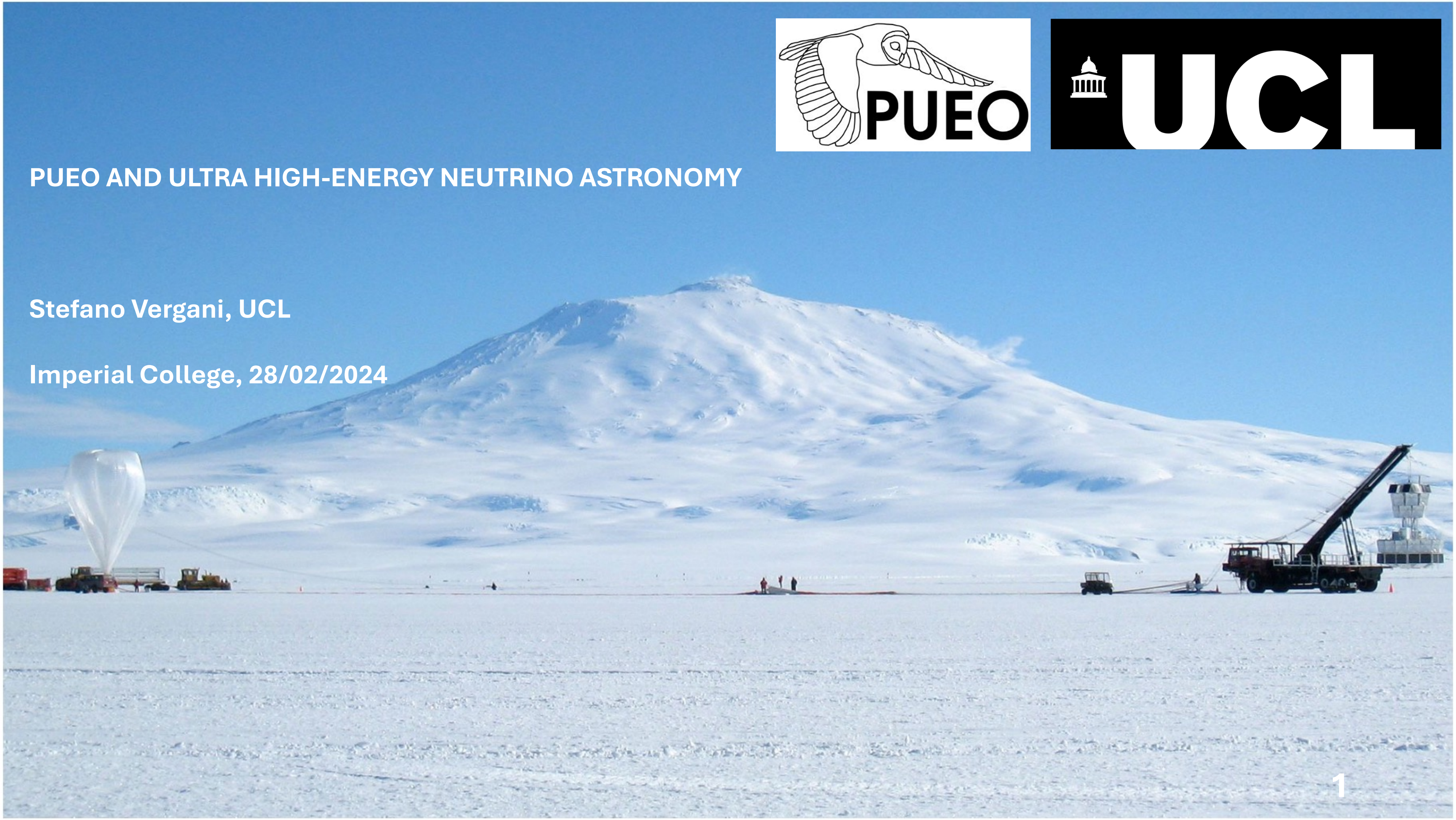
PUEO AND ULTRA HIGH-ENERGY NEUTRINO ASTRONOMY

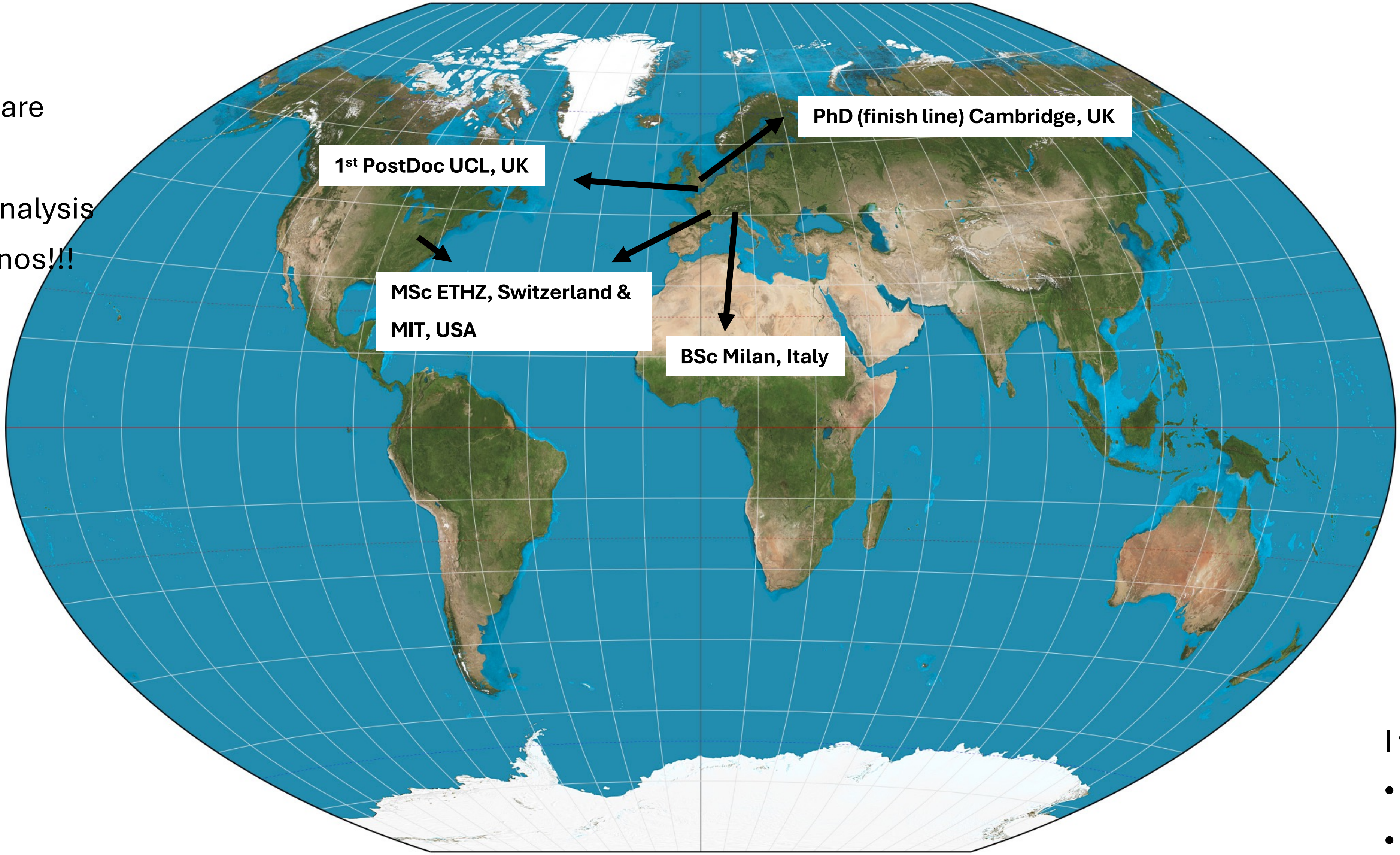
Stefano Vergani, UCL

Imperial College, 28/02/2024



I like:

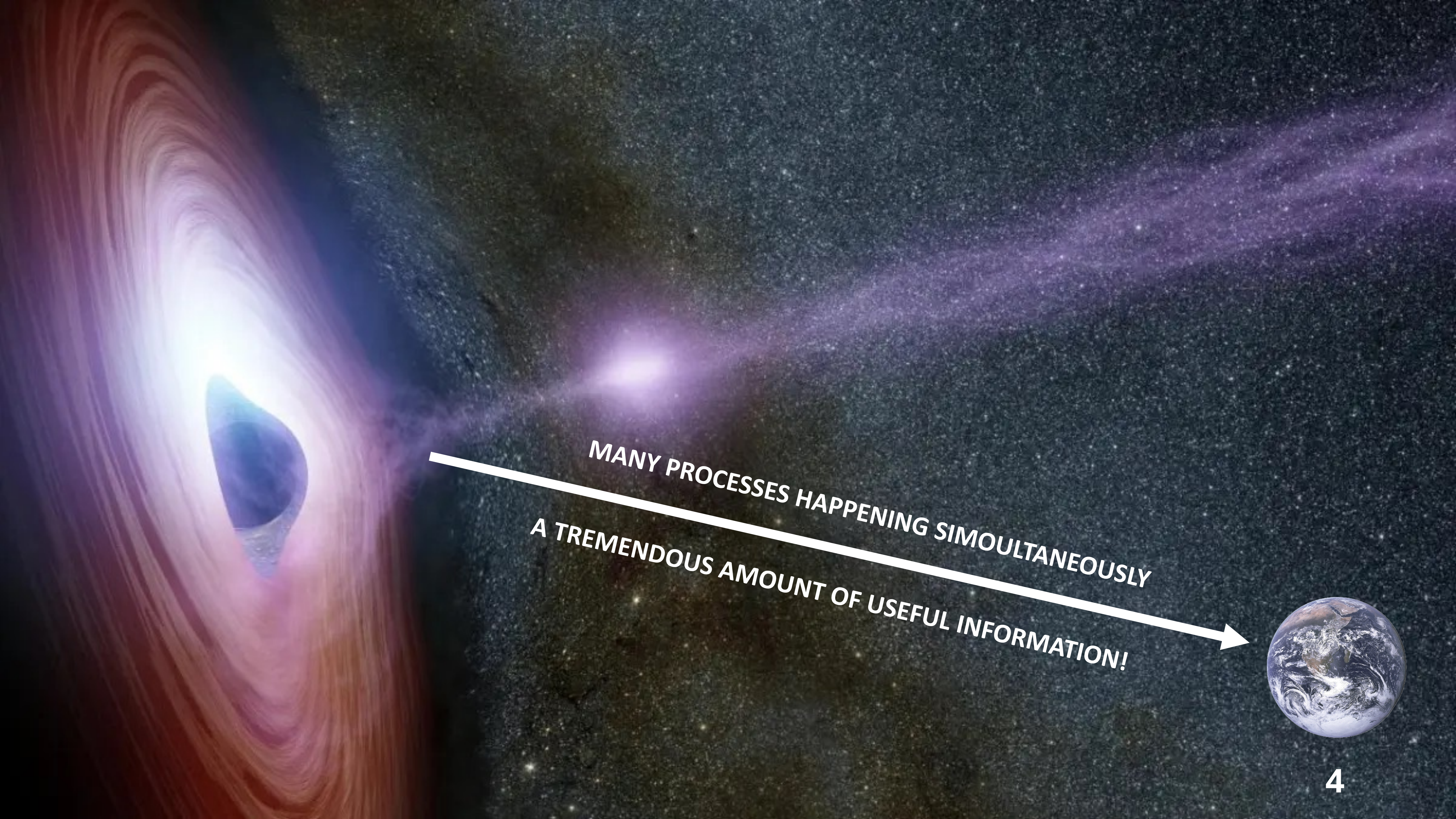
- AI
- Hardware
- DAQ
- Data analysis
- Neutrinos!!!



I work on:

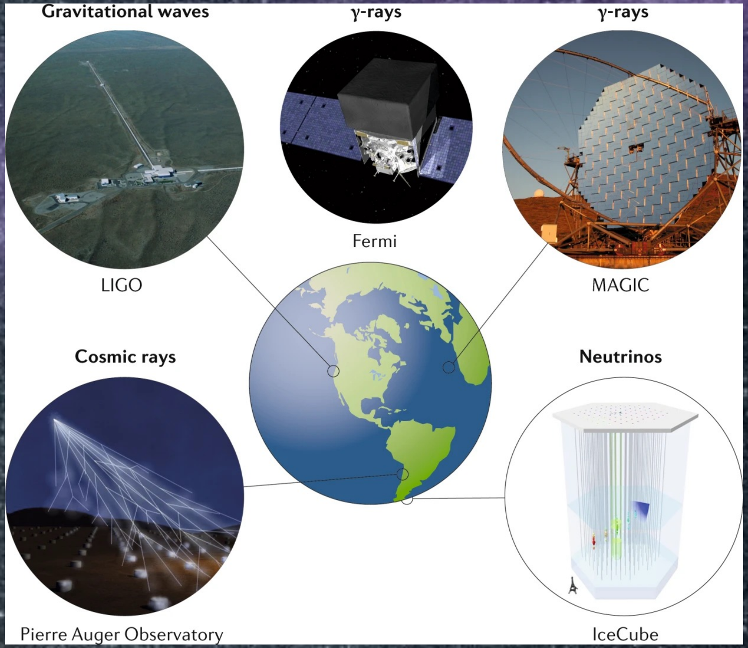
- DUNE
- PUEO

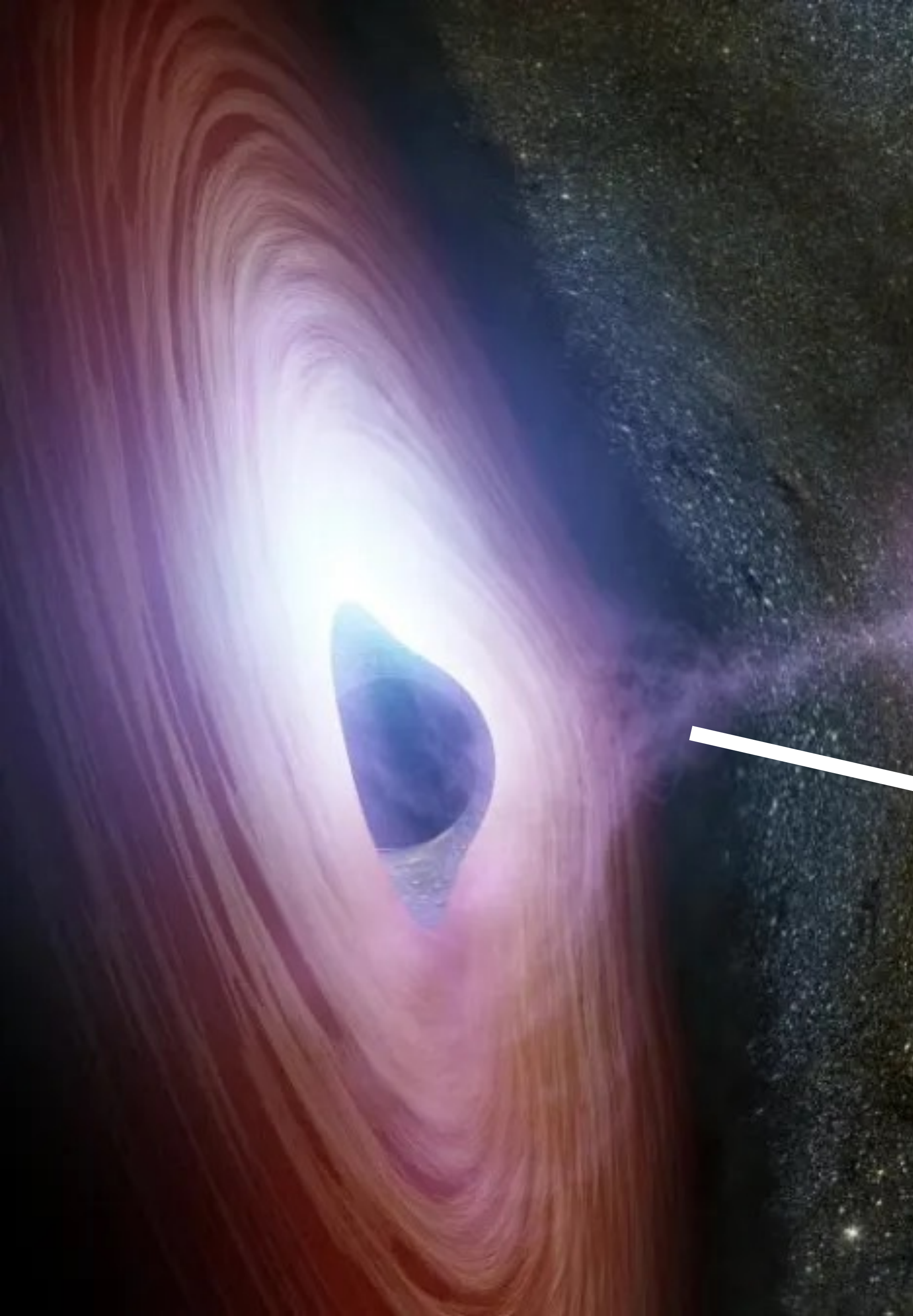
SPACE


MANY PROCESSES HAPPENING SIMOULTANEOUSLY
A TREMENDOUS AMOUNT OF USEFUL INFORMATION!

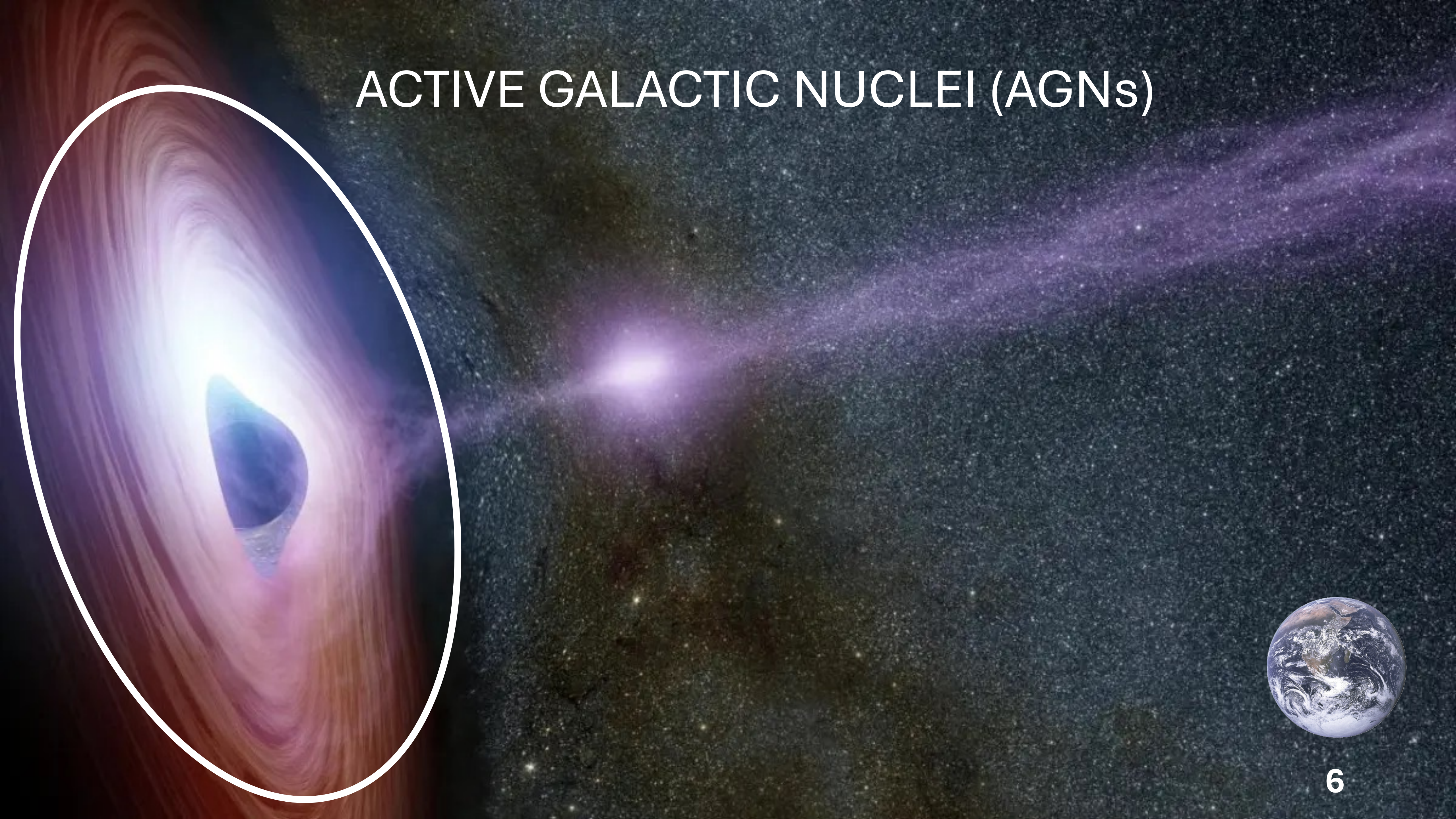
MULTI-MESSENGER ASTROPHYSICS: A NEW ERA

Suggested article Mészáros, P., Fox, D.B., Hanna, C. *et al. Nat Rev Phys* **1**, 585–599 (2019)

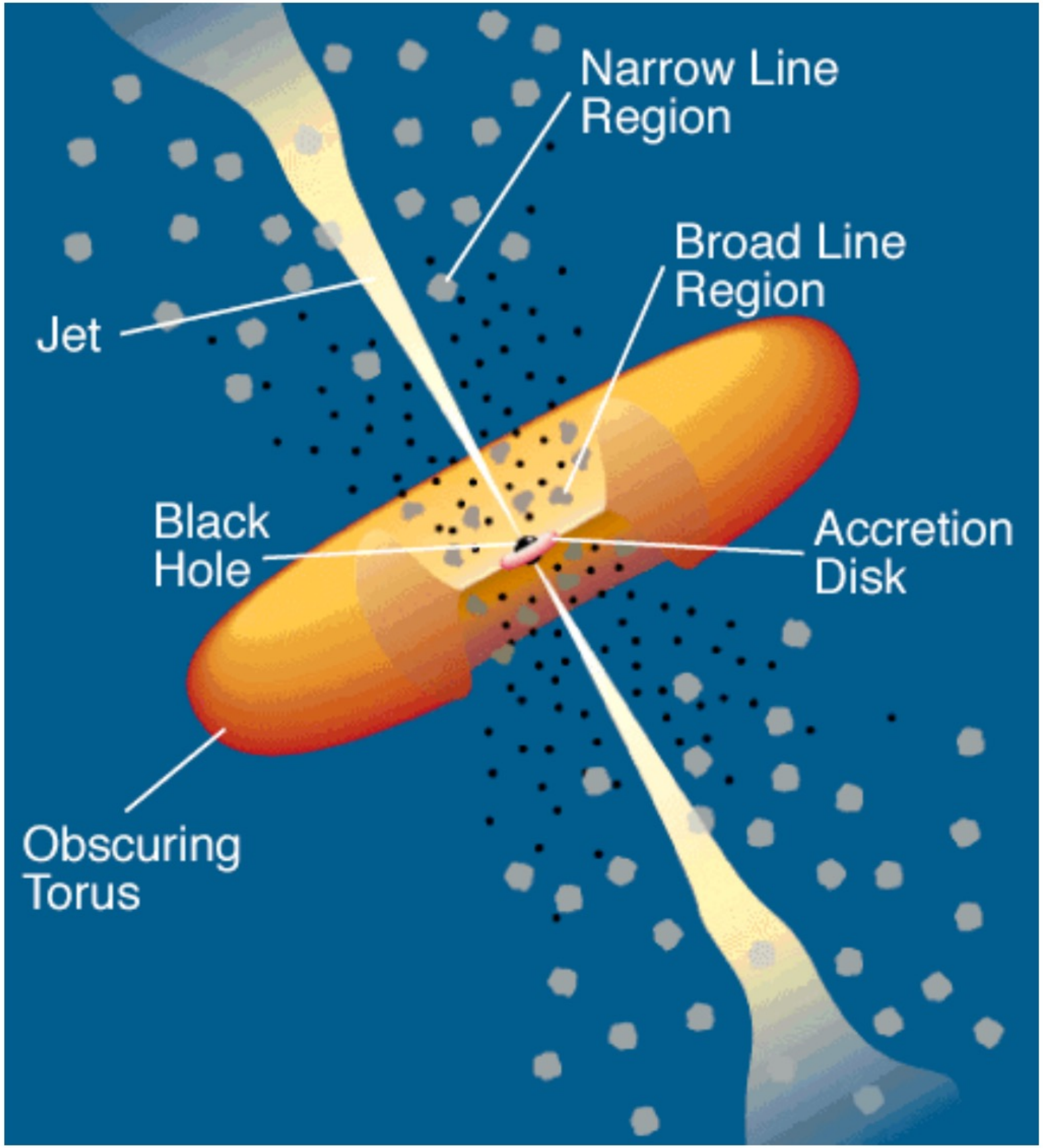




ACTIVE GALACTIC NUCLEI (AGNs)



How big are AGNs?
The nearest, NGC 4395, has an upper limit size of 1 pc. This is a small distance for galactic standards.

