Multi-messenger Astronomy

with High-Energy Neutrinos

QUANTUM · GRAVITY · MULTI · MESSENGER

COST QGMM Workshop 2022

Agustín Sánchez Losa

IFIC (CSIC-UV) | VEGA

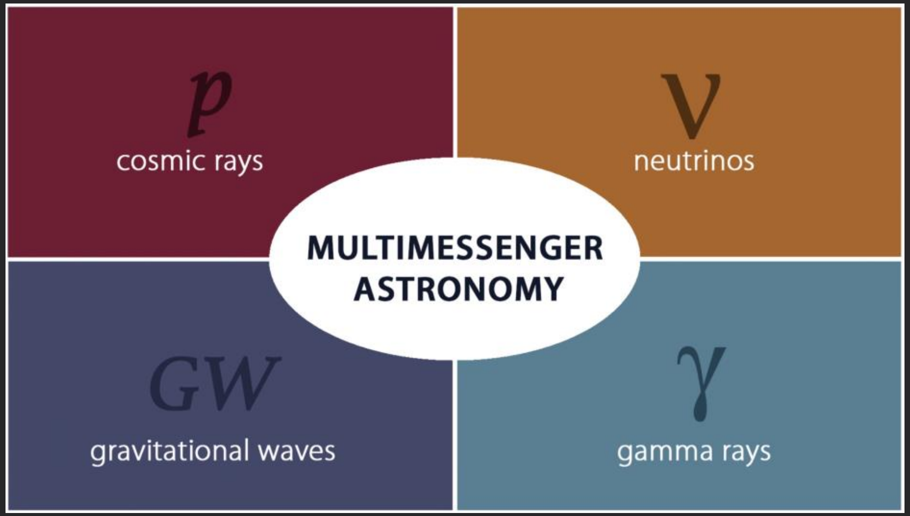
11/07/2022

CSIC IFIC INSTITUT DE FÍSICA CORPUSCULAR VNIVERSITAT DE VALÈNCIA

VEGA Valencia Experimental Group of Astroparticles

Multi-messenger Astronomy

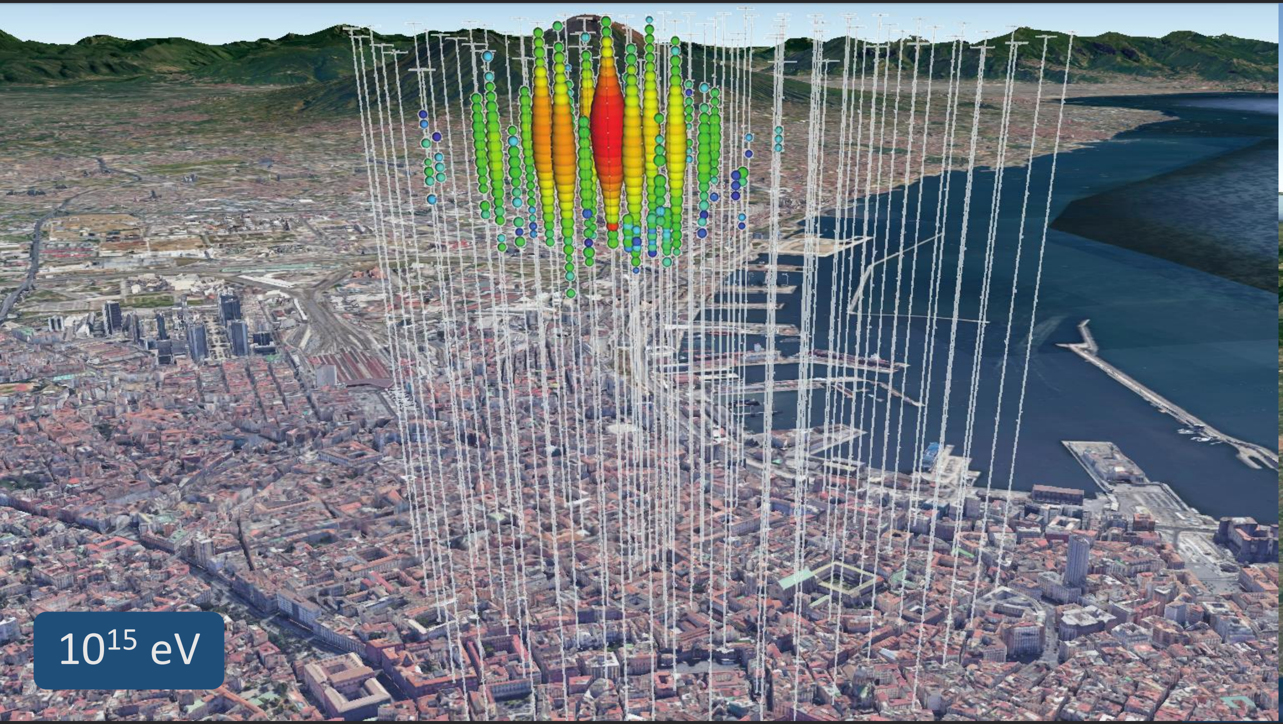
with High-Energy Neutrinos



Credits: IceCube

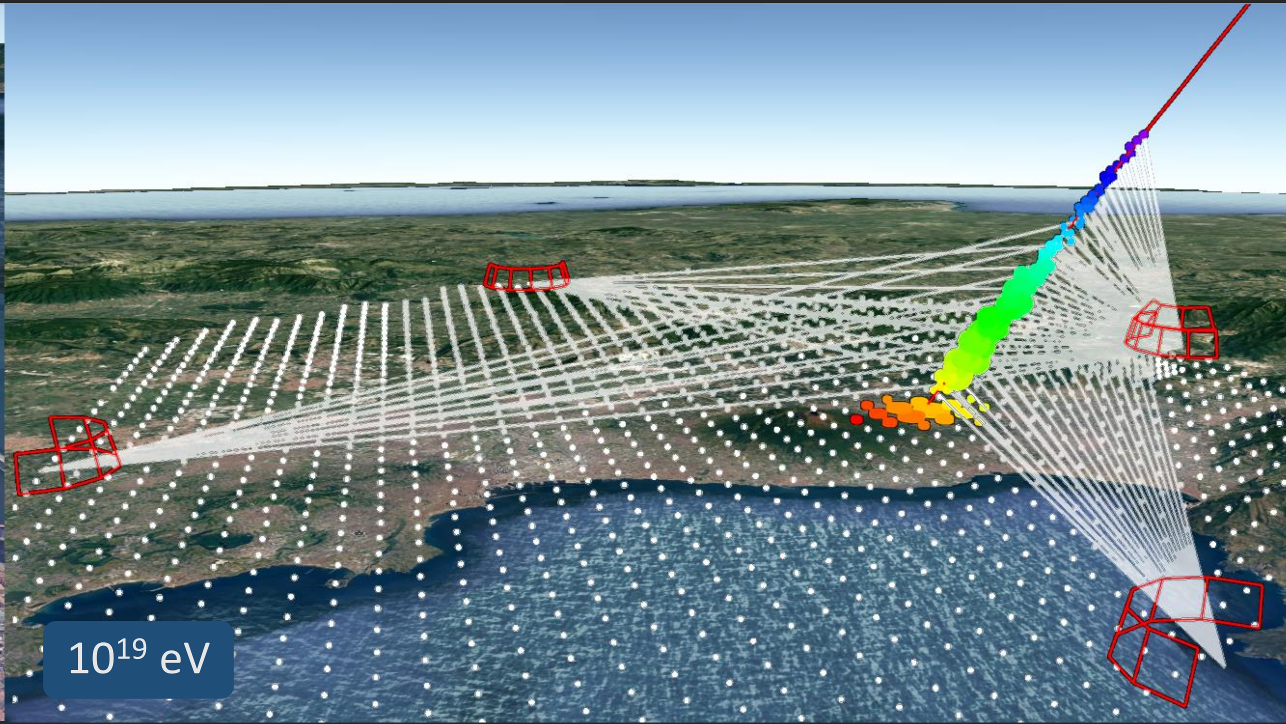
- I. The Messengers
- II. The Experiments
- III. The Searches
- Prologue

The Messengers | Motivation



A 2 PeV ν visiting Naples

[Big Bird | IceCube]



A 50 EeV CR visiting Naples's bay

[AUGER]

Records of energies:

<u>CR</u>: ~10^{20} eV → 300 EeV | Oh-my-God particle, HiRes Fly's Eye (1991) [arXiv:astro-ph/9410067]

<u>Neutrino</u>: ~10^{15} eV → 6.1 PeV | Glashow resonance, IceCube (2021) [Nature 591, 220–224 (2021)]

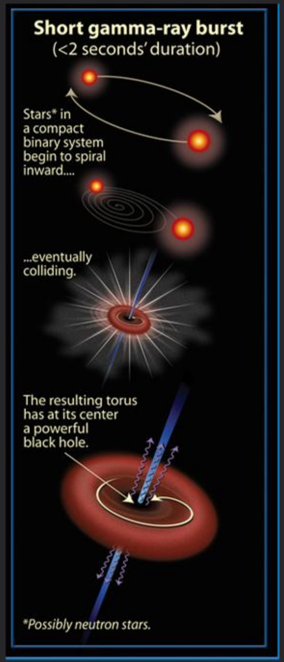
<u>Gamma</u>: ~10^{15} eV → 1.4 PeV | LHAASO J2032+4102, LHAASO (2021) [Nature 594, 33–36 (2021)]

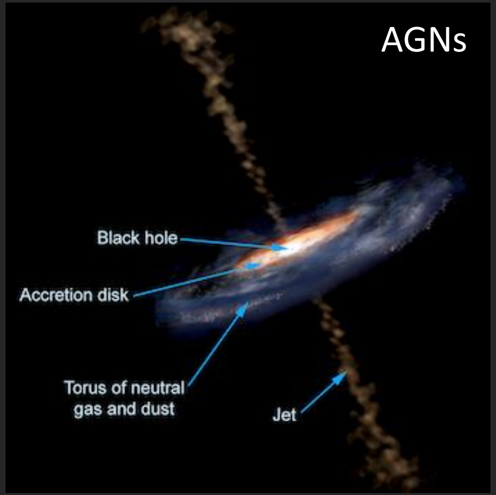
What produce these?

The Messengers | Motivation

Astroparticle Physics: Study of the most extreme accelerators in the Universe!

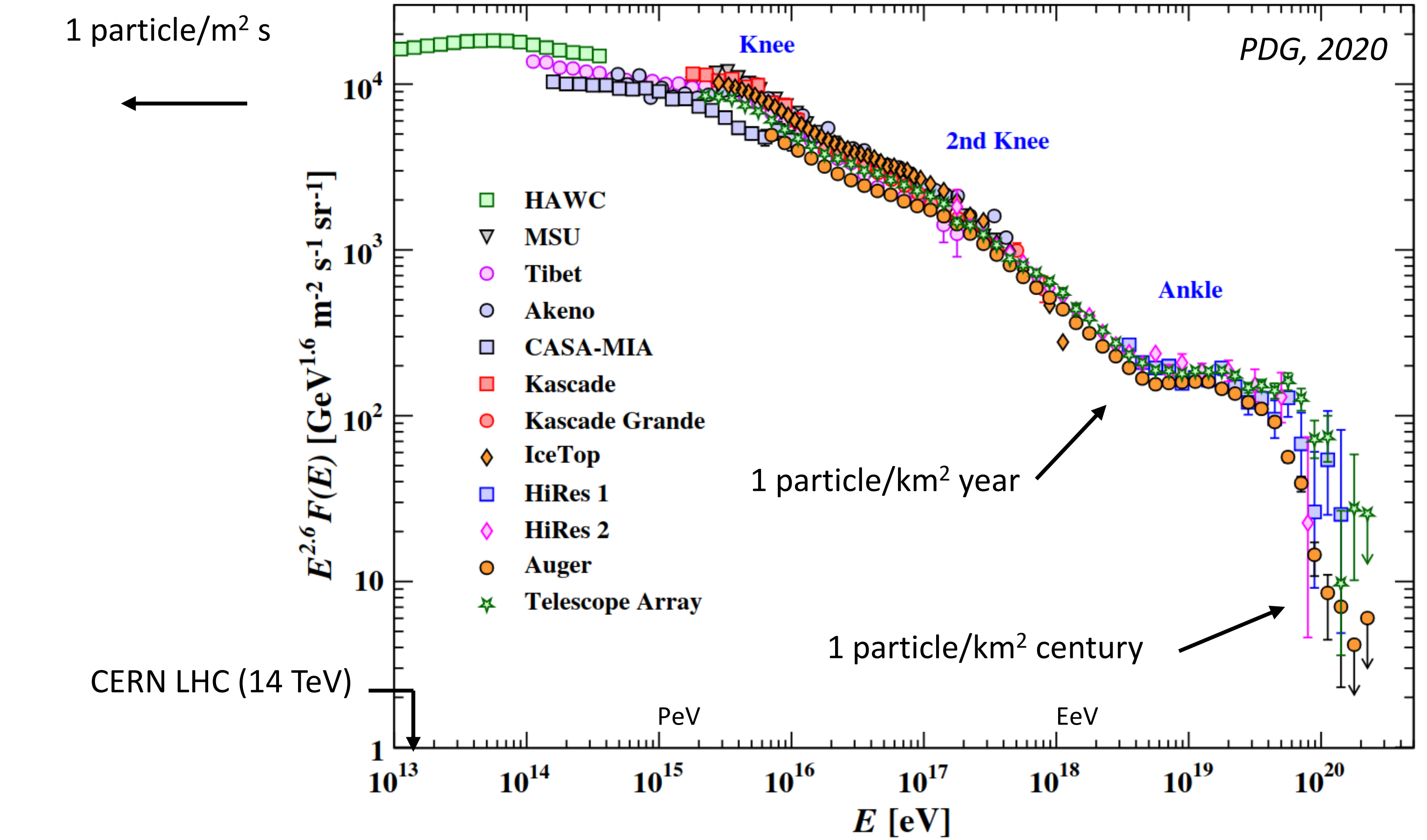
- What is the origin of the high-energy cosmic rays?
- Are the sources galactic or extragalactic?
- How do sources accelerate particles?
- What interactions cause these particles loose their energy?
- How these particles propagate?
- What constrains can we place on fundamental physics?
- What is dark matter?
- Is the speed of light constant?



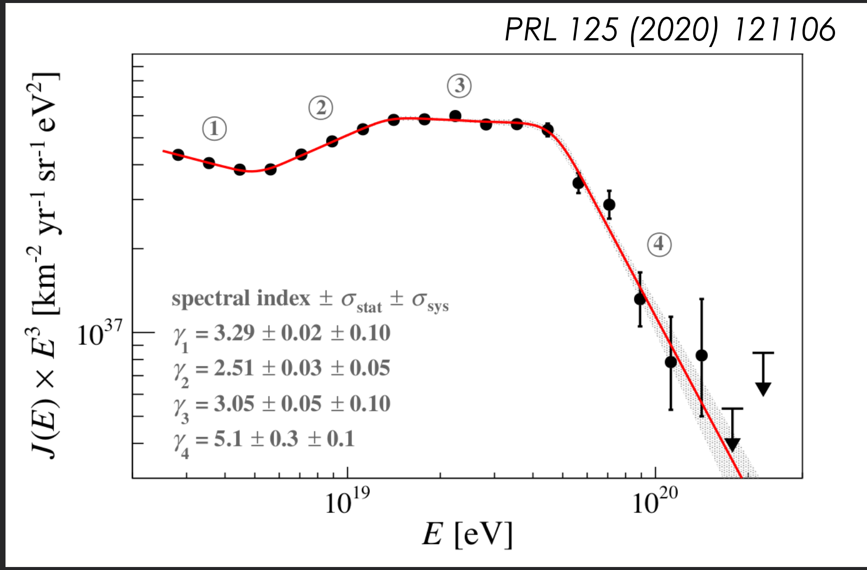


I. The Messengers

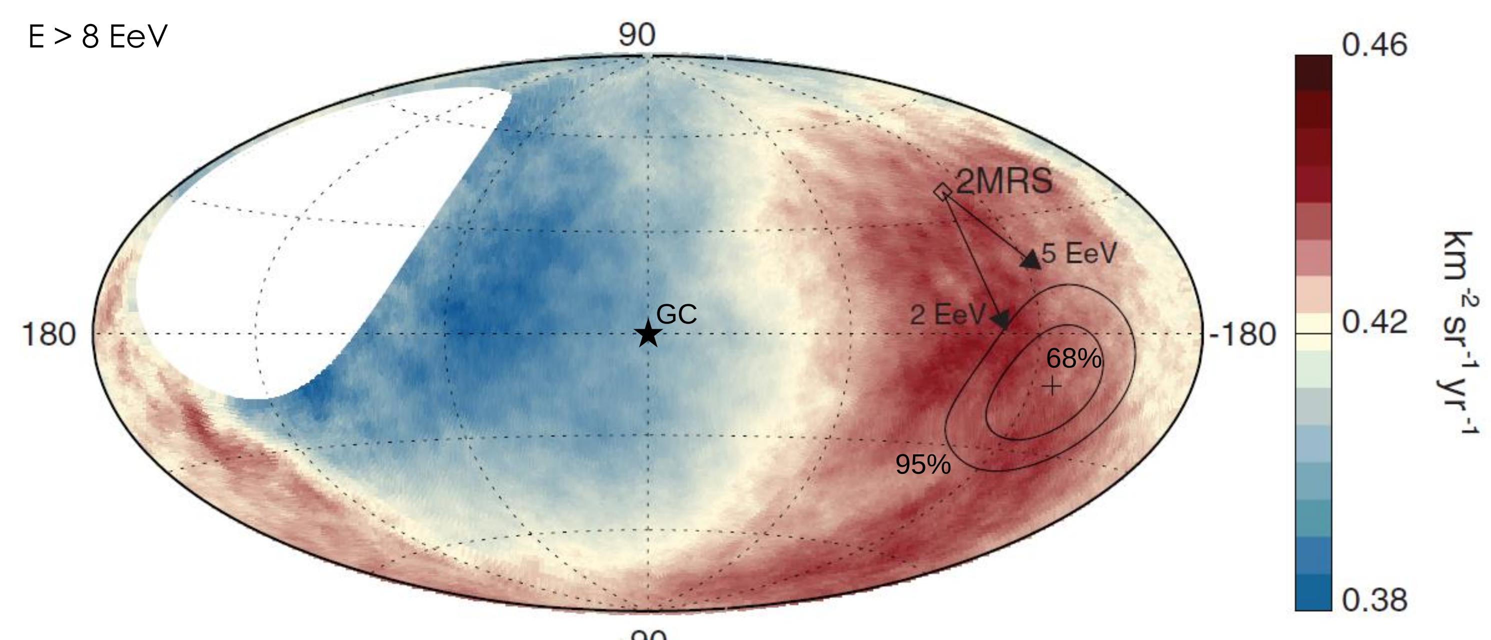
The Messengers | Cosmic Rays



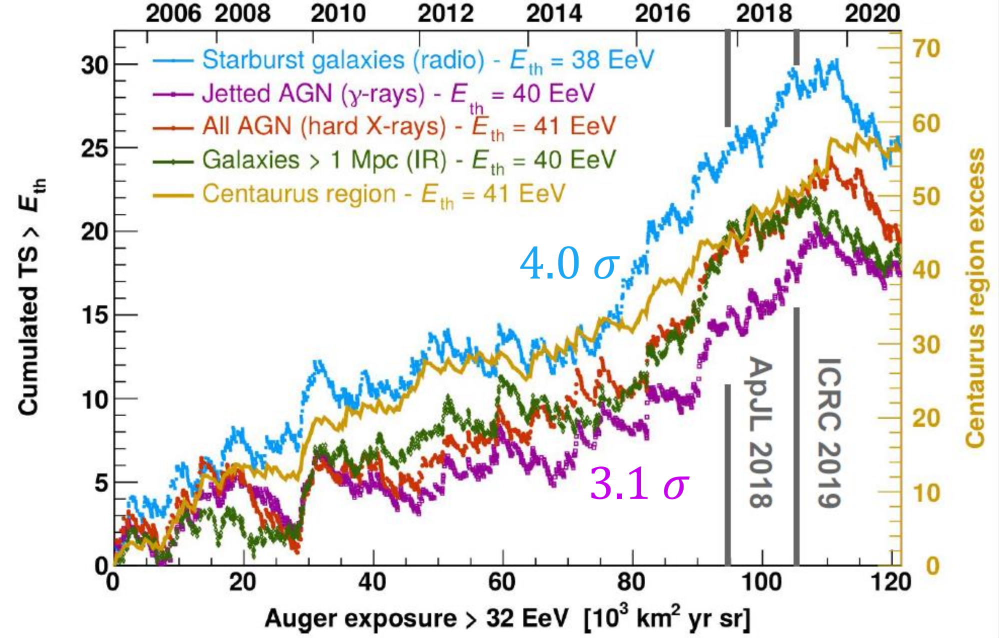
- Ionized nuclei (mostly protons) produced in the cosmos that reach E > 10^{20} eV
- Being charged cannot point back to the source: exception at E > EeV, but low flux (low statistics)
- Telescope Array & Auger
- Extragalactic at E ≳ 0.5 EeV
- Confirmed the cut-off above ~60 EeV



The Messengers | Cosmic Rays



Science 357, 1266 (2017)



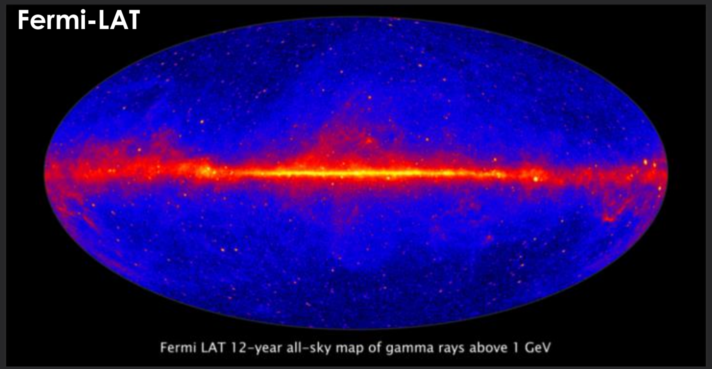
Engel, ICRC 2021

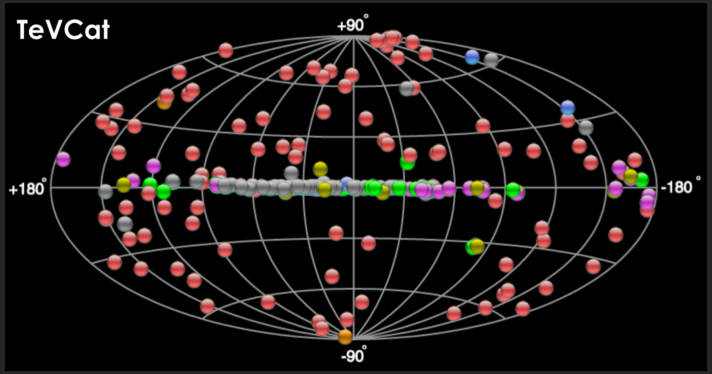
Detected UHECR flux is ~6% greater from one half of the sky than from the opposite one: dipole position suggest extragalactic origin

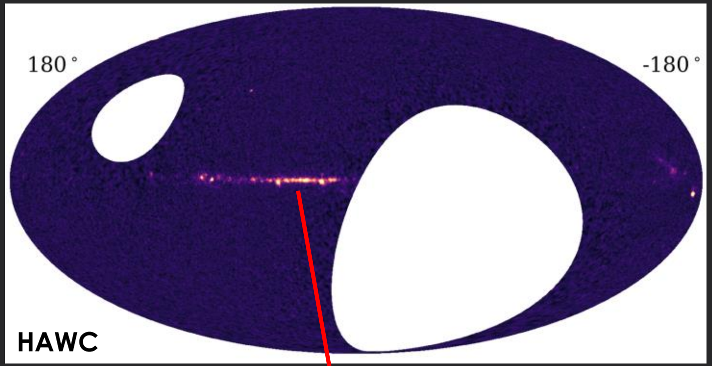
Catalogue search brought the first hint of sources: Starburst galaxies

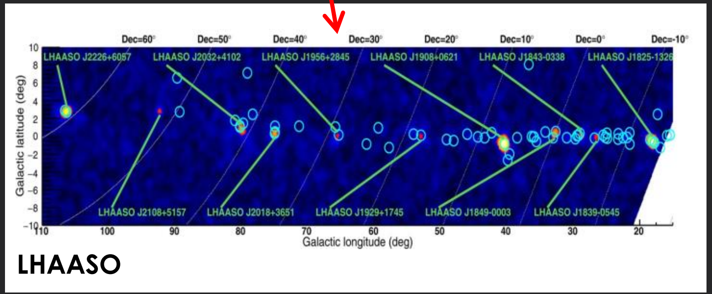
The Messengers | Gamma Rays

- Most energetic part of the electromagnetic spectrum
- Good coverage from GeV up to PeV: satellites (Fermi-LAT), ground arrays (MAGIC, H.E.S.S., VERITAS, CTA, HAWC, LHAASO)
- Key role in multi-messenger astronomy: X-rays also important for Galactic sources
- More than 200 sources detected at > TeV
- First detection of PeV photons from a source
- Drawback: <u>absorption at very high energies</u>

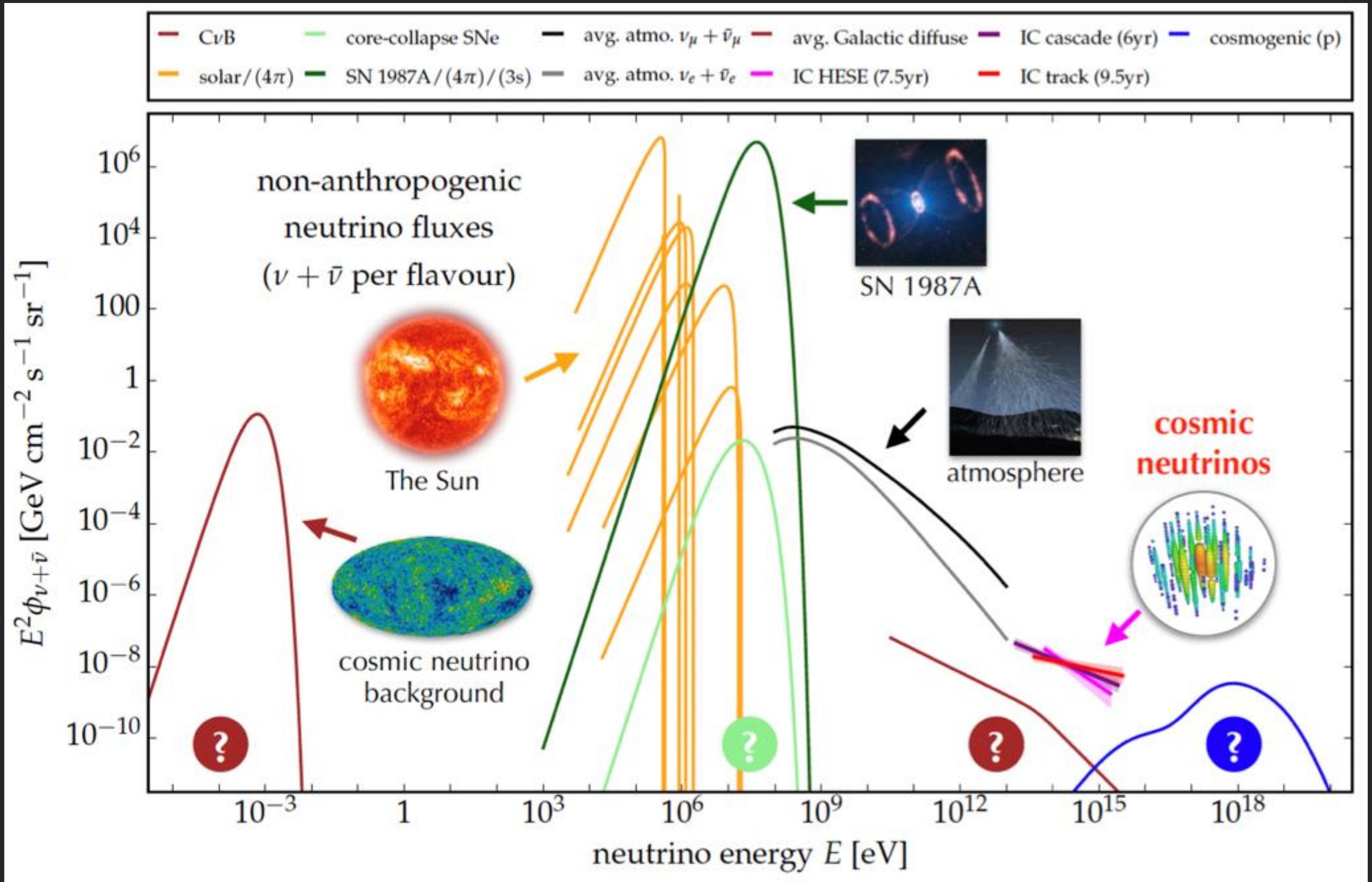








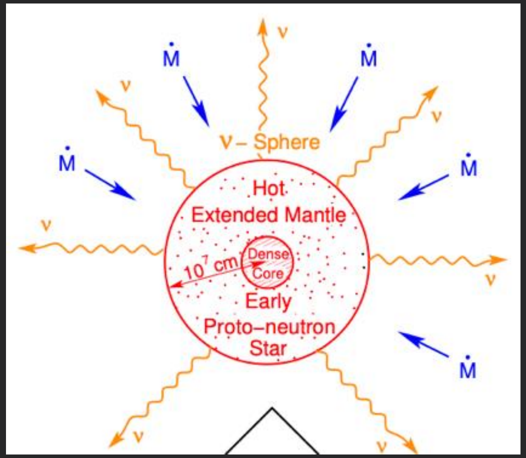
The Messengers | Neutrinos



- Neutrinos are abundantly produced and <u>can travel long distances without being absorbed nor deflected</u>
- Drawback: small cross-section, i.e., interact very rarely
- Require huge detection volumes: arrays of PMTs in natural media (water or ice)
- Neutrino telescopes: IceCube (South Pole), ANTARES (Mediterranean), KM3NeT (Mediterranean), GVD-Baikal (lake Baikal)

