Opening the PeV era in γ-ray astronomy LHAASO highlight

LHAASO
高海拔宇宙线观测站

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

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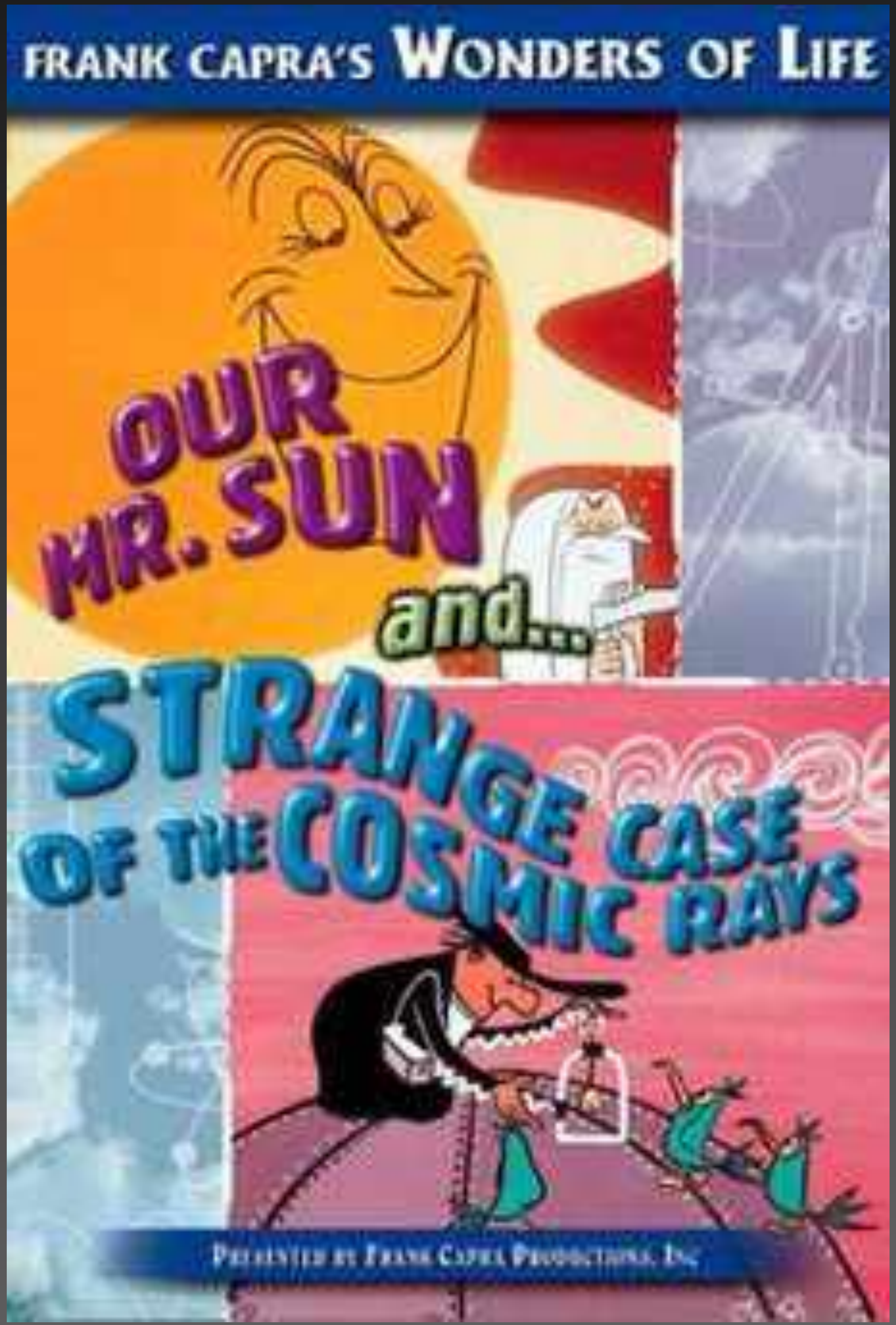
IIHE Inter-University Institute For High Energies,

Brussels, 5th April 2024

Origins of Cosmic Rays

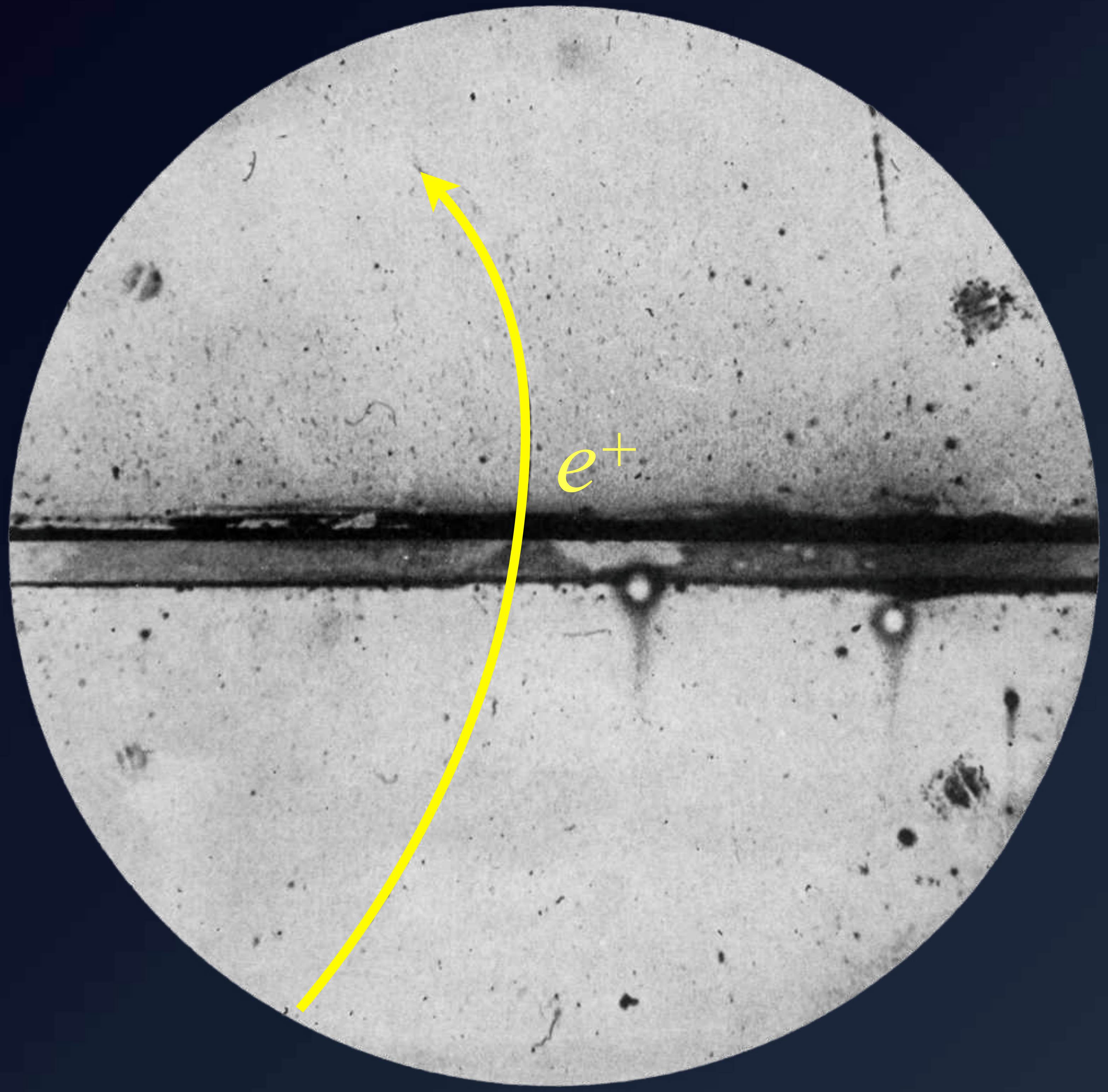
- **Every second ~ 10’000 particle per m^2 reach the earth**
- **Extraterrestrial origin of CR ‘discovered’ by V. Hess in 1912**
- **Standing quests**
  - **WHAT ARE COSMIC RAYS?**
  - **WHERE DO THEY COME FROM?**
  - **HOW COSMIC RAY ARE**
    - **PRODUCED,**
    - **ACCELERATE AND**
    - **PROPAGATE THROUGH THE UNIVERSE?**

F. Capra for W. Disney production, a 1957 movie written by Anderson & Rossi (!)



The name cosmic rays is due to Millikan
"The Origin of the Cosmic Rays" PRL, 32 (1928) 533

The historical roles of Cosmic rays Physics

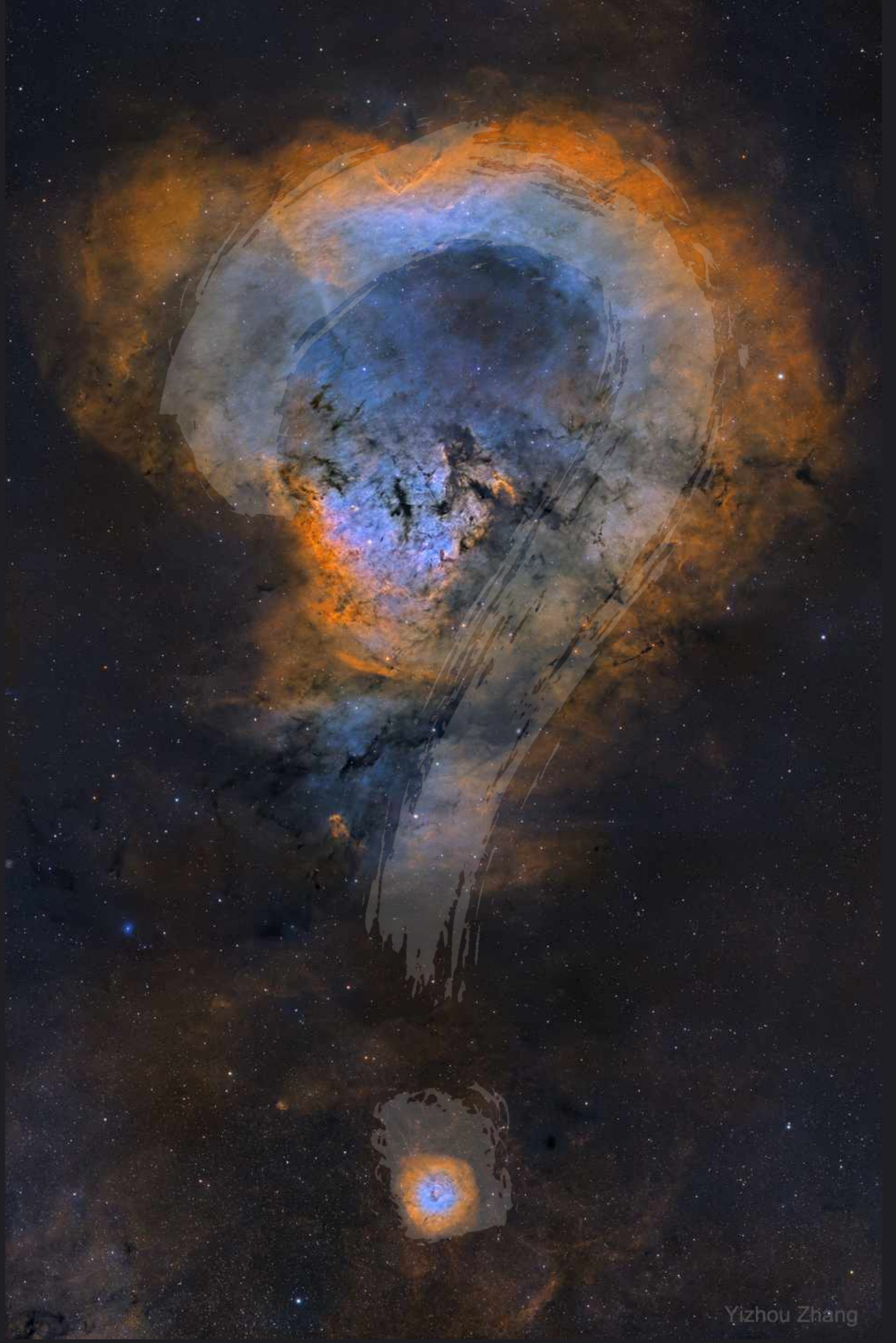


1932: Discovery of the positron, electron antiparticle by Anderson

https://timeline.web.cern.ch/timeline-header/146

- Universe: a laboratory of fundamental and particle physics
- Cosmic ray historical importance
  - *Discovery of antiparticles*
    - ☐ $e^+, \mu, \pi,$ Strange particles
    - ☐ ν flavour mixing, in Solar and atmospheric flux
- Now, TeV astronomy opens to
  - *Most violent processes in the Universe,*
  - *Probe fundamental physics at Extreme energies.*

What are cosmic rays



NGC 7822: Cosmic Question Mark
Image Credit & Copyright: Yizhou Zhang

- **A local phenomenon ?**
- **A more fundamental issue ?**

'4th substance' of the visible Universe.

(after the matter, radiation and magnetic fields)

F. Aharonian

$\rho_{CR} \sim 1\ \mathrm{eV/cm^3}$ Energy Density of CR

$\rho_{gas} \sim 1\ \mathrm{eV/cm^3}$ IS Gas/plasma density

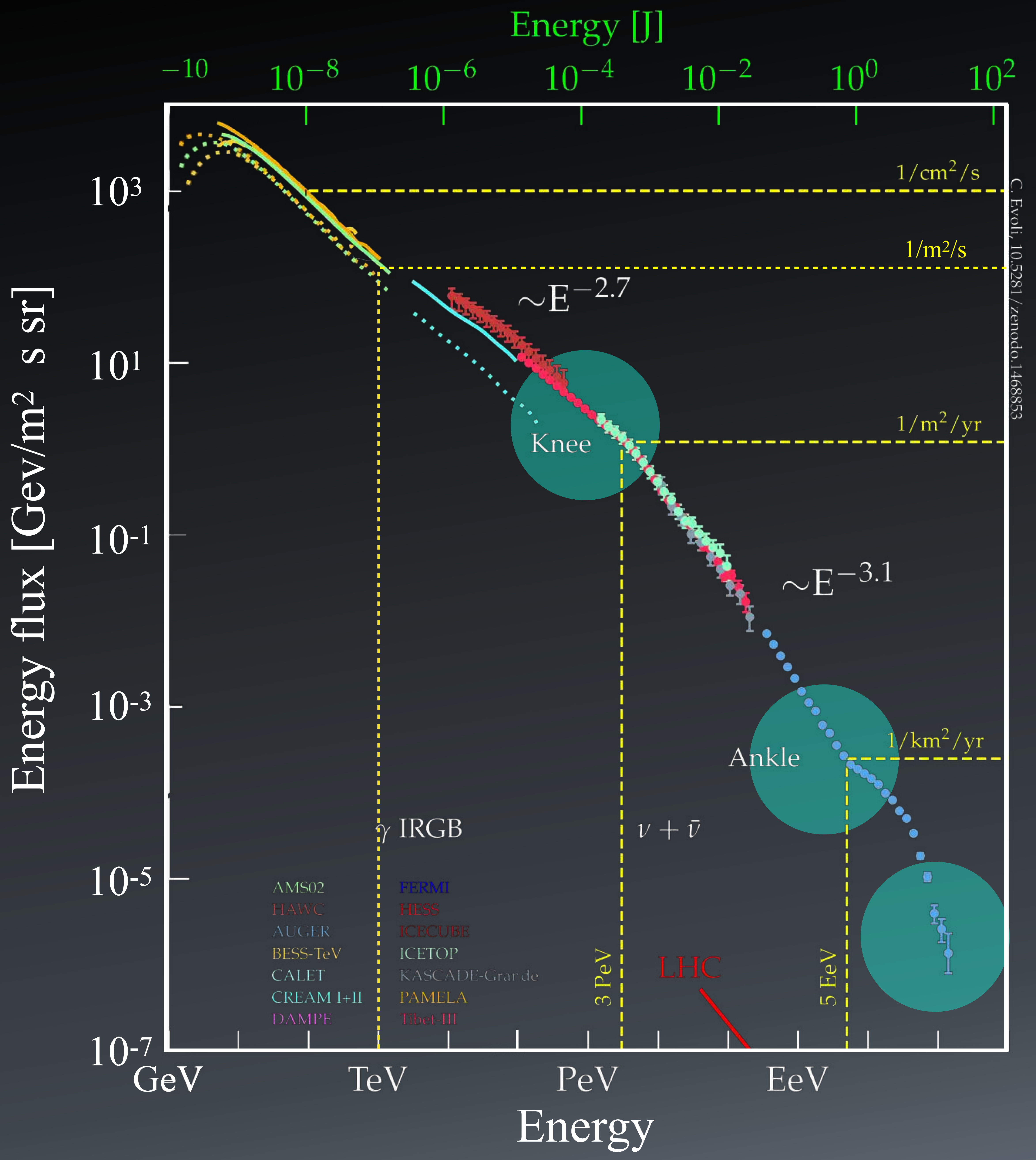
$\rho_{B} \sim 1\ \mathrm{eV/cm^3}$ IS Magnetic Field density

$n_{ISM} \sim 1\ \mathrm{/cm^3}$ IS Particle density

IS= Inter-Stellar

The Riddle of cosmic rays is still unsolved …

…. but we know quite some things



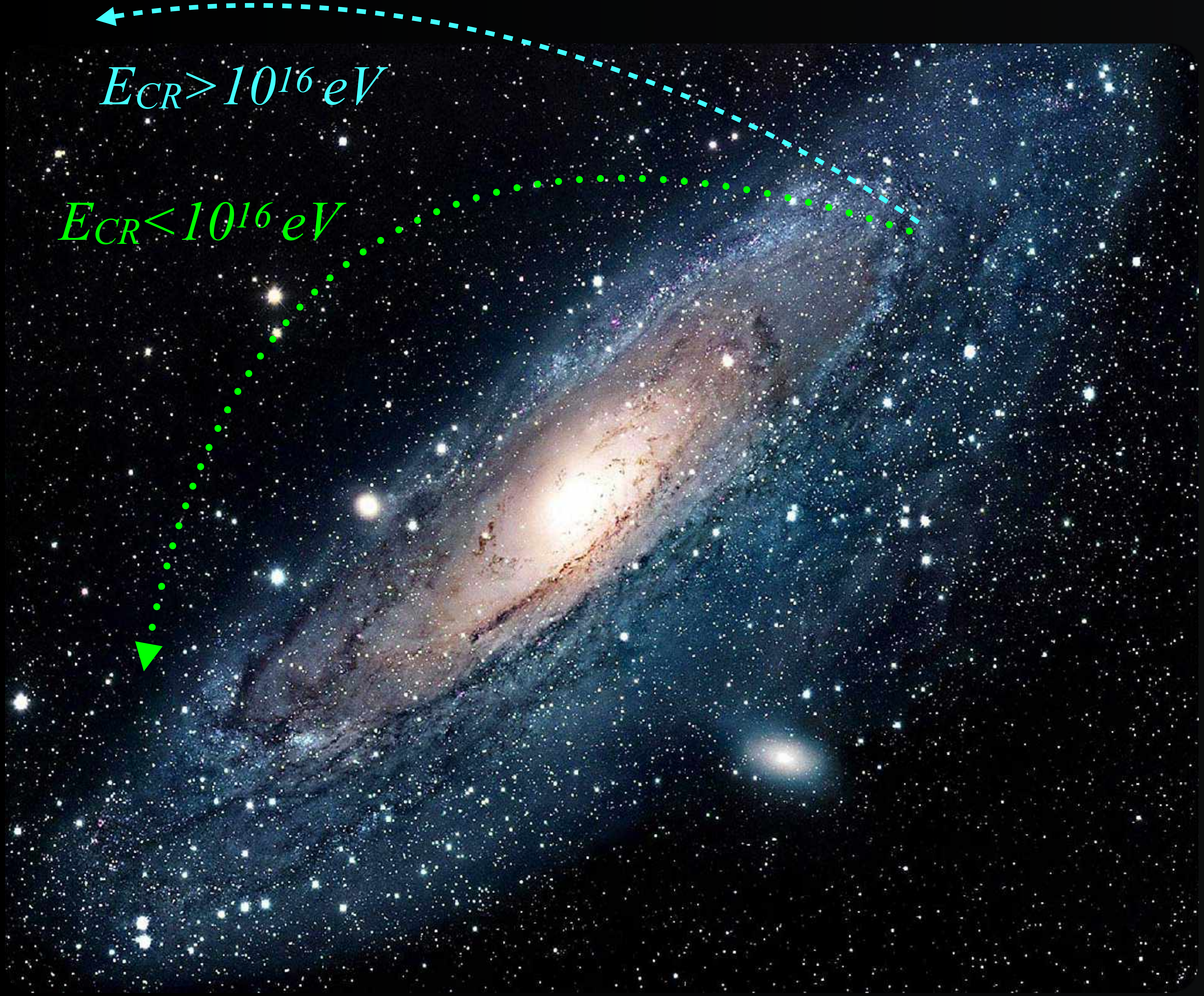
CR spectrum [Flux]

- **CR are relativistic charged particles**
  - *Below the 'knee' 92% protons, 6% Helium, 1% Heavier nuclei and 1% electrons*
  - *Composition changes with energy*
- **Isotropic flux up to Very High Energies**
- **A power law spanning over many decades**

$$I(E) \approx 1.8\ E^{-\alpha} \frac{\text{particles}}{\text{cm}^2 \cdot \text{sr} \cdot \text{GeV}}$$

- **Exhibit features:**
  - ➡ ***Knee*** *~1 PeV Flux~ 1 particle/m²/year*
  - ➡ ***Ankle*** *~EeV Flux ~ 1 particle/km²/year*
  - ➡ ***GZK cut-off*** *(Greisen–Zatsepin–Kuzmin limit)*

The knee: Galactic/Extragalactic



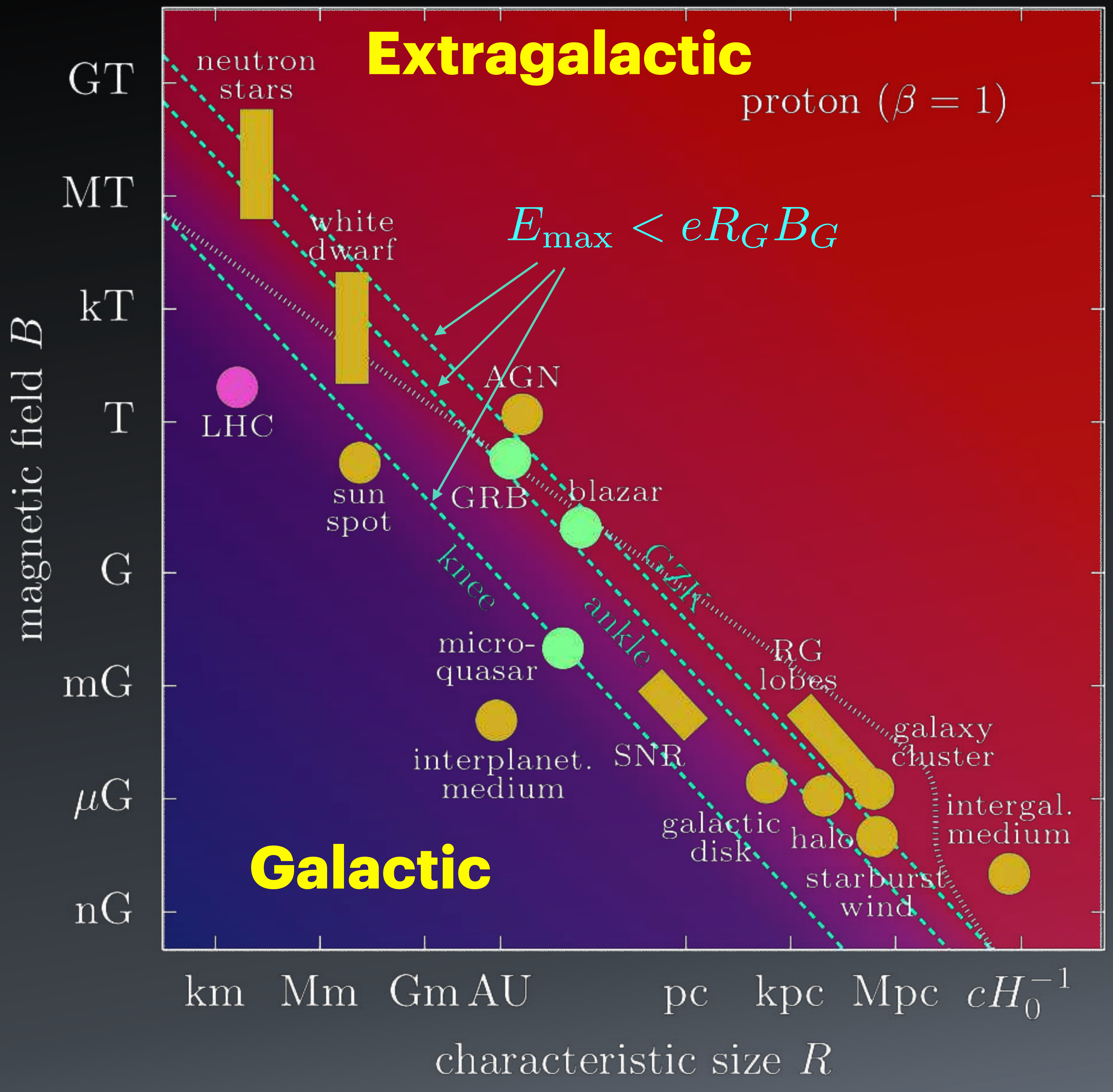
- **Below KNEE Galactic Origin**
  - ➡ ***Larmor Radius.*** $R_L = \frac{pc}{ZeB} \approx \frac{E}{qB}$
  - ➡ ***Galaxy:*** $B_{Gal} \sim \mu G$, $R_{Gal} \sim kpc$

$$\Longrightarrow E_{max} < R_{Gal} \cdot B_{Gal} \sim 10^{16}\ eV$$

- **Propagate diffusively in the galaxy**

  Drift path: $l_s \sim Mpc \gg R_{Gal.}$

- **Power of CR.** $\sim 10^{41}$ erg/s



Hillas criterion

- *'Geometrical' criterion*
  - ➡Confinement by Magnetic field 'trapping'
  - ➡E_{max}= *Minimum to 'escape'*

$$R = \frac{E_{max}}{ZeBc\beta}$$

- More general expression

$$B_{\mu G} \cdot R_{pc} \leq \frac{2E_{PeV}}{z\beta}$$

- Propagation is affected by
  - Intergalactic Magnetic Field
  - Intergalactic Matter/dust
  - Background Photons

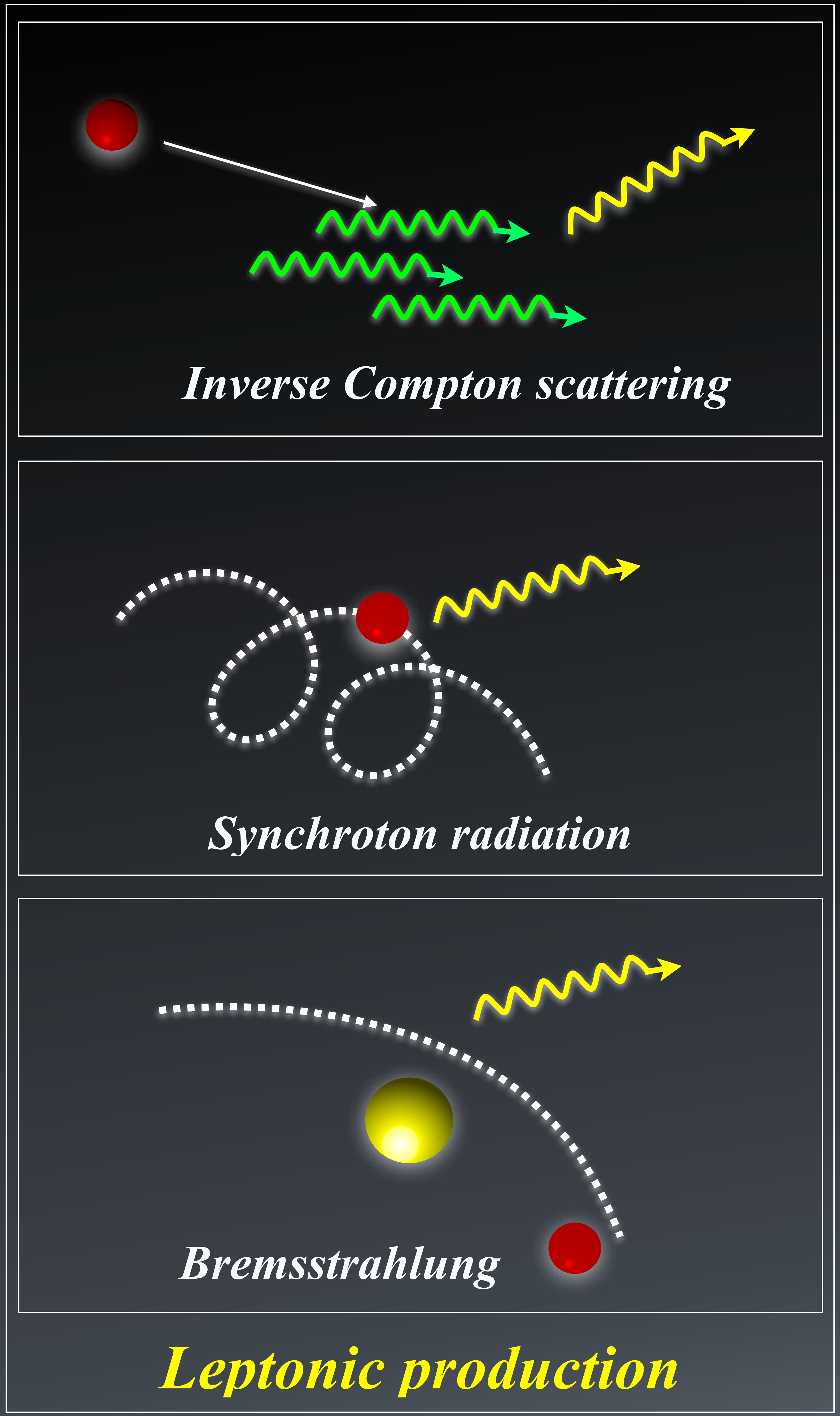
p	γ	ν	**The optimal astronomy messenger**
✓	✓	✓	- Not decaying along its travel path
✗	✓	✓	- Insensitive to Magnetic fields
✗	✗	✓	- Not attenuated by ISM medium
✗	✓	✓	- Penetrating
✓	✓	✗	- Easy to detect

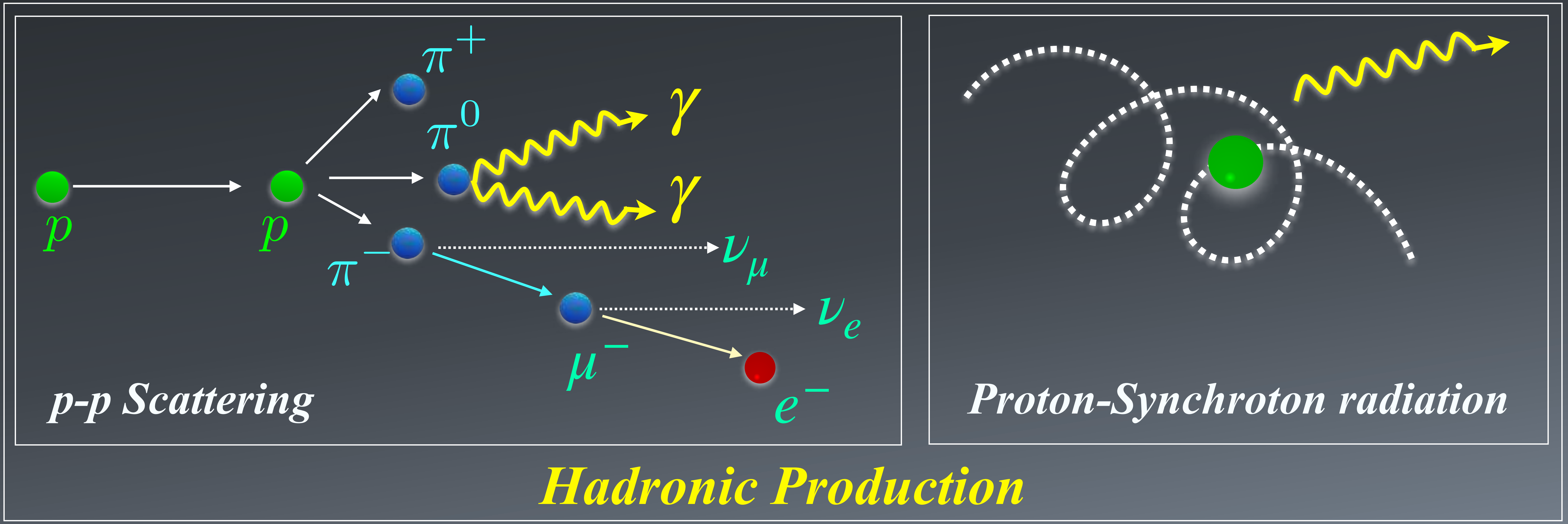
Why γ-ray* Astronomy?

Unique carriers of information about high energy processes in the Universe

- γ ***penetrate (relatively) freely***
- γ ***are effectively detected***
- γ ***are effectively produced***

$*E_\gamma > 1$ GeV

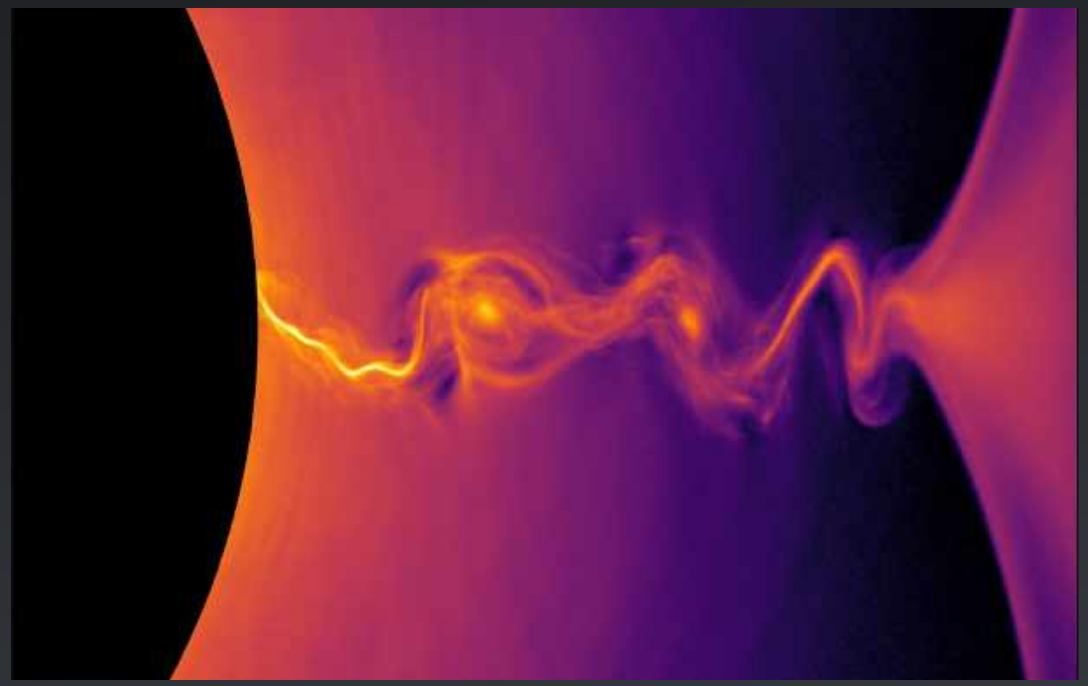




How to become a CR

- **Primary Cosmic rays (CR)**
  - *Directly accelerate:*
    - $p, A, \; e^{\pm}$

➡ ***Acceleration***



➡ ***Escape***

➡ ***Propagation***

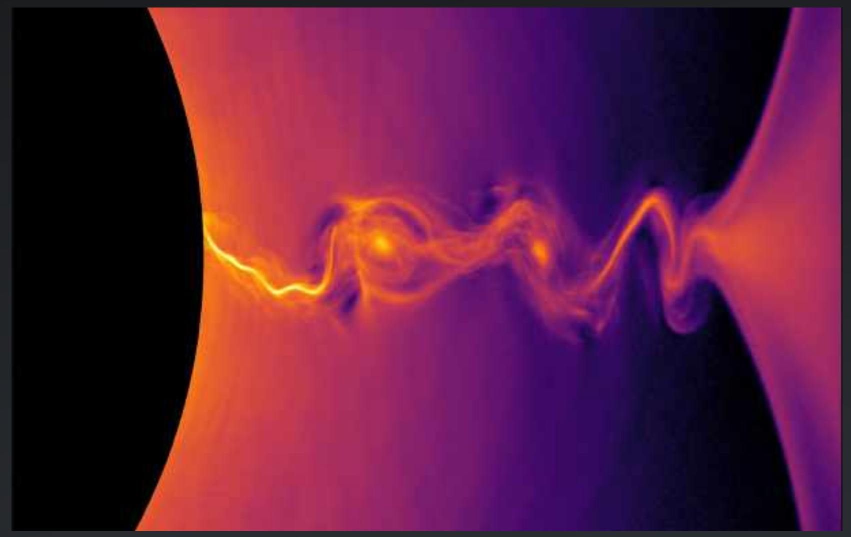
$$f_{acc}(E) \neq f_{esc}(E) \neq f_{prop}(E)$$

How to become a γ

- **Primary Cosmic rays (CR)**
  - *Directly accelerate:*
    - $p, A, \; e^{\pm}$
- **Secondary Cosmic rays**
  - *Produced in interaction with Inter-Stellar Medium (ISM):*
    $A, \bar{p}, \nu, \gamma, e^{+}$

➡ **Acceleration**

$S(E) \propto E^{-\alpha}$



➡ **Escape**

➡ **Production**

$D(E) \propto E^{-\delta}$

➡ **Propagation**

$\Phi(E) \propto E^{-\alpha-\delta}$

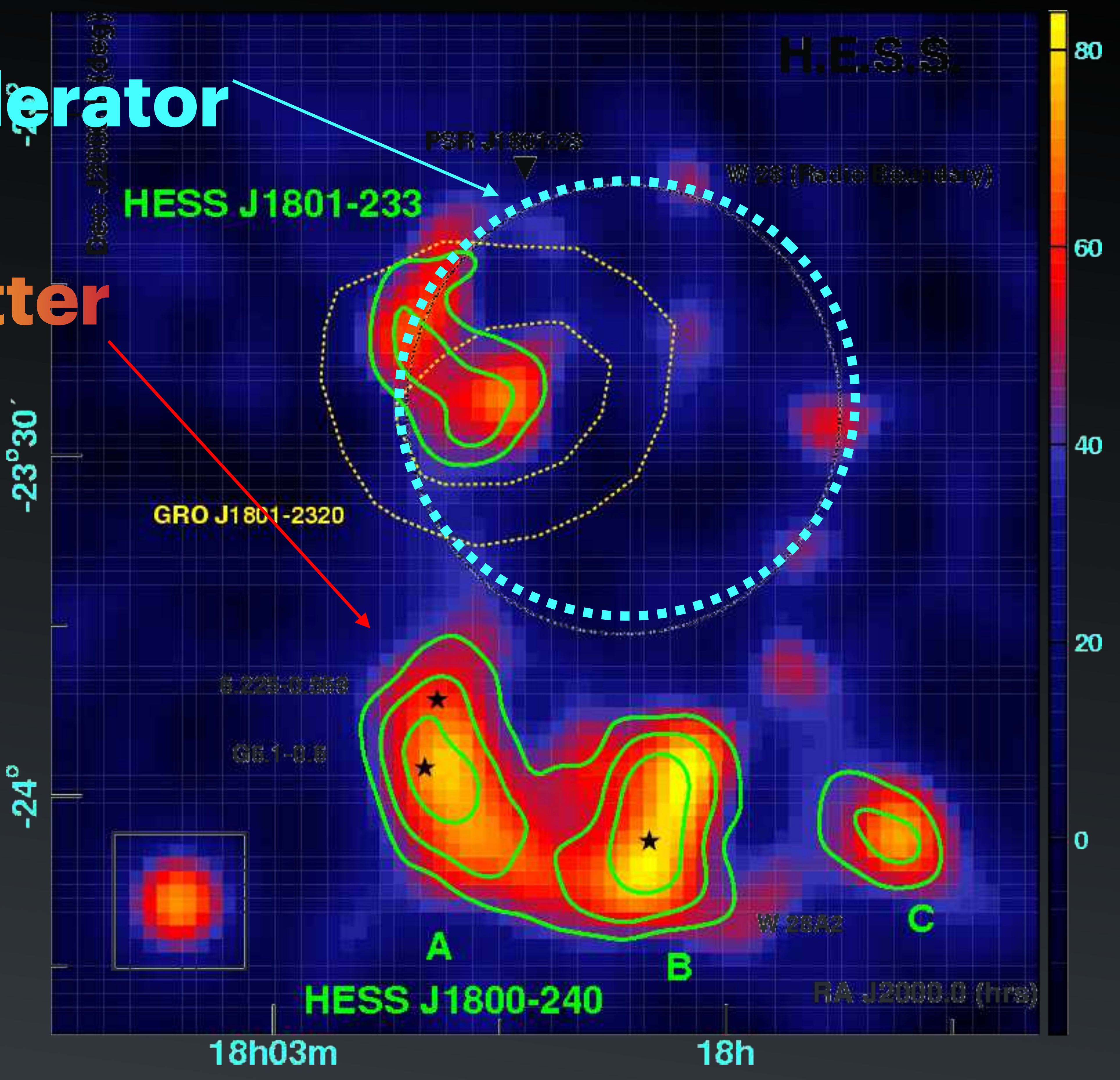
$$f_{acc}(E) \neq f_{esc}(E) \neq f_{prod}(E) \neq f_{prop}(E)$$

γ-ray production = Accelerator + Dense Target

particle accelerator

$\neq$

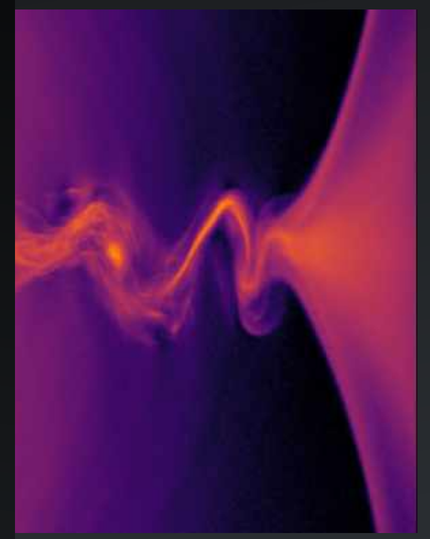
γ-ray emitter



$A, \bar{p}, \nu, \gamma, e^{+}$

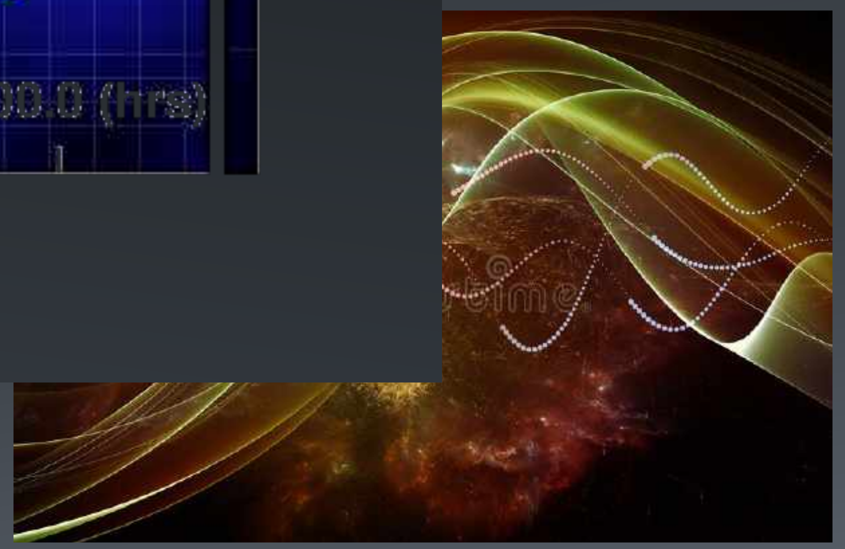
➡ **Acceleration**

$S(E) \propto E^{-\alpha}$



➡ **Escape**

➡ **Production**



$D(E) \propto E^{-\delta}$

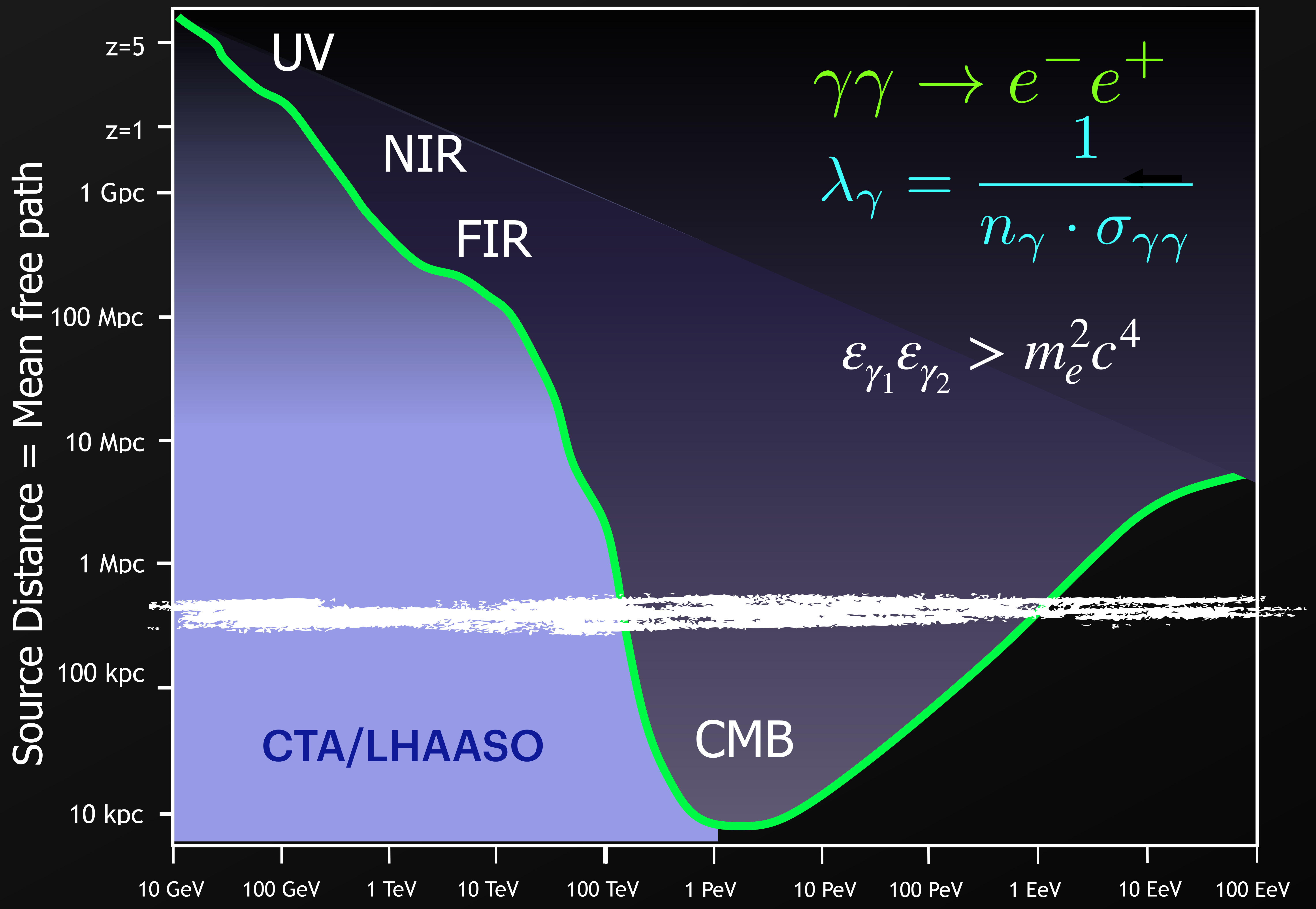
➡ **Propagation**

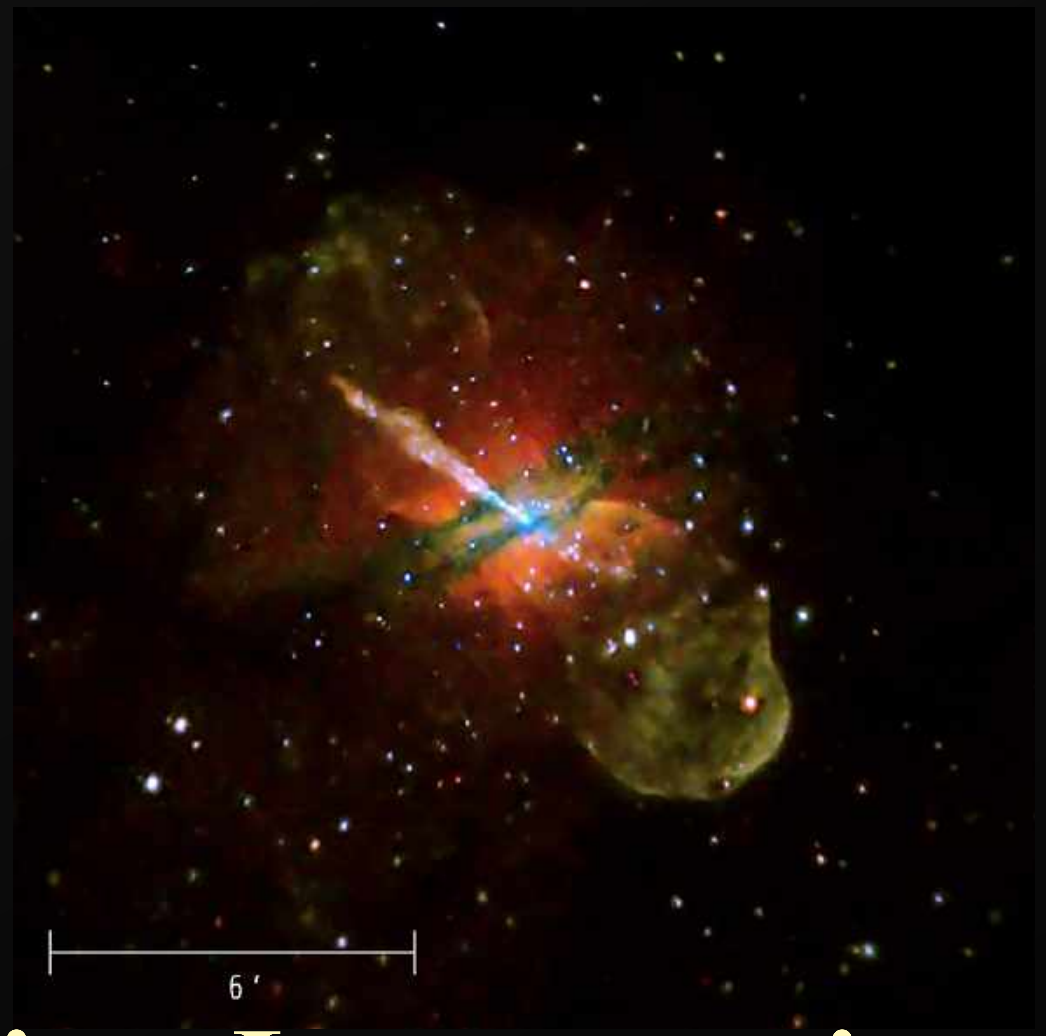
$\Phi(E) \propto E^{-\alpha-\delta}$

$f_{acc}(E) \neq f_{esc}(E) \neq f_{prod}(E) \neq f_{prop}(E)$

How far can we ‘see’ ?