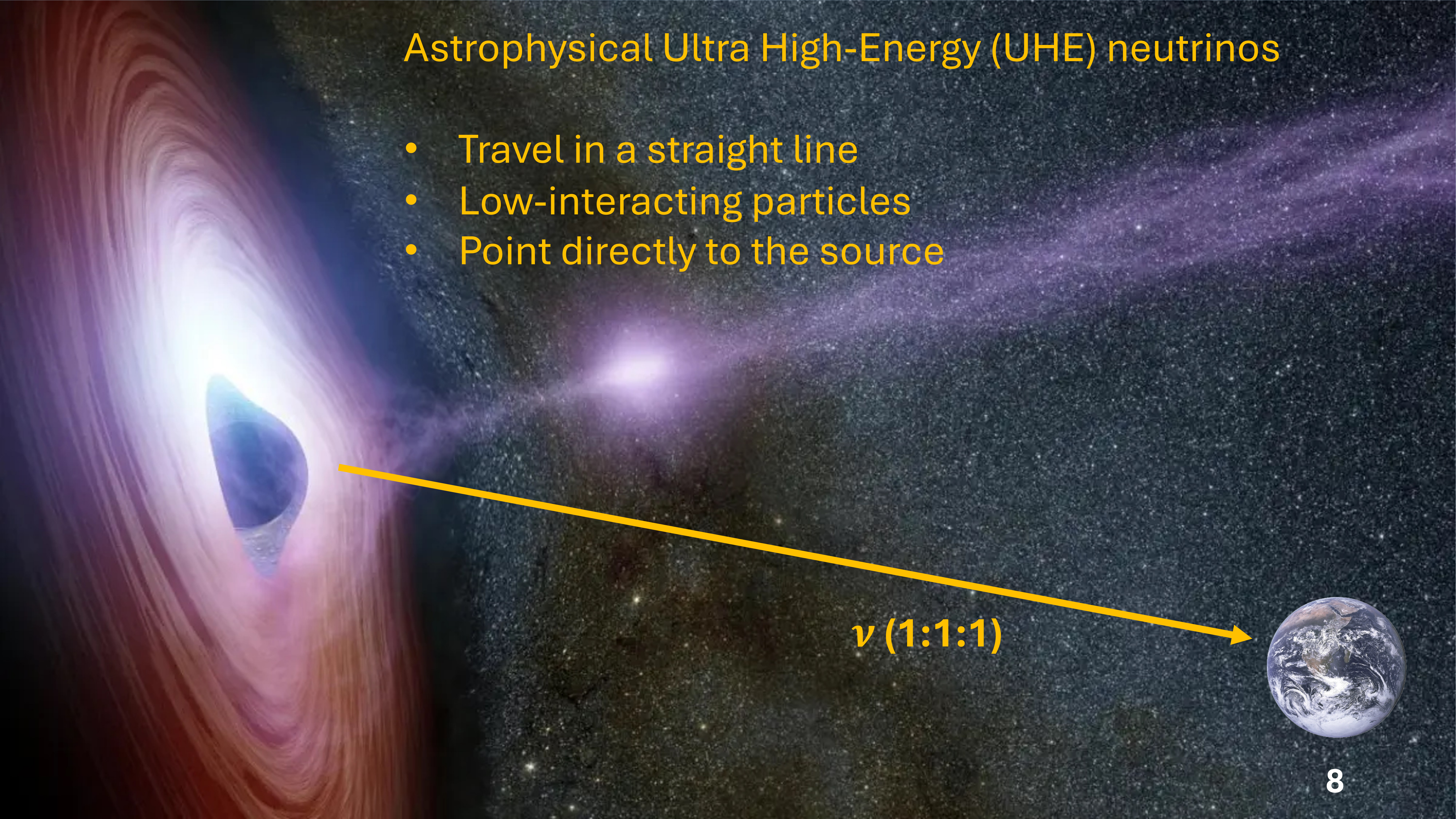


C.M. Urry & P. Padovani

They are powered by gravitational energy.
They have in the centre a massive black hole with mass $\sim 10^6 - 10^9\ M_{Sun}$.

Astrophysical Ultra High-Energy (UHE) neutrinos

- Travel in a straight line
- Low-interacting particles
- Point directly to the source

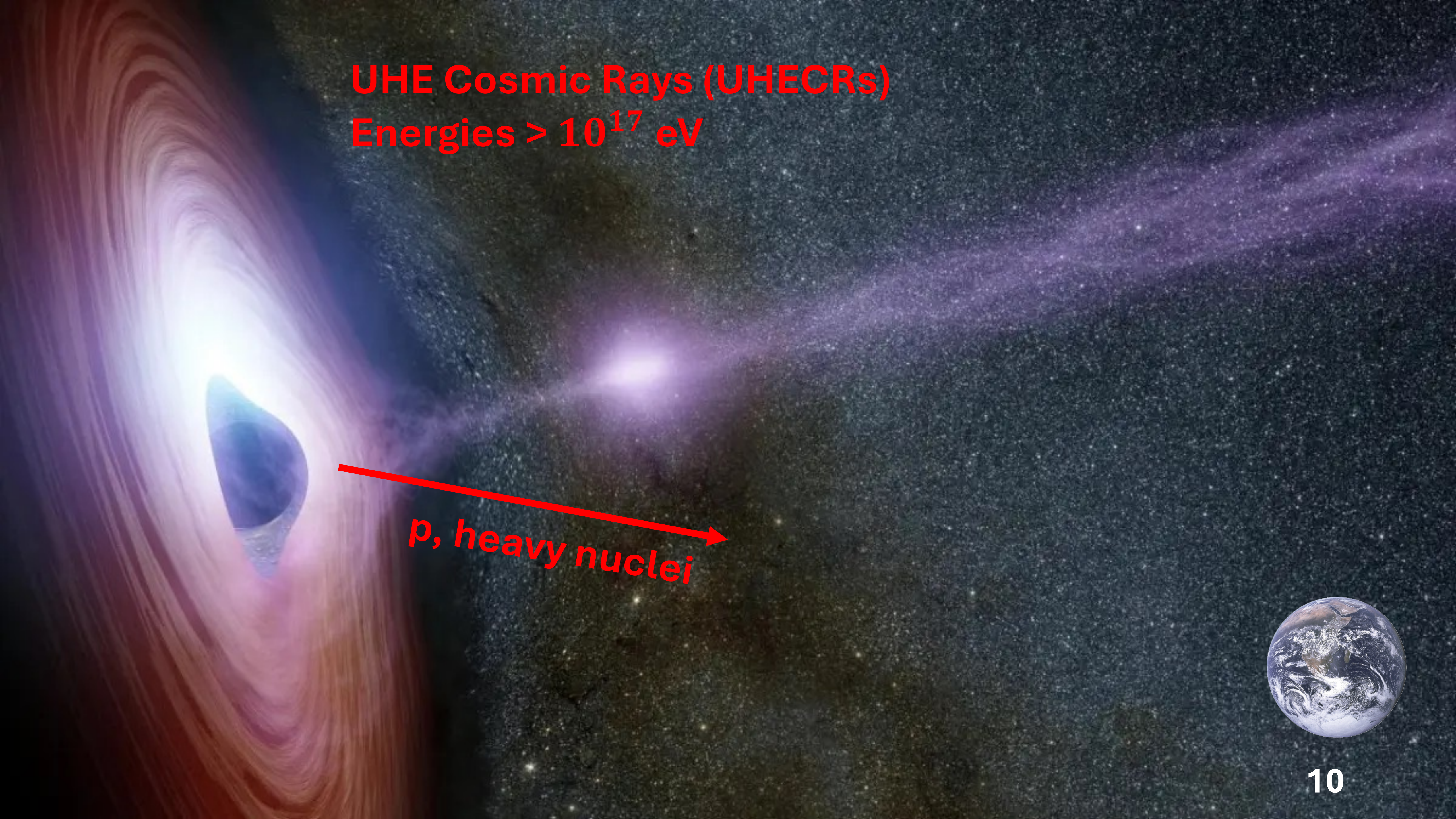


Other possible sources of astrophysics UHE neutrinos:

- Starburst galaxy
- Supernova
- Hypernova
- Neutron star merger
- Black hole merger
- Gamma ray burst
- …

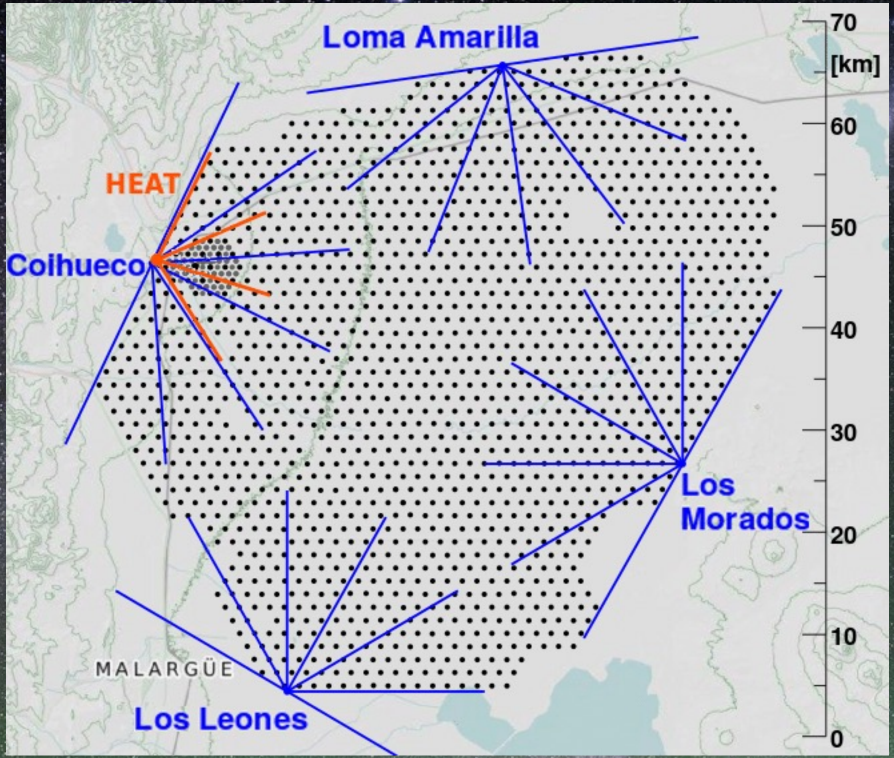
UHE Cosmic Rays (UHECRs)

Energies > 10^{17} eV

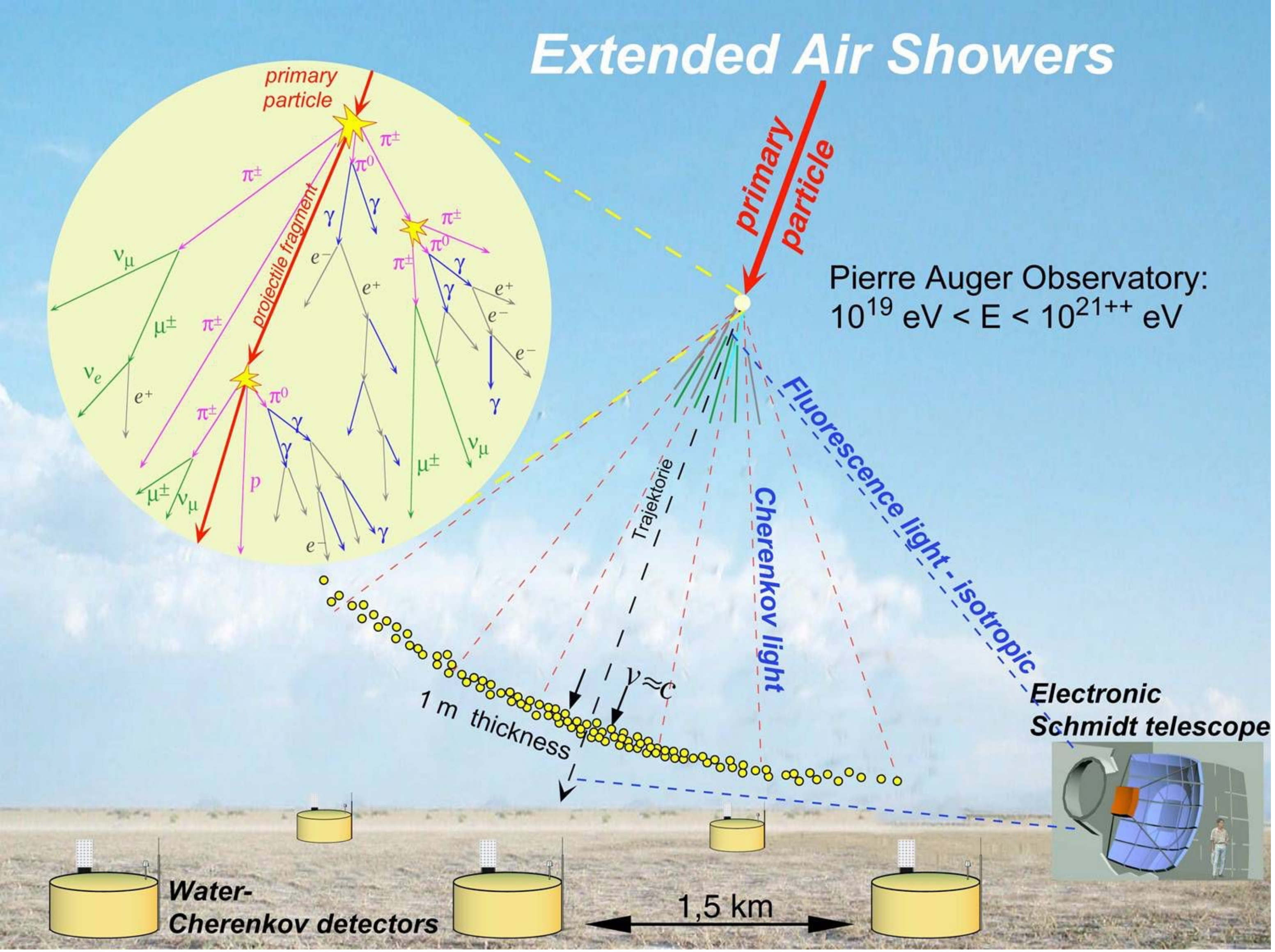


PIERRE AUGER OBSERVATORY: WORLD BIGGEST CR DETECTOR

$3000\ km^2$

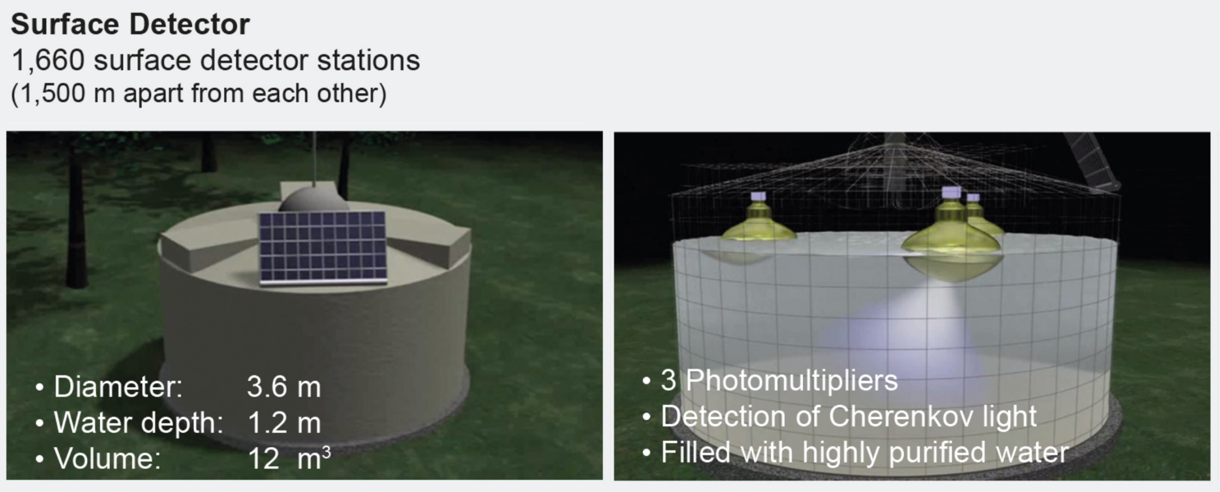


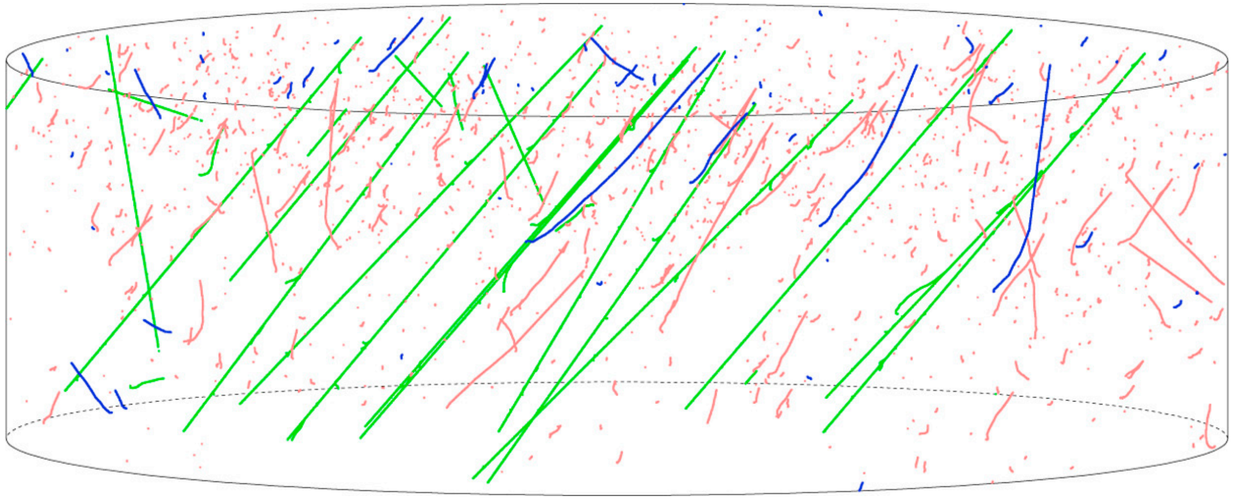
Hybrid detector



- Energetic CR mainly protons and heavy nuclei with absorption length of few 10 g/cm^2.
- They produce primary interaction in upper atmosphere.
- What we observe is mainly muons (~ a few GeV), photons, electrons/positrons (~10 MeV).

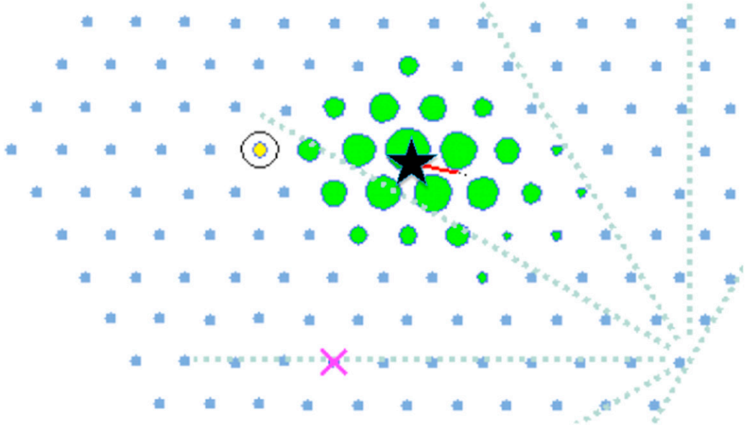
AUGER SURFACE DETECTOR (SD)





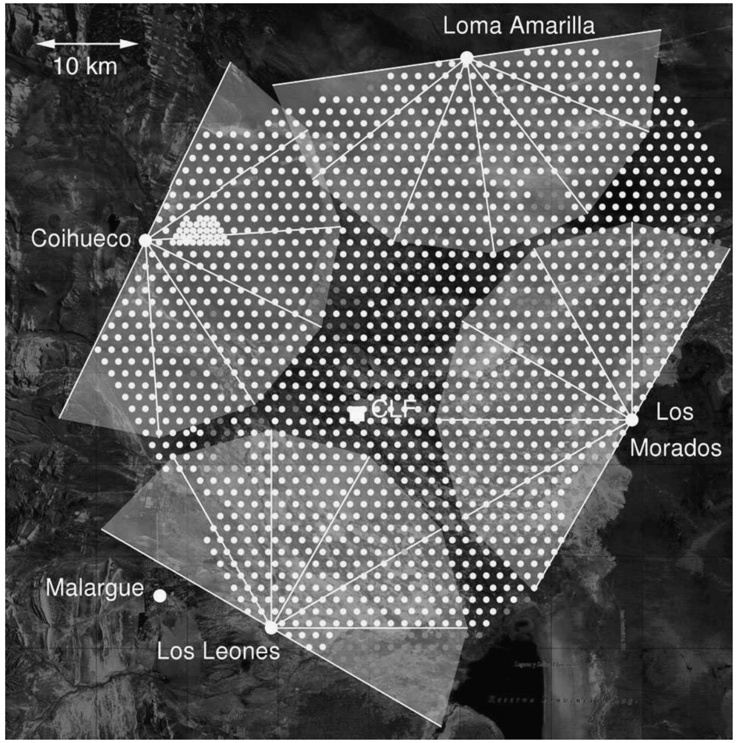
Green: muons, pink: e^+e^- from gammas, blue: e^+e^- entering the tank. From https://doi.org/10.1016/j.nima.2014.05.013

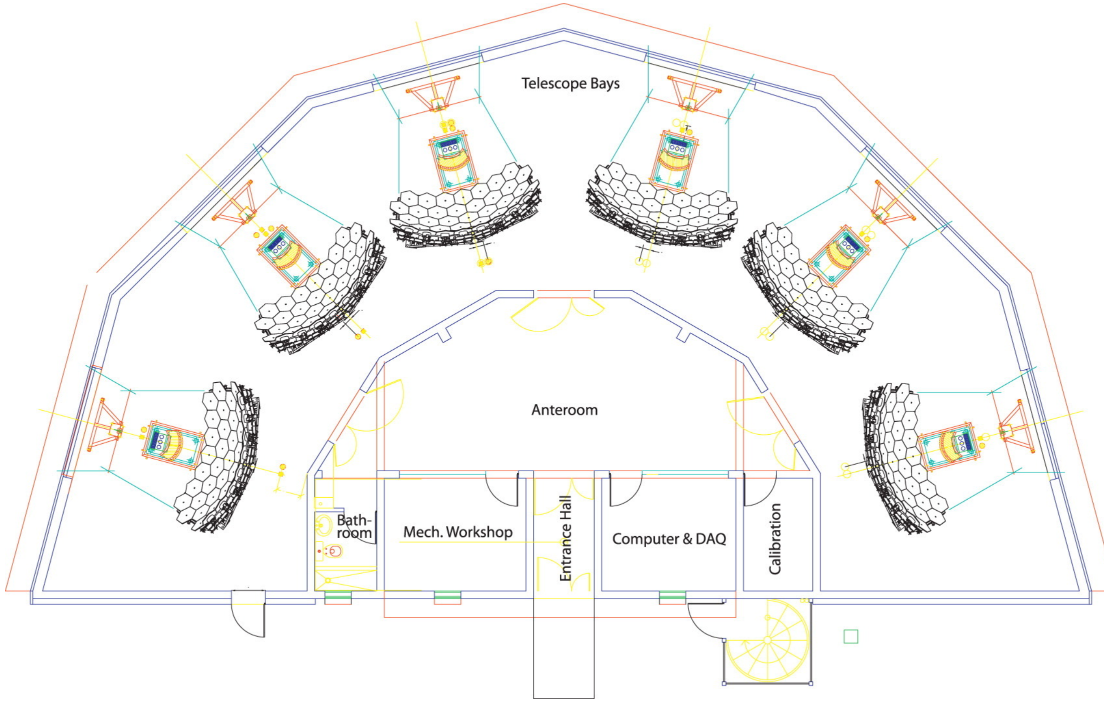
AMOUNT OF LIGHT PROPORTIONAL TO ENERGY

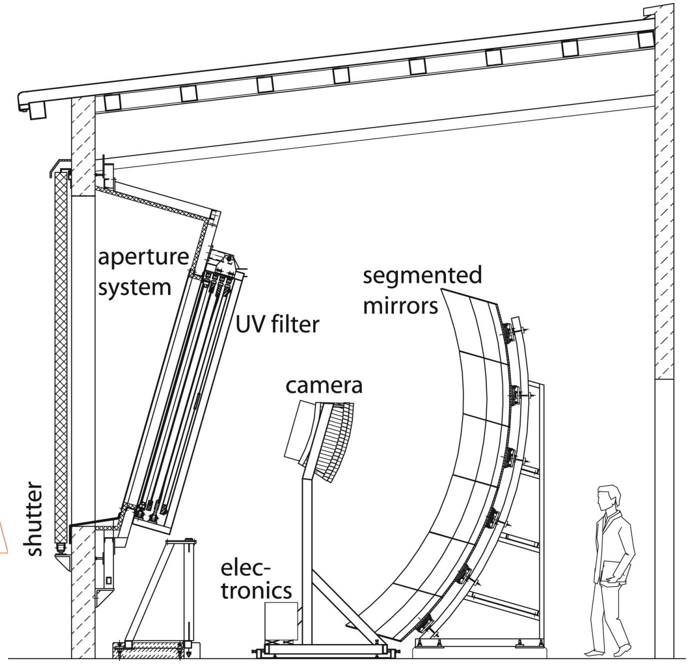


Density of particles decreases rapidly from the shower axis as $1/r^b$ with b~2-4. r = distance from shower axis.

