Origin of Cosmic rays through the eyes of TeV gamma-rays

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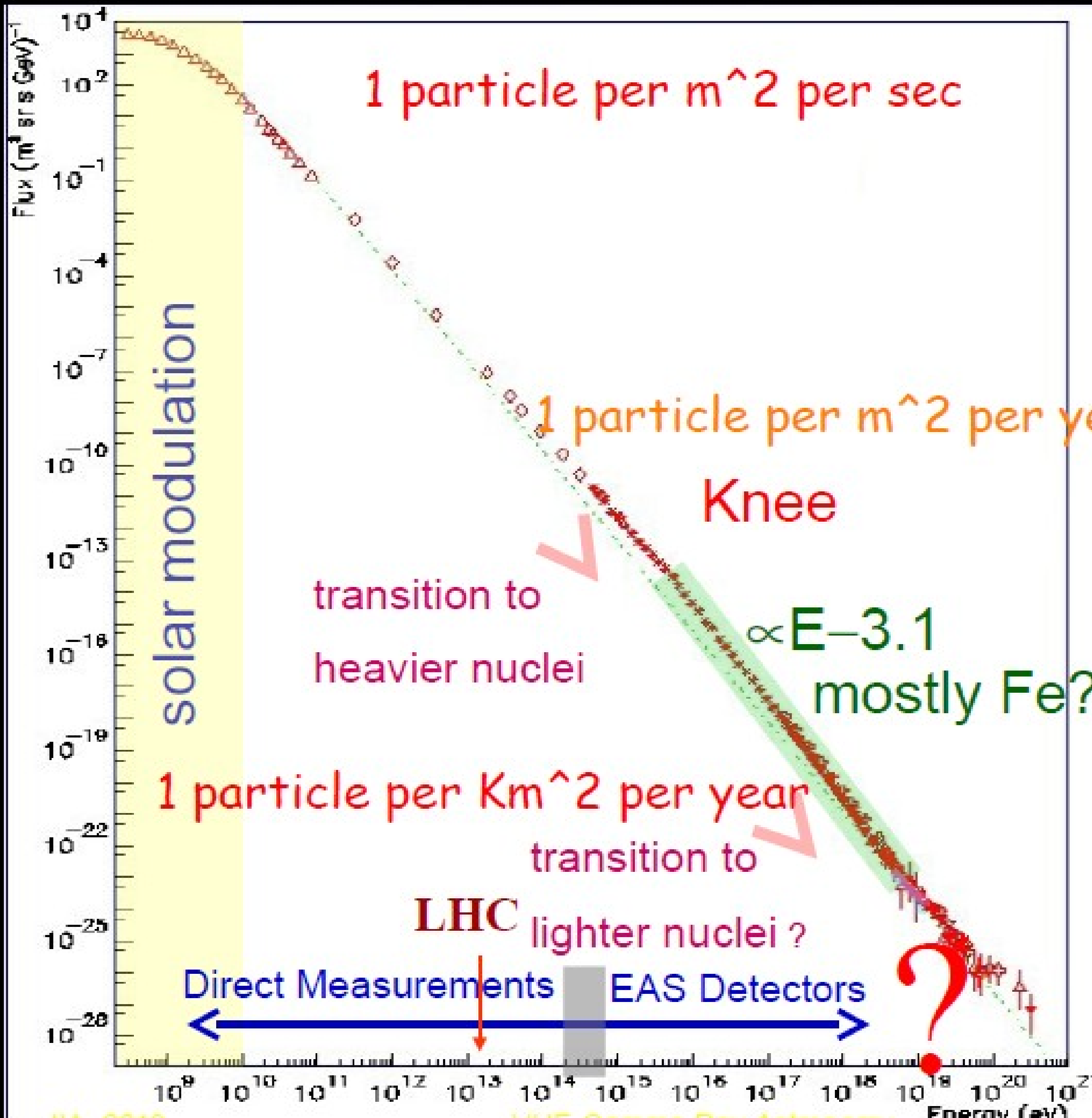
Outline:

- Cosmic rays and TeV Gamma Ray Astrophysics
- How do we see sources cosmic rays ?
- Study a few Galactic sources
- Conclusions and Future directions

TIFR, Mumbai, November 26, 2015

The Cosmic Ray Spectrum



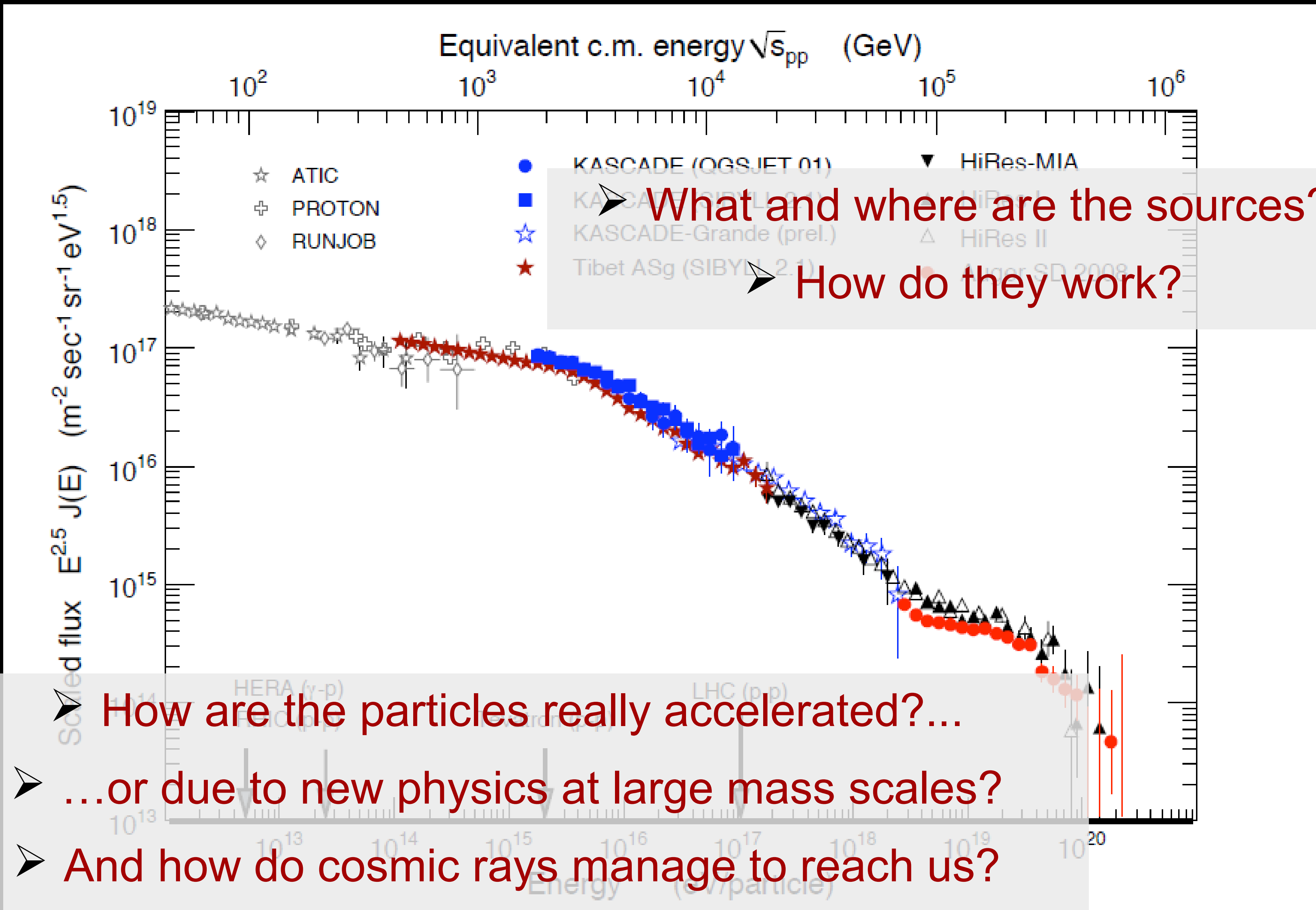
1912 Victor Hess

Won Nobel Prize in 1936

Power Law:

Shock Acceleration predicts FSource ∝ E−2

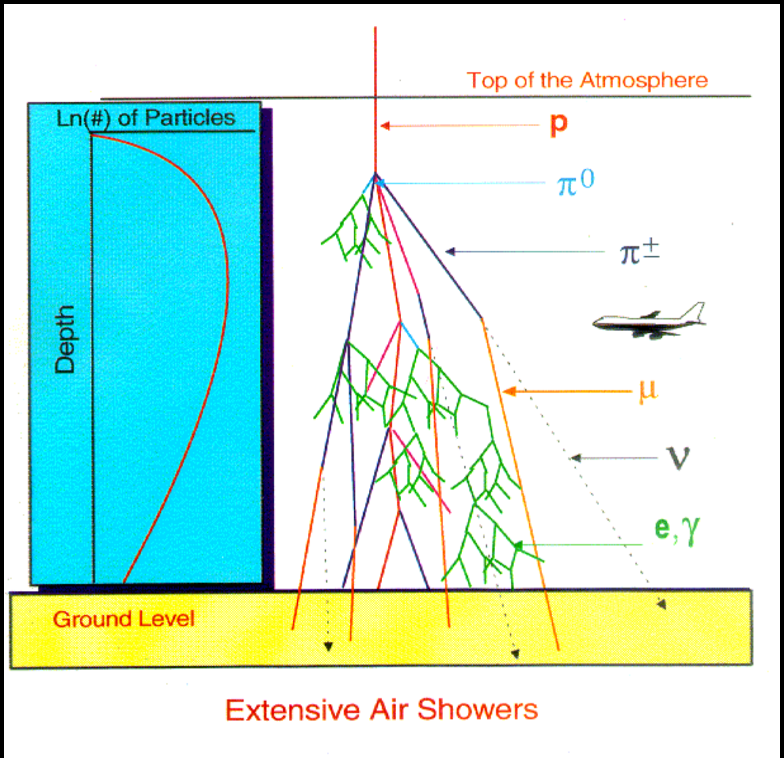
Open questions after 100 years

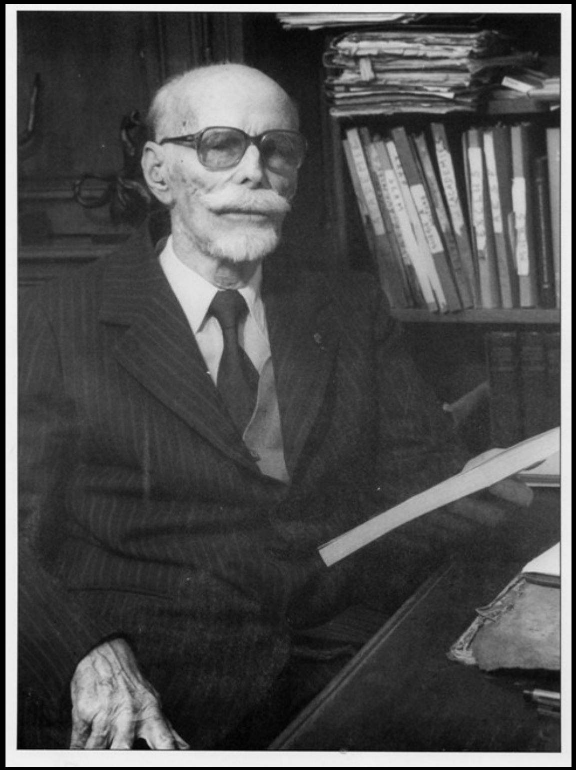


- ➢ What and where are the sources?
- ➢ How do they work?
- ➢ How are the particles really accelerated?...
- ➢ …or due to new physics at large mass scales?
- ➢ And how do cosmic rays manage to reach us?

Cosmic rays (1930-1945)

First detection of Air showers



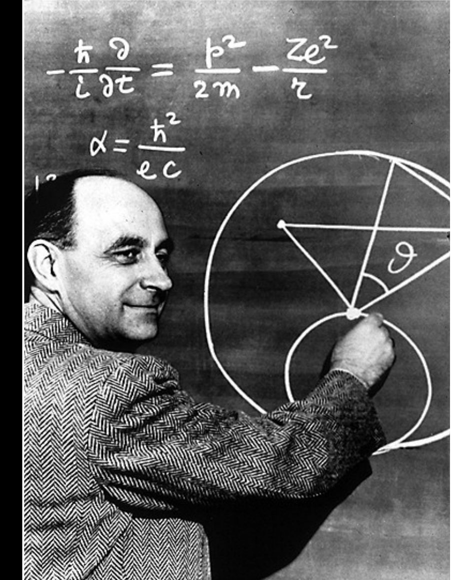


- Hadronic showers:
  - CR + atm. nucleus $\longrightarrow \pi^\circ, \pi^\pm + N^*$
  - $\pi^\pm \longrightarrow \mu^\pm + \nu$
  - $\pi^\circ \longrightarrow \gamma\,\gamma \longrightarrow$ e.m. showers
- Electromagnetic showers:
  - $\gamma \longrightarrow e^+ e^-$ (pair production)
  - $e^\pm \longrightarrow \gamma$ (*bremsstrahlung*)

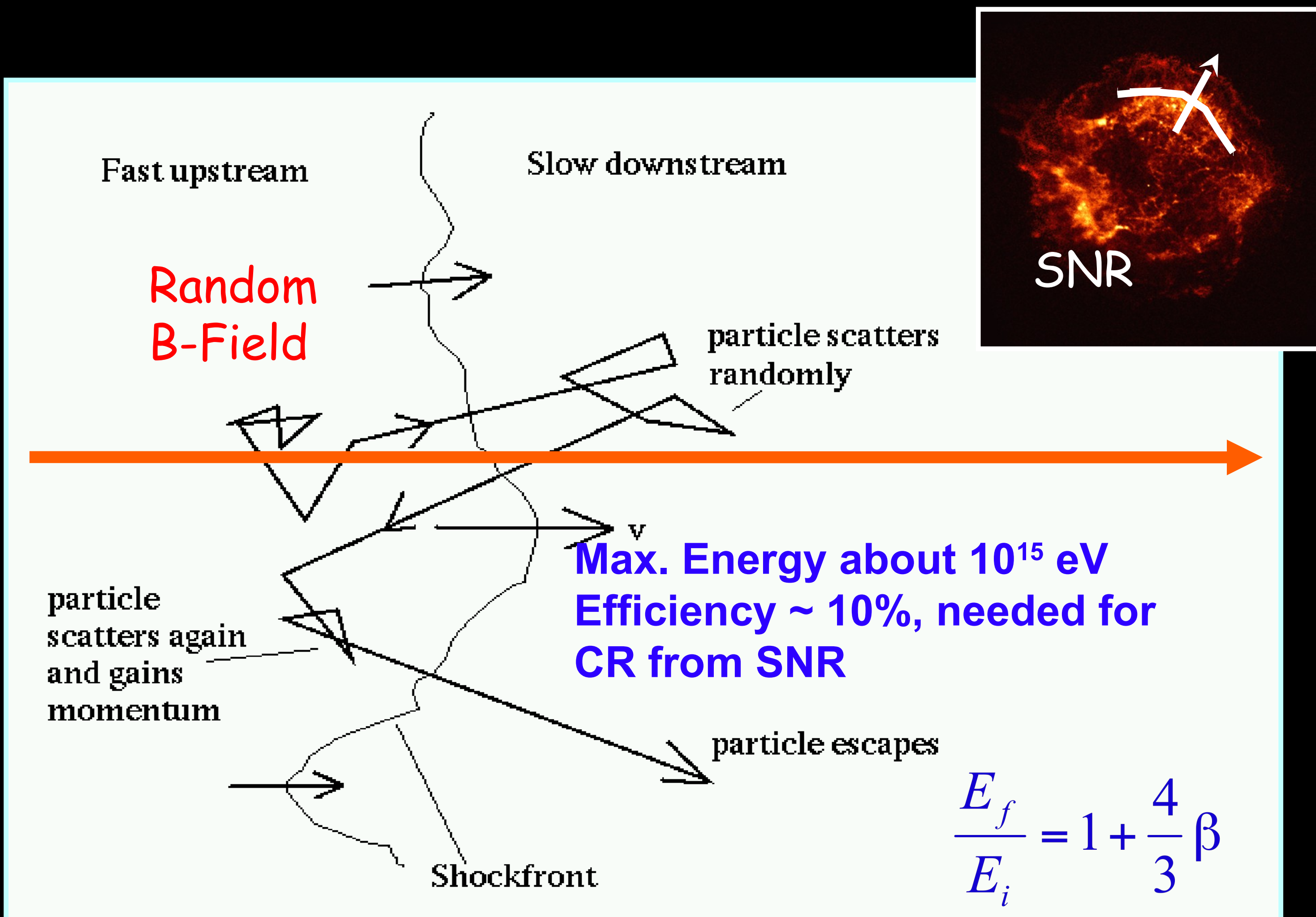
Cosmic rays, gamma rays and neutrinos are all linked

Shock acceleration mechanism

(by Enrico Fermi)



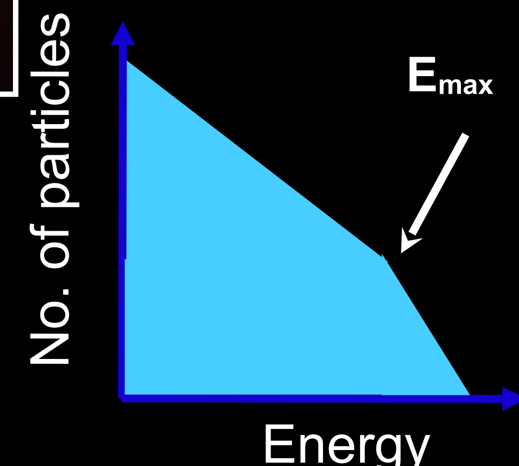
Particles (electrons and hadrons) get scattered many times in shock front and gain energy in each cycle (TeV energies → several 100 years)



Max. Energy about 10^{15} eV
Efficiency ~ 10%, needed for CR from SNR

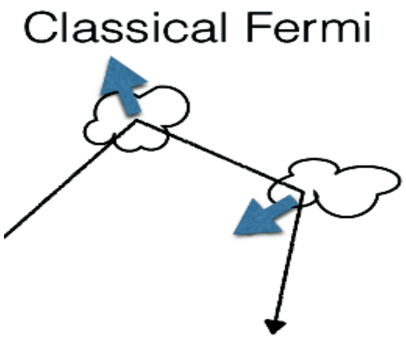
$$\frac{E_f}{E_i} = 1 + \frac{4}{3}\beta$$

Power law spectrum

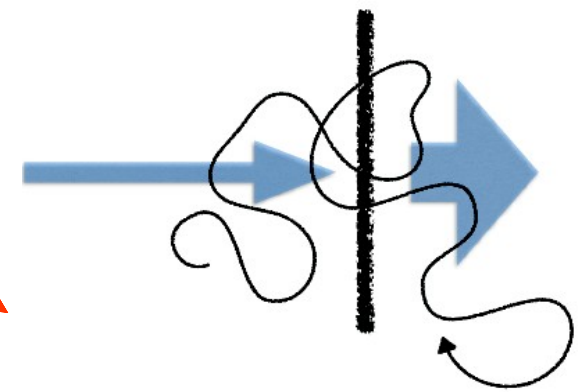


Predicts a $E^{-2.0}$ spectrum

Fermi Acceleration



Stochastic Mechanism
Charged particles collide with clouds in ISM and are reflected from irregularities in galactic magnetic field :
2nd order acceleration



Charged particles can be accelerated to high energies in astrophysical shock fronts :
1st order acceleration

Diffusive Shock Acceleration : an efficient variant of Fermi acceleration
shock compression ratio is 4 (can be easily shown for monatomic gas)
Linear theory , easy to convert energy dissipated in shock into non thermal energy of the particles
Predicts smooth power-law spectrum to high energies
For Emax, non linear theory required due to amplification of B

Magnetic Field Amplification

Linear Theory of DSA : Alfven waves are generated by CR
as they diffuse through the plasma

Insert typical parameters of shock, B values ==> Maximum Energy well below the knee of the spectrum (Lagage and Cesarky, 1983)

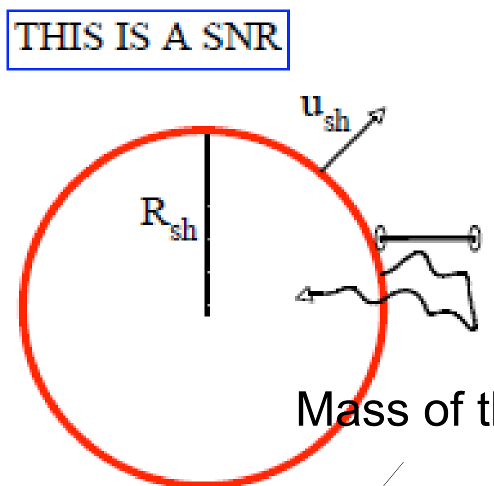
Take energy density of CR, pressure of the cosmic rays =>
Magnetic Field amplification takes place.
(Volk, Drury and McKenzie 1984)

A shock moving with 10^4 km/s, medium ~ 1 proton/cc,
B ~ few micro Gauss

One can show that mangetic field gets enhanced by a factor 1000

==> Linear Theory of DSA breaks down , (Bell and Lucek, 2001)
go over to non-linear theory (fine, but has observable problems, let's discuss this a bit later)

Maxm Energy and Magnetic Field Amplification



$$E_{SN} \approx \frac{1}{2} M_{ej} \dot{R}^2 \implies \dot{R} \propto \left(\frac{E_{SN}}{M_{ej}} \right)^{1/2}$$

Mass of the ejecta

$$\frac{4}{3}\pi R^3 \rho_0 = M_{ej} \implies R \propto \left(\frac{M_{ej}}{\rho_0} \right)^{1/3}$$

The maximum particle rigidity : BRdR/dt

Solving eqn of motion of expanding shell (Sedov-Taylor phase) :

$$\frac{d}{dt}\left(\frac{4\pi}{3} R_s^3 \rho_0 \dot{R}_s \right) = 4\pi R_s^2 P \,. \qquad R \propto t^{2/5}$$

shock velocity drops as $\dot{R} \propto t^{-3/5}$

$$R\dot{R} \propto E_{SN}^{1/2} M_{ej}^{-1/6} \rho_0^{-1/3} t^{-1/5}$$

$$E_{max} \propto B_{sh} t^{-1/5}$$

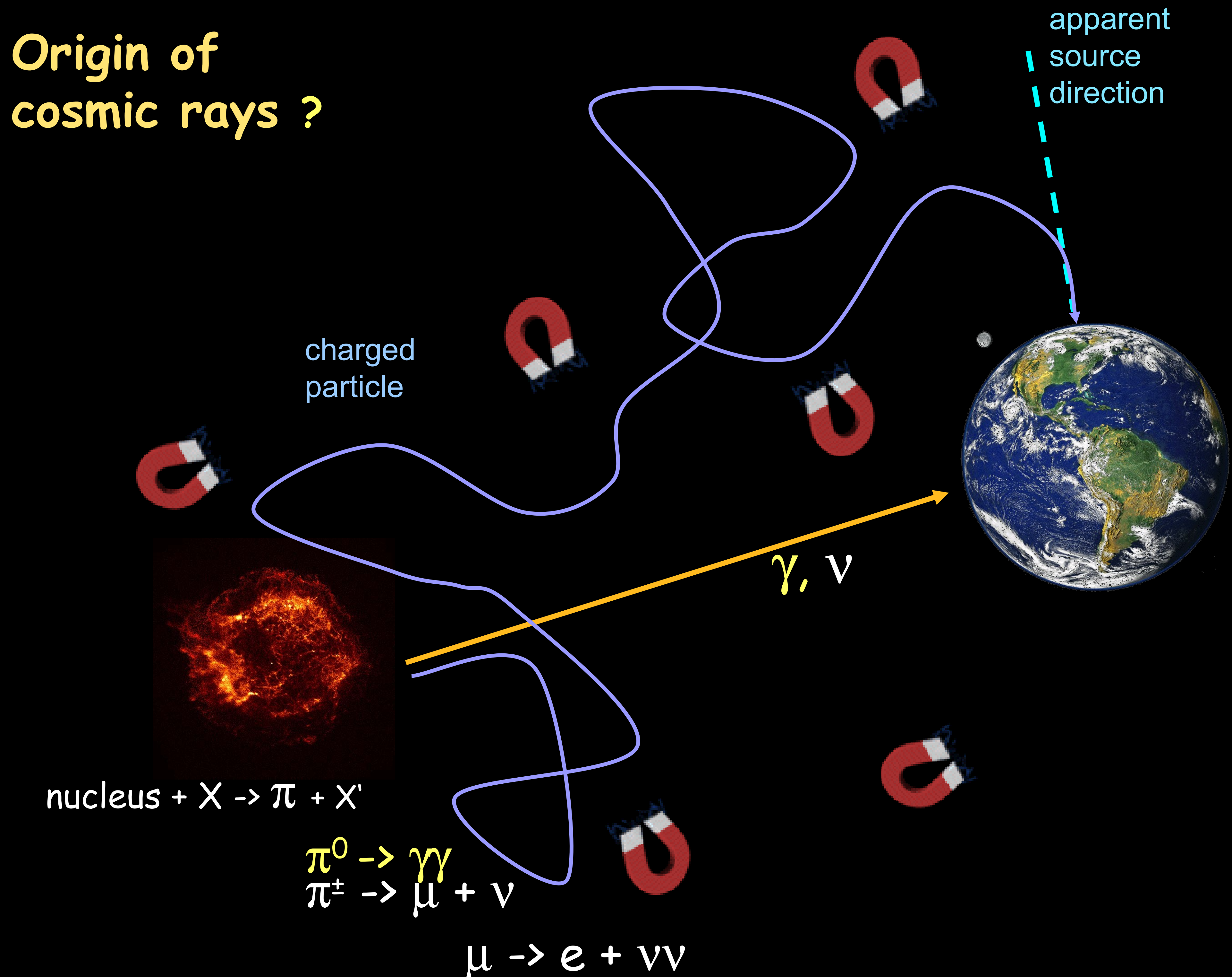
==>

E_{max} decreases with time

Particles with E > E_{max} escape the SNR

McKenzie and Volk (1982)
Bell and Lucek (2001)
Berezhko et al (1996) and others
Ptuskin & Zirakashvili (2003)

How do we see Sources of Cosmic Rays ?



