Lecture 2:
Gamma-ray Astrophysics

Ultra High Energy \\ Cosmic Rays

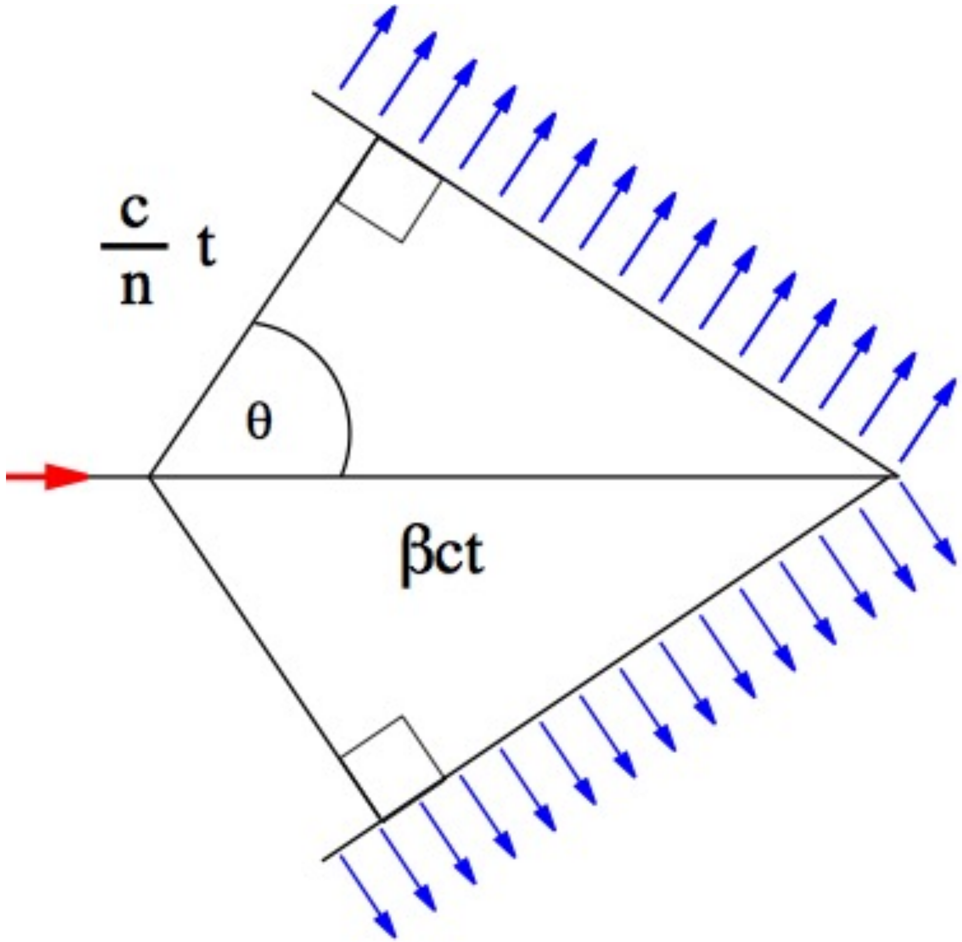
Dmitry Semikoz
APC (Paris)

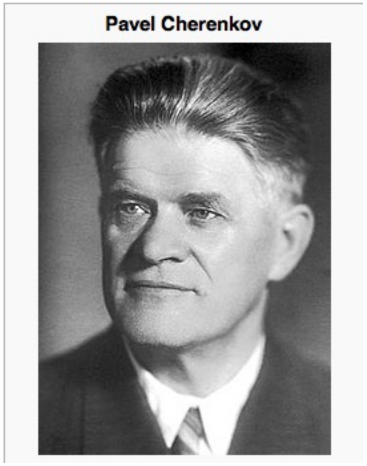
Overview:

- 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

$n = 1.008$ air

$n = 1.33$ 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

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

- Minimal energy of charge particle

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

Main processes used in gamma-ray astrophysics

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

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

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

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

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

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

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

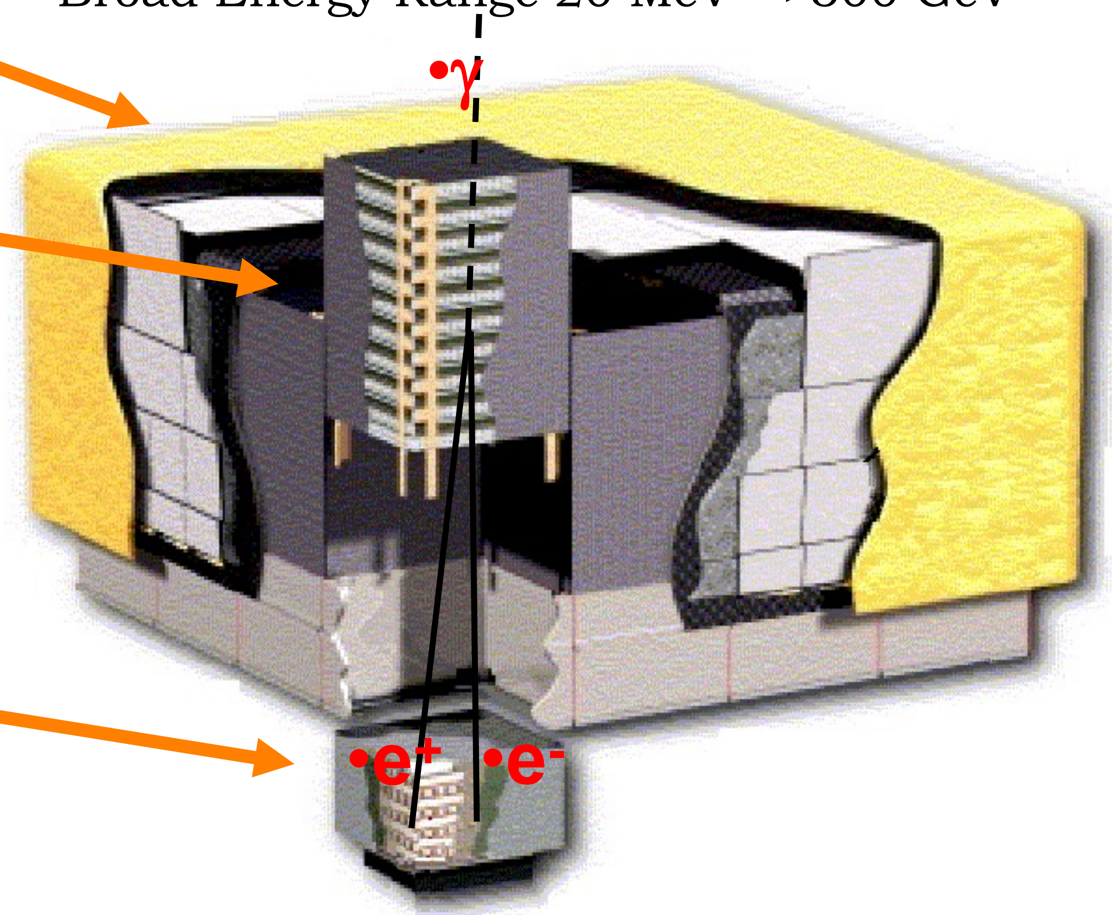
Detection technics

Fermi Large Area Telescope (LAT)

Large Field of View >2.4 sr

Broad Energy Range 20 MeV - >300 GeV

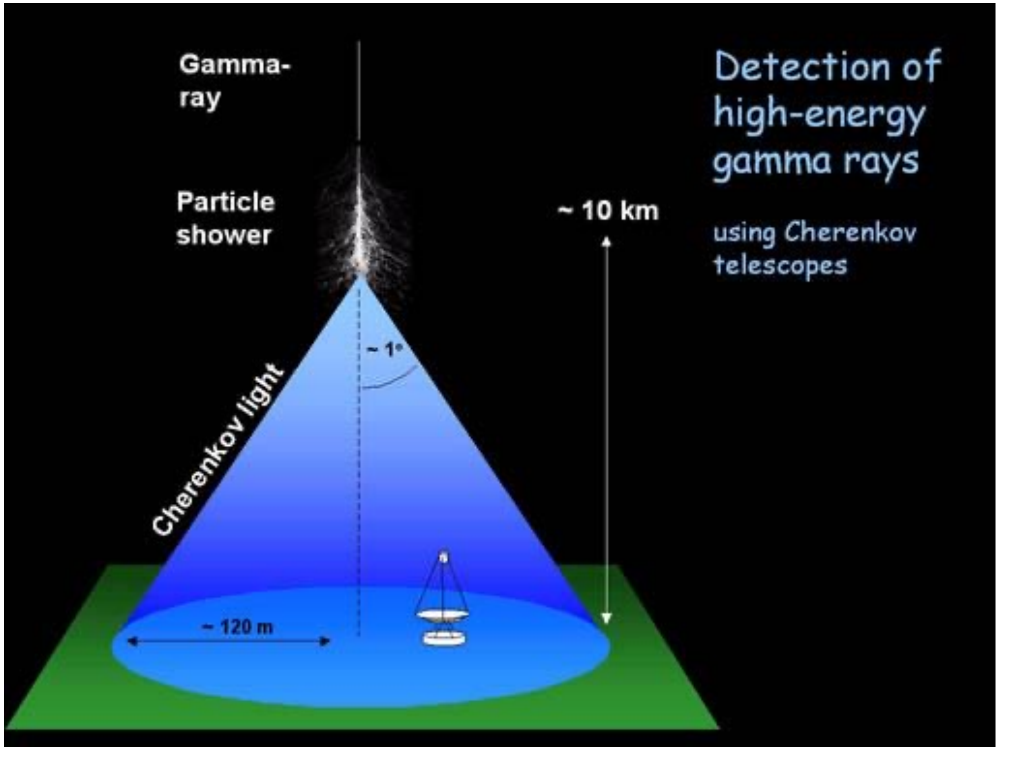
- **ACD**
- scintillator
- 89 tiles
- **Tracker**
- Si strip detectors
- Tungsten foil converters
- pitch = 228 um
- 8.8×10^5 channels
- 18 planes
- **Calorimeter**
- CsI crystals
- hodoscopic array
- 6.1×10^3 channels
- 8 layers



Cherenkov telescopes

Very high energies, above 50 GeV

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

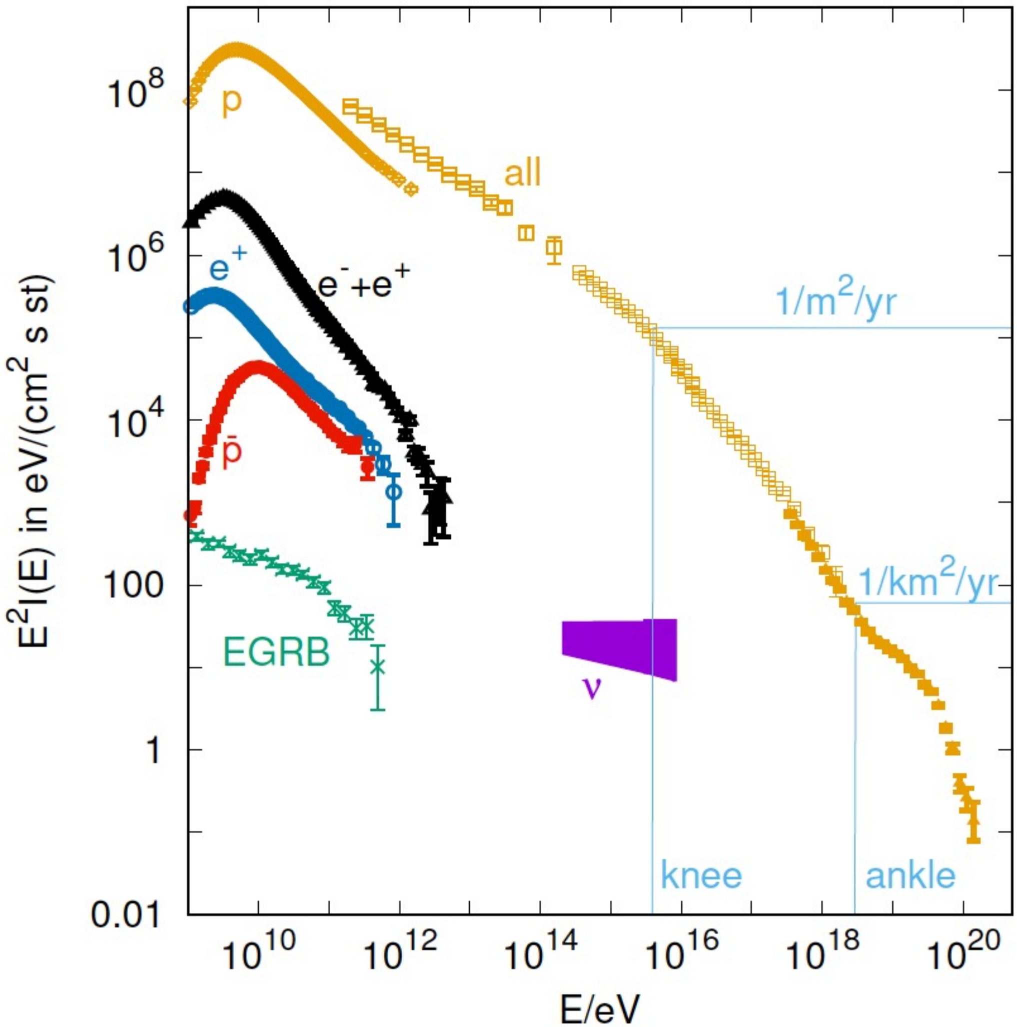


Experimental challenges

- 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)**

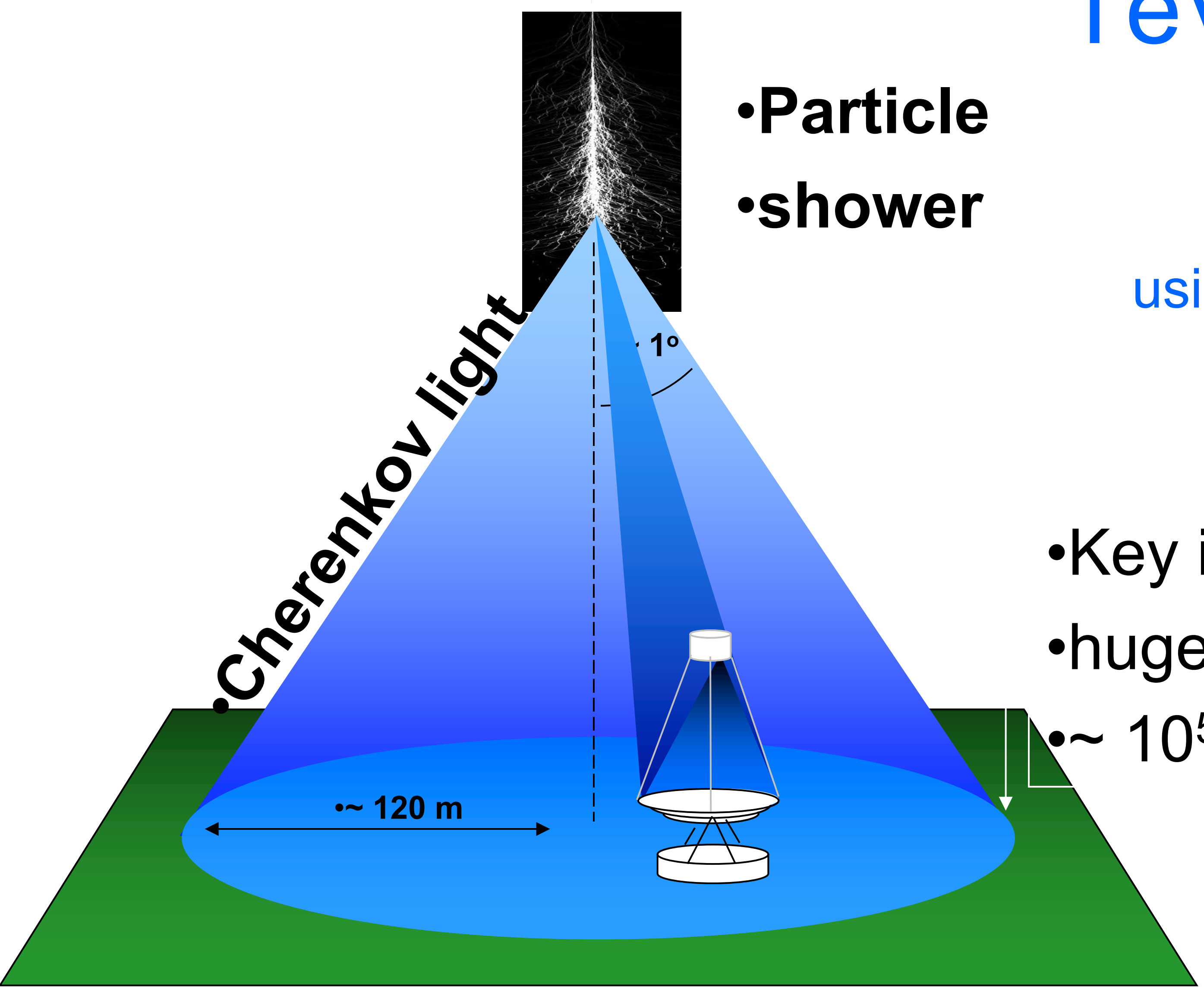
Cosmic rays and gamma



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

Detection of TeV gamma rays

using Cherenkov telescopes



- Key issue:
- huge detection area
- ~ 10^5 m^2

From W.Hofman

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)

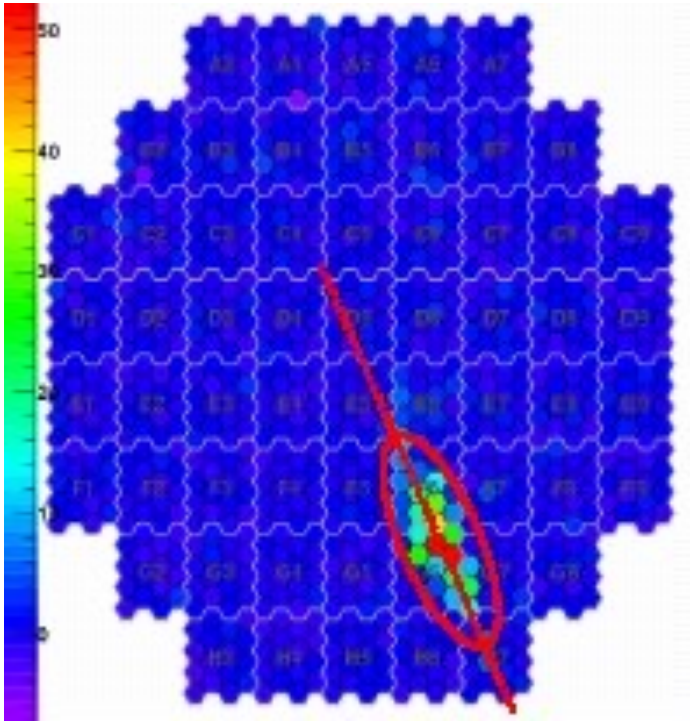
  Hadronic showers:

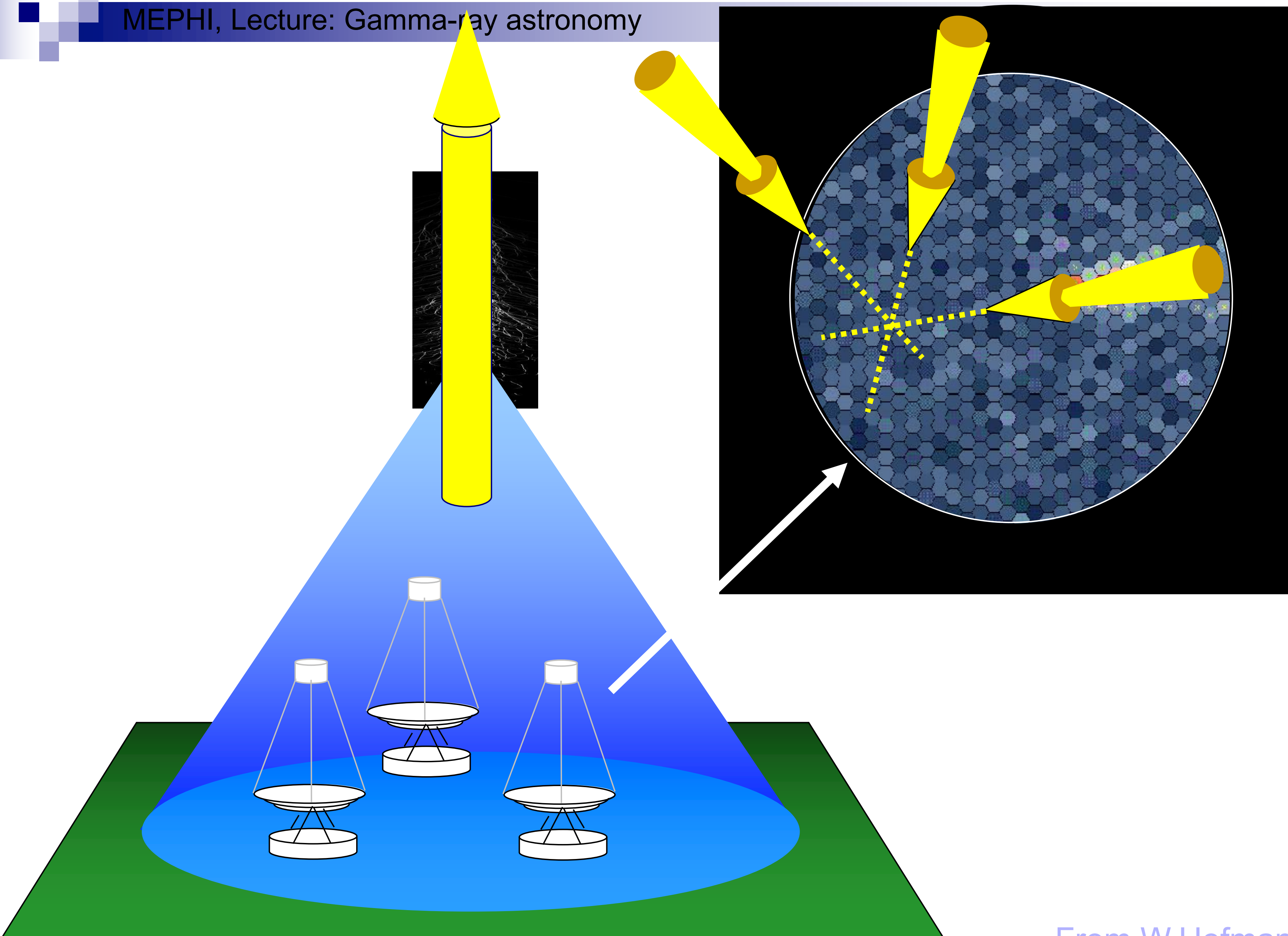
  randomly oriented in the focal plane

- Image light profiles

  (longitudinal and transverse)

  help finding the source position

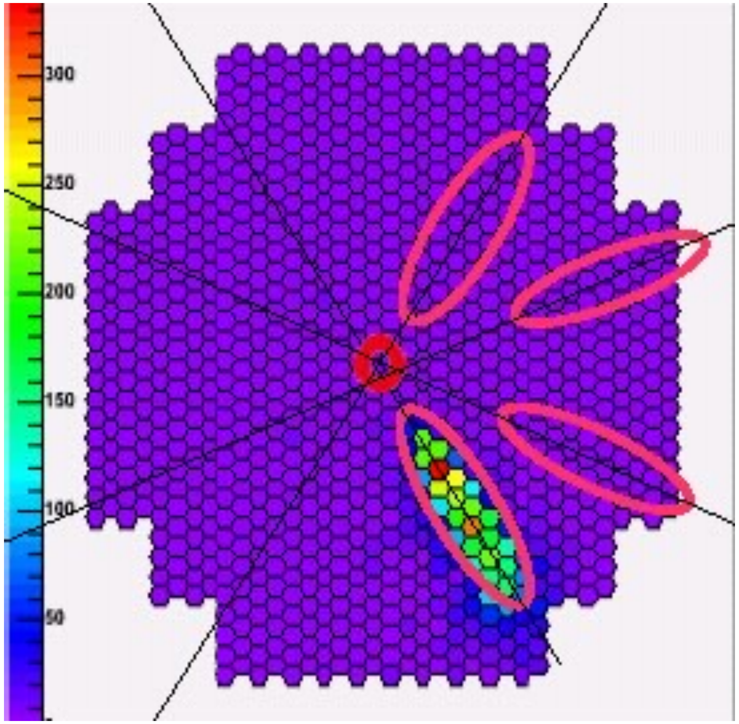


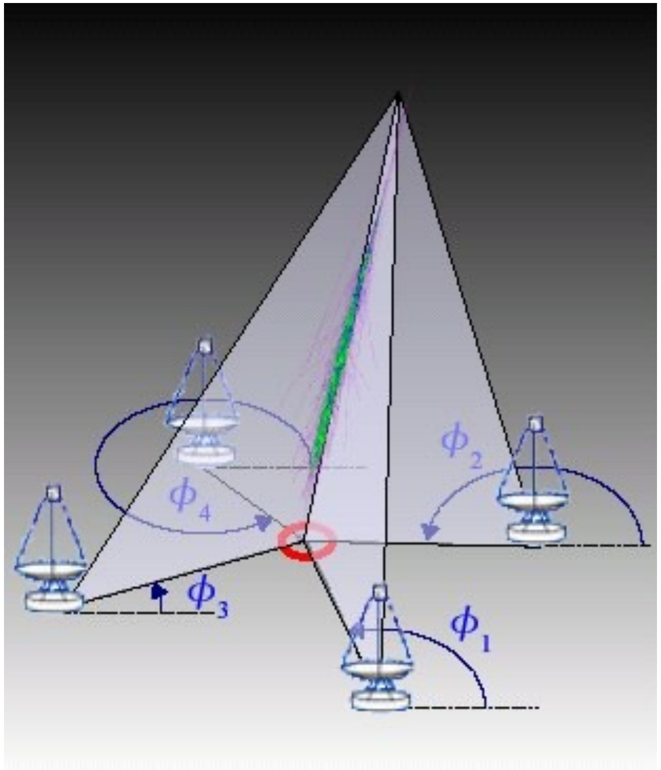


From W.Hofman

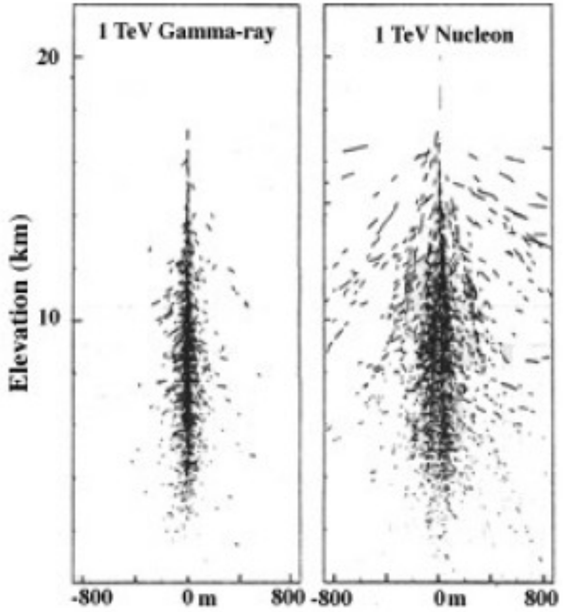
Stereoscopic measurement (e.g. HEGRA, H.E.S.S. VERITAS, MAGIC)

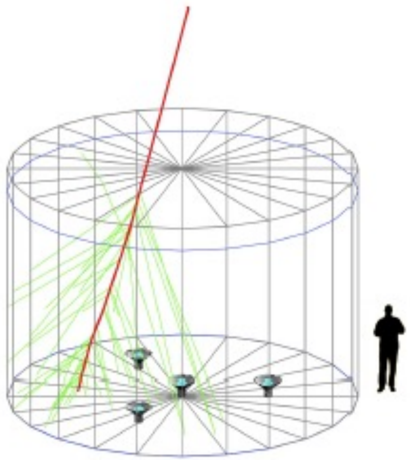
- Direct measurement of the γ**-ray origin** in the field of view (important for extended sources)
- Direct measurement of the **impact on the ground** (important for energy measurement)
- Better hadronic rejection
- Much better angular resolution





Detection Technique of the EAS Arrays



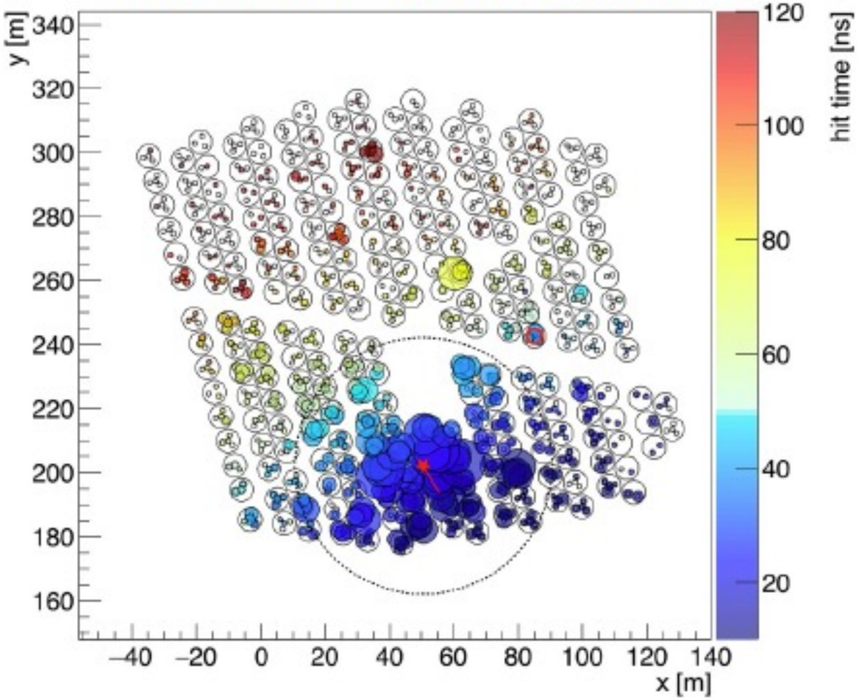


- The particle detectors can be tanks full of water. Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- Gamma/hadron can be discriminated based on the event footprint on the detector. Although is one of the challenges of this kind of detectors.

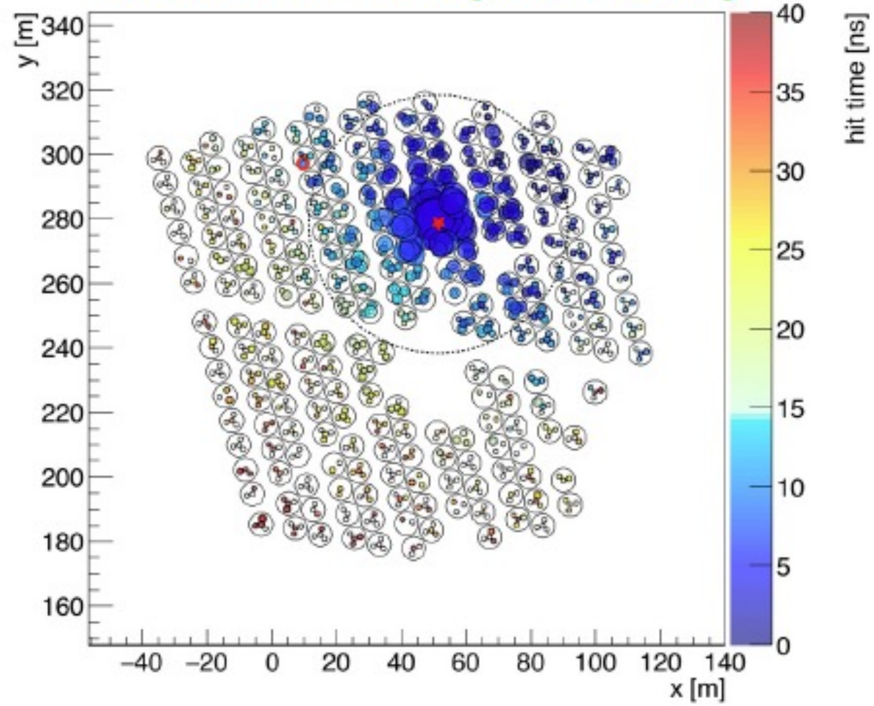
Gamma/Hadron Separation

- Main background is hadronic CR, e.g. 400 γ/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.

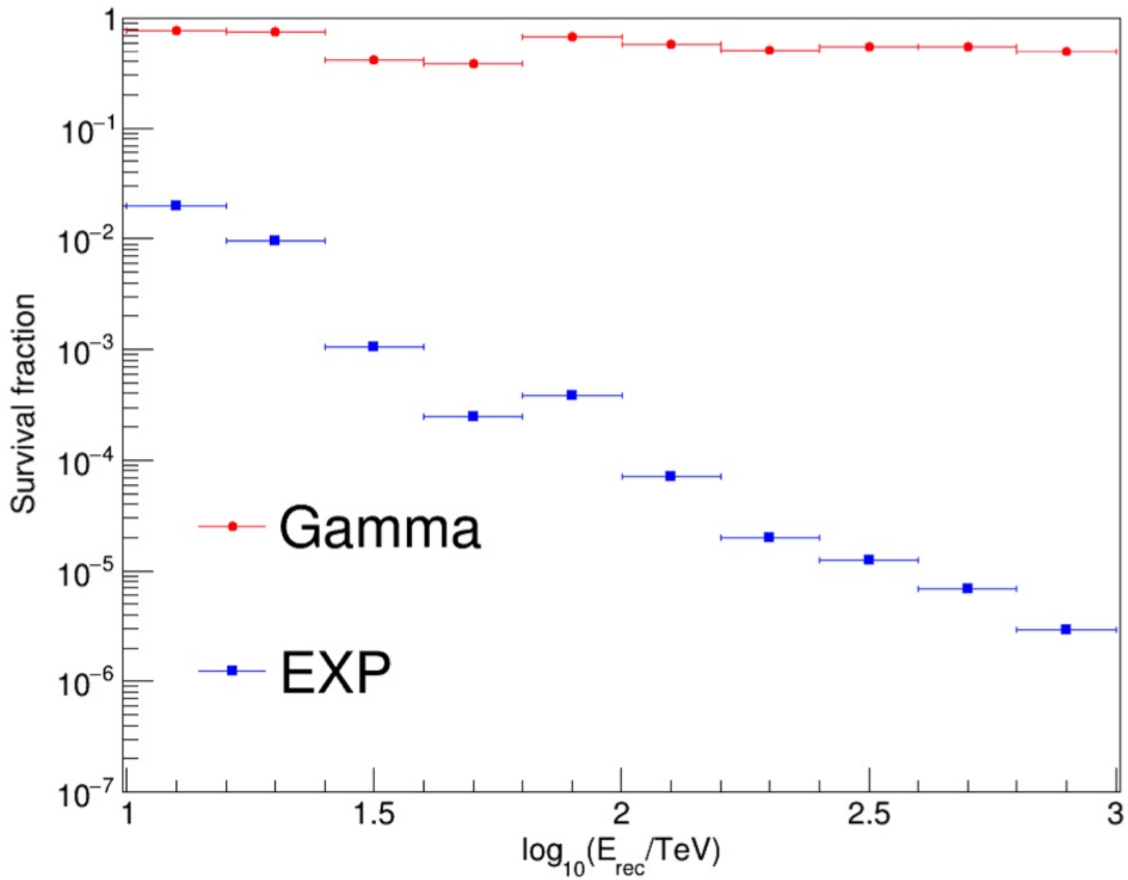
HAWC Data – Hadron Shower



HAWC Data – Likely Gamma Ray



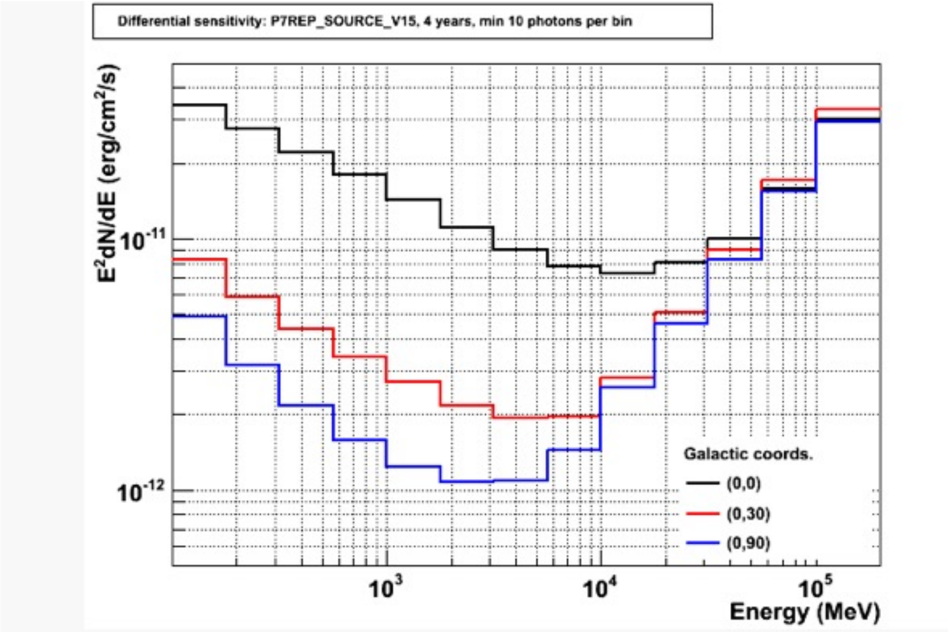
LHAASO hadron cut 2021



•LHAASO talk ICRC Jul 2021

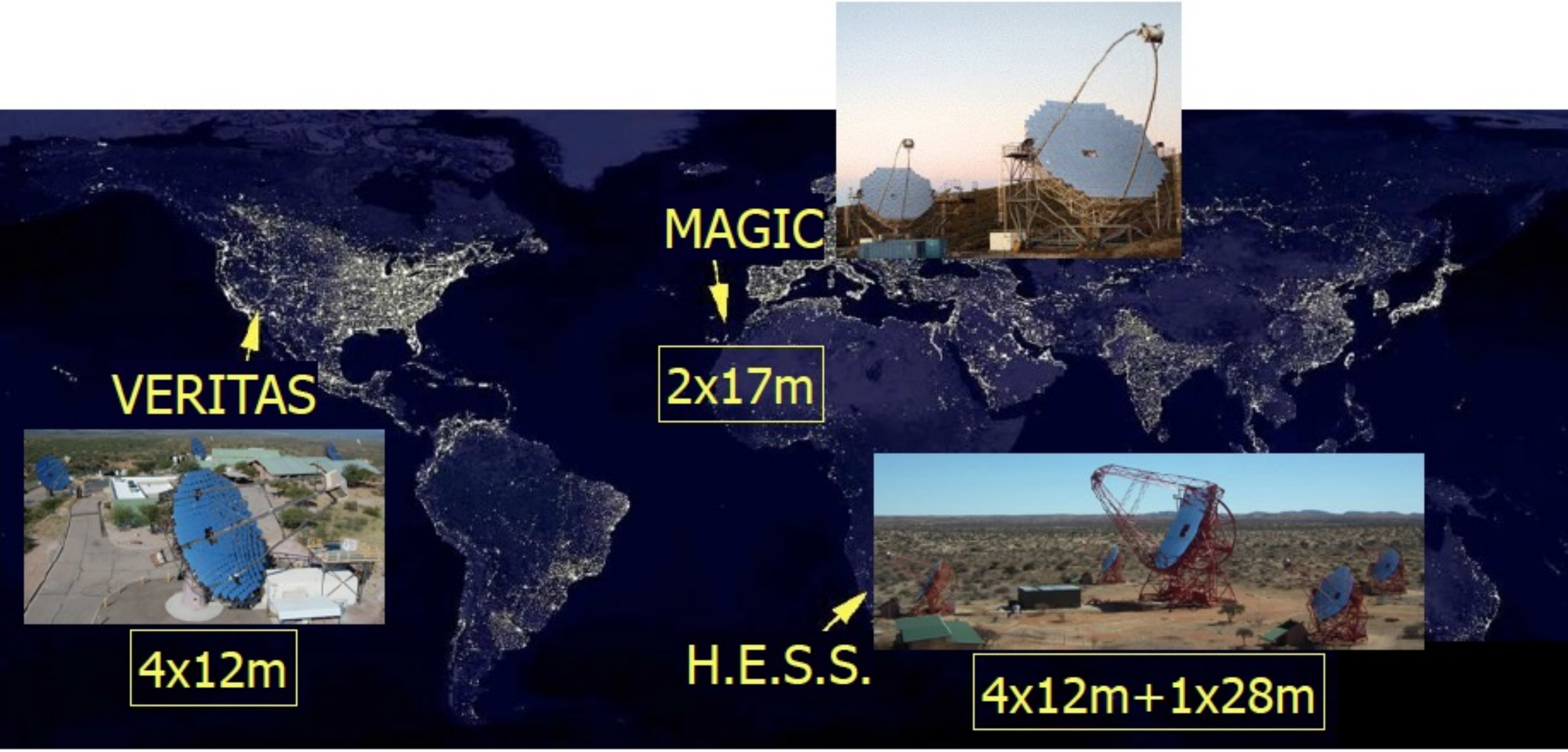
Fermi LAT
gamma-rays
40 MeV-1 TeV

Fermi LAT


Differential sensitivity: P7REP_SOURCE_V15, 4 years, min 10 photons per bin
E^{2}dN/dE (erg/cm^2/s)
10^{-11}
10^{-12}
10^3
10^4
10^5
Energy (MeV)
Galactic coords.
(0,0)
(0,30)
(0,90)

TeV telescopes 50 GeV-20 TeV

Cherenkov telescopes today



•HESS

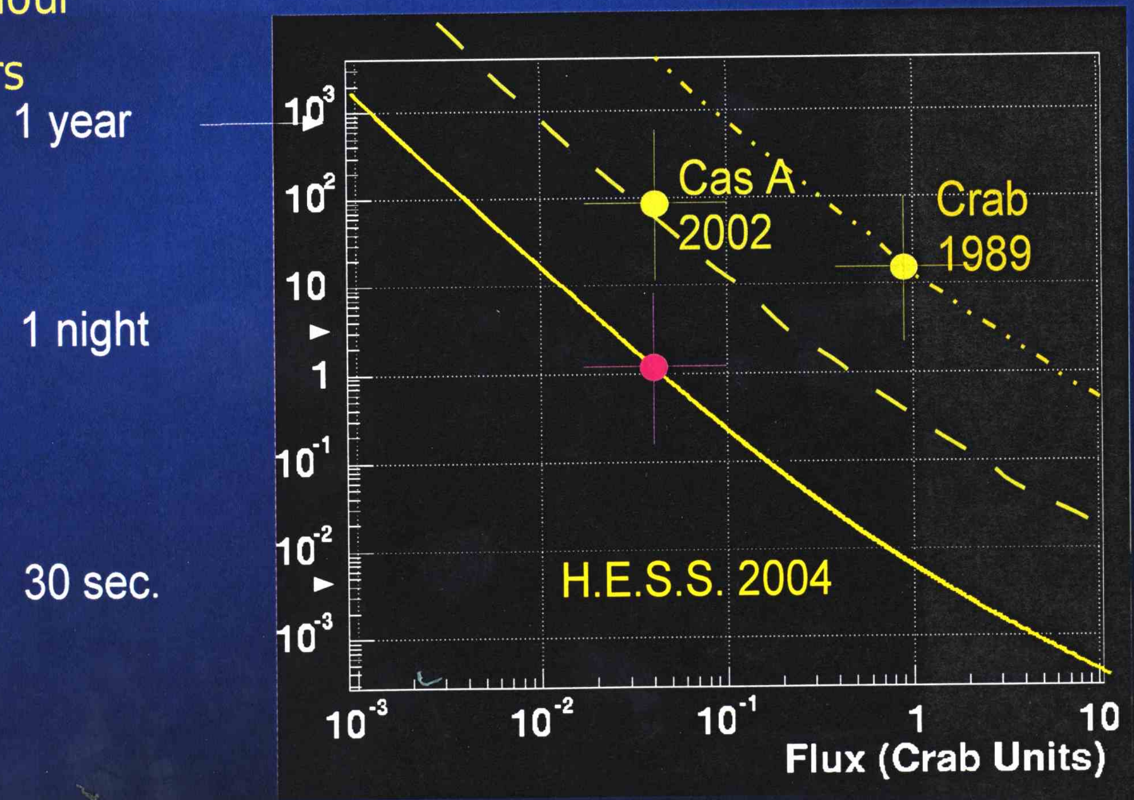
•European Collaboration; M.P.I (Heidelberg)

•4 x 12 m Telescopes

•Completed in Dec. 2003; located in NAMIBIA

H.E.S.S. Sensitivity

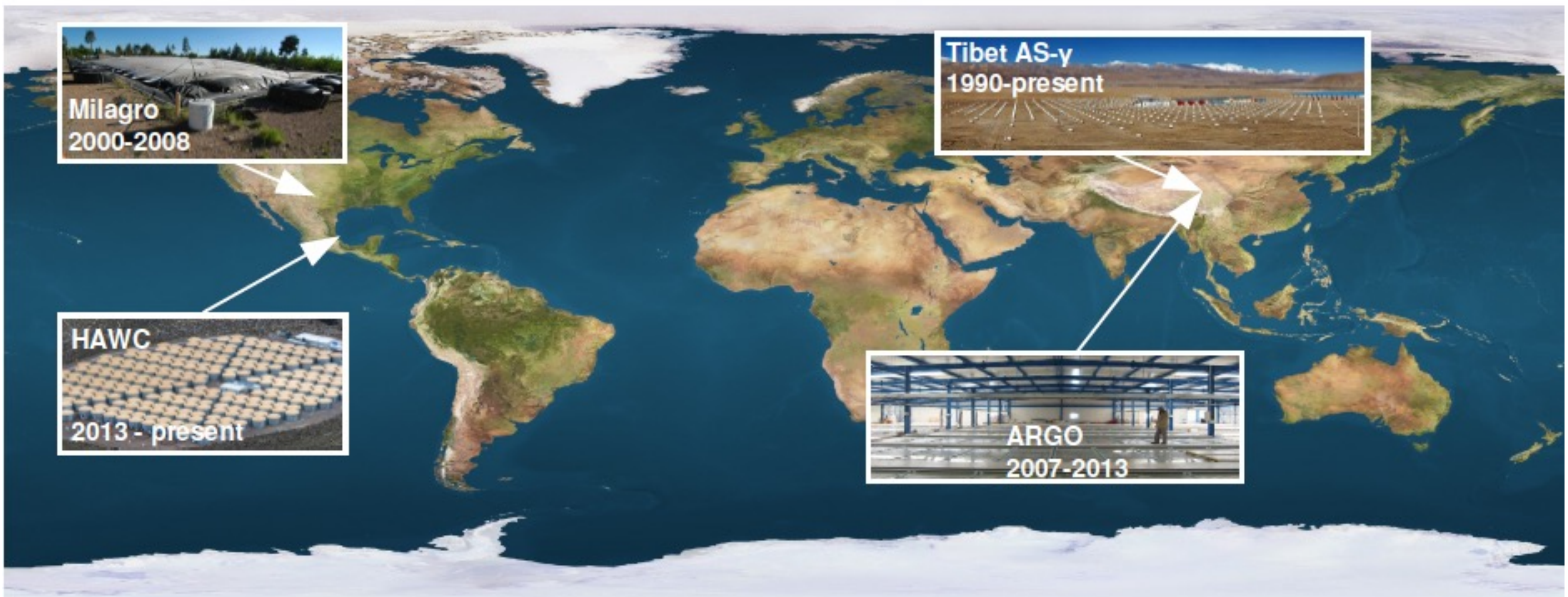
- HEGRA
  - 5% of Crab flux in 100 hours
- H.E.S.S.
  - 5% of Crab in 1 hour
  - 0.5% in 100 hours



