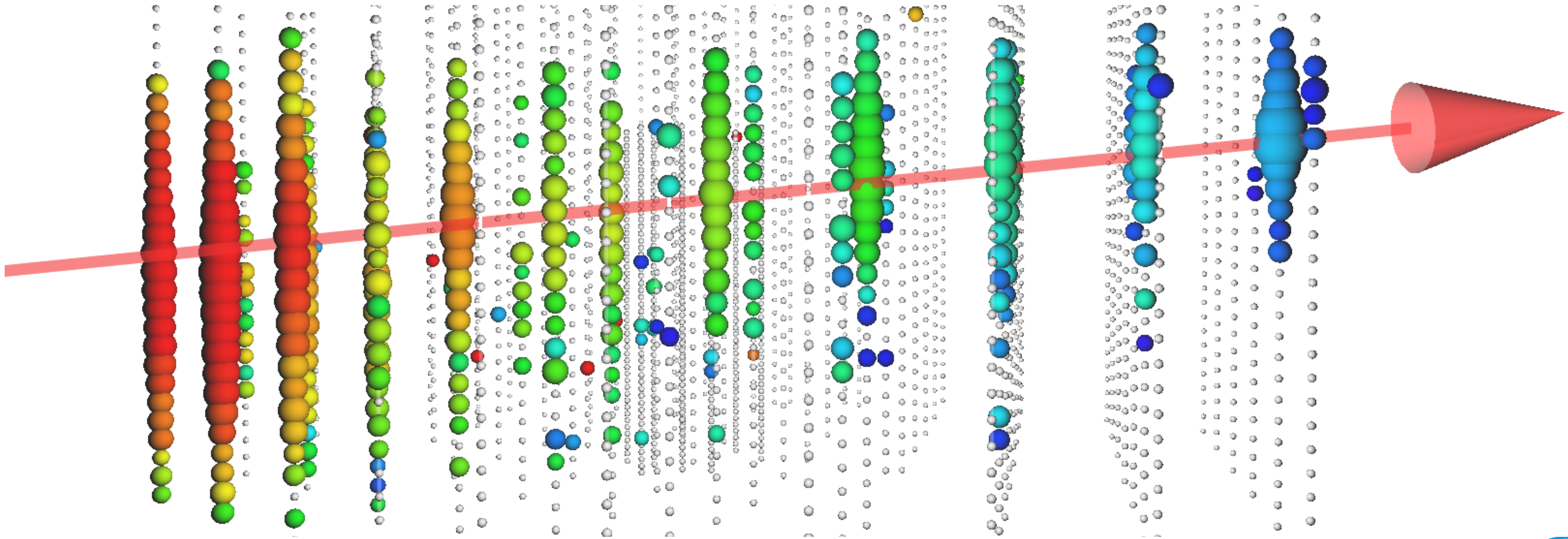
High-energy Neutrino Astronomy: This decade and the next

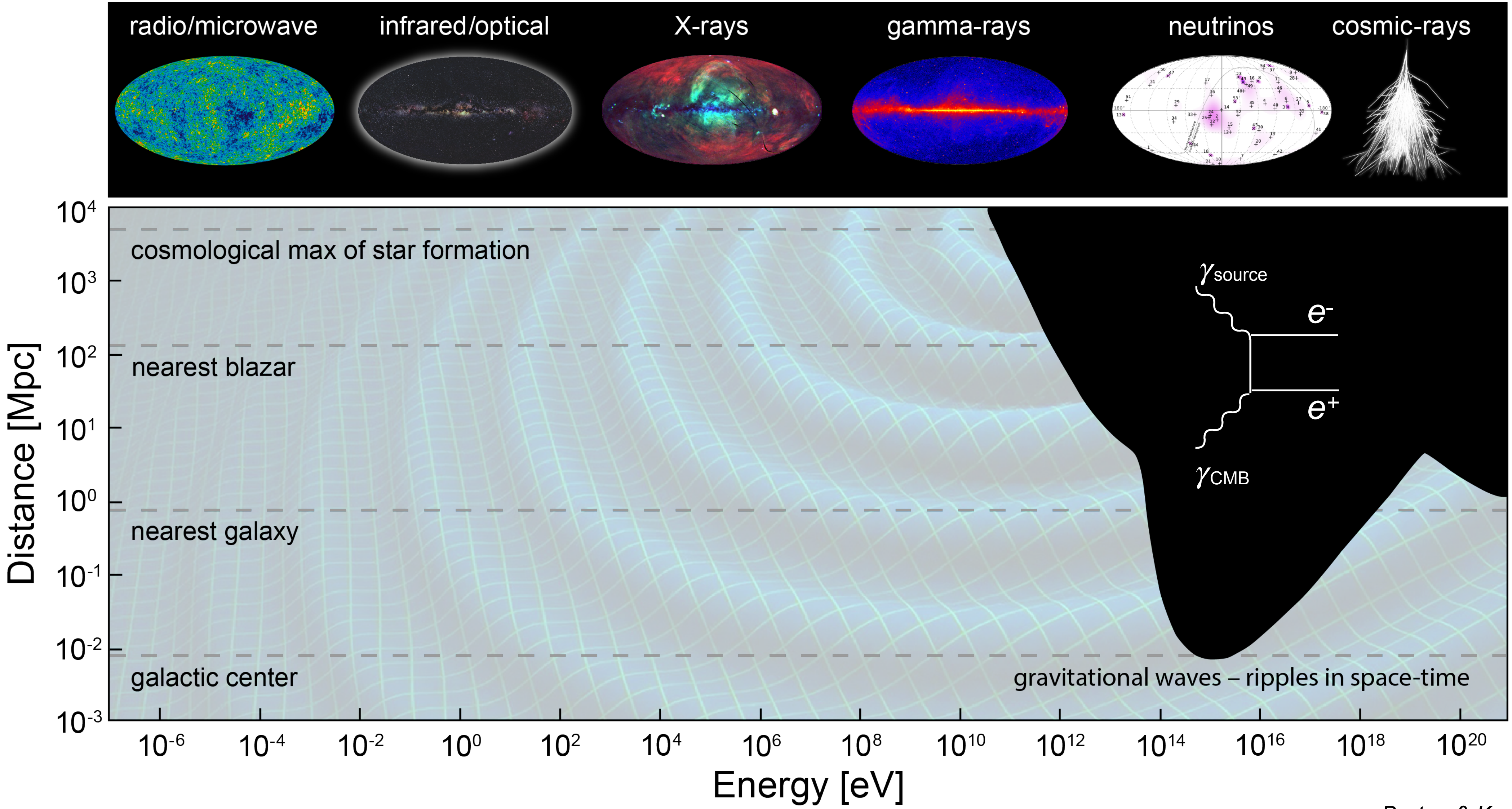
Marek Kowalski, MMA @ EGO, Pisa, 10.10.2022



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

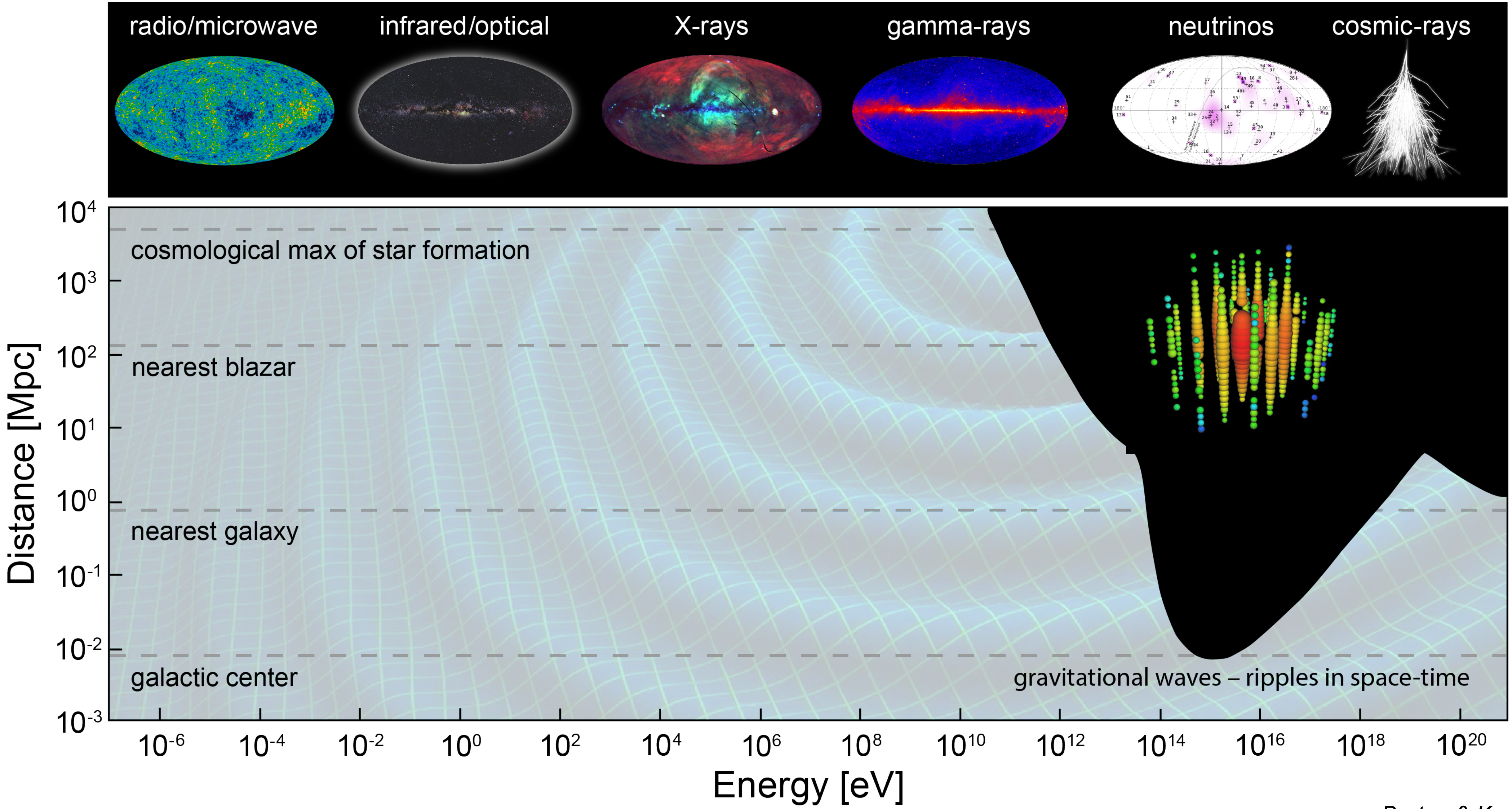
DESY.

