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The Crab Nebula:

observations and a search for UHE γ-ray flares with LHAASO

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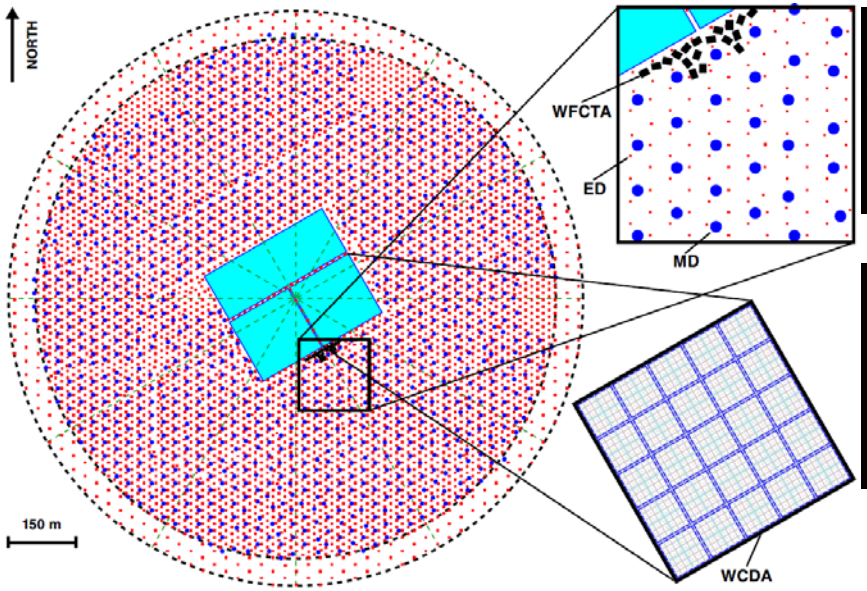
On behalf of the LHAASO collaboration

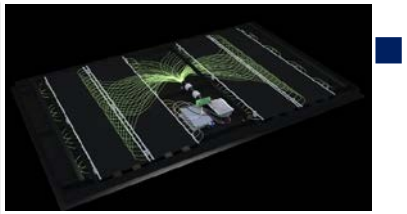
Outline

- LHAASO experiment
- Half of the KM2A detector performance
- Observations of the Crab Nebula
- Search for UHE γ-ray flares
- Summary

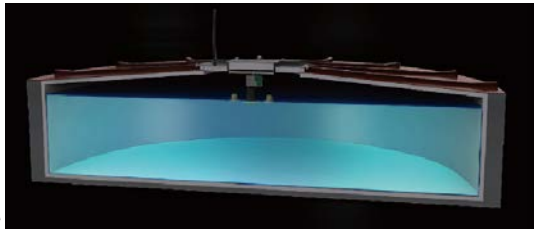
LHAASO experiment

1.3 km²



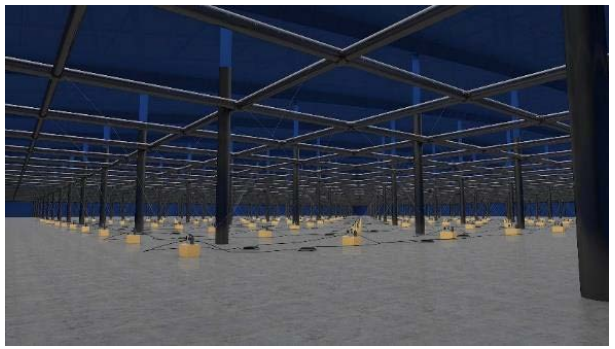


■ **5195 EDs**
- ■ 1 m² each
- ■ 15 m spacing



● **1188 MDs**
- ● 36 m² each
- ● 30 m spacing

◆**18 WFCTs**



□ **3120 WCDs**
- □ 25 m² each

✓Origin of CRs
- ✓ Searching for CR origin
- ✓ Energy spectrum for individual compositions

✓Gamma ray astronomy
- ✓ Searching for TeV γ-ray sources, especially extended and transient ones
- ✓ SNR, PWN, AGN, GRB, binary star, diffuse γ-ray …

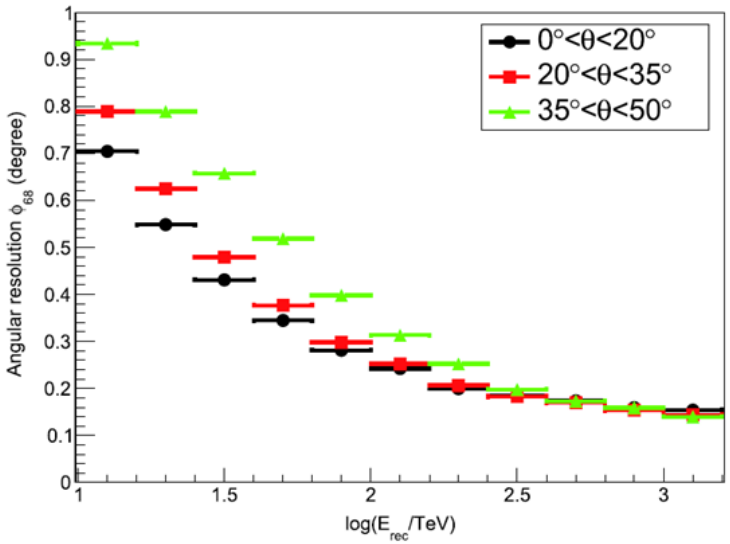
✓New physics frontier
- ✓ Dark matter
- ✓ Lorentz invariance
- ✓ New physics beyond LHC energy