Origin of cosmic rays ?
apparent source direction
charged particle
γ, ν
nucleus + X -> π + X'
π⁰ -> γγ
π± -> μ + ν
μ -> e + νν

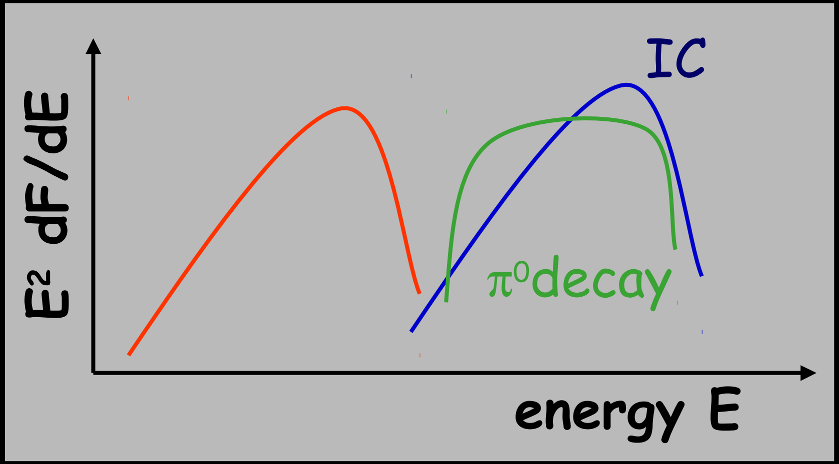
γ-ray astronomy and cosmic rays (CR)

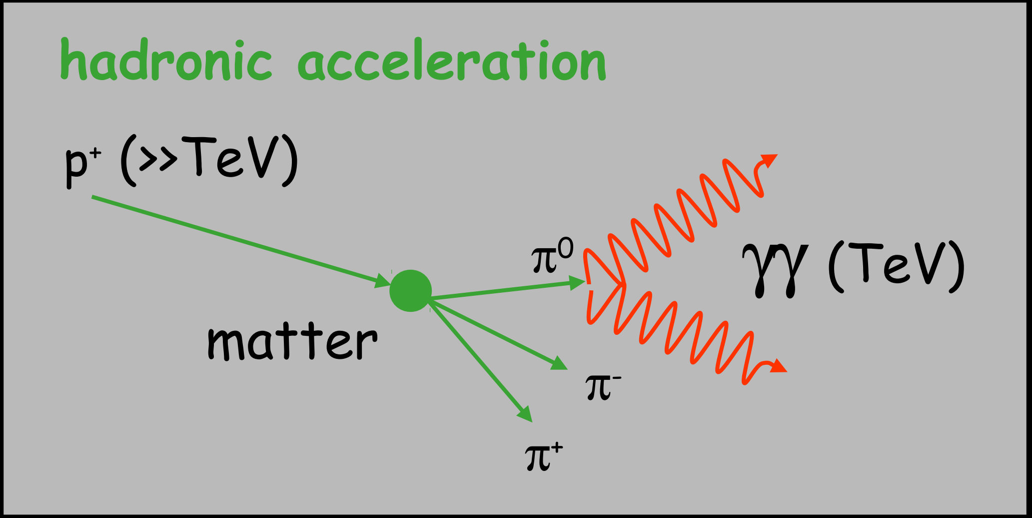
Study origin of CRs,

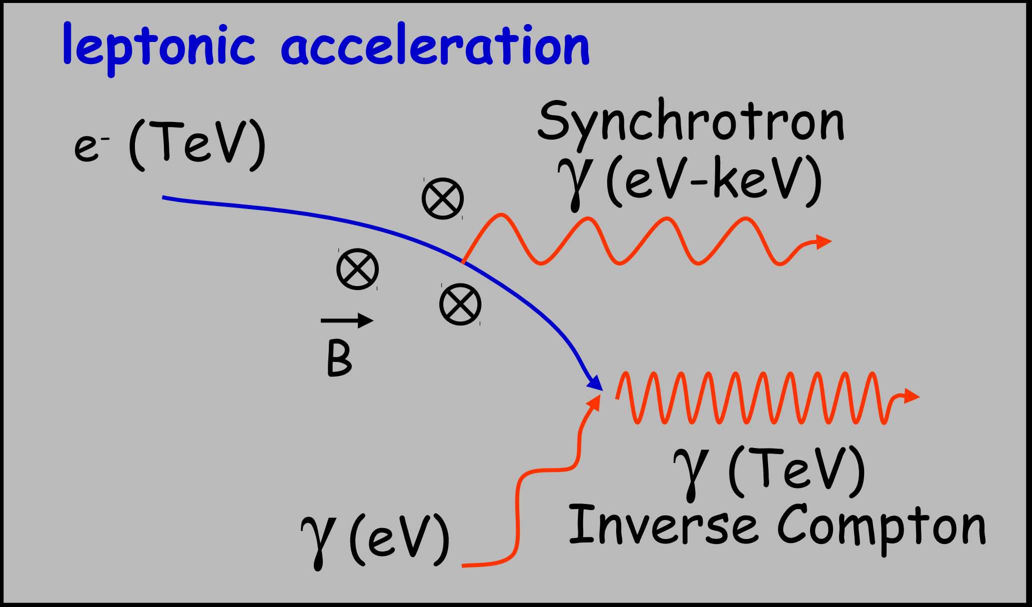
=> search for γ-rays produced by CRs close to source

- discriminate hadronic vs leptonic acceleration

=> shape of spectrum







Very High Energy γ-ray Astronomy

TeV Gamma-rays (10^{12}eV)

- Youngest astronomic discipline
- First significant measurement of TeV γ-ray emission from Crab Nebula by Whipple telescope in 1989
- > 50 hrs for 9 sigma detection

- Current generation since 2004
- 1% of Crab nebula flux
- You can now see TeV gamma rays from Crab nebula in < 2 mins

Pair Conversion Telescopes

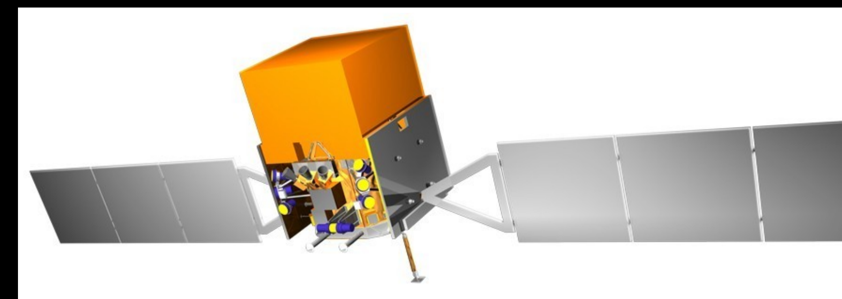
- Fermi Observatory

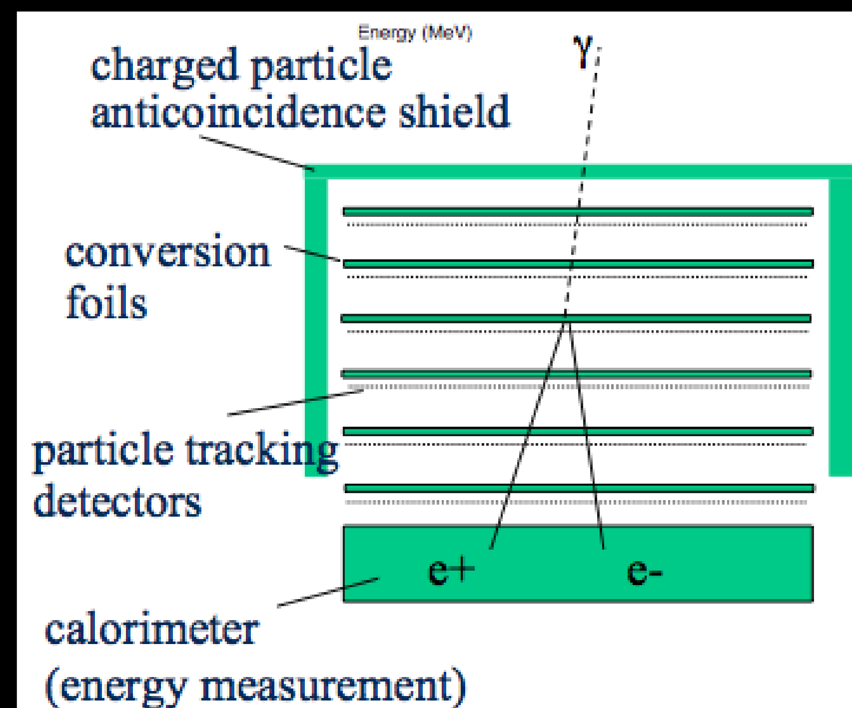
Three main parts:

A tracker to determine the trajectory of the $e^{\pm}$

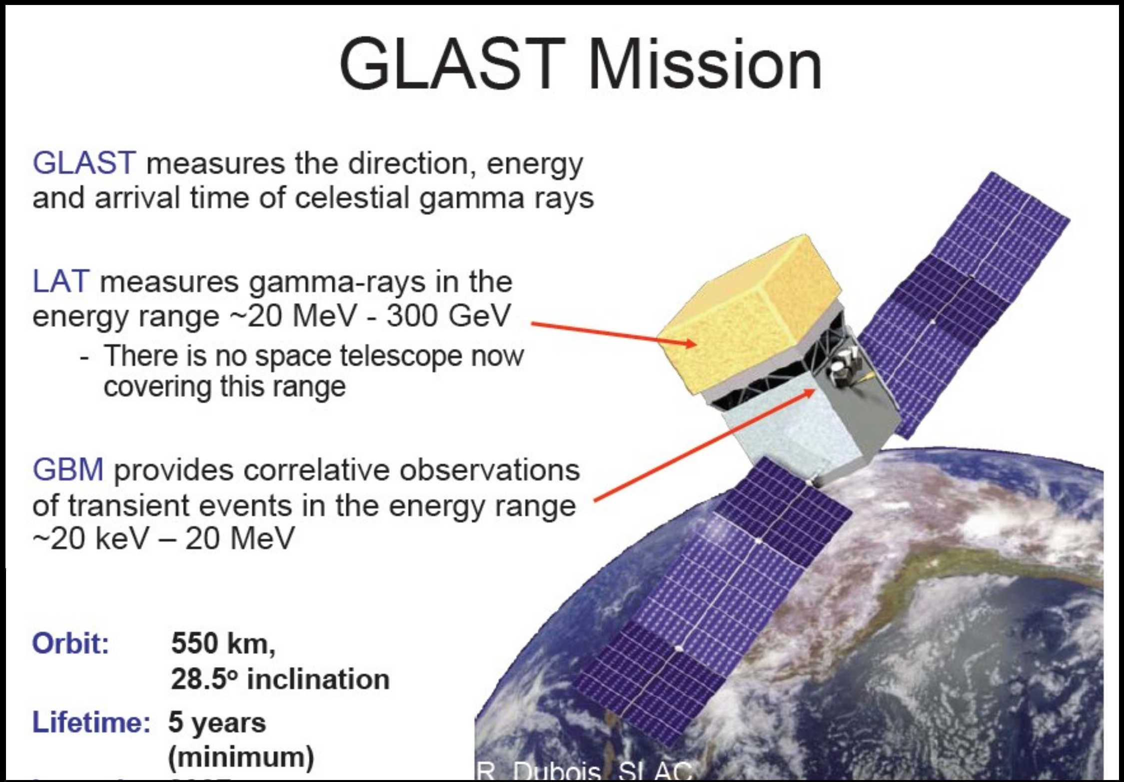
A calorimeter for measuring the energy

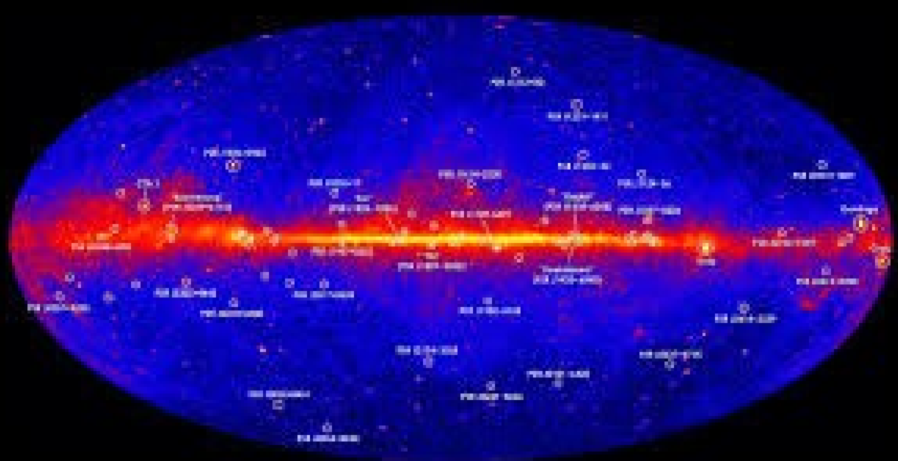
An “active shield” against charged cosmic rays (particle detector set in anti-coincidence)





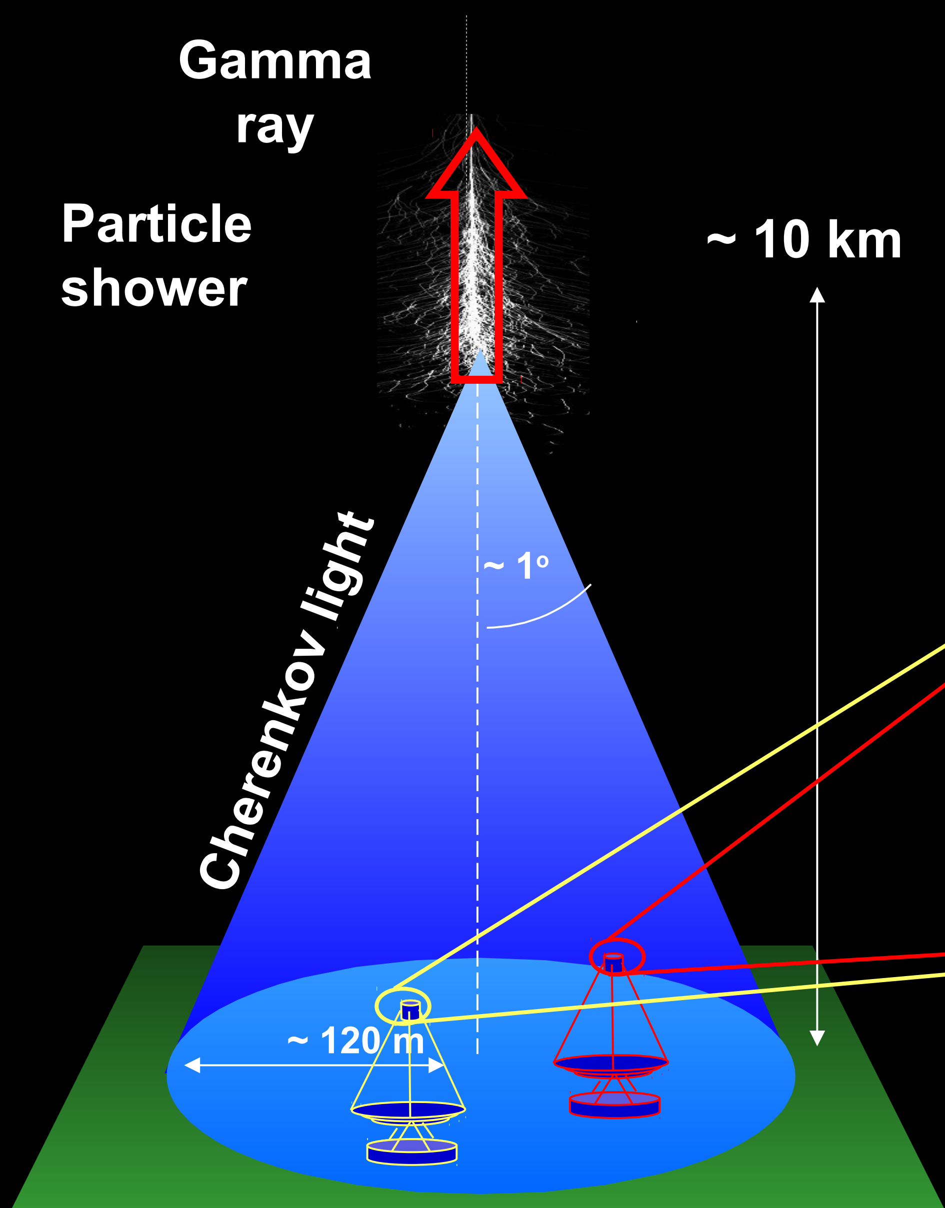
- Skymap for first 4 years
- Renamed as Fermi Observatory



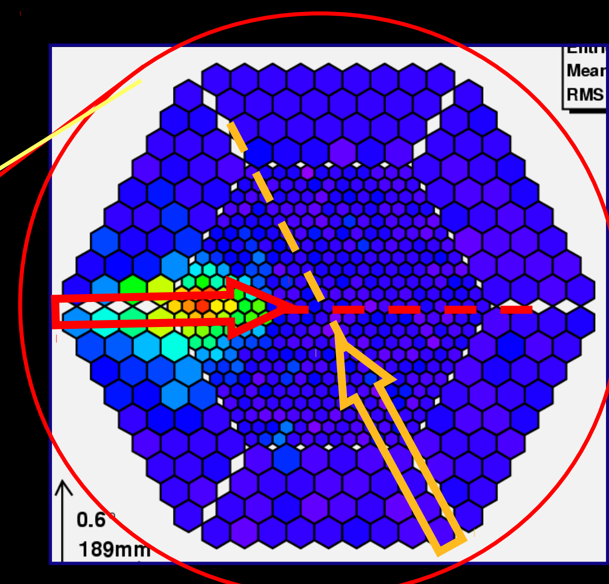


- Launched successfully in 2008 June, delivering a wealth of data on gamma ray sources, > 1500 point sources

Imaging Air Cherenkov Telescopes



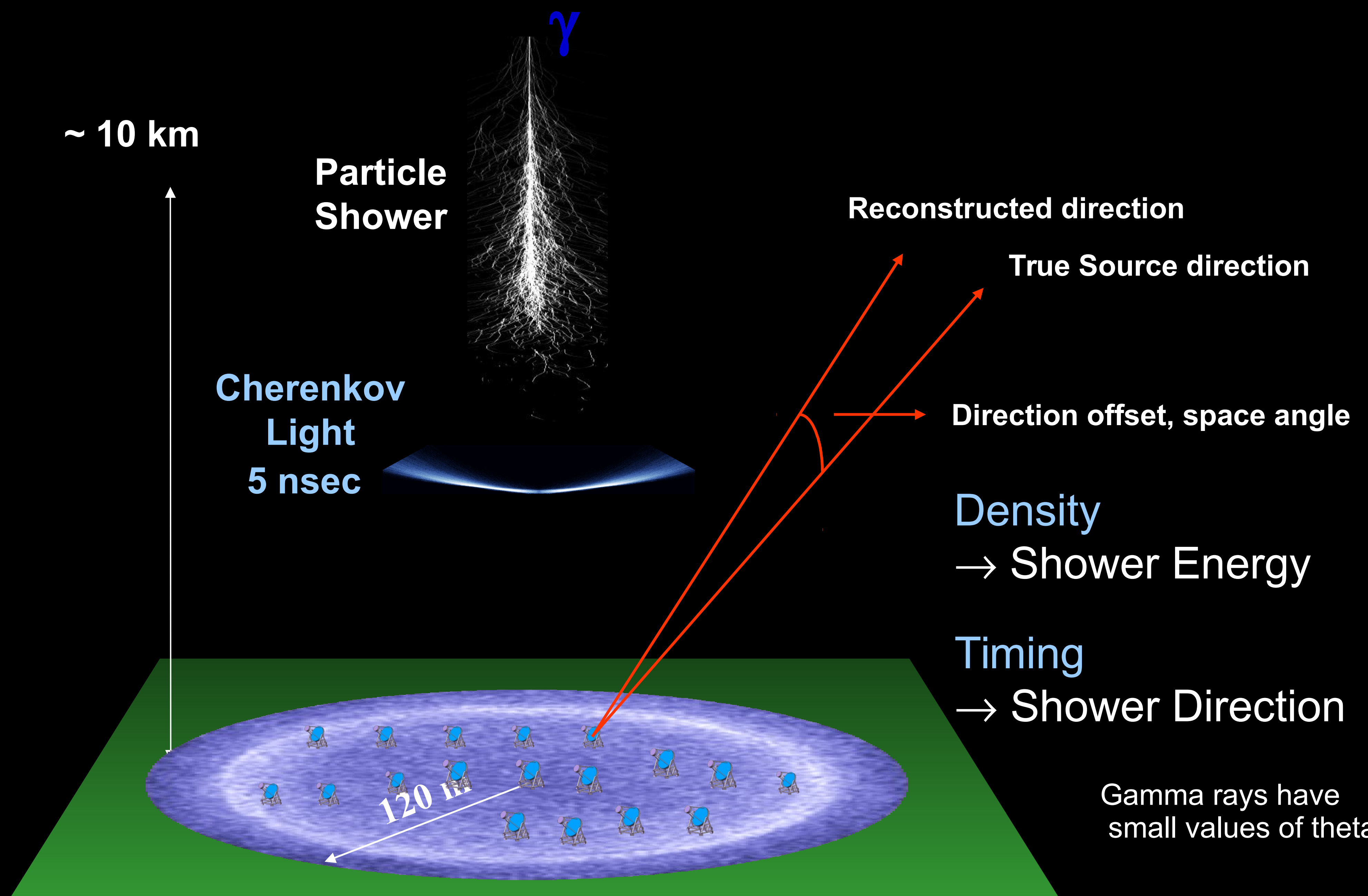
Cherenkov light Image of particle shower in telescope camera