Pushing the energy frontier with neutrinos



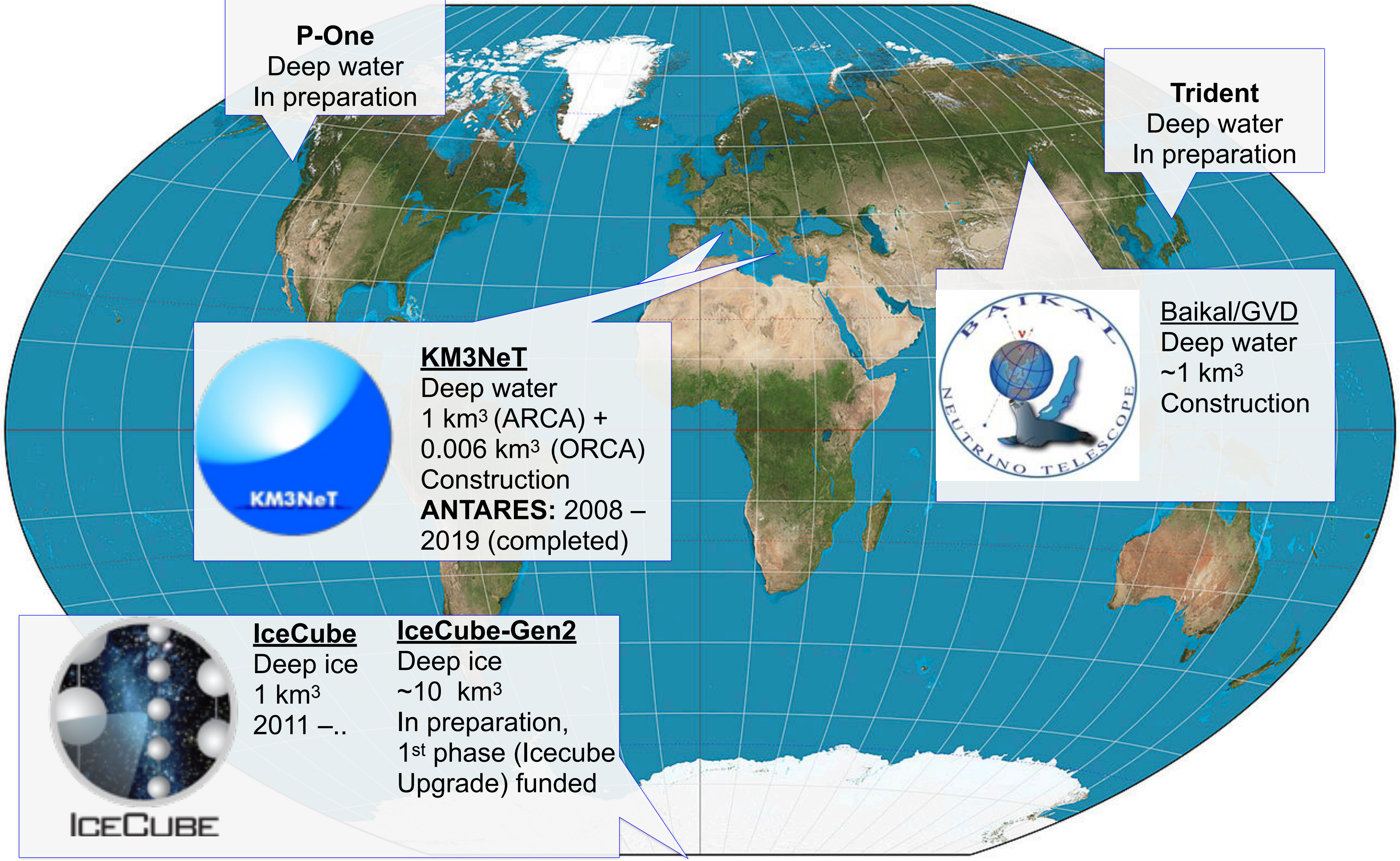
Bartos & Kowalski, IOP 2017

Pushing the energy frontier with neutrinos



Bartos & Kowalski, IOP 2017

The neutrino telescope landscape: GeV (10^9 eV) to tens of PeVs (10^{15} eV)



P-One
Deep water
In preparation

Trident
Deep water
In preparation

KM3NeT
Deep water
1 km^3 (ARCA) +
0.006 km^3 (ORCA)
Construction
ANTARES: 2008 – 2019 (completed)

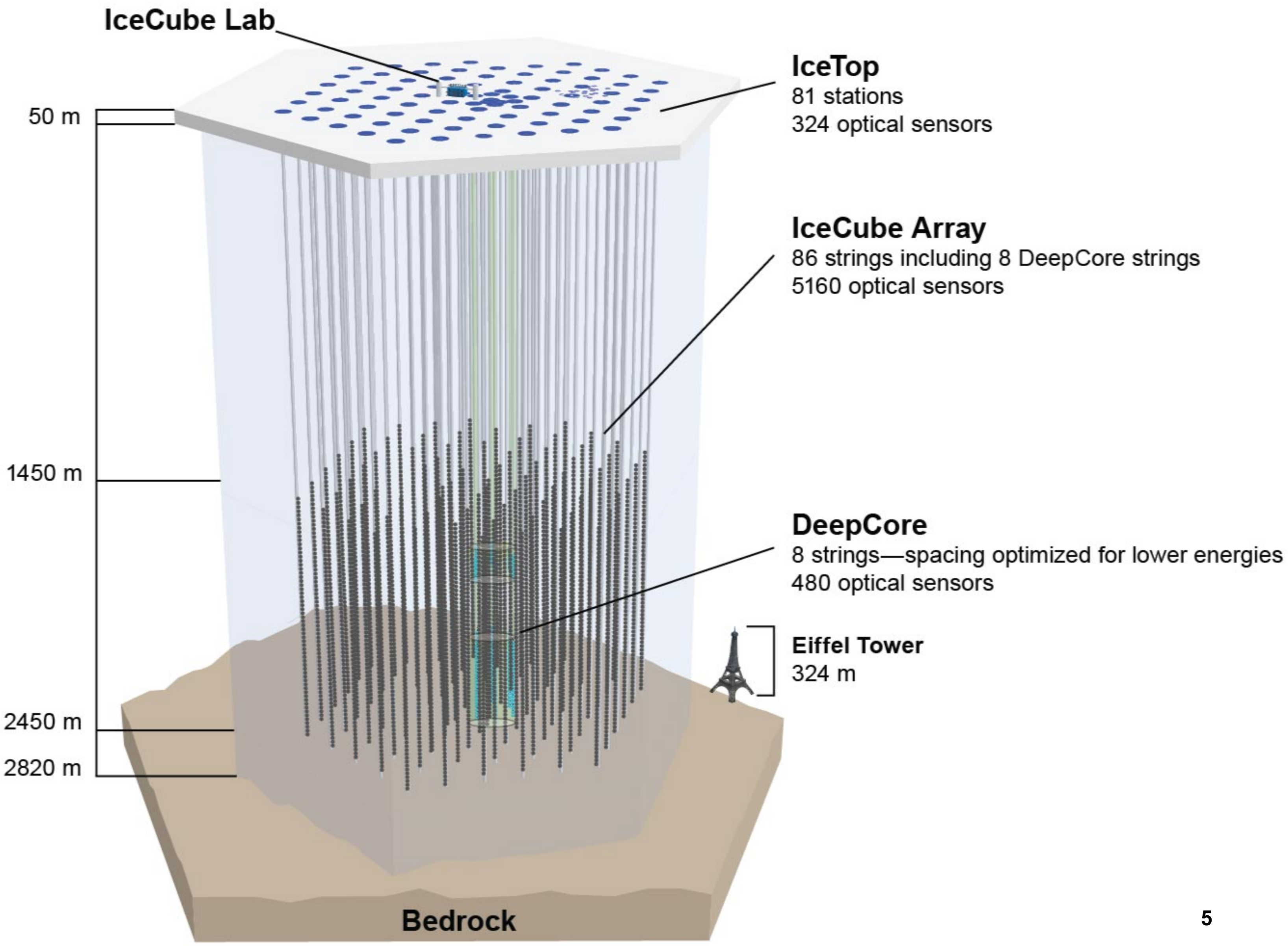
Baikal/GVD
Deep water
~1 km^3
Construction

IceCube
Deep ice
1 km^3
2011 –..

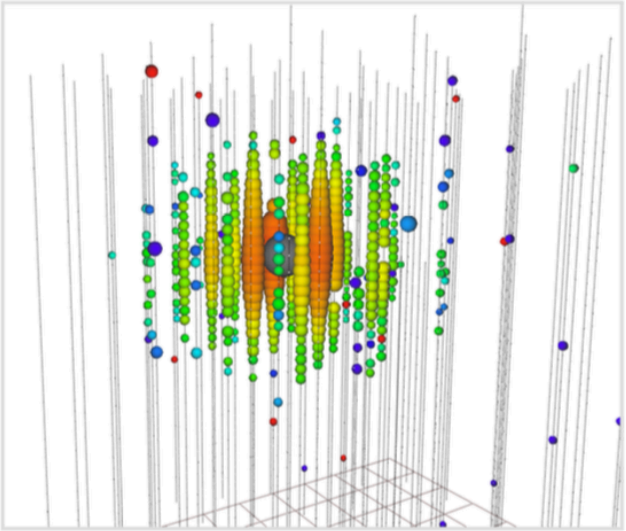
IceCube-Gen2
Deep ice
~10 km^3
In preparation,
1st phase (Icecube Upgrade) funded

The IceCube Neutrino Observatory

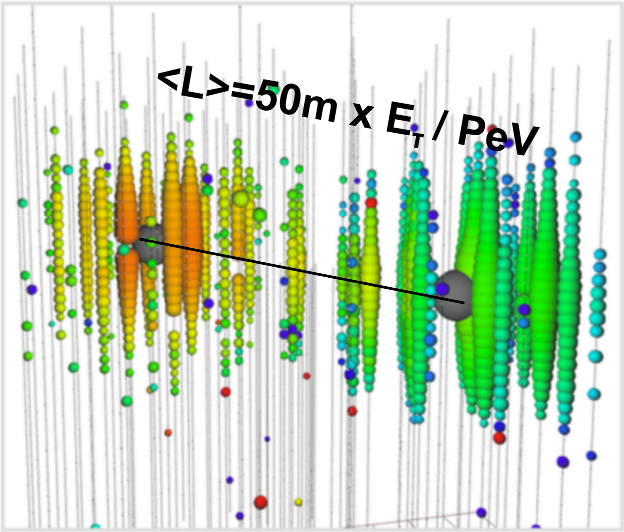
- 5160 PMTs
- 1 km^3 volume
- 86 strings
- 17 m vertical spacing
- 125 m string spacing
- Completed 2010
- Fully operational since 2011



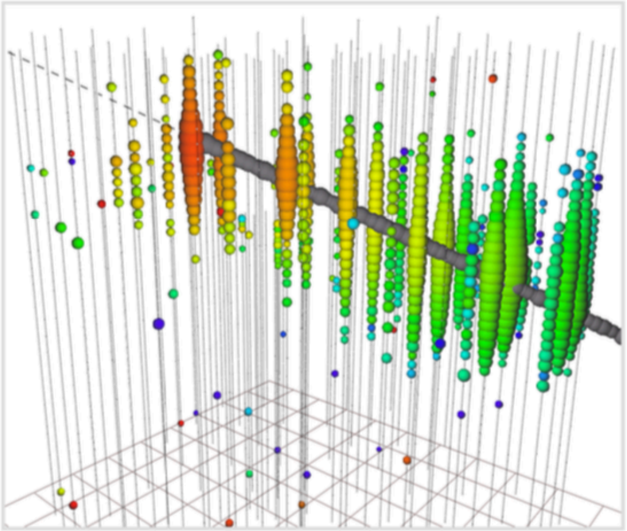
Neutrino Signatures in open water/ice-neutrino telescopes



Electron neutrinos:
isolated cascades



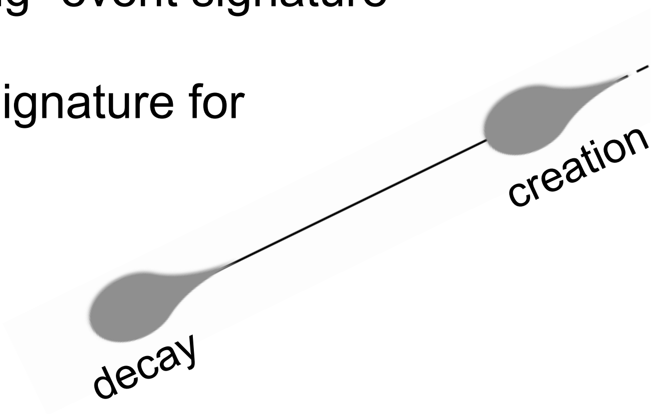
Tau neutrinos:
“double bang”

