拉索发现黑洞是PeV宇宙线加速器

Black Holes Found as PeV Cosmic Ray Accelerators by LHAASO

by Zhen Cao 曹臻, IHEP, CRRC, China

LIP，Lisbon，Portugal，2025-9

高海拔宇宙线观测站

Large High Altitude Air Shower Observatory

拉索鸟瞰，摄于2021-08

LHAASO，拉索

- Location：29º21’ 27.6” N , 100º08’19.6” E
- Altitude: 4410 m
- 2021-07 建成

Content

- Introduction and Experiments
  - Accelerators and Cosmic Rays
- Sky Survey for Source Candidates
- The 1st Catalogue of Microquasars
  - MQs as PeV Particle Accelerators
  - Investigation in Depth of a BH+jet system
- Cosmic Ray Source Papulation in "Knee" Energy Range
- Future Experiments

Acceleration region

B

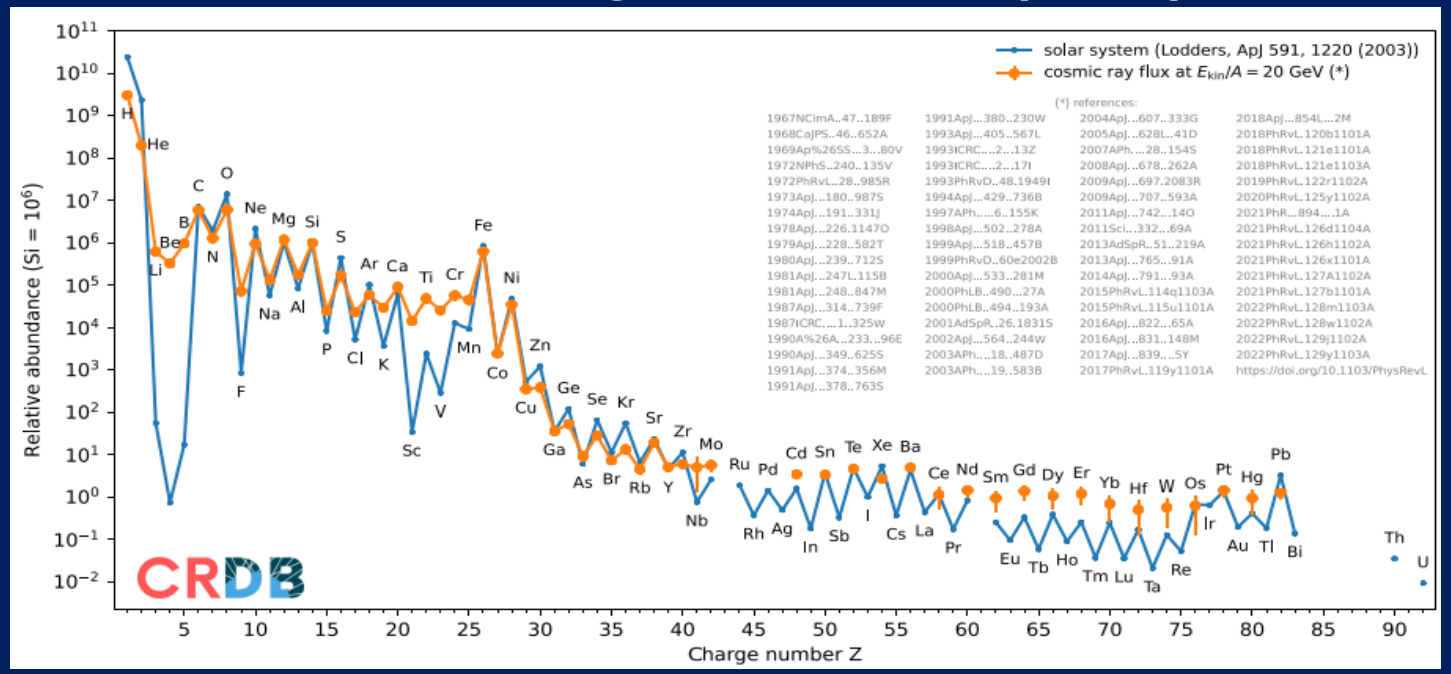
- **LEP**
- **Electron accelerator**
- **E_e 0.1 TeV**

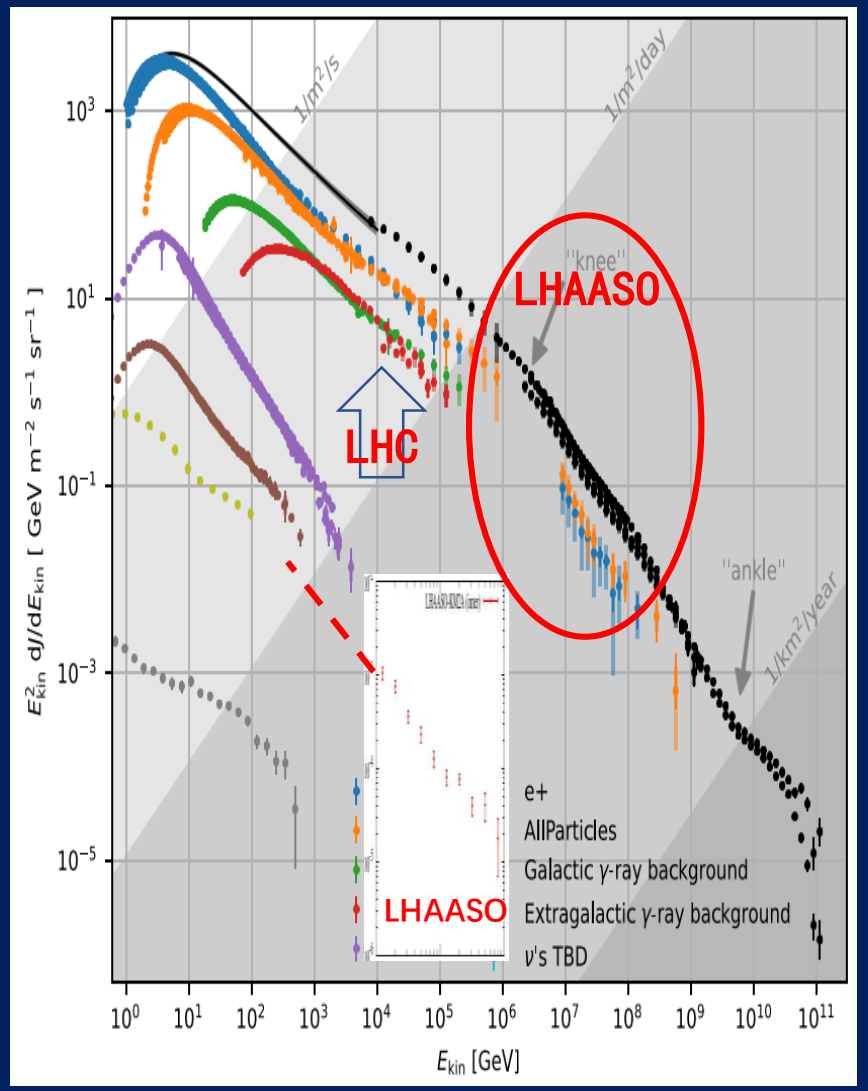
- **LHC**
- **Proton accelerator**
- **E_p 10 TeV**

- **FCC/CEPC**
- **E_e 1 TeV**

宇宙加速器：特性及其存在的证据
Cosmic Accelerators: evidences of existence

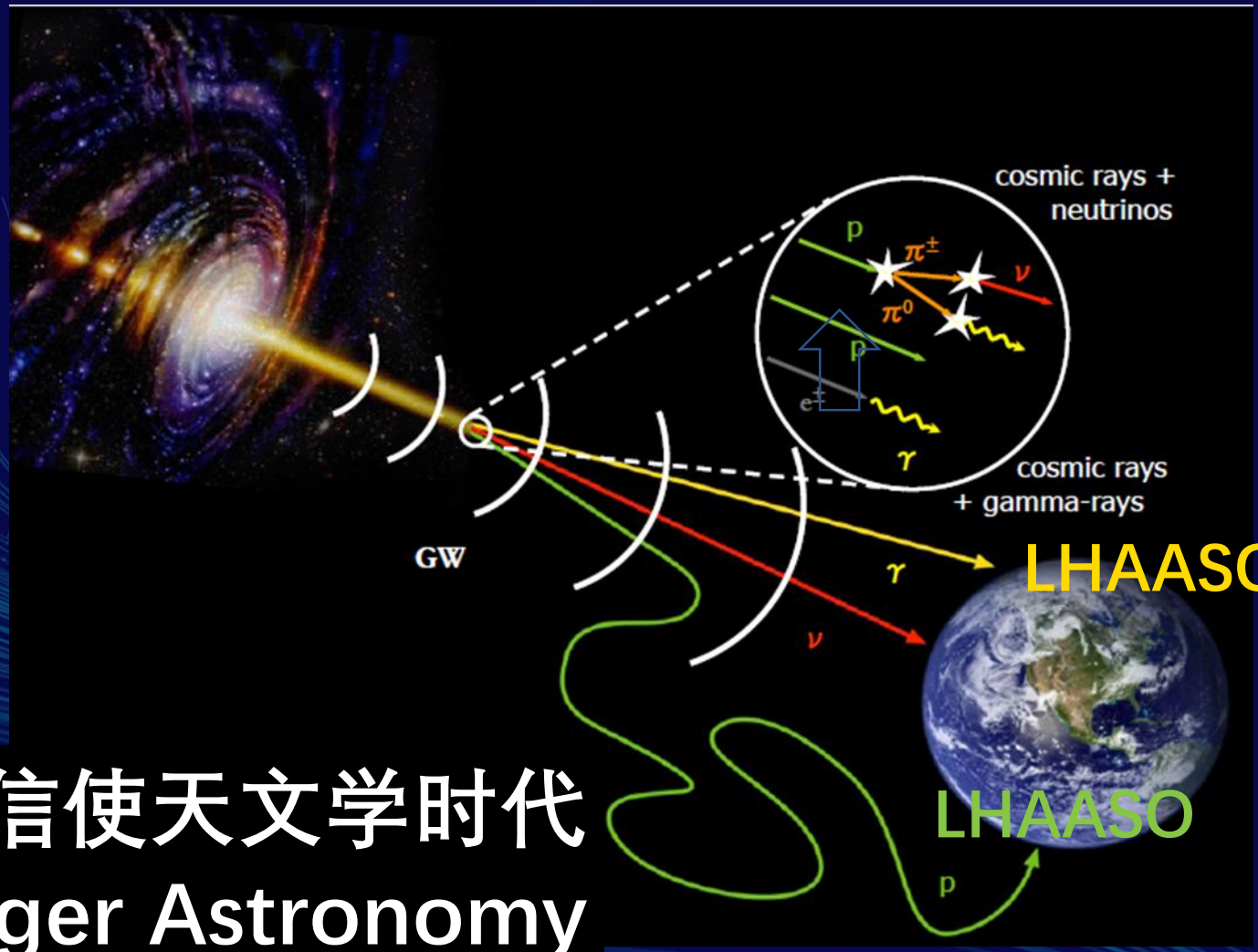
- After 110 years, we have learnt a lot about CRs near the Sun
- Particularly in the era of high precision measurements
- However, their origin is still an open question





宇宙加速器在哪里？怎么才能找到它们？
We knew that the accelerators exist.
Where are they? How to find them?

