LHAASO Status and prospect

11th Neutrino Oscillation Workshop

NOW 2022 Ostuni, 4-11 September 2022

Domenico della Volpe on behalf of LHAASO Collaboration

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

LHAASO Collaboration

LHAASO 高海拔宇宙线观测站

Scientists: 275 Institutions: 31

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[7]National Space Science Center, Chinese Academy of Sciences, 100190 Beijing, China
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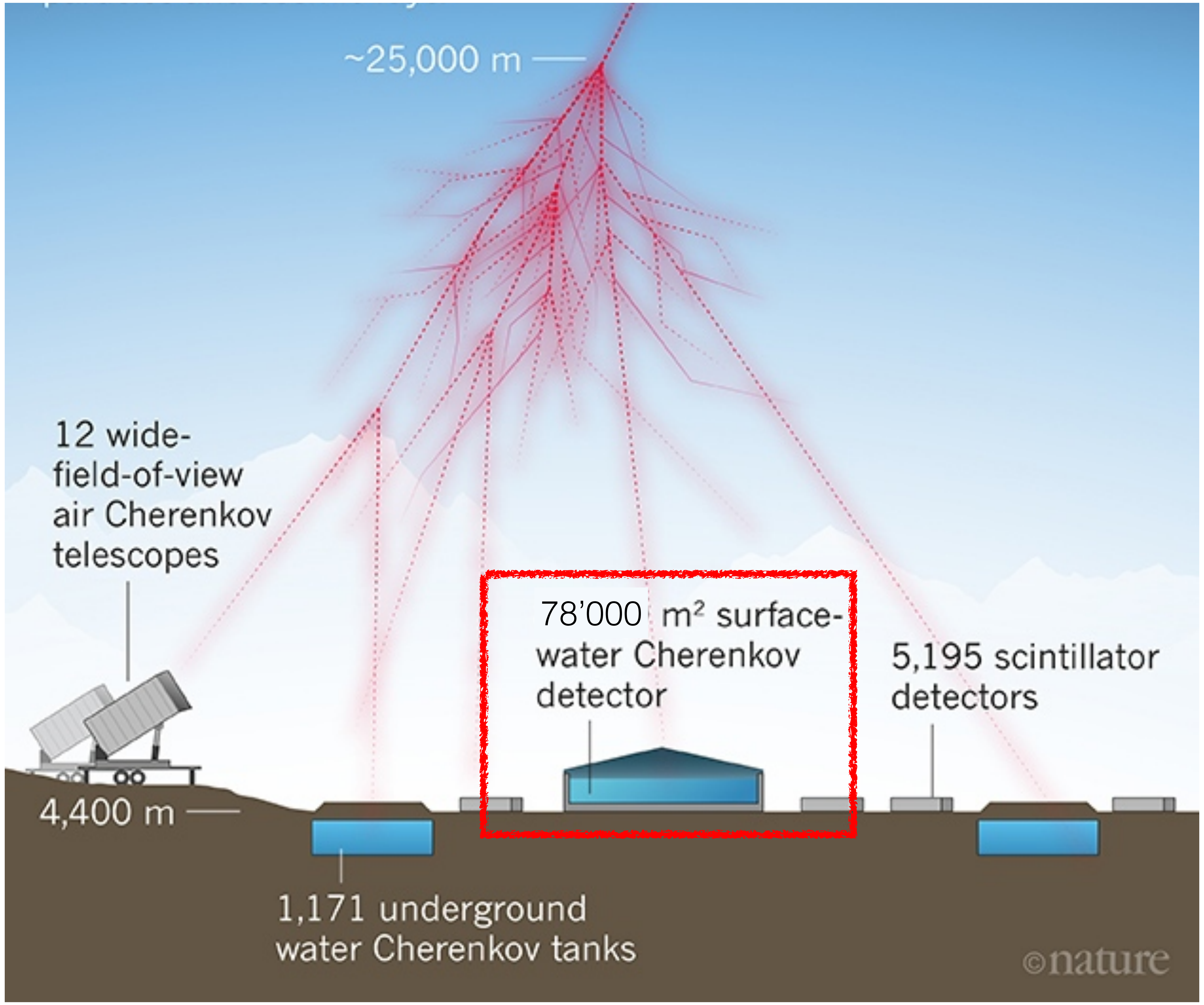
[23]Département de Physique Nucléaire et Corpusculaire, Faculté de Sciences, Université de Genéve, Geneva,
land
[24]Department of Physics, Faculty of Science, Mahidol University, Bangkok, Thailand

Institutions waiting for membership: APS, France

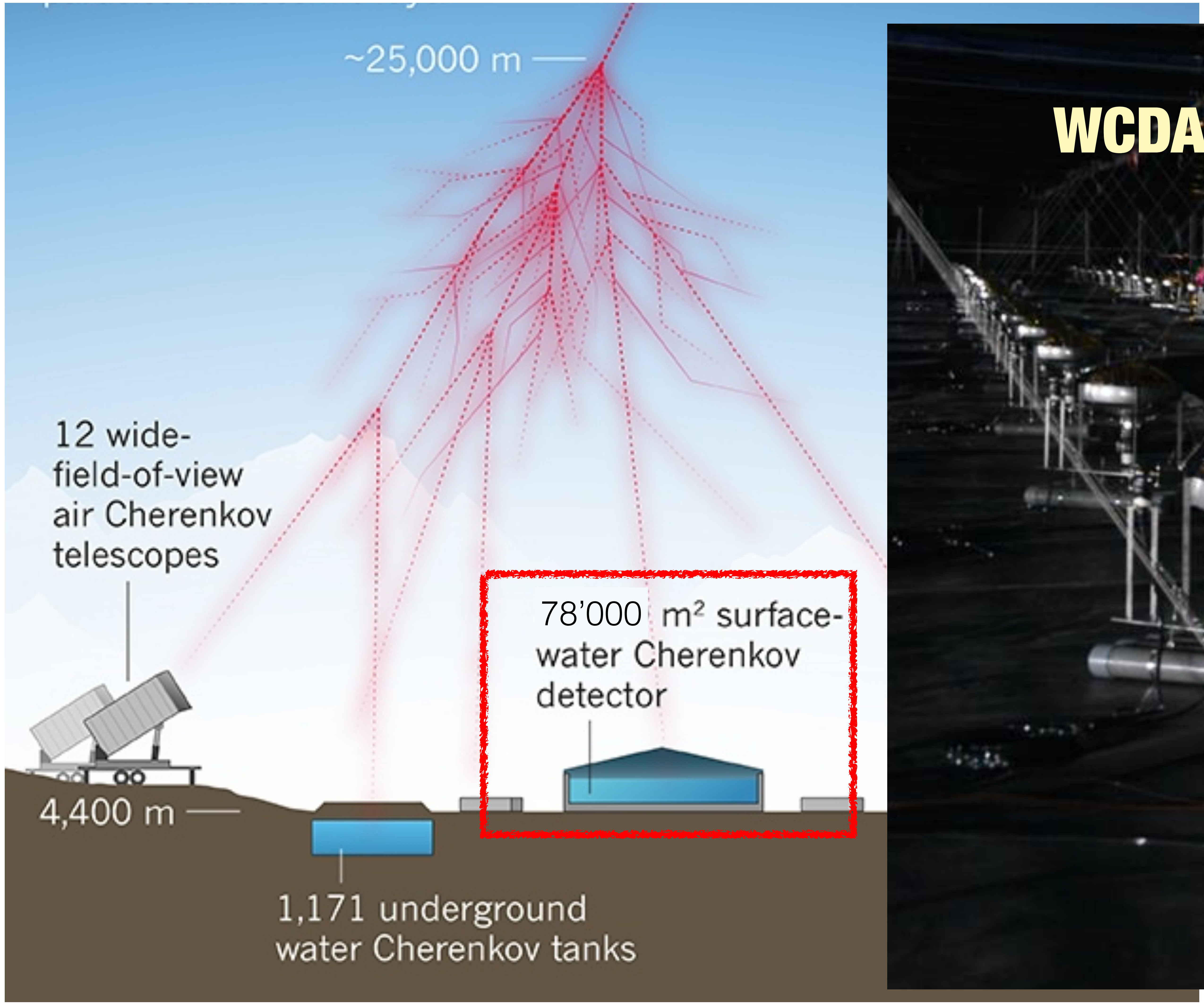
MoU of Collaboration signed: VERITAS, ANTARES, GVD
MoU under discussion CTAO, MAGIC, IceCube

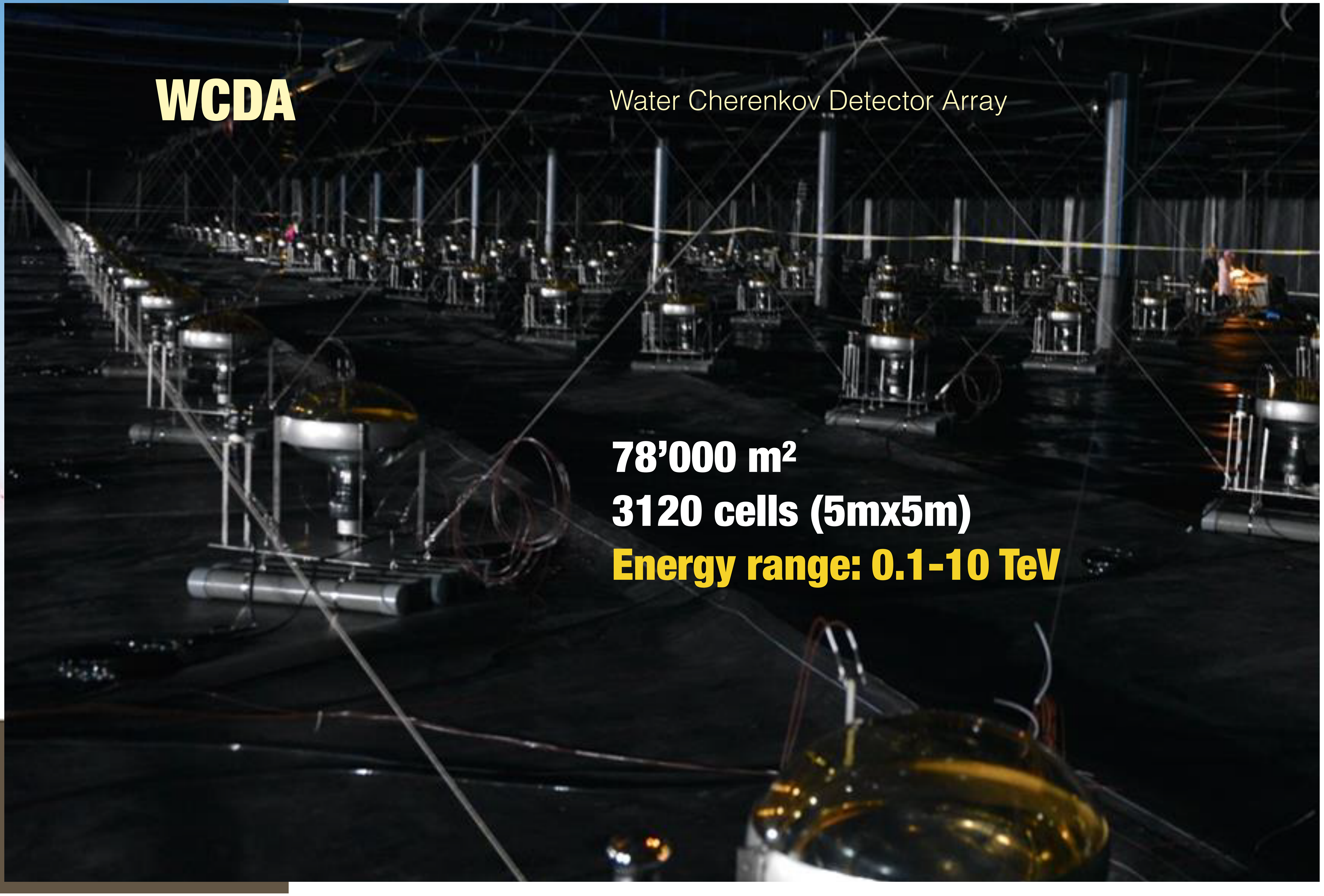
Bird-eyes' View of LHAASO, March, 2021

The LHAASO concepts



The LHAASO concepts

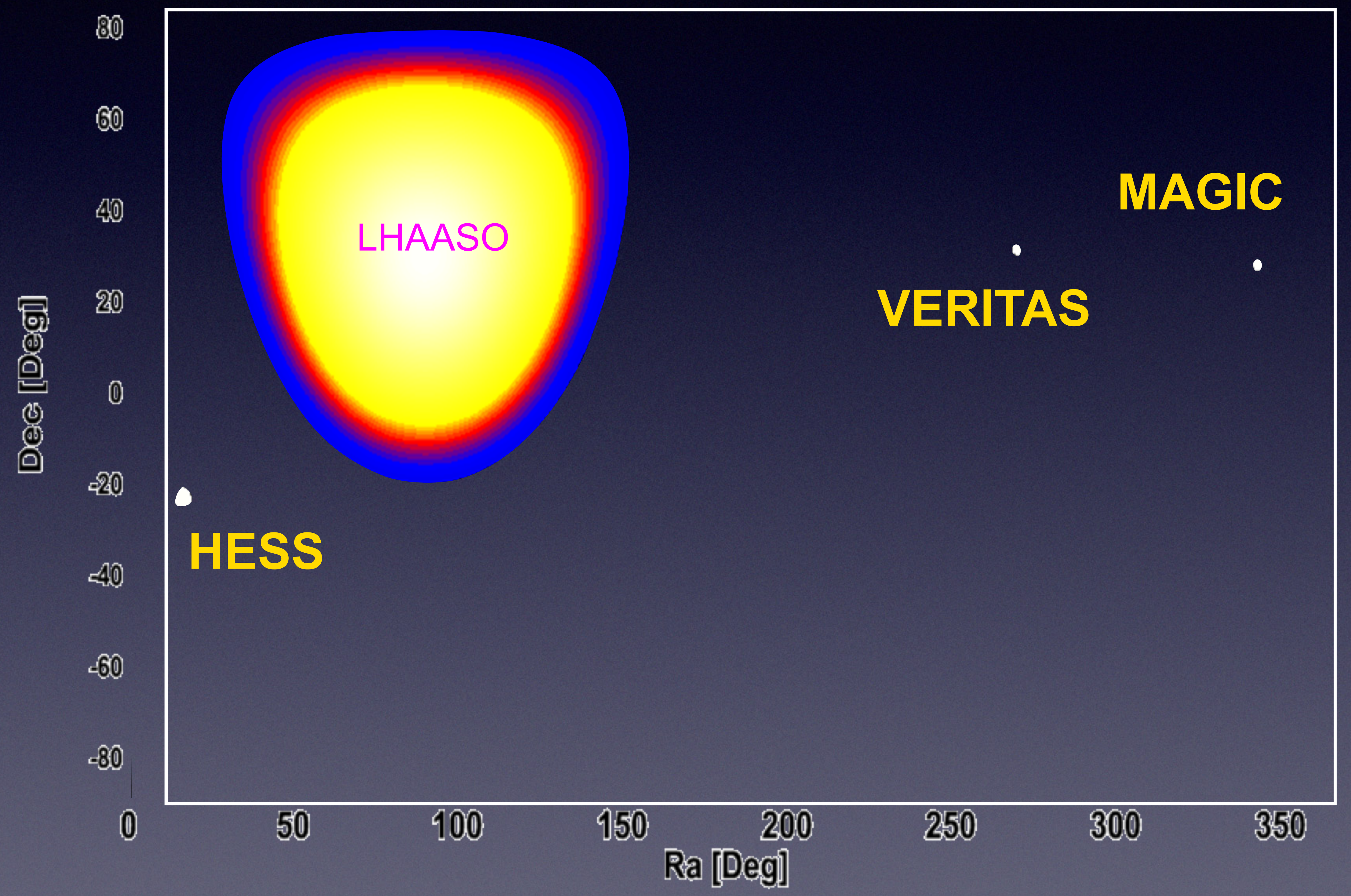




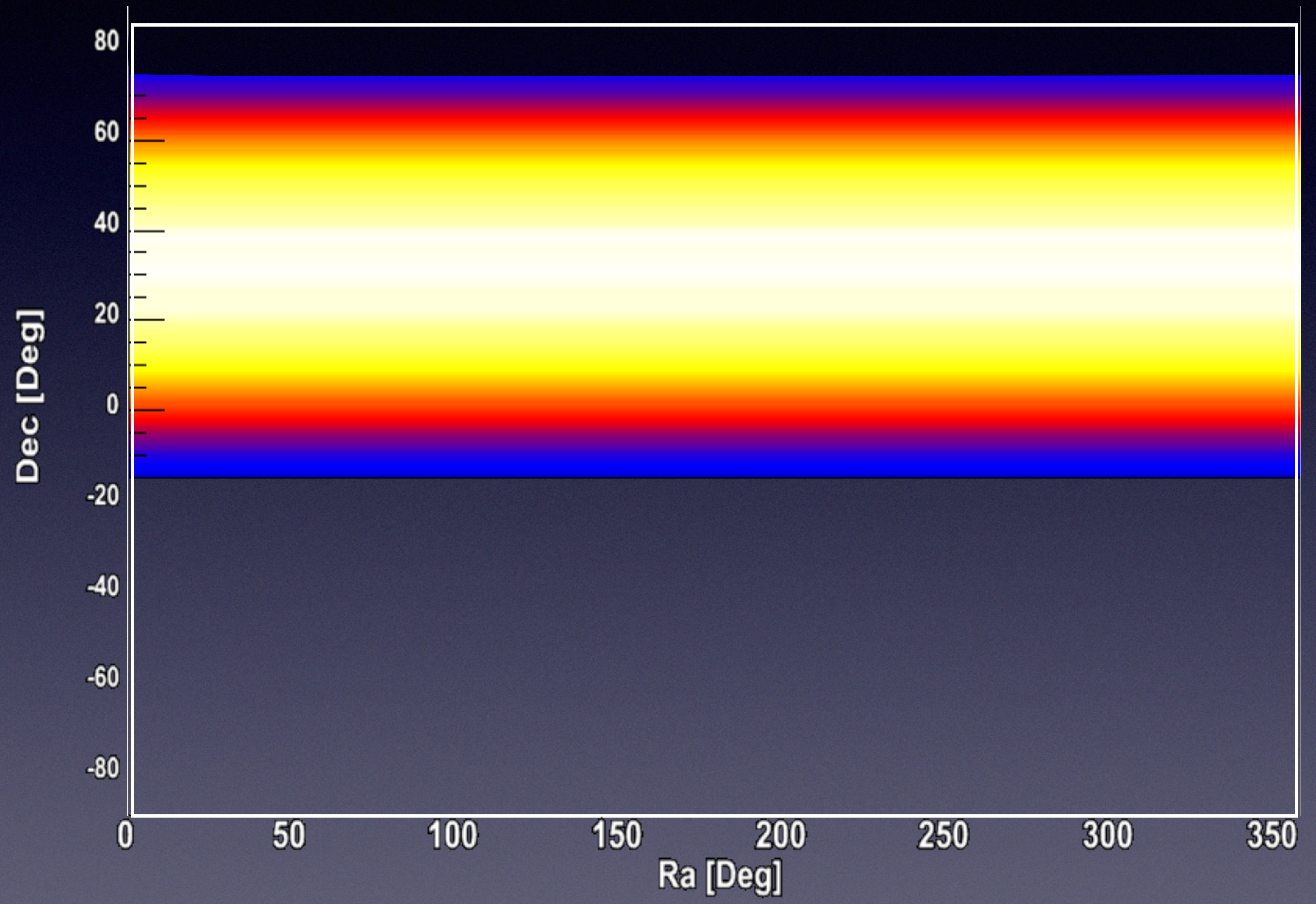
The LHAASO concepts

The LHAASO concepts

Wide FOV γ-ray Astronomy

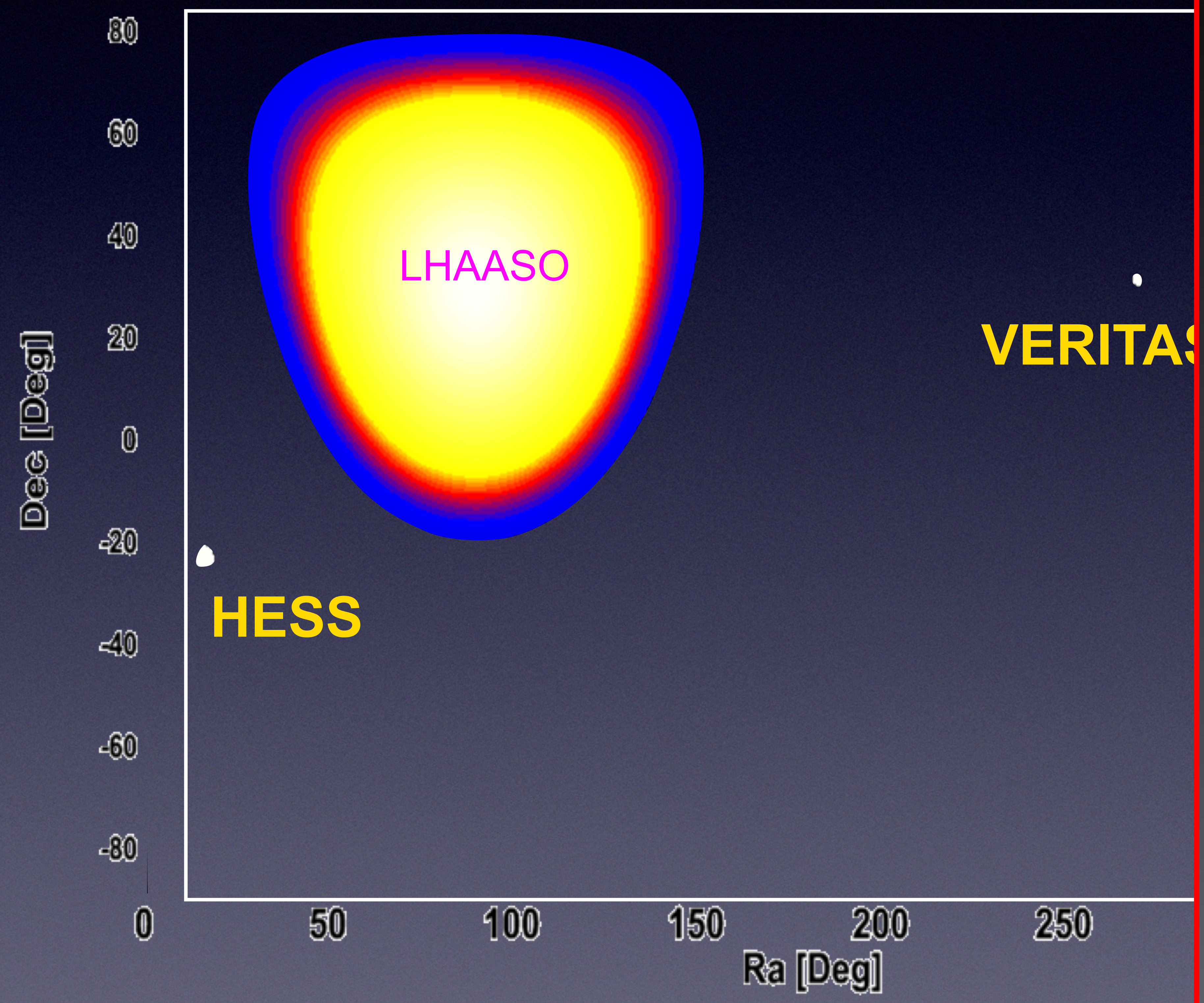


- 1/7 of the sky at any moment



- 60% in the sky per day day (24h)

Wide FOV γ-ray Astronomy



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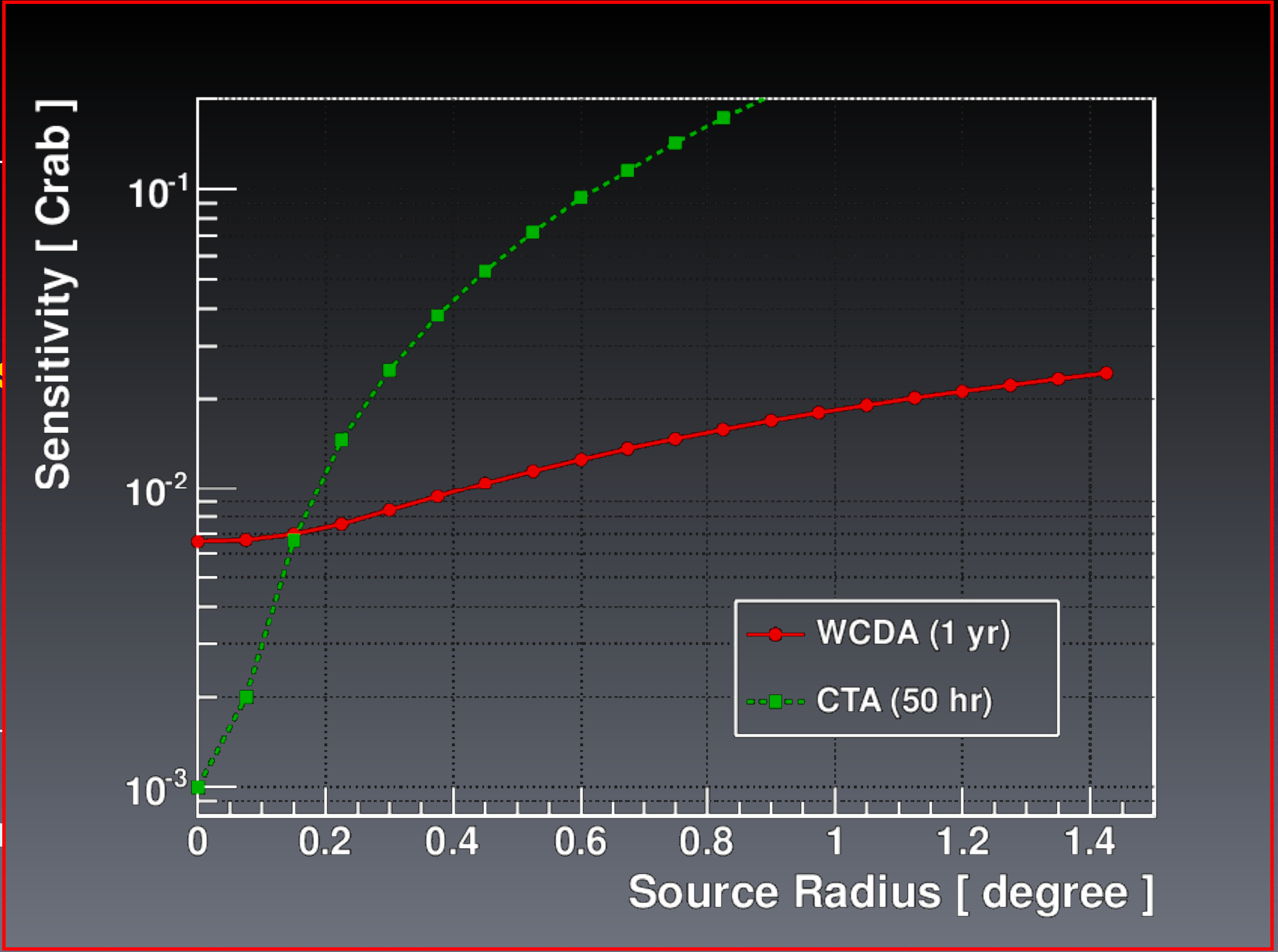
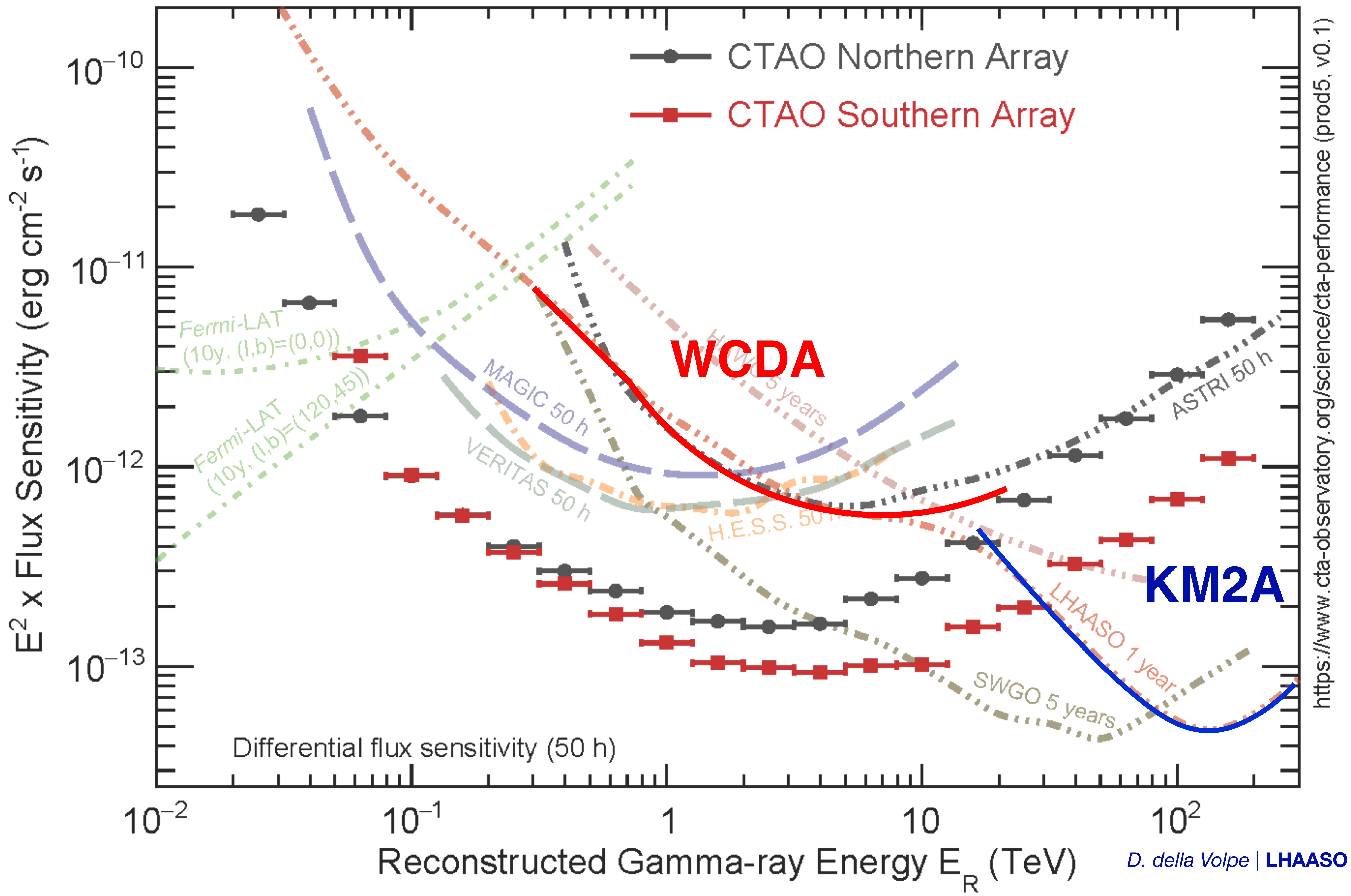
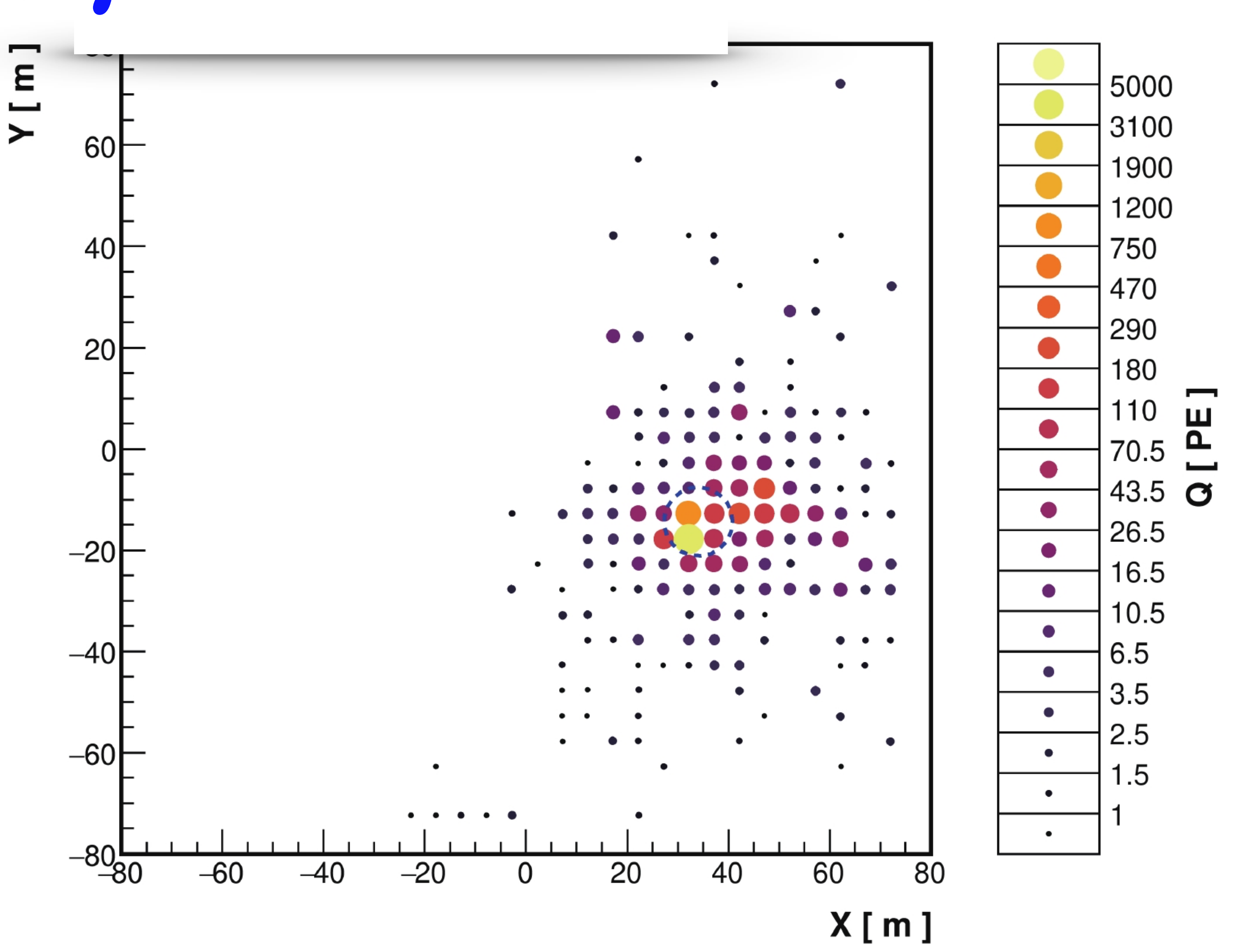