2021 July full operation !!!

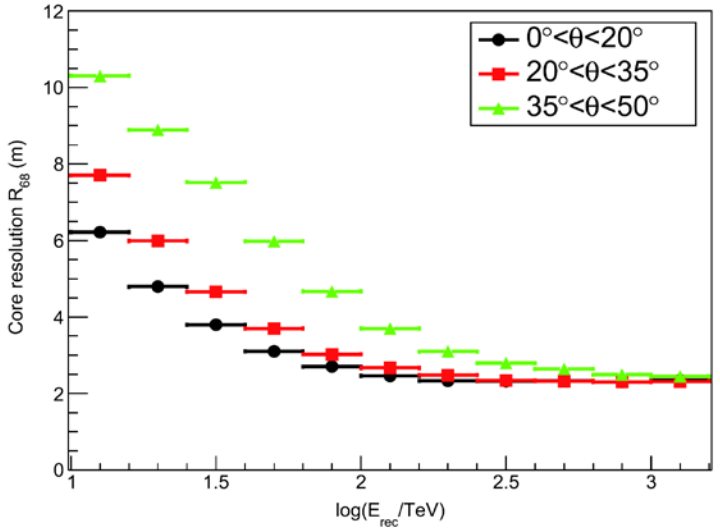
Half of the KM2A detector performance

F. Aharonian *et al* , *Chinese Phys. C* 2021 **45** 025002

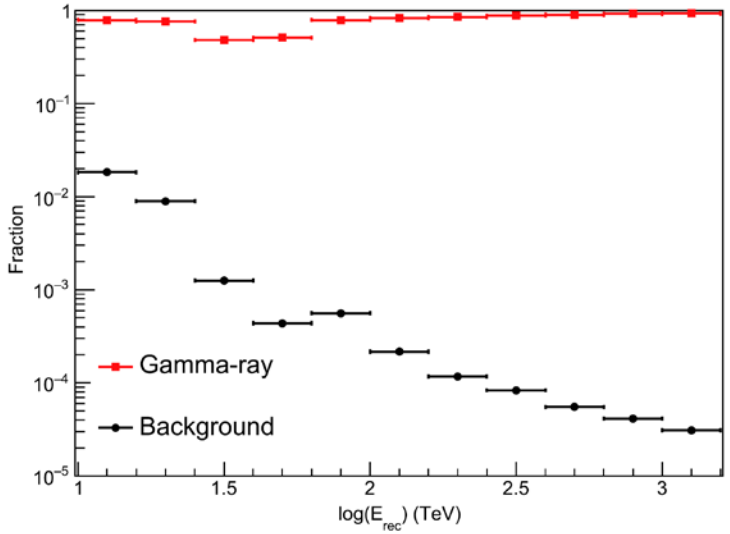
- Data: half of the KM2A
  - 2365 EDs + 578 MDs
- Angular resolution
  - 0.5 ~ 0.8 degree @ 20 TeV and 0.24 ~ 0.3 degree @ 100 TeV
- Core resolution
  - about 4 ~ 9 m @ 20 TeV and 2~4 m @ 100 TeV
- γ/p discrimination
  - Background rejection power ~ 10^4 and γ-ray survival fraction ~80% @ 100 TeV



