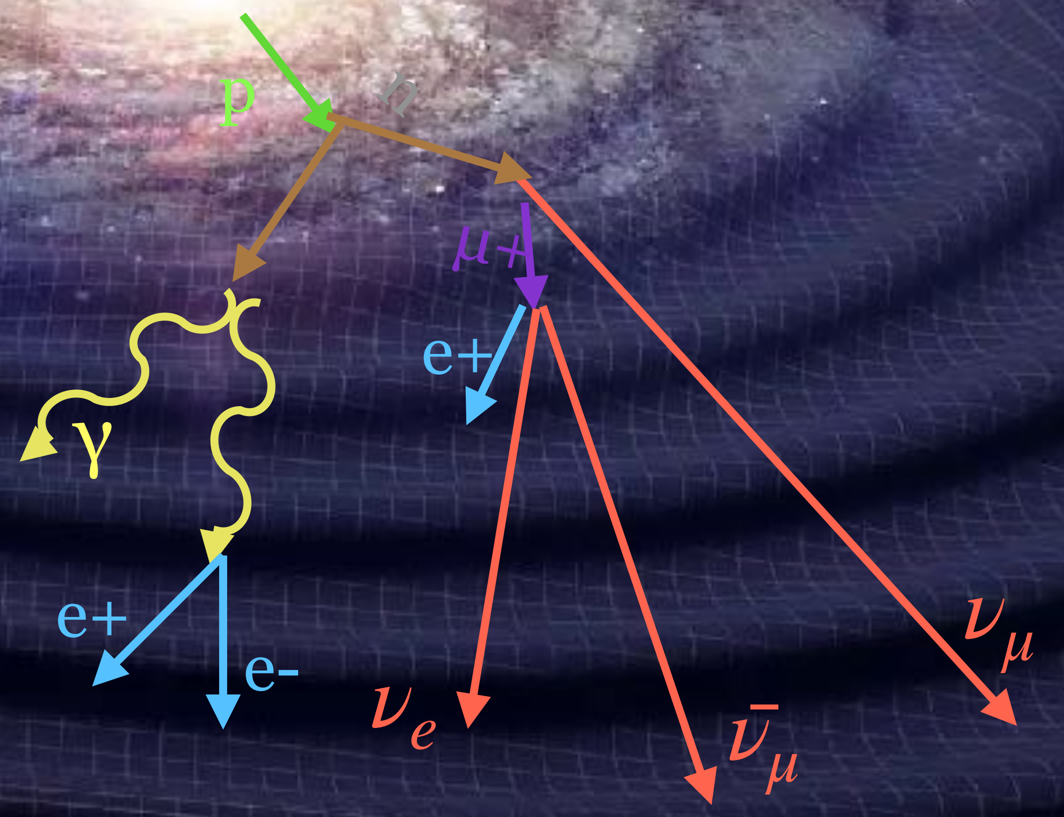


Multi-messenger observations in high-energy astrophysics

Nahee Park

Queen's University

Cosmic Rays : Particles from Outer Space

High energy charged particles, originating in outer space

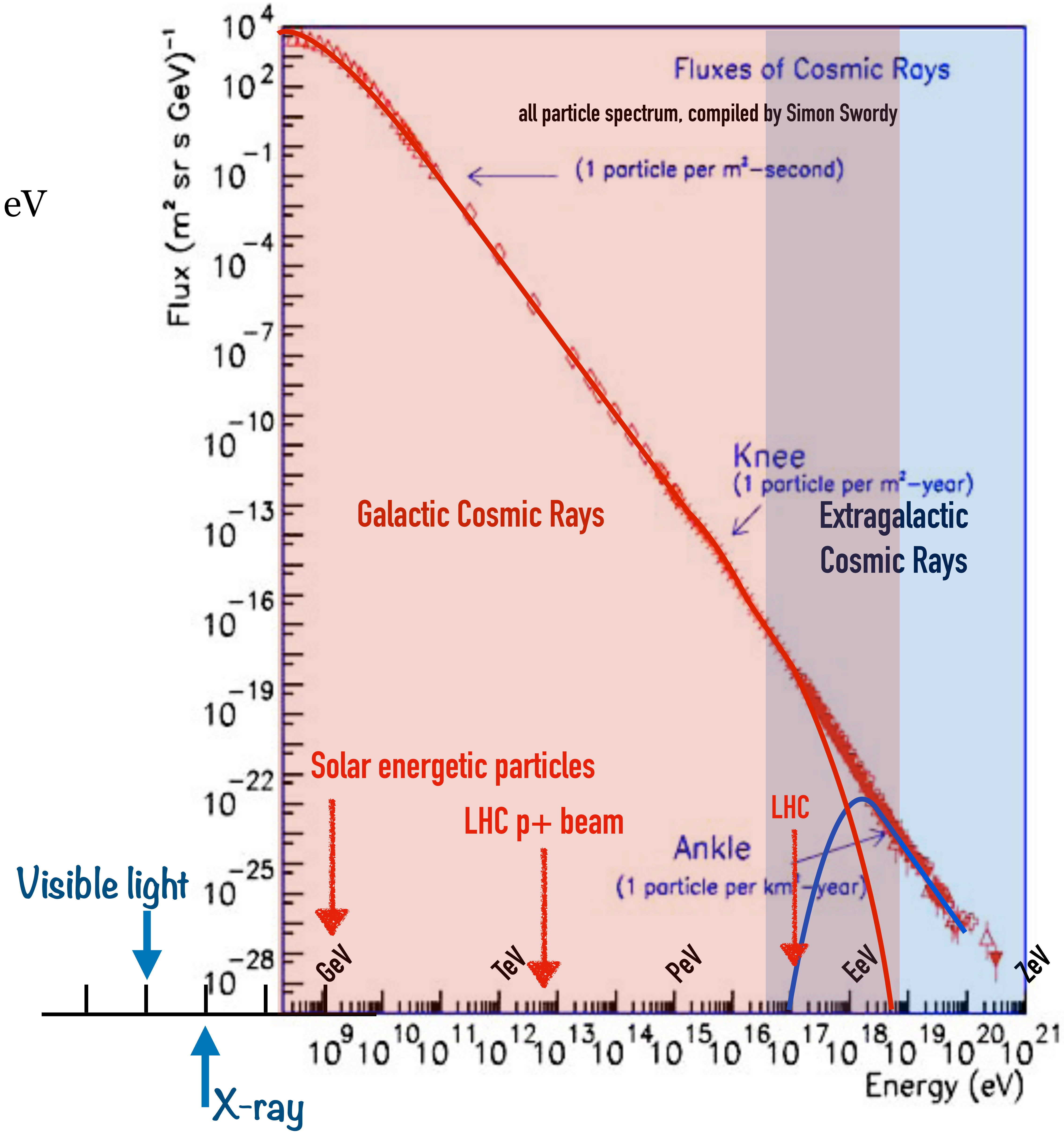
- Mostly nuclei of atoms
  - 85% proton, 12% helium, 2% heavy nuclei, 1% leptons at 10^9 eV
- Spectrum follows a smooth power-law distribution over wide energy range

More than a hundred years old questions…

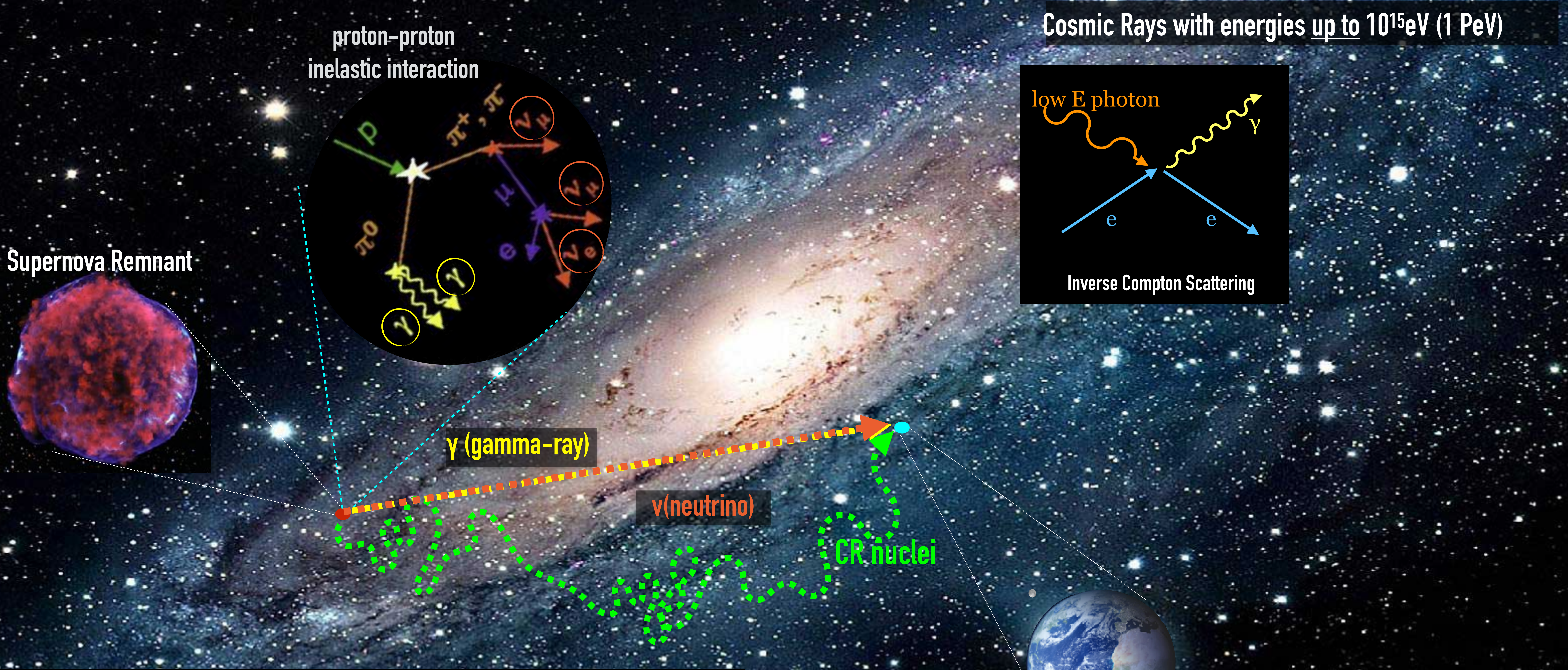
- What is the origin of cosmic rays?
- How do they get their energies?
- How do they propagate to us?