LHAASO Expected Sensitivity

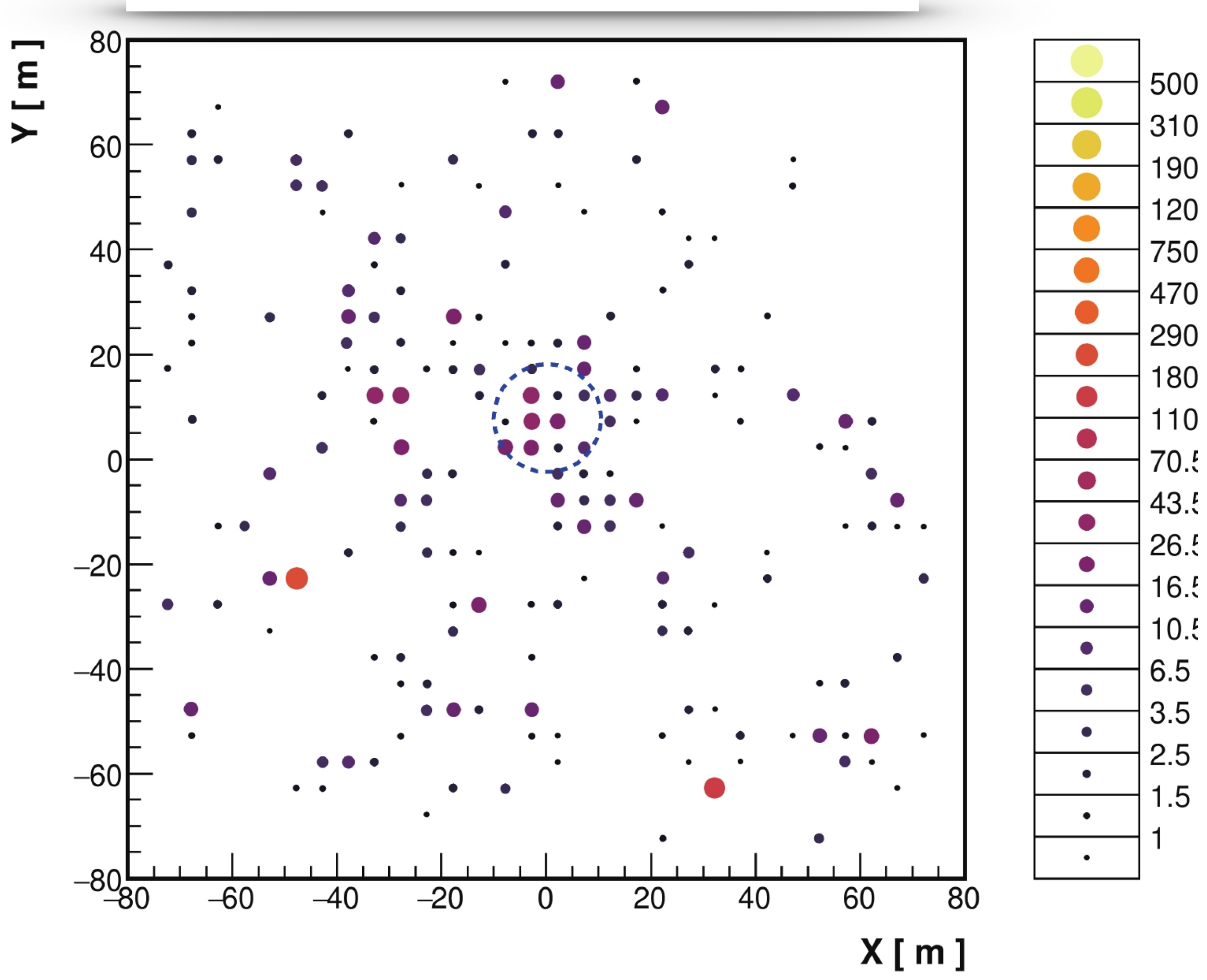


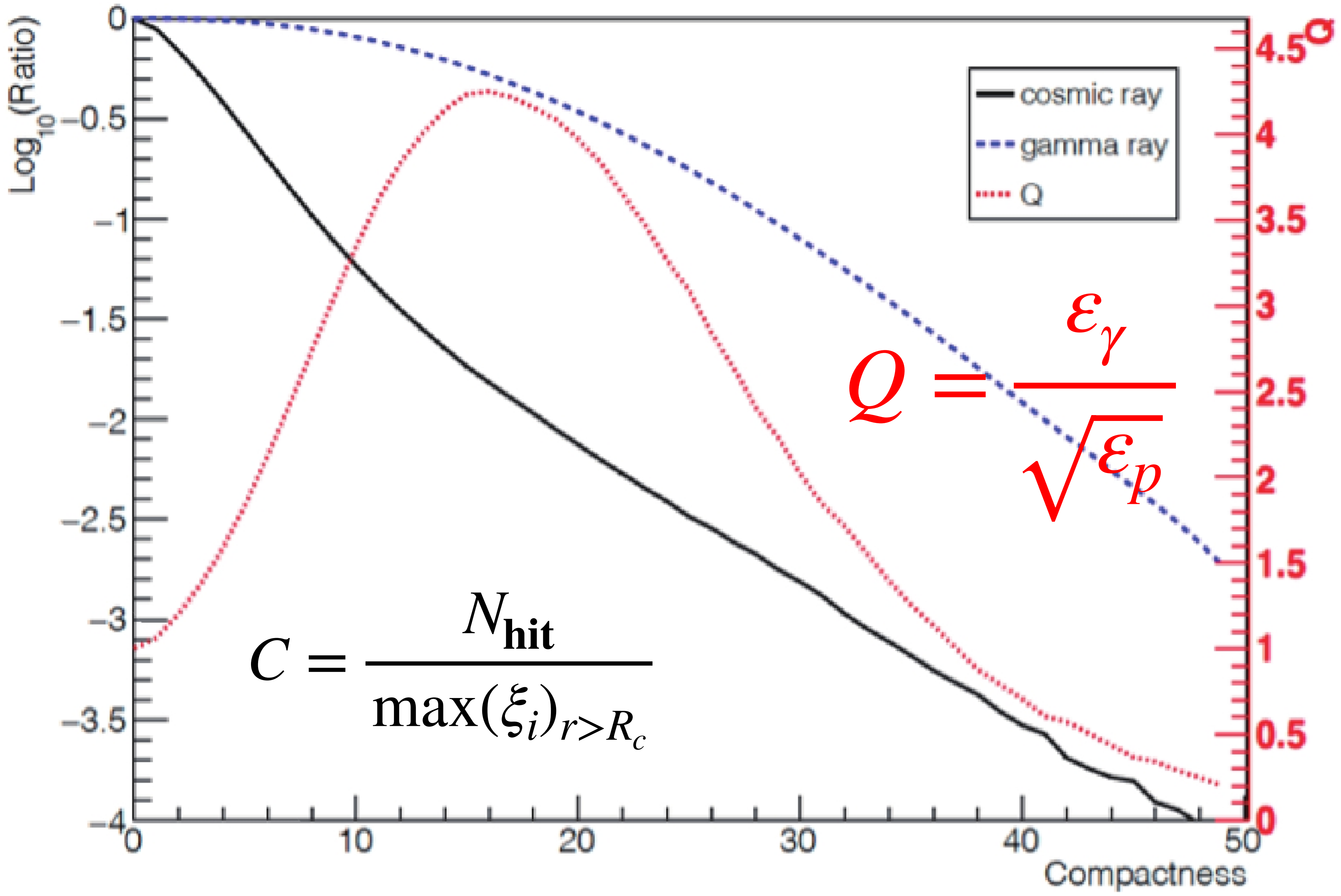
WCDA performance

γ-like event



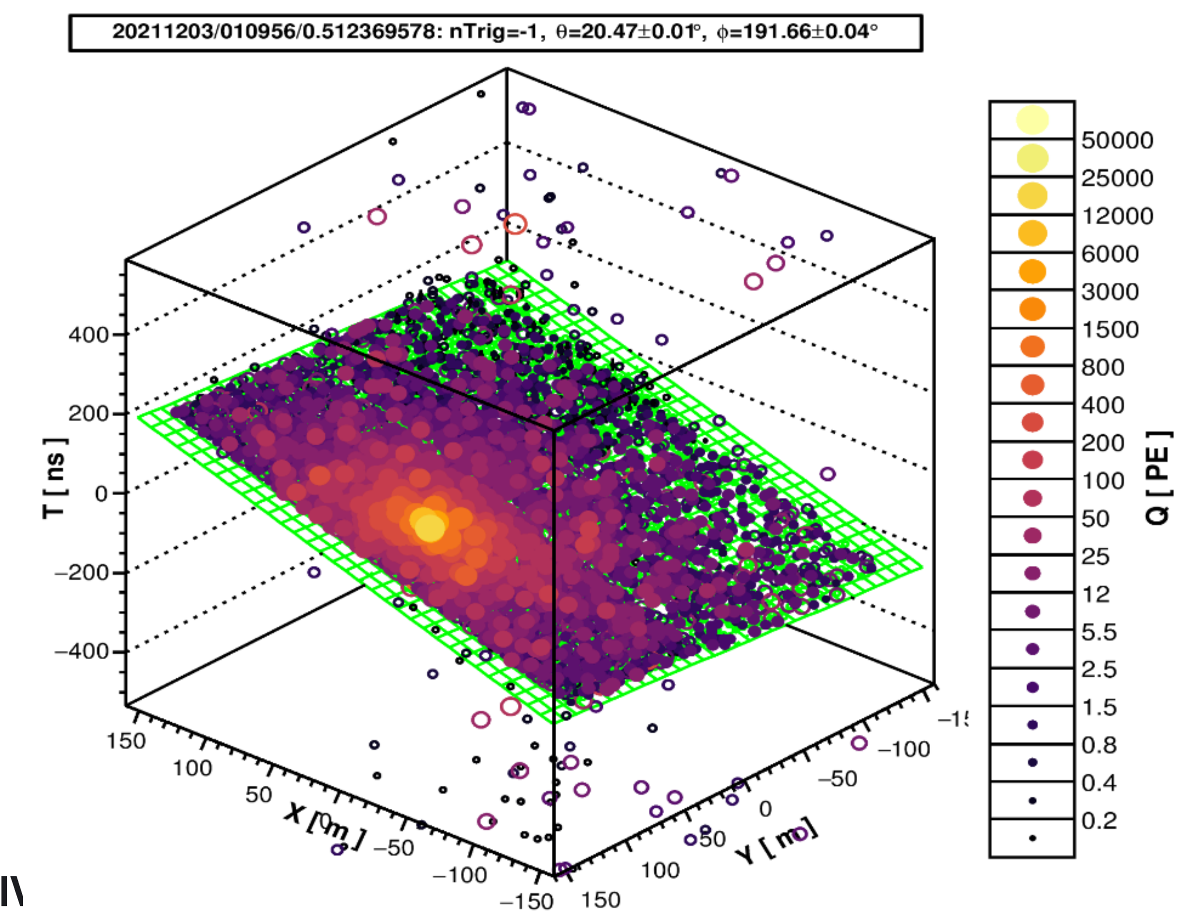
CR-like event

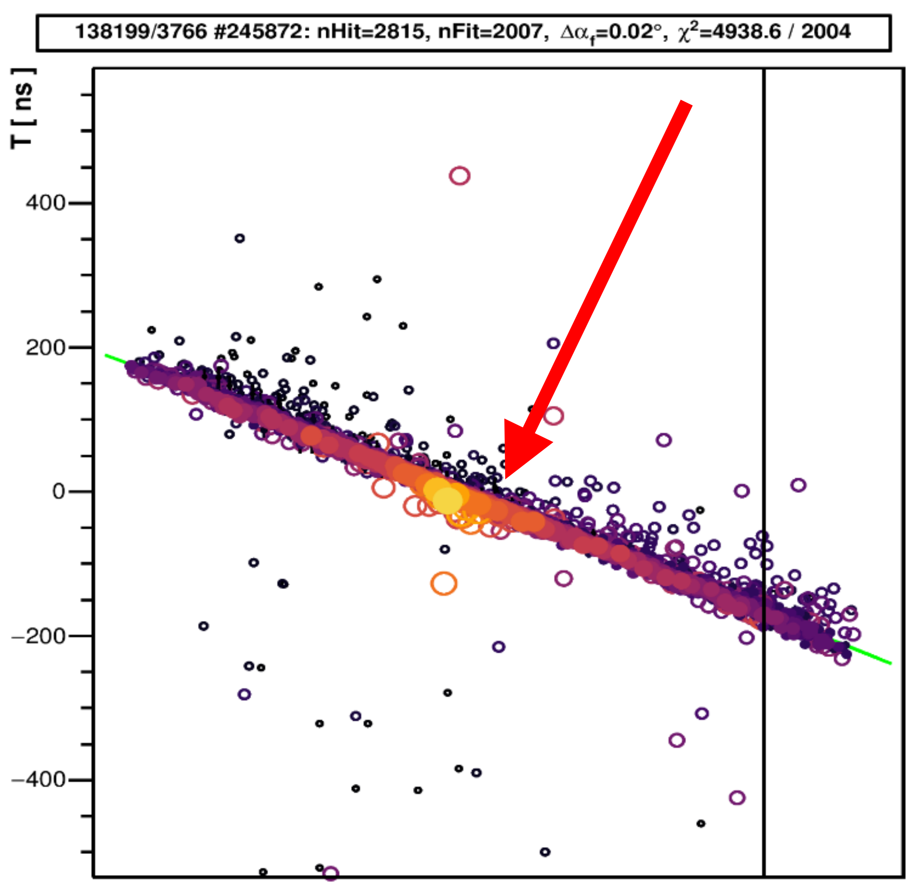




$$Q = \frac{\varepsilon_\gamma}{\sqrt{\varepsilon_p}}$$

$$C = \frac{N_{\mathrm{hit}}}{\max(\xi_i)_{r>R_c}}$$



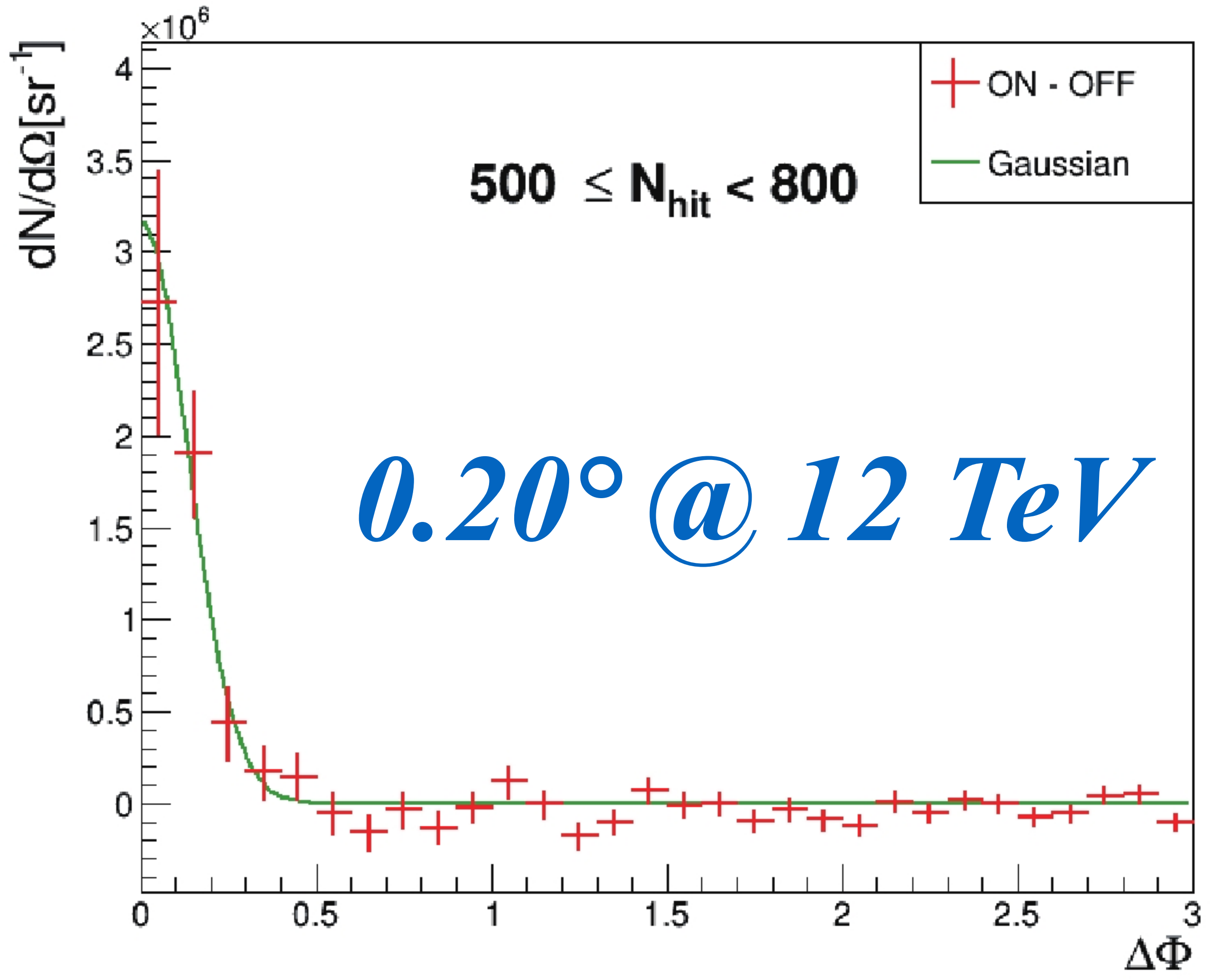


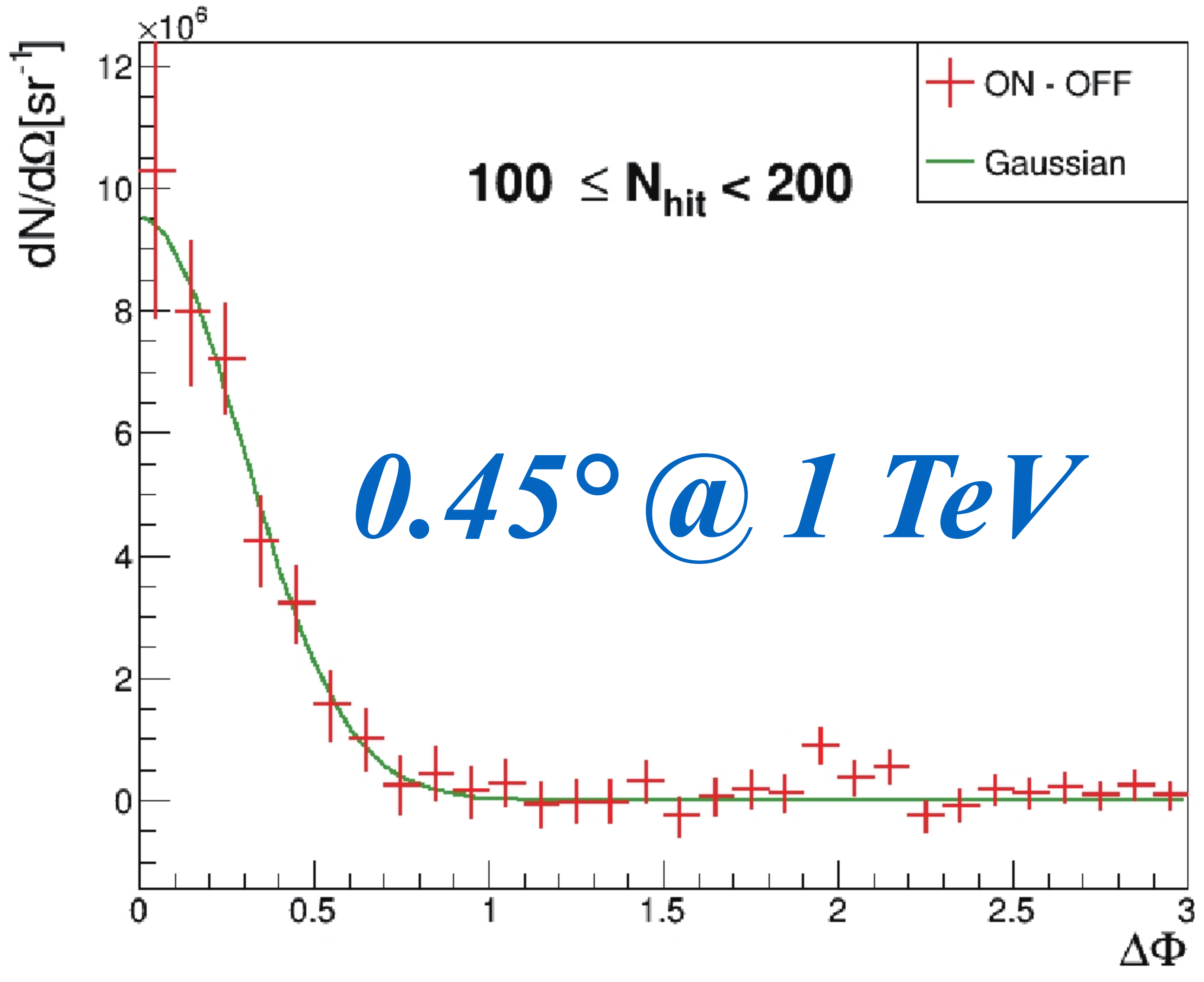
Performance of LHAASO-WCDA and observation of the Crab Nebula as a standard candle

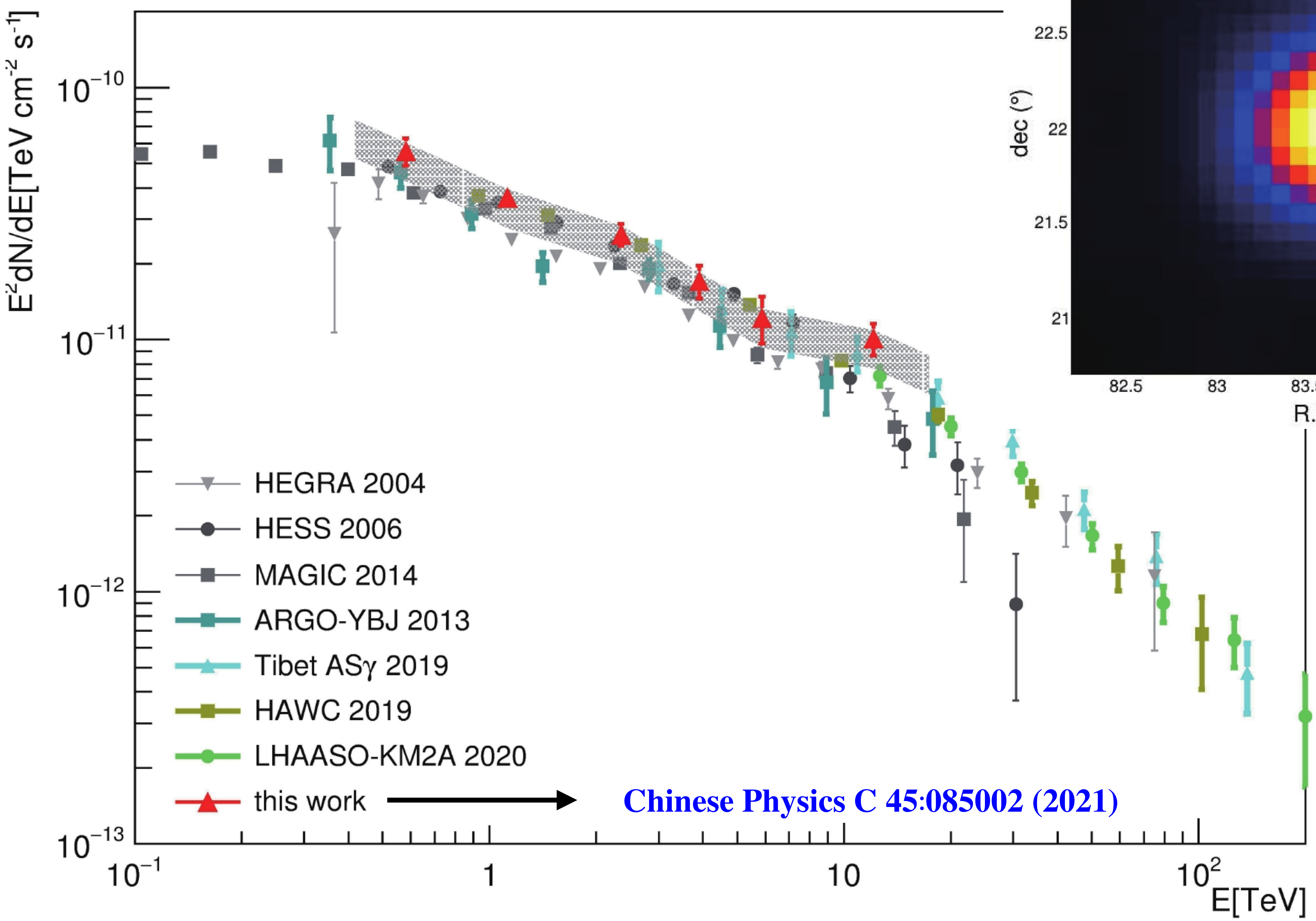
Chinese Physics C 45:085002 (2021)