Angular resolution



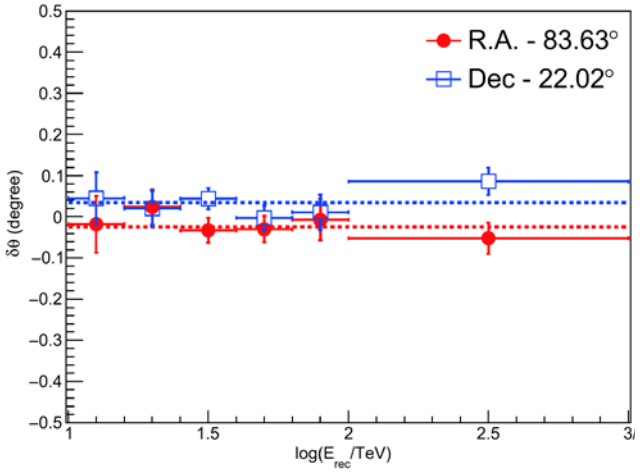
Core resolution

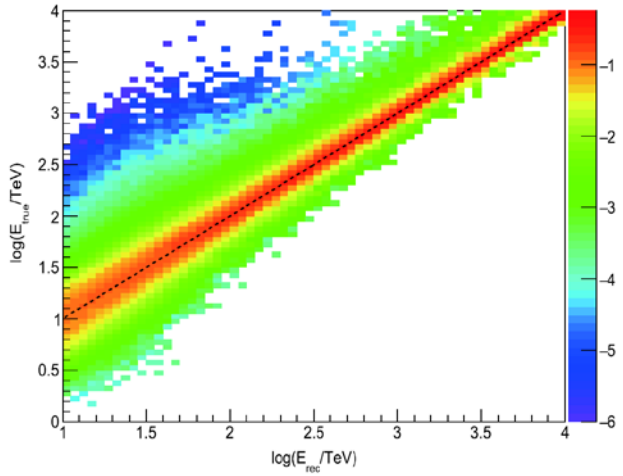


Survival fraction of γ-ray

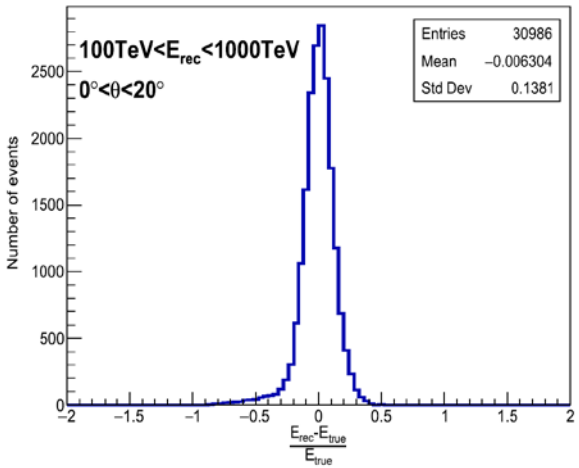
- Pointing accuracy
  - < 0.1 degree
- Energy resolution
  - Θ < 20 degree : 24% @ 20 TeV and 13% @ 100 TeV

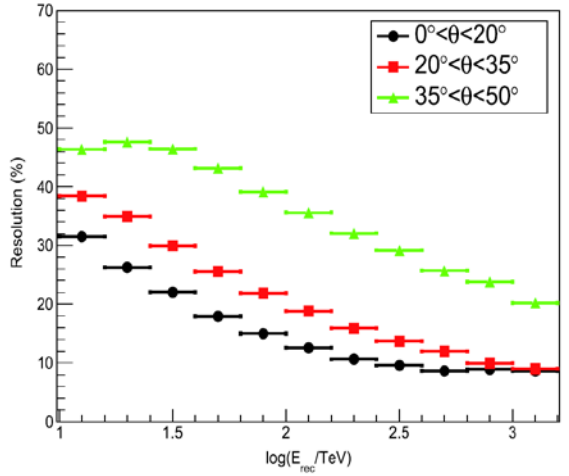
✓ All performance is excellent and KM2A has fully met design expectations.





Pointing accuracy





Energy resolution

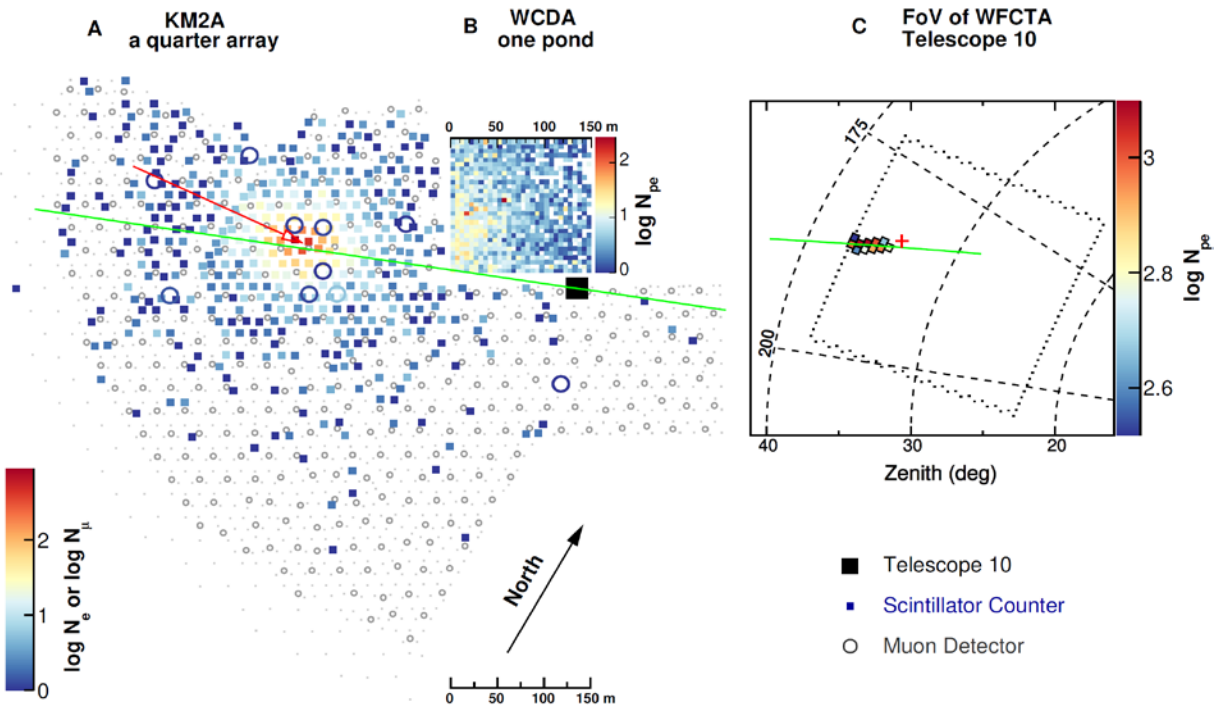
Observations of the Crab Nebula

The LHAASO Collaboration, Science 10.1126/science.abg5137 (2021)

