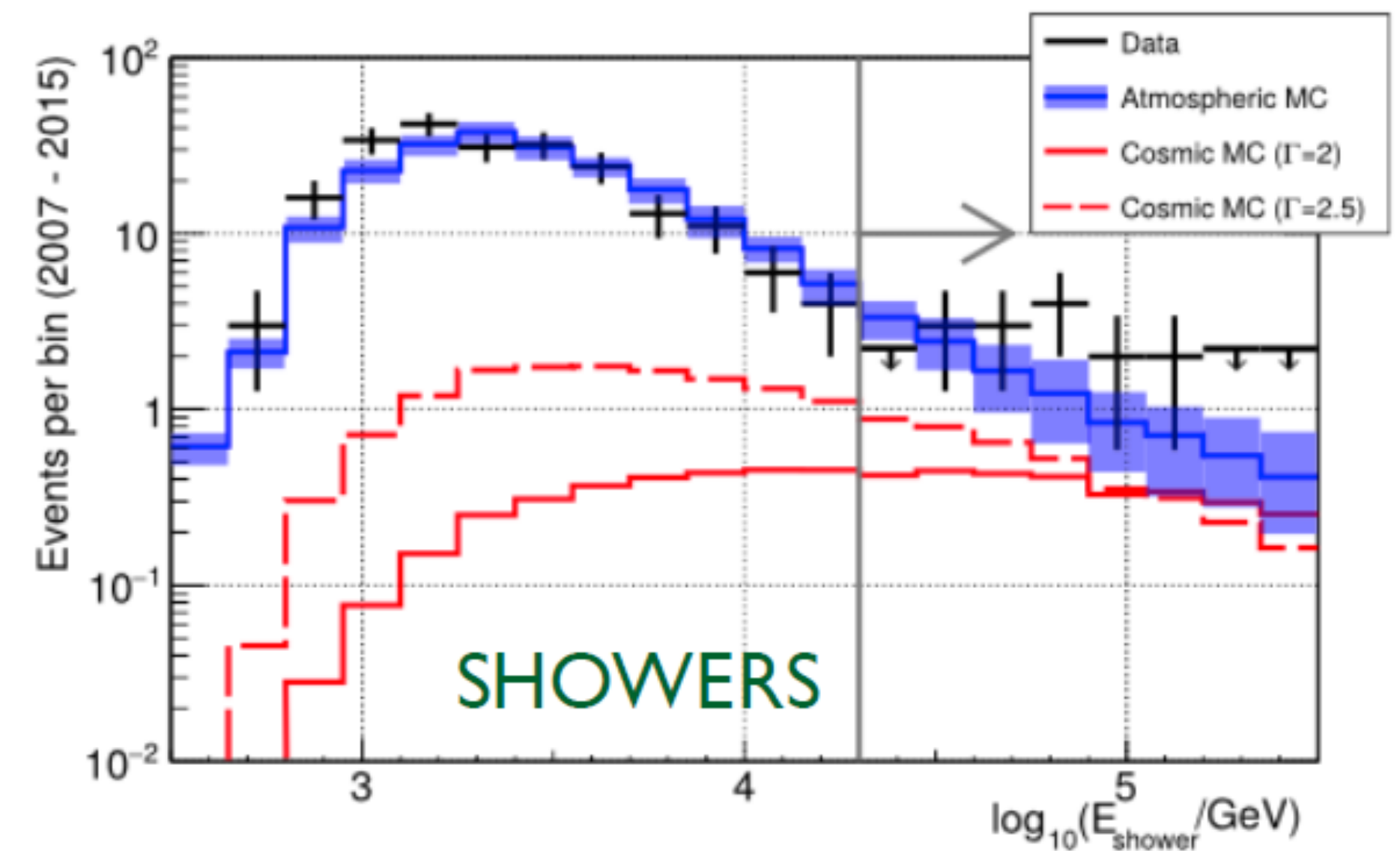
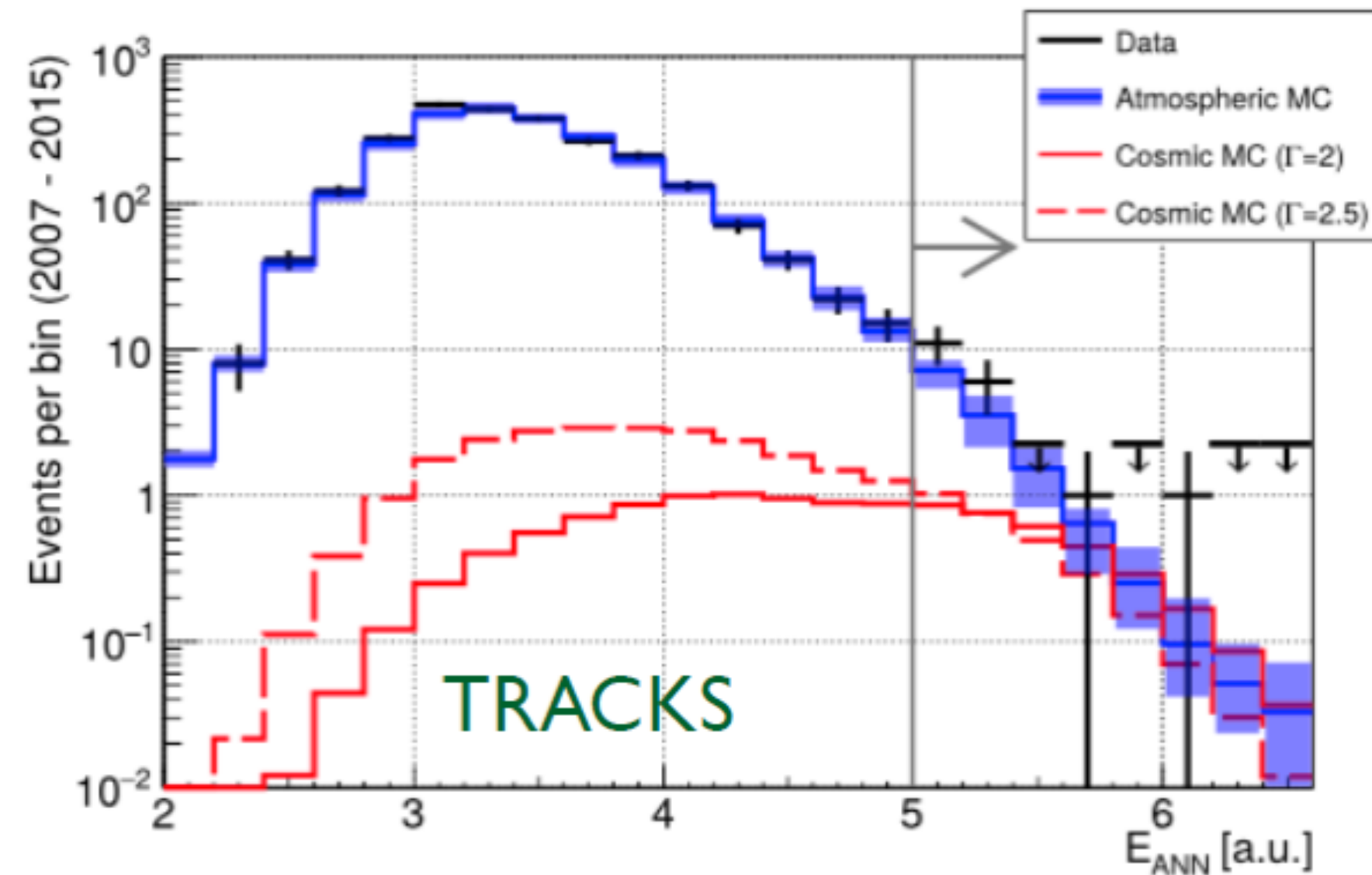
	Tracks	Shower
Angular res. [deg]	0.5°	5°
Energy res.	0.35 log <sub>10</sub> (E <sub>reco</sub> /E <sub>mu</sub> )	10%







- ▶ **Diffuse High Energy neutrino flux: excess of HE neutrinos over the atmospheric neutrino background. Based on the estimate neutrino energy.**



- ▶ **Sample:** 2007-2015, livetime 2450 days
- ▶ **All-flavour analysis** (tracks + showers)
- ▶ Event selection chain + energy-related cut applied to obtain high-purity neutrino sample and maximize the sensitivity
- ▶ Signal modeled according to IceCube flux (Science 342: 1242856, 2013)
- ▶ **Results:**
  - ▶ 33 events (19 tracks + 14 showers) in data when  $24 \pm 7$  (stat.+ syst.) expected from the background
  - ▶  $1.6 \sigma$  excess, null cosmic rejected a 85% CL





► **Point-like events: significant excess in the sky map. Based on the neutrino direction.**

► **Sample:** 2007-2015, livetime 2424 days

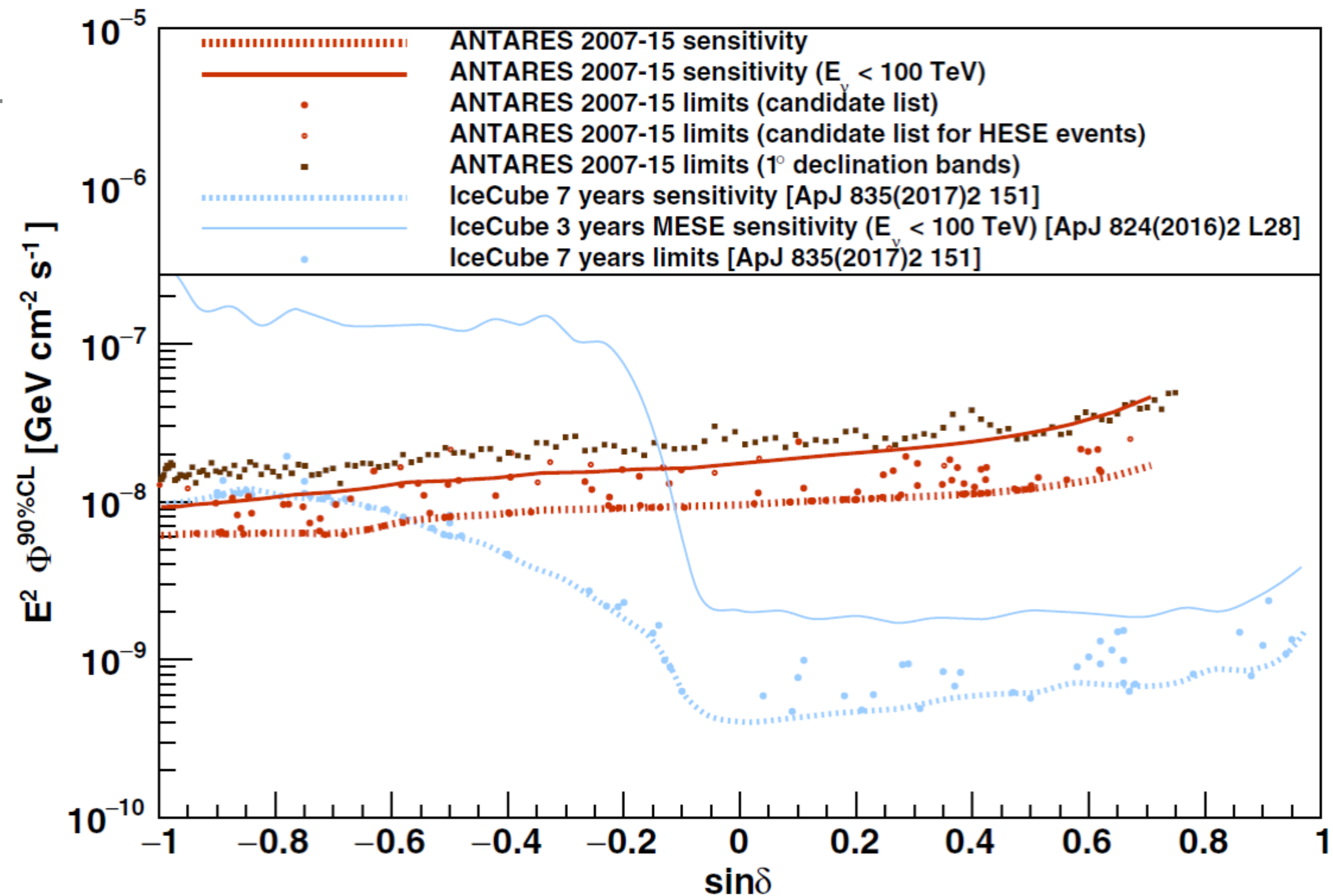
► **All-flavour analysis:** 7622 track-like, 180 shower-like neutrino candidates

► Maximum likelihood method used to search for clusters of  $\nu$ s from point sources

► **Candidate list searches:** 106 known astrophysical objects (Pulsars, SNRs, ...),

► **Sensitivities and upper limits** at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches (Neyman method)

► **Most sensitive limits for a large fraction of the southern sky, especially at neutrino energies below 100 TeV**

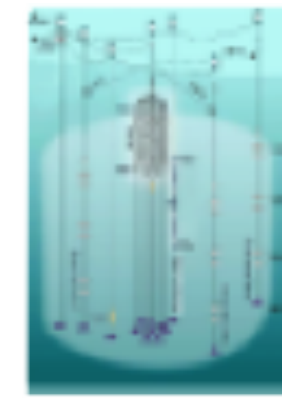




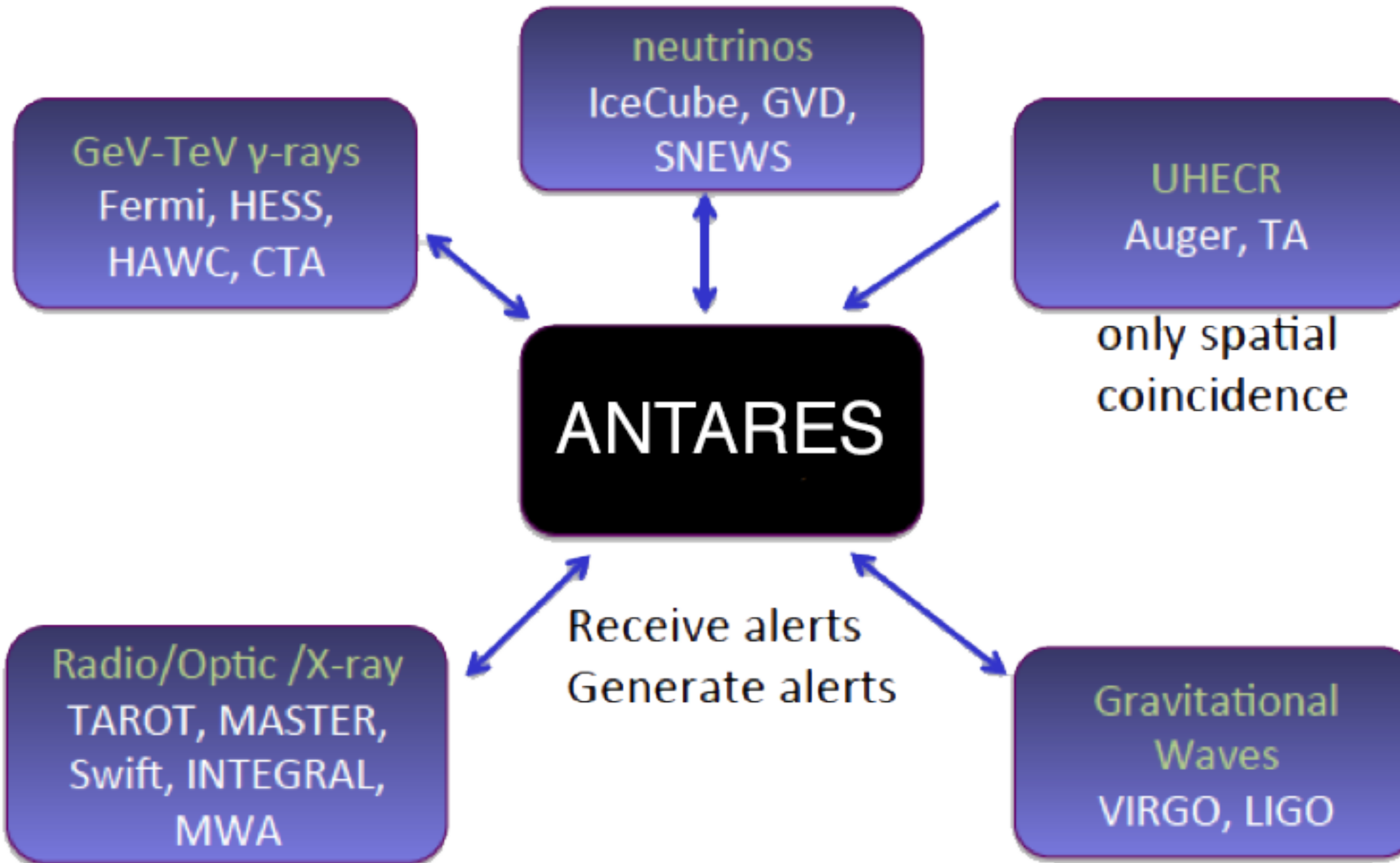
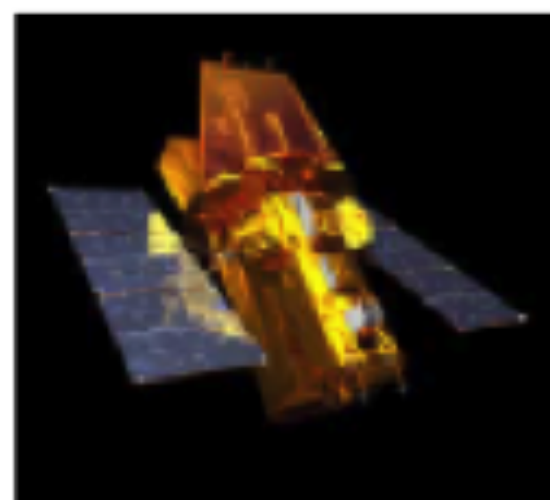
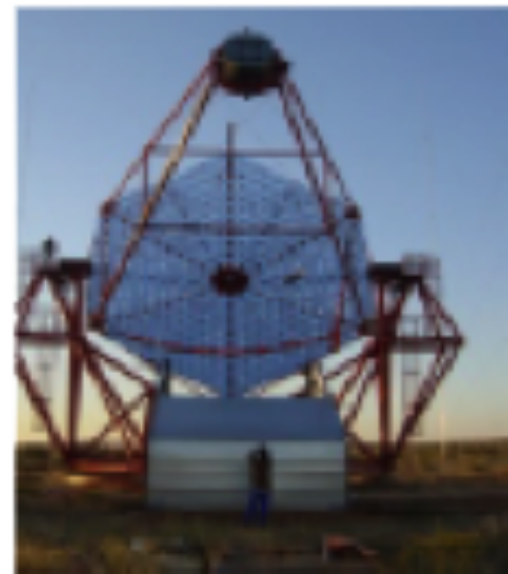
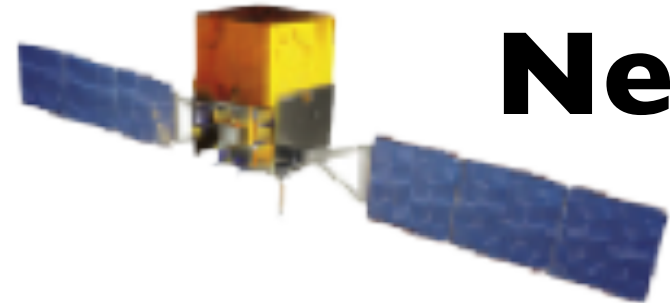
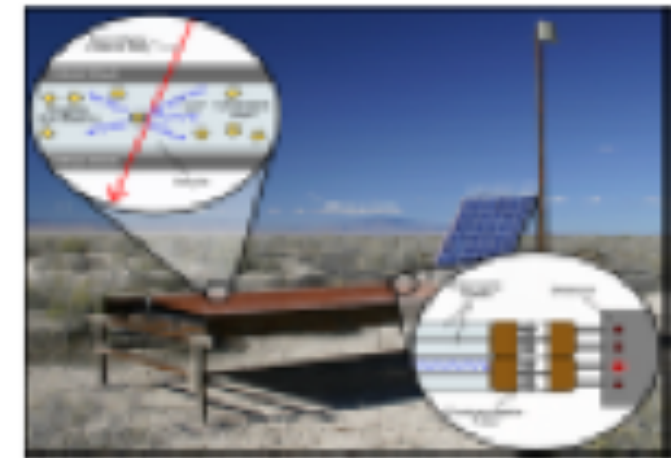


