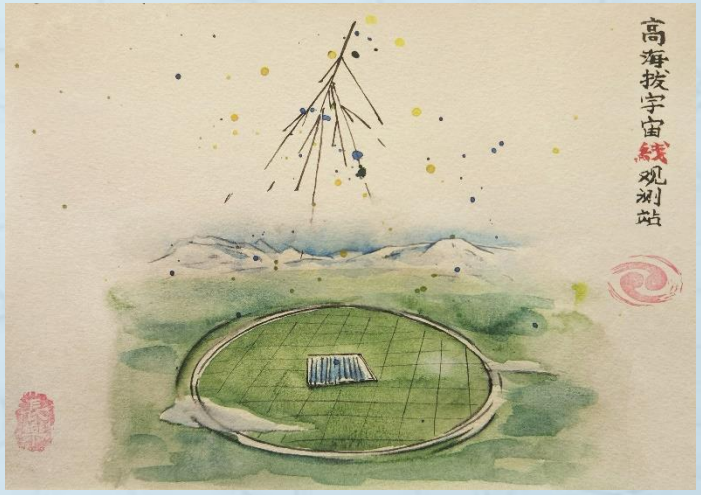
LHAASO
高海拔宇宙线观测站



The Crab Nebula : an electron PeVatron or a Super-pevatron of Cosmic Rays?

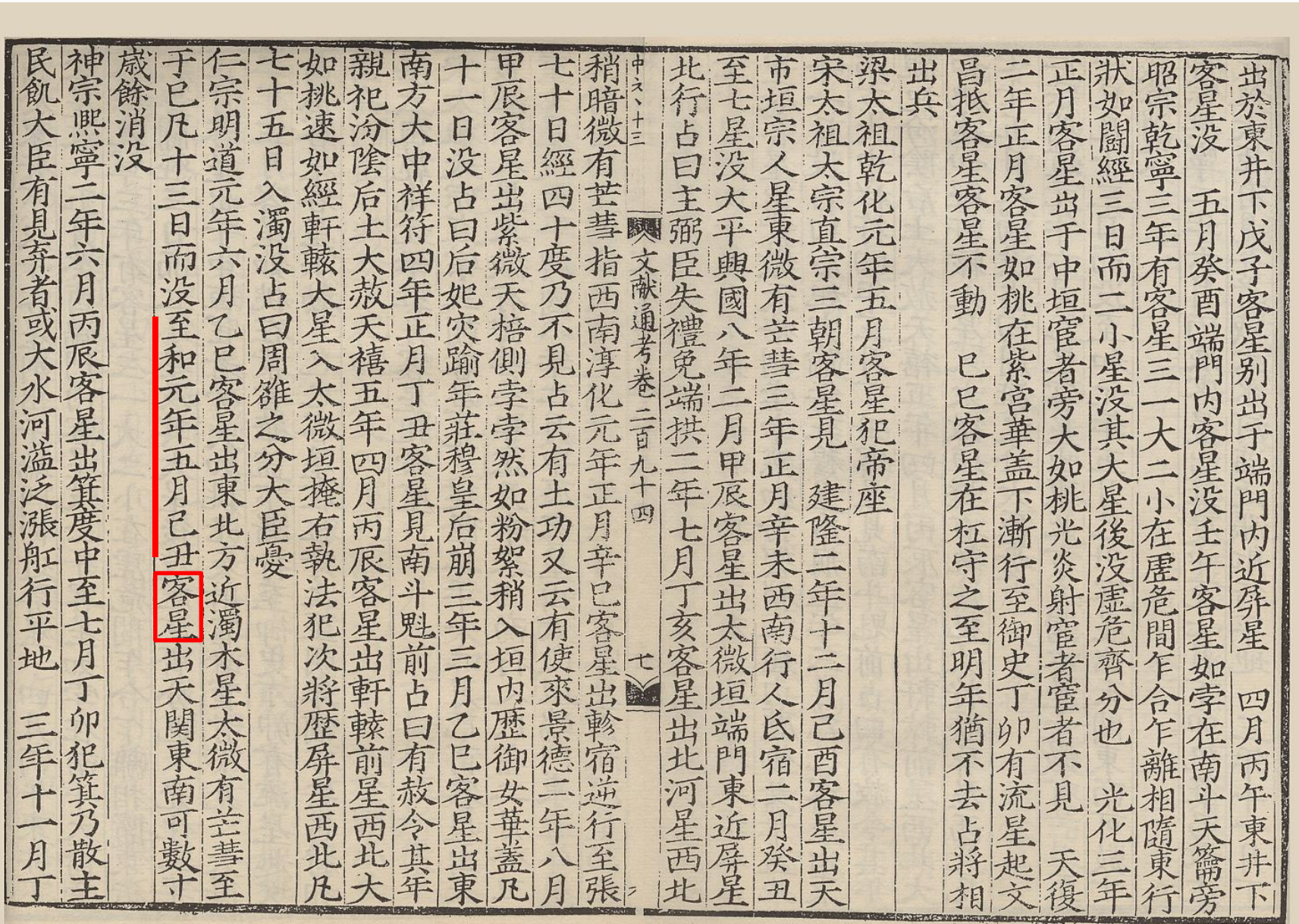
Zhen Cao, **IHEP**

On behalf of LHAASO Collaboration

CTA-Japan Workshop, Tokyo, Feb. 2022

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**


出於東井下戊子客星別出于端門內近帝星　四月丙午東井下
客星沒　五月癸酉端門內客星沒壬午客星如孛在南斗天籥旁
昭宗乾寧三年有客星三一大二小在虛危間乍合乍離相隨東行
狀如鬬經三日而二小星沒其大星後沒虛危齊分也　光化三年
正月客星出于中垣宦者旁大如桃光炎射宦者宦者不見　天復
二年正月客星如桃在紫宮華蓋下漸行至御史丁卯有流星起文
昌抵客星客星不動　己巳客星在杠守之至明年猶不去占將相
出兵
梁太祖乾化元年五月客星犯帝座
宋太祖太宗真宗三朝客星見　建隆二年十二月己酉客星出天
市垣宗人星東微有芒彗三年正月辛未西南行人氐宿二月癸丑
至七星沒大平興國八年二月甲辰客星出太微垣端門東近斛星
北行占曰主弼臣失禮兒端拱二年七月丁亥客星出北河星西北

稍暗微有芒彗指西南淳化元年正月辛巳客星出軫宿逆行至張
七十日經四十度乃不見占云有土功又云有使來景德二年八月
甲辰客星出紫微天棓側孛孛然如粉絮稍入垣內歷御女華蓋凡
十一日沒占曰后妃宂踰年莊穆皇后崩三年三月乙巳客星出東
南方大中祥符四年正月丁丑客星見南斗魁前占曰有赦令其年
親祀汾陰后土大赦天禧五年四月丙辰客星出軒轅前星西北大
如桃速如經軒轅大星入太微垣掩右執法犯次將歷斛星西北凡
七十五日入濁沒占曰周雒之分大臣憂
仁宗明道元年六月乙巳客星出東北方近濁木星太微有芒彗至
于巳凡十三日而沒至和元年五月己丑客星出天關東南可數寸
歲餘消沒
神宗熙寧二年六月丙辰客星出箕度中至七月丁卯犯箕乃散主
民飢大臣有見奔者或大水河溢泛漲舡行平地　三年十一月丁

公元1054年7月4日凌晨

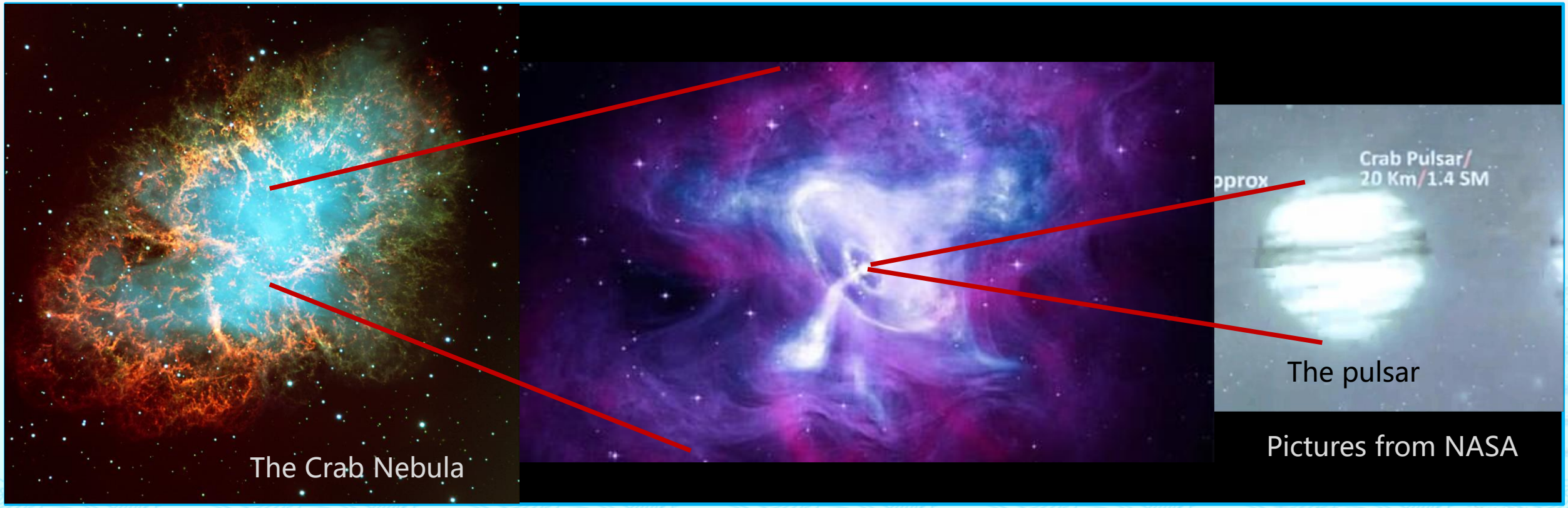
After midnight of July 4, 1054

Star explosion

The Crab: after 977 years

- Constellation: Taurus
- Distance: 6500 ly
- Size of remnant: 11 ly
- Size of inner nebula: 0.6 ly ($\sim 0.005^\circ$)
- Size of pulsar: ~20 km
- Spin period: 33 ms
- $\dot{E} \approx 5 \times 10^{38}$ erg/s

The Crab: remnant, nebula and pulsar



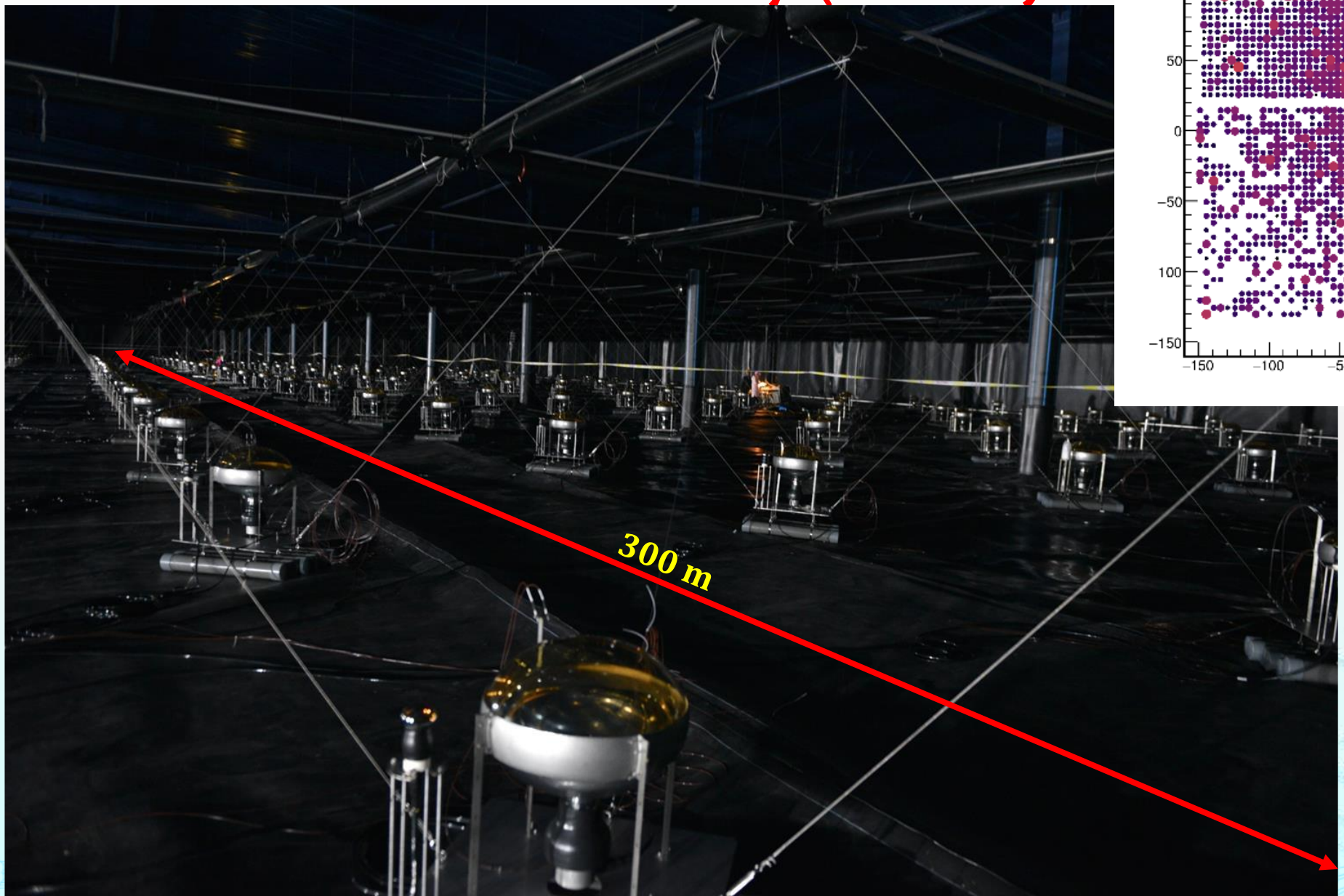
Bird's eye view of LHAASO， 2021-08

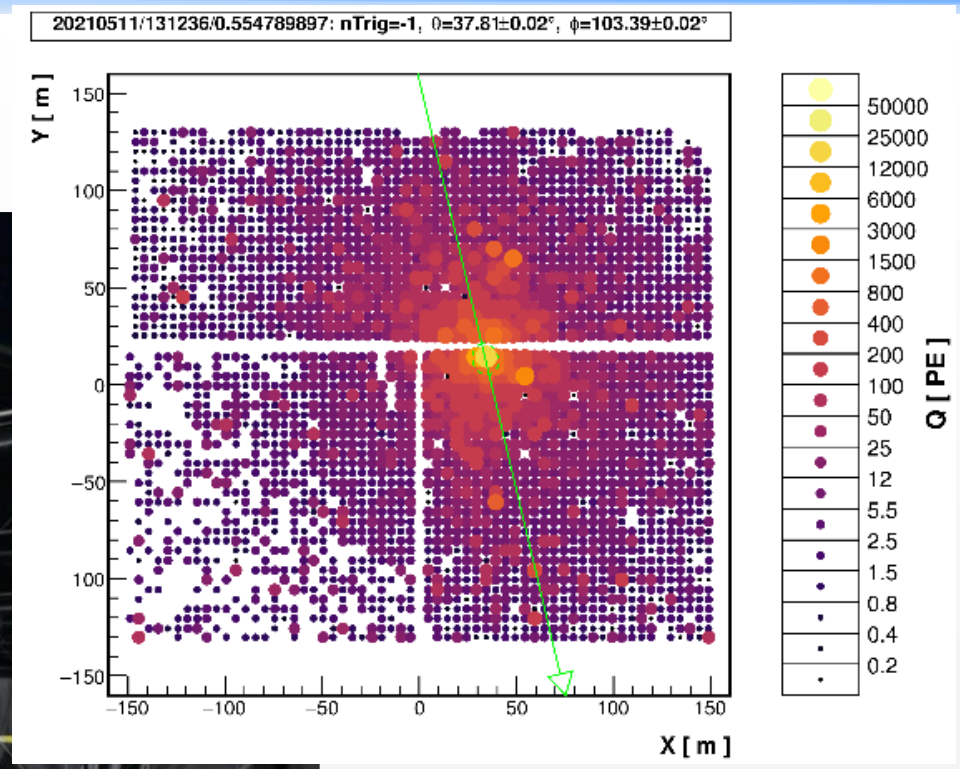
- Location： 29°21' 27.6" N , 100°08'19.6" E
- Altitude: 4410 m
- 2021-07 completed built and in operation