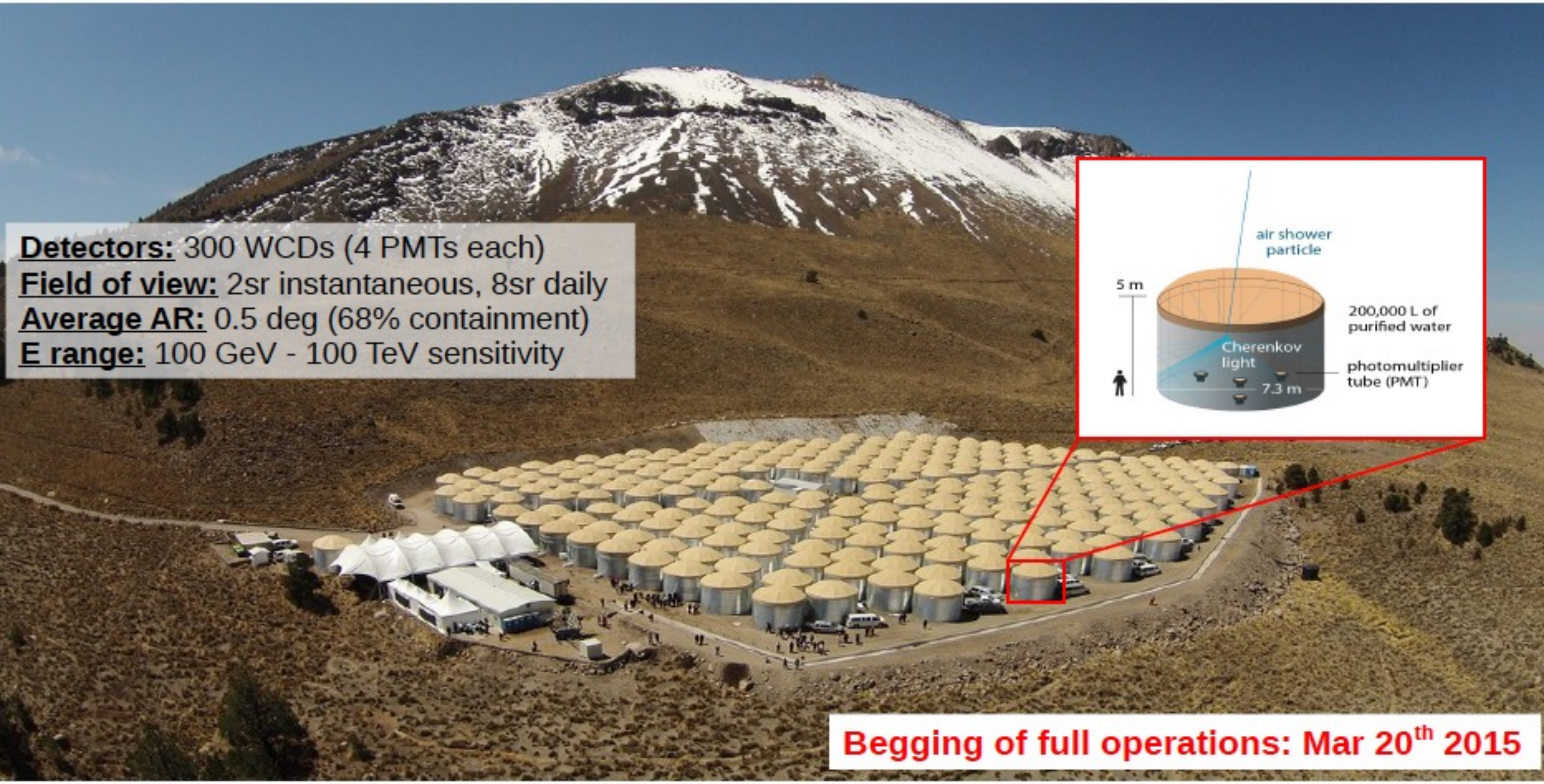
LAST
UCLA

EAS Detectors

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



HAWC Inauguration



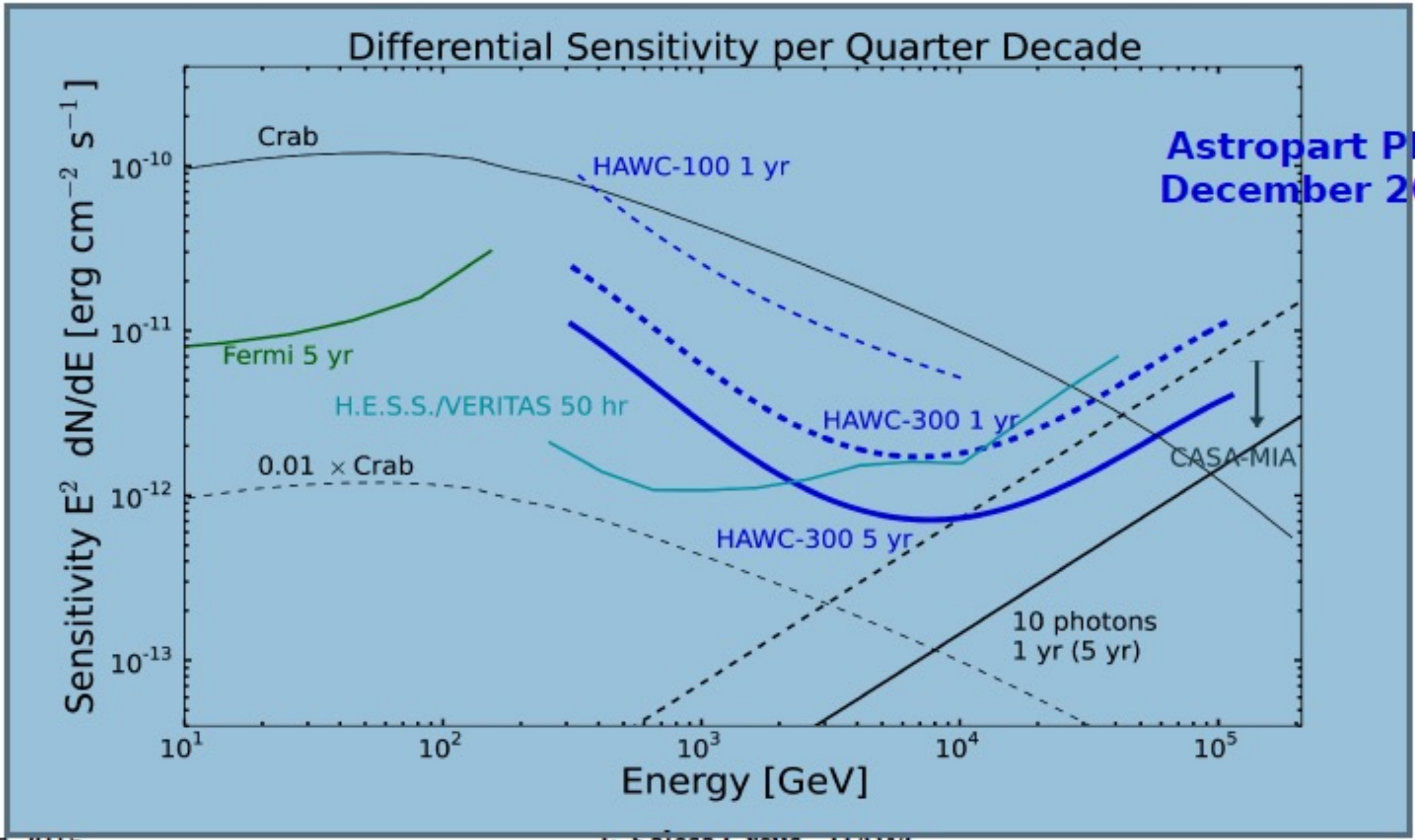
Detectors: 300 WCDs (4 PMTs each)
Field of view: 2sr instantaneous, 8sr daily
Average AR: 0.5 deg (68% containment)
E range: 100 GeV - 100 TeV sensitivity

Begging of full operations: Mar 20th 2015

HAWC Designed Sensitivity

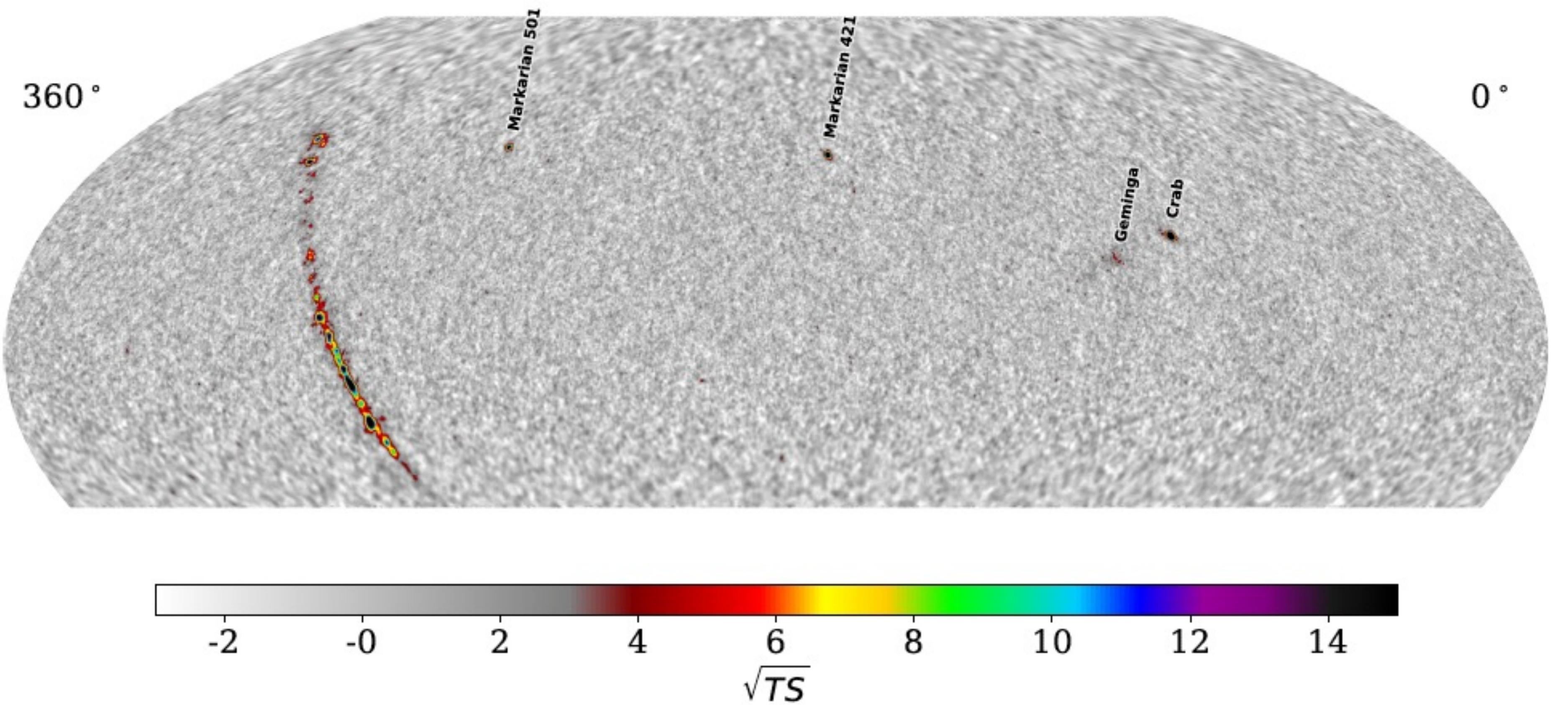
- Instantaneous sensitivity 15-20x less than IACTs.
- Exposure (sr/yr) is 2000-4000x higher than IACTs.

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

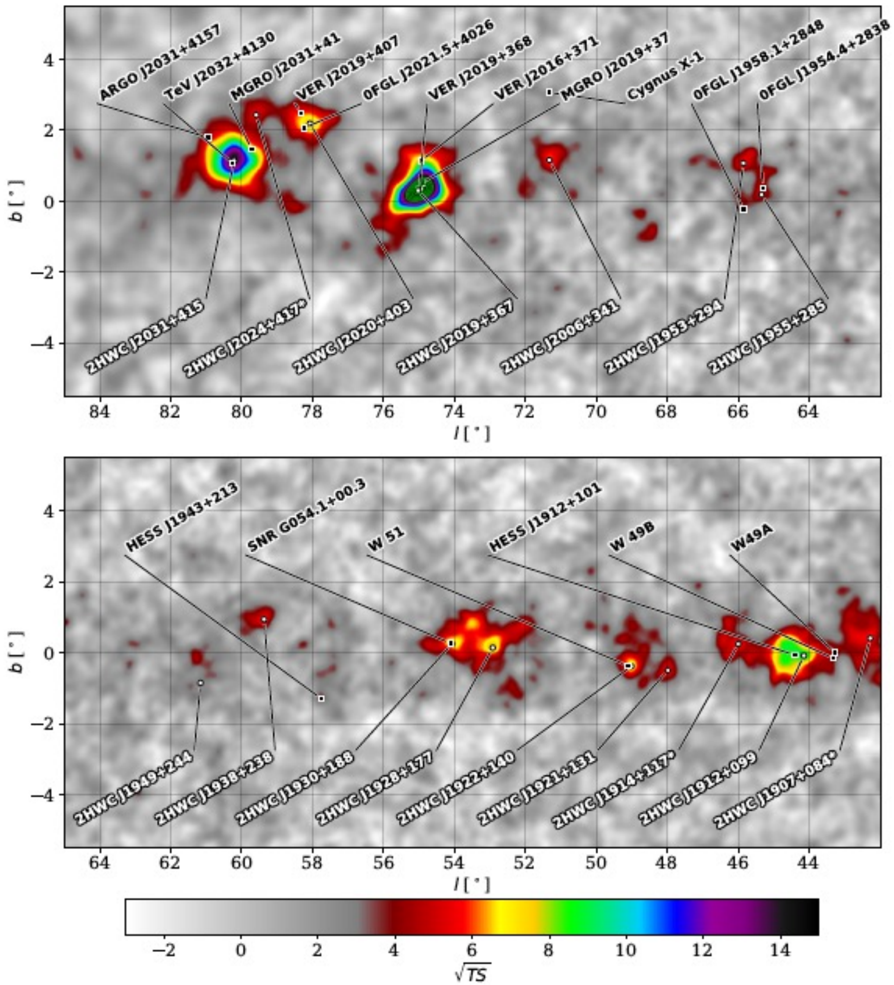


Astropart Phys 50-52, December 2013, 26-32

HAWC sky map


360°
0°
Markarian 501
Markarian 421
Geminga
Crab
-2
-0
2
4
6
8
10
12
14
$\sqrt{TS}$

HAWC galactic plane

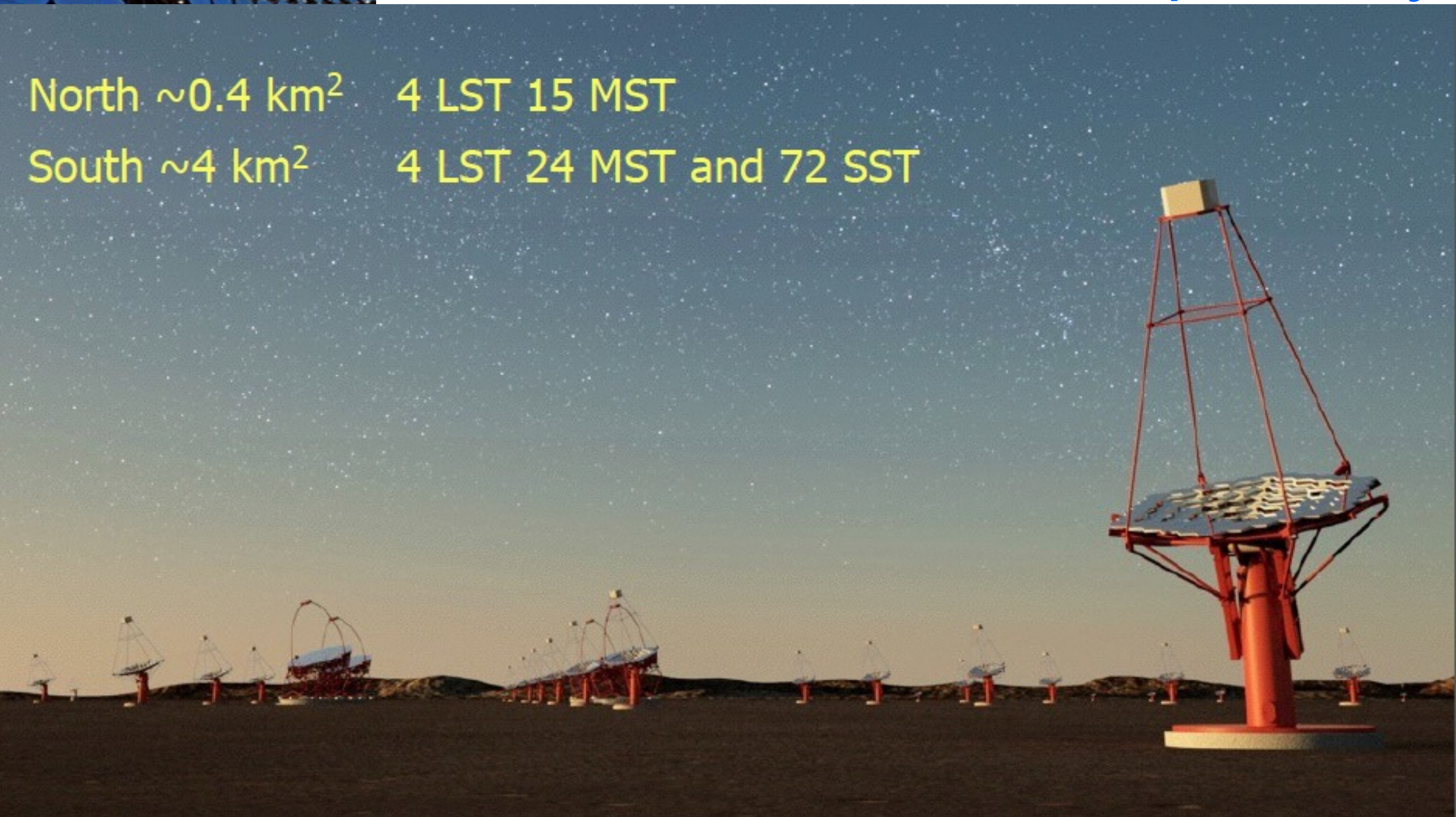


Future TeV telescopes

Wish list

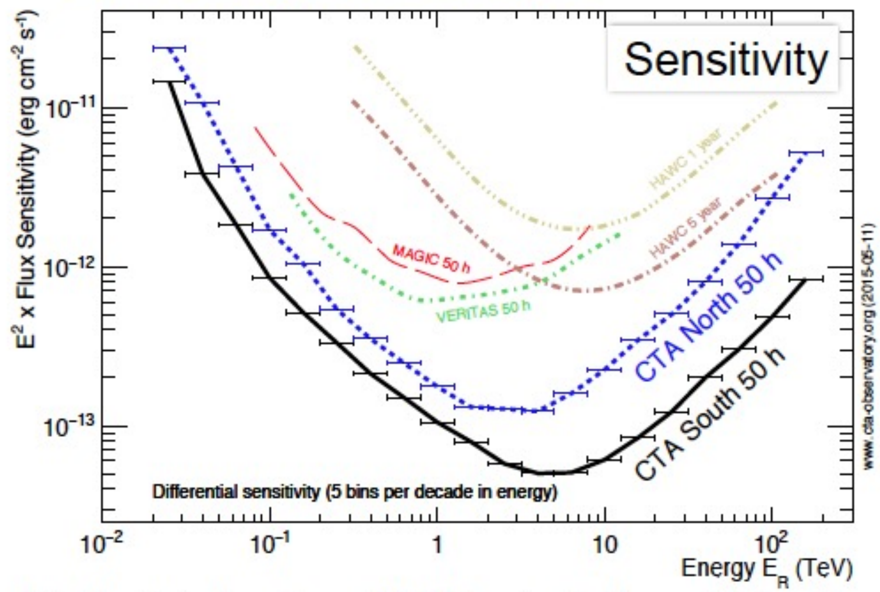
- Higher sensitivity at TeV energies (x 10)
  - more sources
- Lower threshold (some 10 GeV)
  - pulsars, distant AGN, source mechanisms
- Higher energy reach (PeV and beyond)
  - cutoff region of Galactic accelerators
- Wide field of view
  - extended sources, surveys
- Improved angular resolution
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

•CTA The Next Generation: The Cherenkov Telescope Array

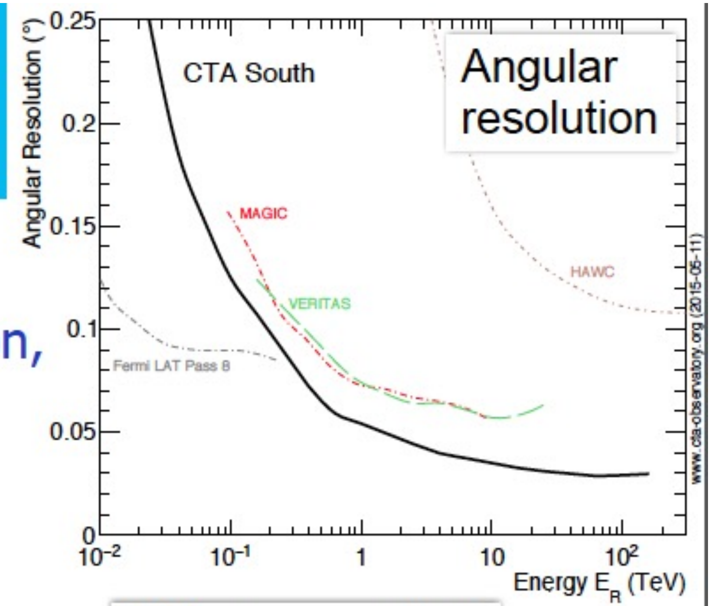


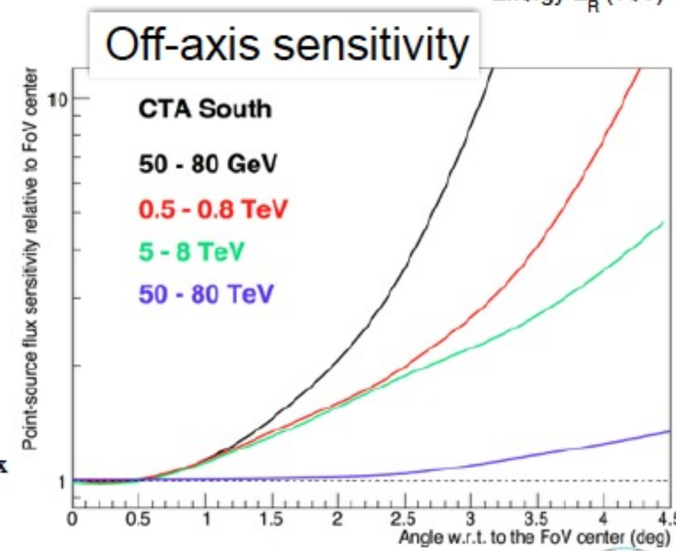
CTA Performance

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

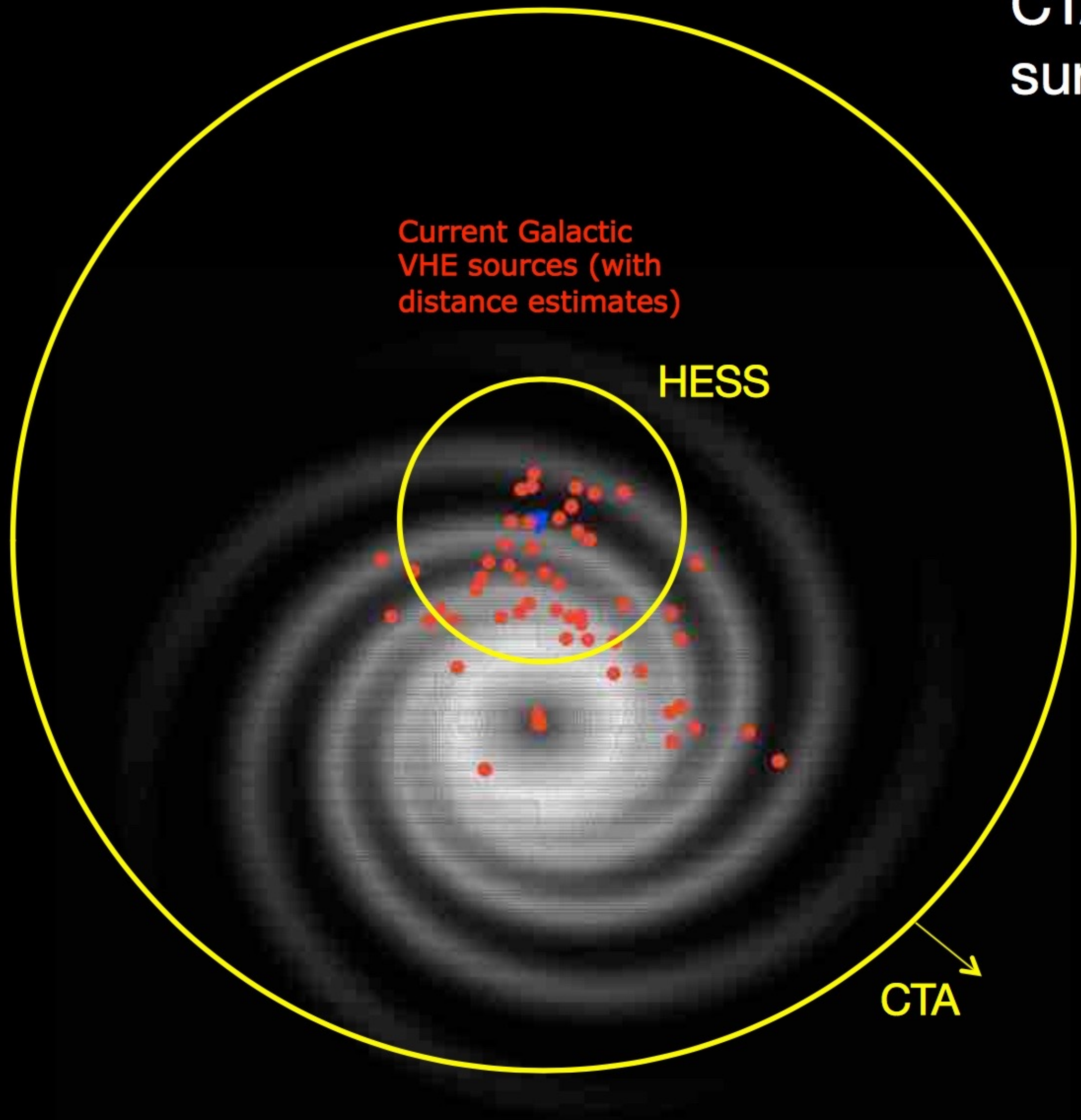


https://portal.cta-observatory.org/CTA_Observatory/performance/SitePages/Home.aspx





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



CTA as ultimate survey machine

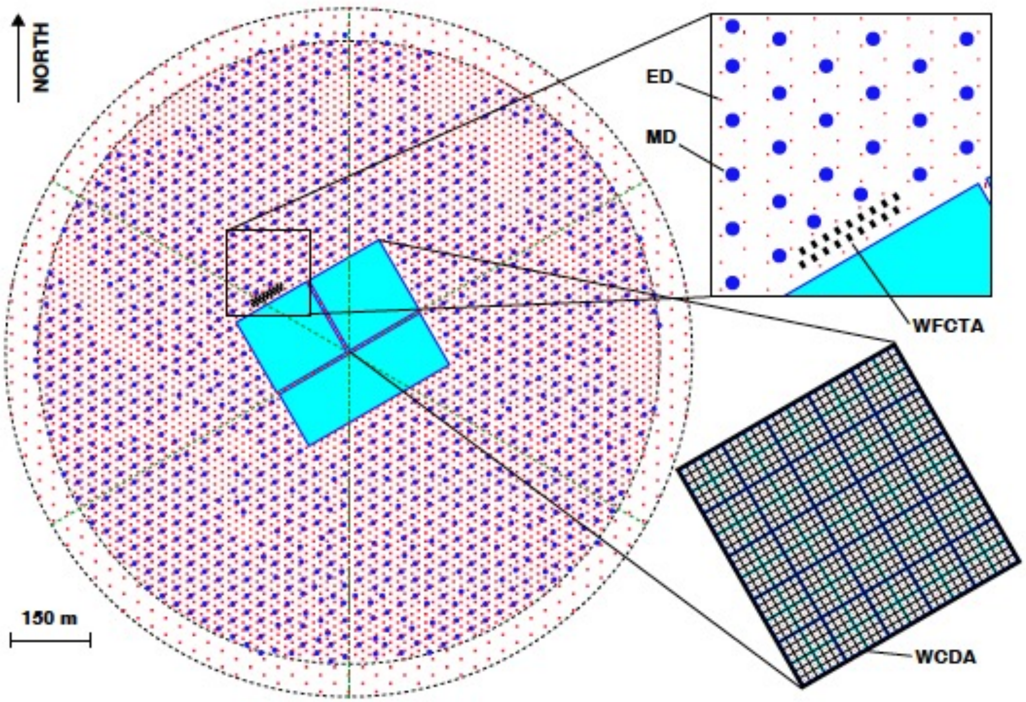
CTA as ultimate machine to study flares

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

Coherent full-sky coverage from two sites

The LHAASO experiment

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

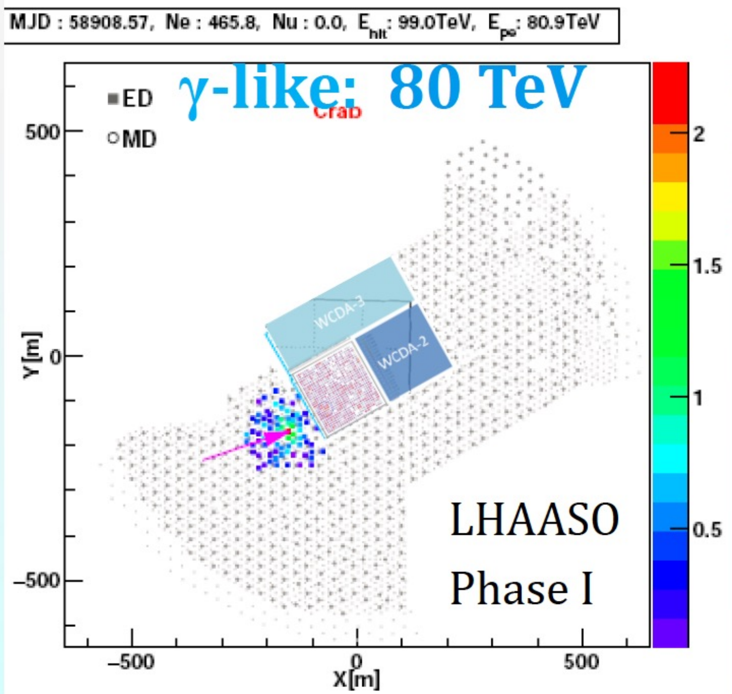


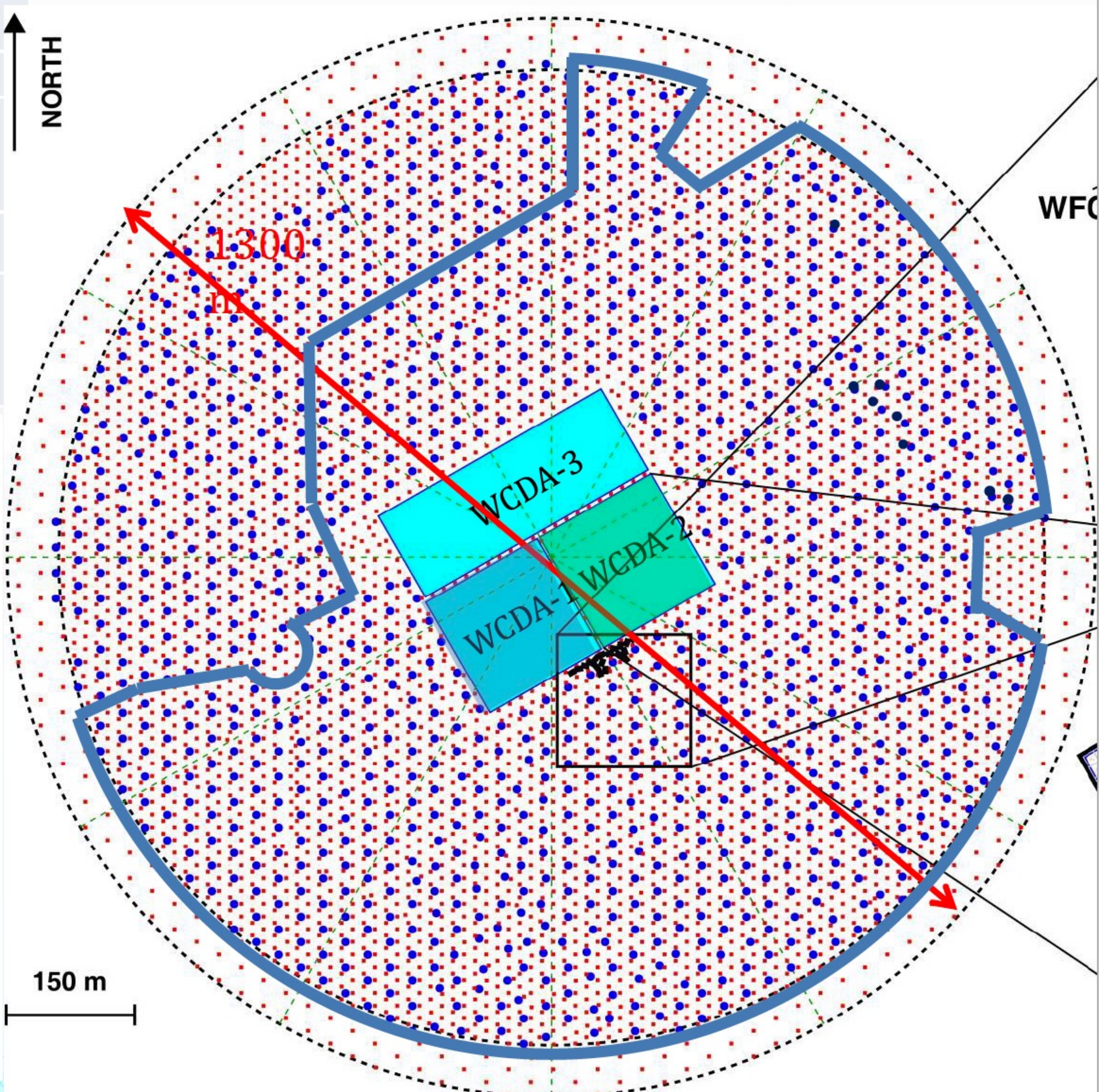
- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m^2.
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.

4410

LHAASO Phase-II: Dec,2020—

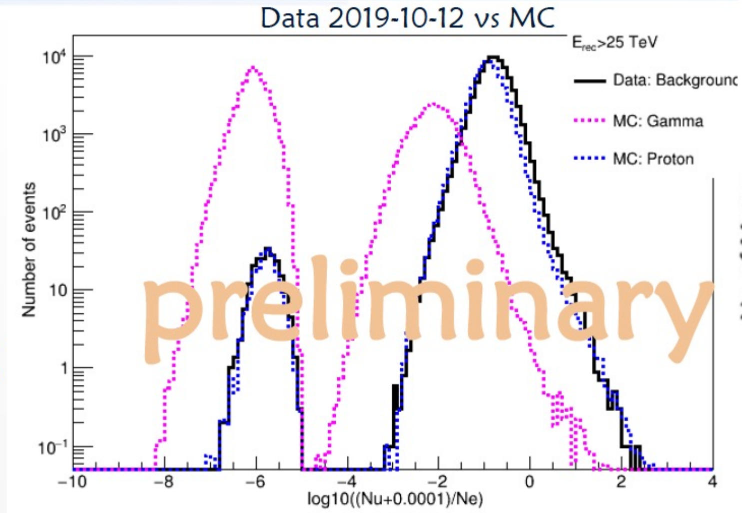
2019-12-12	Muon Counter	Scintillator Detector
operating	594	2514
2010-11-30		
operating	**917**	**3978**
Percentage of designed sensitivity	**88%**	

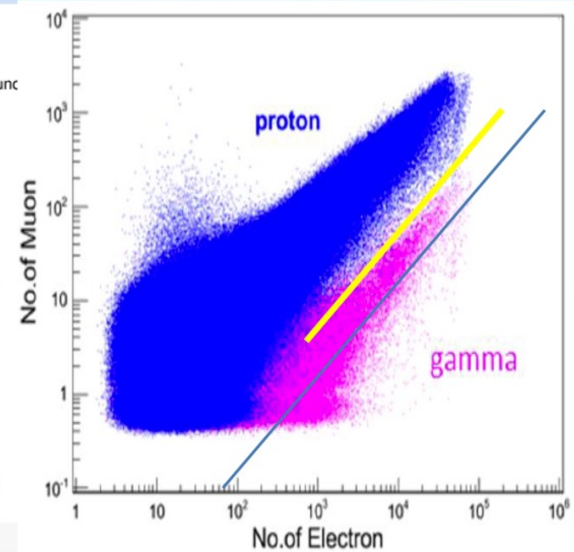


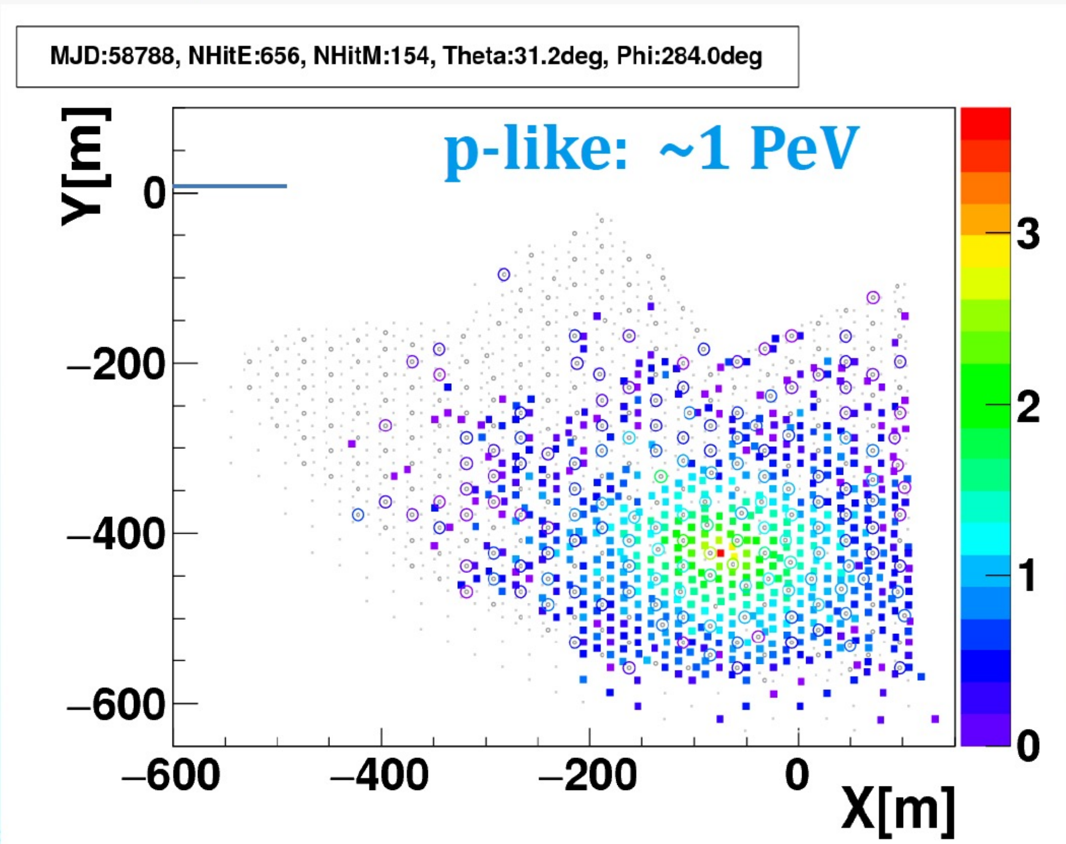


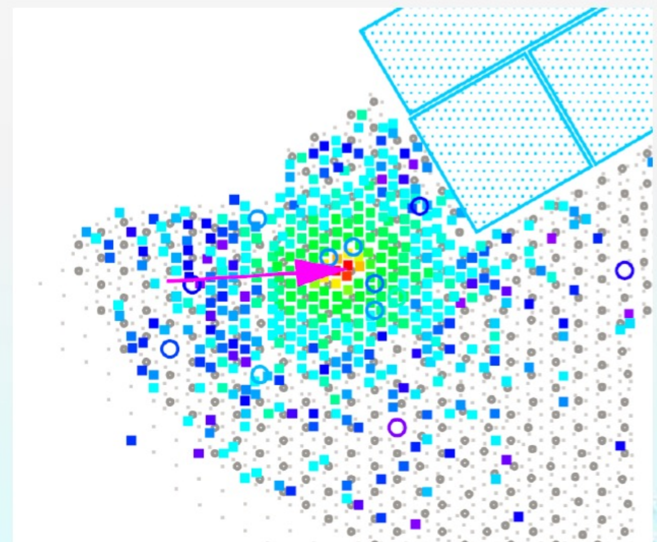
LHAASO
高海拔宇宙线观测站

γ/proton Separation: μ-content



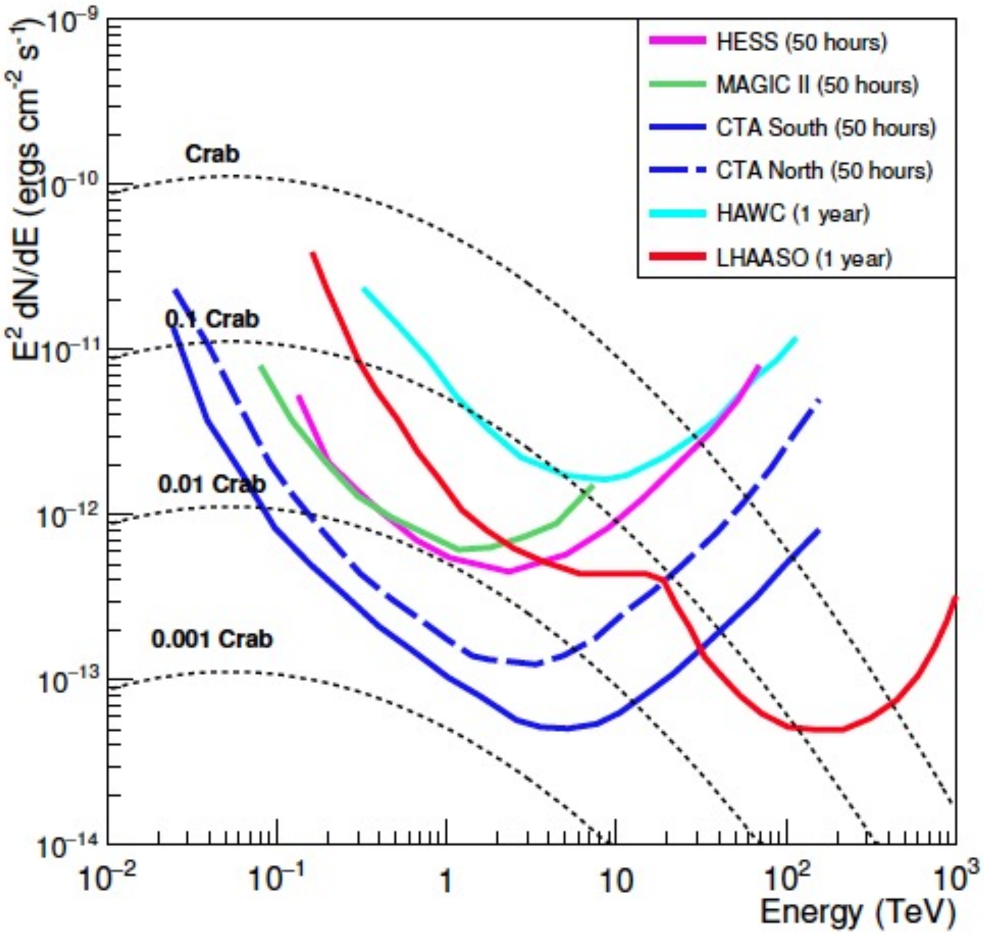






γ-like: ~ 1 PeV

Sensitivity future detectors



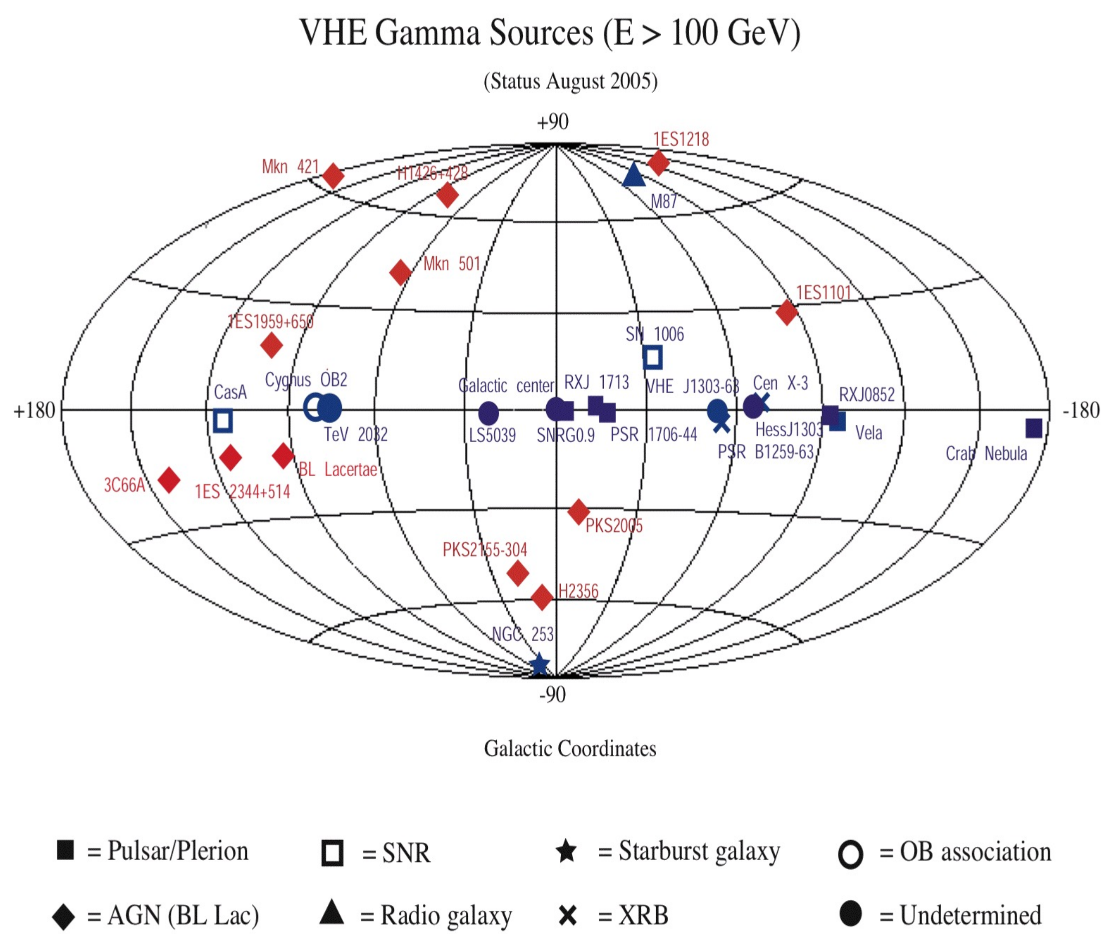
Summary detection

- 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.
- 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 diffuqse background in different parts of Galaxy

