Astrophysical neutrinos

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INFN Sezione di Genova

Content

- Why neutrino astrophysics?
- Are all neutrino energies good for astronomy?
- Big picture of detection possibilities and perspectives.
- IceCube astrophysical neutrino detections.
- KM3NeT and the near future perspectives (also for you!).

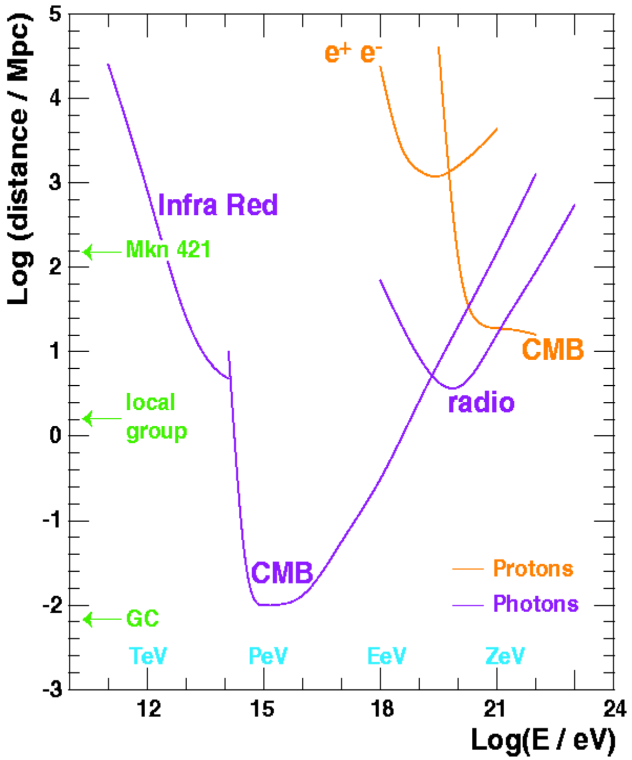
Thanks to Chiara Righi for the invitation!

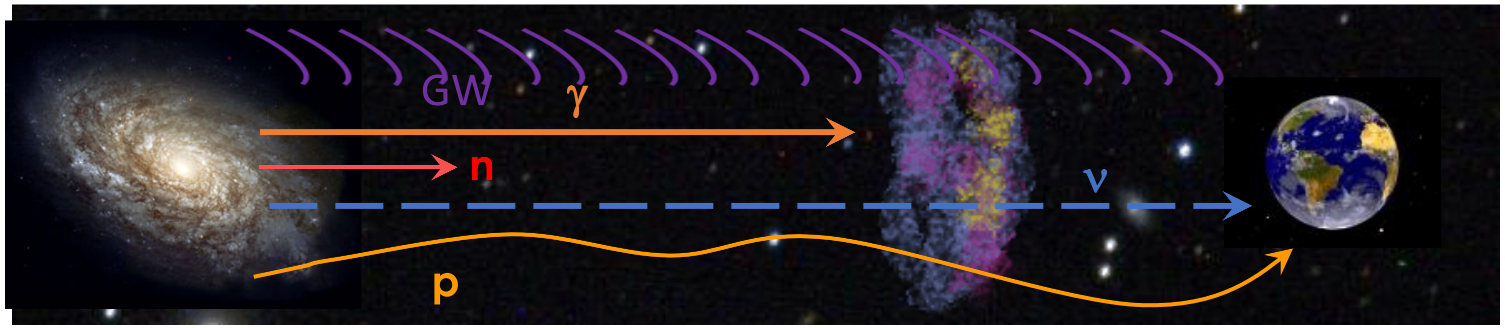
Why Neutrino Astronomy?

Neutrino Astronomy is a quite recent and very promising experimental field.

- Advantages:
  - Photons: interact with CMB and matter (r~10 kpc @1 PeV).
  - Protons: interact with CMB (r~10 Mpc @10^{20} eV) and undergo magnetic fields ($\Delta\theta > 1^o$, $E < 0.5 \cdot 10^{20}$ eV).
  - Neutrons: are not stable (r~10 kpc @10^{19} eV).
- Drawback: large detectors (~GTon) are needed.

Photon and proton mean free range path





Production Mechanisms

p-p interaction is likely to occur when density of gas higher than density of radiation (for example in Starburst Galaxies)

p-gamma interaction is likely to occur when density of radiation higher than density of gas (for example in Blazars)

$$pp \to \pi^+\pi^-\pi^0\ldots$$

$$\pi^+ \to e^+\nu_e\nu_\mu\bar{\nu}_\mu$$
$$\pi^- \to e^-\bar{\nu}_e\bar{\nu}_\mu\nu_\mu$$
$$\pi^0 \to \gamma\gamma$$

$$p\gamma \to \Delta \to \begin{cases} \pi^+ & 1/3 \text{ of cases} \\ \pi^0 & 2/3 \text{ of cases} \end{cases}$$

$$\pi^+ \to e^+\nu_e\nu_\mu\bar{\nu}_\mu$$
$$\pi^0 \to \gamma\gamma$$

The energy of neutrinos is about 1/20 of the primary proton's energy

Initial flavor composition $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

Flavor composition after oscillations $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

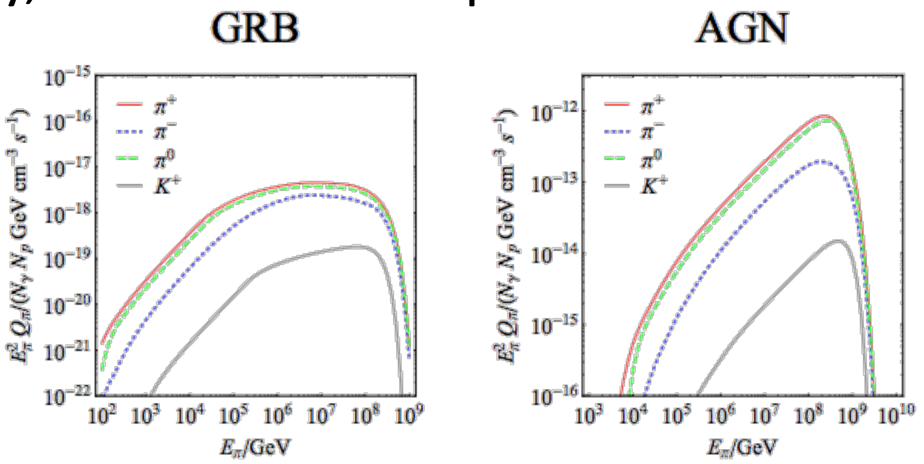
A. Palladino @ Neutrino days 2019

The energy and flavour ratio rules are not exact:

- 1 neutrino is produced in 2 body decay, 2 neutrinos are produced in 3 body decay

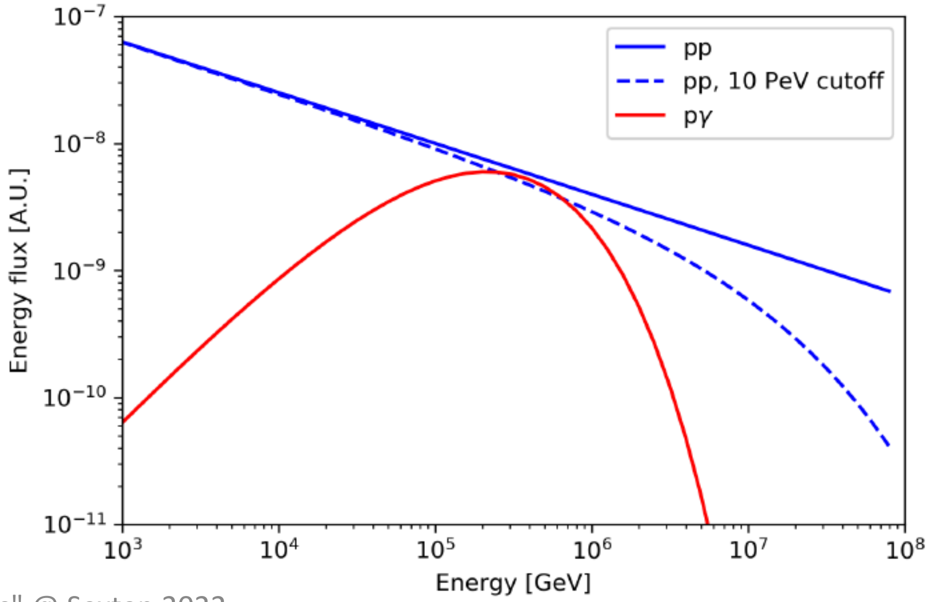
- A certain amount of negative pions can be produced also in the proton-gamma interaction

Hummer et al., APJ 2010



The **shape** of the spectrum and the **amount of $\bar{\nu}_e$** give important information on the production mechanism

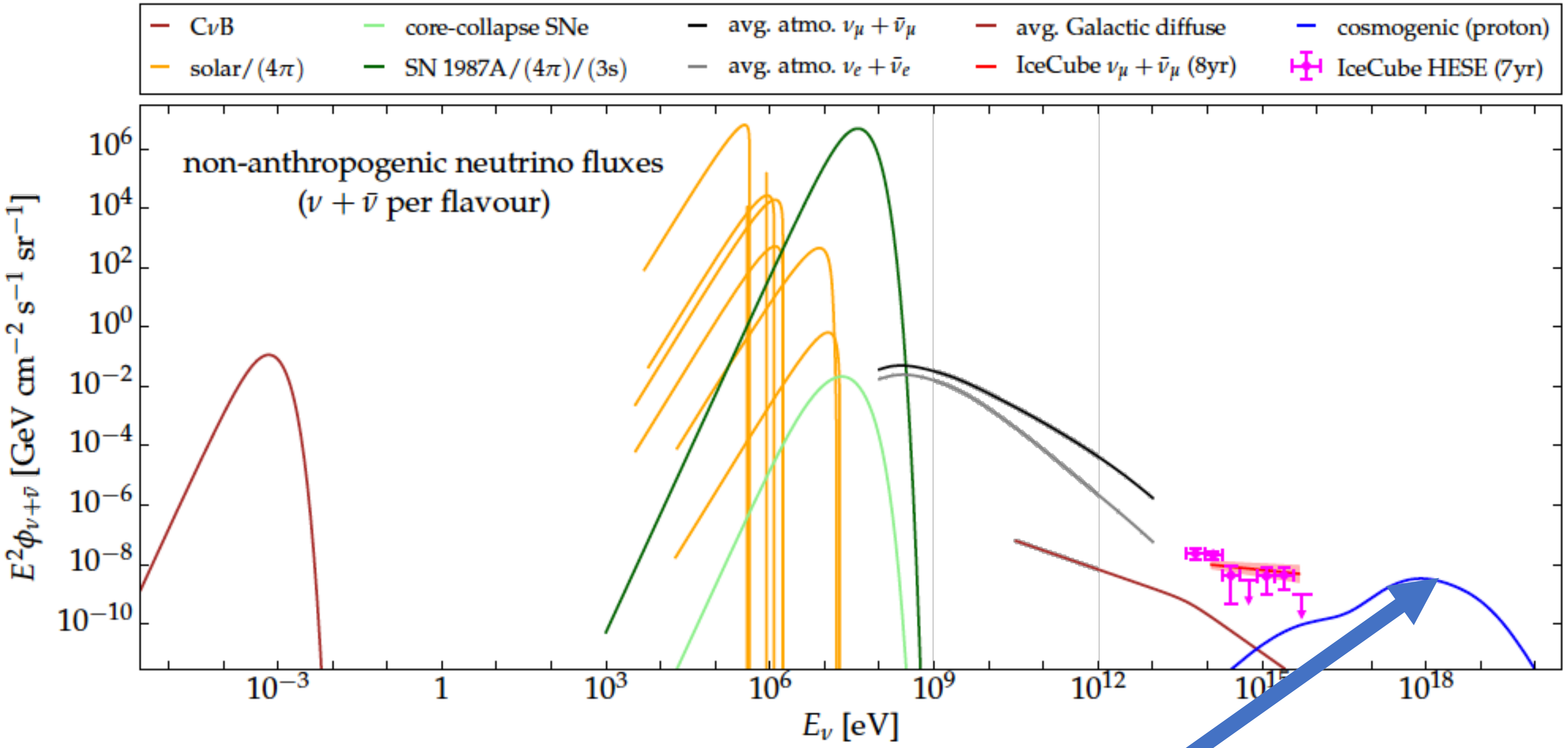
	pp interaction	pgamma interaction
Shape	Power law	Not power law
Cutoff	$\sqrt{E_{cut}^{proton}}$	Depending of the photon spectrum
Energy	$\sim 3/2\ E_\gamma^{hadronic}$	$\sim 3/8\ E_\gamma^{hadronic}$
Electron antineutrinos	1/6 of the total	0



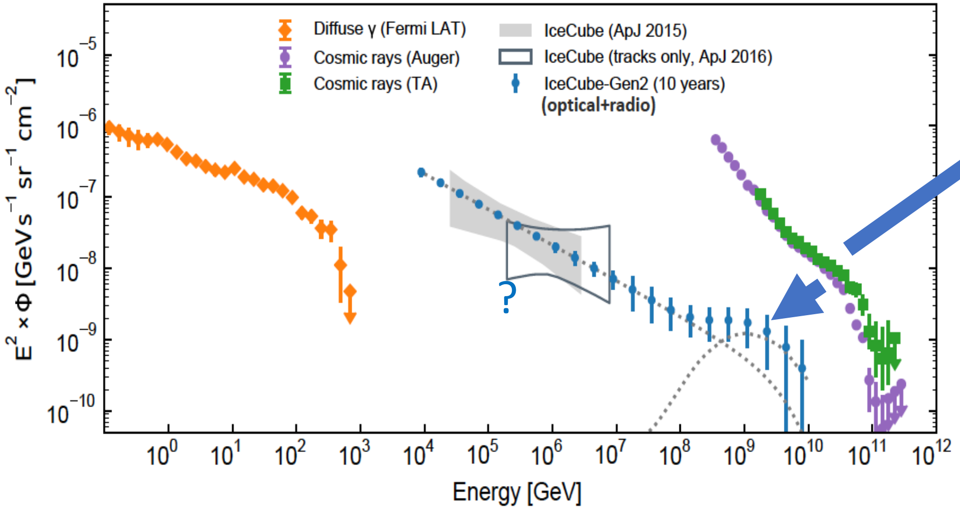
A. Palladino @ Neutrino days 2019

Why high energy neutrinos?

G. de Wasseige @ ICRC2019



A. Kappes @ PAHEN2019



Cosmogenic neutrino flux is predicted from a measured CR flux.

- CR interaction with CMB/IMB.
- Depends on highest CR acceleration energy (10^{20} eV?)
- Depends on ion composition.
- …
- **What is the origin of CRs?**
- **What is the origin of 0.01-1PeV nu?**

Why high energy neutrinos?

