



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

Zhen Cao, IHEP

On behalf of LHAASO Collaboration

COSPAR, Athens, July. 2022



The First Observation 967 years back

- ◆ Song Dynasty Official (司天監) 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屏星 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籬旁
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
狀如闔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 已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屏星
北行占曰主弼臣失禮免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
甲辰客星出紫微天樞側孛孛然如粉絮稍入垣內歷御女華蓋凡
十一日沒占曰后妃灾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
如挑速如經軒轅大星入太微垣掩右執法犯次將歷屏星西北凡
七十五日入濁沒占曰周雒之分大臣憂

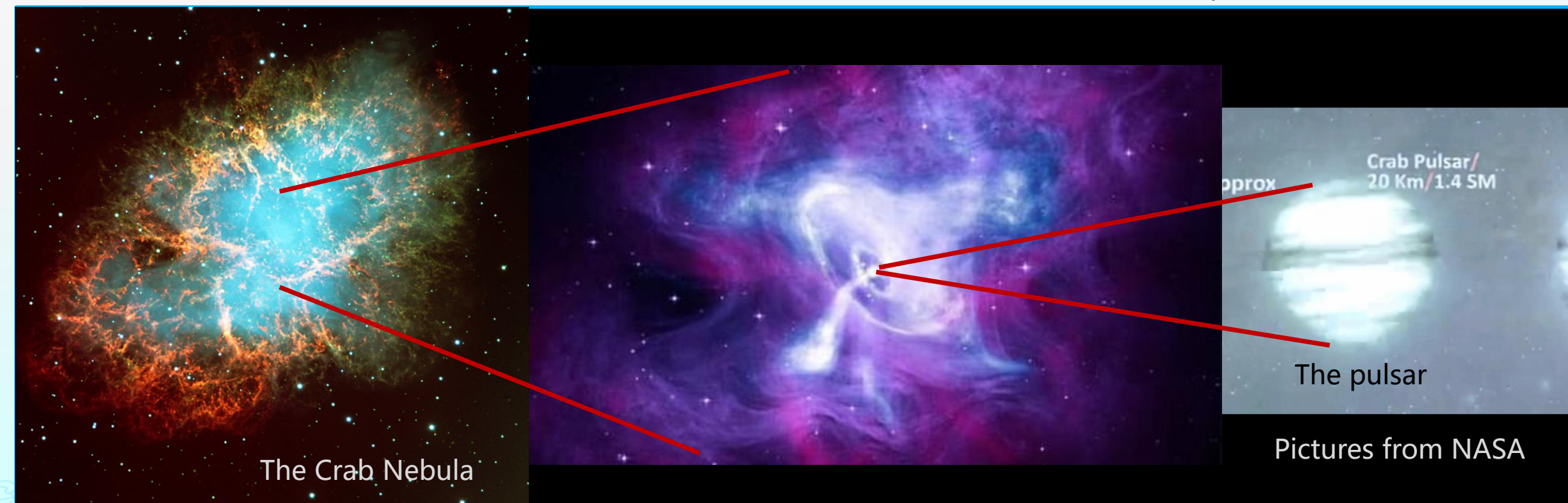
仁宗明道元年六月乙巳客星出東北方近濁木星太微有芒彗至
于已凡十三日而沒至和元年五月己丑客星出天關東南可數寸
歲餘消沒

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

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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



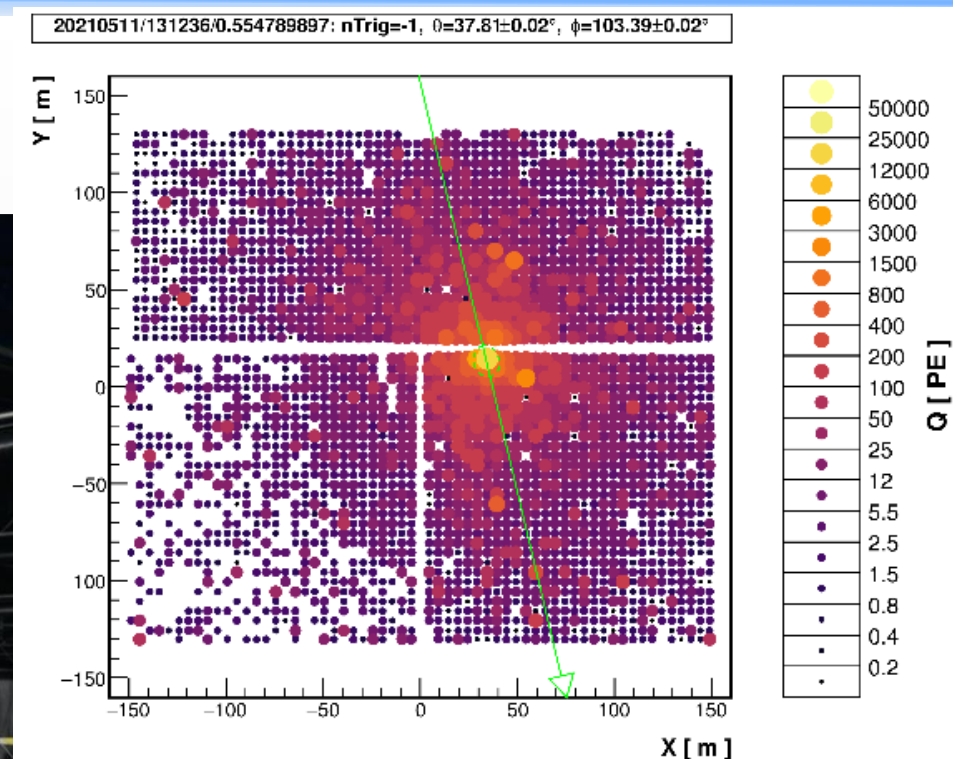
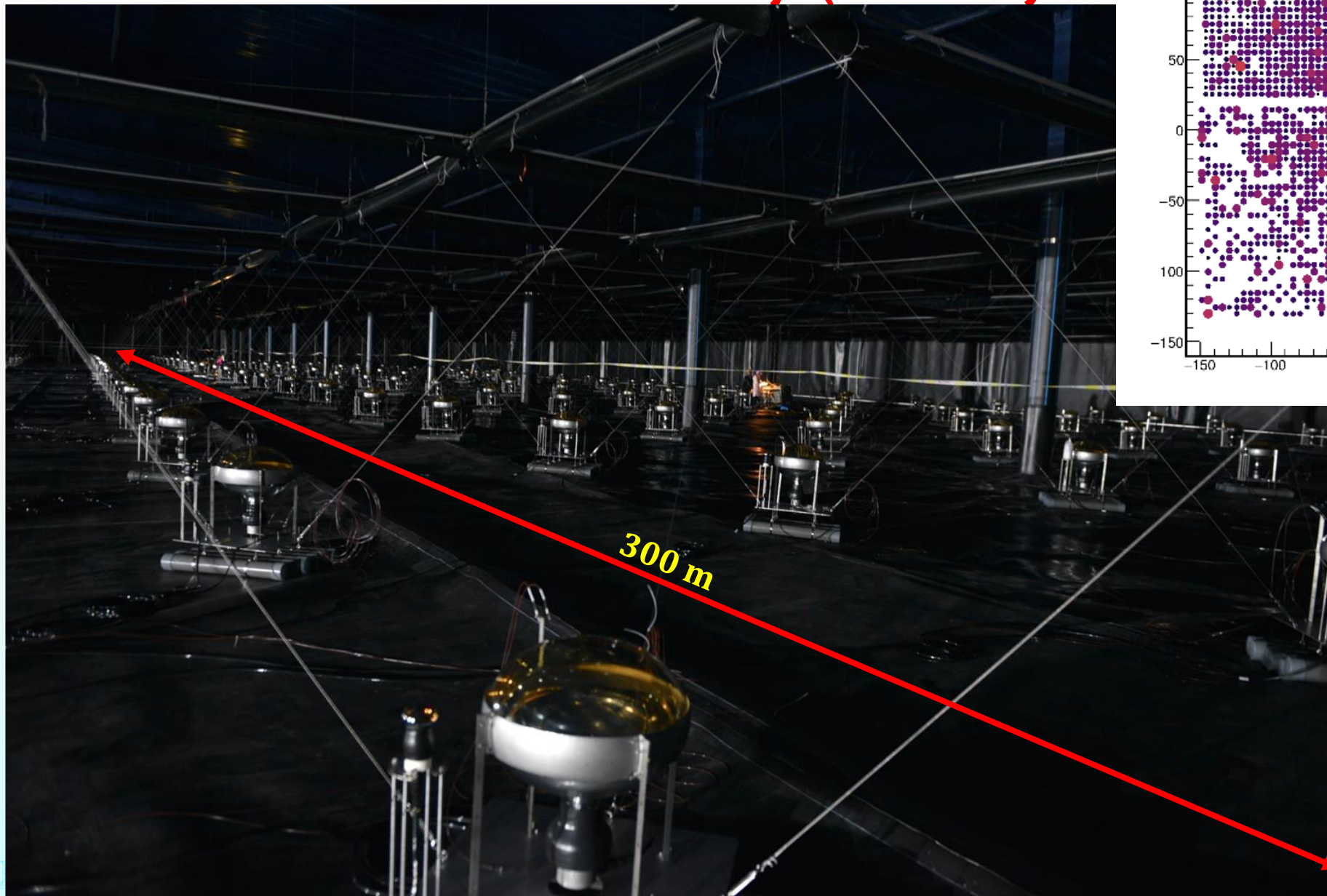
Bird's eye view of LHAASO, 2021-08

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



Area:
1.3 km²
Detectors:
5195 ED
1188 MD
Energy Range:
0.01-10 PeV

Water Cherenkov Detector Array (WCDA)



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

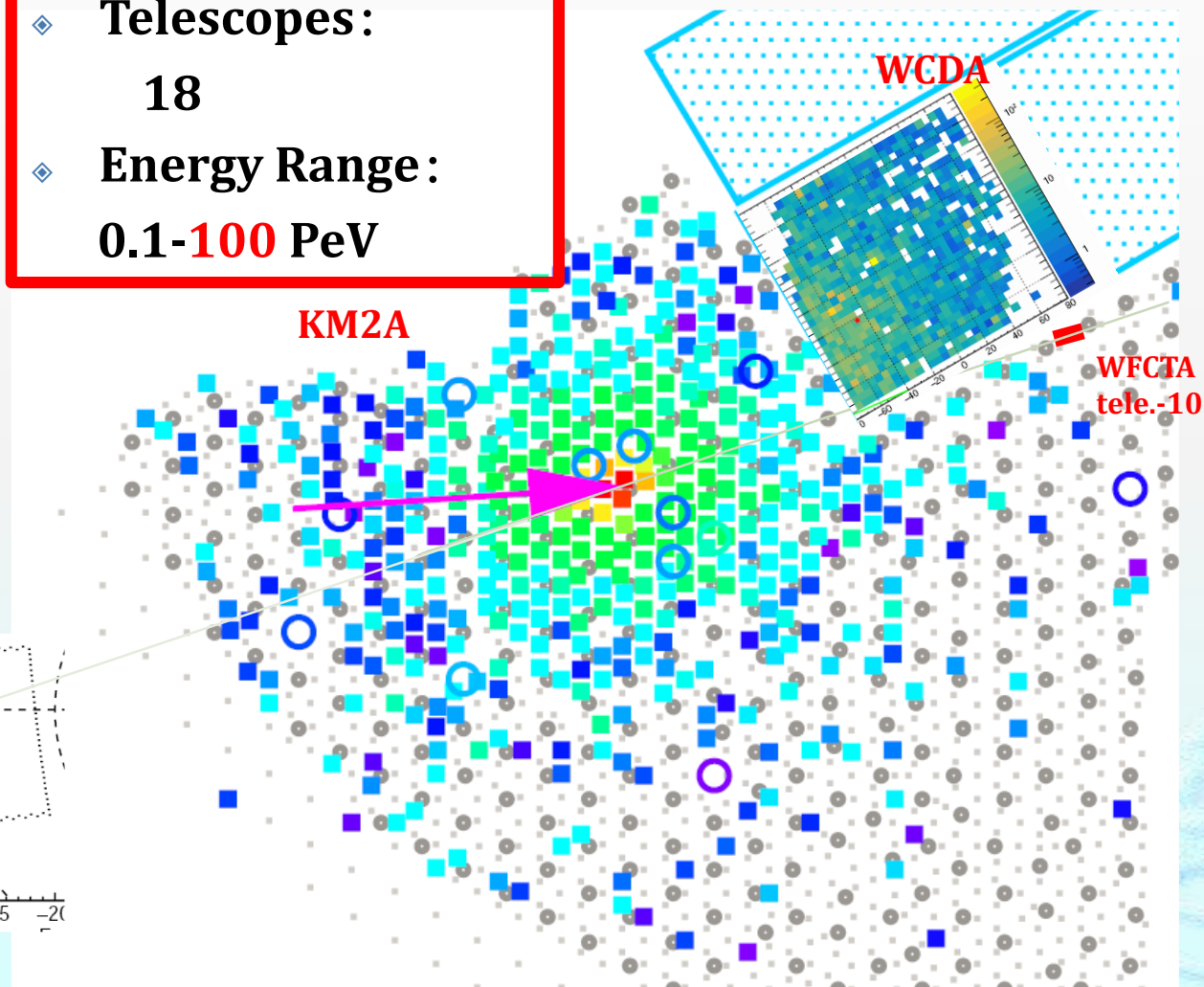
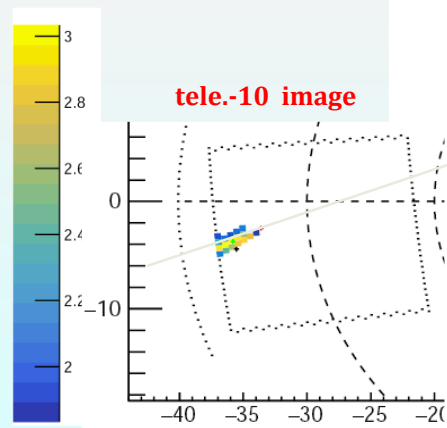
Wide FoV C-Telescope Array (WFCTA)

