

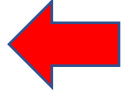
HIGH ENERGY COSMIC RAYS EXPERIMENTS AND FINDING PEVATRONS

Zhen Cao

Institute of High Energy Physics, Beijing

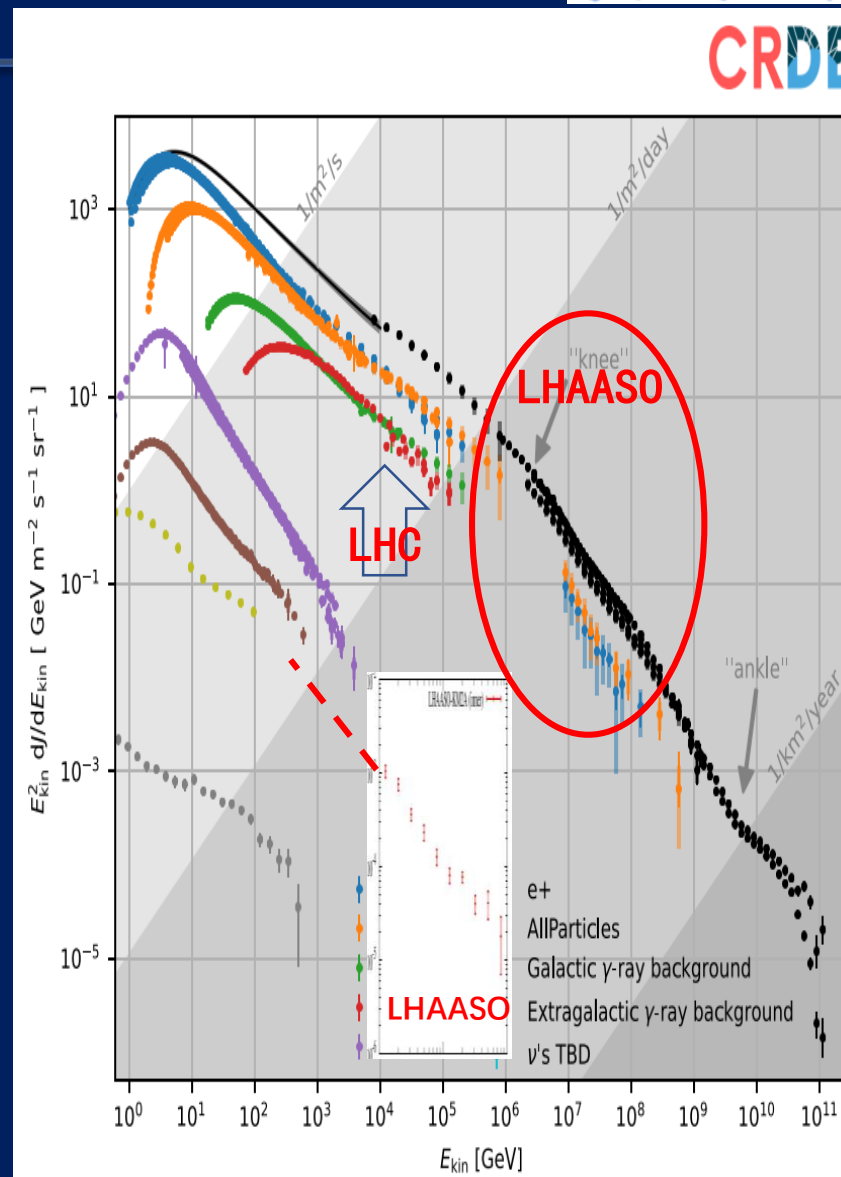
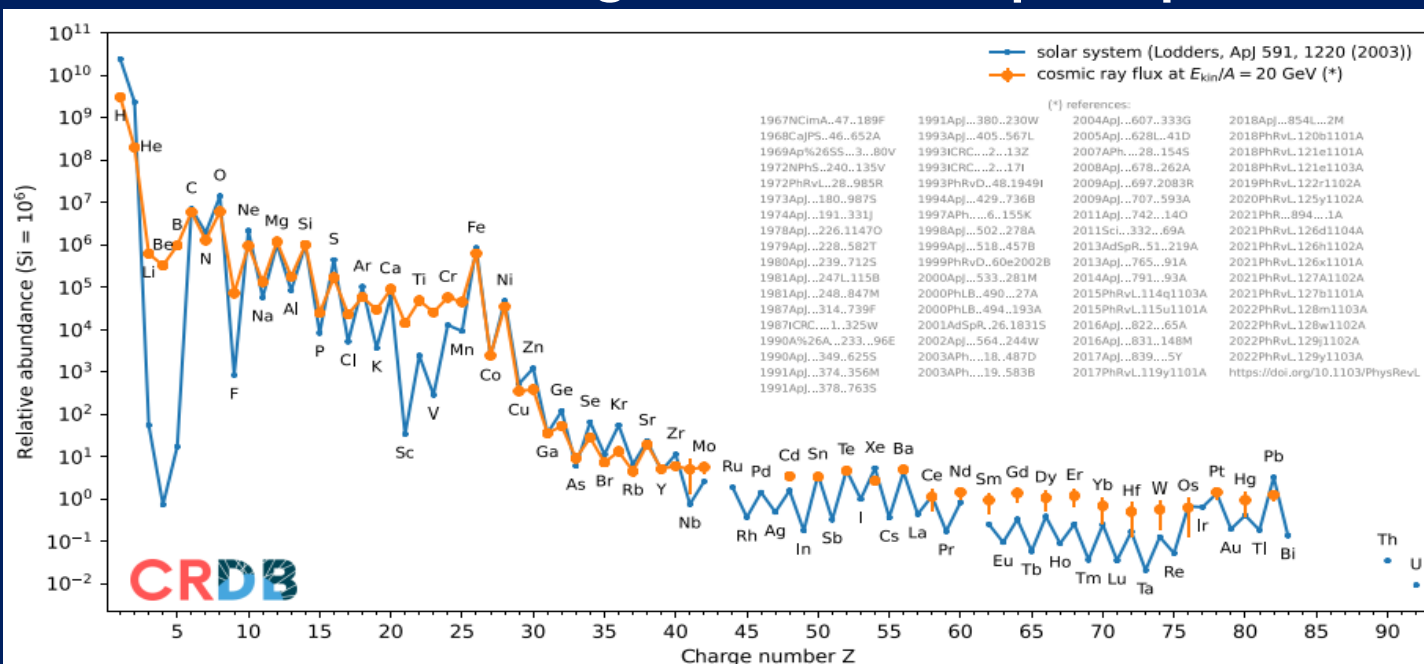
60th Course News from the four interactions, Erice, June 14-22, 2024

Content

- Introduction and Experiments 
- Sky Survey for Source Candidates
- “Extreme” Accelerators
 - 1st CR Super-PeVatron: The Cygnus Bubble
 - Extreme Electron Accelerator: The Crab Nebula and a new source
 - Black Holes as PeVatrons
- Future Experiments

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



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 and UHECRs >1 EeV

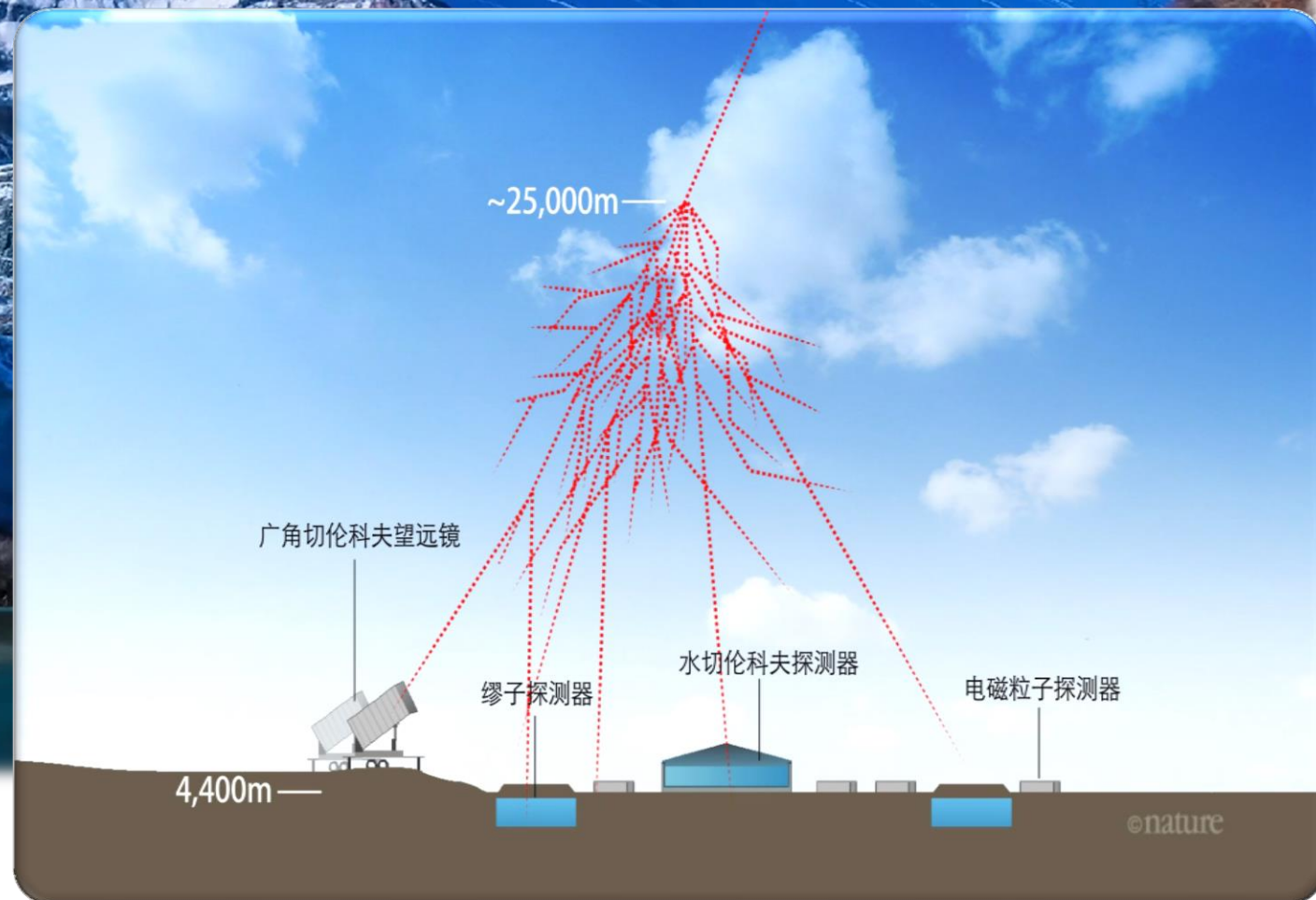
Compositions : individual species H, He and Fe

Anisotropy: (1 TeV to 10 PeV)

New Physics Front: DM, LIV, etc.

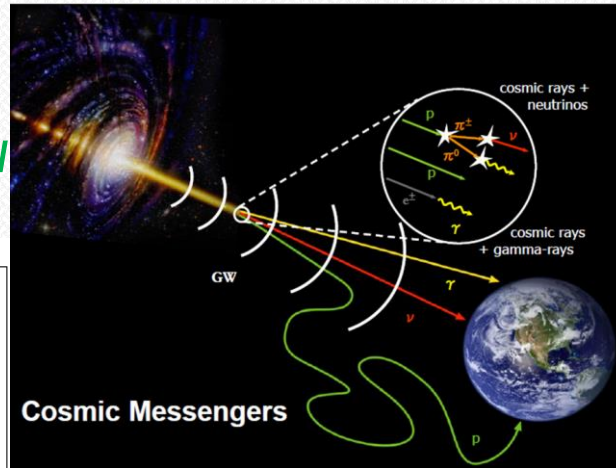
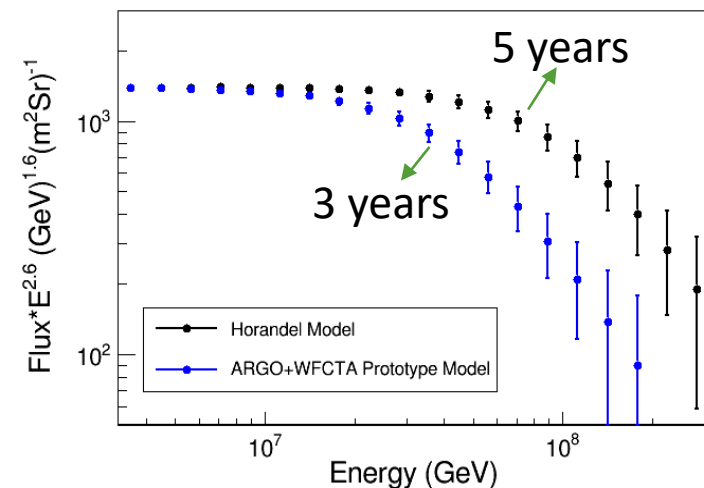
Large High Altitude Air Shower Observatory

LHAASO



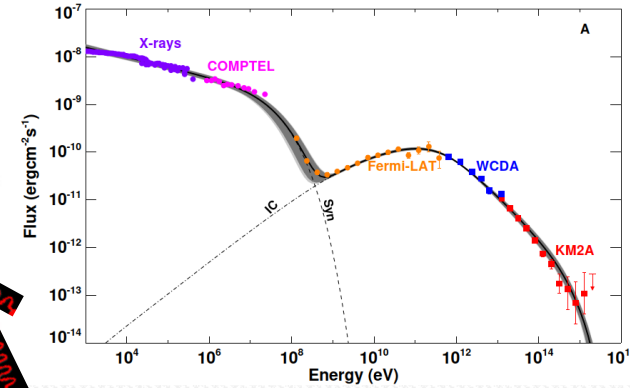
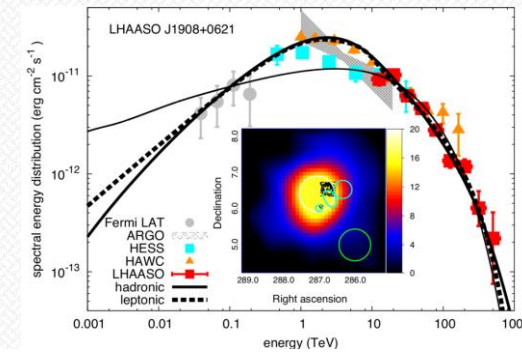
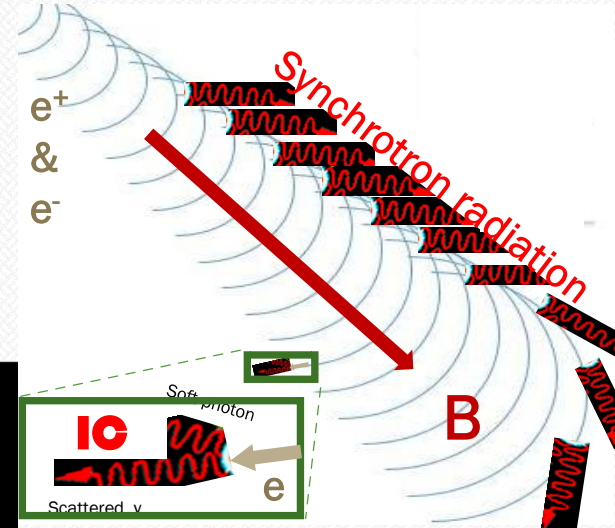
Systematically Study the Problem of Origin of CR

- Route to the ultimate goal: full coverage of
 - Acceleration study at sources
 - Ground measurements of the CR distributions
 - Complete and systematic investigation
- Every thing is essential:
 - High precision measurements
 - Careful phenomenological study



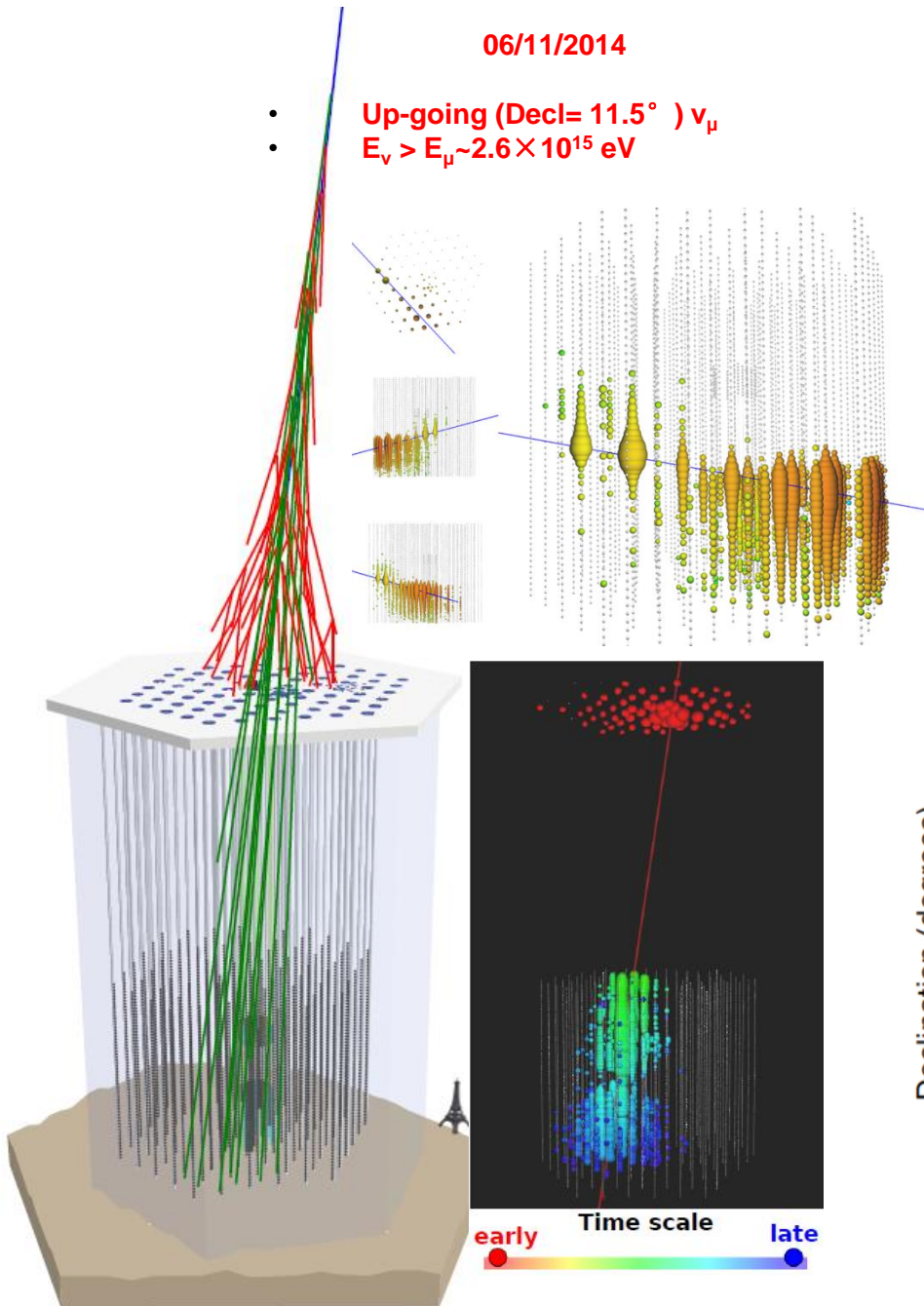
4) High precision measurements of CS distributions on the ground

1) High precision measurement of PeVatrons

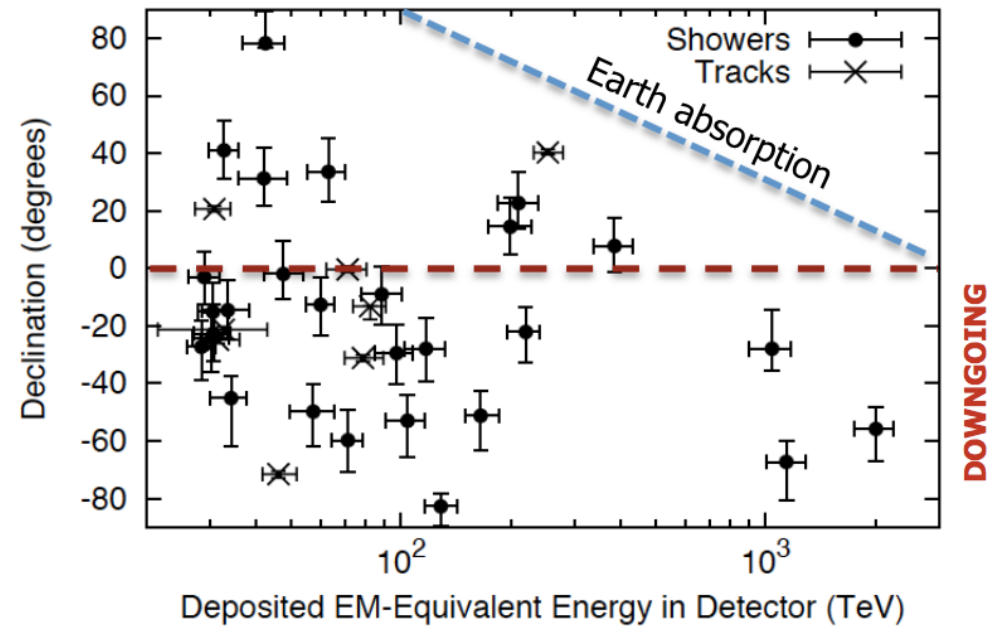
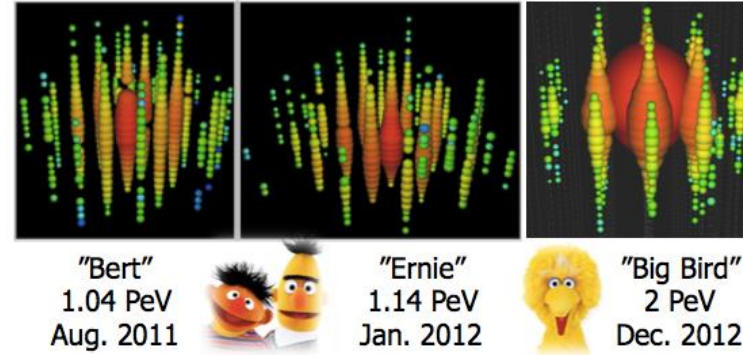


2) Identification of acceleration and radiation mechanism and phenomenological study

3) Phenomenological investigation of CR transportation in the region nearby sources, interstellar, and inter planetary space