LHAASO is
a γ-ray Telescope
and
a CR detector

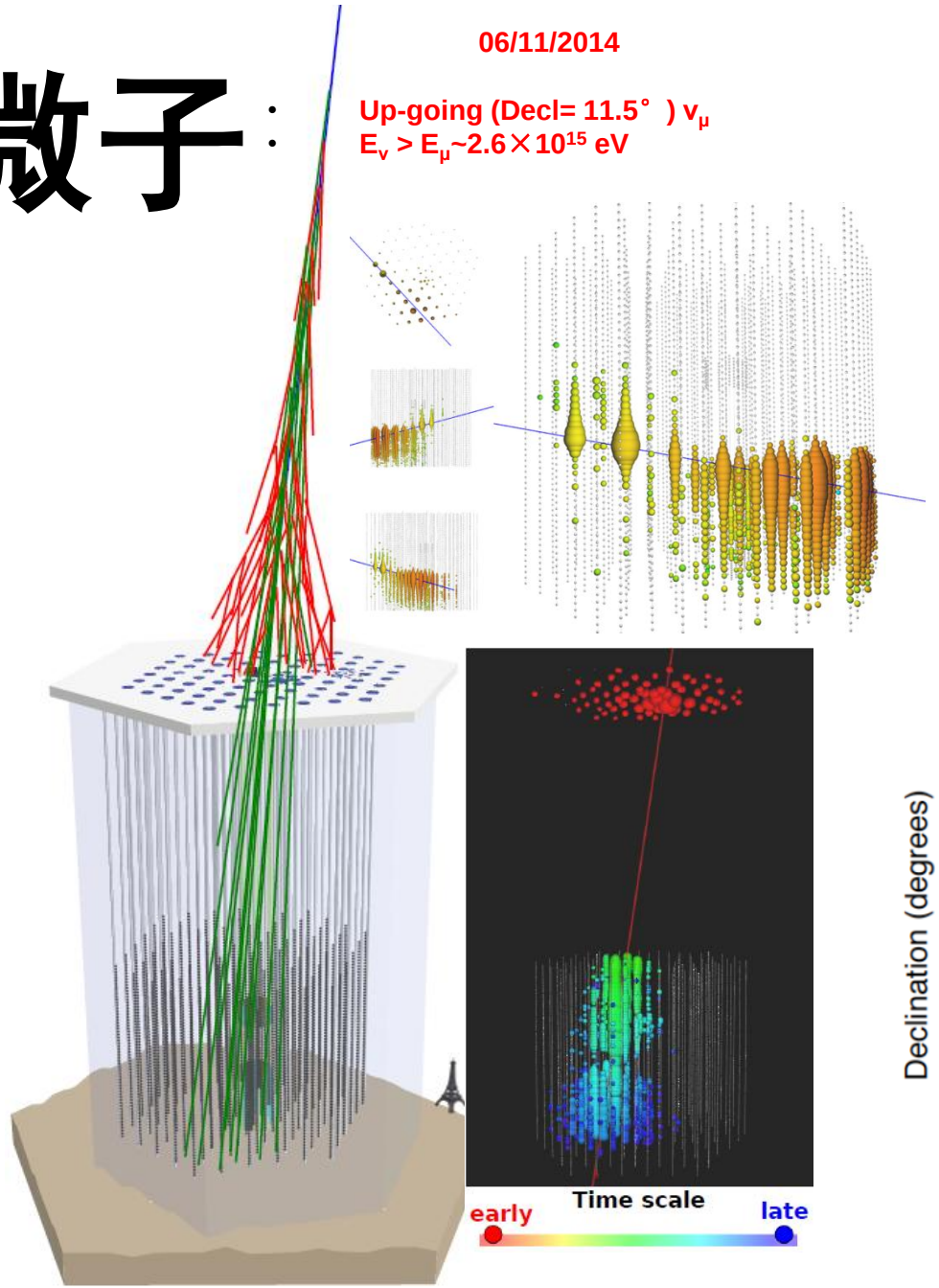


多信使天文学时代
Era of Multi-Messenger Astronomy

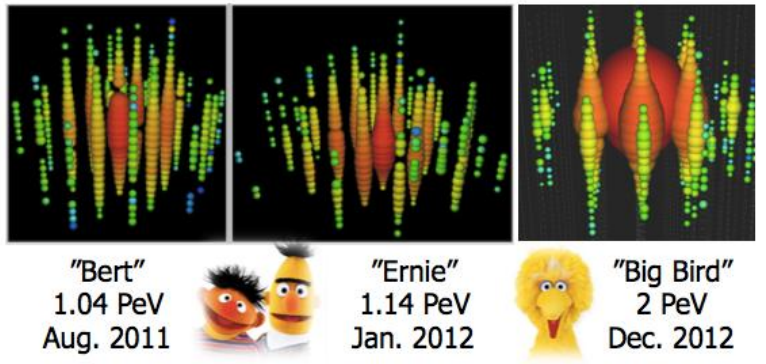
中微子：

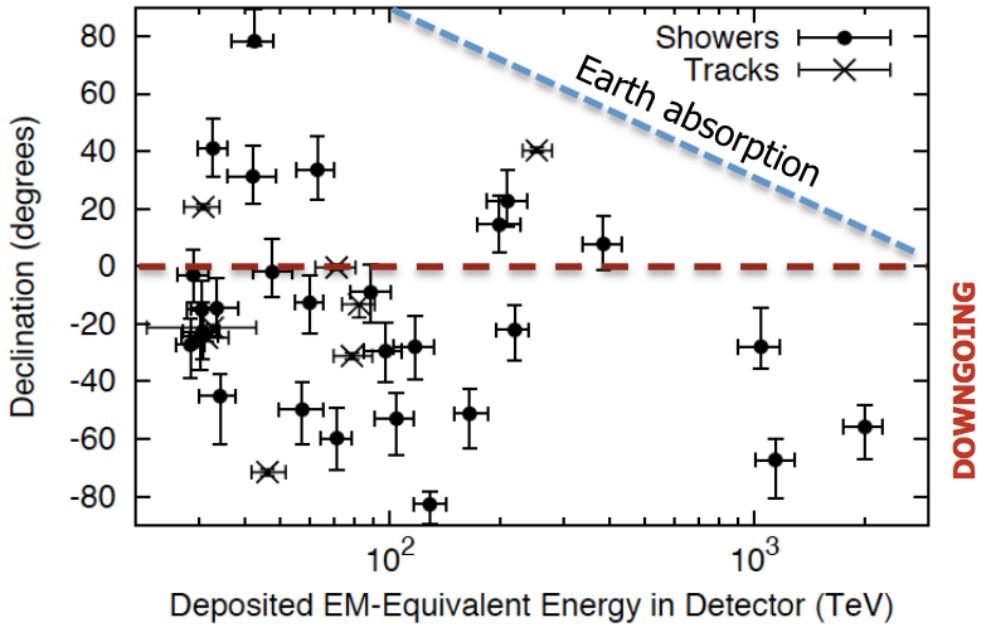
06/11/2014

Up-going (Decl= 11.5˚) ν_μ
$E_\nu > E_\mu \sim 2.6 \times 10^{15}$ eV



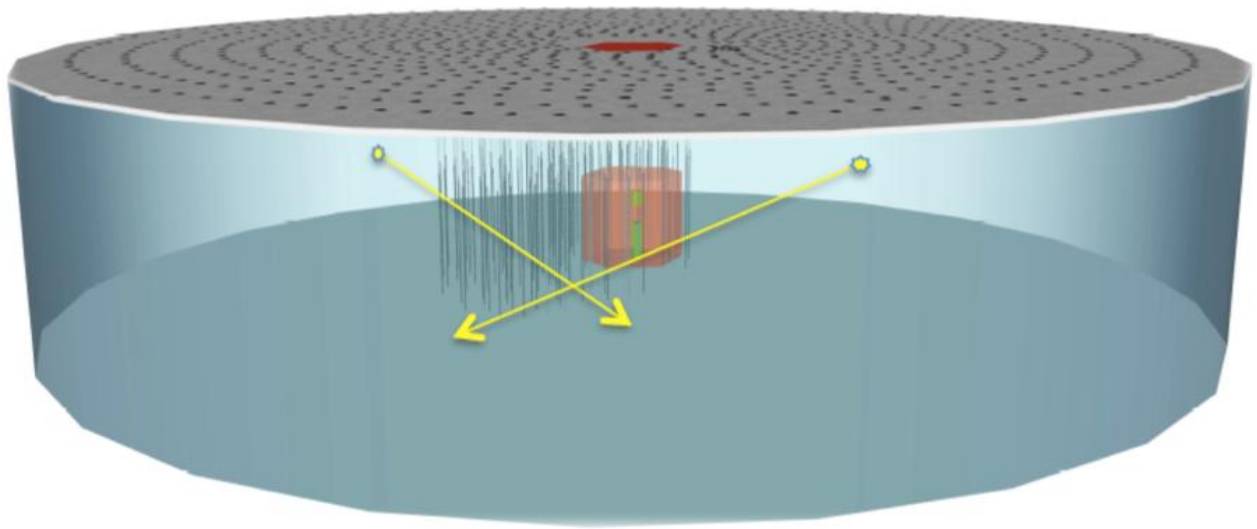
Neutrino Astronomy

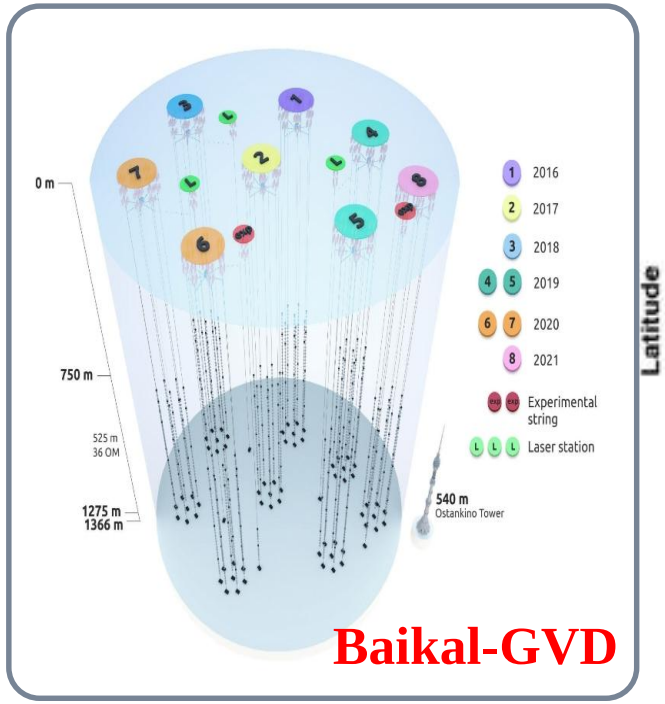


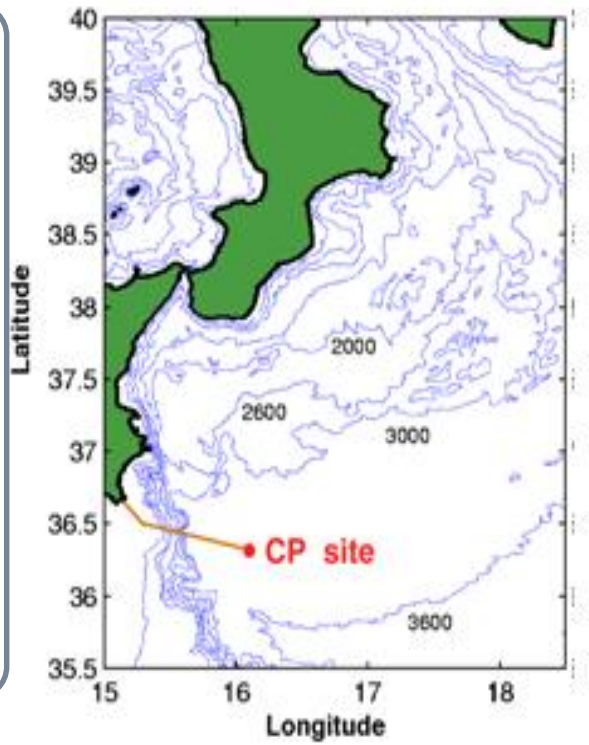


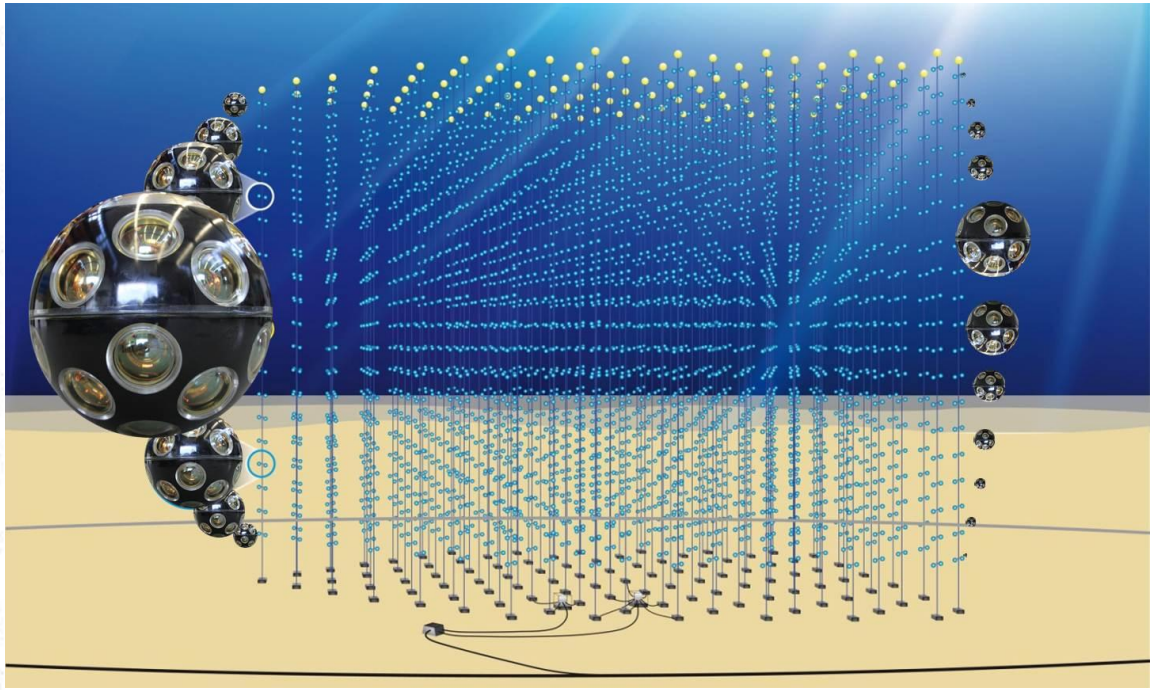
Neutrino Astronomy

- IceCube/Generation-2
- KM3Net
- BaiKal-GVD



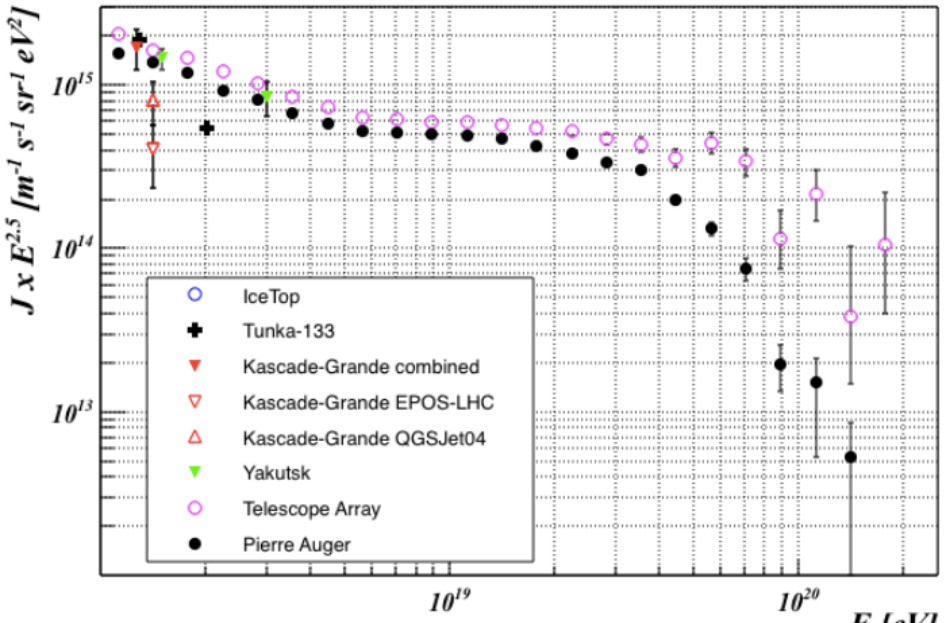


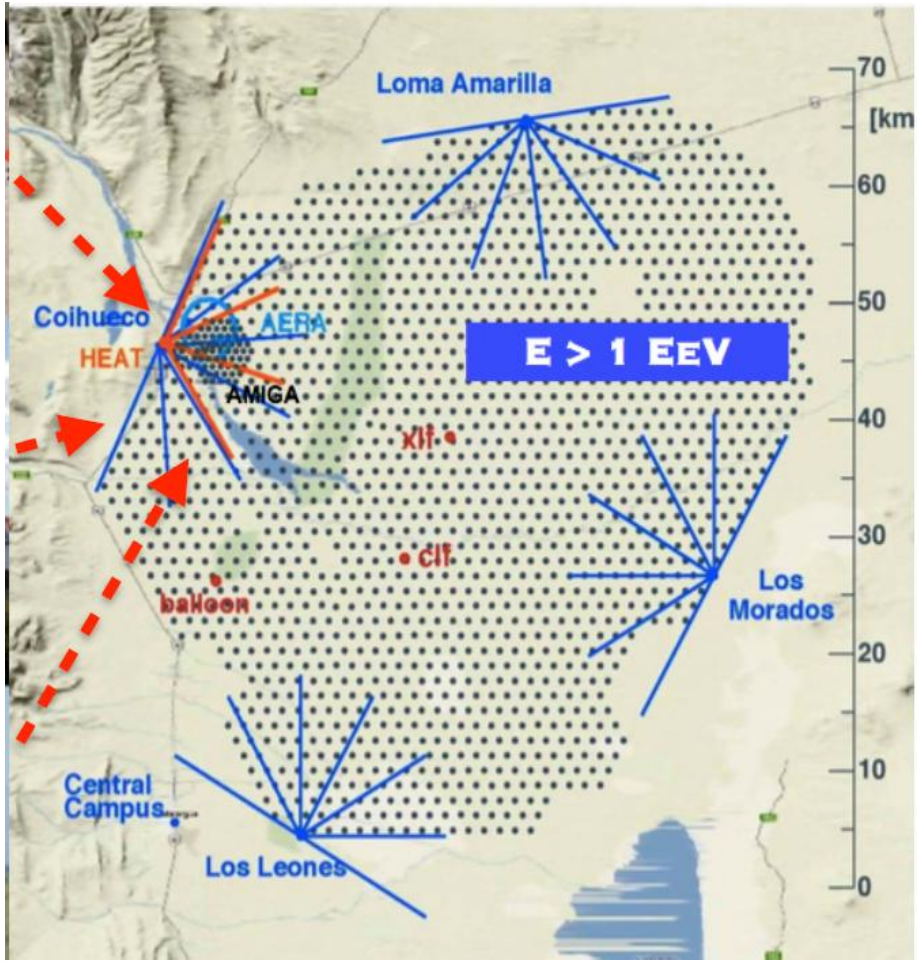




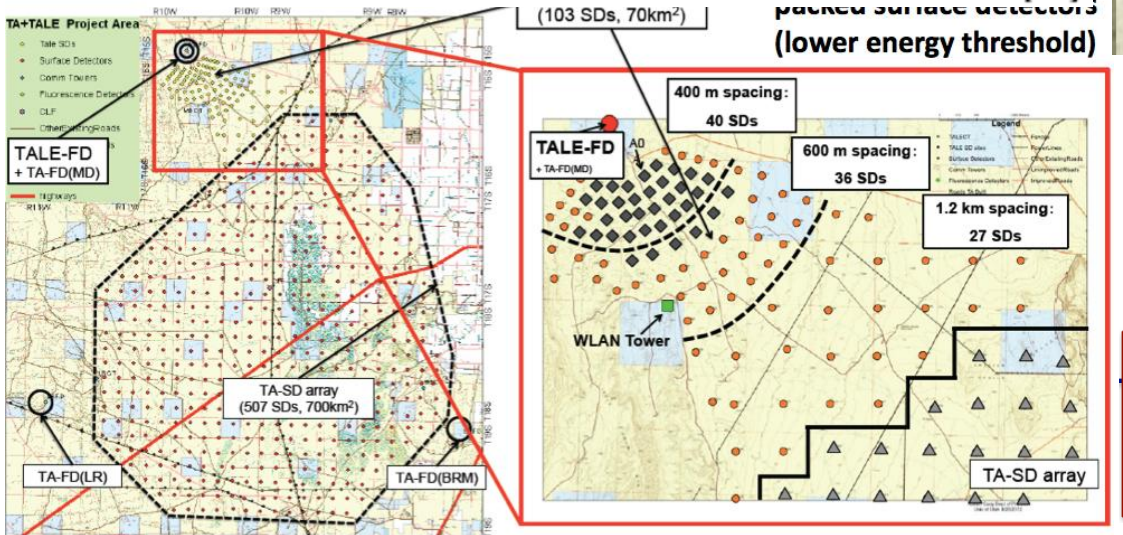
带电宇宙线粒子

UHECR
particle astronomy





1400 m a.s.l. [820 g cm^{-2}]
A ~ 3000 km^2, 1500 m grid
1660 water Cherenkov SD + 24 FD



(lower energy threshold)

1400 m a.s.l. [880 g cm^{-2}]
507 SD, 1.2 km grid, 700 km^2
16 TALE counters, 400 m grid
3 FD (BR,LR,MD/TALE)

X 2

γ –光子

γ-ray Astronomy

Image Atmospheric Cherenkov Telescopes: pointing observation

终极科学目标：发现高能宇宙线源

Scientific Goals

Large High Altitude Air Shower Observatory

LHAASO

γ-ray astronomy:

Survey for sources (above 500 GeV)

PeVatrons (above 100 TeV)

All kind of sources: SNR, PWN, MYC, binary, pulsar, AGN, GRB etc.