Area：
1.3 km^2
Detectors：
5195 ED
1188 MD
Energy Range：
0.01-10 PeV

LHAASO
高海拔宇宙线观测站

Water Cherenkov Detector Array (WCDA)



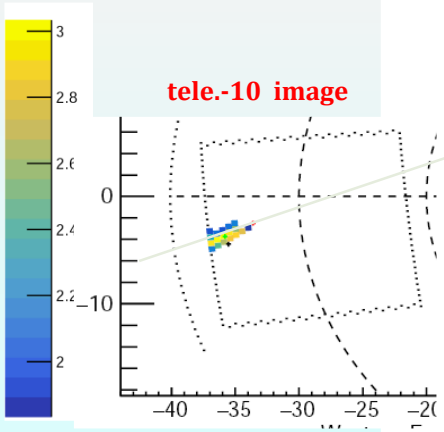


- **Area:**
  78,000 m²
- **Detector units:**
  3120
- **Energy Range:**
  0.1-10 TeV

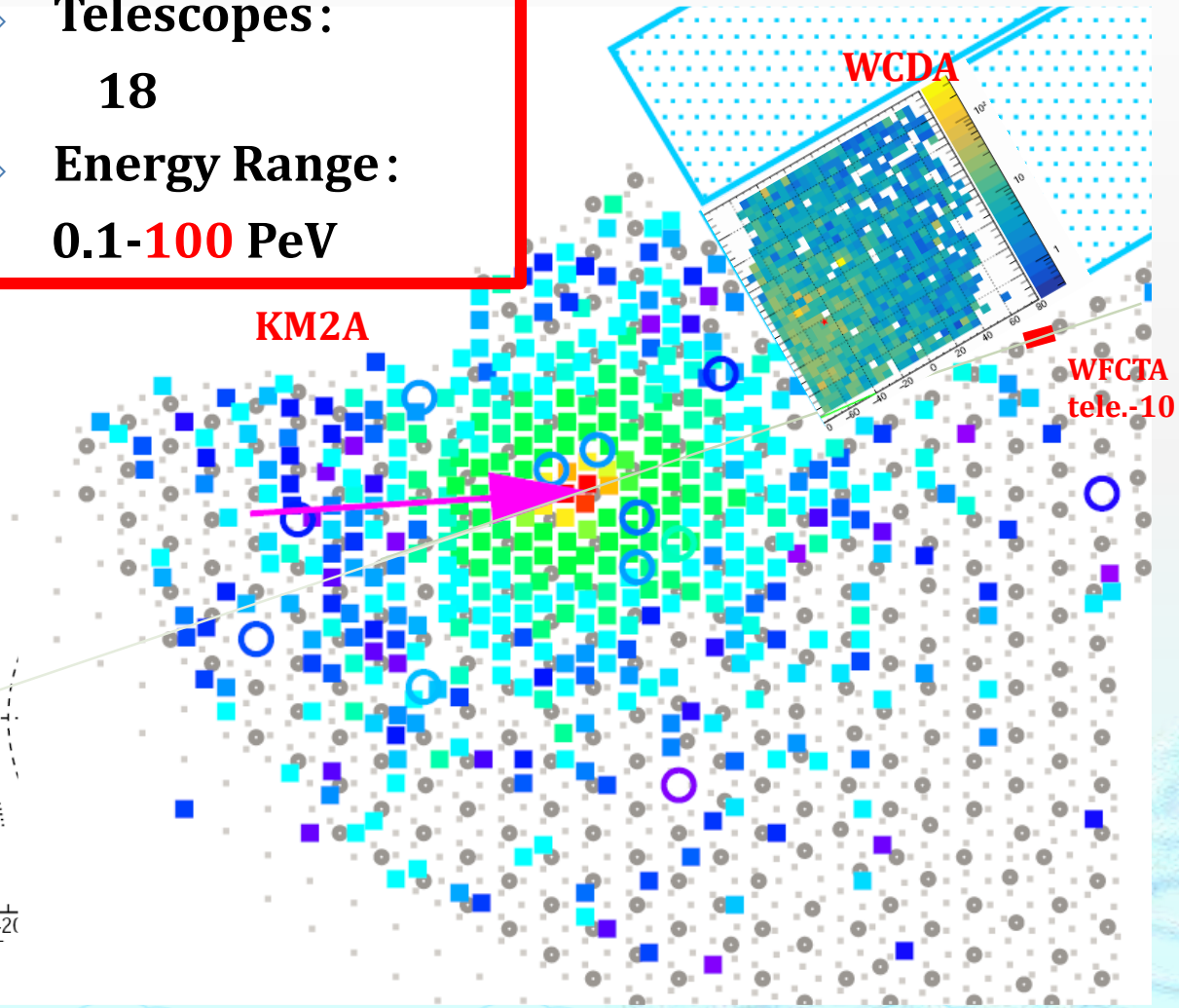
Wide FoV C-Telescope Array (WFCTA)

Cross-checking inside Collaboration

- **Telescopes:**
  18
- **Energy Range:**
  0.1-100 PeV



- WFCTA measured the event simultaneously
  L/W~2.6, N_{pe}~9100 in 11 pixels
- **Energy: 0.9±0.2 PeV**
- KM2A measured the event
  $N_{particle}$~4574 in 395 EDs
- **Energy: 0.9±0.1 PeV**
- **Chance probability: <0.1%**
  N_{μ}~15 in 11 MDs



LHAASO, Science, *373*, 425-430, 2021

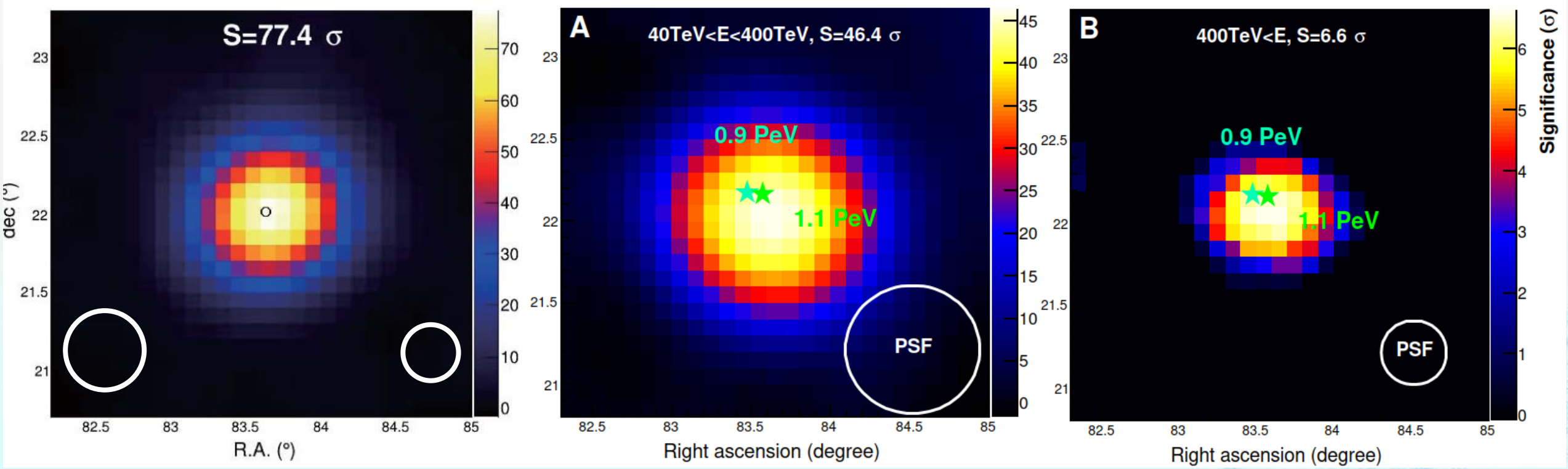
The Crab seeing by WCDA and KM2A

The coverage of 3.5 orders of magnitudes of energy

0.5 - 12 TeV

40-400 TeV

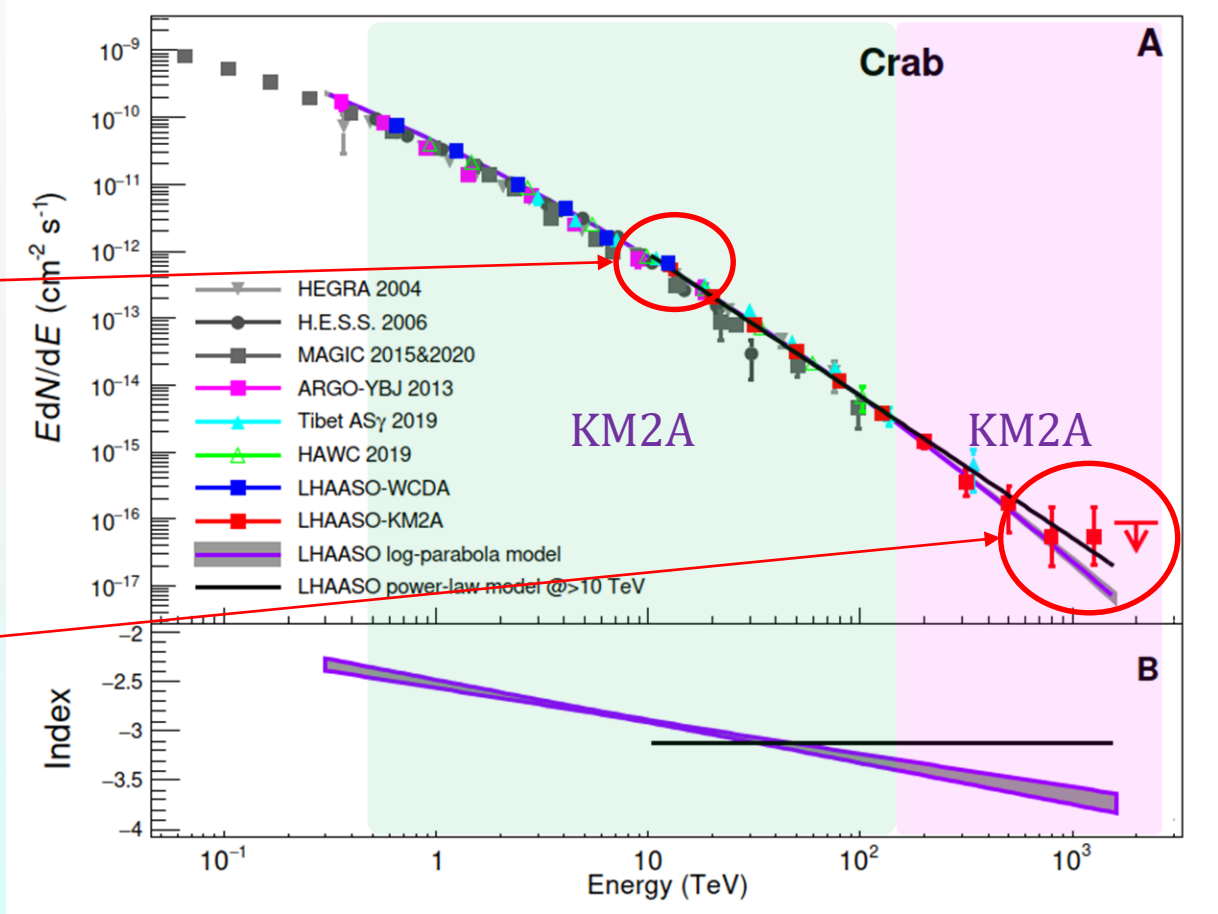
0.4-1.2 PeV



SED of the Crab: "standard Candle" & PeVatron

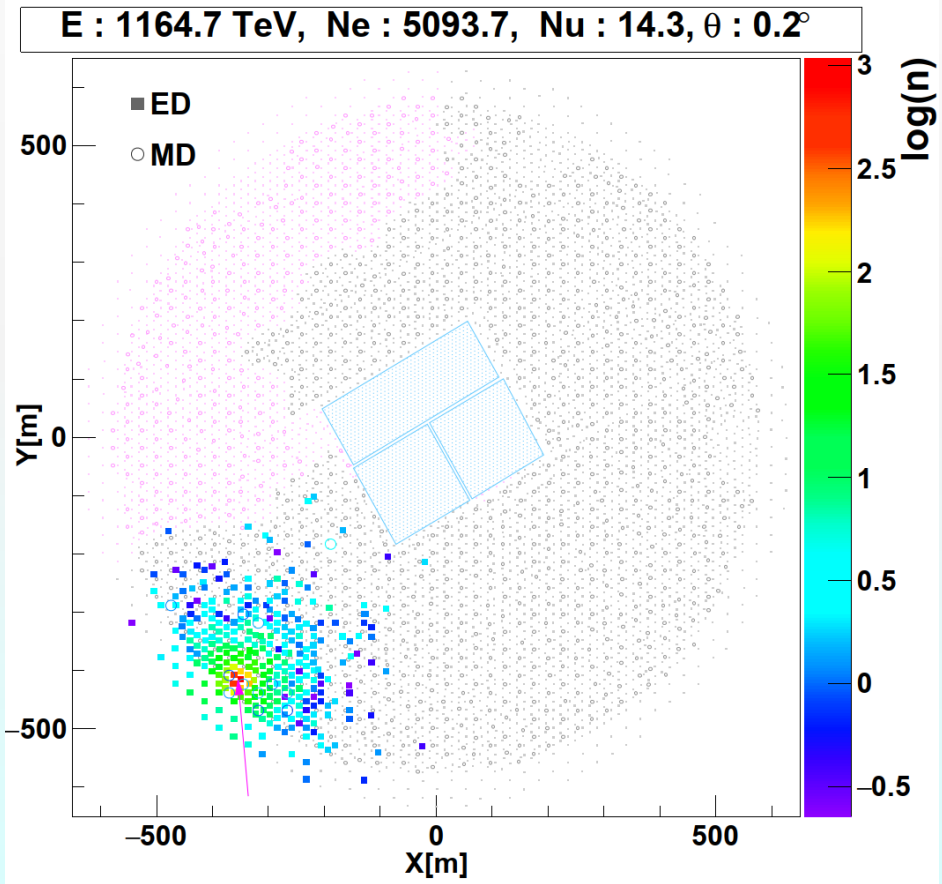
- **LHAASO: (comparison)**
  - Covering 3.5 decades of energy
  - Agreeing with other experiments below 100 TeV
  - Self cross-checking between WCDA & KM2A
- **LHAASO: (discovery)**
  - Unique UHE SED
  - A PeVatron without ambiguity
  - Clear origin: a well-known PWN
- **Challenge basic theory of electron acceleration**

