Hunting for the extreme accelerators in our Universe with multi-messenger observations

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Cosmic Rays : Particles from Outer Space

High energy charged particles, originating in outer space

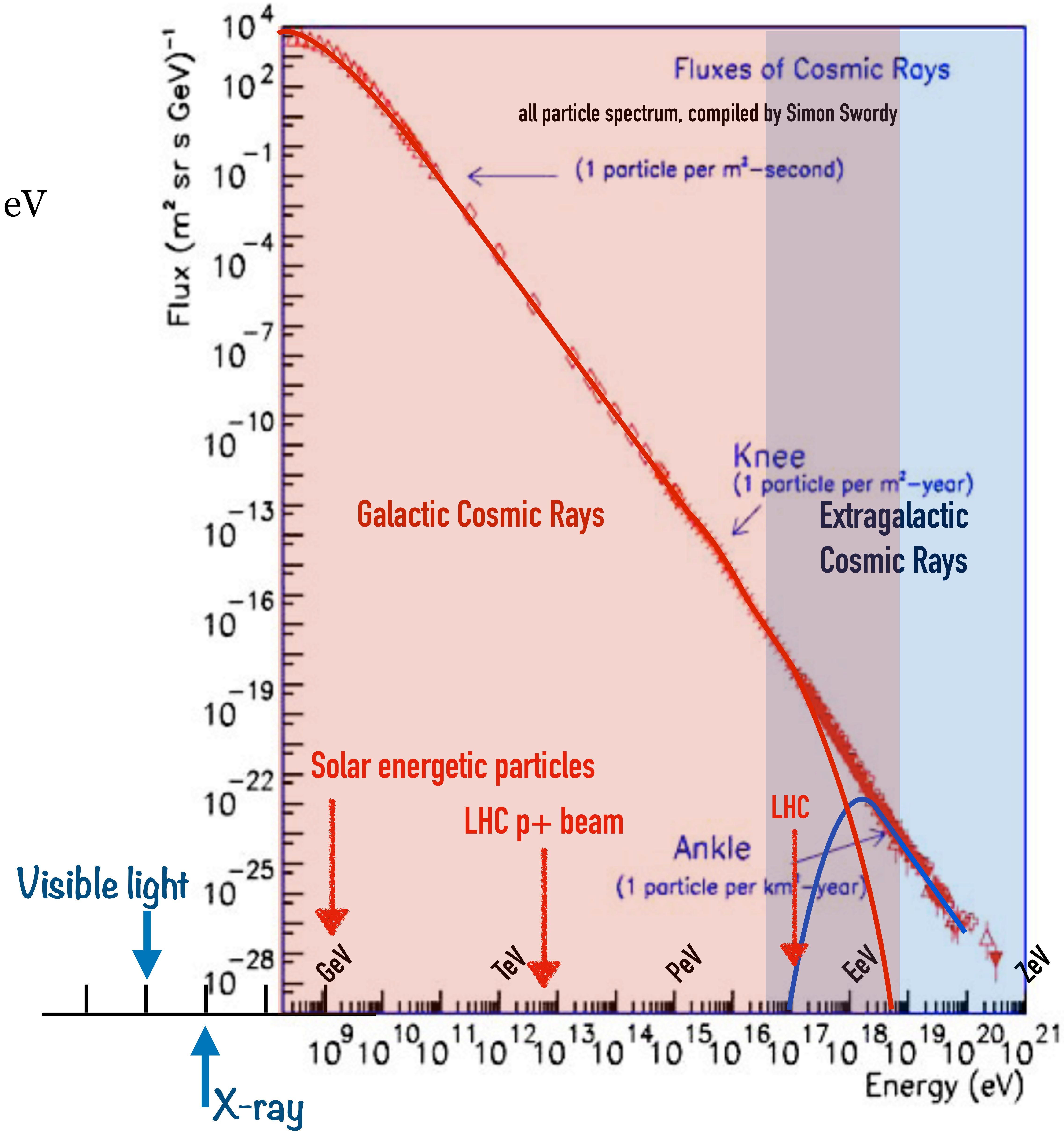
- Mostly nuclei of atoms
  - 85% proton, 12% helium, 2% heavy nuclei, 1% leptons at 10^9 eV
- Spectrum follows a smooth power-law distribution over wide energy range

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 Astro Particles

Cosmic rays

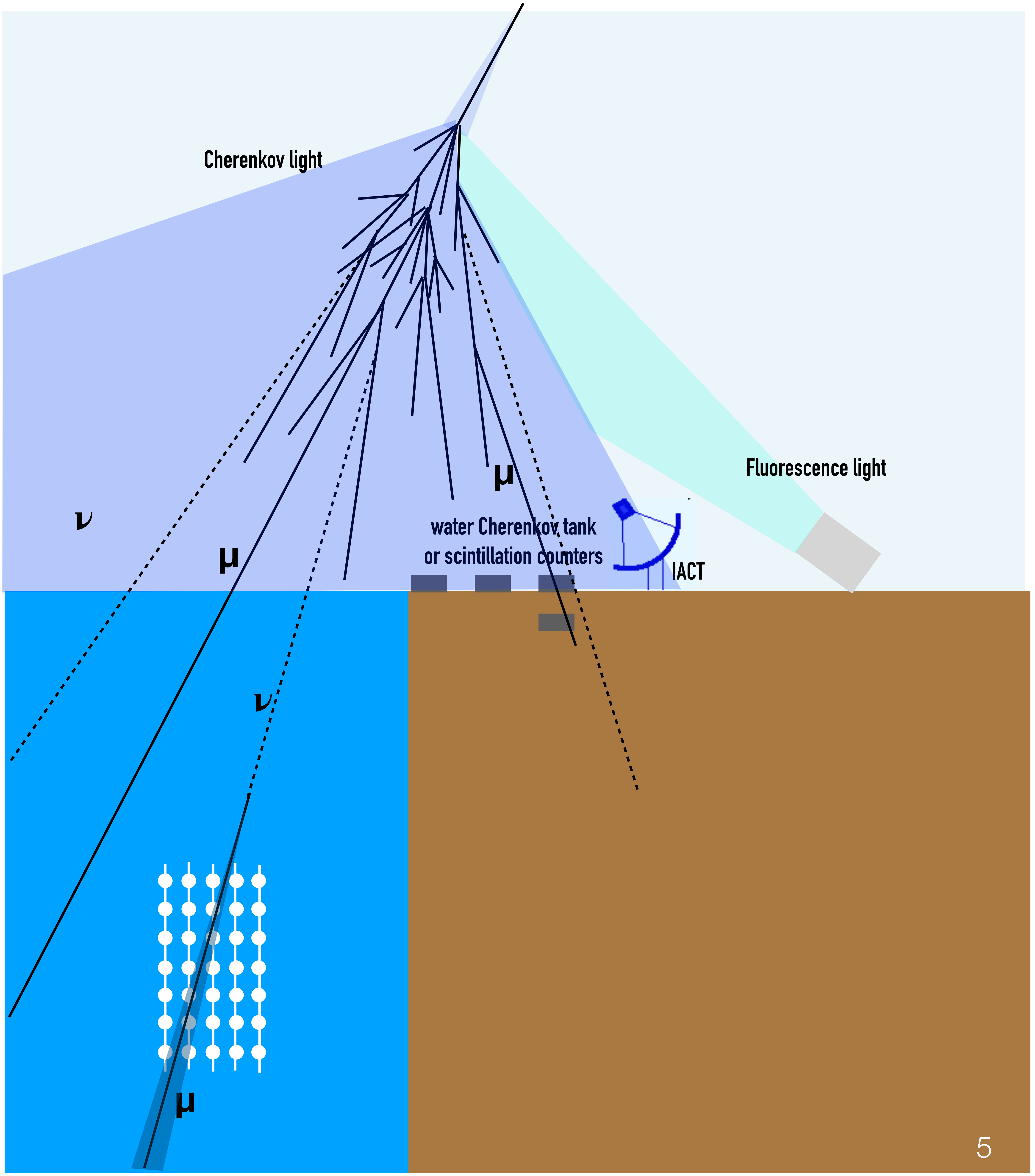
- Space based for energies up to tens of TeV/n : compact particle detectors (charge detector + calorimeter)
- Ground based air shower array for E> 1 TeV/n : detect the air shower by reconstructing secondary particles generated by inelastic interactions in the atmosphere