The γ-ray Horizon



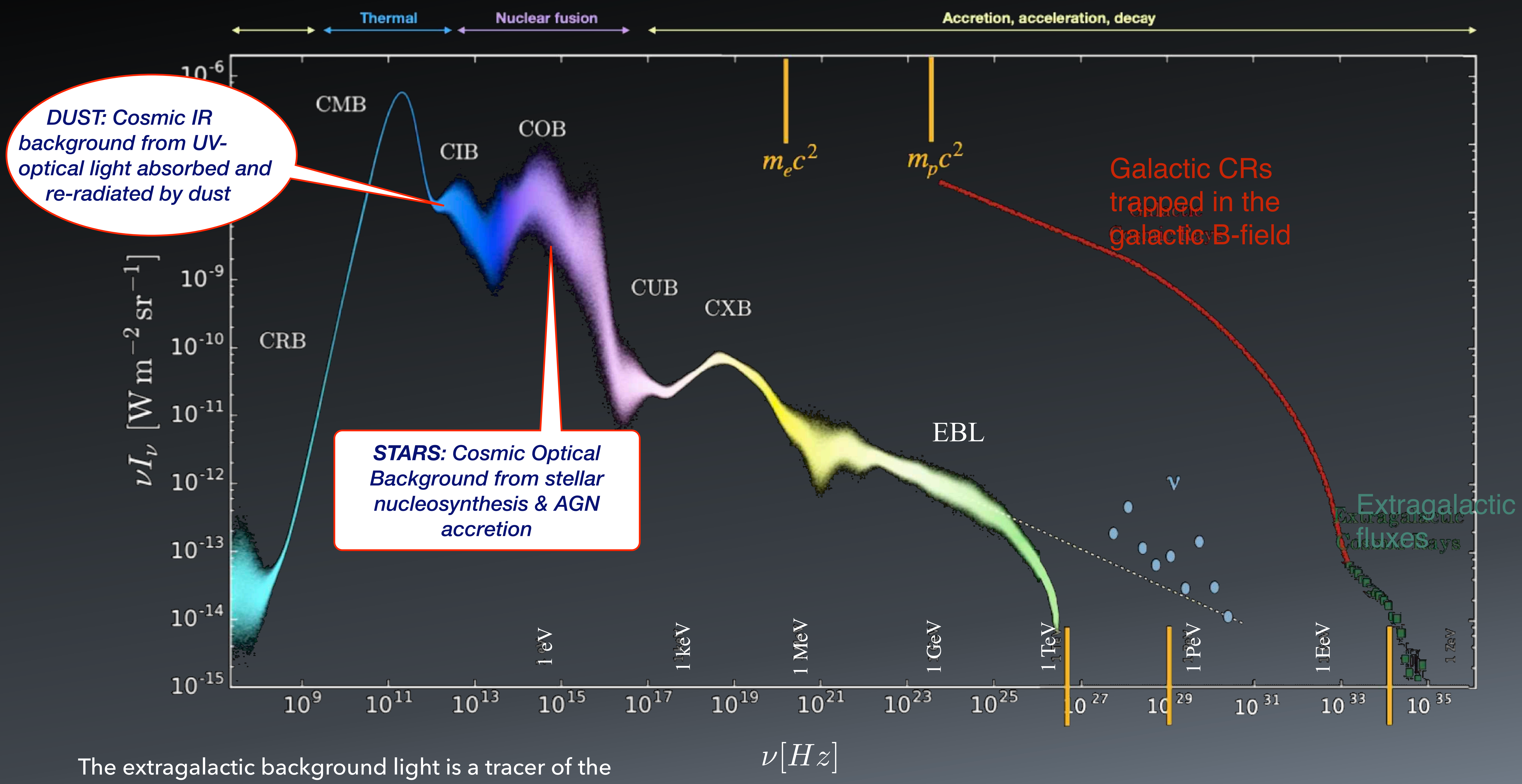


Extra galactic = Low energies

Milky way

Galactic = High energies

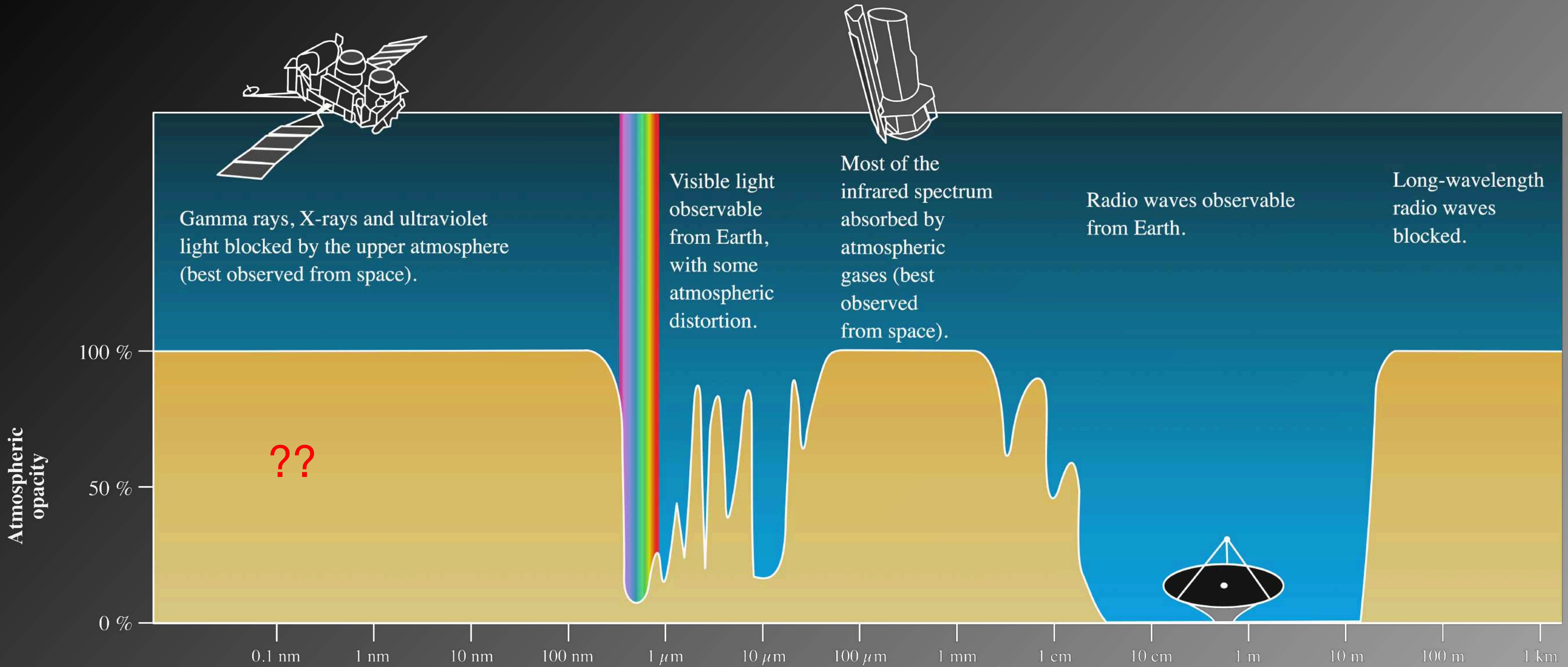
The Universe is not dark ….. full of light



The extragalactic background light is a tracer of the star formation processes across the Universe

R. Walter adapted from De Angelis & Mallamaci, 2018

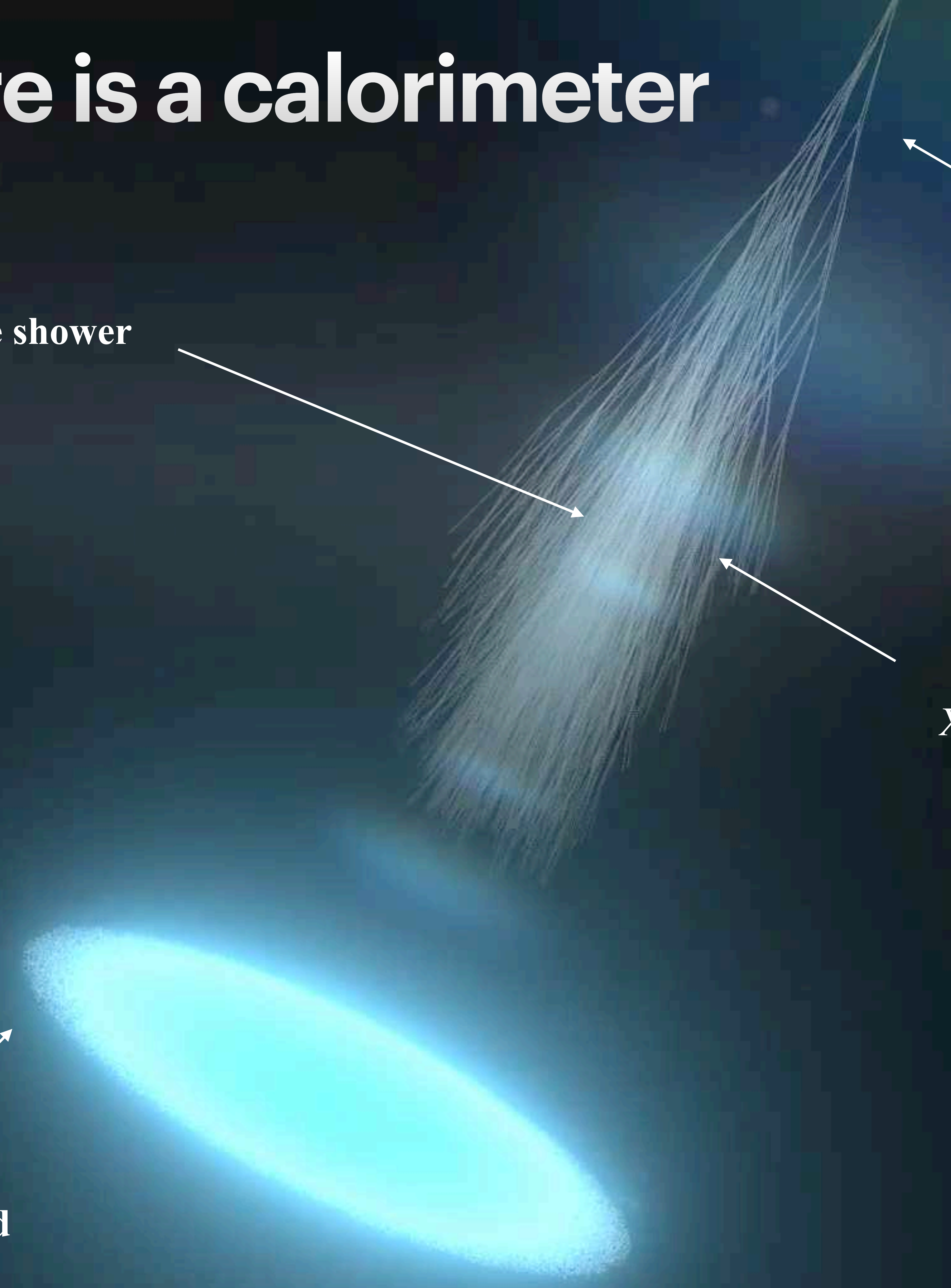
What can we see from ground?



High energy γ

Wavelength $\lambda = \frac{hc}{E}$

The atmosphere is a calorimeter



Extended Array Shower Detectors (EAS)
LHAASO

	Duty-Cycle	Field-of-View	Energy Resolution	Angular resolution	Zenith dependence
EAS	High (≈100%)	Large (2 sr)	20%	0.2°-0.8°	Very Strong $[\cos\vartheta]^7$
IACT	Low (~15%)	Small (5-10 deg)	>10 %	<0.1°	Weak $([\cos\vartheta]^{2.7}$

Imaging Air Cherenkov Telescopes (IACT)
CTA

Ground-based instruments

Bird-eyes' View of LHAASO， March, 2021

LHAASO Collaboration

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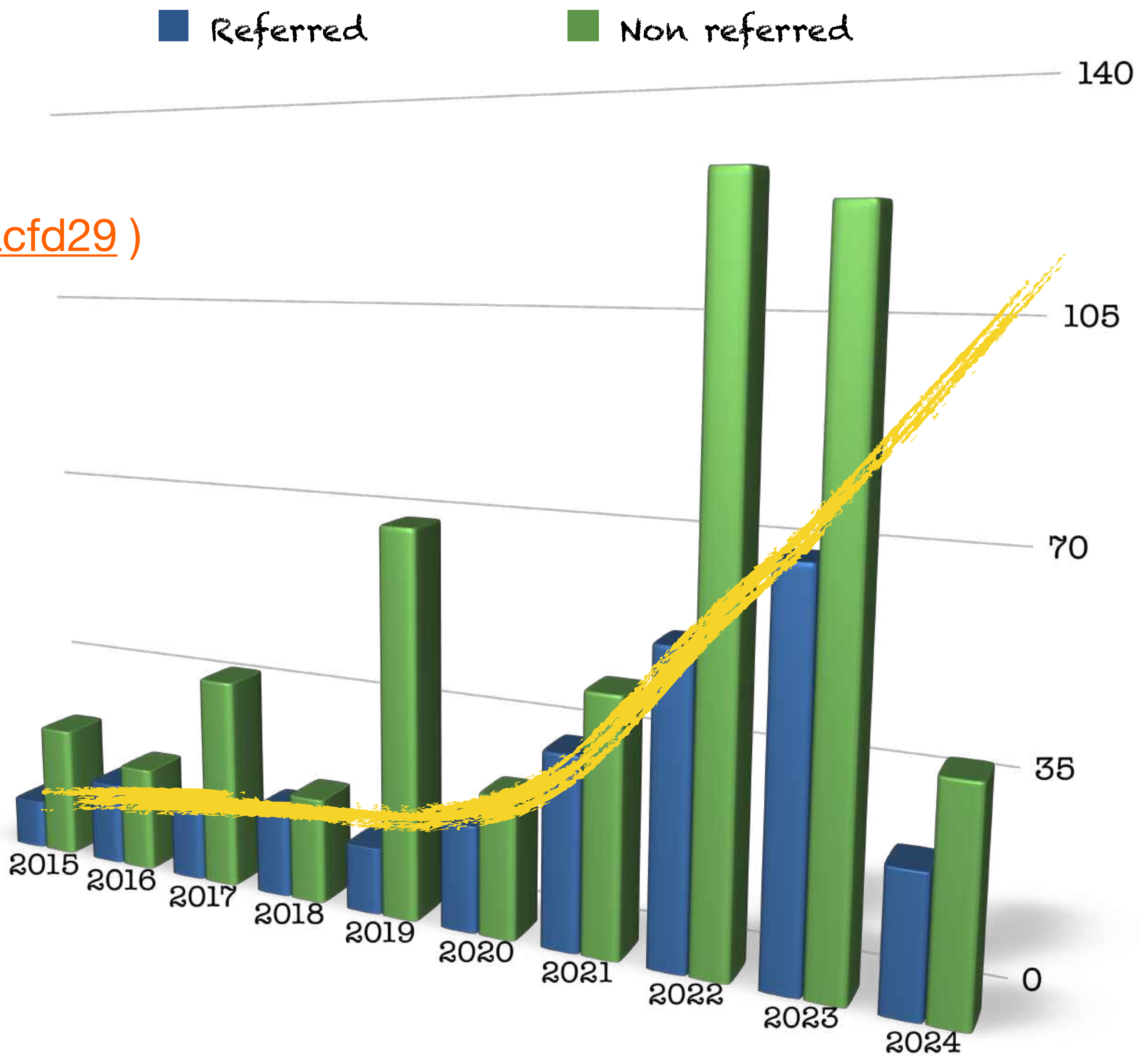
MoU signed: VERITAS, MAGIC, LST/CTAO, eROSITA-DE, ANTARES, Baikal-GVD, KM3NeT MWISP, FAST-CRAFTS, DAMPE

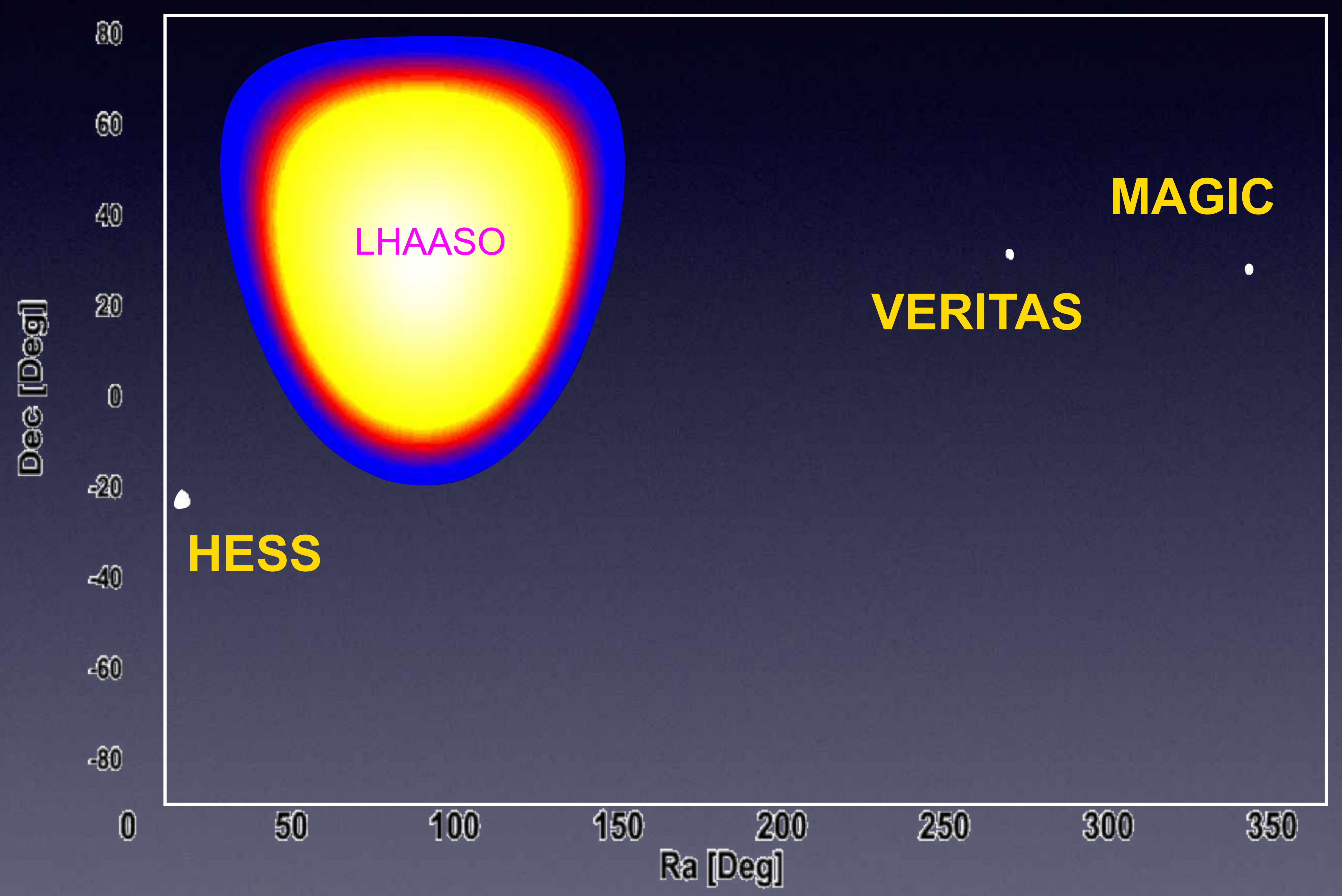
LHAASO Science Book

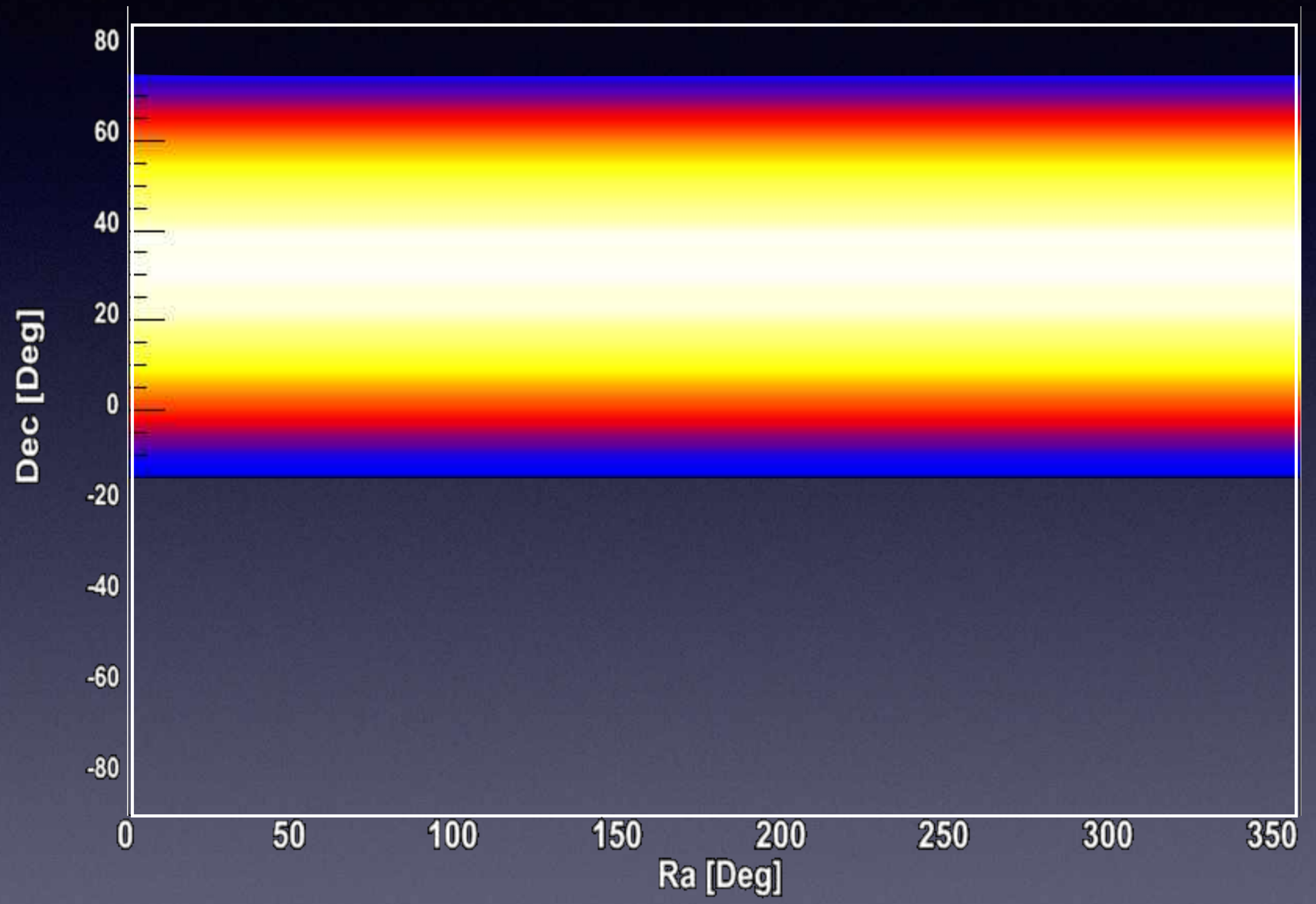
γ-RAY ASTRONOMY

- Galactic γ-ray Physics
  - Source catalog (https://doi.org/10.3847/1538-4365/acfd29)
  - Diffuse emission
- Extra-Galactic γ-ray Physics
- Diffuse flux
- Cosmic rays Physics
  - Composition studies
- Fundamental Physics
  - Dark Matter
  - LIV
- Multi-messenger Astronomy



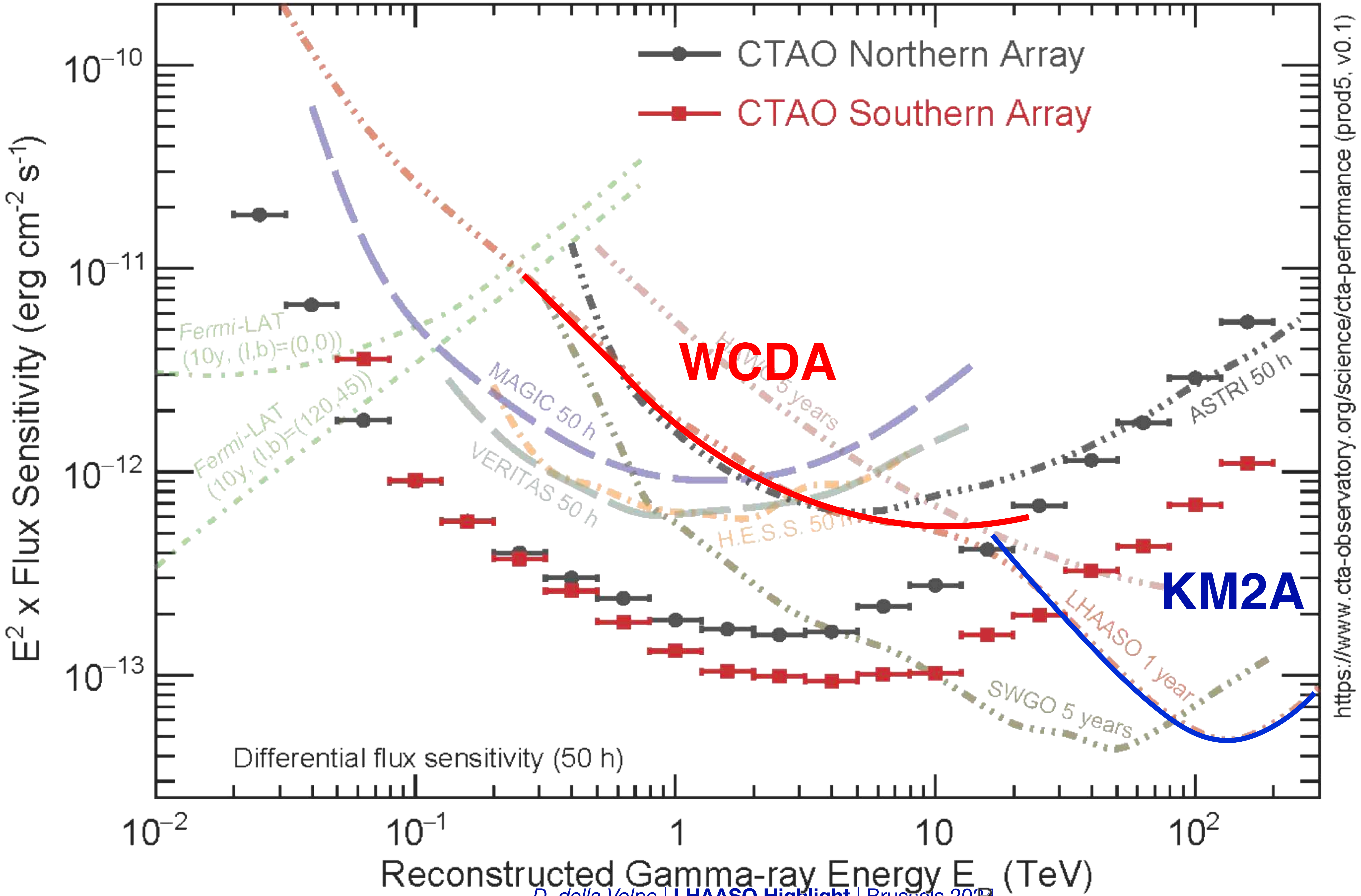
Wide FOV γ-ray Astronomy



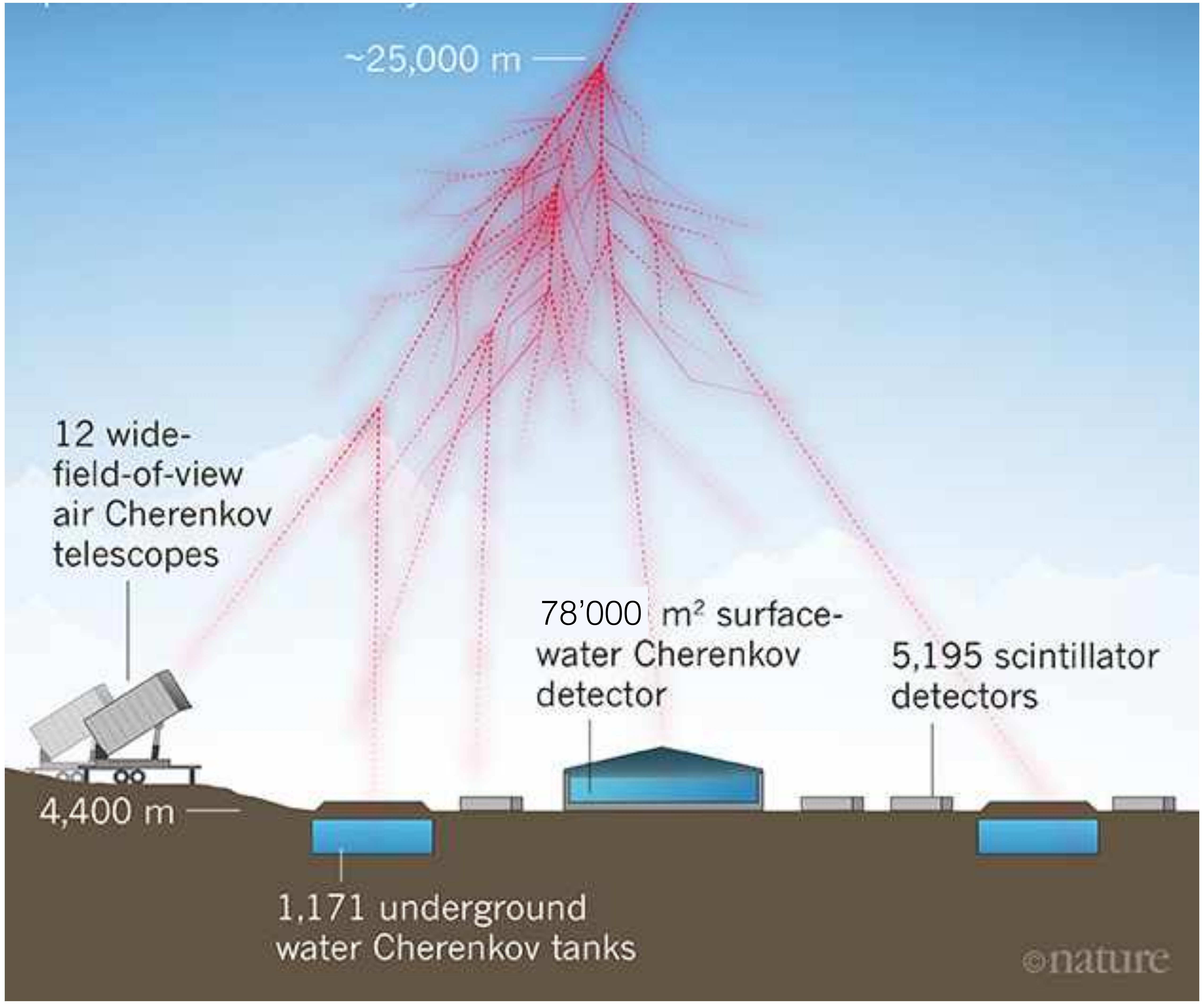


- 1/7 of the sky at any moment
- 60% in the sky per day day (24h)

LHAASO Expected Sensitivity



The LHAASO concepts



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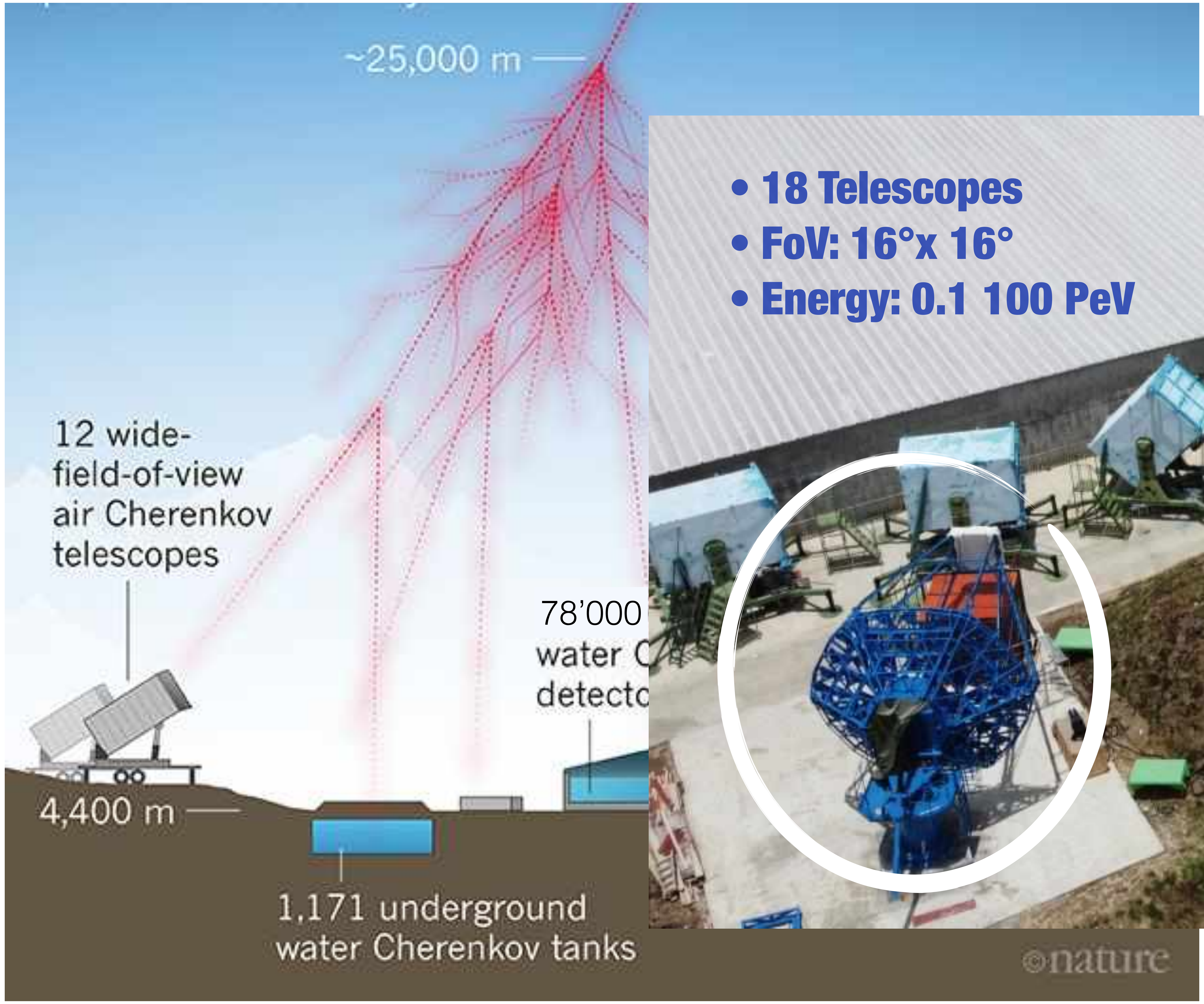

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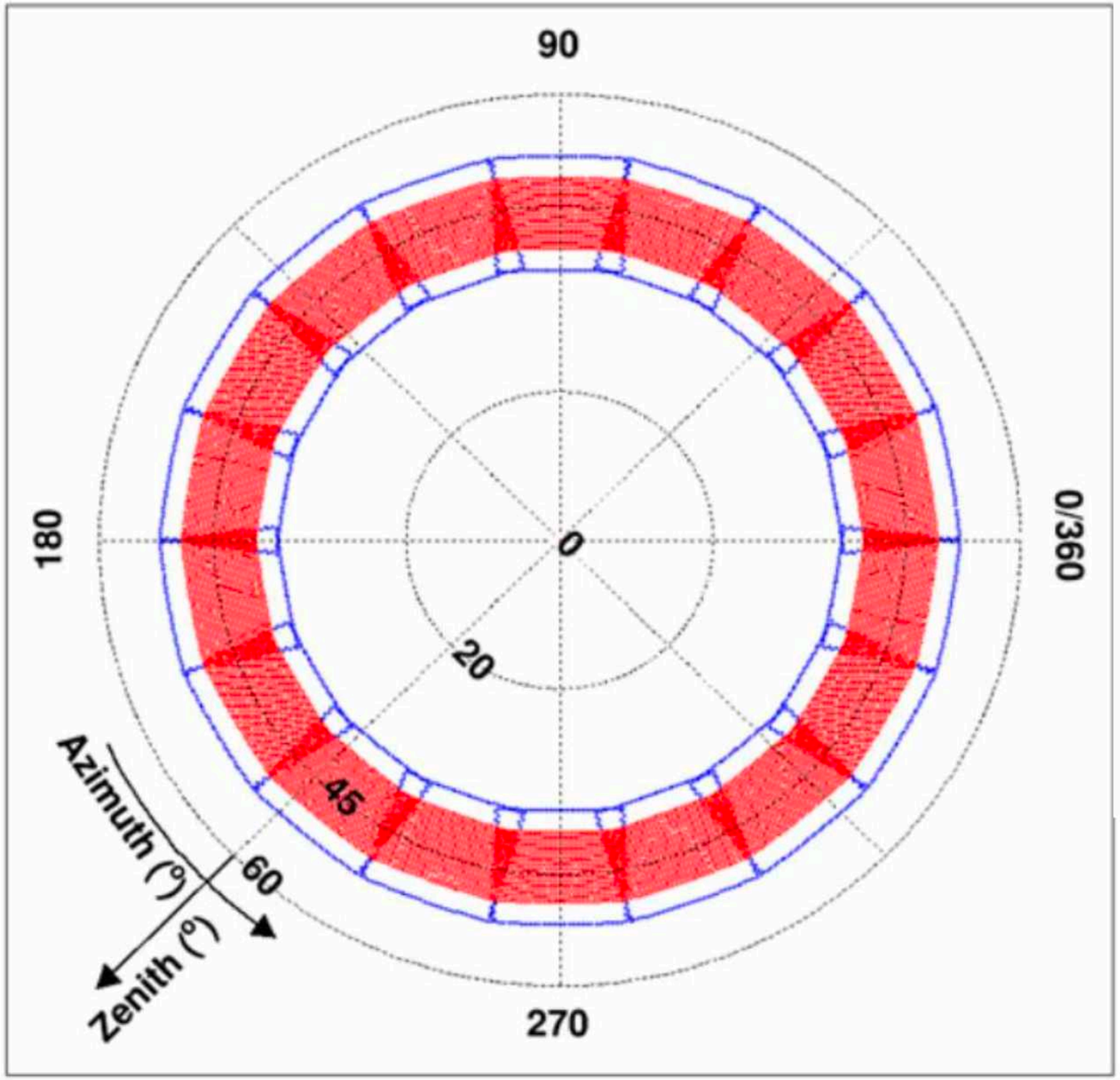

