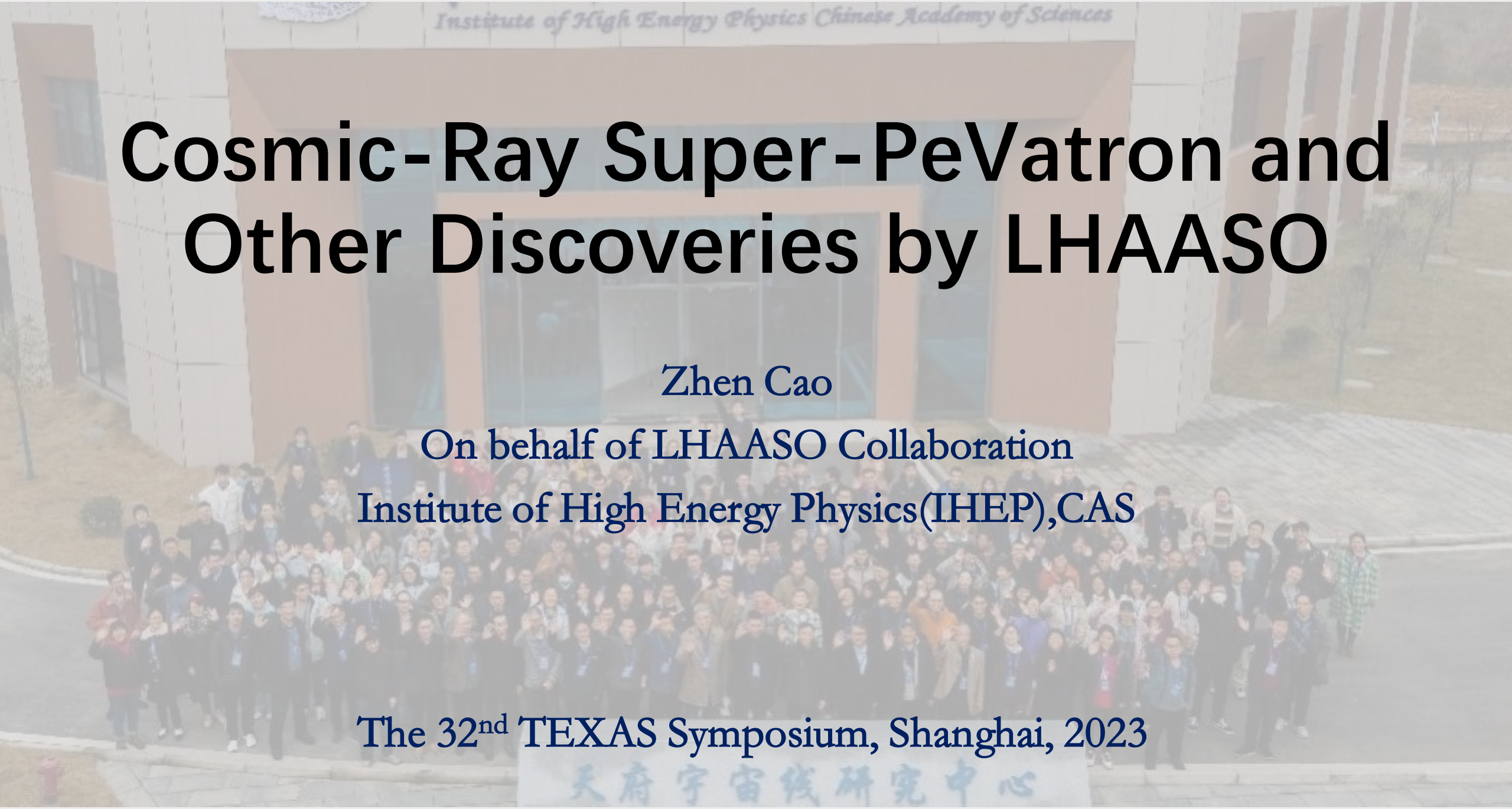


Cosmic-Ray Super-PeVatron and Other Discoveries by LHAASO

Zhen Cao

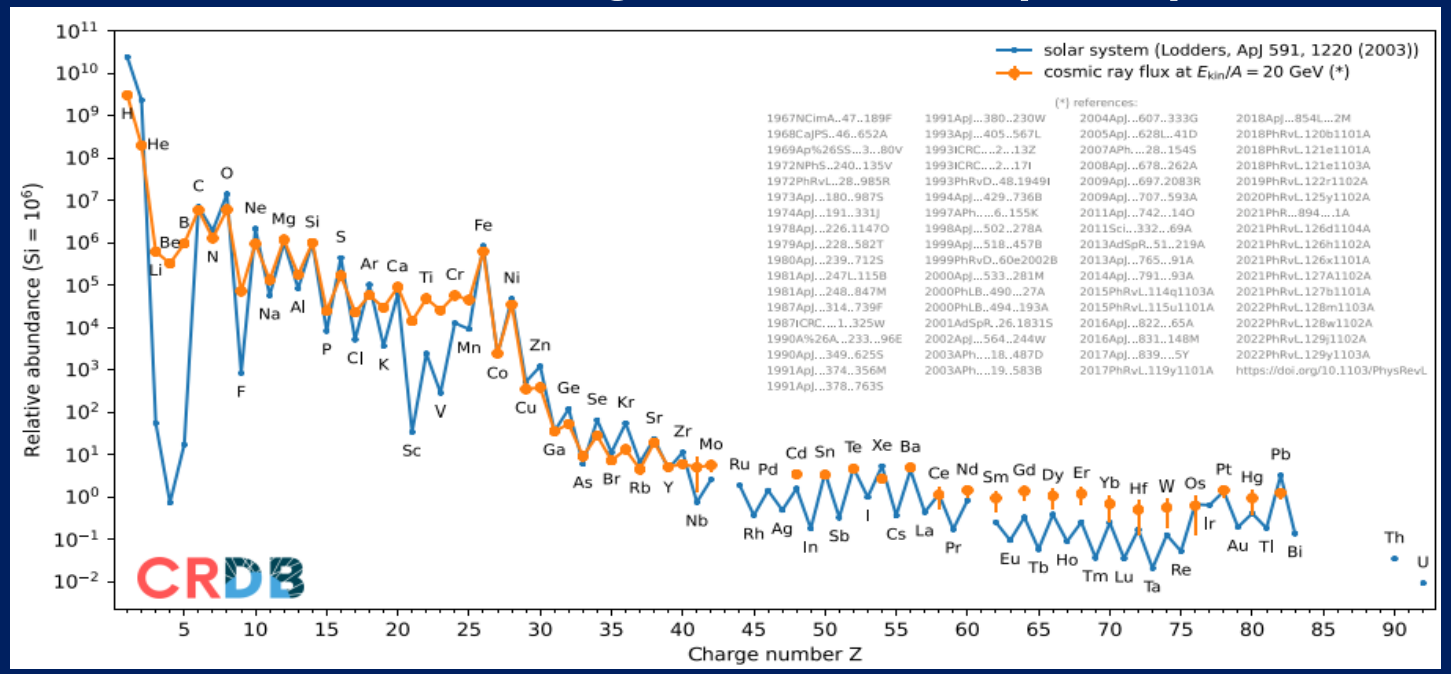
On behalf of LHAASO Collaboration

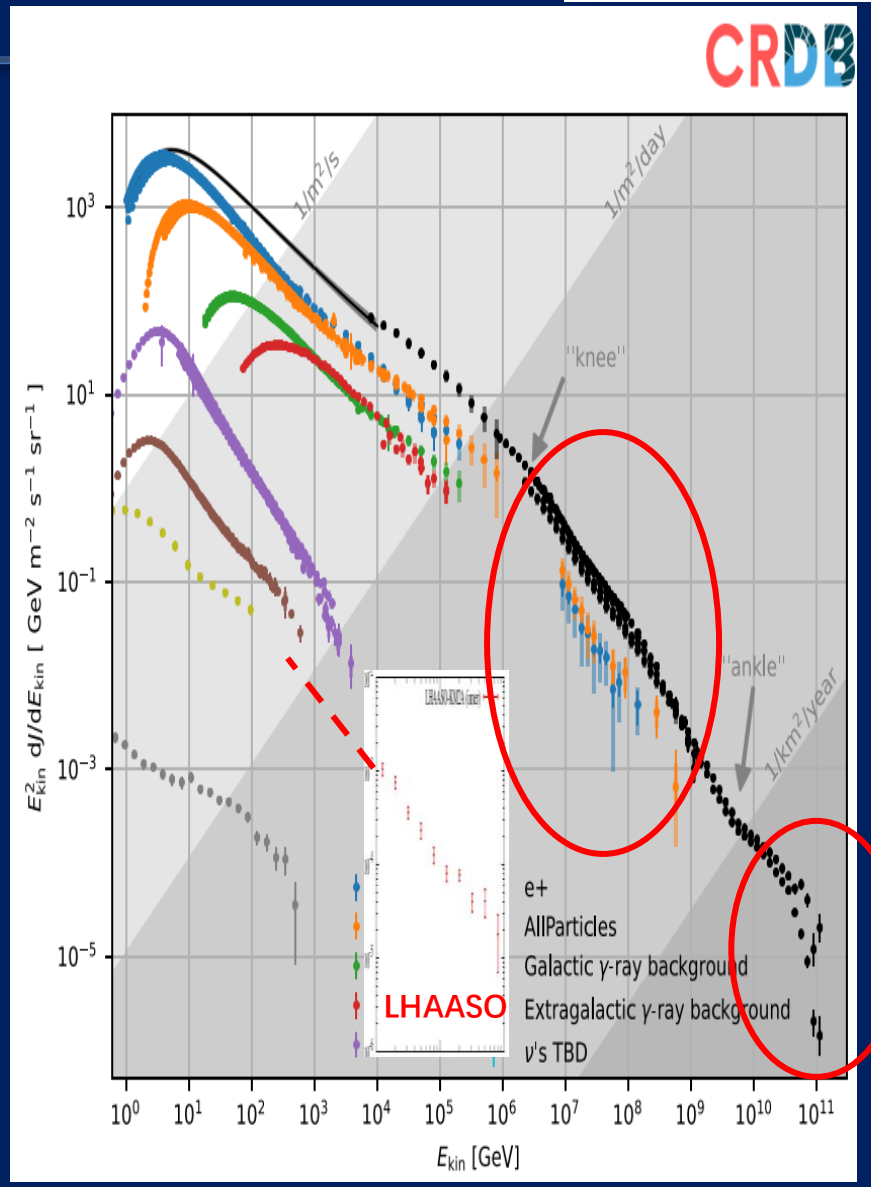
Institute of High Energy Physics(IHEP),CAS

The 32nd TEXAS Symposium, Shanghai, 2023

Cosmic Ray Origin

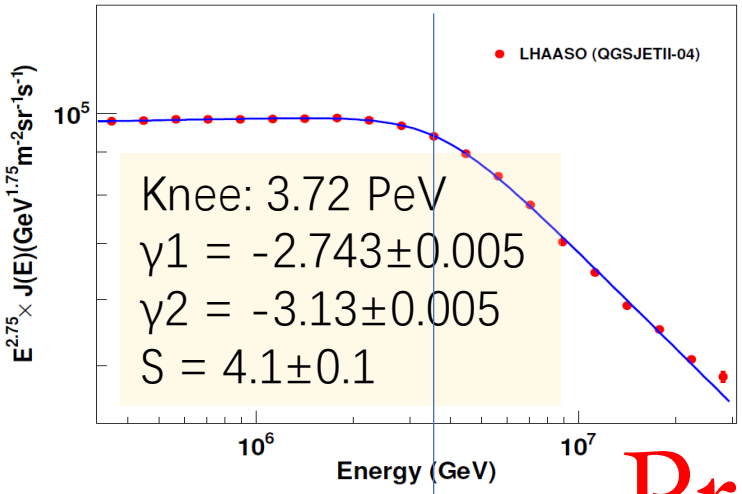
- After 110 years, we have learnt a lot about CRs near the Sun
- Particularly in the era of high precision measurements
- However, their origin is still an open question

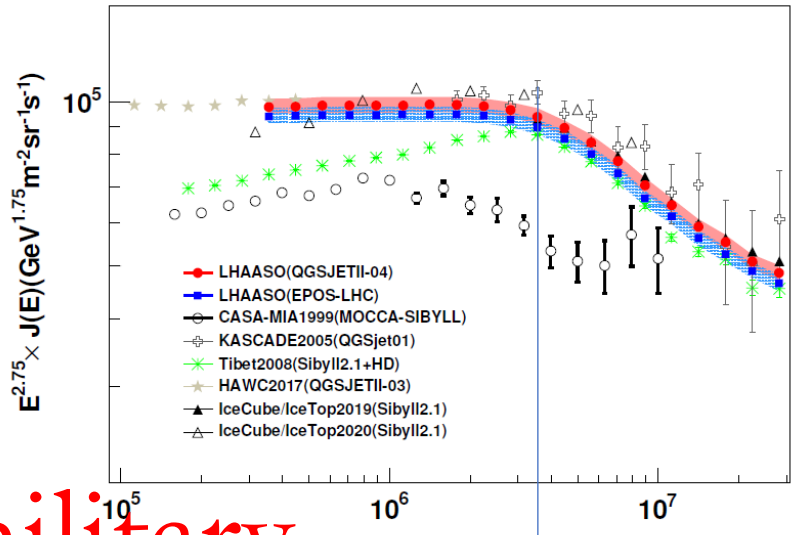




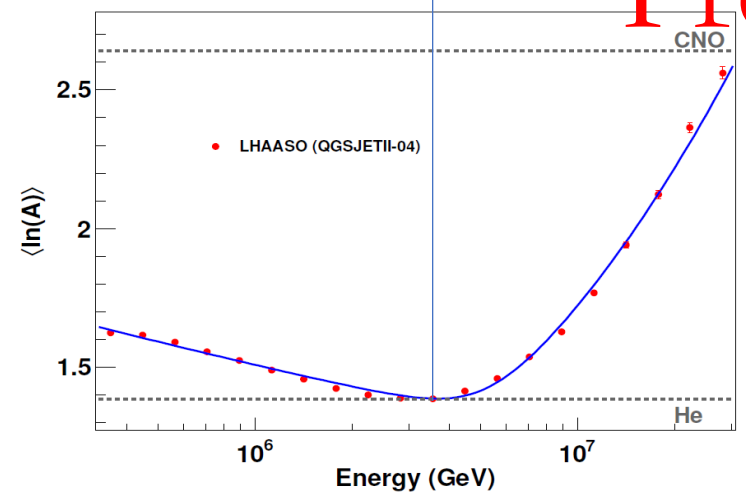
All-particle energy spectrum & composition by LHAASO

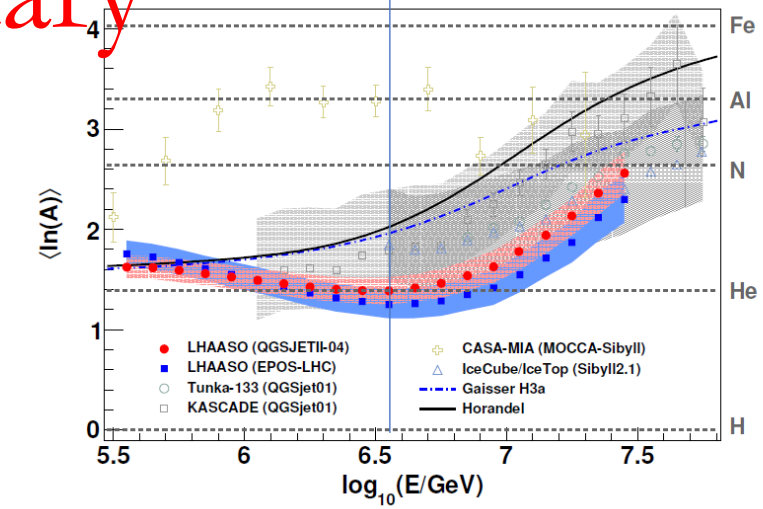
(from 0.3 to 30 PeV)





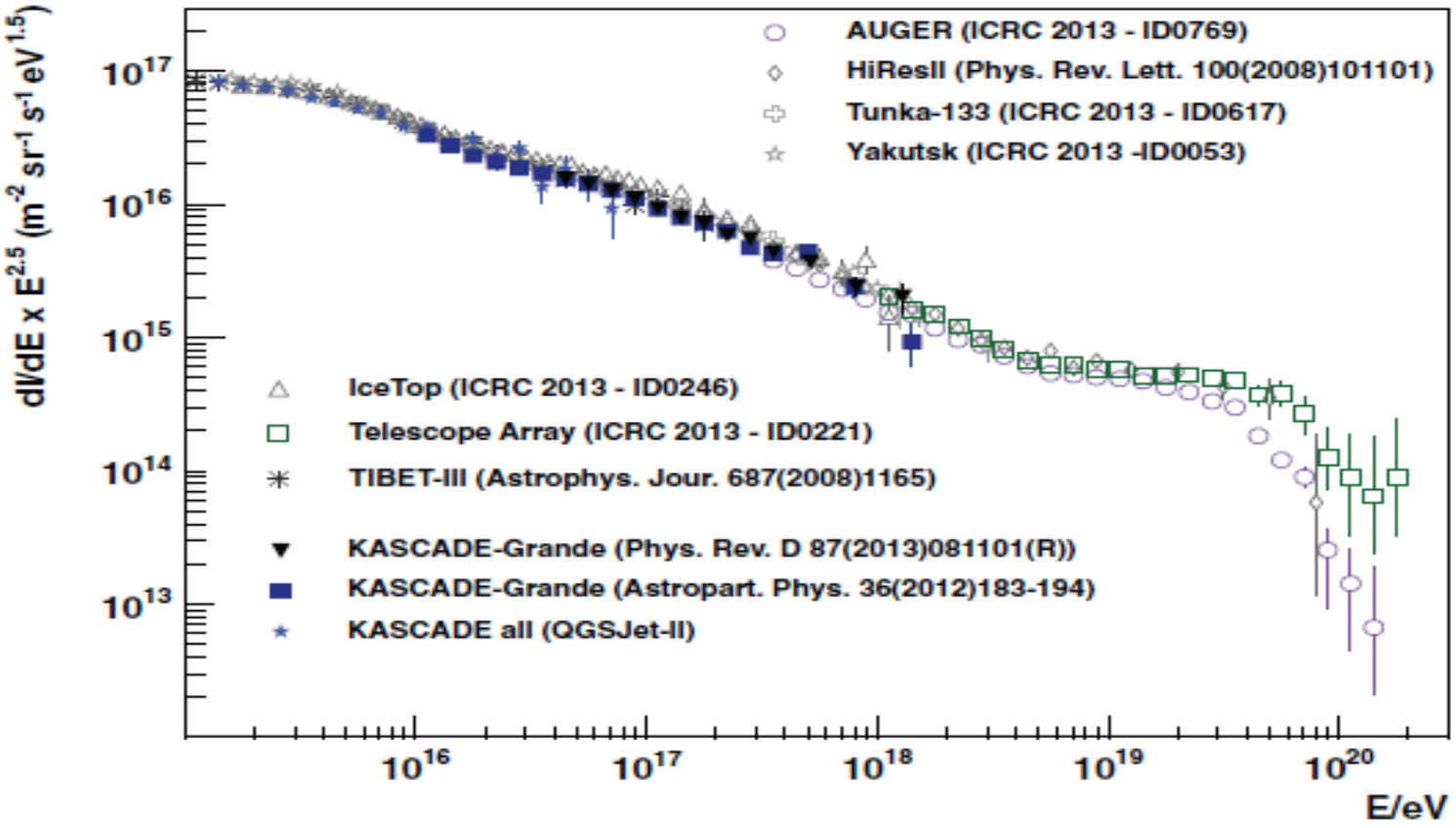
Premilitary





- Systematic uncertainties are sufficiently small
- This unveils a clear correlation between the flux and the composition at the knee

There is still no clue about the origins of CRs between the “knee” and the “ankle”



Galactic sources mainly SNRs

???

