Gamma ray observations above 30 TeV with Lhaaso

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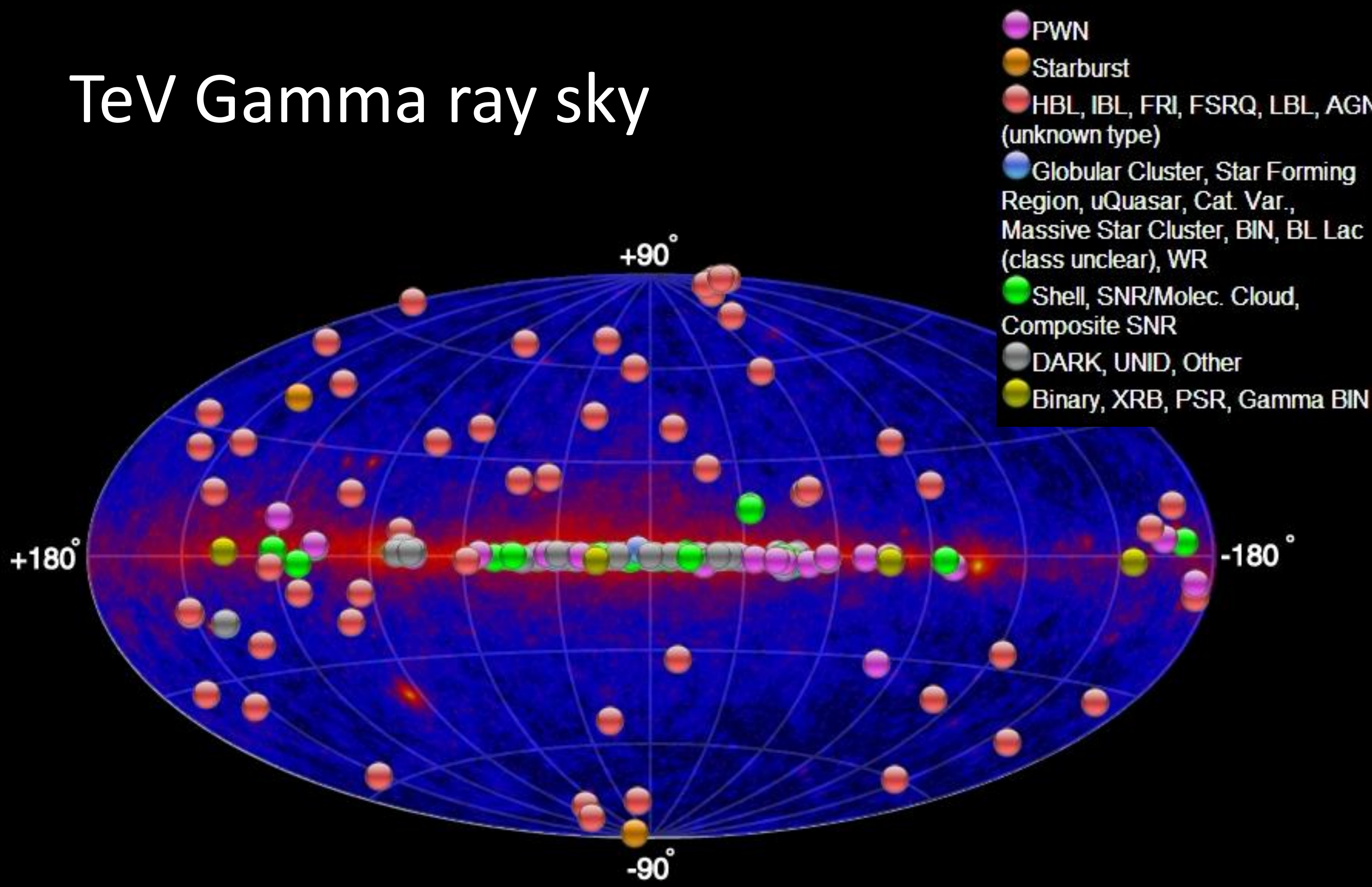
5° Workshop on Air shower detection at high altitude, 26-28 May 2014, Paris

TeV Gamma ray sky



~150 sources

Gamma ray astronomy above 30 TeV

State of the art

~ 150 sources observed above 1 TeV

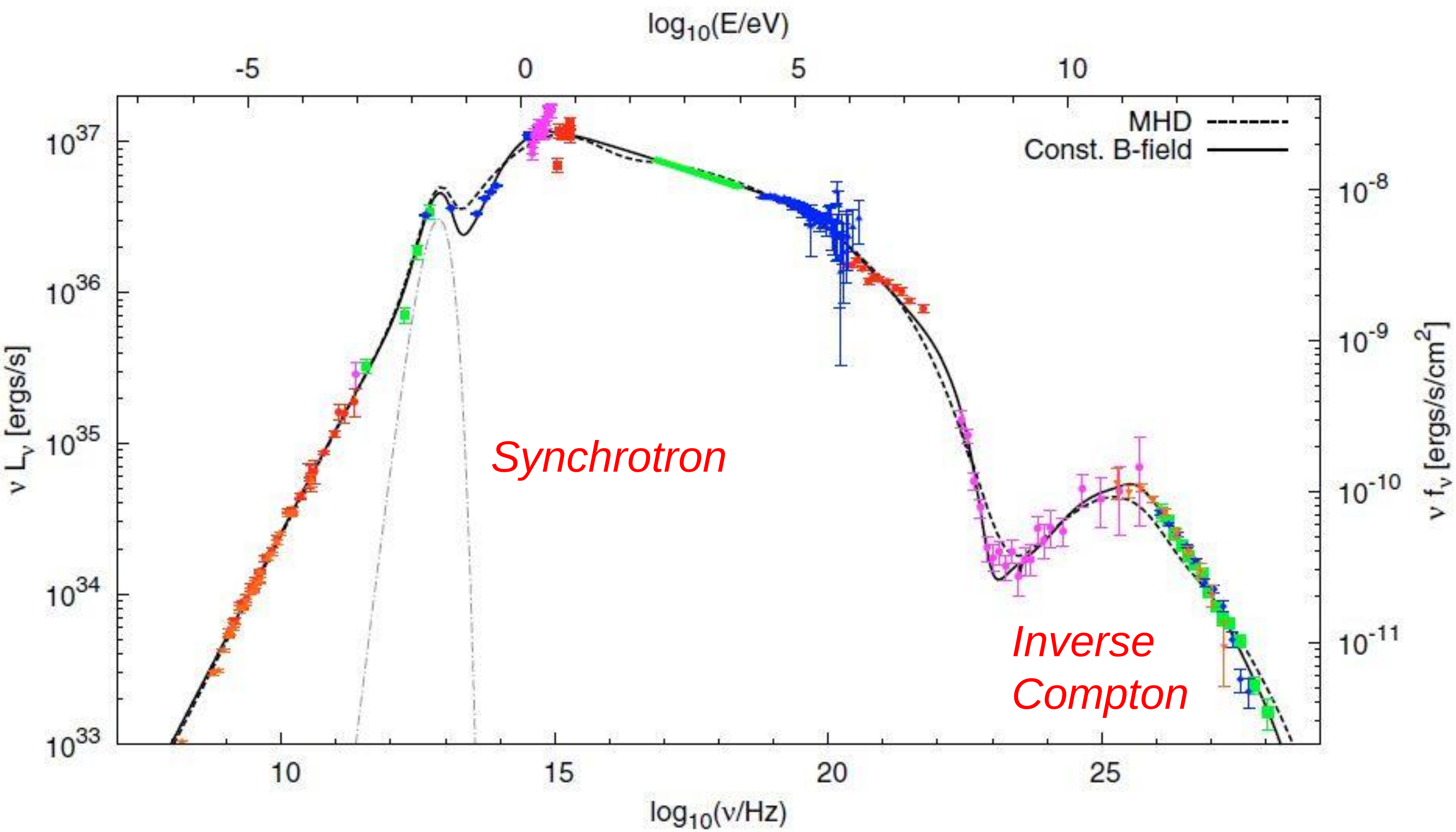
< 10 sources observed above 30 TeV:

- *Crab Nebula*
- *VELA -X*
- *MGRO J2031+41*
- *MGRO J2019+37*
- *MGRO J1908+06*
- *SNR RX J1713.7-3946*

....