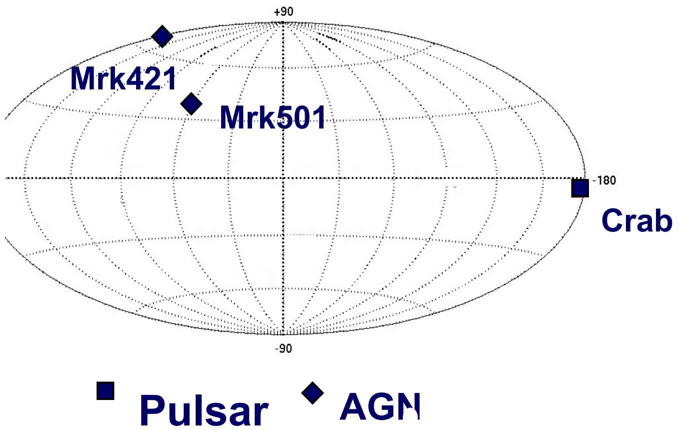
Gamma-ray sky

The VHE γ ray sky

2005

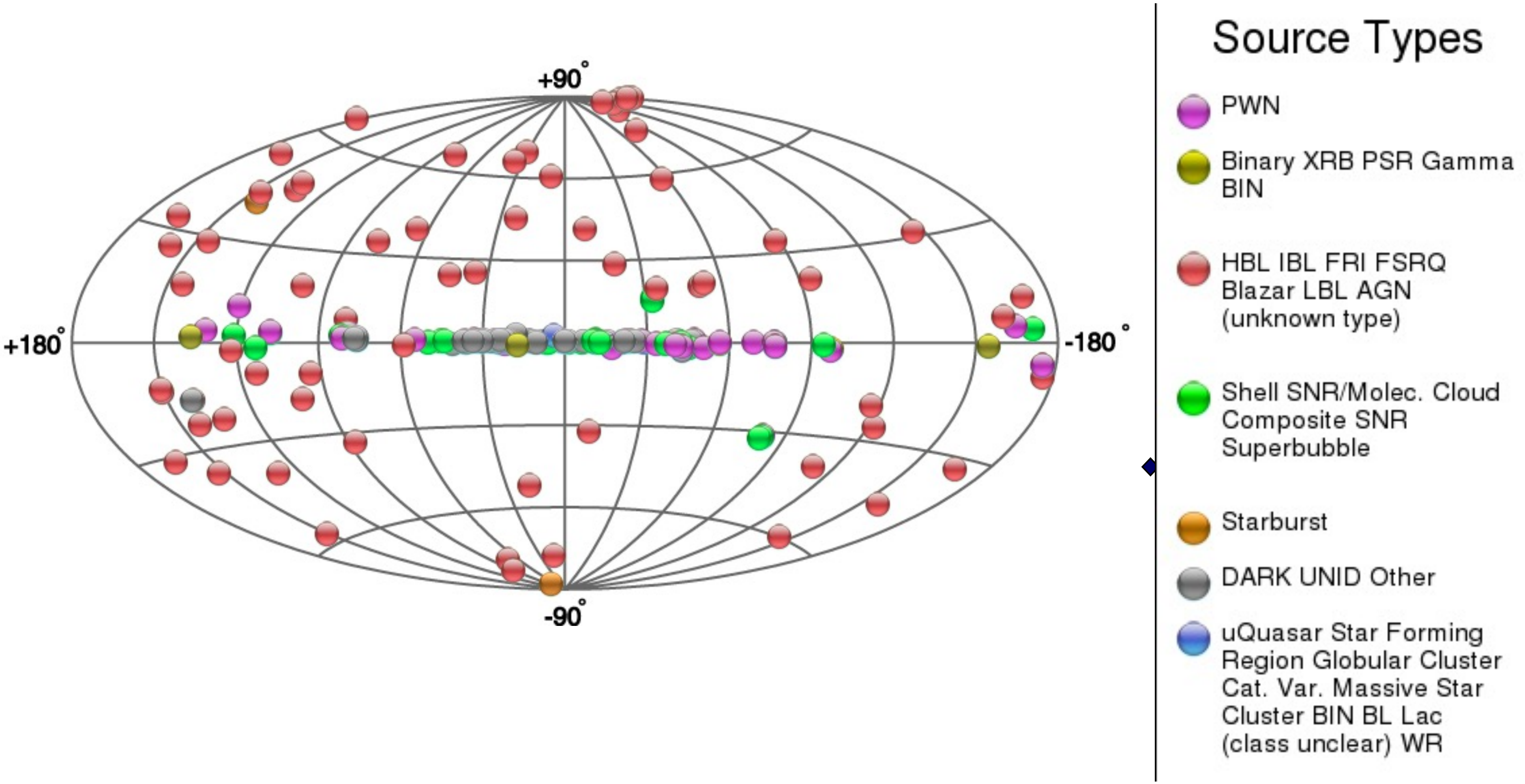


1995



The VHE γ ray sky Dec 2015

176 sources

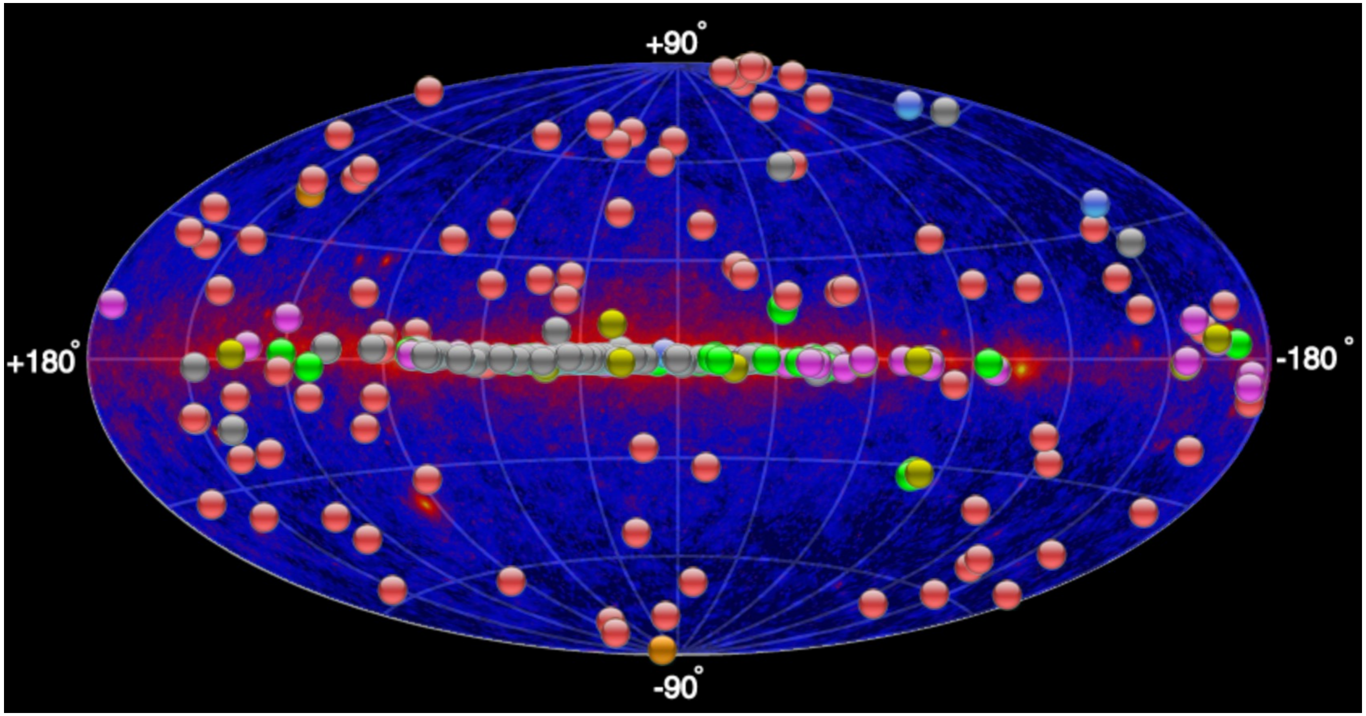


Source Counts

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 γ ray sky Feb 2022

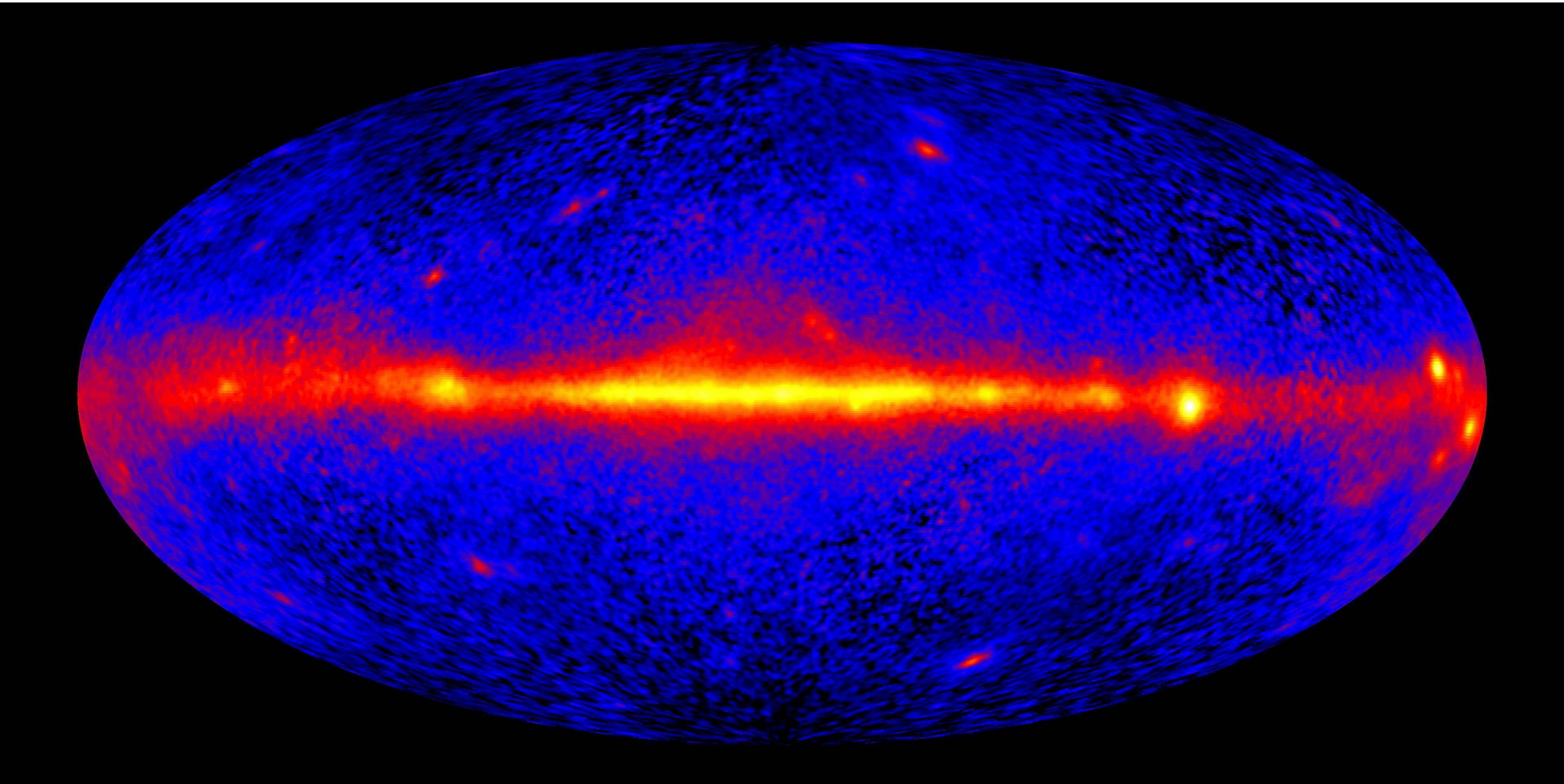
251 sources



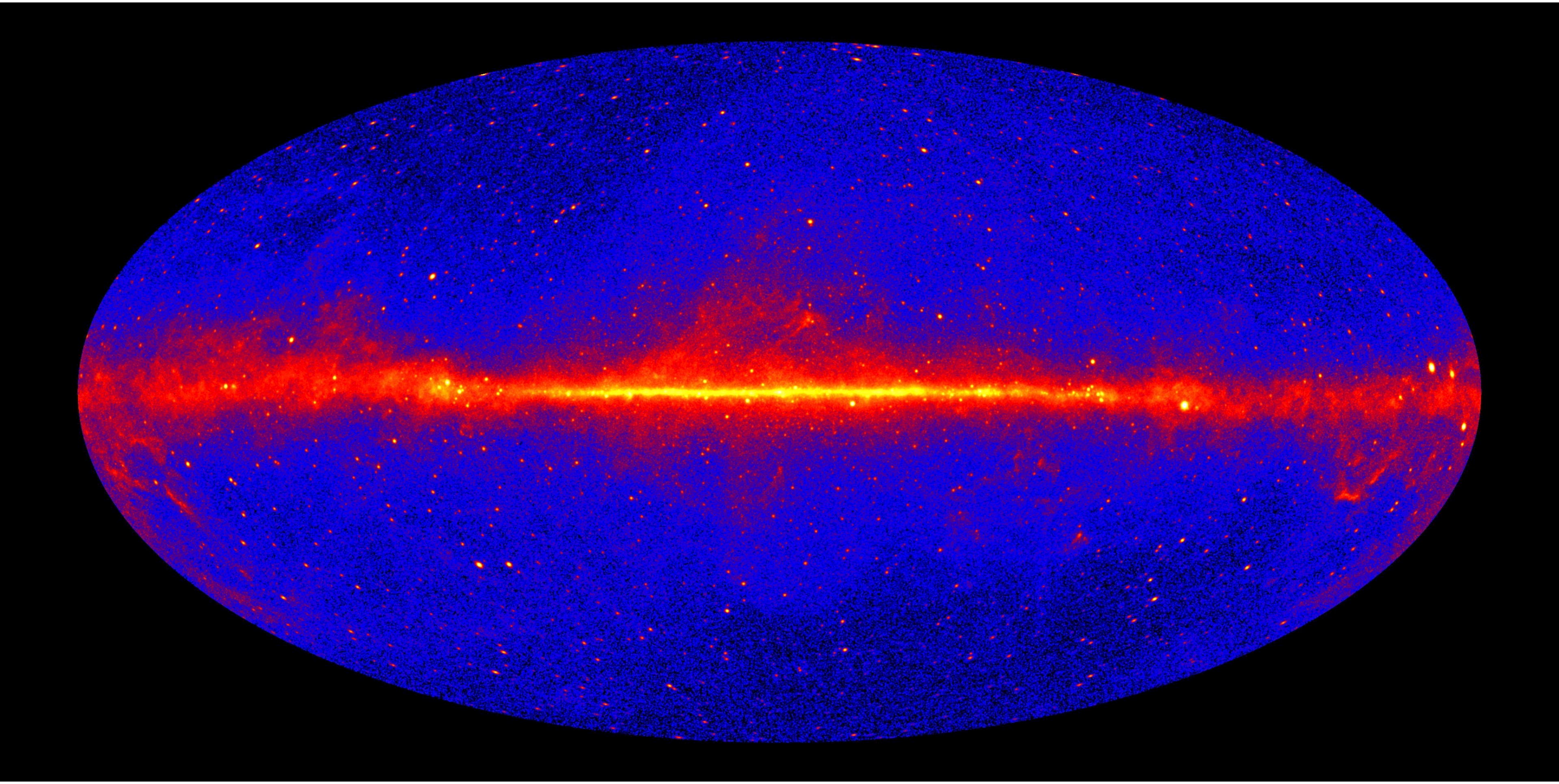
Source Types

- 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

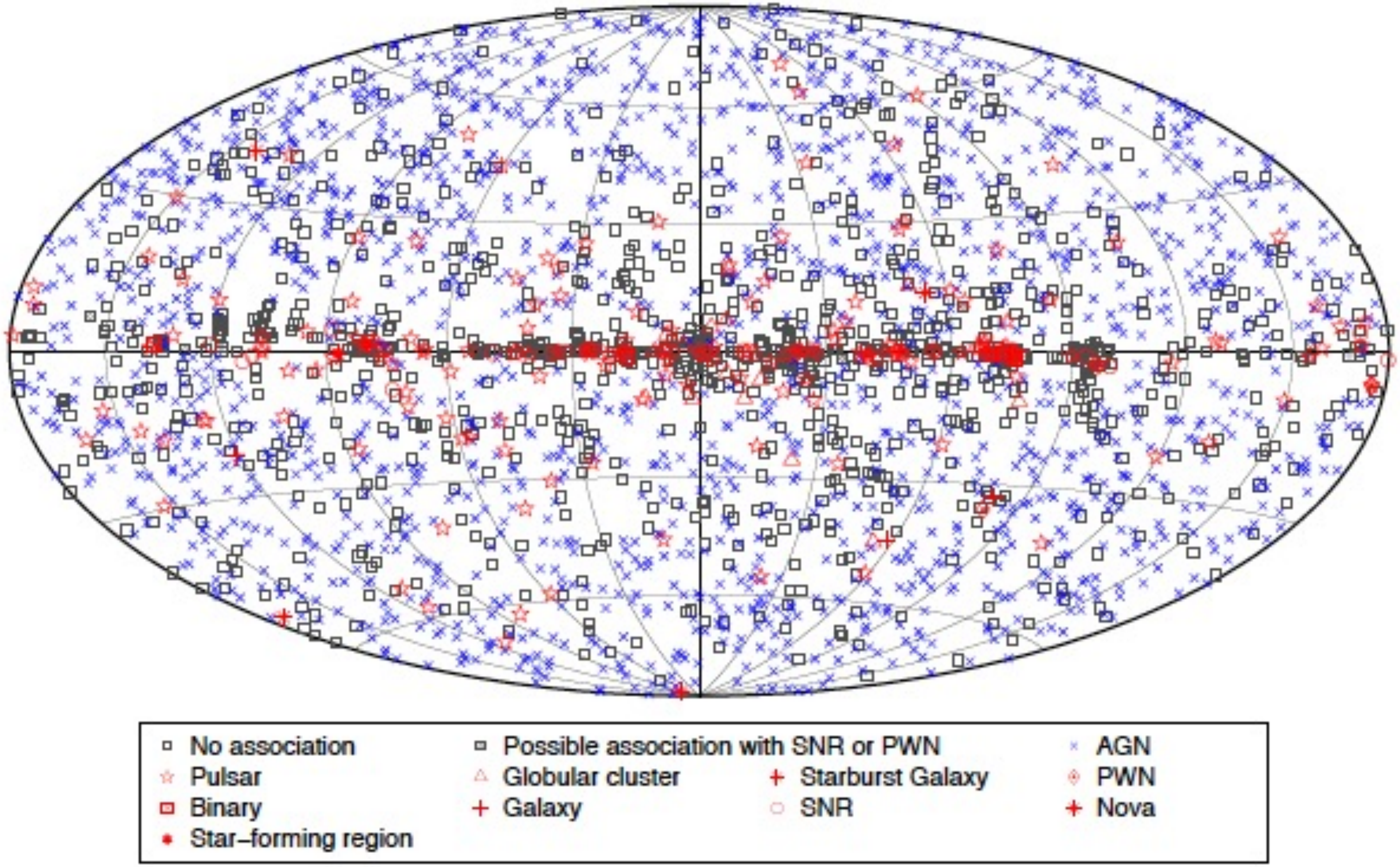
EGRET 9 years 1991 to 2000 all sky 1 GeV. 271 source



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



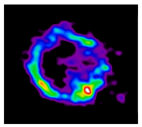
Fermi LAT source 4th catalog: 5000 sources



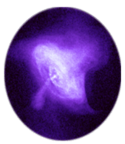
Overview of TeV gamma-ray Science

I. Astronomy and Astrophysics

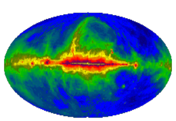
A. Galactic sources



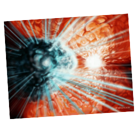
- **Shell-type Supernova Remnants**



- **Pulsar wind nebula**
- **Binary systems**
- **Microquasars**
- **Central black hole**



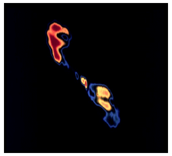
- **Galactic Diffuse Emission**



- **Galactic Cosmic Ray Origin**
- **Dark sources**

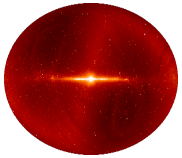
Overview of gamma-ray Science

B. Extra Galactic sources

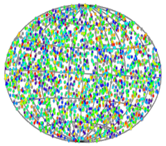


Radio galaxies

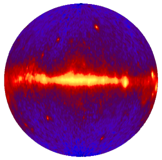
- **Blazars**



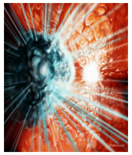
- **Extragalactic Background Light**



- **Gamma Ray Bursts**



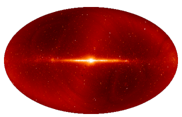
- **Unidentified Sources**



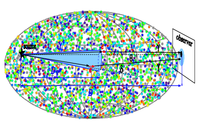
- **Ultra-High Energy Cosmic Ray Origin**

Overview of gamma-ray Science

Cosmology

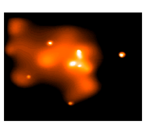


- **Extragalactic Background Light**
- **Primordial magnetic field**

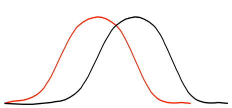


- **Distant Gamma Ray Bursts (GeV)**

Particle physics

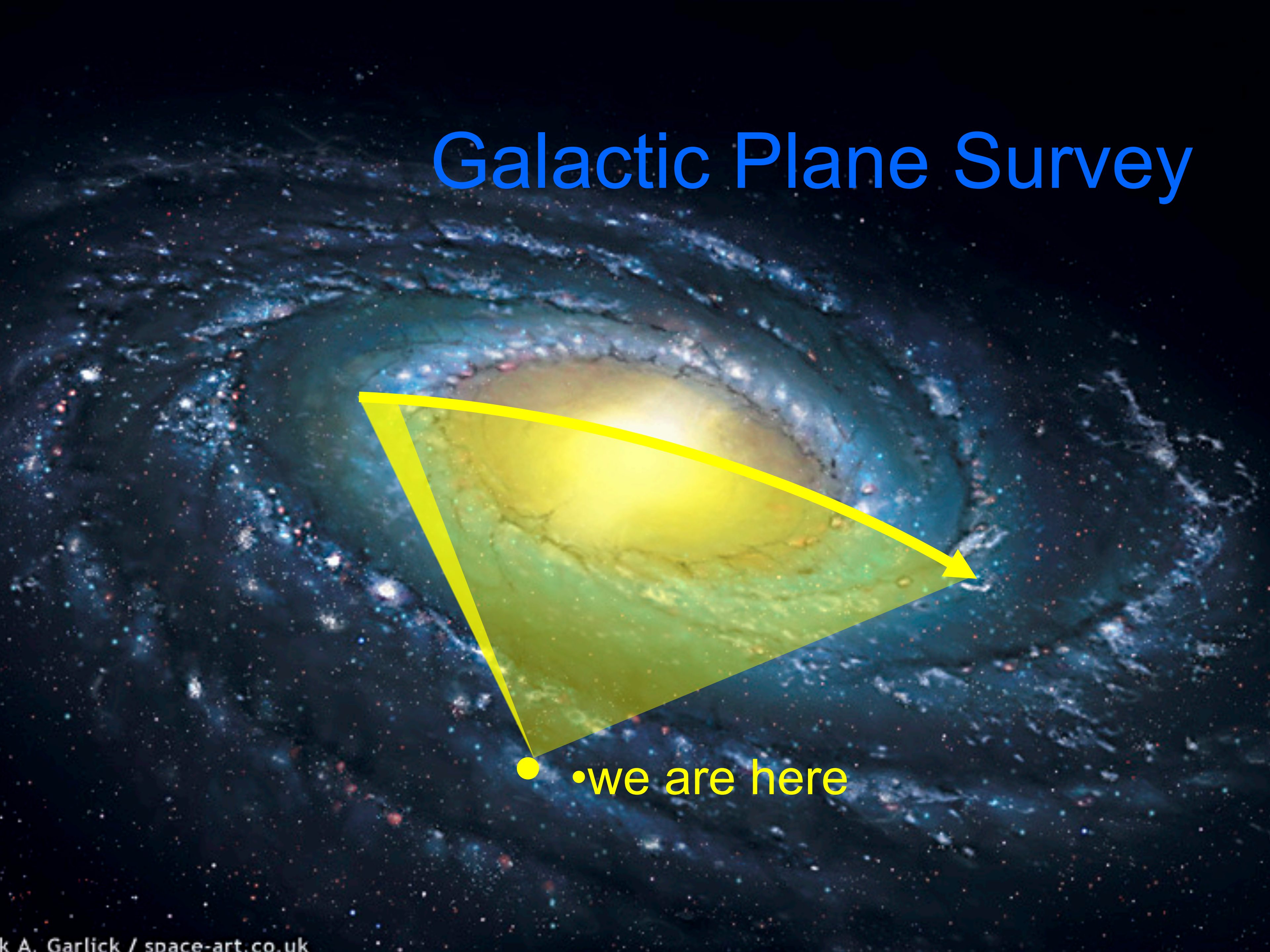


- **Dark Matter**

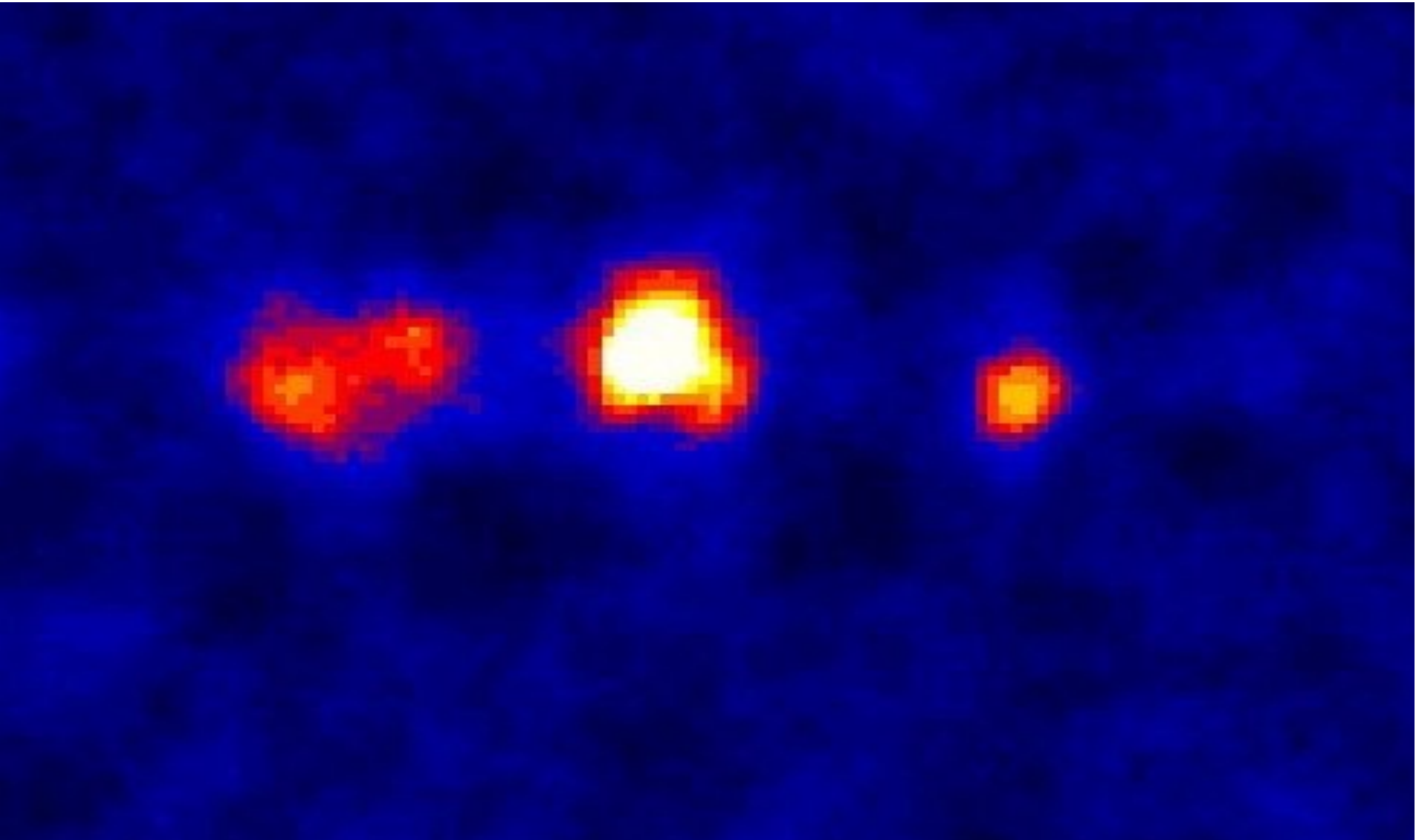


- **Lorentz symmetry violation**

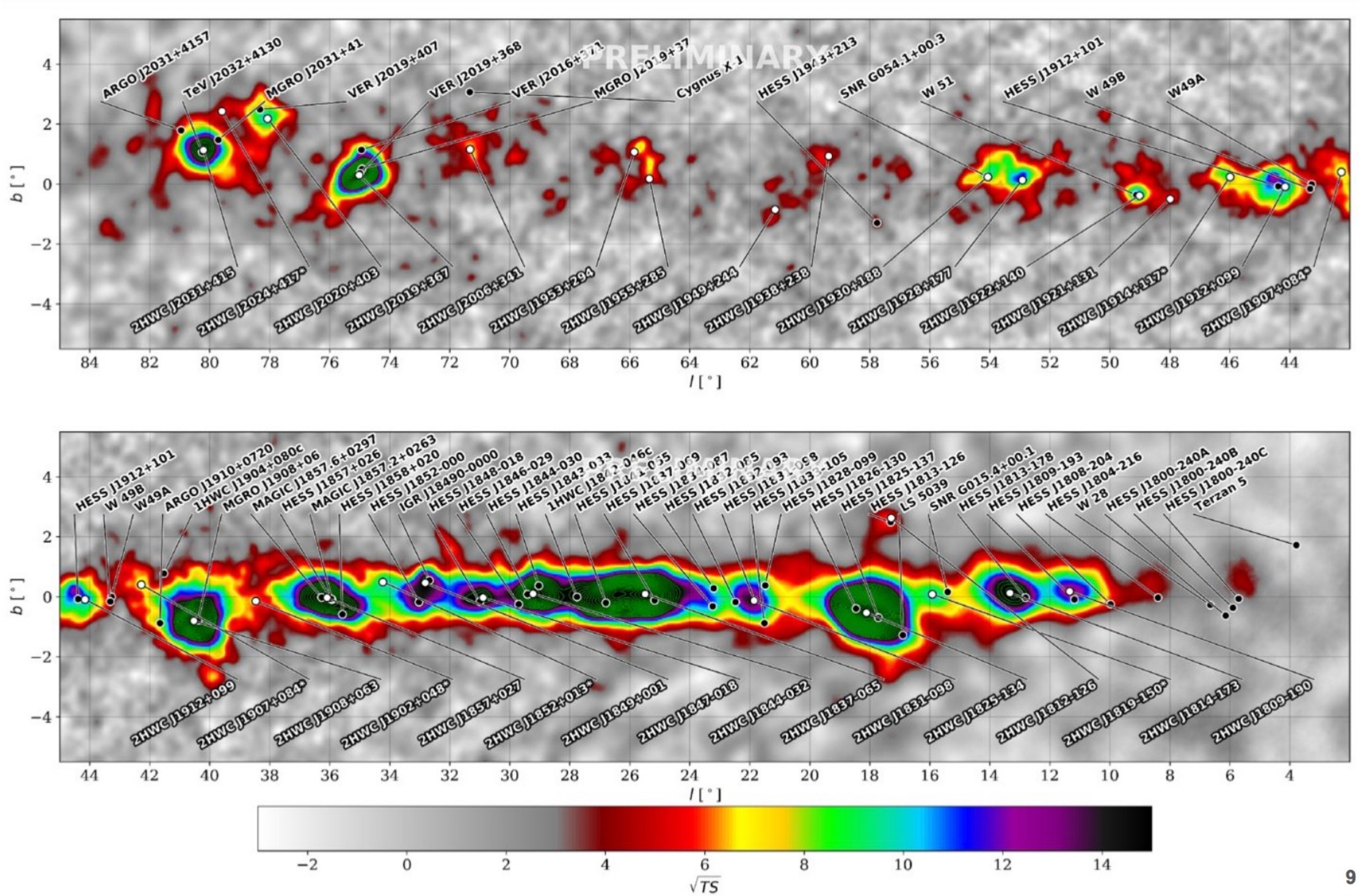
Galactic sources below 100 TeV


Galactic Plane Survey
•we are here
k A. Garlick / space-art.co.uk

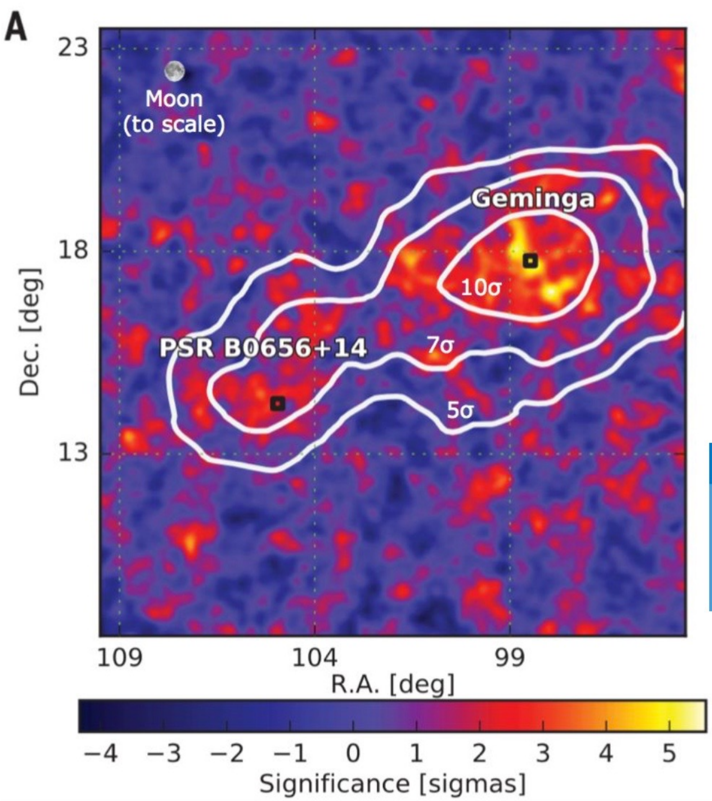
H.E.S.S Galactic Plane Survey



HAWC inner Galaxy



HAWC Geminga SN



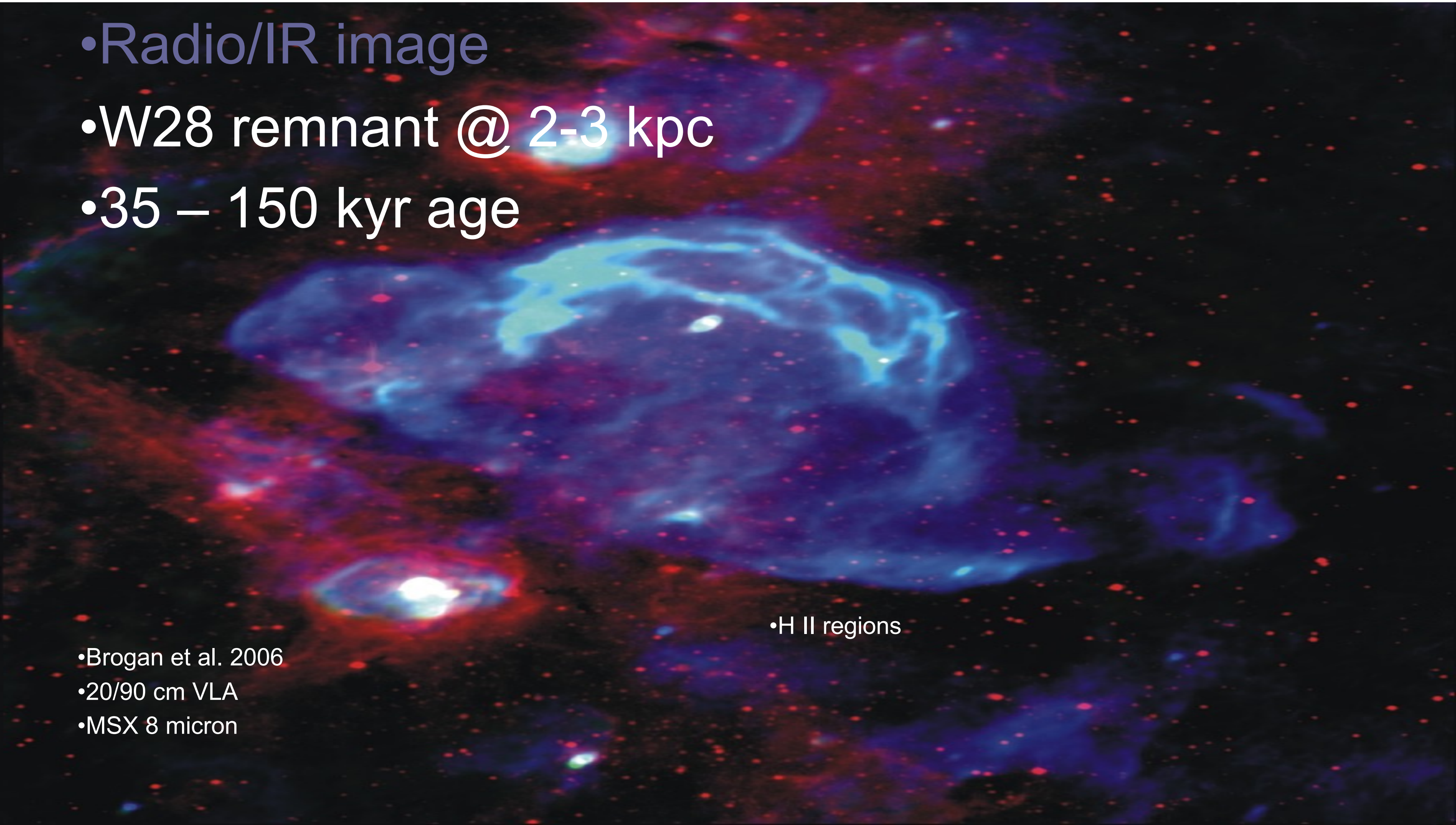
- **HAWC observes extended emission from both the Geminga and Monogem (PSR B0656+14) pulsars**
- **These are both nearby, middle-aged pulsars that could be producing the observed local positrons**

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

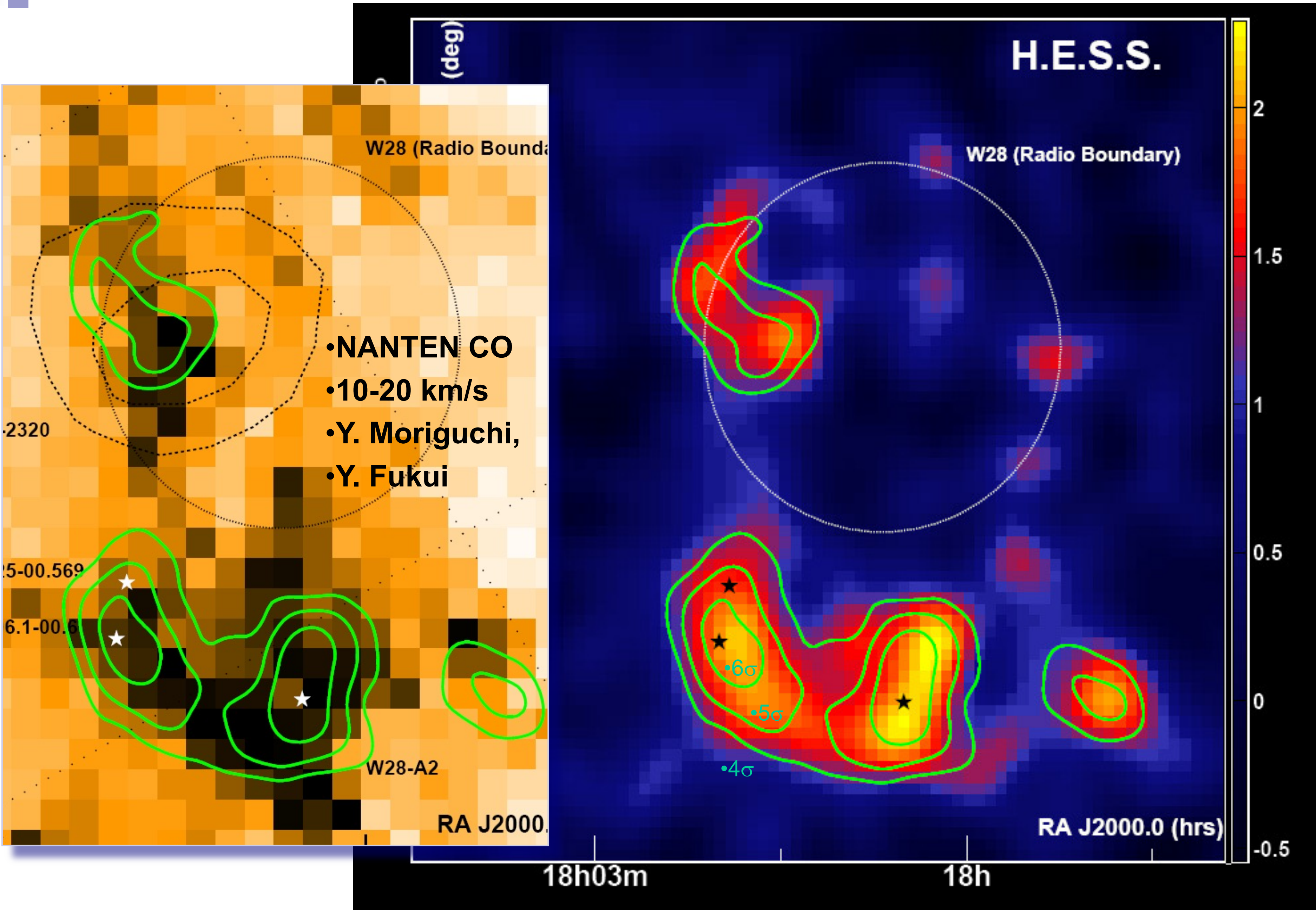
Science 358 (2017) no.6365, 911-914

Old SNRs & interacting SNRs

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

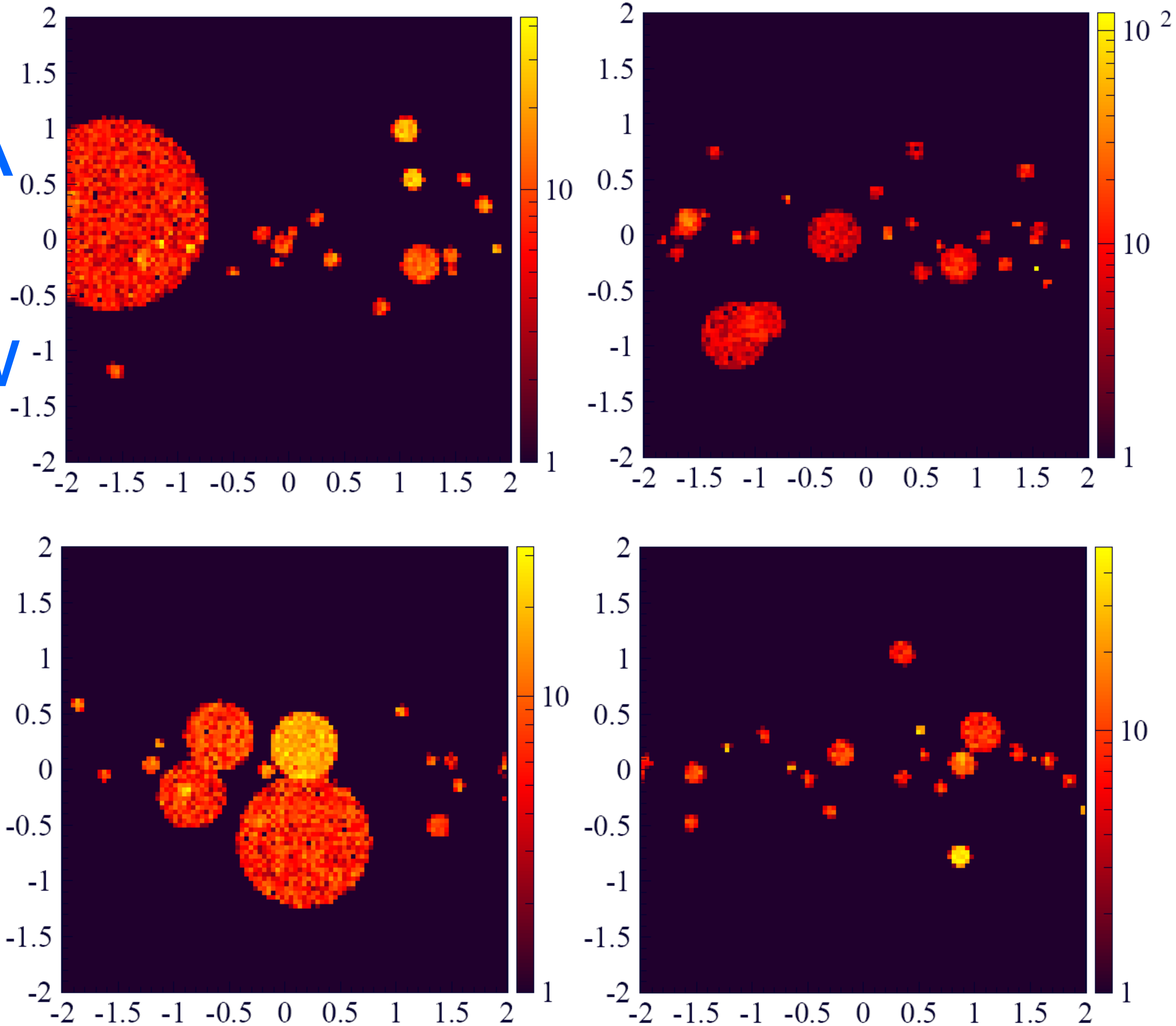


•Brogan et al. 2006
•20/90 cm VLA
•MSX 8 micron


H.E.S.S.
W28 (Radio Boundary)
W28 (Radio Bounda
•NANTEN CO
•10-20 km/s
•Y. Moriguchi,
•Y. Fukui
-2320
25-00.569
6.1-00.6
W28-A2
RA J2000.
•6σ
•5σ
•4σ
RA J2000.0 (hrs)
18h03m
18h
(deg)
2
1.5
1
0.5
0
-0.5

MEPHI

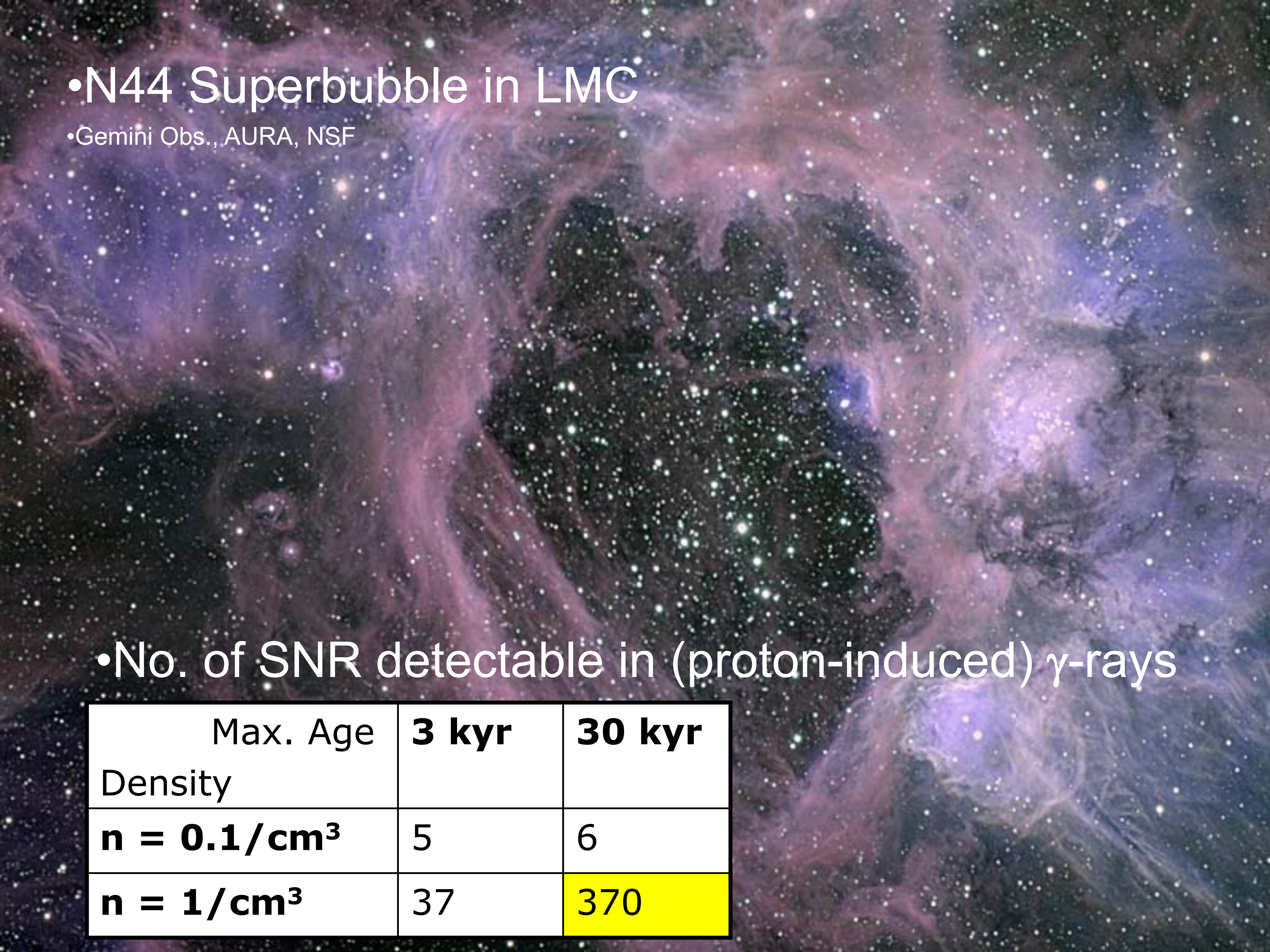
A CTA field of view



- SNR models
- using DAV 9
- n = 1
- ε = 0.1

- (consistent
- with HESS
- plane scan)