Extragalactic sources

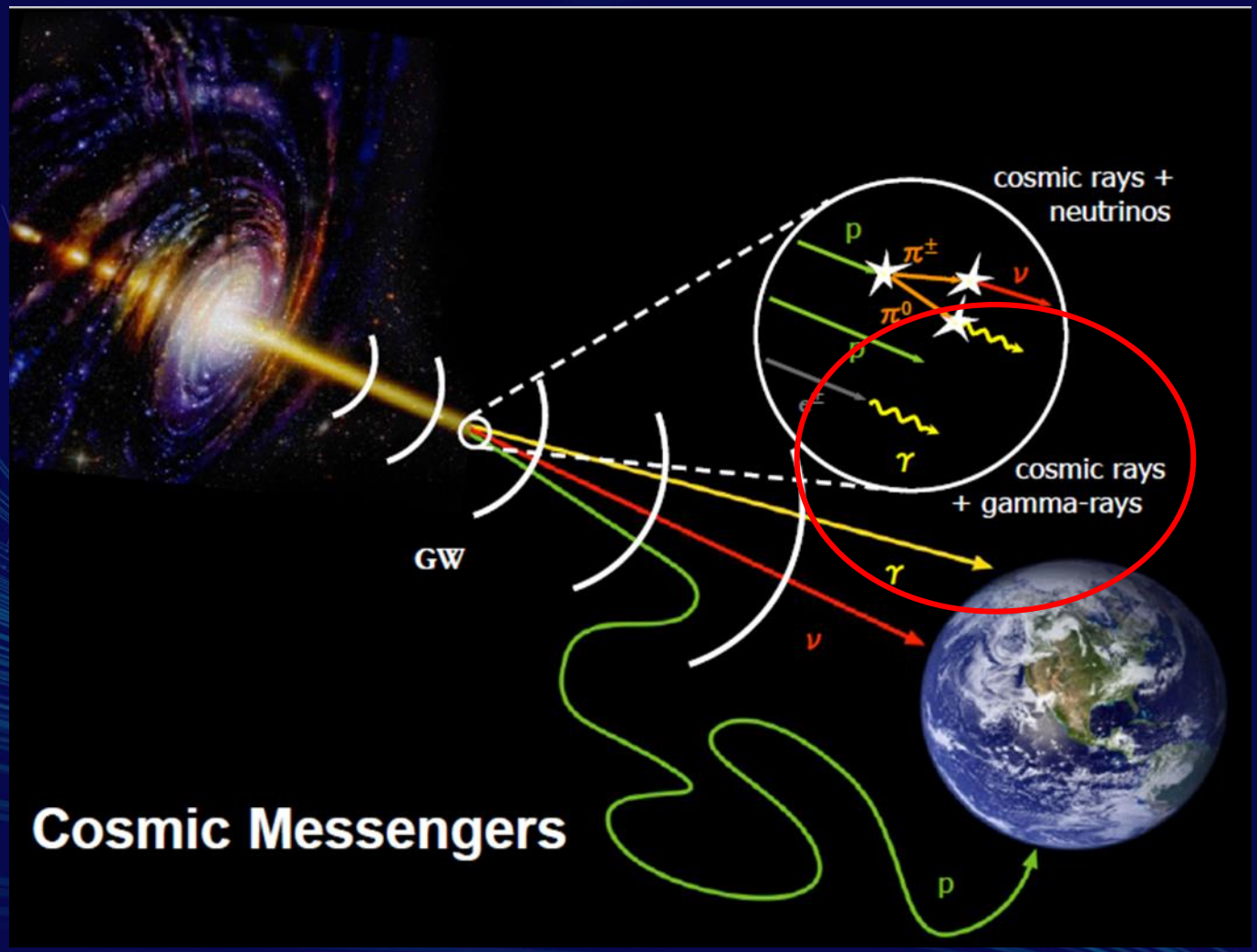
Physics Procedia 61 (2015) 425-434.arXiv:1910.03721v1

Multi-messenger Astronomy Era

Among all messengers,

γ-rays are the most promising

in CR origin searches



The ultimate goal is to identify origins of CRs

Scientific Goals

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

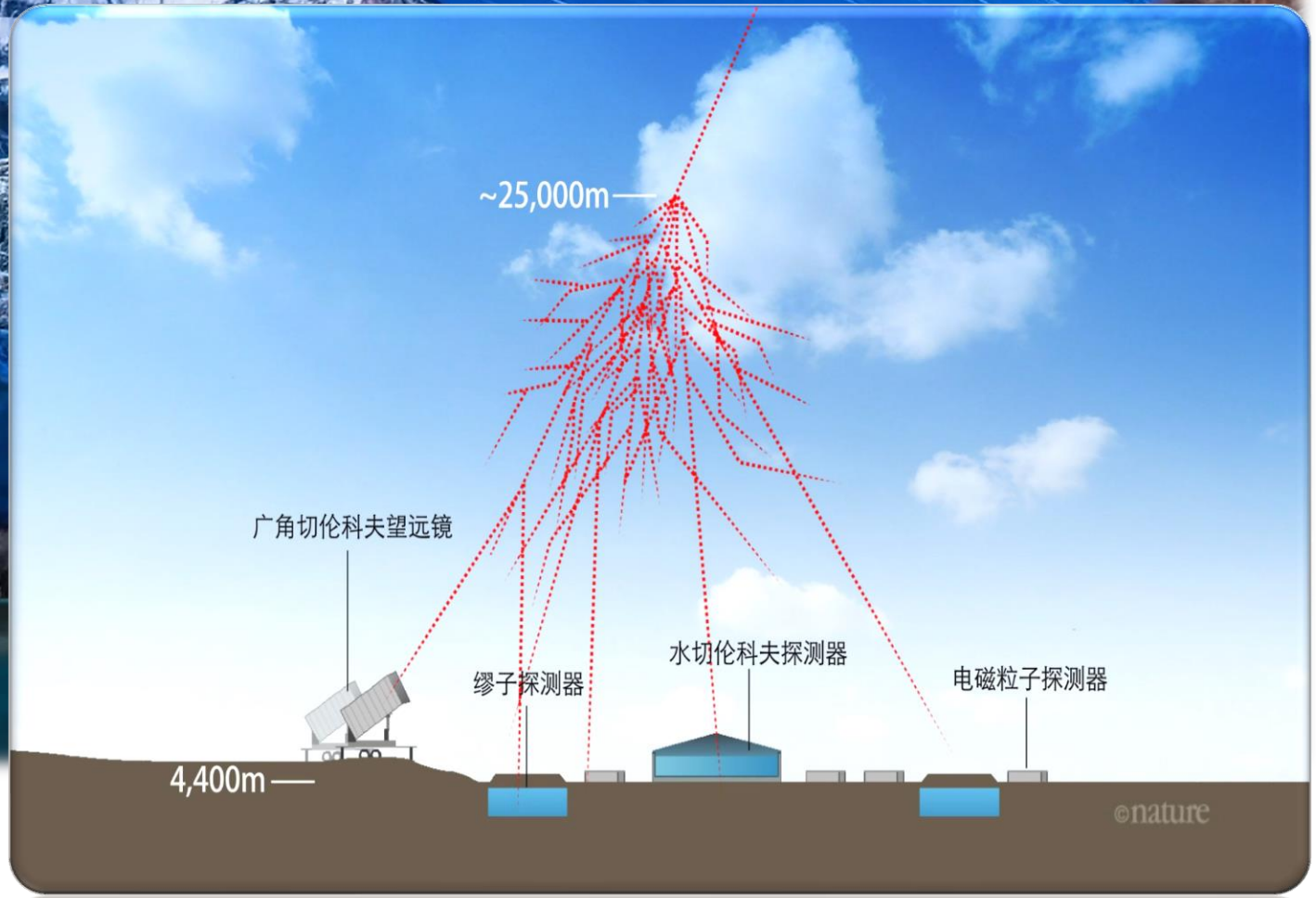
Compositions : individual species H, He and Fe

Anisotropy: (1 TeV to 10 PeV)

New Physics Front: DM, LIV, etc.

Large High Altitude Air Shower Observatory

LHAASO

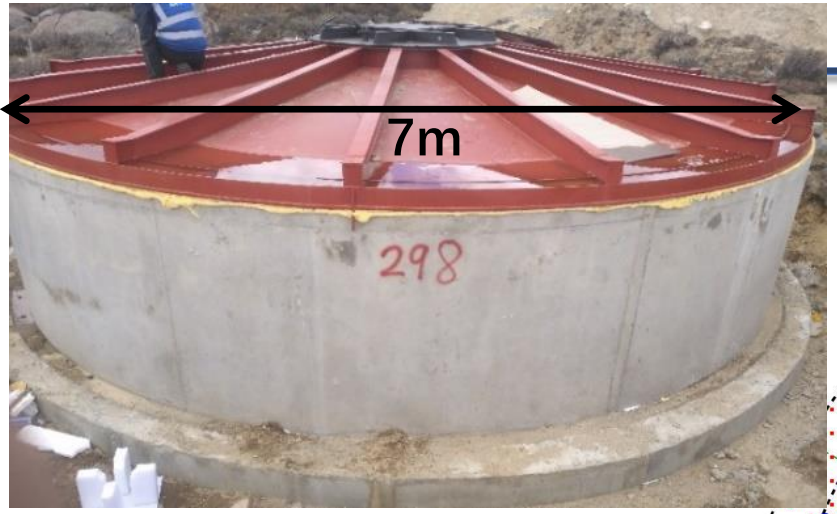


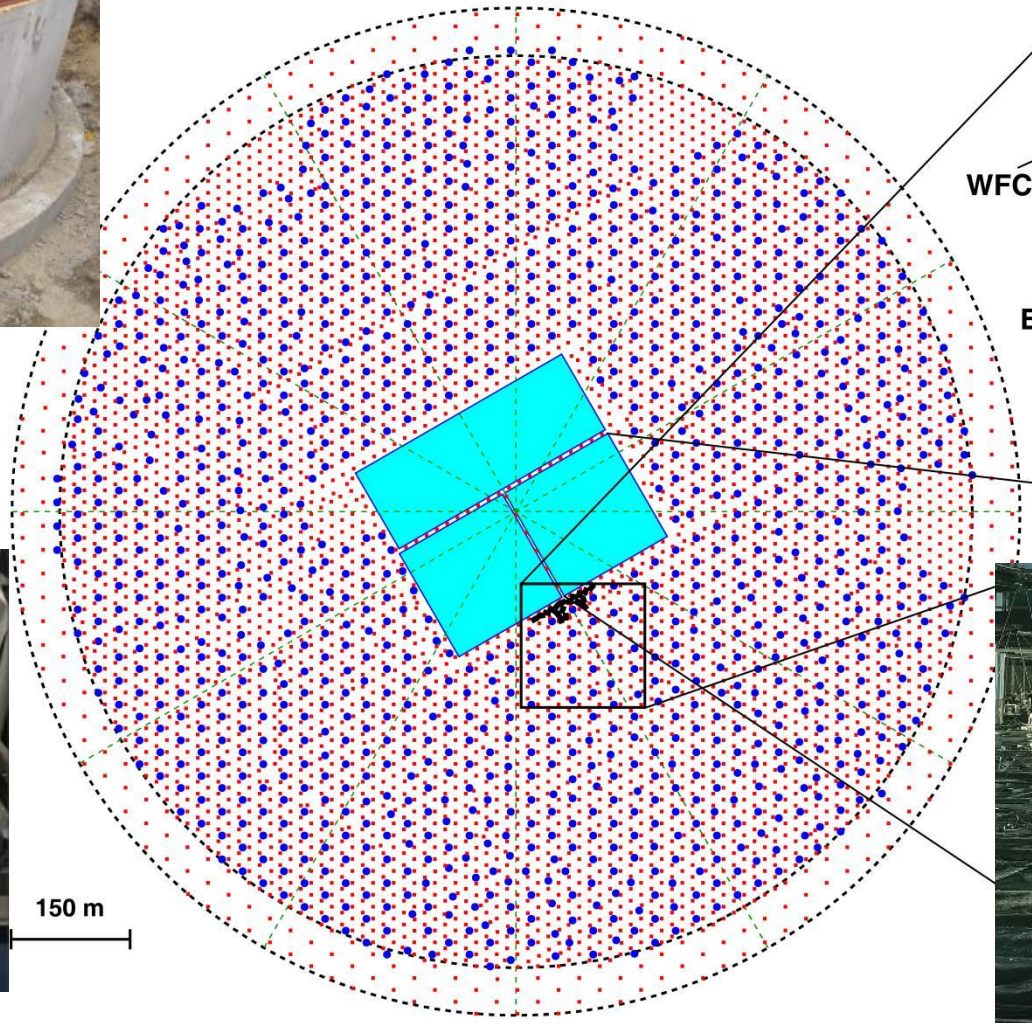
The Site

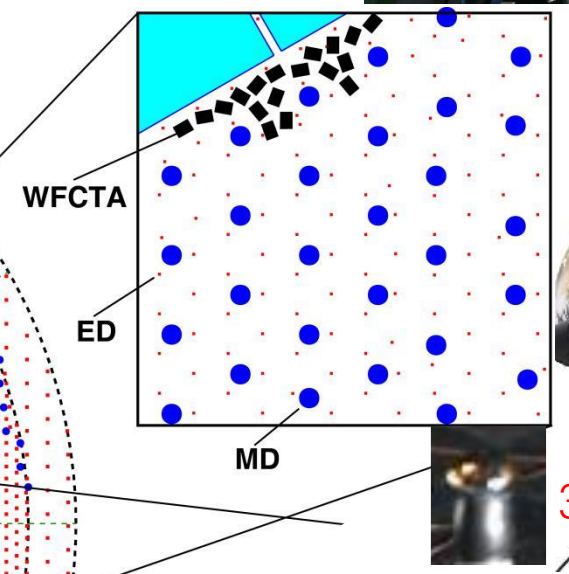
- **Location：29º21’ 27.6” N , 100º08’19.6” E**
- **Altitude: 4410 m**
- **2021-07 completed built and in operation**

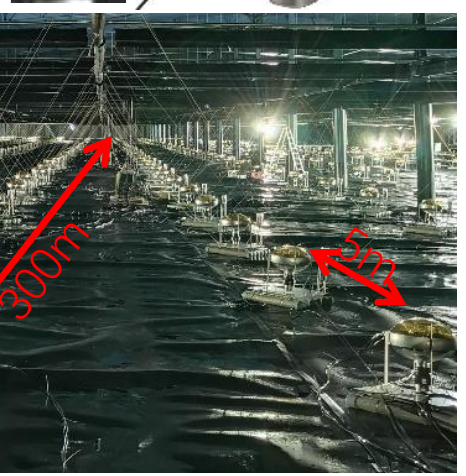
LHAASO, *Nature* Astronomy *5:849 (2021)*