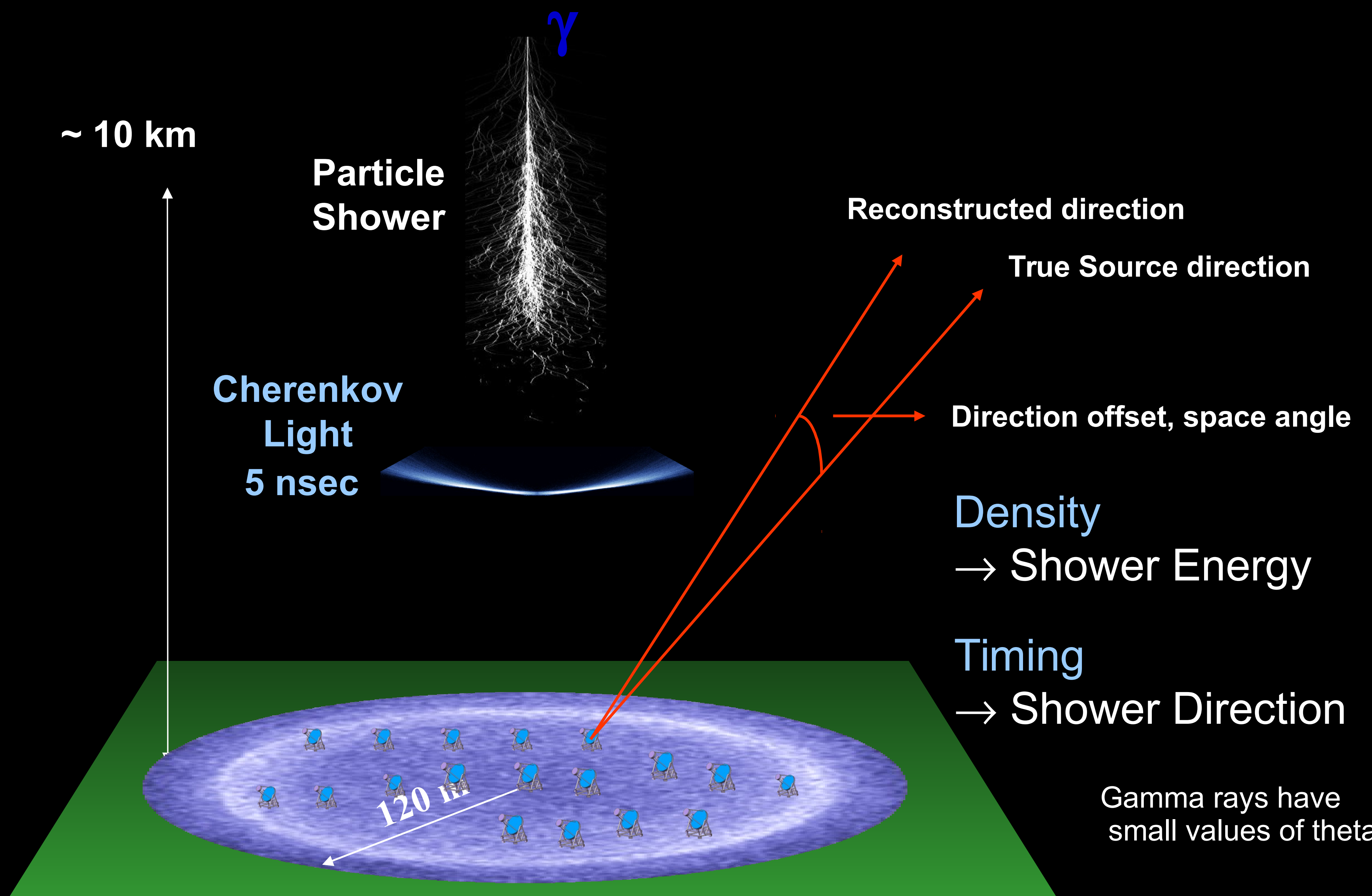
reconstruct:
arrival direction, energy
have to reject hadron background

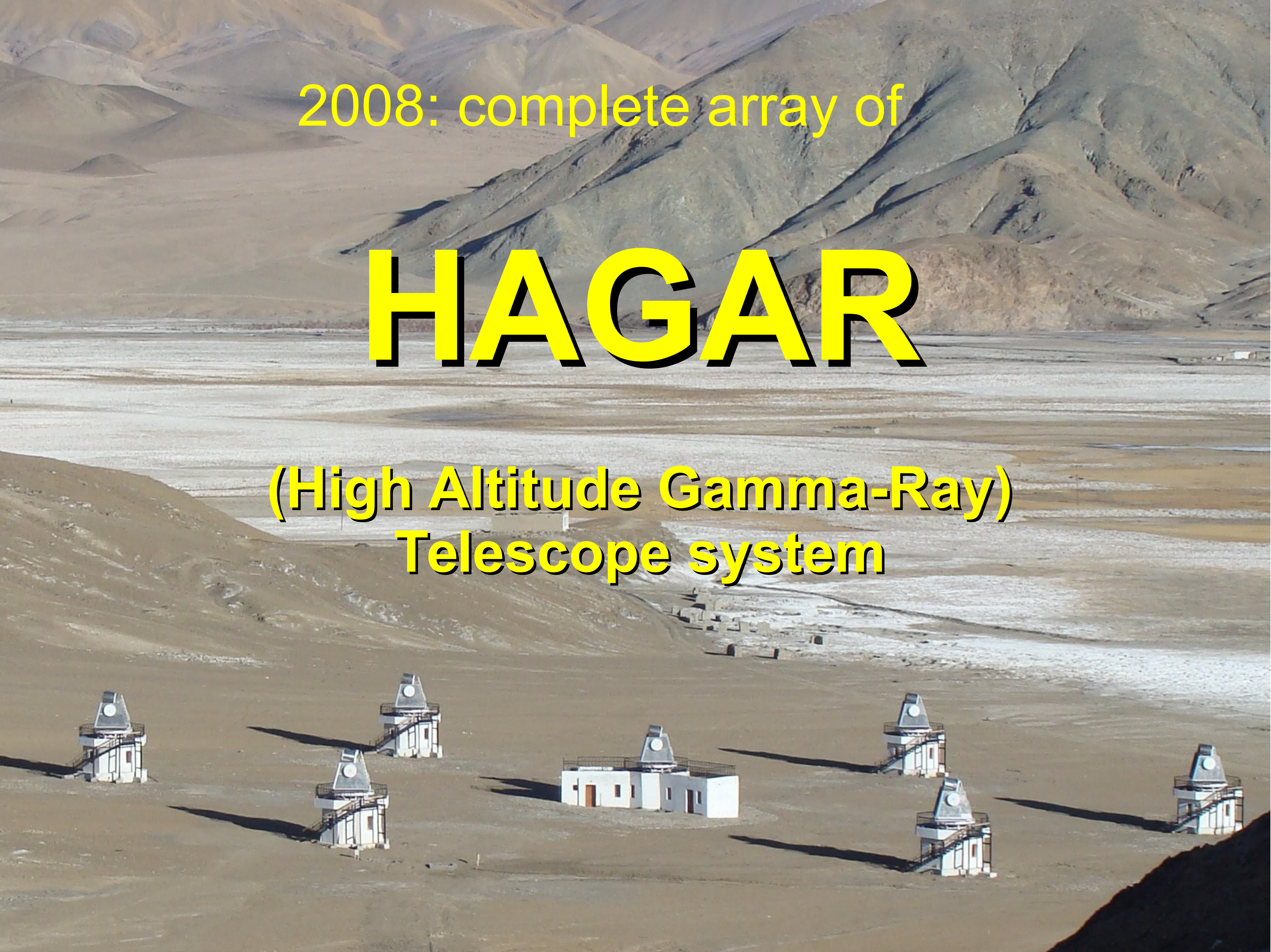
Current generation of IACTs

Detection of Cosmic Rays and Gamma Rays using Wavefront Sampling Technique

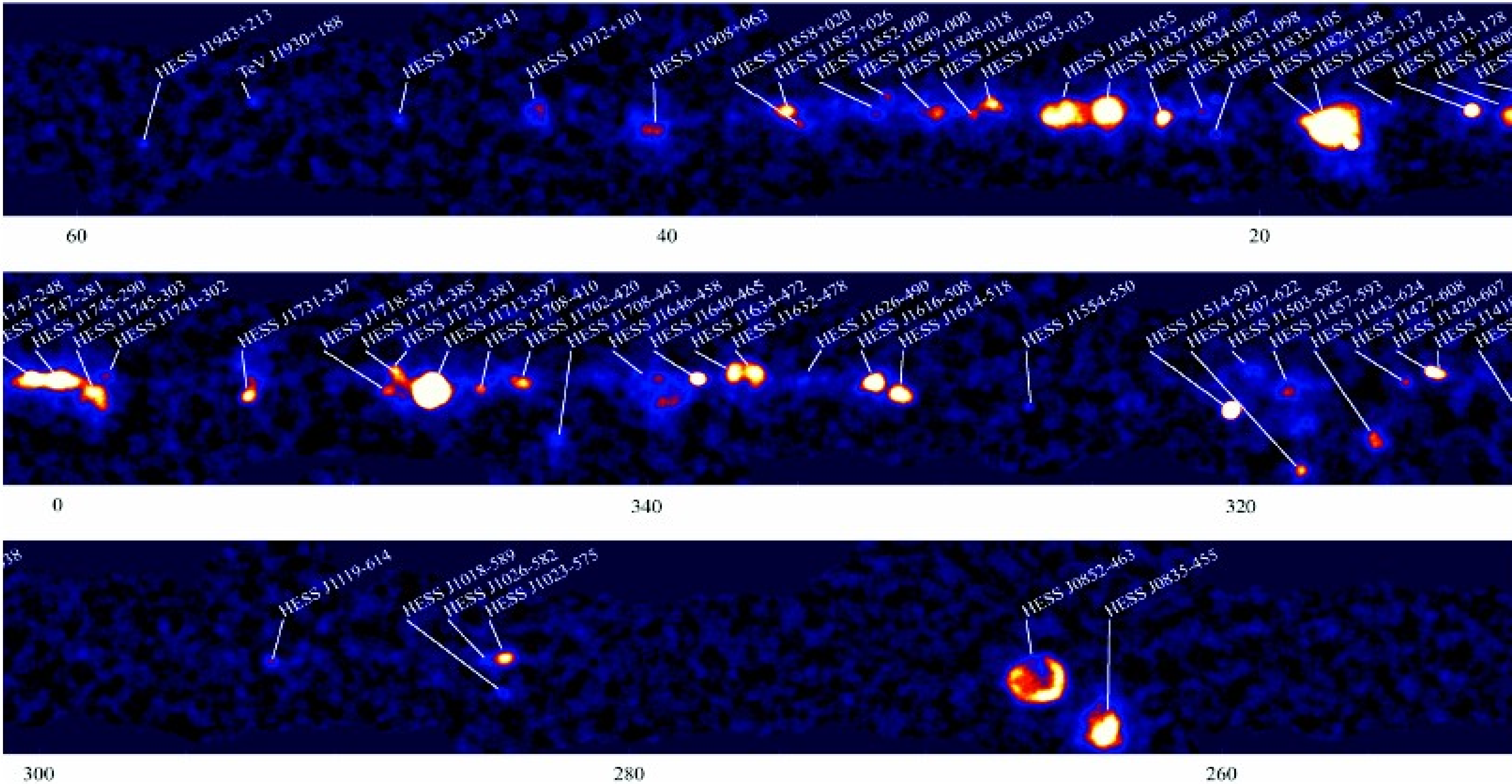


Detection of Cosmic Rays and Gamma Rays using Wavefront Sampling Technique




2008: complete array of
HAGAR
(High Altitude Gamma-Ray)
Telescope system

The Milky Way as seen by H.E.S.S



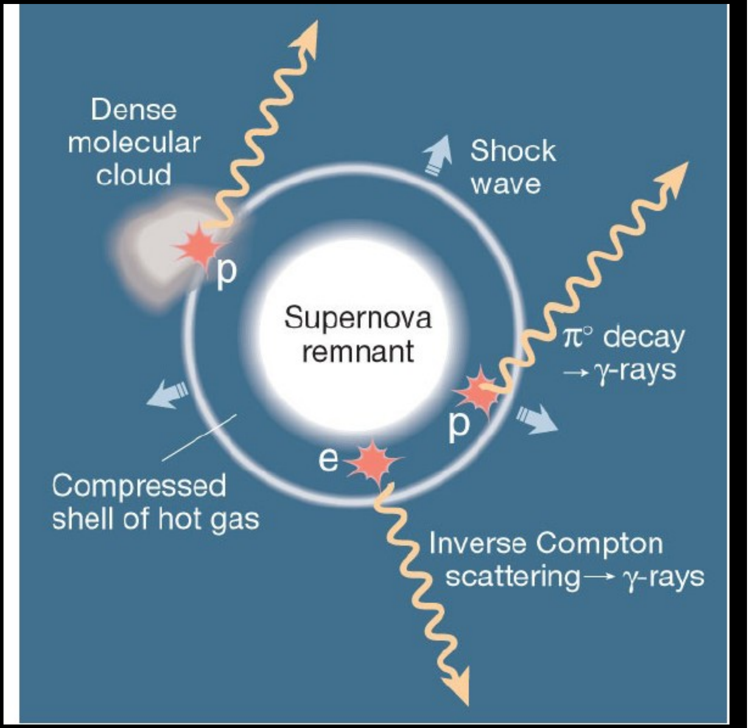
Numerous galactic sources seen : PWNe, SNRs, Unidentified gamma ray objects , in total > 75 interesting objects

Sources of galactic cosmic rays

prime candidates: **Supernova Remnants**

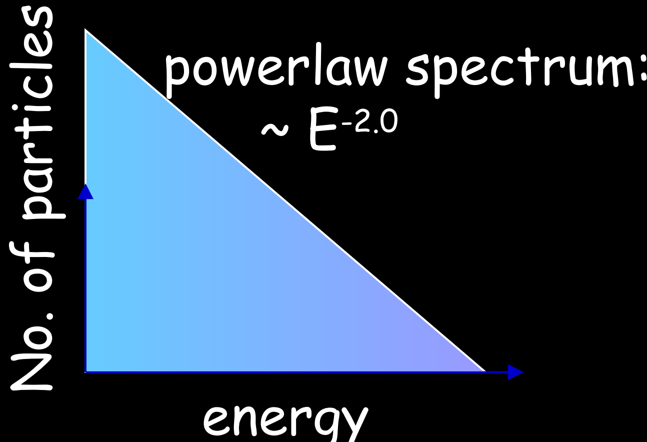
- Energetics ~ 10^{51} ergs (rate 1/30 years)
- Necessary power to GCR population.
- E>100TeV acceleration time: ~1000 years via non linear amplification of seed B and 10% efficiency

(Bell and Lucek 2001)



End of the lifetime of a star when it runs out of fuel, pressure imbalance creates core to collapse and release of huge energy.

A blast wave ejects the star's envelope into ISM (shock) and leaves behind a debris (neutron star or a Pulsar or White Dwarf depending on mass)



One of the most important ones : Crab (Taurus constellation) in 1054 AD

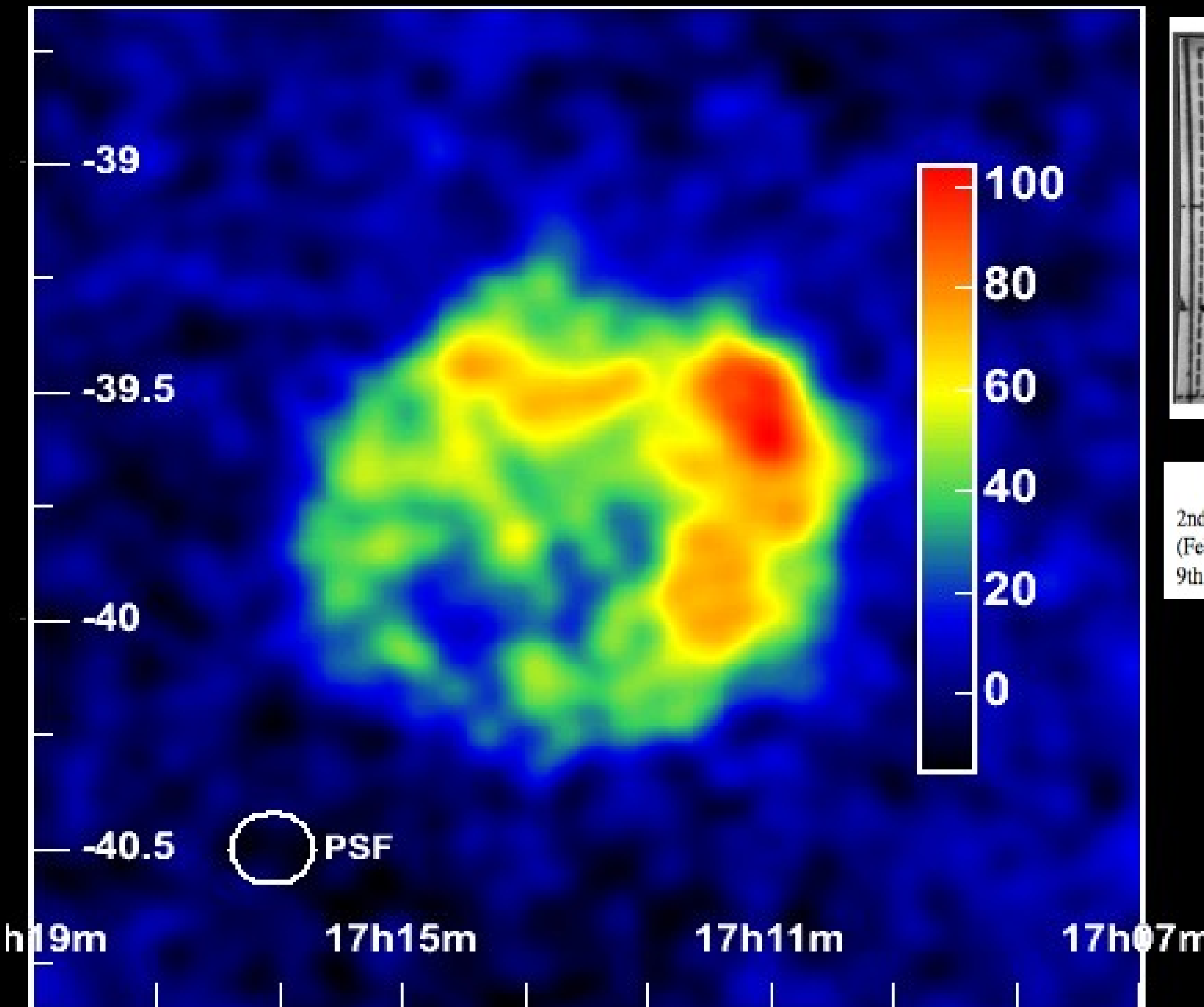
(recorded by Chinese astronomers)

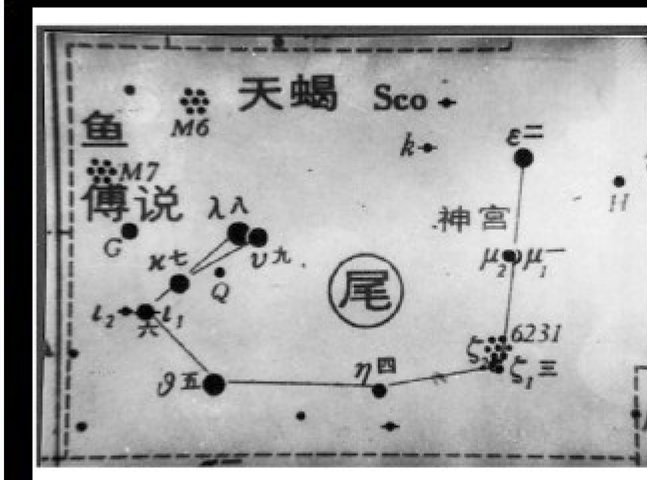
The last in our galaxy is Kepler's SNR (1604)

One of the recent ones is SN1987A in LMC

H.E.S.S. RXJ 1713.7-3946

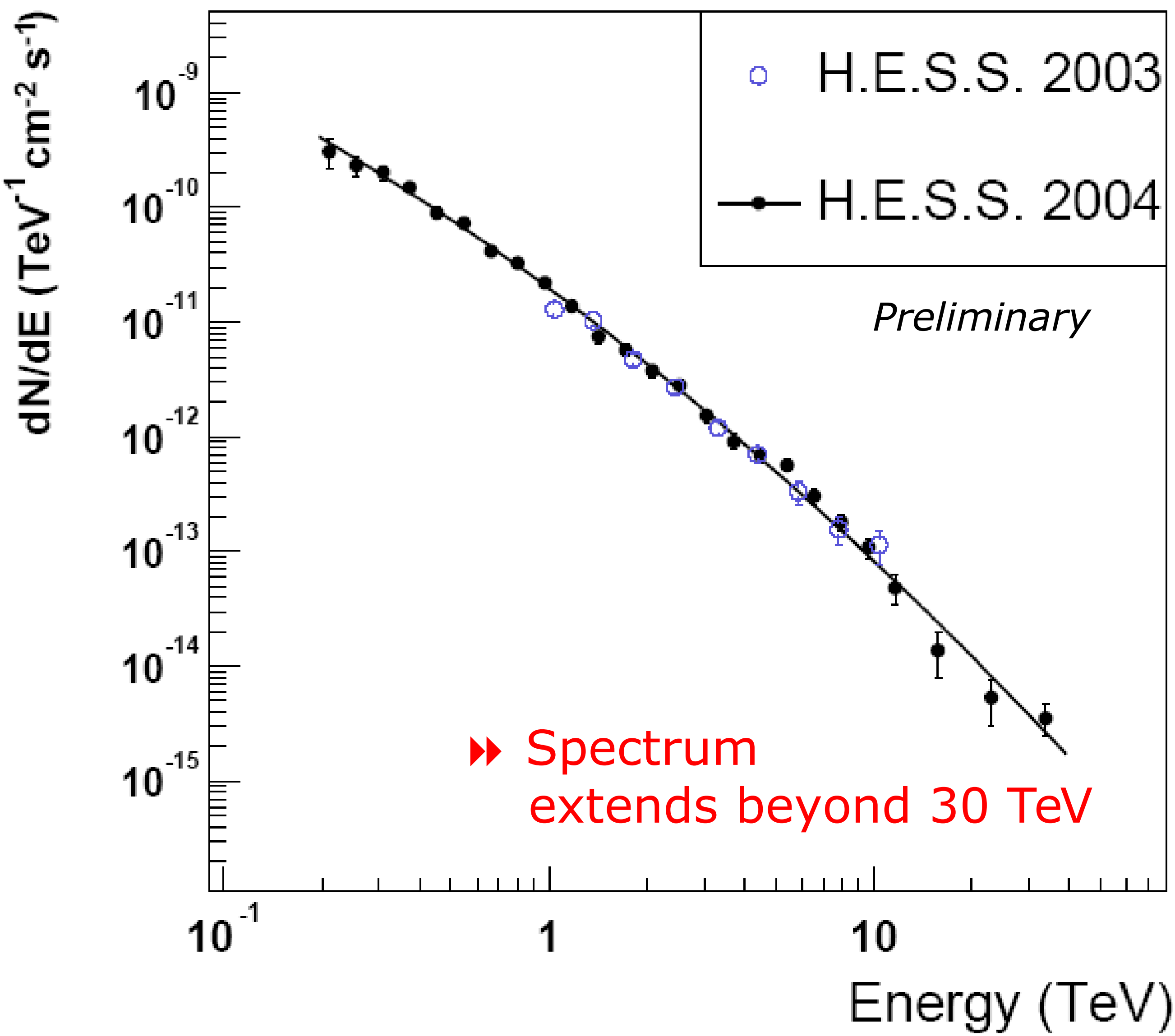
First-ever astronomical TeV image

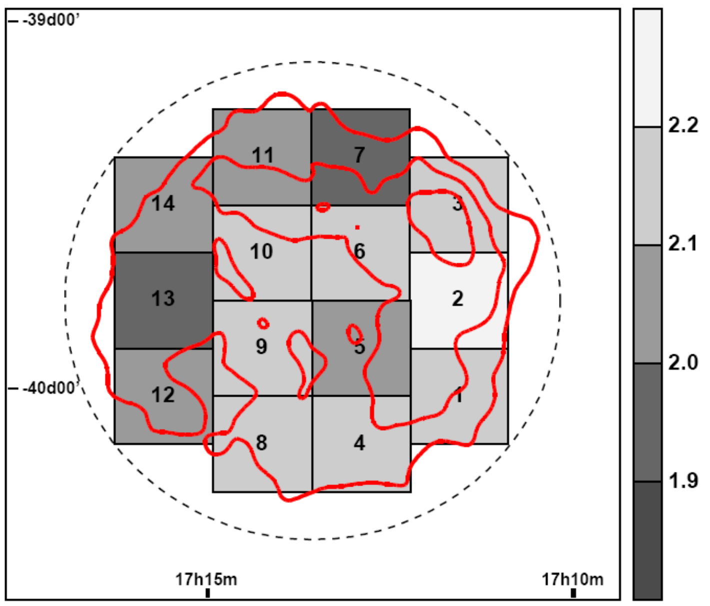




"A guest star appeared within the asterism Wei during the 2nd lunar month of the 18th year of the Tai-Yuan reign period (February 27 — March 28, AD393), and disappeared during the 9th lunar month (October 22 — November 19, AD393)."