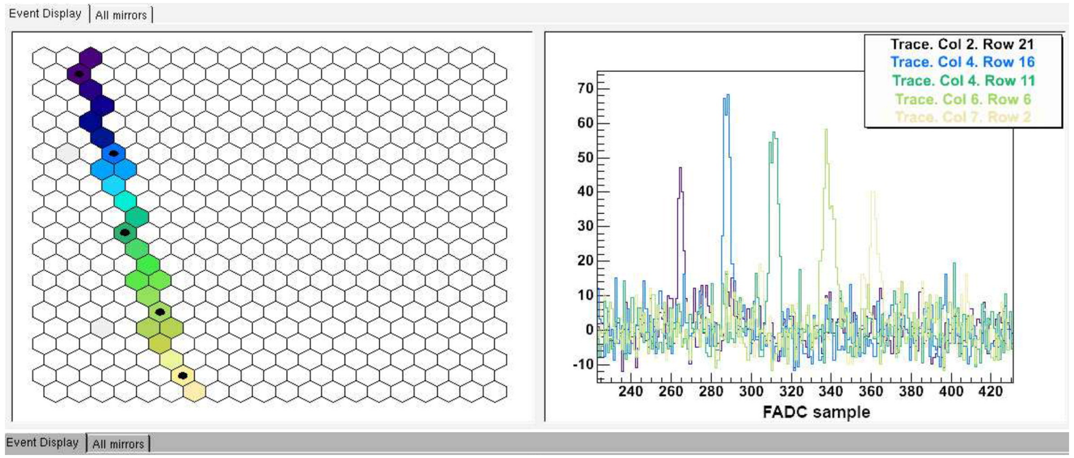
AUGER FLUORESCENCE DETECTOR (FD)



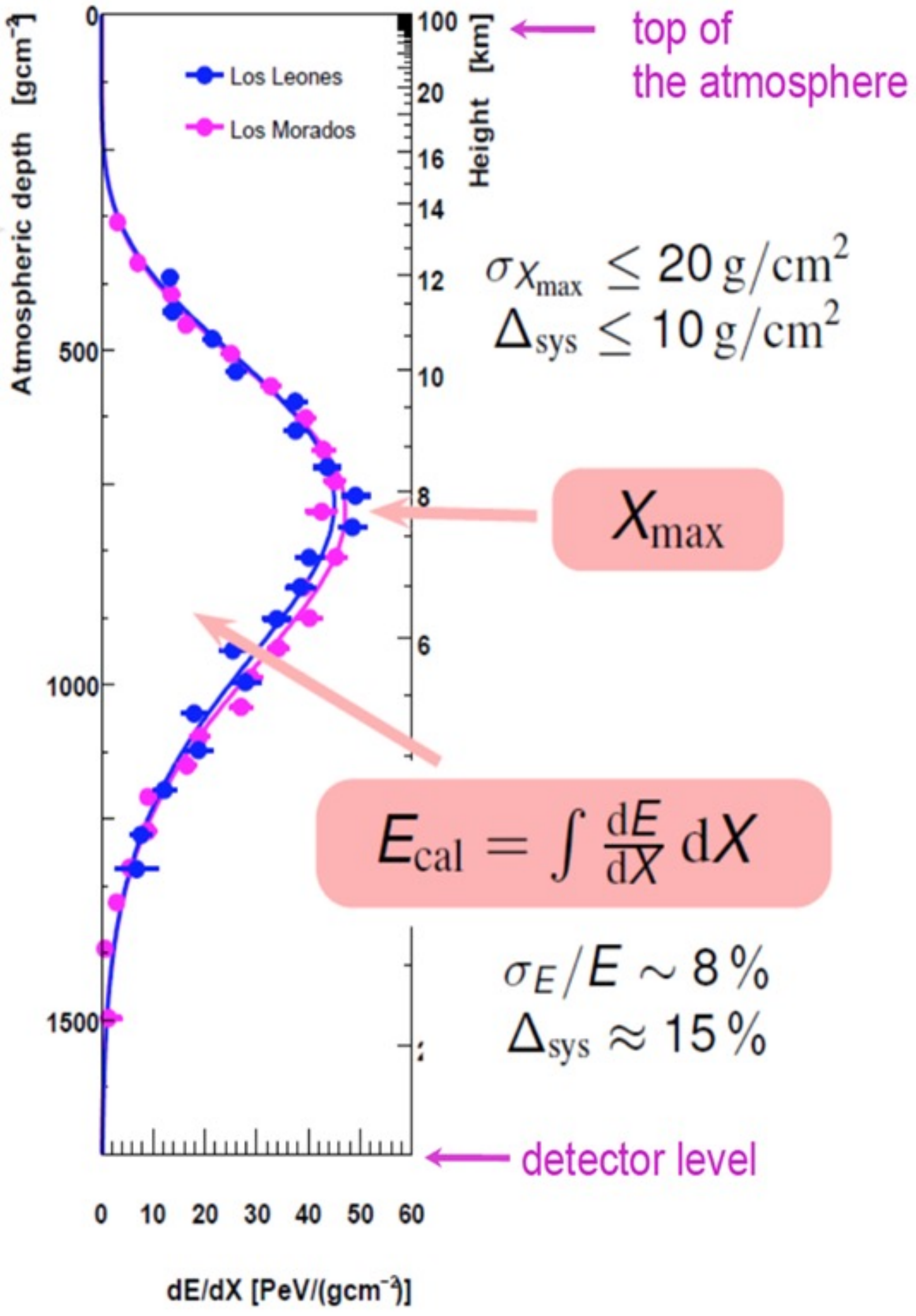




Charged particle in air shower interact with atmospheric nitrogen producing ultraviolet light. Trails can be observed for up to 15 km.



Time resolution 100 ns.
Credits https://doi.org/10.1016/j.nima.2010.04.023

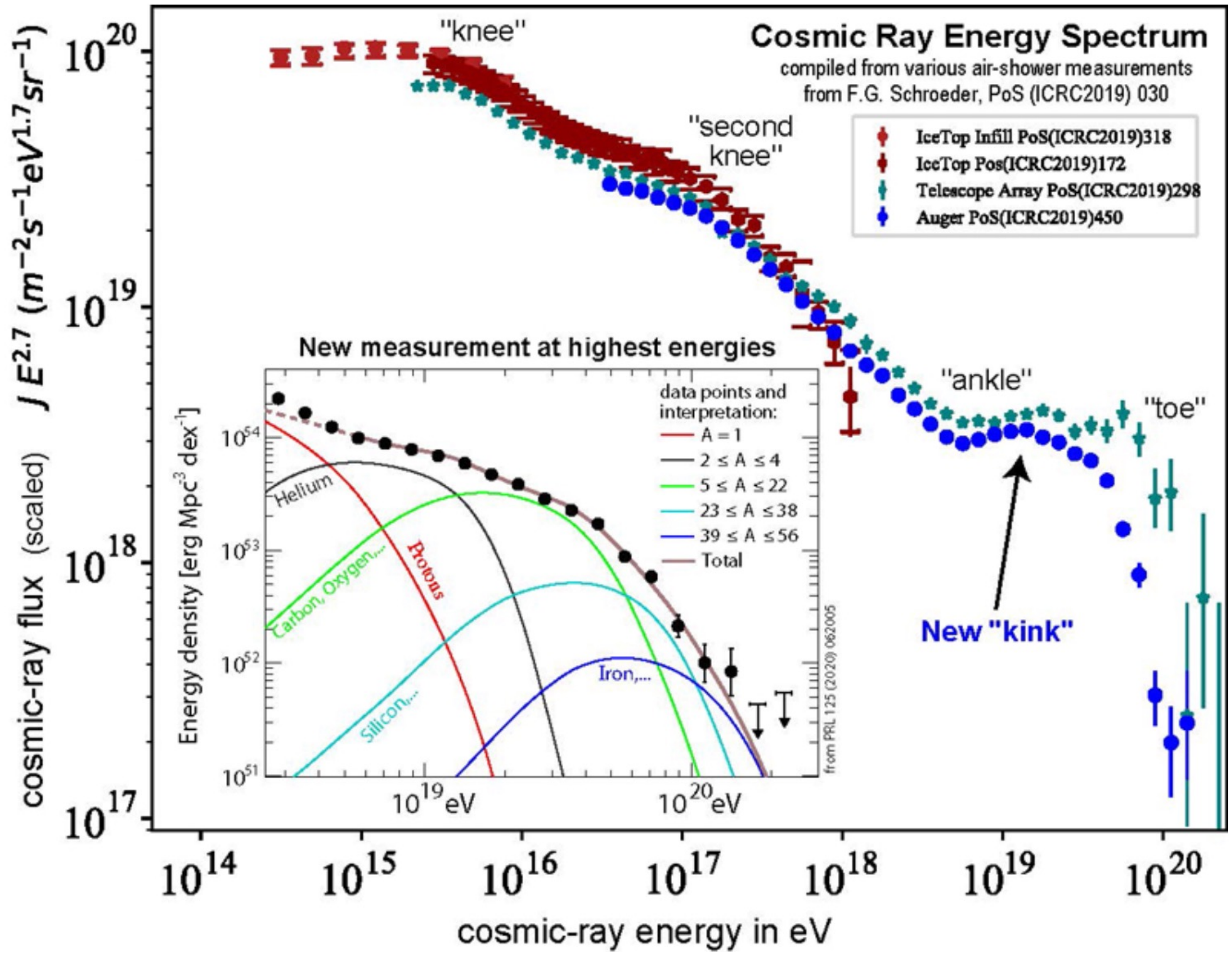


Energy deposited by EAS Extensive Air Shower (EAS)

- The number of emitted fluorescence photons is proportional to the energy deposited in the atmosphere.
- By measuring the rate of fluorescence emission as a function of atmospheric slant depth *X*, an air fluorescence detector measures the *longitudinal development profile* dE/dX(X) of the air shower.
- The integral of this profile gives the total energy dissipated electromagnetically, which is approximately 90% of the total energy of the primary cosmic ray.
- X_{max} is determined by the composition of the primary.

X = atmospheric slant depth = total amount of air (measured in grams per square centimeter, g/cm²) that an incoming cosmic ray particle traverses as it enters the Earth's atmosphere and moves towards the detector on the ground

COMPOSITION AND ORIGIN OF UHECRs



- From second knee: extragalactic sources.
- From ankle: extragalatic sources dominate.

TWO MODELS OF PRODUCTION OF UHECRs

Bottom-up -> acceleration of low energy particles. Protons and electrons are accelerated to up to 10^{20} eV due to Fermi's diffusive shock acceleration mechanism and other processes. Large sources with fast shock and strong magnetic fields are required:

- AGNs
- Gamma-ray bursts

Top-down -> exotic sources:

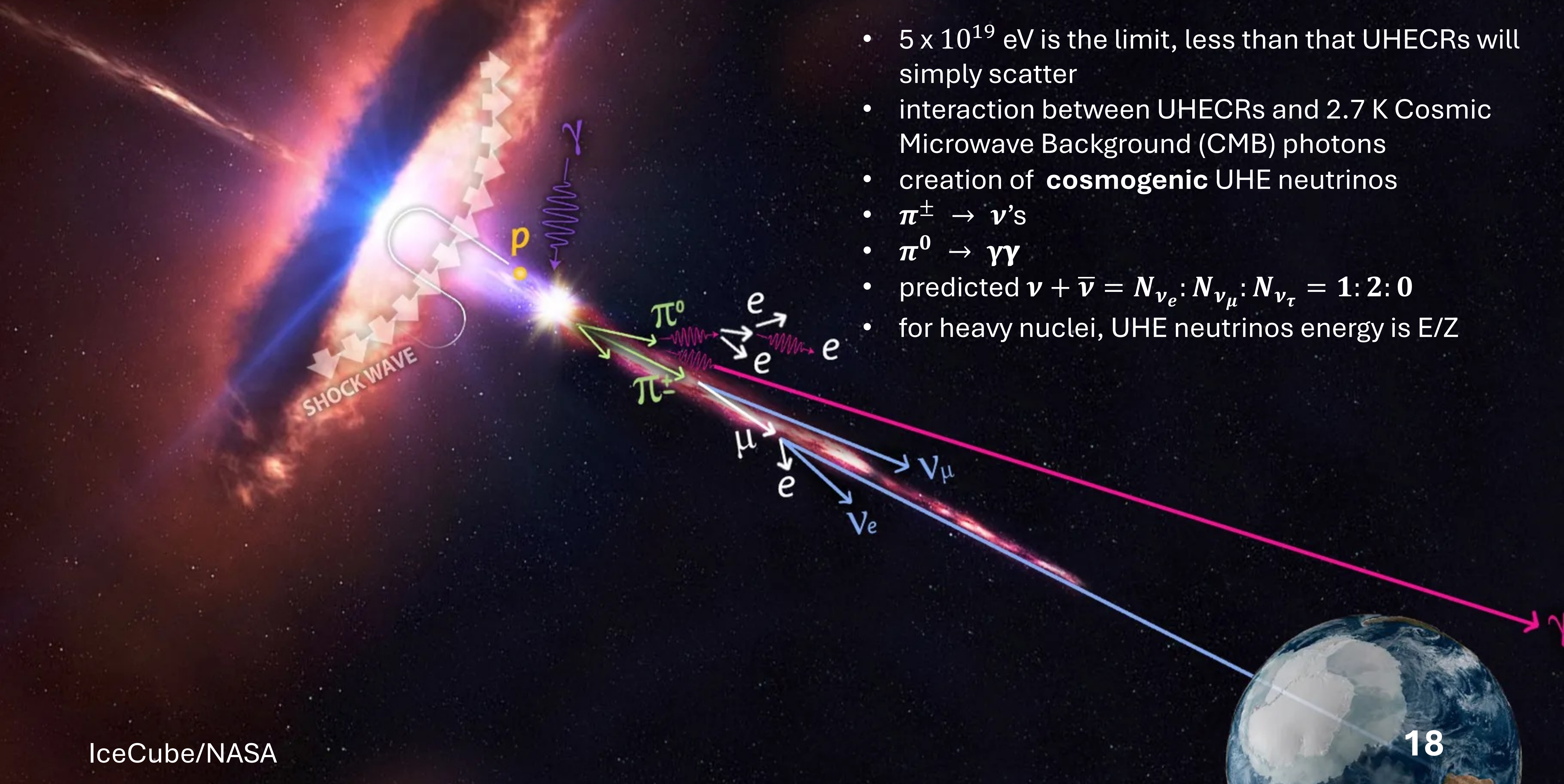
- Decay of heavy dark matter particles
- Topological defects
- Cosmic strings

For top-down models photons should dominate over nucleons, but this is not supported by Auger data → top-down models are currently disfavoured.

Suggested reading [arXiv:astro-ph/0301039]

Greizen-Zatsepin-Kuzmin (GZK) Limit

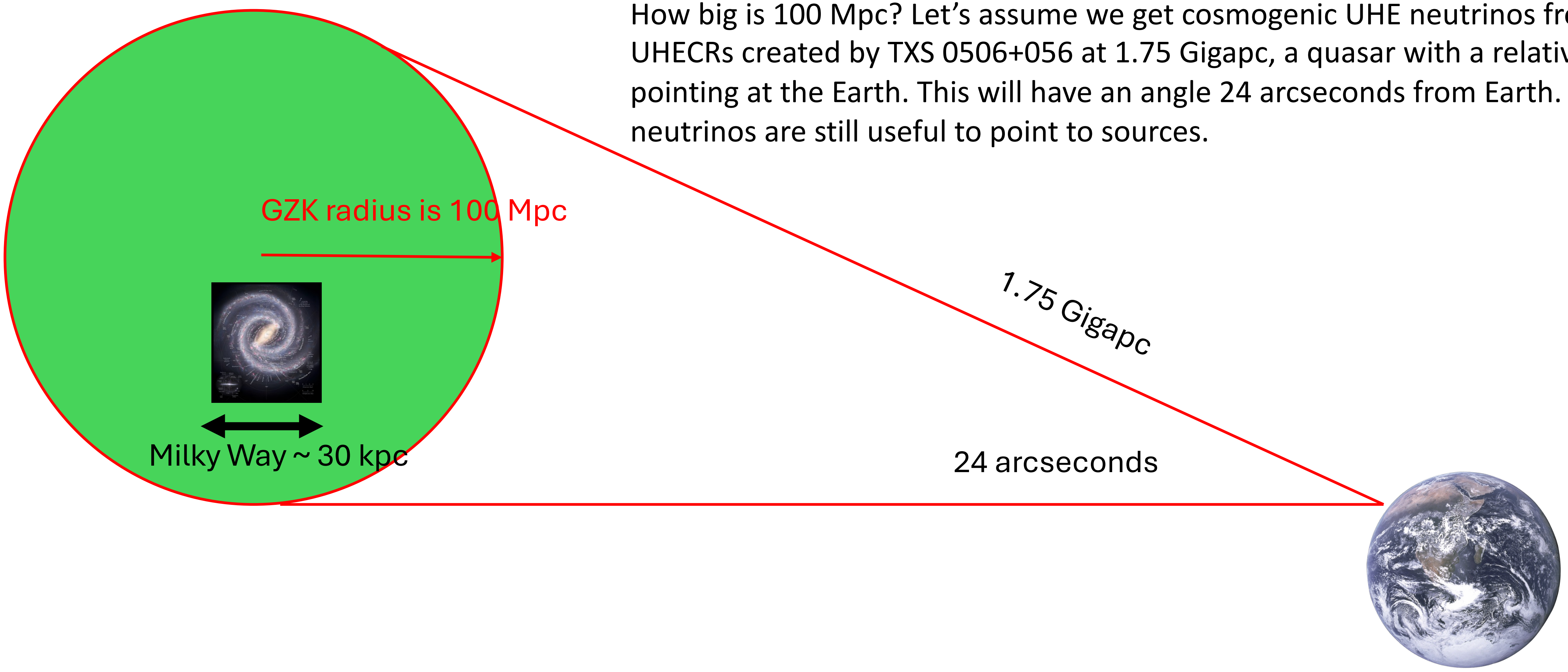
- 5×10^{19} eV is the limit, less than that UHECRs will simply scatter
- interaction between UHECRs and 2.7 K Cosmic Microwave Background (CMB) photons
- creation of **cosmogenic** UHE neutrinos
- $\boldsymbol{\pi^{\pm}} \rightarrow \boldsymbol{\nu}$'s
- $\boldsymbol{\pi^{0}} \rightarrow \boldsymbol{\gamma\gamma}$
- predicted $\boldsymbol{\nu + \bar{\nu} = N_{\nu_e} : N_{\nu_\mu} : N_{\nu_\tau} = 1:2:0}$
- for heavy nuclei, UHE neutrinos energy is E/Z

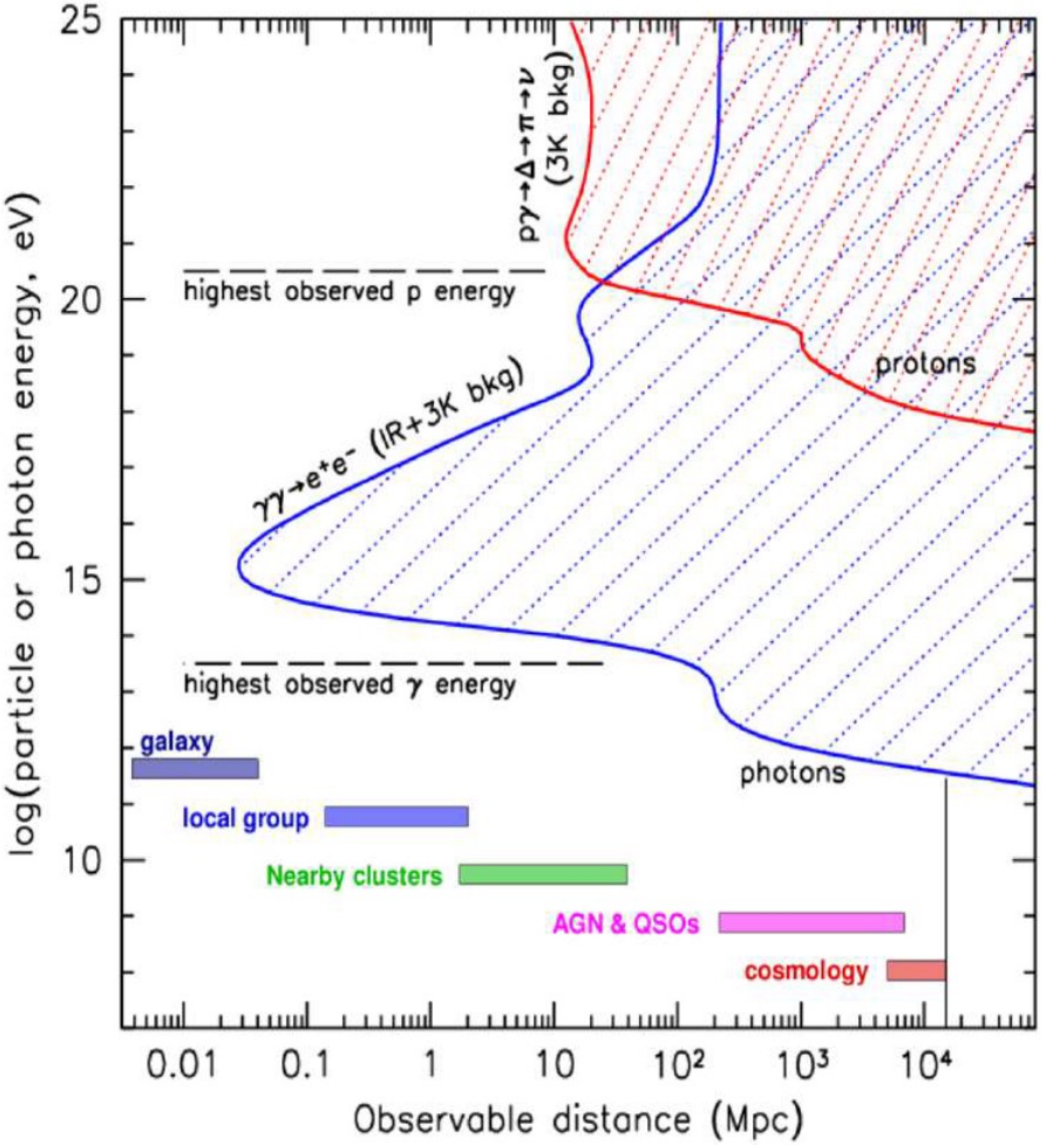


IceCube/NASA

Greizen-Zatsepin-Kuzmin (GZK) Limit

How big is 100 Mpc? Let’s assume we get cosmogenic UHE neutrinos from UHECRs created by TXS 0506+056 at 1.75 Gigapc, a quasar with a relativistic jet pointing at the Earth. This will have an angle 24 arcseconds from Earth. So GZK neutrinos are still useful to point to sources.