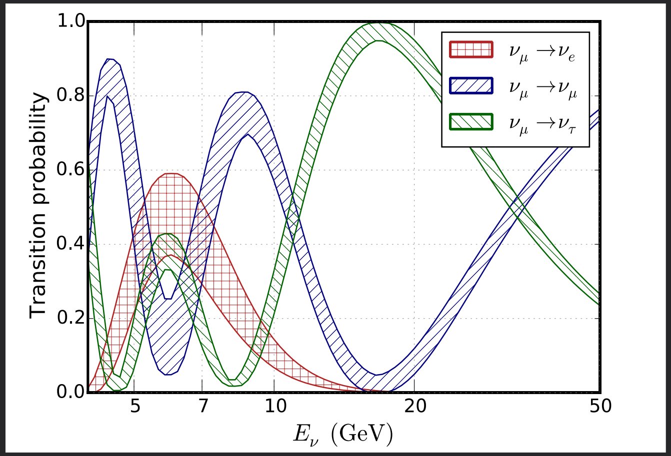
The Messengers | Neutrinos

Low Energy
~ MeV



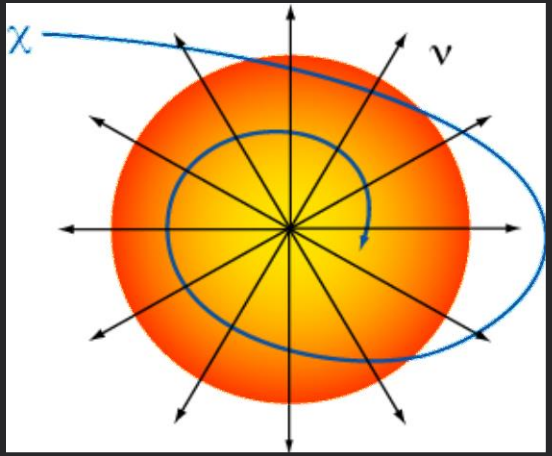
CCSN detection

Low Energy
> 10 GeV



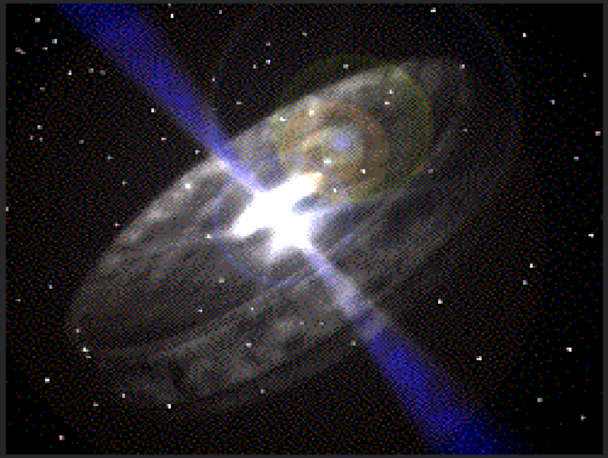
ν oscillations

Medium Energy
10 GeV < E_ν < 10 TeV



Dark matter search

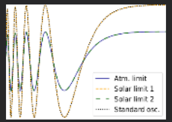
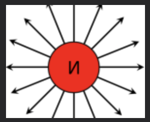
High Energy
E_ν > 1 TeV



ν from extra-terrestrial sources
Origin and production mechanism of HE CR

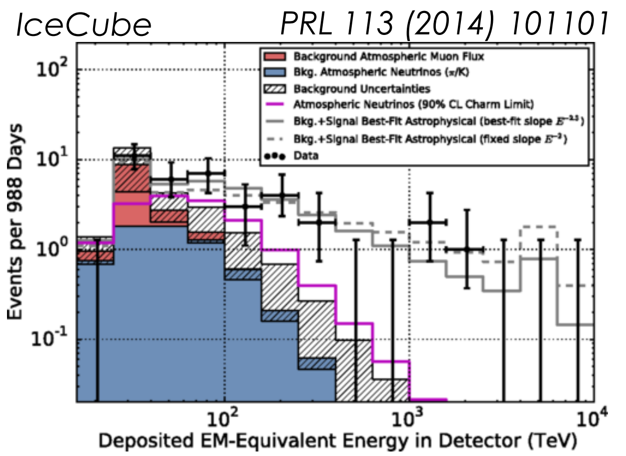
E

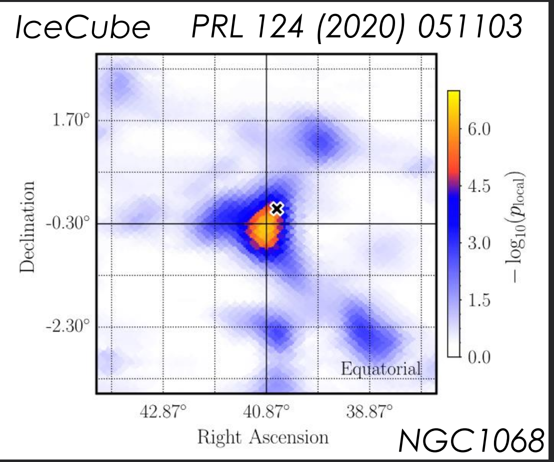
…and exotic searches

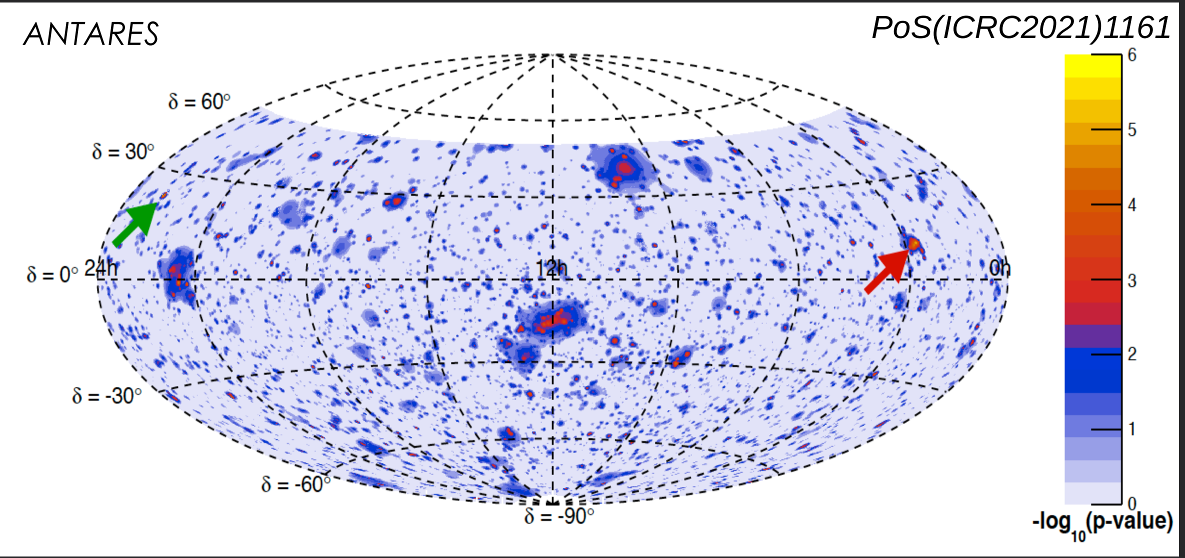




The Messengers | Neutrinos

- Diffuse flux of cosmic neutrinos detected in 2014: energy range 100 TeV-PeV
- Independent excess at 1.8σ measured by ANTARES
- No significant sources detected, yet several evidences: best is NGC 1068 (AGN) at 3σ
- TXS0506 blazar case discussed later

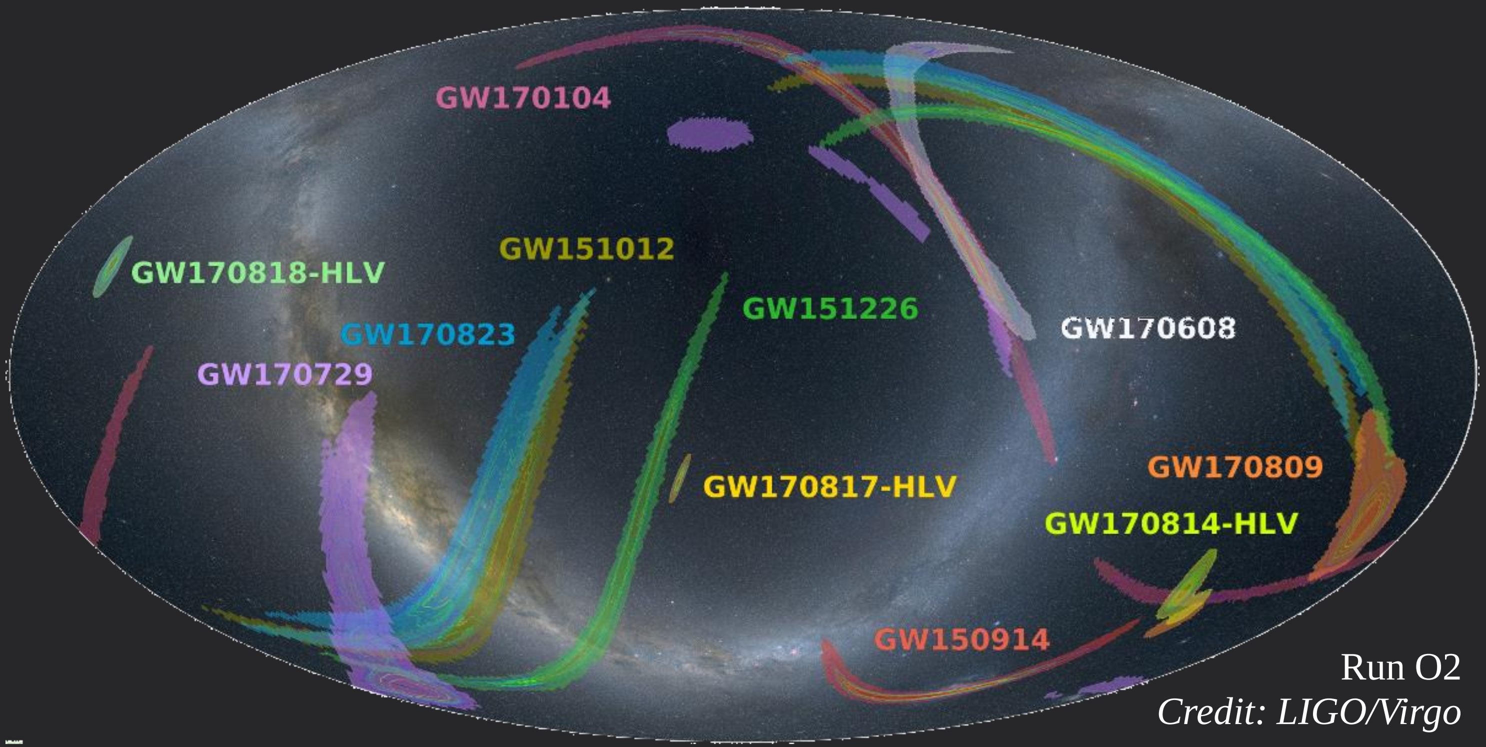






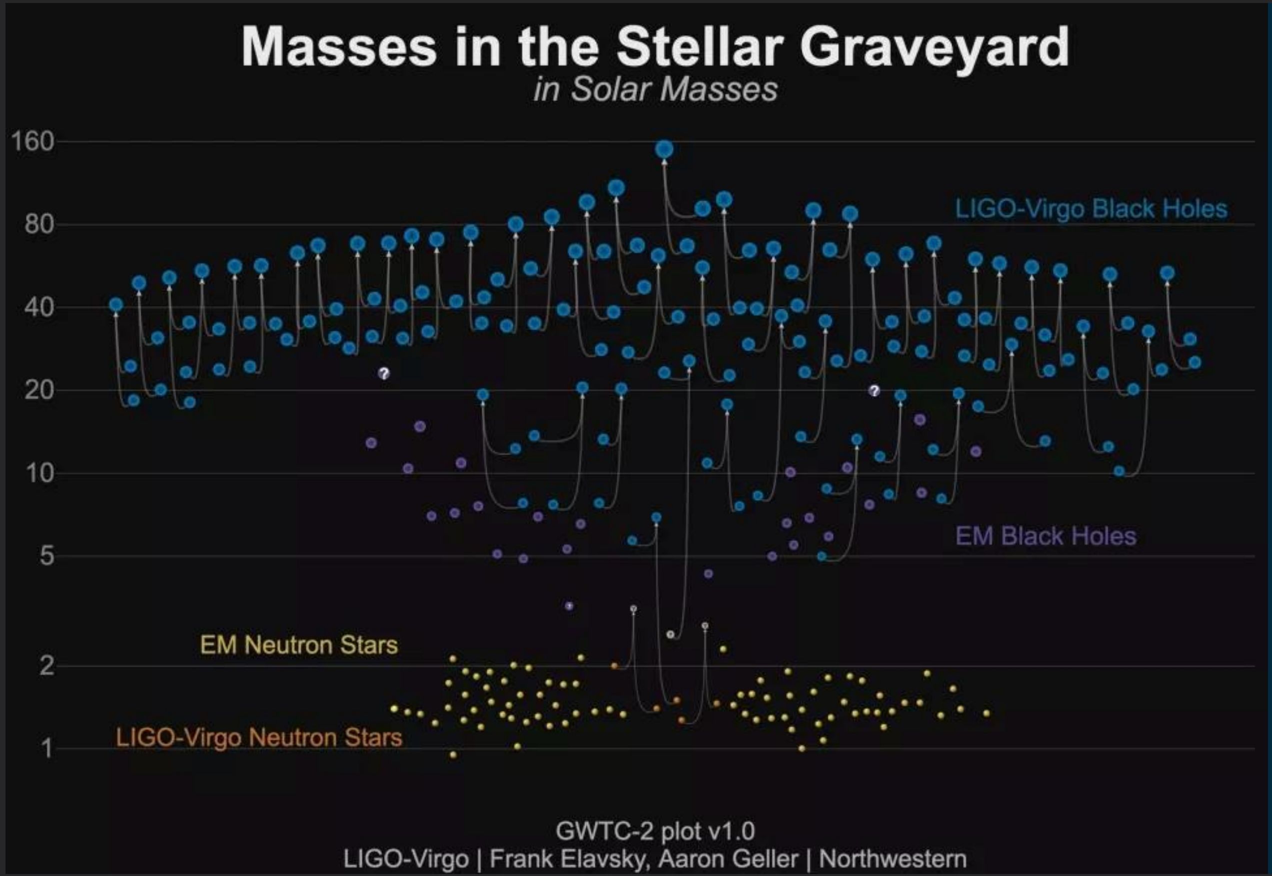
The Messengers | Gravitational Waves

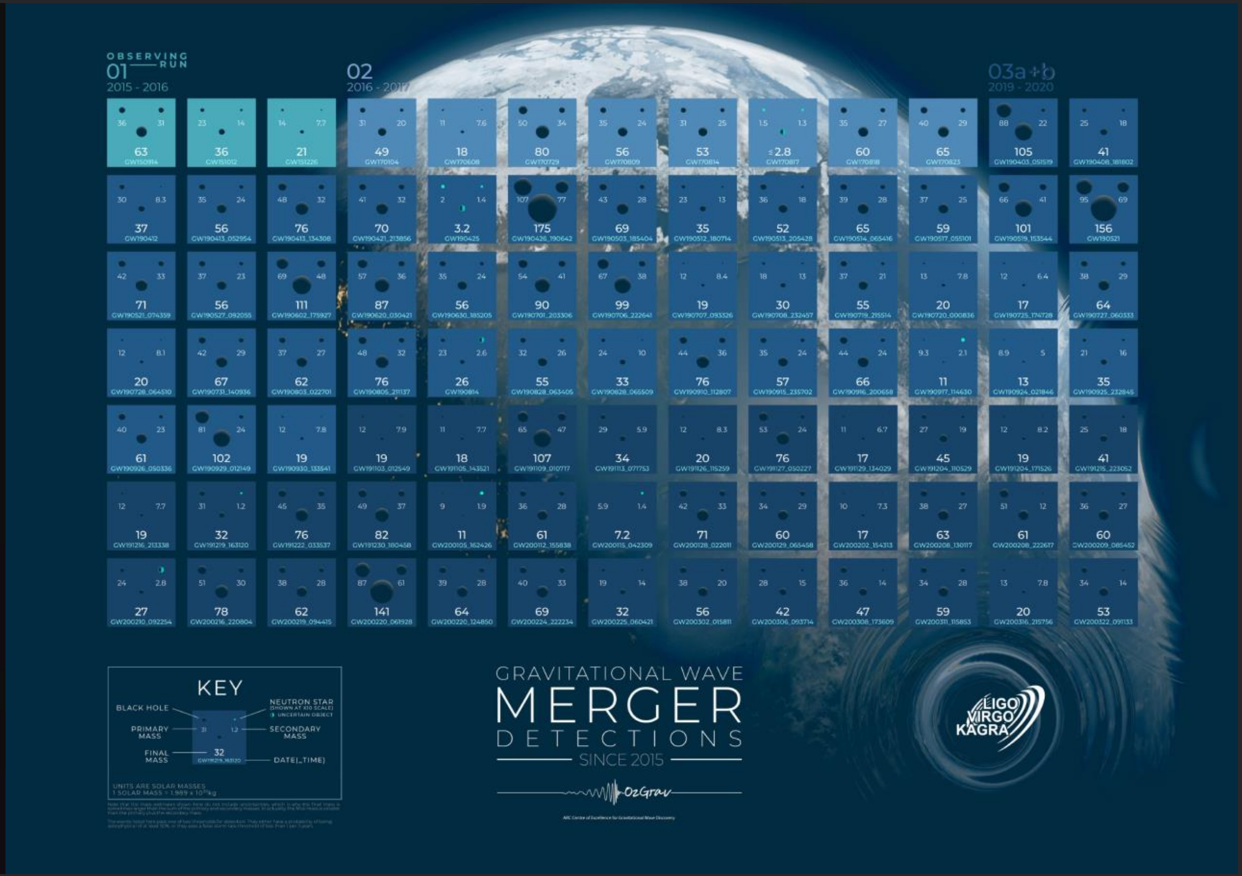
- Gravitational waves were predicted in 1916 by Einstein. However it took almost a century to detect them (2015).
- They are created by accelerated masses.
- Technically difficult to detect. It requires very precise instruments and very large bodies, e.g. merge of black holes.
- Localization improves with more detectors.



Run O2
Credit: LIGO/Virgo

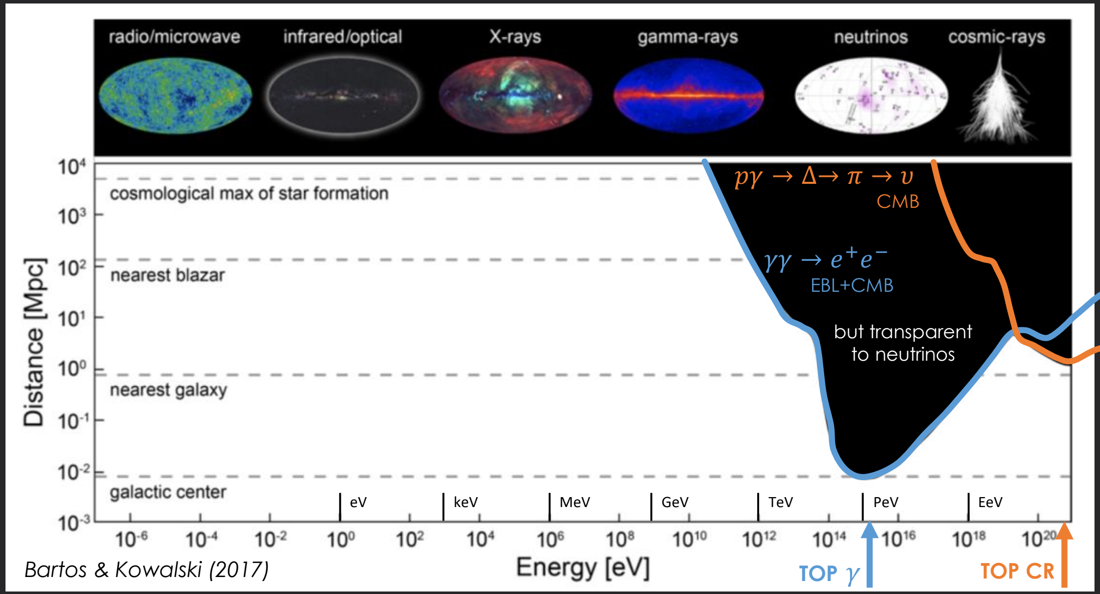
The Messengers | Gravitational Waves



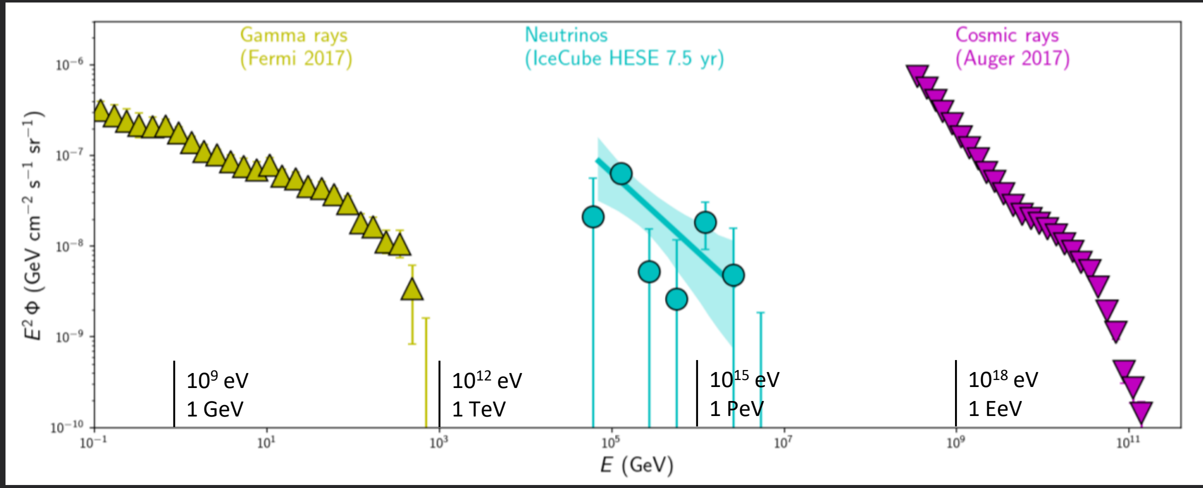


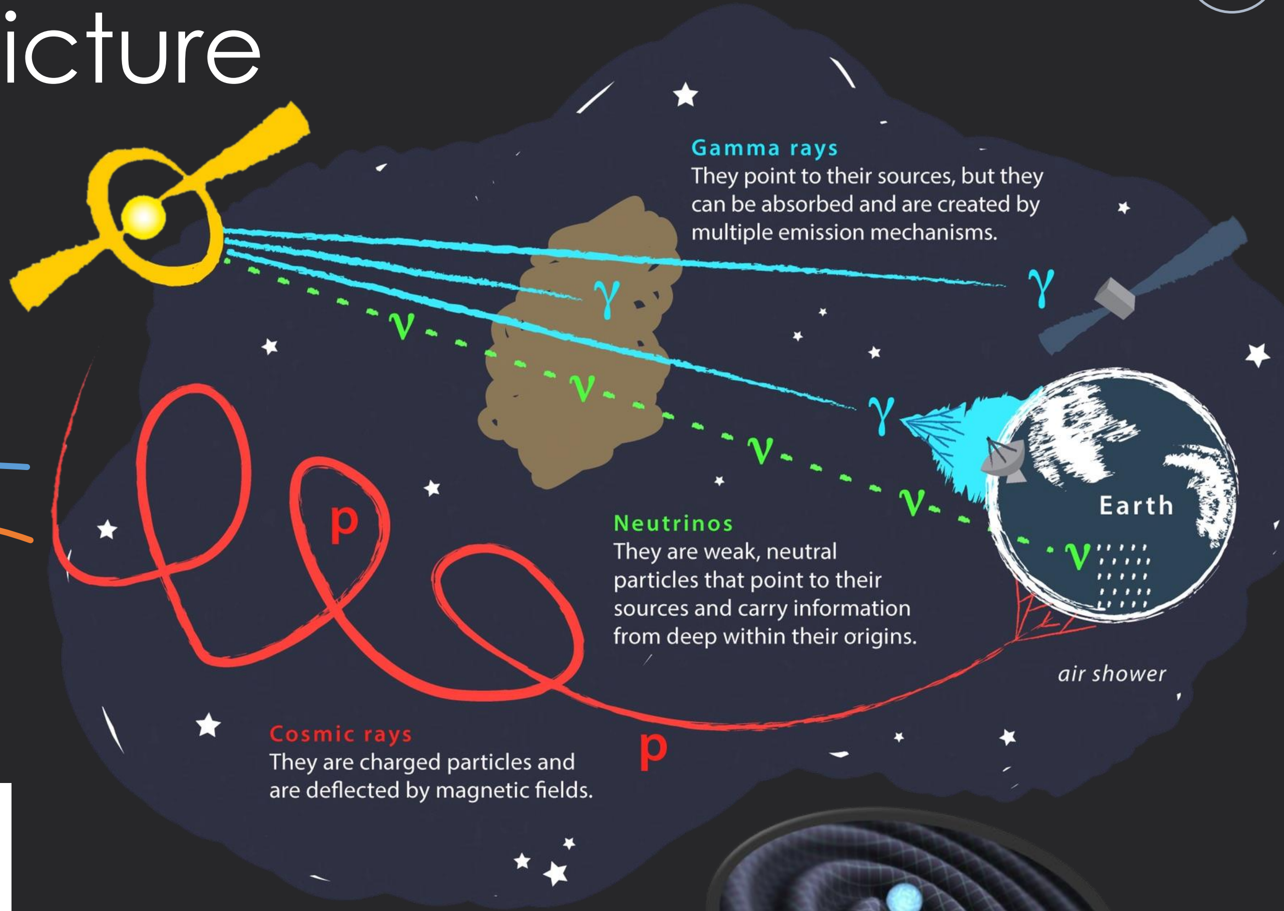
Already 3 catalogs published with almost 100 GW events detected

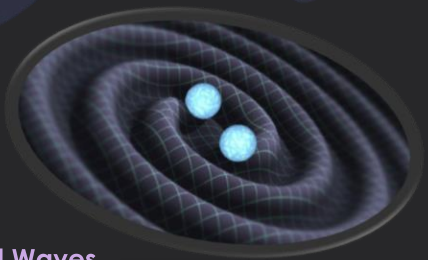
The Messengers | Full picture



Bartos & Kowalski (2017)