Difficulties

- Bending in the magnetic field
- Lots of interaction in their way to Earth



Source of Galactic Cosmic Rays?



Cosmic-rays are bending inside the magnetic field.

Gamma-rays are generated by both *leptons & hadrons*!

VHE neutrino are generated only by hadrons!

Source of Extragalactic Cosmic Rays?

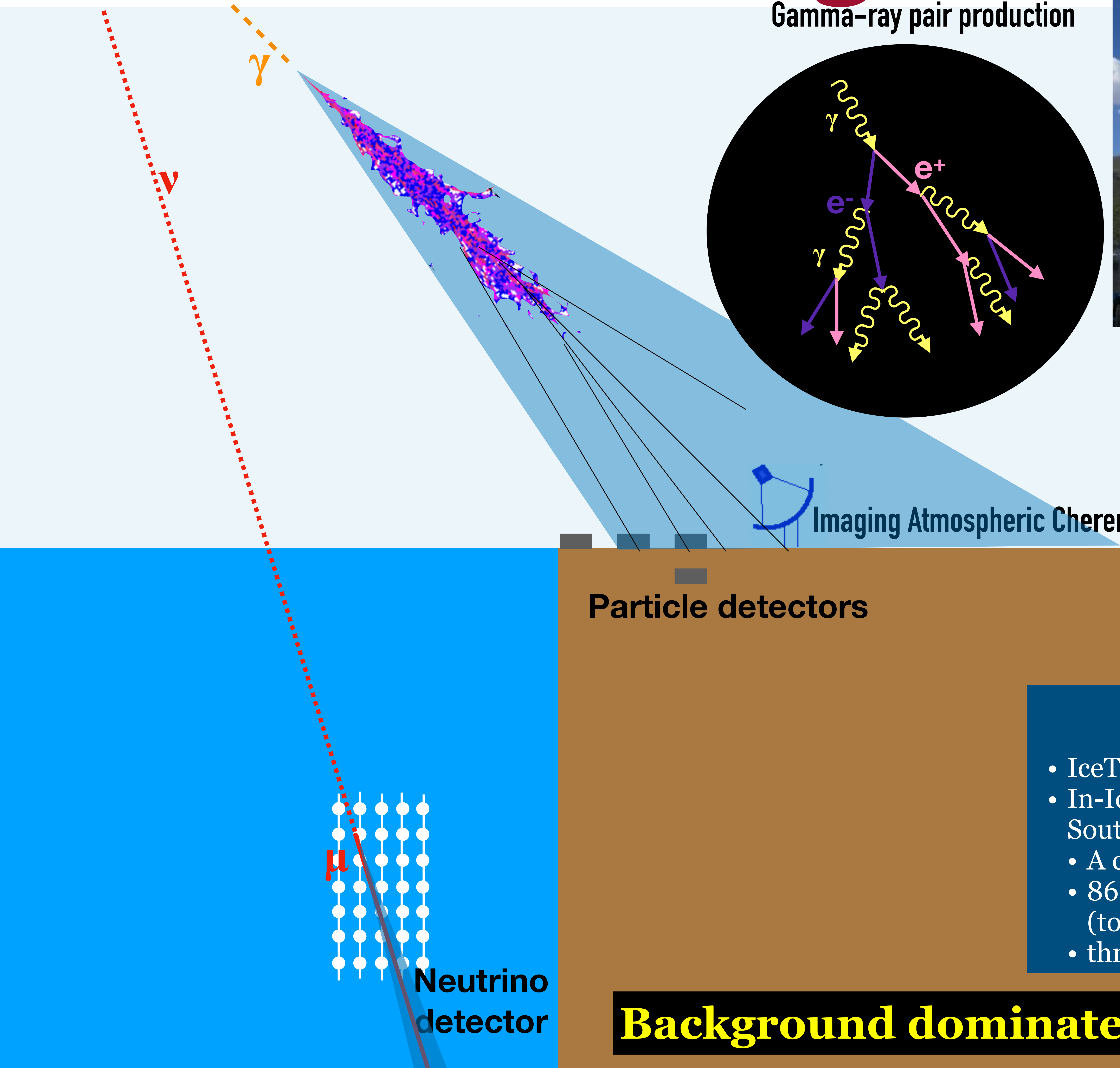
Cosmic Rays with energies higher than 10^{17}eV (100 PeV)

Horizon of VHE gamma-ray (>100 GeV (10^{11} eV)) : z~1

Neutrinos do not interact and image the sky in regions from which even X-rays cannot escape ***→Hard to Detect!!***

Detection of High Energy Astro Particles

Detection of High Energy Astro Particles



VERITAS

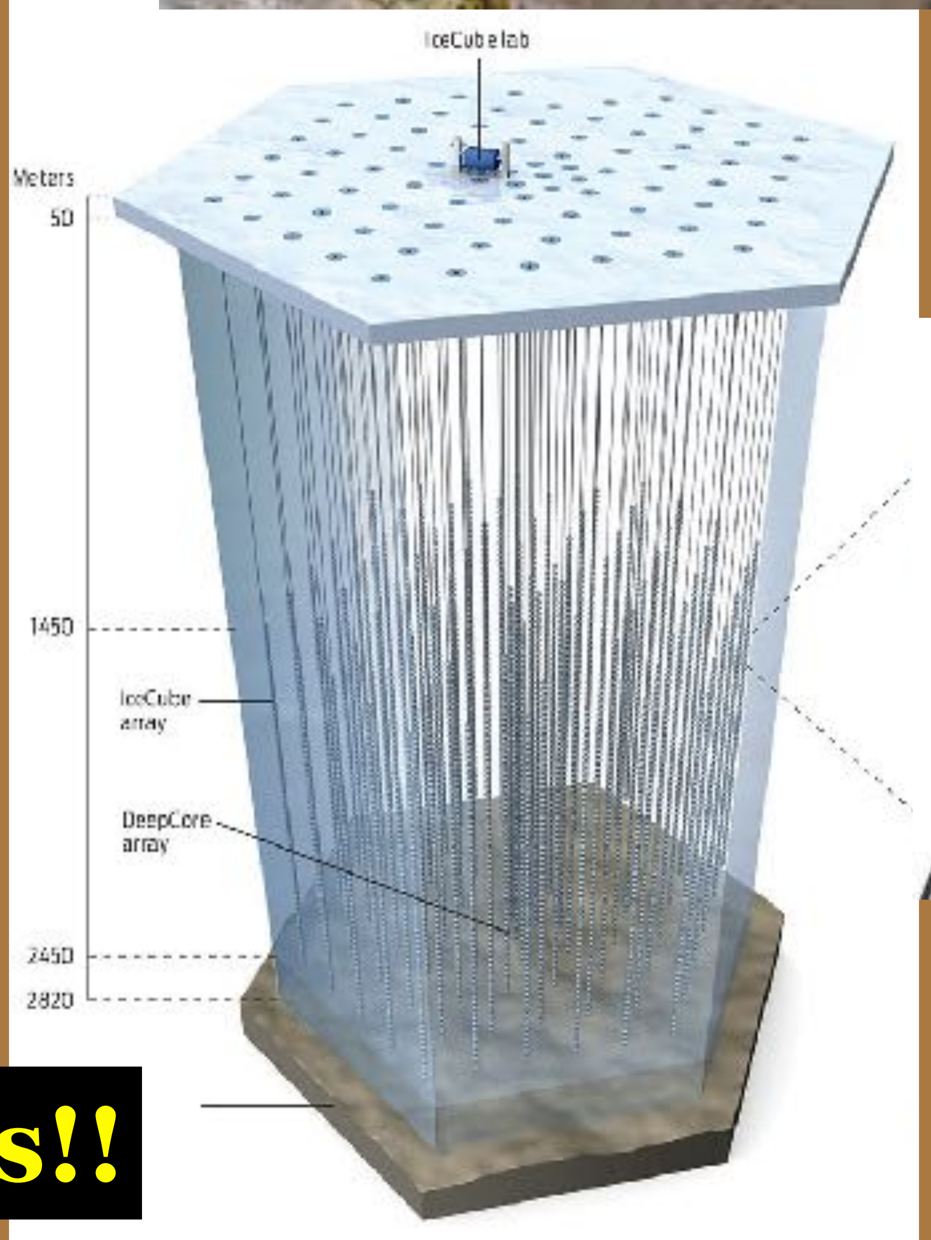
- Located at 1.3 km a.s.l.
- 4 telescopes, each with 12 m optical reflector with a camera w/ 499 PMTs
- 100 GeV upto >30 TeV