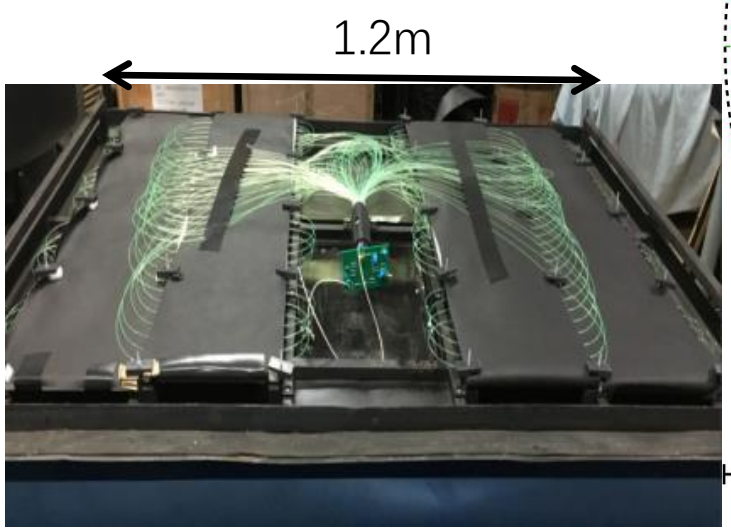
LHAASO Layout





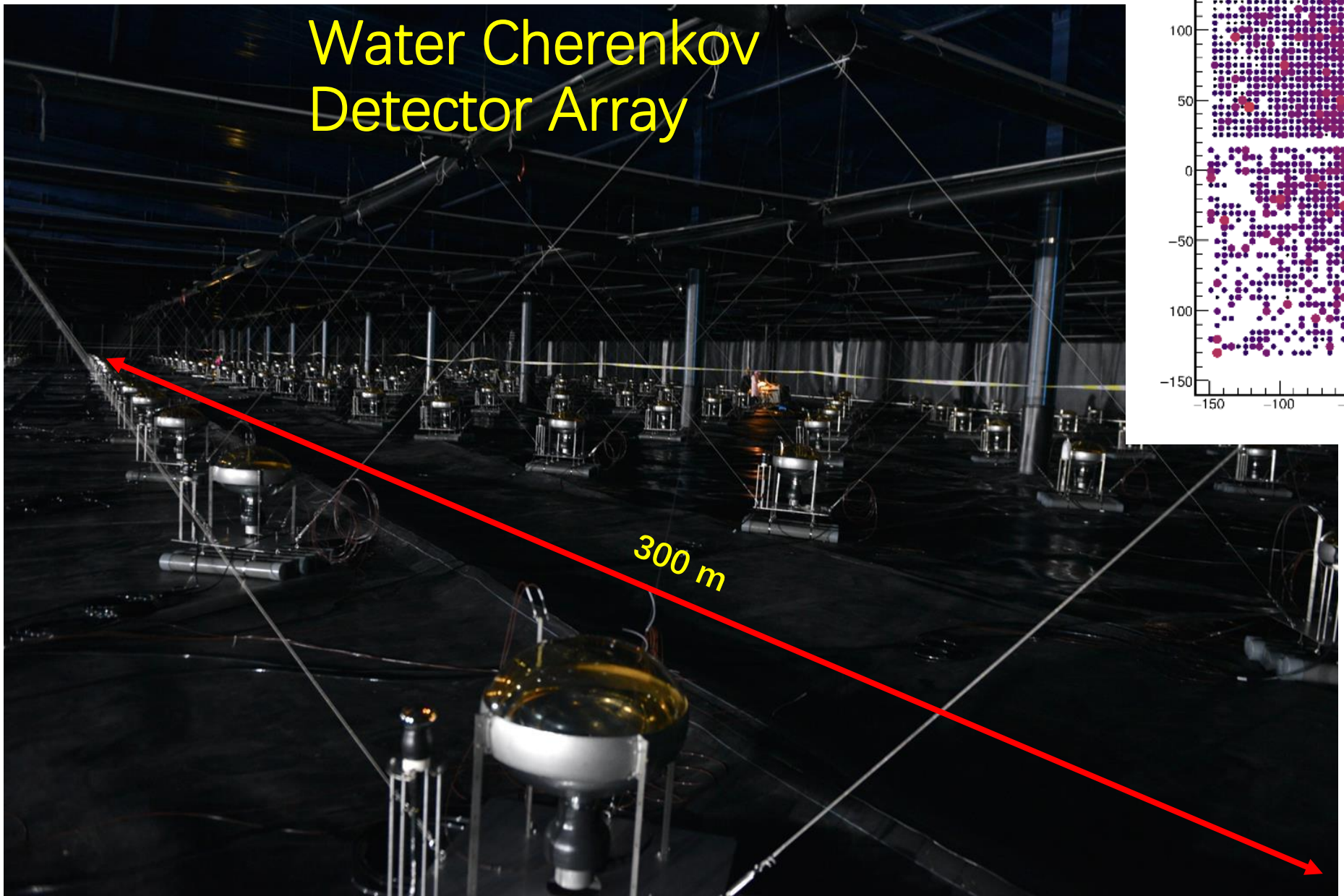


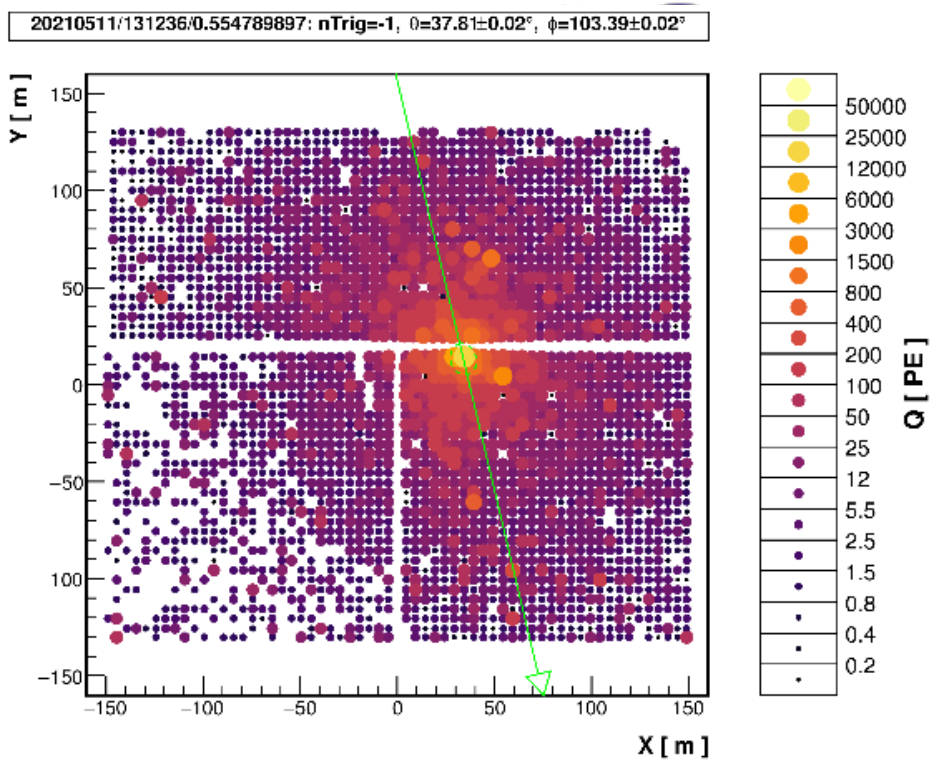




LHAASO-WCDA

Water Cherenkov Detector Array

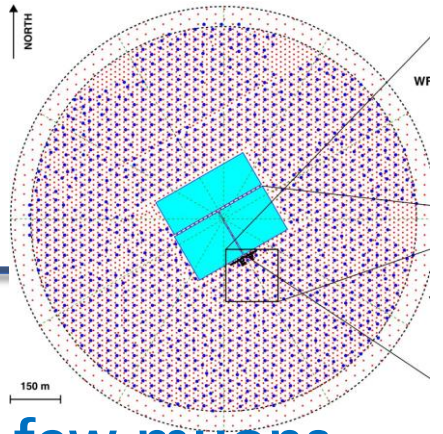




- Area:
  78,000 m^2
- Detector units:
  3120
- Energy Range:
  0.1-10 TeV

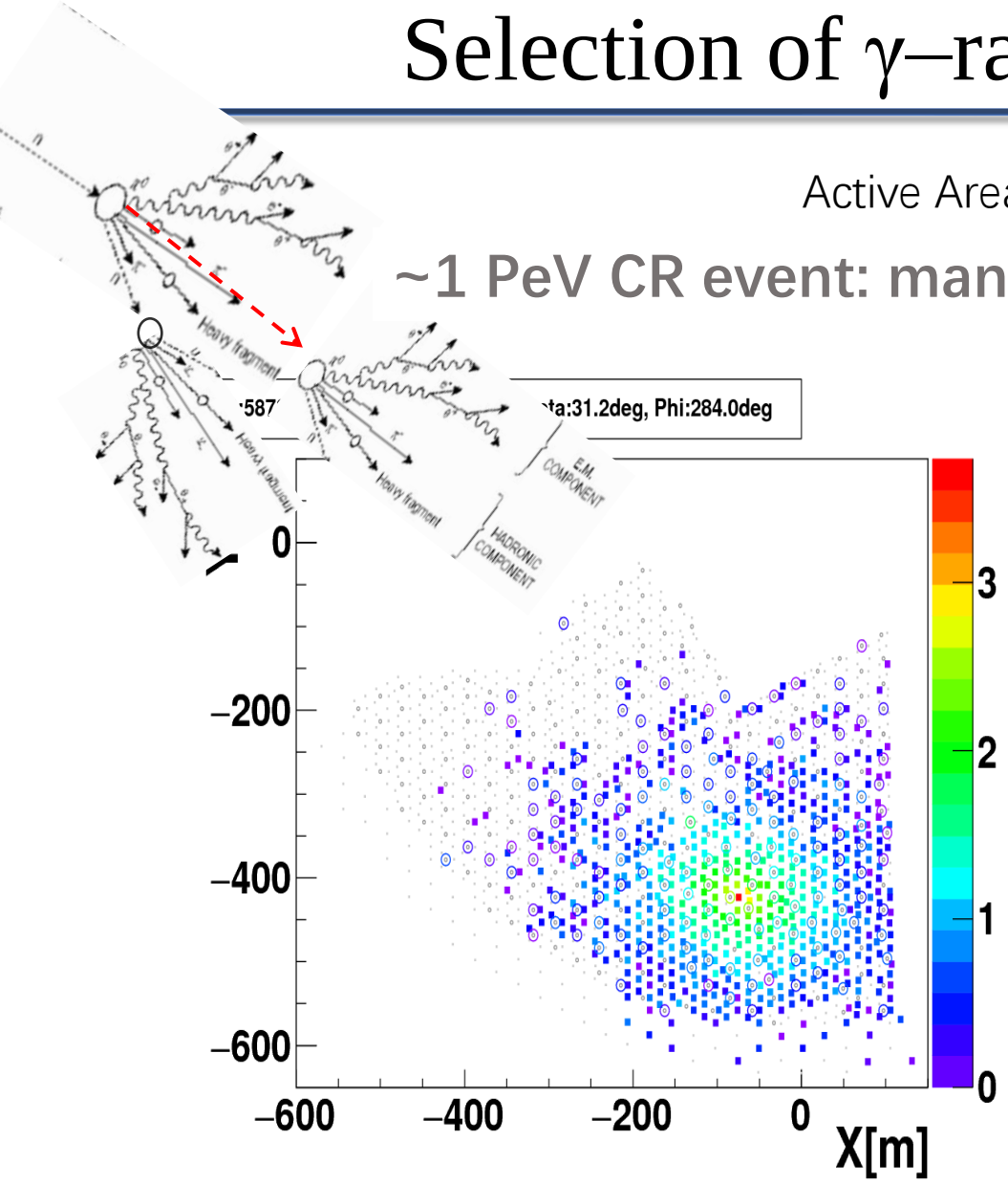
LHAASO-KM2A

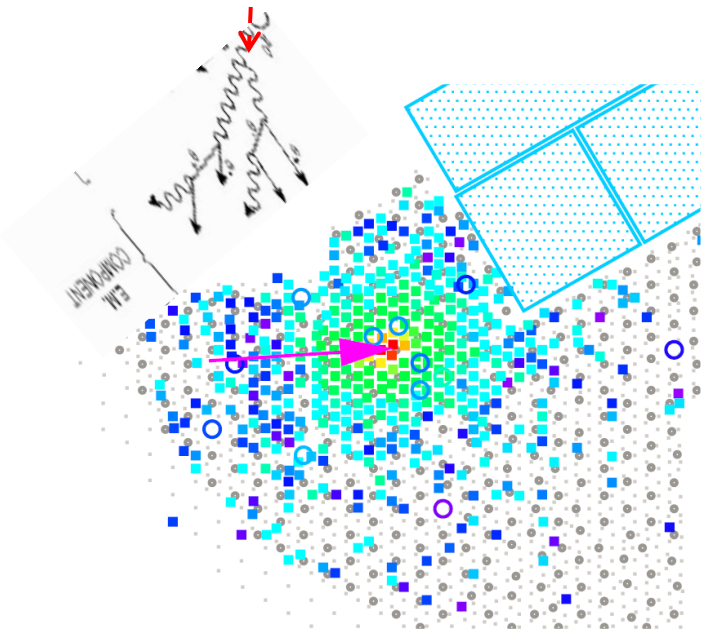
Selection of γ–rays out of CR background



Active Area for Muons vs. Array Area: 4%

~1 PeV CR event: many muons ~ 1 PeV γ–ray event： very few muons from the Crab





- Area：
  1.3 km^2
- Detectors：
  5216 ED
  1188 MD
- Energy Range：
  0.01-10 PeV

Multi-Messenger Collaboration Network

ANTARES (NT)

KM3Net (NT)

LST/CTA-N (CT)

MAGIC(CT)

GVD (NT)

VERITAS (CT)

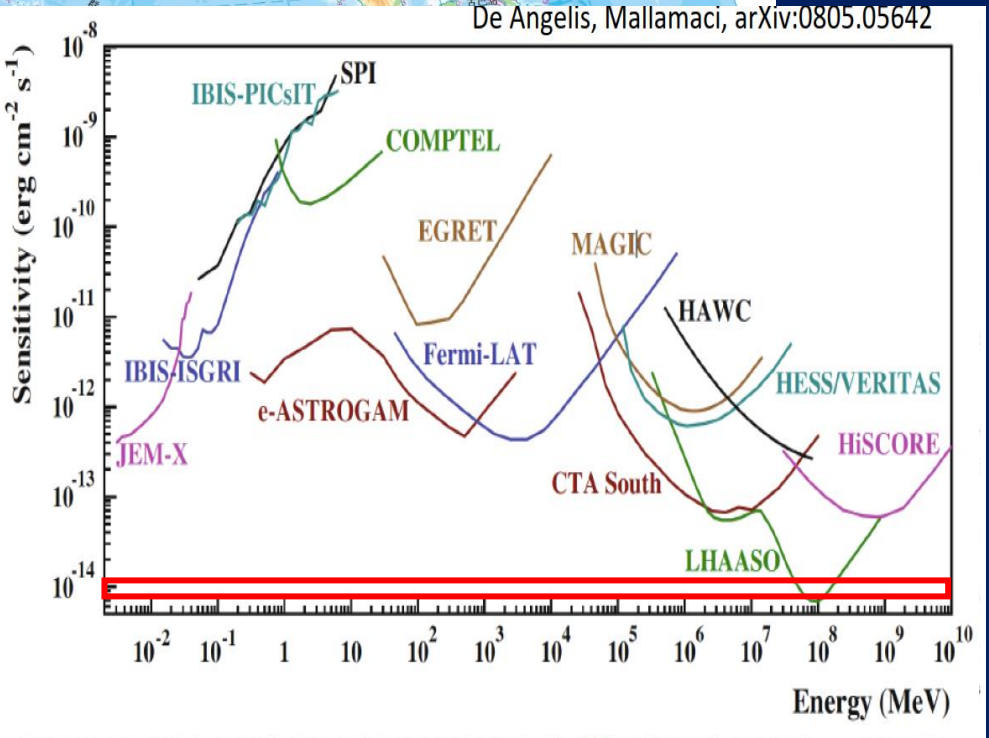
LHAASO Coll.:
6 countries
31 institution
285 members

IceCube(NT)

Space borne Exp.

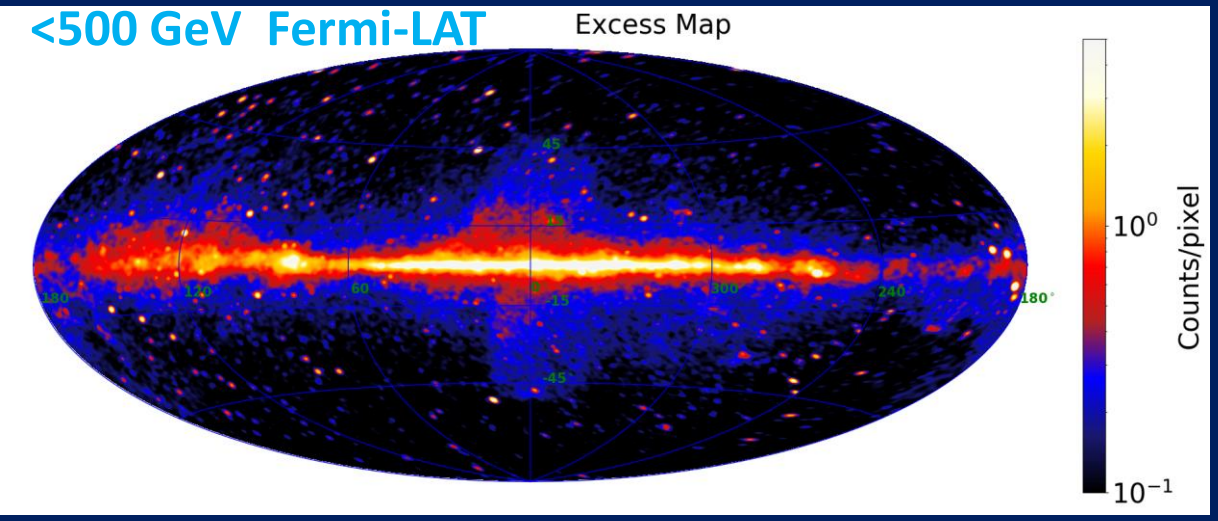
eROSITA(X-ray)

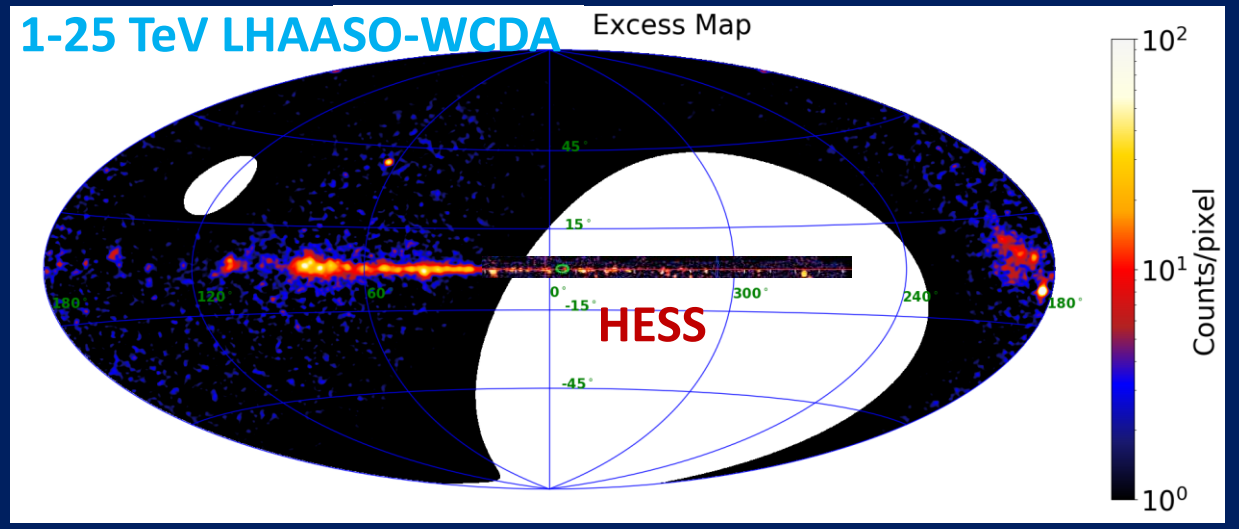
DAMPE(γ-ray, CR)

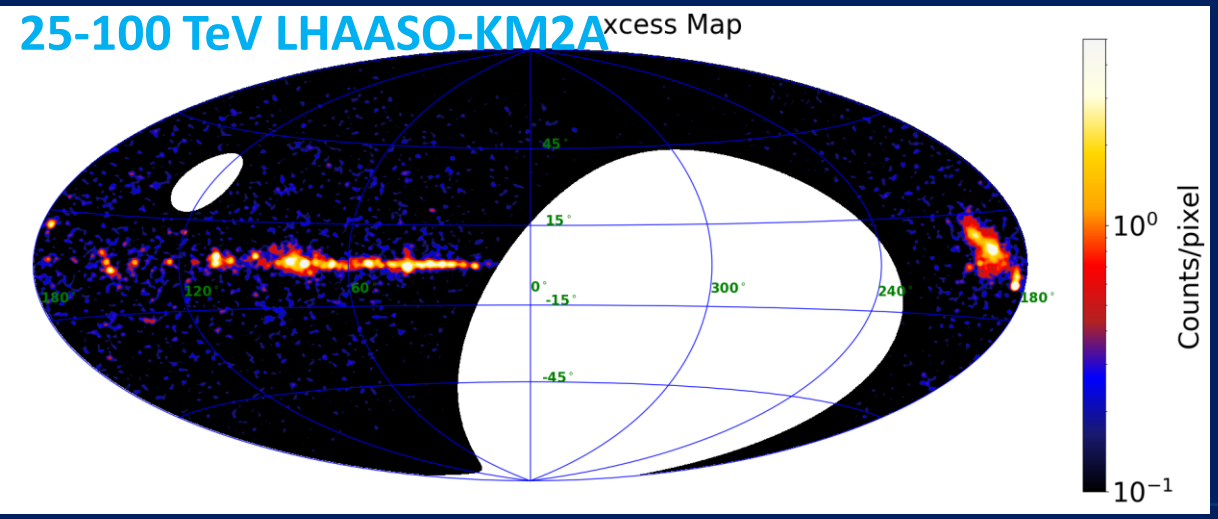


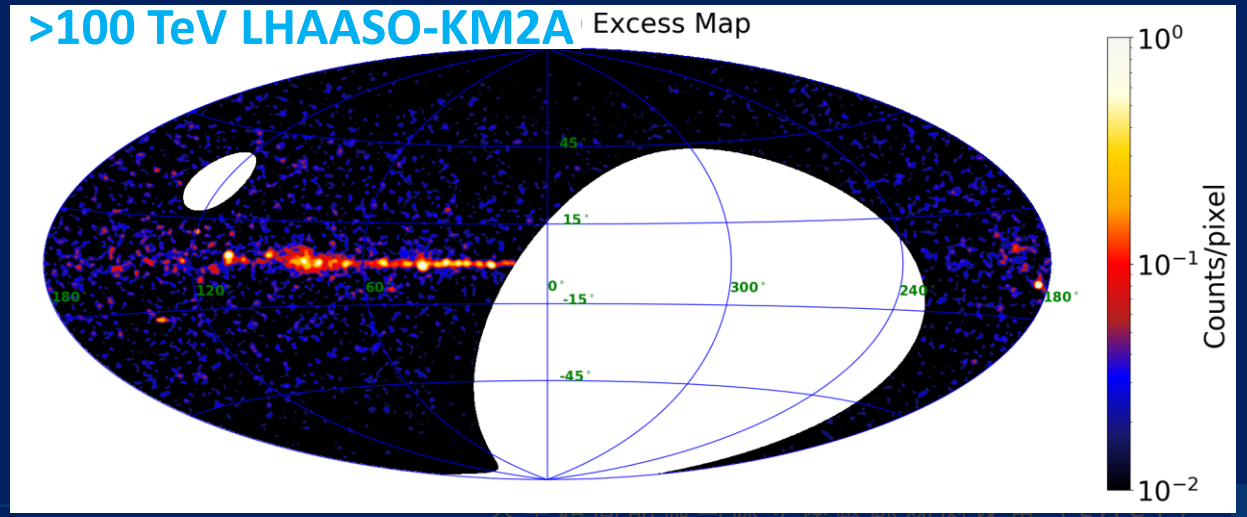
UHE γ-ray Astronomy: sources and diffuse emission

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

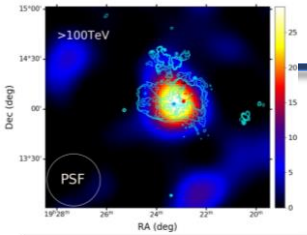








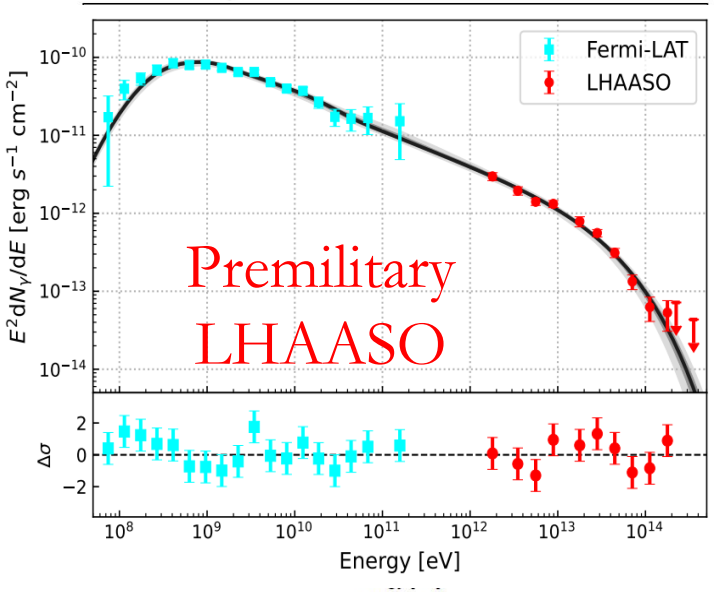
Possible Source Candidates

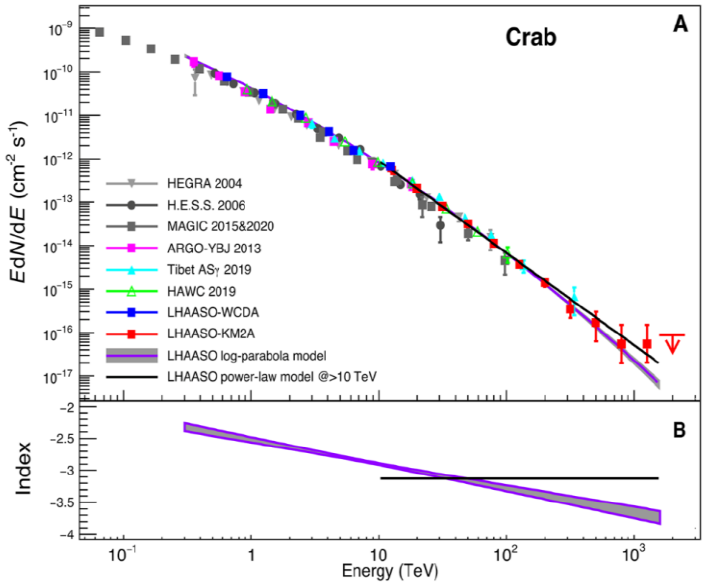


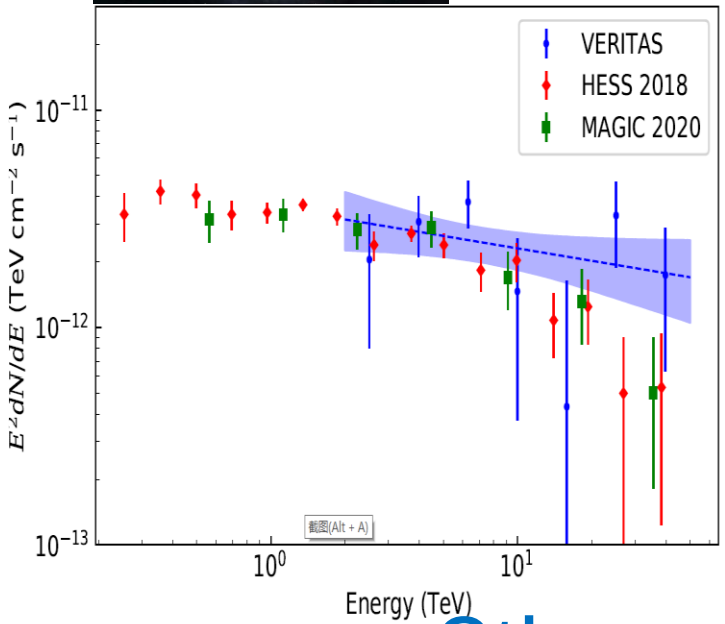
W51C

Crab

G.C.







...