Cross-checking inside Collaboration



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

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



The Crab seeing by WCDA and KM2A

The coverage of 3.5 orders of magnitudes of energy

1 - 12 TeV

PSF: 0.22°

Pointing accuracy: 0.01°

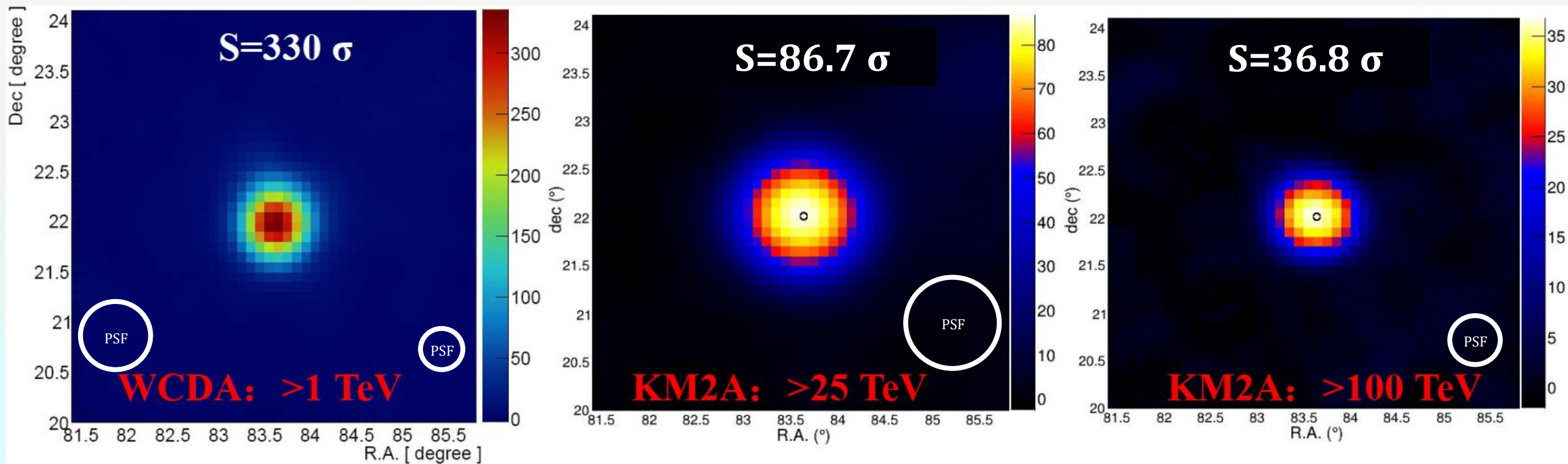
25-100 TeV

0.30°

0.1-1.2 PeV

0.15°

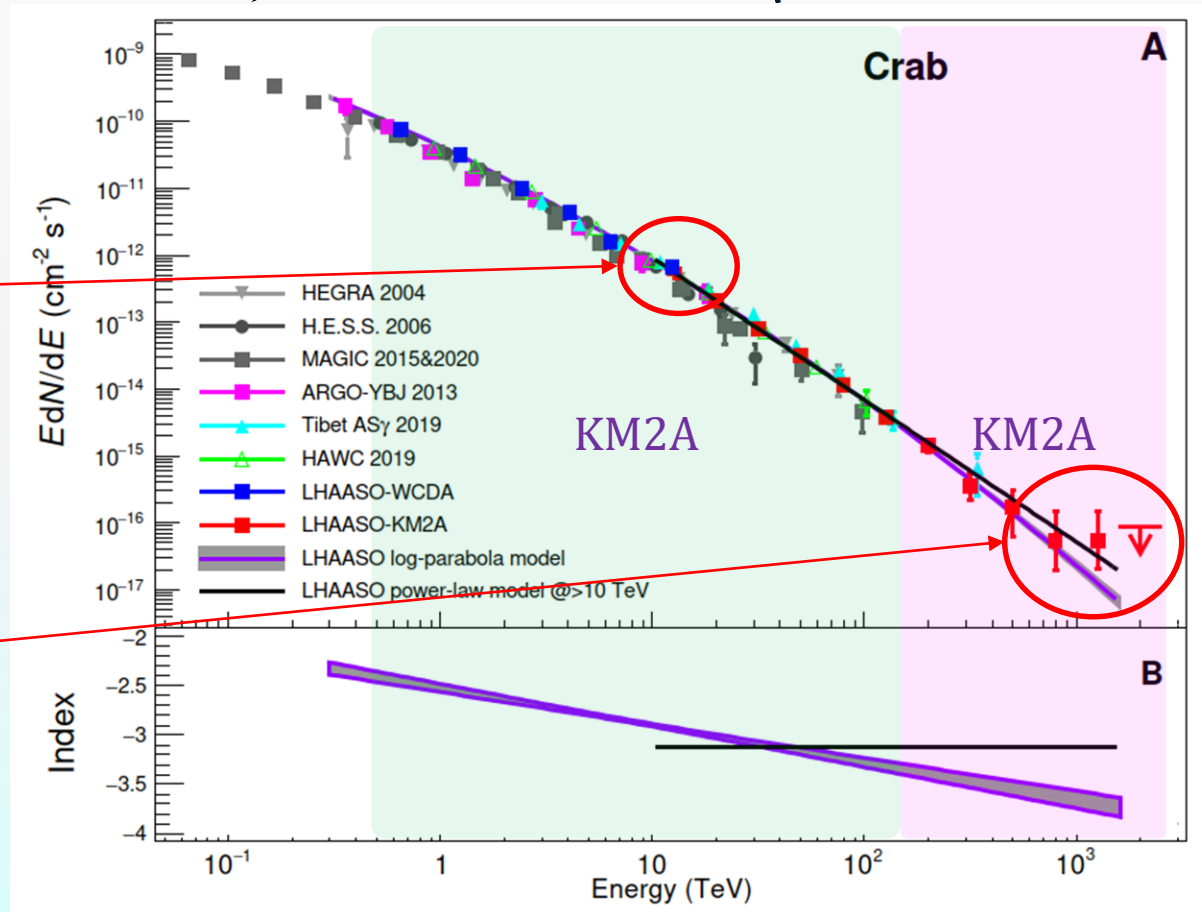
(from NASA)



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

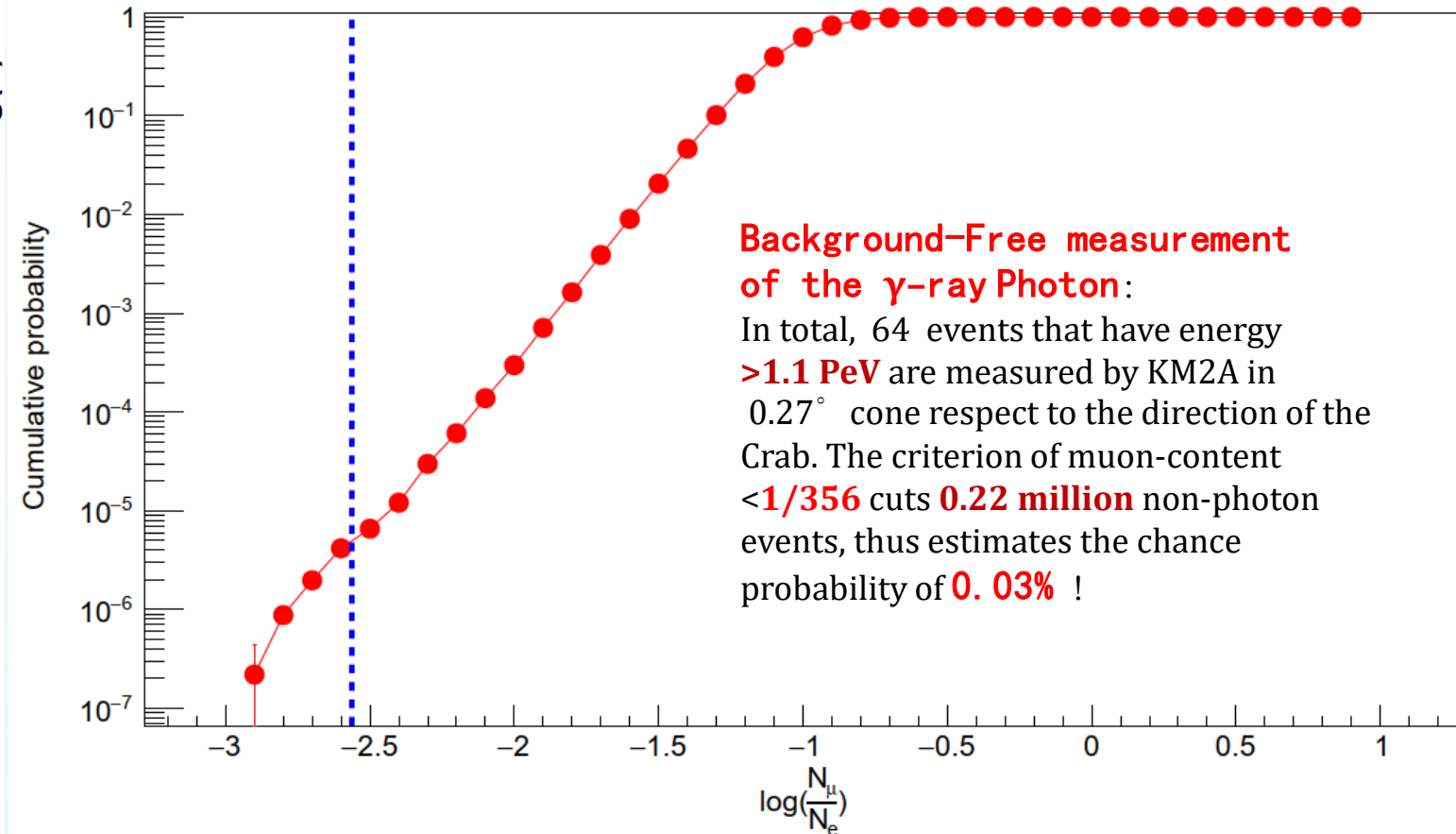
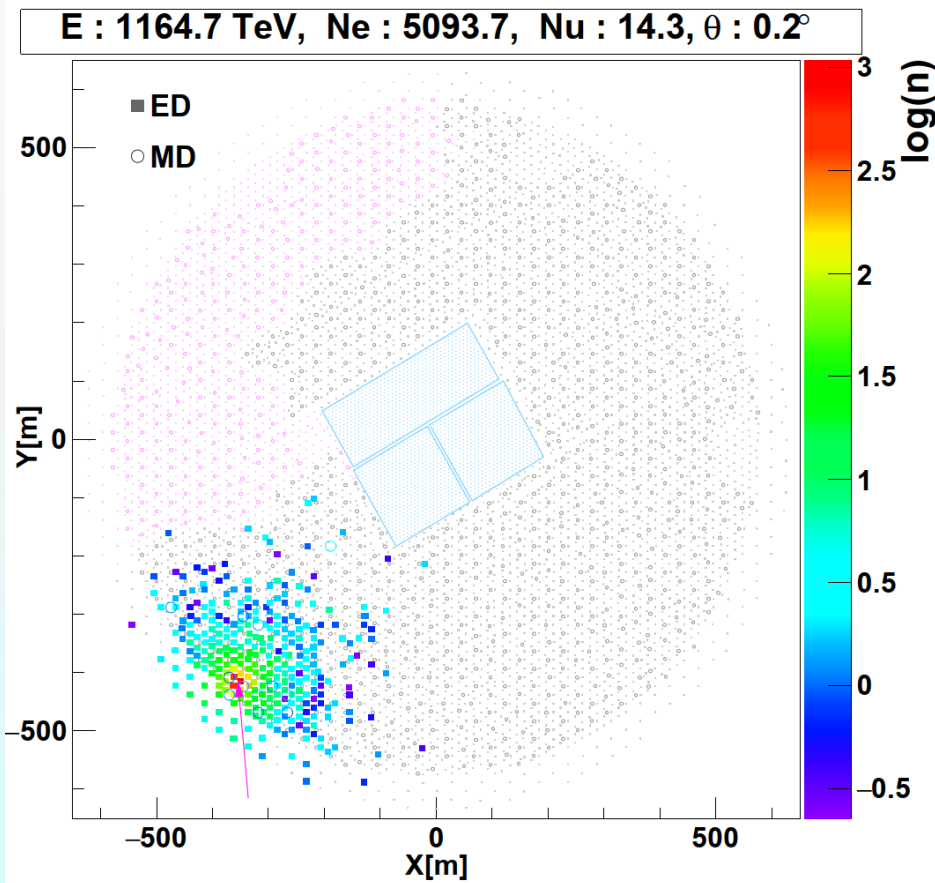
Zhen Cao, *et al.*, LHAASO, *Science*, p425-430, 2021