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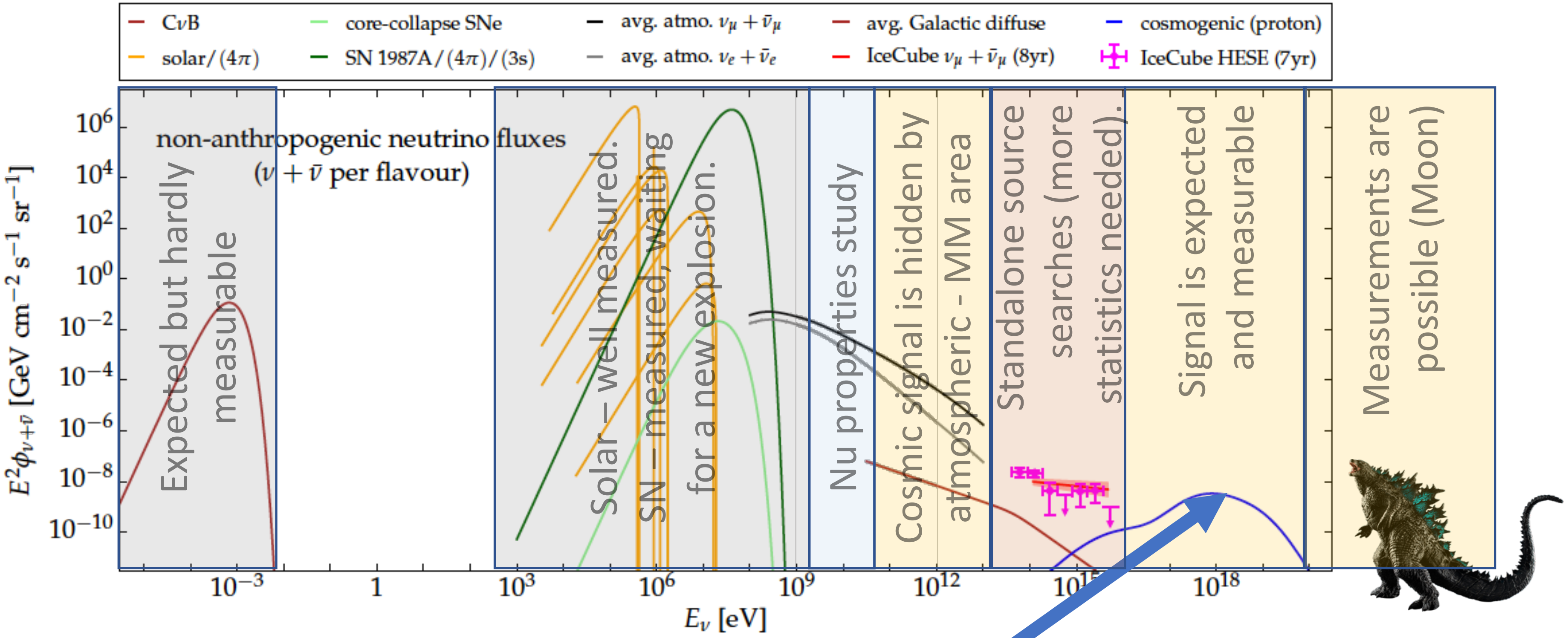

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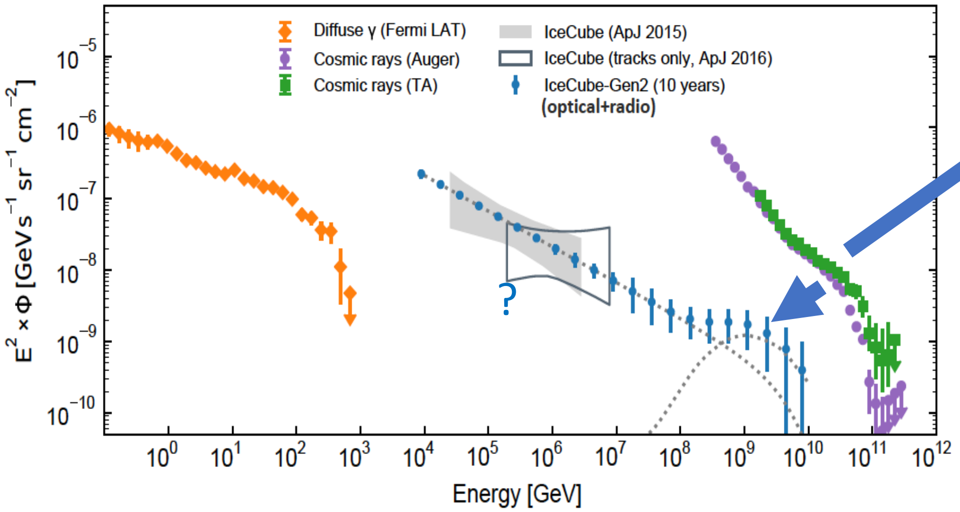

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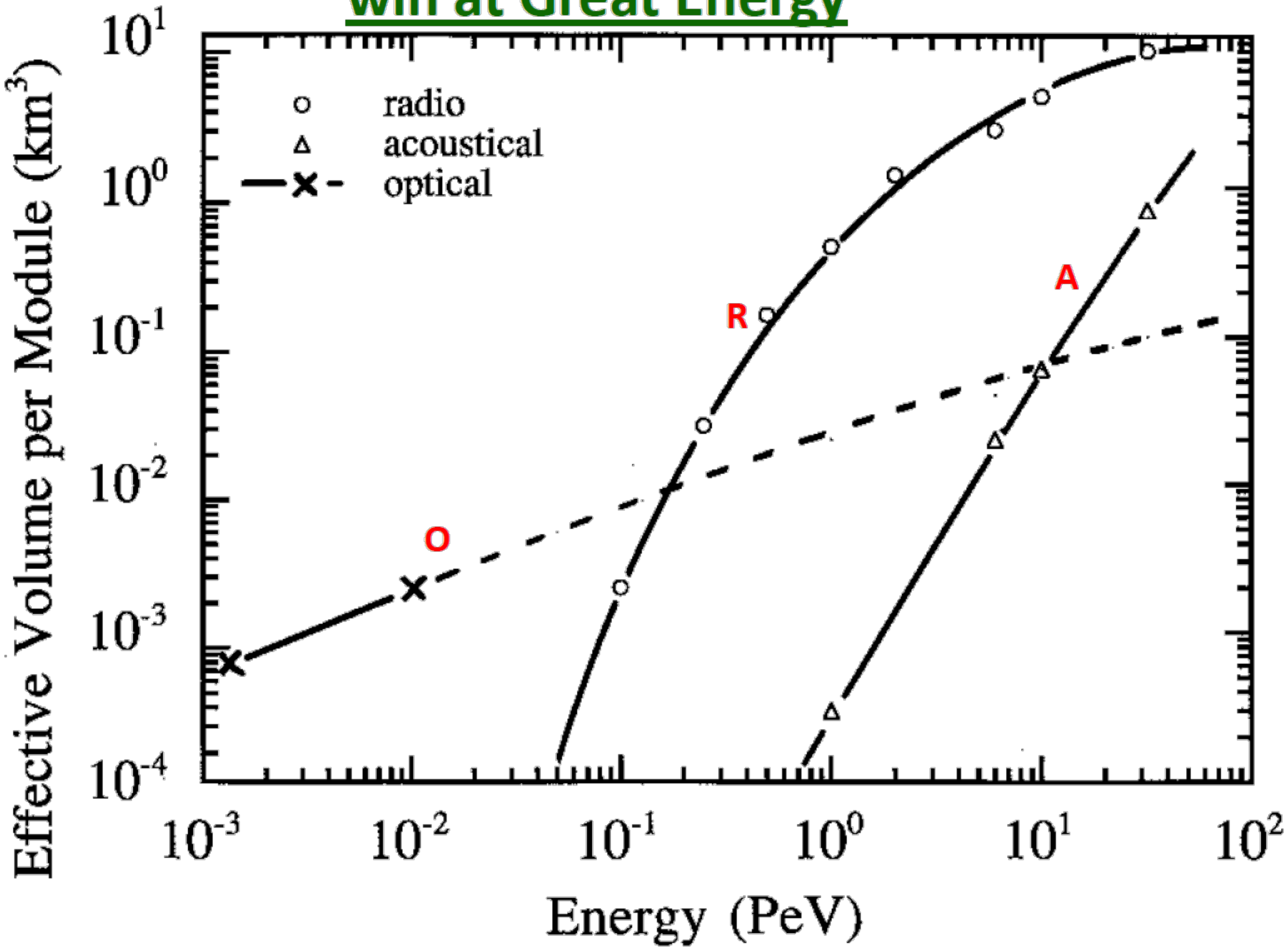
Big picture of possibilities

This talk is mostly on the IceCube (and MM) results and KM3NeT perspectives.

	Ice	Water	Air	Permafrost	Salt	Moon
light	**IceCube**	ANTARES, **KM3NeT,** Baikal, P-ONE	ASHRA, TRINITY, POEMMA, AUGER	?	?	?
radio	ARA, ARIANNA, ARIA, IceCube-Gen2 Radio, RNO, Radar	-	*On mountain:* TAROGE, TAROGE-M, BEACON, GRAND, *On balloon/satellite* ANITA, PUEO	maybe	maybe	NuMoon LUNASKA, RESUN
sound	SPATS (IceCube)	SAUND, ACORNE, AMADEUS (ANTARES), Baikal	?	maybe	maybe	?

For acoustic in permafrost & salt, please see R. Lahmann review at ARENA2018.
AUGER is a hybrid EAS detector (water Cerenkov tanks, fluorescence detectors, muon detectors) +radio, + HEAT.

Why Radio and maybe eventually Acoustic Detection win at Great Energy



Buford Price http://aether.lbl.gov/www/projects/neutrino/rand/rand.html

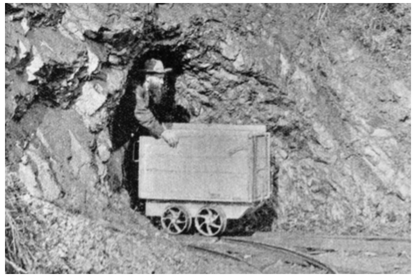
Summary of Perspectives

- **SubPeV-PeV** neutrino observations starts to be a routine with IceCube
  - Extension with a sparse array for PeV energies.
  - Moving towards >5km^3 Global Neutrino Observatory.
  - Still the best technology for TeV-PeVs.
  - Angular res. 0.1^o (track) – 1^o (cascade) in water.
  - Lower energy extensions below 10 GeV.
- **Radio wins for E>PeV** energy effectiveness/cost.
  - UHE energy extension of IC (IC Gen2-Radio) is a radio detector that will merge best from ARA and ARIANNA technologies. The best for E~10PeV (2025+).
    - Angular resolution is not great for MM (<7^O)?
  - Similar detector in Greenland to complete the view (RNO-G)?
  - Radar technic to push towards lower energies (subPeV-PeVs)?
  - Acoustic is still not explored well. Hybrid detectors?
- **Tau neutrino** search is possible **with CR detectors** and it is very efficient for **100 PeV-1 EeV**:
  - Mountain antennas are competitive with in ice for sensitivities.
  - Imaging Air Shower systems on satellites (POEMMA) are promising for E~10PeV-10EeV.
  - ANITA->PUEO seems to be the best in next future for E>10EeV (2022).
- **Moon** observations are unbeatable for **ZeV**. Signals are unknown until you have rich fantasy. Observation possibility included as a part of radio observatories (looking forward for SKA).

bigger mine – more gold

mastering new methods.

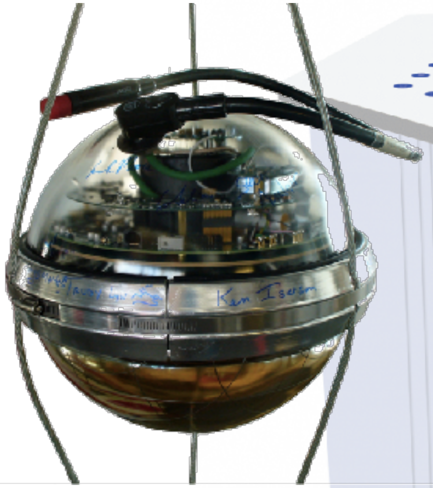
reusing CR detection methods

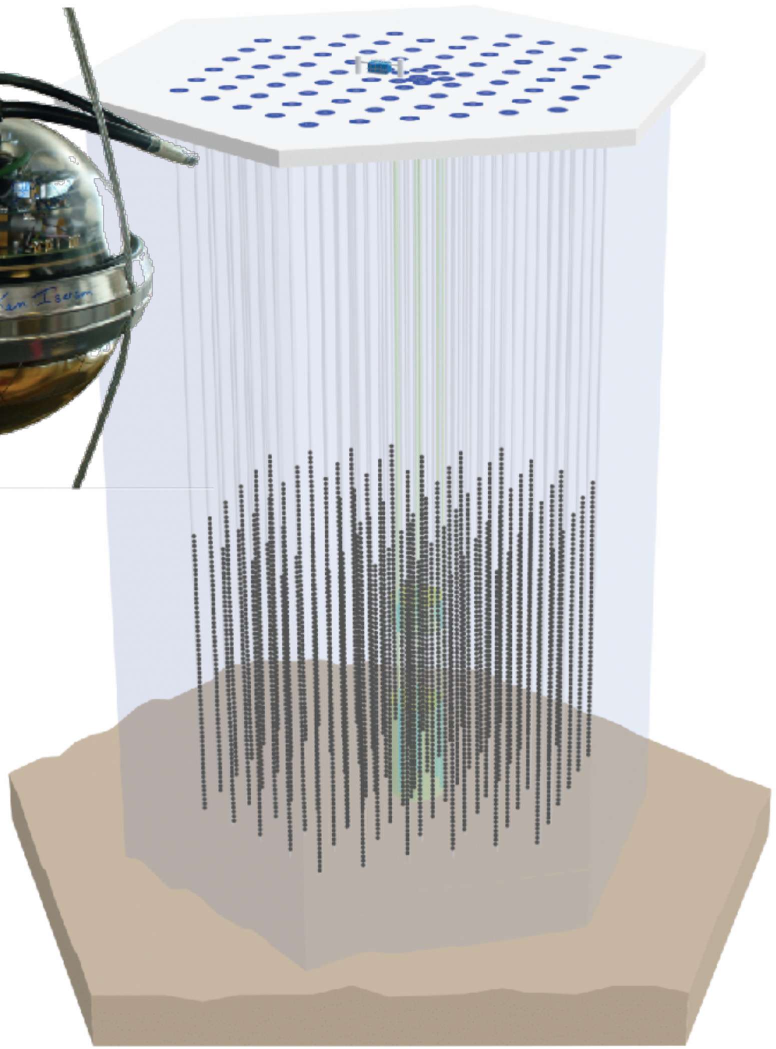


ROAARRH!

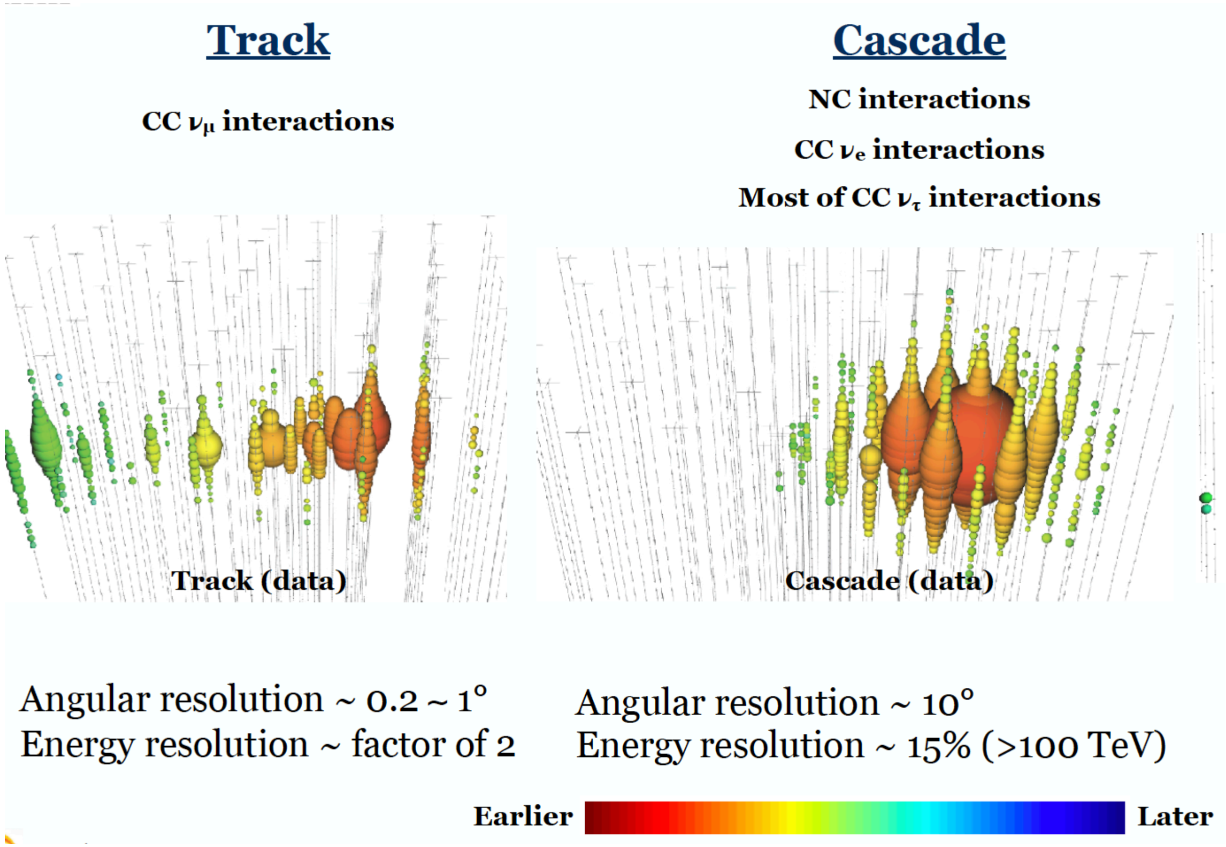
IceCube neutrino detector

- 5160 digital optical modules (DOMs) deployed at depths between ~1.5-2.5 km.
  - Single 8’’ PMT technology.
  - Non isotropic light propagation with high scattering.
  - Stable environment, low optical background (K40).
- Denser in-fill for O(10) GeV neutrinos (DeepCore).
- Surface air shower array (IceTop).
- Construction finished in Dec 2010.