SNR

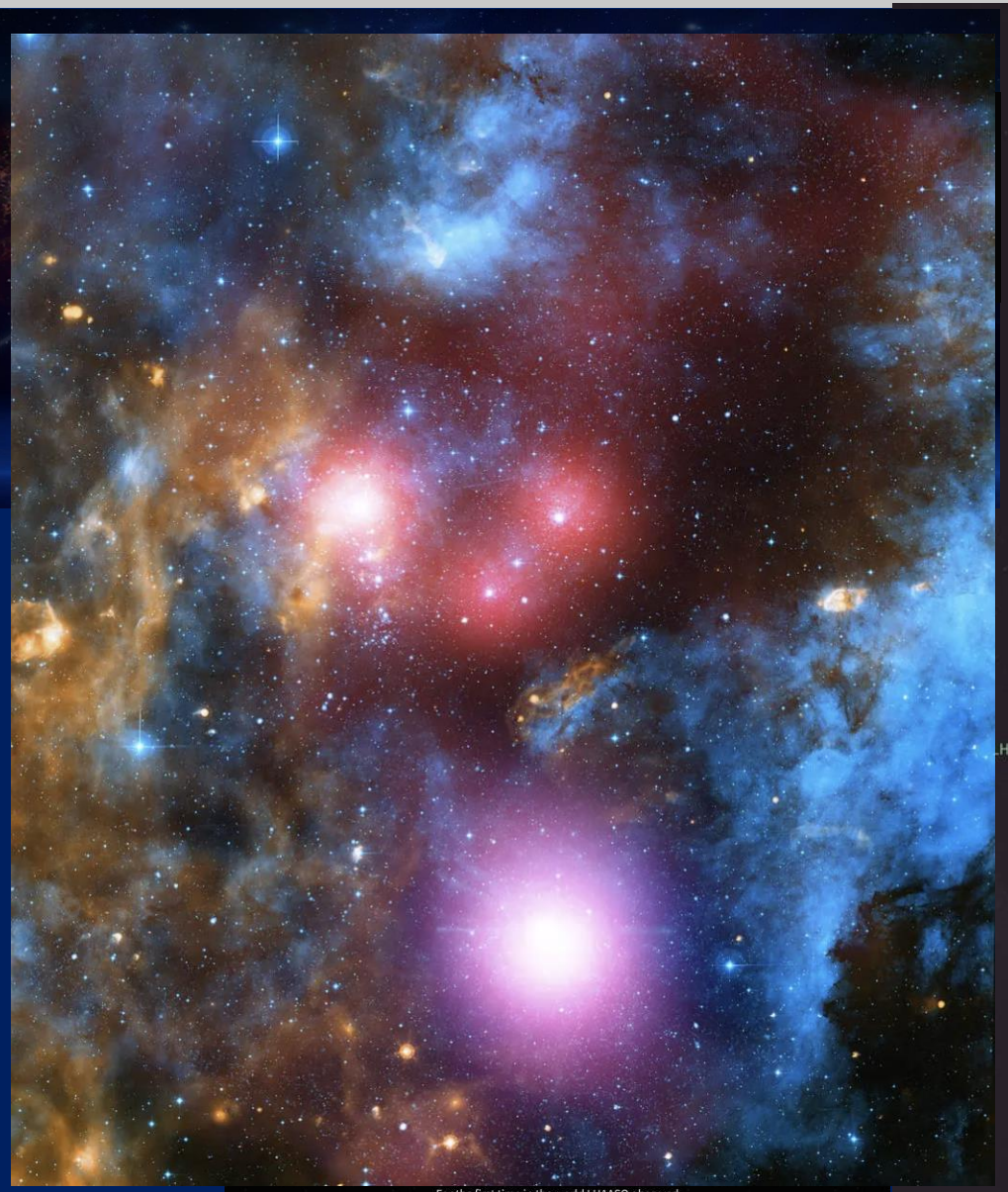
PWN

Other sources

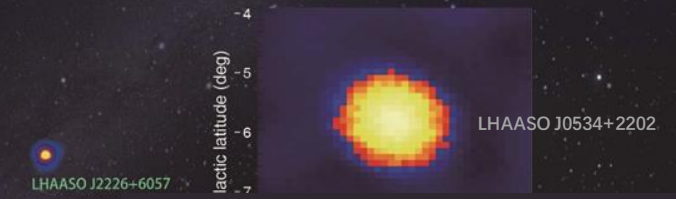
Many types of sources have the potential to accelerate particles to 1 PeV and above

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

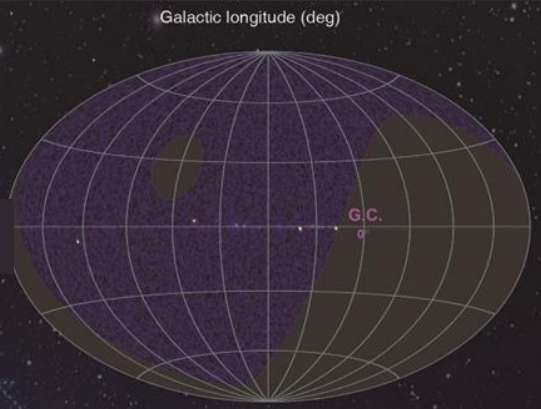
The 1st CR-Source Candidate by LHAASO



Cygnus Bubble, *Science Bulletin*, arXiv:2310.10100



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

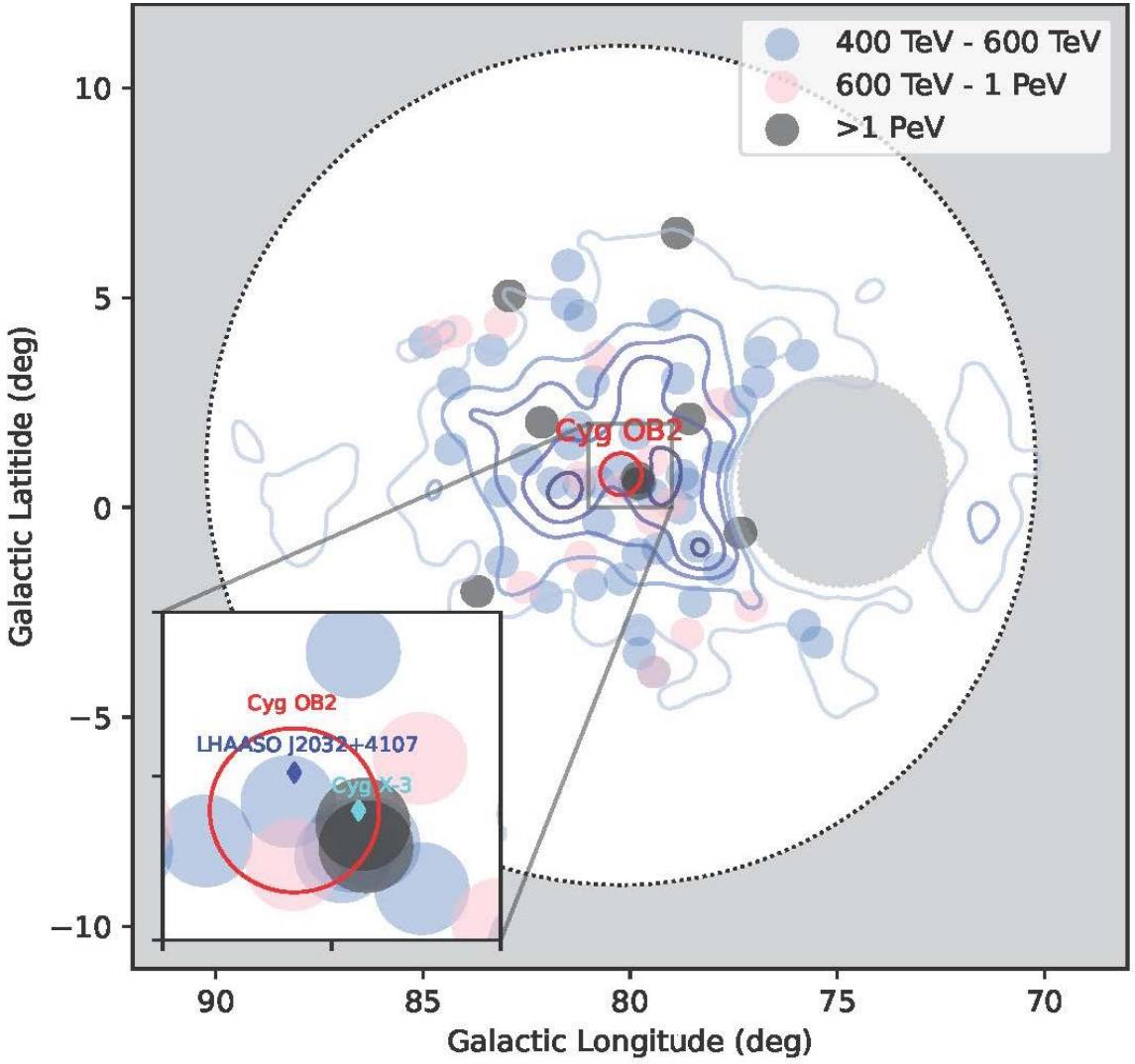


2.5 PeV

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

A Bubble of UHE γ's centered at a complex core

Cygnus OB2, binary J2032+4107, MQ X-3



8 γ's above 1 PeV!

Energy (TeV)	Ne	Nu	Theta (deg)	Dr (m)
1087	5904	13	19.4	143
1188	5480	14	34.4	73
1208	6939	13	14.2	131
1350	6938	8	27.1	43
1379	6469	9	17.4	52
1421	6258	7	12.7	57
1784	6665	13	18.0	41
2481	13815	29	33.0	99

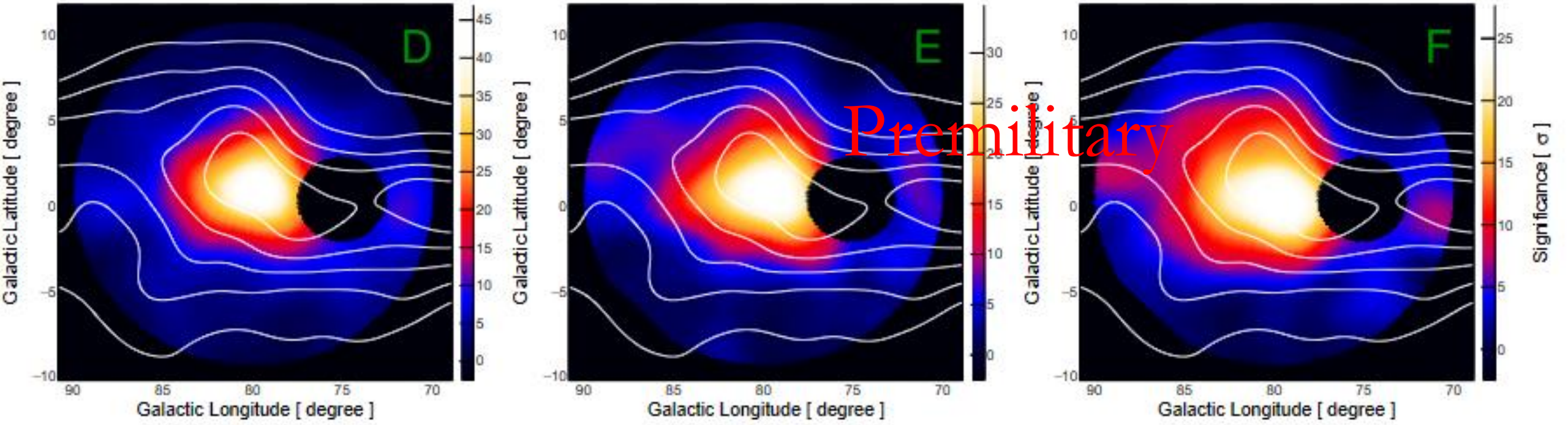
- PeV Photons are scattered in the Bubble, and seem not to associate with any small scale sources

Association with HI gas distribution over ~200 pc

- The significance map is smoothed with a Gaussian kernel=1.0°
- The contour is from HI4PI 21-cm line survey

◆ Clear correlation with gas distribution indicating a hadronic origin of photons in the Bubble

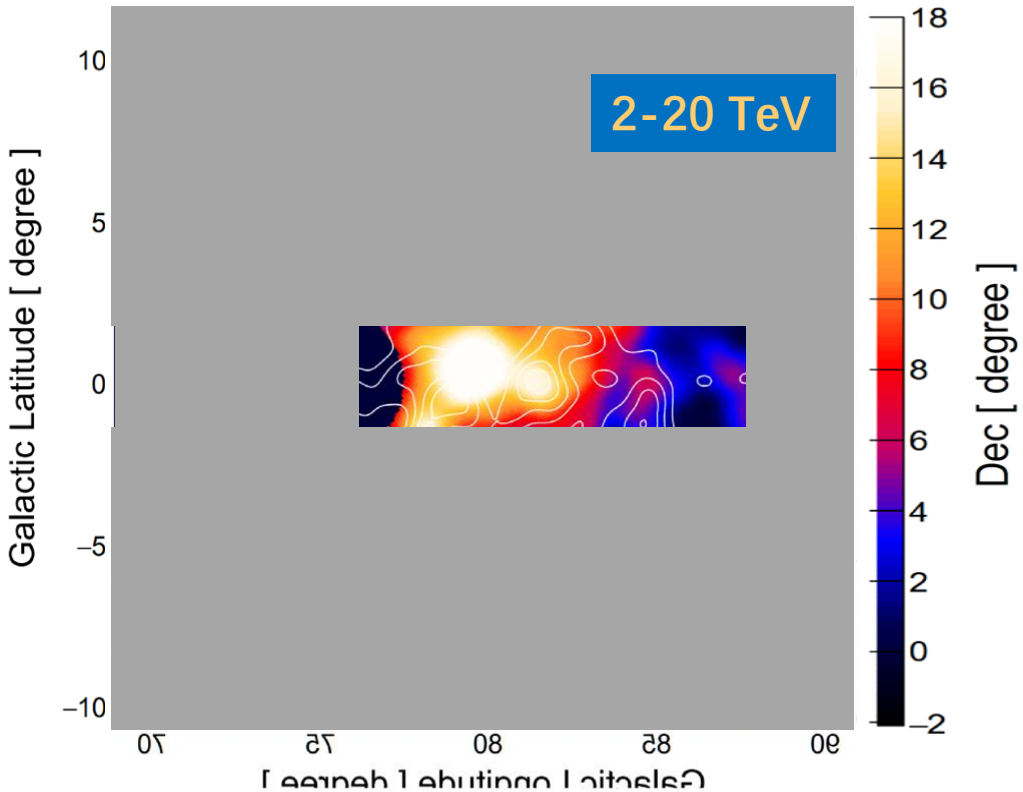
◆ The signal is elongated along the disck and extends to 10°