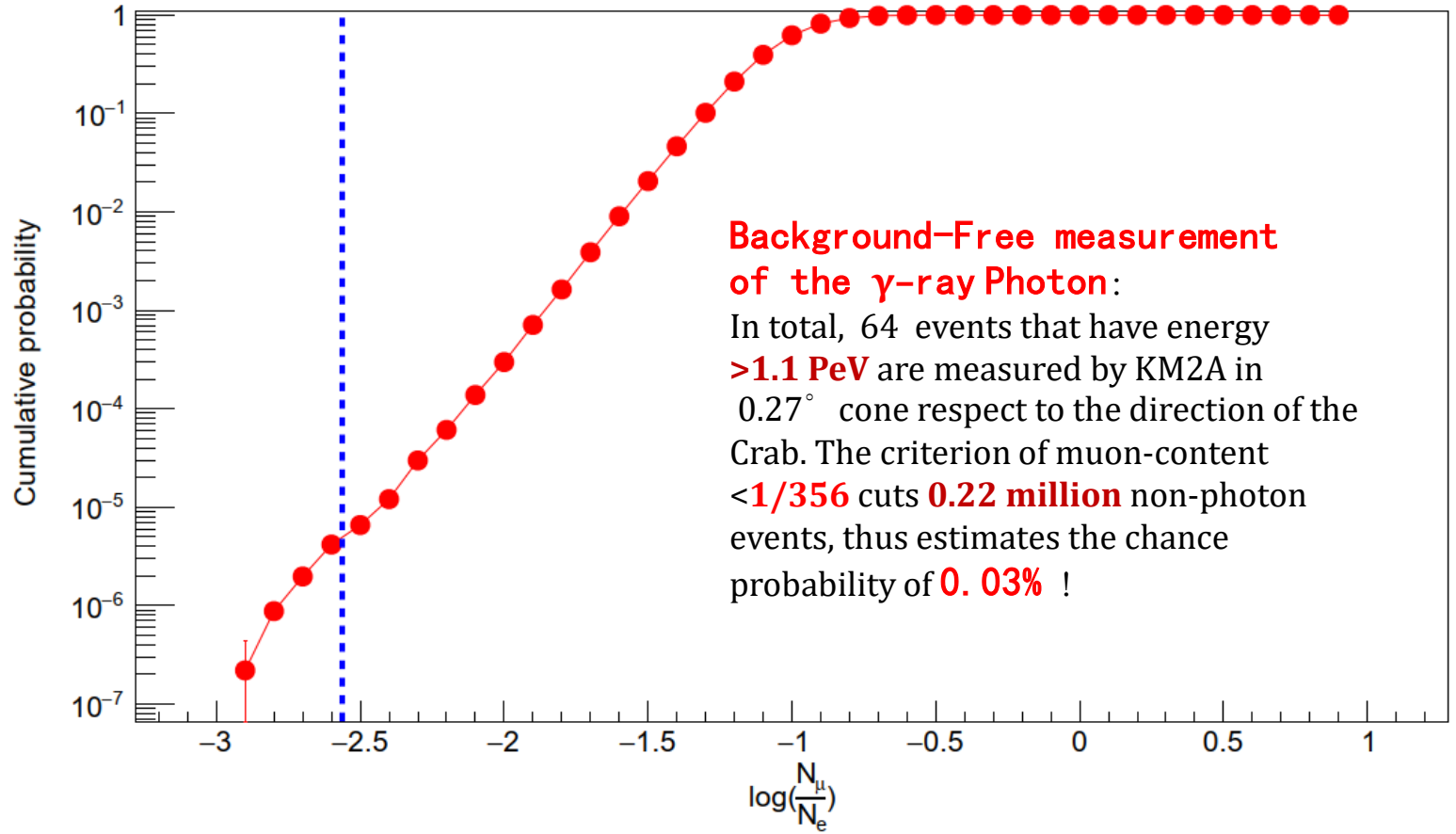
Zhen Cao, *et al.*, LHAASO, *Science*, p425-430, 2021



1.1 PeV Photon from the Crab Direction Record by KM2A

LHAASO, Science, *373*, 425-430, 2021



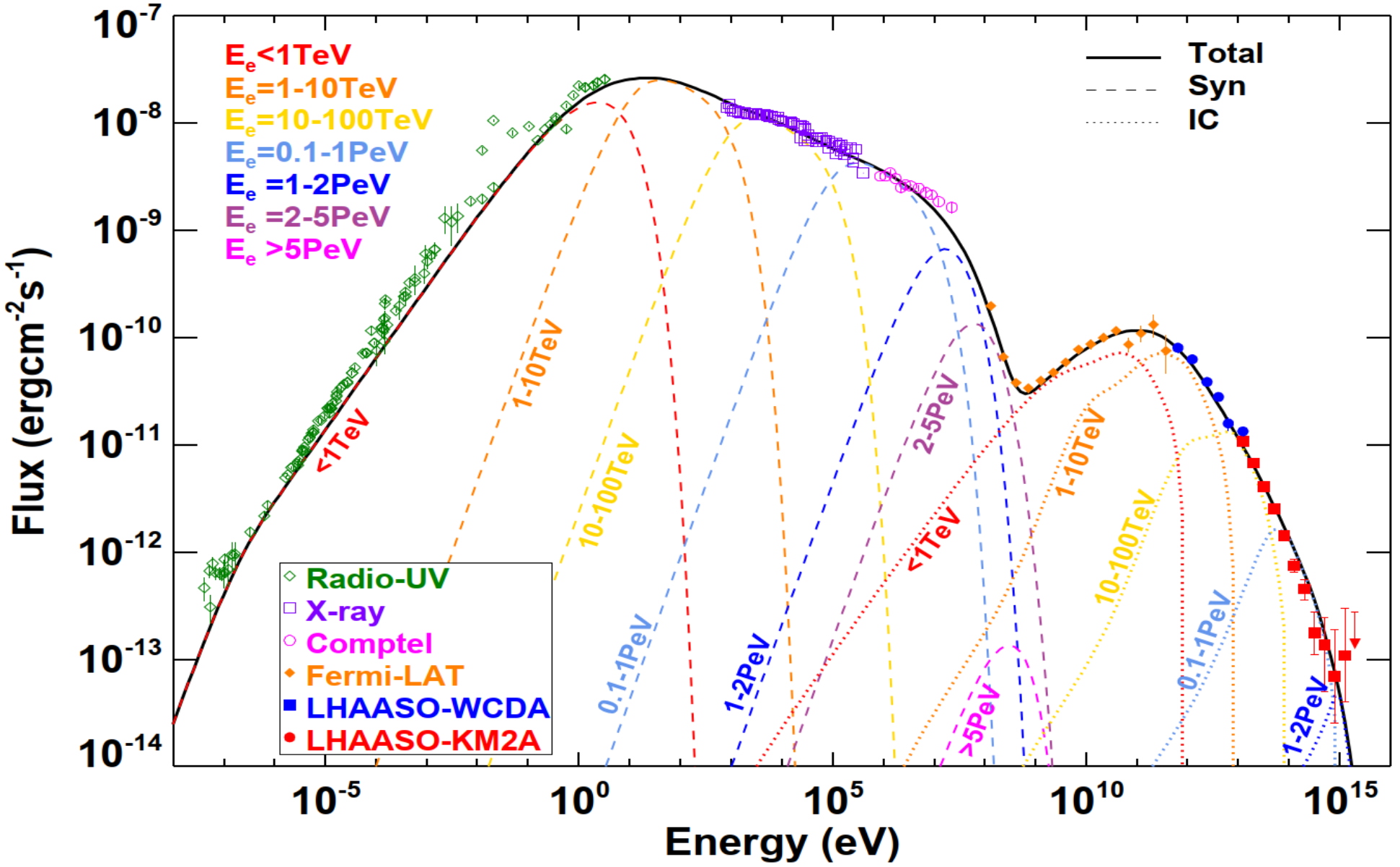


Background-Free measurement of the γ-ray Photon:

In total, 64 events that have energy **>1.1 PeV** are measured by KM2A in 0.27° cone respect to the direction of the Crab. The criterion of muon-content **<1/356** cuts **0.22 million** non-photon events, thus estimates the chance probability of **0.03%** !

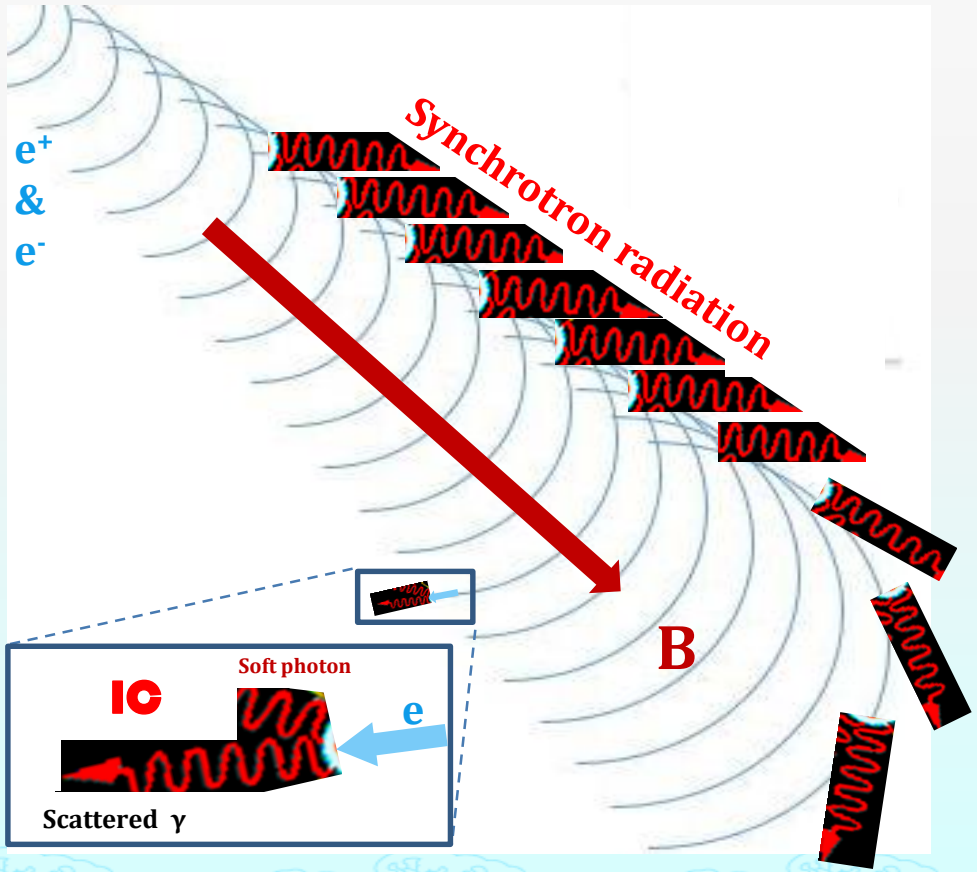
Electronic Origin of the Crab Radiation

- 22 decades
- One bulk of e^+s & e^-s
- Synchrotron radiation
- Inverse Compton scattering

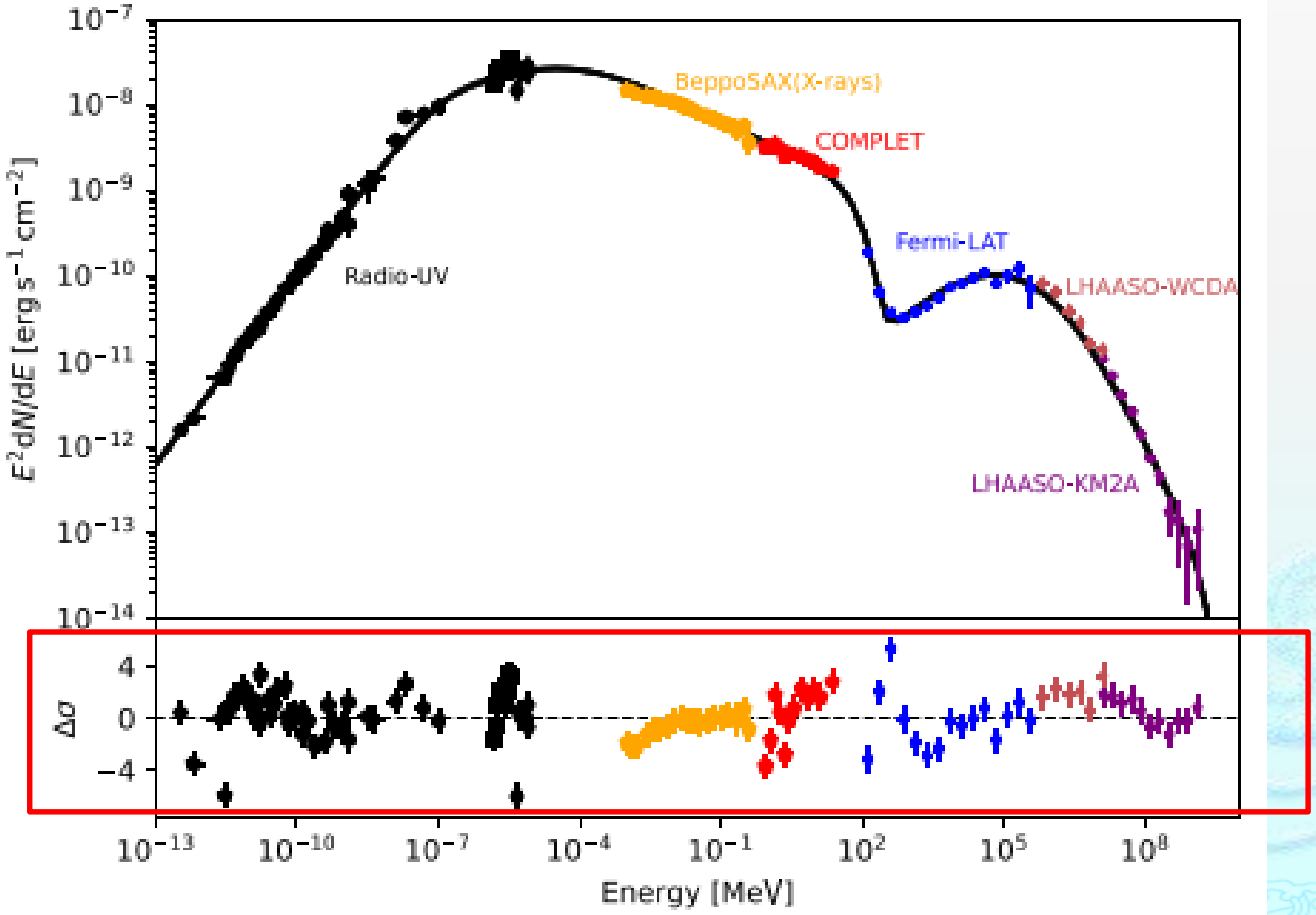


“Extreme Electron PeVatron”

- 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, in press, arXiv:2201.03796



~PeV Photon in the One-zone Model

a serious challenge!