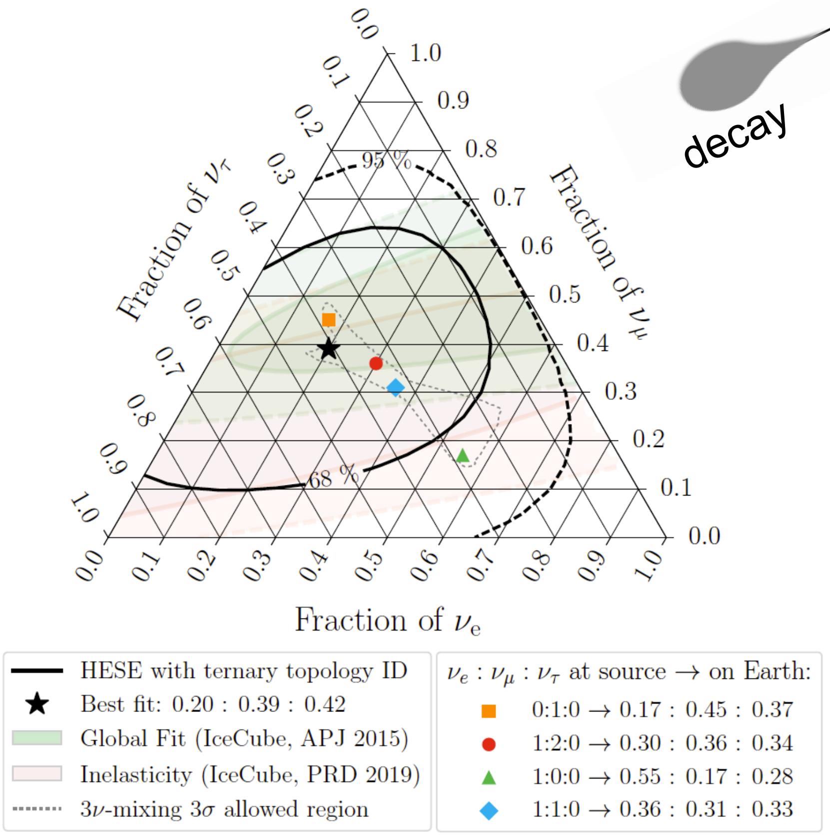


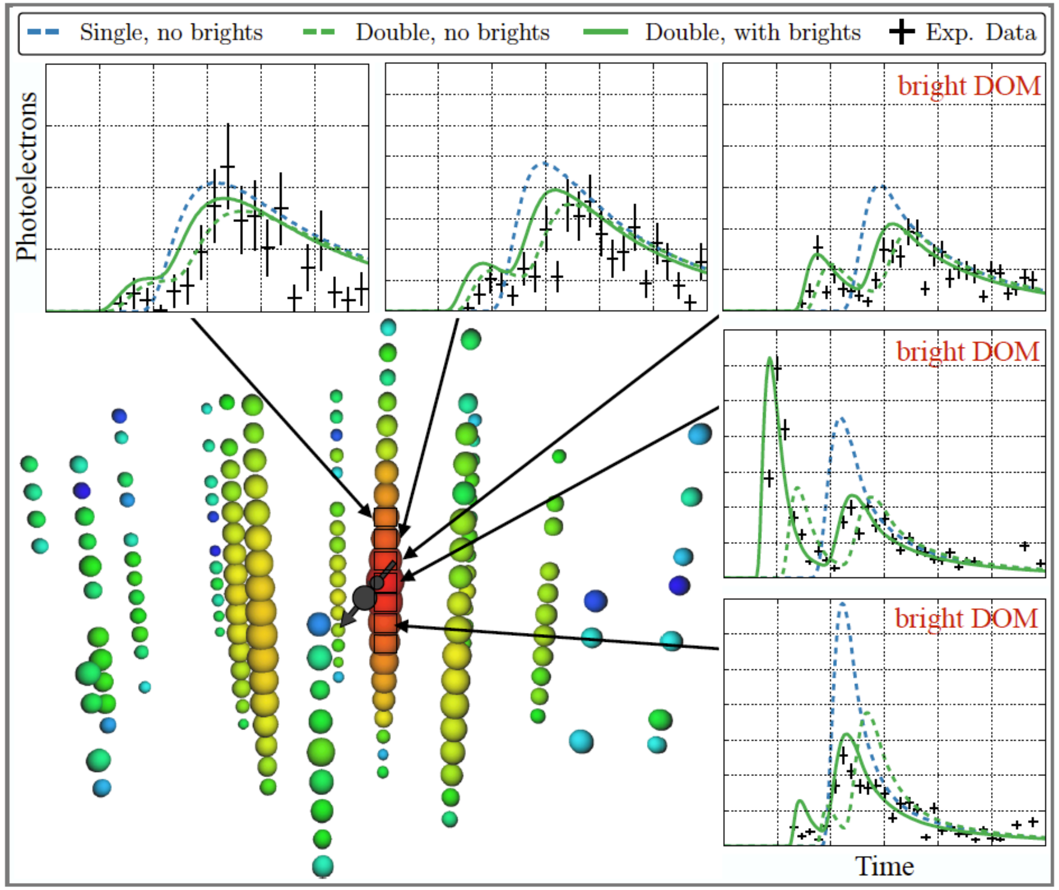
Muon neutrinos:
track-like events

First cosmic tau-neutrino event(s) candidates

- First convincing “Double-Bang” event signature detected by IceCube
- Tau-neutrinos smoking gun signature for astrophysical origin





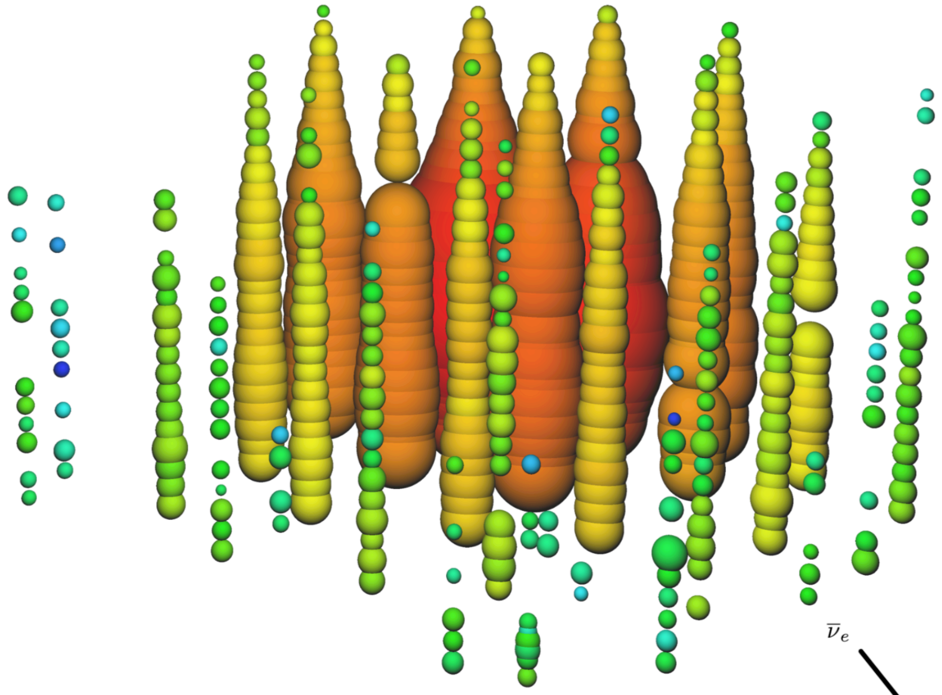


https://arxiv.org/abs/2011.03561
EPJ-C (2022)

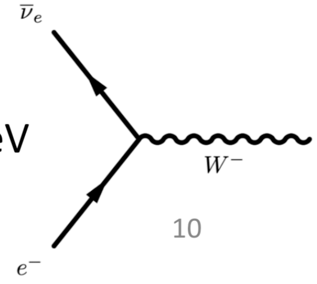
First hint of electron anti-neutrino

W boson (Glashow) resonance

Nature **591,** 220–224 (2021)



W boson resonance , nuebar 6.3 PeV
IceCube, 2021



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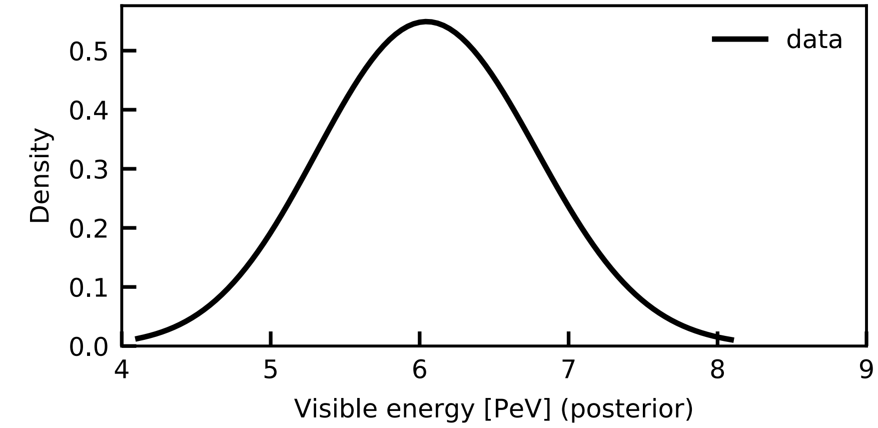
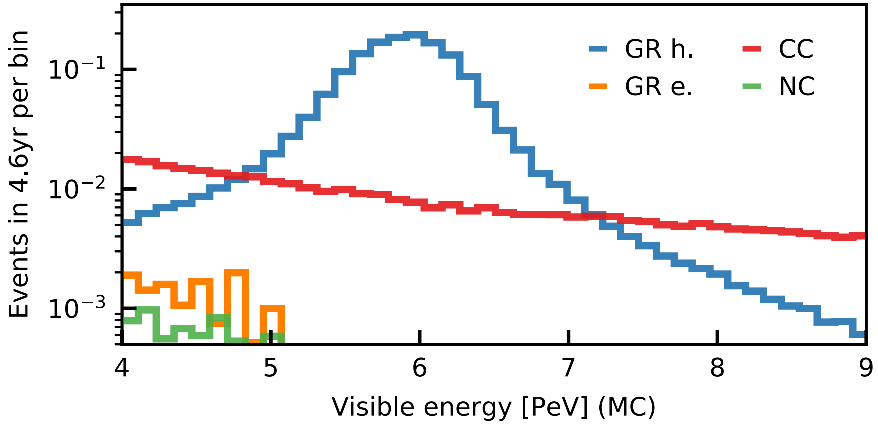
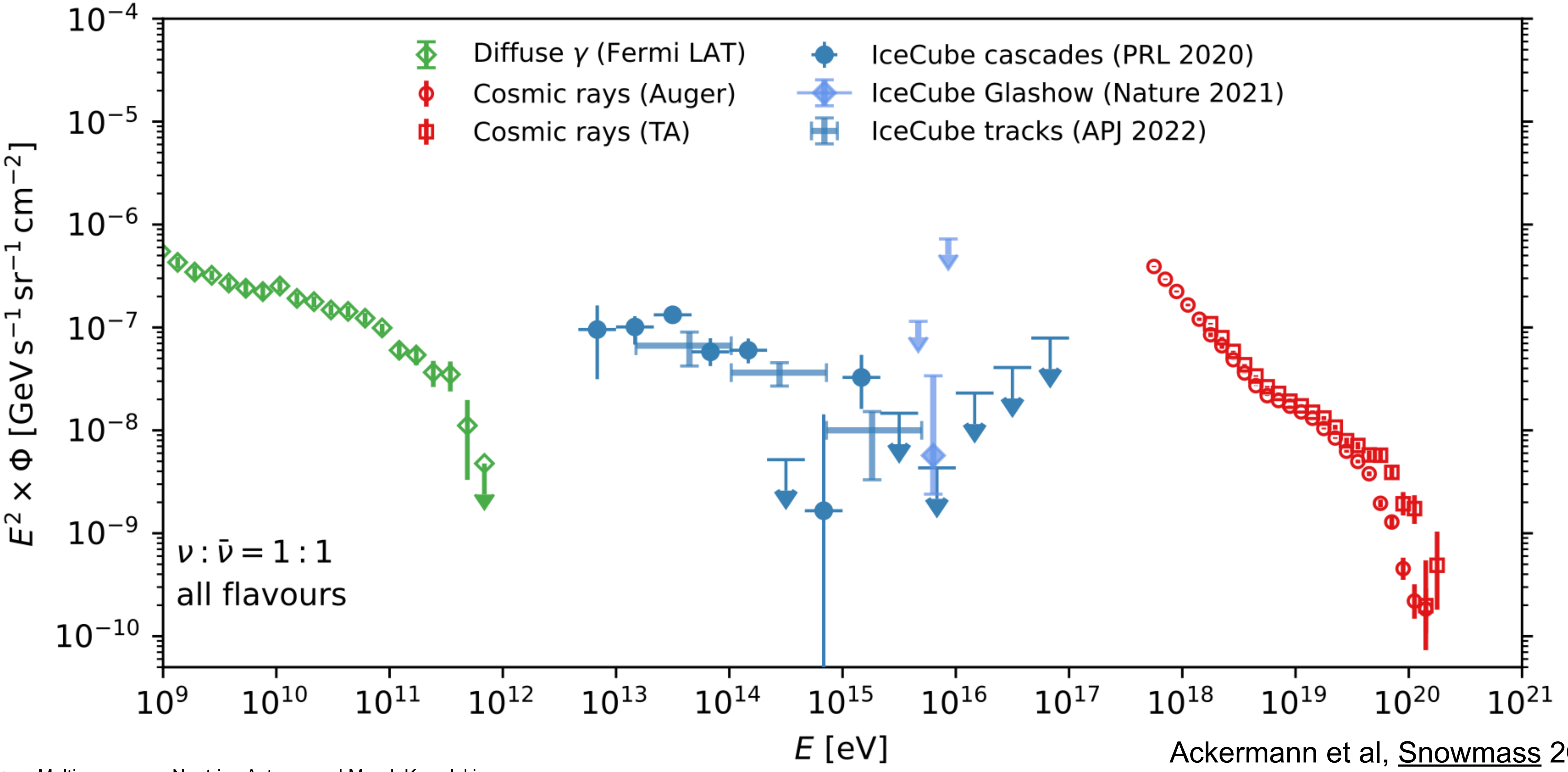