HAWC

- Located at 4.1km a.s.l.
- 300 water tanks
- 100 GeV upto >30 TeV

IceCube

- IceTop: Surface veto array
- In-Ice array :1.45 km below the South Pole
  - A cubic kilometer active volume
  - 86 strings with optical module (total 5160 optical modules
  - threshold : ~ 100 TeV



Background dominated measurements!!

Multi-messenger High Energy Astrophysics

To accelerate particles to the energies of cosmic rays we observed on Earth, we need much more extreme environments than our Sun

- In our Galaxy: Supernova remnants, pulsar, pulsar wind nebulae, **nova**, binaries, Galactic center, **microquasar jet interactions**, …
- Outside our Galaxy: Supermassive black holes (blazars, radio galaxies), starburst galaxies, **gamma-ray bursts**,….

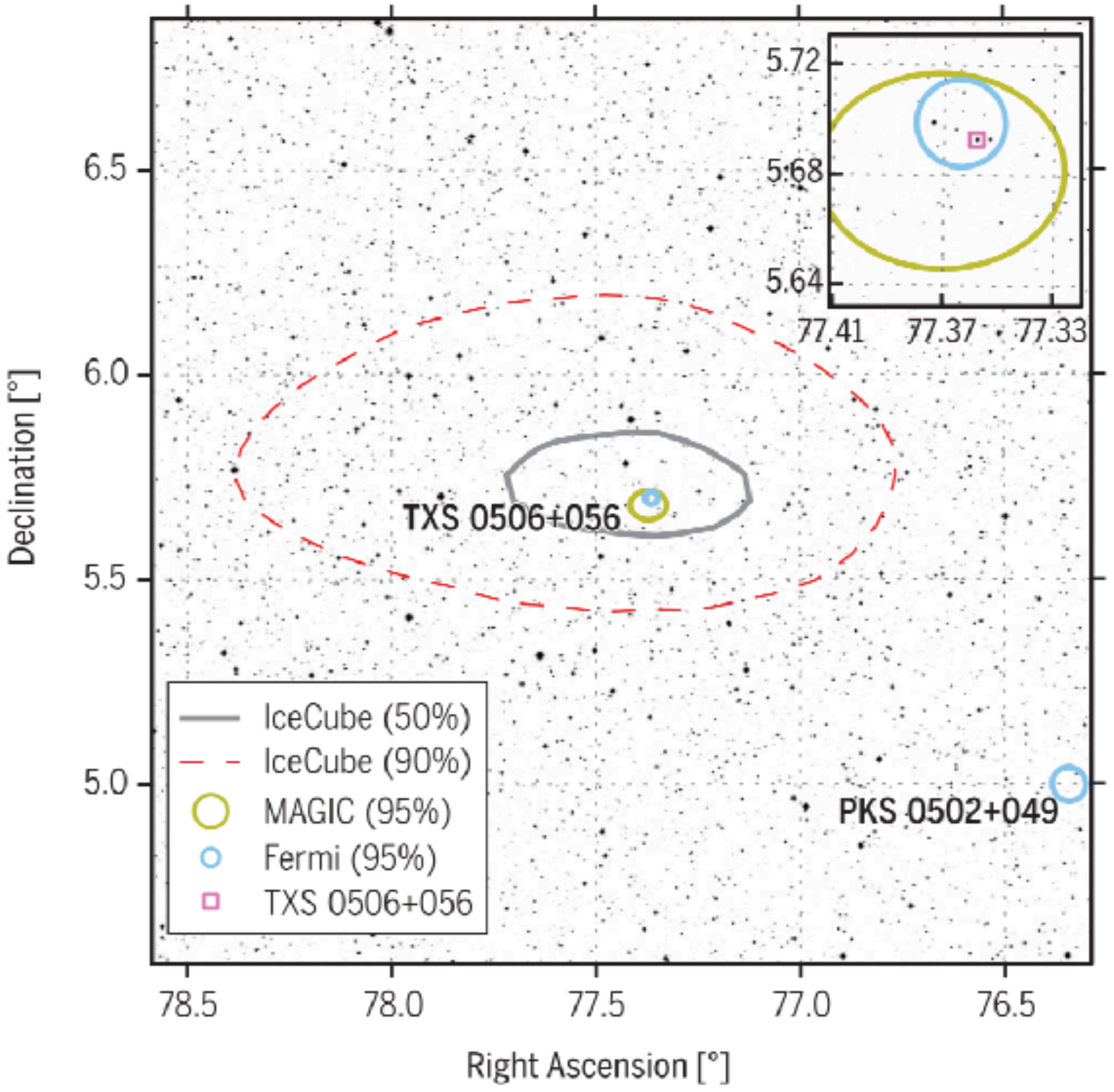
Observation of multiple messengers from the Universe provide the most direct way of studying the high-energy(HE) particle dynamics in our Universe

- Cosmic-ray observations provide energies and compositions of HE particles.
- HE gamma-ray observations provide the direct measurements of HE particles accelerators for both leptonic + hadronic particles.
- HE neutrino observations provide the direct measurements of HE particle accelerators for hadronic particles. Can probe larger portion of the Universe than HE gamma-rays.

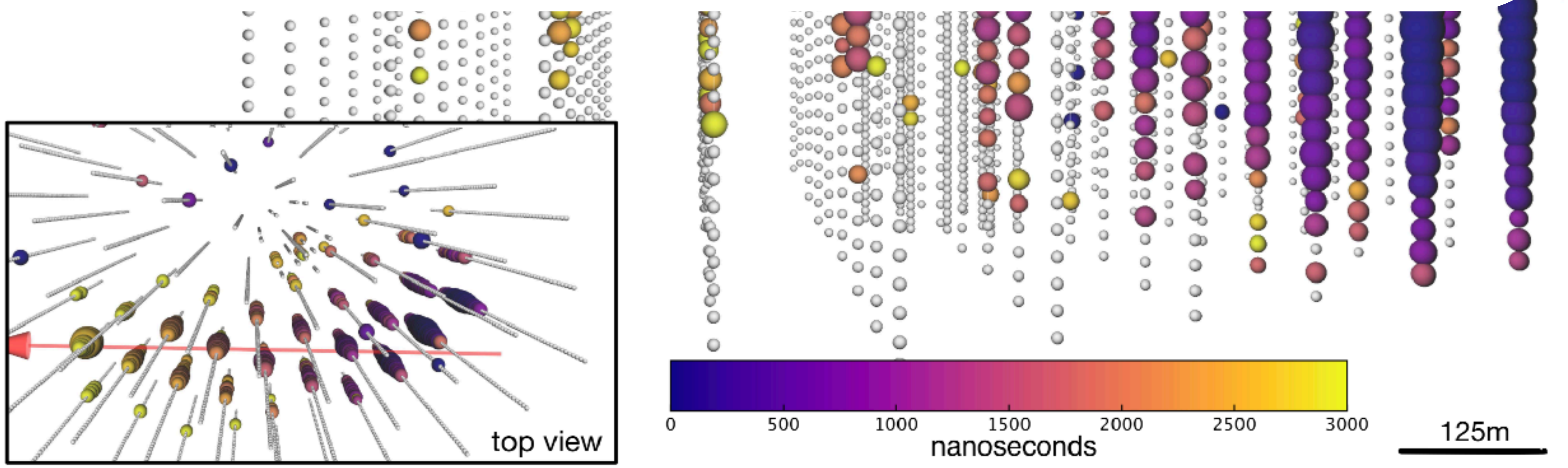
Multi-messenger High-energy Astrophysics (2)