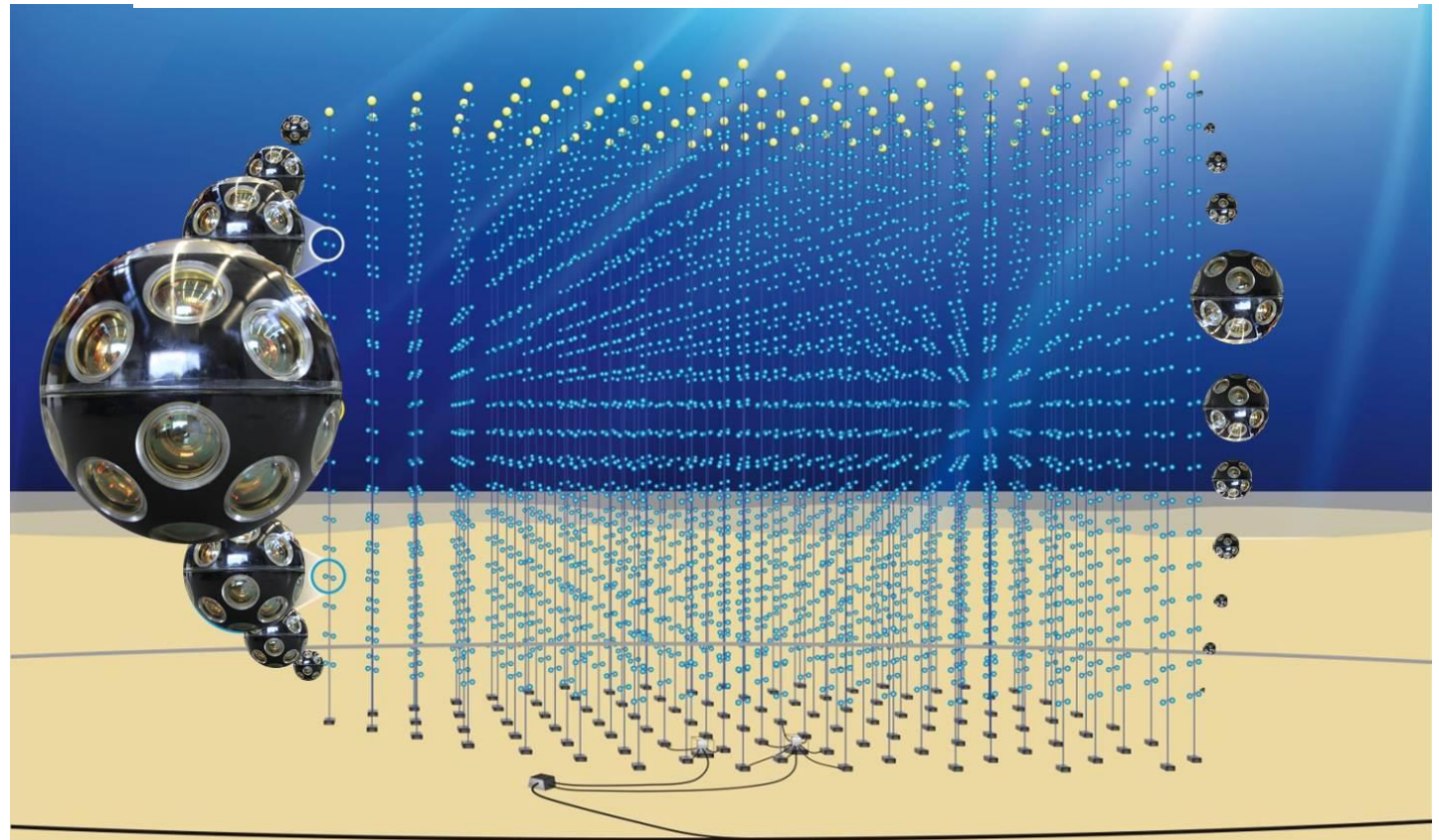
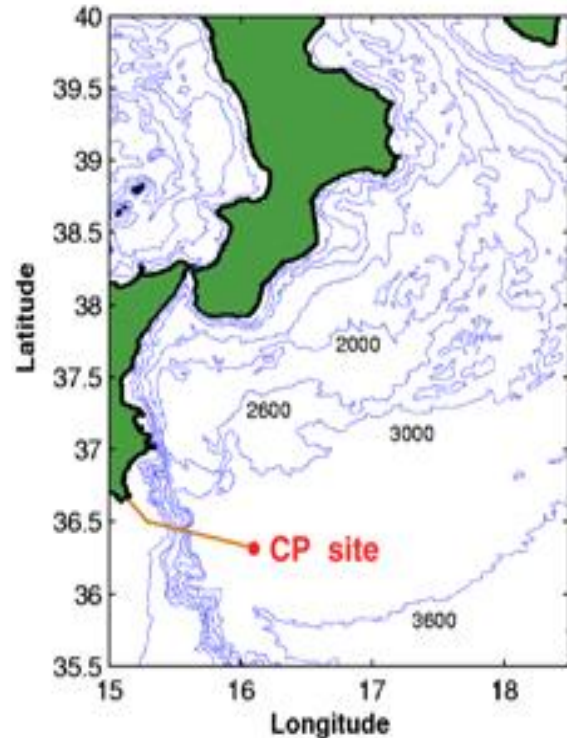
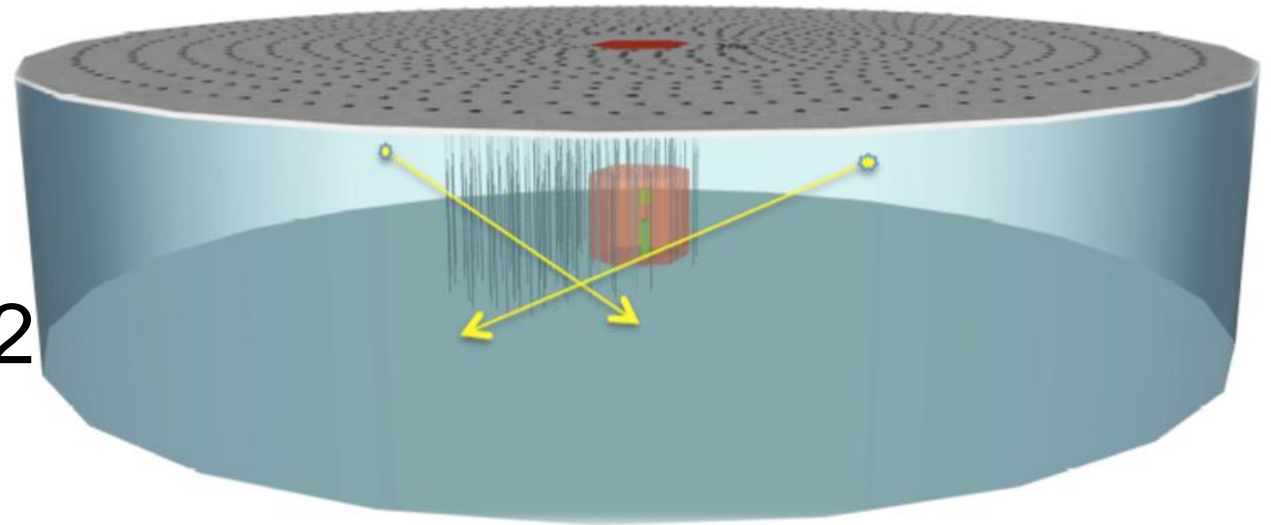


Neutrino Astronomy

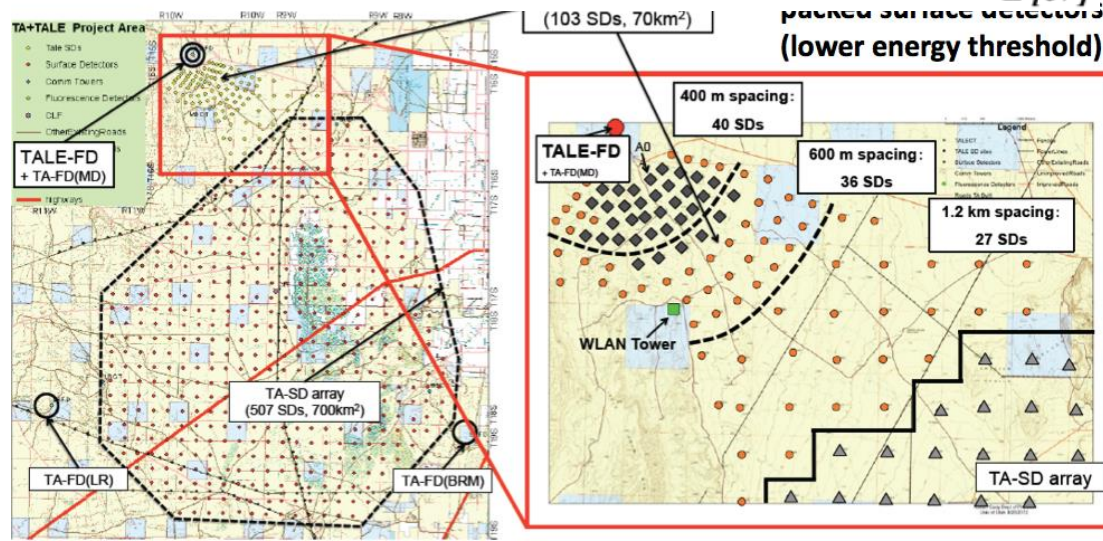
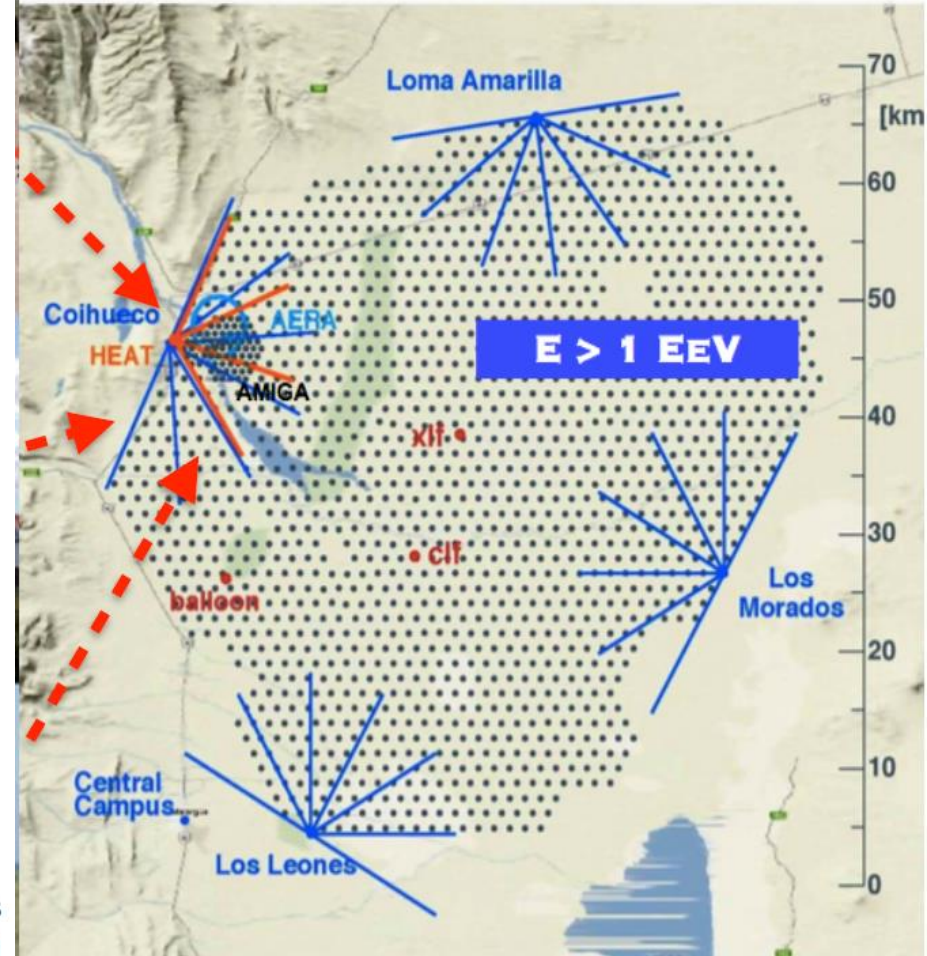
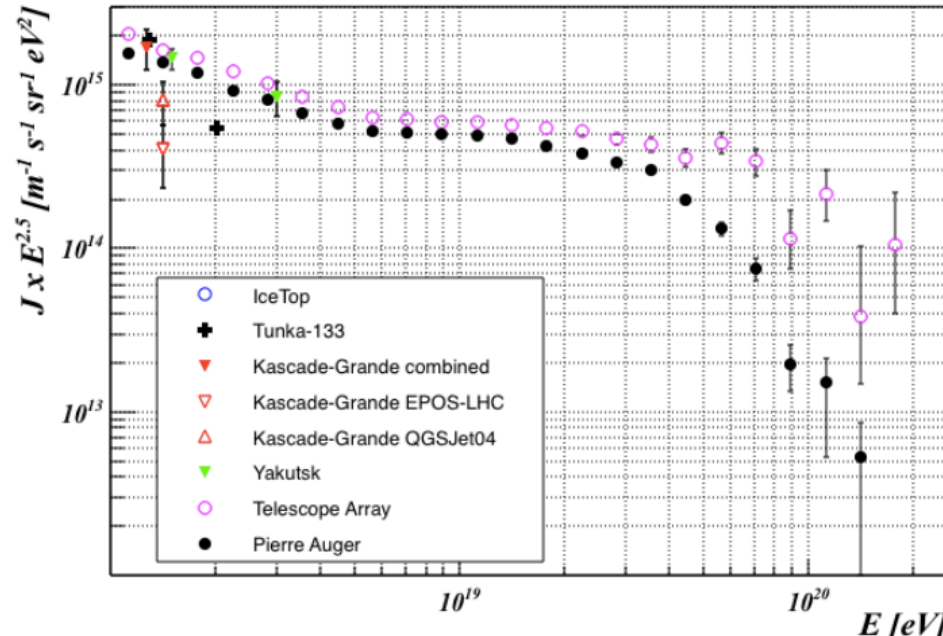


Neutrino Astronomy

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



UHECR particle astronomy



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

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)

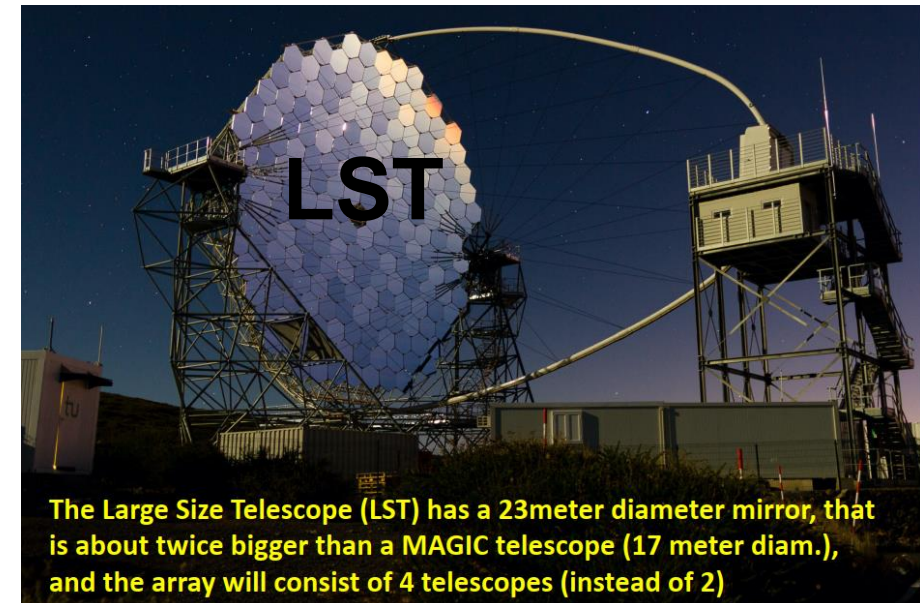
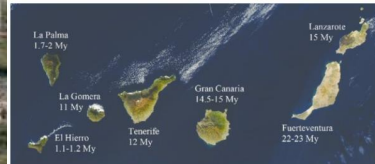
X4 ?

γ -ray Astronomy

Image Atmospheric Cherenkov Telescopes: pointing observation

Observatorio Roque de los Muchachos (2200 meter a.s.l.)
La Palma, Canary islands (Spain)

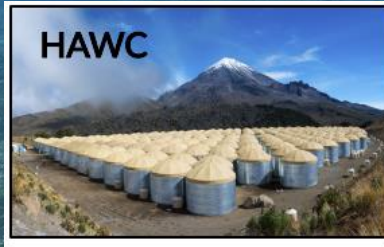
MAGIC



Ground Detector Array: surveying

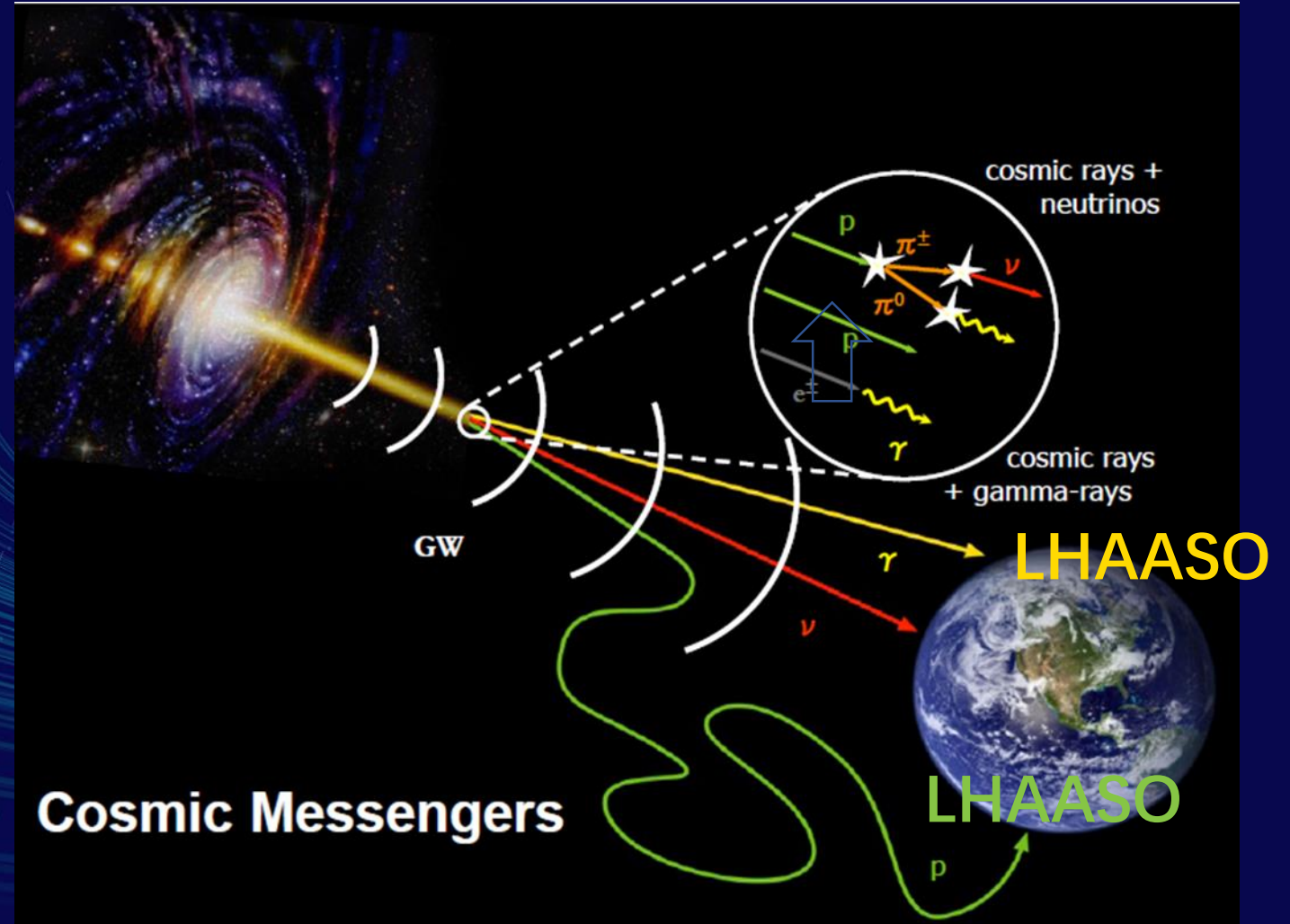
Bird's eye view of LHAASO, 2021-08

- **Location:** $29^{\circ}21'27.6''$ N , $100^{\circ}08'19.6''$ E
- **Altitude:** 4410 m
- **2021-07 completed built and in operation**

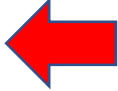


LHAASO: Dual purposes Instrument

LHAASO is
a γ -ray Telescope
and
a CR detector

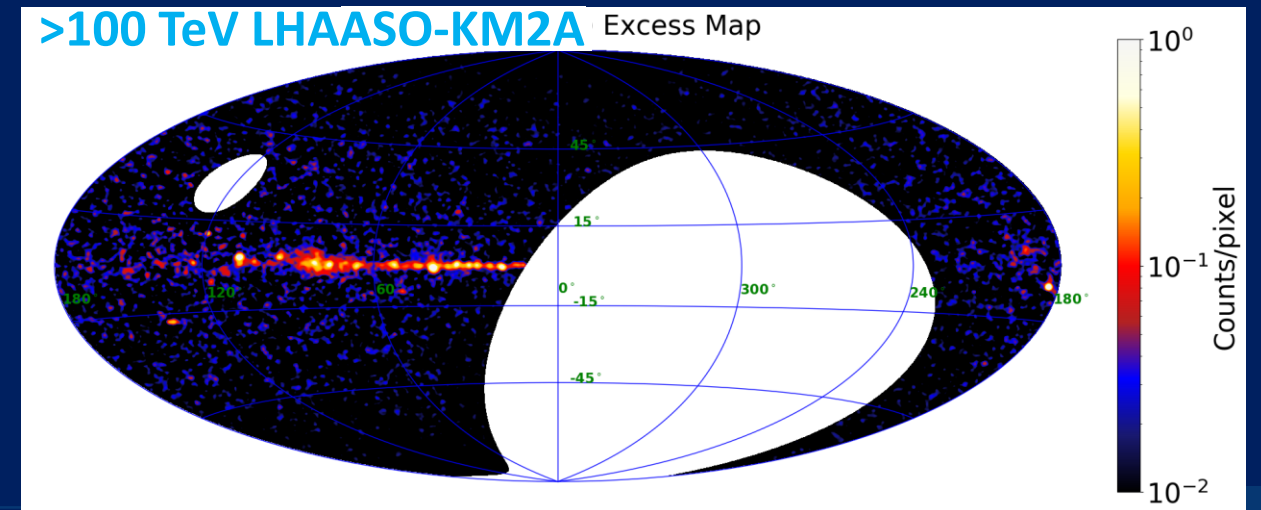
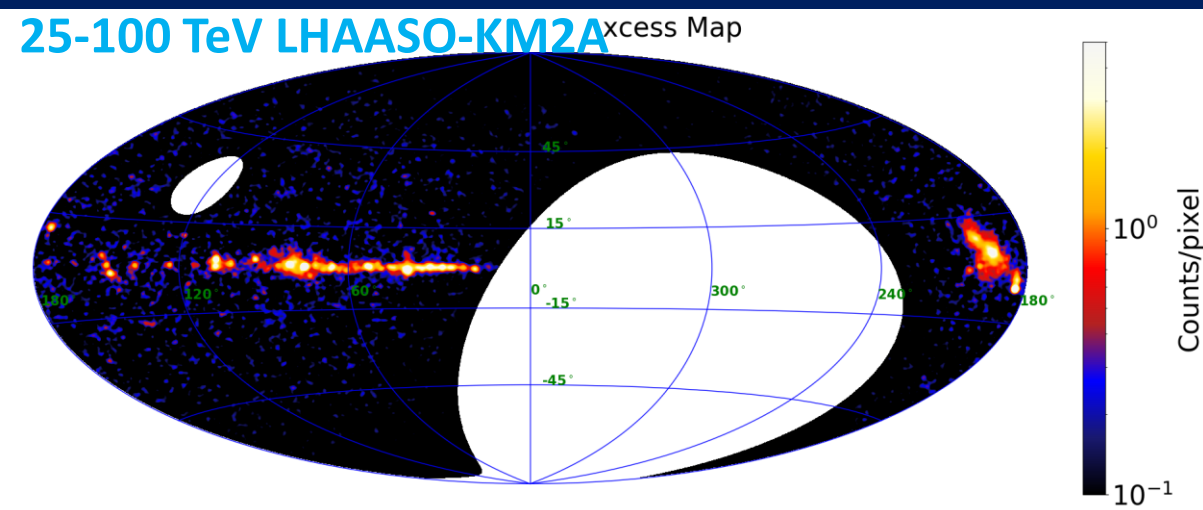
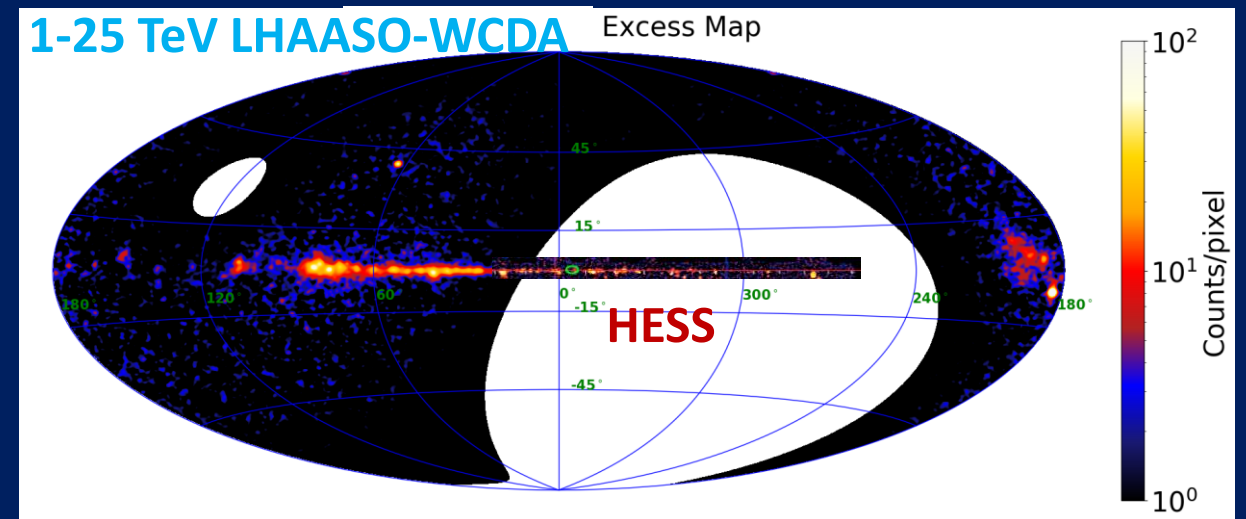
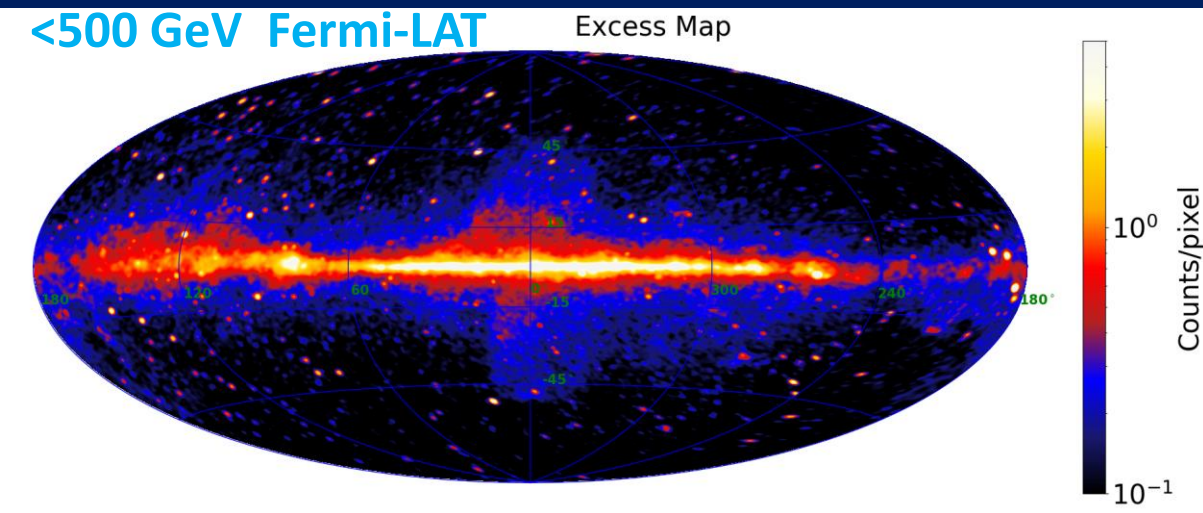


