

# Lecture 2a: Gamma-ray Astrophysics

Ultra High Energy  $\gamma$  Cosmic Rays

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*APC (Paris)*

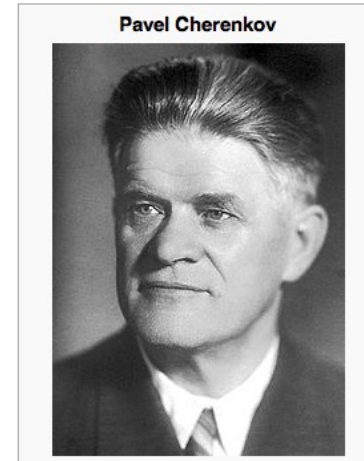
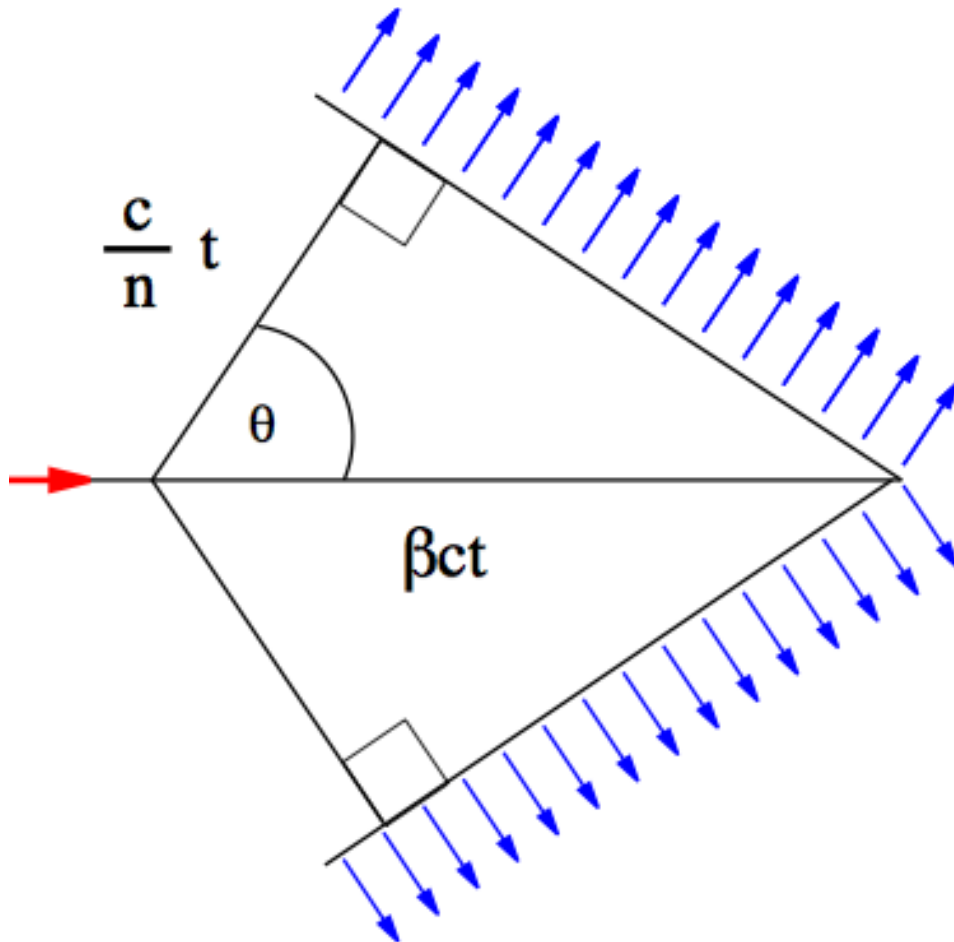
# Overview:

- Cherenkov radiation
- Detection technics
- Present and future experiments
- Galactic gamma-ray sources and diffused background
- Extragalactic sources and backgrounds
- Study of intergalactic magnetic fields
- Knee in cosmic rays from gamma-rays
- Conclusions



# Cherenkov radiation

# Cherenkov radiation



Discovery 1934

Nobel prize 1958

# Cherenkov radiation

$$V > V_m = c / n$$

$n$  is refractive index of medium

$$n = 1.008 \text{ air}$$

$$n = 1.33 \text{ water}$$

The charged particles polarize the molecules, which then turn back rapidly to their ground state, emitting prompt radiation

*Cherenkov light is emitted under a constant Cherenkov angle with the particle trajectory, given by*

$$\cos \delta = \frac{V_m}{V} = \frac{c}{nV} = \frac{1}{\beta n}$$

$$\gamma_{\min} = \frac{n}{\sqrt{n^2 - 1}}$$

- Minimal energy of charge particle

# Main processes used in gamma-ray astrophysics

$$\gamma + \gamma_B \Rightarrow e^- + e^+$$

$$e^\pm + \gamma_B \Rightarrow e^\pm + \gamma$$

$$e^\pm + B \Rightarrow e^\pm + \gamma_{synch}$$

$$e^\pm + A_B \Rightarrow e^\pm + A_B + \gamma_{brems}$$

$$P + \gamma_B \Rightarrow N + \pi$$

$$P + P_B \Rightarrow N + N + \sum \pi$$

$$\pi^0 \Rightarrow 2\gamma$$

# Detection techniques

# Fermi Large Area Telescope (LAT)

Large Field of View  $>2.4$  sr

Broad Energy Range 20 MeV -  $>300$  GeV

- **ACD**

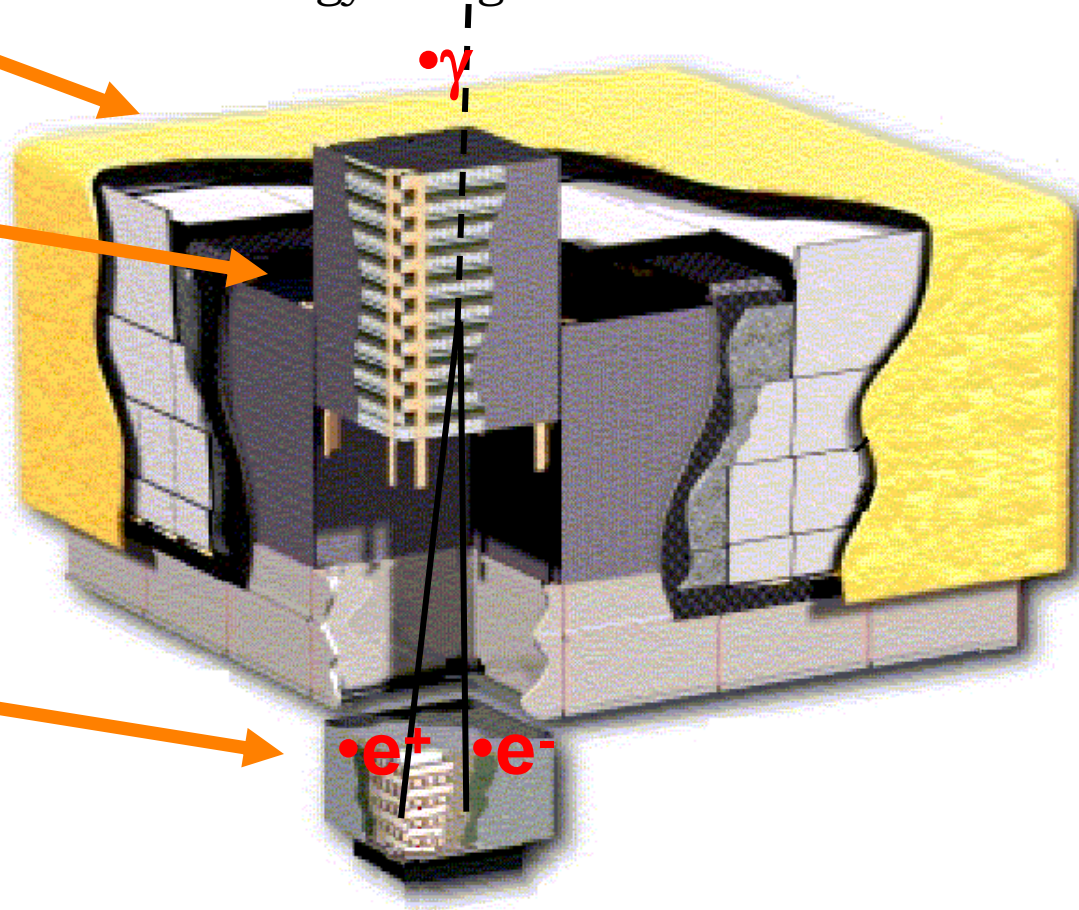
- scintillator
- 89 tiles

- **Tracker**

- Si strip detectors
- Tungsten foil converters
- pitch = 228  $\mu\text{m}$
- $8.8 \times 10^5$  channels
- 18 planes

- **Calorimeter**

- CsI crystals
- hodoscopic array
- $6.1 \times 10^3$  channels
- 8 layers

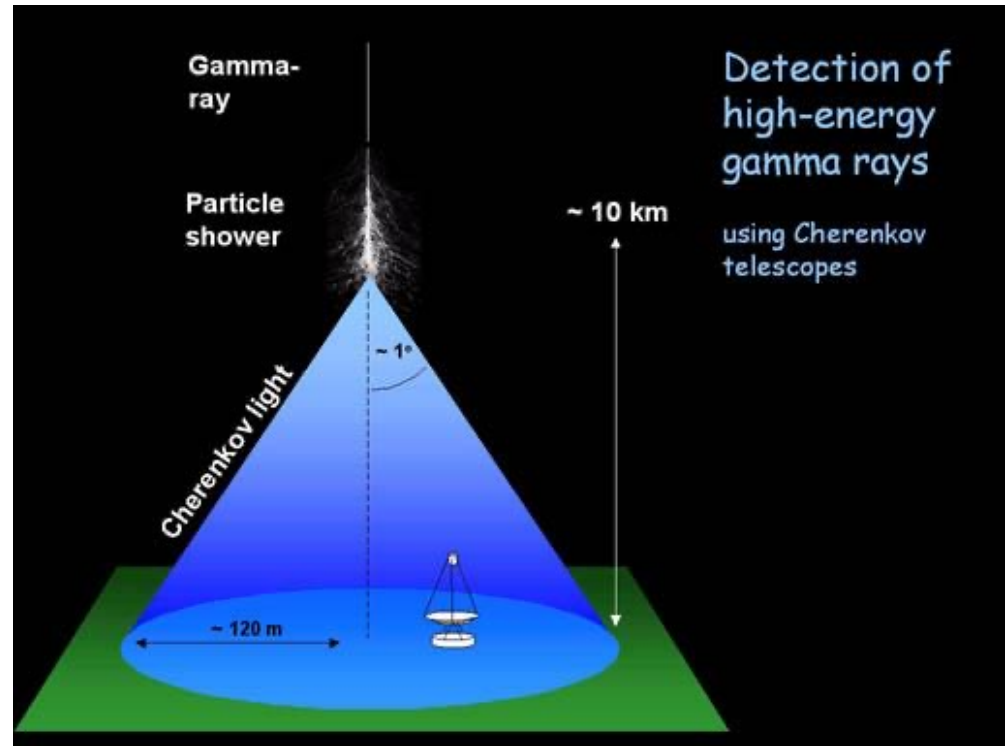




# Cherenkov telescopes

Very high energies, above 50 GeV

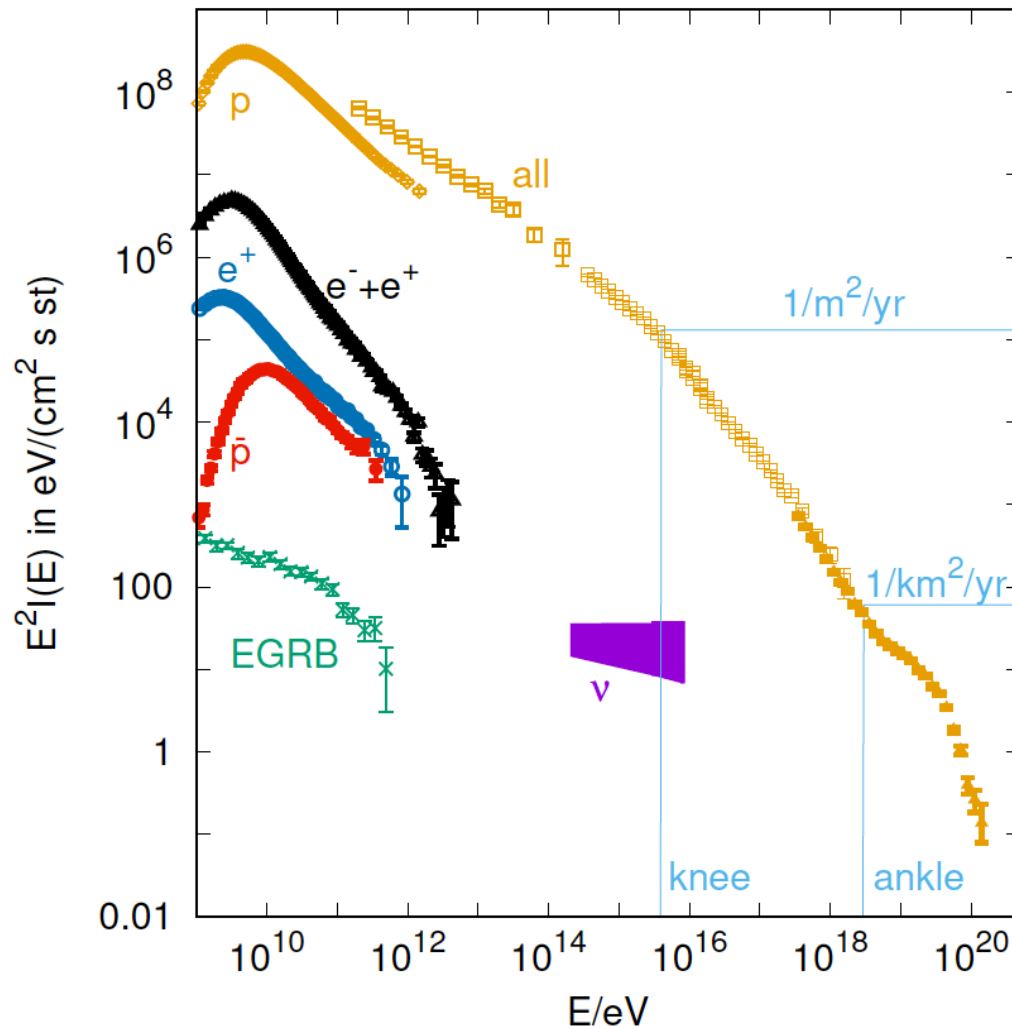
- Crab nebula: flux(  $E > 1 \text{ TeV}$  )  
 $= 2 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$
- Large effective detection areas ( $> 30\,000 \text{ m}^2$ ) needed
- -> Back to the ground
- Use the atmosphere as a
- huge calorimeter and
- detect  $\gamma$ -ray-induced
- atmospheric showers
- through Cherenkov light
- 



# Experimental challenges

- Reduce the energy threshold as much as possible  
Try to get some overlap region with space observations
- Increase flux sensitivity
- **Remove the huge background** of showers induced by charged particles (**cosmic ray protons, ions and electrons**)

# Cosmic rays and gamma



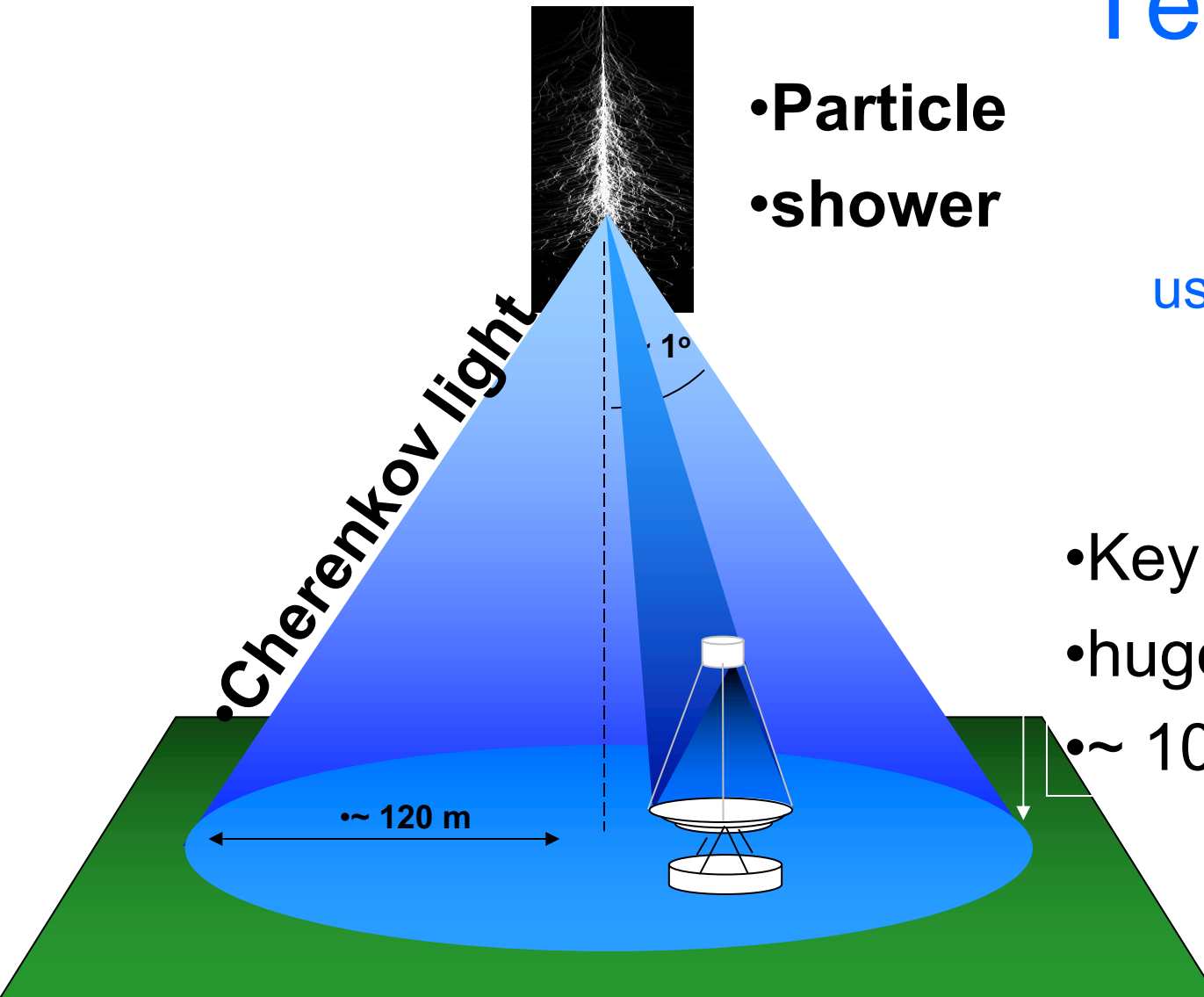
- From M.Kachelriess and D.S. Prog. Part. Nucl. Phys.
- 1904.08160

# Detection of TeV gamma rays

using Cherenkov telescopes

- Particle
- shower

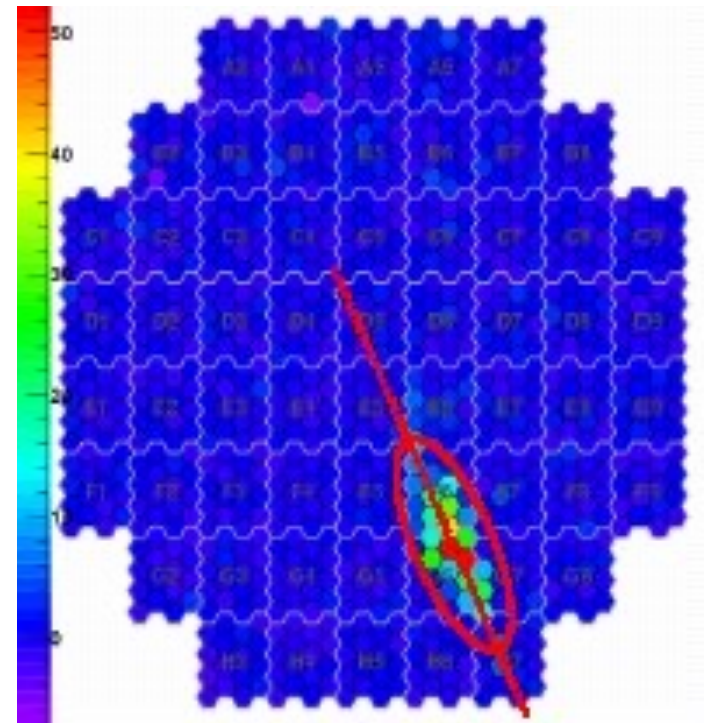
• Cherenkov light

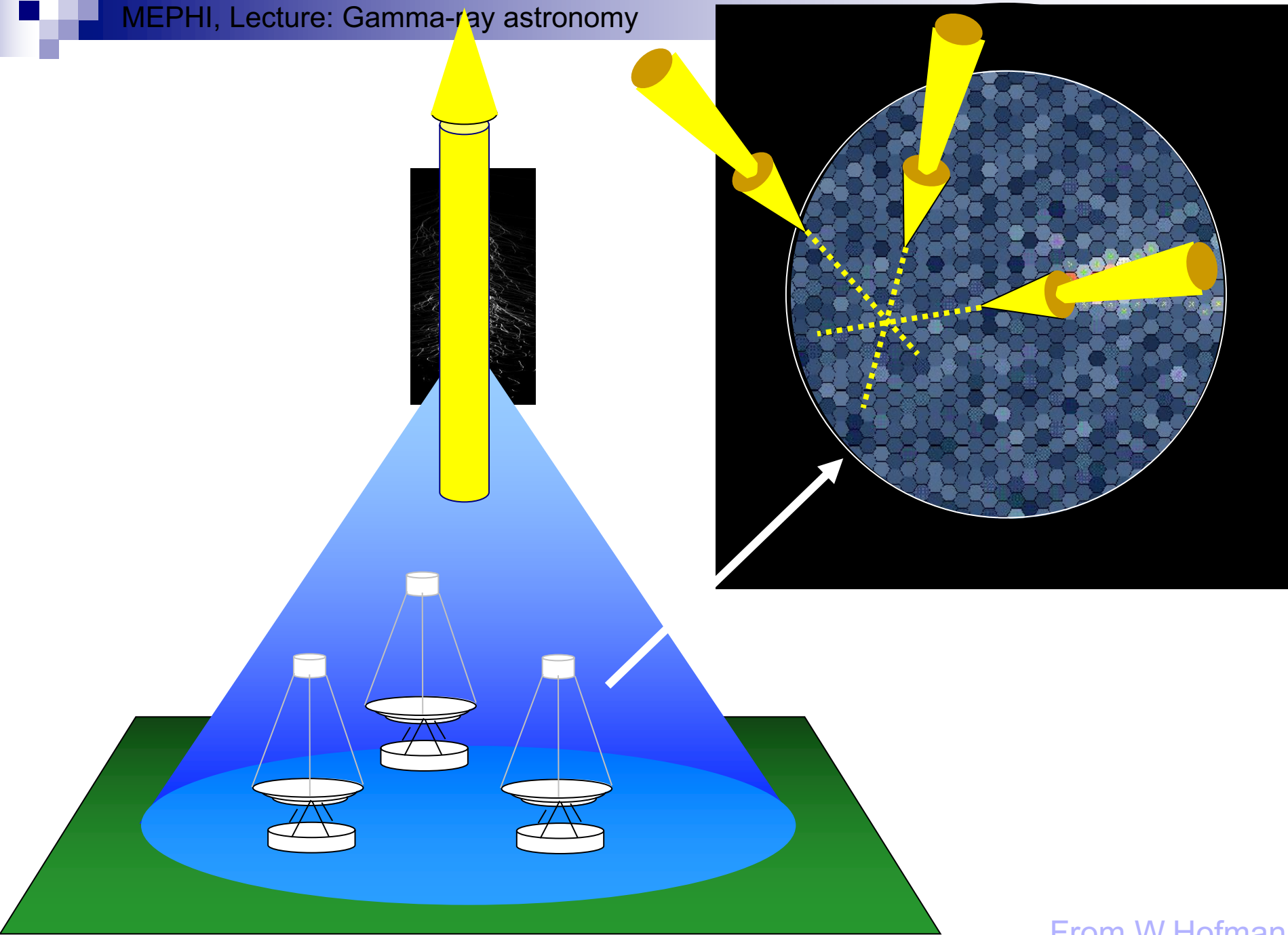


- Key issue:
- huge detection area
- $\sim 10^5 \text{ m}^2$

# Hardonic rejection

- Image shape:
  - Electromagnetic showers:
    - elongated, quasi-elliptic shape
  - Hadronic showers:
    - more irregular shape
- Image direction:
  - Electromagnetic showers:
    - point to the source (the center of the field of view)
  - Hadronic showers:
    - randomly oriented in the focal plane
- Image light profiles (longitudinal and transverse)
  - help finding the source position

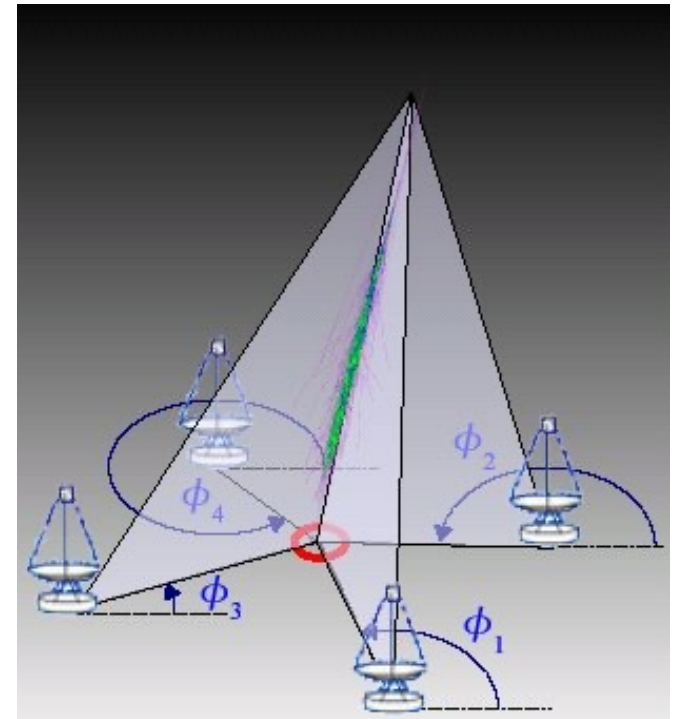
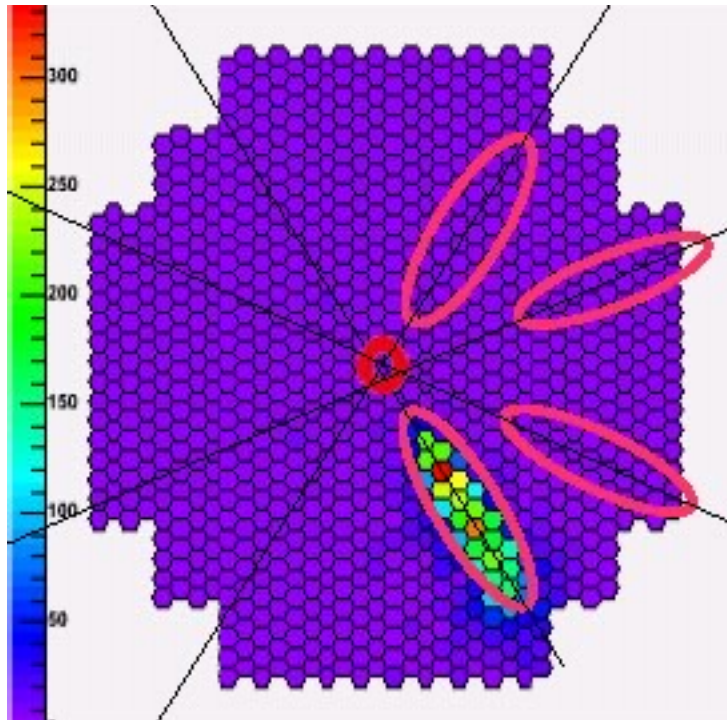




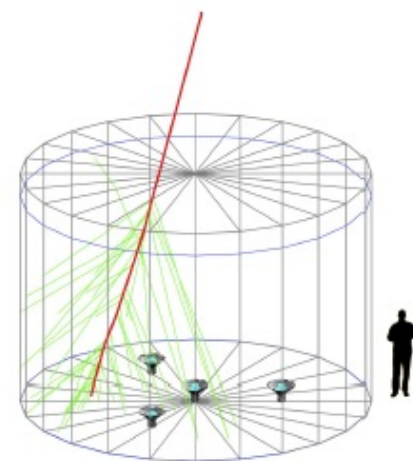
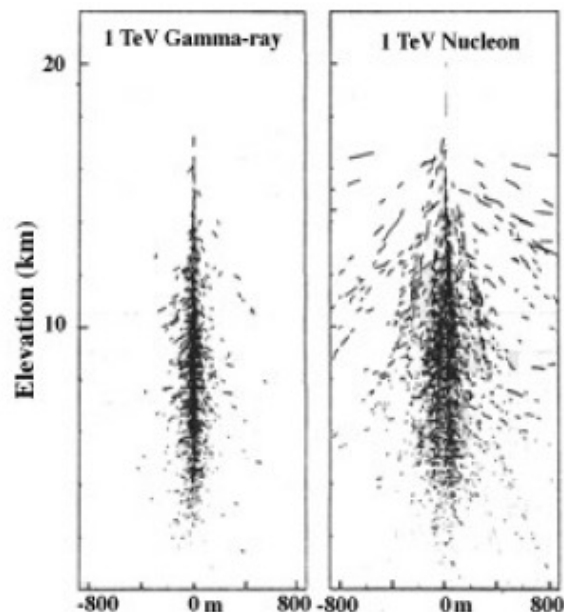


# Stereoscopic measurement (e.g. HEGRA, H.E.S.S. VERITAS, MAGIC)

- Direct measurement of the  $\gamma$ -ray **origin** in the field of view (important for extended sources)
- Direct measurement of the **impact on the ground** (important for energy measurement)
- Better hadronic rejection
- Much better angular resolution



# Detection Technique of the EAS Arrays

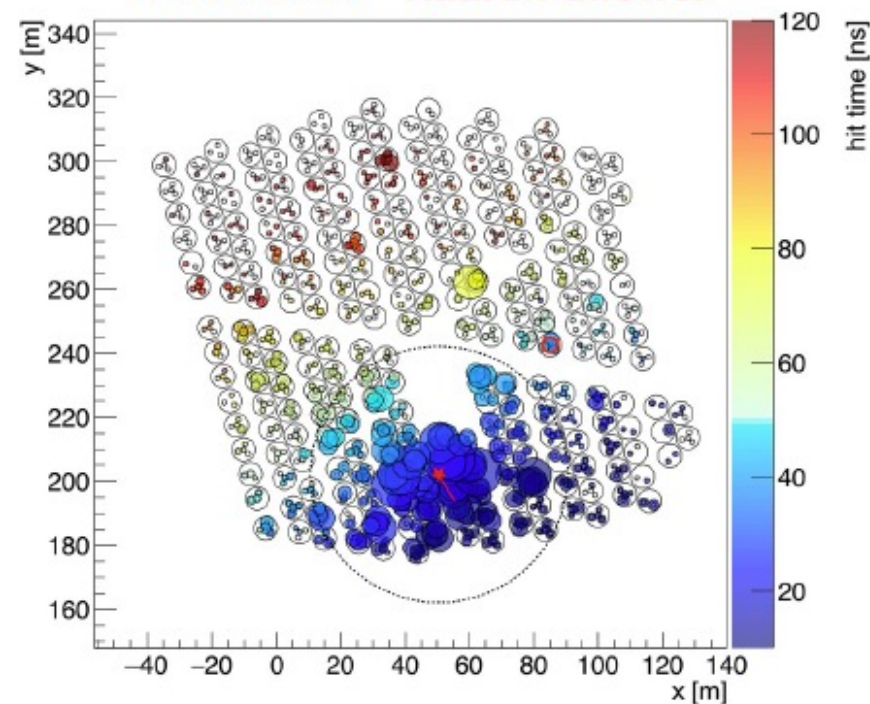


- The particle detectors can be tanks full of water. Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- Gamma/hadron can be discriminated based on the event footprint on the detector. Although is one of the challenges of this kind of detectors.

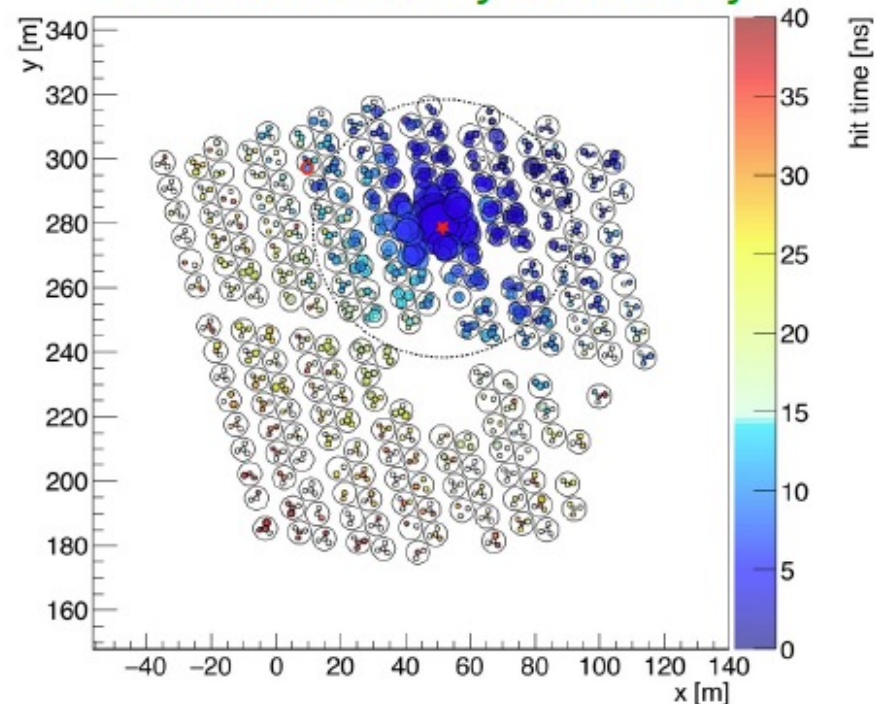
# Gamma/Hadron Separation

- Main background is hadronic CR, e.g. 400  $\gamma$ /day from the Crab vs 15k CR/s.
- In gamma-ray showers, most of the signal at ground level is located near the shower axis.
- In charged cosmic rays tend to "break apart", much messier signals at ground level.

HAWC Data – **Hadron Shower**

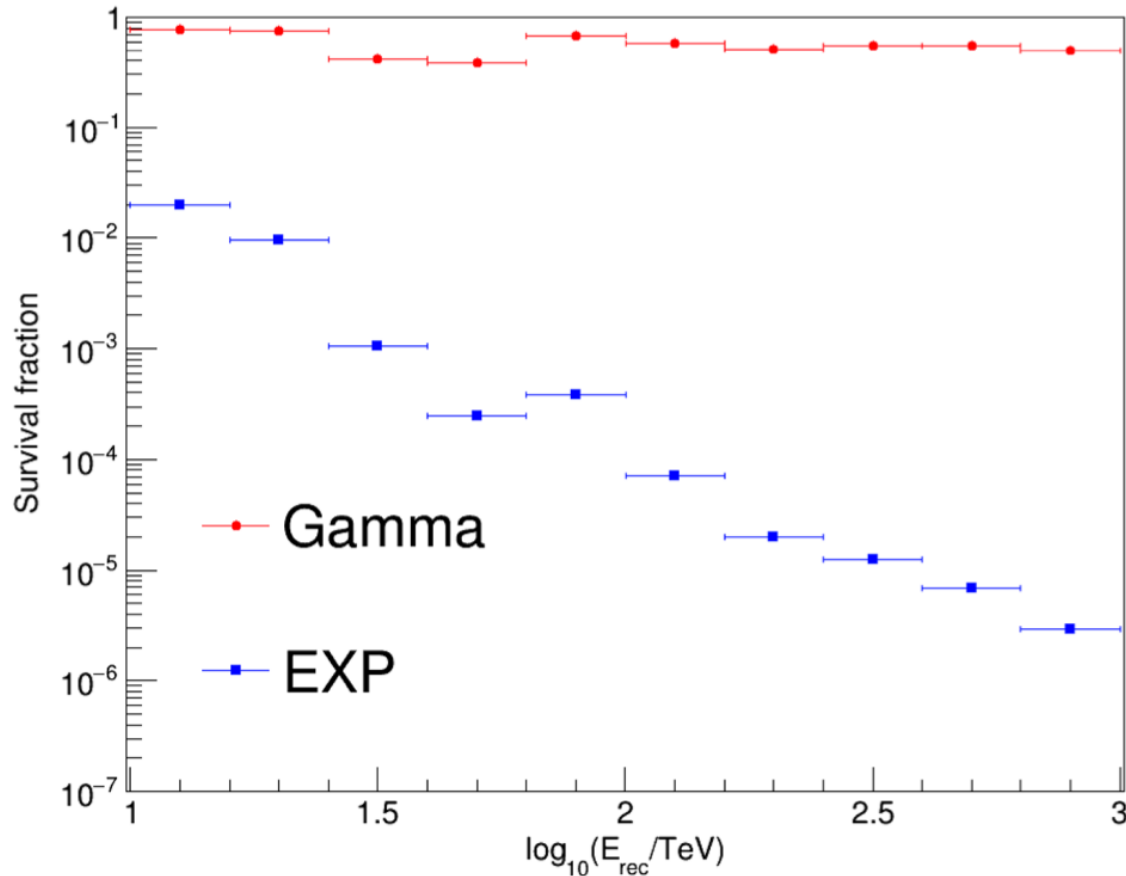


HAWC Data – **Likely Gamma Ray**





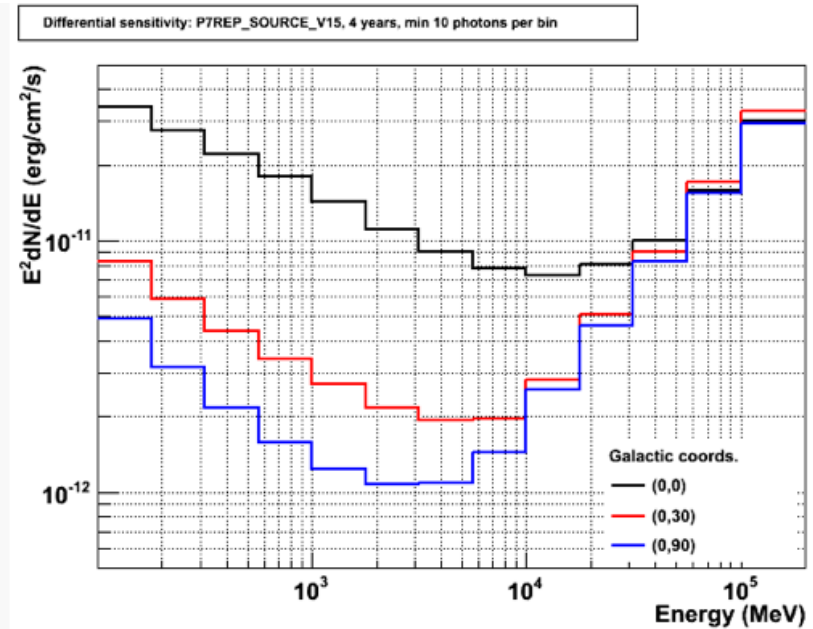
# LHAASO hadron cut 2021



•LHAASO talk ICRC Jul 2021

# Fermi LAT gamma-rays 40 MeV-1 TeV

# Fermi LAT





# TeV telescopes

## 50 GeV-20 TeV

# Cherenkov telescopes today

VERITAS



4x12m

MAGIC



2x17m

H.E.S.S.



4x12m+1x28m

# • HESS

- European Collaboration; M.P.I (Heidelberg)
- 4 x 12 m Telescopes
- Completed in Dec. 2003; located in NAMIBIA







# H.E.S.S. Sensitivity

- **HEGRA**

- 5% of Crab flux in 100 hours

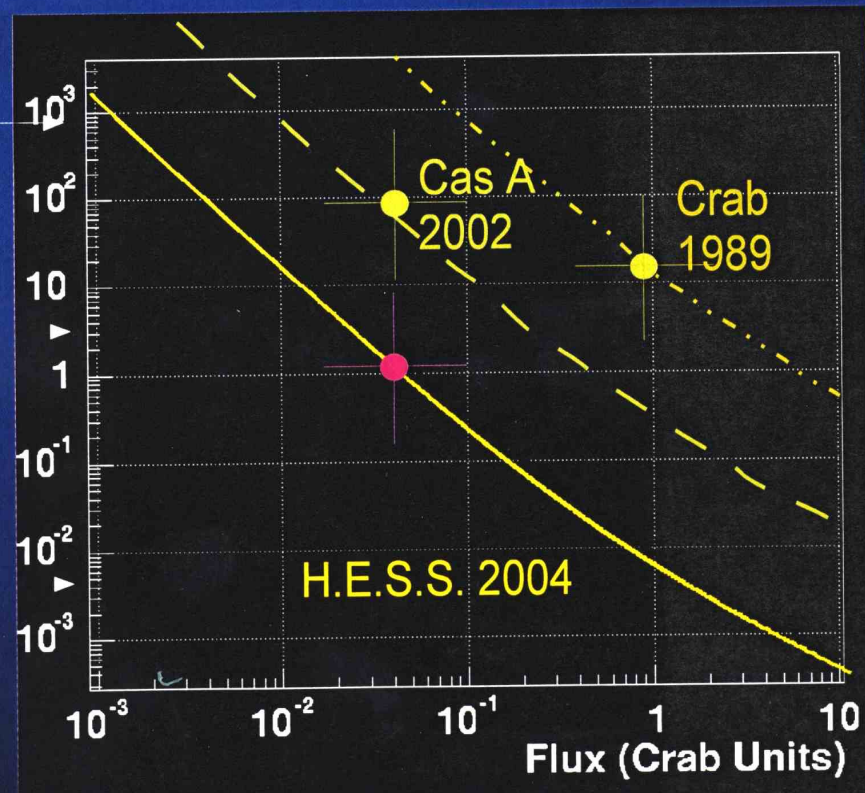
- **H.E.S.S.**

- 5% of Crab in 1 hour
- 0.5% in 100 hours

1 year

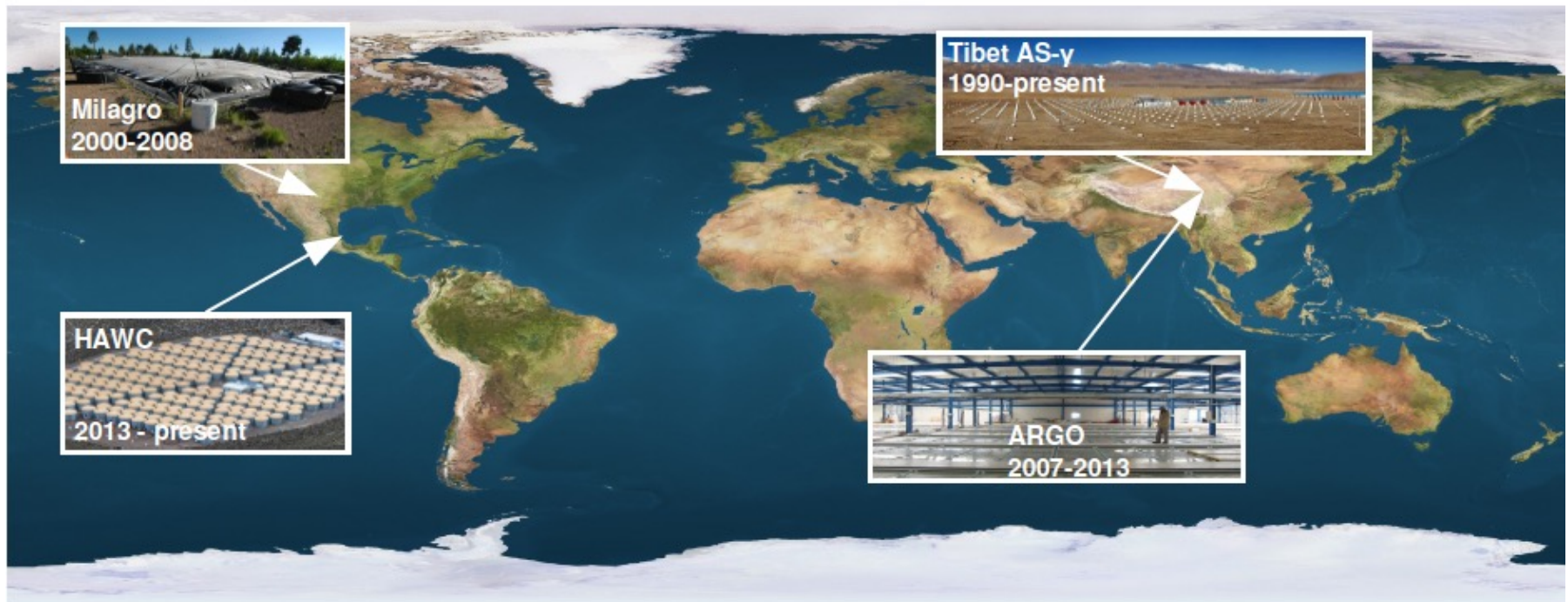
1 night

30 sec.



# EAS Detectors

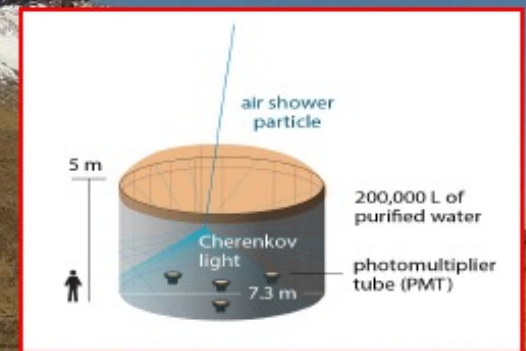
- Several EAS arrays have been operational using different detection techniques.
- It is time for second generation experiments like HAWC.





# HAWC Inauguration

**Detectors:** 300 WCDs (4 PMTs each)  
**Field of view:** 2sr instantaneous, 8sr daily  
**Average AR:** 0.5 deg (68% containment)  
**E range:** 100 GeV - 100 TeV sensitivity



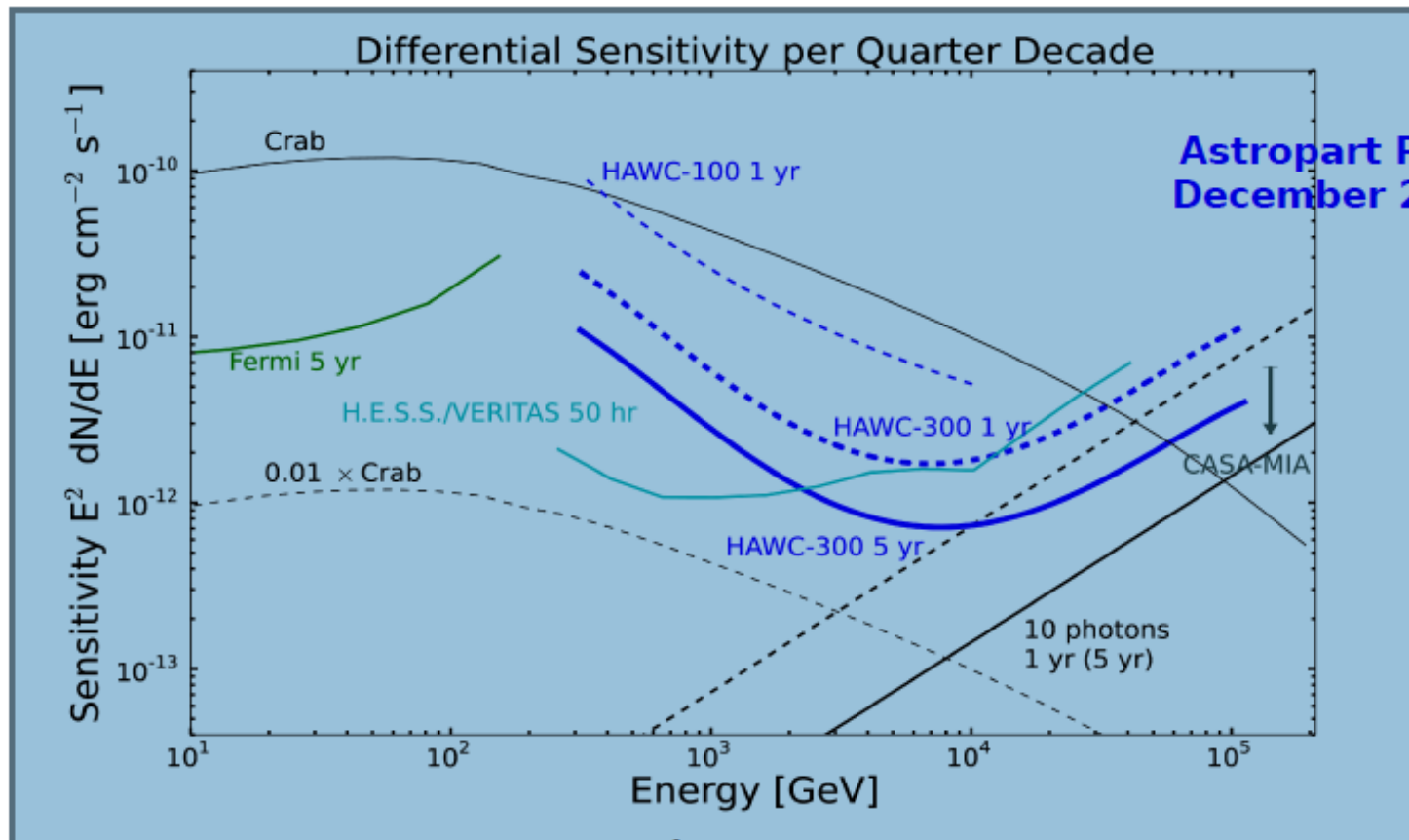
**Begging of full operations: Mar 20<sup>th</sup> 2015**



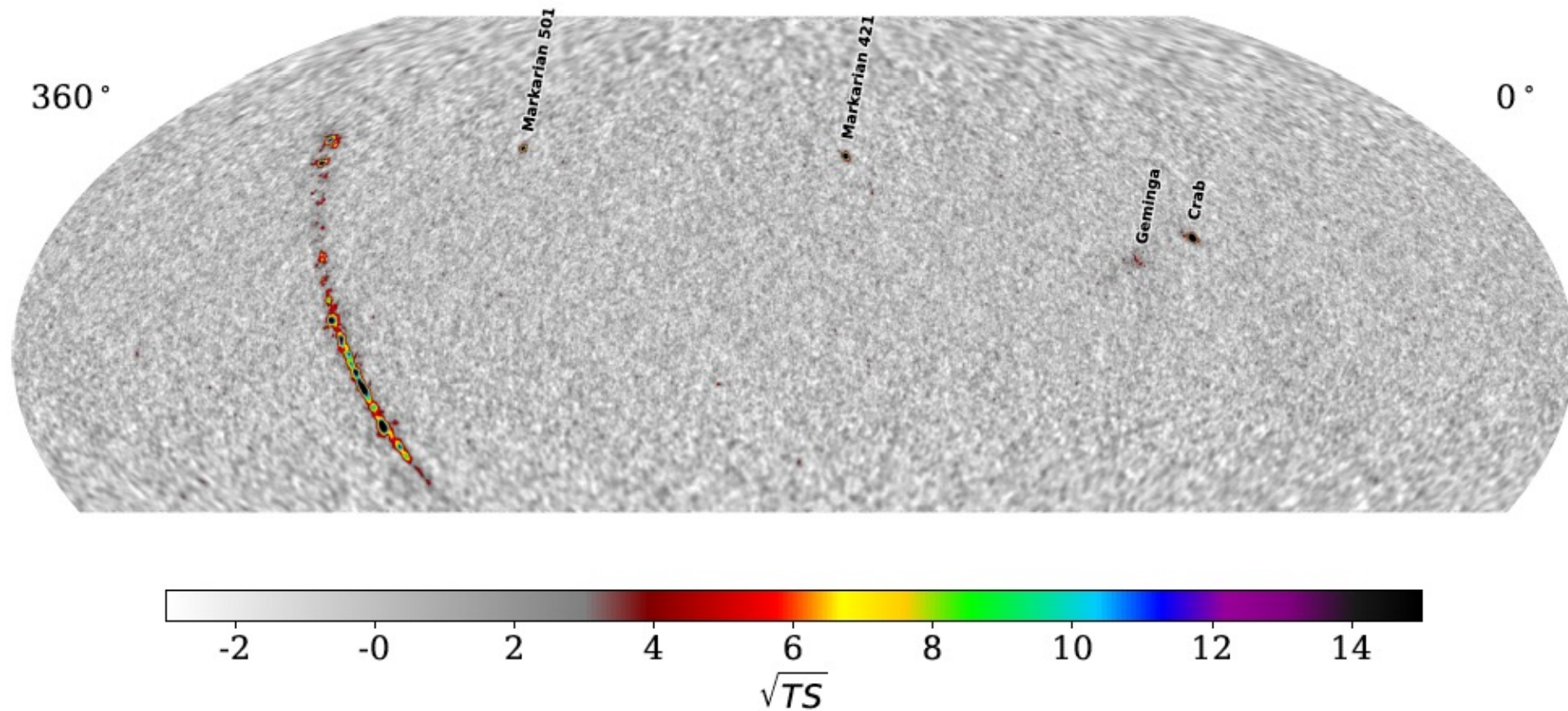
# HAWC Designed Sensitivity

- Instantaneous sensitivity 15-20x less than IACTs.
- Exposure (sr/yr) is 2000-4000x higher than IACTs.