Event topologies and selections

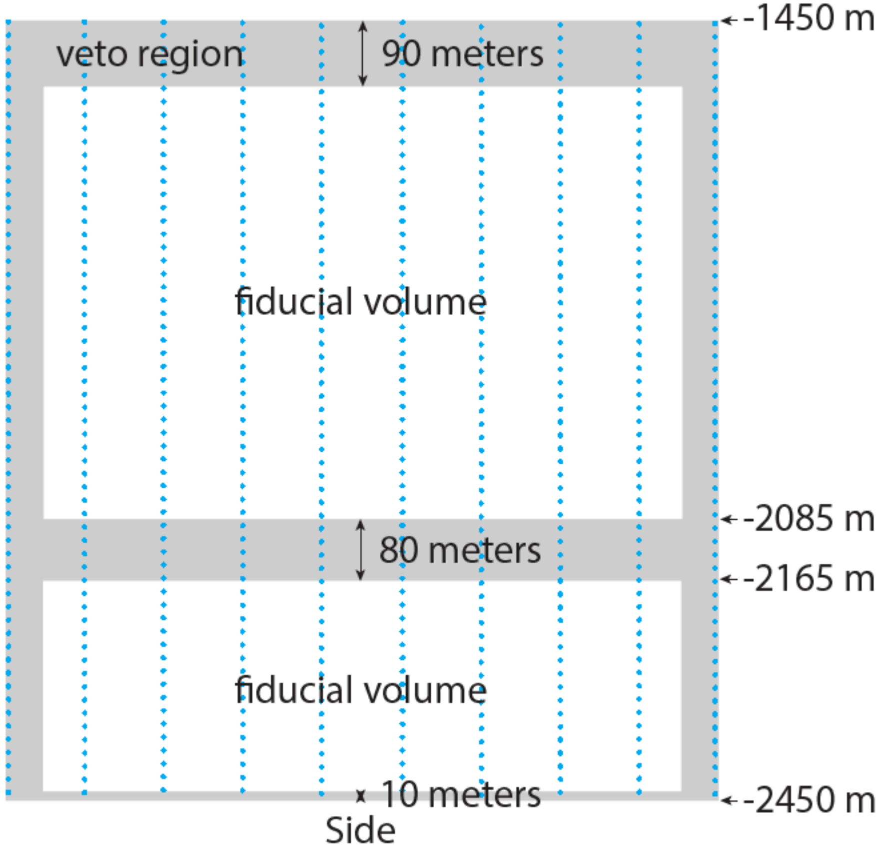


Suppress atm. muon background:
- up-going going events.
  PeV nu-mus can't traverse Earth!
- SE– starting events.

Suppress atm. muon background:
- Cascade-like.
- SE– starting events.

Suppress atm nu background:
- High Energy (HE). Cosmic spectrum is harder.
- Starting inside the detector (SE– starting events).

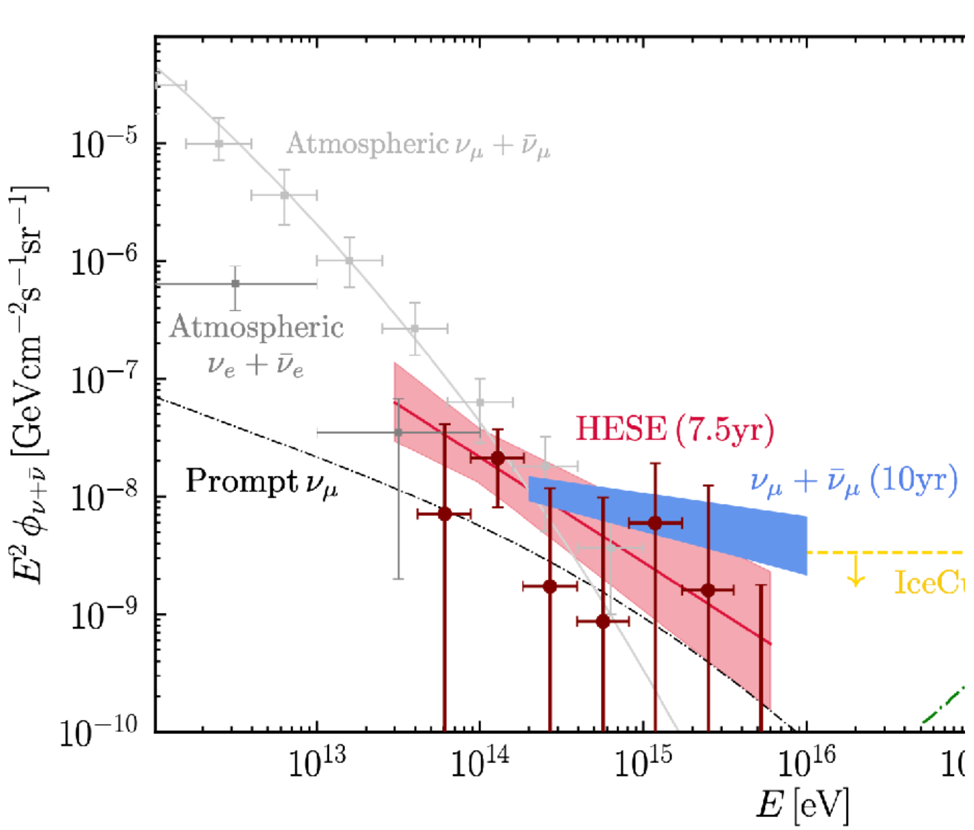
High Energy Starting Events (HESE)

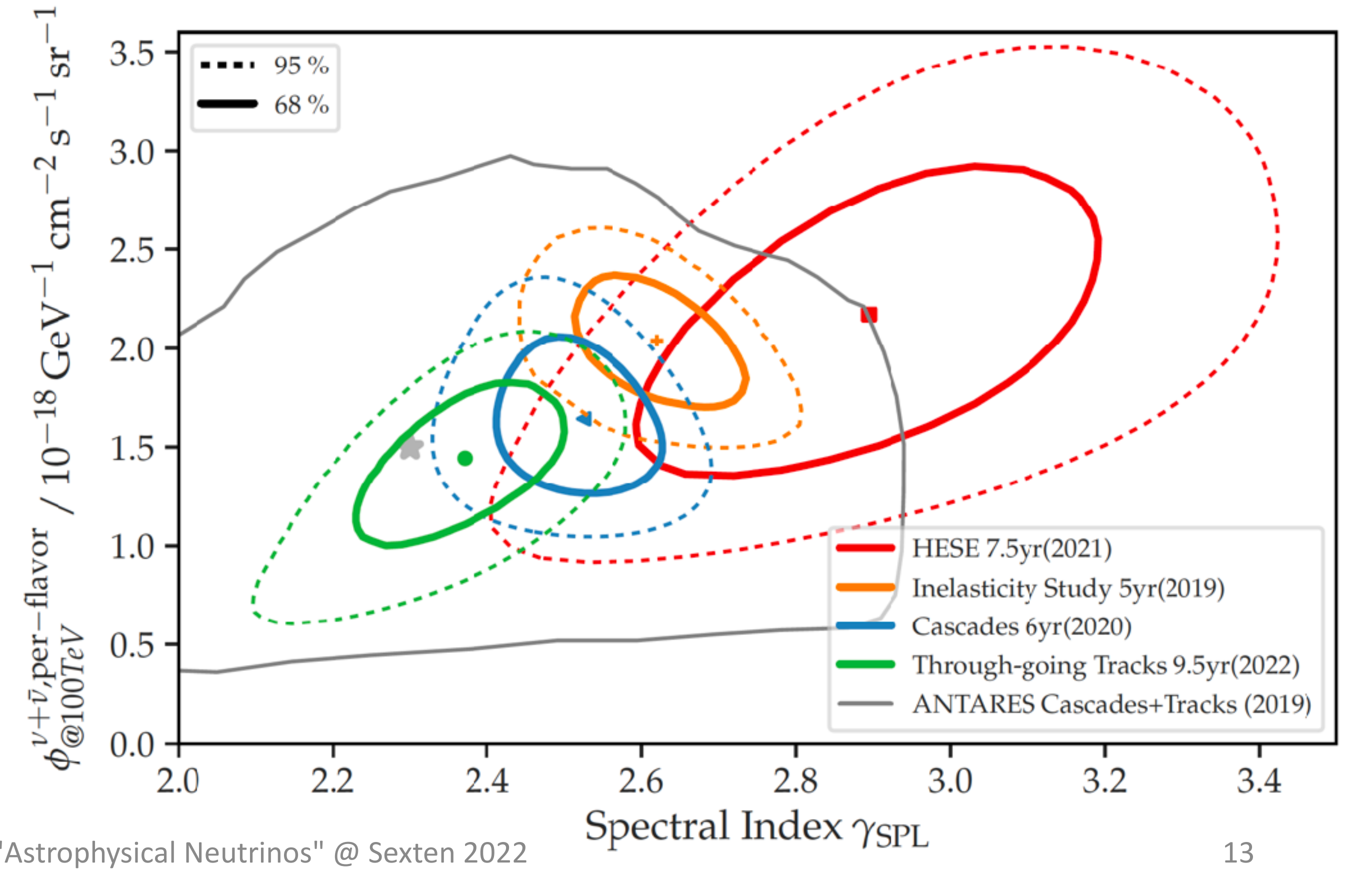


- Suppresses part of the atm. nu accompanied with muons (shallower detector would be better!).
- 6±3.4 muons per 2 years (662 days).

Diffuse flux measurement with different event selections

- Some tension between track events (Northern Hemisphere, >200 TeV, harder spectrum) and IC HESE (all sky >30 TeV, softer spectrum).
    - Cascade selection (>TeV, all flavour, all sky) somehow in between.
- Baikal (preliminarily) confirms this diffuse flux (25 tracks+cascades, 9.7 atm. mu, 3.4 atm. nu, 16 IC $E^{-2.46}$) at p-value 0.0022 (3-sigma), Zh. Dzhilkibaev @ NEUTRINO2022.

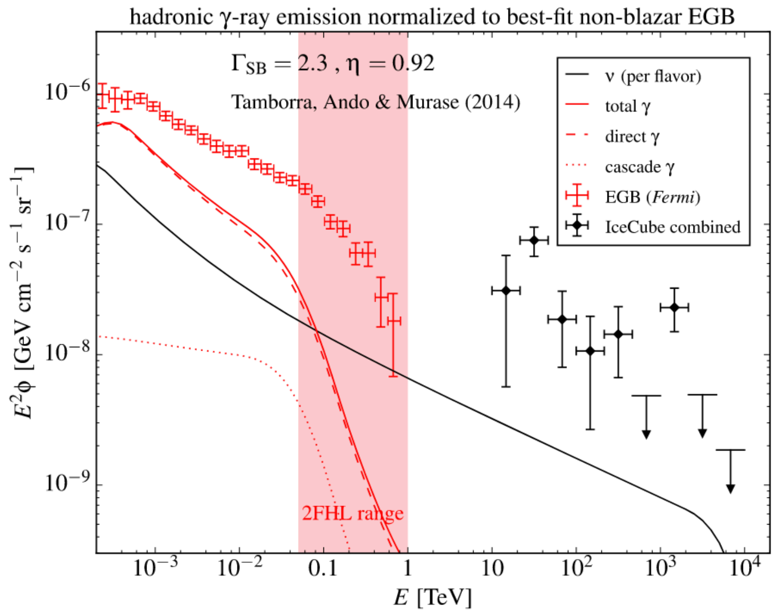




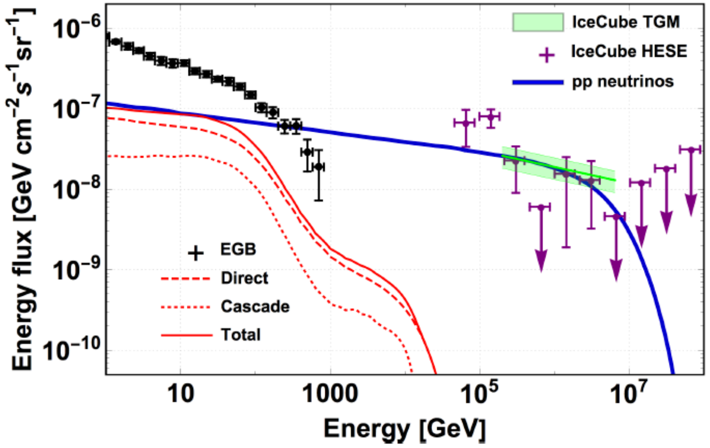
N. Park@NEUTRINO2022

Can p-p sources explain IC diffuse flux?

- Star-forming Galaxies (SFG) and, generally, p-p models that should be in agreement with Extra-Galactic Background in 0.05-1 TeV would produce an order of magnitude lower flux then IC HESE. **The individual γ-ray luminosity functions are normalized to the observed infrared (IR) luminosity function from Herschel.**
- Relaxing the **γ-ray luminosity** requirement to fit with IR, (multiple class of the sources having HE neutrino emission), one can explain ~100% of the IC TGM flux and ~40% of the IC HESE (+Gal +atm ~94%), and ~50% of the IC cascade events.
  - Hadronically powered gamma-ray galaxies (starburst galaxy NGC253, Ultra-Lumious Infra Red Galaxy ULIRG Arp220) can be good candidates. IC 7 years point-source sensitivity is ~10 times above the expected nu-flux from a single source.

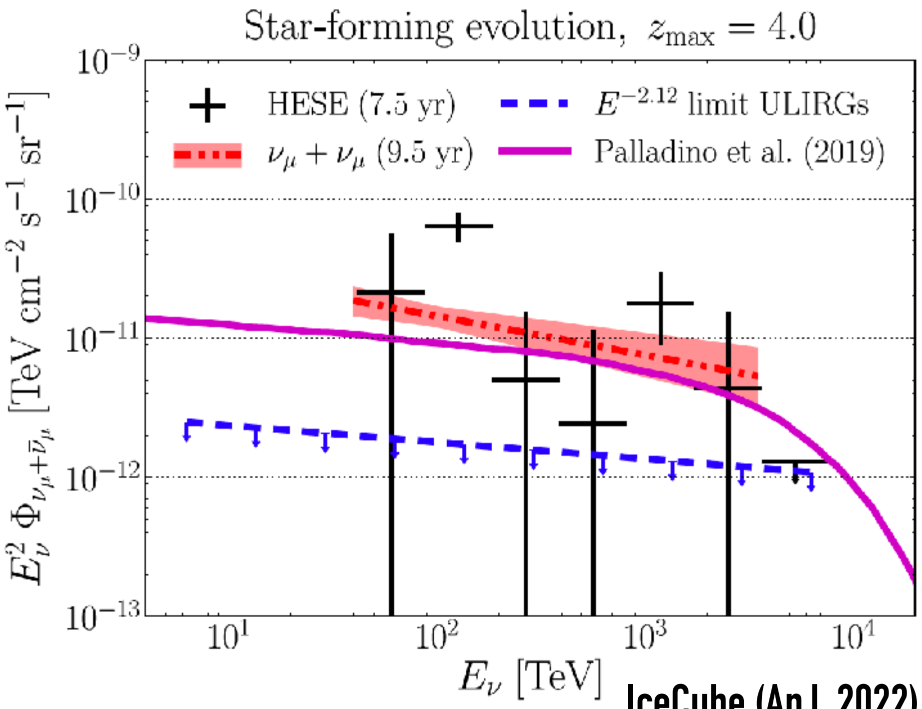


K. Bechtol et al. *et al* 2017 *ApJ* **836** 47



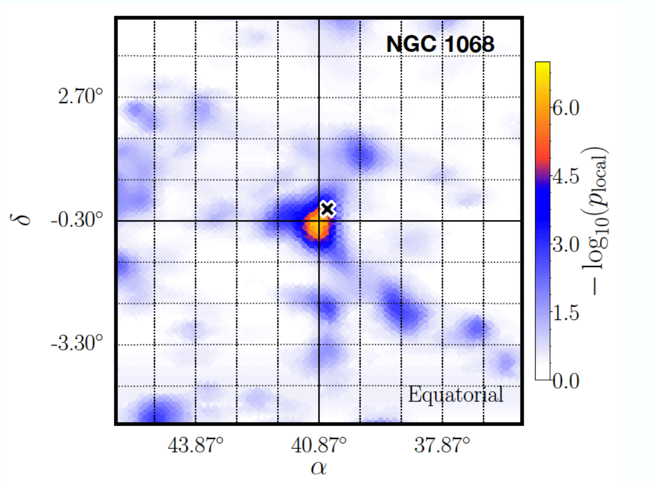
A. Palladino *et al* JCAP09(2019)004

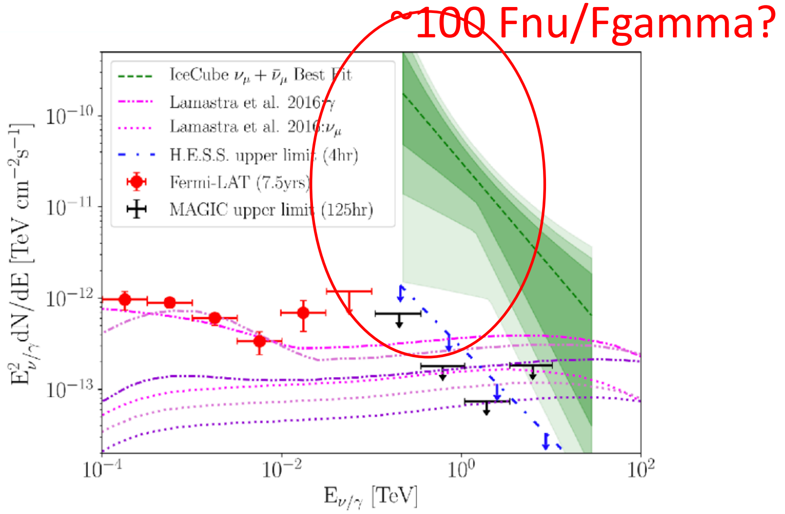
- How many such PeVatrons are detectable by CTA?
  - 1e-3 Mpc^{-3} NGC253 like. For 100 Mpc radius ~125 sources.
  - 6.7e-6 Mpc^{-3} Arp 220 like. For 100 Mpc radius ~0.8 sources.