- assuming
- 1 mCrab



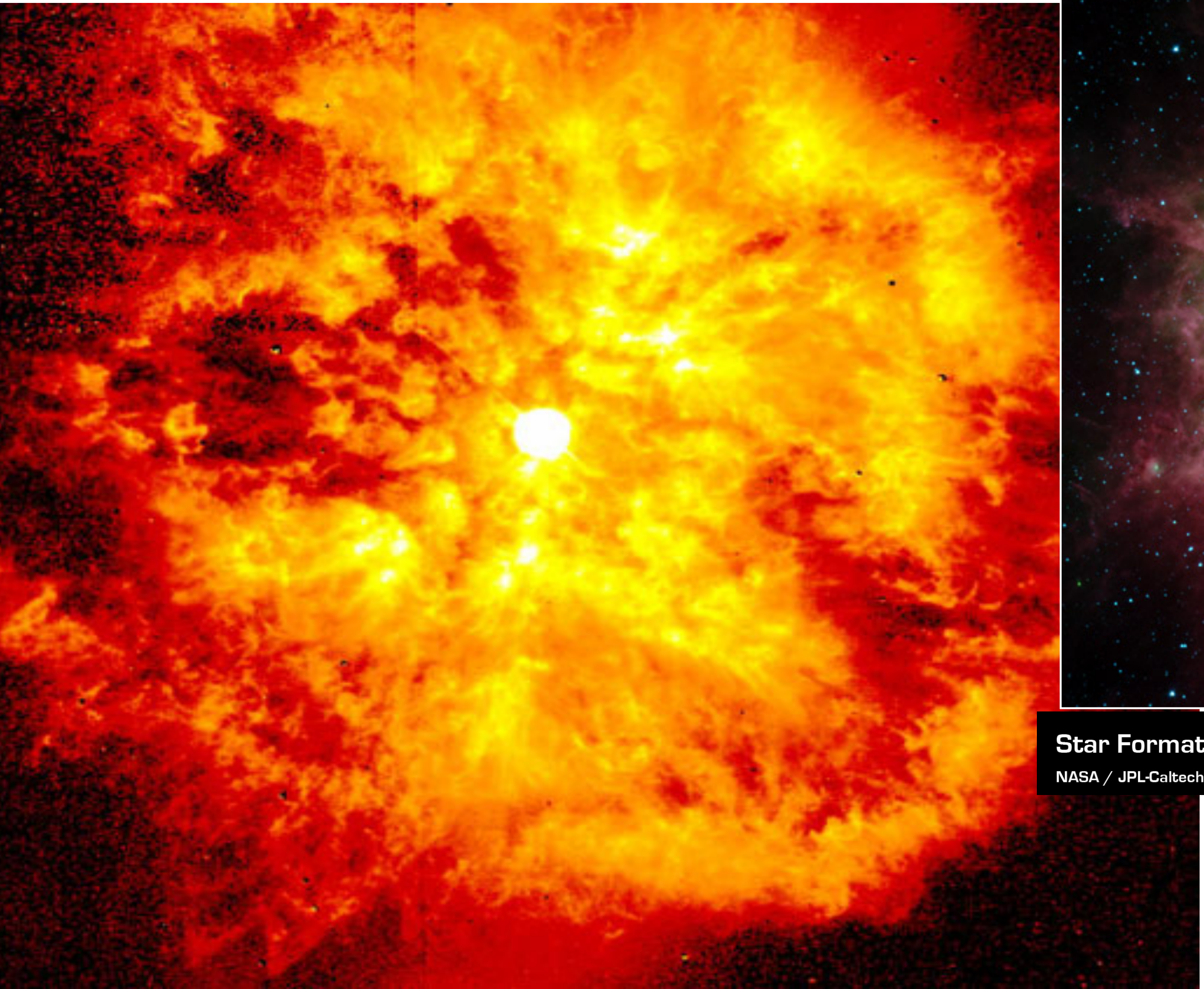
•N44 Superbubble in LMC

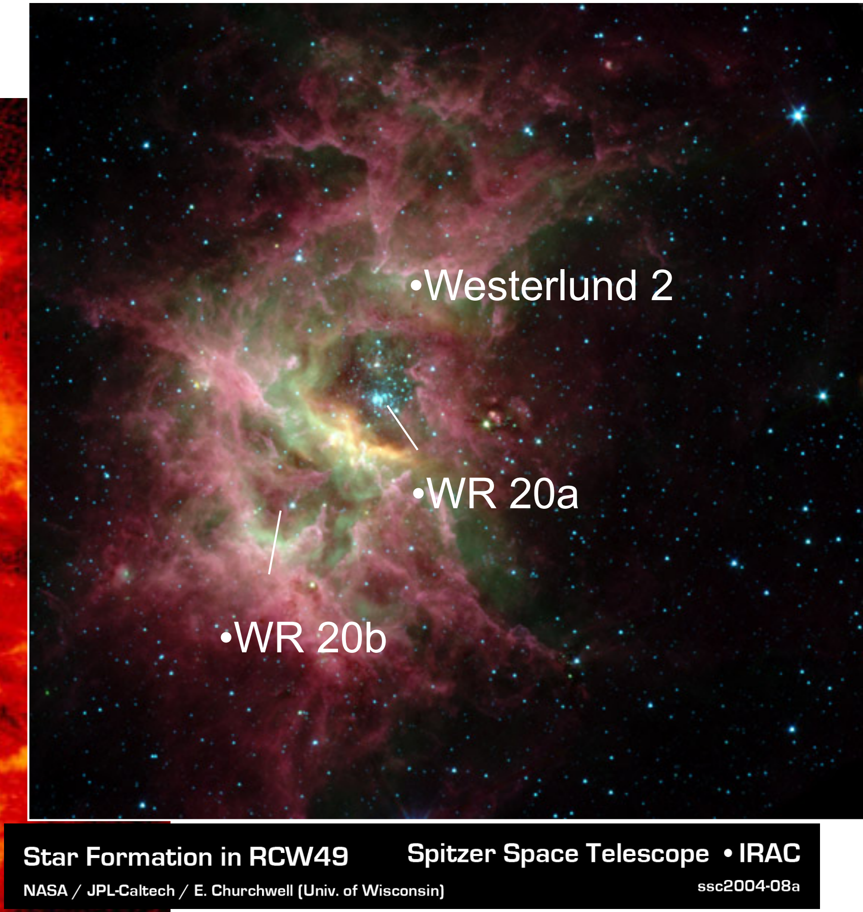
•Gemini Obs., AURA, NSF

•No. of SNR detectable in (proton-induced) γ-rays

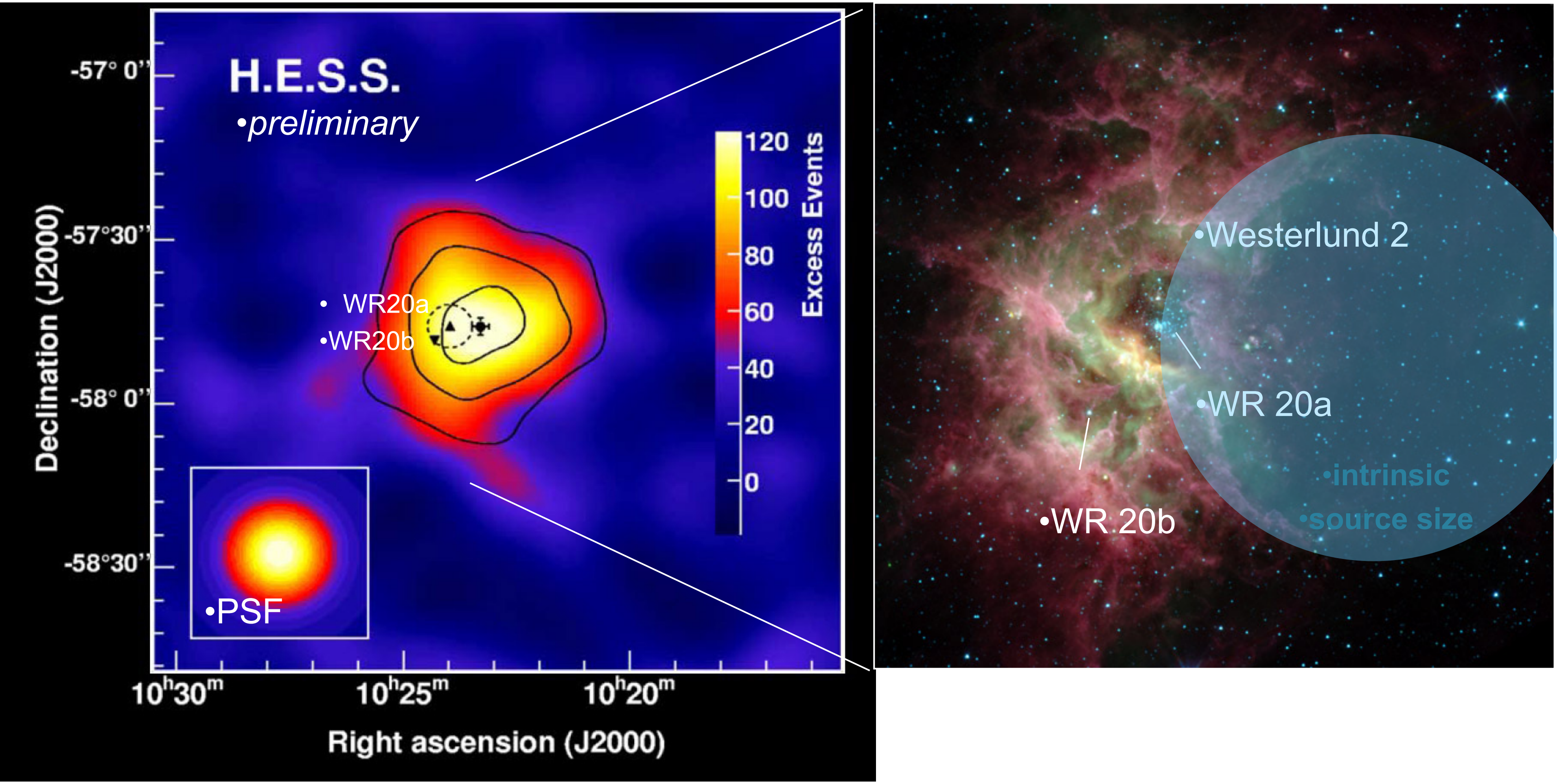
Max. Age / Density	3 kyr	30 kyr
$n = 0.1/cm^3$	5	6
$n = 1/cm^3$	37	370

RCW 49:
Stellar Winds as Cosmic Accelerators





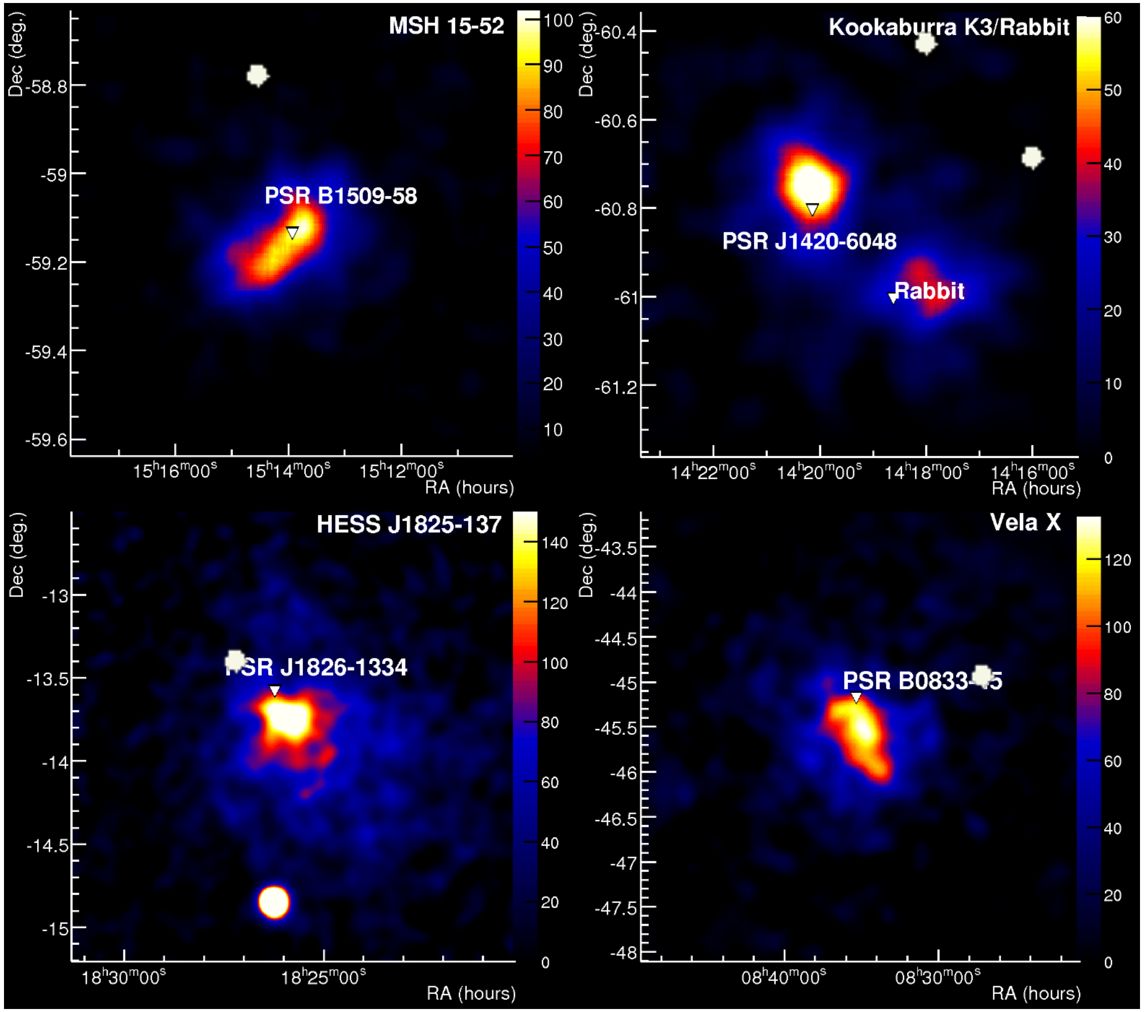
HESS J1023-575



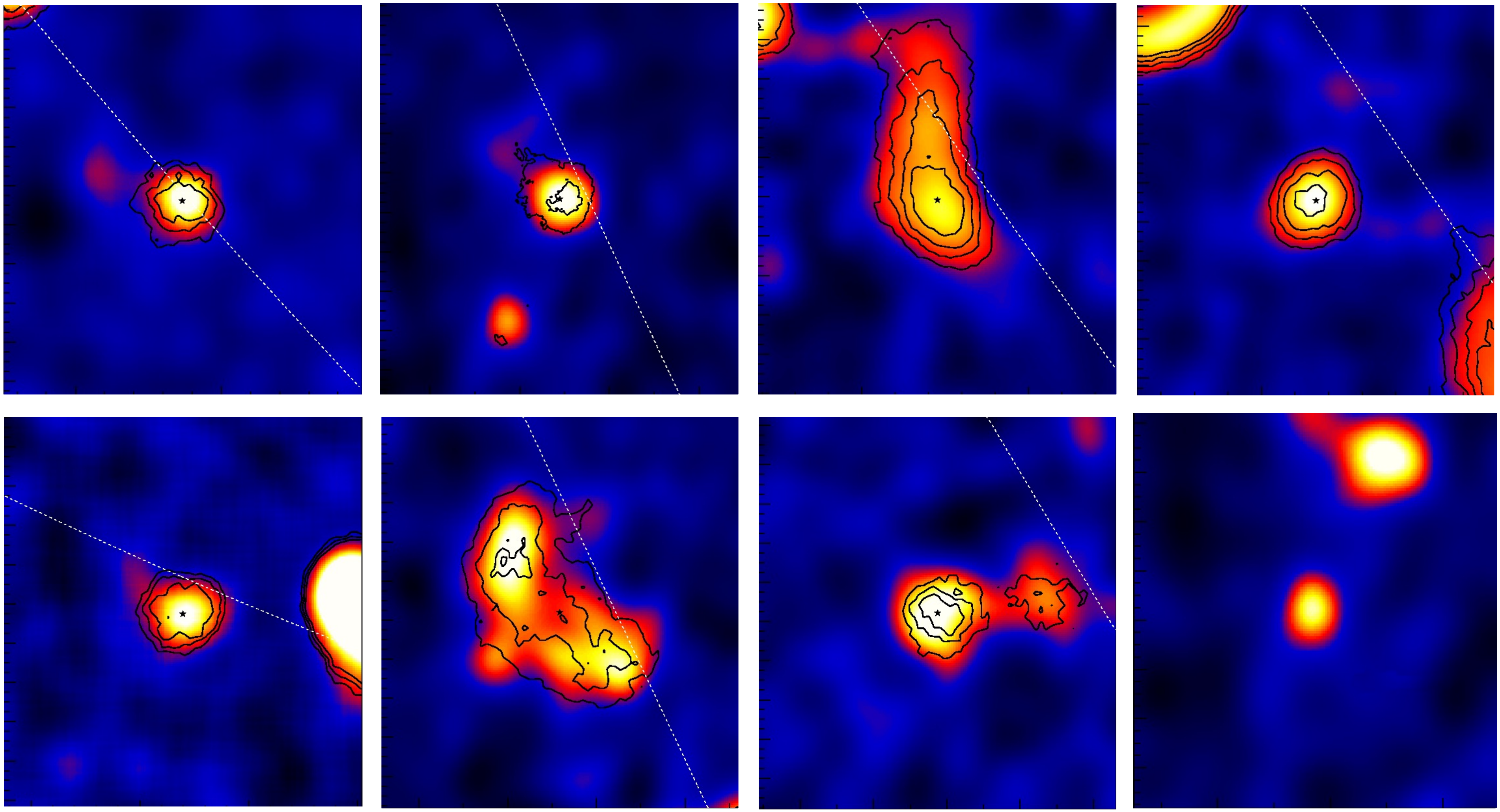
Pulsar Wind Nebulae

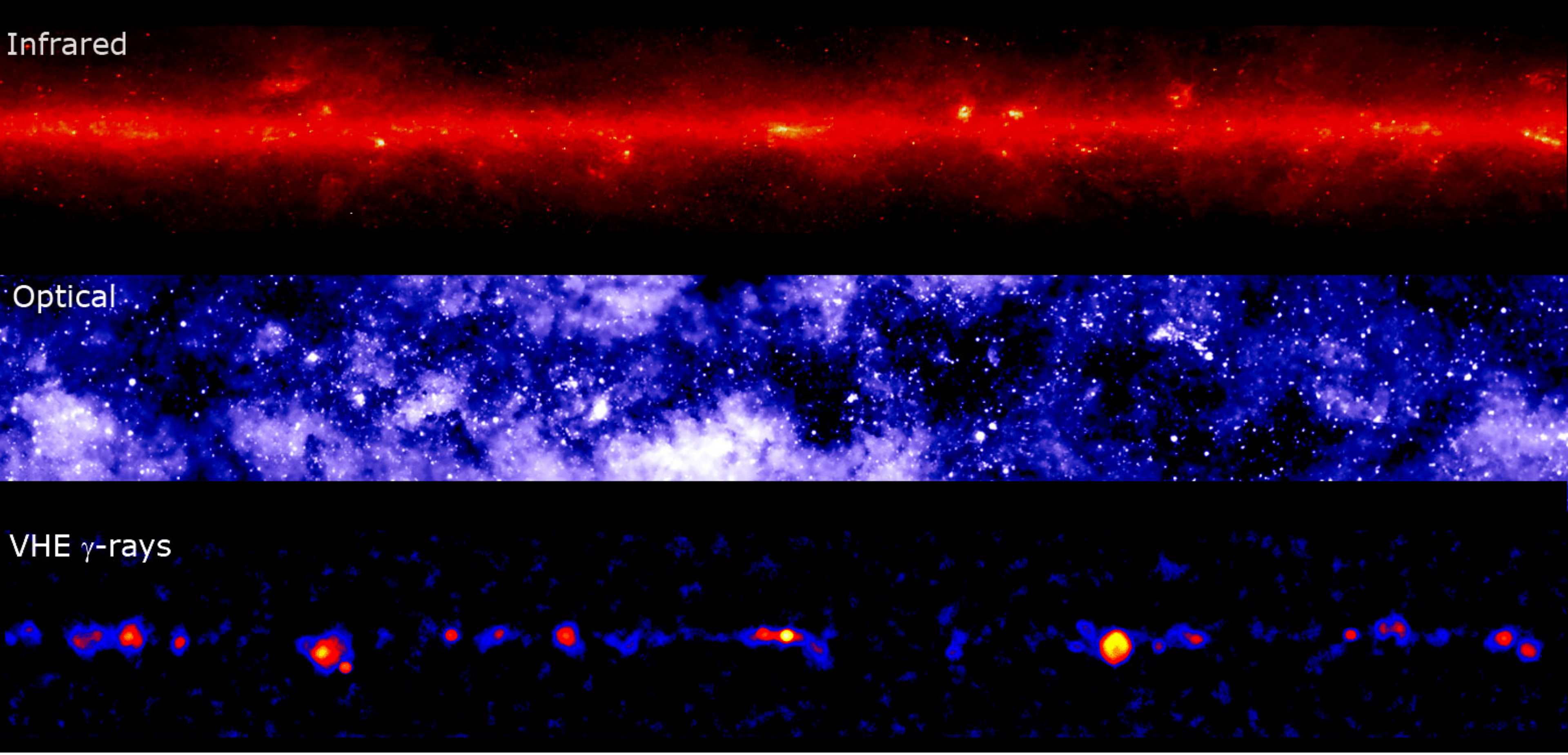
Extended

γ-ray sources



"Dark" sources: Objects which only shine in gamma rays !

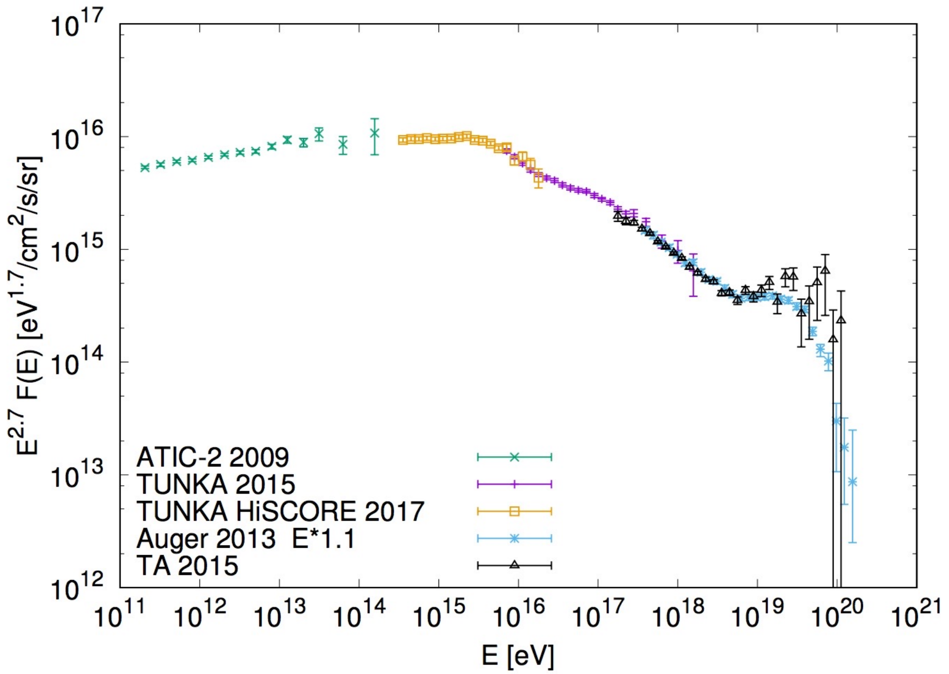




•The age of real VHE gamma ray astronomy has started

Galactic sources with E>100 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 eperiments

- Sources which accelerate cosmic rays up to knee called PeVatrons

HAWC 100 TeV sources

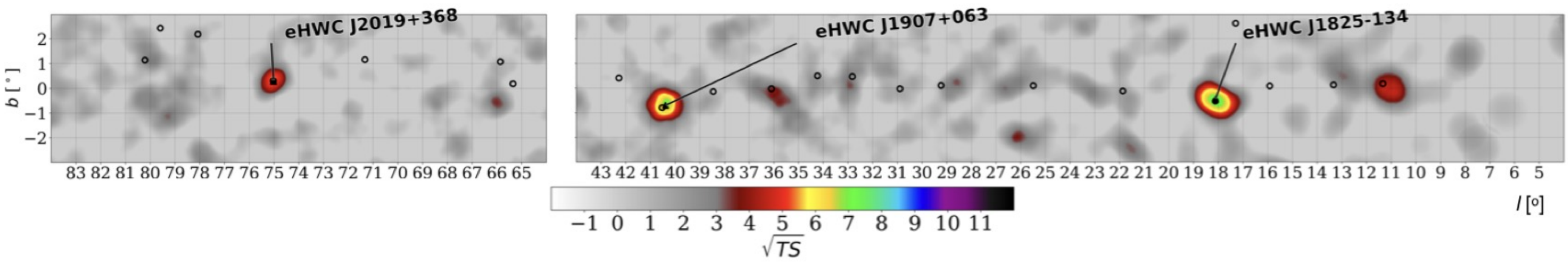
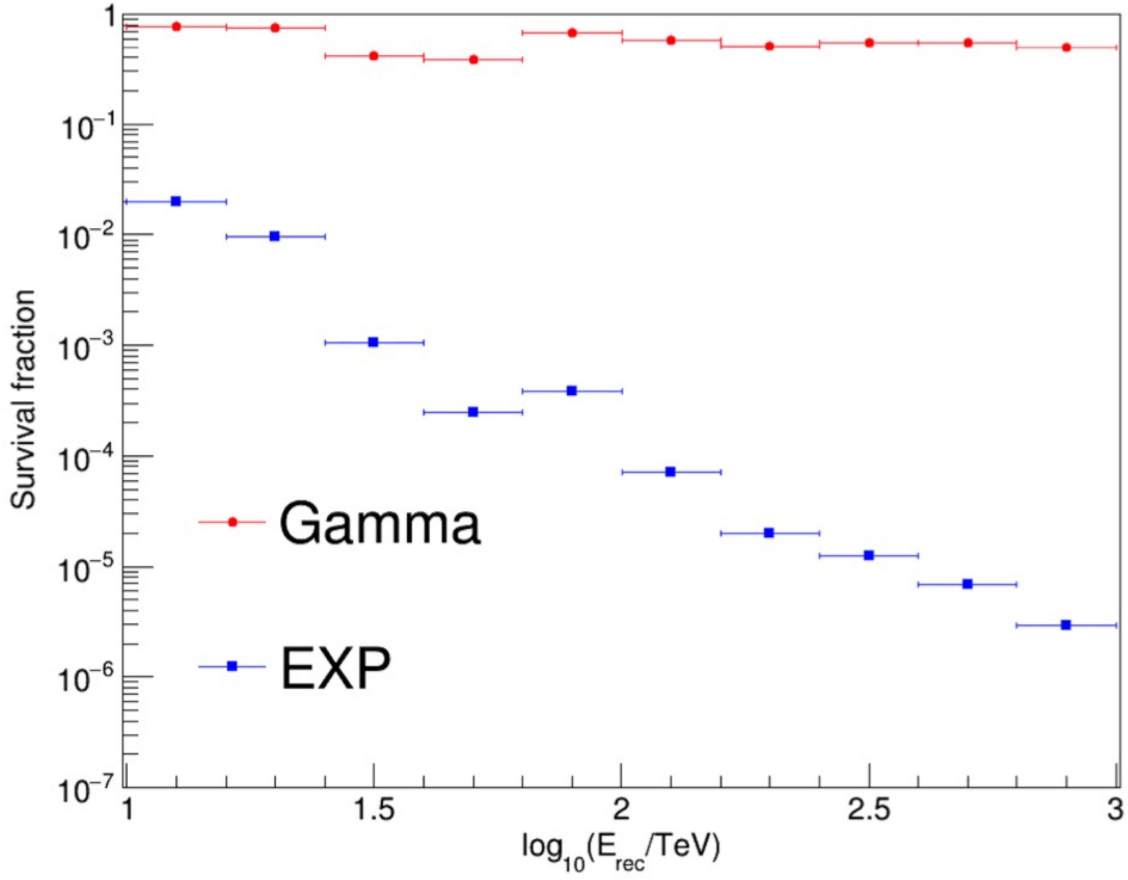


FIG. 2. The same as Figure 1, but for $\hat{E} > 100$ TeV. The symbol convention is identical to Figure 1.

LHAASO hadron cut 2021

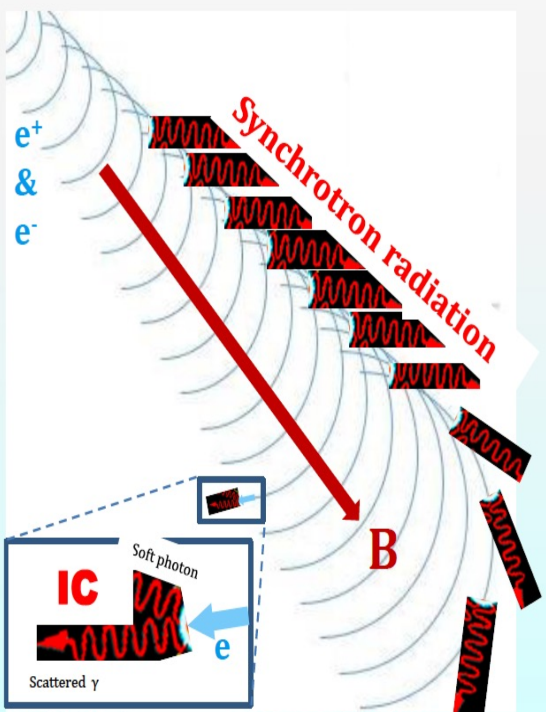


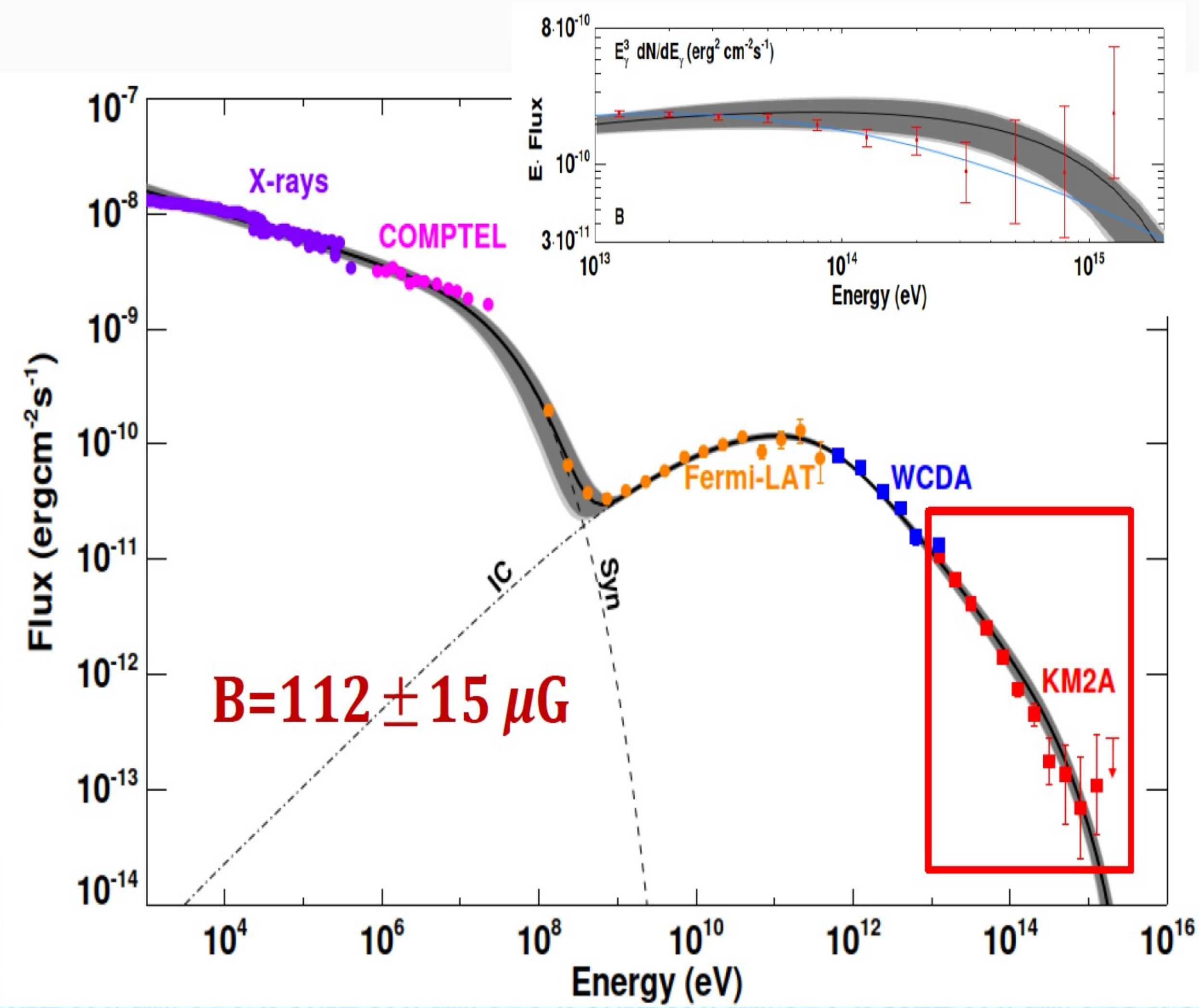
- LHAASO talk ICRC Jul 2021

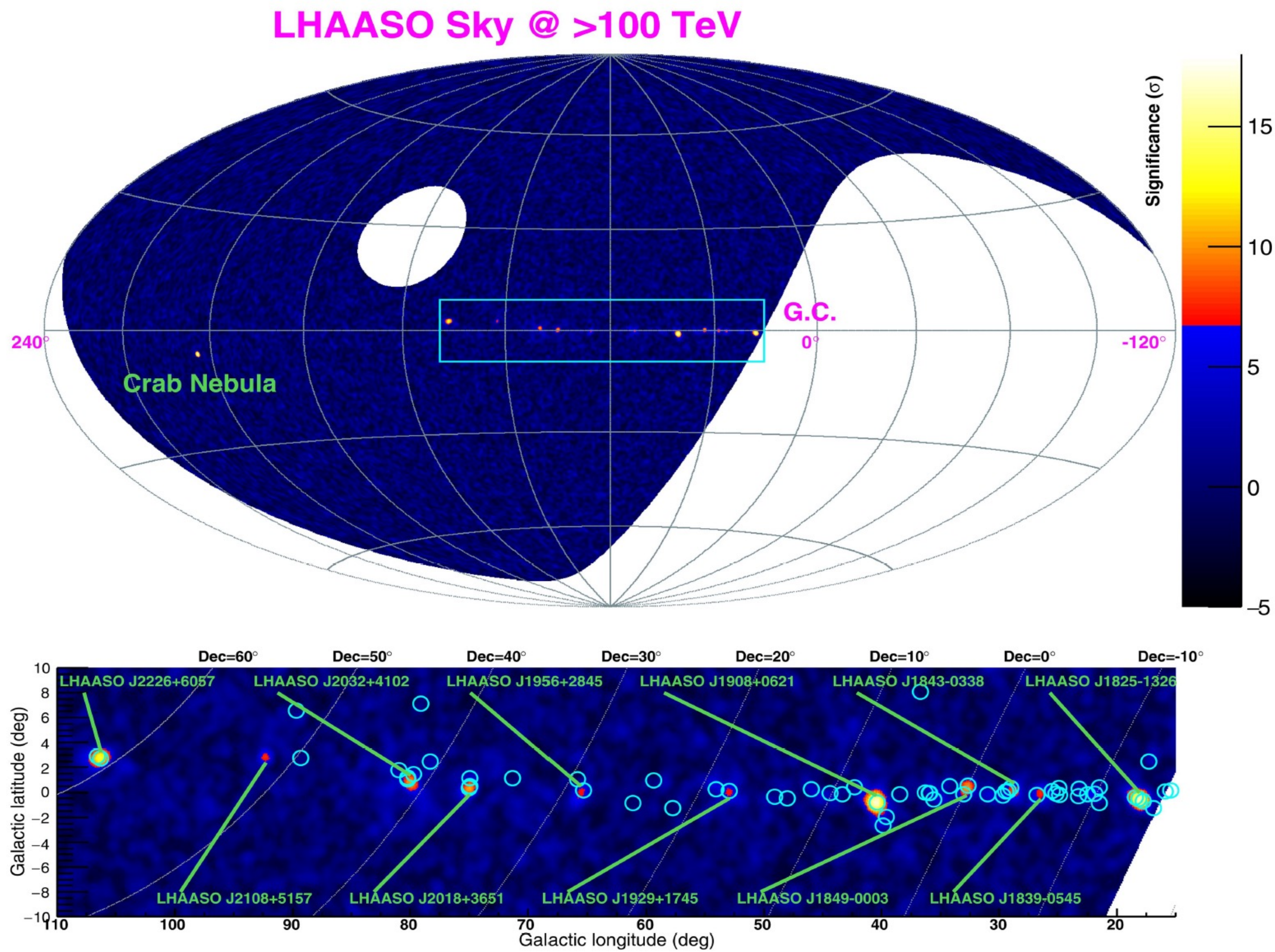
SED of the Crab: "standard Candle" & PeVatron

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

- MHD calculation
  - Nebula formation
  - Size of ~0.6 ly
- One Zone Model, up to 50 TeV
- 4σ deviation above 50 TeV





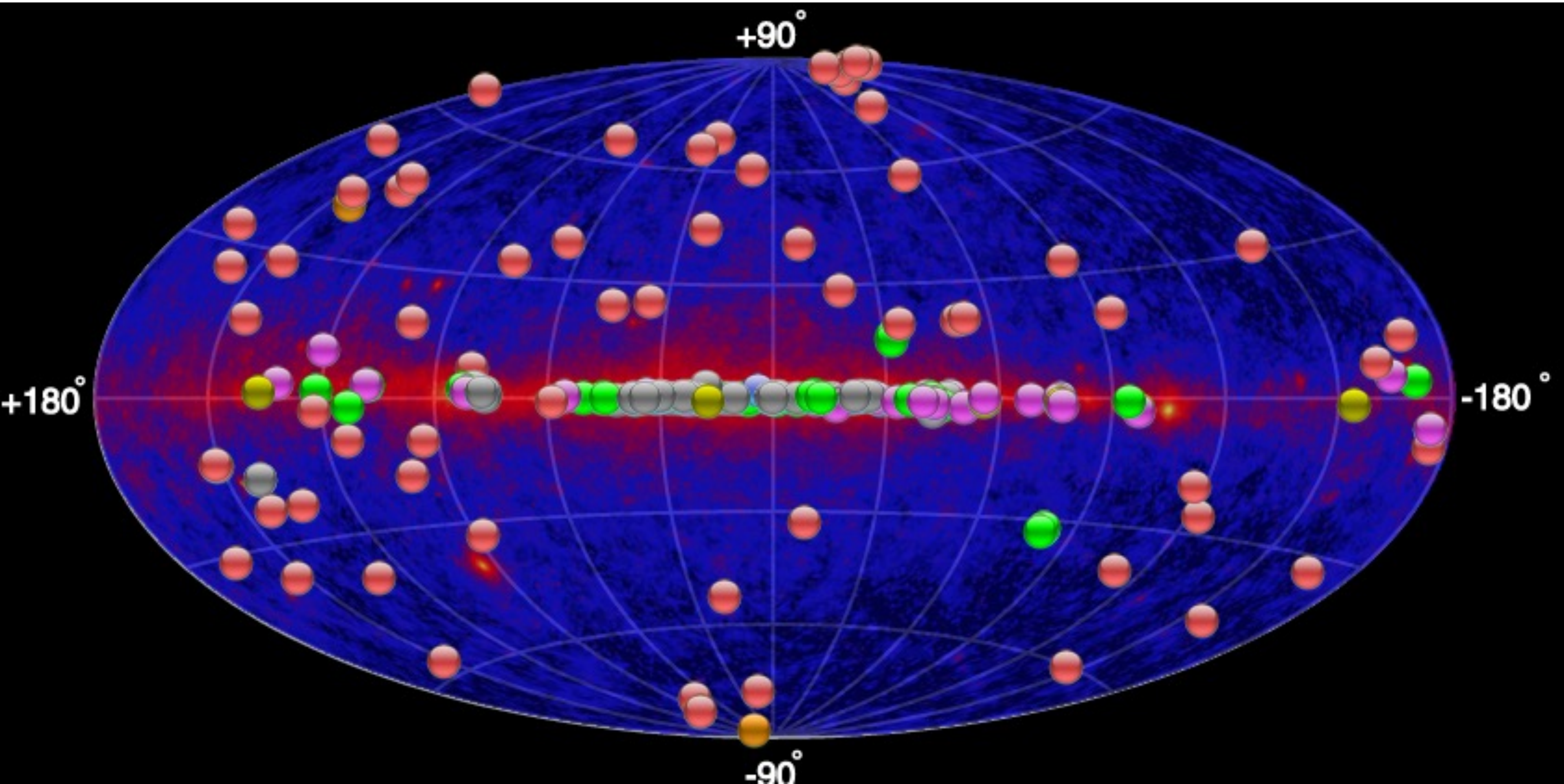


Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

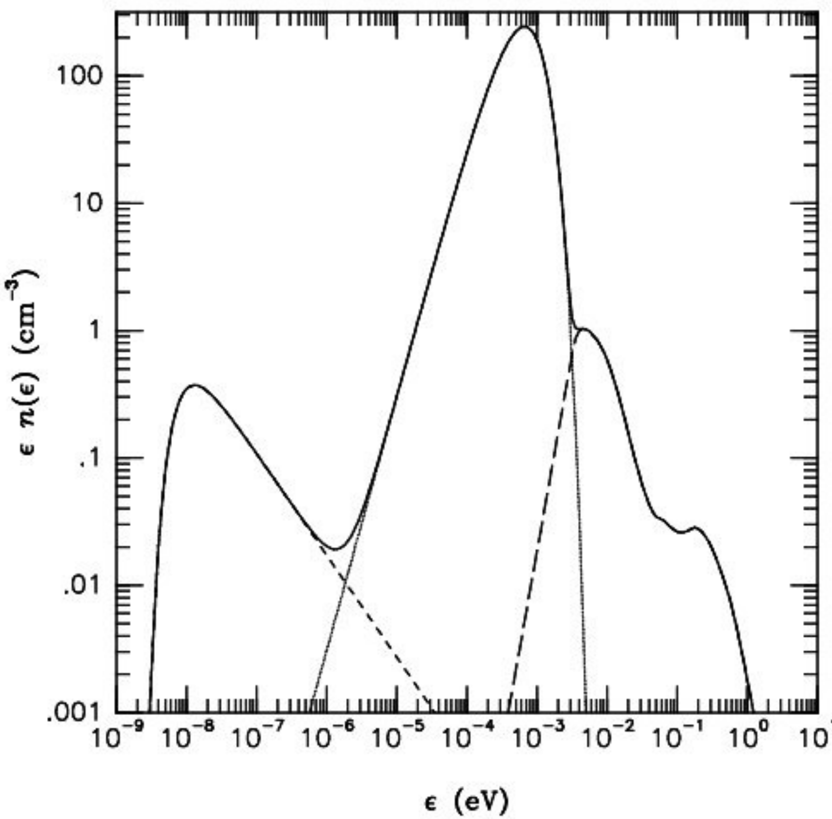
•Nature, May 17 2021

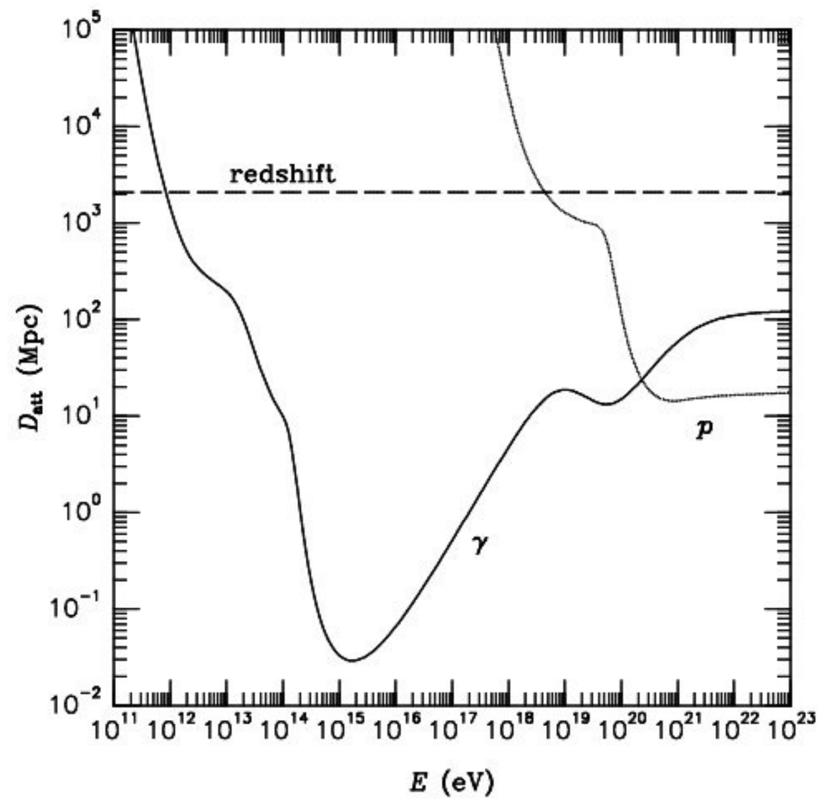
Extra-galactic gamma-ray sources and extragalactic background light

1000 sources in GeV and 60 in TeV



Diffuse backgrounds





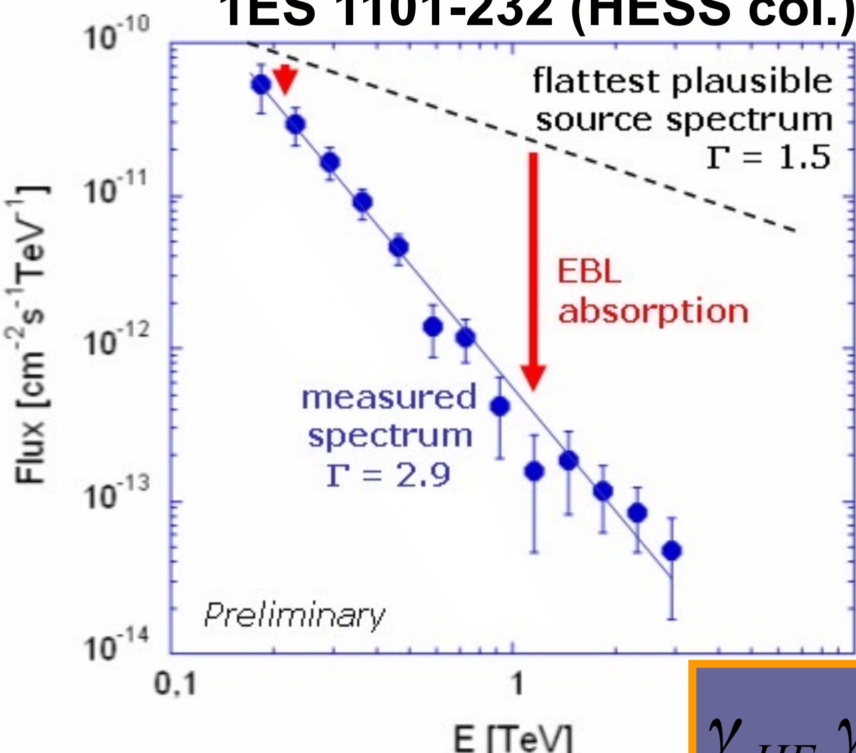
Extrag. Background Light

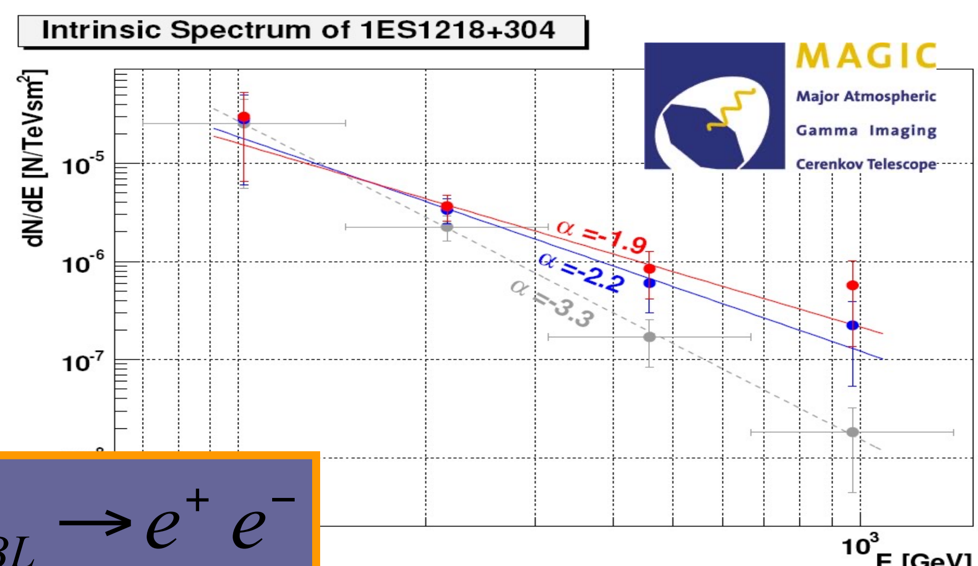
Cosmological radiation from star formation and evolution.

Spectral signature from gg absorption for Eg ~ 50-2000 GeV.

Use measured AGN spectra to constrain EBL.

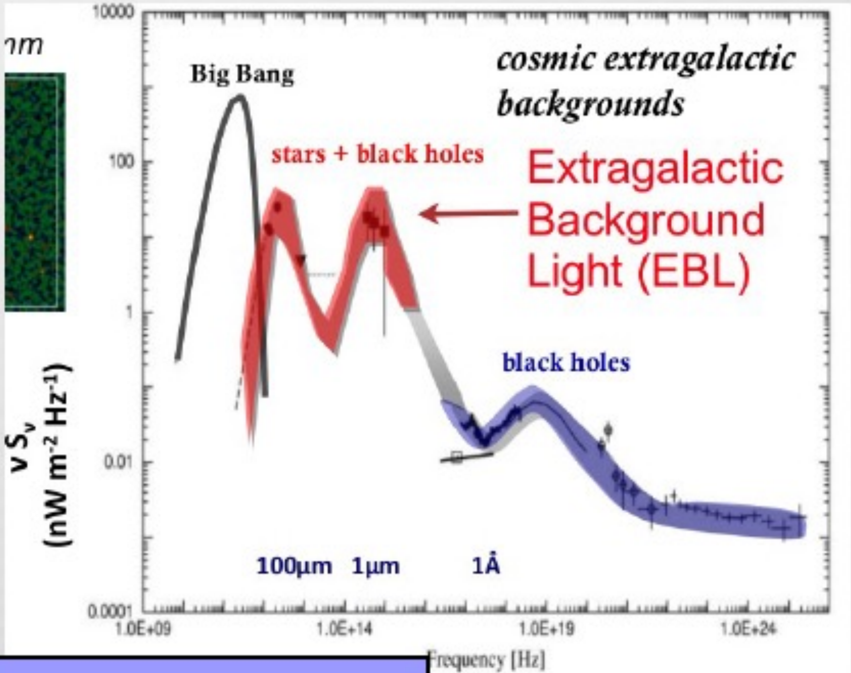
1ES 1101-232 (HESS col.)