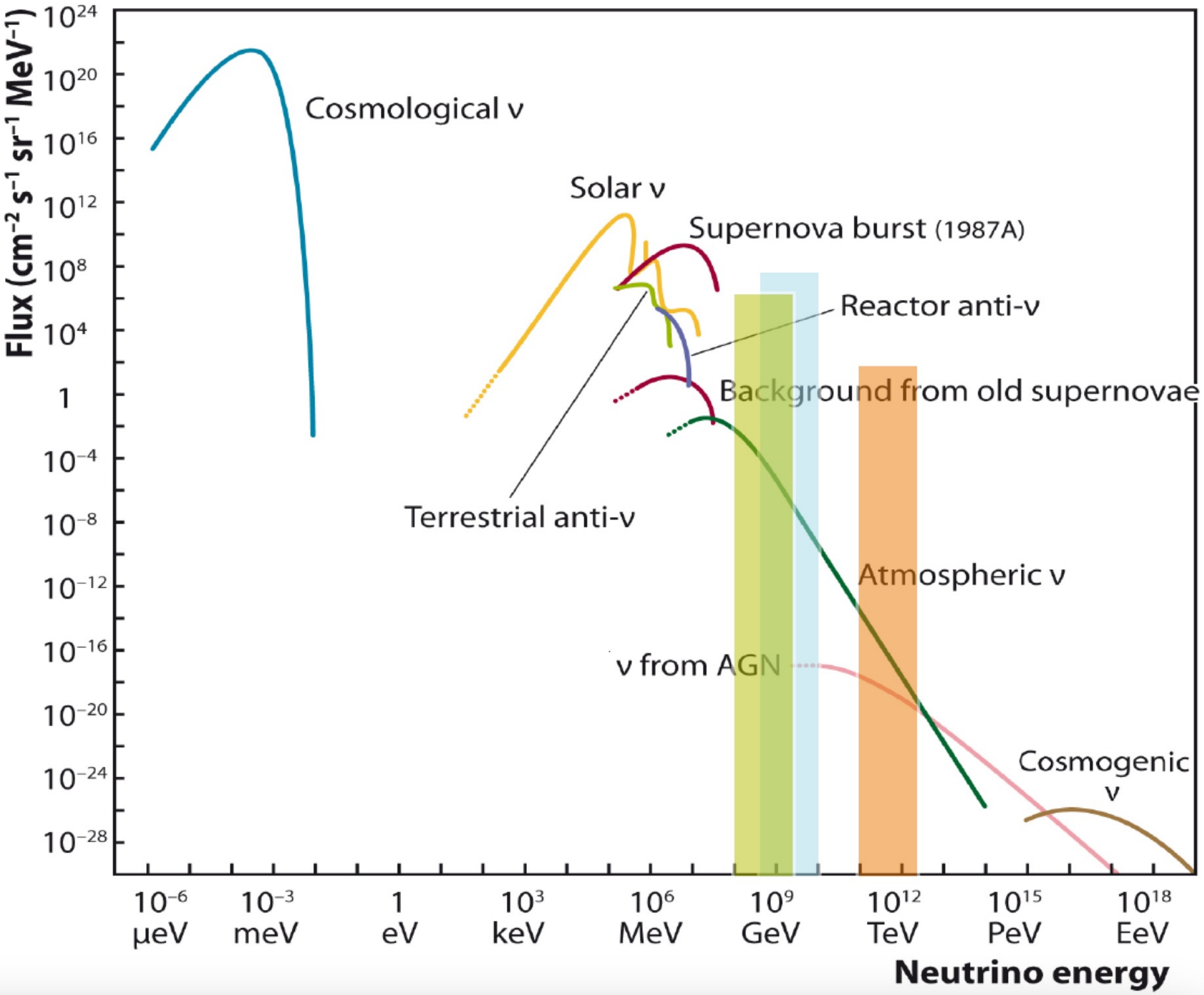


Credits to Peter Gorham

Gamma rays become very hard to detect at these energy scales and distances.

Grand Unified Neutrino Spectrum

- Booster beam
- NuMI beam
- LHC 'beam'

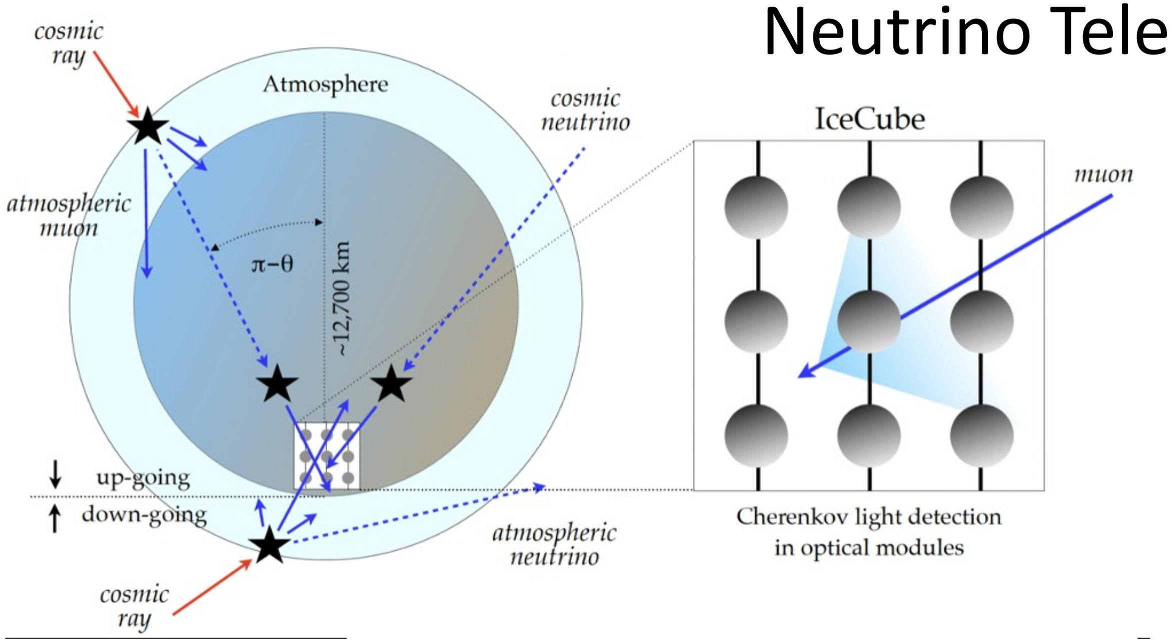


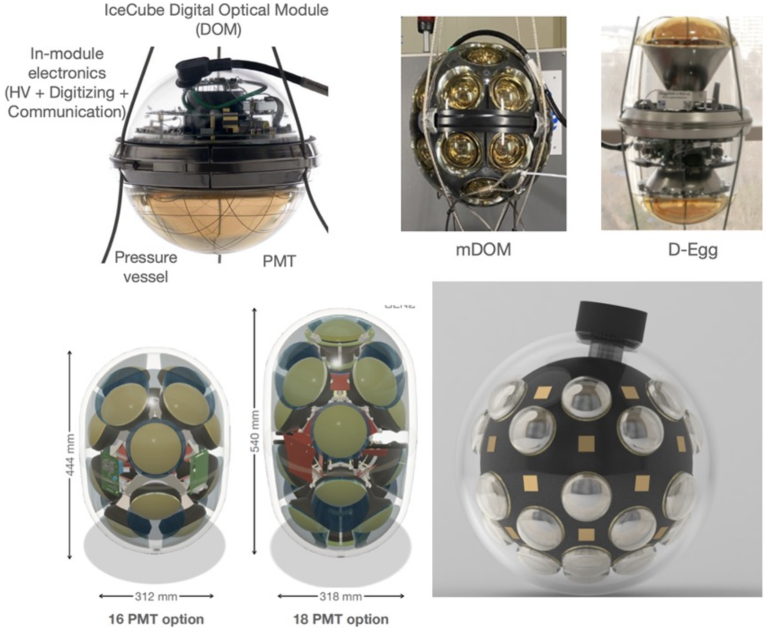
SUMMARY OF DIFFERENT SOURCES OF INFORMATION

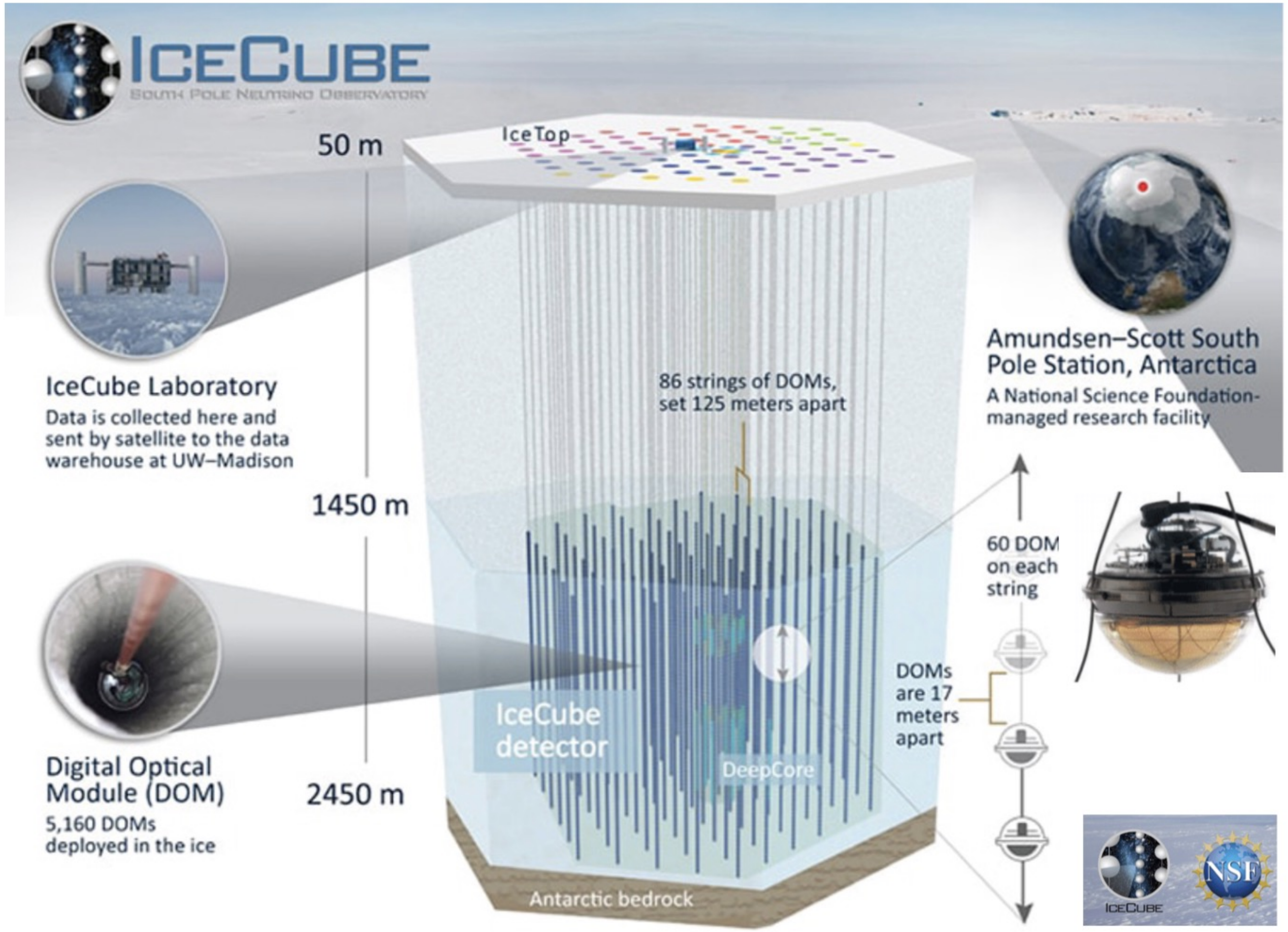
SOURCE	PROS	CONS
Astrophysical UHE neutrinos	Point directly to the source, not deflected.	Very hard (but not impossible) to detect.
Cosmogenic UHE neutrinos (GZK + neutron decay)	They could provide valuable information.	They do not point directly at the source
UHECRs	Very easy to detect.	They give very limited information, they can be deflected by magnetic fields.
Gamma rays	Useful to understand some processes.	Almost impossible to detect them at certain energies and distances.

ICE

Neutrino Telescopes: IceCube



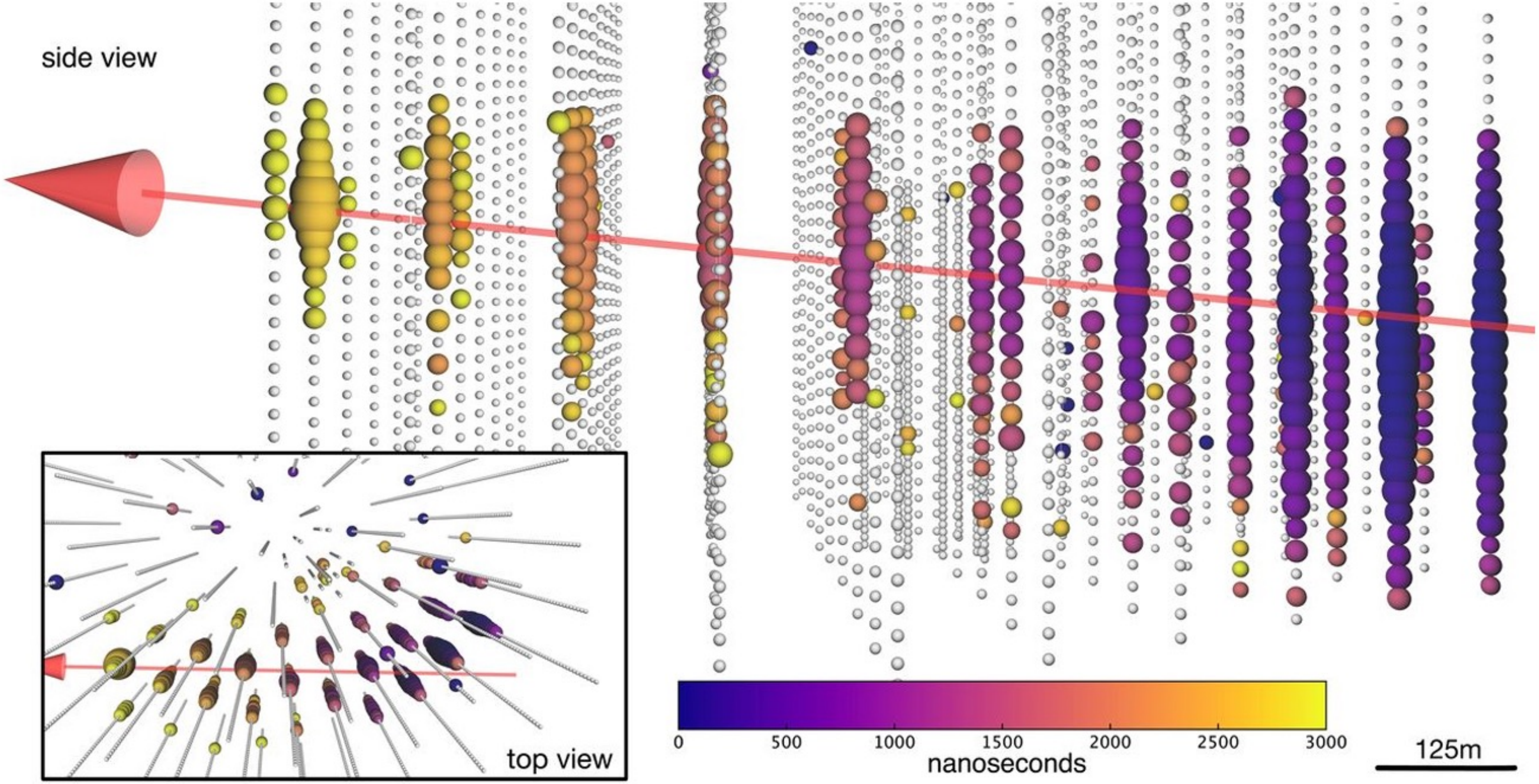




1 cubic kilometer

Teresa Montaruli for the IceCube Collaboration 2023 J. Phys.: Conf. Ser. 2429 012026

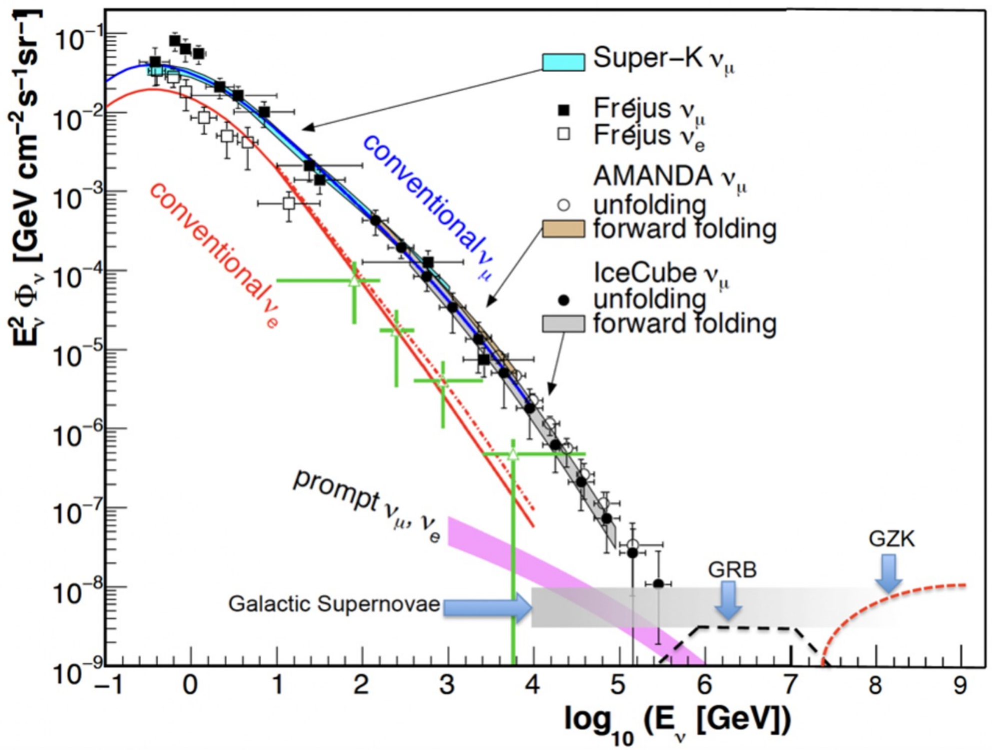
IceCube: triggering events

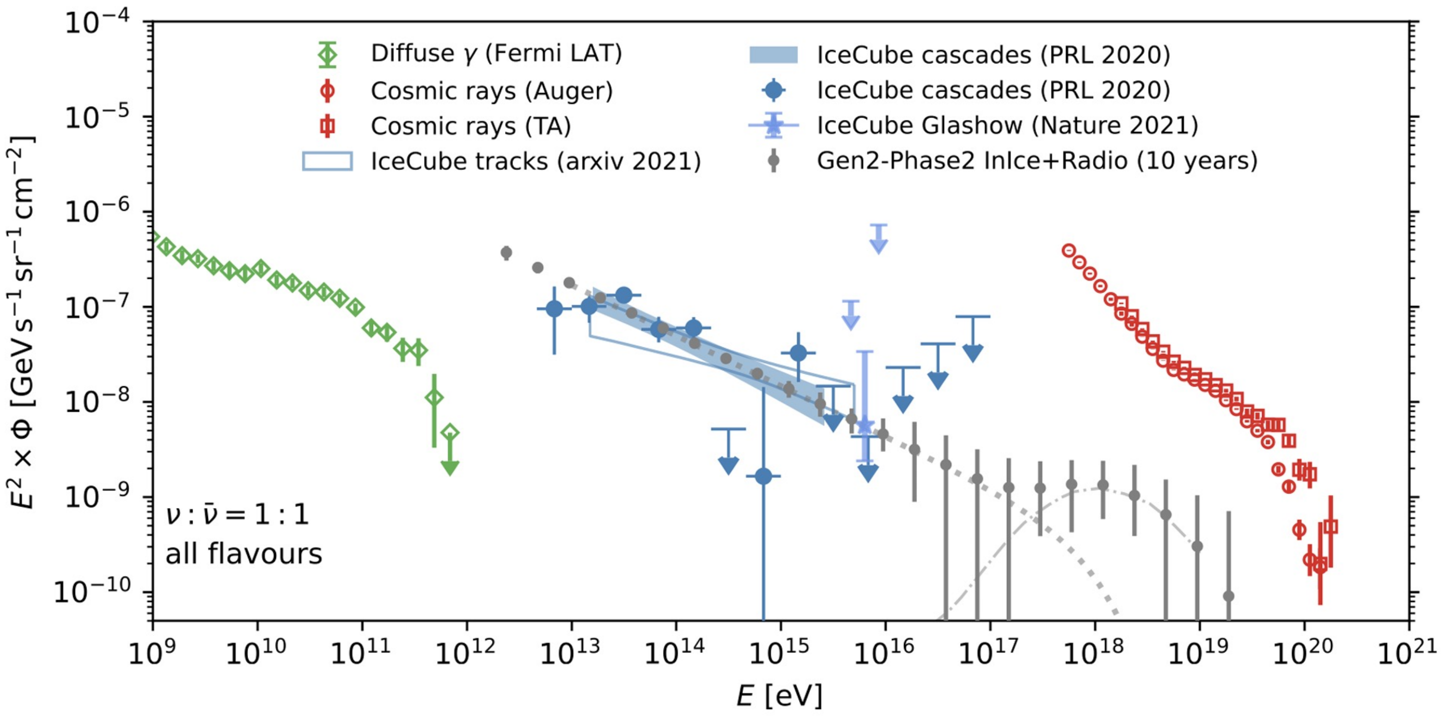


- An event view of IC170922, a 290 TeV track that occurred on September 22, 2017.
- Pointed to the blazar TXS0506+056.
- Fermi and MAGIC confirmed that blazard was in a flaring state.