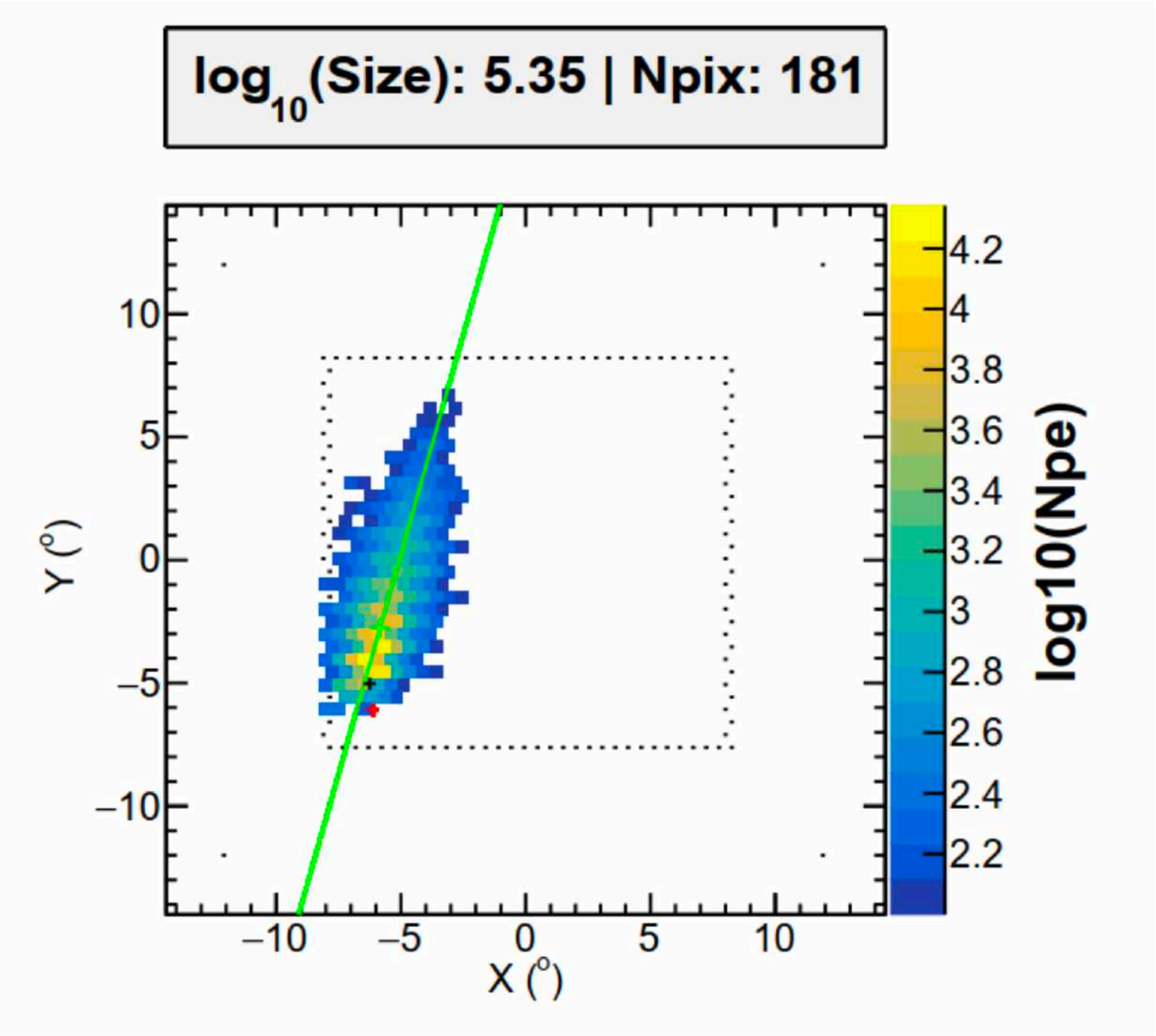

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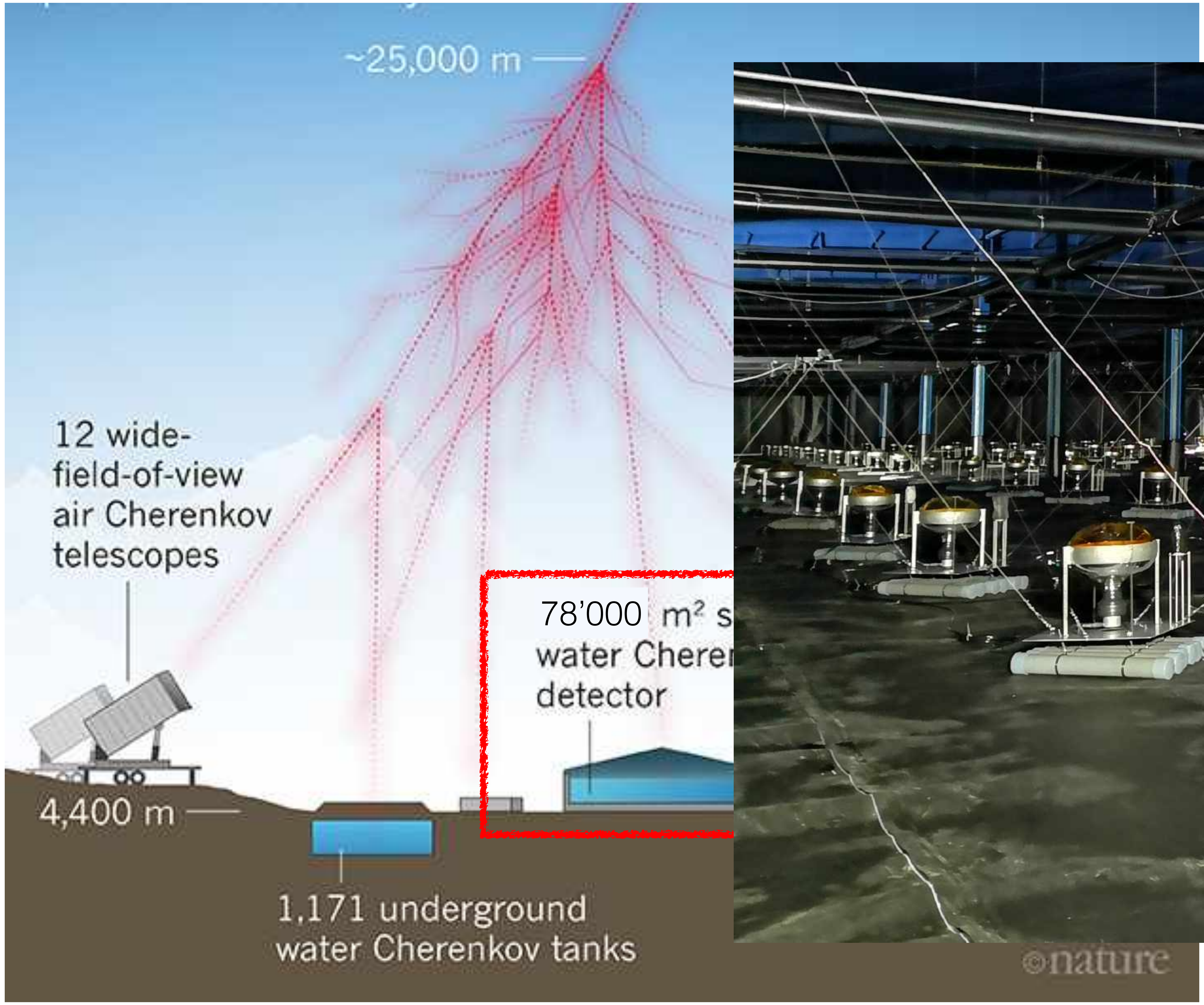

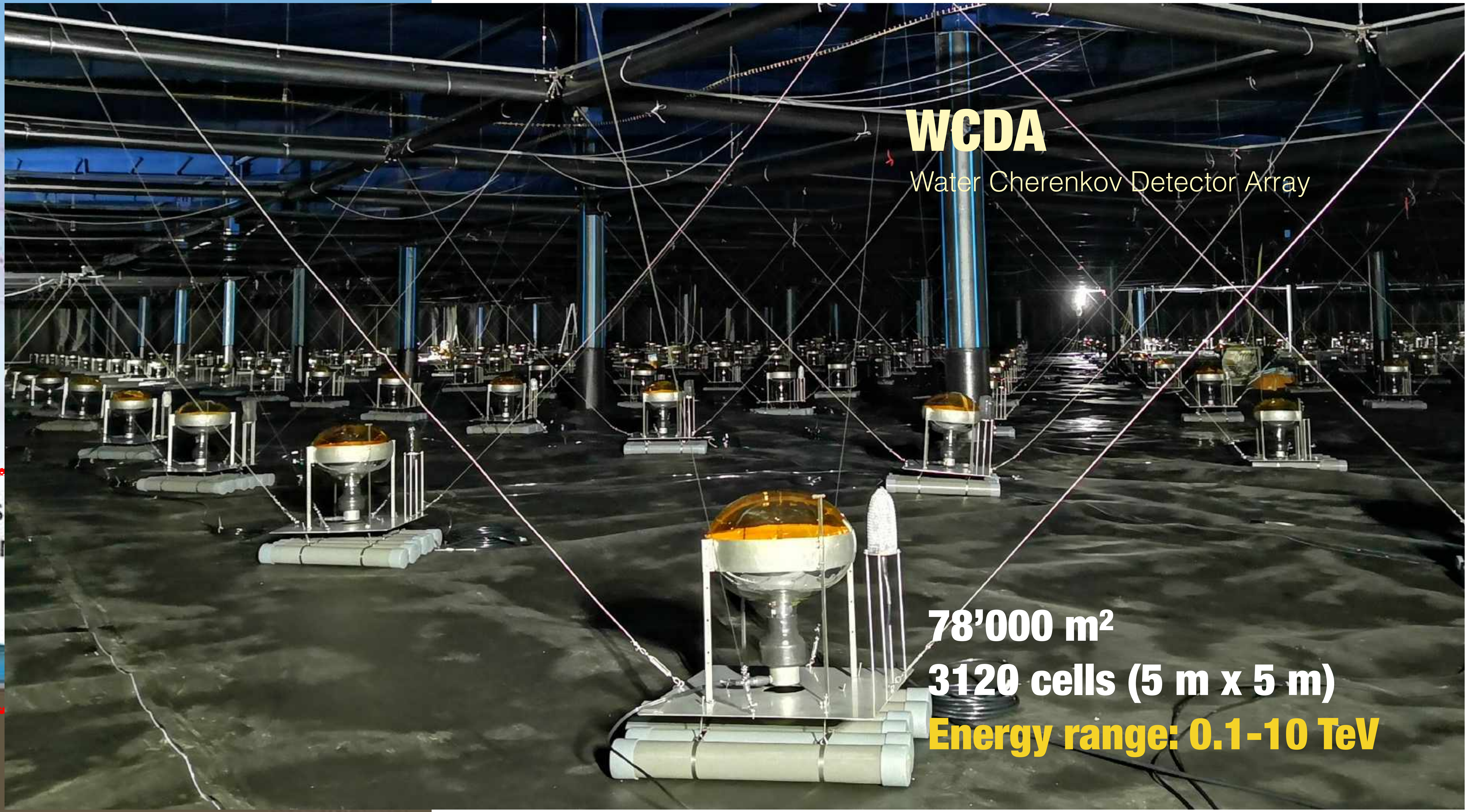

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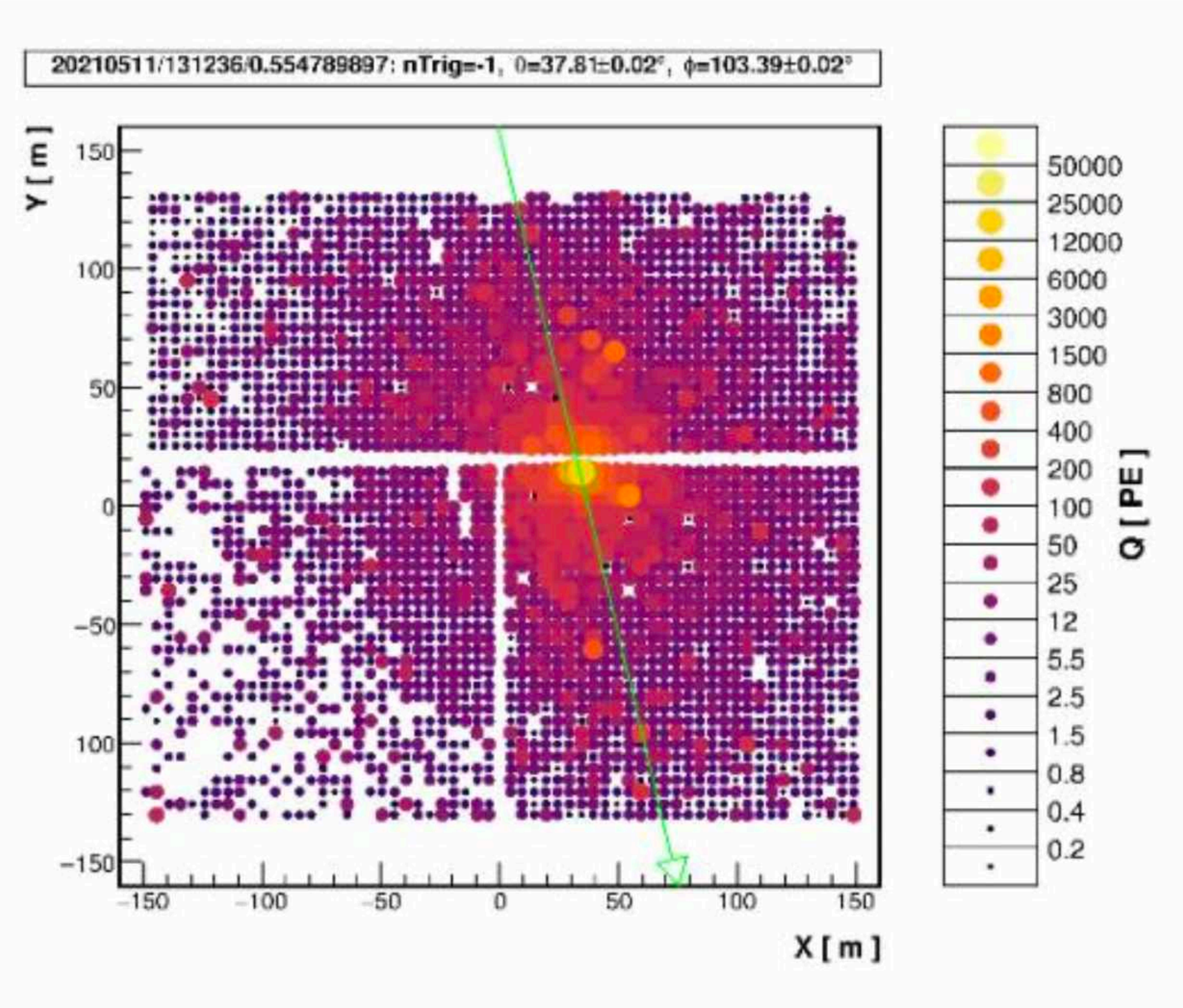
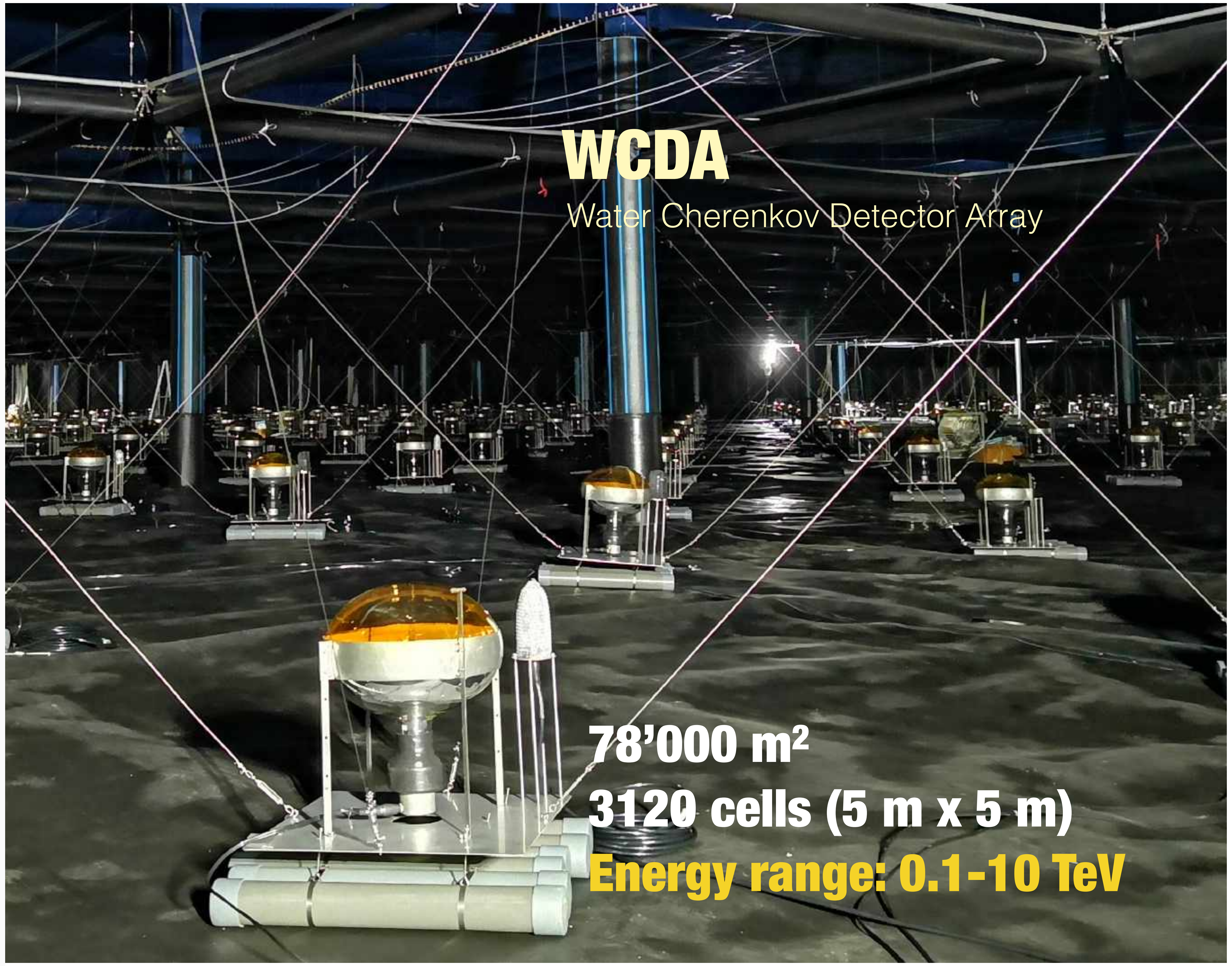
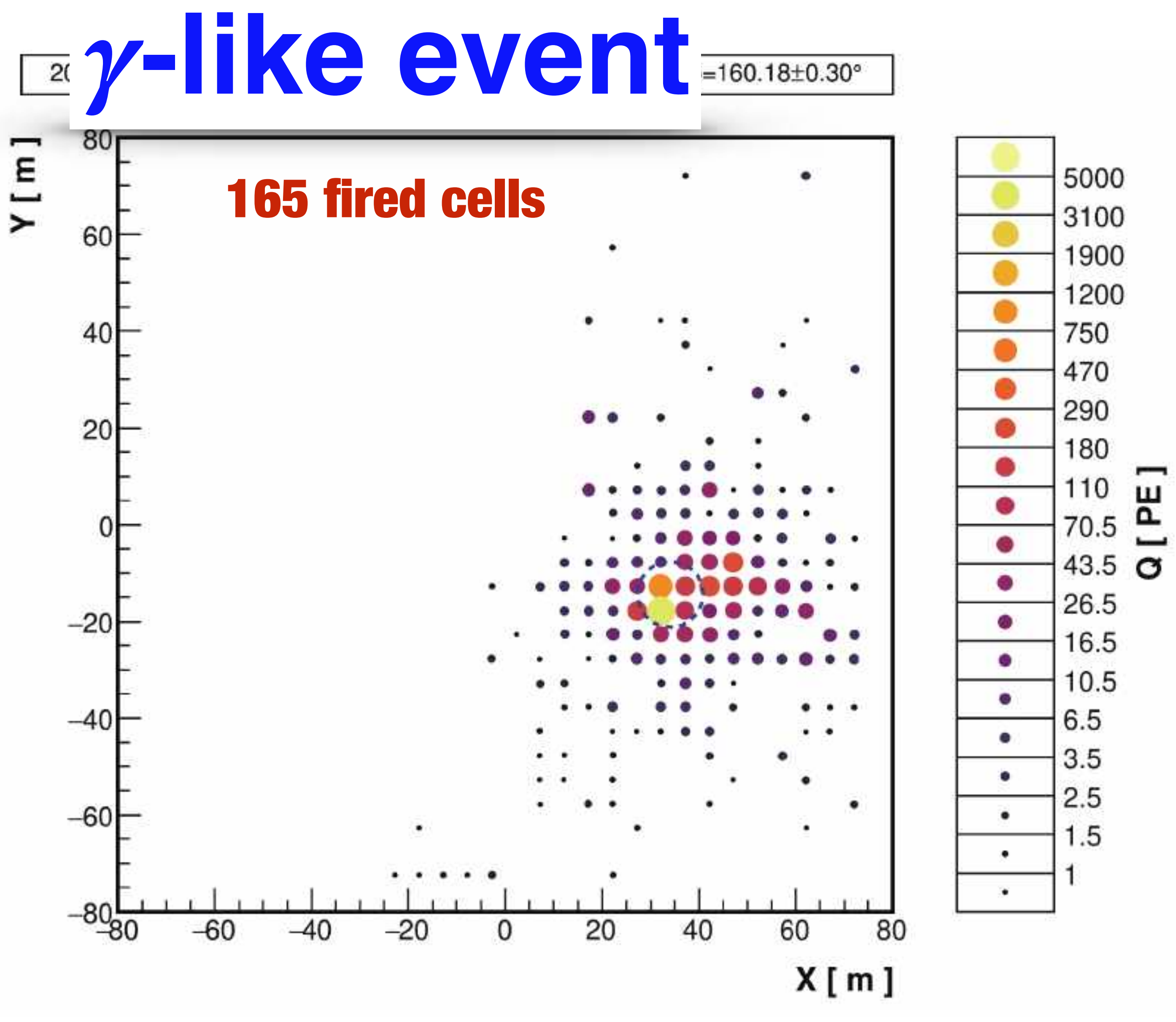
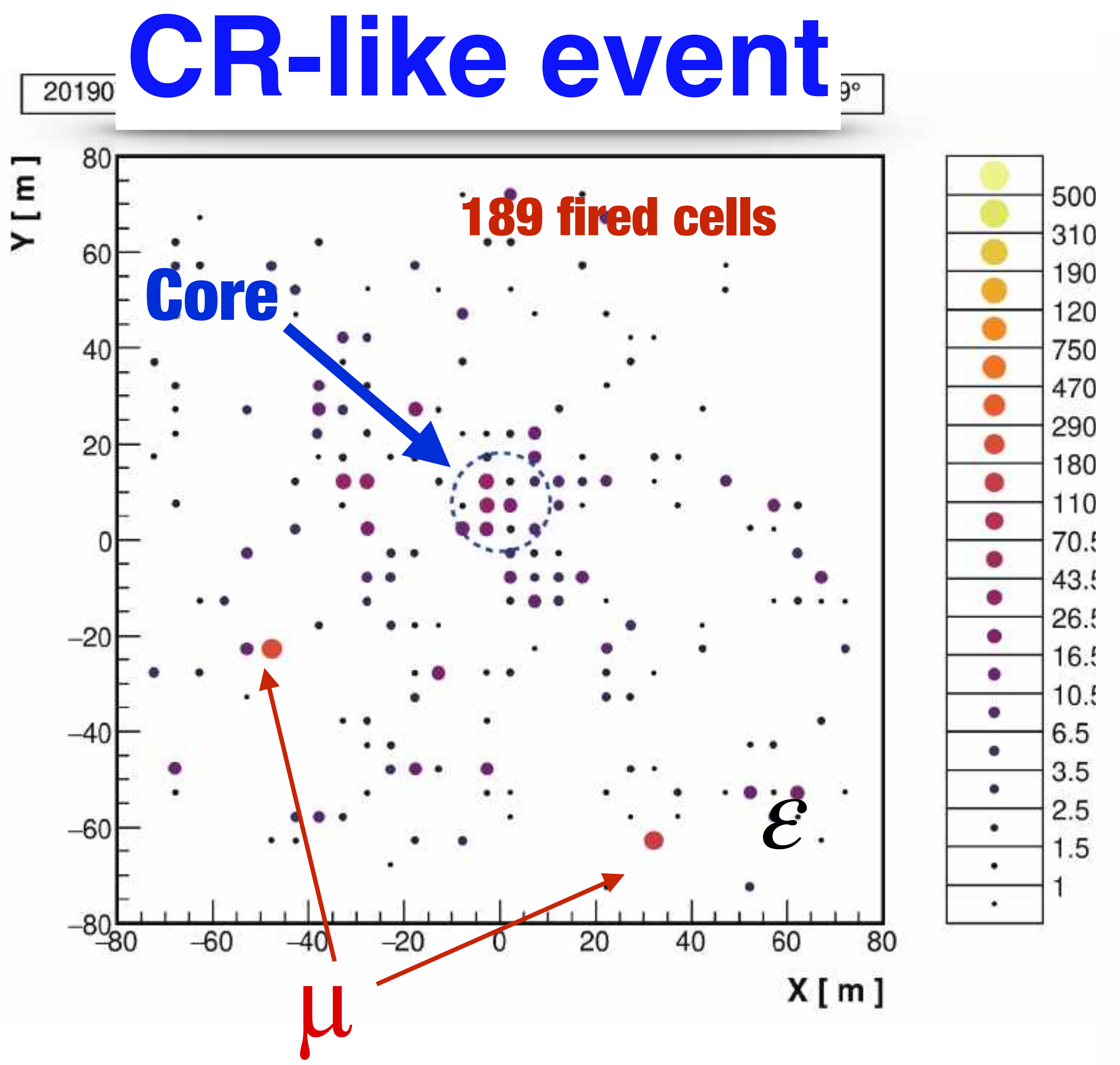
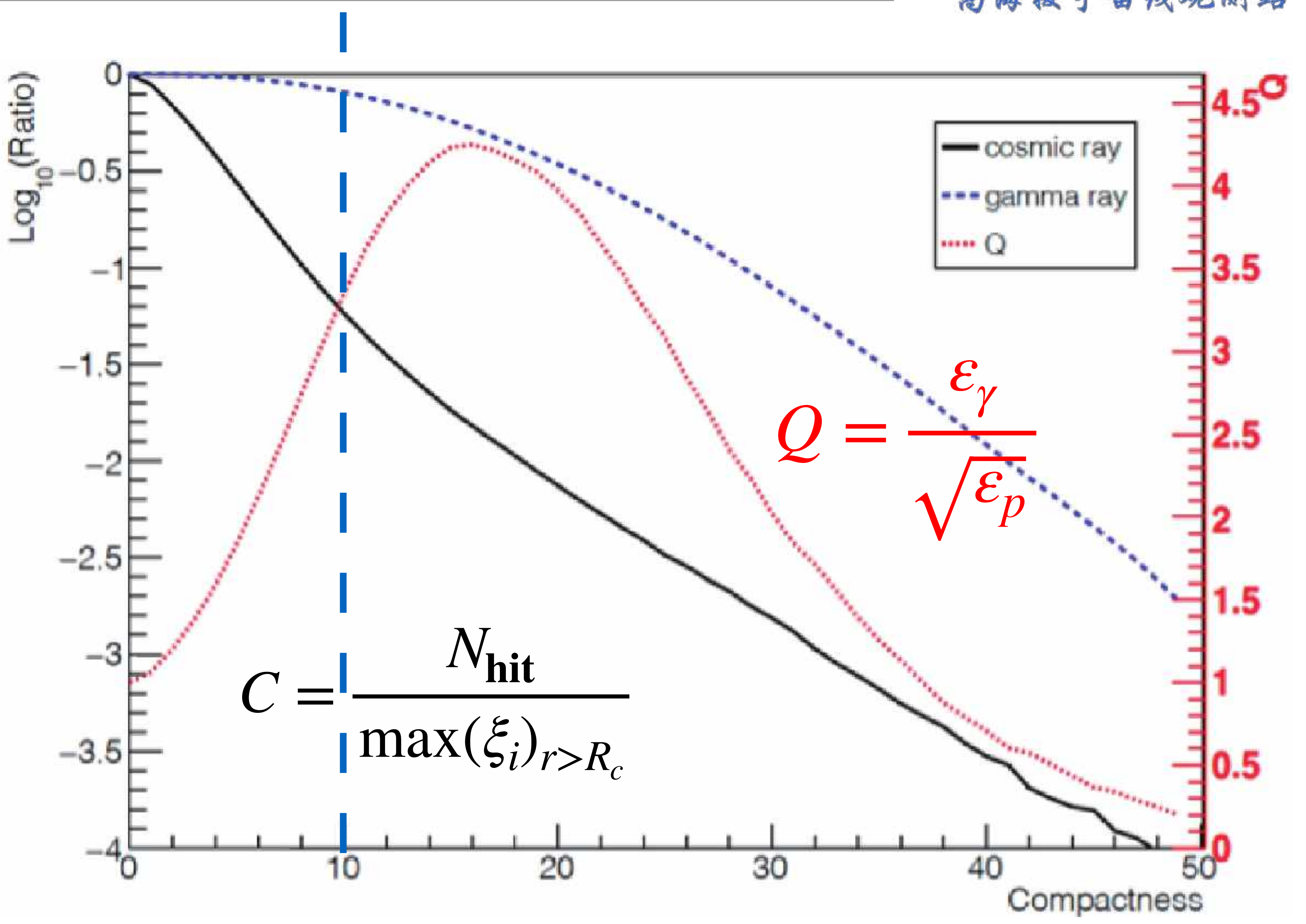


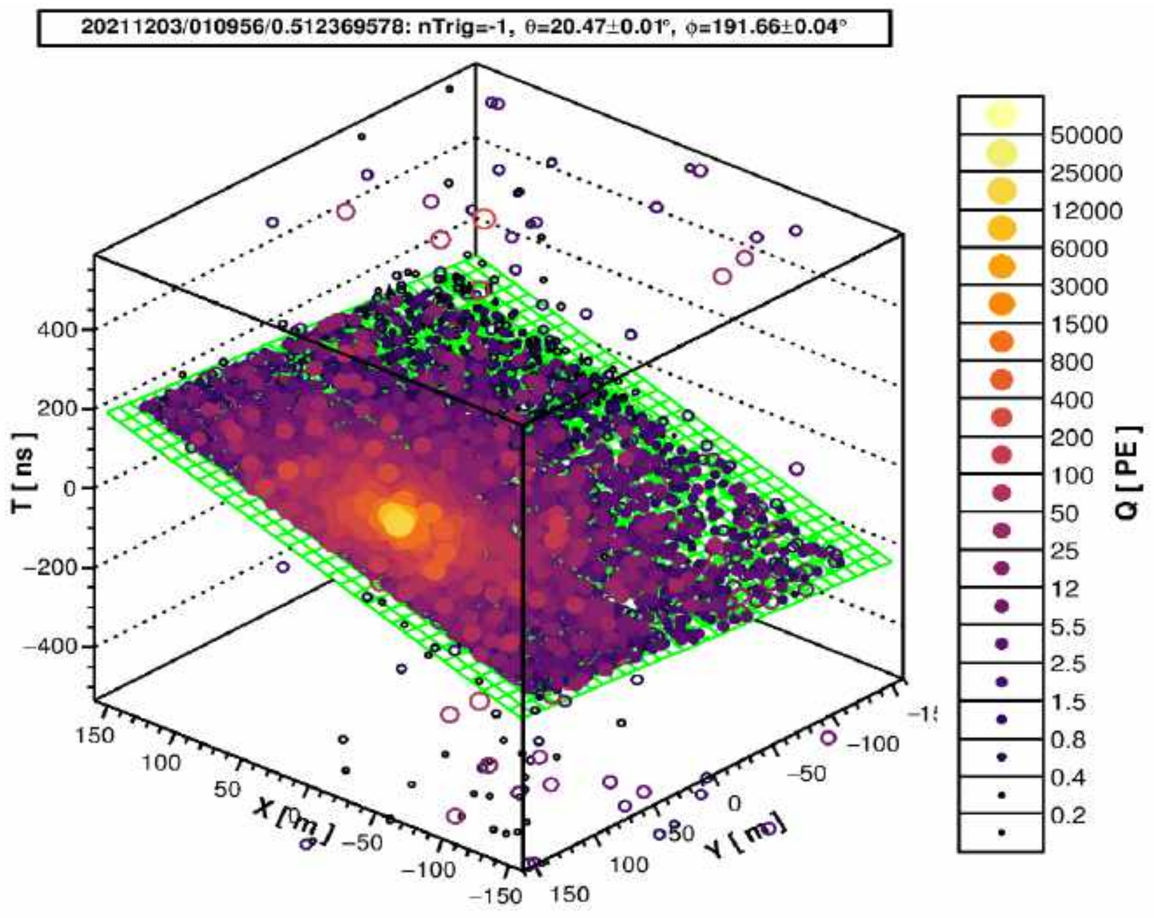


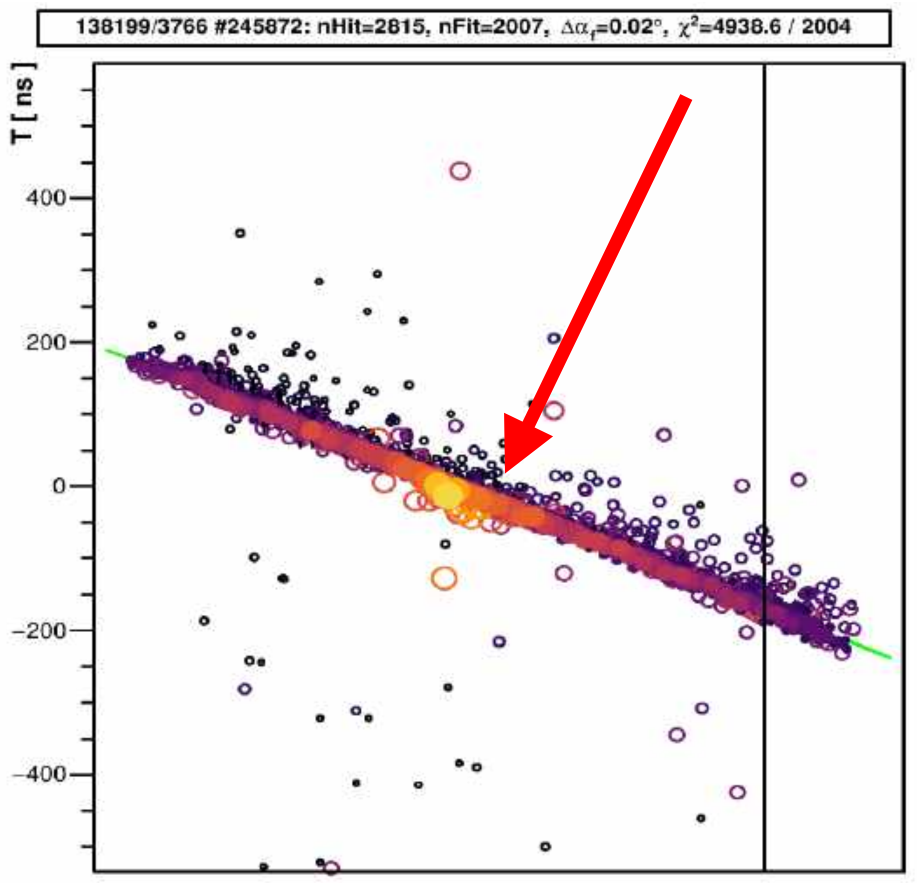
WCDA performance











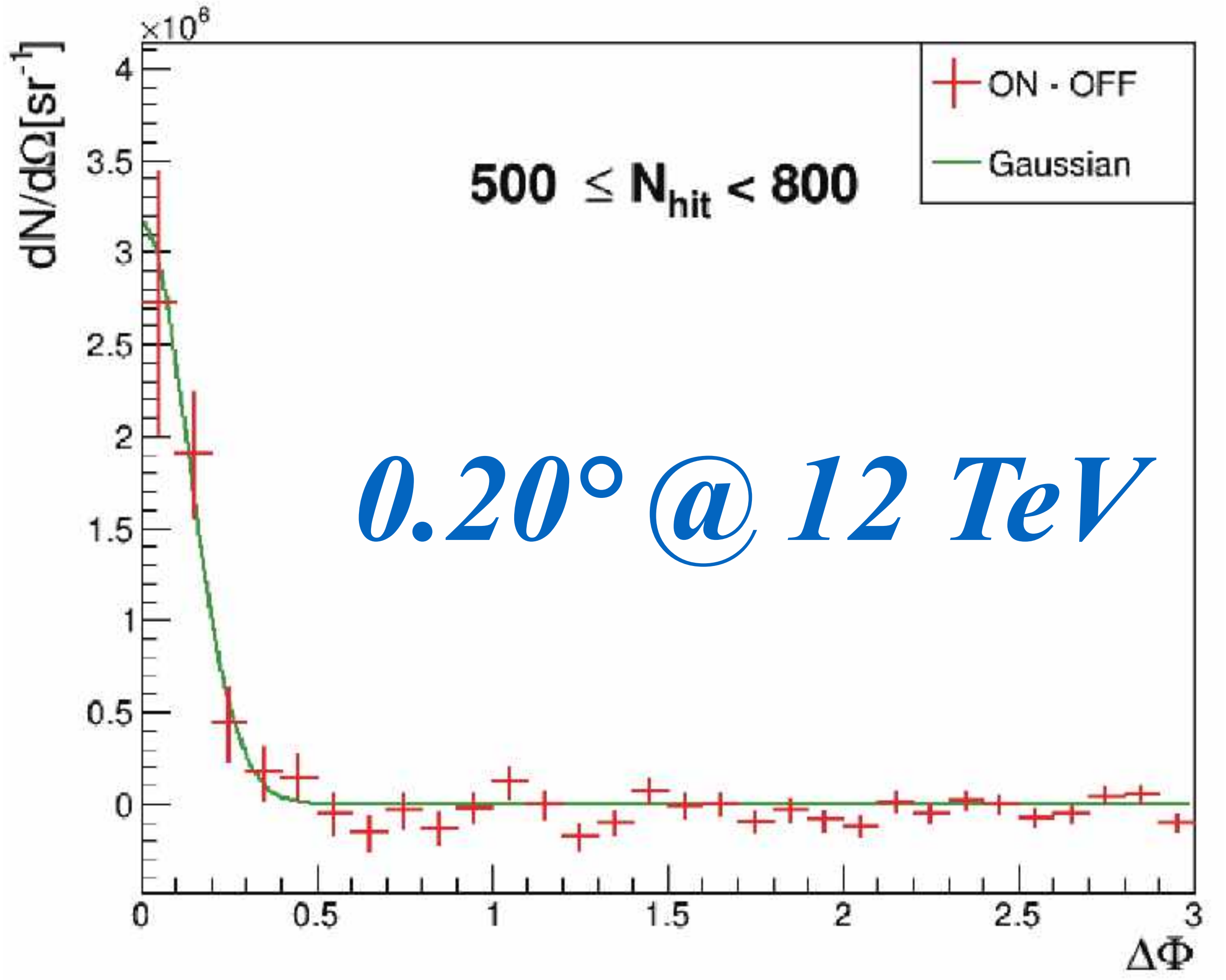
Performance of LHAASO-WCDA and observation of the Crab Nebula as a standard candle

Chinese Physics C, Volume 45, Number 8 (2021)