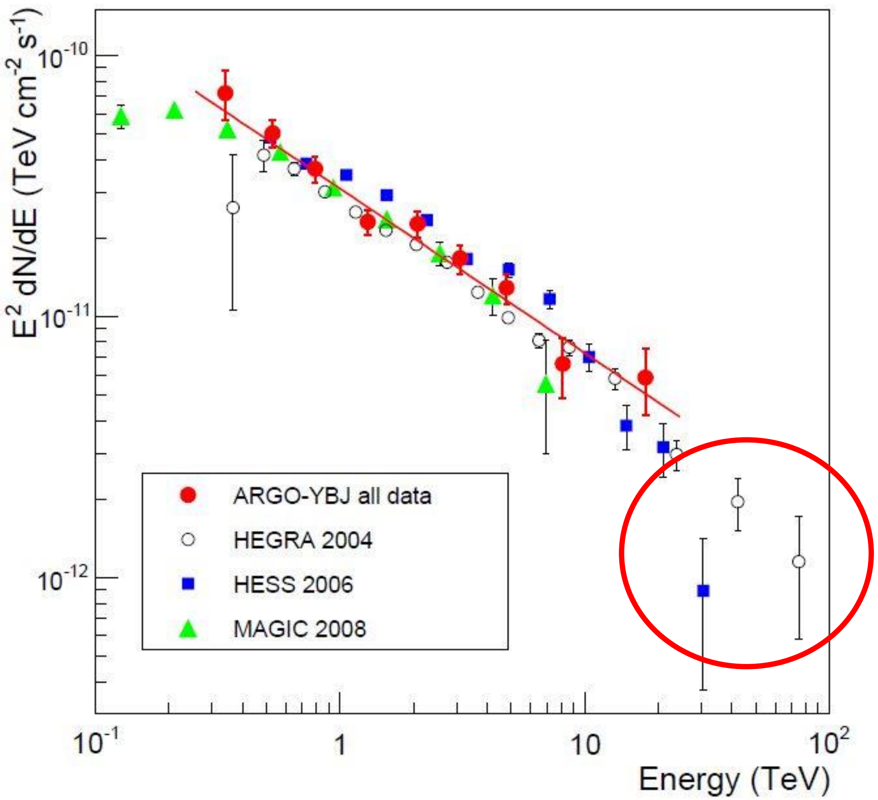
No photons detected above 100 TeV

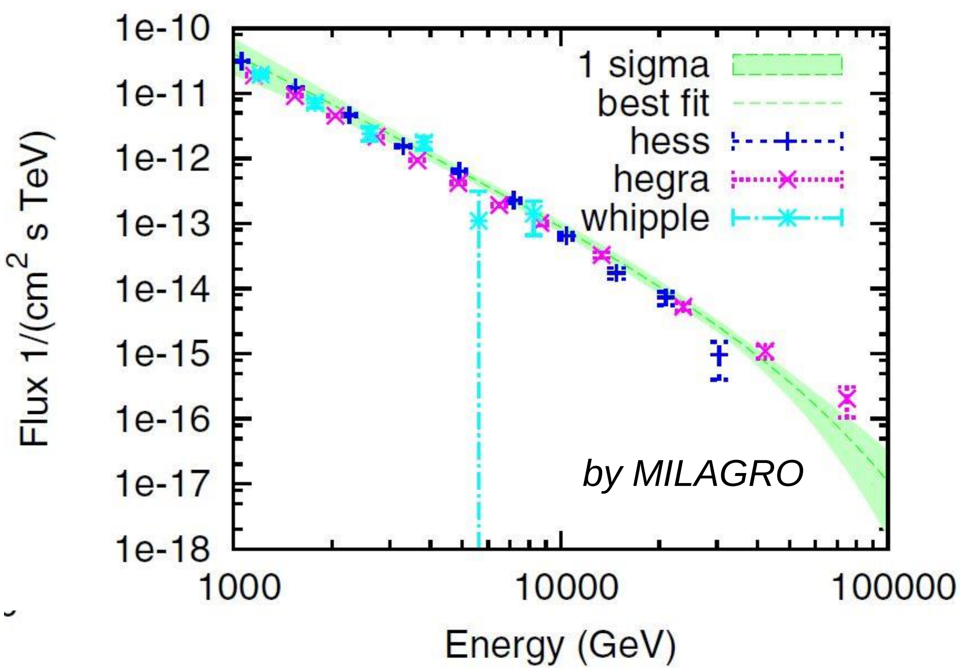
Crab Nebula - multiwavelenght SED



- *Leptonic emission*
- *Electron energy up to 10^{15} eV*

TeV Crab Nebula data



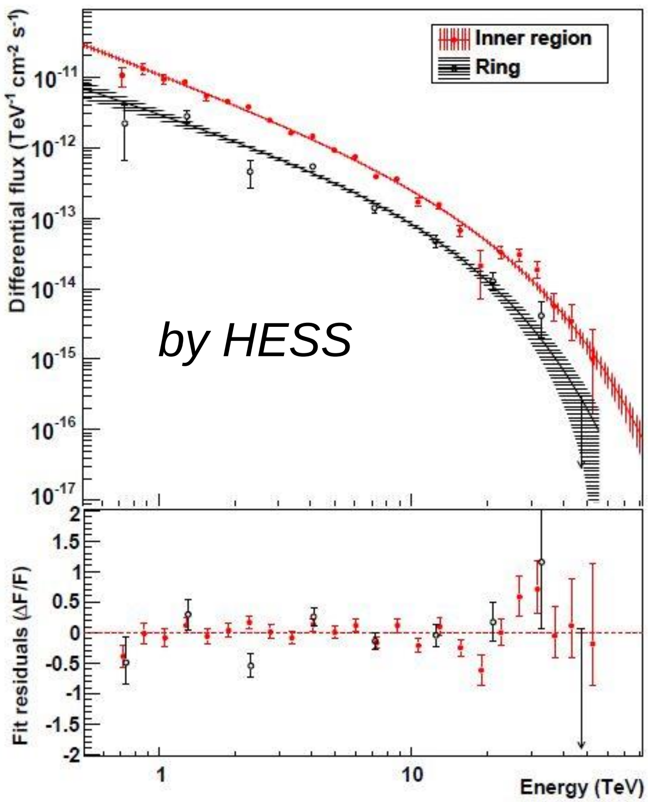


Above 30 TeV: few data and large error bars

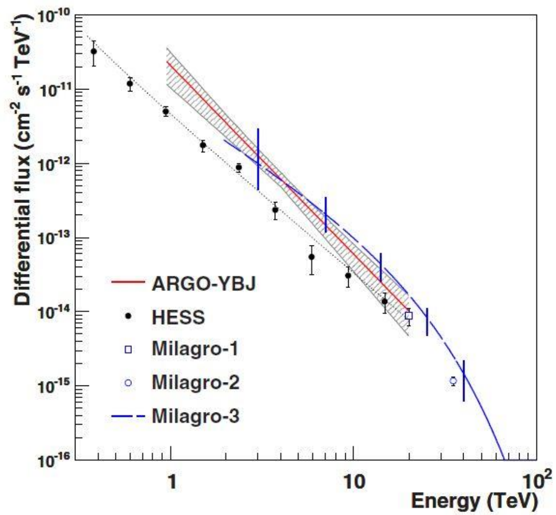
GeV Flares observed → IC component above 10 TeV ?

Other Pulsar Wind Nebulae...

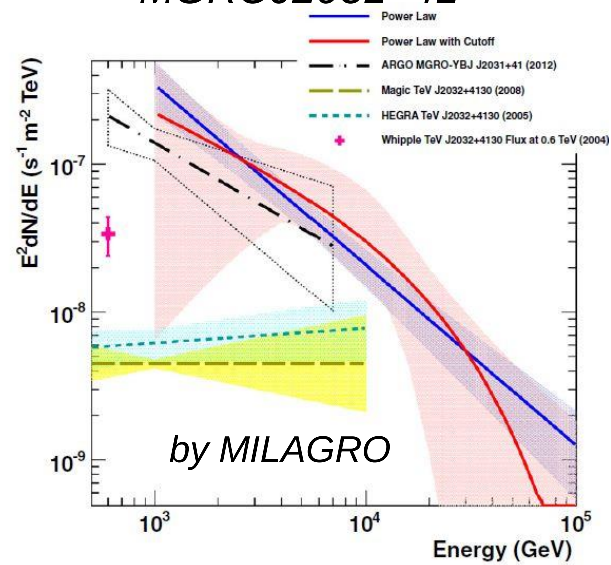
VELA -X

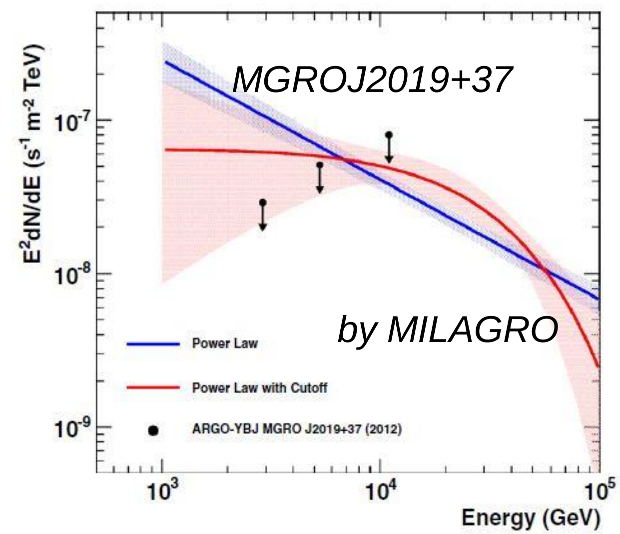


MGROJ1908+06



MGROJ2031+41

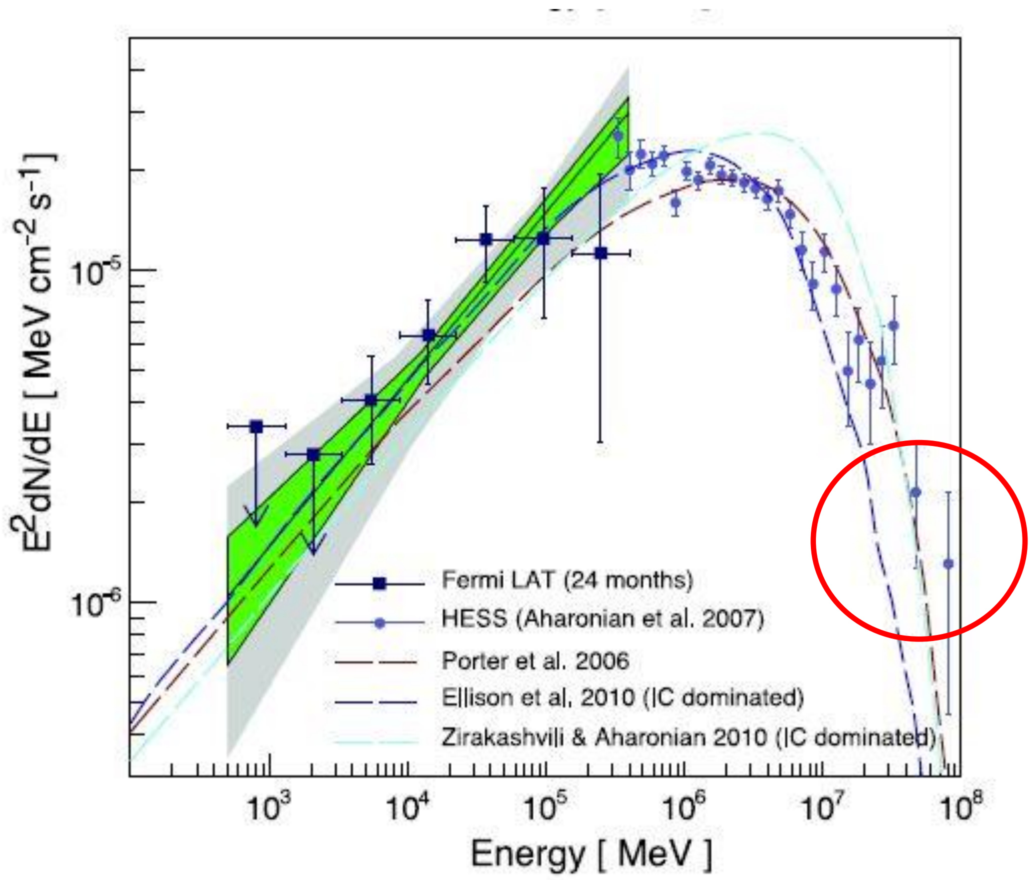




Data above 30 TeV are very scarce

An other example: SNR RX J1713.7-3946

the only SNR data above 30 TeV



The measurement of SNR spectrum above 30 TeV is very important !

Why data above 30 TeV are important

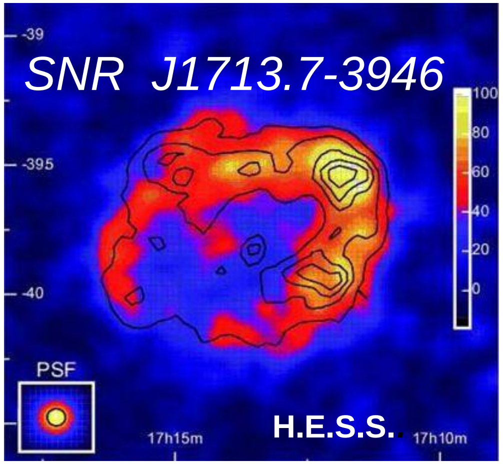
Searching for cosmic ray sources

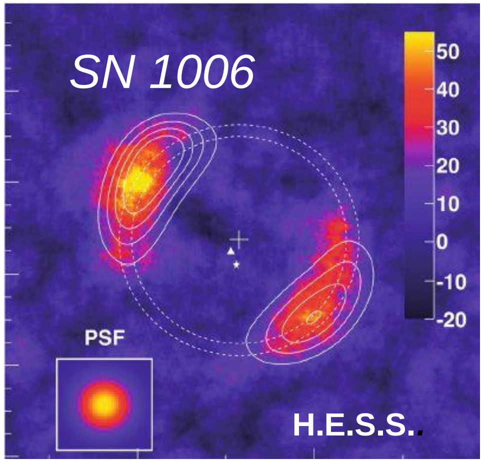
- It is generally believed that cosmic rays of energy at least to the knee (~3 10^{15} eV) are accelerated in our Galaxy
- SNRs are the favorite sites for the acceleration of Galactic cosmic rays
    - SN explosions could supply the total energy of Galactic c.r. if one assume that 10% of the SN kinetic energy is converted into c.r. motion
    - Diffusive Shock Acceleration (DSA) mechanism in young (< few 10^3 years) expanding SN shells can generate a power law spectrum of relativistic particles