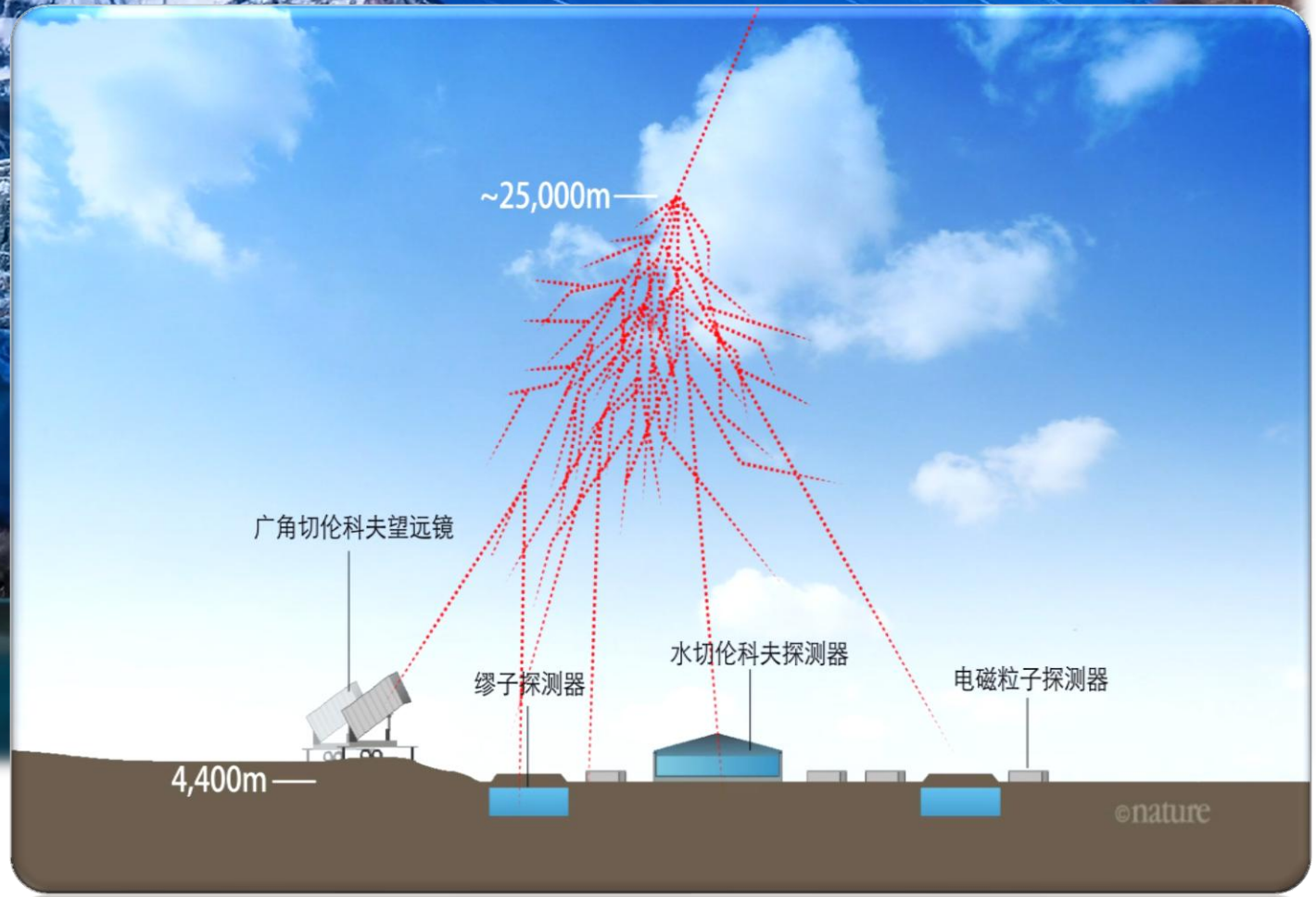
Cosmic Ray Physics:

The knees

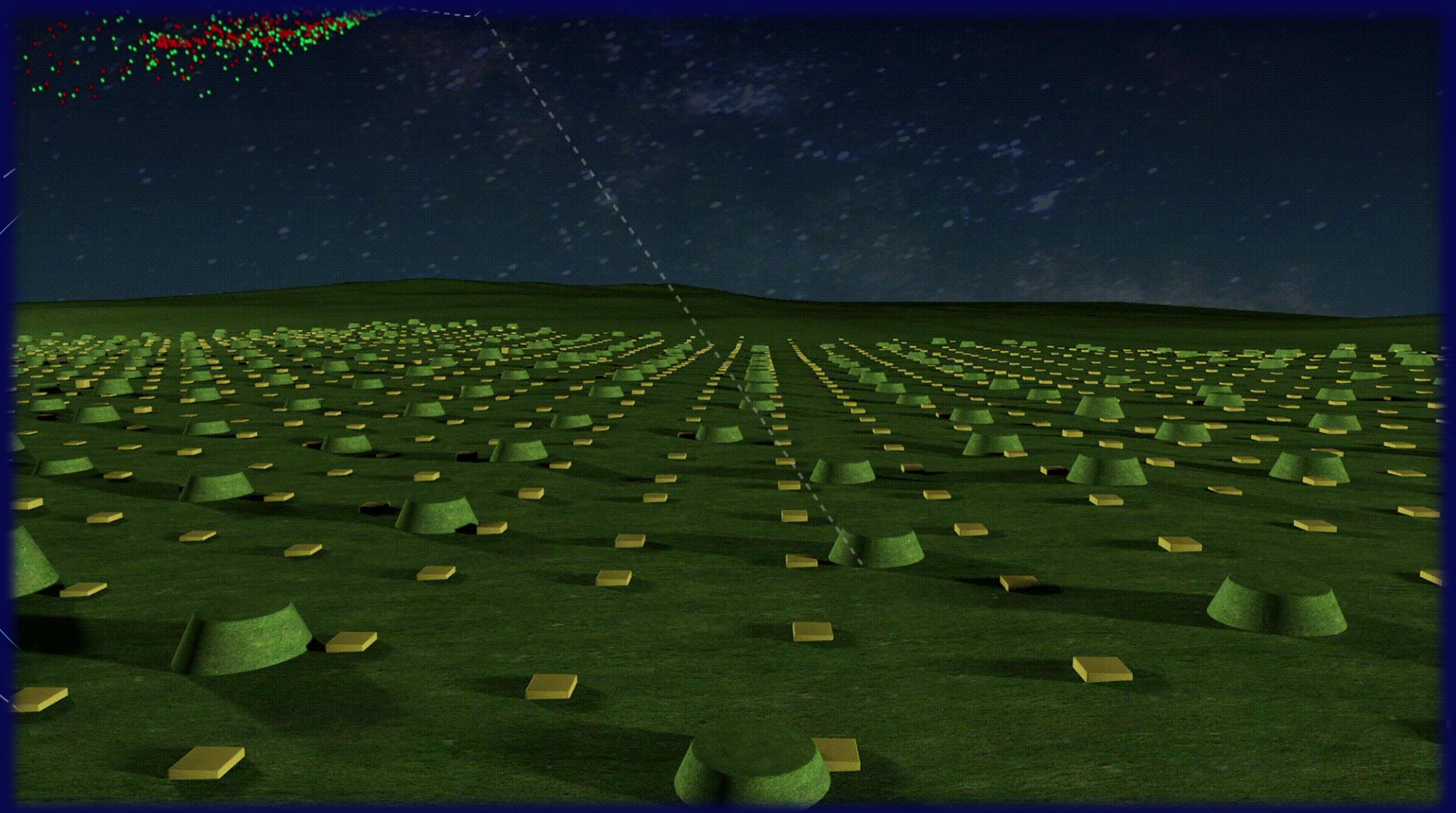
Compositions : individual species H, He and Fe

Anisotropy: (1 TeV to 10 PeV)

New Physics Front: DM, LIV, etc.



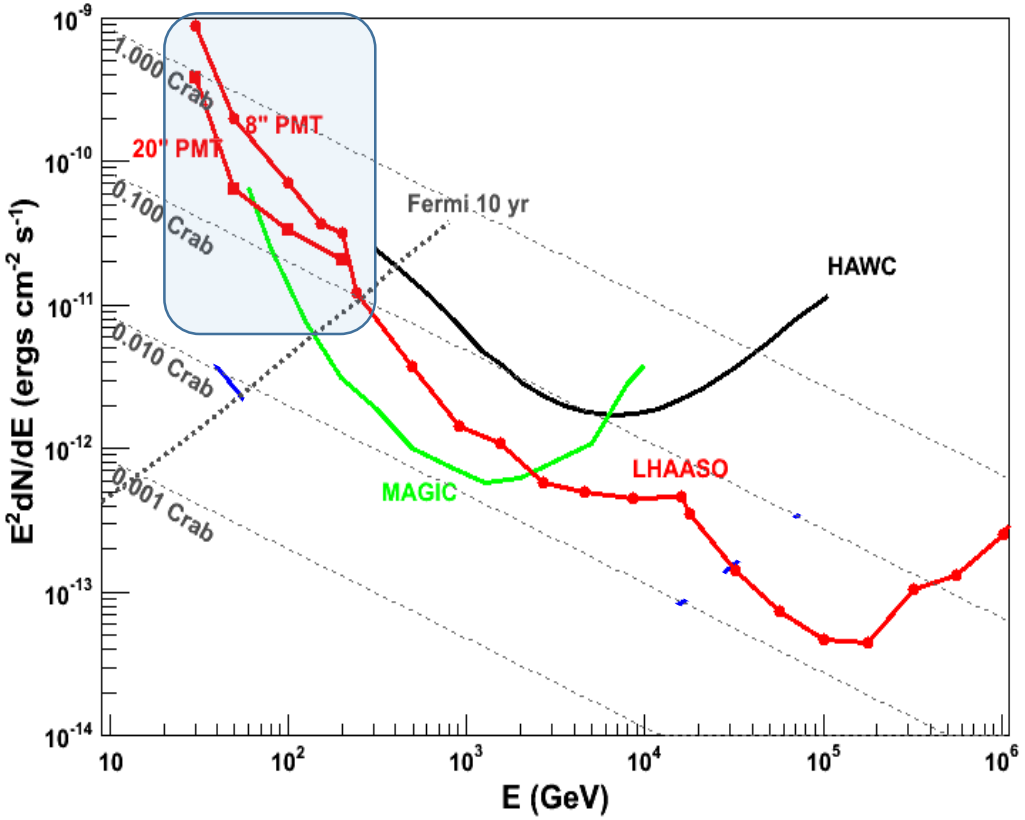
The principle of cosmic ray detection of LHAASO

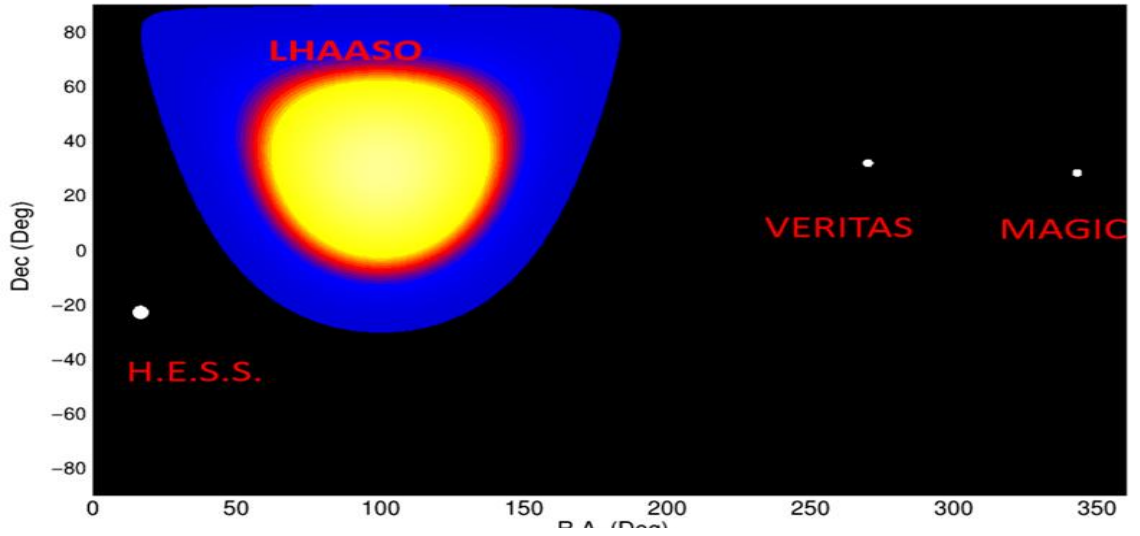


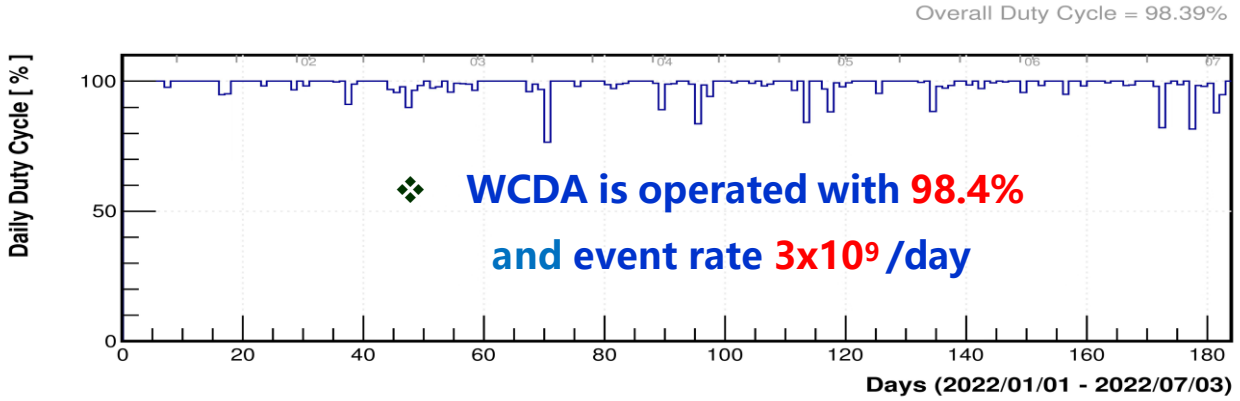
到来的“信使”化作“阵雨”洒落在“拉索”阵列上，一场“雨”持续的时间只有几纳秒

Complementary Observations: survey vs. pointing

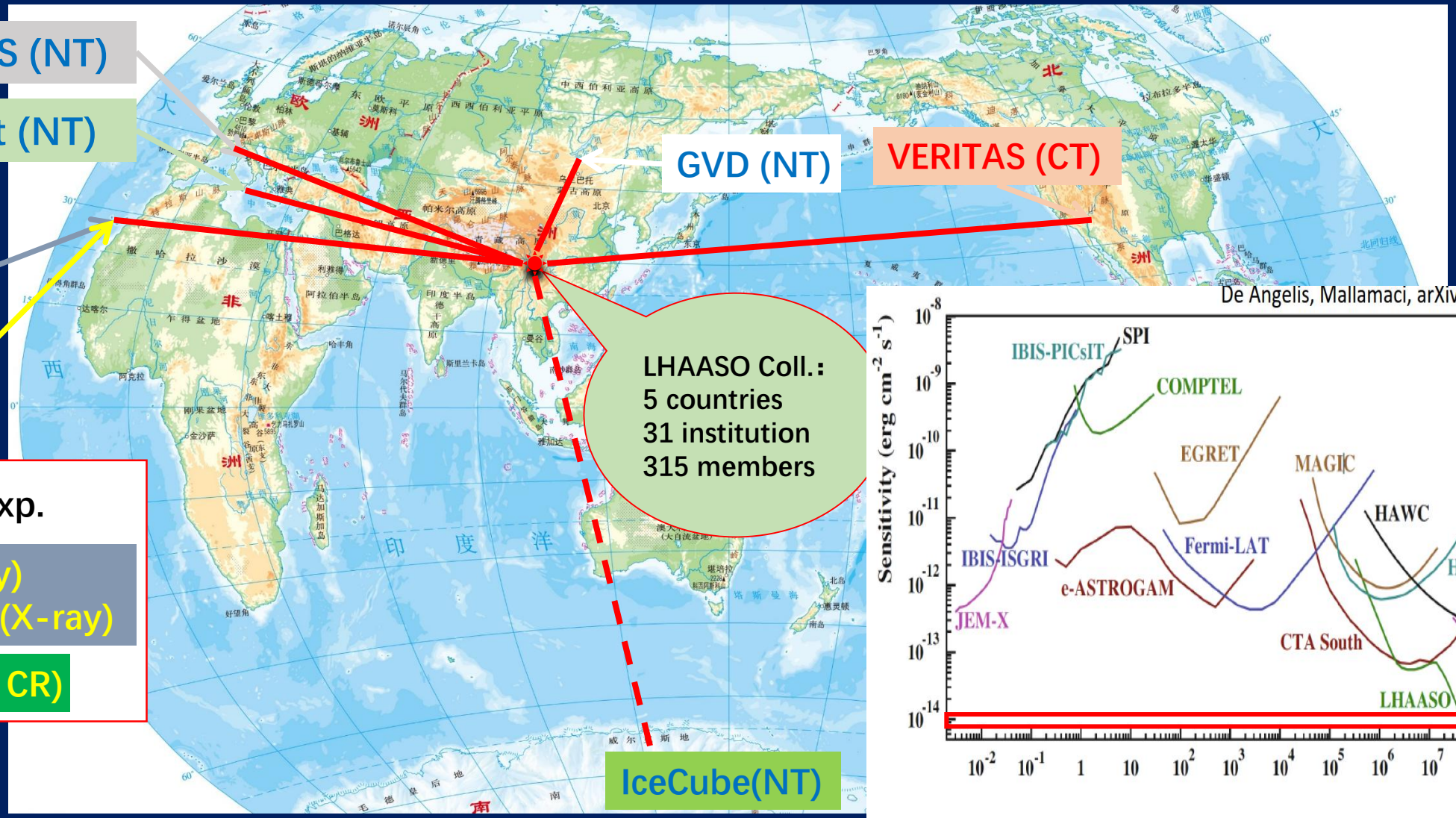
- Time-domain astronomy vs. steady radiation
- VHE vs. UHE bands







Multi-Messenger Collaboration Network



Space borne Exp.

eROSITA(X-ray)
Einstein Probe(X-ray)

DAMPE(γ-ray, CR)