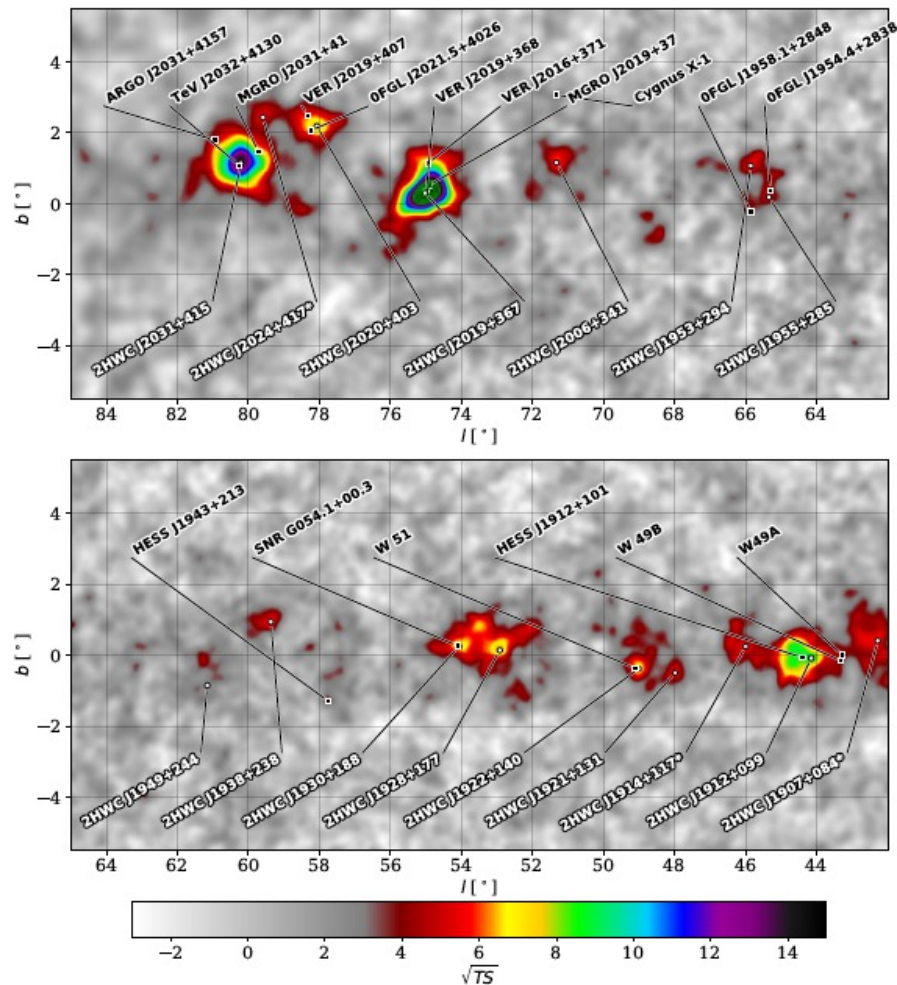
Survey > half the sky to:  
40 mCrab [ $5\sigma$ ] (1yr)  
<20 mCrab [ $5\sigma$ ] (5yr)



# HAWC sky map



# HAWC galactic plane



# Future TeV telescopes

# Wish list

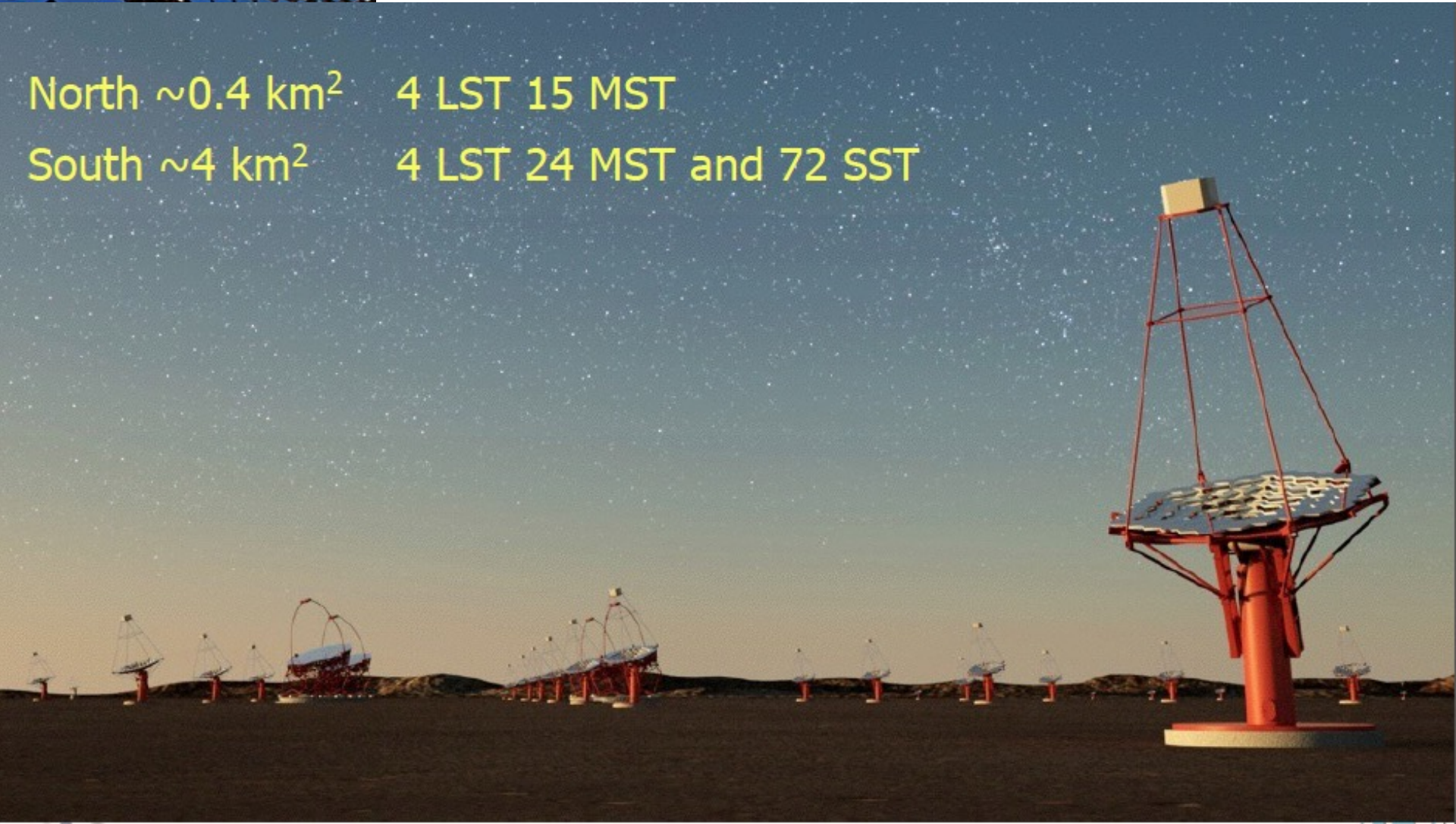
- Higher sensitivity at TeV energies (x 10)
  - more sources
- Lower threshold (some 10 GeV)
  - pulsars, distant AGN, source mechanisms
- Higher energy reach (PeV and beyond)
  - cutoff region of Galactic accelerators
- Wide field of view
  - extended sources, surveys
- Improved angular resolution
  - structure of extended sources
- Higher detection rates
  - transient phenomena



# • CTA

## The Next Generation: The Cherenkov Telescope Array

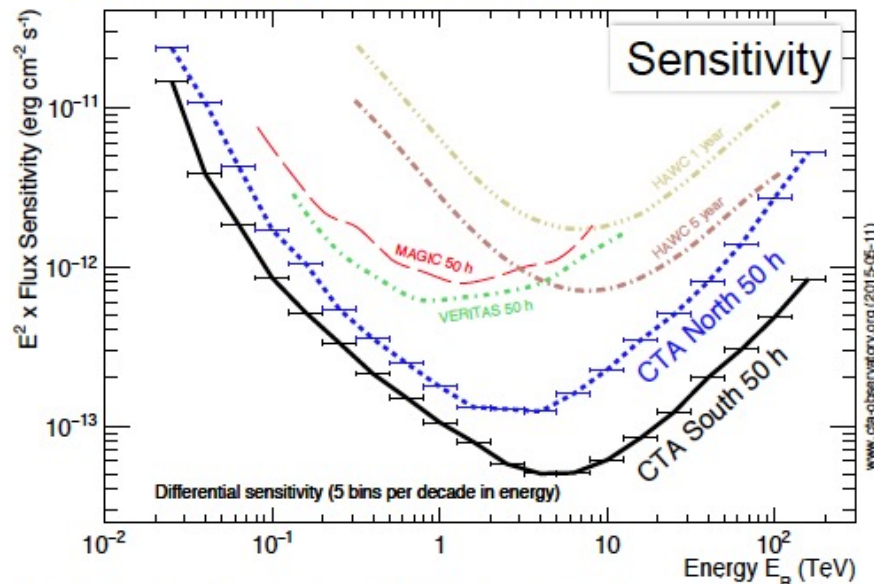
North  $\sim 0.4 \text{ km}^2$     4 LST 15 MST  
South  $\sim 4 \text{ km}^2$     4 LST 24 MST and 72 SST





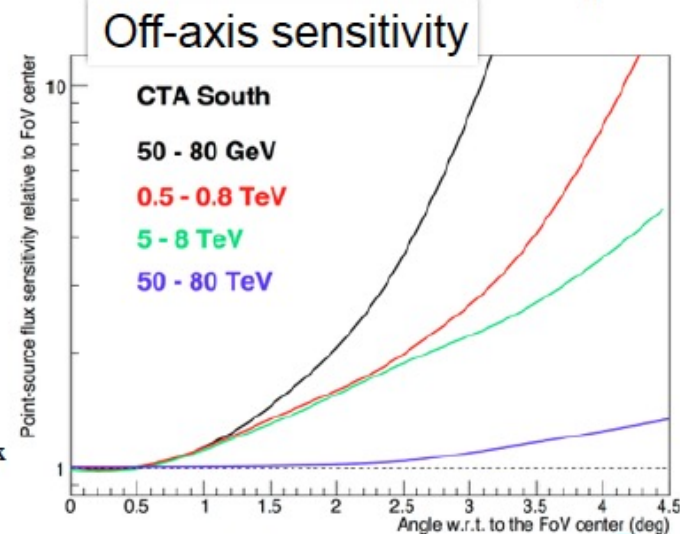
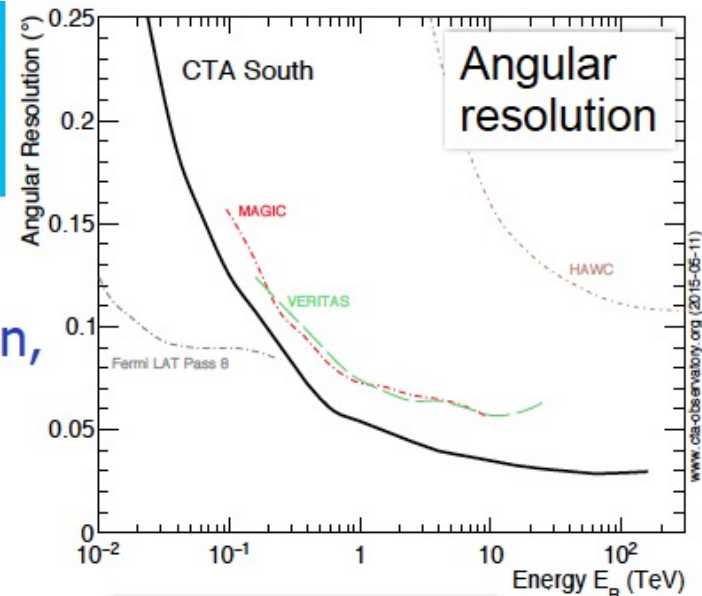
# CTA Performance

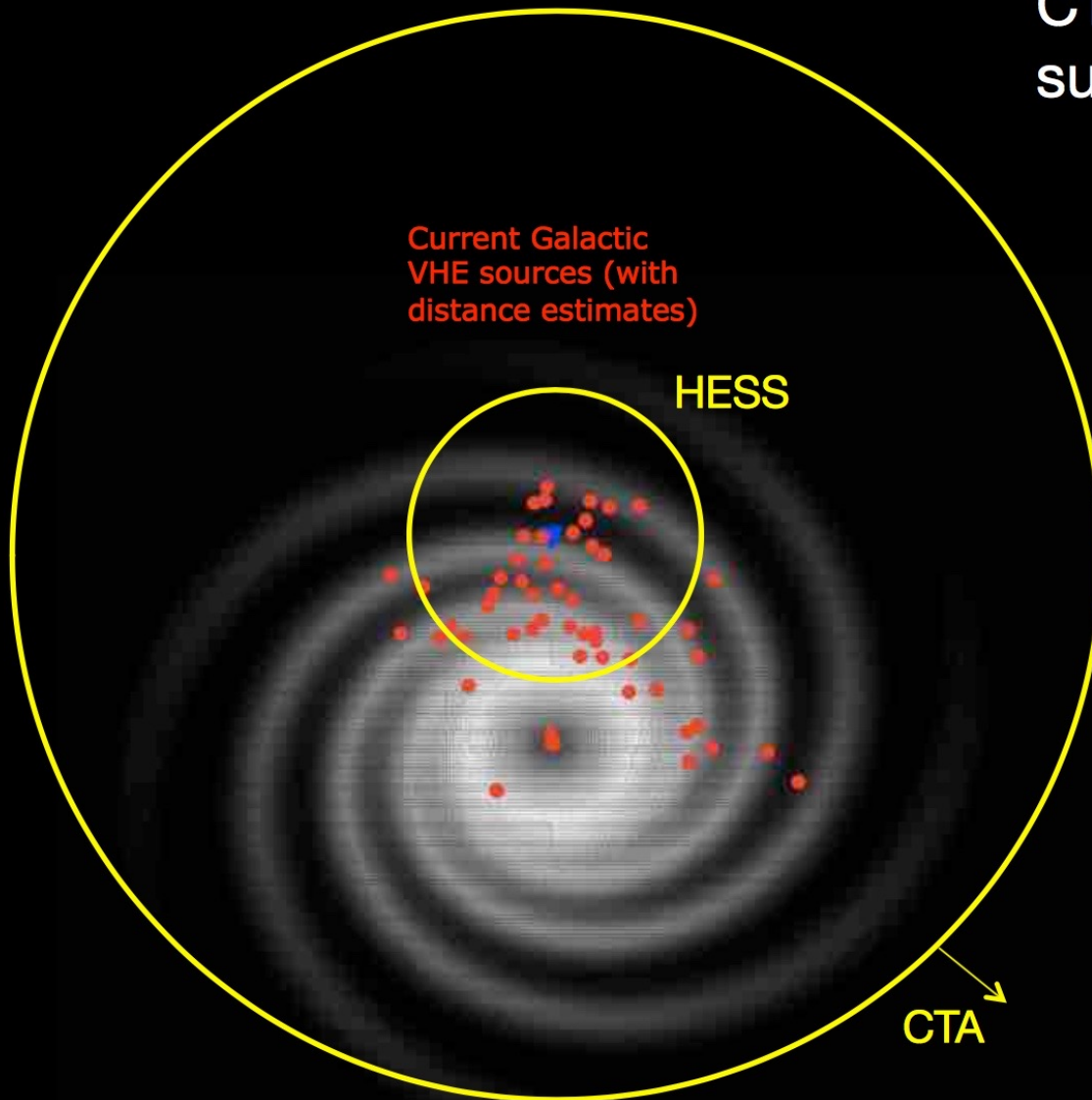
- > Result of large-scale simulations (900 telescopes for layout optimisation, CTA-GRID) and analysis



[https://portal.cta-observatory.org/CTA\\_Observatory/performance/SitePages/Home.aspx](https://portal.cta-observatory.org/CTA_Observatory/performance/SitePages/Home.aspx)

- > MC Prod3 started recently – more realistic estimation of CTA performance





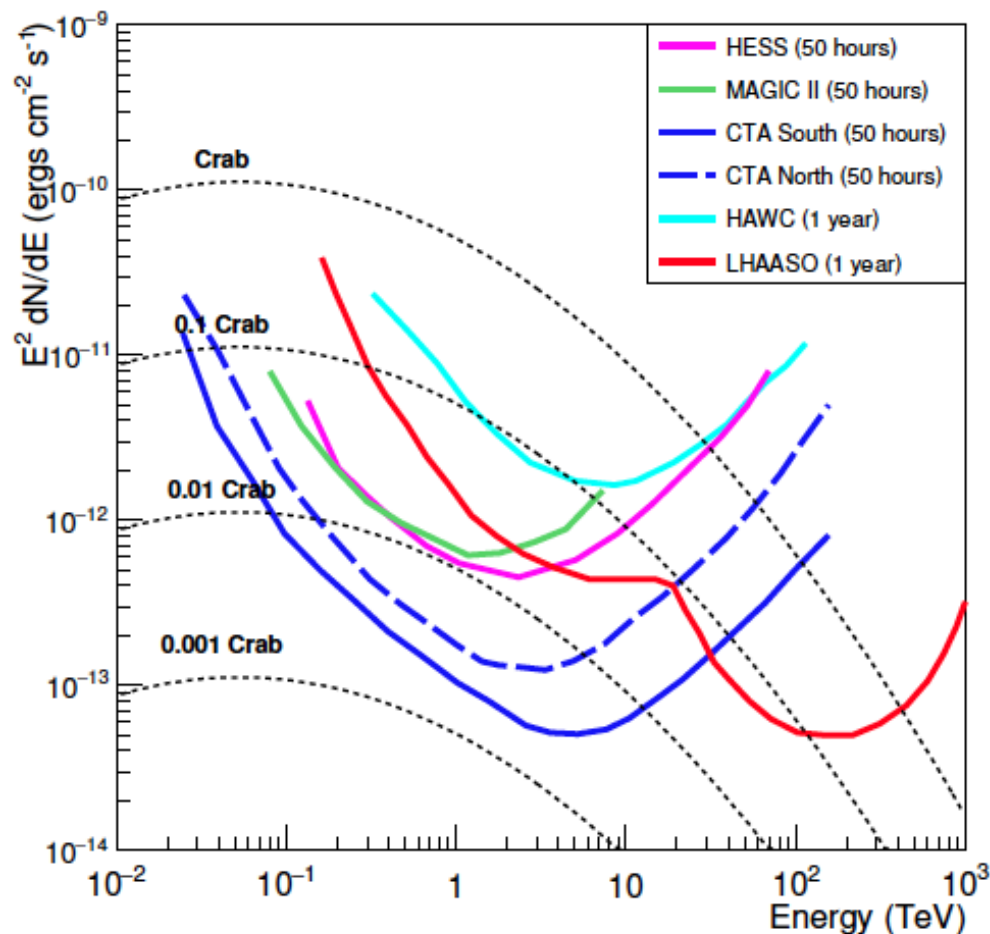
CTA as ultimate  
survey machine

CTA as ultimate  
machine to  
study flares

at 25 GeV, for flares  
10000 times more  
sensitive than Fermi

Coherent full-  
sky coverage  
from two sites

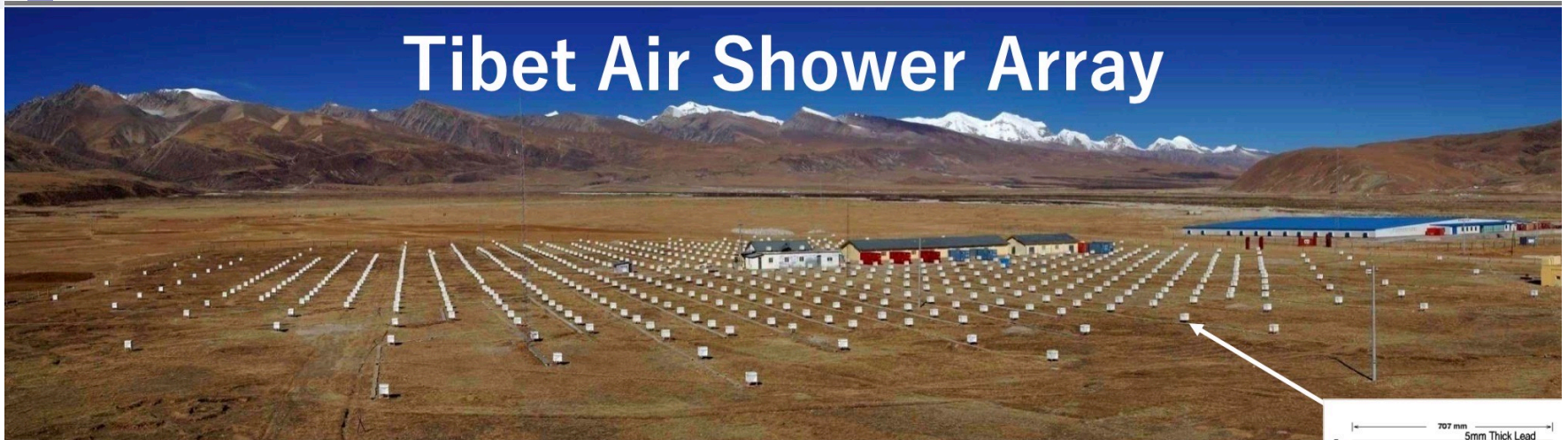
# Sensitivity future detectors



$E > 100 \text{ TeV}$   
telescopes



# Tibet Air Shower Array

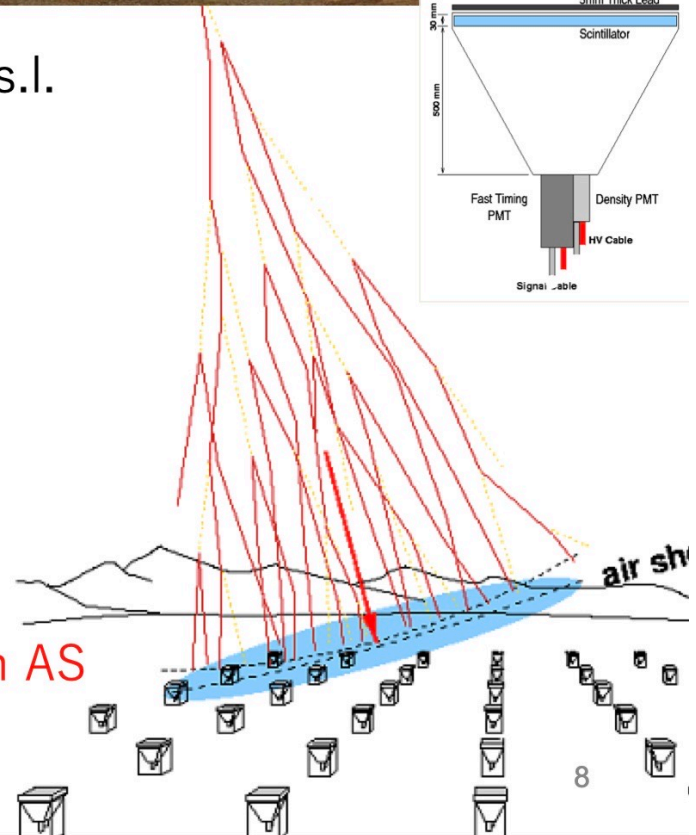
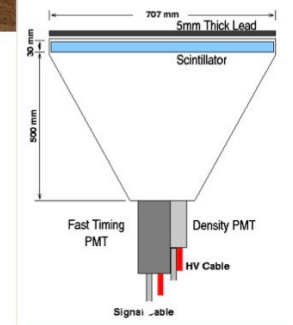


□ Site: Tibet ( $90.522^{\circ}\text{E}$ ,  $30.102^{\circ}\text{N}$ ) 4,300 m a.s.l.

## Present Performance

- # of detectors  $0.5 \text{ m}^2 \times 597$
- Effective area  $\sim 65,700 \text{ m}^2$
- Angular resolution  $\sim 0.5^{\circ}$  @10TeV  
 $\sim 0.2^{\circ}$  @100TeV
- Energy resolution  $\sim 40\%$ @10TeV  $\gamma$   
 $\sim 20\%$ @100TeV  $\gamma$

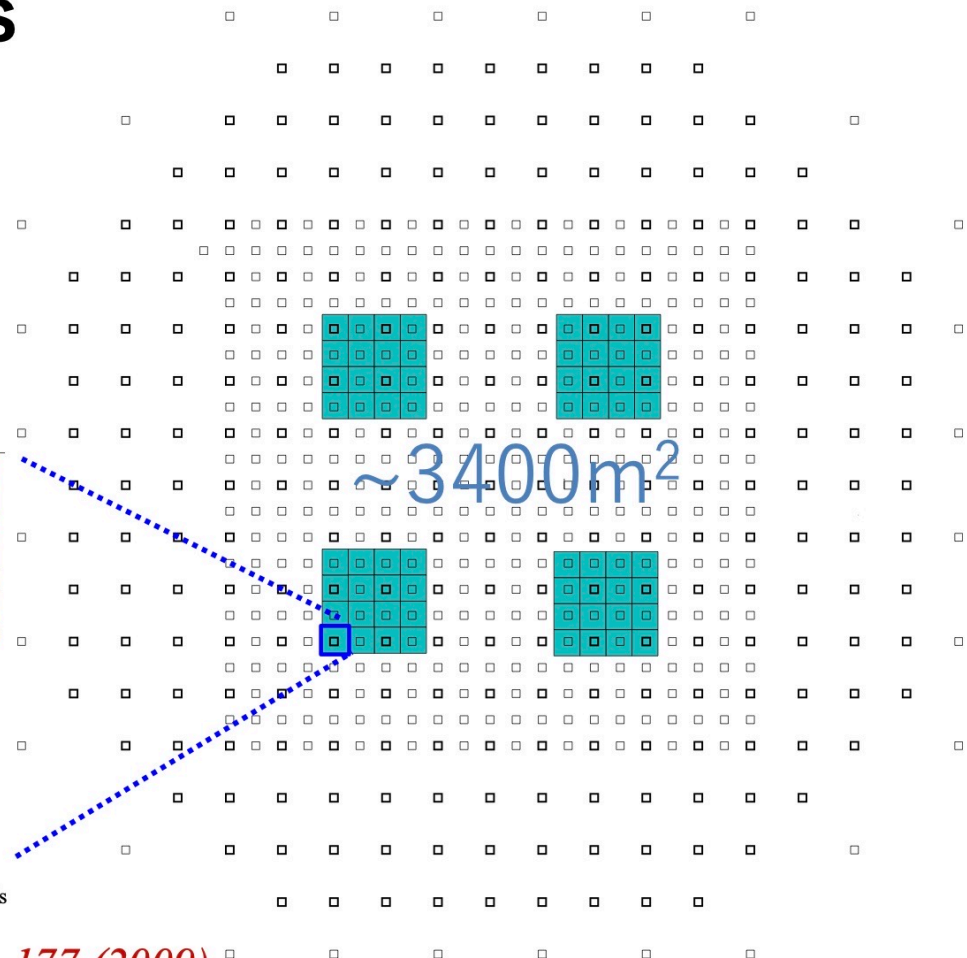
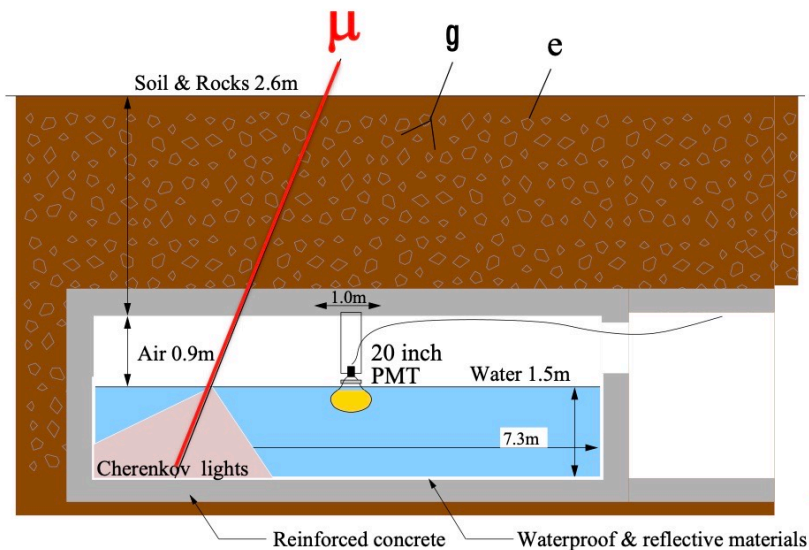
→ Observation of secondary (mainly  $e^{+/-}$ ,  $\gamma$ ) in AS  
 Primary energy : 2<sup>nd</sup> particle densities  
 Primary direction : 2<sup>nd</sup> relative timings





# Underground Water Cherenkov Muon detectors

- ✓ 2.4m underground ( $\sim 515\text{g/cm}^2 \sim 9X_0$ )
- ✓ 4 pools, 16 units / pool
- ✓  $7.35\text{m} \times 7.35\text{m} \times 1.5\text{m}$  deep (water)
- ✓ 20"  $\Phi$  PMT (HAMAMATSU R3600)
- ✓ Concrete pools + white Tyvek sheets



*Basic idea: T. K. Sako+, Astropart. Phys. 32, 177 (2009)*

Measurement of # of  $\mu$  in AS  $\rightarrow \gamma/\text{CR}$  discrimination

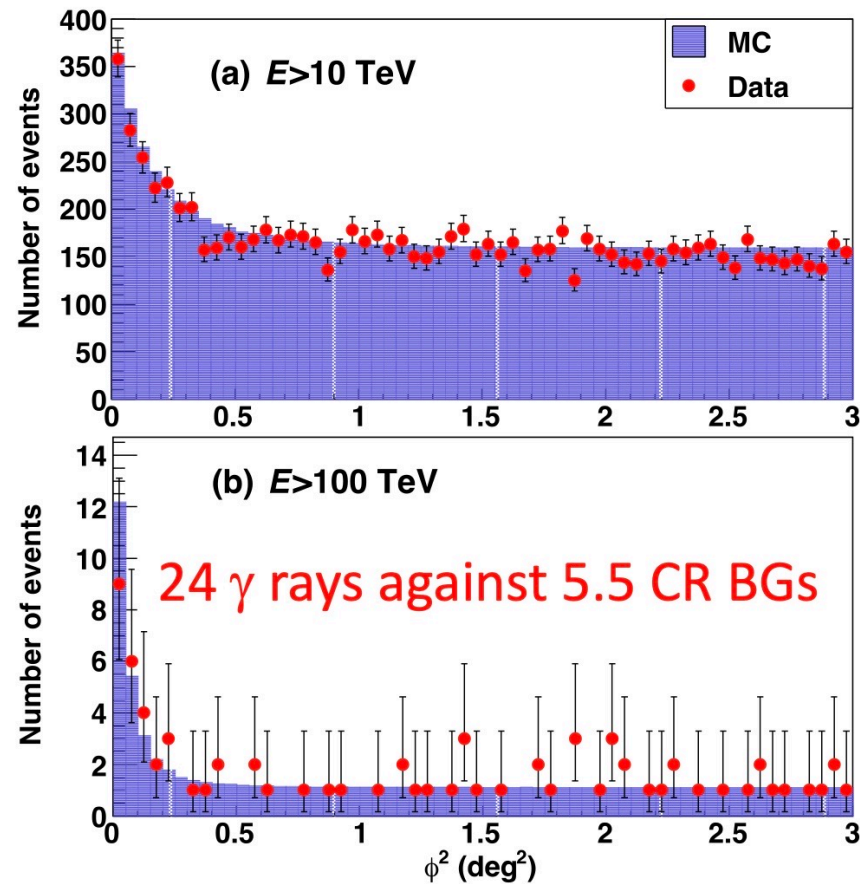
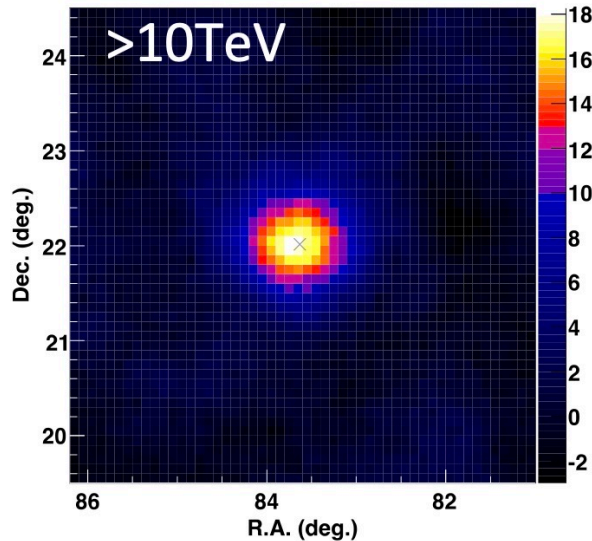
DATA: February, 2014 - May, 2017    Live time: 719 days





# Gamma-ray Emission from Crab

## Data vs MC



First detection of sub-PeV  $\gamma$  ( $5.6\sigma$ )  
 UHE  $\gamma$ -ray astronomy started!

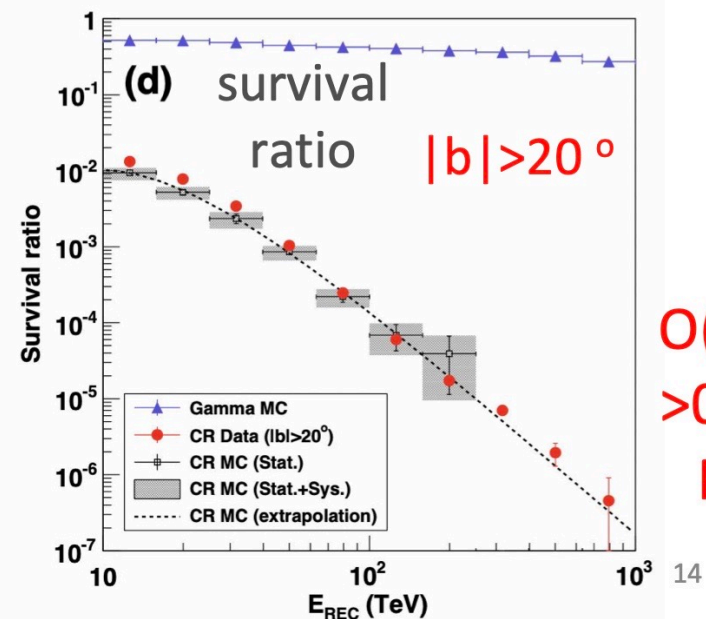
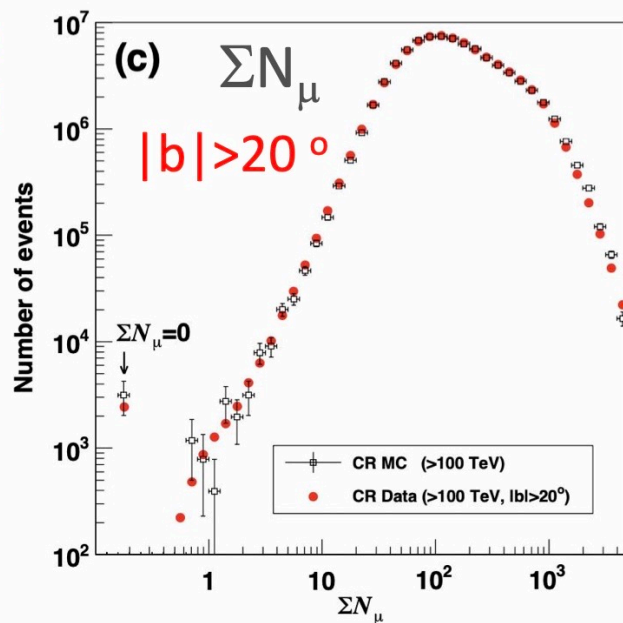
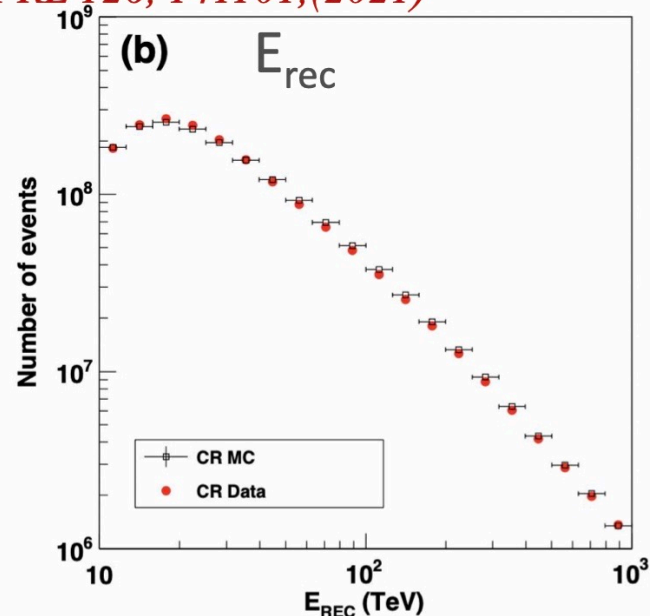
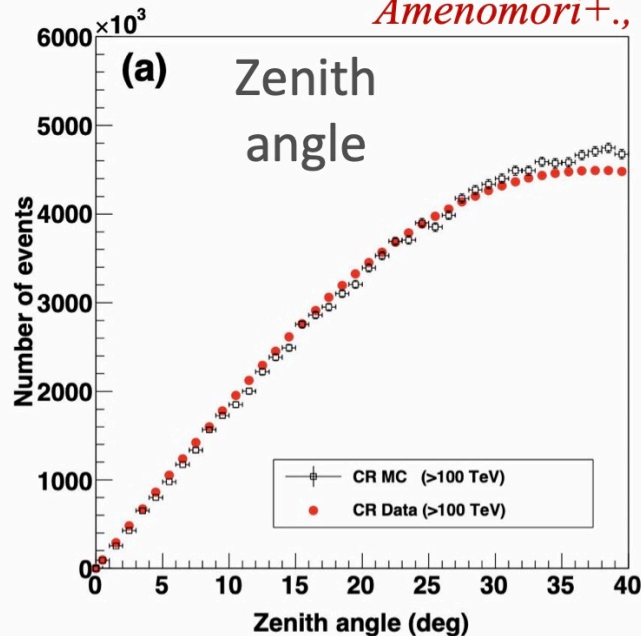
*Amenomori+, PRL, 123, 051101, (2019)*



CR MC  
vs.  
DATA

Reasonable  
agreement!

*Amenomori+., PRL 126, 141101, (2021)*





# Event Distribution >100 TeV (Fig.1) Tight muon cut

*Amenomori+., PRL 126, 141101, (2021)*

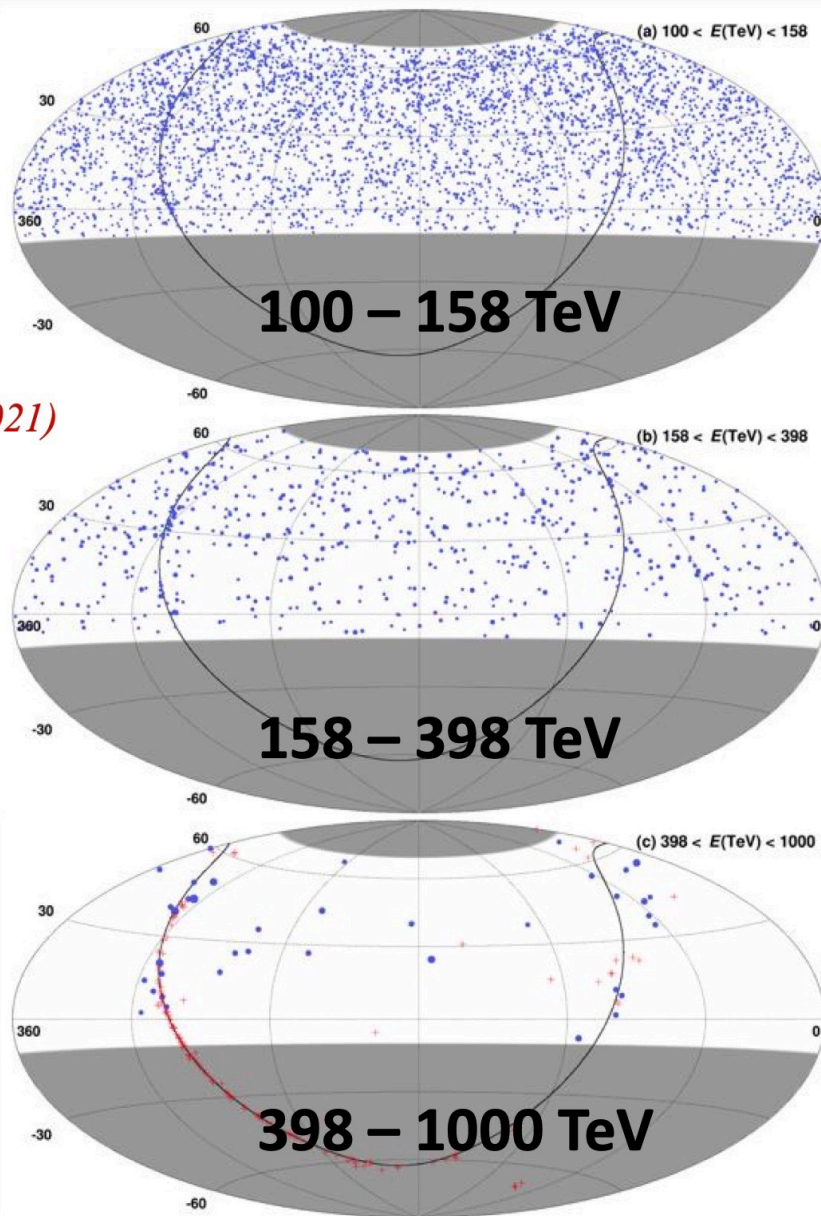
Blue points:  
Tibet AS +MD  
(Circle size  $\propto$  Energy)

Red plus marks:  
TeV sources  
(TeVCat catalog)

>0.398 PeV ( $10^{2.6}$  TeV)  
38 events in our FoV

→ Not from known TeV sources!  
& No signal > 10 TeV around them

Equatorial coordinates

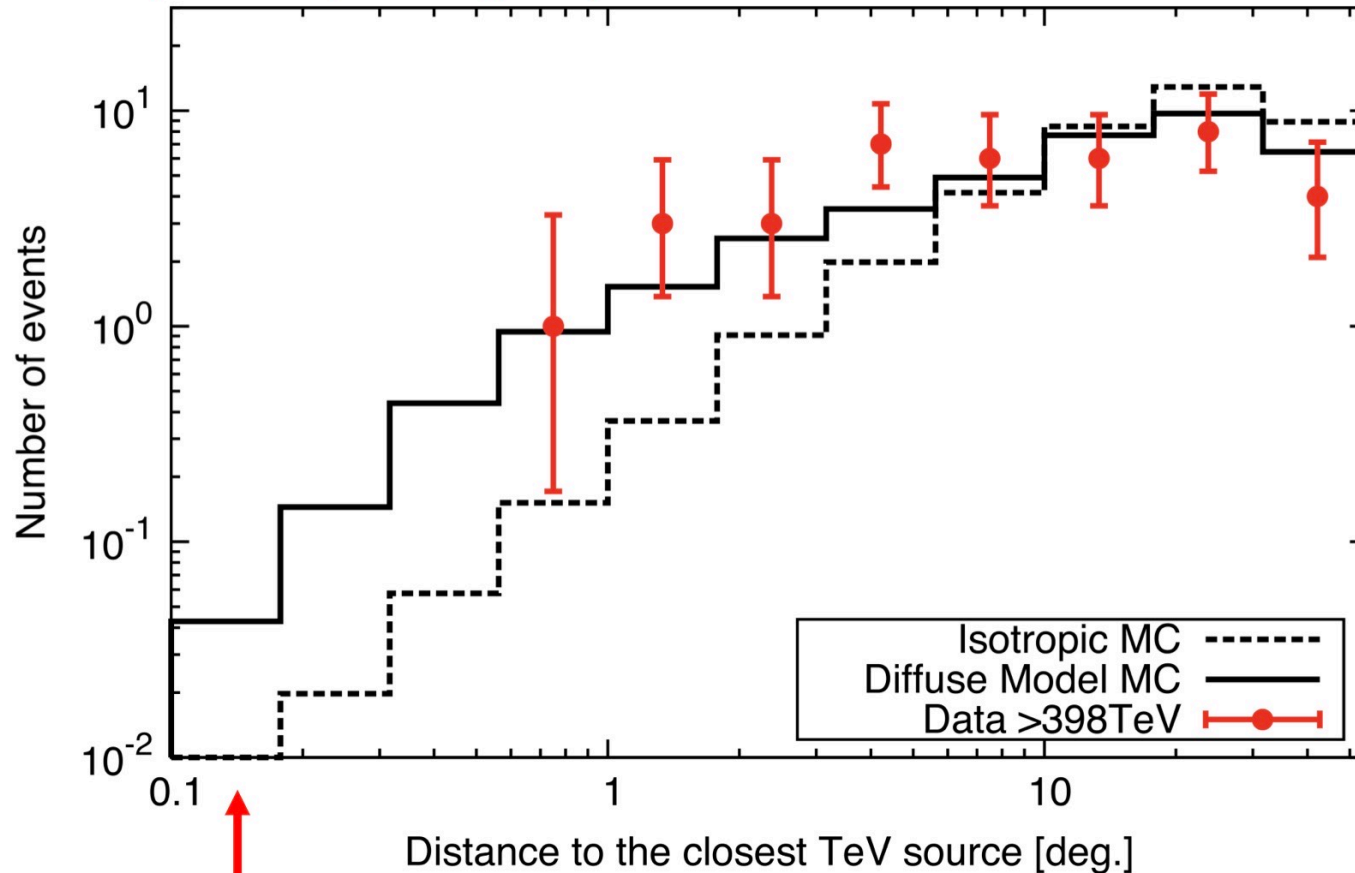






## Distribution of distance to the closest TeV source (deg) for events $> 0.398$ PeV

*Amenomori+., PRL 126, 141101, (2021)*



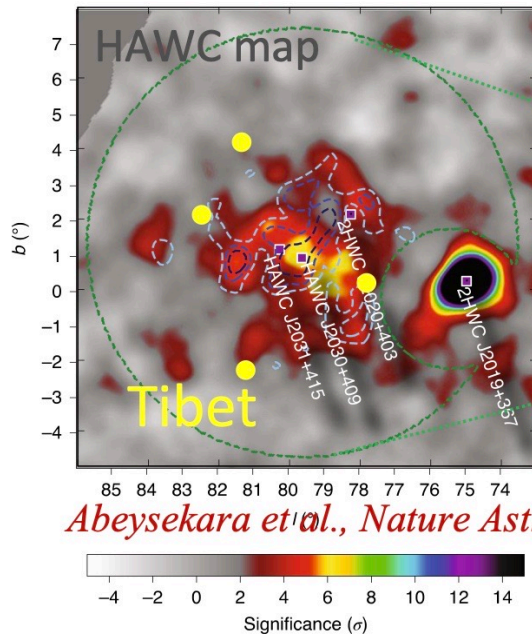
Surprisingly, no peak around 0  $\rightarrow$  no correlation with known TeV sources!

*Diffuse Model: Lipari & Vernetto, PRD 98, 143003, (2018)*

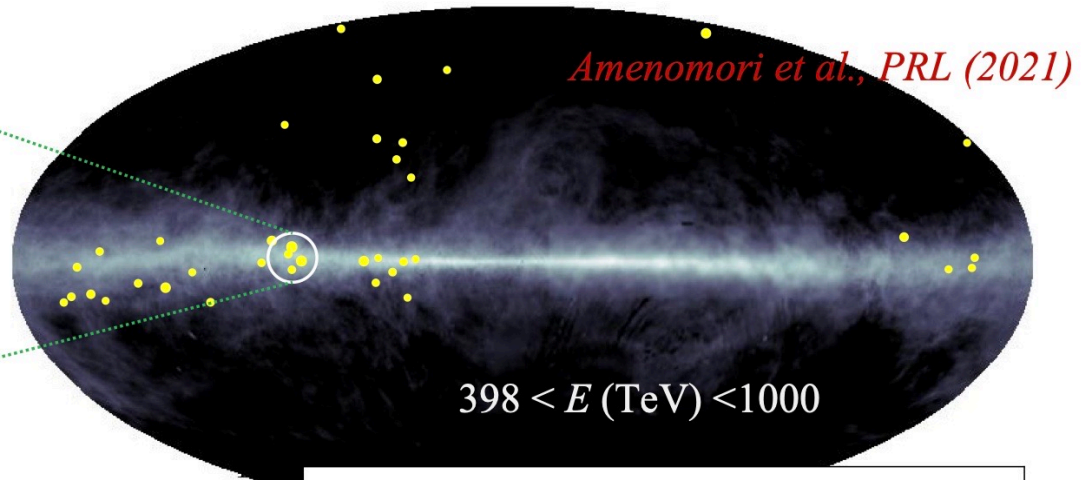


# Cygnus Cocoon Region

We found 4 events in the circle with radius  $4^\circ$

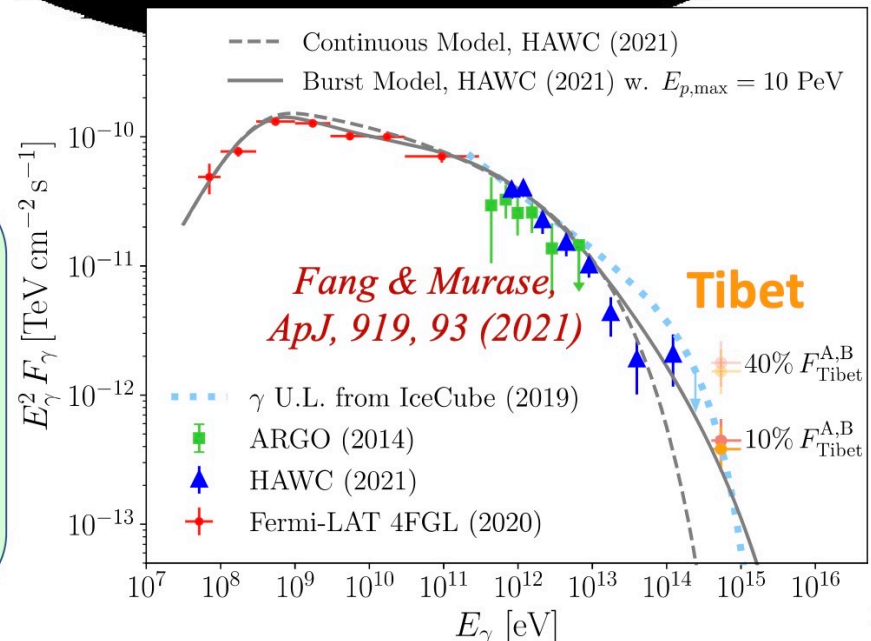


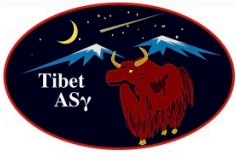
*Abeysekara et al., Nature Astronomy (2021)*



*Amenomori et al., PRL (2021)*

- ✓ Star forming region (Cyg. OB2)
- ✓  $\pi^0$  decay model ( $\pi^0$  shoulder)
- ✓ Spectral softening  $> 10$  TeV  
→ CRs escape from the source a long time ago?
- ✓ Spectrum extends up to PeV?





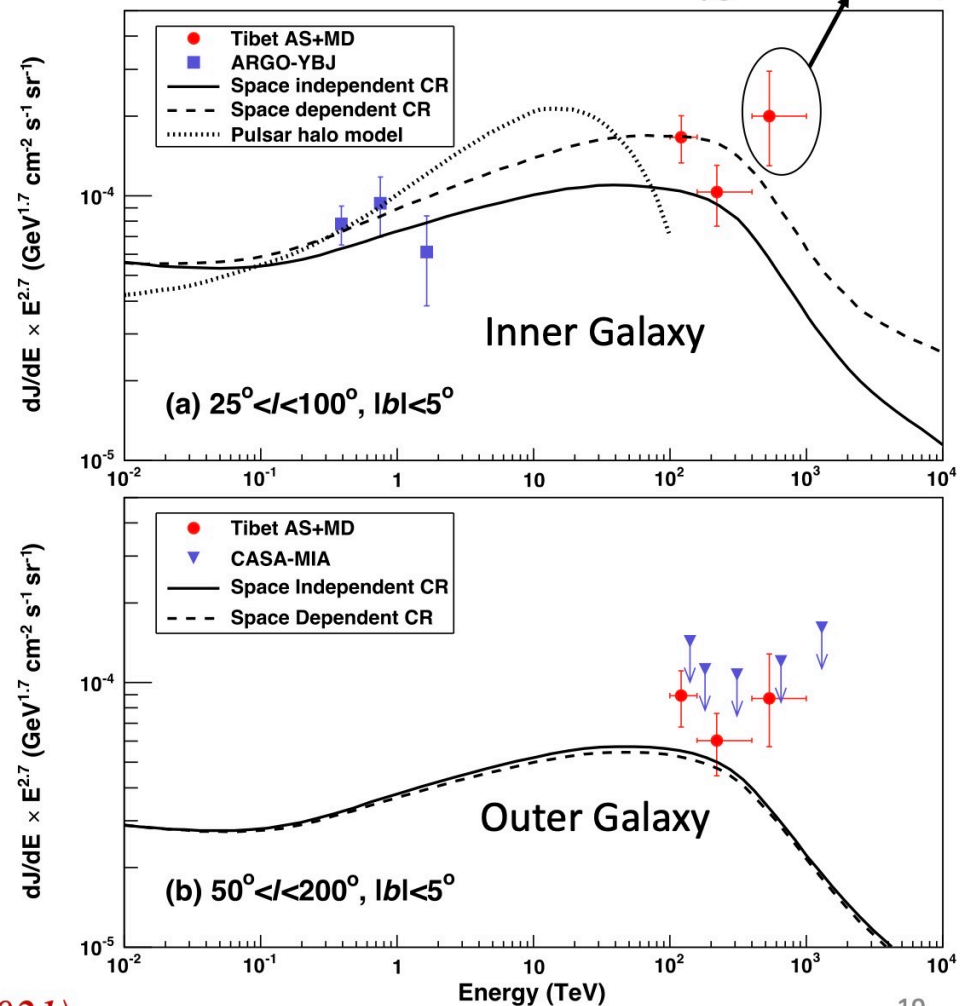
# Energy Spectrum (Fig.4)

After excluding the contribution from the known TeV sources (within  $0.5^\circ$  in radius) listed in the TeV source catalog ( $\sim 13\%$  to the diffuse flux, but no contamination to events  $> 0.398$  PeV)

The measured fluxes are reasonably consistent with Lipari's galactic diffuse gamma-ray model assuming the hadronic cosmic-ray origin.

*Models: Lipari & Vernetto, PRD 98, 143003, (2018)*

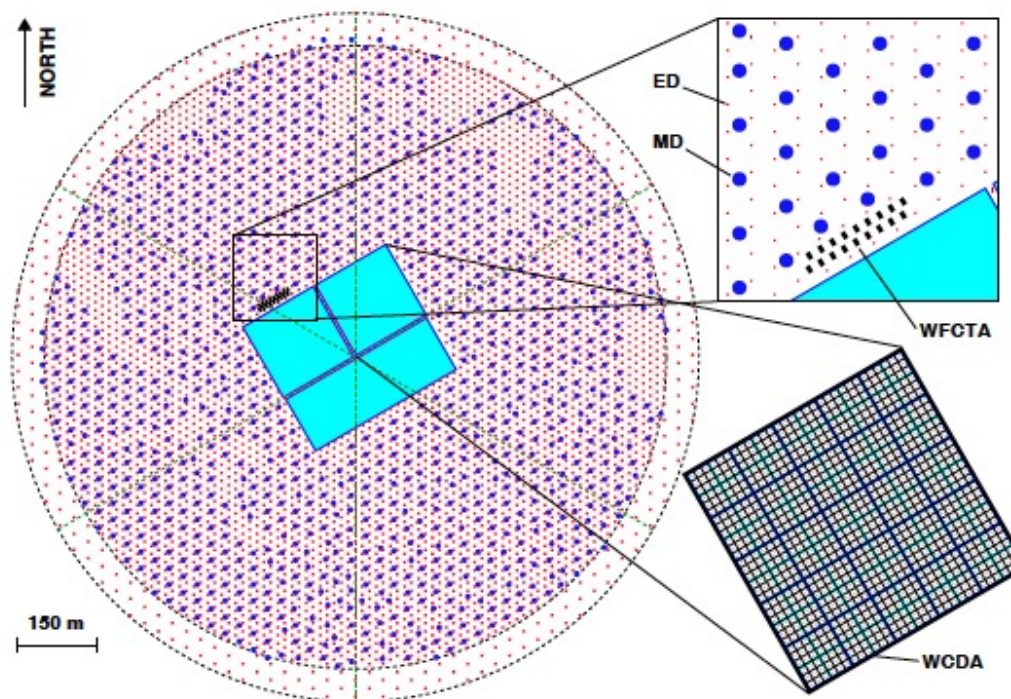
4 ev / 10 ev from  
Cygnus cocoon ( $< 4^\circ$ )



*Amenomori+., PRL 126, 141101, (2021)*

# The LHAASO experiment

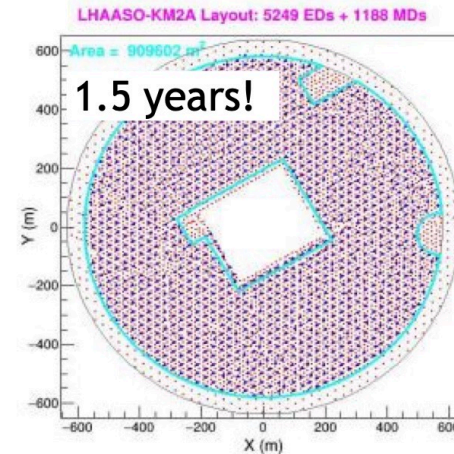
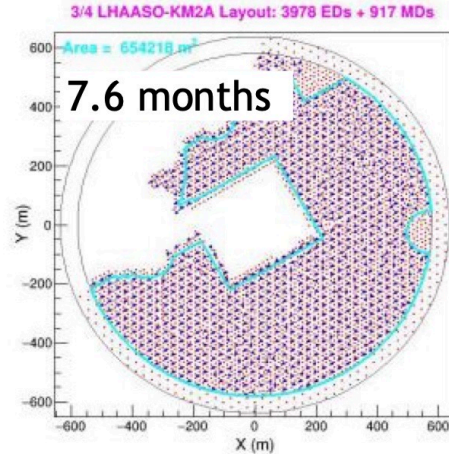
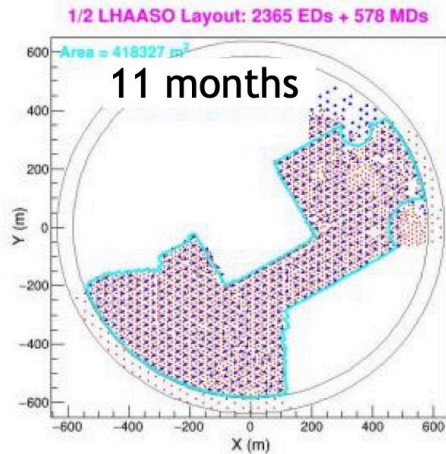
- 1 km<sup>2</sup> array, including 4941 scintillator detectors 1 m<sup>2</sup> each, with 15 m spacing.
- An overlapping 1 km<sup>2</sup> array of 1146, underground water Cherenkov tanks 36 m<sup>2</sup> each, with 30 m spacing, for muon detection (total sensitive area  $\approx$  42,000 m<sup>2</sup>).



- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m<sup>2</sup>.
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.