- **Electron Energy:** $E_e = 2.15(E_\gamma/1\ \mathrm{PeV})^{0.77}\ \mathrm{PeV} \sim 2.3\ \mathrm{PeV}$
- **Size of the accelerator responsible to the ~PeV electrons**

$$(B/100\mu\mathrm{G})(\ell/1\ \mathrm{pc}) \geq 0.023\ (E_\gamma/1\ \mathrm{PeV})^{0.77}$$

  - $\ell \gtrsim 0.025$ pc, implying not associated with flares that last few days
  - $\ell \lesssim 0.18$ pc, assuming not beyond the inner nebula

- **Acceleration Rate:**

$$\eta = \mathcal{E}/B = 0.14\ (B/100\mu\mathrm{G})(E_\gamma/1\ \mathrm{PeV})^{1.54} \sim 0.16$$

  - A factor of ~1000 larger than diffusive shock acceleration in SNR
  - η must be < 1 according to ideal MHD — challenge !!
  - If E_γ~3.5 PeV — impossible !!!

The Crab Nebula: two torus

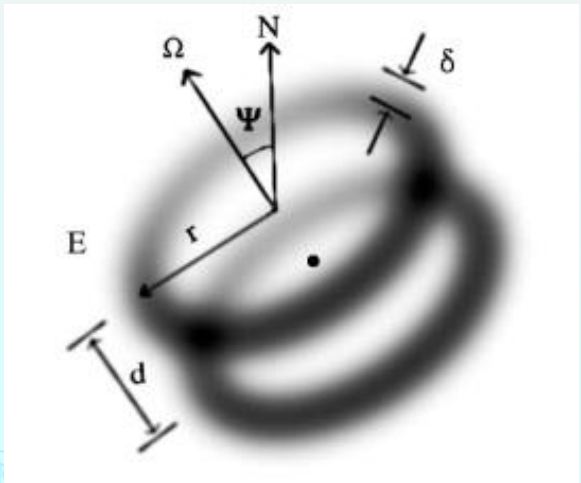
- Fitting of the nebula
- Parameters: ψ,ζ,r,δ,d.

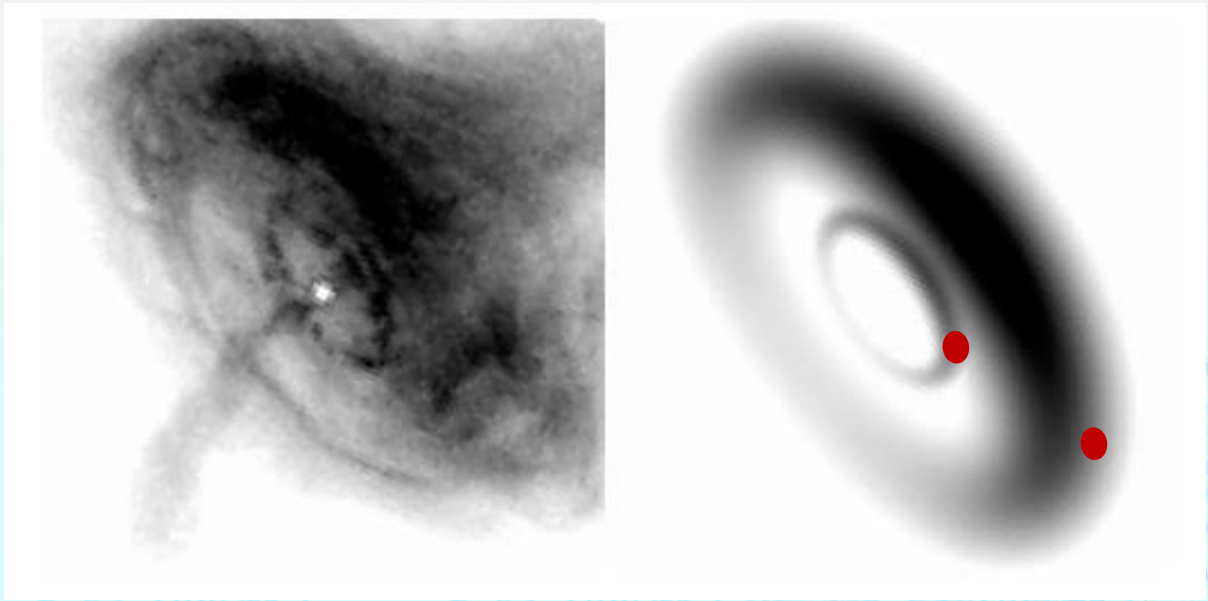
ζ is the angle between the line of sight to N.

β is the bulk velocity of the postshock flow.

Inner: r=15.6 arcsec = 0.0043° + δ =3" , about 0.59 ly or 0.18 pc
Outer: r=41.3 arcsec = 0.0115° + δ =6" , about 1.49 ly or 0.46 pc
1.1 PeV photon could be emitted from even smaller region ≳0.025 pc

Object	Ψ	ζ	r (arcsec)	δ	β	Point Source	Torus
Crab (inner).....	124.0 ± 0.1	61.3 ± 0.1	15.60 ± 0.03	3.0*	$0.490^{+0.005}_{-0.006}$	...	1.0×10^5
Crab (outer).....	126.31 ± 0.03	$63.03^{+0.02}_{-0.03}$	$41.33^{+0.02}_{-0.03}$	5.9*	0.550 ± 0.001	...	1.1×10^7
Vela	$130.63^{+0.05}_{-0.07}$	$63.60^{+0.07}_{-0.05}$	$21.25^{+0.03}_{-0.02}$	3.0*	$0.44^{+0.004}_{-0.003}$	...	1.3×10^6
SNR G54.1+0.3	91^{+4}_{-5}	147 ± 3	4.6 ± 0.1	1.1 ± 0.1	$0.62^{+0.04}_{-0.03}$	1701	602
PSR J2229+6114	103 ± 2	46 ± 2	9.3 ± 0.2	2.5*	0.49 ± 0.02	2221	1113
PSR B1706−44	175^{+3}_{-4}	55 ± 3	$3.5^{+0.2}_{-0.1}$	0.74*	$0.65^{+0.03}_{-0.04}$	384	168
PSR J0538+2817	155 ± 8	99 ± 8	$6.3^{+1.0}_{-0.7}$	$1.7^{+0.3}_{-0.7}$	$0.54^{+0.09}_{-0.08}$	2442*	52



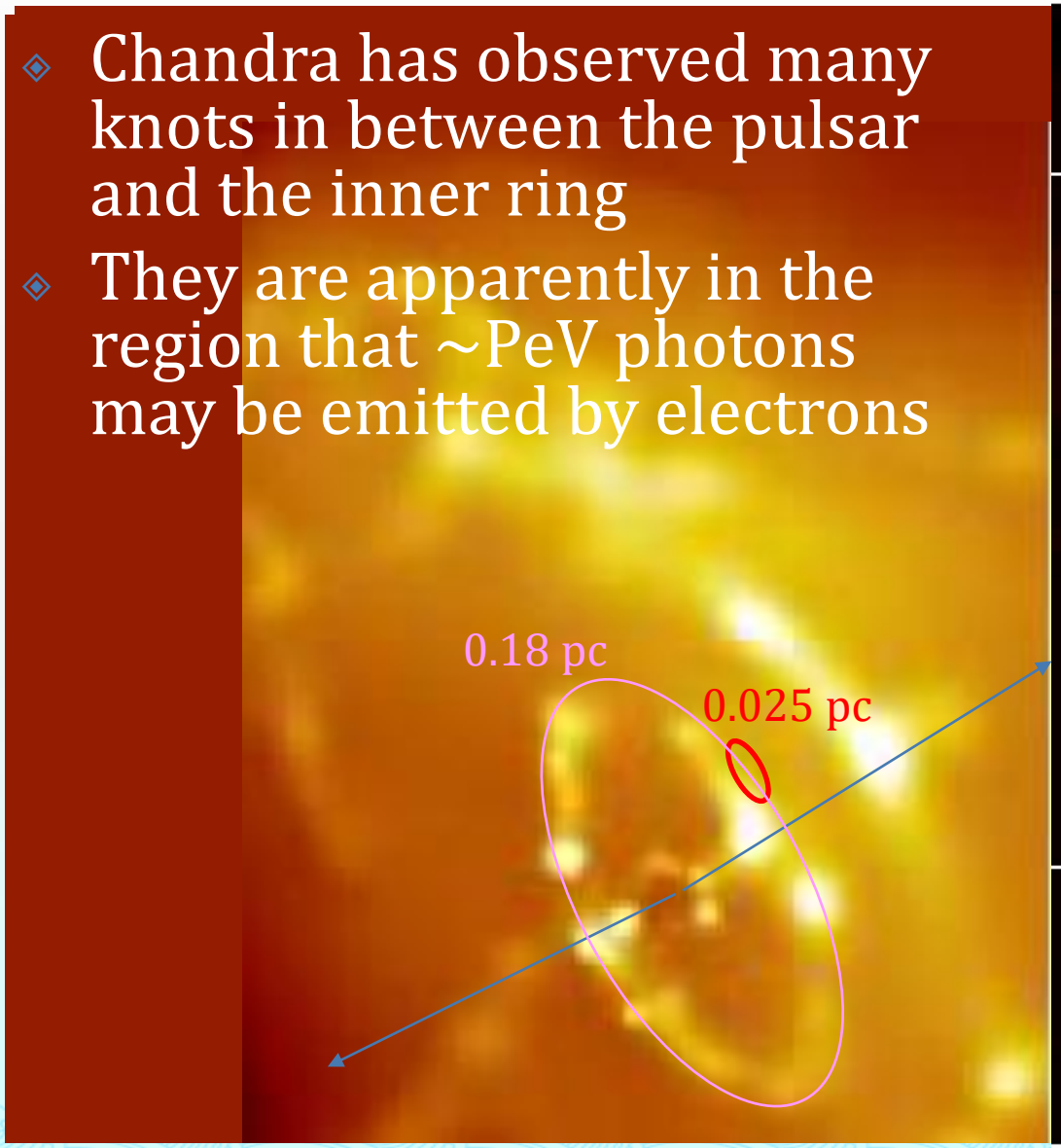


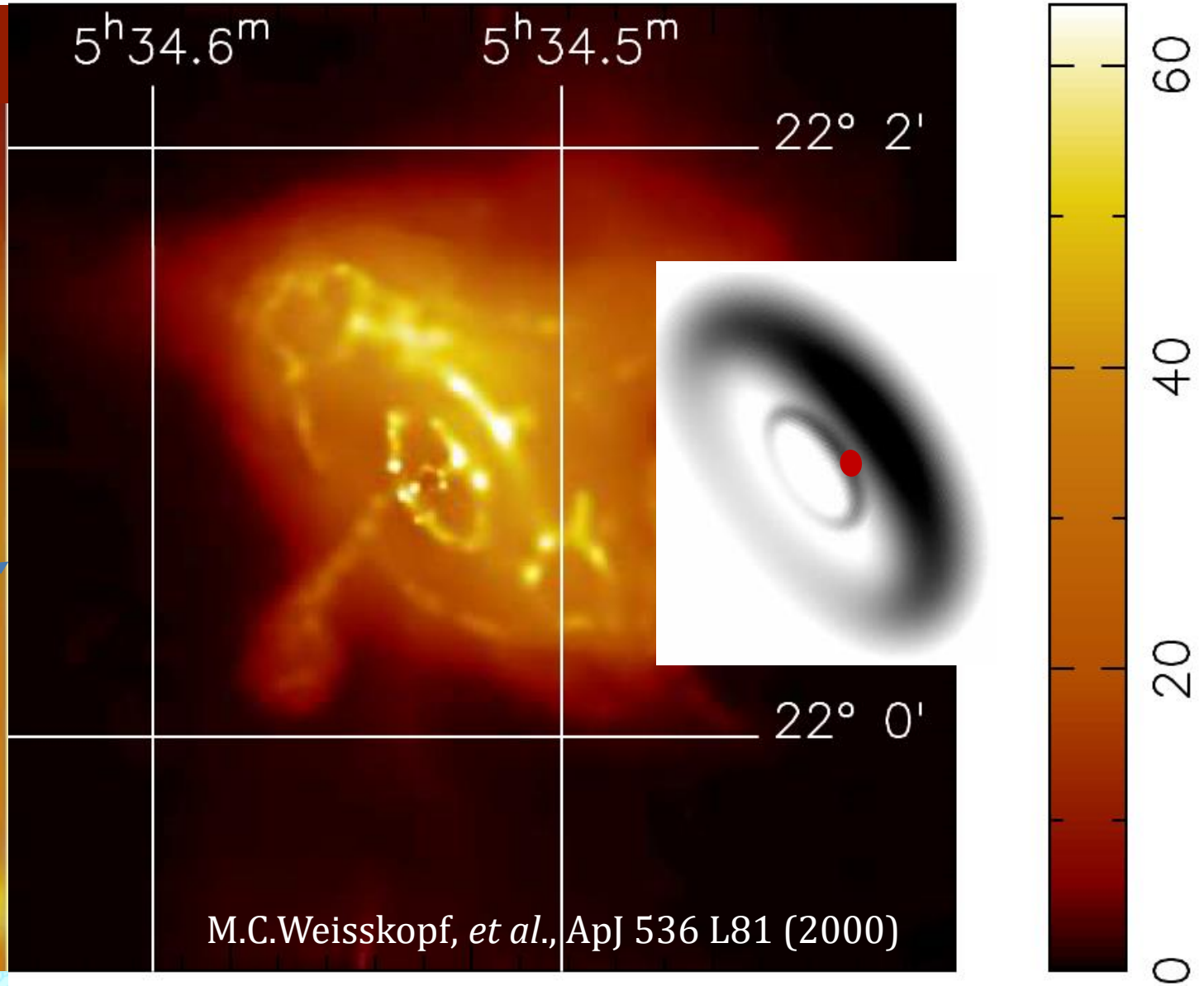
2667 s observation by Chandra in 1999

C.-Y. Ng and Roger W. Romani, ApJ 601, 479–484 (2004)

Inner ring, jets and knots

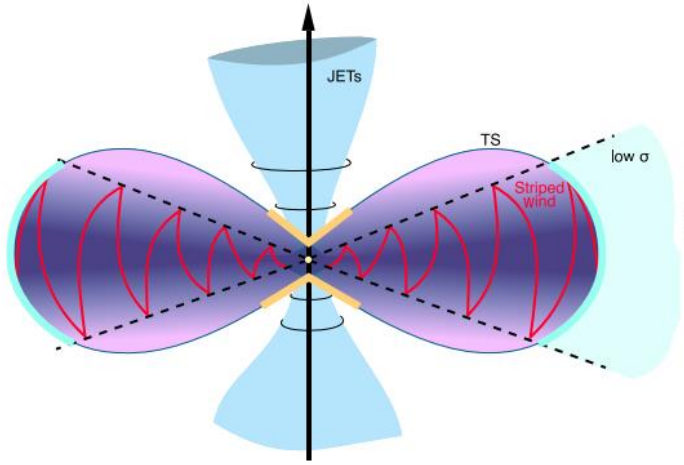
- Chandra has observed many knots in between the pulsar and the inner ring
- They are apparently in the region that ~PeV photons may be emitted by electrons