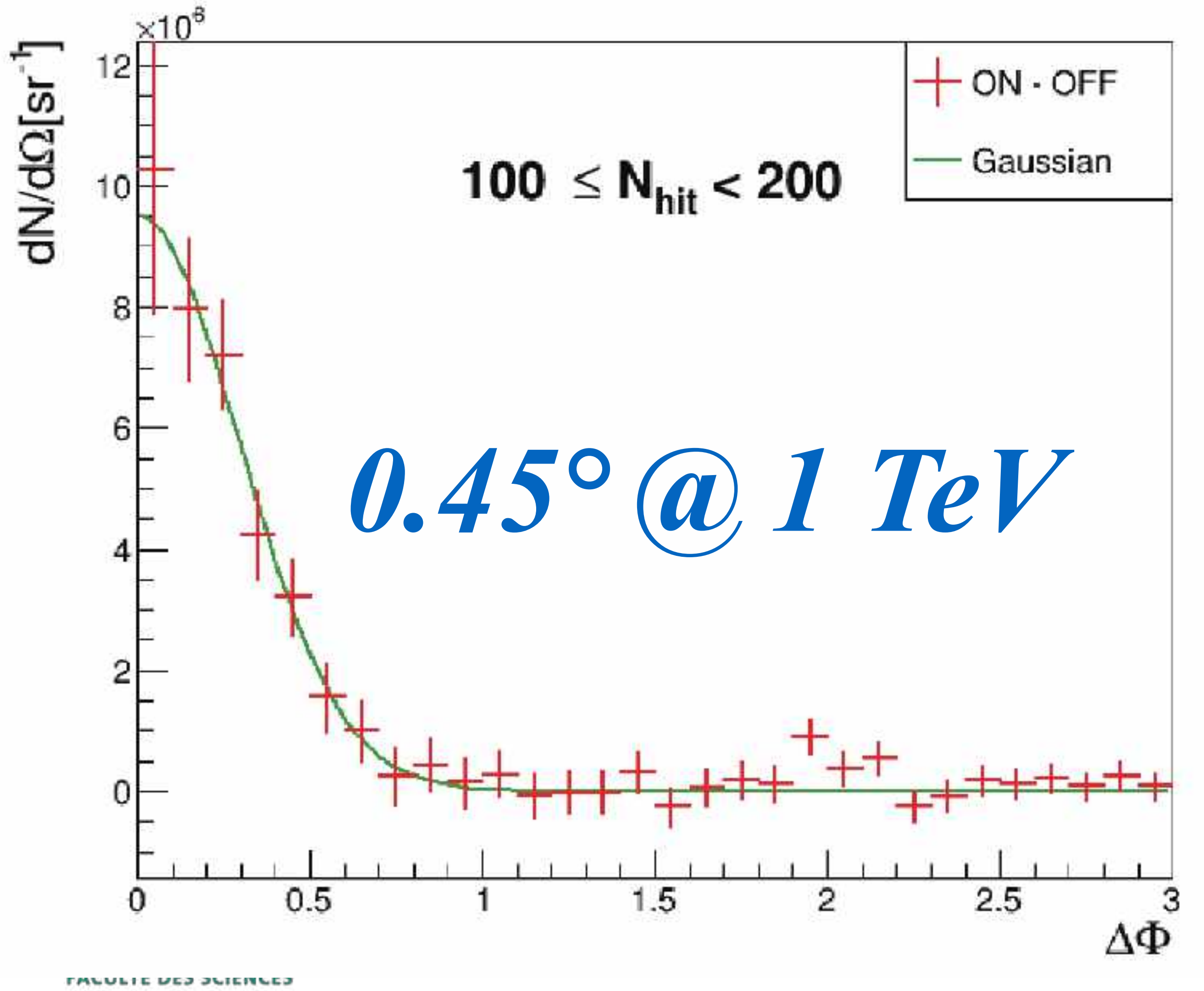
http://doi.org/10.1088/1674-1137/ac041b

WCDA performance on Crab

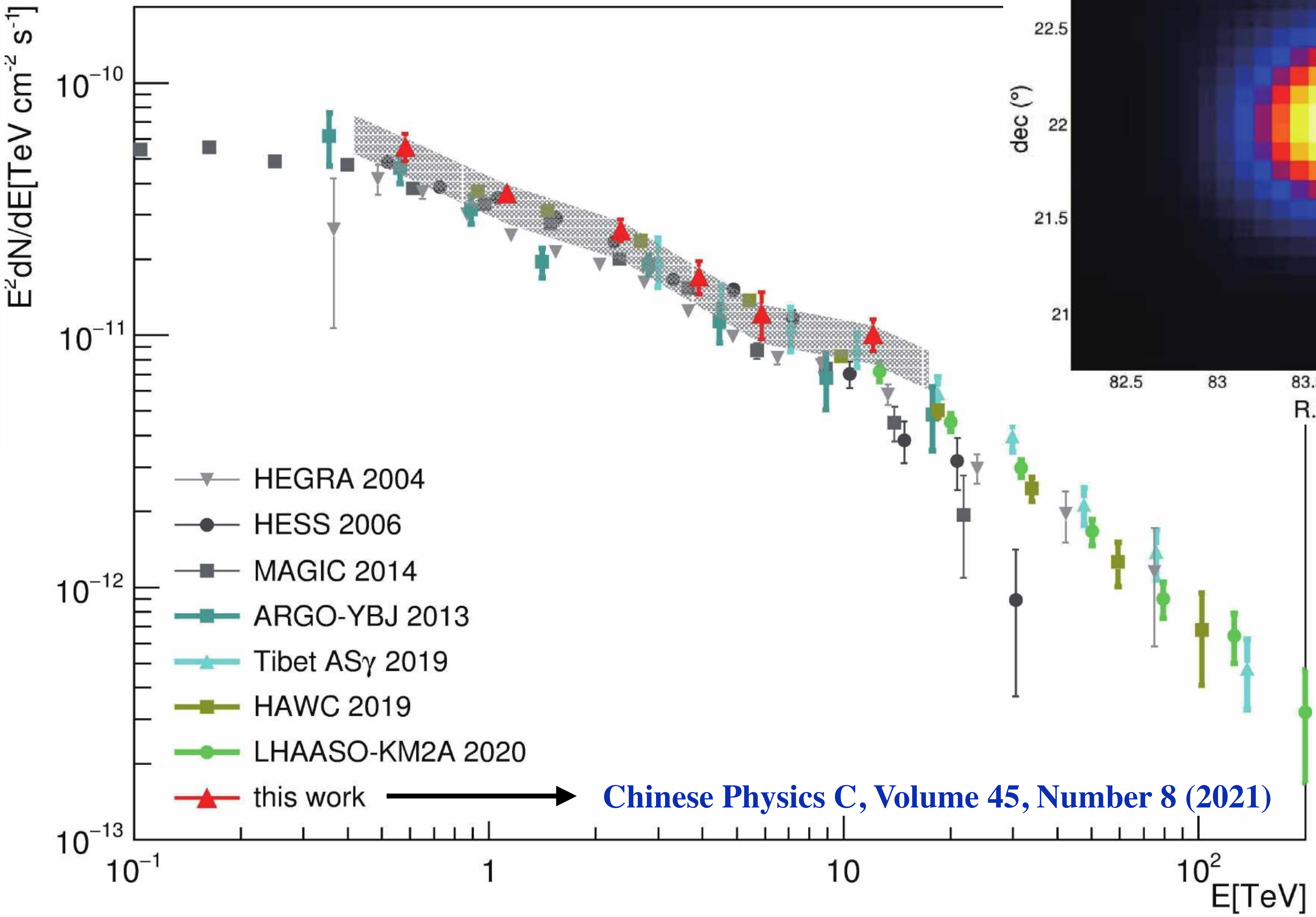
Angular resolution



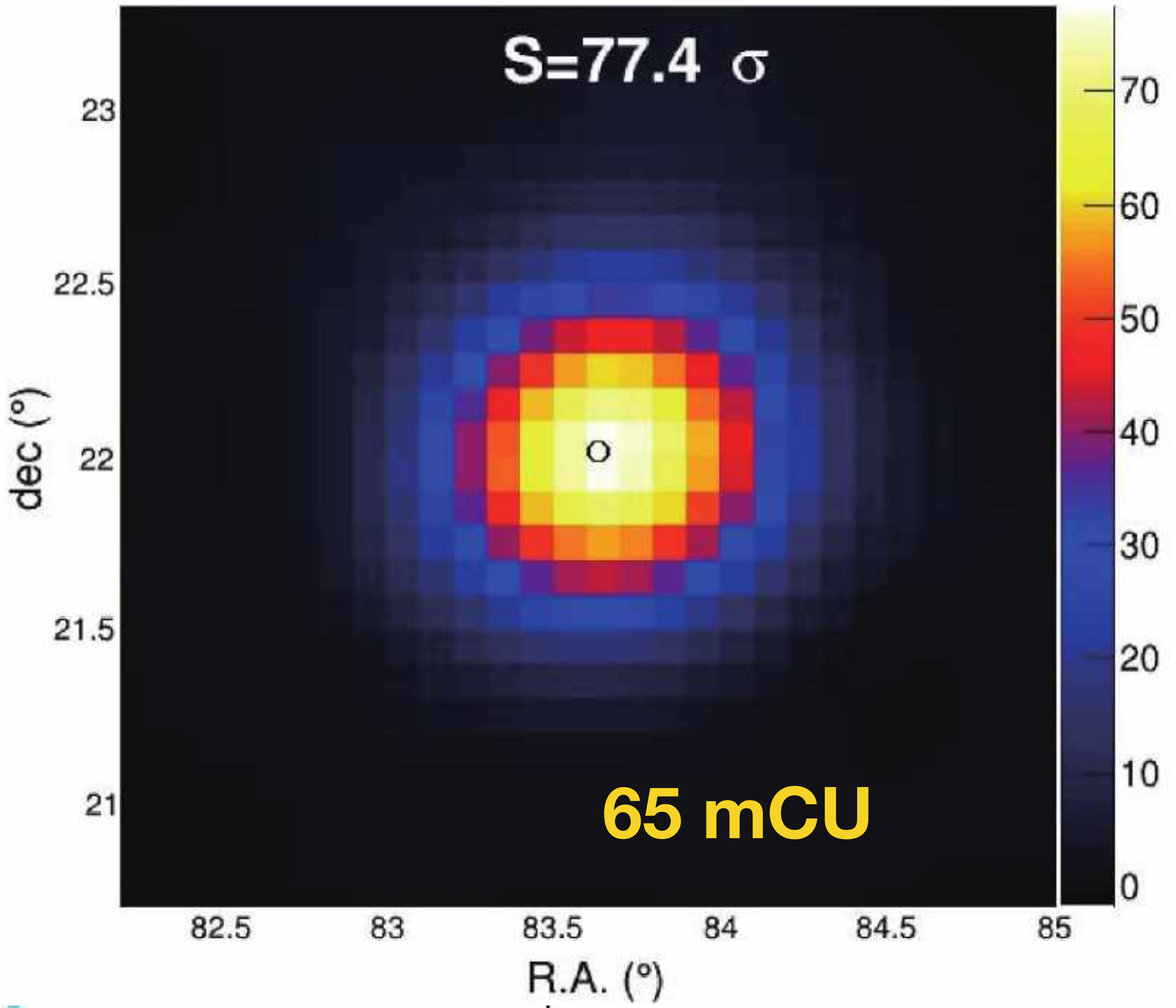
0.20° @ 12 TeV



0.45° @ 1 TeV

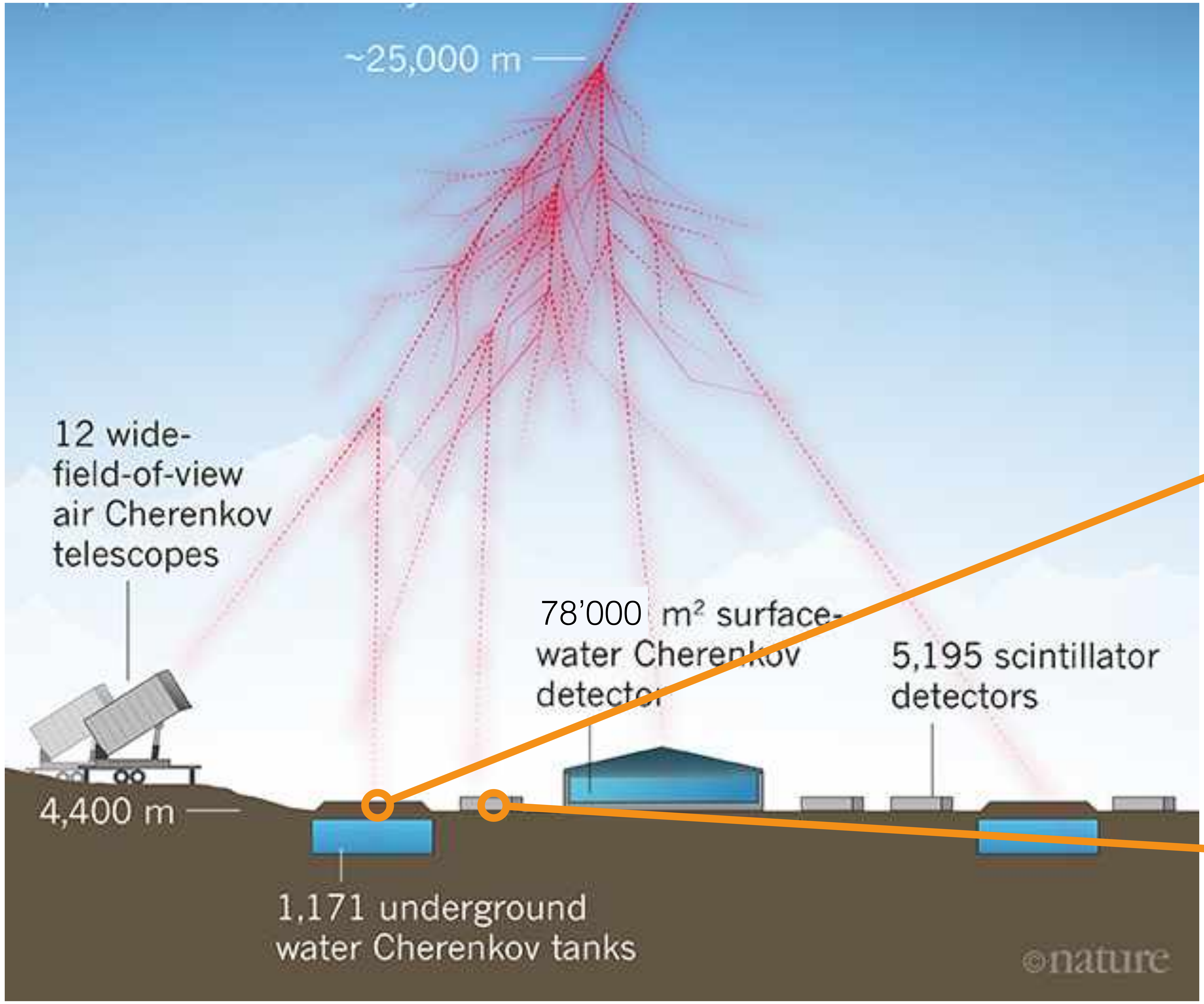


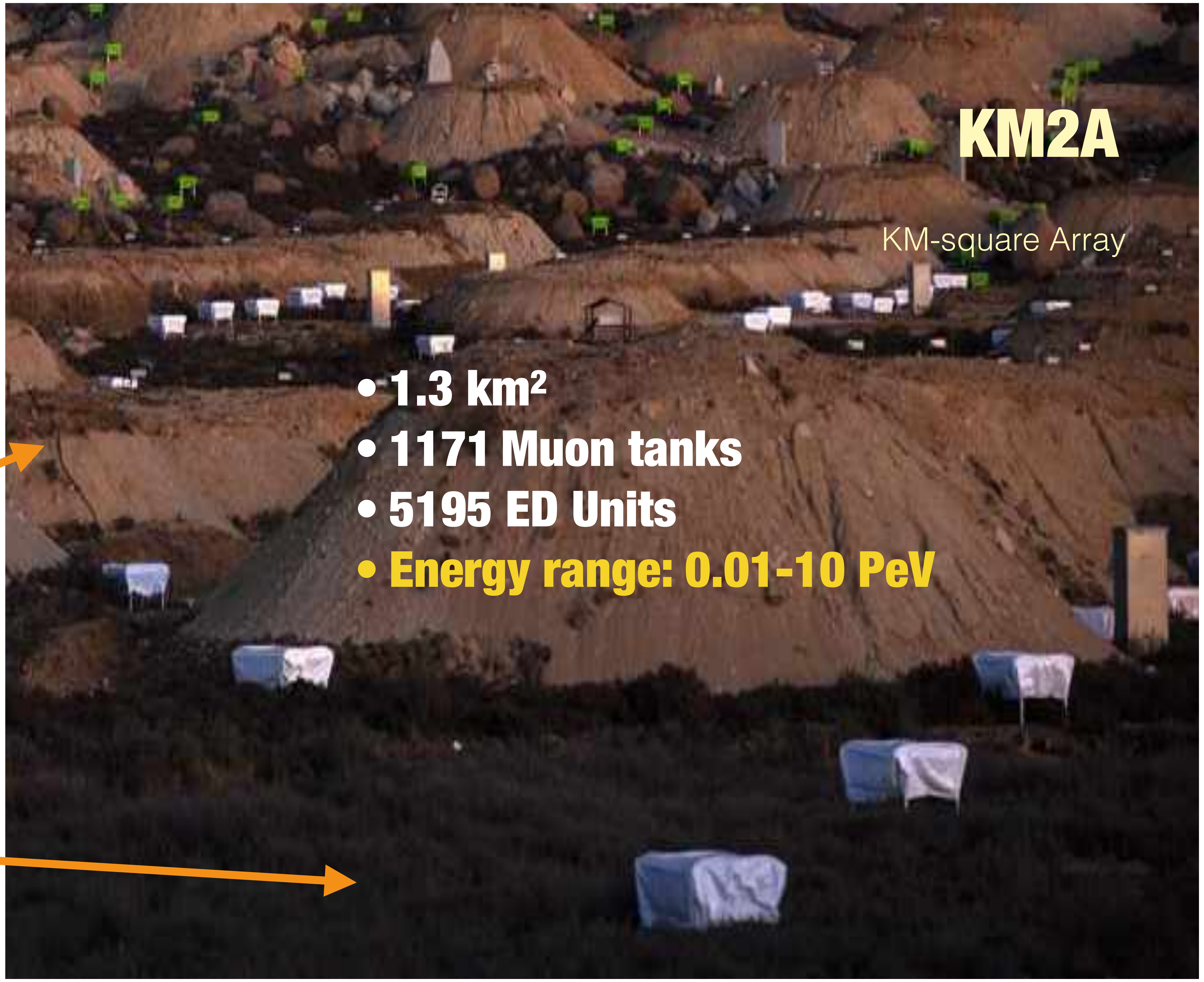
Chinese Physics C, Volume 45, Number 8 (2021)



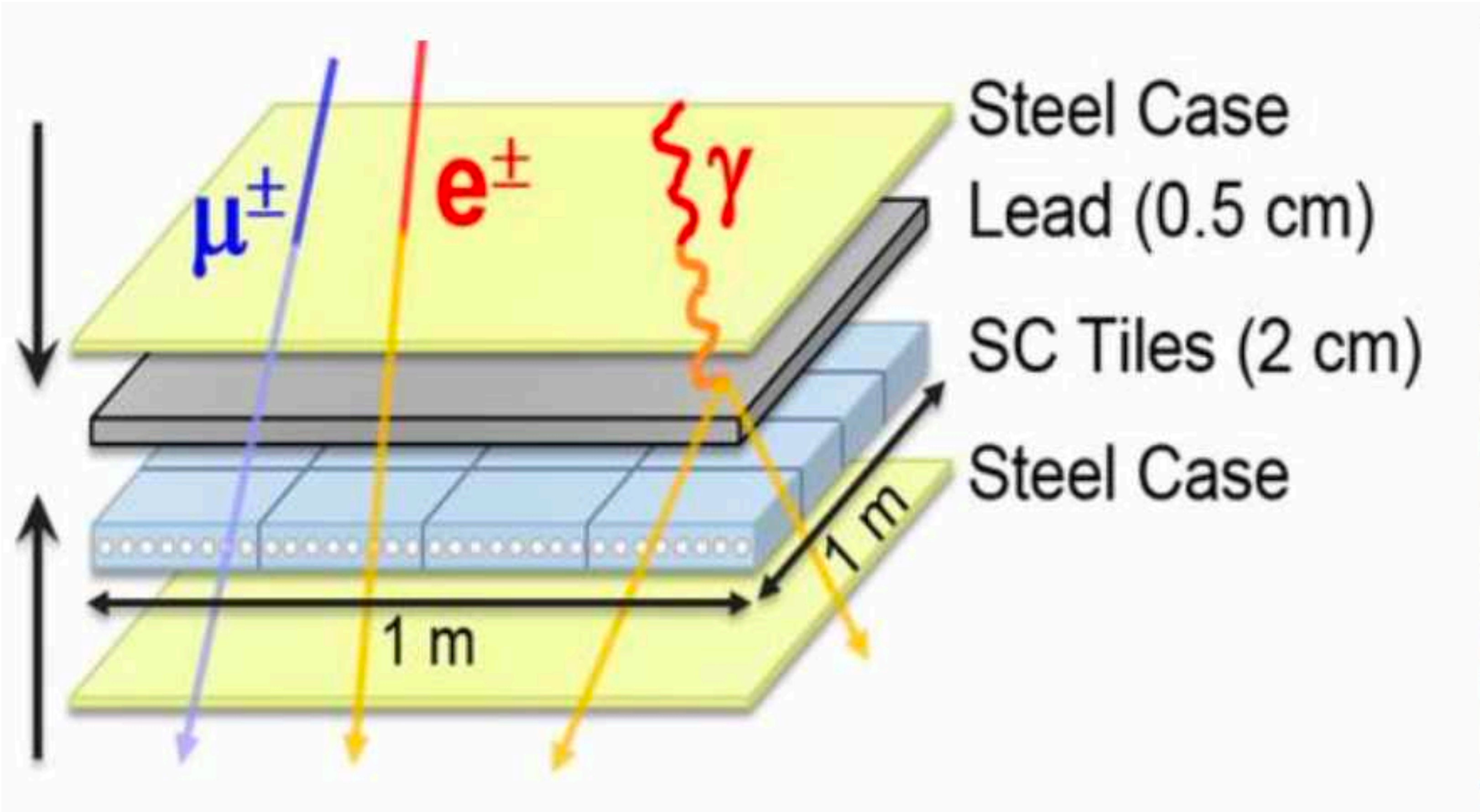
1 year

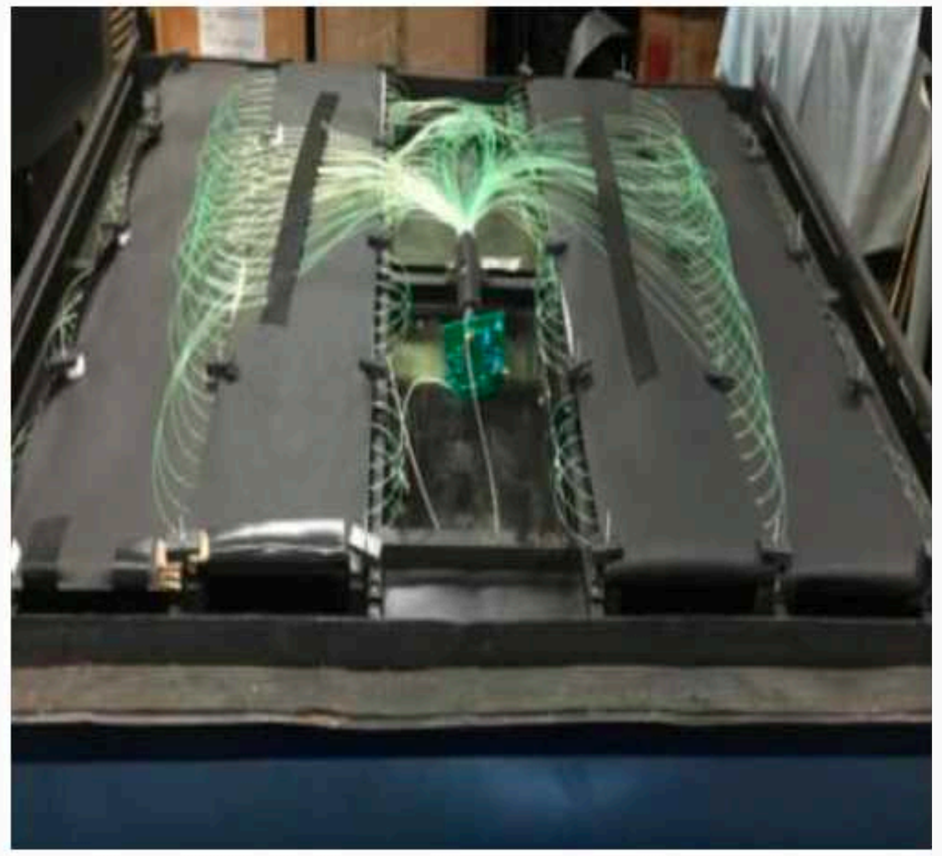
The LHAASO concepts

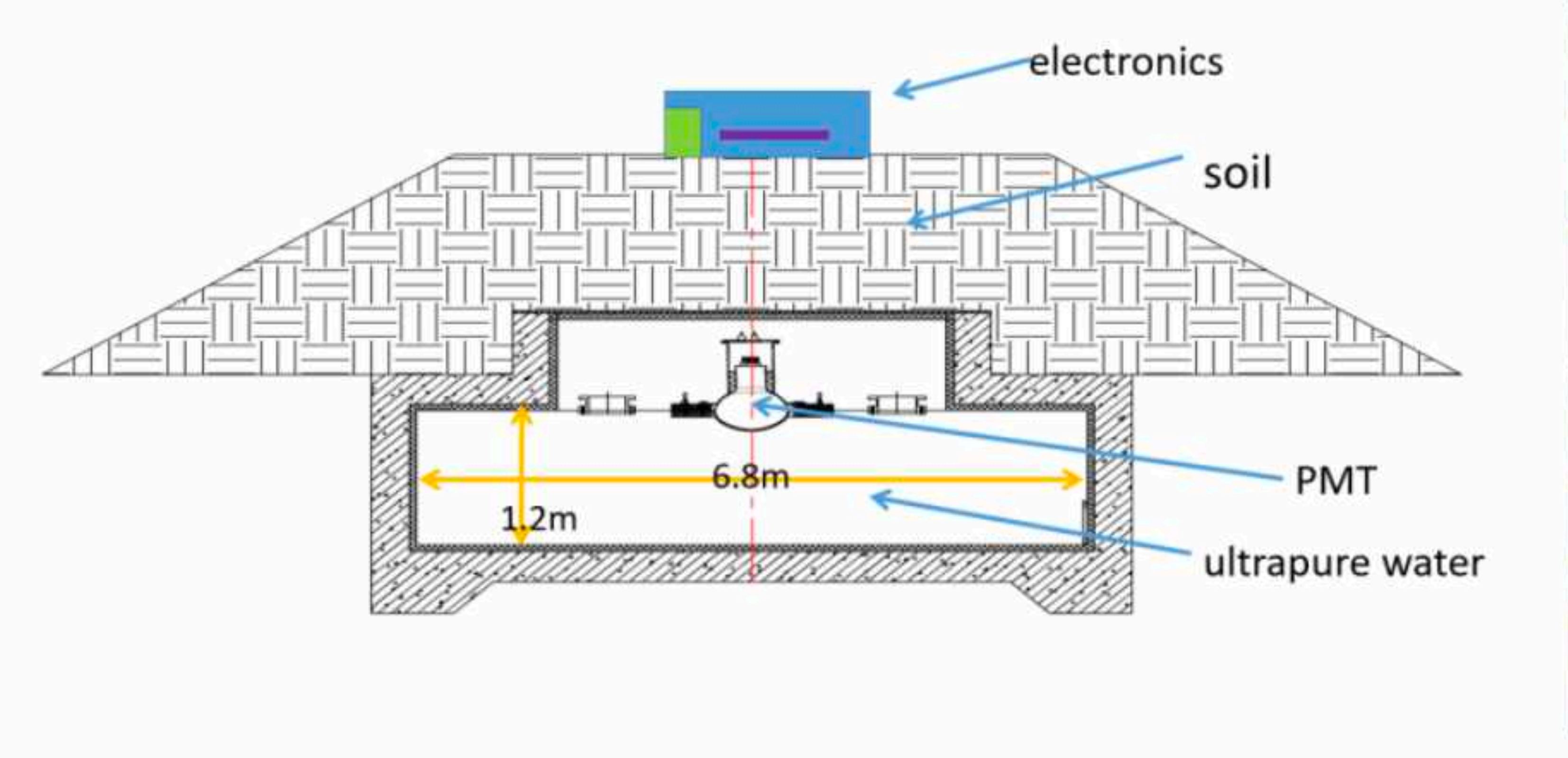


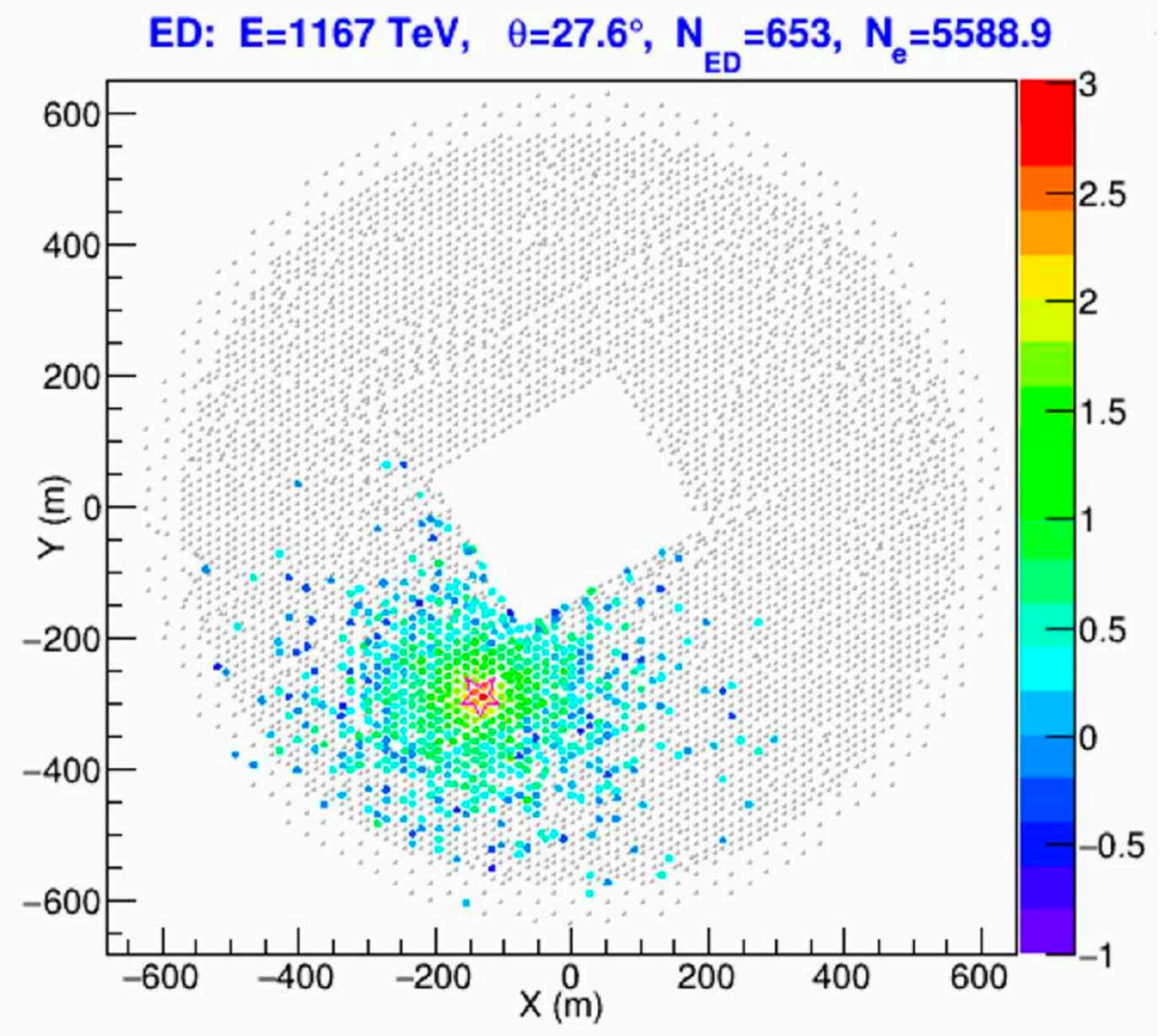


The LHAASO concepts









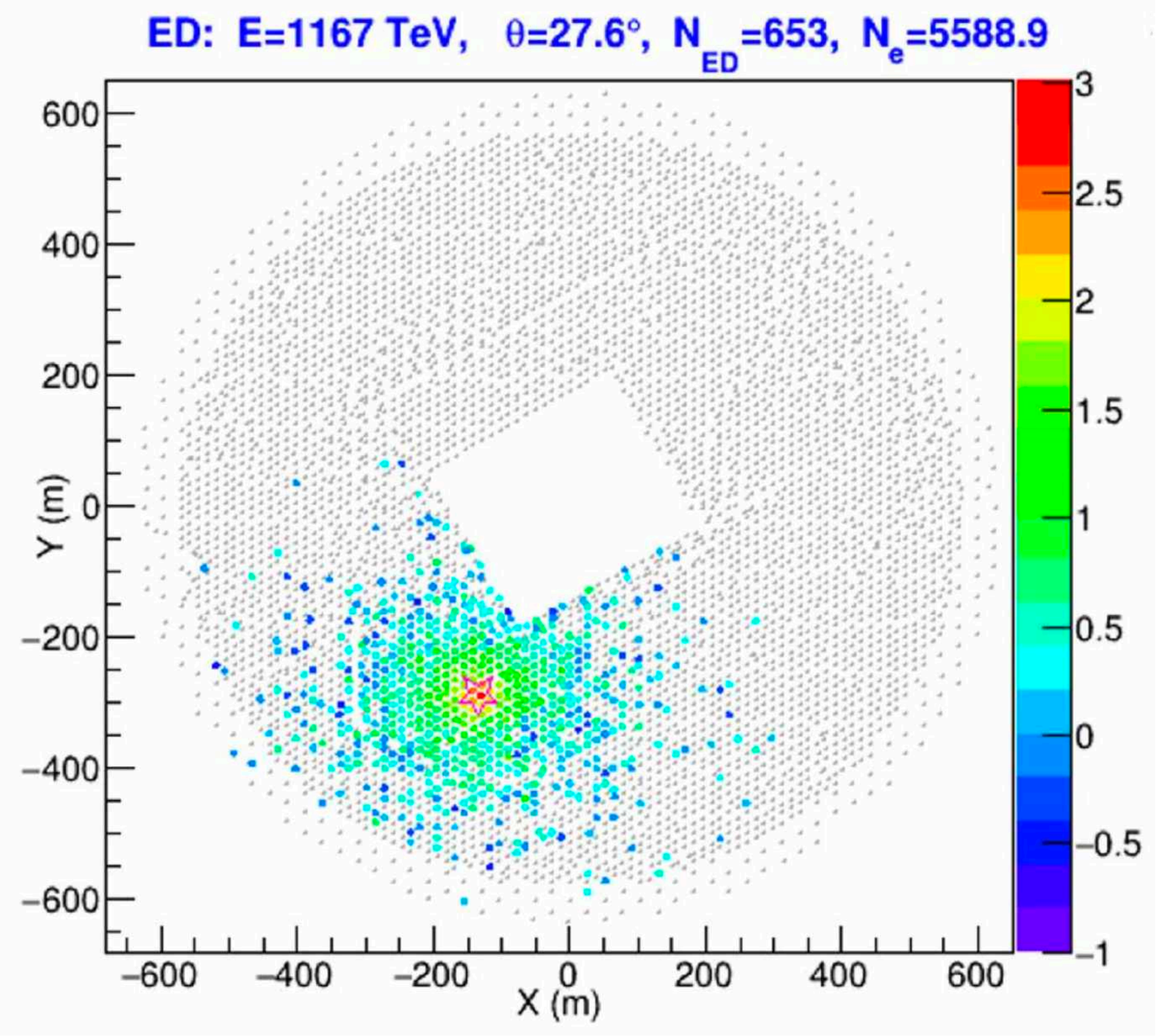
Event reconstruction with KM2A

- Get the particle density ρ at $r_0 = 50$ m using a NKG profile

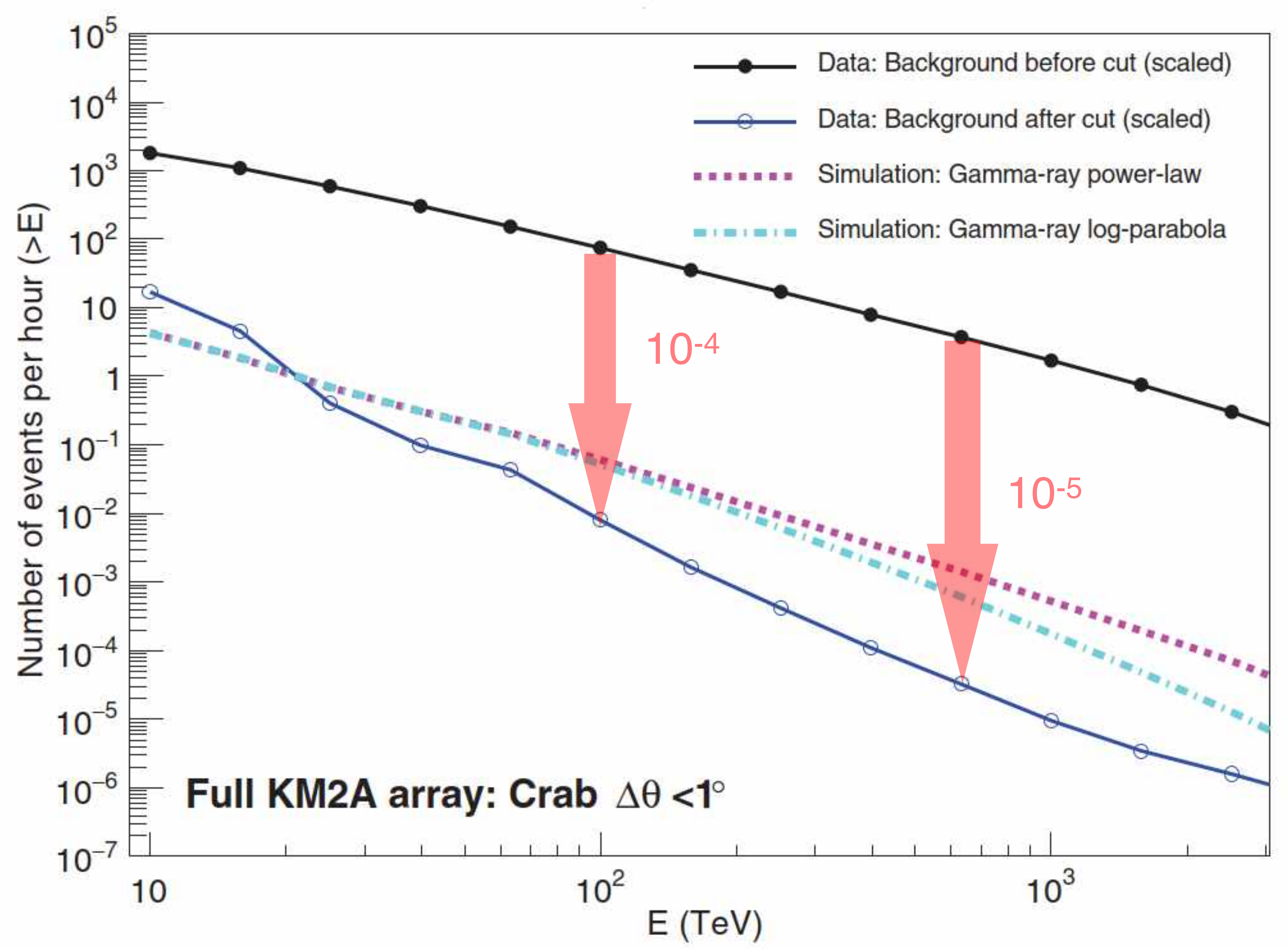
$$\rho = N_e \cdot c(s) \cdot \left(\frac{r}{r_0}\right)^{s-\alpha} \cdot \left(1 + \frac{r}{r_0}\right)^{s-\beta}$$

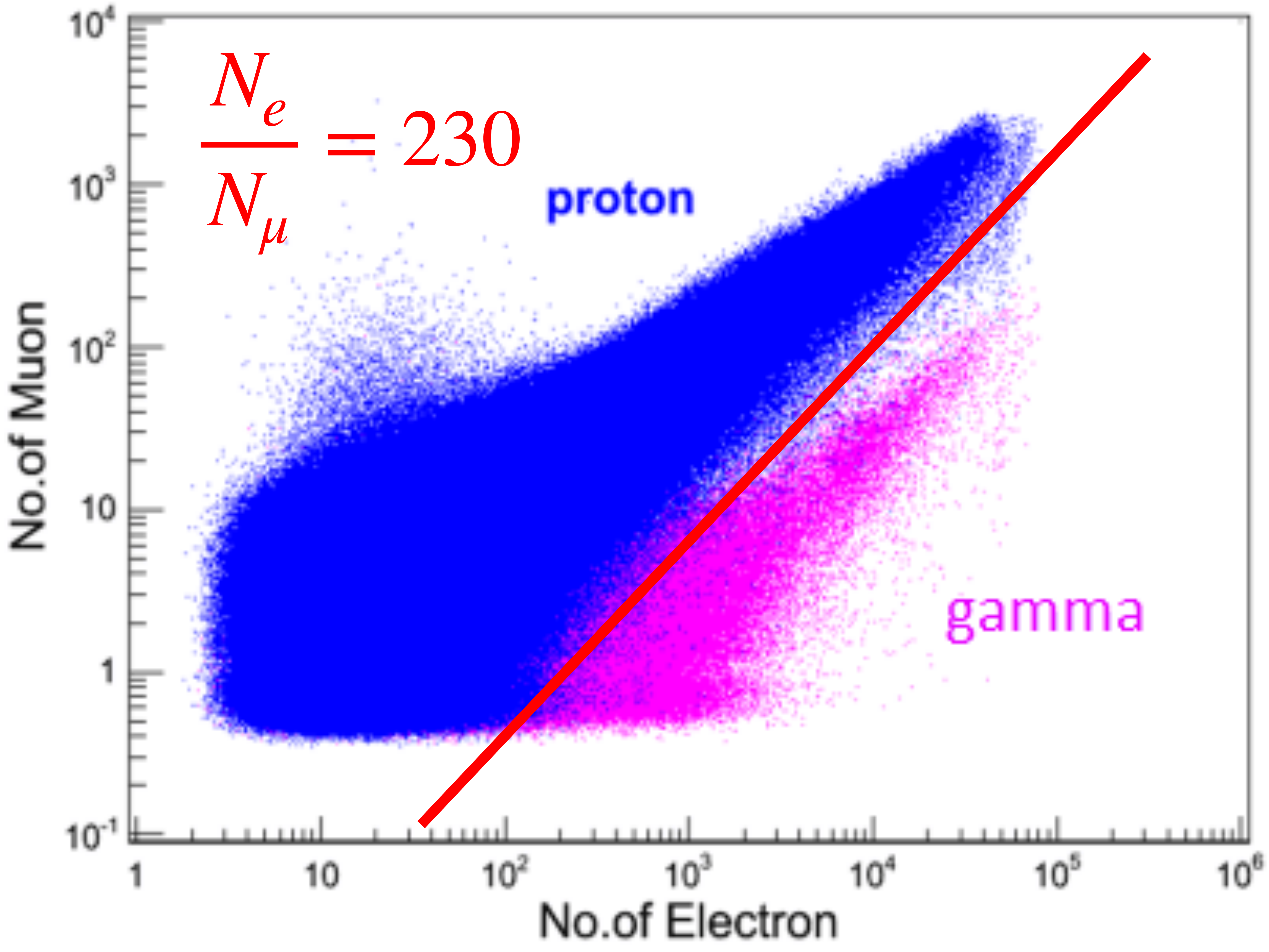
- Primary energy reconstructed as a quadratic polynomial in ρ_{50} as

$$log(E_{rec}/TeV) = \alpha(\vartheta) \cdot [\rho_{50}]^2 + b(\vartheta) \cdot [\rho_{50}] + c(\vartheta)$$

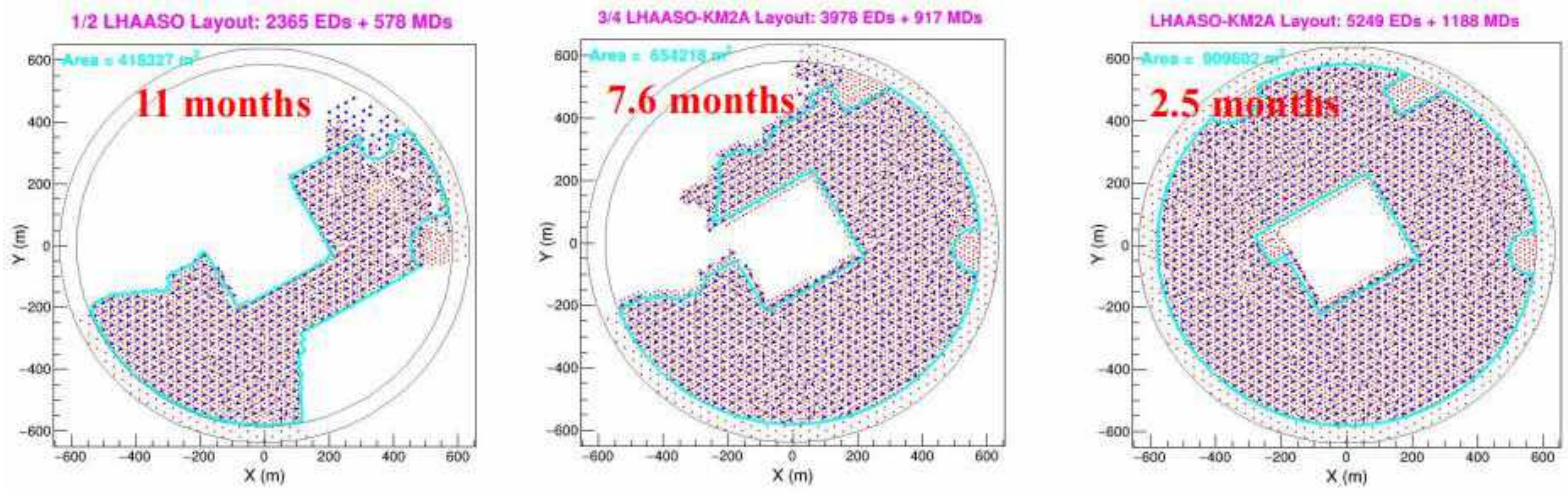


Excellent CR background rejection

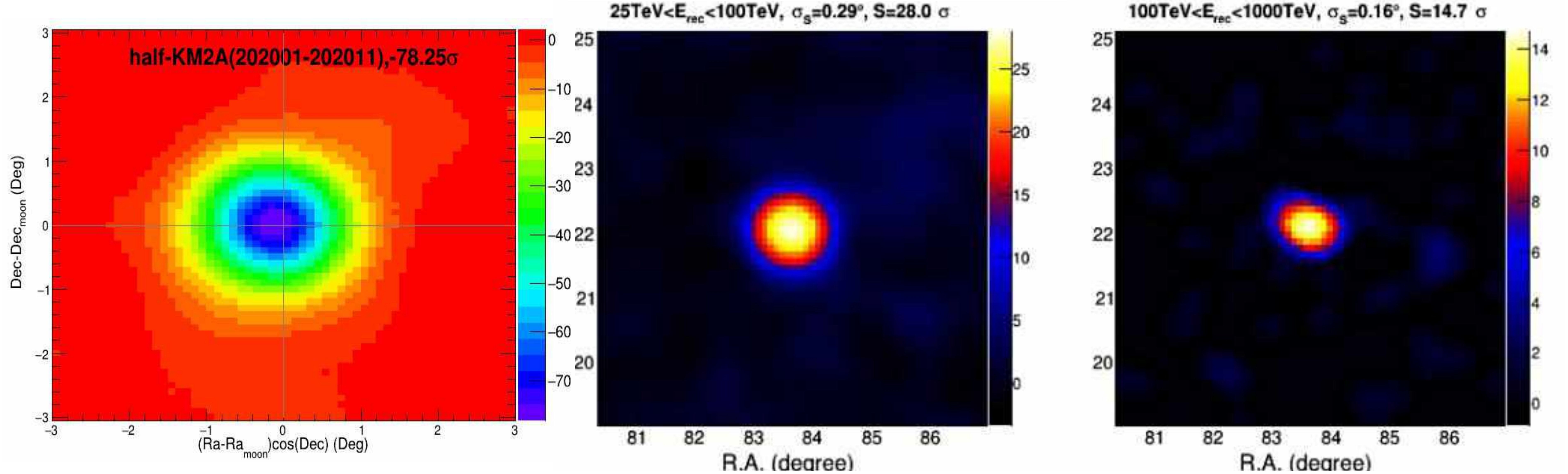




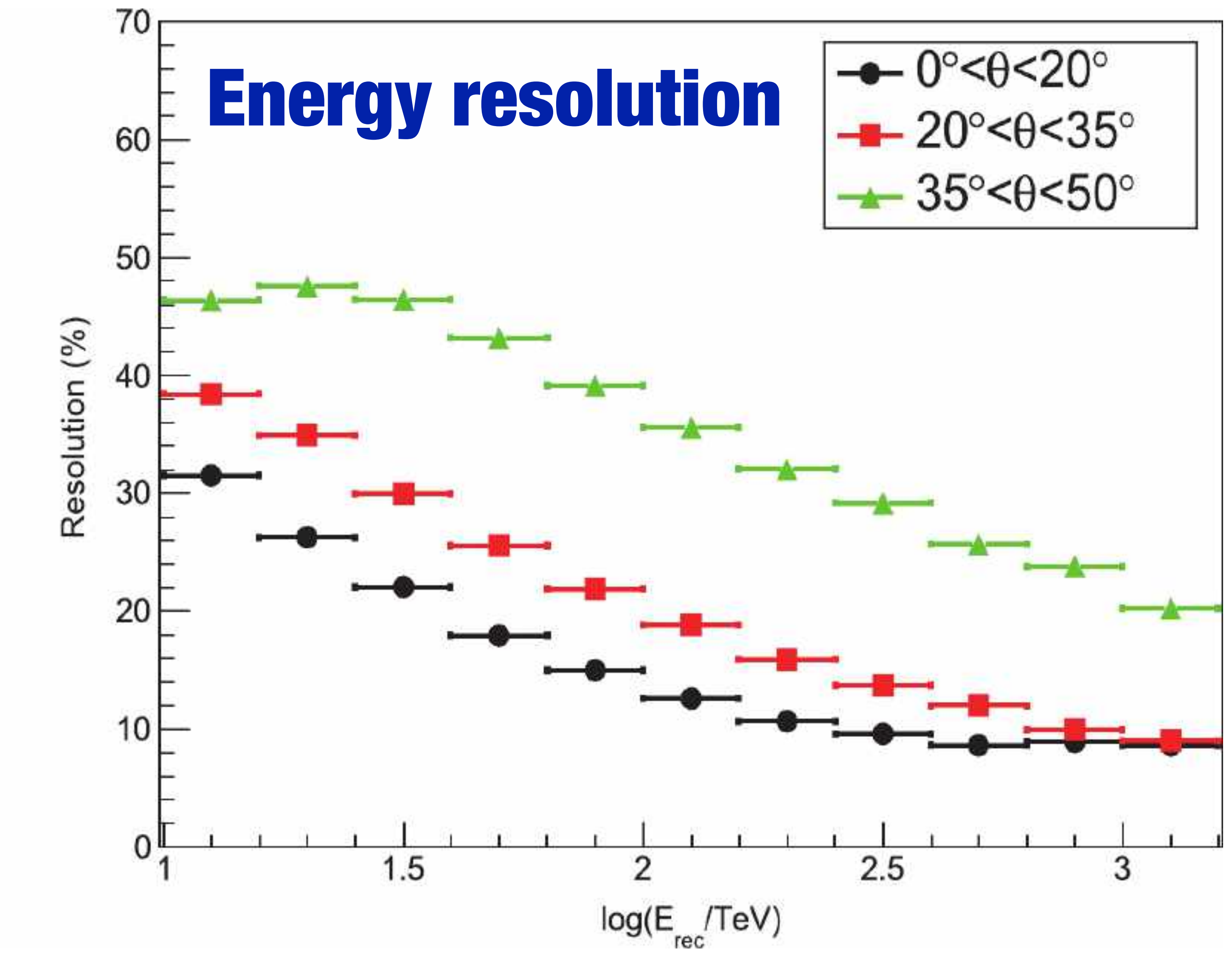
KM2A Performance

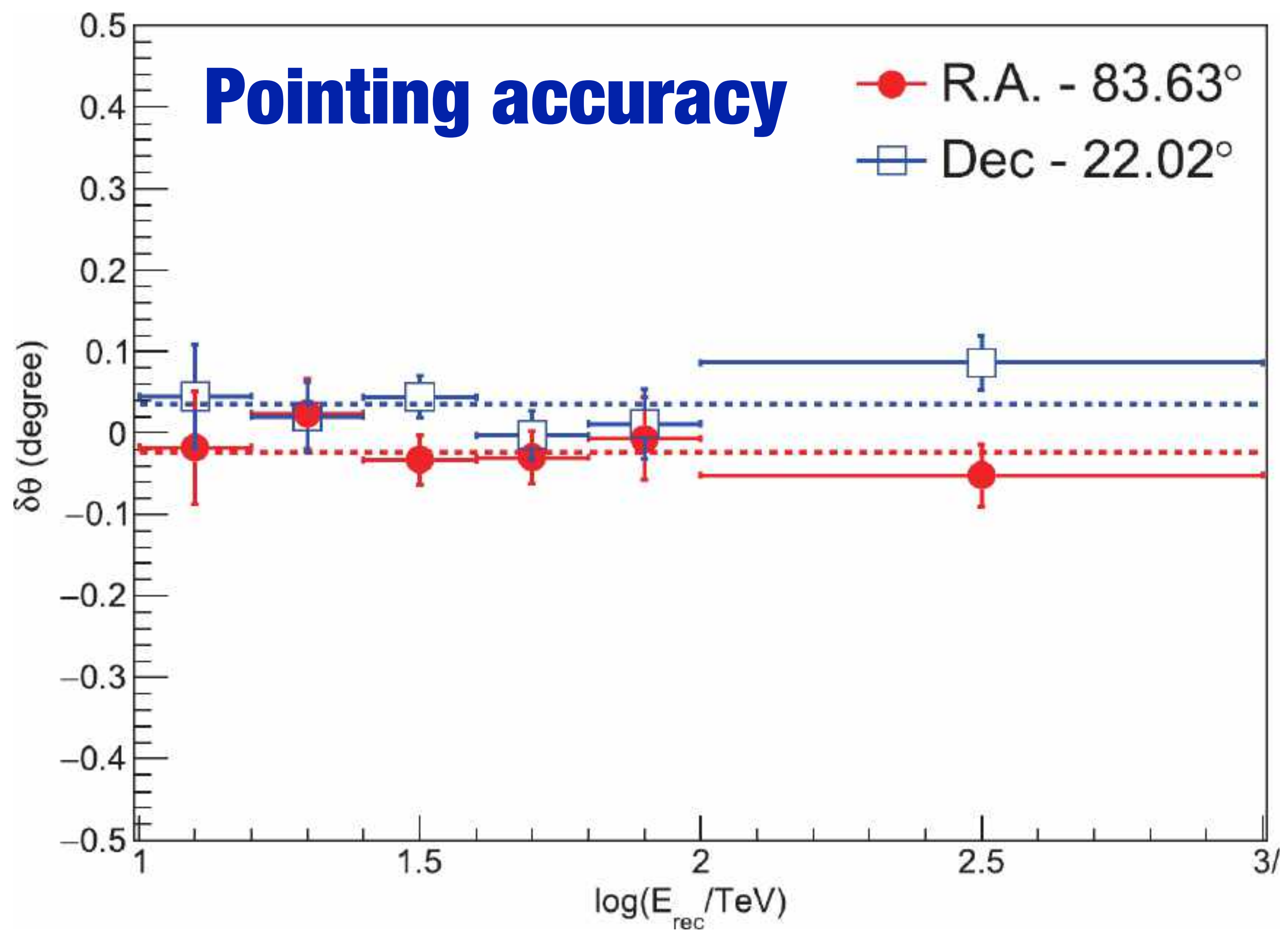


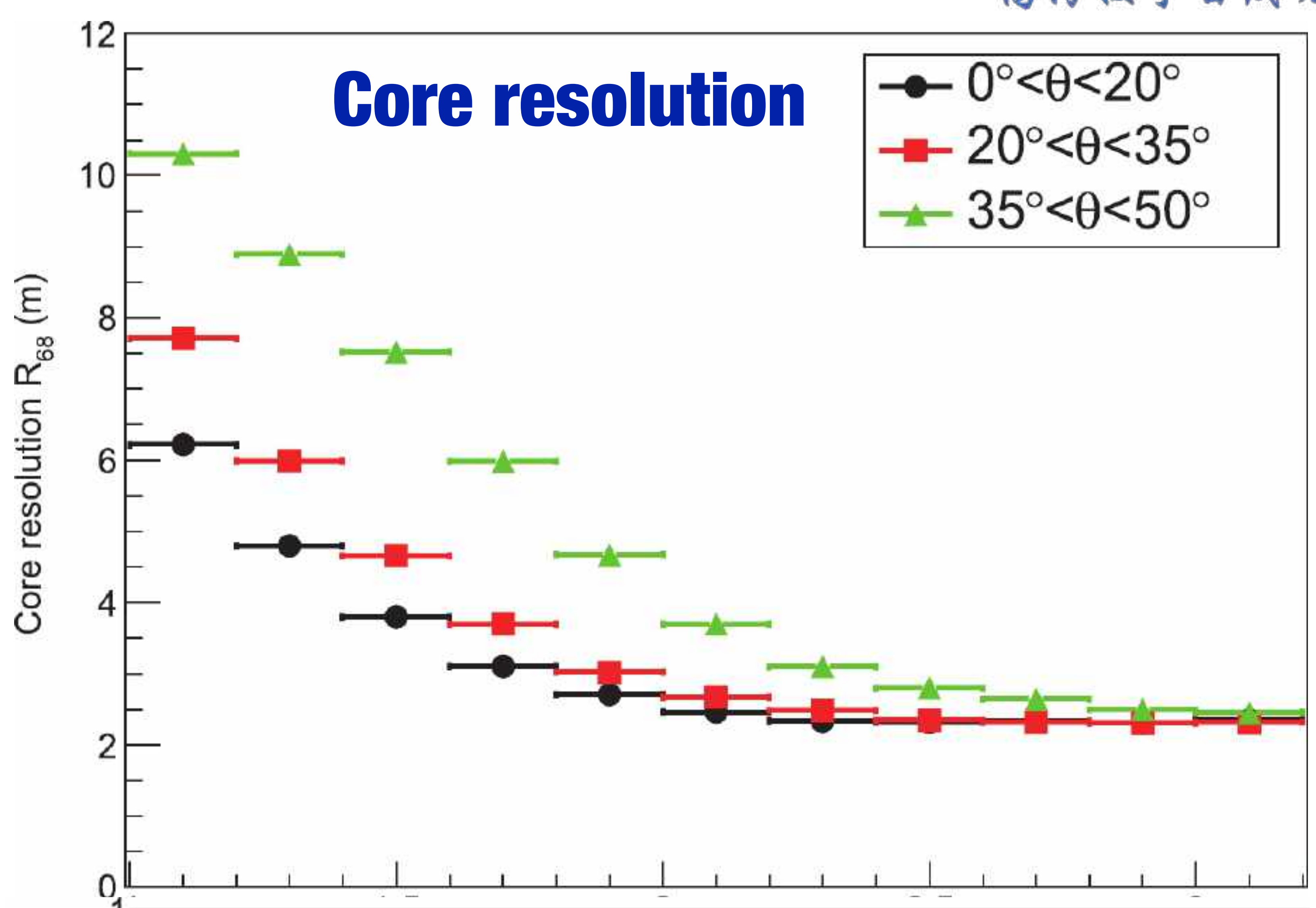
1/2 **KM2A**: *2019.12-2020.11* 3/4 **KM2A**: *2020.12 - 2012.07* **FULL KM2A**: *2021.07*