## Gamma-ray Coordinates Network (GCN)

<https://gcn.gsfc.nasa.gov/>



AMON  
Astrophysical Multimessenger Observatory Network







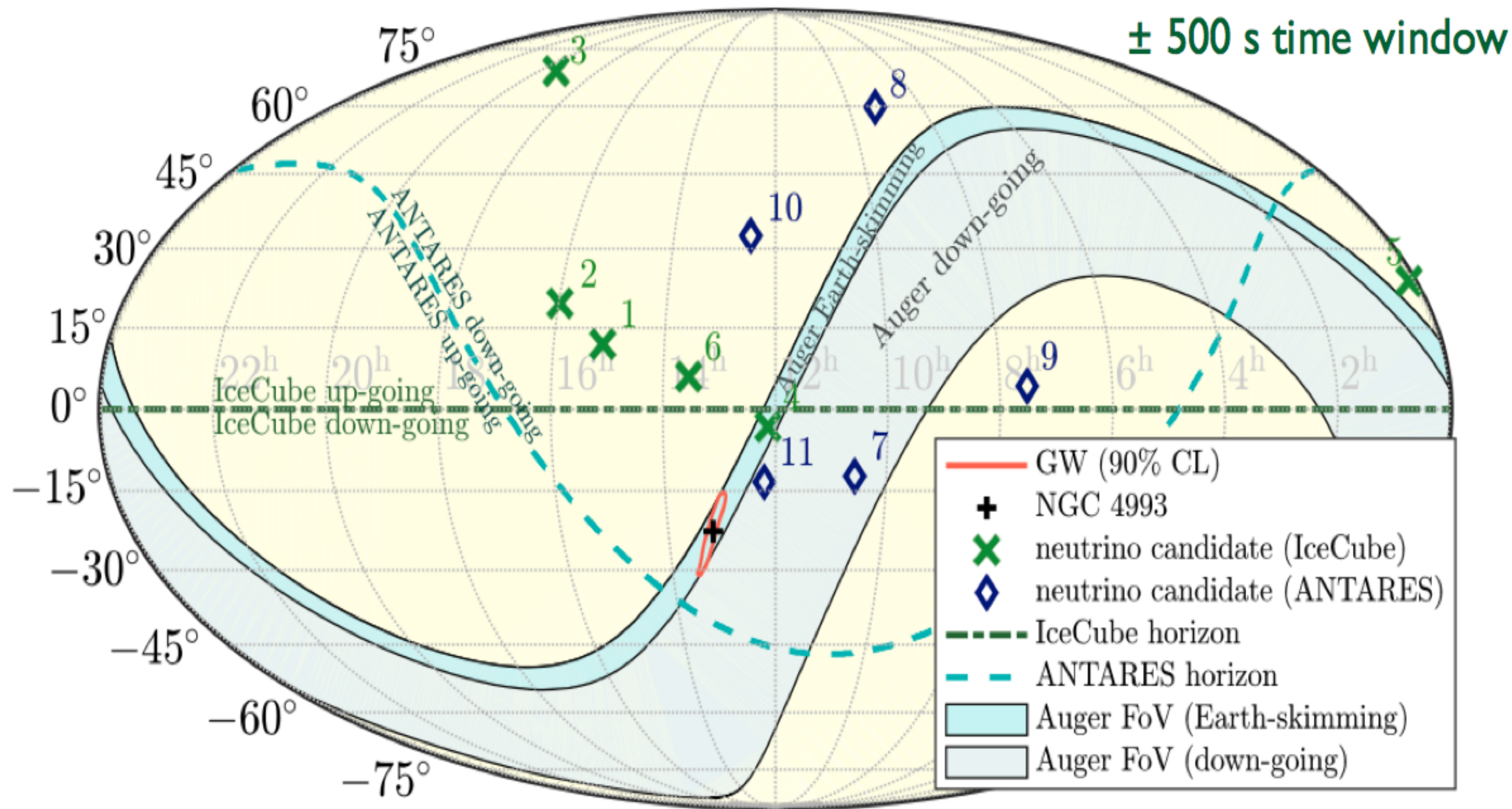
Recent spotlight on the GW events detected by the Ligo-Virgo Collaboration:

- ▶ GW150914 (BBH merger)
- ▶ GW151226 (BBH merger)
- ▶ LVT151012 (candidate)
- ▶ GW170104 (BBH merger)
- ▶ **GW170817 (NS merger)**
- ▶ No *space-time* coincidences with neutrino from the region of interest at 90% C.L.
- ▶ The jet of the NS-NS event (GW170817) was not aligned to our Line of Sight to provide a visible neutrino signal → **upper limit on the neutrino fluence from each events over the whole spectrum**
- ▶ **ANTARES and a few KM3NeT lines operational for Virgo/LIGO run 03 !**



ApJL 848 L12 (2017)

ApJL 850 L35 (2017)



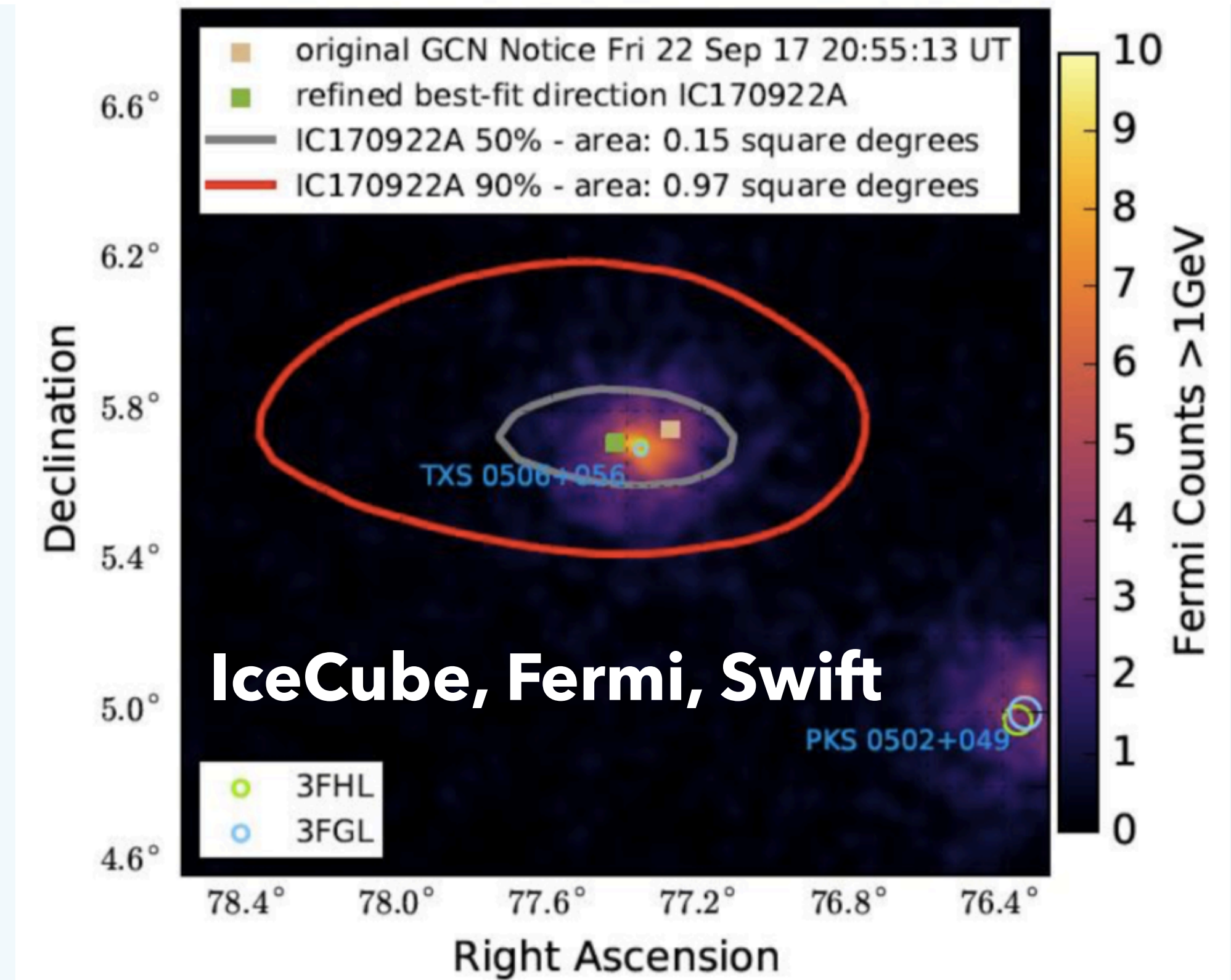
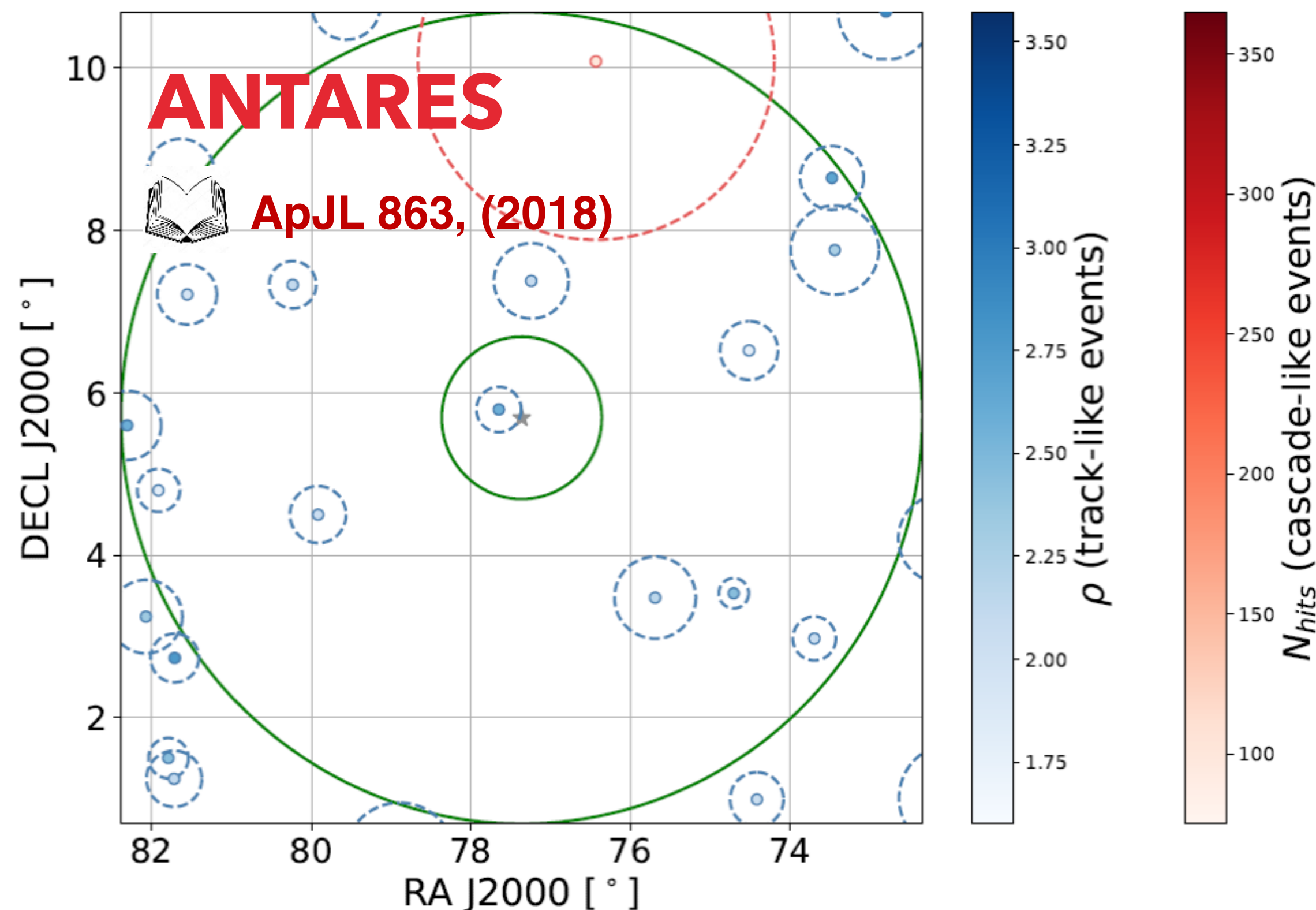




# ANTARES EVALUATION OF TXS 0506+056

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- ▶ **High-energy neutrino** was recorded with **IceCube** at September 22, 2017. Its arrival direction is consistent with the location of the **known gamma-ray blazar** TXS 0506+056, observed to be in a **flaring state**.
- ▶  **$3\sigma$**  significance on the correlation between the neutrino and the Blazar



- ▶ No upgoing muon neutrino candidate event was recorded within  $3^\circ$  around the IC170922A direction within  $\pm 1$  hr centered on the event time.
- ▶ This source has been scrutinized following the ANTARES standard point- source method. When considering that 107 sources have been investigated, the post-trial p-value for TXS 0506+056 corresponds to 87%.



## Astronomy Research with Cosmics in the Abyss (ARCA)



- ▶ **Scientific goal:**  
astrophysical neutrinos  
[TeV-PeV neutrinos]
- ▶ **Italian site**
- ▶ vertical spacing between DOMs: ~35 m
- ▶ horizontal spacing between DUs: ~90 m

## Oscillation Research with Cosmics in the Abyss (ORCA)



- ▶ **Scientific goal:**  
neutrino mass hierarchy  
[1 GeV-100 GeV neutrinos]
- ▶ **French site**
- ▶ vertical spacing between DOMs: ~6 m
- ▶ horizontal spacing between DUs: ~20 m