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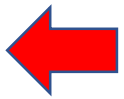
- Gamma Ray Source Survey Results 
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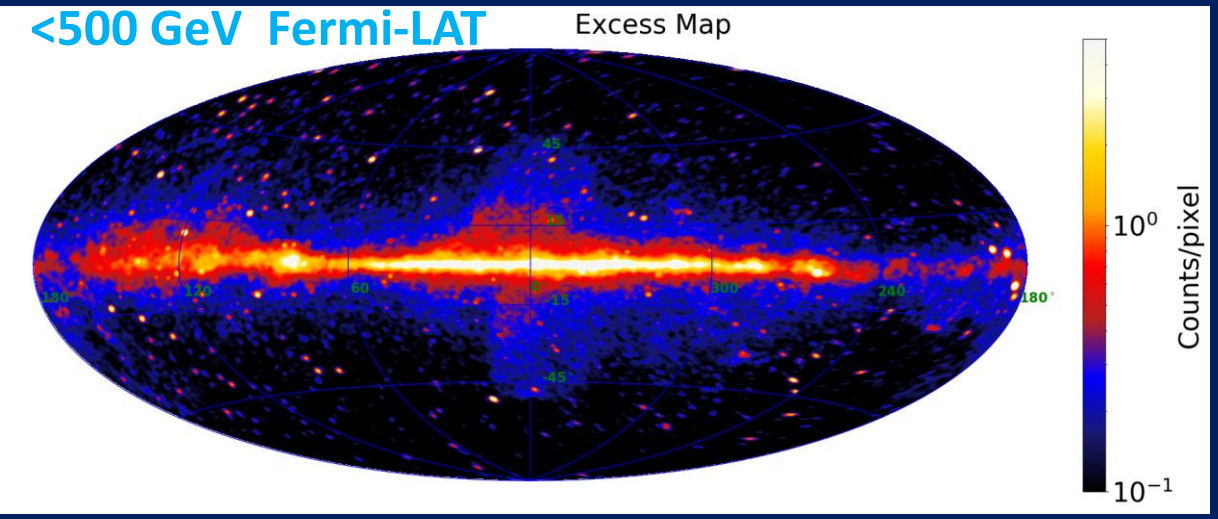
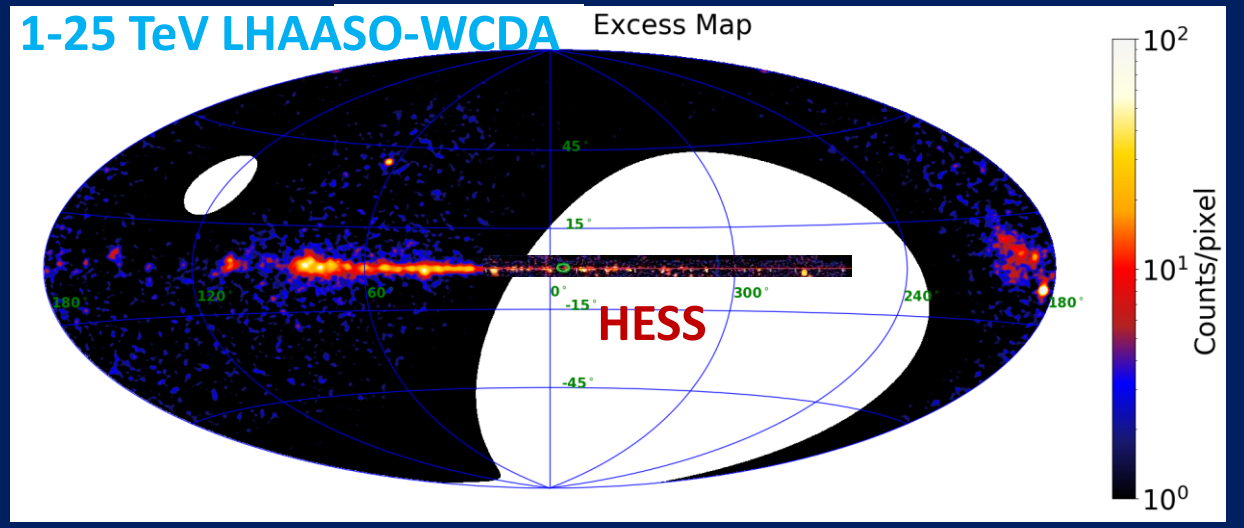
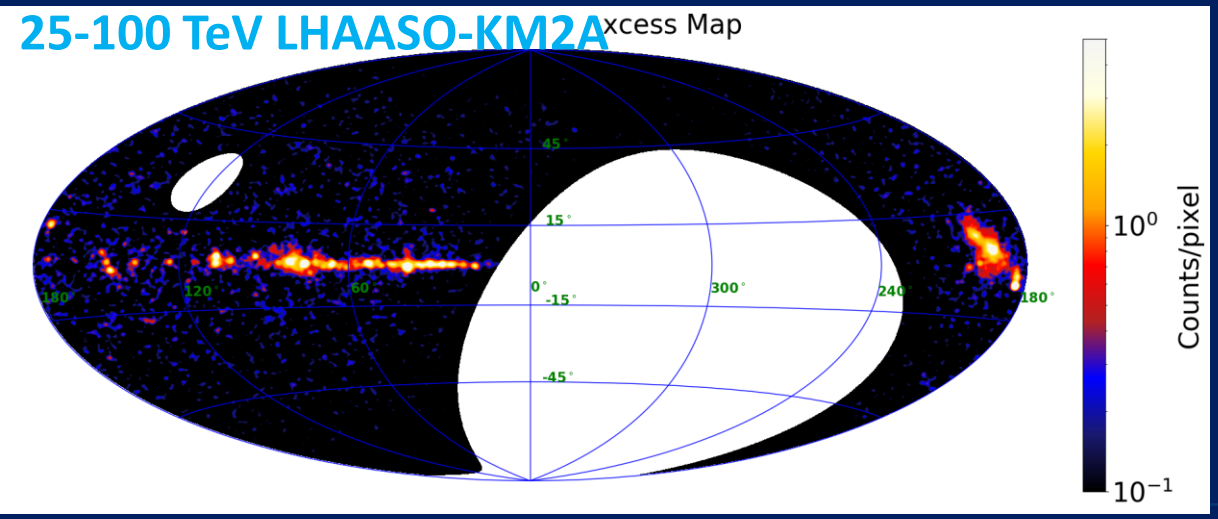
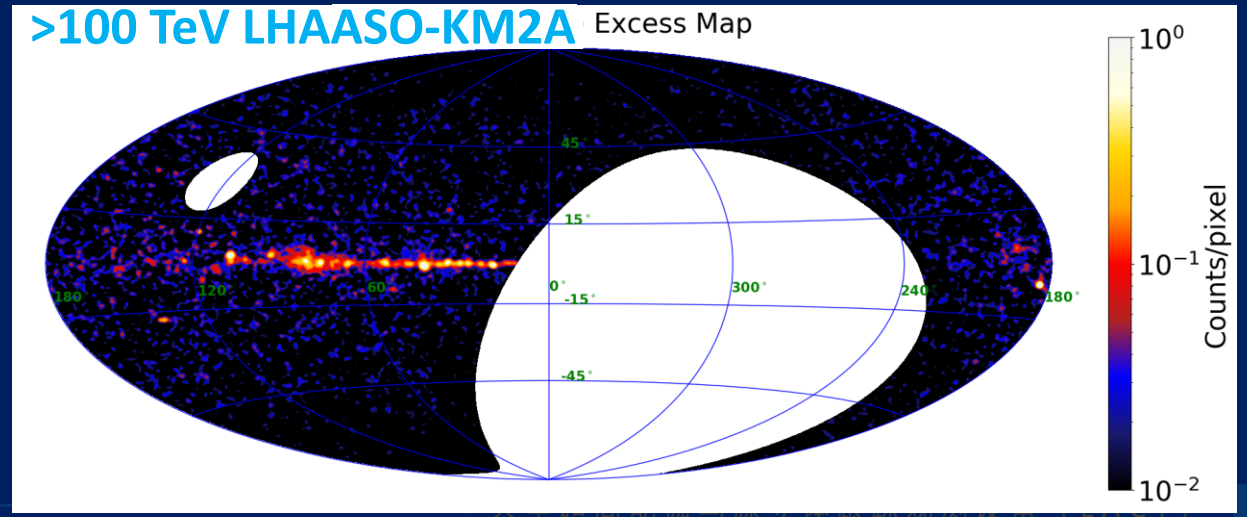
UHE γ-ray Astronomy: **survey for sources**

- **Survey discovered 30+ new sources, 40+ PeVatrons and diffuse γ-ray emission**

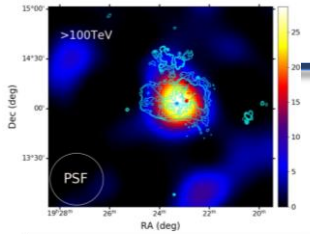








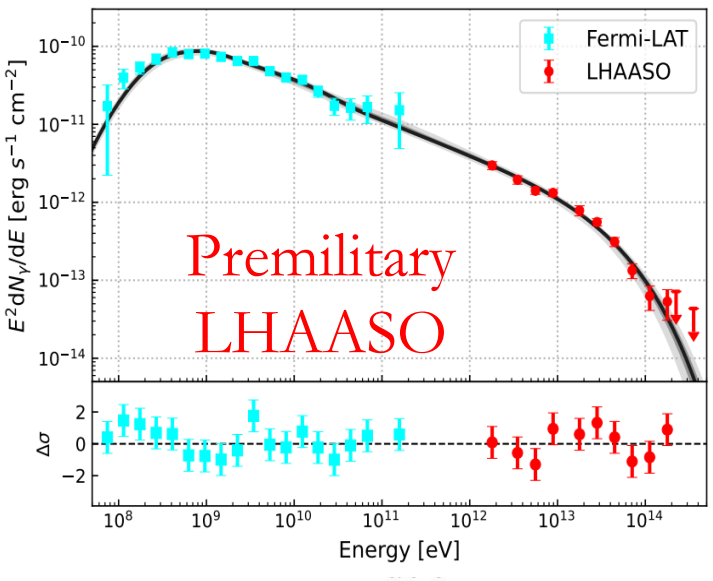
宇宙线源的候选天体Possible Source Candidates



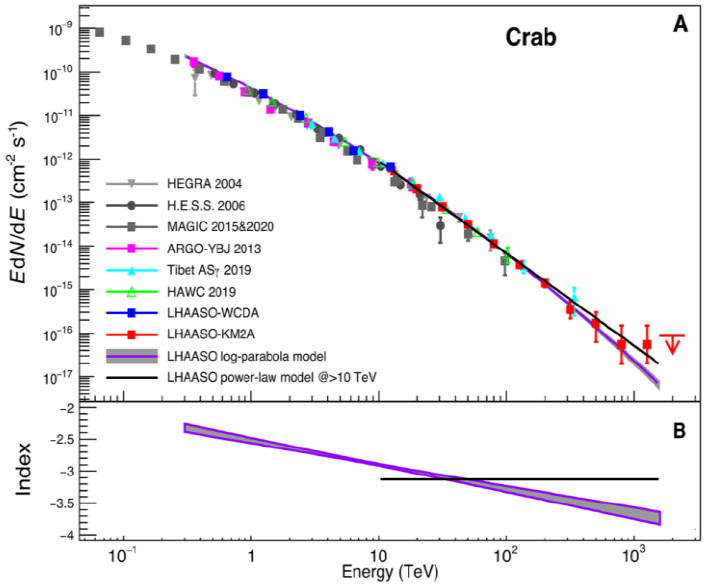
W51

Crab

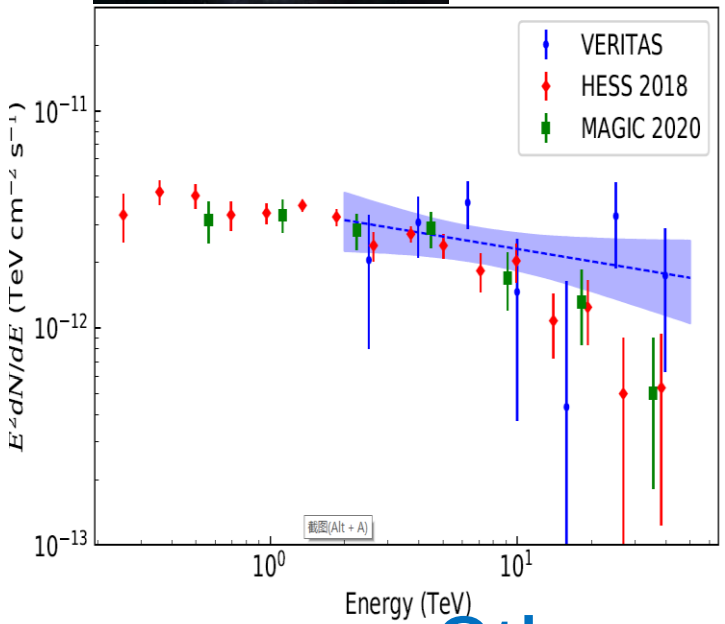
G.C. by IACTs



SNR



PWN



...

Other sources

Many types of γ-ray sources have the potential to accelerate particles to 1 PeV and above

A&A 671, A12 (2023)
Science 10.1126/science.abg5137 (2021).
The Astrophysical Journal, 913:115 (11pp), 2021 June 1

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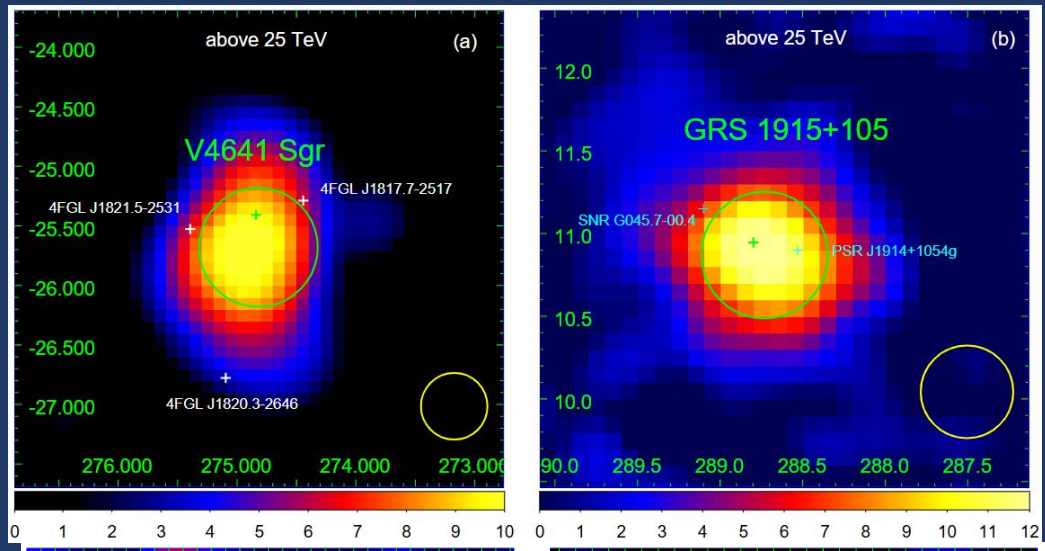
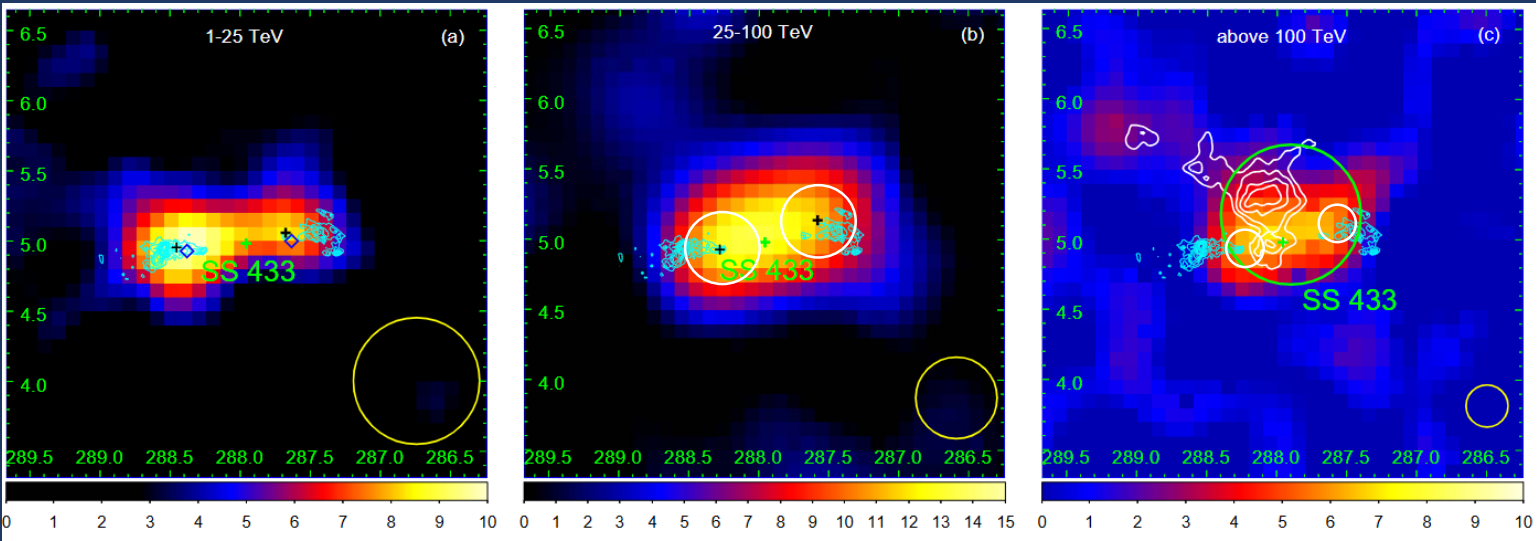
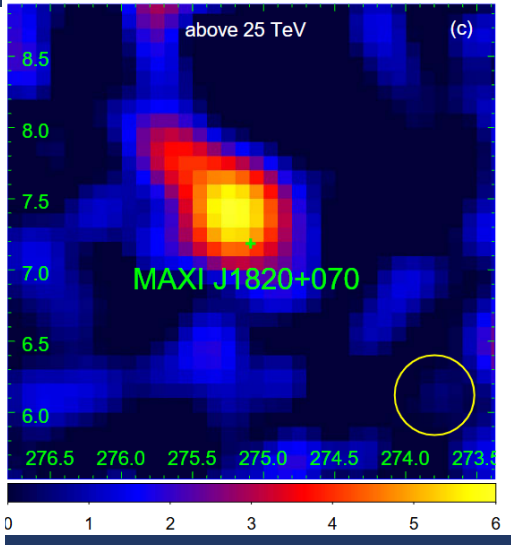
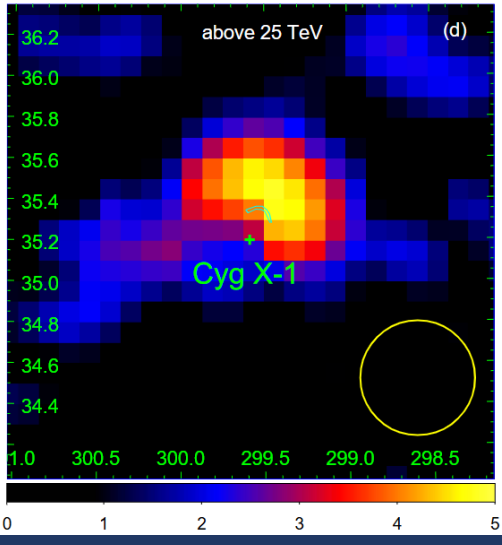
Black Holes and Jets: μQs