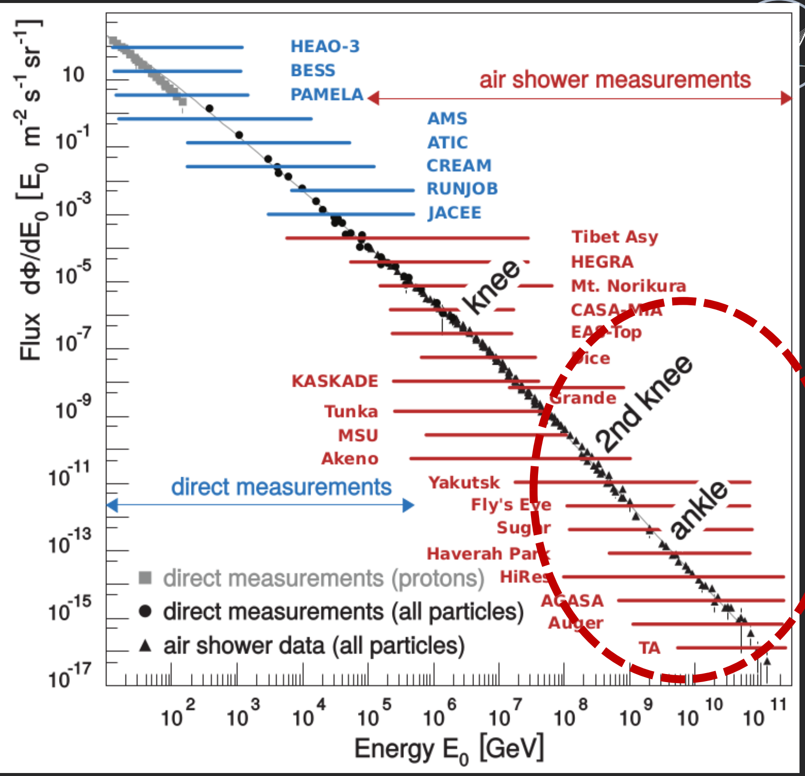
Gravitational Waves

They can complete the multi-messenger picture by being another detected counterpart in events were huge mases are strongly accelerated

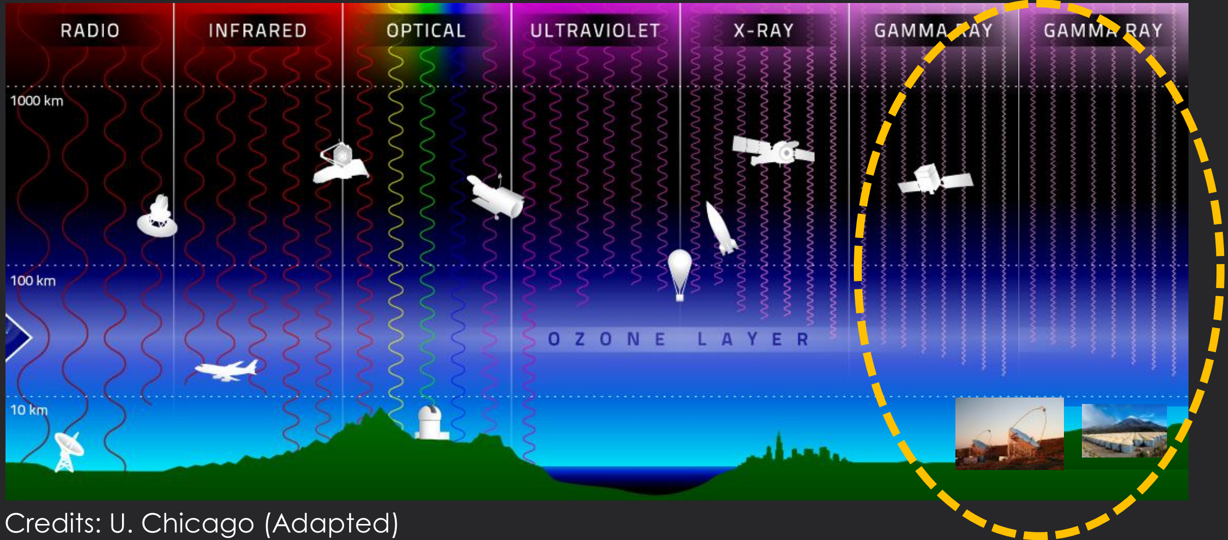
II. The Experiments

The Experiments

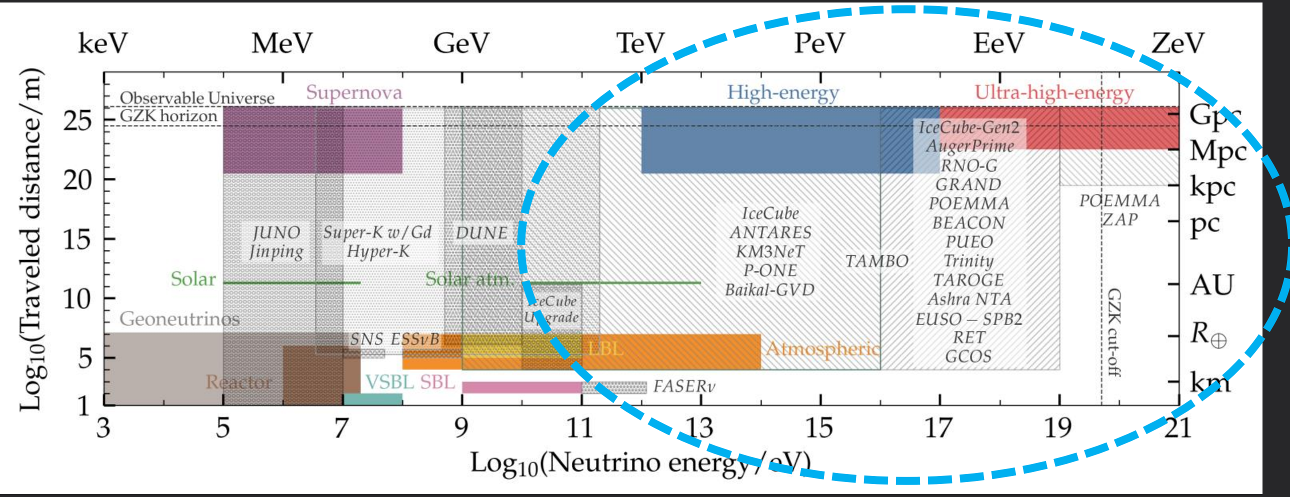
- Gamma rays @ GeV-TeV
  - Satellites
  - IACTs
  - Air Shower Arrays
- Cosmic Rays @ EeV
  - Air Shower Arrays
- Neutrinos @ >TeV
  - Neutrino Telescopes
  - Radio arrays
- Gravitational Waves



Adapted from
Prog. Part. Nucl. Phys., 63:293–338, 2009



Credits: U. Chicago (Adapted)



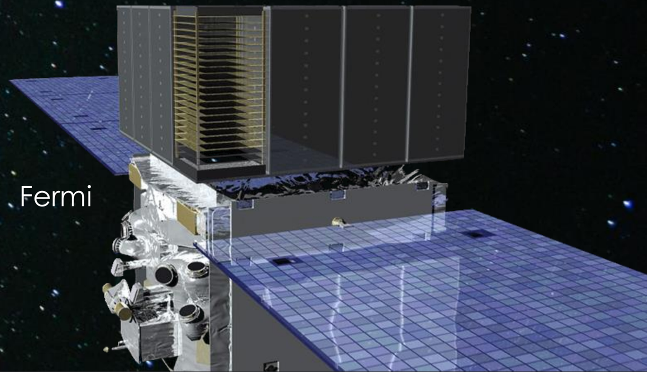
"High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper"
Ackermann et. al. (2022) [arXiv:2203.08096]

The Experiments | γ-ray: Satellites

- Multiple technologies:
  - X-ray (Galactic sources): coded masks
    Swift BAT: 15 – 150 keV
  - γ-ray: gamma trackers
    Agile GRID: 30 MeV – 50 GeV
    Fermi LAT: 20 MeV – 300 GeV
- Other instruments on board (Swift XRT, Super-AGILE, Fermi GBM,…)
- (Mostly) continuous operation
- Wide FoV instruments & full sky coverage
- Subdegree angular resolutions (*)
- Size limitations → constrained to lower energies

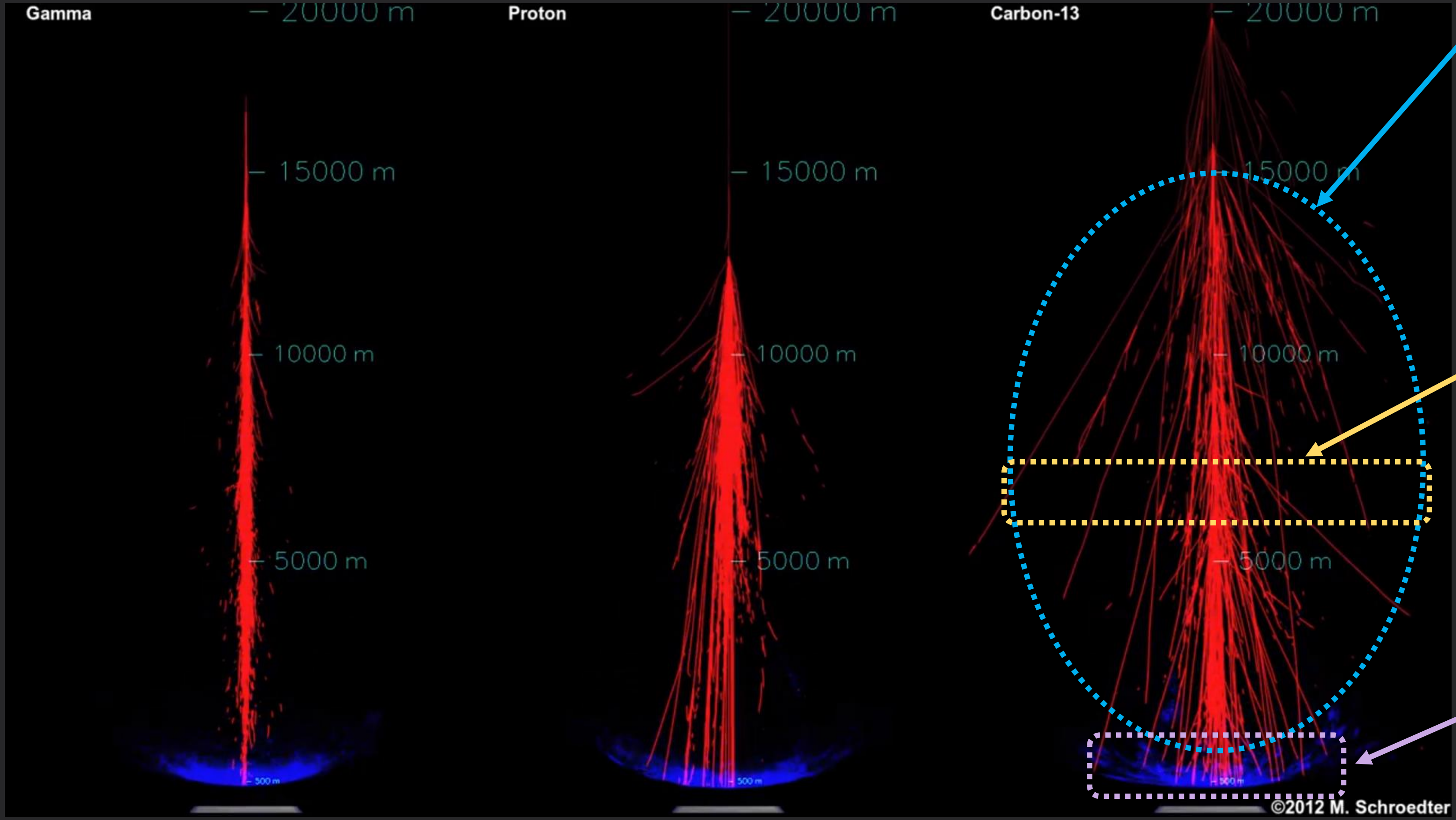

Swift (X-rays)


Agile


Fermi

(*) strongly energy dependent

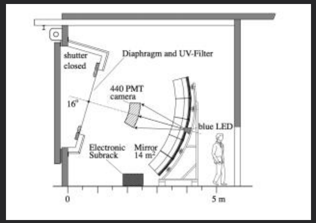
The Experiments | Air Showers



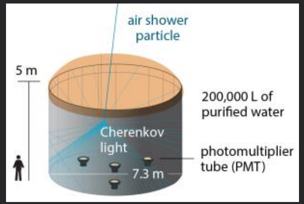
(400 GeV)

You can either detect:

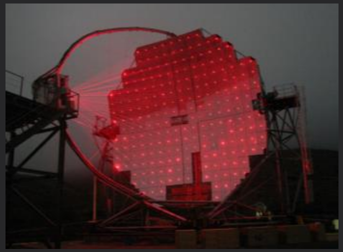
- Fluorescence: omnidirectional (wide FoV), "slow" pulse (~µs)



- Charged particles: requires to be reached by the shower



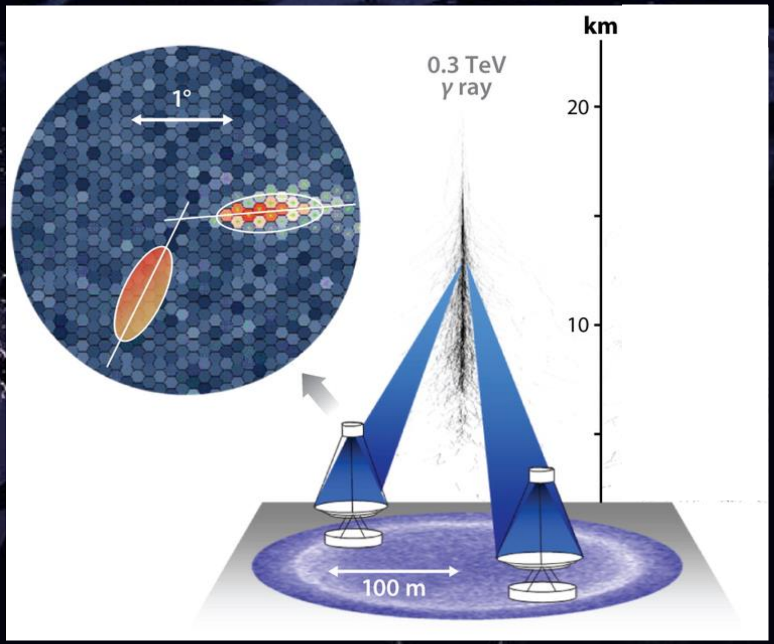
- Cherenkov light: directional (narrow FoV), "fast" pulse (~ns), require night sky



- Radio pulses: above 100 PeV, geomagnetic deflection of charged particles (important only in air) and the Askaryan effect both mostly over e^+/e^- pairs

The Experiments | γ-ray: IACTs

Arrays of Cherenkov Telescopes

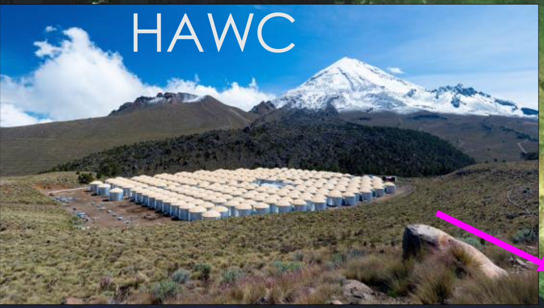


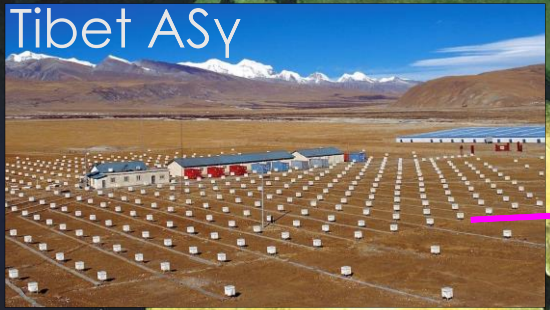
- GeV – TeV range

H.E.S.S.	30 GeV – 10 TeV
VERITAS	100 GeV – 30 TeV
MAGIC	50 GeV – 30 TeV

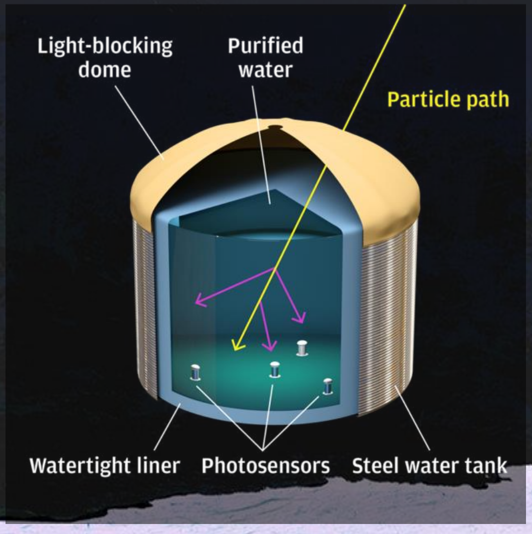
- Narrow FoV instruments (< 5°)
- Subdegree angular resolutions (< 0.1°)
- Need good weather & dark nights
- Pointing instrument: limited coverage

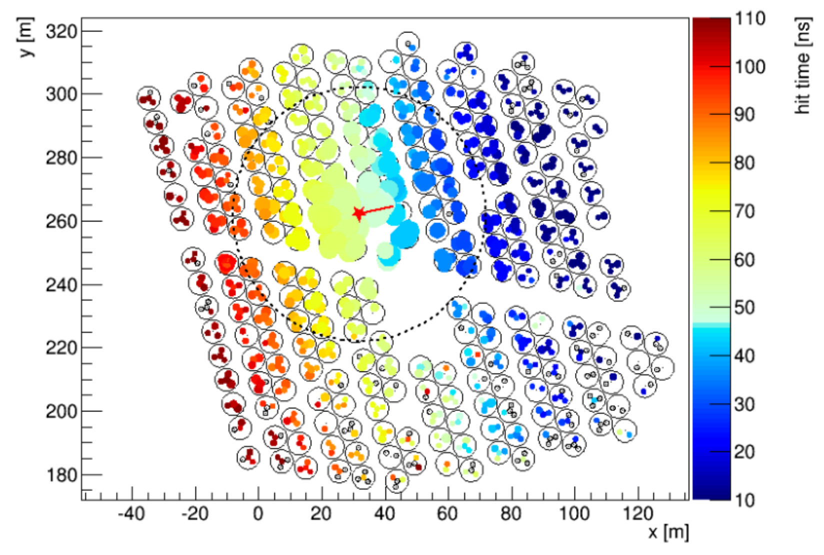
The Experiments | γ-ray: Air Shower Arrays





Arrays of Water Cherenkov Tanks



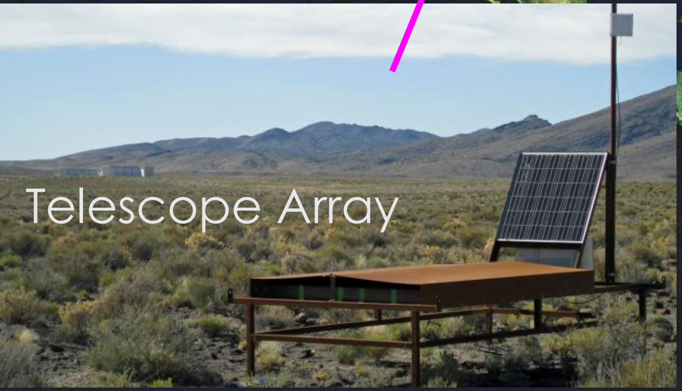


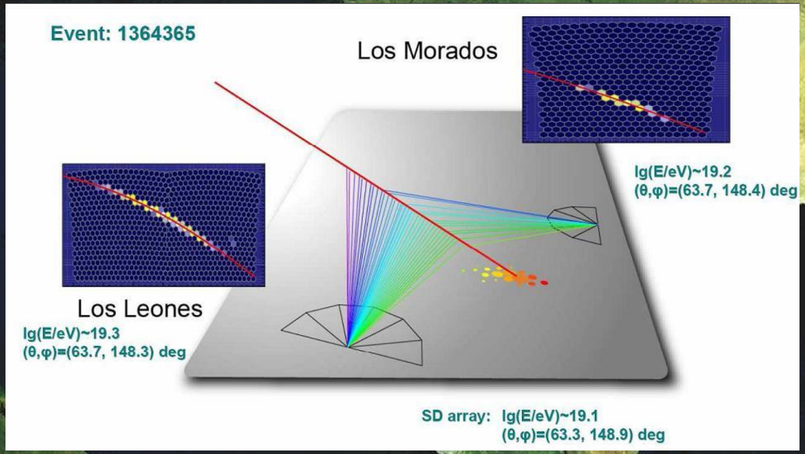
- TeV – PeV range

Tibet ASγ	1 TeV –	1 PeV
HAWC	100 GeV –	100 TeV
LHAASO	100 GeV –	1 PeV

- Wide FoV instruments (2 sr / half sky)
- Subdegree angular resolutions (< 0.3°)
- (Mostly) continuous operation
- Sky at declination coverage

The Experiments | CR: Air Shower Arrays





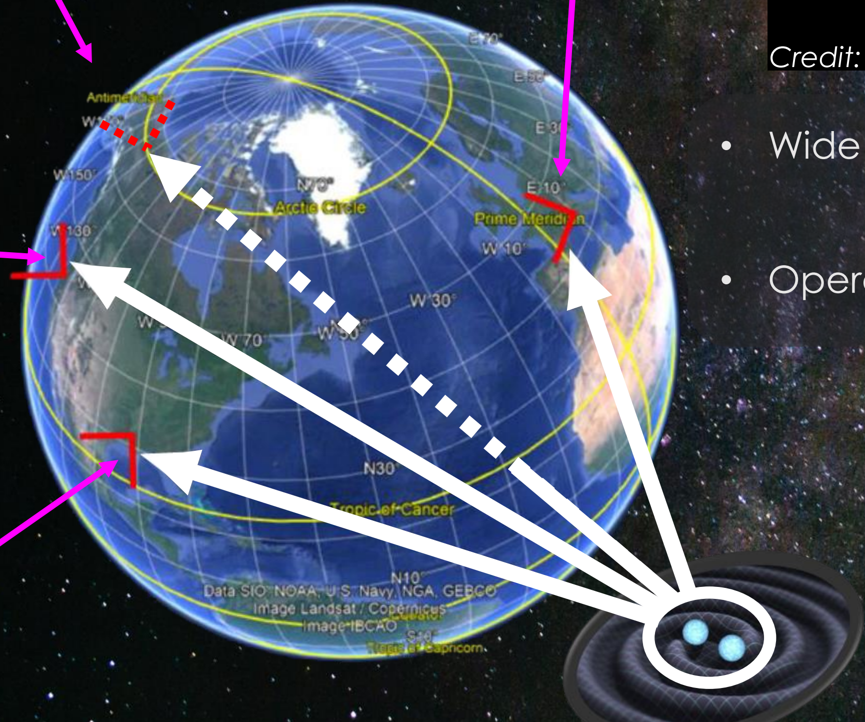
Arrays of Water Cherenkov Tanks
+
Fluorescence Telescopes

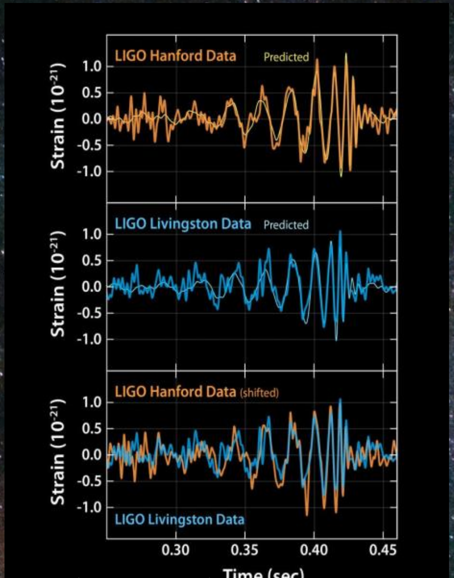
- PeV – EeV range

TA	4 PeV – 100 EeV
Auger	6 PeV – 100 EeV

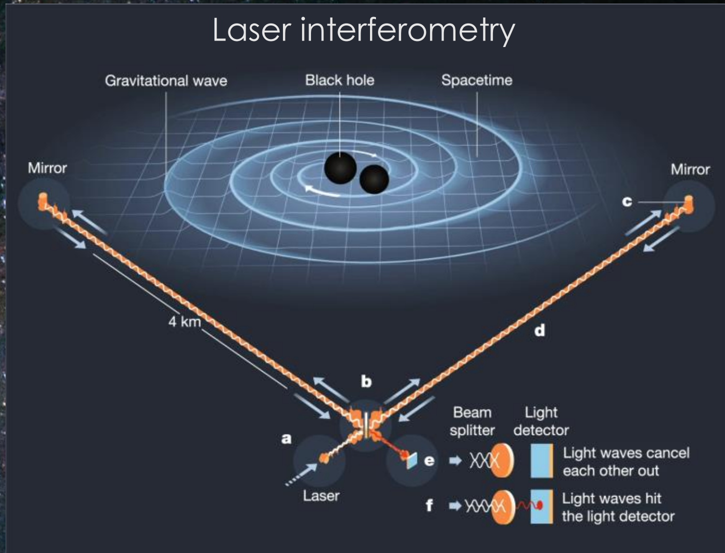
- Wide FoV instruments (2 sr / half sky)
- Subdegree angular resolutions
- (Mostly) continuous operation
- Sky at declination coverage

The Experiments | Gravitational Waves





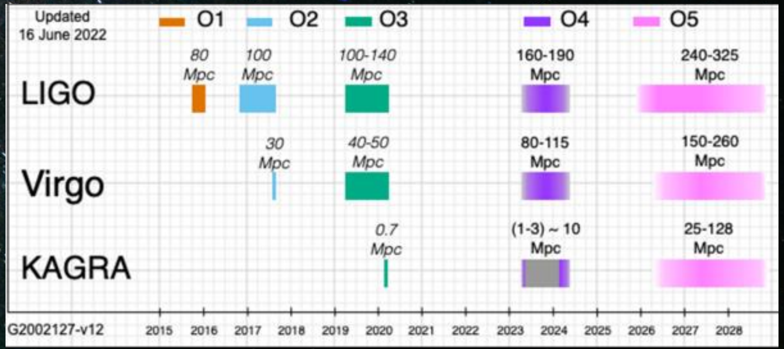
Credit: LIGO/Virgo



Nature 568, 469–476 (2019)

- Wide FoV instruments (whole sky)
- Operation in runs

- Bad angular resolutions:
  O(100) – O(1000) sq. deg.
  Best ~30 sq. deg. for GW170817 (3 detectors)



The Experiments | Neutrino Telescopes

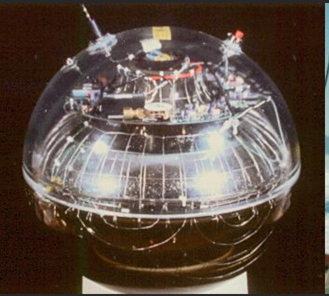
The recipe: (Markov, ICHEP 1960)

- Use large dense transparent volumes (water or ice) to target neutrino interactions

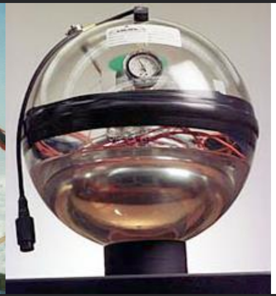
Cosmic neutrino flux → 1 km^3

- Monitor them with light sensors to detect the Cherenkov light emitted by the outgoing particles

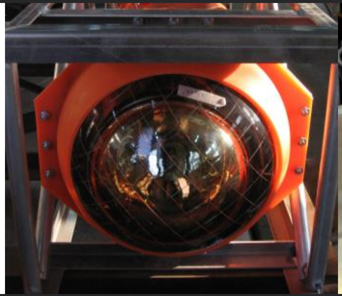
Photomultiplier tubes (PMTs)