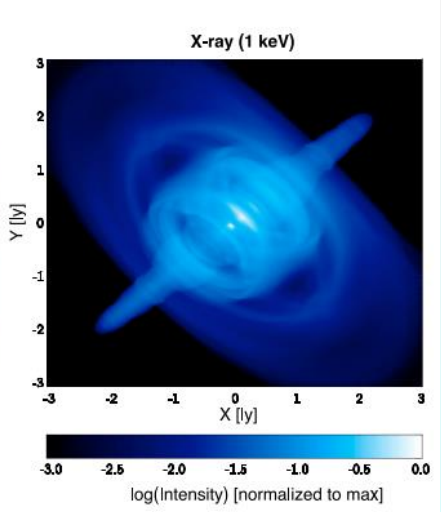


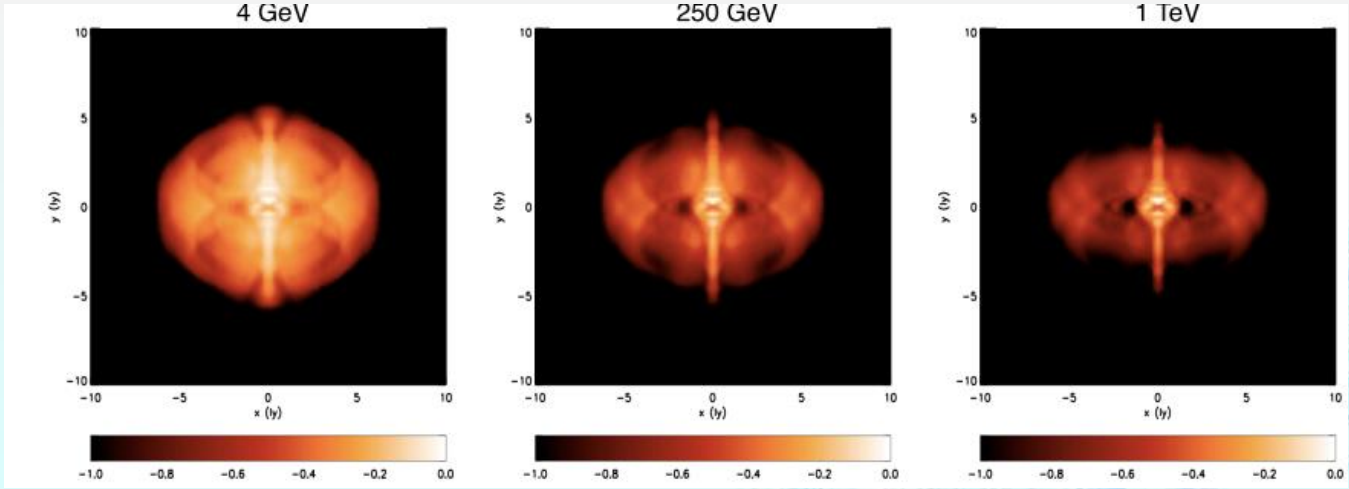


MHD simulation for Nebula Morphology

- X-ray and γ–ray （IC-process）
- Size ~50” by Chandra ~52” by HESS
  - C.-Y. Ng and Roger W. Romani, ApJ 601, 479–484 (2004)
  - H. E. S. S. Collaboration, Nat. Astron., 4, 167–173(2020)
  - Simulation is done by Volpi, D.; Del Zanna, L.; Amato, E.; Bucciantini, N., Astron. Astrophys., 485, 337–349(2008)