- Very important !!
- New CR source population particularly at energy E >3 PeV

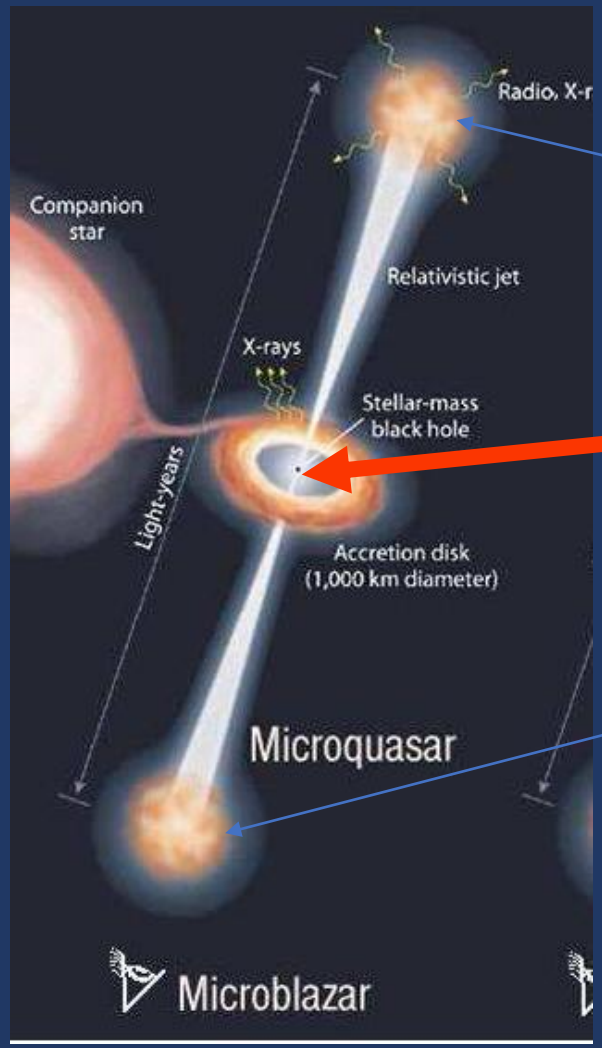


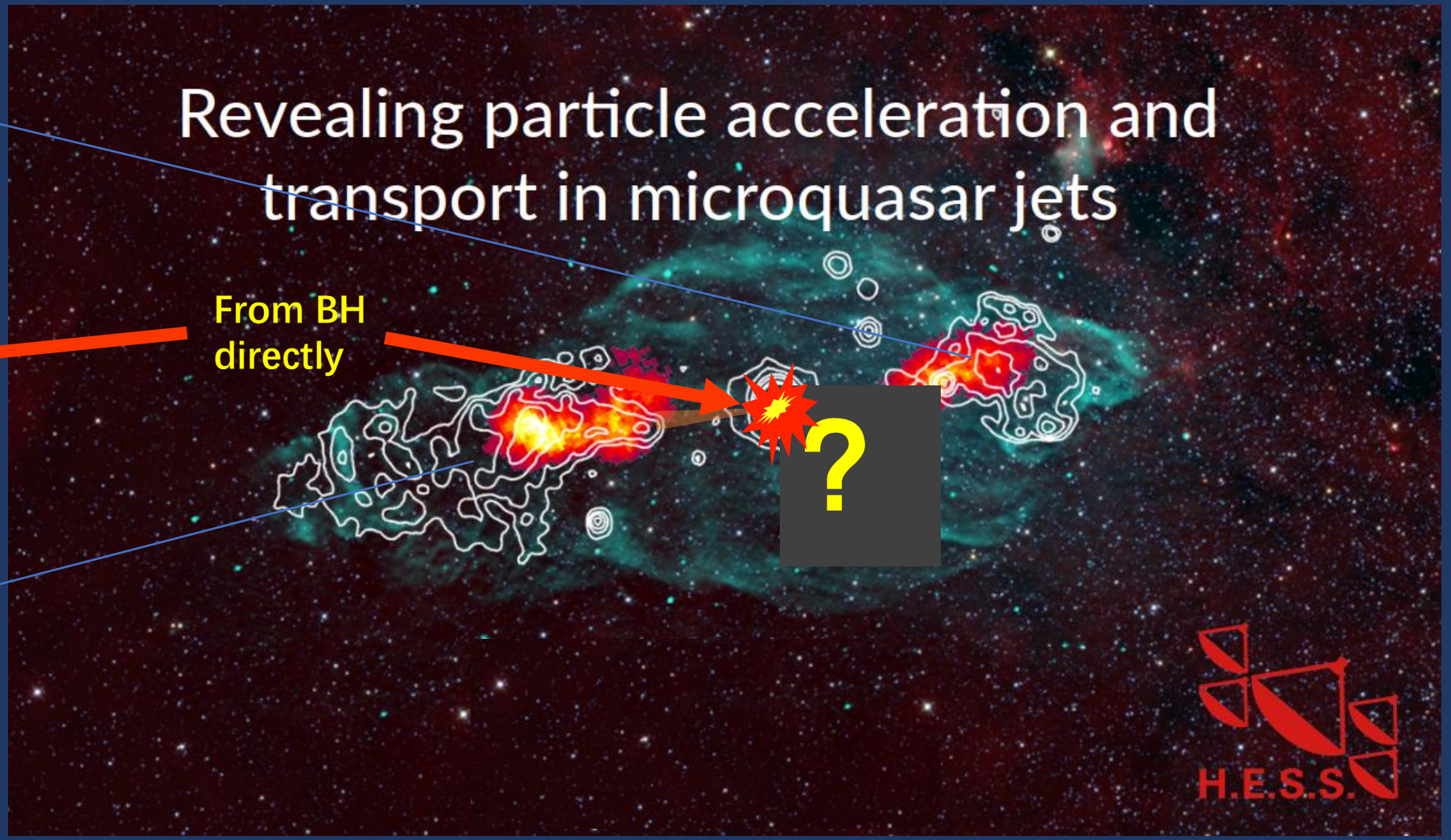






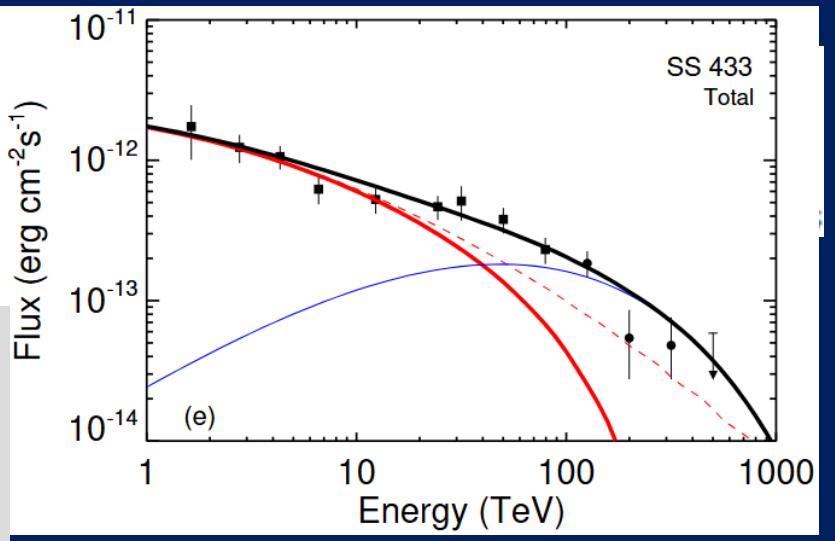
MicroQuasar: SS433 etc.

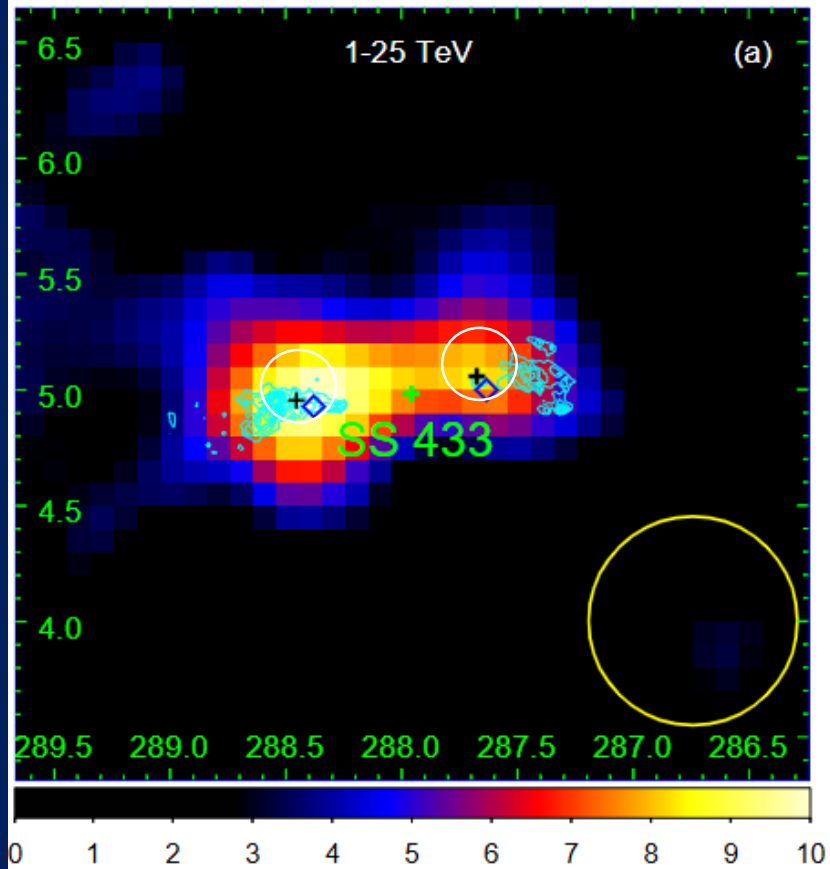


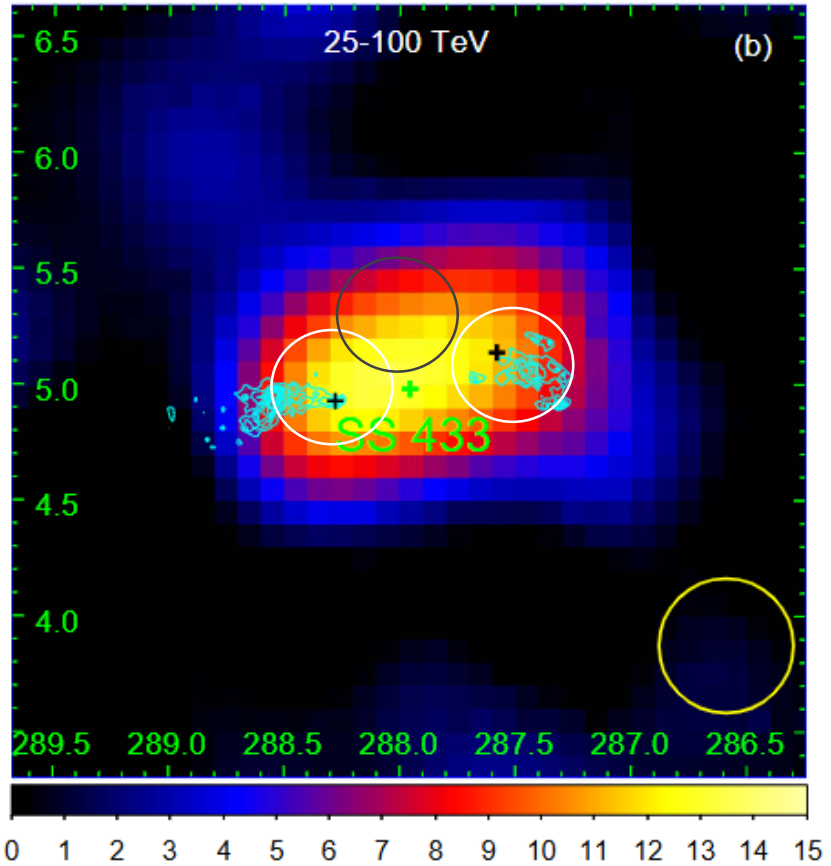


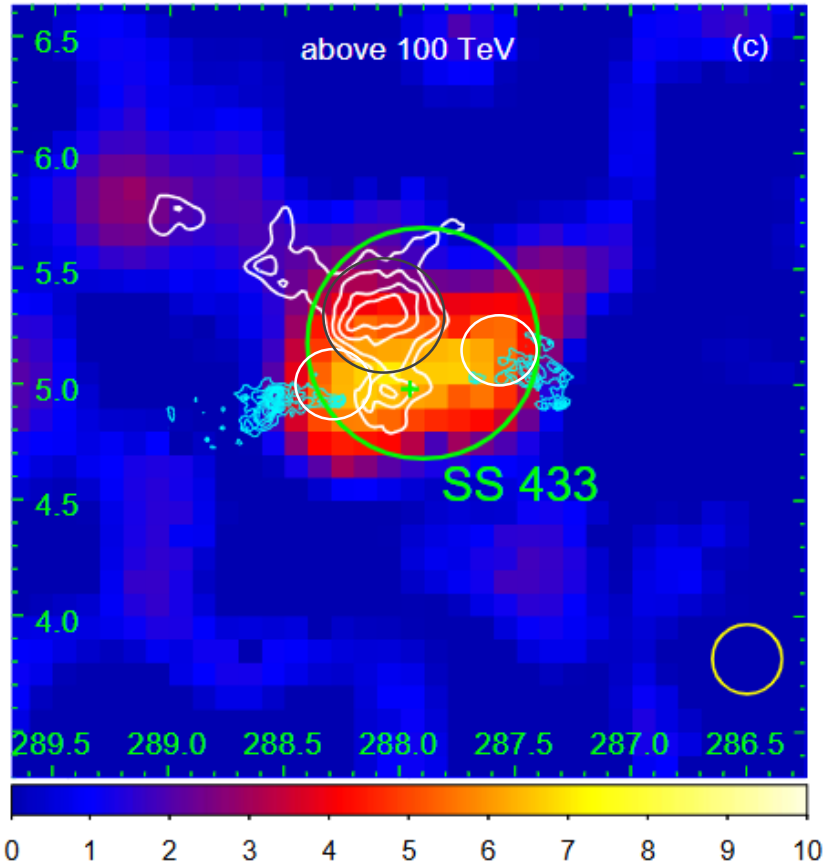
Black Holes and Jets

- LHAASO measured them clearly
- At low energy, the jets
- At higher energies, BH itself may have shown up