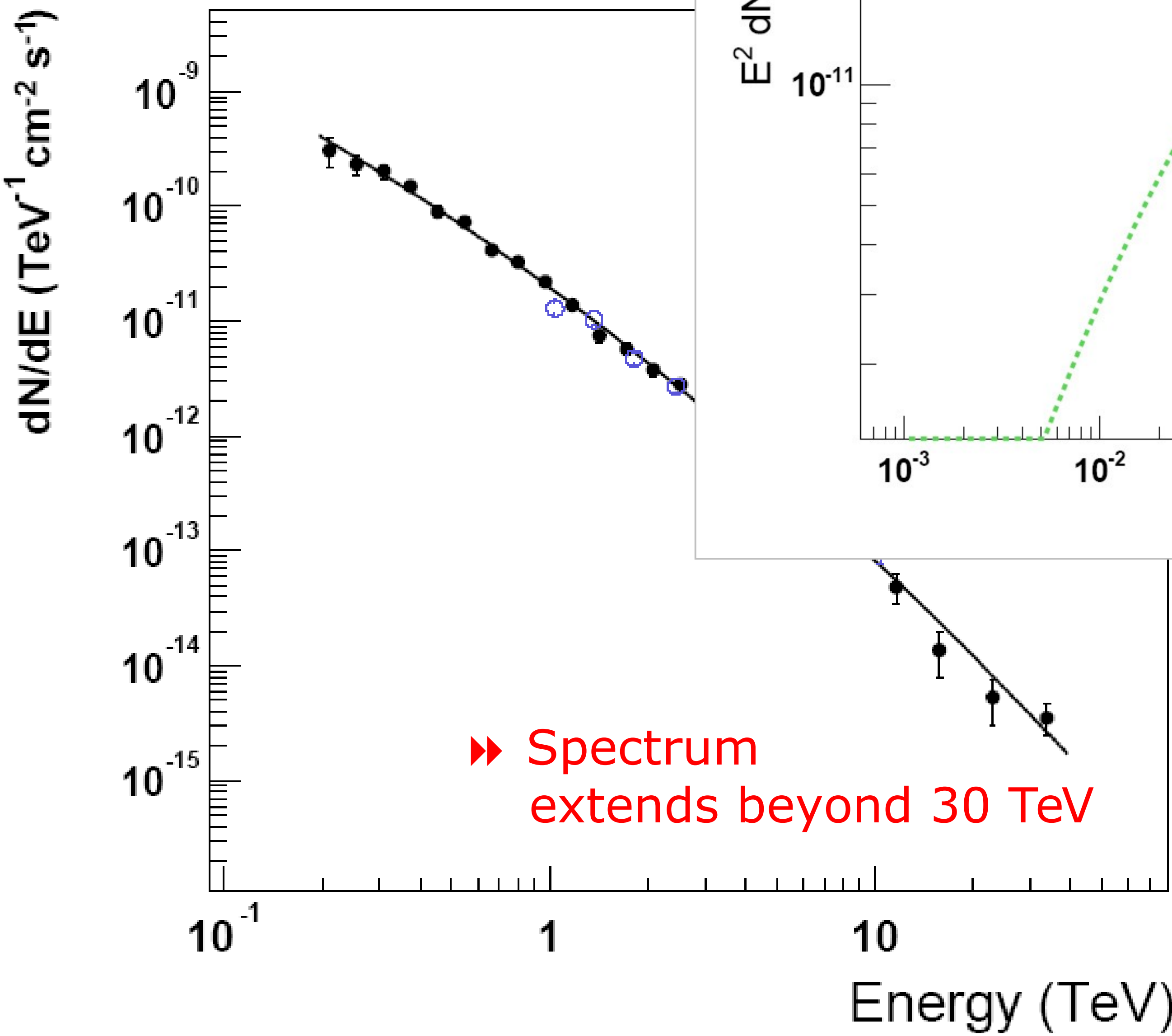
Spectra

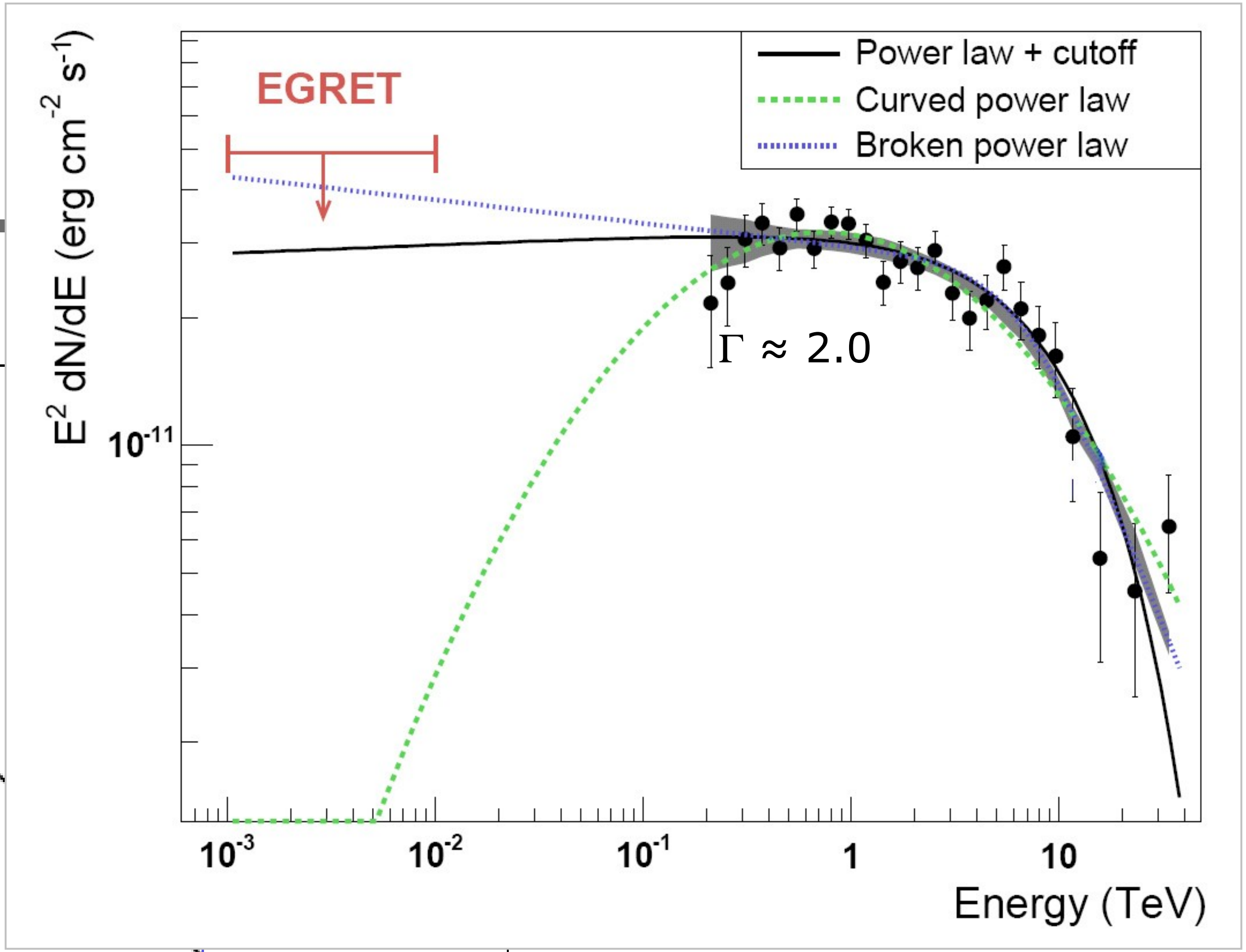




- Index ~ 2
- Little variation across SNR
- Cutoff or break at high energy not clear ??

Spectra

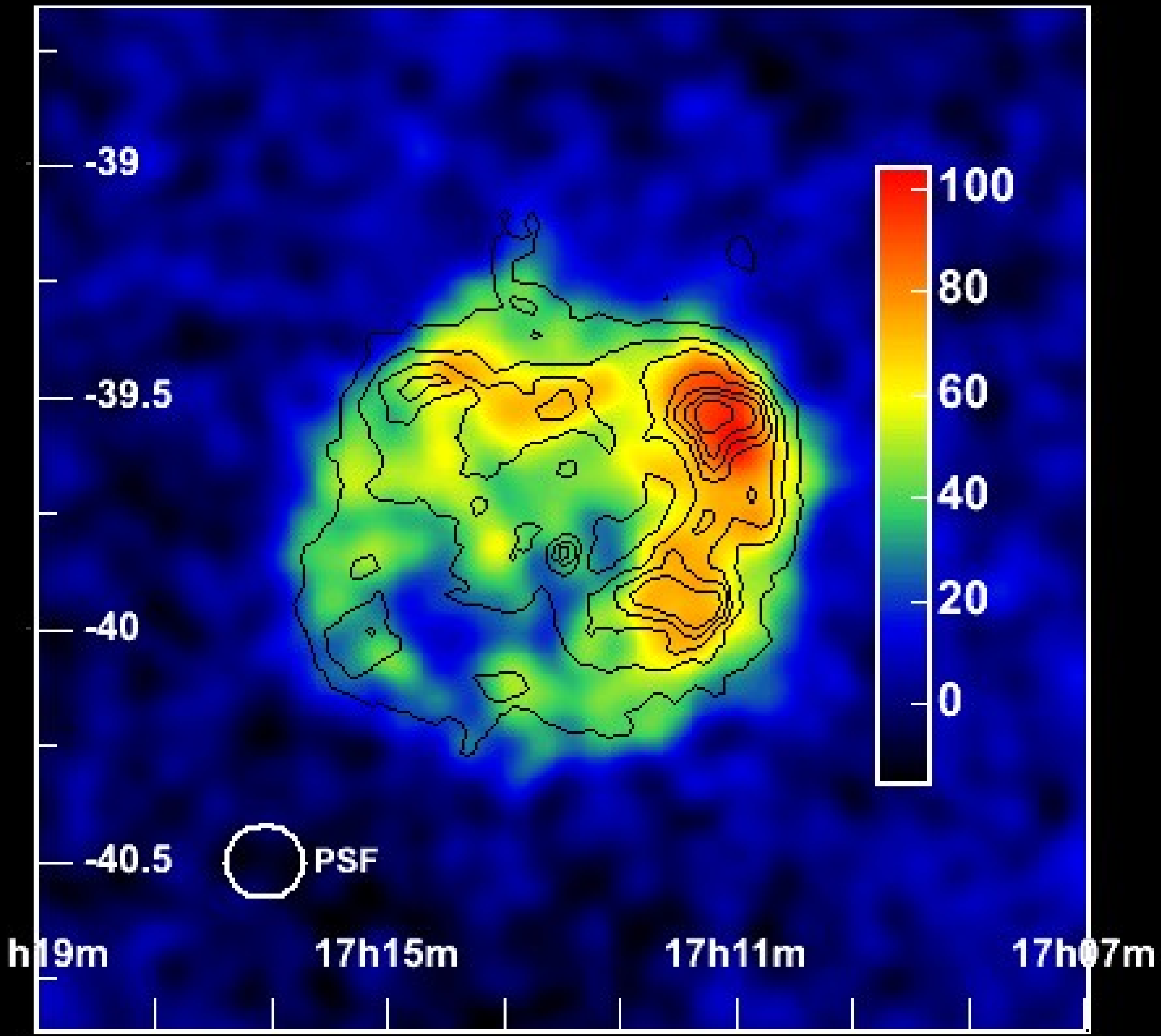




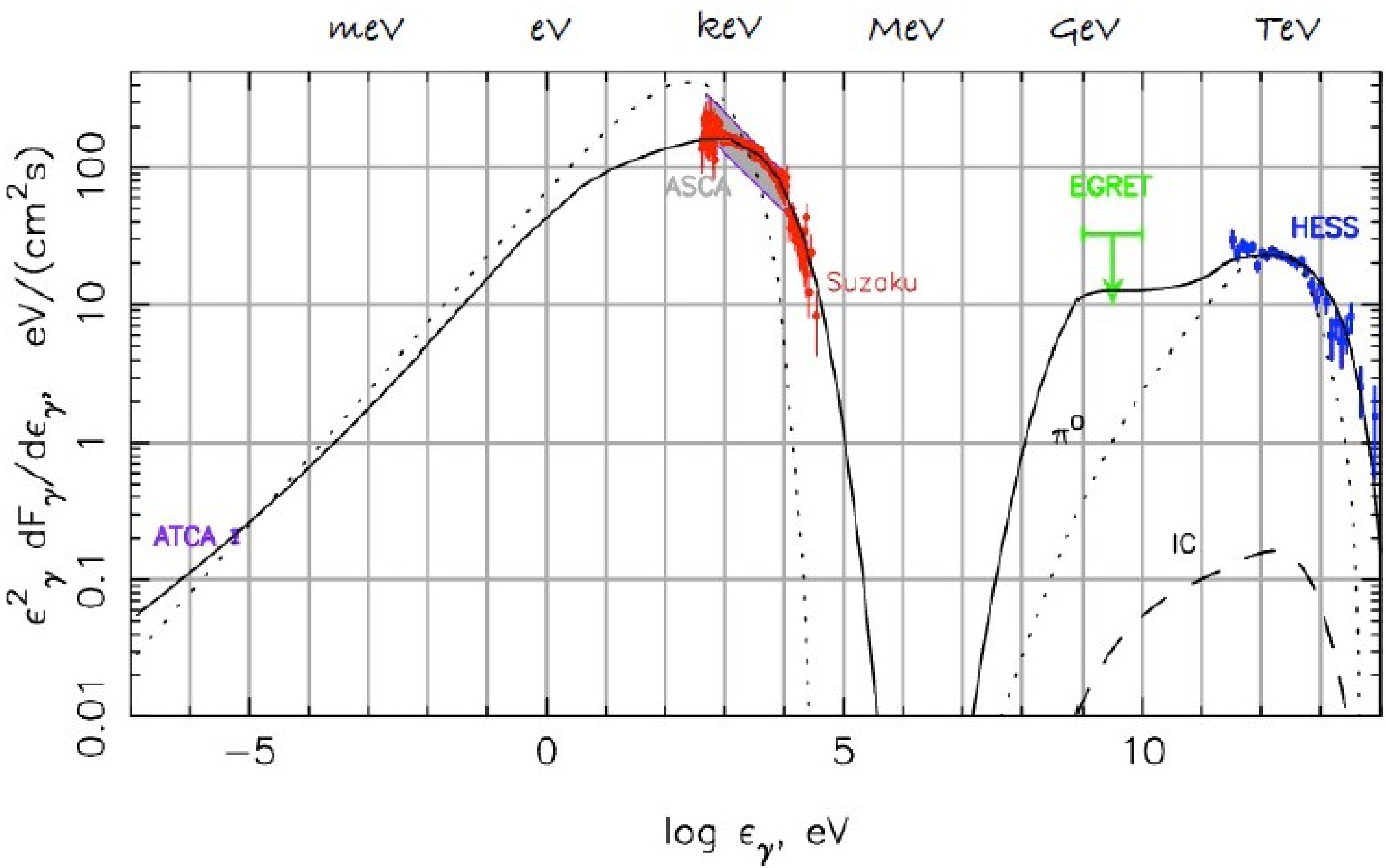
- Spectrum extends beyond 30 TeV

- Index ~ 2
- Little variation across SNR
- Cutoff or break at high energy

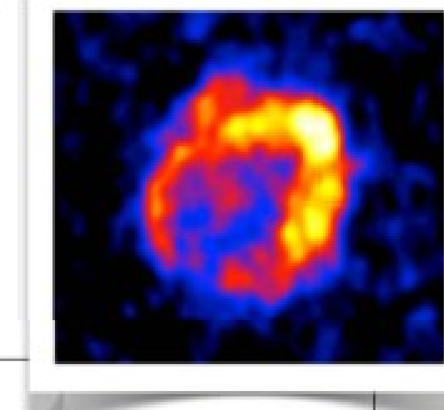
Correlation with (ASCA) X-rays

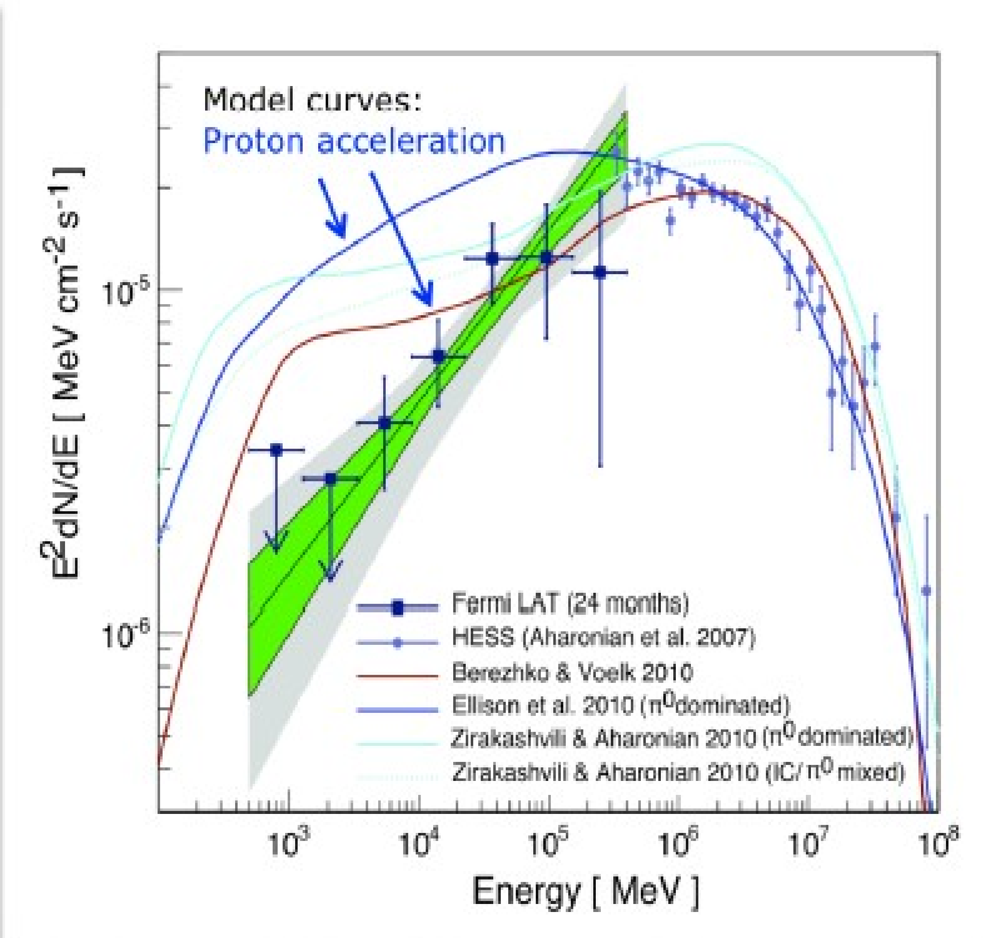


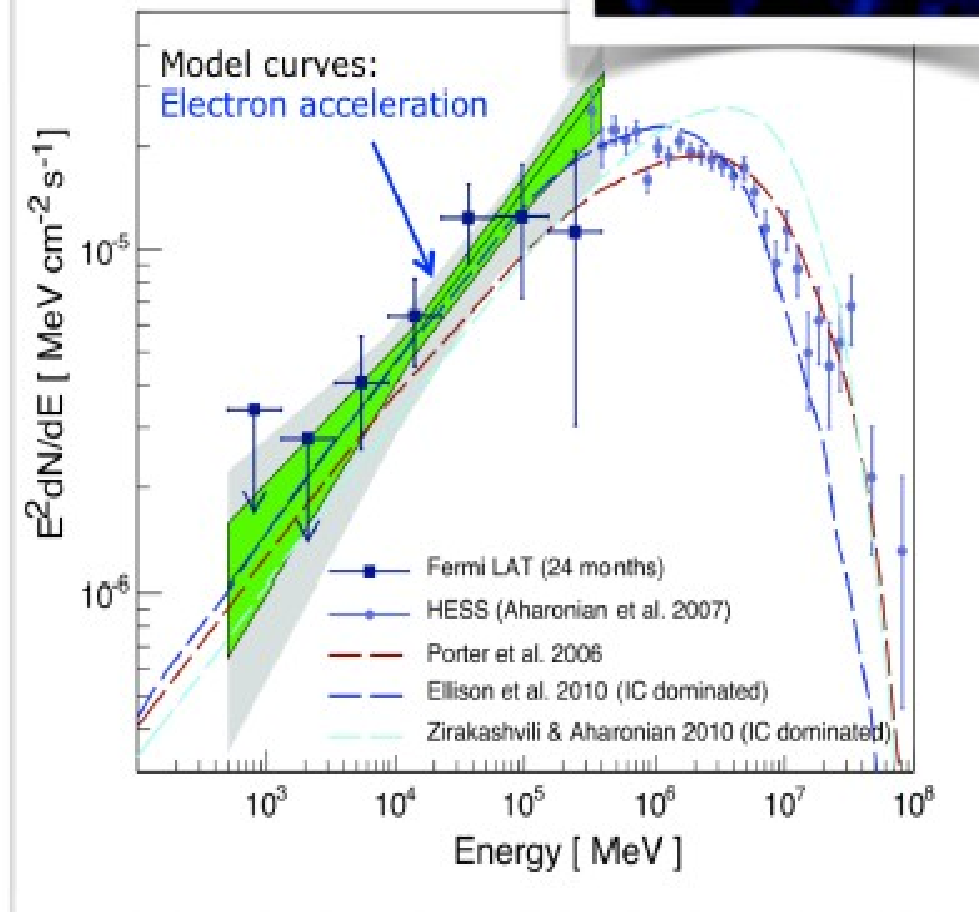
Supernova Remnant RX J1713.7-3946



The best candidate? RX J1713.7-3946

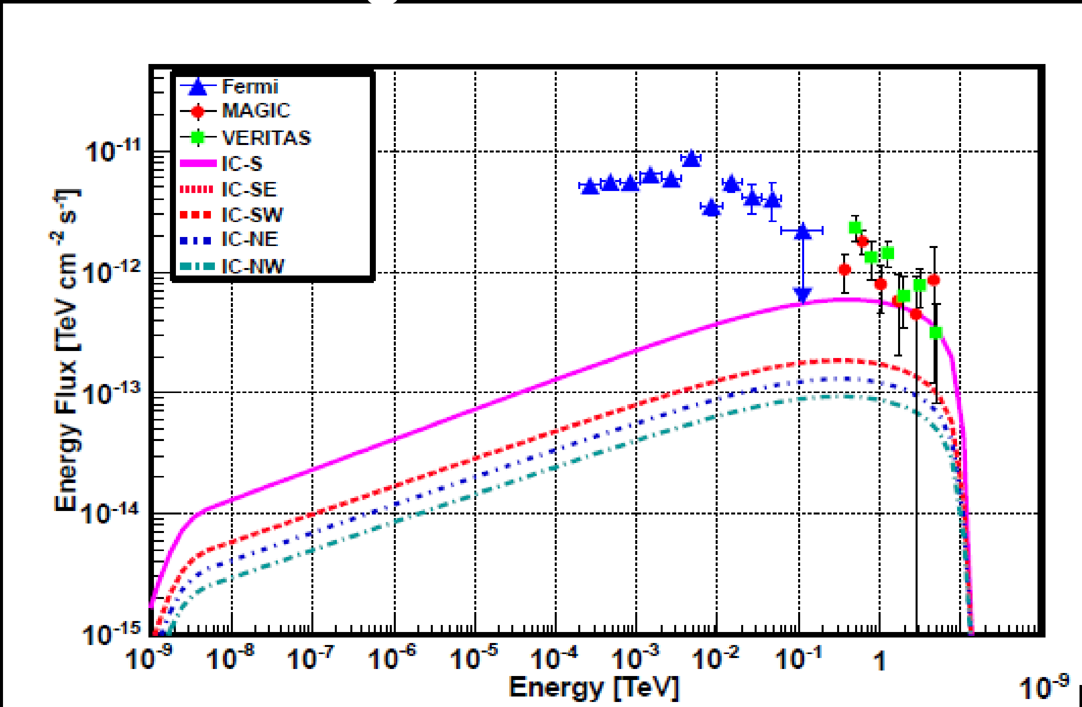






- It seems that the lepton-dominated case is favored, given the Fermi-LAT measurement and the low ambient gas density.