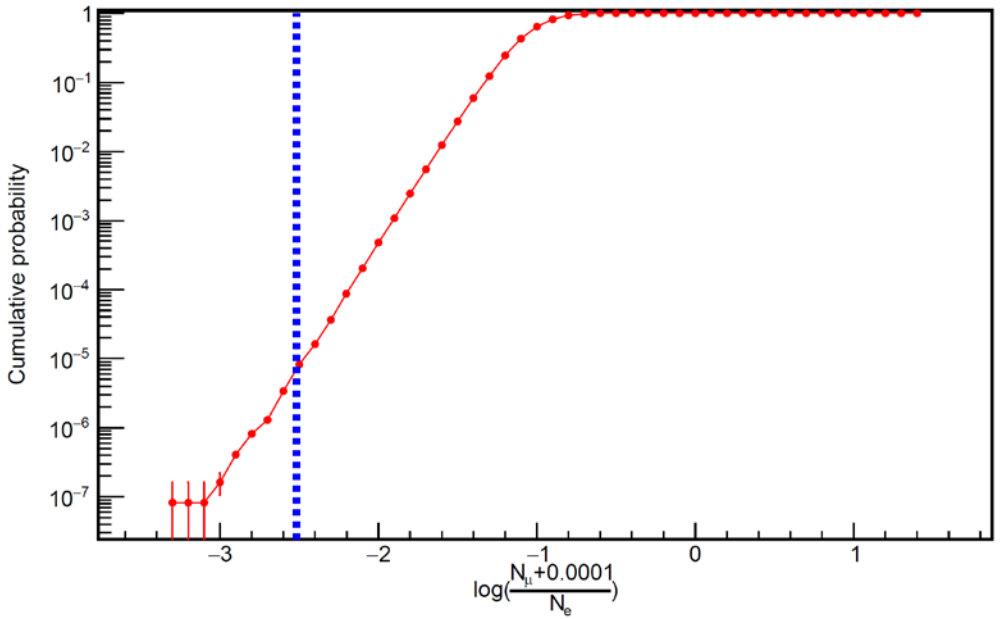
0.88 PeV γ-ray event

- Energy : 0.88 ± 0.11 PeV
- The chance probability of misidentifying a cosmic ray as a gamma : ~ 0.1%

- Ne : **4996** particles, Nu : **15** muons, log((Nu+0.0001)/Ne)= **-2.52**
- Zenith angle : **33.9** degree
- **0.21** degree from the Crab Nebula



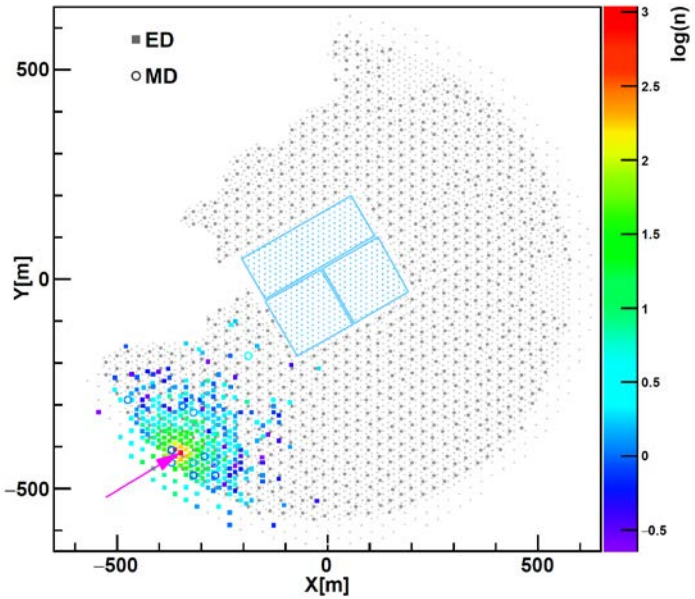
Cumulative probability distribution



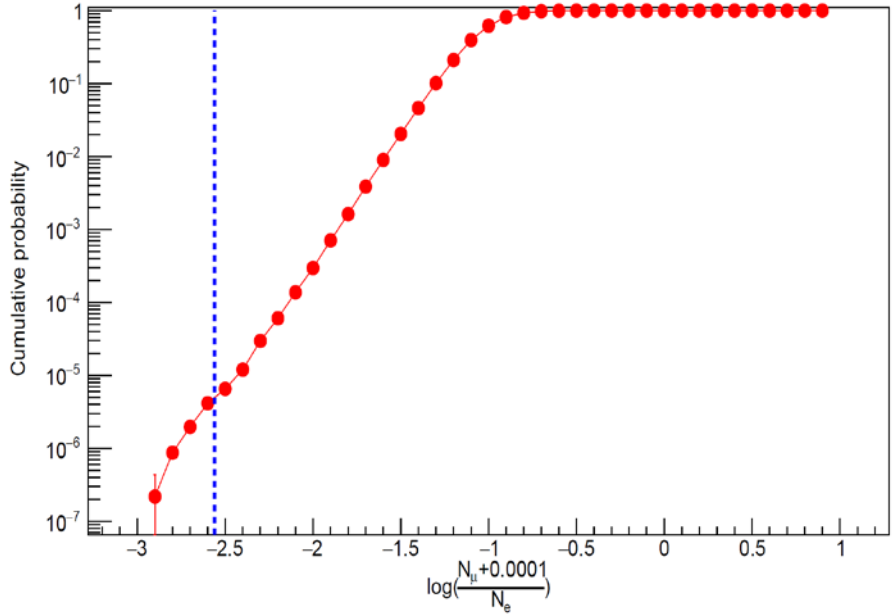
1.12 PeV γ-ray event

- Three-quarter KM2A : 3978 EDs + 917 MDs
- Energy : 1.12 ± 0.09 PeV
- The chance probability of misidentifying a cosmic ray as a gamma : ~ 0.03%