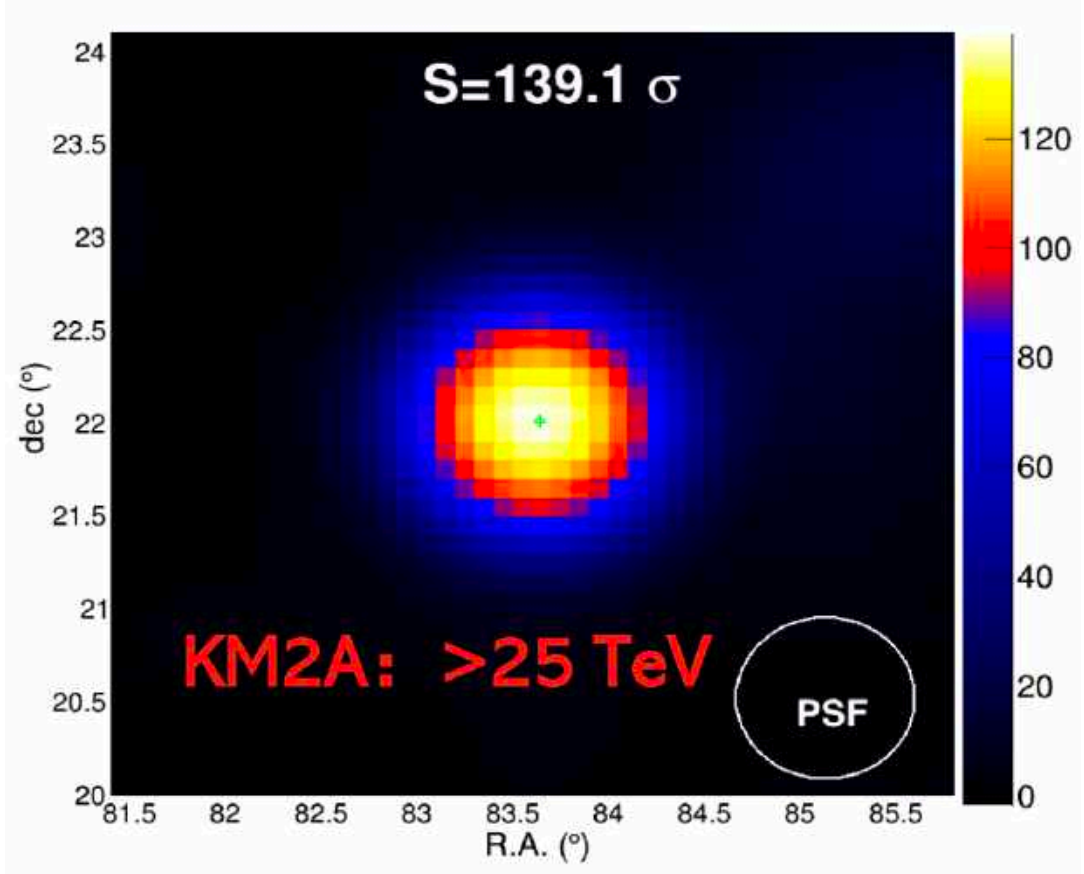


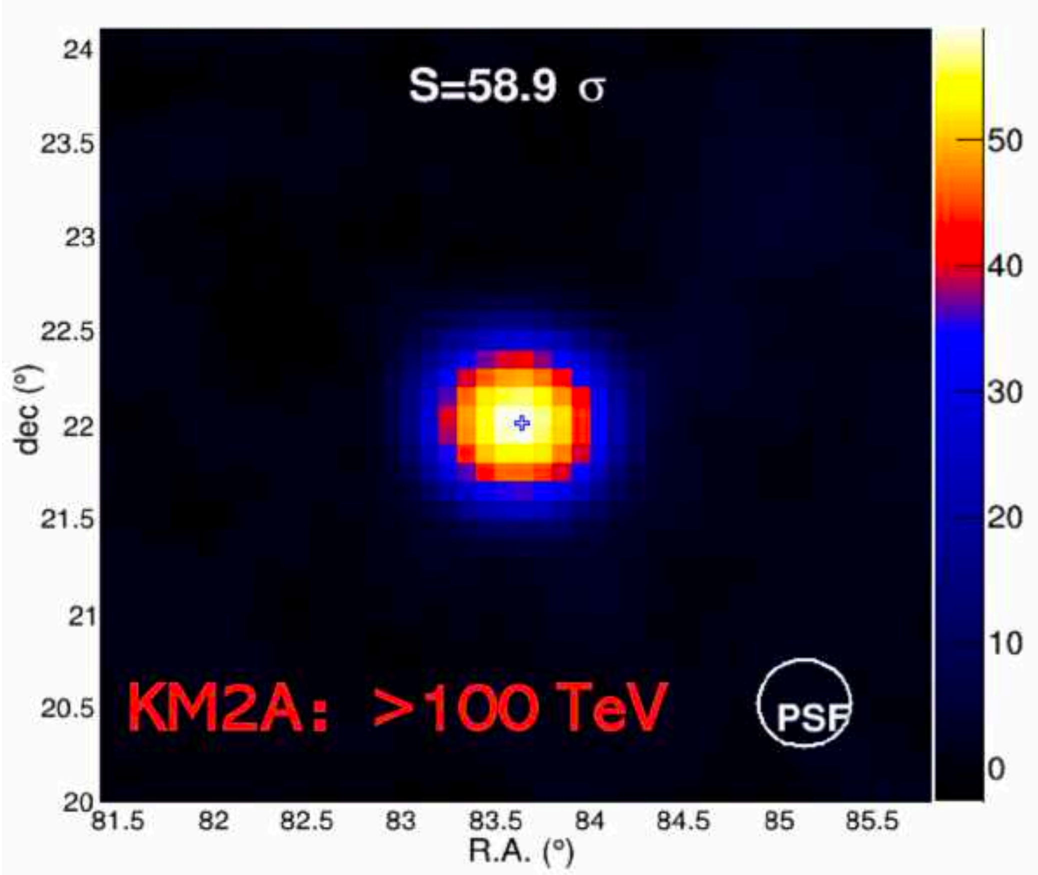
KM2A Performance

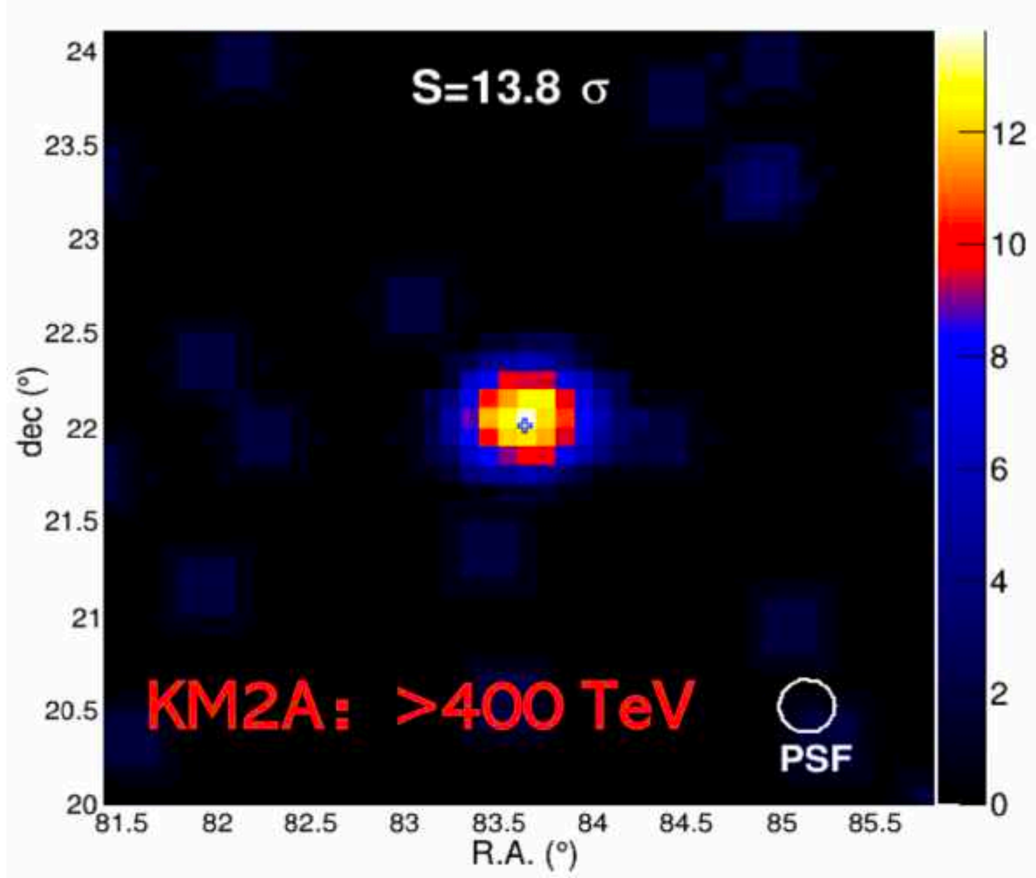


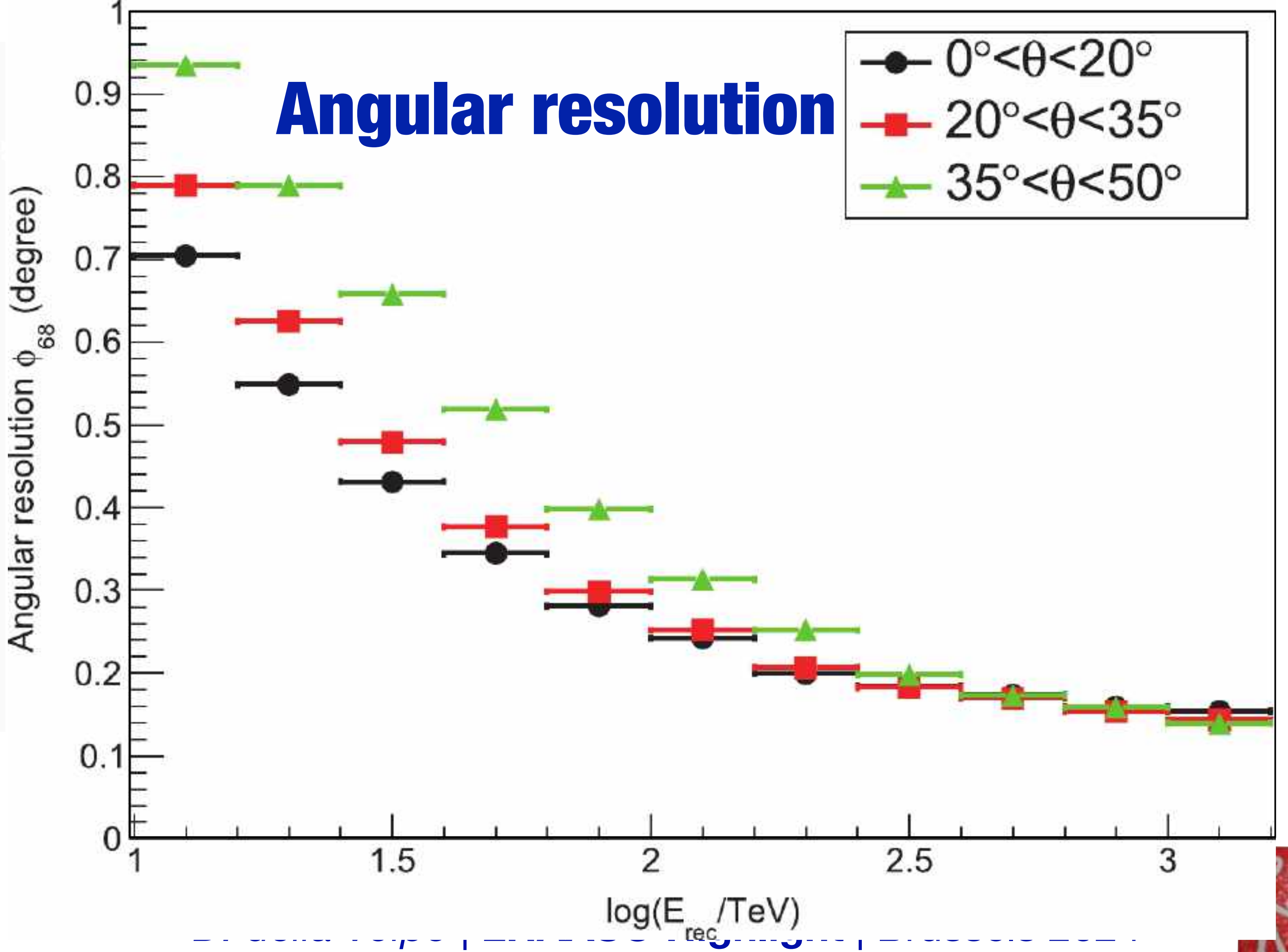












Observation of the Crab Nebula with LHAASO-KM2A − a performance study
Chinese Physics C, Volume 45, Number 2 (2021)
http://doi.org/10.1088/1674-1137/abd01b

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

LHAASO
高海拔宇宙线观测站

First LHAASO catalog

The First LHAASO Catalog of Gamma-Ray Sources

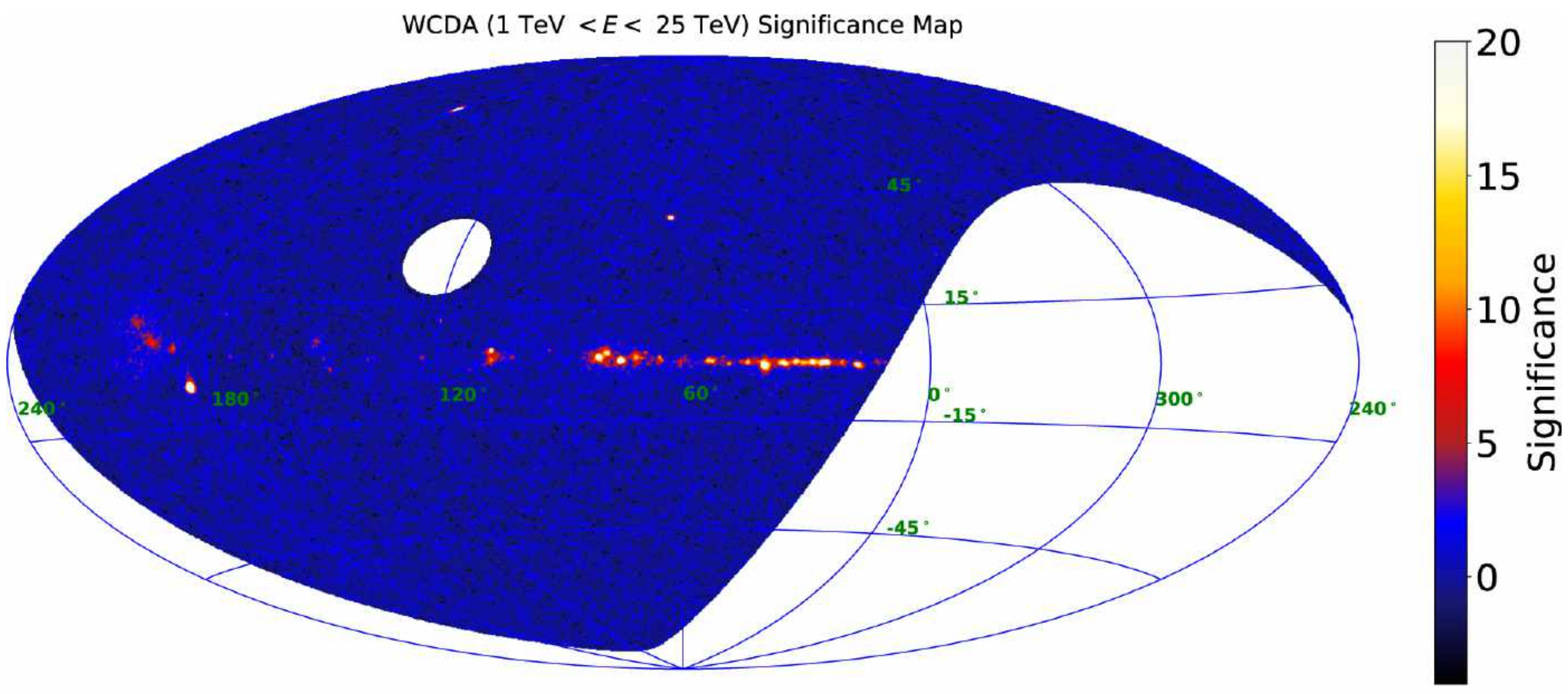
The Astrophysical Journal Supplement Series, **271:25** , 2024 March

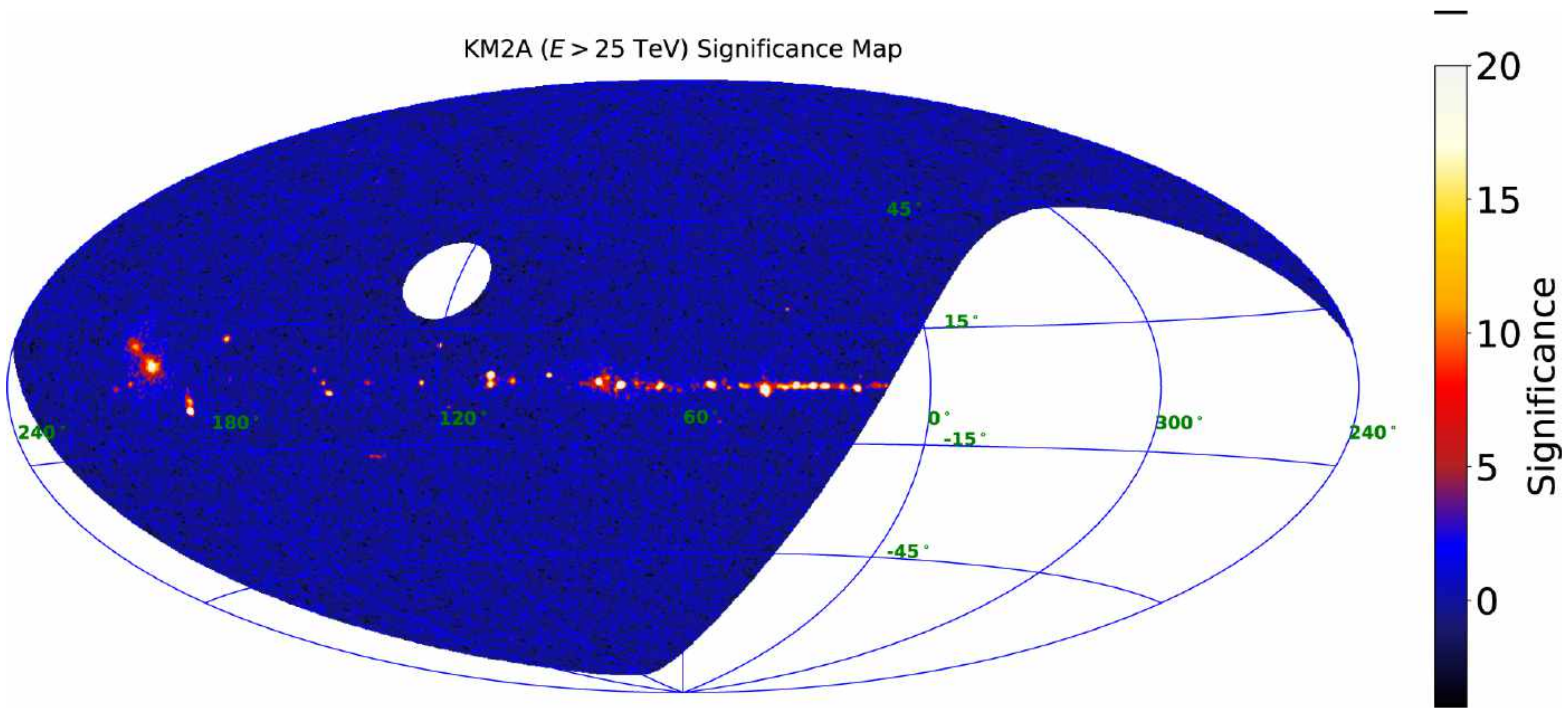
https://doi.org/10.3847/1538-4365/acfd29

First LHAASO γ-ray sources catalog

- In total, 90 sources with extension < 2° are observed. 32 new sources
  - 51% (35/69) 1-25TeV sources are UHE sources.
  - 57% (43/75) >25TeV sources are UHE sources.
  - 19% (8/43) UHE sources are not detected at 1-25TeV

A new class of objects??





Cao et al., DOI: 10.48550/arXiv.2305.17030. & ICRC2023, Inquiry No. 519 ,Shaoqiang Xi

First LHAASO γ-ray sources catalog

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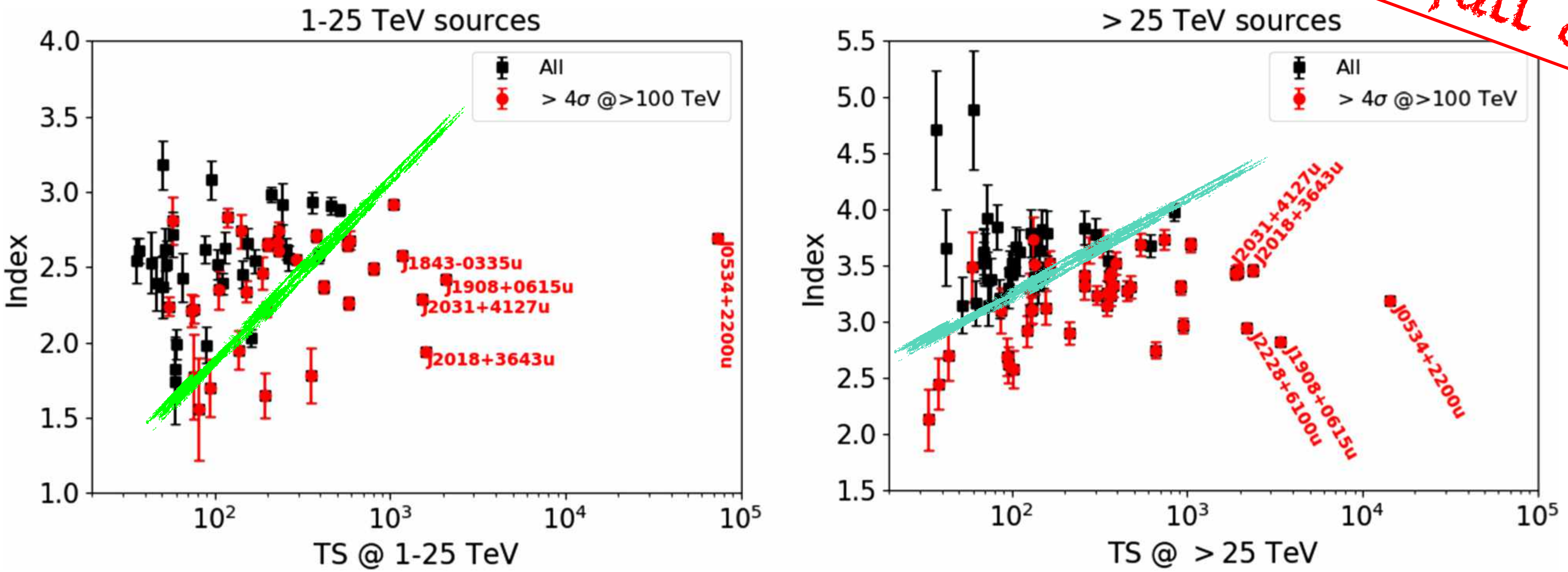
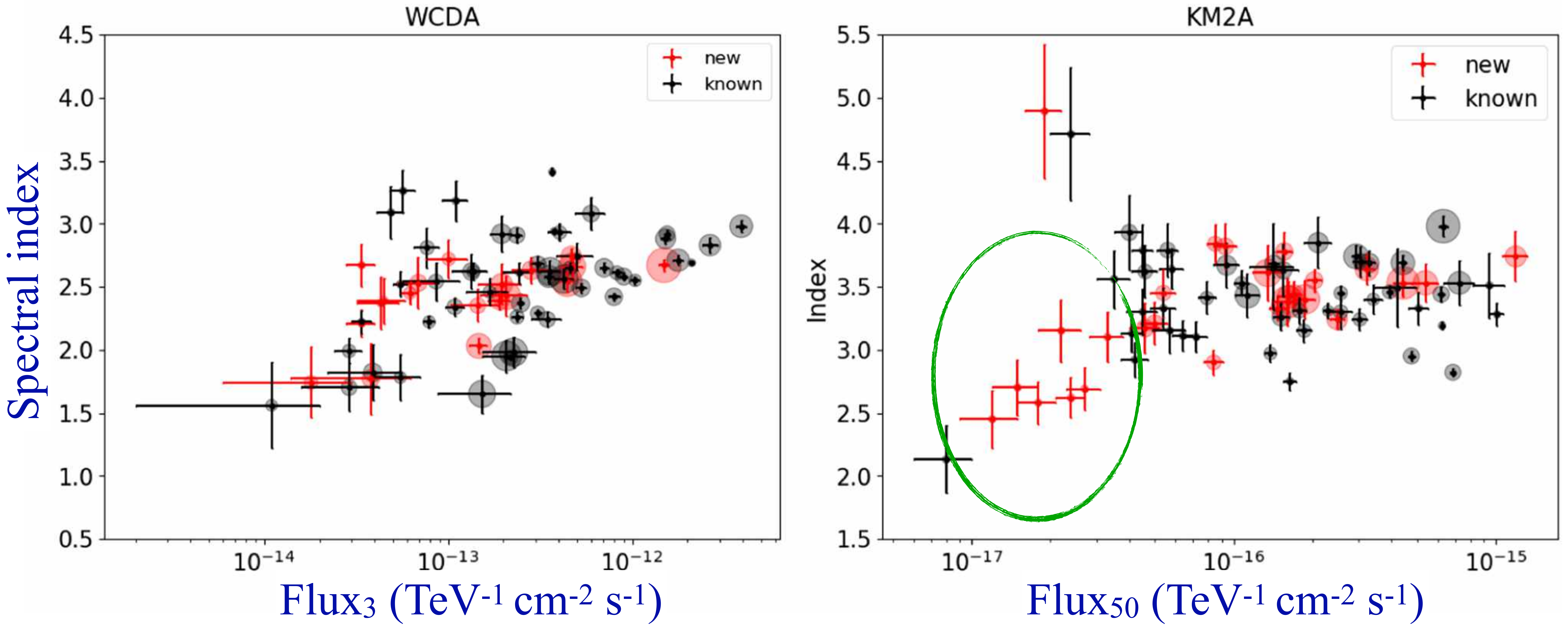
  - 57% (43/75) >25TeV sources are UHE sources.
  - 19% (8/43) UHE sources are not detected at 1-25TeV (new class?)

Milky Way is full of UHE !

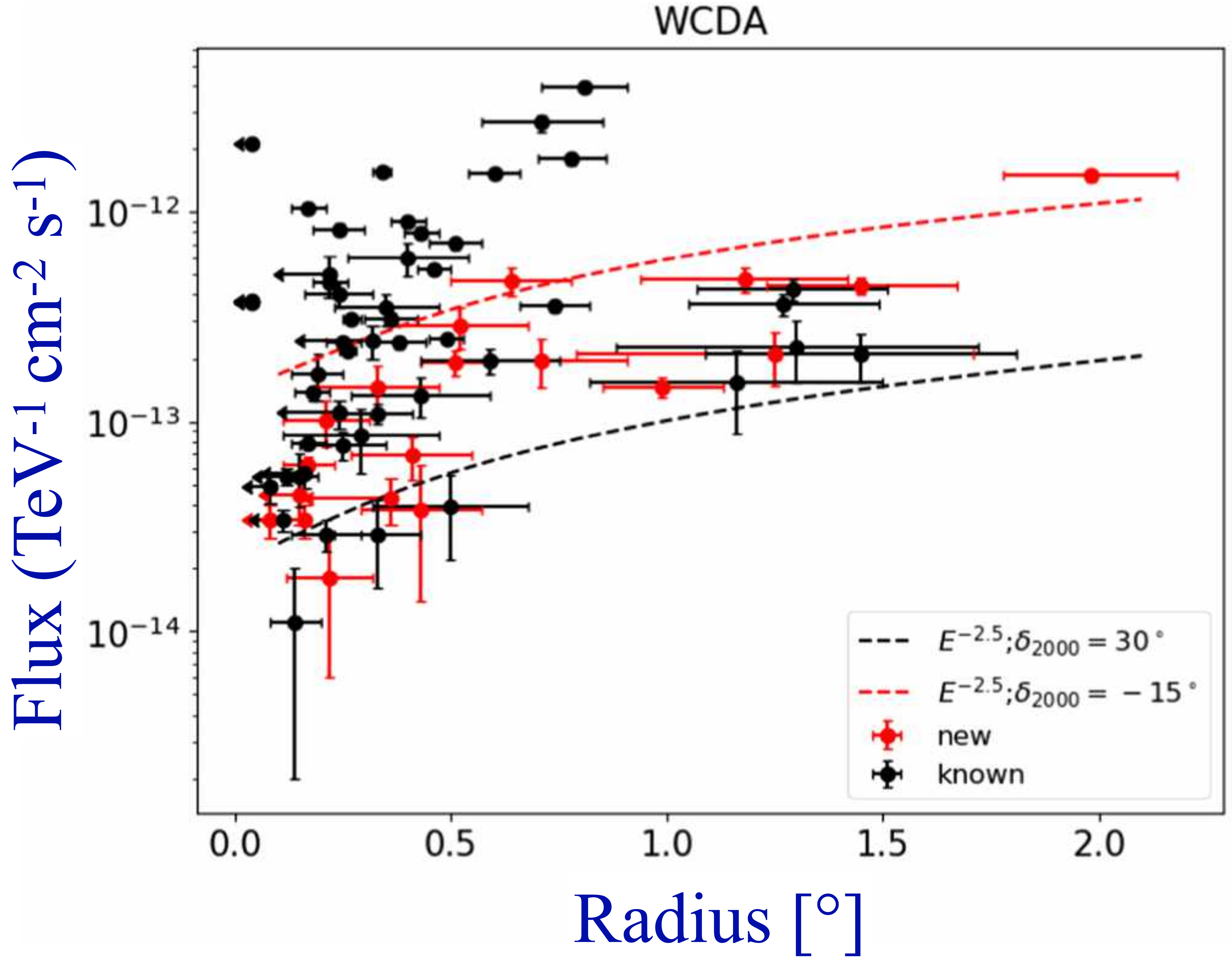


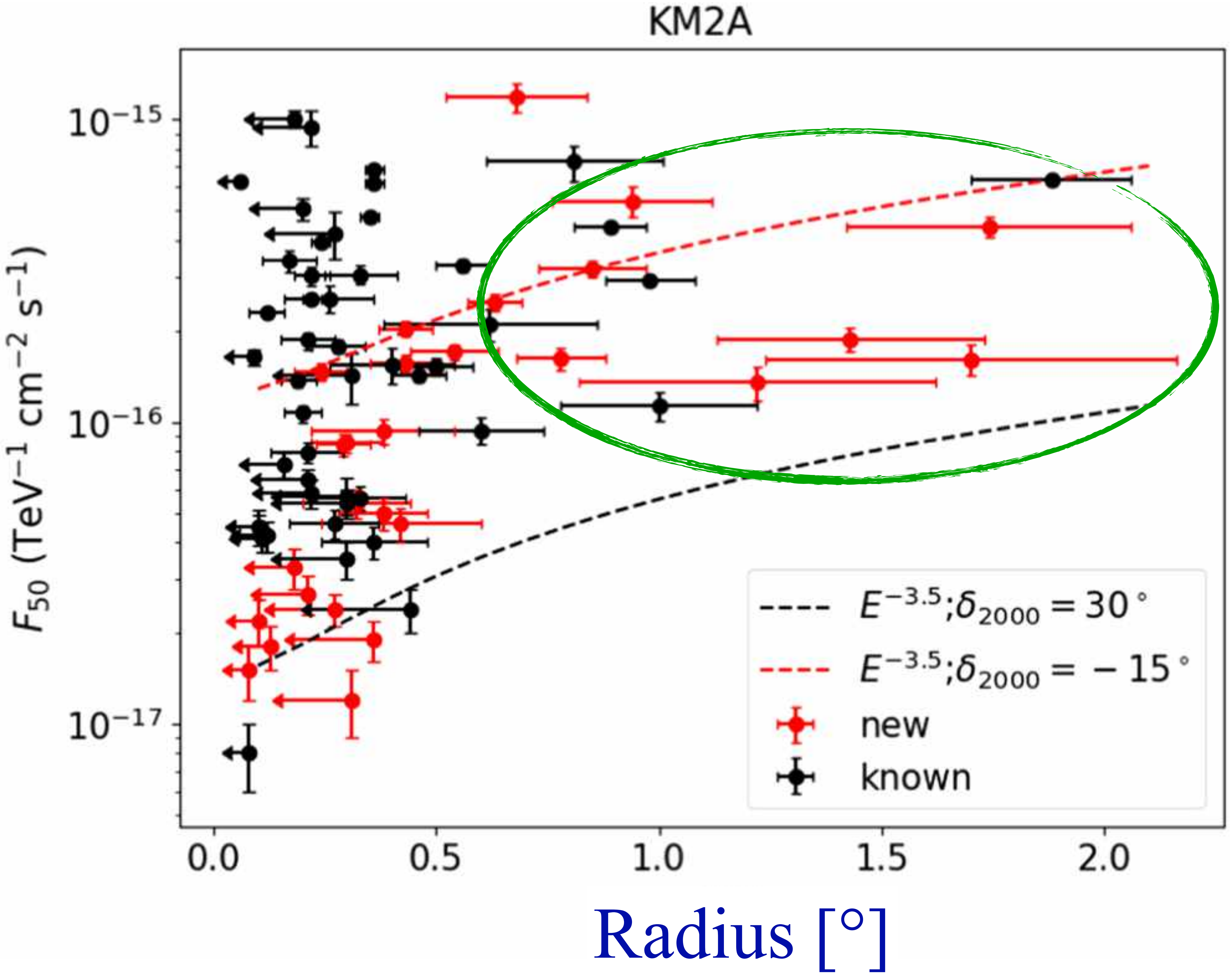
γ-ray sources - Differenzial Flux



- WCDA in good agreements with previous
- KM2A is filling holes
  - High discovery potential

γ-ray sources - Differenzial Flux





- WCDA in good agreements with previous
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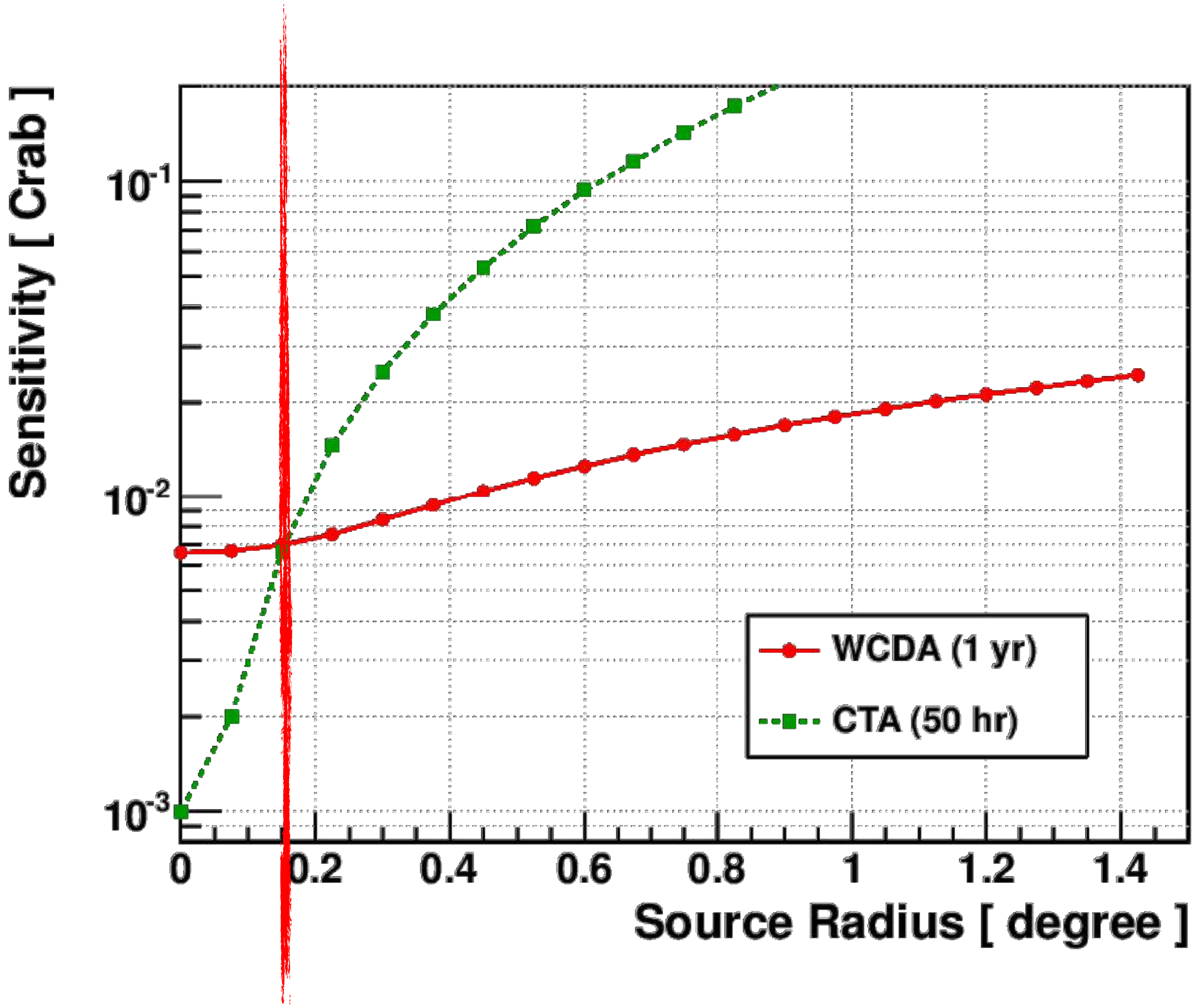
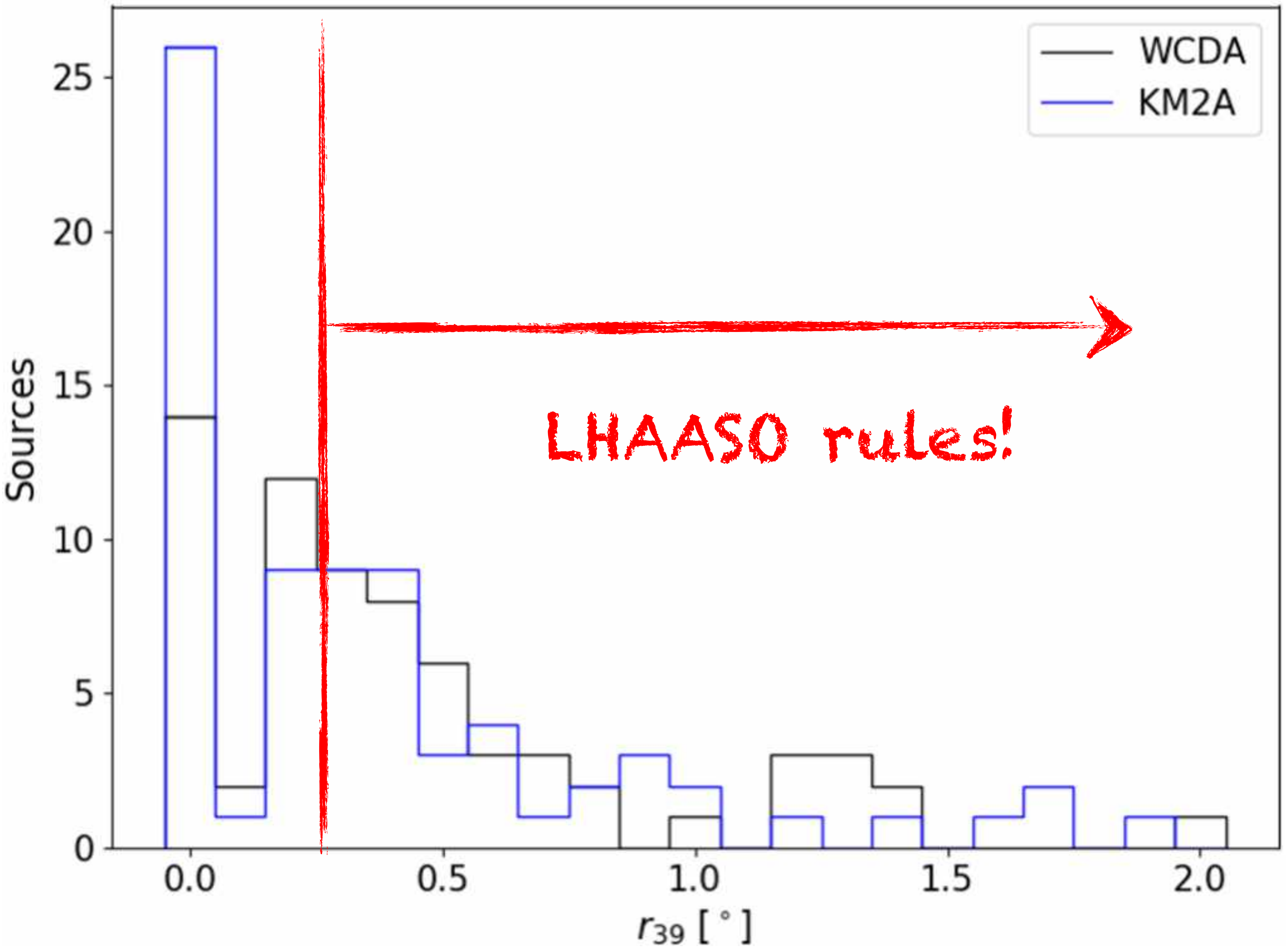
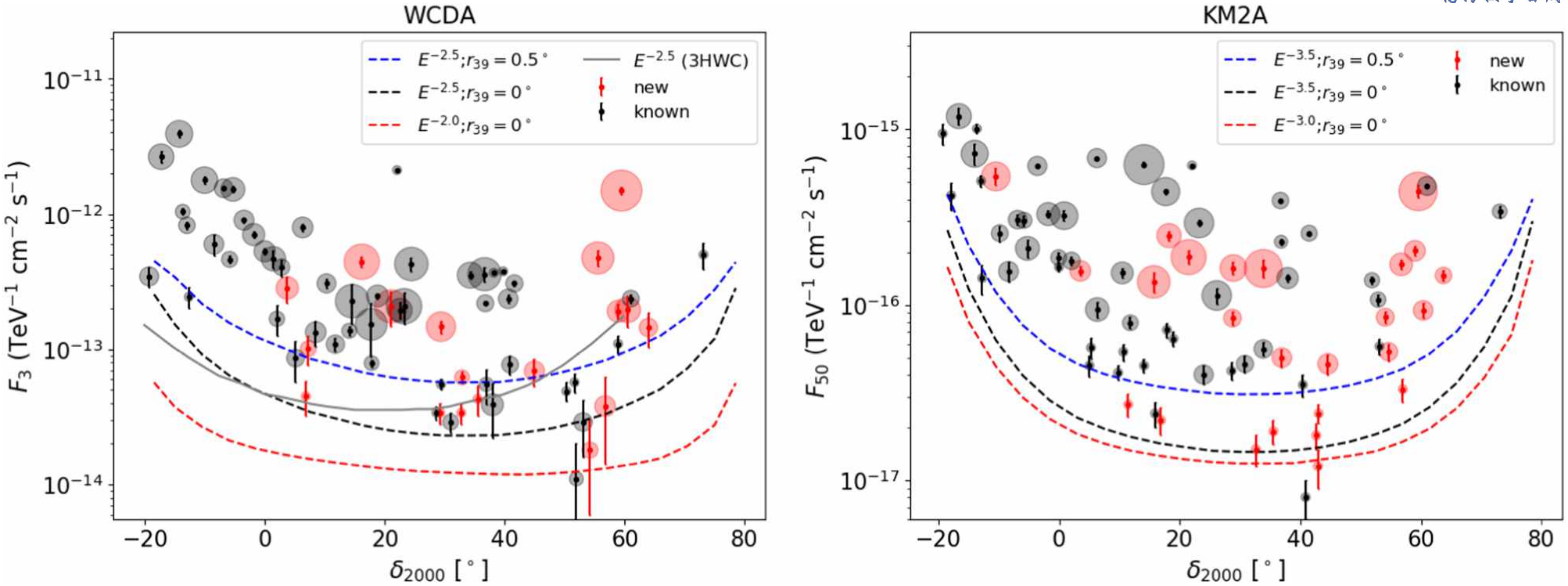
65 sources with extended morphology