VHE gamma rays (E>100 GeV)

- Detecting the air shower by imaging very fast flash of Cherenkov radiations generated by secondary particles (Imaging Atmospheric Cherenkov Telescope) or by measuring the secondary particles
- Background : cosmic-ray air showers
  - IACT
    - Cosmic ray shower : 300Hz
    - Signal from Crab pulsar wind nebula:1-2 Hz

HE neutrino (E>few tens of TeV)

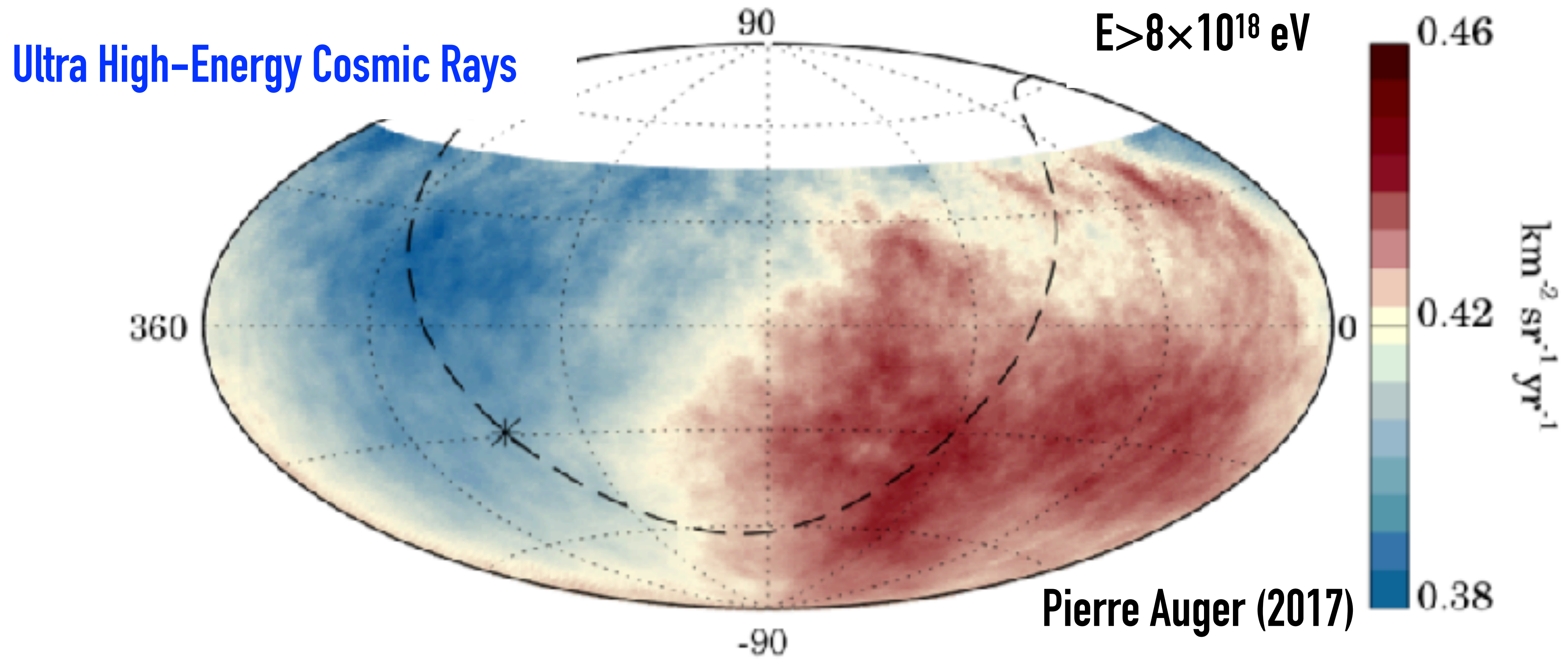
- by imaging very fast flash of Cherenkov radiations generated by weak interaction of neutrinos in water or ice
- Background : cosmic-ray shower induced μ & ν
  - Atmospheric μ: 10^{11}/year, atmospheric ν :10^5/year
  - cosmic ν : ~100/yr



What we know about extreme accelerators

Cosmic rays

- Large scale anisotropy detected at $E>8\times10^{18}$ eV (10% level) by Pierre Auger collaboration
  - The composition at this energy is heavier than expected.
  - Studies of source population on-going



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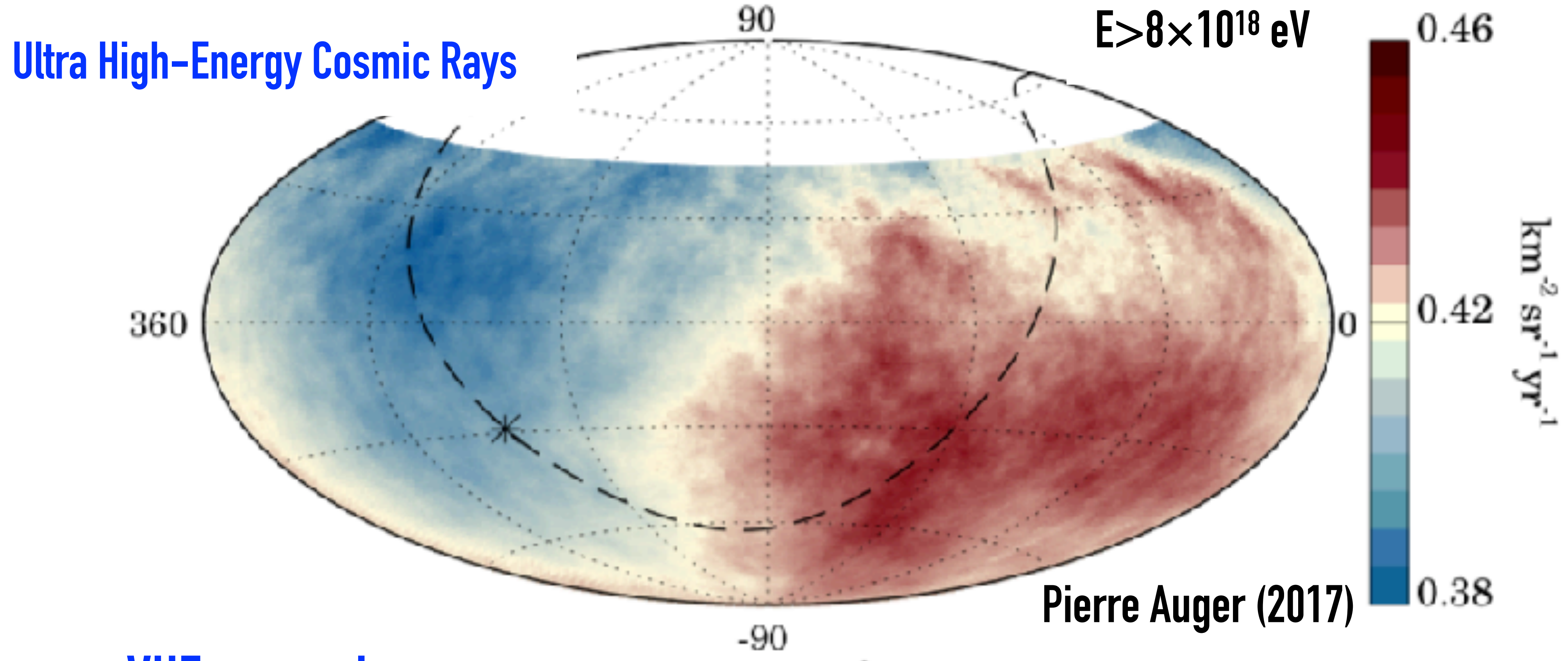
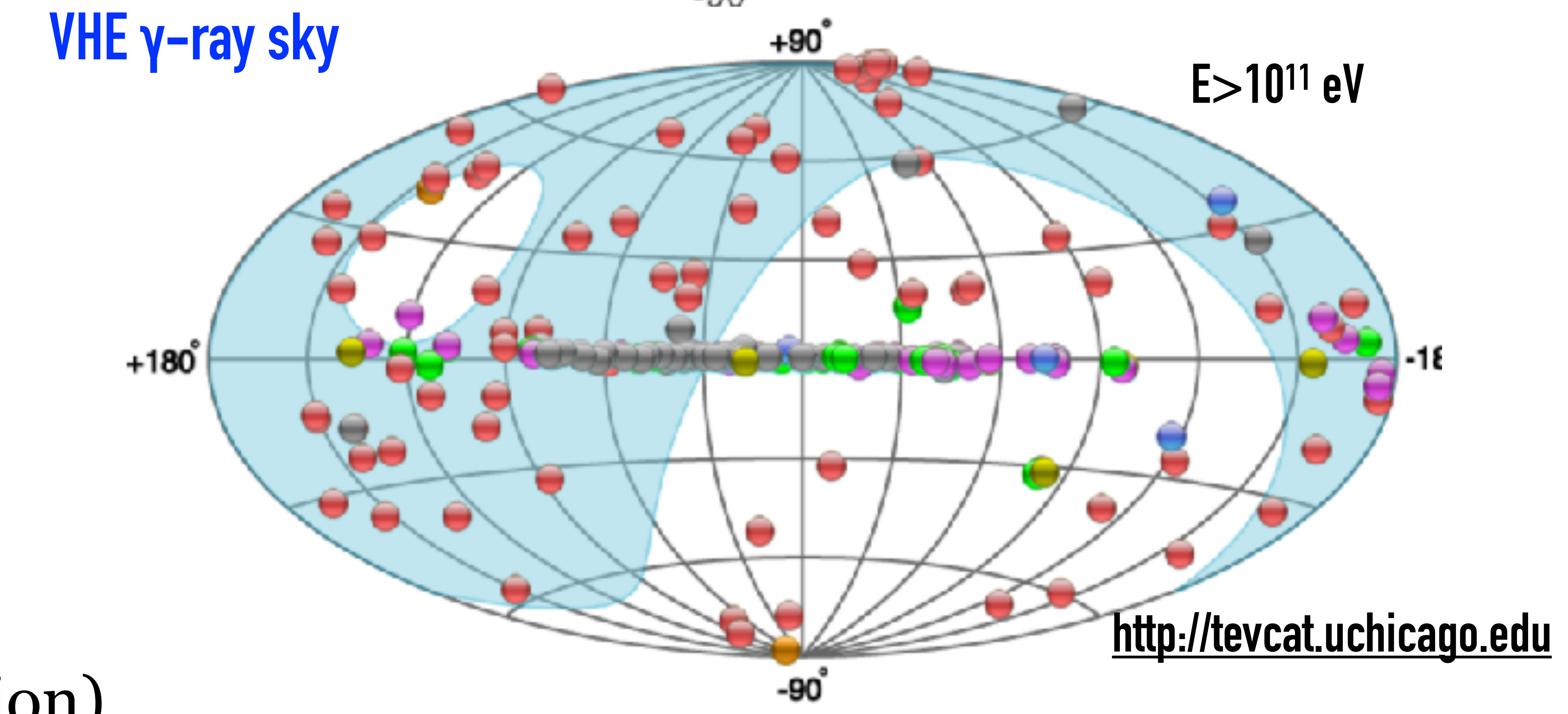