1.1 PeV Photon

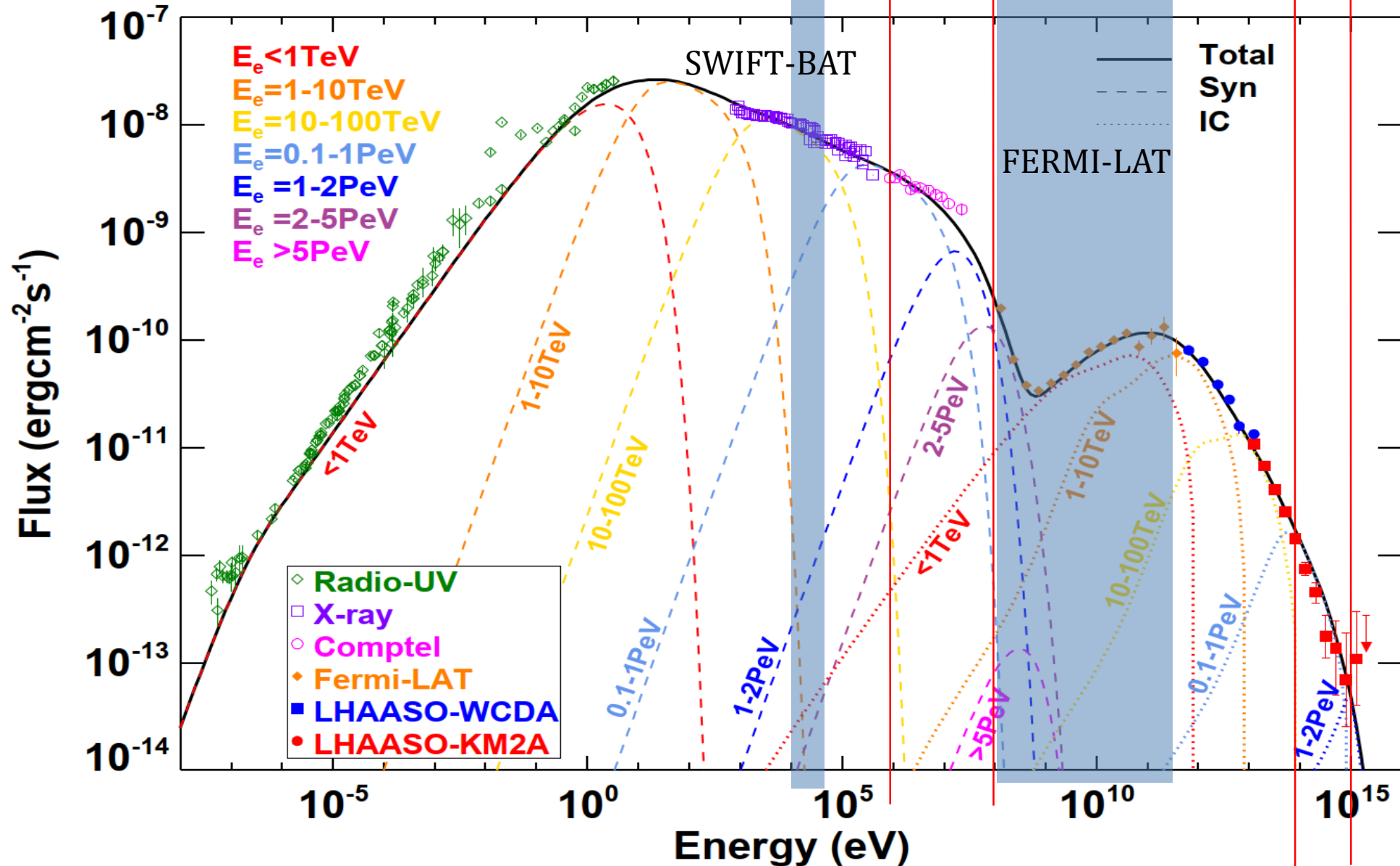
from the Crab Direction Record by KM2A

LHAASO, Science, 373, 425-430, 2021



Electronic Origin of the Crab Radiation

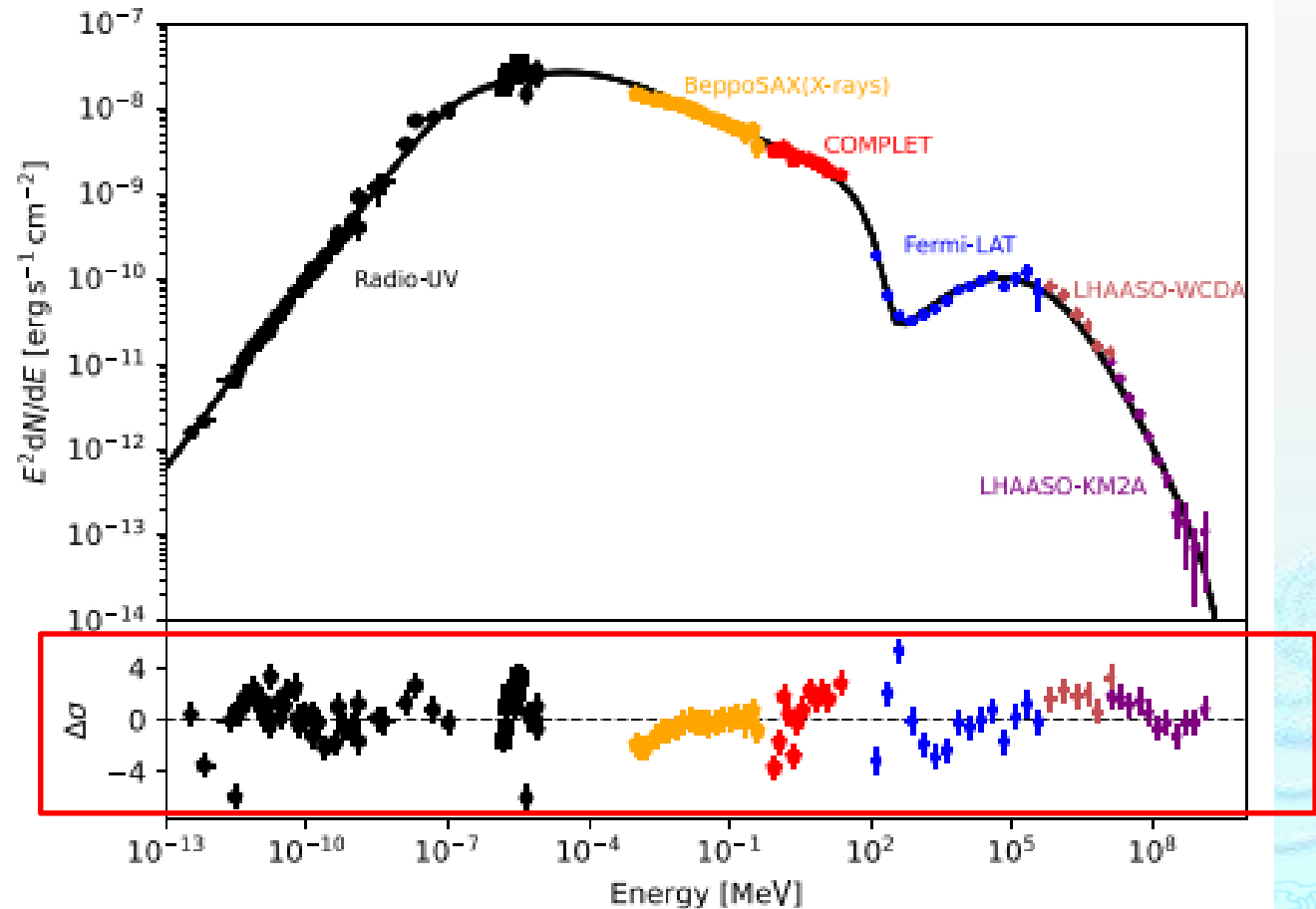
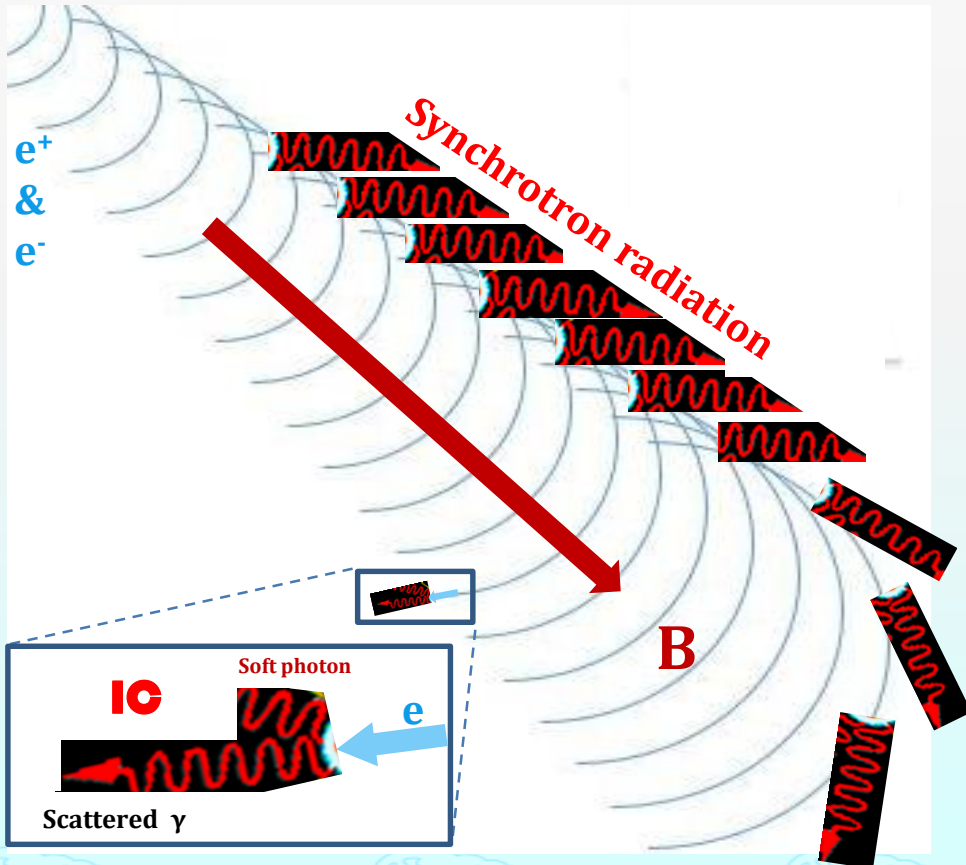
- ◆ 22 decades
- ◆ One bulk of e^+ s & e^- s
- ◆ Synchrotron radiation
- ◆ Inverse Compton scattering



“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, **924** 42 (2022), [arXiv:2201.03796](https://arxiv.org/abs/2201.03796)



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

- ◆ Electron Energy: $E_e = 2.15(E_\gamma/1 \text{ PeV})^{0.77} \text{ PeV} \sim \mathbf{2.3 \text{ PeV}}$
- ◆ Size of the accelerator responsible to the ~PeV electrons
 $(B/100\mu\text{G})(\ell / 1 \text{ pc}) \geq \mathbf{0.023 (E_\gamma/1 \text{ PeV})^{0.77}}$
 - ◆ $\ell \gtrsim \mathbf{0.025 \text{ pc}}$, implying not associated with flares that last few days
 - ◆ $\ell \lesssim \mathbf{0.18 \text{ pc}}$, assuming not beyond the inner nebula
- ◆ Acceleration Rate:
 $\eta = \mathcal{E}/B = \mathbf{0.14 (B/100\mu\text{G})(E_\gamma/1 \text{ PeV})^{1.54} \sim 0.16}$
 - ◆ 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 !!!**

The Crab Nebula: two torus

- ◆ Fitting of the nebula
- ◆ Parameters: $\psi, \zeta, r, \delta, d$.