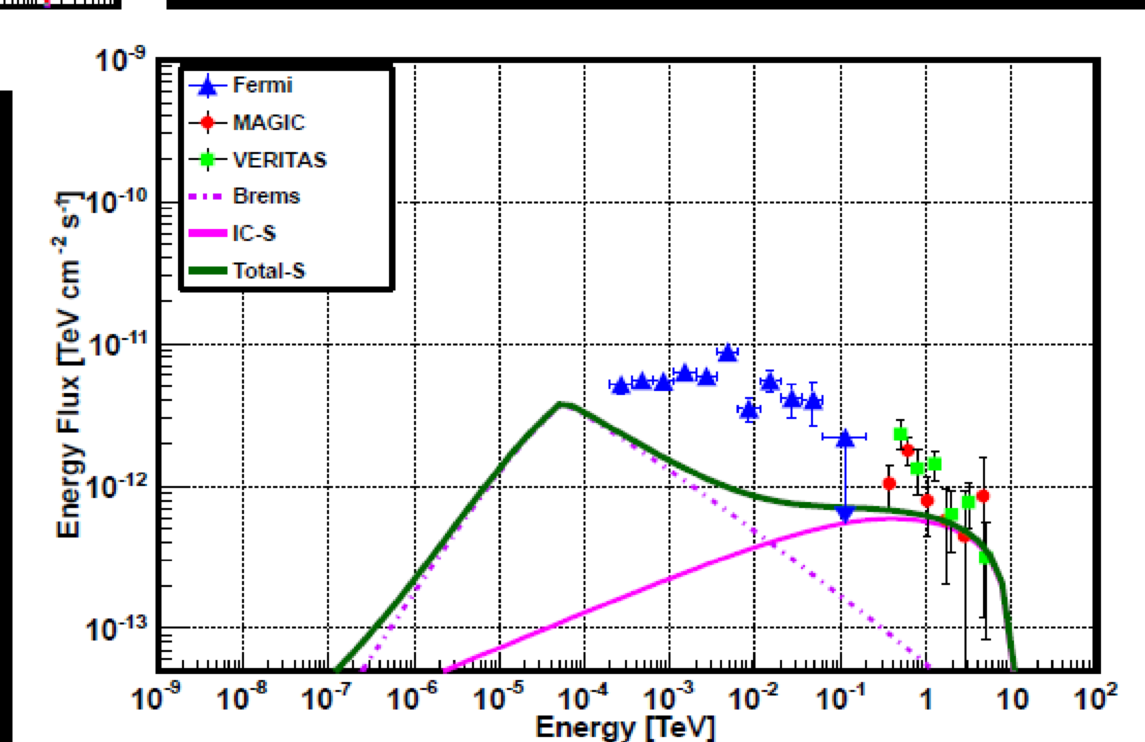
GeV-TeV modelling with SNRs : Shell regions in CasA



Calculate IC spectra for the Southern region, cannot be explained by a pure leptonic model.
(IC + bremmstrahlung)

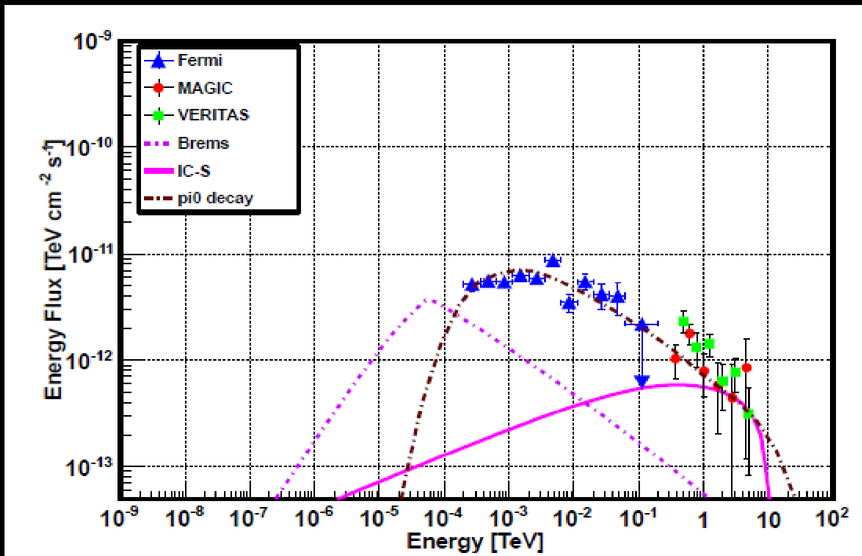
$$\frac{dN}{d\gamma} = N_e\, \gamma^{-\alpha}\, \exp\left(-\frac{\gamma}{\gamma_{max}}\right)$$

Parameters	Values
γ_{max}	3.0×10^7
n_H	$10\ cm^{-3}$
α	2.54
Energy (W_e)	4.5×10^{48} erg



L.Saha, T.Ergin, PM et al, A&A 563 (2014)

GeV-TeV modelling with SNRs : Shell regions in CasA



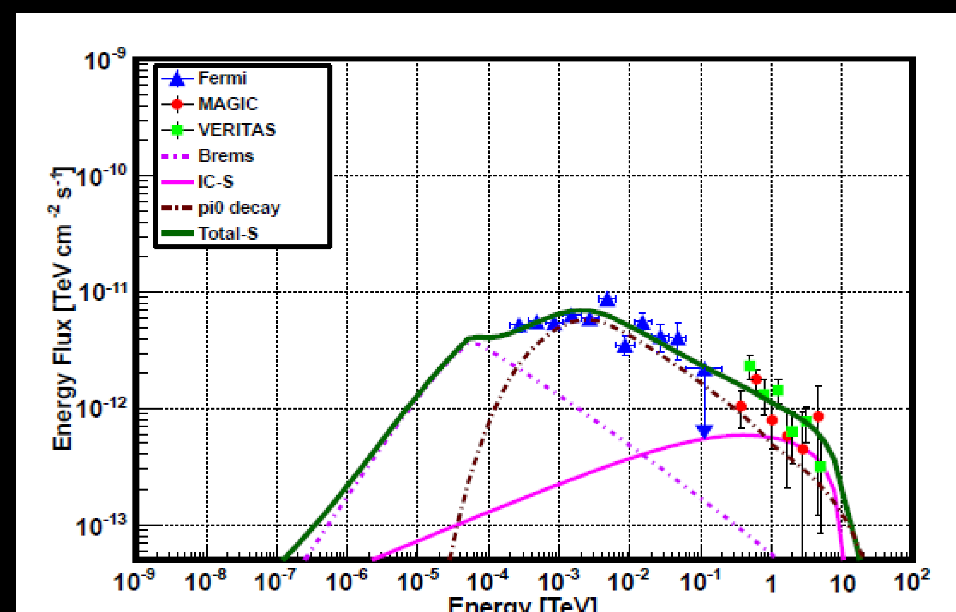
Parameters	Set-I (hadronic)	Set-II (hadronic+leptonic)
ρ	2.05 ± 0.05	1.14 ± 0.2
β	**2.36 ± 0.02**	2.45 ± 0.02
E_p^{max} (TeV)	100	100
E_p^{break} (GeV)	17	17
Energy (W_p) (erg)	**5.7** $\times 10^{49}$	3.07×10^{49}
χ^2/dof	2.5	1.9

L.Saha, T.Ergin, PM et al, A&A, 563 (2014)

Invoke hadronic model, also Lepto-hadronic model

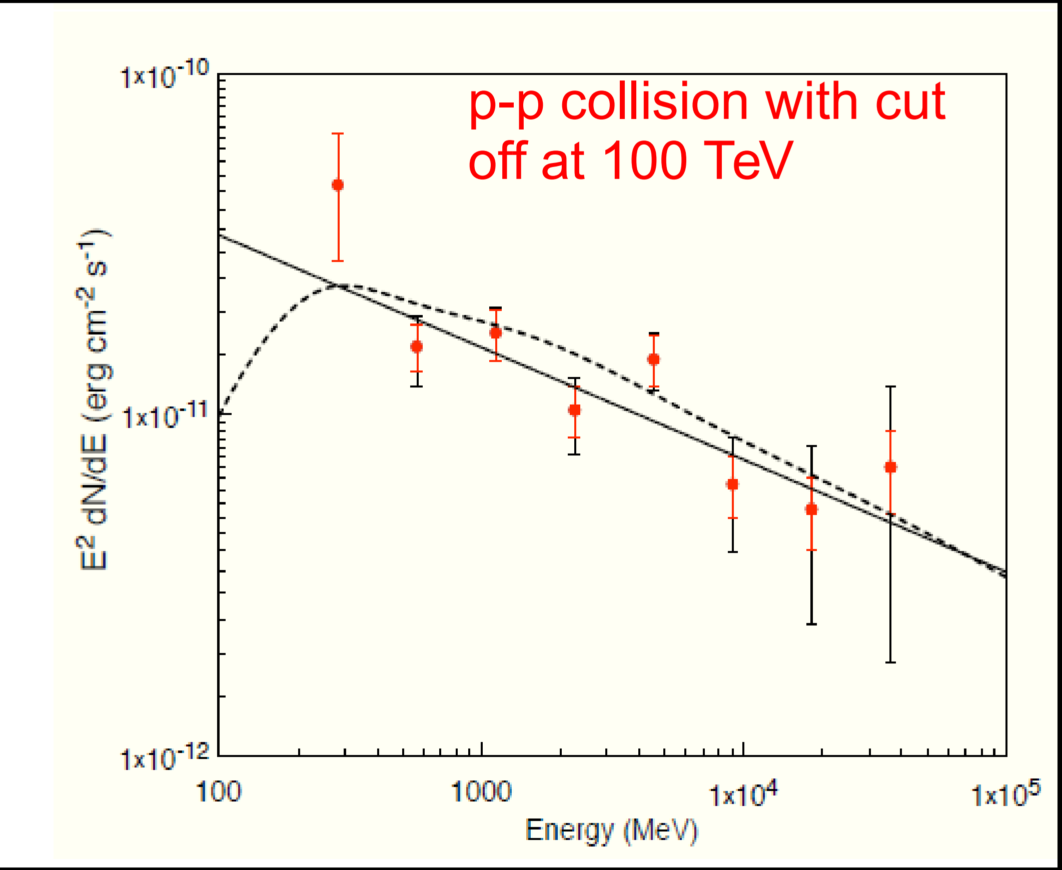
Reasonable fit parameters for lepto-Hadronic model, CasA a Pevatron ?
We need to extend the energies to 50 TeV or beyond

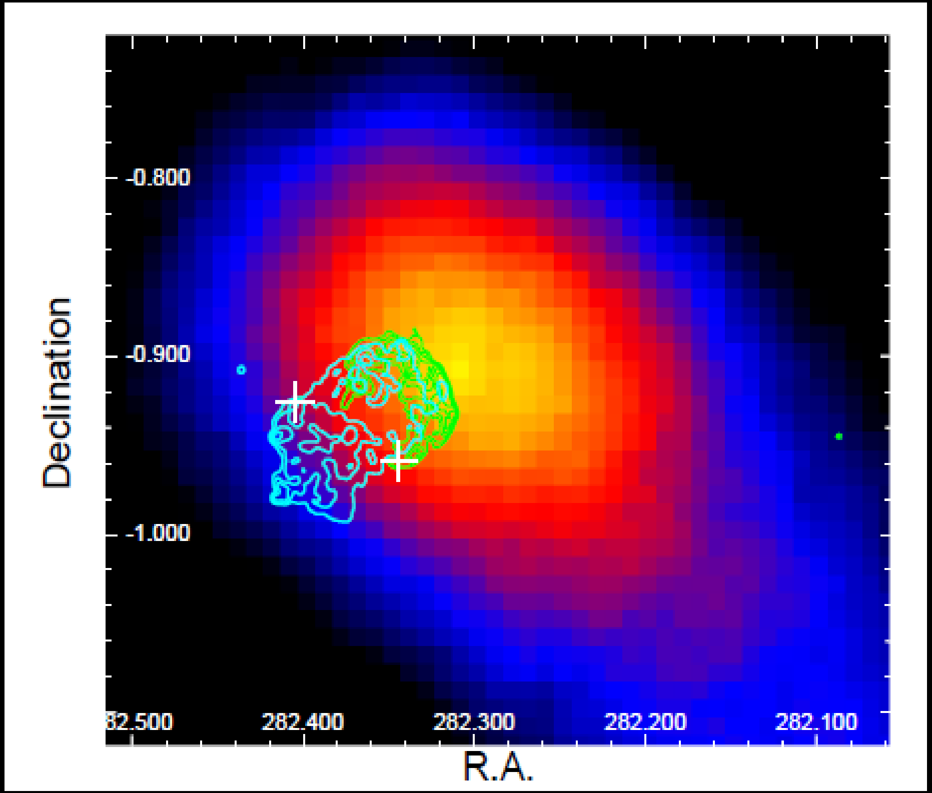
- Magnetic field amplication : > 200
- micro Gauss
- ~ 2% of CR energy to magnetic
- energy (low) => MH waves by
- cosmic rays may not be enough
- (Bell et al, 2004, Lucek and Bell 2001)



GeV-TeV physics with SNRs : 3C391

- Radio bright SNR
- Two OH maser spots at 1720 MHz
- Distance of 7.2 Kpc from H1 obs.
- Observations of CO(J = 1->0)
- ==> presence of molecular clouds





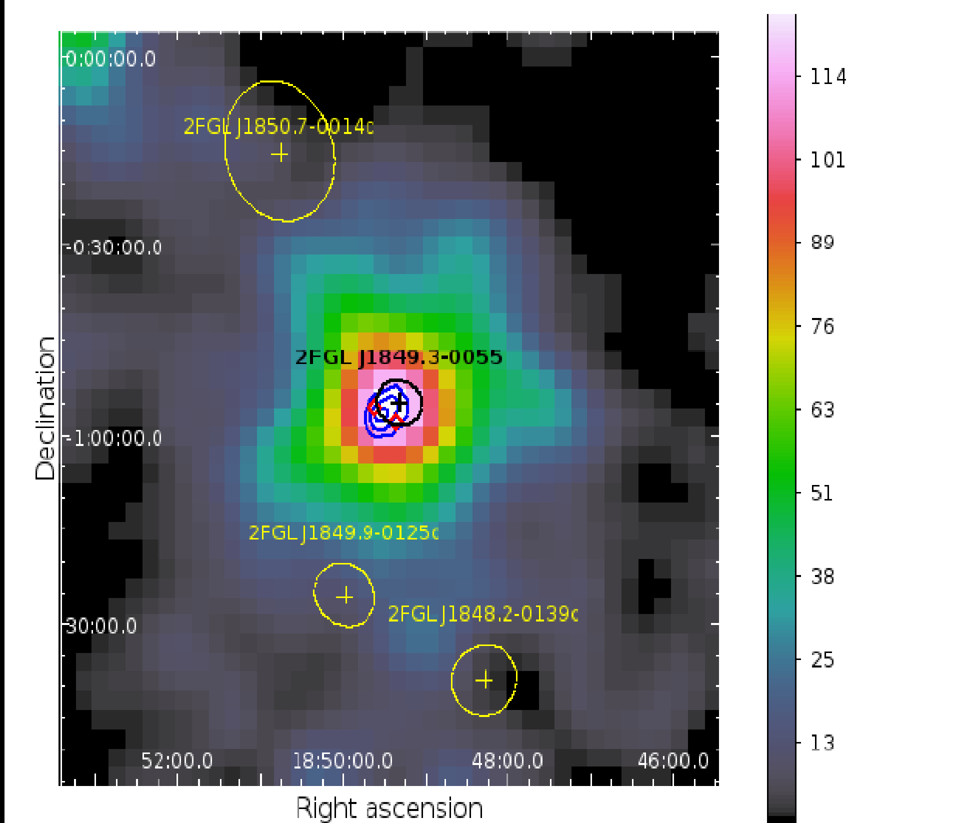
1FGL J1849.0-0055.

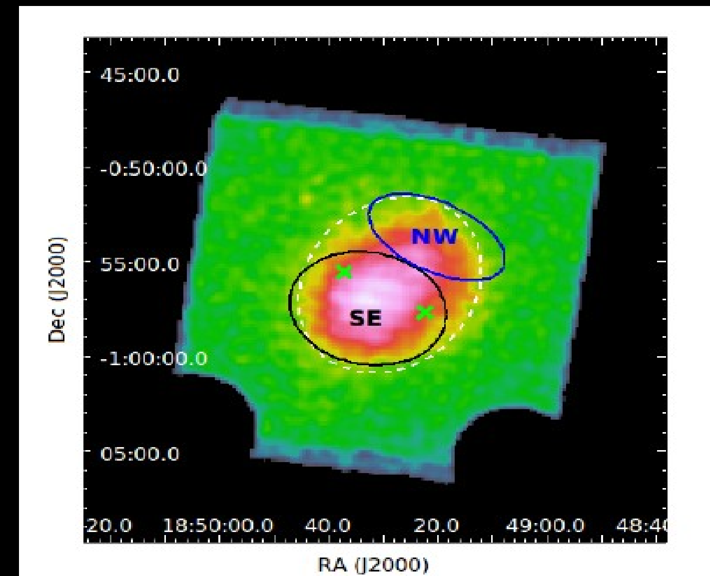
D. Castro & P. Slane - ApJ, 717, 372

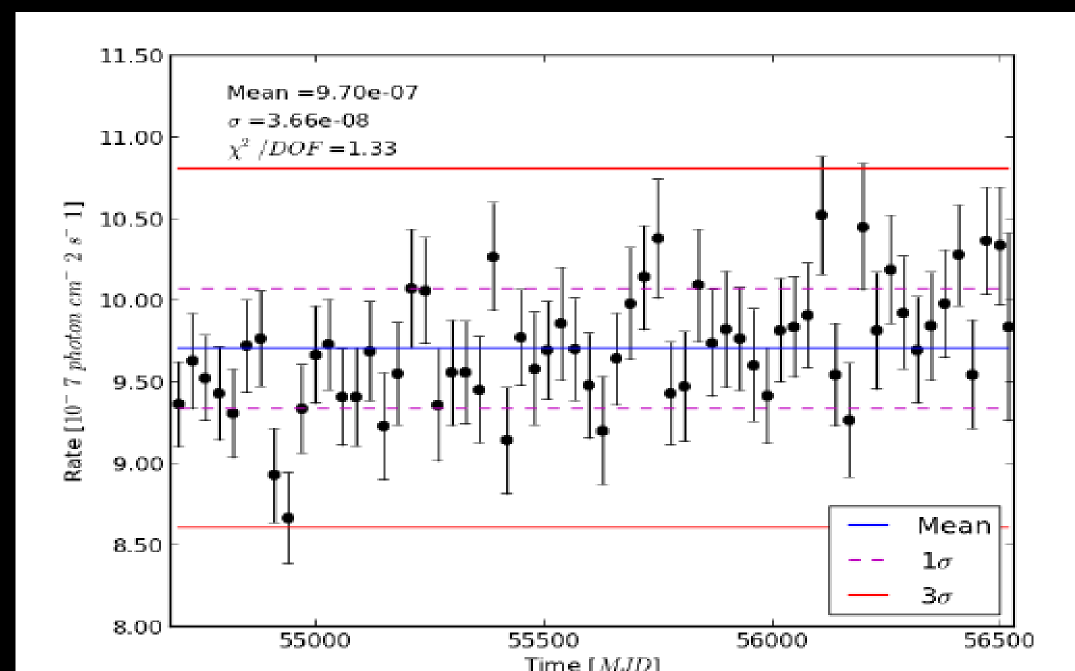
GeV-TeV physics with SNRs : 3C391

- Analyzed 4 years of Fermi-data from MM morphology SNR 3C391, detected at > 14 sigma.

Model	Intergral Photon Flux $[\times 10^{-8}$ ph cm^{-2} s$^{-1}]$	Γ_1	Γ_2	E_b [MeV]	TS
PL	8.48±0.21	2.27±0.03	–	–	164
LP	2.43±0.37	2.34±0.07	0.35±0.38	2430	176
BPL	1.48±0.31	−1.15	2.65±0.05	865	187

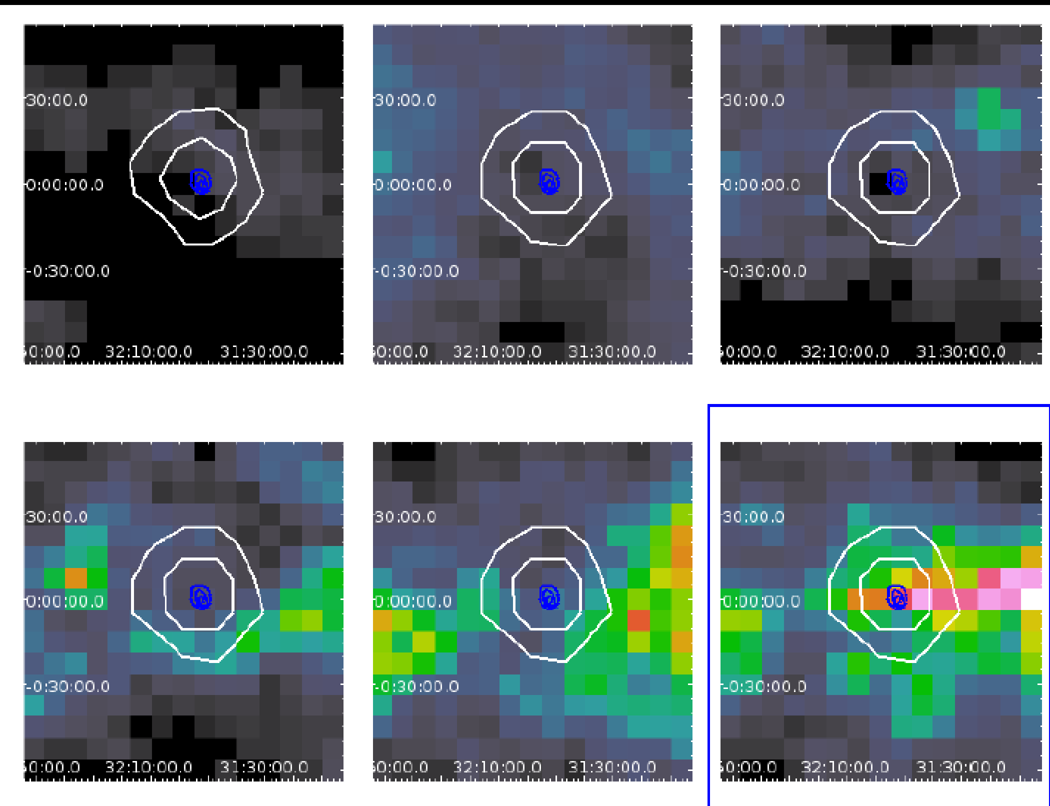






T.Ergin, L.Saha, PM, et al, ApJ 790 (2014)