DUMAND


Baikal


AMANDA


IceCube


NEMO


ANTARES


GVD


KM3NeT

You got yourself a huge tracking calorimeter

Long story short…

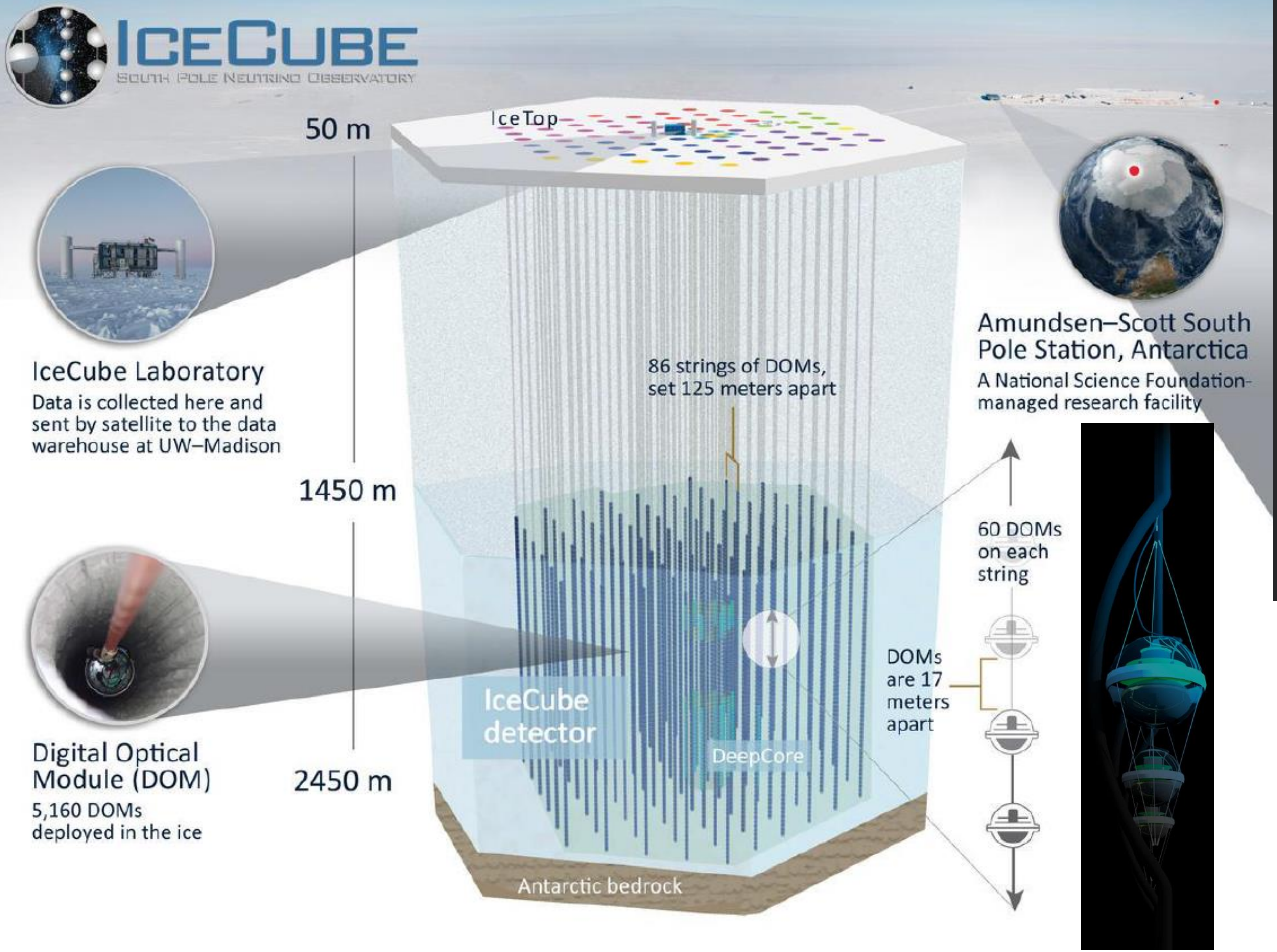
The Experiments | Neutrino Telescopes

- Operating in full configuration:
  - ANTARES (*) 0.01 km^3
  - IceCube 1 km^3
- Under construction:
  - KM3NeT 1 + 0.006 km^3
  - Baikal GVD ~1 km^3
- In planning phase:
  - IceCube-Gen2 ~8 km^3
  - P-ONE >1 km^3

(*) Shut down Feb'22

Largest Neutrino Telescope so far

Built between 2005 – 2011 around its predecessor Amanda (d. 2009)



IceTop: 1 km^2 air shower array

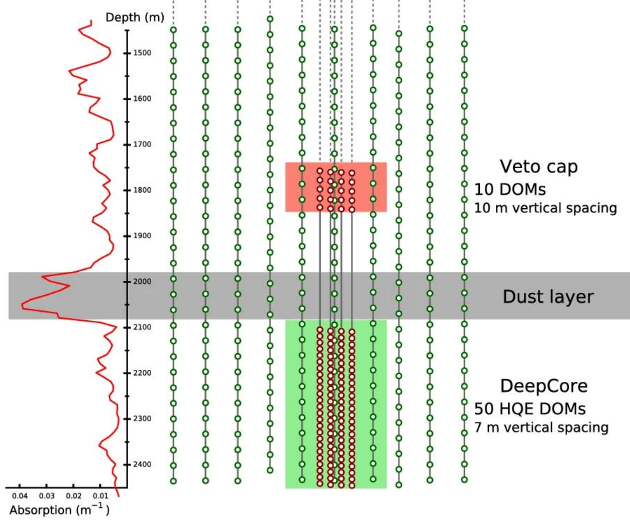
- PeV – EeV range
- 162 ice tanks
- CR studies together IceCube array

IceCube array: 86 strings

- TeV – PeV range
- String spacing 125 m
- DOM spacing of 17 m

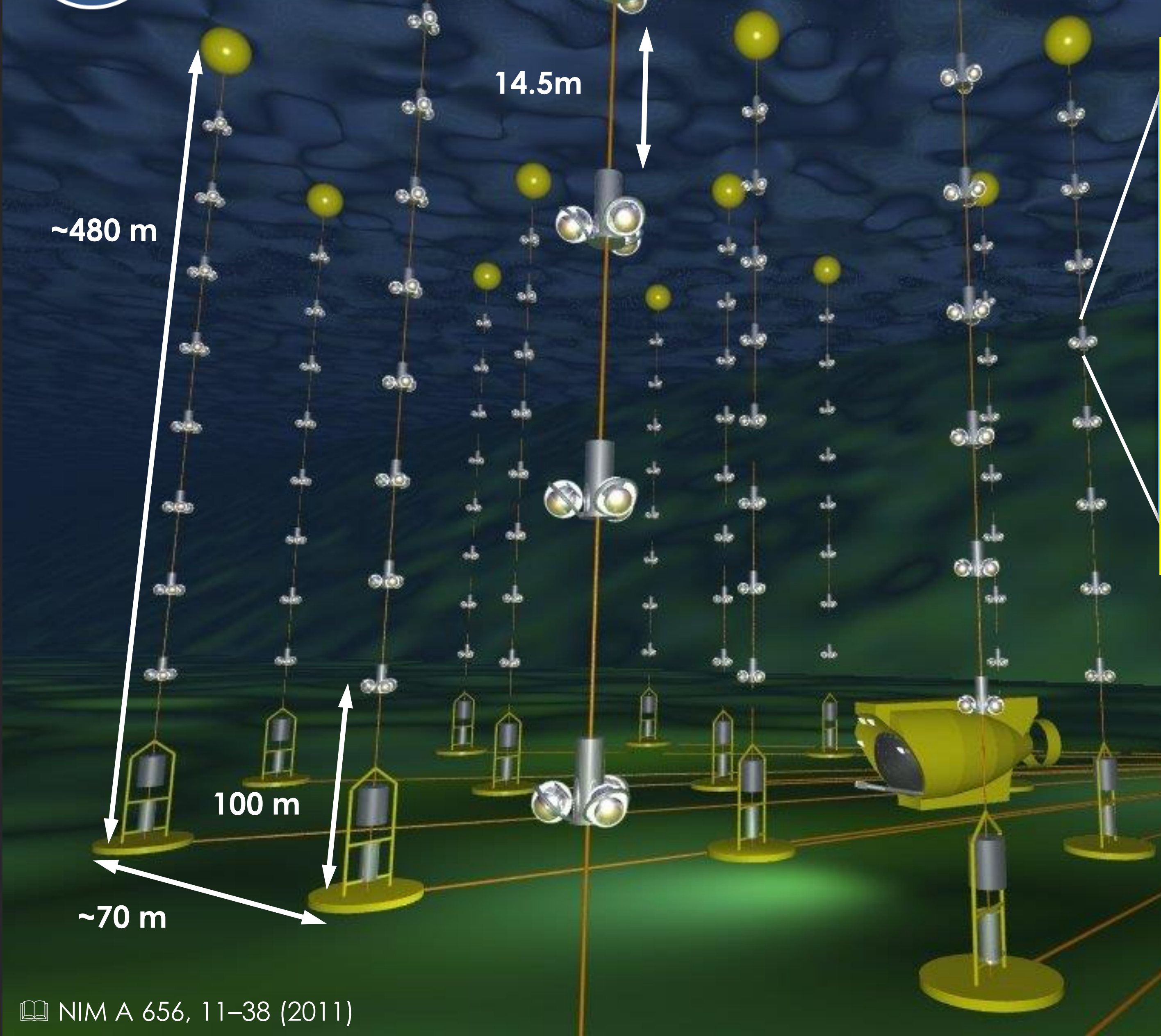
DeepCore: 8 strings

- GeV range
- String spacing ~70 m
- DOM spacing of 7 m + veto cap



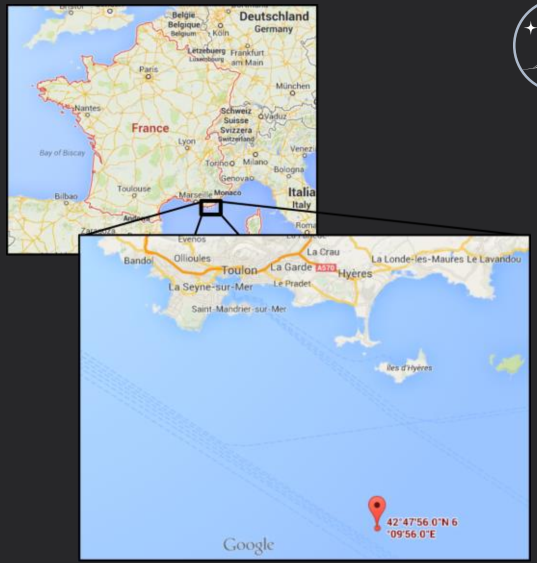
ANTARES

- String-based detector;
- Downward-looking (45°) PMTs;
- 2475 m deep;



- 12 detection lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

📖 NIM A 656, 11–38 (2011)

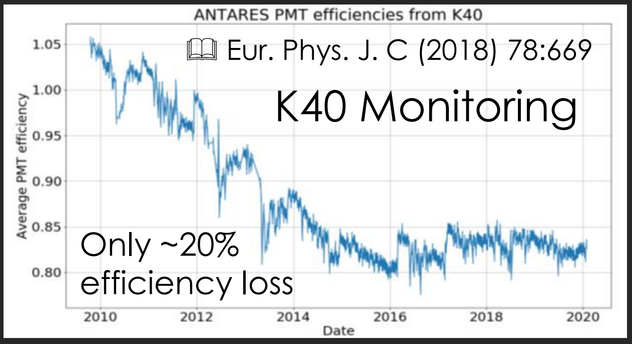


2006 | First detector line
2007 | Continuous data taking
2008 | Detector completed (12 lines)
2022 | Data taking terminated

More than 15 years taking data!

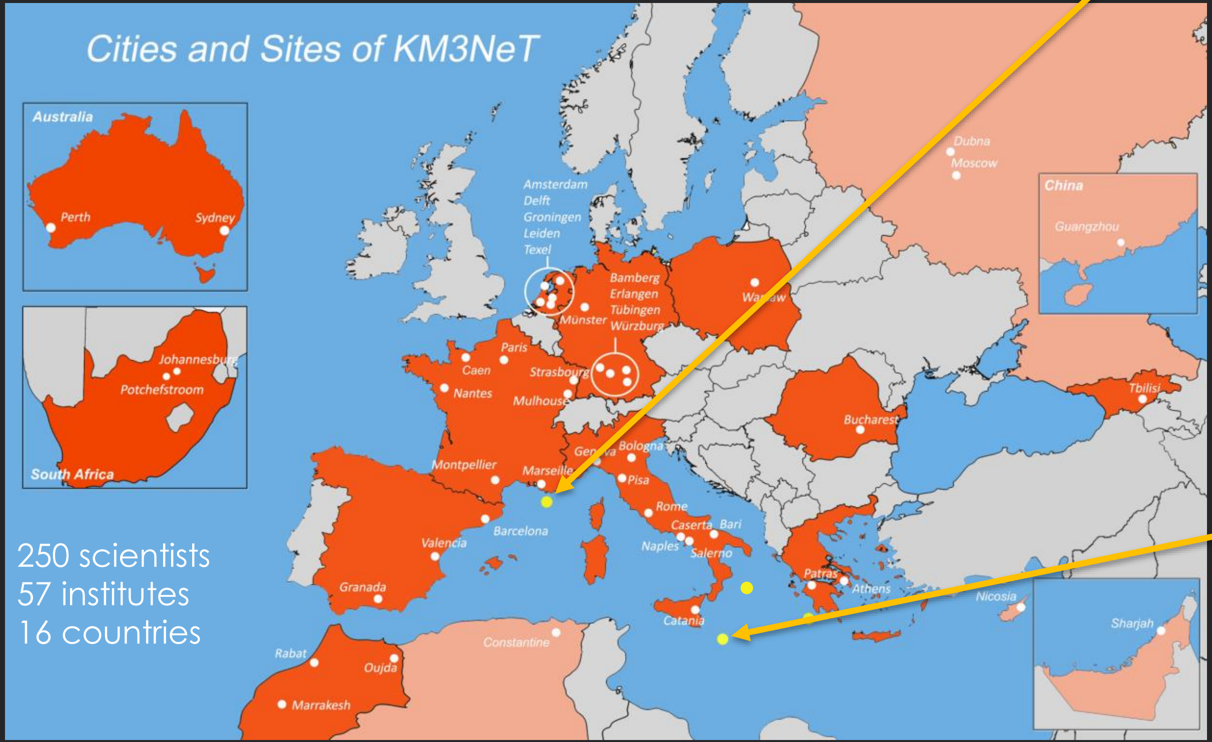
TeV – PeV range

Largest NT on North Hemisphere for years

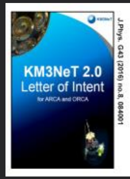


KM3NeT

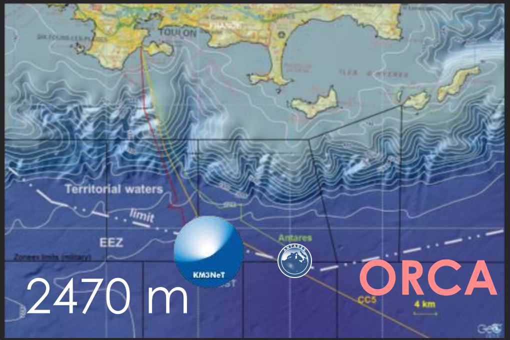
Multi-site, deep-sea infrastructure
Single collaboration, Single technology
Two outstanding physics cases



250 scientists
57 institutes
16 countries

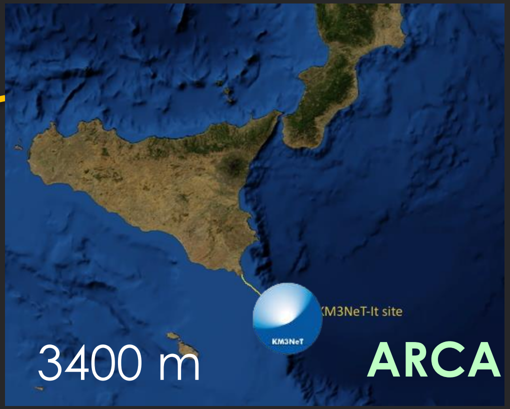


📖 KM3NeT 2.0: Letter of Intent
http://dx.doi.org/10.1088/0954-3899/43/8/084001
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

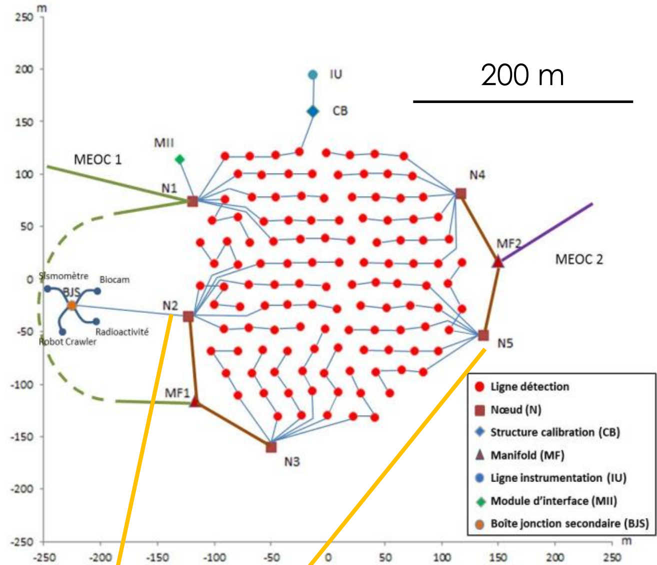


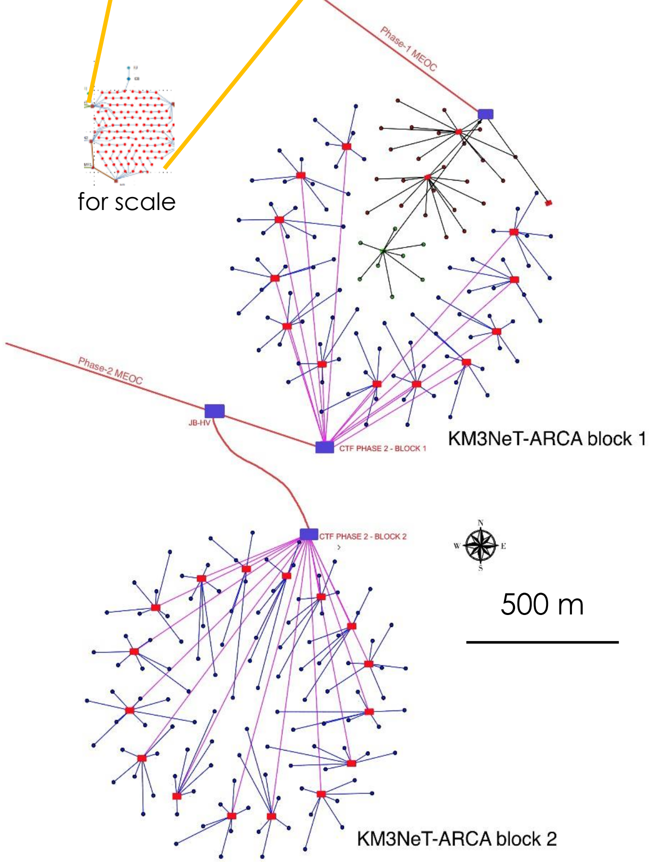
Oscillation Research with Cosmics in the Abyss

	ORCA	ARCA
Strings	115	115 × 2
String spacing	20 m	90 m
DOM spacing	9 m	36 m
Instrumented mass	7 Mton	500 × 2 Mton
Energy range	GeV	TeV – PeV

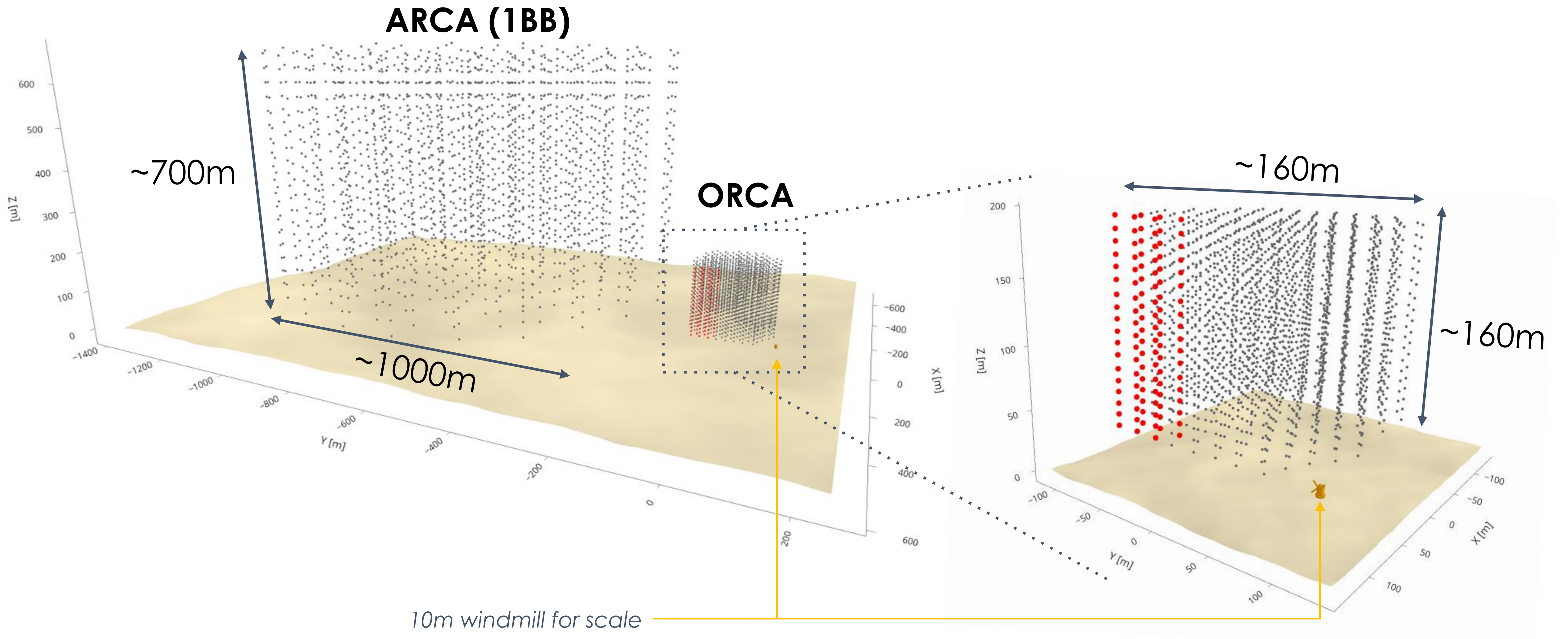


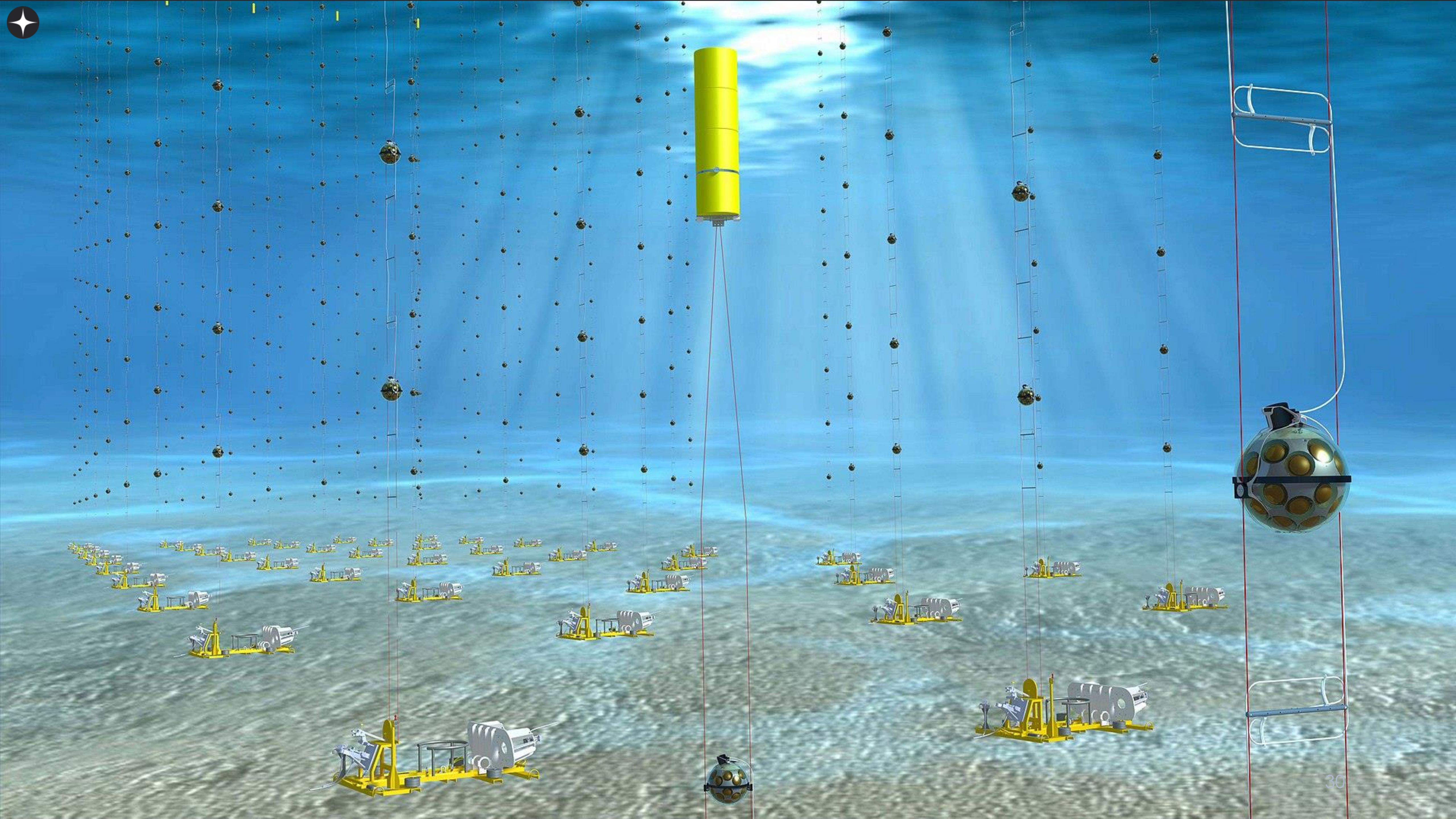
Astroparticle Research with Cosmics in the Abyss





The Experiments | KM3NeT: ARCA vs ORCA

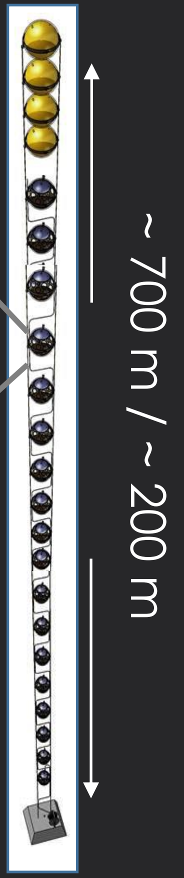




The Experiments | KM3NeT: Technology

Digital Optical Module (DOM)

- Multi-PMT : 31 x 3'' PMTs
- 3 x cathode area w.r.t. ANTARES OM
- Single photon counting
- Directional information
- Inspiring design for IceCube-Gen 2 & Hyper-K mPMT
- Gbit/s on optical fibre
- Positioning & timing



Detection Unit (DU)

- 18 DOMs
- Low-drag design

Modular deployment

- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reusable

The Experiments | KM3NeT: Deployment

1. Furling
2. Deployment
3. Connection
4. Unfurling

https://www.youtube.com/watch?v=TMjEQKshOqw

https://www.youtube.com/watch?v=71T5M-JtcRQ

ARCA19 *(14/06/2022)*

KM3NeT Neutrino @km3net · Jun 14

‼️ KM3NeT/ARCA19 is a fact ‼️

The campaign was a complete success, everything was accomplished as foreseen. In only two weeks we more than doubled our #detector!

We now have
2 new junction boxes perfectly working
11 new lines + the 8 we already had

Let's catch some #neutrinos!

22 46

https://twitter.com/km3net/status/1536748657977851904

ORCA10 *(23/11/2021)*

KM3NeT Neutrino @km3net · Nov 23, 2021

🎉WE HAVE SUCCESSFULLY DEPLOYED 4 NEW **ORCA** LINES🎉

Congratulations and many thanks to the teams who made this possible!