IceCube (ApJ, 2022)

Apparently, no neutrino emission is found from 75 ULRIGs (z<0.13) in IC 2022 analysis (7.5 years of data).





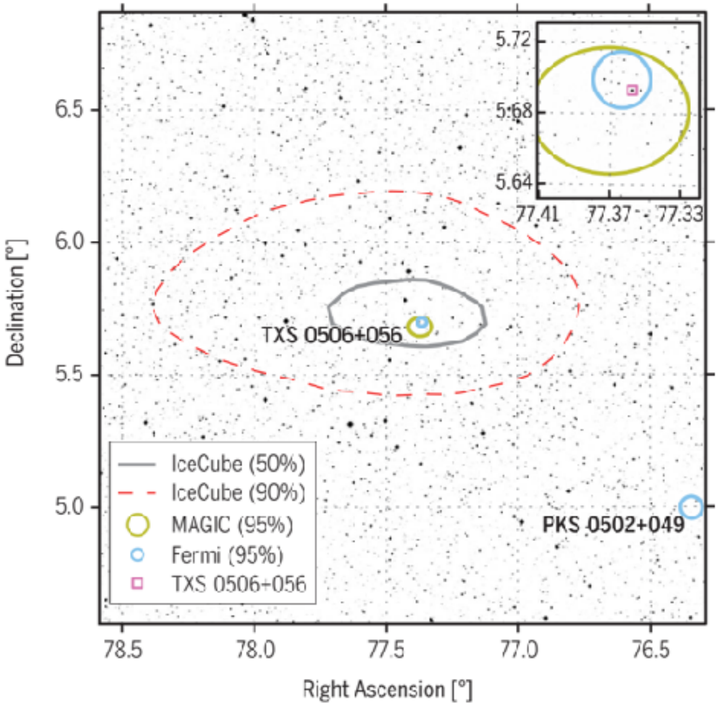
IceCube (PRL, 2020)

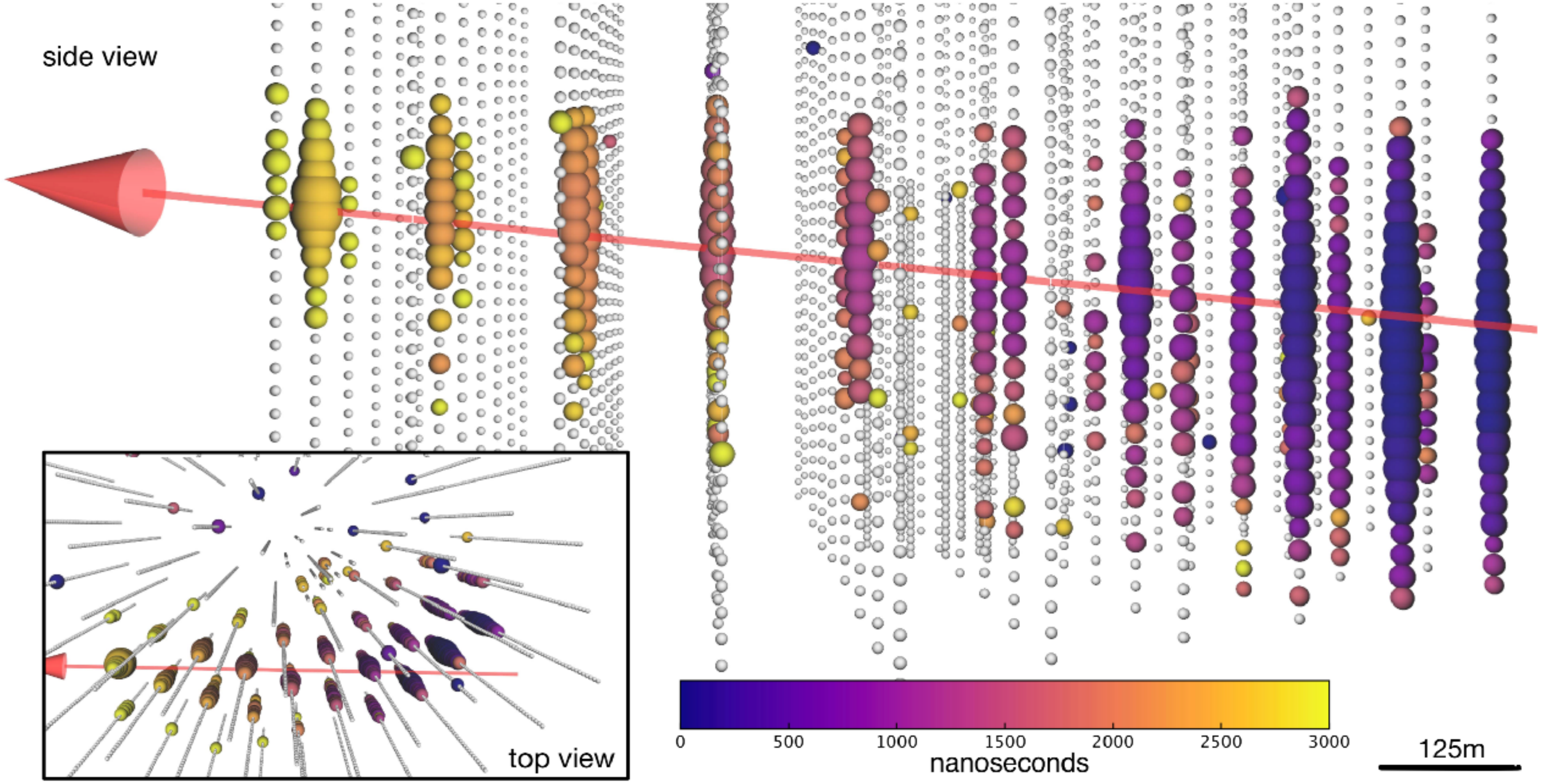
Point search with 10 years of data. **The most significant source in the Northern hemisphere: nearby Seyfert galaxy NGC 1068 w/ significance of 2.9σ.**

GeV gamma-ray based catalogue search inconsistent with background w/ 3.3σ (**NGC 1068, TXS 0506+056, PKS 1424+240 and GB6 J1542+6129 stacked**).

IC170922A coincidence with TXS 0506+056

- Extreme high energy neutrino alert from IceCube followed by detection of very high energy photons from a flaring blazar





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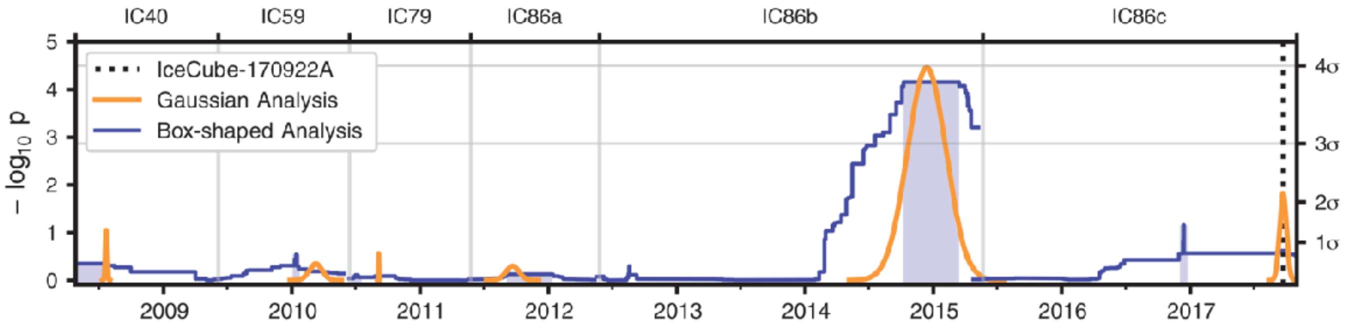
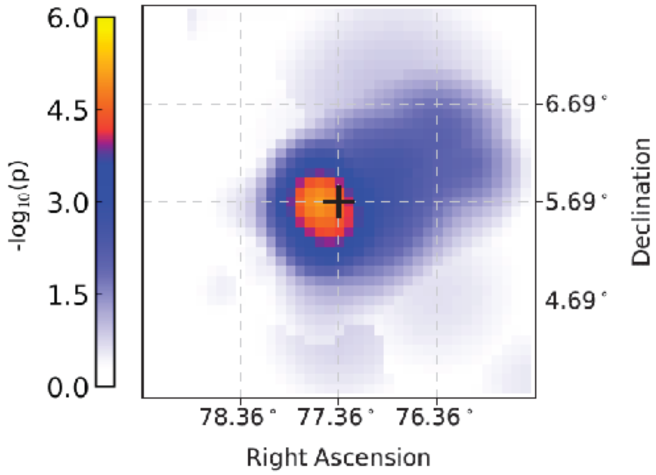
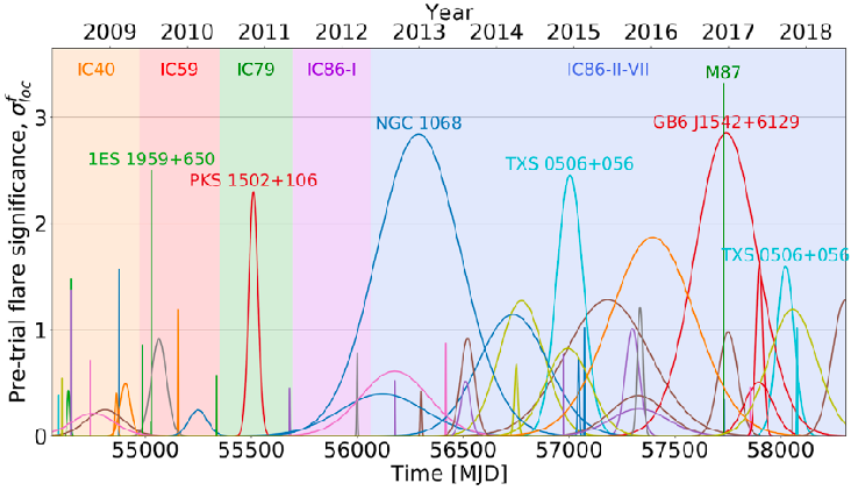
- **Archival search found neutrino excess around 2014 around TXS 0506+056**
  - 13 ± 5 events above the background over 100 days: significance of 3.5σ.
  - No gamma flare. This flare has different mechanism respect to the one from **IC170922A?!**



IceCube Science, 361 6398 (2018)





IceCube, ApJL 920 L45 (2021)

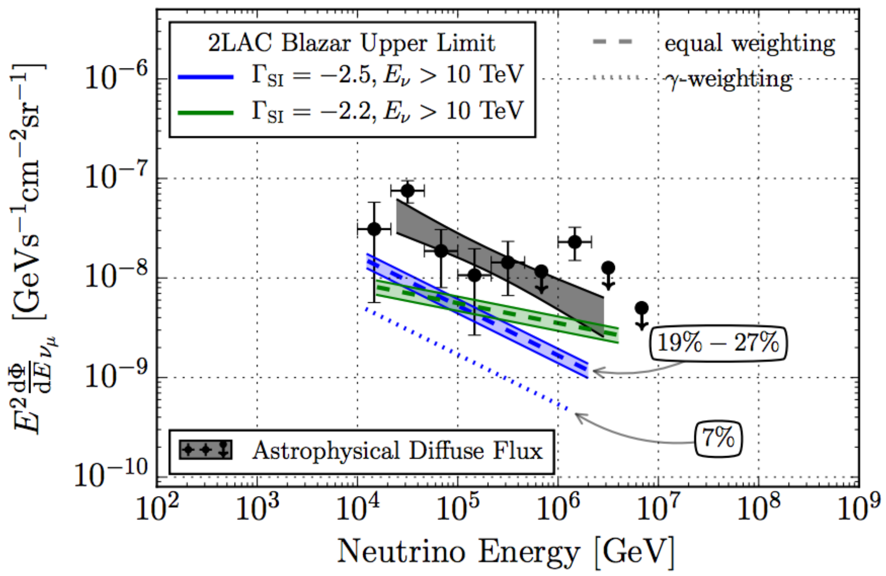
10 years multi-flare search from a catalog
4 best locations (flares): **M87, TXS 0506+056, GB6 J1542+6129, NGC 1068**, corresponding to a post-trial p-value of 3sigma (stacking). Only TXS has 2 flares. M87 not seen in the time integrated search (short flare with 3 nu neutrinos).

Source	R.A. [deg]	δ [deg]	$\hat{n}_s$	$\hat{\gamma}$	$\hat{t}_0$ [MJD]	$\hat{\sigma}_T$ [days]	$-\log_{10}(p_{loc})$	$F_{90\%} \times 10^4$ [TeV cm^{-2}]
TXS 0506+056	**77.35**	**5.70**	$10.0^{+5.2}_{-4.2}$ $7.6^{+6.1}_{-5.8}$	$2.2^{+0.3}_{-0.3}$ $2.6^{+0.5}_{-0.6}$	57000^{+30}_{-30} 58020^{+40}_{-40}	62^{+27}_{-27} 42^{+42}_{-28}	**2.77**	**1.7**

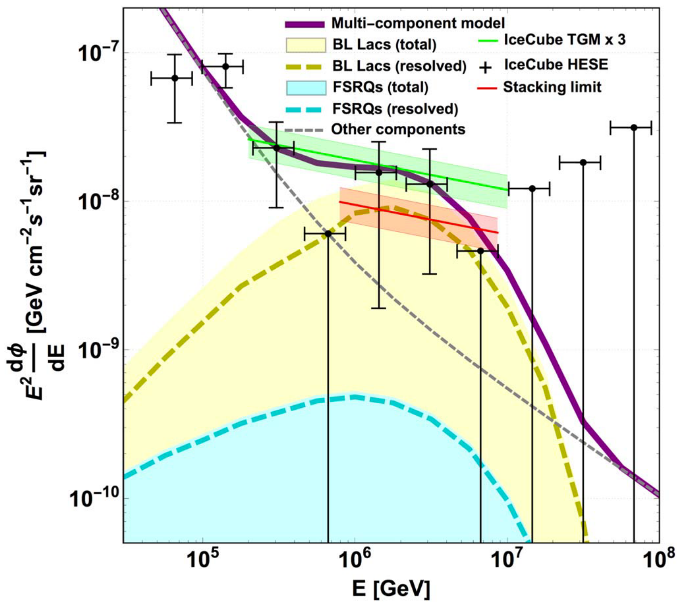
N. Park@NEUTRINO2022

Can blazars explain IC diffuse flux?