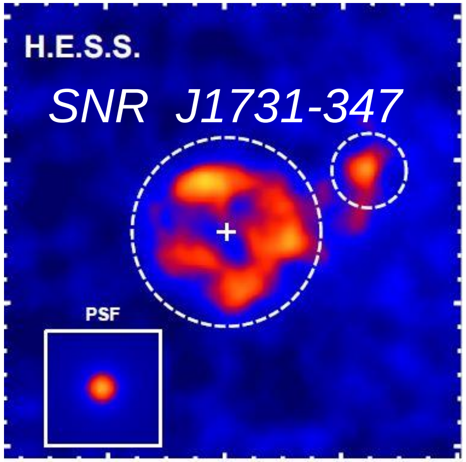
Searching for cosmic ray sources

- Gamma rays up to a few TeV have been observed from ~10 SNRs
- The emission regions matches well the expanding shells or Molecular Clouds nearby

➡ Particles are effectively accelerated in the SNR shocks







Searching for cosmic ray sources

BUT

- The relative contribution of protons and electrons to the observed flux is still unclear

- In a few cases, the «hadronic footprint» has been probably observed, but the proton energy doesn't seem to reach the cosmic ray knee

→ Gamma astronomy above 30 TeV could give the definitive answer of the question whether the SNRs are the long sought *Pevatrons*

TeV gamma ray emission

Leptonic emission

- Inverse Compton scattering of electrons on low energy photons:
  - Cosmic Microwave Background (CMB)
  - Infrared, optical photons
  - Synchrotron photons
  - .....

- Bremsstrahlung

Hadronic emission

- π^0 decay from proton/nuclei interactions with the ambient nuclei

Inverse Compton scattering

1) Thomson regime

$E_e \, \varepsilon \ll 4 \, m_e^2$ (ε = seed photon energy)

Costant cross section: Thomson cross section)

Electron spectrum $E^{-\alpha}$ $\longrightarrow$ Gamma ray spectrum $E^{-\beta}$, $\beta = (\alpha + 1)/2$

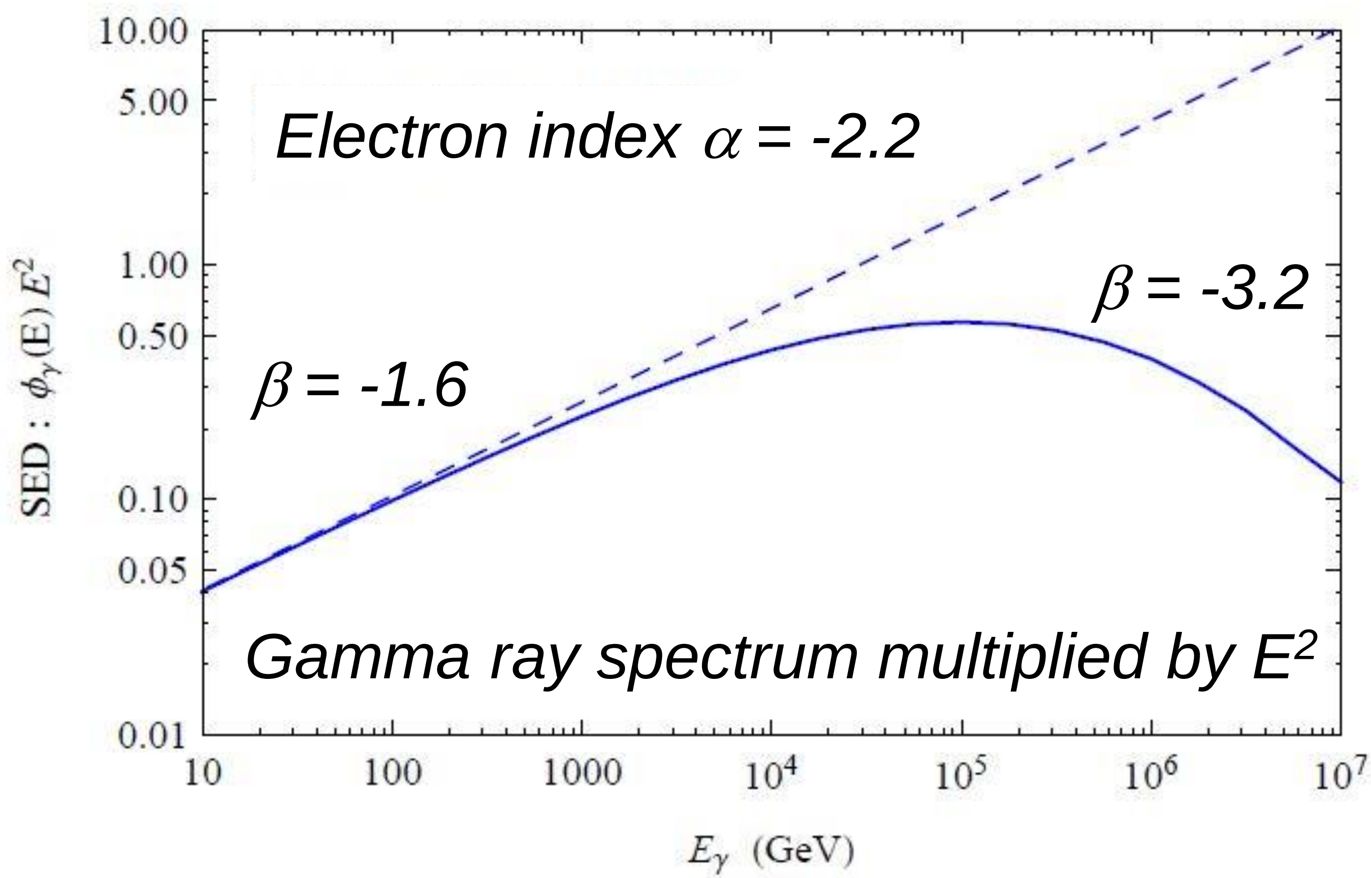
2) Klein-Nishina regime

The cross section decreases

Photon index $\beta = \alpha + 1$

In case of CMB seed photons, the KN regime starts below 100 TeV

Inverse Compton scattering on CMB



The steepening begins below 100 TeV

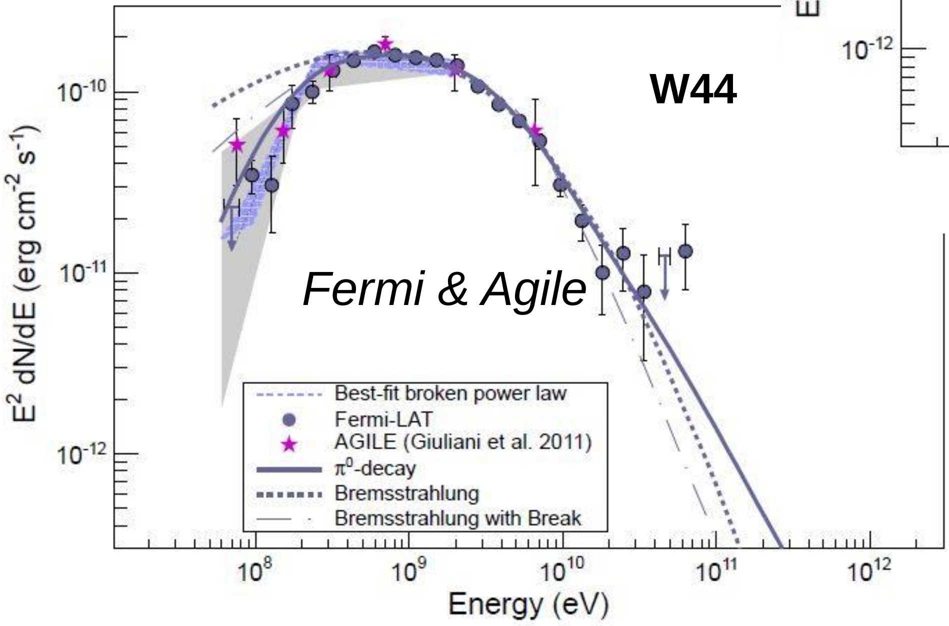
Hadronic interactions

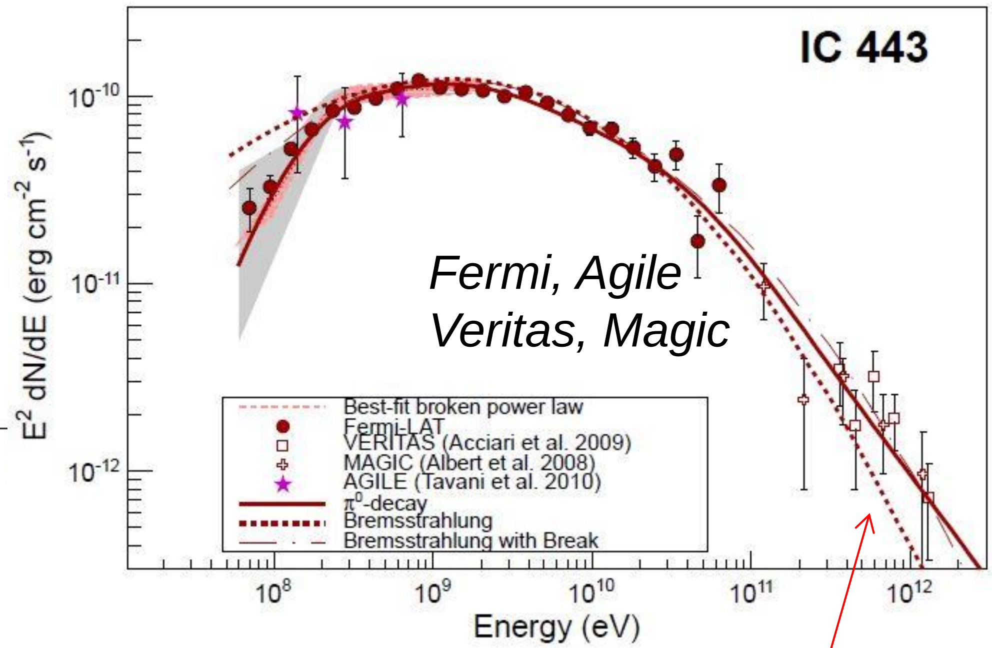
p p $\longrightarrow$ π^0 + other particles $\qquad$ π^0 $\longrightarrow$ **2** γ

- The gamma ray spectrum is simmetric around $m_\pi/2$ = 67.5 MeV in a log-log scale (π^0 bump)
- Above a few GeV has the same slope of the parents protons
- There is no suppression at high energy as IC, unless the parent proton spectrum has a cutoff
- The emission depends on the environment *gas density*
  In SNR the gas density can range from ~ 0.01 cm^{-3} up to ~1000 cm^{-3} in case of *Molecular Clouds*