Neutrino events in a direction of a flaring blazar, TXS 0506+056

- Extremely high-energy through-going track alert of IceCube (IC170922A) triggered multi-messenger observations for TXS 0506+056
  - Detection of GeV/TeV gamma-ray flaring of the blazar (3σ chance of coincidence)



- (Potentially) first direct detection of hadronic accelerator for E> 1 PeV (10^{15} eV)
  - Significantly increasing the total energy emitted by this object
  - Excluding pure leptonic model
  - Current models generally agree on disfavoring pure hadronic models
  - Setting stringent constraints on Lorentz Invariance Violation

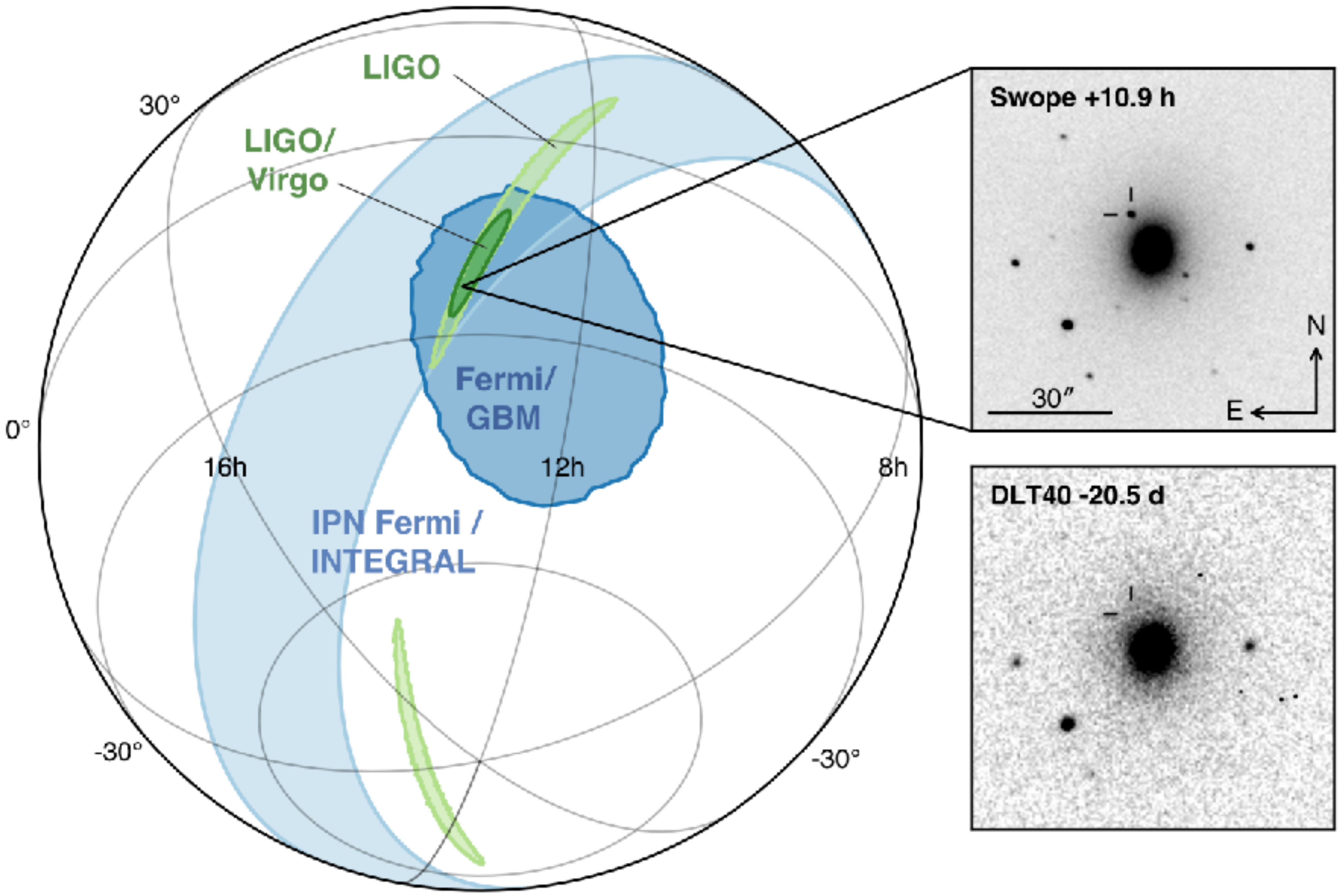


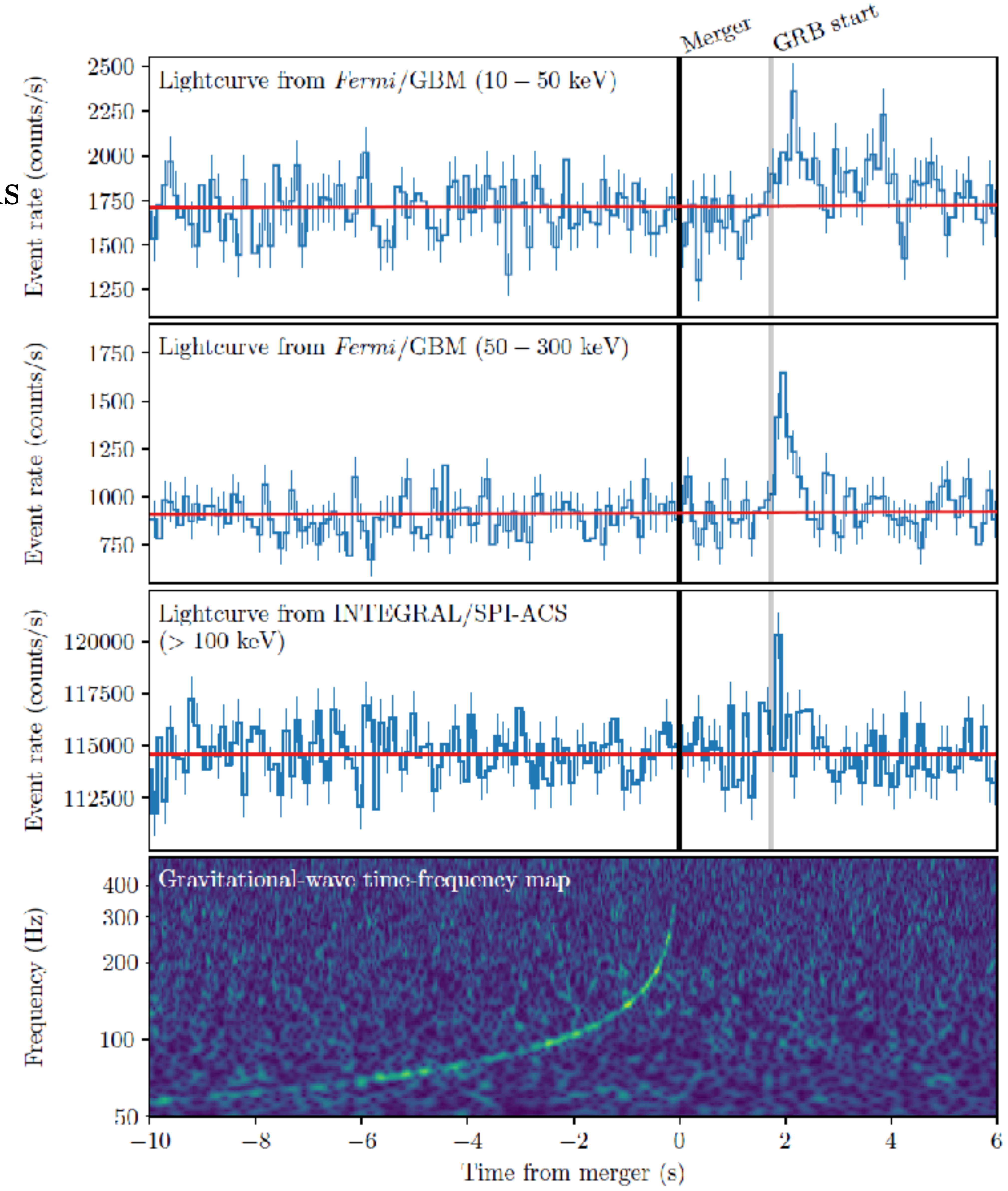
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS, VLA/17B-403 teams (Science 2018)

Multi-messenger High-energy Astrophysics for GW events

GW170817-GRB 170817A event

- Neutron star-neutron star merger>>short gamma-ray burst
  - ☆ Detection of gravitational wave followed by EM/neutrino observations (detection up to a few hundreds of keV energy range)
- No gamma-ray observed (> MeV)