Gamma rays (>100 GeV)

- 220 sources detected from Galactic & extragalactic sky - combined reports from several IACTs & air shower arrays
  - Most of sources can be explained by leptonic emission
  - Some hadronic sources are detected, but, with a cut-off lower than 100 TeV
  - Indirect evidence of PeV accelerator at the Galactic center (under investigation)
- VHE gamma-ray event horizon at z~1 (for E>200 GeV)



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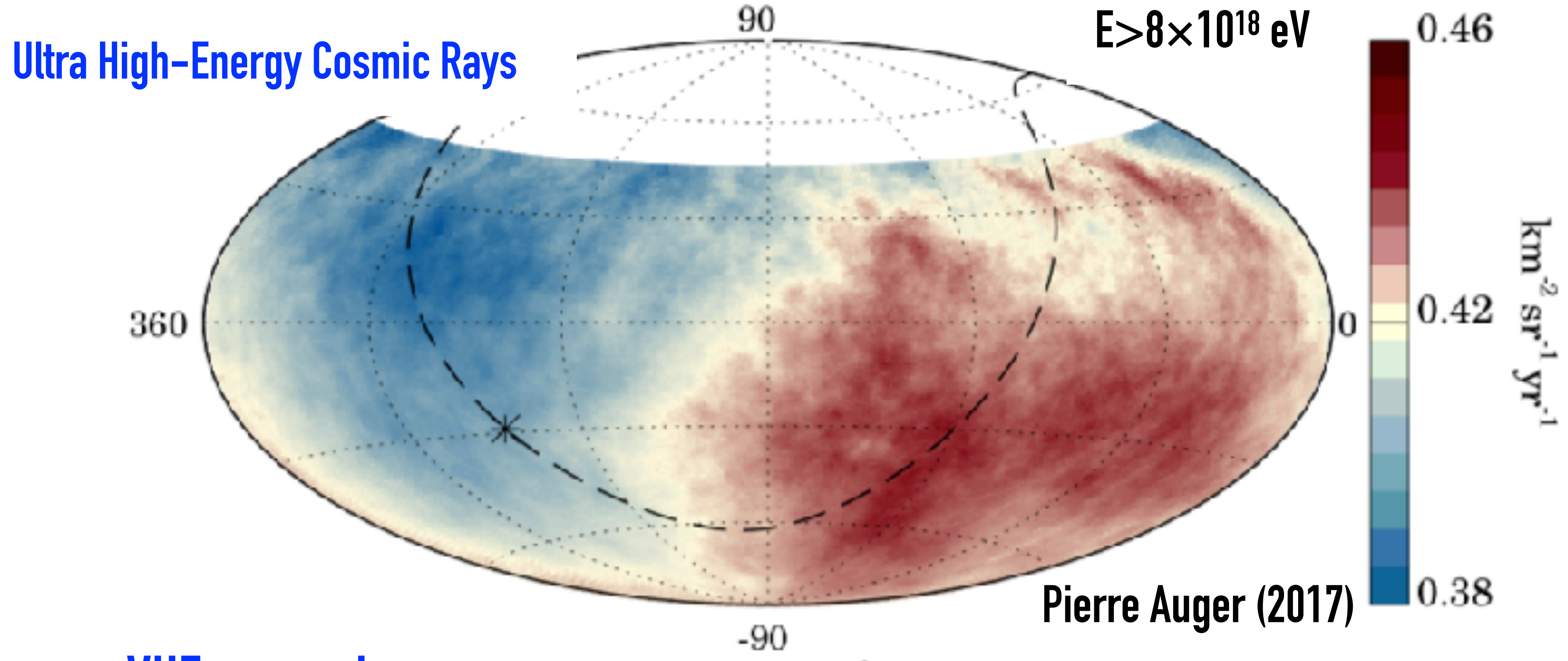
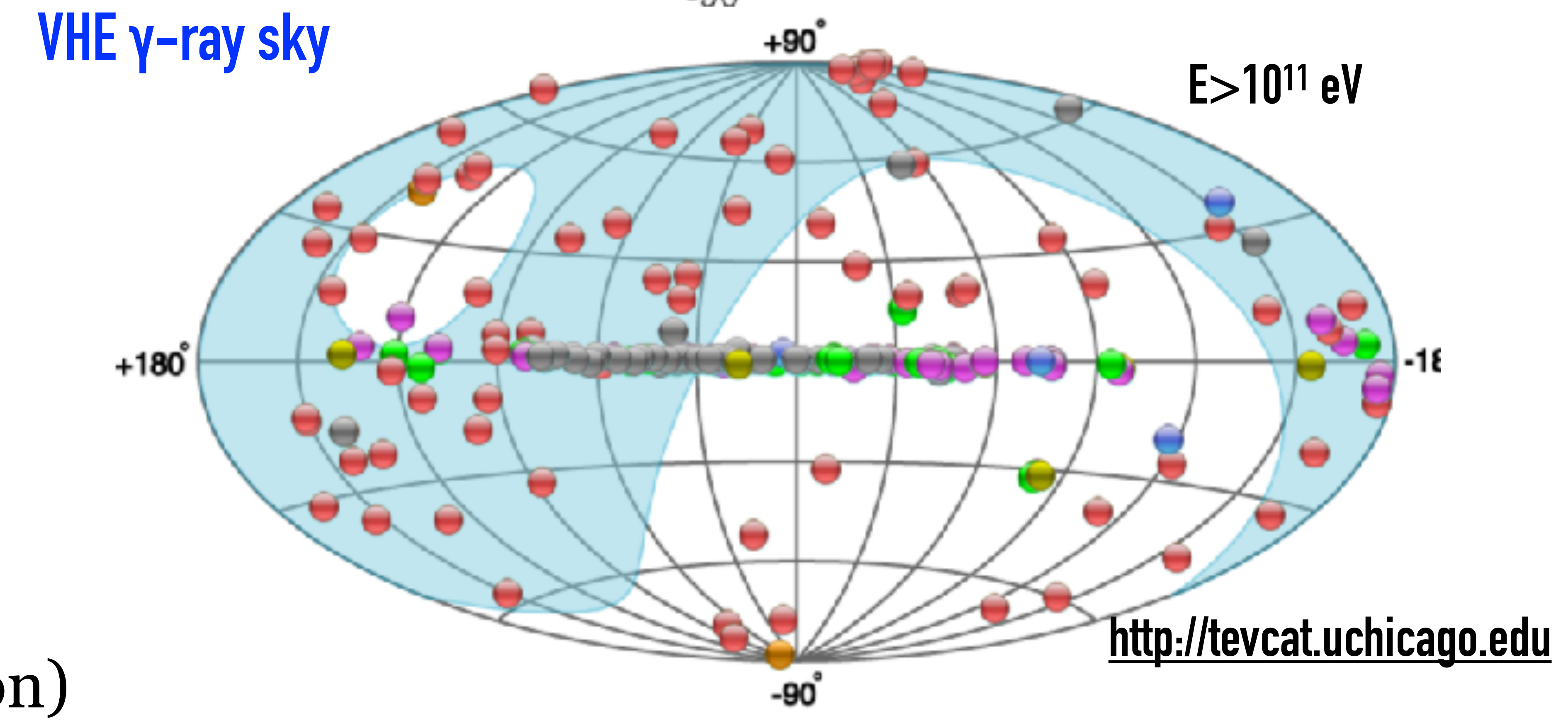
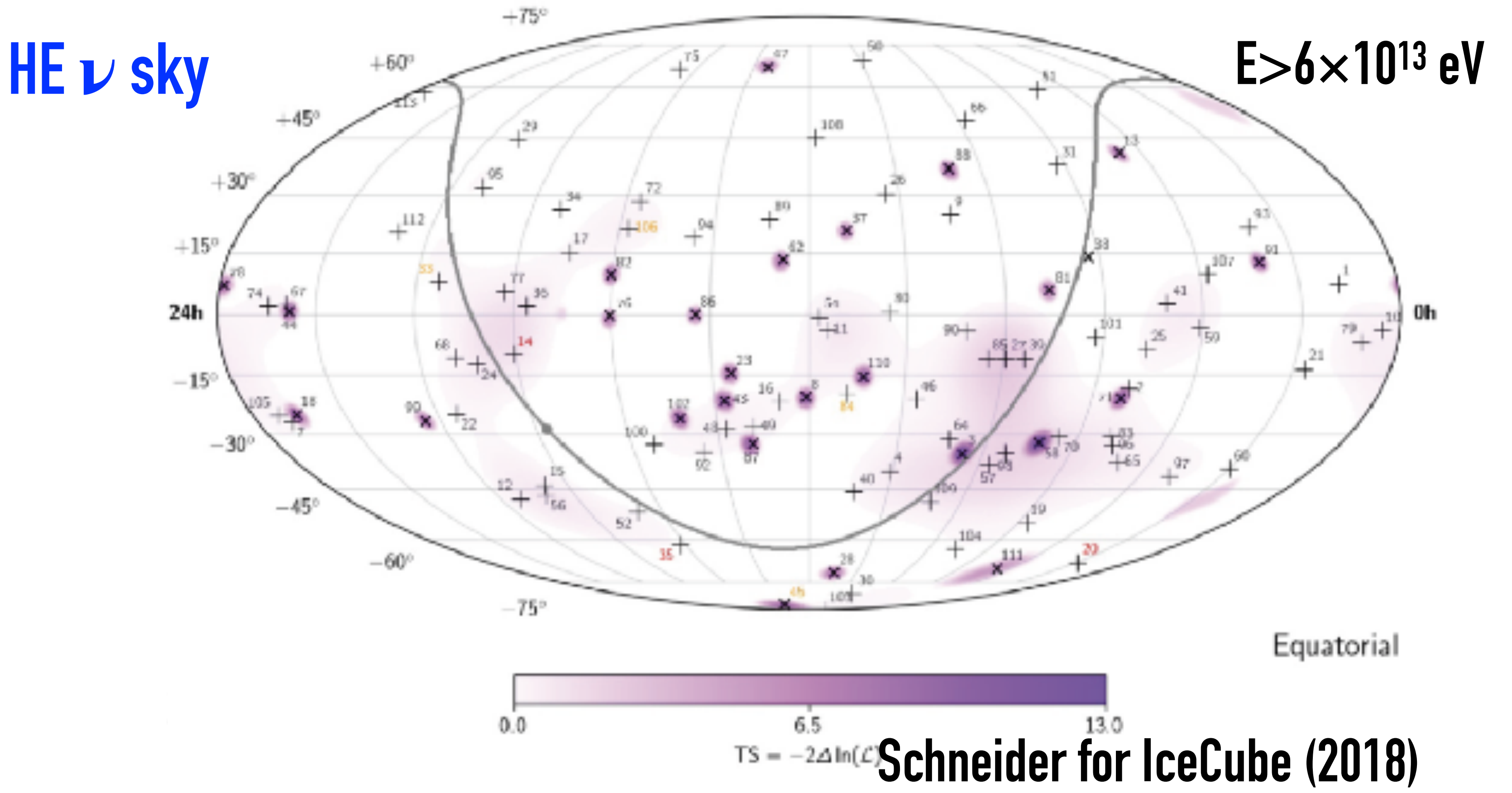
Neutrinos (>60 TeV)

- Diffuse astrophysical neutrino flux detected by IceCube collaboration
- No clear neutrino source has been identified