- Ne : **5094** particles
- Nu : **14** muons
- Zenith angle : **12.9** degree
- log((Nu+0.0001)/Ne)= **-2.56**
- **0.15** degree from the Crab Nebula



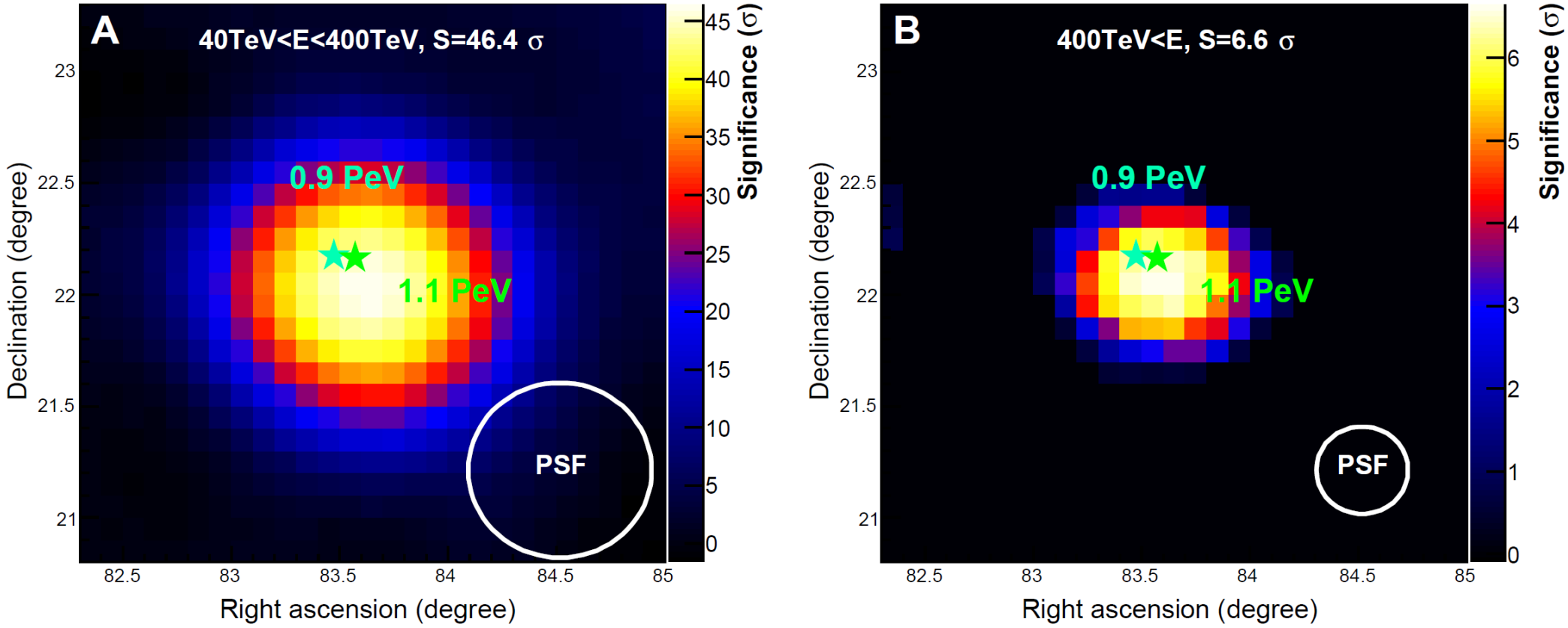
Particles distribution



Cumulative probability distribution

Significance maps of the Crab Nebula

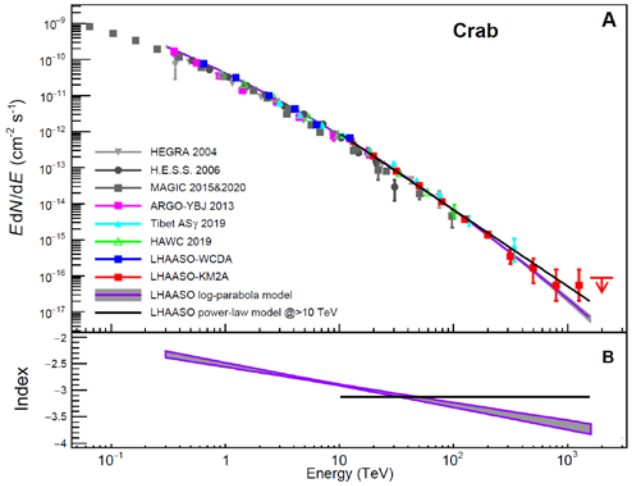
- **Data** : half of the KM2A + three-quarter KM2A
- 46.4 standard deviations in the energy range from 40 to 400 TeV
- 6.6 standard deviations at the energy above 400 TeV.