Two observations of π^0 bumps

Gamma ray spectra multiplied by E^2

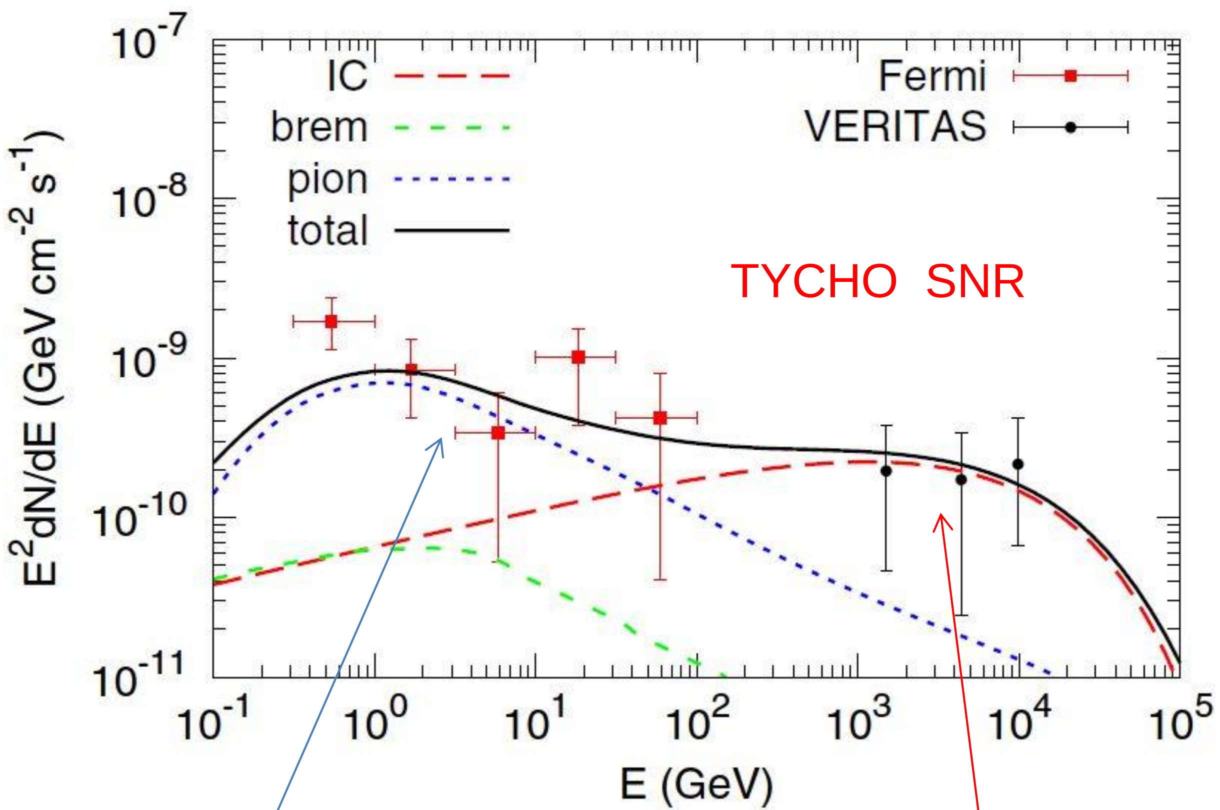




Hadrons are accelerated up to a few tens of TeV

Spectra are very soft !

Hadronic + leptonic



Yuan et al., 2013

Hadronic emission
π^0 decay

Leptonic emission
Electron Inverse Compton with a cutoff in the electron spectrum

Things are not simple...

Each SNR is individual and has a unique behaviour
In general one expects a combination of leptonic and hadronic emission

The relative contributions depend on:

- Ratio of the injected electrons and protons
- Electrons and protons spectra (Power law? Breaks ? Cutoff ?)
- Particle confinement, escape time
- Density of target material for proton interactions
- Density of low energy seed photons for electron IC
- Magnetic field strength (synchrotron emission)
- SN type
- SNR age and morphology
- Presence of Molecular Clouds
- Absorption of gamma rays
- *......*

Multi-wavelength studies can help

BUT…

In this complex scenario, one thing is clear:

A power law spectrum reaching 100 TeV without a cutoff is a very strong indication with of the hadronic origin of the emission

Inverse Compton is suppressed by the Klein Nishina effect

Photons of few hundreds of TeV are a clear signature of acceleration of 10^{15} eV protons

→ Gamma ray astronomy above 30 TeV is a fundamental tool to discover Pevatrons

Are γ rays above 30 TeV absorbed in our Galaxy ?

Gamma ray absorption in the Galaxy

Pair production $\gamma \gamma \longrightarrow e^+ e^-$

Energy threshold: $s = 2 E_1 E_2 (1\text{-}\cos\theta) > 4 m_e^2$

$E_1 = 1$ TeV $E_2 \sim 1$ eV *star light*
$E_1 = 100$ TeV $E_2 \sim 10^{-2}$ eV *IR - dust emission*
$E_1 = 1000$ TeV $E_2 \sim 10^{-3}$ eV *CMB*

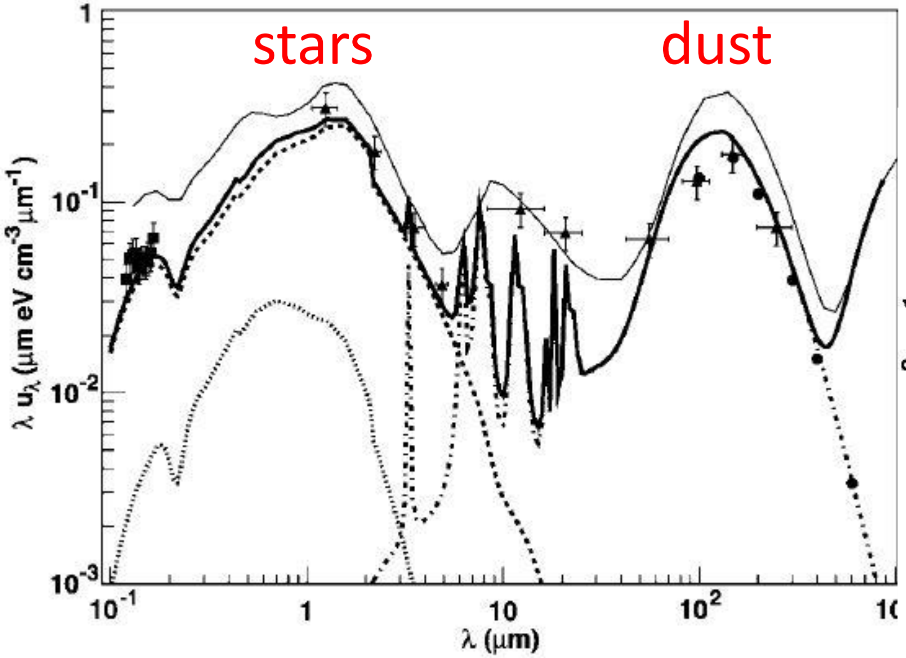
The gamma ray flux is absorbed: $\mathbf{I = I_0 e^{-\tau}}$

The absorption coefficient τ depends on the gamma ray energy and on the density and energy of target photons

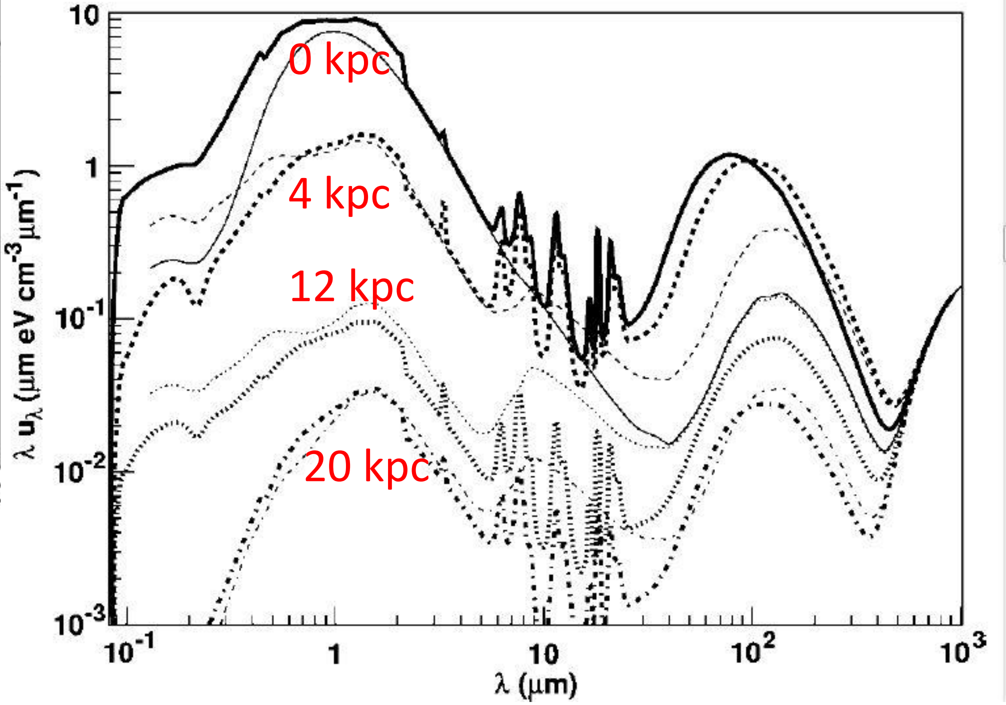
➡ The amount of absorption depends on the source location in the Galaxy

Gamma ray absorption in the Galaxy

Local radiation field



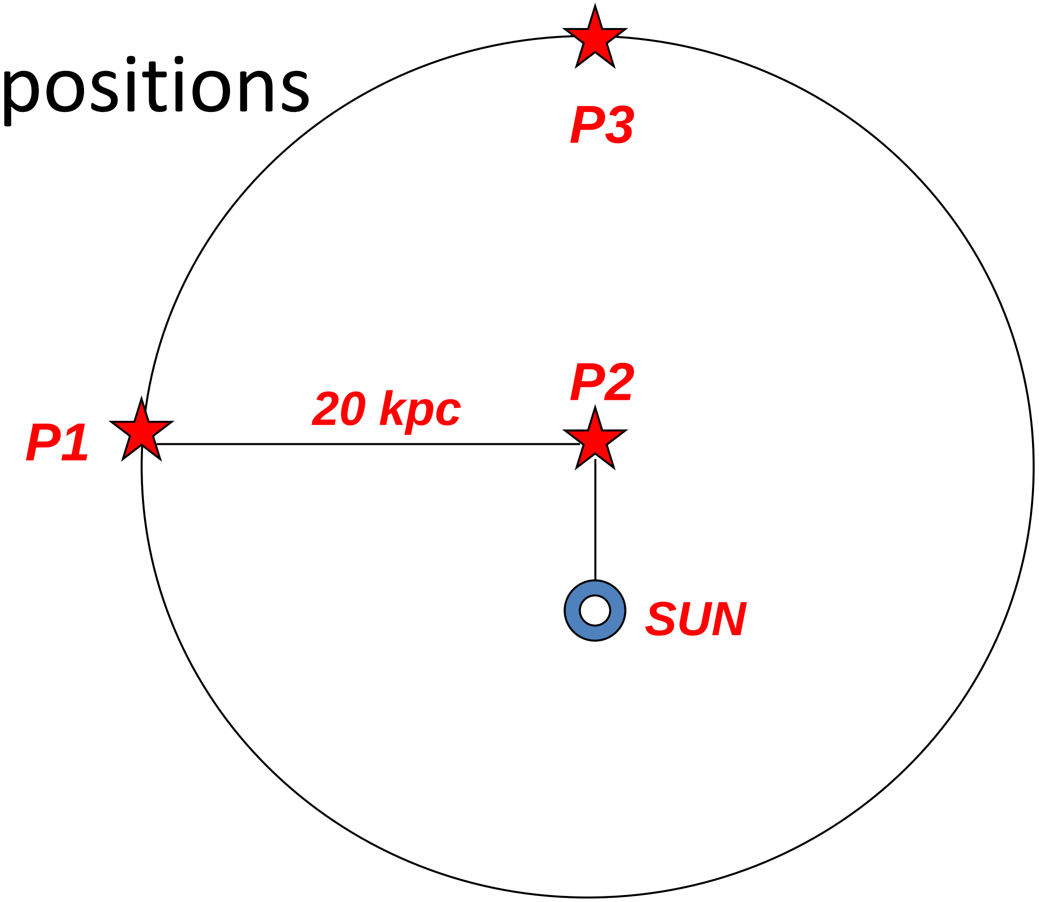
Radiation field for different distances from the galactic center