Due to the bad weather we stopped the sea operation, and will deploy more lines next time

Happy ORCA10 data taking!
(PS: note the 10 peaks Jürgen points at)

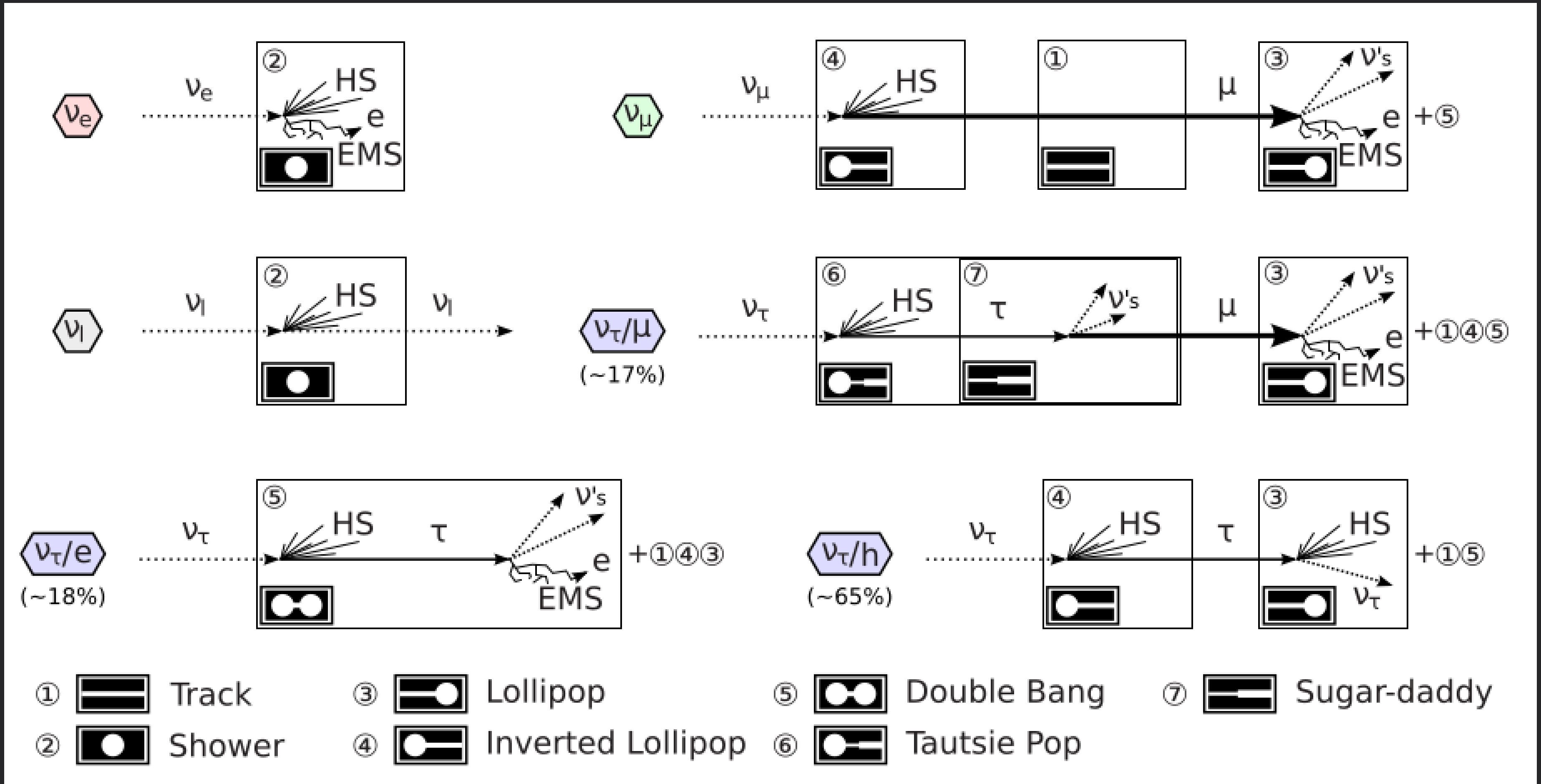
18 36

https://twitter.com/km3net/status/1463067300777631744

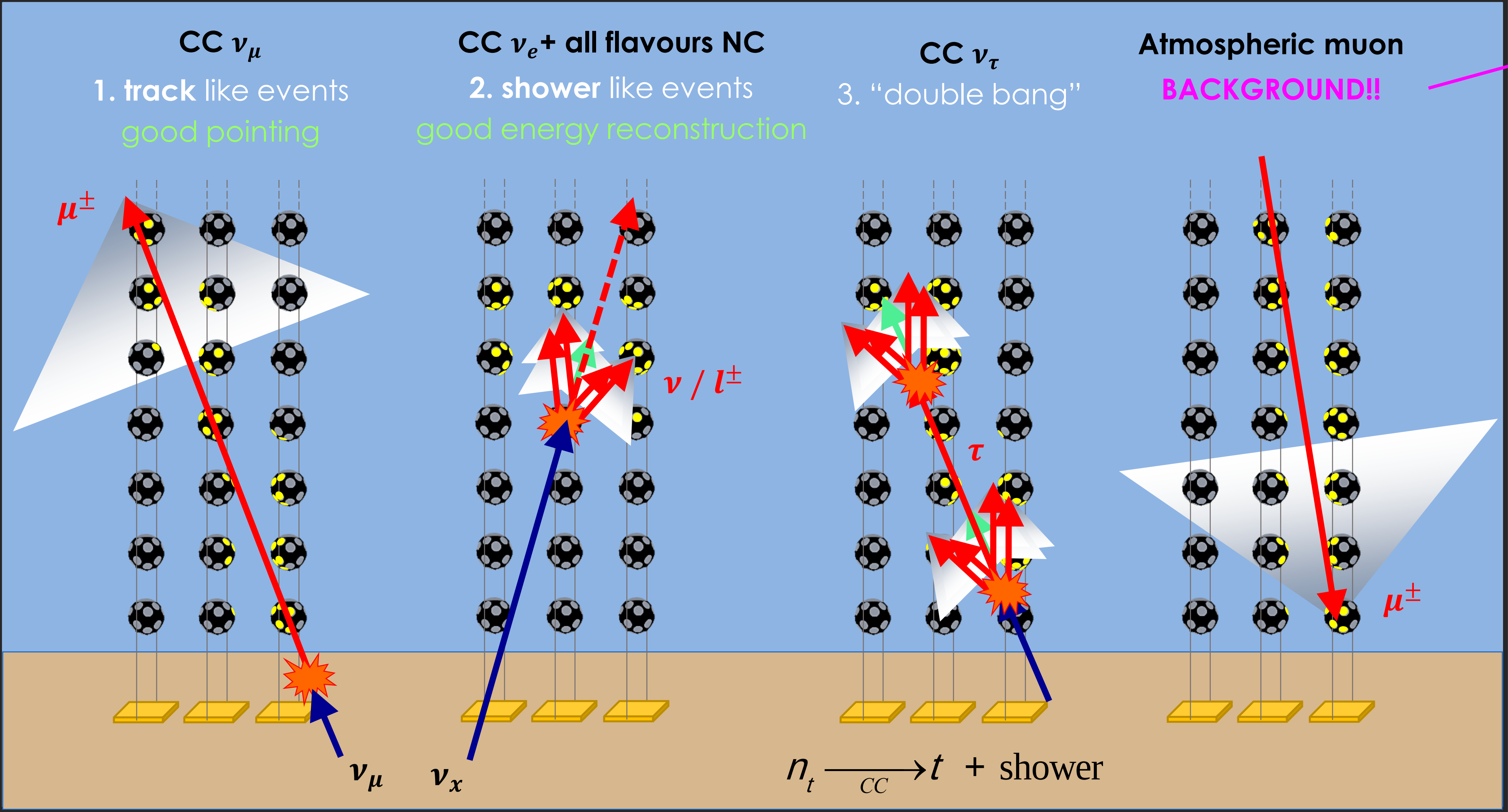
Plus a recent sea operation adding 4 DUs (Neutrino 2022)

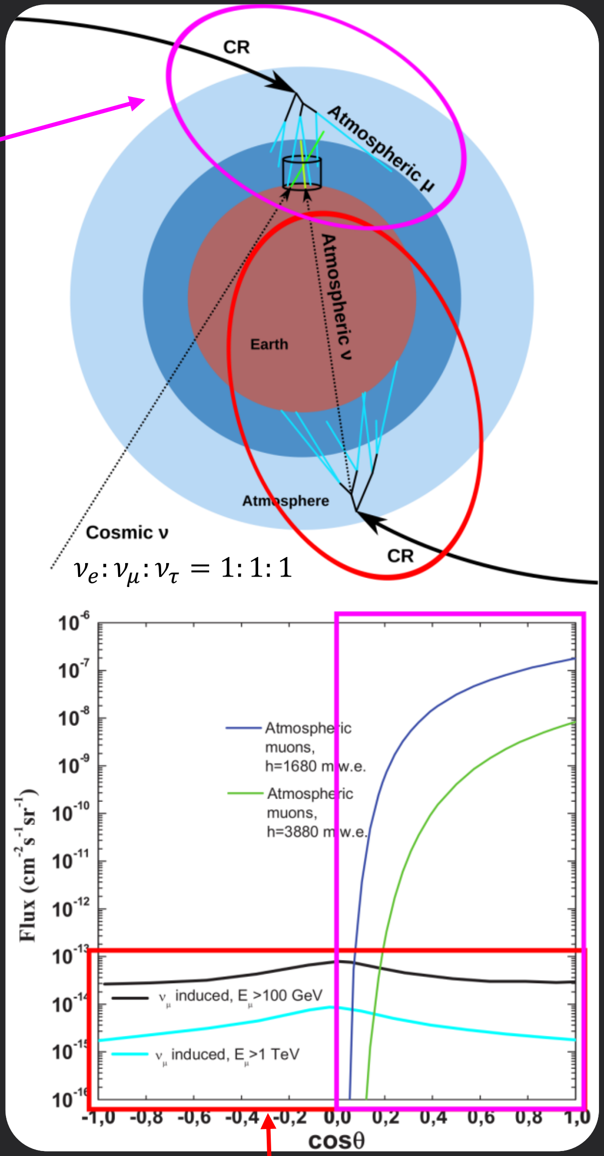
Neutrino Telescopes | Topologies

DON'T PANIC



2 main topologies | 2 main backgrounds



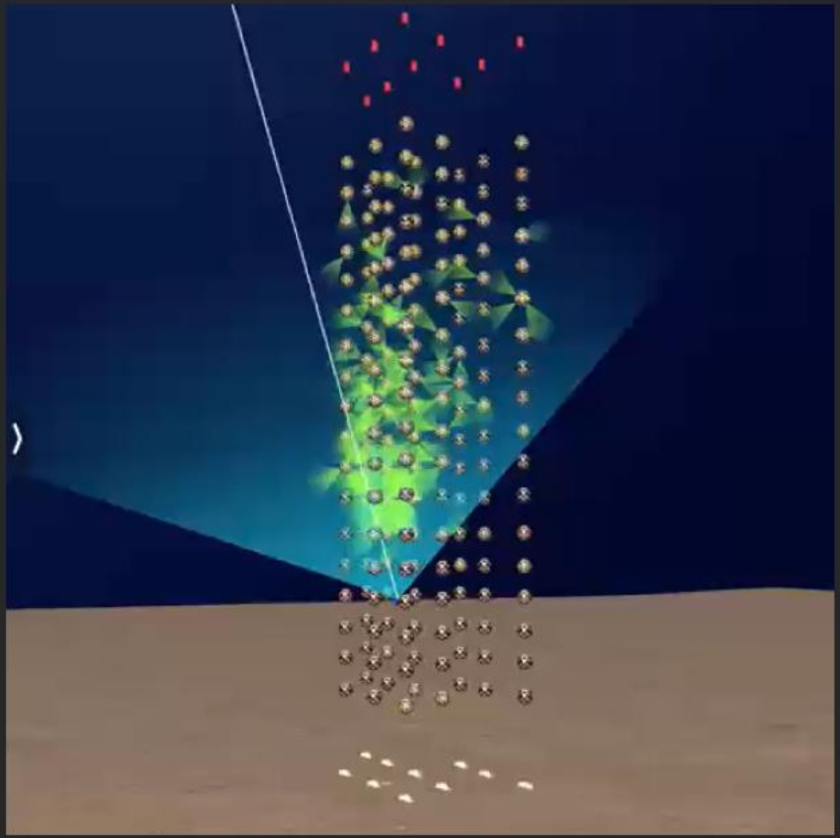


$\nu_e : \nu_\mu : \nu_\tau = 1:2:0$

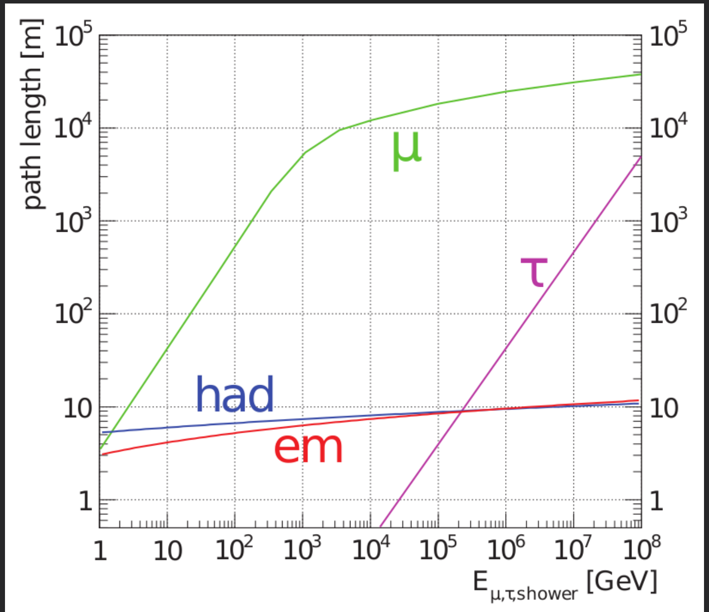
Neutrino Telescopes | 2 main topologies

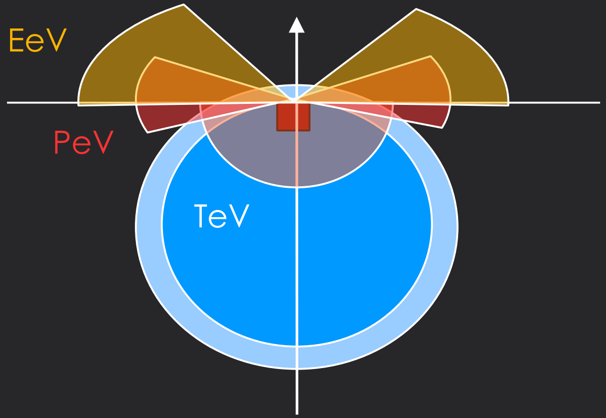
TRACK

$\nu_{\mu/\tau\to\mu}$-CC



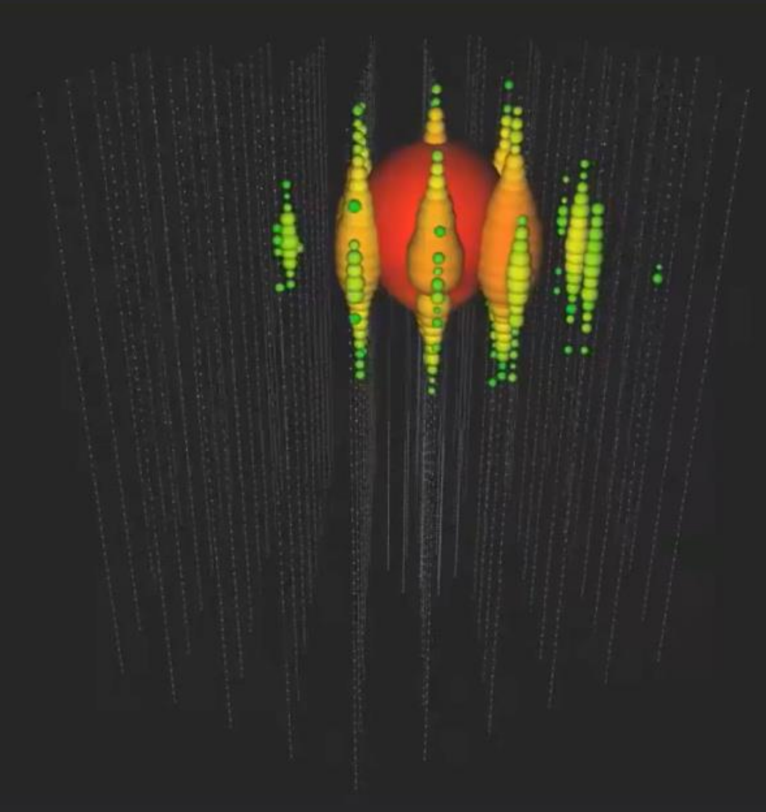
https://www.youtube.com/shorts/B7cbc7OHCbM





SHOWER

$\nu_{e/\mu/\tau}$-NC + $\nu_{e/\tau\to e}$-CC

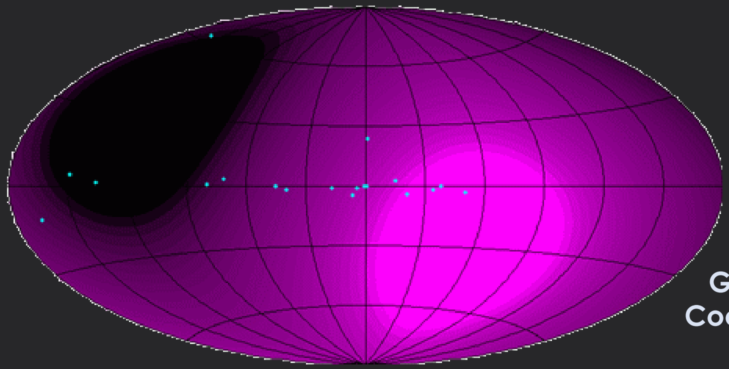


https://www.youtube.com/watch?v=y6cmY-ibgys

Neutrino Telescopes | Ice vs Water

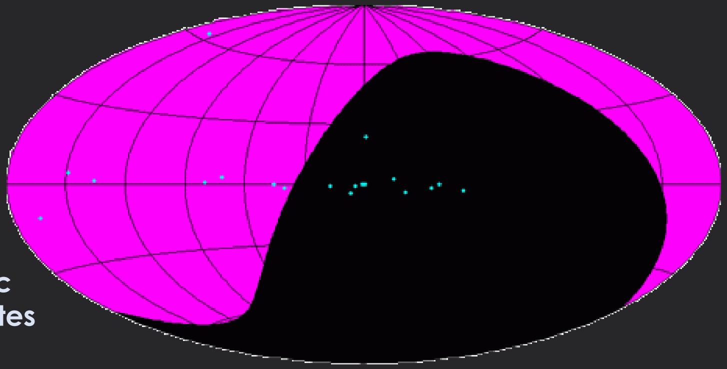
- Good optical properties of sea water (low scattering) → optimal pointing accuracy
- Mediterranean sea location: ideal to look at the Southern sky (including Galactic Centre) through upward-going neutrinos

In fact: fields of view from South Pole and from the Mediterranean Sea are complementary

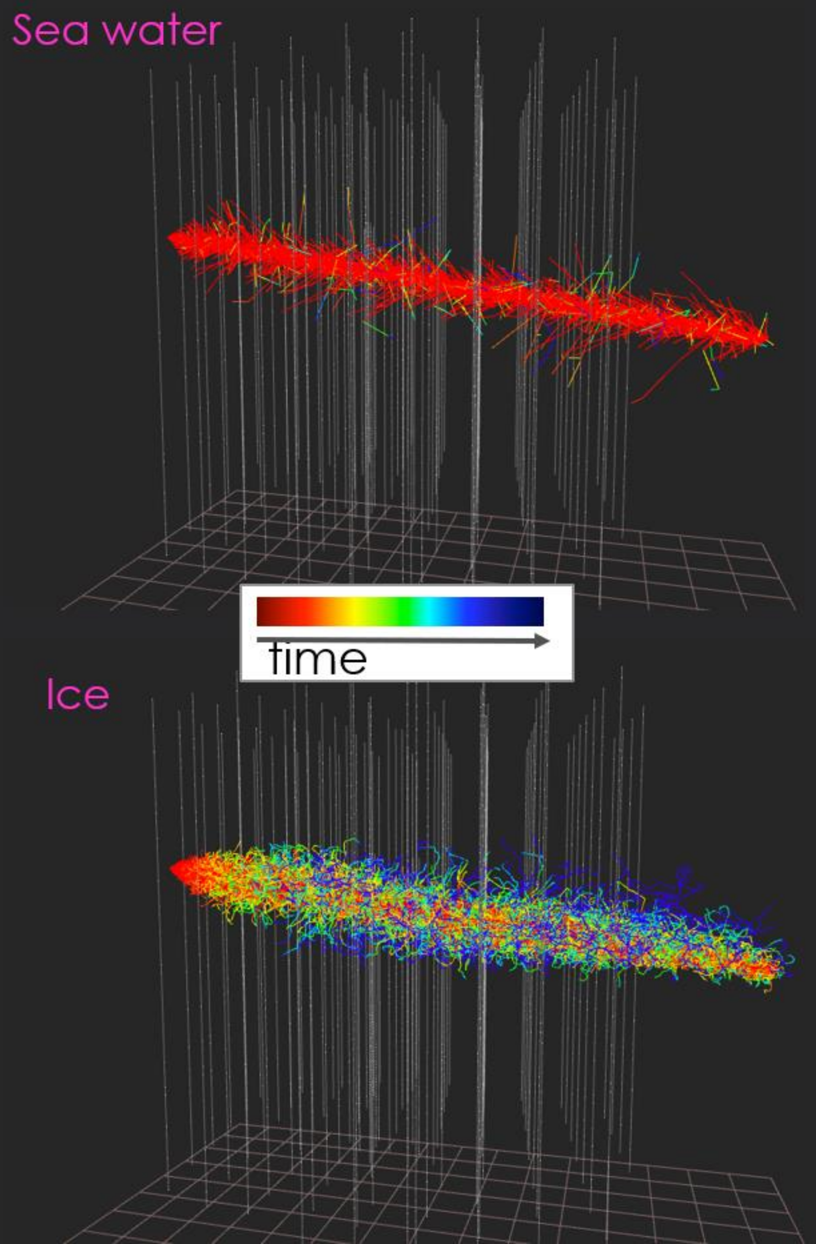


Mediterranean Sea (~43º North)

Galactic Coordinates



South Pole



Neutrino Telescopes | Angular resolution

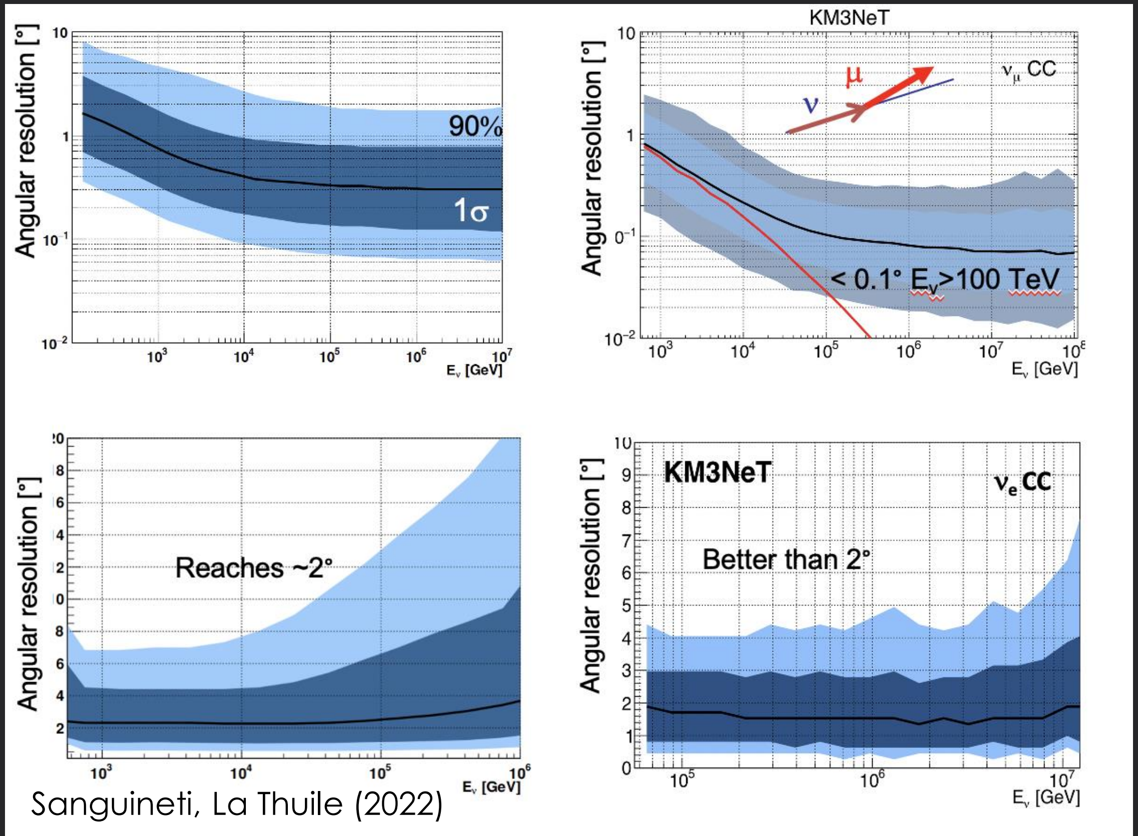
- Ang. res. depends strongly of energy (and data quality selection)
- Much better ang. res. for tracks than for showers... also beter in water than in ice
- Typically subdegree median ang. res. on tracks above TeV; not in showers, can worsen with energy

- Energy resolution better for showers (containment) while on tracks deposited energy: statistical use of energy estimators in analysis
- Reconstruction techniques still under improvements