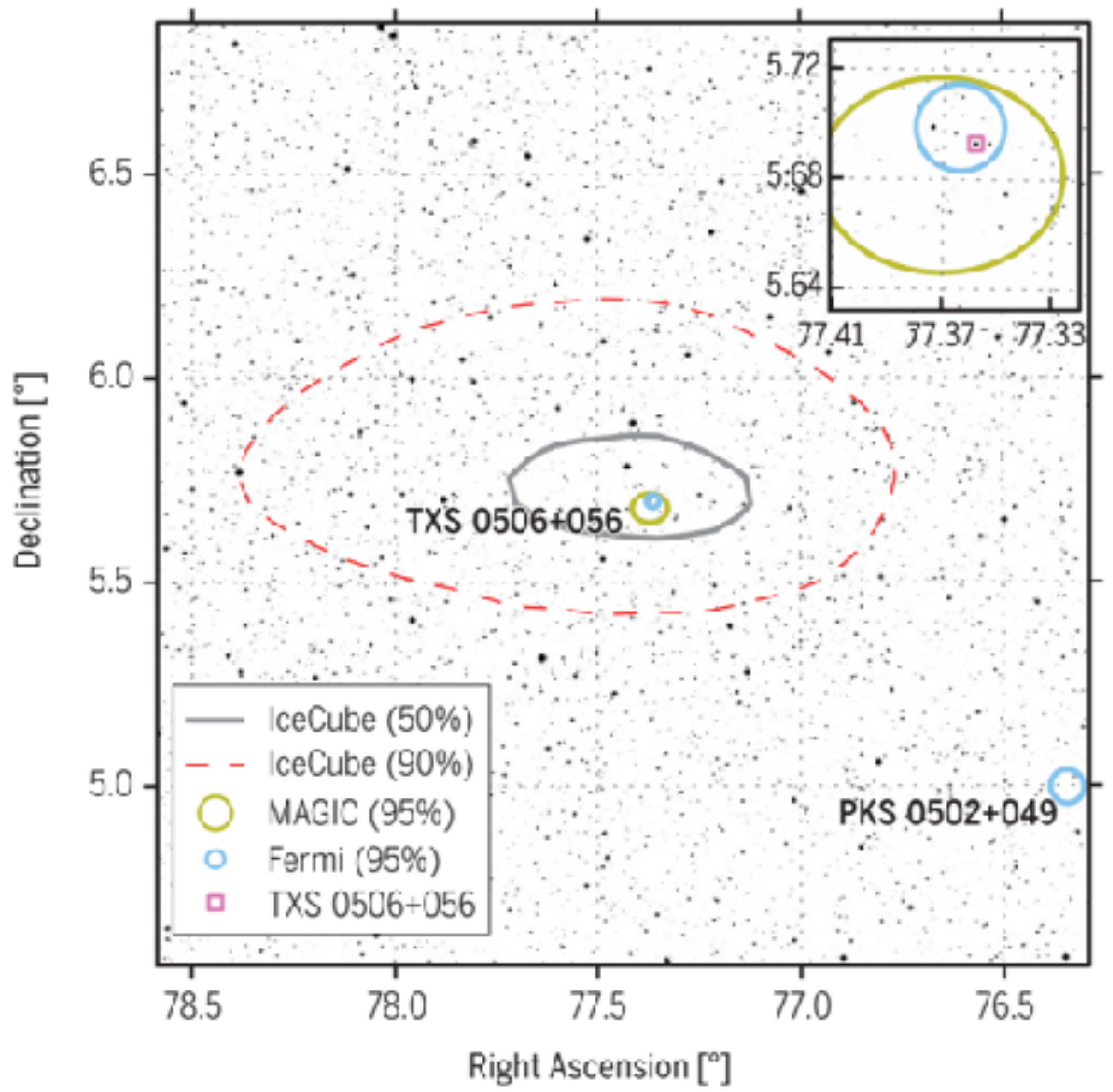




HE multi-messenger observations

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
  - Chance of correlation by background is rejected with 3σ
    - (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)

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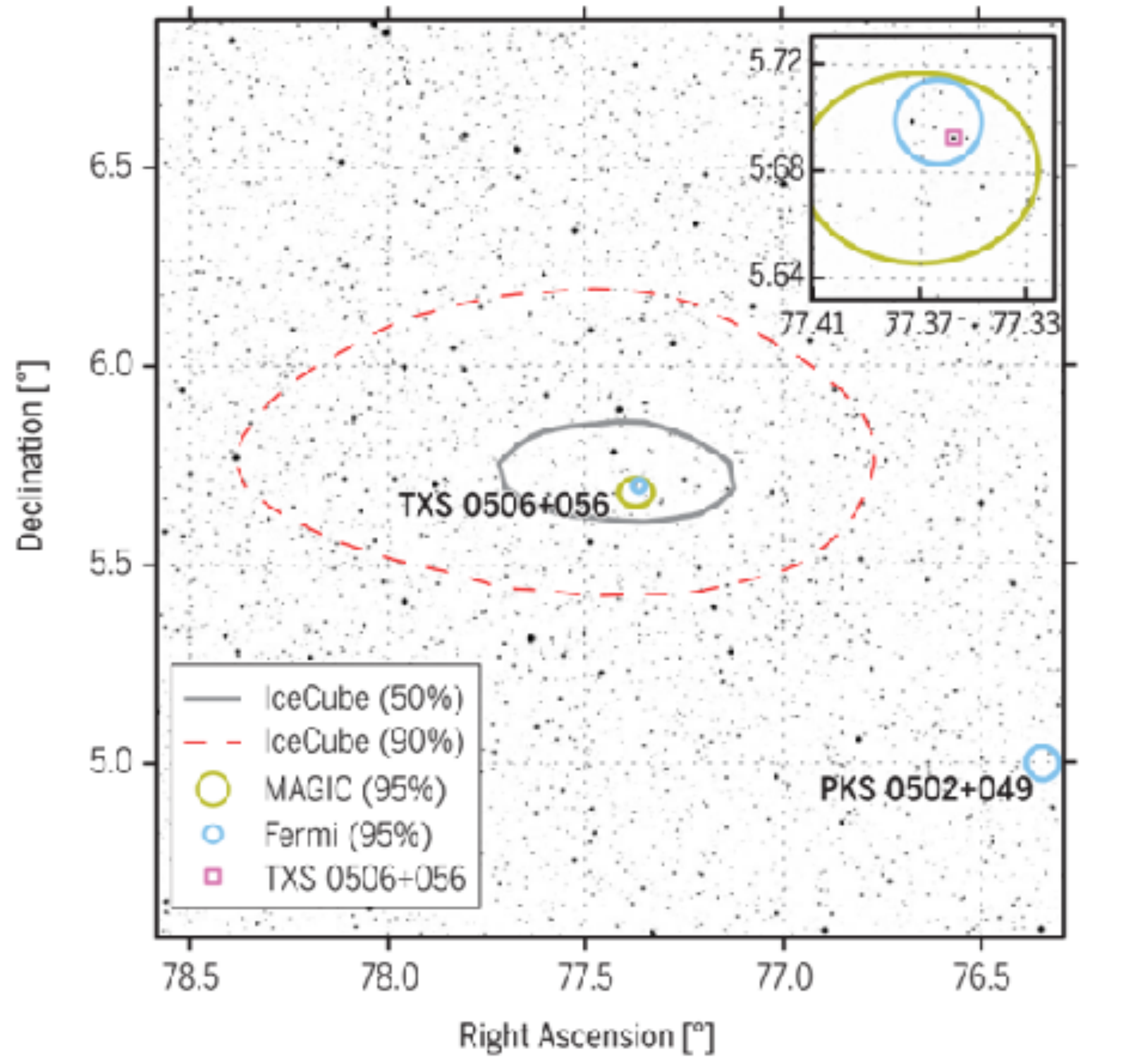
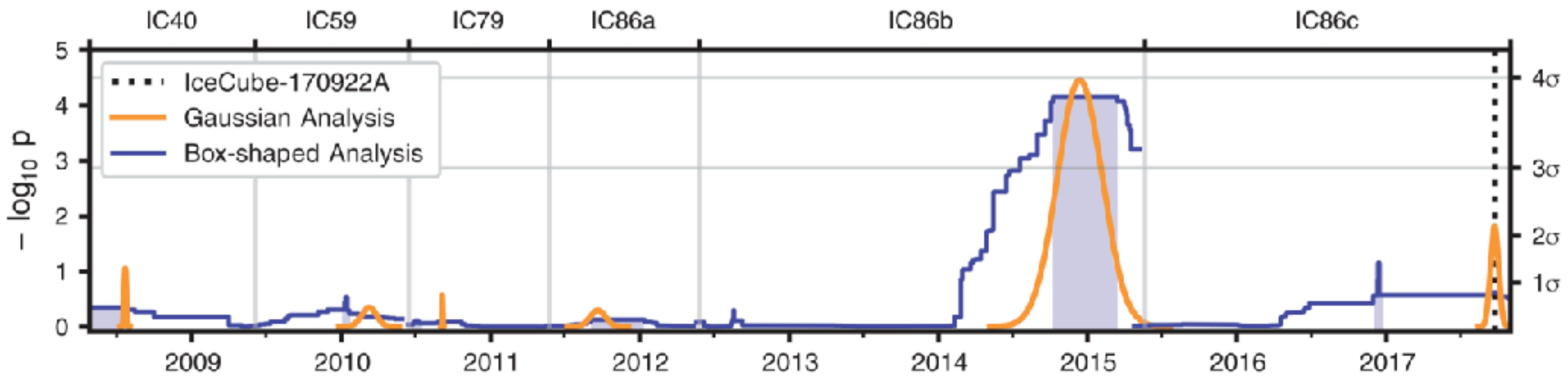


- IceCube archival data found a hint of time depended neutrino emission in 2014 w/ 13 ± 5 events over 100 days (significance of 3.5σ)
  - No alert exited for this type of events. Follow-up observation coverage only by the sky survey instruments



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HE multi-messenger observations @ my lab. in near future