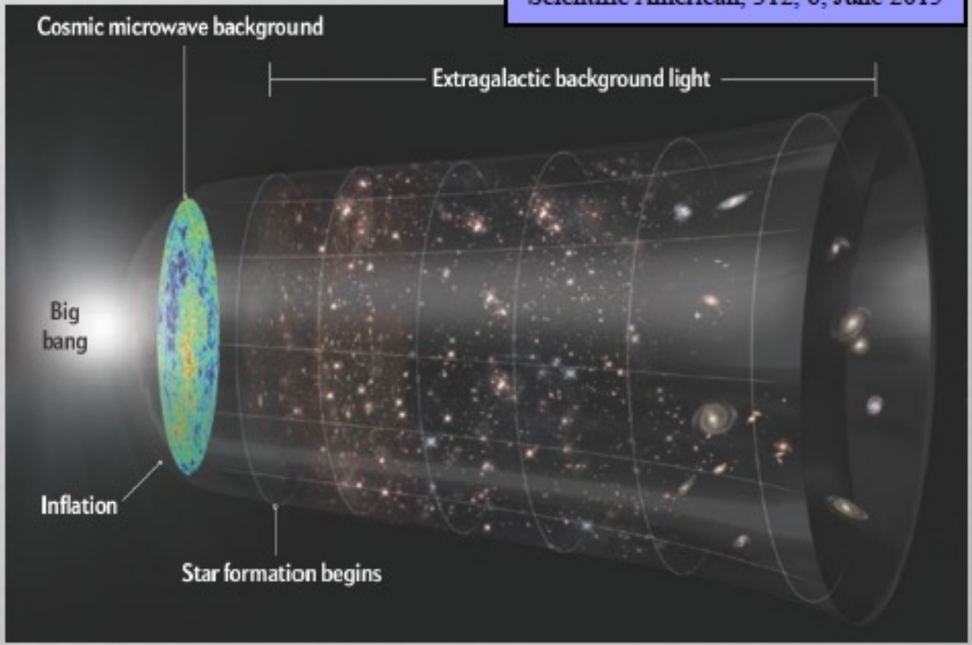
$$\gamma_{HE}\,\gamma_{EBL} \rightarrow e^{+}\,e^{-}$$

Diffuse extragalactic backgrounds



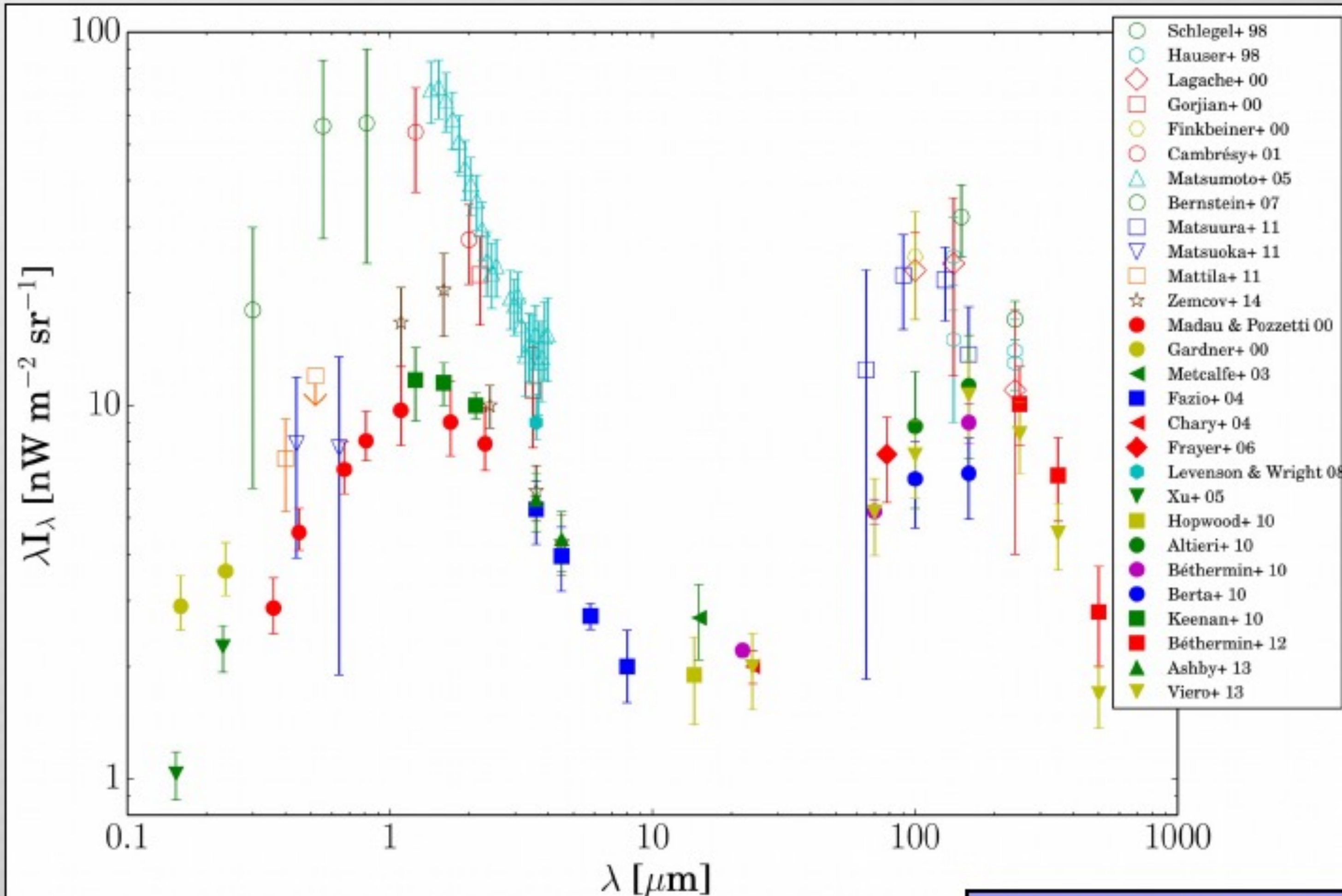
From Genzel's lecture @ 2013 Jerusalem Winter School

Scientific American, 312, 6, June 2015



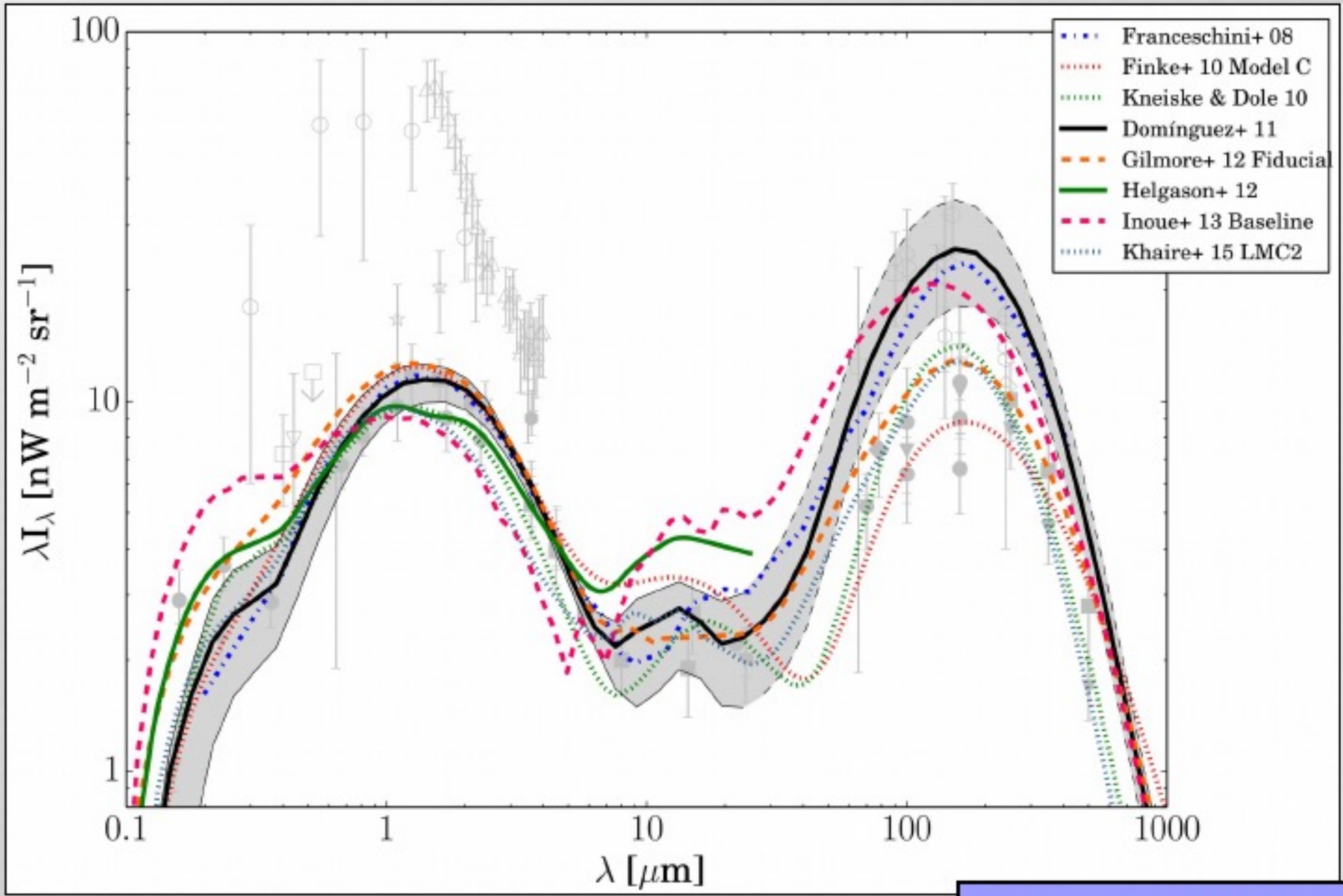
- The EBL is the accumulated diffuse light produced by star formation processes and accreting black holes over the history of the Univere from the UV to the far-IR.
- It contains fundamental information about galaxy evolution, cosmology, and it is essential for the full energy balance of the Universe.

Local EBL: Data and Models



Domínguez & Primack, 15 in prep.

Local EBL: Data and Models



Domínguez & Primack, 15 in prep.

Gamma-Ray Attenuation

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

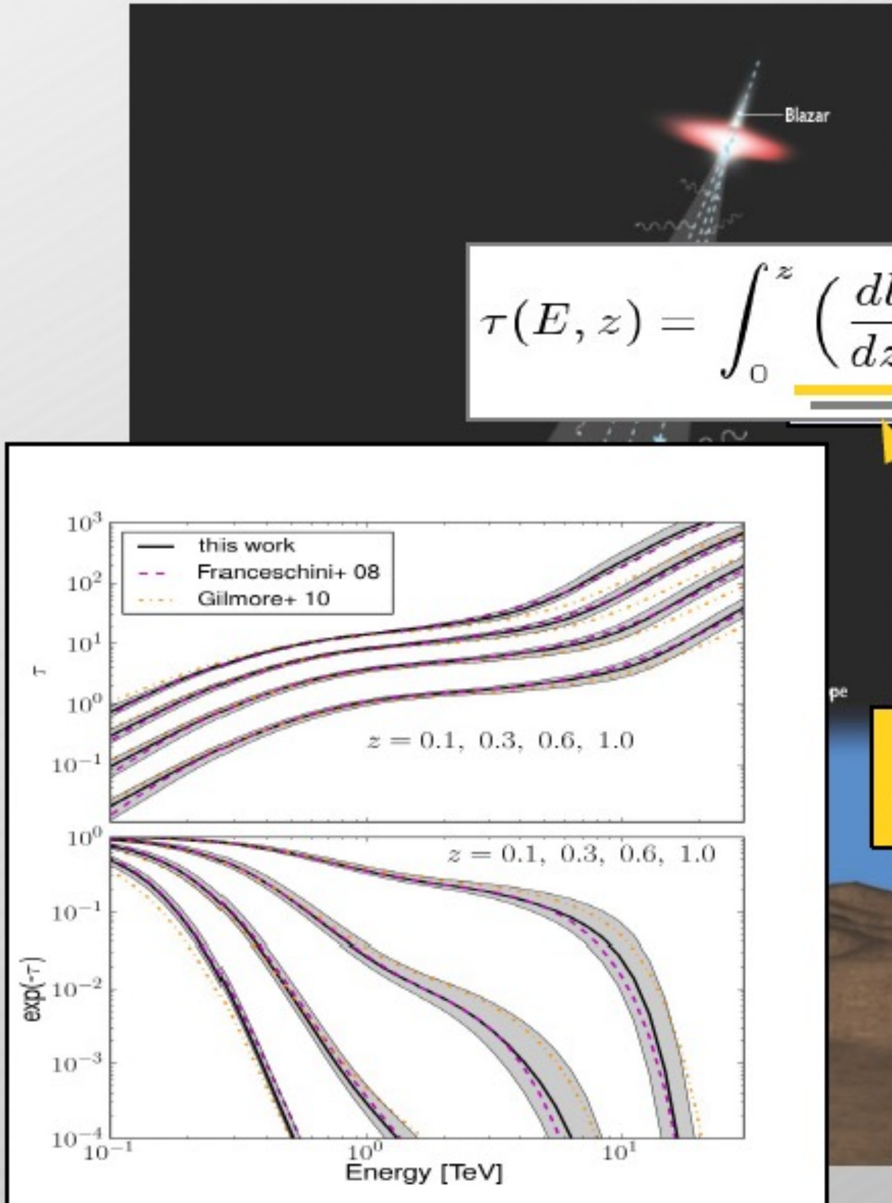
$$\tau(E,z) = \int_0^z \left(\frac{dl'}{dz'}\right) dz' \int_0^2 d\mu \frac{\mu}{2} \int_{\varepsilon_{min}}^{\infty} d\varepsilon' \, \sigma_{\gamma\gamma}(\beta') n(\varepsilon', z')$$

Distance (cosmology)

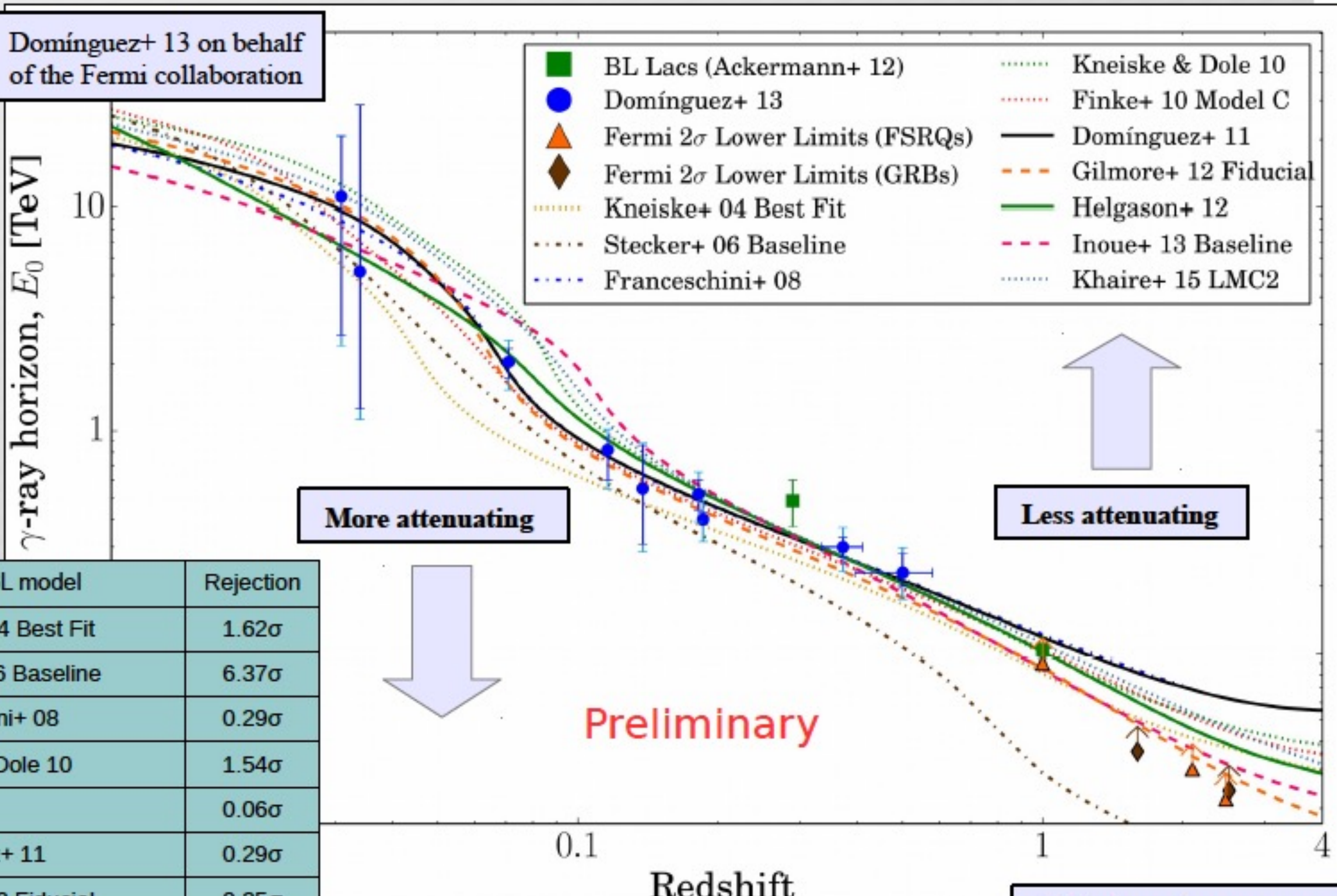
Interaction angle

Cross section

EBL photon density evolution (cosmology)



Cosmic γ-ray Horizon: Results

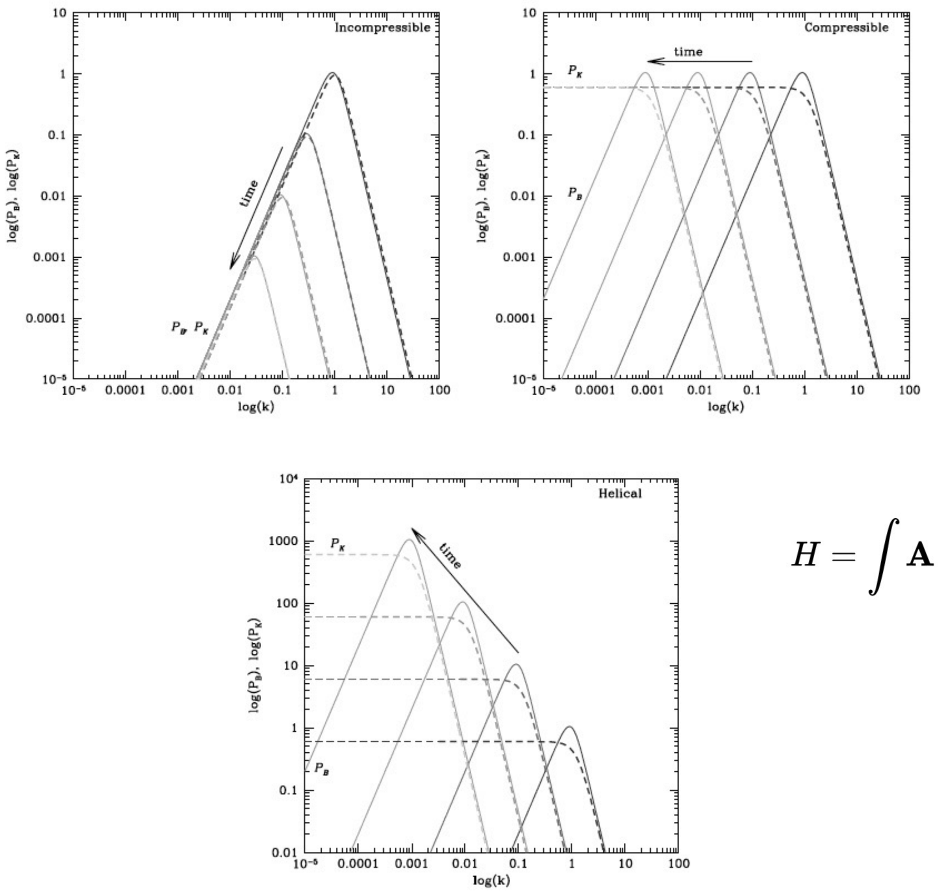


EBL model	Rejection
Kneiske+ 04 Best Fit	1.62σ
Stecker+ 06 Baseline	6.37σ
Franceschini+ 08	0.29σ
Kneiske & Dole 10	1.54σ
Finke+ 10	0.06σ
Domínguez+ 11	0.29σ
Gilmore+ 12 Fiducial	0.25σ
Helgason+ 12	0.09σ
Inoue+ 13 Baseline	2.12σ
Khaire+ 15 LMC2	1.27σ

Preliminary data courtesy of Marco Ajello

Extra-galactic sources and determination of magnetic field

Early Universe evolution of spectrum of IGMF



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

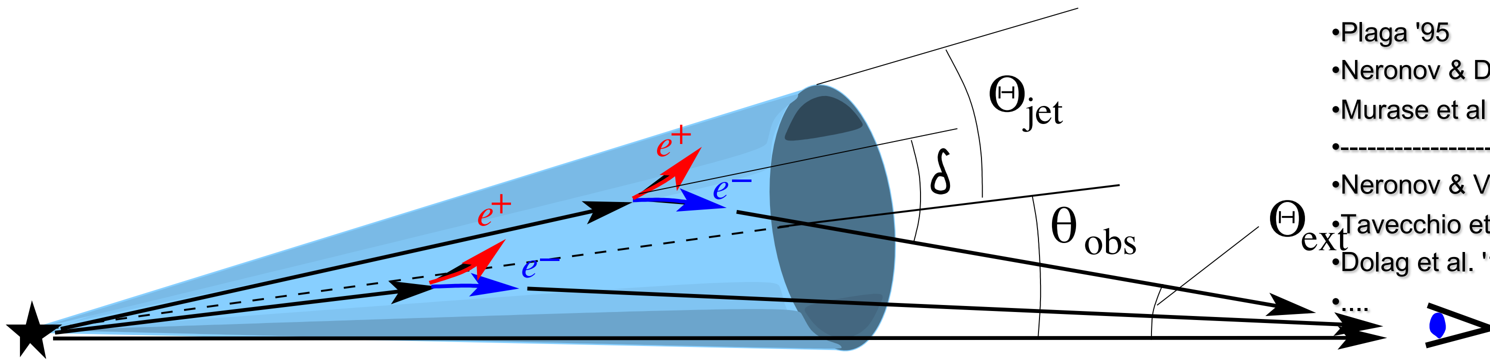
•R.Durrer and A.Neronov, A&A Rev. 21 62, [1303.7121].

Constrants 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 Due to plasma heating	1.2 – 6.4 nG [19–40] 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



•Plaga '95
•Neronov & D.S. '07, '09
•Murase et al 08
•-----------------------------
•Neronov & Vovk '10
•Tavecchio et al. '10
•Dolag et al. '10
•....

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

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

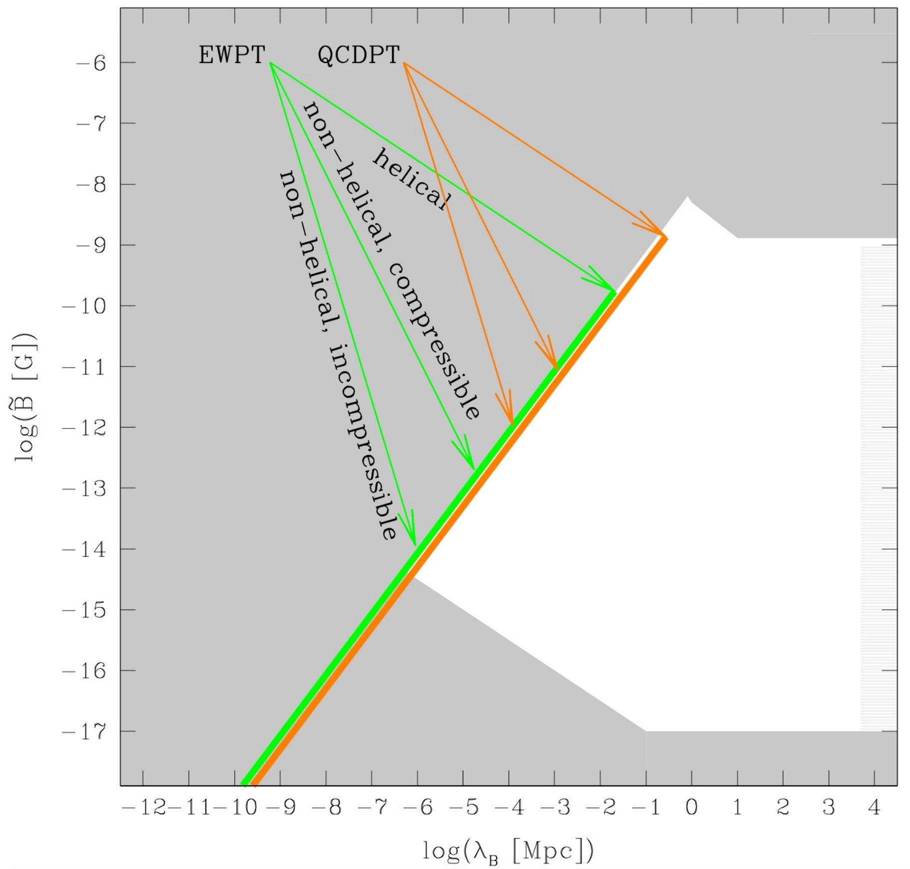
$$E_{\gamma 0} = 2E_e \qquad \lambda_e = \frac{1}{n_{\mathrm{CMB}}\sigma_{ICS}} \sim 1 \text{ kpc}$$

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

•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
- Fraction of voids on the way of primary photon
- Ratio of point source flux at E_γ and $E_{\gamma 0}$

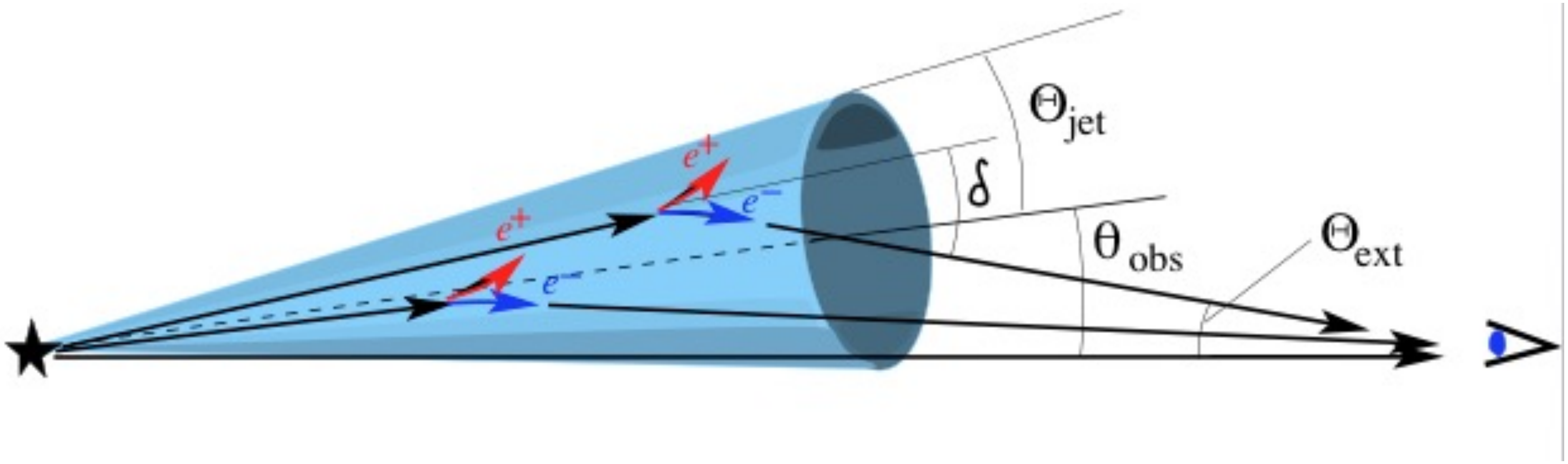
$$\alpha = \frac{\sum E_\gamma}{E_e}$$

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

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

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

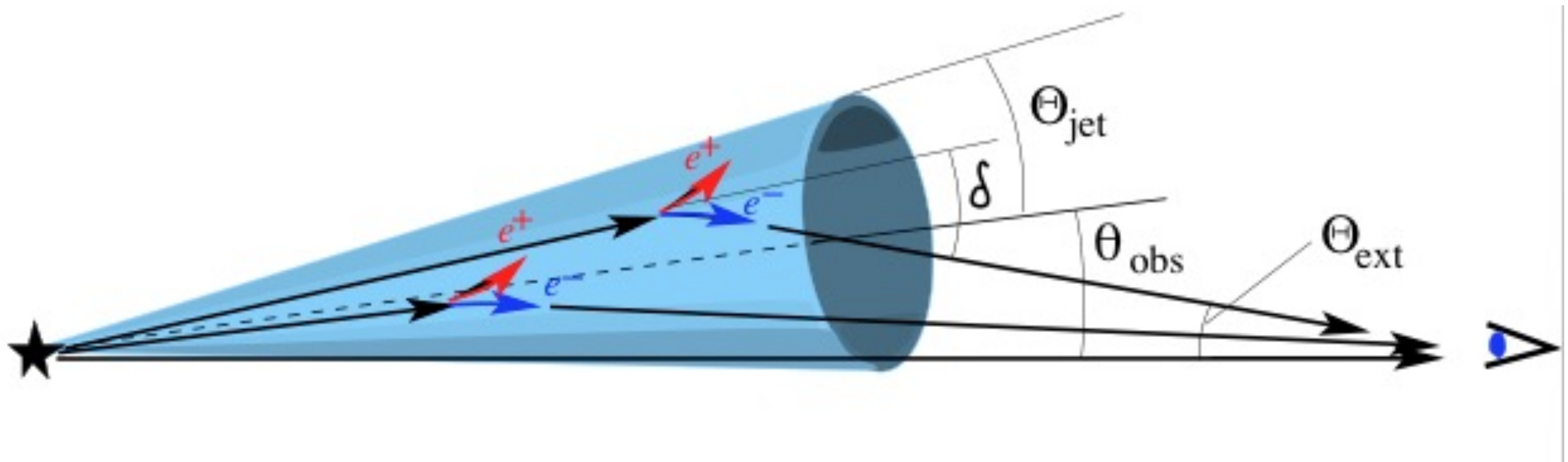
•Imaging of cascade: 3-d cascade needed



•3-d cascade in turbulent EGMF

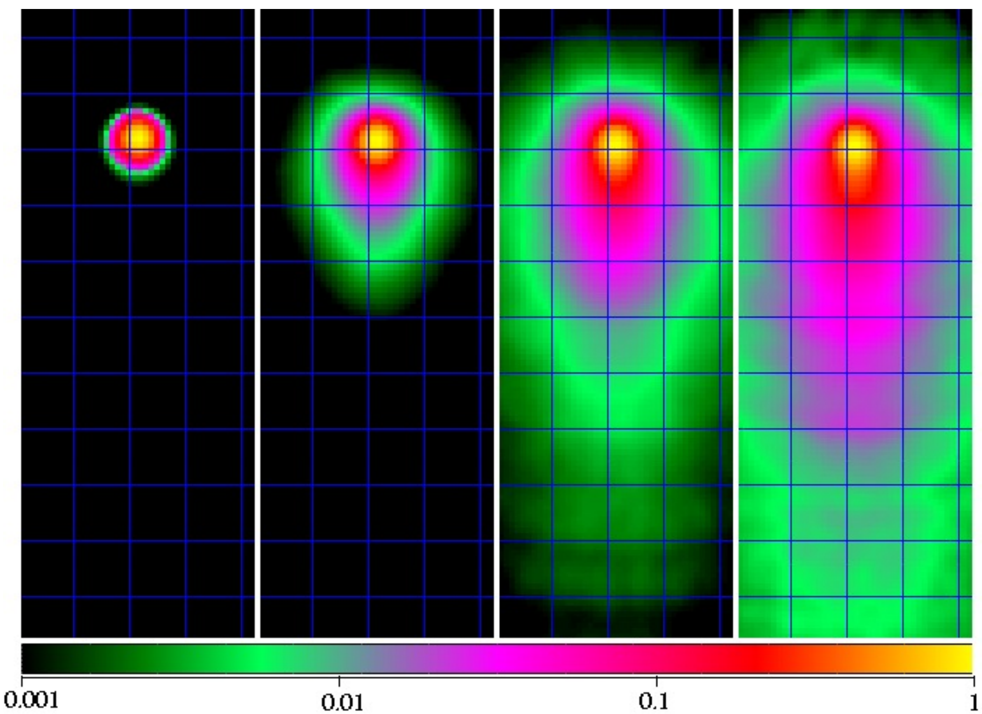
•A.Neronov, D.S., M.Kachelriess, S.Ostapchenko and A.Elyev , 2009

•Imaging of cascade: EGMF

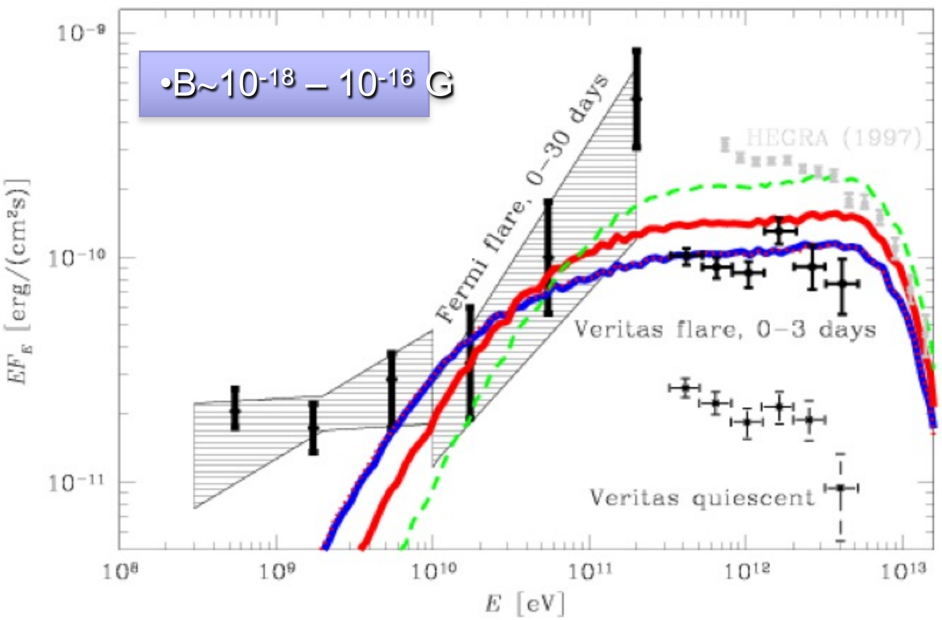


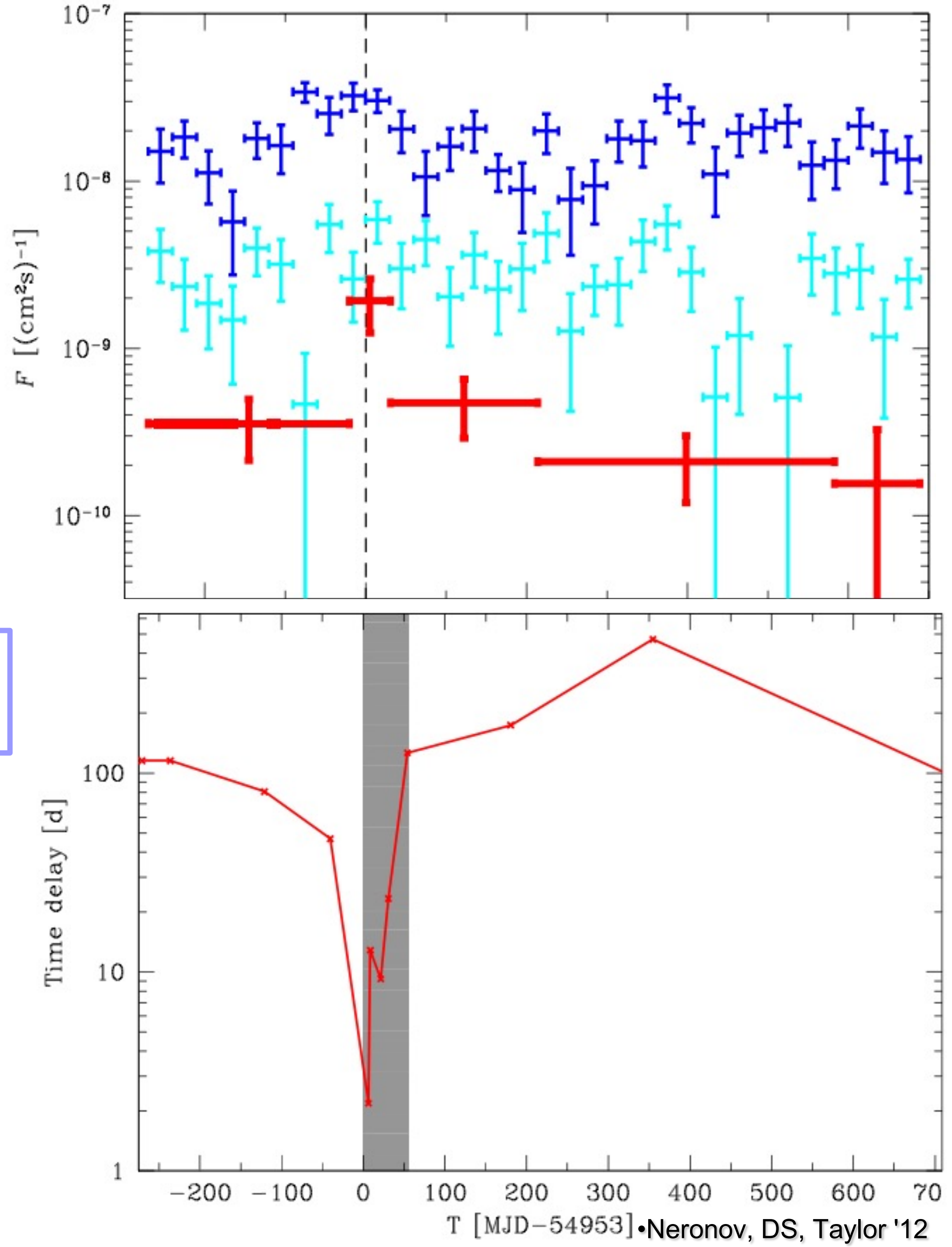
•**Imaging**: cascade component forms an extended emission around initially point source.

• – detectability depends on the telesope 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



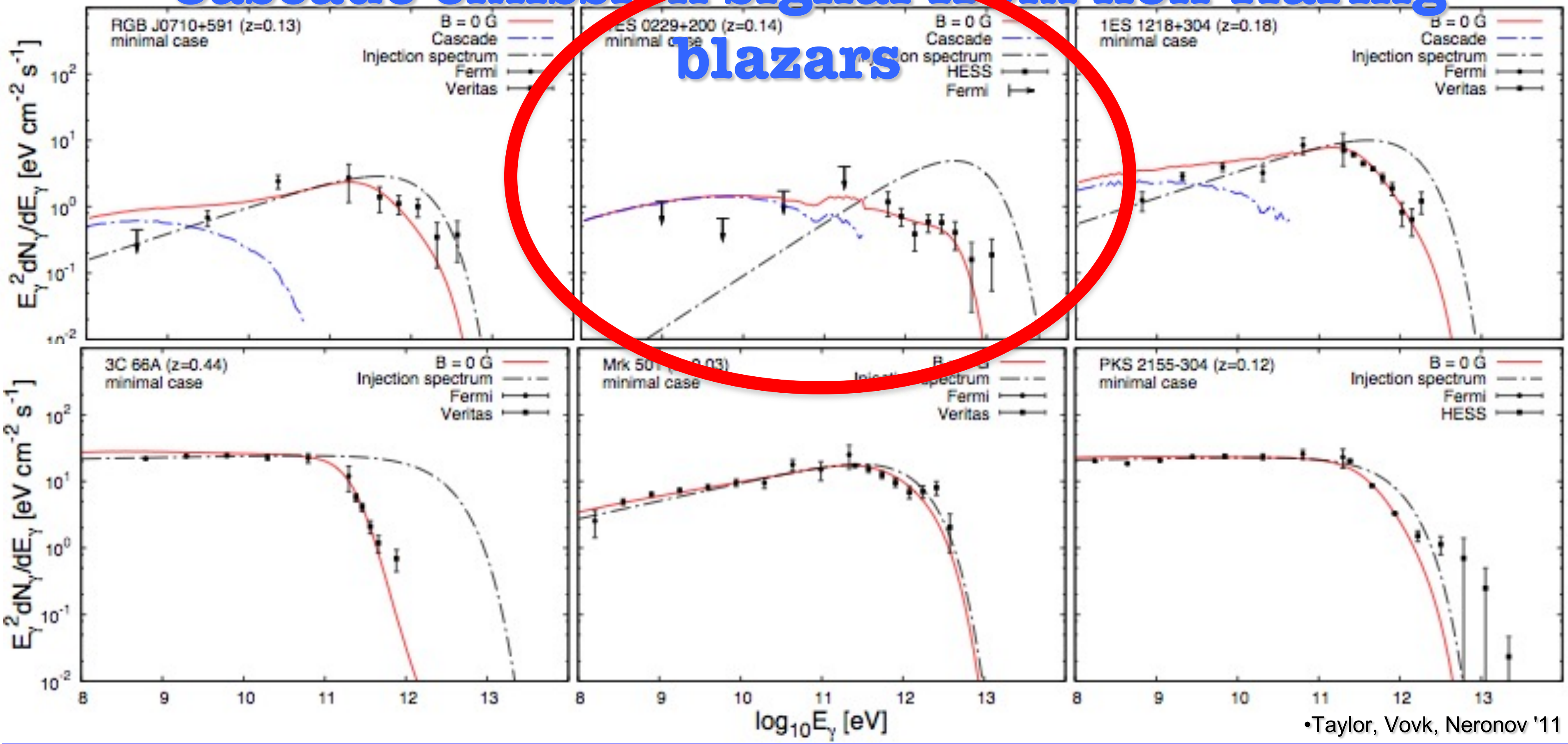


•Neronov, DS, Taylor '12

- •The flare occurred during the multiwavelength campaing, 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 ~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.

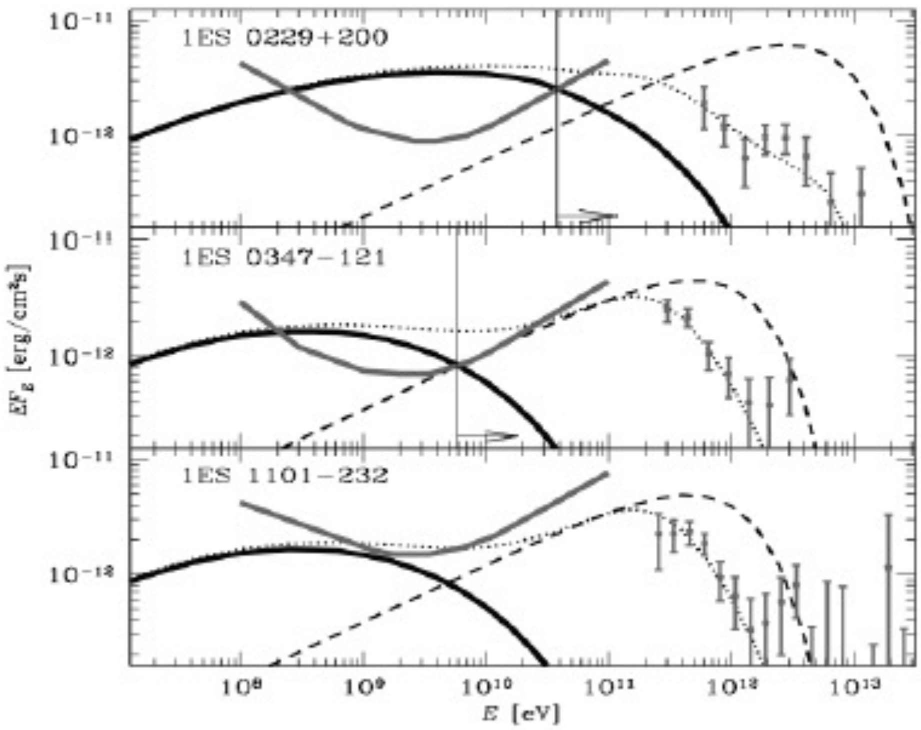
•.... waiting for the Big one

•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

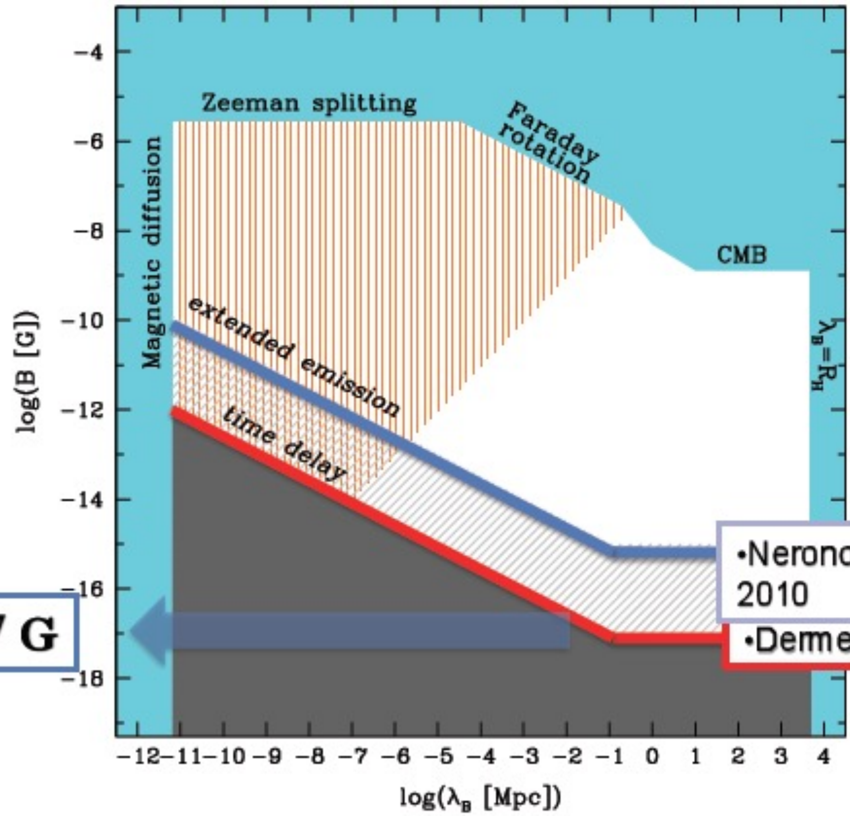
....

• 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.



•$B_{IGM}>10^{-17}$ G

•Neronov, Vovk, 2010, Tavecchio et al. 2010

•Dermer et al., 2011, Taylor et al. 2011

•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.

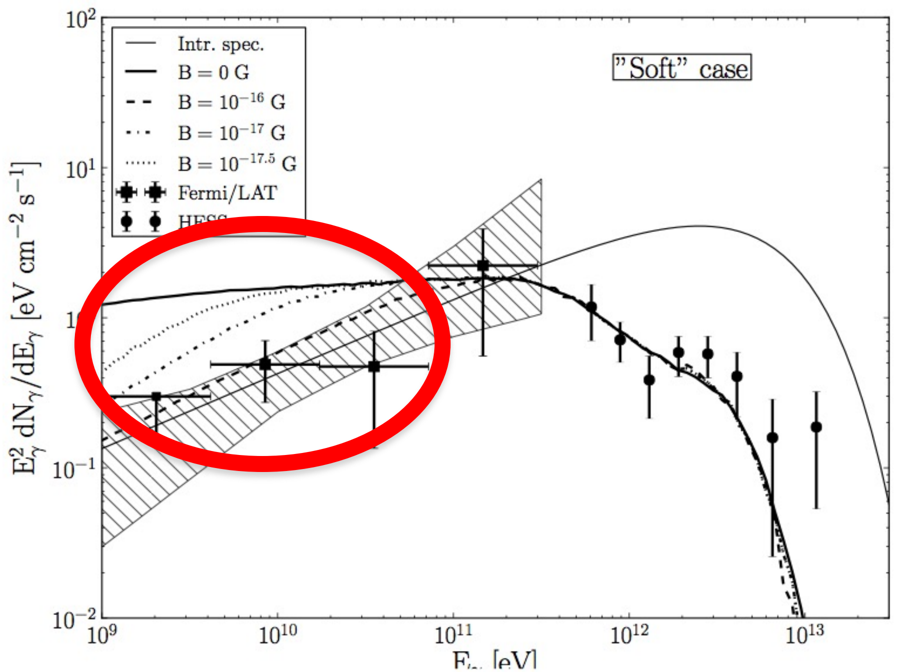
• The hardest VHE blazar 1ES 0229+200

•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 ~10 TeV energy band, where γ-ray emission is strongly attenuated by the pair production effect.

•Most of the primary γ-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.

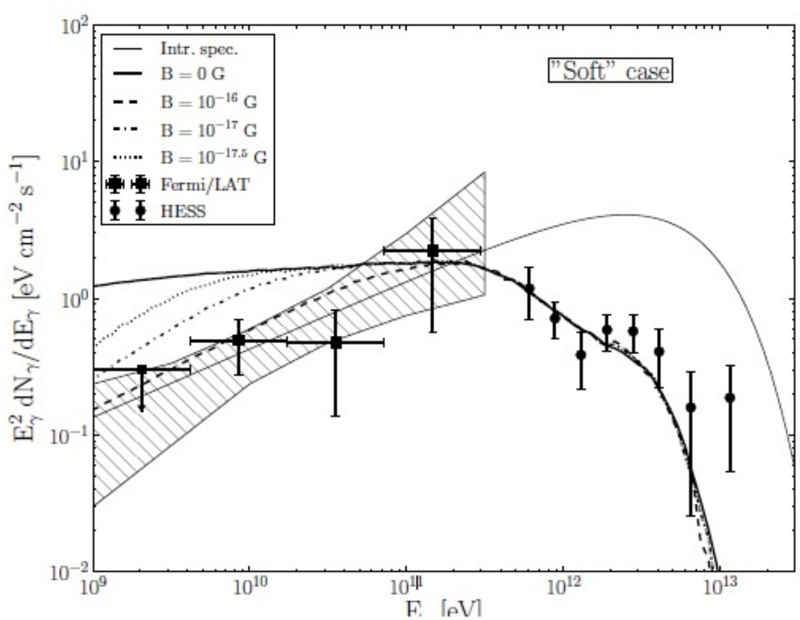
•The source is stable in the VHE band: no variability is found between observations made over ~5 yr time span.