Moskalenko et al, 2006 ApJL 640, 155

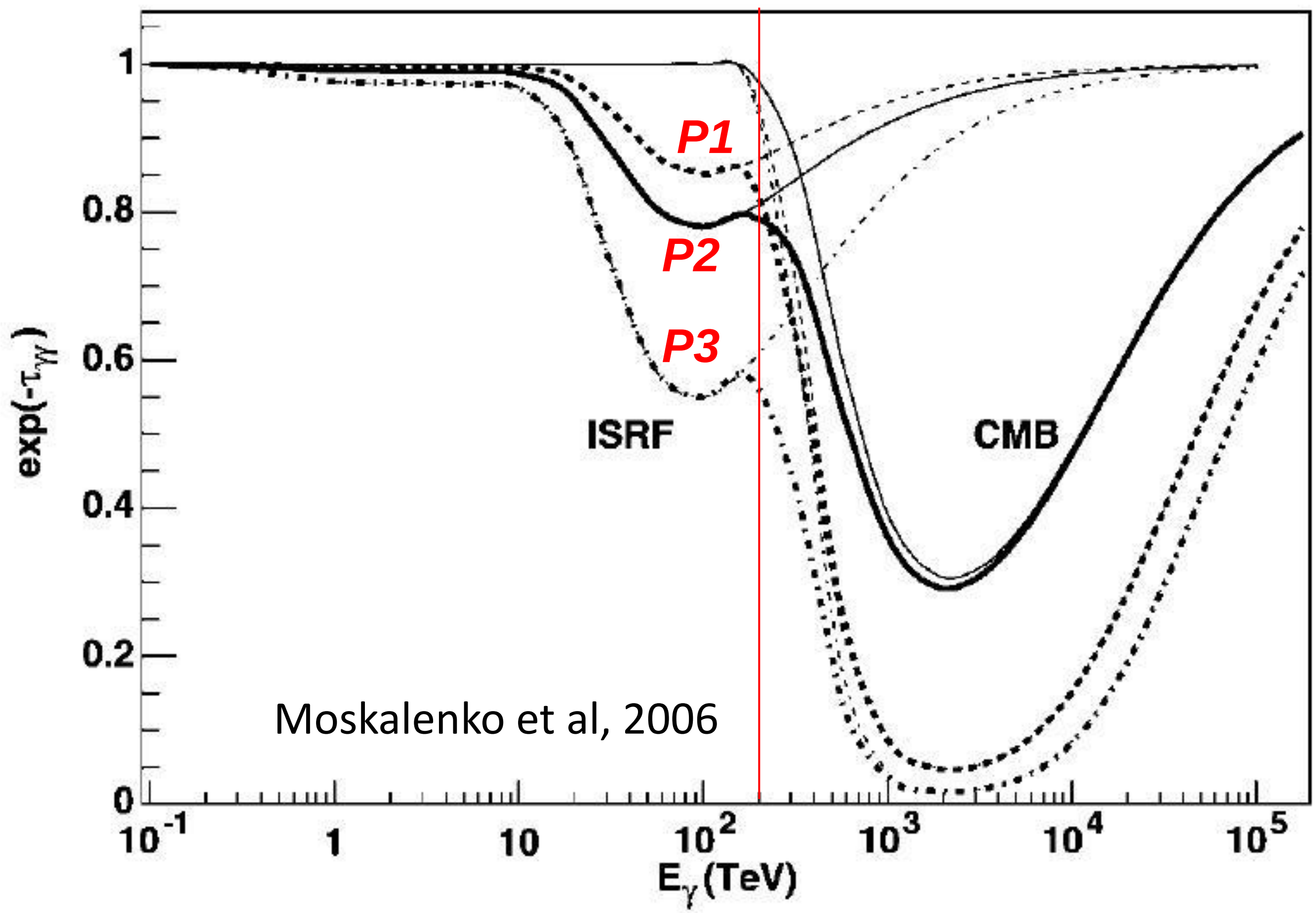
Gamma ray absorption in the Galaxy

3 source positions



Distance Sun – Galactic centre 8.5 kpc

Gamma ray absorption in the Galaxy

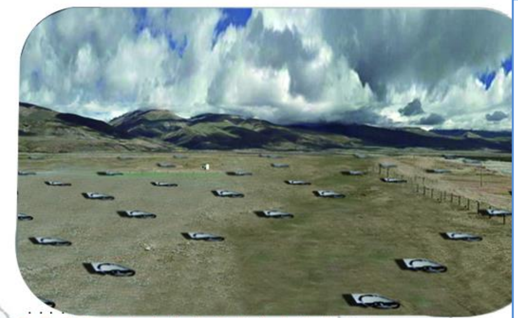


Low attenuation up to ~200 TeV for P1 and P2

What LHAASO can see

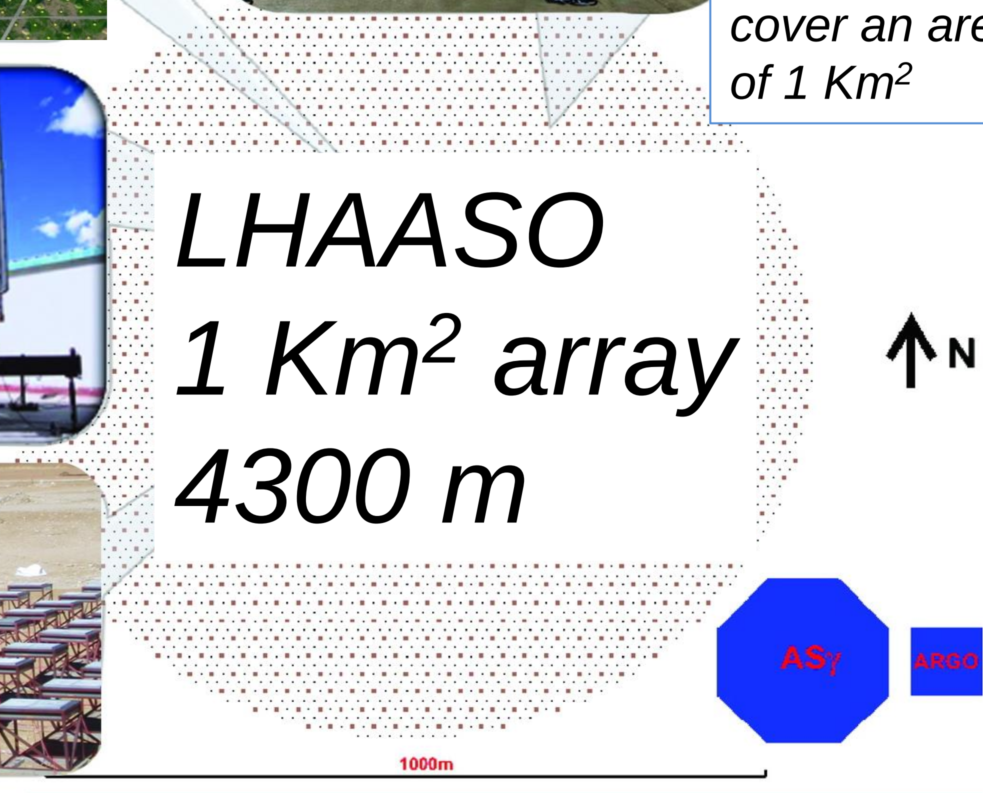
LHAASO – A multi component experiment

Four 90000 m^2 Water Cherenkov detectors. Each one has the size of HAWC



6100 scintillator detectors and 1200 μ detectors cover an area of 1 Km^2

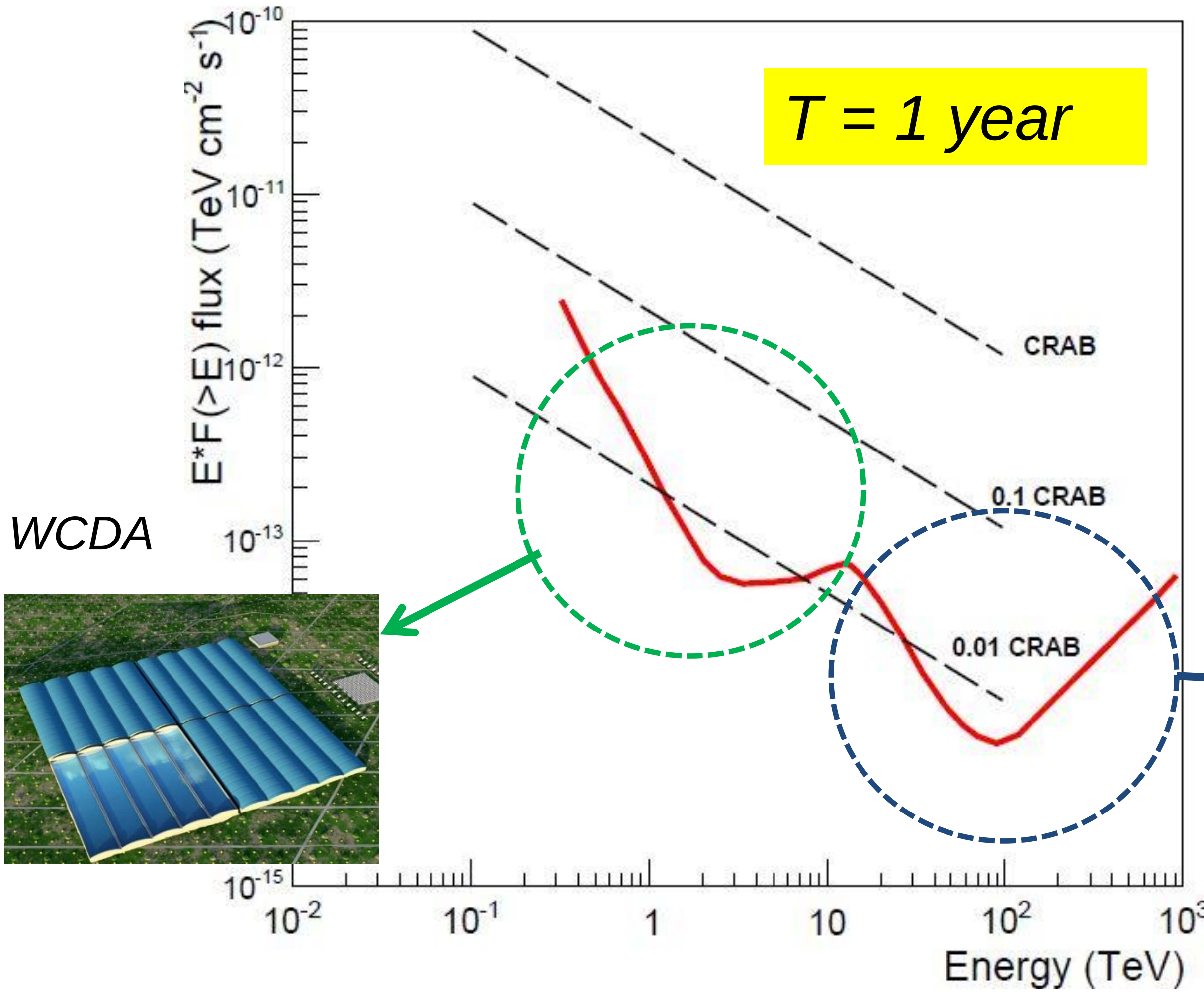
24 Wide FOV air Cherenkov image Telescopes