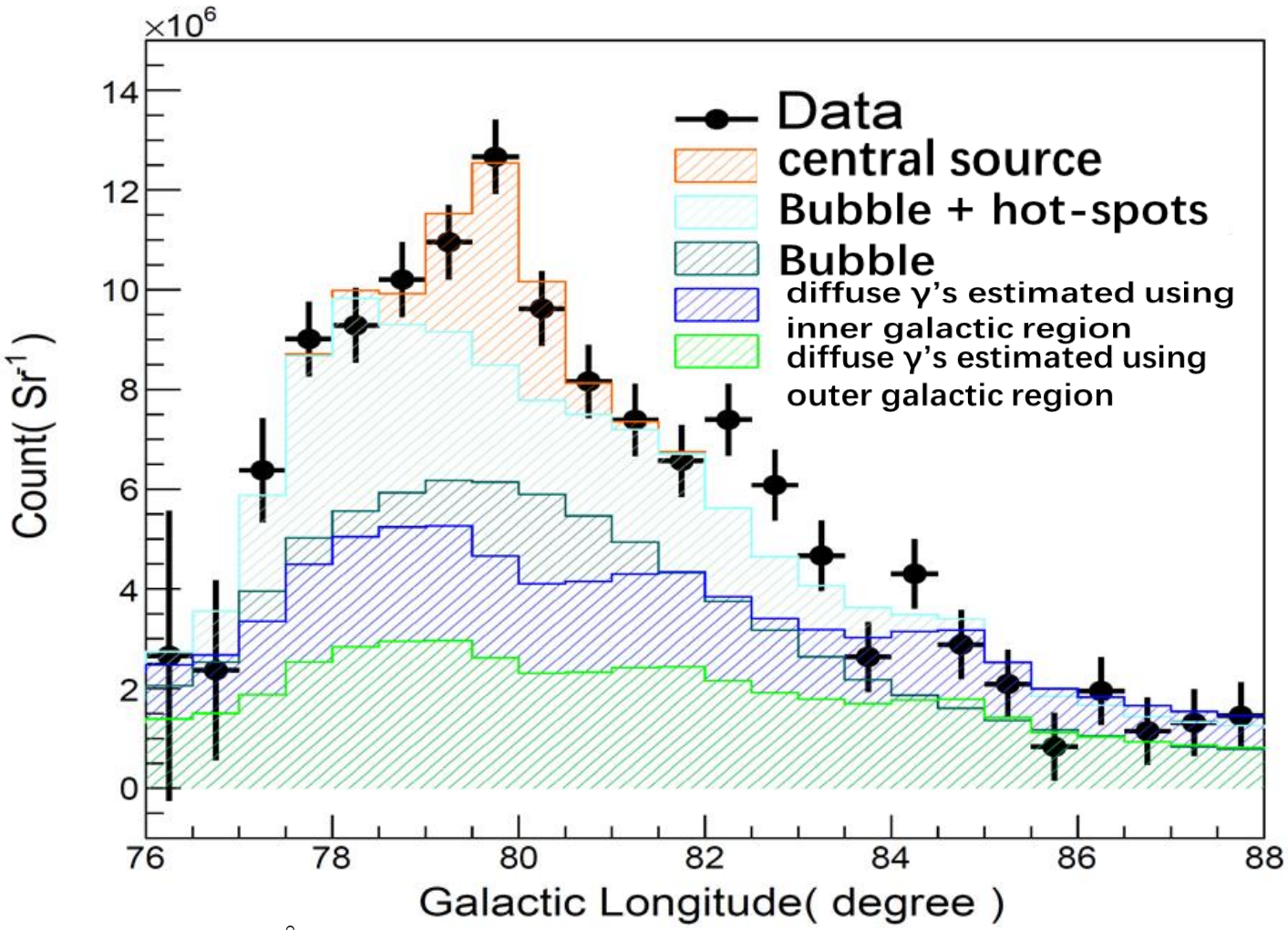


The Bubble at 2-20 TeV by WCDA

1-D Flux in ±2°

Clampy structure of the Bubble: hot spots

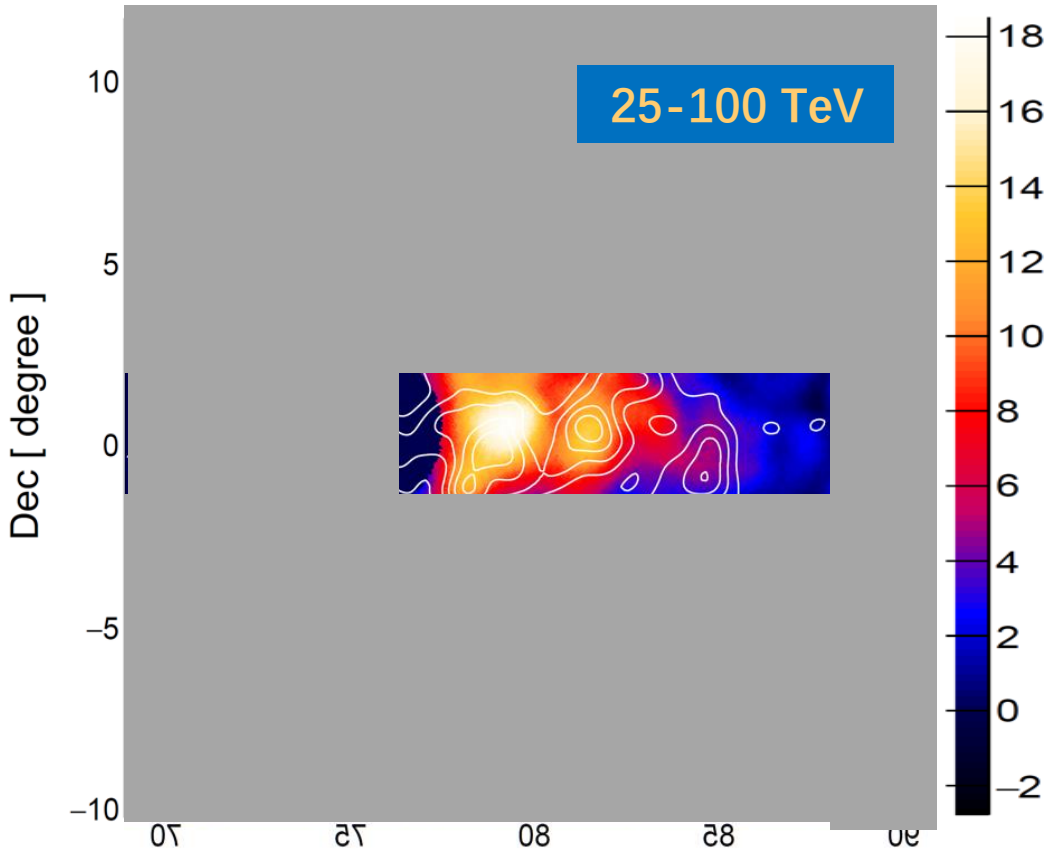


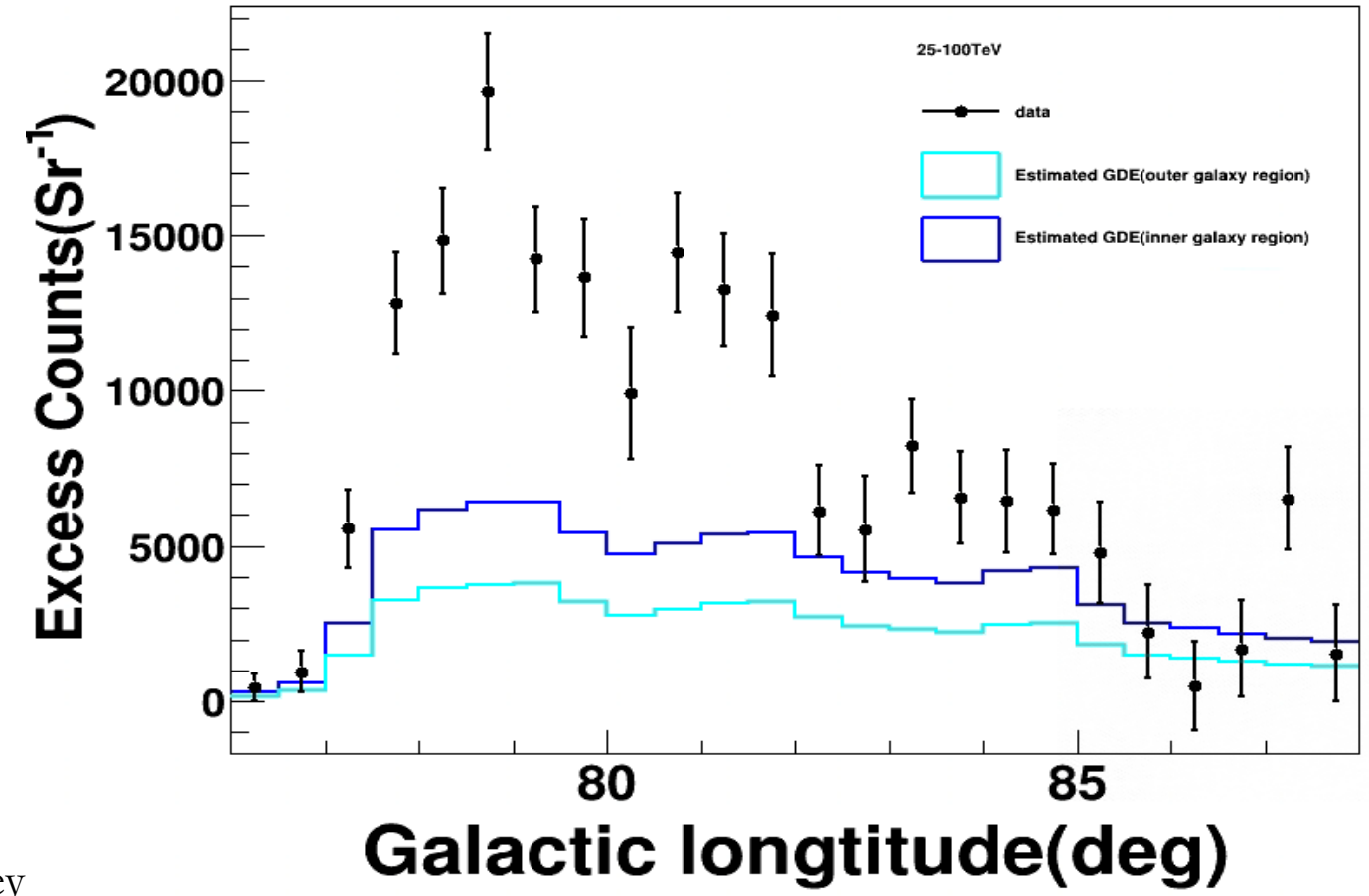


- The contour is from CfA galactic CO survey
- The significance map is smoothed with a Gaussian kernel of $\sigma=0.3^{\circ}$

The Bubble at 25-100 TeV by KM2A

1-D Flux in ±2°

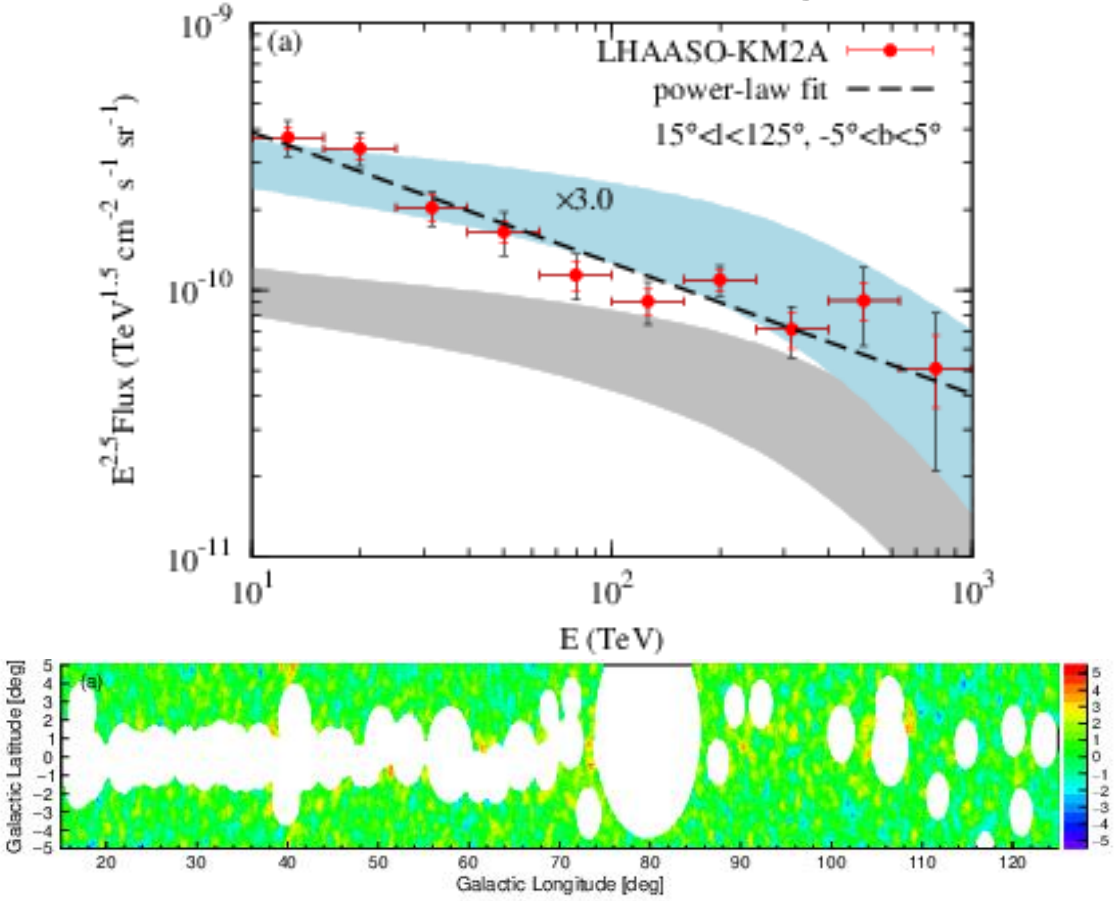




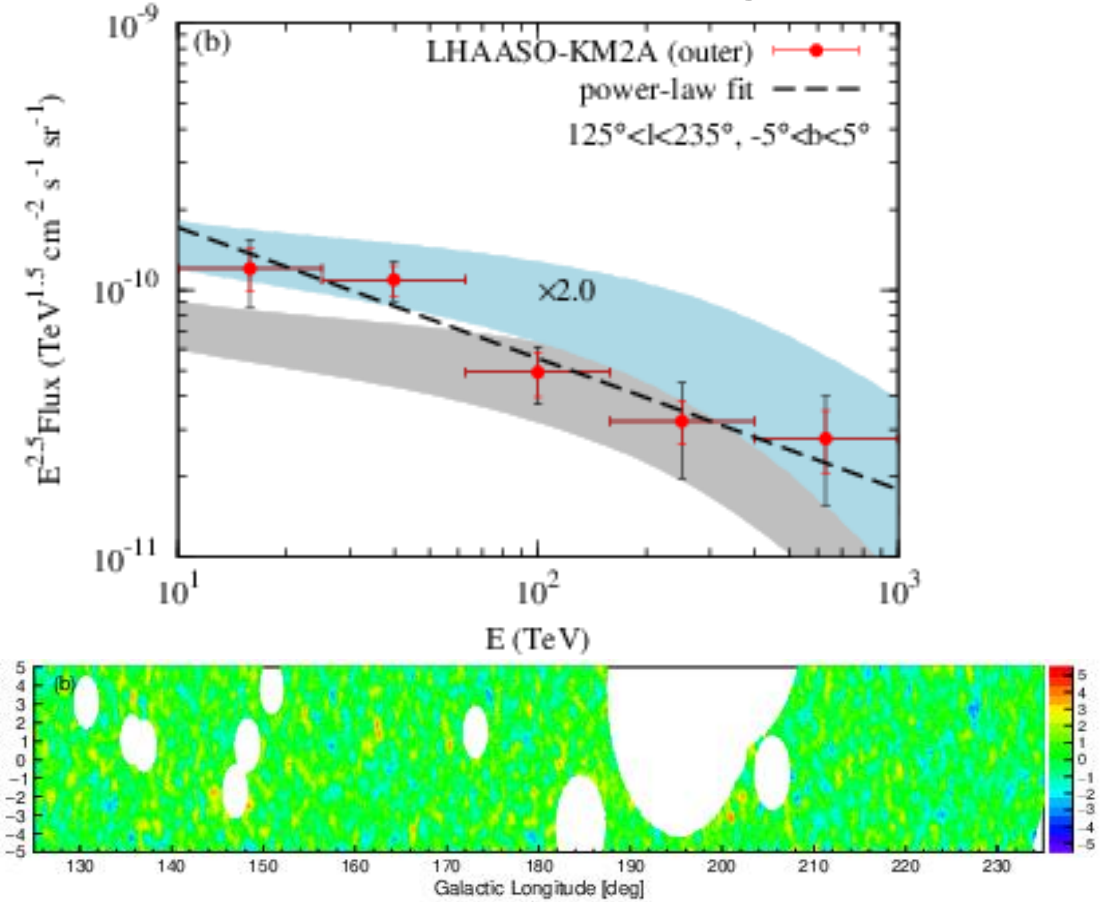
- The contour is from CfA galactic CO survey
- The significance map is smoothed with a Gaussian kernel of $\sigma=0.3^{\circ}$

LHAASO measured the Galactic Diffuse Emission

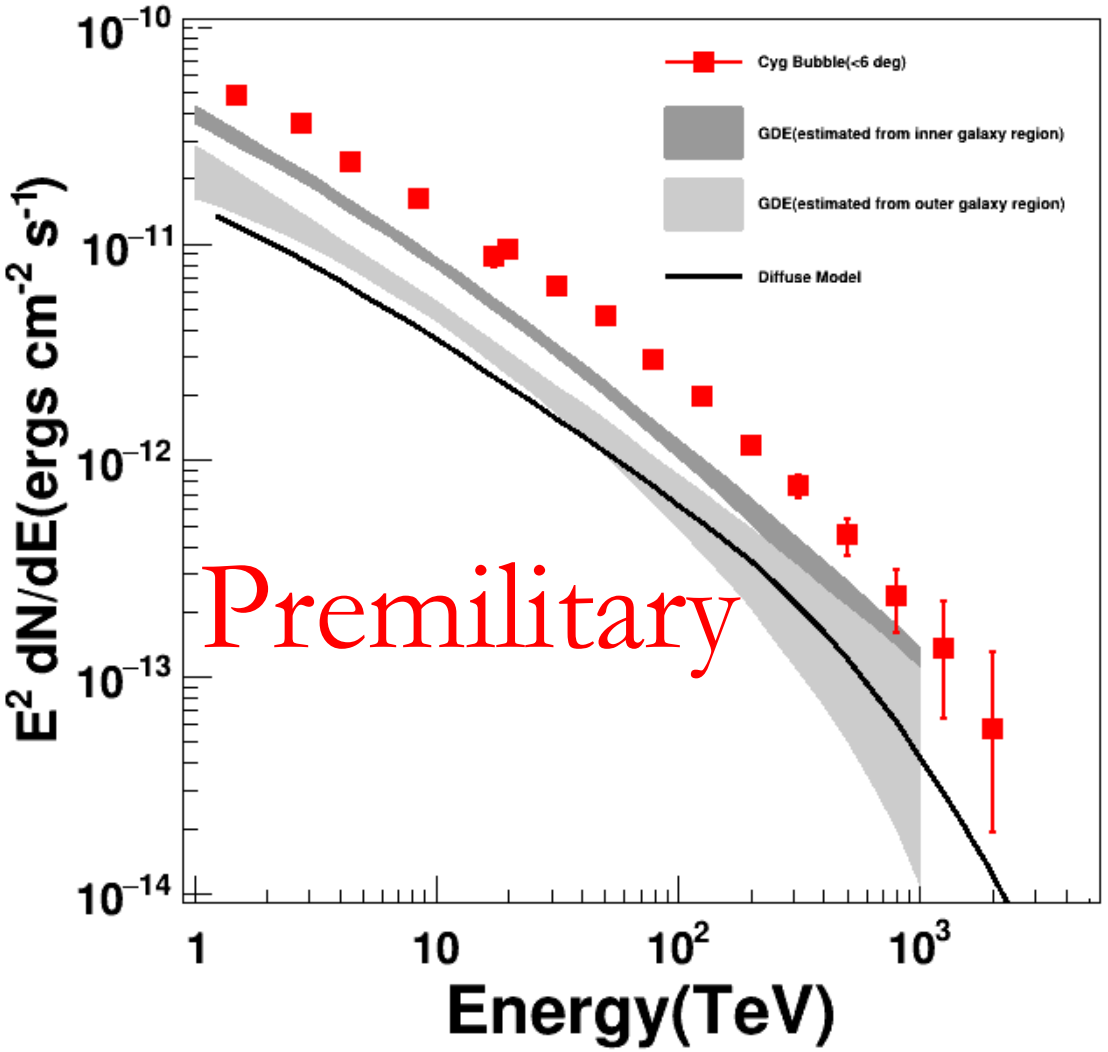
Inner Galactic Region



Outer Galactic Region



Spectral Energy Distribution of the Bubble

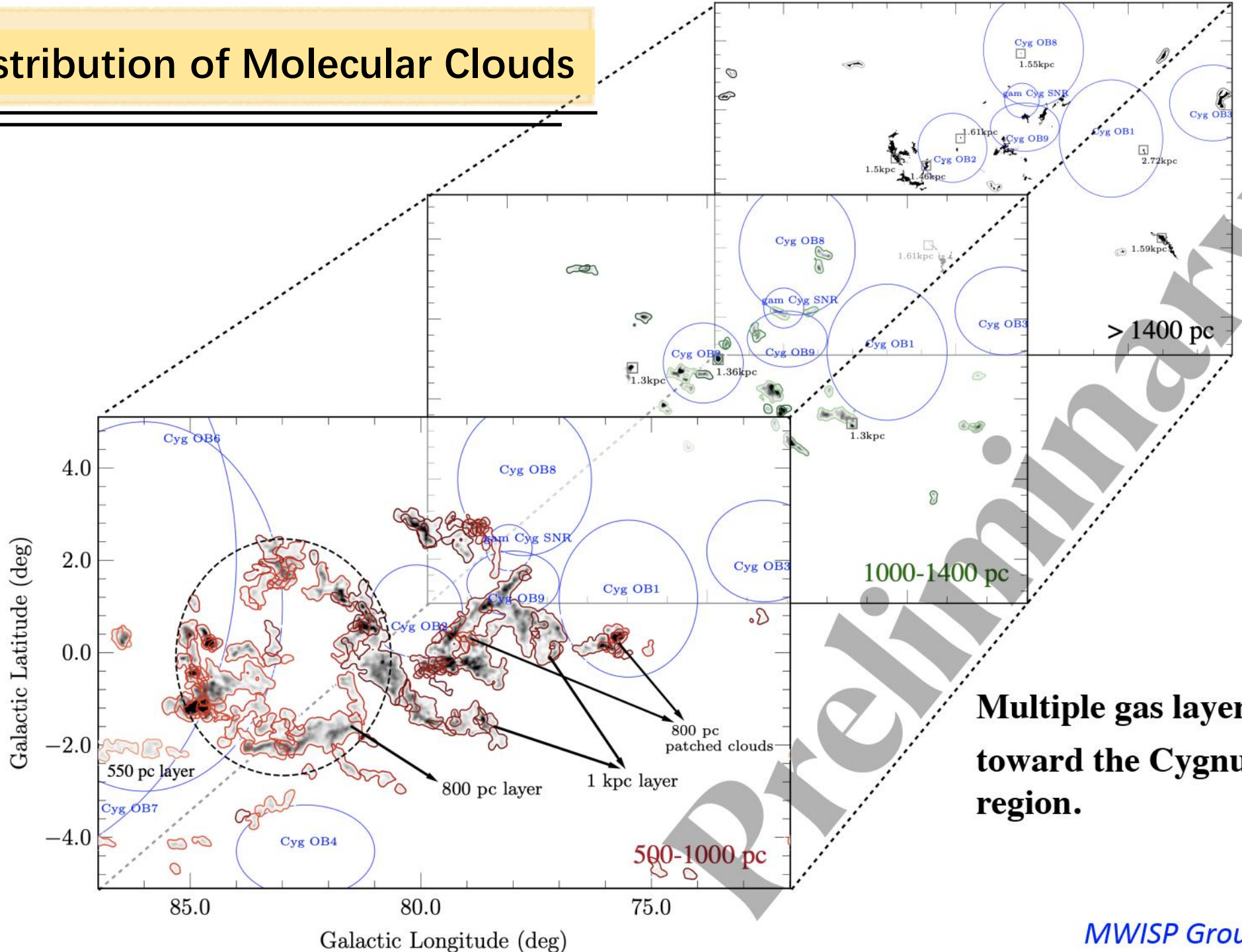


Energy Bin	Non	Nb
400TeV-630TeV	42	6.8
630TeV-1PeV	14	1.9
1PeV-1.6PeV	6	0.6
1.6PeV-2.5PeV	2	0.2

Almost background free

- The spectrum spans 3 decades up to 2 PeV
- Spectral index ~ 2.7
- No indication of cut-off in the spectrum

3-D distribution of Molecular Clouds

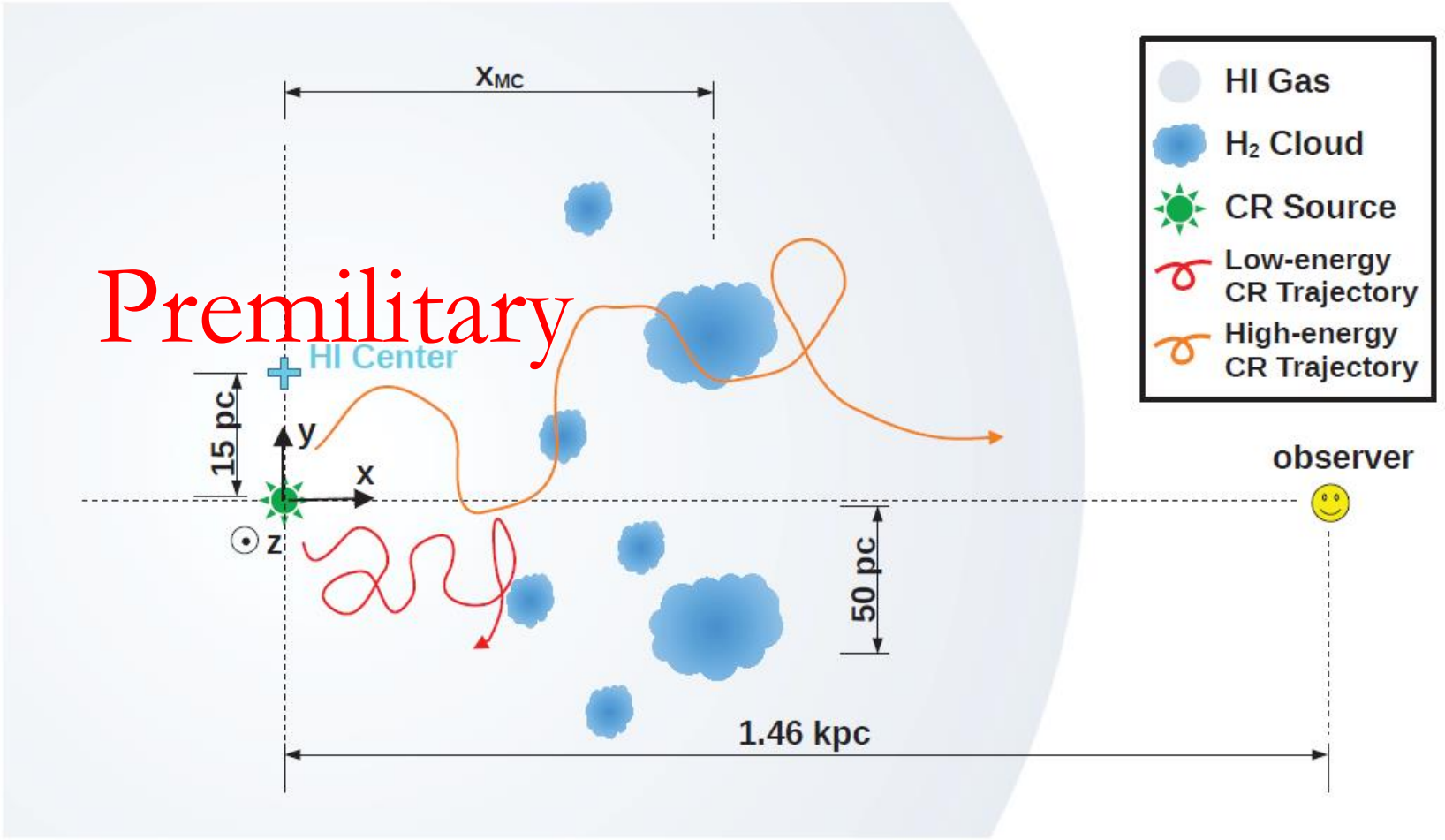


Multiple gas layers toward the Cygnus region.