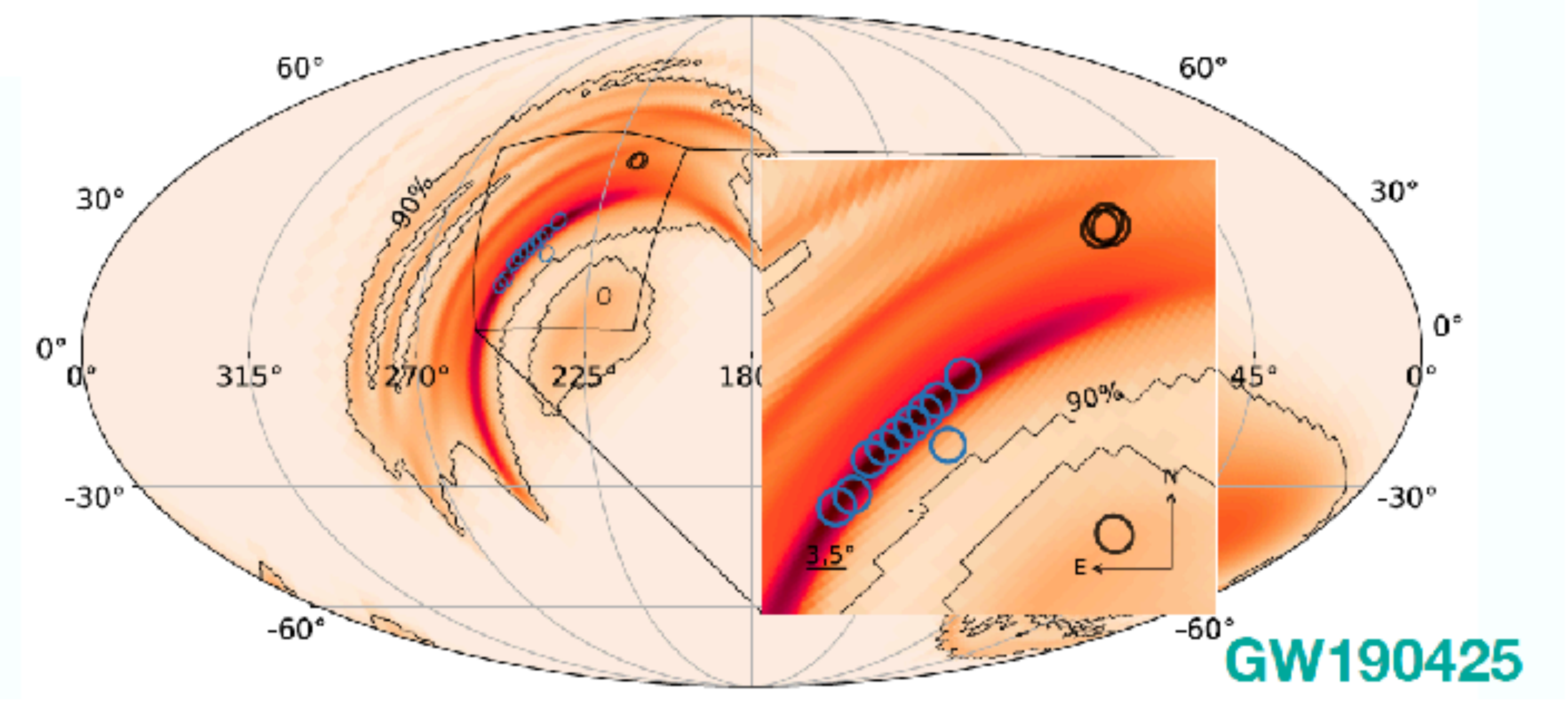


LIGO, Virgo, Fermi-LAT, and INTEGRAL (APJL2017)

Gravitational wave followup observations

Gamma-ray observations

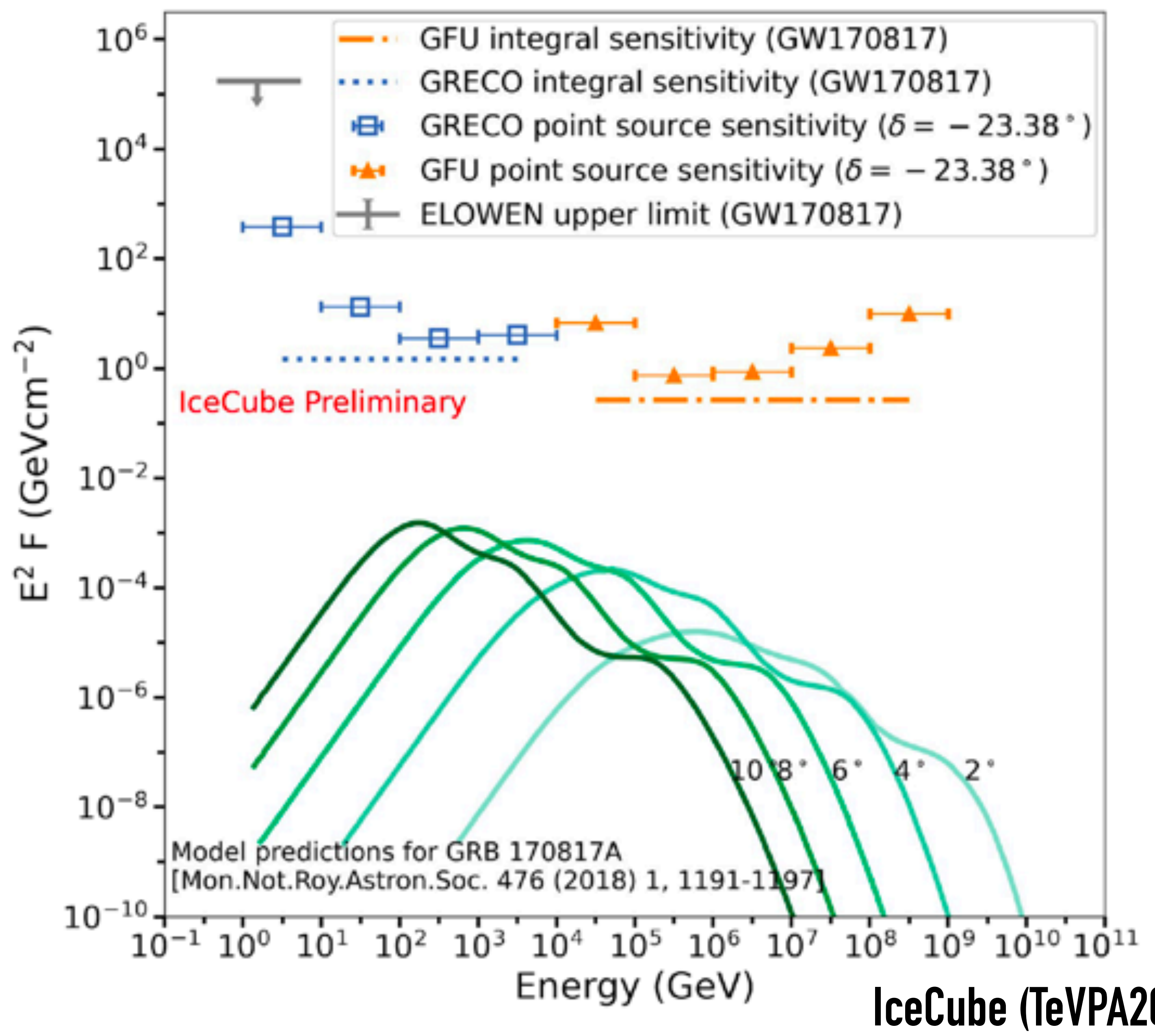
- IACT observations: limited by uptime and small field of view
  - Automatic tiling observations are currently used.
  - ~ 10 events were followed. No detection.
- Air shower array observations: limited by low energy sensitivity



VERITAS (TeVPA2022)

Neutrino observations

- All GW events are followed by IceCube
  - No detection
  - Larger amount of background due to the large GW position uncertainty