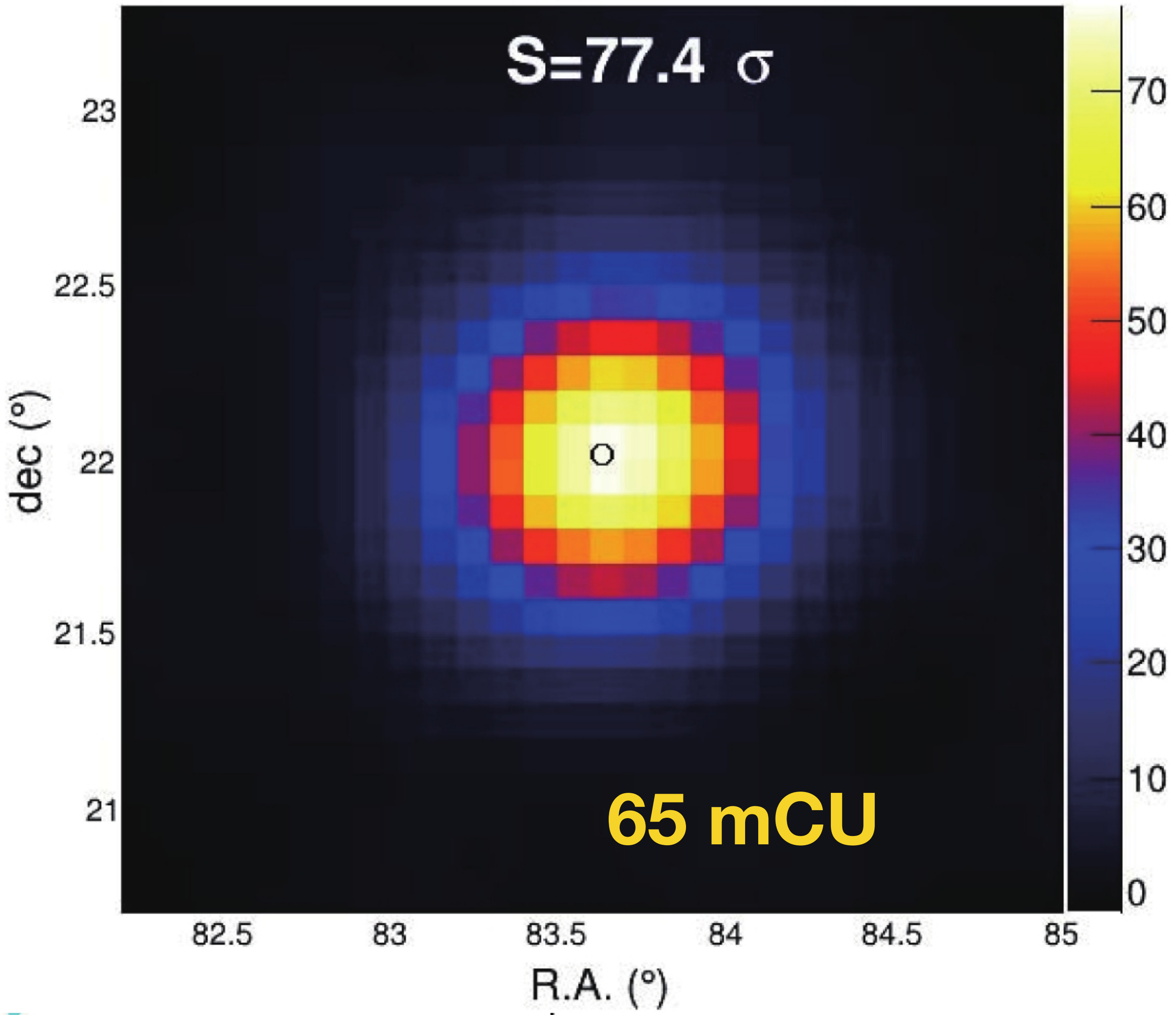
WCDA performance on Crab

Angular resolution

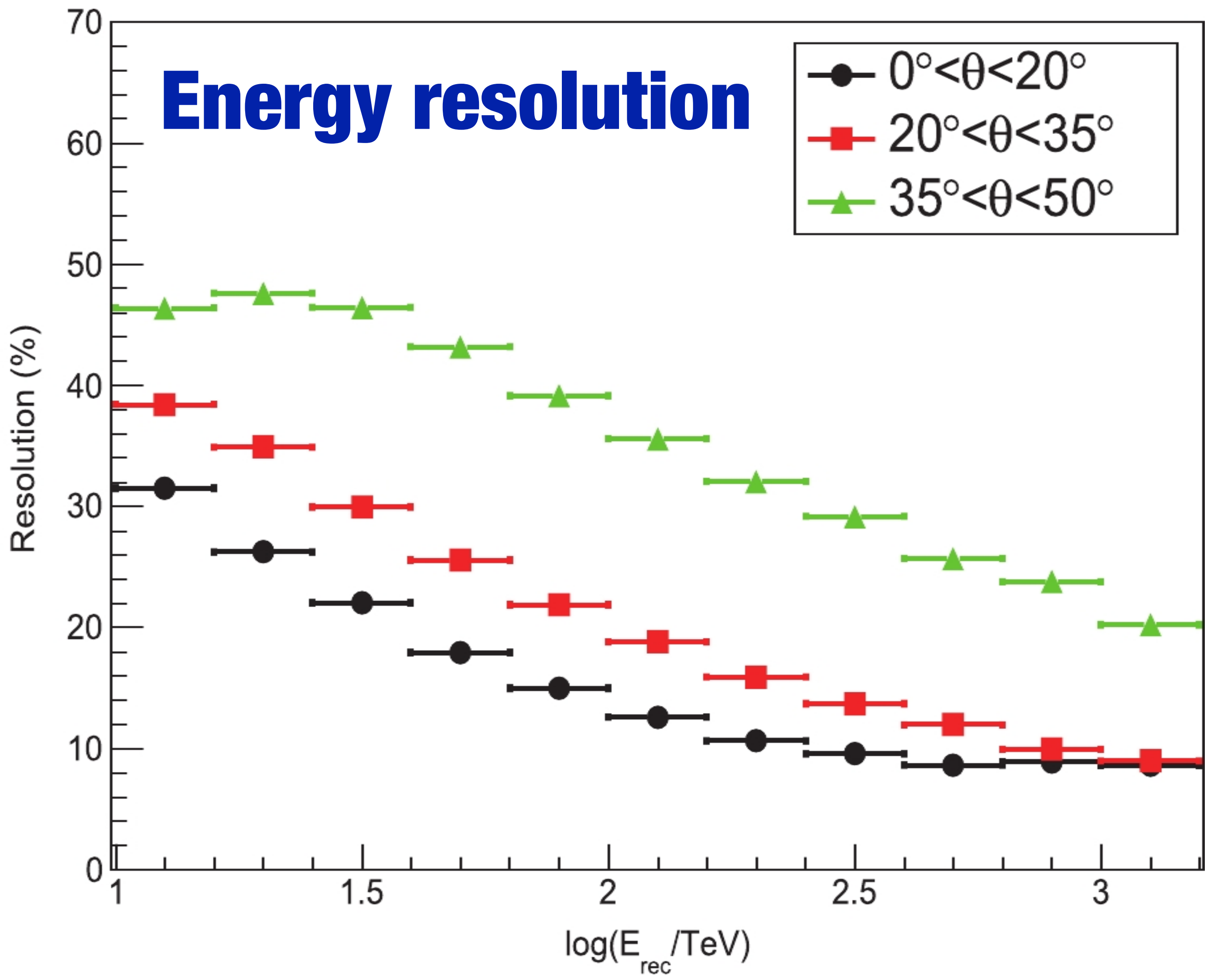


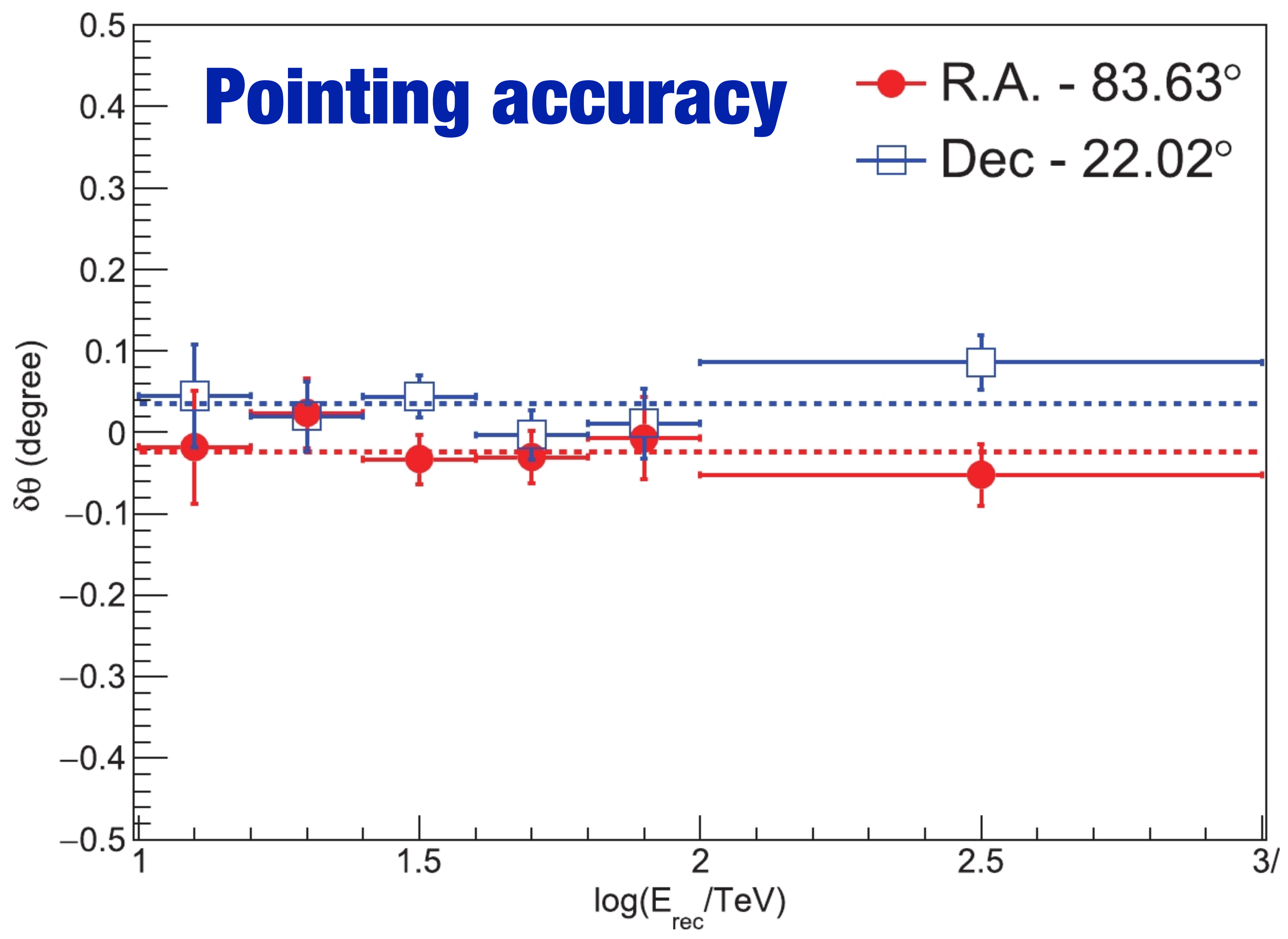


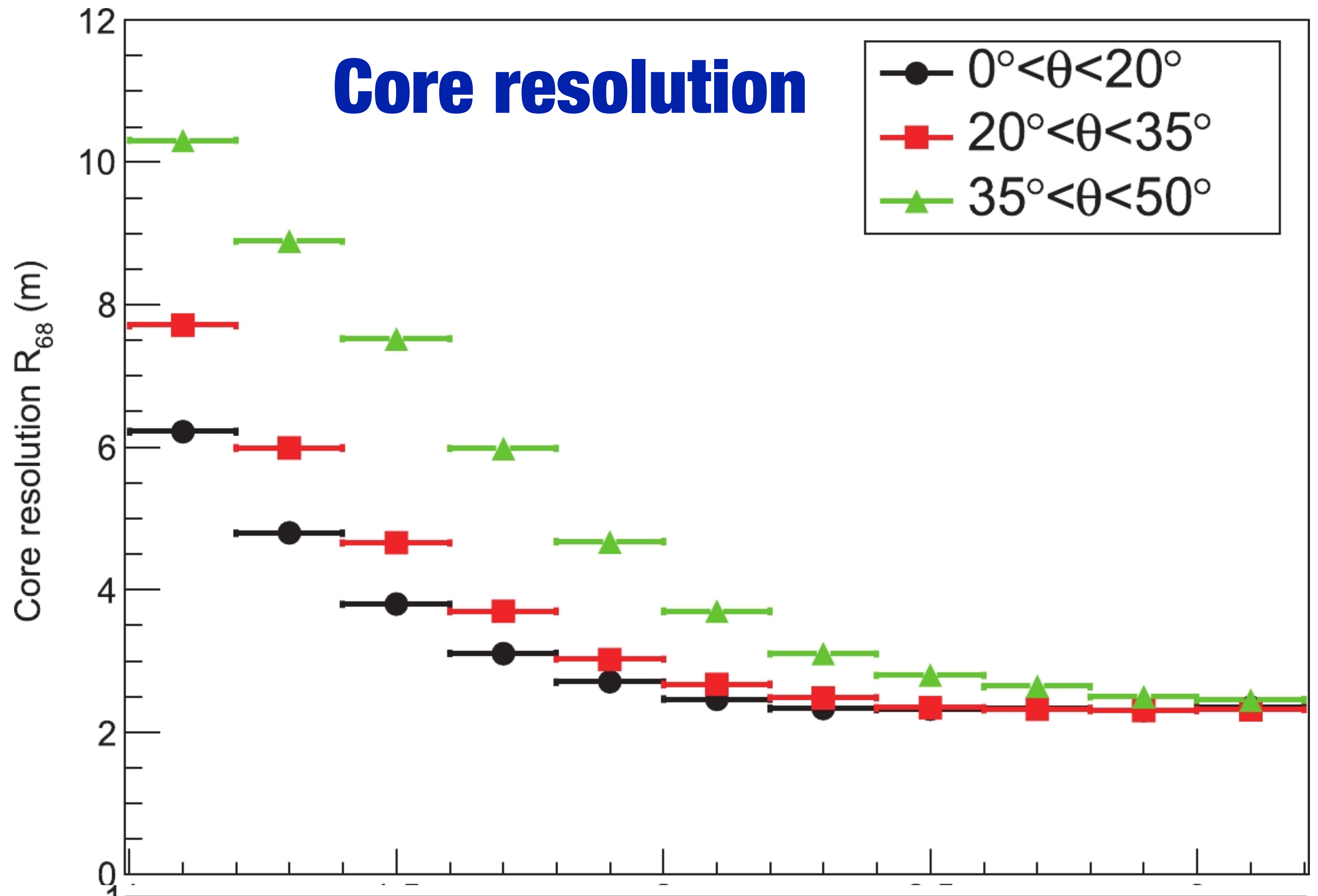


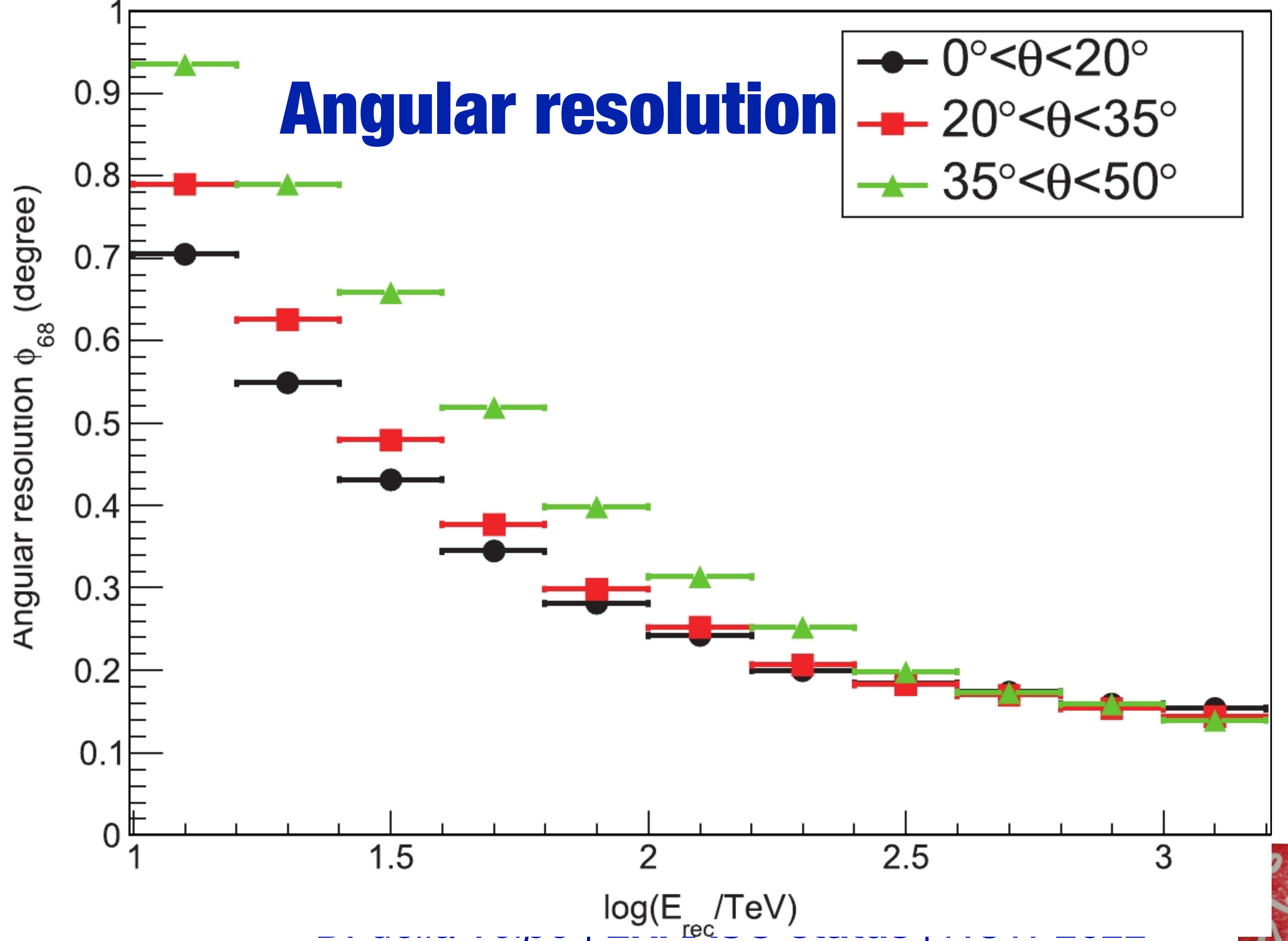


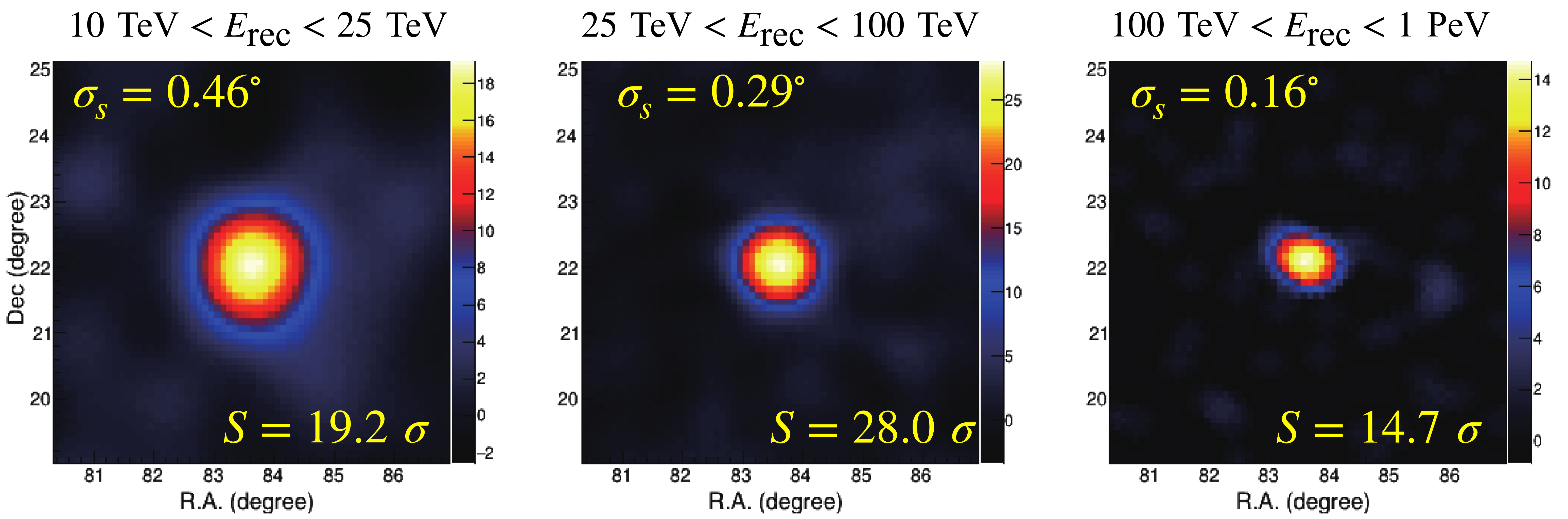
KM2A Performance



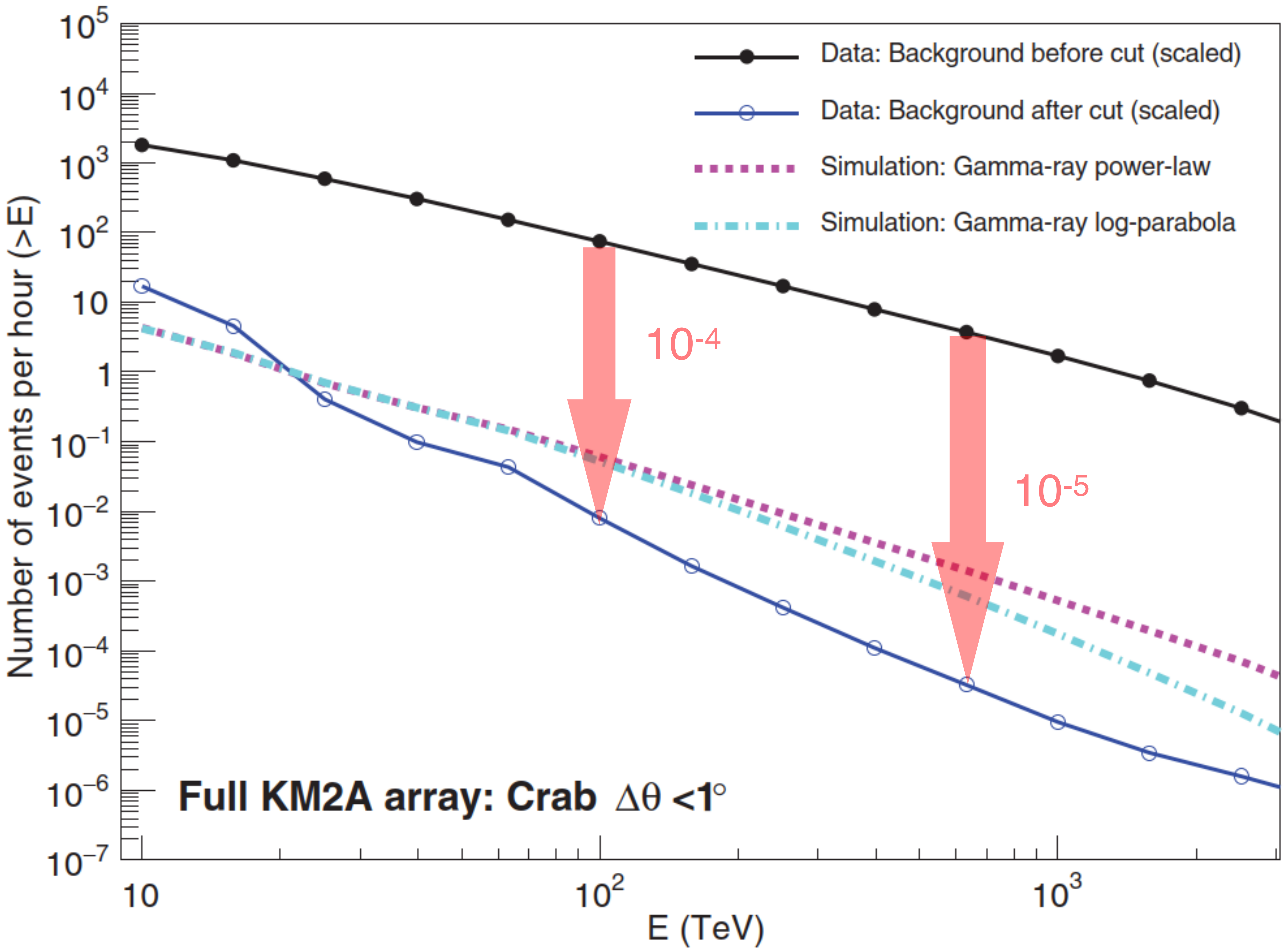


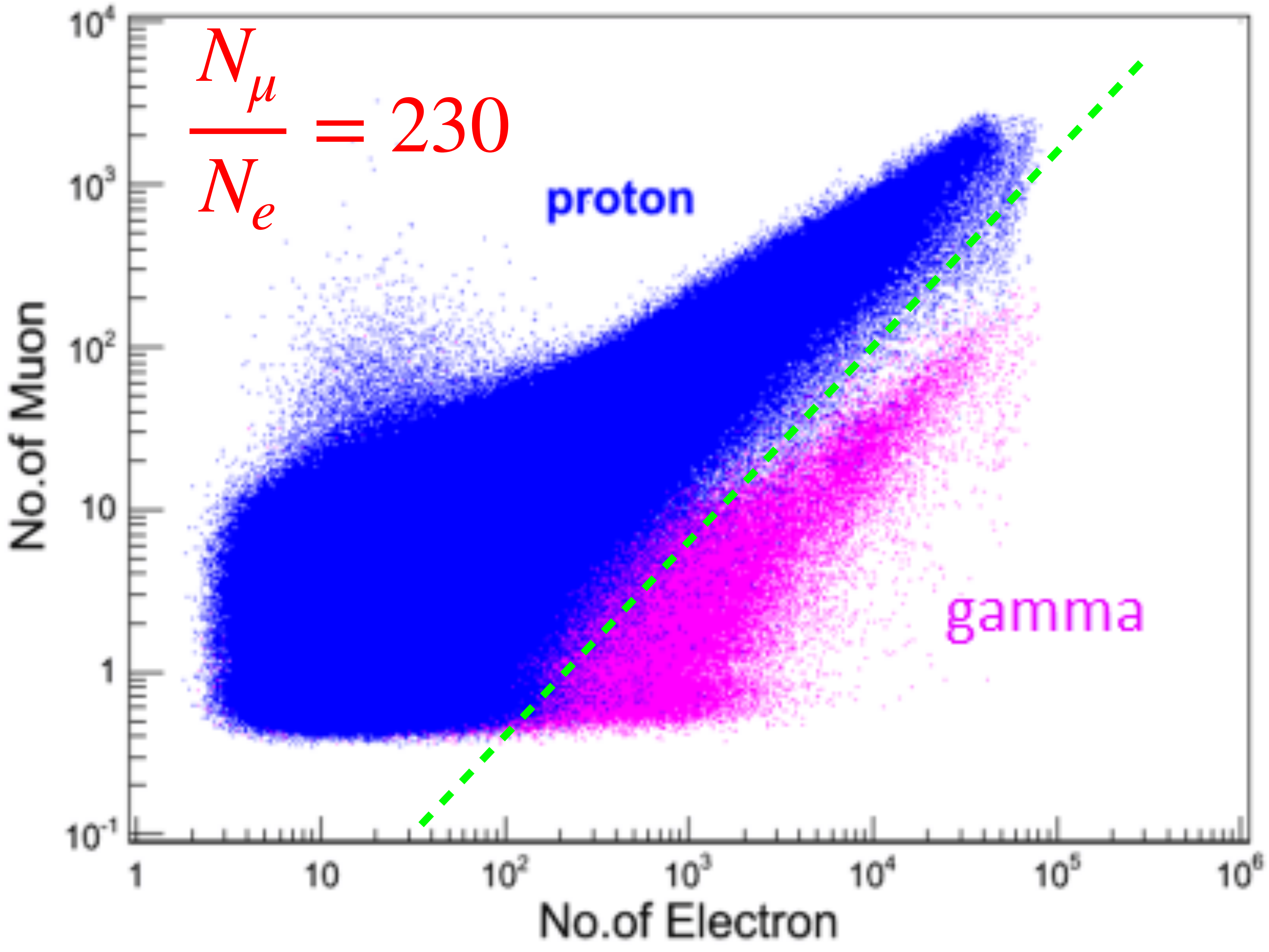




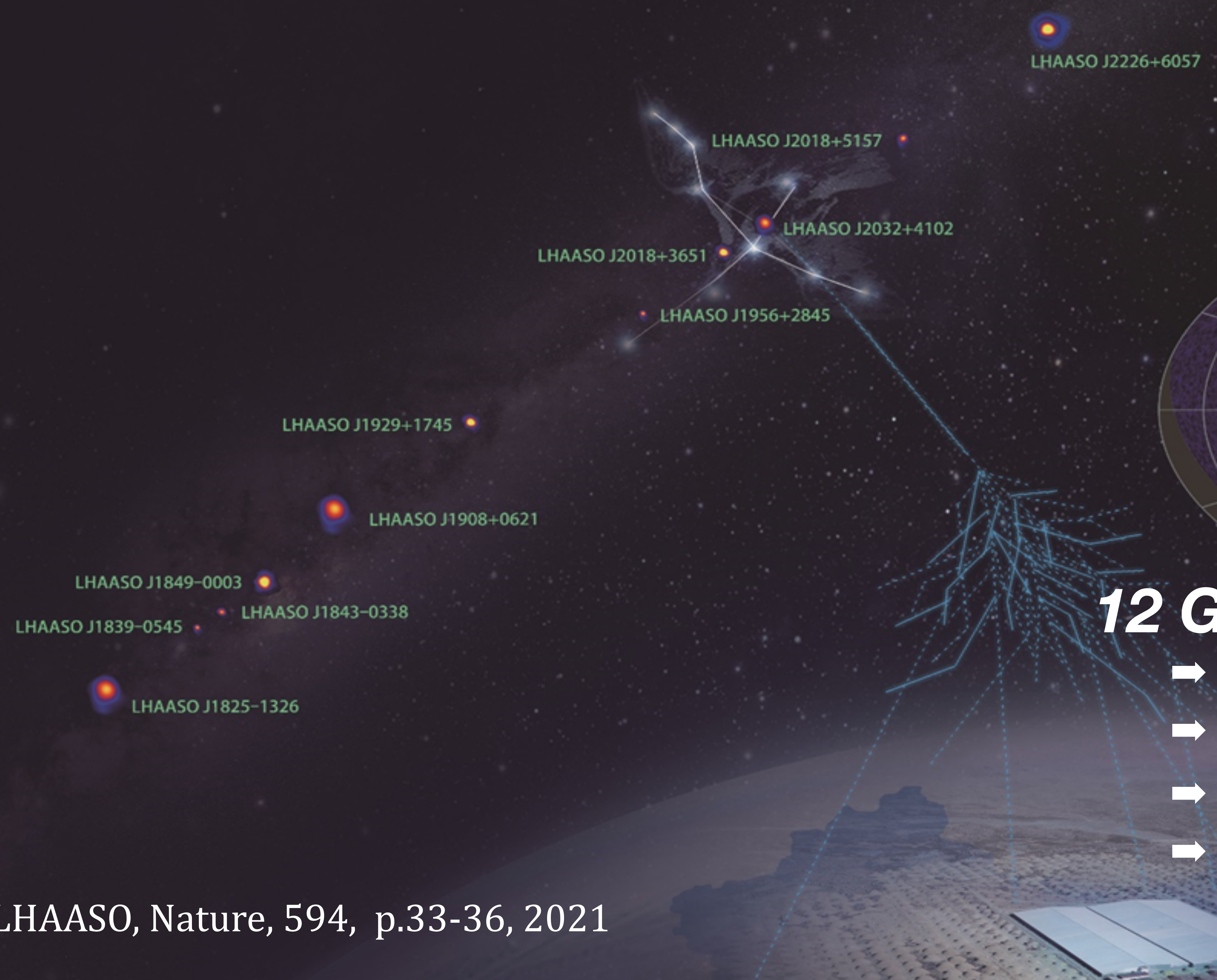


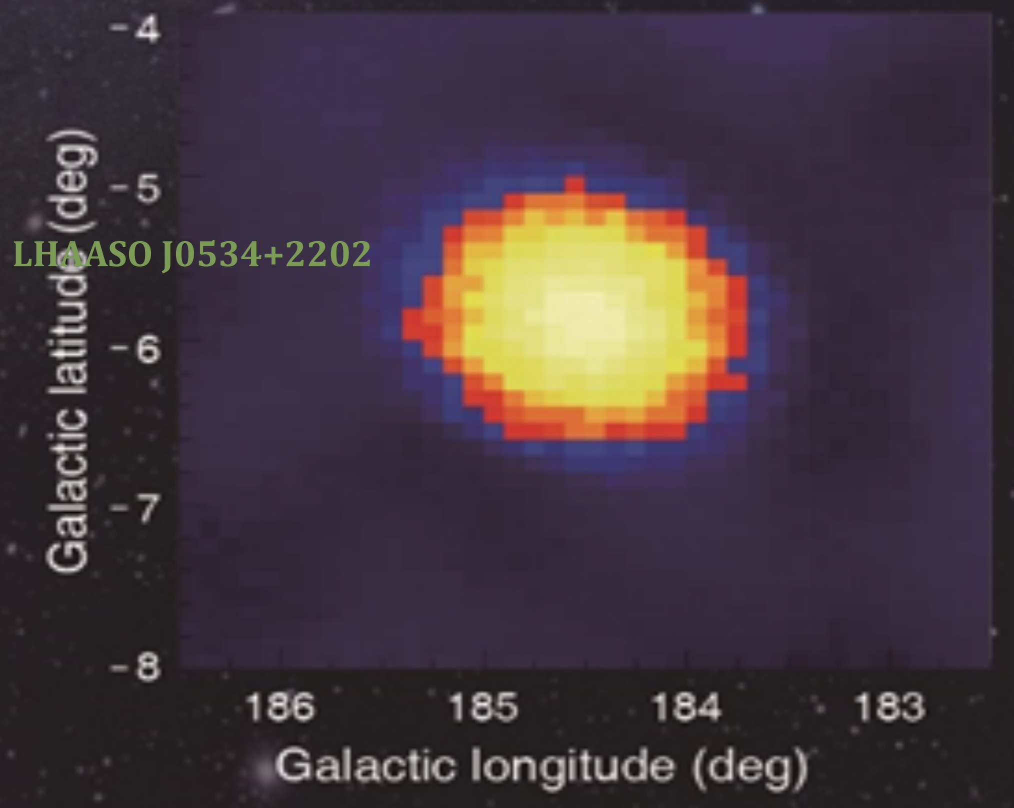
Excellent CR background rejection

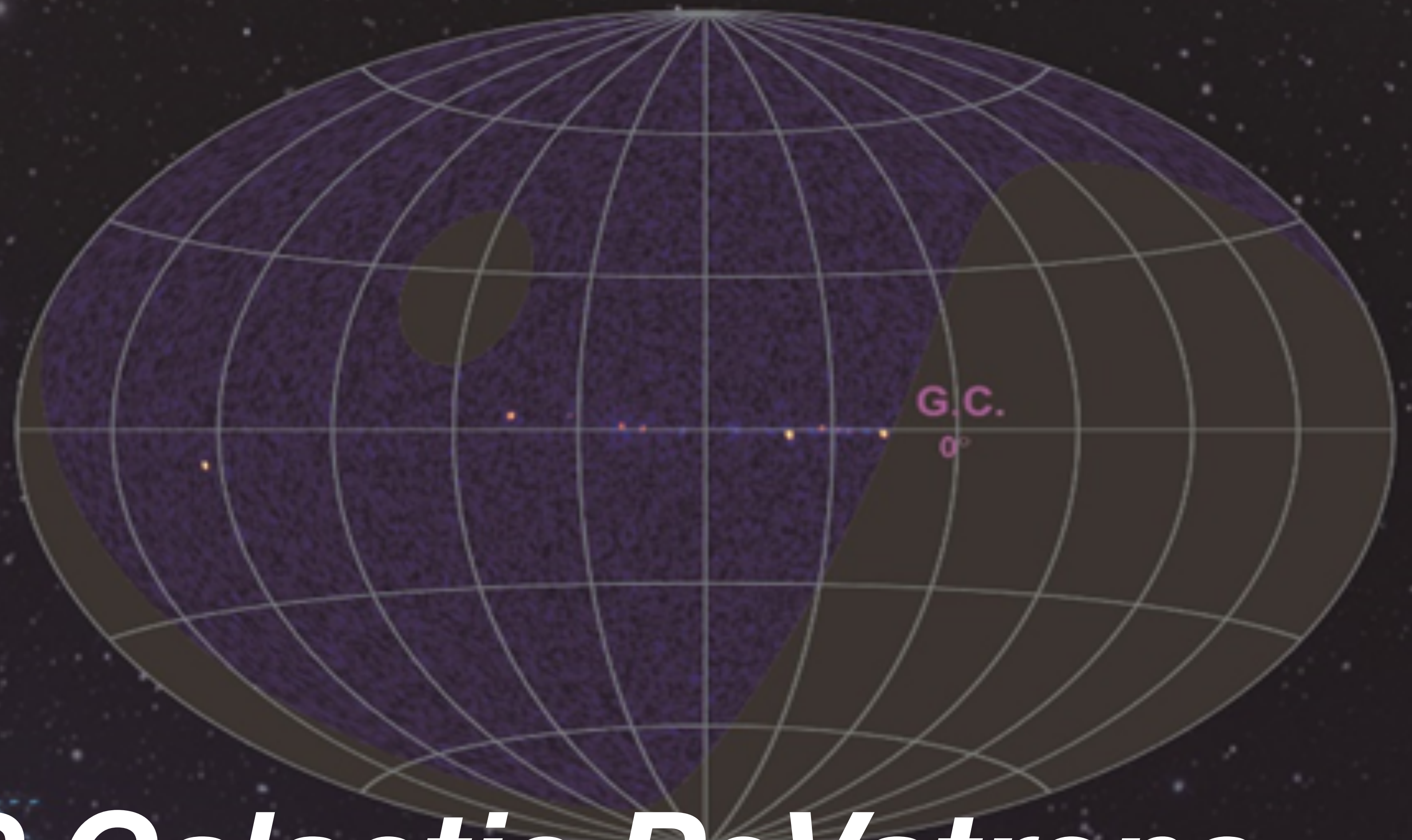




KM2A Survey





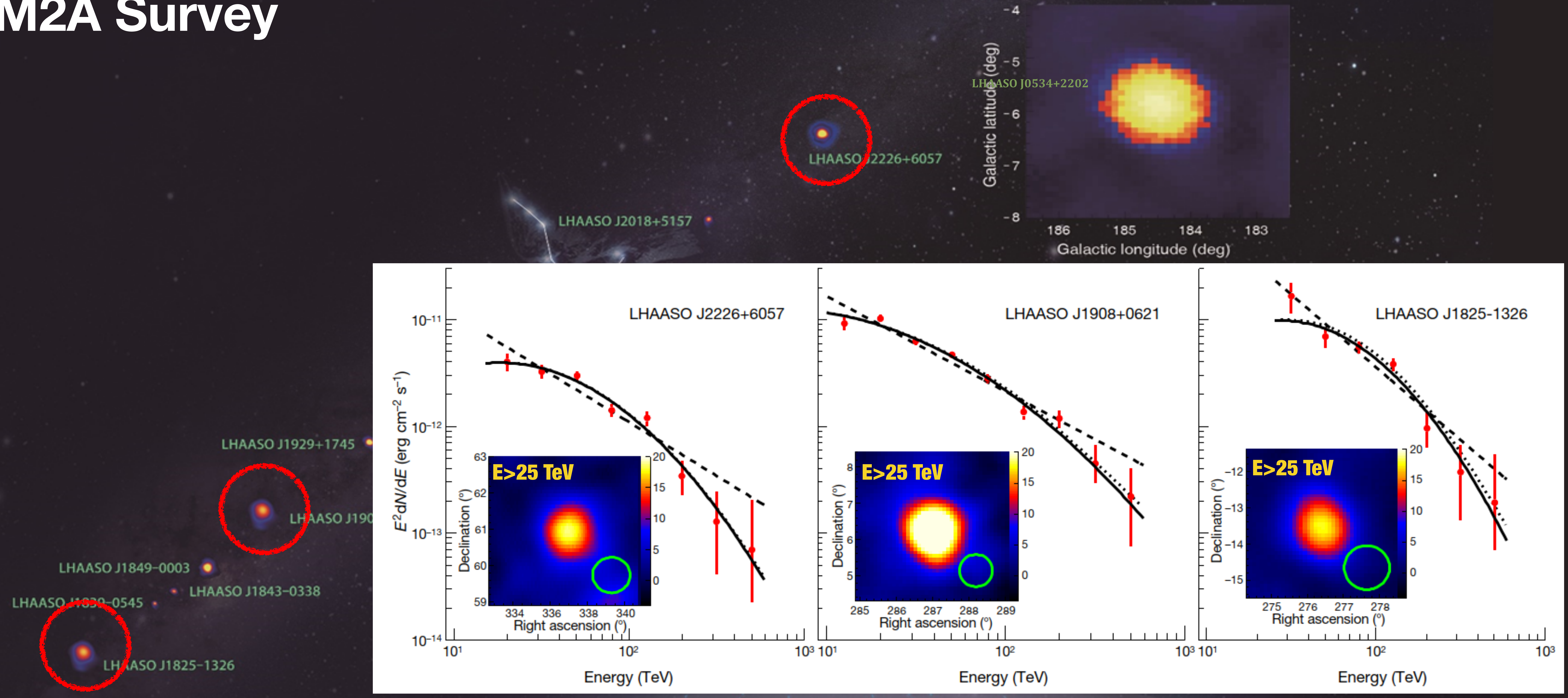


12 Galactic PeVatrons

- ➡ High quality Significantce >7σ
- ➡ BGK-free： CR rejection rate <10^{-4}
- ➡ High Statistics： 530 UHE photons
- ➡ Multiple Type of Sources

LHAASO, Nature, 594, p.33-36, 2021

KM2A Survey

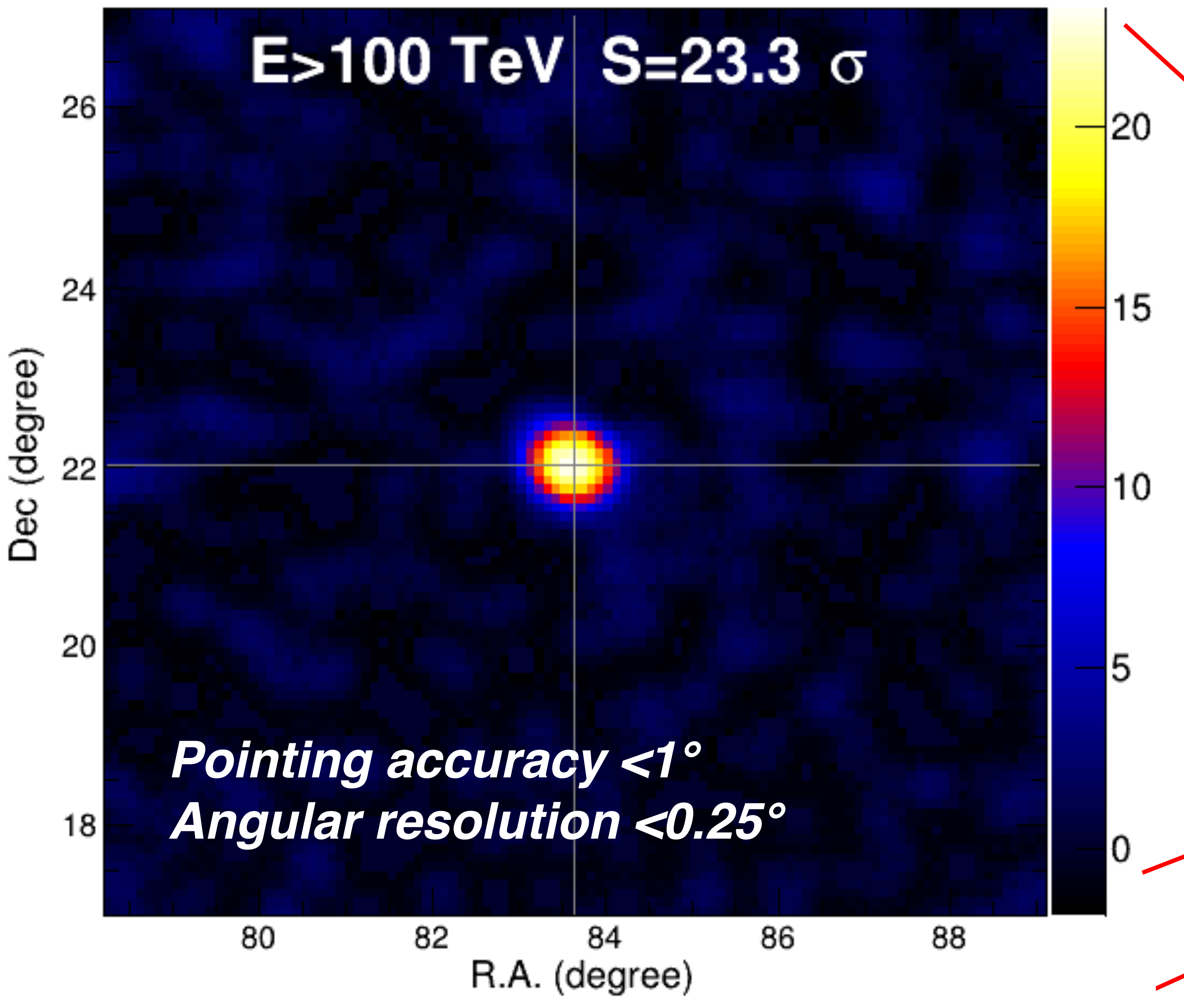


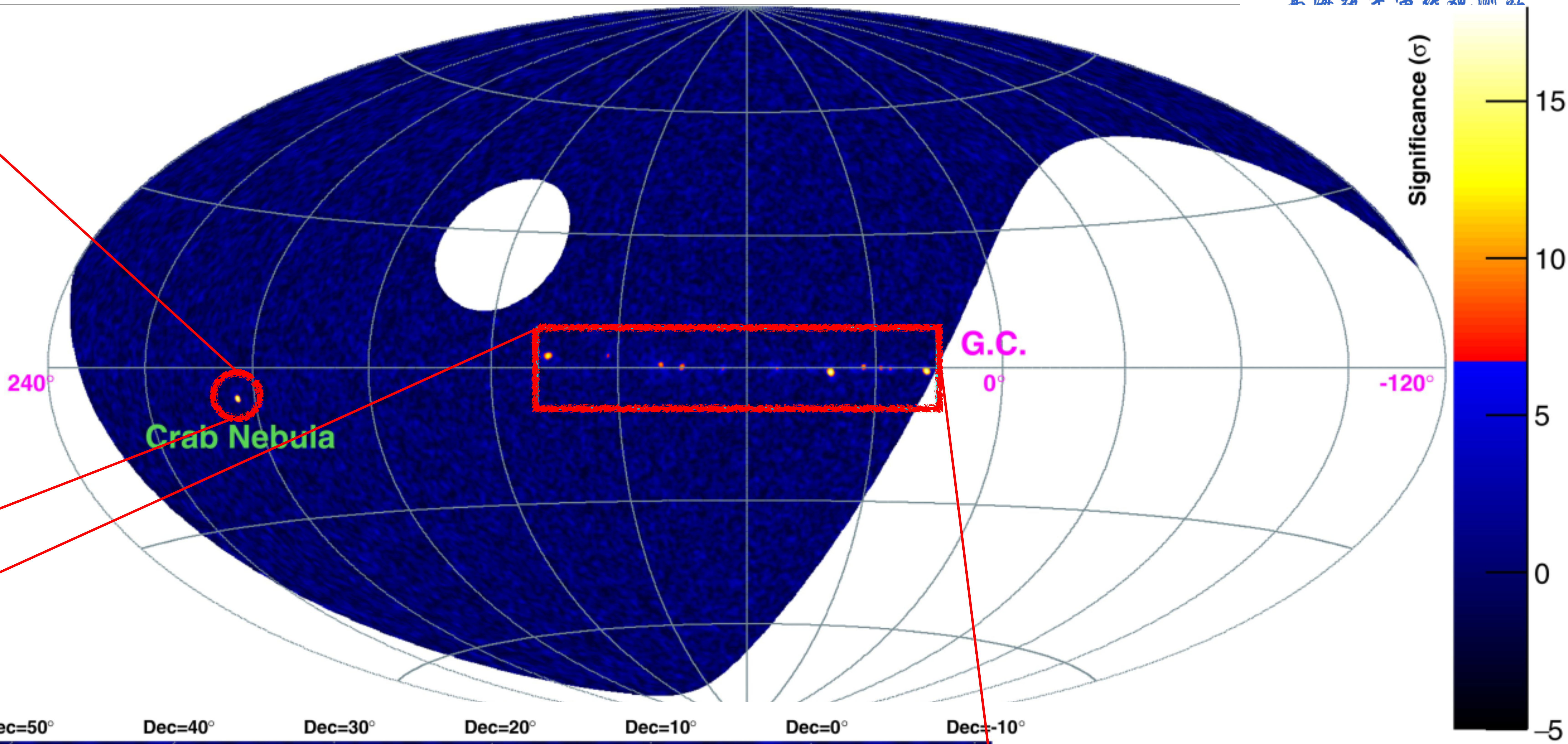
None of the three brightest PeVatrons (>1 CU@100 TeV) show an evident of cut-off in SED

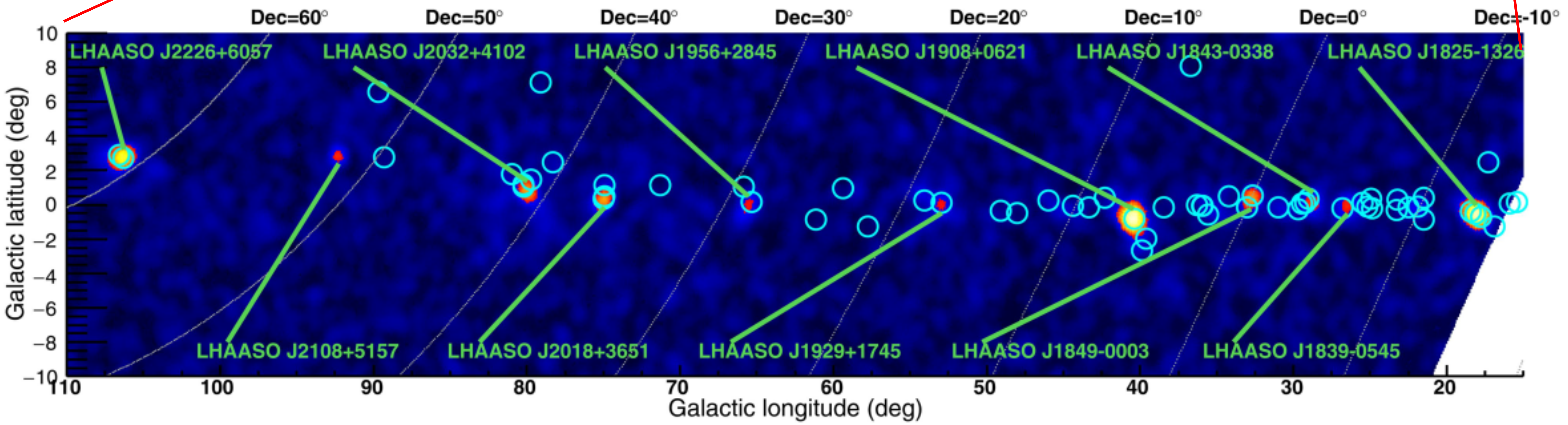
- Updates using newer data show continuous extension to higher energies

LHAASO, Nature, 594, p.33-36, 2021

Sky Map for UHE γ–ray (0.1-1 PeV)