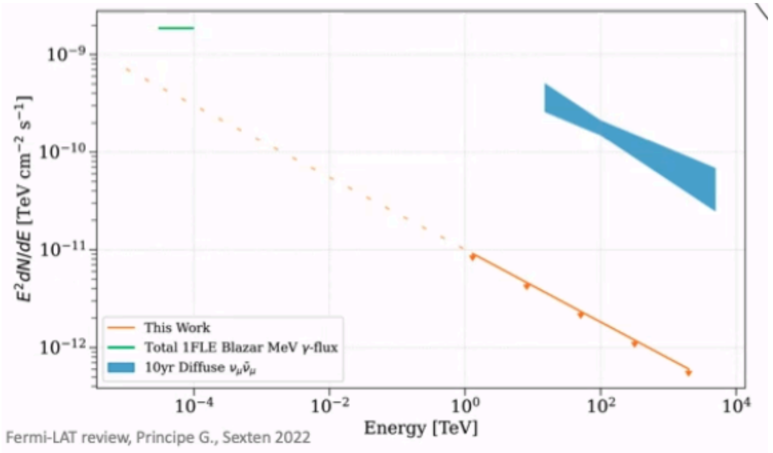
- Resolved blazars cannot contribute more than 20-25% to the flux of HESE.
- Considering unresolved (more faint blazars) the high energy (Enu>1 PeV) part can be explained by blazars.



IceCube, APJ 2017



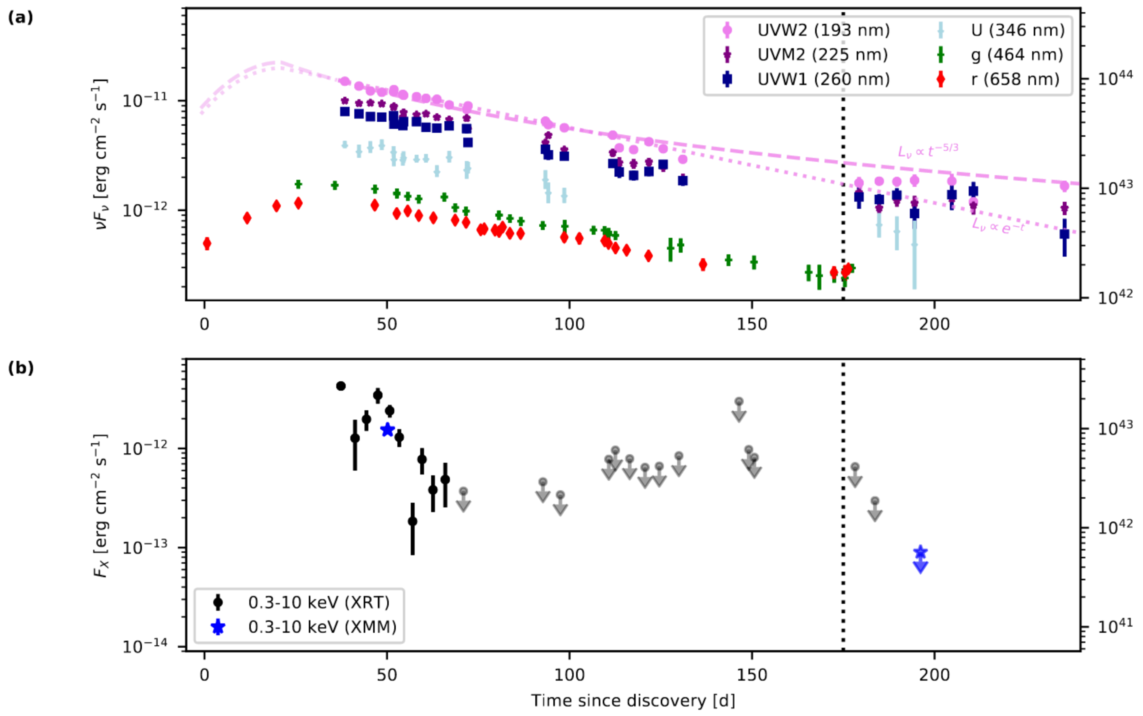
A. Palladino et. Al 2019



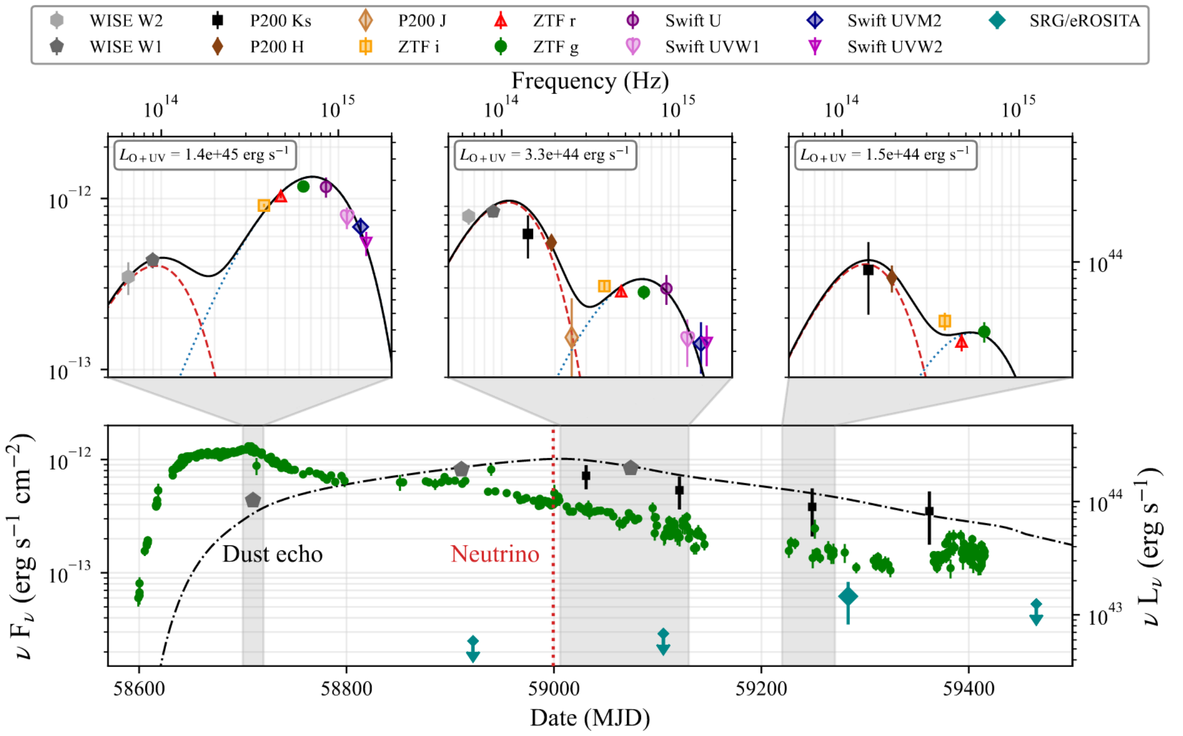
UL from the stacking analysis (134 blazars) are 1.0% of the diffuse flux (IC 2022).
As you've seen in G. Principe talk!

Can we still explain majority of TGM with unresolved blazars?

Tidal Disruption Events



R. Stein et al, Nature Asto. 2021



S. Reucht et al, PRL 2022

Coincidence with radio-emitting tidal disruption event, p-value 0.5% (2.8sigma), considering brightness in bolometric energy flux as AT2019dsg is 0.2% (3.1sigma).

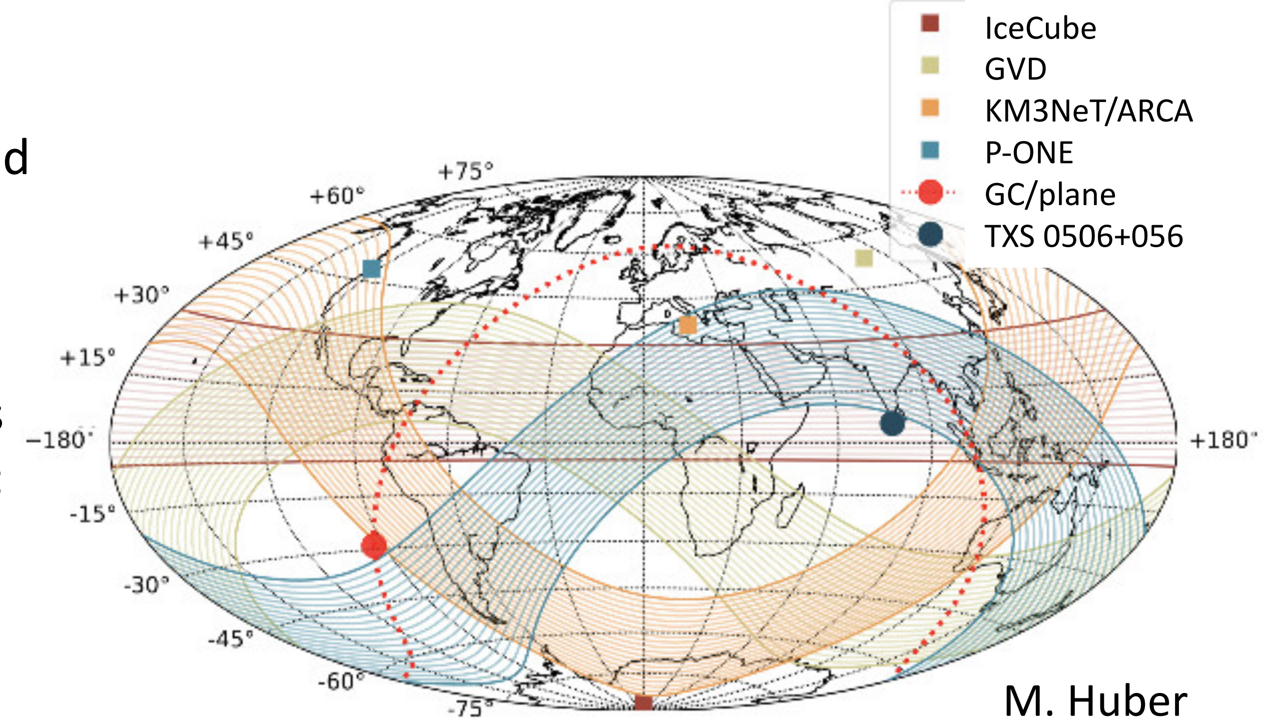
Observations, including a bright dust echo and soft late-time X-ray emission support a TDE origin of this flare.

- AT2019dsg+AT2019fdr with optical flux is a coincidence with p-value=0.034% (3.4sigma),
- IceCube diffuse flux from the TDEs detected before AT2019dsg and AT2019fdr has been constrained to be at most ~1.3% (~26%) in the jetted (non-jetted) TDE case. R. Stein, IC, PoS ICRC2019 (2020) 1016

Cherenkov 3D arrays (water/ice)

- Transition to routine detection of 100TeV-PeV neutrinos is happened last years (IC, ANTARES, Baikal).
  - Extensive method is still effective to learn more!
  - Collaboration with other multi-messengers is the key strategy.
  - >5 km^3 GNO global observatory in future. GNN network (IC, ANTARES/KM3NeT, Baikal-GVD) is active since many years.

- Golden channel – through-going muons
  - "Upgoing" since only nu can traverse the Earth and produce mu.
  - High energy since <10 TeV is atmospheric nu dominated.
  - At around 100 TeV, less than 20% of the neutrinos with next-to vertical direction can cross the Earth; at 1 PeV the rate reduces to 5%.
  - Effective band is 20-30 degrees.

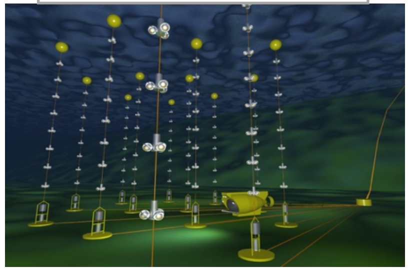


M. Huber

- High field of view (depends on the event selection).
- No manual instrument pointing (but for non-pole instruments the sky visibility varies with time).
  - It is possible to enhance the triggering for some regions of interest (GC for example).

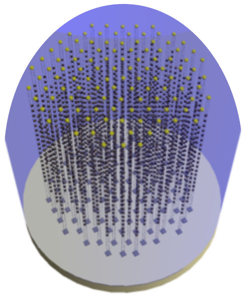
Geometries

12 lines
25 sectors/line

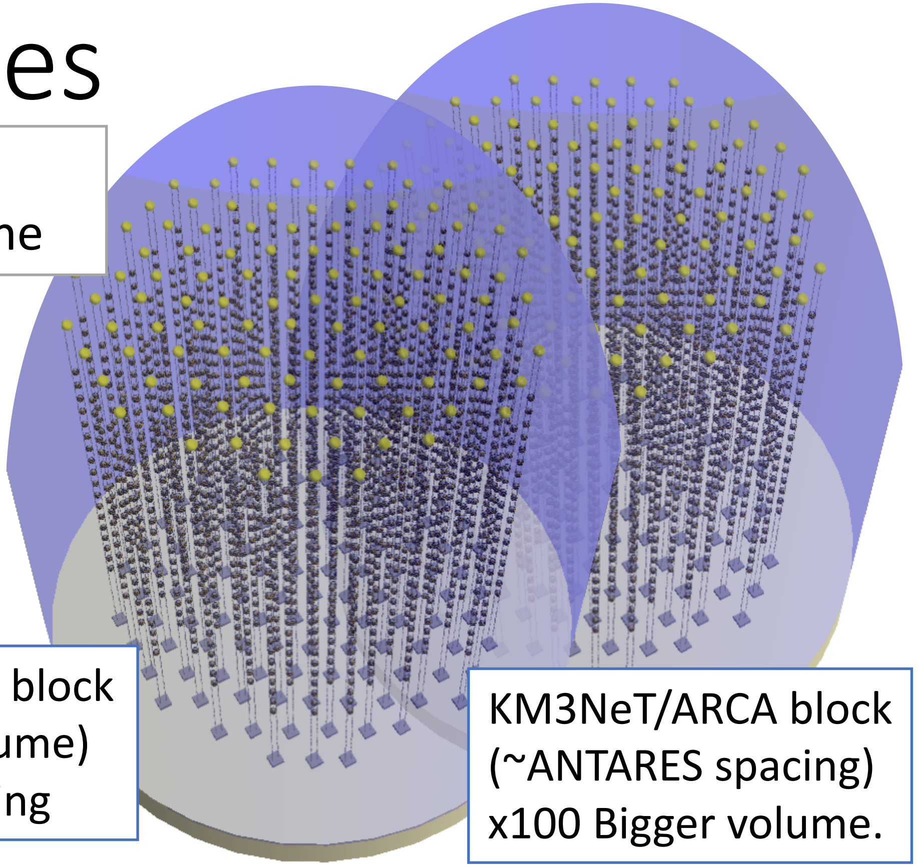


ANTARES
depth 2.5 km

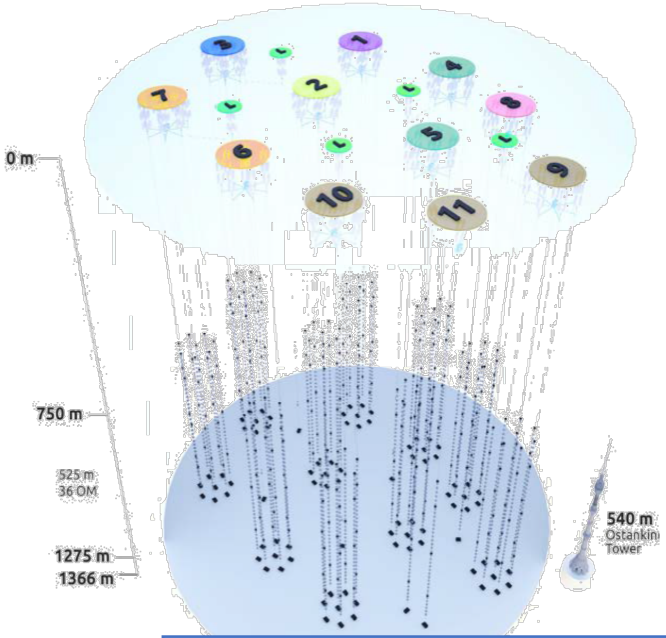
115 lines
18 DOMs/line



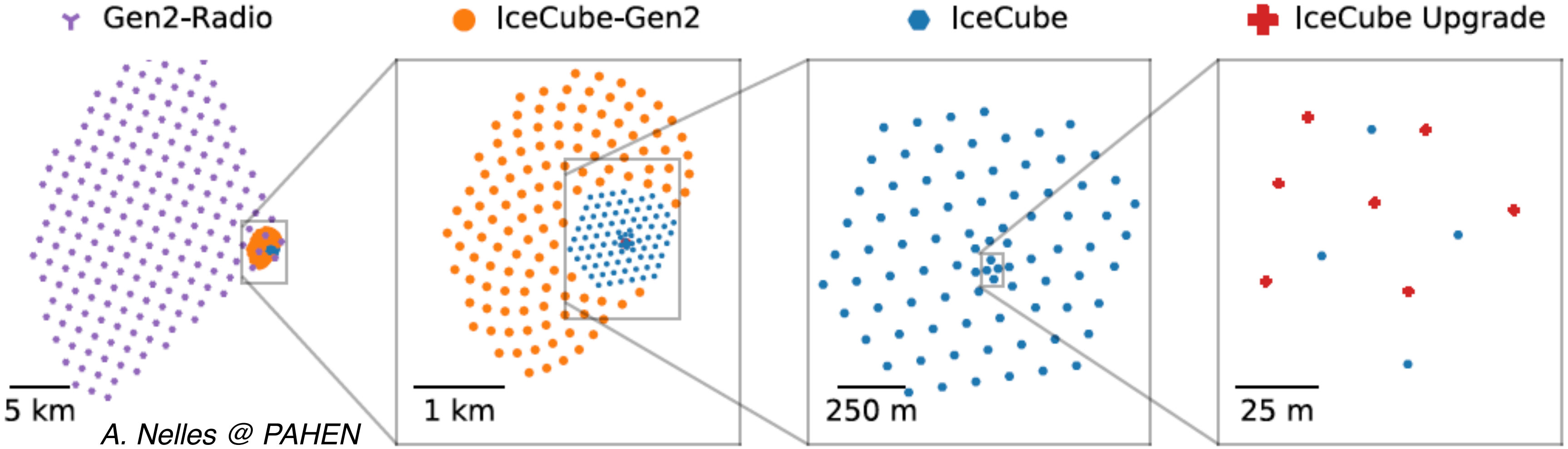
KM3NeT/ORCA block
(~ANTARES volume)
x3 denser spacing



KM3NeT/ARCA block
(~ANTARES spacing)
x100 Bigger volume.