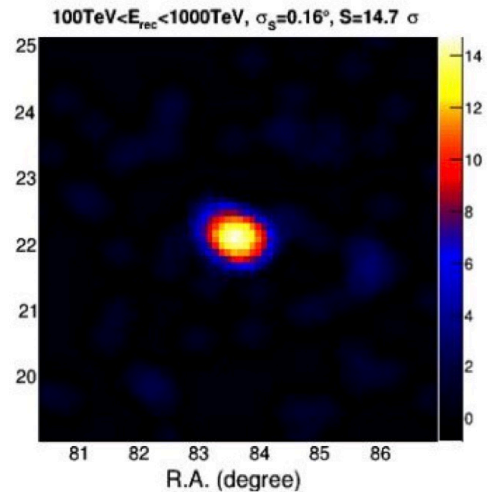
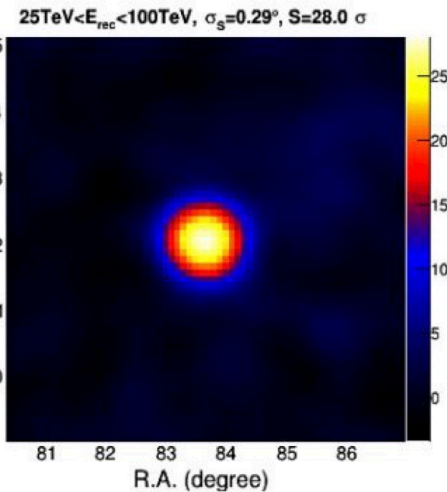
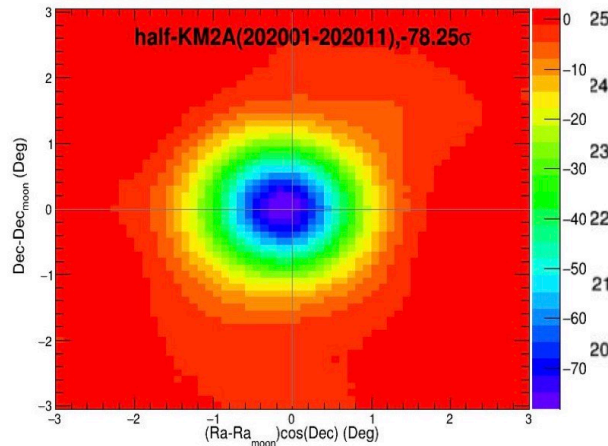
# LHAASO detector - KM2A



1/2: 20191217->20201130

3/4: 20201201->20210719

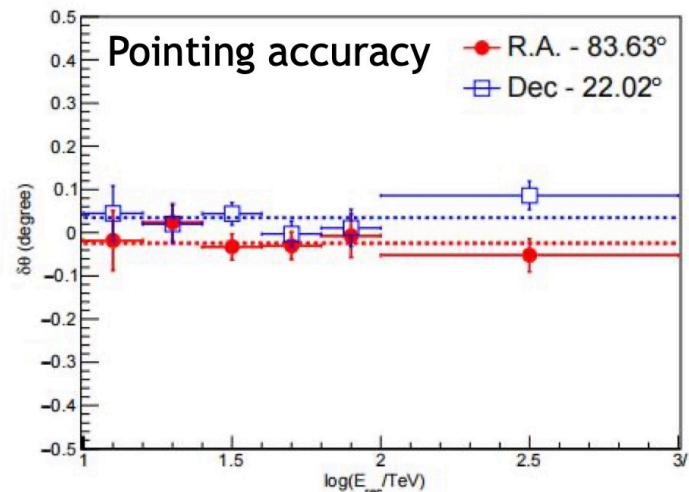
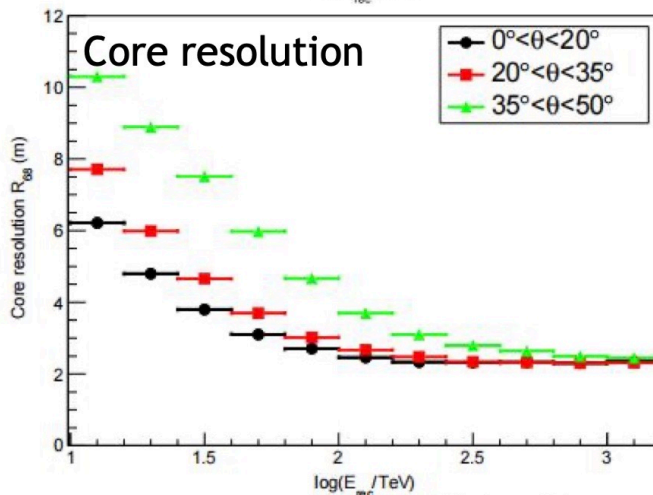
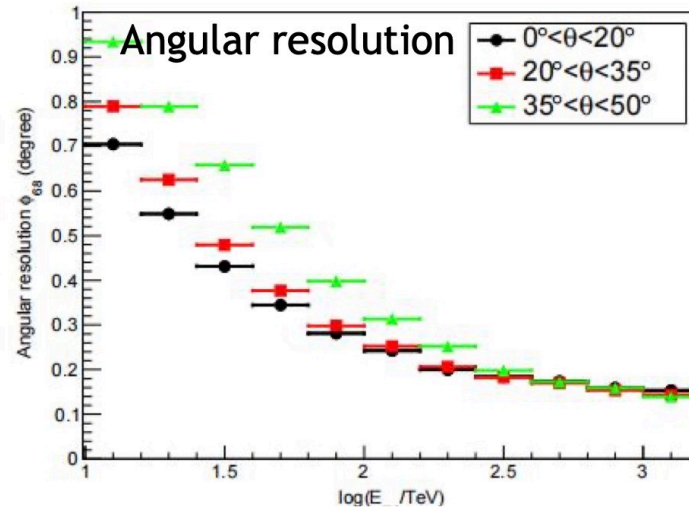
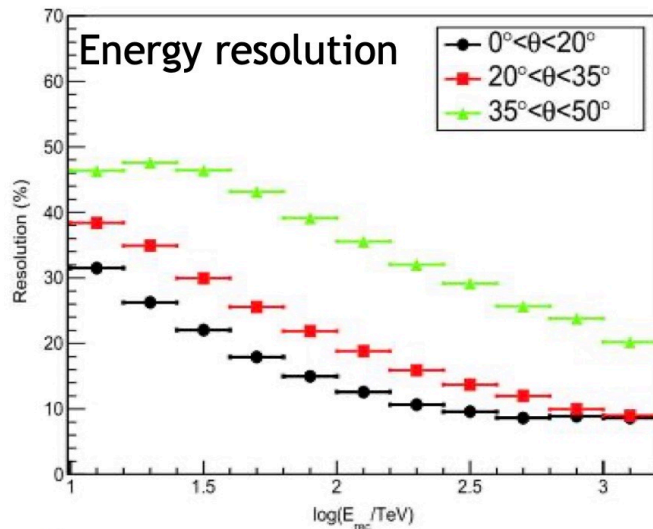
Full: 20210720->



Chin. Phys. C, 45, 025002 (2021) 11



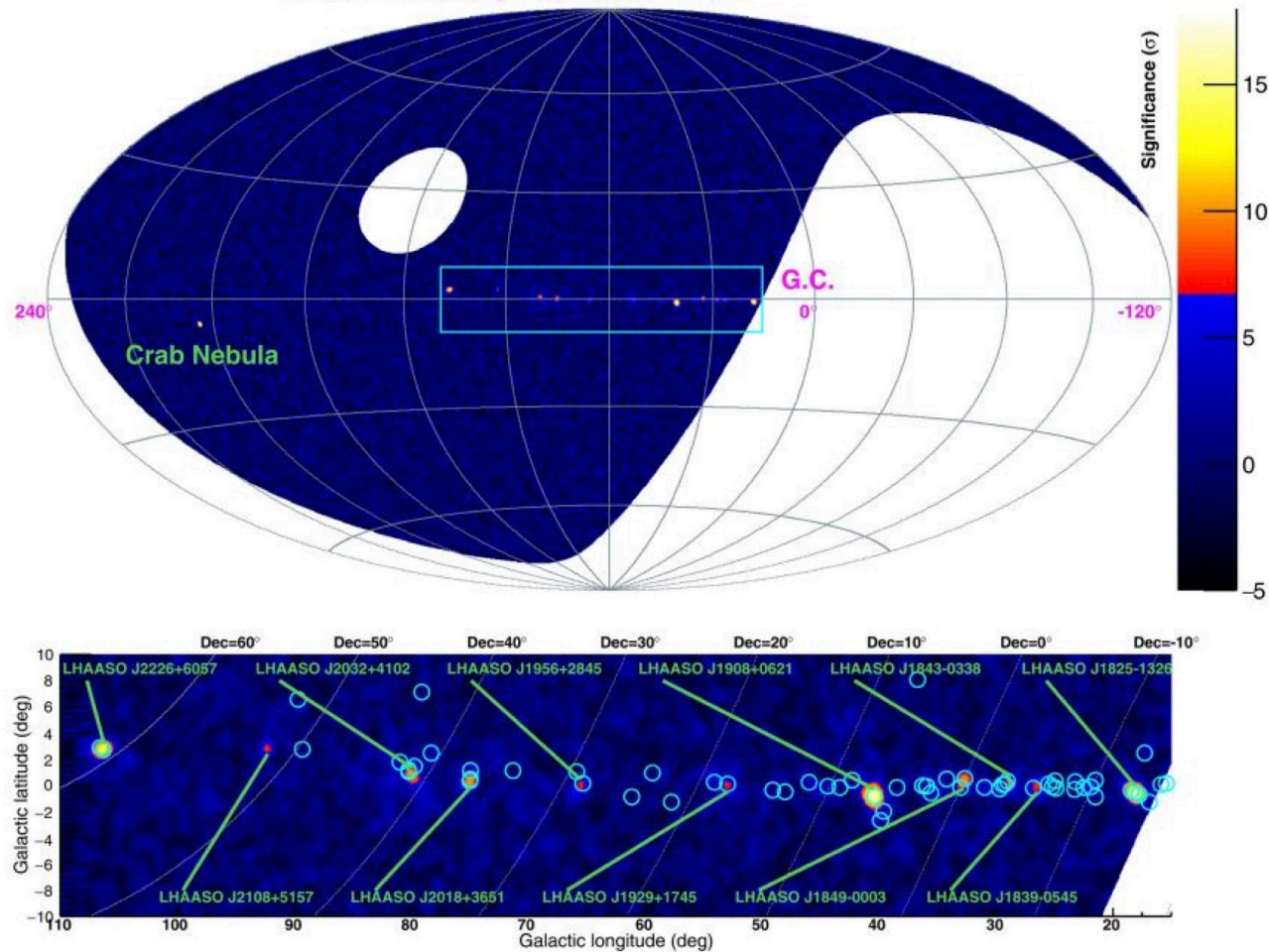
# LHAASO detector - KM2A



# Survey of the UHE sky with 1/2 array

LHAASO Sky @ >100 TeV

Nature, 594, 33 (2021)

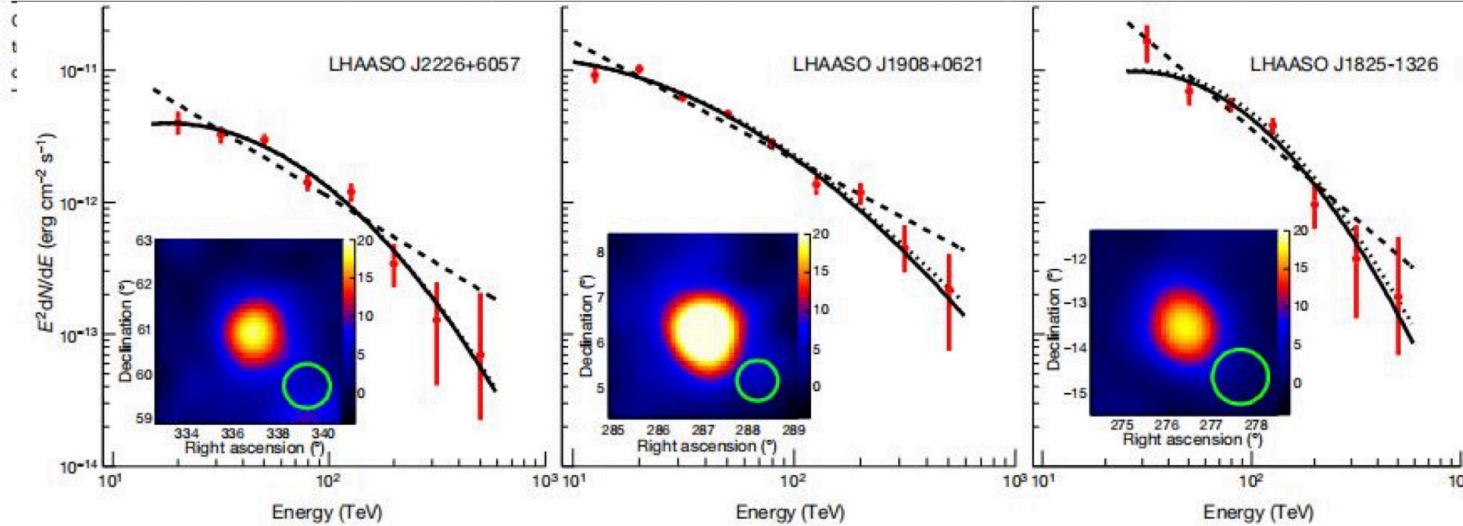


# Survey of the UHE sky with 1/2 array

Table 1 | UHE  $\gamma$ -ray sources

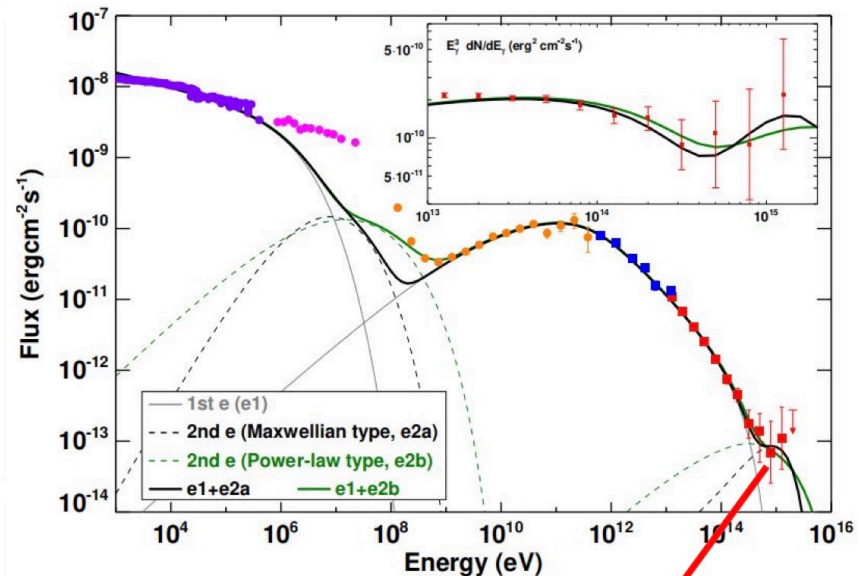
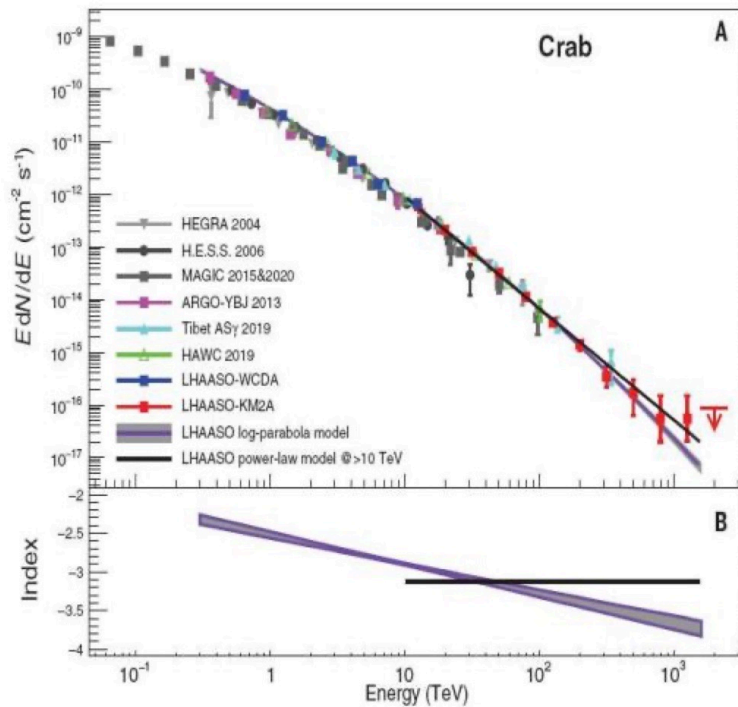
Nature, 594, 33 (2021)

Source name	RA (°)	dec. (°)	Significance above 100 TeV ( $\times\sigma$ )	$E_{\max}$ (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	$0.88 \pm 0.11$	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	$0.42 \pm 0.16$	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	$0.21 \pm 0.05$	0.70(0.18)
LHAASO J1843-0338	280.75	-3.65	8.5	$0.26 - 0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	-0.05	10.4	$0.35 \pm 0.07$	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	$0.44 \pm 0.05$	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 - 0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	$0.42 \pm 0.03$	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	$0.27 \pm 0.02$	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	$1.42 \pm 0.13$	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	$0.43 \pm 0.05$	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	$0.57 \pm 0.19$	1.05(0.16)





# Crab nebula: Electron PeVatron

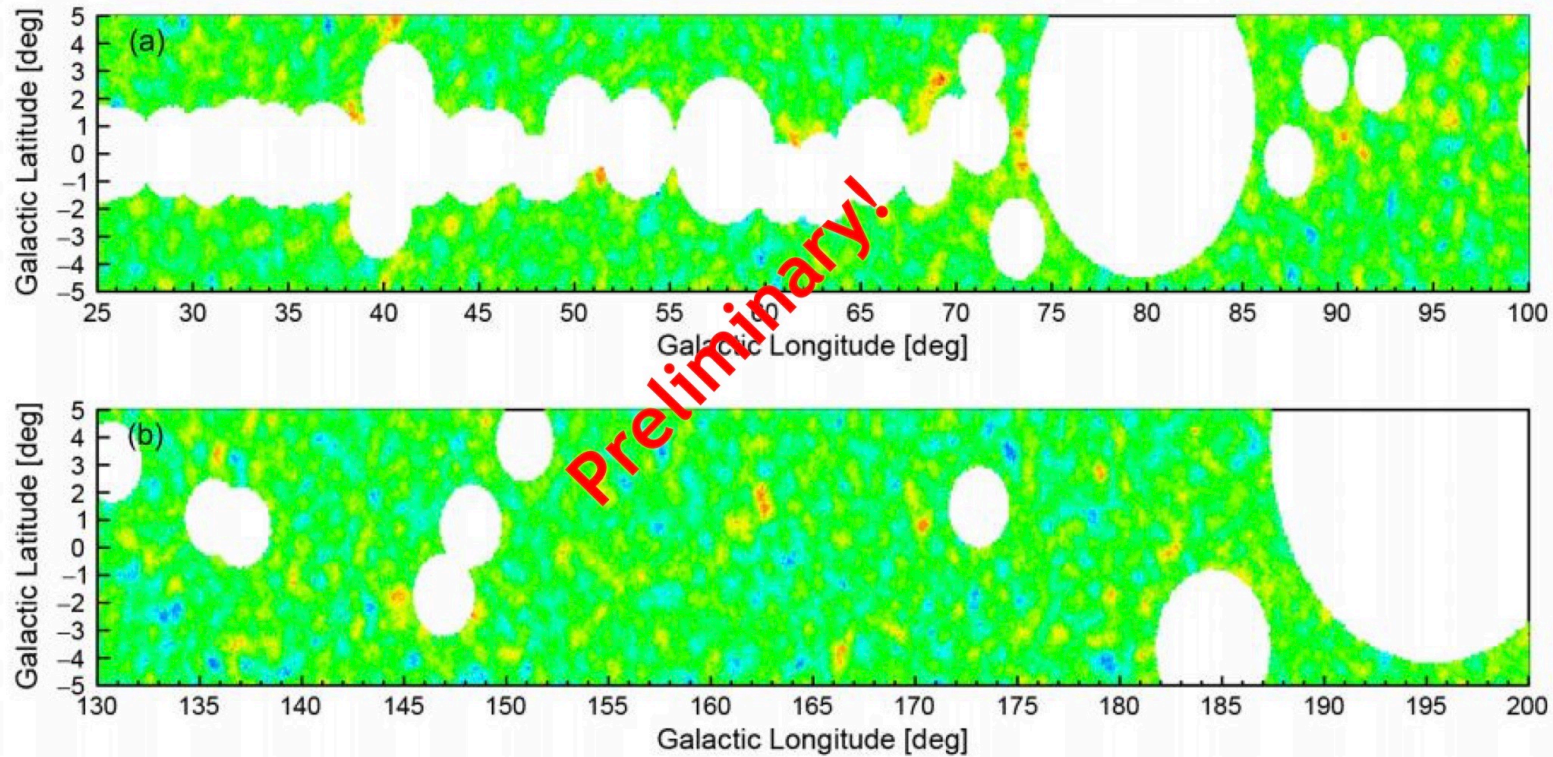


Possible new feature?

Science, 373, 425 (2021)



# Diffuse gamma rays from Galactic plane



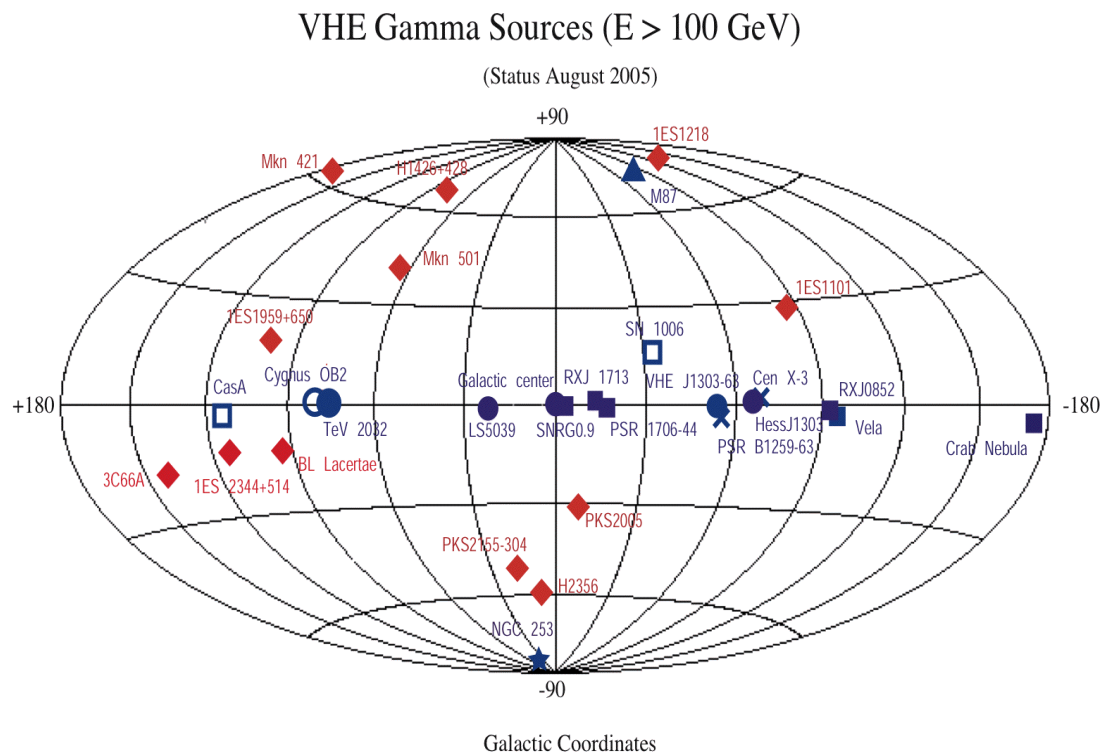
# Summary detection

- Fermi LAT made breakthrough in study of gamma-ray sky at 100 MeV-100 GeV energies.
- Cherenkov telescopes with sensitivity in range 100 GeV-20 TeV develop in generations. Last generation HESS /MAGIC /VERITAS was build around 2005-2010, next CTA will be in 2025.
- Water Cherenkov Detectors with was not very good in 10-100 TeV energy domain, new generation LHAASO just built compete in 10-100 TeV energy domain with Cherenkov telescopes.
- Tibet and HAWC was first to detect  $E > 100$  TeV sources. Tibet first detected diffuse gamma-ray background at  $E > 100$  TeV.
- LHAASO just constructed. It will discover many galactic sources in 100 TeV domain and study details of diffuse background in different parts of Galaxy

# Gamma-ray sky

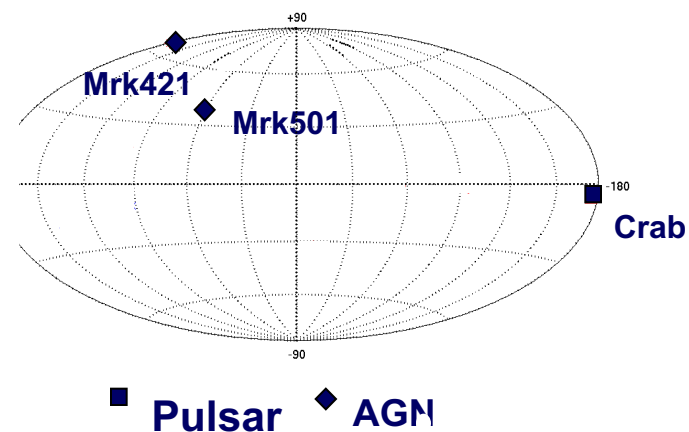
# The VHE $\gamma$ ray sky

2005



- = Pulsar/Plerion      □ = SNR      ★ = Starburst galaxy      ○ = OB association
- ◆ = AGN (BL Lac)      ▲ = Radio galaxy      ✕ = XRB      ● = Undetermined

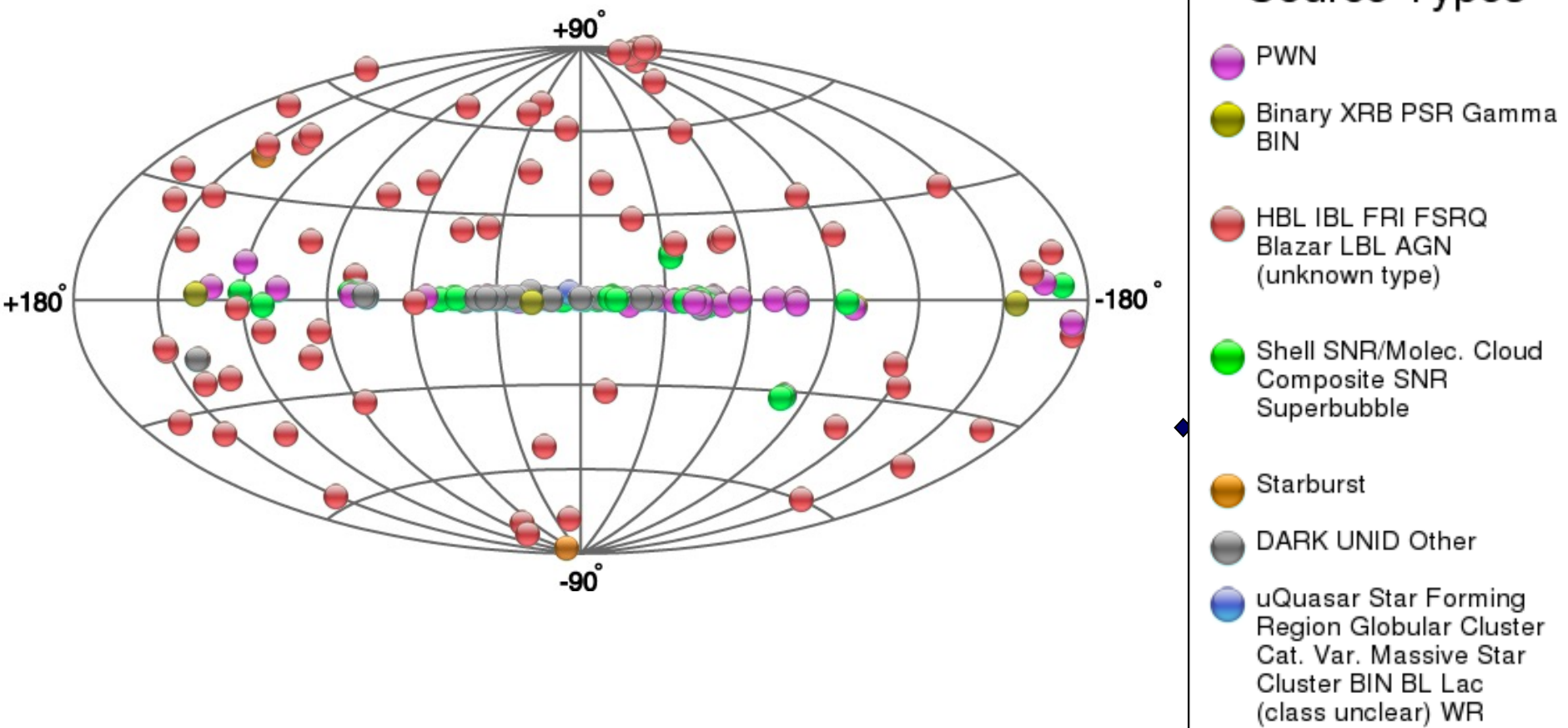
1995





# The VHE $\gamma$ ray sky Dec 2015

176 sources



# Source Counts

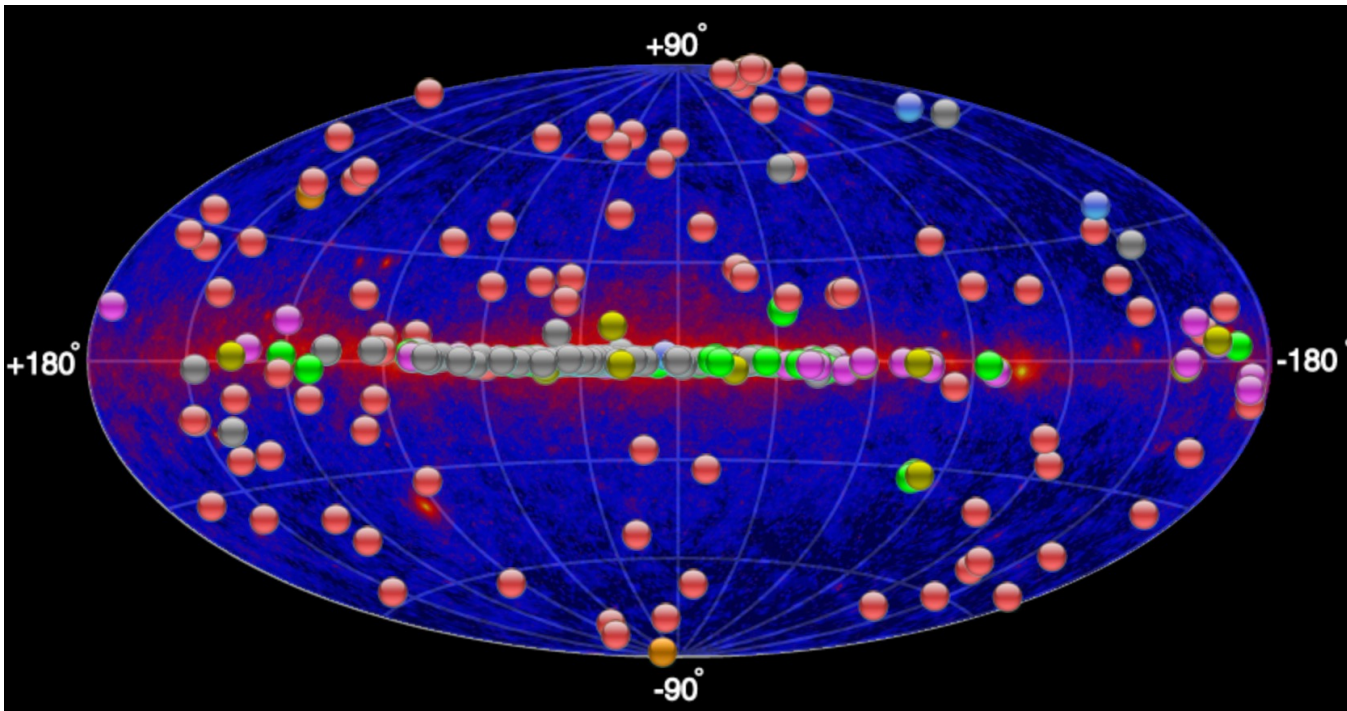
Source Type*	1995	2005	2015
Pulsar Wind Nebula (e.g. Crab, MSH 15-52 ...)	1	5	37
Supernova Remnants (e.g. Cas-A, RXJ 1713 ...)	0	4	15
Binary systems (B1259-63 etc)	0	1	6
X-ray binary	0		4
Galactic Center	0	0	1
		1	
Superbubble	0	1	2
Star clusters	0	0	4
Molecular clouds	0	0	2
BL LACs (e.g. Mkn 421, PKS 2155 ...)	2	9	55
FSRQ	0	0	5
AGNs (M87, Cen A)	0	1	4

# The VHE $\gamma$ ray sky Feb 2023

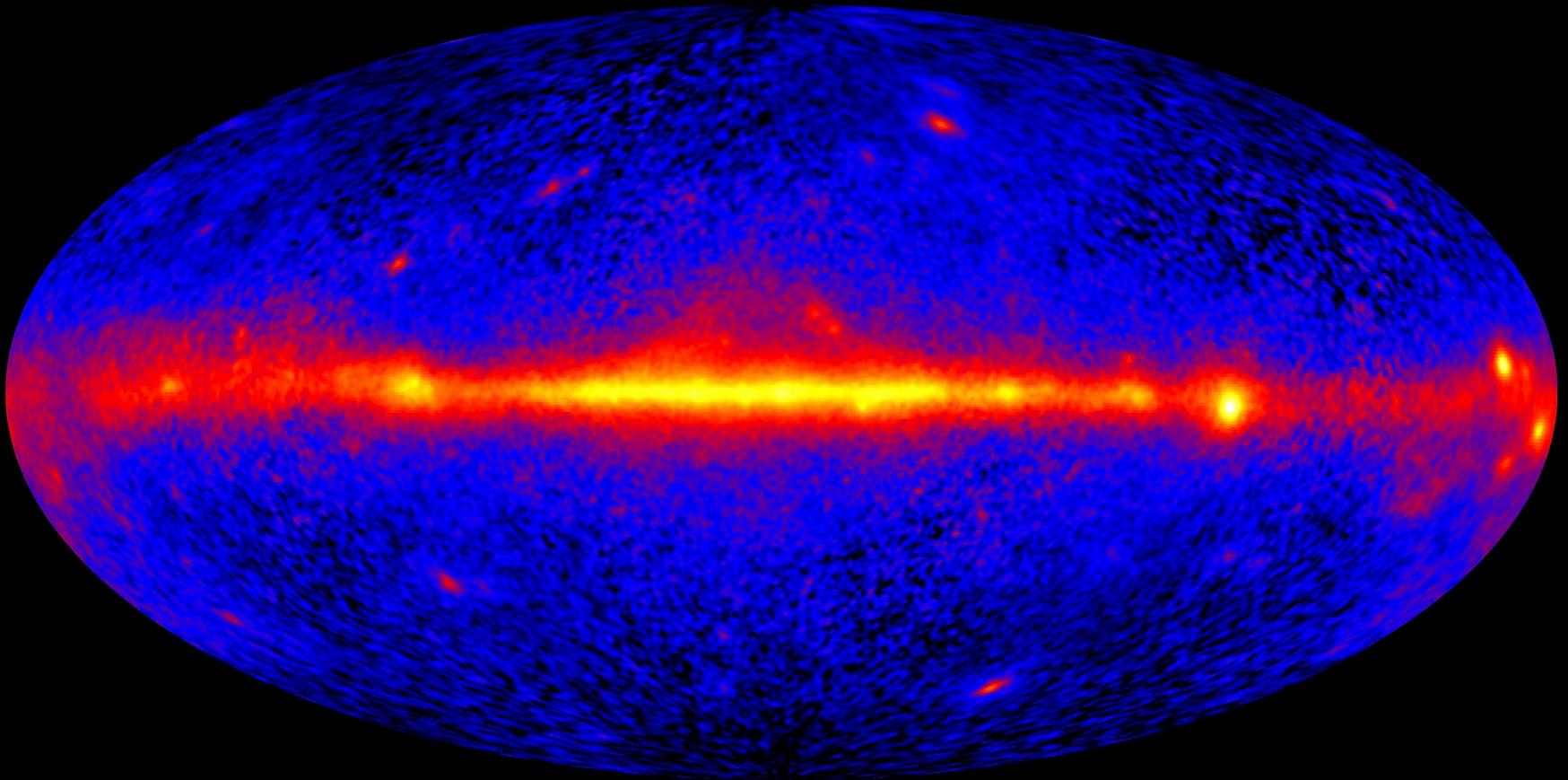
252 sources

## Source Types

- PWN TeV Halo  
PWN/TeV Halo
- XRB Nova Gamma BIN  
Binary PSR
- HBL IBL GRB FSRQ LBL  
AGN (unknown type) FRI  
Blazar
- Shell Giant Molecular  
Cloud SNR/Molec. Cloud  
Composite SNR  
Superbubble SNR
- Starburst
- DARK UNID Other
- Star Forming Region  
Globular Cluster Massive  
Star Cluster BIN  
uQuasar Cat. Var. BL  
Lac (class unclear) WR

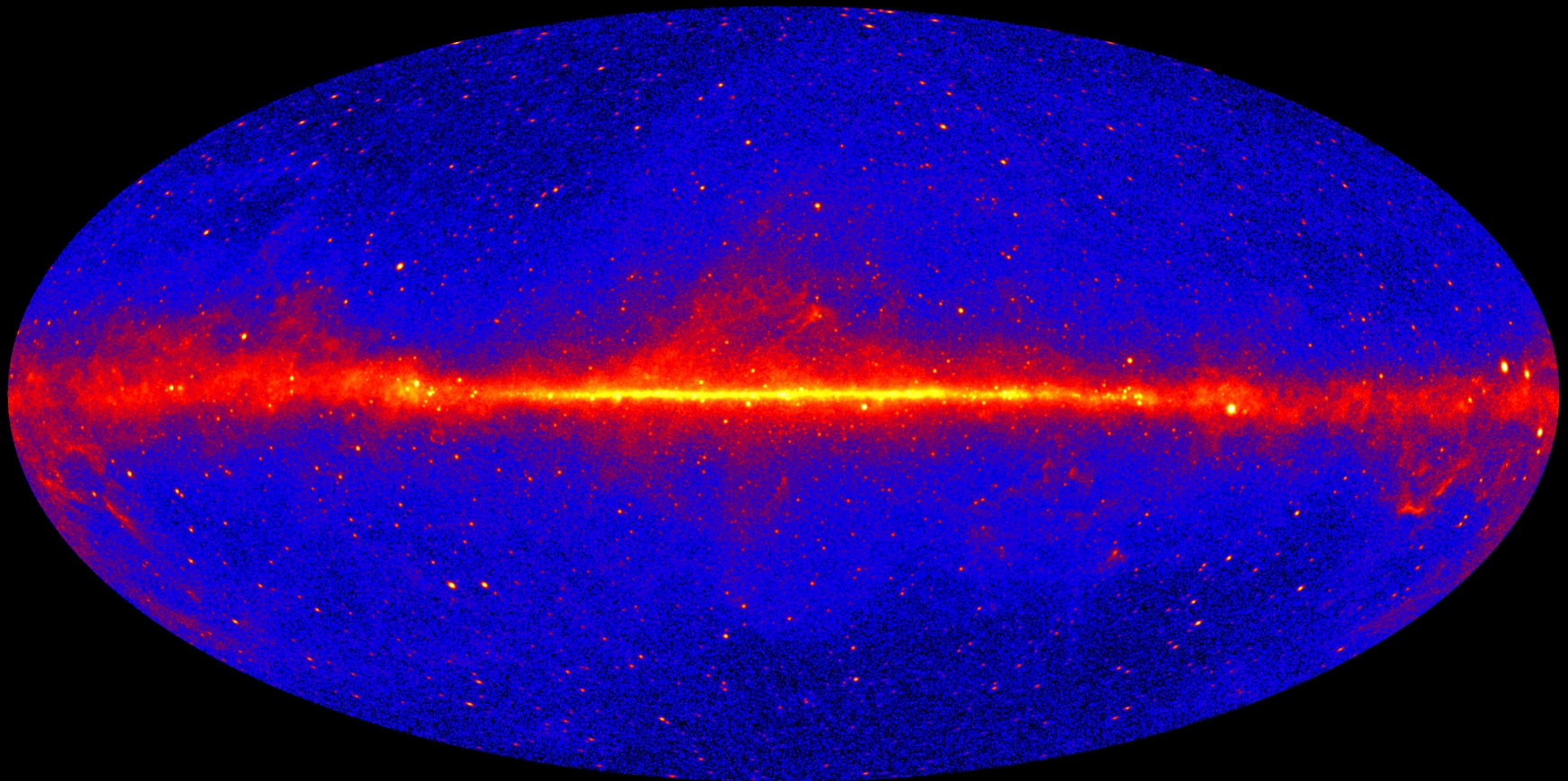


EGRET 9 years 1991 to 2000  
all sky 1 GeV. 271 source

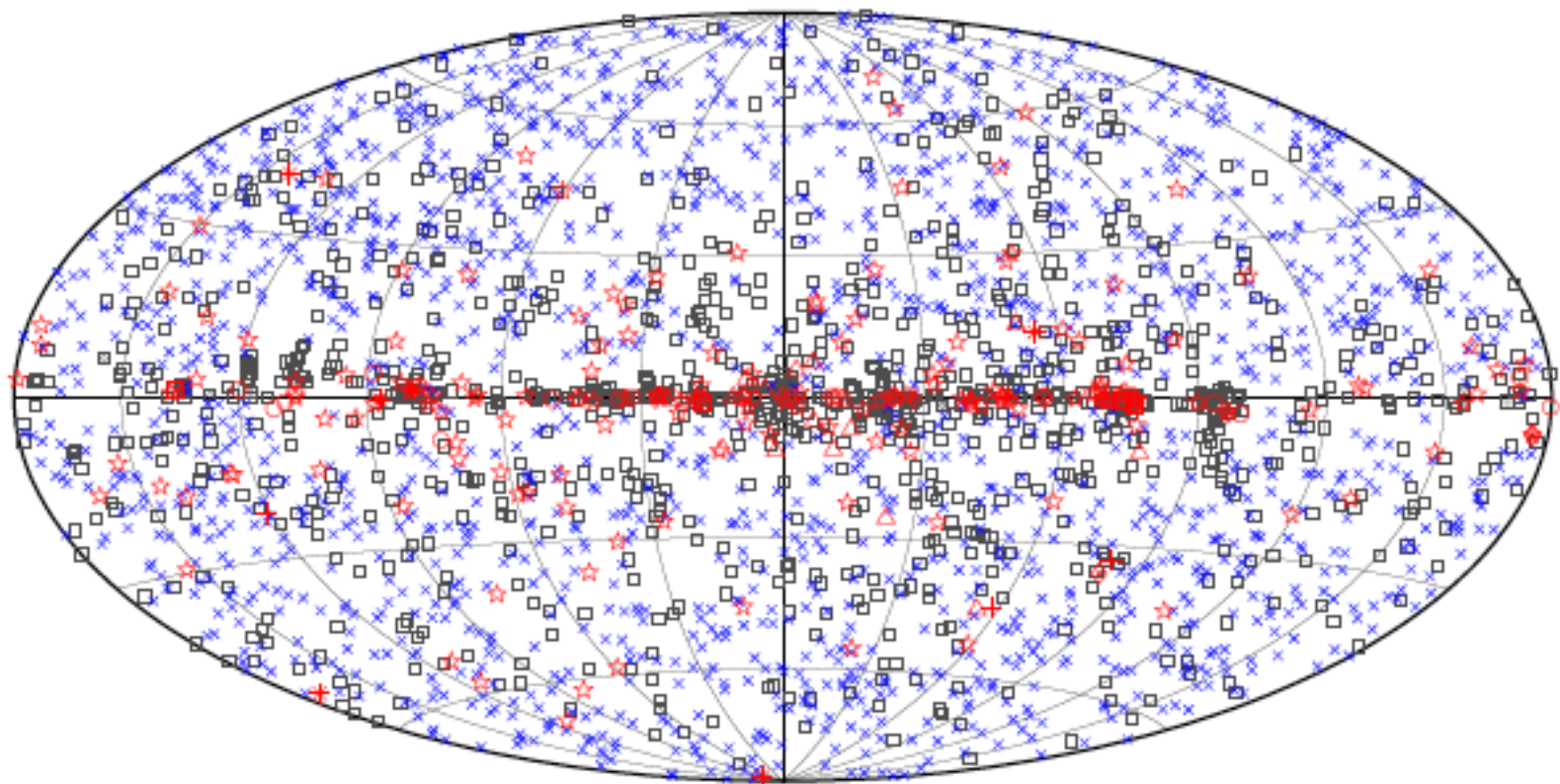




# Fermi LAT 9 years 2008 to 2017 all sky 1GeV. 5000 sources



# Fermi LAT source 4th catalog: 5000 sources

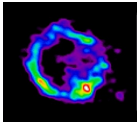


- |                       |  |        |
|-----------------------|--|--------|
| □ No association      | □ Possible association with SNR or PWN | × AGN  |
| ☆ Pulsar              | △ Globular cluster                     | ◇ PWN  |
| □ Binary              | + Galaxy                               | + Nova |
| • Star-forming region | ○ SNR                                  |        |

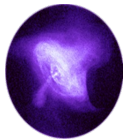
# Overview of TeV gamma-ray Science

## I. Astronomy and Astrophysics

### A. Galactic sources



- Shell-type Supernova Remnants

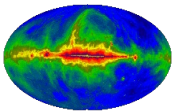


- Pulsar wind nebula

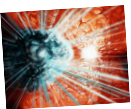
- Binary systems

- Microquasars

- Central black hole



- Galactic Diffuse Emission

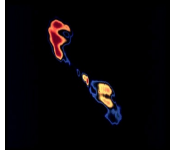


- Galactic Cosmic Ray Origin

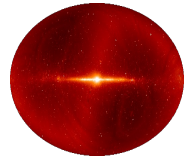
- Dark sources

# Overview of gamma-ray Science

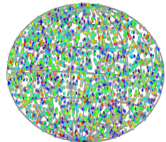
## B. Extra Galactic sources



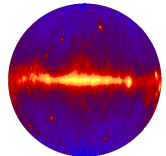
### Radio galaxies



- **Blazars**

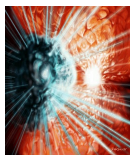


- **Extragalactic Background Light**



- **Gamma Ray Bursts**

- **Unidentified Sources**

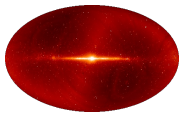


- **Ultra-High Energy Cosmic Ray Origin**

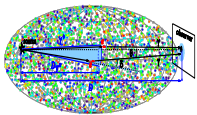


# Overview of gamma-ray Science

## Cosmology

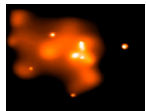


- **Extragalactic Background Light**
- **Primordial magnetic field**

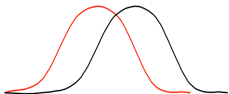


- **Distant Gamma Ray Bursts (GeV)**

## Particle physics



- **Dark Matter**



- **Lorentz symmetry violation**

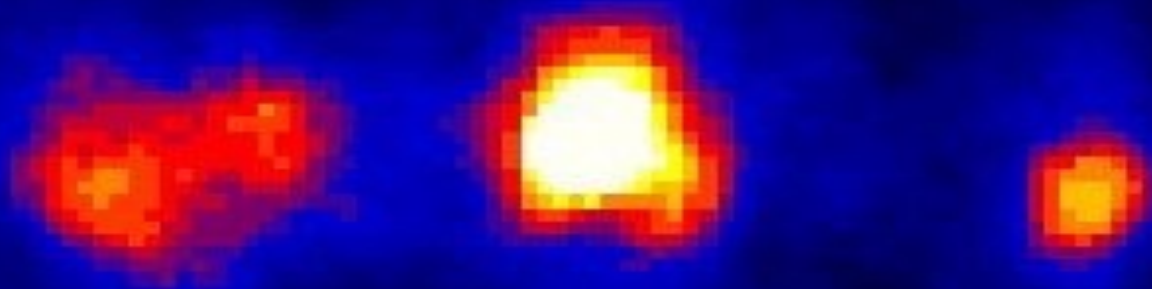
# Galactic sources below 100 TeV

# Galactic Plane Survey



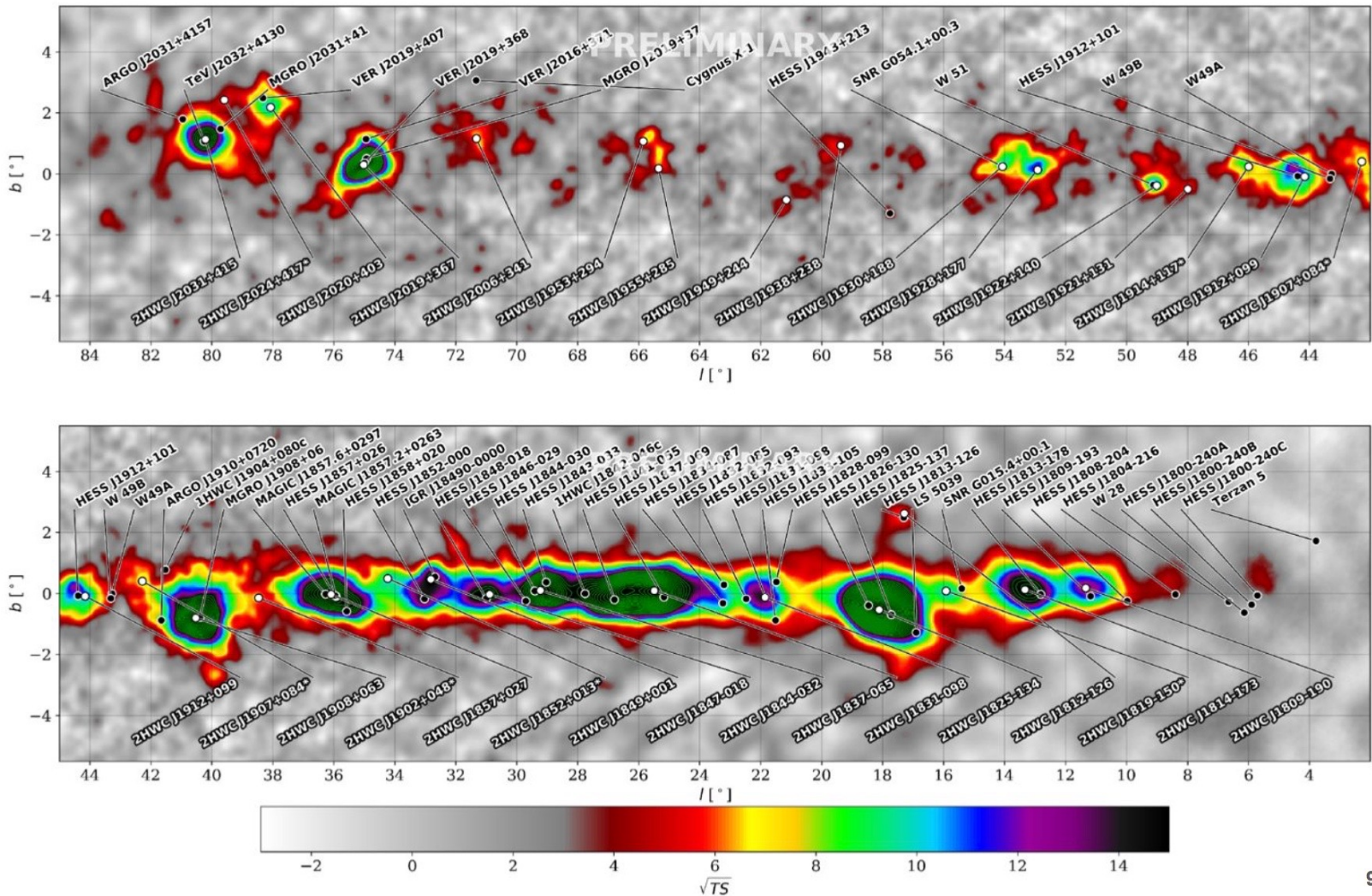
• we are here

# H.E.S.S. Galactic Plane Survey

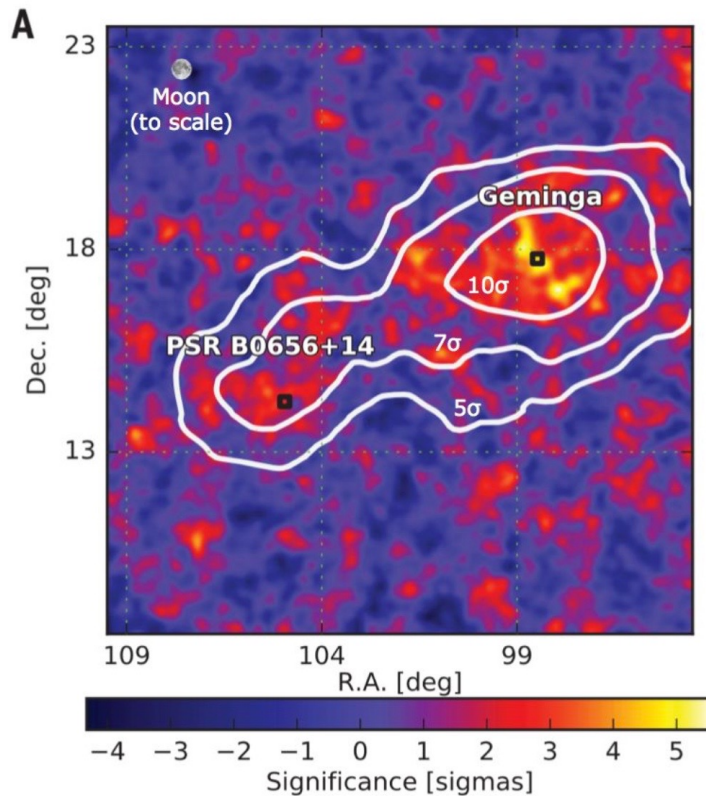




# HAWC inner Galaxy



# HAWC Geminaga SN



- HAWC observes extended emission from both the Geminga and Monogem (PSR B0656+14) pulsars
- These are both nearby, middle-aged pulsars that could be producing the observed local positrons

	Geminga	Monogem
$\dot{E}$ [erg/s]	$3.2 \times 10^{34}$	$3.8 \times 10^{34}$
Age [yr]	$3.42 \times 10^5$	$1.1 \times 10^5$
Dist. [pc]	250	288

Science 358 (2017) no.6365, 911-914

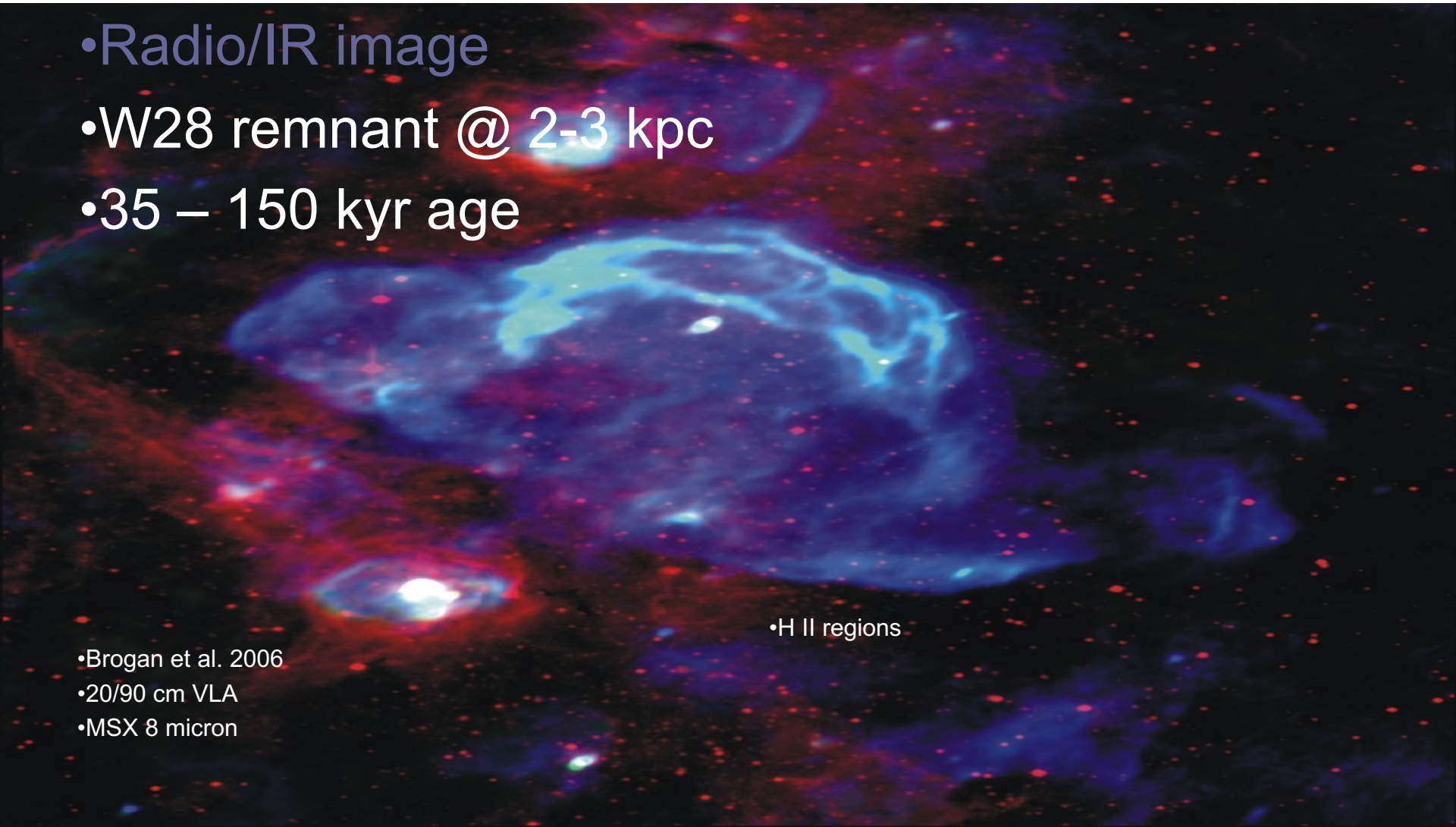


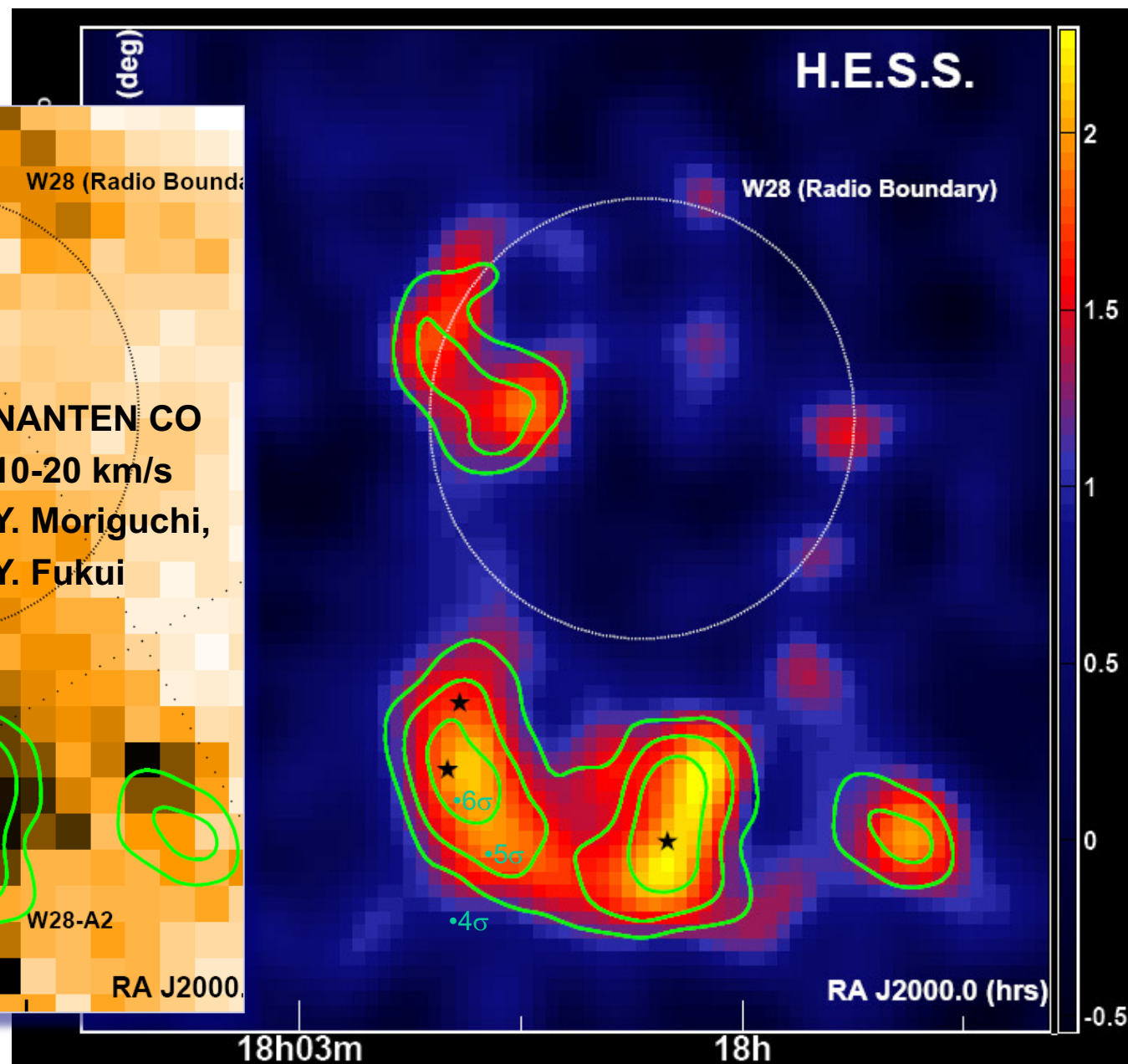
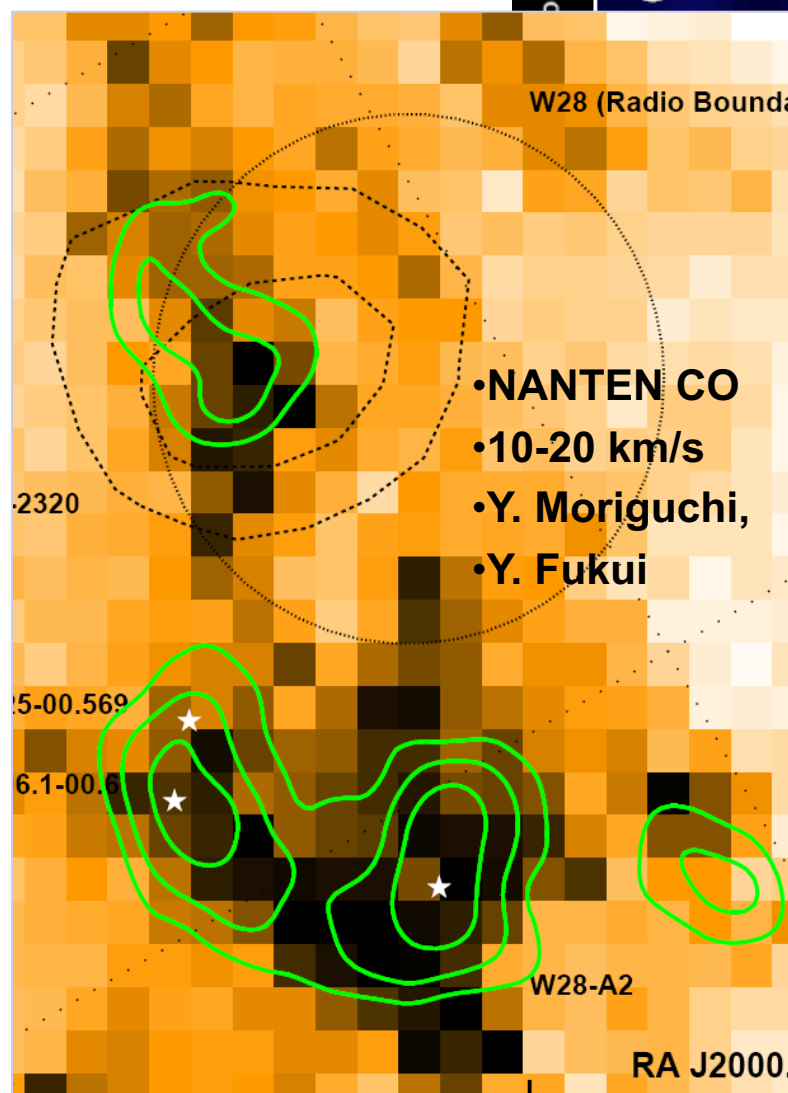
# Old SNRs & interacting SNRs