Content

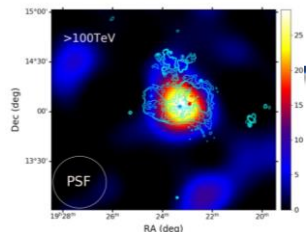
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UHE γ -ray Astronomy: **survey for sources**

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



Possible Source Candidates



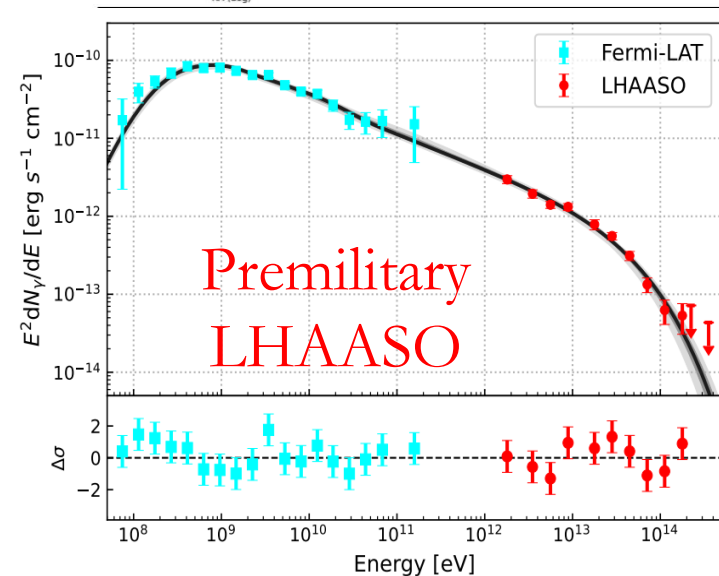
W51C



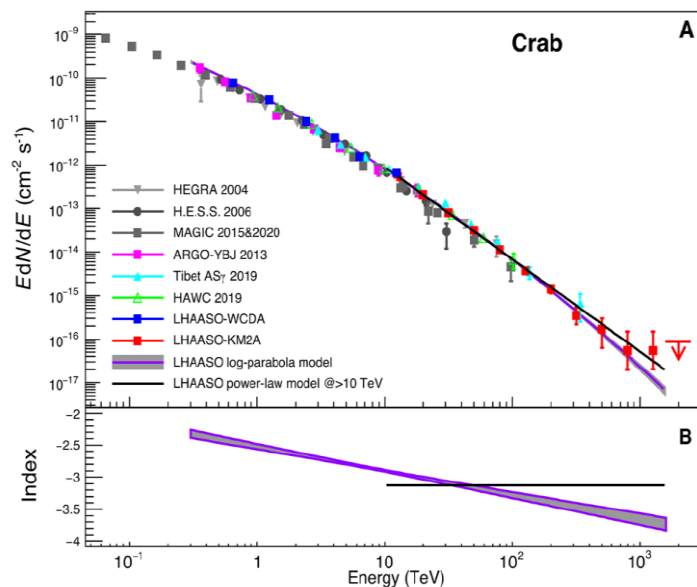
Crab



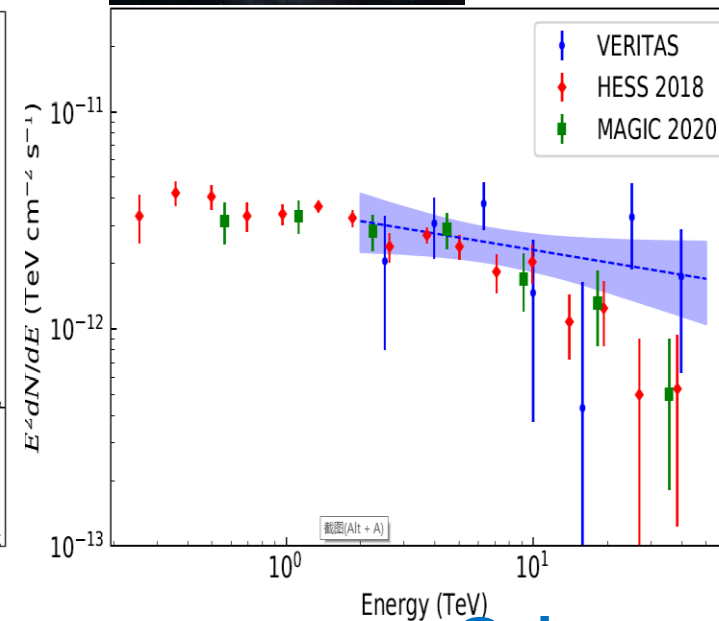
G.C. by IACTs



SNR



PWN



Other sources

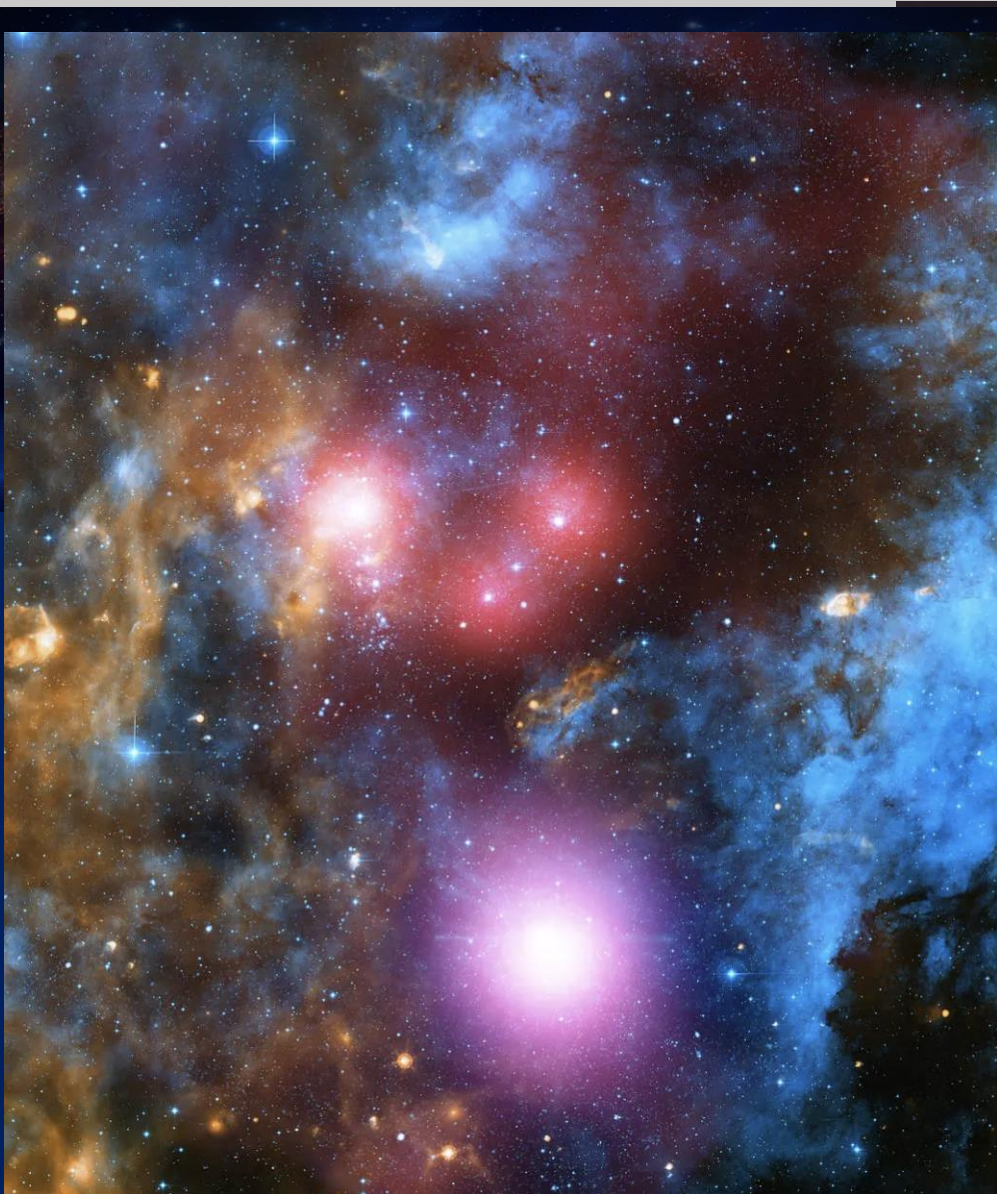
Many types of sources have the potential to accelerate particles to 1 PeV and above

A&A 671, A12 (2023)

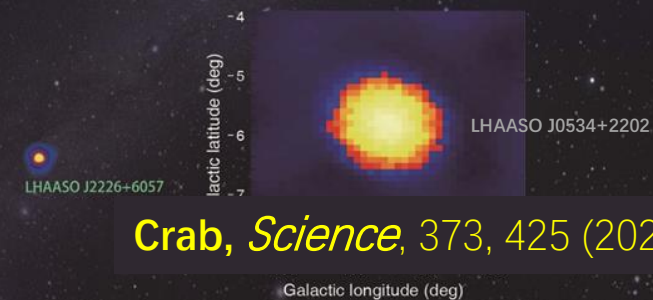
Science 10.1126/science.abg5137 (2021).

The Astrophysical Journal, 913:115 (11pp), 2021 June 1

The 1st CR-Source Candidate by



Cygnus Bubble,
Science Bulletin,
arXiv:2310.10100



2.5 PeV

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

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**Acceleration
region**

B



• **LEP**

• **Electron
accelerator**

• $E_e \lesssim 0.1 \text{ GeV}$

• **LHC**

• **Proton
accelerator**

• $E_p \lesssim 10 \text{ TeV}$

• **FCC/CEPC**

• $E_e \lesssim 1 \text{ TeV}$

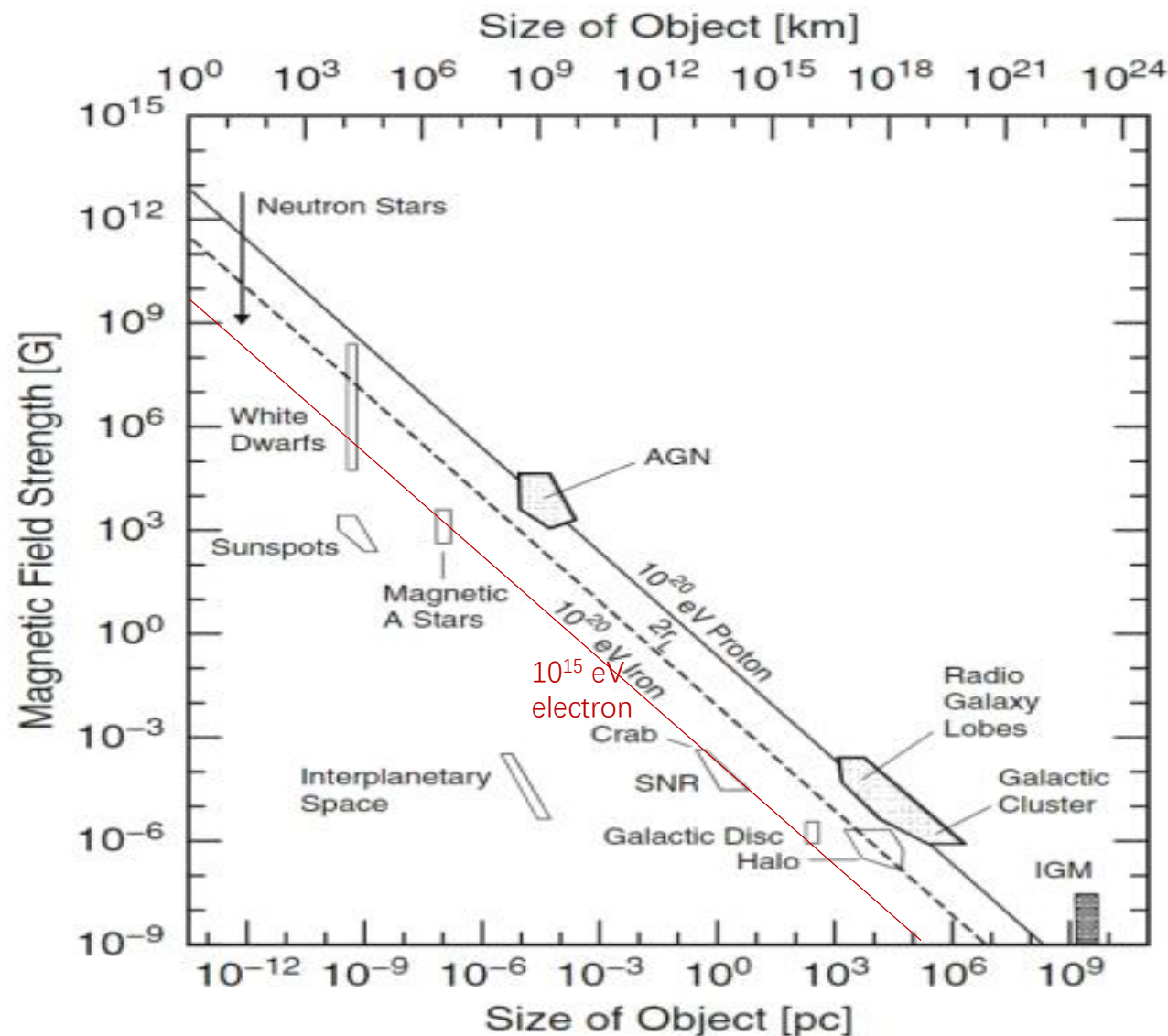
Necessary Condition: Hillas Diagram

The size of the source
vs.

The magnetic field

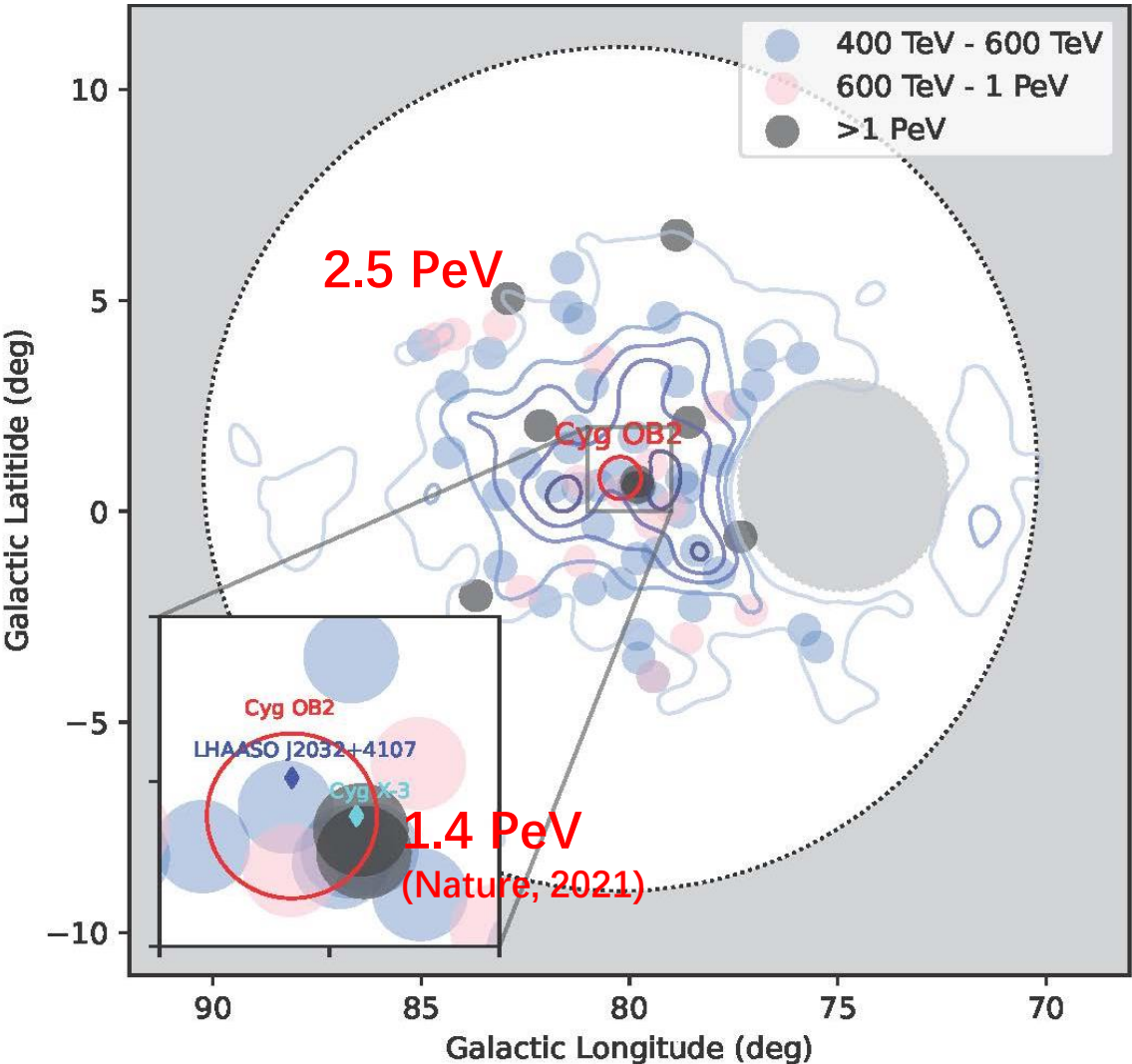
Two issues:

1. Confinement
2. Acceleration rate



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

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



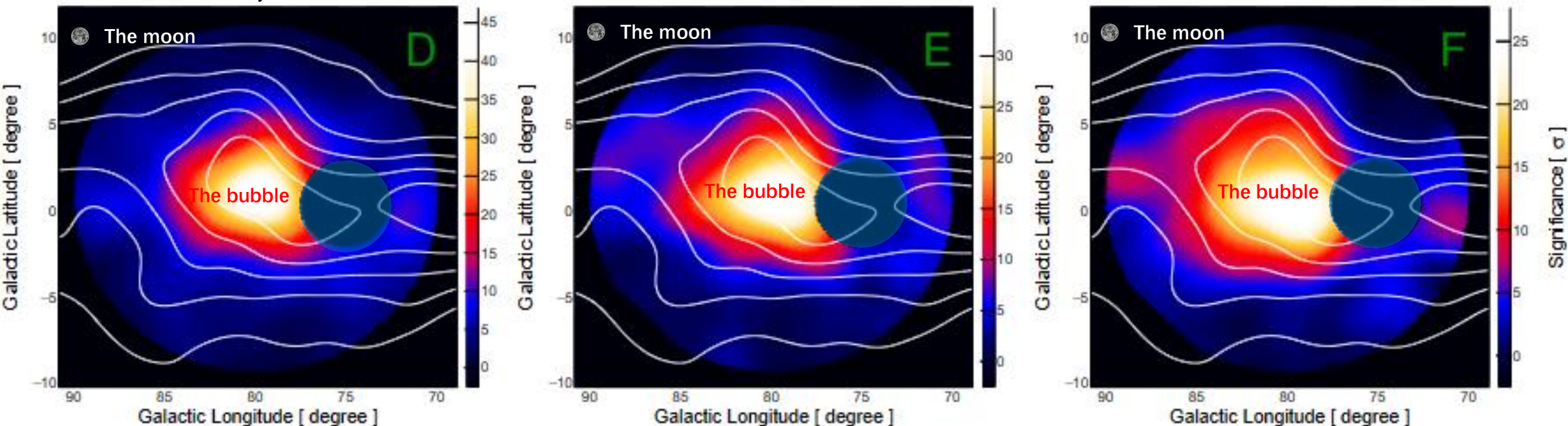
8 γ 's above 1 PeV!