doi:10.21468/SciPostPhysProc.13

IceCube: results

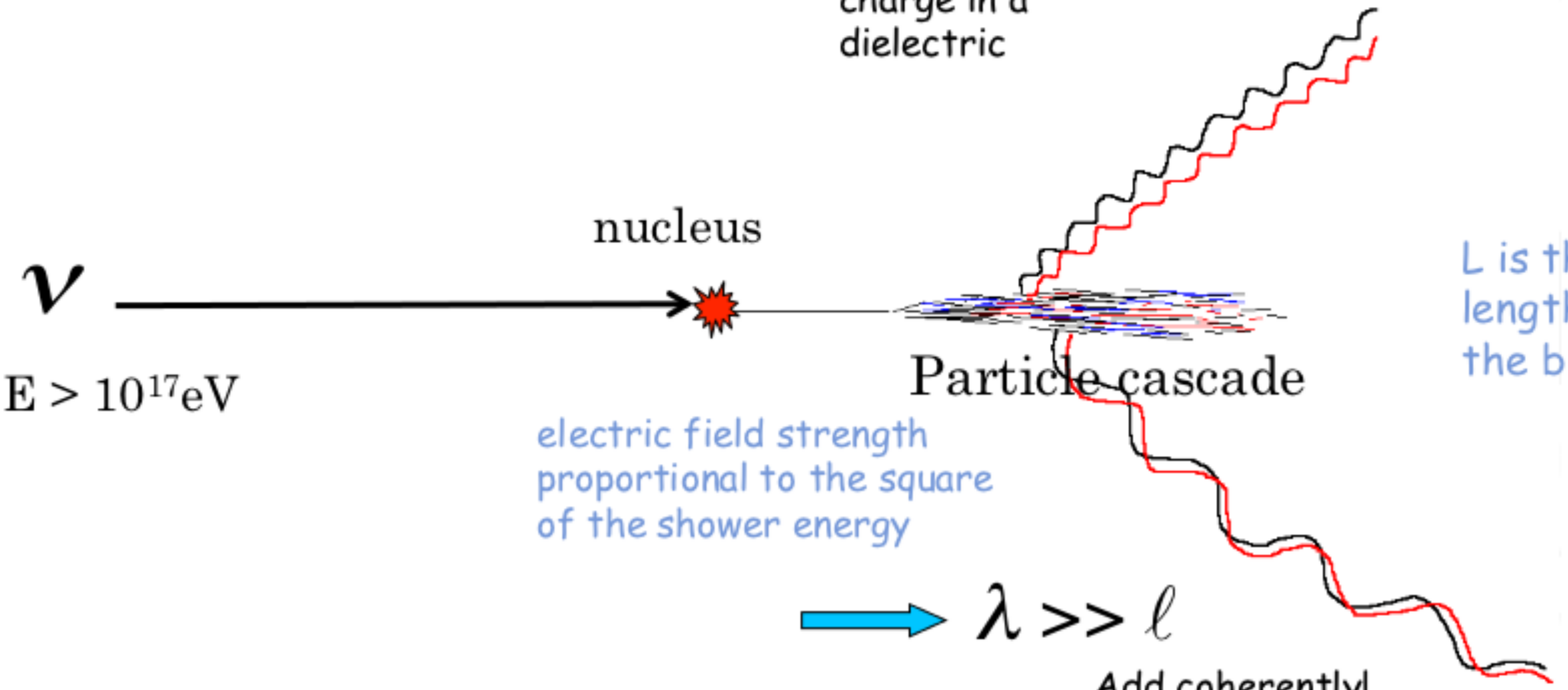




Teresa Montaruli for the IceCube Collaboration 2023 J. Phys.: Conf. Ser. 2429 012026

Askaryan radiation

charge asymmetry in particle shower development results in a 20% excess of electrons over positrons in a particle shower → moves as a compact bunch, a few cm wide and ~1cm thick → Moving net charge in a dielectric → wavelengths shorter than the bunch length suffer from destructive interference

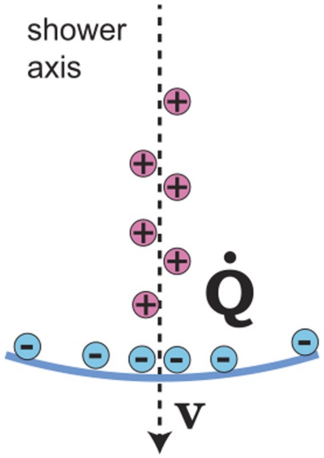


electric field strength proportional to the square of the shower energy

→ $\lambda >> \ell$

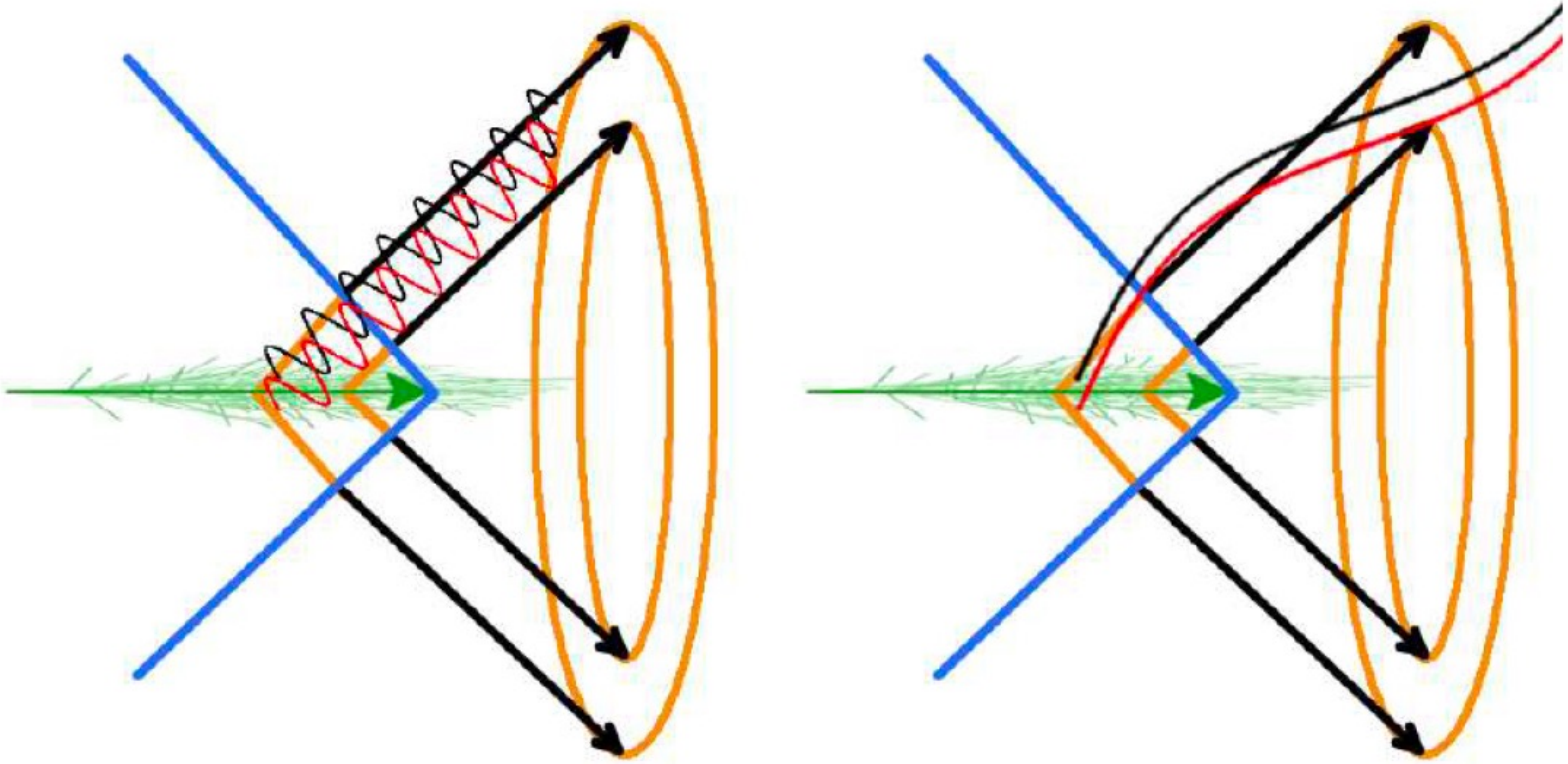
Add coherently!

L is the length of the bunch



https://thespectrumofriemannium.wordpress.com/2012/10/17/log047-the-askaryan-effect/

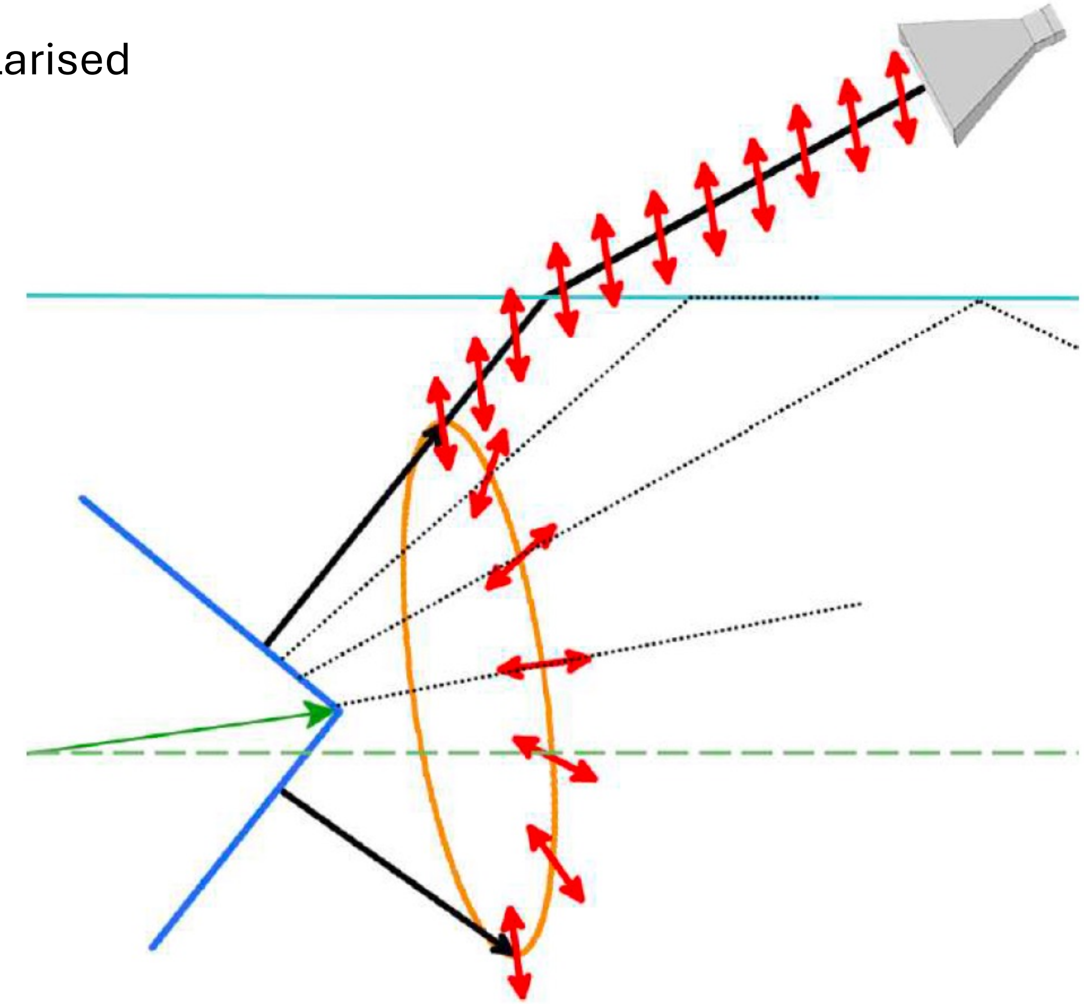
Askaryan radiation: coherency



From Luke Batten PhD’s thesis, March 2022

Askaryan radiation: polarisation

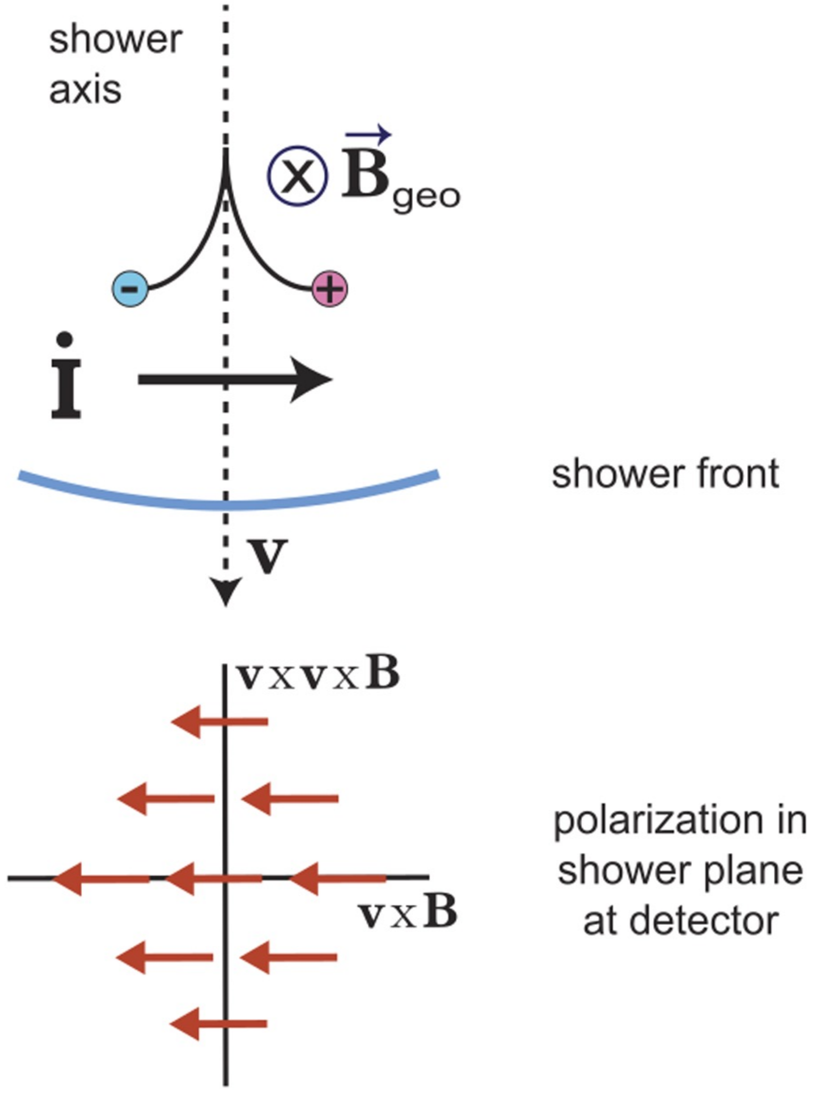
Askaryan radiation is vertically polarised



From Luke Batten PhD's thesis, March 2022

Geomagnetic emission

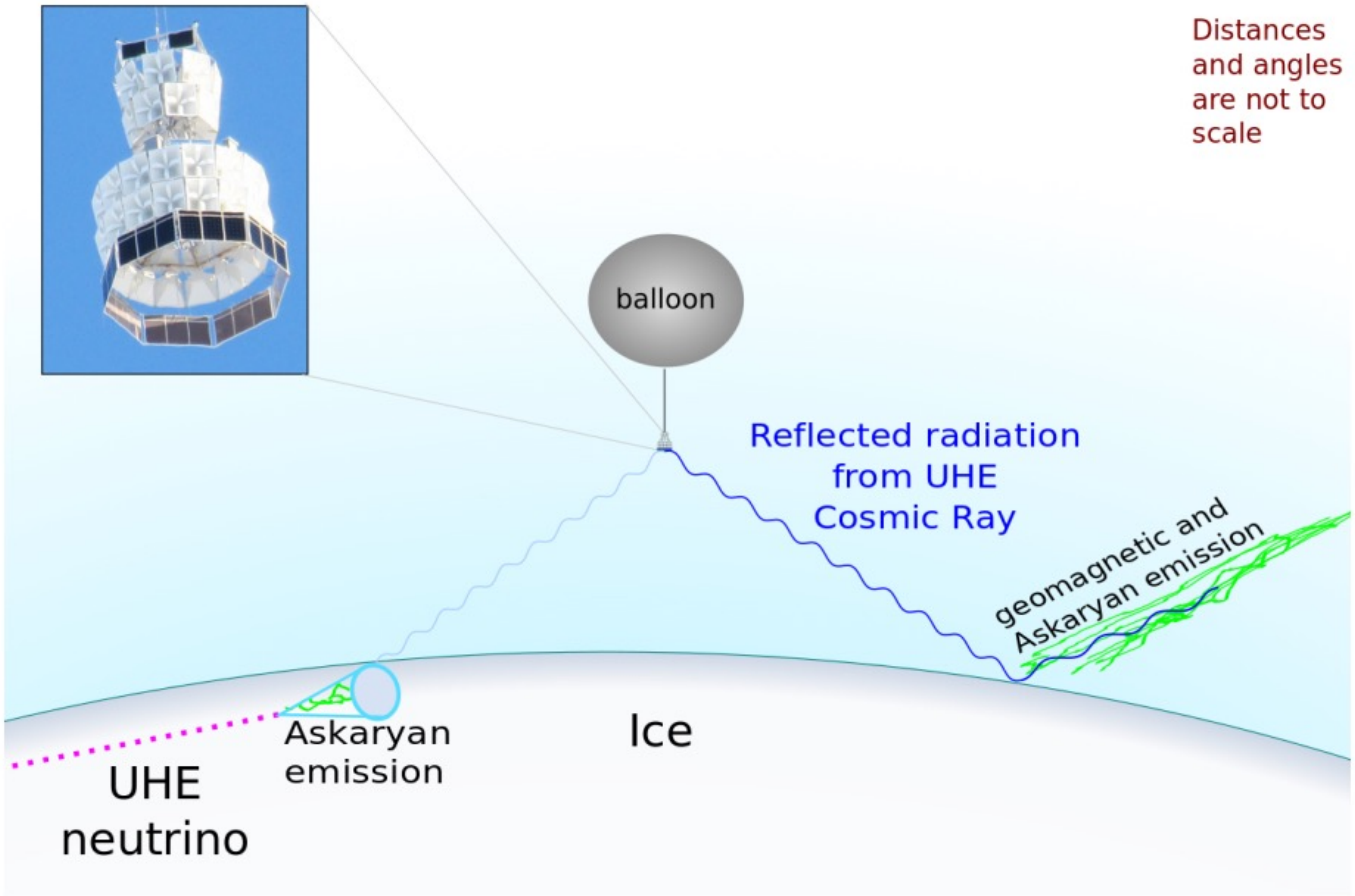
Geomagnetic emission is horizontally polarised



Geomagnetic emission

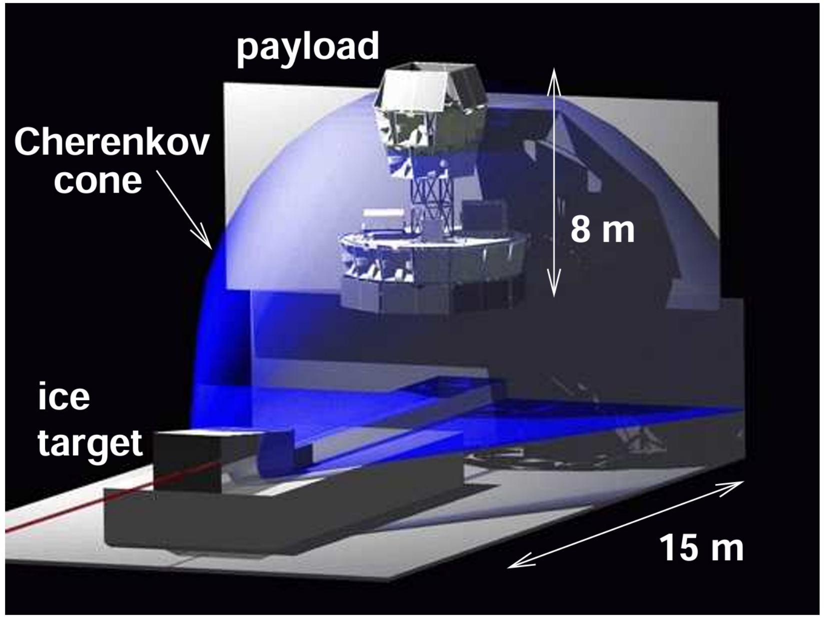
Paudel et al., ICRC2021

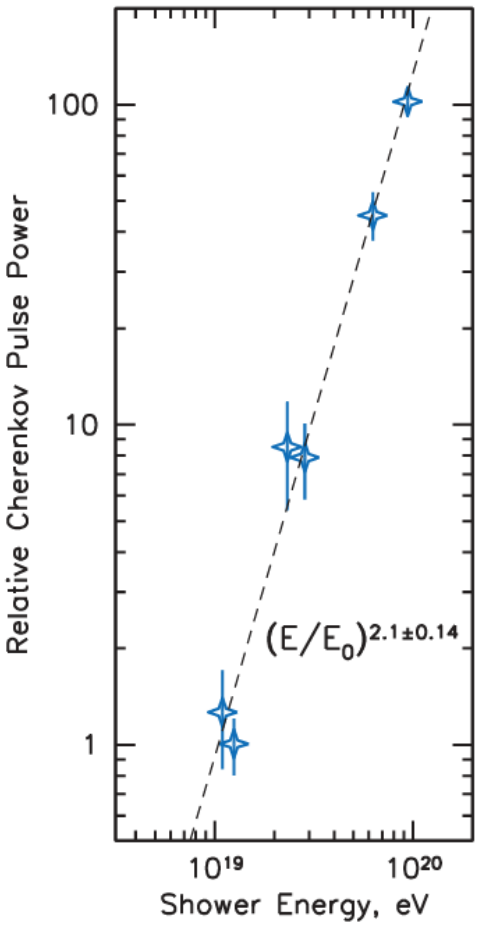
Antarctic Impulsive Transient Antenna (ANITA)



arXiv:1903.11043

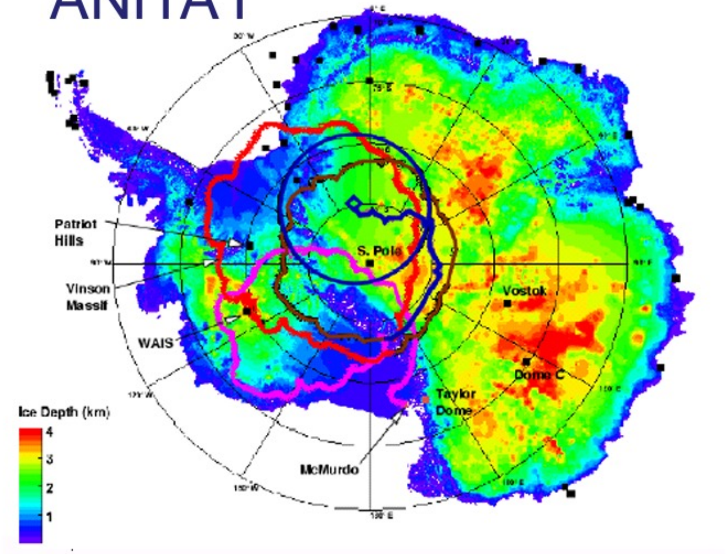
First measurement of Askaryan radiation in ice