ANTARES | KM3NeT/ARCA

TRACKS

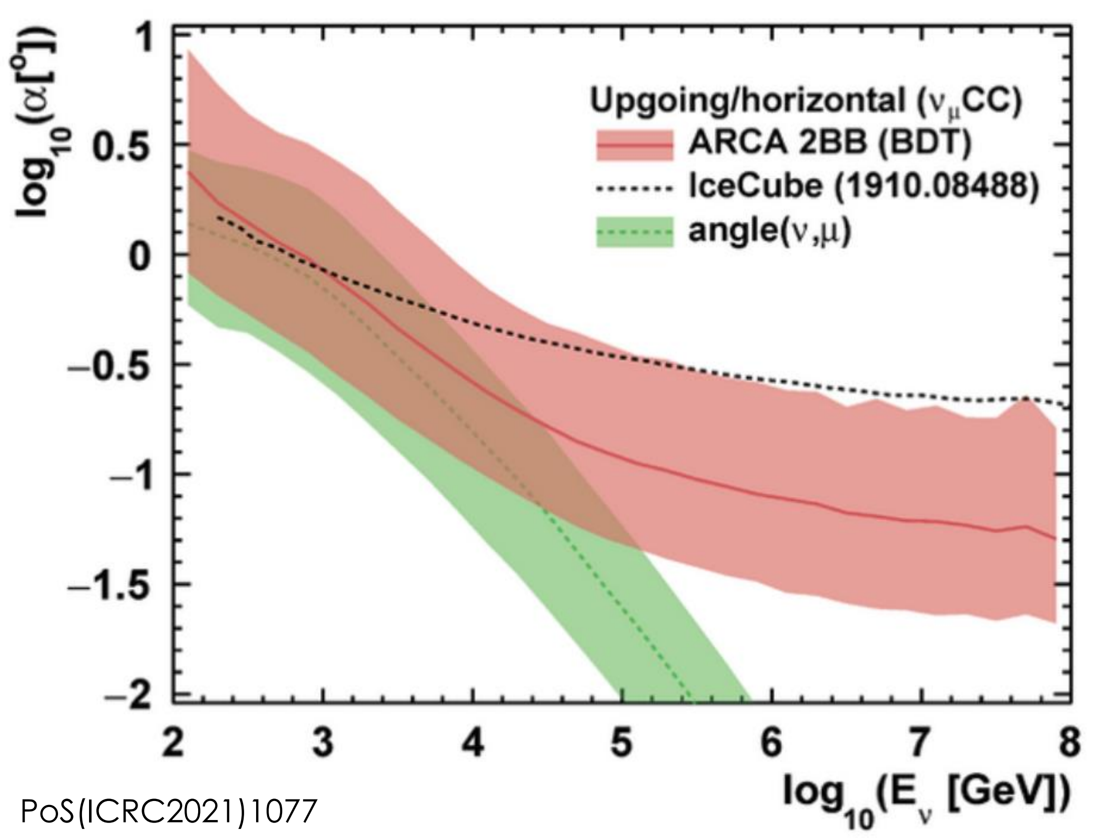
SHOWERS



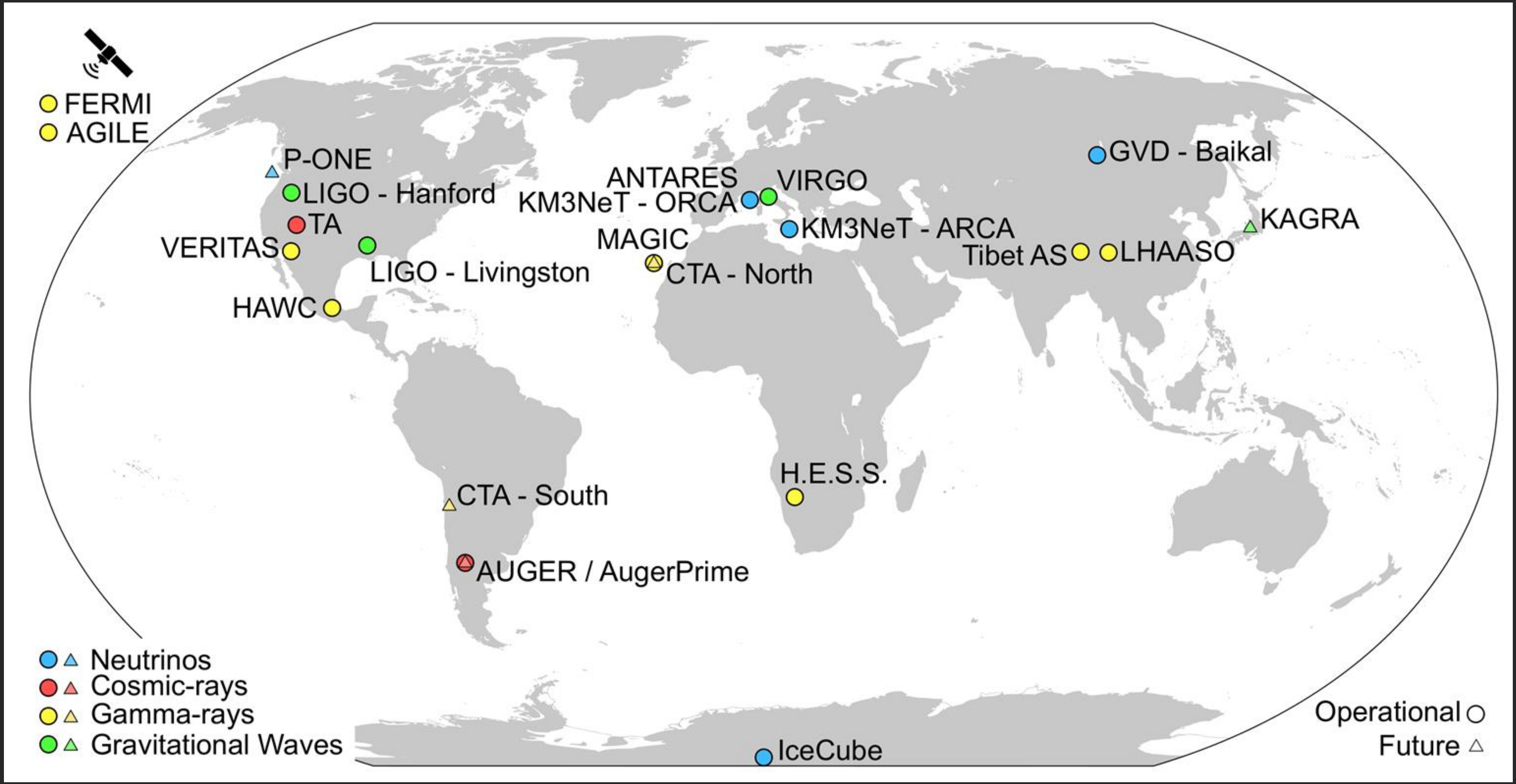
Energy resolution ~ 30%

Energy resolution < 5%

KM3NeT/ARCA vs IceCube



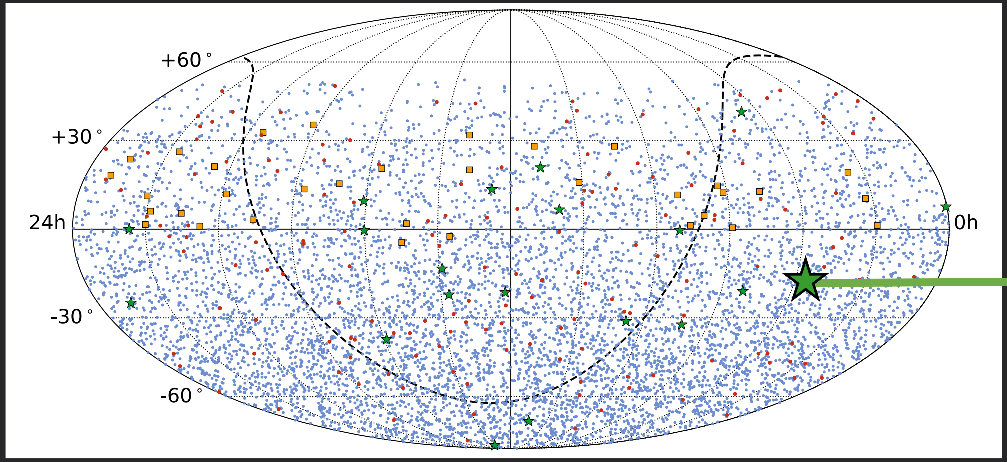
The Experiments | Worldwide coverage

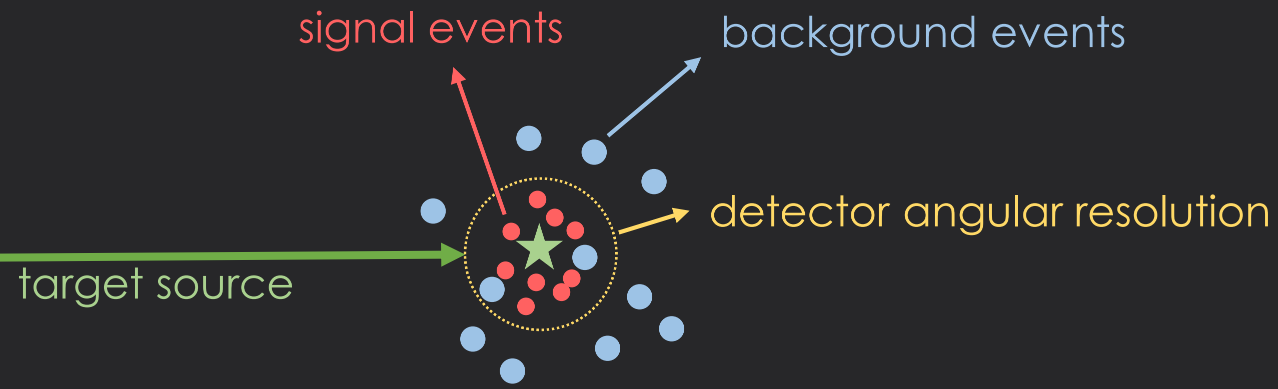


III. The Searches

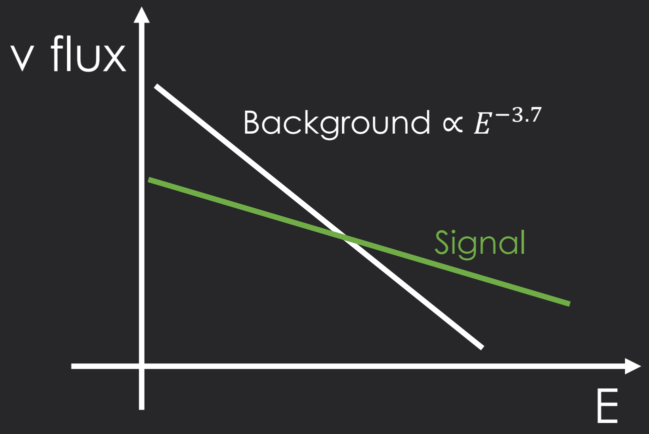
The Searches | Direction-Energy-Time

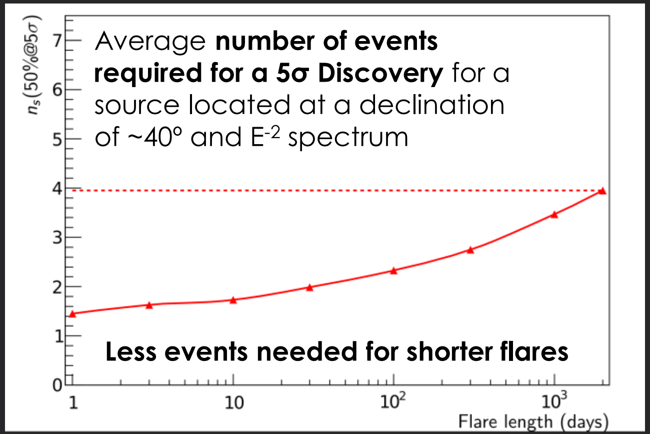
- **Spatial** distribution: compatible with point-like/extended sources?



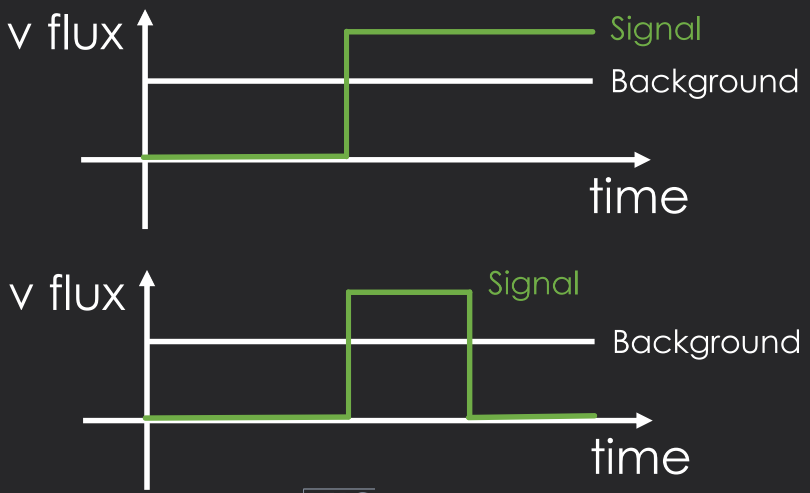


- **Energy** spectrum: compatible with signal expectation?



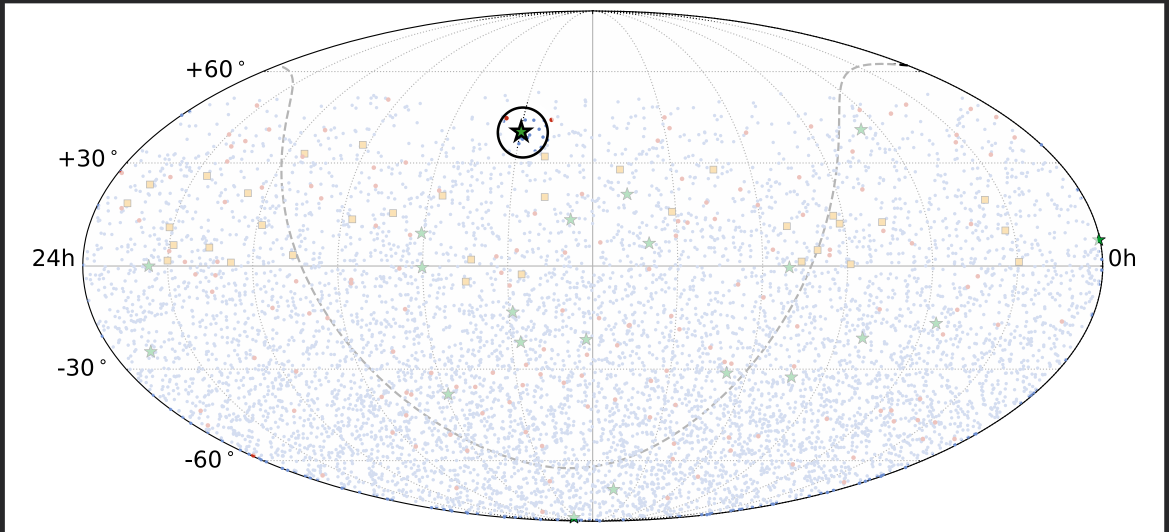


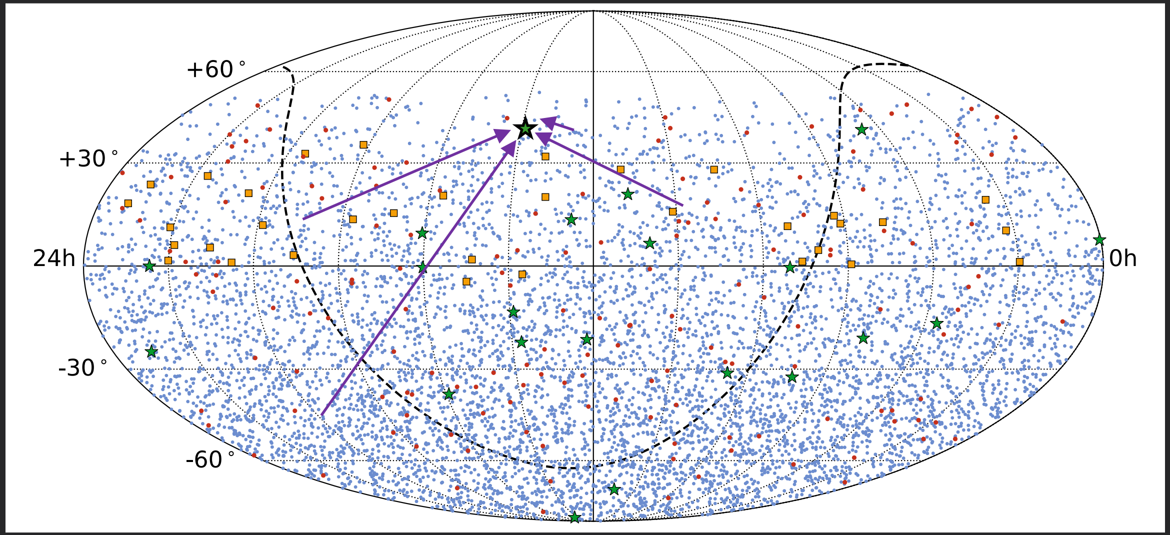
- Arrival **time**: limited to a transient signal hypothesis?



The Searches | Binned vs Unbinned

Recipe: Spatial-Energy-Time correlations





Binned

- cut-and-count methods
- **fast**: (quasi) **real-time analyses**
- straightforward
- important for cross check
- comparing with Poisson expected background

Unbinned

- likelihood methods
- sophisticated: longer implementation
- **weighting neutrino properties**
- Provides **better sensitivities**
- comparing with null hypothesis

$$\mathcal{L} = \left[\prod_{i=1}^{N} P(x_i)\right] e^{-\mathcal{N}}$$

$$P(x) = \mathcal{N}_s P_s(x) + \mathcal{N}_b P_b(x)$$

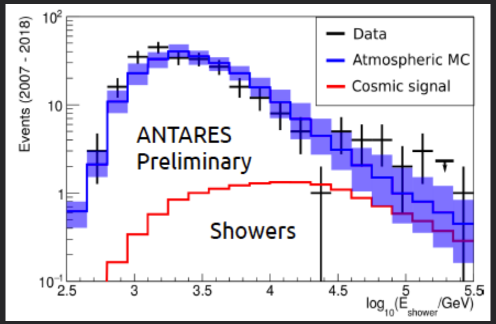
$$\ln \mathcal{L} = \sum_{i=1}^{N} \ln\left[\mathcal{N}_s P_s(x) + \mathcal{N}_b P_b(x)\right] - \left[\mathcal{N}_s + \mathcal{N}_b\right]$$

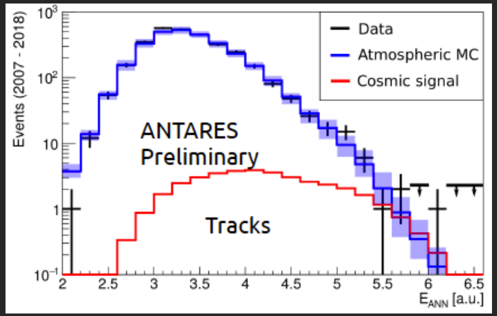
Sample of a simple extended likelihood

Signal PDFs $P_s = S^{space} \cdot S^{energy} \cdot S^{time}$

Background PDFs $P_b = B^{space} \cdot B^{energy} \cdot B^{time}$

The Searches | Diffuse searches





ANTARES search **full sky diffuse flux**
PoS(856)ICRC2019

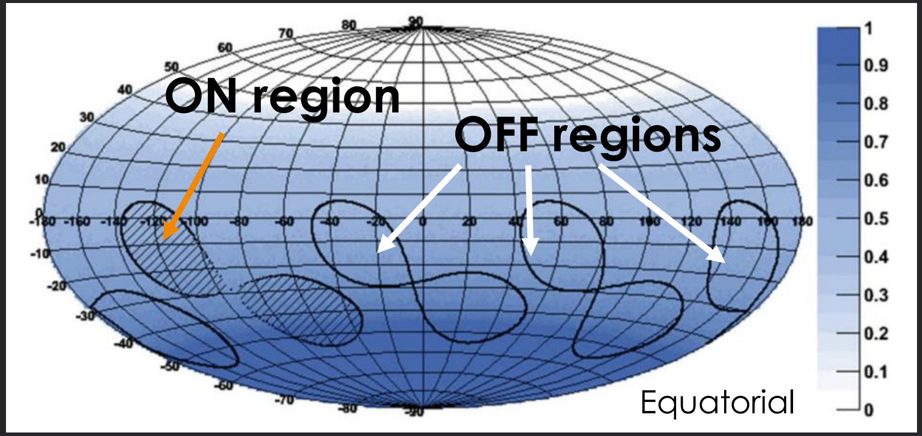
Optimization:
- Event selection chain
- energy estimator threshold (minimizes MRF)

↓

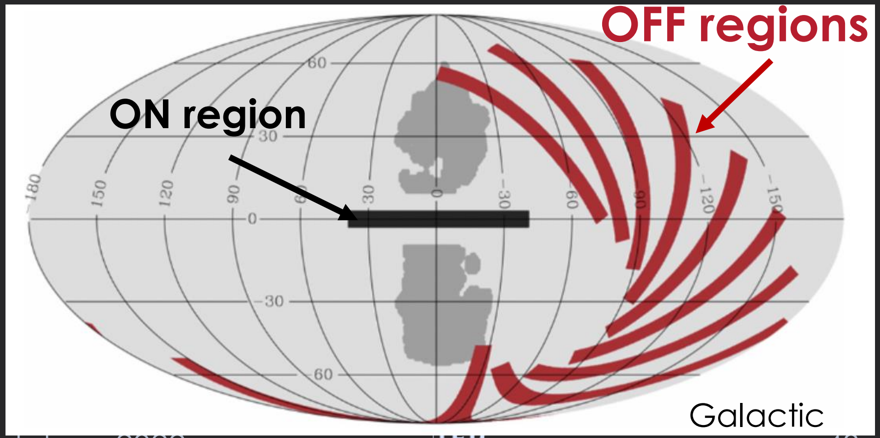
- obtain a high-purity neutrino sample
- maximise sensitivity

2007 – 2018 (livetime 3380 days)
All-flavour analysis: tracks + showers
MC background: 36 ± 8 (stat.+syst.) events
Observed events:
50 events (27 tracks + 23 showers)
Compatible with IceCube flux
1.8σ excess

ANTARES search for **diffuse flux from Fermi Bubbles** (MRF)
Eur. Phys. J. C 74 (2014) 2701

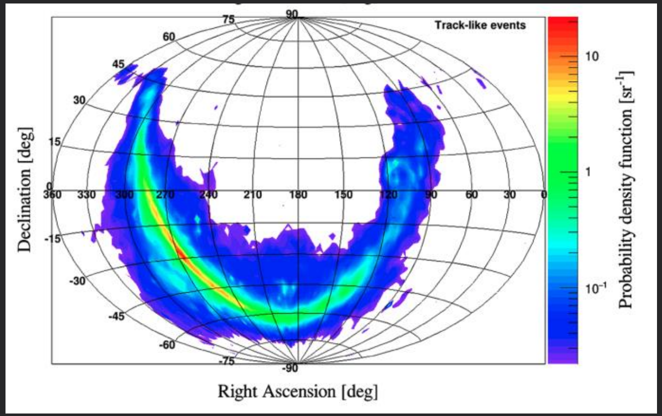


ANTARES search for **diffuse flux from Galactic Ridge** (MRF)
PLB 760 (2016) 143-148



ANTARES search for **Galactic diffuse flux**
Phys. Rev. D 96 (2017) 062001

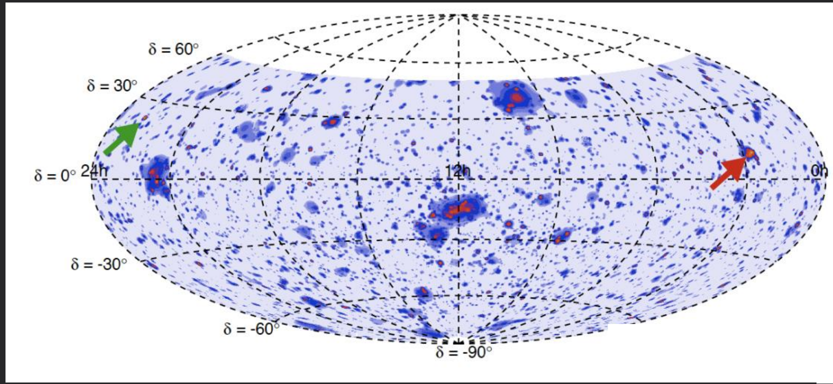
"KRAγ" model used to derive of the expected full-sky neutrino flux induced by Galactic CR interactions



The Searches | Source searches

All-sky search

PoS(ICRC2021)1161

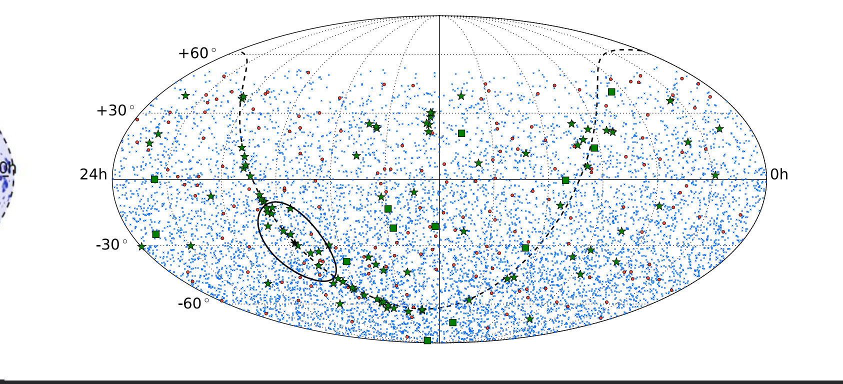


- Sky divided into a grid with a finer spacing than the typical event reconstruction uncertainty
- TS evaluated in each bin of the grid
- Cluster with largest TS → all-sky hotspot

- **Advantage**: unbiased by EM observations (no prior assumptions regarding directions in the sky)
- **Disadvantage**: large trial factor

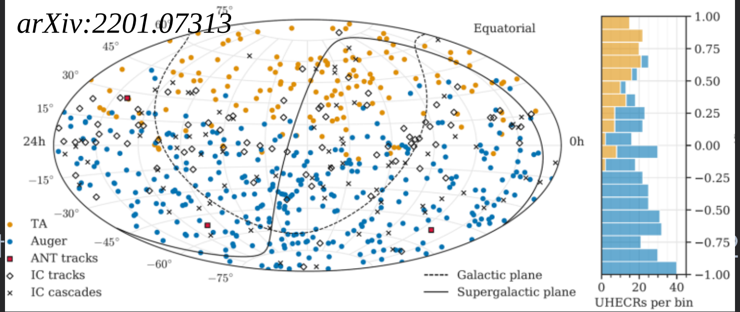
Source list search

PoS(ICRC2021)1161



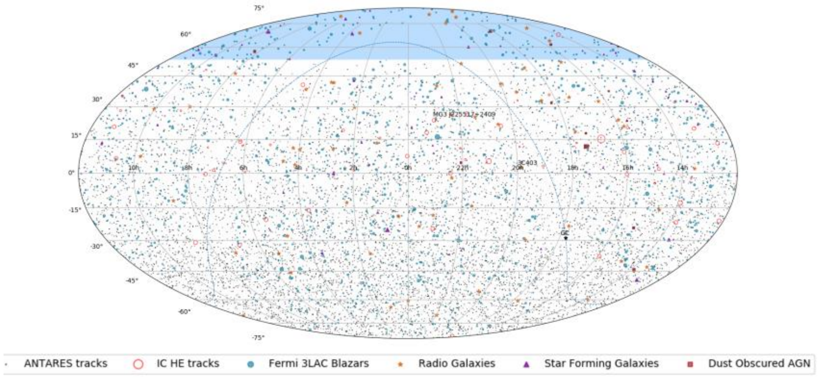
- Investigated directions: location of selected γ-ray sources
- TS evaluated for each source

- **Advantage**: reduced trial factor
- **Disadvantage**: biased (the brightest ν sources may differ from the brightest γ-ray sources)



Stacking search

ApJ 911 (2021) 48



- Search for an excess from several sources
- Stacking: all the sources in the catalog analysed together → one TS per catalog

$$TS = \frac{1}{\sum_j w_j} \sum_{j=1}^{N_{\text{sources}}} w_j \cdot TS_j$$

- **Advantage**: sensitive to individually weak sources that produce a significant cumulative signal
- **Disadvantage**: biased

The Searches | Transient searches

Multi-messenger correlations:

- **nu+γ** (TXS 0506+056)
- **nu+nu** (alerts + neutrino flares)
- **nu+γ/TDEs/radio**
- **GW+γ** (GW170817)
- **GW+nu** (follow-up)
- **GRB+nu** (follow-up)
- **CR-nu**

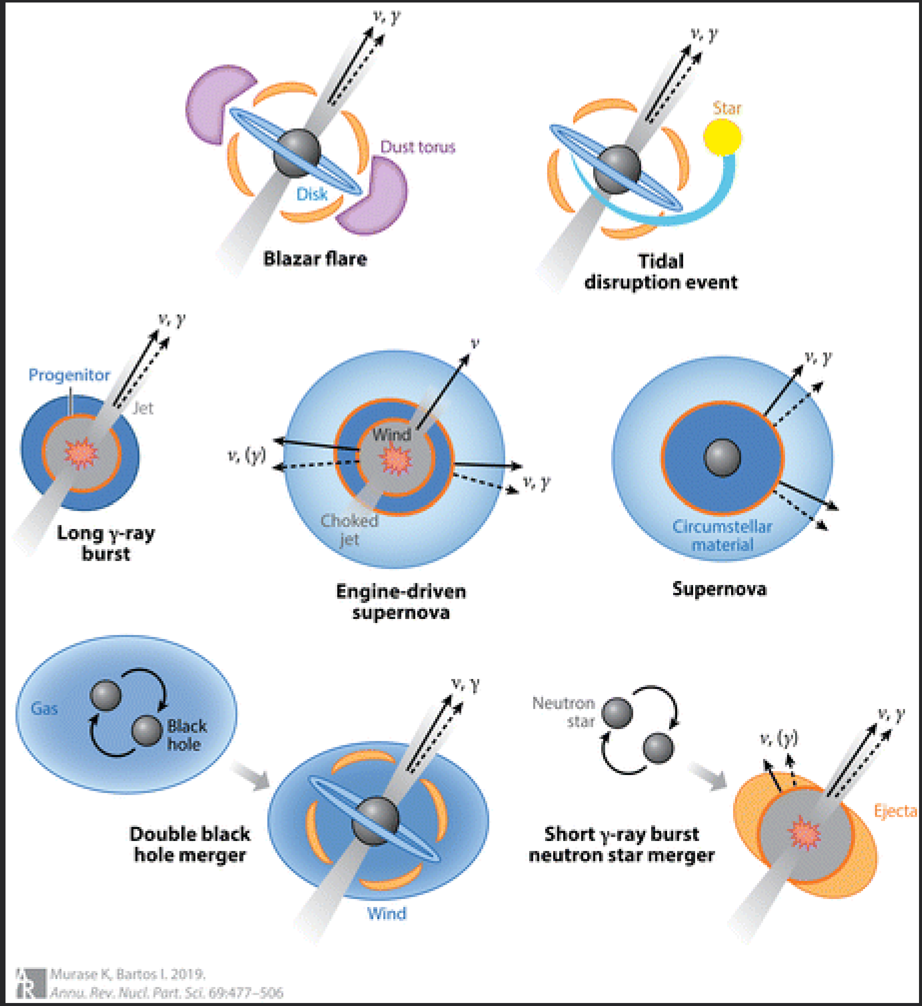
Other searches:

Transient

- Untriggered
- Generated Alerts (TAToO, CCSN)
- FFT analysis (LE, periodic signal)

No Transient

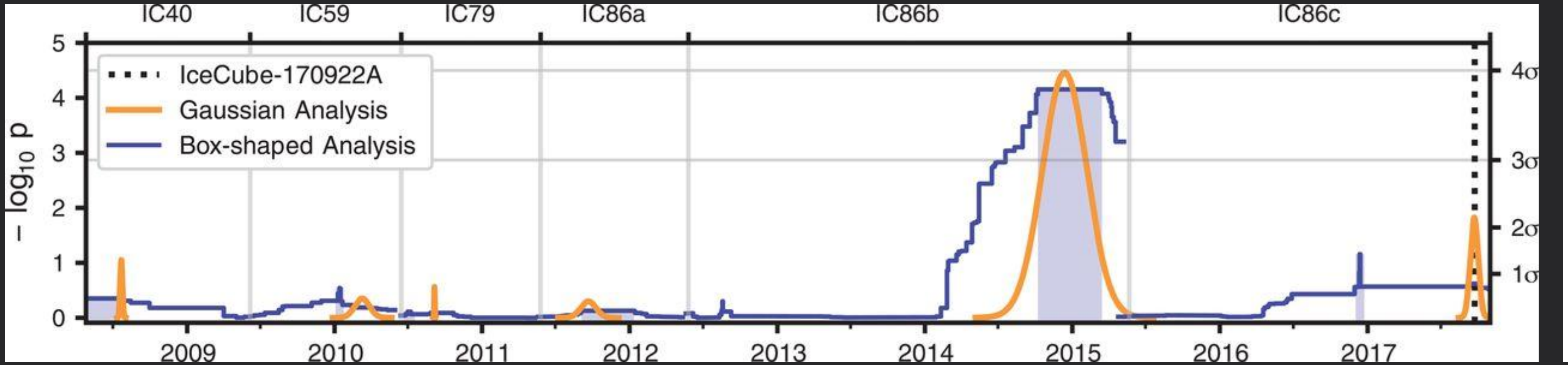
- Dark matter
- Oscillations
- Exotics
- …