KM3NeT 2.0 Letter of Intent: J.Phys. G43 (2016) 084001

**Detection Unit (DU):**  
18 Digital Optical Modules (DOMs)

**DOM: 31 PMTs per DOM**



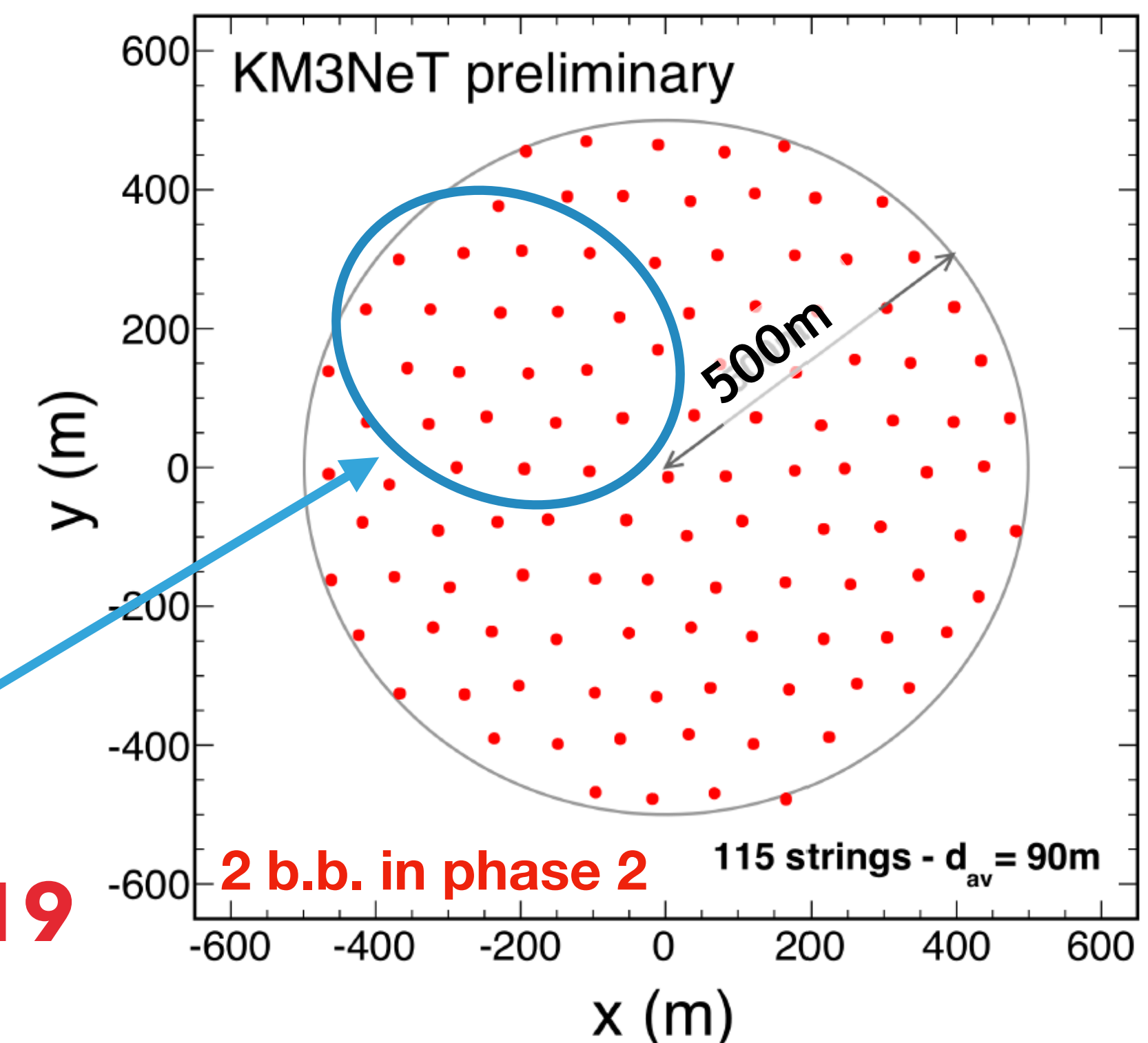




## ARCA → High Energy neutrino astronomy

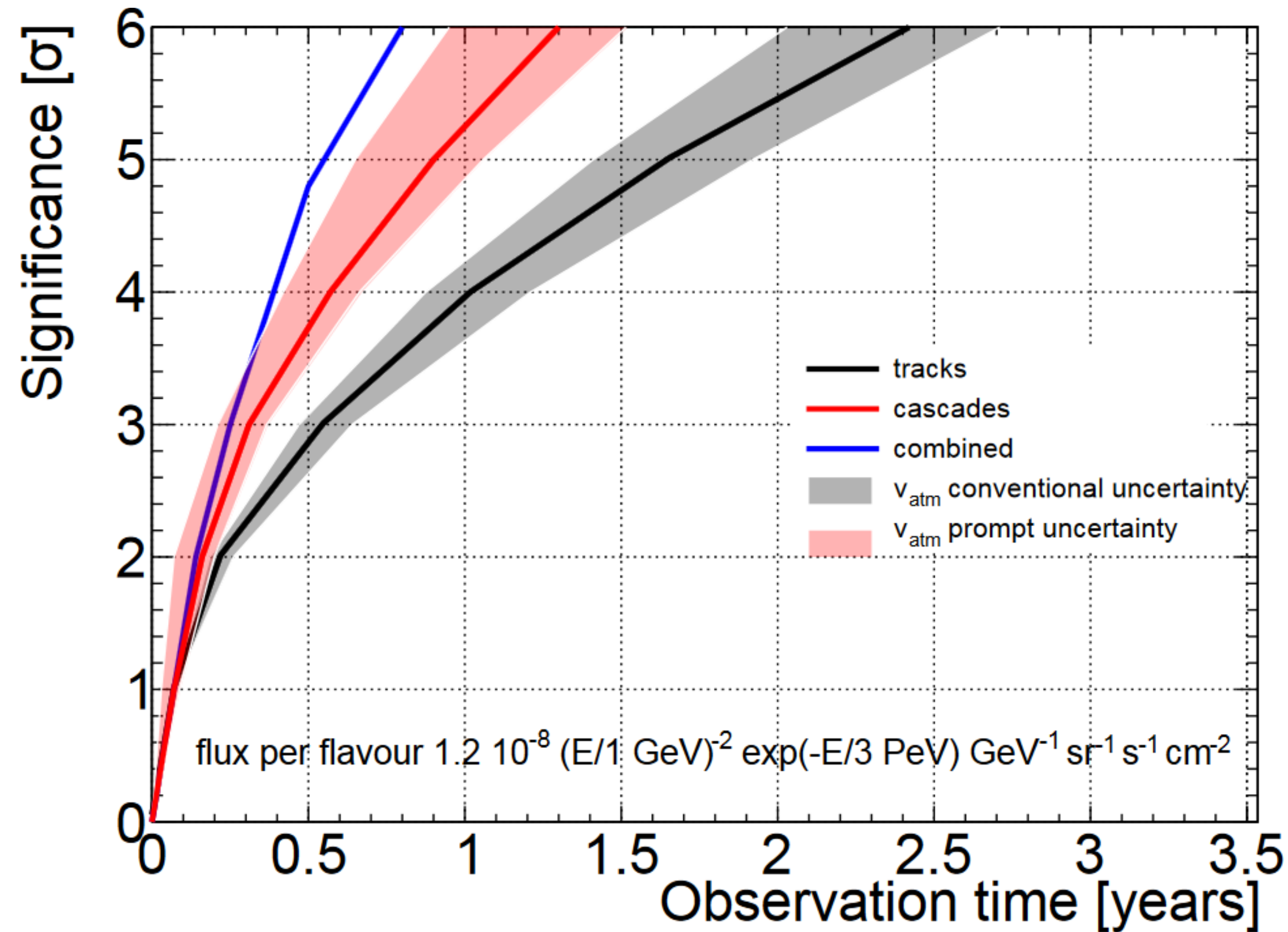
- ▶ 3 strings deployed Dec 2015 & May 2016
- ▶ 2 out of 3 operated, string #3 with short in power system, recovered
- ▶ New sea-operations by Fall 2018, resume of operations thereafter
- ▶ Full restoration of sea-bed network by mid-2019
- ▶ In construction: **Phase 1: 24 strings, Funded: 2018-2019**
- ▶ Phase 2: Partially funded: 2019-2021
  - ▶ >1 km<sup>3</sup> instr. Vol. (**2 building blocks ,1 building block = 115 strings**)

	Tracks	Showers
Angular res.	0.1°	2°
Energy res.	$0.3 \log_{10}(E_{\text{reco}}/E_{\text{mu}})$	5%



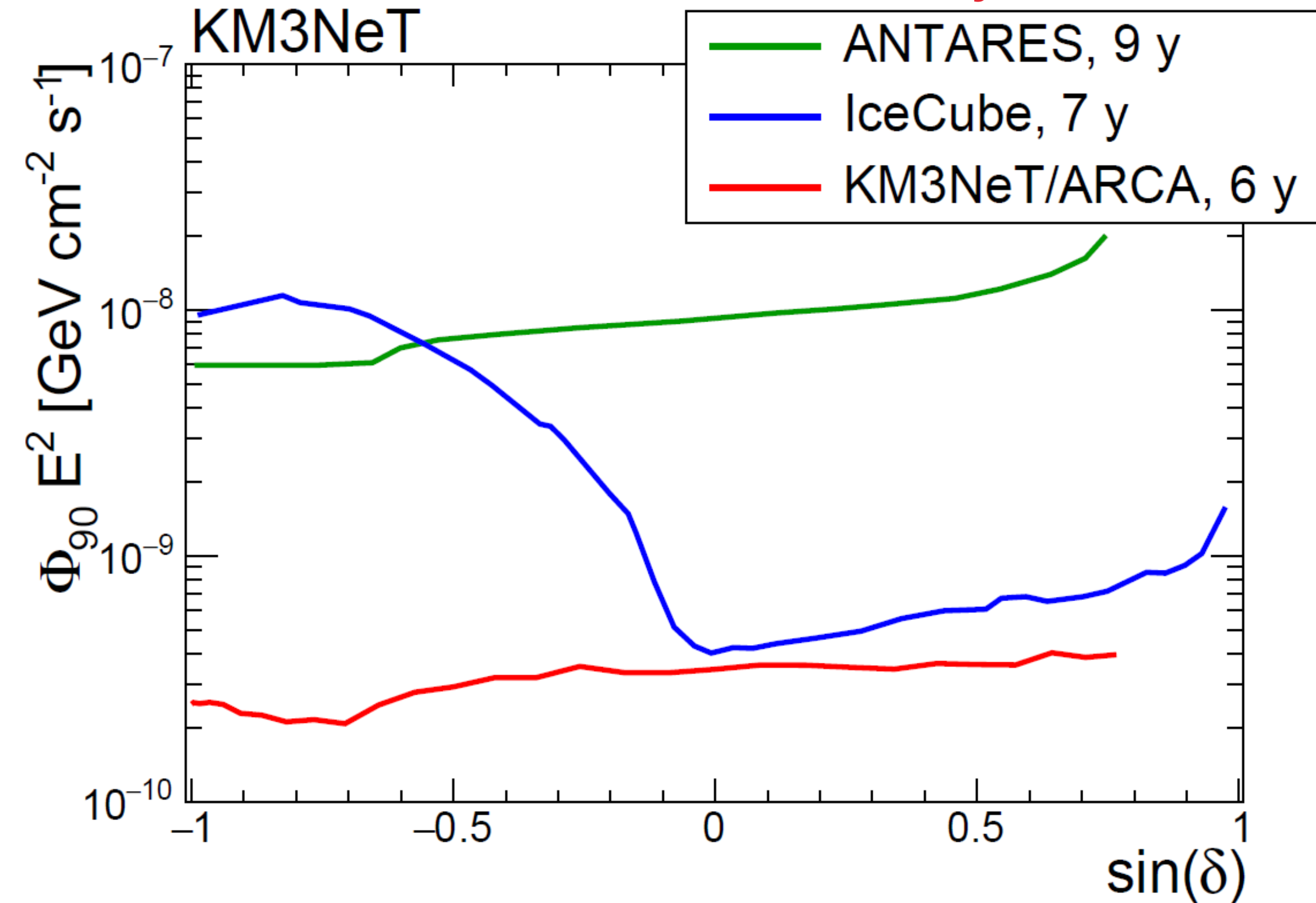


## Discovery to a diffuse neutrino flux



- Expected  $5\sigma$  significance on diffuse IC flux in  $< 1$  year
- Goal: don't just re-discover the IceCube flux, investigate it!

## Point sources sensitivity



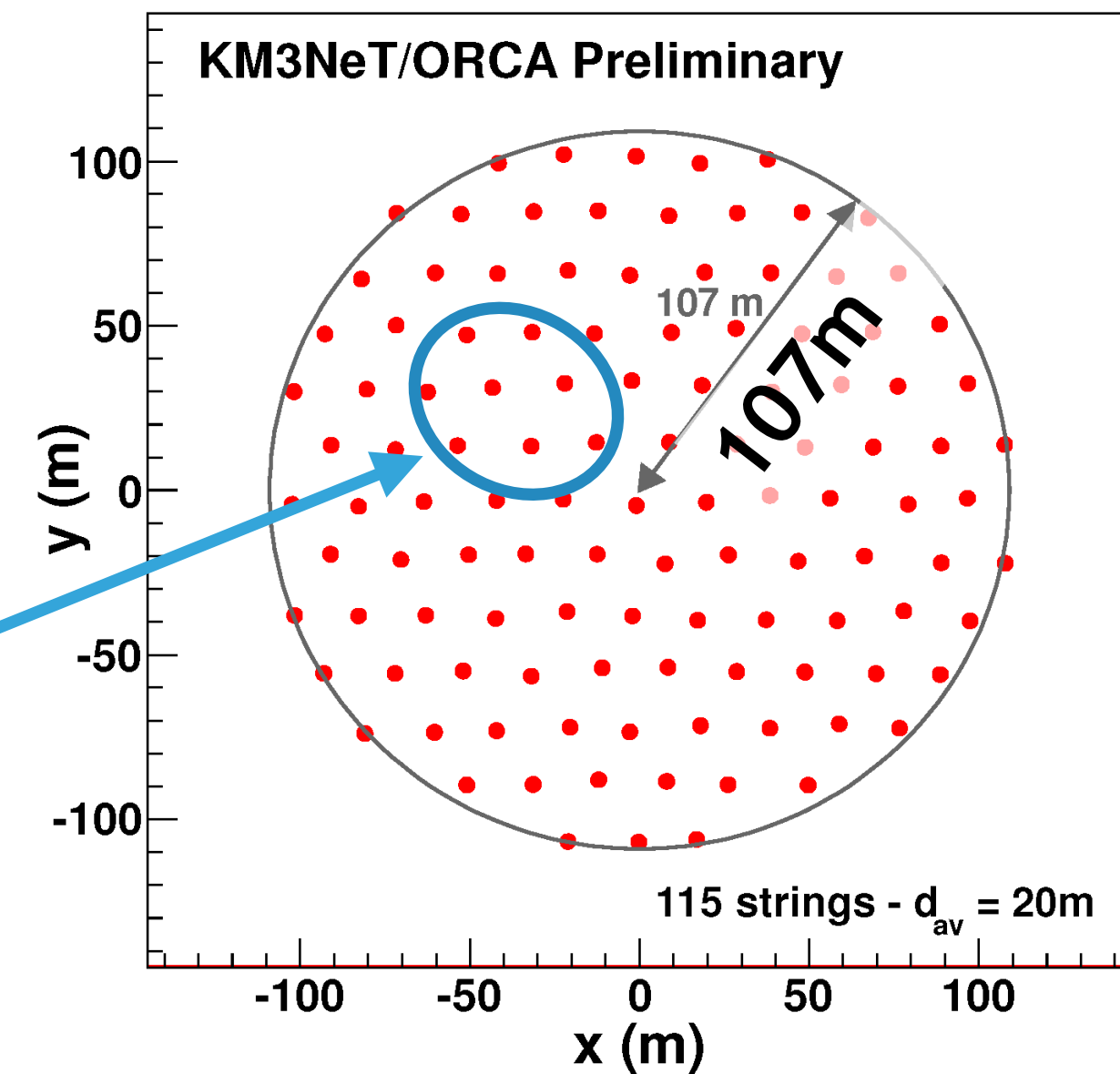
- KM3NeT ARCA (phase 2) will have the sensitivity to see galactic sources and will improve the ANTARES sensitivity of an order of magnitude



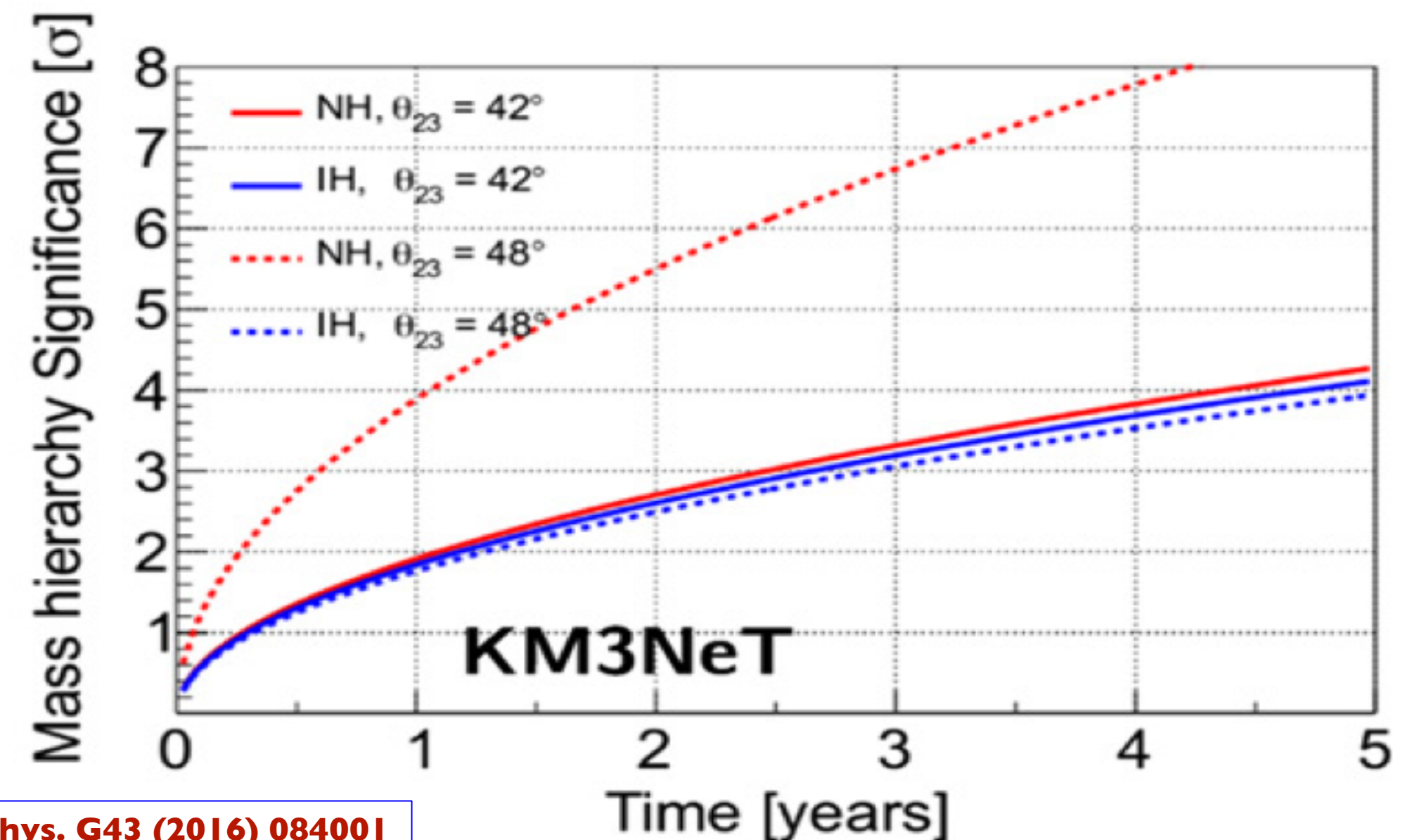
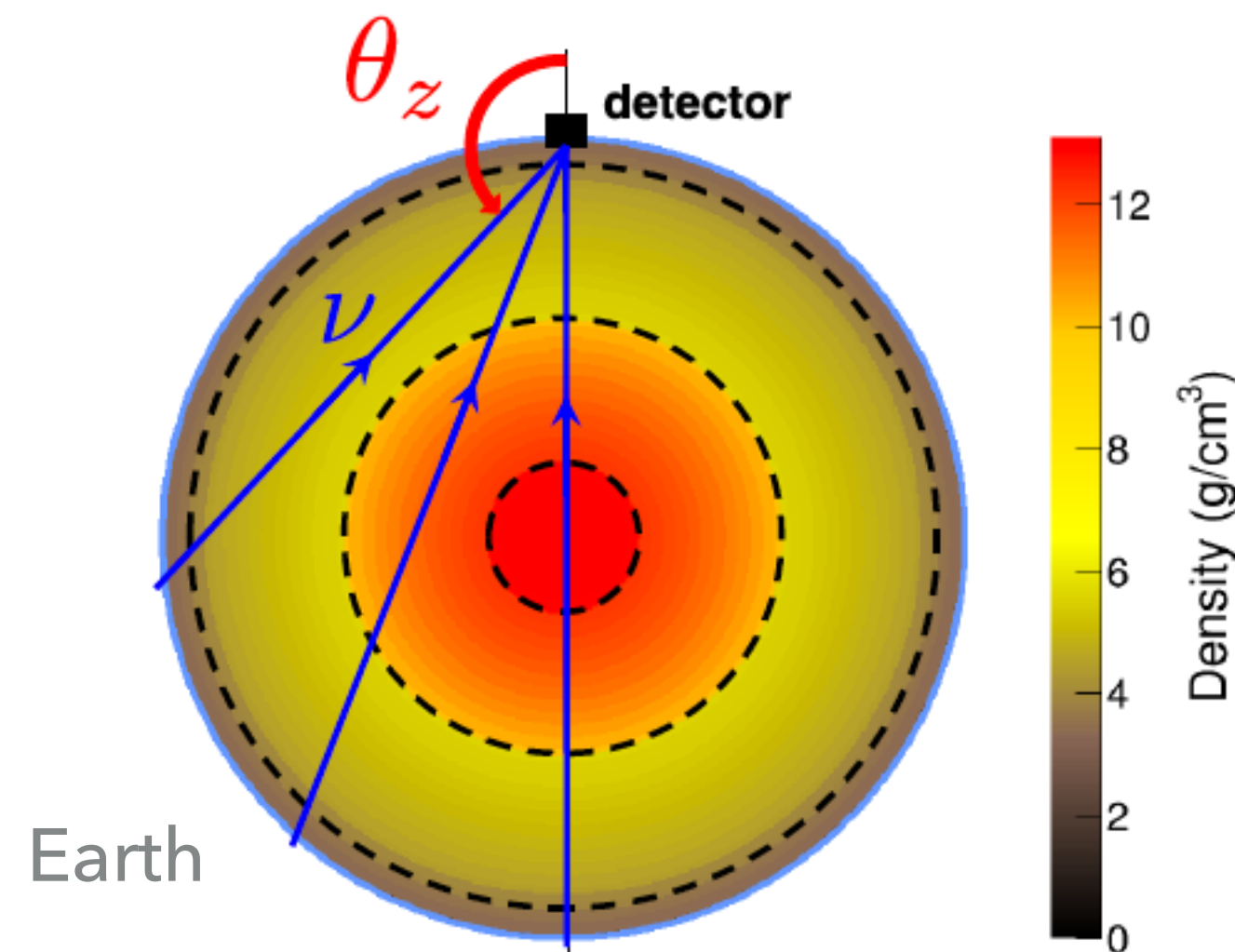


## ORCA → Neutrino Mass Hierarchy

- ▶ Worst case:  $3\sigma$  in 4 years
- ▶ Best case:  $> 5\sigma$  in 3 years
- ▶ Successful deployment & operation of first string (Sept 2017)
- ▶ Cable problem, replacement in summer 2018, then resume operations
- ▶ DOM and DU assembly proceeding Deployment after repairs
- ▶ In construction: **Phase 1: 7 strings, Funded: 2018-2019**
- ▶ Phase 2: 1 building block (115 strings)



- ▶ **Signature of the neutrino mass hierarchy:**  
energy-zenith distribution of atmospheric neutrinos





 **ANTARES: more than 10 years of continuous data taking!**

... and still stably ongoing!