Multimessenger spectroscopy

…with 10 years of IceCube data



Ackermann et al, Snowmass 2022

Multimessenger spectroscopy

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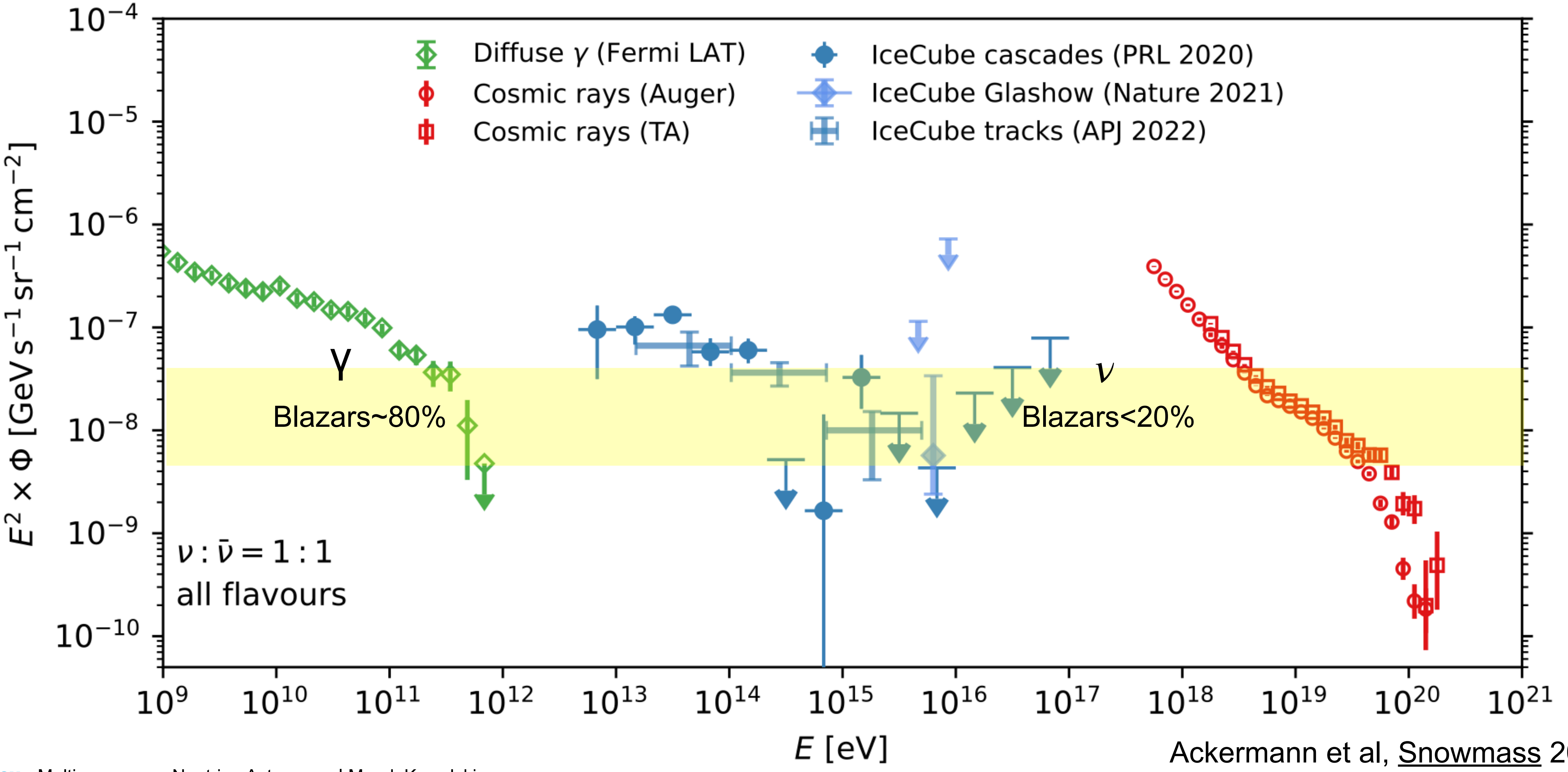
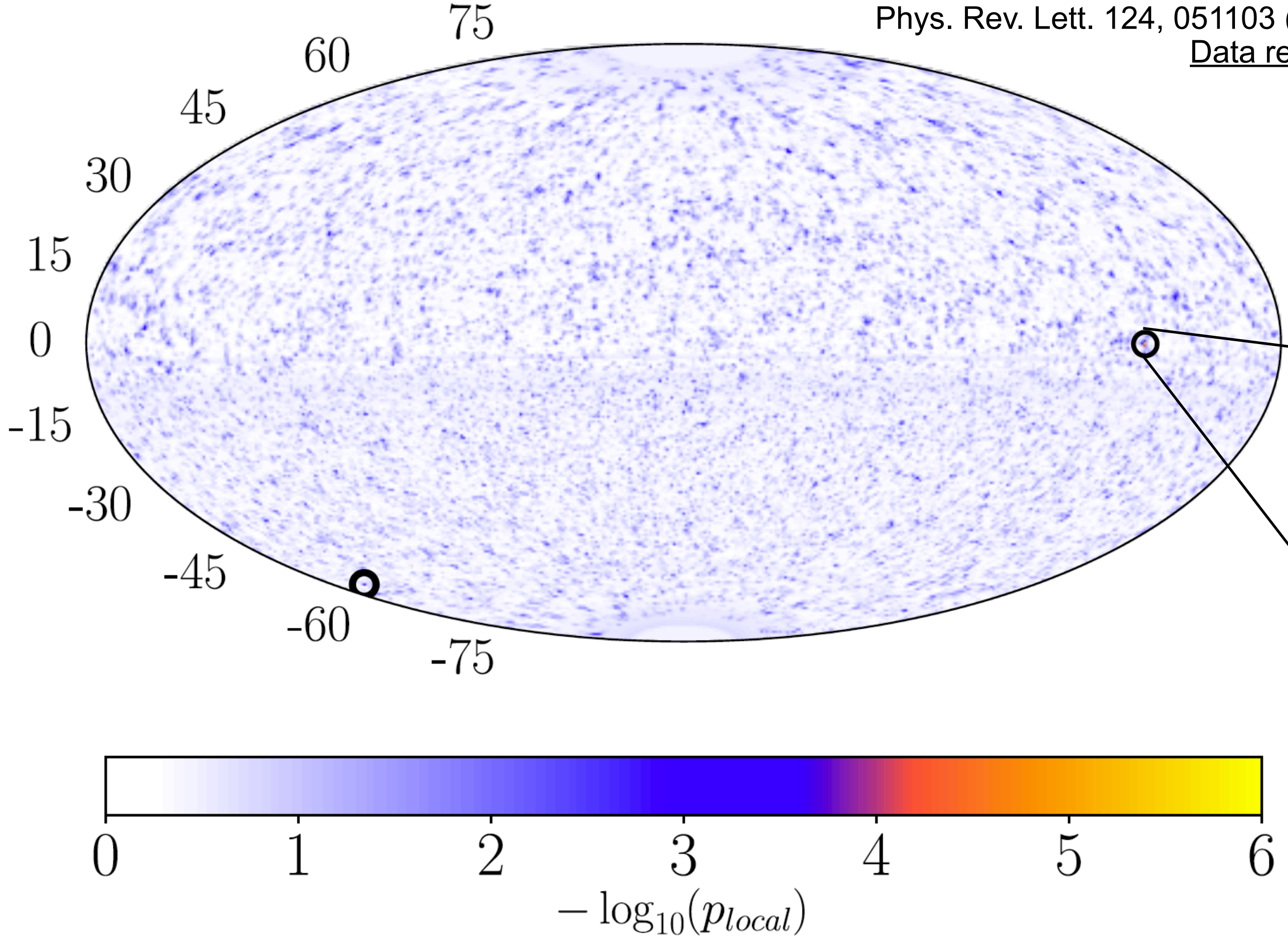
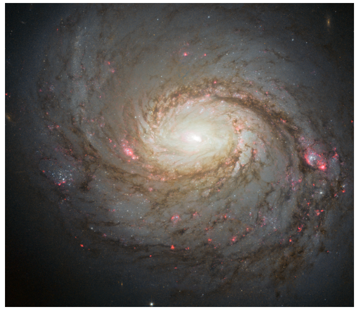


Ackermann et al, Snowmass 2022

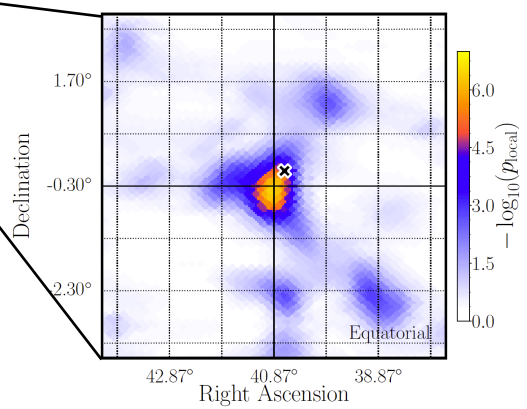
Time-integrated point source searches with 10 years of IC data

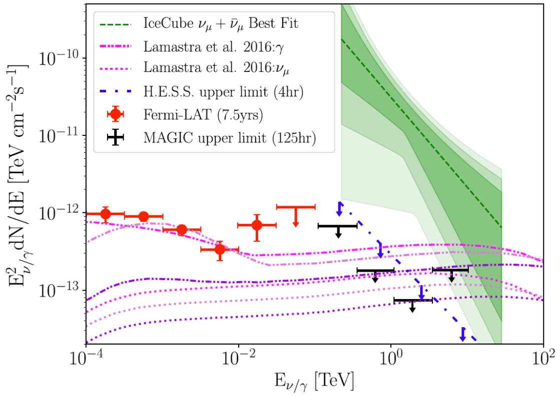
Phys. Rev. Lett. 124, 051103 (2020)
Data release