Baikal-GVD block
16-18 clusters
Cluster: 288 OM on 8 lines



A. Nelles @ PAHEN

Status of current water/ice telescopes

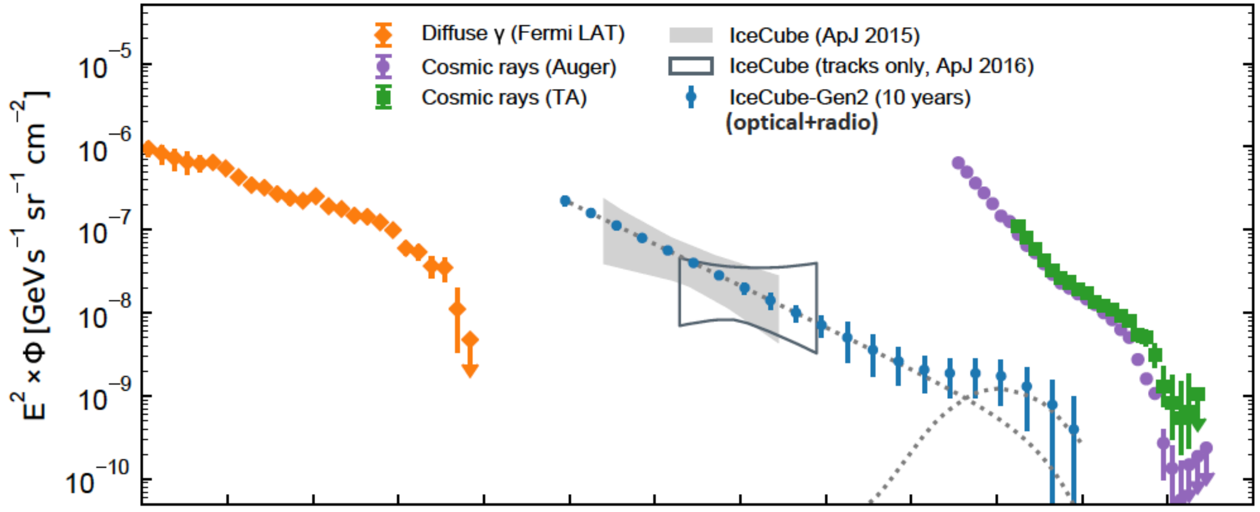
- ANTARES decommissioned in May 2022 after 14 years of operation.
- KM3NeT/ARCA
  - Since beginning of July KM3NeT/ARCA is taking data with 19 strings.
  - Thanks to recent Italian funding, the budget for the **first block realization is funded together with a part of the second block**. Short time construction (3 years) and installation are foreseen.
    - • 946 DOMs integrated (52 DUs worth), 37 DUs integrated.
- IceCube
  - More than 10 years for data collected.
  - Preparation for the IcuCube-Upgrade installation (dense, R&D for Gen2). Pandemic delays (drilling in 2024-25, deployment in 2024-26).
  - IceCube-Gen2 R&D (x8 active volume, radio array).
- Baikal
  - 10 clusters, 5 laser stations, experimental strings.
  - Deployment rate – 2 clusters/year GVD (1 km3) in 2026.
- P-ONE
  - Cabled sea-bed, prototype lines installed (Ch. Spannfellner et al. PoS, ICRC2021:1197, 2021).

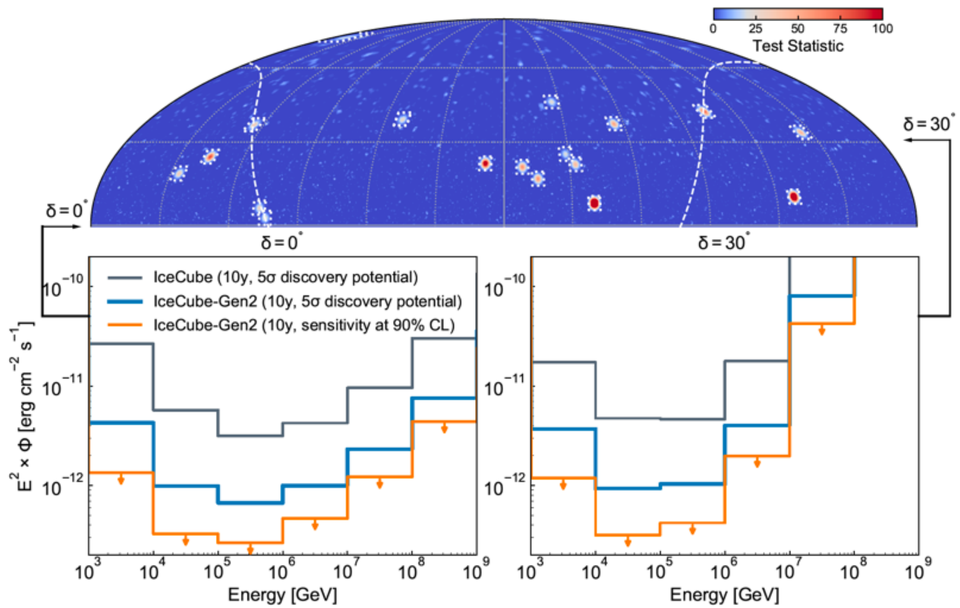
A. Heijboer @ NEUTRINO2022

N. Park @ NEUTRINO2022

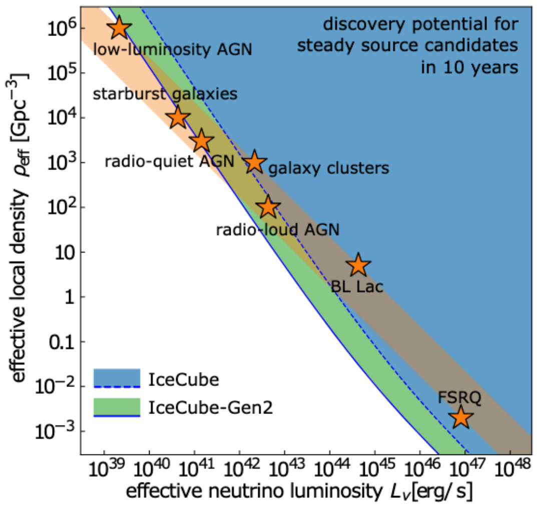
Zh. Dzhilkibaev @ NEUTRINO2022

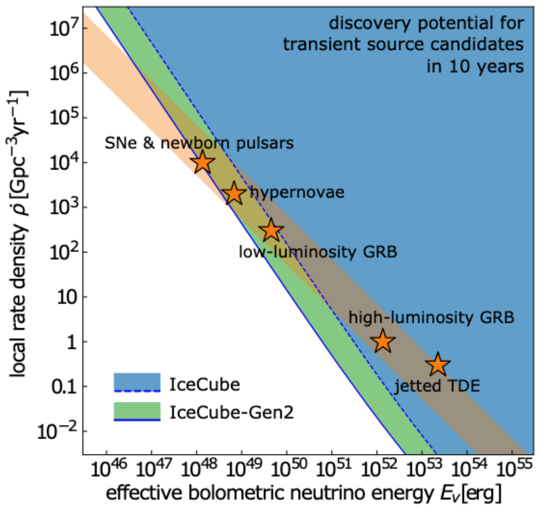
IceCube-Gen2





IceCube-Gen2 (arXiv: 2008.04323)



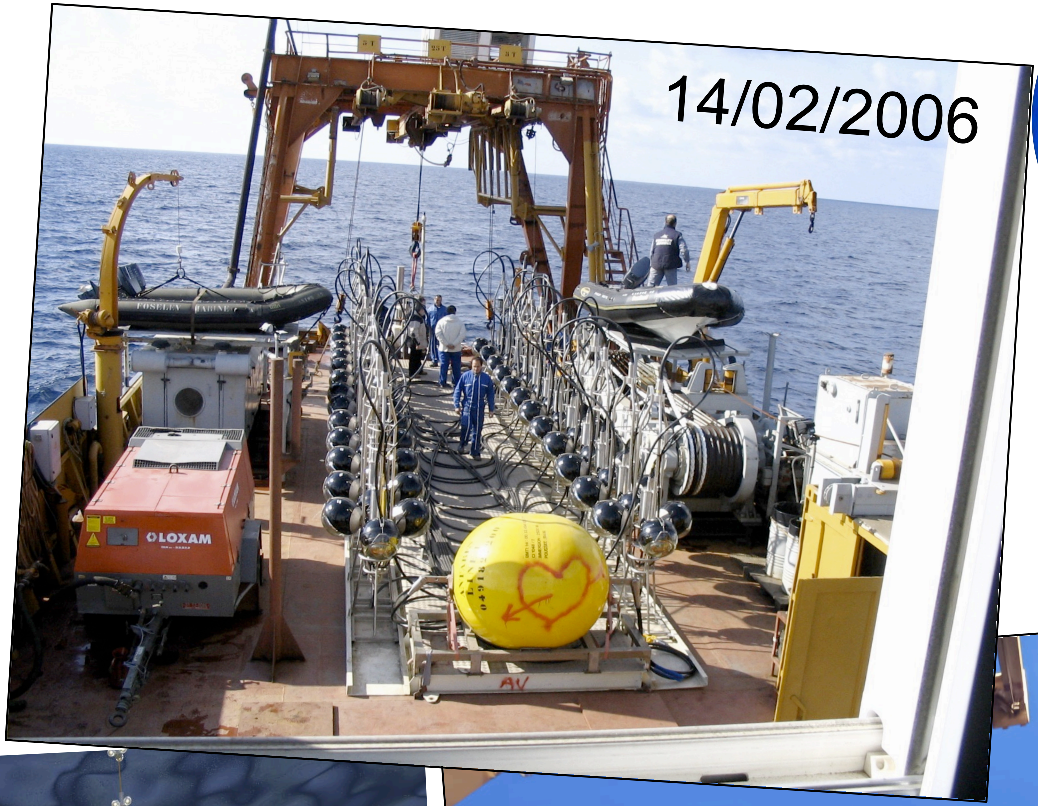


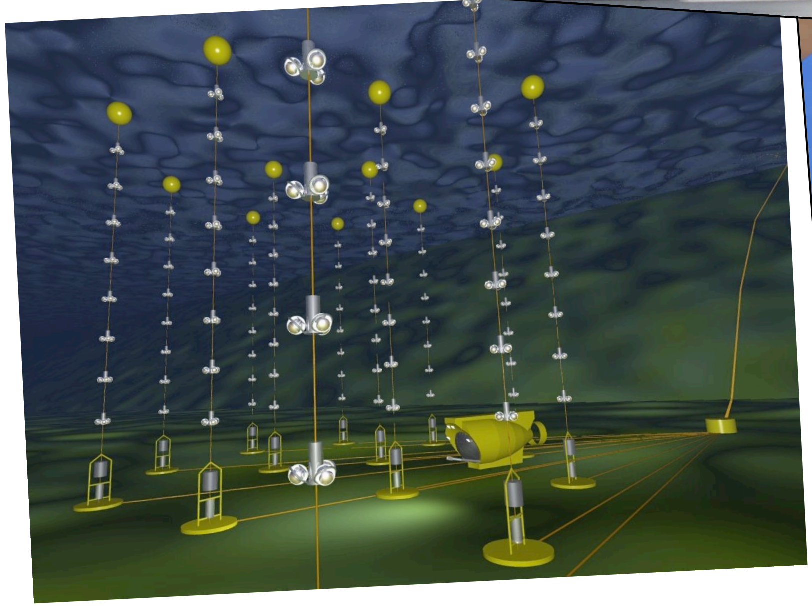
- Optical array: Eight times larger active volume compared to IceCube filled with improved optical module based on the R&D studies from IceCube Upgrade
- Surface air shower array: Matching with the optical array throughput, ~40 times higher coincident events
- Radio array: ~ 500 km2 area of the antenna array for the detection of EeV neutrinos

N. Park @ NEUTRINO2022

ANTARES

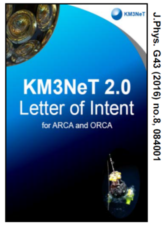
- First Under-Sea neutrino telescope
- Precursor to KM3NeT
- Decommissioned 3 weeks ago after 14 years of operation.
- Competitive results
  - Northern hemisphere
  - Galactic plane
  - Dark matter

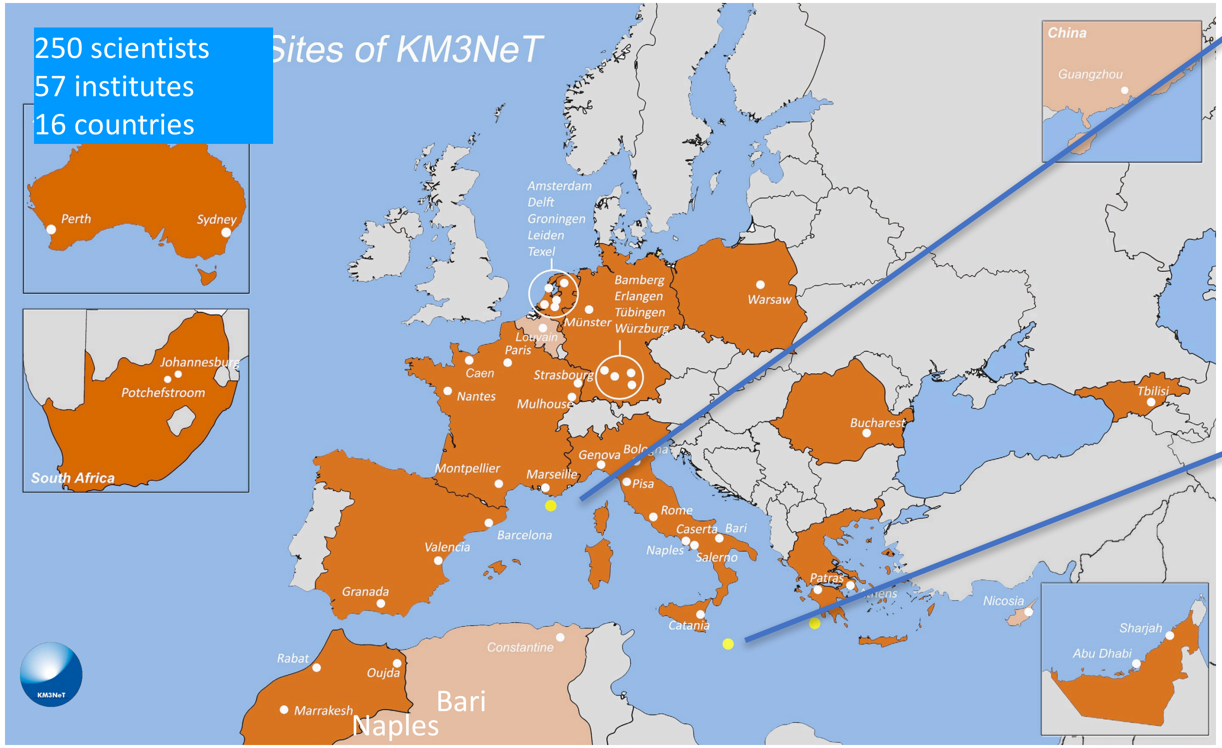




KM3NeT

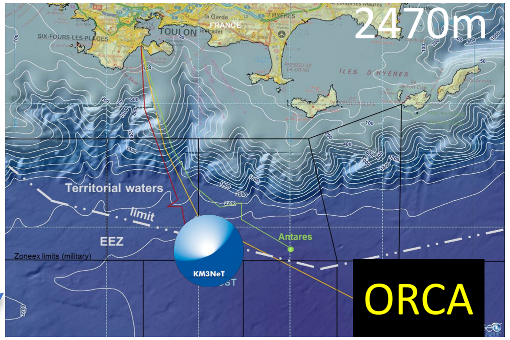
- Multi-site, deep-sea neutrino telescope
- Selected by ESFRI roadmap
- Single collaboration, Single technology