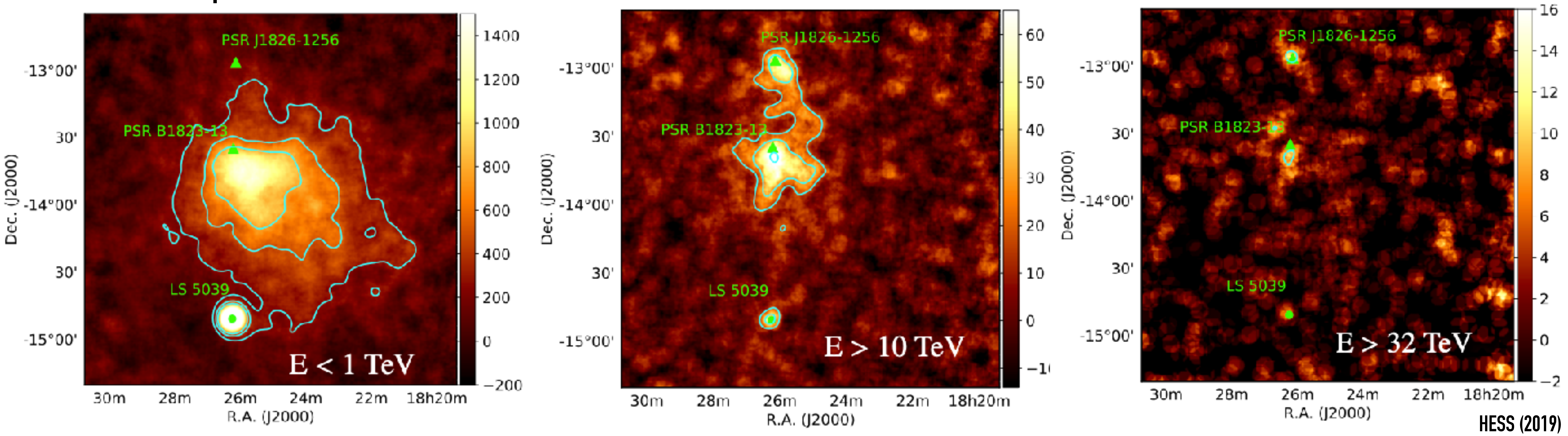
Following up neutrino events with VHE gamma-ray telescope

- A single high-energy neutrino event follow-up observations (e.g. IC170922A)
- Time depended neutrino events follow-up observation (e.g. 2014 neutrino flaring in 2014)

Study of time independent emission with VHE gamma-ray & neutrinos

- Study of luminous unidentified sources w/ hard index up to > 50 TeV
  - VHE gamma-ray with VERITAS provide a detailed morphology of the sources
    - ✦ Generally expect the extension of the leptonic emission to reduce as energy goes higher (due to radiative cooling time)
  - Neutrino may provide constraining upper limits for the hadronic emission, if not detection

e.g. HESS J1825-137 (PWN) - leptonic dominated emission



HESS (2019)

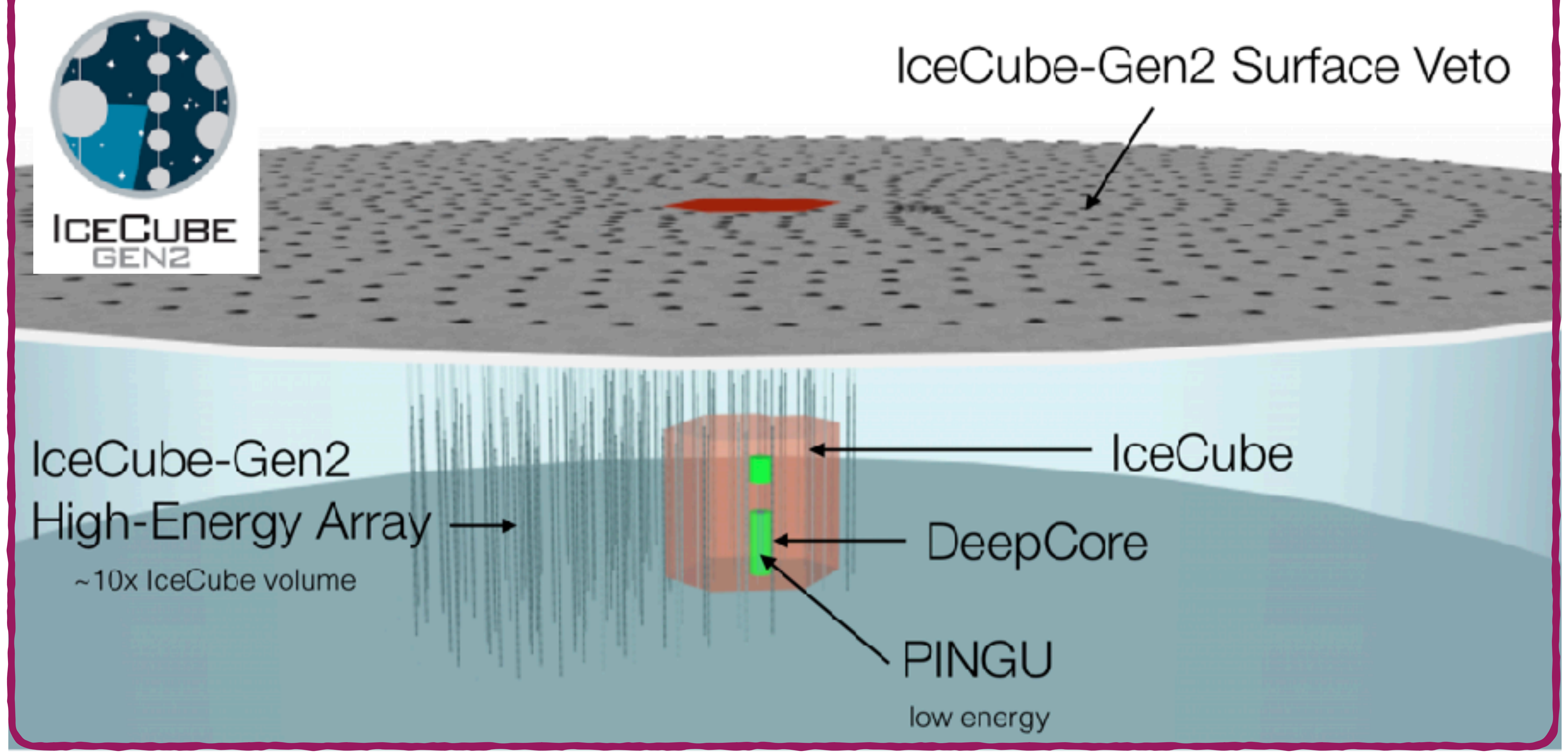
Moving forward

We need more powerful VHE neutrino telescopes

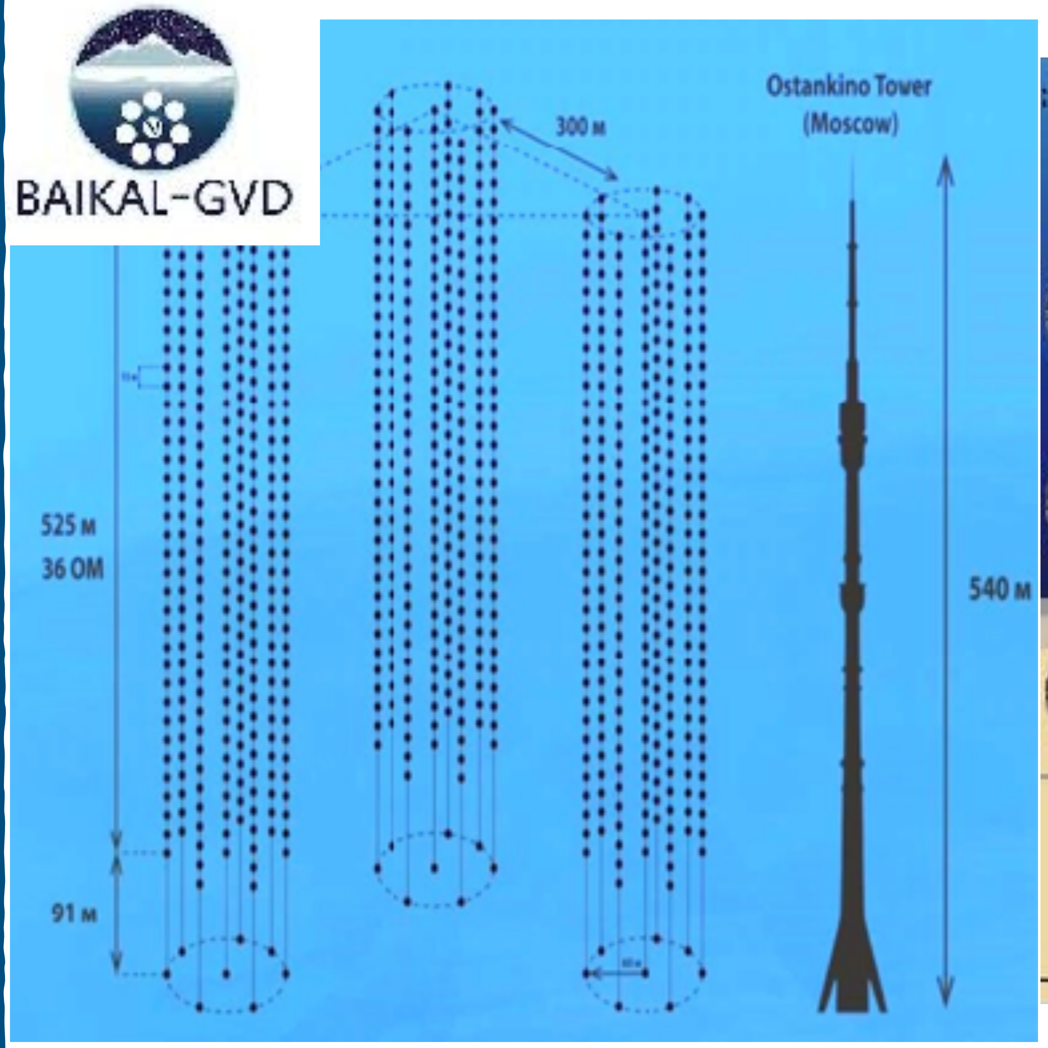
- Larger detector area
- Higher light collection efficiency
- Better angular resolution