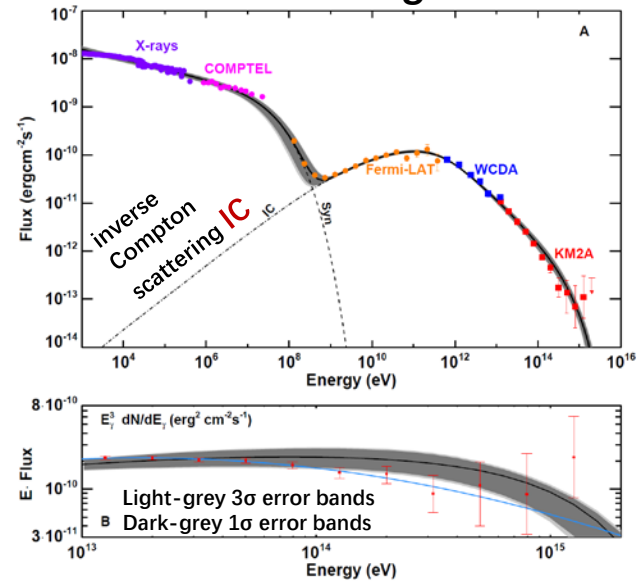
Significance maps of the Crab Nebula

Energy spectrum

- This measurement extends the energy range to 1.1 PeV. The energy dependent spectral index implies a gradual steepening from 2.5 at 1 TeV to 3.7 at 1 PeV.
- Within the idealized synchrotron-IC one-zone model, the KM2A spectral points from 10 TeV to 1 PeV agree with the IC γ-ray prediction within the statistical uncertainties.
- Between 60 and 500 TeV, a deviation of **4 σ** significance indicates a steeper spectrum than the one-zone model predictions.
- The possible excess around 1 PeV indicates an opposite tendency i.e. a hardening of the spectrum.