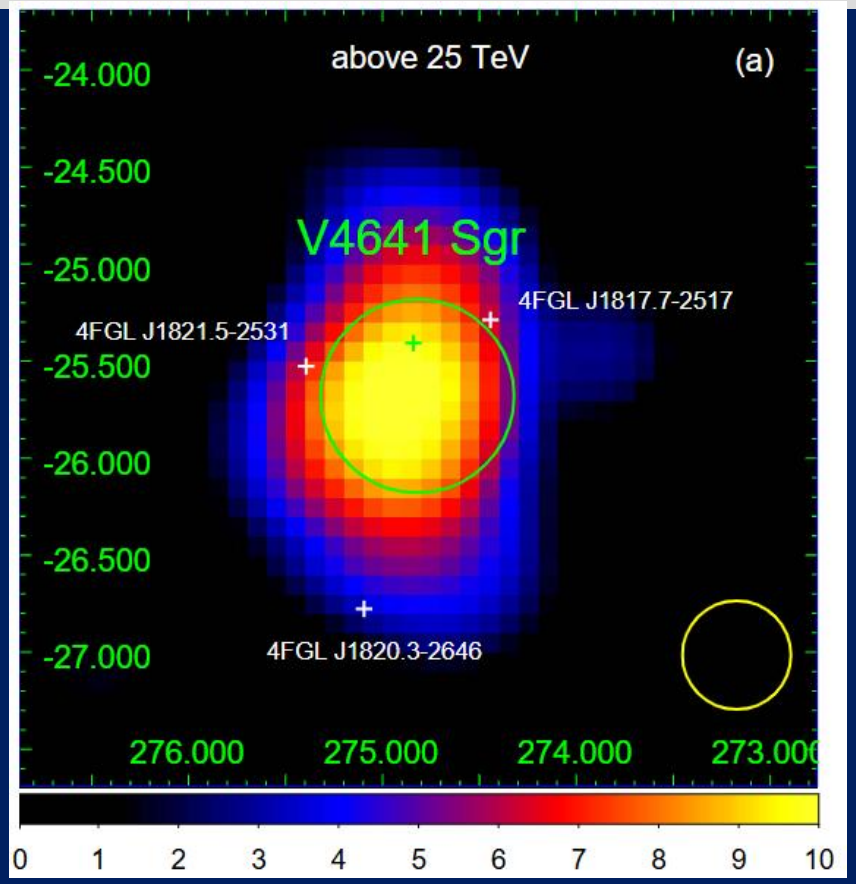


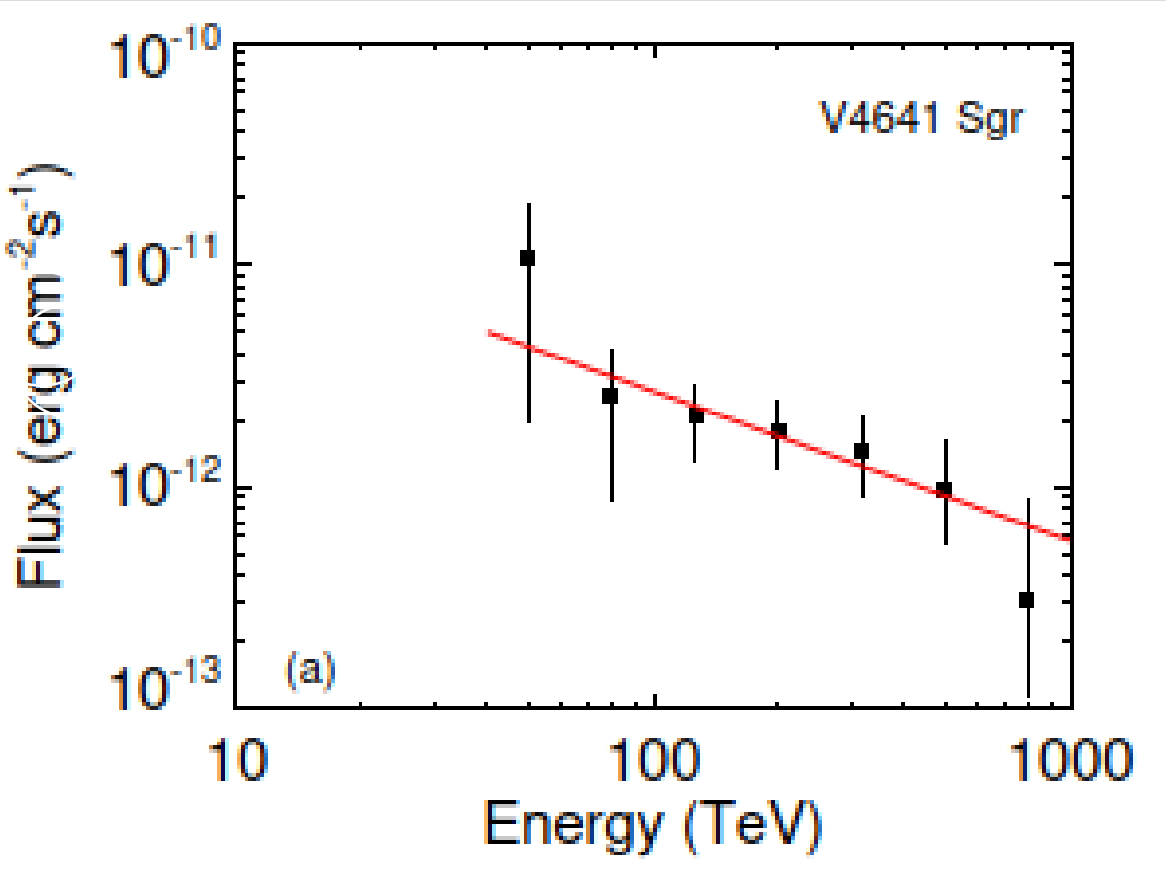


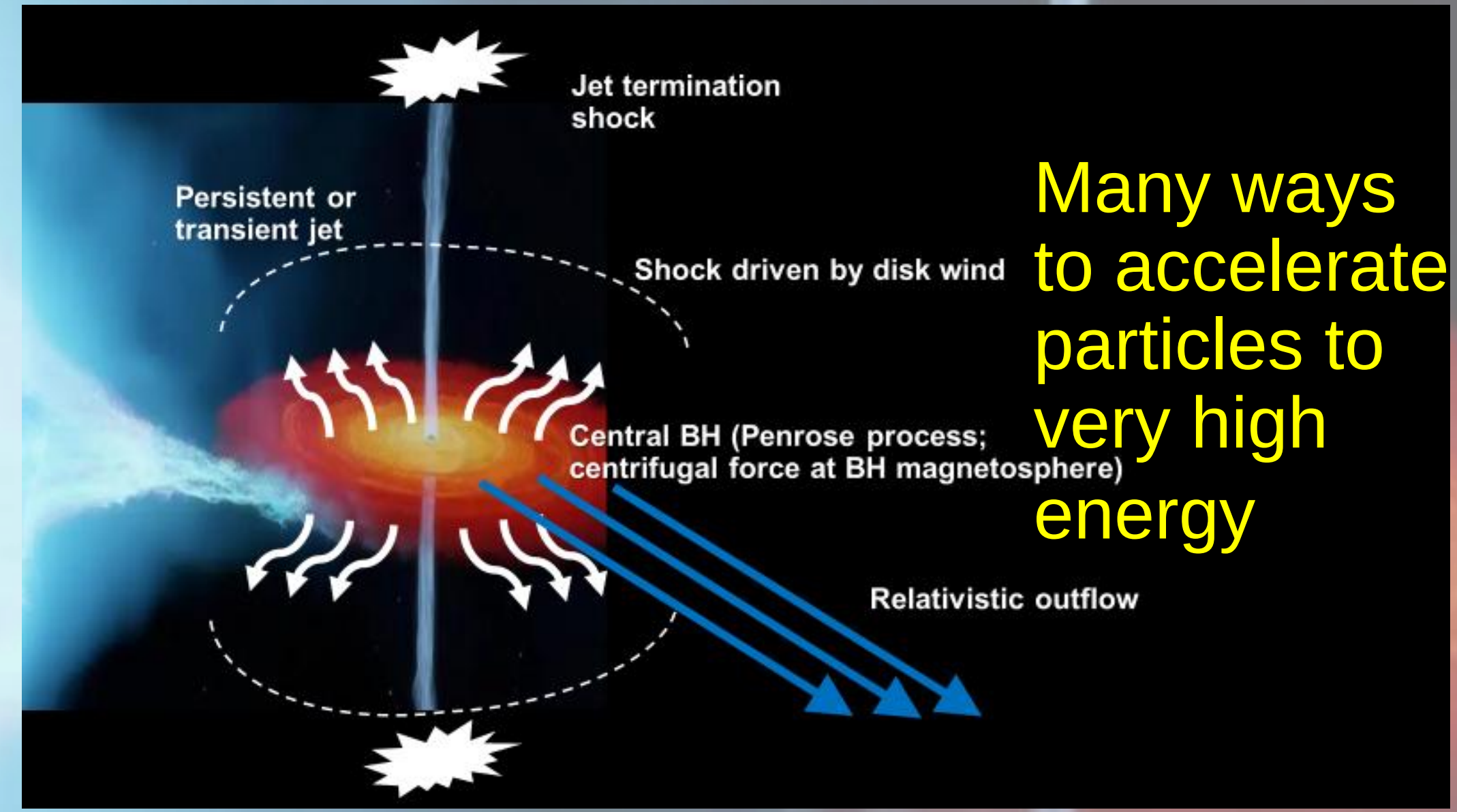


Black Hole as a super-PeVatron?

Very difficult to detect: not only due to the distant: ~20,000 light-year !
But also out of main field of view of LHAASO: a source in southern hemisphere
Powerful accelerator generating particle at E >10 PeV !!







Many ways to accelerate particles to very high energy

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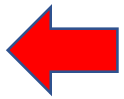
- Cosmic Ray Source Papulation in “Knee” Energy Range 
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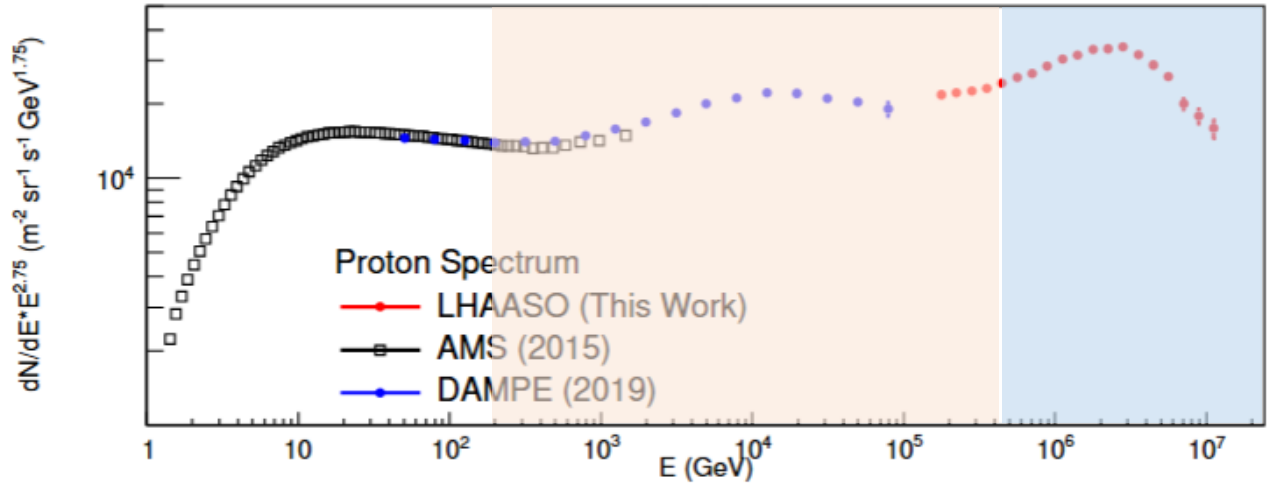
What LHAASO Observations Tell Us…

They are HE Cosmic Ray Sources

- **Many evidences collected for the SNRs accelerate CRs to very high energy, W 51, W 44, IC 433, Cas A**
- **IC 433 amazingly shows the π^0-decay spectrum extending to tens of TeV without indication of cut-off feature**
- **Almost all of them cut at energies around 10 TeV or even lower**
- **Before the SNR contribution completely dying away, the on-set of a new component is observed with the hardening of the spectrum**
- **Stronger enhancement of the flux than that observed in 10 TeV range**



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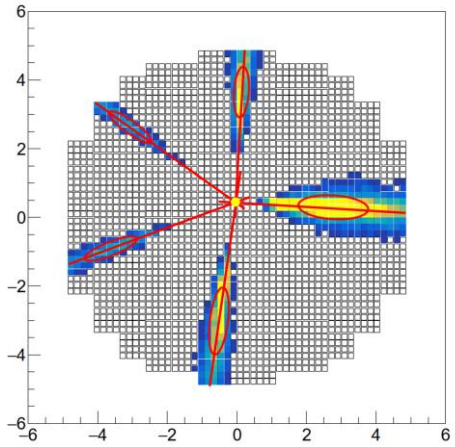
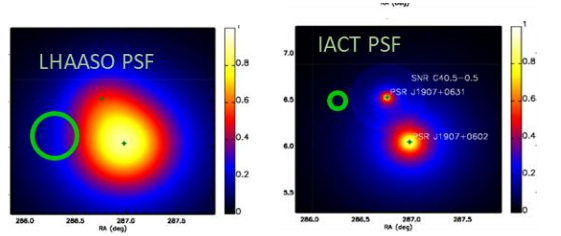
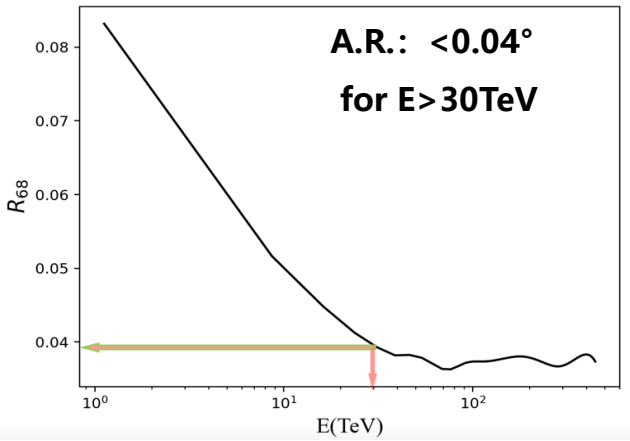
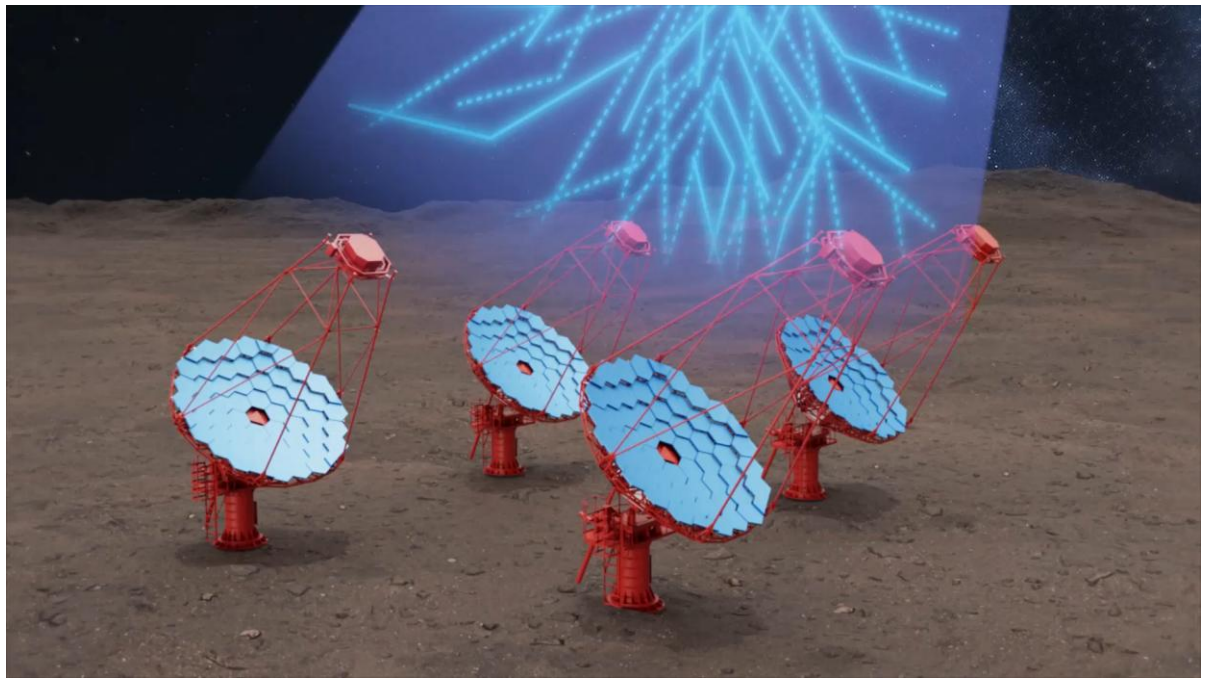
LACT as the upgrading of LHAASO

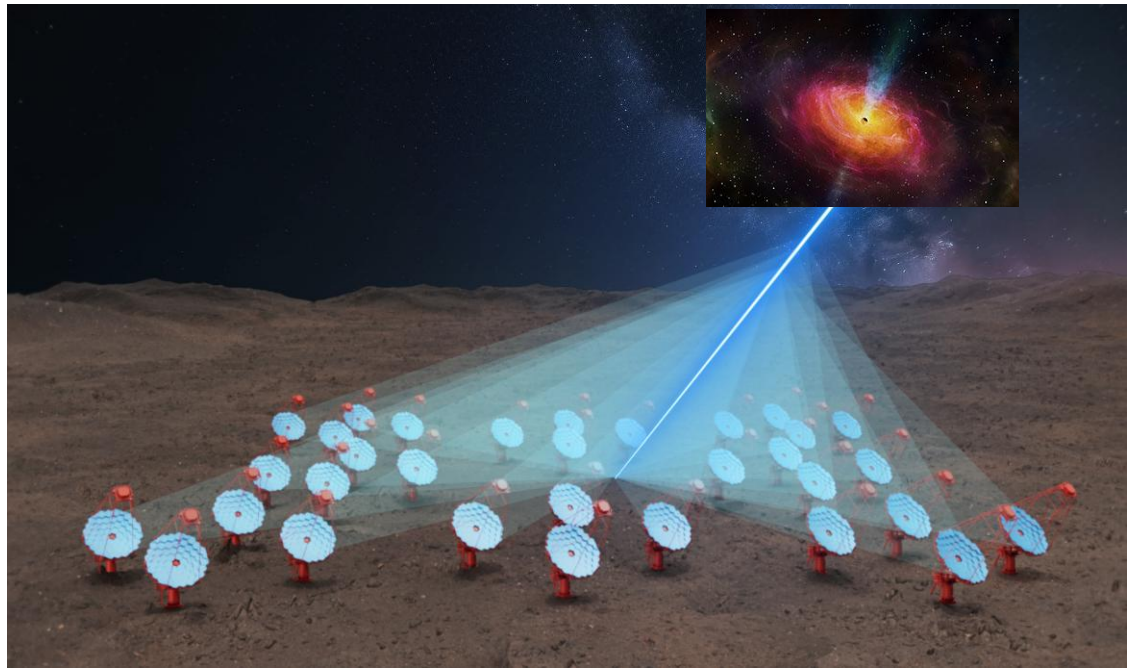
- **Stereo measurement of Cherenkov image**
  - **At least 4 telescopes simultaneously**
- **Reconstruction**
  - Angular resolution **0.04° for E**>30 TeV