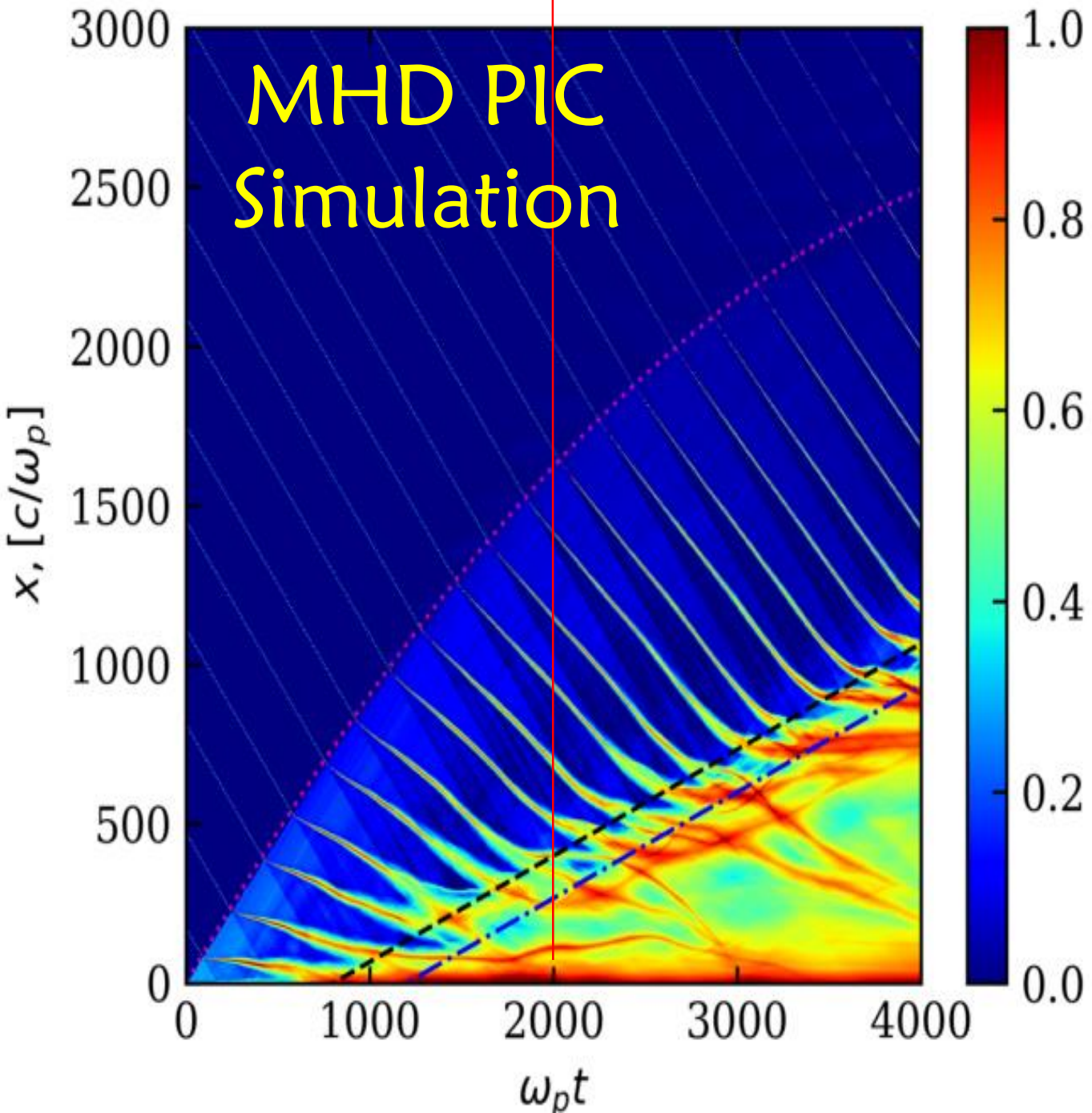




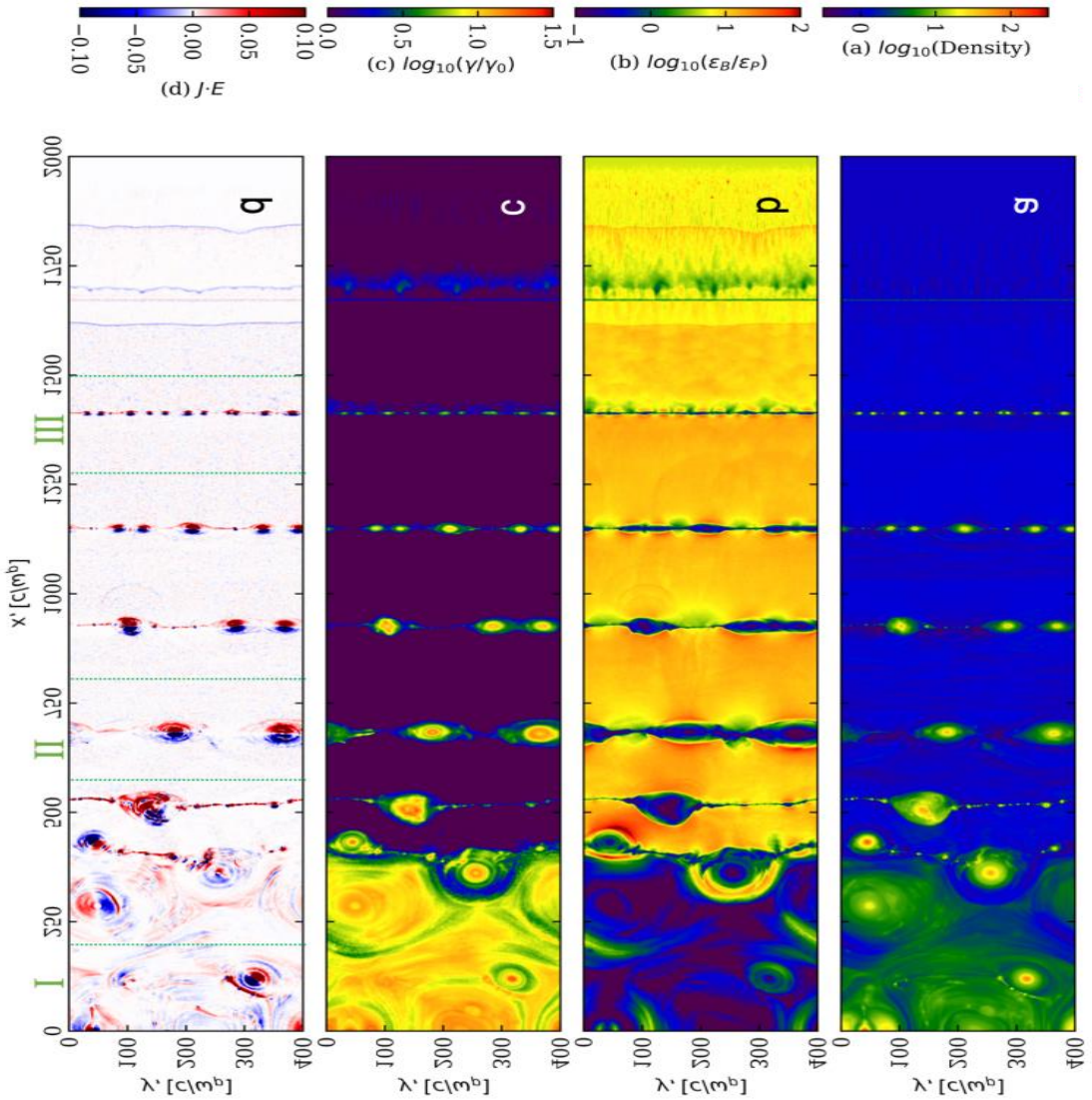


E. Amato and Barbara Olmi, Universe, 7, 448(2021)

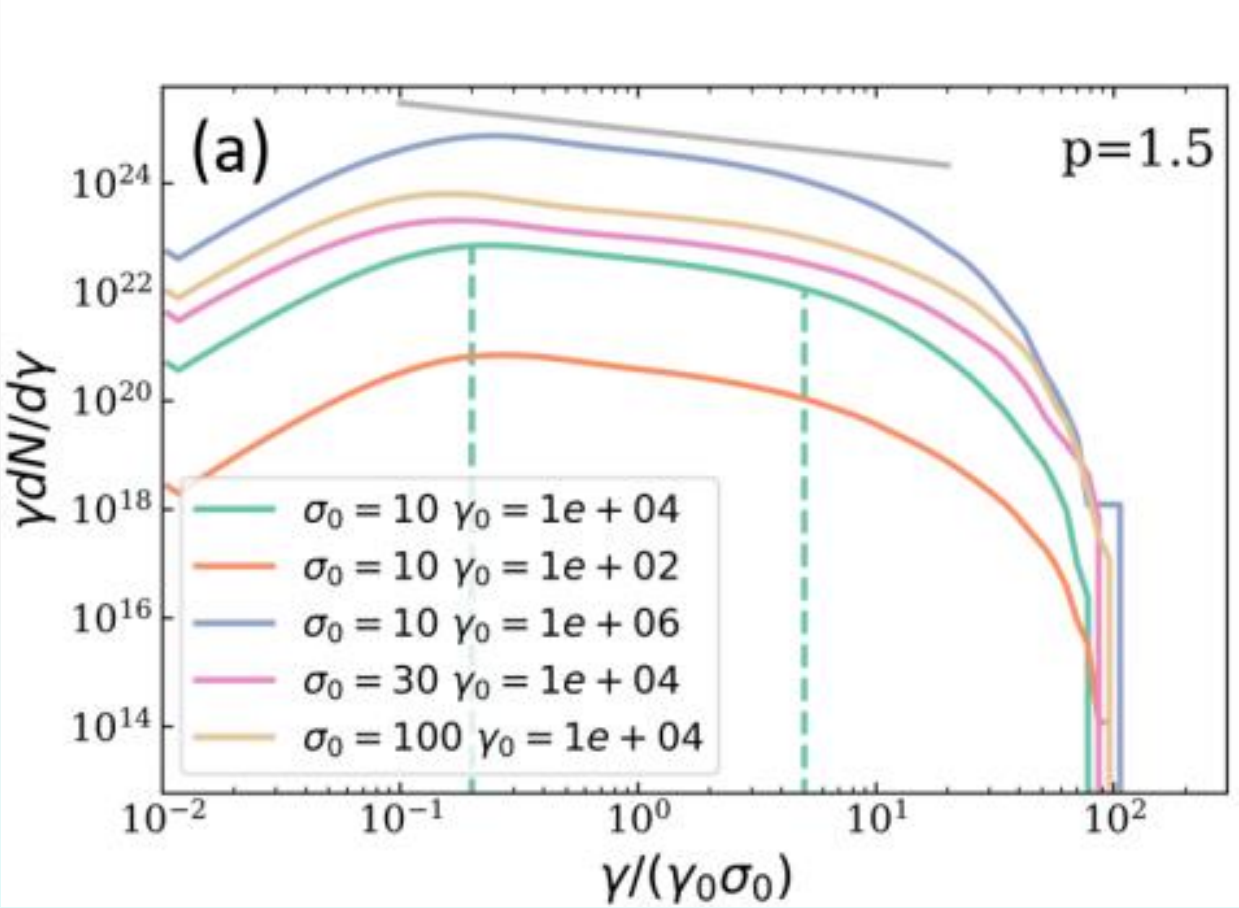
MHD PIC Simulation

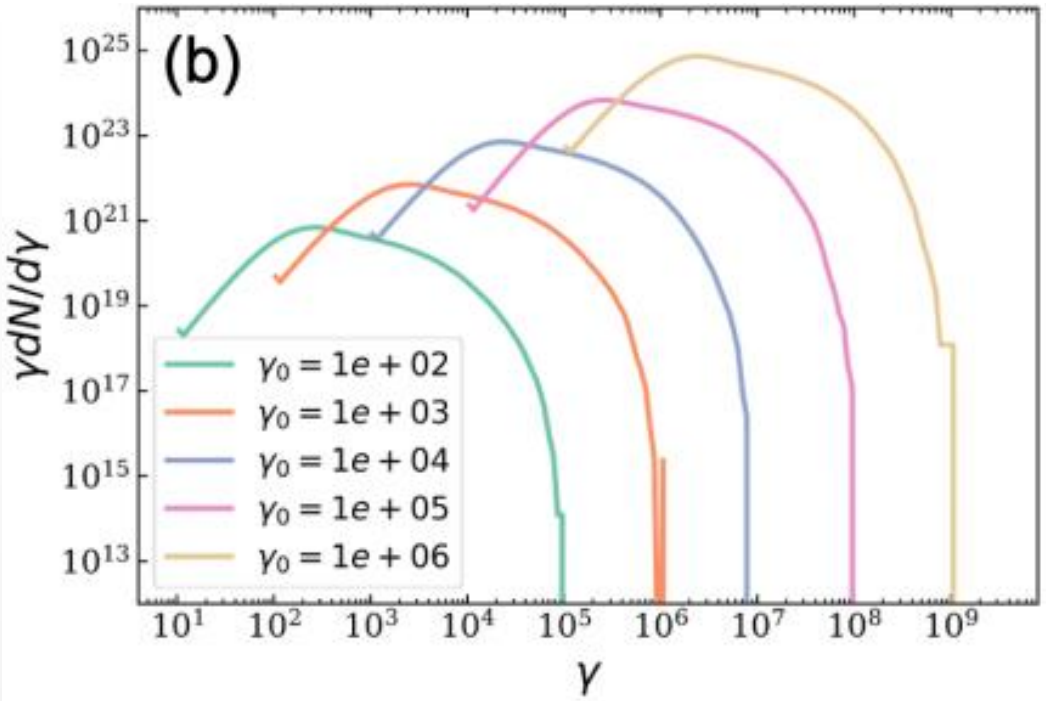


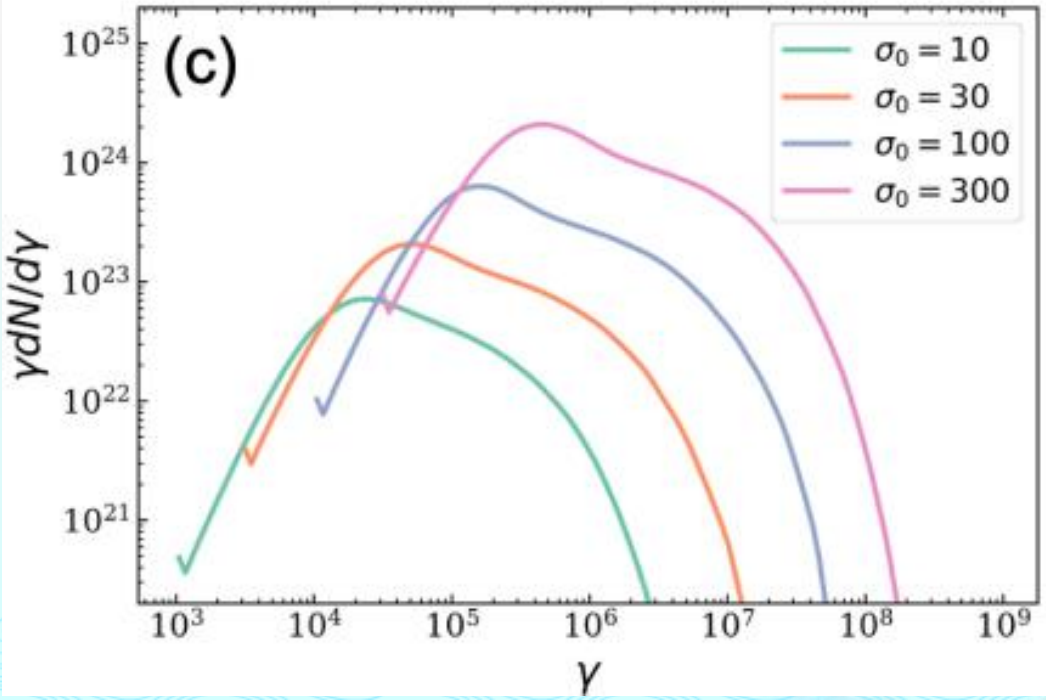
Yingchao Lu et al., ApJ 908, 2, 147 (2021)



Electron E-Spectrum



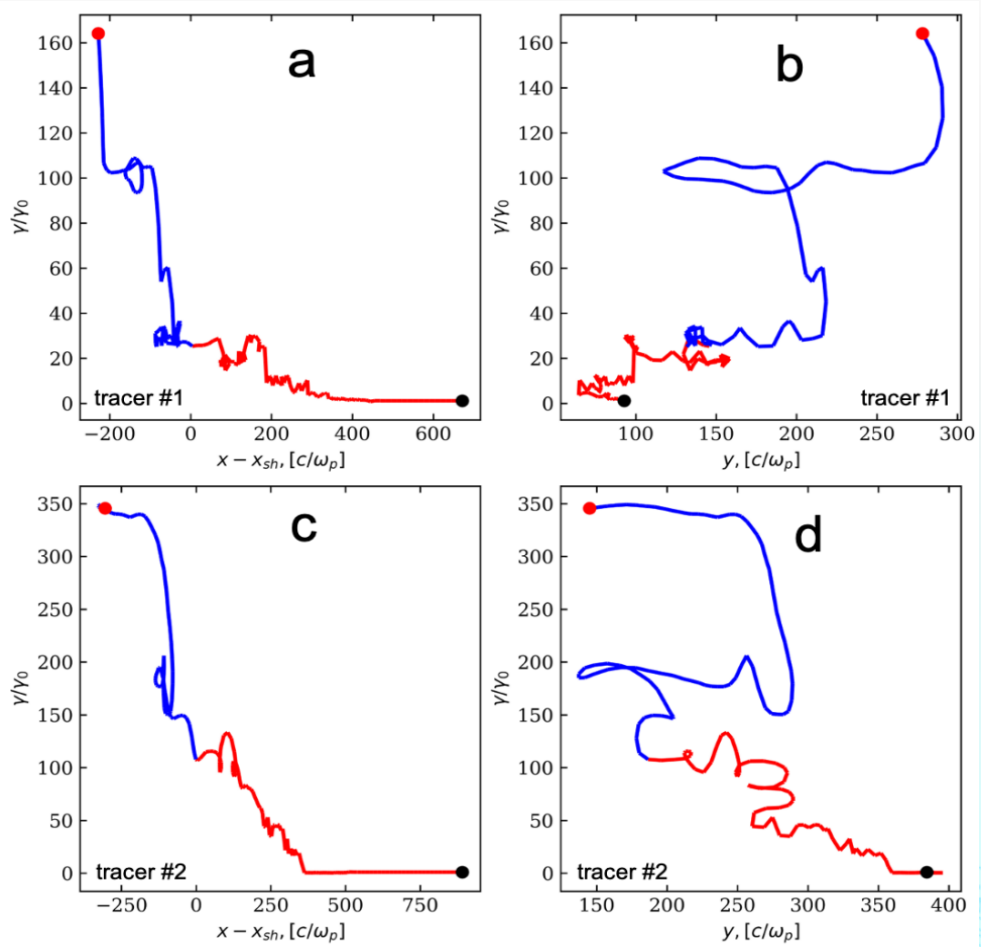


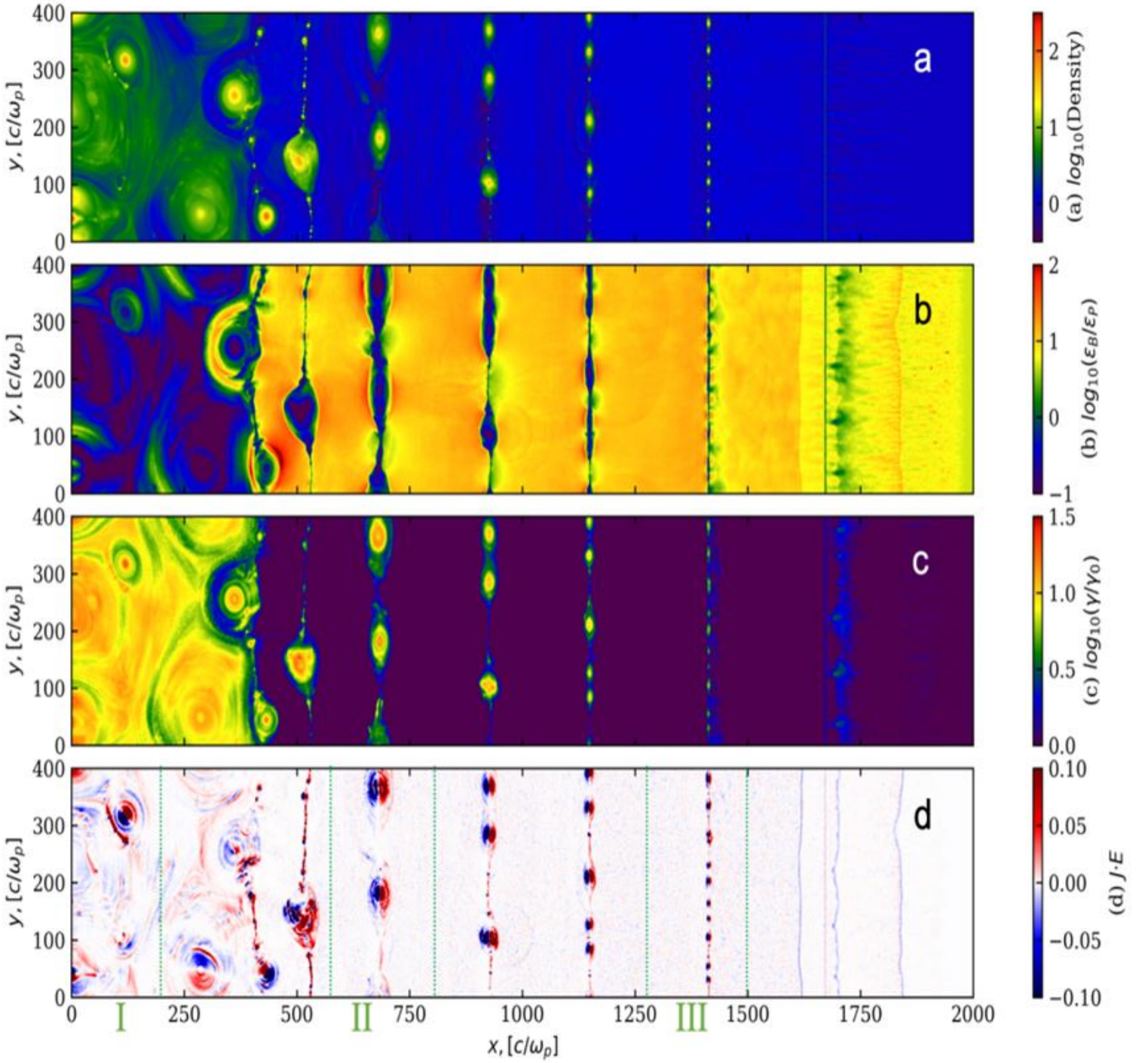


- it seems not impossible to reach 1 PeV, but quite extreme!