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

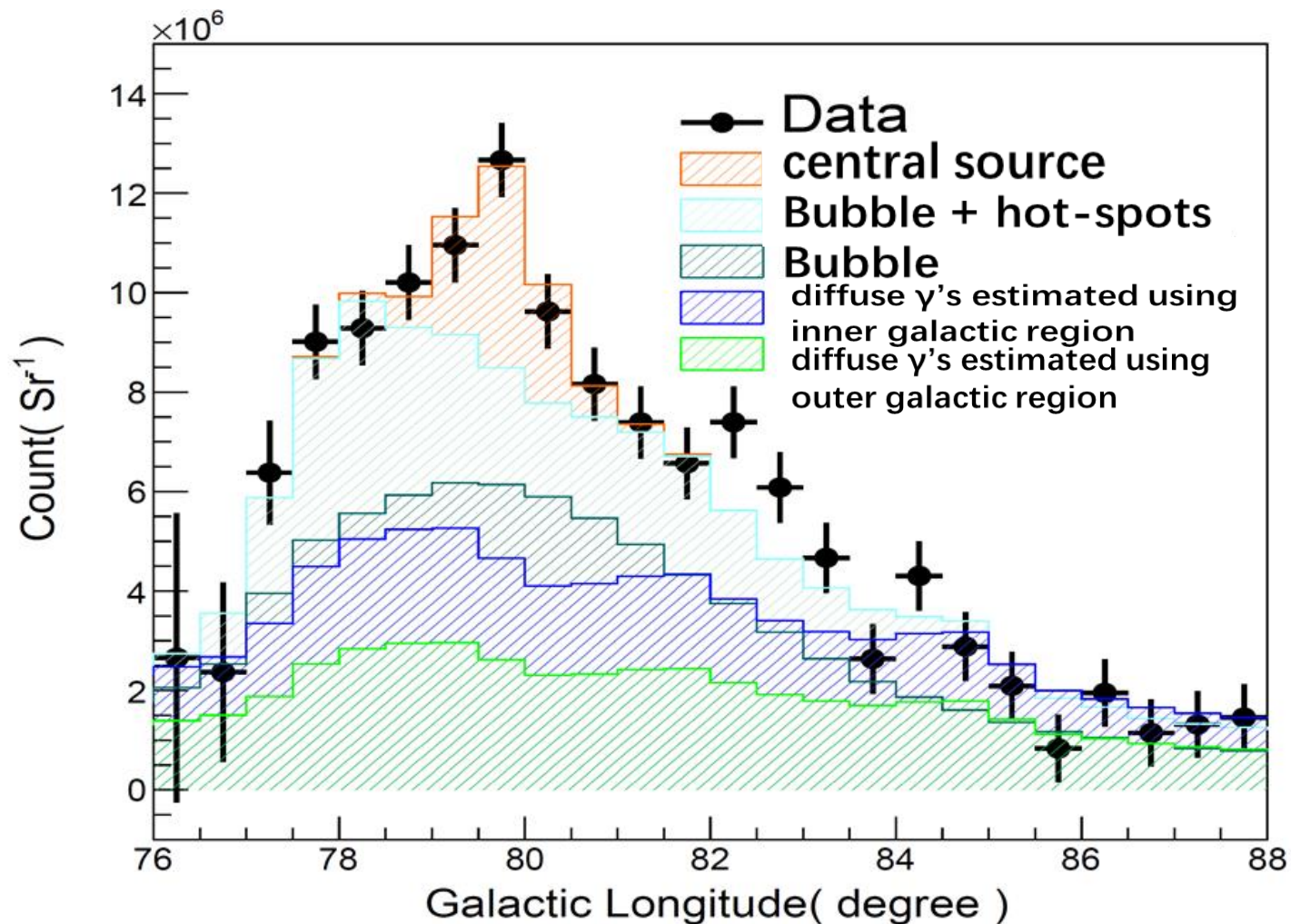
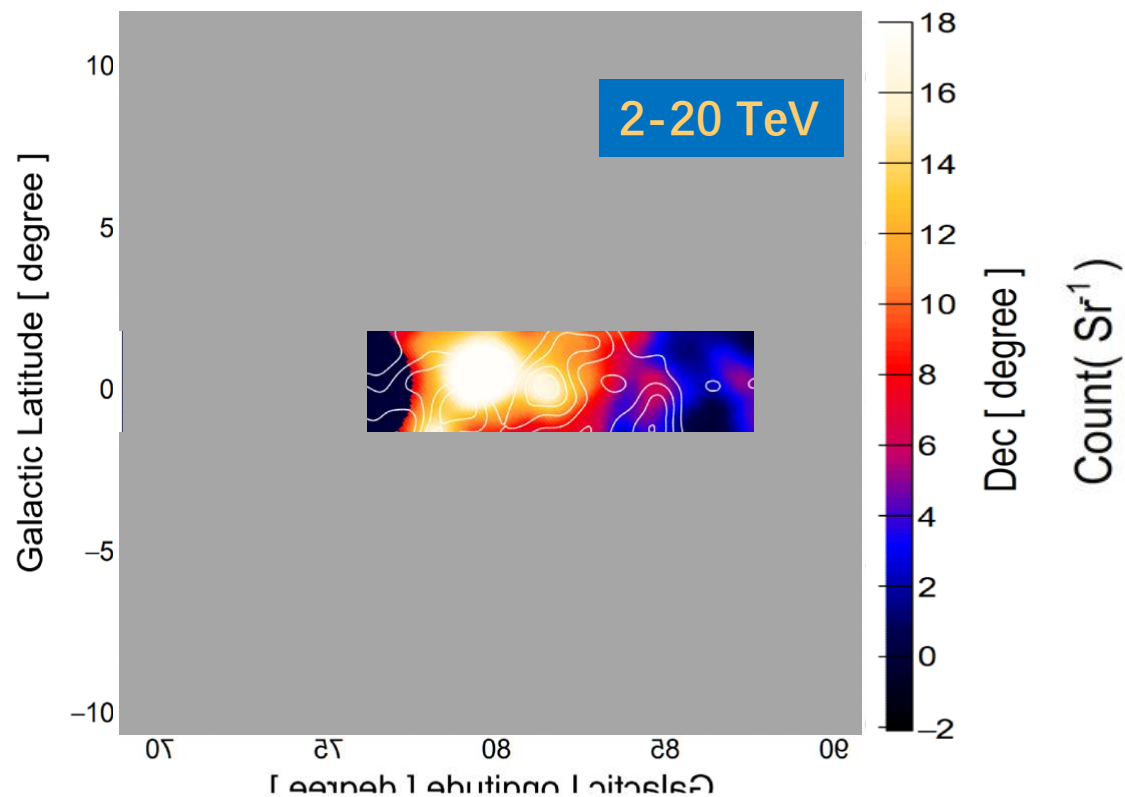
Association with HI gas distribution over ~ 200 pc

- 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 disk and extends to 10°



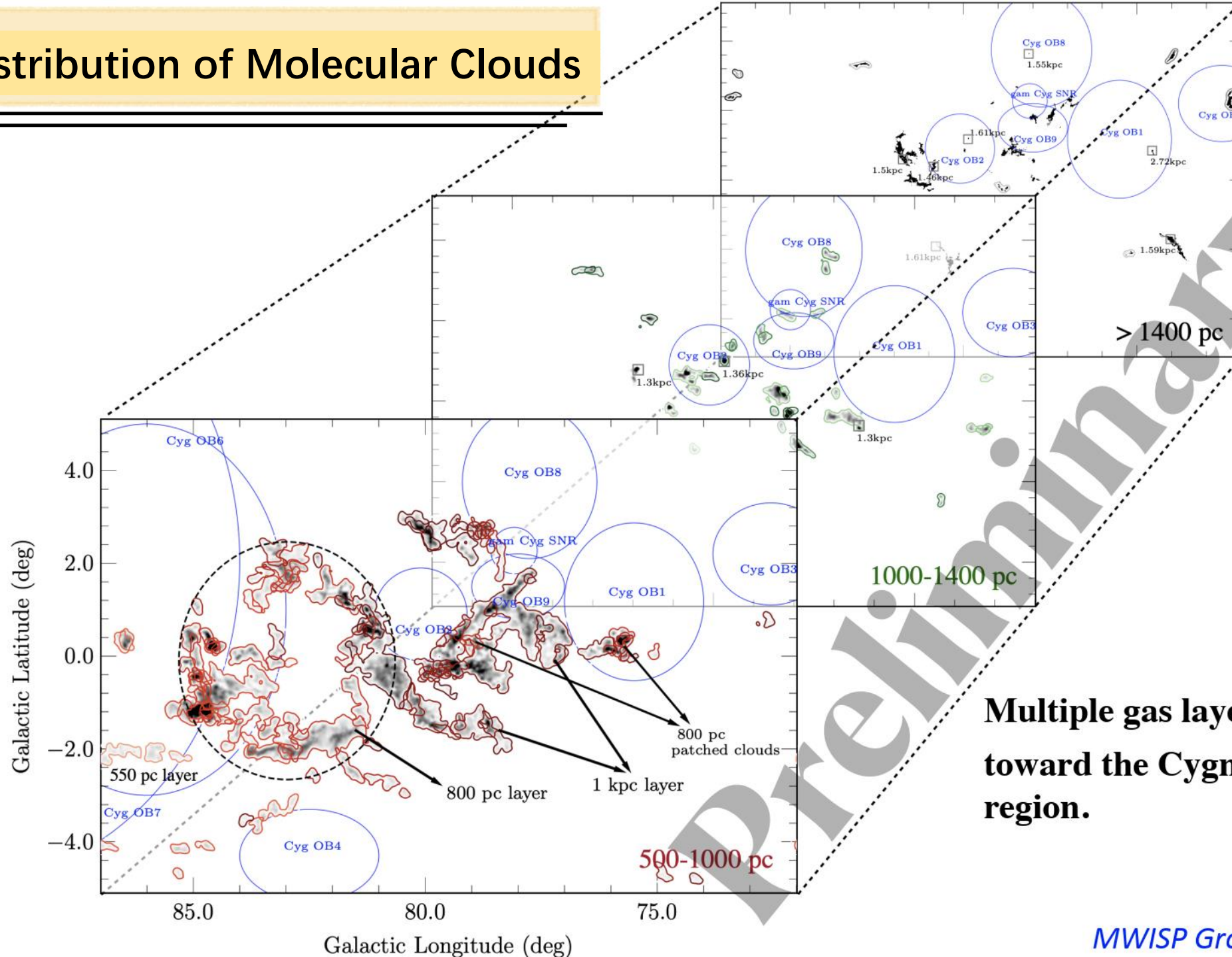
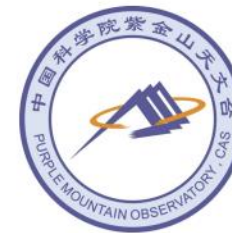
The Bubble at 2-20 TeV by WCDA

Clumpy structure of the Bubble: hot spots



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

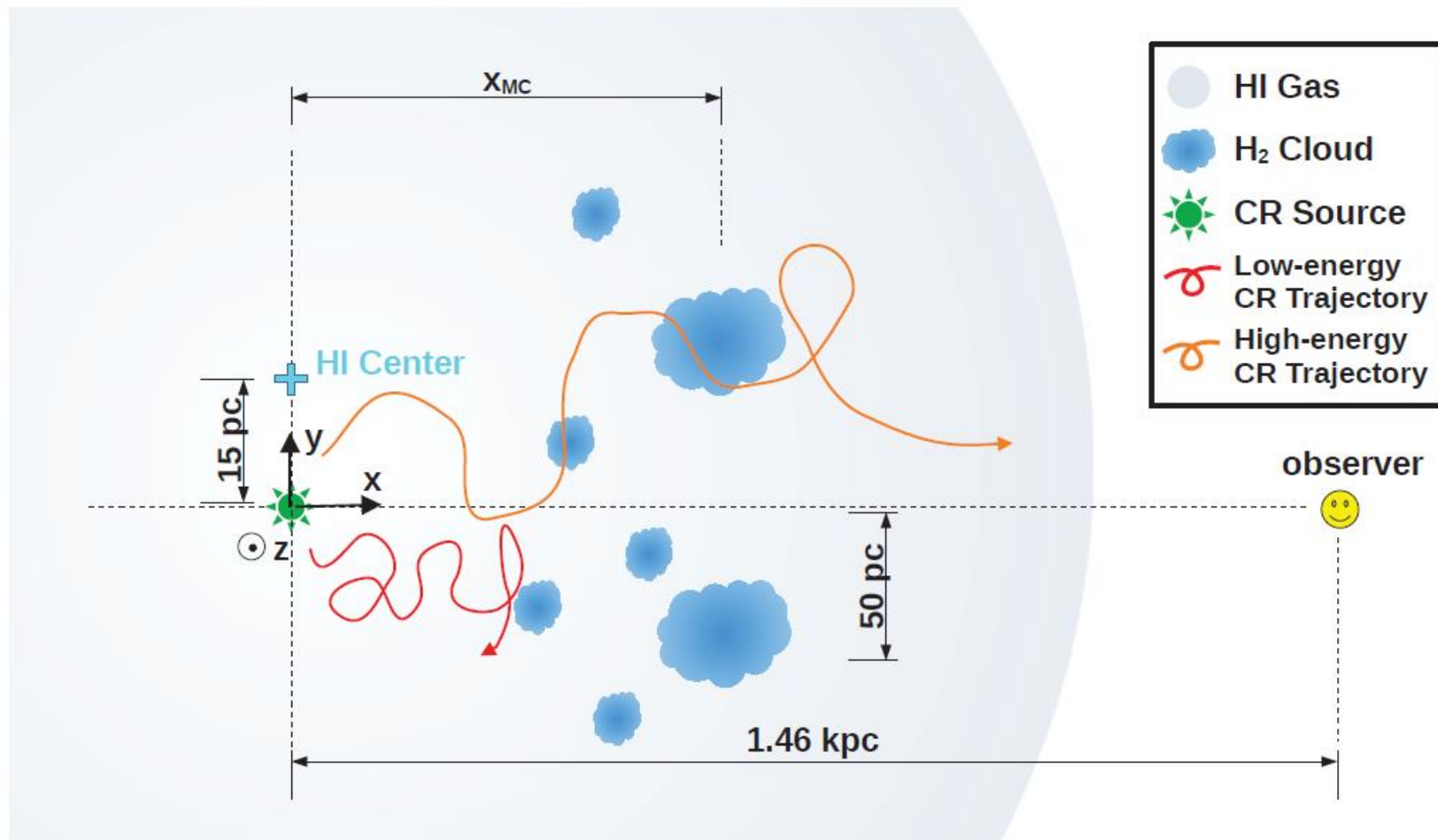
3-D distribution of Molecular Clouds



**Multiple gas layers
toward the Cygnus
region.**

HE Protons injection from the core region

- High energy cosmic rays escape from the accelerator in the core
- Diffusing through the H I gas and producing γ 's in p-p collisions
- Hitting on clumpy molecular clouds making hot-spots
- Slow diffusion $\sim 1\%DC$ in ISM

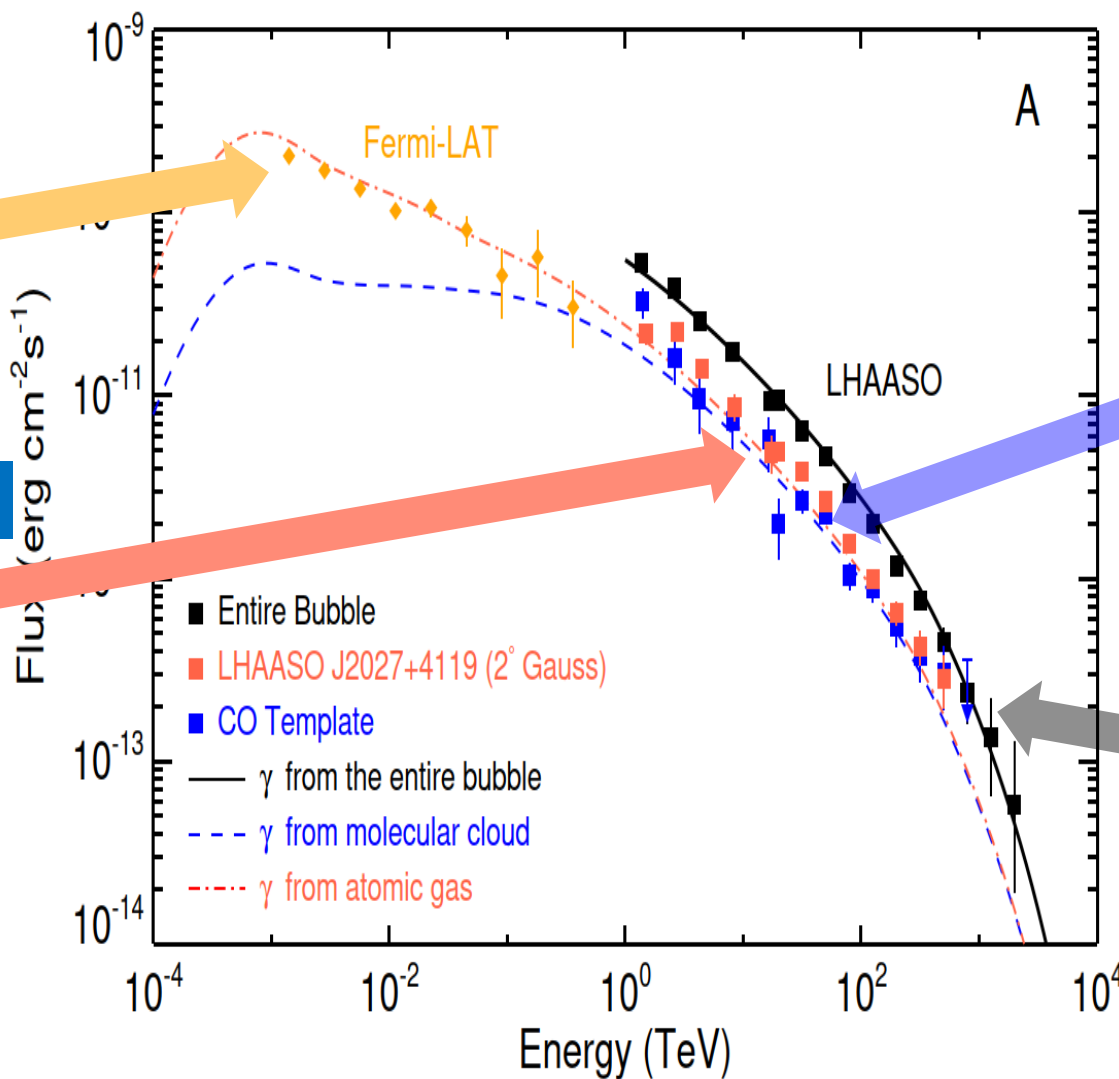
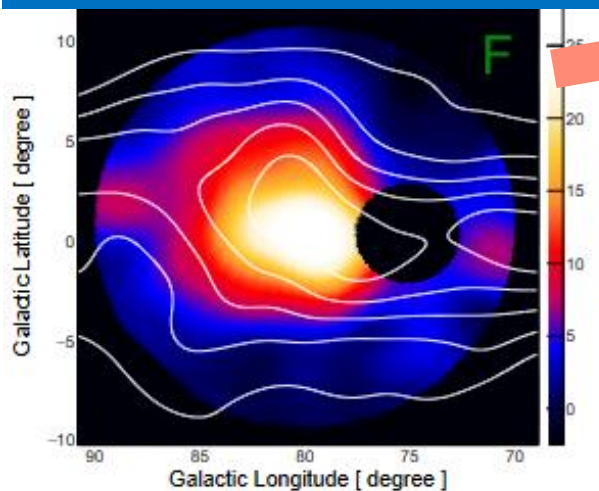


Model w 3 components : SED over 8 decades

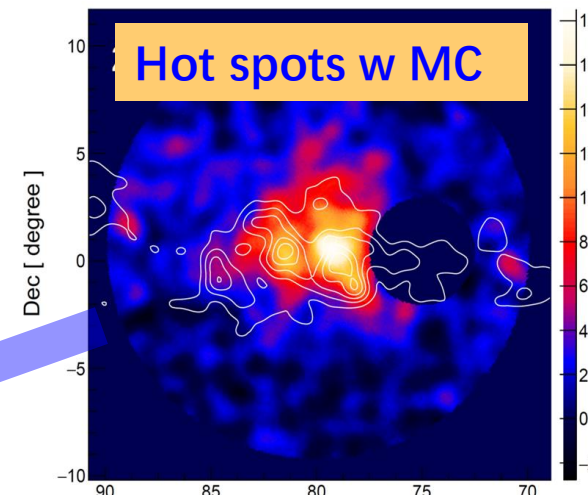
Fermi Cocoon



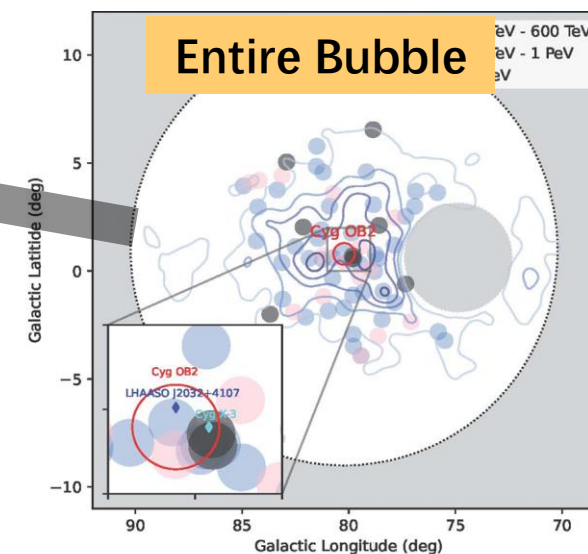
Extended Bubble w HI gas



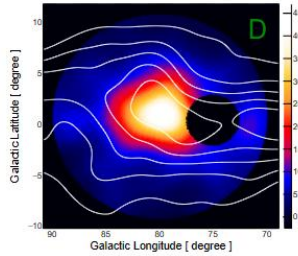
Hot spots w MC



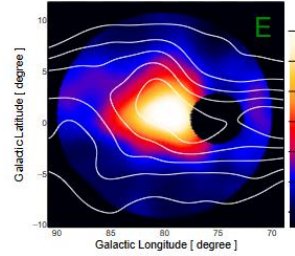
Entire Bubble



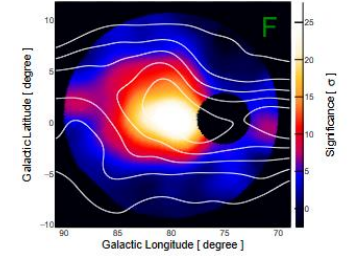
Model: Diffuse CR's generate γ 's Spatial Profile over 10° from the core