MWISP Group, to be submitted

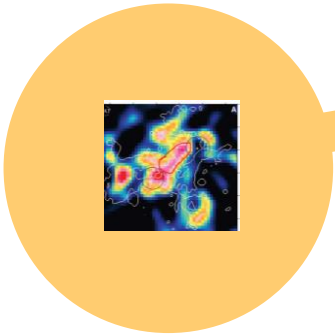
HE Protons injection from the core region

- High energy cosmic rays escape from the accelerator in the core
- Diffusing through the H1 gas and producing γ's in p-p collisions
- Hitting on clampy molecular clouds making hot-spots
- Slow diffusion ~1%DC in ISM

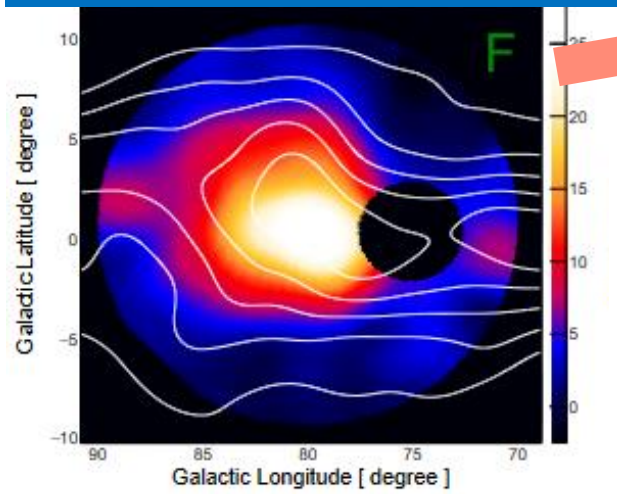


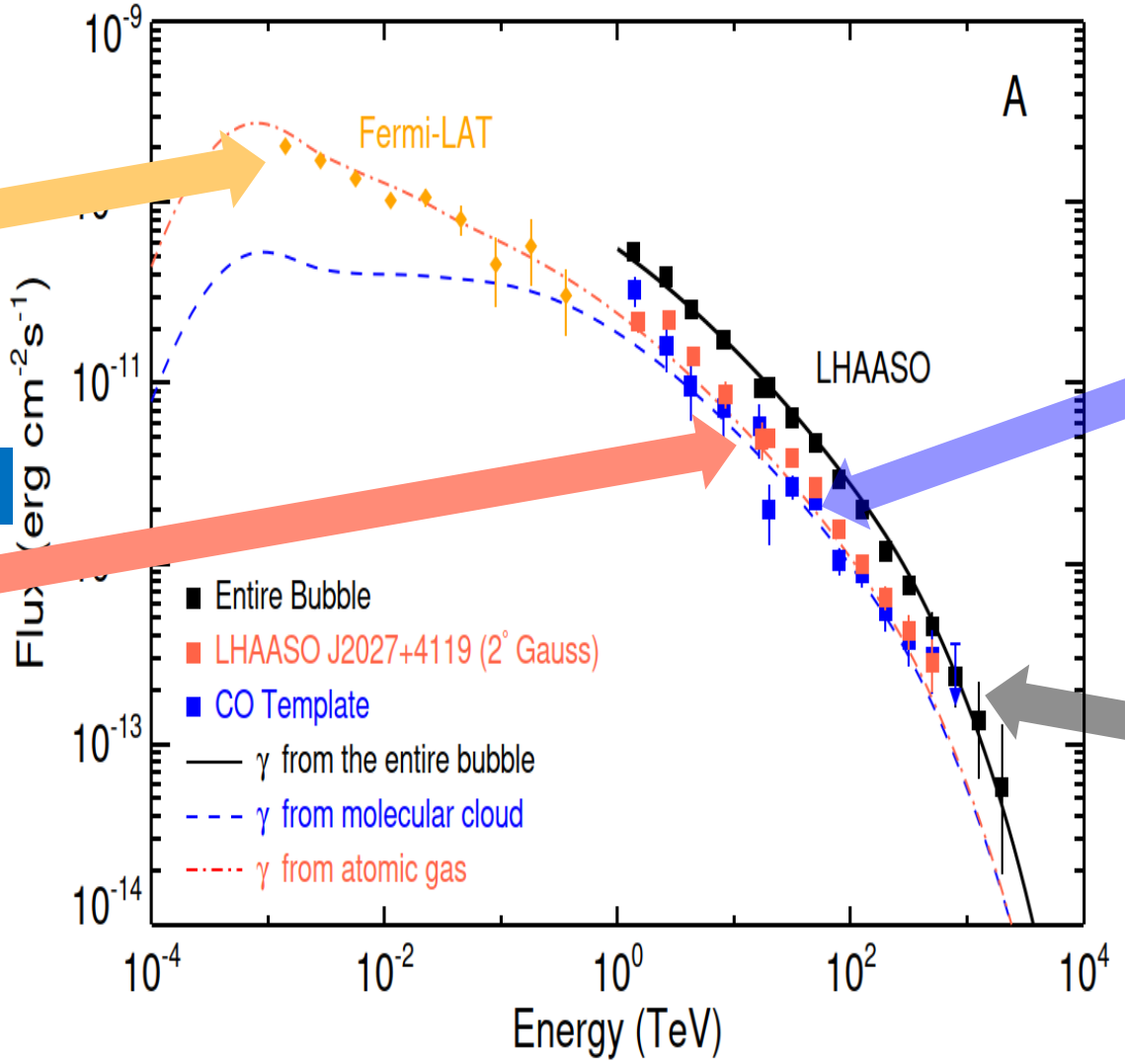
Model w 3 components : SED over 8 decades

Fermi Cocoon

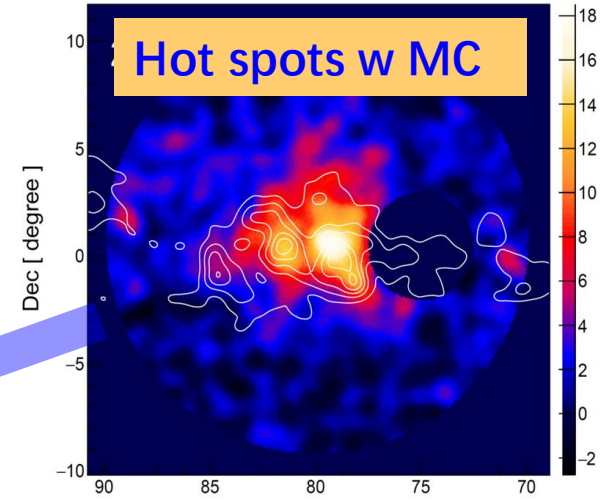


Extended Bubble w HI gas

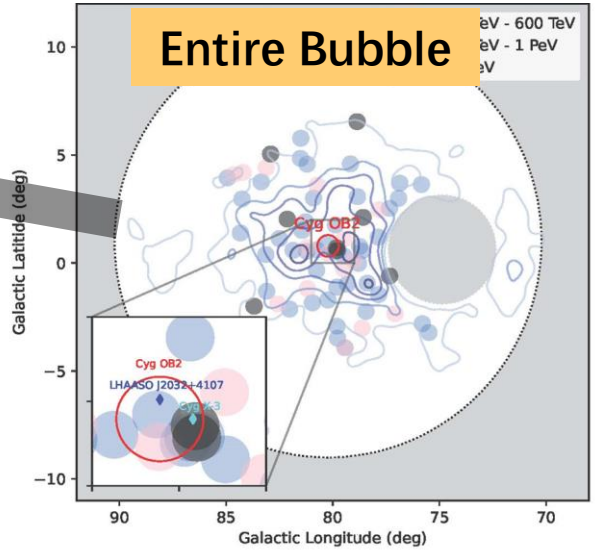




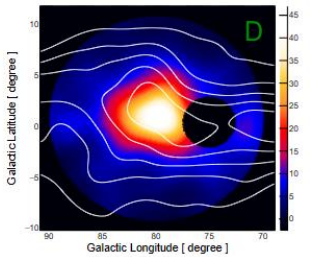
Hot spots w MC

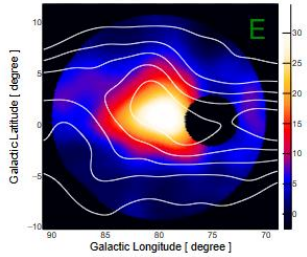


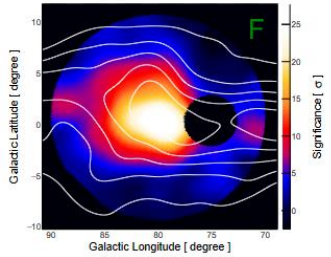
Entire Bubble

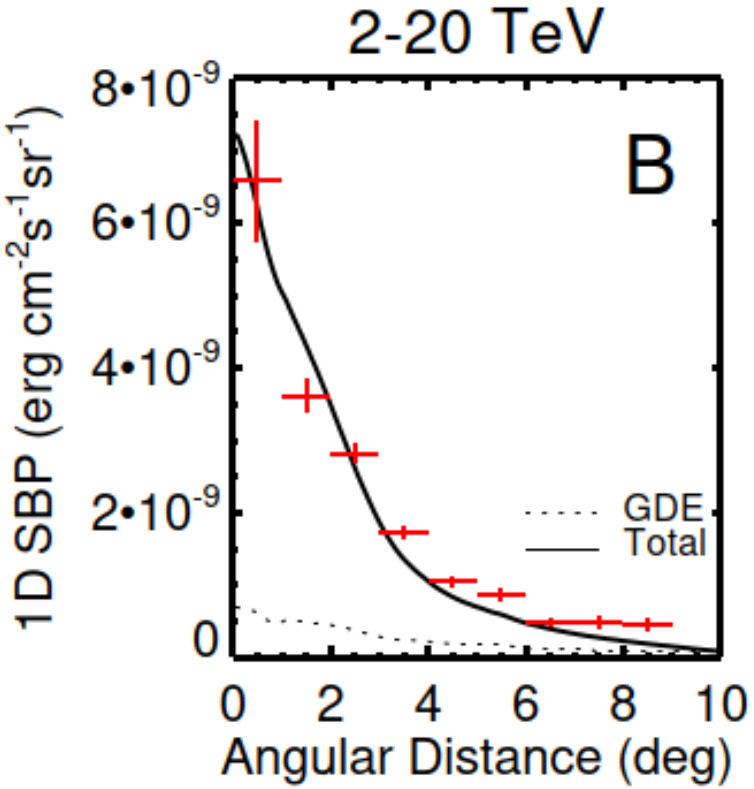


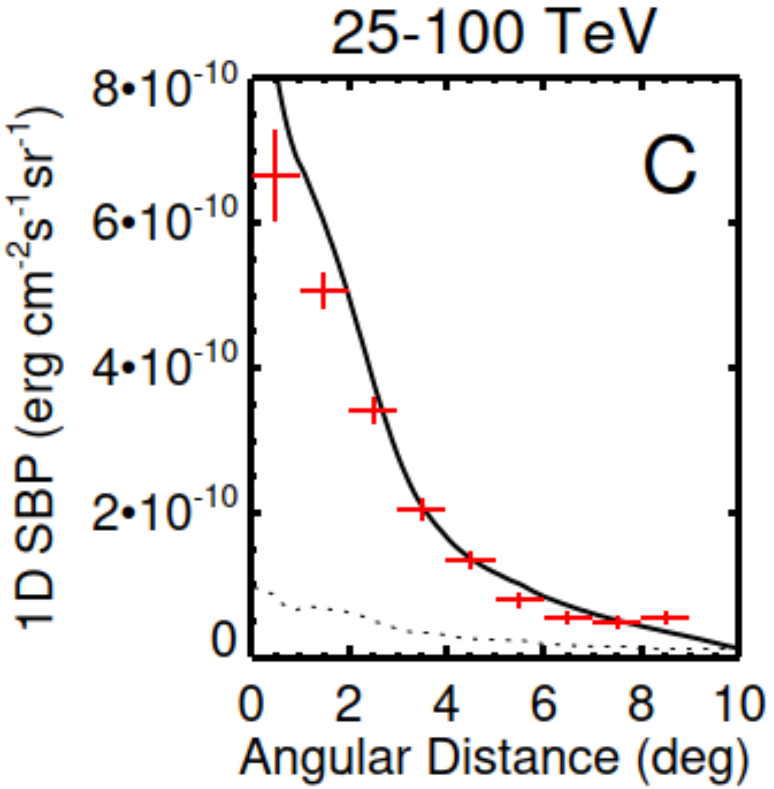
Model: Diffuse CR's generate γ's Spatial Profile over 10° from the core

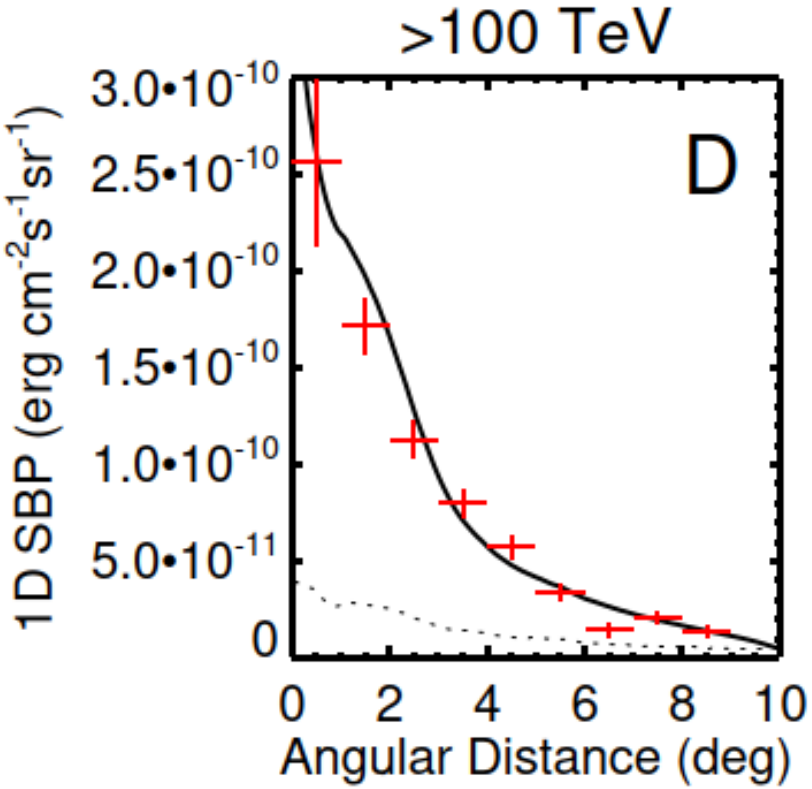




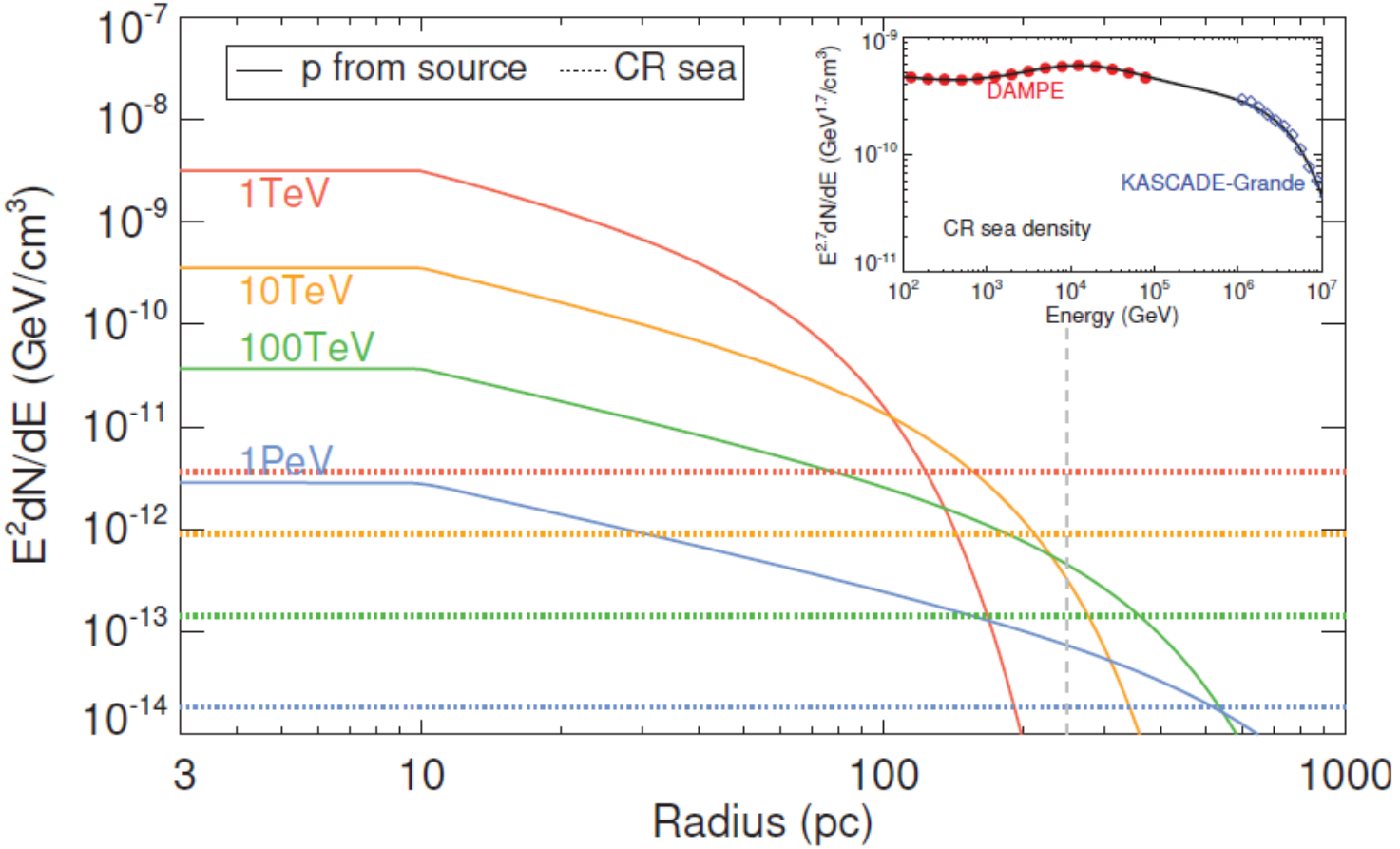








Derived Cosmic Ray bubble over ~200 pc



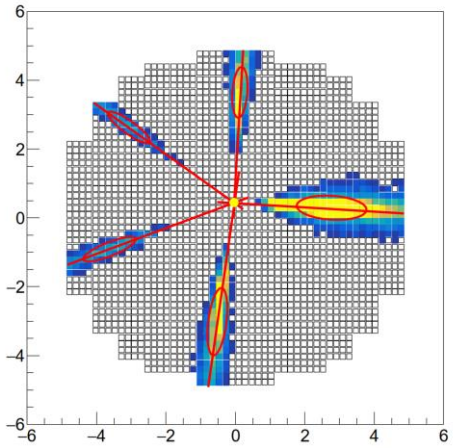
- There is a large cosmic ray bubble
- A rather small propagation ecoefficiency around the source
- The size of the visible bubble depends on the level of diffuse γ-rays