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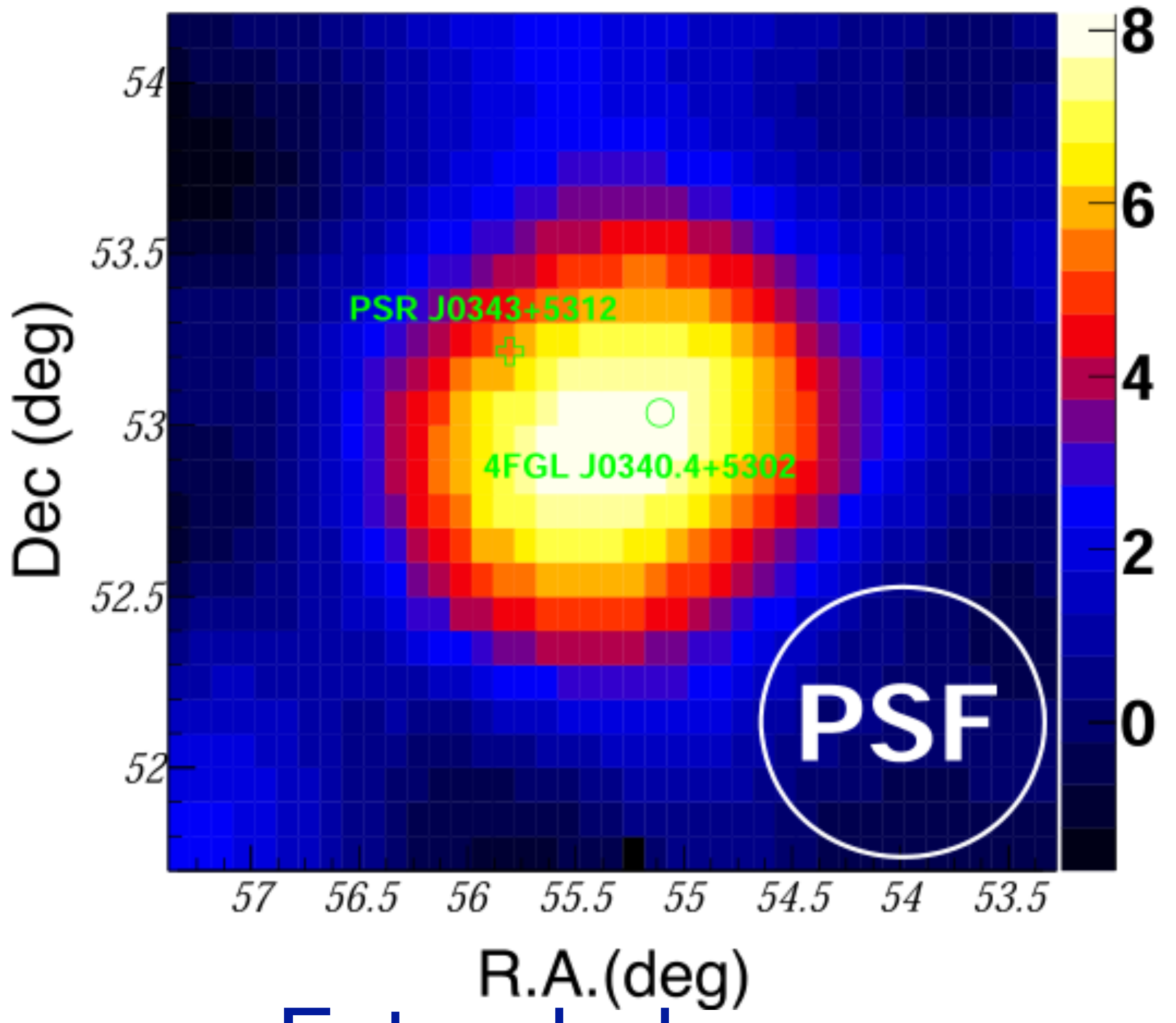
New γ-ray Sources

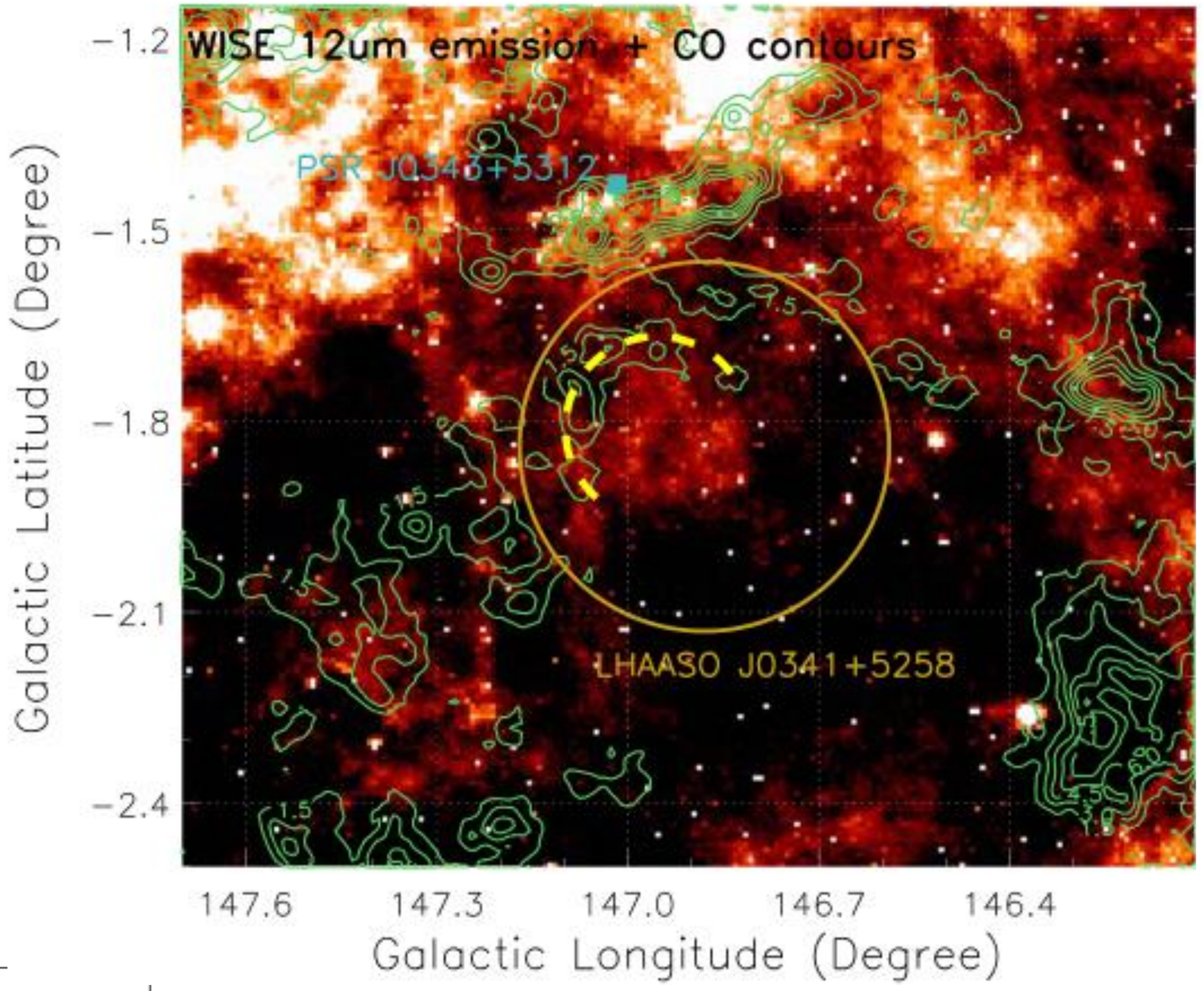
Discovery of LHAASO J0341+5258

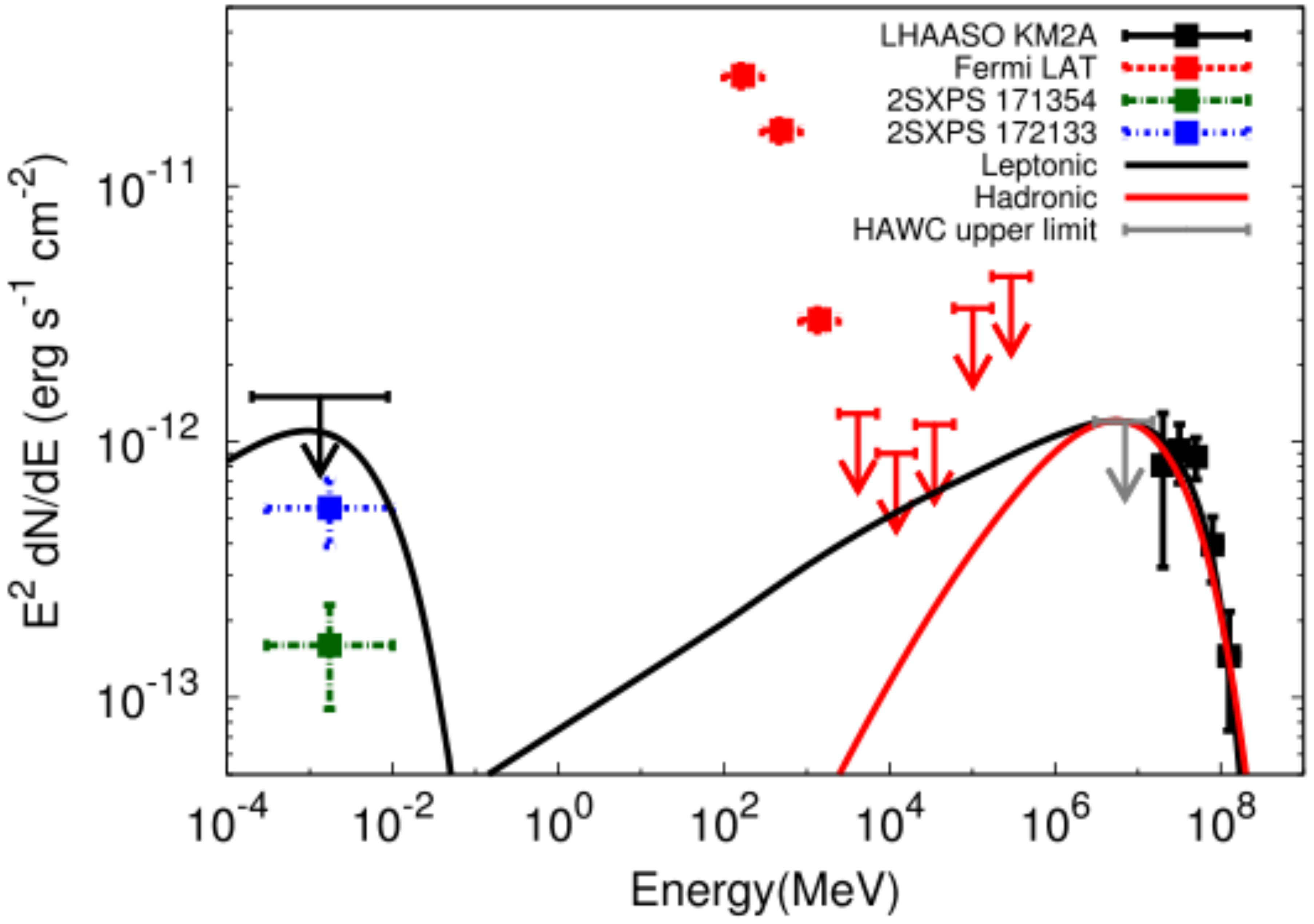
LHAASO coll. **ApJL 917:L4** (2021)

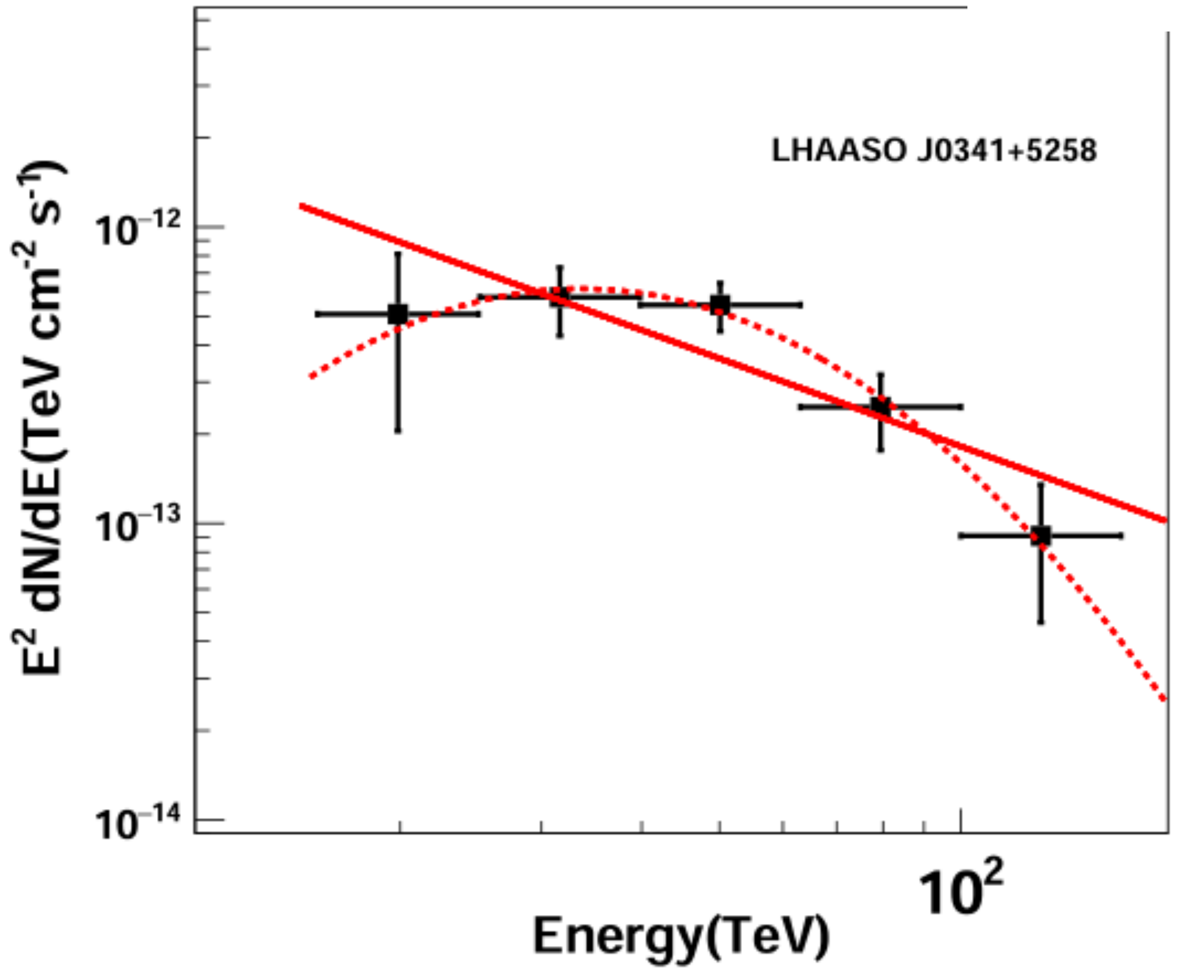


Extended source

$0.29^\circ \pm 0.06^\circ_{stat} \pm 0.02^\circ_{sys}$







No clear counterpart at other wave length.

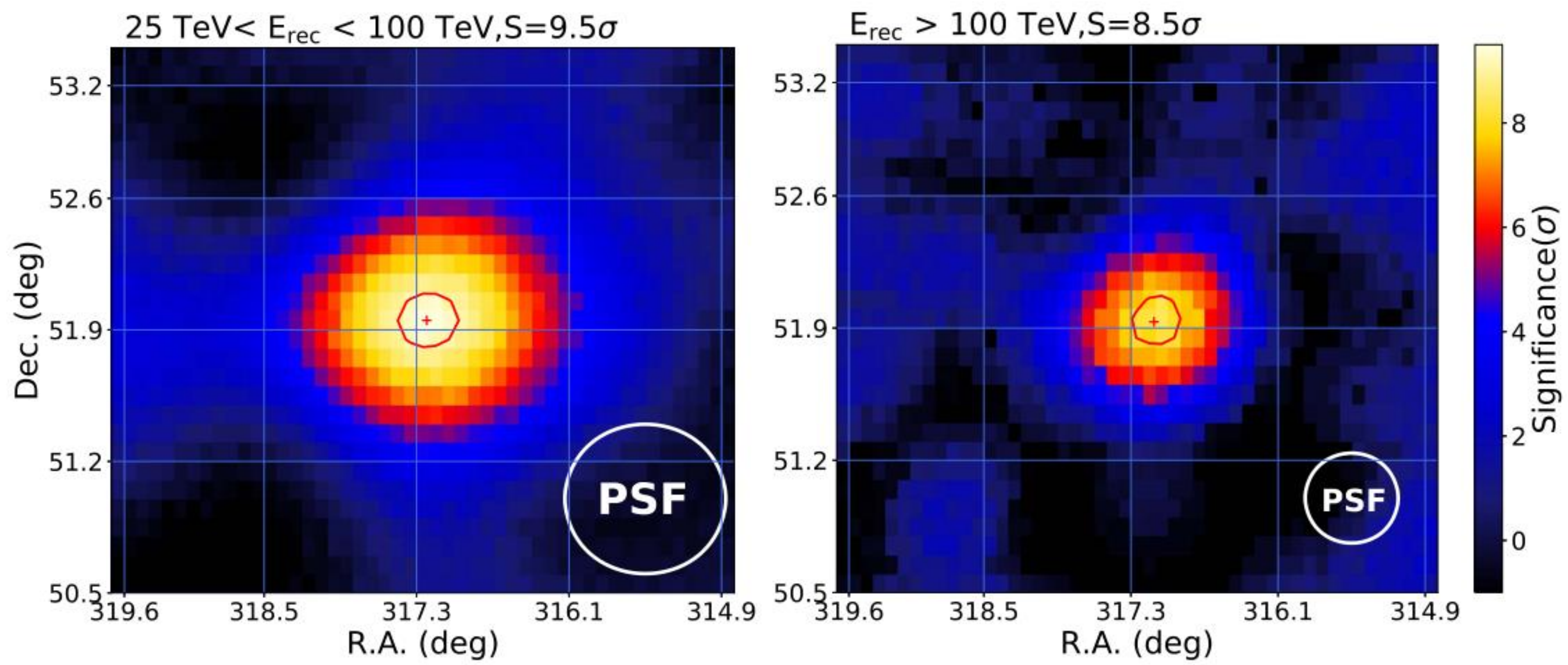
Lack of an energetic pulsar or a young SNRr in the vicinity

$\Rightarrow$ Challenge, both the leptonic and hadronic scenarios.

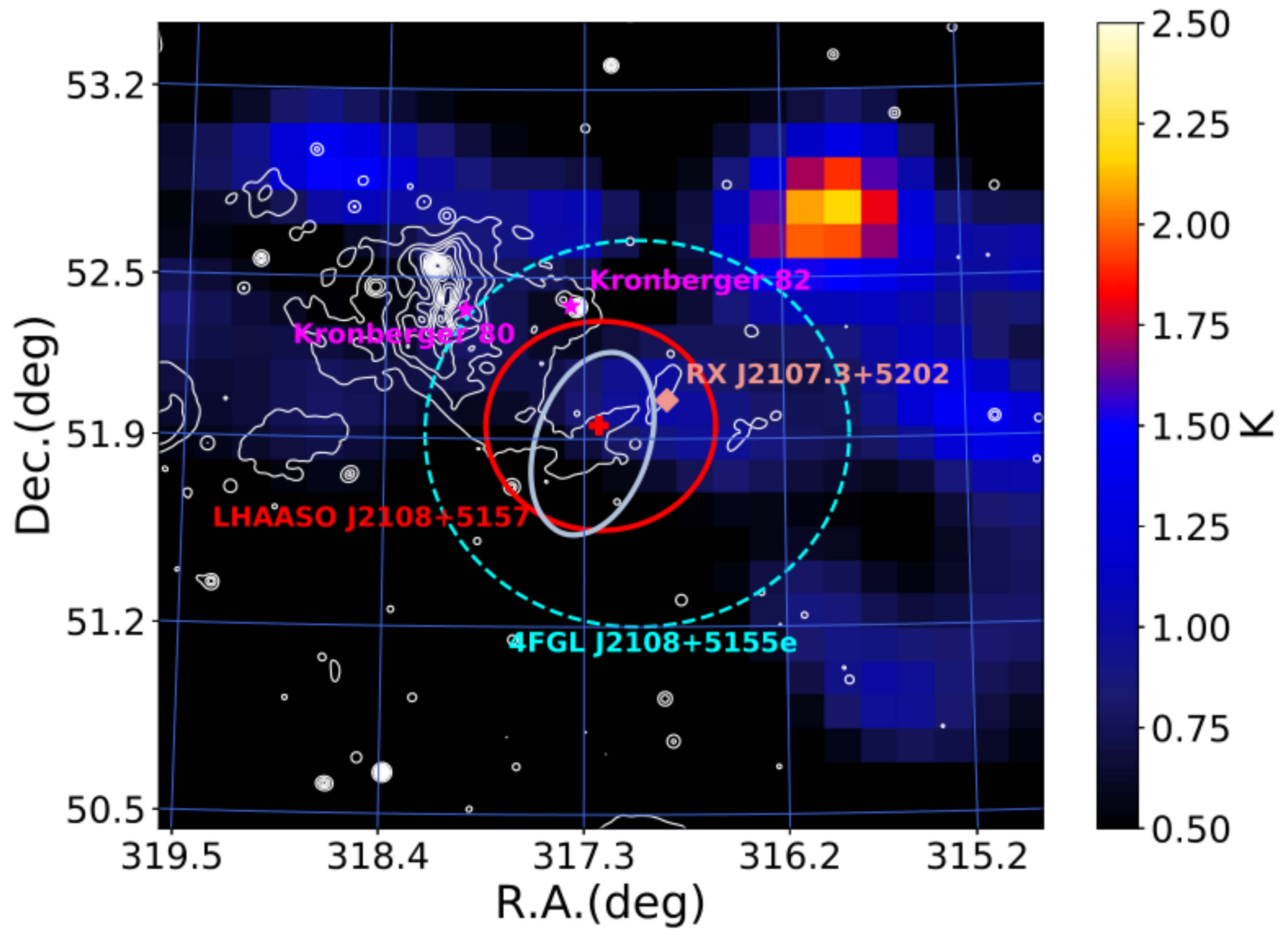
Discovery of LHAASO J2108+5157

New VHE and UHE source

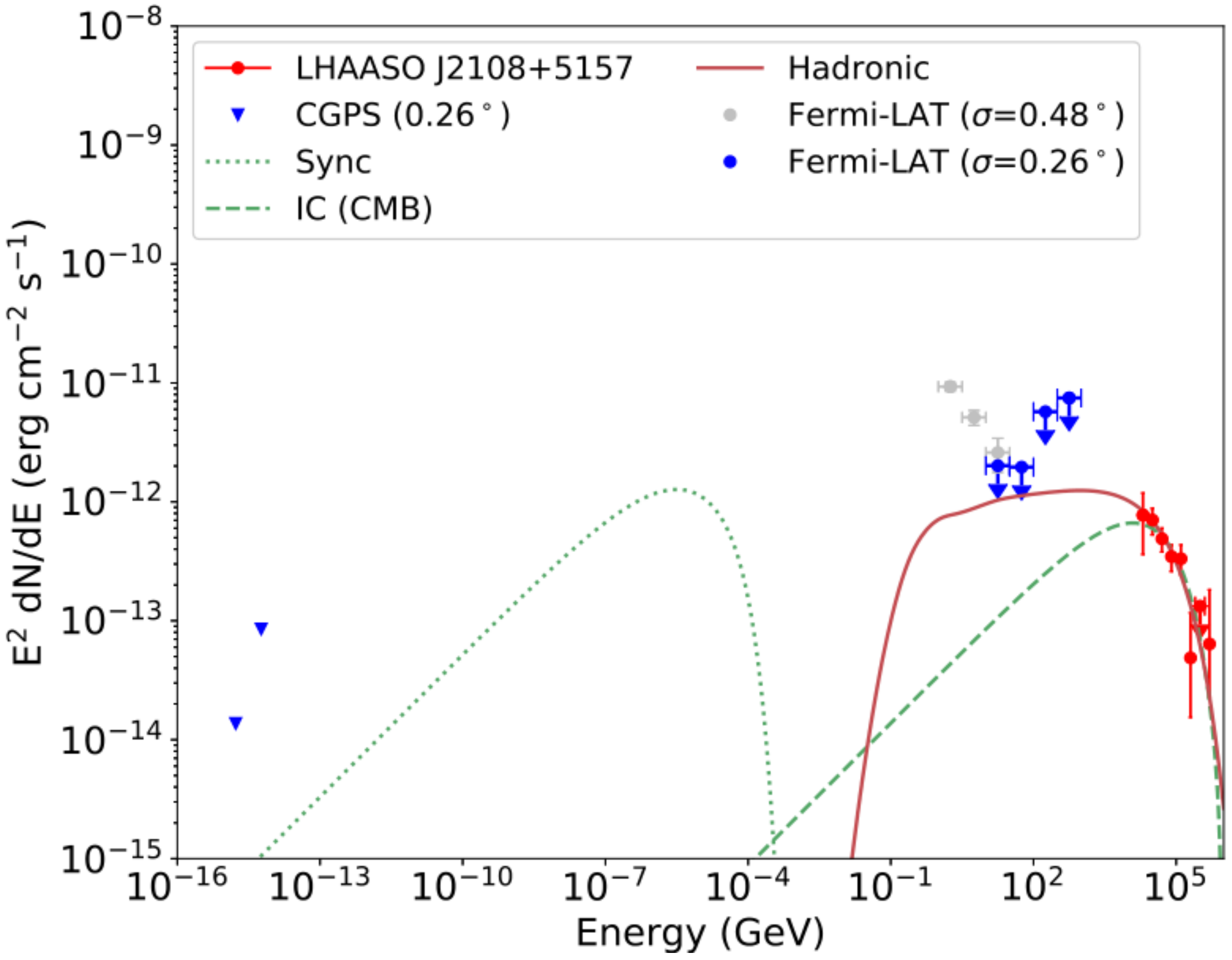
$E_{\max} = 434 \pm 49$ TeV



Point-like source with extension <0.26°.



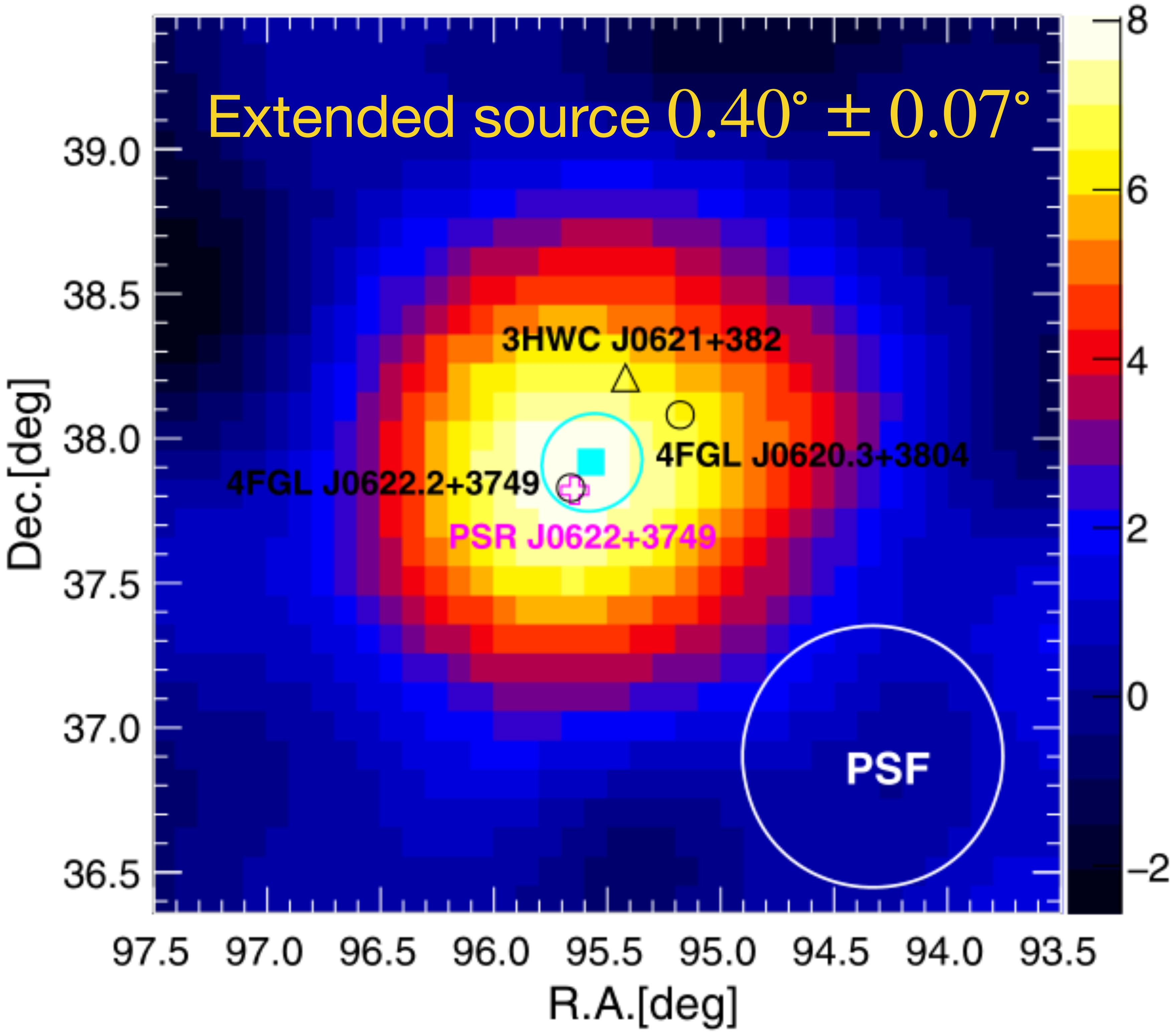
No clear counterpart at other wavelengths.



Compatible with both electron and proton acceleration but Giant MC nearby suggest hadronic origin

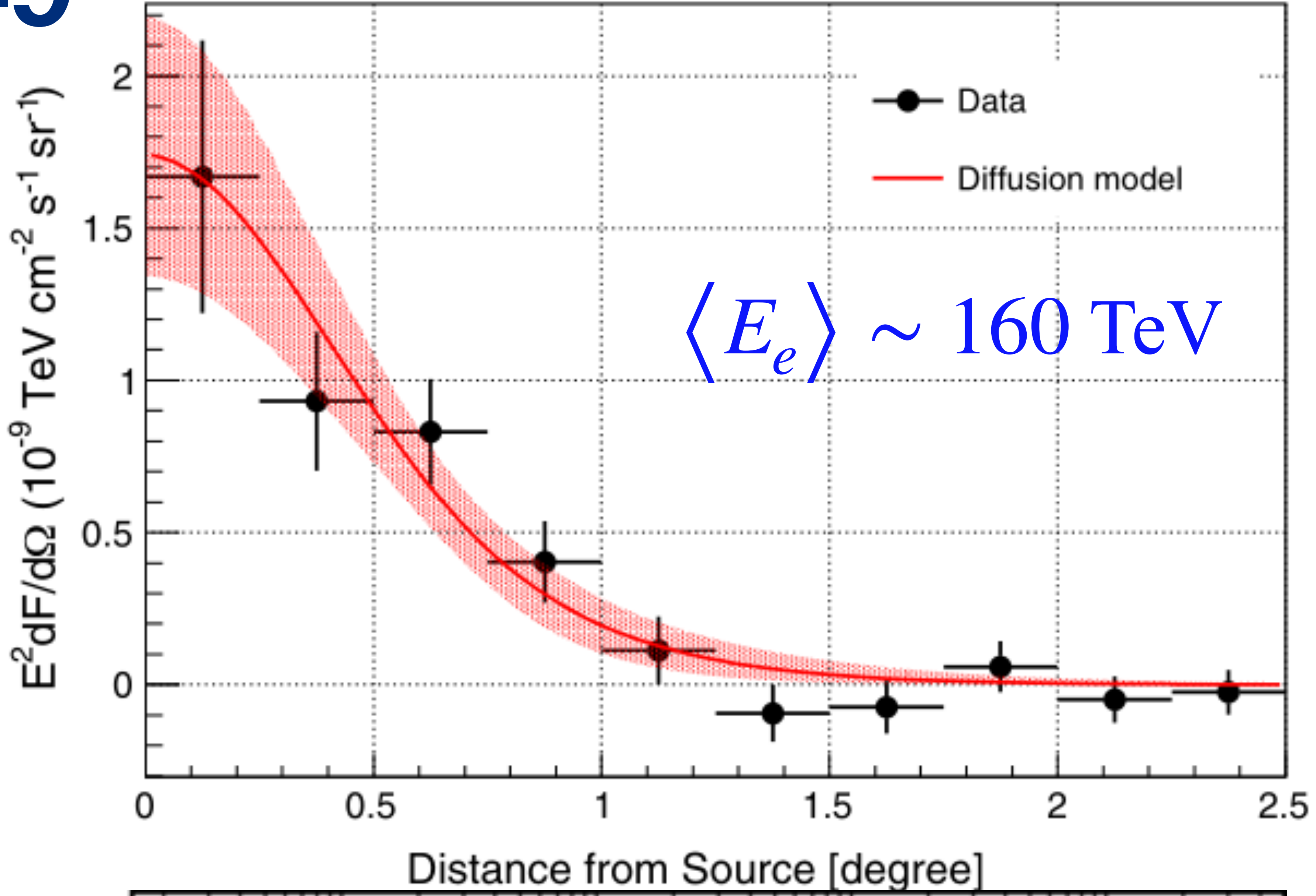
LHAASO coll. **ApJL 919:L21** (2021)

Discovery of pulsar halo PSR J0622+3749

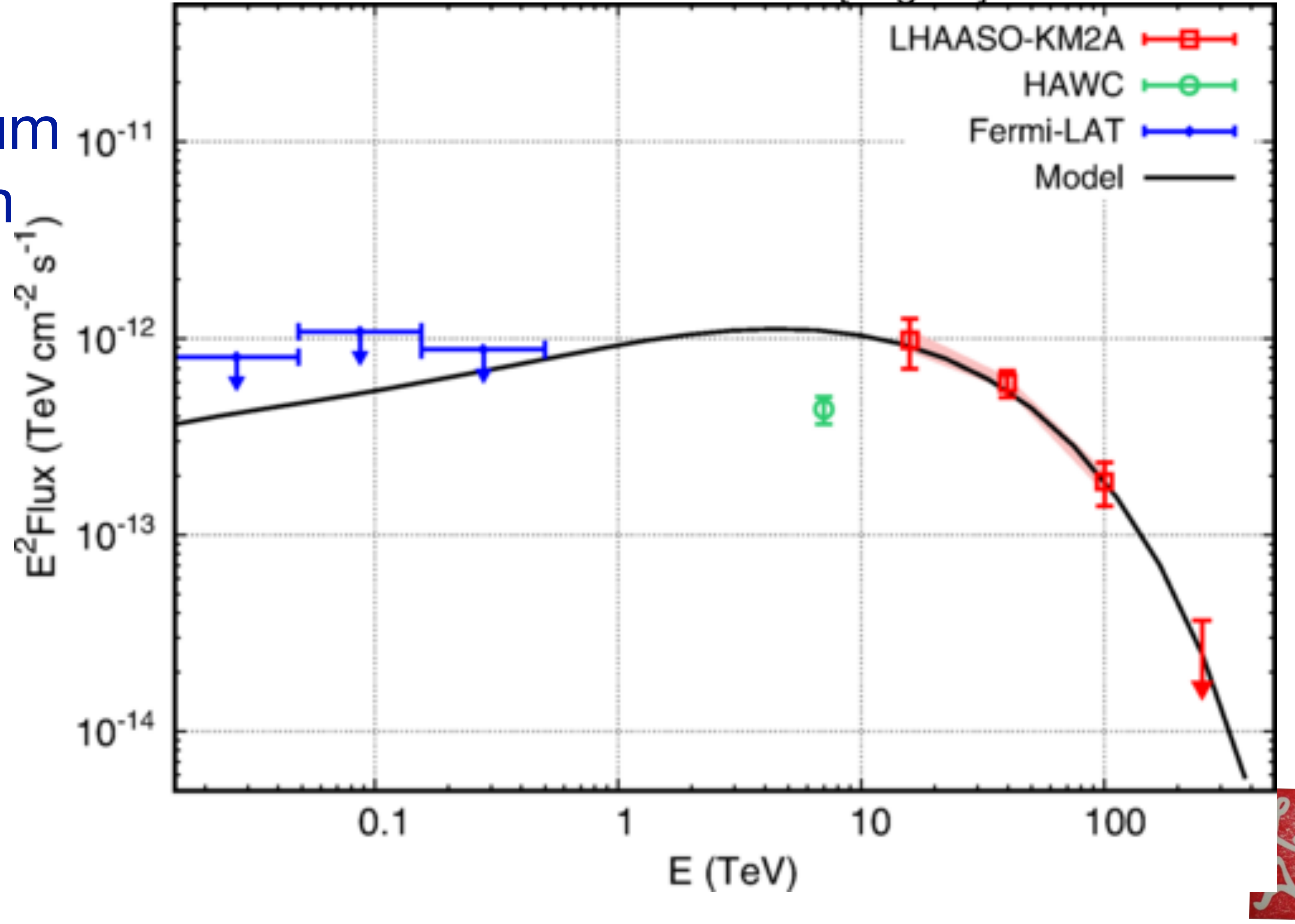


Slow diffusion of electron

$$D \approx 8.9^{+4.5}_{-3.9} \cdot \left(\frac{d}{1.6\ \mathrm{kpc}}\right)^2 \cdot 10^{27}\ \mathrm{cm^2\ s^{-1}}$$