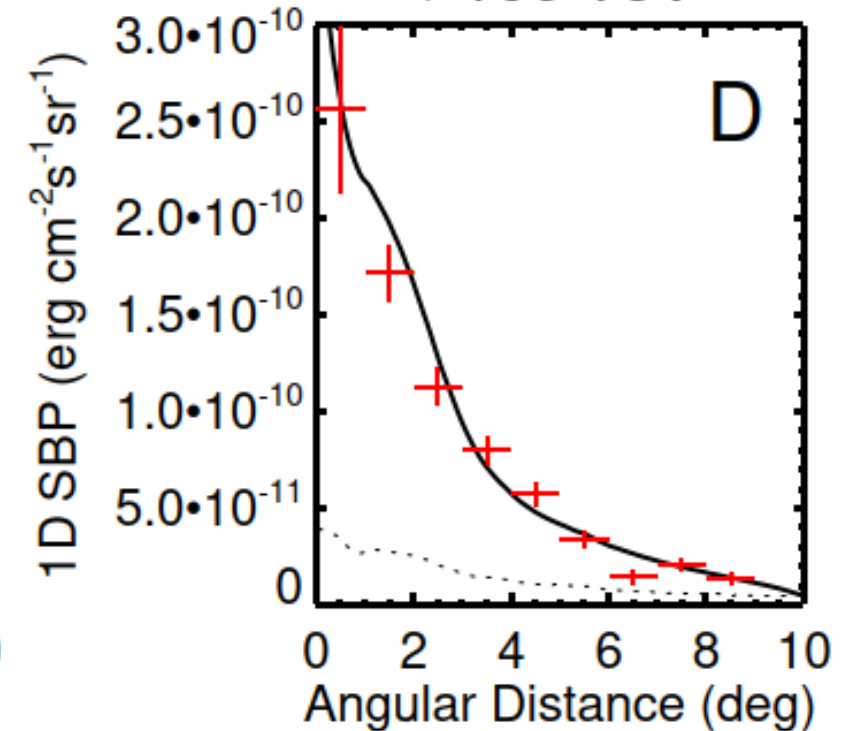
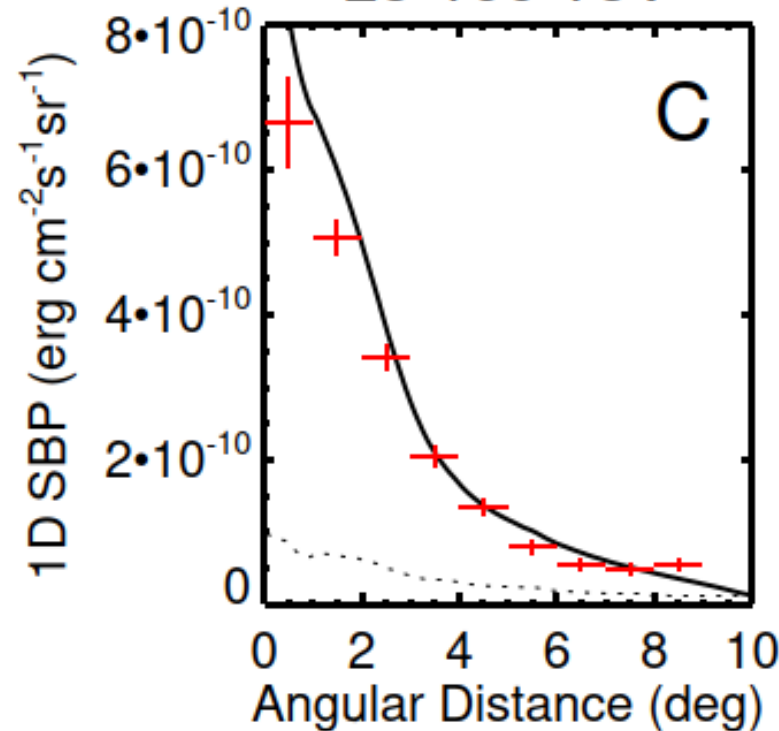
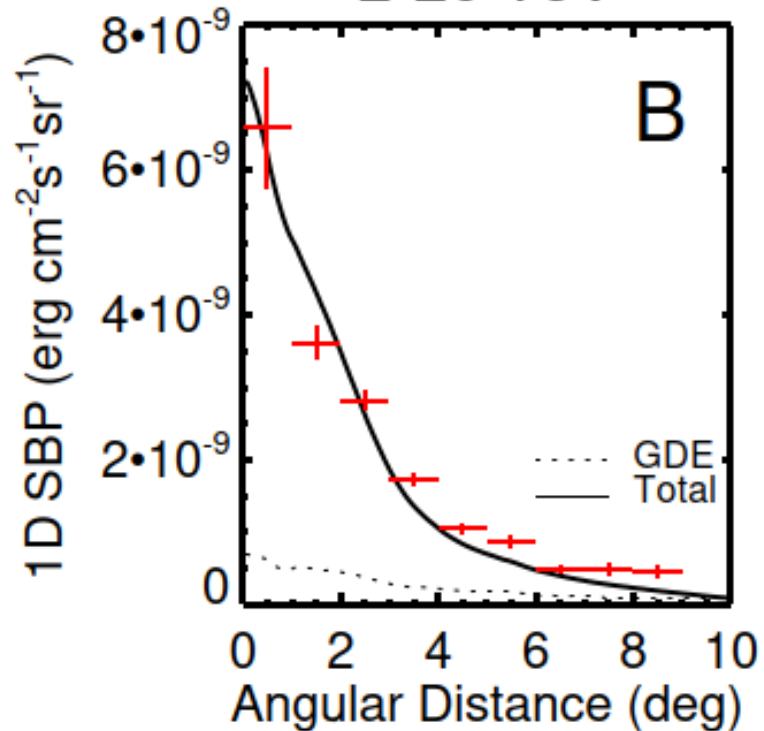
2-20 TeV



25-100 TeV



>100 TeV



The 1st CR-Source Candidate

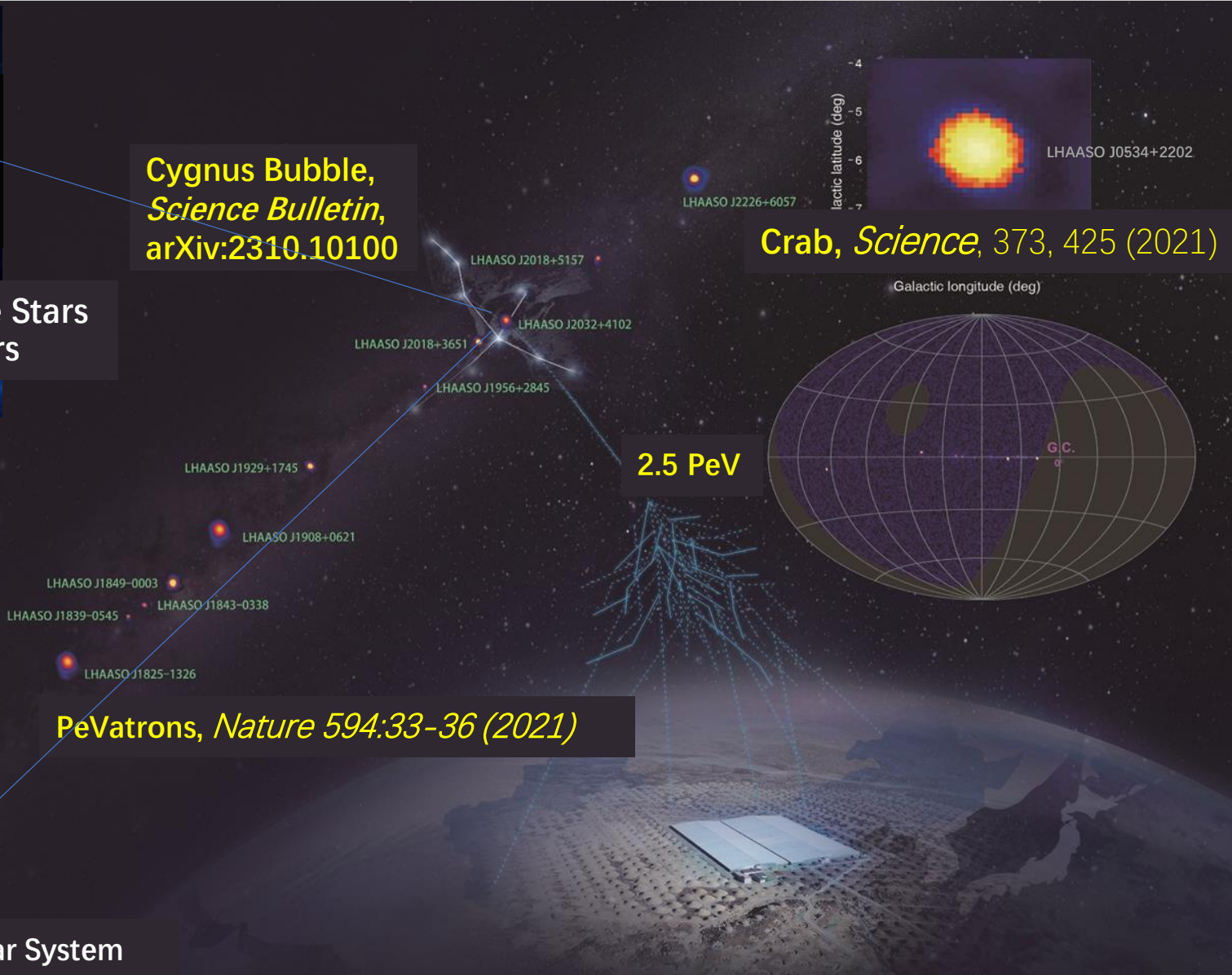


54 O-type B-type Stars
3 Wolf-Rayet Stars

Cygnus Bubble,
Science Bulletin,
arXiv:2310.10100

Size of Solar System

For the first time in the world LHAASO observed

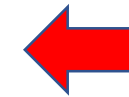


Crab, *Science*, 373, 425 (2021)

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

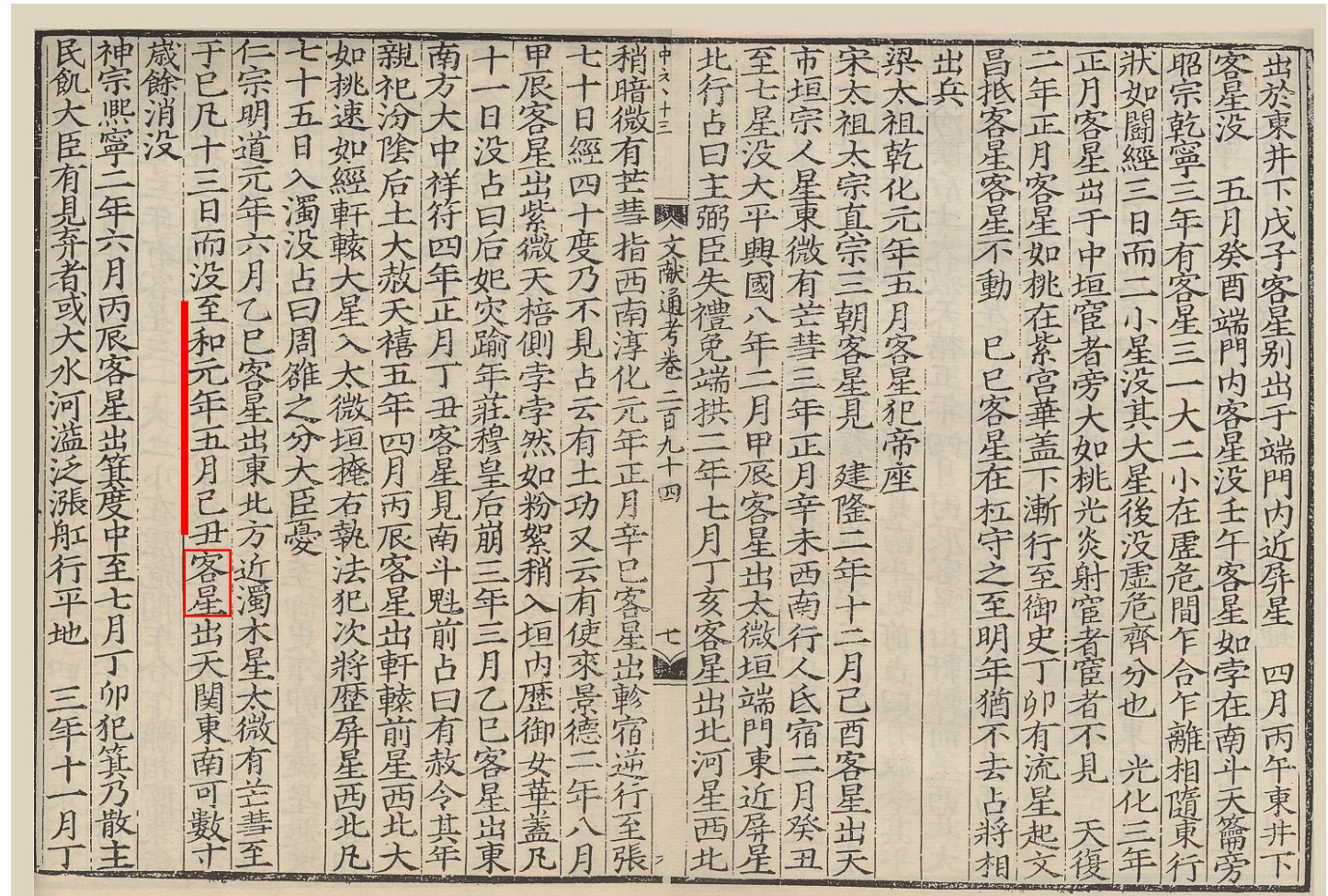
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The First Observation 967 years back

- Song Dynasty Official (司天监) recorded the “guest star”
- The first identified Supernova
- The accurate occur time: the night of July, 4th, 1054



The Crab: after 970 years

- constellation: Taurus
- distance: 6500 ly
- ◆ size of remnant: 11 ly
- ◆ size of inner nebula: 0.18 pc
- ◆ size of pulsar: ~30 km
- ◆ spin period: 33 ms
- ◆ $\dot{E} \approx -5 \times 10^{38}$ erg/s

The Crab: remnant

nebula

pulsar

The Crab Nebula

Crab Pulsar/
20 Km/1.4 SM

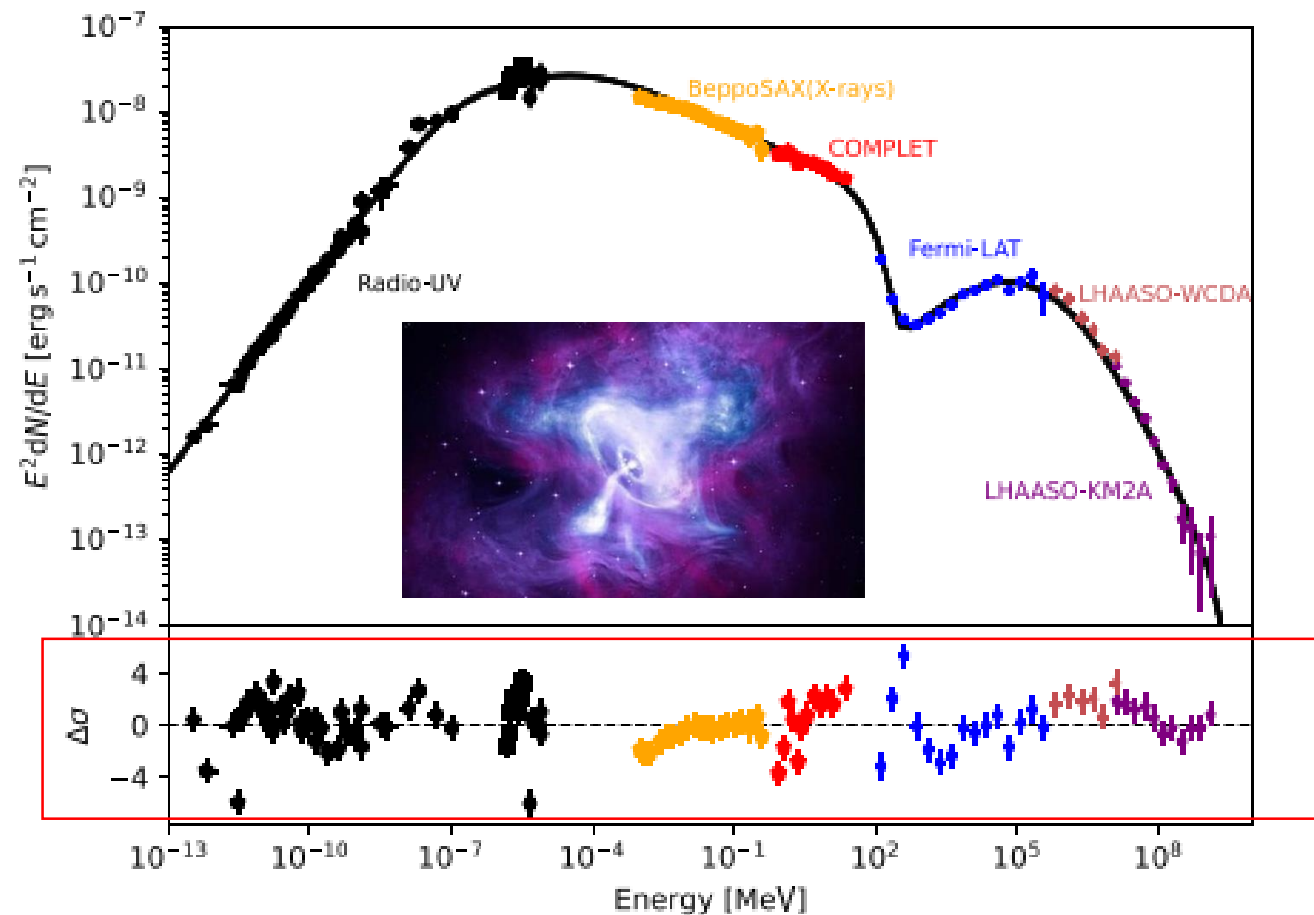
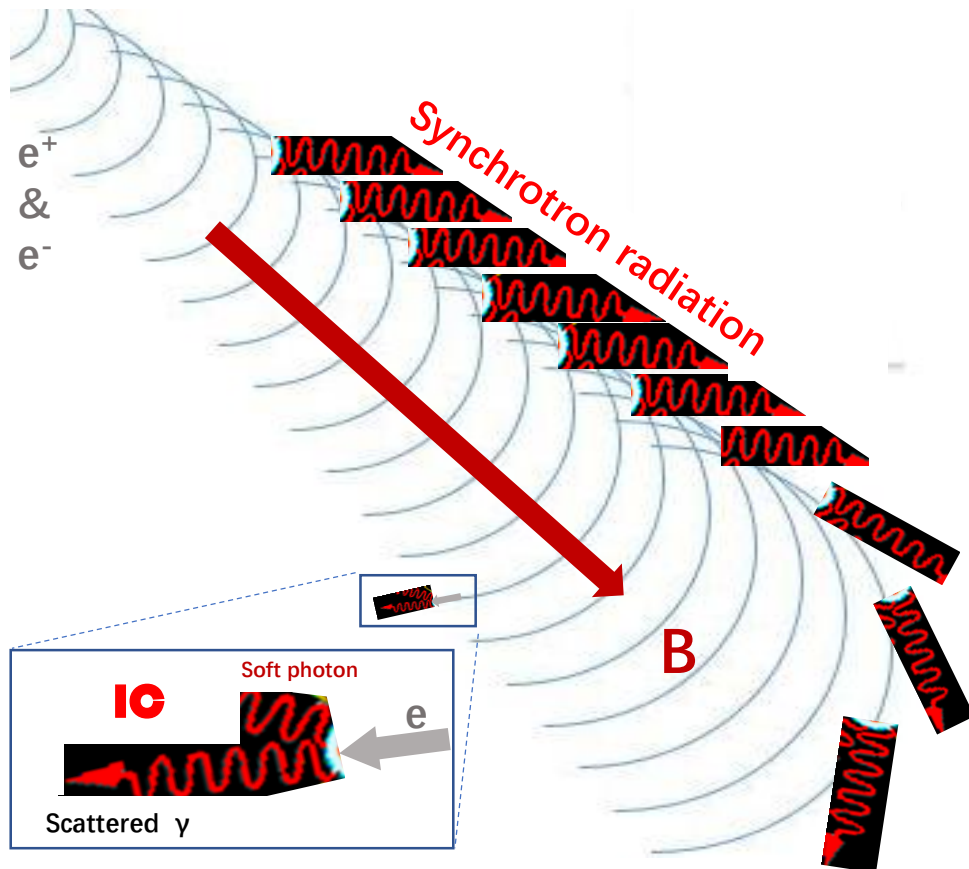
The pulsar

Pictures from NASA

“Extreme Electron PeVatron”

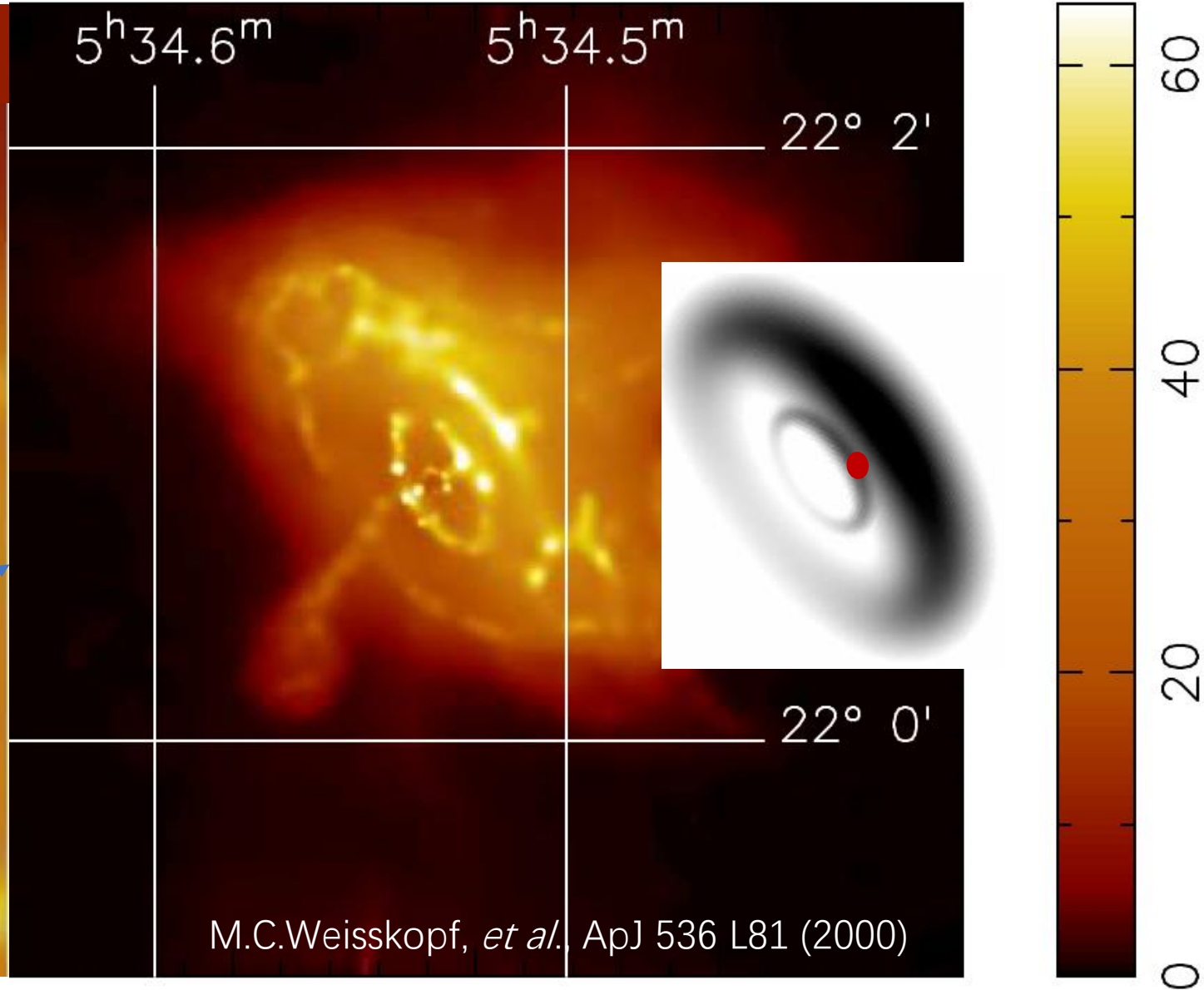
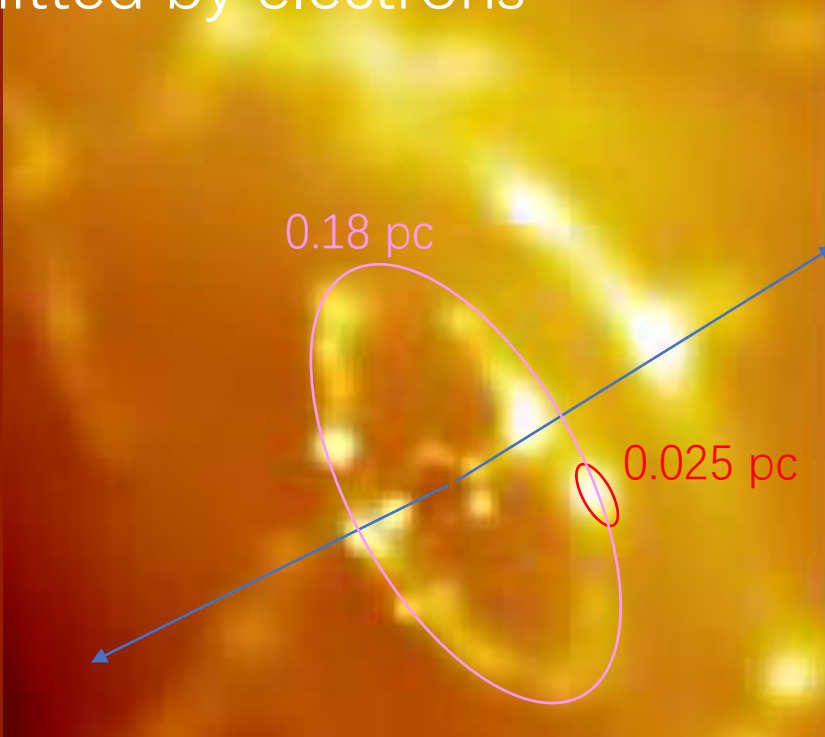
- One-zone Leptonic Model: non-negligible fact, however...
- It is hardly to be recognized as a “reasonably good fitting”
- Too simple?