- Radio/IR image
- W28 remnant @ 2-3 kpc
- 35 – 150 kyr age

• H II regions

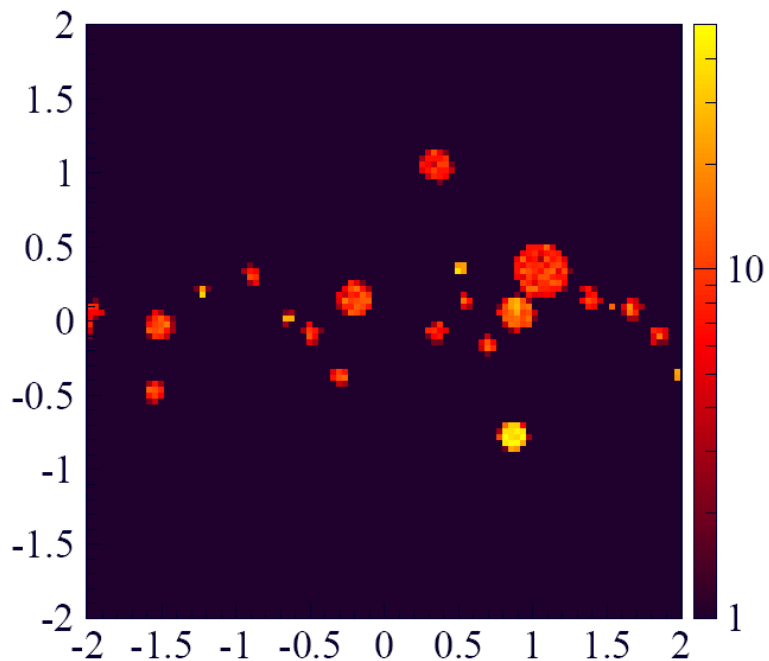
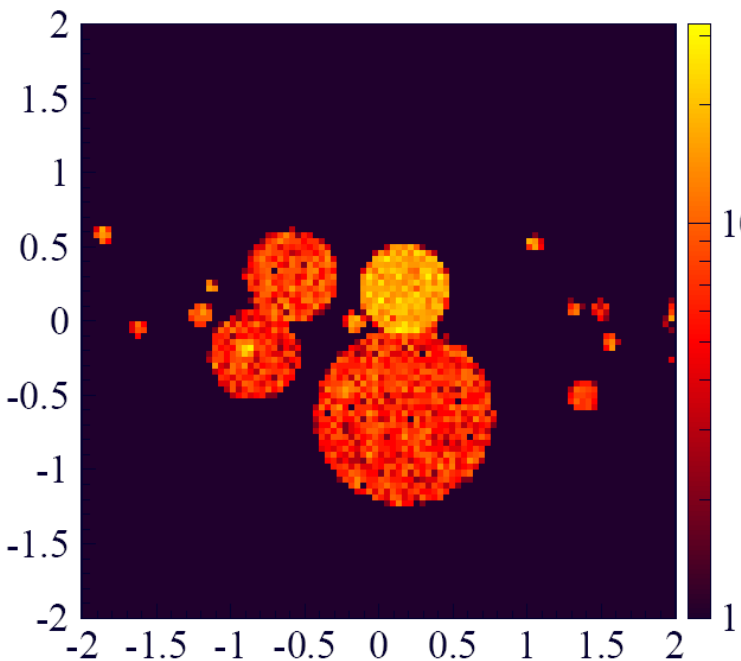
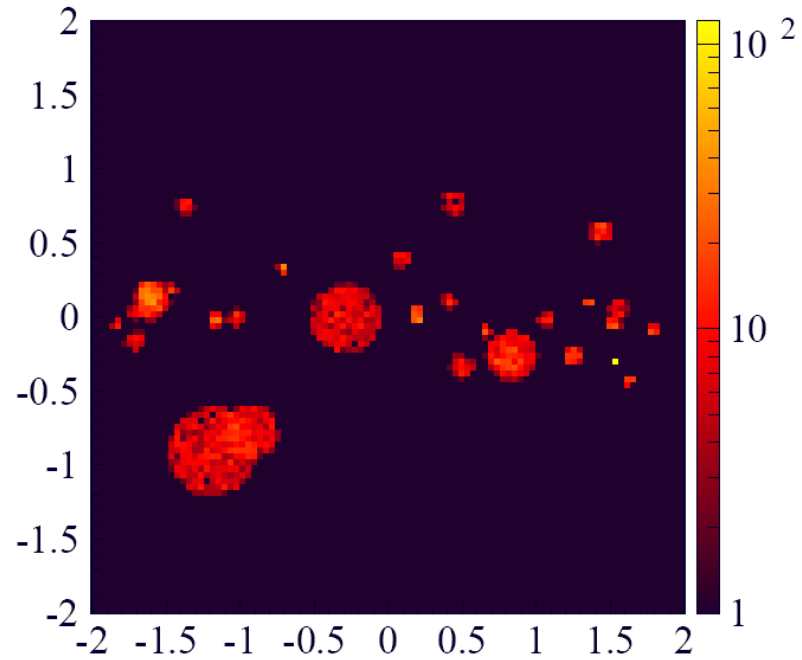
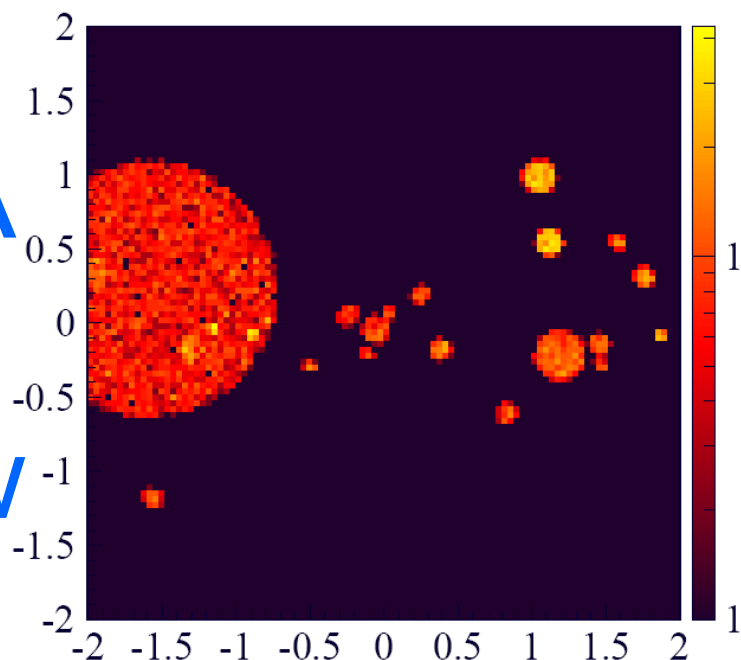
- Brogan et al. 2006
- 20/90 cm VLA
- MSX 8 micron







# A CTA field of view



- SNR models
- using DAV 9
- $n = 1$
- $\epsilon = 0.1$

- (consistent
- with HESS
- plane scan)

- assuming
- 1 mCrab

# •N44 Superbubble in LMC

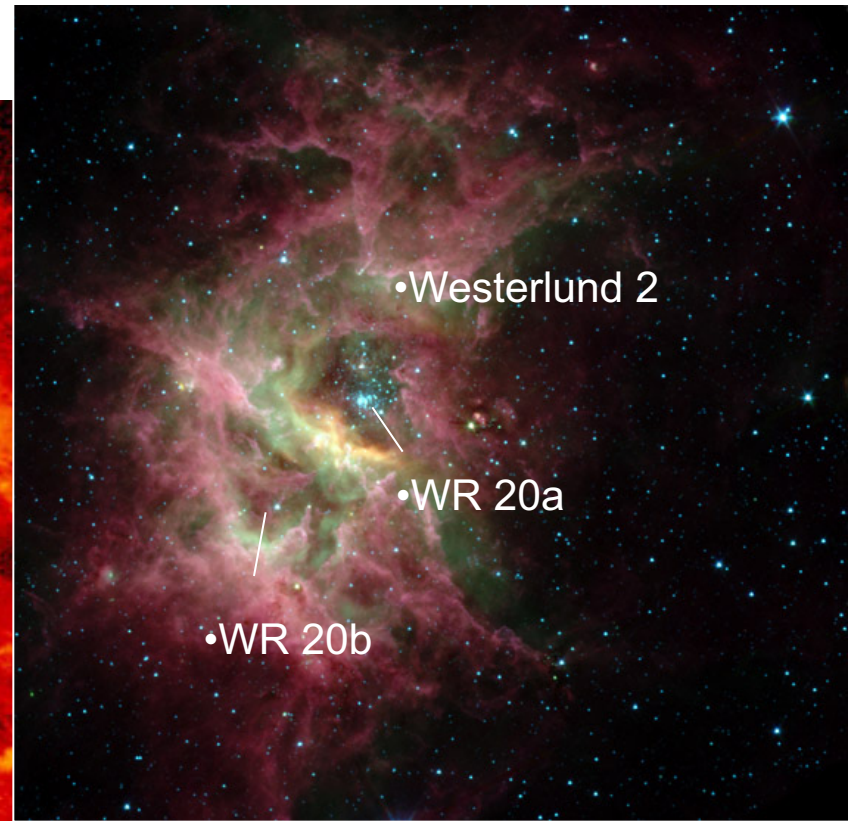
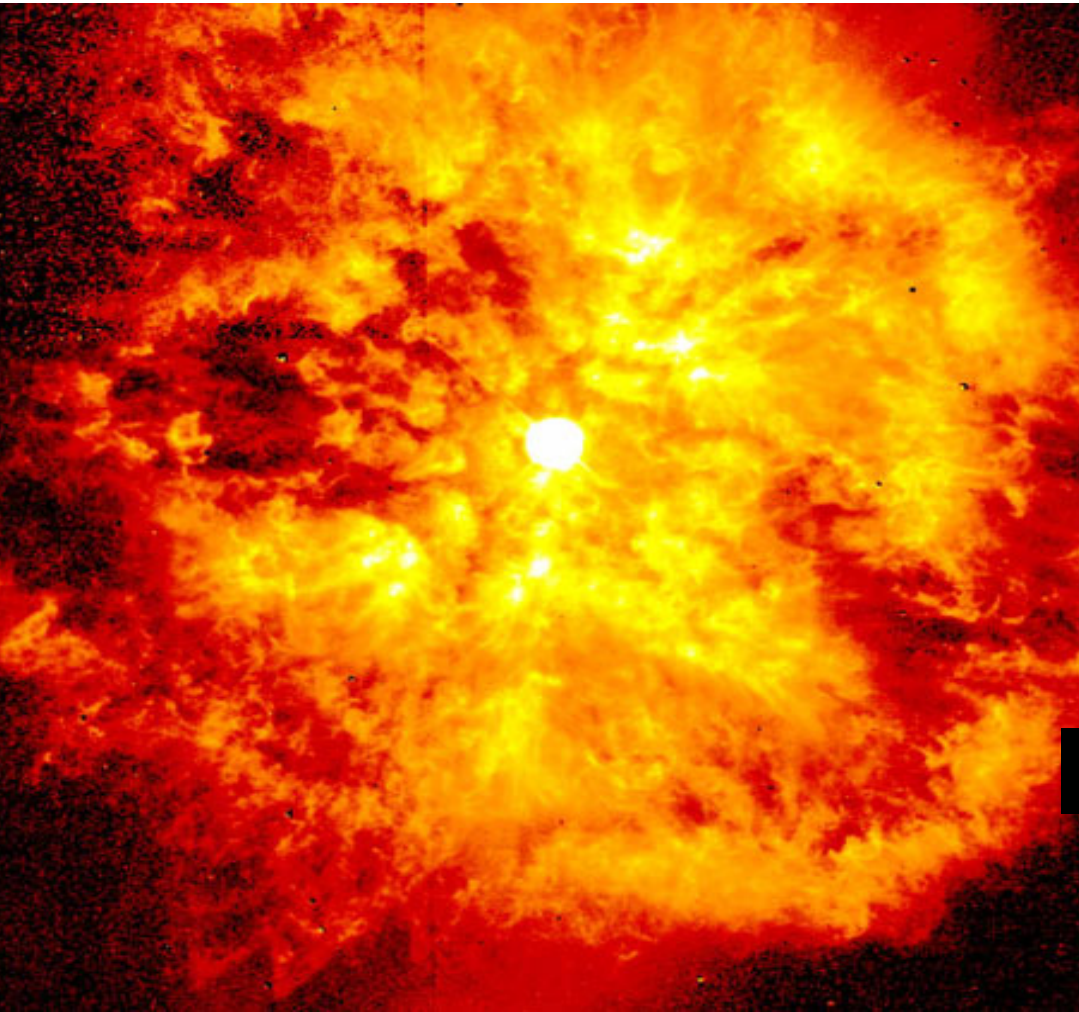
•Gemini Obs., AURA, NSF

•No. of SNR detectable in (proton-induced)  $\gamma$ -rays

Max. Age	<b>3 kyr</b>	<b>30 kyr</b>
Density		
<b><math>n = 0.1/\text{cm}^3</math></b>	5	6
<b><math>n = 1/\text{cm}^3</math></b>	37	<b>370</b>



# RCW 49: Stellar Winds as Cosmic Accelerators



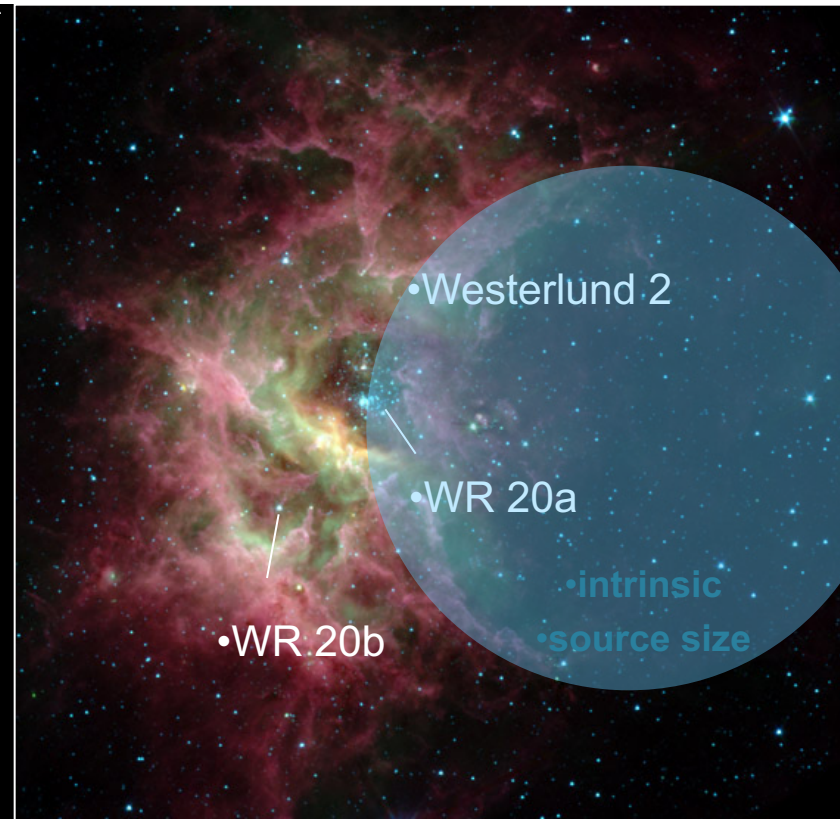
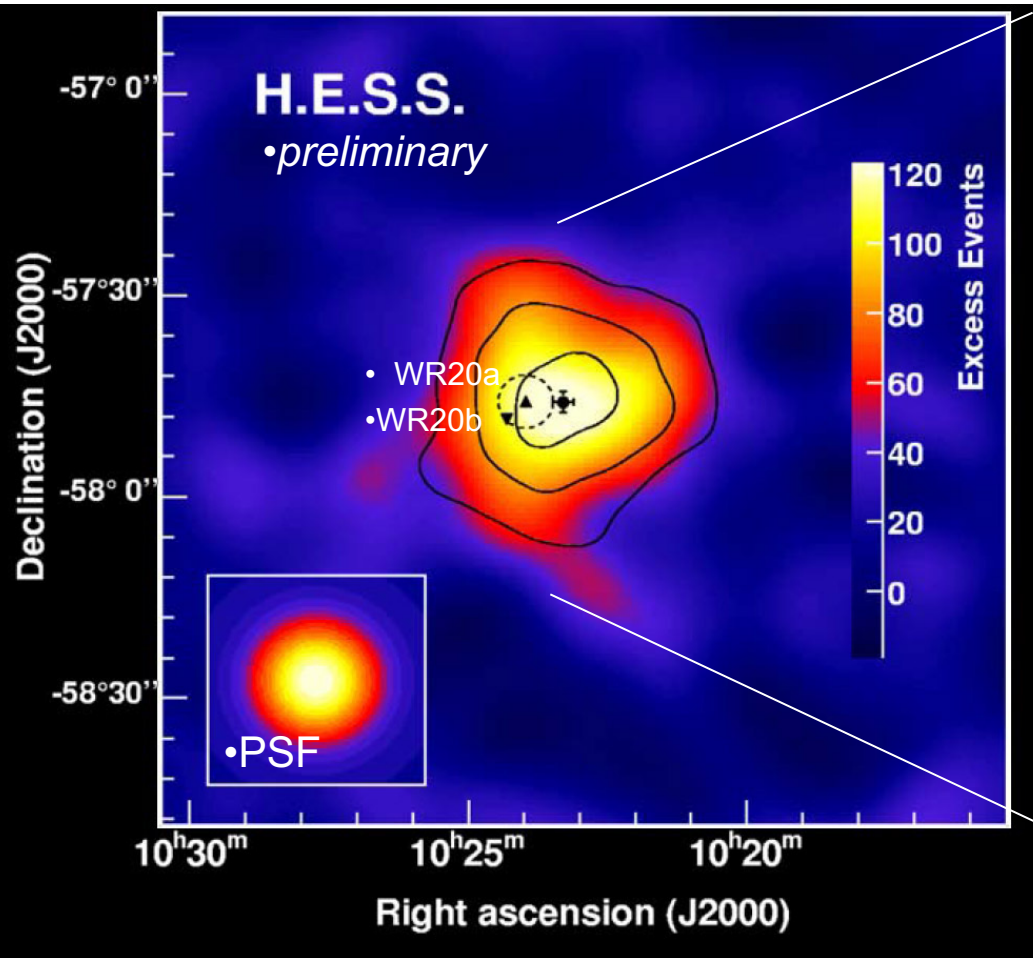
Star Formation in RCW49

Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / E. Churchwell (Univ. of Wisconsin)

ssc2004-08a

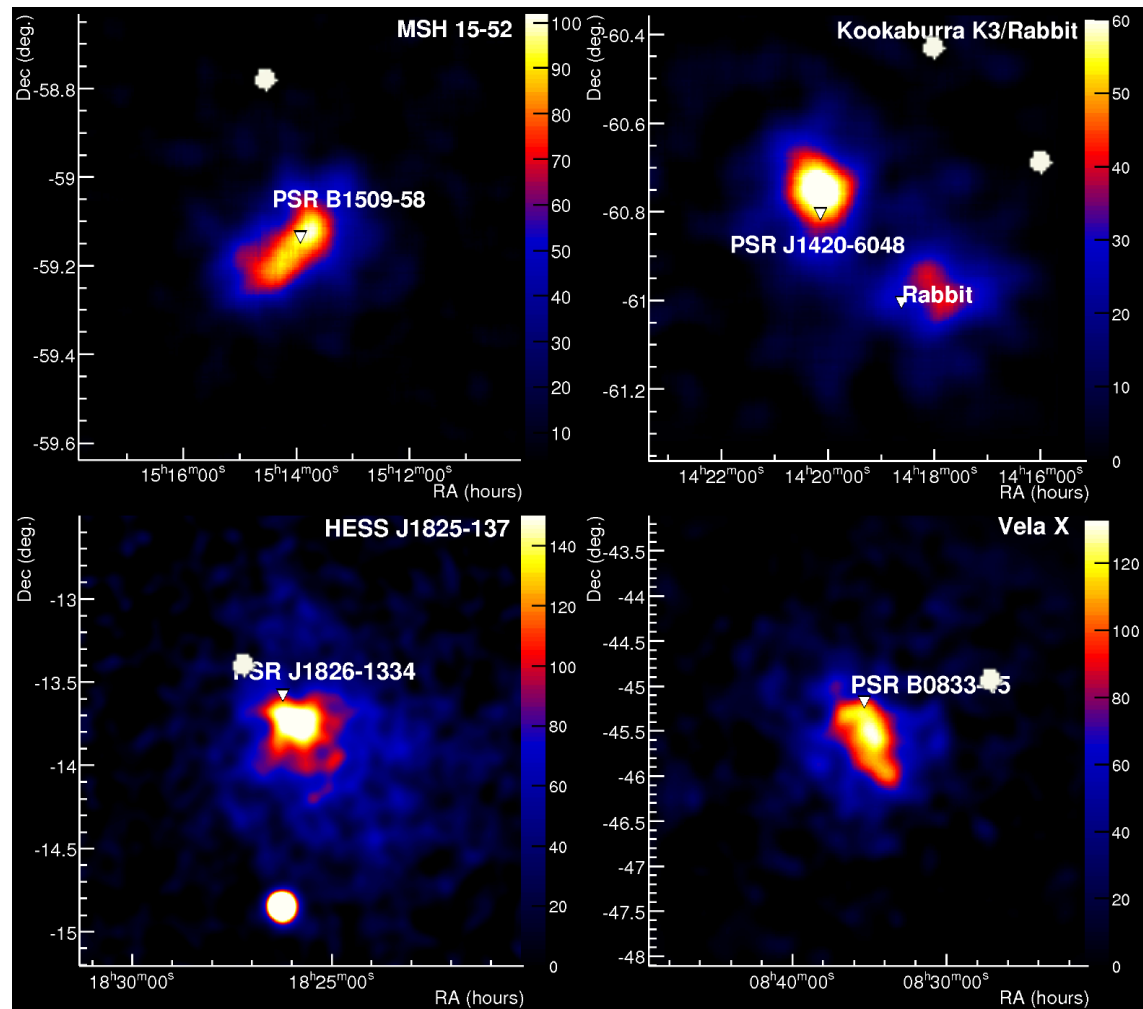
# HESS J1023-575



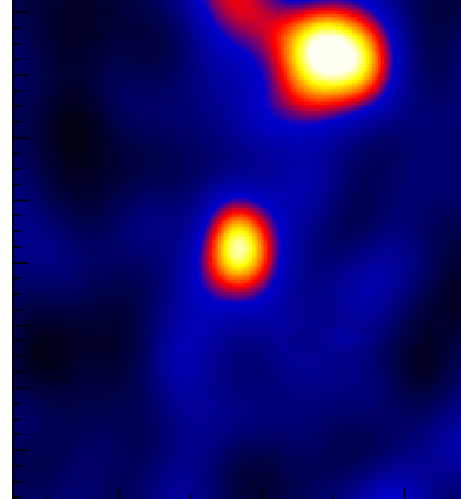
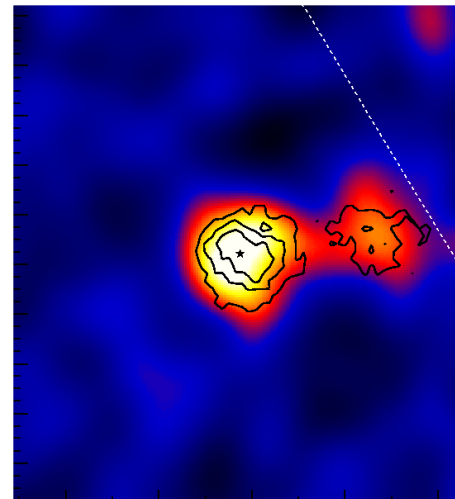
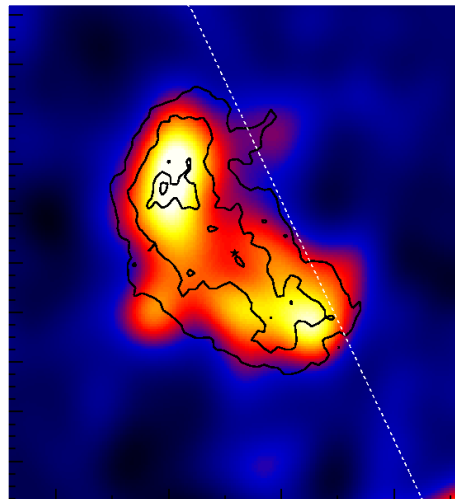
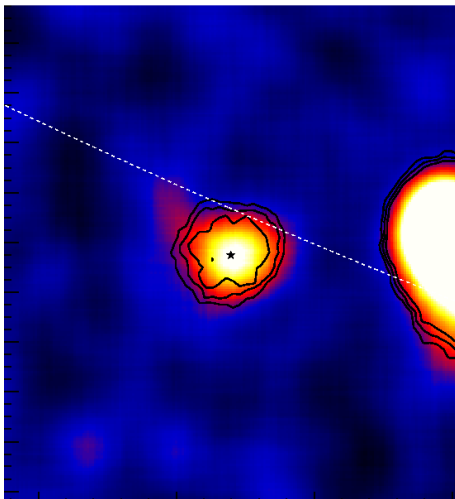
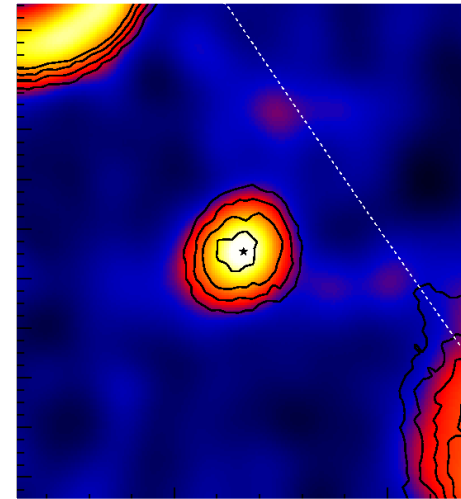
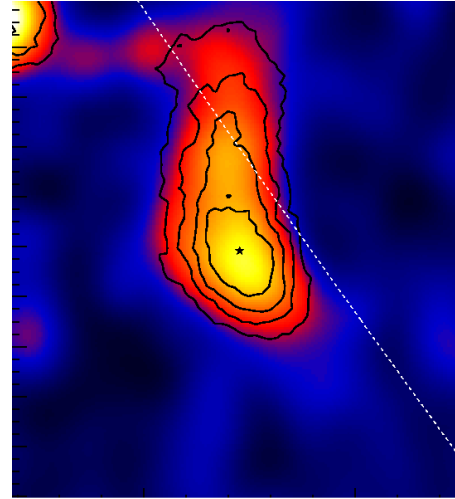
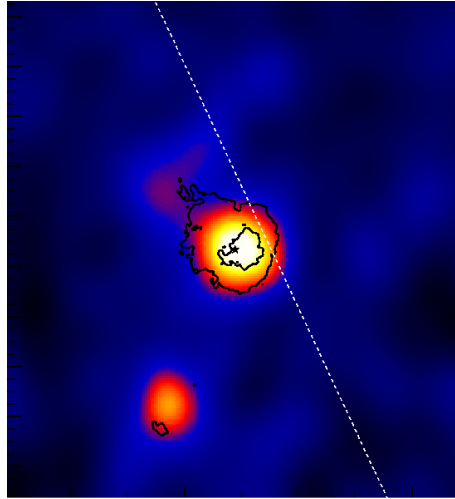
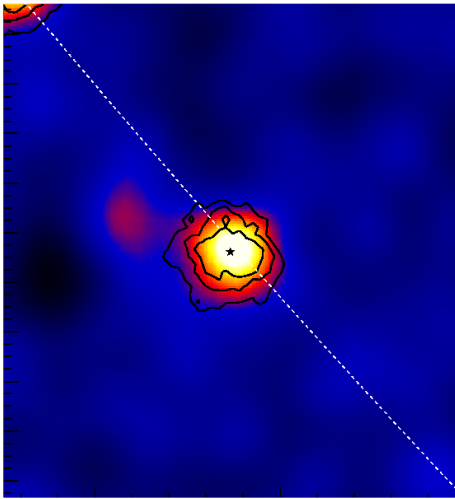


# Pulsar Wind Nebulae

Extended  
γ-ray sources



# “Dark” sources: Objects which only shine in gamma rays !



Infrared

Optical

VHE  $\gamma$ -rays

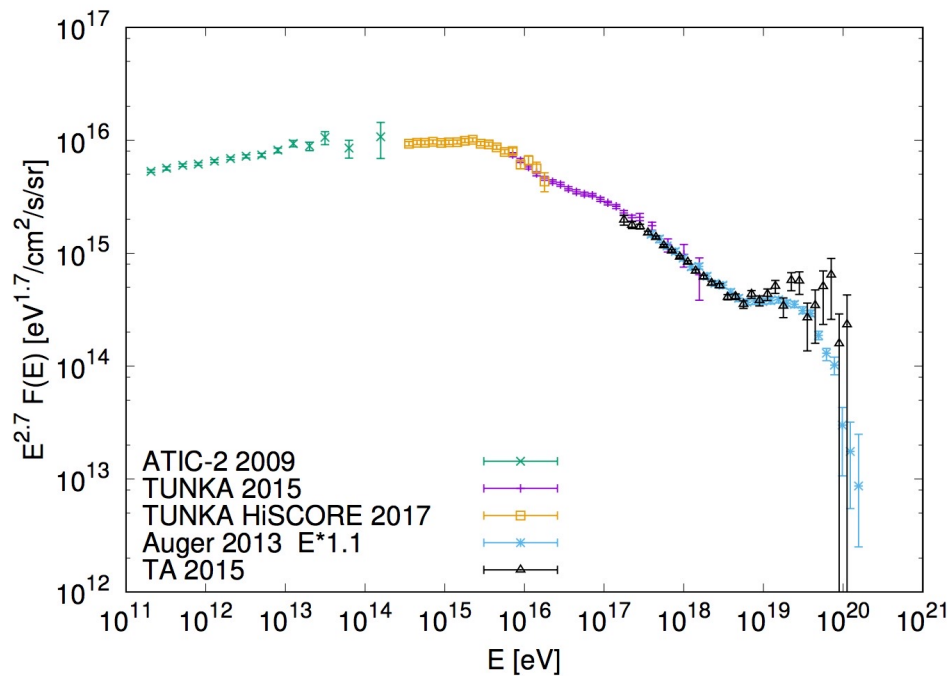
• *The age of real VHE*

*gamma ray astronomy has started*

# Galactic sources with $E > 100 \text{ TeV}$ PeVatrons



# Knee in CR spectrum



- Knee was discovered by Kulikov
- and Khristiansen in data of MSU
- Experiment in 1958
- It was confirmed by all new
- independent experiments

- Sources which accelerate cosmic rays up to knee called PeVatrons

# HAWC 100 TeV sources

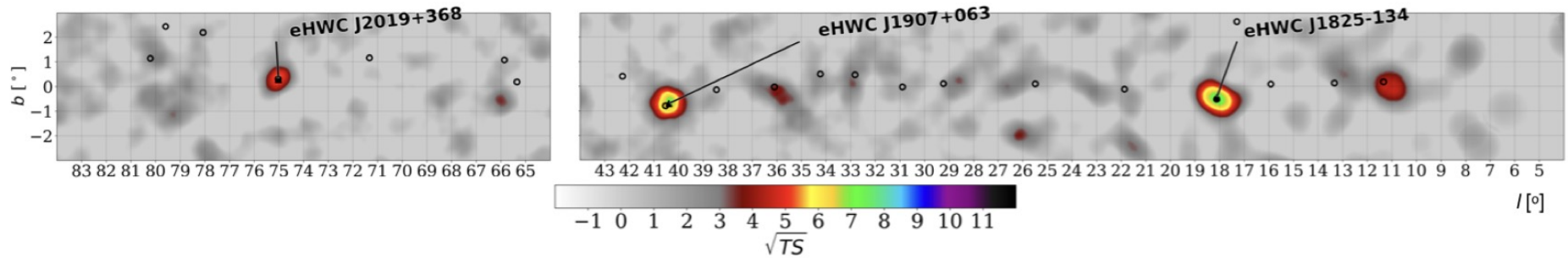
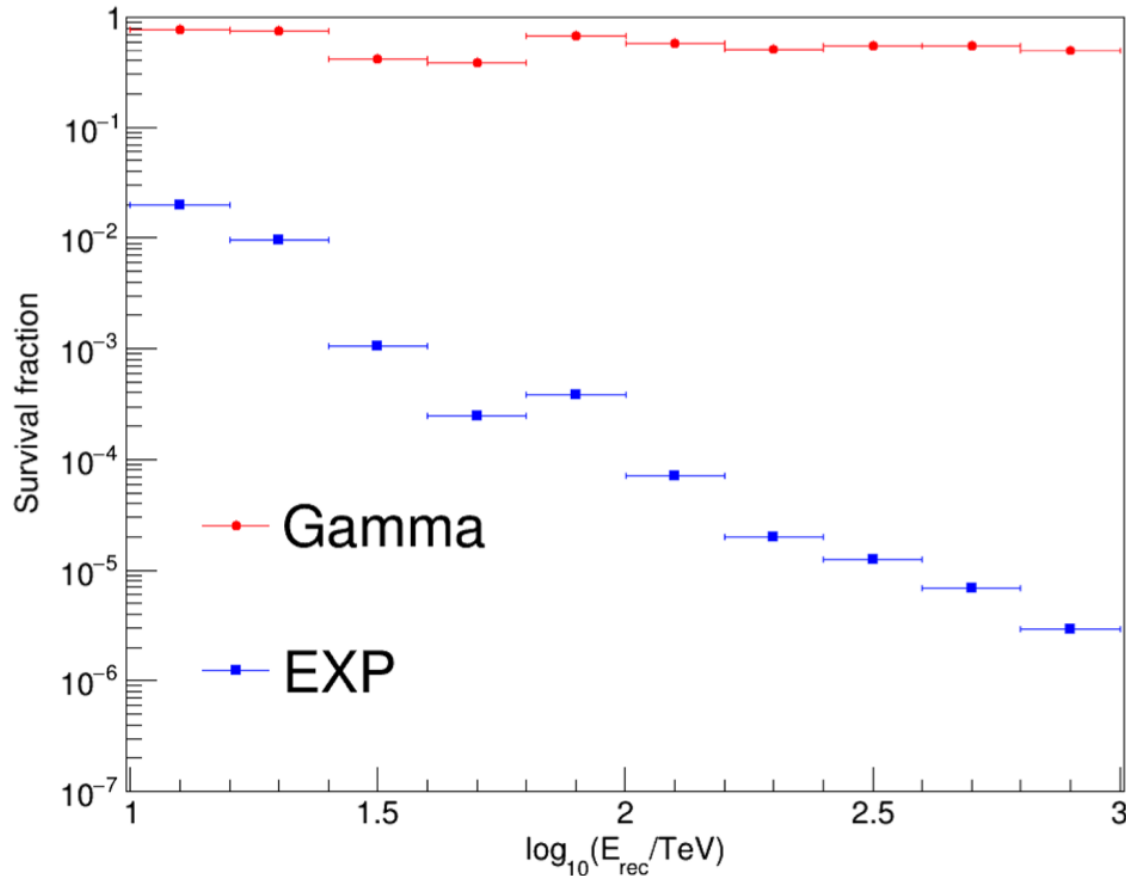


FIG. 2. The same as Figure 1, but for  $\hat{E} > 100$  TeV. The symbol convention is identical to Figure 1.

# LHAASO hadron cut 2021



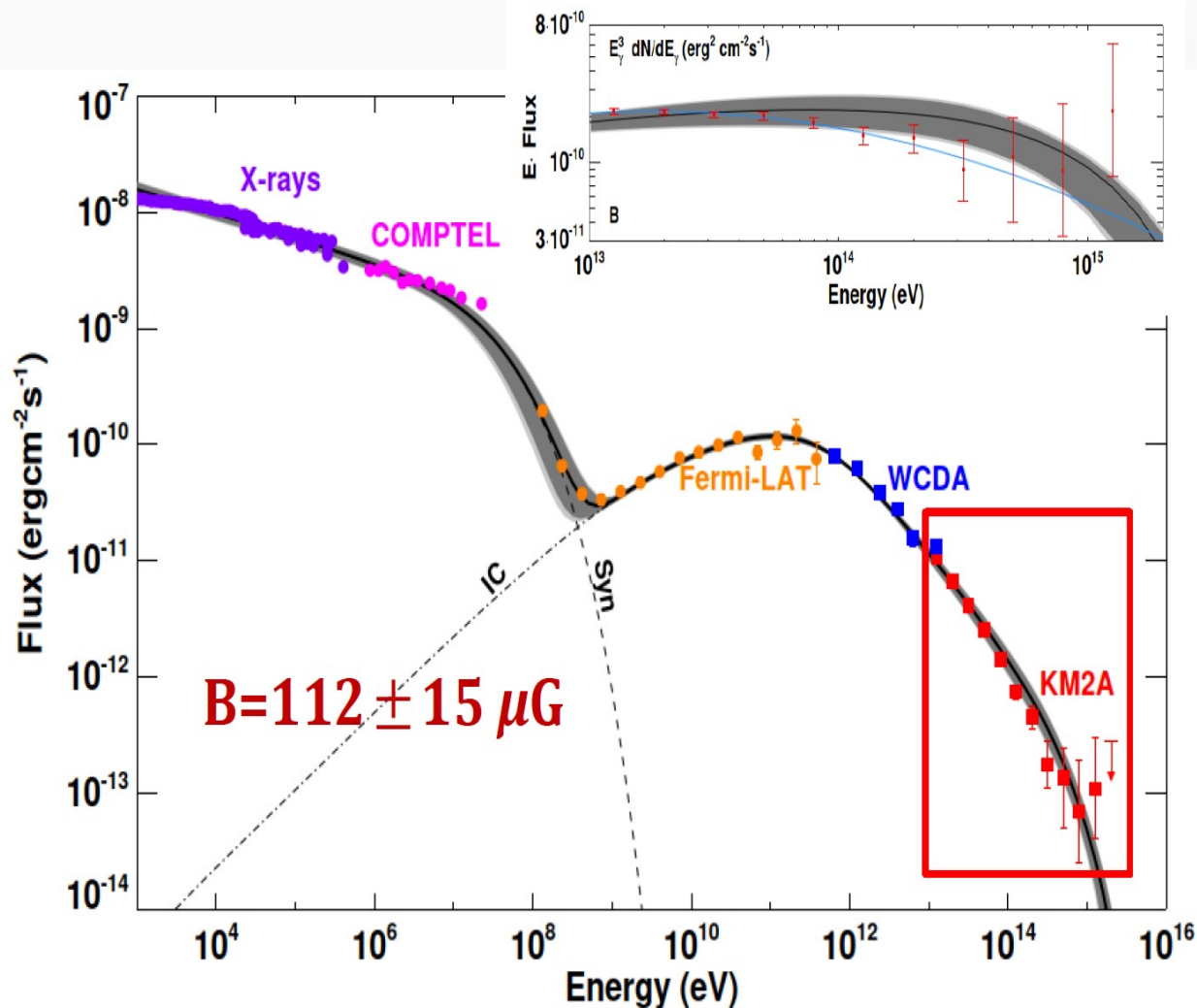
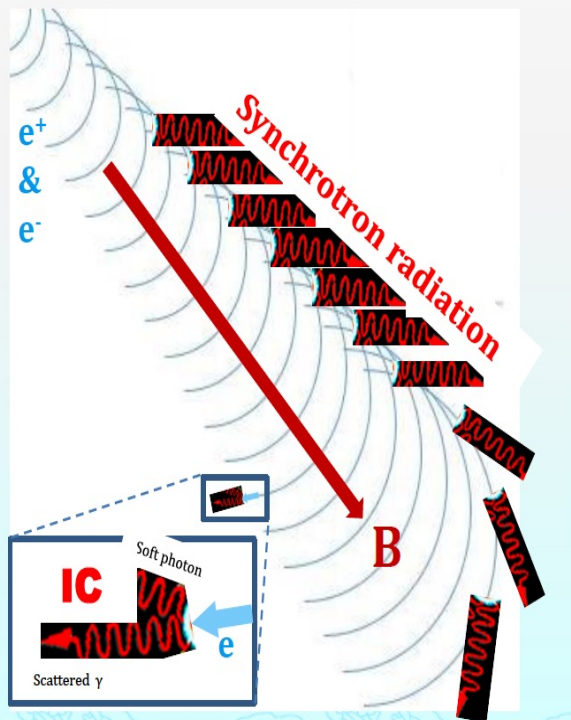
•LHAASO talk ICRC Jul 2021



# SED of the Crab: “standard Candle” & PeVatron

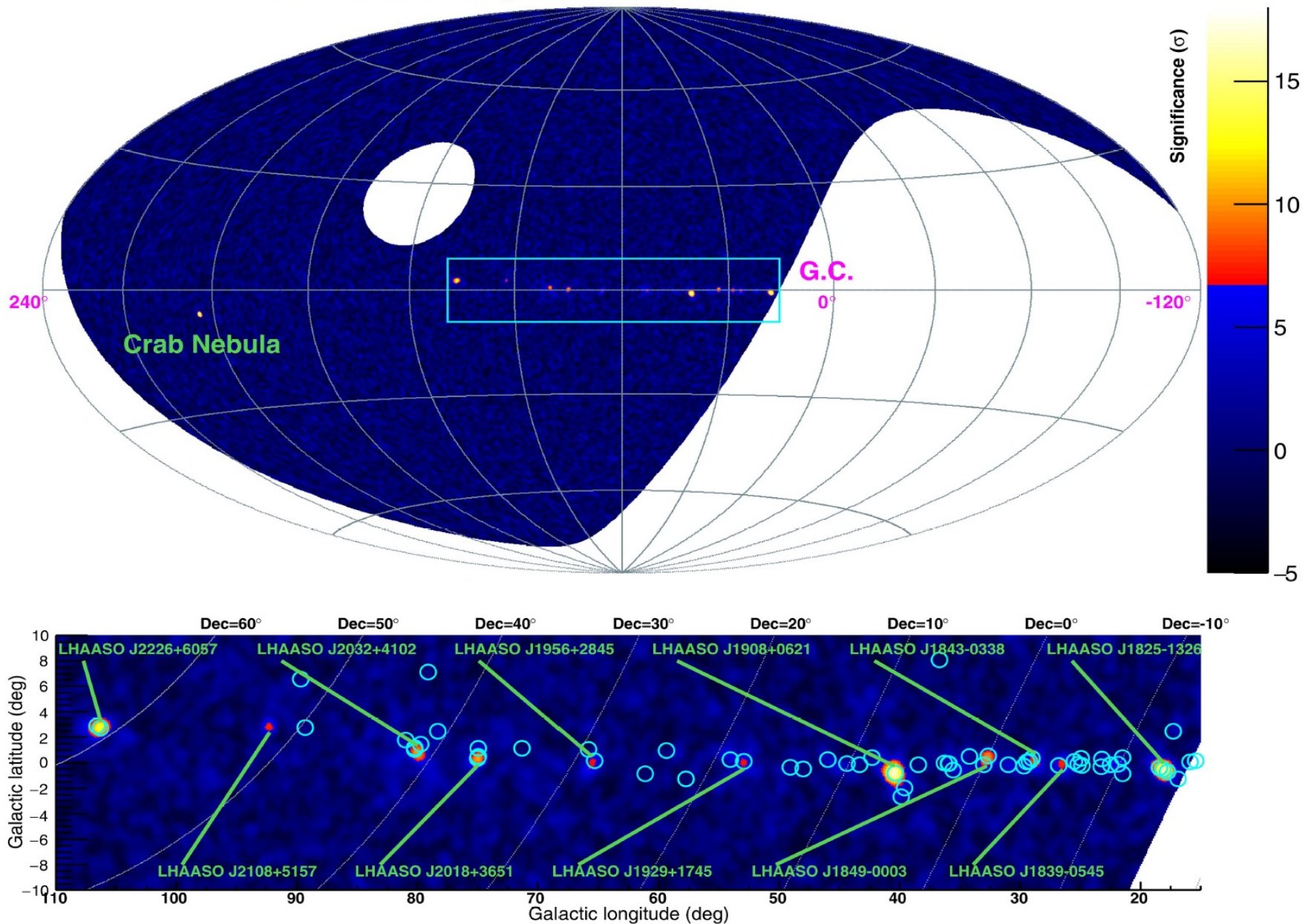
*LHAASO, Science, 373, 425-430 (2021)*

- ◆ MHD calculation
  - ◆ Nebula formation
  - ◆ Size of  $\sim 0.6$  ly
- ◆ One Zone Model, up to 50 TeV
- ◆  $4\sigma$  deviation above 50 TeV





# LHAASO Sky @ >100 TeV

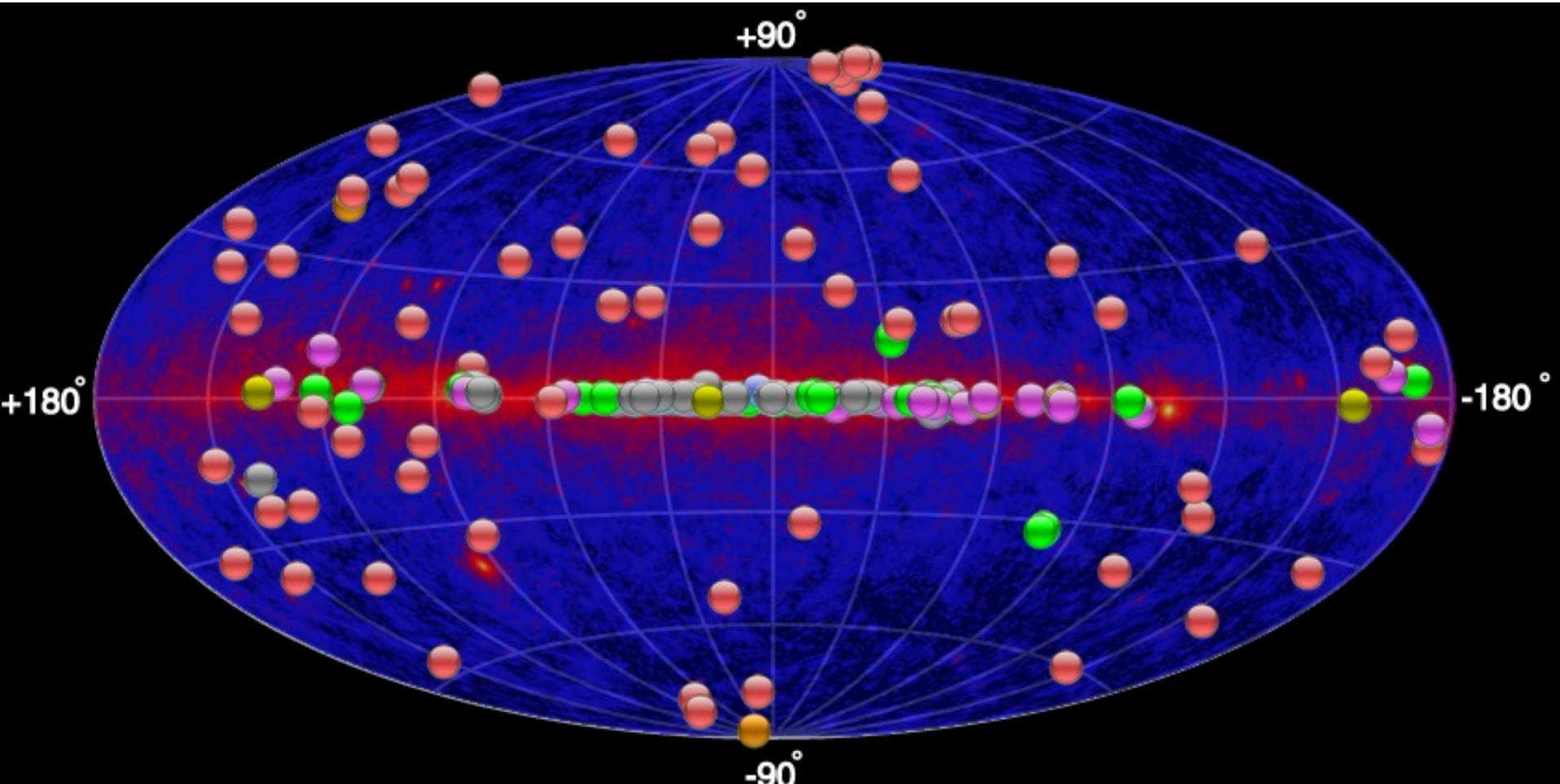


**Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV.** The circles indicate the positions of known very-high-energy  $\gamma$ -ray sources.

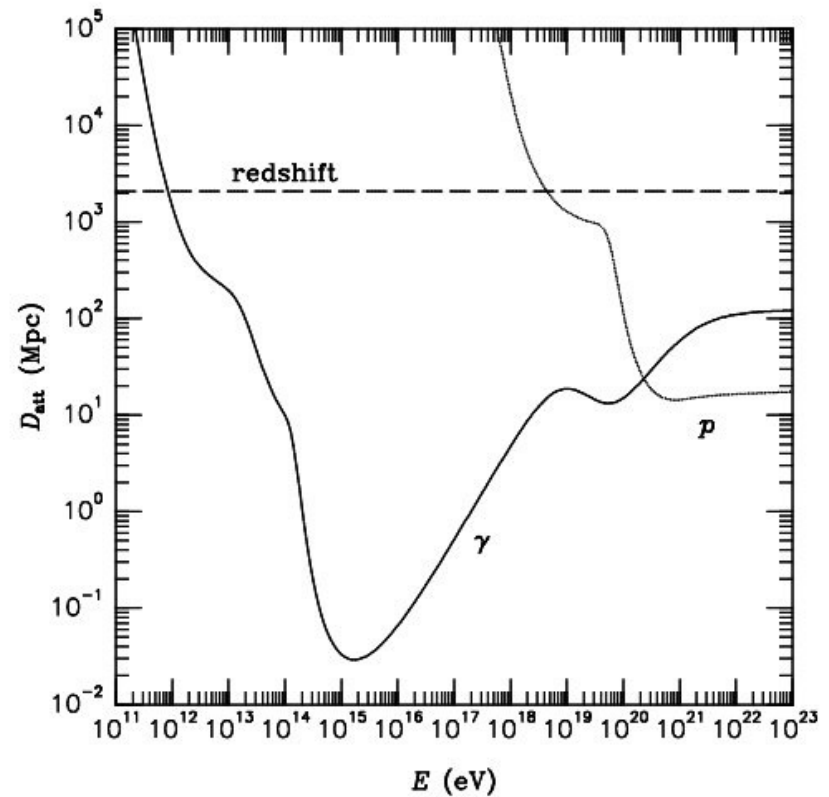
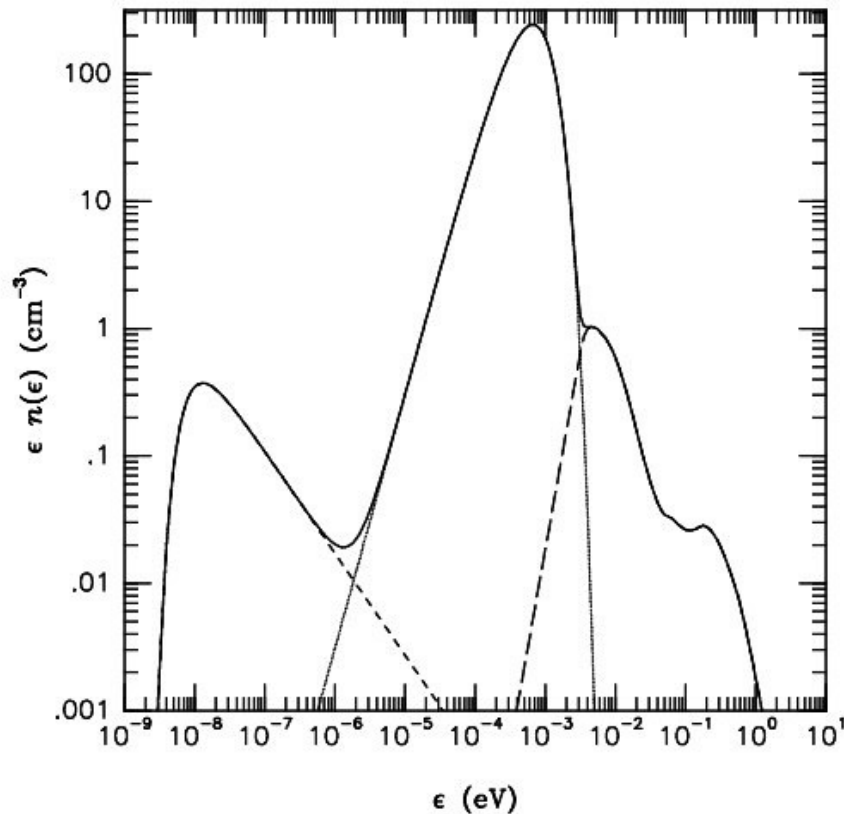
•Nature. May 17 2021

# Extra-galactic gamma-ray sources and extragalactic background light

# 1000 sources in GeV and 60 in TeV



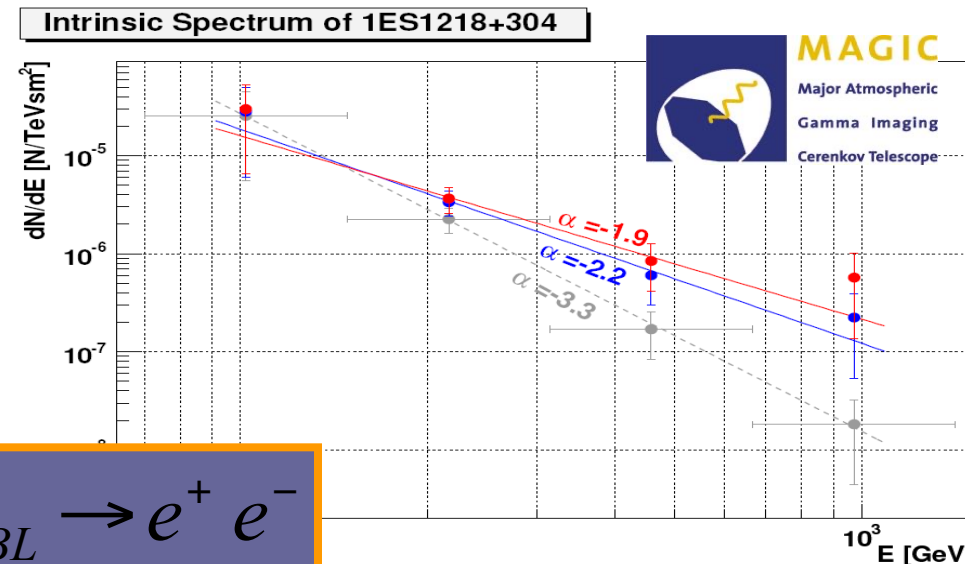
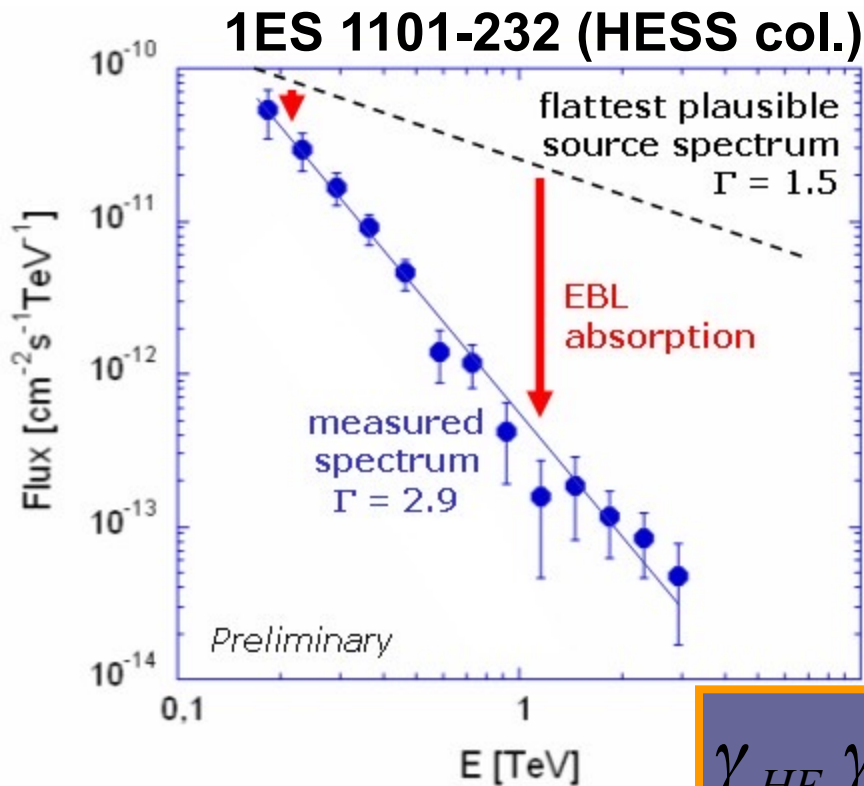
# Diffuse backgrounds





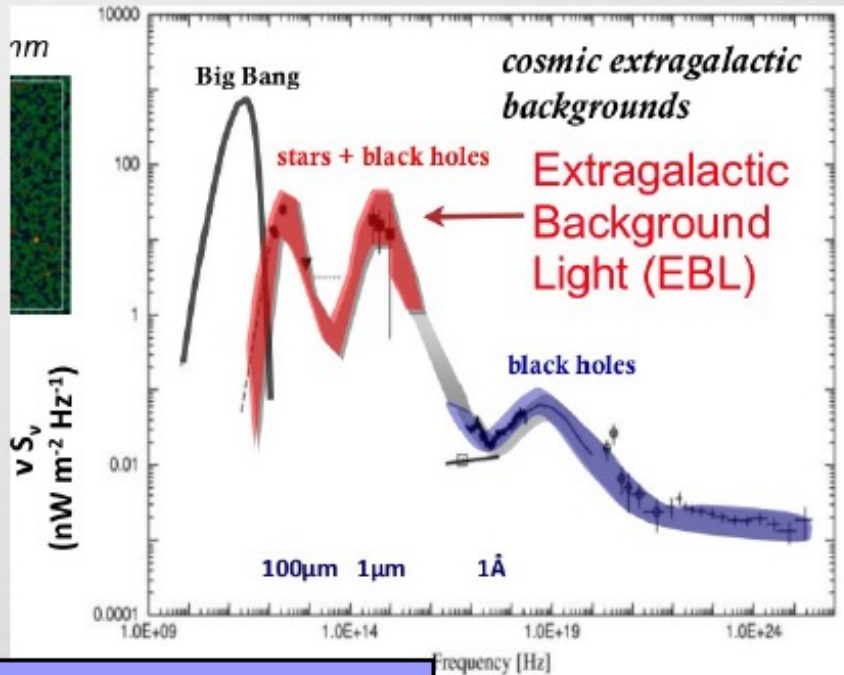
# Extrag. Background Light

Cosmological radiation from star formation and evolution.  
Spectral signature from gg absorption for  $E_g \sim 50\text{-}2000$  GeV.  
Use measured AGN spectra to constrain EBL.