 **ANTARES: solid results from various searches of astrophysical neutrino emission**

- ▶ (point-like, diffuse, extended regions, dark matter, ...)

 **Active multi-messenger program:**

- ▶ Neutrino alerts distribution, participation to GCN and AMON
- ▶ External alerts reception, prompt analysis
- ▶ Offline multi-messenger analysis.
- ▶ Combined analyses with IceCube (point sources, galactic plane, time correlation...).

 **ANTARES: neutrino telescope in the Northern hemisphere looking for neutrinos in coincidence with GW events expected during the Ligo/Virgo O3, waiting for KM3NeT**

 **Best practice and multi-messenger searches ported to KM3NeT!**



 **Neutrinos are an indispensable ingredient of multi-messenger astronomy**

 **KM3NeT will be soon competitive in astrophysical researches and in the basic neutrino physics**

## OTHER TOPICS NOT COVERED HERE:

### ▶ **Fast Radio Bursts (FRB):**

- arXiv:1807.04045

### ▶ **Neutrino oscillations and NMH:**

- Phys. Lett. B 714 (2012) 224
- ... Works on going

### ▶ **Indirect Dark Matter searches**

- Phys. Lett. B **759** (2016) 69-74
- Phys. Lett. B **769** (2017) 249
- Physics of the Dark Universe 16 (2017) 41
- JCAP05(2016)016

### ▶ **Magnetic Monopoles:**

- JHEP **07** (2017) 054

### ▶ **Sea and Earth Science**

- Scientific Reports 7(2017): 45517
- Jou. Geophysical Research 122(2017) 2291
- Ocean Dynamics 64 (2014)507-517
- PLoS ONE 8(2013): e67523
- Deep-Sea Research I 58(2011)875



A group of dolphins is swimming in the blue ocean. One dolphin in the center is looking up towards the camera. The water is a deep blue with some whitecaps. The dolphins are dark grey or black.

# Thank you

**During operation on the ANTARES/ KM3NeT site, last summer**



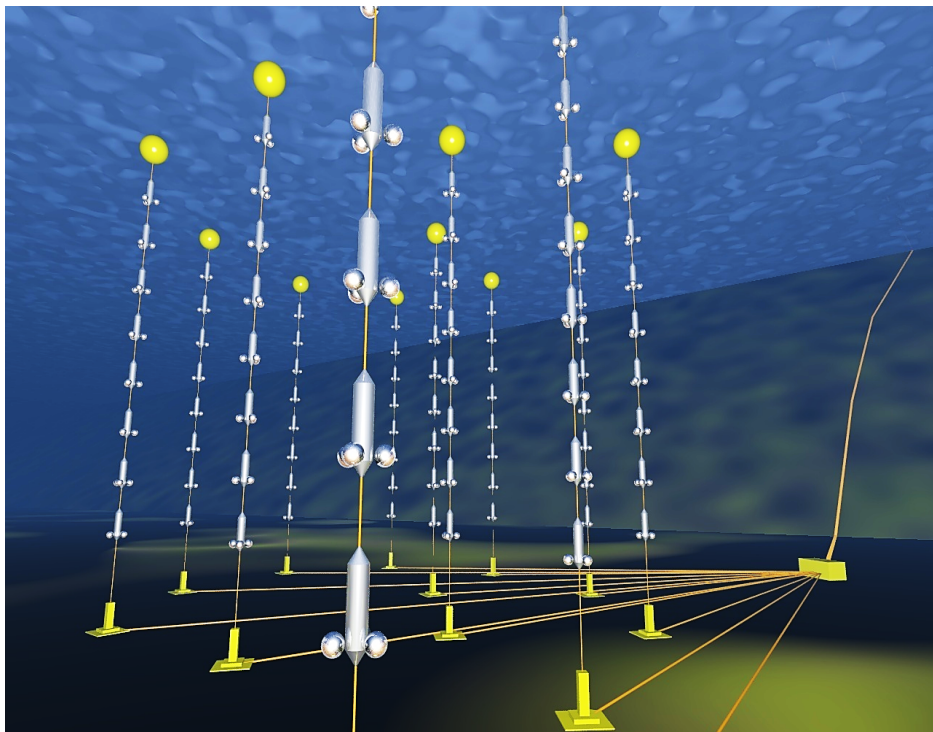


BACKUP

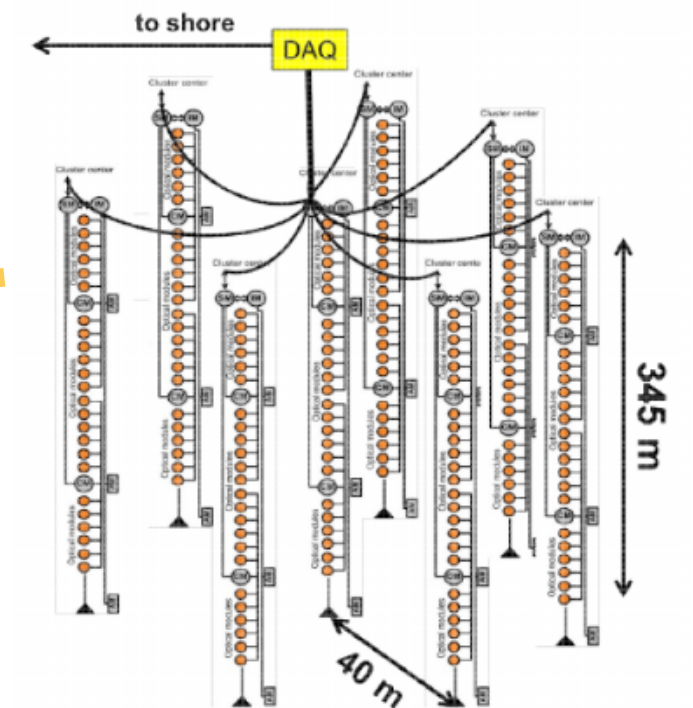
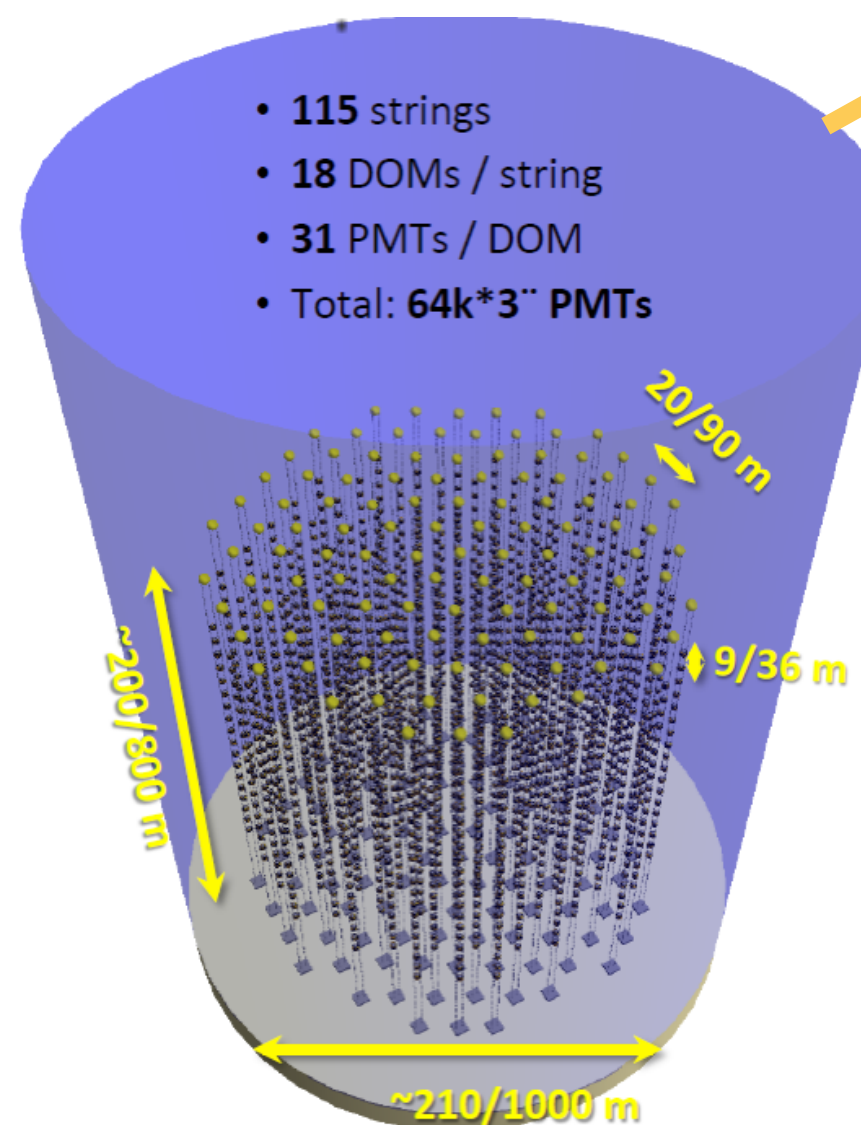
# NEUTRINO TELESCOPES