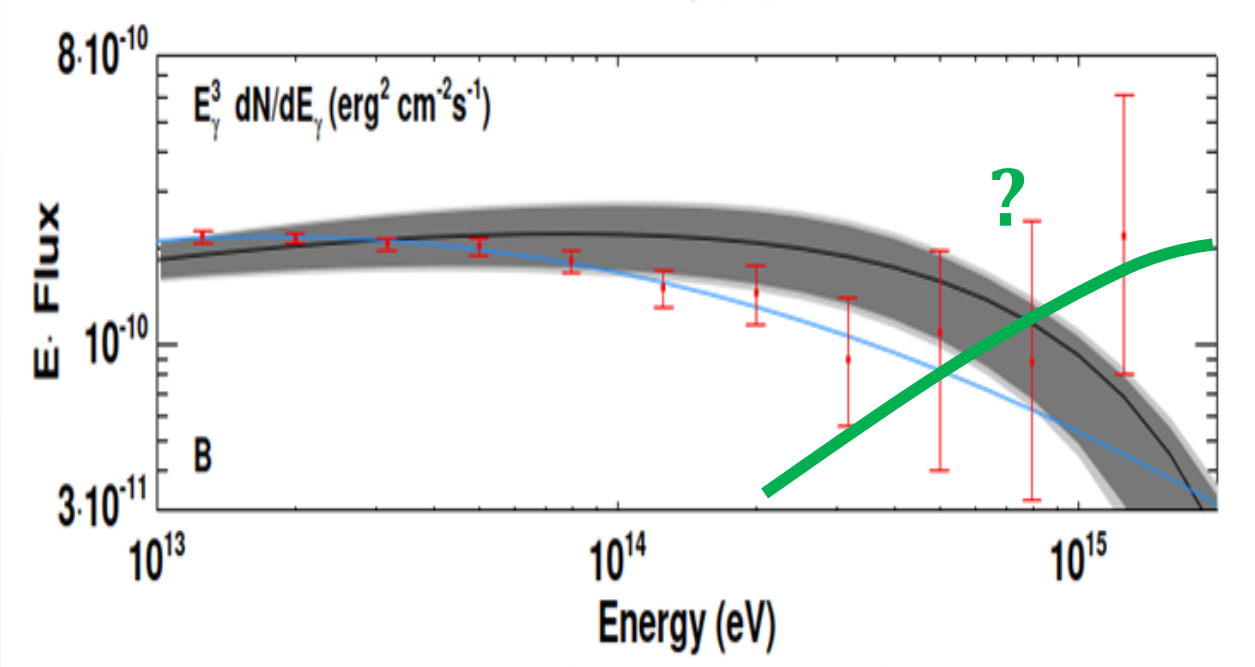
LHAASO
高海拔宇宙线观测站

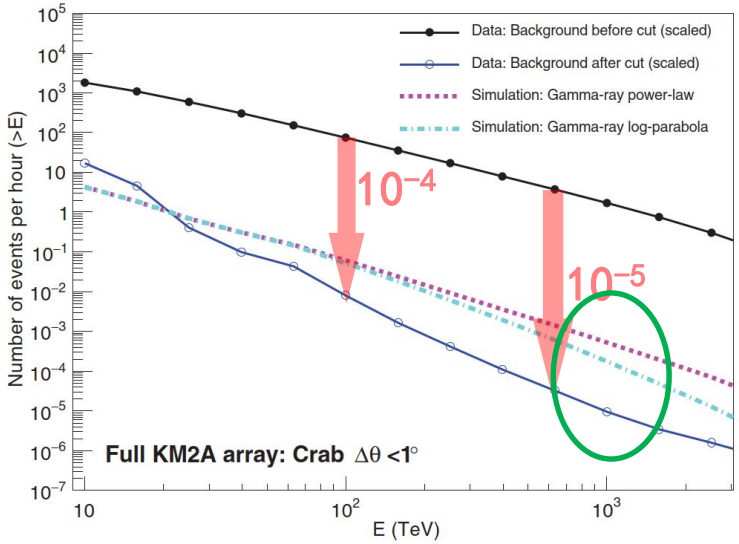
Two examples of electron trajectories





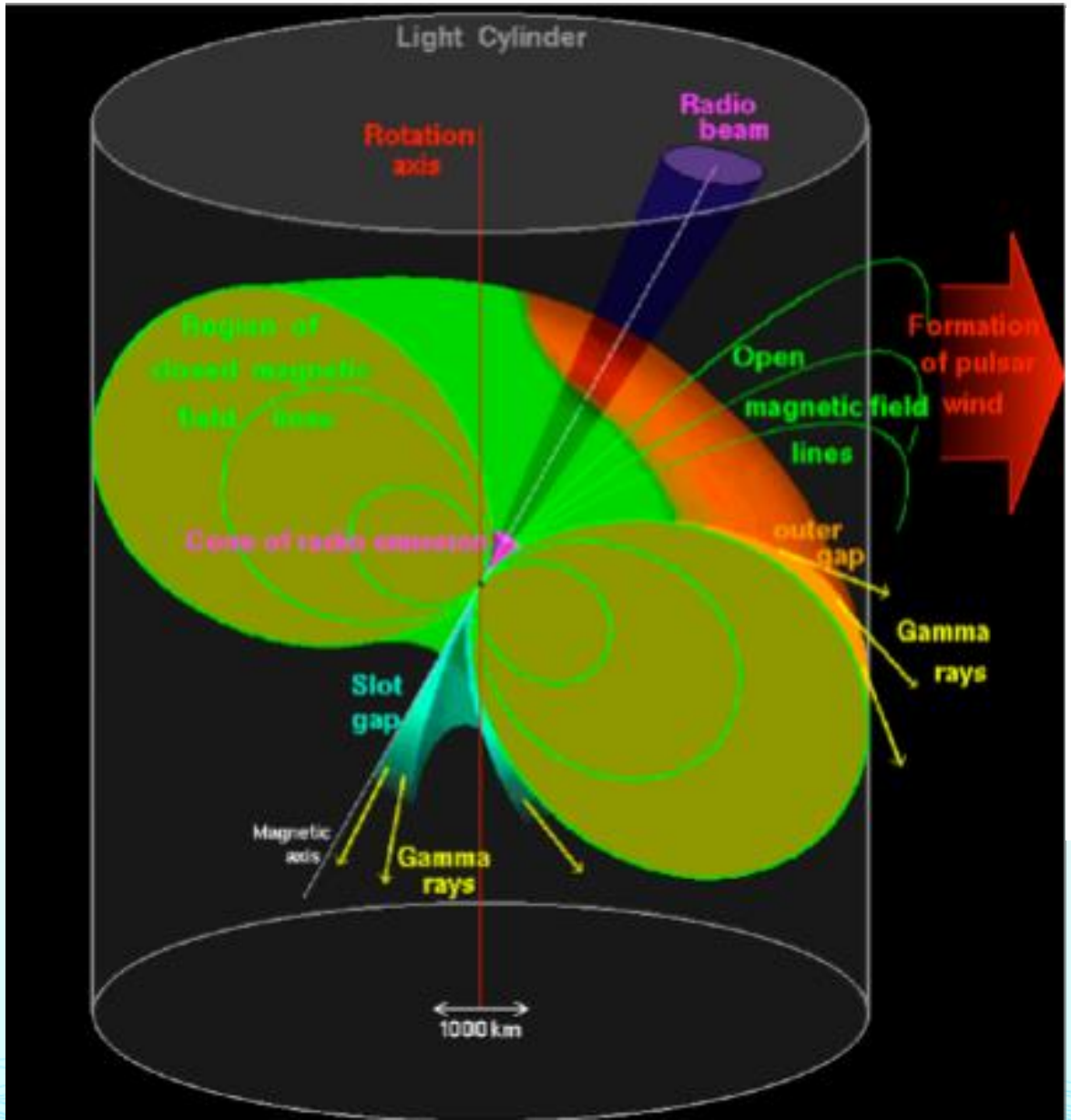
The other possibility ……

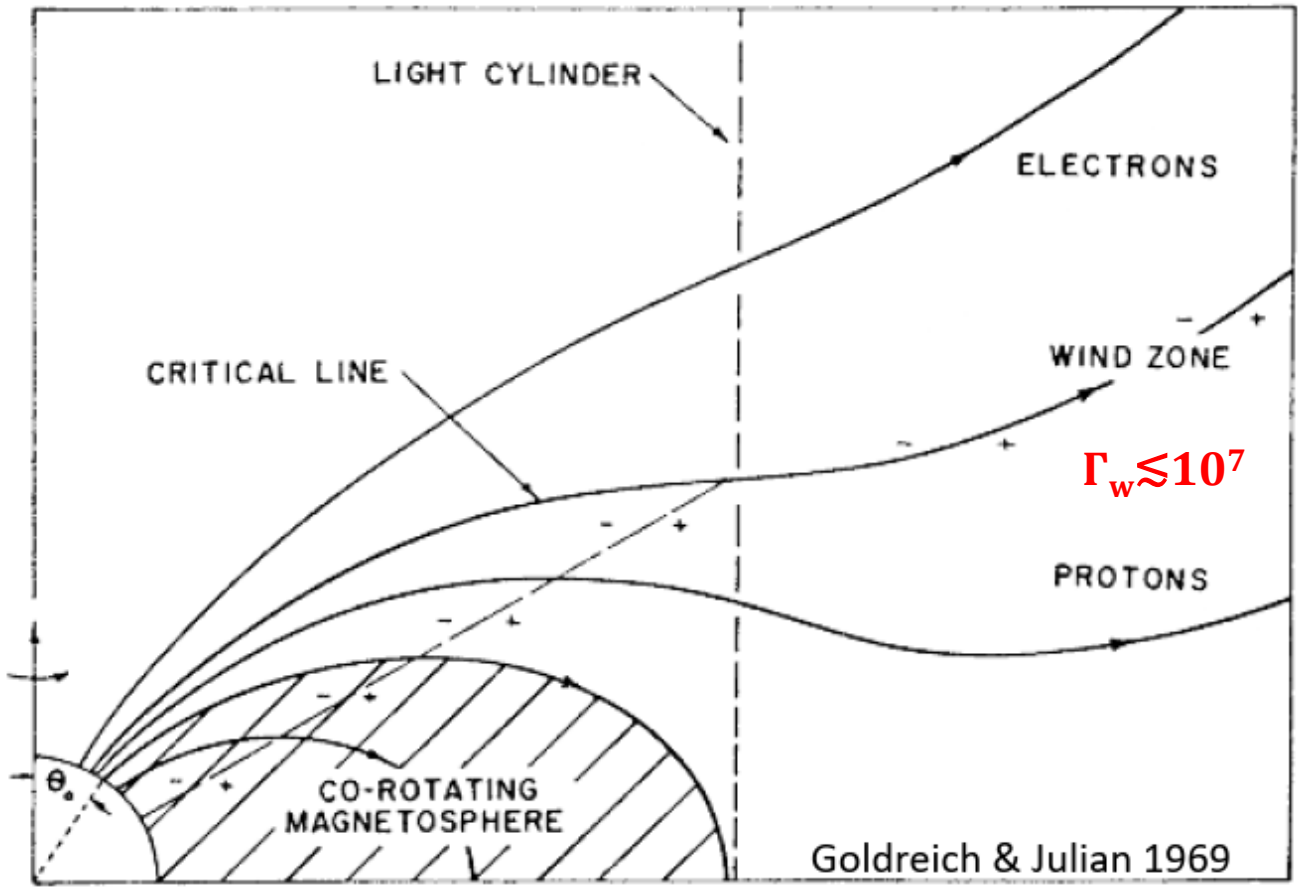




- The one-zone electron model may not be the best choice for UHE photons
- A 4σ-deviation from LHAASO data for $E_\gamma > 50$ TeV is observed
- A new component?
- We may need 3 more yrs for statistics to clarify
- 1~2 PeV photons per yr by LHAASO

Are there protons?





PULSAR WIND ENERGY FLUX:

$$\dot{E} = \kappa \dot{N}_{GJ} m_e \Gamma c^2 \left(1 + \frac{m_i}{\kappa m_e}\right)(1+\sigma)$$

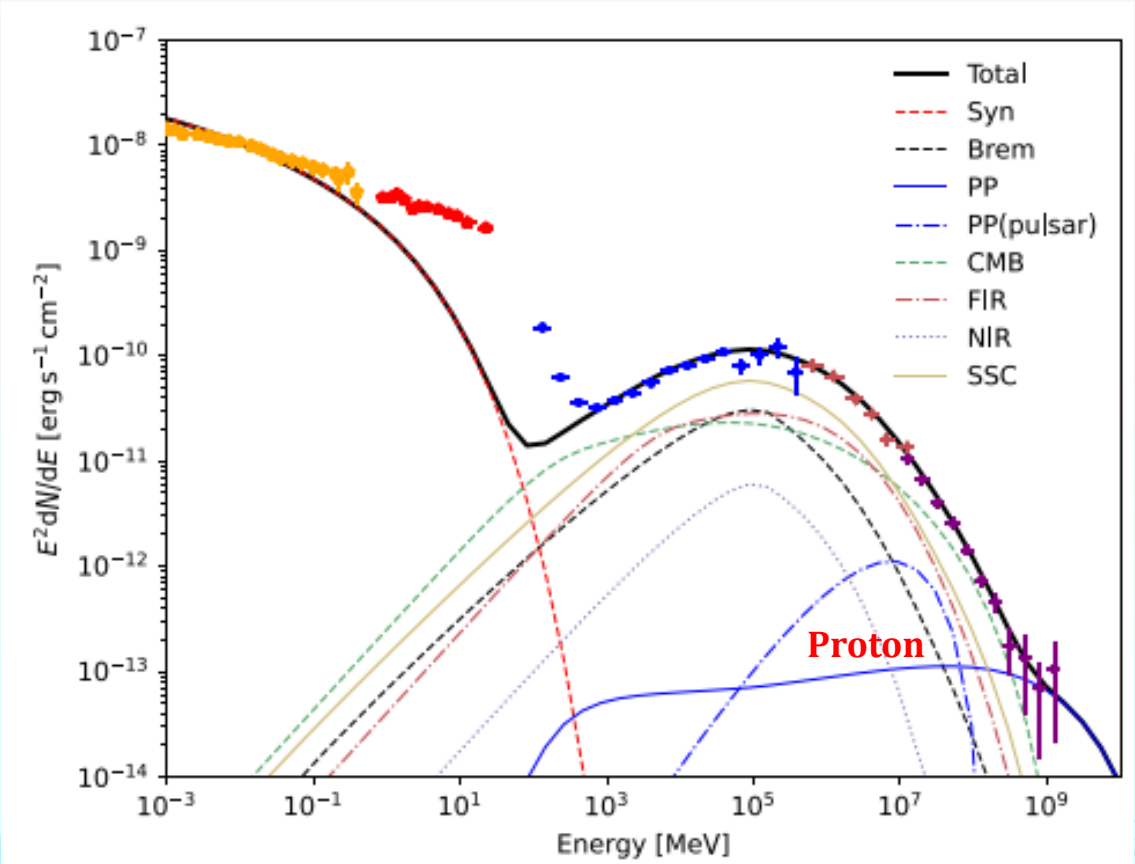
From Elena Amato's CDY talk (2022)

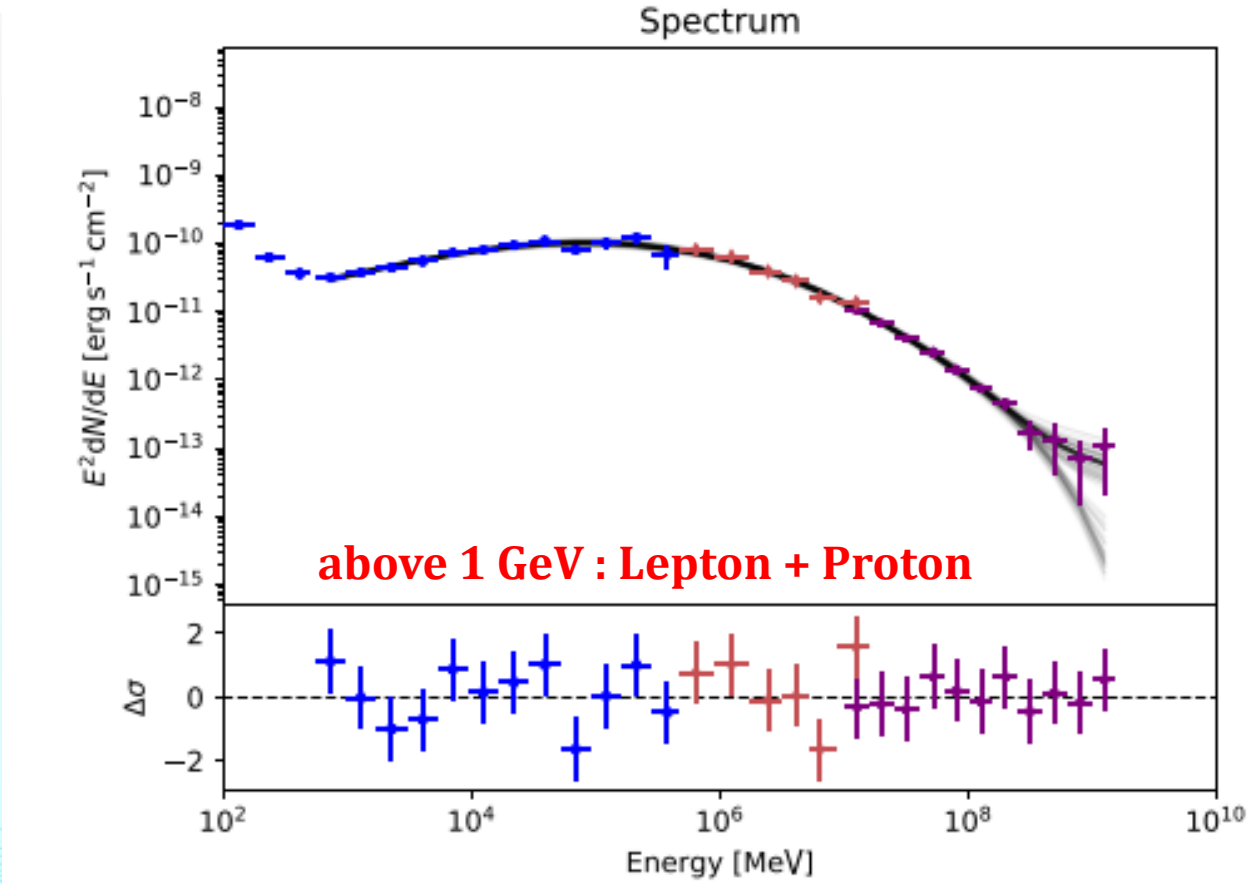
$$\sigma = \frac{B^2}{4\pi\, n_+\, m_e\, c^2\, \Gamma^2}$$