γ-ray sources - Source size



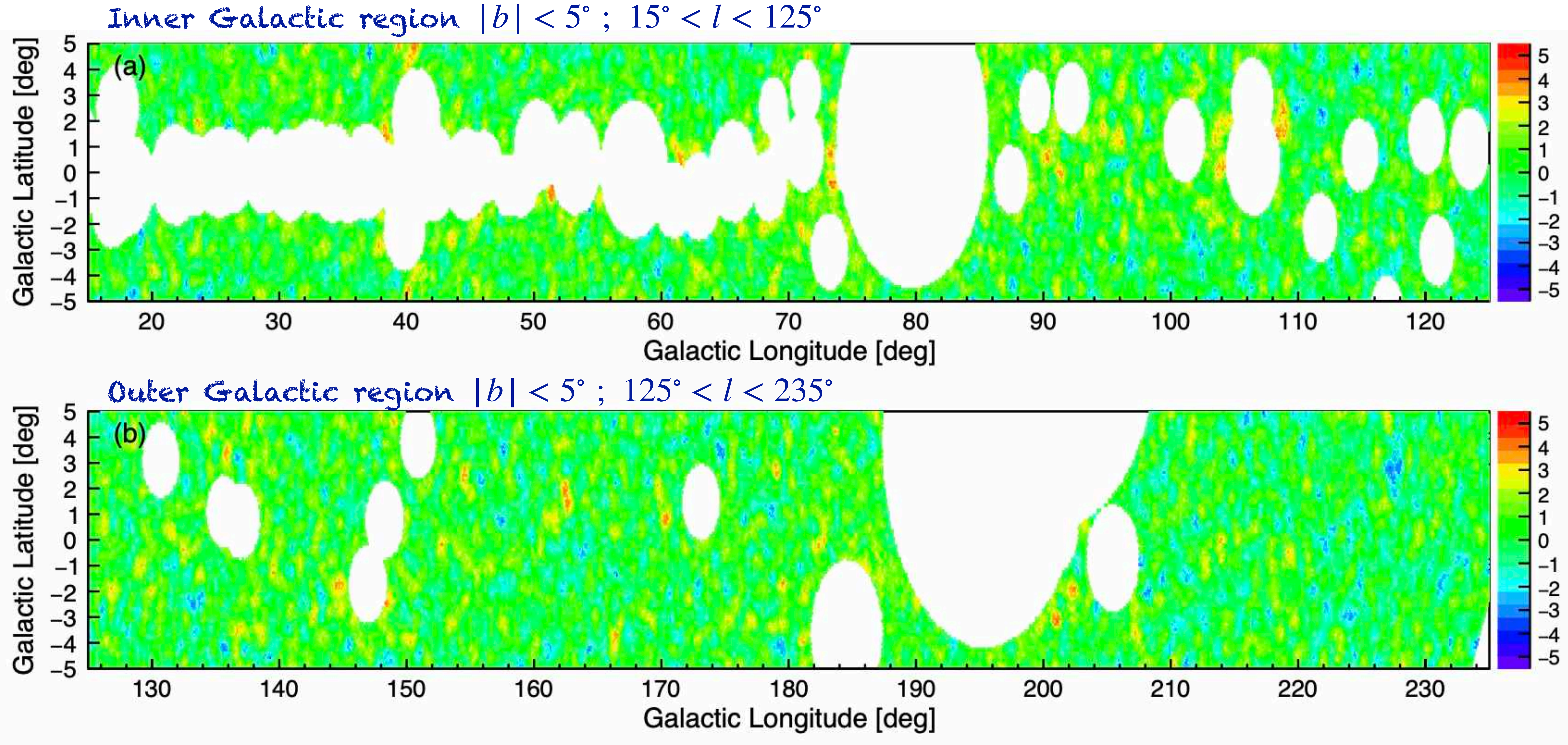


γ-ray sources - Differenzial Flux



- Sensitivity for point source in agreement with expectation
- First assessment on extended source sensitivity

Diffuse γ-ray Emission



Removed Source

- LHAASO Source with 5σ pre-trial significance
- TevCat Sources masked

$$R = 5 \cdot \sqrt{\sigma_{PSF}^2 + \sigma_{ext}^2}$$

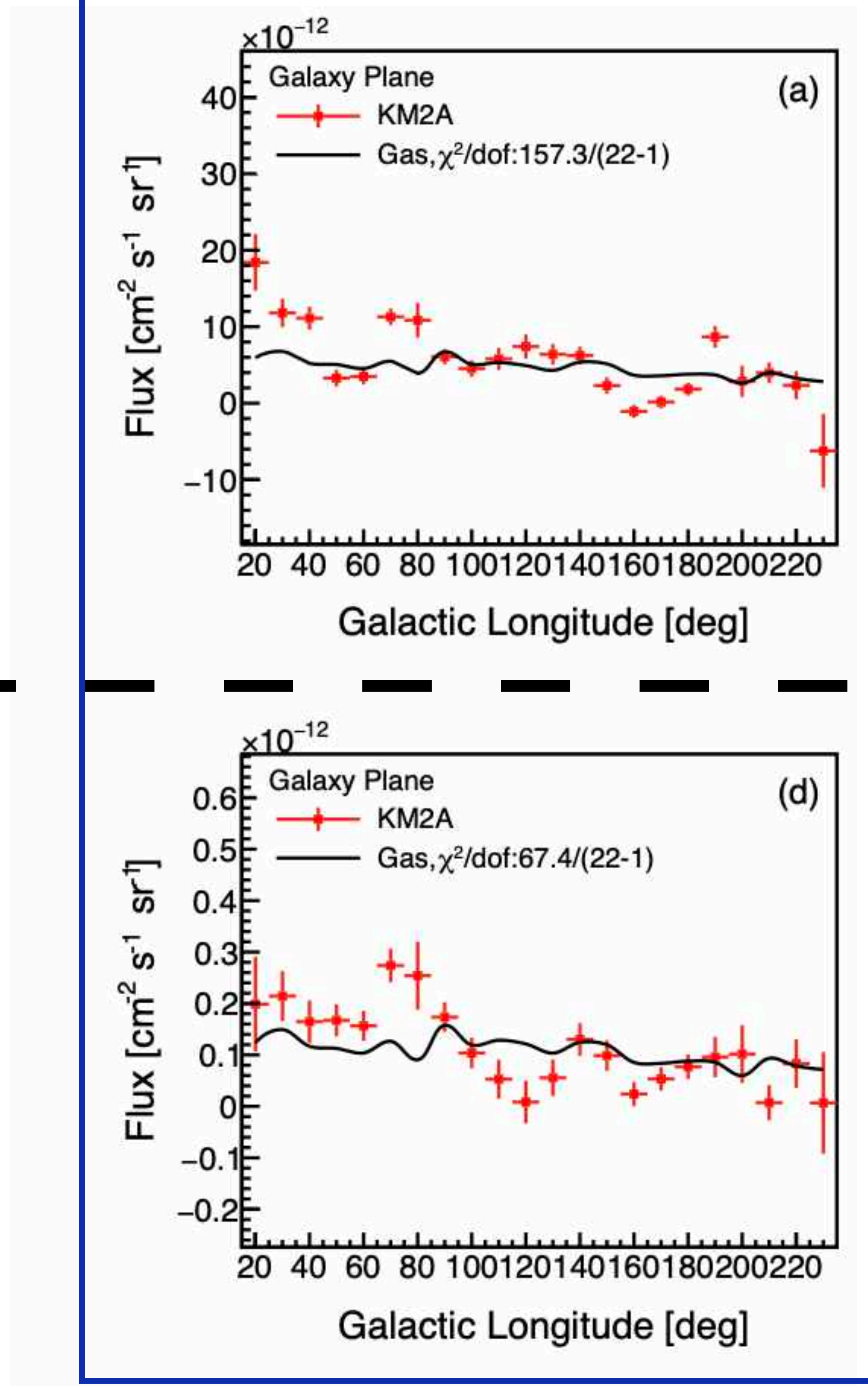
For TevCat and KM2A overlapping source KM2A parameters are used to mask them

Coordinate bin $0.1^\circ \times 0.1^\circ$

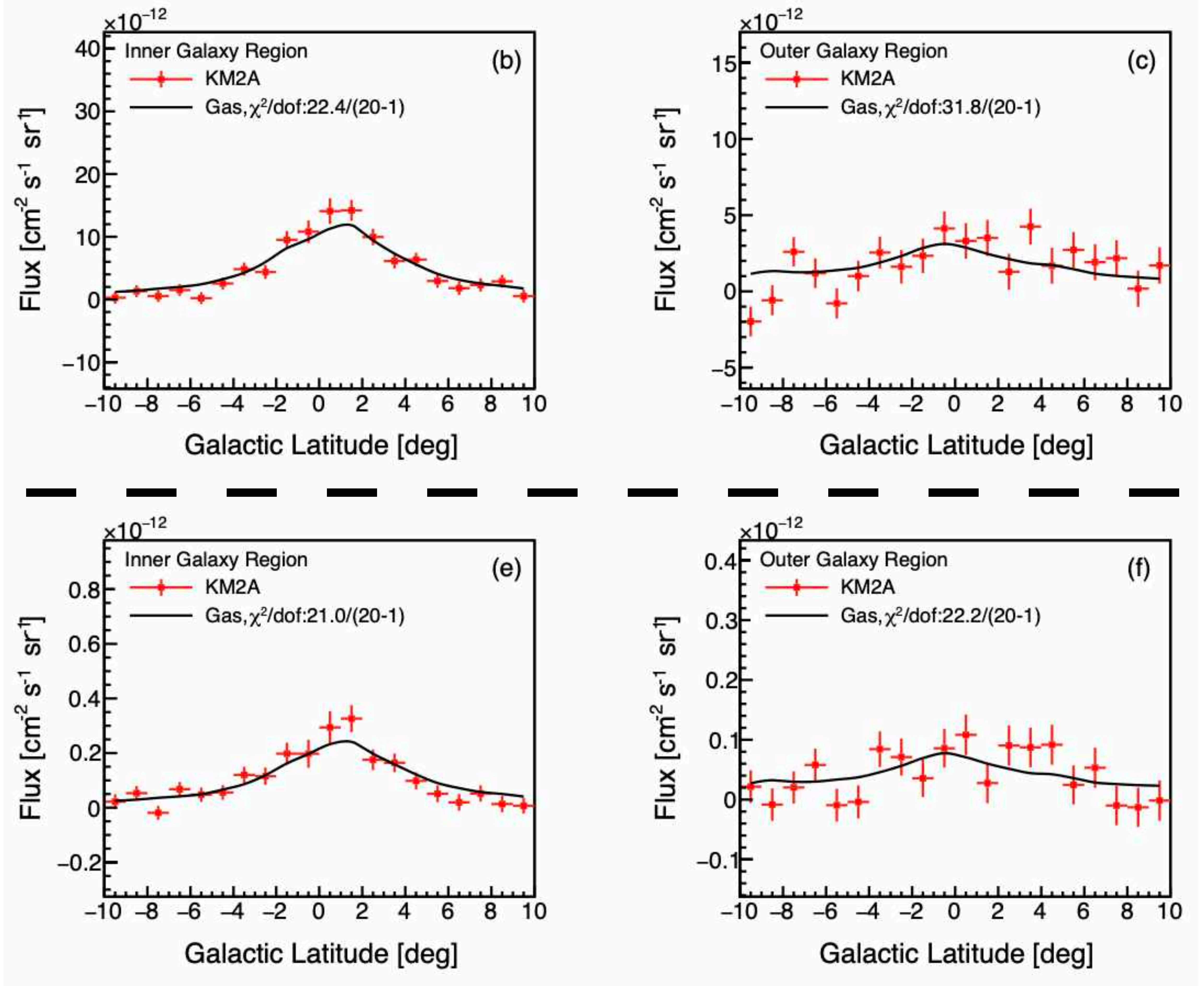
Energy bin $\Delta\ log(E_{IN}) = 0.2$; $\Delta\ log(E_{OUT}) = 0.4$

Diffuse γ-ray Emission

$10\ \mathrm{TeV} < E < 63\ \mathrm{TeV}$



The longitudinal distributions: slightly deviates from the dust distribution (PLANCK).



The latitude distributions are consistent with the dust distribution (PLANCK).

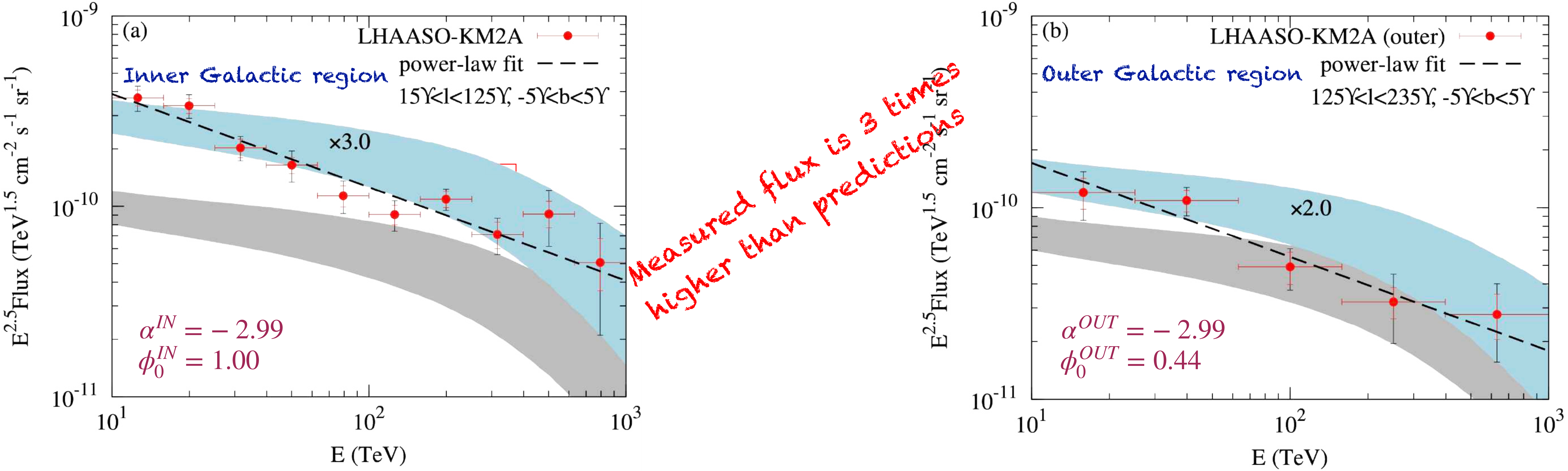
$16\ \mathrm{TeV} < E < 1\ \mathrm{PeV}$

Inner

Outer

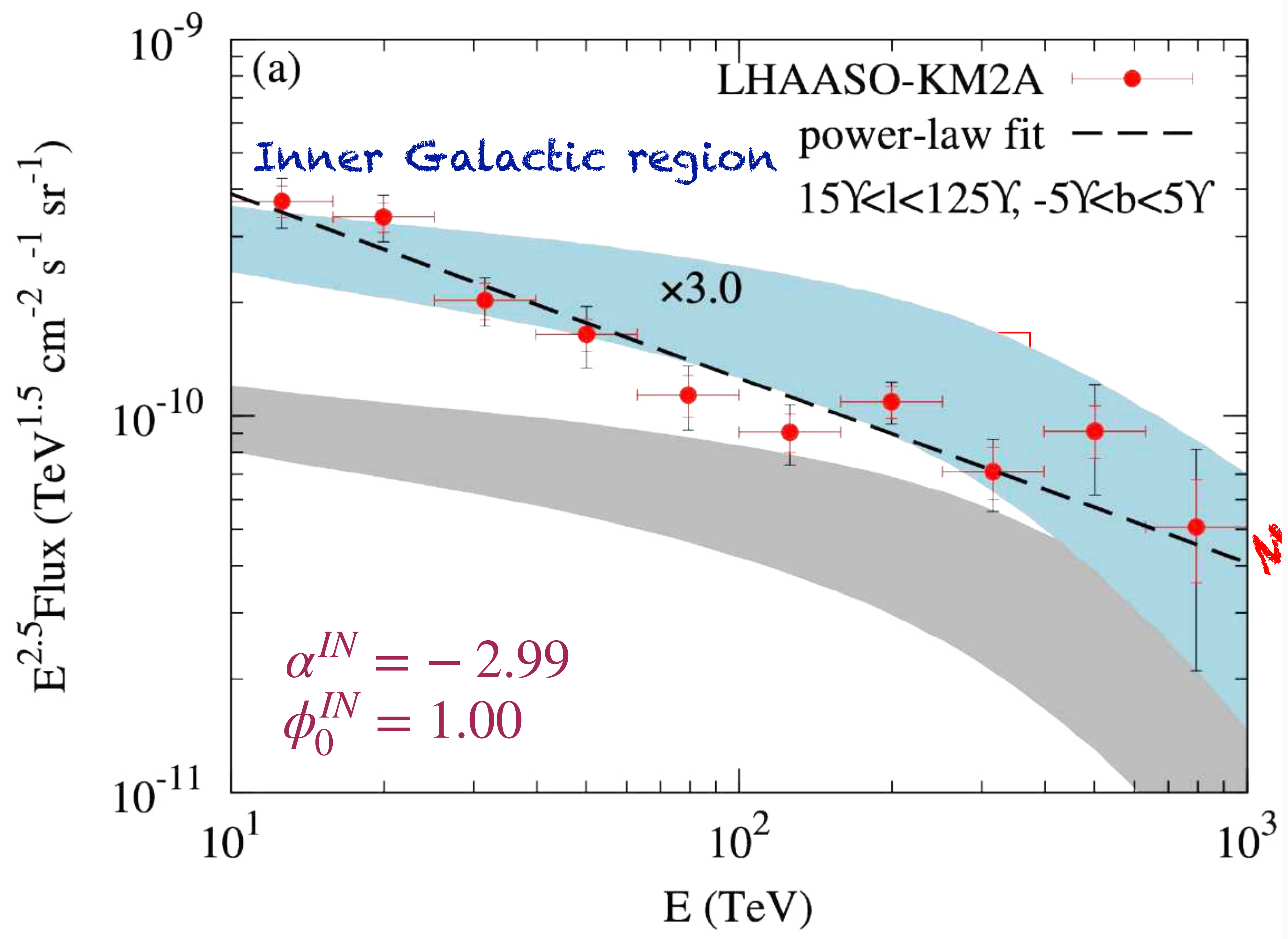
Diffuse γ-ray Emission

Model prediction using
local CR spectra && gas column denisity



- Flux modelling assumes uniform CR in the Galaxy + ISM distribution (PLANCK dust map)
- More dramatic discrepancy for Inner galactic region
- Additional diffuse sources? Propagation effects?
- Well many possible scenarios….. more data can shed light

Diffuse γ-ray Emission



Model prediction using
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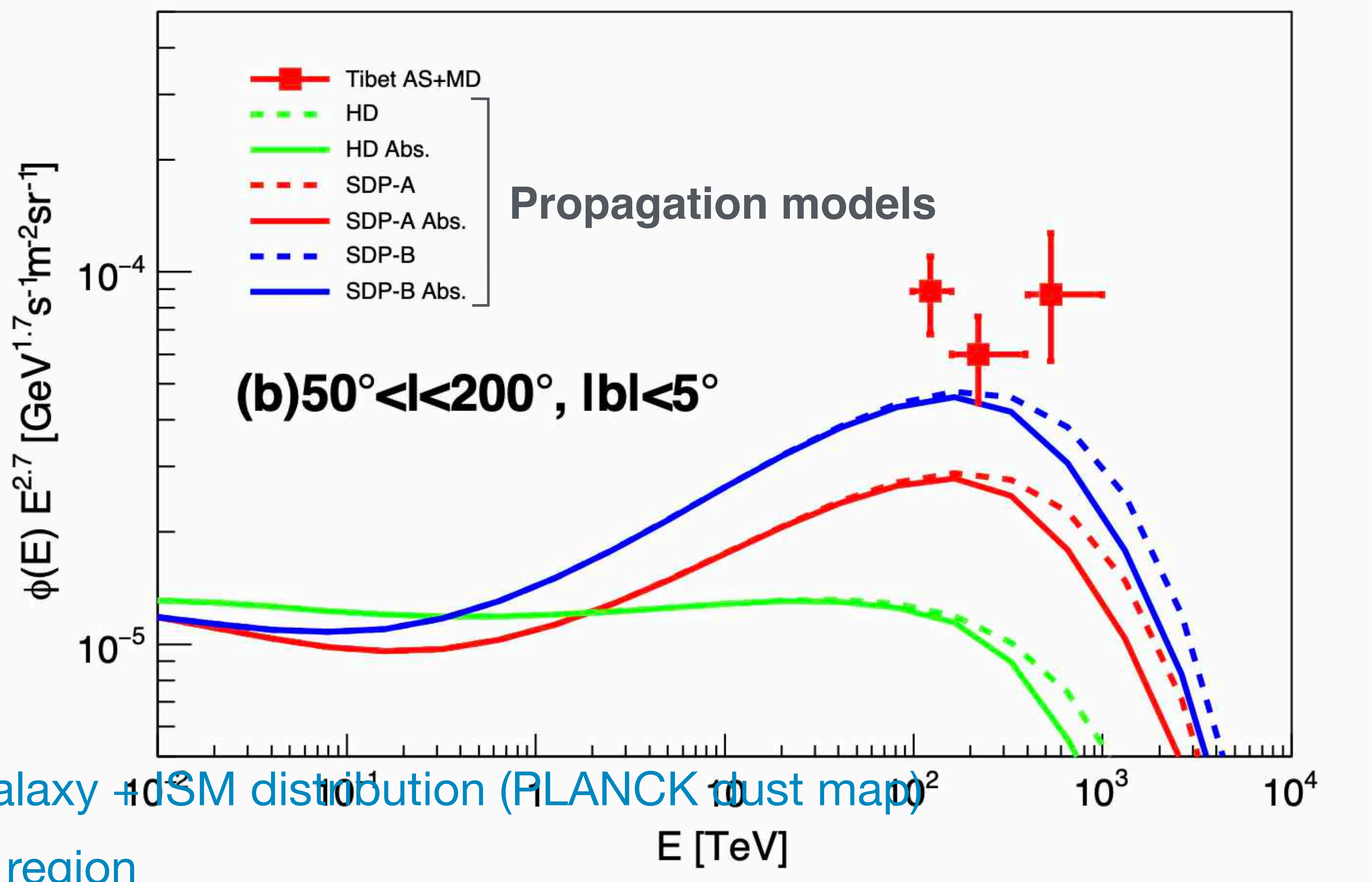

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- Additional diffuse sources? Propagation effects?
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Cosmic Rays

Measurements of All-Particle Energy Spectrum and Mean Logarithmic Mass of Cosmic Rays from 0.3 to 30 PeV with LHAASO-KM2A

PHYSICAL REVIEW LETTERS 132, 131002 (2024)

https://doi.org/10.1103/PhysRevLett.132.131002

All-particle Spectrum

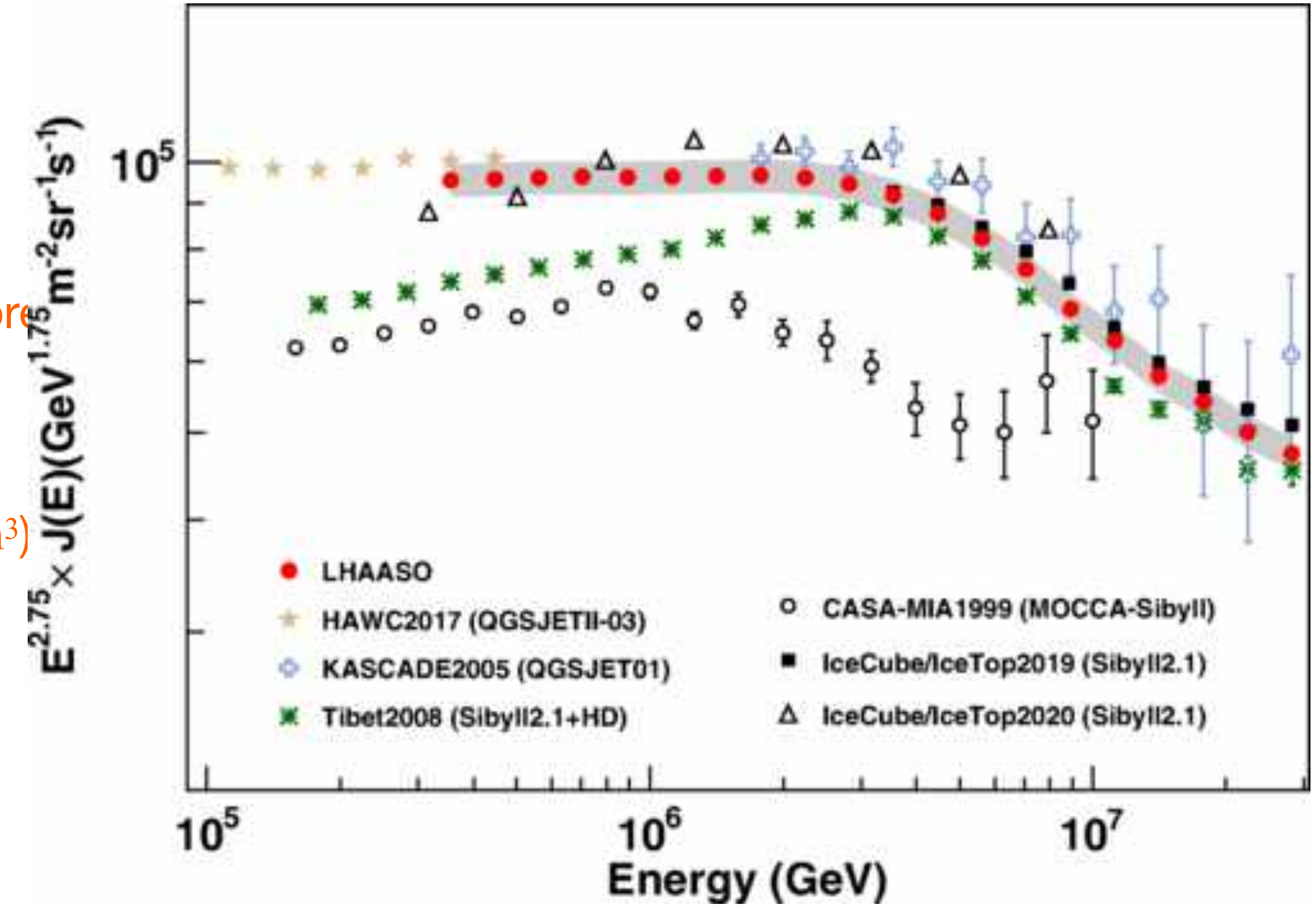
- Based on KM2A with a certain care at muon correct reconstruction
  - Atmospheric pressure variation
    - CIC - Constant Intensity Cut (> 0.6%)
  - Fake muon by high energetic charge particle in shower core
    - Particle in a ring 320-420m form KM2A center
- Shower max at 600 g/cm^3 at knee
  - Use zenith angles between 10° (600 g/cm^3) -30° (690 g/cm^3)

$$N_{e\mu} = N_e + 2.8 \cdot N_\mu$$ **Composition independent**

Composition models

$$\log_{10}(E/\mathrm{GeV}) = p_0 + p_1 \log_{10}(N_{e\mu})$$

$$J(E) = \frac{\Delta N(E)}{\delta E \cdot A_{eff} \cdot T}$$ **Flux measured**



$$J(E) = \Phi_0 \cdot E^{\gamma_1} \times \left[1 + \left(\frac{E}{Eb}\right)^s\right]^{(\gamma_2-\gamma_1)/2}$$ **Flux Fit**

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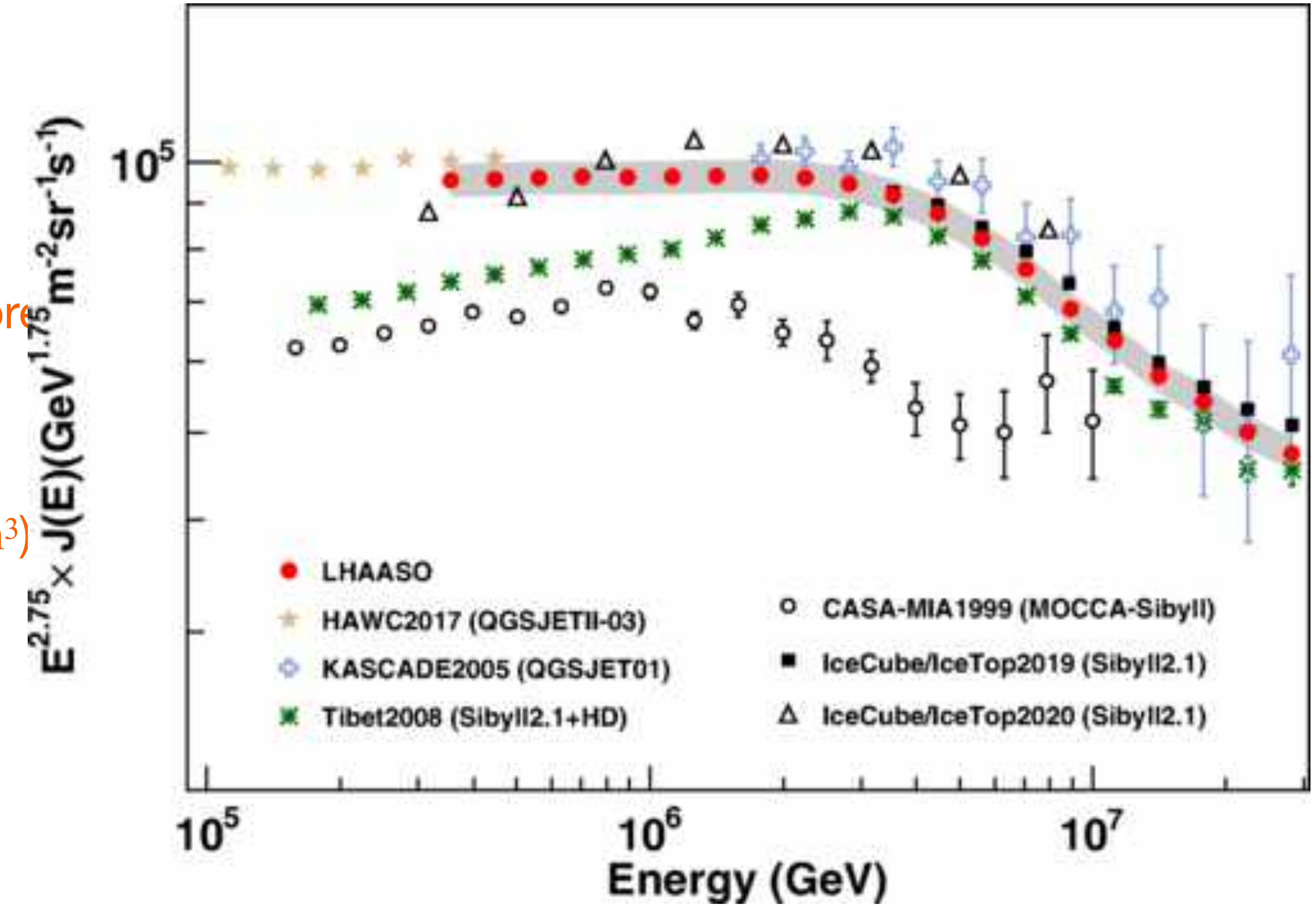
$$N_{e\mu} = N_e + 2.8 \cdot N_\mu$$ **Composition independent**

Composition models

$$\log_{10}(E/\mathrm{GeV}) = 2.791 + 0.993 \log_{10}(N_{e\mu})$$

$$J(E) = \frac{\Delta N(E)}{\delta E \cdot A_{eff} \cdot T}$$ **Flux measured**



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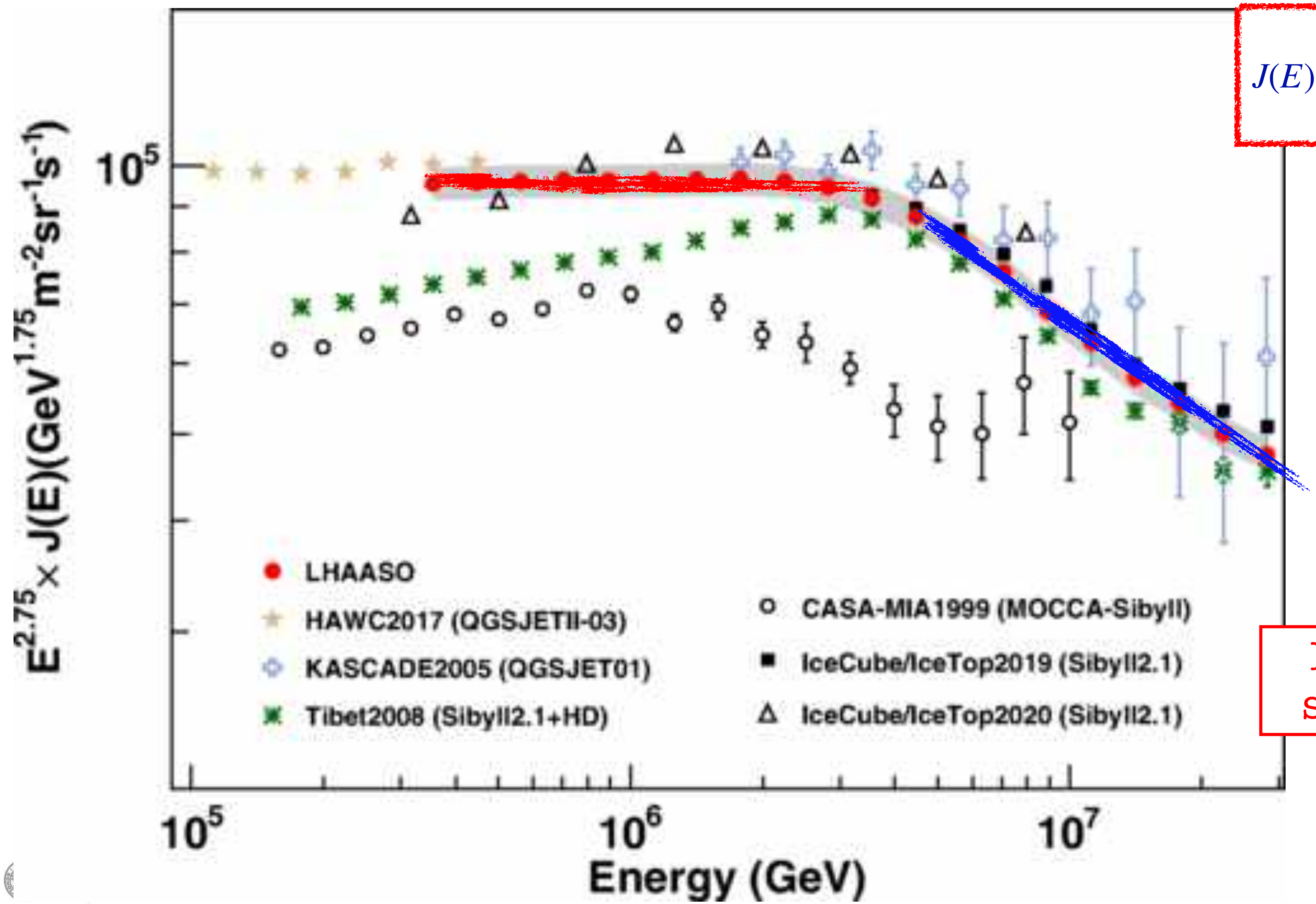


$$J(E) = \Phi_0 \cdot E^{\gamma_1} \times \left[1 + \left(\frac{E}{Eb}\right)^s\right]^{(\gamma_2-\gamma_1)/2}$$ **Flux Fit**

knee $E_b = 3.67 \pm 0.05_{stat} \pm 0.15_{sys}$ PeV

$s = 4.2 \pm 0.1_{stat} \pm 0.5_{sys}$

$\gamma_1 = -2.7413 \pm 0.0004_{stat} \pm 0.0050_{sys}$

$\gamma_2 = -3.128 \pm 0.005_{stat} \pm 0.027_{sys}$

Most precise measurement of spectrum between 0.3-3 PeV!!

$<\ln(A)>$ of Cosmic rays

$$N_\mu \propto A \cdot \left(\frac{E}{A \cdot \varepsilon_c}\right)^\beta$$

$$\langle \ln(N_\mu) \rangle = x_0 + x_1 \cdot \langle \ln(A) \rangle$$

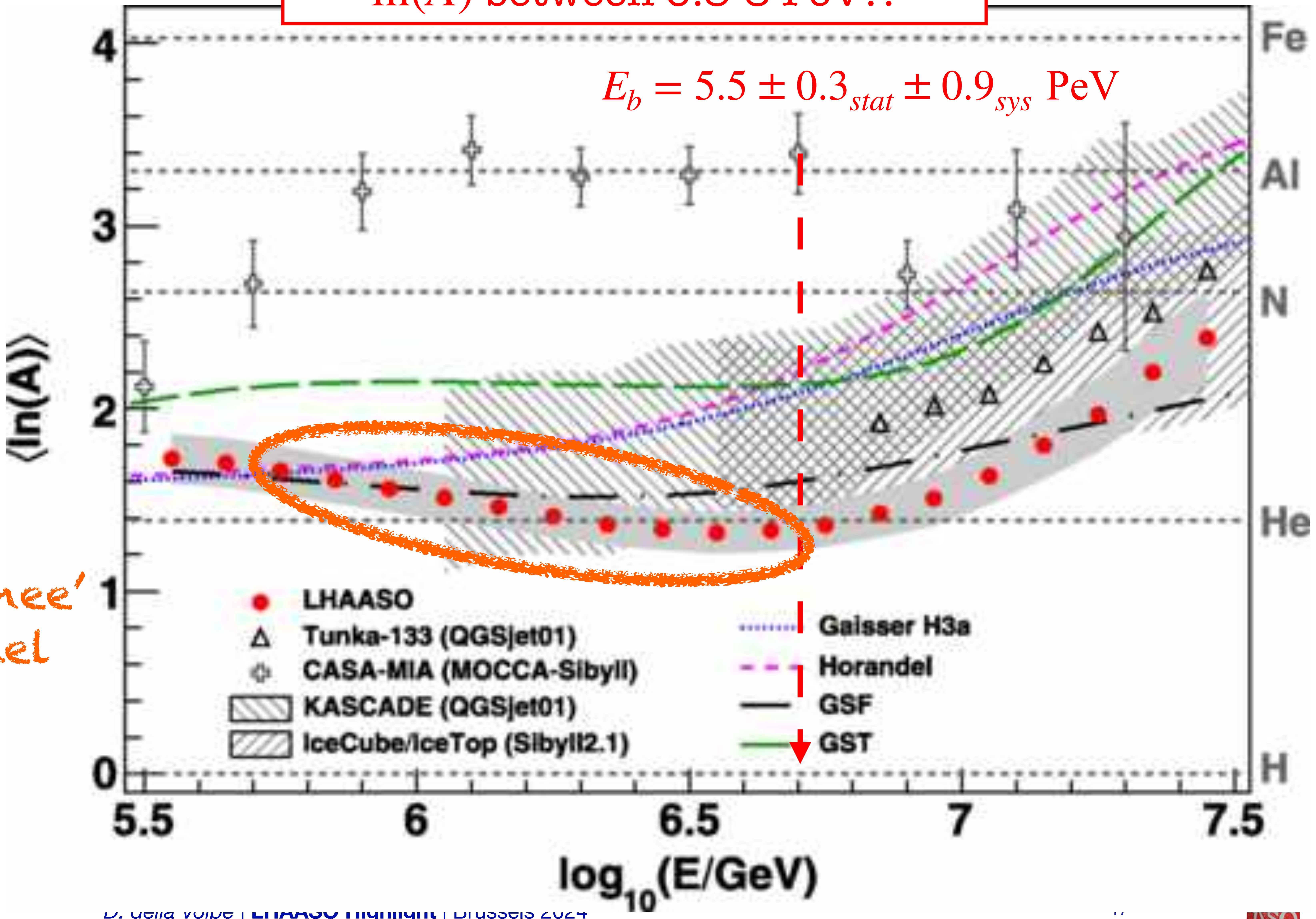
x_0: $\langle \ln(N_\mu) \rangle_H$; x_1: $1-\beta$

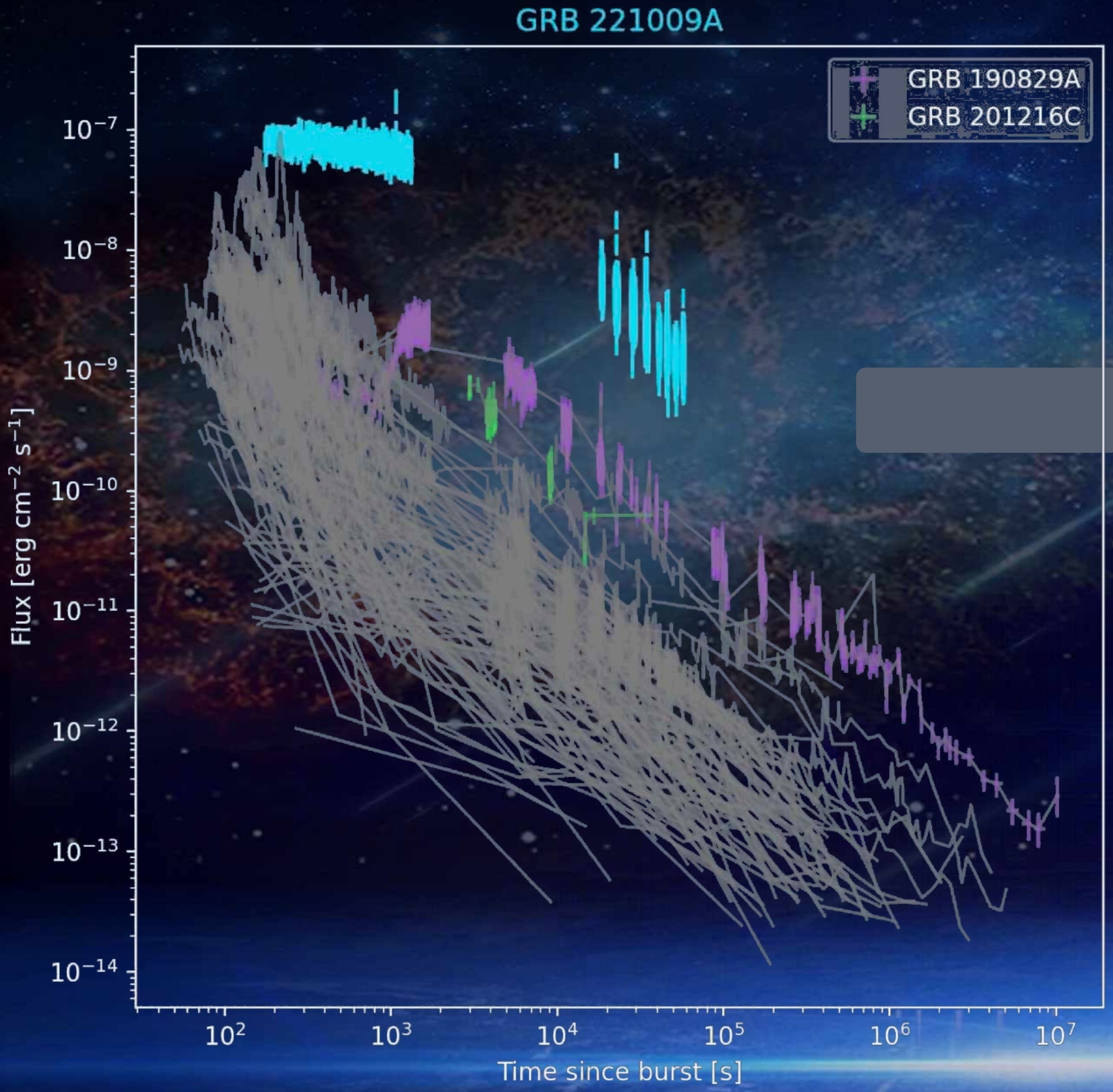
Energy dependent
Fitted with MC in $\log(E)$ bins of 0.1

The lightening below the 'knee' not reproduced by any model

Food for thoughts ....