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ANTARES  
KM3NeT/ORCA

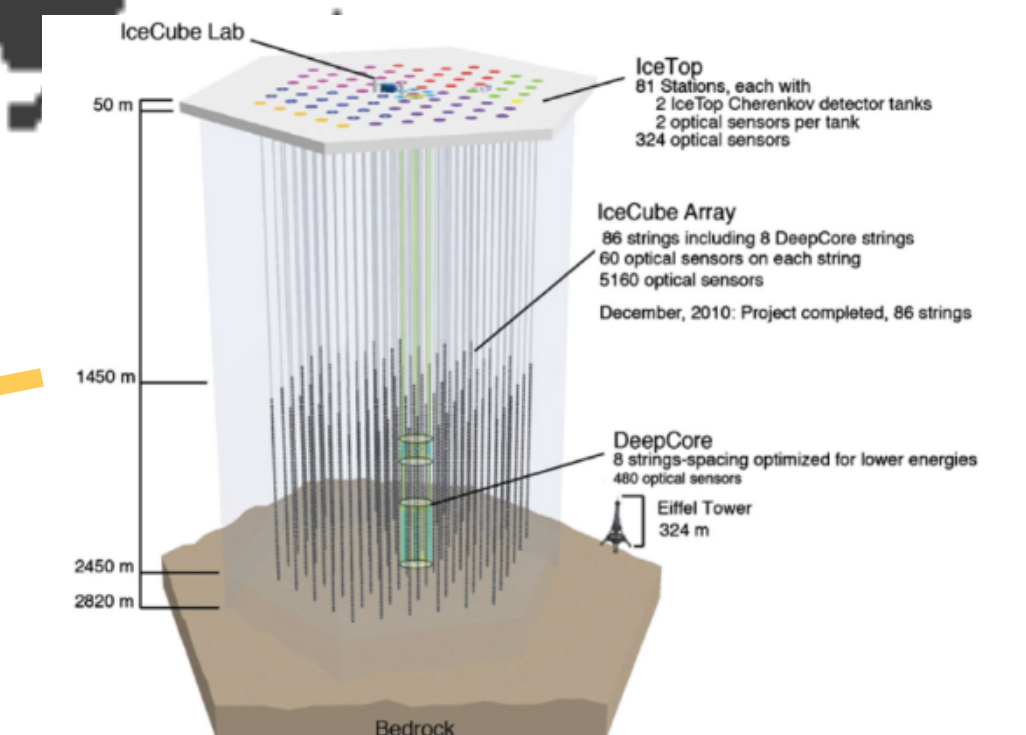


KM3NeT/ARCA



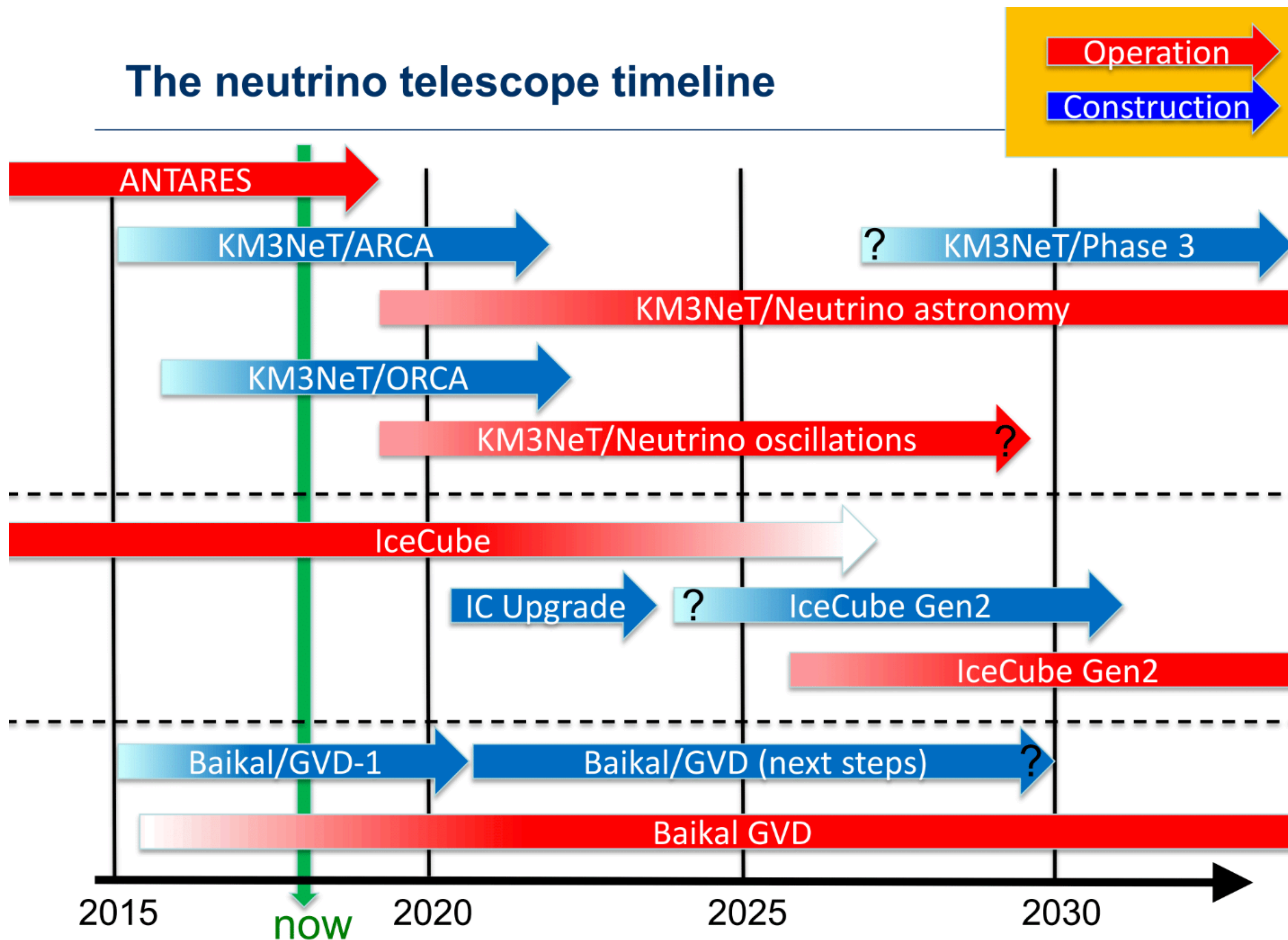
BAIKAL

IceCube

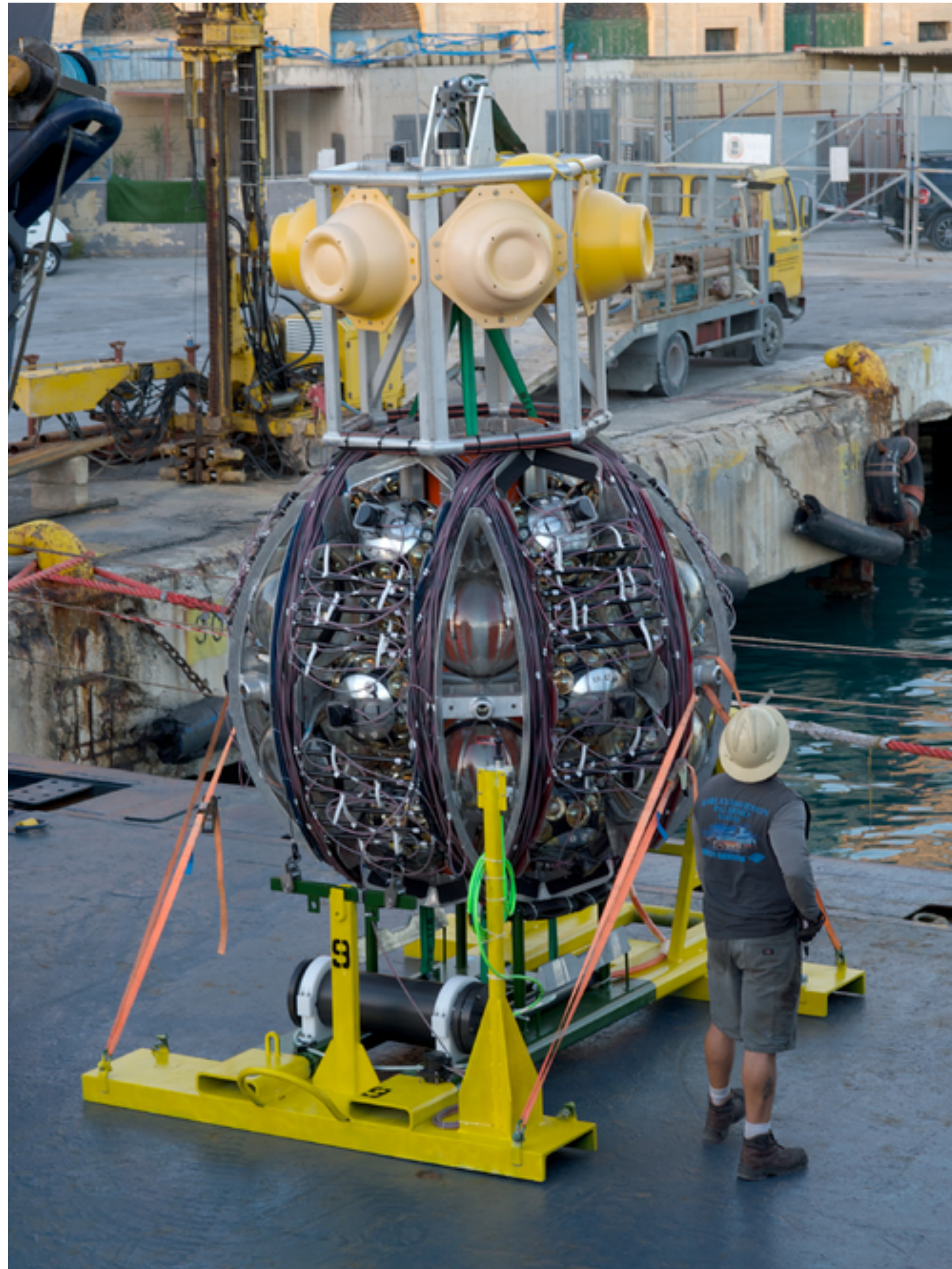




### The neutrino telescope timeline





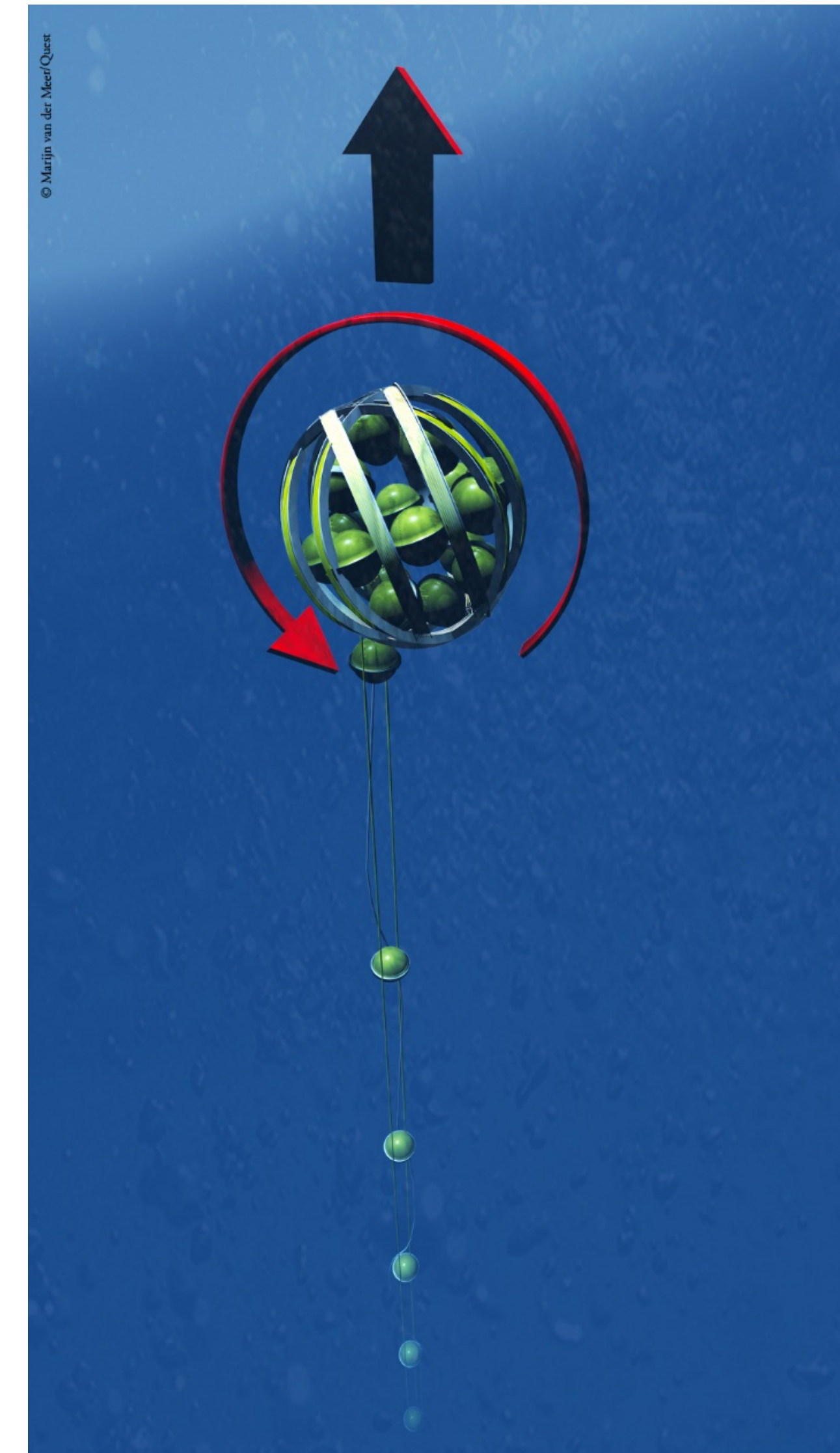


← The DU is furled in the Launcher Vehicle (the LOM), which is deployed on the sea-bed.

Mechanical release by ROV



Unfurling →  
Several DUs per sea operation





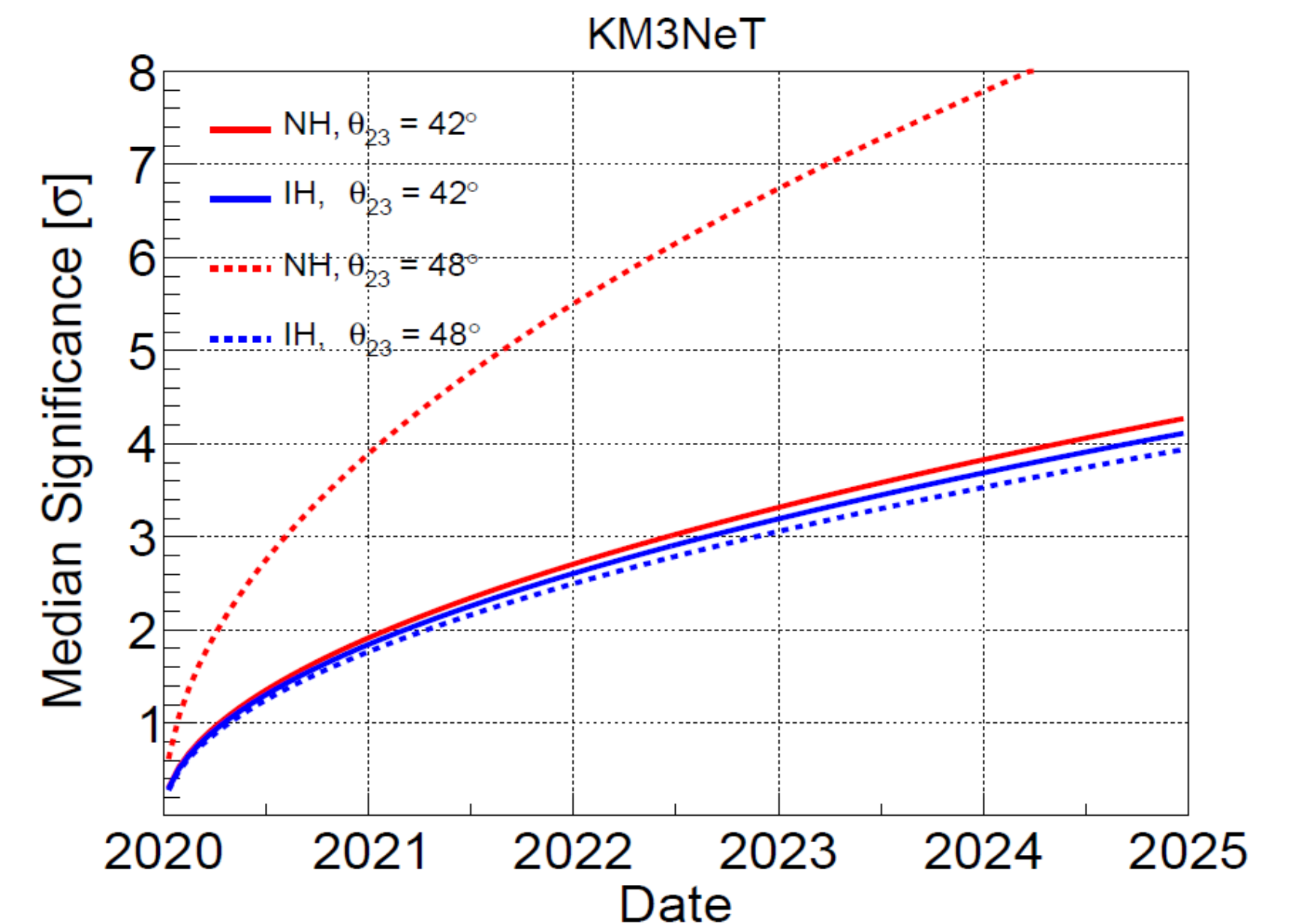
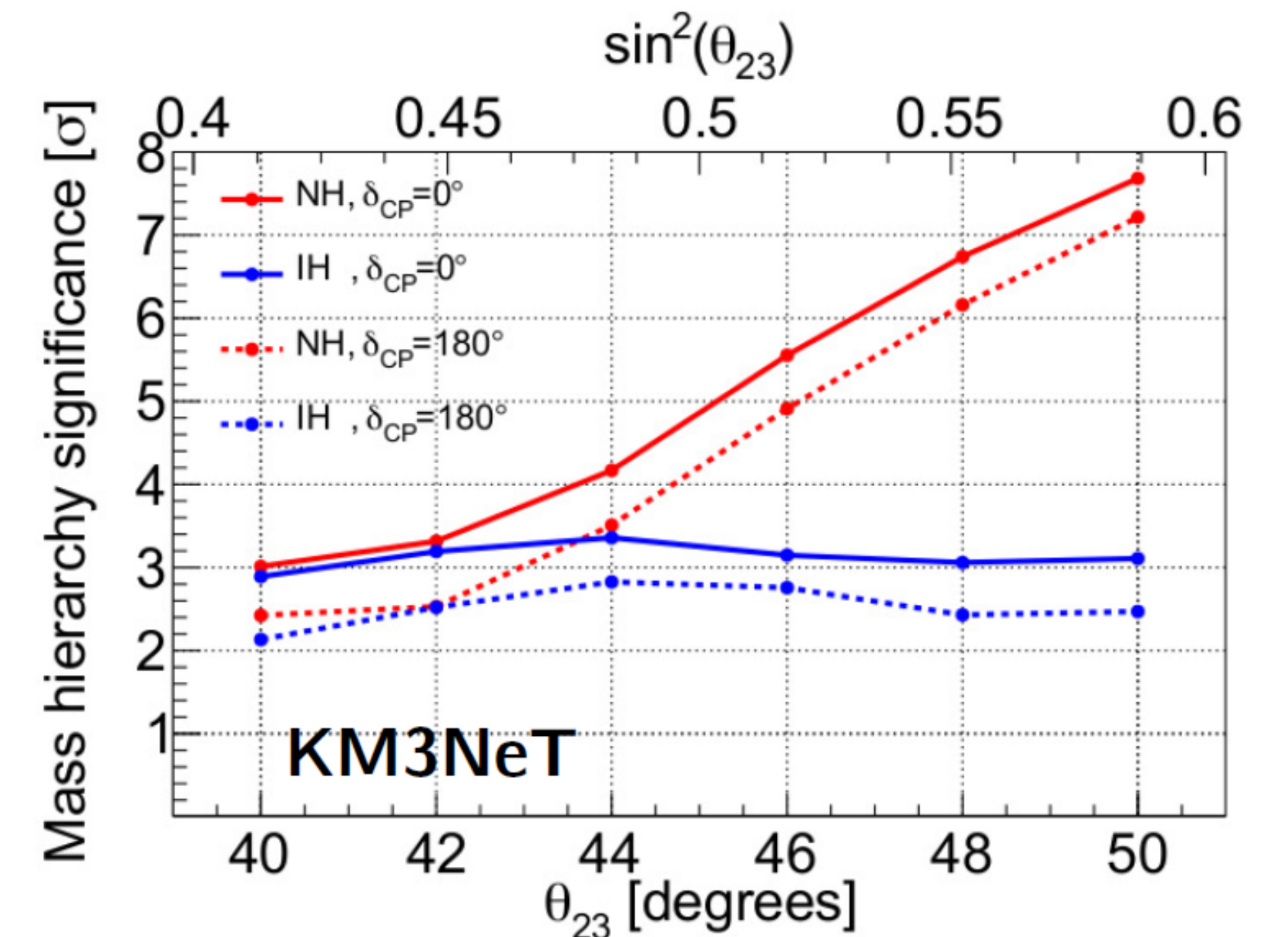
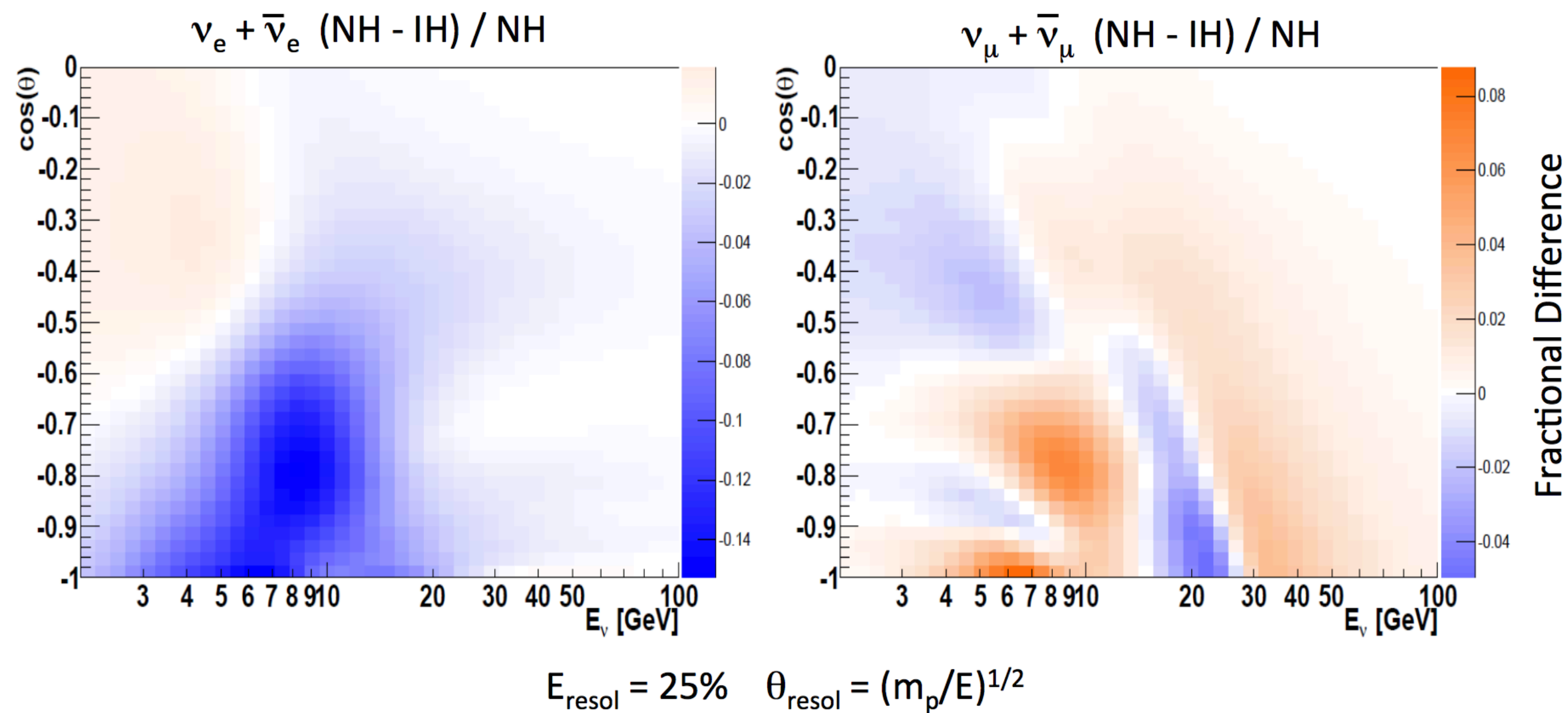


## Signature of the neutrino mass hierarchy → energy-zenith distribution of atmospheric neutrinos

Measurement requires

- best possible resolution in energy and zenith
- separation  $\nu_e/\nu_\mu$
- detailed understanding of systematics

- ▶  $\sim 3\sigma$  MH sensitivity in 3 years
- ▶ **Best case** scenario (NH and  $\theta_{23}=48^\circ$ ) could achieve  $>5\sigma$  by mid 2021 (1.5 years)