L. Nie et al., ApJ, **924** 42 (2022), [arXiv:2201.03796](https://arxiv.org/abs/2201.03796)



Inner ring, jets and knots

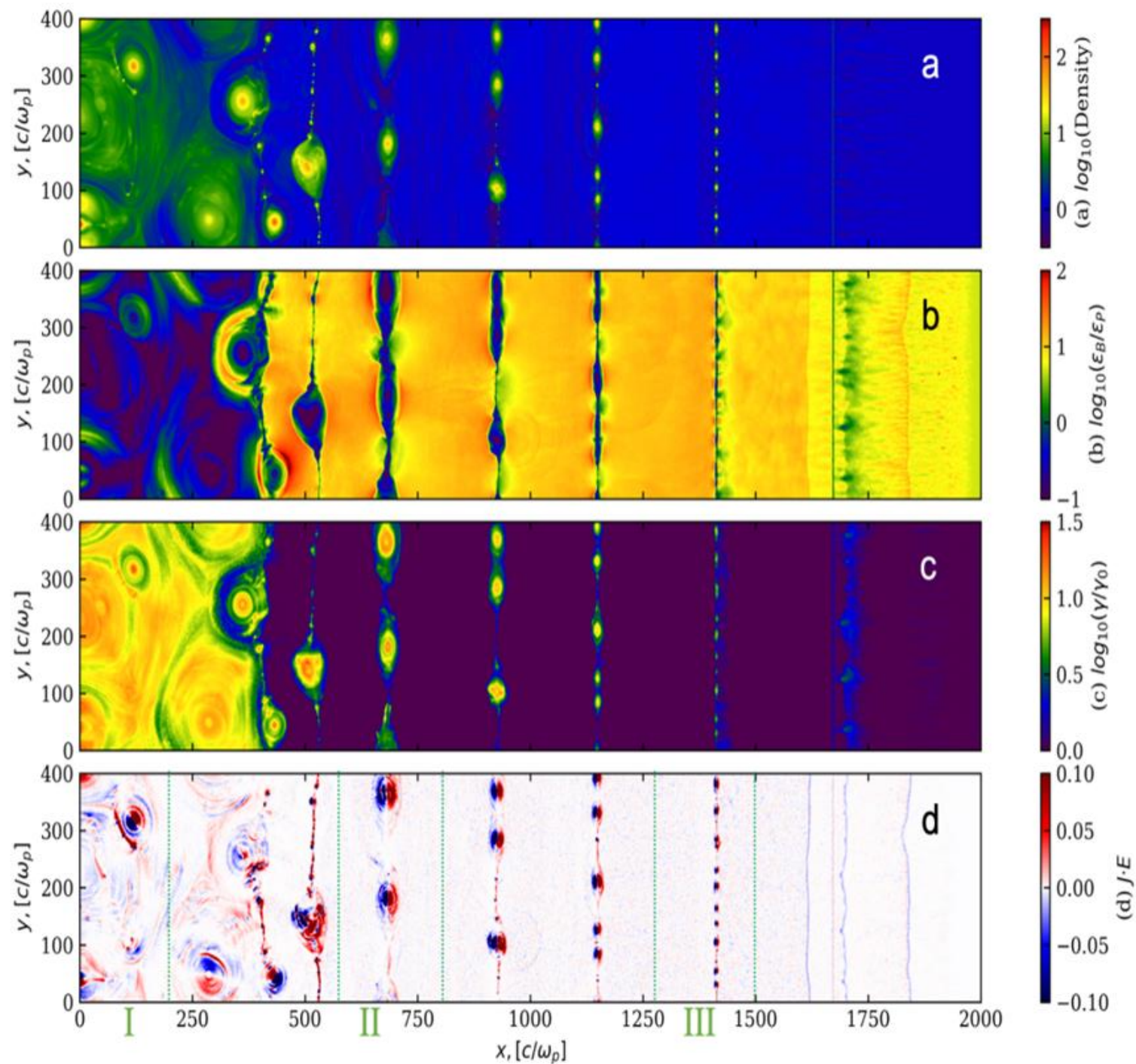
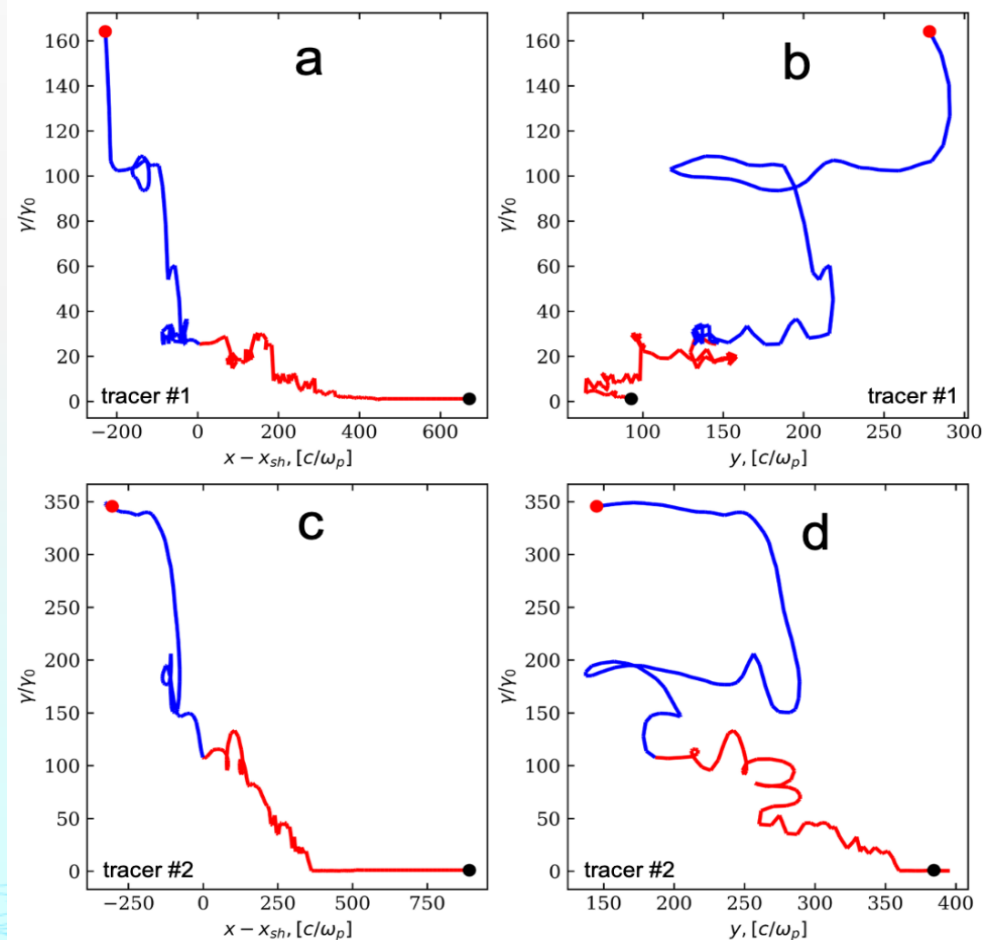
- Chandra has observed many knots in between the pulsar and the inner ring
- They are apparently in the region that \sim PeV photons may be emitted by electrons



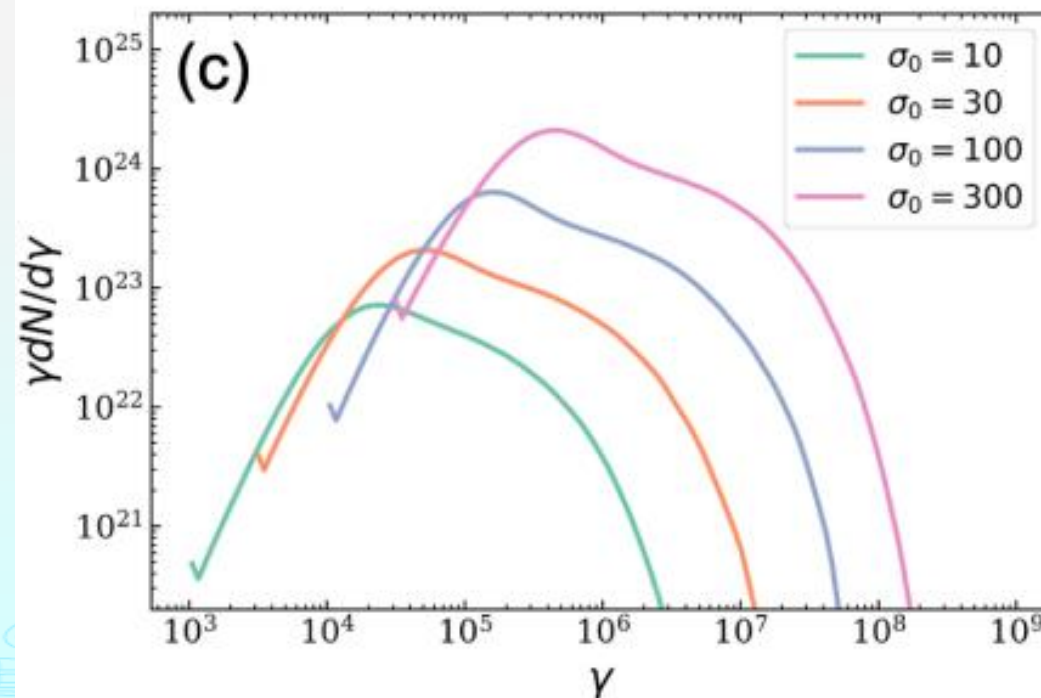
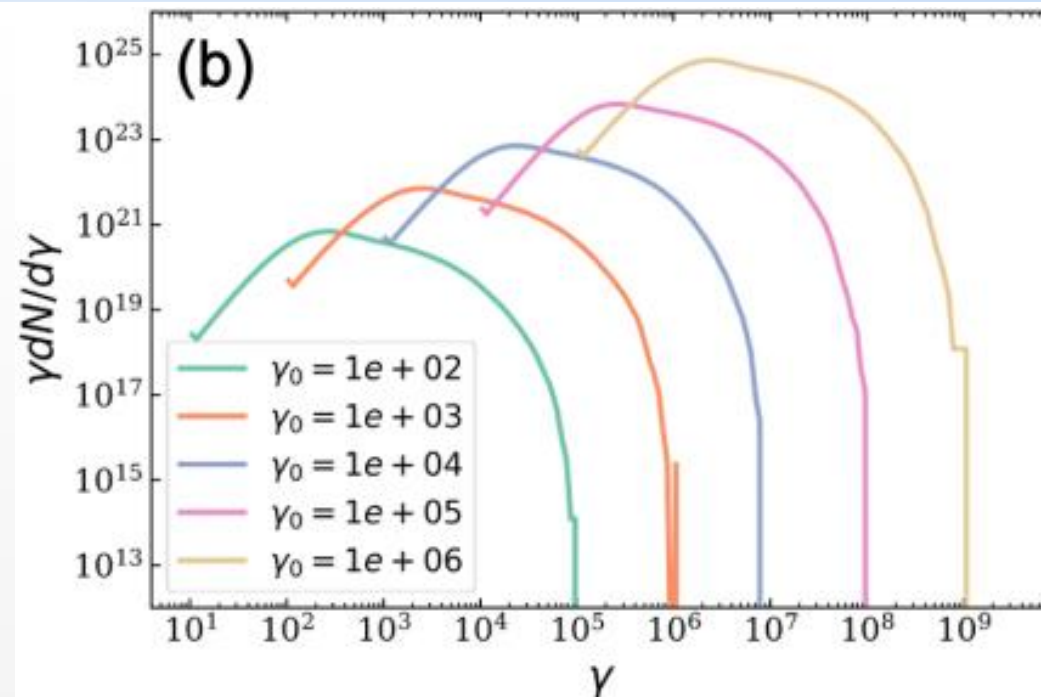
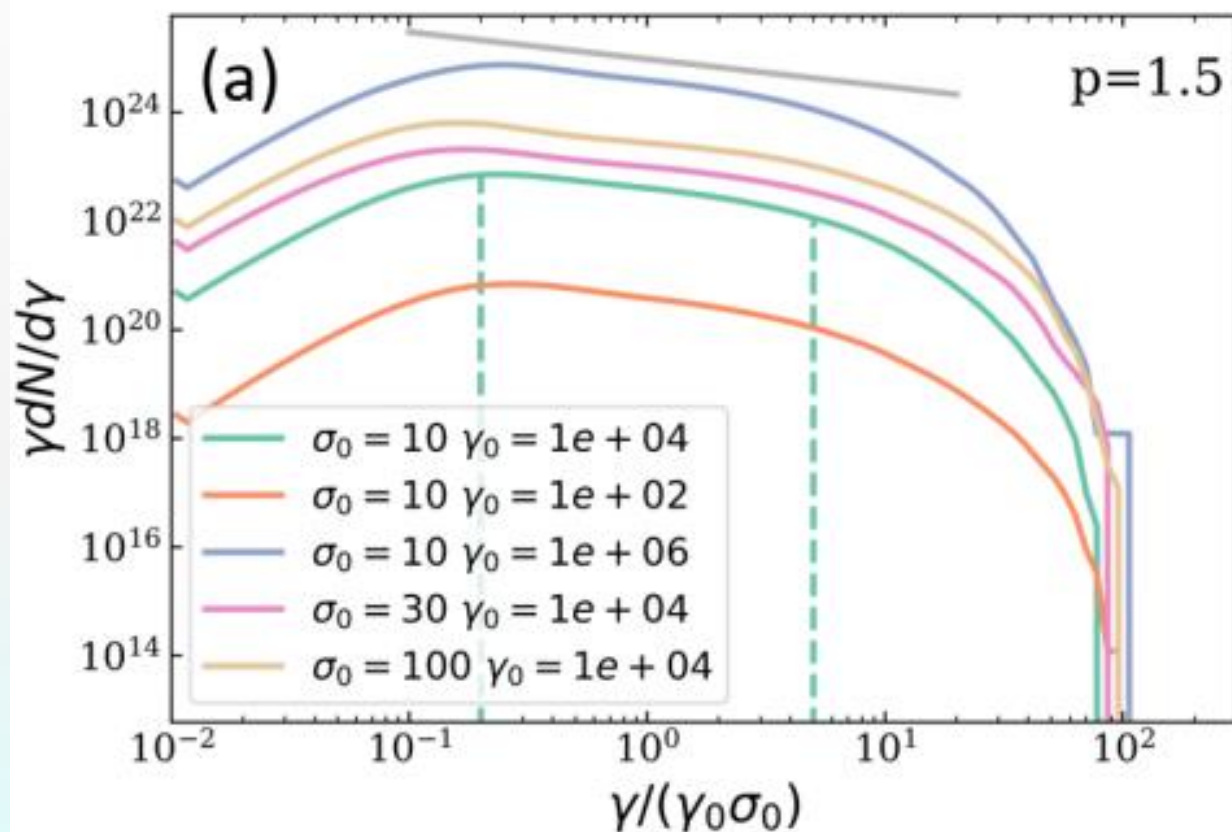
1.4 PeV Photon in the One-zone Model a serious challenge!

- ◆ Electron Energy: $E_e = 2.15(E_\gamma/1 \text{ PeV})^{0.77} \text{ PeV} \sim \mathbf{2.8 \text{ PeV}}$
- ◆ Size of the accelerator responsible to the $\sim \text{PeV}$ electrons
$$(B/100\mu\text{G})(\ell / 1 \text{ pc}) \geq 0.023 (E_\gamma/1 \text{ PeV})^{0.77}$$
 - ◆ $\ell > 0.027 \text{ pc}$, implying not associated with flares that last few days
 - ◆ $\ell < 0.18 \text{ pc}$, assuming not beyond the inner nebula
- ◆ Acceleration Rate:
$$\eta = \mathcal{E}/B = 0.14 (B/100\mu\text{G})(E_\gamma/1 \text{ PeV})^{1.54} \sim \mathbf{26\%}$$
 - ◆ A factor of $\sim \mathbf{1000}$ larger than diffusive shock acceleration in SNR
 - ◆ η must be < 1 according to ideal MHD — **challenge !!**
 - ◆ If $E_\gamma \sim 3.5 \text{ PeV}$ — **impossible !!!**

Two examples of electron trajectories



Electron E-Spectrum

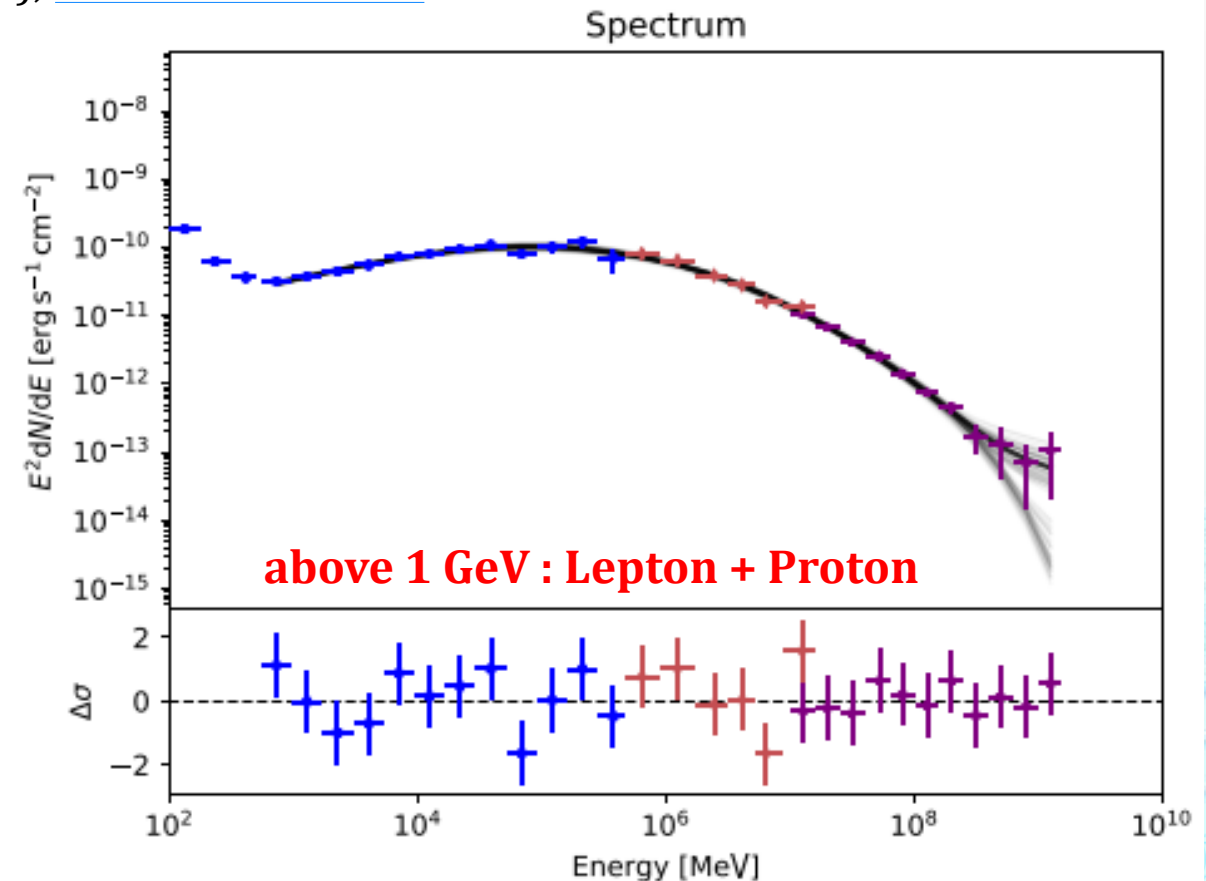
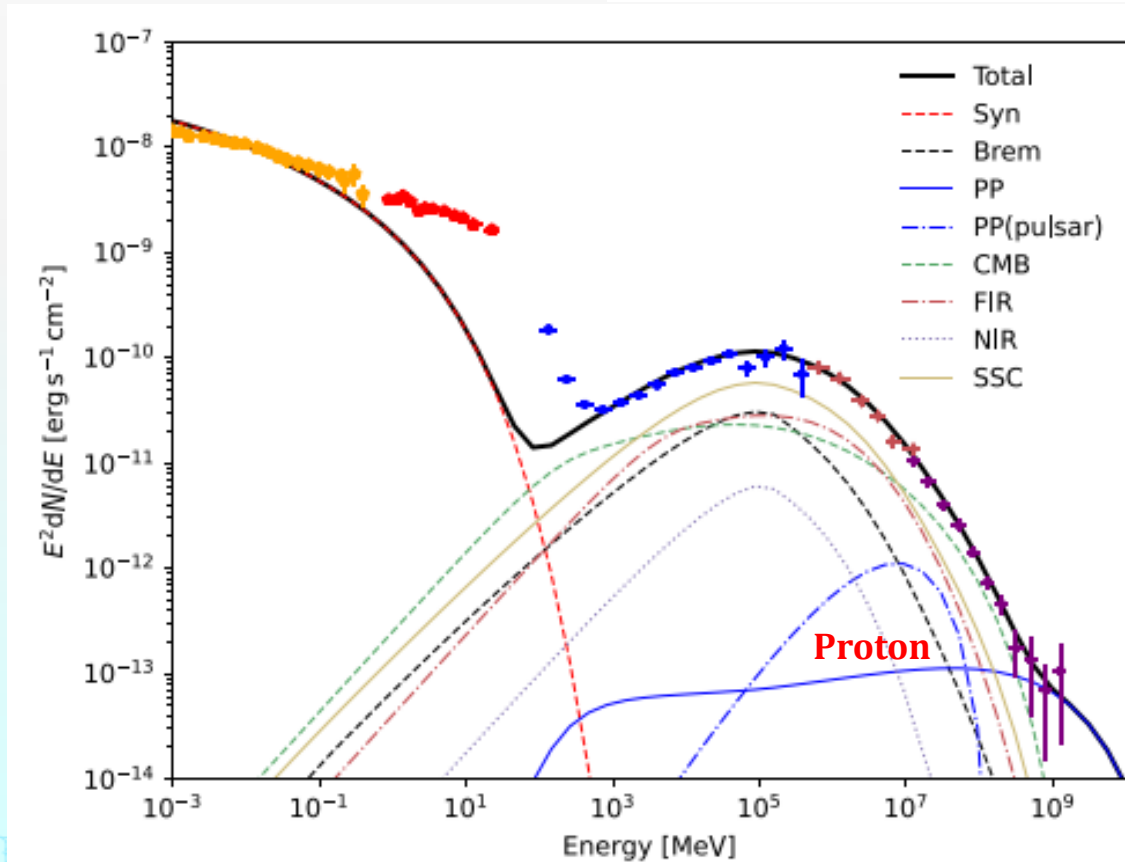


- ◆ it seems not impossible to reach 1 PeV, but quite extreme!