Seems to be a better interpretation

- Relaxing the tension of 2.3 PeV electron's acceleration
- Origin of CRs above the knee: a Super-PeVatron

L. Nie et al., ApJ, in press, arXiv:2201.03796

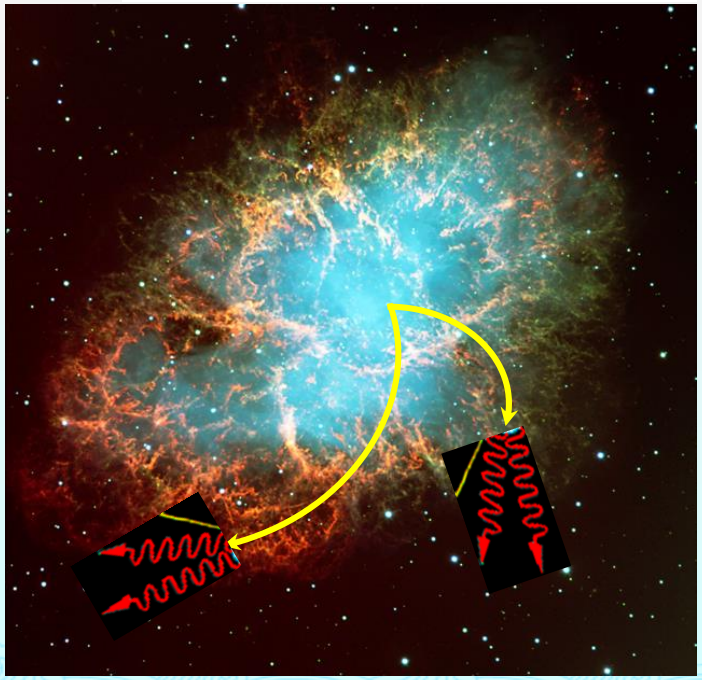




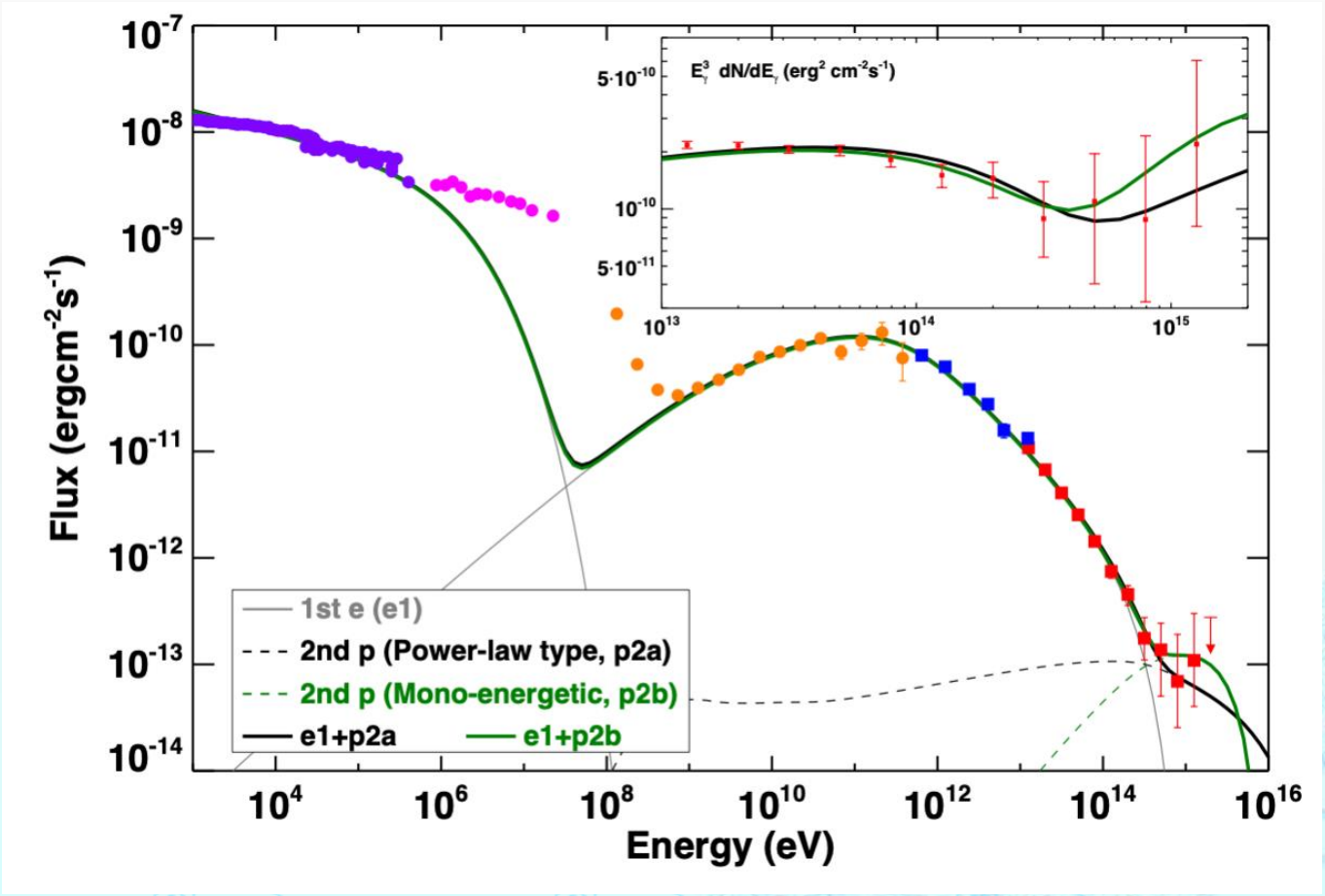
Even some monoenergetic protons

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

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



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

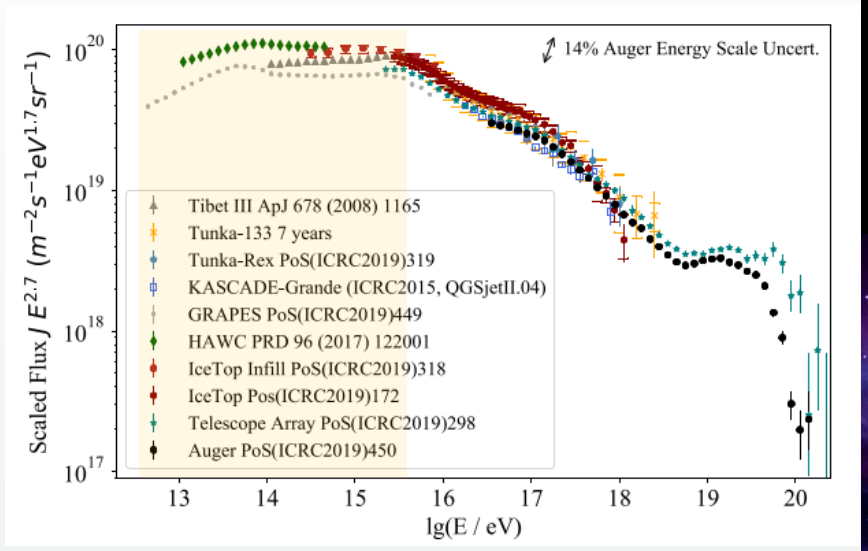


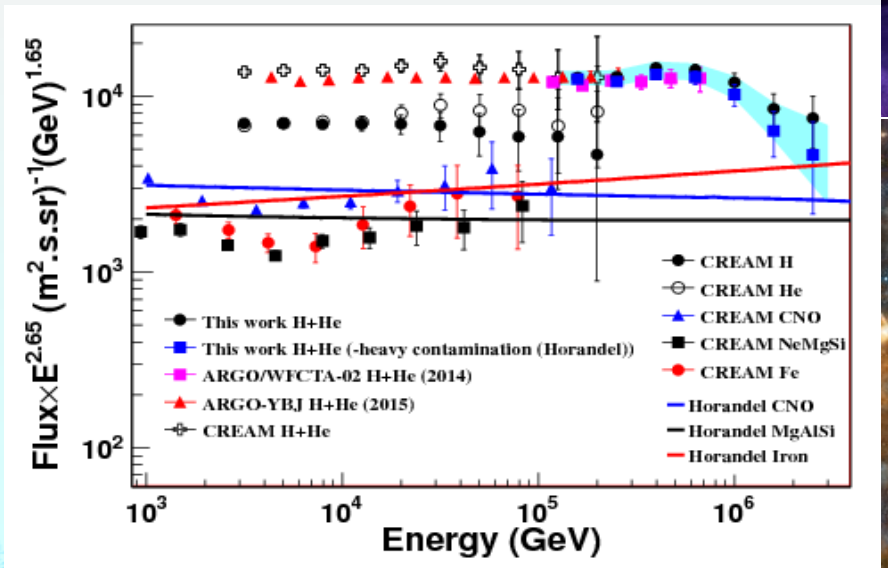
CR Origins

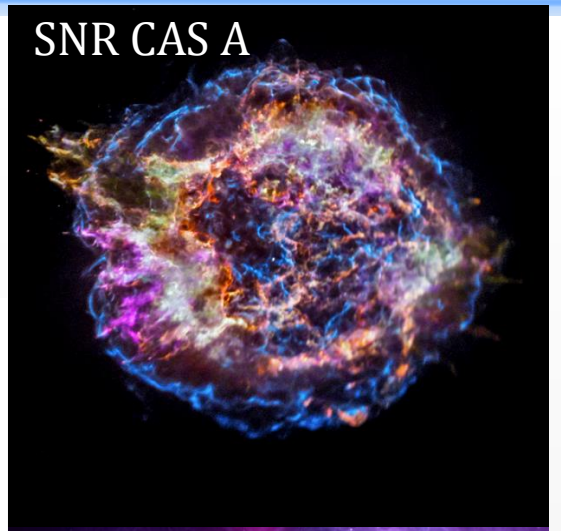
- **Supernova Remnants**
  - Nominal origins of CRs may not be able to contribute to the spectrum above the knee
  - LHAASO will measure the E_{max} of them

- **Pulsar Wind Nebulae**
  - Seems to be that young PWNe are likely to be the origins of CR above the knee, at least a big fraction of the contribution

- **Young Massive-star Clusters**
  - Seems very encouraging that YMCs play important roles as the origin of CRs above the knee as well
  - LHAASO has detected few photons ~ 1 PeV in the Cyg cocoon region, and the highest at 1.4 PeV

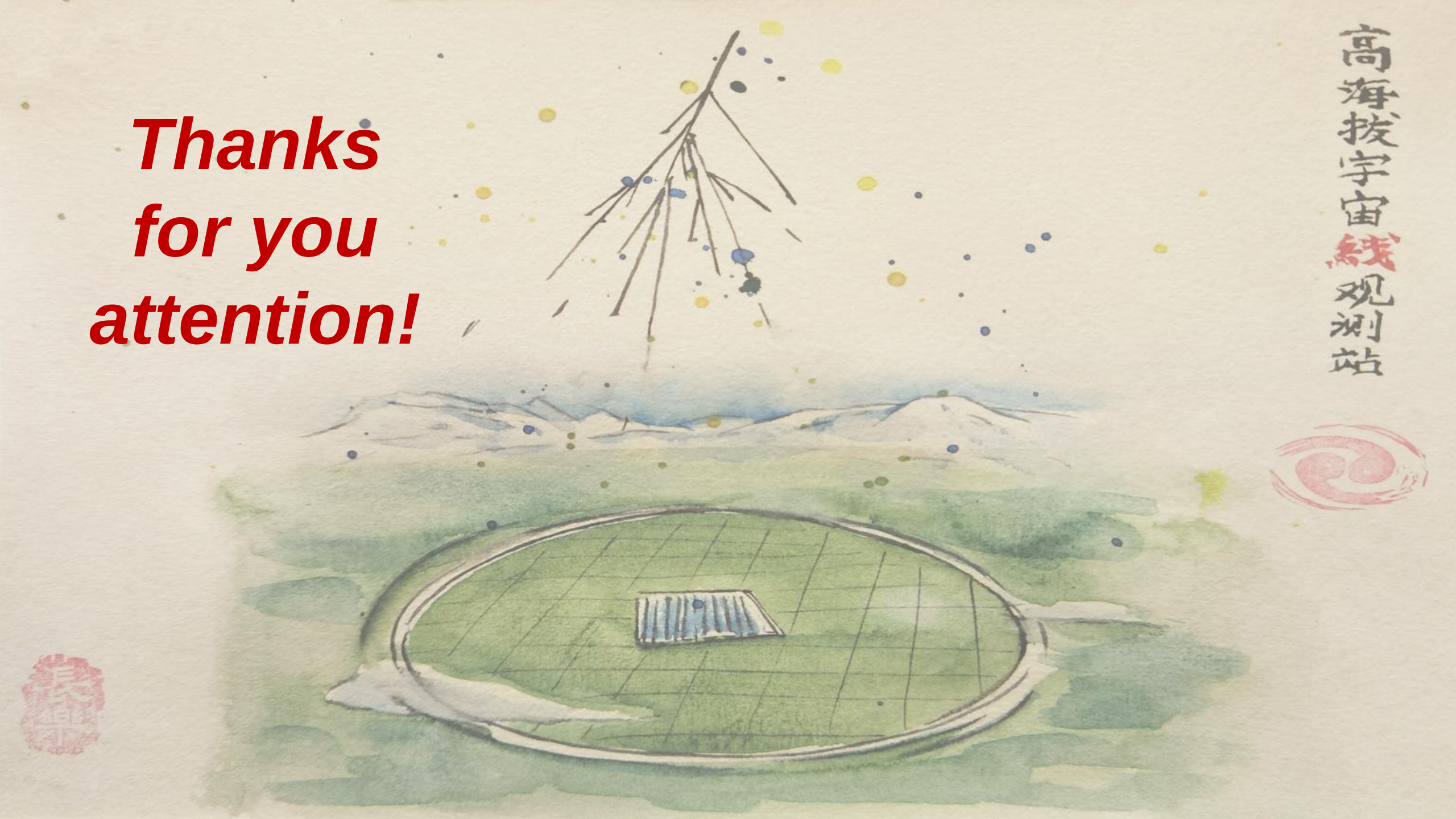






Conclusion

- LHAASO detected PeV photons from the Crab
- LHAASO precisely measured the SED over 3.5 orders of magnitudes in energy
- One zone leptonic model works reasonably well for the radiation over a wide energy range, with some difficulties at high energies and poses strong challenges to fundamental theory and models
- Additional protonic component helps to relaxing the tension and simultaneously solving the puzzle of origin of CRs above the knee
- Further observation with LHAASO is crucial in providing more accurate primary spectrum of the protons as the input for the interstellar propagation of the CRs
- LHAASO has a capability of detecting 1~2 ph/yr around 1 PeV from the Crab
- LHAASO is also able to measure the CR proton spectrum above the knee that could be compared with the results of propagation studies


Thanks
for you
attention!
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