Most significant excess:
NGC1068 @ 2.9 sigma

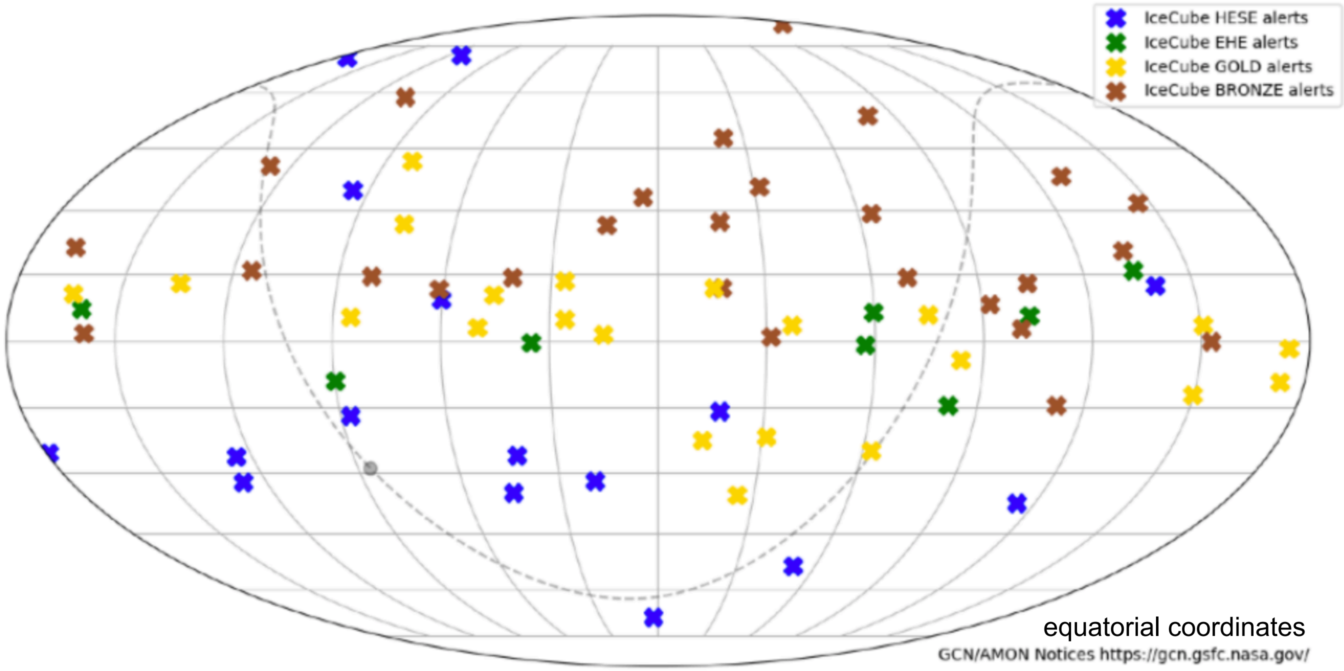


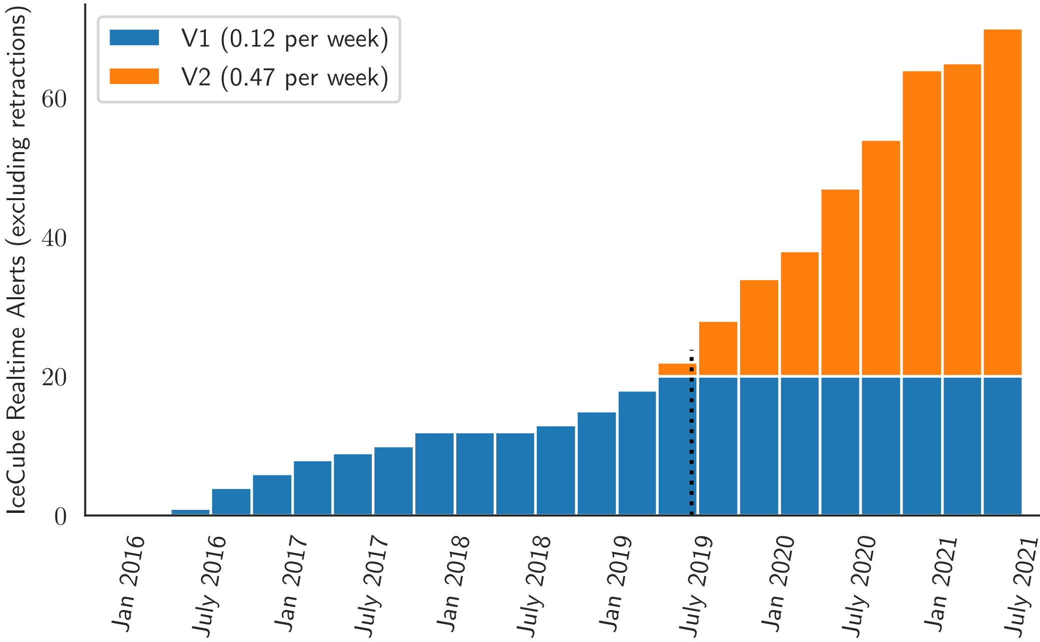


Improved point source analysis on the way

Realtime high-energy neutrino alerts

Public alert stream running since April 2016, >100 alerts so far





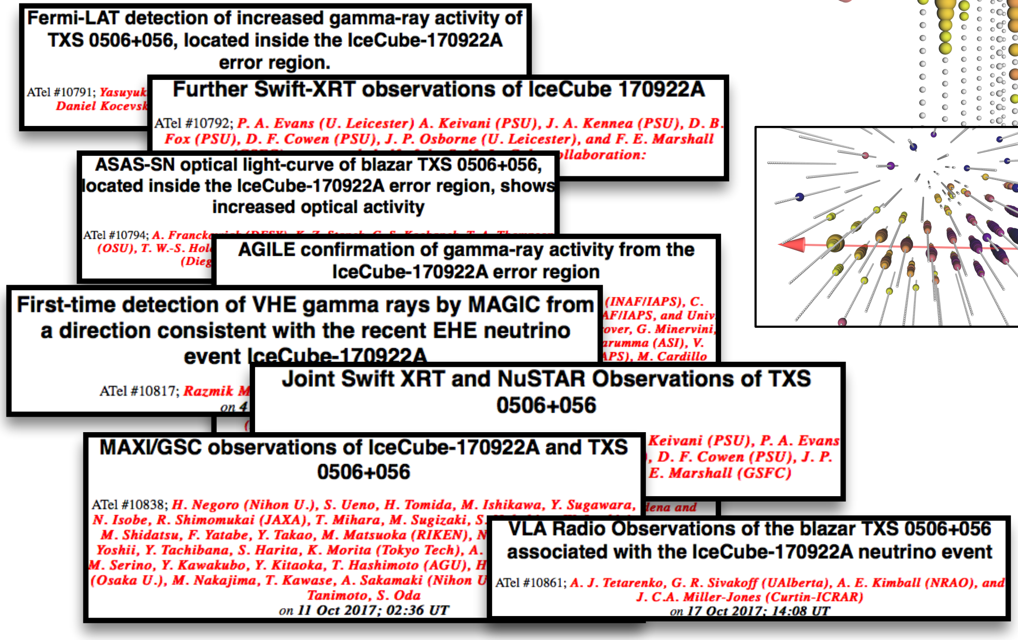
Stein, ICRC 2021

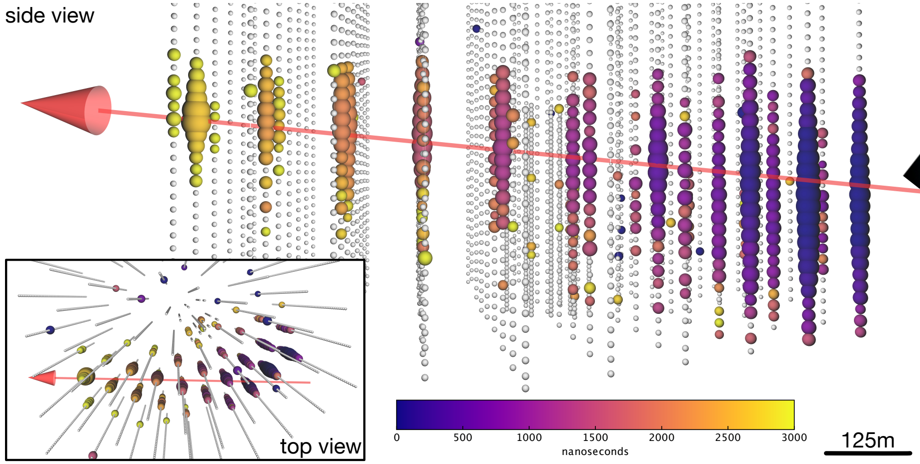
V1: HESE/EHE stream [Astropart. Phys., 92, 30 (2017)]
V2: Improved and unified stream with Gold/Bronze classification (> 0.5/0.3 probability for astro. origin)

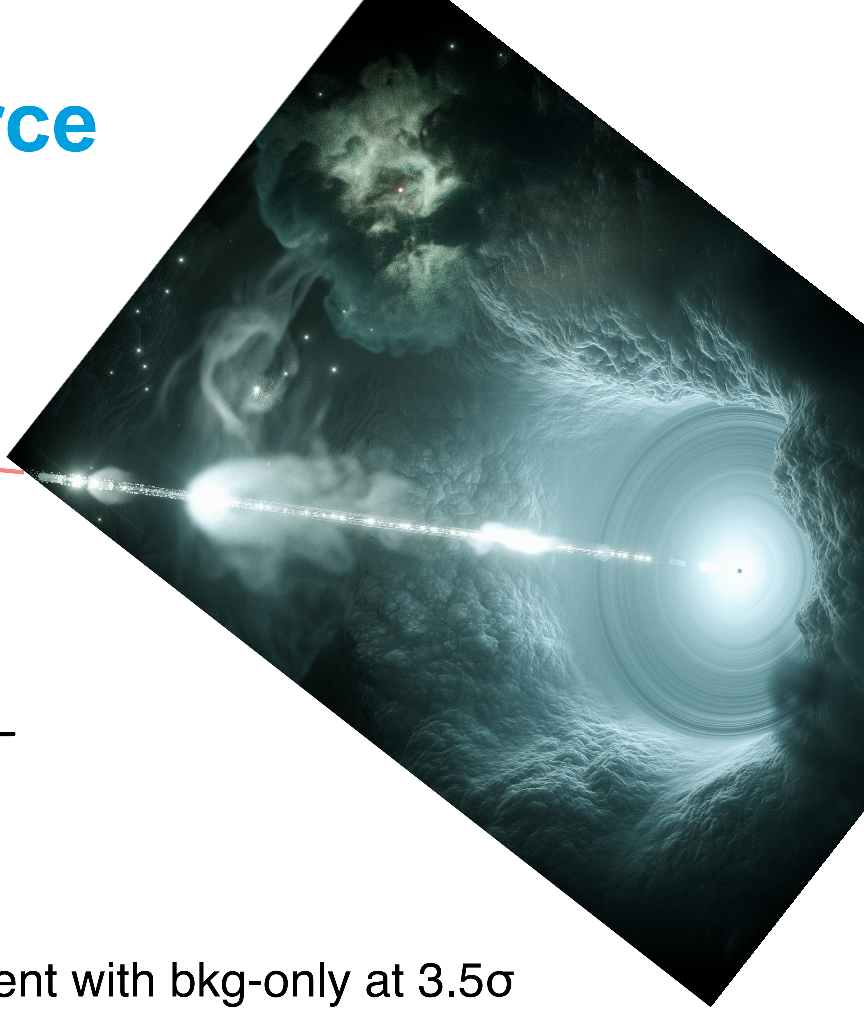
Blaufuss et al, ICRC 2019

TXS 0506+056 - first neutrino point source

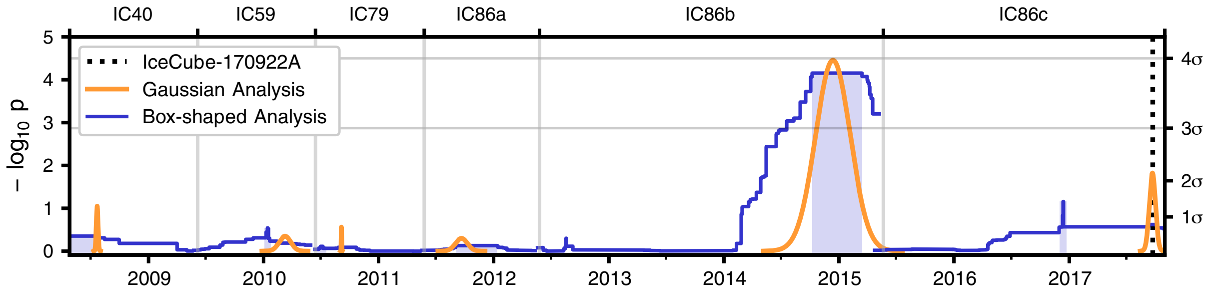
A flaring Blazar in spacial and temporal coincidence with IC170922A





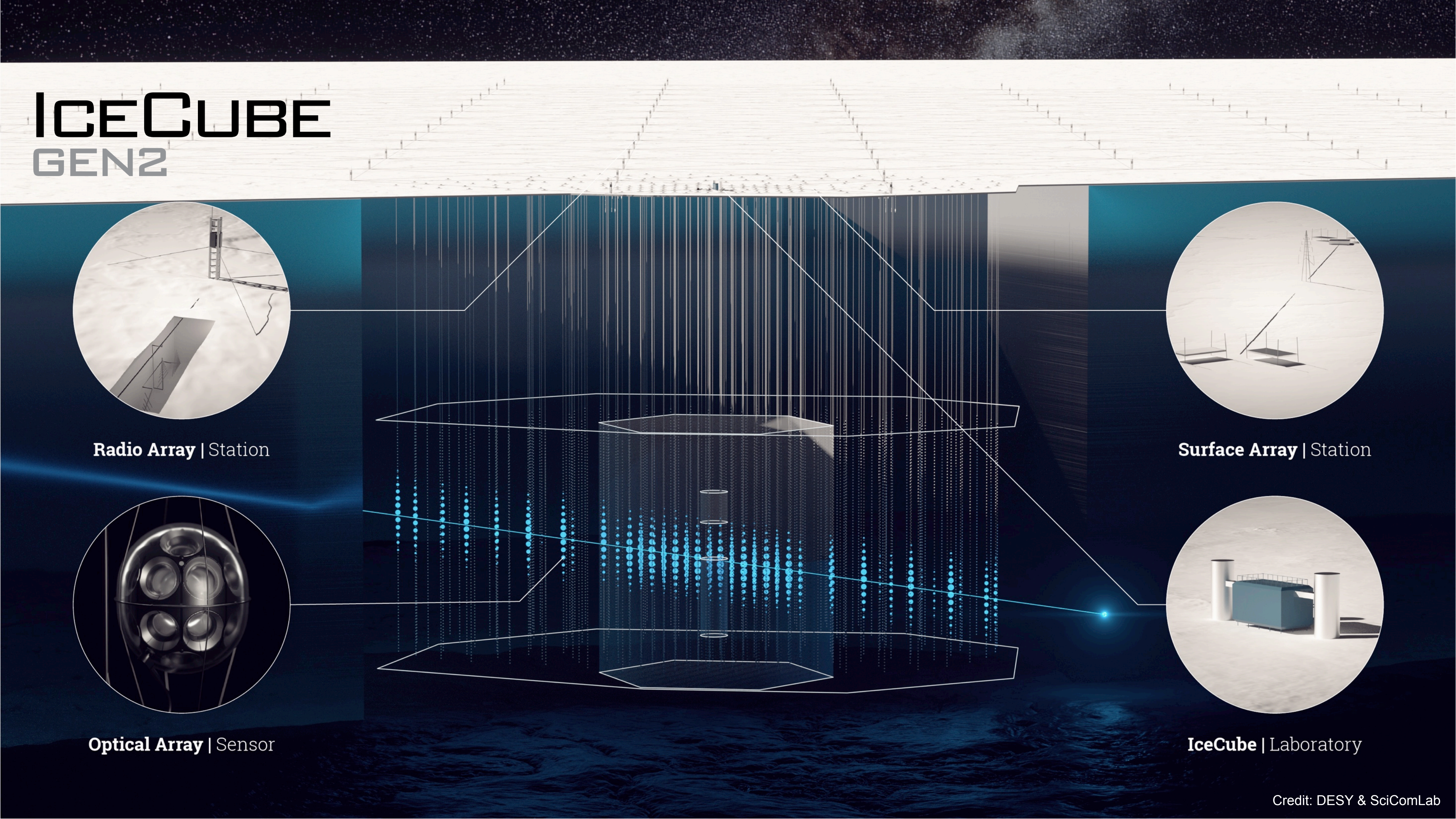


Archival analysis: Inconsistent with bkg-only at 3.5σ
(In addition of the 3σ flaring Blazar coincidence)