Seems to be a better interpretation

- ◆ Relaxing the tension of 2.8 PeV electron's acceleration
- ◆ Origin of CR protons at **~ 25 PeV**: a Super-PeVatron

L. Nie et al., ApJ, **924** 42 (2022), [arXiv:2201.03796](https://arxiv.org/abs/2201.03796)

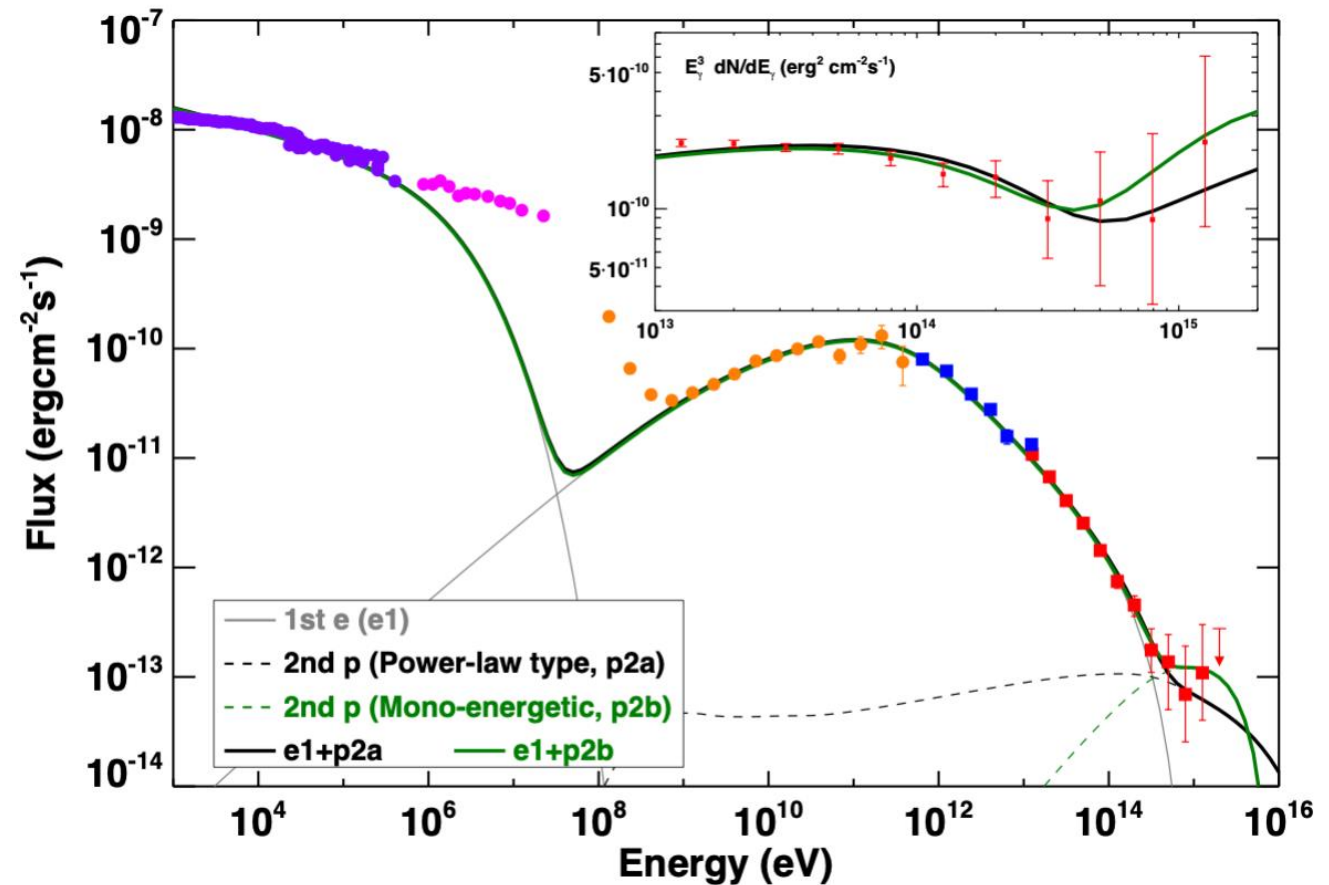
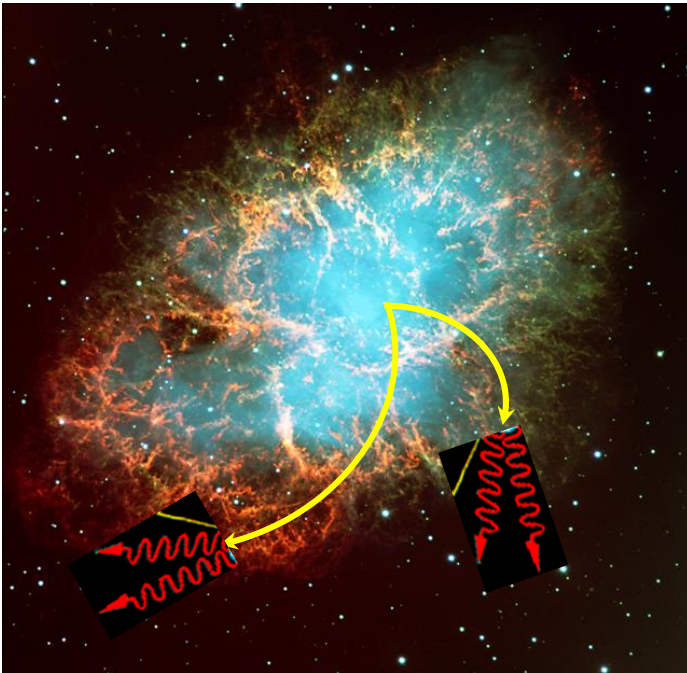


Even some monoenergetic protons

- Directly from the pulsar with a bulk gamma factor of $\Gamma_w \sim 10^7$ of the wind

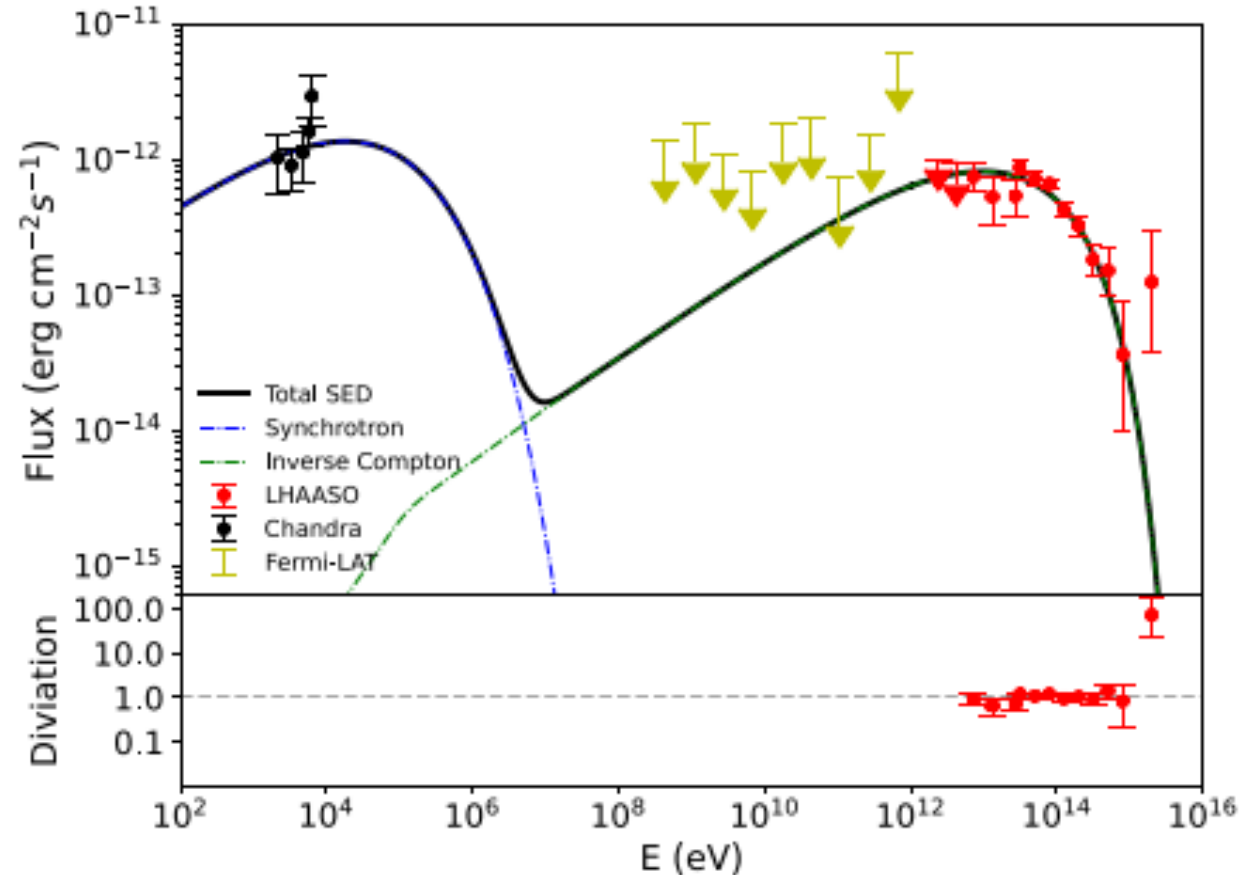
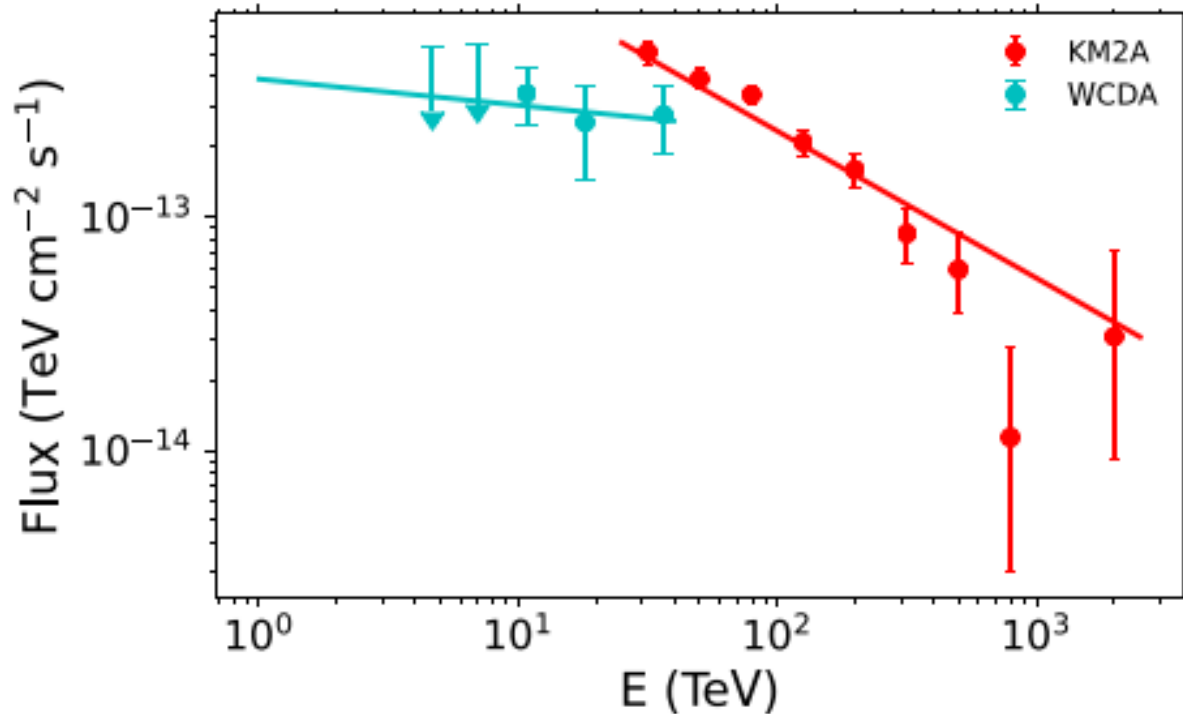
$$\frac{dN_p}{dE_p} \propto \delta(E_p - 10 \text{ PeV})$$

p-p interaction
in SNR ejecta,
generating π^0
and decay in
 γ 's

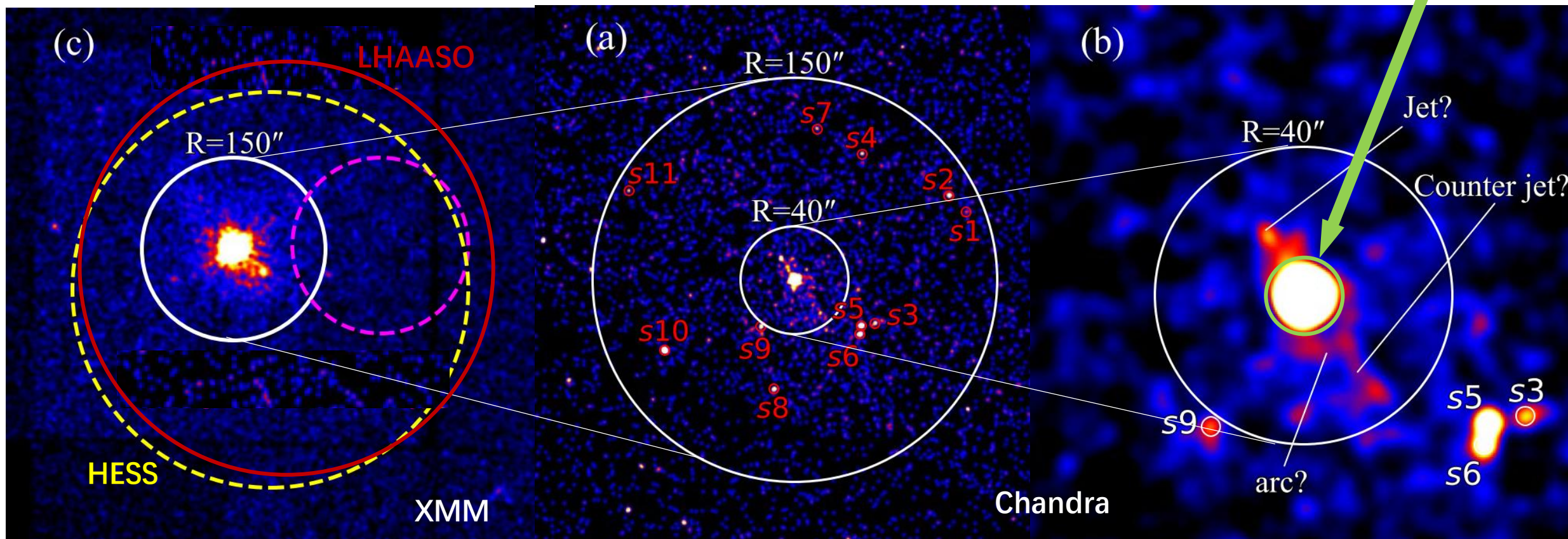


A newly discovered PWN is generating

- γ -photons at energy > 2 PeV
- Posting challenges again, but in different way



X-ray observation found the size of acceleration region $R < 0.4$ pc at 7 kpc, i.e. $10''$

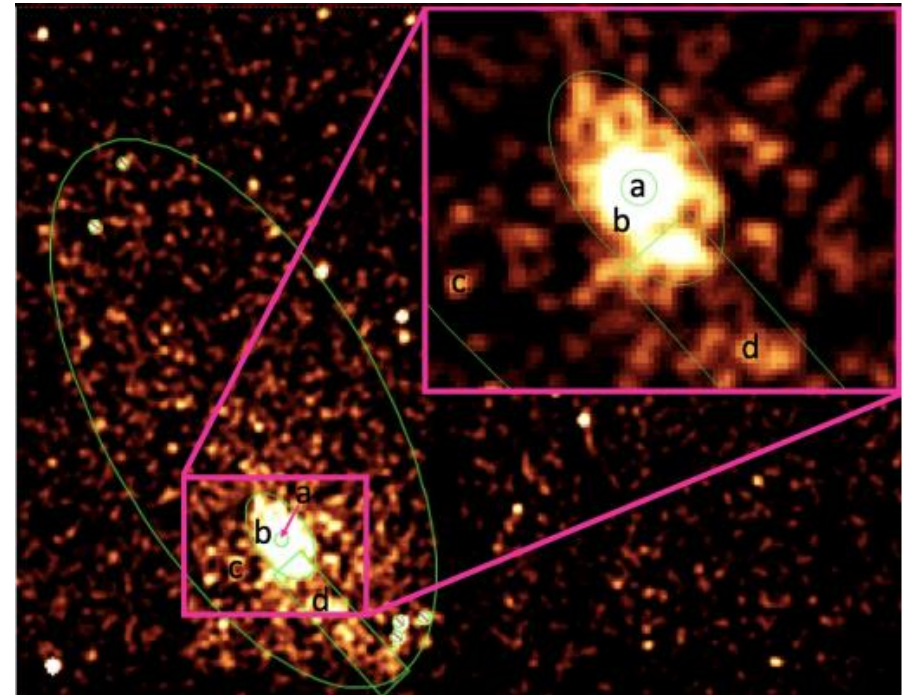
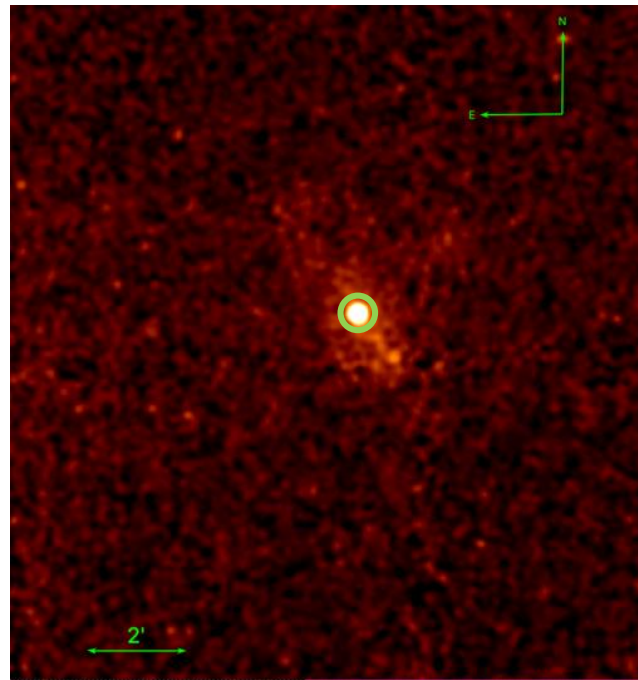


Challenge: $\eta \sim 50\%$

Confining particles inside the accelerator

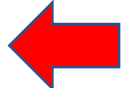
$B \sim 3 \mu\text{G}$

size $\sim 1 \text{ pc}$

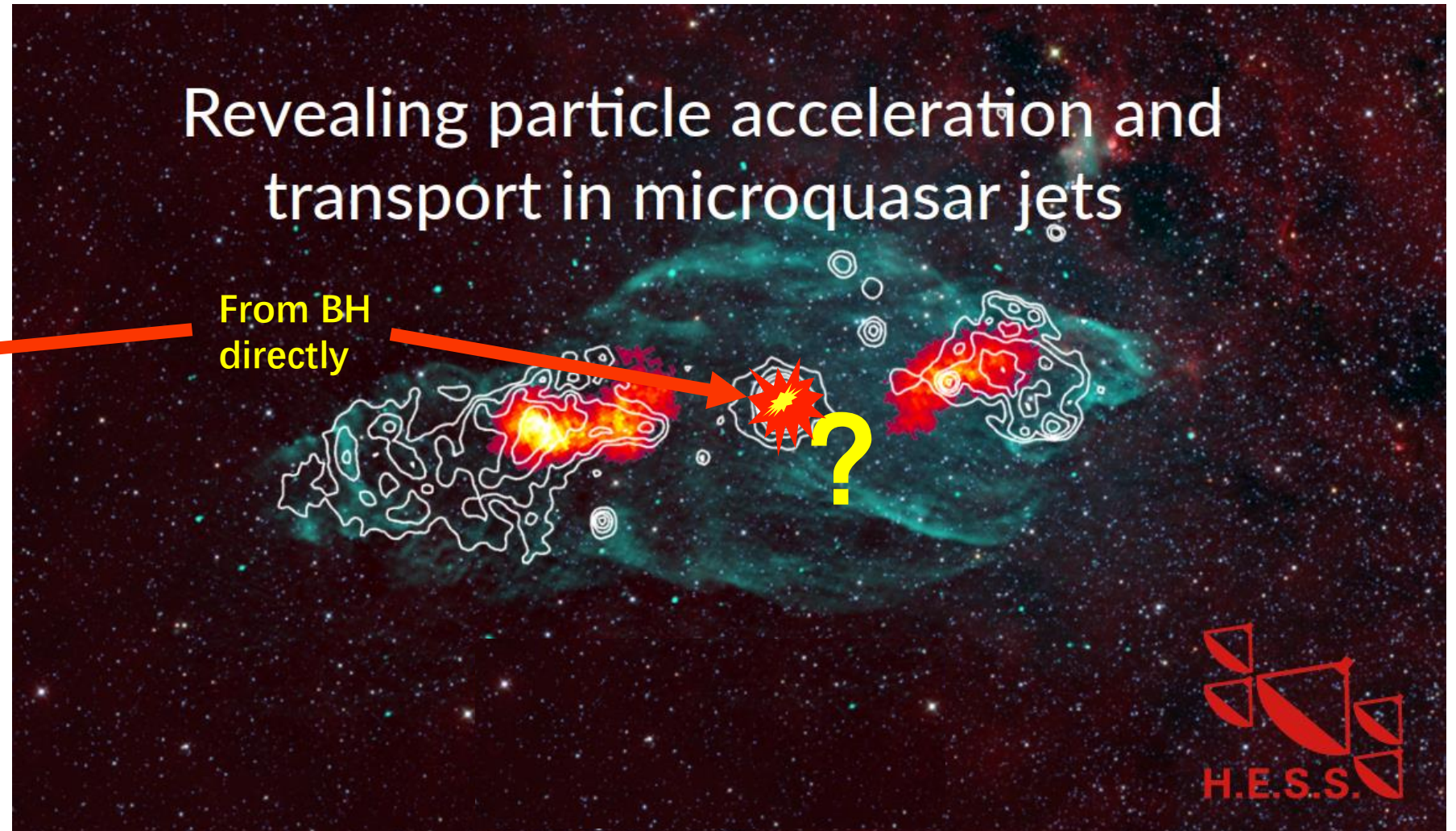
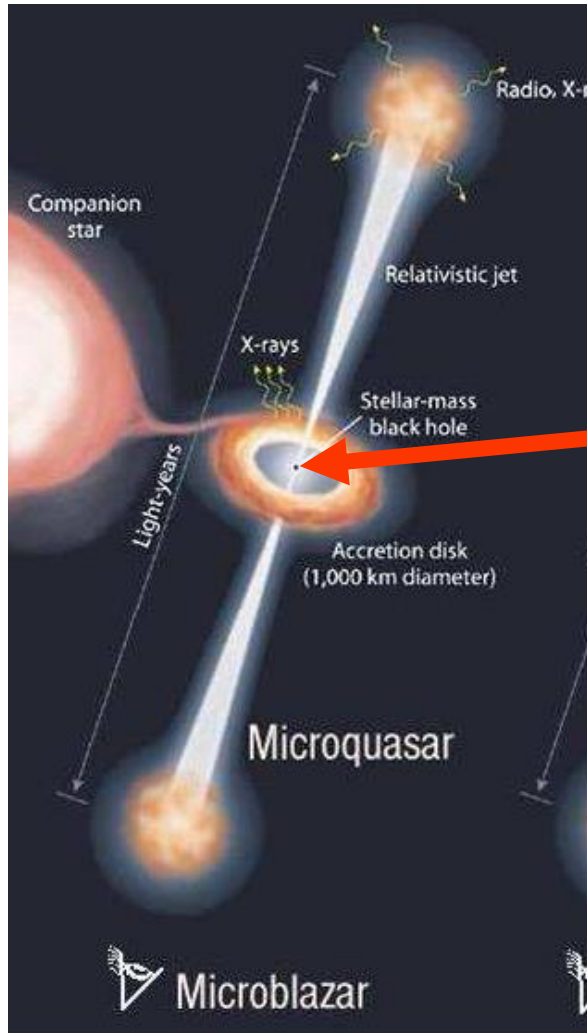


acceleration rate must be at the level of **50% !**

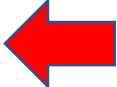
Content

- Introduction and Experiments
- Sky Survey for Source Candidates
- “Extreme” Accelerators
 - 1st CR Super-PeVatron: The Cygnus Bubble
 - Extreme Electron Accelerator: The Crab Nebula and a new source
 - Black Holes as PeVatrons 
- Future Experiments

Micro-Quasar: SS433 etc.