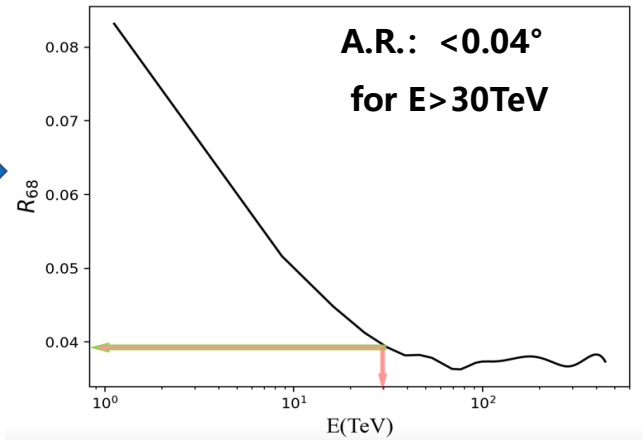
Conclusion and Out look

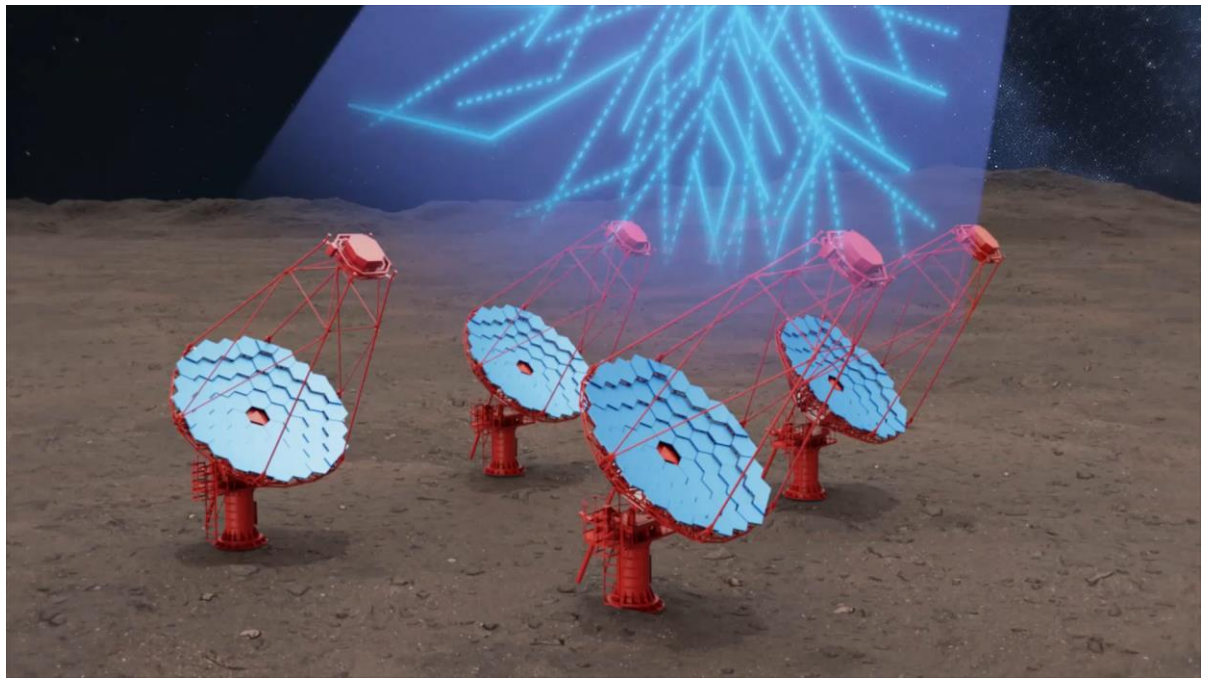
- Many Cosmic Ray Source Candidates are found by all-sky survey of LHAASO
- A huge Bubble of UHE γ-ray in Cygnus X is detected with spectrum beyond 1 PeV implying the existence of a **Super-PeVatron injecting CR above 10 PeV**
- CR interact with atomic gas and clampy molecular clouds on the way diffuse out very slowly forming the bubble and hot-spots
- The observation implies a large cosmic ray bubble extending hundreds of pc as the 1st candidate of the origin of cosmic rays beyond the knee

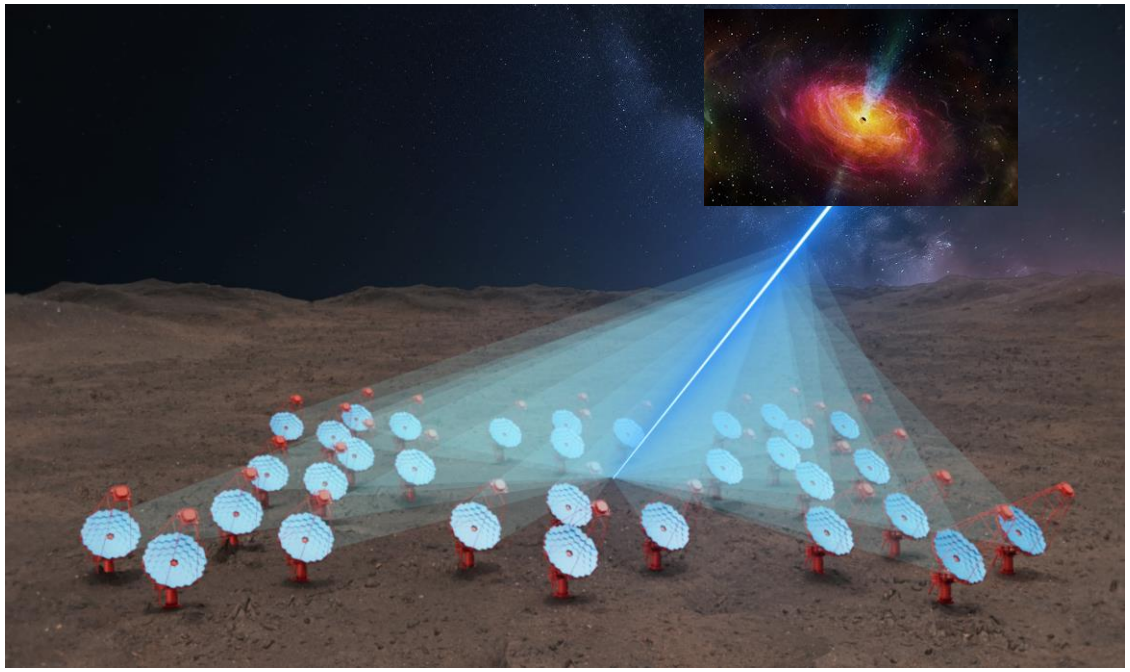
LACT as the upgrading of LHAASO

- **Stereo measurement of Cherenkov image**
  - **At least 4 telescopes simultaneously**
- **Reconstruction**
  - Angular resolution **0.05° for E**>30 TeV



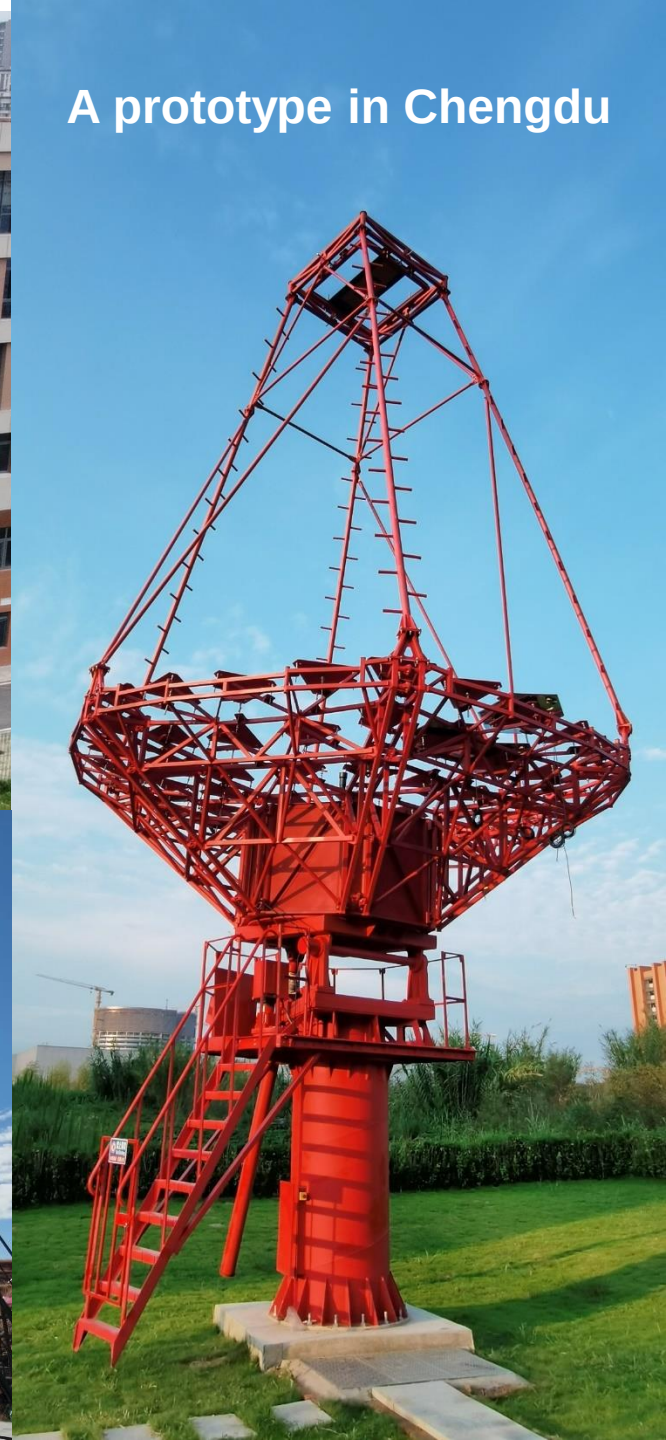






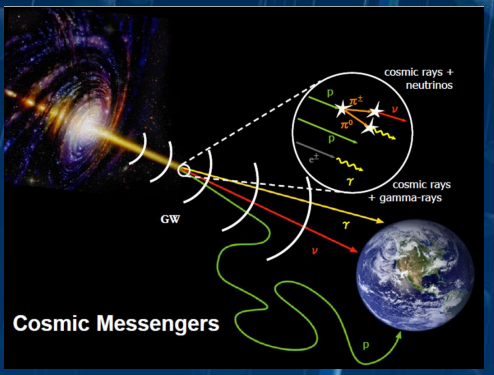
A prototype in LHAASO

A prototype in Chengdu



High Energy Underwater Neutrino Telescope

H U N T



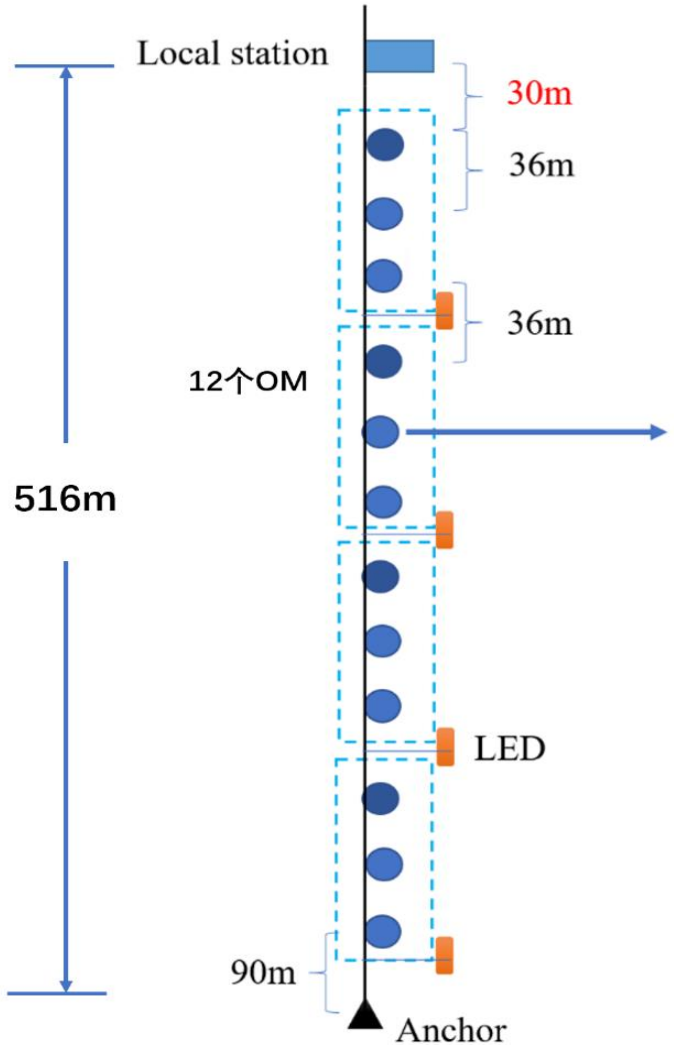
- **探测对象：**测量全类型中微子的簇射事例和径迹事例
- **角分辨:** ~0.1° (tracks), <3°(cascades).
- **能量分辨:** ΔlogE~0.3(tracks), ΔE~10-30% (cascades).
- Discovering Neu sources (>100 TeV) at the level of 5σ within several years.

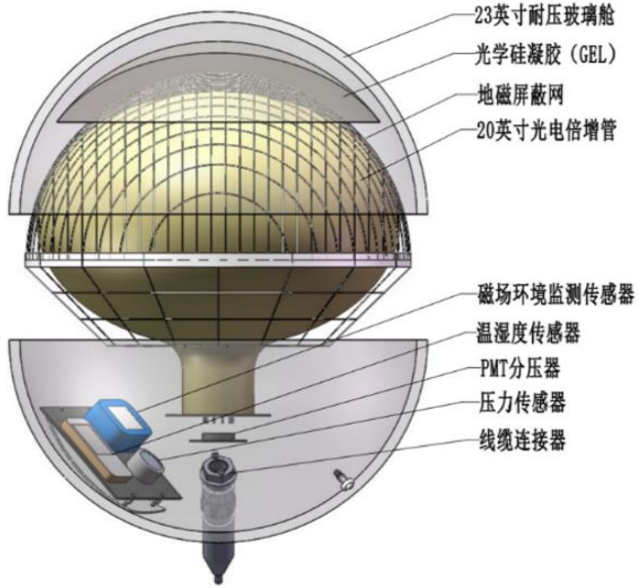
36 m

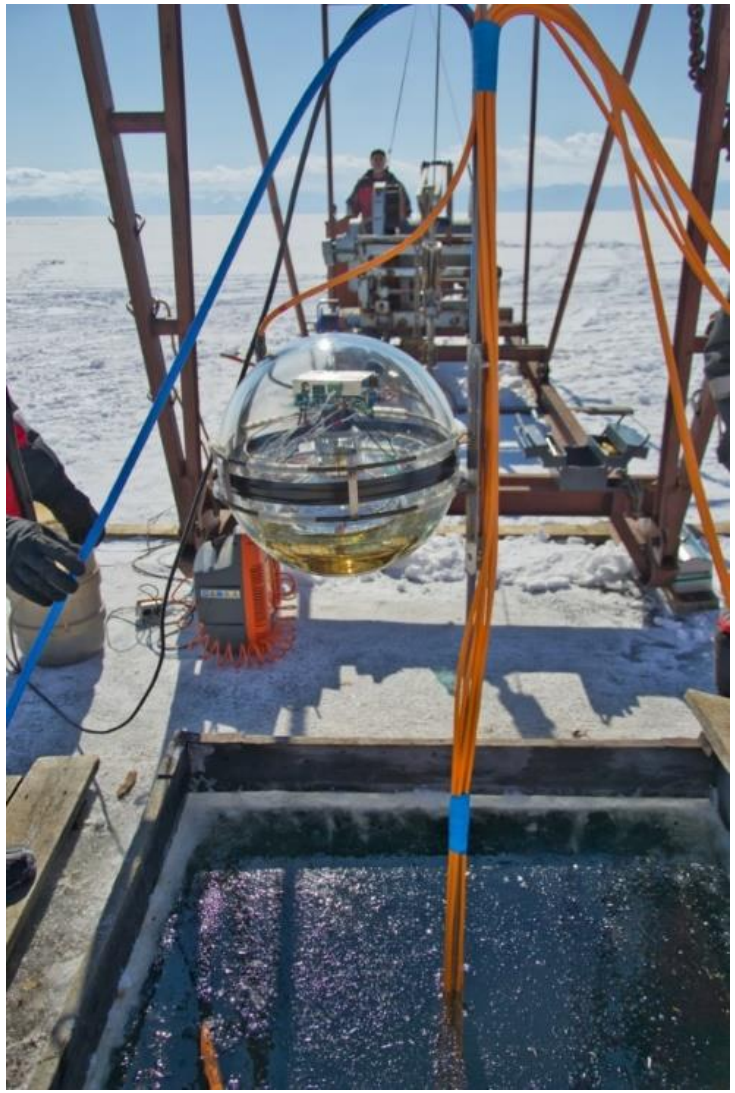
- **探测器面积：** 6×6 = 36 km^2, ~**30 km^3**
- **每串间距：** D_{string} ~ 130 m
- 串内探测器**单元间距：** D_{OM} ~36 m
- 为了测量事例的簇射分布，**length of string**：~860 m
- ~2,304 strings with 24 DOMs，~**5.5 DOMs**

130 m

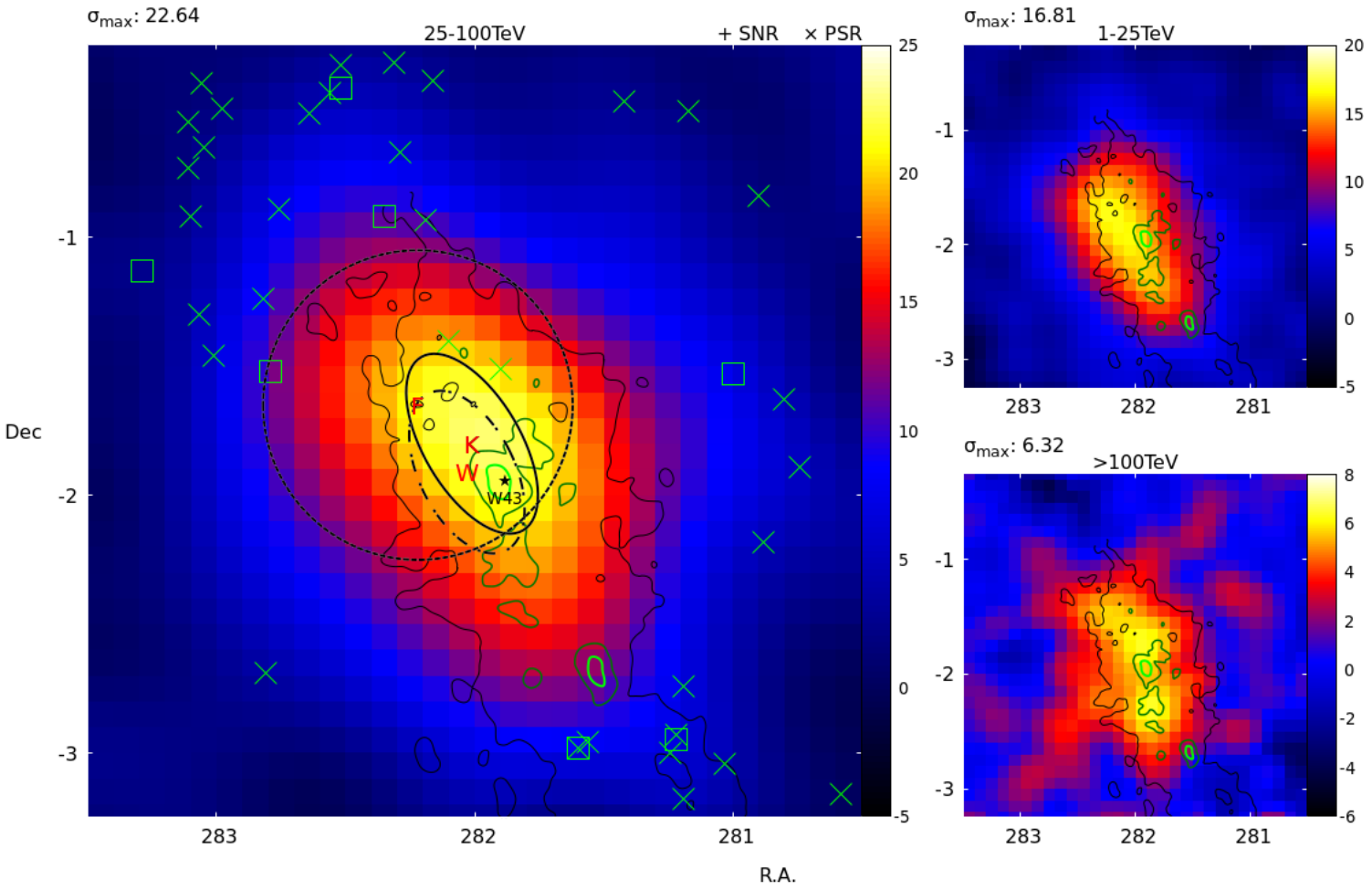
预先研究计划：　24年春，在贝加尔湖投放样机







Other cluster-W43



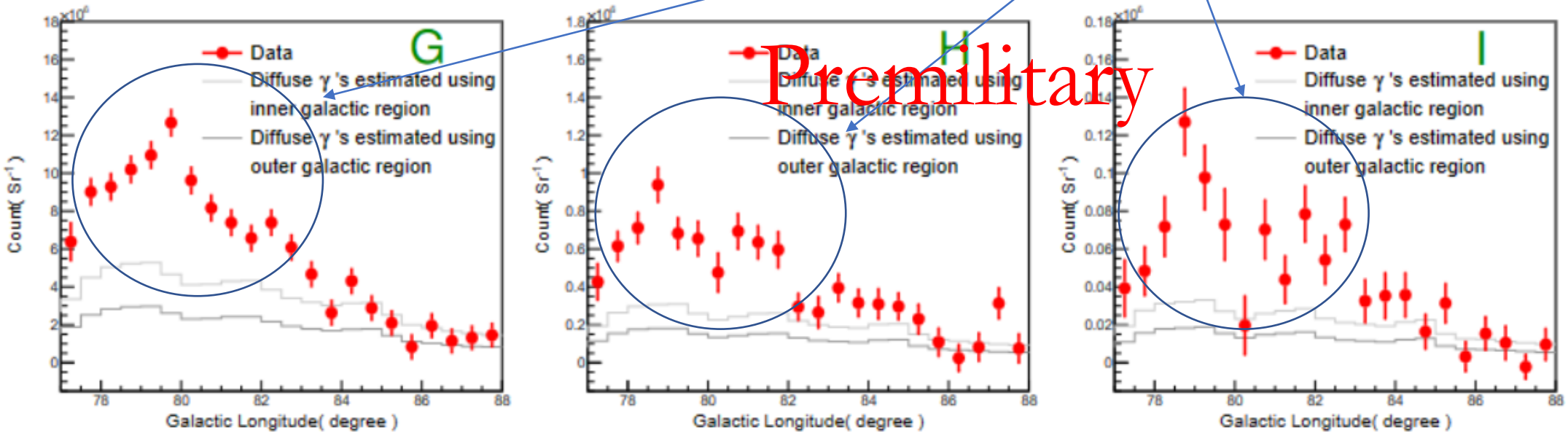
- ◆W43 is a galactic mini-starburst region.