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

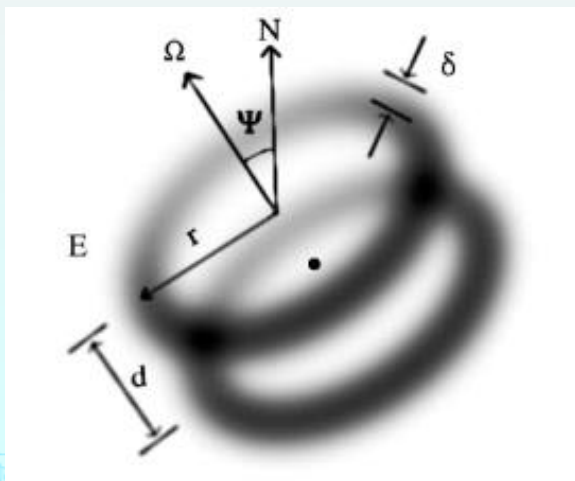
β is the bulk velocity of the post shock flow.

Inner: $r=15.6 \text{ arcsec} = 0.0043^\circ + \delta=3''$, about 0.59 ly or 0.18 pc

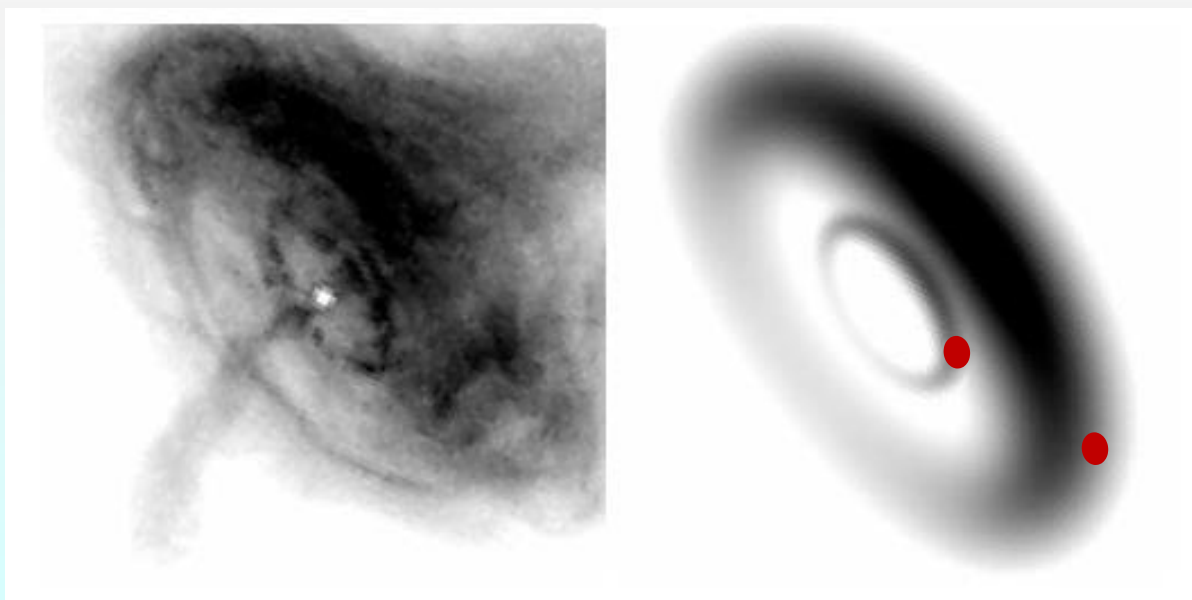
Outer: $r=41.3 \text{ arcsec} = 0.0115^\circ + \delta=6''$, about 1.49 ly or 0.46 pc

1.1 PeV photon could be emitted from even smaller region $\gtrsim 0.025 \text{ pc}$

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



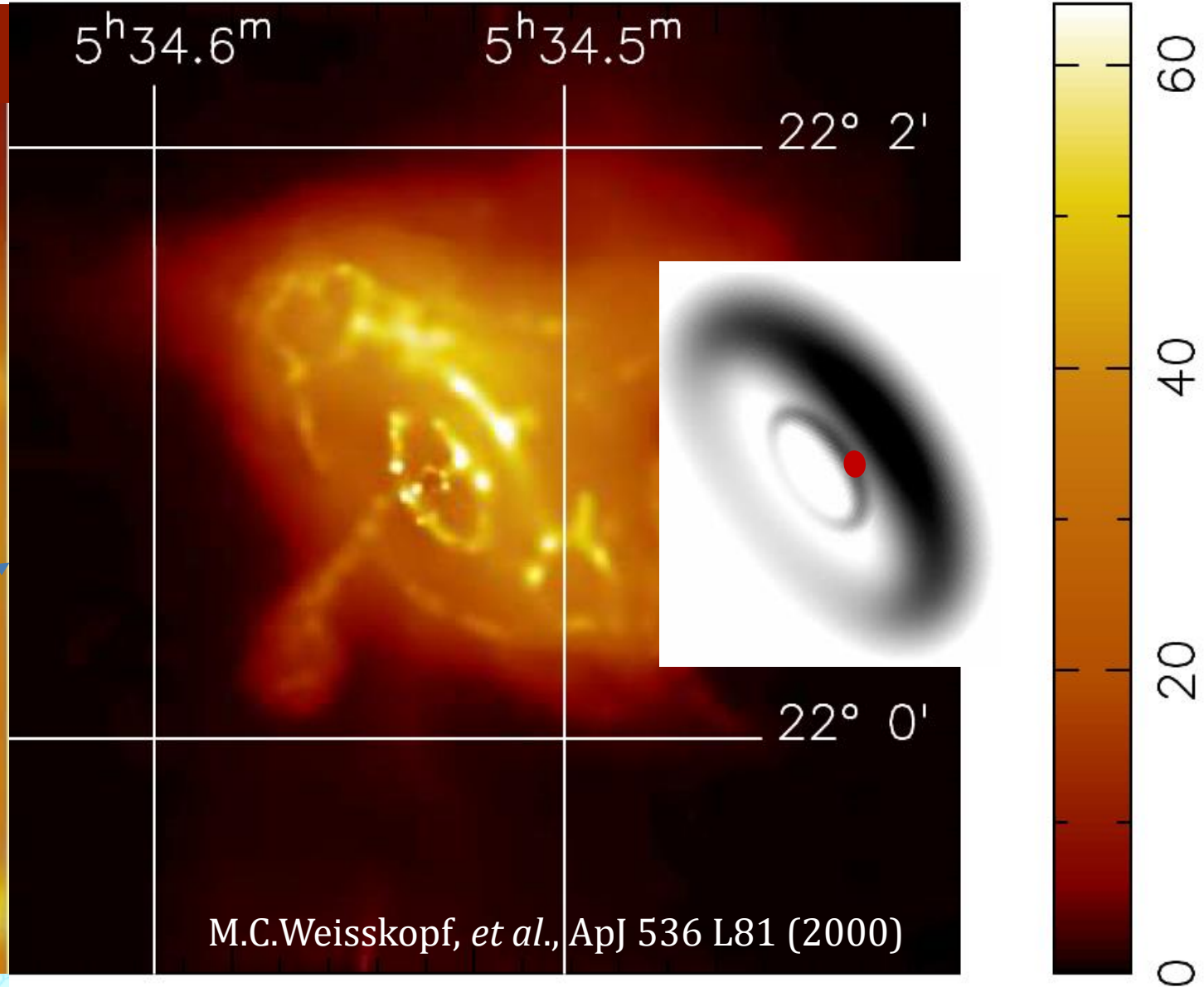
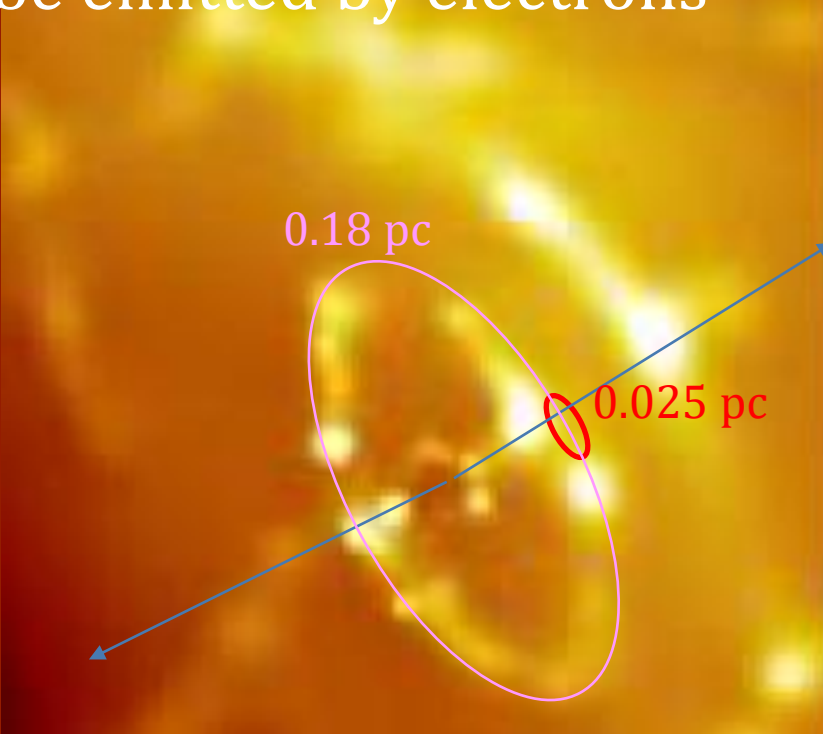
2667 s
observation
by Chandra
in 1999



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 $\sim$ PeV photons may be emitted by electrons



MHD simulation for Nebula Morphology

◆ X-ray

and γ -ray (IC-process)