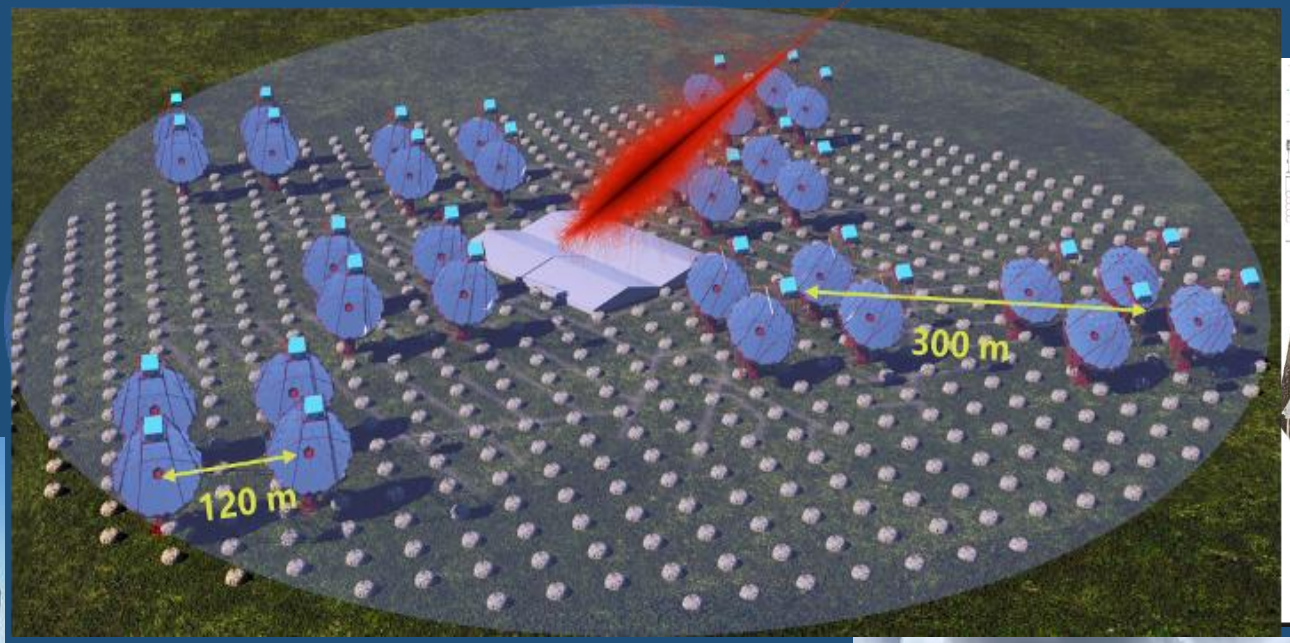








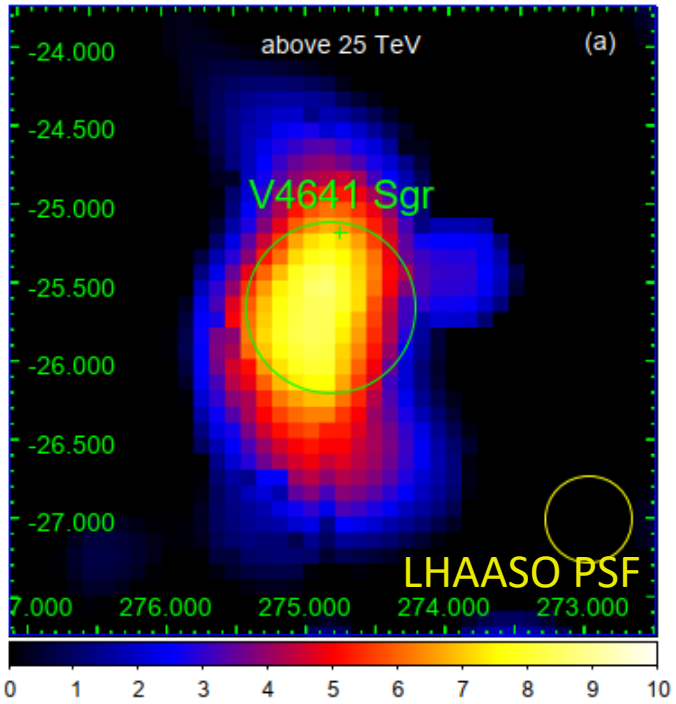
LACT : an IACT array in LHAASO

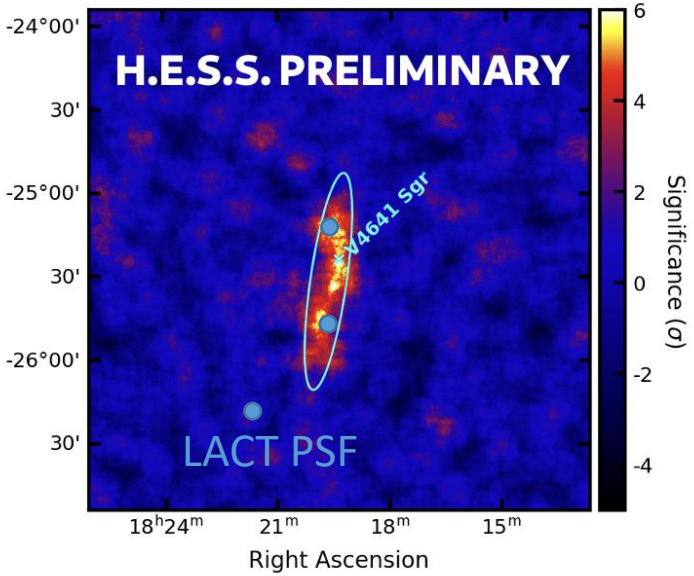


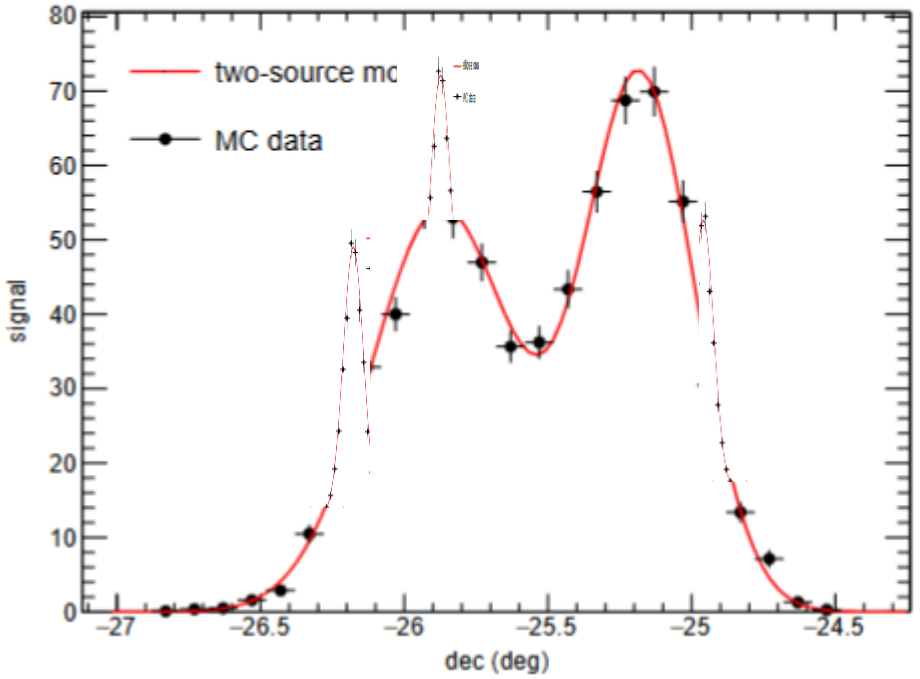
- Funded
- 8X4 array at LHAASO site
- 6-m telescopes
- two proto type telescopes
- First light soon in this year!

Jet Termination vs central accelerator

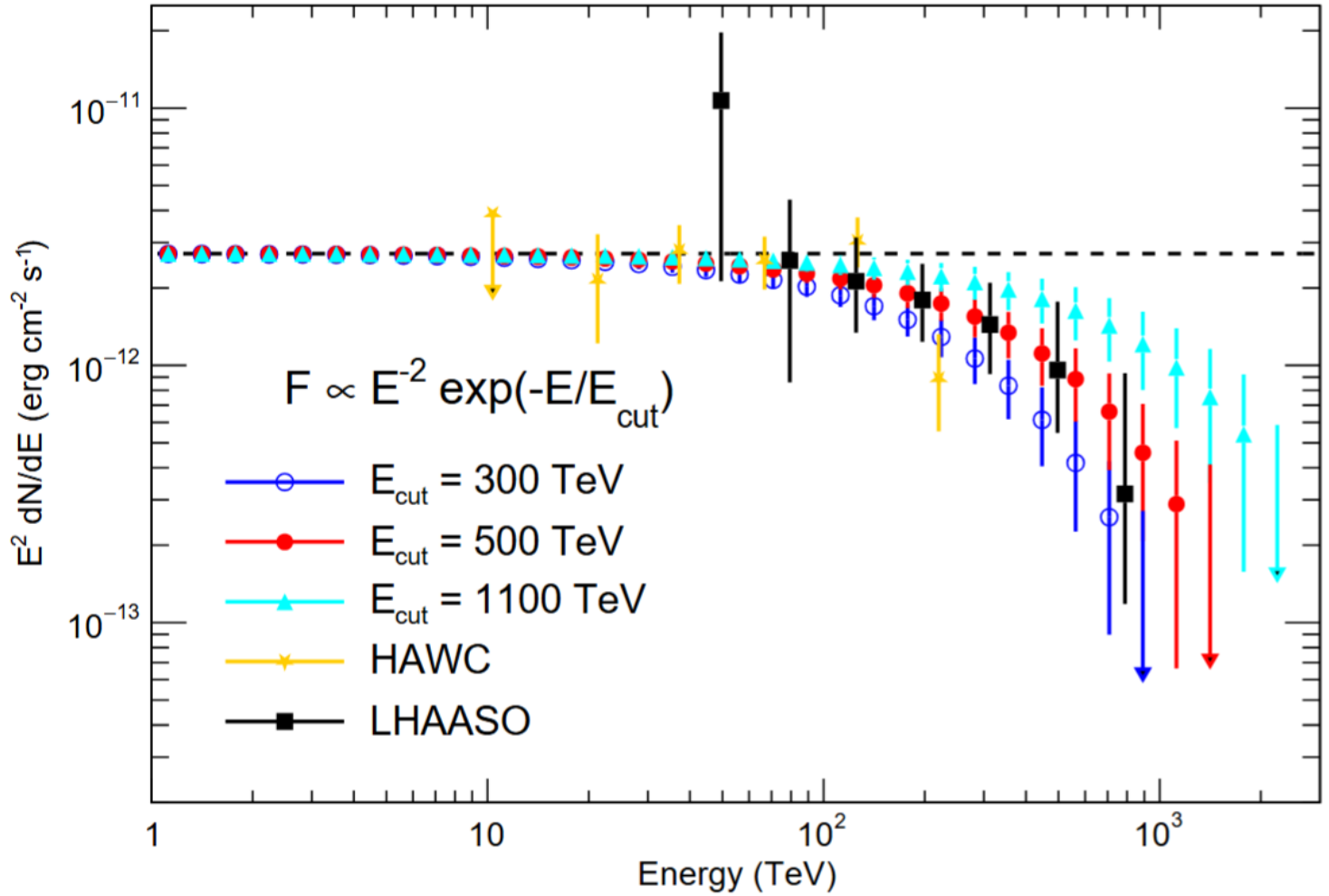
- LHAASO vs. LACT (either two point sources or complex morphology)



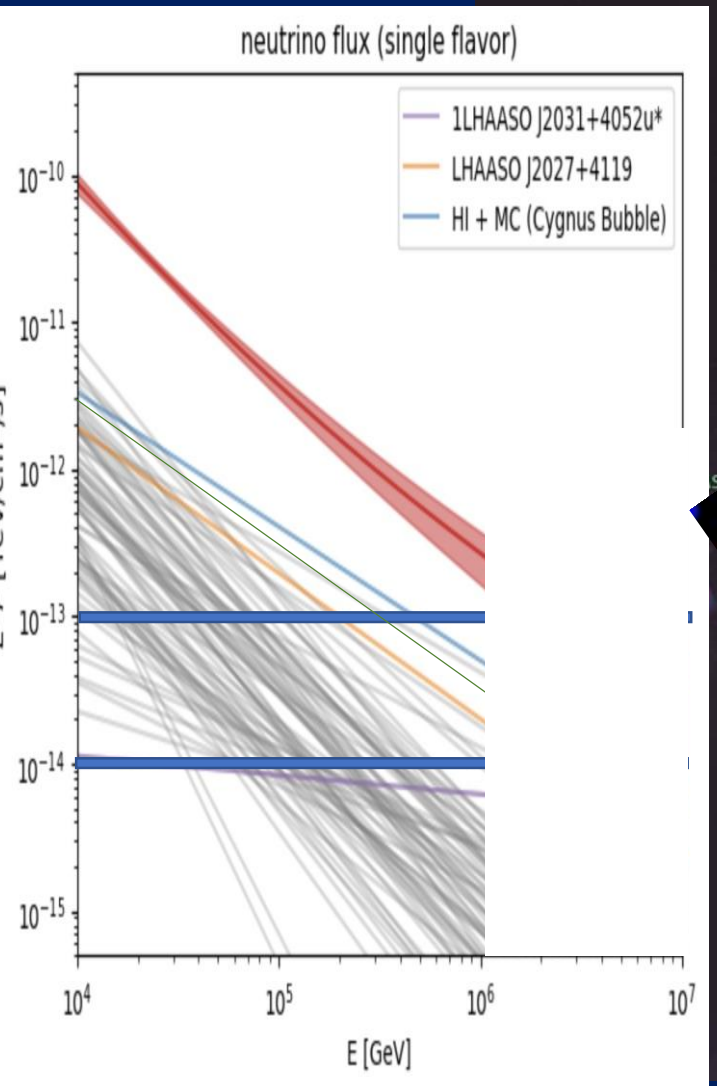




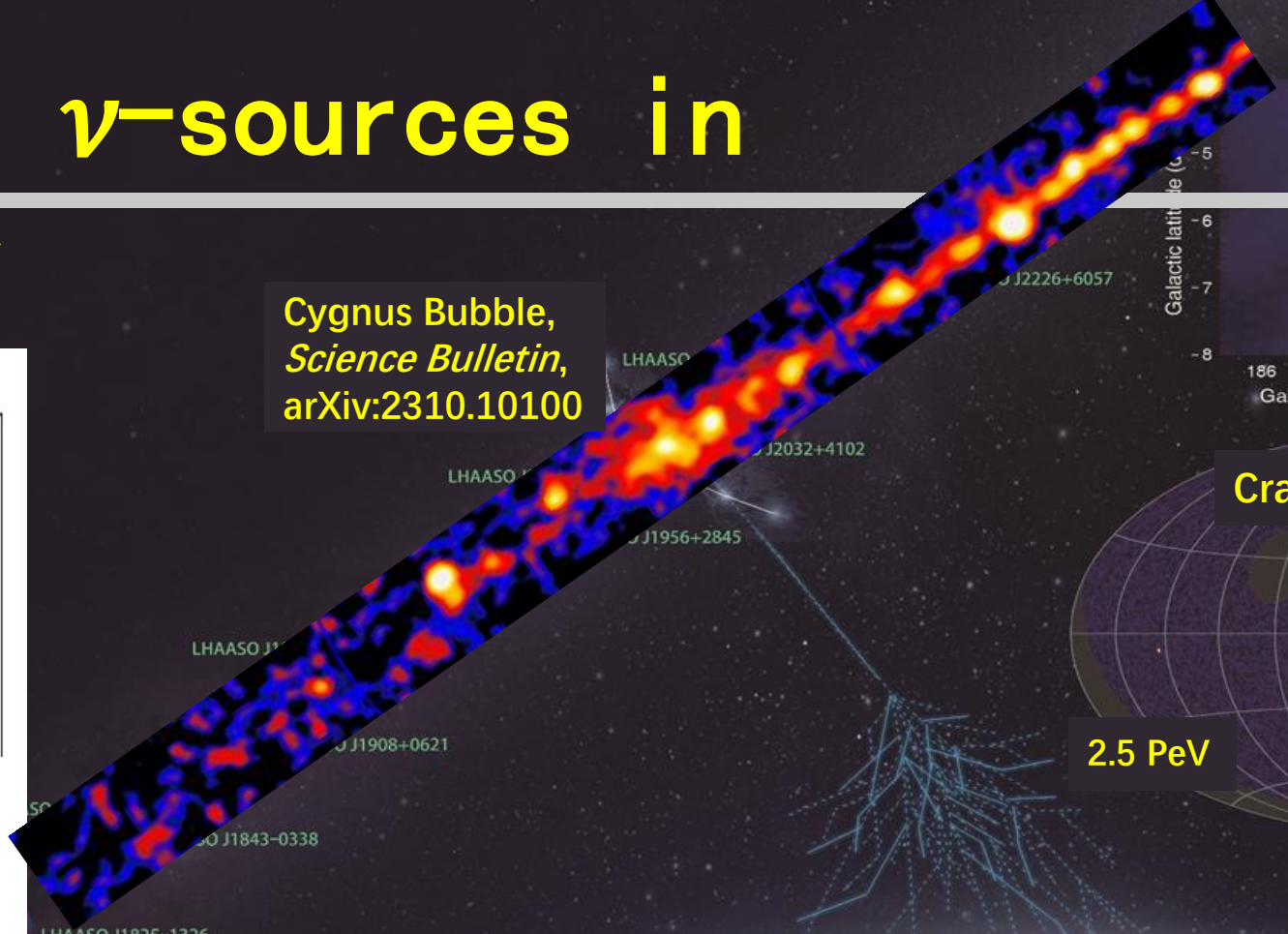
Expected flux measured in one year with the 4 Telescopes of LACT for different assumed cut-off energy E_{cut}