Most precise measurement of $\ln(A)$ between 0.3-3 PeV!!






```
TITLE:    GCN CIRCULAR
NUMBER:   32677
SUBJECT:  LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18
TeV
DATE:     22/10/11 09:21:54 GMT
FROM:     Judith Racusin at GSFC  <judith.racusin@nasa.gov>

Yong Huang, Shicong Hu, Songzhan Chen,  Min Zha, Cheng Liu, Zhiguo Yao and
Zhen Cao report on behalf of the LHAASO experiment

We report the observation of GRB 221009A, which was detected by Swift (Kennea
et al. GCN #32635), Fermi-GBM (Veres et al. GCN #32636, Lesage et al. GCN #32642),
Fermi-LAT (Bissaldi et al. GCN #32637), IPN (Svinkin et al. GCN #32641) and so on.

GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at
RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the significance above
100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d.,
where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRBs.

The LHAASO is a multi-purpose experiment for gamma-ray astronomy (in the energy
band between 10^11 and 10^15 eV) and cosmic ray measurements.
```

Very high-energy gamma-ray emission beyond 10 TeV from GRB 221009A

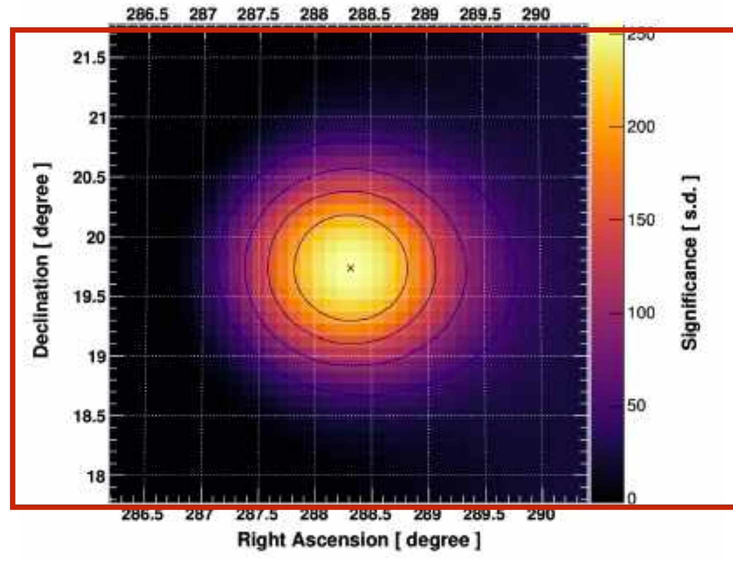
SCIENCE ADVANCES, *Vol* **9**, Issue **46** (**2023**)
https://doi.org/10.1126/sciadv.adj2778

The BOAT - GRB221009

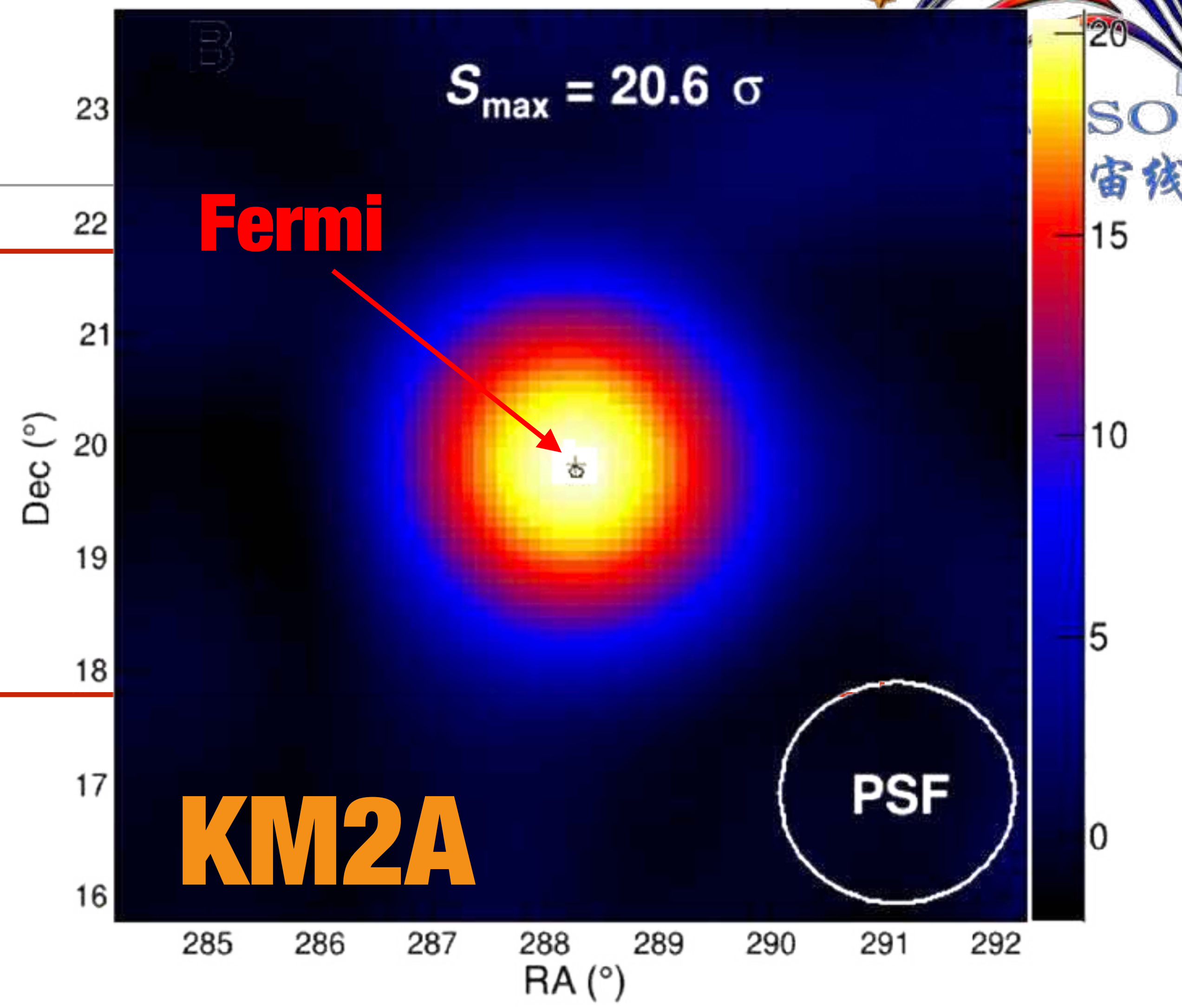
Brightest Of All Times

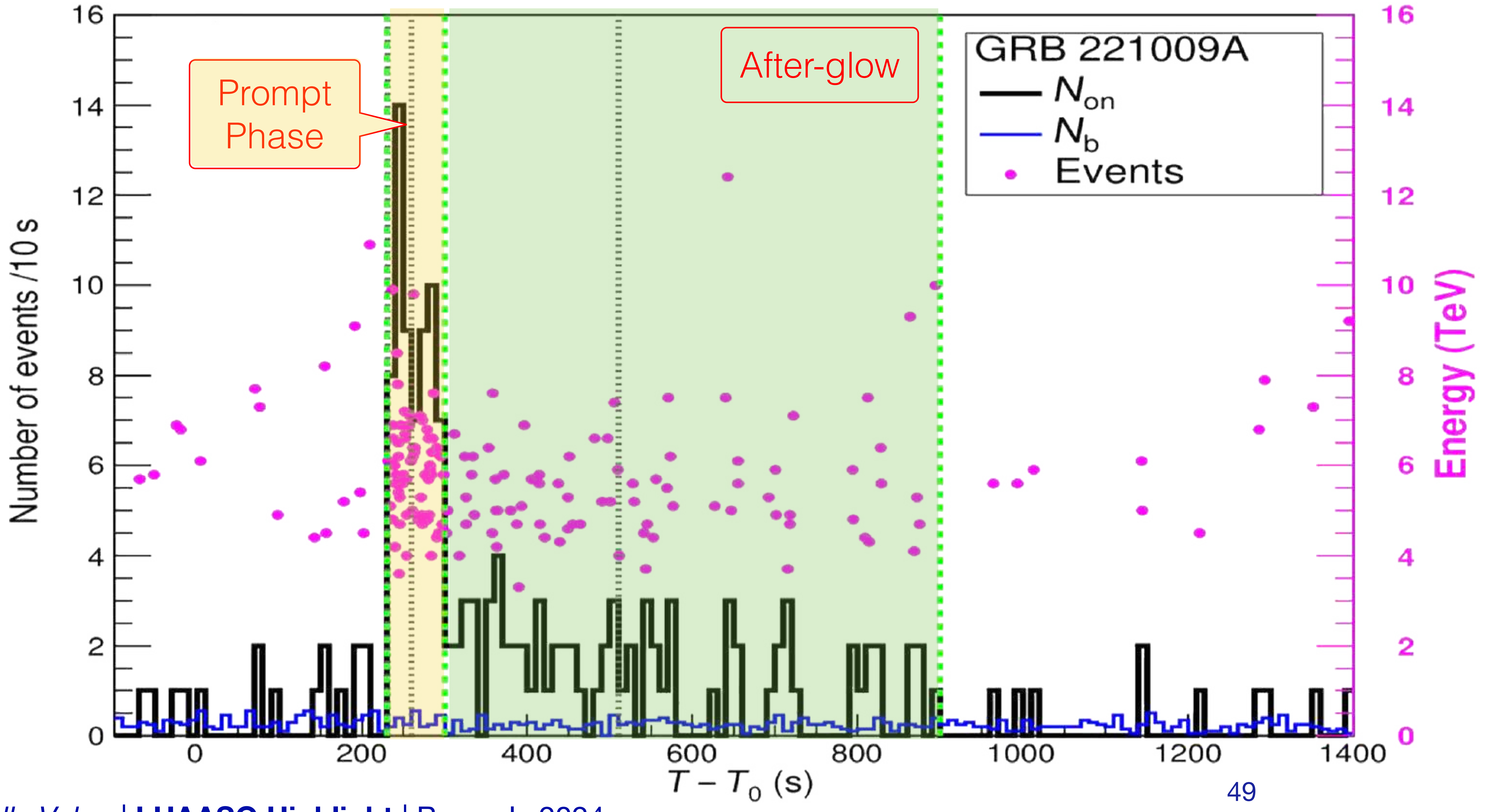
GRB221009A

- Brightest of all time
  - $z = 0.151 \Rightarrow \sim 753\text{Mpc}$
  - $E \sim 10^{55}$erg (isotropic)
  - 5000 γ (WCDA - E< 0.5 TeV)
  - 142 γ (KM2A - E >3.0 TeV)
- Detection of γ with energy above 10 TeV
- First detection of a HE cutoff in GRB $\gamma -$ ray spectrum
- Constraint on
  - GRB Physics
  - Dark Matter
  - Axion-like particle
  - Lorentz Invariant Violation



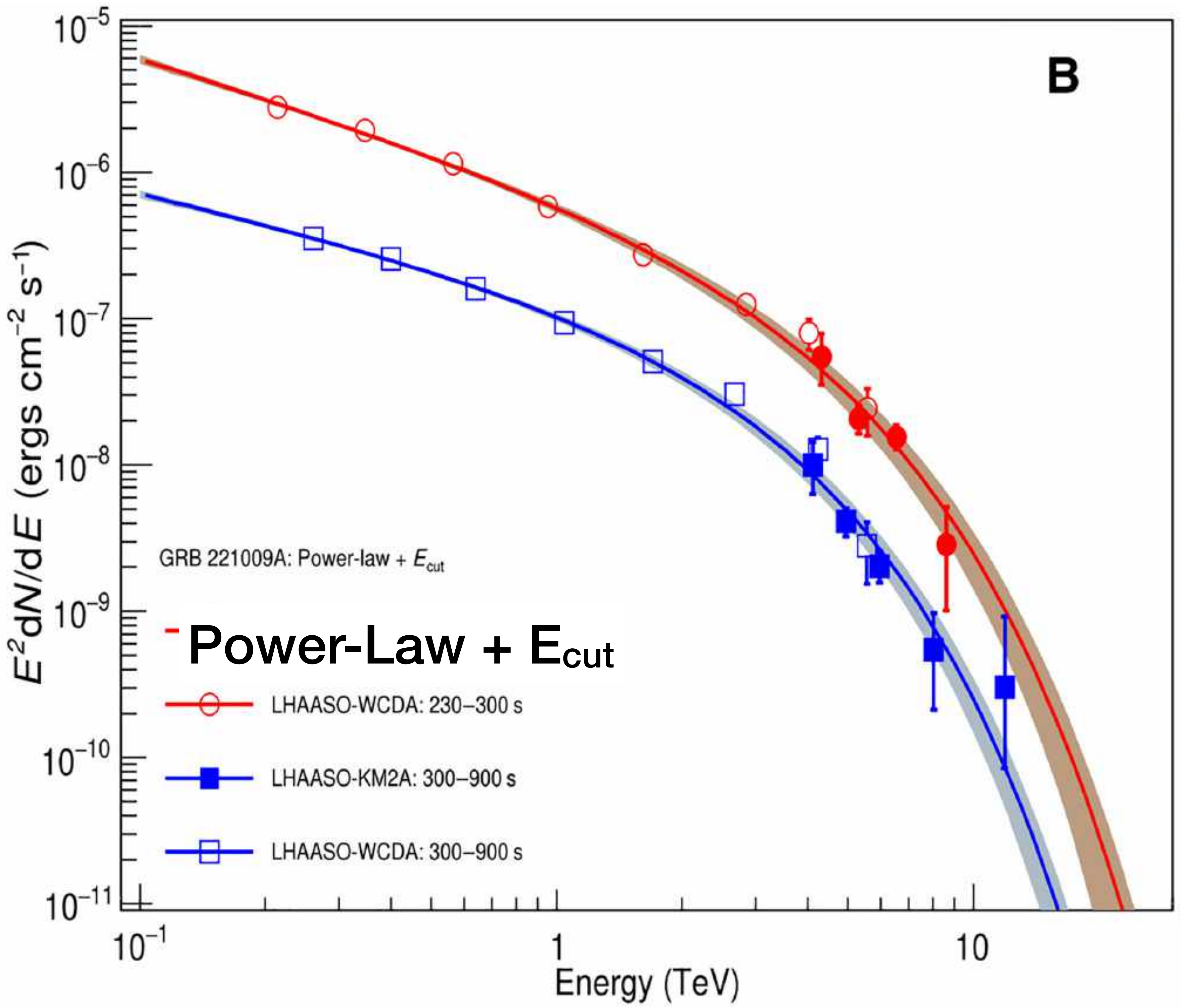
WCDA



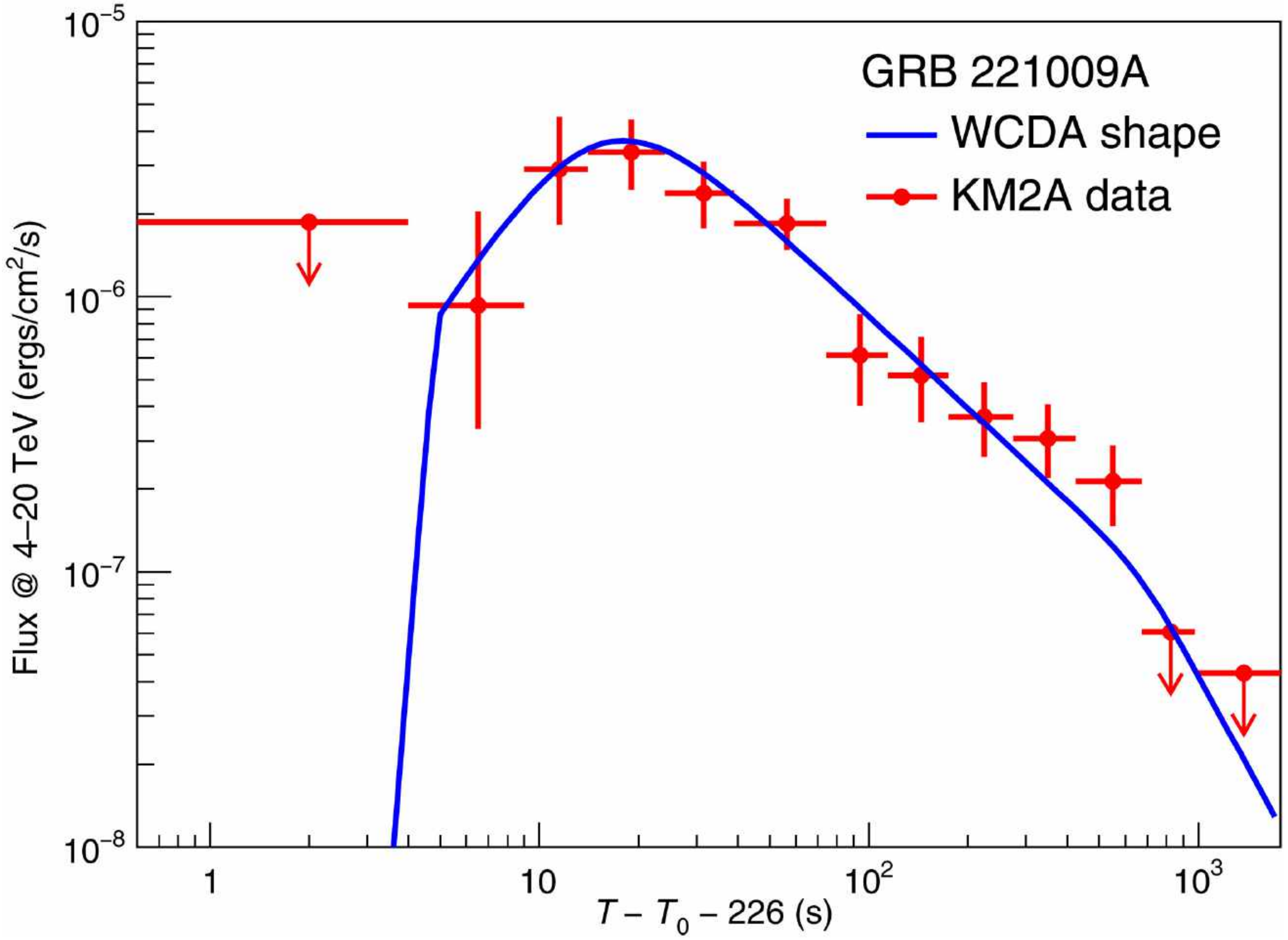


LHAASO , *Sci. Adv.* **9**, eadj2778 (2023)

GRB221009A SED



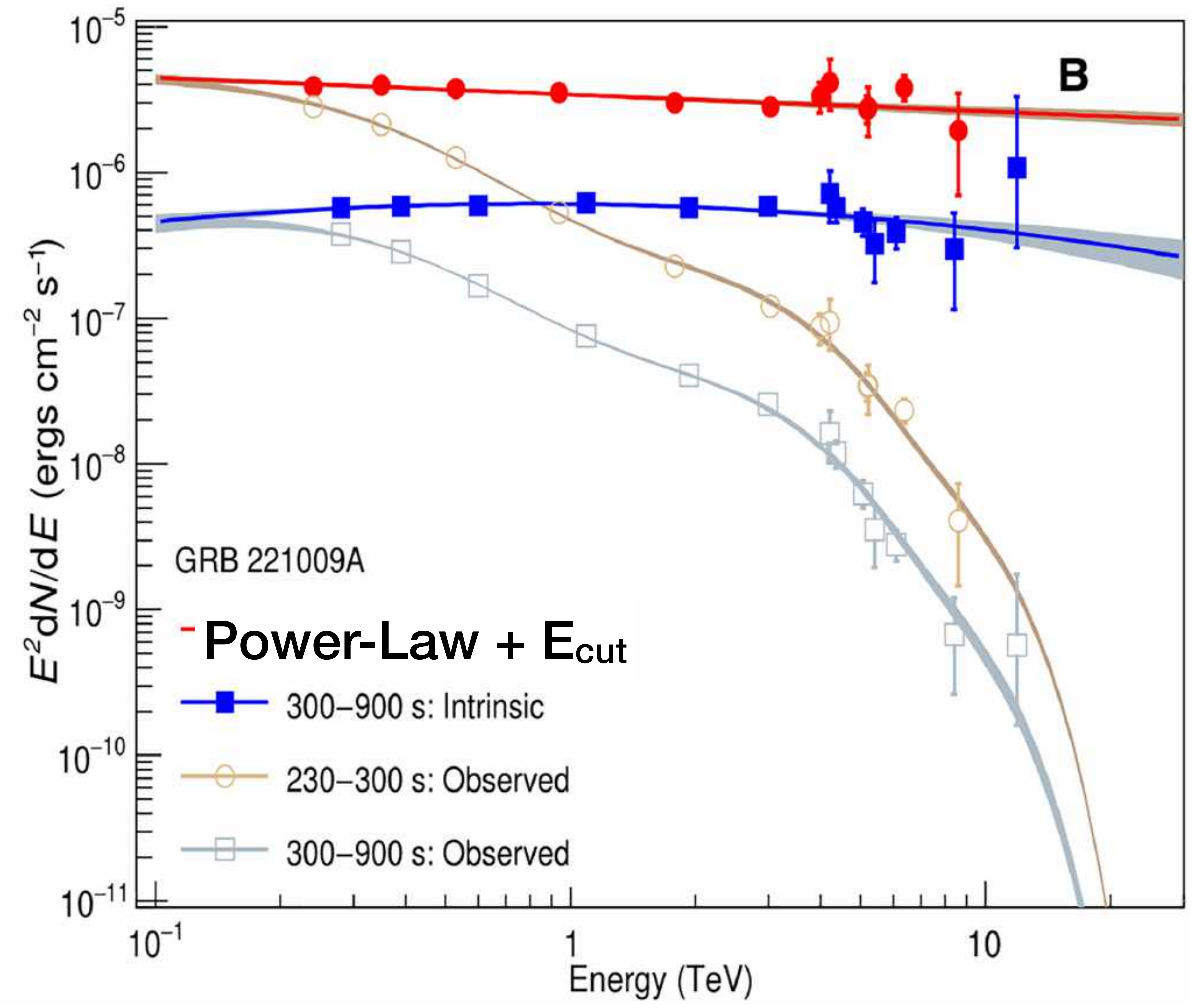
- Good agreement between WCDA + KM2A in the prompt Phase



- Power-Law + Cut-off favoured over Log-Parabola
- Several EBL model for correction
  - Saldana-Lopez
  - LHAASO constraint

LHAASO , *Sci. Adv.* **9**, eadj2778 (2023)

GRB221009A SED



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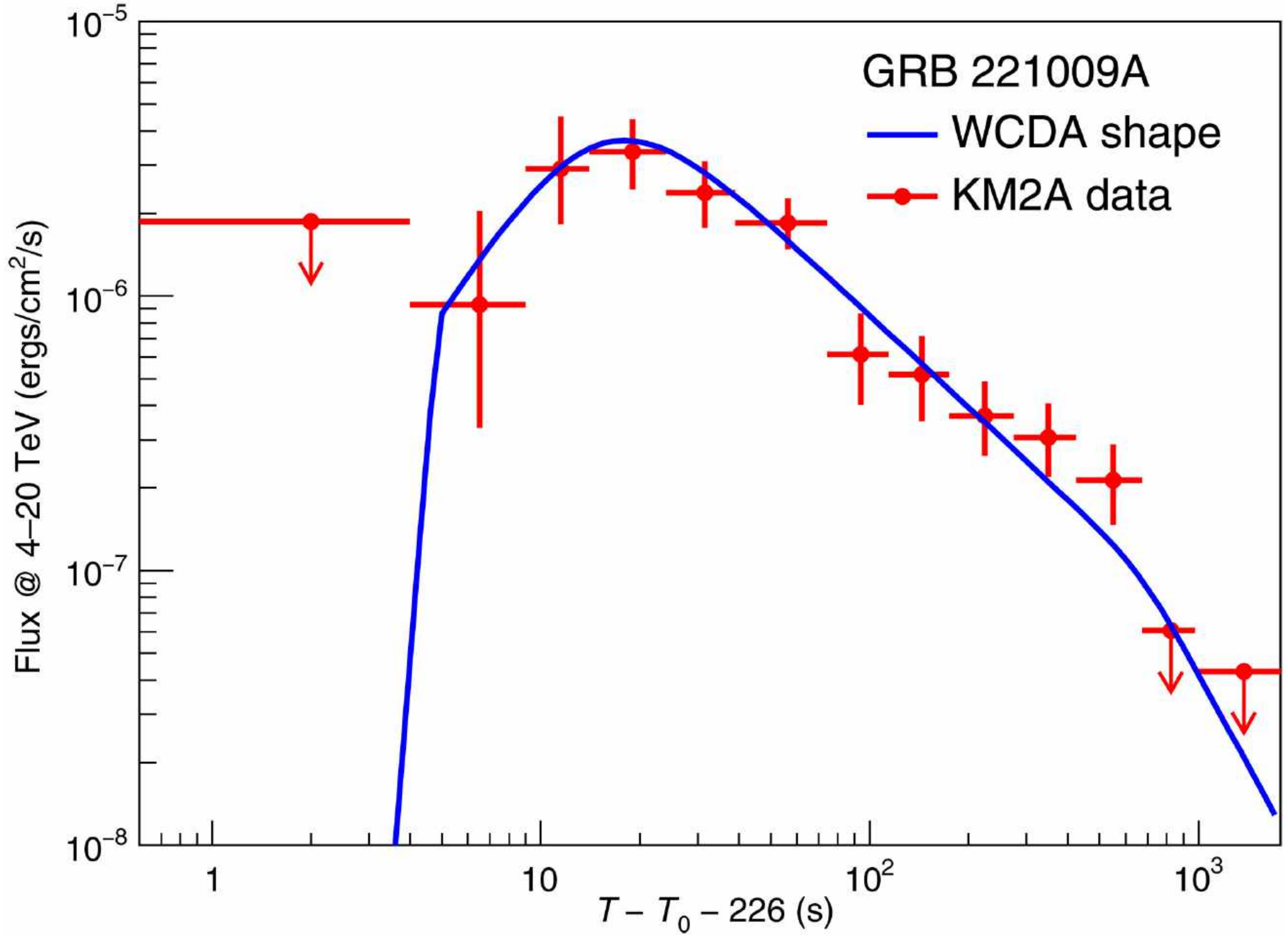

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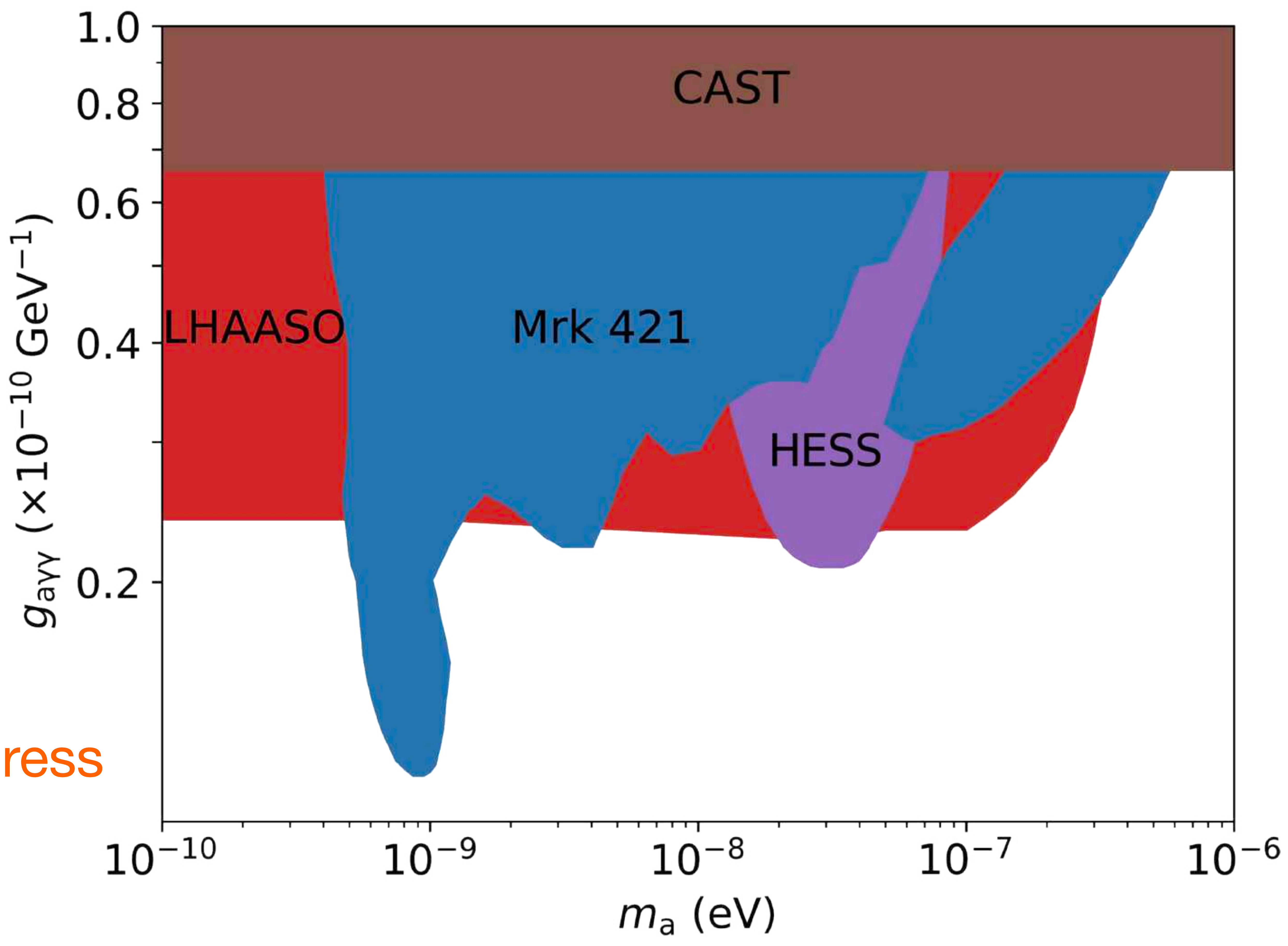
LHAASO , *Sci. Adv.* **9**, eadj2778 (2023)

GRB221009A New Physics - Axion like particle

EBL absorption can be modified by New Physics

- ➡ LIV
- ➡ Dark matter - self interacting
- ➡ GRB physics
- ➡ Axion-like particle



Axion-like particle

- Good candidate for Dark matter
- HE γ-rays in $a \rightarrow \gamma\gamma$ $\Rightarrow$ EBL absorption suppress
  - ➡ higher transparency of space.

LHAASO improved limit on coupling $g_{a\gamma\gamma}$ for $m_a < 10^{-9}$ eV

GRB221009A LIV Limits

LHAASO
高海拔宇宙线观测站

$$E^2 \simeq p^2c^2 \left[1 - \sum_{n=1}^{\infty} s \left(\frac{E}{E_{QG,n}}\right)^n\right]$$

Modified dispersion relation

$s = -1$ Sub-luminal
$s = +1$ Super-Luminal

$$E_{QG} < E_{Pl} \approx \sqrt{\hbar c^5/G} \simeq 1.22 \times 10^{19} \text{ GeV}$$

$$v(E) = \frac{\partial E}{\partial p} \approx c \left[1 - s\frac{n+1}{2}\left(\frac{E}{E_{QG,n}}\right)^n\right]$$

Energy dependent γ velocity

$$\Delta t_{LIV} = s\frac{n+1}{2}\frac{E_h^n - E_l^n}{E_{QG,n}^n}\int_0^z \frac{(1+z')^n}{H(z')}dz'$$

LIV delay

$$F(E,t) = A\left(\frac{E}{\text{TeV}}\right)^{-\gamma} e^{-E/E_{cut}} \times \left[\left(\frac{t}{t_b}\right)^{-\omega\alpha_1} + \left(\frac{t}{t_b}\right)^{-\omega\alpha_2}\right]^{-\frac{1}{\omega}}$$

https://arxiv.org/abs/2402.06009v1

GRB221009A LIV Limits

$E_{QG} < E_{Pl} \approx \sqrt{\hbar c^5/G} \simeq 1.22 \times 10^{19}$ GeV

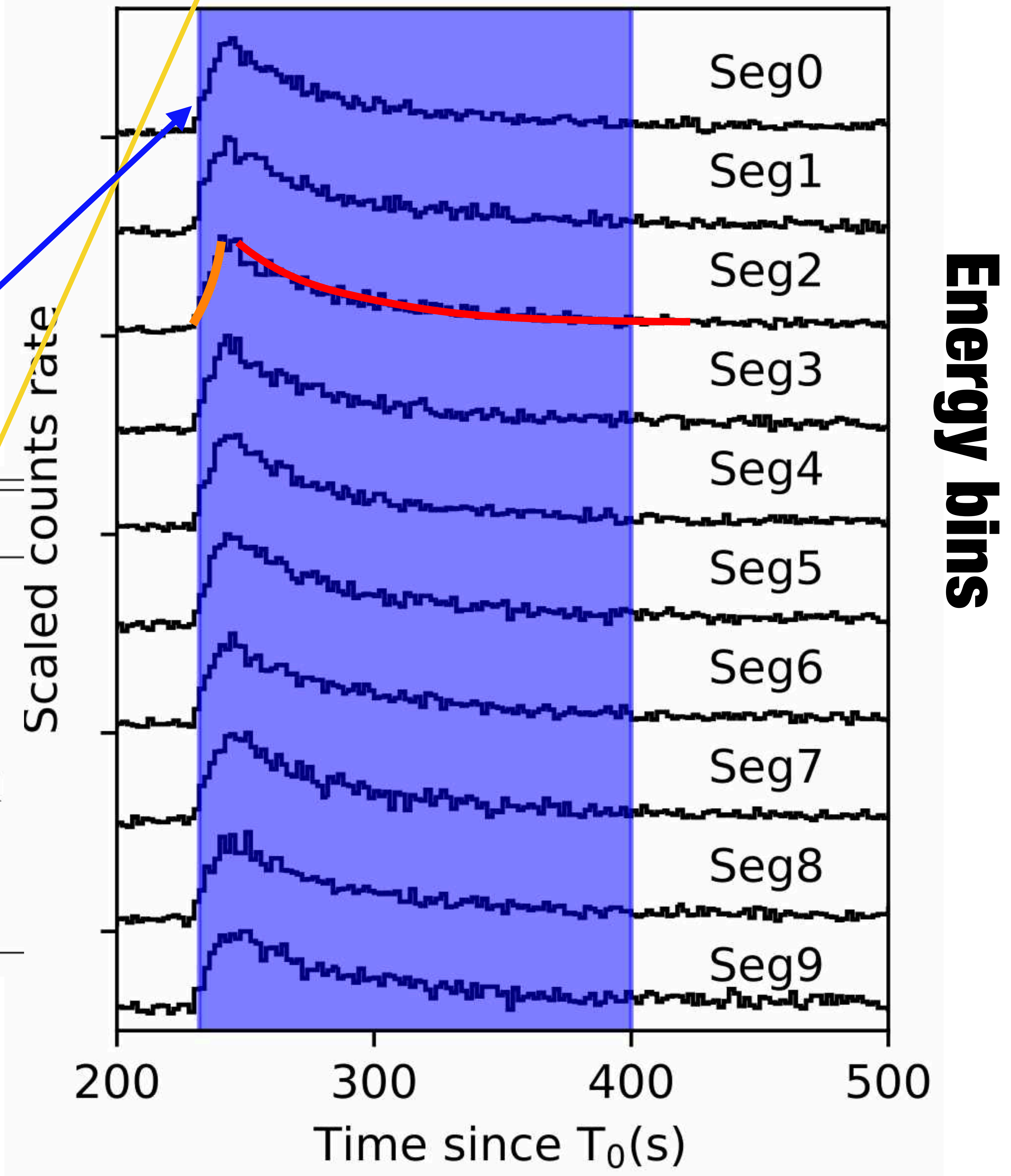
$$F(E,t) = A\left(\frac{E}{\text{TeV}}\right)^{-\gamma} e^{-E/E_{cut}} \times \left[\left(\frac{t}{t_b}\right)^{-\omega\alpha_1} + \left(\frac{t}{t_b}\right)^{-\omega\alpha_2}\right]^{-\frac{1}{\omega}}$$

$$\eta_1 = s \cdot E_{Pl}/E_{QG,1}$$

$$\eta_2 = 10^{-15} \times s \cdot E_{Pl}^2/E_{QG,2}^2$$

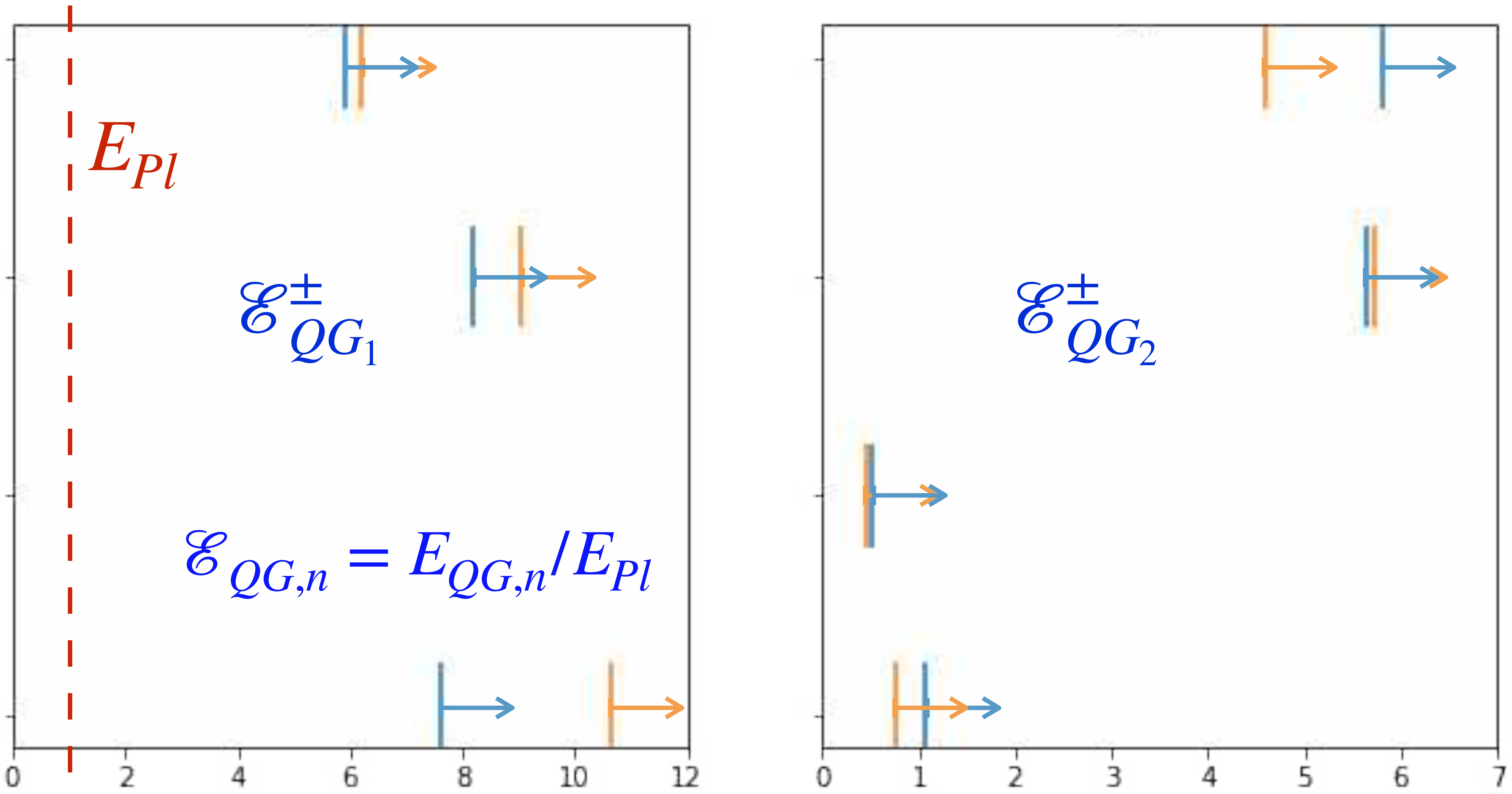
$$\gamma(t) = a\log(t) + b$$

Method	Cross correlation function			Maximum likelihood		
	η^{LL}	η^{BF}	η^{UL}	η^{LL}	η^{BF}	η^{UL}
η_1	−0.25	0.05	0.18	−0.11	0.01	0.12
η_2	−0.60	0.25	0.64	−0.31	0.02	0.32
	superluminal		subluminal	superluminal		subluminal
$E_{QG,1}$ [10^{20} GeV]	0.5		0.7	1.1		1.0
$E_{QG,2}$ [10^{11} GeV]	5.0		4.8	7.0		6.9



https://arxiv.org/abs/2402.06009v1

LIV Limits - A summary



Review https://arxiv.org/abs/2308.03031v3

LHAASO https://arxiv.org/abs/2402.06009v1

MAGIC Phys. Rev. Lett. 125, 021301 (2020)

Fermi Phys. Rev. D 87, 122001 (2013), 1305.3463

- GRB221009A was at small z=0.151
  - not the best for LIV sensitivity
- Limit by LHAASO using this single GRB not stringent

GRB	090510[a]	190114C	221009A
Red Shift	0.903	0.425	0.151
ΔE [TeV]	10^{-4} — 0.03	0.3 — 1	0.2 — 7
$\Delta T_{\rm obs}$ [s]	0.15 — 0.217	30 — 60	9 — 14
$\mathcal{E}^{(\sigma)}_{\rm QG,1}$	11^- 5.2^+	0.23^- 0.45^+	5.9^- 6.2^+
$\mathcal{E}^{(\sigma)}_{\rm QG,2}/10^{-8}$	0.7^- 0.77^+	0.46^- 0.52^+	5.8^- 4.6^+

The same analysis for 3 different and same method show significant fluctuations

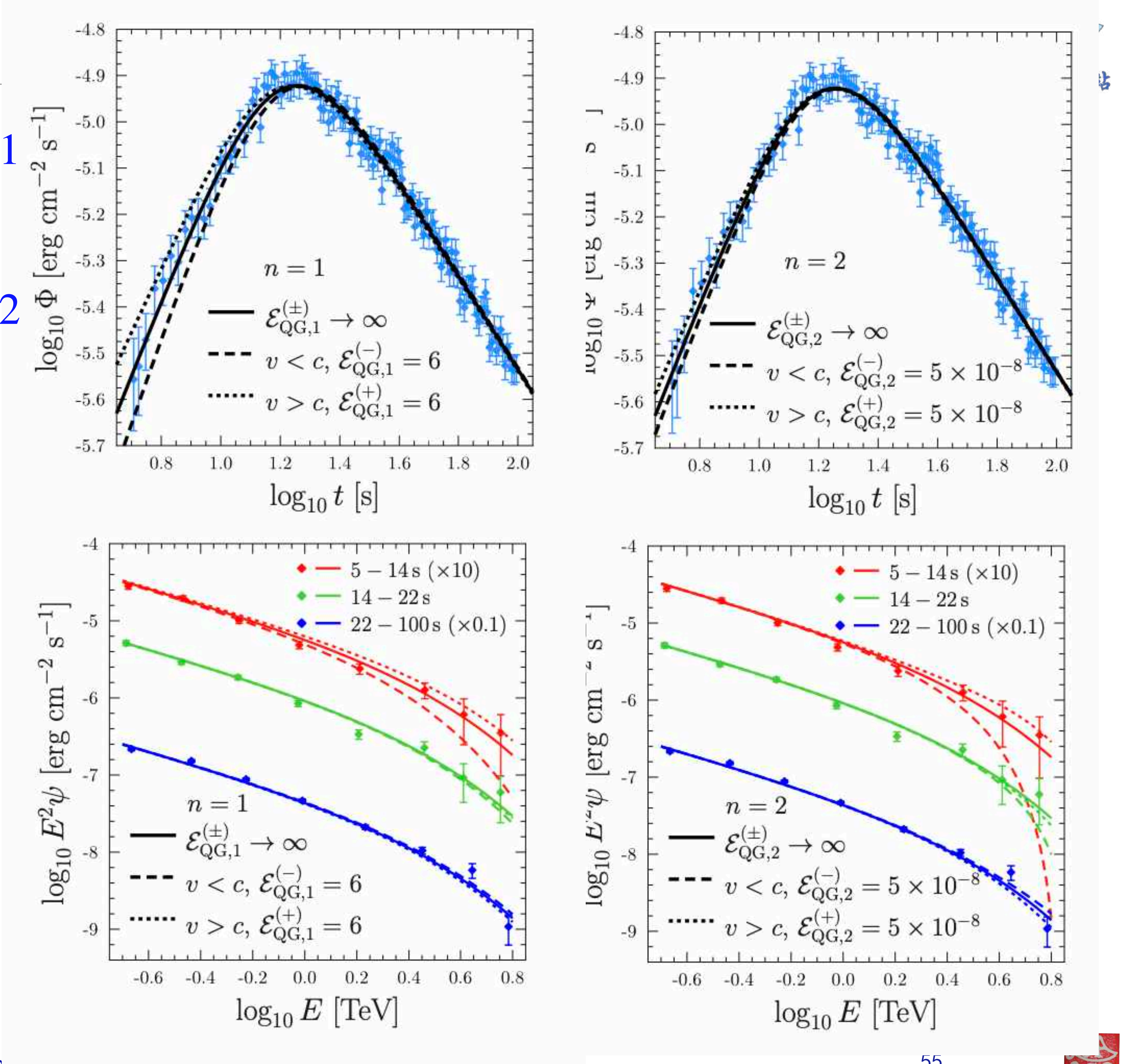
https://arxiv.org/abs/2308.03031v3

GRB221009A LIV Limits

$$\Delta t_{LIV,z=0.151}(E) = s \begin{cases} 5.7\ s\ \dfrac{E/TeV}{\mathscr{E}_{QG,1}} & n=1 \\ 7.5\ s \left(\dfrac{E/TeV}{10^8 \mathscr{E}_{QG,2}}\right)^2 & n=2 \end{cases}$$

$$\mathscr{E}_{QG,n} = E_{QG,n}/E_{Pl}$$

	Best fit	95% confidence interval
A[a]	8.1	6.5 — 9.8
$C_{a.c.}$	0.25	0.24 — 0.26
t_b[b]	16.0	14.3 — 17.6
α_1	1.6	1.1 — 2.0
α_2	−1.02	−1.08 — −0.95
ω	1.5	0.8 — 2.1
γ	2.93	2.84 — 3.02
E_{cut}[c]	3.1	2.1 — 4.1
$\mathcal{E}^{(\sigma)}_{QG,1}$	—[d]	$\mathcal{E}^{(-)}_{QG,1} \geqslant 5.9$; $\mathcal{E}^{(+)}_{QG,1} \geqslant 6.2$
$\mathcal{E}^{(\sigma)}_{QG,2}$	—[e]	$\mathcal{E}^{(-)}_{QG,2} \geqslant 5.8 \times 10^{-8}$; $\mathcal{E}^{(+)}_{QG,2} \geqslant 4.6 \times 10^{-8}$