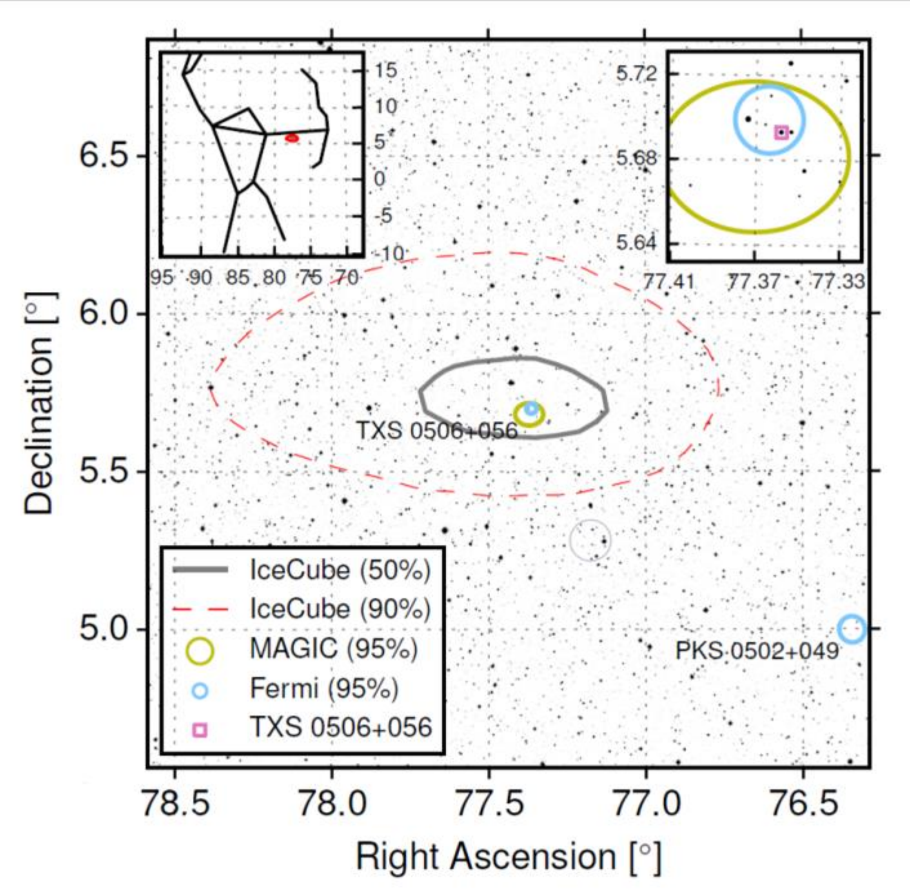
Ann.Rev.Nucl.Part.Sci. 69 (2019) 477

The Searches | nu+γ: TXS 0506+056

- On Sep 22nd 2017 an IceCube **neutrino** event (IC170922A) was detected in coincidence with **gamma rays** (Fermi & MAGIC) from the blazar TXS 0506+056 in a flaring state (3σ)
- Archival data revealed a previous neutrino emission from the same blazar (3.5σ, independent)
- Second best source in ANTARES 13yr search (2.8σ pre-trial)



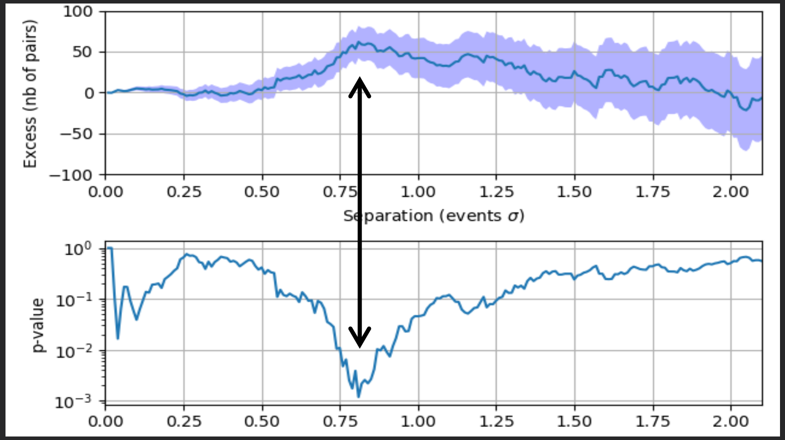
Science 361, 147-151 (2018)



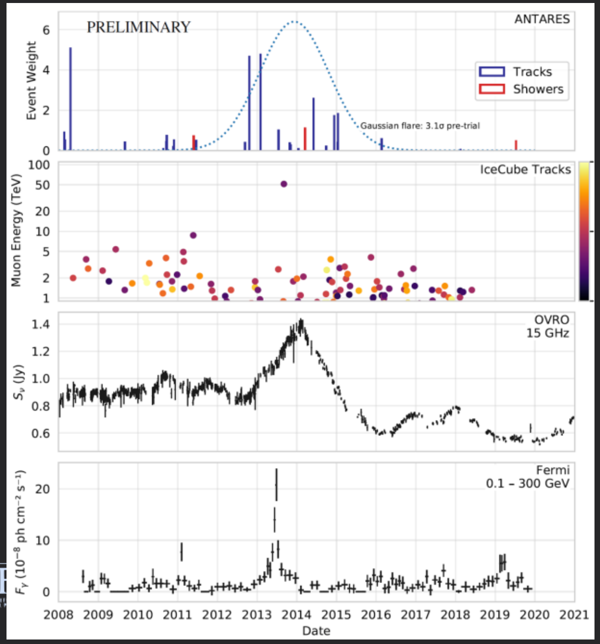
The Searches | nu+γ/radio & TDEs

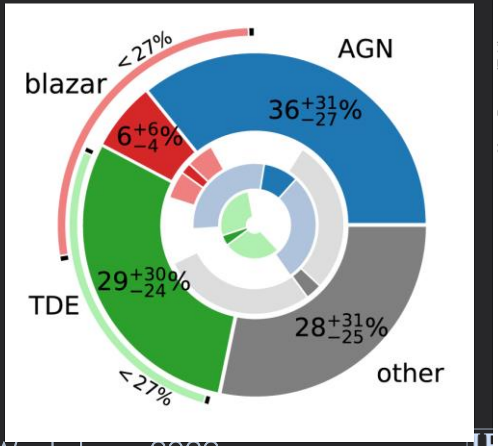
- **IC190730A → PKS 1502+106** (strong radio flare): blazar not active at the time of the alert [ApJ 912 54 (2021)]
- **IC200107A → 3HSP J095507.9** (strong X-ray flare): large position uncertainty containing lots of sources [ApJ 902, 29 (2020), A&A 640, L4 (2020)]
- Hints of **radio-emitting blazars correlating with neutrinos** both in IceCube (4.1σ) & ANTARES (2.3σ) [ApJ 908 157 (2021), PoS(ICRC2021)1164]
- Potential **radio-gamma-ANTARES neutrino** association: J0242+1101 (nu-flare 3.1σ pre-trial) [PoS(ICRC2021)972]
- Blazars most abundant extragalactic gamma-ray sources (80%): based on IceCube data they contribute <30% of total neutrino flux [ApJ 921 (2021) 1-45]
- **Tidal Disruption Events** (optical) & IC neutrinos spatially coincident:
  - IC191001A → AT2019dsg [Nat. Astron.5, 510(2021)]
  - IC200530A → AT2019fdr [arXiv:2111.09390]
  - IC191119A → AT2019aalc [arXiv:2111.09391]
- **More events needed & better localization…**

Simple pair counting shows hint of correlation at sub-degree angular scale



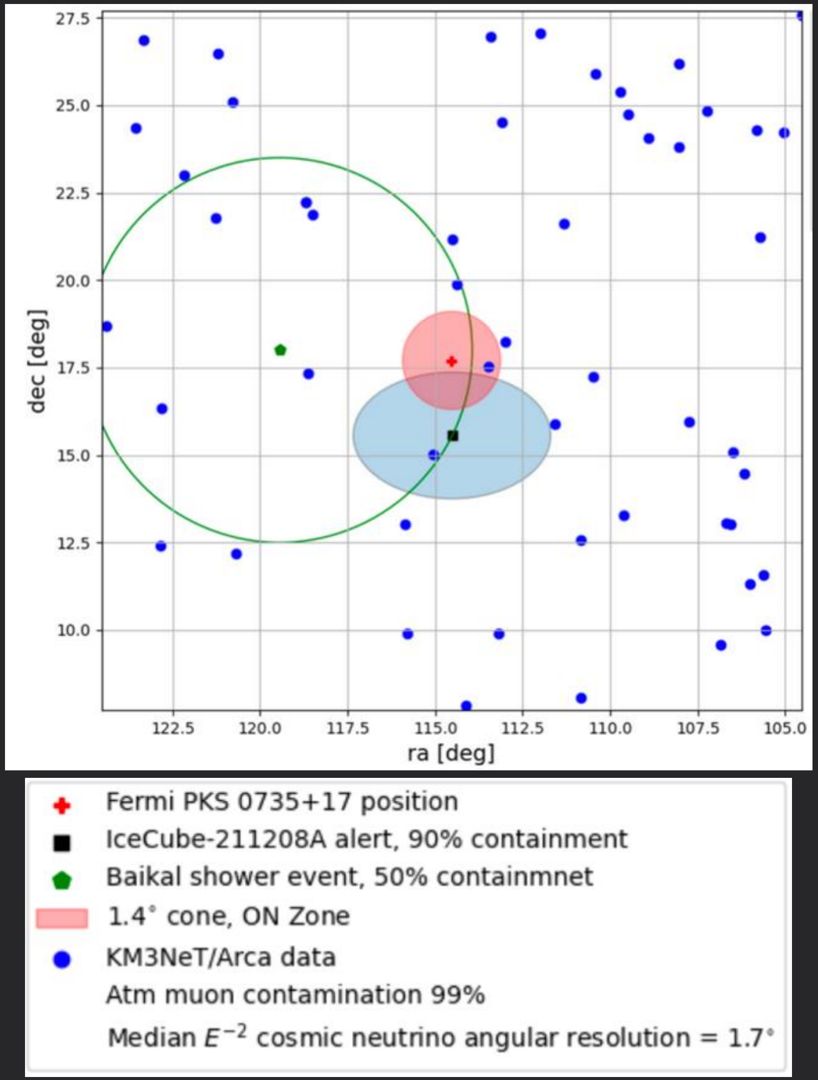
J0242+1101: potential radio-γ-nu association





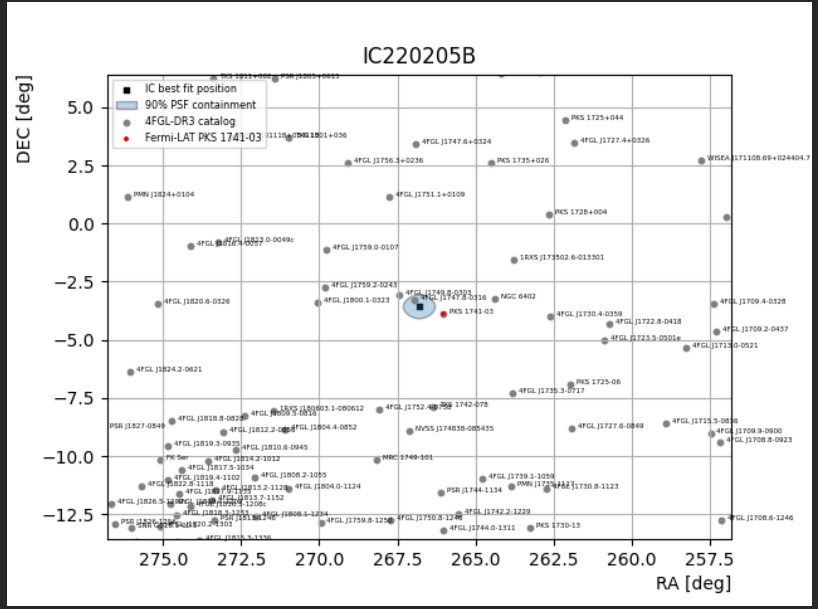
The Searches | nu+nu: alerts & blazars

IC211208A

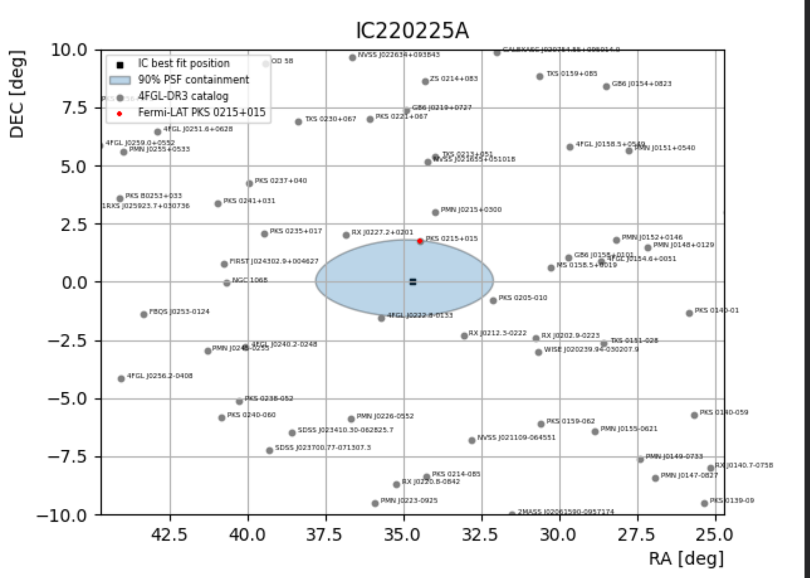


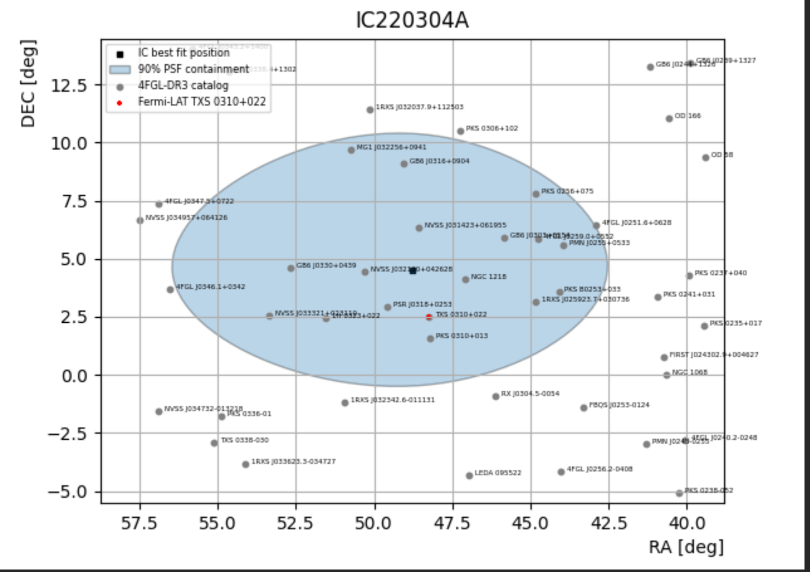
Heijboer, Neutrino (2022)

- Several recent IceCube alerts possibly associated with Blazars
- Follow up with both ORCA and ARCA, and ANTARES



IC alert	Potential blazar
IC211208A	PKS 0735+17
IC220205B	PKS 1741-03
IC220225A	PKS 0215+15
IC220304A	TXS 0310+022



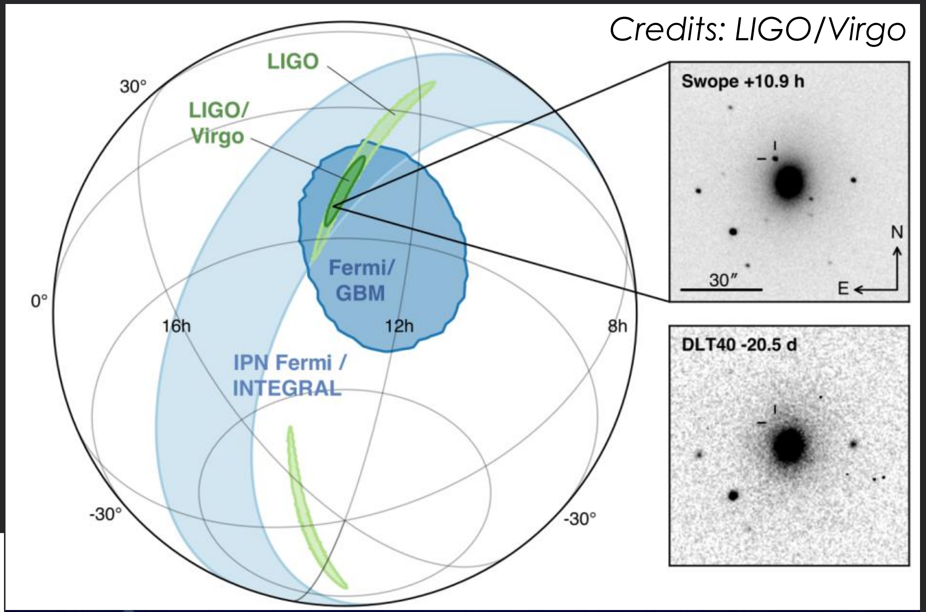


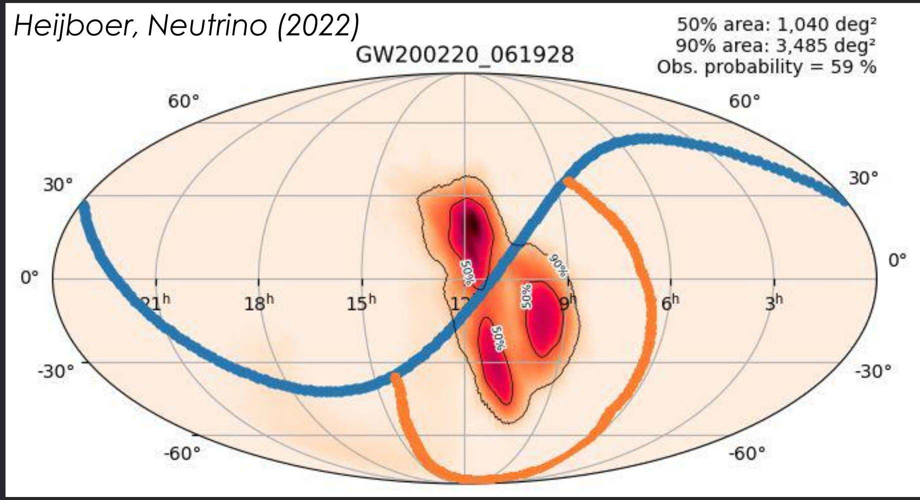
The Searches | GW+γ: GW170817

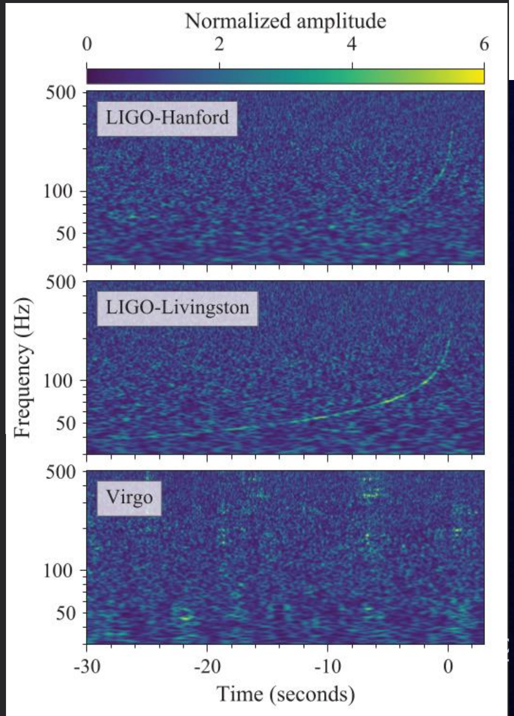
On Aug 17th 2017 a gravitational wave (**GW170817**) was detected by LIGO-Virgo and less than 2 seconds after, a Gamma-ray Burst (**GRB170817A**) was detected by Fermi and INTEGRAL.

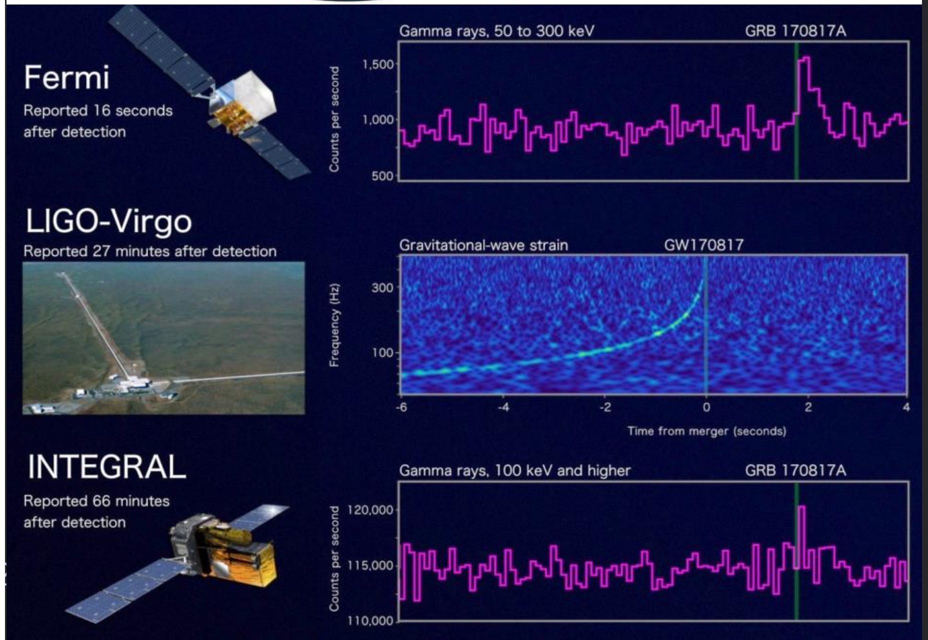
The GW was caused by two neutron stars merging.

That single event confirmed what is called Kilonova, a type of short gamma ray bursts.









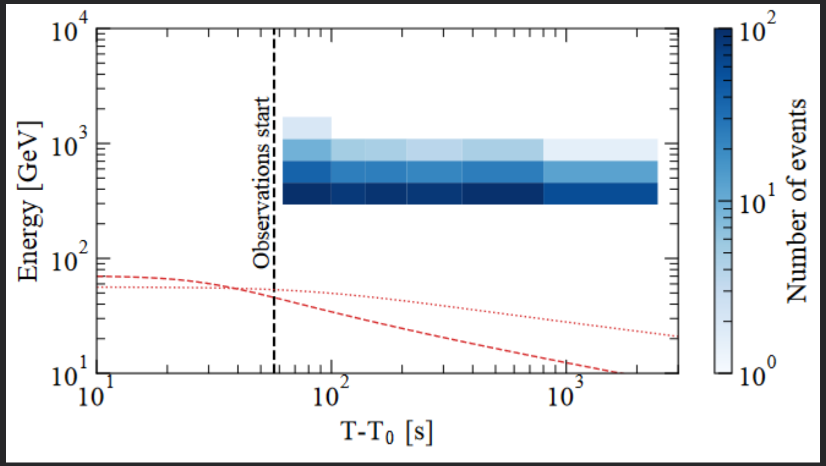
Follow-up of Gravitational Wave events (run 03) with ORCA

- Search for 1000s in 30 degree area around the GW confidence region.
- Limits on neutrino flux of 55 GW events in MeV and GeV-TeV ranges.

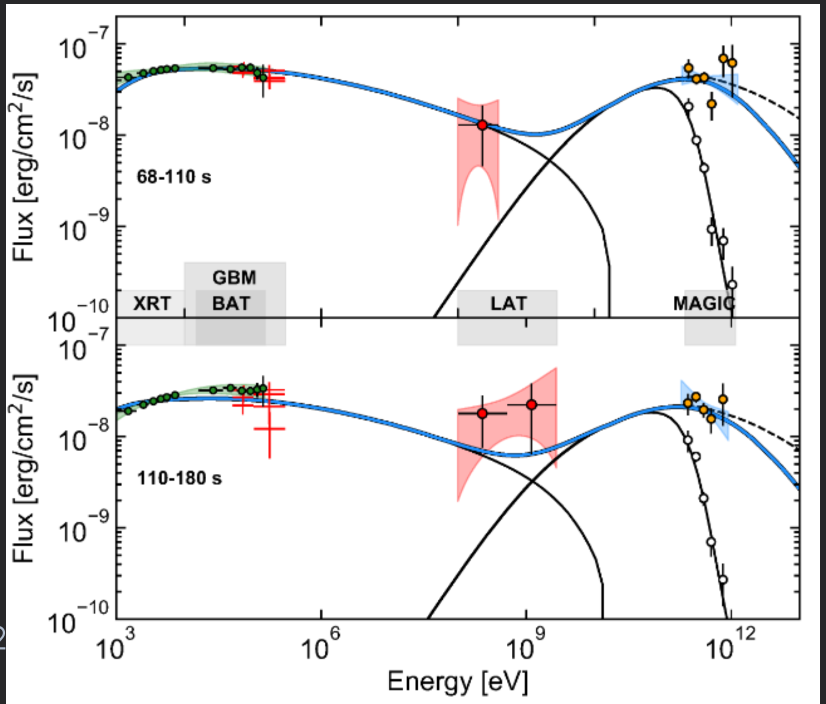
The Searches | Alert systems

- MM events are usually the result of a **follow-up campaign** (worldwide coverage + satellites).
- Regular announcements in Gamma-ray Coordinates Network (**GCN**) and Astronomer's Telegram (**ATEL**).
- **MoUs** between experiments.
- **AMON** program can use sub-threshold data from different experiments.
- **Astro-COLIBRI** (https://astro-colibri.com/) online platform centralizing events information.
- **IceCube alert system**, provides on the order of 10 (20) gold (bronze) alerts per year.
- **ANTARES events trigger** a prompt optical, radio, and X-ray follow-up → TAToO program: work in progress in KM3NeT.
- Pointing instruments, IACTs, designed for rapid follow-up (light-weight structure).