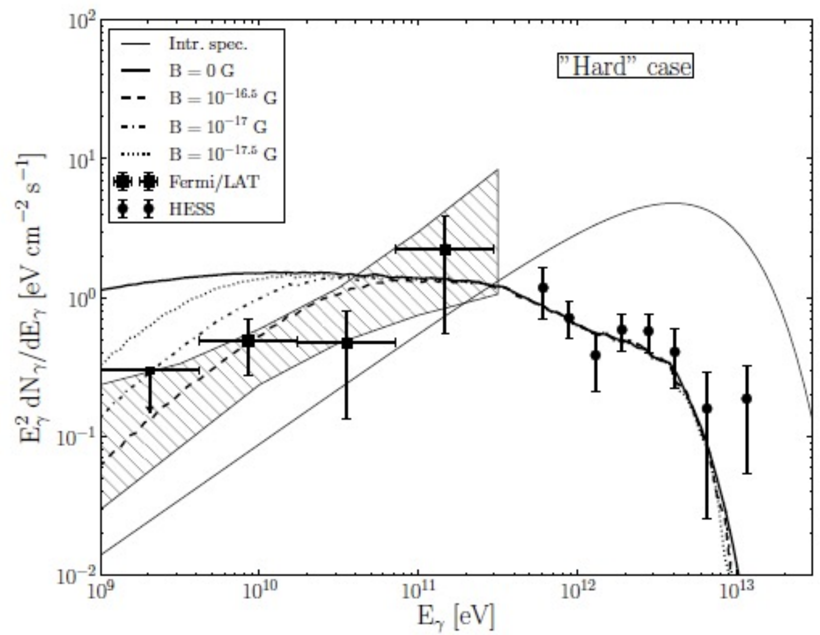


$$\Gamma = 1.36 \pm 0.25$$

•Vovk, Taylor, Neronov, and DS 1112.2534

EGMF from 1ES 0229+200





EGMF limits from 5 blazars

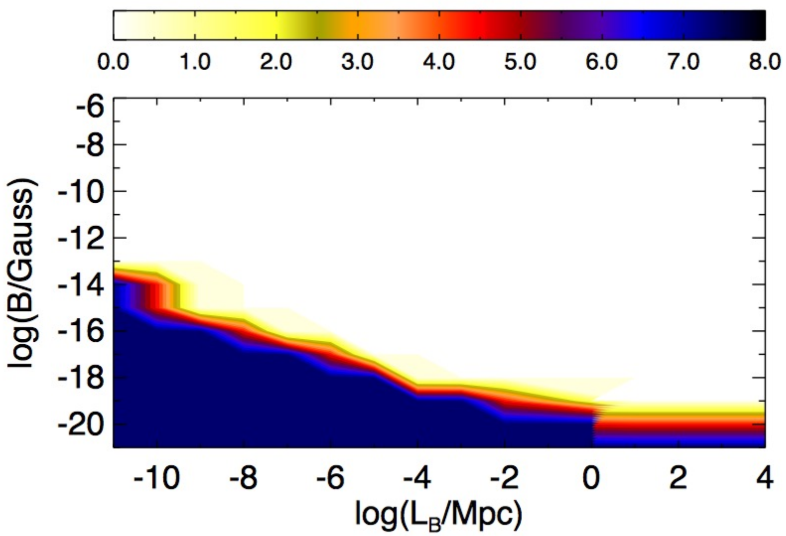


FIG. 4.— The values of parameter space of B and L_B ruled out or the combined *conservative* results of Section 4.1 for all of our bjects. The contours represent the significance a particular region f parameter space is ruled out, in number of sigma, as indicated y the bar. These constraints assume the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

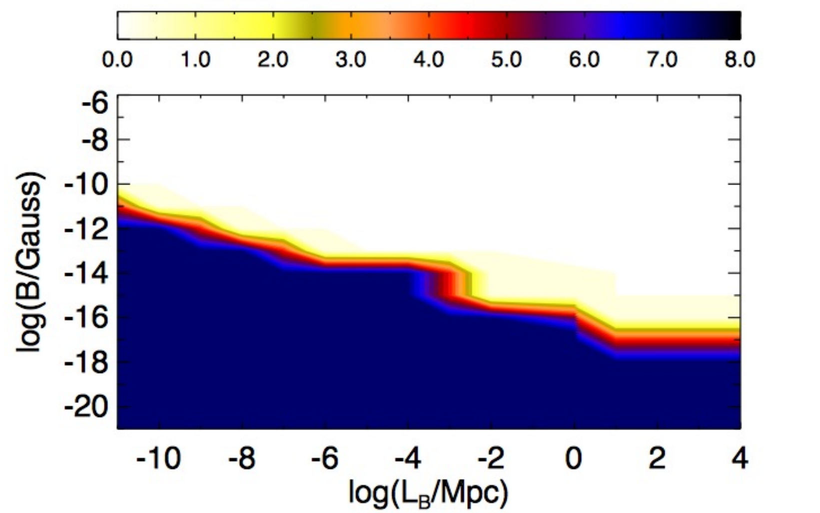
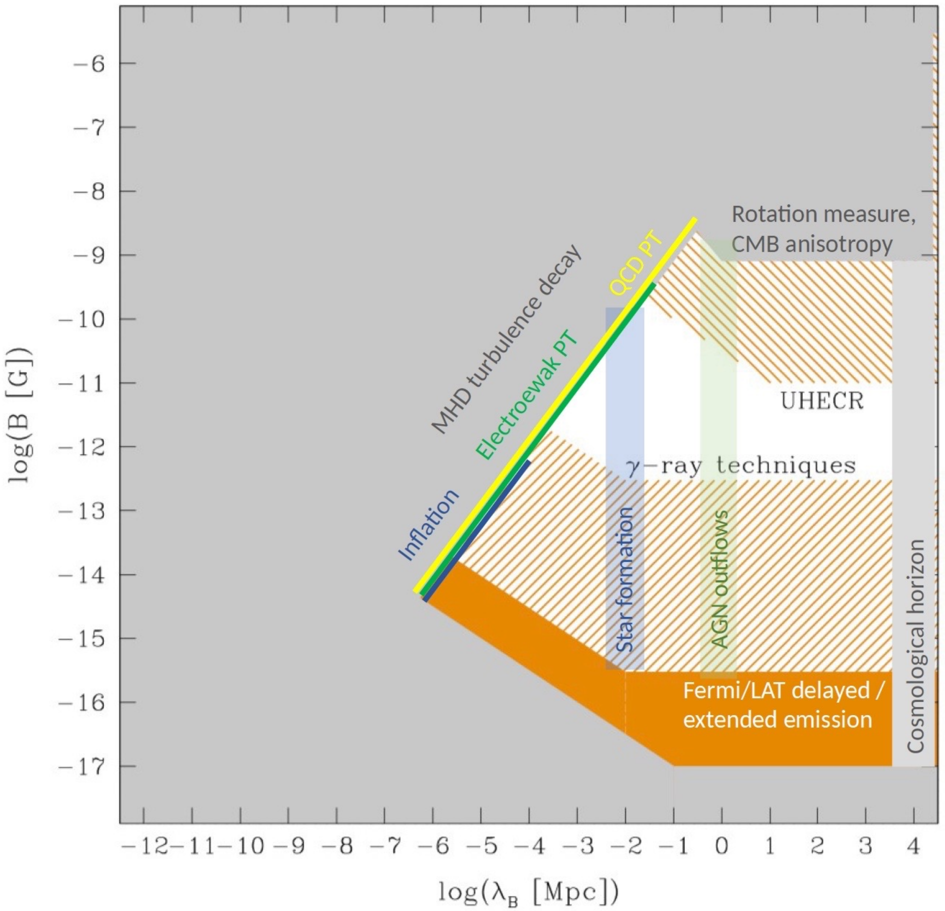


FIG. 7.— The same as Figure 4, only with less conservative assumptions. Here $F_{cascade,min} = F_{cascade,max}$, and the cascade was calculated assuming $t_{\rm blazar} = 1/H_0$ and E_{max} is the maximum observed VHE photon bin from the source.

- 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 H0 problem)?

Detection of 10 pG IGMF

- Cosmological IGMF

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

- Primary photon optical depth distance

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

  - Electron travel energy loss distance

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

  - Secondary photon energy

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

- Kalashev et al, 2007.14331

Conditions to detect 10 pG IGMF

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

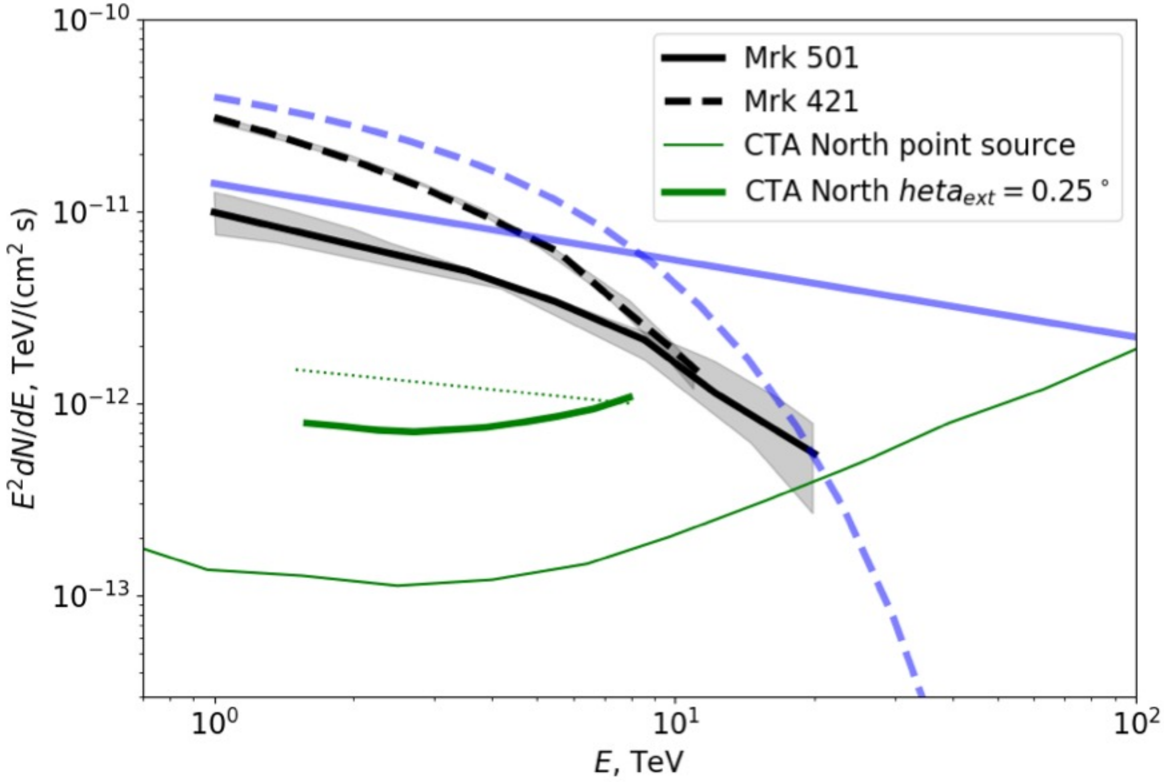
(a) large primary point-source power in the 100 TeV energy range,

(b) detectability of extended emission in multi-TeV energy range, and

(c) presence of primordial IGMF in the several Mpc region around the source.

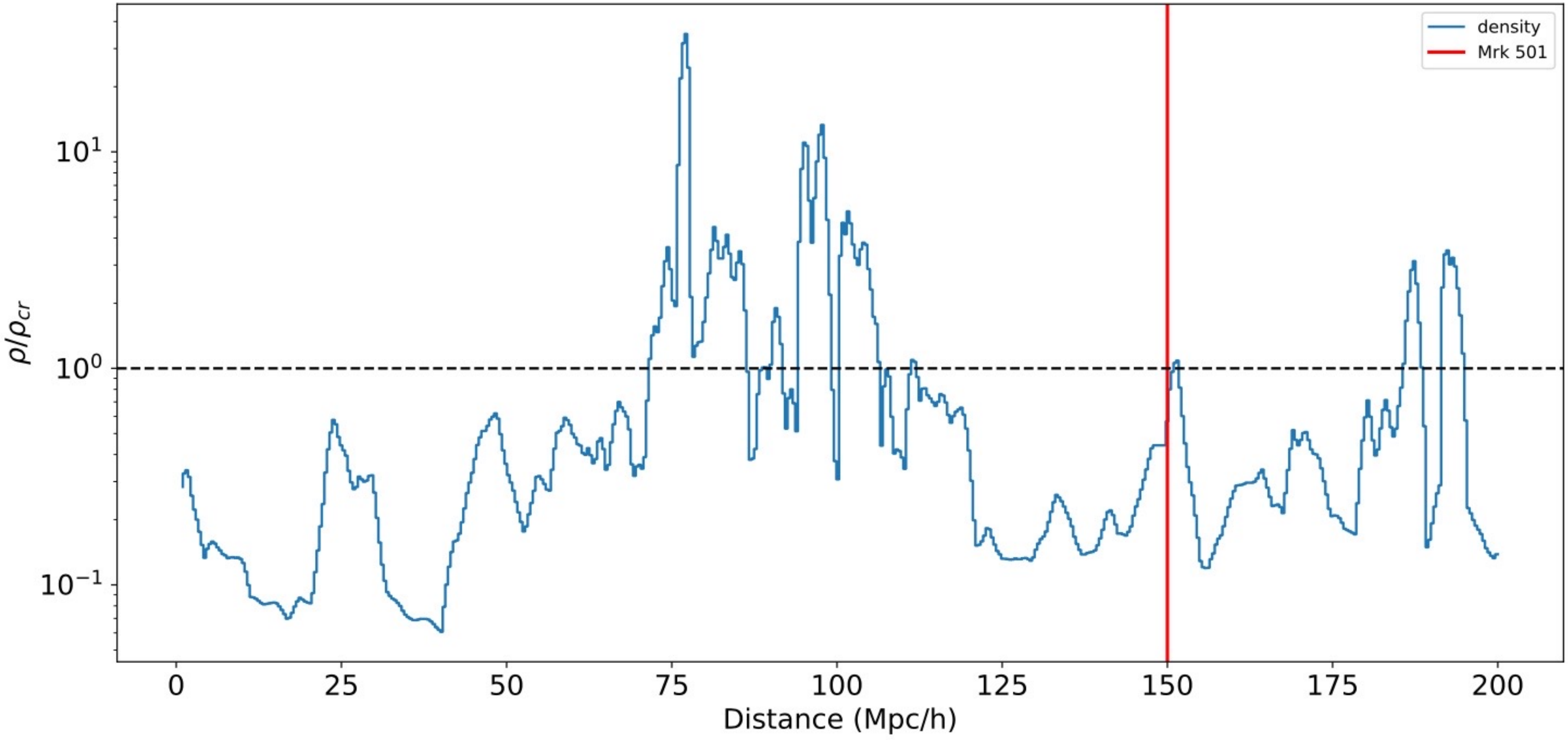
• Kalashev et al, 2007.14331

Spectrum Mkn 421 and Mkn 501



•Kalashev et al, 2007.14331

IGMF on LOS to Mkn 501



•Kalashev et al, 2007.14331

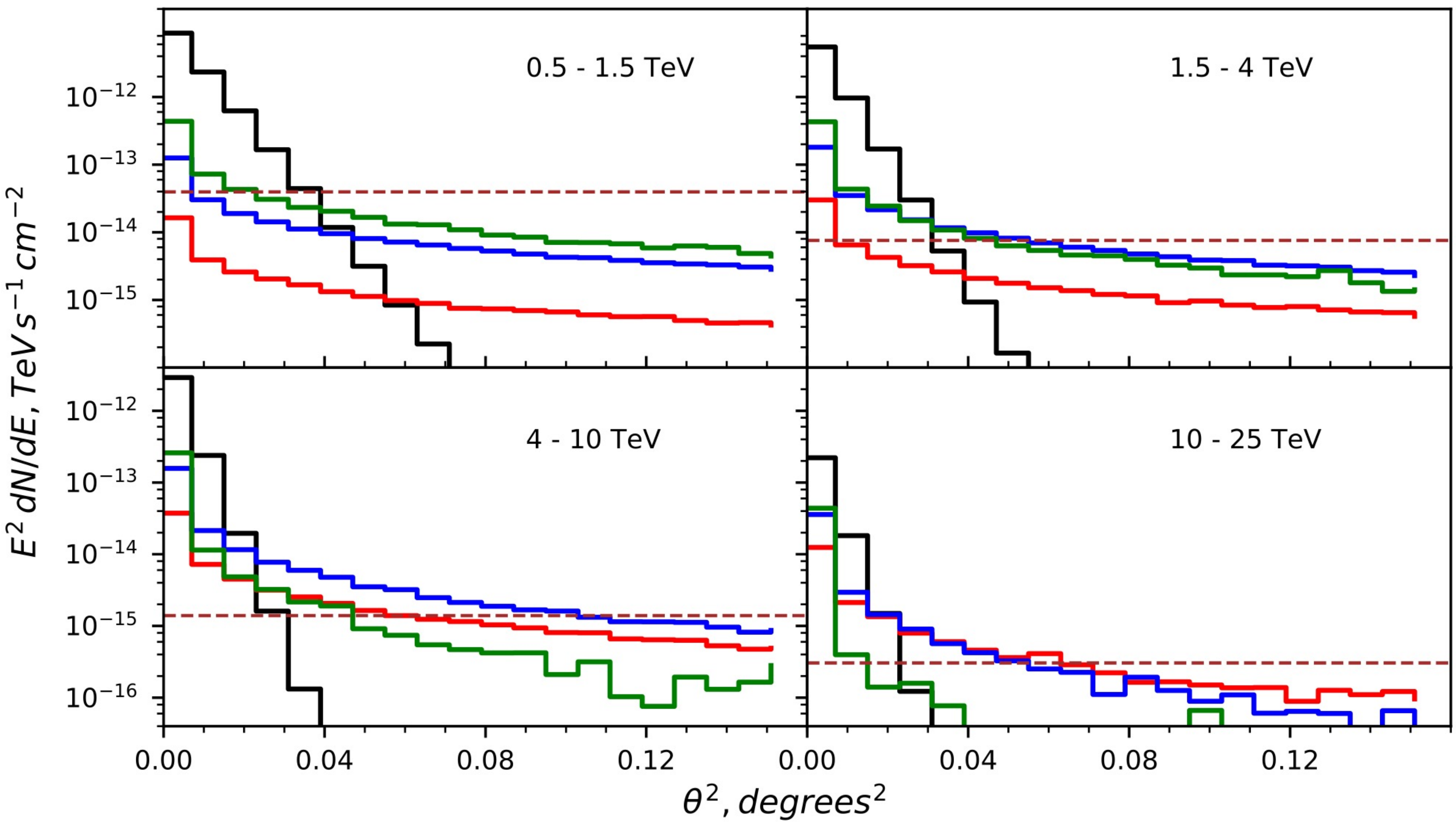
3D cascade extended emission

$$\Theta_{ext,max} = \frac{R_{ext}}{D} \simeq 0.24^\circ \left[\frac{\Theta_{jet}}{10^\circ}\right] \left[\frac{E_{\gamma 0}}{100\ \mathrm{TeV}}\right]^{-1.6} \left[\frac{D}{120\ \mathrm{Mpc}}\right]^{-1} \simeq 0.24^\circ \left[\frac{\Theta_{jet}}{10^\circ}\right] \left[\frac{E_\gamma}{8\ \mathrm{TeV}}\right]^{-0.8} \left[\frac{D}{120\ \mathrm{Mpc}}\right]^{-1} \quad (12)$$

$$T_{ext,max} = D\Theta^2_{ext,max}/c \simeq 8 \left[\frac{\Theta_{jet}}{10^\circ}\right]^2 \left[\frac{E_\gamma}{8\ \mathrm{TeV}}\right]^{-1.6} \mathrm{kyr}$$

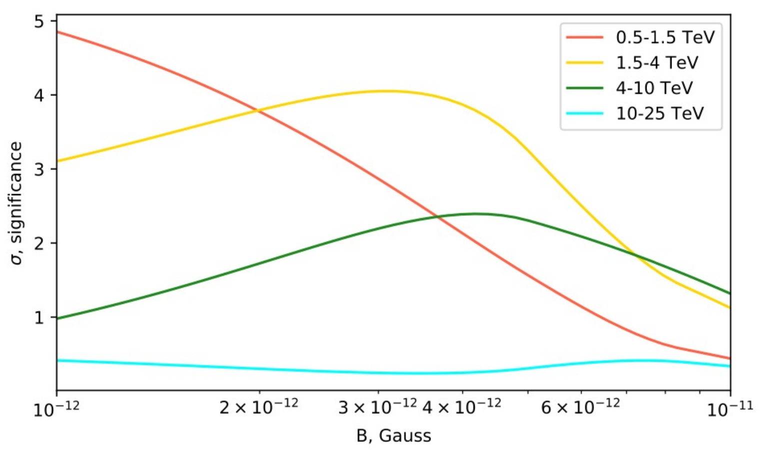
- Kalashev et al, 2007.14331

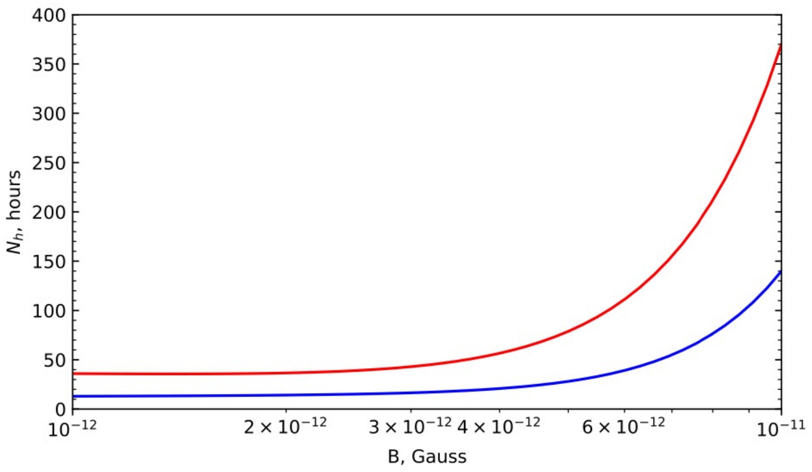
Extended emission around Mkn 501



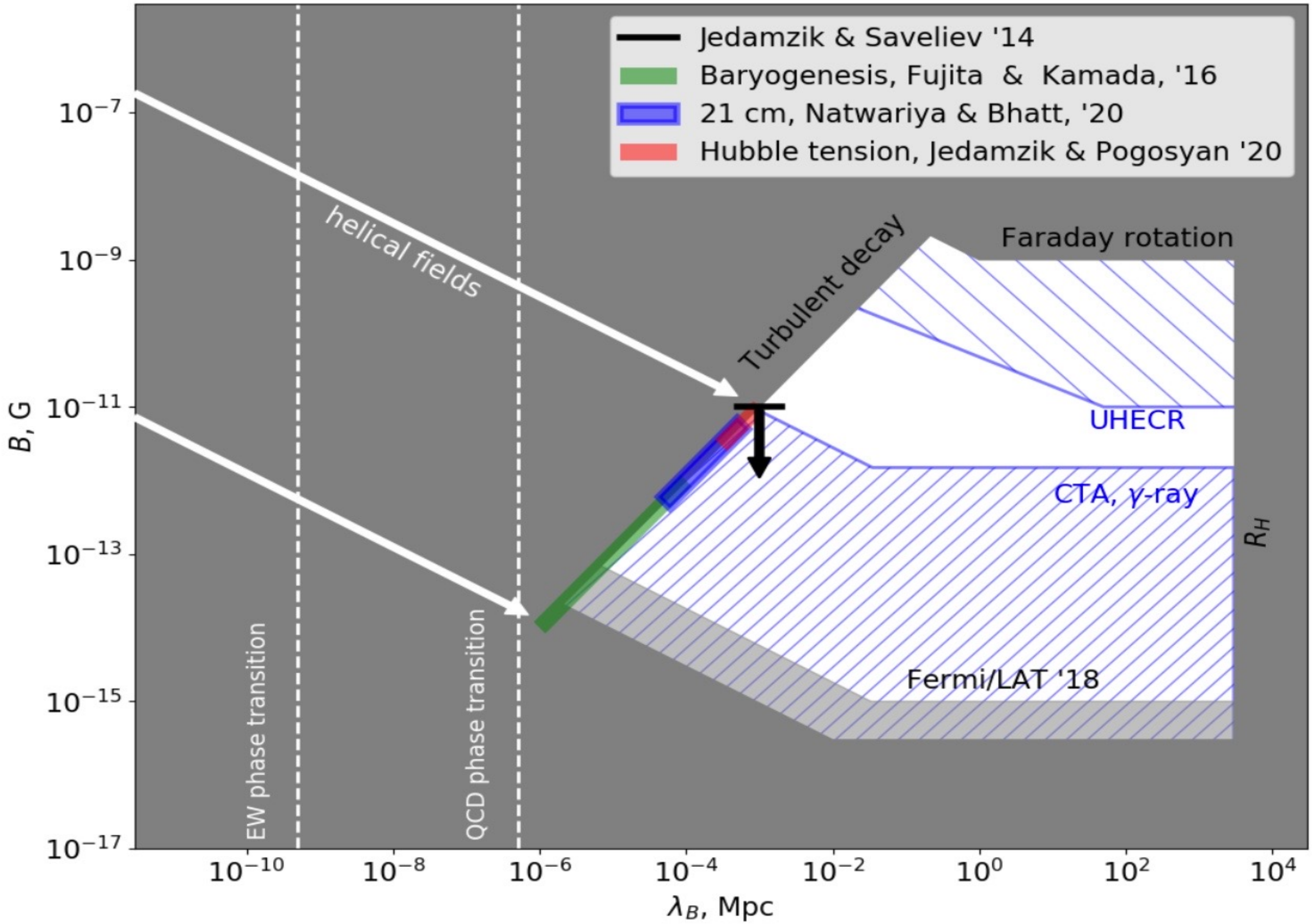
•Kalashev et al, 2007.14331

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

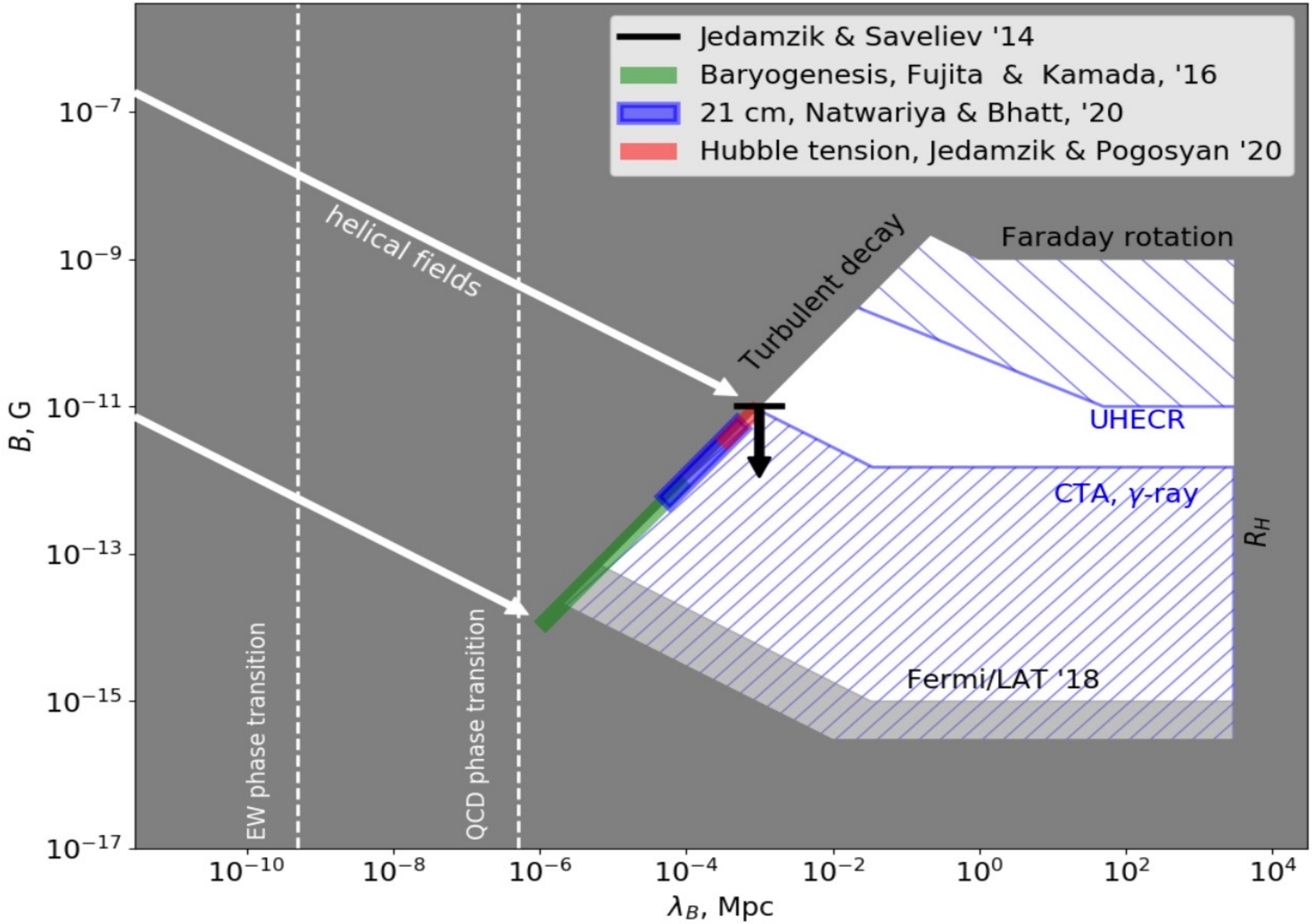




- Kalashev et al, 2007.14331



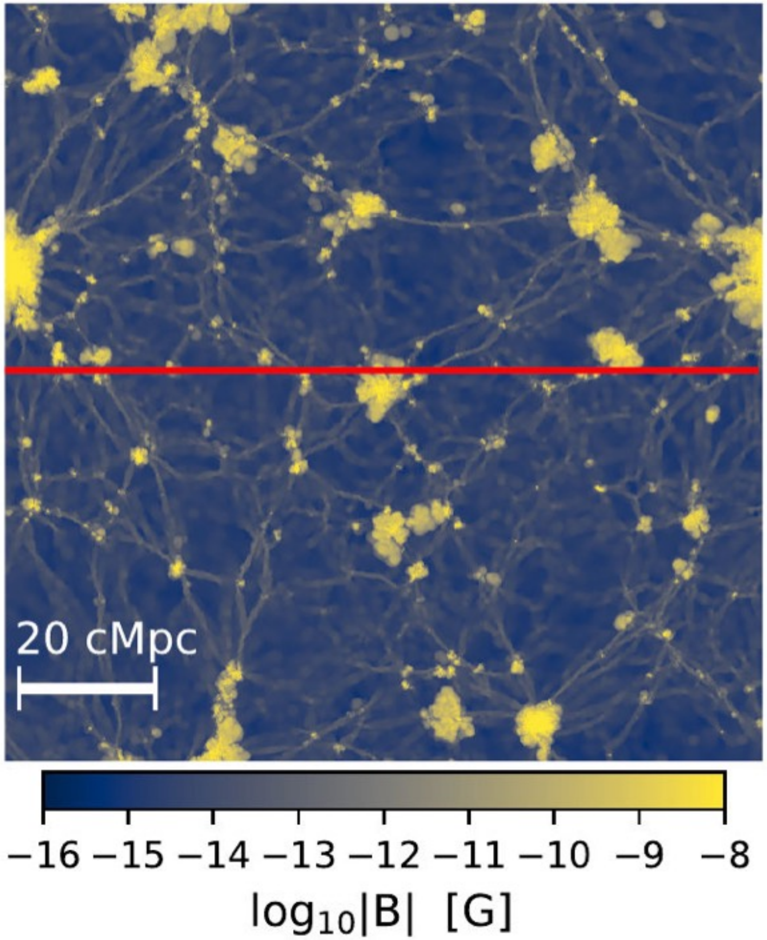
•Kalashev et al, 2007.14331



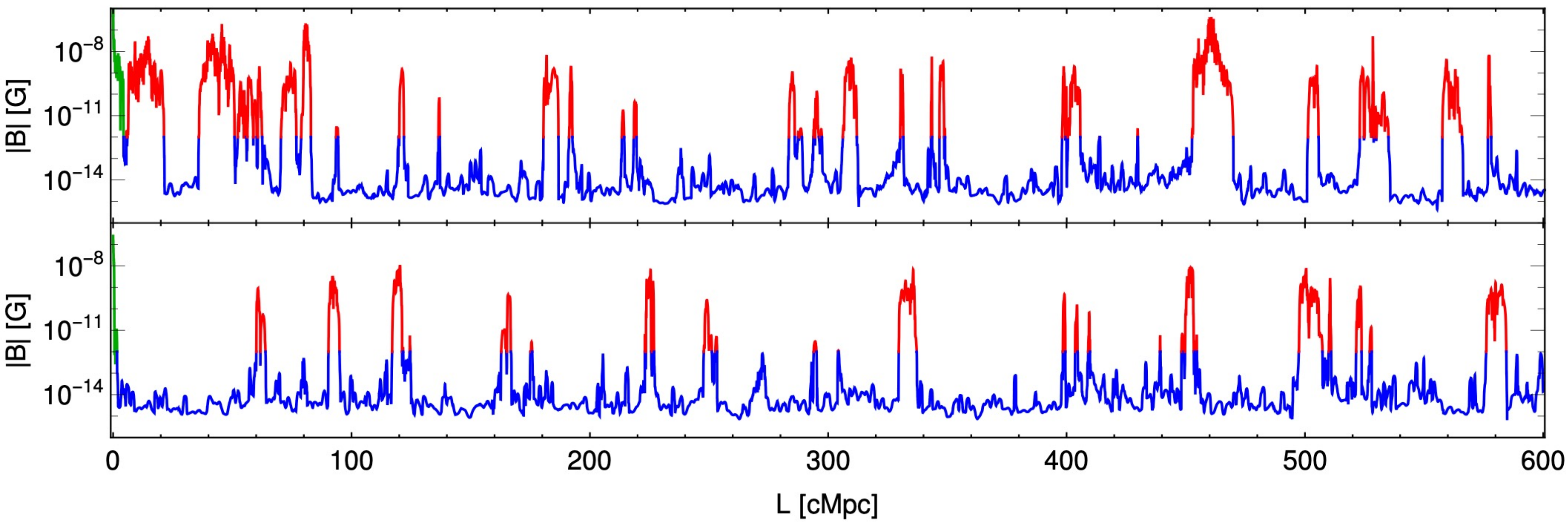
•Kalashev et al, 2007.14331

Inter-Galactic Magnetic Field and AGN feedback

3D magnetic field in ILLUSTRIS-TNG

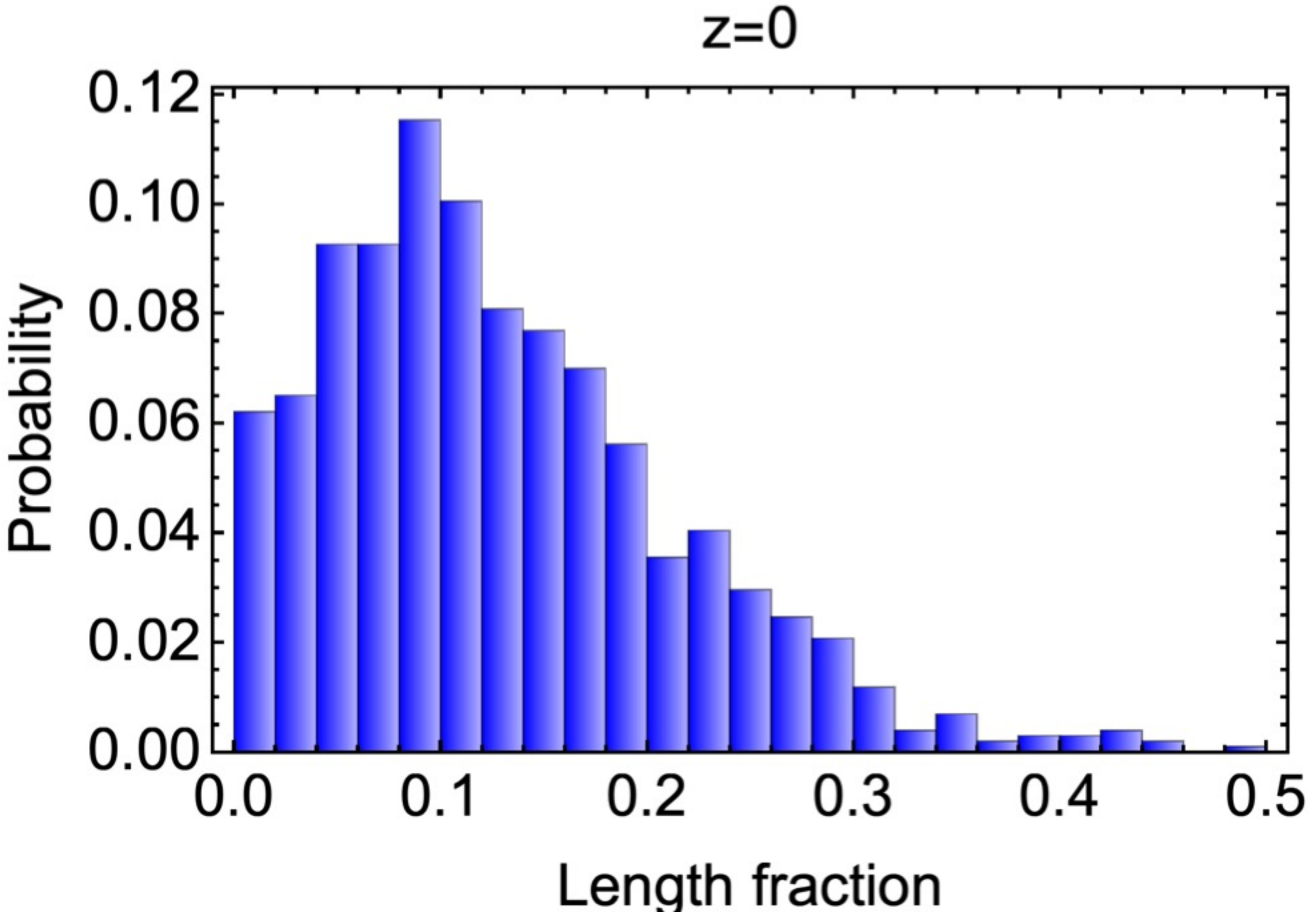


IGMF on LOS and magnetic bubbles

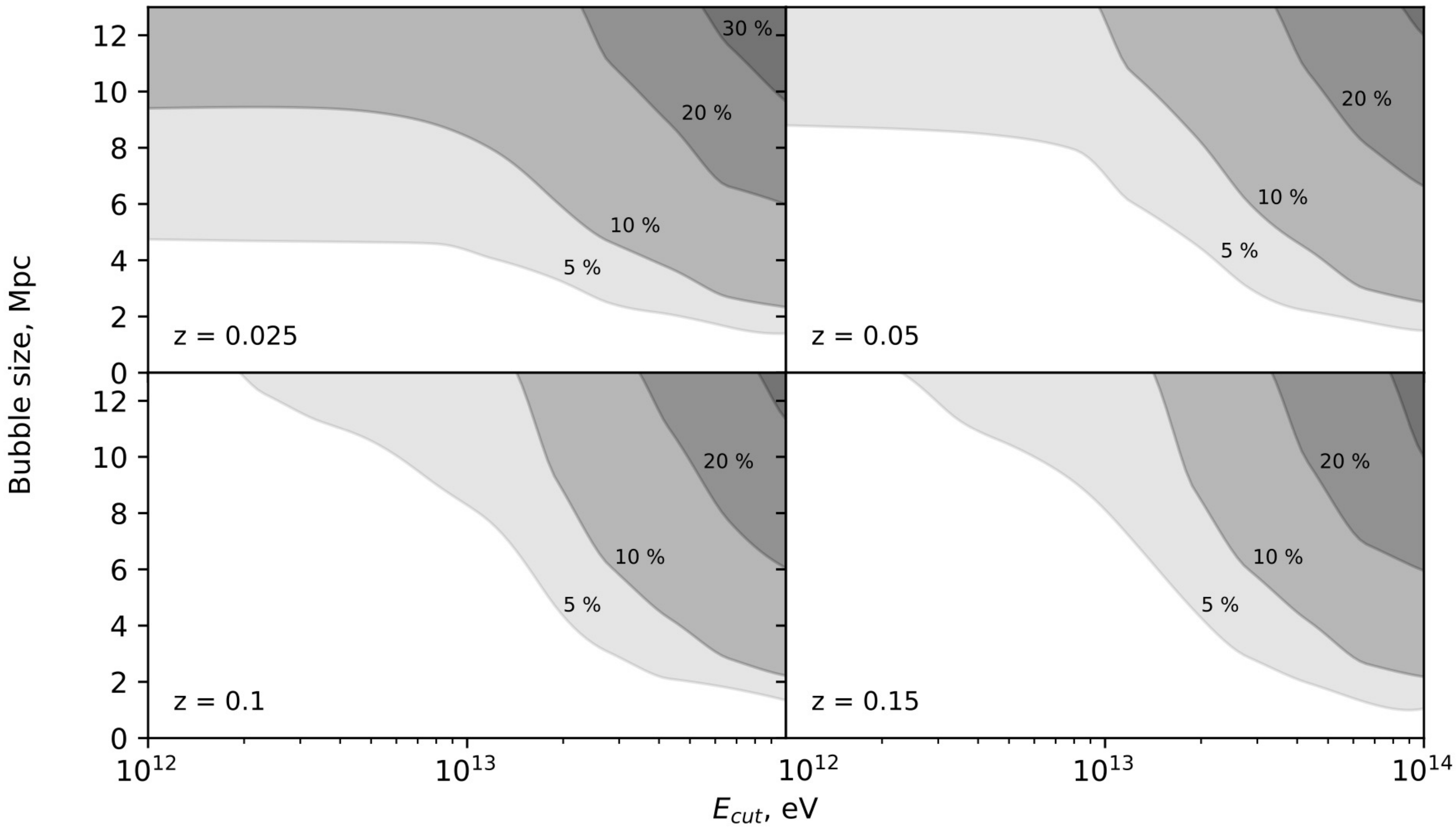


- Bondarenko et al, 2106.02690

Probability to have strong MF on LOS

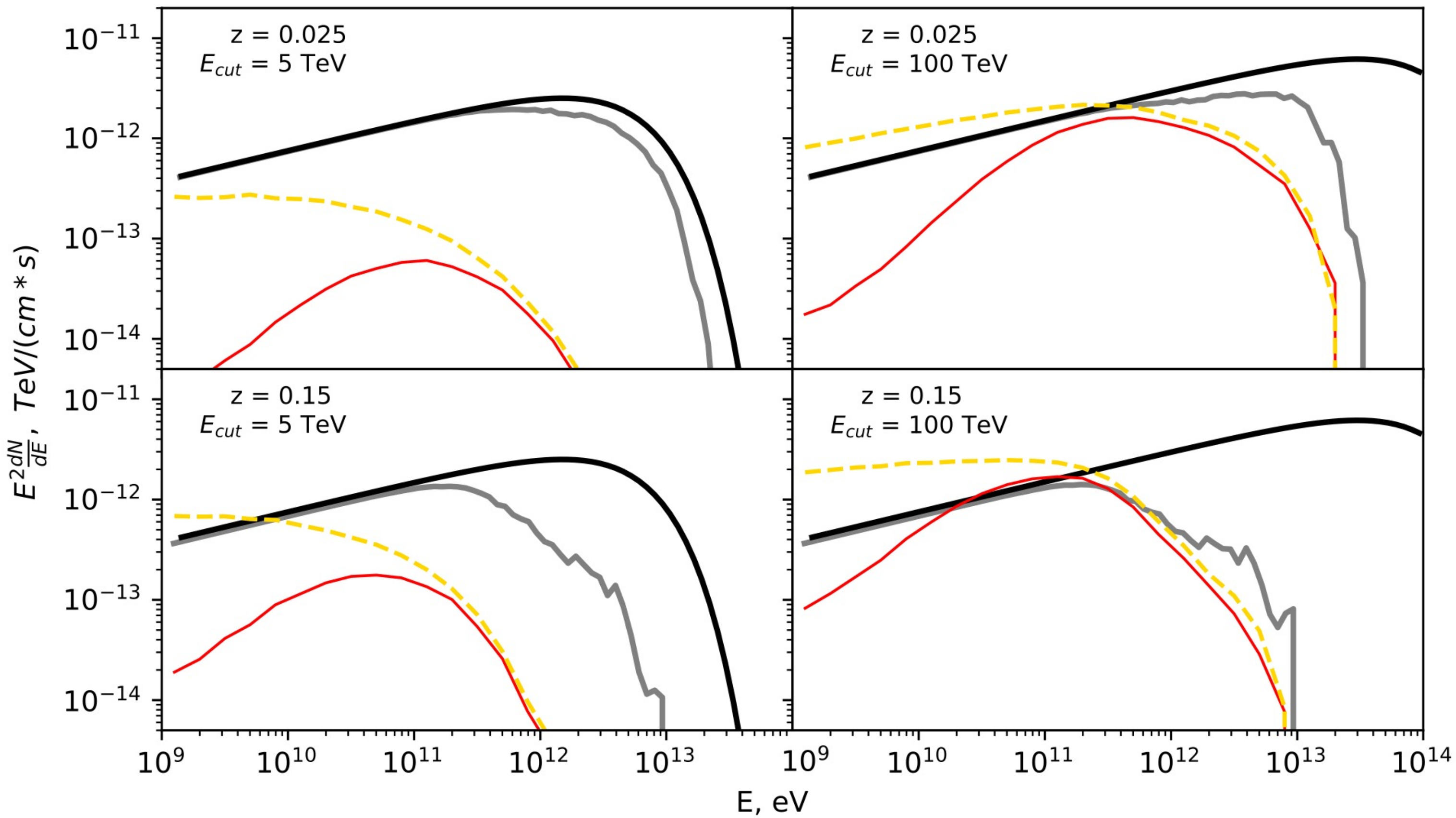


Part of cascade « eaten » by host bubble



- Bondarenko et al, 2106.02690

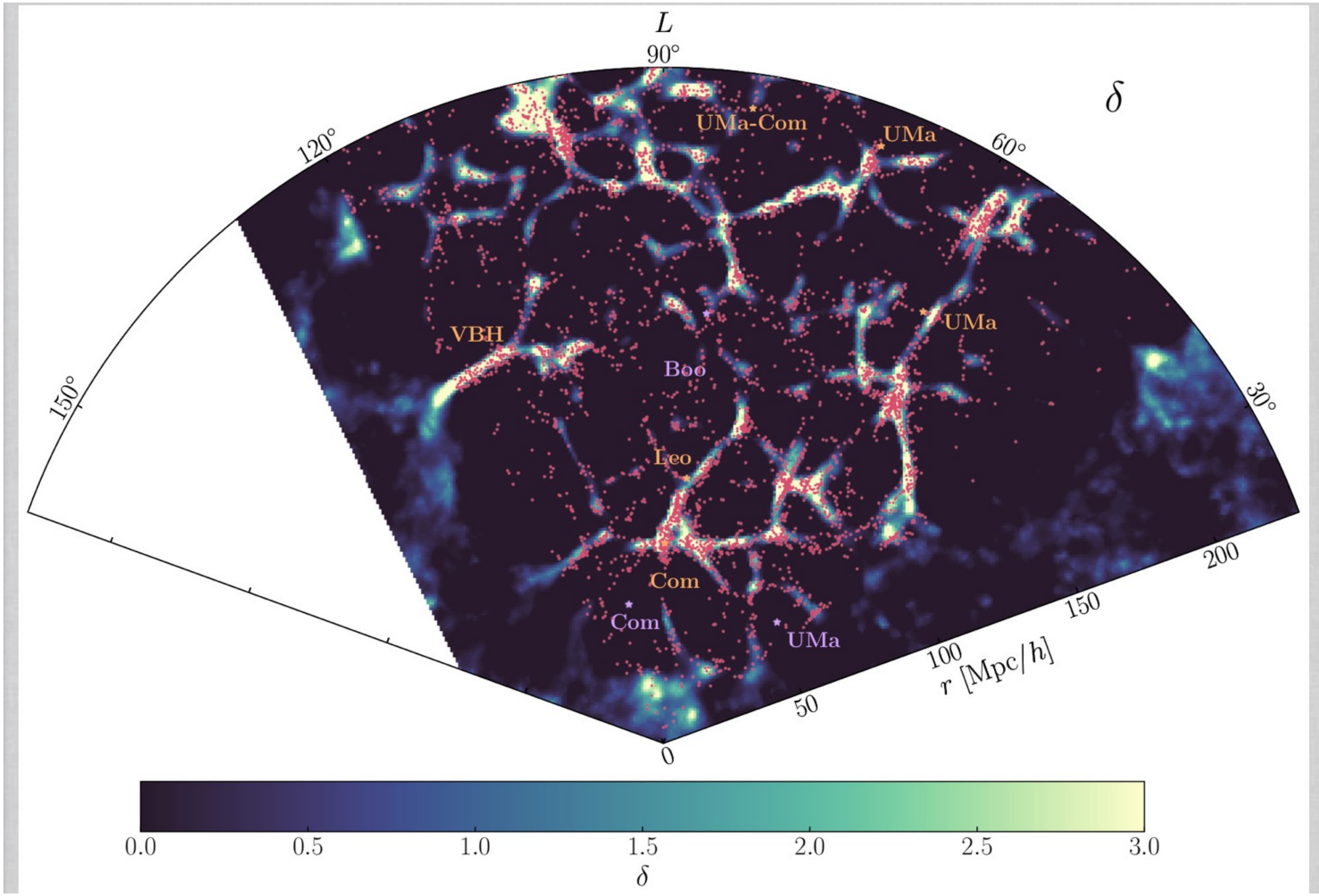
Spectra of blazars



- Bondarenko et al, 2106.02690

Detection of Inter-Galactic Magnetic Field from inflation

BORG LSS and RAMSES MHD

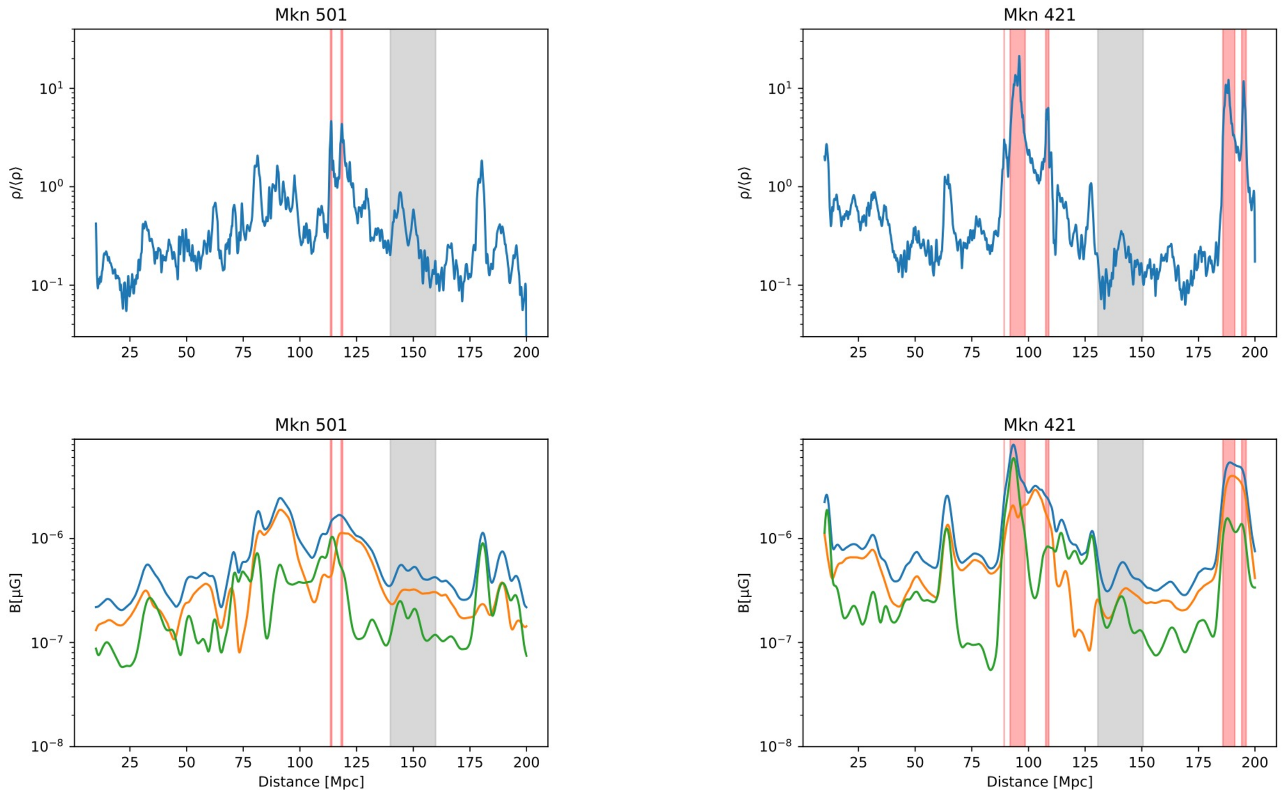


TeV blazars within 250 Mpc

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

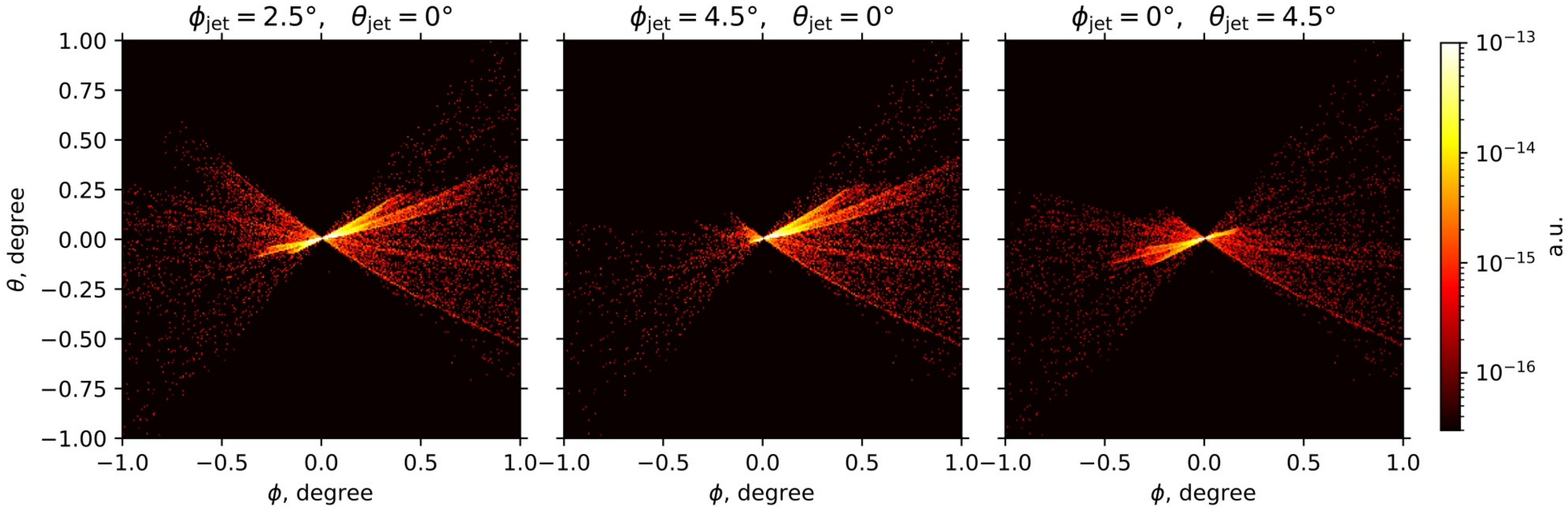
•A.Korochkin et al, 2111.10311.