Consistent with scenario of particles in the turbulent medium around pulsars as inferred from the of Geminga and Monogem



Name	P [s]	$\dot{P}$ [10^{14}s · s−1]	L_{sd} [10^{34}s · erg−1]	τ [kyr]	d [kpc]
J0622+3749	*0.333*	*2.542*	*2.7*	*207.8*	*1.60*
Geminga	*0.237*	*1.098*	*3.3*	*342.0*	*0.25*
Monogem	*0.385*	*5.499*	*3.8*	*110.0*	*0.29*

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LHAASO Coll. **PhysRevLett. 126,24** (2021): 241103

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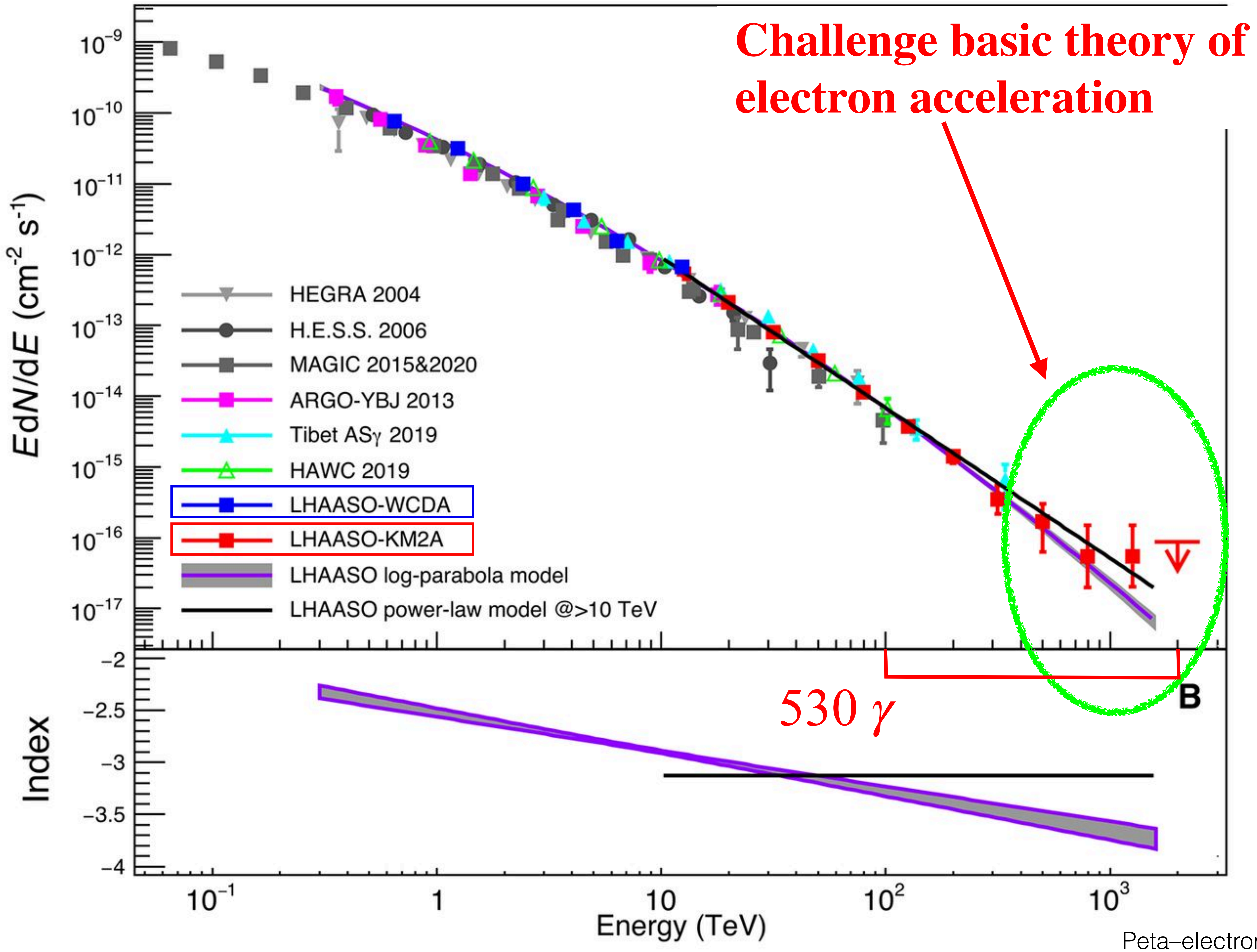
Crab Nebula in the PeV

Crab SED



LHAASO SED Measurement:

- Covering 3.5 decades of energy
- Agreeing with other experiments below 100 TeV
- Self cross-checking between WCDA & KM2A

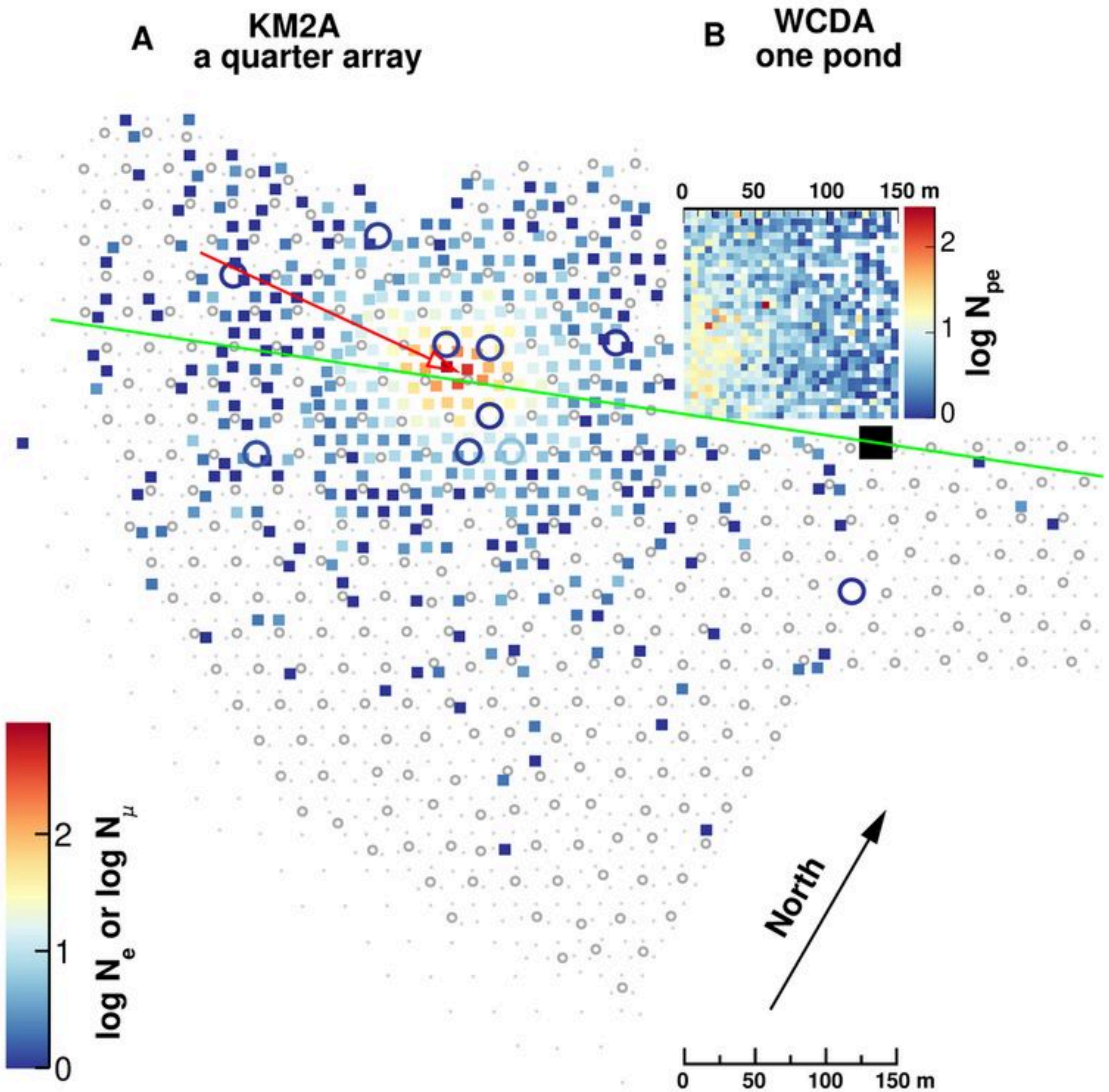
A Pevatron:

- Unique UHE SED
- A PeVatron without ambiguity
- Clear origin: a well-known PWN

Observation of the Crab Nebula with LHAASO-KM2A – a performance study
F. Aharonian *et al* 2021 *Chinese Phys. C* **45** 025002
DOI: 10.1088/1674-1137/abd01b

Peta–electron volt gamma-ray emission from the Crab Nebula
Science 23 Jul 2021:
Vol. 373, Issue 6553, pp. 425-430
DOI: 10.1126/science.abg5137

Highest energy photons from Crab (1.1 PeV)



Science 23 Jul 2021:
Vol. 373, Issue 6553, pp. 425-430
DOI: 10.1126/science.abg5137

$$E_e = 2.15 \cdot \left(\frac{E_\gamma}{\text{PeV}}\right)^{0.77} \text{PeV}$$

$$E_e \simeq 2.3 \text{ PeV}$$

Leptonic

Nie, L *et al* **ApJ** 924:42, (2022)

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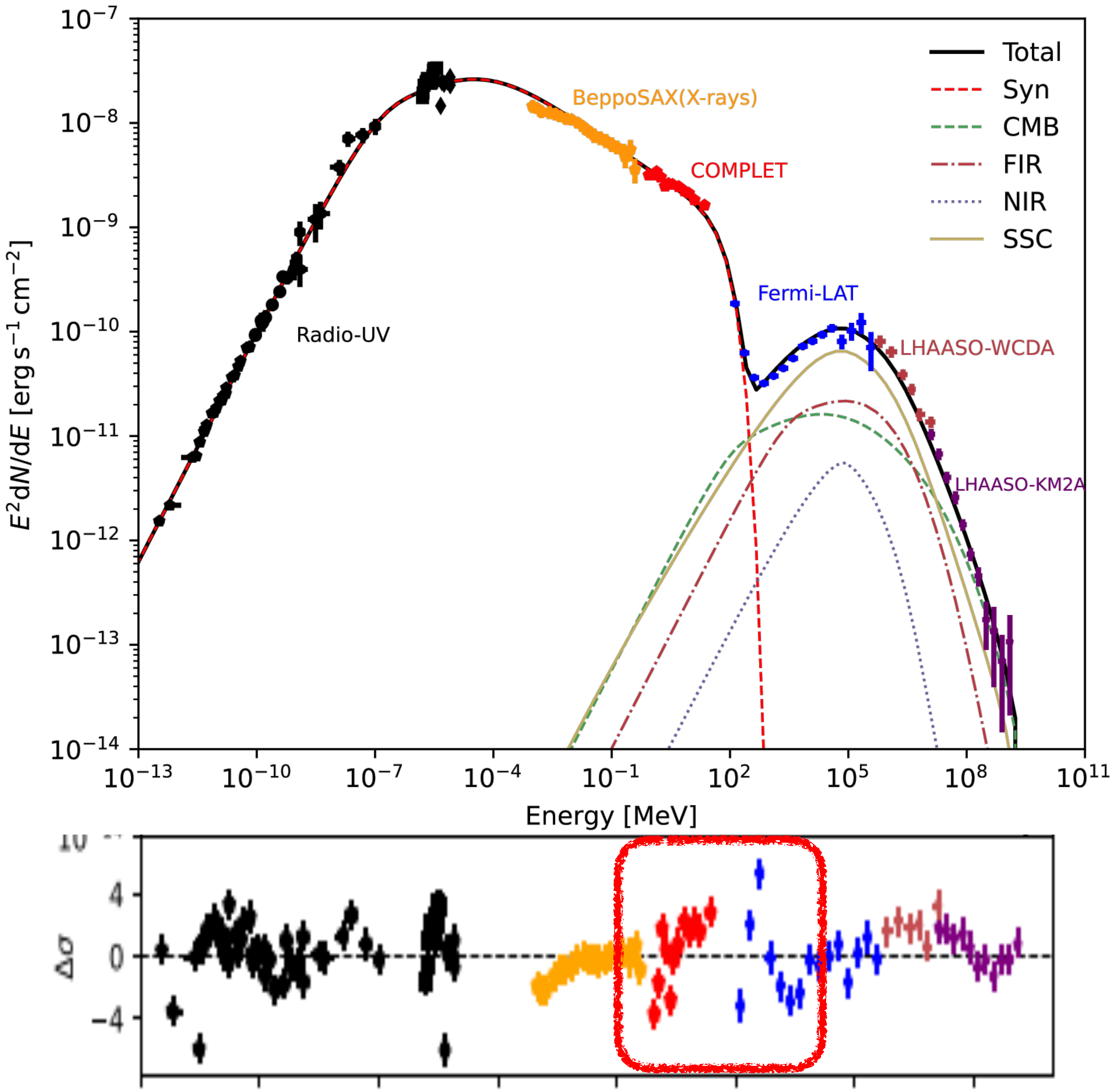
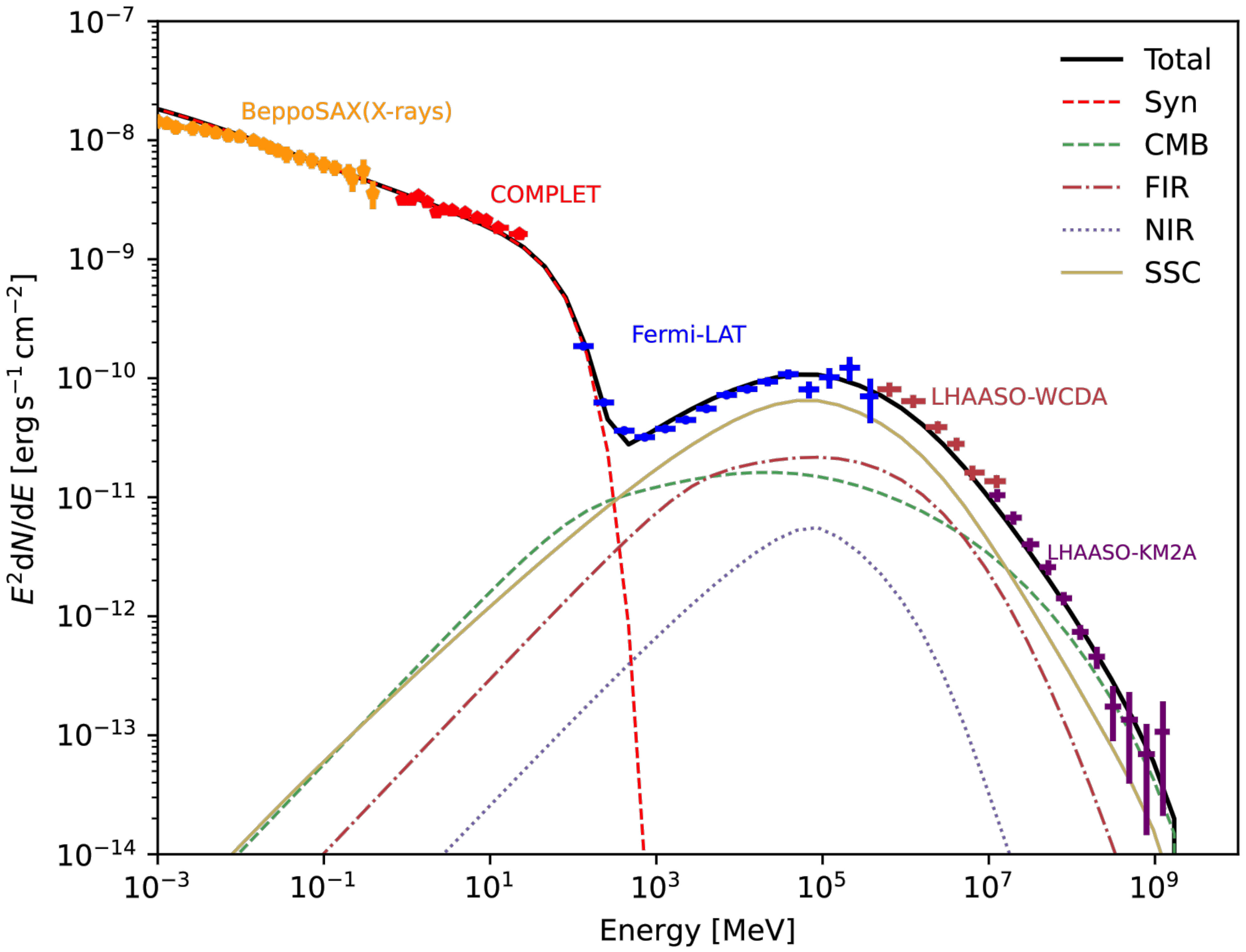




$$\eta = 0.265^{+0.0034}_{-0.0032}$$

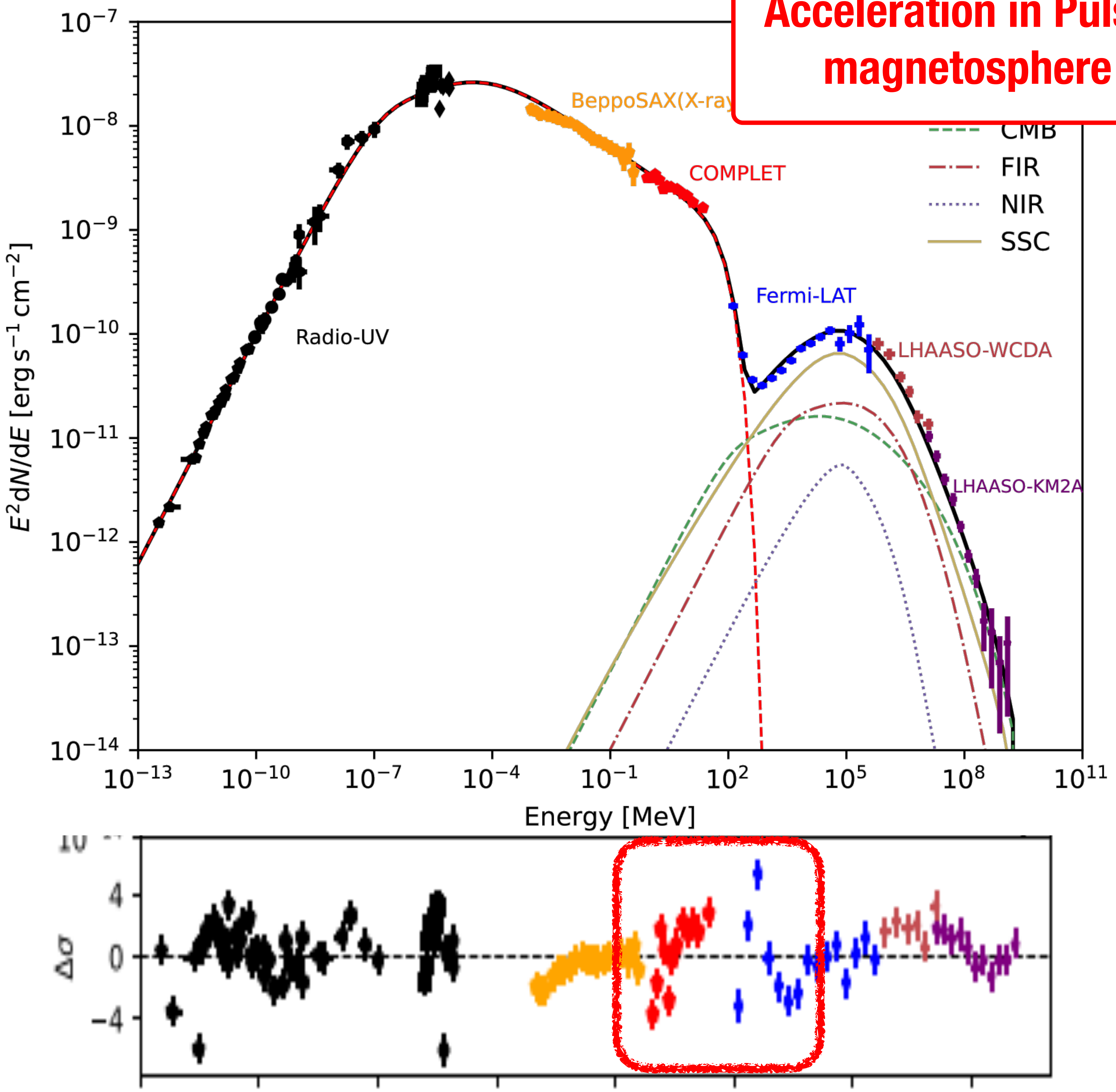
$$B_{PWN} = 129.42^{+1.8}_{-1.78}\ \mu\mathrm{G}$$

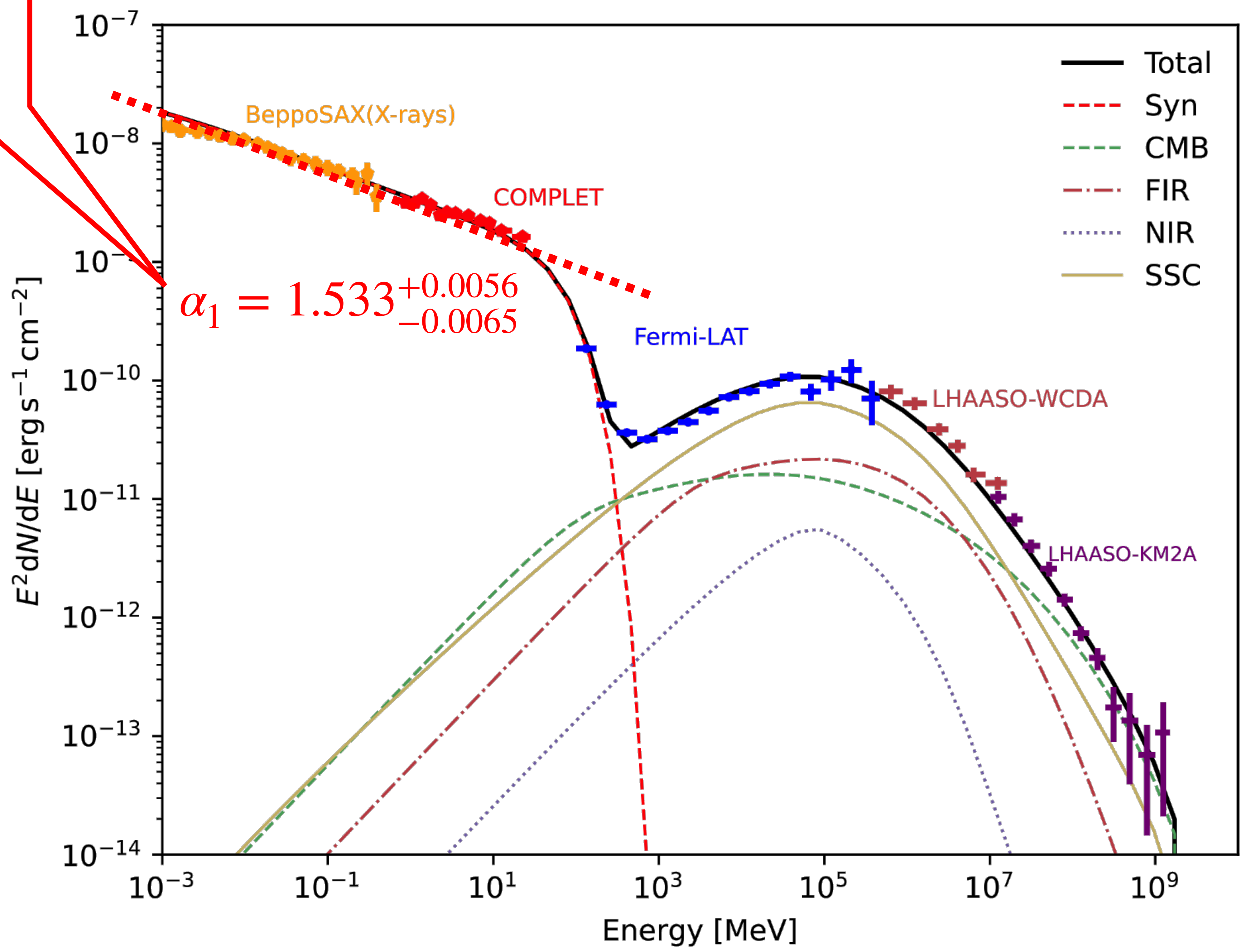
$$E_{\mathrm{cut}} = 154^{+5.9}_{-6.1}\ \mathrm{GeV}$$

Leptonic

Nie, L *et al* **ApJ** 924:42, (2022)

Acceleration in Pulsar magnetosphere





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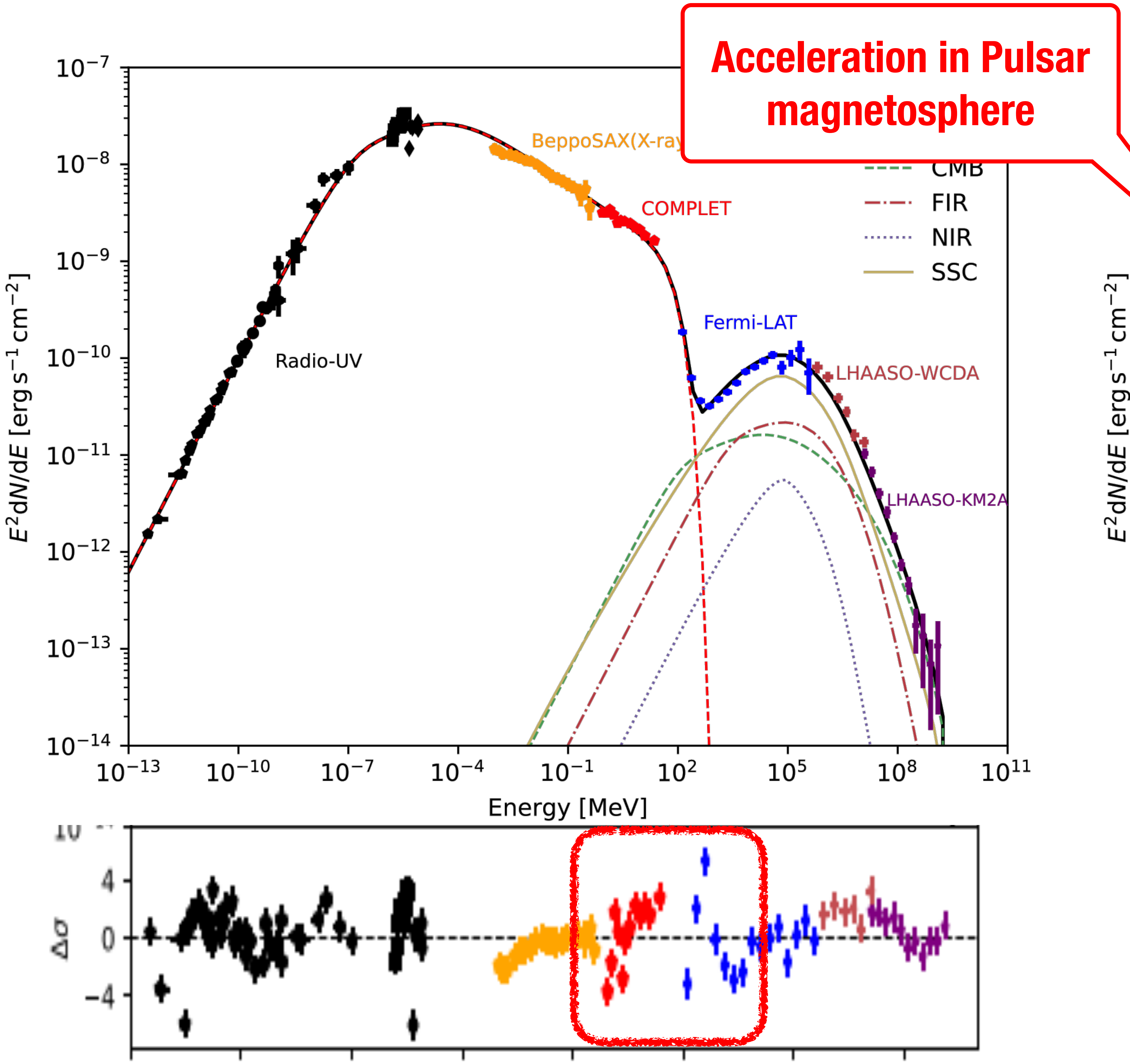

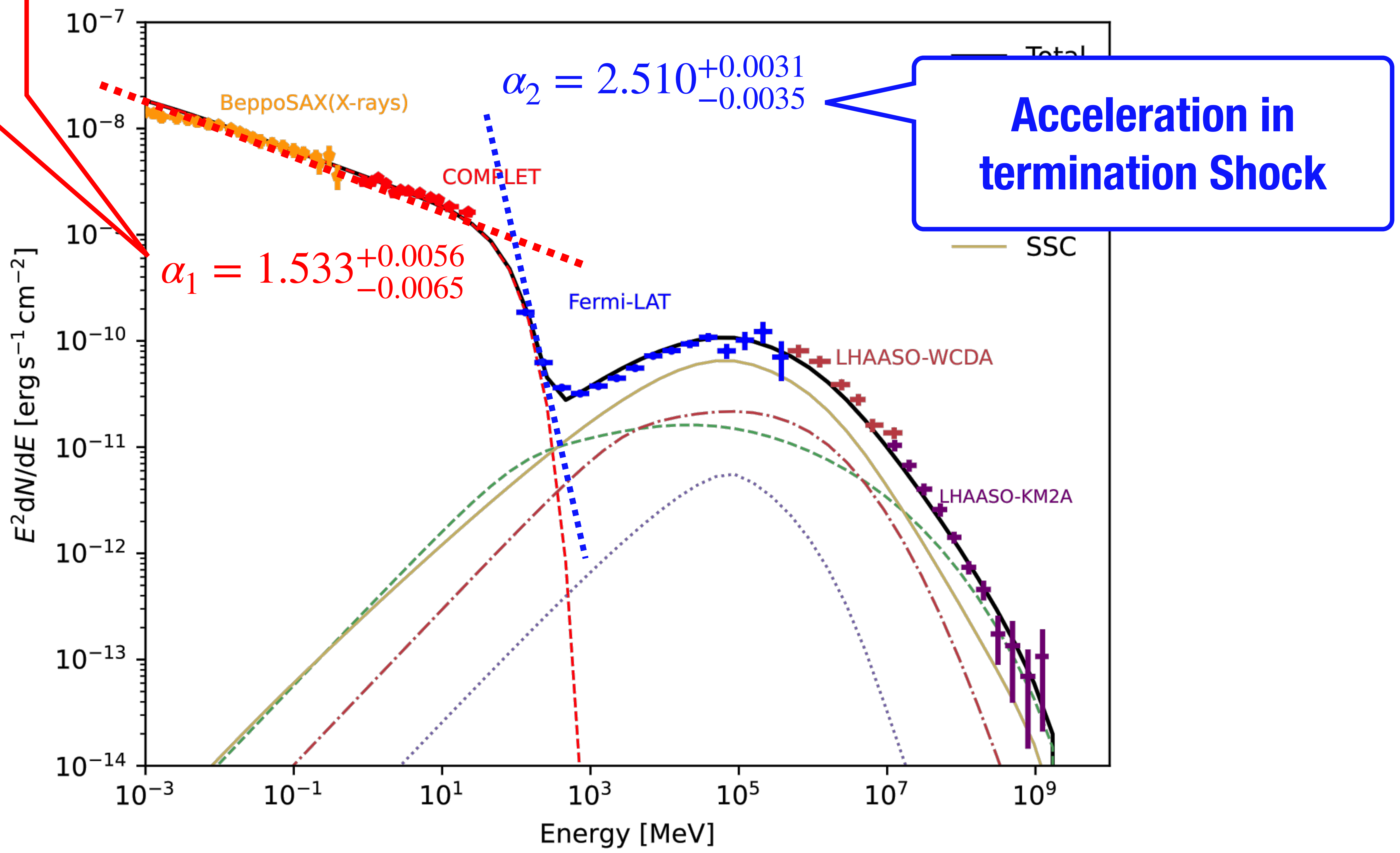

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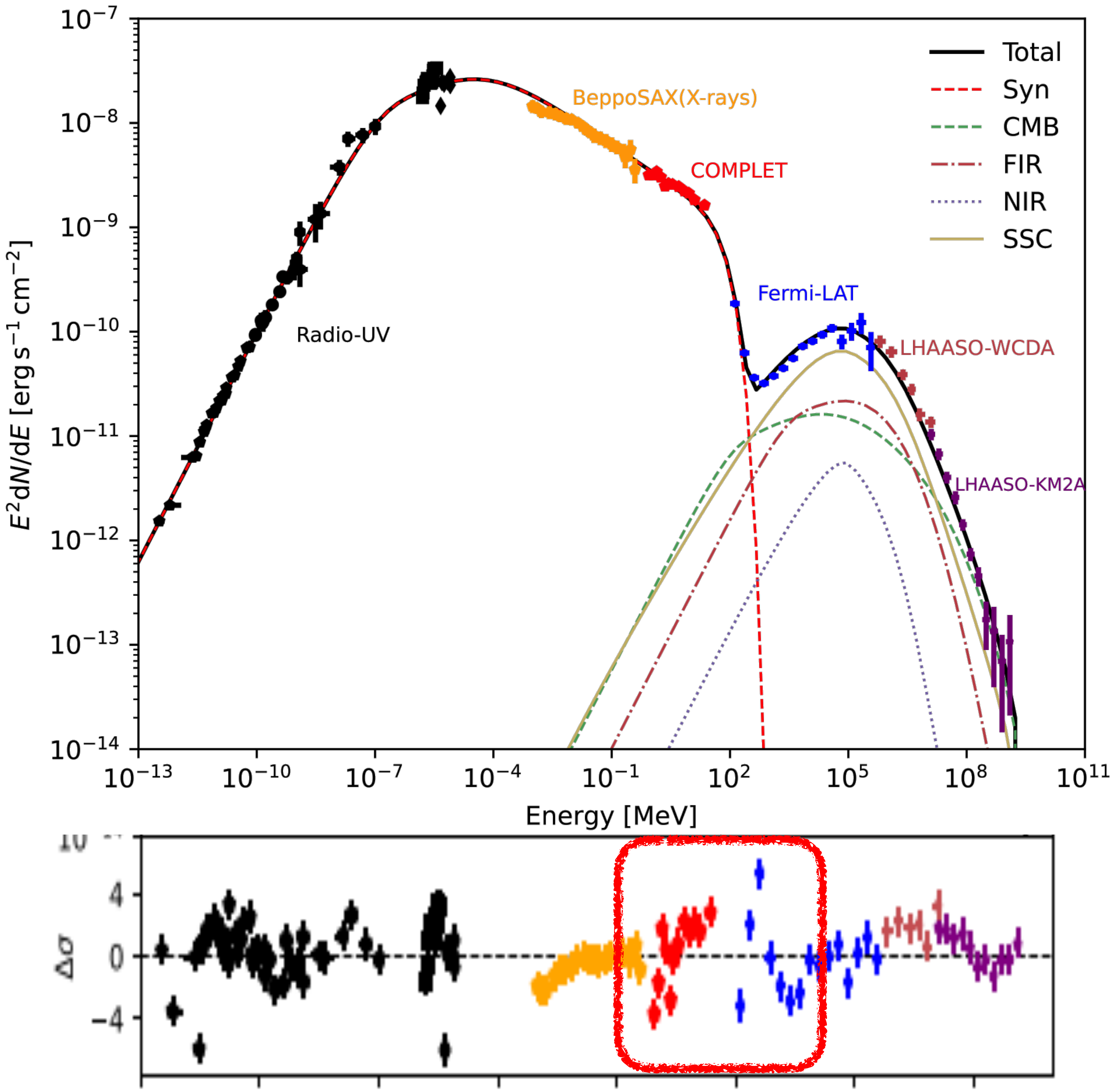
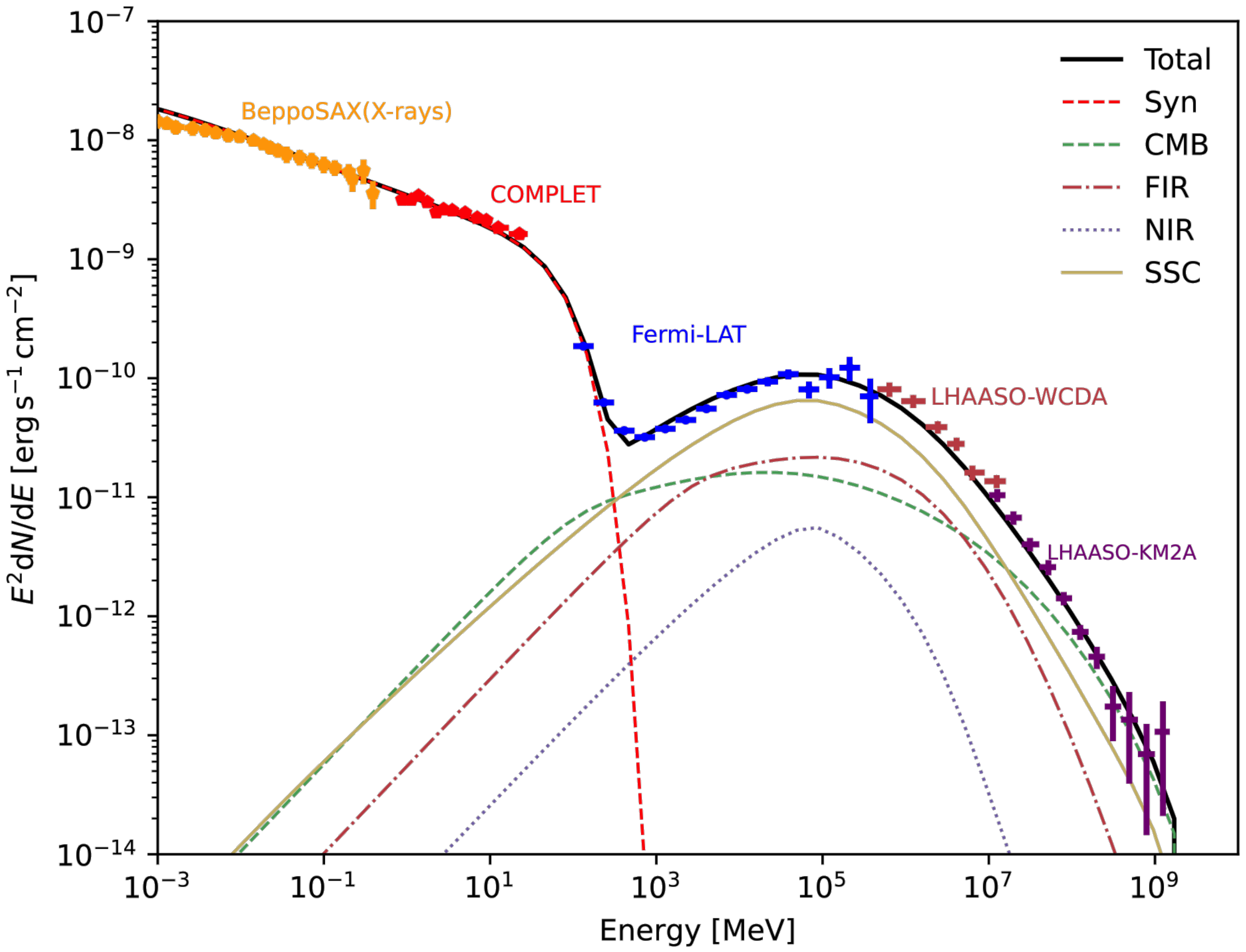
Leptonic+Hadronic?