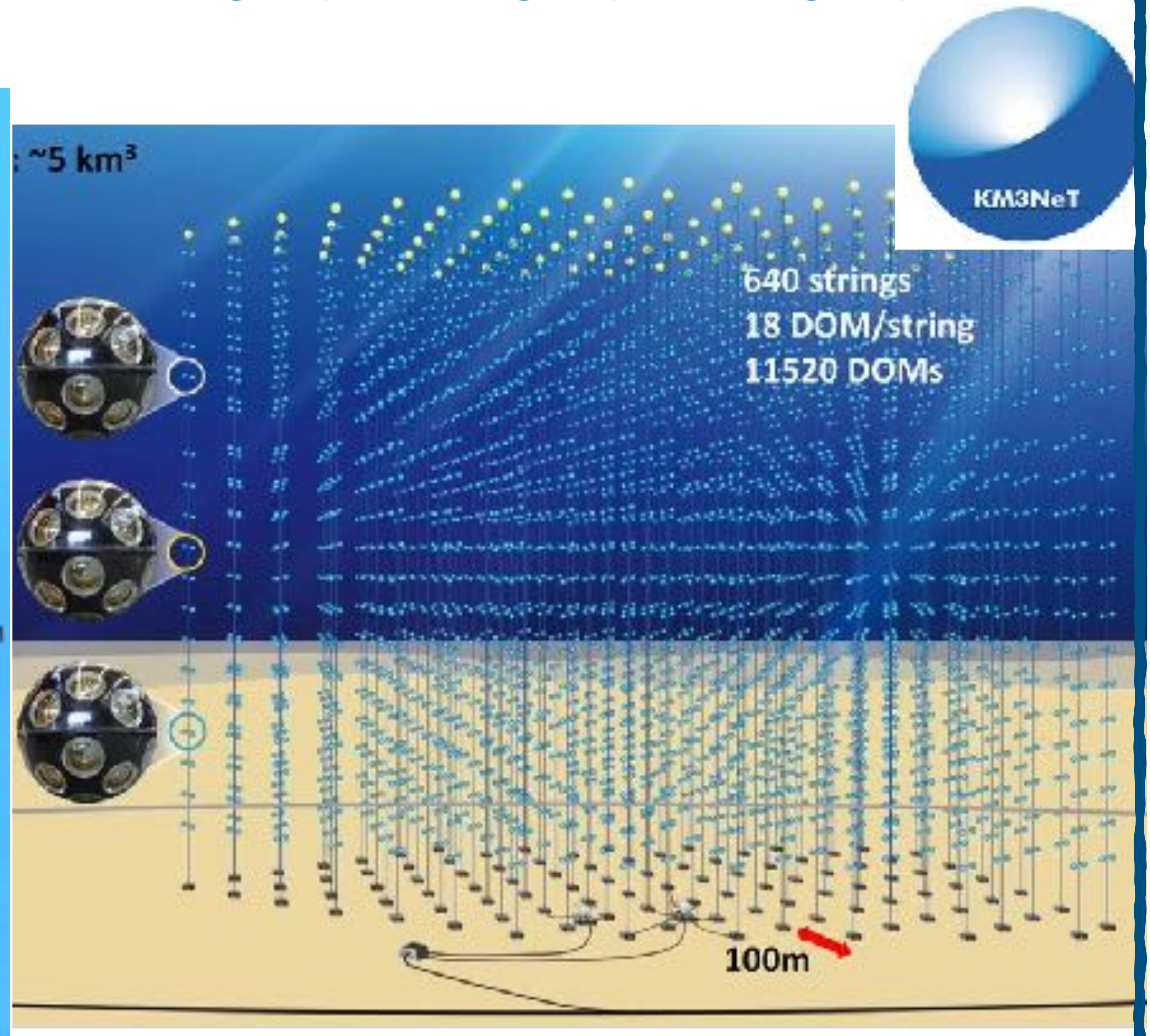
→ Up to 10 times better sensitivity

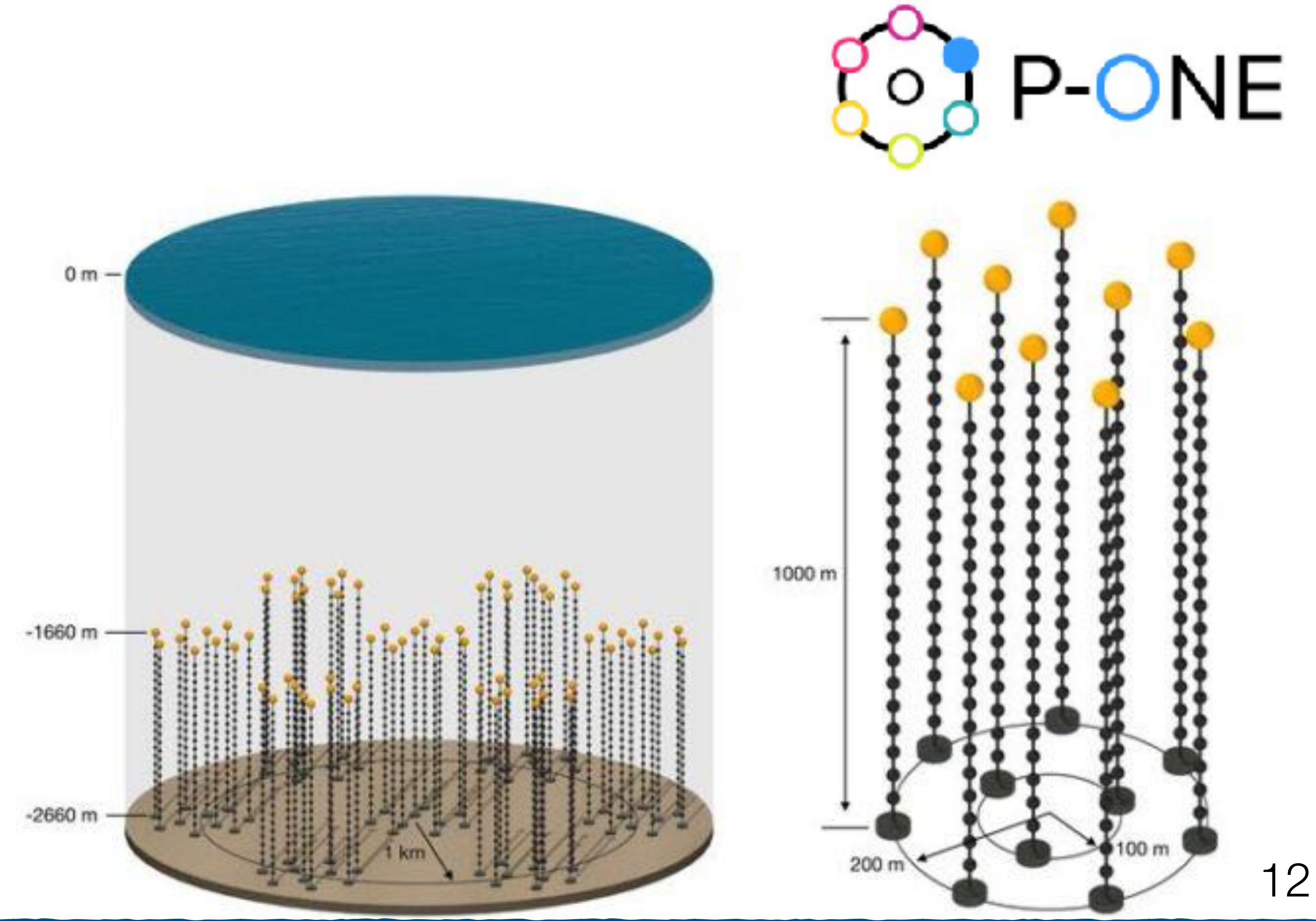
Under ice, located at Southern hemisphere