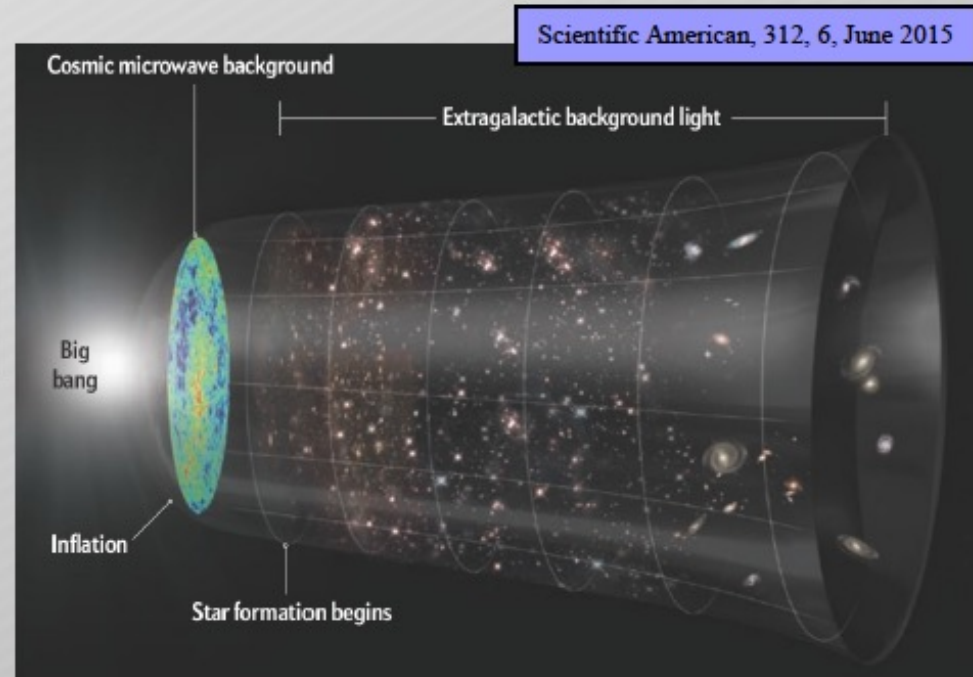


$$\gamma_{HE} \gamma_{EBL} \rightarrow e^+ e^-$$

# Diffuse extragalactic backgrounds

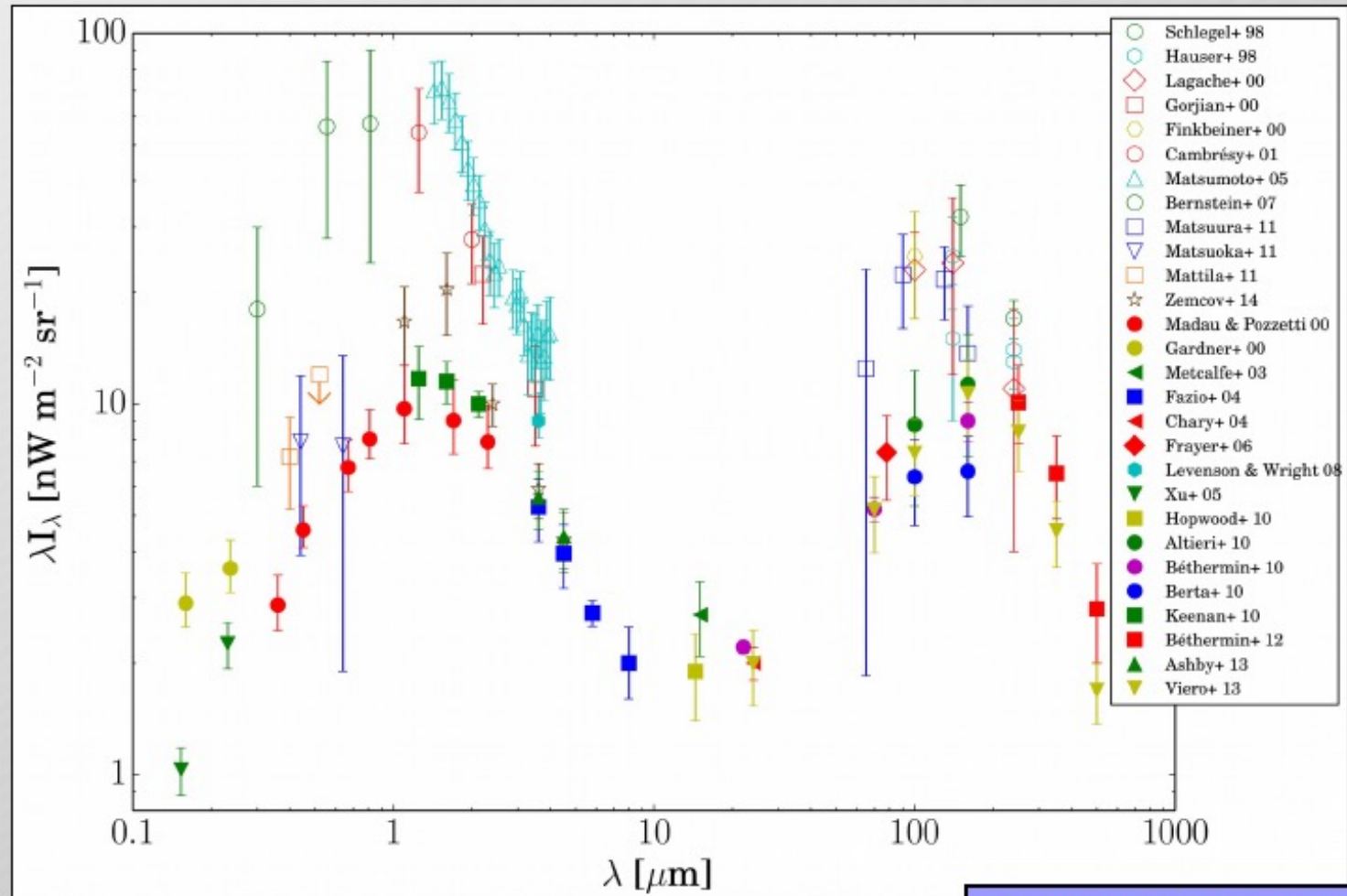


From Genzel's lecture @ 2013  
Jerusalem Winter School



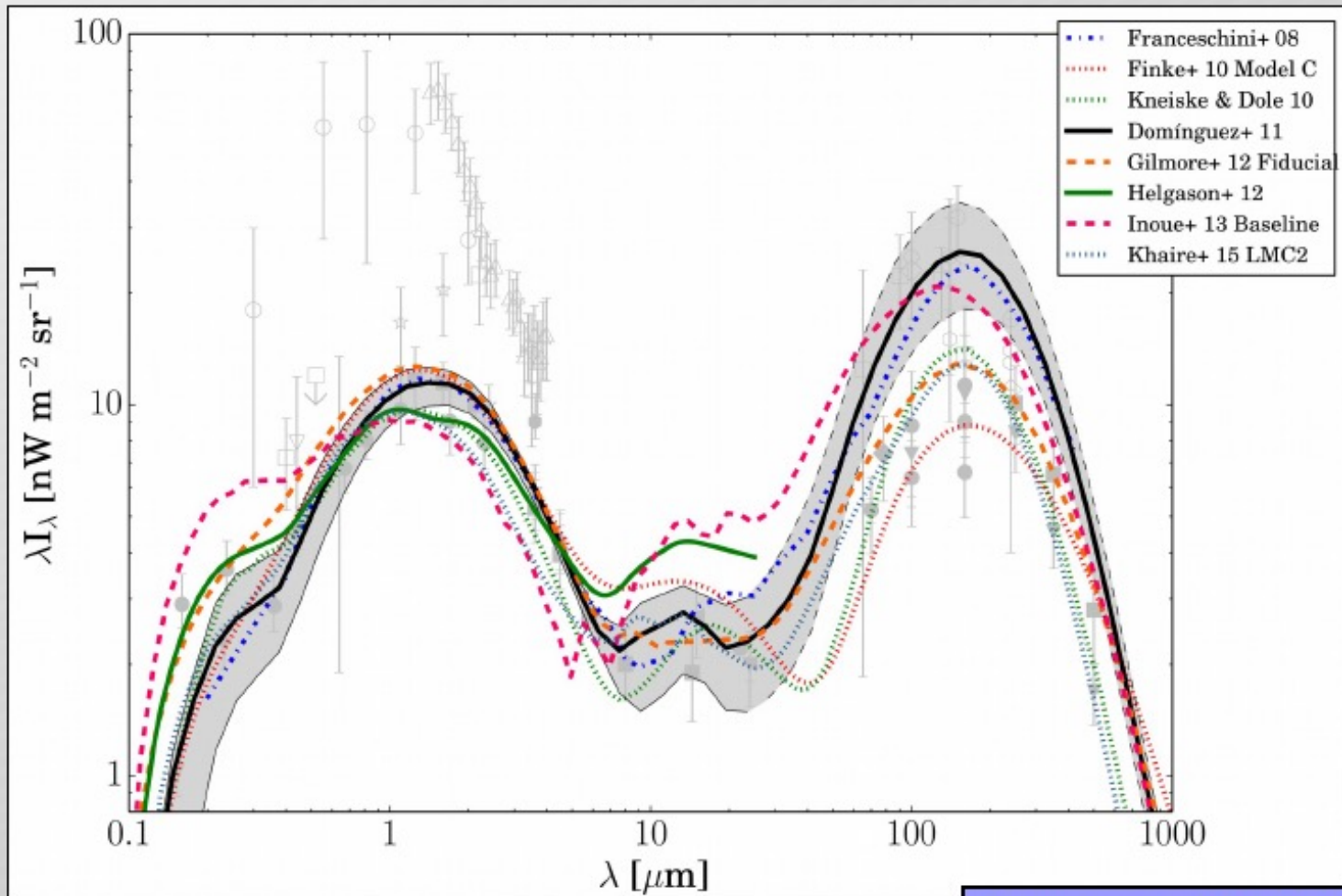
- The EBL is the accumulated diffuse light produced by star formation processes and accreting black holes over the history of the Universe from the UV to the far-IR.
- It contains fundamental information about galaxy evolution, cosmology, and it is essential for the full energy balance of the Universe.

# Local EBL: Data and Models



Dom nguez & Primack, 15 in prep.

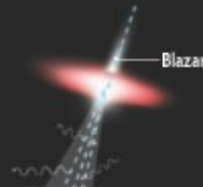
# Local EBL: Data and Models



Domínguez & Primack, 15 in prep.

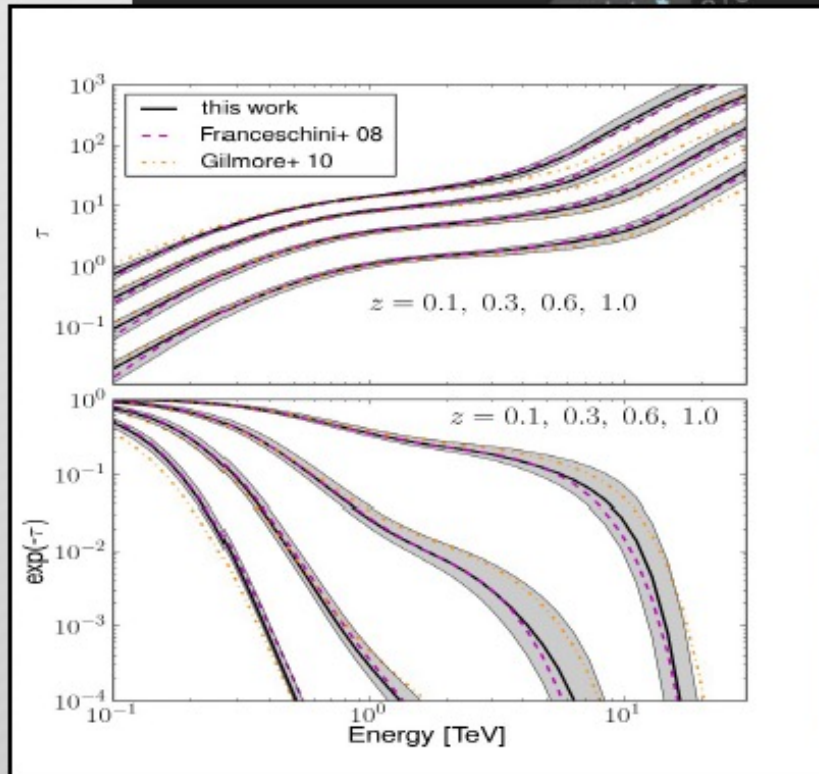


# Gamma-Ray Attenuation



$$\left. \frac{dN}{dE} \right|_{obs} = \left. \frac{dN}{dE} \right|_{int} \exp[-\tau(E, z)]$$

$$\tau(E, z) = \int_0^z \underbrace{\left( \frac{dl'}{dz'} \right)}_{\text{Distance (cosmology)}} dz' \int_0^2 d\mu \underbrace{\frac{\mu}{2}}_{\text{Interaction angle}} \int_{\epsilon_{min}}^{\infty} d\epsilon' \underbrace{\sigma_{\gamma\gamma}(\beta')}_{\text{Cross section}} \underbrace{n(\epsilon', z')}_{\text{EBL photon density evolution (cosmology)}}$$



Distance  
(cosmology)

Interaction  
angle

Cross section

EBL photon density evolution  
(cosmology)

# Cosmic $\gamma$ -ray Horizon: Results



Domínguez+ 13 on behalf  
of the Fermi collaboration

$\gamma$ -ray horizon,  $E_0$  [TeV]

10  
1

More attenuating

Less attenuating

Preliminary

0.1

Redshift

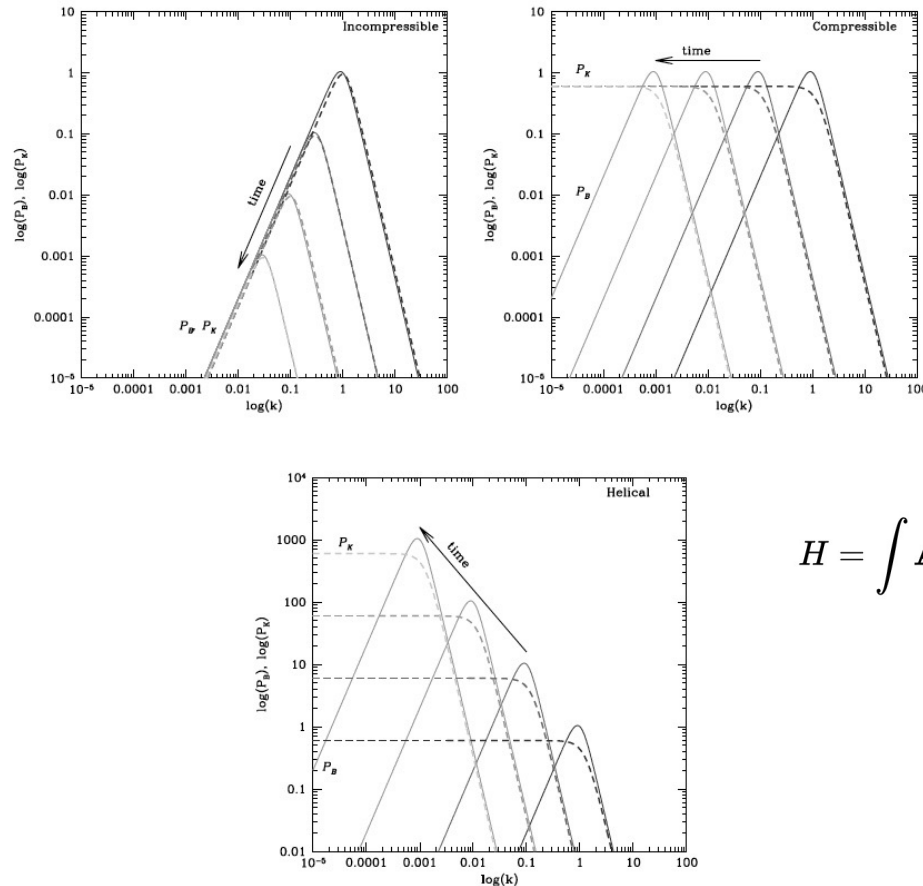
Preliminary data courtesy  
of Marco Ajello

- BL Lacs (Ackermann+ 12)
- Domínguez+ 13
- ▲ Fermi  $2\sigma$  Lower Limits (FSRQs)
- ◆ Fermi  $2\sigma$  Lower Limits (GRBs)
- ⋯ Kneiske+ 04 Best Fit
- ⋯ Stecker+ 06 Baseline
- ⋯ Franceschini+ 08
- ⋯ Kneiske & Dole 10
- ⋯ Finke+ 10 Model C
- Domínguez+ 11
- - - Gilmore+ 12 Fiducial
- Helgason+ 12
- - - Inoue+ 13 Baseline
- ⋯ Khaire+ 15 LMC2

EBL model	Rejection
Kneiske+ 04 Best Fit	1.62 $\sigma$
Stecker+ 06 Baseline	6.37 $\sigma$
Franceschini+ 08	0.29 $\sigma$
Kneiske & Dole 10	1.54 $\sigma$
Finke+ 10	0.06 $\sigma$
Domínguez+ 11	0.29 $\sigma$
Gilmore+ 12 Fiducial	0.25 $\sigma$
Helgason+ 12	0.09 $\sigma$
Inoue+ 13 Baseline	2.12 $\sigma$
Khaire+ 15 LMC2	1.27 $\sigma$

# Extra-galactic sources and determination of magnetic field

# Early Universe evolution of spectrum of IGMF



$$H = \int \mathbf{A} \cdot \mathbf{B} d^3\mathbf{r}$$

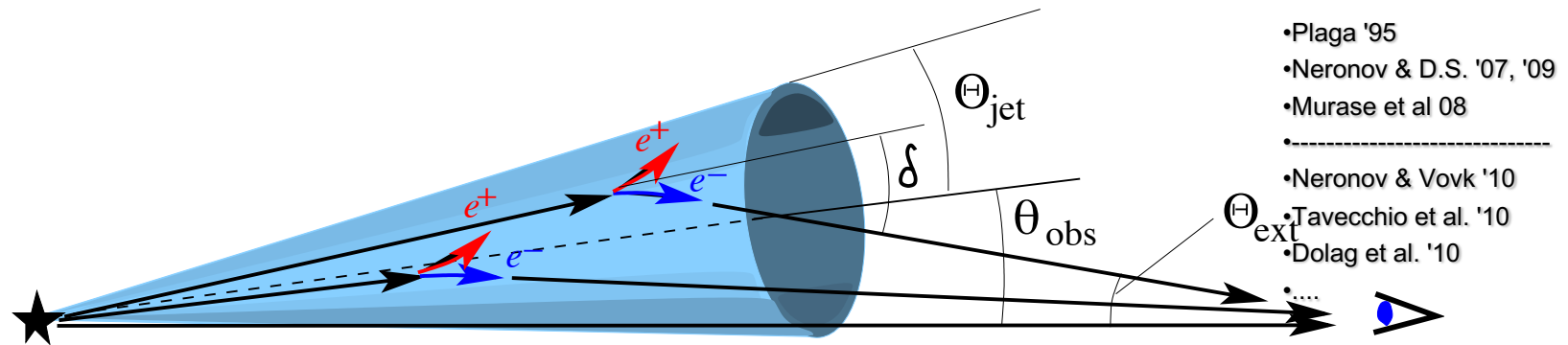


# Constraints on PMF

TABLE I: Constraints on scale-invariant magnetic Fields

Principal effect	Upper limit
Spectral distortions	30 – 40 nG [14–17]
Anisotropic expansion	3.4nG [18]
CMB temp. anisotropies:	
Due to magnetic modes	1.2 – 6.4 nG [19–40]
Due to plasma heating	0.63 – 3 nG [16, 38, 41–44]
CMB polarization	1.2nG [21–23, 40, 45–54]
Non-Gaussianity bispectrum	2 – 9 nG [38, 55–64]
Non-Gaussianity trispectrum	0.7nG [65]
Non-Gaussianity trispectrum with inflationary curv. mode	0.05nG [66]
Reionization	0.36 nG [41, 67–70]

# • IGMF measurement with gamma-ray telescopes



•γ-rays with energies above ~0.1 TeV are absorbed by the pair production on the way from the source to the Earth.

$$D_{\gamma_0} = \frac{1}{n_{\text{IR}} \sigma_{PP}} \propto 150 \text{ Mpc} \frac{4 \text{ TeV}}{E} \frac{10 nW / (m^2 sr)}{(\nu F(\nu))_{\text{IR}}}$$

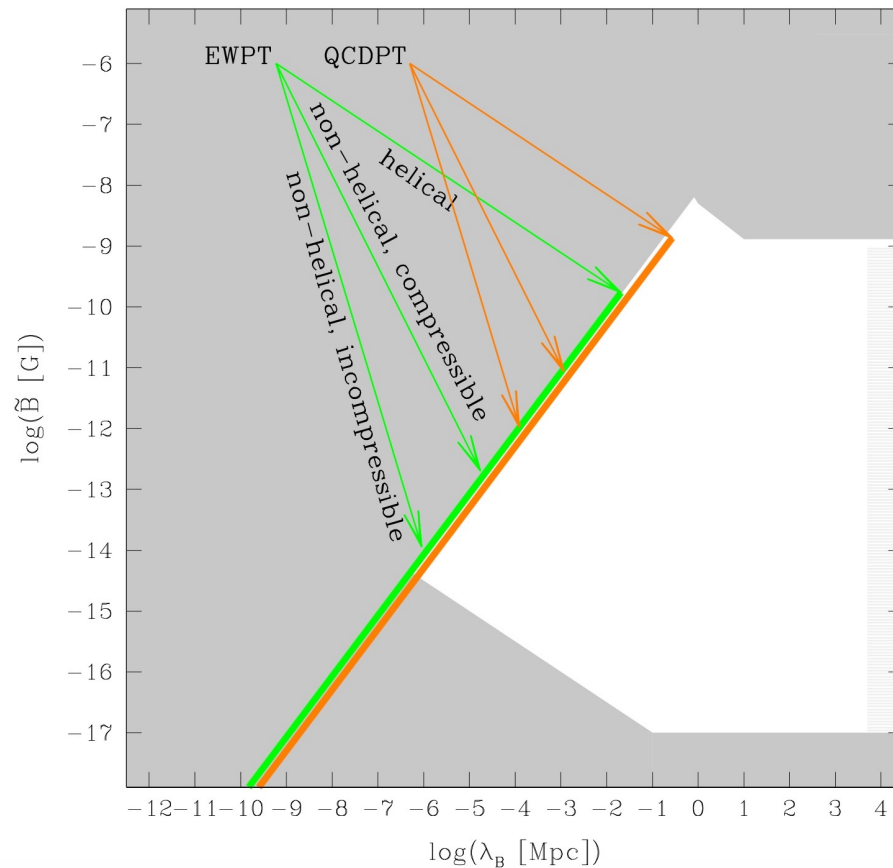
• $e^+e^-$  pairs re-emit γ-rays via inverse Compton scattering of CMB photons.

$$E_{\gamma_0} = 2E_e \quad \lambda_e = \frac{1}{n_{\text{CMB}} \sigma_{\text{ICS}}} \sim 1 \text{ kpc}$$

•Inverse Compton γ-rays could be detected at lower energies.

$$E_{\gamma} = 12 \text{ GeV} \left( \frac{E_e}{2 \text{ TeV}} \right)^2$$

# IGMF from phase transitions



• R. Durrer and A. Neronov, A&A Rev. 21 62, [1303.7121].

# Cascade component

- Fraction of electron energy in secondary photons in direction of observer

$$\alpha = \frac{\sum E_{\gamma}}{E_e}$$

- Fraction of voids on the way of primary photon

$$D_{void} = \Delta D_{\gamma_0}$$

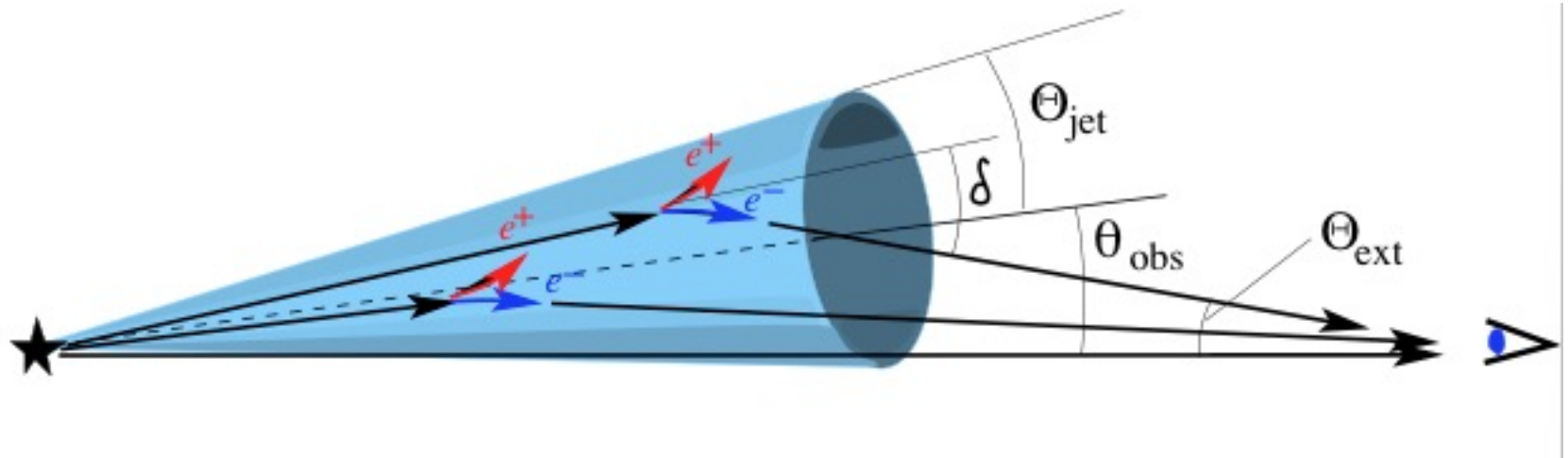
- Ratio of point source flux at  $E_{\gamma}$  and  $E_{\gamma_0}$

$$R = F(E_{\gamma_0}) / F(E_{\gamma})$$

$$F_{\text{ext}} = \alpha \cdot R \cdot \Delta \cdot e^{-\tau(E_{\gamma}, z)} \left\langle F_{PS}(E_{\gamma}) \right\rangle$$



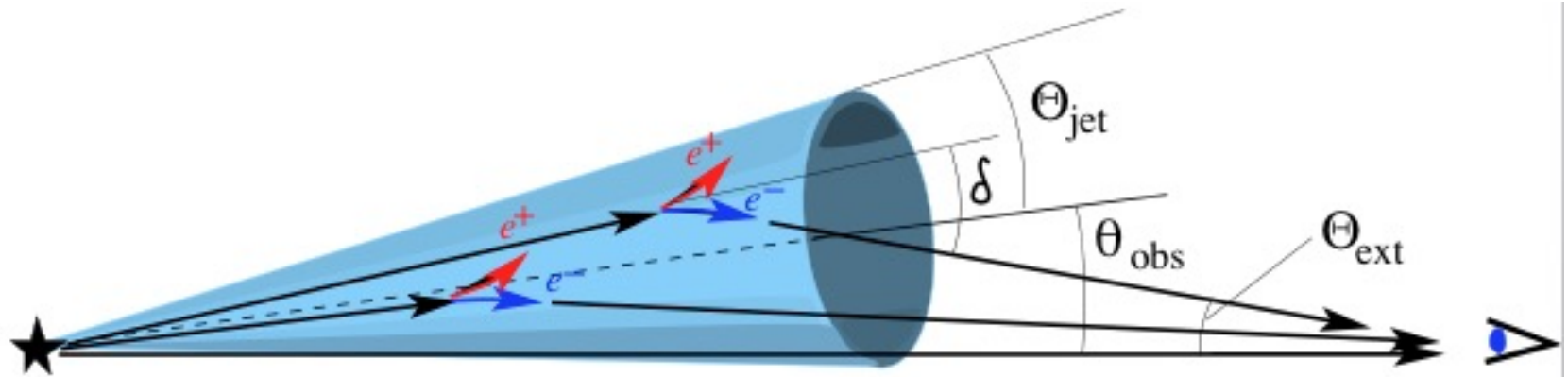
- Imaging of cascade: 3-d cascade needed



- 3-d cascade in turbulent EGMF

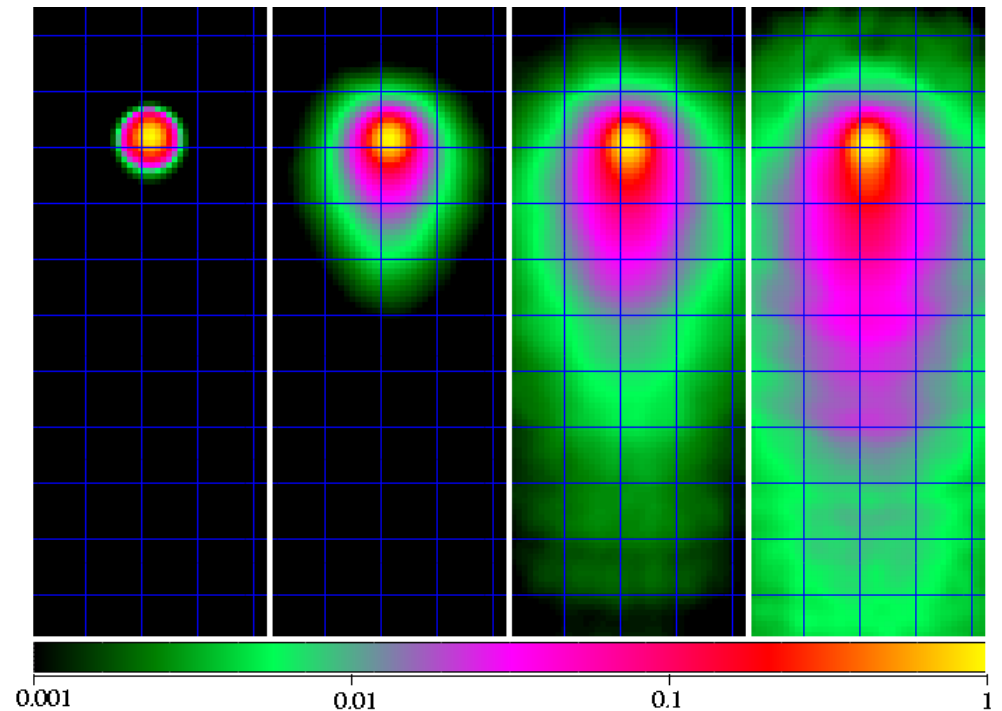
- A.Neronov, D.S., M.Kachelriess, S.Ostapchenko and A.Elyev , 2009

## • Imaging of cascade: EGMF

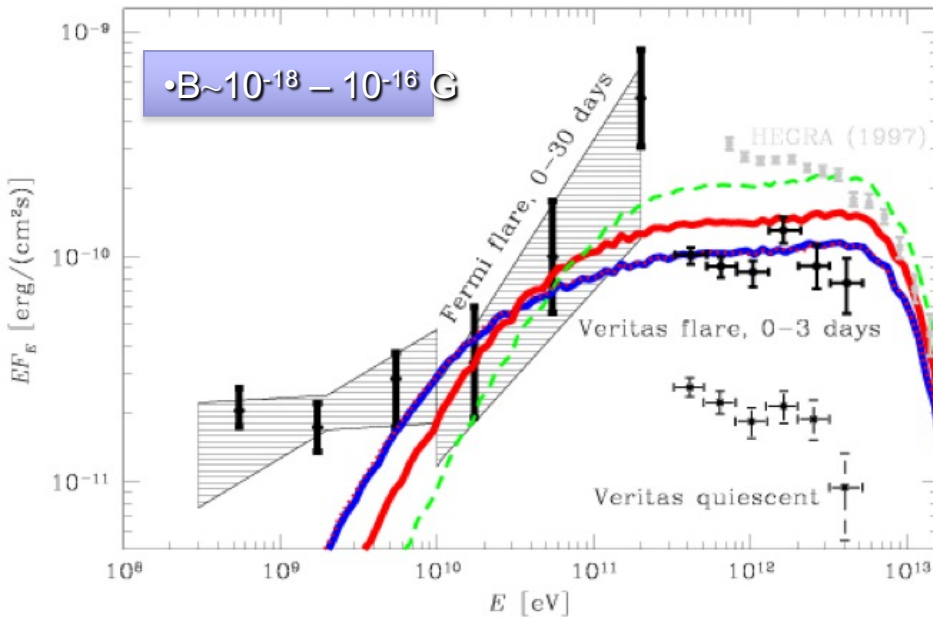


• **Imaging**: cascade component forms an extended emission around initially point source.

- - detectability depends on the telescope PSF and on the scale of angular deflections of  $e^+e^-$  pairs (i.e. on the strength of EGMF)



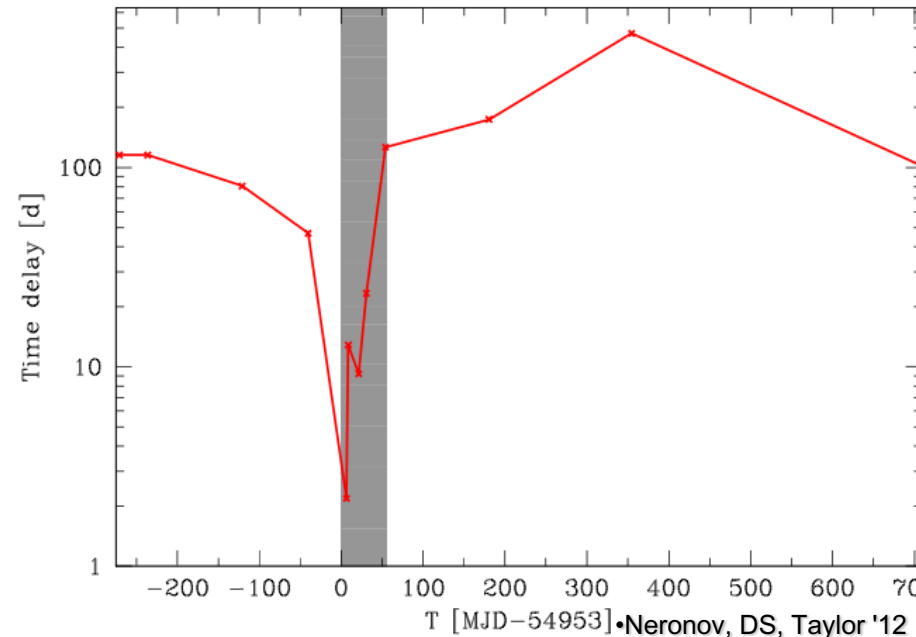
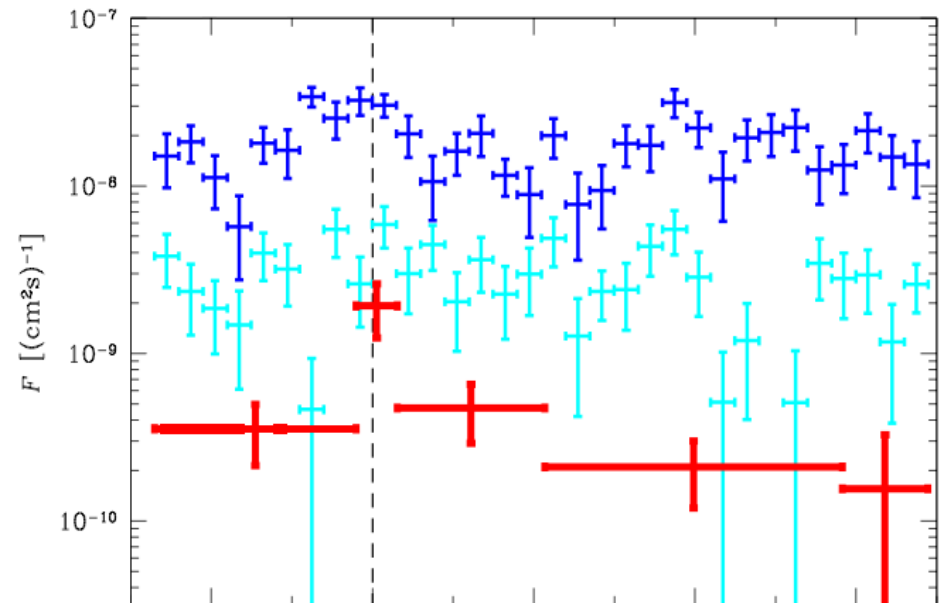
# • Search for the time-delayed cascade emission



• The flare occurred during the multiwavelength campaign, including HE and VHE observations.

• Fermi data indicate that the flare lasted 30-50 days, but the VHE observations cover only the first three days of the flare.

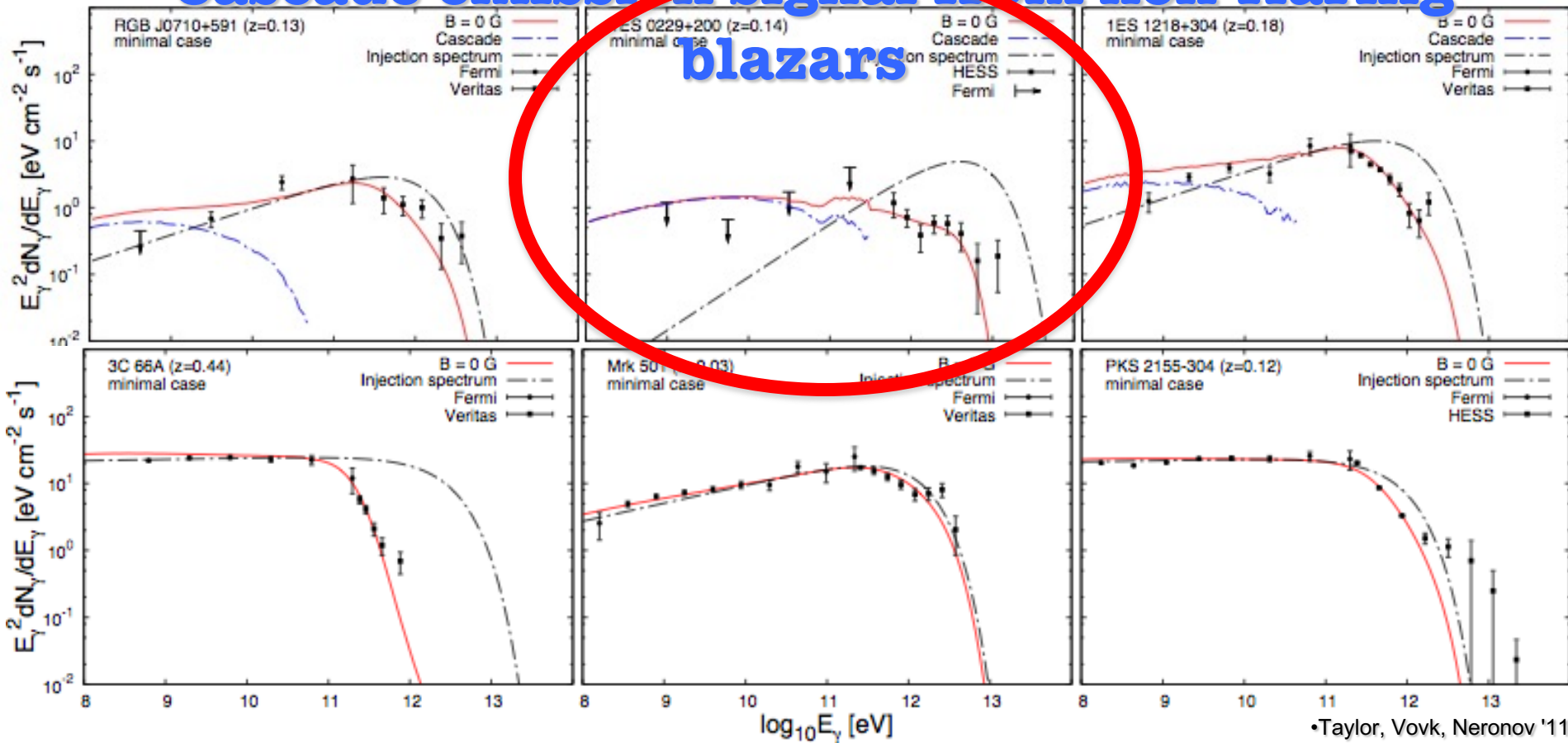
• Fermi data indicate a peculiar hardening of the spectrum above  $\sim 10$  GeV during the flare. One possibility for the explanation of the hard component is the cascade emission suppressed at low energies by too-large time delay.



# e.-m.cascade signatures in the spectrum of blazars



# • Cascade emission signal from non-flaring blazars



•Taylor, Vovk, Neronov '11

•So far, (published) HE-VHE monitoring campaigns did not succeed to catch exceptionally bright flares of VHE blazars simultaneously in Fermi and ground-based telescopes, which would be most suitable for the search of the time-delayed cascade emission.

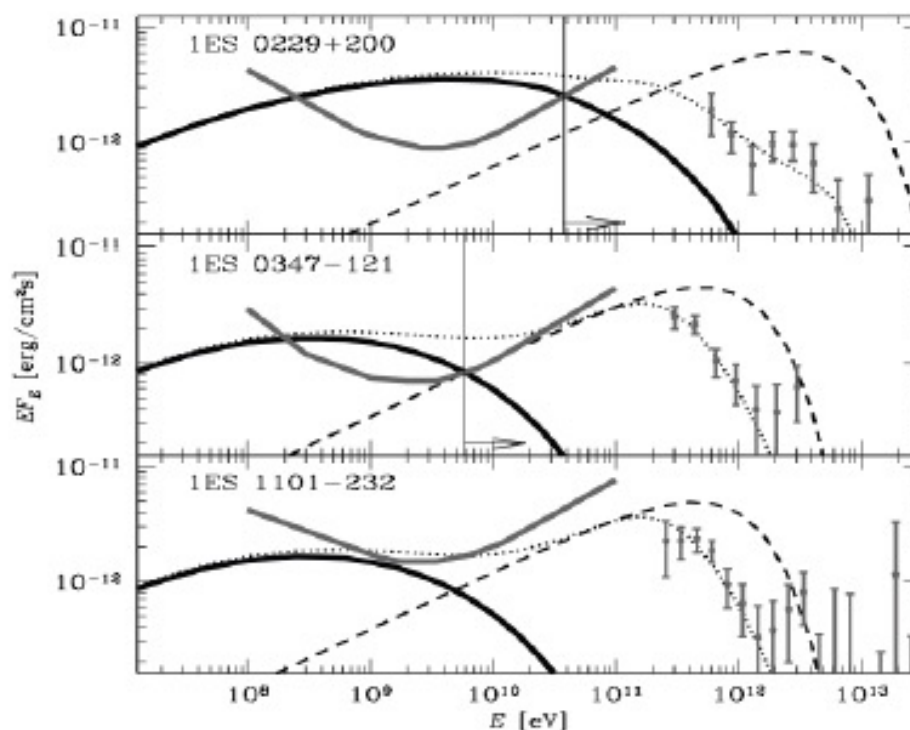
•.... waiting for the Big one

•Meanwhile, non-observation of the cascade signal in sources in which it would be detectable in the B=0 case, imposes lower bounds on the strength of intergalactic magnetic field at the level of

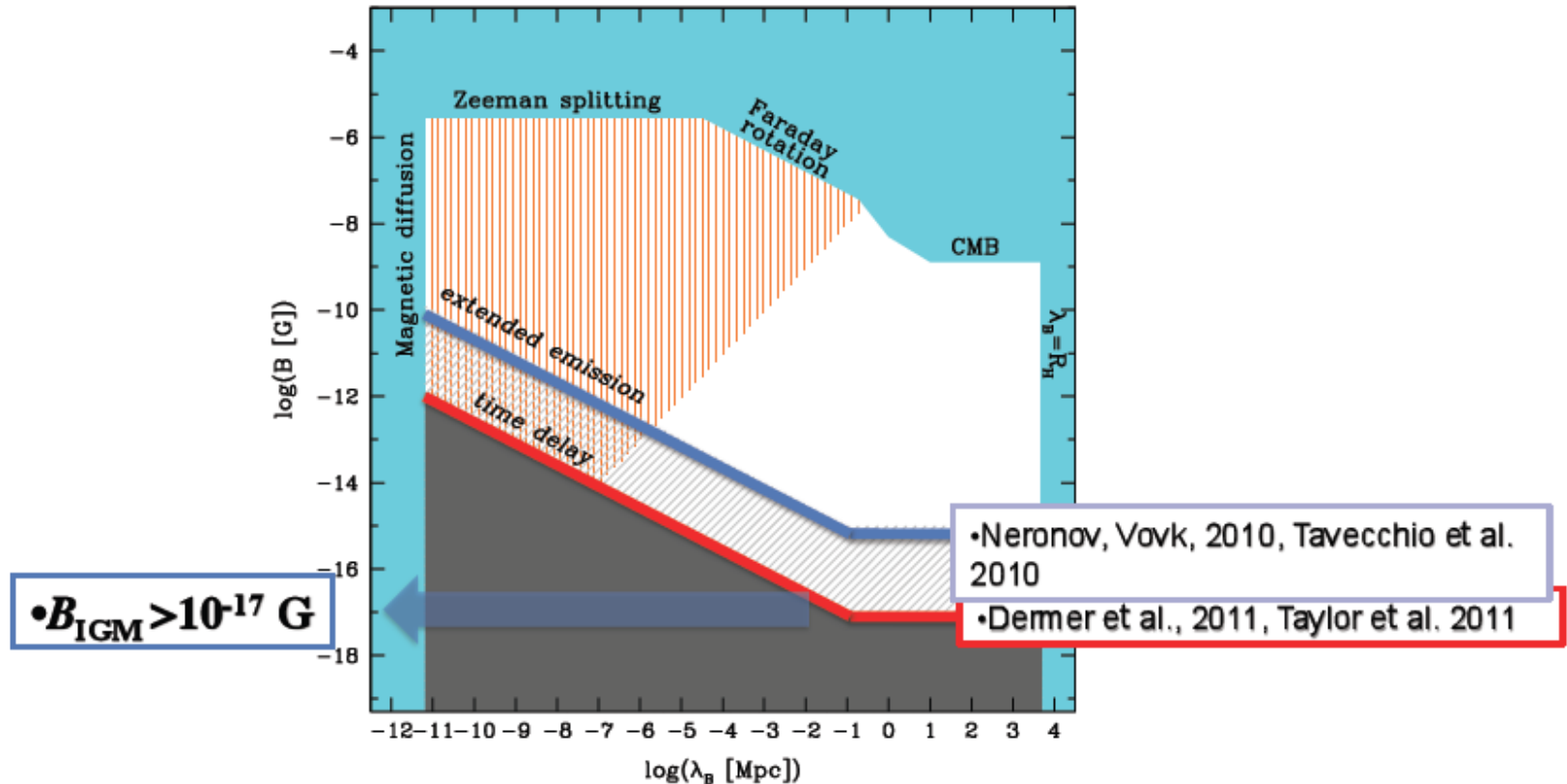
.....

# • Search for the GeV cascade signal in Fermi data

Neronov, Vovk '10



- Search for the GeV counterparts of the hard spectrum far-away sources of TeV gamma-rays within 1 year of Fermi telescope exposure did not reveal the cascade emission component.



•Non-detection of the cascade signal in the GeV band indicates that electrons and positrons are deflected by non-negligible IGMF which should have strength in excess of  $10^{-17}$  G.

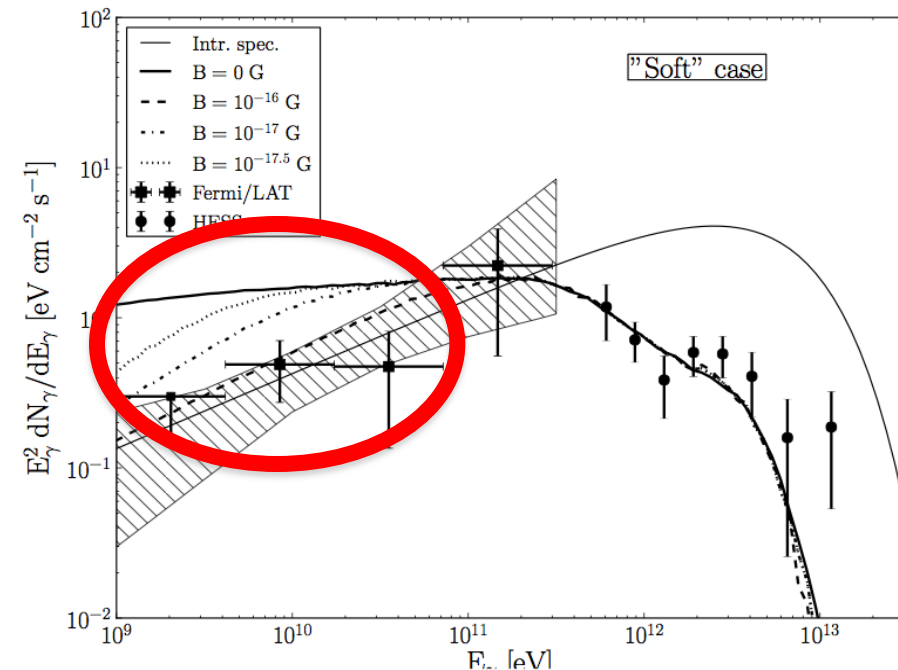
# • The hardest VHE blazar 1ES 0229+200

• Blazar 1ES 0229+200 is considered to be the best candidate for the search of the cascade emission because it has very hard VHE spectrum extending into the  $\sim 10$  TeV energy band, where  $\gamma$ -ray emission is strongly attenuated by the pair production effect.

• Most of the primary  $\gamma$ -ray beam power is removed and transferred to the cascade emission which should appear in the GeV energy band.

• The source is extremely weak in the Fermi energy band. It is detected only in the 3-year long exposure.

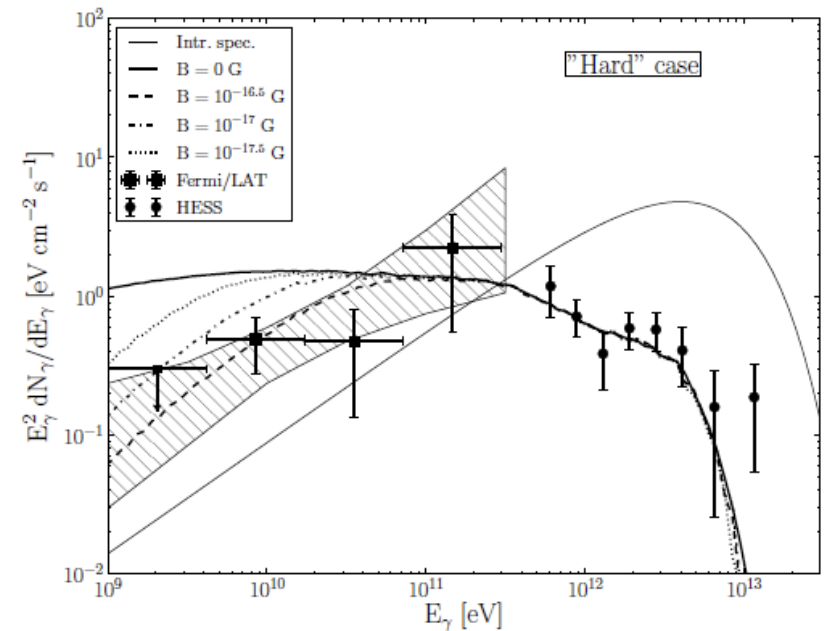
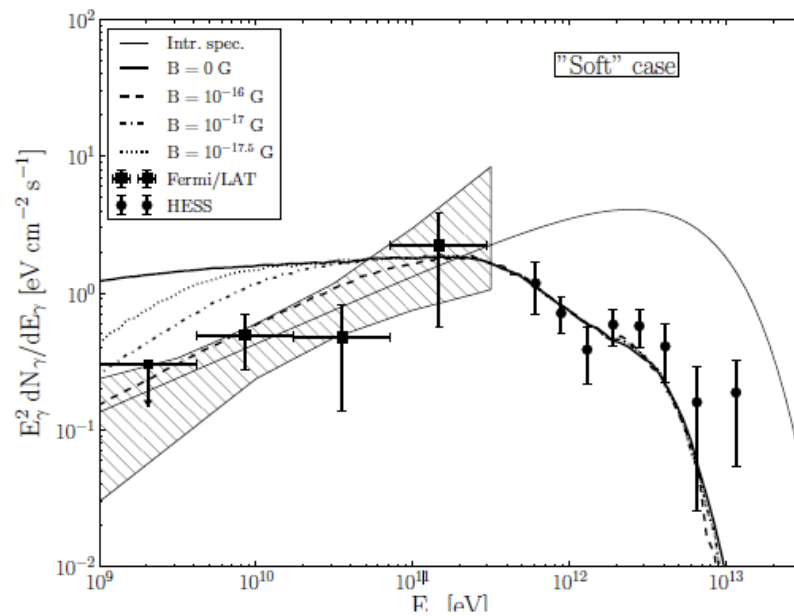
• The source is stable in the VHE band: no variability is found between observations made over  $\sim 5$  yr time span.



$$\Gamma = 1.36 \pm 0.25$$



# EGMF from 1ES 0229+200



# EGMF limits from 5 blazars

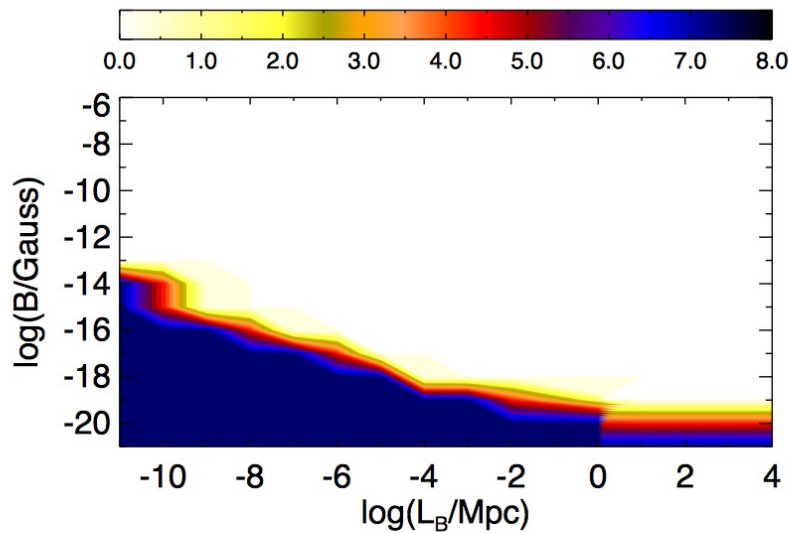


FIG. 4.— The values of parameter space of  $B$  and  $L_B$  ruled out for the combined *conservative* results of Section 4.1 for all of our objects. The contours represent the significance a particular region of parameter space is ruled out, in number of sigma, as indicated by the bar. These constraints assume the Finke et al. (2010) EBL model and  $\theta_j = 0.1$  rad.

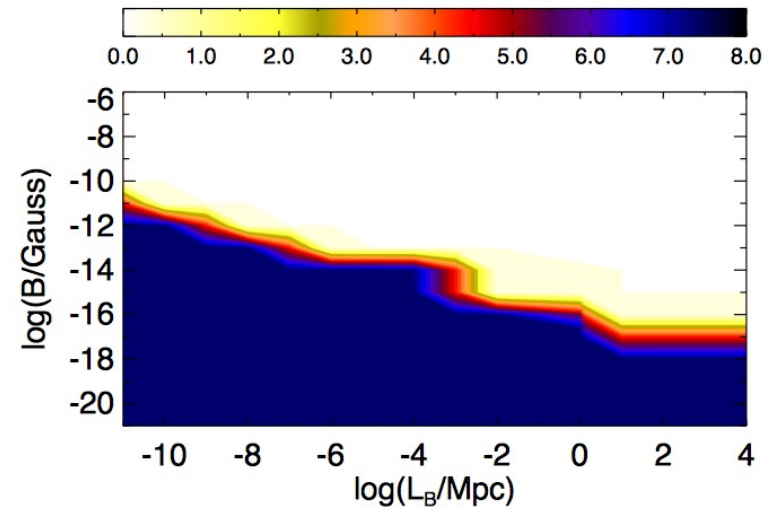
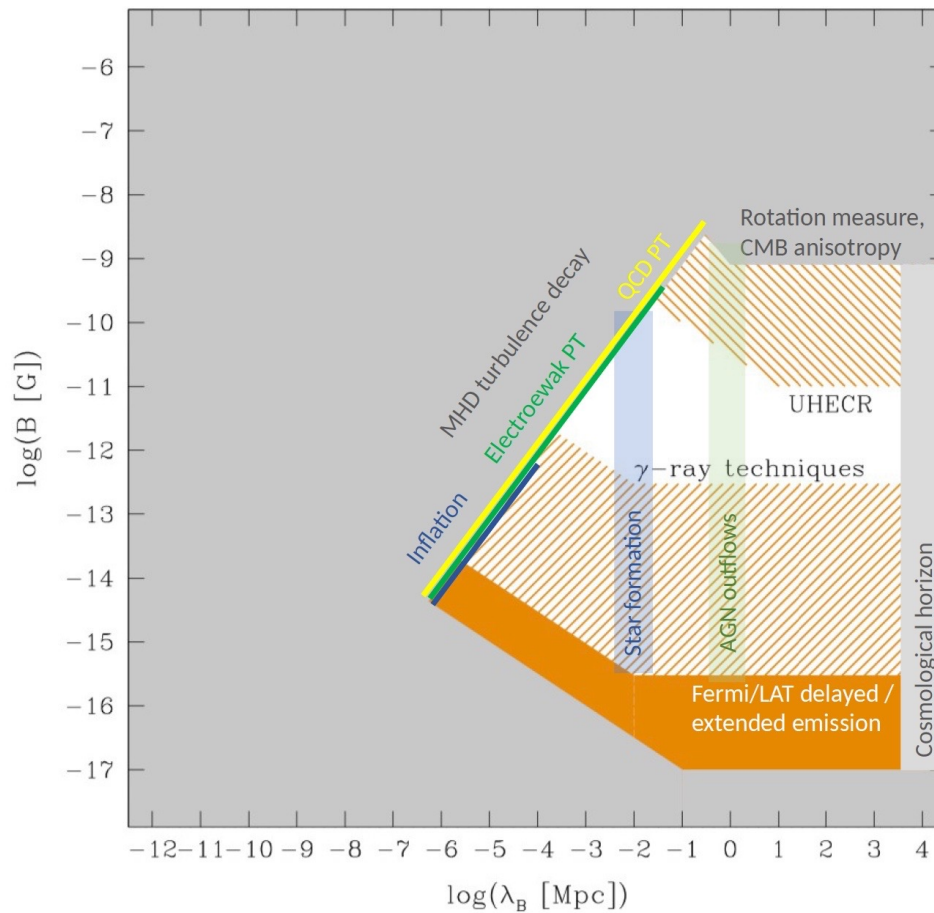


FIG. 7.— The same as Figure 4, only with less conservative assumptions. Here  $F_{\text{cascade},\text{min}} = F_{\text{cascade},\text{max}}$ , and the cascade was calculated assuming  $t_{\text{blazar}} = 1/H_0$  and  $E_{\text{max}}$  is the maximum observed VHE photon bin from the source.

•Finke et al, 1510.02485

# Detection of IGMF



• R. Durrer and A. Neronov, A&A Rev. 21 62, [1303.7121].

*Can gamma-telescopes  
detect 10 pG IGMF (one  
which can help with  $H_0$   
problem)?*



# Detection of 10 pG IGMF

- Cosmological IGMF

$$B \sim 10^{-11} \left[ \frac{\lambda_B}{1 \text{ kpc}} \right] \text{ G}$$

- Primary photon optical depth distance

$$\lambda_{\gamma 0} \simeq 2.5 \left[ \frac{E_{\gamma 0}}{100 \text{ TeV}} \right]^{-1.6} \text{ Mpc}$$

- Electron travel energy loss distance

$$D_e \simeq 7 \left[ \frac{E_e}{50 \text{ TeV}} \right]^{-1} \text{ kpc}$$

- Secondary photon energy

$$E_{\gamma} \simeq 8 \left[ \frac{E_e}{50 \text{ TeV}} \right]^2 \text{ TeV}$$

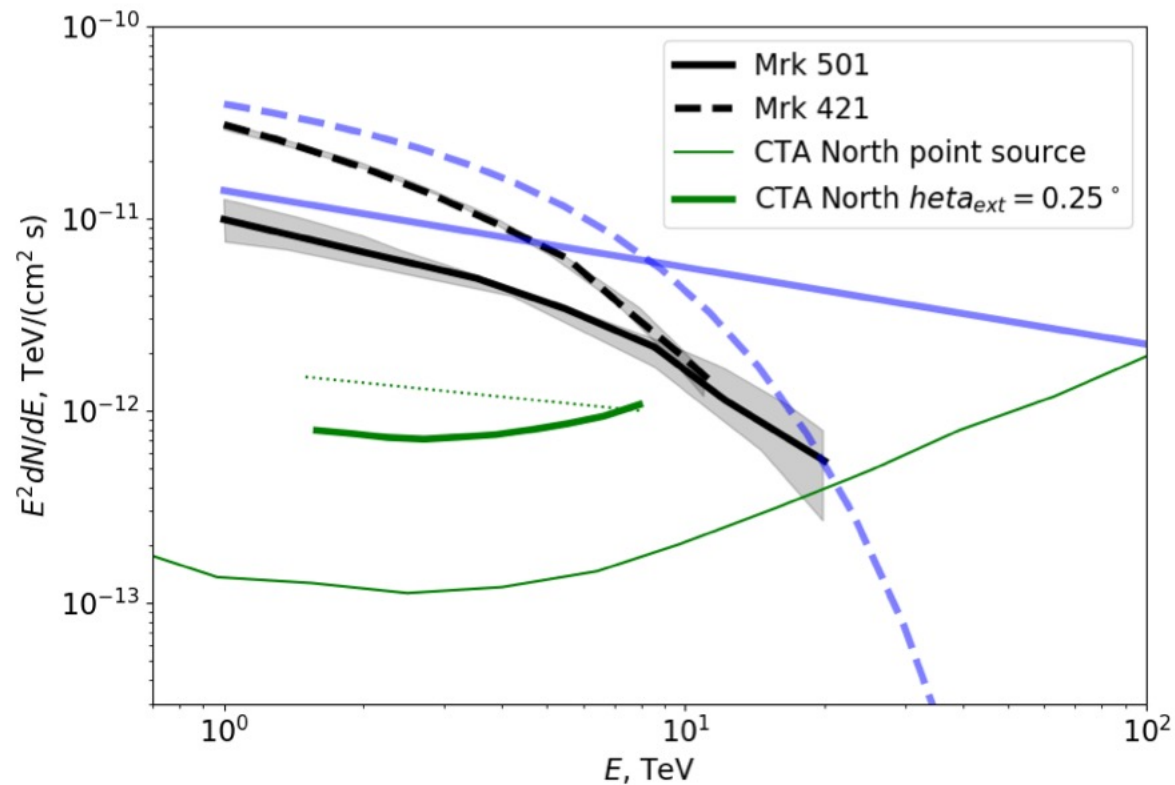
•Kalashev et al, 2007.14331

# Conditions to detect 10 pG IGMF

Probe of the strongest fields  $B \lesssim 10^{-11}$  G requires

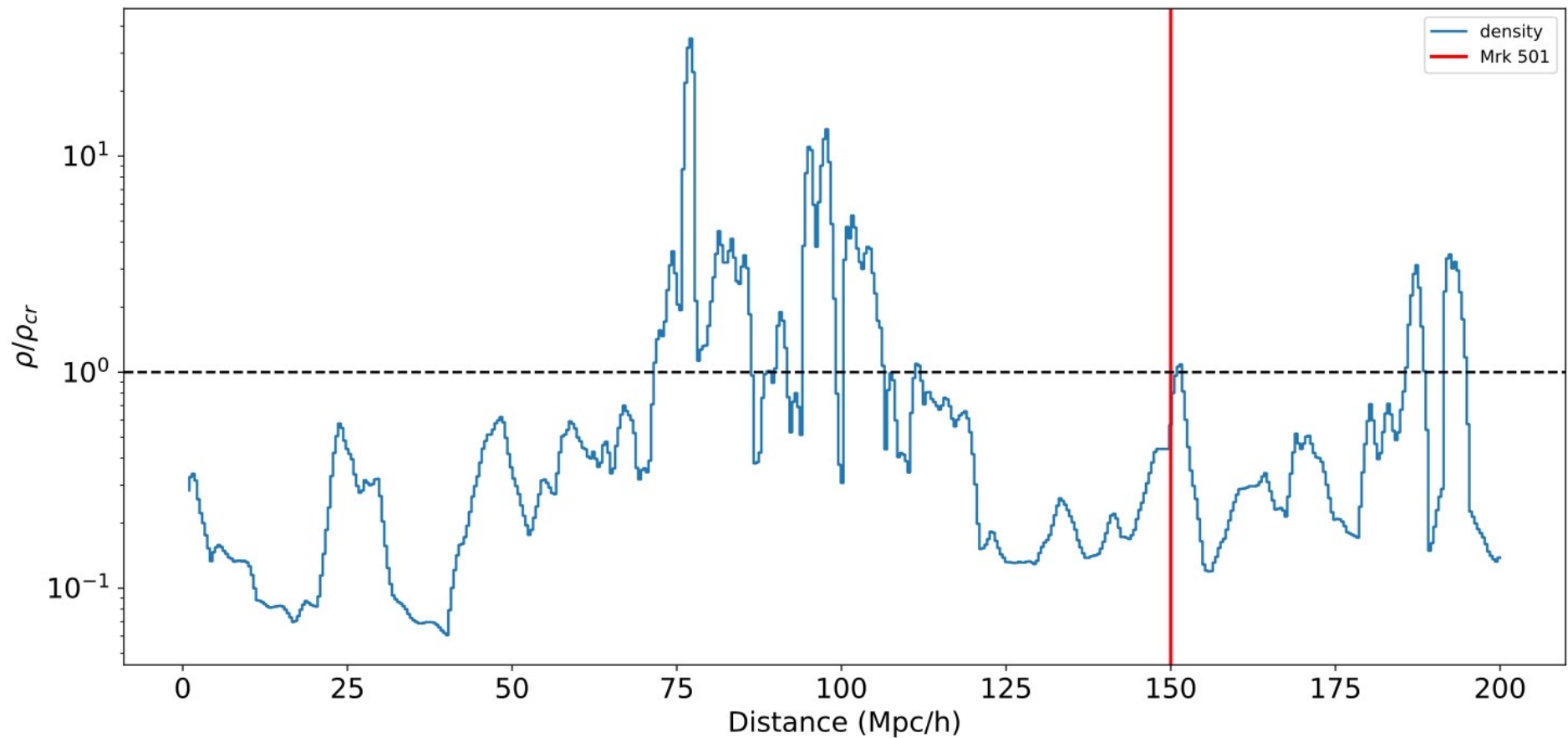
- (a) large primary point-source power in the 100 TeV energy range,
- (b) detectability of extended emission in multi-TeV energy range, and
- (c) presence of primordial IGMF in the several Mpc region around the source.