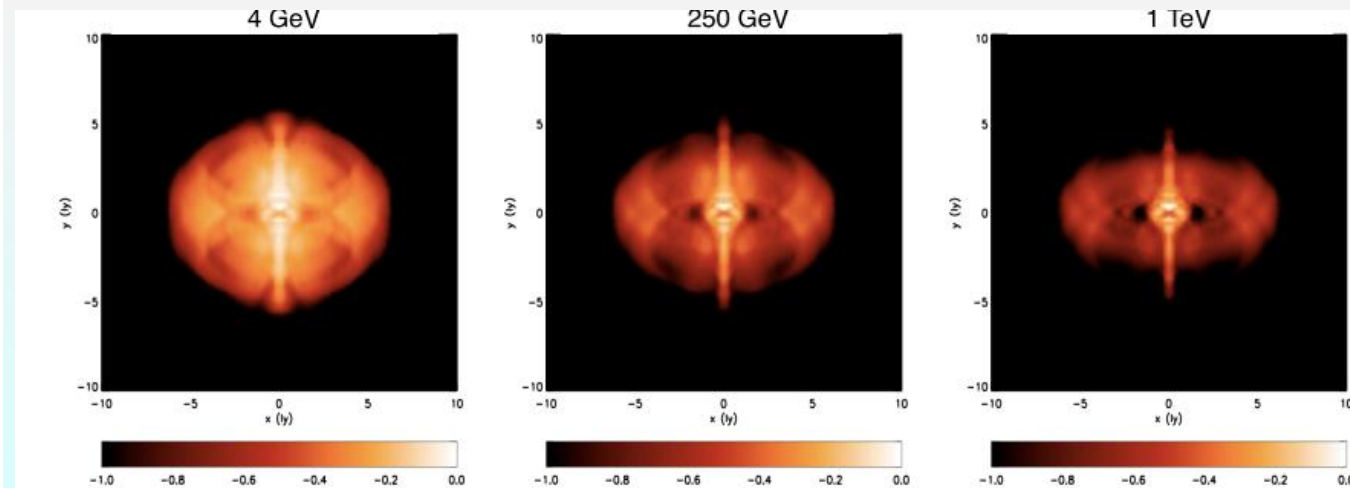
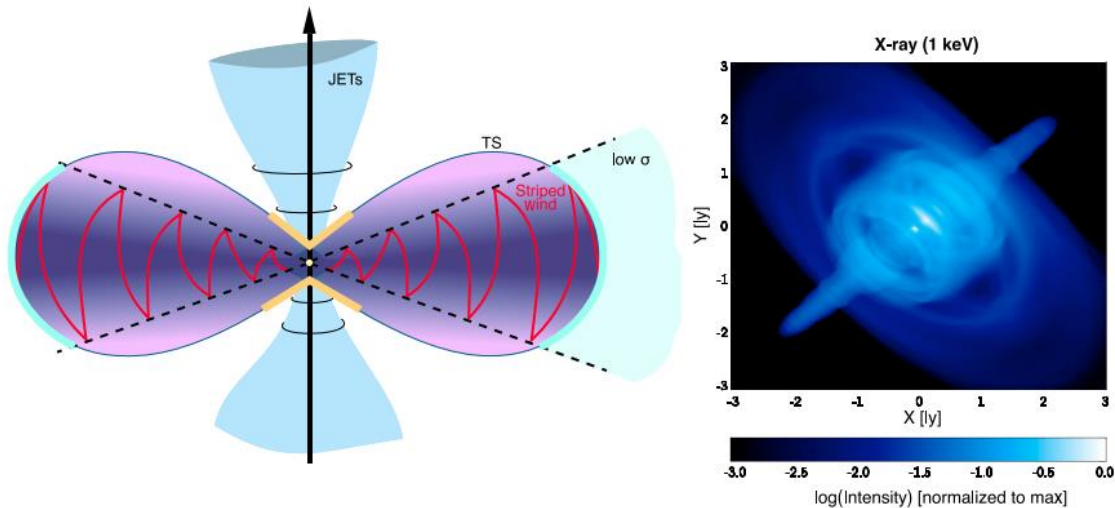
◆ Size $\sim 50''$ by Chandra

$\sim 52''$ 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)

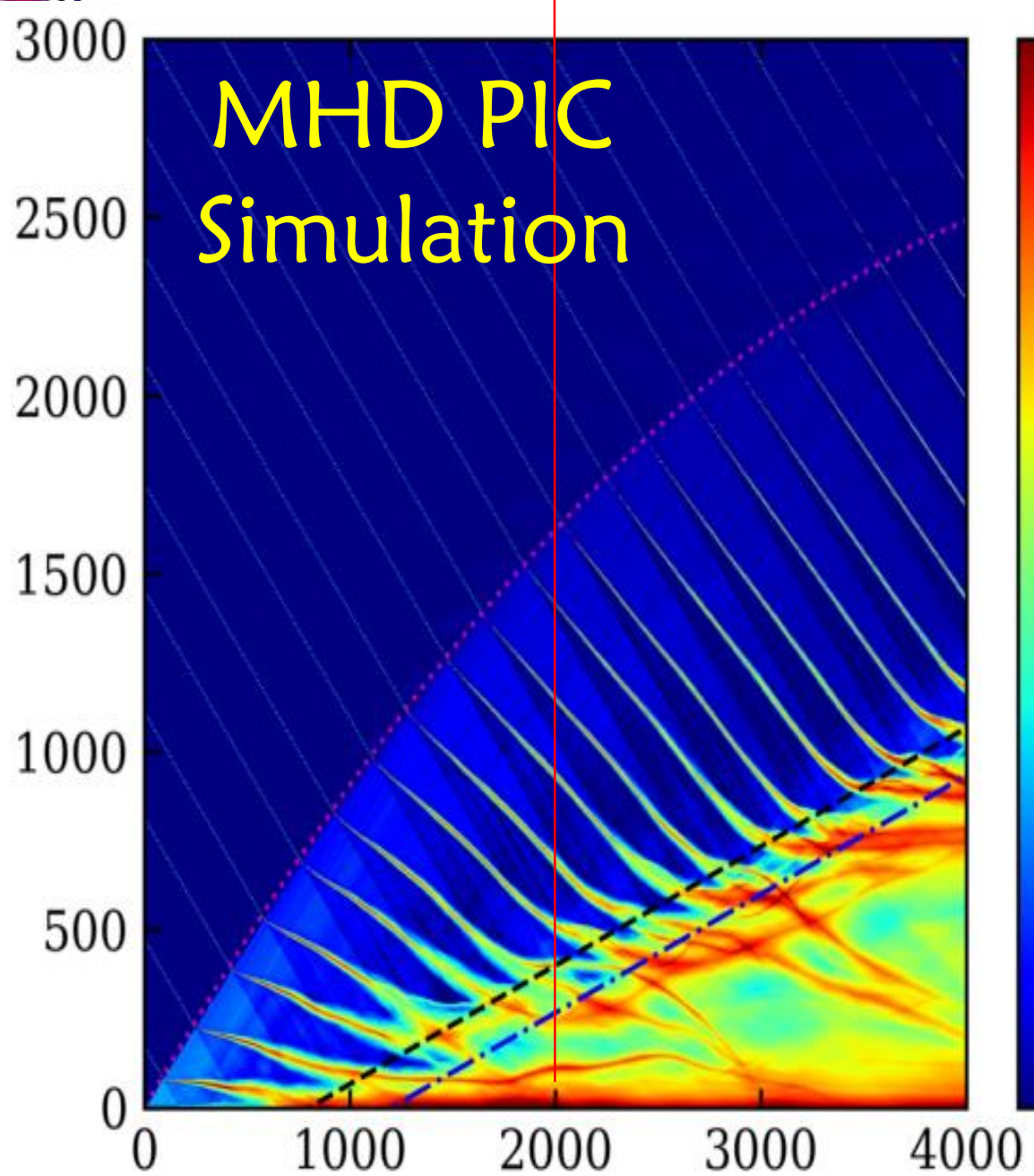
◆ Simulation is done by Volpi, D.; Del Zanna, L.; Amato, E.; Bucciantini, N., Astron. Astrophys., 485, 337–349(2008)