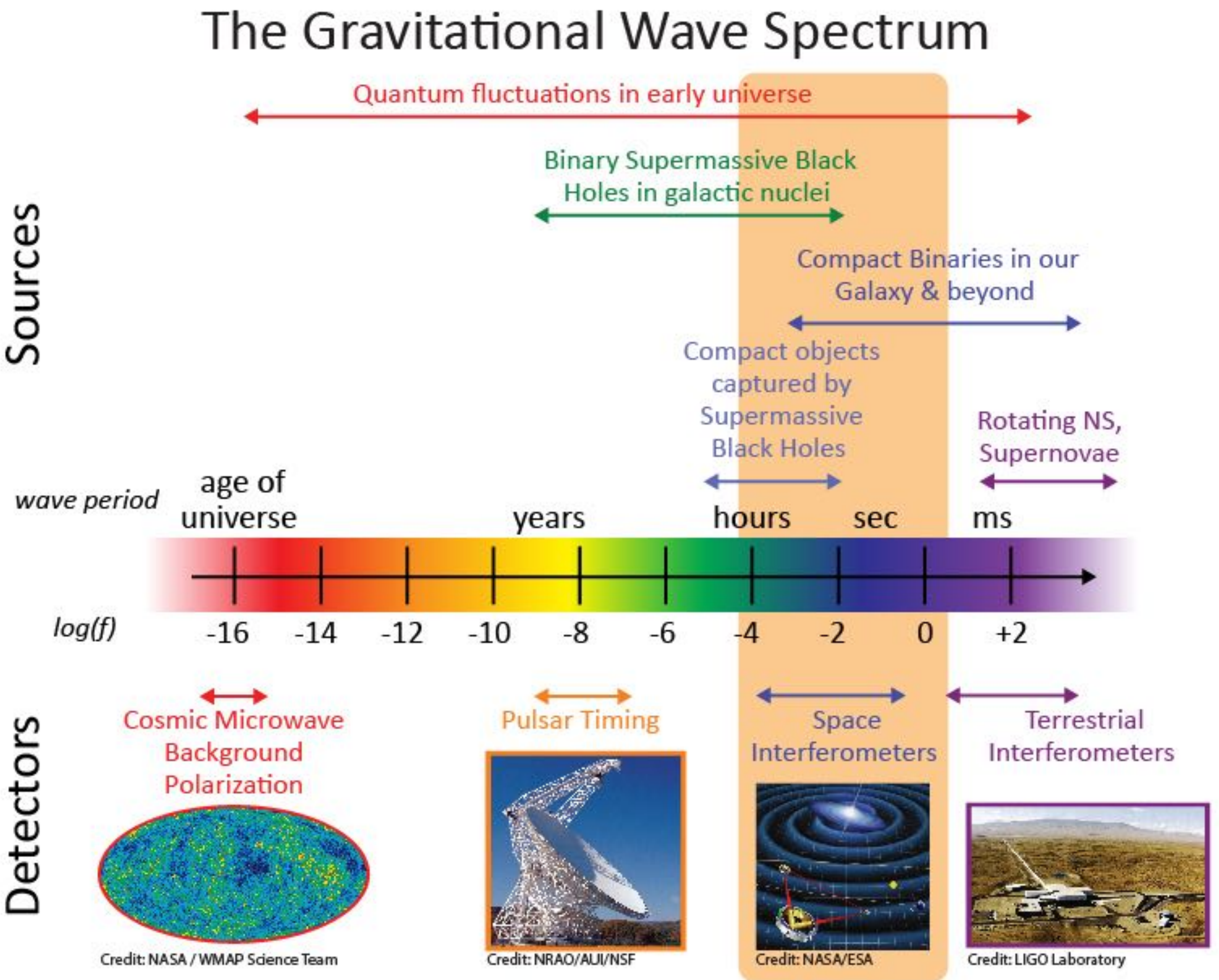
IceCube (TeVPA2022)

Future Multimessenger observations in LISA era

Can these environments accelerate particles to high energy?

- Acceleration mechanism?
- Nature of acceleration?

- Detection of HE particles would provide direct evidence for the accelerations of these particles
  - Information of environment (magnetic field, relativistic shock, environment density, radiation density,...)
  - Information on the energetics of the system
- Neutrino observation is particularly good at probing opaque systems that are not reachable by EM waves



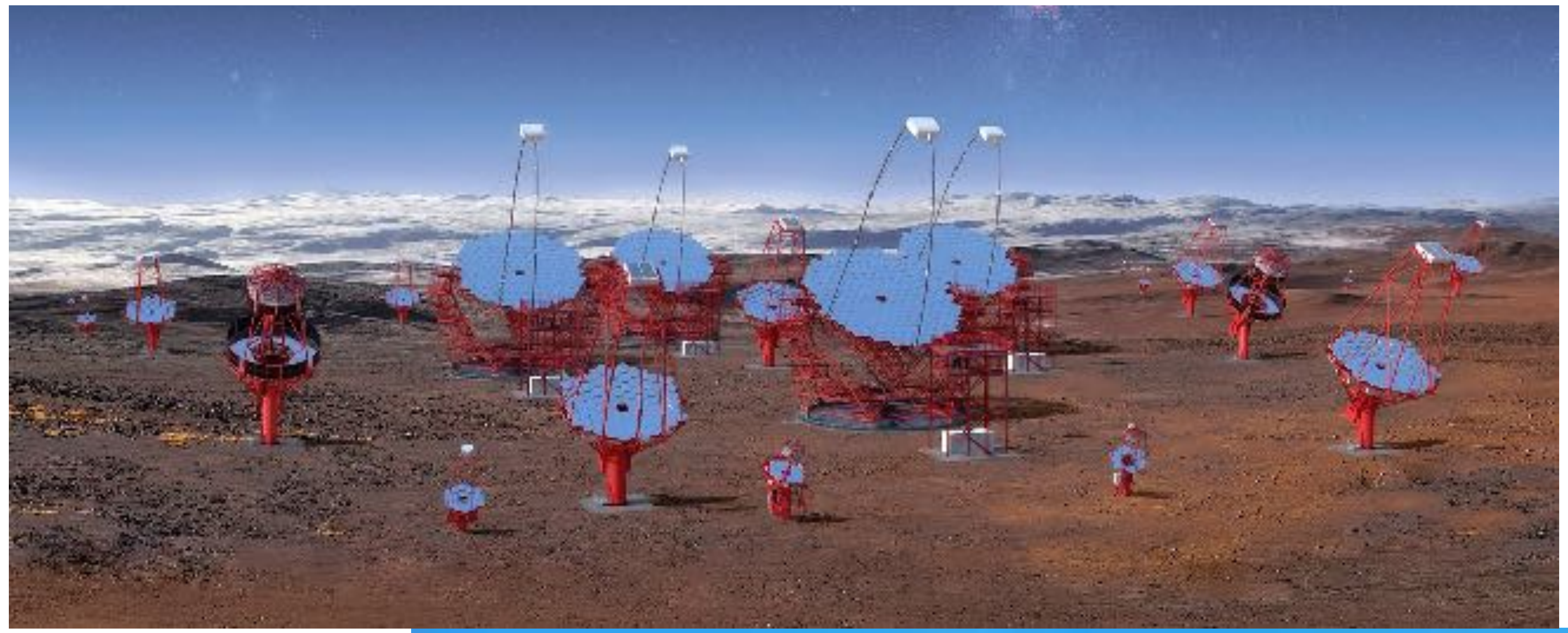
Testing fundamental physics (LIVs, ….)