400 burst detectors for high energy secondary particles near the core of showers

LHAASO integral sensitivity for a Crab like source

WCDA



Angular resolution:

30 TeV ~0.4°
100 TeV ~0.3°

Energy resolution:

30 TeV ~30%
100 TeV ~20%

KM2A

TeV sources in the LHAASO FOV

From TeVCat :

71 sources culminating at zenith angle < 40°

LHAASO latitude = *30° N* -10° < decl < 70°

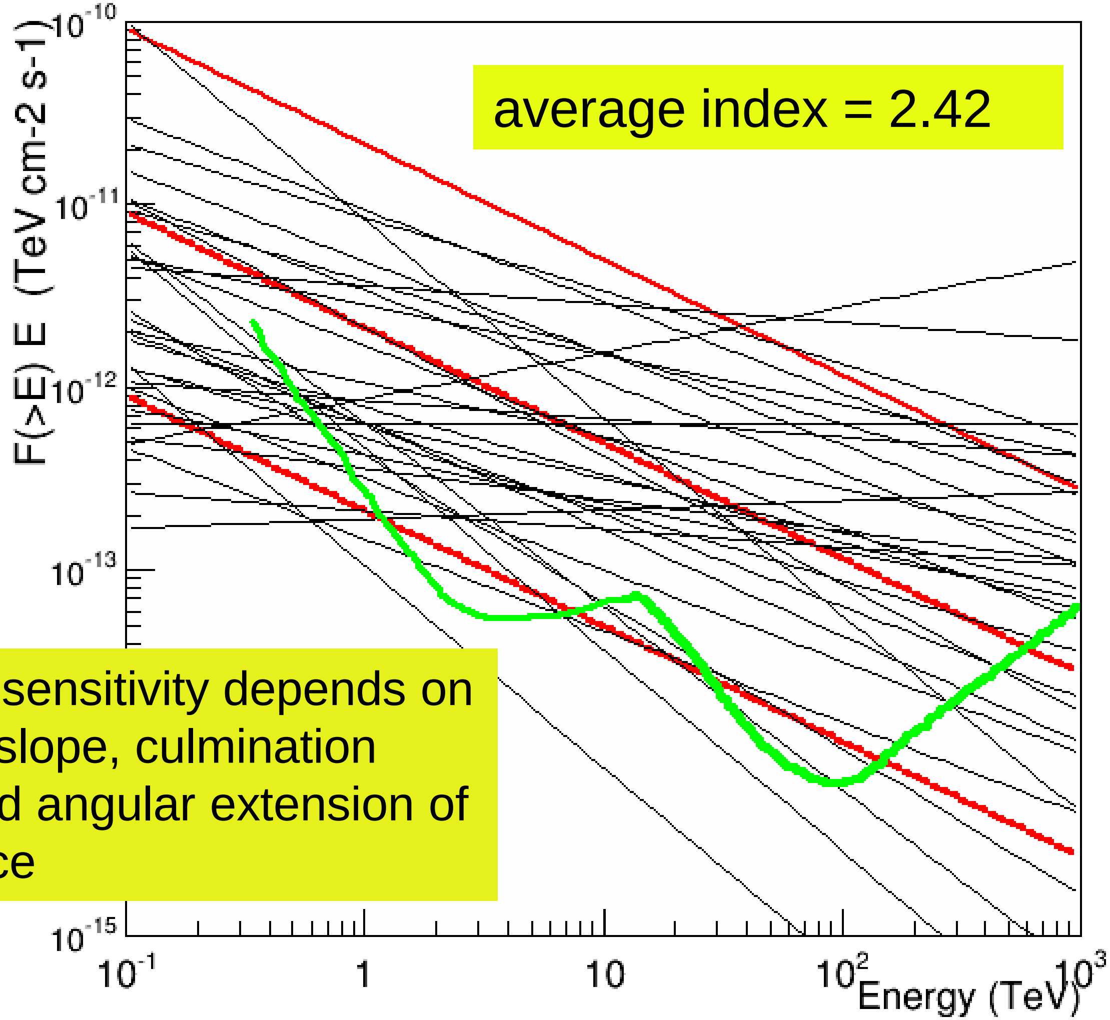
- 31 galactic →
- 40 extragalactic

13	Unidentified
9	Pulsar Wind Nebulae
6	Shell Supernova Remnant
2	Binary System
1	Massive Star Cluster

70% of Galactic sources are extended

→ Probably the fluxes are higher then what measured by IACT

Extrapolated spectra up to 100 TeV



Extrapolation of TeV spectra assuming no cutoff

CRAB

CRAB x 0.1

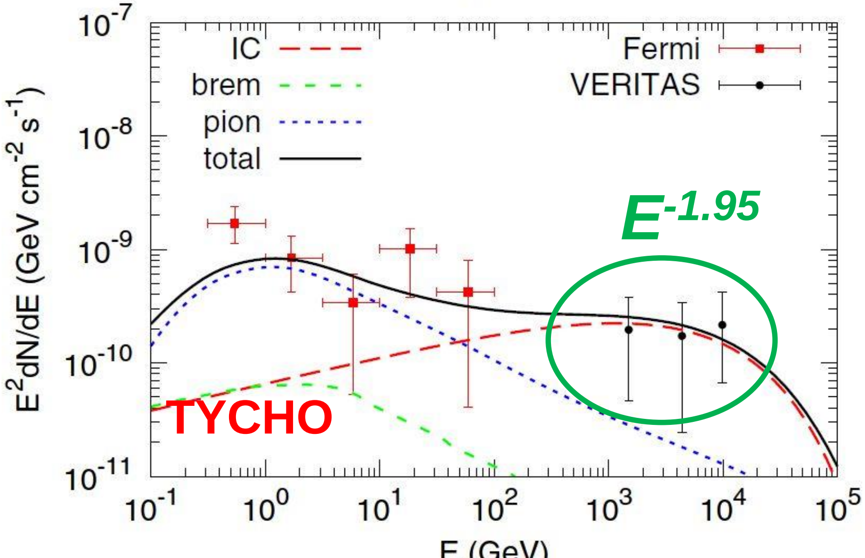
CRAB x 0.01

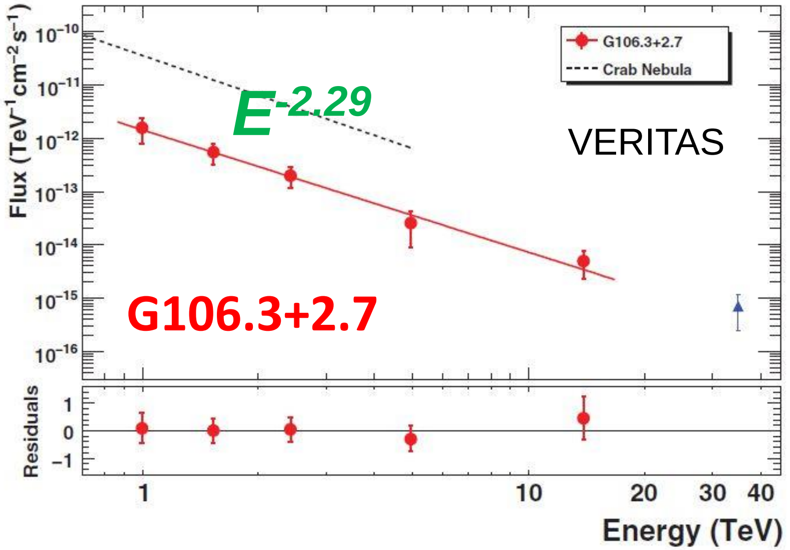
The real sensitivity depends on spectral slope, culmination angle and angular extension of the source

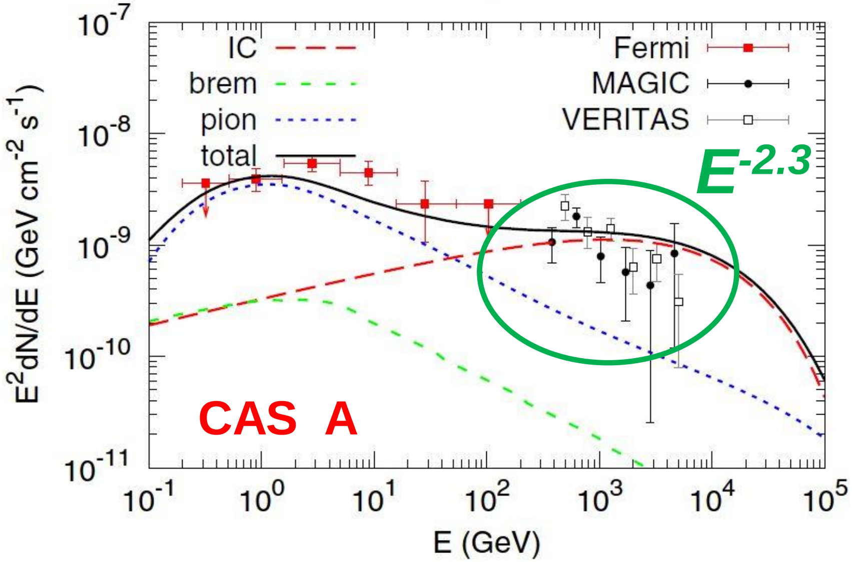
6 Shell SNRs

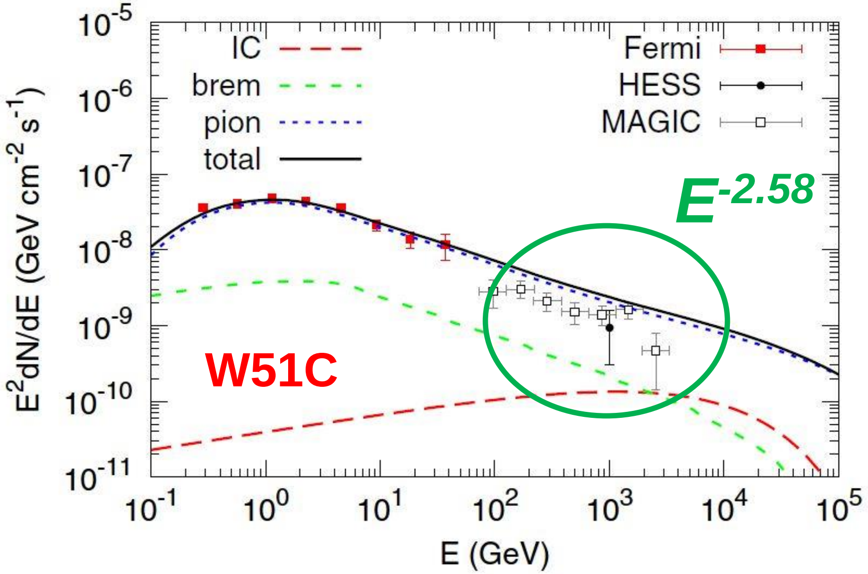
Source	Zenith angle culm.	F > 1 TeV (c.u.)	Energy range	Spectral index	Angular Extension (σ)
Thyco	34°	0.009	1-10	1.95	
G106.3+2.7	31°	0.03	1-20	2.29	0.3° x 0.2°
Cas A	29°	0.05	0.5-10	2.3	
W51	16°	0.03	0.1-5	2.58	0.12°
IC443	7.5°	0.03	0.1-2	3.0	0.16°
W49B	21°	0.005	0.3-10	3.1	