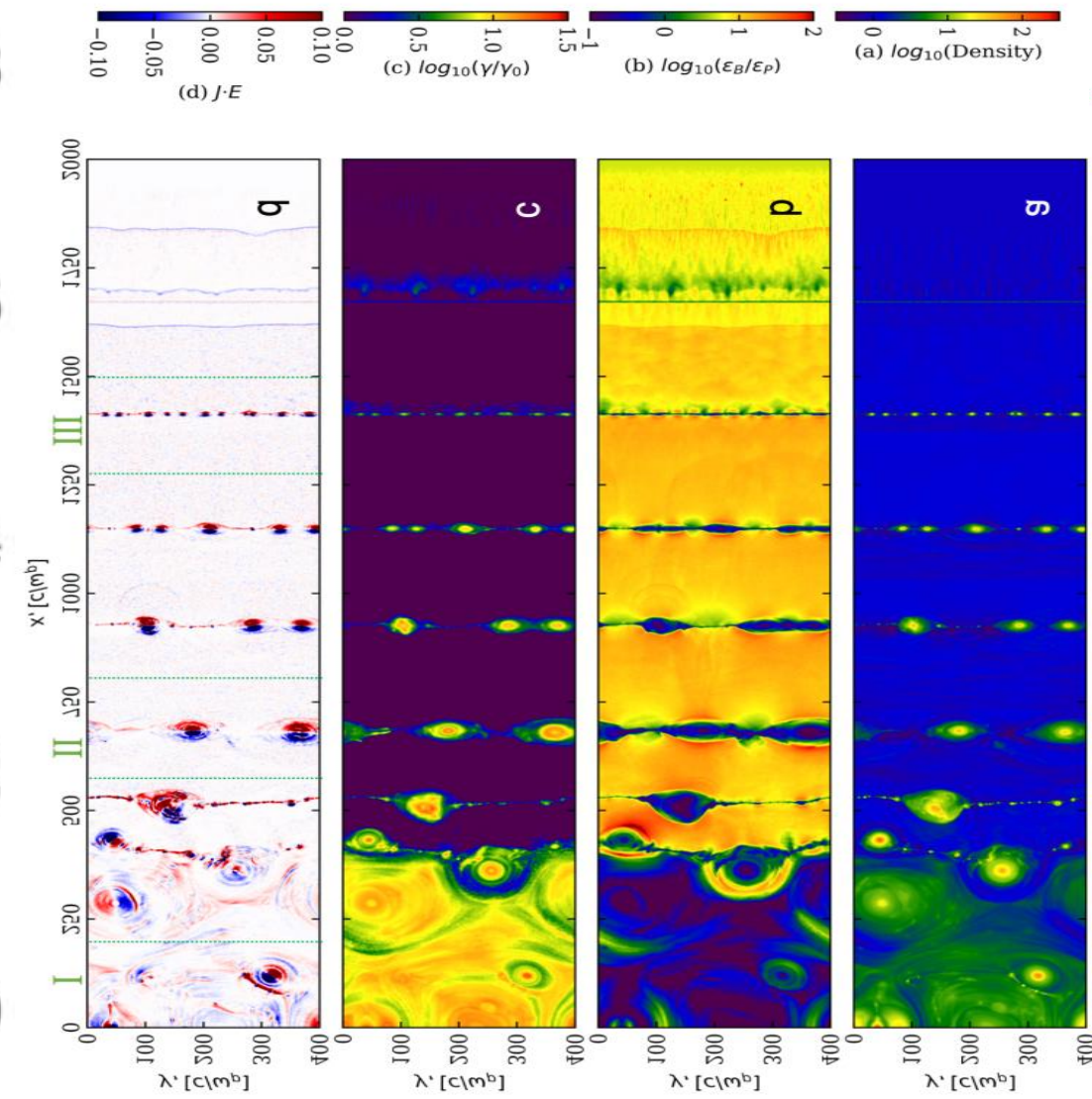
MHD PIC Simulation

$x, [c/\omega_p]$

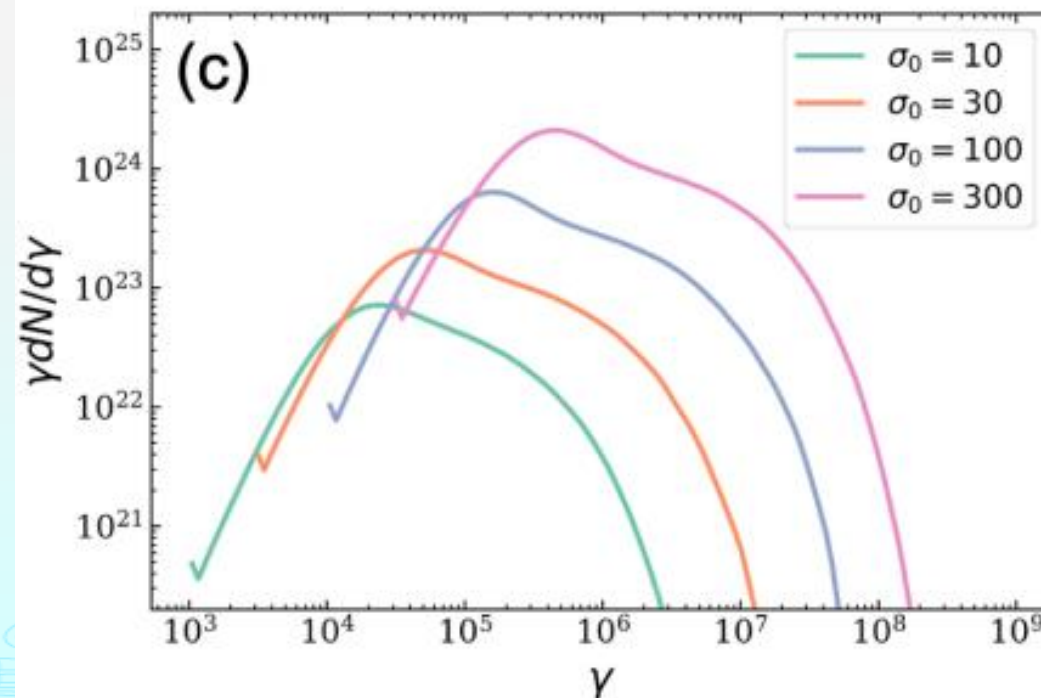
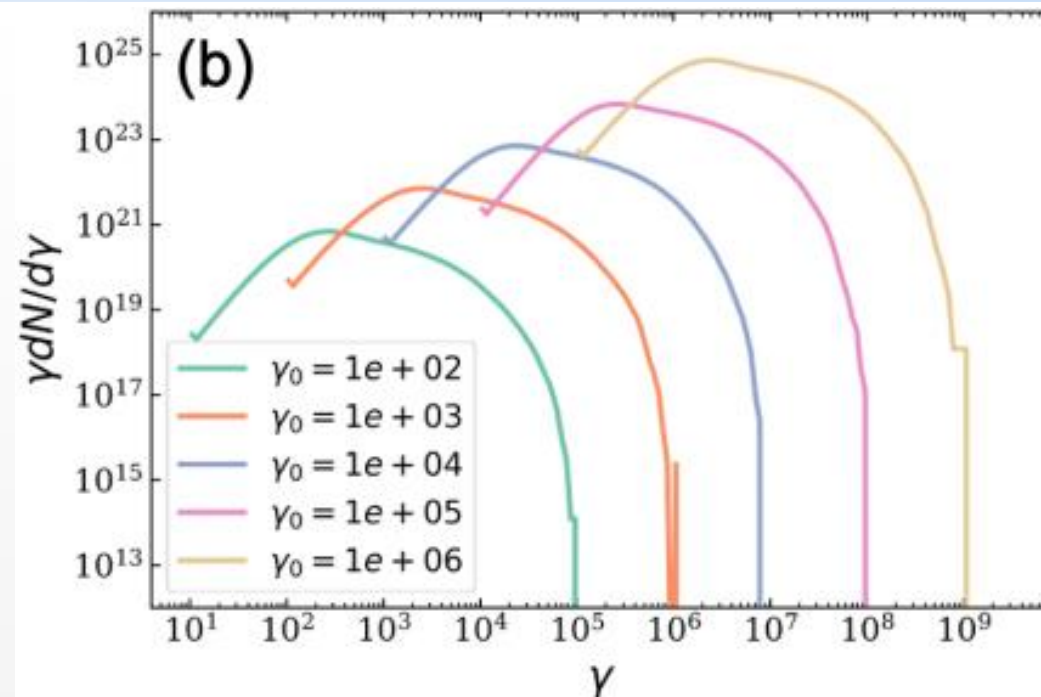
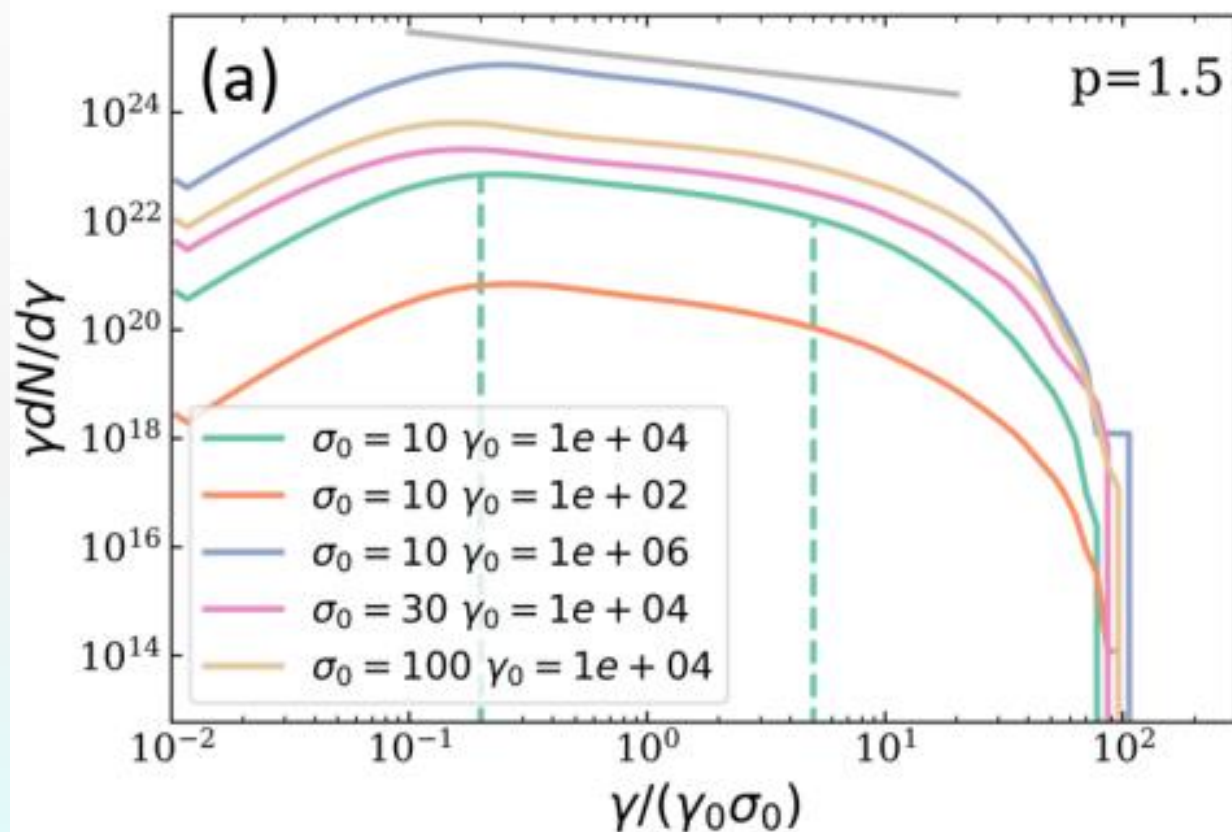


$\omega_p t$

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

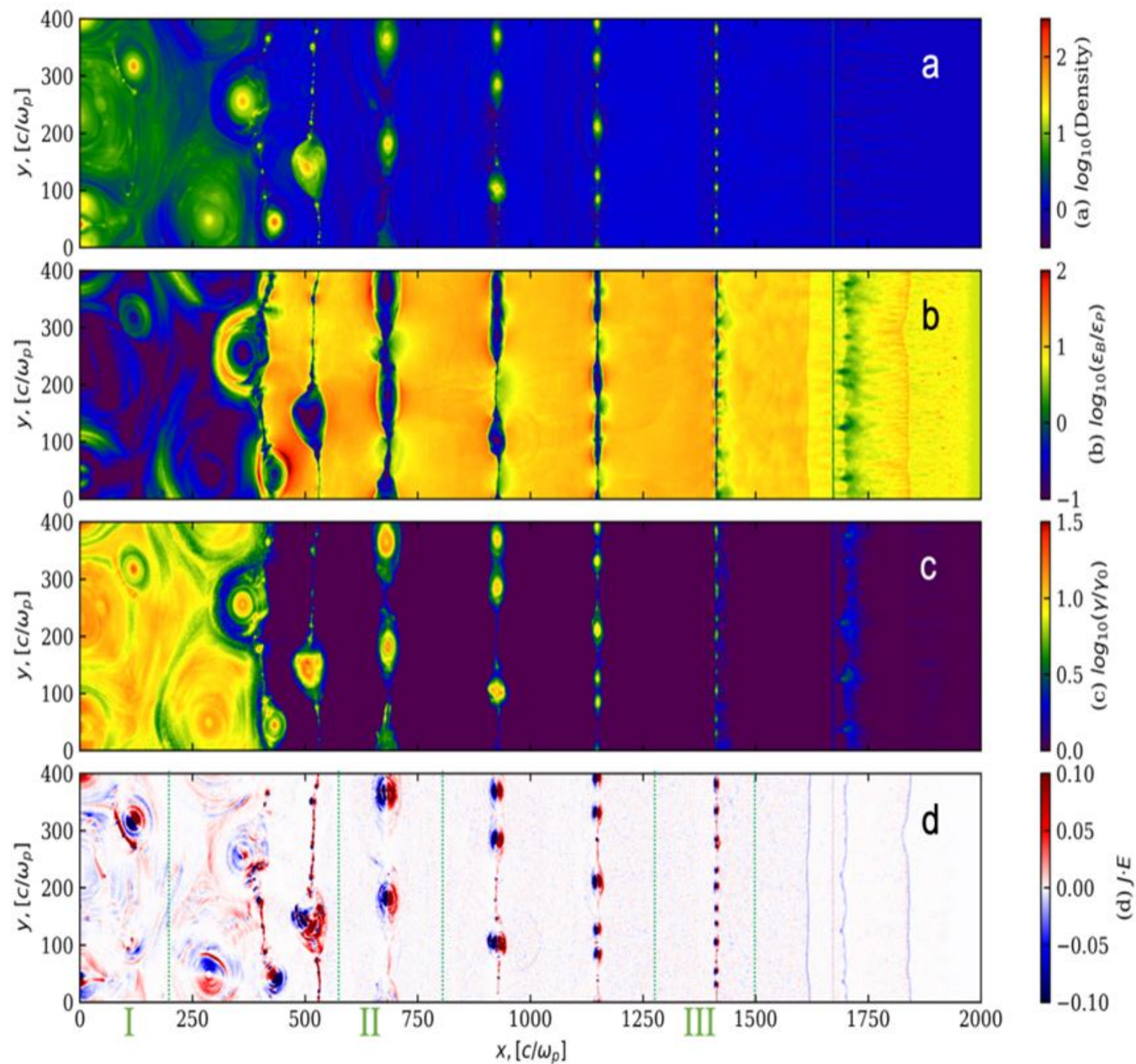
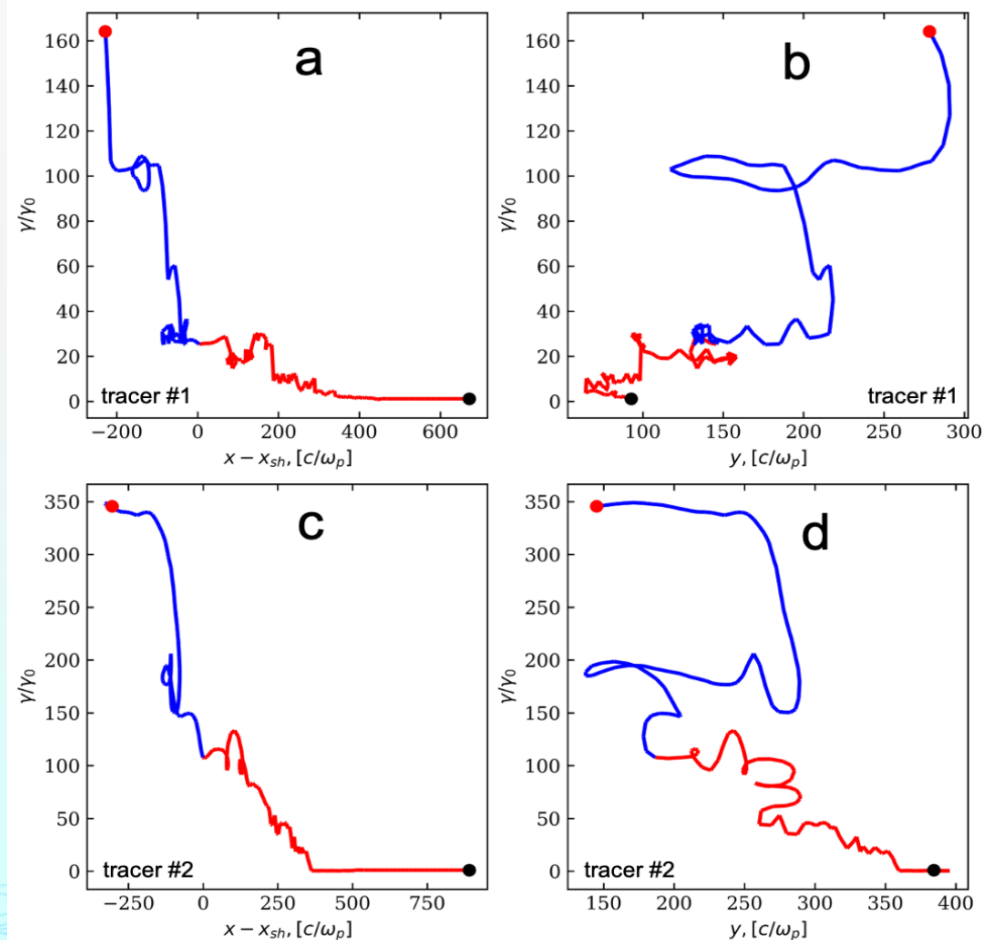