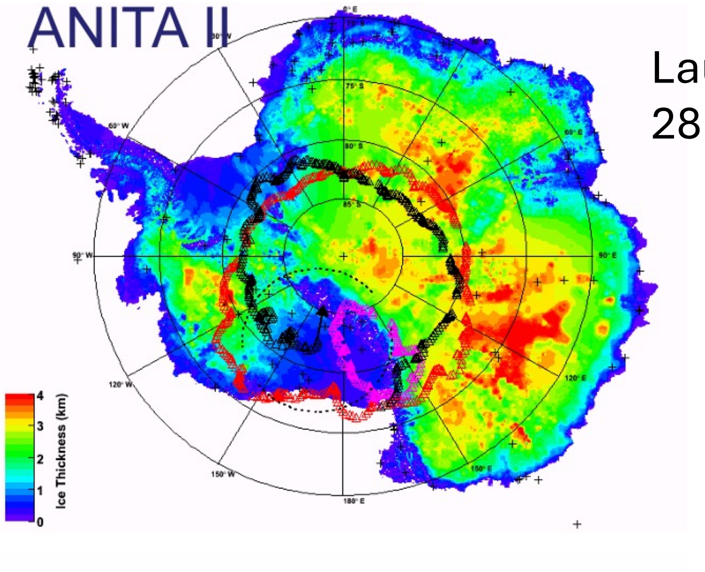
arXiv:hep-ex/0611008

ANITA I



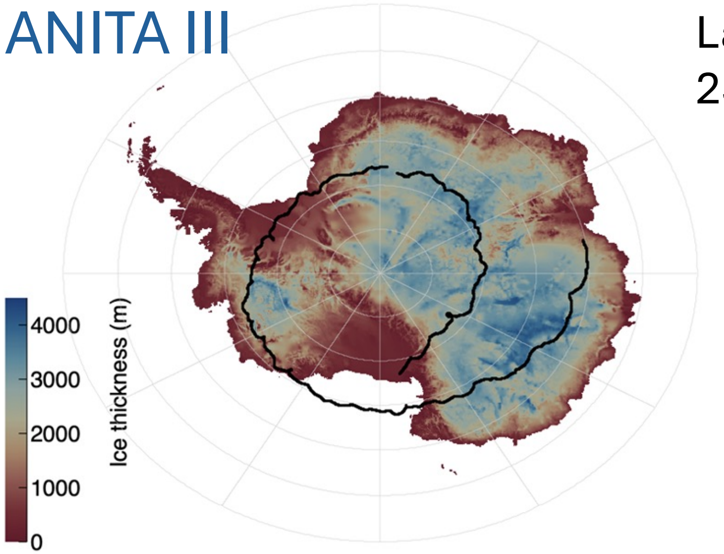
Launched in 2006
36 days of flight

ANITA II



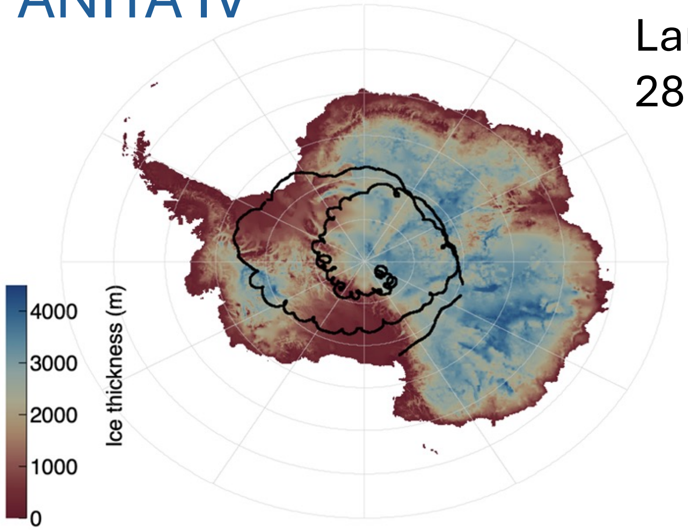
Launched in 2008
28.5 days of flight

ANITA III

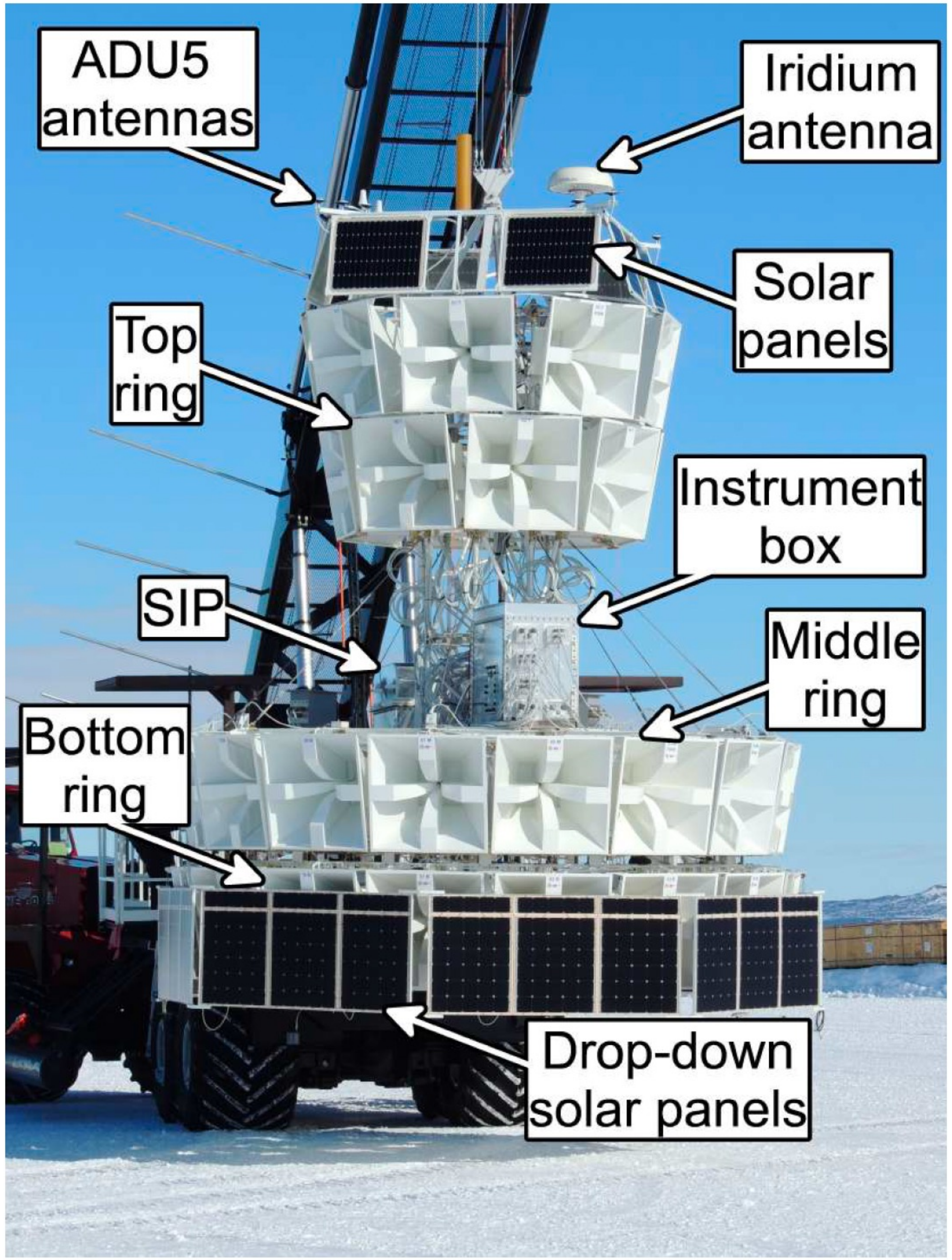


Launched in 2014
23 days of flight

ANITA IV



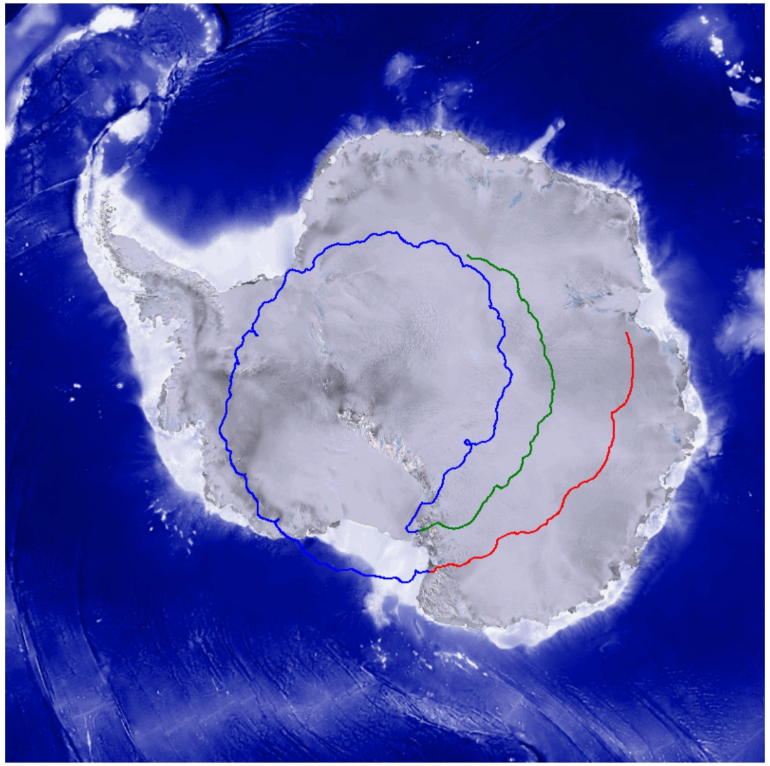
Launched in 2016
28 days of flight

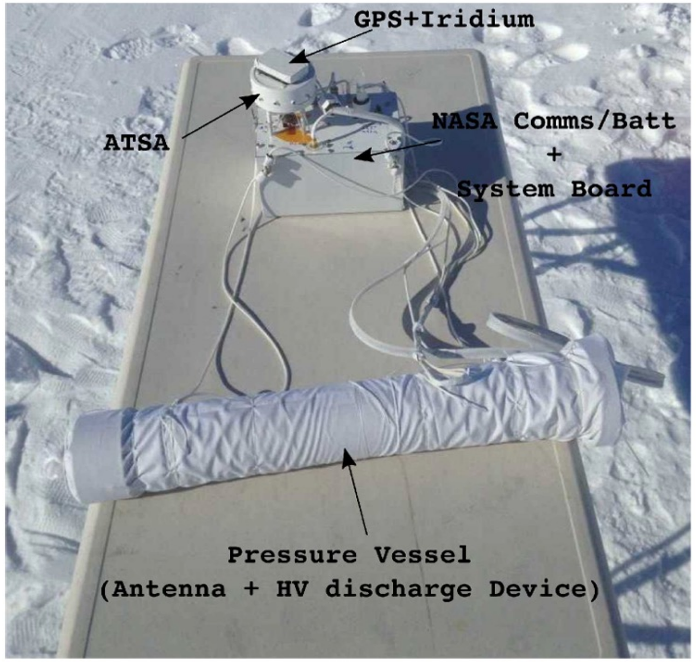


8 m

- ANITA radio array divided into 3 rings (top, middle, bottom) and 16 azimuthal phi-sectors -> full 360-degree coverage in azimuth in each of the rings.
- 48 high-gain quad ridged horn antennas, each one aperture of 1 m^2.
- Each antenna is separated from the next antenna of the same ring by 22.5 degrees.
- Band 200 – 1200 Mhz

ANITA and HiCal



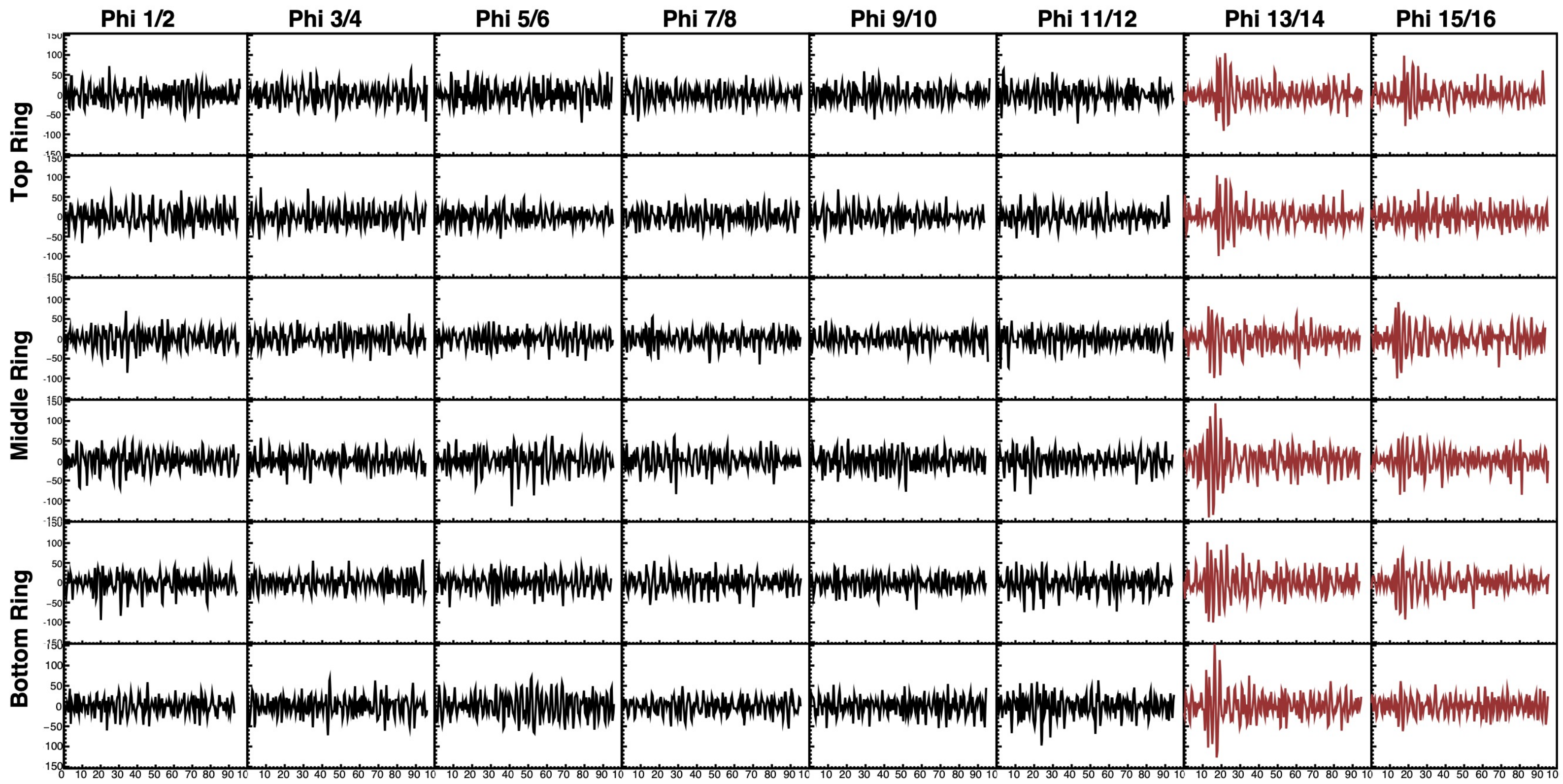


- Measurement of the reflectivity of ice
- Calibration of ANITA

Blue: 1st orbit ANITA III, red: 2nd orbit ANITA III, green: HiCal orbit

DOI: 10.1142/S2251171717400025

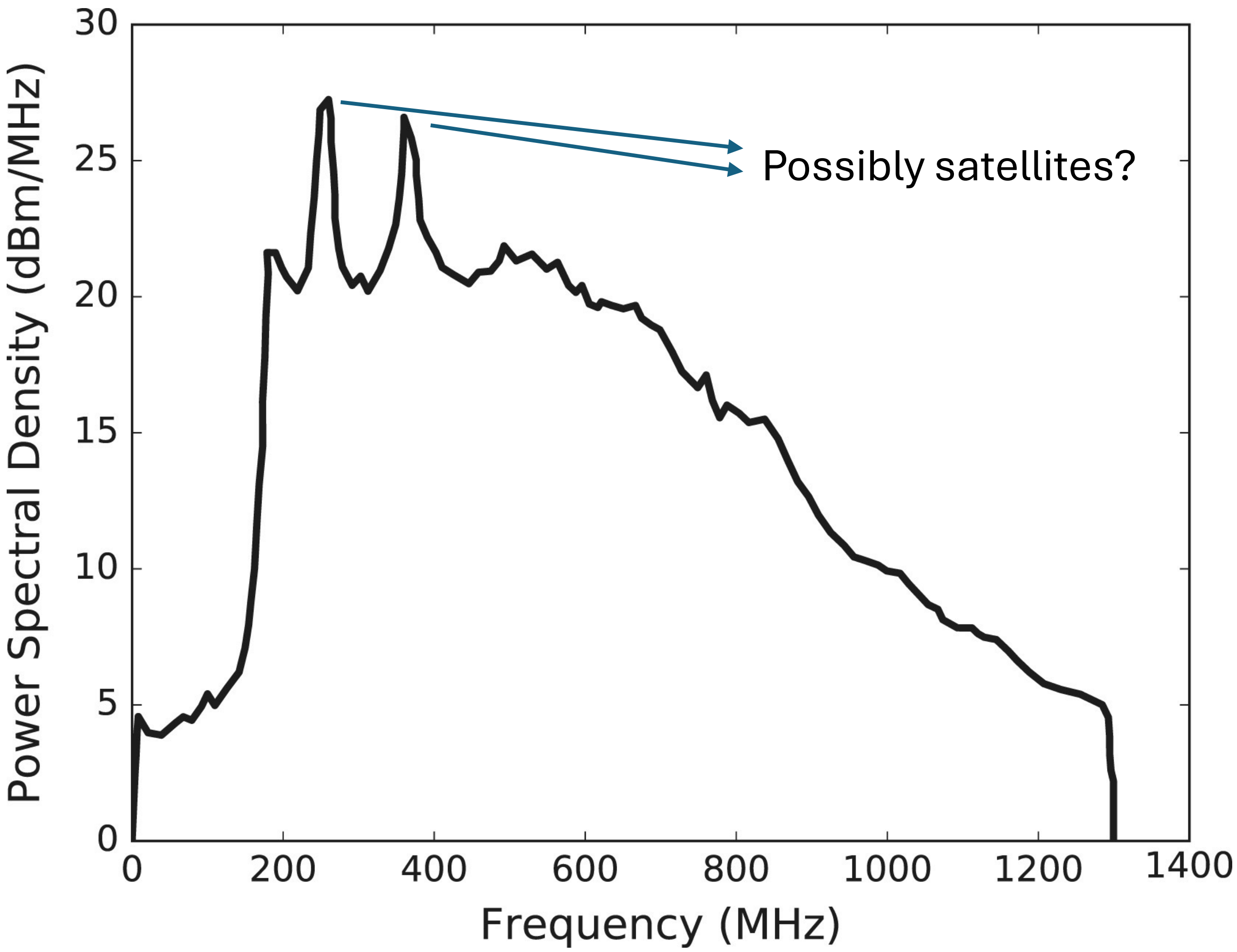
Trigger for ANITA



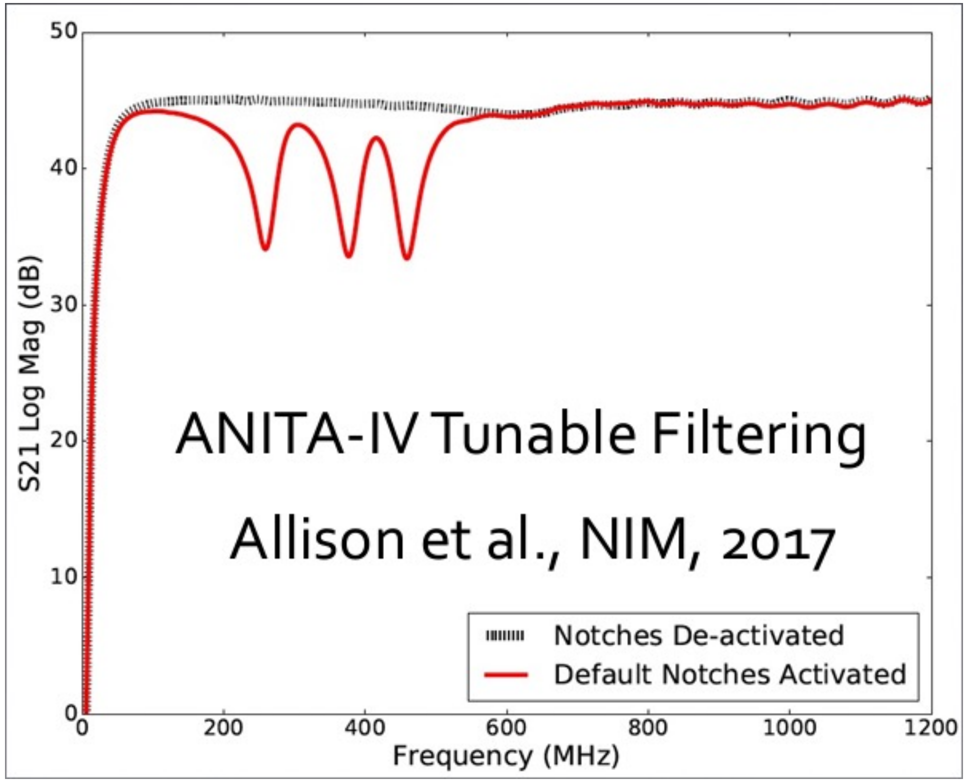
It is impossible to store everything, and circuits must have the lowest power consumption possible -> very simple trigger with two main conditions:

1. Square each point in time, sum over the expected time window.
2. If one antenna is above a certain threshold, look for trigger from nearby antennas.