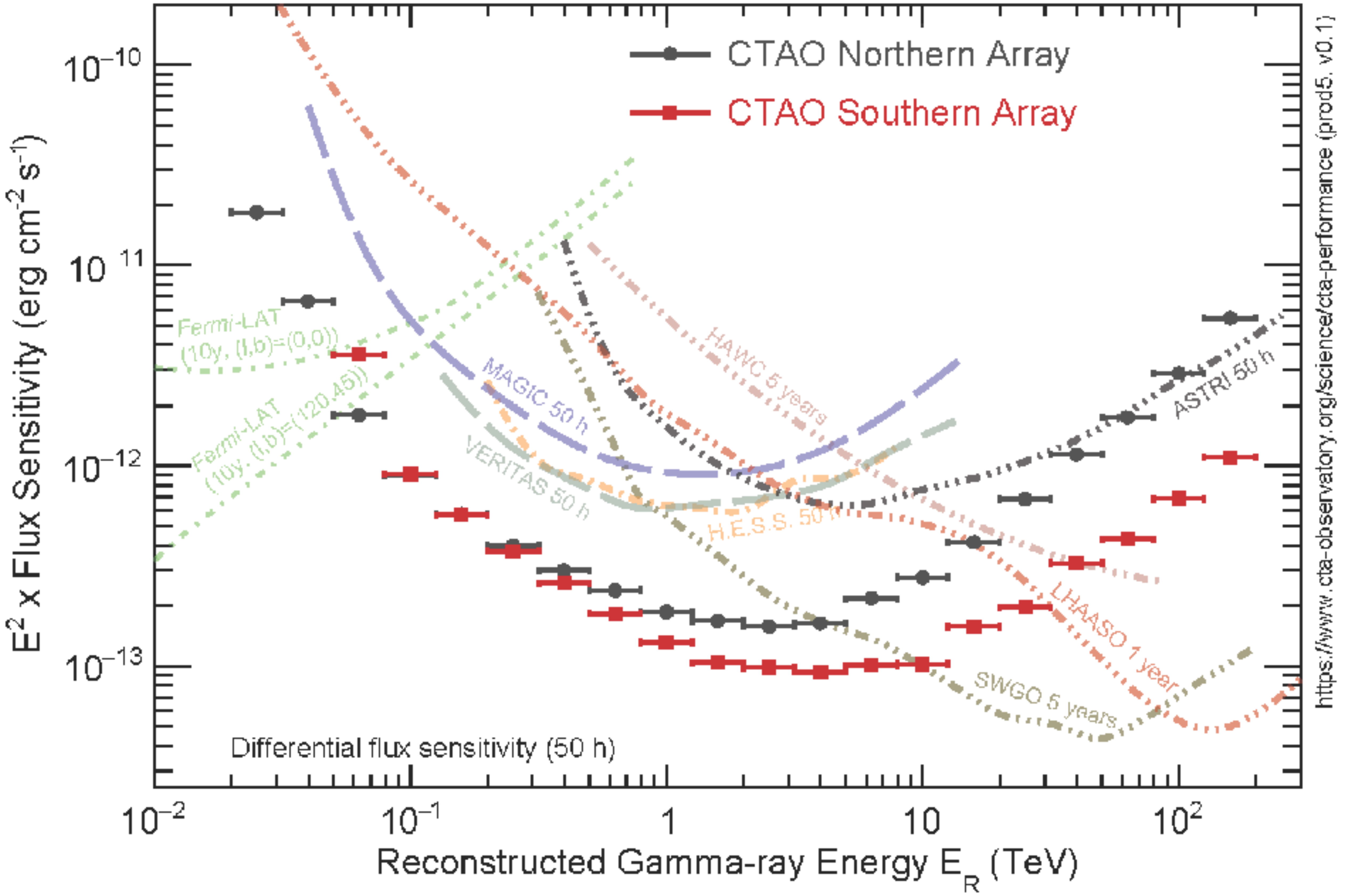
Future gamma-ray observatories

VHE gamma-ray observatories

- Cherenkov Telescope Array Observatory (CTAO)
  - Two sites (Chile @ South, La Palma@ North), larger telescope array (50 telescopes @ South, 13 telescopes @ North)
  - ~ 10 times better sensitivity than the current generation
  - Site preparation is ongoing, aiming to start construction in 2023

- Large air shower arrays
  - LHAASO @ North, potentially SWGO @ South





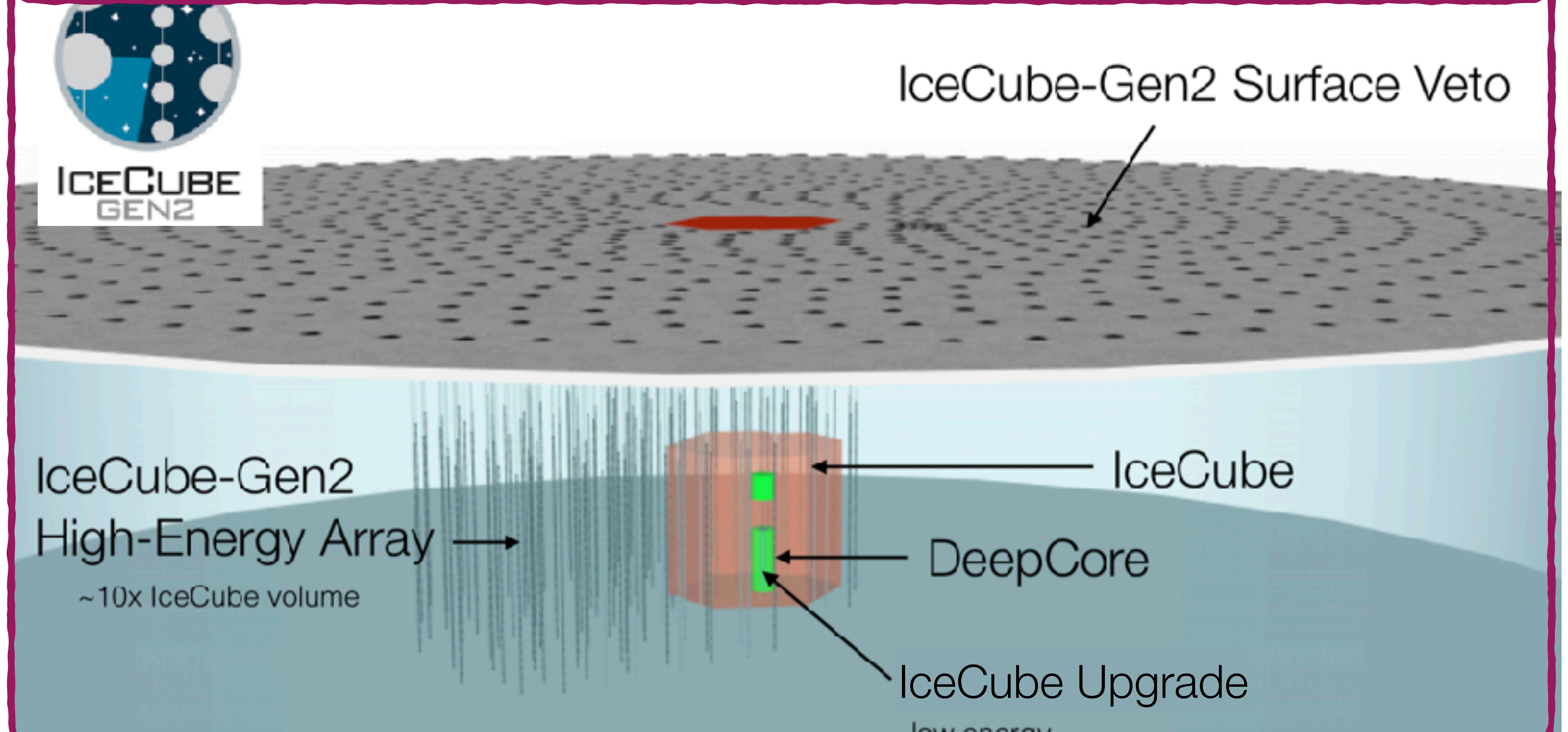
Future Neutrino Telescopes

IceCube is still operating well (10+ years)

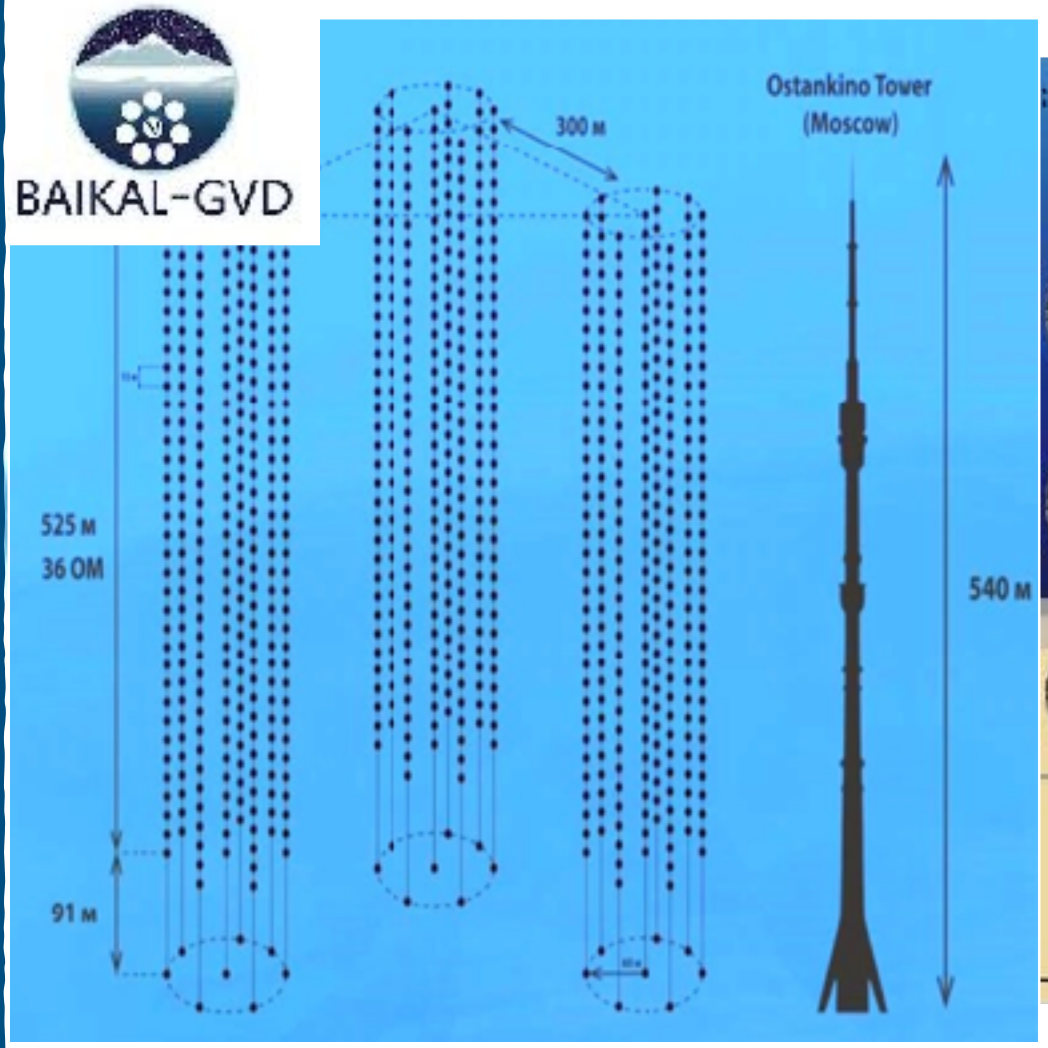
Next generation neutrino telescopes under construction & in-design