[KM3NeT 2.0: Letter of Intent](#)

J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001



Oscillation Research
with **C**osmics **I**n the **A**byss

Astroparticle Research
with **C**osmics **I**n the **A**byss

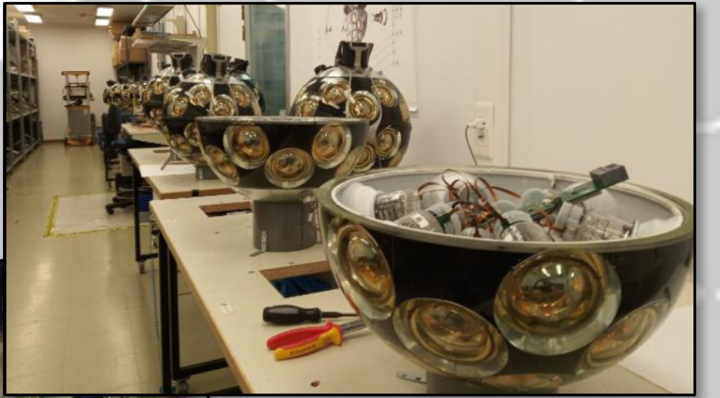
Connection nodes of
european multidisciplinary seafloor & water column observatory
emso

KM3NeT - production ongoing

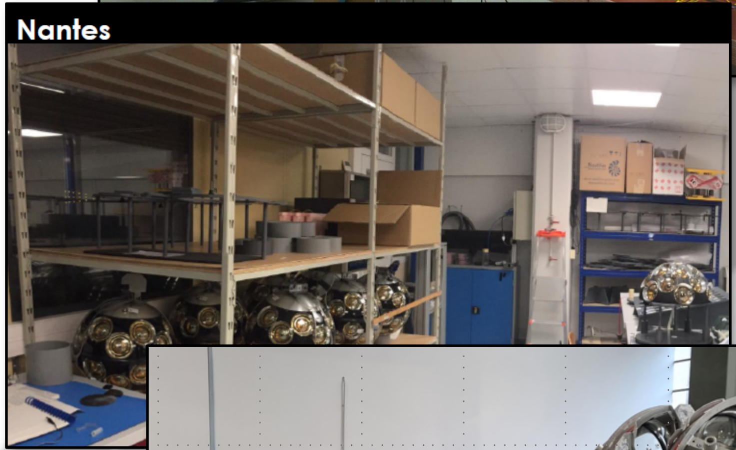
Amsterdam

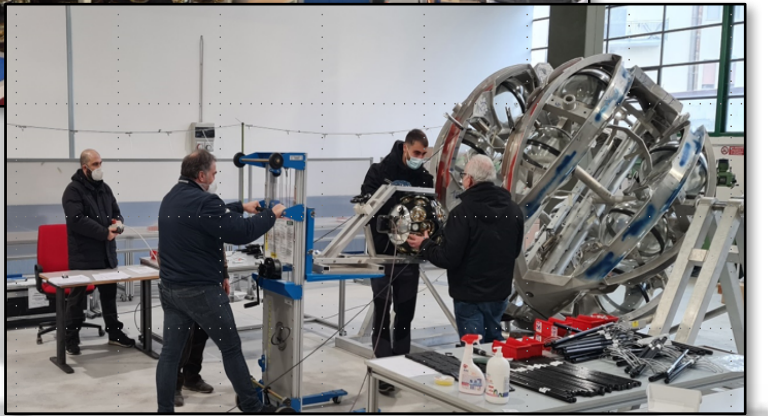
Erlangen

Athens



Genova



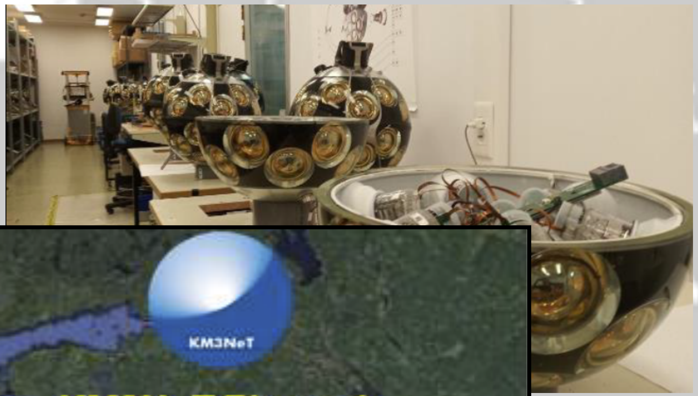


Bologna

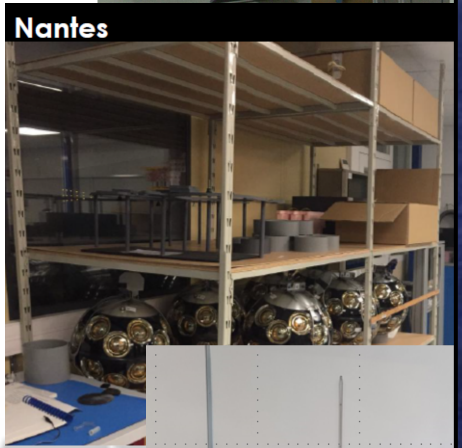
Catania

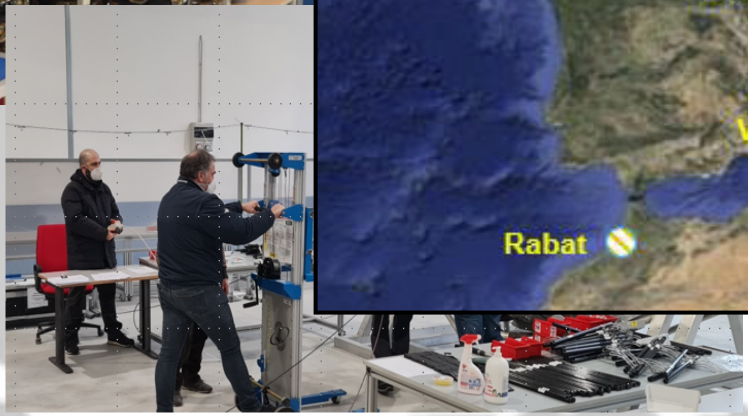
KM3NeT - production ongoing

Athens



Amsterdam

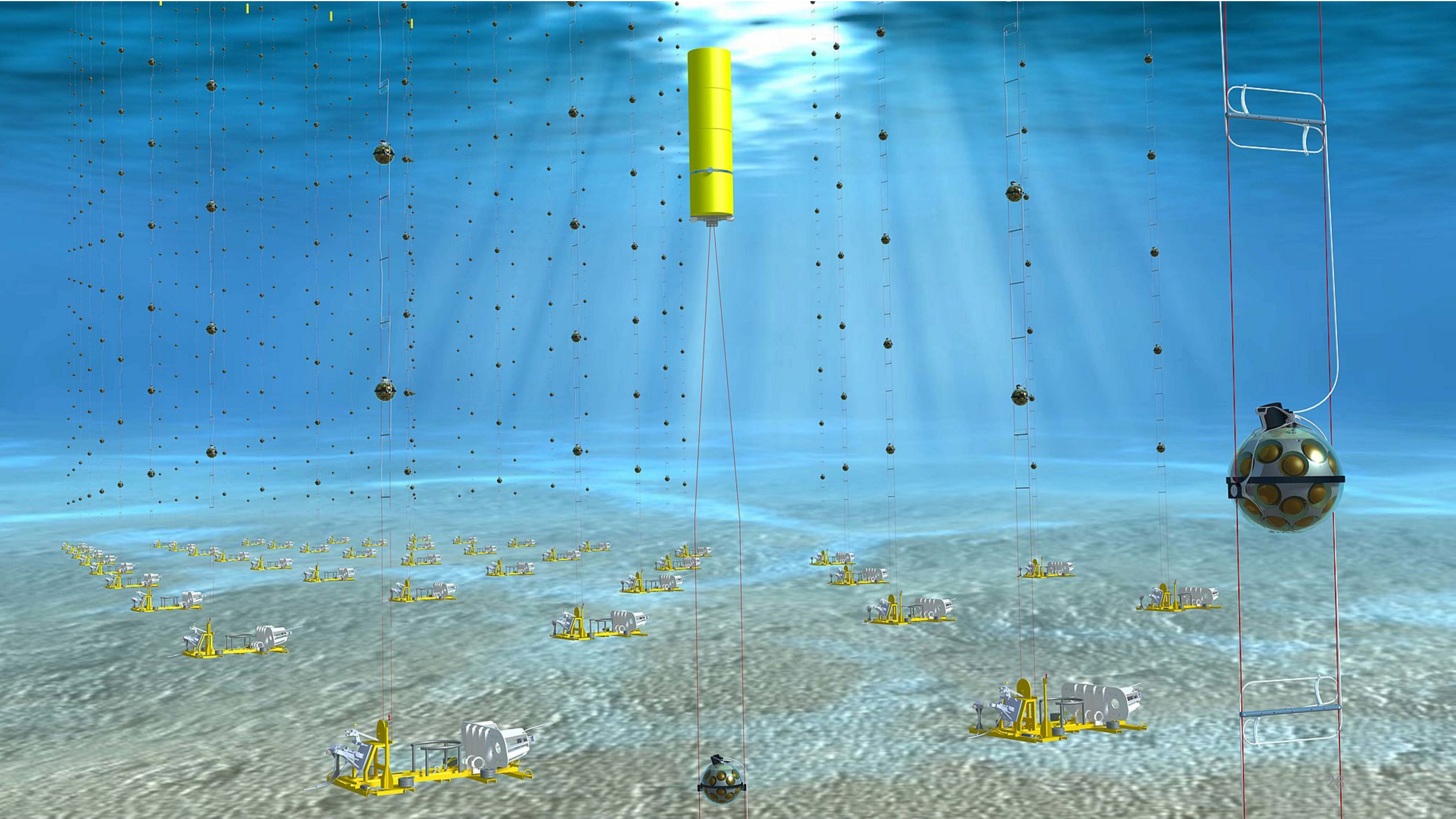




Genova

Catania

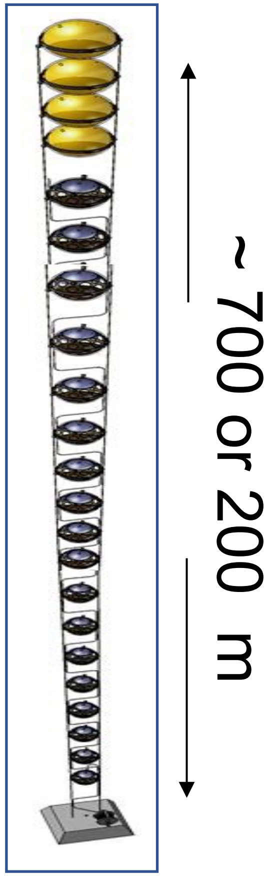
Bologna



Technology

Digital Optical Module (DOM)

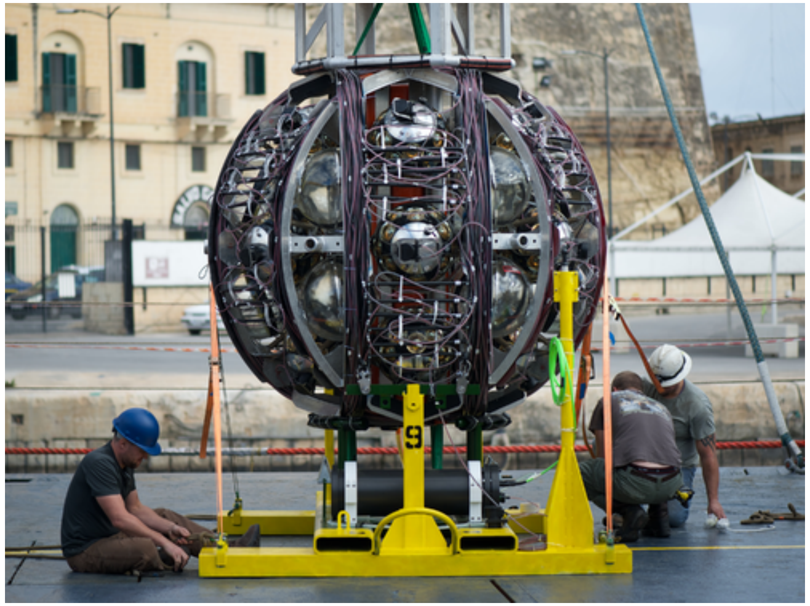
- Multi-PMT : 31 x 3” PMTs
- Gbit/s on optical fiber
- Positioning & timing



Detection Unit (DU)

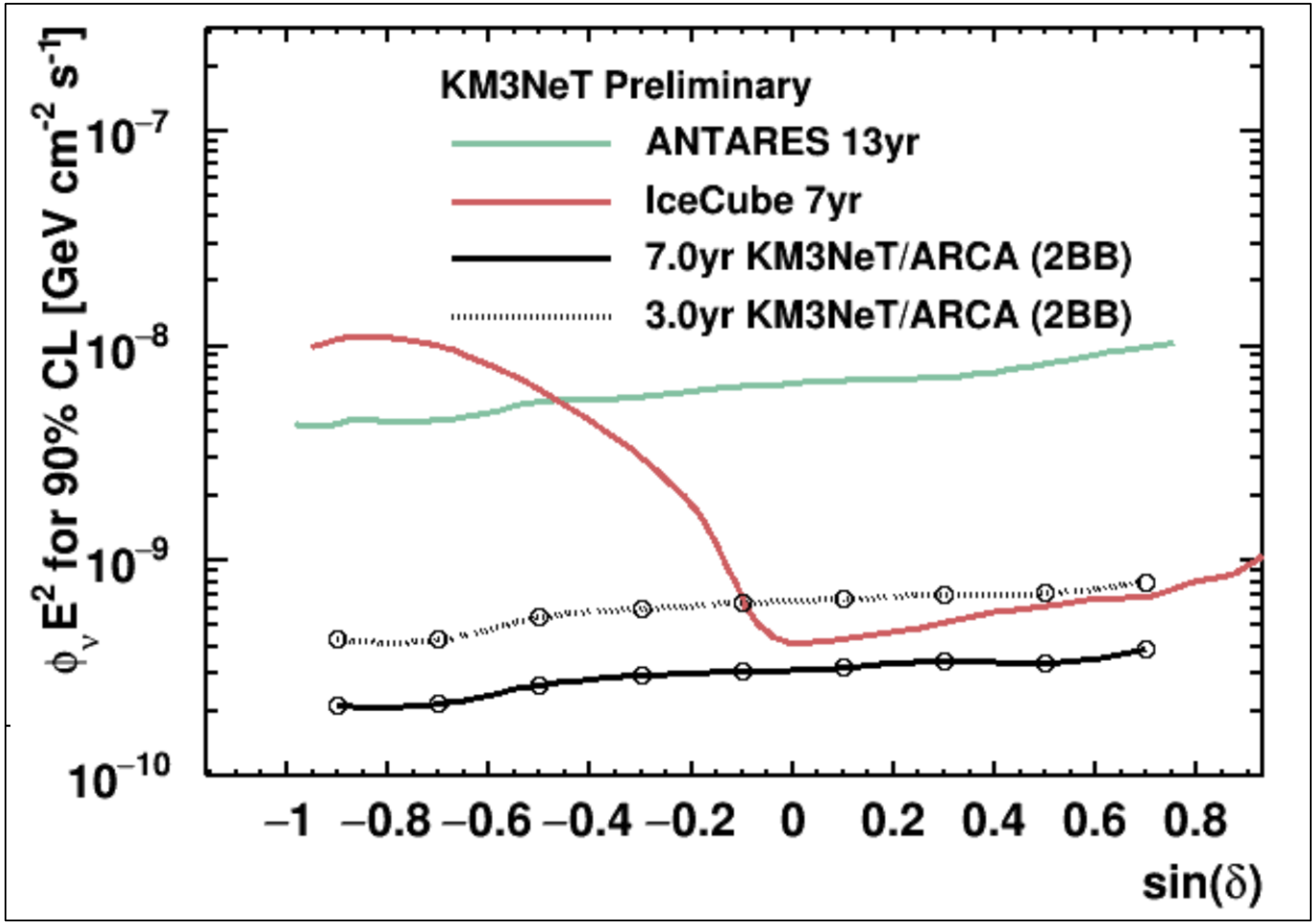
- 18 DOMs
- Low-drag design

Deployment Vehicle

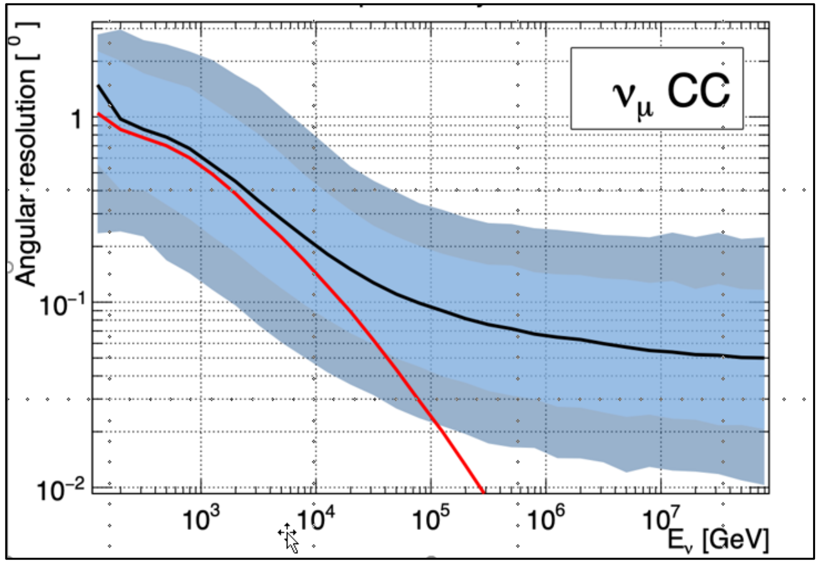


- Rapid deployment
- Multiple DUs per sea campaign
- Autonomous/ROV unfurling
- Reusable