IGMF on LOS



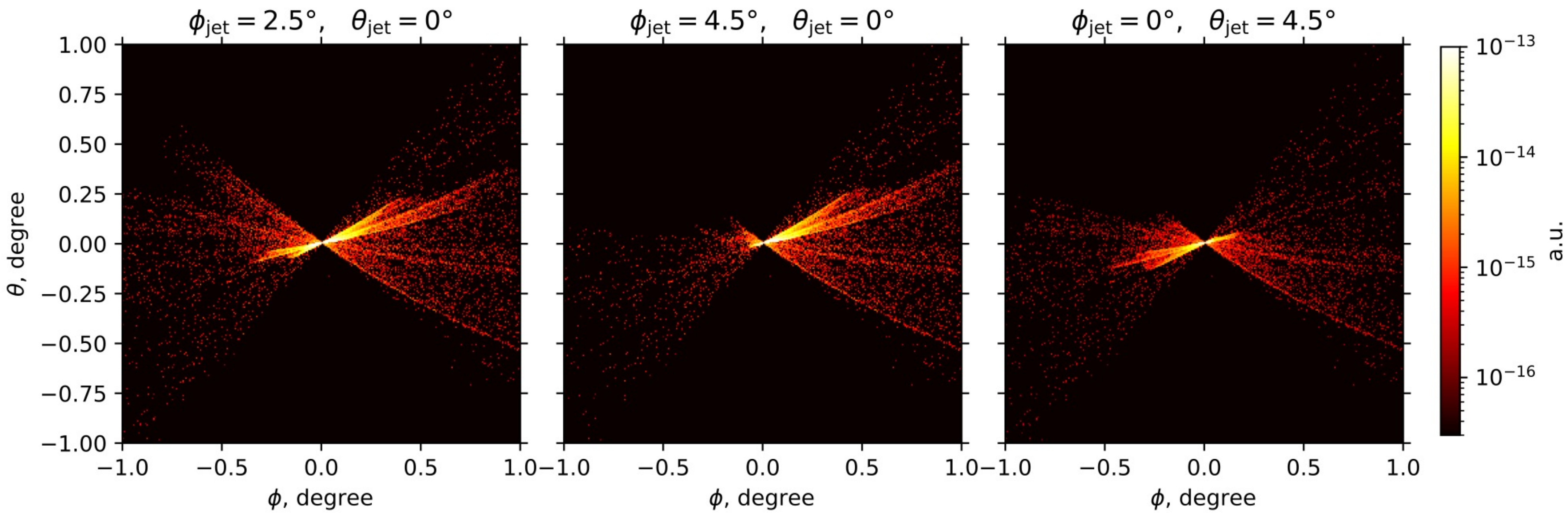
- A.Korochkin et al, 2111.10311.

IGMF on LOS

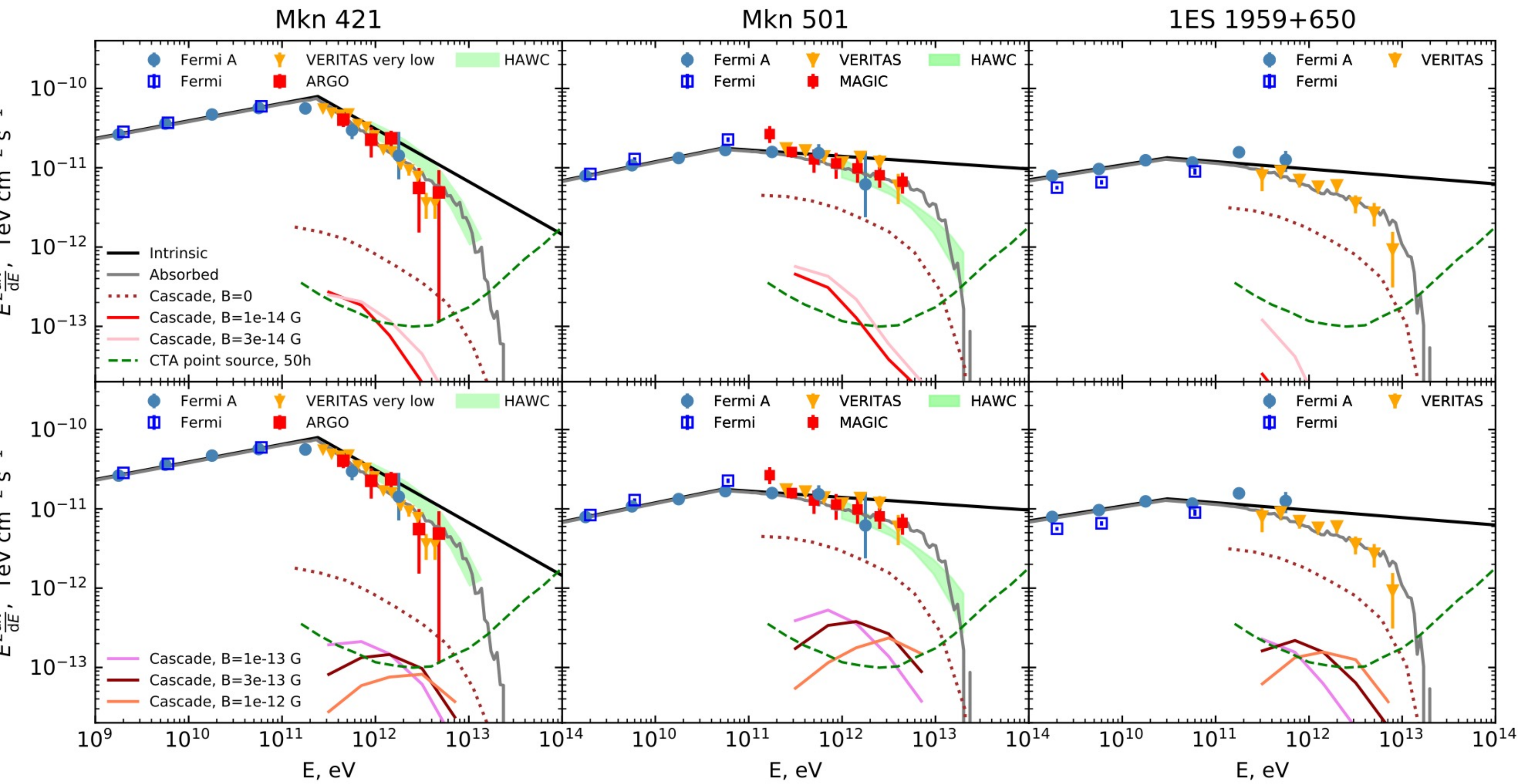


• A.Korochkin et al, 2111.10311.

IGMF on LOS



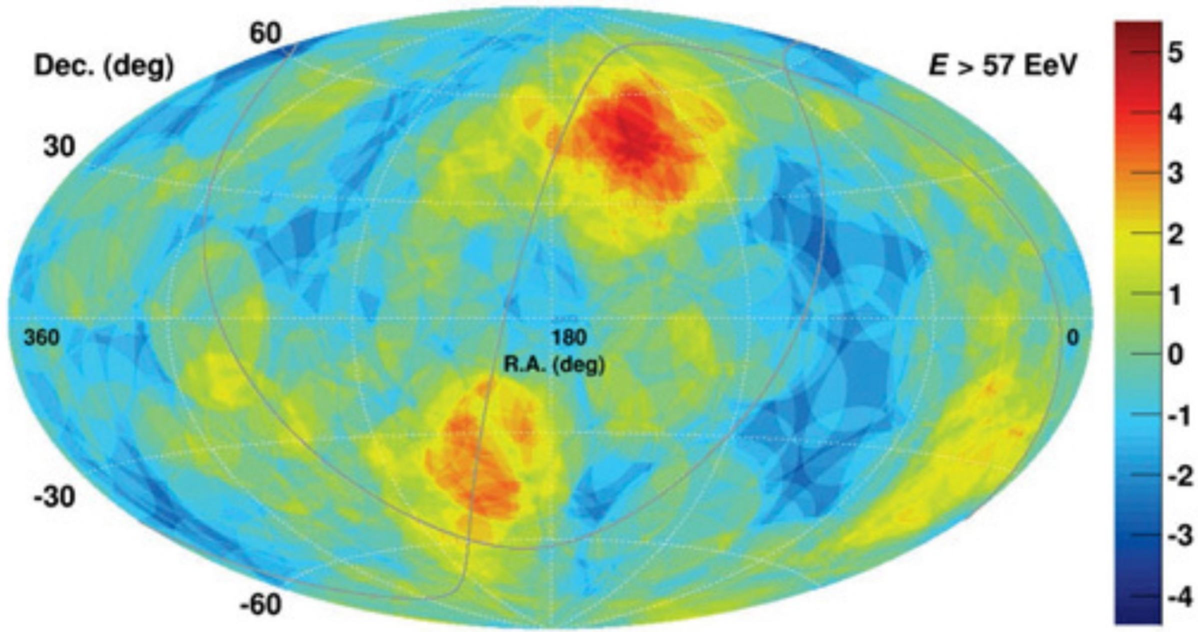
- A.Korochkin et al, 2111.10311.



•A.Korochkin et al, 2111.10311.

Inter-Galactic Magnetic Field detection with UHECR

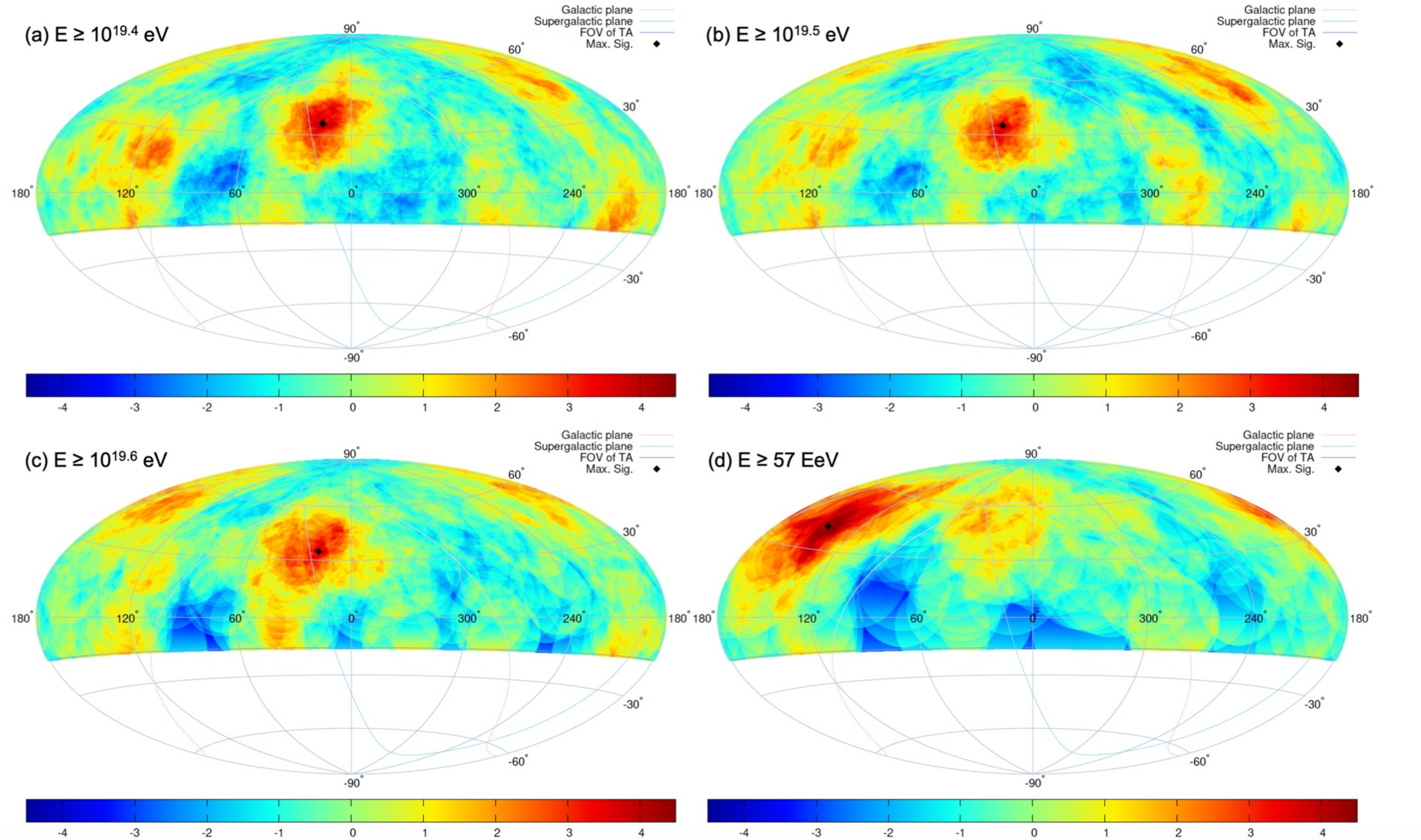
Auger-TA sky map



Full sky map combining the Telescope Array and Pierre Auger data events with E > 5.7×10 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.

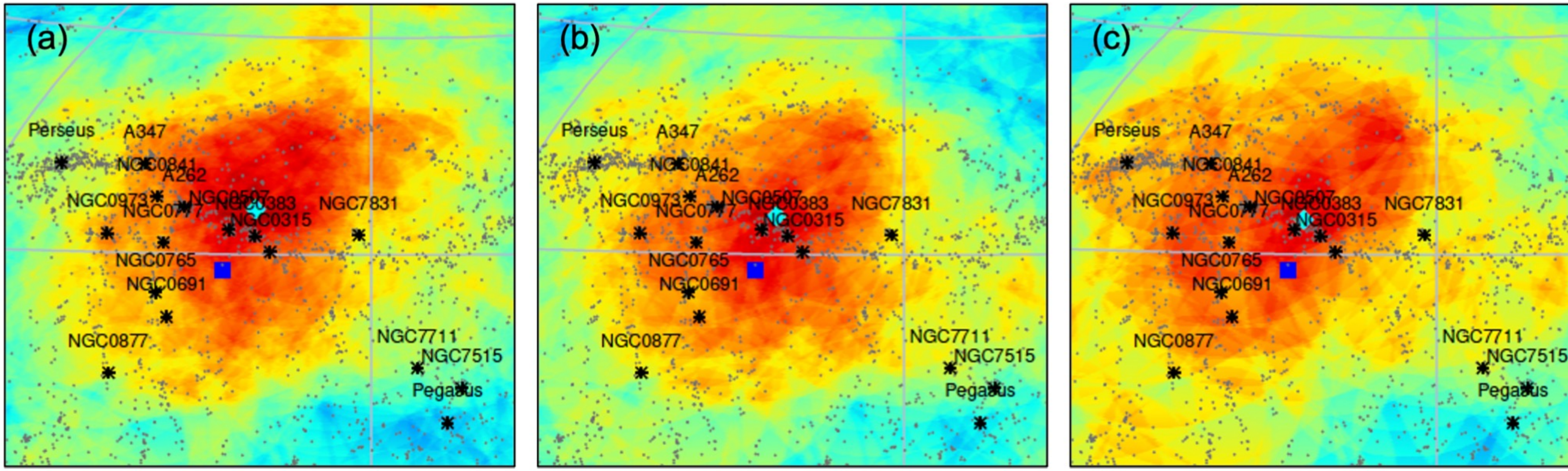
- Auger & TA collaboration

TA sky map



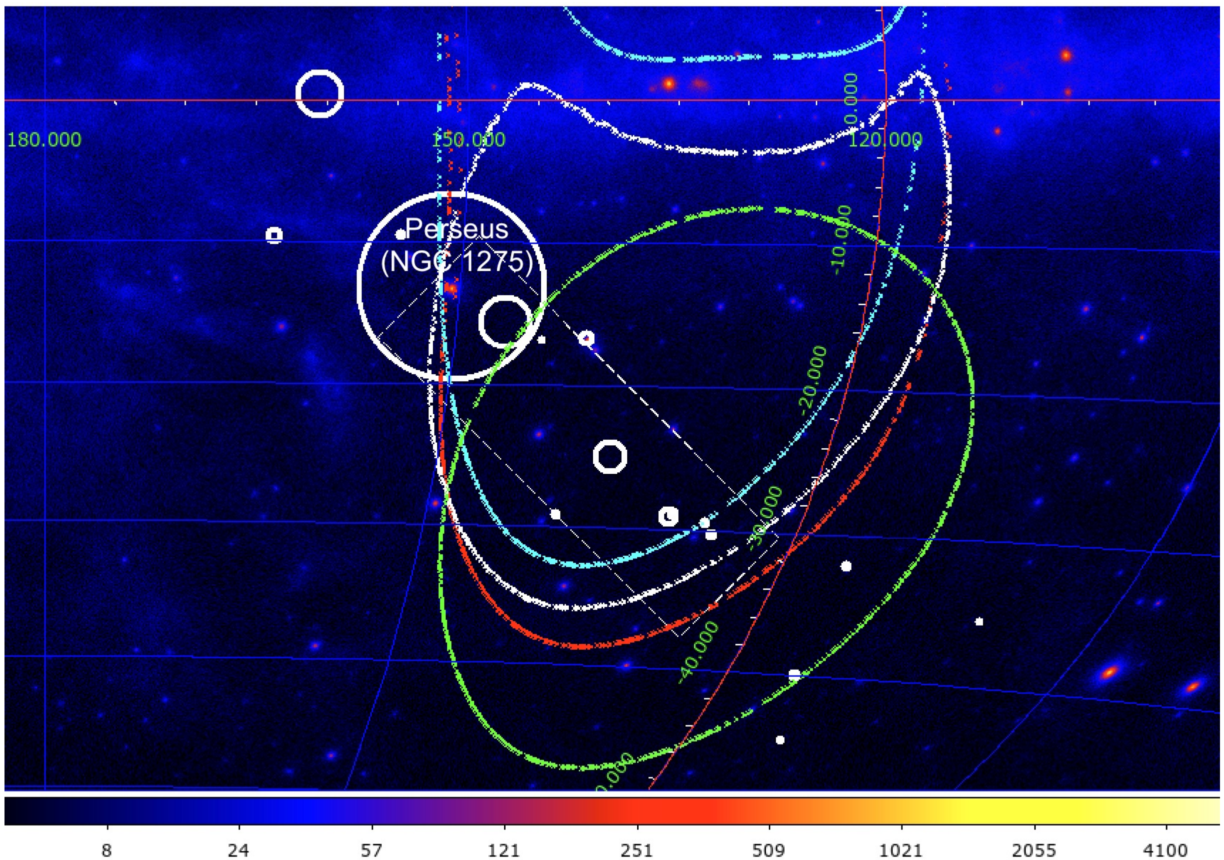
•TA collaboration, 2110.14827

TA sky map of Perseus-Pisces SC



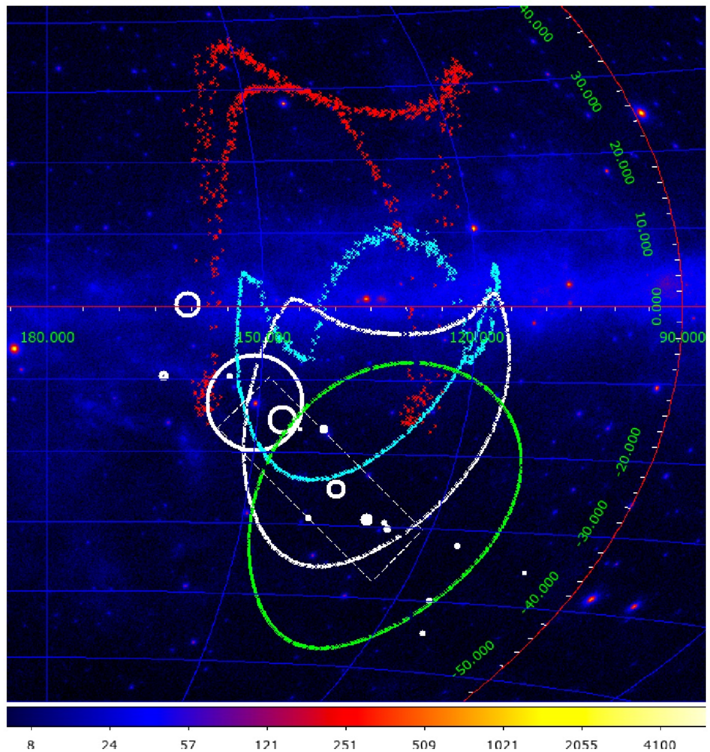
- TA collaboration, 2110.14827

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



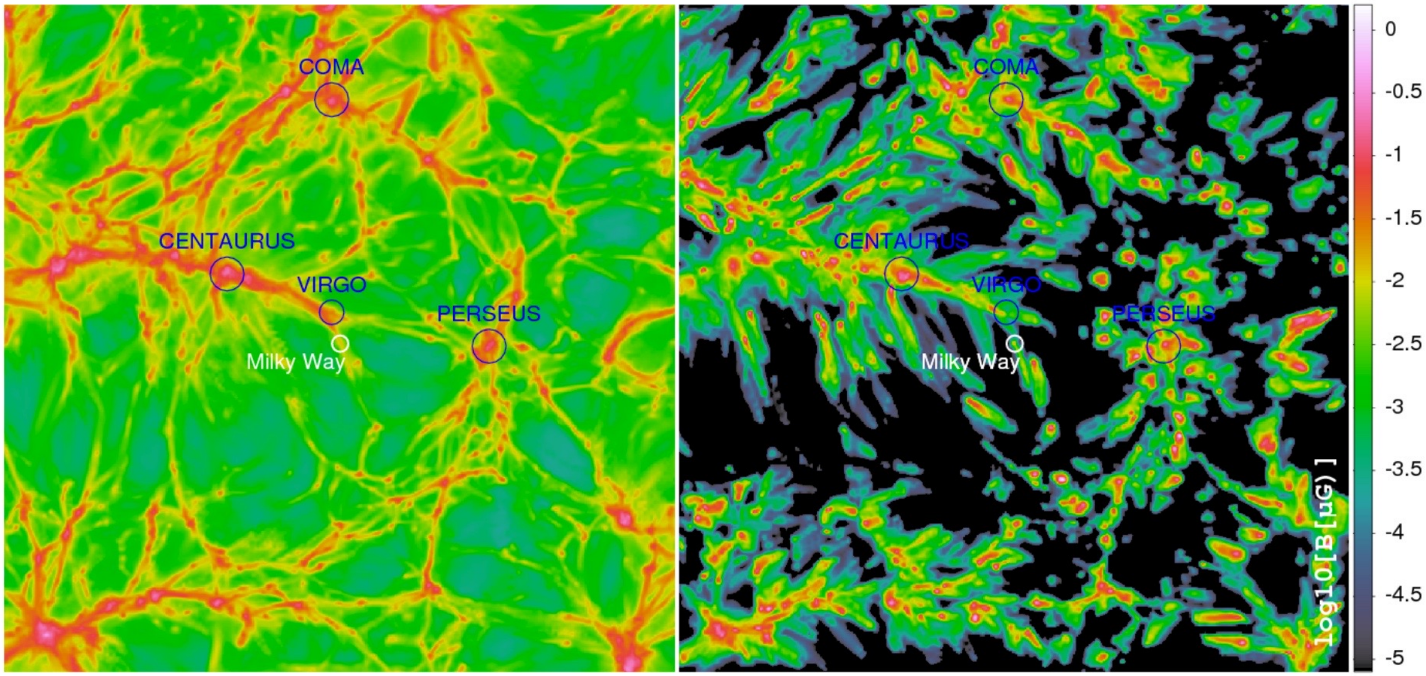
•A.Neronov, D.S. and O.Kalashev, 2112.0

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



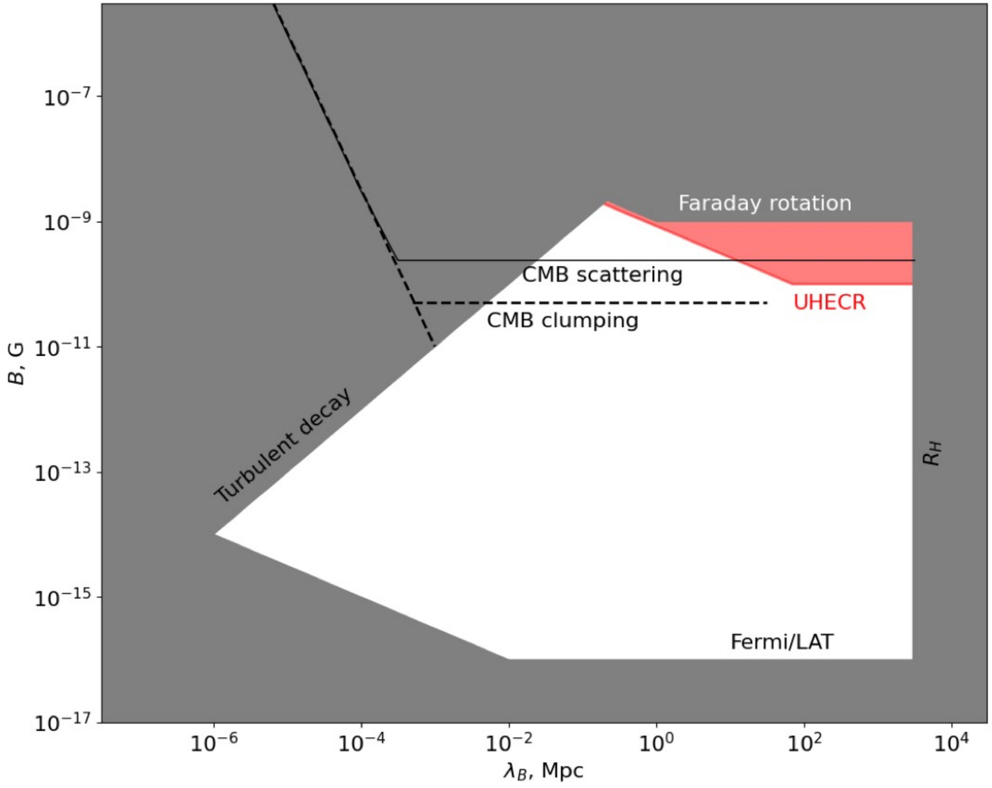
•A.Neronov, D.S. and O.Kalashev, 2112.0820

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



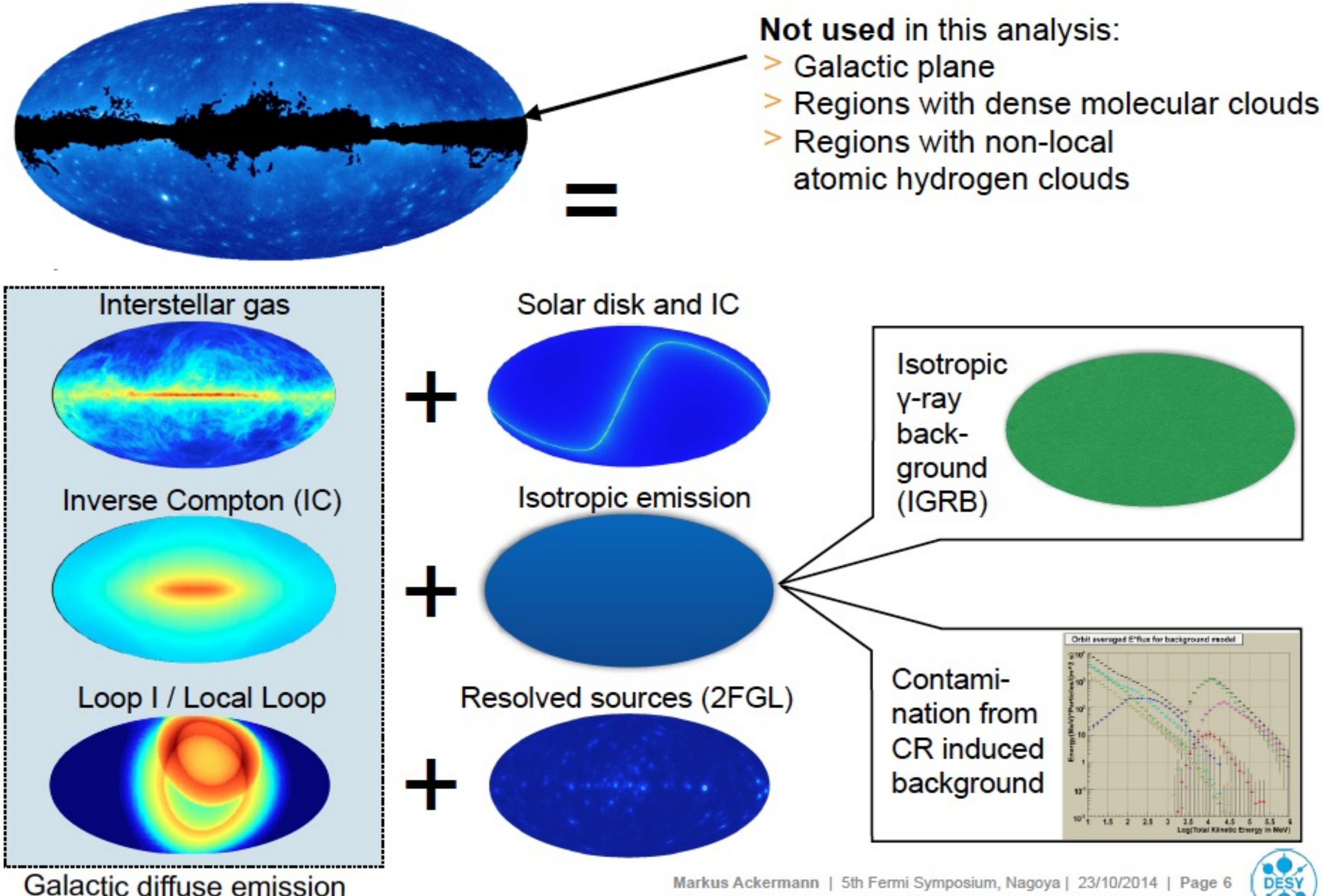
•A.Neronov, D.S. and O.Kalashev, 2112.0820

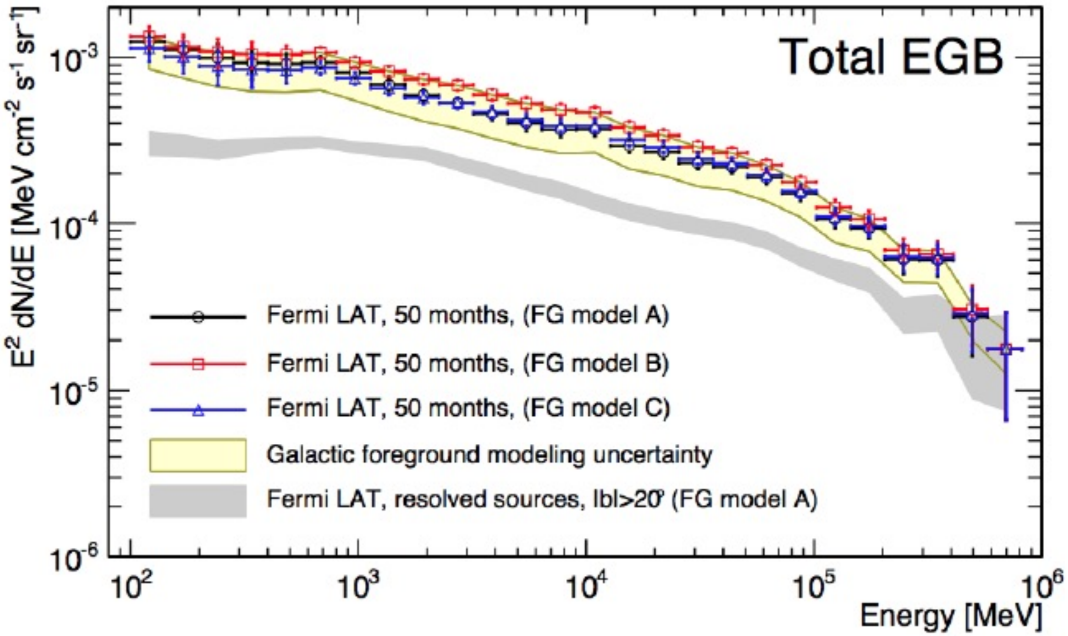
Summary

- *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

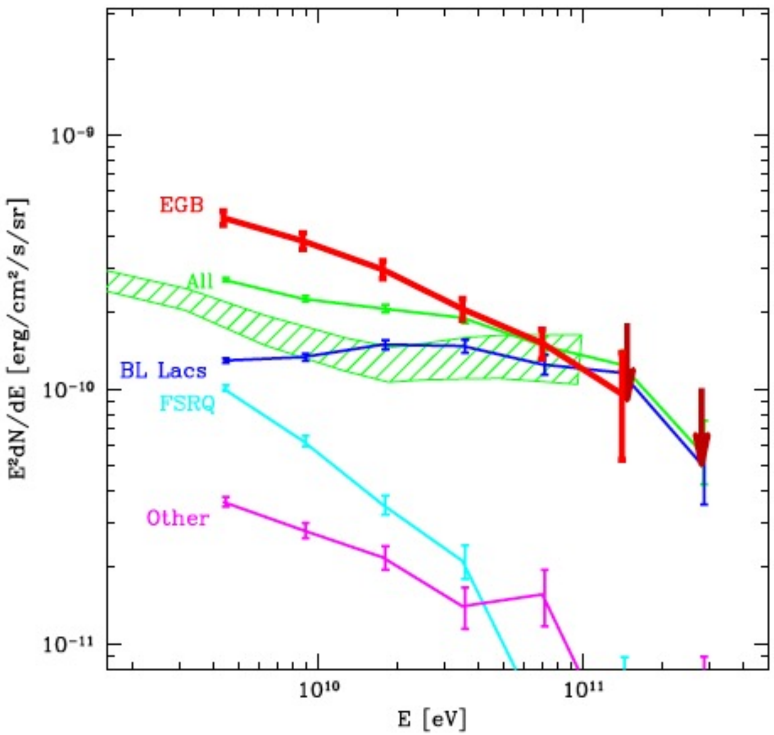
Derivation of the isotropic gamma-ray background

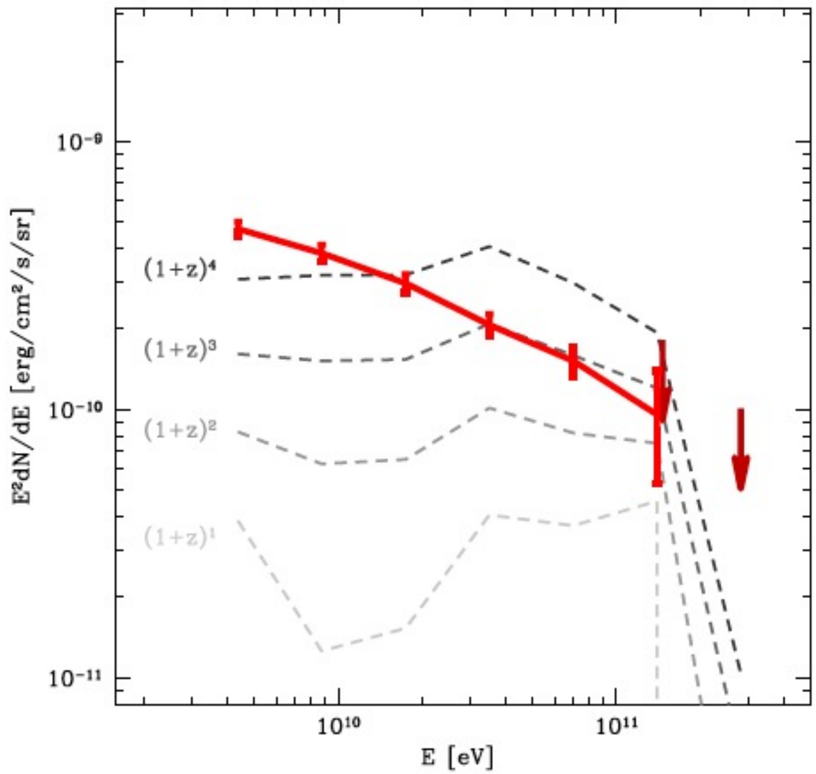




- **Sum of the intensities** of IGRB and the resolved high-latitude sources.
- Contribution of high-latitude Galactic sources **<< 5%.**
- Spectrum can be parametrized by **power-law with exponential cutoff**.
- Spectral index **~ 2.3**, cutoff energy **~ 350 GeV.**

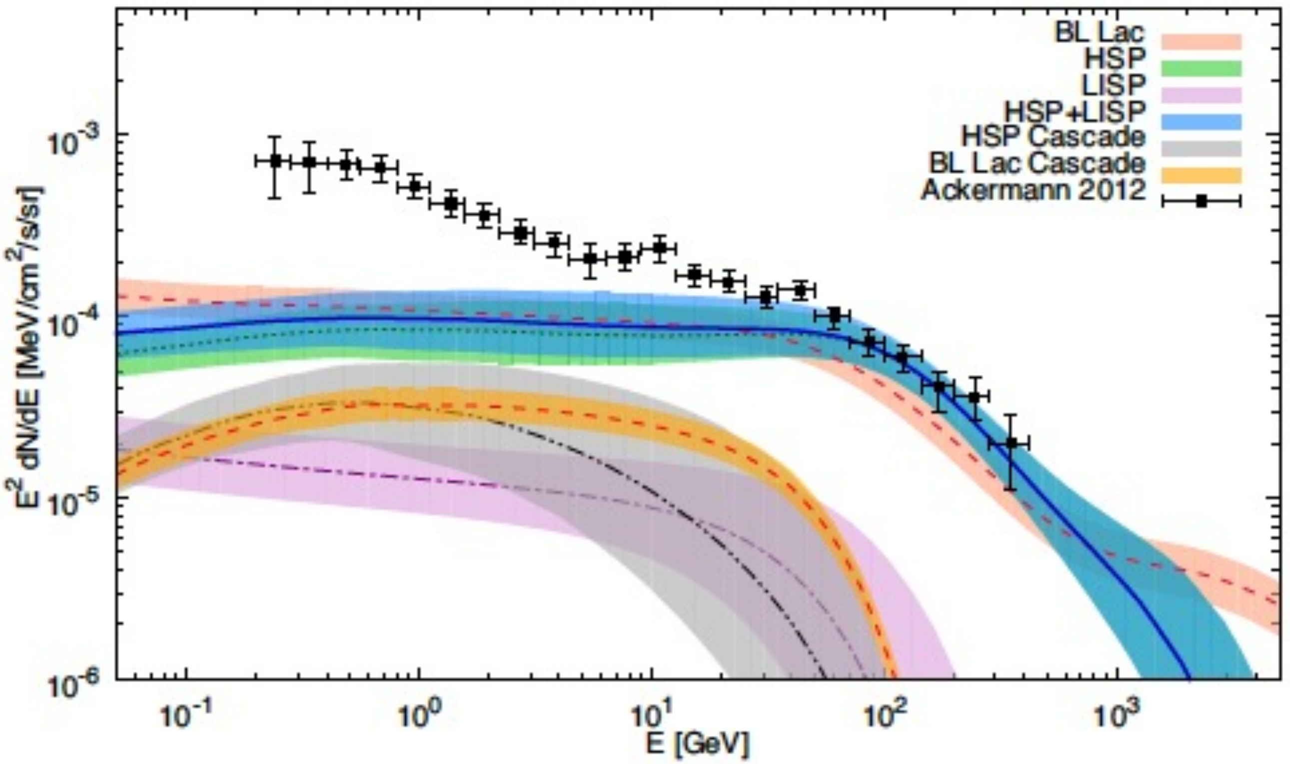
BL Lacs give main contribution to diffuse gamma-ray flux





A.Neronov, D.S. Astrophys.J. 757 (2012) 61

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



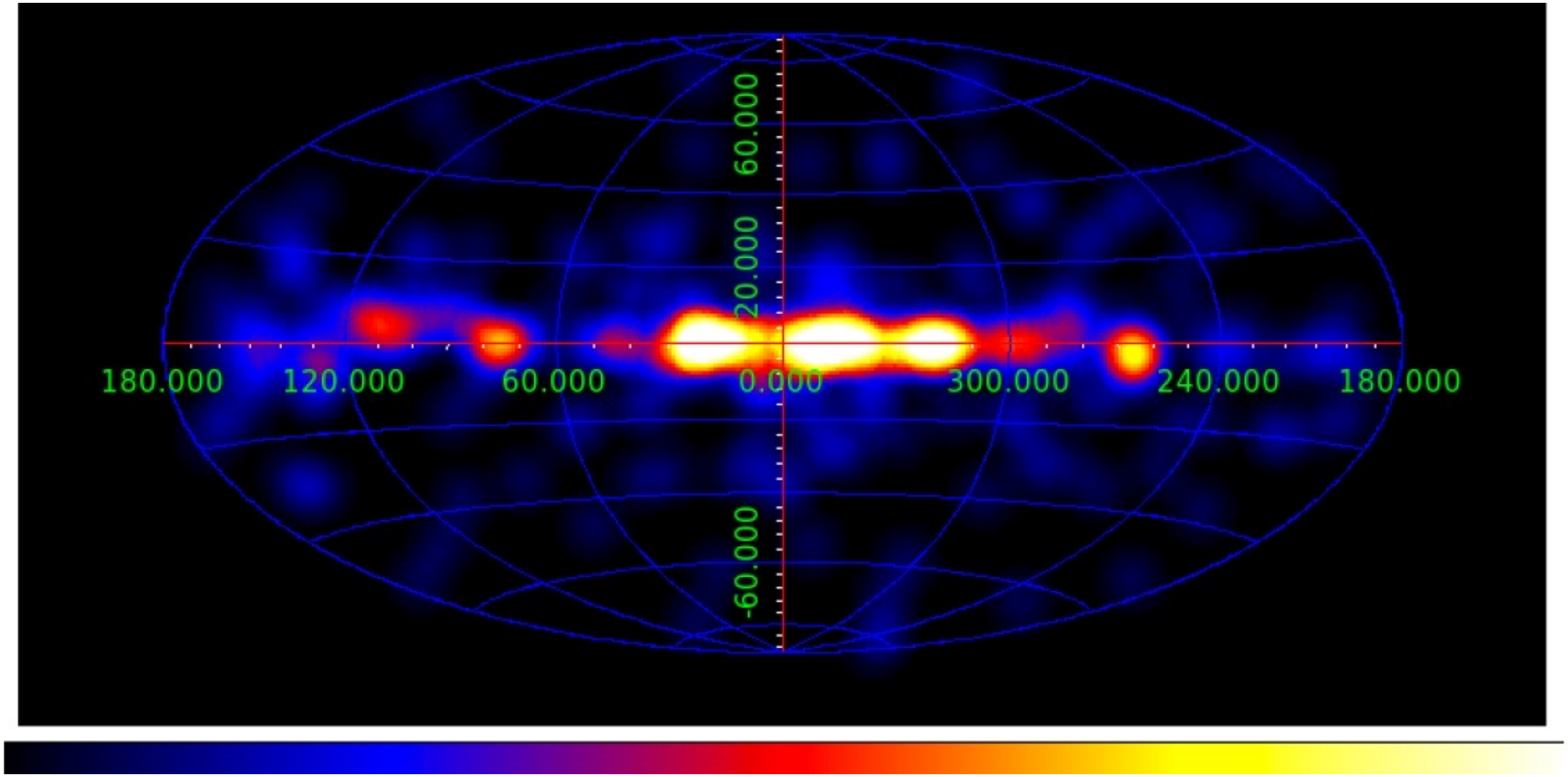
•M. Di Mauro et al, arXiv:1311.5708

Fermi confirmed resolution of BL Lac sources above 50 GeV

cm^{-2} 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 $[8 \times 10^{-12}, 1.5 \times 10^{-11}]$ ph cm^{-2} 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 γ-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

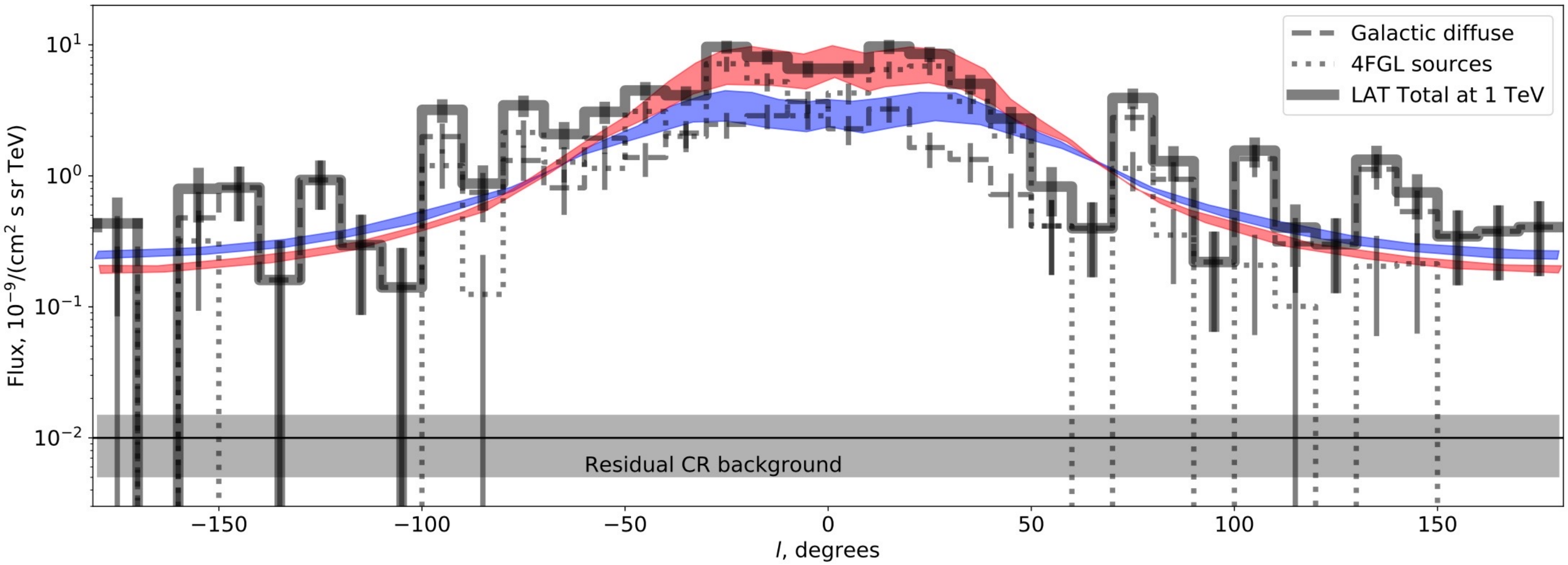
- **Fermi collaboration, arXiv:1511.00693**