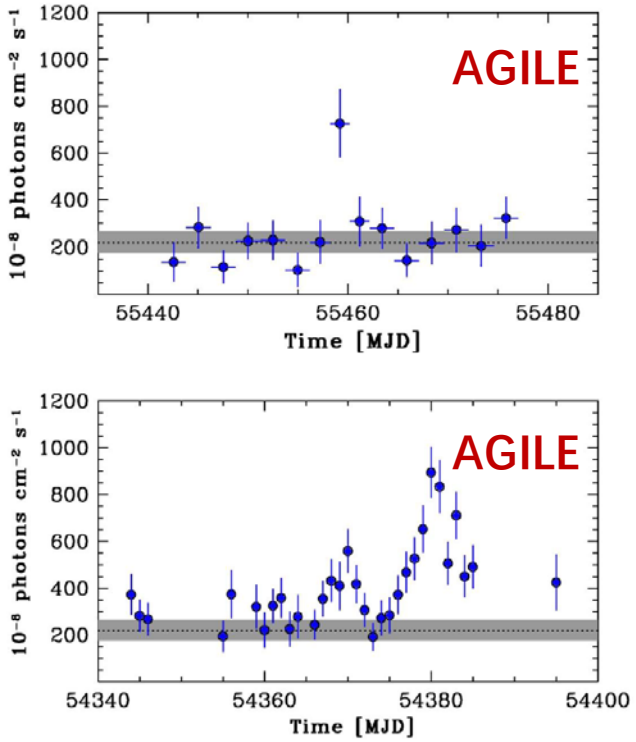
Flux and fitting results



Spectral energy distribution

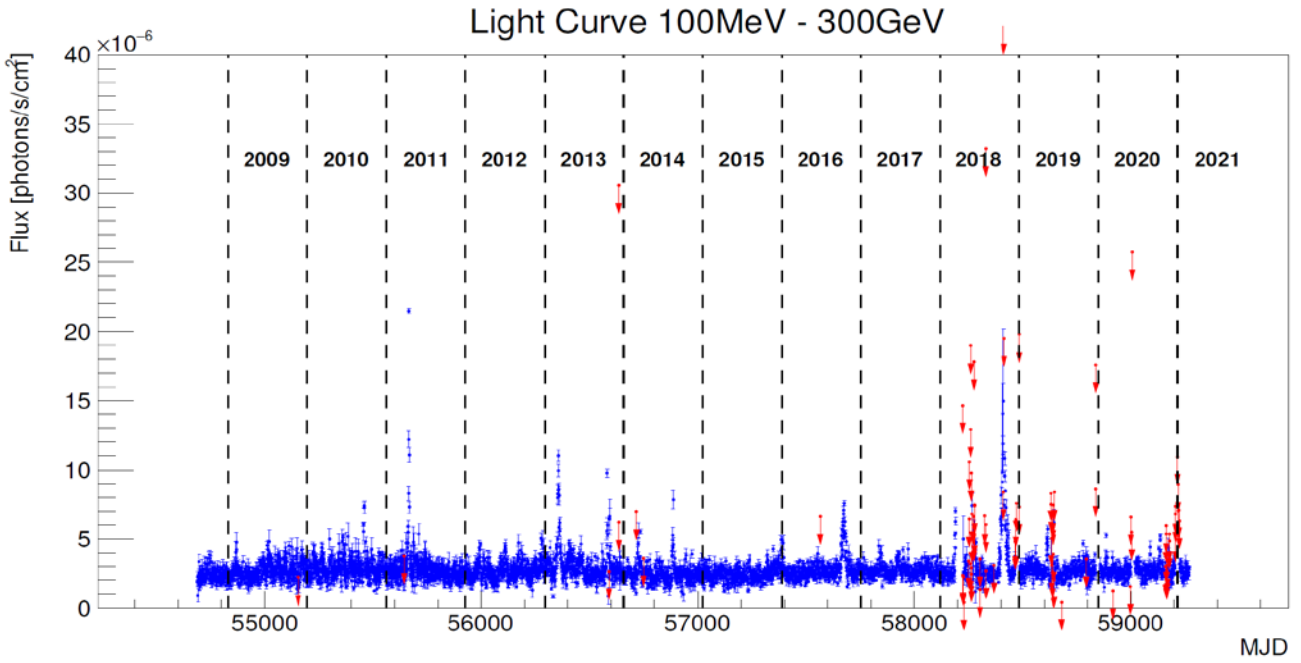
Search for UHE γ-ray flares

- The γ-ray flares around GeV from the Crab Nebula have been observed many times by AGILE and Fermi-LAT.
- These observations challenge the standard models for particle acceleration in pulsar wind nebula. The origin is not fully understood.
- **No UHE flares are observed with a rough search.**



Tavani M. et al. **Science**, 2011, 331: 736-739

Fermi-LAT



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/source/Crab_Pulsar

Summary

- Half of the KM2A detector performance has been verified, including angular resolution, core resolution, γ ray/background discrimination, pointing accuracy, and energy resolution, the results show half of the KM2A has an excellent performance.

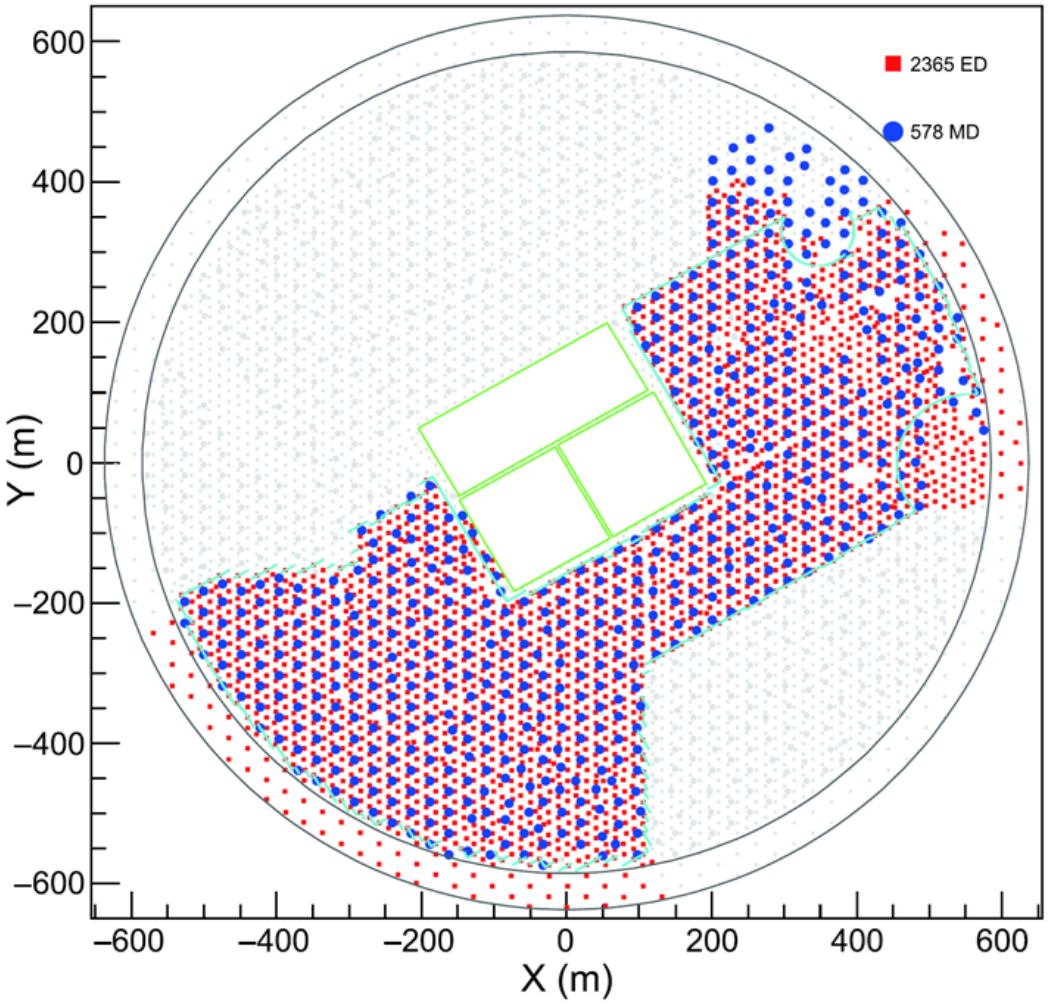
- PeV γ-ray events from the Crab Nebula has been detected. The significance and energy spectrum of the Crab Nebula are reported.

- No obvious UHE flares have been found yet, the flares monitor software will be optimized for high sensitivity to the light variation and we will keep monitoring the Crab Nebula.

Thanks!