# Spectrum Mkn 421 and Mkn 501



•Kalashev et al, 2007.14331

# IGMF on LOS to Mrk 501



•Kalashev et al, 2007.14331



## 3D cascade extended emission

$$\Theta_{ext,max} = \frac{R_{ext}}{D} \simeq 0.24^\circ \left[ \frac{\Theta_{jet}}{10^\circ} \right] \left[ \frac{E_{\gamma 0}}{100 \text{ TeV}} \right]^{-1.6} \quad (12)$$

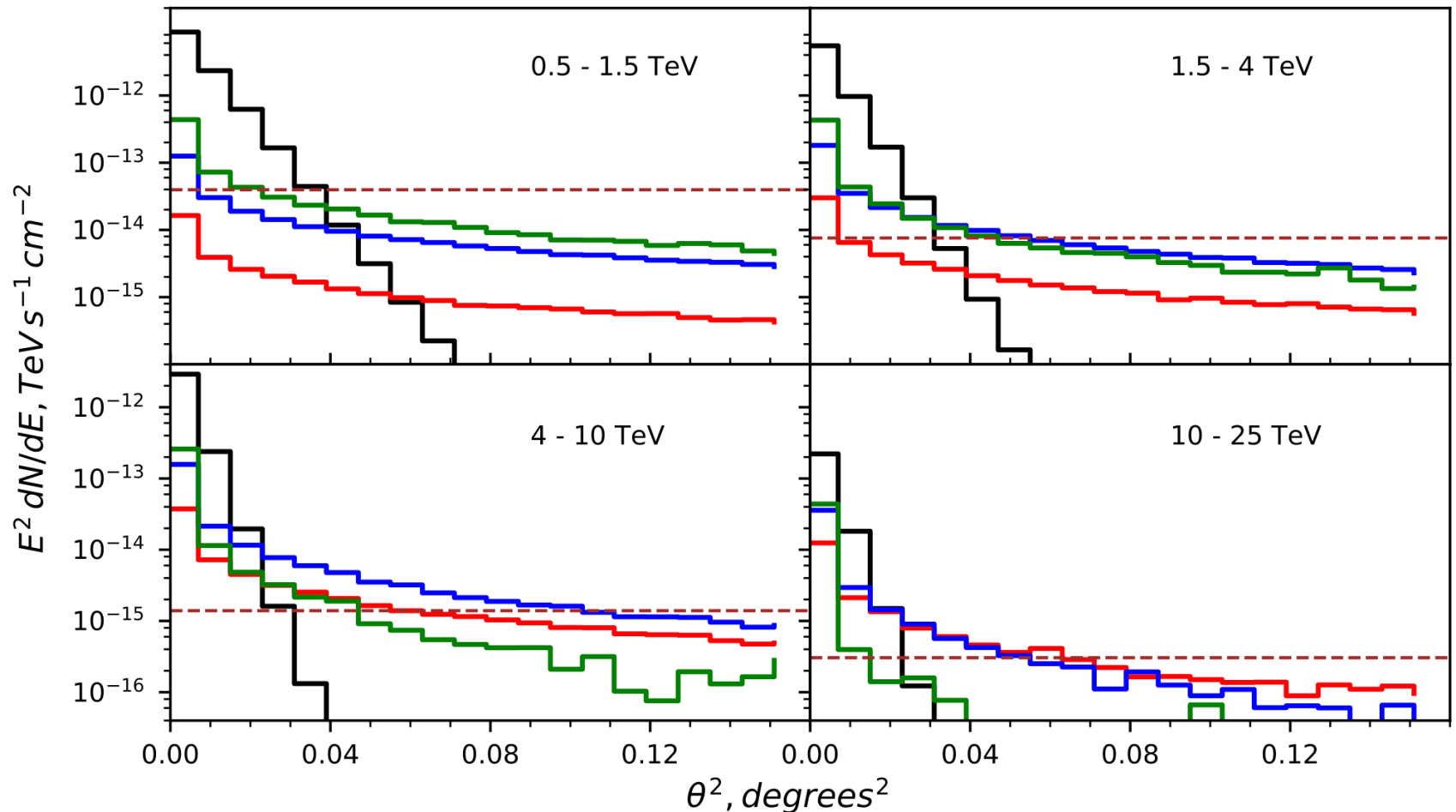
$$\left[ \frac{D}{120 \text{ Mpc}} \right]^{-1} \simeq 0.24^\circ \left[ \frac{\Theta_{jet}}{10^\circ} \right] \left[ \frac{E_\gamma}{8 \text{ TeV}} \right]^{-0.8} \left[ \frac{D}{120 \text{ Mpc}} \right]^{-1}$$

$$T_{ext,max} = D\Theta_{ext,max}^2/c \simeq$$

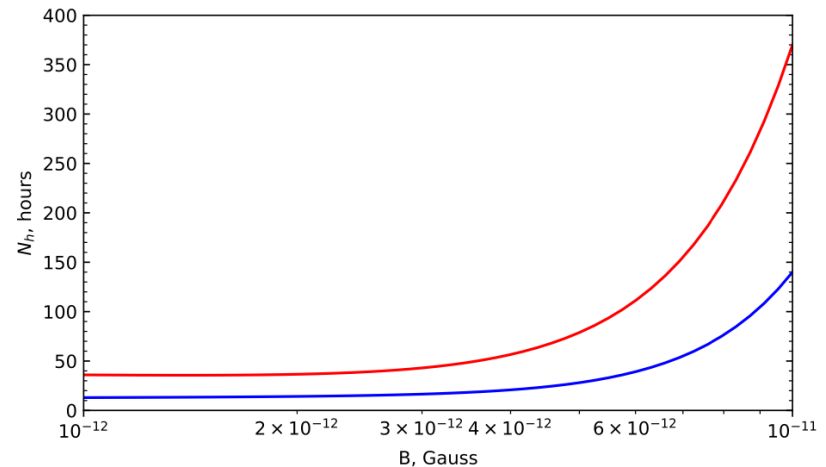
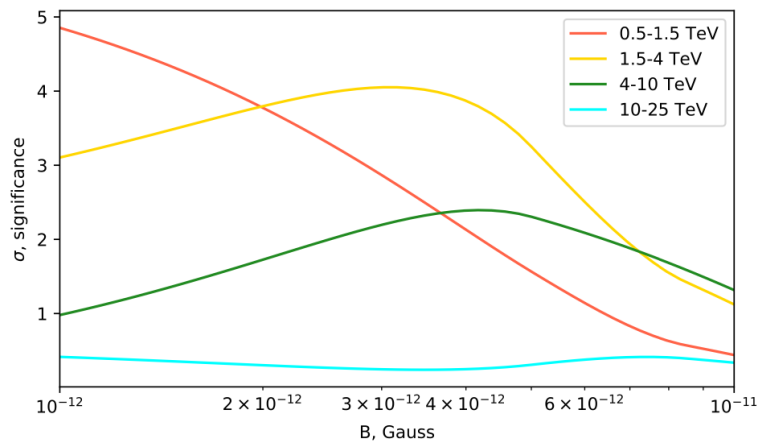
$$8 \left[ \frac{\Theta_{jet}}{10^\circ} \right]^2 \left[ \frac{E_\gamma}{8 \text{ TeV}} \right]^{-1.6} \text{ kyr}$$

•Kalashev et al, 2007.14331

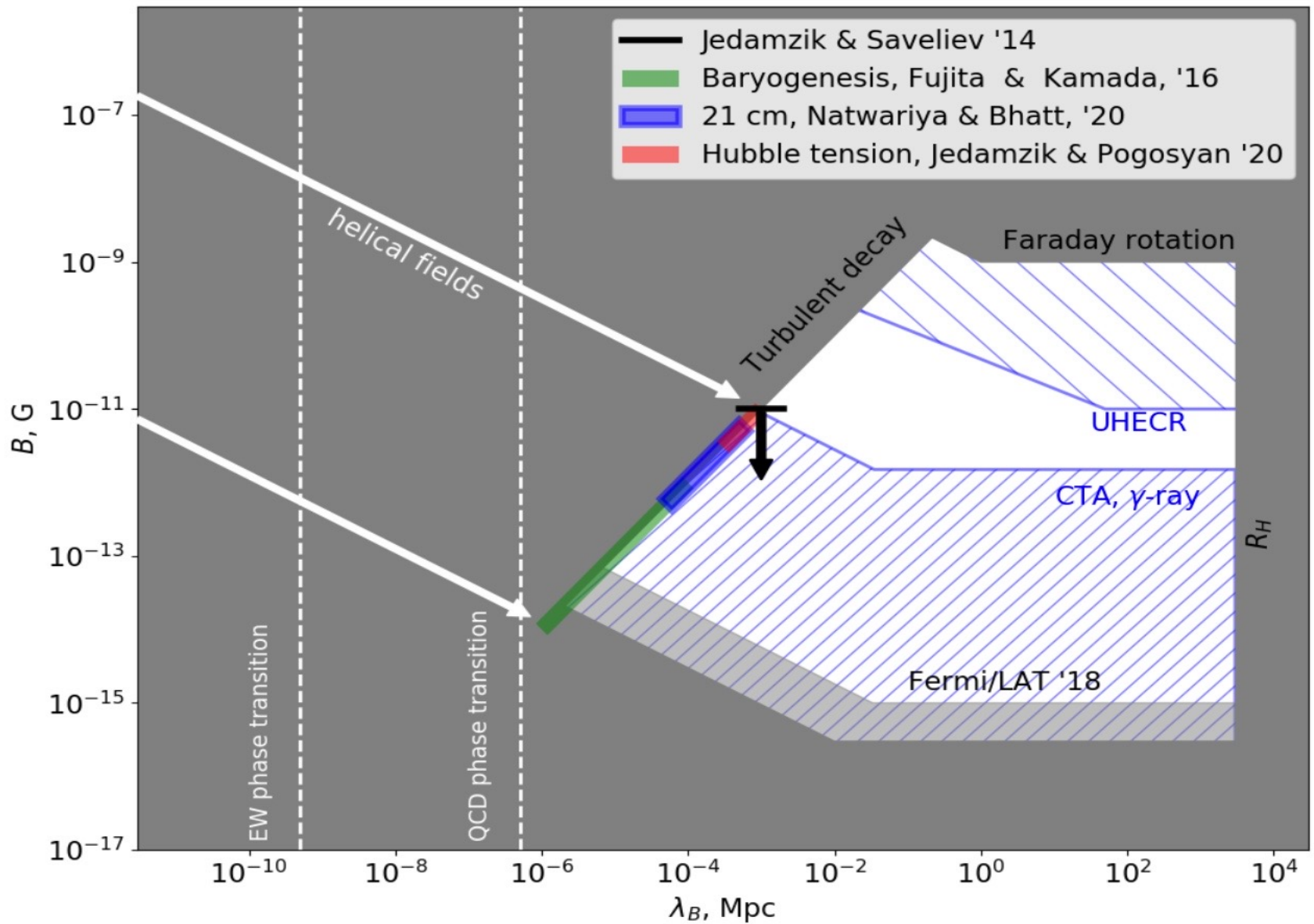
# Extended emission around Mkn 501



# Detection of extended emission around Mkn 501 by CTA North for 1-10 pG IGMF

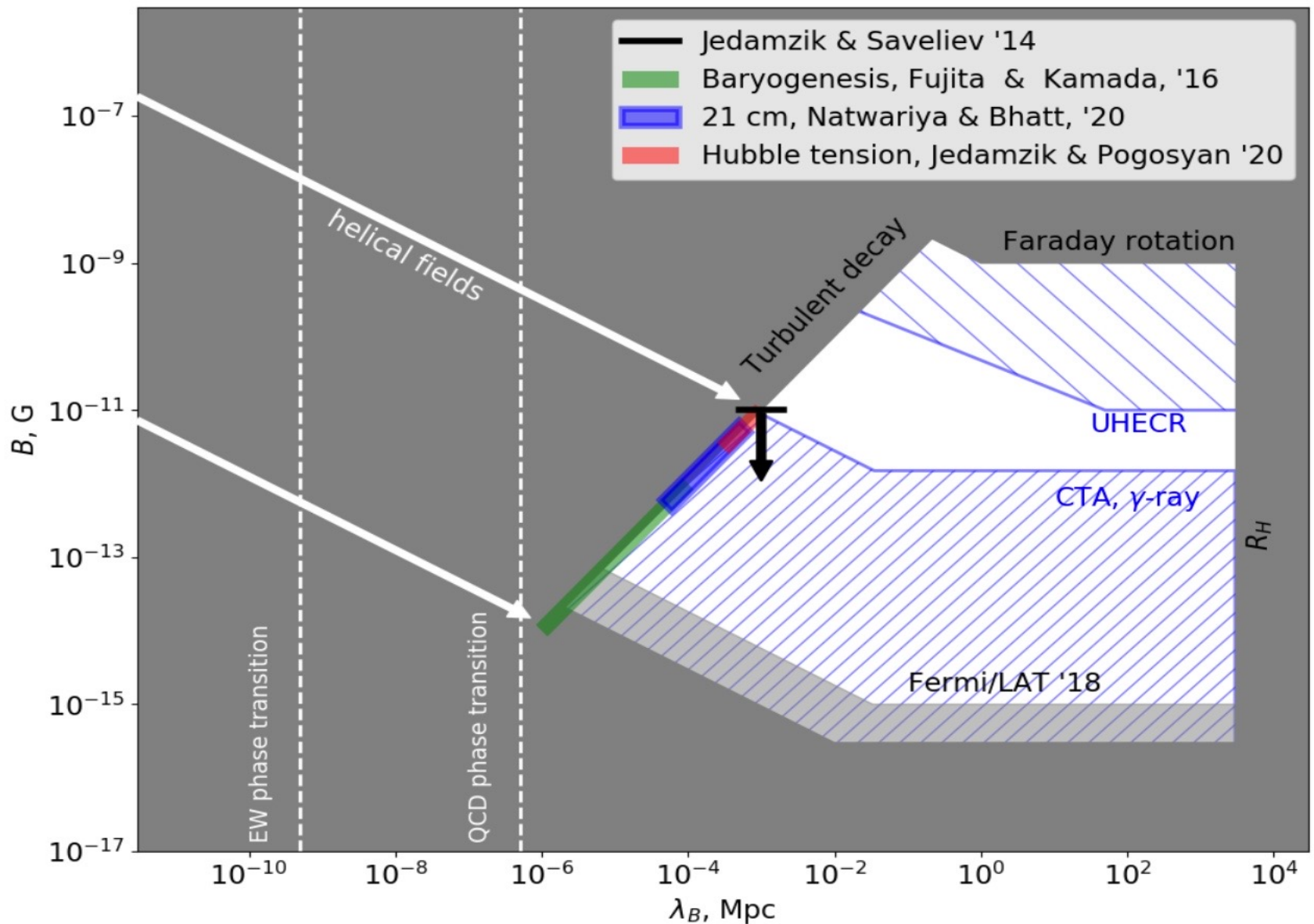


•Kalashev et al, 2007.14331



•Kalashev et al, 2007.14331

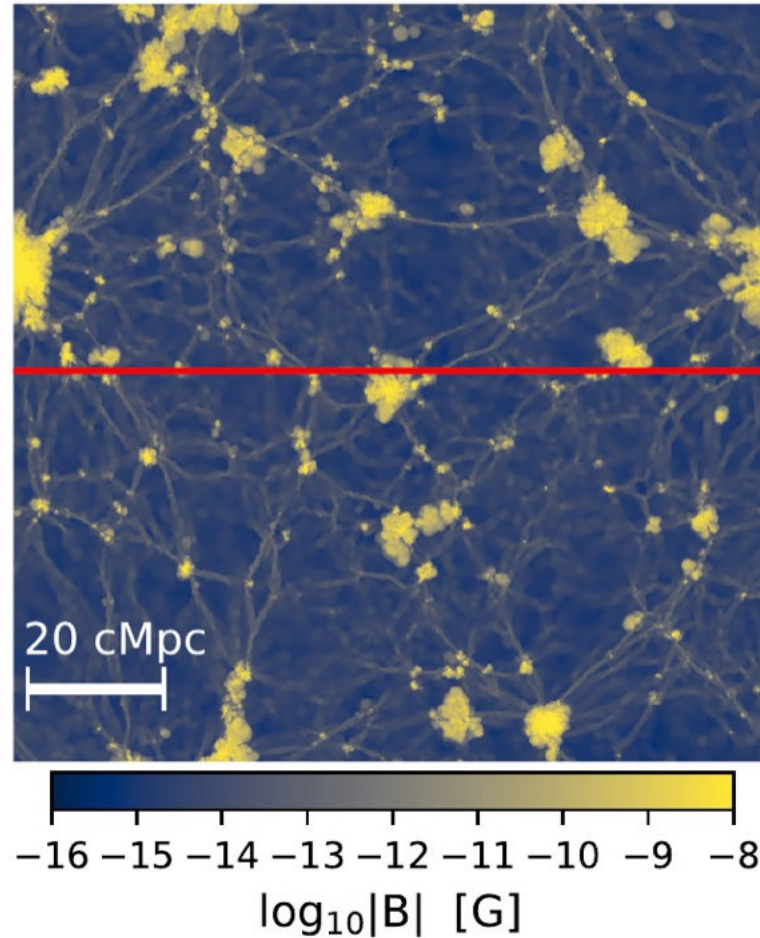




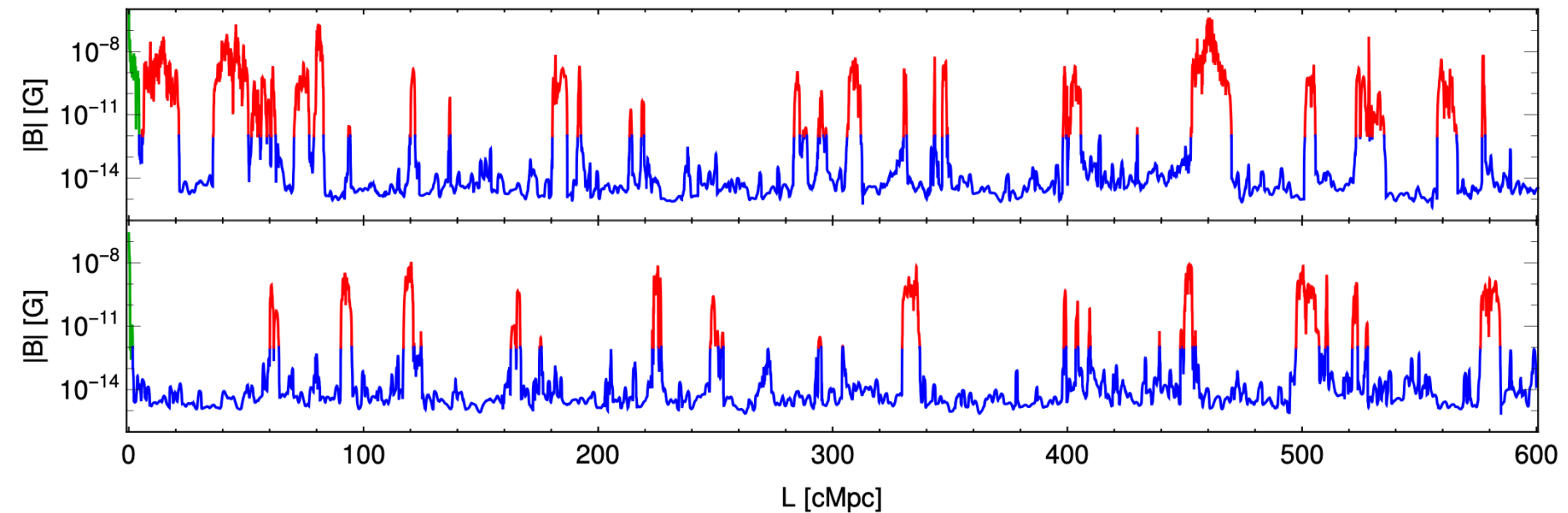
•Kalashev et al, 2007.14331

# *Inter-Galactic Magnetic Field and AGN feedback*

# 3D magnetic field in ILLUSTRIS-TNG



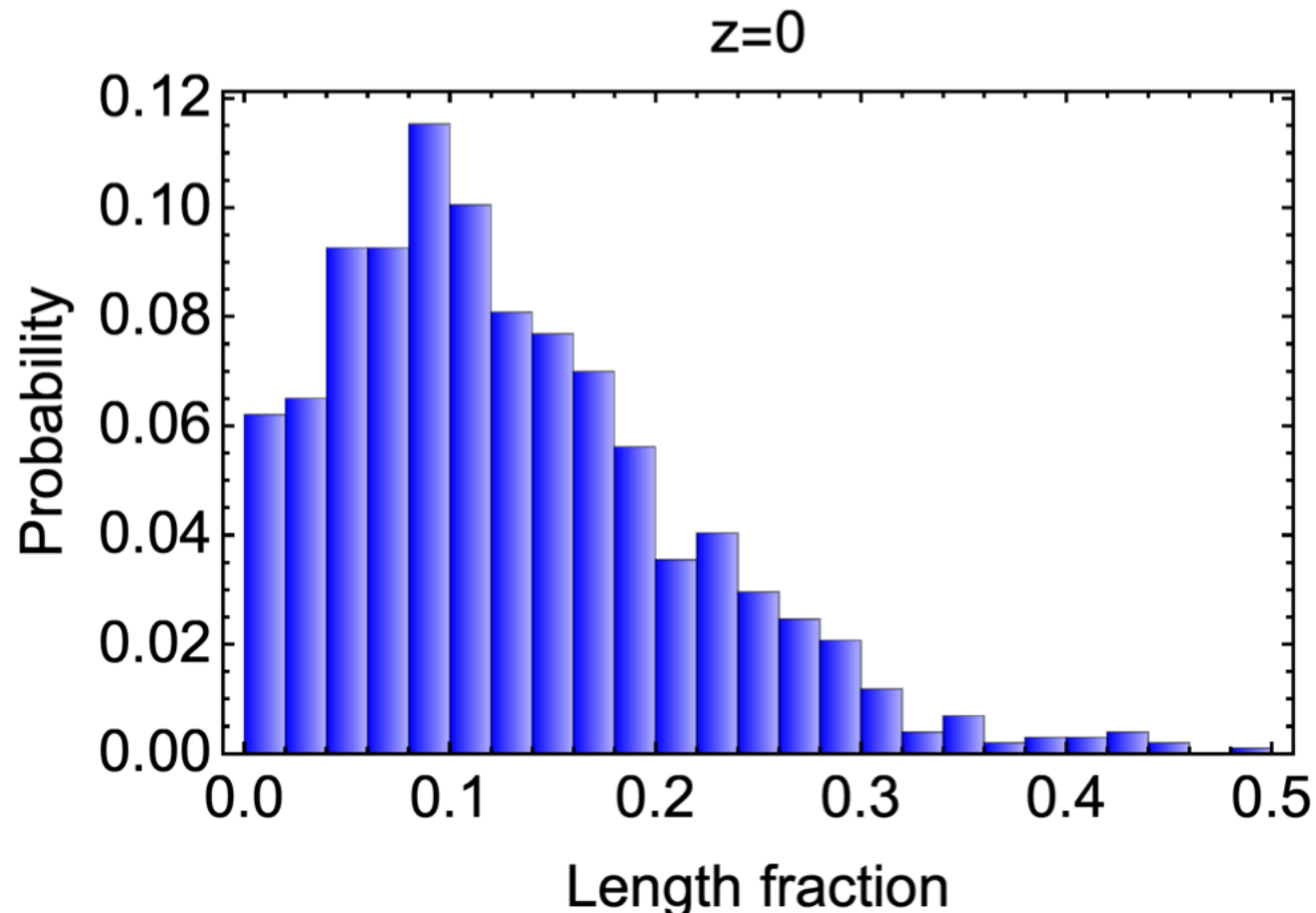
# IGMF on LOS and magnetic bubbles



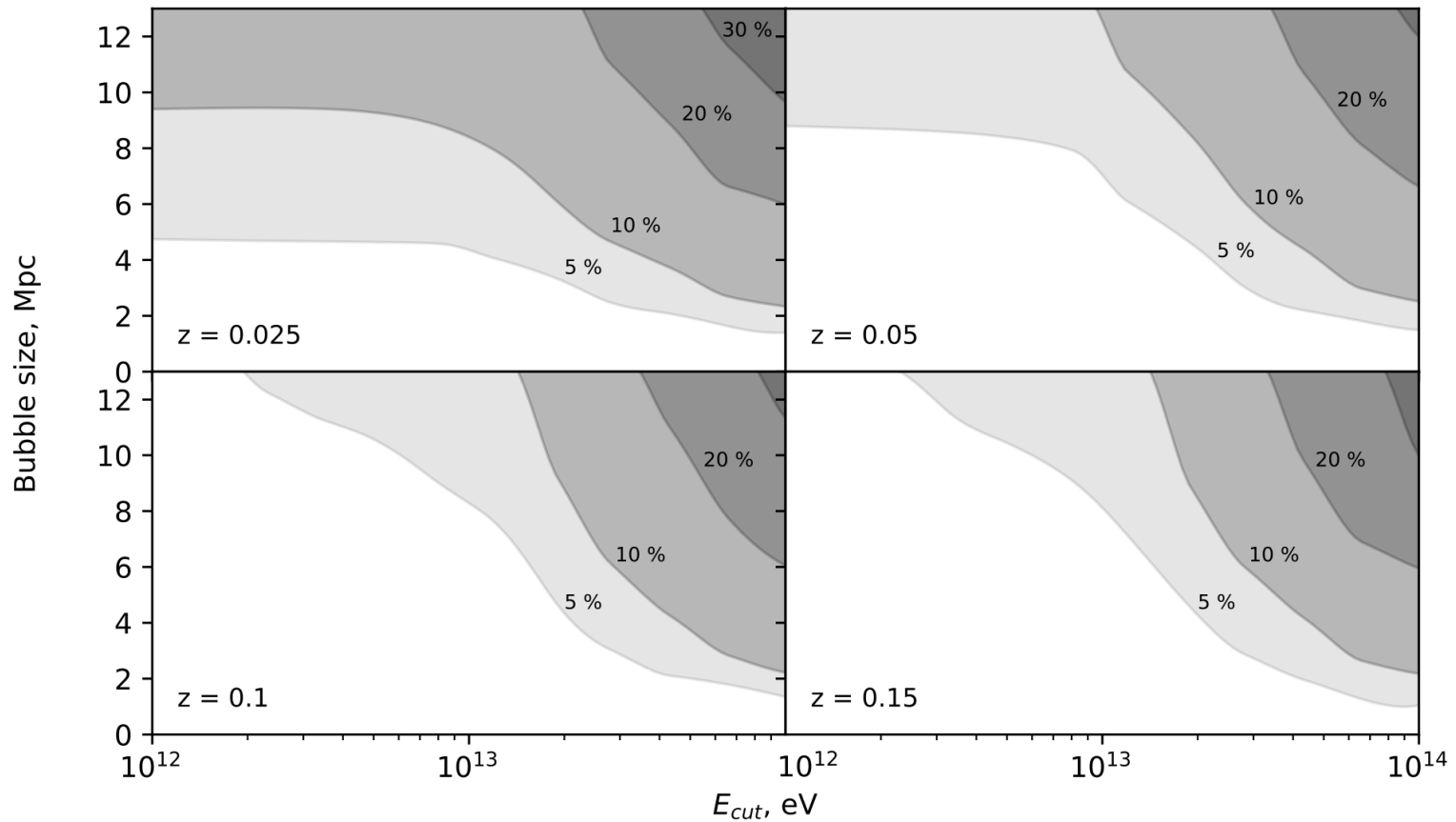
•Bondarenko et al, 2106.02690



# Probability to have strong MF on LOS

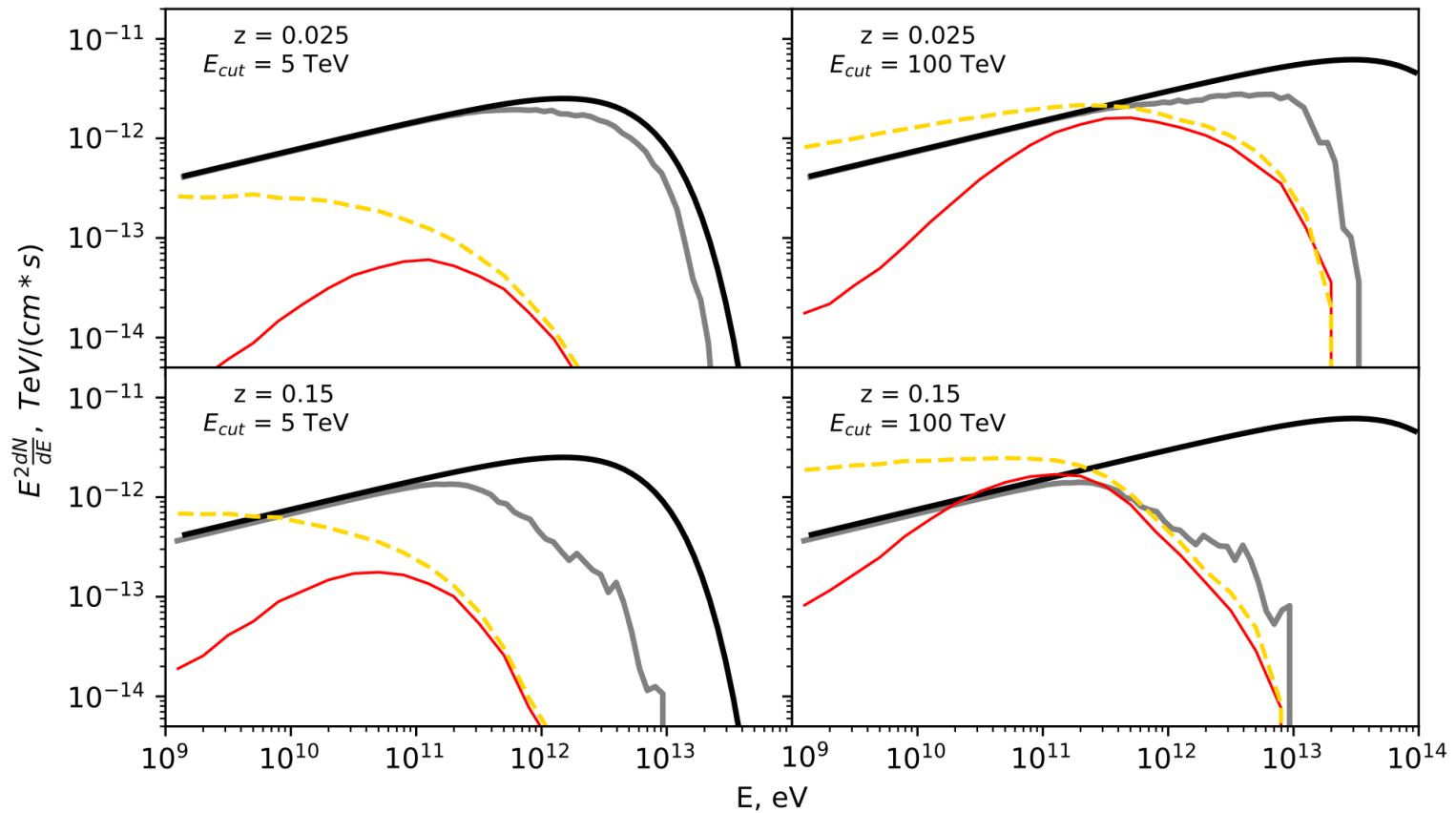


# Part of cascade « eaten » by host bubble



•Bondarenko et al, 2106.02690

# Spectra of blazars

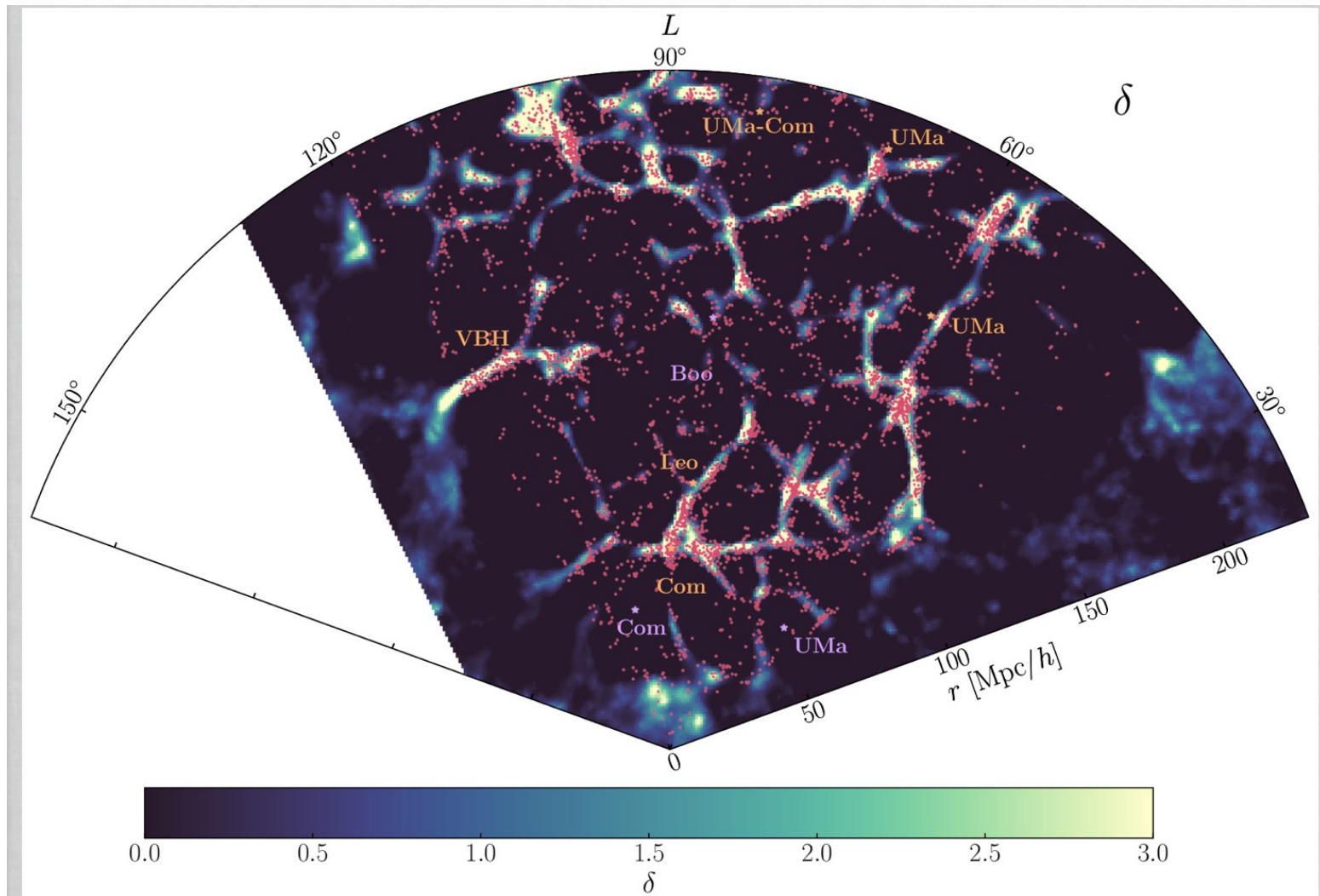


•Bondarenko et al, 2106.02690

# *Detection of Inter-Galactic Magnetic Field from inflation*



# BORG LSS and RAMSES MHD

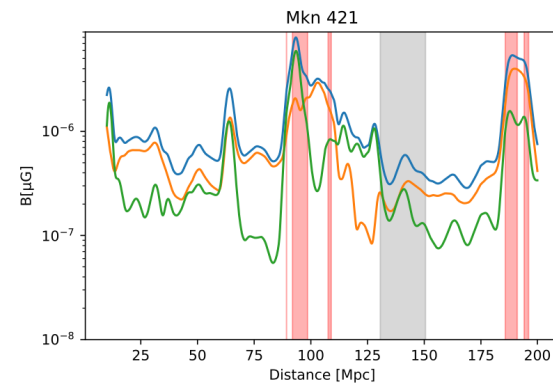
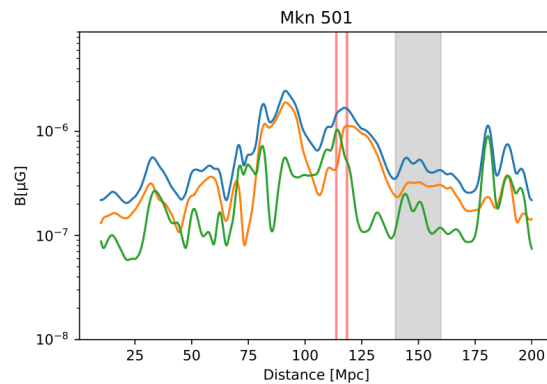
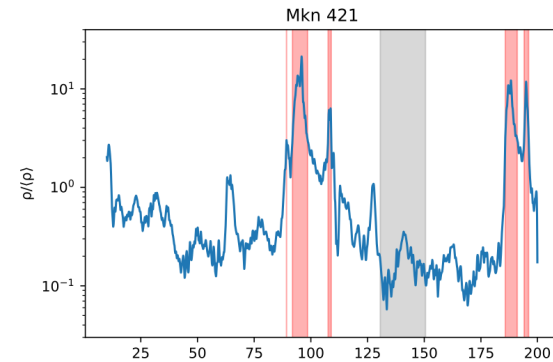
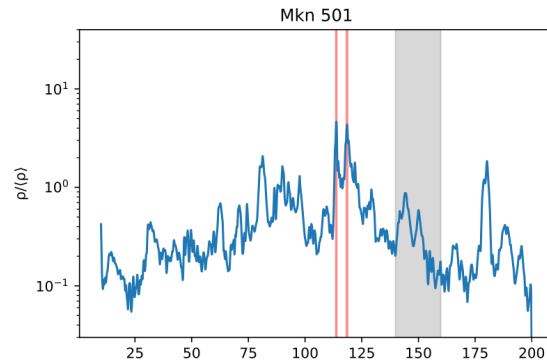


# TeV blazars within 250 Mpc

Name	RA	Dec	$z$	$F_{1\text{TeV}}, \text{TeV cm}^{-2} \text{s}^{-1}$
Mkn 421	166.11	38.21	0.031	$2 \times 10^{-11}$
Mkn 501	253.47	39.76	0.033	$1 \times 10^{-11}$
QSO B2344+514	356.77	51.7	0.044	$4 \times 10^{-12}$
Mkn 180	174.11	70.16	0.046	$8 \times 10^{-13}$
1ES 1959+650	299.99	65.15	0.047	$6 \times 10^{-12}$
AP Librae	229.42	-24.37	0.04903	$4 \times 10^{-13}$
TXS 0210+515	33.57	51.75	0.04913	$2 \times 10^{-13}$

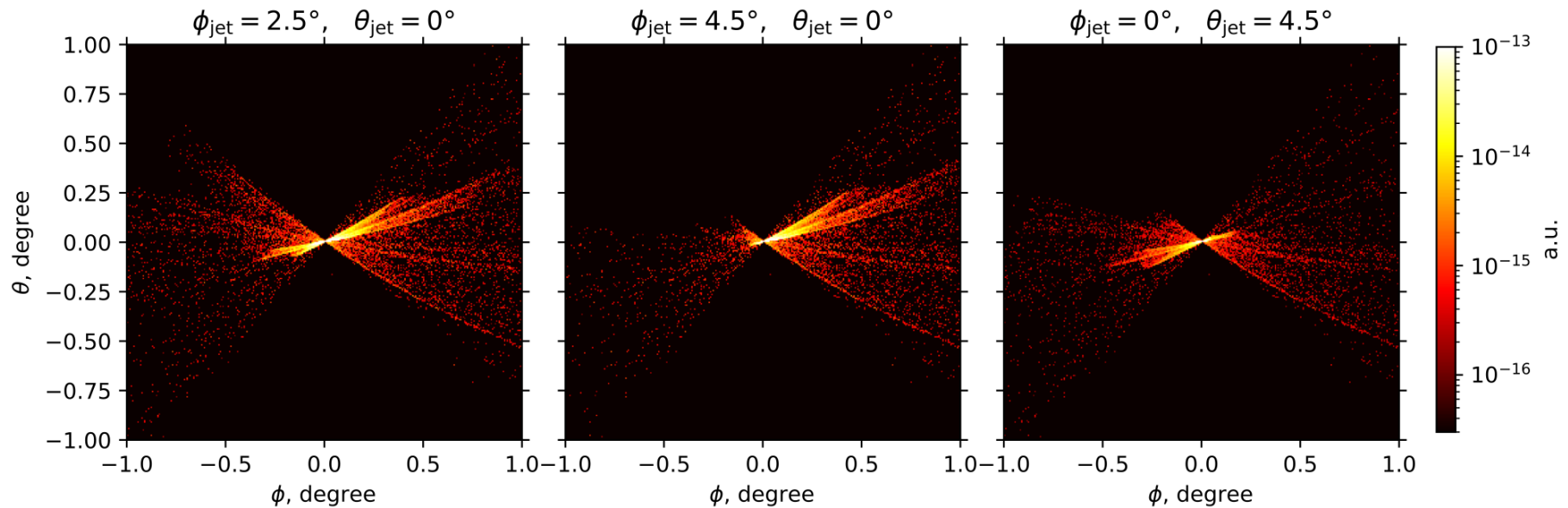
•A.Korochkin et al, 2111.10311.

# IGMF on LOS



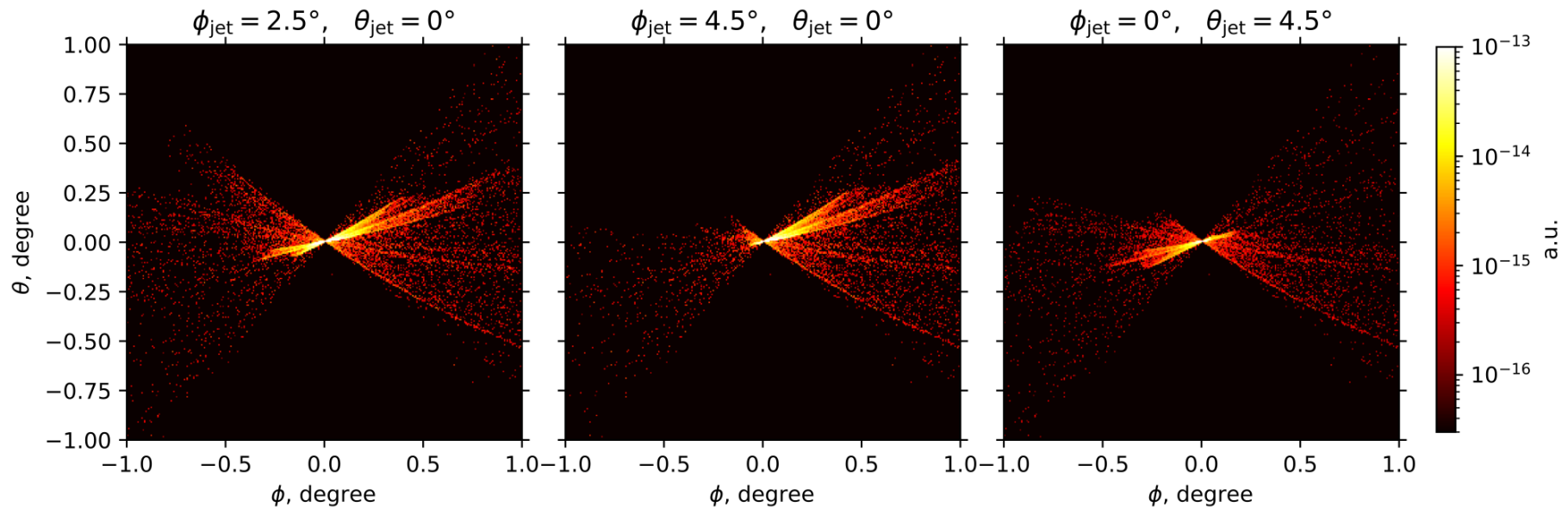
•A.Korochkin et al, 2111.10311.

# IGMF on LOS



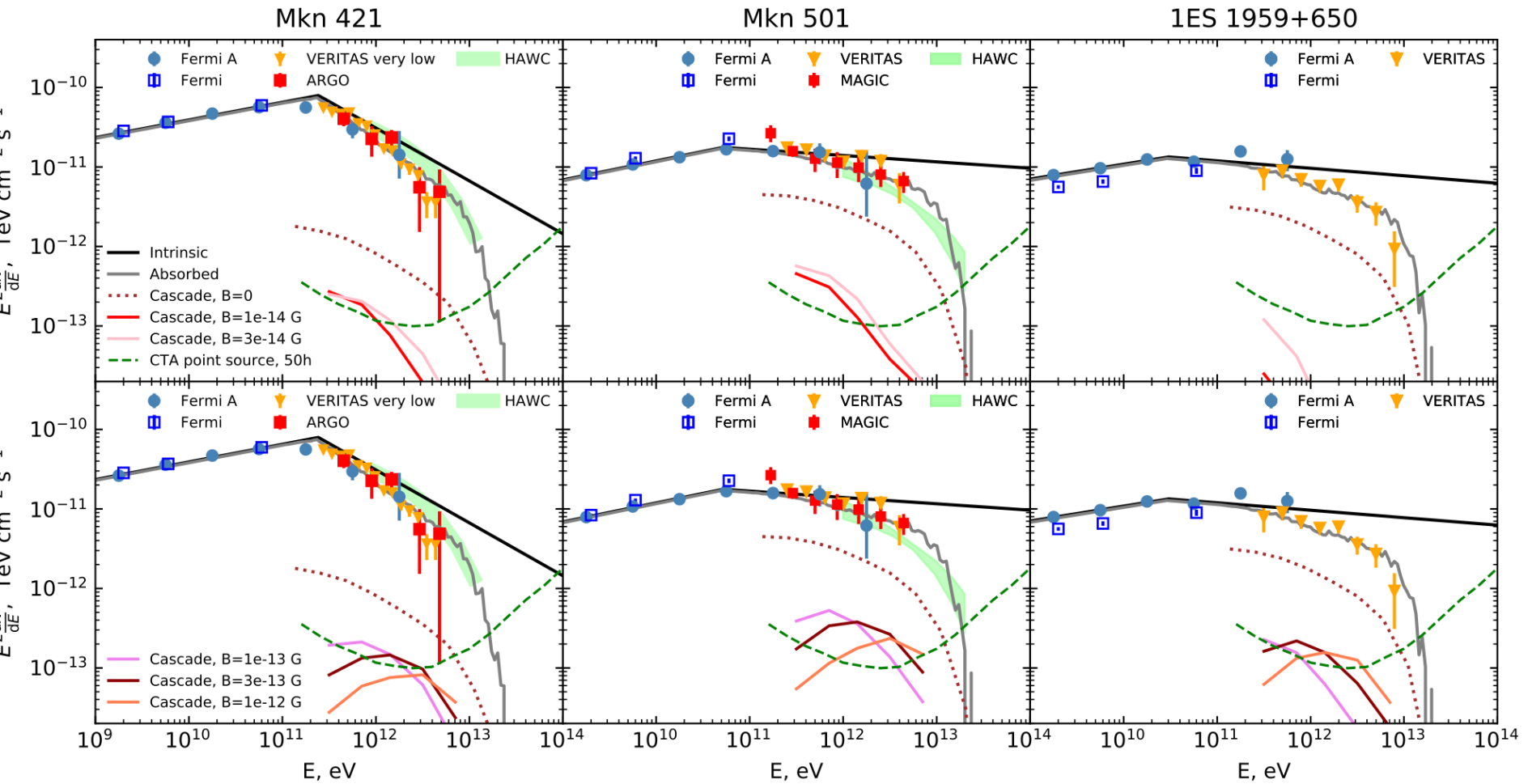
•A.Korochkin et al, 2111.10311.

# IGMF on LOS



•A.Korochkin et al, 2111.10311.

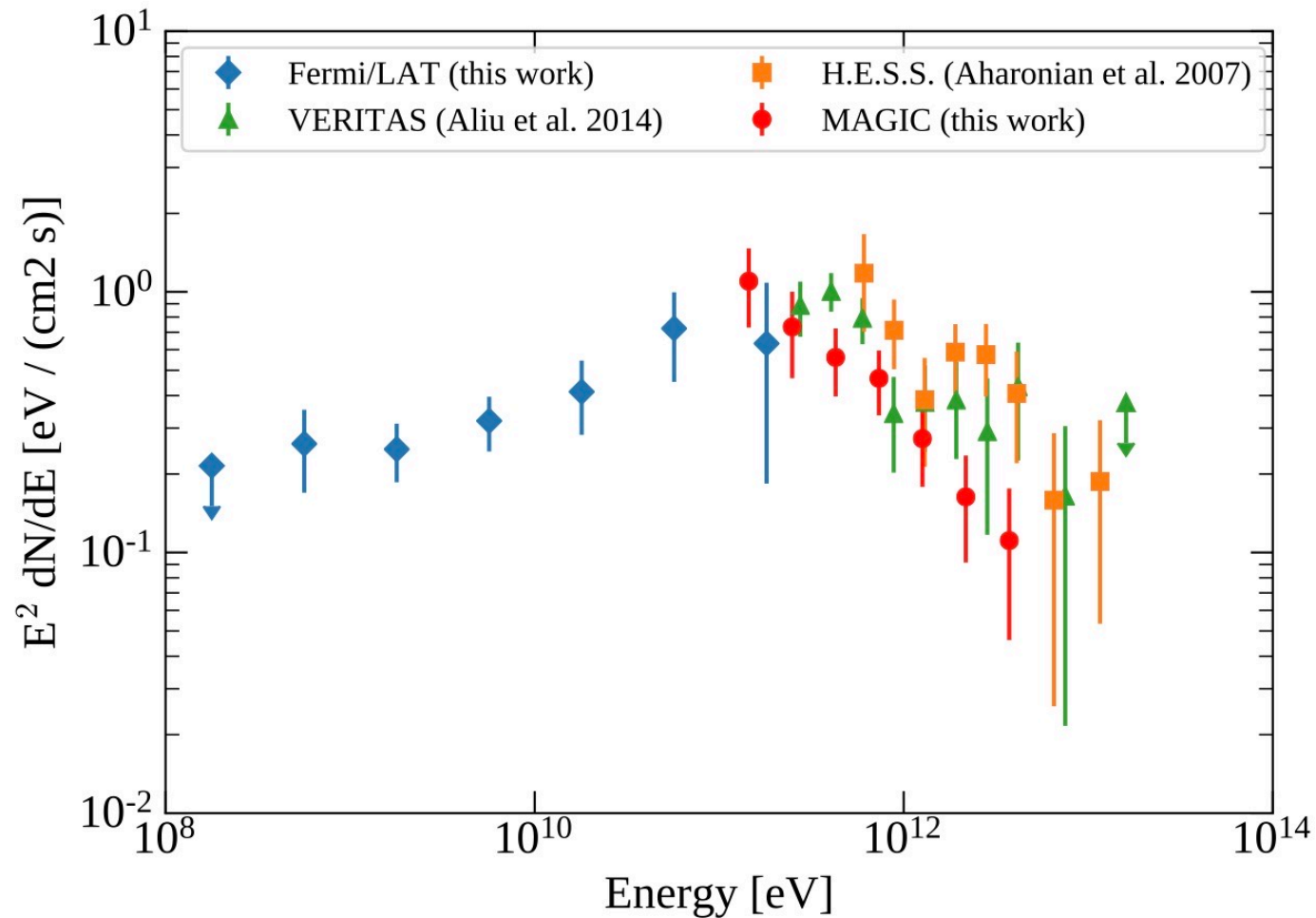




•A.Korochkin et al, 2111.10311.