Science 361 (2018) no.6398, 147-151

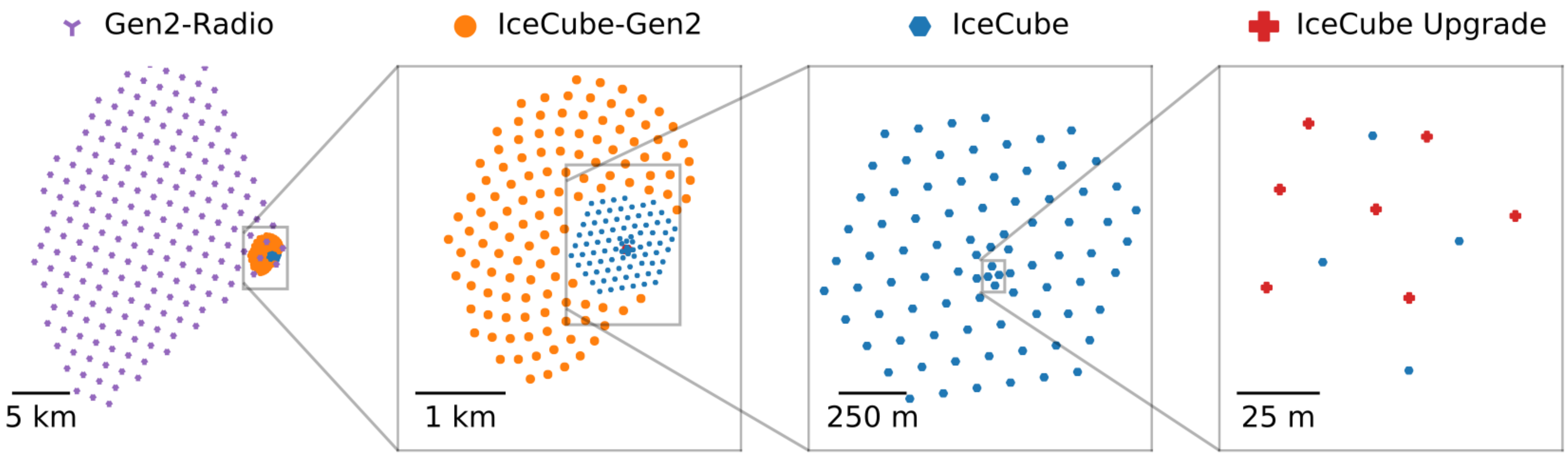
Much more learned: Structured jet, proposed and confirmed (Ros et al, A&A 2020);
Perhaps even periodic: Becker-Tjus et al, 2022?



ICECUBE
GEN2
Radio Array | Station
Surface Array | Station
Optical Array | Sensor
IceCube | Laboratory
Credit: DESY & SciComLab

The IceCube Gen2 facility at the South Pole

A wide-band observatory (10^9 to 10^{20} eV) using several detection technologies – optical, radio, and surface veto – to maximize the science



IceCube-Gen2 planed construction: 2025-2033

completed in 2010

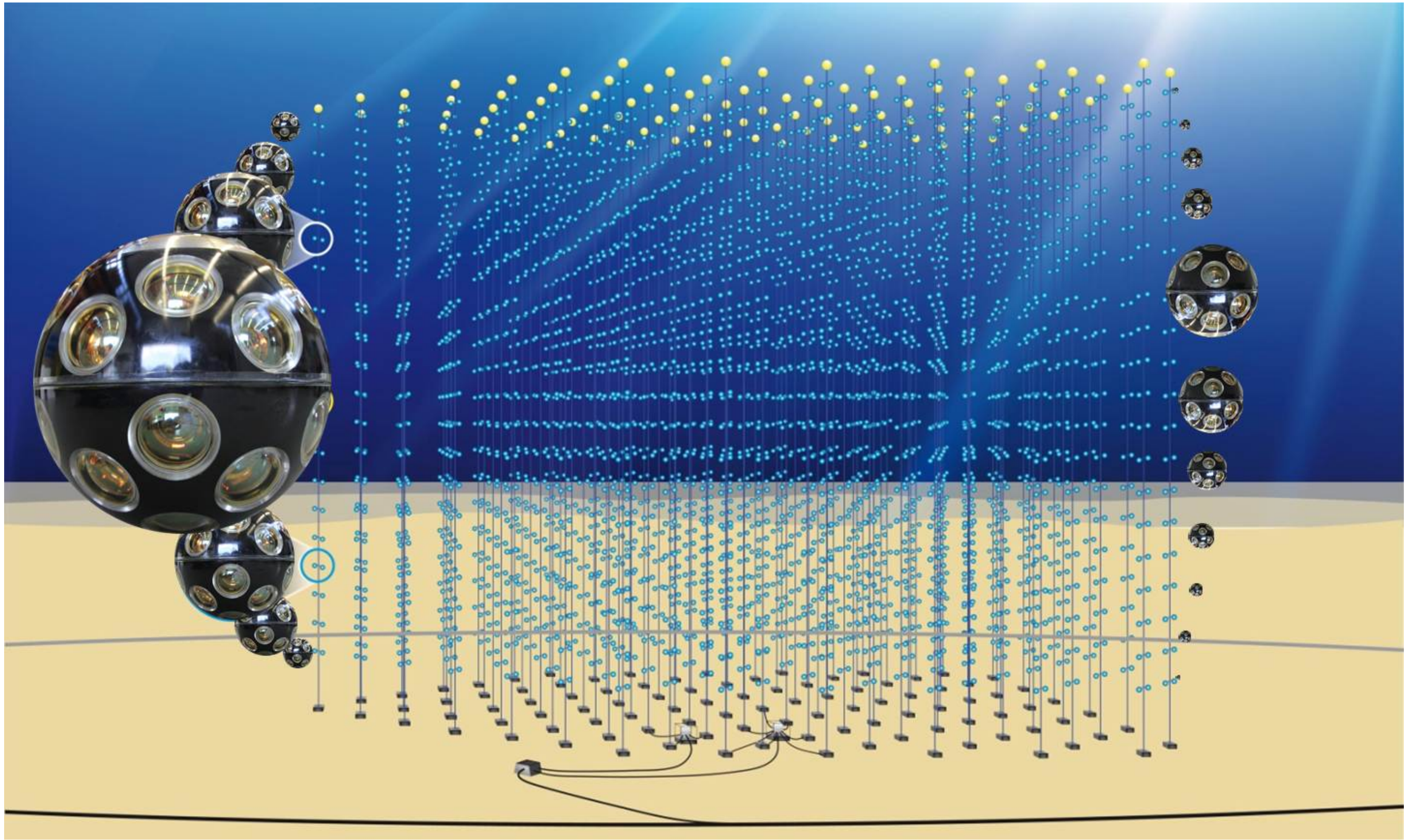
under construction

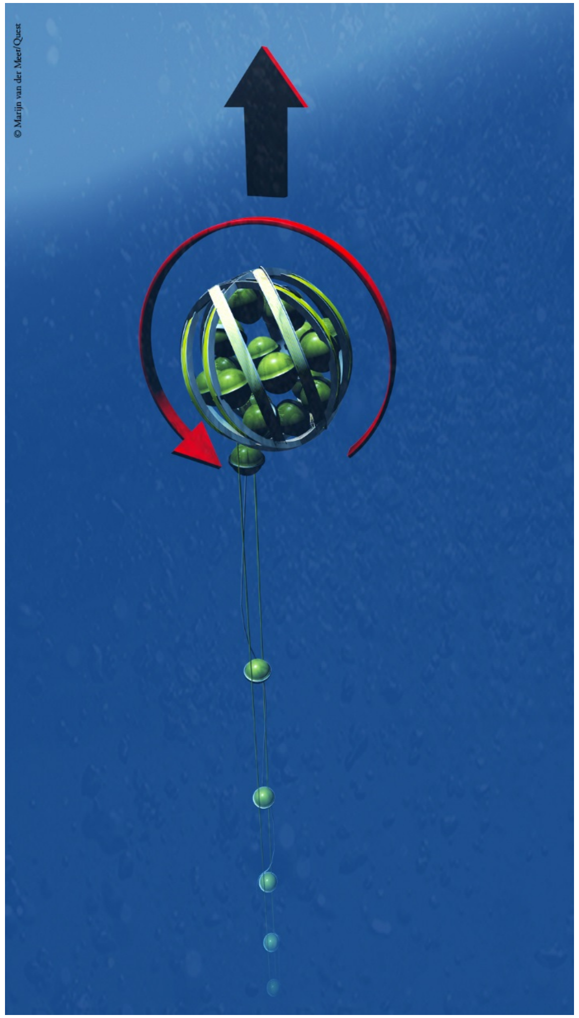
- Point source sensitivity ~5 x IceCube
- Event rate 5-10 that of IceCube
- Significantly expanded energy range

Gen2 white paper: 2008.04323

KM3NeT

KM3NeT consists of "blocks" of 115 strings/detector units with 18 Digital Optical Modules. Two blocks for high energy (ARCA) and one for low energy (ORCA) under construction. Superb angular resolution and complementary hemisphere to IceCube.