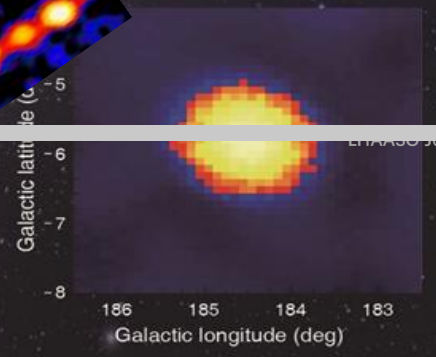


Guaranteed ν-sources in our galaxy

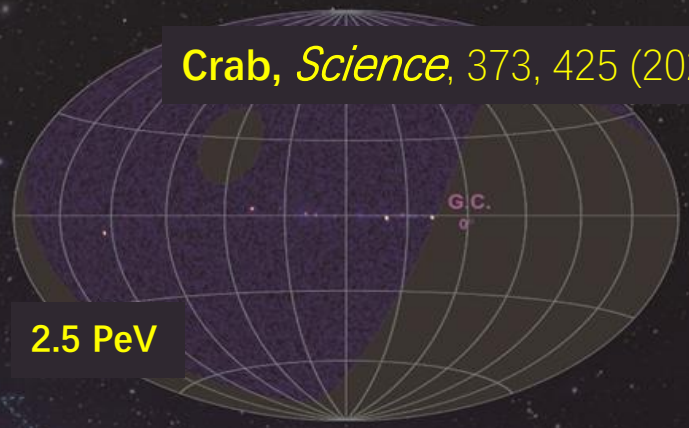


Cygnus Bubble, *Science Bulletin*, arXiv:2310.10100





Crab, *Science*, 373, 425 (2021)

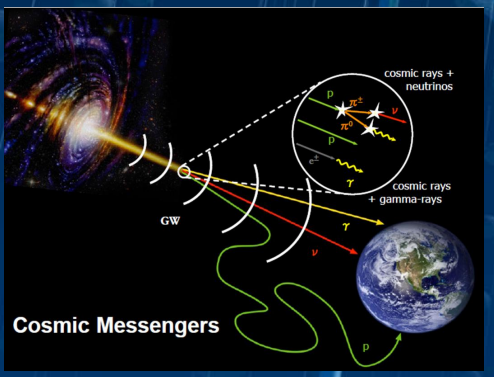


2.5 PeV

PeVatrons, *Nature 594:33-36 (2021)*

High-energy Underwater Neutrino Telescope

H U N T



36 m

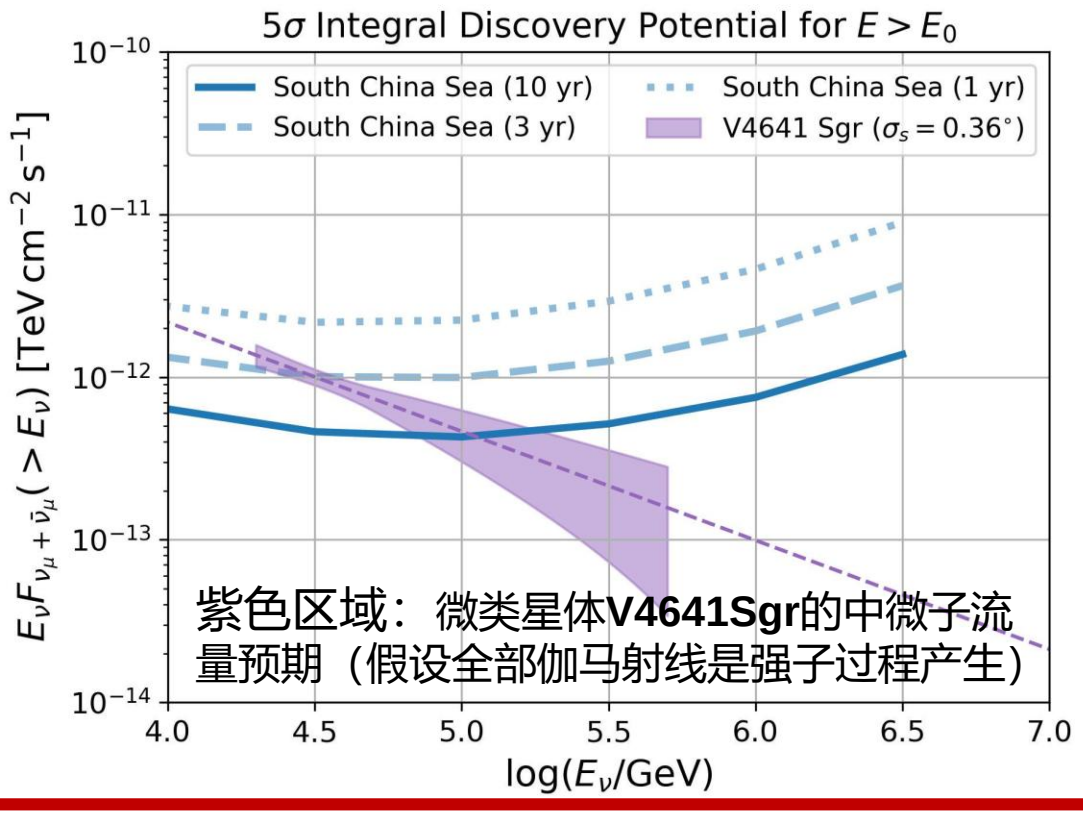
130 m

- Resulution ~0.1°(tracks), <3°(cascades)
- Energy resolution: ΔlogE~0.3(tracks)
  ΔE~10-30% (cascades).
- Discovering Neu sources (>100 TeV) at the level of 5σ within several years

- Volume： 6×6 = 36 km^2, **~30** km^3
- Separations of strings： Dstring ~ 130 m
- Separation of optical modules： DOM ~36 m
- Length of each string： ~860 m
- ~2,300 strings, 24 OMs in each string， 55000 OMs in total

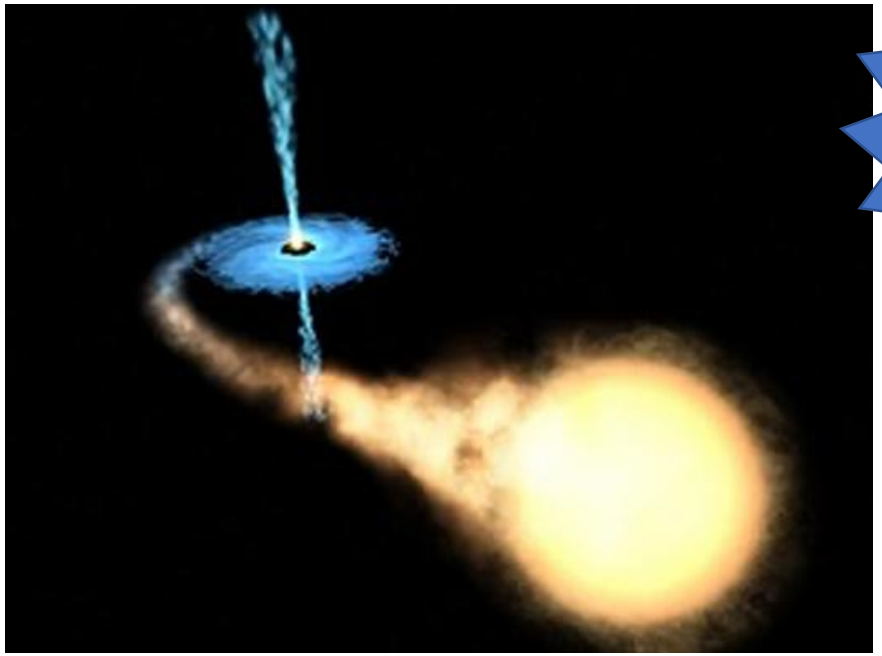
性能预期（确定第一个黑洞宇宙线加速器！最强源）

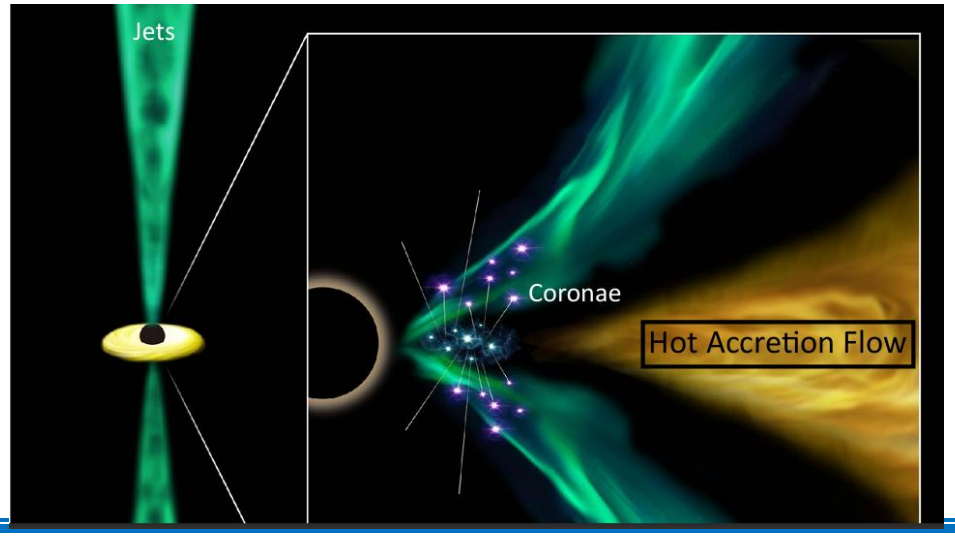
- 2年对10 TeV以上的缪中微子实现5σ观测；
- 10年对100 TeV以上缪中微子实现5σ观测。



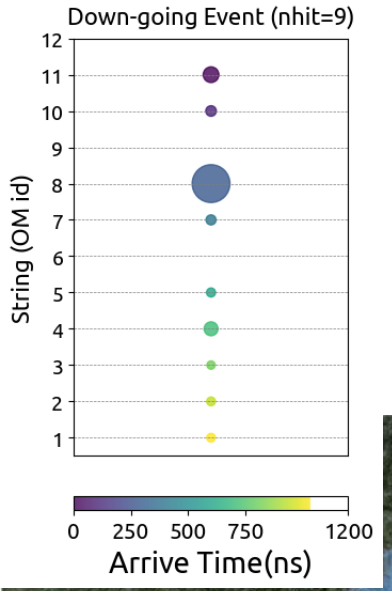
紫色区域：微类星体**V4641Sgr**的中微子流量预期（假设全部伽马射线是强子过程产生）

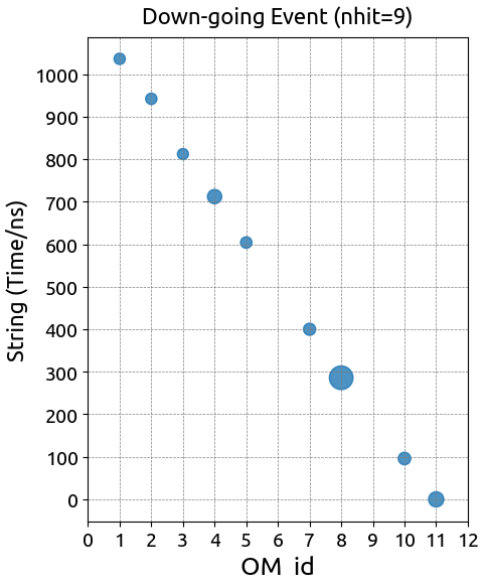
发现

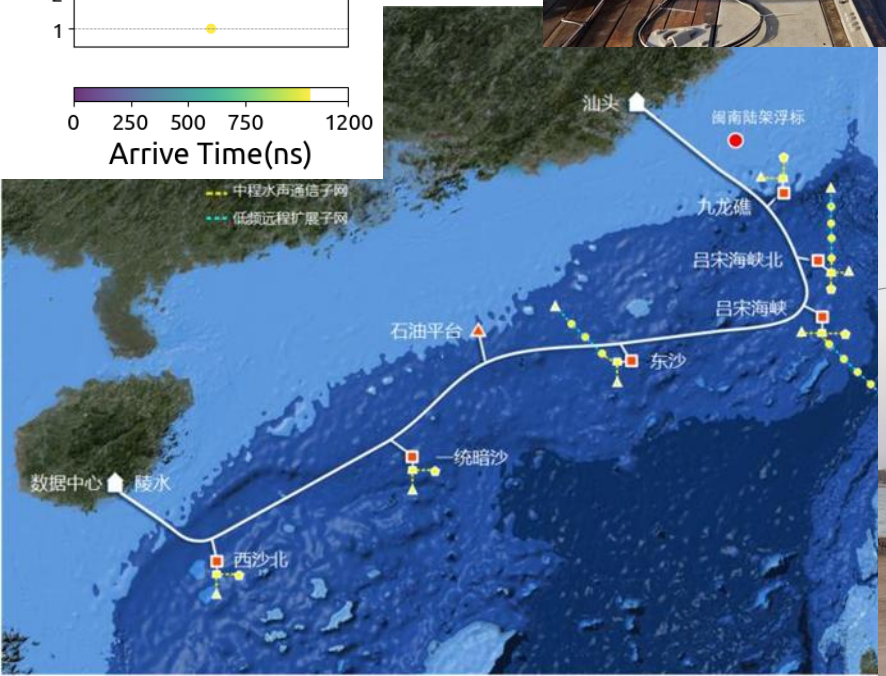


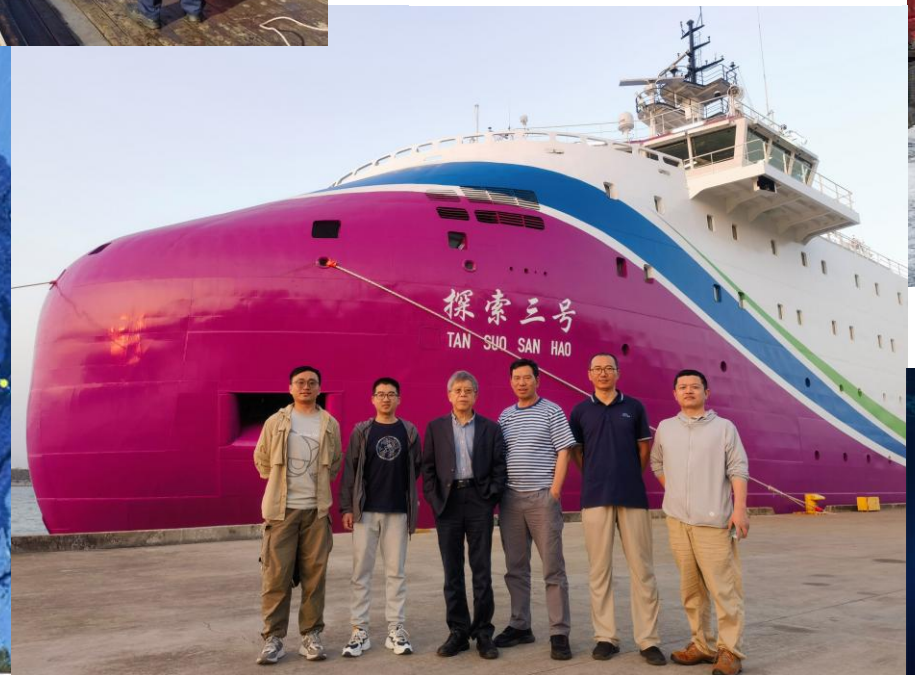


Prototype tests at GVD at L. Baikal and in South China sea









Summary

- LHAASO has been making discovery of PeVatrons in the Milky Way
- Among the discoveries, the 1st Black-Hole PeVatron catalog unveiled the new potential CR accelerator population
- Cosmic Ray Super-PeVatron is found among the BH+jet systems
- SS433 is found a nearly perfect example of its kind, and they may supply sufficient CRs in the ‘knee’ region
- Proton/Helium spectra evidence the compact objects may be the major supplier of CR at/above the knee
- In future, the improved spatial resolution will bring the investigations for the mechanism much deep
- Detection of Neutrinos from the PeVatrons will put the last piece of puzzle in