SNR GeV-TeV spectra

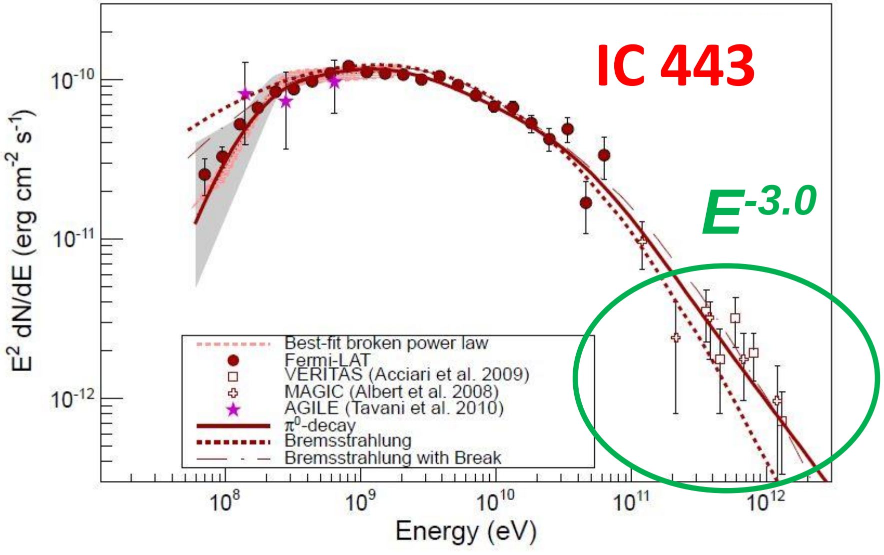


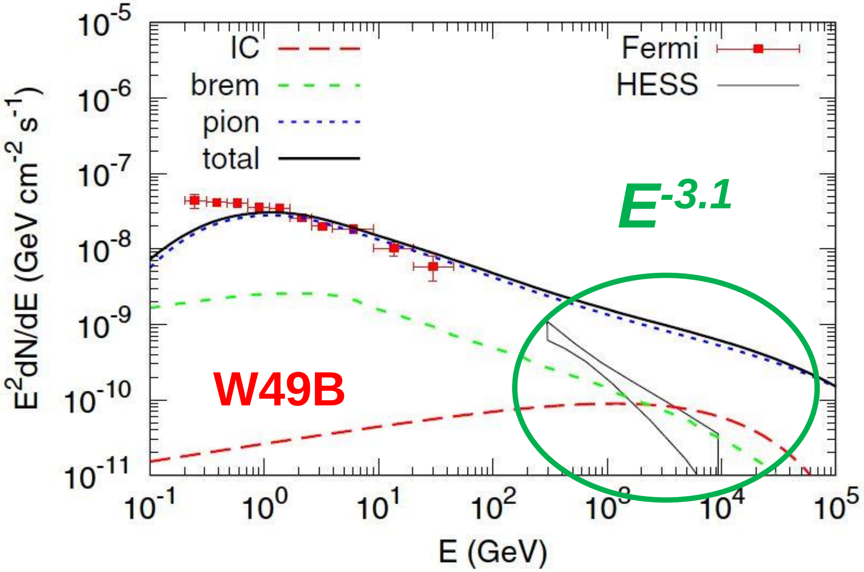






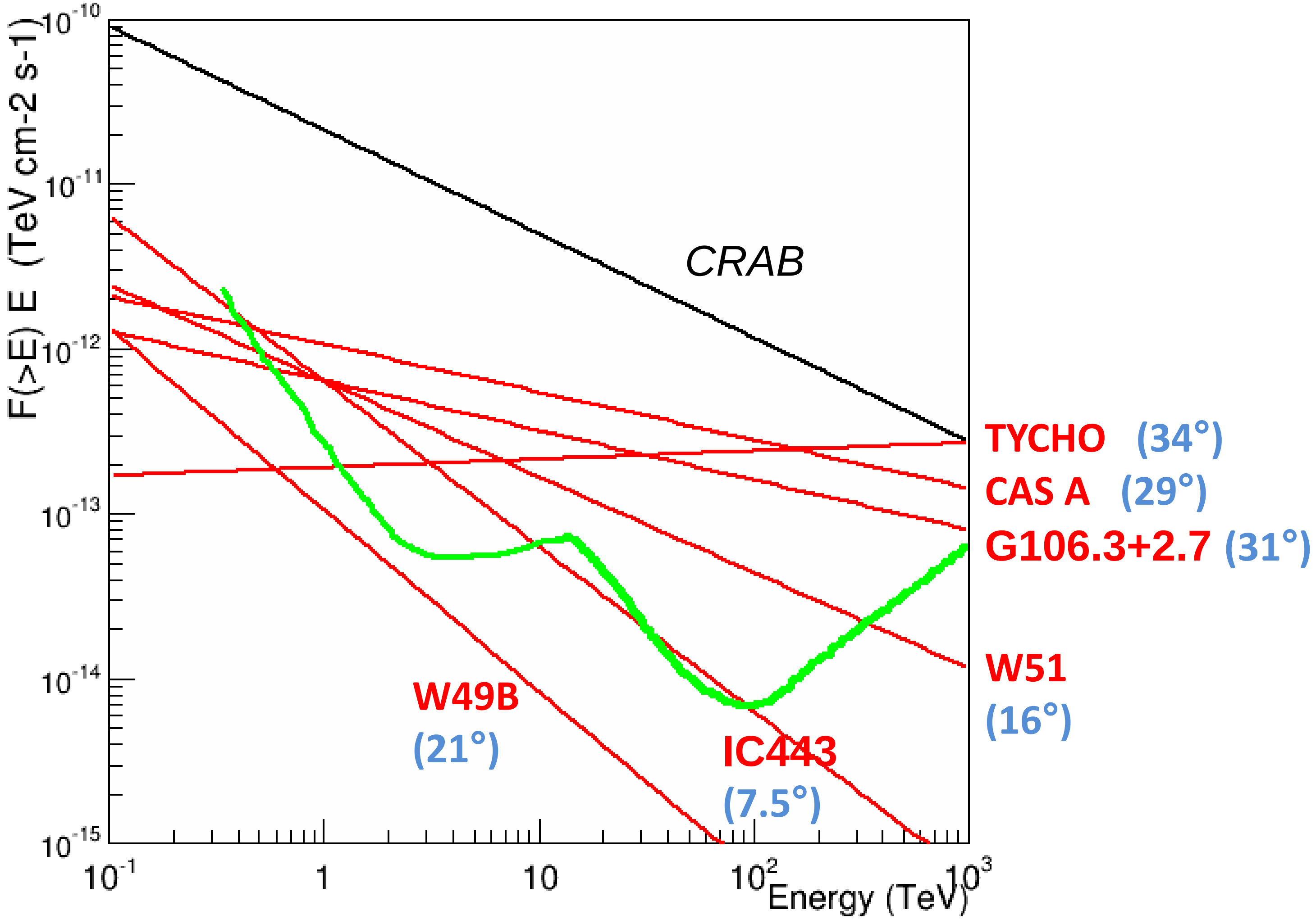
SNR GeV-TeV spectra





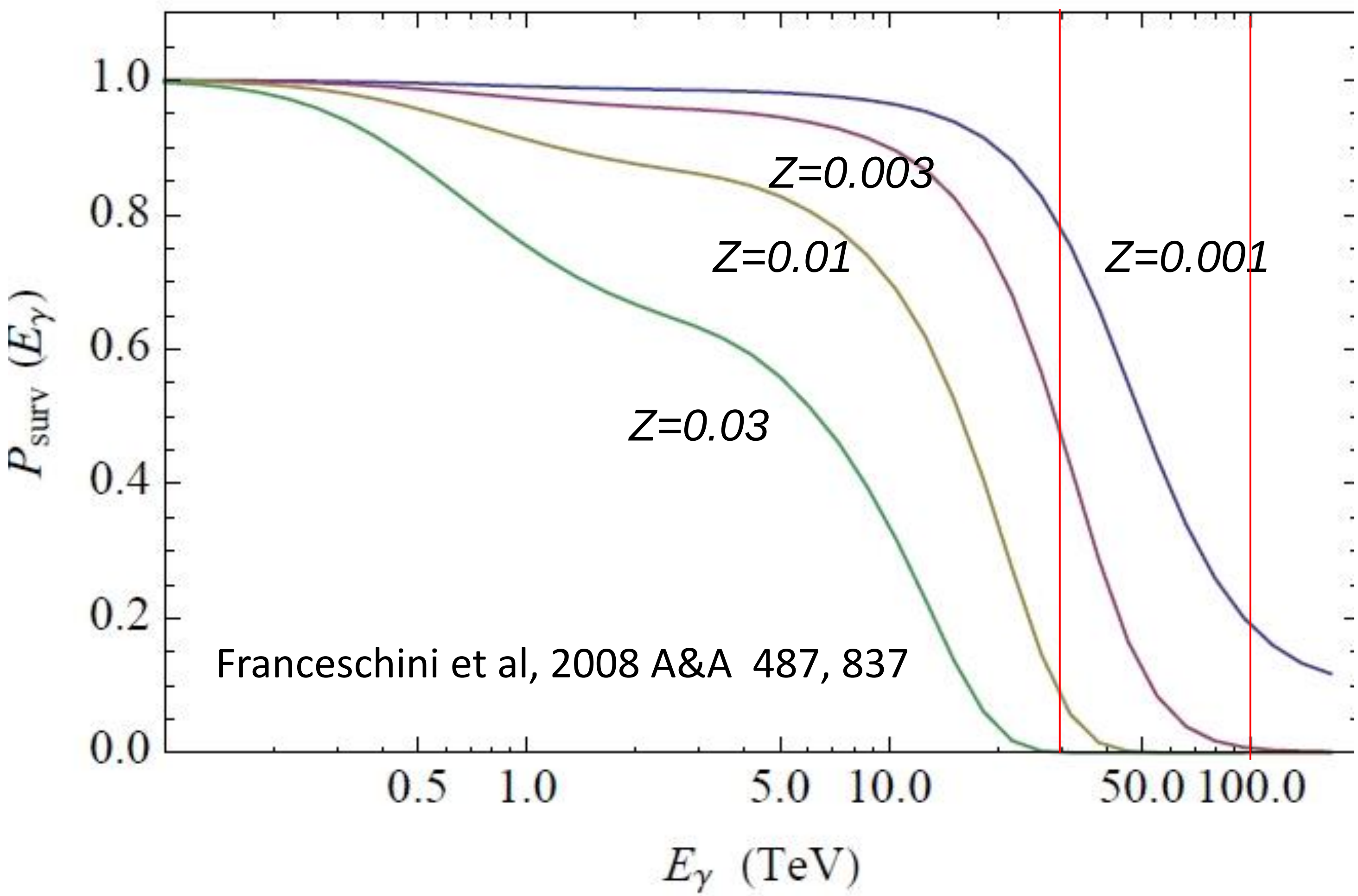
No cutoff observed in the 6 TeV spectra

SNRs extrapolated spectra



Extragalactic astronomy above 30 TeV ?