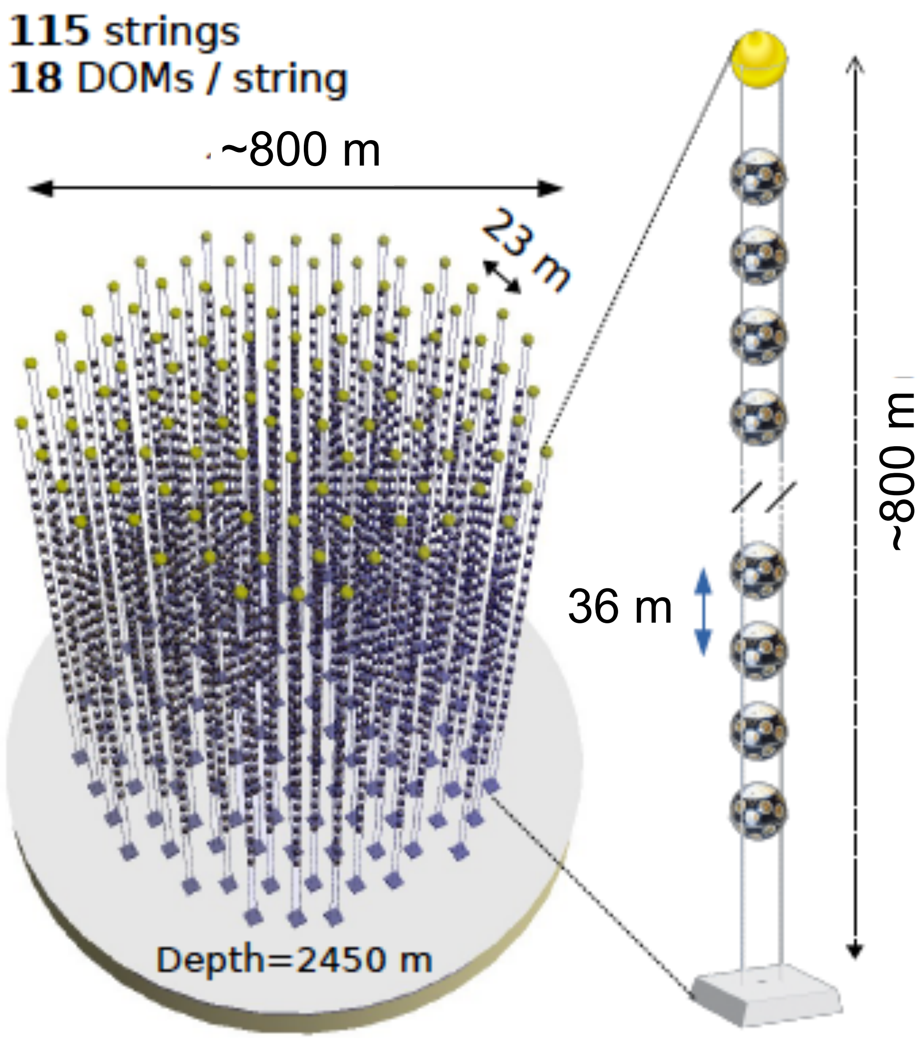




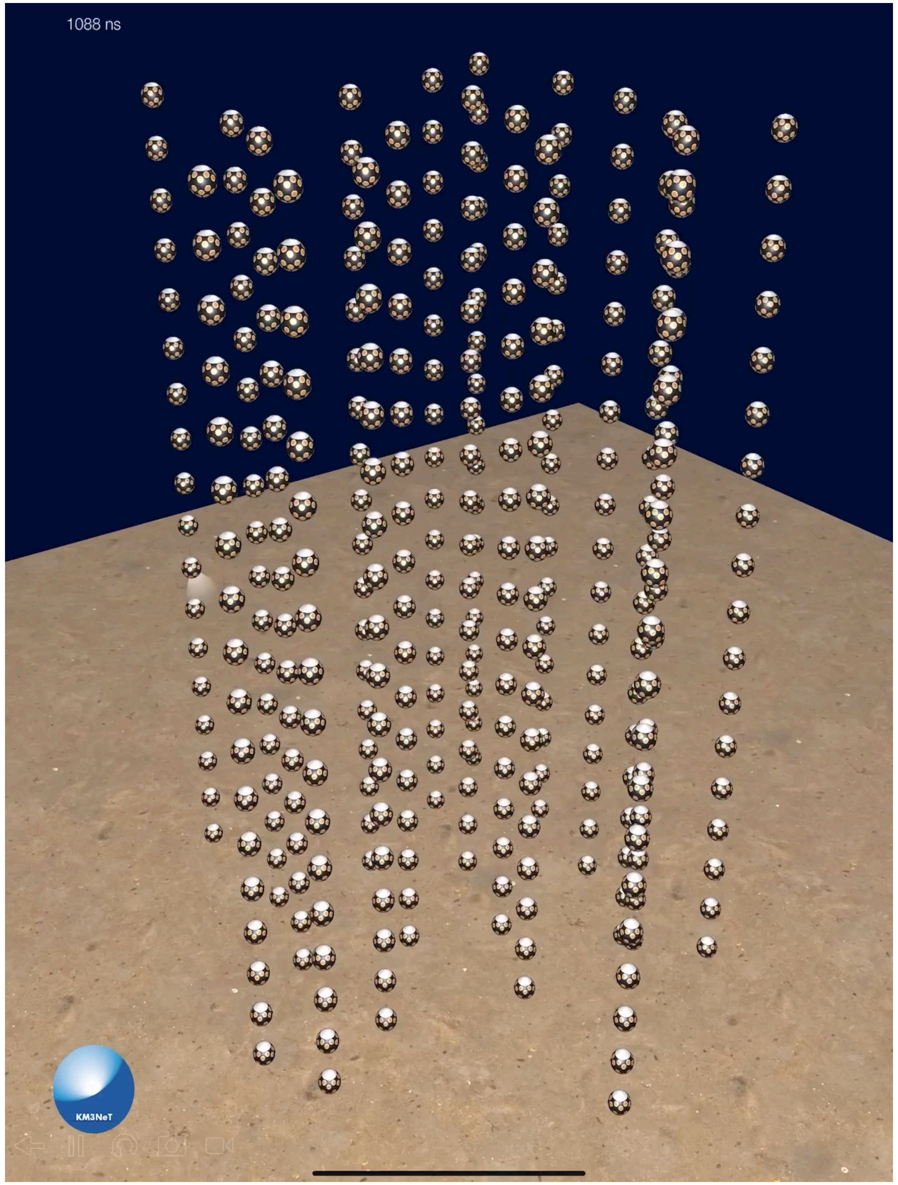
KM3NeT 2.0 Letter of Intent, arXiv:1601.07459

KM3NeT

Construction in full swing



One of two ARCA building blocks

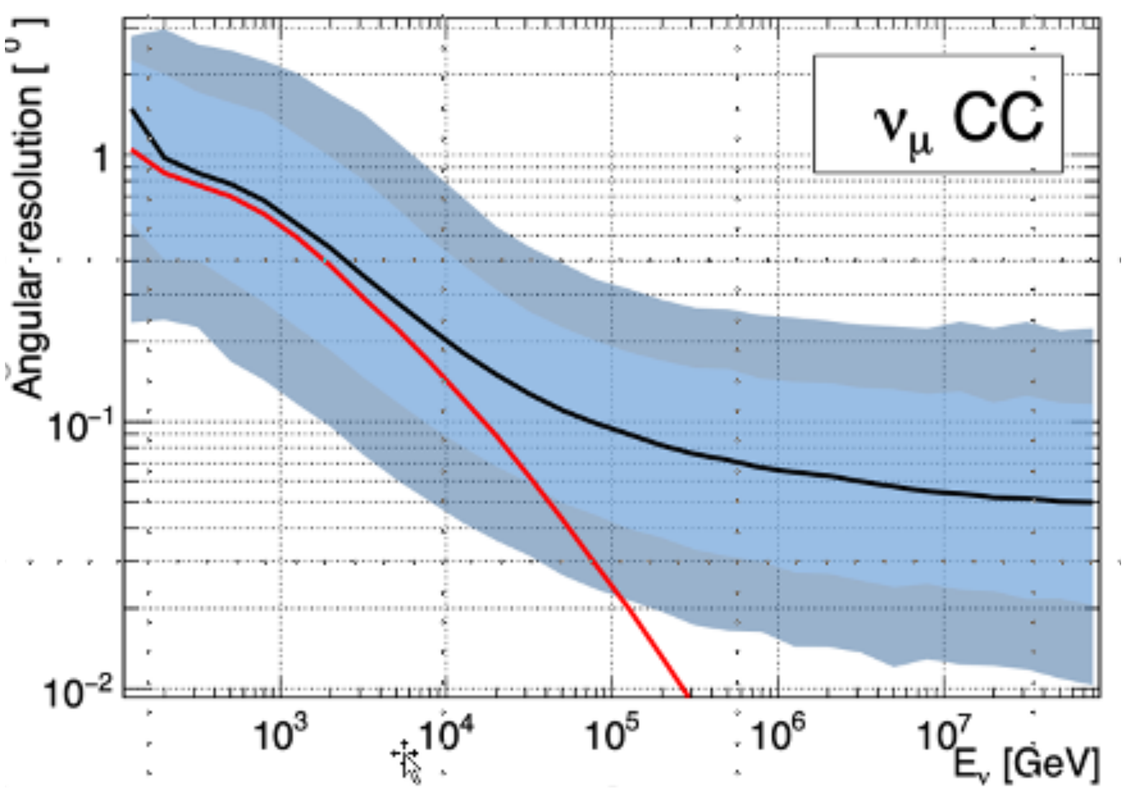


Event with 19 detection units (of ARCA array)

KM3NeT

Two building blocks currently under construction

Angular resolution of KM3NeT



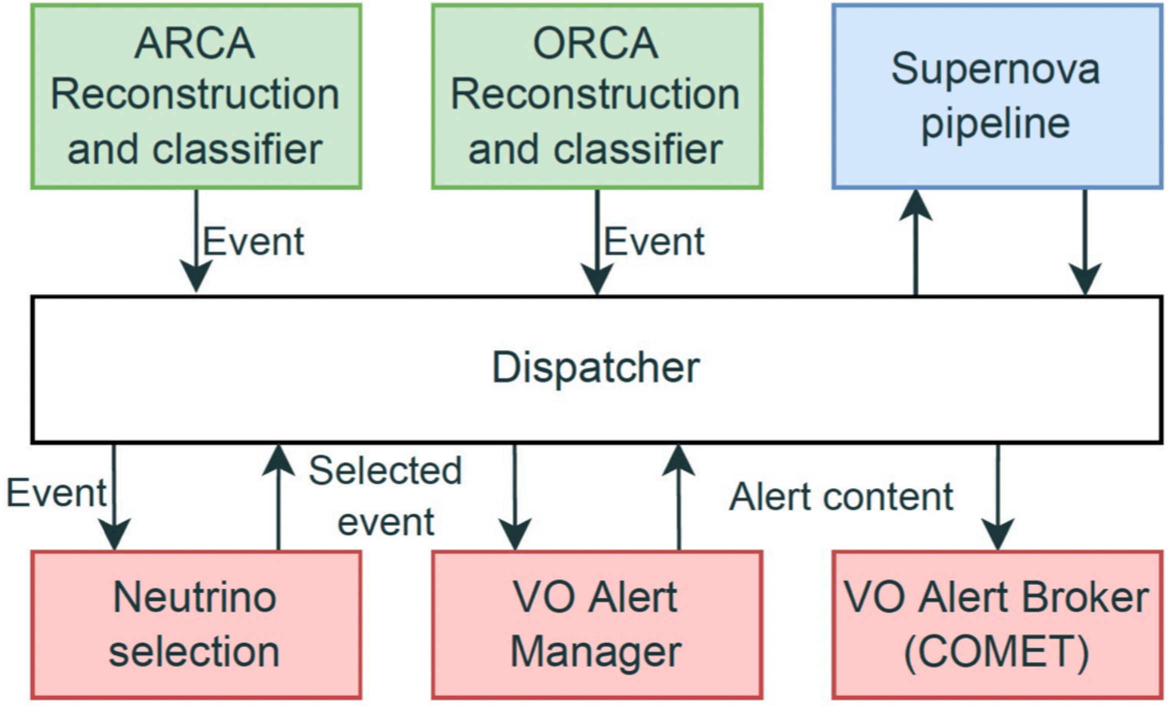


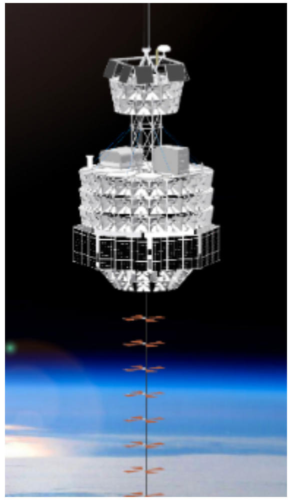
Diagram describing the alert generation

First public alerts from sub-array expected by spring 2023

The highest-energy frontier: EeV (10^{18} eV)

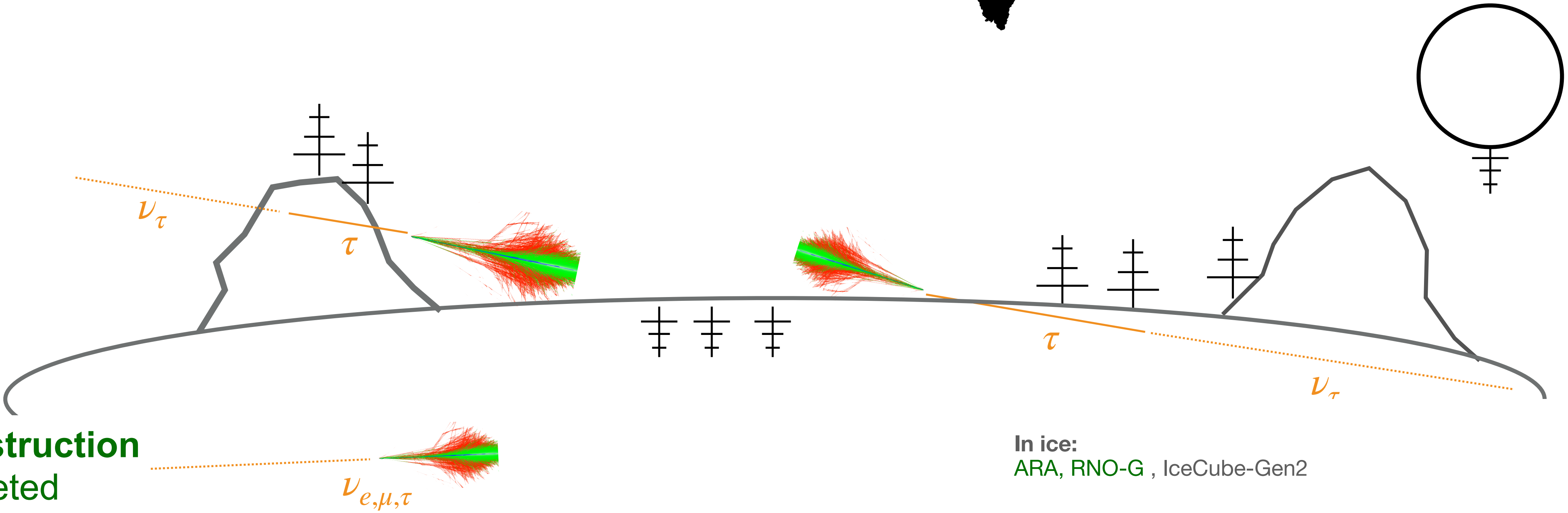
On ground:
Radio: ARIANNA**, ARA**, GRAND, BEACON, TAROGE, IC-Gen2. **RNO-G***
Air-Cherenkov: TRINITY
Water-Cherenkov: Pierre Auger Observatory**, TAMBO
Combination: GCOS