Nie, L *et al* **ApJ** 924:42, (2022)





Leptonic+Hadronic?

Nie, L *et al* **ApJ** 924:42, (2022)

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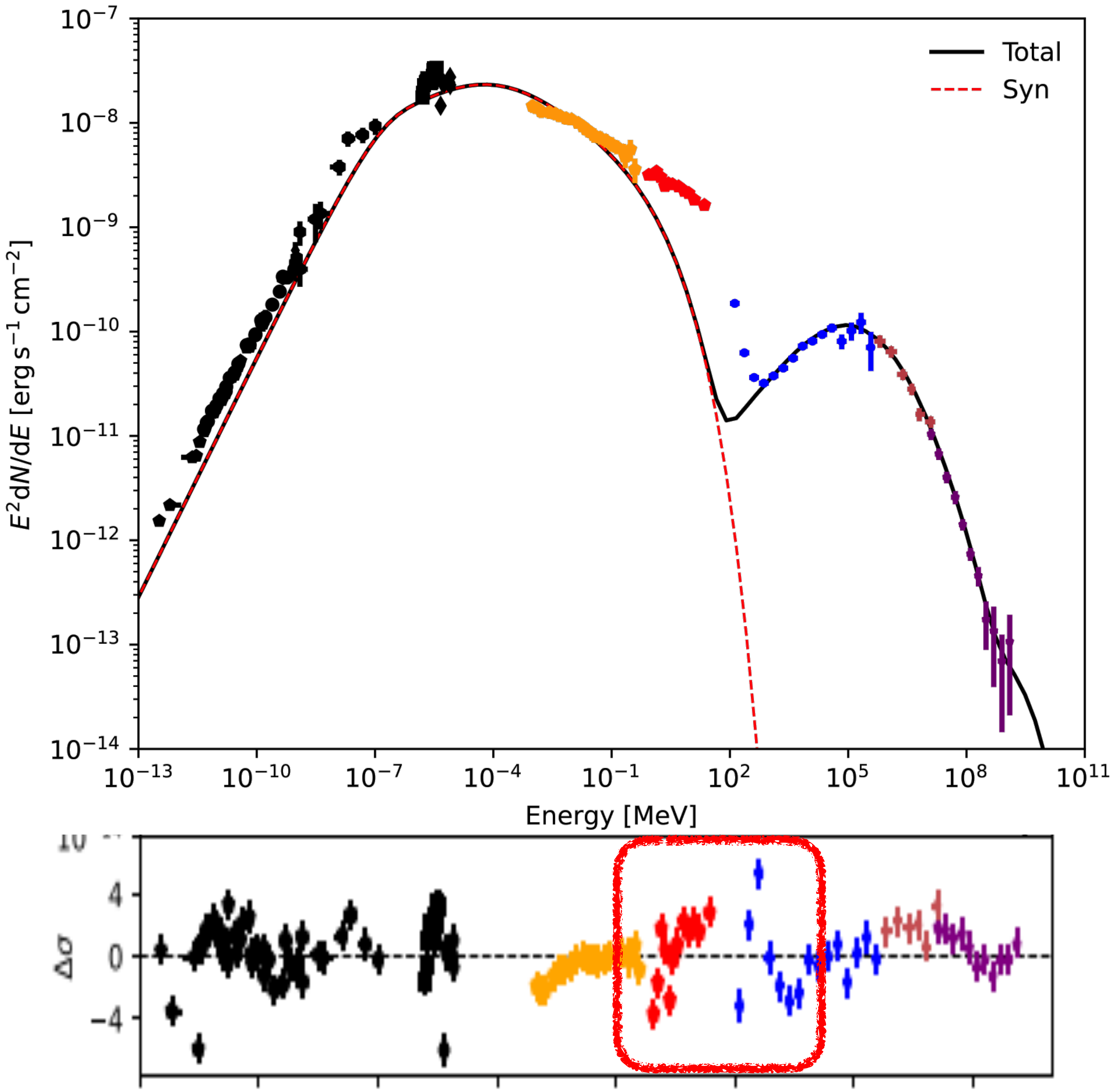
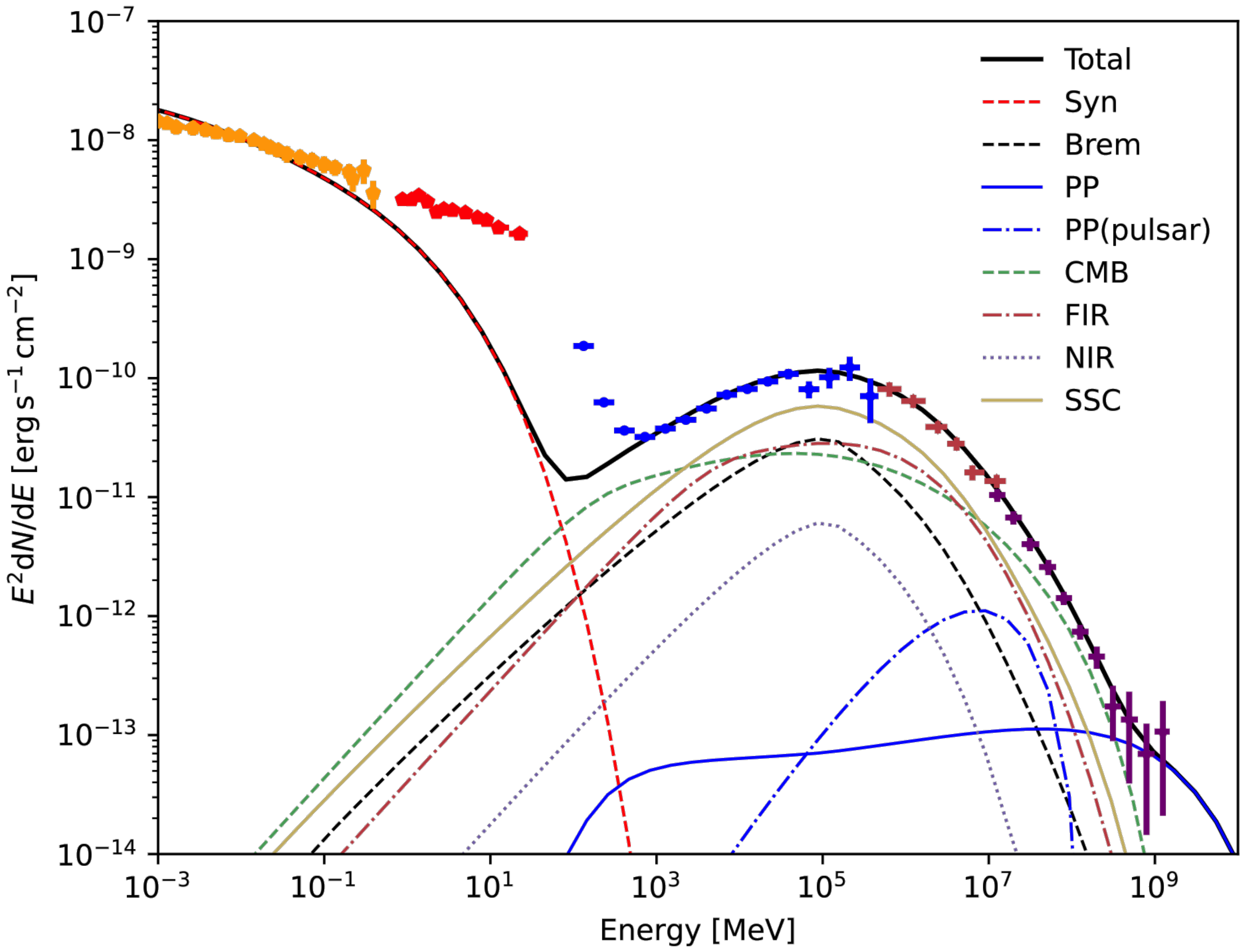
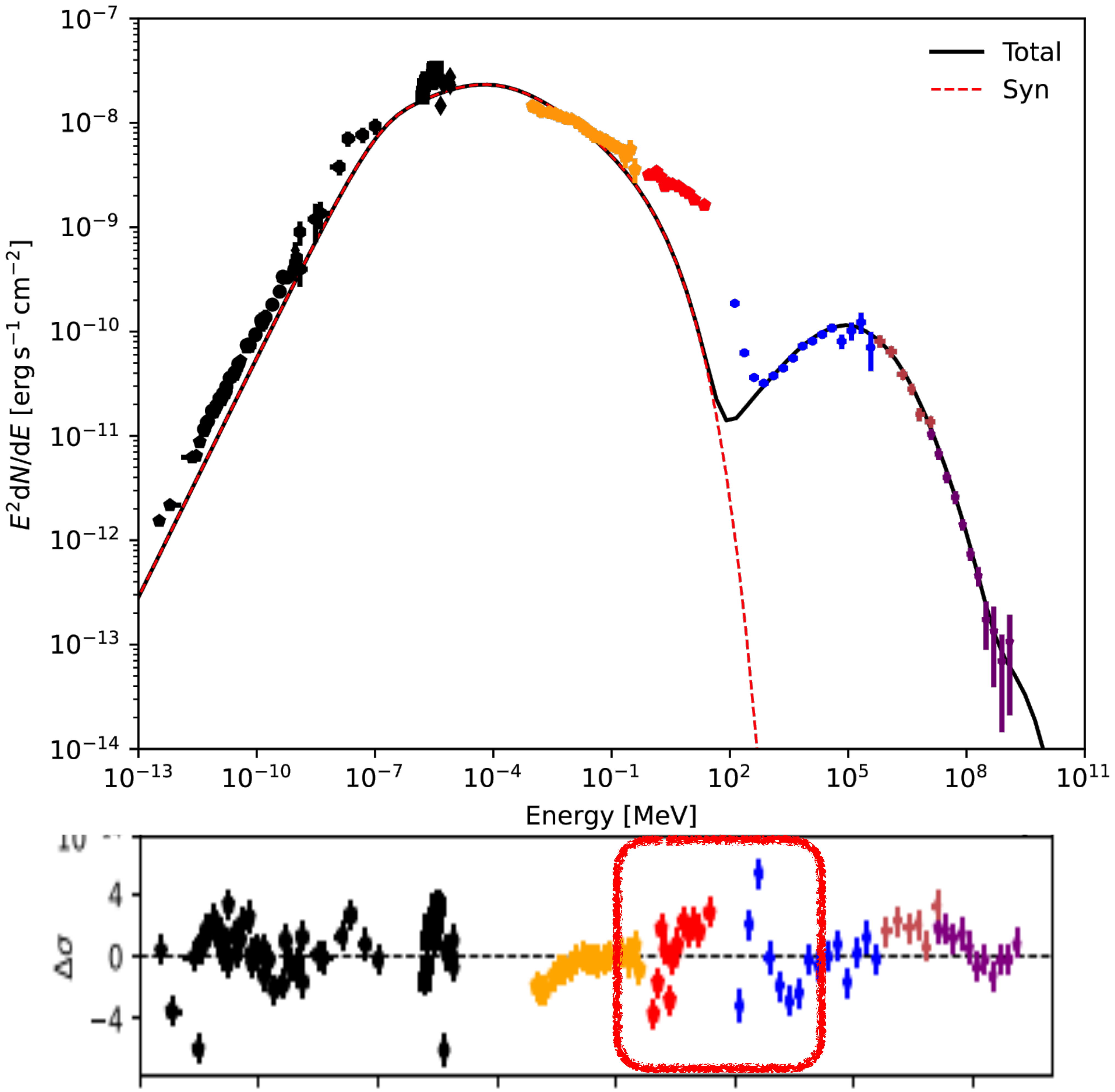
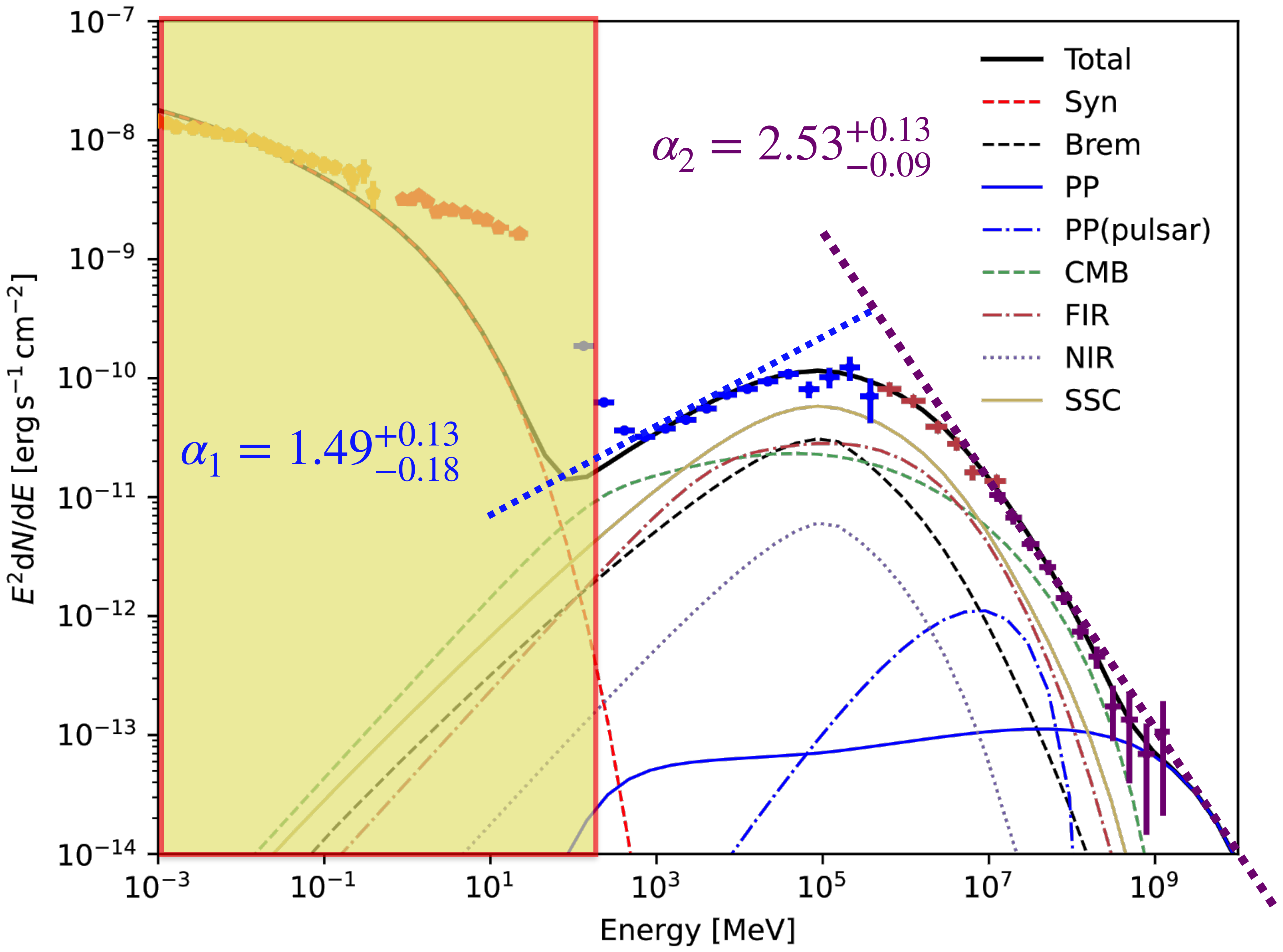




Leptonic+Hadronic?

Nie, L *et al* **ApJ** 924:42, (2022)





Leptonic+Hadronic?

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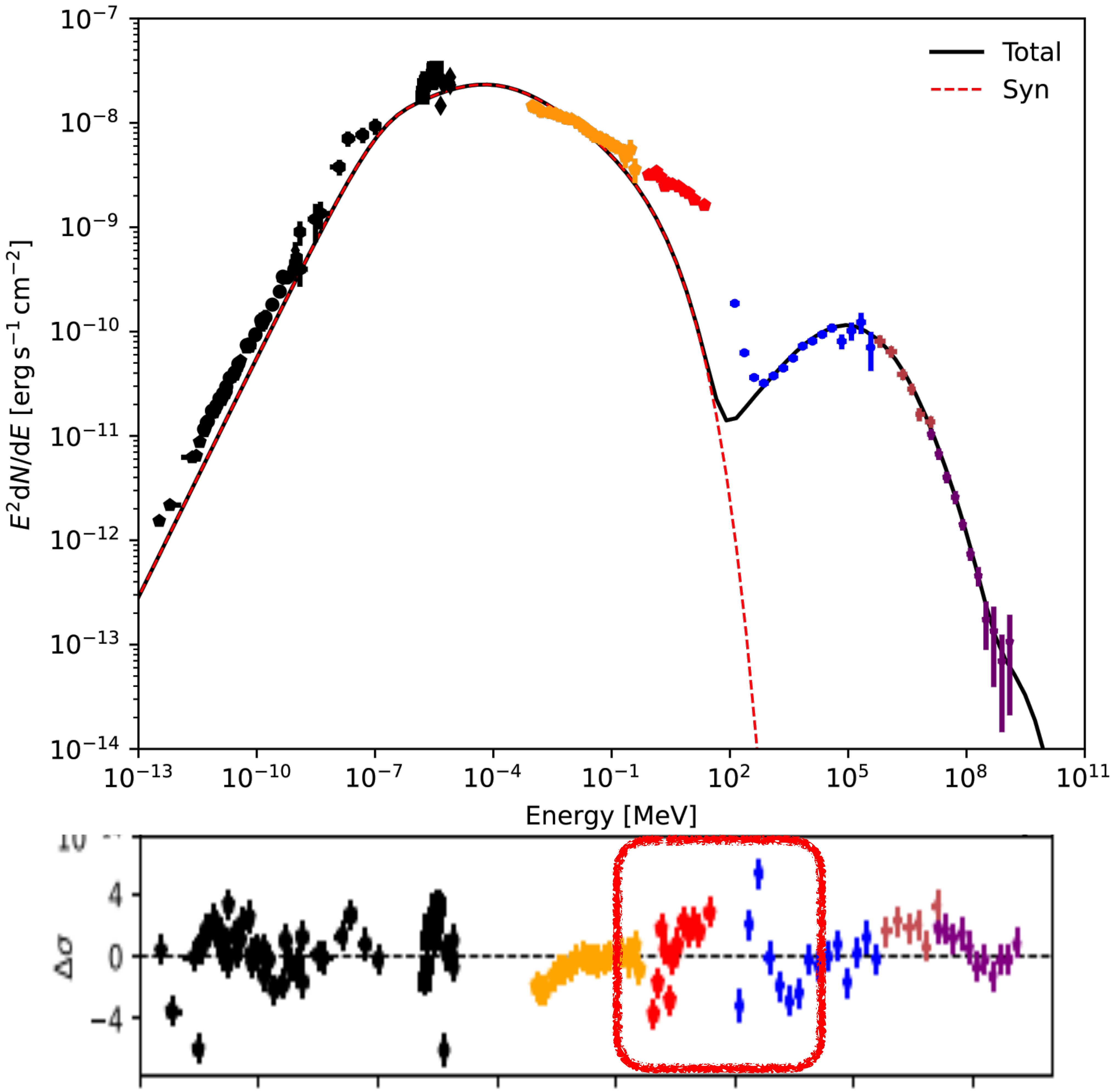

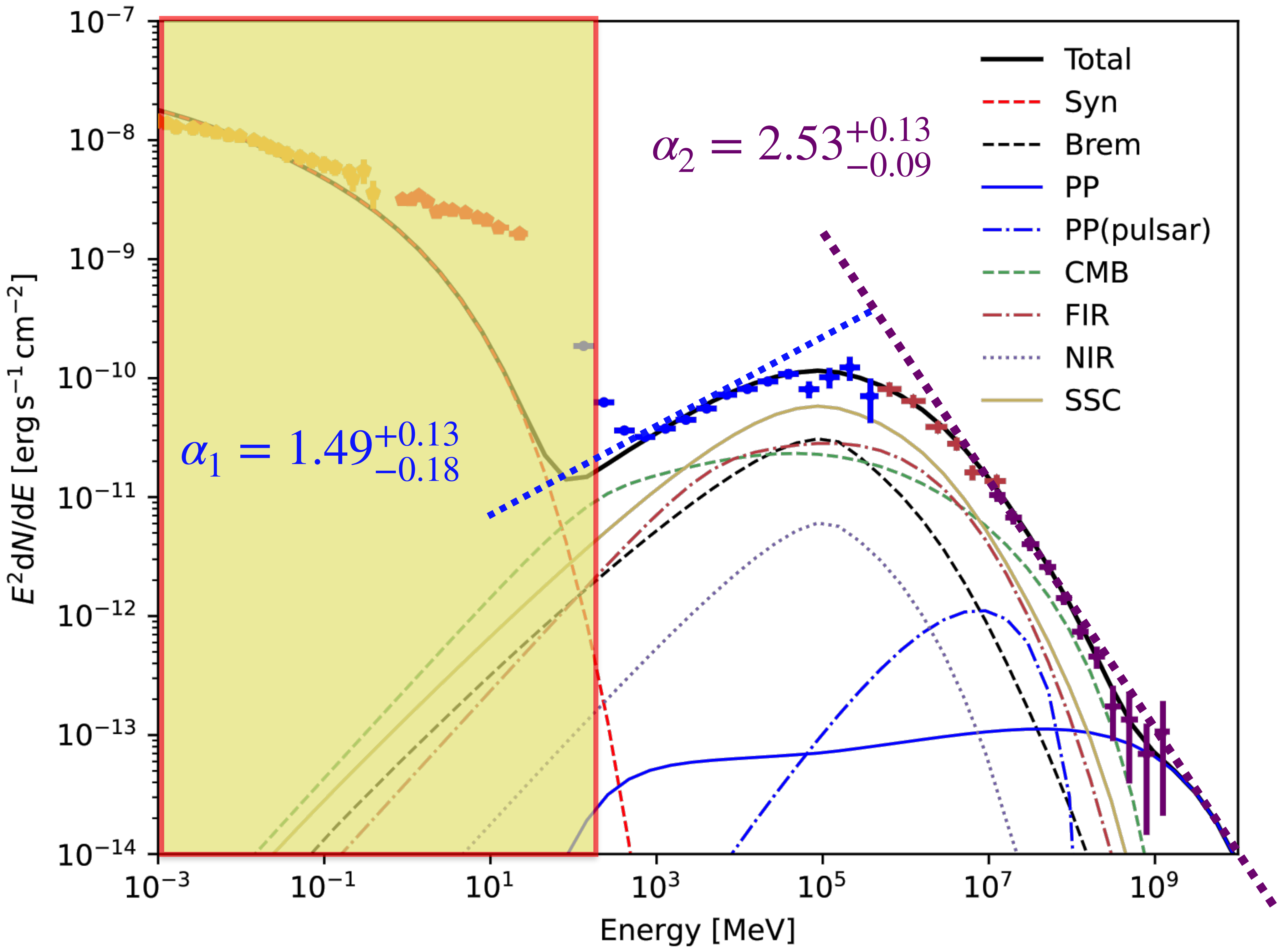

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$$B_{PWN} = 102.33^{+23.36}_{-6.83}\ \mu\mathrm{G}$$

$$E_{\mathrm{cut}} = 204^{+71}_{-75}\ \mathrm{GeV}$$

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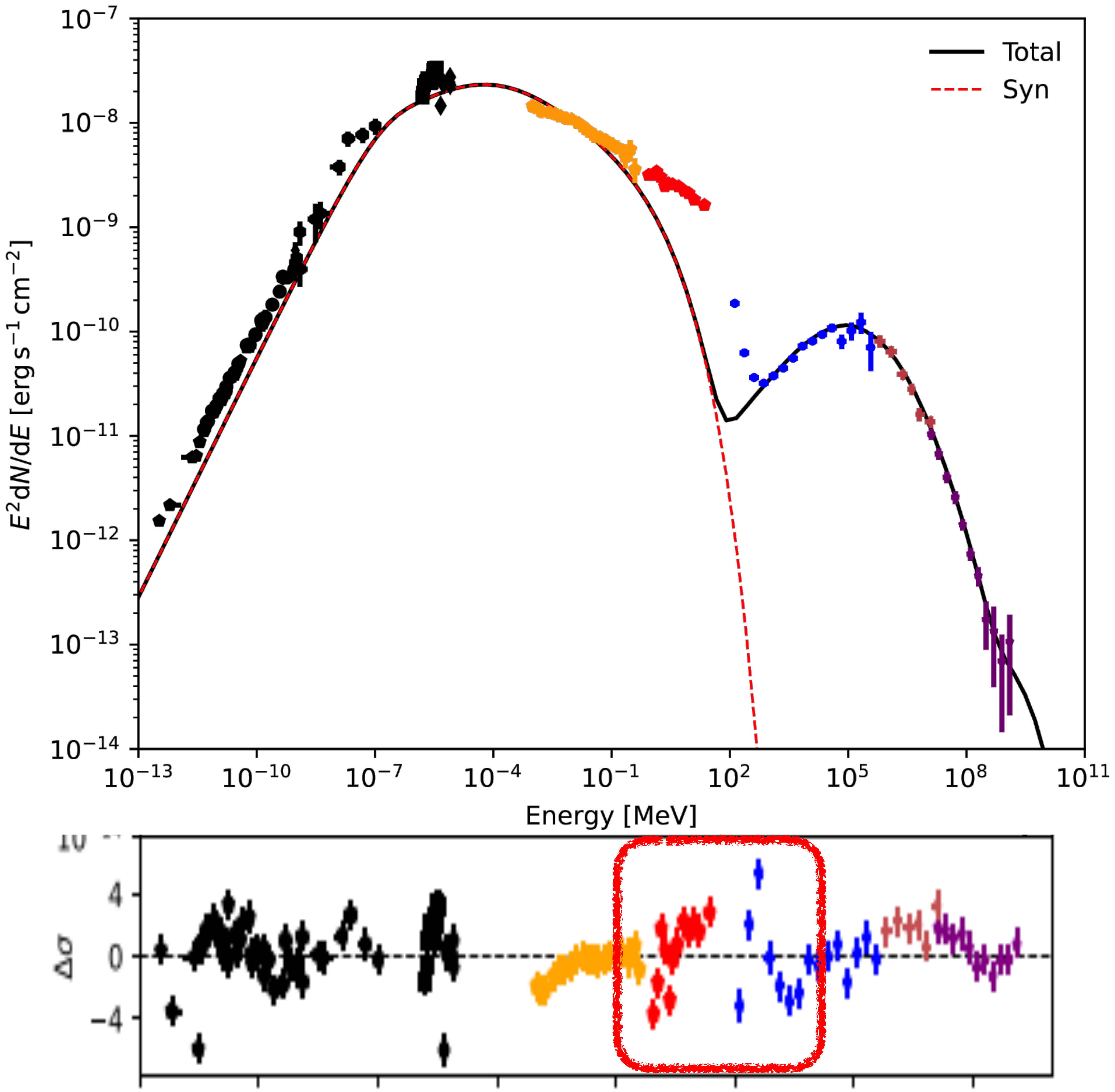

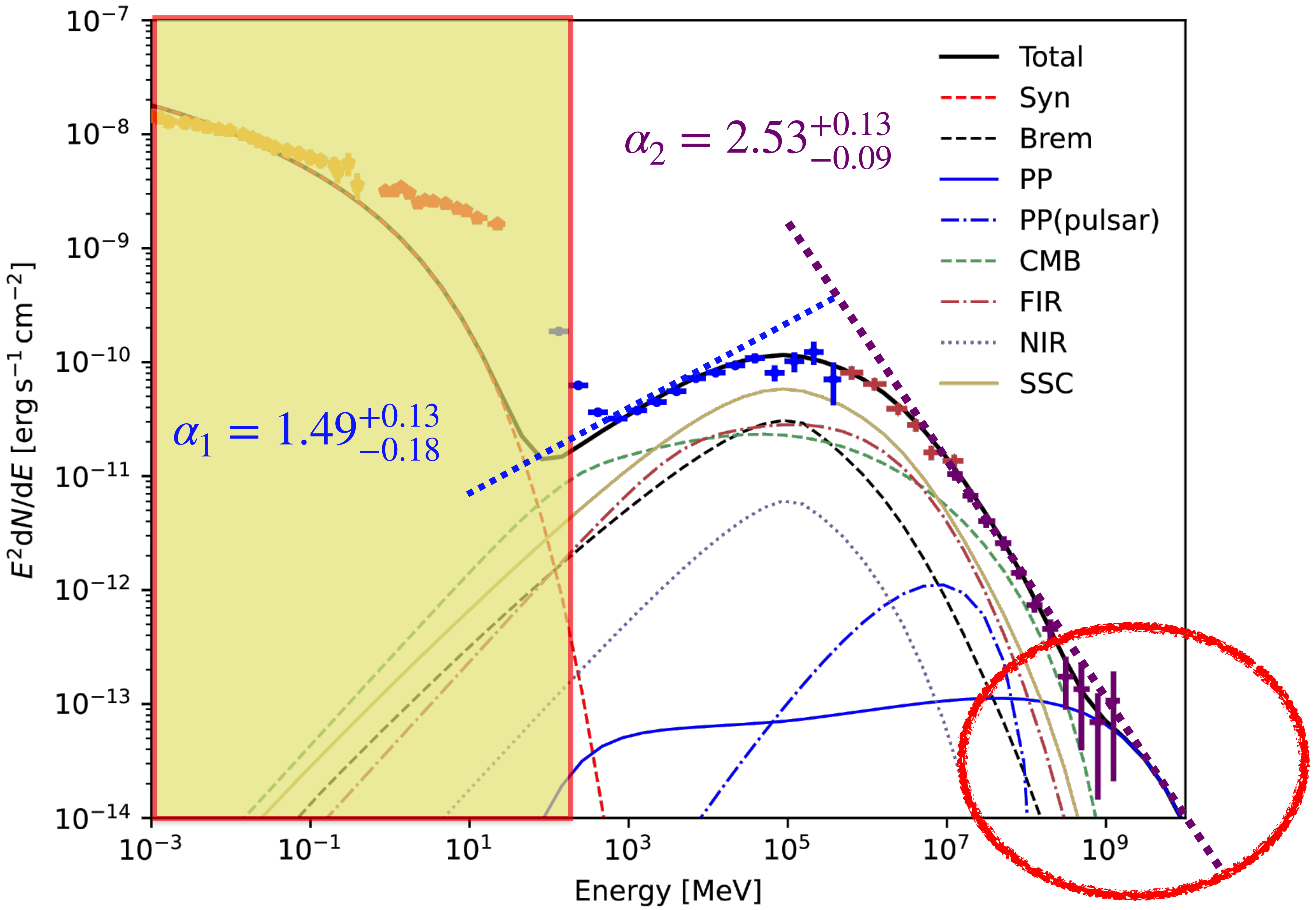

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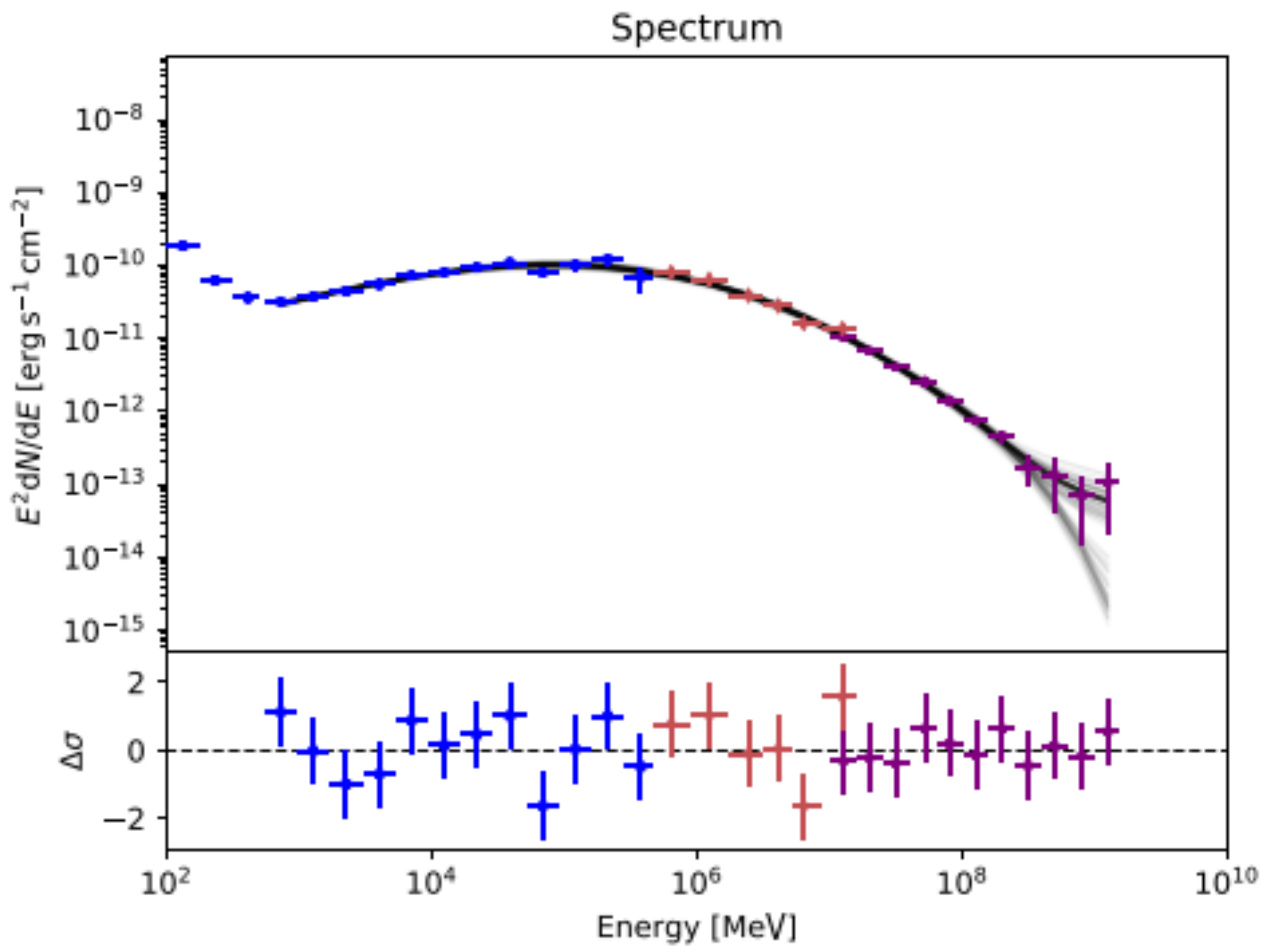