Backup

half of the KM2A layout



Fiducial area ~ 0.4 km^2

Origin of the PeV γ ray and electrons

- Assume the PeV γ ray is produced in the nebula
- The relation of the photon energy and the parent electron energy is :

$$E_e \simeq 2.15\left(E_\gamma/1PeV\right)^{0.77} PeV$$

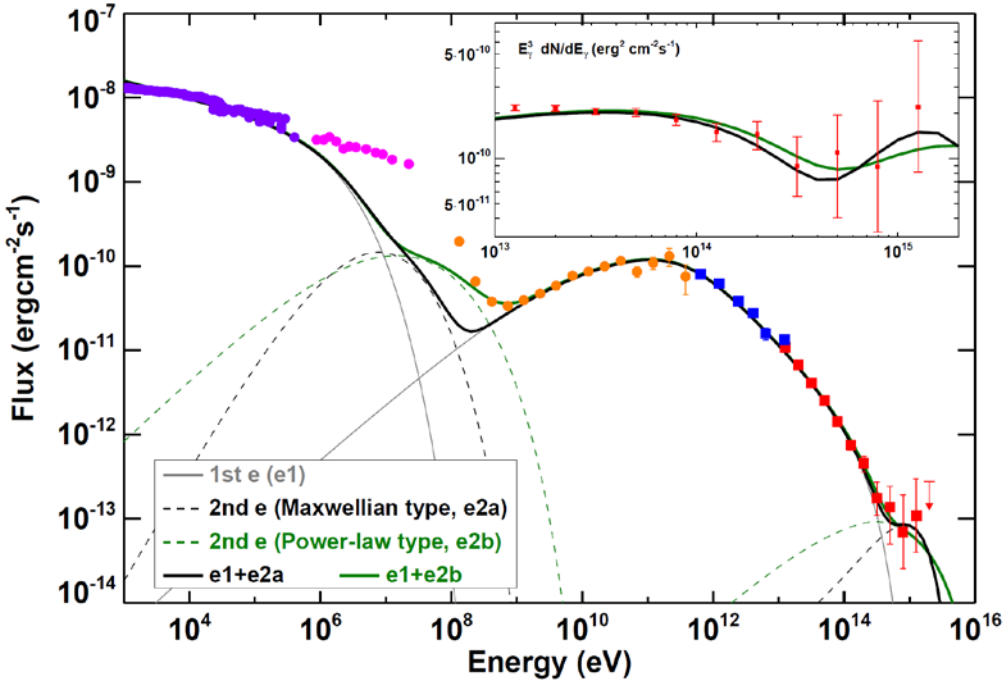
  - for the 1.1 PeV photon, the energy of the parent electron is 2.3 PeV

- The detection of ~ 1PeV photons implies an acceleration rate that overcomes the synchrotron losses of the parent electrons up to PeV energies, with an acceleration rate exceeding 15% of the theoretical limit

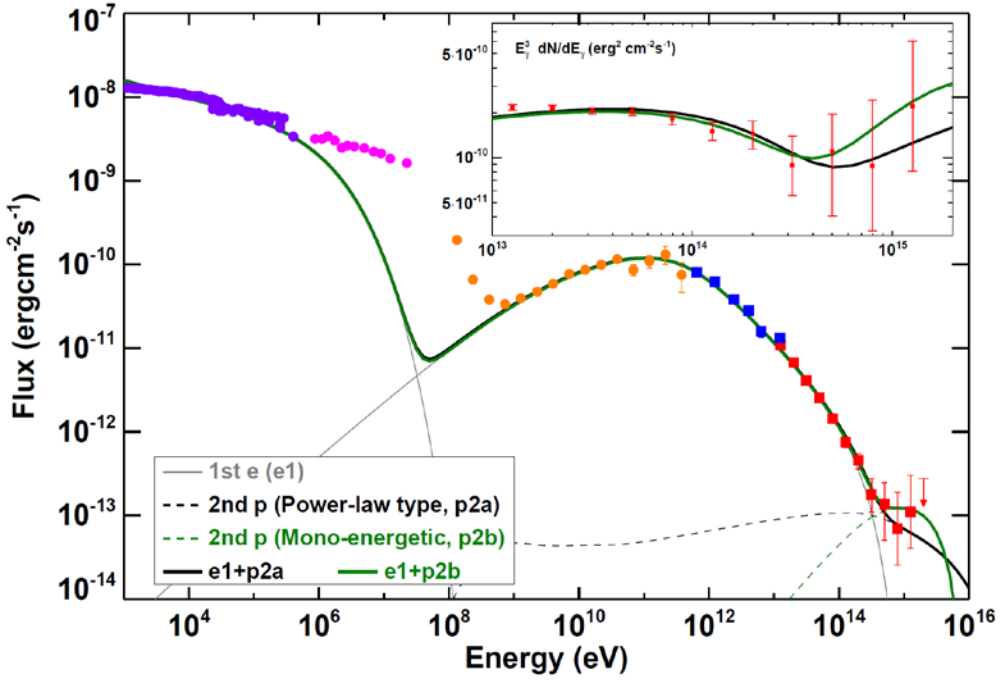
The LHAASO Collaboration, Science 10.1126/science.abg5137 (2021)

Leptonic or hadronic origin of the γ-ray emission above 60 TeV

- Adding a second population of PeV electrons, the two-component leptonic model fits the data well.
- The production of hadronic gamma rays in the Crab Nebula is less likely but cannot be excluded.
- **It is too early to make a conclusion with the inadequate statistics.**



Leptonic model



Lepto-hadronic model

The LHAASO Collaboration, Science 10.1126/science.abg5137 (2021)