- Signal with energy above 100TeV is detected from W43, which is positionally correlated with gas distribution.

Galactic diffuse emission?

- Large uncertainty from galactic diffuse emission measurement. LHAASO’s result implies there are unresolved sources or strong positional correlated diffuse emission.

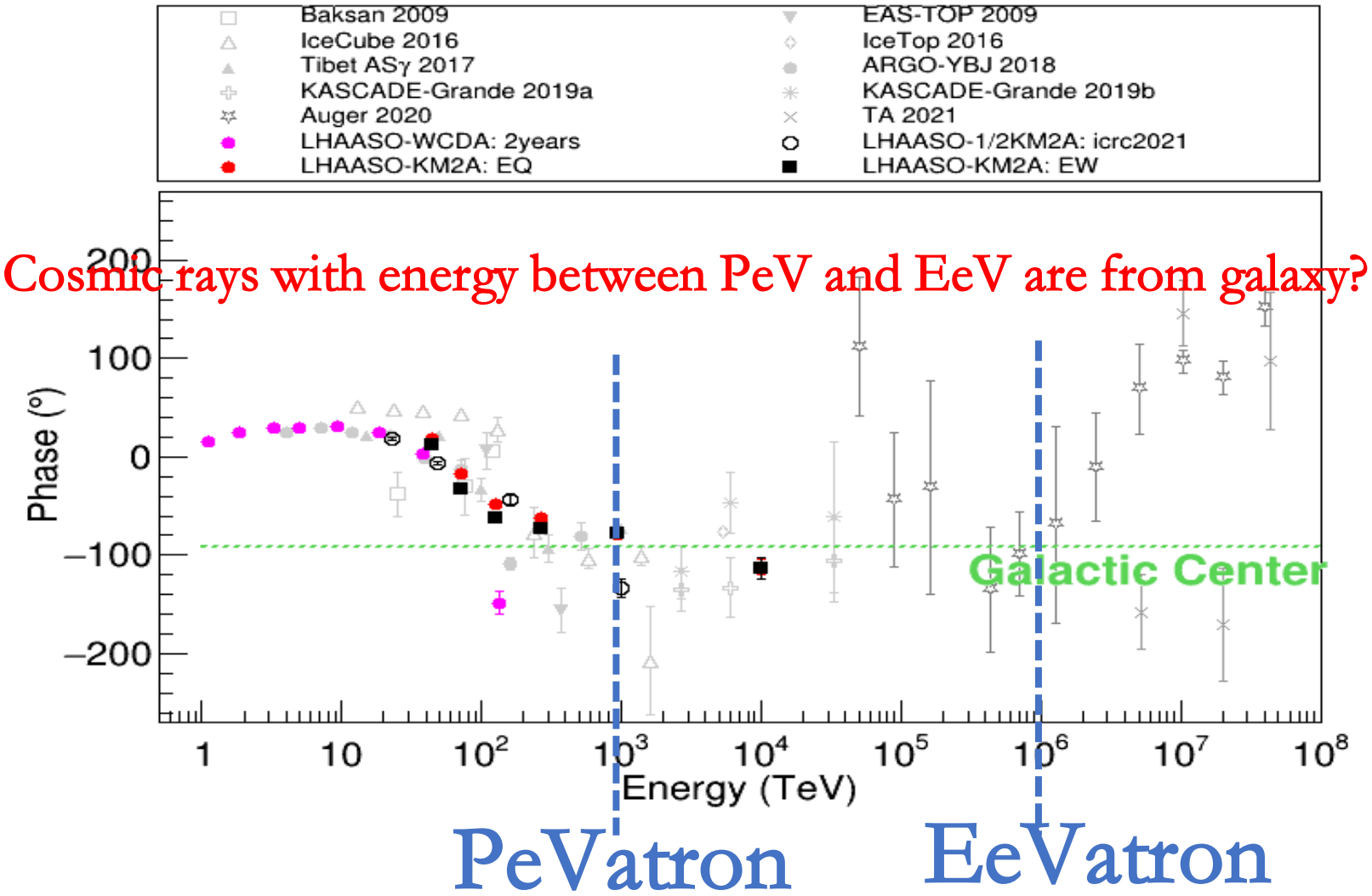
- Even though we can not rule out the contribution from GDE , the **main part** should from local accelerator.



Outline

- Introduction
- Cygnus region analysis
- Other cluster
- Conclusion

Cosmic ray anisotropy

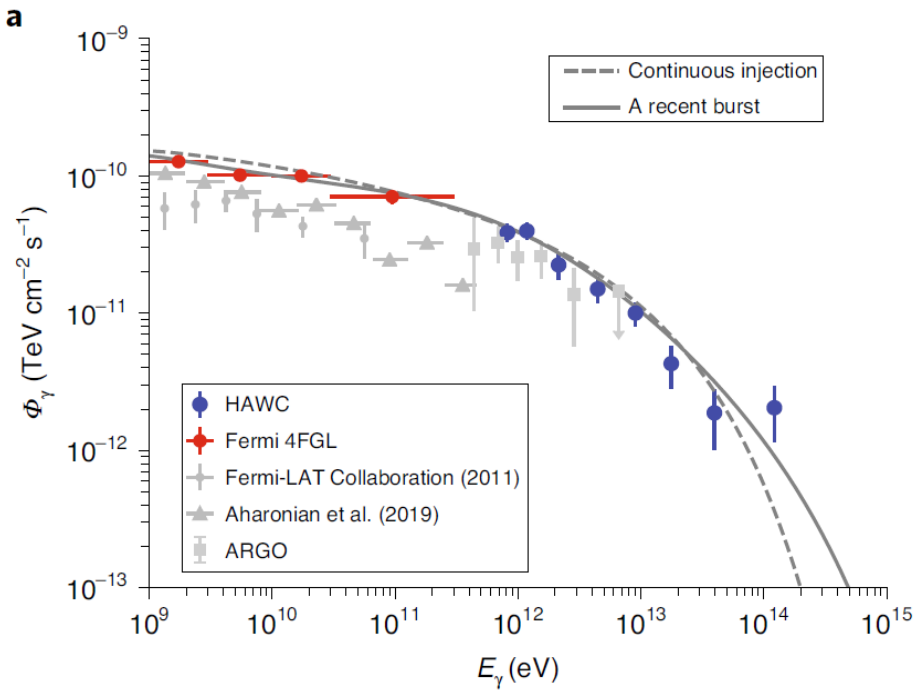


- There should be sources in our galaxy can accelerate particles to PeV or even up to EeV from the measurement of CRs at earth.

Possible candidates

Source name
LHAASO J0534+2202
LHAASO J1825-1326
LHAASO J1839-0545
LHAASO J1843-0338
LHAASO J1849-0003
LHAASO J1908+0621
LHAASO J1929+1745
LHAASO J1956+2845
LHAASO J2018+3651
LHAASO J2032+4102
LHAASO J2108+5157
LHAASO J2226+6057

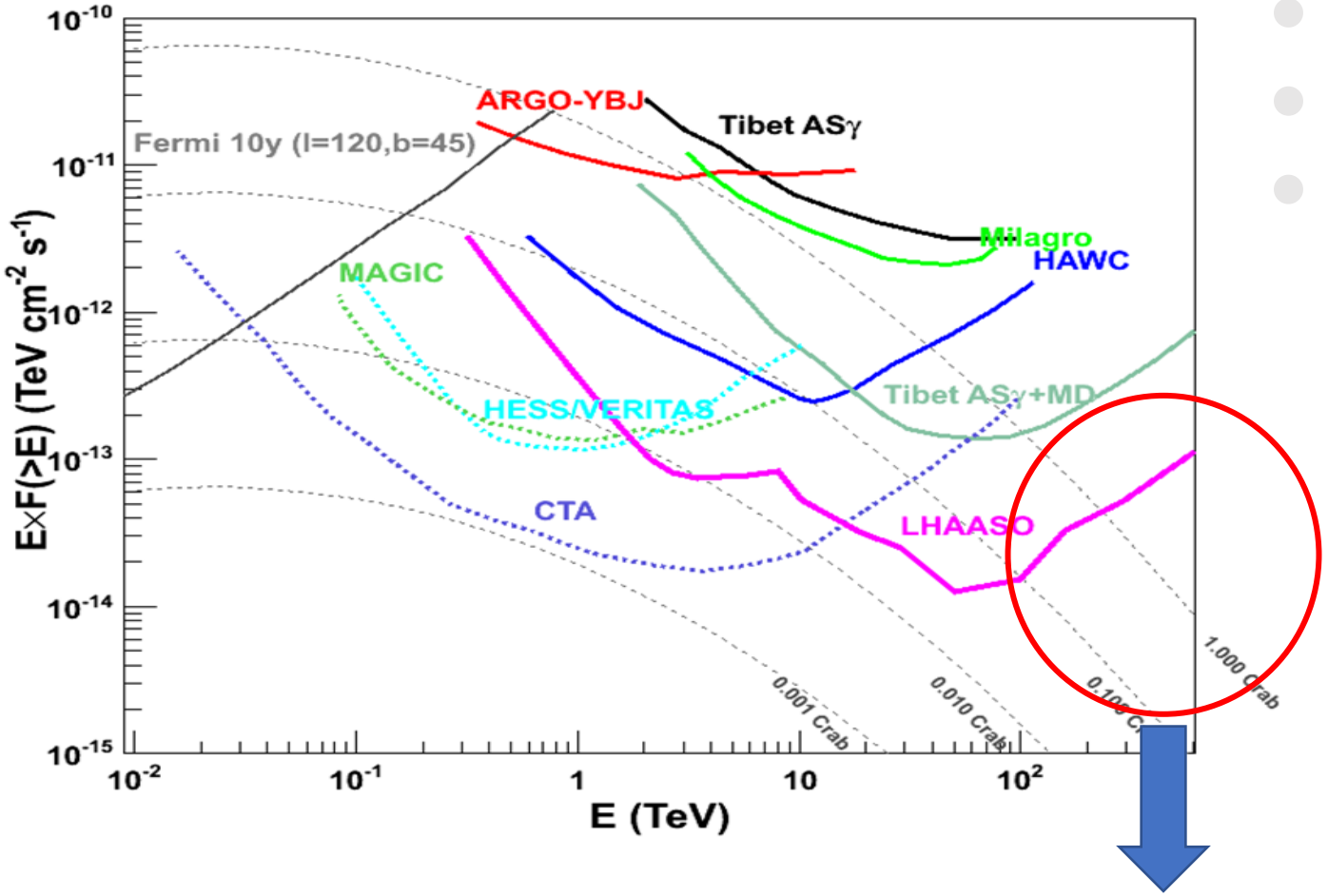
- The first **PeV** photo was detected from this source, which makes it a promising PeVatron candidate



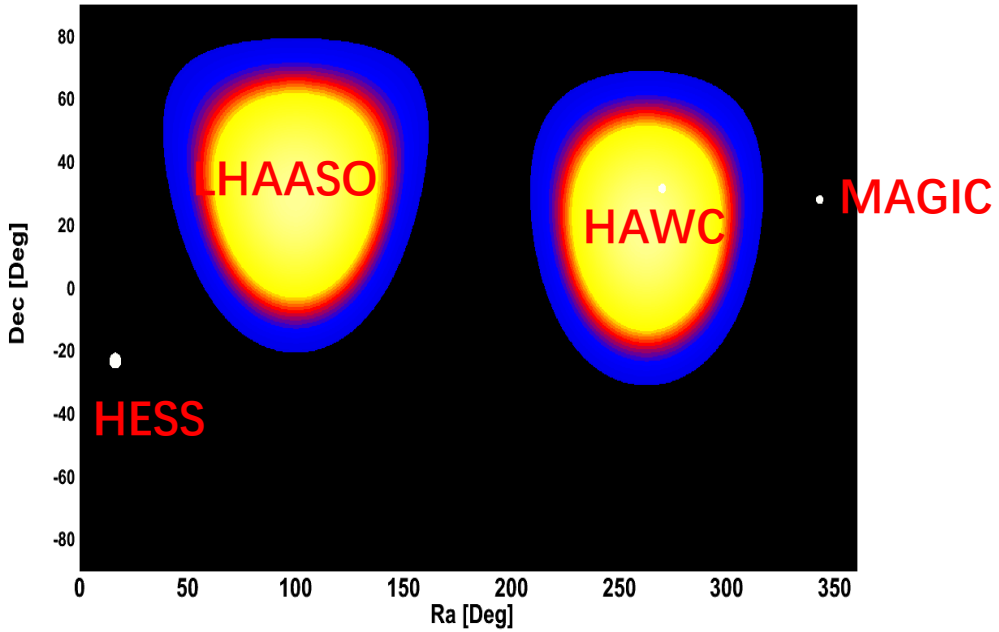
Is it correlated with Cygnus Cocoon?

Nature 594, 33–36 (2021)
Nat Astron 5, 465–471 (2021)

LHAASO sensitivity



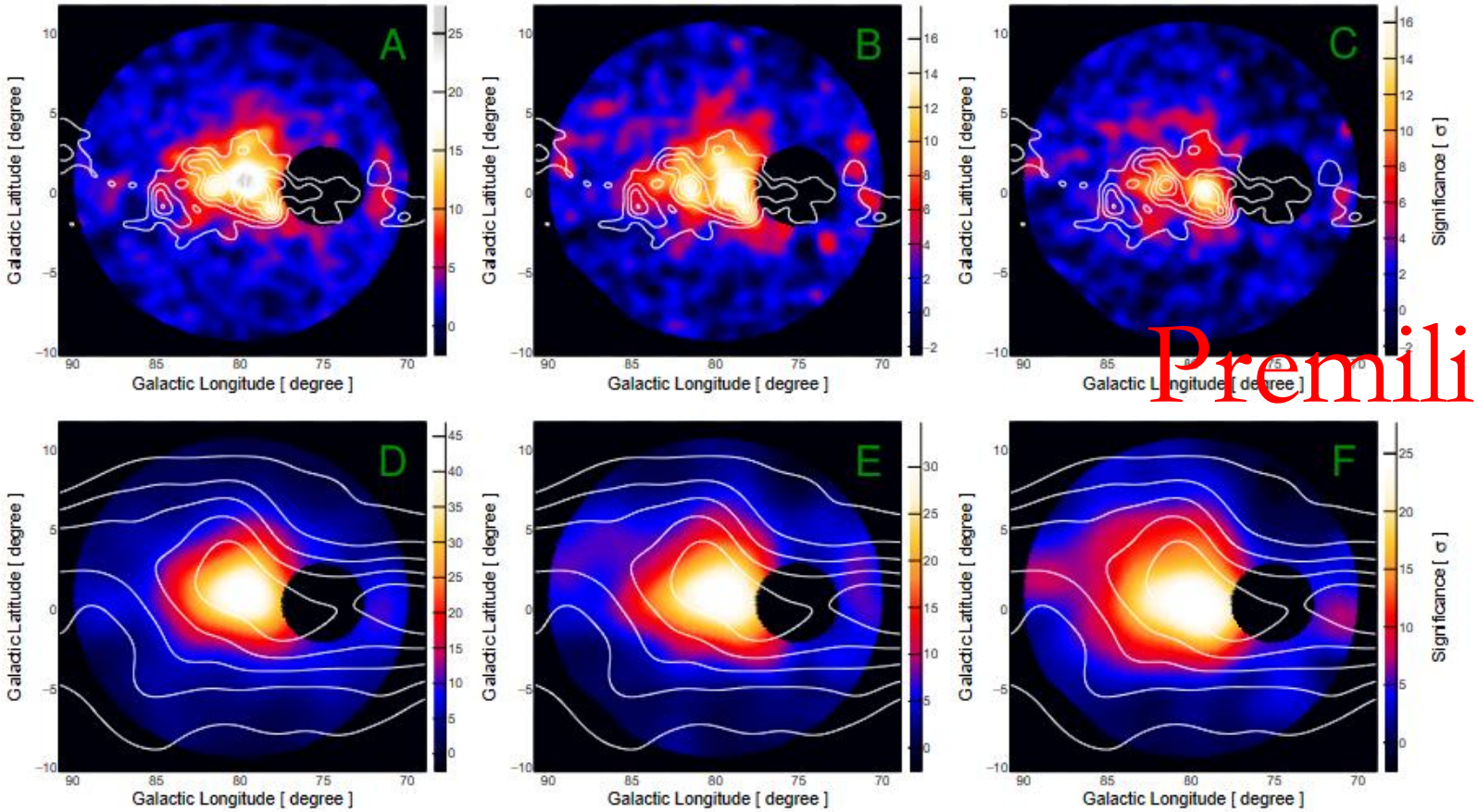
- High sensitivity: ~1% Crab @3TeV@100TeV
- Wide energy range: sub-TeV to 10 PeV
- Large FOV:~1.8 sr



The most sensitive gamma ray detector to explore this highest energy range

Correlation with Clouds

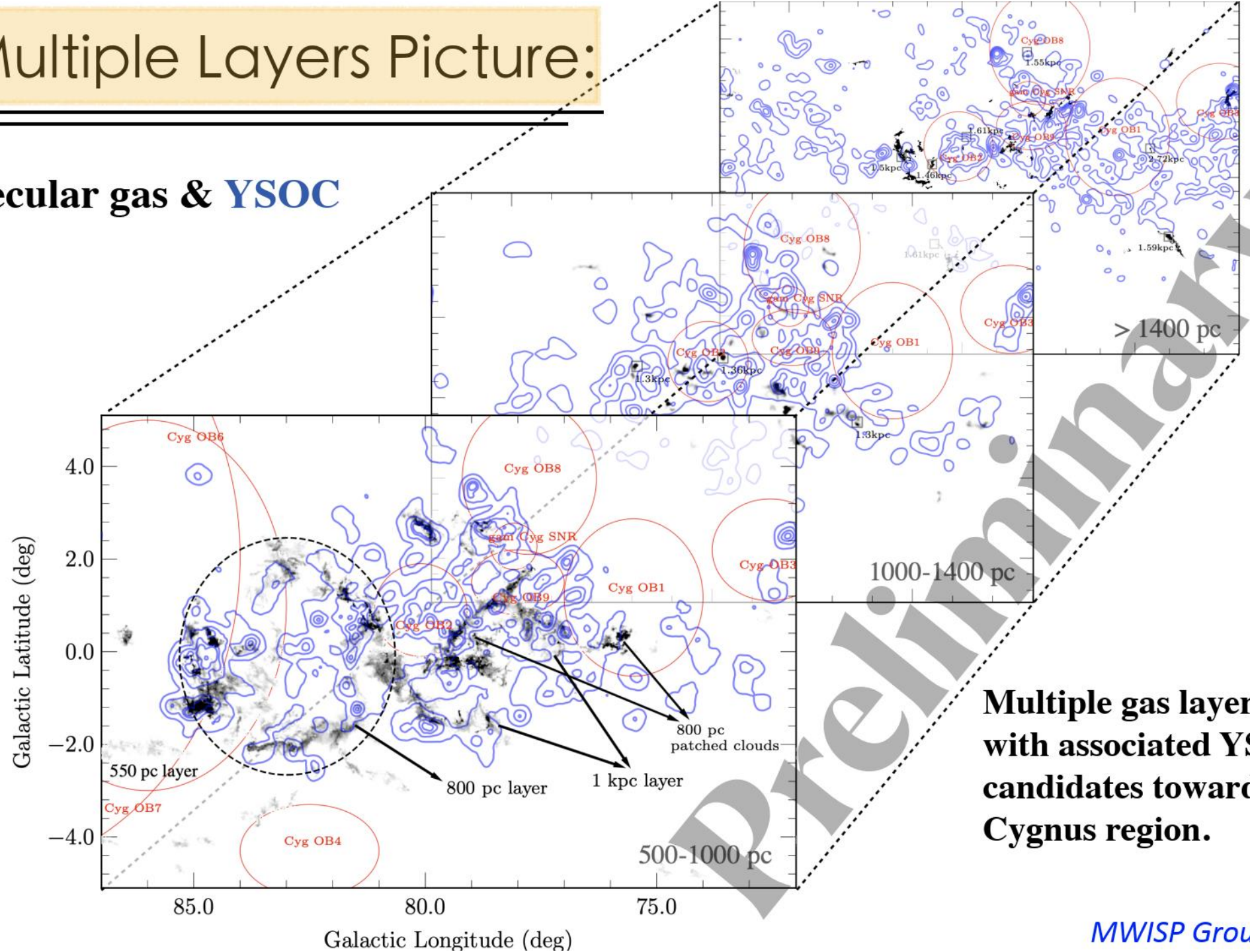
- The significance map is smoothed with a Gauss kernel=0.3^0(upper) and 1.0^0(lower);
- The contour is from CfA galactic CO survery (upper) and HI4PI 21-cm line survey(lower) ;



- Clear correlation with gas distribution, which indicates a hadronic origin.
- The signal is asymmetry and can at least extend to 10deg.

4, Multiple Layers Picture:

Molecular gas & YSOC



Multiple gas layers with associated YSO candidates toward the Cygnus region.

MWISP Group, to be submitted