Trigger for ANITA: removing Carrier Wave (CW)



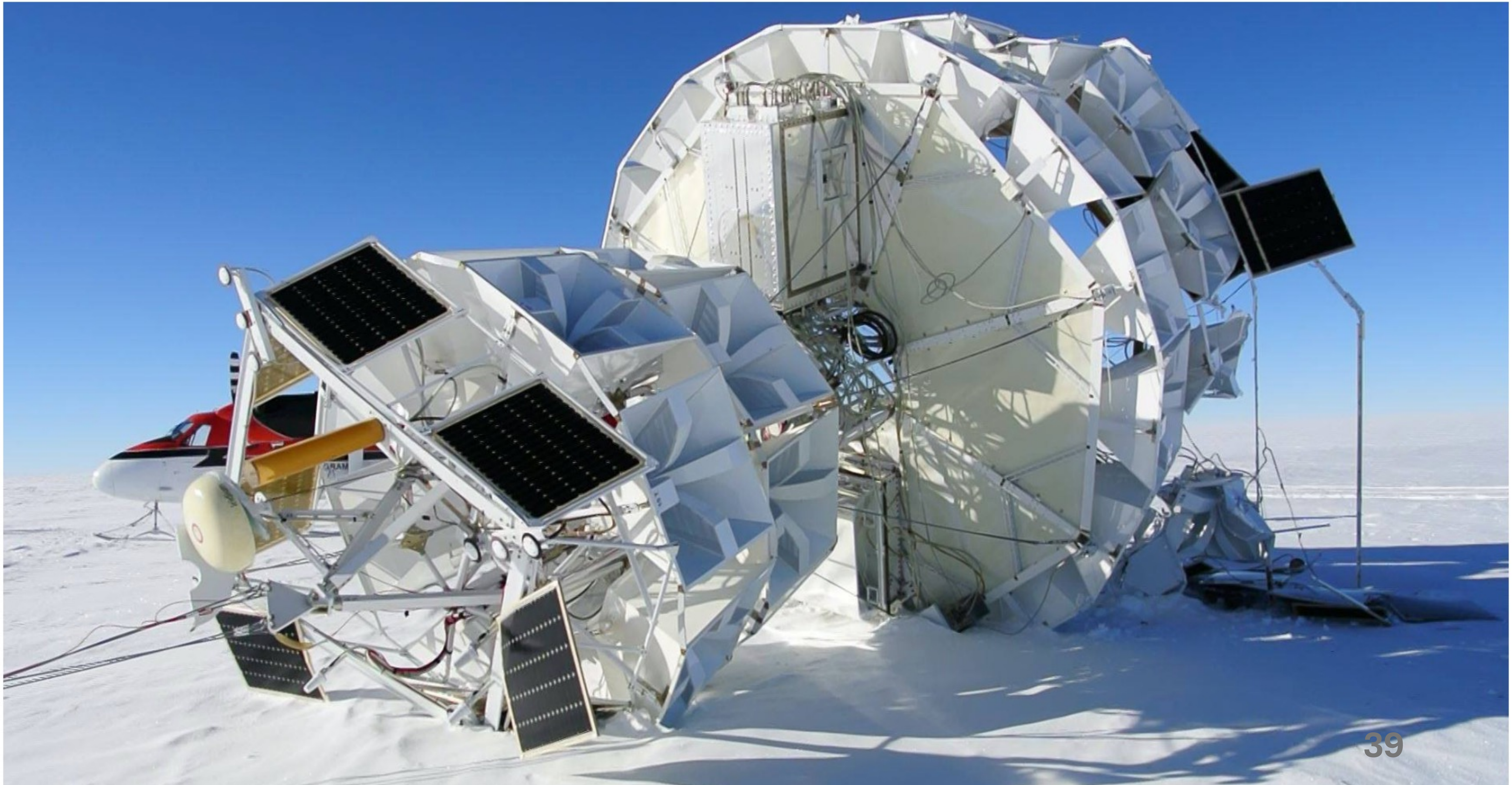
Removed in ANITA I – III with software
In ANITA IV with hardware (tunable notch filters)



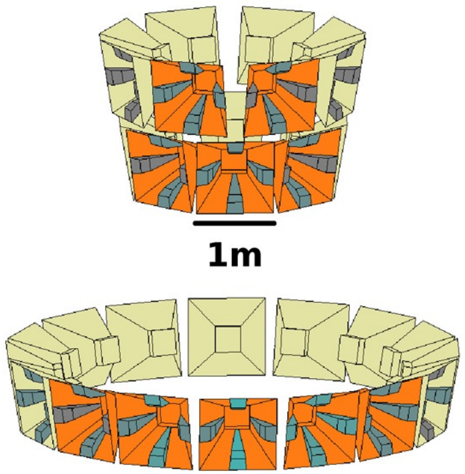
https://doi.org/10.1016/j.nima.2018.03.059

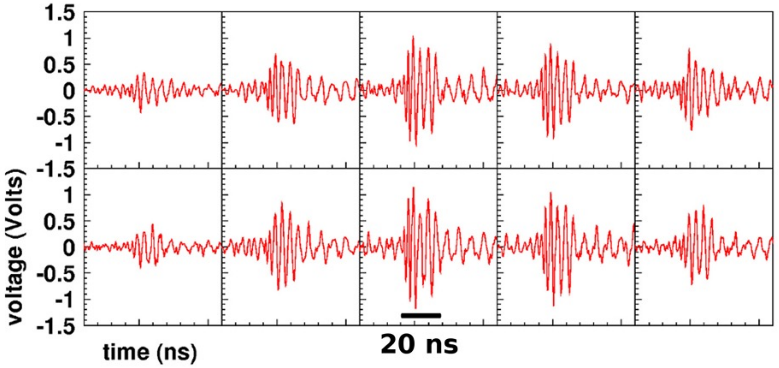
Take off…

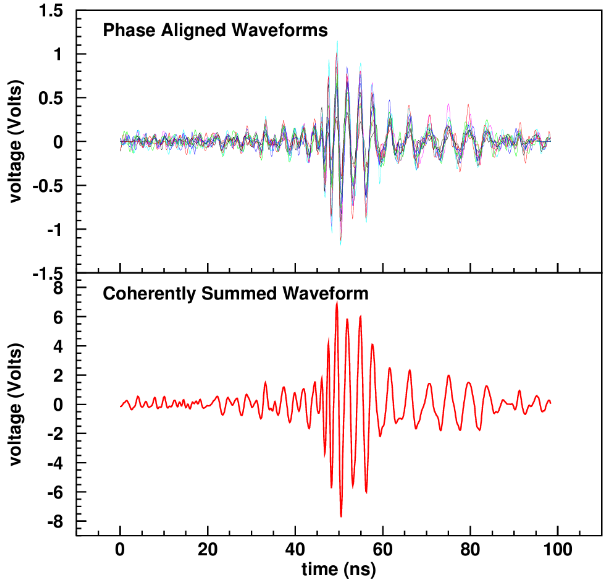
…and landing!

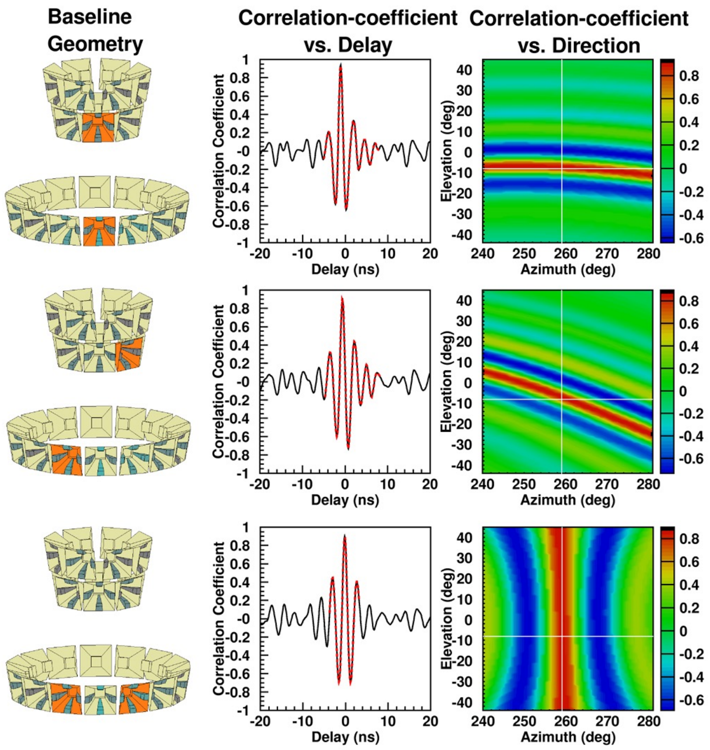


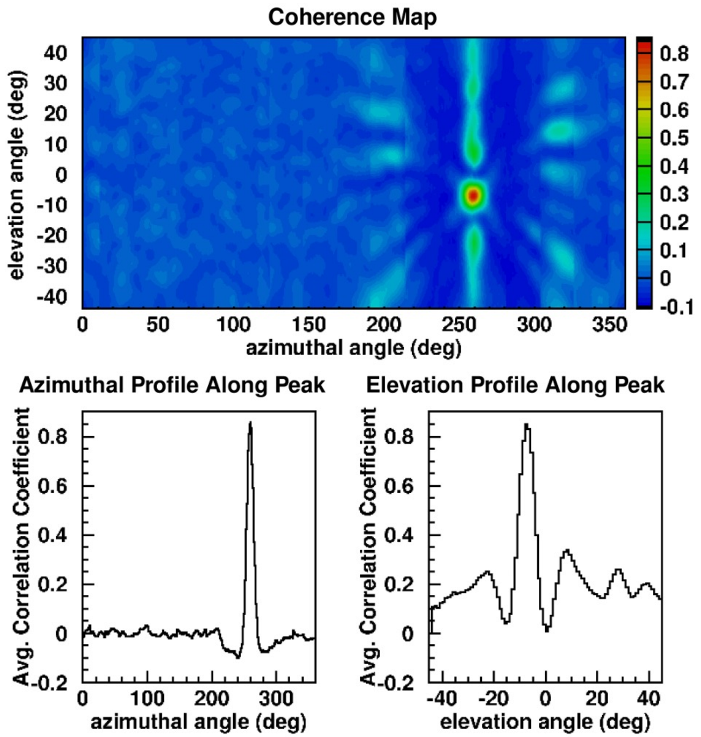
Offline analysis: interferometry





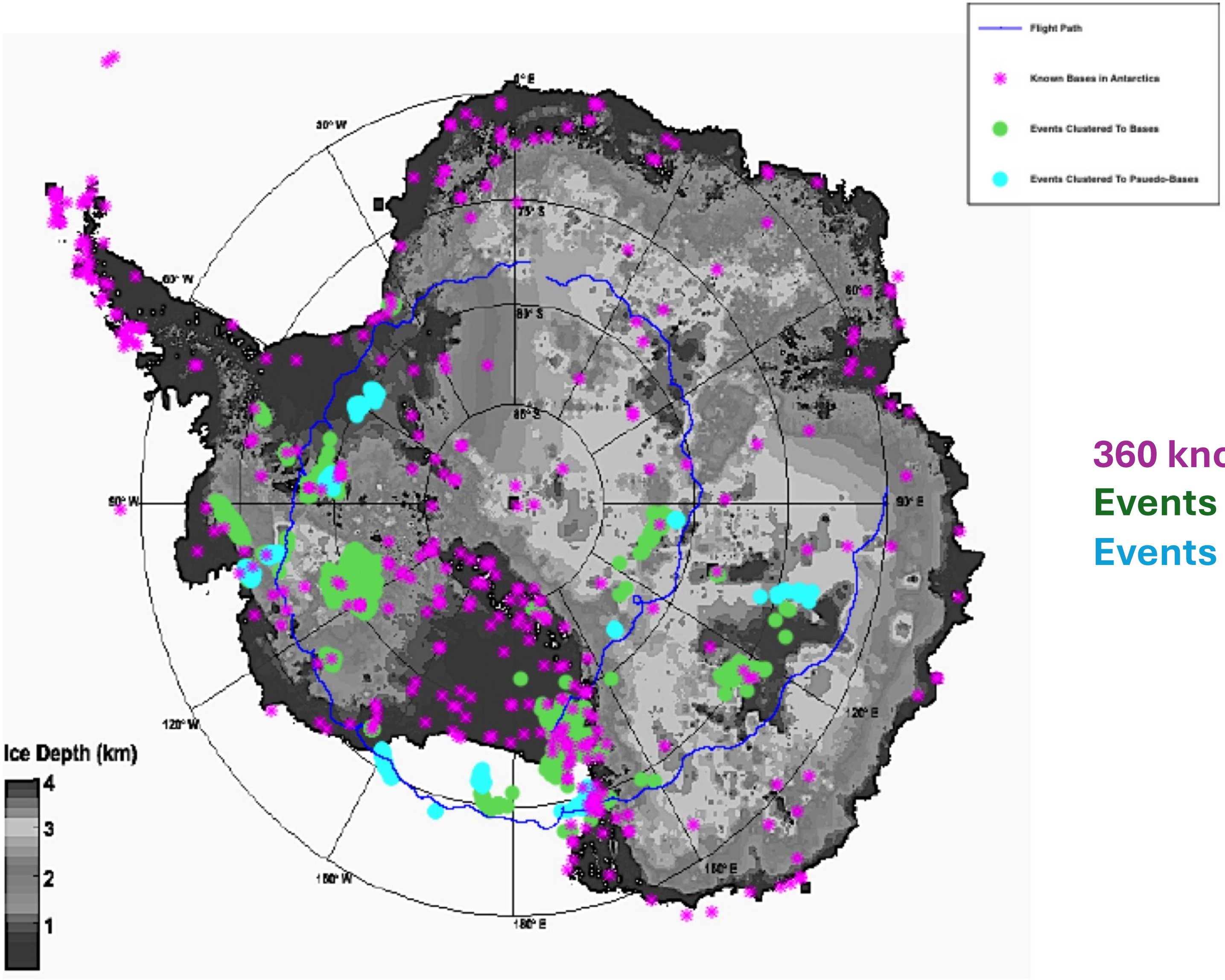






arXiv:1304.5663

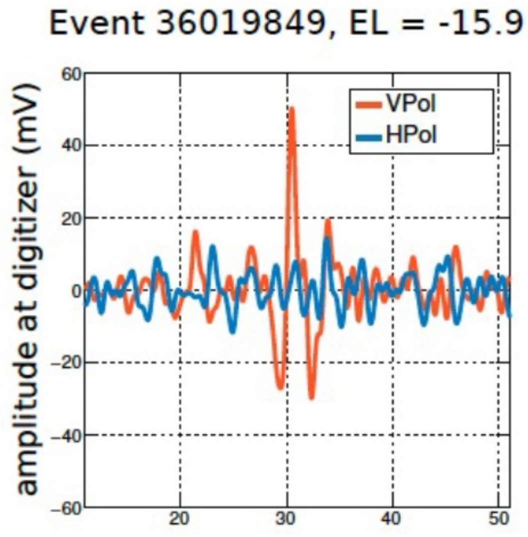
Offline analysis: clustering man-made noise



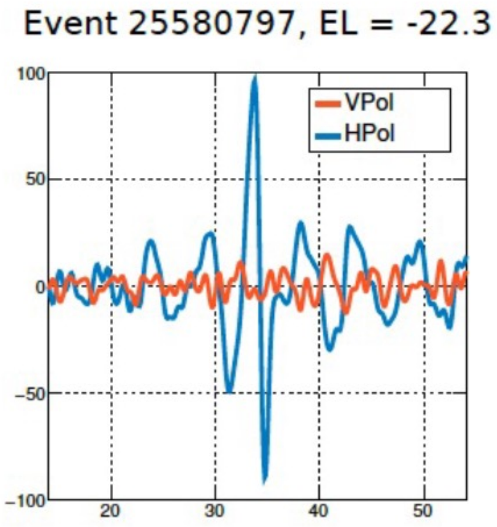
360 known bases in Antarctica
Events clustered to base
Events clustered to pseudo-base

From Ben Strutt PhD's thesis, January 2017

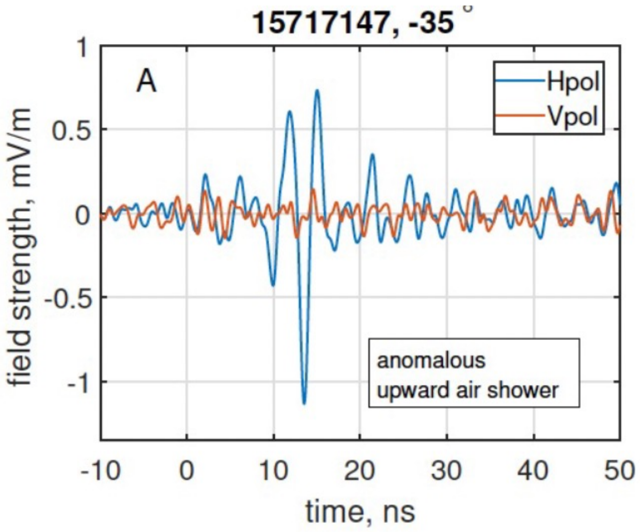
Offline analysis: results



Example neutrino candidate



Example CR candidate



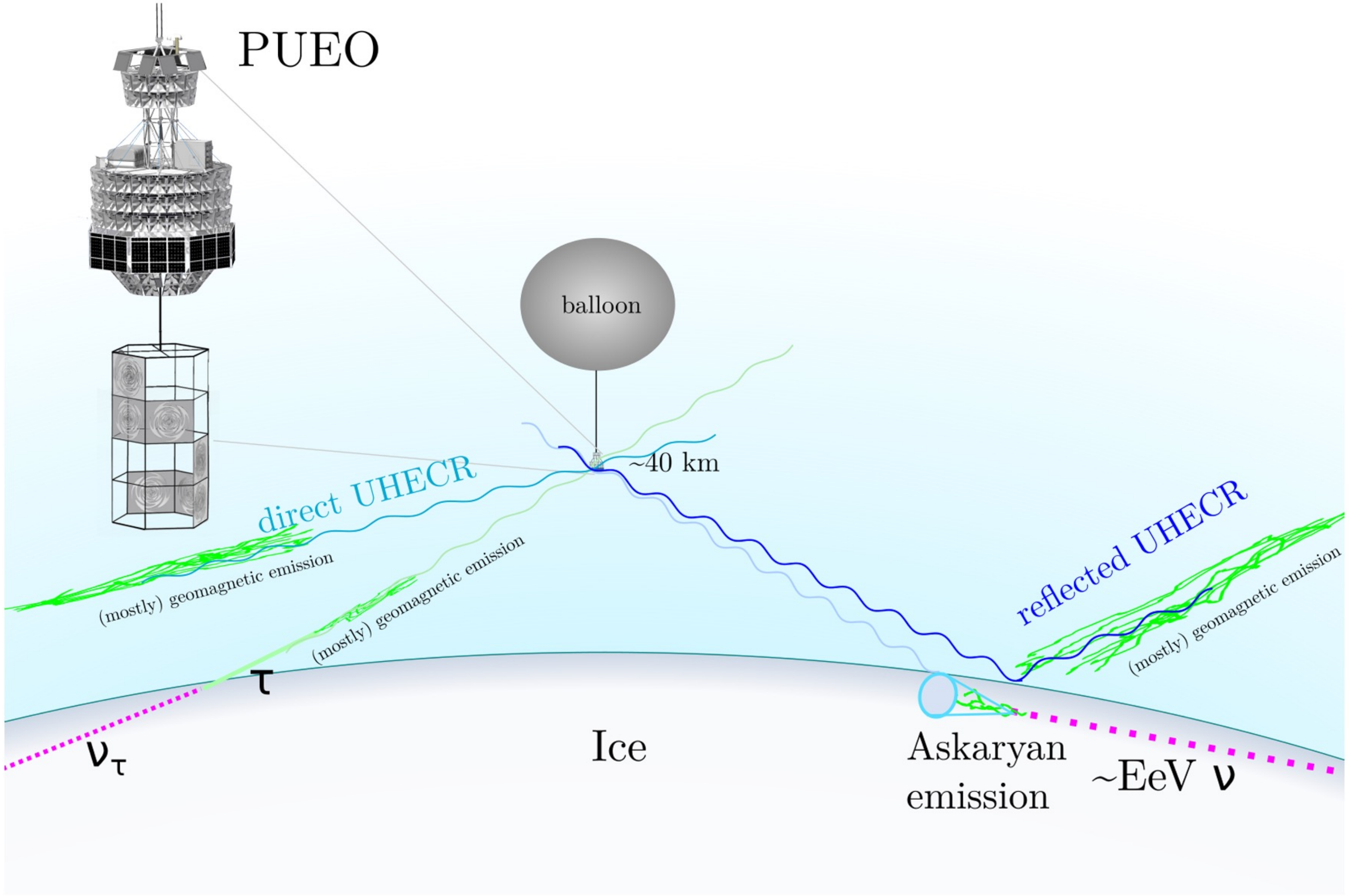
"mystery event"

arXiv:2010.02892

- Completed four successful flights between 2006 and 2016.
- ANITA has seen ~100 ultra-high energy cosmic ray events and it placed the best constraints on the UHE neutrino flux between $10^{19.5} - 10^{21}$ eV.
- All ANITA flights have seen 1 or 0 candidate events on a background of ~1 in the main neutrino search (Askaryan channel). -> Sadly, no discovery.

The **pueo** (**Asio flammeus sandwichensis**) is a subspecies of the short-eared owl and is endemic to Hawaii. The pueo is one of the more famous of the various physical forms assumed by ‘aumkua (ancestor spirits) in Hawaiian culture.

Payload for Ultrahigh Energy Observations (PUEO)



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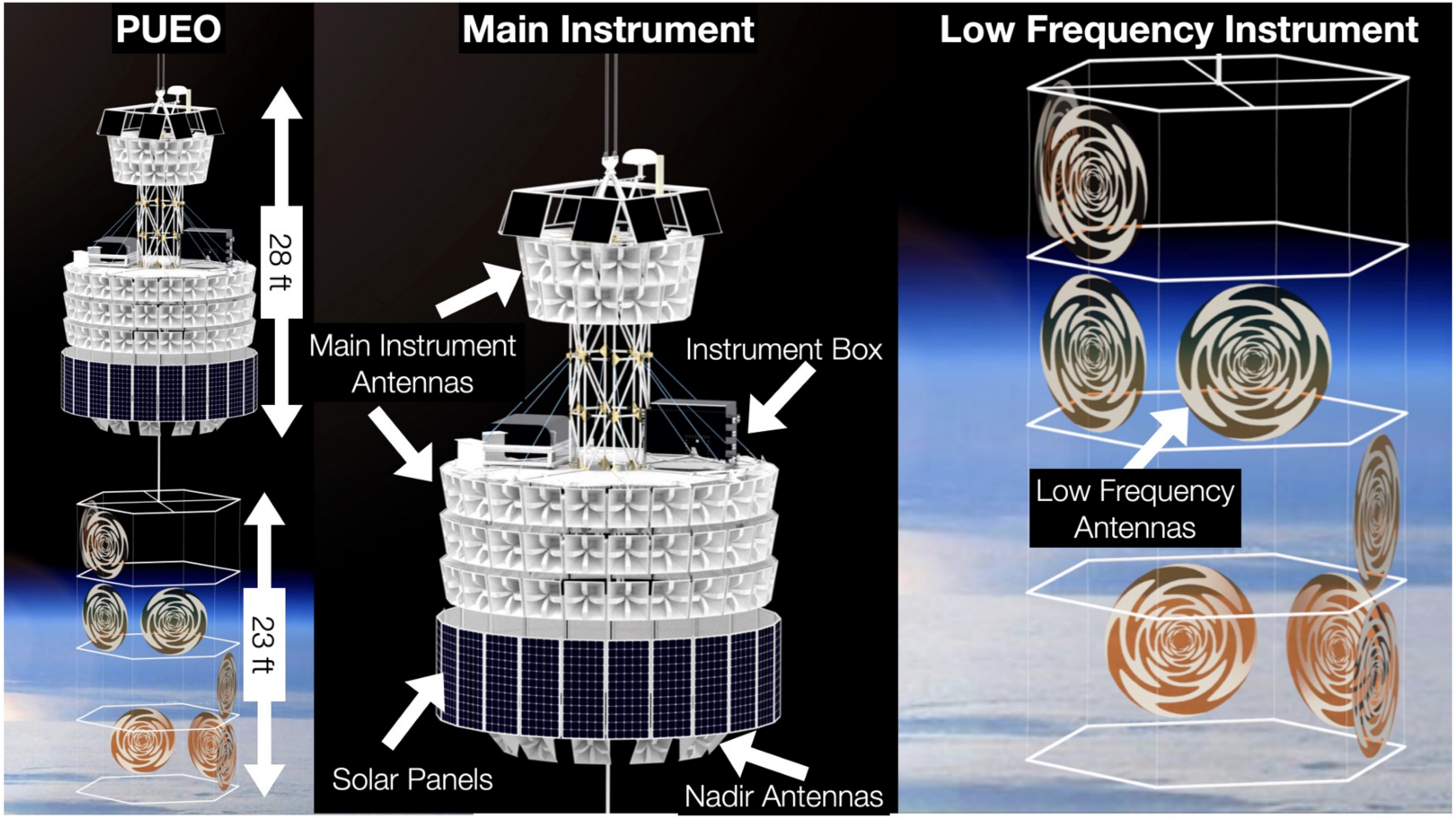
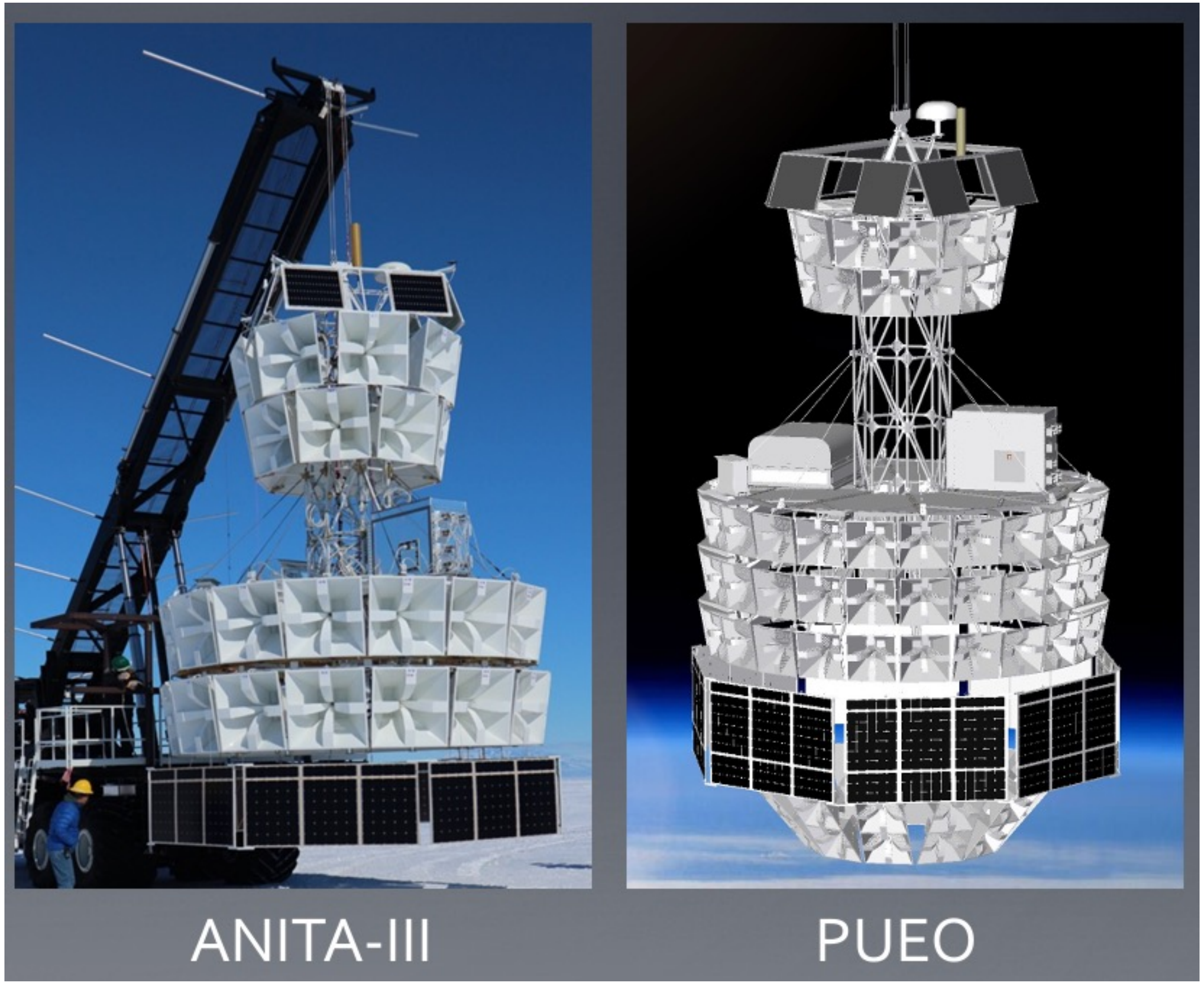