GeV-TeV modelling with SNRs

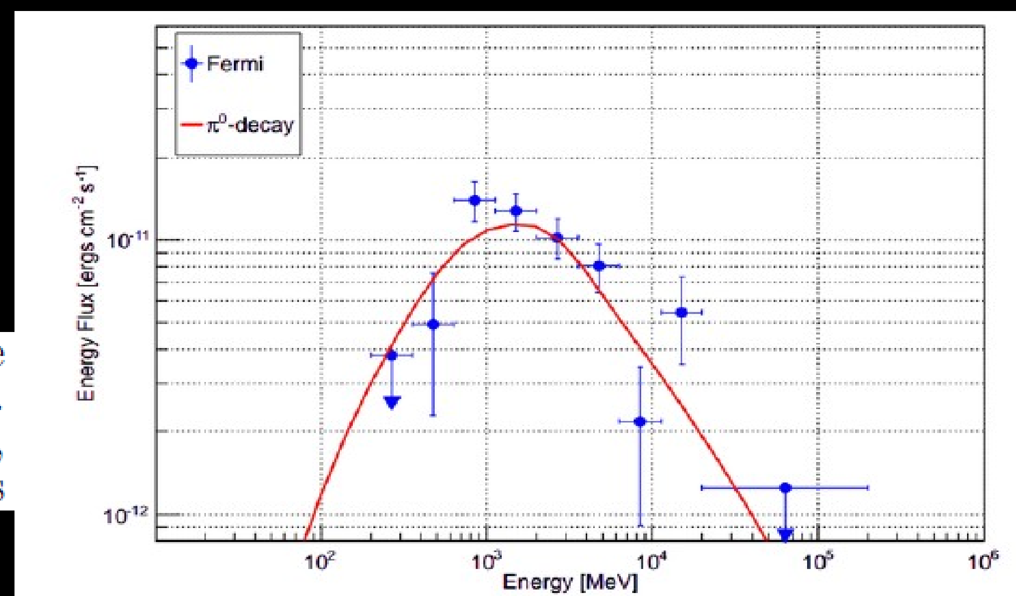


Estimate mass of cloud ~ 7 x 10^4 Msun
Density of protons ~ 387 protons/cm3

$$\frac{dN}{dE_p} = N_1 E_p^{-\alpha} \text{ for } E_p < E_{br}$$

$$= N_2 E_p^{-\beta} exp\left(-\frac{E_p}{E_{p_{max}}}\right) \text{ for } E_{br} \leq E_p \leq E_{p_{max}}$$

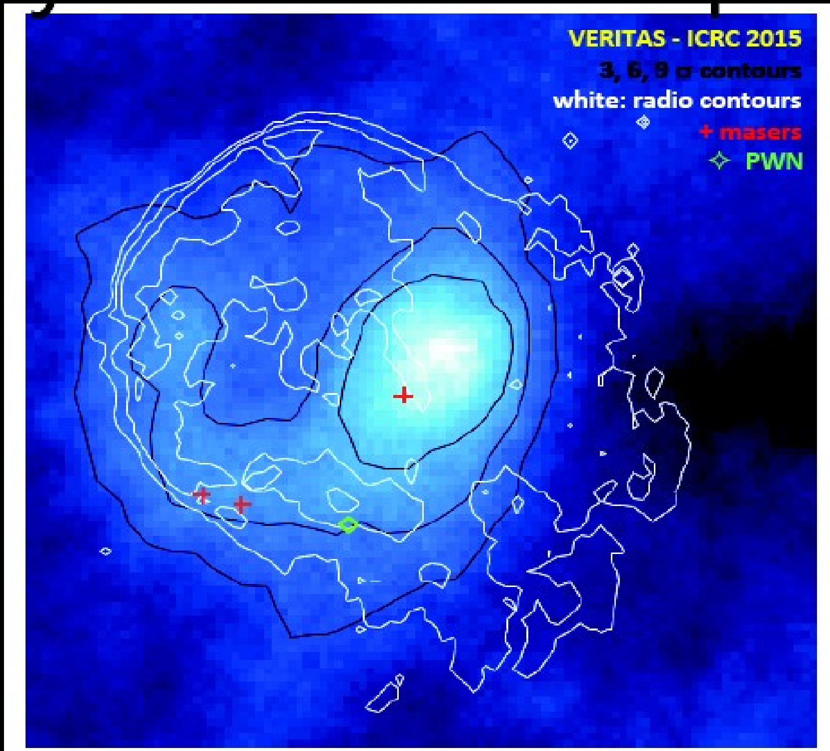
The best fit parameters for the proton spectrum are obtained by a χ^2-fitting procedure to the flux points. The estimated parameters are $\alpha = 2.5 \pm 0.04$, $\beta = 3.0 \pm 0.07$, and E_{br} at 8 GeV. The χ^2/dof is



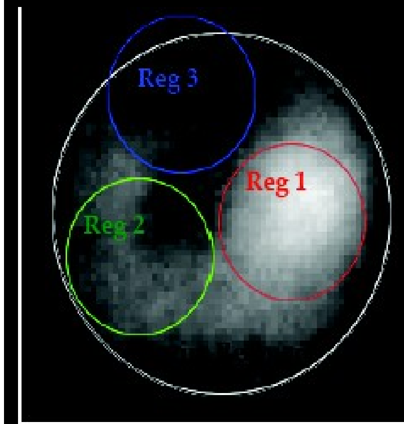
Computed TeV flux ~ 0.05% at 1 TeV :
difficult with current generation instruments but ok for future generation telescopes

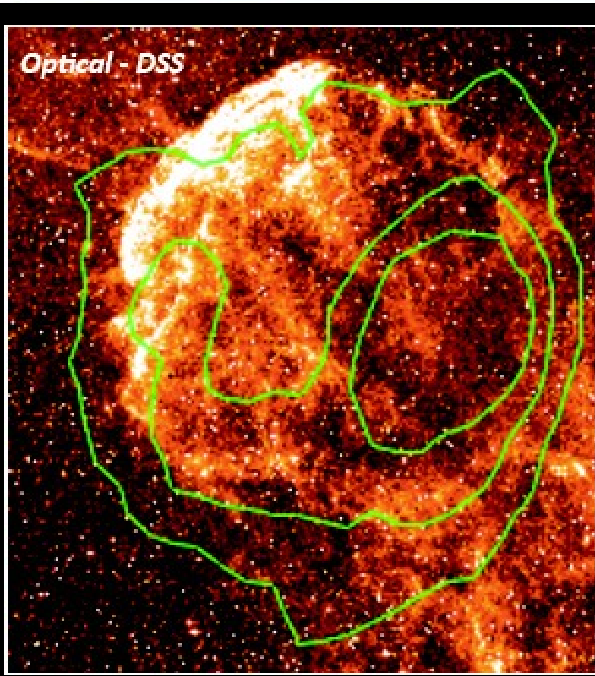
T.Ergin, L.Saha, PM, et al, ApJ 790 (2014)

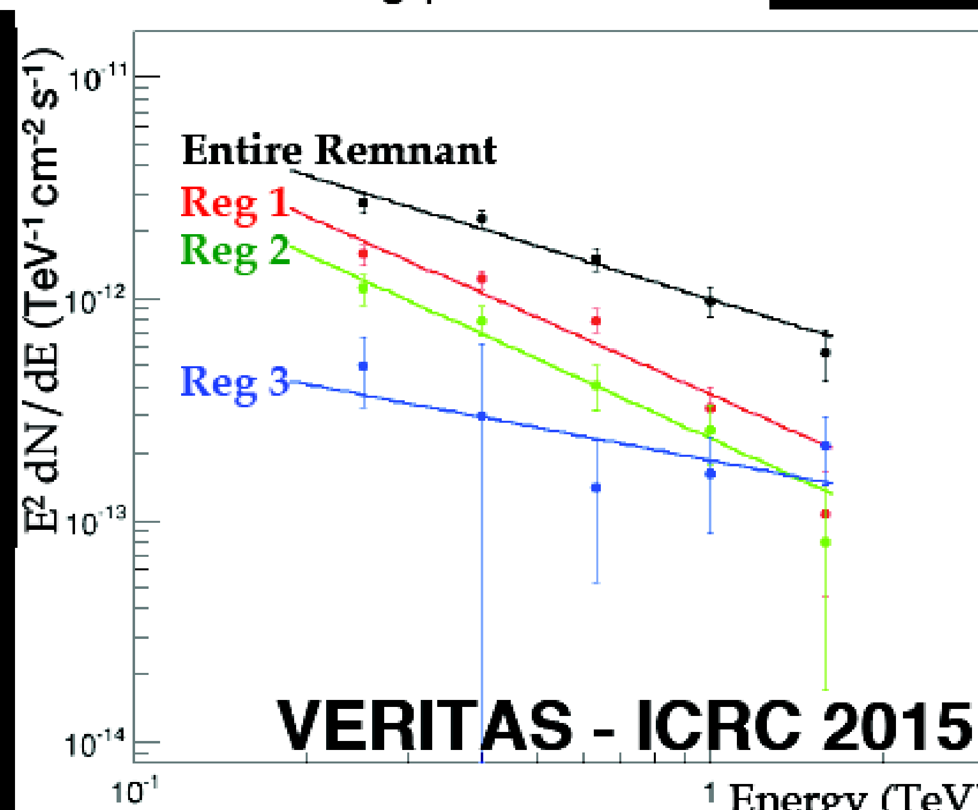
Multi wavelength Study of IC443 (Jellyfish Nebula)



- TeV emission fills the northeast lobe and SNR/MC interaction regions.
  - Strongest where maser emission brightest.
- Entire shell appears to be accelerating particles.

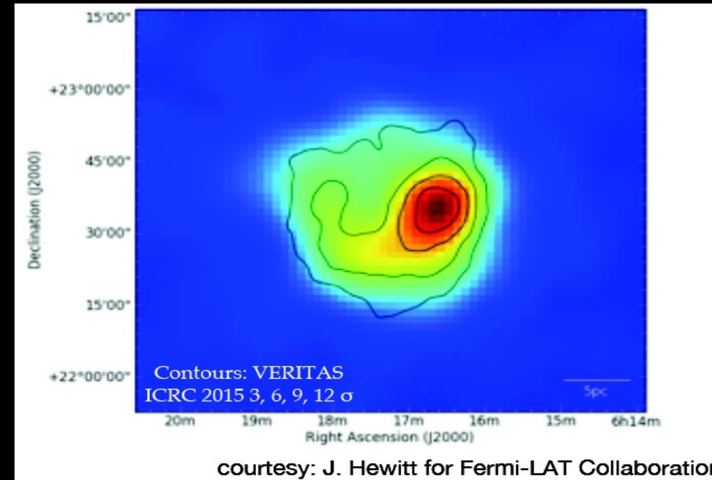


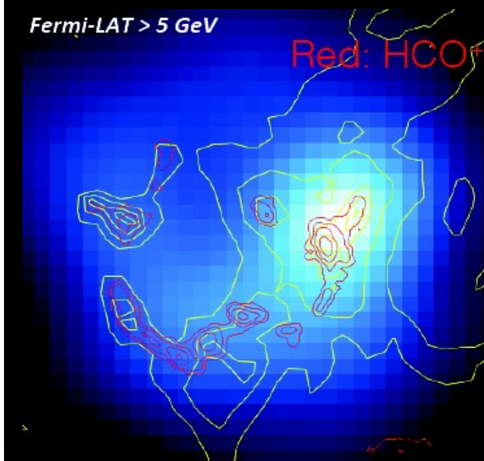


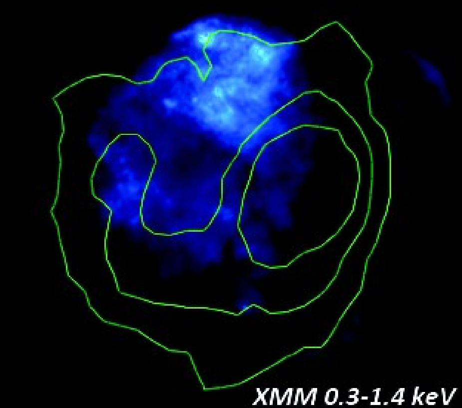


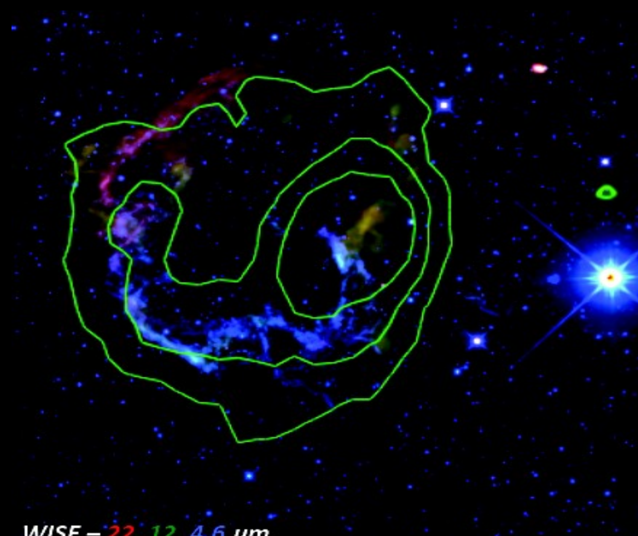
T. B. Humensky, ICRC 2015

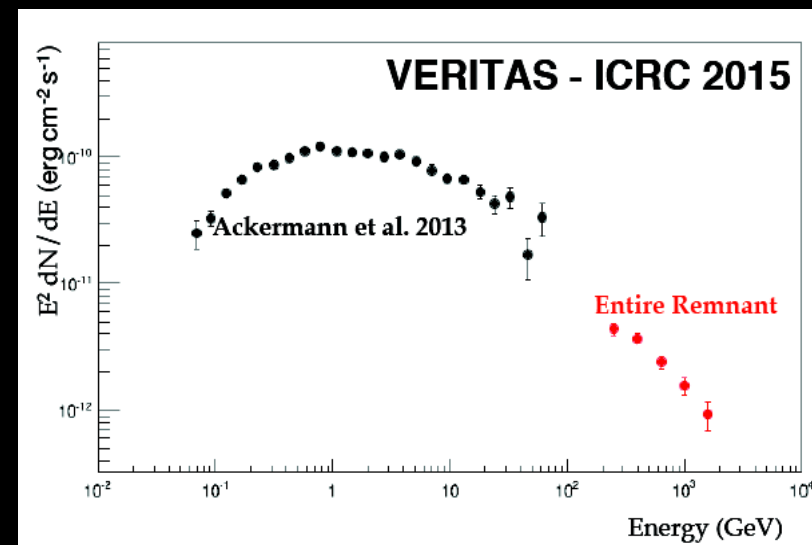
- GeV, TeV emission show remarkable spatial correlation.
- Smooth transition from GeV to TeV range also suggests a single population of CRs.







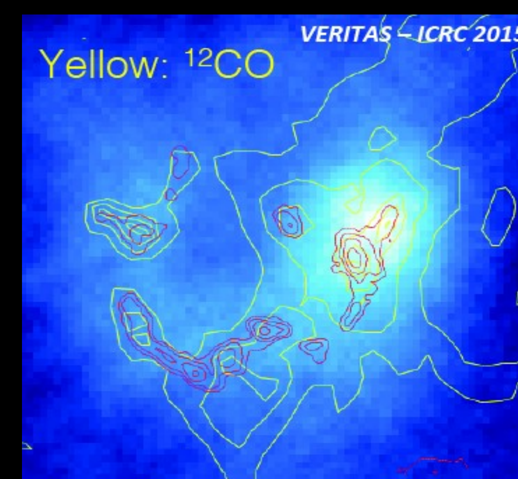




- Emission anticorrelates with thermal X-rays.

Spectra from different regions allows study of environmental dependence of cosmic ray diffusion

- GeV / TeV emission correlate most strongly with shocked gas.
- Suggests emission dominated by CRs interacting with gas in contact with shock front.



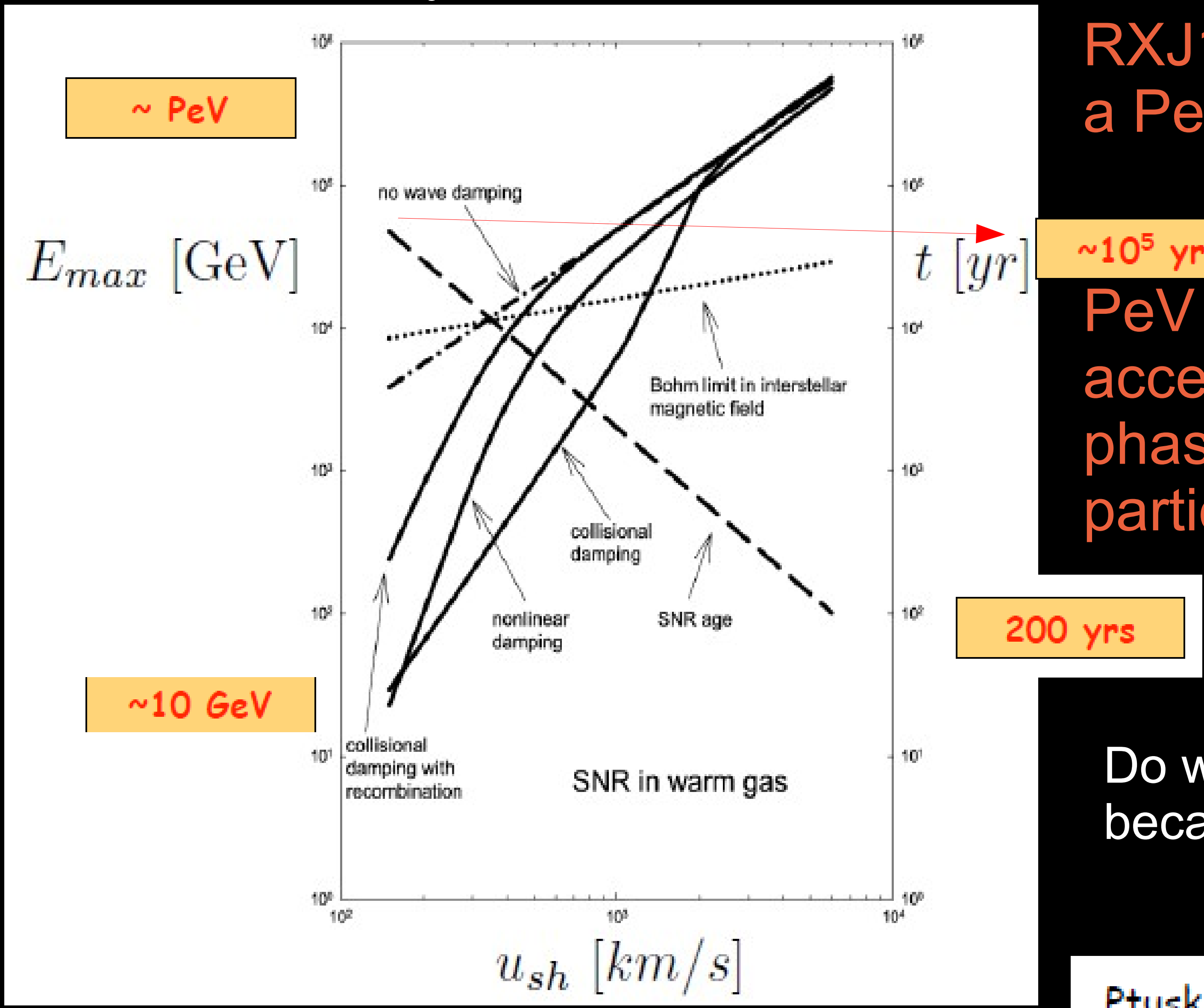
Acceleration in Supernova Remnants

Some (Experimentalist's) Questions:

- Do SNR shocks accelerate particles to VHE energies? ✓
- What is the p/e ratio among accelerated particles?
- What is the acceleration rate / acceleration time?
- Where does acceleration cut off? Do SNR accelerate CRs up to the knee – are there Pevatrons in our Galaxy?
- Why do we see fewer TeV SNRs ? Source distribution in the galaxy ?

Particle Escape and Maximum Energies

Relate the maxm energy to the age of the SNR, use MHD simulations
Bohm limit not justified because of non-linearities



RXJ1713 was probably a PeVatron

PeV particles are accelerated at Sedov phase, high energy particles escape first

Do we see fewer TeV SNRs because of this ?

Ptuskin & Zirakashvili, 2003

Acceleration in Supernova Remnants

Problems for Theoreticians :

- Do SNR shocks accelerate particles to VHE energies? ✓
- Non Linear DSA predicts a very hard spectrum, contrary to what observations show !!!
- Accelerate to the knee by non-linear amplification of the seed magnetic field (Bell & Lucek 2001)
- Energy dependent diffusion can be large, but then should produce anisotropy, why don't we see it ?
- How efficiently is shock kinetic energy converted to CR energy? How do CRs escape from the SNRs ?
- Can magnetic field amplification via plasma instabilities alter the shock compression ratio ?

Caprioli, JCAP (2012)

Future Directions

Immediate Steps in future

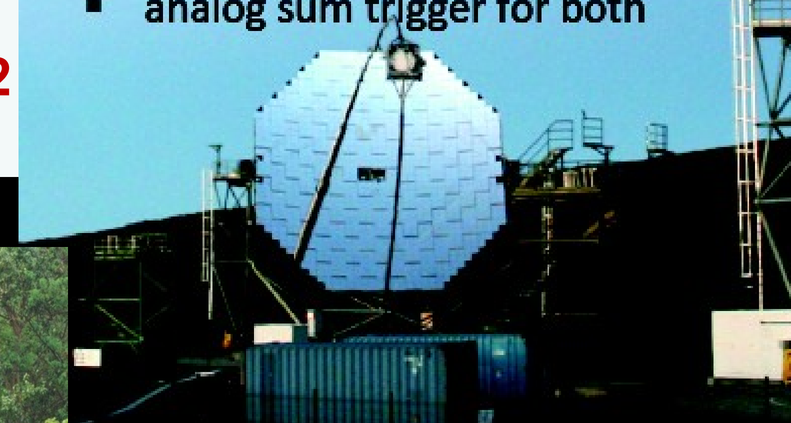
VERITAS Upgrade

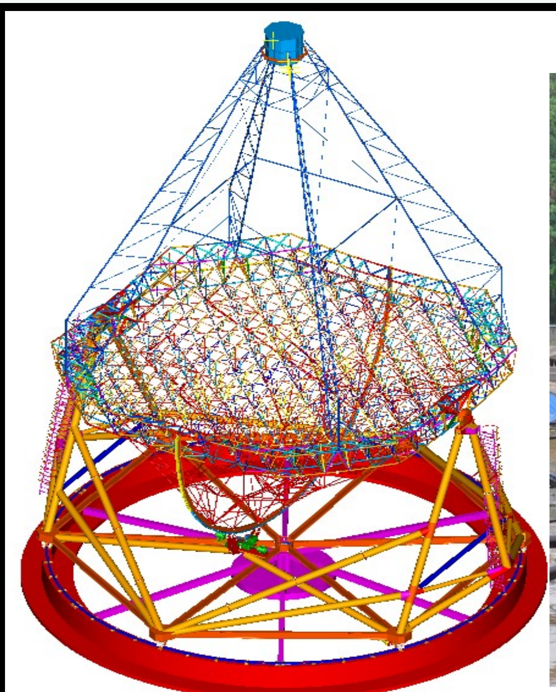
Year	Item	Status
2009	Relocation of Telescope 1	Complete
2010	Network Upgrade	Complete
2011	Trigger Upgrade: faster, more flexible telescope trigger.	Complete
2012	**Camera Upgrade: replacement of all 2,000 PMTs with high-QE devices.**	**Completed : Summer 2012**

MAGIC:
Two 17 m telescopes

Upgrade of older MAGIC I camera in pro

- Unification of subsystems and reado
- Improved reliability and sensitivity
- 576 ➜ 1039 pixels
- enlarged trigger area
- analog sum trigger for both





MACE @ HANLE

Hanle: 4200 m asl, 32.7N

Giant 28 mt telescope : H.E.S.S. II

~600 m^2 mirror area
0.07° pixels
~20 GeV peak trigger rate in stand-alone mode
trigger modes: stand-alone & coincidence 2/5

How to do even better with Ch. telescopes ?