TeV from (long)GRB190114C
Nature 575 (2019) 455

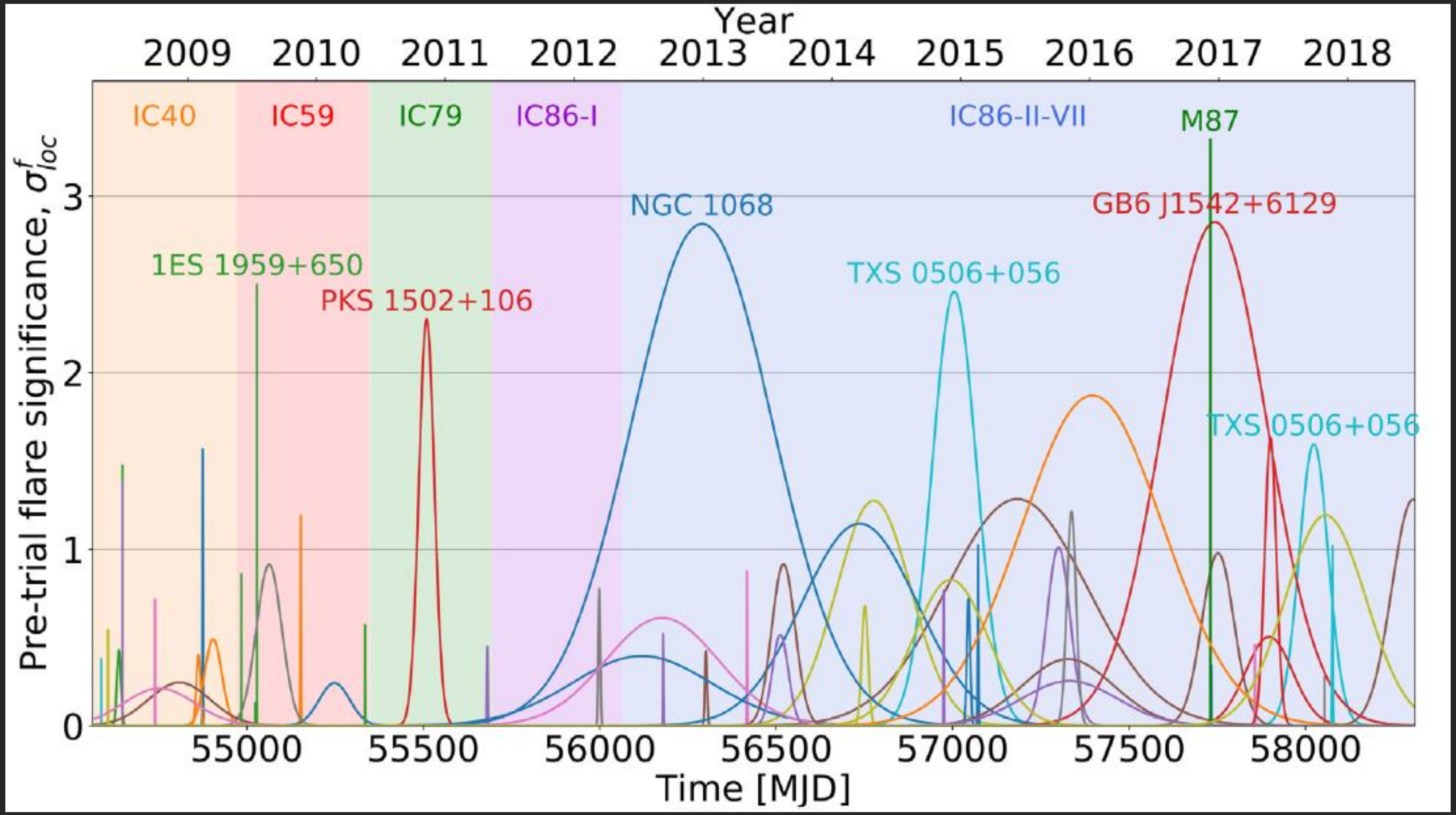


IC from (long)GRB190114C
Nature 575 (2019) 455



The Searches | nu+nu: neutrino flares

ApJL 920 (2021) L45



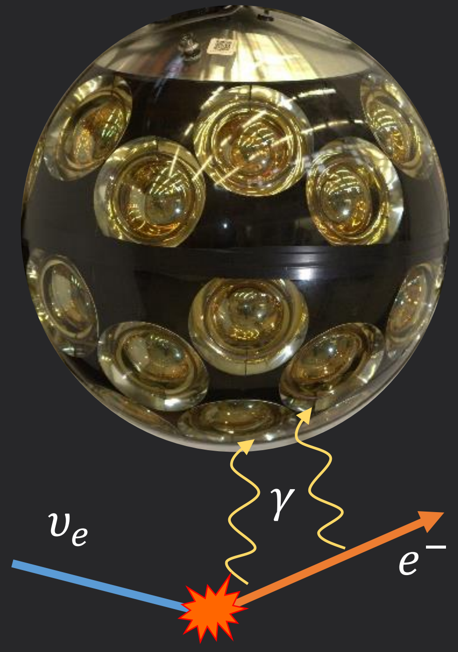
IceCube untriggered **neutrino flares** on candidate sources:

- blazars, AGNs, starburst galaxies and Galactic sources
- M87 ~2 min flare: most significant (3.4 σ pre-trial)
- TXS 0506+056: only observed multi-flare source of the catalogue

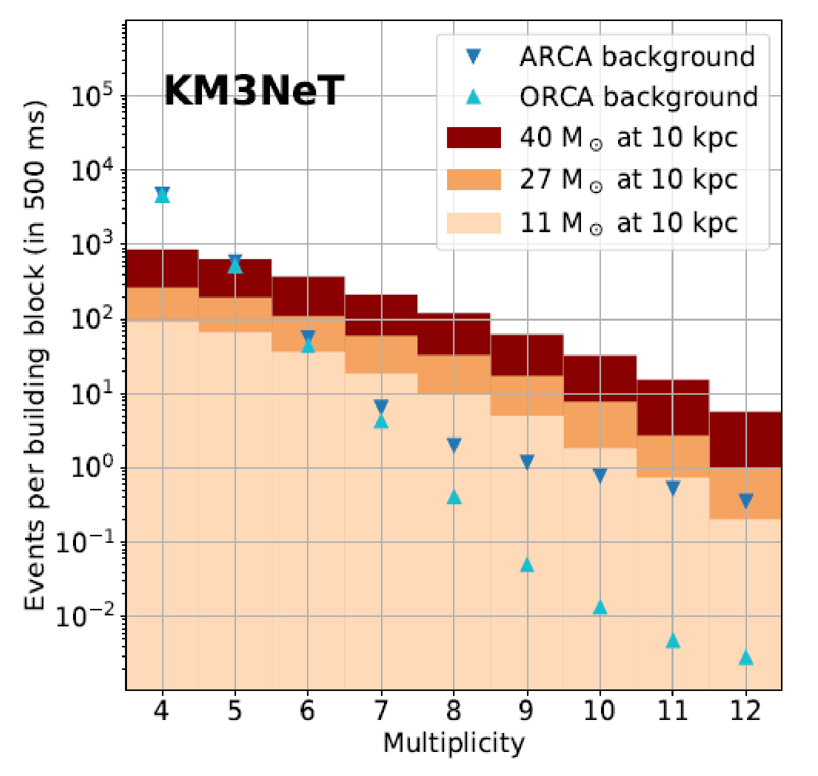
Idea: look up for neutrino correlations with other neutrino telescopes

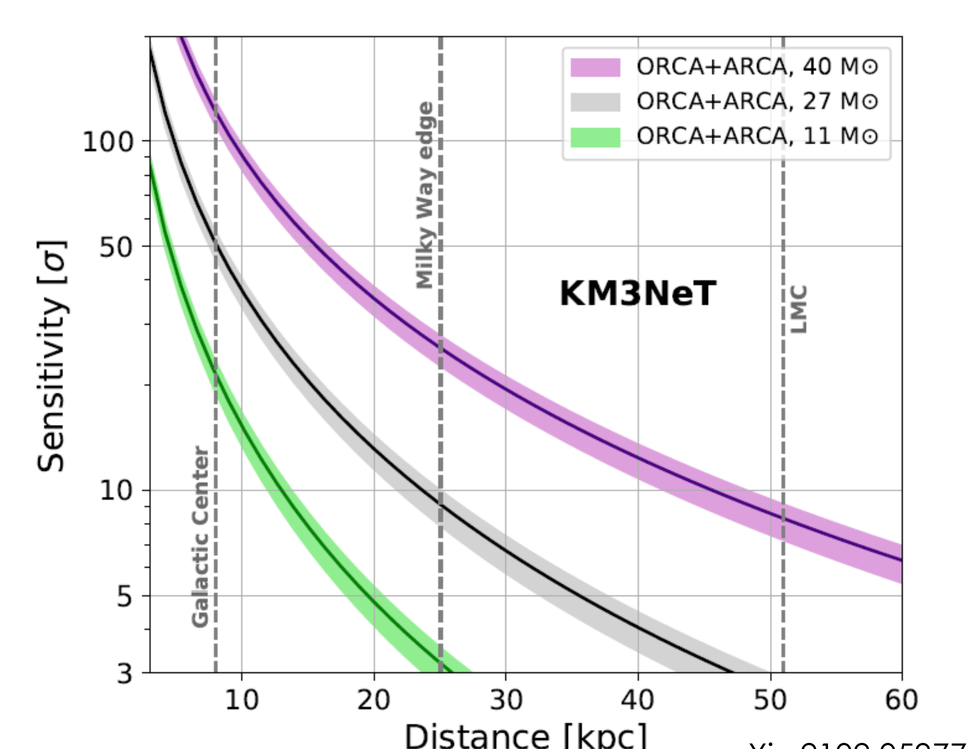
CCSN on Neutrino Telescopes

Aiello, S. et al. Eur. Phys. J. C 81, 445 (2021)



Each single DOM can act as a detector

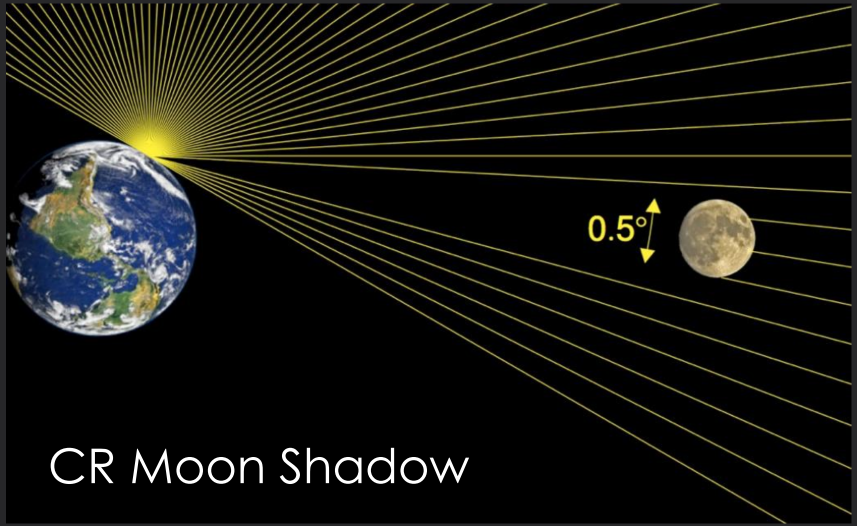




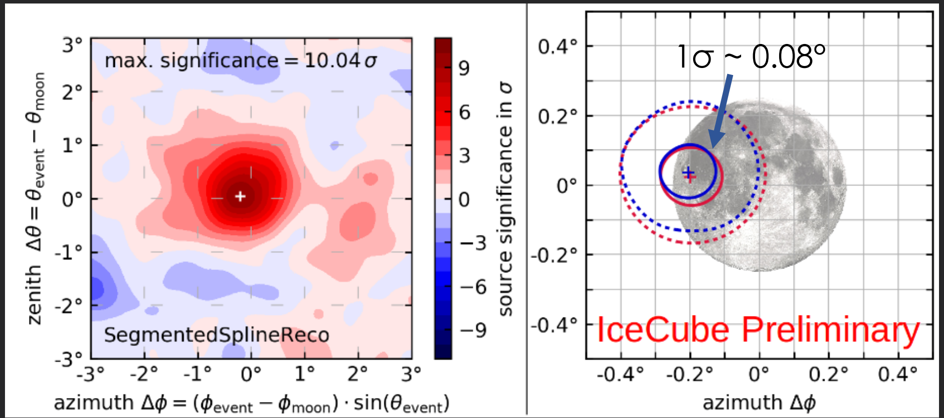
arXiv:2102.05977

- Increase of the DOM rates due to many MeV neutrinos from the collapse
- Alert system already operational!
- Integrated in SNEWS network
- Currently (ORCA6) would trigger on e.g. 27 $M_{\odot}$ at ~10 kpc

The Searches | Shadows in CR

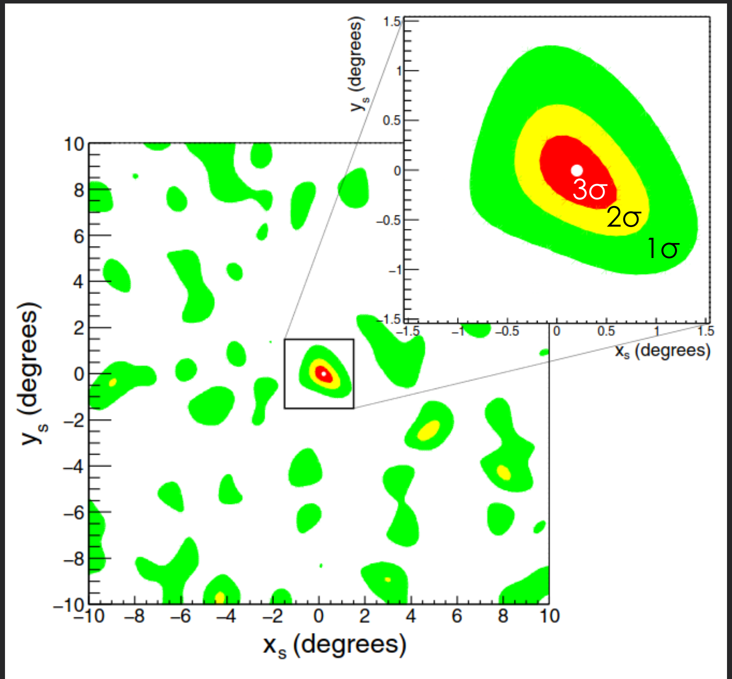


IceCube Moon Shadow



PoS(ICRC2021)1087

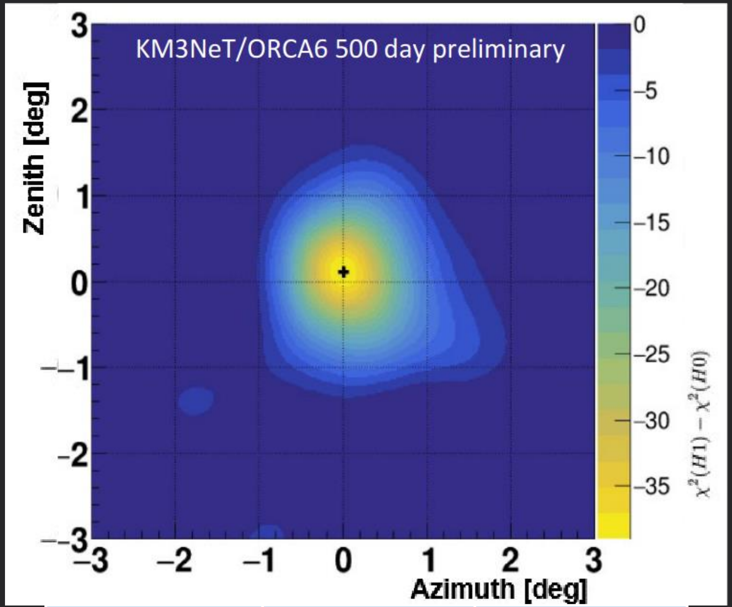
ANTARES Sun Shadow



	SUN	MOON
Resolution	0.59° ± 0.10°	0.73° ± 0.14°

Phys. Rev. D 102, 122007 (2020)

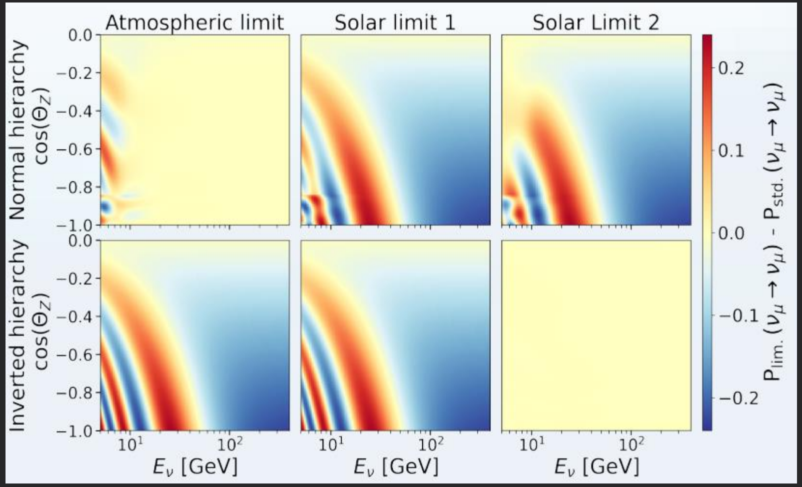
KM3NeT/ORCA6 Sun Shadow



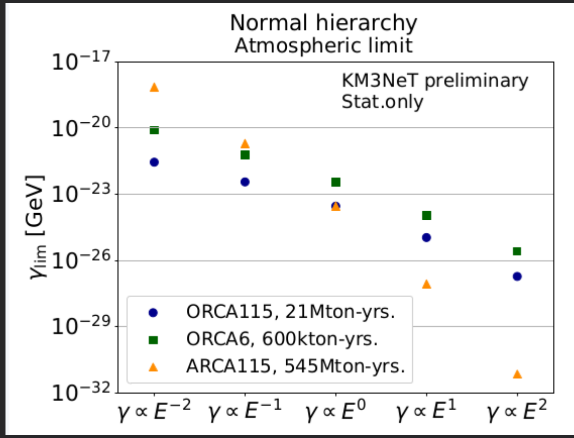
	SUN	MOON
Significance	6.0 σ	4.4 σ
Resolution	0.68° ± 0.12°	0.54° ± 0.16°

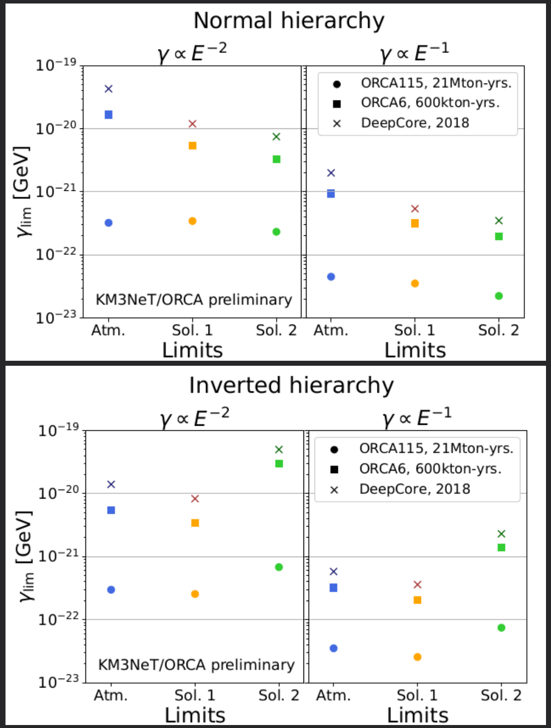
Heijboer, Neutrino2022

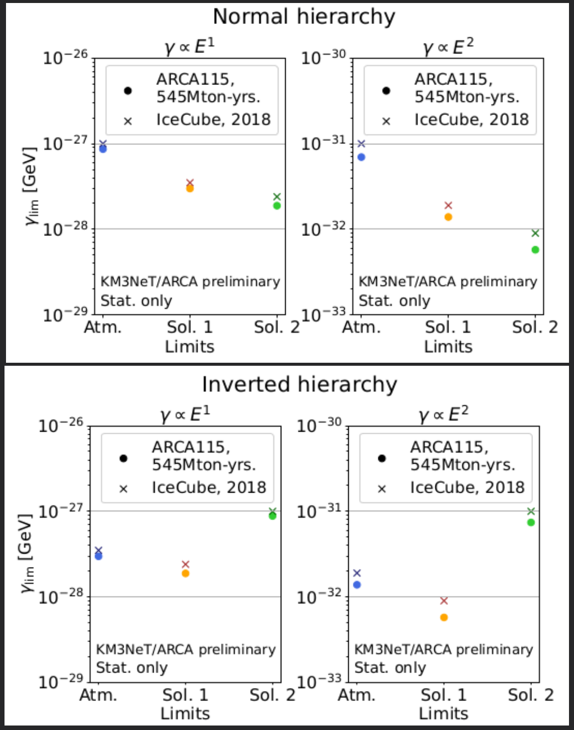
Neutrino Decoherence in NT

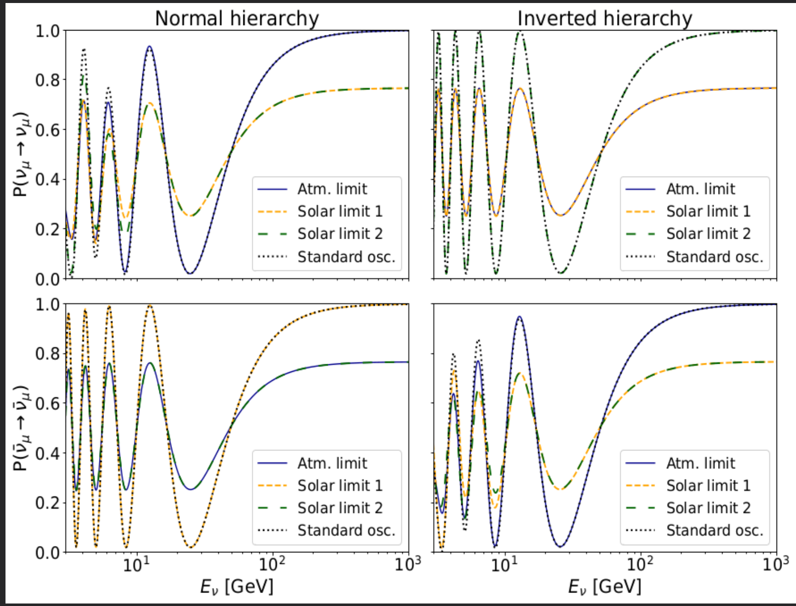


Lessing, P0297 Neutrino 2022









- Deviations with respect to standard oscillations
- Energy dependent: oscillations in multiple ranges (e.g. KM3NeT/ARCA & ORCA)
- KM3NeT: limits already better than IceCube with partial detectors

Prologue

Next generation experiments

CR

- **Auger Prime** (upgrade ongoing): composition measurements, composition selected anisotropy, particle physics with air showers.
- **Telescope Array** (upgrade ongoing): larger area (×4) ~2800km2, FD upgraded.

γ

- **CTA** (construction): arcmin AR, ×10 sensitivity, larger FOV, complete coverage of the Sky (South+North), wide E range (20GeV-300TeV), rapid follow-up.
- **LHAASO** (fully operational): already giving results, PeVatron finder, also CRs.
- **SWGO** (design phase): air shower array in the South, complementary to LHAASO.

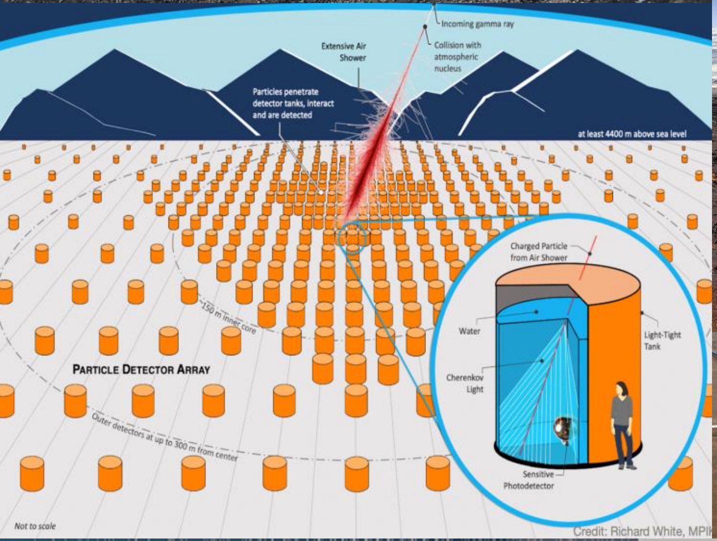
ν

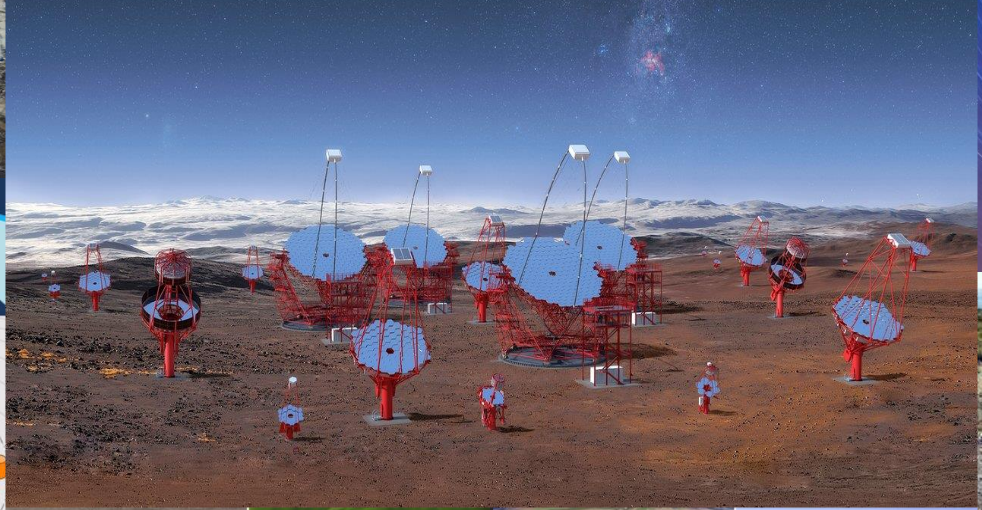
- **KM3NeT** (construction): AR < 0.2 º, good coverage of the Galaxy.
- **IceCube-Gen2** (2024-2032): better AR, larger detection volume (IceCube ×10 sensitivity), wide E range (up to EeV energies).

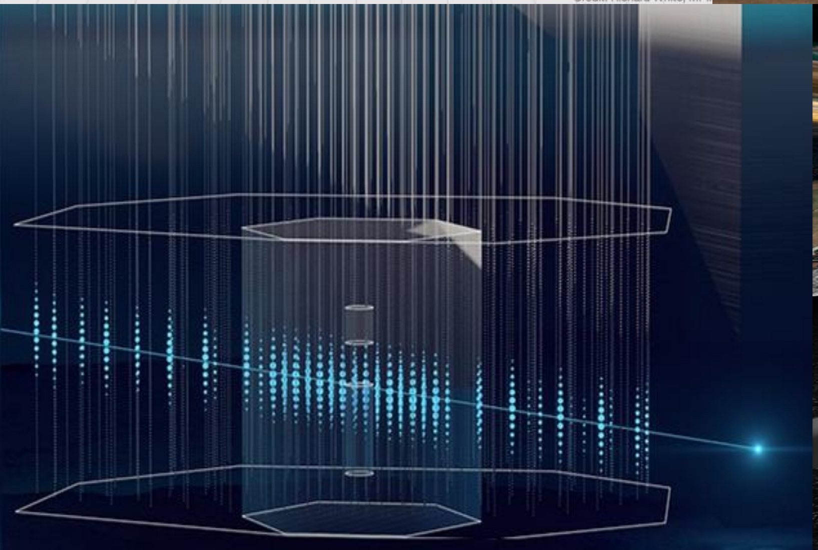
GW

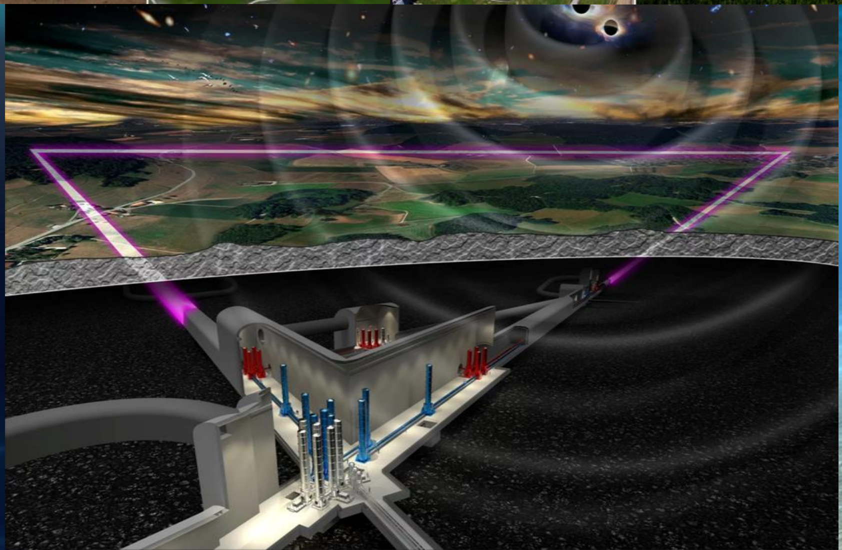
- **LIGO/Virgo/KAGRA** (upgrades): run O4 (mid-December 2022).
- **Einstein telescope** (design phase): ×10 sensitivity

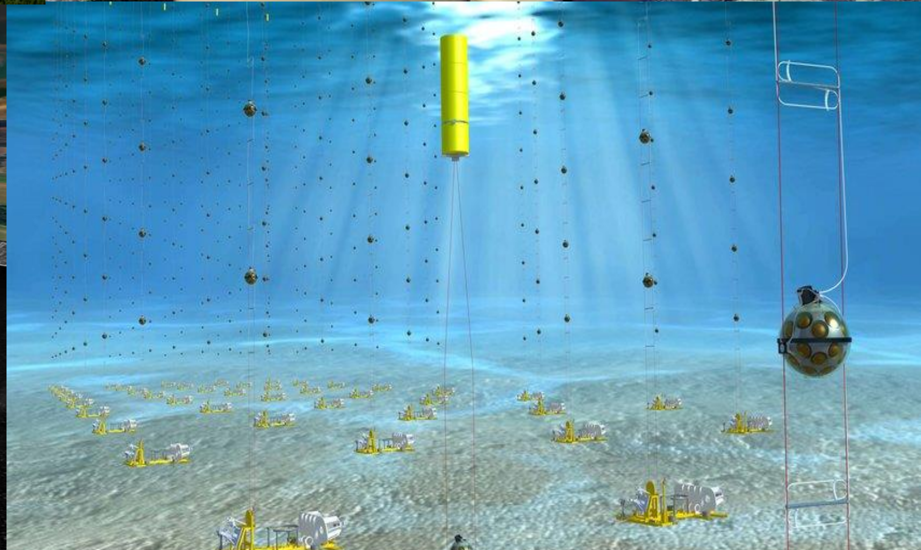
Not a complete list,
many more proposed instruments!











Summary

- Great advances in Astroparticle Physics in the last decade: **experiments reaching discovery sensitivities**
- High-energy multi-messenger astronomy very popular: **first coincidences detected and several interesting candidates**
- Multi-messenger observations provide a more **complete way to study the sources**: two or more fundamental forces involved
- Statistics are still low but **plenty of new/improved detectors in operation soon**

Thanks for your attention

COST QGMM Workshop 2022

Valencia Experimental Group of Astroparticles