Electron E-Spectrum

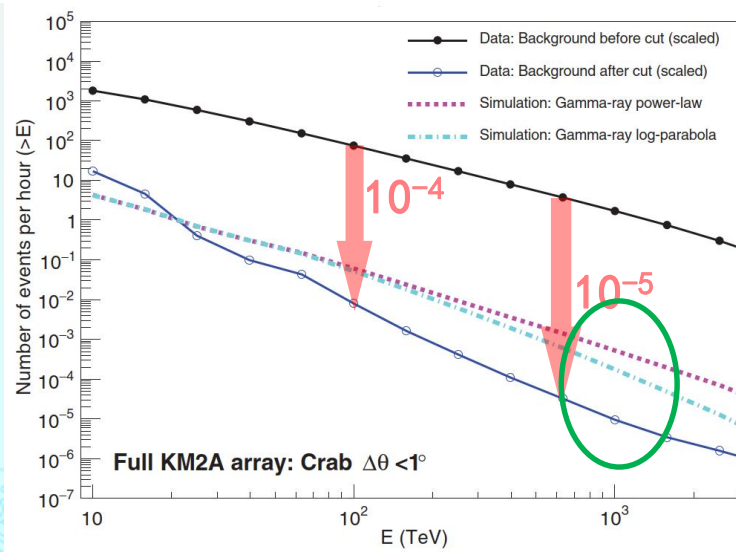
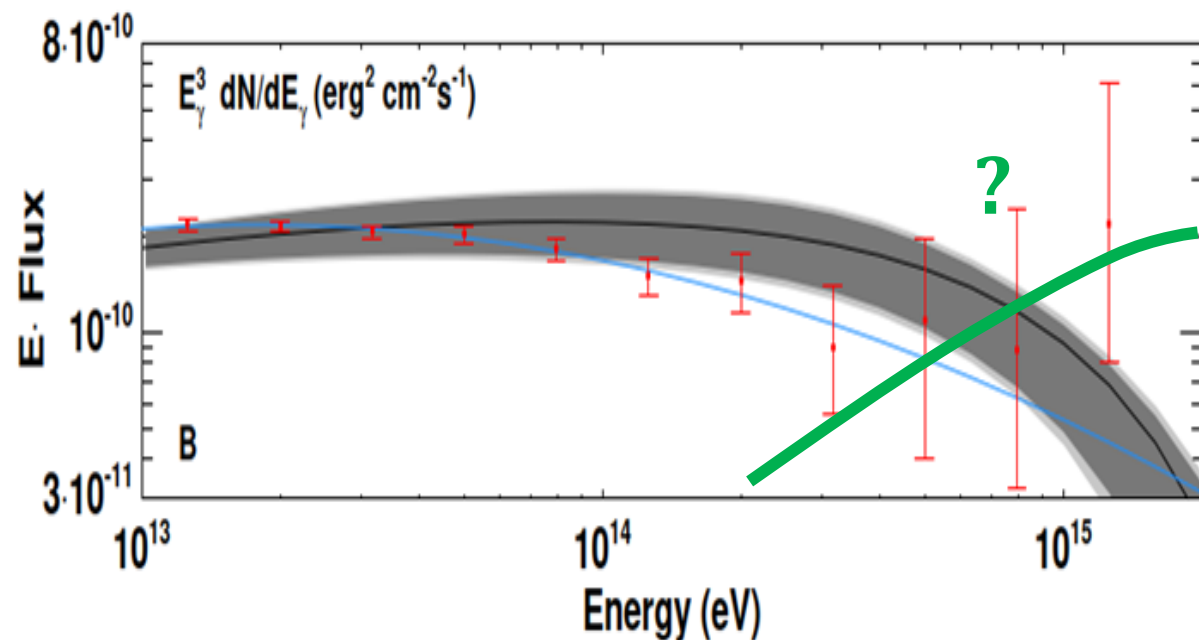


- ◆ it seems not impossible to reach 1 PeV, but quite extreme!

Two examples of electron trajectories

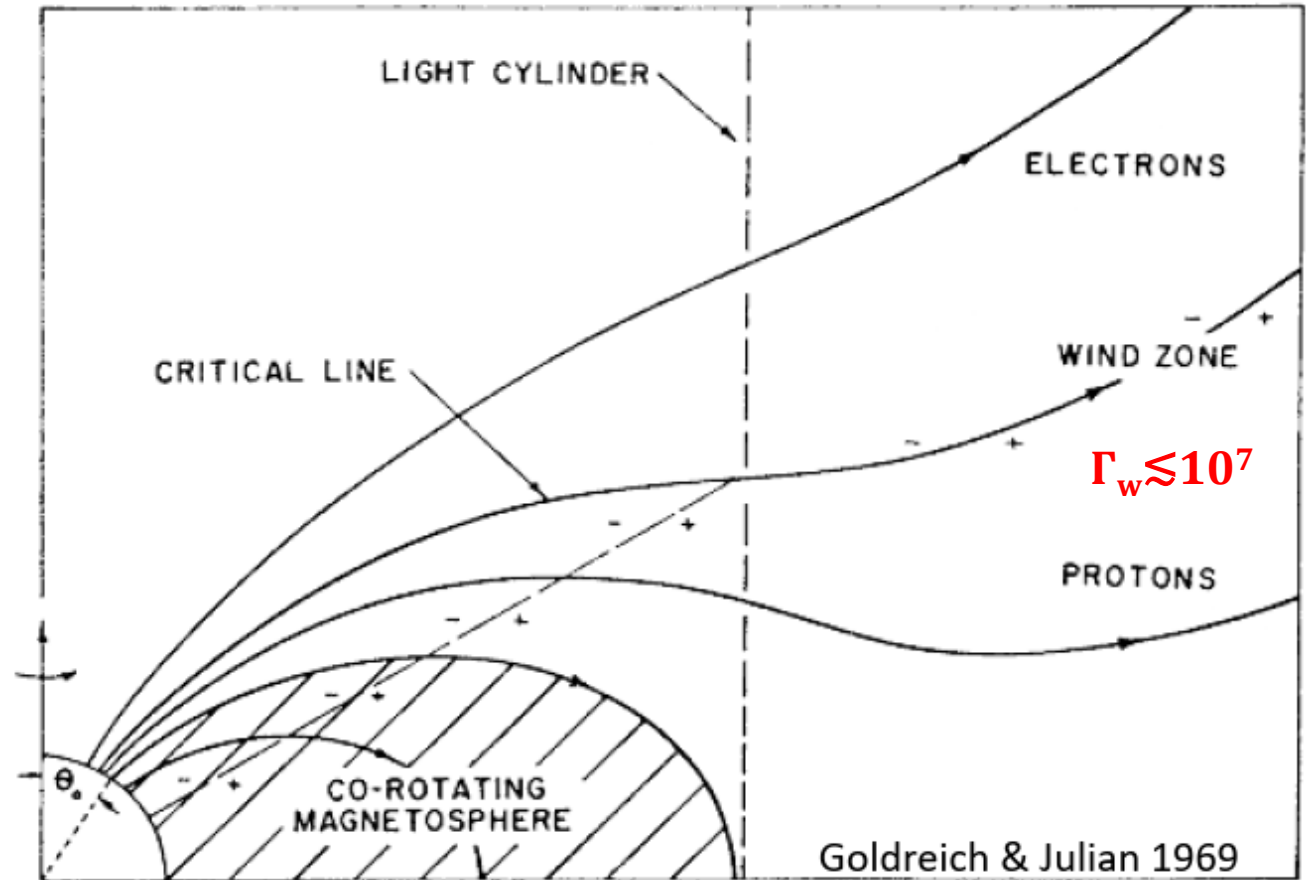
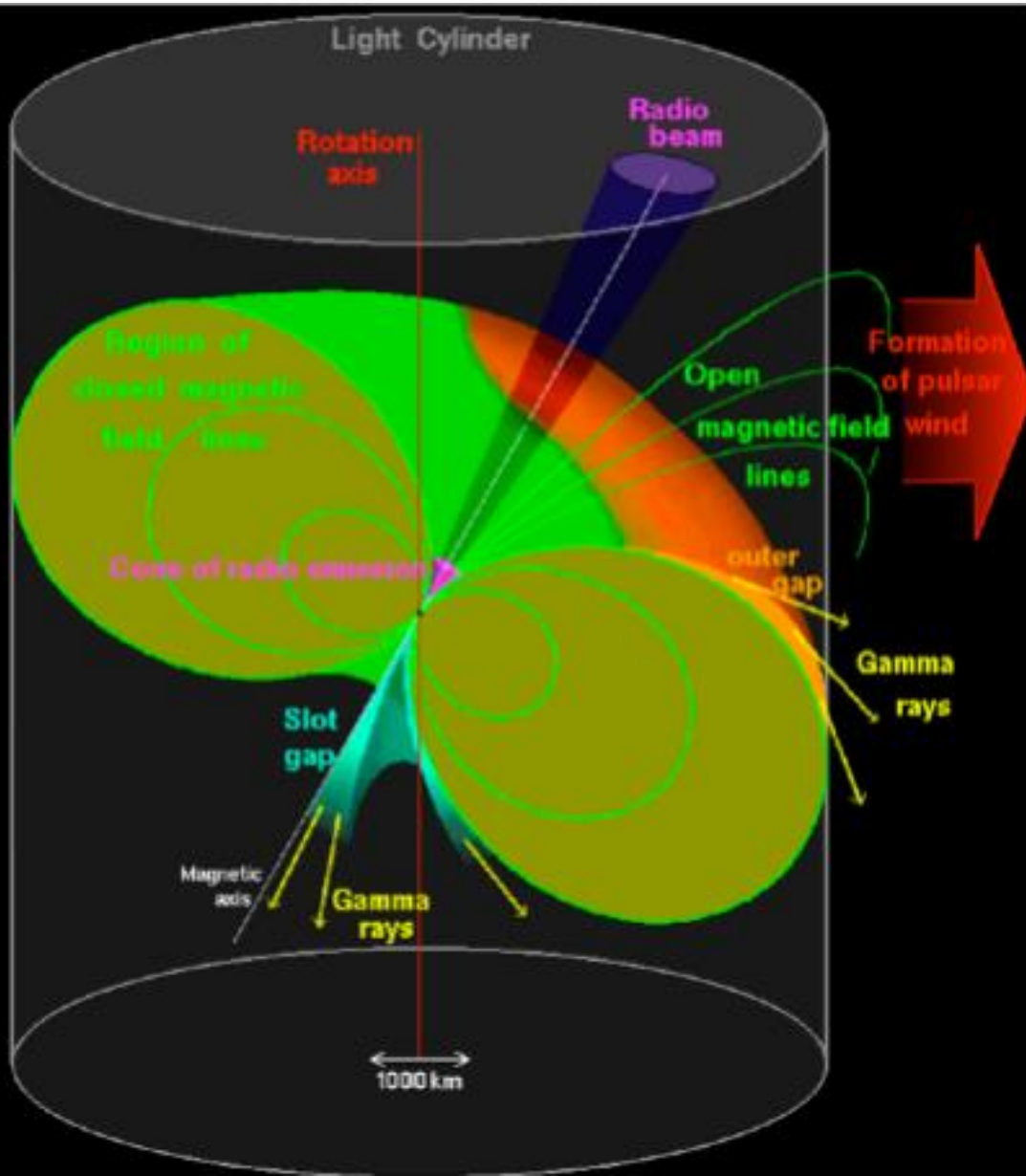