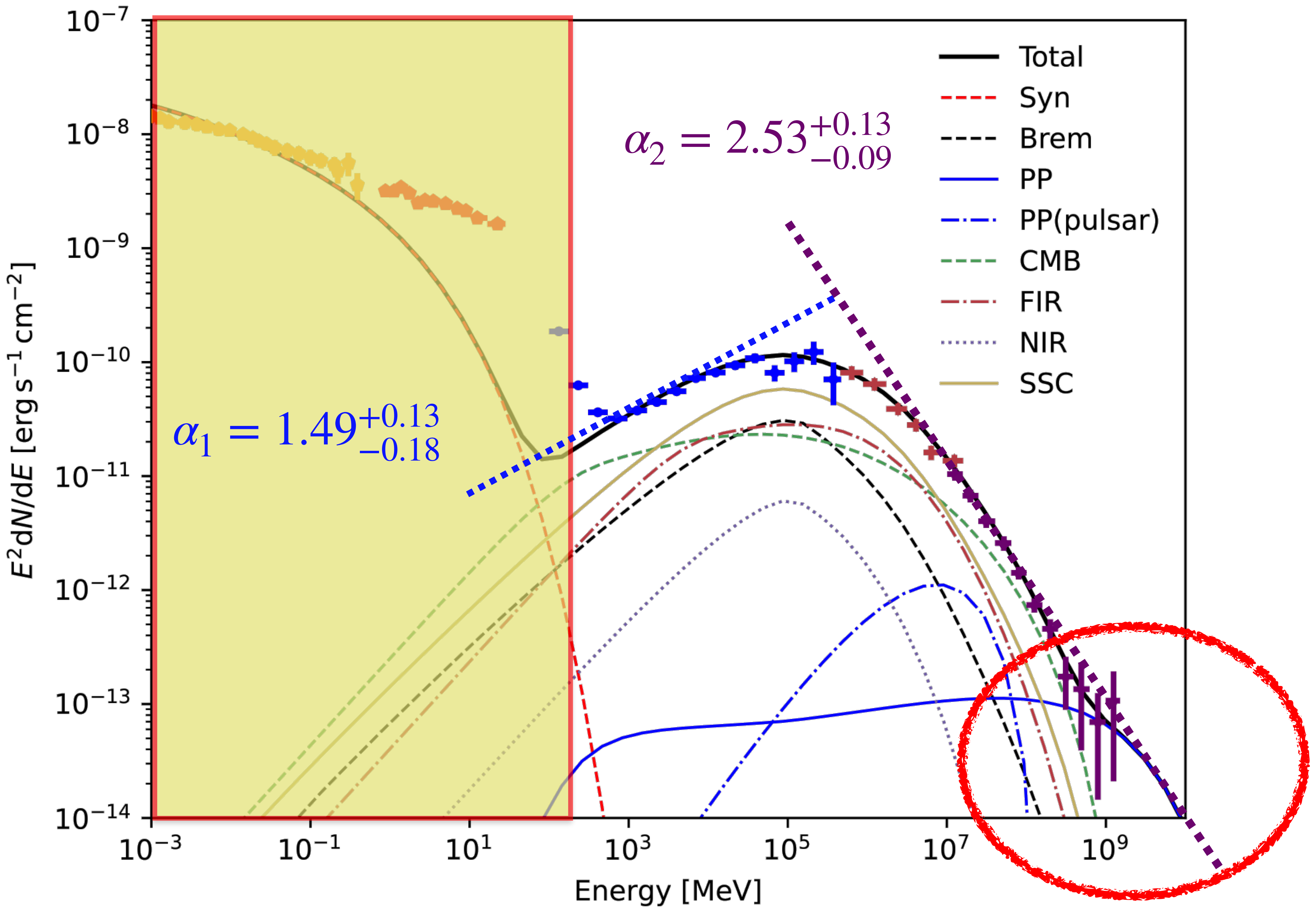

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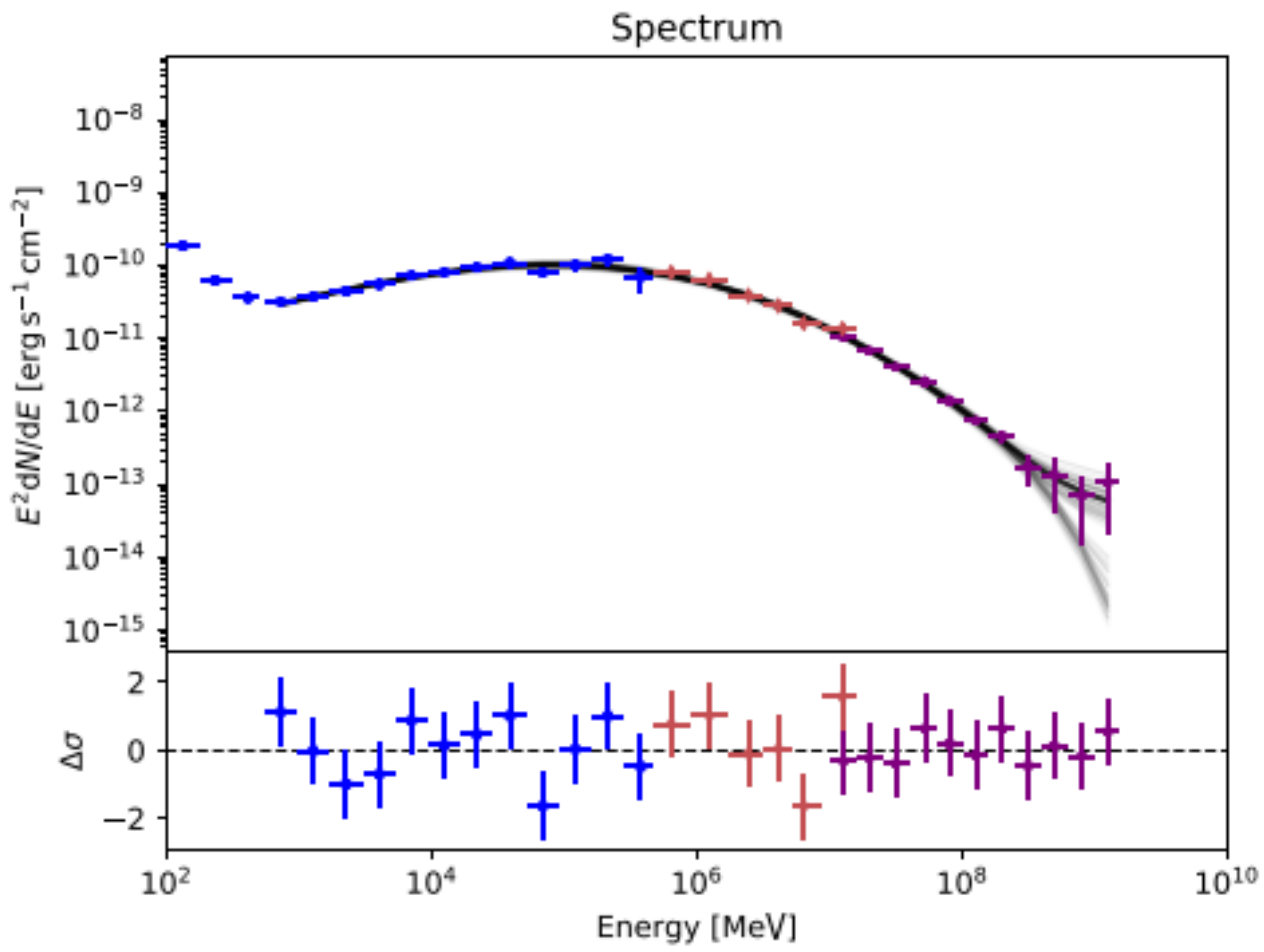
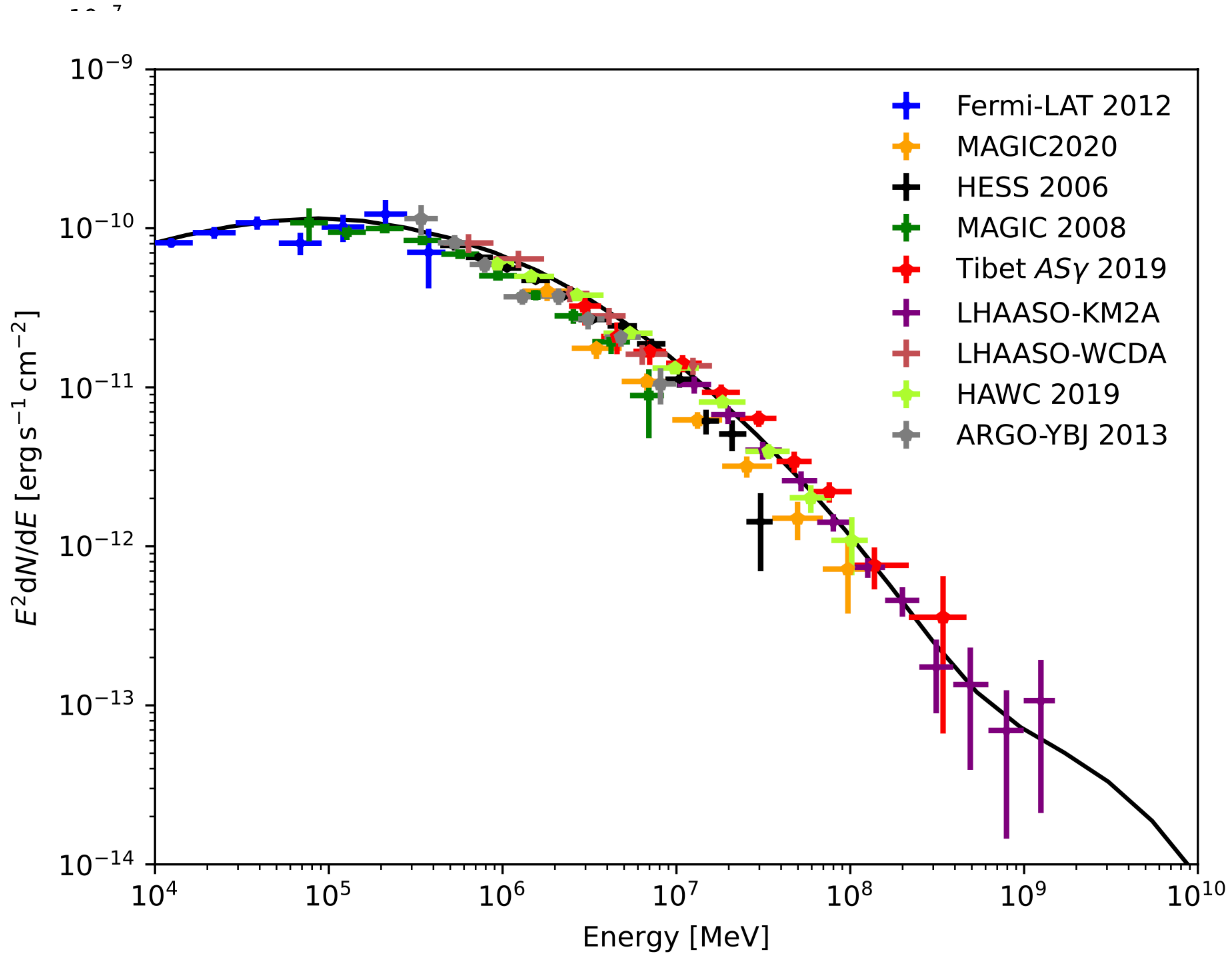




Lorentz Invariant Violation

Superluminal LIV effects

- LIV interaction in SM lagrangian alters standard on-shell condition of a particle energy-momentum relation in special relativity.

Modified dispersion relation

Superluminal

$$E_\gamma^2 - p_\gamma^2 \pm |\alpha_n| p_\gamma^{n+2} = m^2$$

Subluminal

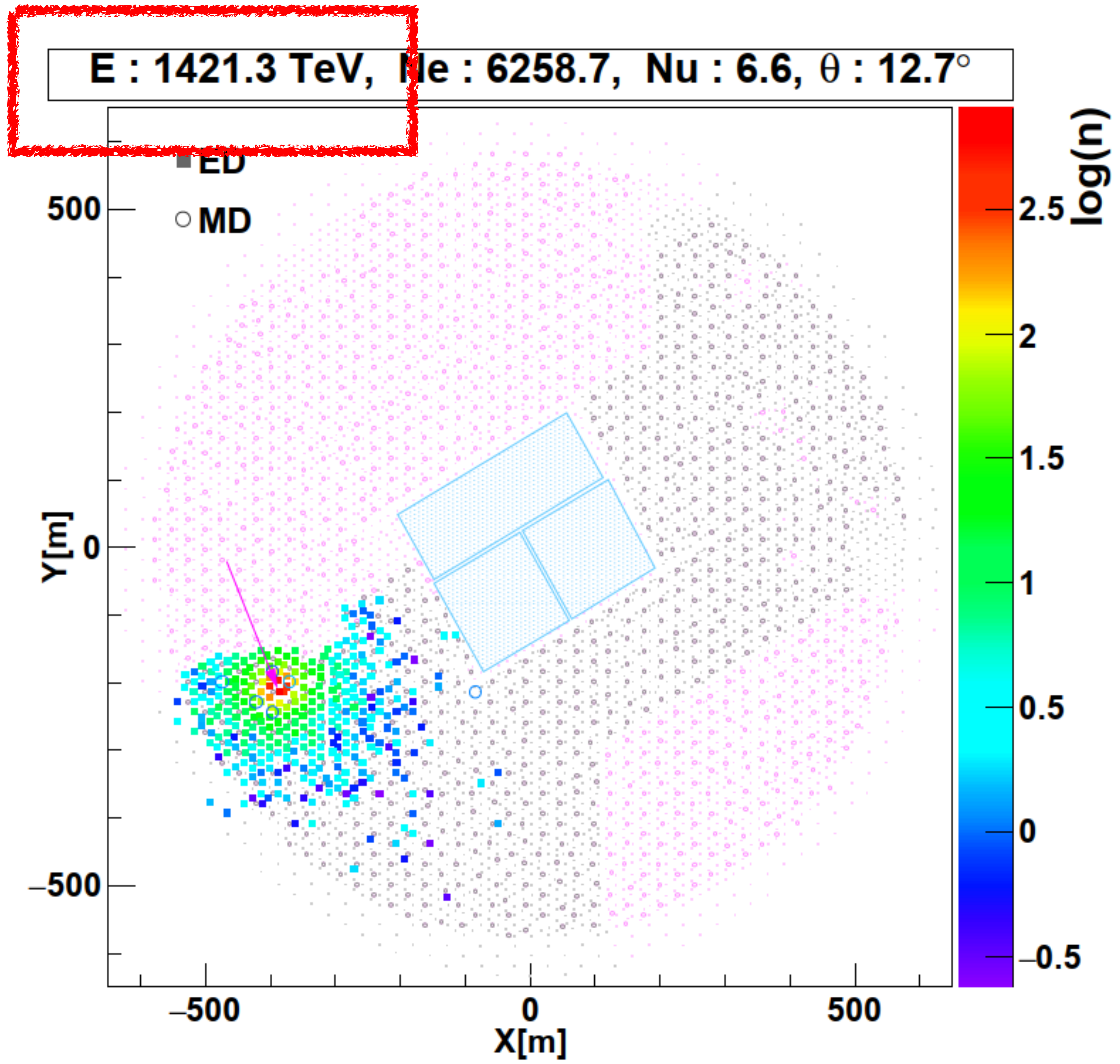
n^{th} LIV order

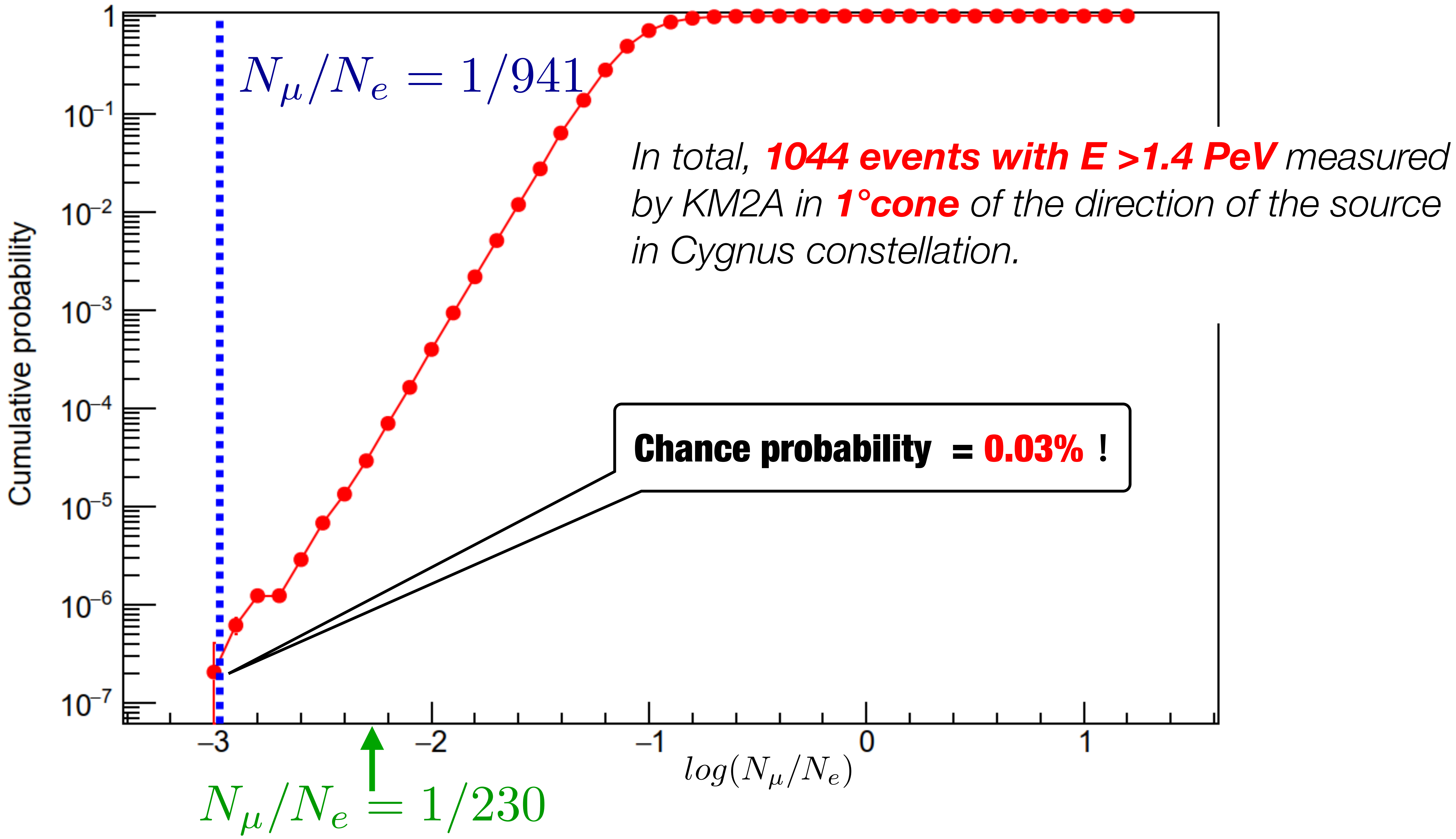
$$E_{\mathrm{LIV}}^{(n)} = \alpha_n^{-1/n}$$

LIV energy scale

- Astrophysical sources are ideal targets to search for the LIV effects because
  - extremely high-energy processes + the long distance to Earth
    - ➡ Accumulation of the tiny effect.
- What can (is being) studied
  - energy-dependent time delay from pulsars
  - γ-ray bursts (GRBs)
  - flaring active galactic nuclei (AGN)
  - the vacuum Cherenkov emission
  - the vacuum birefringence
  - ***the decay or splitting of photons***

Highest ever recorded gamma from Cygnus region





Excellent CR background Rejection Power

- Simultaneous detection of number of measured muons and electron in a shower
  - Cutting on ratio $N_\mu/N_e<1/230$
- BG-free Photon detection (N_γ >10 N_{CR}) for showers E>100 TeV from the Crab

LIV limits from LHAASO

$$f(E) = \phi_0 \left(\frac{E}{E_)}\right)^{-\alpha - \beta \ln(E/E_0)} \qquad H(E - E_{\rm cut})$$

Source	L (kpc)	$E_{\rm max}$ (PeV)	$E_{\rm cut}^{95\%}$ (PeV)
J0534+2202	2.0	0.88	$0.75^{+0.043}_{-0.043}$
J2032+4102	1.4	1.42	$1.14^{+0.06}_{-0.06}$

LHAASO coll. 2022 (PRL 128:051102)

$\gamma \to e^- e^+$ **Astapov - JCAP04(2019)054**

$$\alpha_0 \leq \frac{4m_e^2}{E_\gamma^2 - 4m_e^2},$$

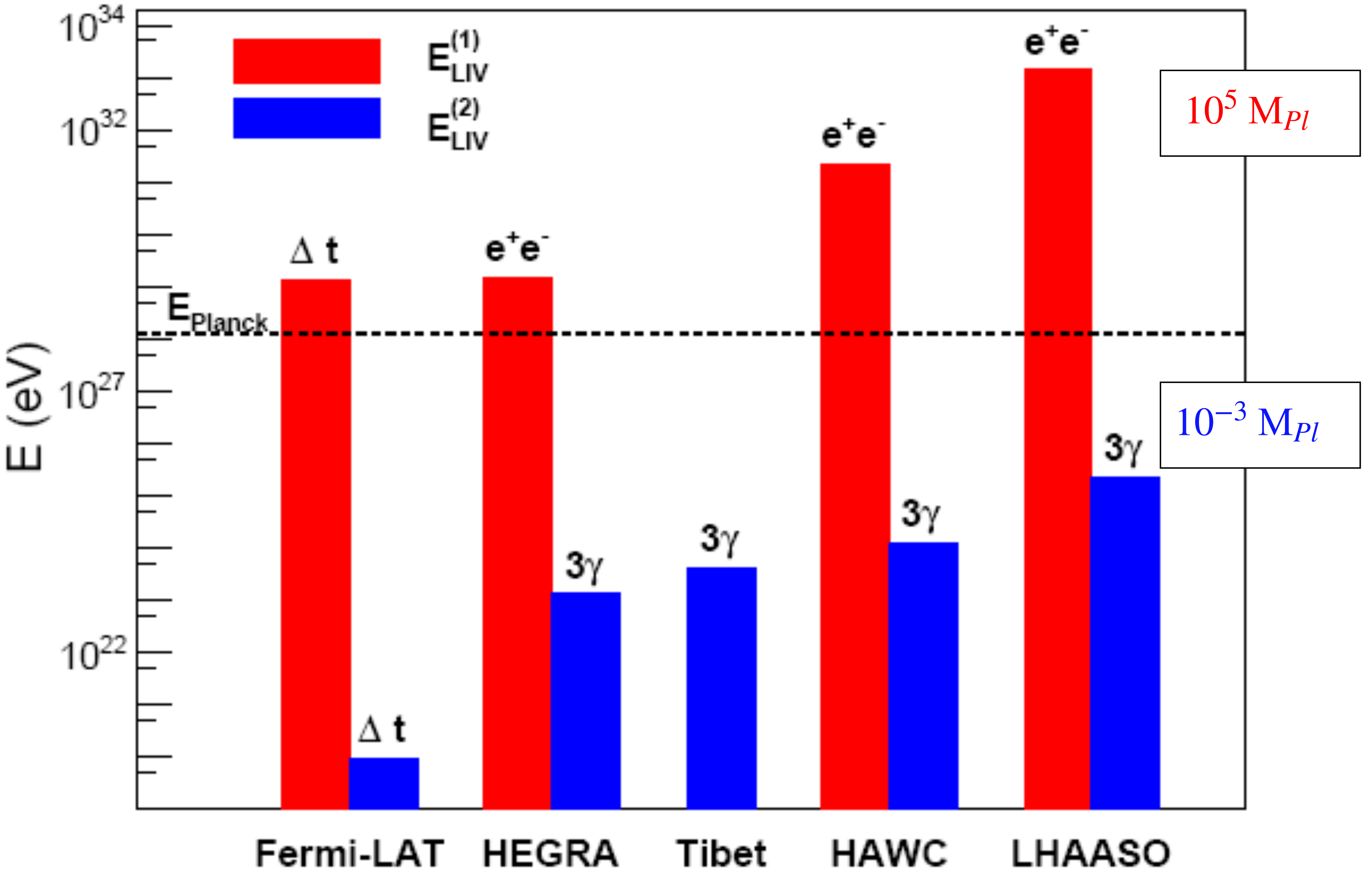
$$E_{LIV}^{(1)} \geq 9.57 \times 10^{23} \mathrm{eV} \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^3,$$

$\gamma \to 3\gamma$

$$\Gamma_{\gamma\to3\gamma} = 5 \times 10^{-14} \frac{E_\gamma^{19}}{m_e^8 E_{LIV}^{(2)10}},$$

$$E_{LIV}^{(2)} > 3.33 \times 10^{19} \mathrm{eV} \left(\frac{L}{\mathrm{kpc}}\right)^{0.1} \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{1.9}.$$

HAWC - PRL 124, 131101 (2020)



1 order of magnitude improvement on current limits

Cosmic Rays

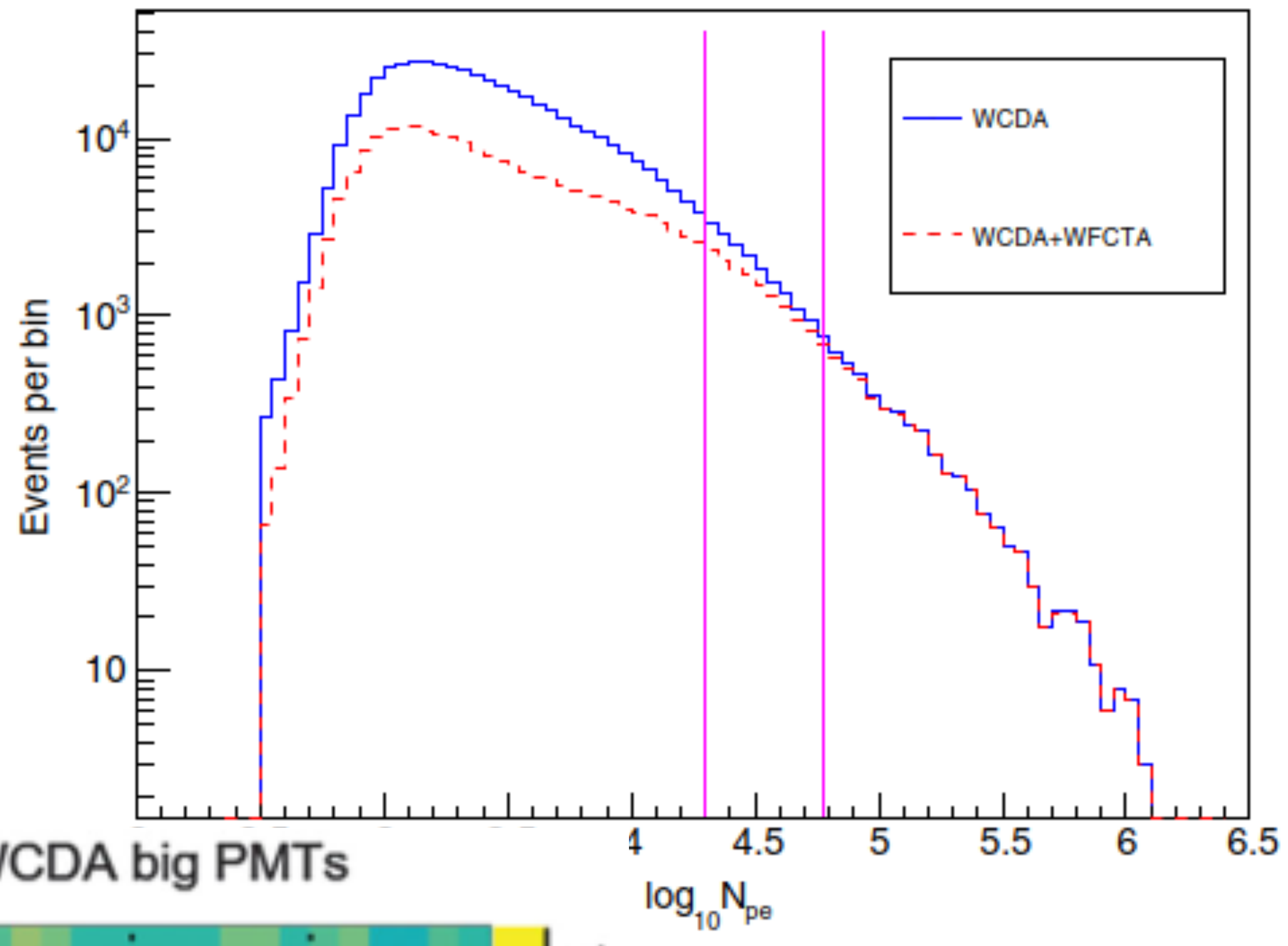
Absolute energy scale propagates from WCDA to

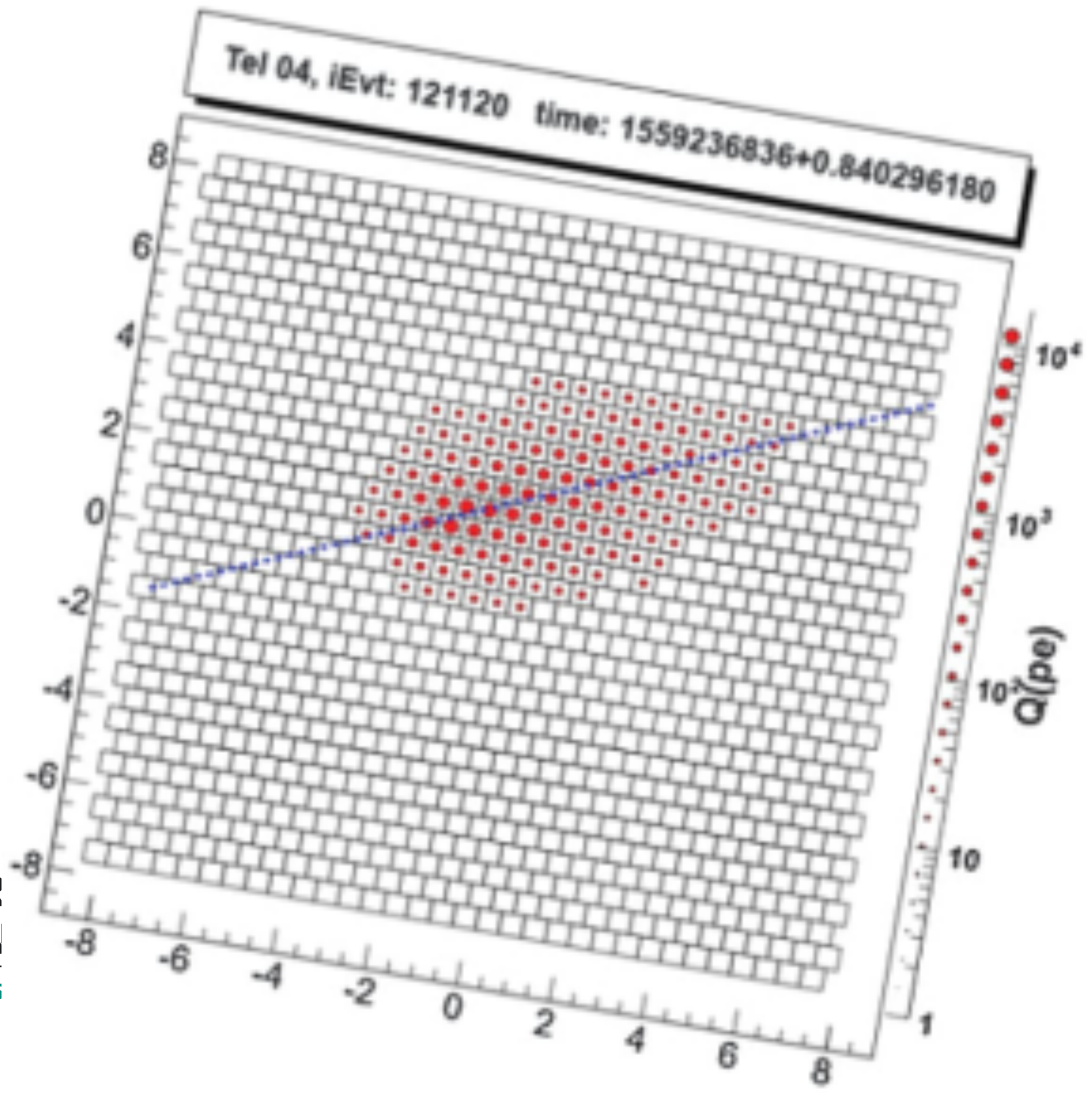
It is impossible for WFCTA to measure Moon shadow shifts directly buy..

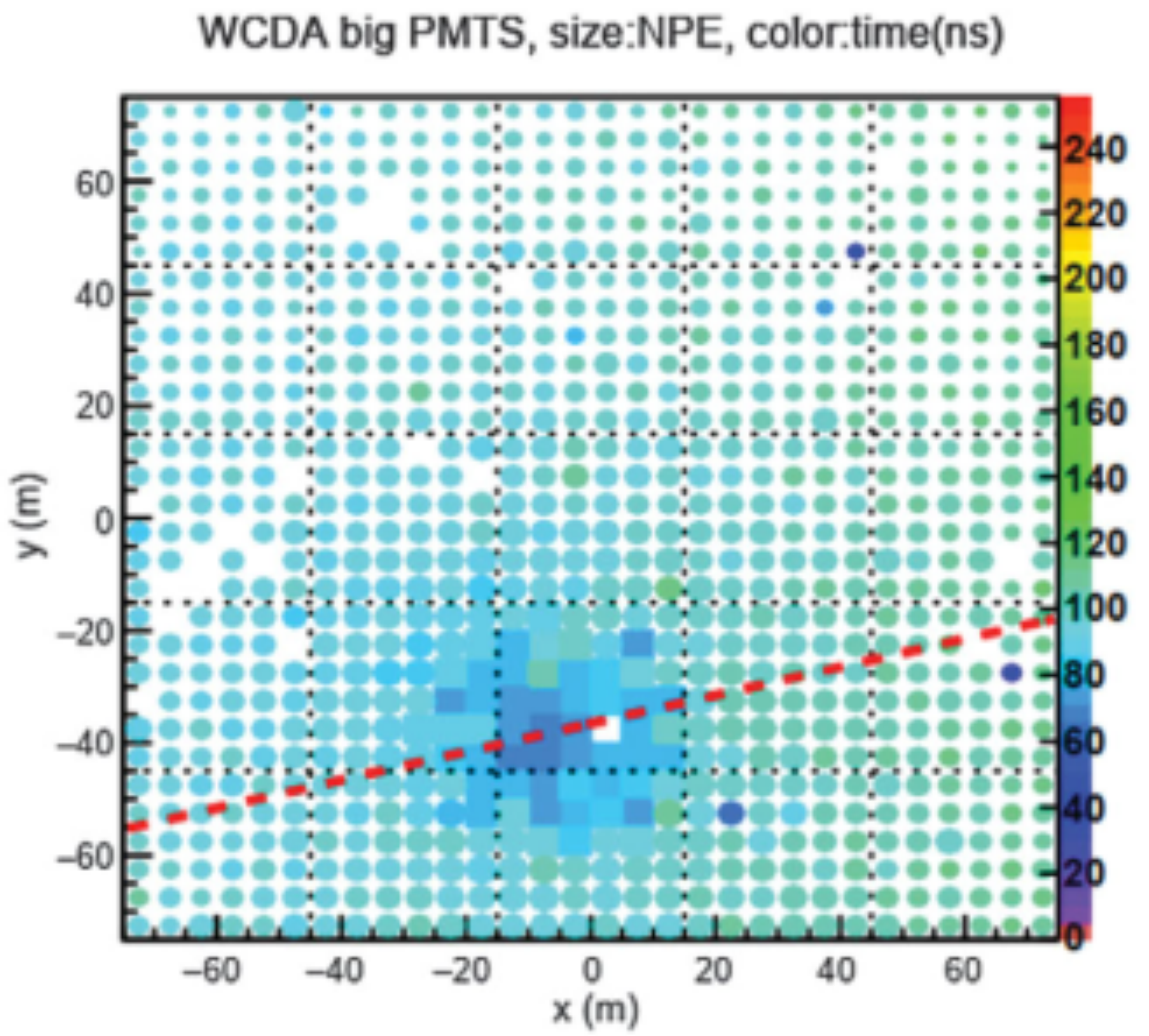
The absolute energy scale obtained by WCDA-1 can be propagated to WFCTA by using common-triggered events.