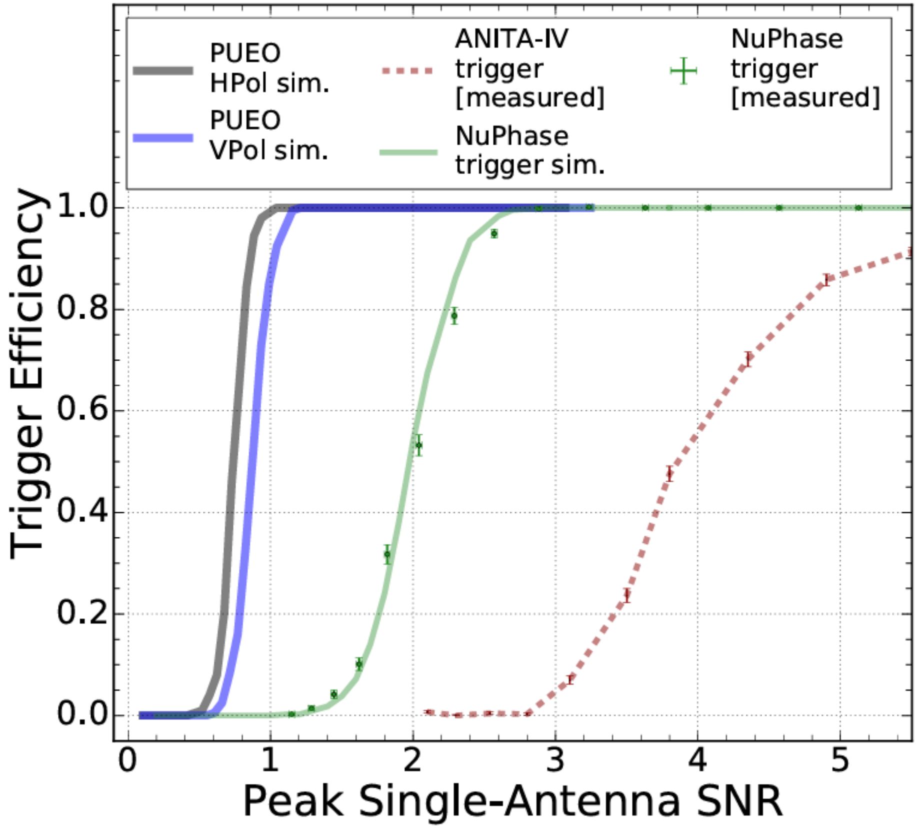
PUEO
Main Instrument
Low Frequency Instrument
28 ft
23 ft
Main Instrument Antennas
Instrument Box
Solar Panels
Nadir Antennas
Low Frequency Antennas

Two sets of antennas

- Main instrument has a modified frequency range 300 MHz-1200 MHz -> smaller antennas (33% in each dimension) -> more antennas!
- Low frequency instrument has frequency range 50MHz to 300MHz.

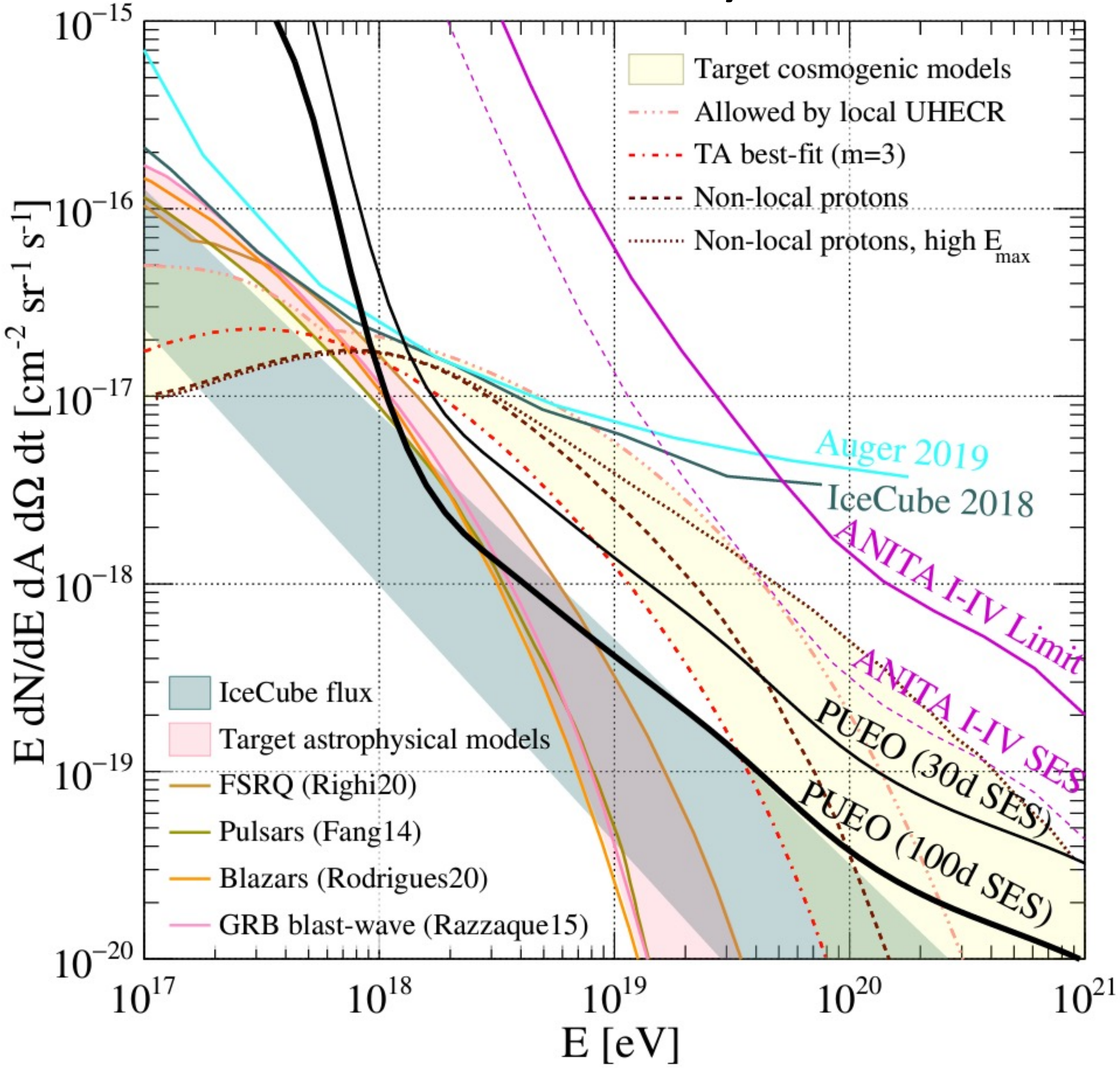


An improved trigger



- Noise is incoherent, signal is coherent.
- When adding signal from N antennas, Signal-To-Noise (SNR) improves as $\sqrt{N}$.
- RFSoCs (Radio-Frequency System-on Chip) allow us to perform a sort of interferometric trigger on the go with very low power consumption.
- To save energy, first triggering one column, if positive, second one.
- Result is a better trigger with lower threshold.

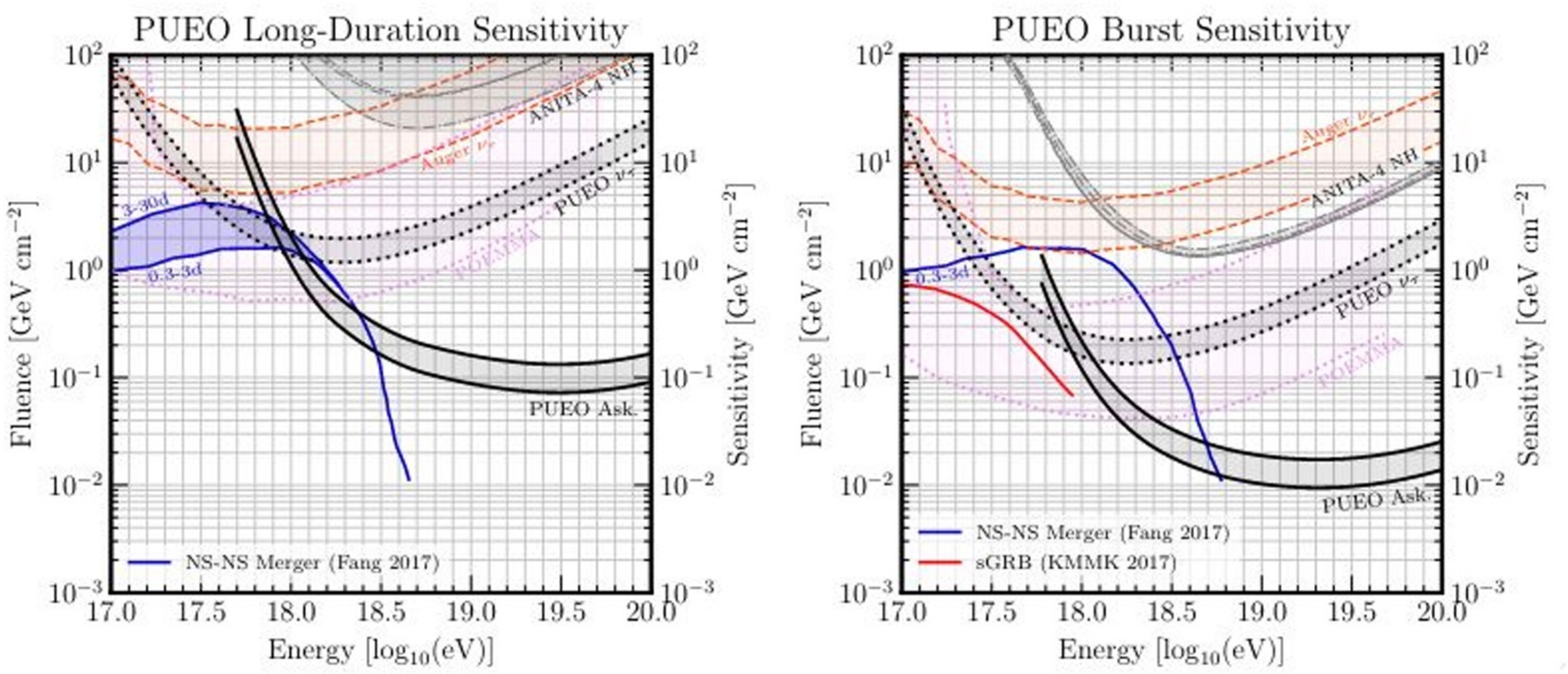
Sensitivity



- Lower threshold
- Best resolution at the highest energy

arXiv:2010.02892

Sensitivity

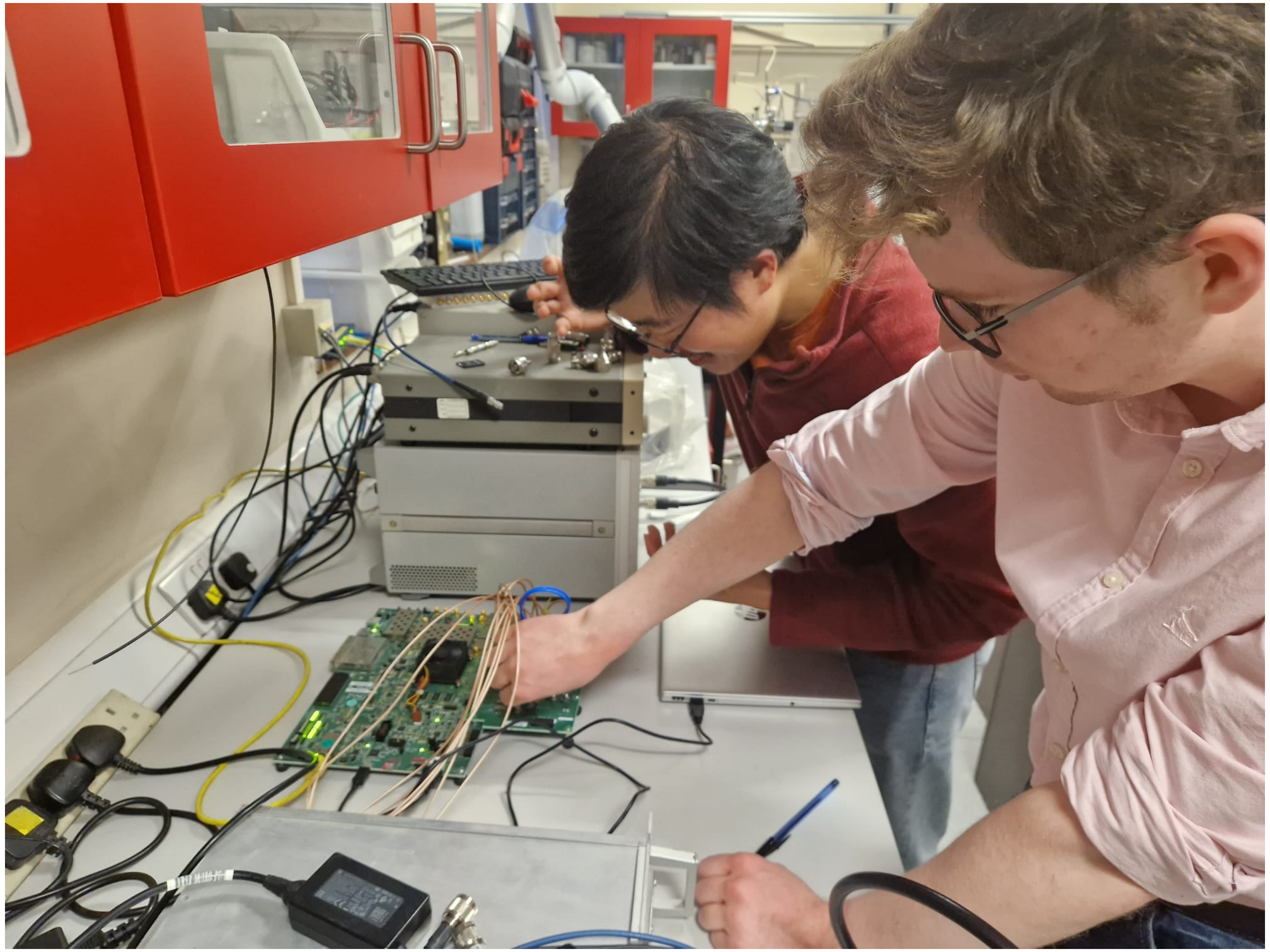


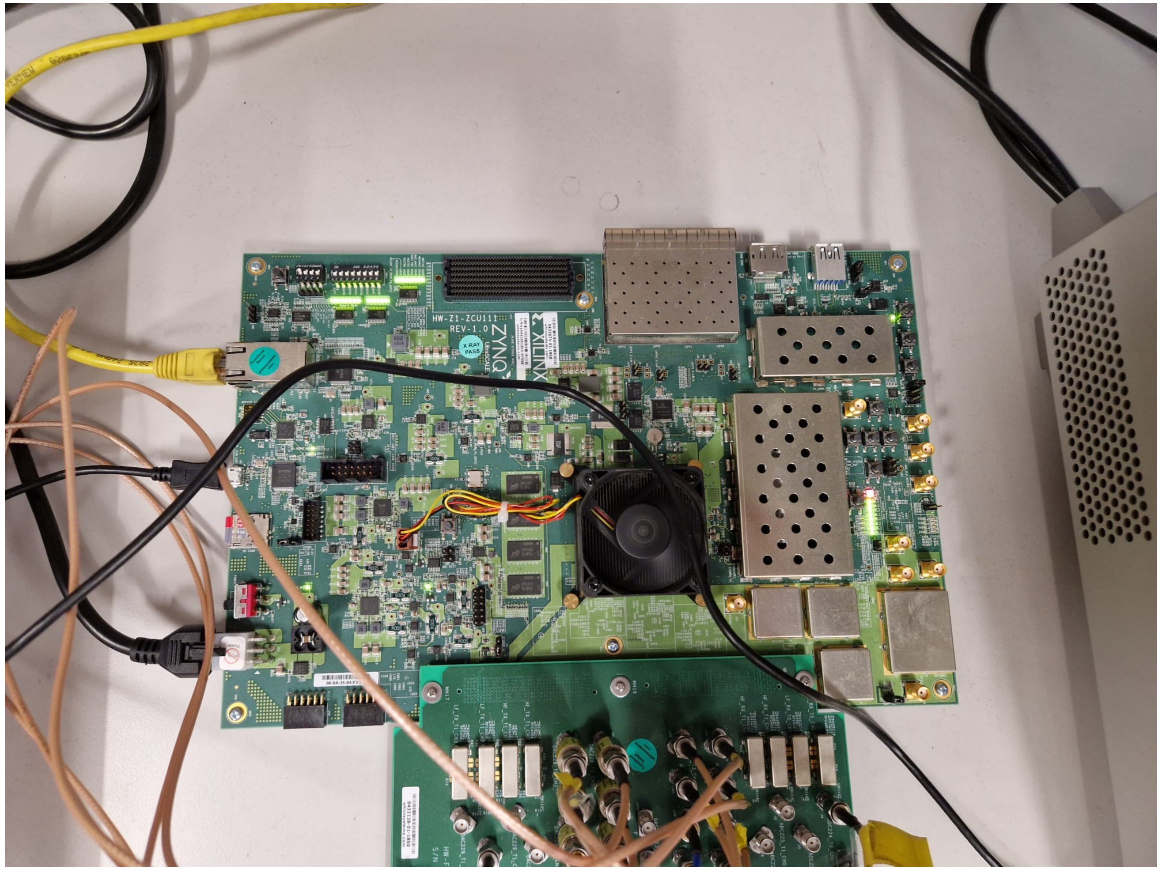
arXiv:2010.02892

Potential transient sources:

- Neutron star mergers
- Short gamma ray bursts

UCL PUEO Team

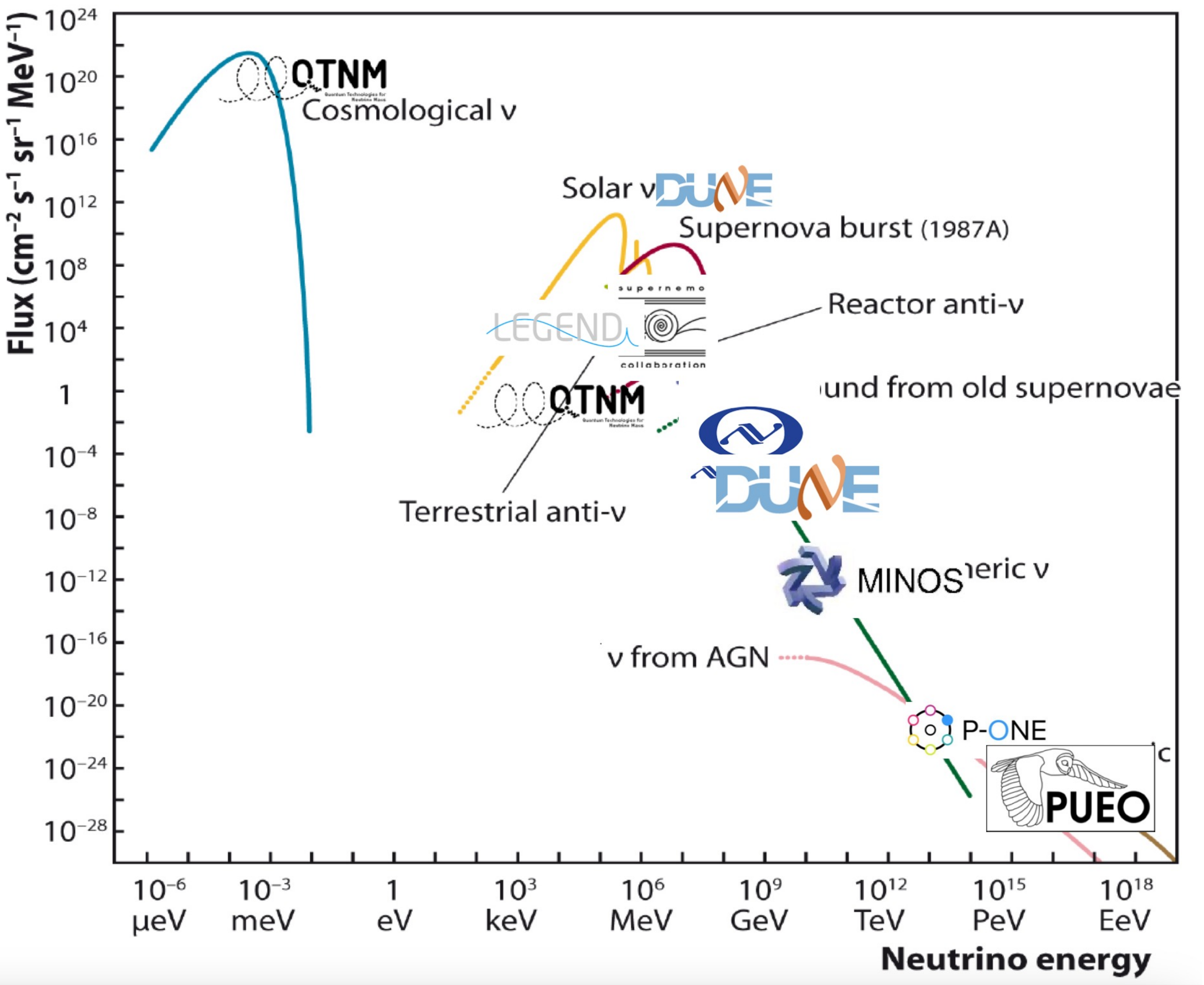




Our team is working on:

- RFSoc
- Simulation and data analysis
- Hardware R&D

Neutrino experiments on different energy scales



PUEO will fly in December 2025, see you there!