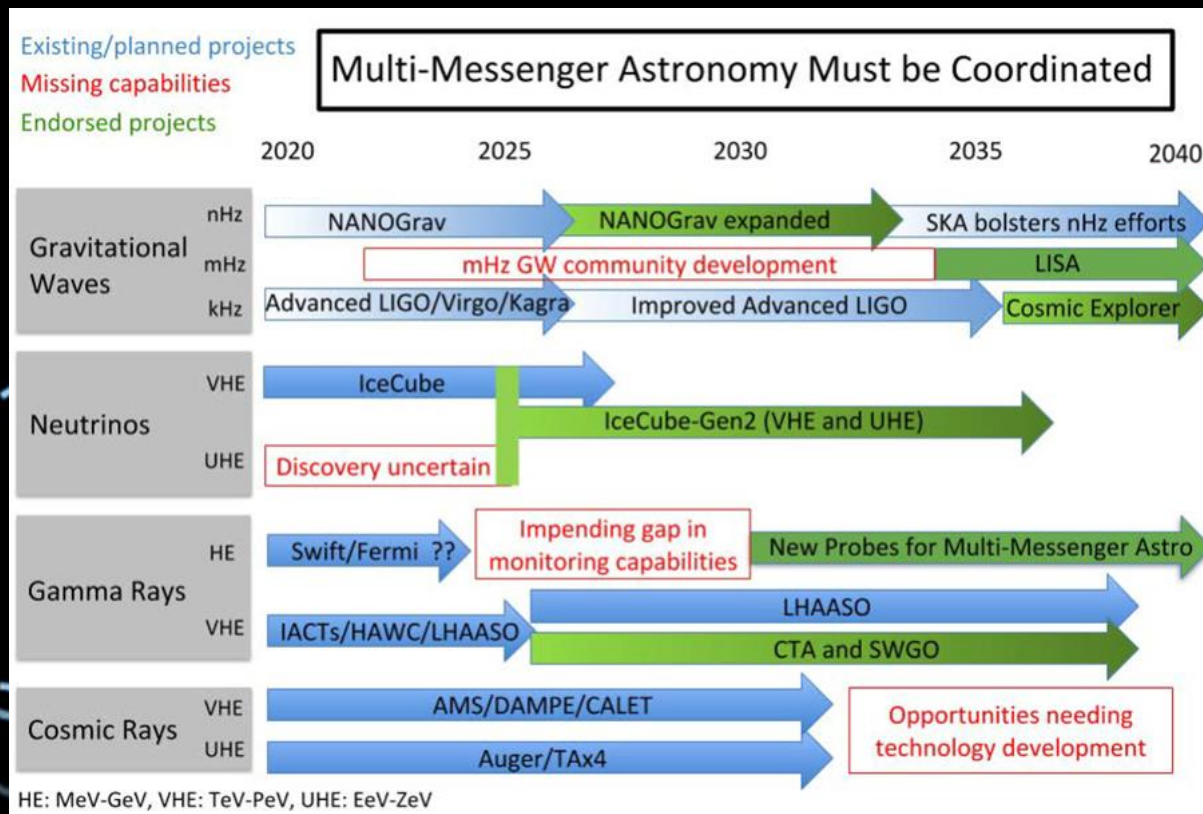
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US Views for Multi-Messenger Astronomy

《Astro-2020》

Cosmic Messengers



GW

γ

ν

p

Next generation of IACT arrays

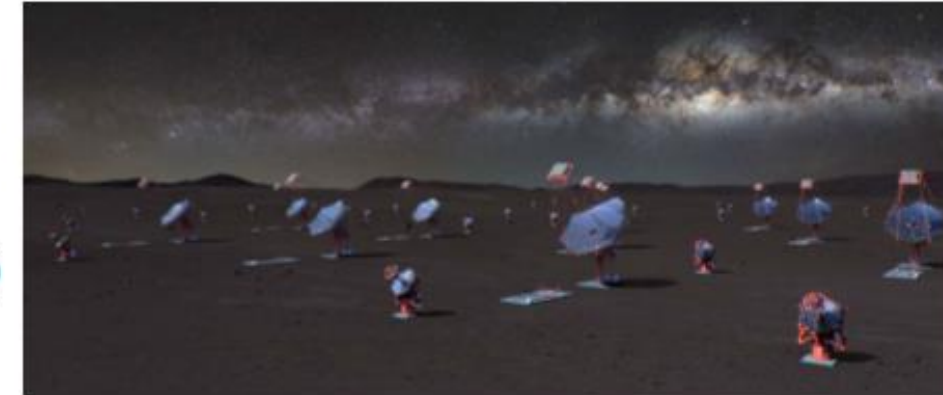


ASTRI Mini-Array

- 9 telescopes at the Teide observatory (Canary islands)
- 4.3 m diameter
- Schwarzschild-Couder modified design (2 mirrors)
- FoV: 10.5 deg
- 0.19 deg/pixel (SiPM based camera)

CTAO (south site)

- 53 telescopes in the Atacama desert
- 2 LST → 23 m diameter, 1M, FoV > 4.5°, PMT camera (INAF leadership, PNRR funds)
- 14 MST → 12 m diameter, 1M, FoV > 7°, PMT camera
- 37 SST → 4.3 m diameter, 2M, FoV > 9°, SiPM camera, (INAF leadership, PNRR funds)
- CTAO north site → 4 LST and 9 MST

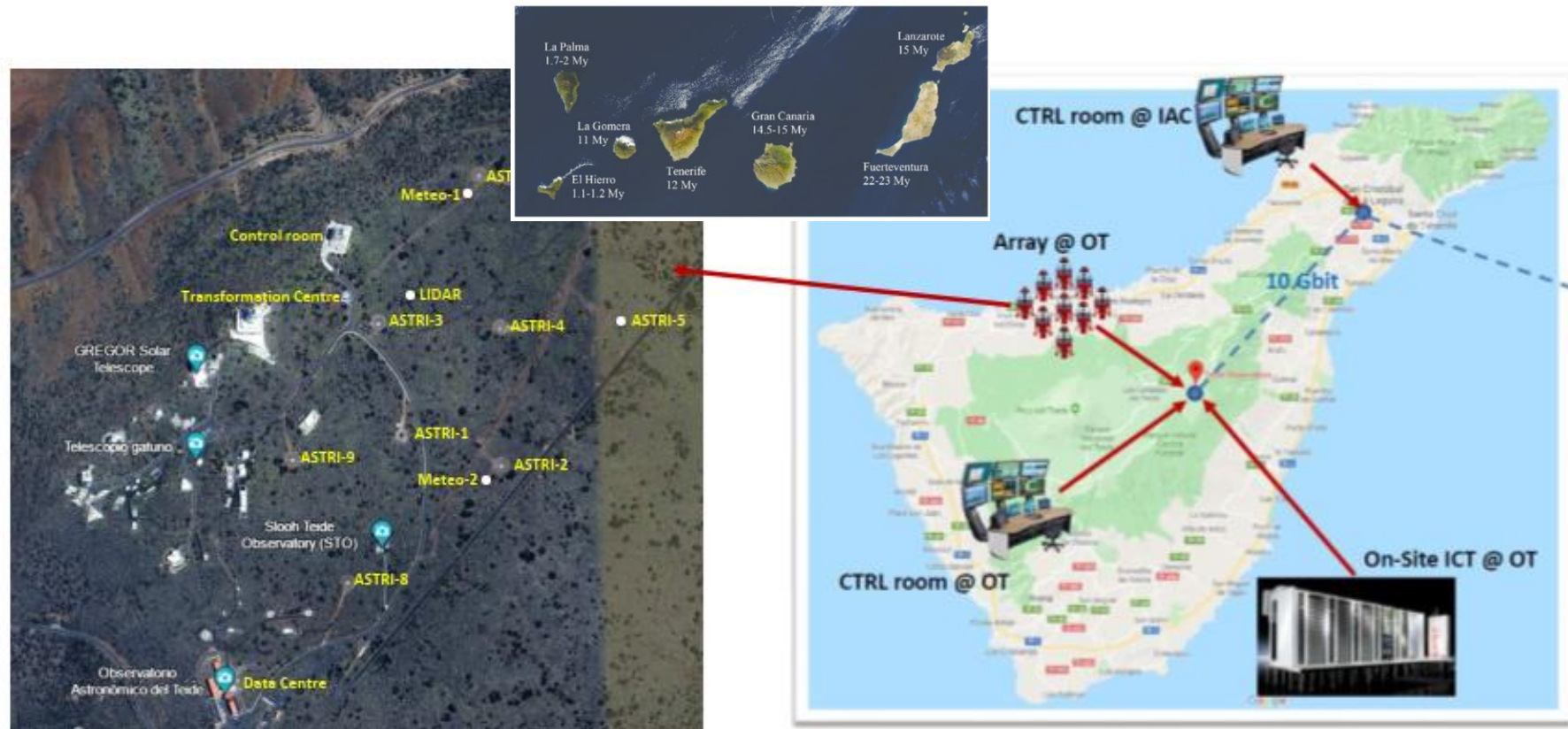


LACT (Large Array of Cherenkov Telescopes)

- 32 telescopes at LHAASO site
- 6m diameter
- Davis-Cotton design (one mirror)
- FoV: 8 deg
- 0.19 deg/pixel (SiPM based camera)

High Resolution Coverage in UHE γ -ray Band

- ASTRI: 9 SSTs
- At the Observatorio del Teide in Tenerife (Spain)



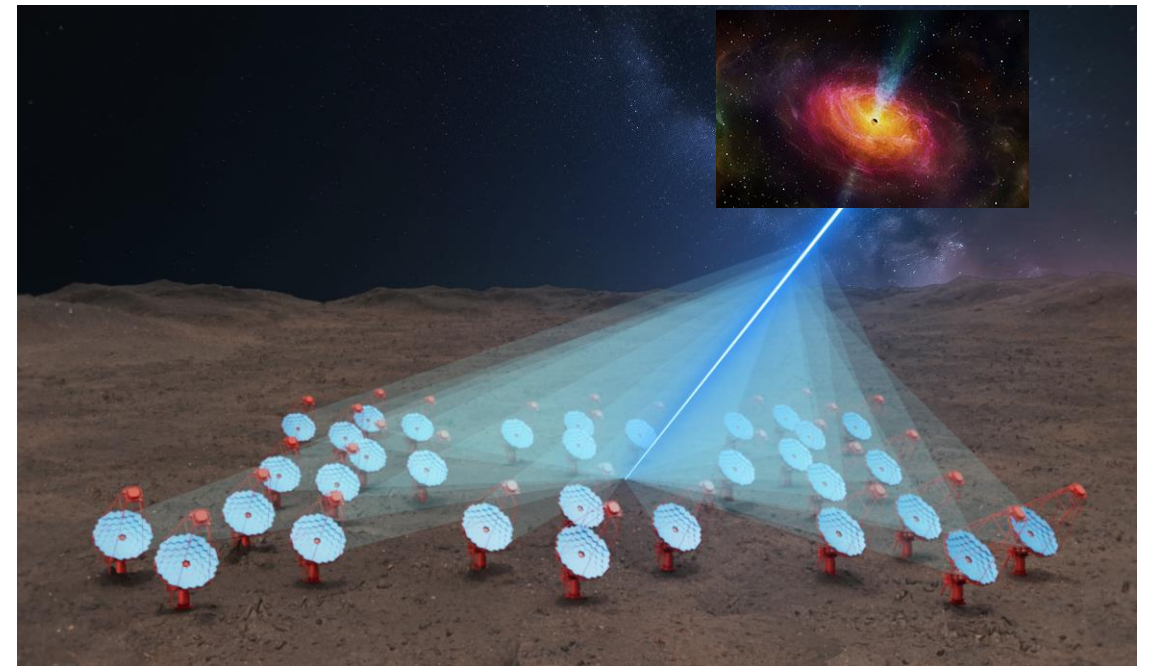
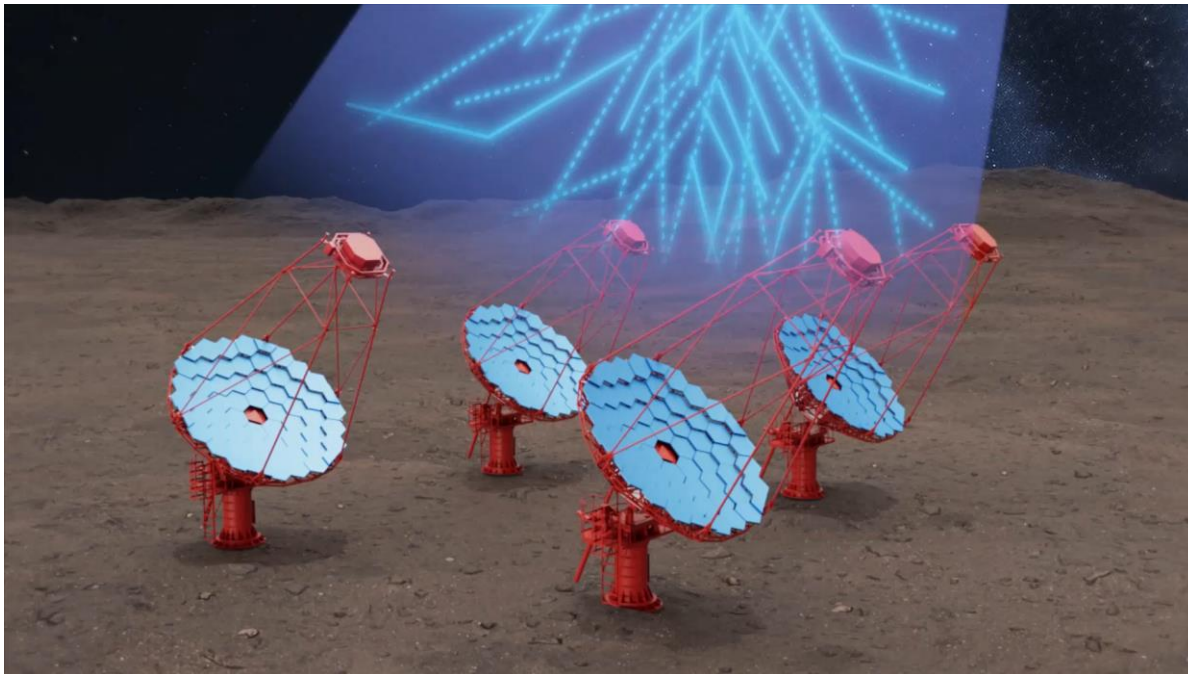
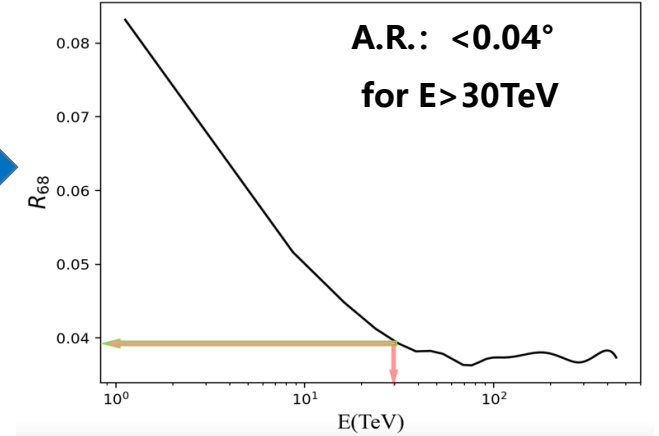
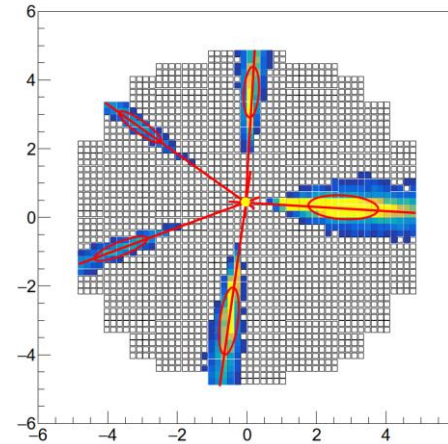
LACT as the upgrading of LHAASO

➤ Stereo measurement of Cherenkov image

- ❑ At least 4 telescopes simultaneously

➤ Reconstruction

- ❑ Angular resolution **0.04°** for $E > 30$ TeV





A prototype in Chengdu



A prototype in LHAASO



Existing/planned projects

Missing capabilities

Endorsed projects

Multi-Messenger Astronomy Must be Coordinated

2020

2025

2030

2035

2040

Gravitational Waves

nHz

mHz

kHz

NANOGrav

NANOGrav expanded

SKA bolsters nHz efforts

mHz GW community development

LISA

Advanced LIGO/Virgo/Kagra

Improved Advanced LIGO

Cosmic Explorer

Neutrinos

VHE

UHE

IceCube

KM3net, Baikal-GVD

IceCube-Gen2 (VHE and UHE)

Discovery uncertain

P-One, TRIDENT, HUNT

Gamma Rays

HE

VHE

Swift/Fermi ??

Impending gap in monitoring capabilities

New Probes for Multi-Messenger Astro

IACTs/HAWC/LHAASO

LHAASO

ASTRI, LACT

CTA and SWGO

Cosmic Rays

VHE

UHE

AMS/DAMPE/CALET

HERD

LHAASO

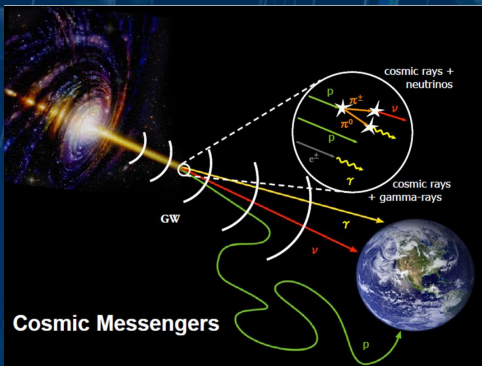
Auger/TAx4

Opportunities needing technology development

HE: MeV-GeV, VHE: TeV-PeV, UHE: EeV-ZeV

High-energy Underwater Neutrino Telescope

H U N T



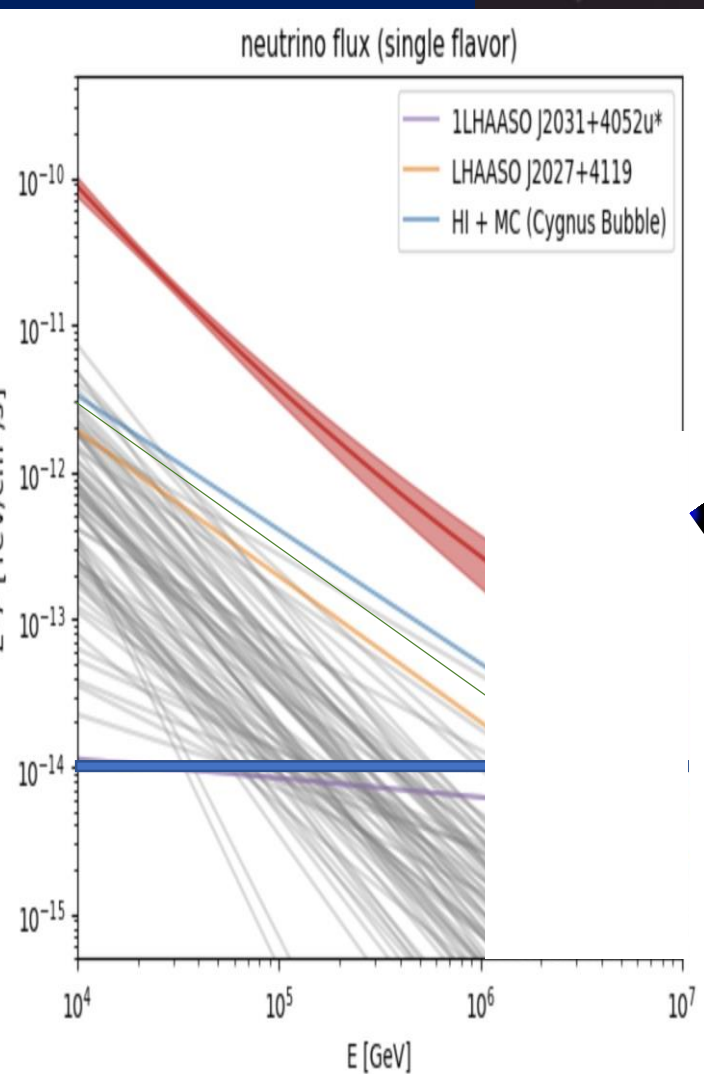
- Resolution $\sim 0.1^\circ$ (tracks), $< 3^\circ$ (cascades)
- Energy resolution: $\Delta \log E \sim 0.3$ (tracks)
 $\Delta E \sim 10-30\%$ (cascades).
- Discovering Neu sources (> 100 TeV) at the level of 5σ within several years

- Volume: $6 \times 6 = 36 \text{ km}^2$, **$\sim 30 \text{ km}^3$**
- Separations of strings: $D_{\text{string}} \sim 130 \text{ m}$
- Separation of optical modules : DOM $\sim 36 \text{ m}$
- Length of each string: $\sim 860 \text{ m}$
- $\sim 2,300$ strings, 24 OM in each string, 55000 OM in total

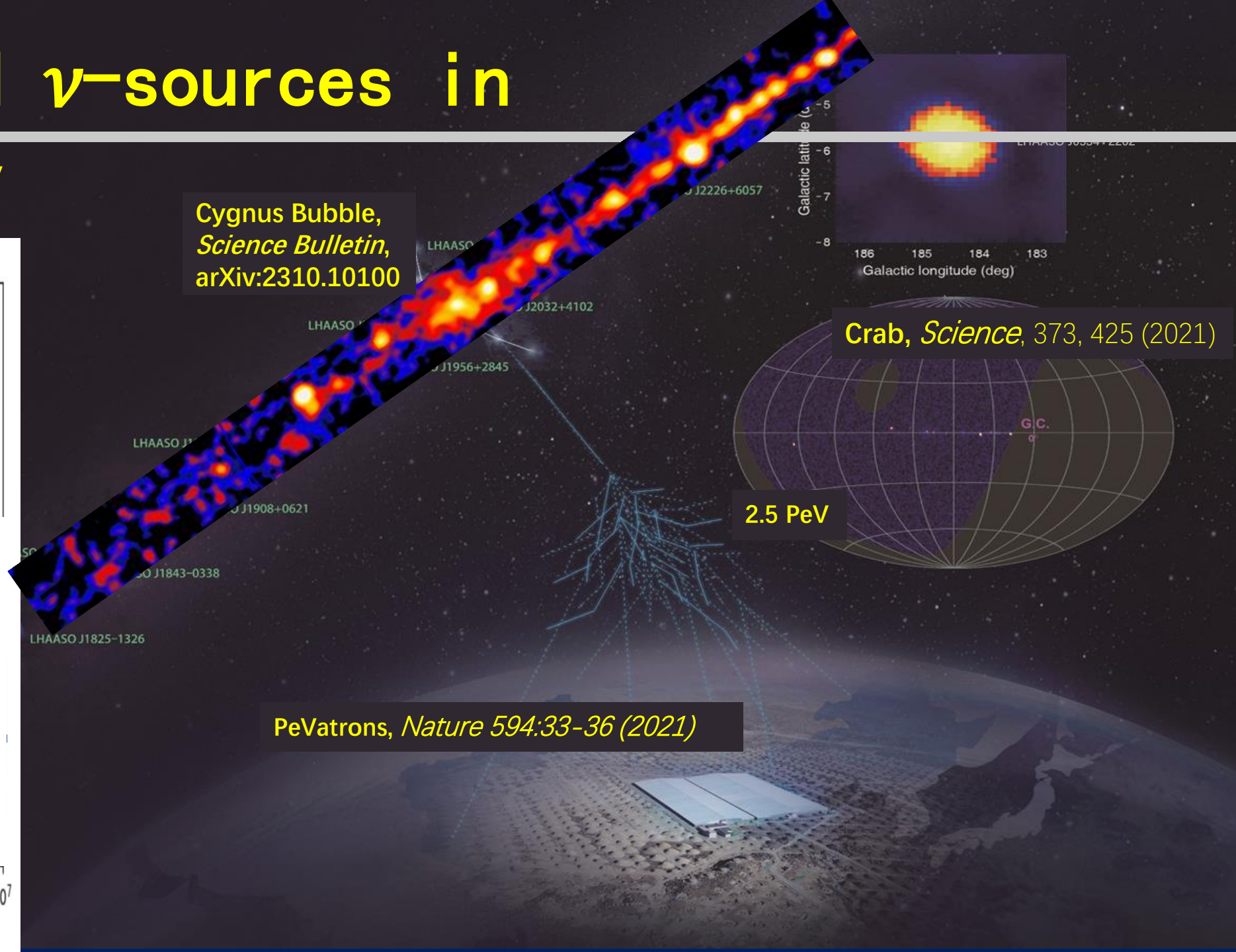
36 m

130 m

Guaranteed ν -sources in our galaxy



Cygnus Bubble,
Science Bulletin,
arXiv:2310.10100



Summary

- **Astroparticle Physics enters Multi-Messenger era**
- **Systematic Researches on Experimental and Phenomenological platforms are demanded**
- **Experiments on γ -rays, neutrinos and UHECRs are enhanced**
- **Discoveries Pose Challenges: “Extreme Accelerators”**
- **Many large scale experiments proposed to address fundamental issues**