Above Ground:
Ballons: ANITA*, **PUEO***, EUSO-SPB
Satellites: POEMMA



PUEO

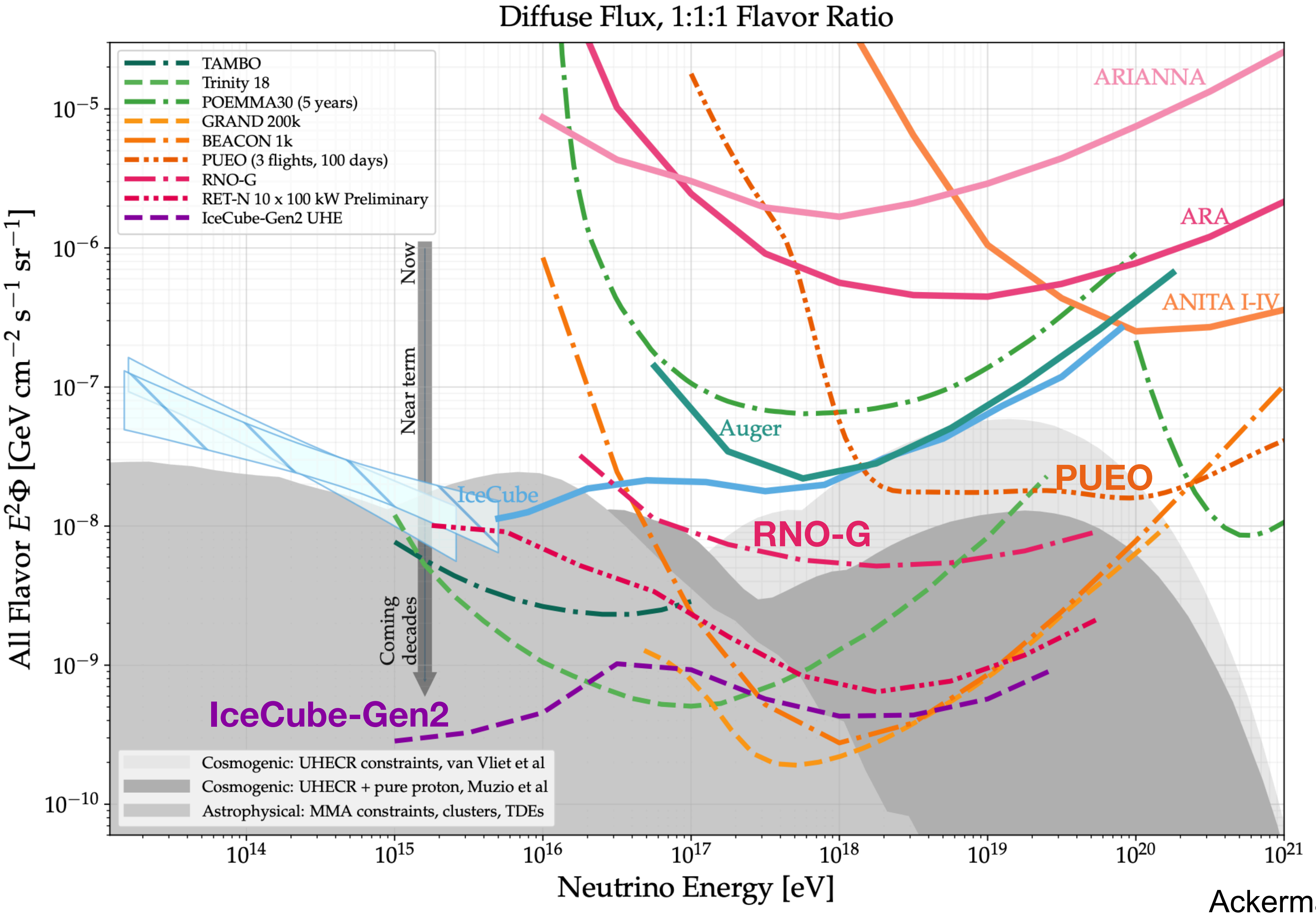
RNO-G
Radio Neutrino Observatory - Greenland



*in construction
**completed

In ice:
ARA, RNO-G , IceCube-Gen2

The highest-energy frontier: EeV (10^{18} eV)



Ackermann et al, Snowmass 2022

Multimessenger astronomy with realtime high-energy neutrino alerts

Selected other follow-up observations based on public data

IC190730A ➔ PKS 1502+106
15th brightest GeV Blazar, with strong radio flare
[Rodriguez et al, Britzen et al]

IC 200107A ➔ BZB / 3 HSP J0955+3551
strong X-ray flare [Paliya et al, Petropoulou et al]

IC191001A ➔ AT2019dsg
Bright TDE with evidence for outflows from radio observations [Stein et al]

IC200530A ➔ AT2019fdr
Super-bright TDE in AGN with IR dust echo
[Stein et al]

AT2019fdr, AT2019dsg, as well as neutrino coincidence detected via AMPEL

Neutrino astronomy with single neutrino associations:

- Single neutrinos probe the full Universe, limited by follow-up capacities and source confusion.
- p-value $\gtrsim 10^{-3}$ for long duration counterparts
- # sources $\propto$ # cosmic neutrinos,

AMPEL

Coincidences not very significant: need for more cosmic neutrinos and follow-up capacities!

Outlook: The Multimesseger connection exemplified with TDEs

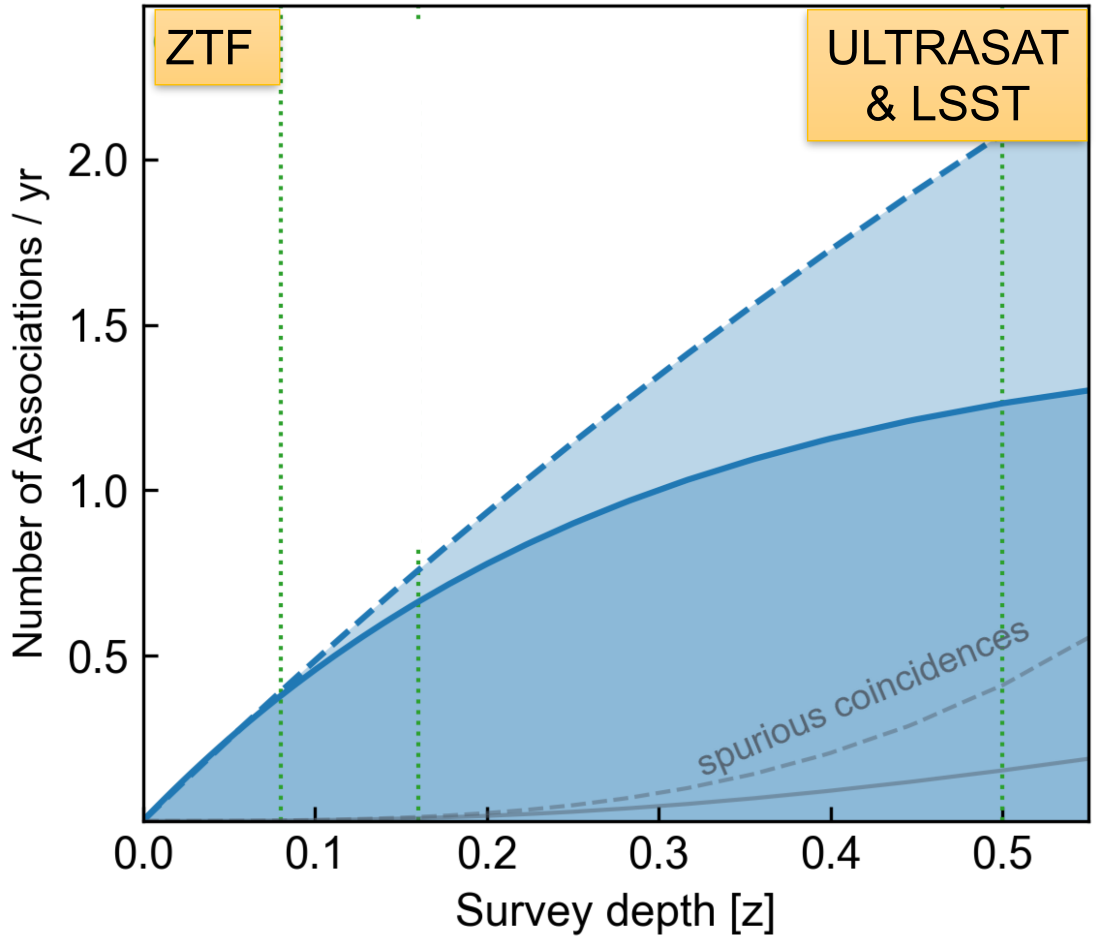
Can we map the history of cosmic ray production via neutrino alerts and follow-up observations?

Currently, with **ZTF** we can detect potential TDE only to redshift of ~0.1.

LSST and ULTRASAT will allow to detect TDEs to a redshift ~0.5.

If TDEs established as high-energy neutrinos and cosmic ray sources, we can **map history of cosmic ray production through cosmic time** through multi-messenger observations.

Similar argument applies to Blazars and a range of other em. wavelength



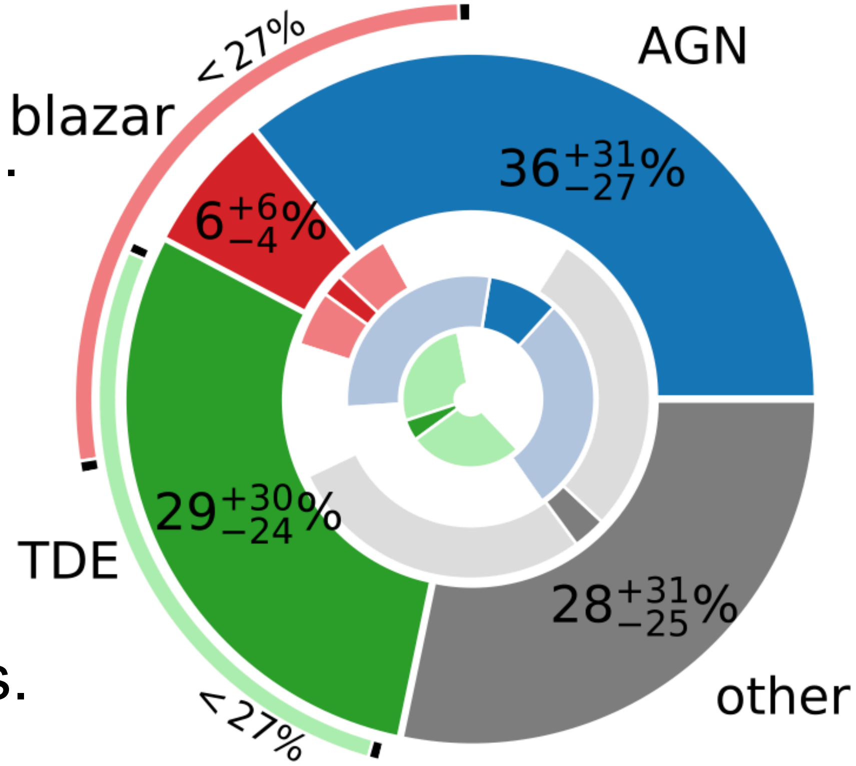
Expected rate of TDE/neutrino coincidences with IceCube alerts, normalized to current coincidence rate

Enabling Multimessenger neutrino astronomy

Large majority of alerts still without identified counterpart.
Major source classes unknown. [Speculation allowed! →].

A fantastic puzzle to figure out, requiring:

- More, well resolved neutrinos
- Wide-field (ideally all sky) EM counterpart discovery obs.
- Follow-up from radio to gamma-rays to identify features
- Multimessenger search automatization following FAIR principles



Bartos et al. 2022

Conclusion

- IceCube, completing construction 11 years ago, already delivered several breakthroughs in neutrino astronomy and pushed the boundaries in cosmic ray science as well as neutrino physics.
- KM3NeT under construction, with ccompletion anticipated for 2026, about to deliver public alerts with unprecedented resultion. Baikal-GVD also starting to deliver on its promise.
- Next generation/decade detectors optimized to harvest the enormous scientific opportunities, e.g. 10 times larger alert statistics and expanded sensitivity up to 10^{20} eV in energy.
- Multimessenger observations & techniques essential for exploiting full potential of neutrino astronomy.