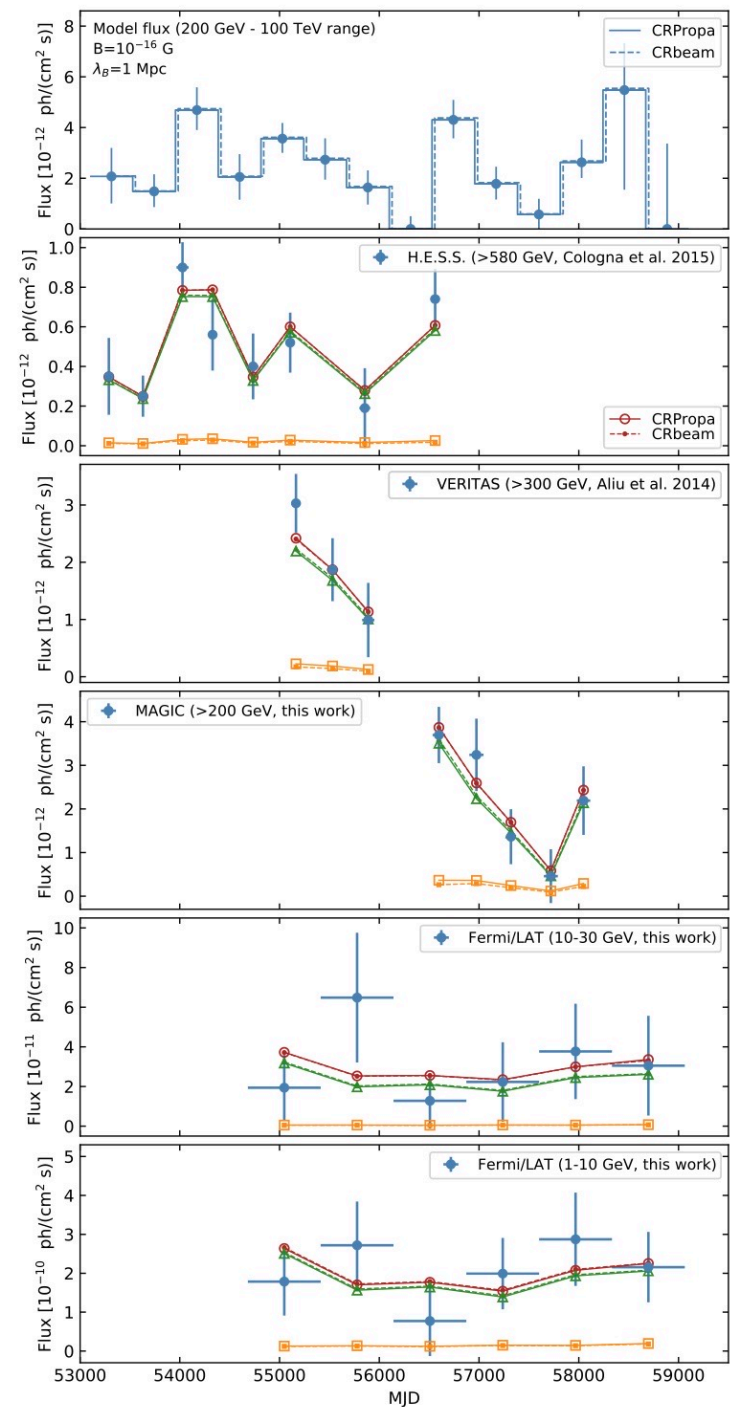
# *Inter-Galactic Magnetic Field by MAGIC*

# Cosmological magnetic field from 1ES 0229+200 measurements 2210.03321

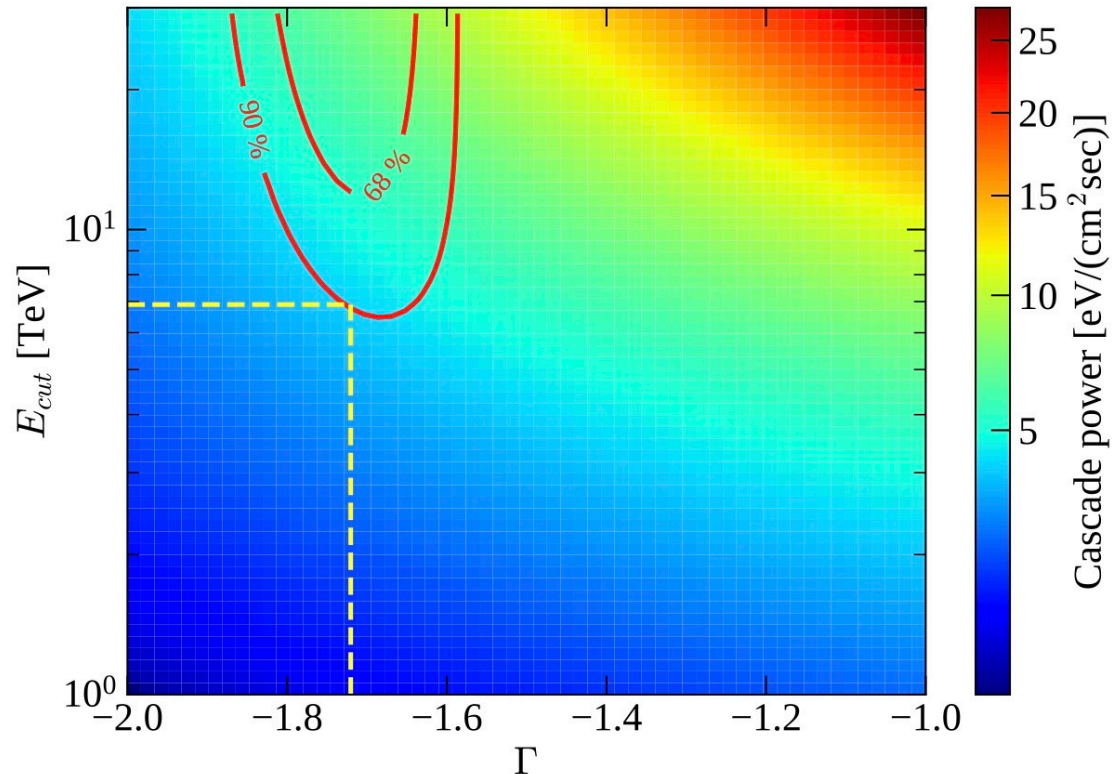


# Flux of 1ES 0229+200 in gamma-rays

2210.03321



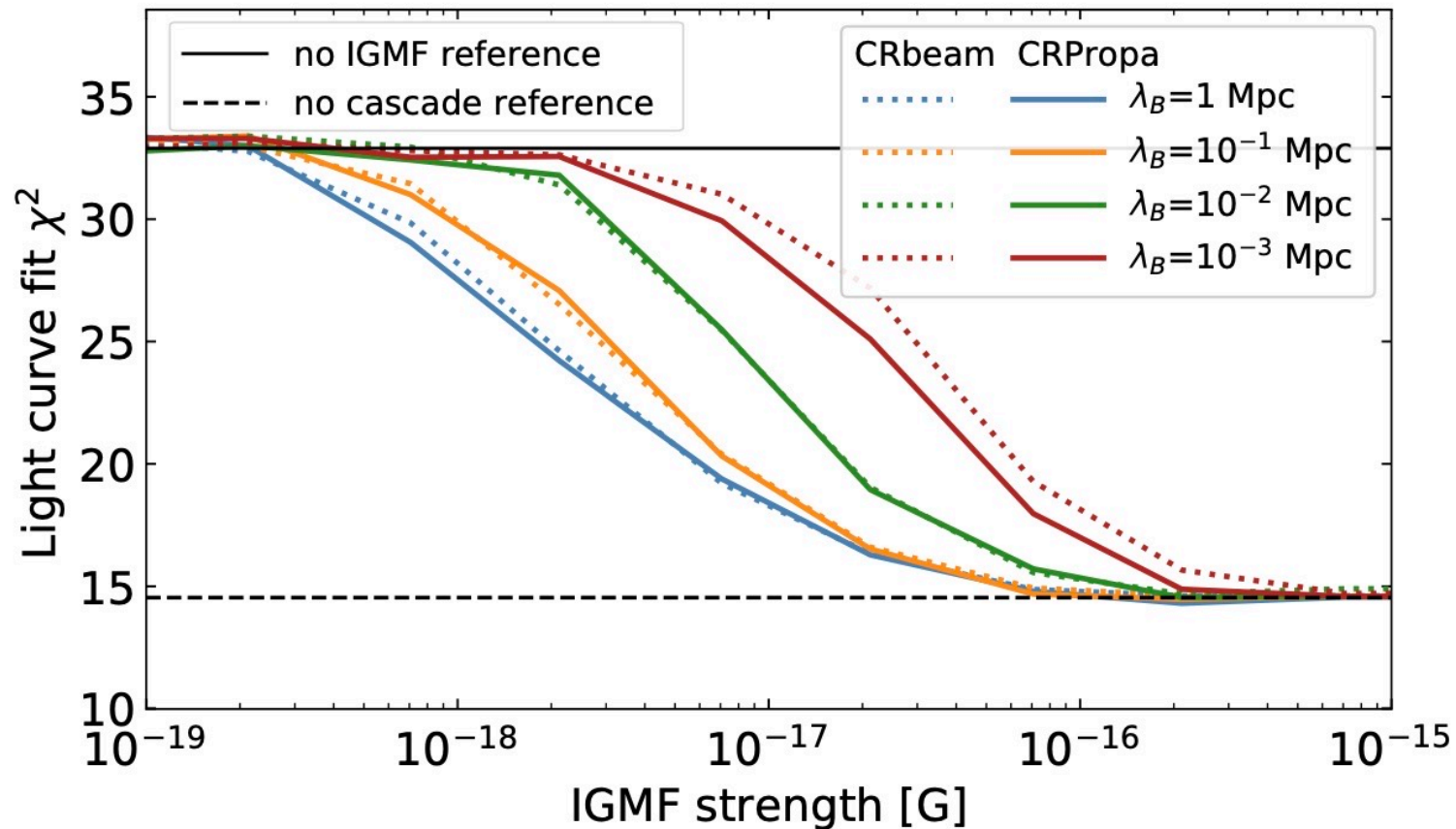
## Flux of 1ES 0229+200 in gamma-rays



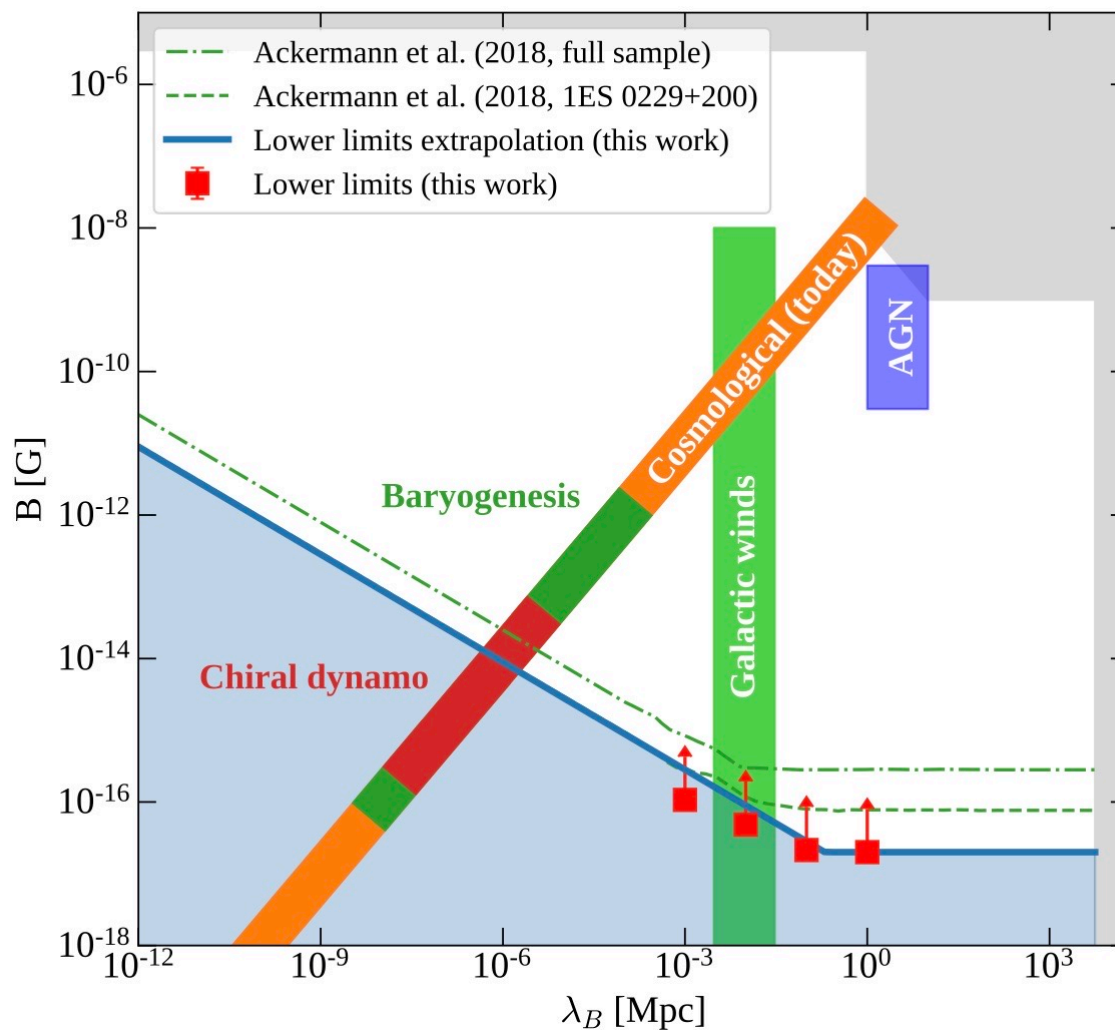
**Fig. 3.** The scan of the cascade power in the  $\Gamma - E_{\text{cut}}$  parameter space along with the 68% and 90% confidence contours from the  $\chi^2$  fit. At 90% confidence level the minimal cascade, marked with the yellow dashed lines, corresponds to  $\Gamma \approx 1.72$  and  $E_{\text{cut}} \approx 6.9$  TeV.



# Flux of 1ES 0229+200 in gamma-rays



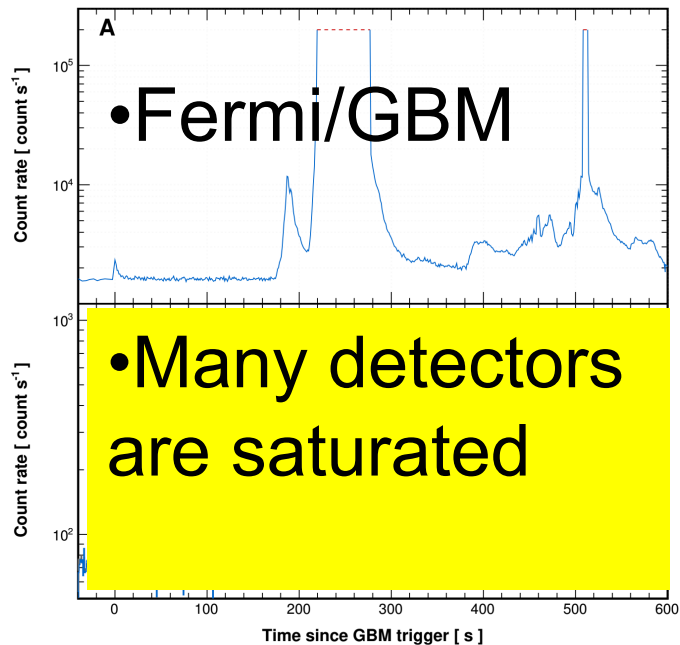
## Magnetic field from 1ES 0229+200, 2210.03321



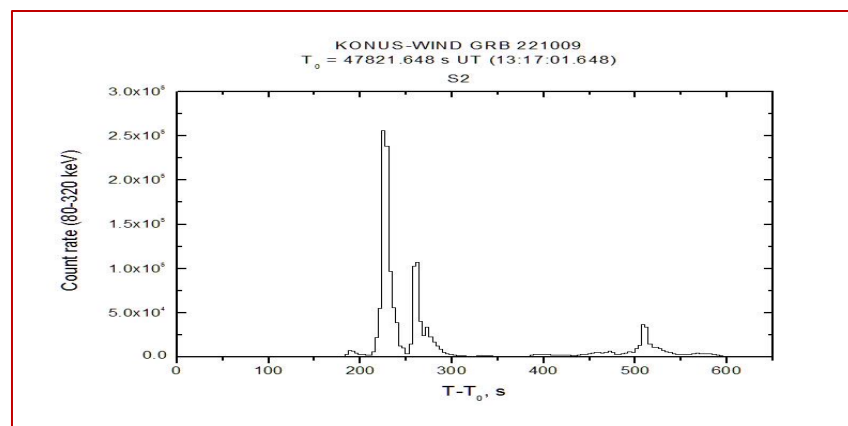
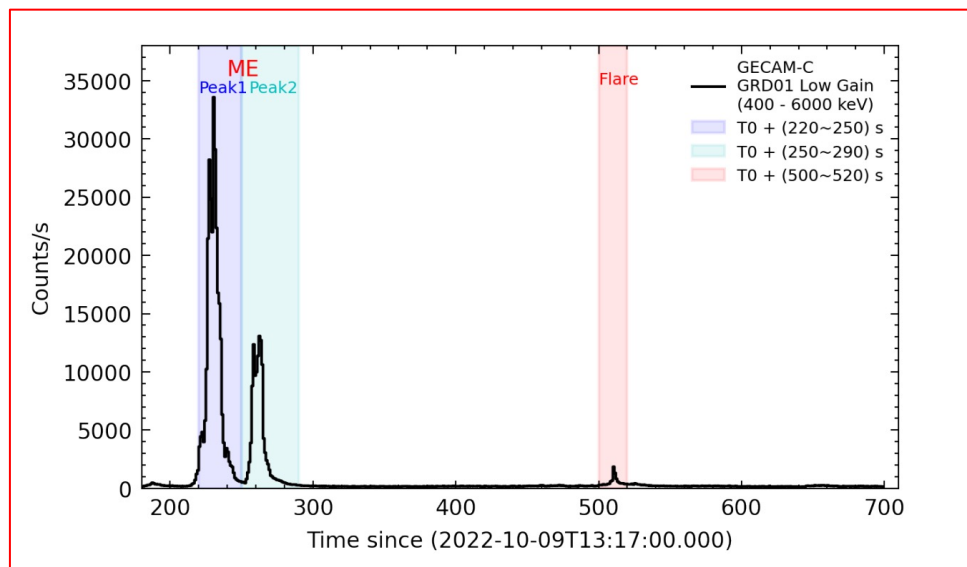
# *Inter-Galactic Magnetic Field from BOAT GRB*

## GRB 221009A: brightest-of-all-time (BOAT) GRB

- Triggered on a weak precursor
- Fluence:  $>5 \times 10^{-2} \text{ erg/cm}^2$ , low redshift ( $z=0.151$ )
- deriving an enormous energy  $E_{\gamma, \text{iso}} \sim 10^{55} \text{ erg}$



## GECAM/Konus-Wind Observations of GRB 221009A

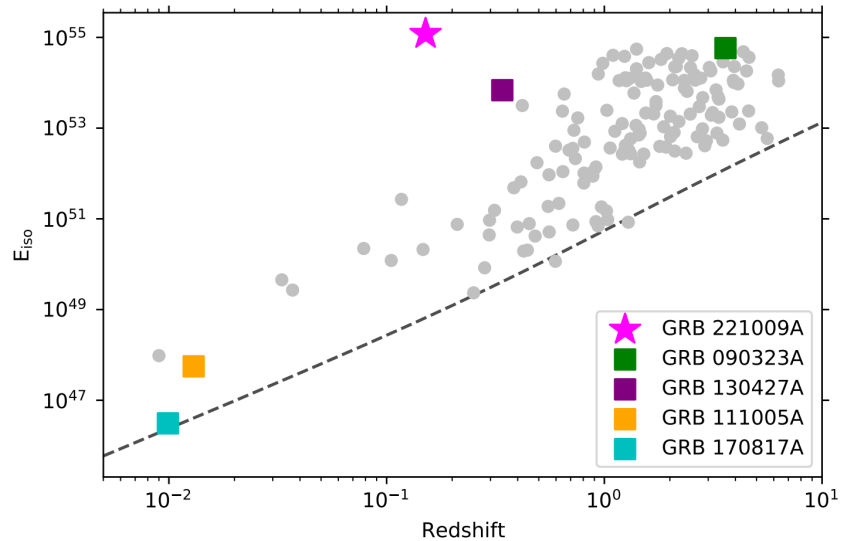
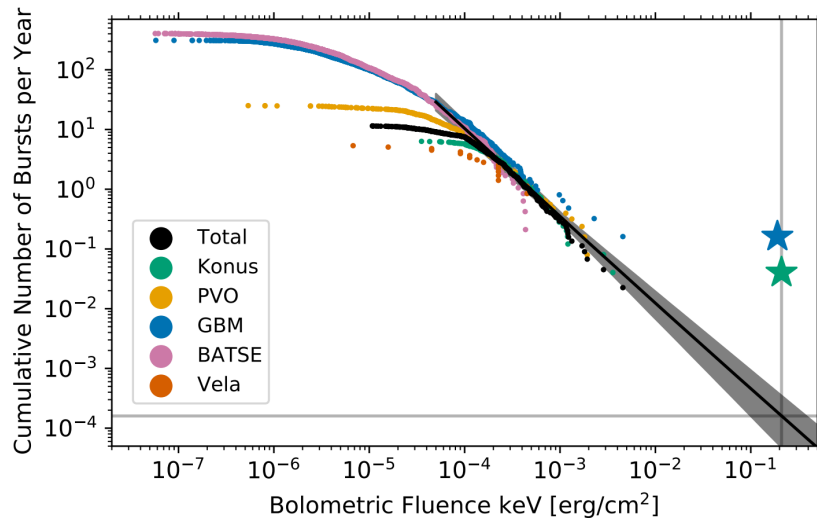


•  $E_{\text{iso}} \sim 1.5 \times 10^{55} \text{ erg}$

• Main peak 1 lasts  
~10 s



# •GRB 221009A: A very rare event



•Fluence:  $>5 \times 10^{-2} \text{ erg/cm}^2$

• $R_{\text{GRB}} \leq 6.1 \times 10^{-4} \text{ Gpc}^{-3} \text{ yr}^{-1}$

• $z=0.151$  volume  $\sim 1 \text{ Gpc}^3$

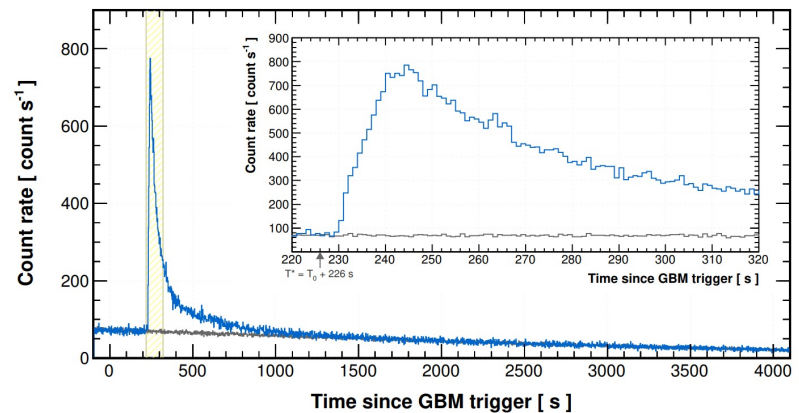
• $R < 10^{-3} \text{ yr}$

•Buns et al. 202

## LHAASO GRB221009A

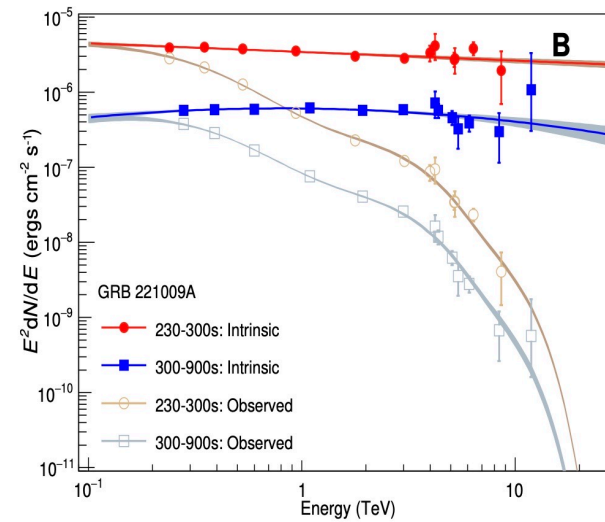
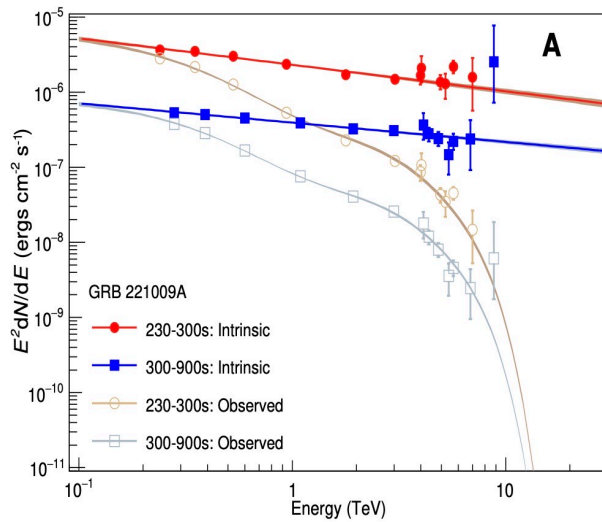
- LHAASO detection of GRB 221009A: first GRB seen by a extensive air shower detector
- High statistics: >60,000 photons above 0.2TeV (LHAASO-WCDA)
- TeV count rate light curve: Smooth temporal profile – **external shock origin**

•First time detection of the TeV afterglow onset !

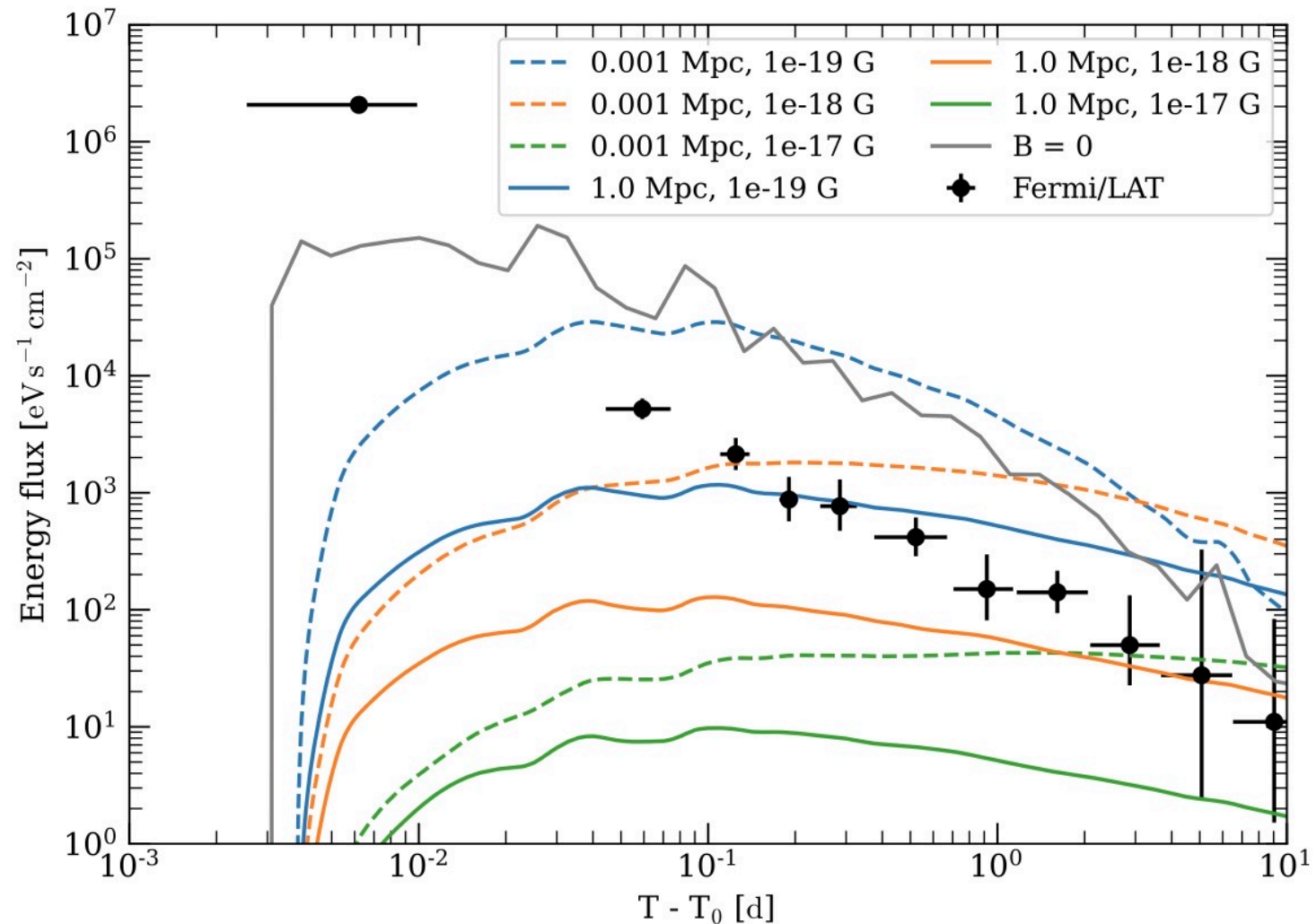


009A

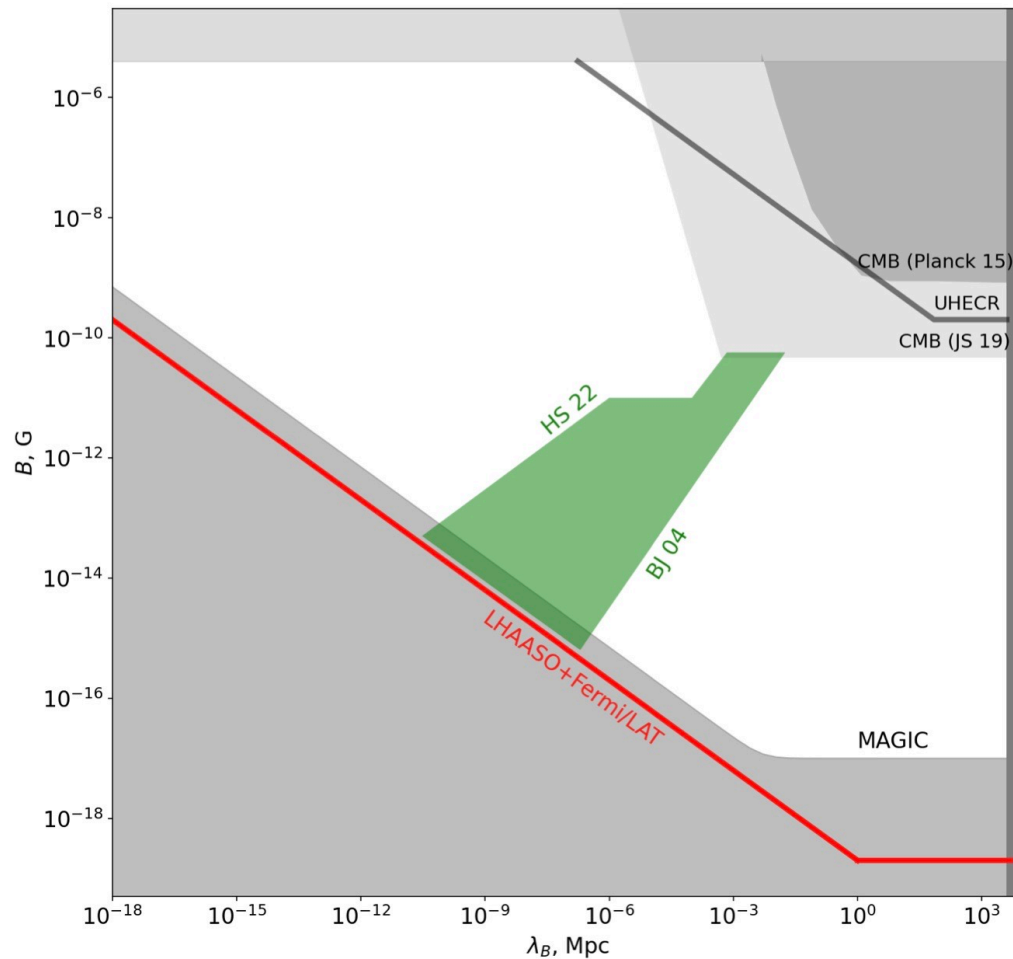
# Flux from BOAT GRB in in LHAASO



## Flux from BOAT GRB in Fermi and cascade contribution



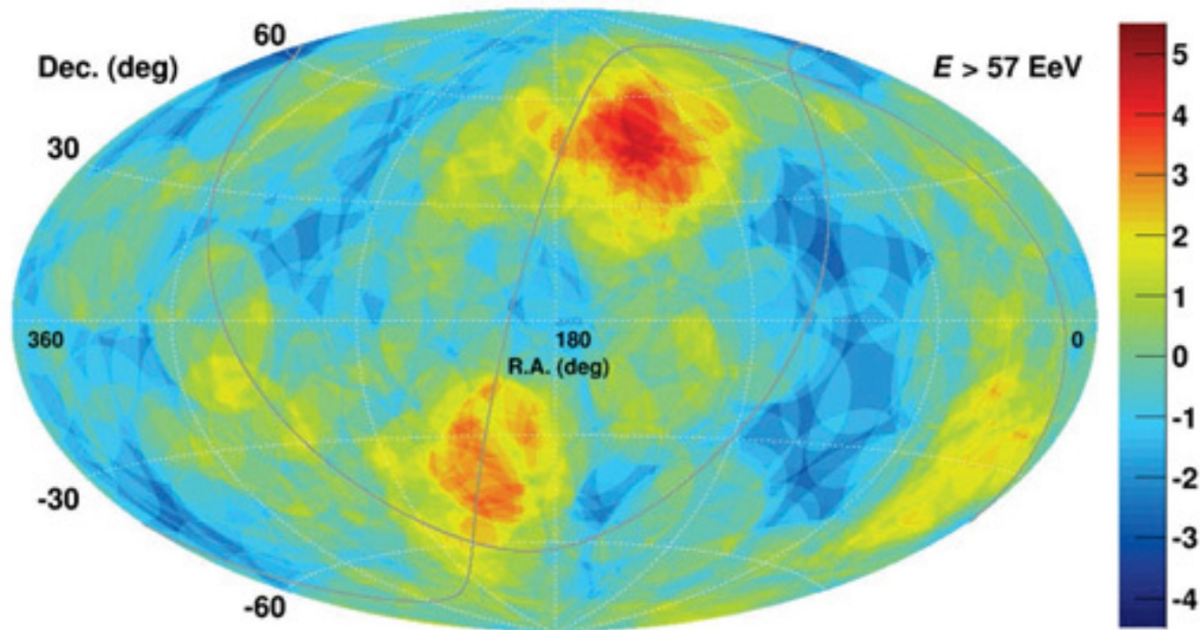
# Constraint on IGMF from BOAT GRB, 2306.07672





# *Inter-Galactic Magnetic Field detection with UHECR*

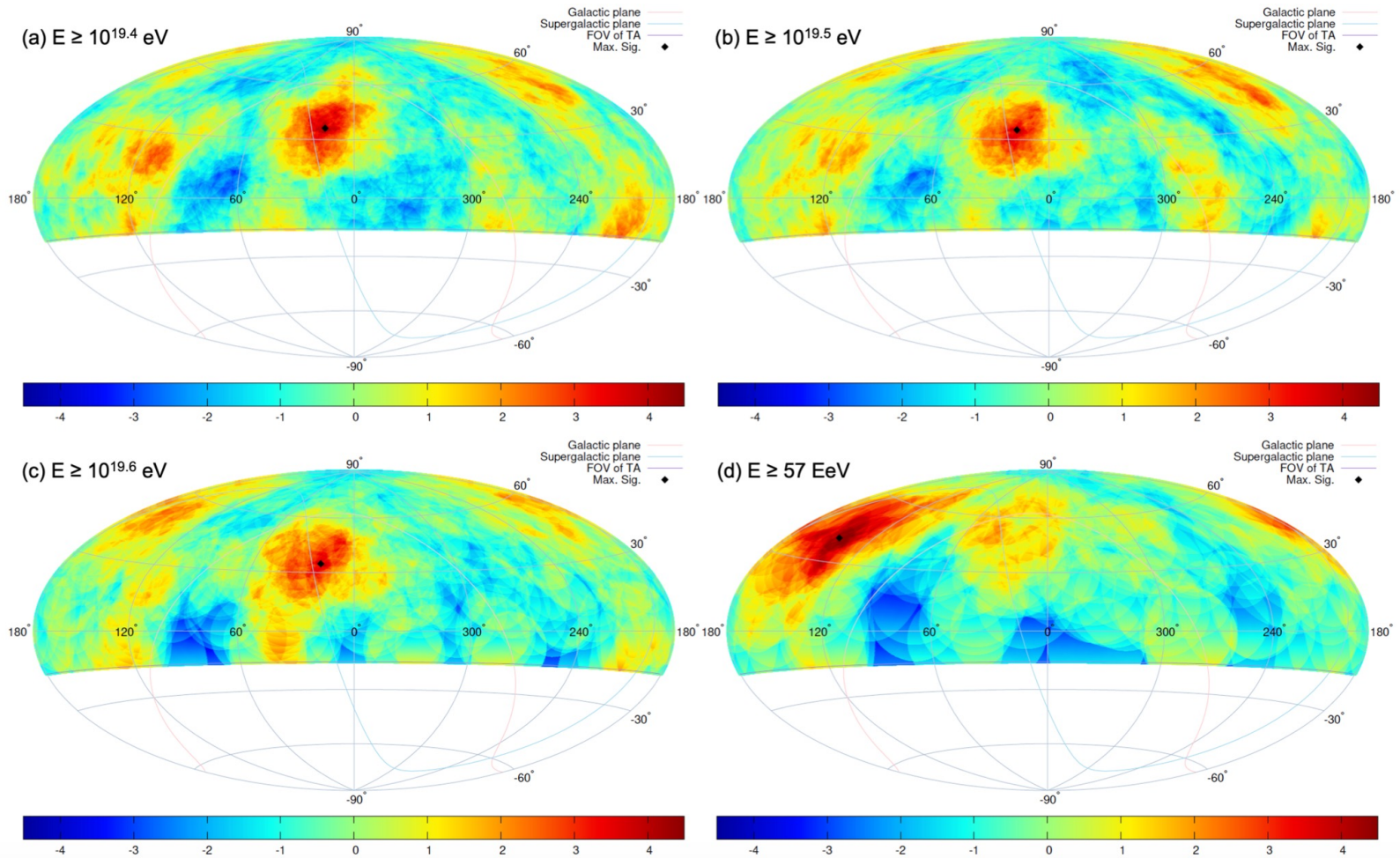
# Auger-TA sky map



Full sky map combining the Telescope Array and Pierre Auger data events with  $E > 5.7 \times 10^{19}$  eV. The events have oversampling with a 20 @BULLET radius circle. The Telescope Array data set includes 109 events, representing the first 7 years of data collection. The Auger data set includes 157 events, representing 10 years of data. No correction was made for the energy scale difference between the Telescope Array and Pierre Auger data sets.

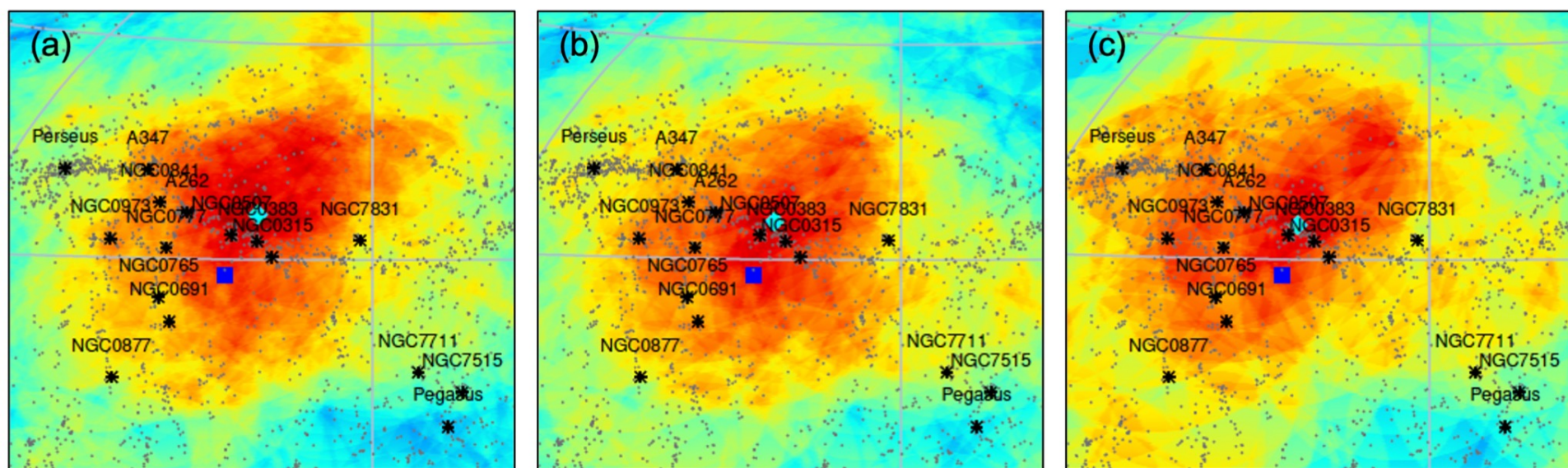
- Auger & TA collaboration

# TA sky map



•TA collaboration, 2110.14827

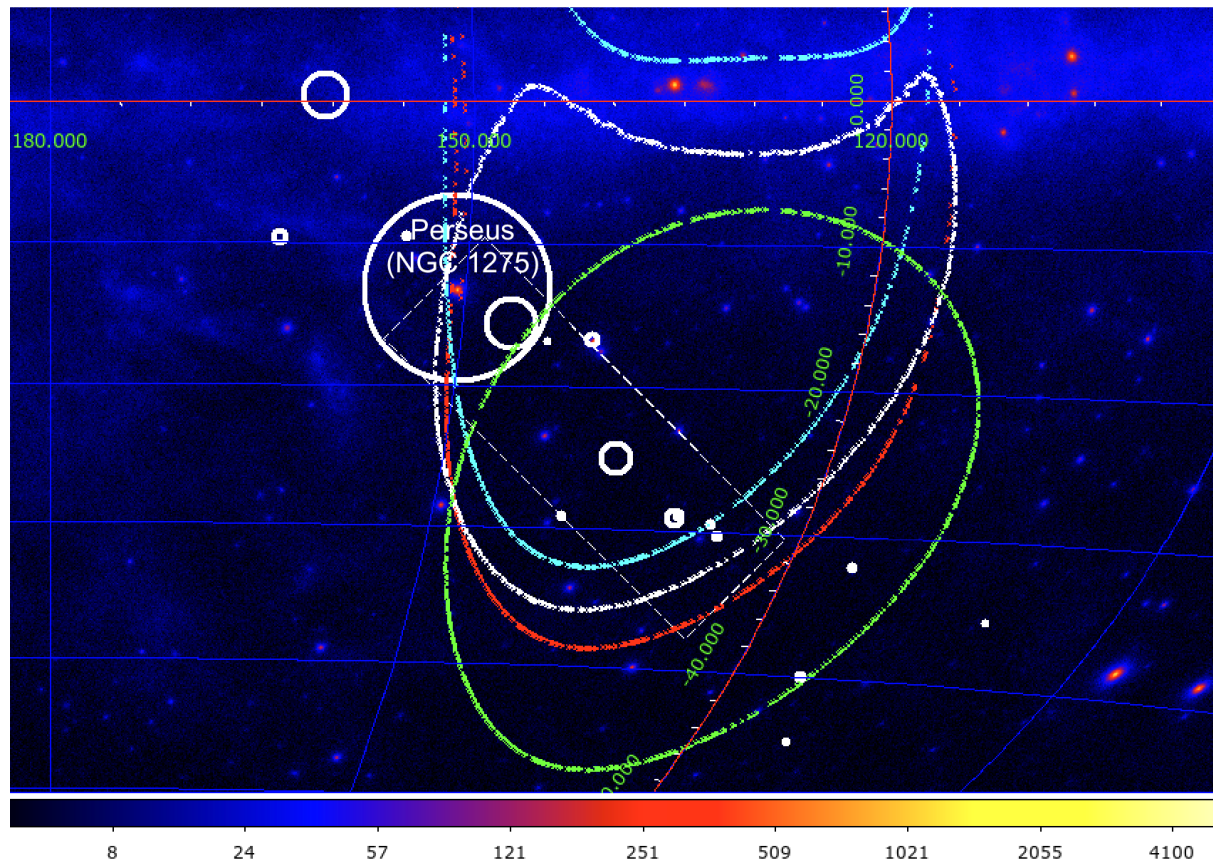
# TA sky map of Perseus-Pisces SC



•TA collaboration, 2110.14827



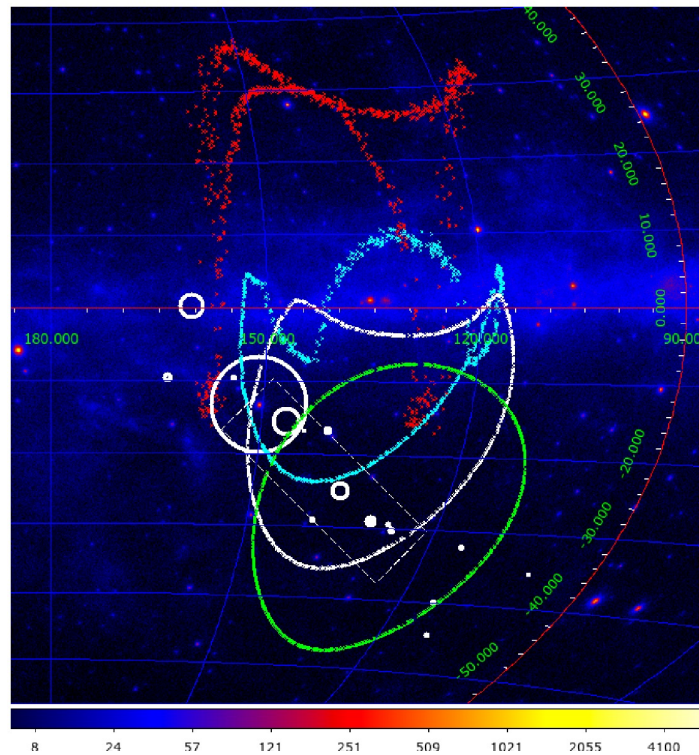
# Deflection of UHECR protons with 25 EeV energy by several GMF models



- A.Neronov, D.S. and O.Kalashev, 2112.0

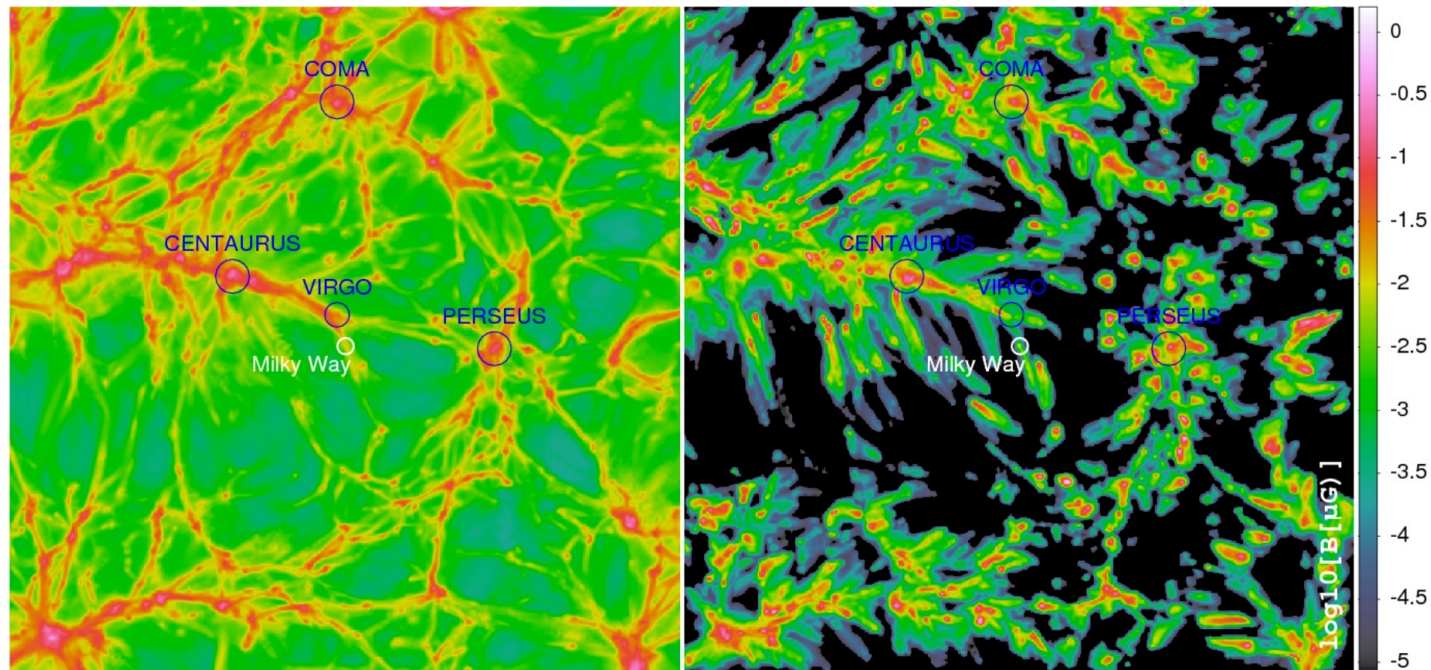


# Deflection of UHECR C, He and p with 25 EeV energy by JF12 GMF



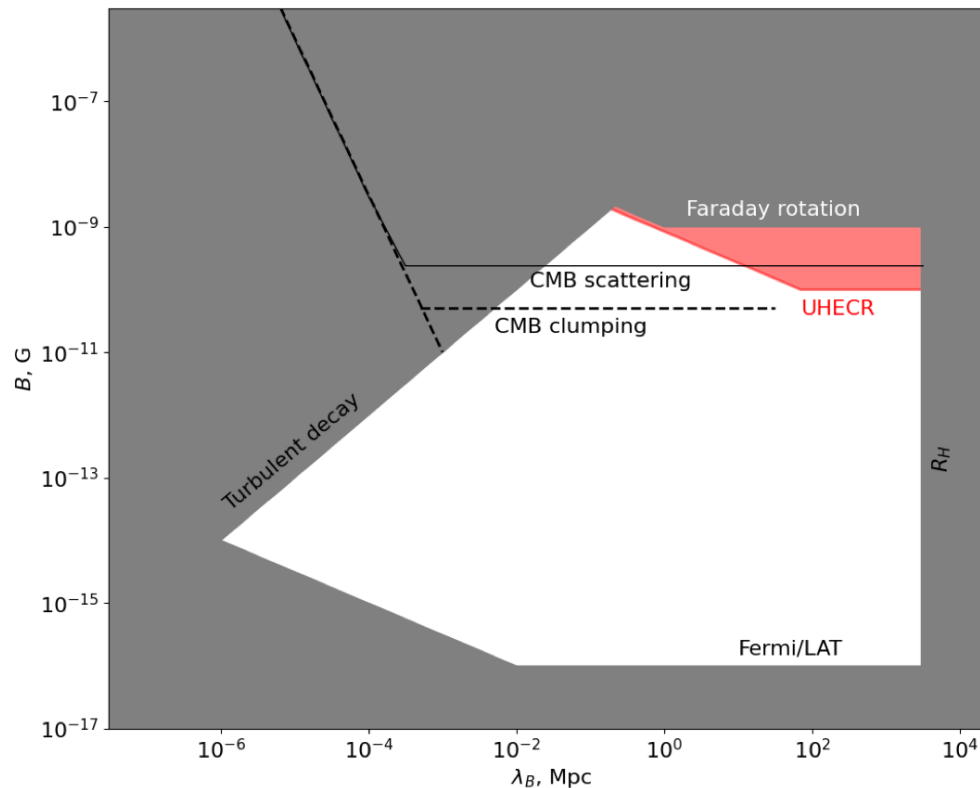
- A.Neronov, D.S. and O.Kalashev, 2112.0820

# Primordial IGMF and MF from astrophysical processes



- S. Hackstein et al, **MNRAS** (2017) 1-11, [1710.01353].

# Limit on IGMF in Taurus void from UHECR observations



- A. Neronov, D.S. and O. Kalashev, 2112.0820

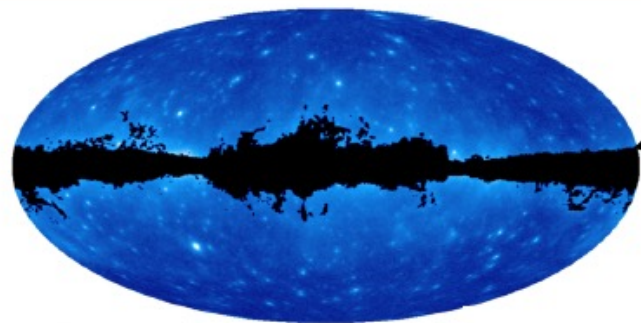
# Summary

- *Inter-Galactic Magnetic Fields in the voids of LSS with strength up to 10 pG can be found from high precision blazar spectra/time delay/ extended emission measurements by CTA*
- *Astrophysical MF can affect measurements on level, which depends on LOS to source*
- *Primordial MF from inflation can be found by measurement of extended emission with network of blazars*
- *IGMF in voids can be measured by UHECR detection from sources, Perseus-Pisces supercluster is first example*

# Diffuse gamma-ray background



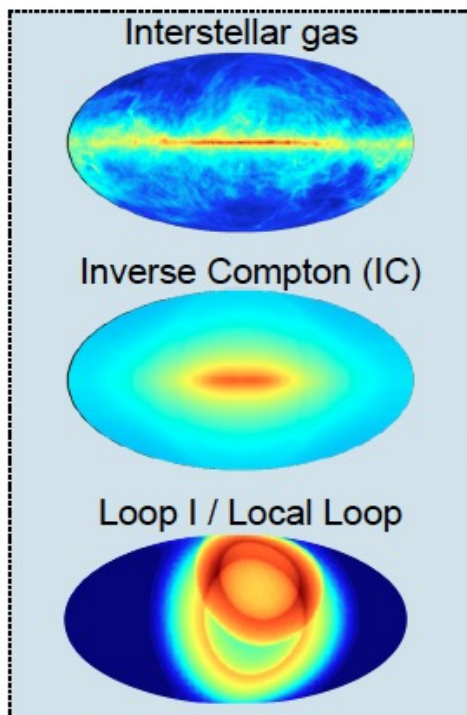
## Derivation of the isotropic gamma-ray background



**Not used in this analysis:**

- > Galactic plane
- > Regions with dense molecular clouds
- > Regions with non-local atomic hydrogen clouds

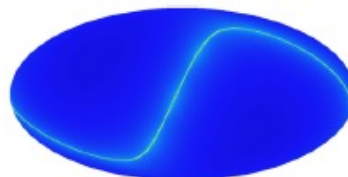
=



Galactic diffuse emission

+

Solar disk and IC



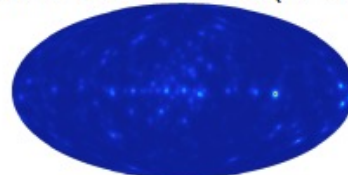
+

Isotropic emission

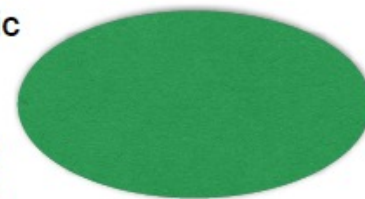


+

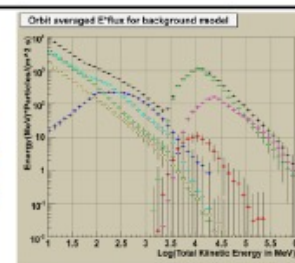
Resolved sources (2FGL)

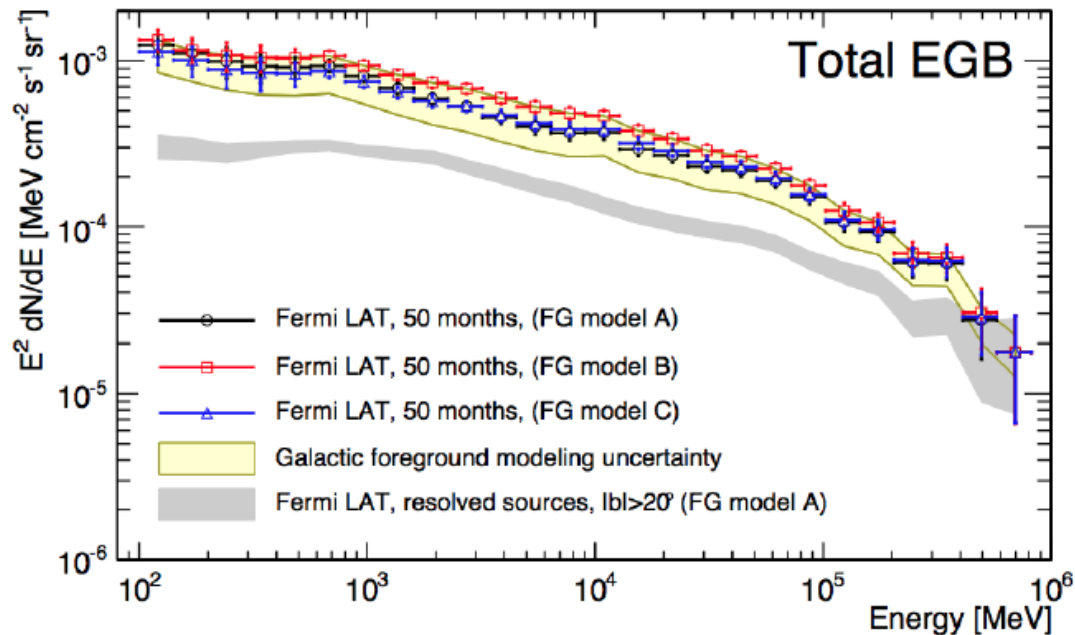


Isotropic  
γ-ray  
back-  
ground  
(IGRB)



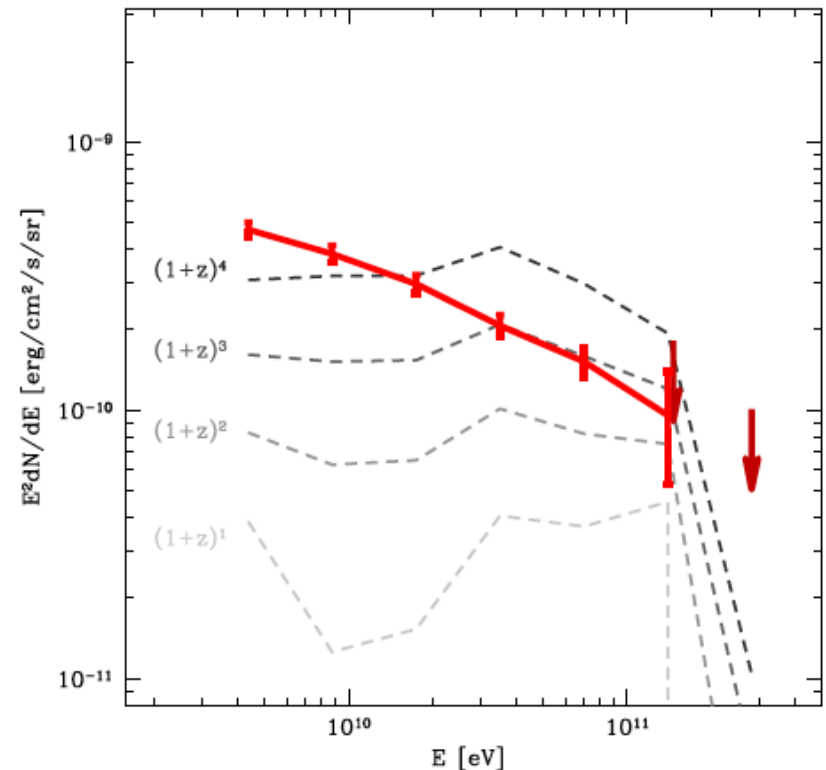
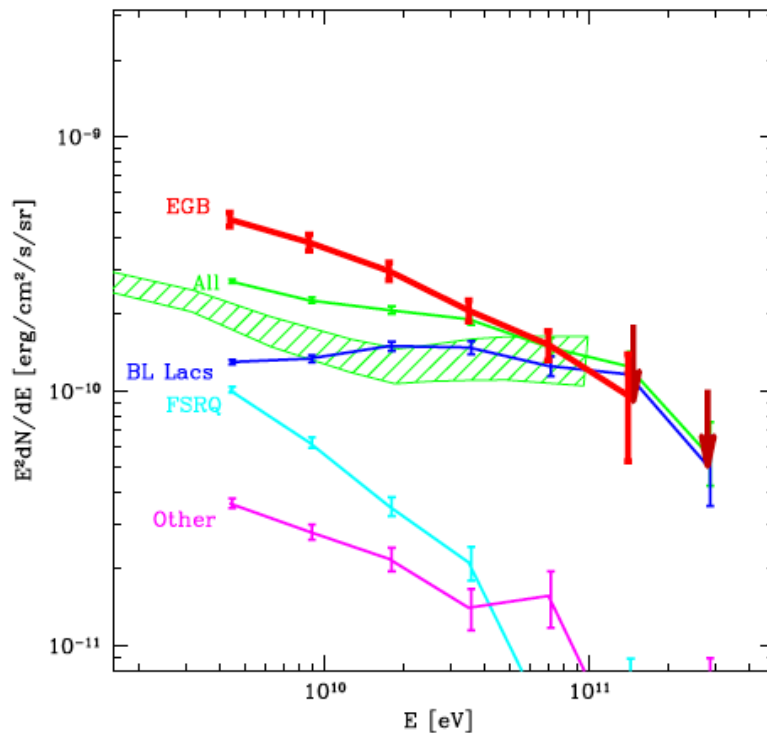
Contami-  
nation from  
CR induced  
background



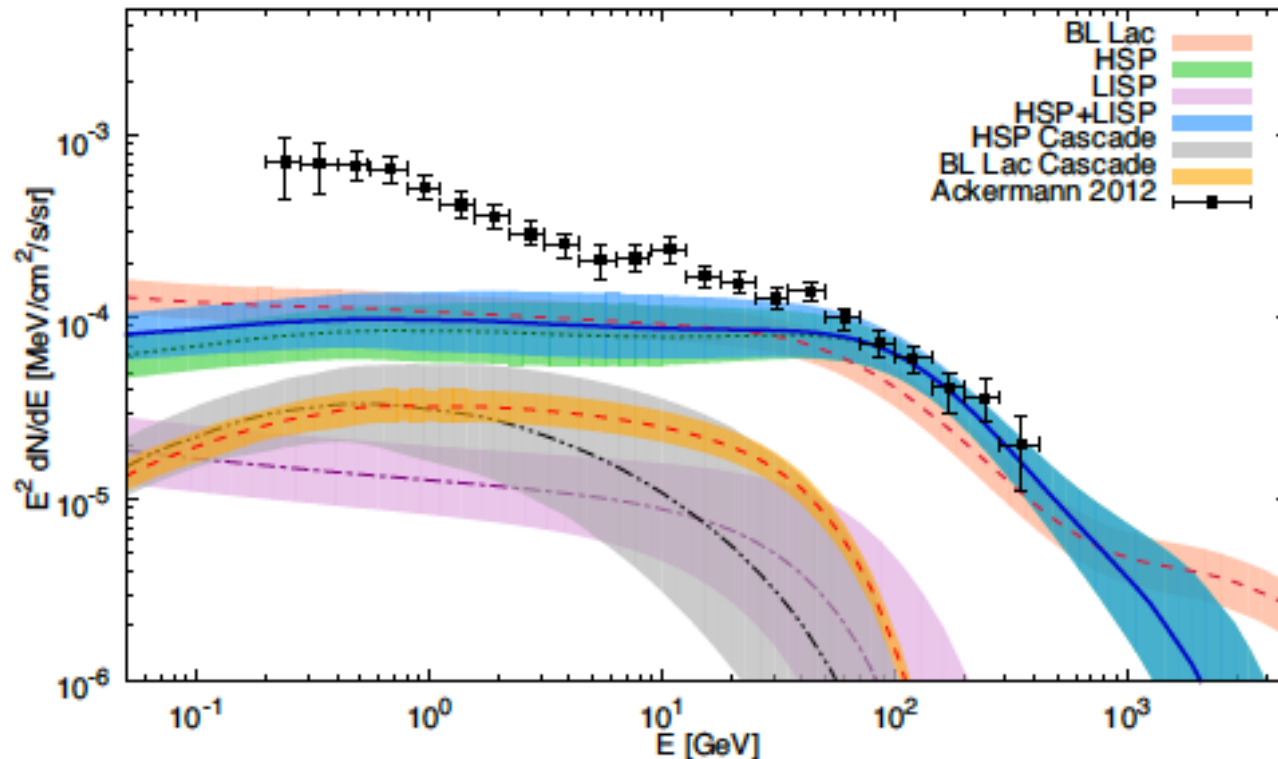


- > **Sum of the intensities** of IGRB and the resolved high-latitude sources.
- > Contribution of high-latitude Galactic sources  **$\ll 5\%$** .
- > Spectrum can be parametrized by **power-law with exponential cutoff**.
- > Spectral index  $\sim 2.3$ , cutoff energy  $\sim 350$  GeV.