The other possibility



- ◆ 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:

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

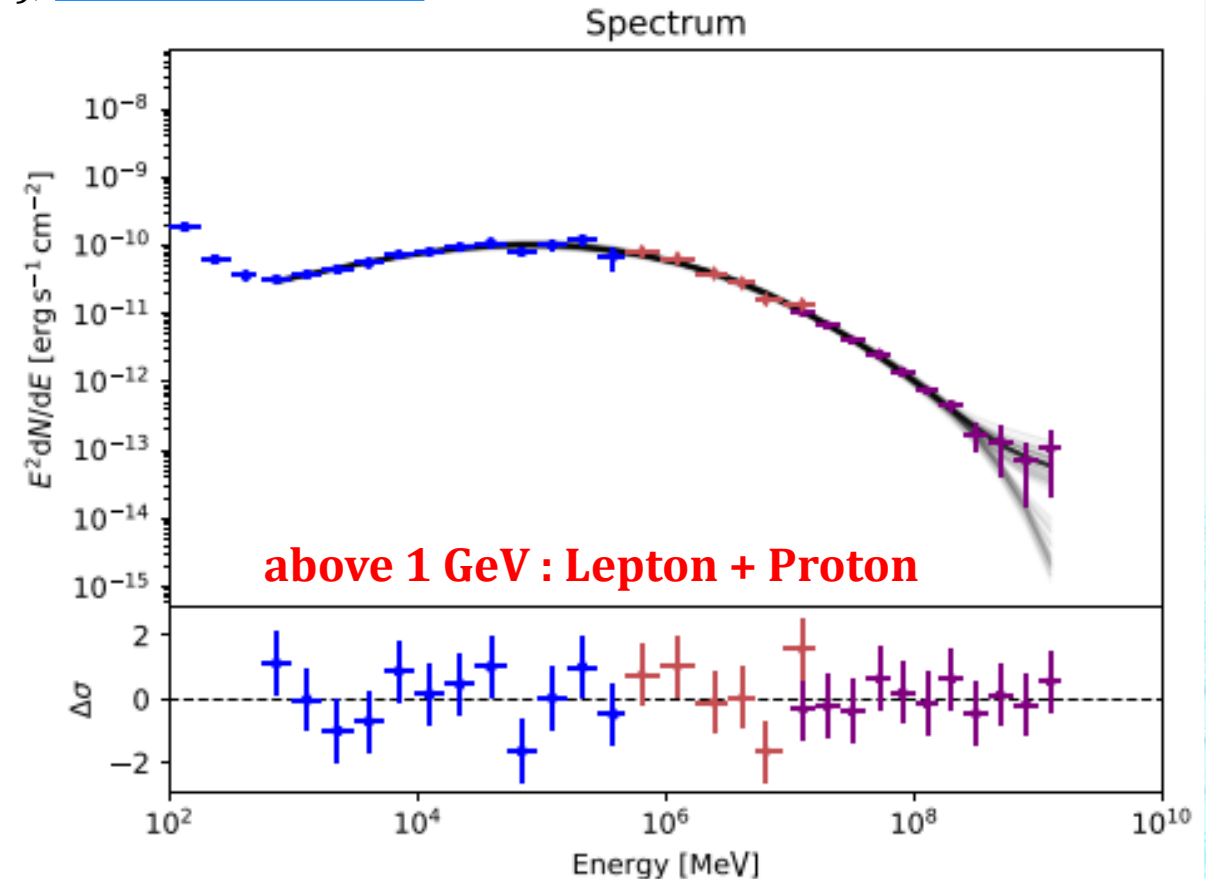
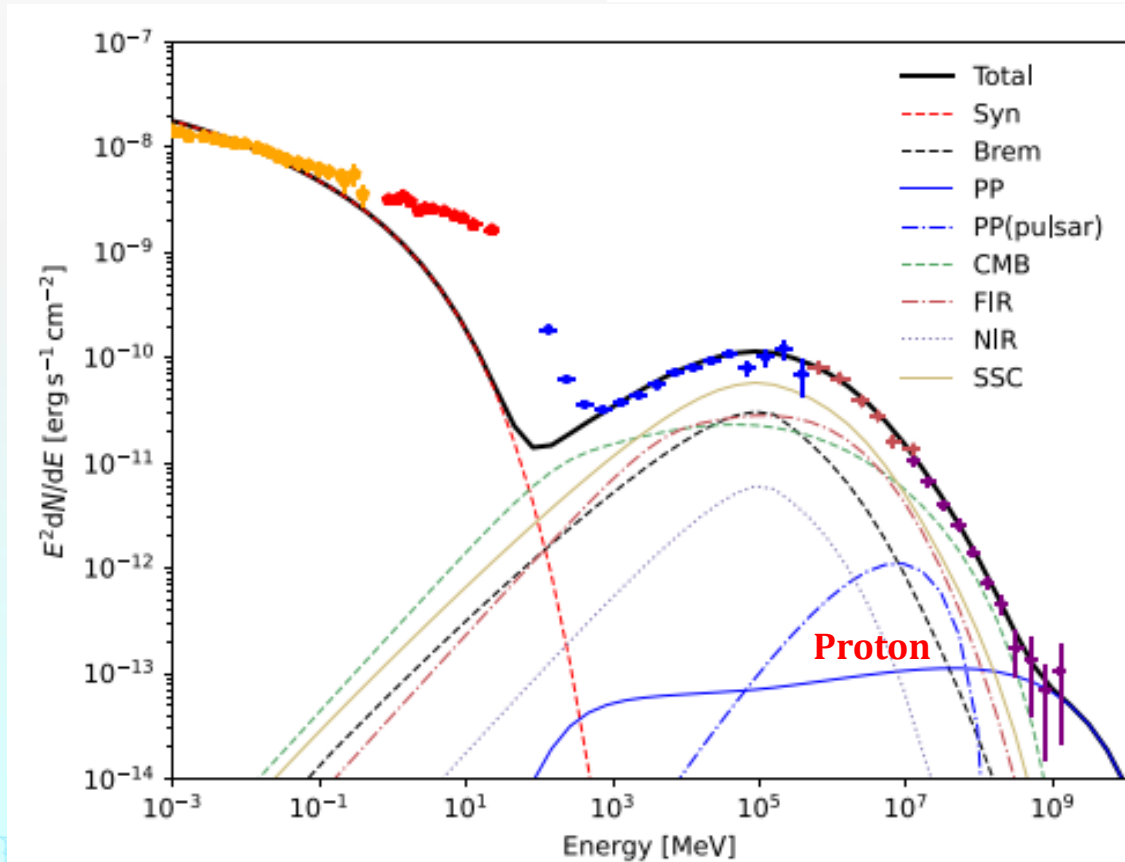
From Elena Amato's CDY talk (2022)

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

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, **924** 42 (2022), [arXiv:2201.03796](https://arxiv.org/abs/2201.03796)

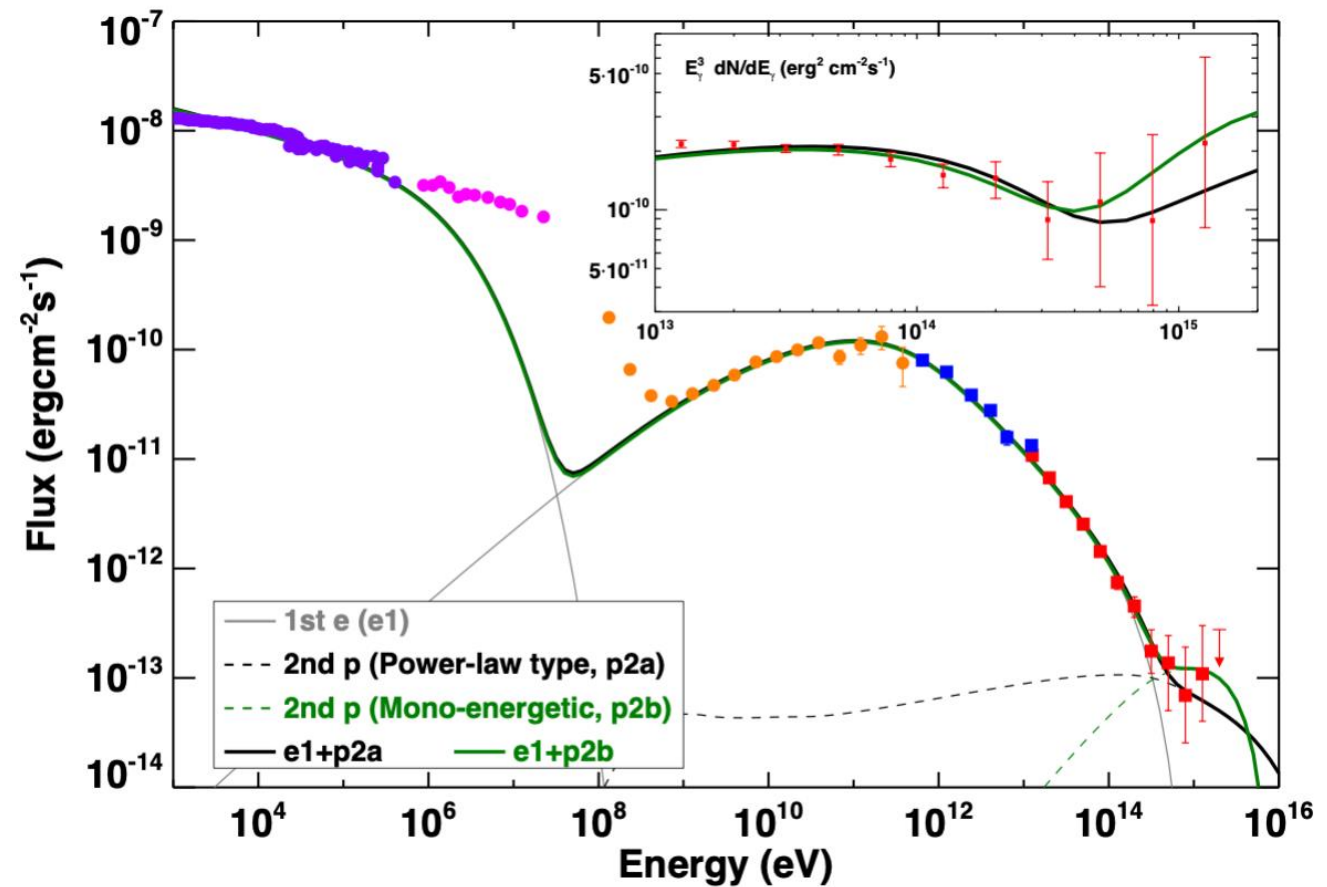
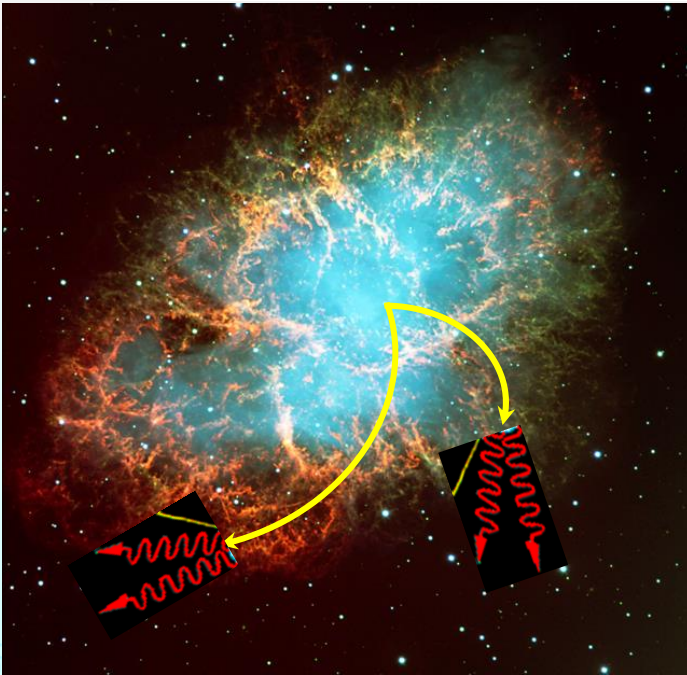


Even some monoenergetic protons

- 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



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