Sky map E> 1TeV
10 years Fermi



- A.Neronov and D.S. , 1907.06061

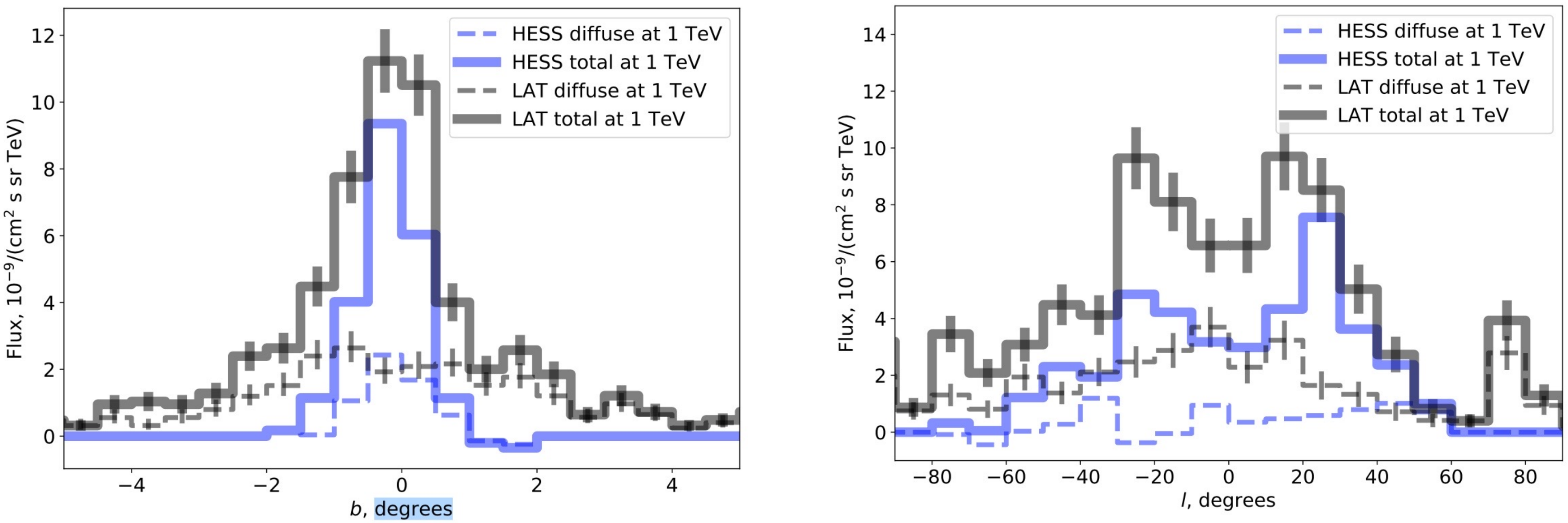
Galactic Plane |b|<2 deg, 1 TeV



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

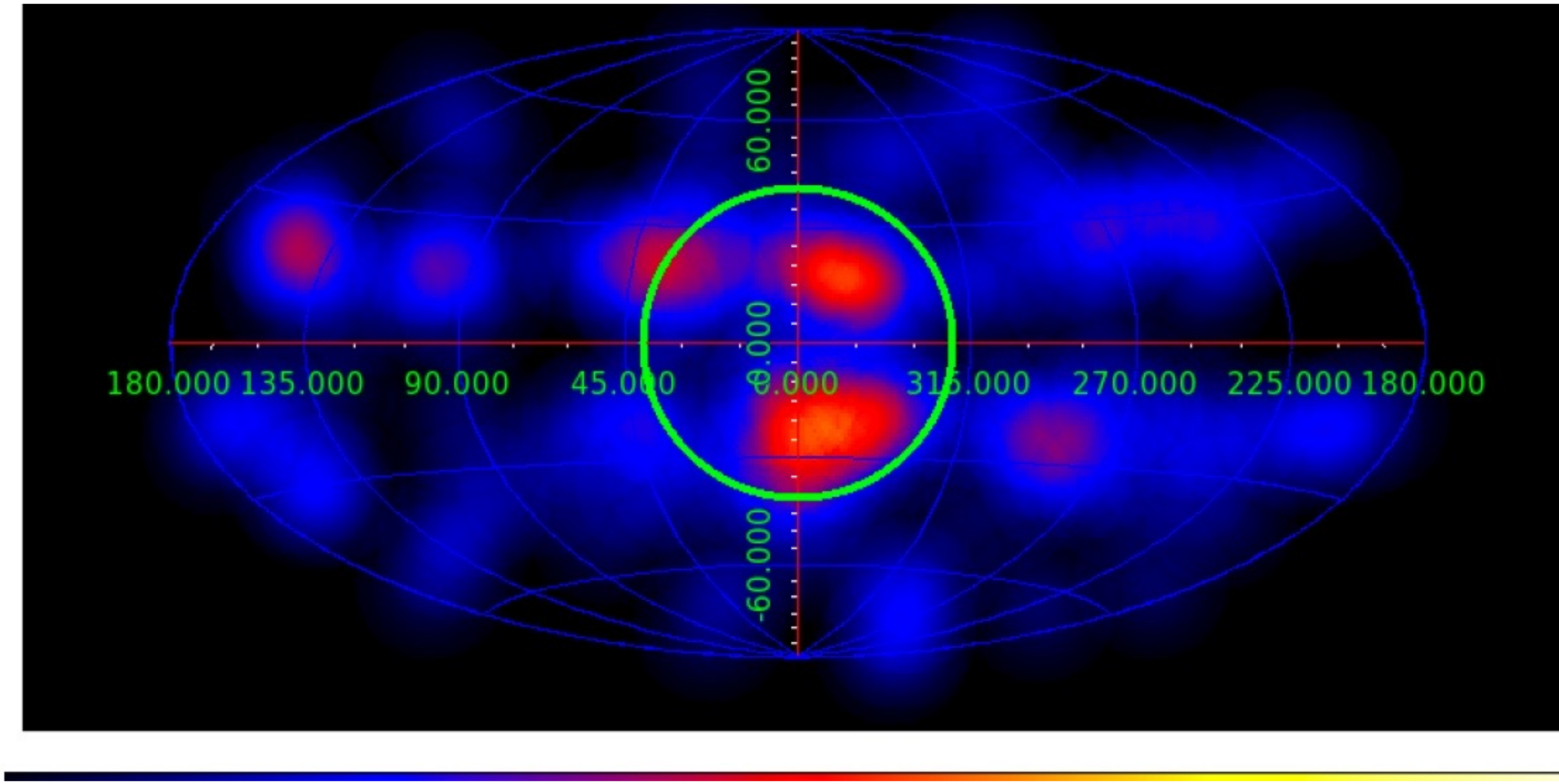
- A.Neronov and D.S. , 1907.06061

Galactic Plane, Fermi and HESS



- A.Neronov and D.S. , 1907.06061

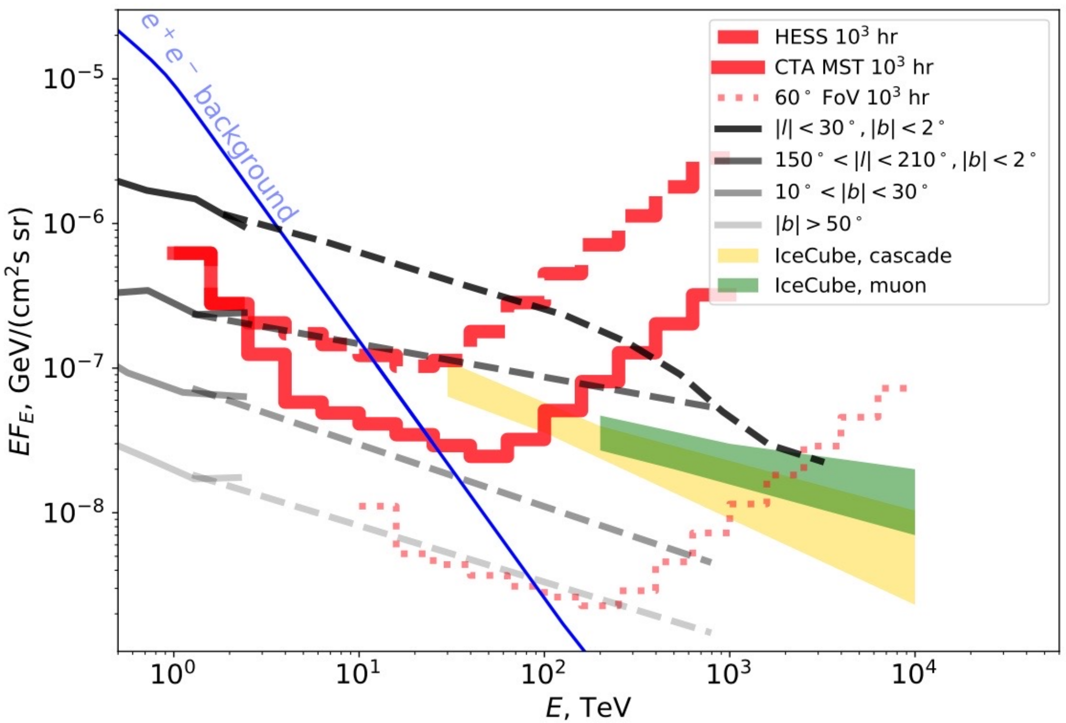
Sky map 1TeV no galactic plane |b|> 10 deg



•A.Neronov and D.S. , 1907.06061

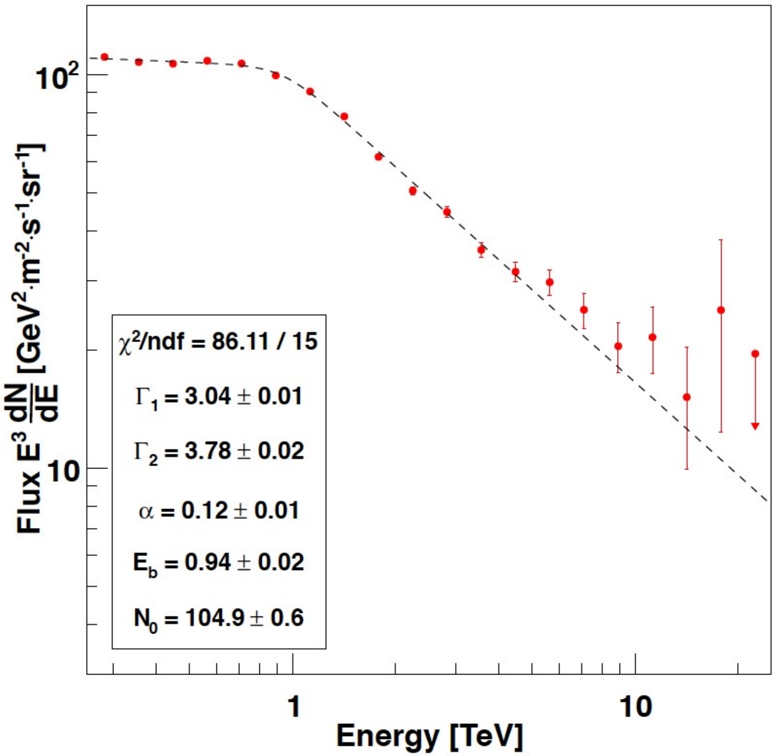
Gamma-ray sky at 10-100 TeV with Cherenkov telescopes

Galactic diffuse flux at 10-100 TeV energies with Cherenkov



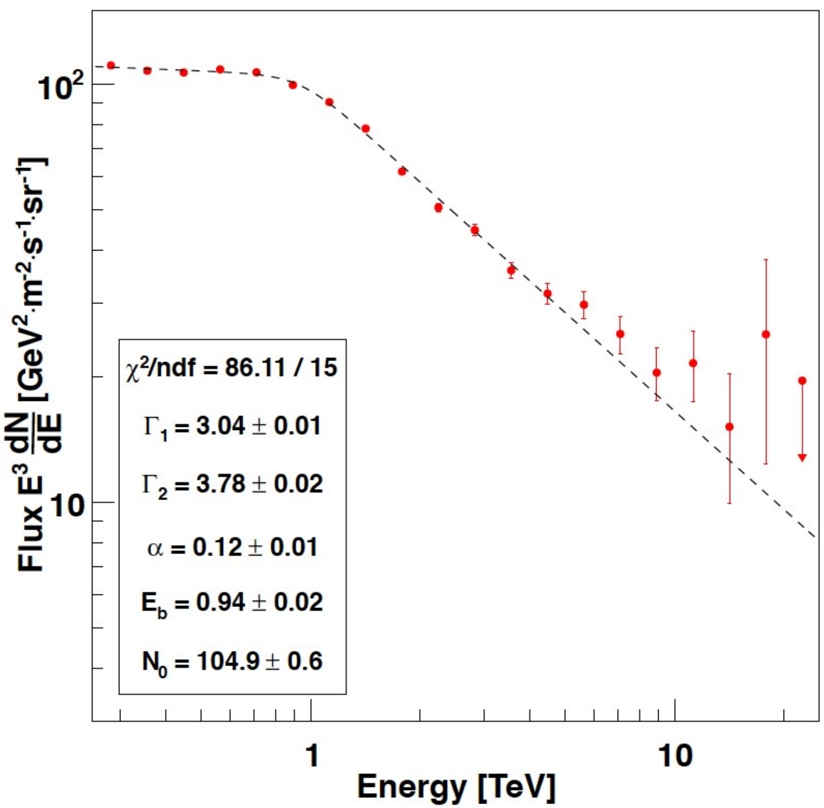
•A.Neronov and D.S. , astro-ph/2001.00922

Electron + positron measurements by HESS 2004- March 2010



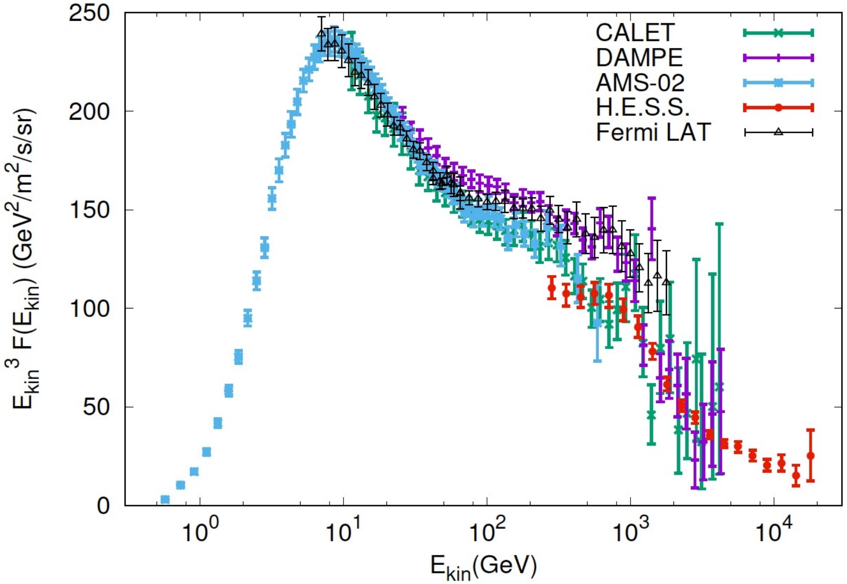
•HESS collab. 2017

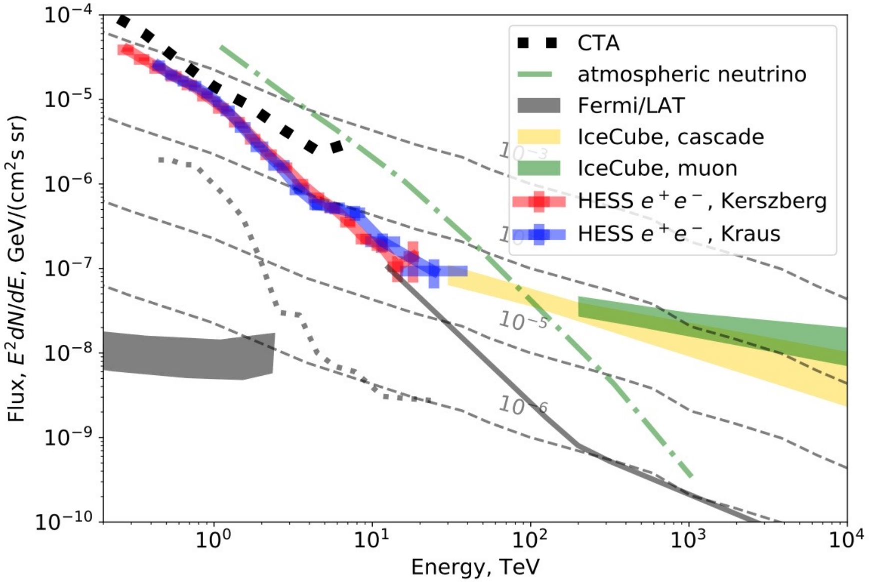
Electron+ positron+ diffuse gamma measurements by HESS 2004- March 2010



•HESS collab. 2017

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

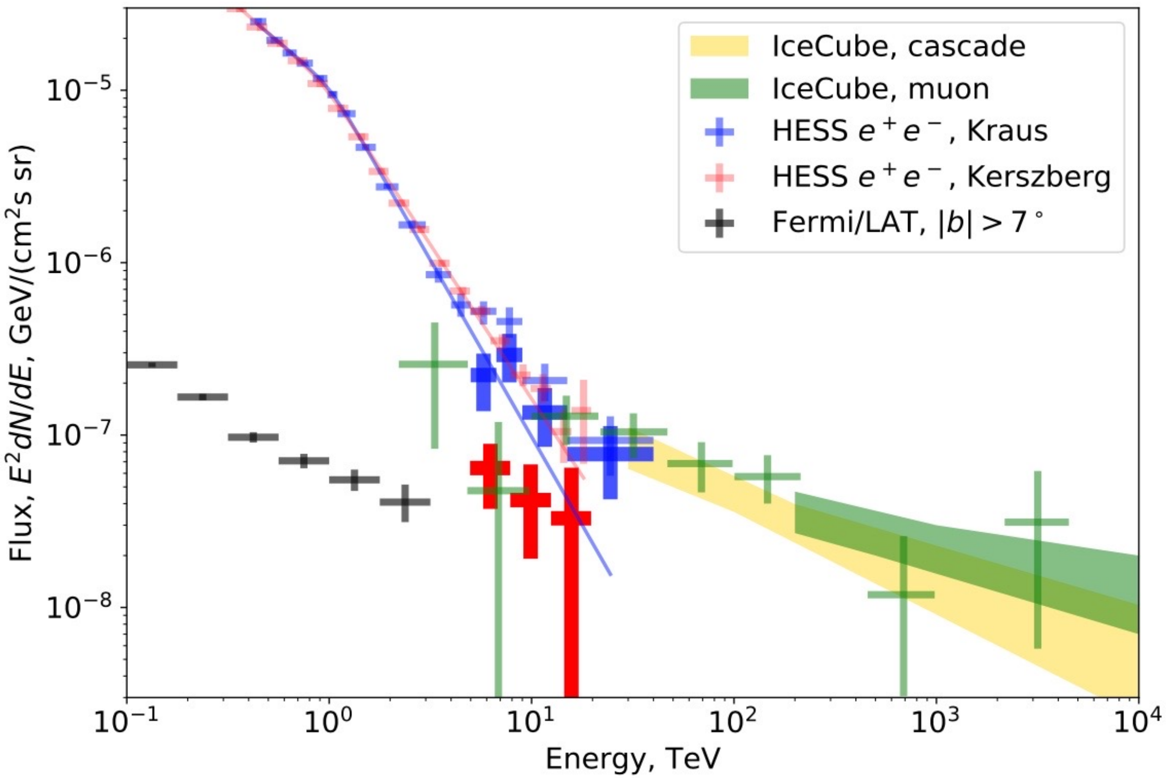




- M.Kachelriess and D.S.,
- Cosmic ray models,
- review astro-ph/1904.08160

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

New component in HESS data

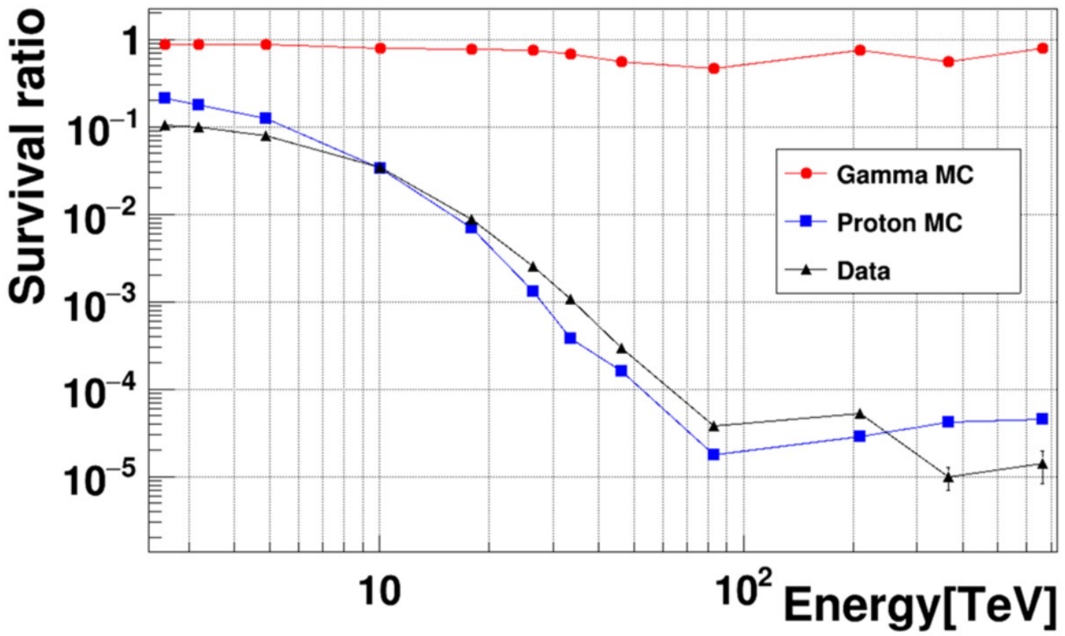


•A.Neronov and D.S. , astro-ph/2001.00922

Gamma-ray sky at E>100 TeV with HAWC and LHAASO

γ/P discrimination of ¼ KM2A

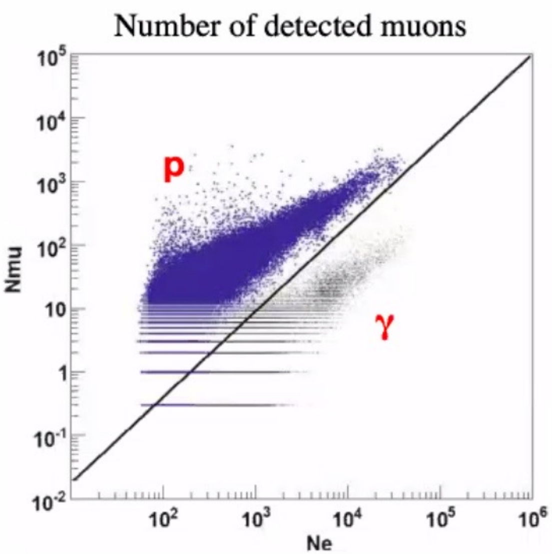
Background rejection >10^4@100 TeV

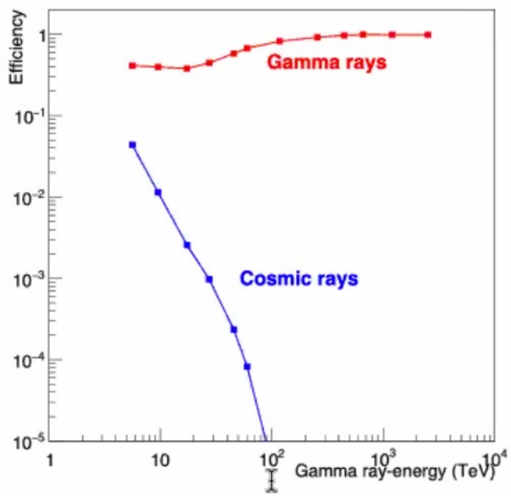


• LHAASO meeting Jan 2020

KM2A performance - 3

S. Cui et al. / Astroparticle Physics 54 (2014) 86–92

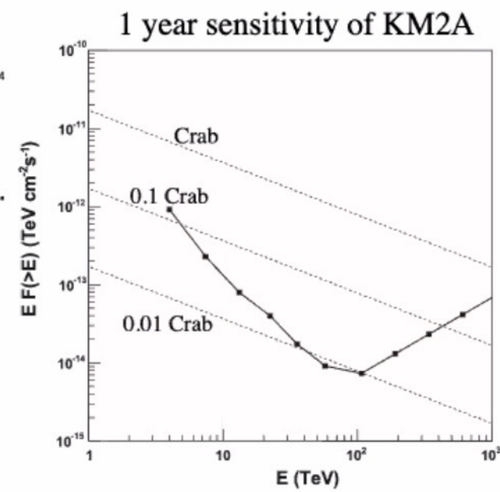




Fraction of surviving gamma and p-induced events after the selection cut.

The large area of the MD array of KM2A allow *rejection of cosmic ray background at a level of 10^{-5} at about 100 TeV*.

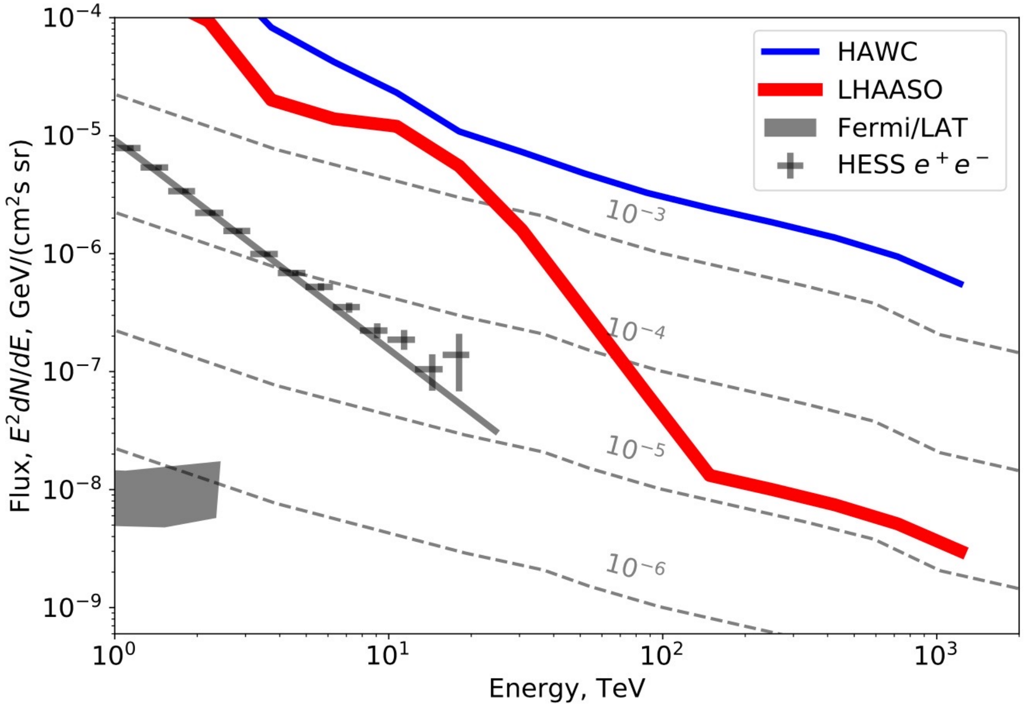
Above 100 TeV, in the *'back-ground free'* regime, 10 signal events are taken to measure the sensitivity of array.



At 50 TeV 1,700 events from Crab, expected

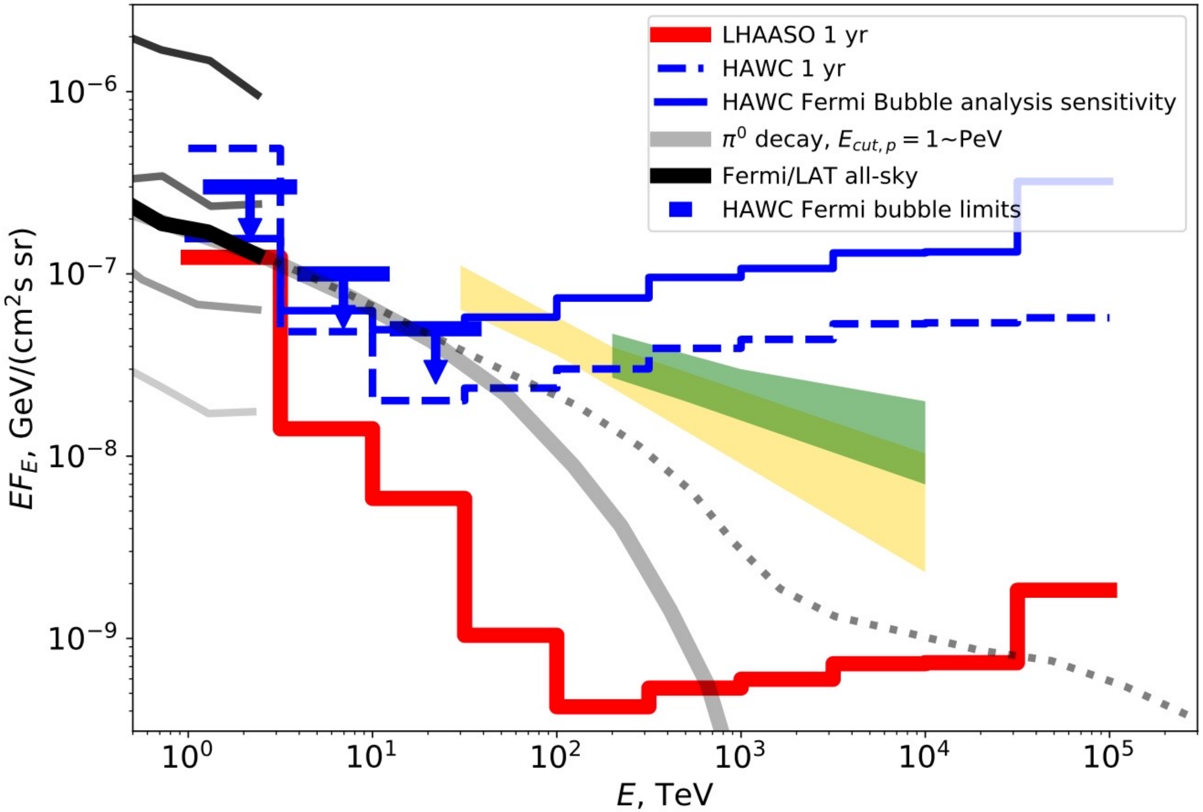
•LHAASO meeting Jan 2020

HAWC and LHAASO hadron cut



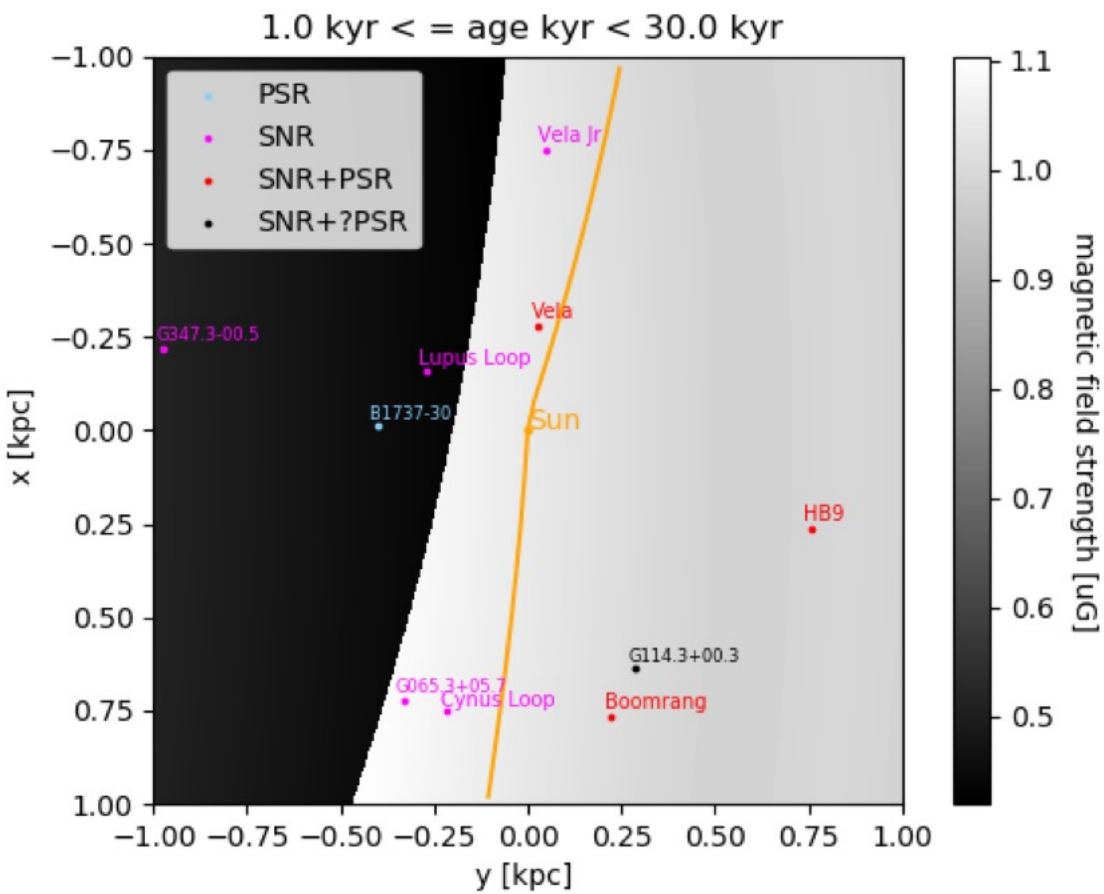
•A.Neronov and D.S. , astro-ph/2001.11881

HAWC and LHAASO sensitivity to diffuse gamma



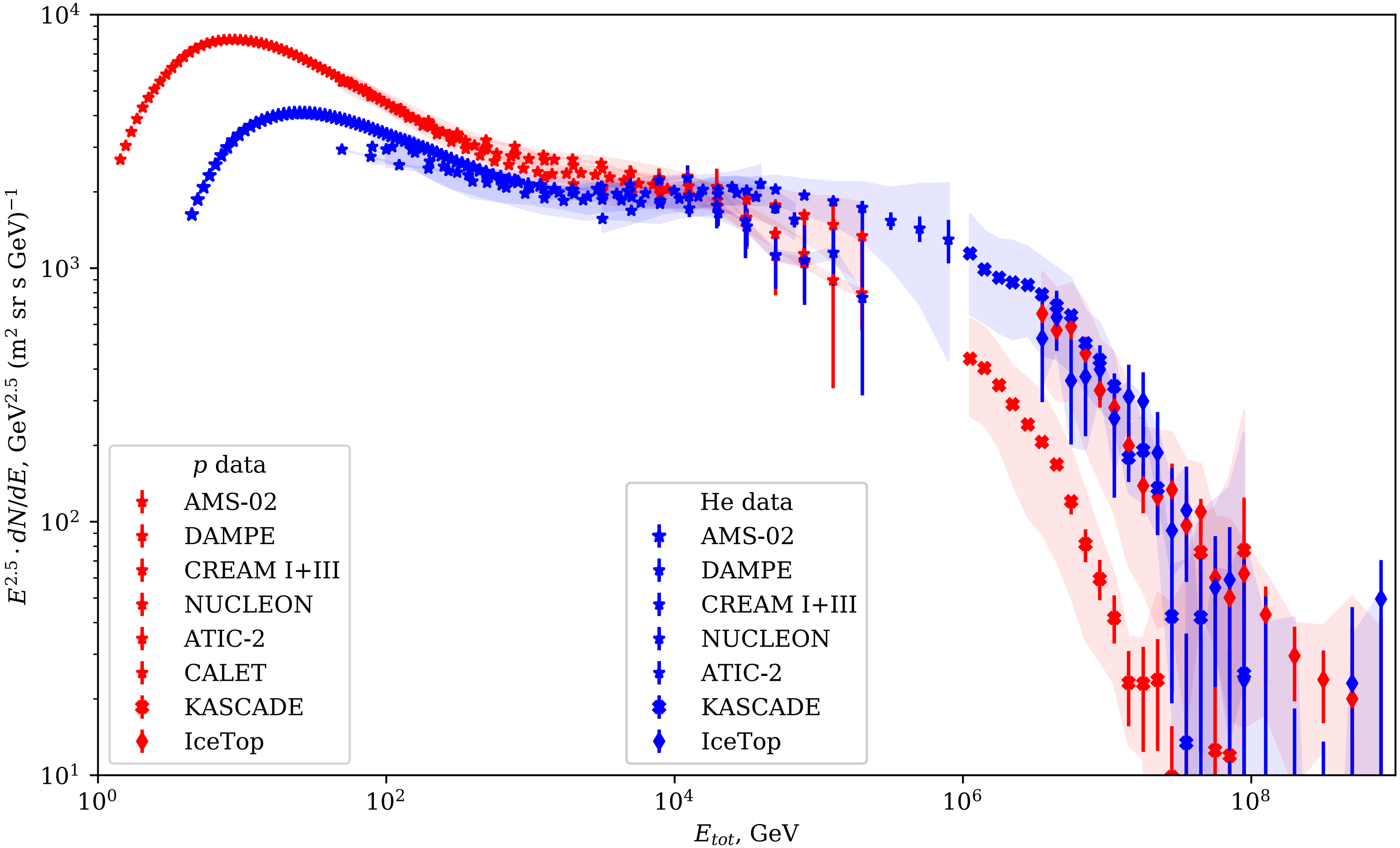
•A.Neronov and D.S. , astro-ph/2001.11881

Nearby young SN

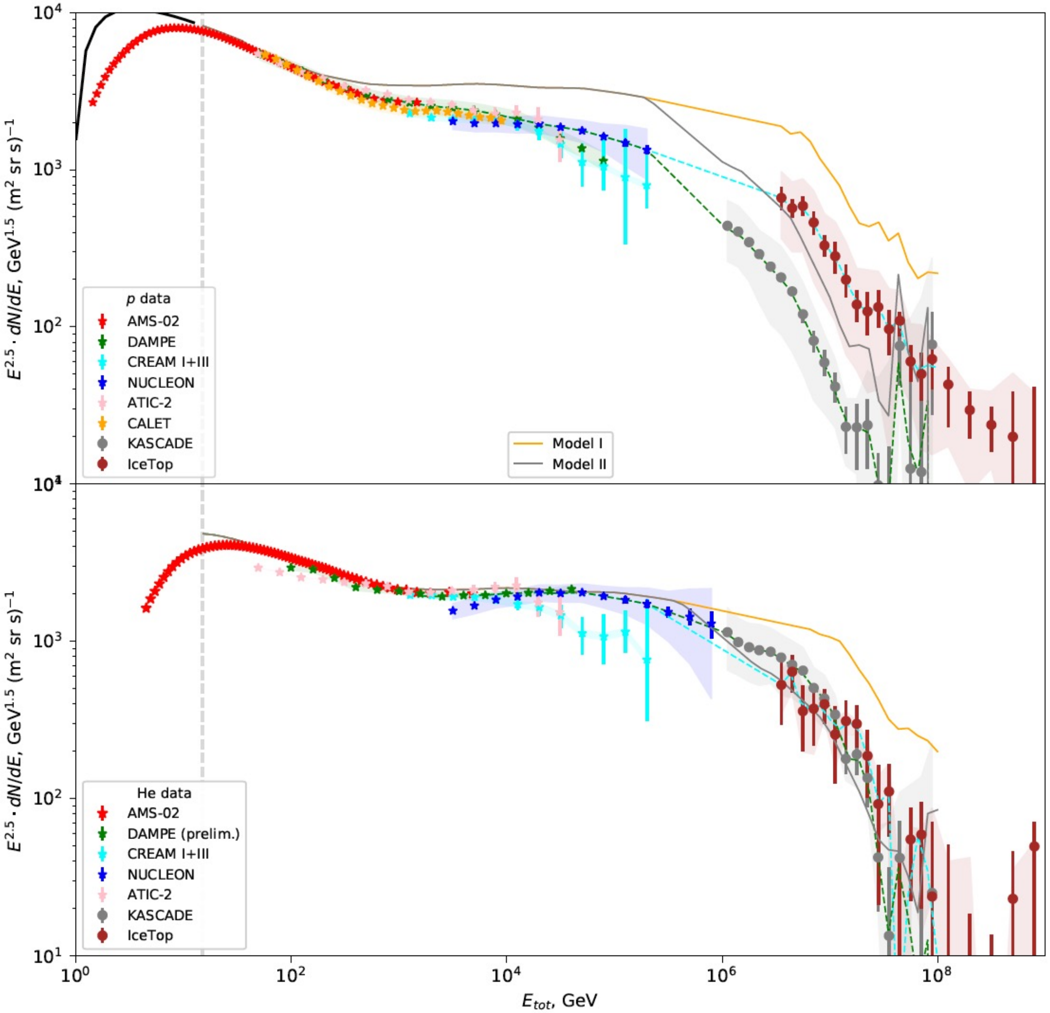


•M. Bouyahiaoui, M. Kachelriess, and. D.S. , astro-ph/2001.00768

Local cosmic ray flux

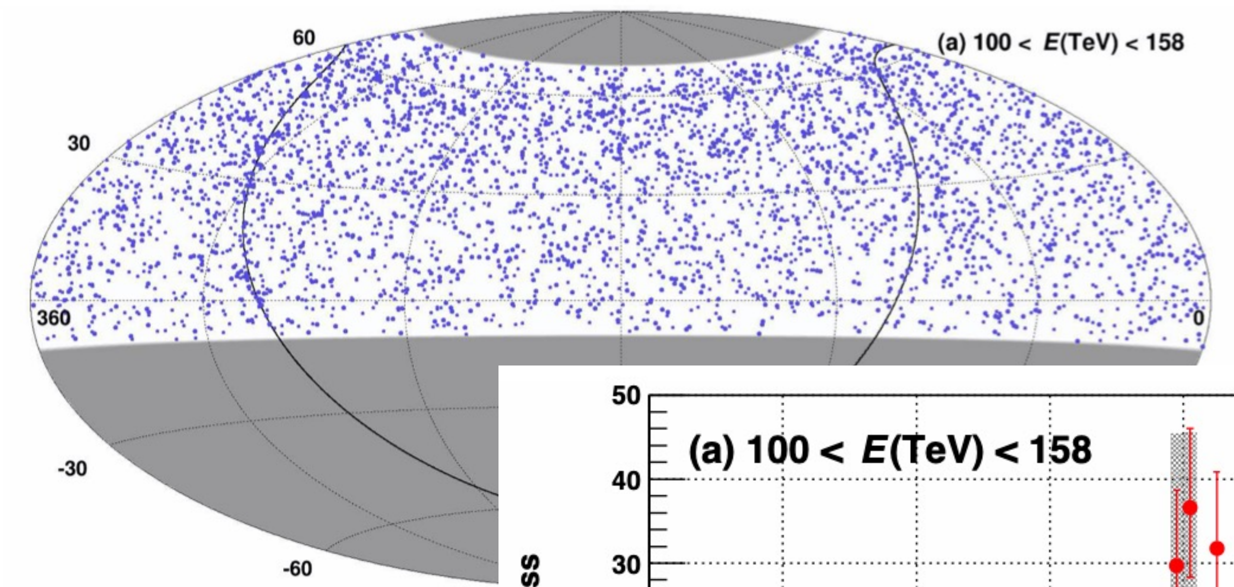


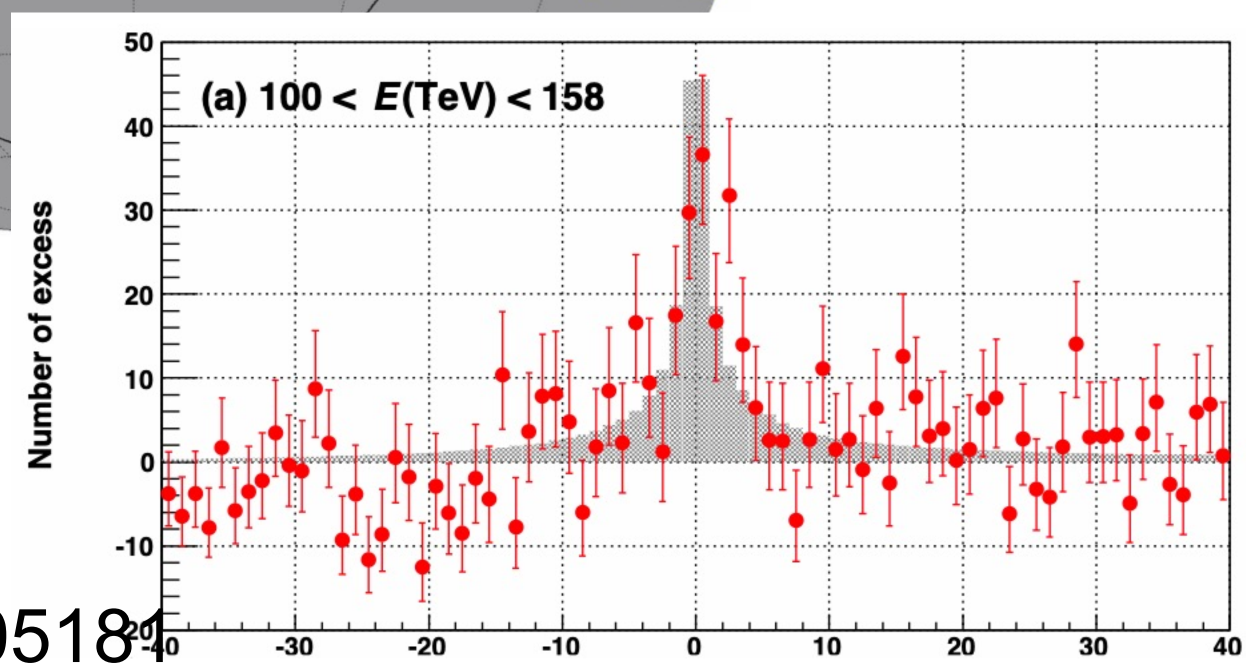
Cosmic ray flux models in outer Galaxy



•S.Koldobskiy, A.Neronov and D.S., arXiv:2105.00959

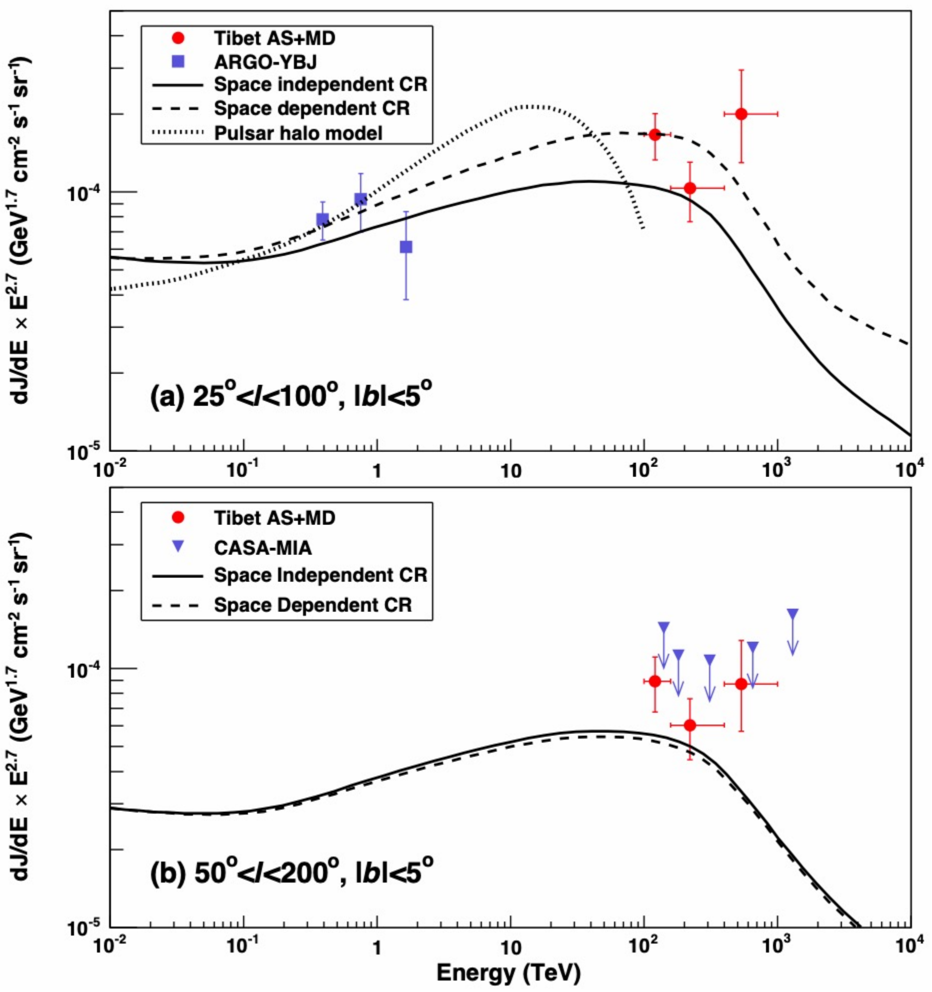
Tibet AS-g gamma-ray sky





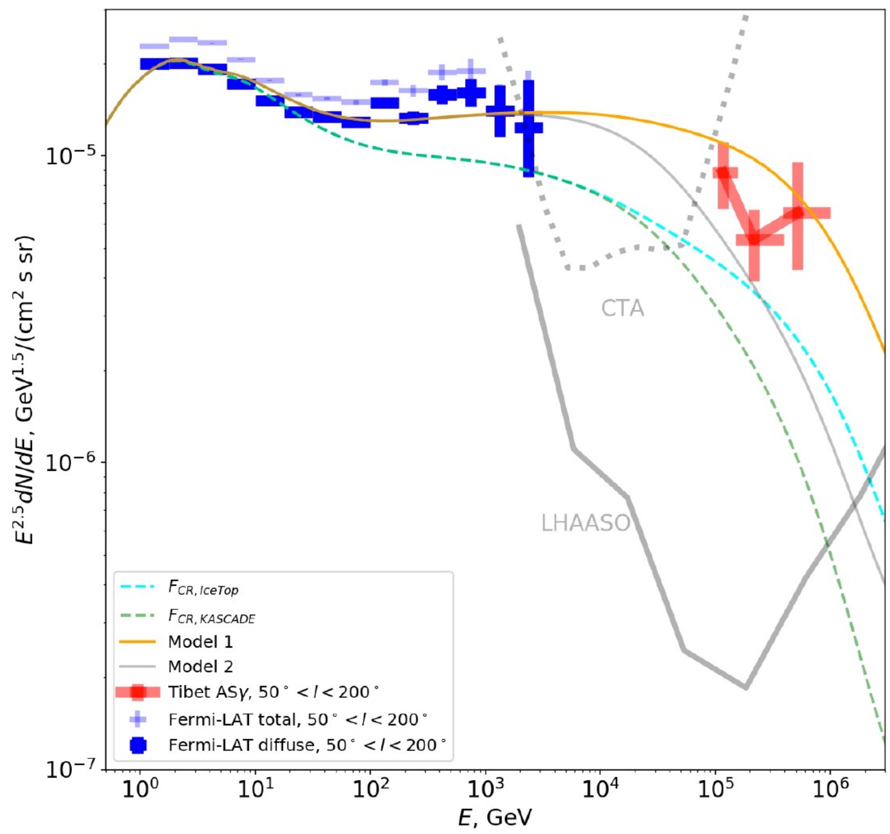
•arXiv:2104.05181

Tibet AS-g diffuse gamma-rays



• arXiv:2104.05181

Gamma-ray flux in outer Galaxy



- S.Koldobskiy, A.Neronov and D.S., arXiv:2105.00959

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

Summary

- *New detector LHAASO start operation and give 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*
- *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*