Under water, located at Northern hemisphere



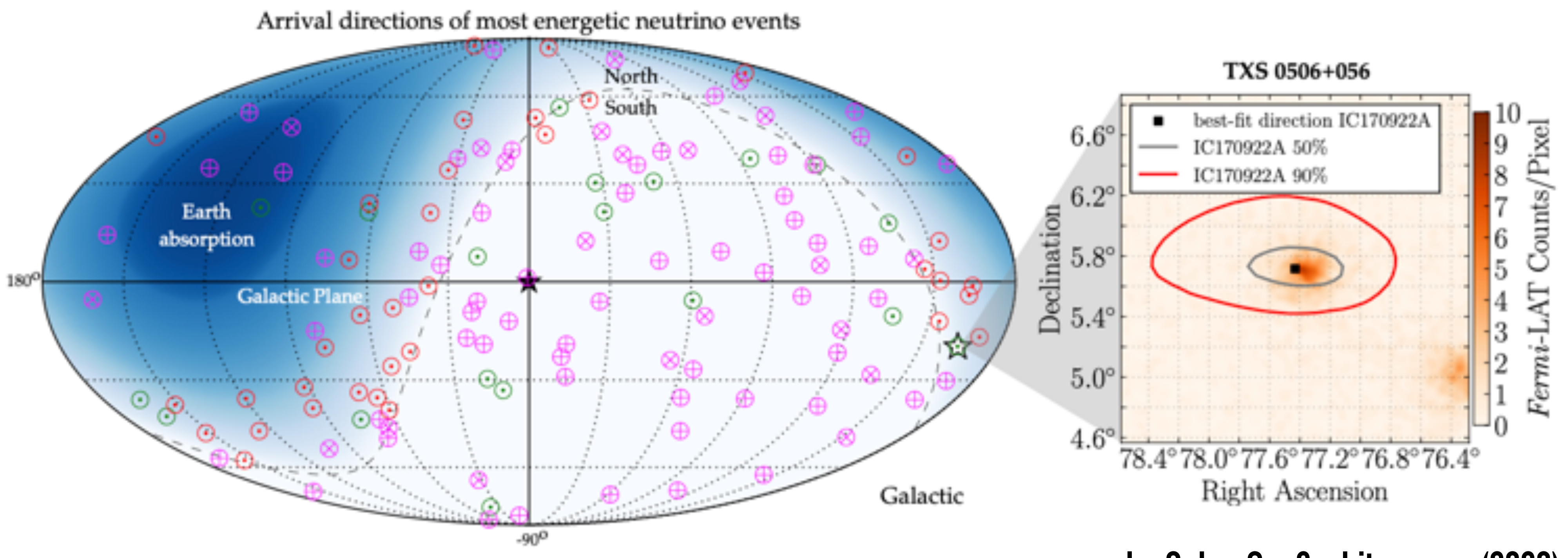




Summary

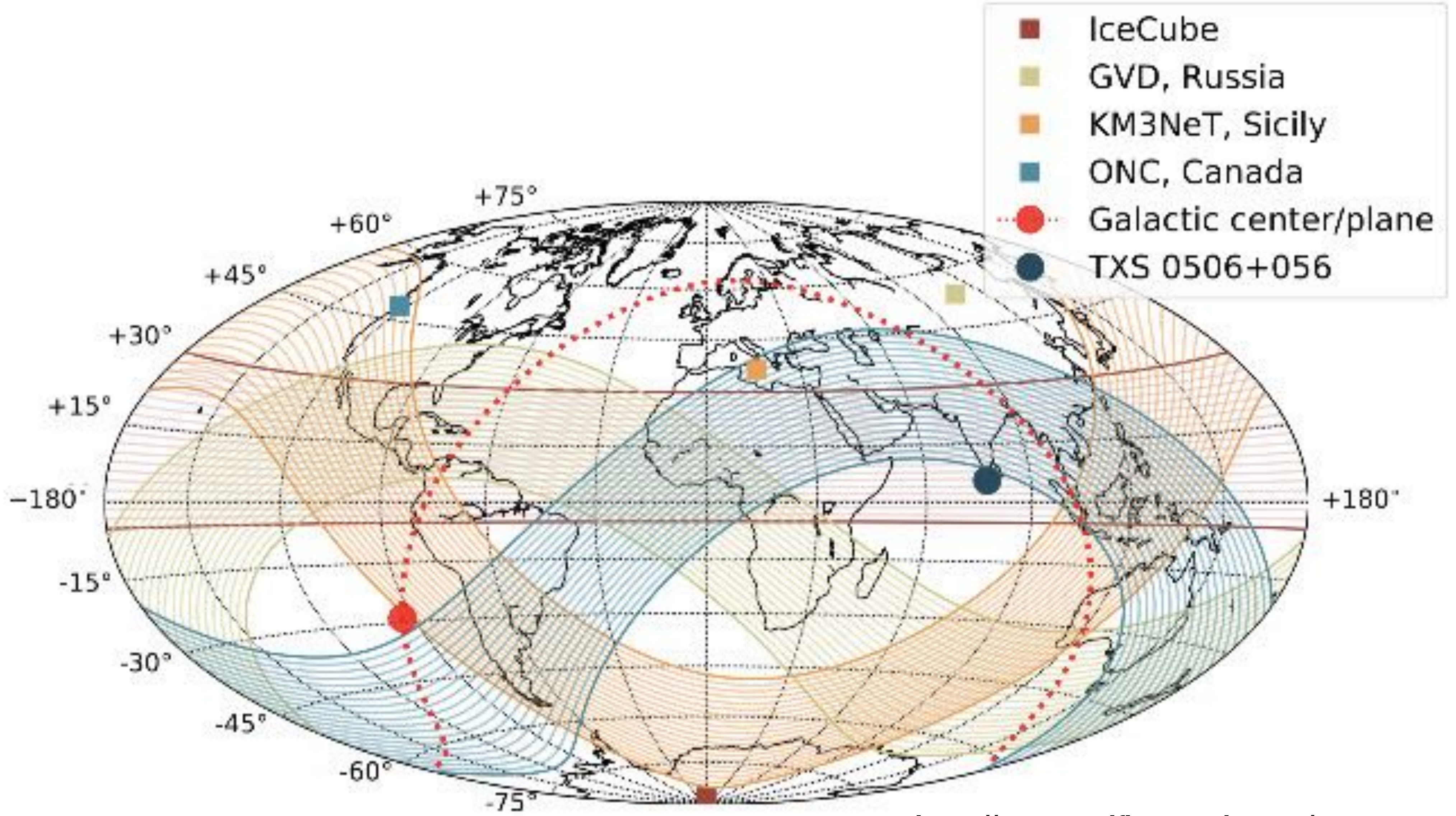
We are living in an exciting era!

- Closer to answer the century old questions on the origins of cosmic rays
  - Detection of large anisotropy of cosmic rays
  - Detection of >200 VHE gamma-ray (>100 GeV) sources
  - Firm detection of astrophysical neutrino flux
    - ✦ Several evidences toward the sources of HE neutrinos



IceCube-Gen2 white paper (2020)

- We will explore the Universe beyond today's discoveries to hunt for the extreme accelerators
  - Using current instruments
    - ✦ Get more dedicated multi-messenger observations
  - Building more powerful neutrino telescopes
    - ✦ Develop more sensitive optical module
    - ✦ Construct bigger neutrino telescopes



https://www.pacific-neutrino.org/p-one