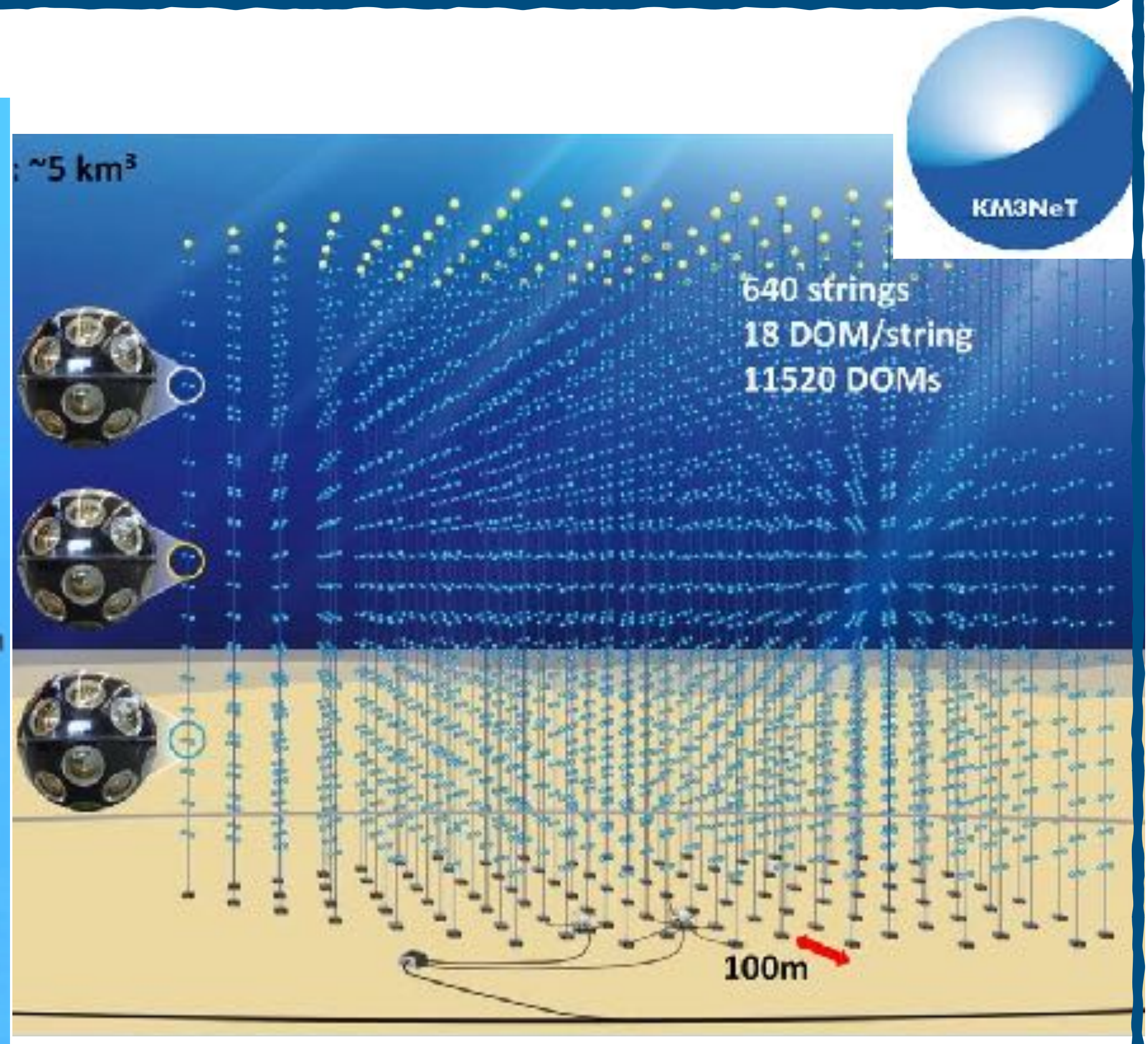
- Larger detector area
- Higher light collection efficiency
- Better angular resolution

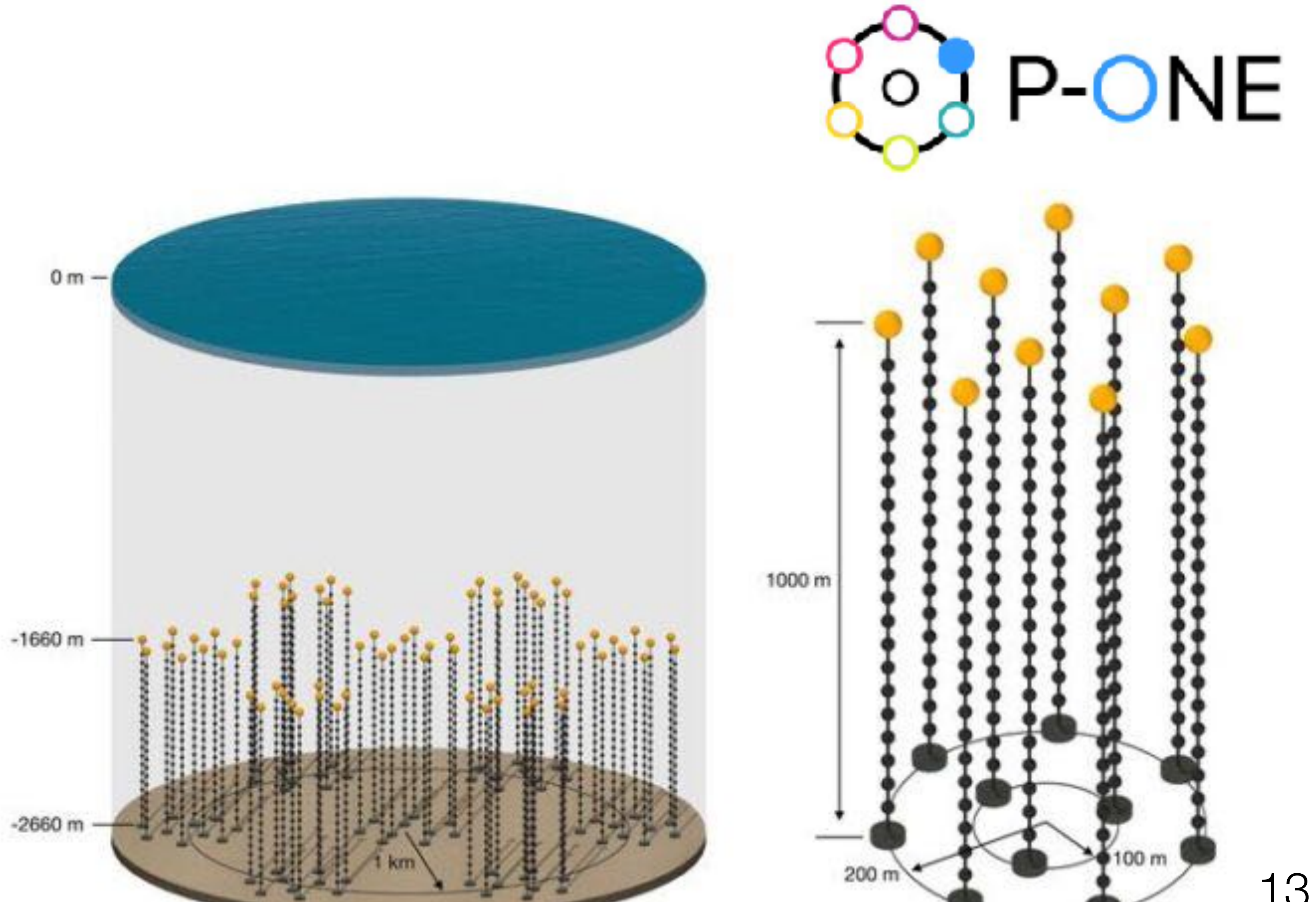
Under ice, located at Southern hemisphere



Under water, located at Northern hemisphere







P-ONE neutrino telescope

New neutrino telescope planning to be build at Cascadia Basin

- Utilizing the existing infrastructure of ONC (Ocean Networks Canada)
- Final goal is a 70 string detector w/ active volume of few cubic kilometer
- Pathfinders deployed and taking data
- Planning to submit a funding proposal for demonstrator