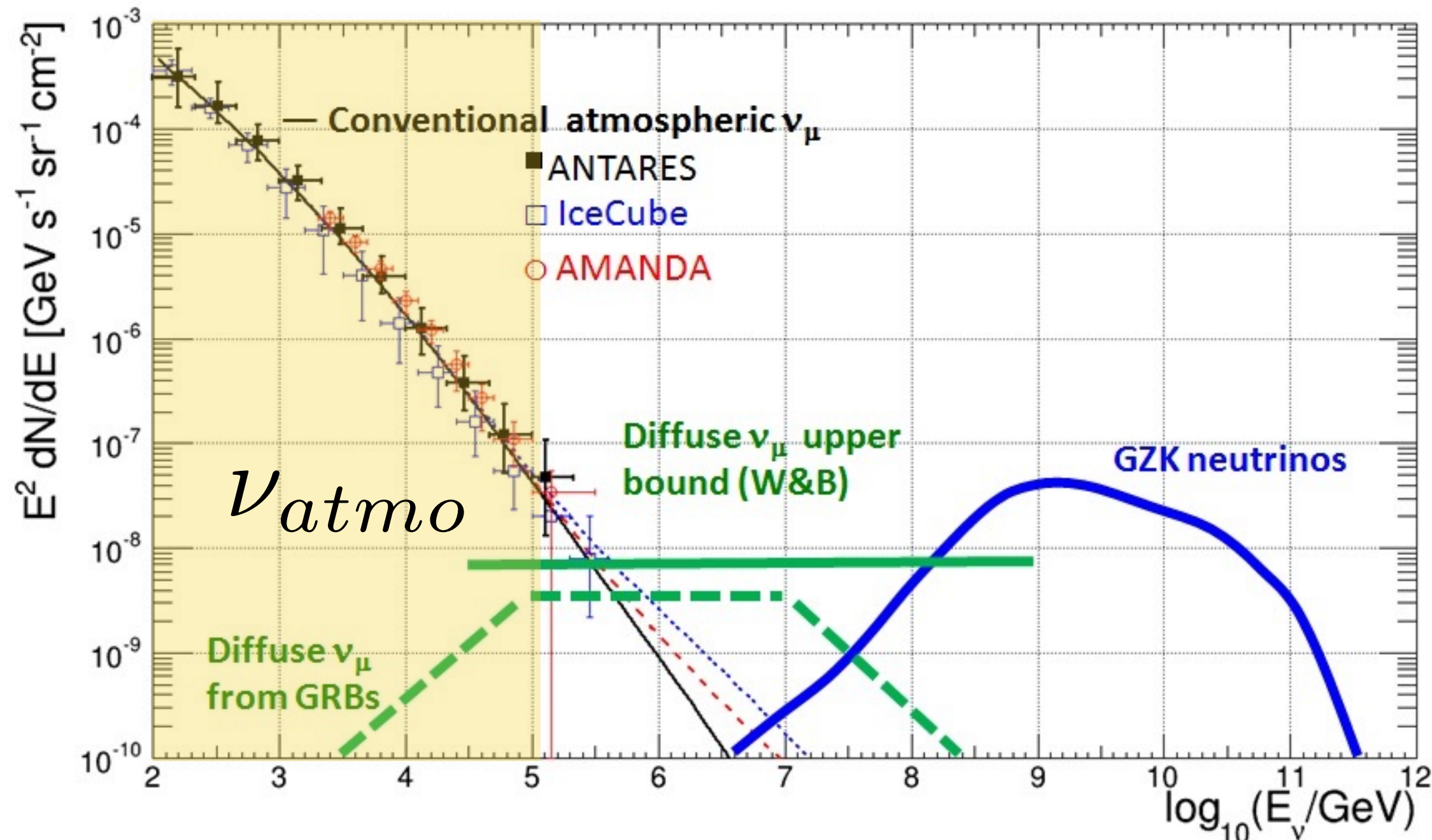




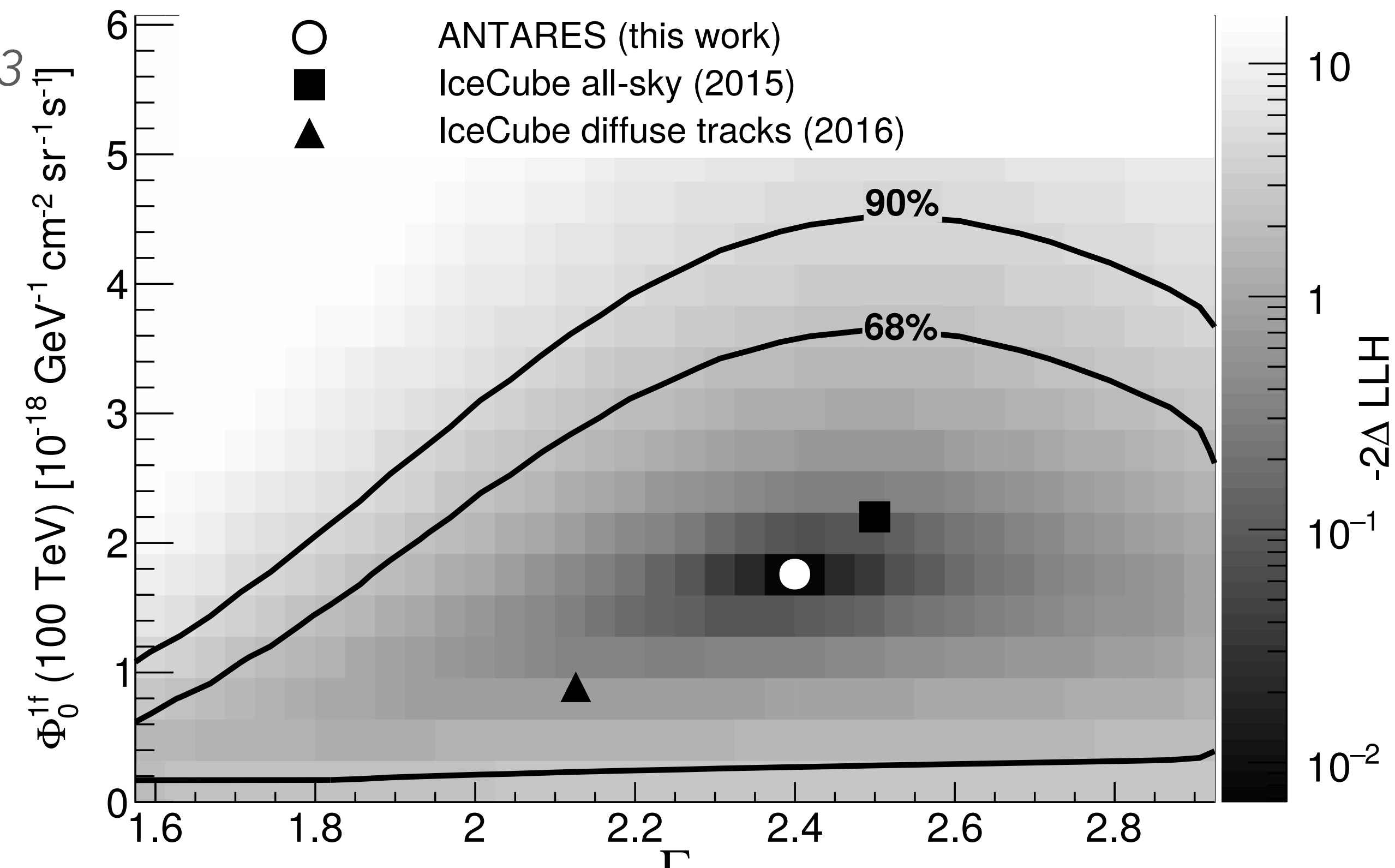
- ▶ Description of the cosmic signal and of the atmospheric background with a power law with different spectral indexes. The cosmic signal is expected to be harder than the atmospheric neutrino flux:

$$\frac{dN}{dE} = \phi_0 \cdot E^{-\Gamma}$$

- ▶ Search for an excess of high energy neutrinos
- ▶ First observation of a cosmic neutrino signal IceCube 2013



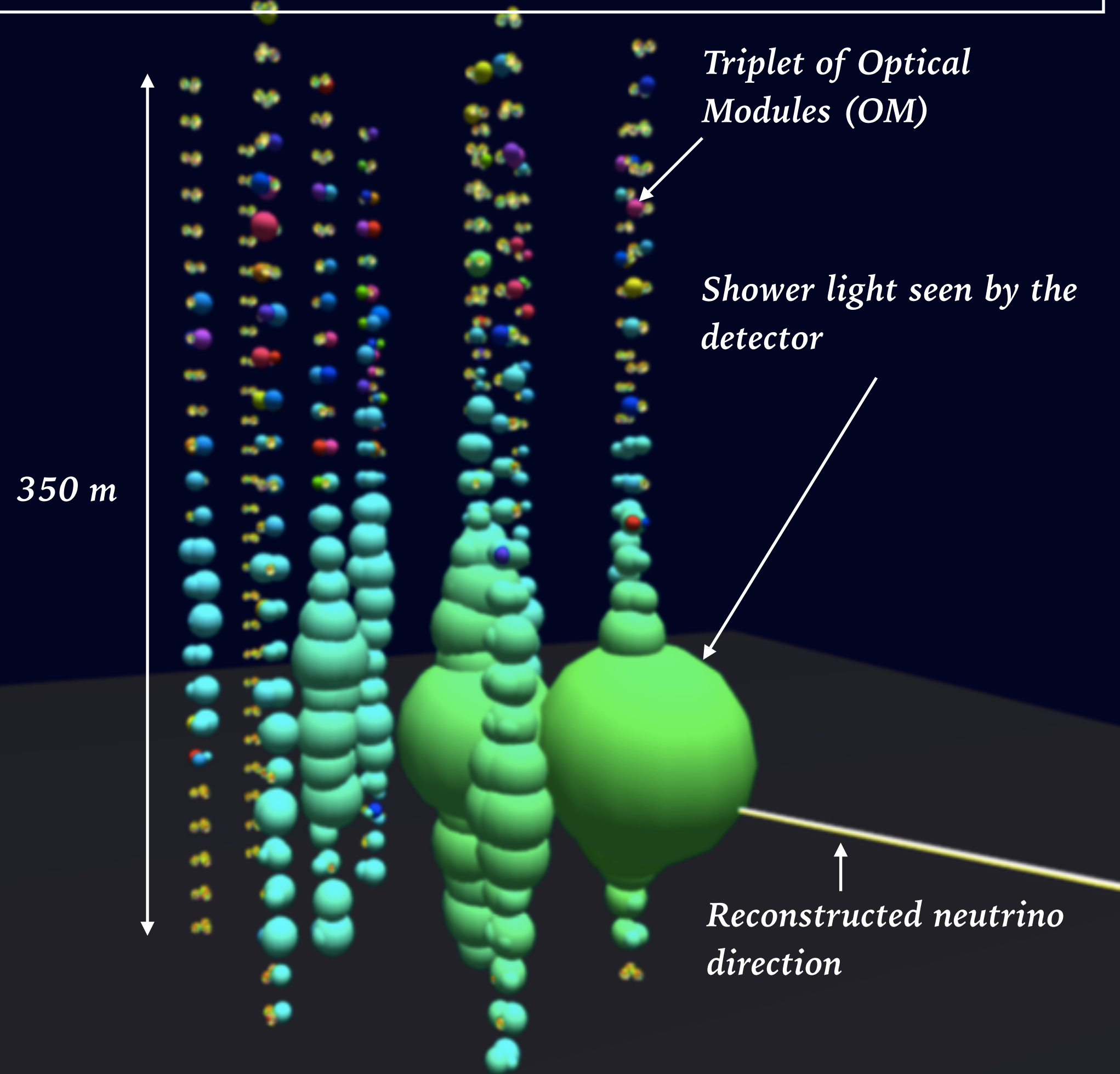
- ▶ Likelihood profile in the spectral index/normalization space
- ▶ Flat minimum region that exclude extremely hard spectra or intense fluxes





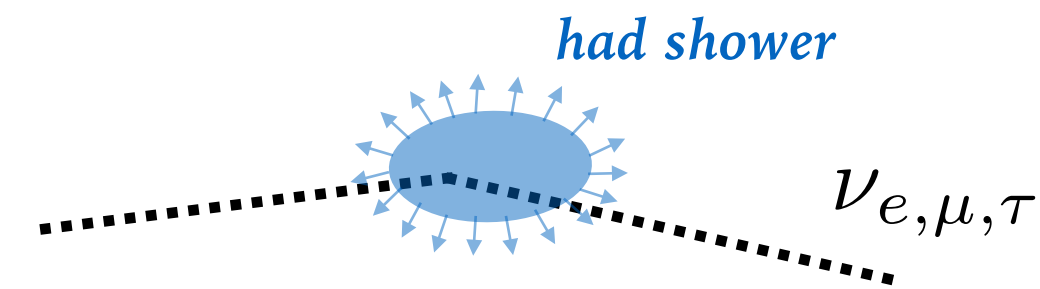


ANTARES event display: shower event with ~65 TeV reco energy  
run: 38472 date: 13-1-2009

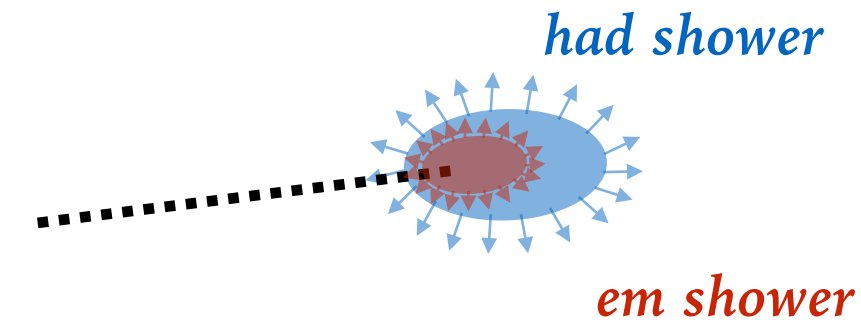


Sea bed

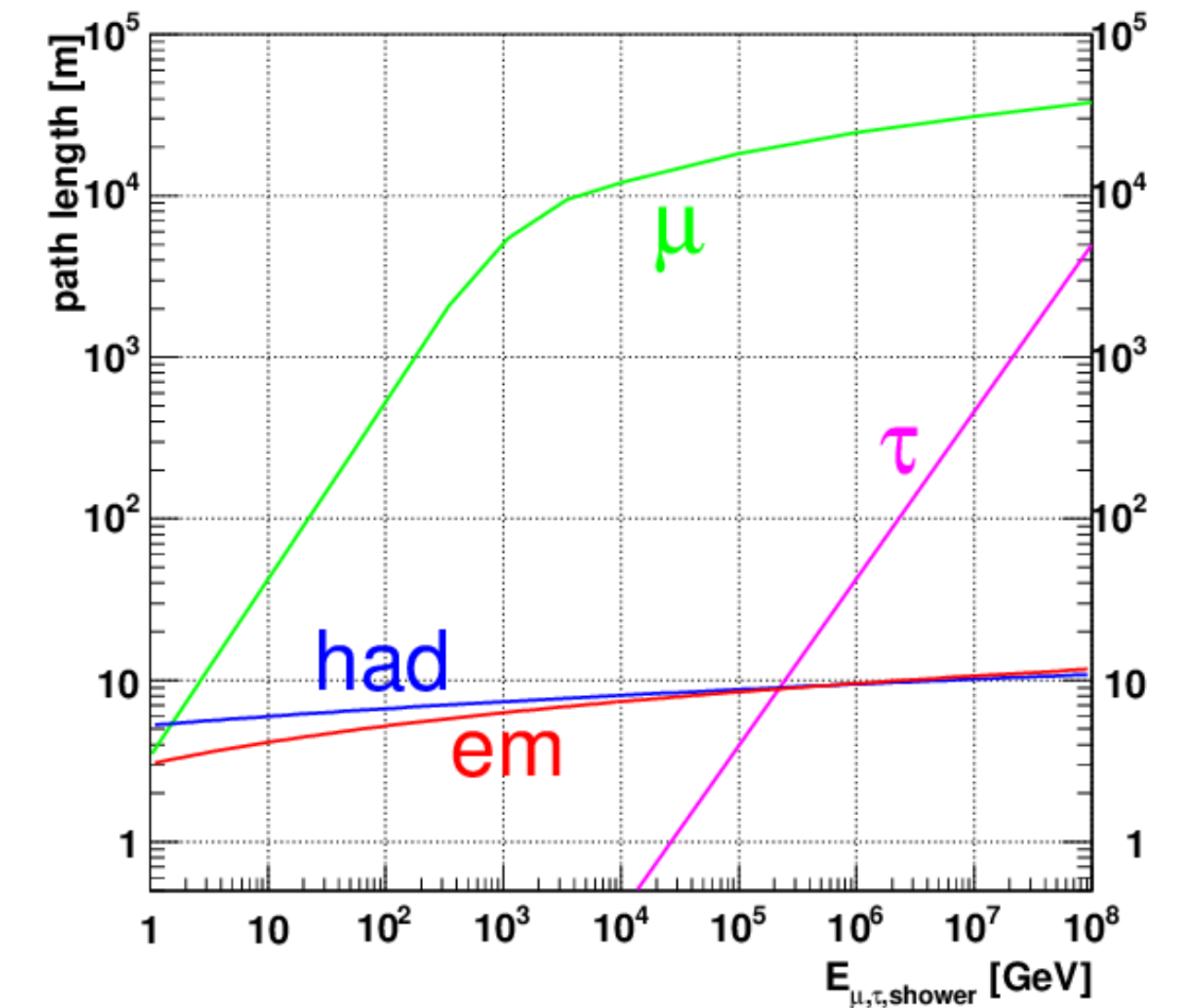
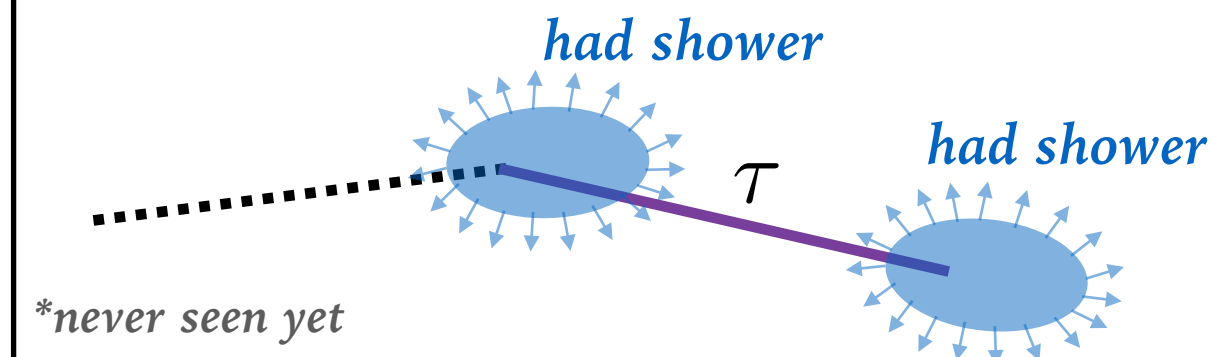
All flavours Neutral Currents (NC)



Electron neutrinos Charge Current (CC)

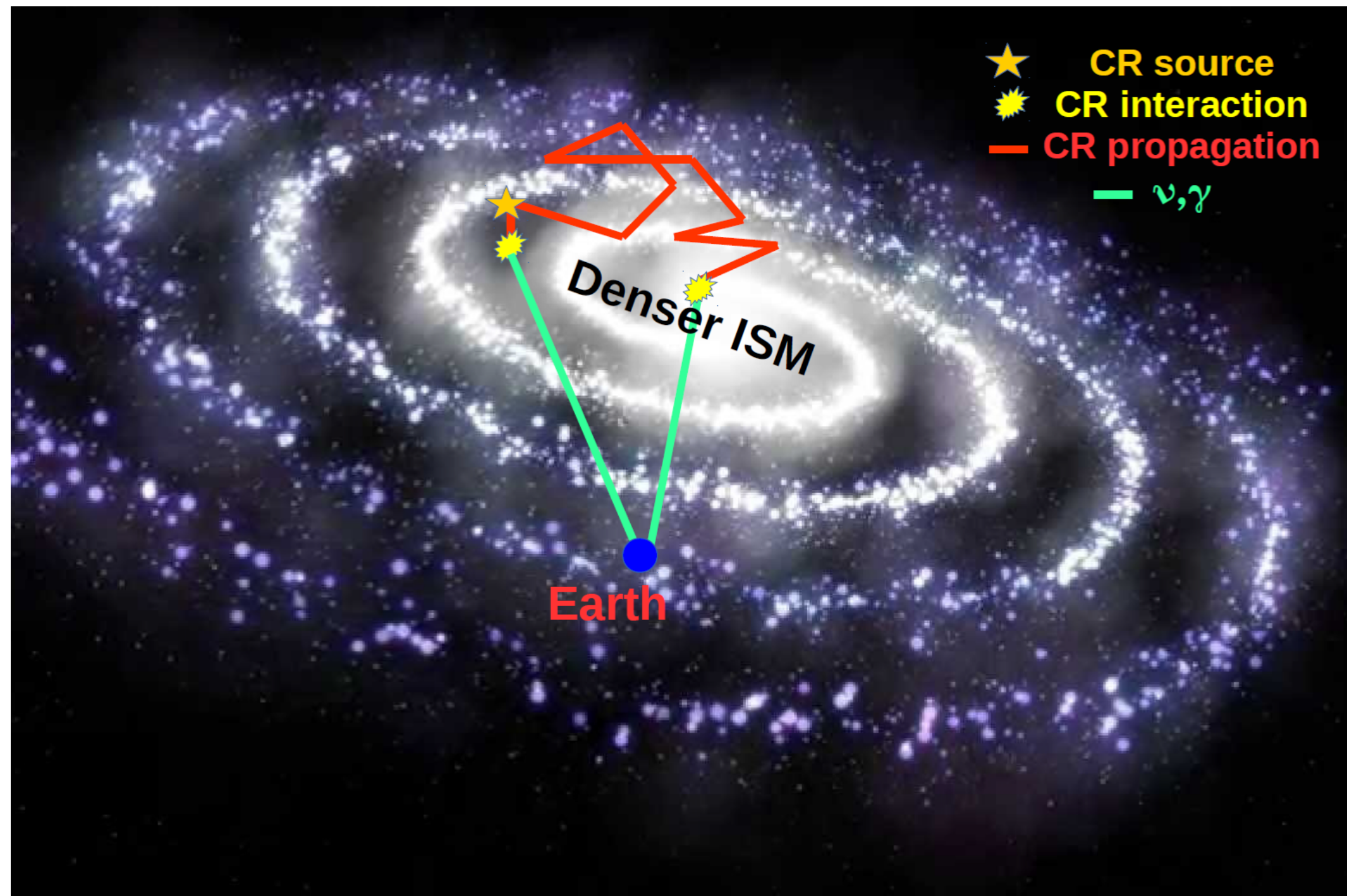


Tau neutrinos CC "Double Bang"