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

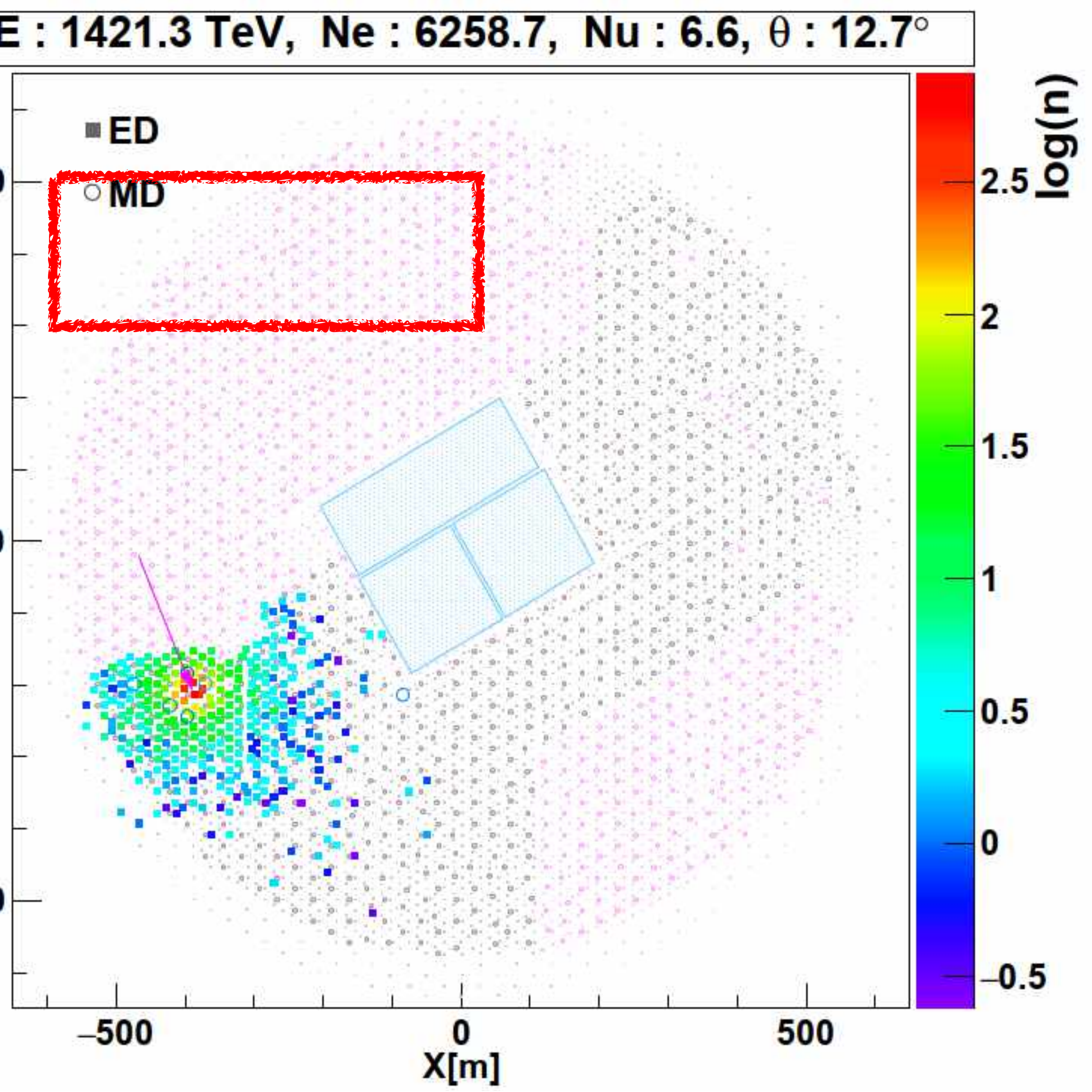
n^{th} LIV order

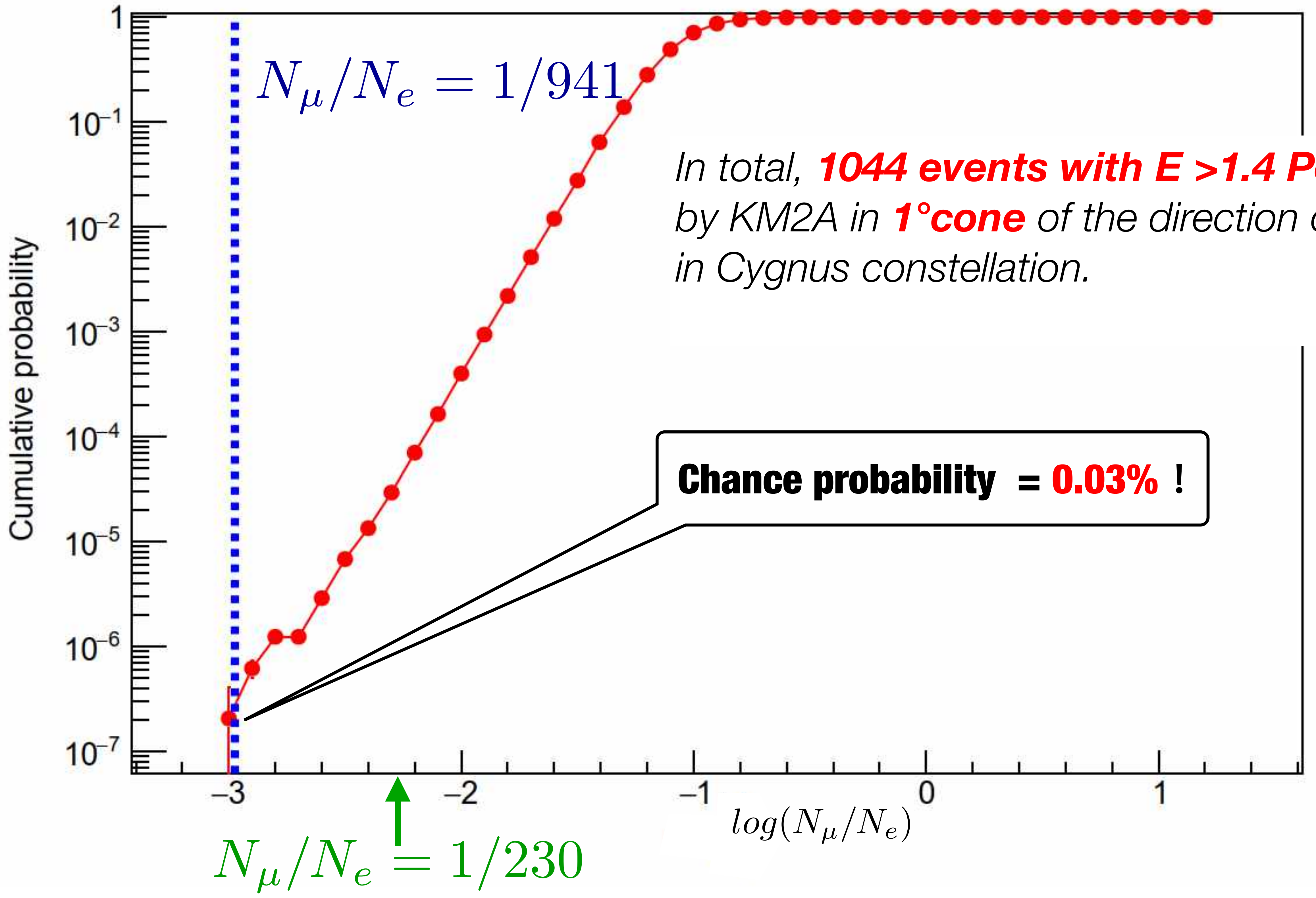
$$E_{\mathrm{LIV}}^{(n)} = \alpha_n^{-1/n}$$

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***

led 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 ($N_\gamma > 10\ N_{CR}$) for showers E>100 TeV from the Crab

LIV limits from LHAASO

Source	L (kpc)	E_{max} (PeV)	$E_{cut}^{95\%}$ (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)

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

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

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

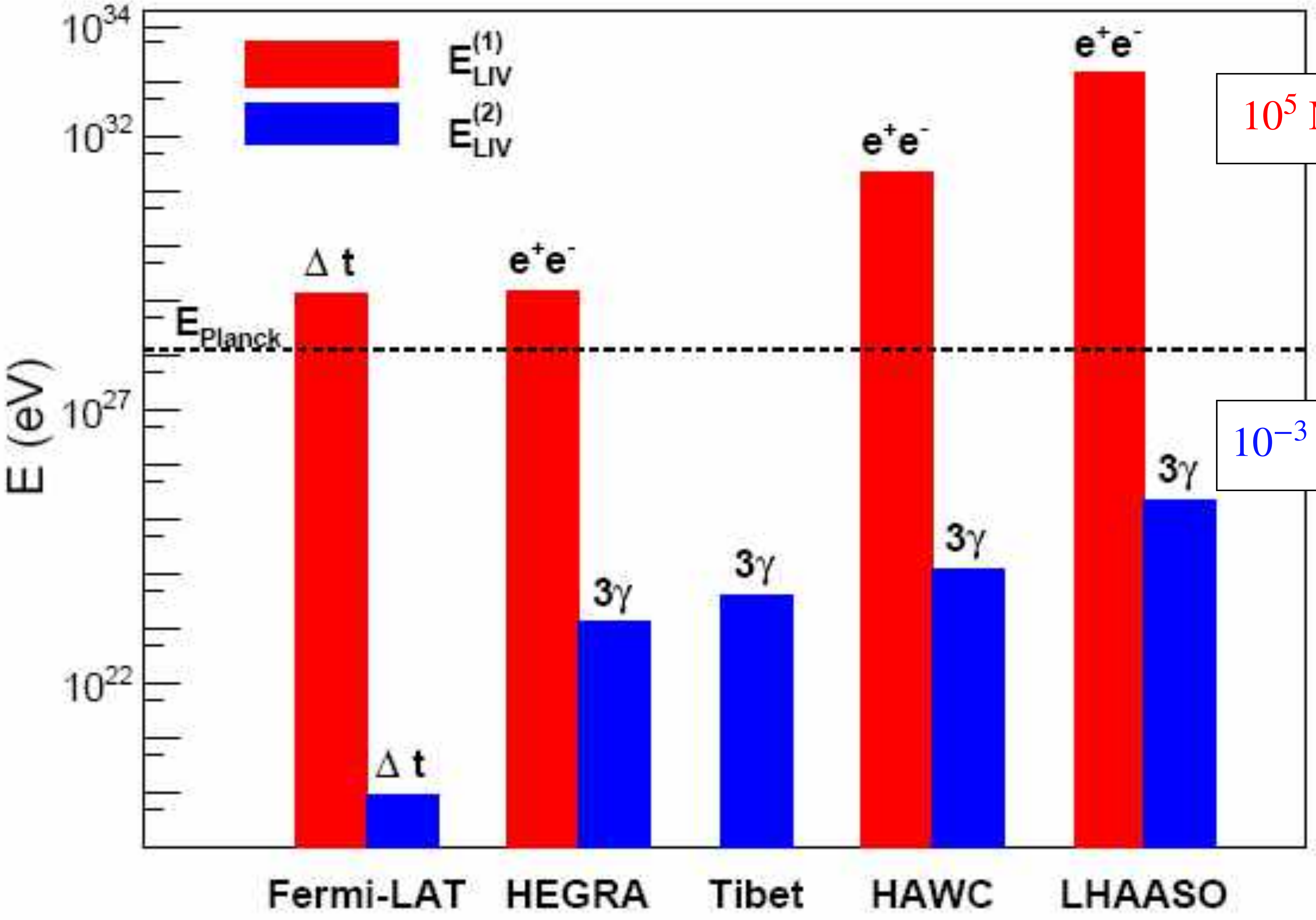
$$E_{LIV}^{(1)} \geq 9.57 \times 10^{23} \mathrm{eV} \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^3,$$

$\gamma \rightarrow 3\gamma$

$$\Gamma_{\gamma\rightarrow 3\gamma} = 5 \times 10^{-14} \frac{E_\gamma^{19}}{m_e^8 E_{LIV}^{(2)10}},$$

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

HAWC - PRL 124, 131101 (2020)



10^5 M_{Pl}

10^{-3} M_{Pl}

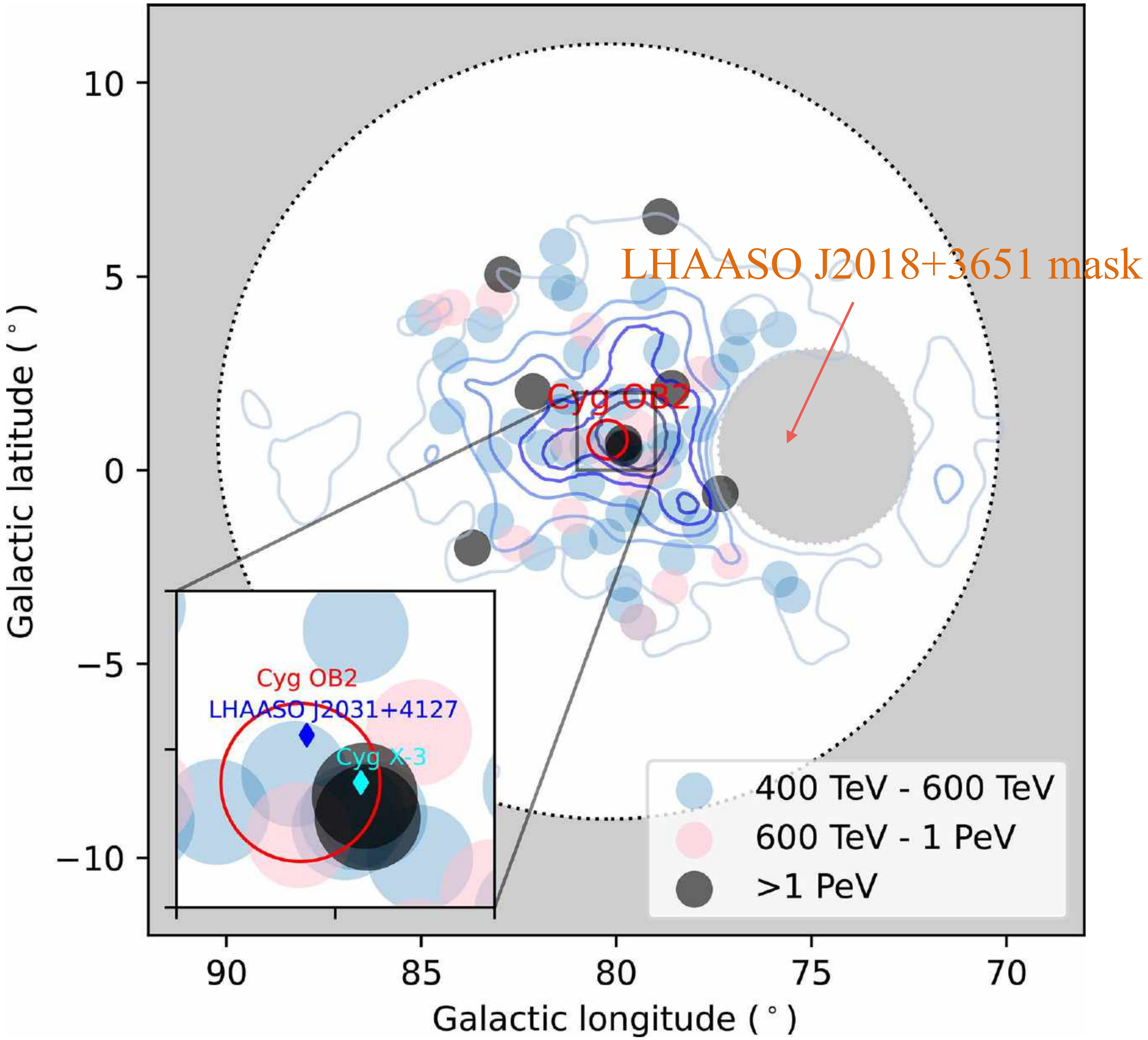
1 order of magnitude improvement on current limits

Cygnus SuperBubble

- An ultrahigh-energy c-ray bubble powered by a super PeVatron
- *Science Bulletin 69 (2024) 449–457*
- https://doi.org/10.1016/j.scib.2023.12.040
-

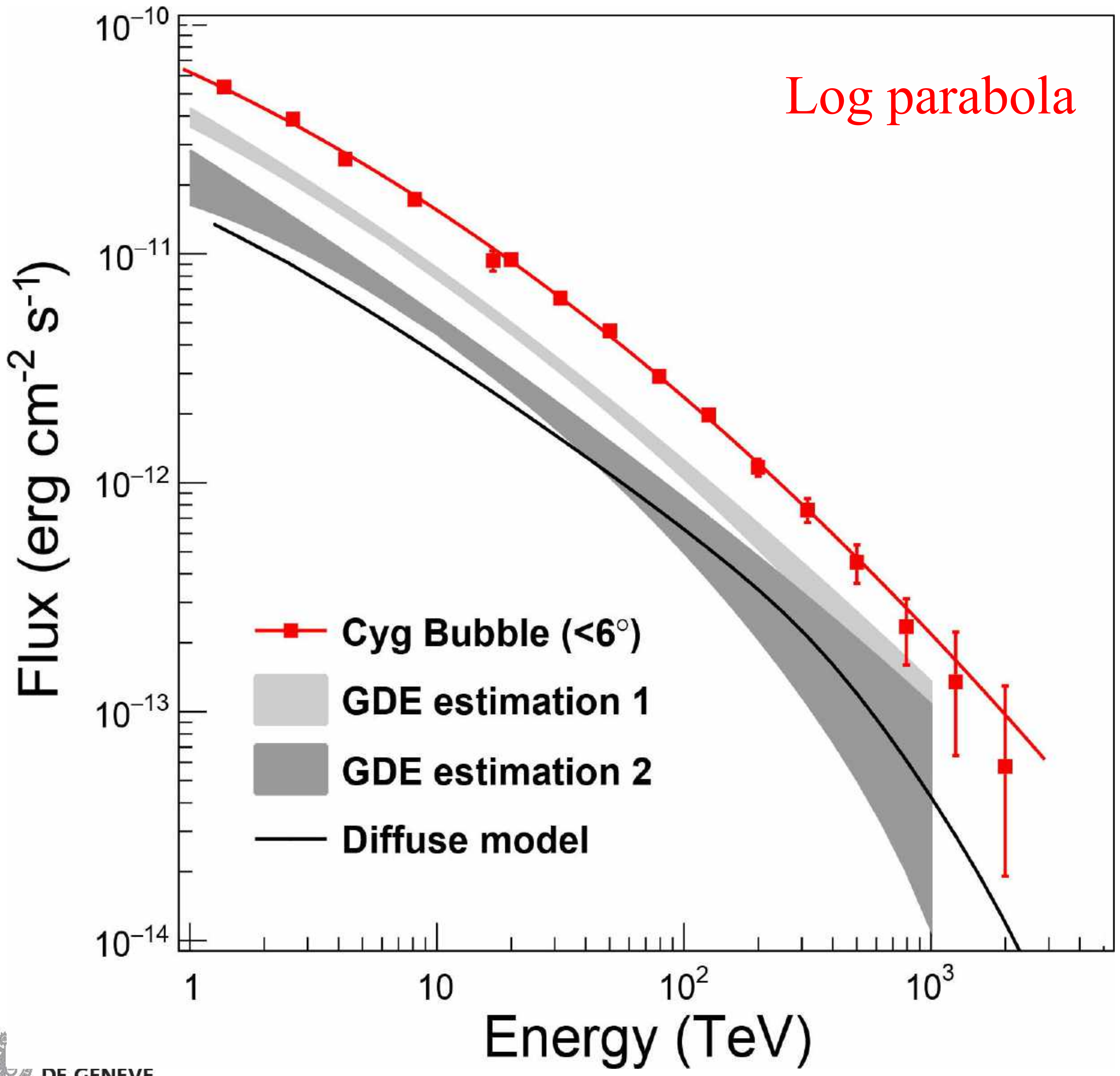
Cygnus region

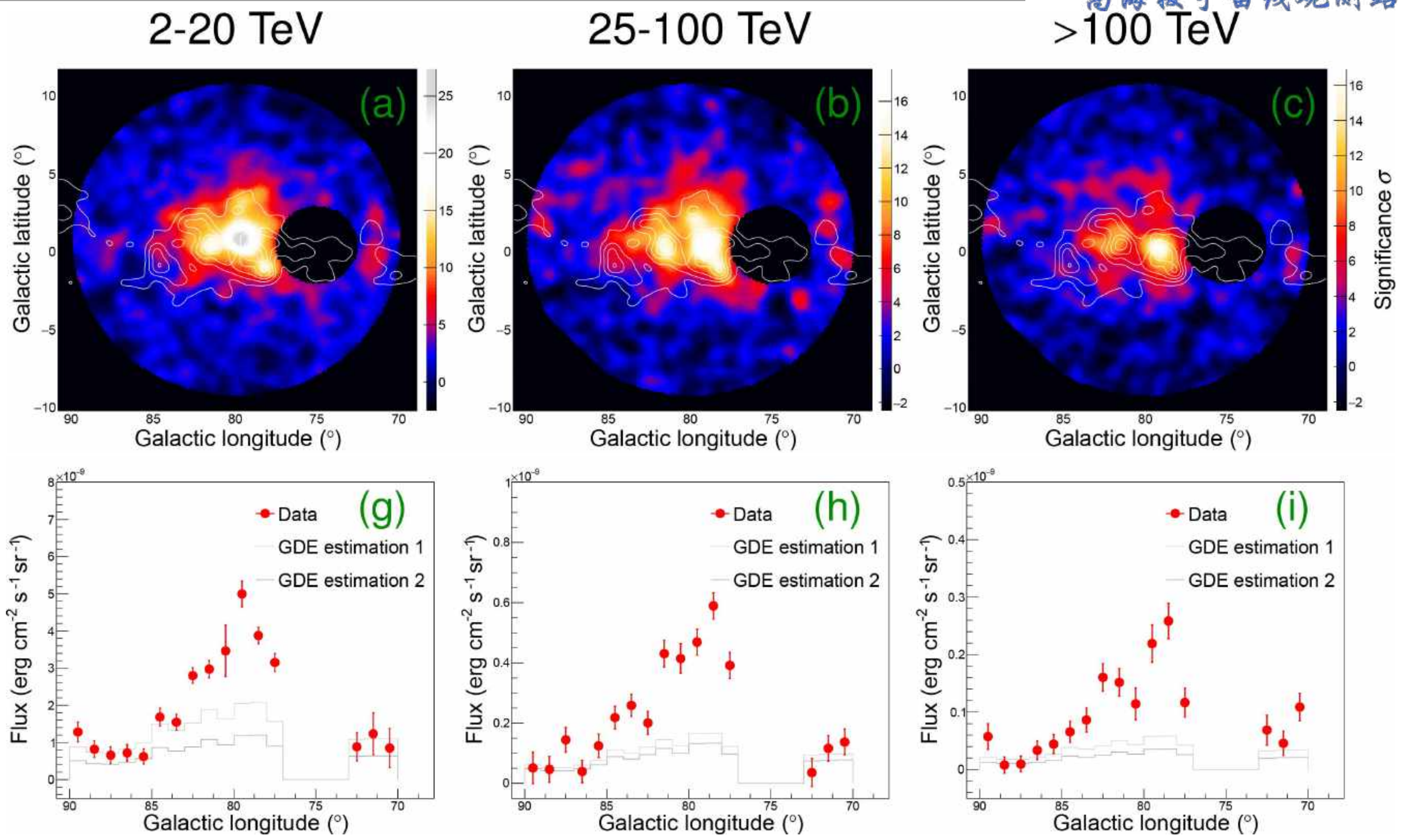
- An extremely complex region. One of the most intensive and nearby star-forming regions in the Milky Way harbouring several Wolf–Rayet stars, hundreds of O-type stars grouped in powerful OB associations.
- In addition it contains vast atomic (HI) and molecular gas complexes with masses exceeding 10^6 $M_\odot$.
- New measurements;
  - 3200 γ-like events above 100 TeV from LHAASO J2032+4102 within the radius 10°.
    - 66 γ above 400 TeV (9.5 CR bkg)
    - 8 γ above 1 PeV (0.75 CR bkg)
  - Spectrum extend down to 2 TeV thanks to WCDA, the spectral measurements have been extended
- 3D fitting -Spatial and spectral parameter simultaneously fitted with ML



The Cygnus bubble

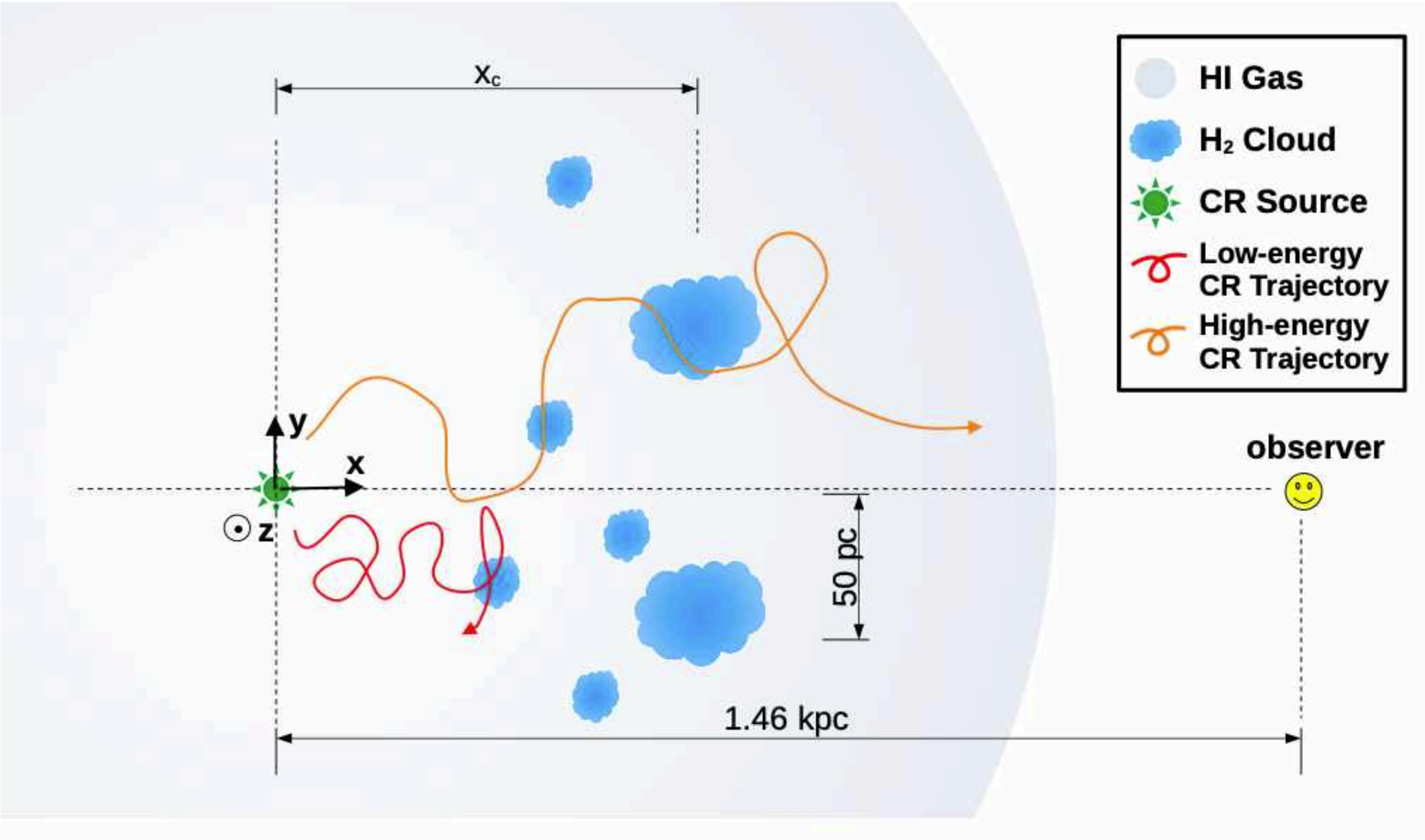
$$\Gamma = (2.72 \pm 0.02) + (0.11 \pm 0.02) \cdot \log_{10}(E/10\ \text{TeV})$$





- Clear evidence of a bubble of 6° radius
- Spectrum extending from 2 TeV to 2 PeV without any cut-off
- Well above the robust diffuse flux estimation

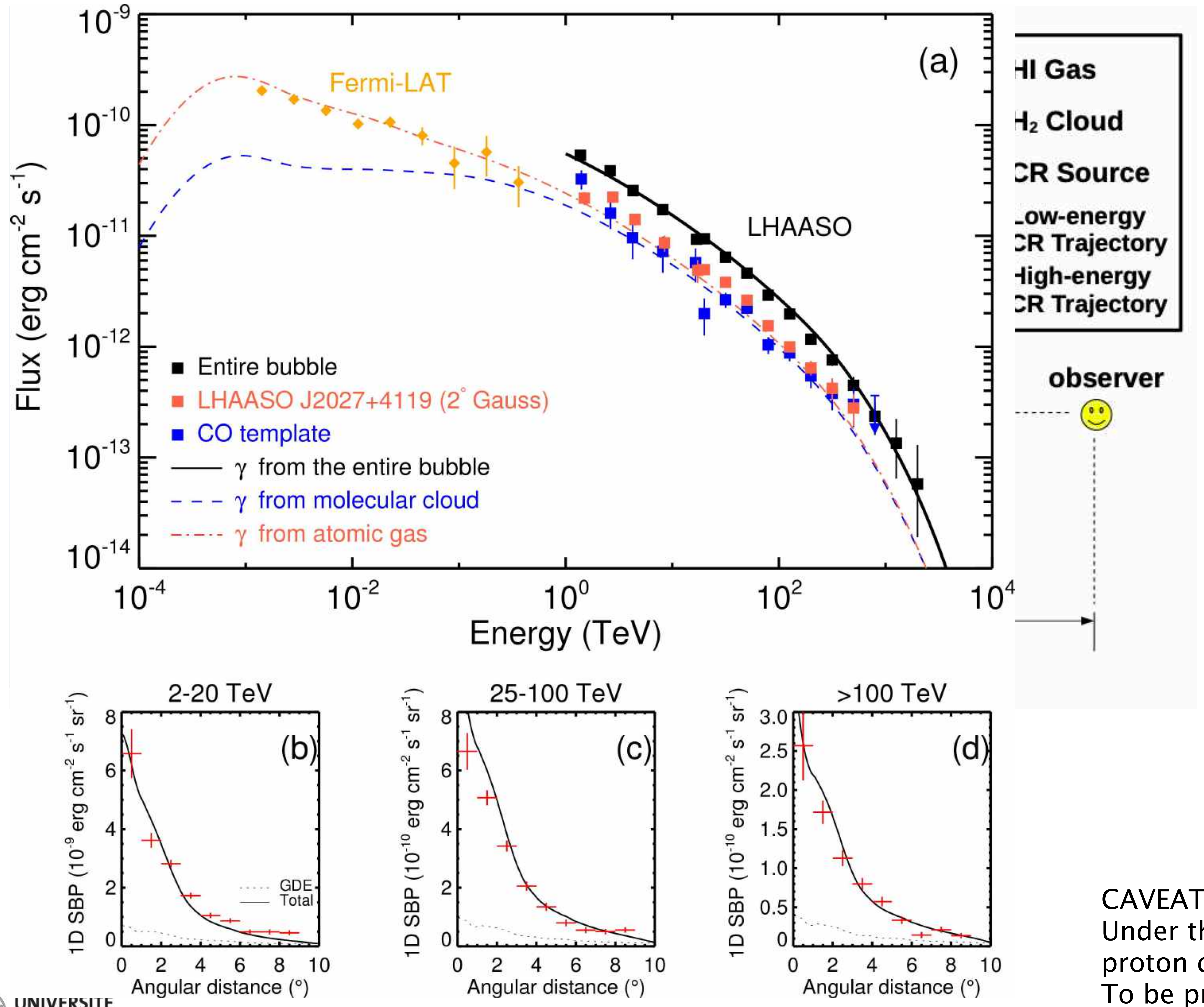
A toy model of the bubble



- Complex structure but compatible with a natural scenario
  - Pevatrons locate in the core
    - Cygnus OB2 good candidate (age 10^7 yrs, wind speed ~300 km/s, mechanical power 10^{39} erg/s)
  - GeV to multi PeV protons/nuclei injected and propagating through circumstellar gas producing γ-ray
- The 3D HI & clumsy molecular gas component and γ-ray distribution are compatible with a proton radial distribution $\propto 1/r$
- A fit of SED and 1D γ-ray lateral profile
  - $E^{-2.2}$ proton acceleration spectrum
  - 5 PeV exponential cut-off
    - just a fir parameter not the end of injection spectrum

CAVEAT:
Under this assumption the model predicts significant excess of of > 100 TeV proton density (compared to the CR sea) up to several hundred parsecs (10°).
To be proved more statistics beyond 6° needed.

A toy model of the bubble



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LHAASO
高海拔宇宙线观测站

Large Array of Cherenkov Telescope - LACT

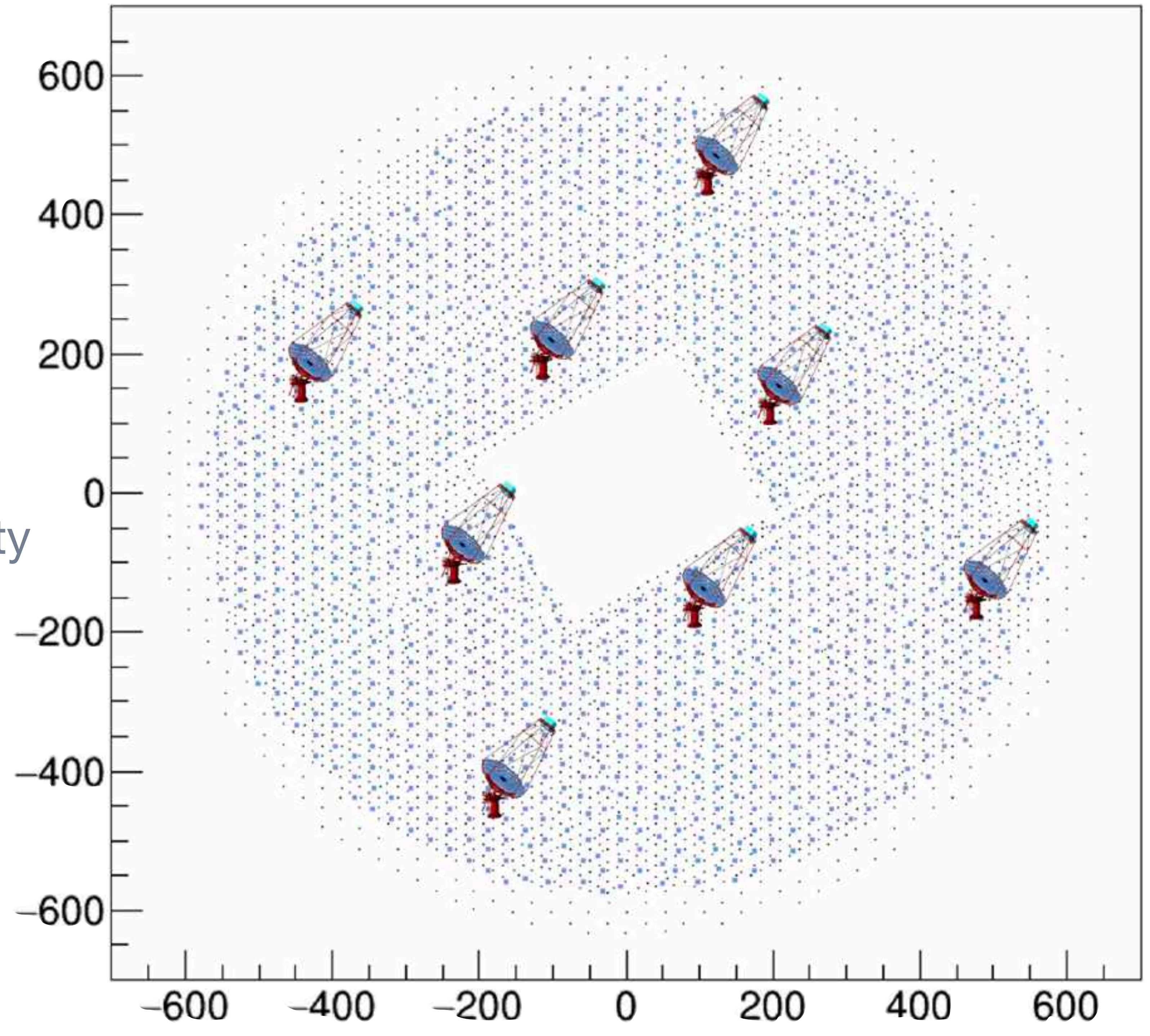
LACT

An array of 32 telescopes

- ✦ Expected angular resolution ~ 0.05°
- ✦ Every range E>10 TeV
- ✦ Effective Area for E> 30 TeV ~ 4 km^2
- ✦ Two modes of operations
  - ➡ 4 sub array of 8 telescopes
  - ➡ 1 single array of 32 telescopes

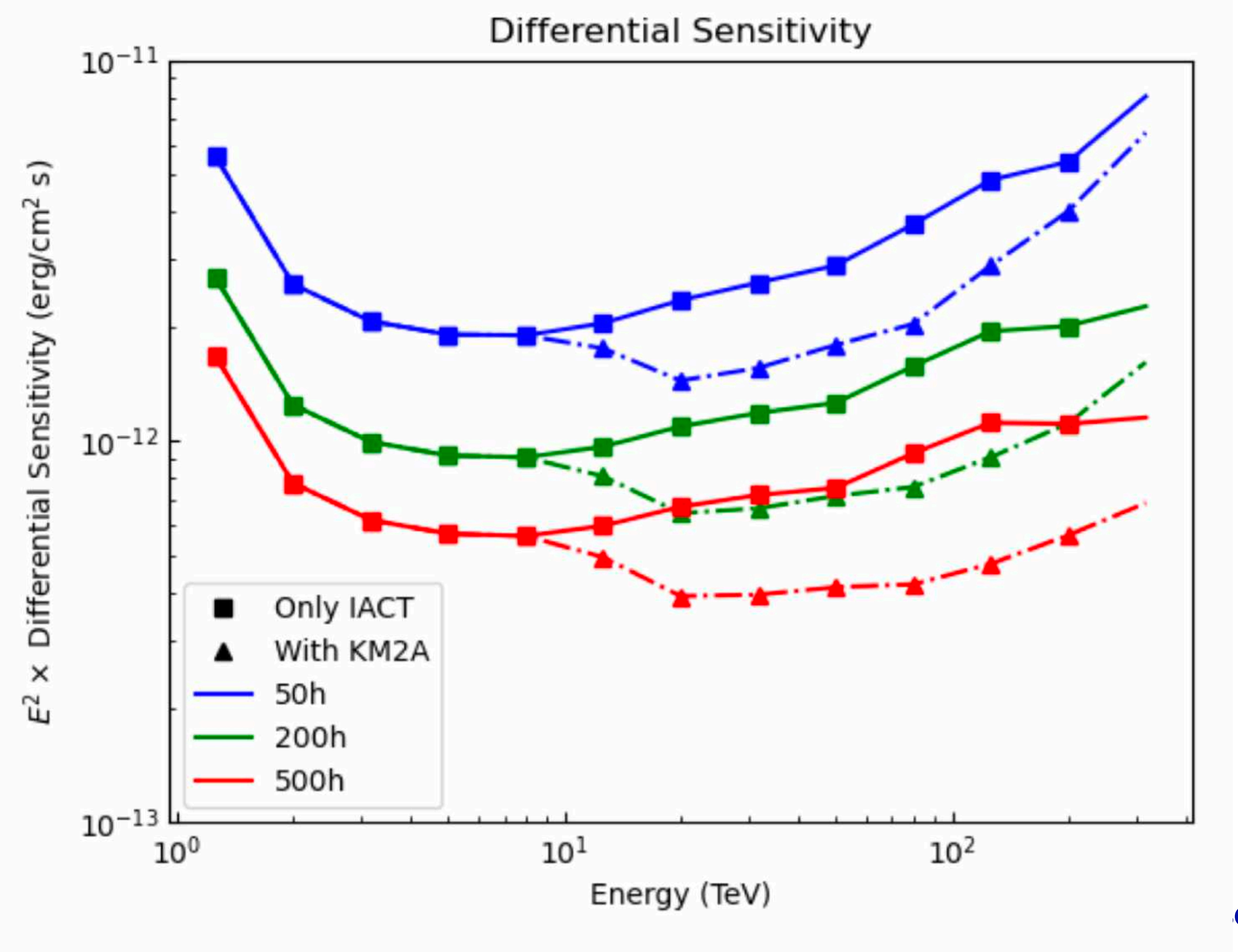
Optical type	*Davies-Cotton*
Mirror Size	*6 m*
FoV	*9.6°*
Pixel size	*0.2° (1")*
# pixels	*2224*
Sensor	*SiPM*
Focal Length	*8 m*

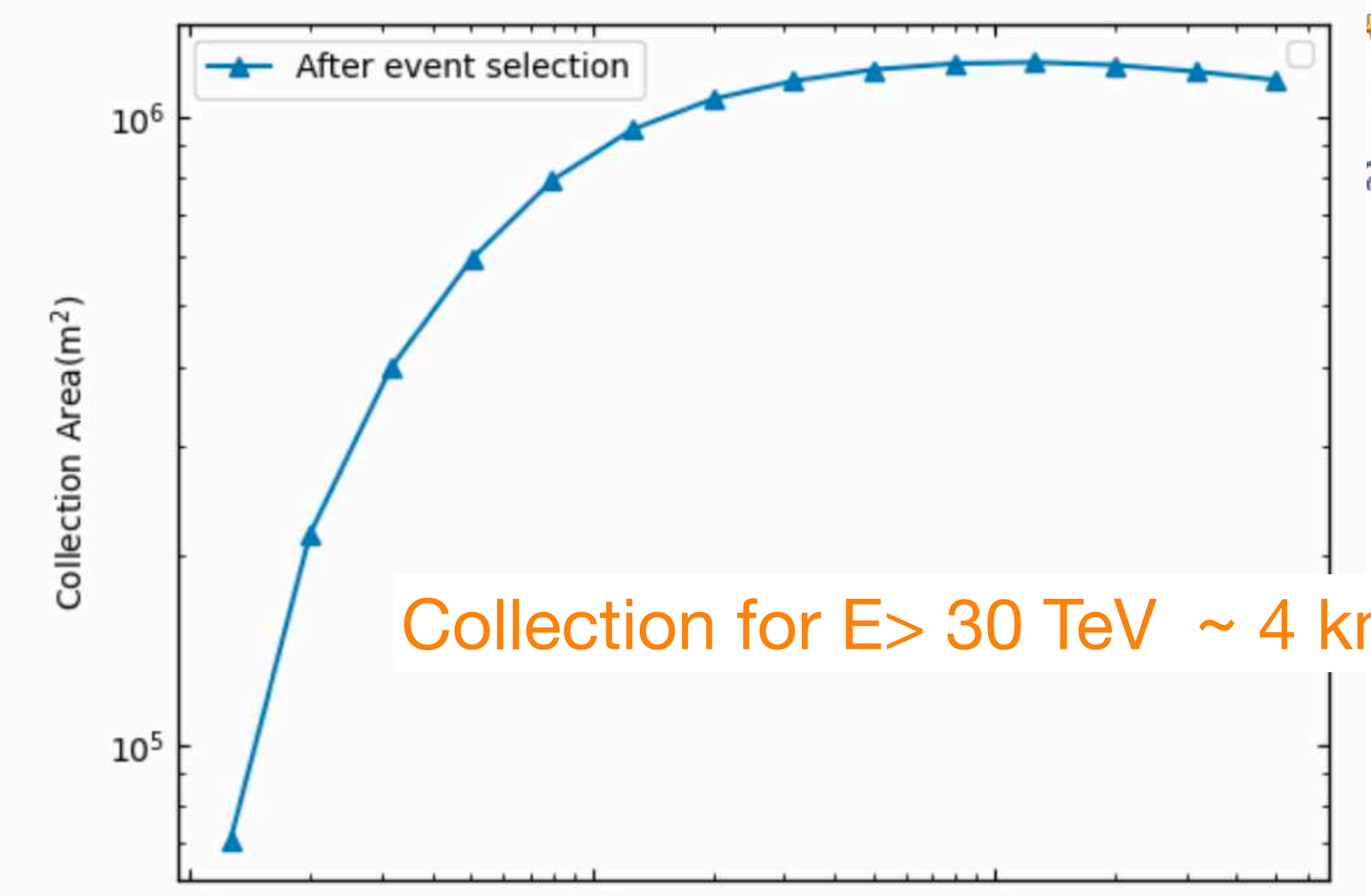
- Work in synergy with KM2A
  - Use KM2A muon identification
    - to improve h/γ separation $\Longrightarrow$ improve sensitivity
  - Improve angular resolution above 30 TeV
    - Morphology of extended source
  - Study complex areas
    - Cygnus bubbles
  - Improve energy resolution



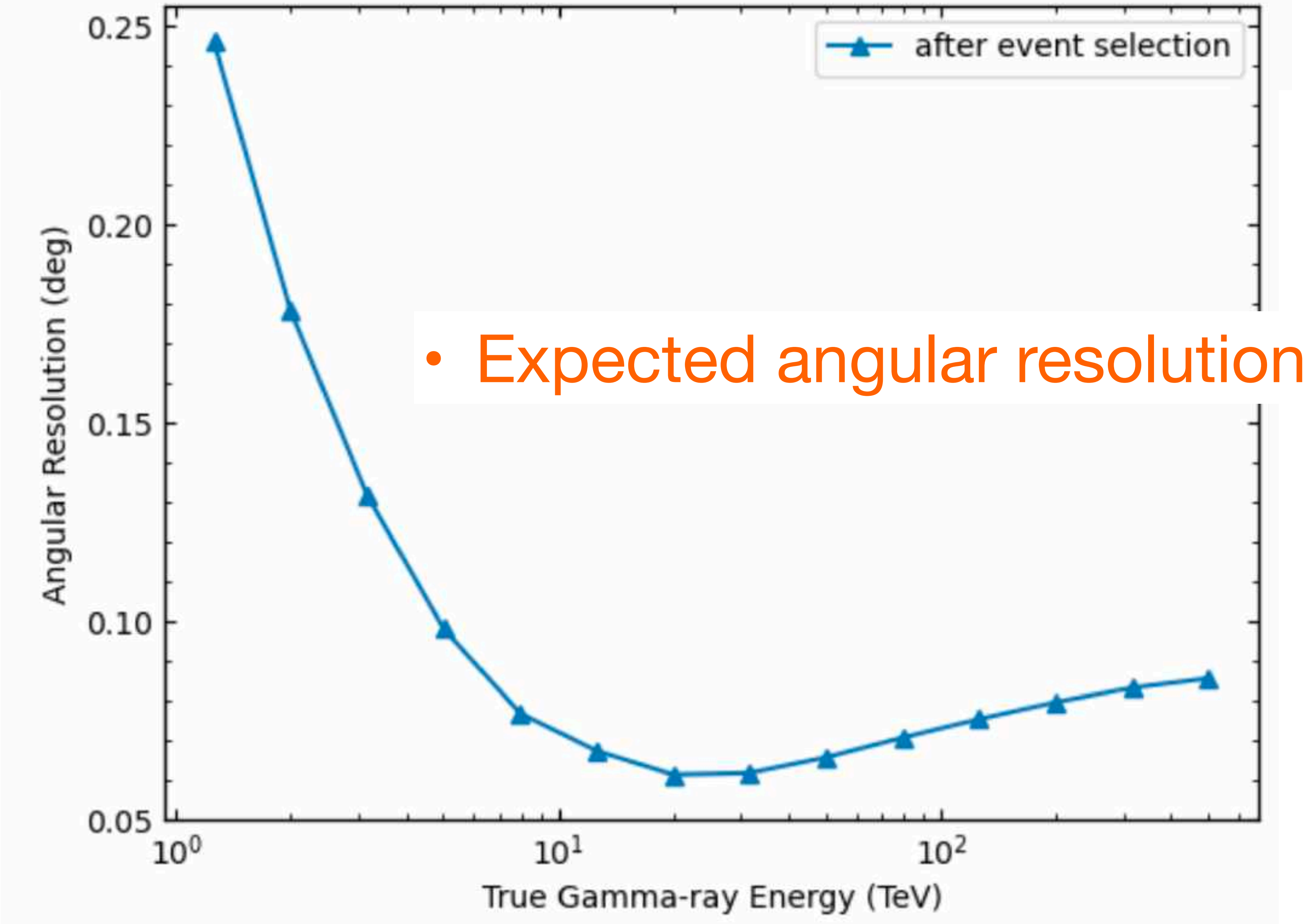
Study for 8 Telescope array

- An array of 8 telescopes
- Separation ~ 350 m
-





Collection for E> 30 TeV ~ 4 km^2



- Expected angular resolution ~ 0.05°

Thanks You for your attention