A future Cherenkov observatory needs:

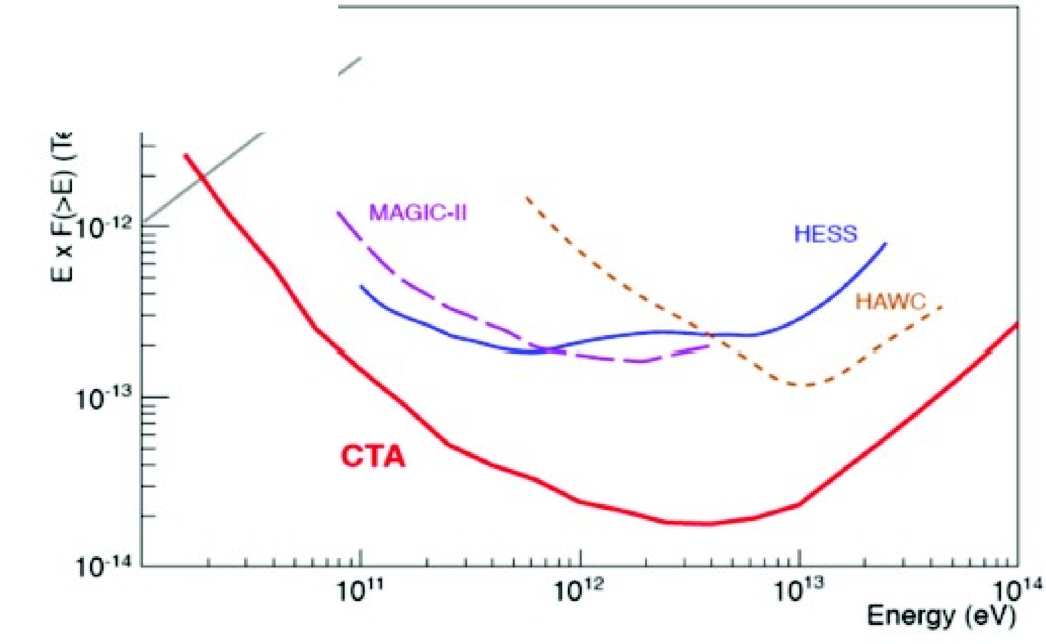
for E > TeV:
bigger collection area
(i.e. large array of telescopes, wider FOV)

more events

for E < TeV:
better background rejection
(i.e. large array of telescopes, wider FOV for multiple shower images)

better events

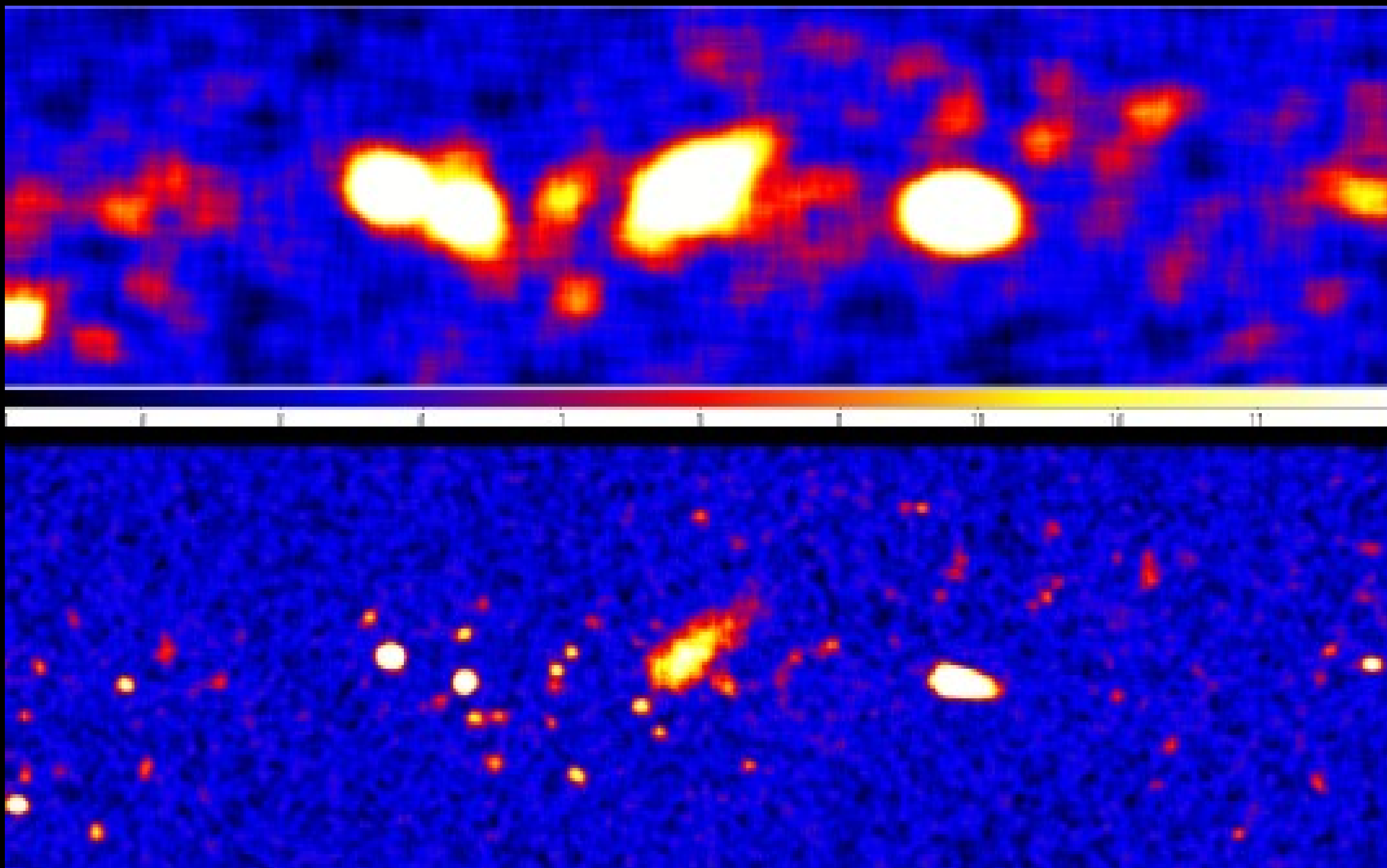
MC ~ at least 10 times better Sensitivity, ~ 5 x angular resolution may be possible



Improved Angular Resolution : What it brings ?

German Hermann

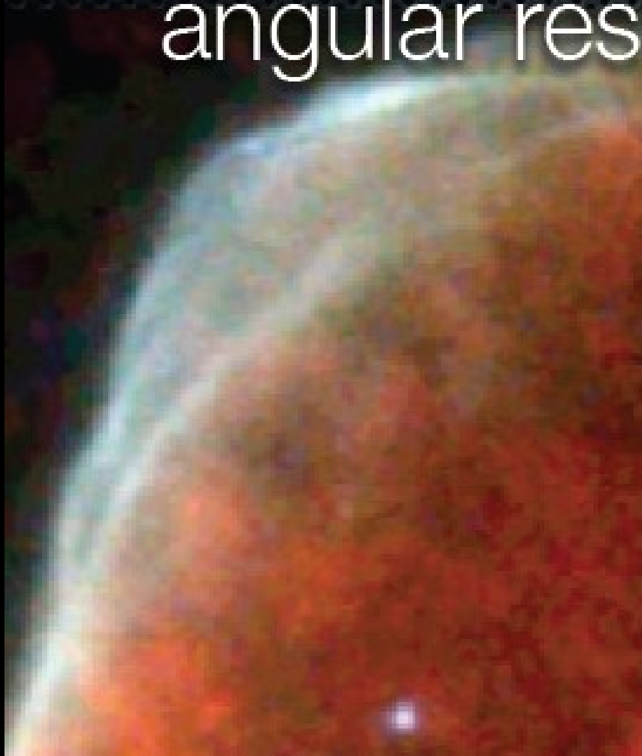
angular resolution: 0.2 deg



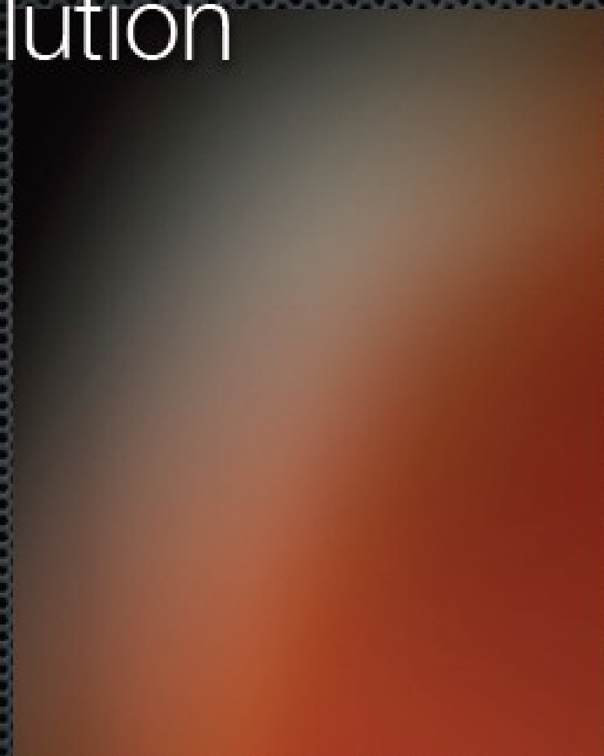
angular resolution: 0.05 deg

Galactic Physics : Cosmic Ray Origin ?

- … sensitivity, and angular resolution



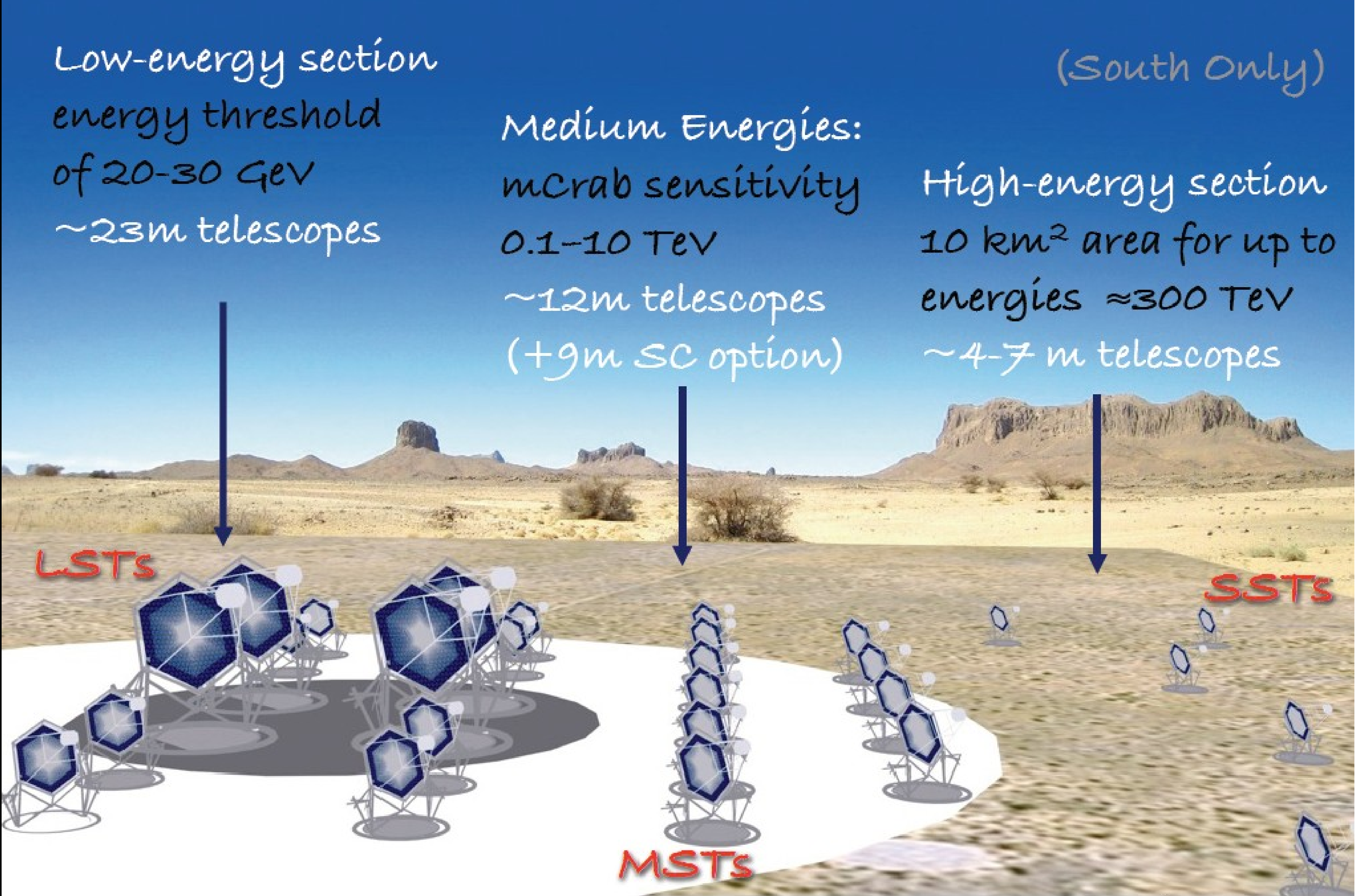
0.004°
XMM 10 keV



0.1°
current generation IACT

0.02°
CTA/AGIS
@ few TeV

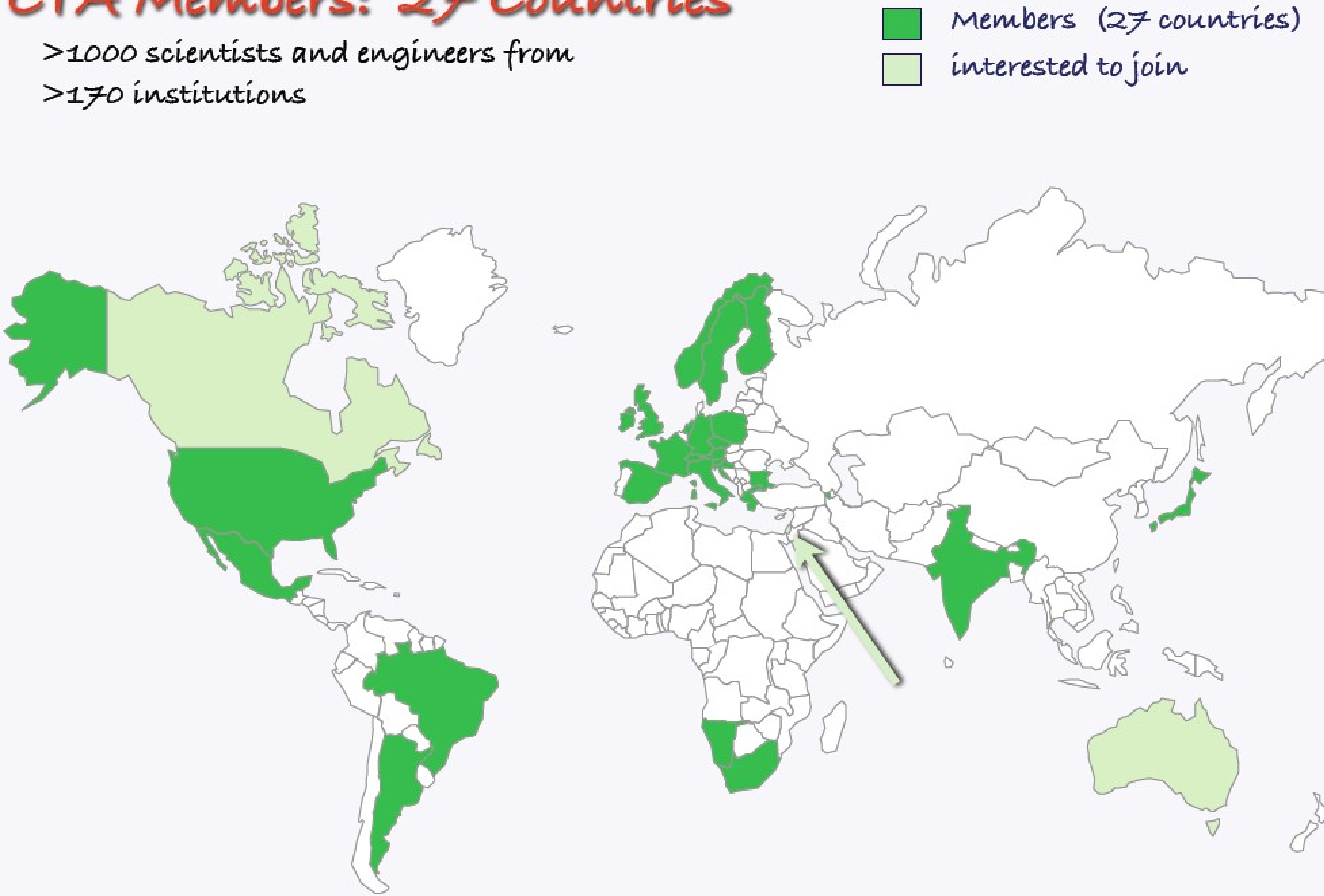
A real observatory with ≈ 100 telescopes.



CTA Members: 27 Countries

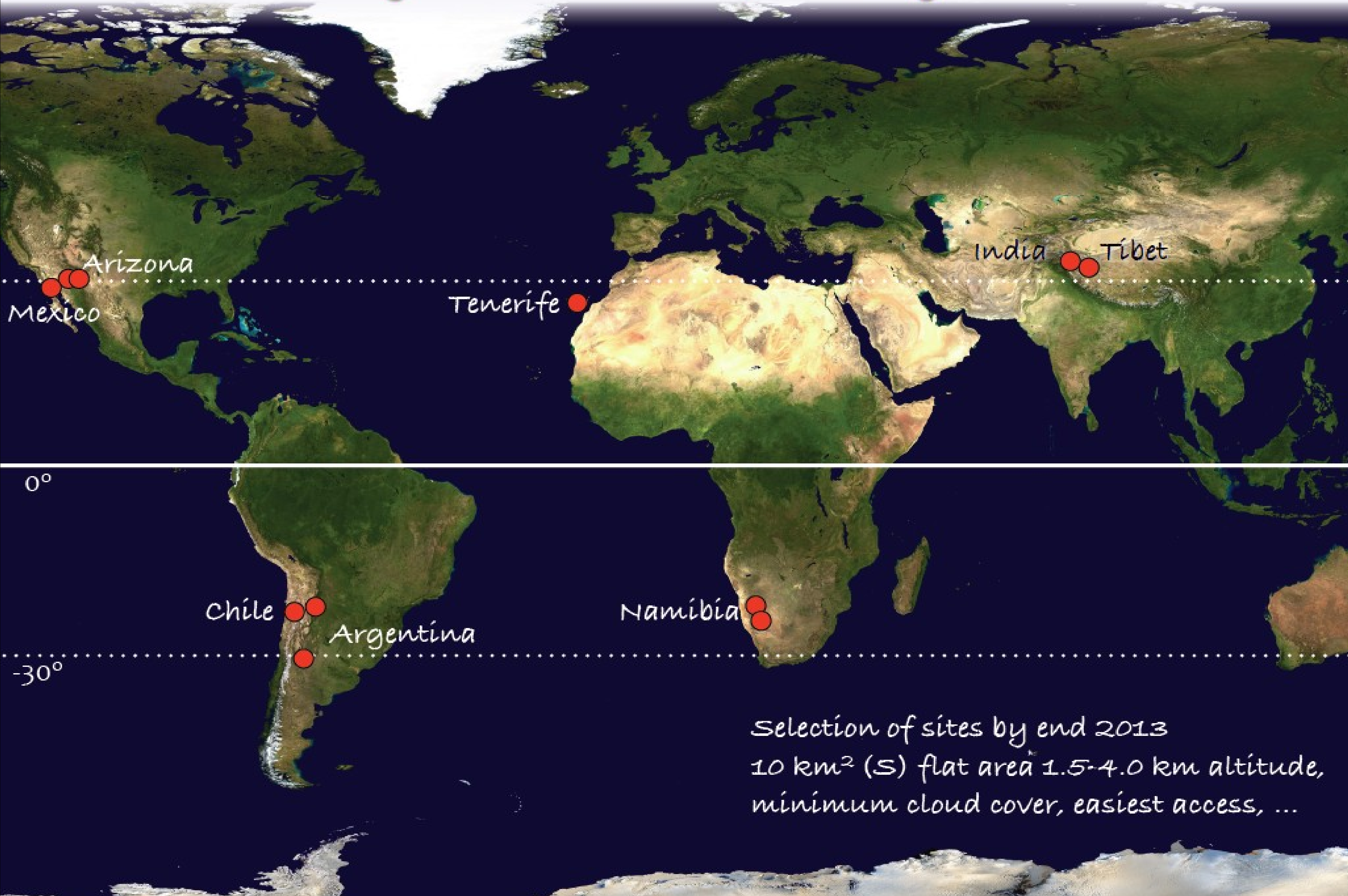
>1000 scientists and engineers from

>170 institutions



Argentina, Armenia, Austria, Brazil, Bulgaria, Czech Republic, Croatia, Finland, France, Germany, Greece, India, Italy, Ireland, Japan, Mexico, Namibia, Netherlands, Norway, Poland, Slovenia, Spain, South Africa, Sweden, Switzerland, UK, USA

One observatory with two sites - operated by one consortium



Selection of sites by end 2013
10 km² (S) flat area 1.5-4.0 km altitude,
minimum cloud cover, easiest access, ...

Indian Participation in CTA (SINP, TIFR, IIA, BARC)

- Site Survey at Hanle (IIA/TIFR)
- Simulations for optimizing array configurations (SINP, BARC, TIFR) : Production at full scale at SINP APC cluster : 1st center outside Europe
- Calibration for the camera of the prototype LST (SINP) : Technical responsibility Pratik Majumdar / Varsha Chitnis
- Other tasks being identified and worked upon in collaboration with TIFR (Array Control Software)
- Expression of Interest (EoI) submitted to CTA, make a proper budget and submission soon for funding

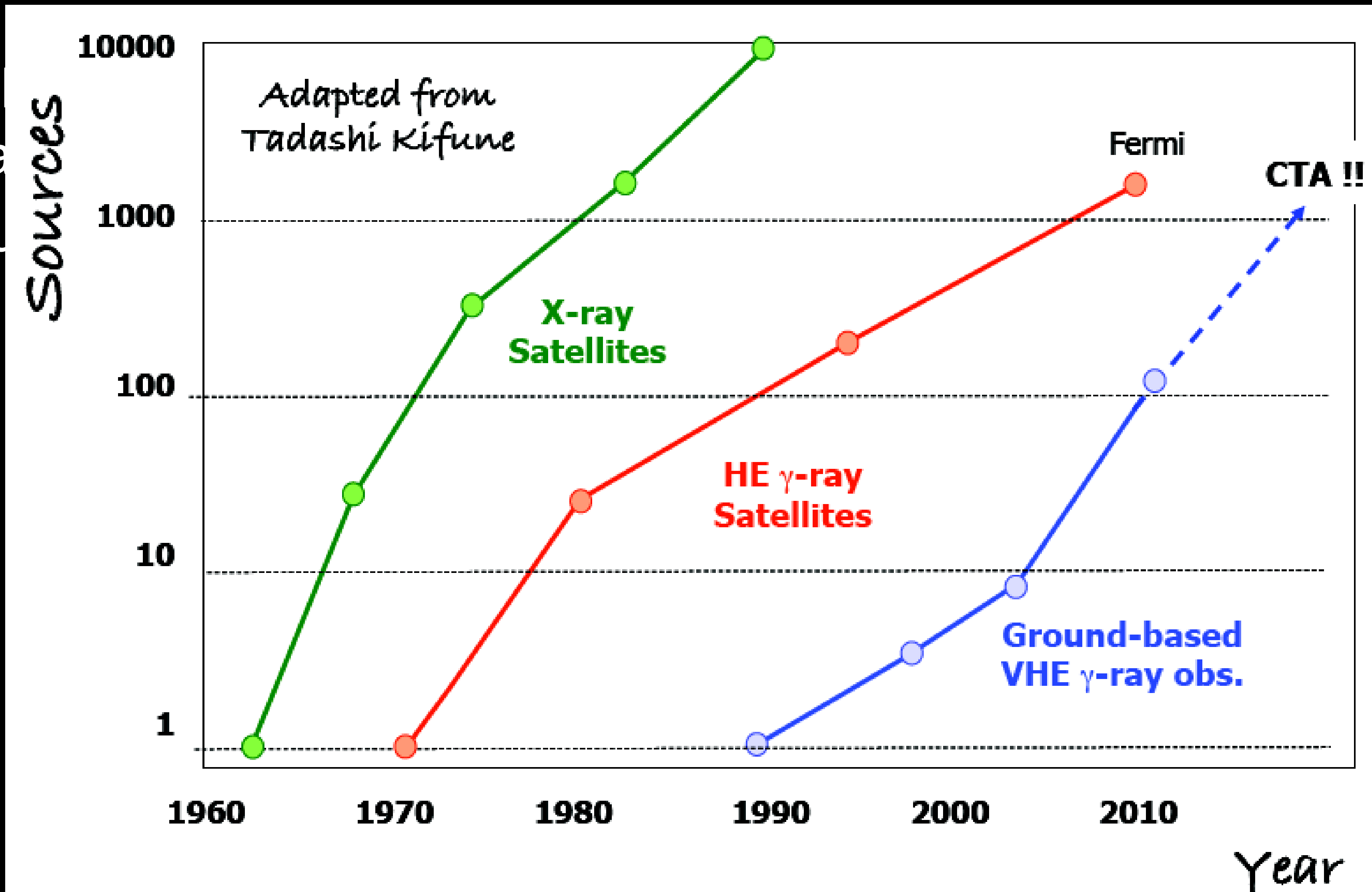
Conclusions

- VHE Gamma Ray Astronomy slowly establishing itself within mainstream astronomy
- Current generation instruments have given a wealth of data to do astrophysics/particle physics

Supernova remnants:	Nature 432 (2004) 75
Microquasars:	Science 309 (2005) 746, Science 312 (2006) 1771
Pulsars:	Science 322 (2008) 1221, Science 334 (2011) 69,
Galactic Centre:	Nature 439 (2006) 695
Galactic Survey:	Science 307 (2005) 1839
Starbursts:	Nature 462 (2009) 770, Science 326 (2009) 1080
Active Galactic Nuclei:	Science 314 (2006) 1424, Science 325 (2009) 444
EBL:	Nature 440 (2006) 1018 Science 320 (2008) 752
Dark Matter:	PRL 96 (2006) 221102, PRL 106, 161301 (2011)
Lorentz Invariance:	PRL 101 (2008) 170402
Cosmic Ray Electrons:	PRL (2009)

Conclusions

- VI … hin ma …
- Cu … a to do …



Conclusions - II

- Studied shell regions of Cas A : we show leptonic mechanisms cannot satisfactorily explain GeV-TeV data together.