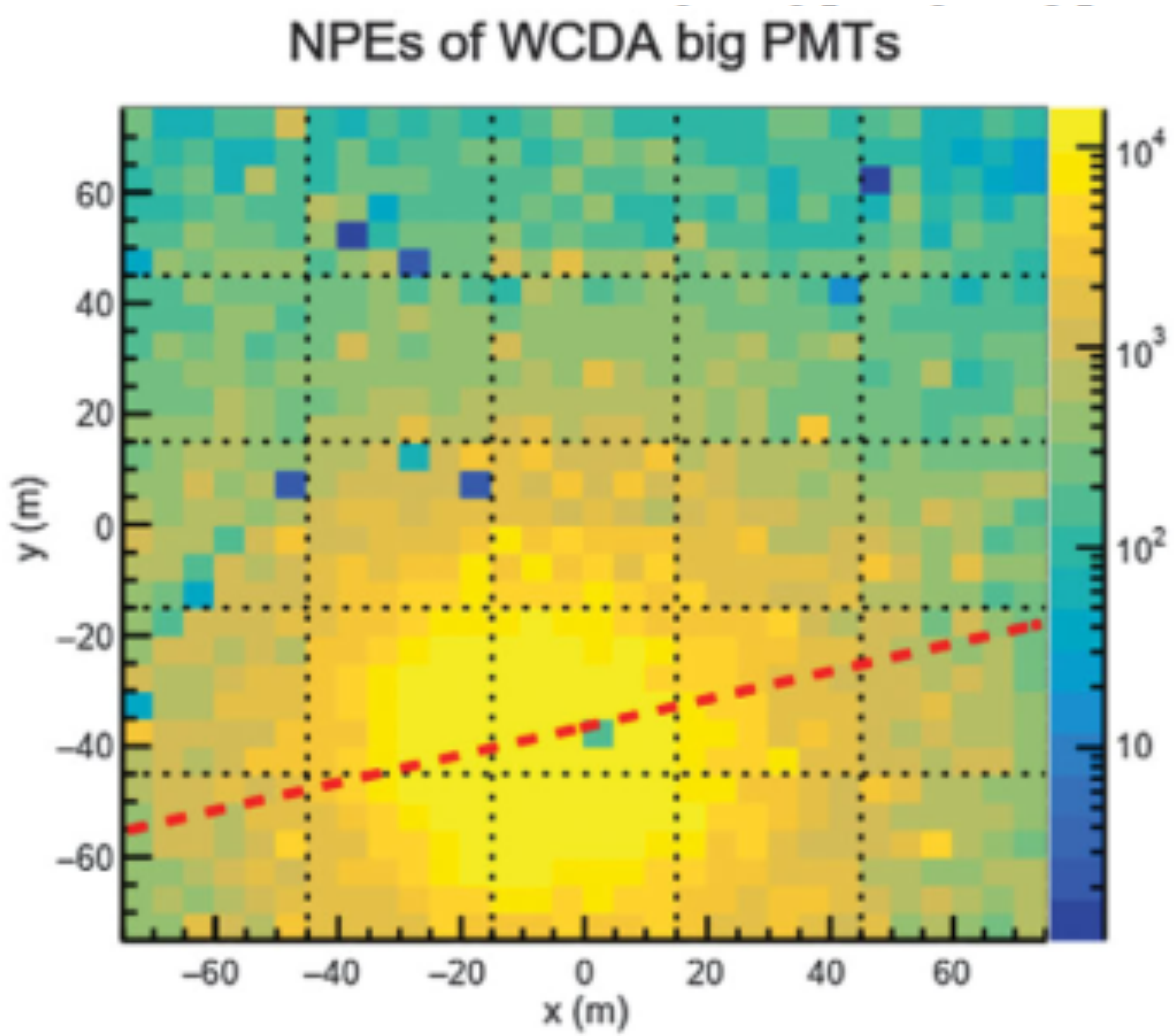
Data Set of WCDA-1+WFCTA:

- Telescope FoV: 22°<Zenith angles <38°
- N_{hit}>200 (Energy Proxy for WCDA)
- 20k<N_{pe}<60k Energy Proxy for WFCTA)
- shower cores fall inside WCDA-1:



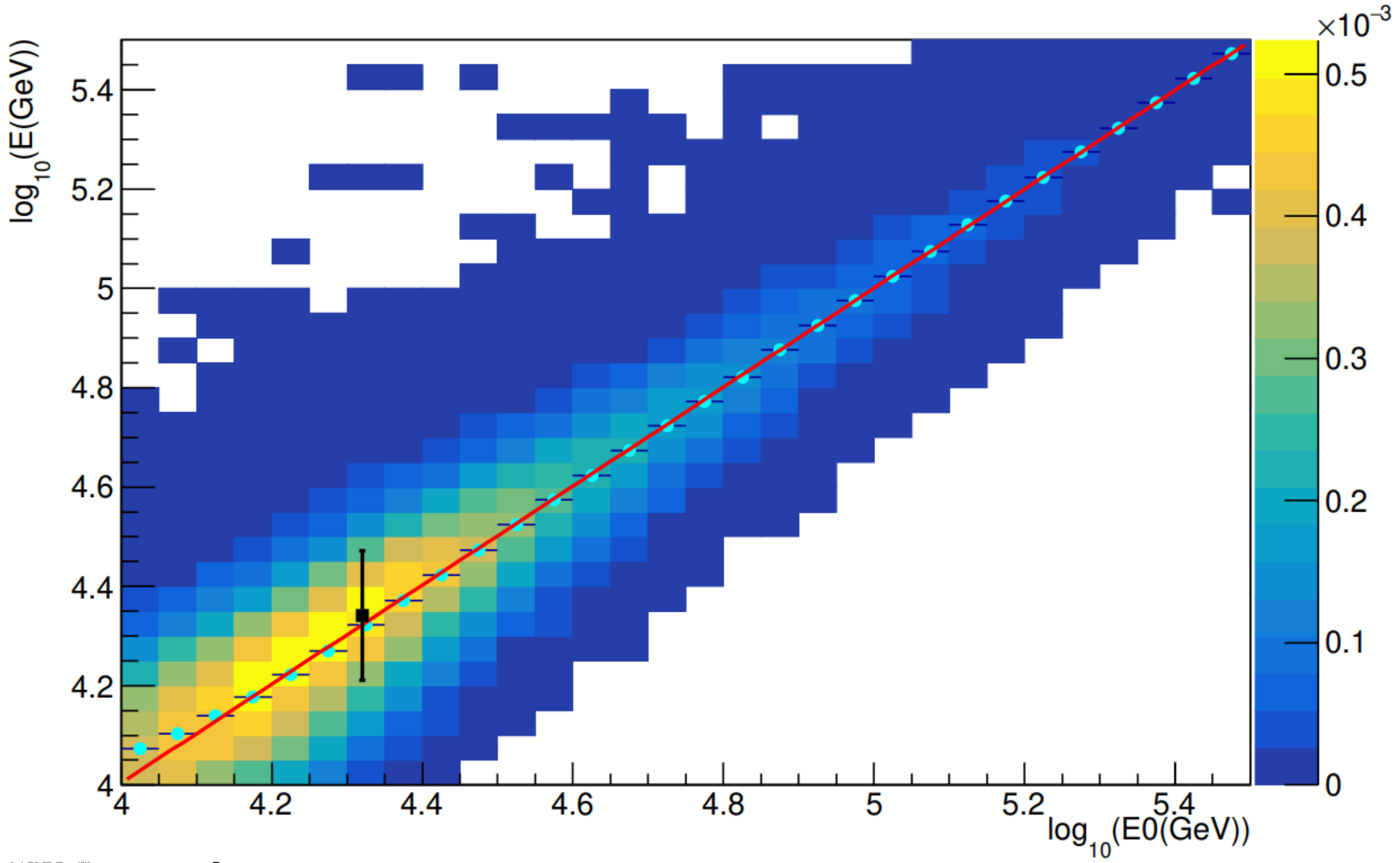






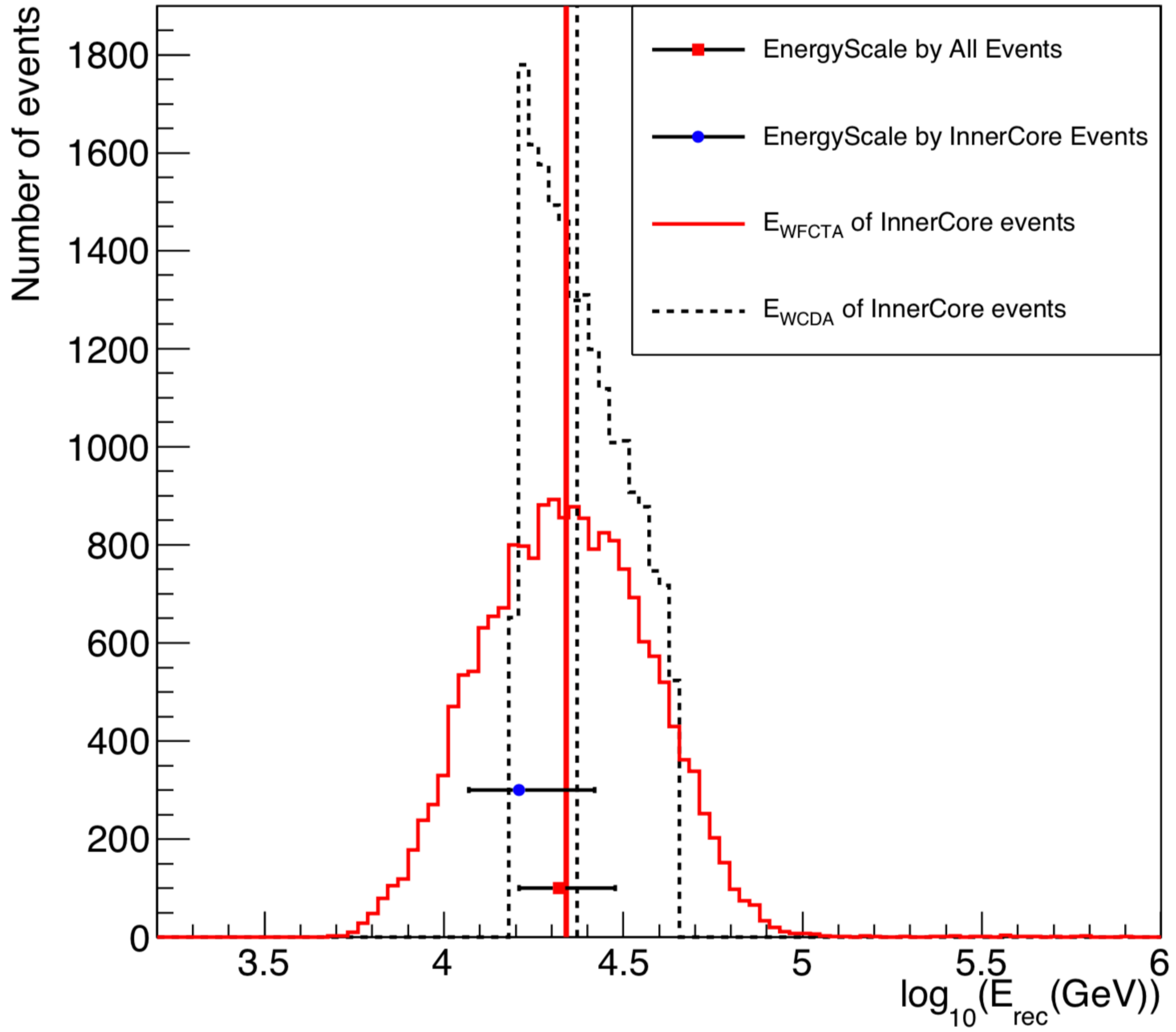
Absolute energy scale of WFCTA

- And then the absolute energy scale obtained by WCDA is propagated to WFCTA by using the common trigger events.
  - The energy reconstructed by WFCTA is 21.9 ±0.1 TeV;
  - 23.4±0.1±1.3 TeV by the formula of the absolute energy scale.
  - The two energies are consistent with each other within uncertainties.
- It is the first time that the Cherenkov telescopes have the absolute energy scale.



WCDA Calibration result (8 months, one pool)：

✓21.0 ±6.5 TeV for all events
✓16.2 ±6.2 TeV for shower core falling inside WCDA.
✓The uncertainty largely dominated by the low statistics. After 4 years, the uncertainty will be < 10%.

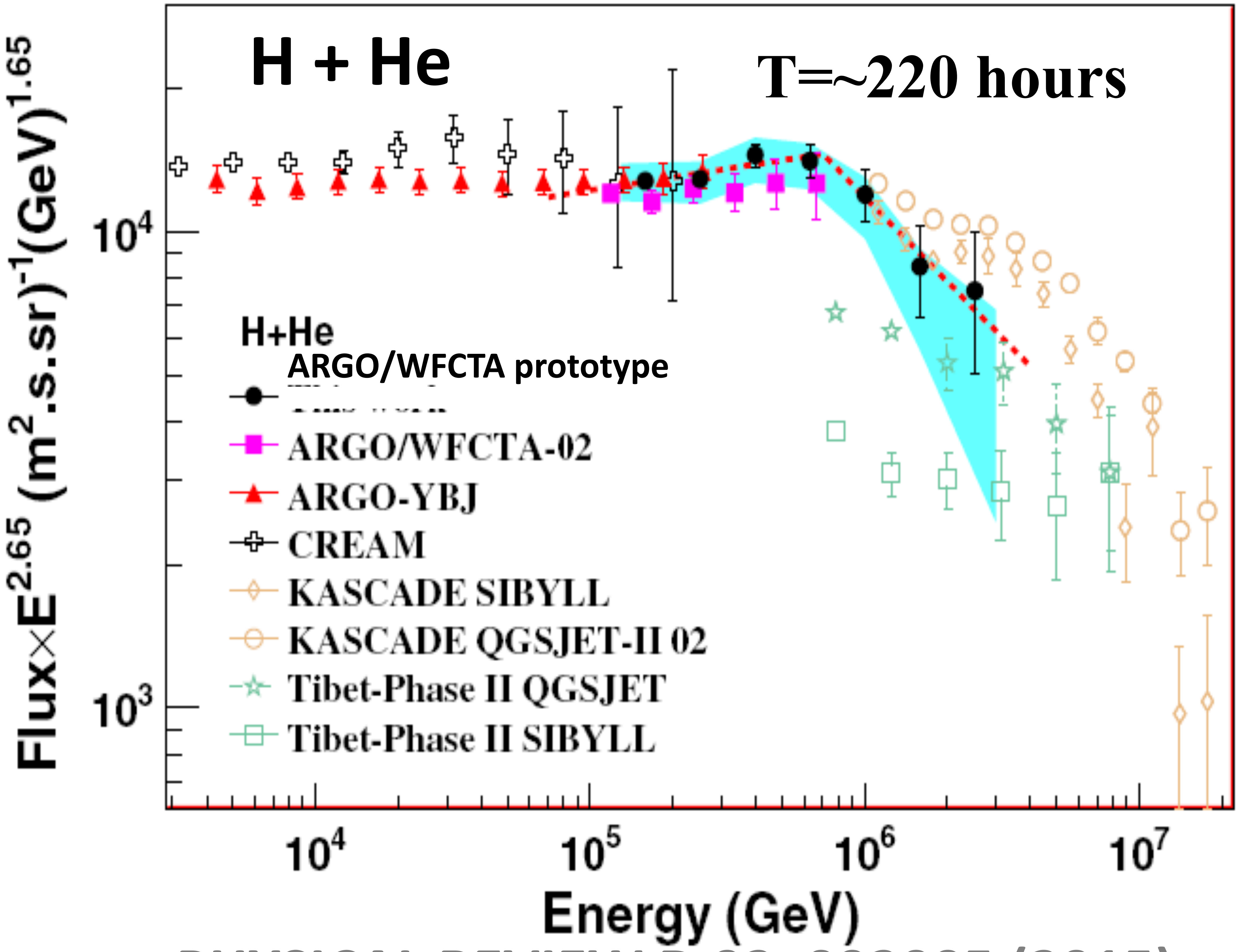


LHAASO Collaboration, Phys. Rev. D 104, 062007 (2021)

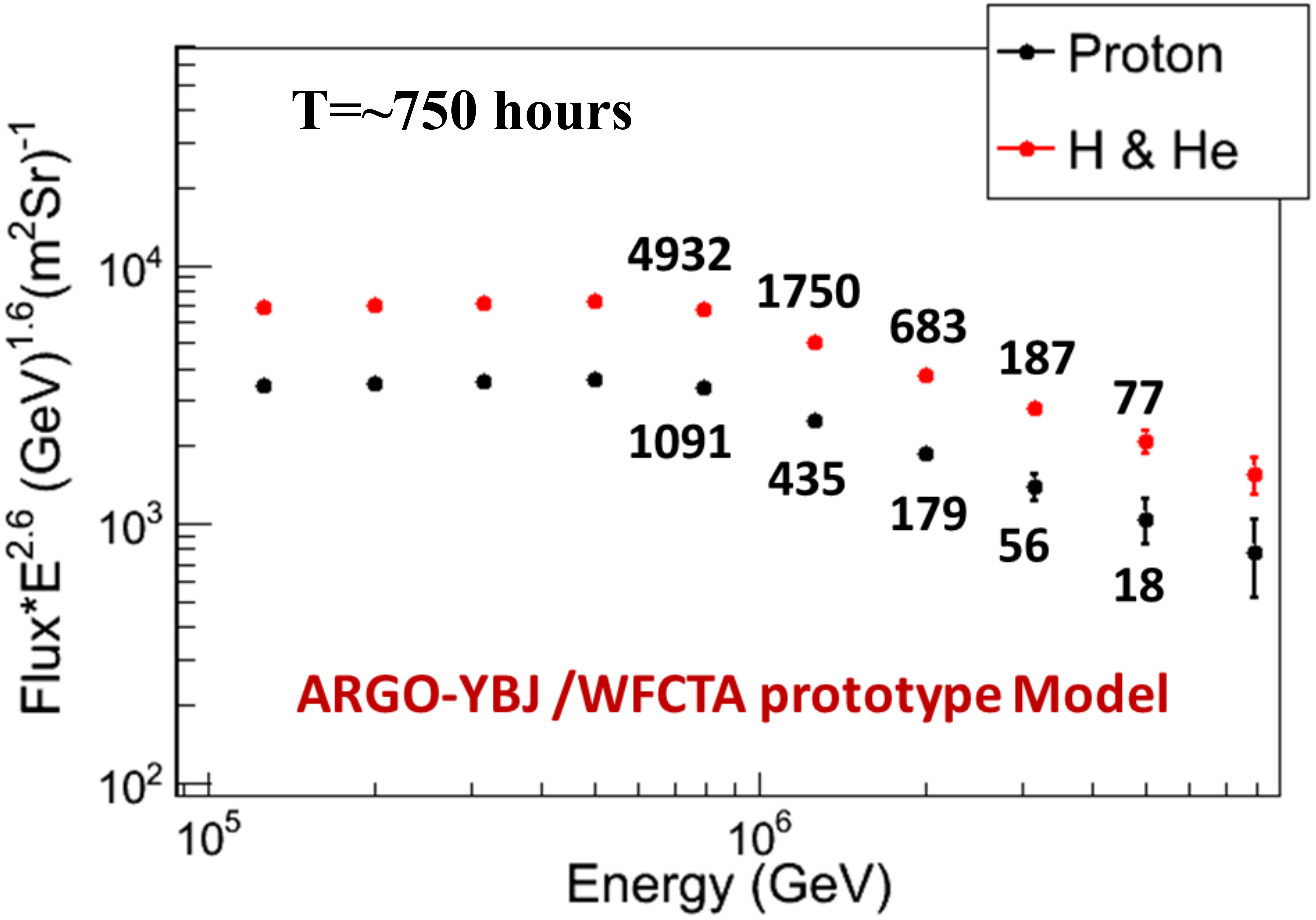
H and H+He spectra expectation by LHAASO

ARGO-YBJ + a Cherenkov prototype
The knee of H&He spectrum at
(700±230) TeV is measured

by six telescopes of LHAASO (zenith 60°)
during period of 2020.11 ~ 2021.04

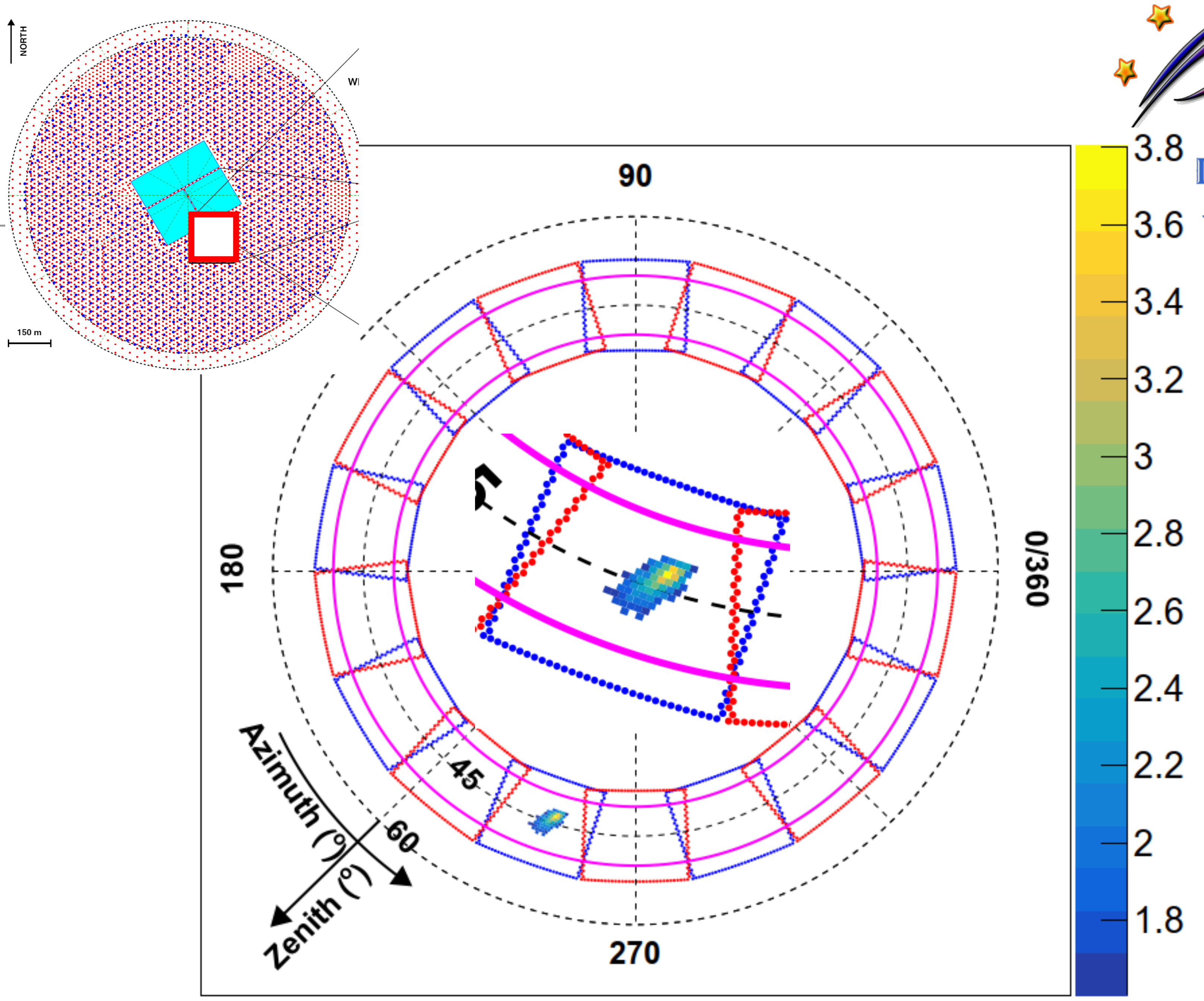


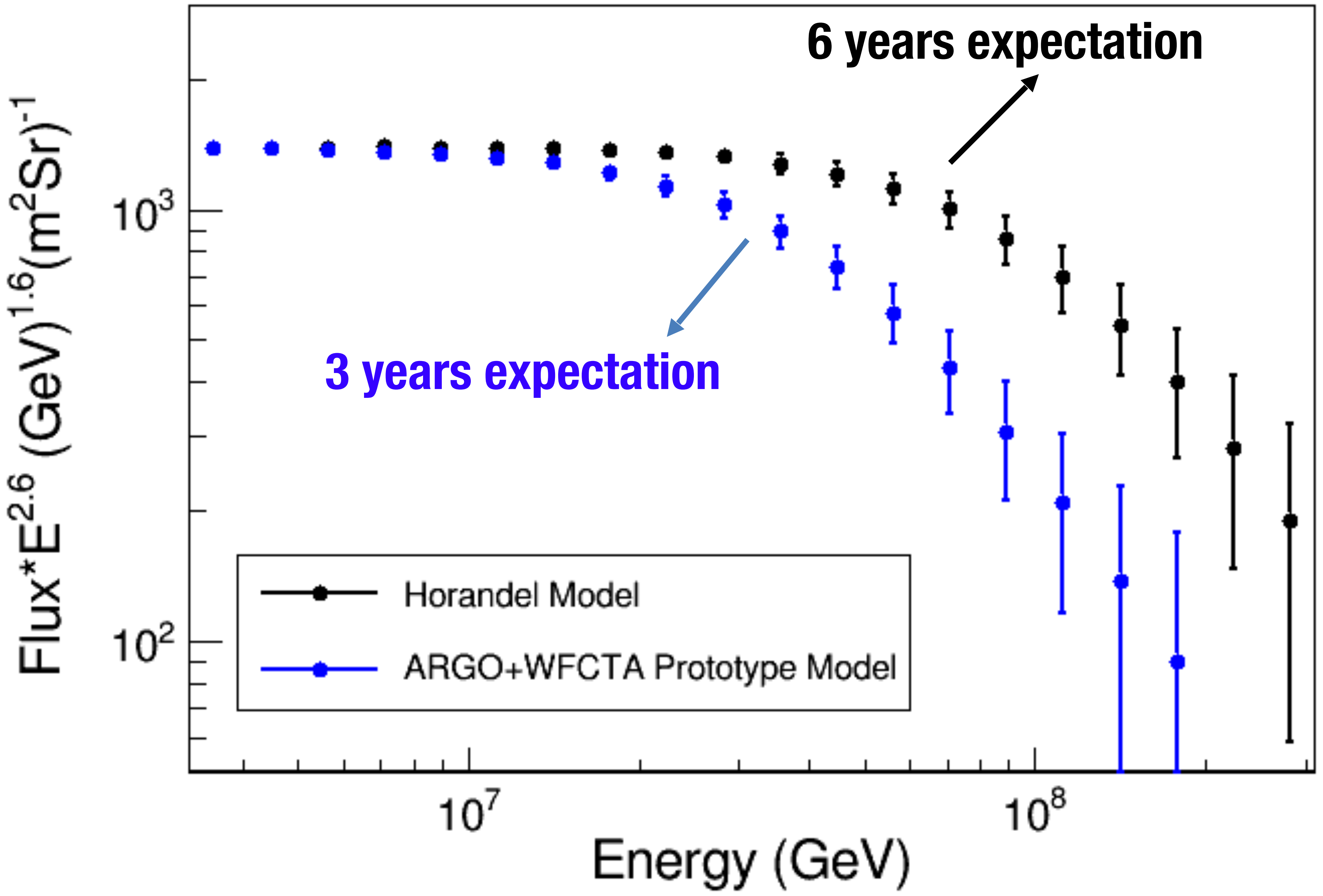
PHYSICAL REVIEW D 92, 092005 (2015)

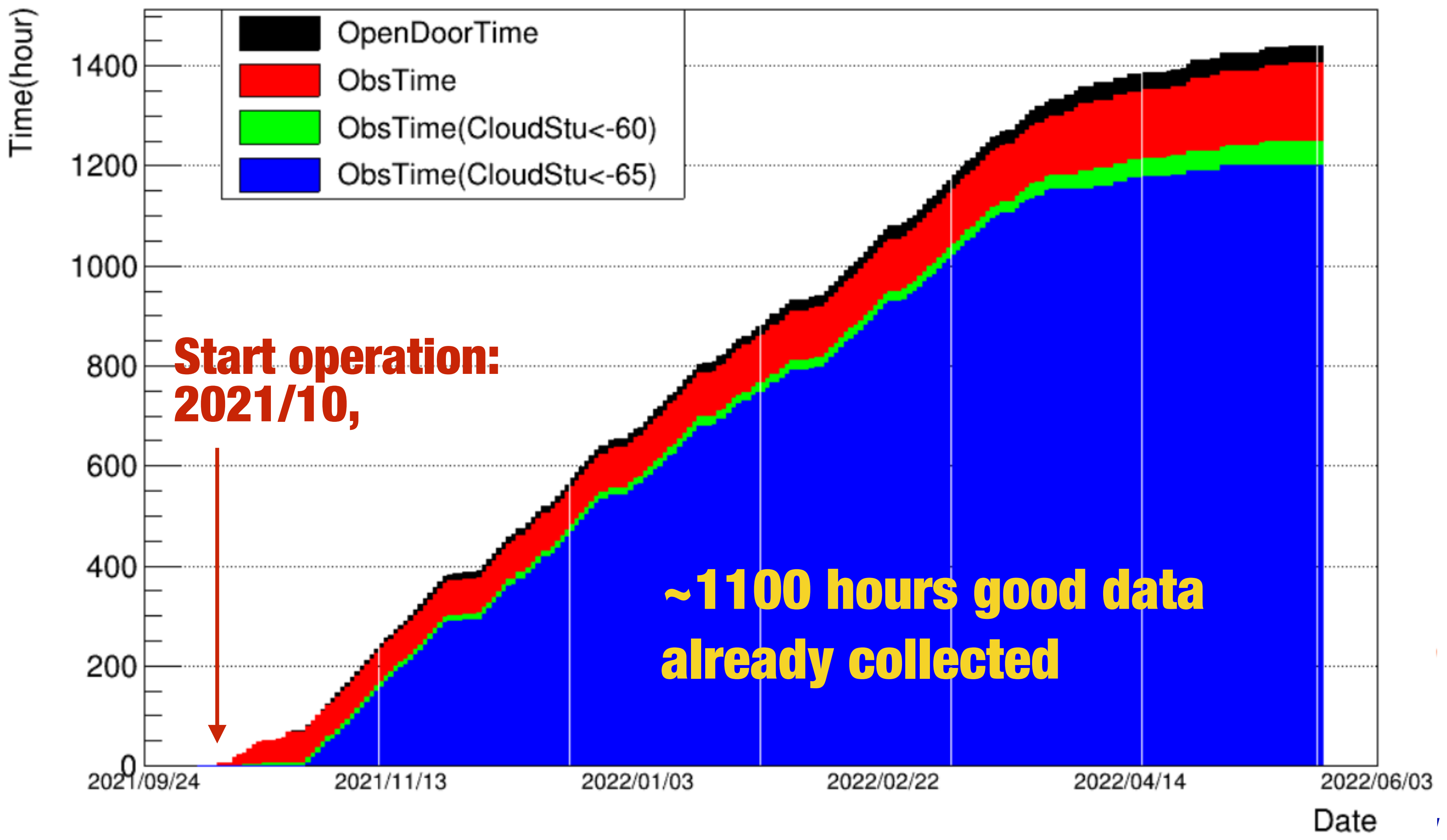


Iron knee expectation by LHAASO

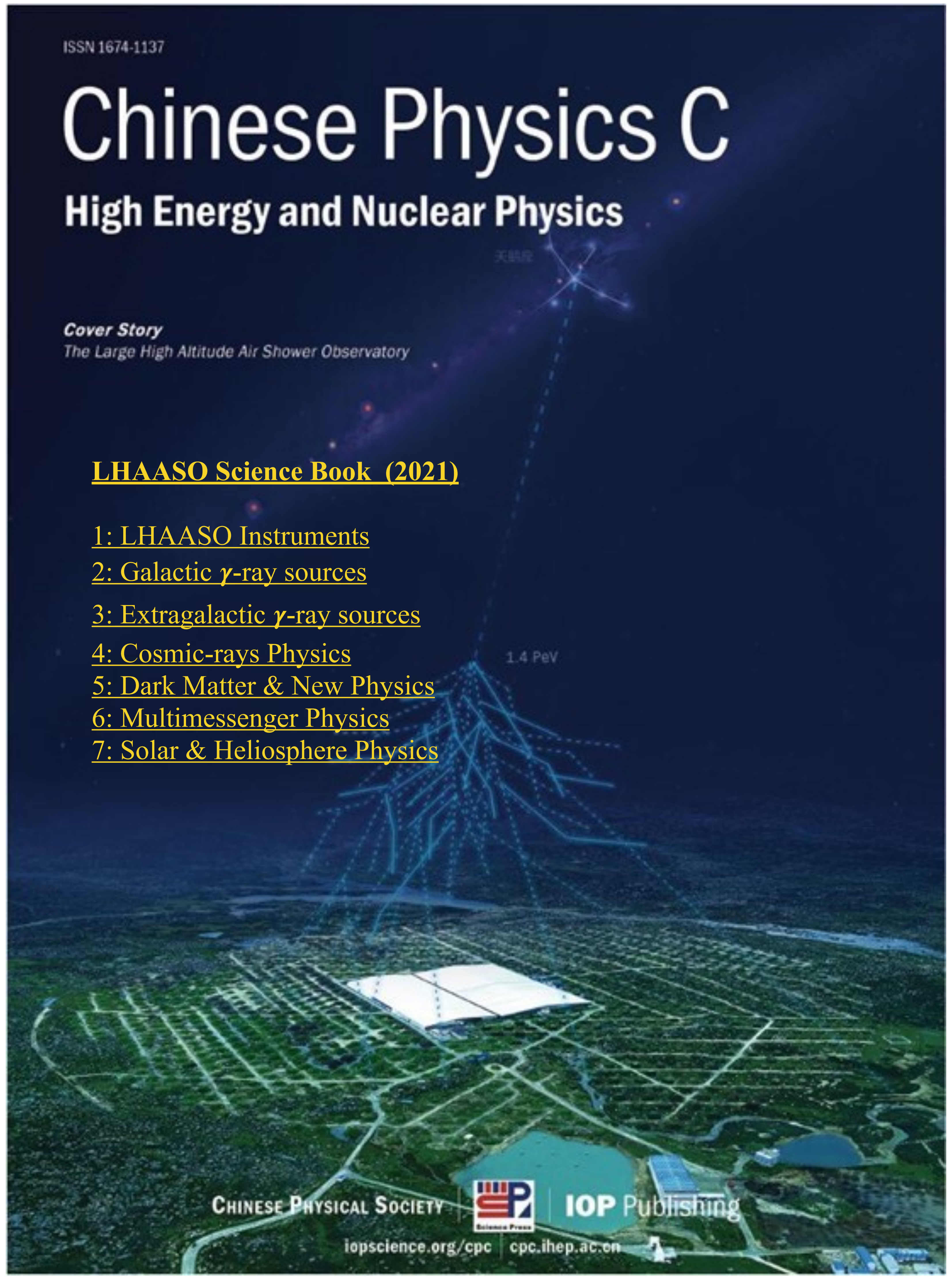
- Iron knee energy spectra observation：
  - 18 telescopes point to zenith 45, cover azimuth 0-360
  - WFCTA + KM2A (full array is used)
  - Energy range：several PeV - 200 PeV
- H and H+He can also be measured in this mode.



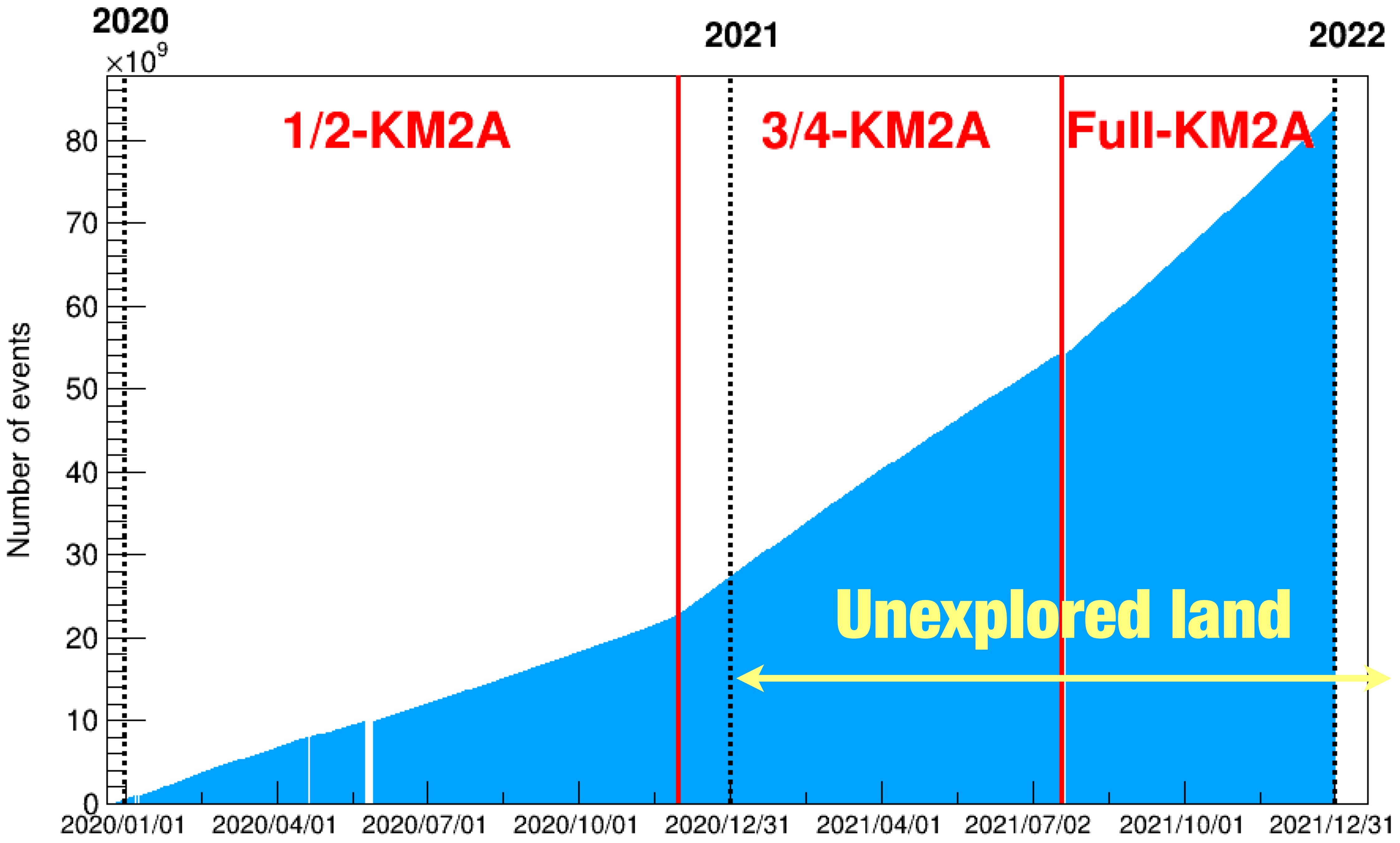




Conclusion



- The results published so far can be considered as the tip of the iceberg, being achieved with a partial array,



- In the coming years, we expect many breakthrough discoveries by LHAASO that could dramatically change the current understanding of the most energetic and extreme phenomena of the non-thermal Universe.

Stay Tuned …… and join LHAASO

Thank you!