Gamma ray attenuation for extragalactic sources

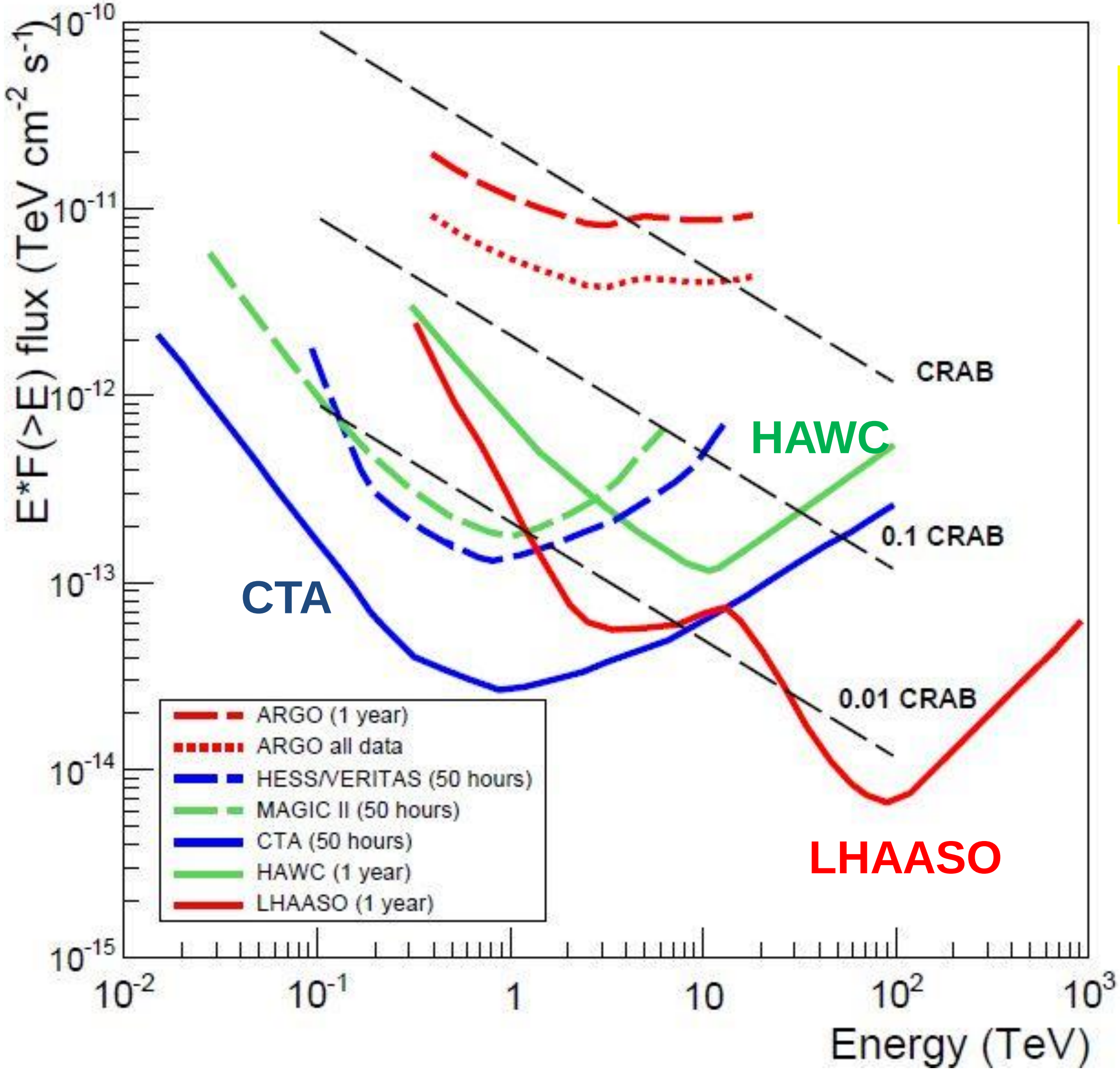


3 “close” extragalactic sources

Source	Zenith angle culm.	type	Distance (z)	Flux (c.u.)	Spectral index
M82	39°	Star burst	0.001	0.009	2.5
M87	18°	Radio Galaxy	0.0044	Variable Flux up to 10% Crab	2.2
NGC1275	11°	Radio Galaxy	0.019	Variable at VHE ?	4.1

Comparison of Lhaaso sensitivity with other detectors

Integral sensitivity for a Crab like source

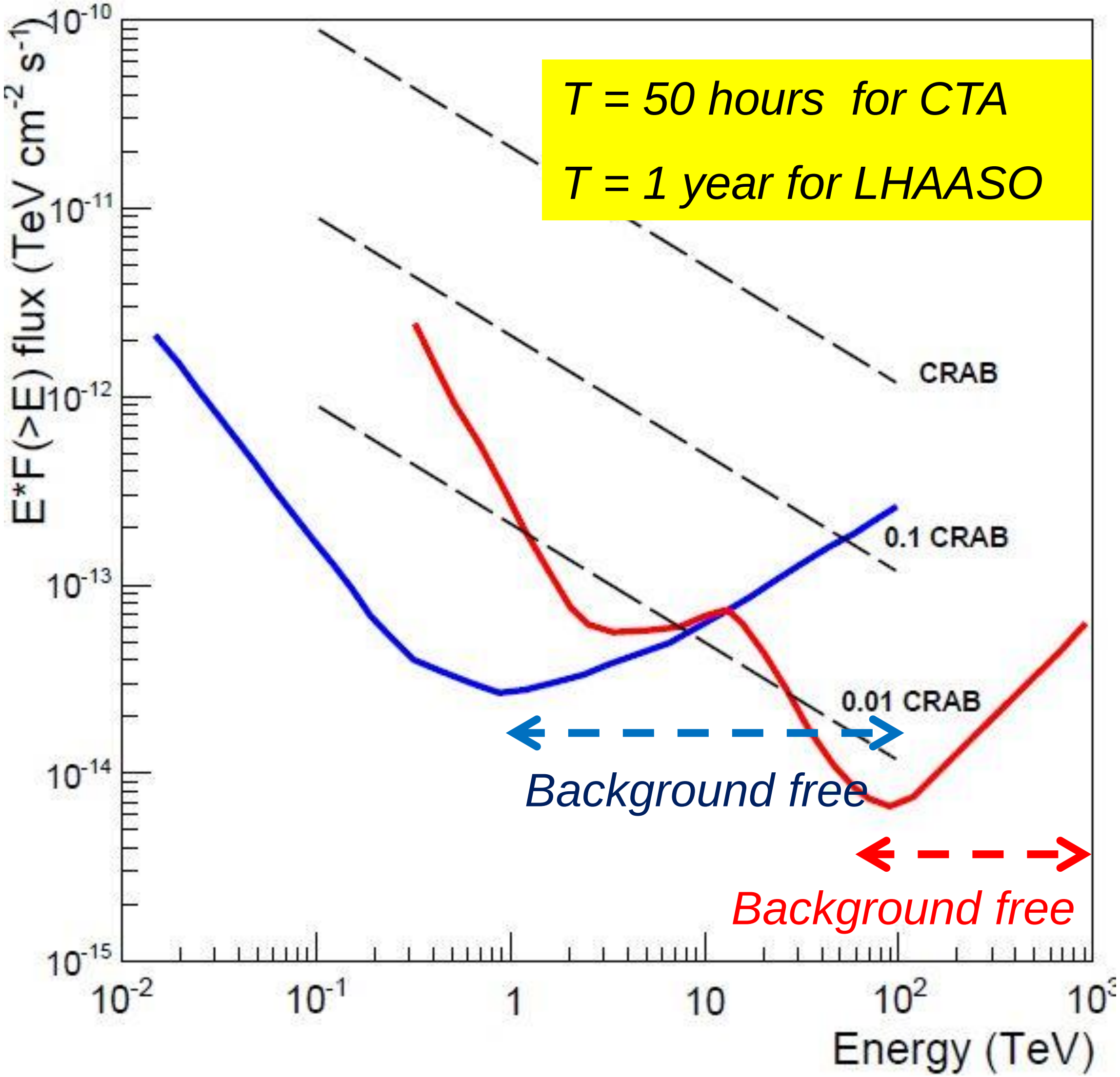


T = 50 hours for IACTs

T = 1 year for EAS arrays

1 year for EAS arrays means ~1500-2200 of observation hours for each source (about 4-6 hours per day)

LHAASO and CTA integral sensitivity



5 σ detection

$N_\gamma / N_p^{1/2} > 5$

The sensitivity increases with $T^{1/2}$

Background free
$N_p = 0$

Detection requirement:
$N_\gamma \geq 10$

The sensitivity increases with T

Comparison of LHAASO and CTA sensitivities

Energy	LHAASO/ CTA sensitivity
> 10 TeV	0.9
> 30 TeV	5
> 80 TeV	30

T = 50 hours for CTA

T = 1 year for LHAASO

The big advantage of LHAASO is in sky survey

Galactic Plane survey at 80 TeV

Sky region to be scanned ($-6° < b < 6°$, $\Delta l < 140°$)

In one year every point of the sky region is observed for a time:

LHAASO: $T1 \approx 5h \times 365$ days $\approx$ 1800 h

CTA: $T2 \approx 24h \times 365$ days $\times f_{dc} / N_{steps} \approx$ 13 h

$F_{dc} \approx 0.15$ Cherenkov duty cycle
$N_{steps} \approx 100$ number of pointings to cover the region (steps of 4°)

LHAASO sensitivity $\approx$ CTA sensitivity x 20 at E > 30 TeV
x 100 at E > 80 TeV

Sky survey at 80 TeV

$\Omega_{tot} \approx 7$ sr sky region to be scanned ($-10° < decl < 70°$)

In one year every point of the region can be observed for a time:

LHAASO: $T1 \approx 5h \times 365$ days $\approx$ 1800 h

CTA: $T2 \approx 24h \times 365$ days $\times f_{dc} / N_{cells} \approx 0.8$ h

$f_{dc} \approx 0.15$ Cherenkov duty cycle
$N_{steps} \approx 1600$ number of pointings (step of 4°)

LHAASO sensitivity ≈ CTA sensitivity x 300 at E > 30 TeV
x 1900 at E > 80 TeV

Conclusions

- Gamma ray astronomy at energies 30-200 TeV is a field of research completely new
- Even a non-detection would be a discovery
- The LHAASO sensitivity allow to measure the flux of almost all known TeV sources extrapolated to 100 TeV and study in detail possible cutoffs
- Very promising perspectives for galactic sources. SNRs are Pevatrons?
- Not so promising for extragalactic sources (only a few very close radio galaxy or starburst galaxy could be detected)
- Lhaaso has no competitors for sky survey: in one year it can survey the Northen sky at 100 TeV at a level < 0.01 Crab