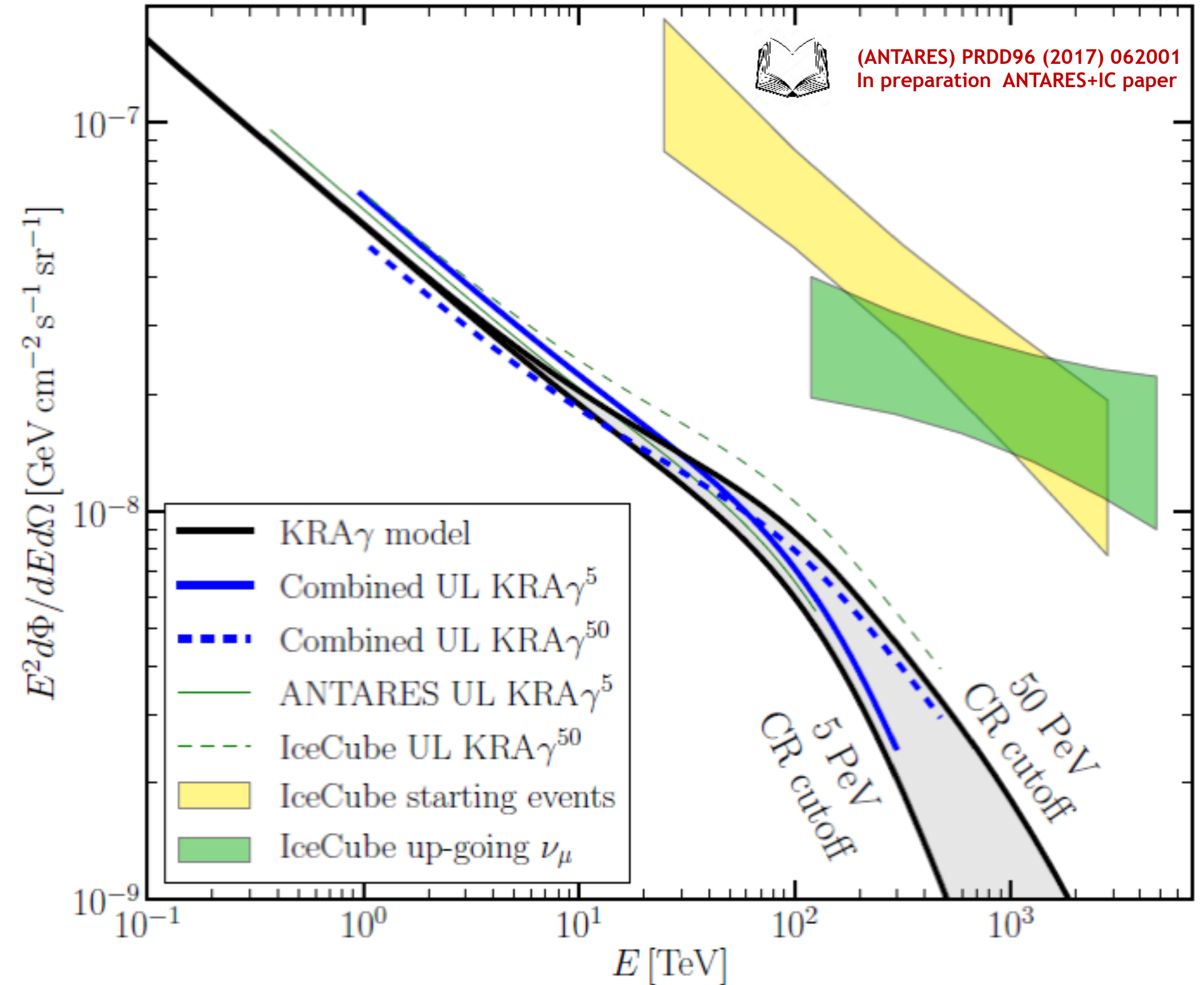


- Path length of leptons and showers from  $\nu$  CC interactions in water vs. energy.
- **HAD** and **EM** shower always contained in ~10 m
- 1 PeV  $\tau$  can travel for 50 m





- ▶ Neutrinos allow testing **CRs propagation**
- ▶ Dense matter regions boost  $\gamma$  and  $\nu$  fluxes
- ▶ Models can be tuned to  $\gamma$  and CR observations
- ▶ **Northern Hemisphere optimal point of view for galactic CRs**

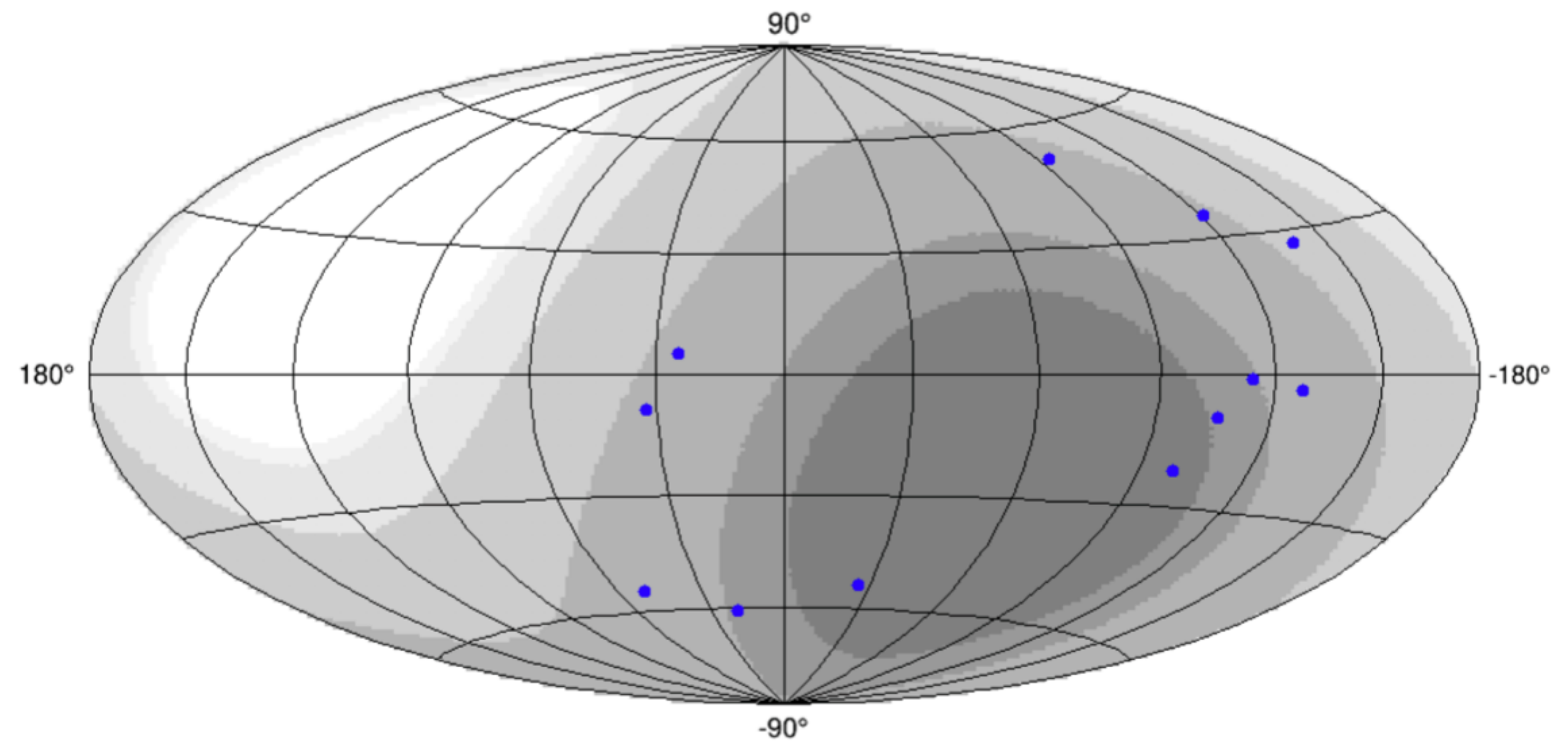
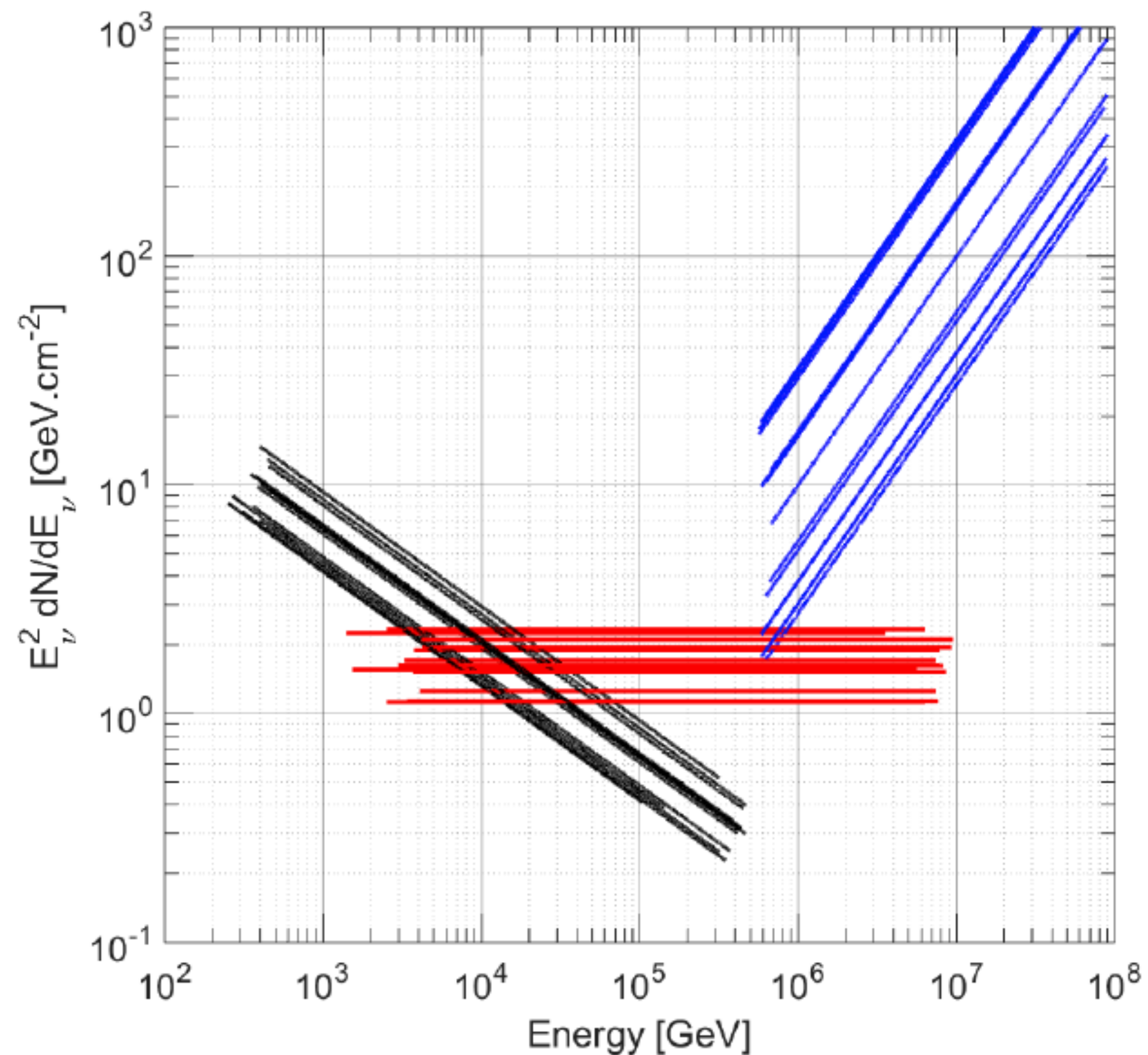


- ▶ **Result:** total flux contribution of diffuse Galactic neutrino emission <8.5% of the total diffuse IC astrophysical signal ( $E_\nu > 30$  TeV)





- ▶ Jan. 2013 – Jan. 2017 analysis.
- ▶ 16 FRB (Parkes, UTMOST, ASKAP) → 12 in the FoV during the data taking.
- ▶  $\pm 6\text{h}$  search period in  $2^\circ$ .
- ▶ Event selection optimization – 1 seen neutrino =  $3\sigma$  discovery.
- ▶ No events found → limits set.







WIMPs accumulate in massive celestial objects (Sun, Galactic Centre, ...)

- ▶ Neutrinos could be produced in WIMP-WIMP annihilation
- ▶ Clean signal and low expected background

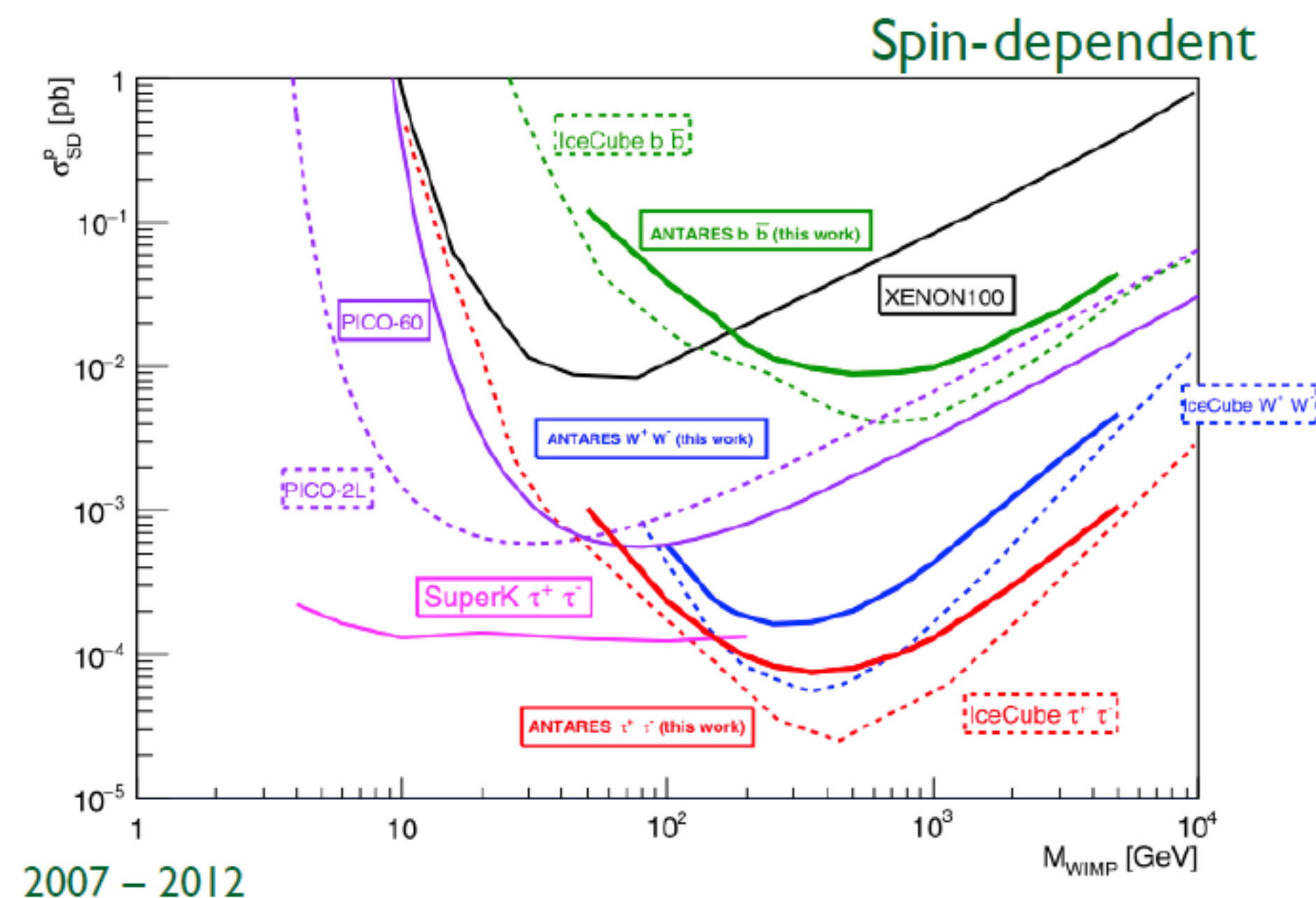
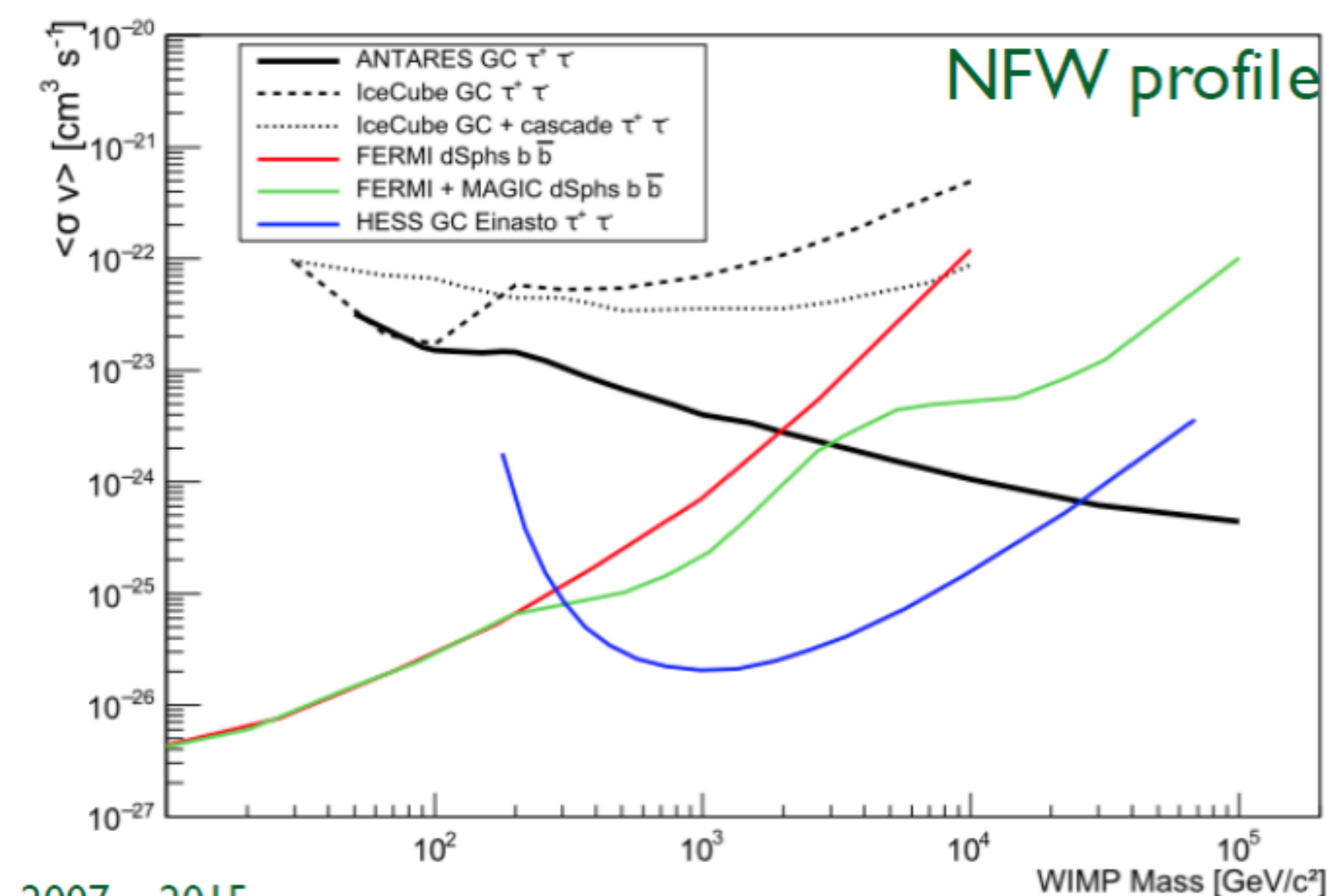
**Ingredients** used in the analysis:

- ▶ Signal energy spectra for each considered WIMP mass and annihilation channel:

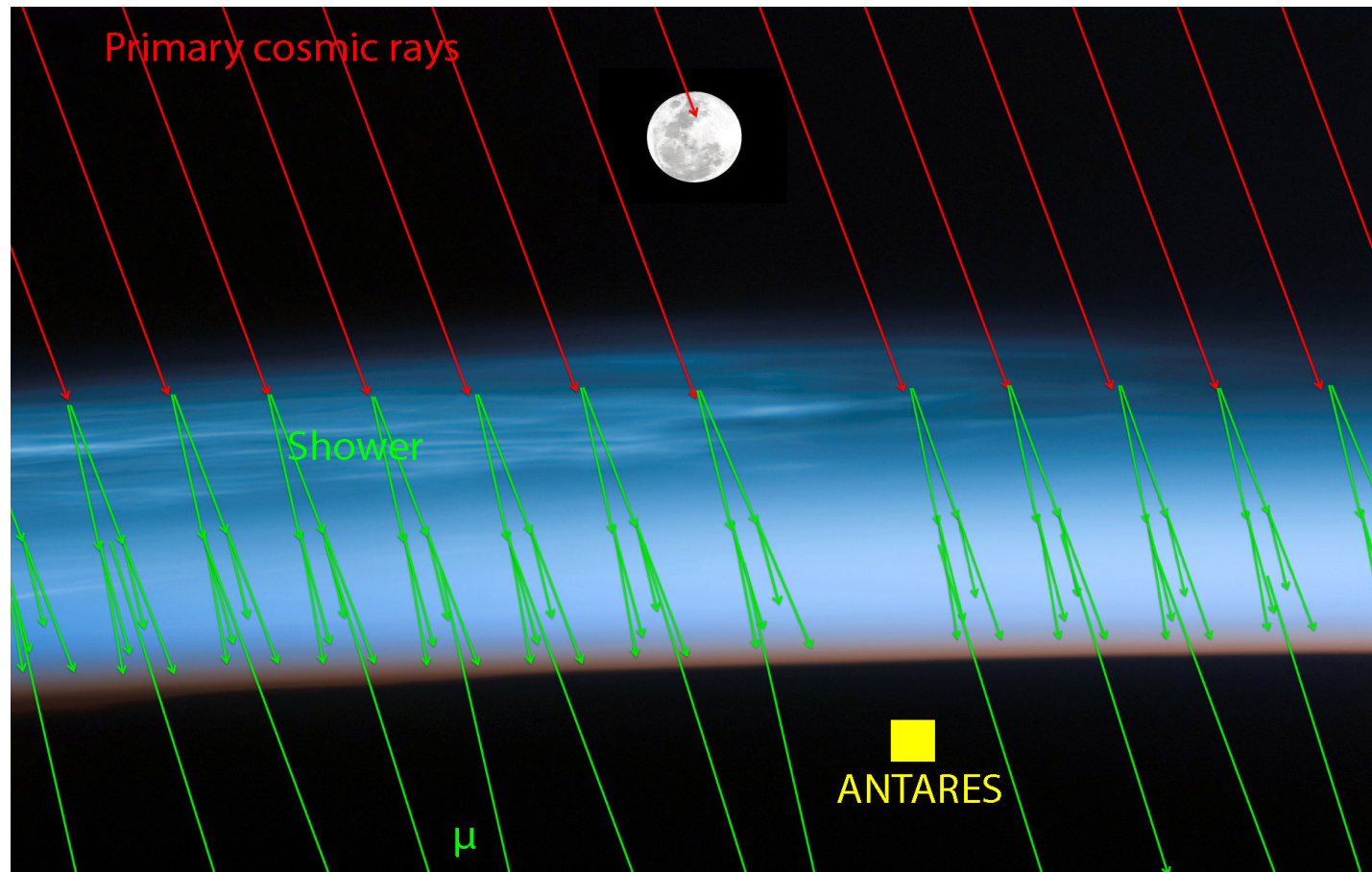
$$WIMP + WIMP \rightarrow b\bar{b}, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, \nu\bar{\nu}$$

- ▶ Spatial distribution of dark matter in the source:
  - Point-like (Sun)
  - NFW, Burkert, McMillan halos (GC)

- ▶ **No excess** above background observed;
- ▶ Upper limits derived, as a function of the WIMP mass and annihilation channel on
  - ▶ spin-(in)dependent WIMP-nucleon scattering cross-section (**Sun**)
  - ▶ thermally averaged annihilation cross-section (**Galactic center**)



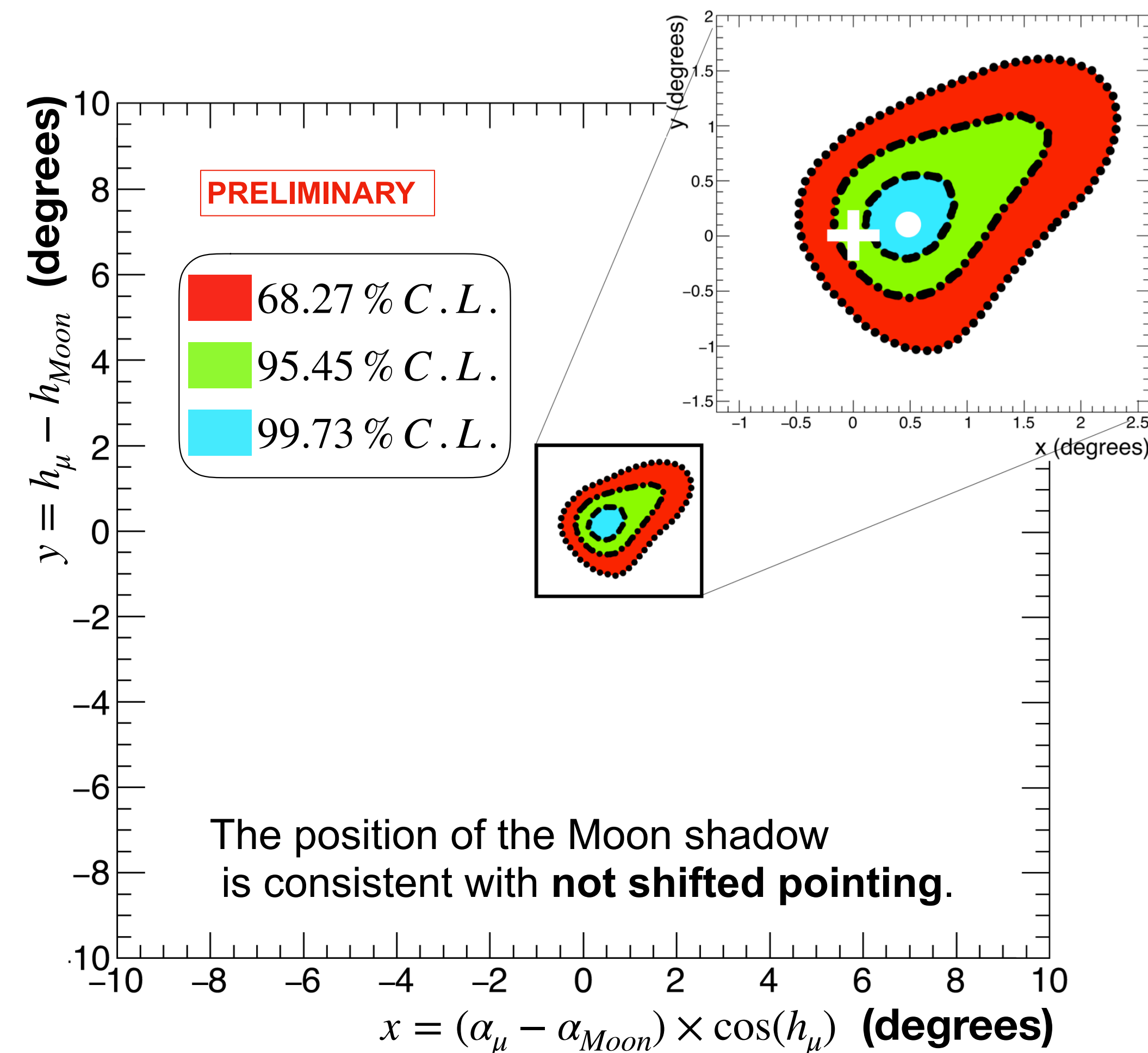
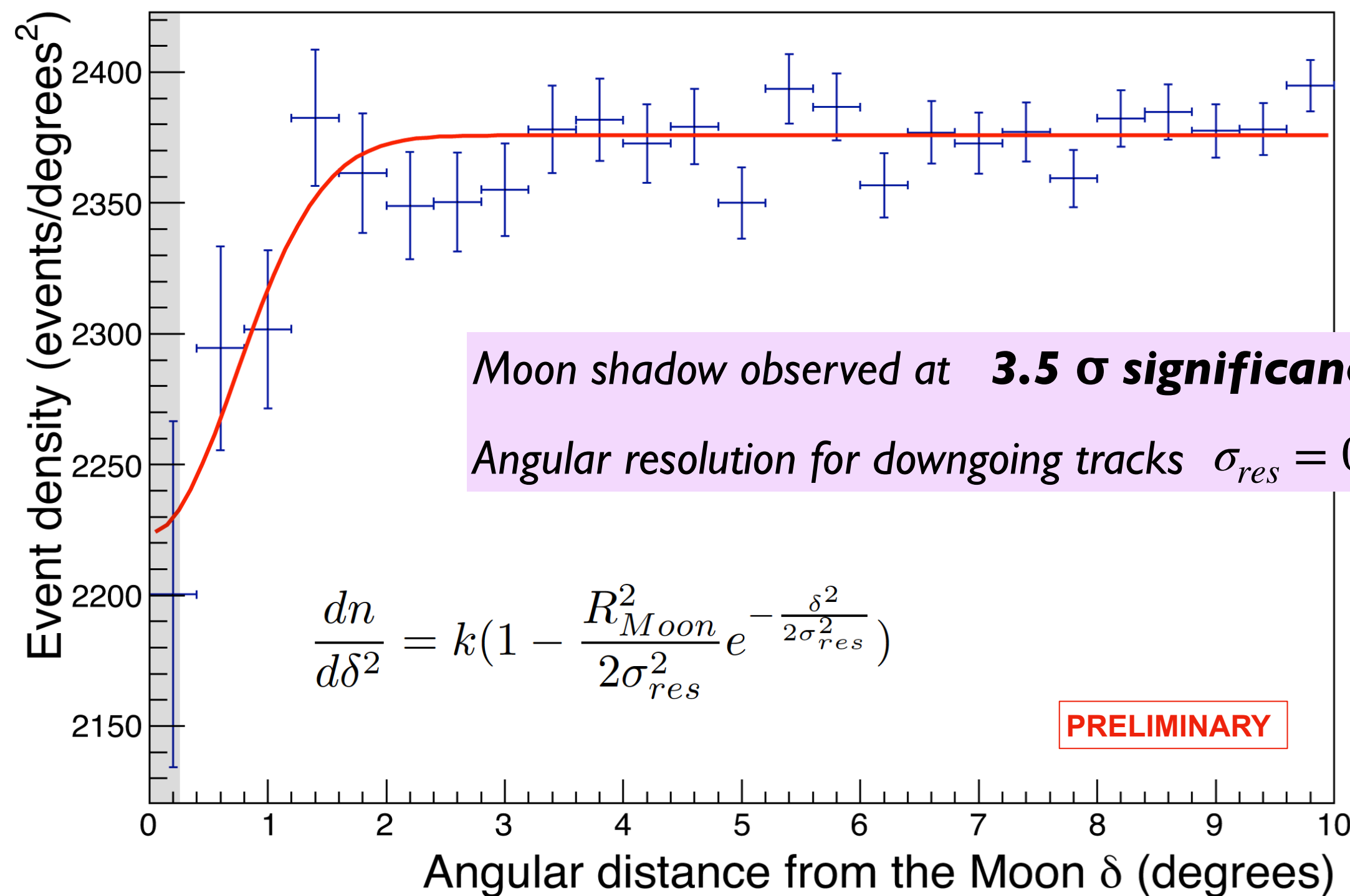




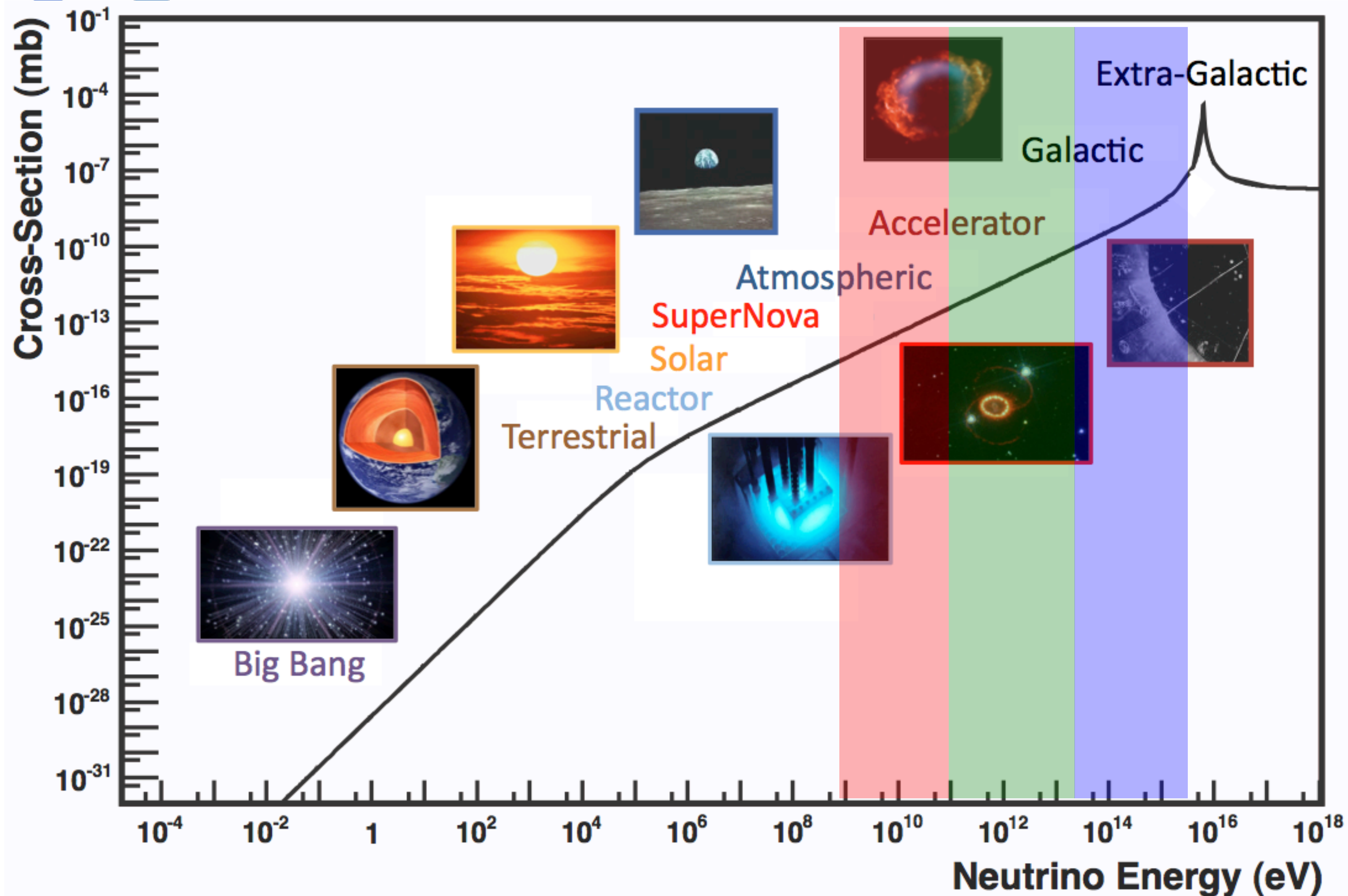
[arXiv:1807.11815](https://arxiv.org/abs/1807.11815)

One possibility to measure the pointing accuracy is to measure the shadow of the Moon, i.e. the deficit in the atmospheric muon flux in the direction of the Moon induced by absorption of cosmic rays.

Data from 2007-2016 -







- ▶ **1 - 100 GeV:**  
neutrino mass hierarchy w. atmospheric flux
- ▶ **100 GeV - 30 TeV:**  
various galactic (TeV gamma) sources
- ▶ **30 TeV - 3 PeV:**  
IceCube signal (astrophysical flux)