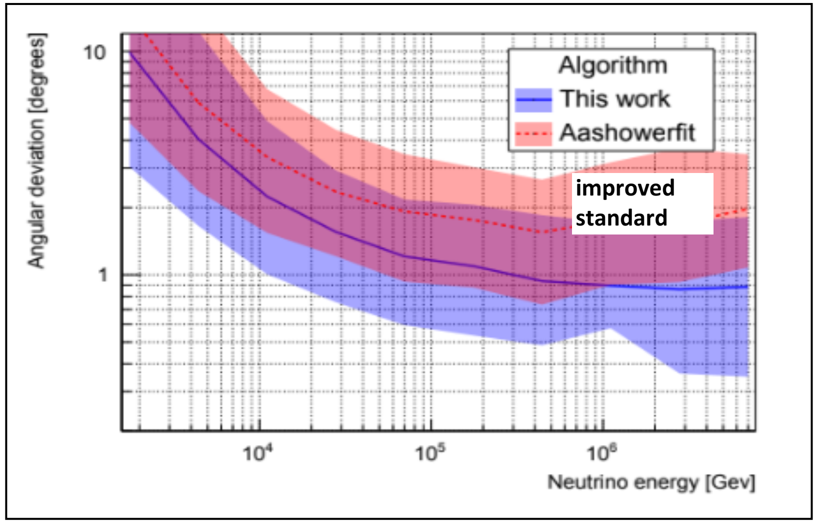
Cosmic neutrino sources search



track-like



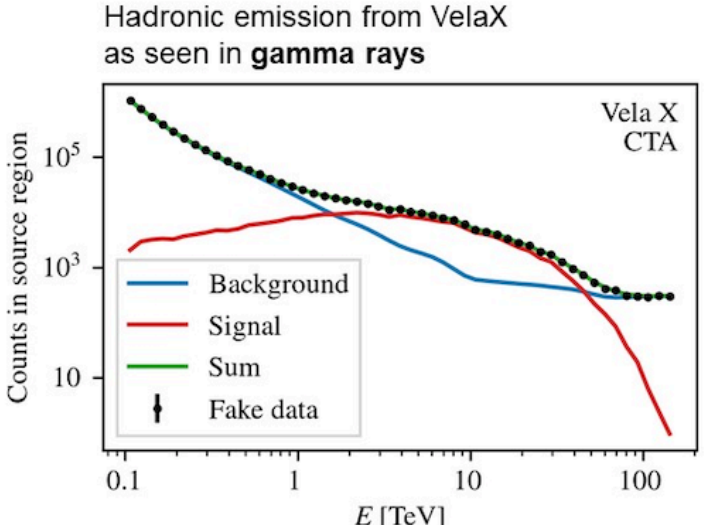
shower-like

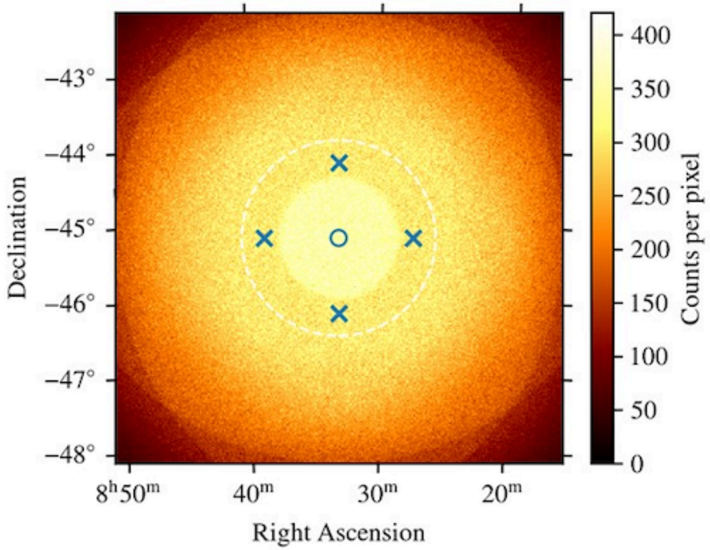


A superior direction resolution for showers is expected (due to the isotropic water properties and low scattering).
Same physics as IceCube + visibility of the **Galactic Center (plane) with the upgoing track events**!

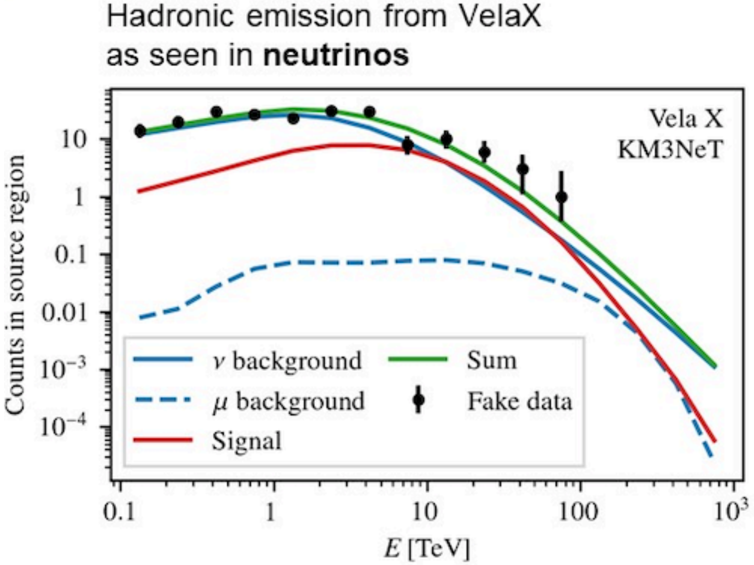
Common data analysis with CTA - hadronic model testing

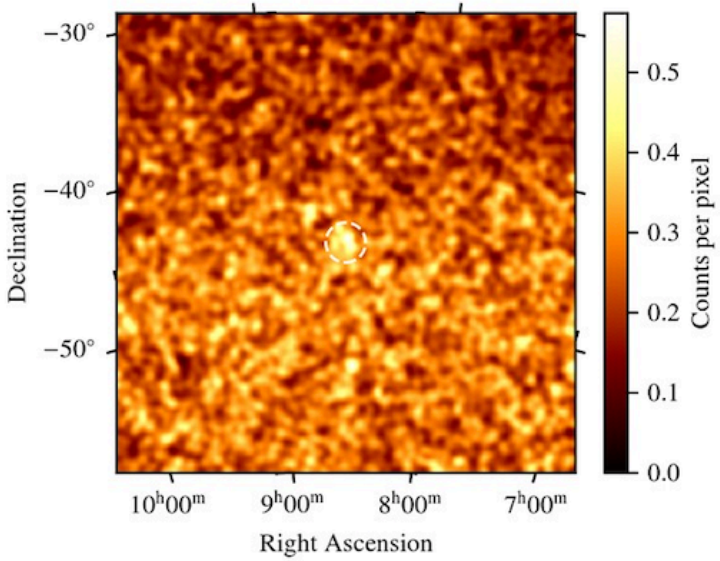
200h of CTA data





10 years of KM3NeT data (2 BB)





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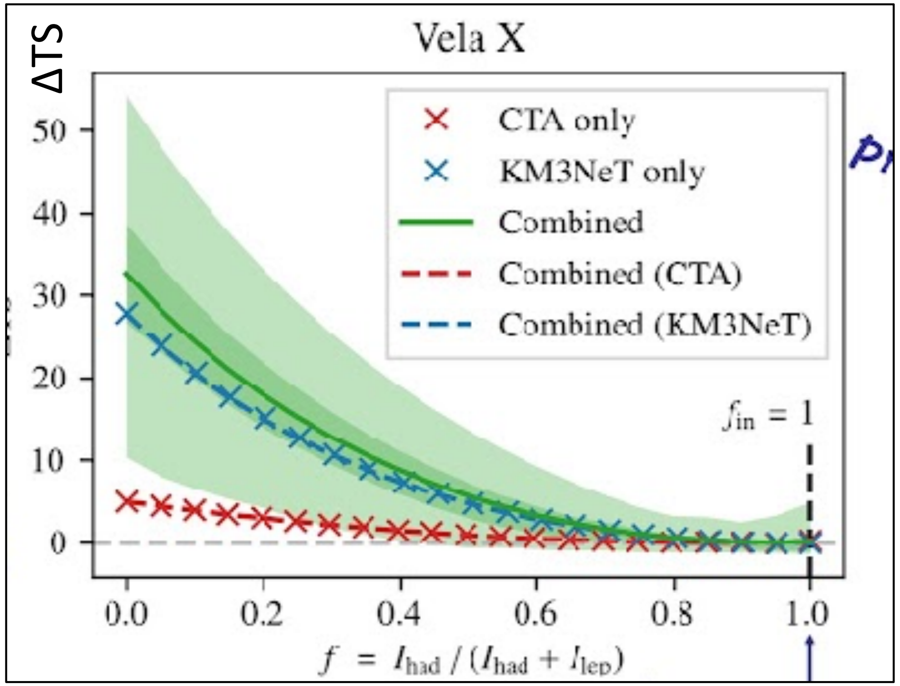
Common data analysis with CTA

Hadronic model testing

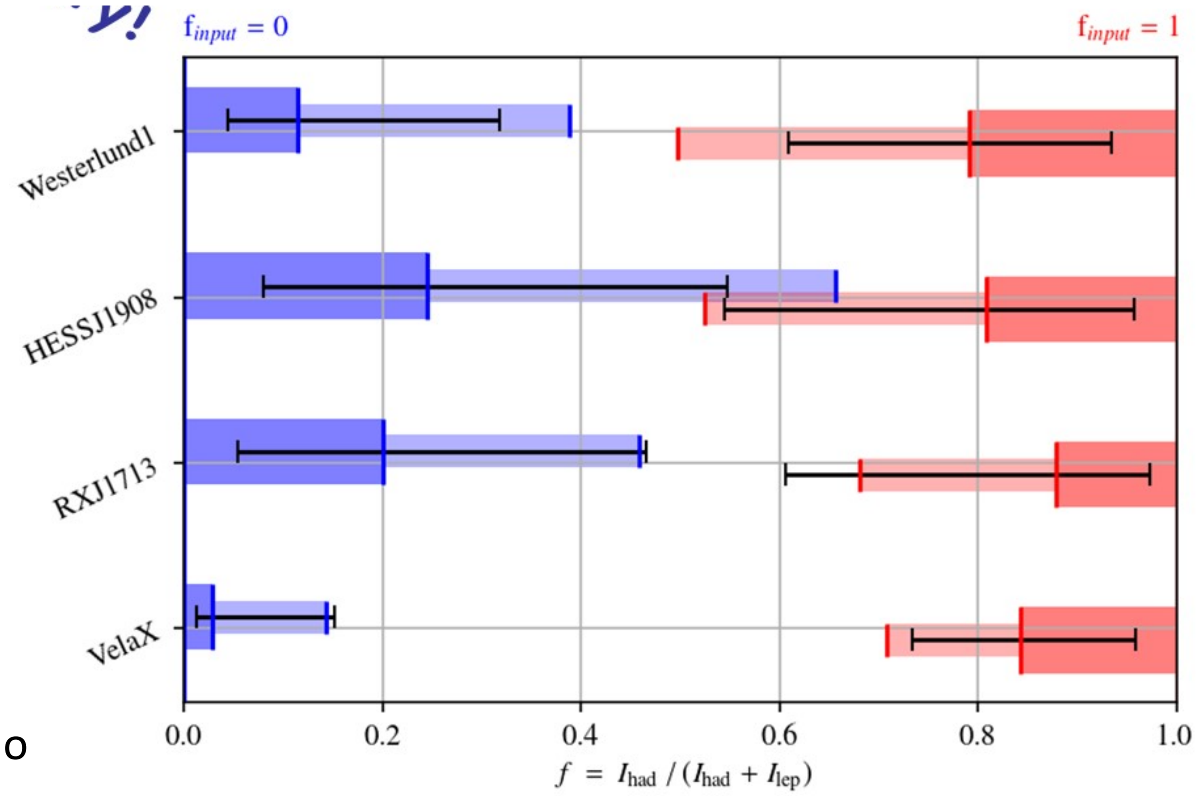
This analysis was performed using gammapy (driven by the CTA group @ ECAP).

2 input scenarios (purely leptonic, f=0, purely hadronic f=1).
Purely leptonic – Inverse Compton gamma production.
Purely hadronic – pion decay (p-p).



Input scenario

Quantiles (68%, 90%) of the best fit values and average size of 68% credible intervals.



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Neutrino detector IRFs

- gammapy for gamma:
  - Effective area
  - Angular PSF
  - Energy dispersion
  - Background

- Neutrino detection features:
  - Several neutrino types (nu/anti-nu, flavour) and interaction (CC, NC, Glashow).
  - Several neutrino reconstructions (track, shower) and event selections (track, shower, HESE, upgoing etc).
  - Several backgrounds – atmospheric muons, neutrinos.
  - Variable detector configurations/efficiency? (Also for CTA?)

- First implementations by KM3NeT collaboration (T. Gal, M. Smirnov et al) **not official yet!** https://gitlab.in2p3.fr/escape2020/virtual-environment/irf-from-km3net/
- Track channel only (the biggest contribution to the sensitivity for point sources).
  - numu + anti-numuCC average effective area, PSF and E dispersion.
  - Atmospheric muon background.
  - Atmospheric neutrino background.
  - Based on T. Unbehaun et al. analyses, extending to open science.
  - Future development in the framework of ESCAPE & EOSC-Future initiatives.

Some conclusions

- Diffuse neutrino flux is measured by several detectors and in several event selections (sensitive to different flavours and energy ranges).
  - This is not the cosmogenic CR flux.
  - This is (probably) not the “partner” of the EBL gamma flux (from p-p interactions).
- Several sources identification (TXS 0506+056, NGC 1068, M87, TXS GB6 J1542+6129, PKS 1424+240). They are of different types: blazar (BL Lac/FSRQ ?), Starburst galaxy...
- No dominant single sources and, probably, no dominant source type is responsible for this flux.
  - Current detector sensitivities are $\lesssim$order of magnitude below expected emissions from single (steady) sources.
  - We need stacking/catalogues search, transient searches. Collaboration with MM partners is essential.
  - Neutrino detectors are excellent for understanding source acceleration mechanisms.
  - The major part of the expected neutrino sources should be reachable with the next generation detectors.
    - EeV sensitive detectors have access to the guaranteed cosmogenic flux.

*This work has been supported by European Union’s Horizon 2020 Programme under the **AHEAD2020 project** (grant agreement n. 871158).*