# BL Lacs give main contribution to diffuse gamma-ray flux



# BL Lacs give main contribution to high energy part of diffuse gamma-ray flux



• M. Di Mauro et al, arXiv:1311.5708

# Fermi confirmed resolution of BL Lac sources above 50 GeV

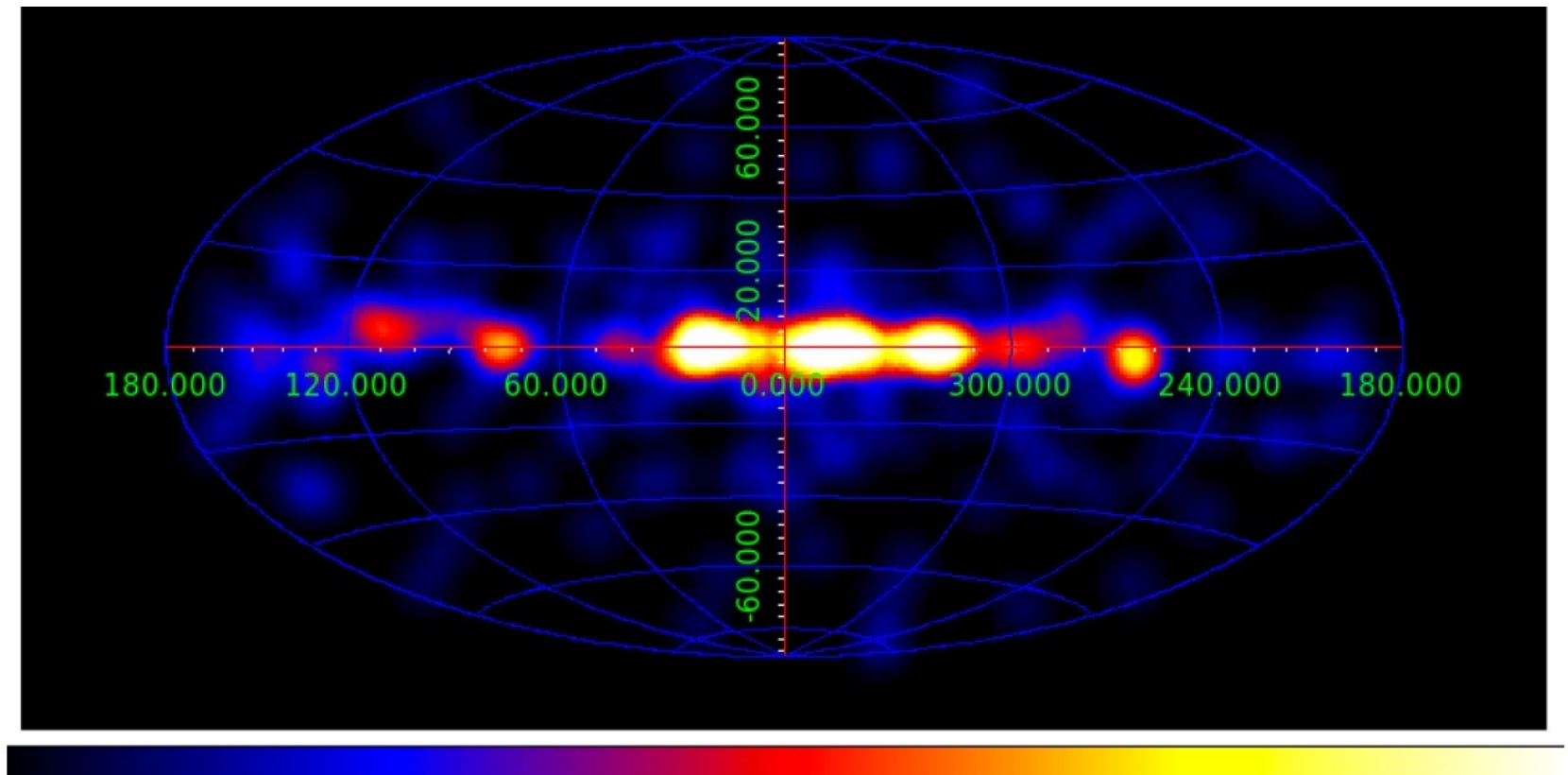
$\text{cm}^{-2} \text{s}^{-1}$ ). We employ a one-point photon fluctuation analysis to constrain the behavior of  $dN/dS$  below the source detection threshold. Overall the source count distribution is constrained over three decades in flux and found compatible with a broken power law with a break flux,  $S_b$ , in the range  $[8 \times 10^{-12}, 1.5 \times 10^{-11}] \text{ ph cm}^{-2} \text{s}^{-1}$  and power-law indices below and above the break of  $\alpha_2 \in [1.60, 1.75]$  and  $\alpha_1 = 2.49 \pm 0.12$  respectively. Integration of  $dN/dS$  shows that point sources account for at least  $86^{+16}_{-14}\%$  of the total extragalactic  $\gamma$ -ray background. The simple form of the derived source count distribution is consistent with a single population (i.e. blazars) dominating the source counts to the minimum flux explored by this analysis. We estimate the density of sources

•Fermi collaboration, arXiv:1511.00693



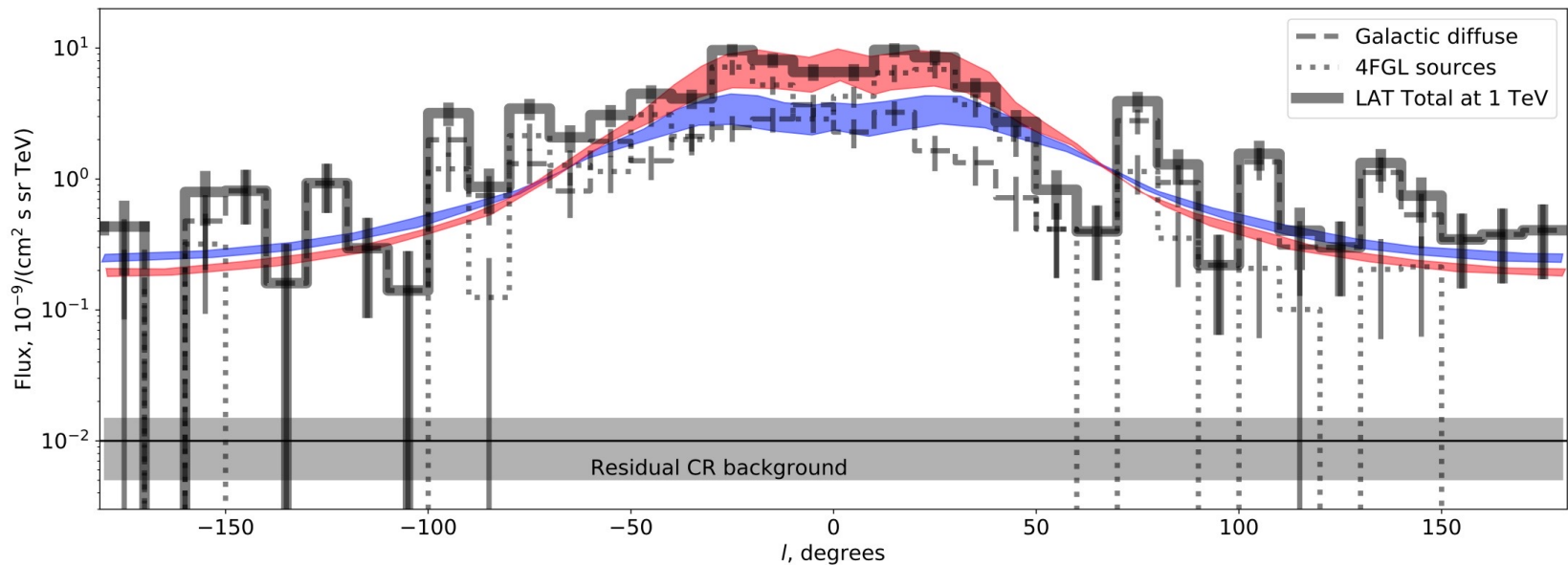
# Sky map $E > 1\text{TeV}$

## 10 years Fermi



- A.Neronov and D.S. , 1907.06061

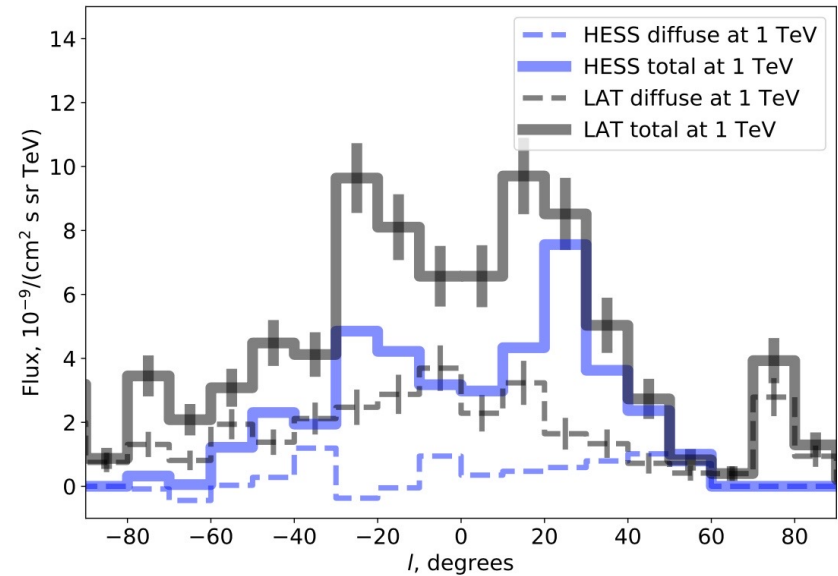
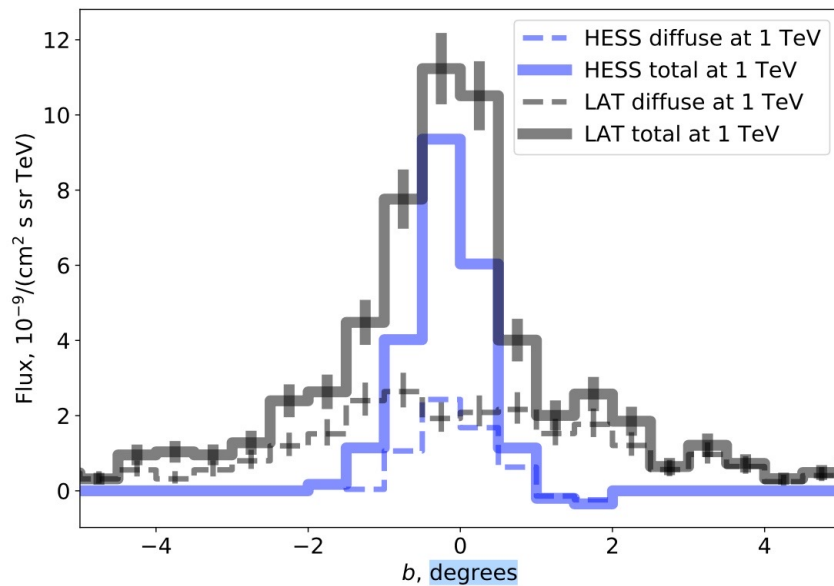
# Galactic Plane $|b| < 2$ deg, 1 TeV



• Red and blue lines: model predictions from Cataldo et al , 1904.03894

• A.Neronov and D.S. , 1907.06061

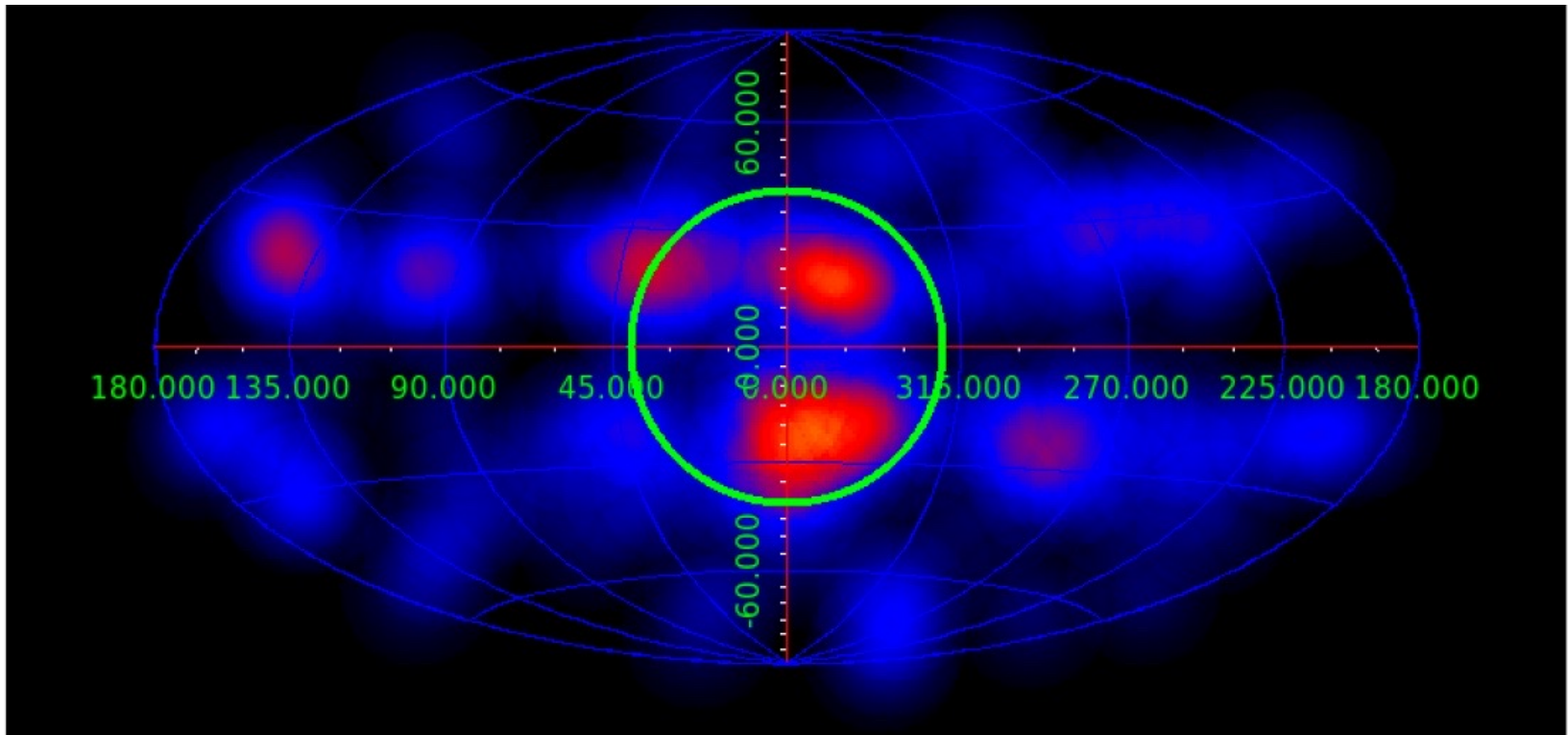
# Galactic Plane, Fermi and HESS



• A.Neronov and D.S. , 1907.06061

# Sky map 1TeV

no galactic plane  $|b| > 10$  deg

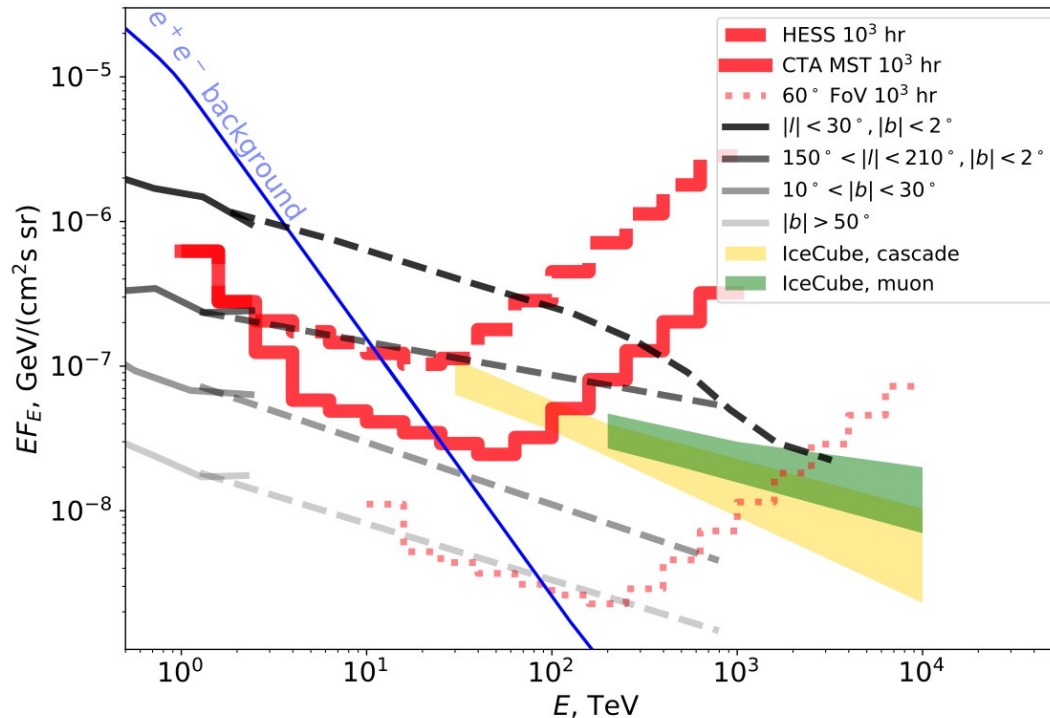


•A.Neronov and D.S. , 1907.06061

*Gamma-ray sky at 10-  
100 TeV with  
Cherenkov telescopes*

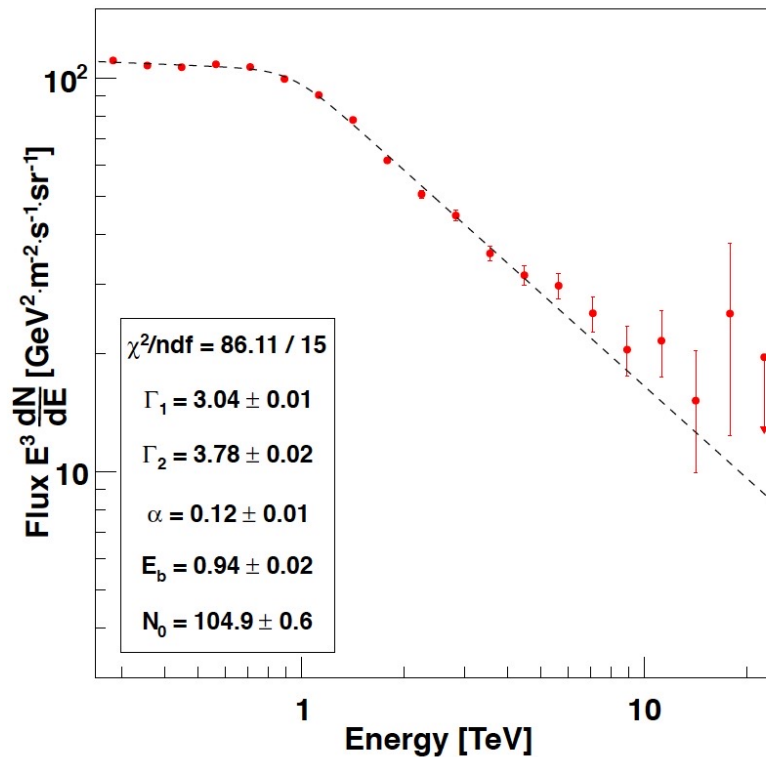


# Galactic diffuse flux at 10-100 TeV energies with Cherenkov

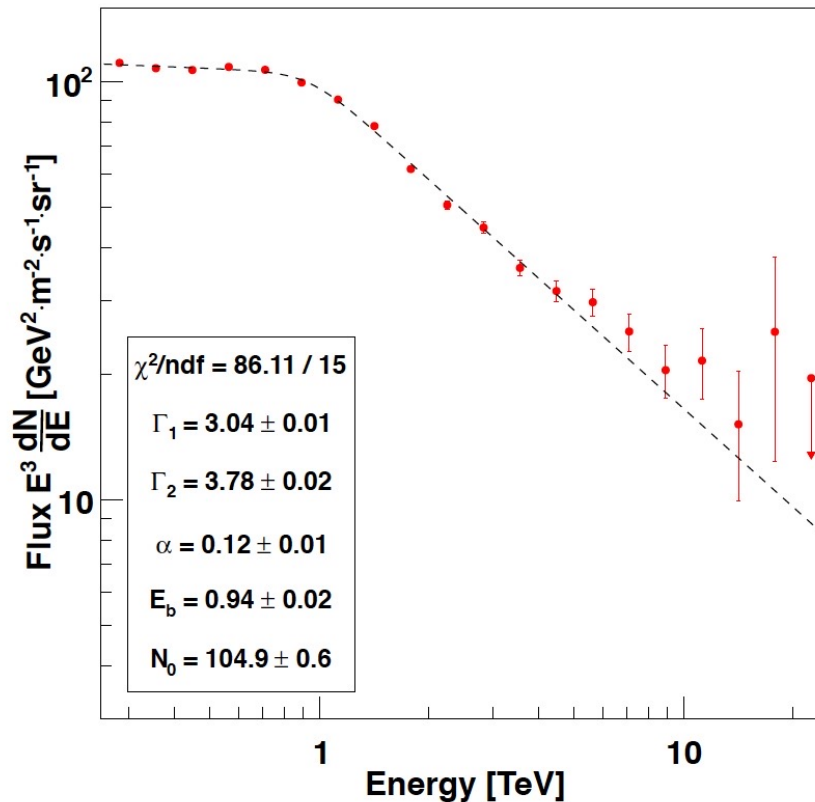


•A.Neronov and D.S. , astro-ph/2001.00922

# Electron + positron measurements by HESS 2004- March 2010

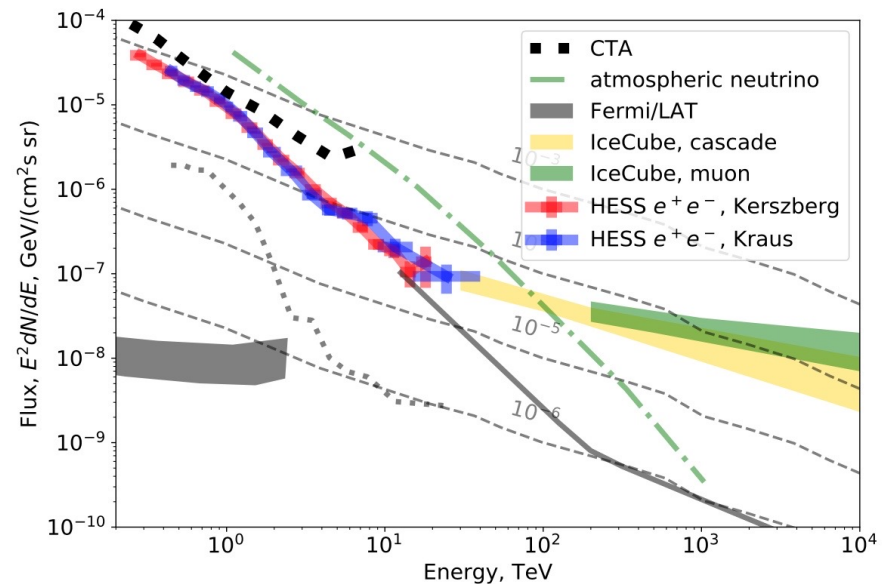
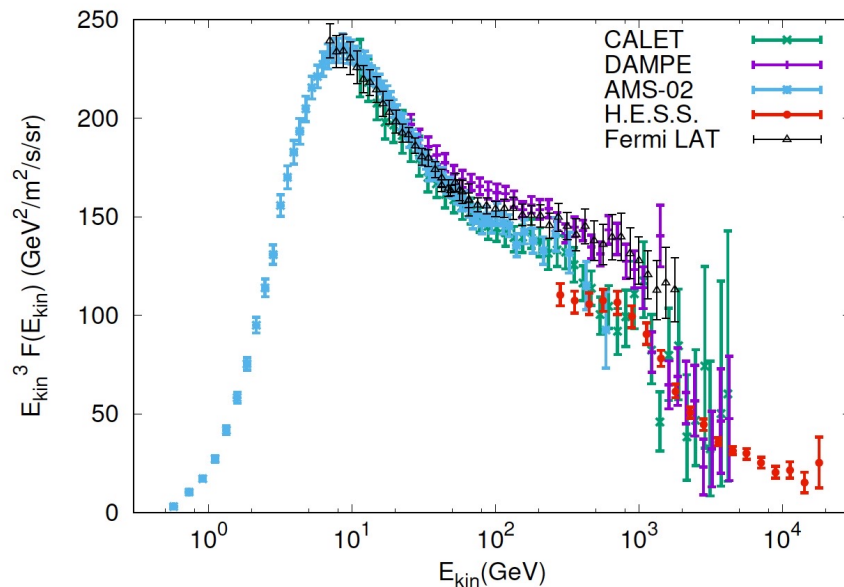


# Electron+ positron+ diffuse gamma measurements by HESS 2004- March 2010



•HESS collab. 2017

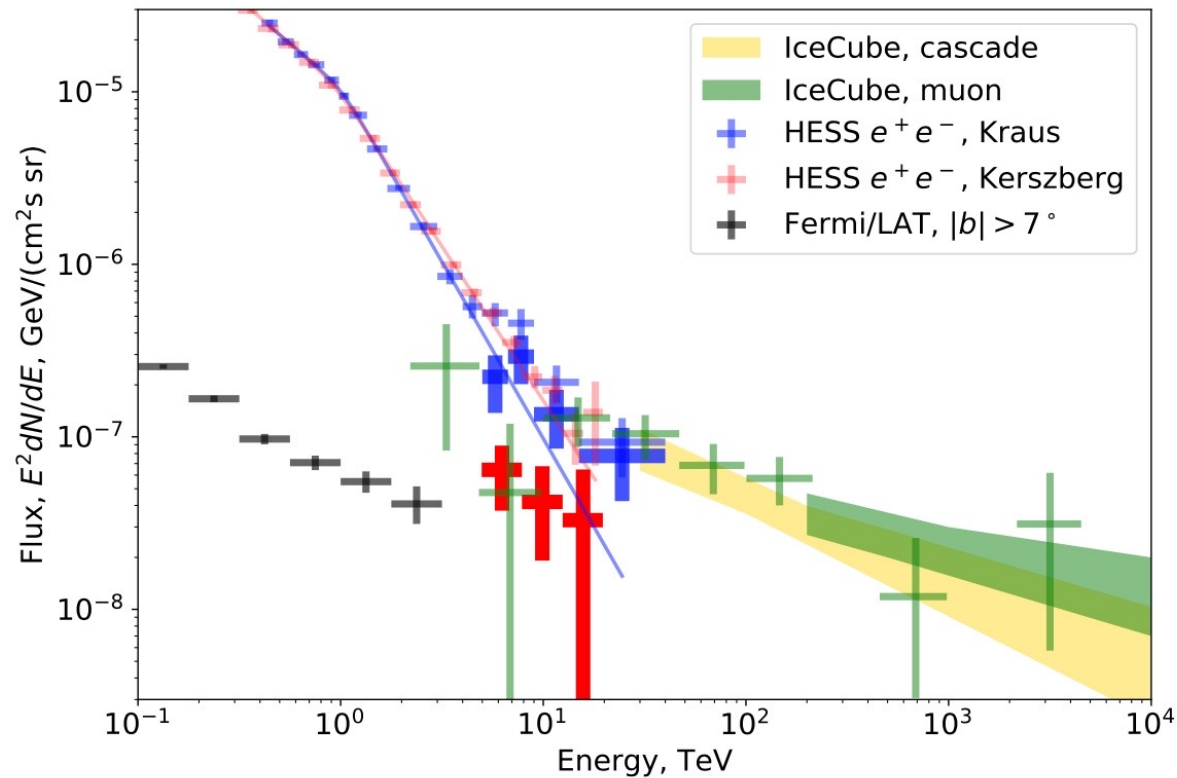
# Electron+ positron+ diffuse gamma measurements by HESS 2004- March 2010



- M. Kachelriess and D.S.,
- Cosmic ray models,
- review astro-ph/1904.08160

- A. Neronov and D.S.,
- astro-ph/2001.00922

# New component in HESS data



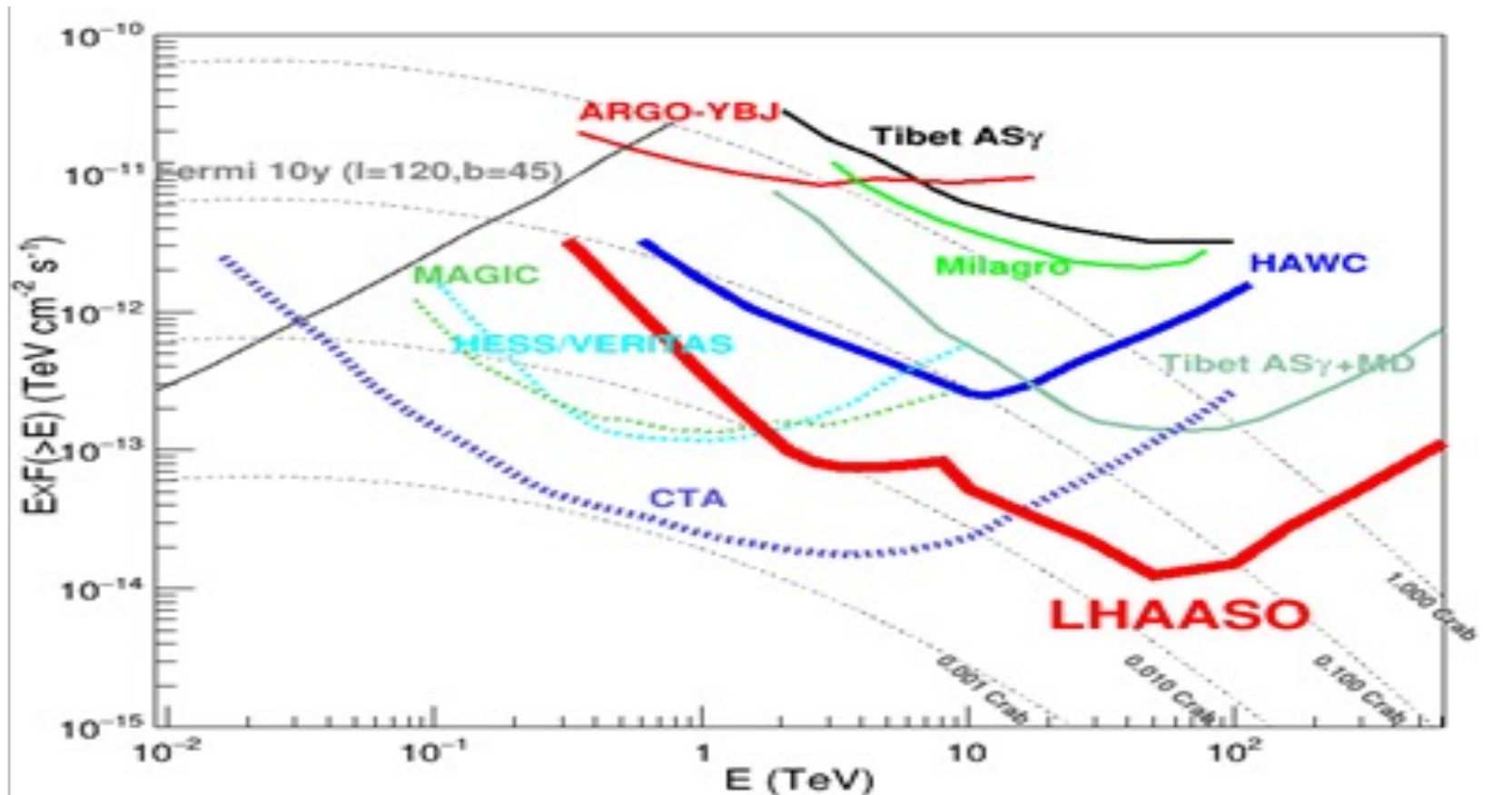
•A.Neronov and D.S. , astro-ph/2001.00922



# *Gamma-ray sky at $E > 100$ TeV by LHAASO*

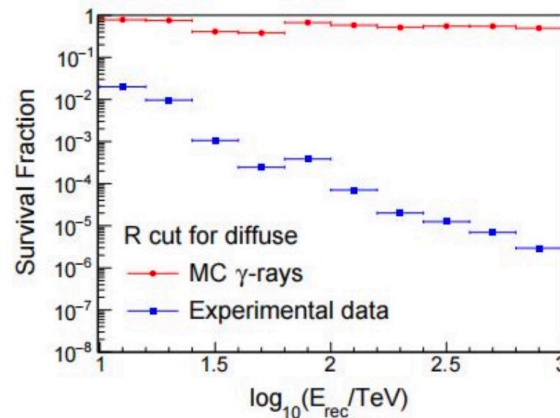
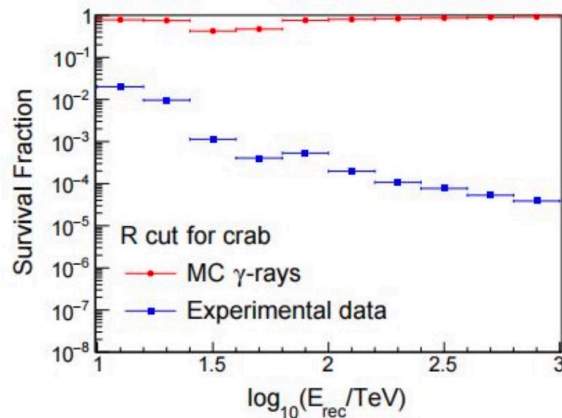
# LHAASO sensitivity

- With large FOV and high sensitivity, LHAASO is an ideal detector for sky survey to search VHE and UHE sources!



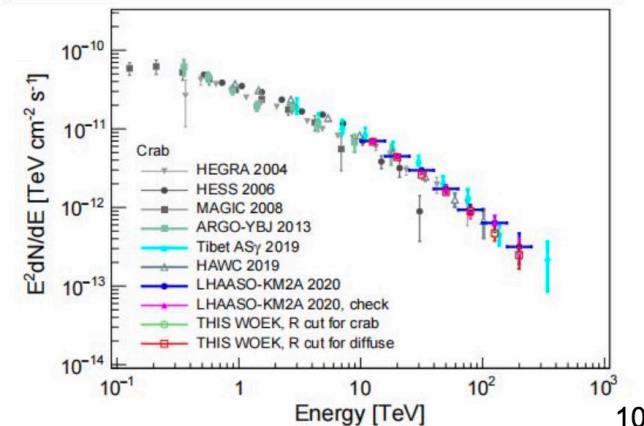
# Gamma/CR discrimination

$$R = \log \left( \frac{N_{\mu} + 0.0001}{N_e} \right)$$

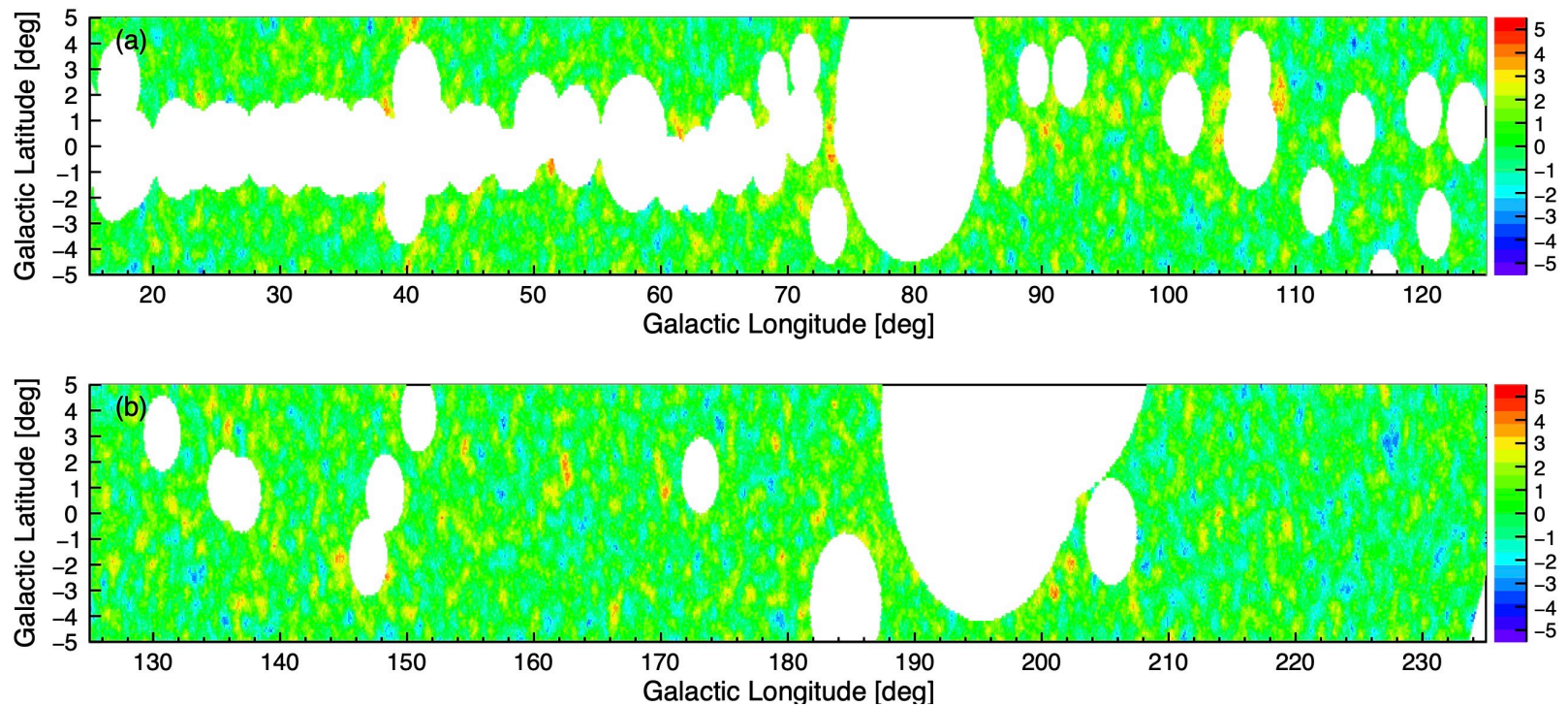


$\log(E_{\text{rec}}/\text{TeV})$	$R$ for crab	$R$ for diffuse
1.0 – 1.2	–5.11	–5.00
1.2 – 1.4	–5.24	–3.20
1.4 – 1.6	–5.95	–5.96
1.6 – 1.8	–6.08	–6.17
1.8 – 2.0	–2.34	–2.50
2.0 – 2.2	–2.35	–2.69
2.2 – 2.4	–2.36	–2.79
2.4 – 2.6	–2.36	–2.74
2.6 – 2.8	–2.36	–2.75
2.8 – 3.0	–2.36	–2.79

- R cuts adjusted from the Crab analysis to enable a higher  $Q=S/B^{1/2}$  factor
- Efficiencies change from ~90% to ~60%

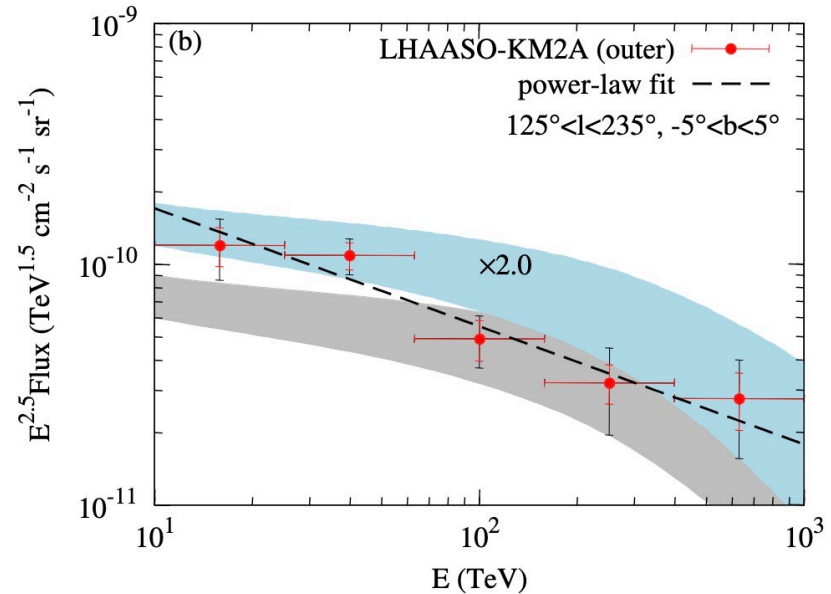
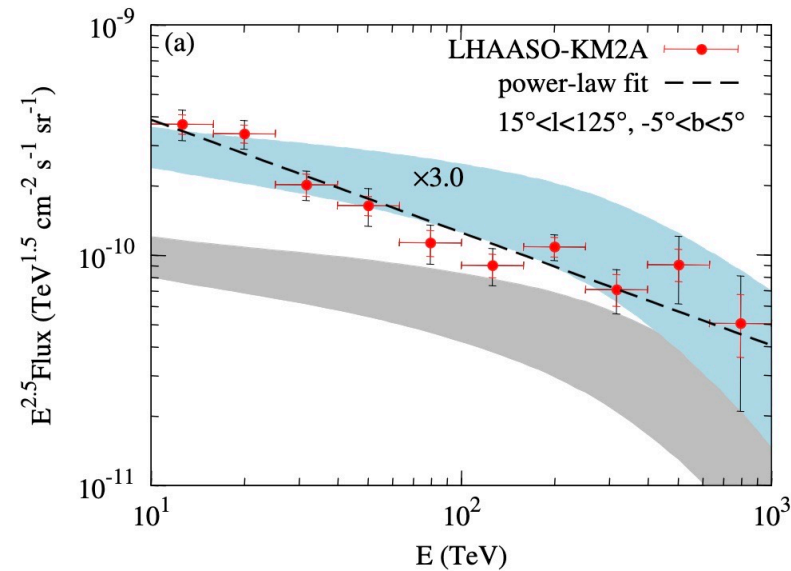


# Mask LHAASO



•LHAASO collaboration arXiv: 2305.0537

# LHAASO diffuse

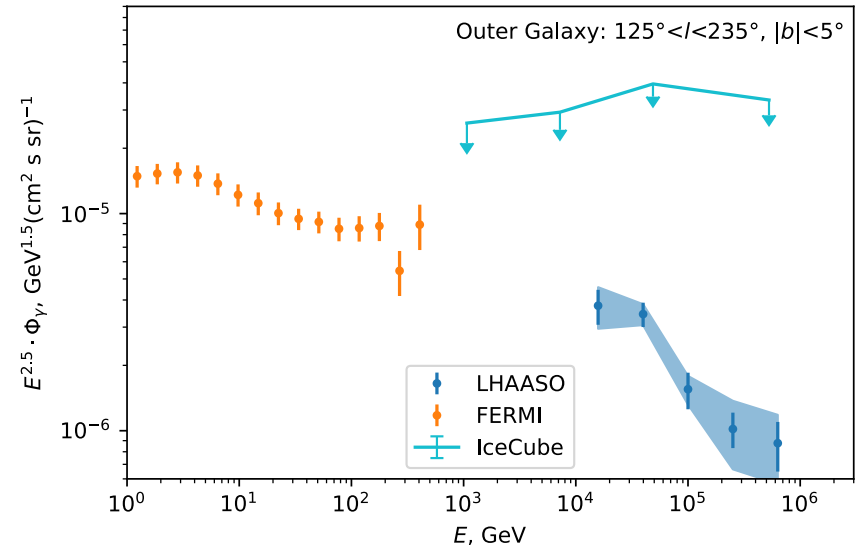
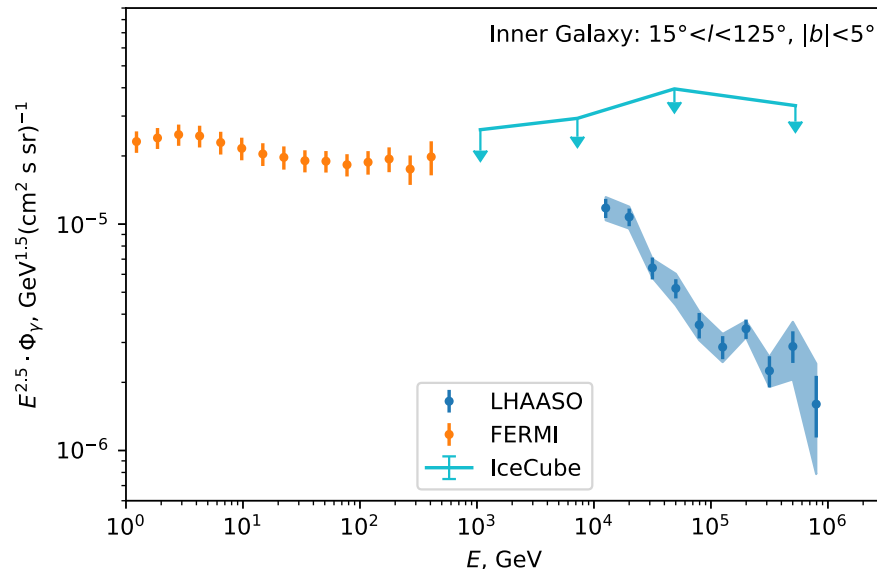


$$\Xi^{A,A'}(E, l, b) = \int_0^\infty ds n_{\text{gas}}^{A'}(\mathbf{x}) I_{\text{CR}}^A(E, \mathbf{x})$$

$$I_\nu(E, l, b) = \sum_{A,A'} \int_E^\infty dE' \Xi^{A,A'}(E', l, b) \frac{d\sigma^{AA' \rightarrow \nu}(E', E)}{dE}$$



# Gamma-ray flux in inner and outer Galaxy



• IceCube data from IceCube 7 years limit on Kra-gamma model approximated to  $|b| < 5$

• LHAASO data from 2305.05372

• Fermi from R. Zhang et al,

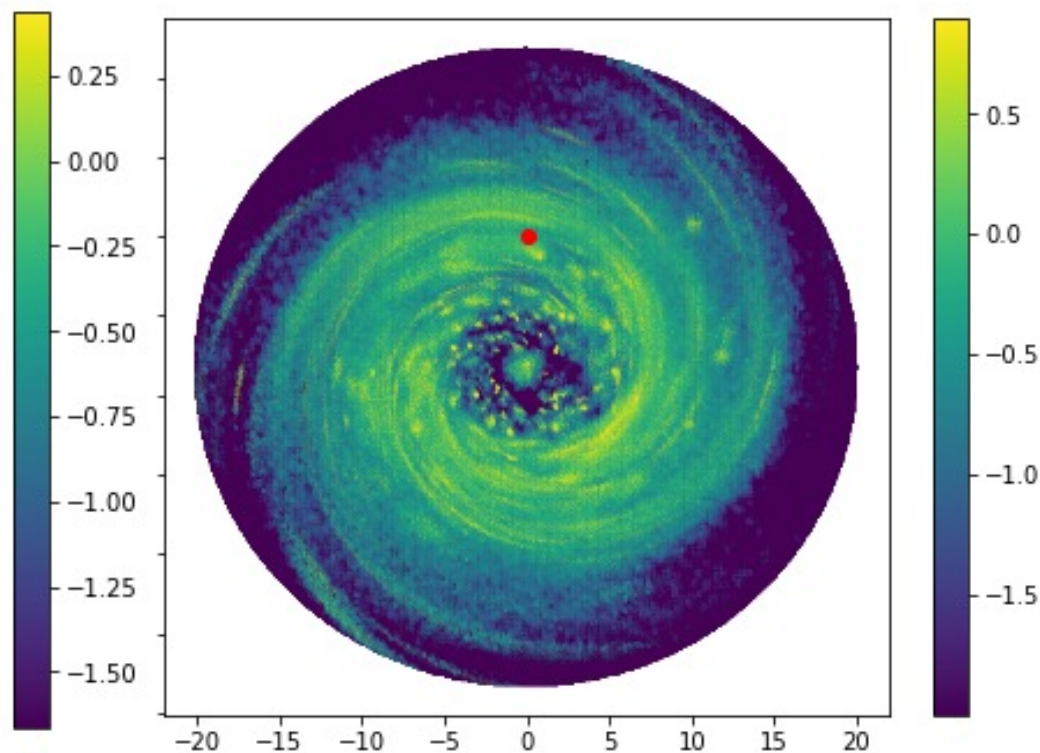
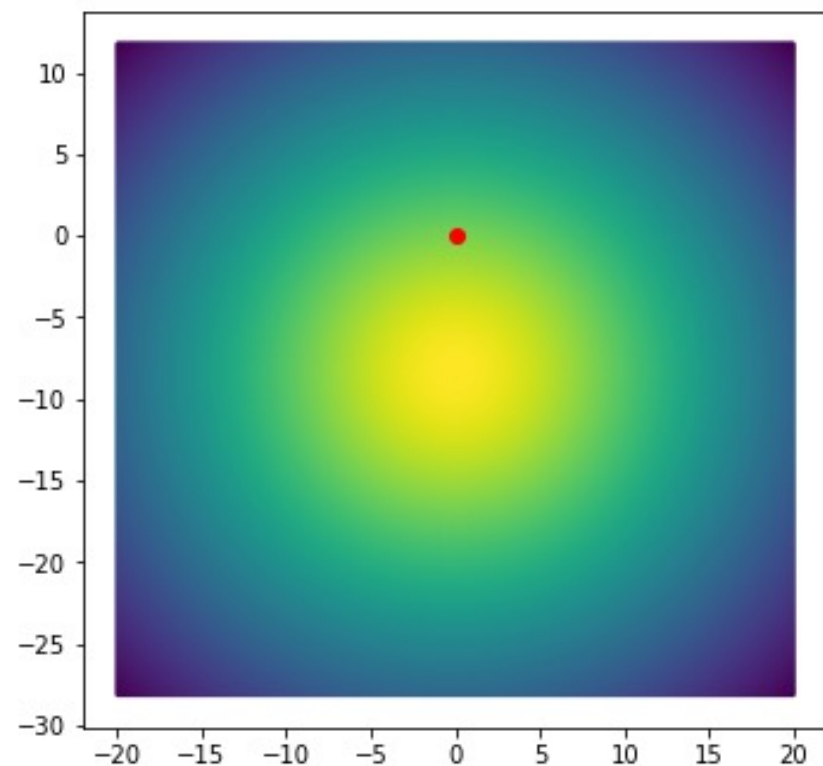
• 2305.06948

Gamma-ray flux in LHAASO is same  $1/E^3$ ,  
but combination with Fermi looks different.

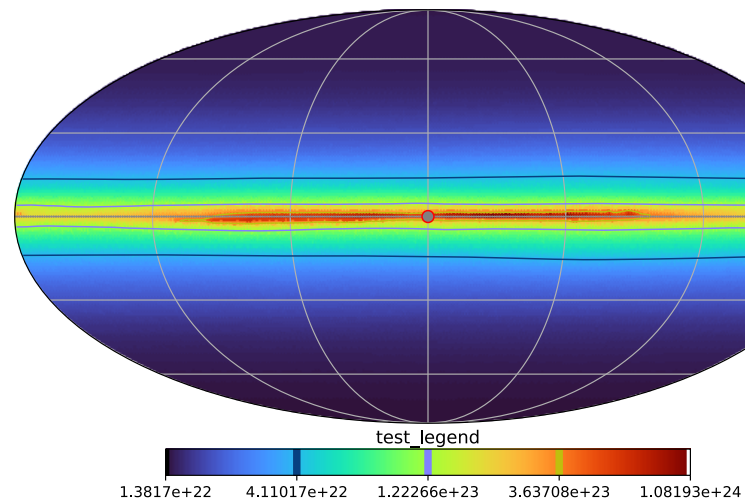
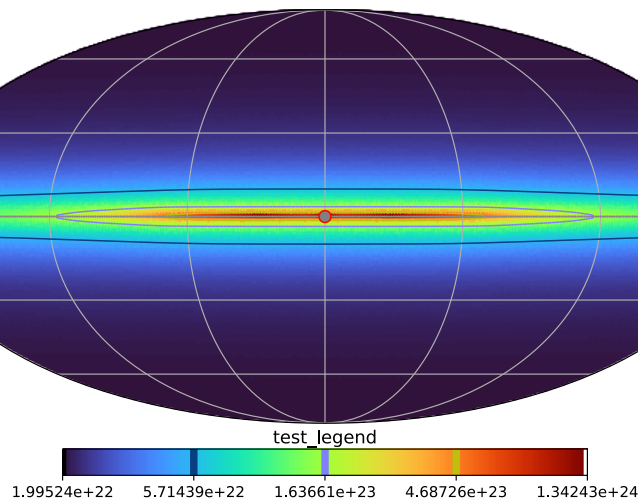
# •1 PeV CR density in the Gal. plane

•Lipari & Vernetto (2018)

•G.Giacinti & D.S.,  
2305.10251



# Diffuse gamma-ray flux from Galaxy



- Isotropic diffusion model
- Anisotropic diffusion model

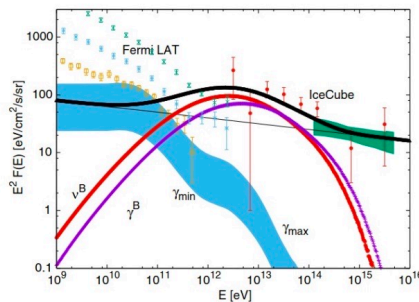
• G. Giacinti, S. Koldobsky, A. Neronov and D.S., 2024

# High latitude diffuse gamma-ray flux

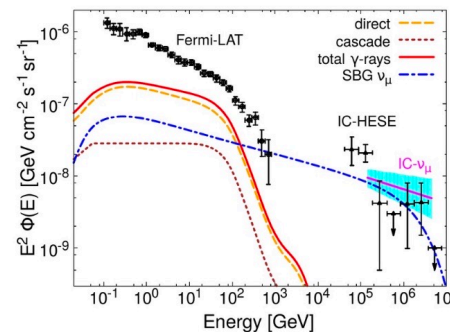
Sub-PeV energy neutrino spectrum is inconsistent with diffuse gamma-ray flux from blazars.  
But no arrival direction correlation with Galactic plane either.

→ *Other emission sources?*

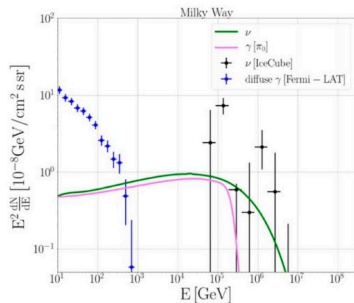
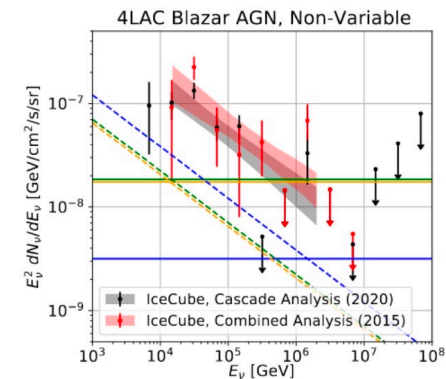
Local Pevatron (Bouyahiaoui+ '20)



Starburst galaxies (Peretti+ '20)



AGNs (Smith+ '21)

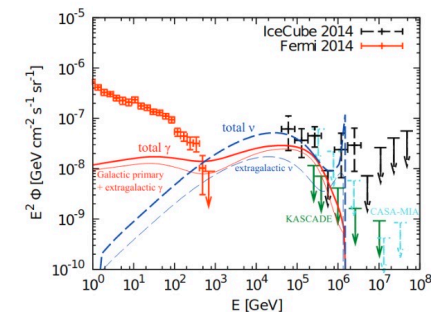


CR halo (Recchia+ '21)

Different TeV gamma-ray signal in each case



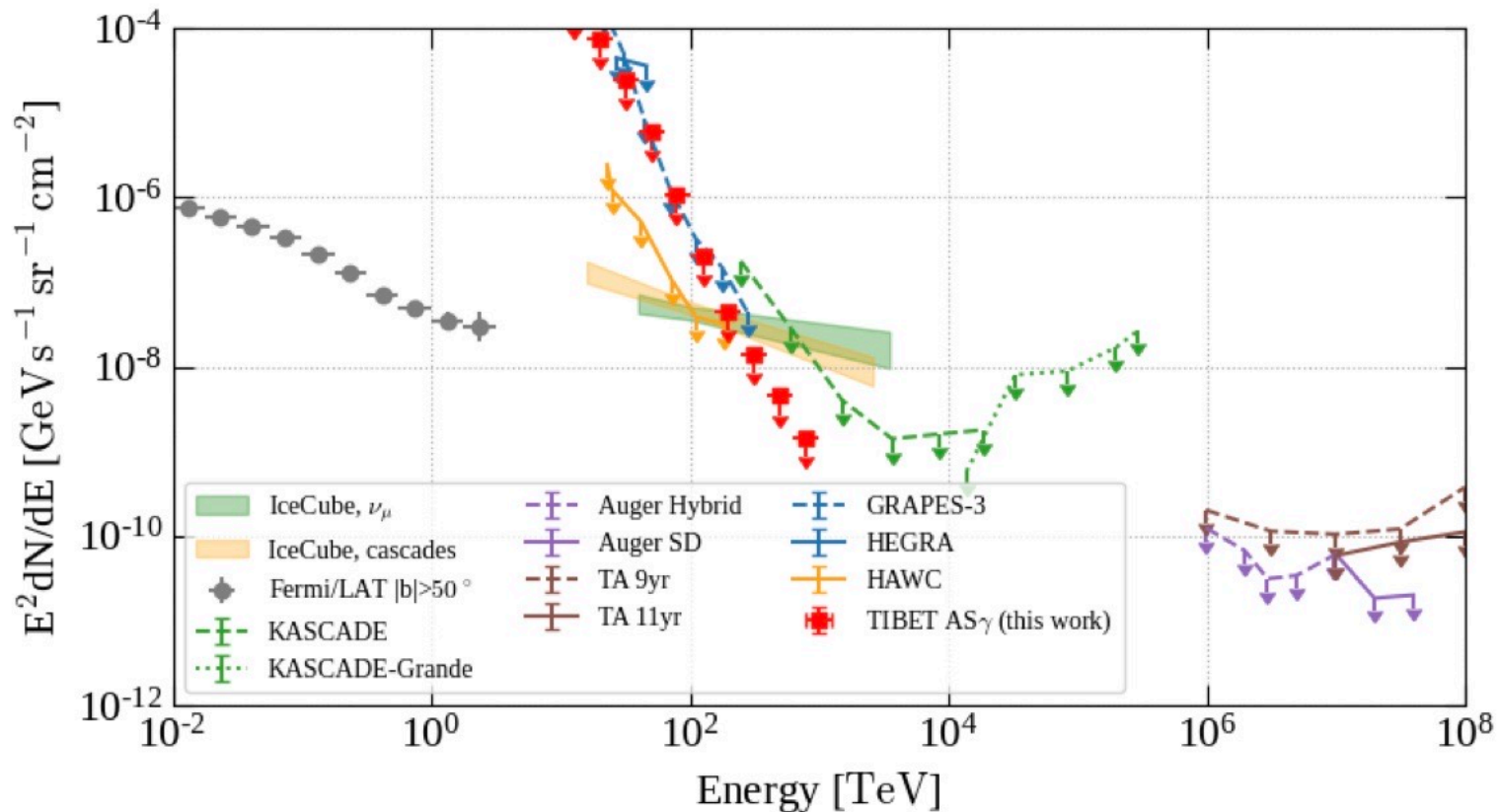
Sub-PeV measurements of the diffuse gamma-ray flux may be decisive to clarify the origin of both neutrino and gamma-ray emission.



Dark matter (Murase+ '15)

• From Ye.Vovk, Dec 2022, CR workshop talk

# Constraint on local source, halo models and DM models



• A. Neronov, D.S. and Ye. Vovk, 2021



# Open questions for near future study

- Cosmic ray spectrum non-universality in Galaxy, origin of knee, transition from galactic to extragalactic CR
- Gamma-ray astronomy at  $E > 100$  TeV sources, point and extended sources, leptonic/hadronic sources, diffuse background and relation to cosmic rays and neutrinos
- Neutrino flux from Galaxy, diffused and point sources (see Neutrino lecture)

# Summary

- *New detector LHAASO started operation and gave first results in 10 TeV -1 PeV energy range. CTA as best detector in 100 GeV-10 TeV energy range will start in few years.*
- *Galactic sources will be studied by LHAASO. New domain 100 TeV-1 PeV opened 4-→43*
- *Extragalactic sources are observed up to redshift  $z=1$ . Can help to study EBL.*
- *Cosmological magnetic fields with strength up to 10 pG can be found in the voids of LSS.*
- *Cosmic rays around knee in Galaxy can be studied by gamma-ray and neutrino telescopes*