- Hadronic scenarios studies, we find a lepto-hadronic model fits the data best (minimum chisq). Future : extend to higher energies with CTA will be very important , where are the PeVatrons ?

- Magnetic field amplication : but low conversion efficiency ~ 2% of CR energy to magnetic energy => MH waves by cosmic rays may not be enough (Bell et al, 2004, Lucek and Bell 2001)

- With Fermi and future IACTs (LST and SST) we start to shed light on particle acceleration mechanisms in cosmic rays.

Backup Slides

Gamma Ray Astrophysics : p-p interactions

Let's calculate the spectrum of neutral pions:

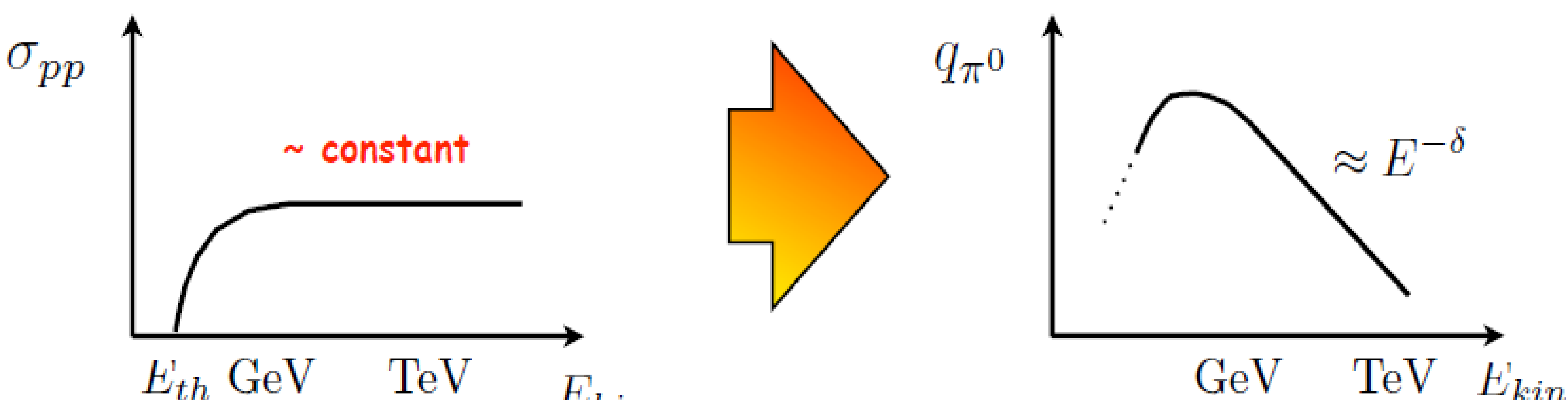
We assume a power law spectrum for CRs: $N_p(E_p) \propto E_p^{-\delta}$

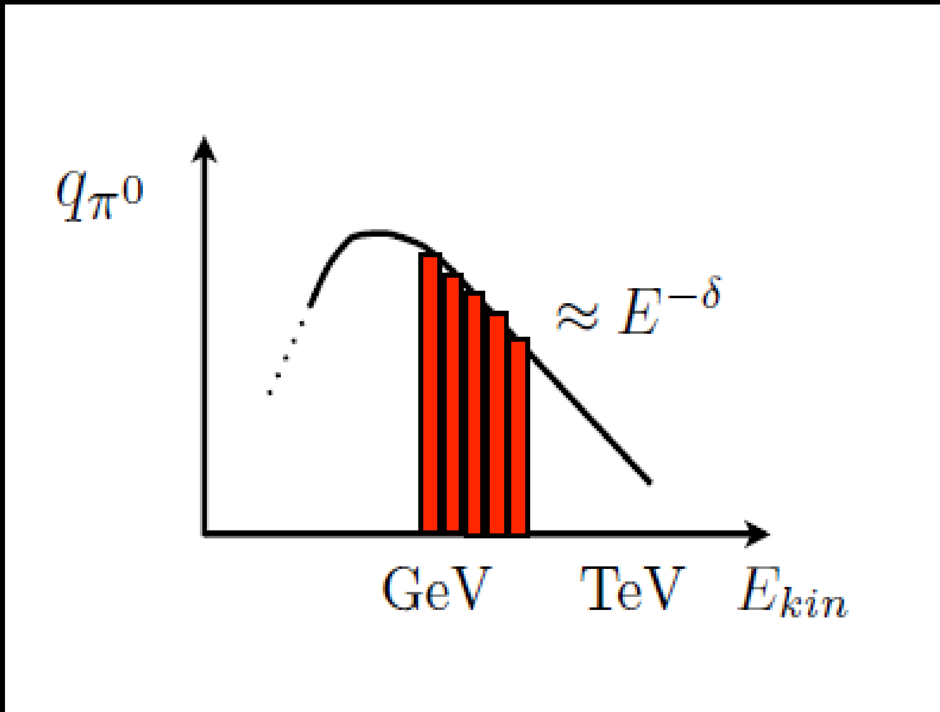
Fraction of proton kinetic energy transferred to pion (from data): $f_{\pi^0} \approx 0.17$

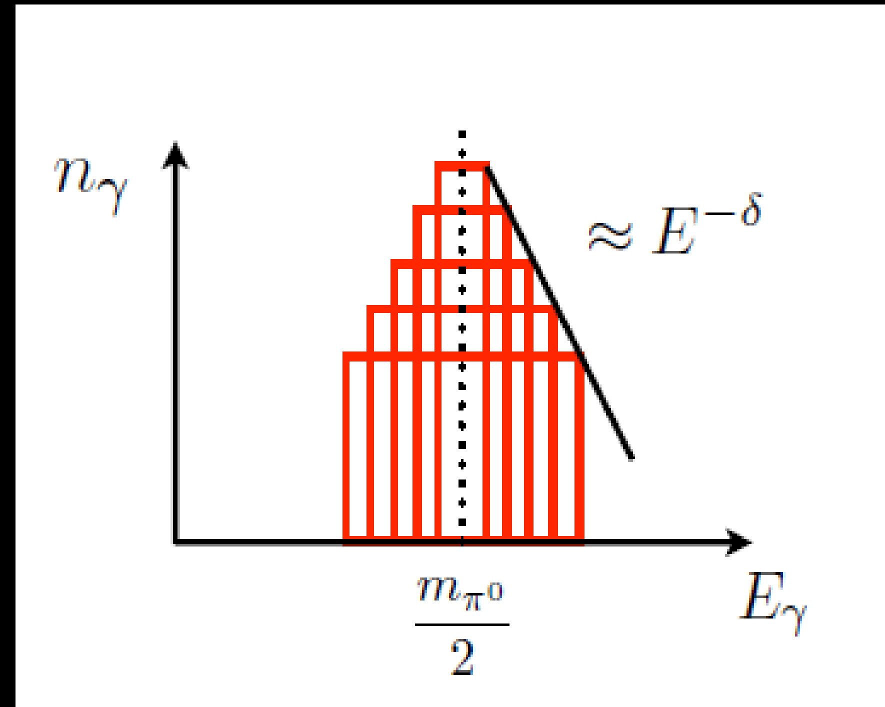
production rate

total cross section

$$q_{\pi^0} = \int \mathrm{d}E_p \; N_p(E_p) \; \delta(E_{\pi^0} - f_{\pi^0} E_{p,kin}) \; \sigma_{pp}(E_p) \; n_{gas} \; c$$





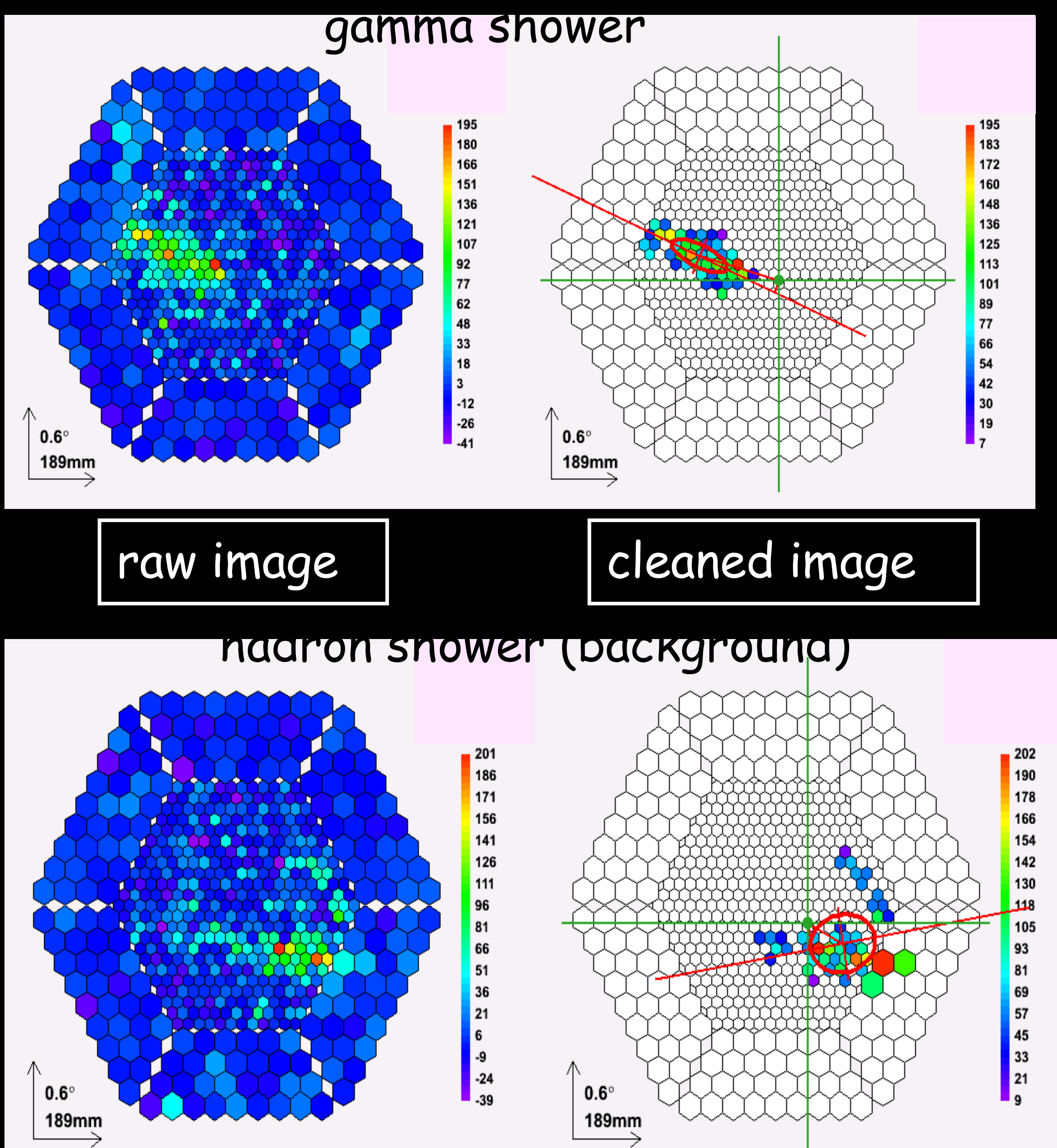


(1) proton-proton interactions: $(\alpha = \delta)$

(2) inverse Compton scattering: $(\alpha = \frac{\delta + 1}{2})$

(3) relativistic Bremsstrahlung: $(\alpha = \delta)$

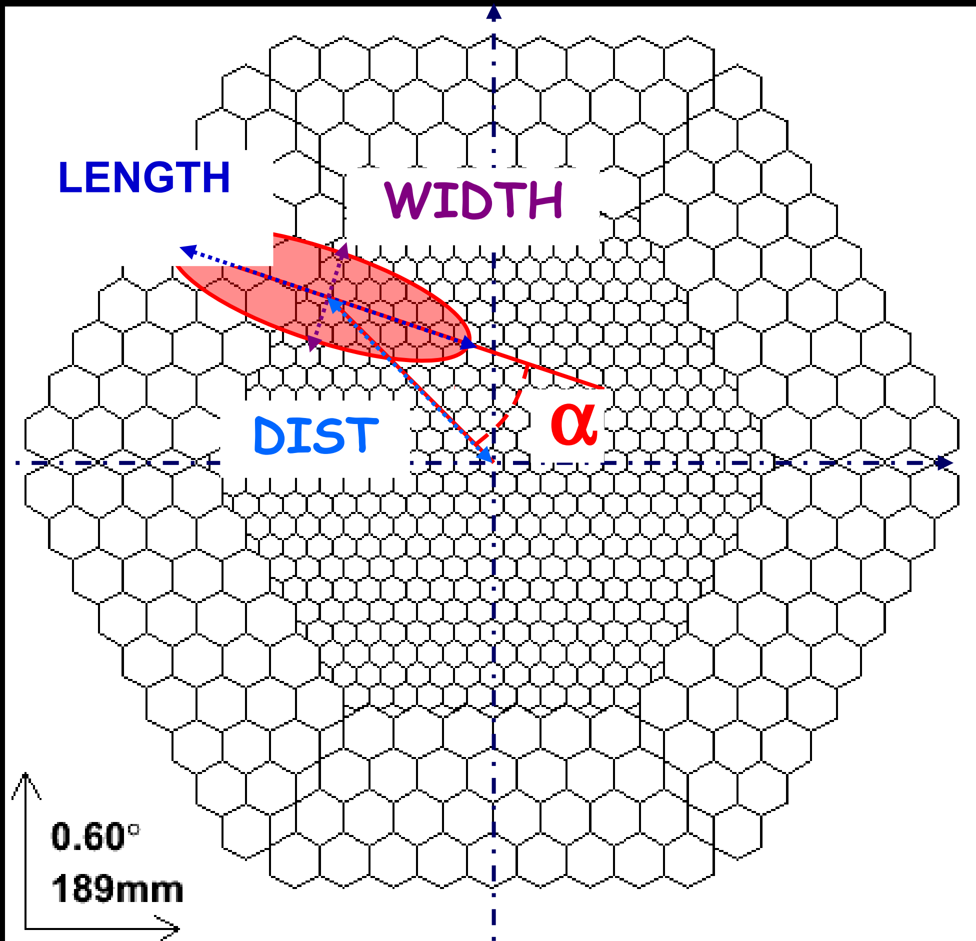
Background Rejection

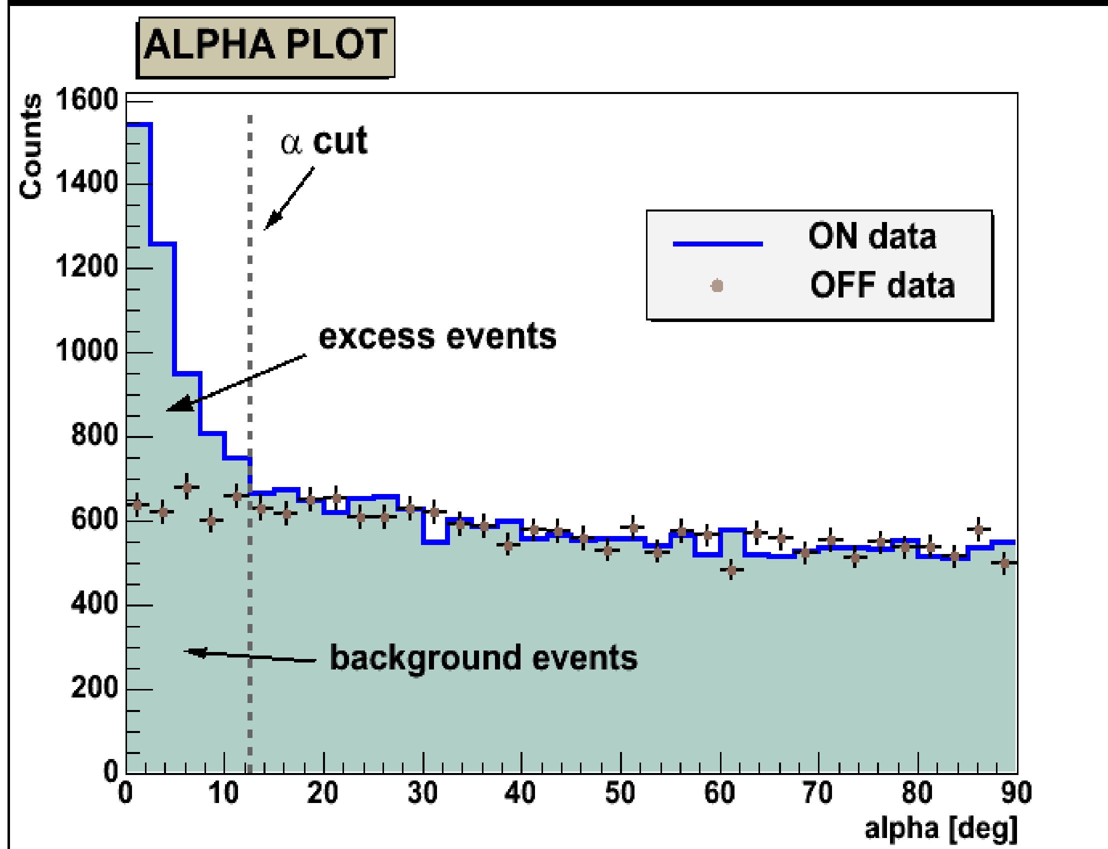


Main Background:

- **Cosmic Ray (hadron) showers**
- **$>10^4$ times more numerous than γ-ray showers**
- **Reject based on shower shape**

Standard "Hillas" Analysis





Background rejection with multidimensional cuts on Hillas parameters:
Length, Width, Dist, Alpha, Size

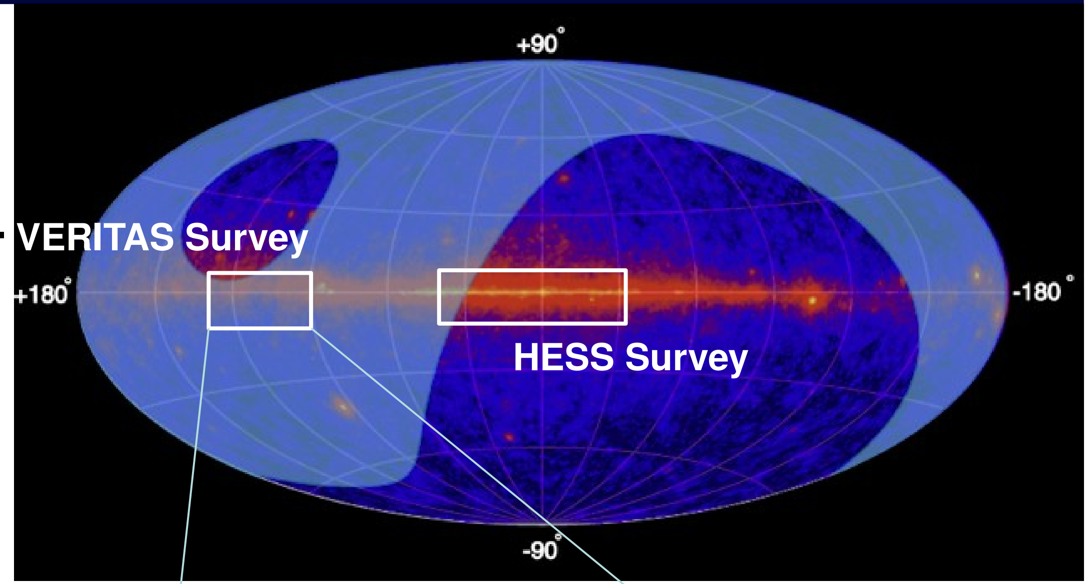
Hadron background:
- isotropic arrival direction
- flat Alpha distribution

Gammas:
- excess in source direction

Cygnus Sky Survey in the North

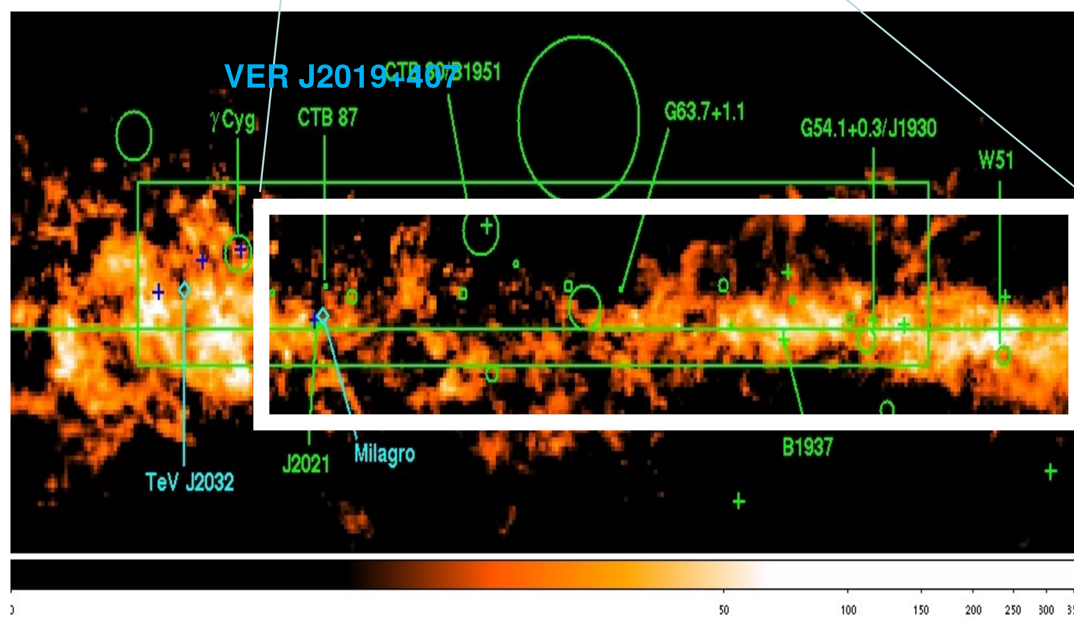
VHE Sky Surveys:

- **HEGRA (97-02):** North, ~25% Crab.
- **HESS (03-04):** South, ~3% Crab.
  and extended (05-08).
- **Milagro (01-07):** North, ~35% Crab
  at E > 10 TeV.

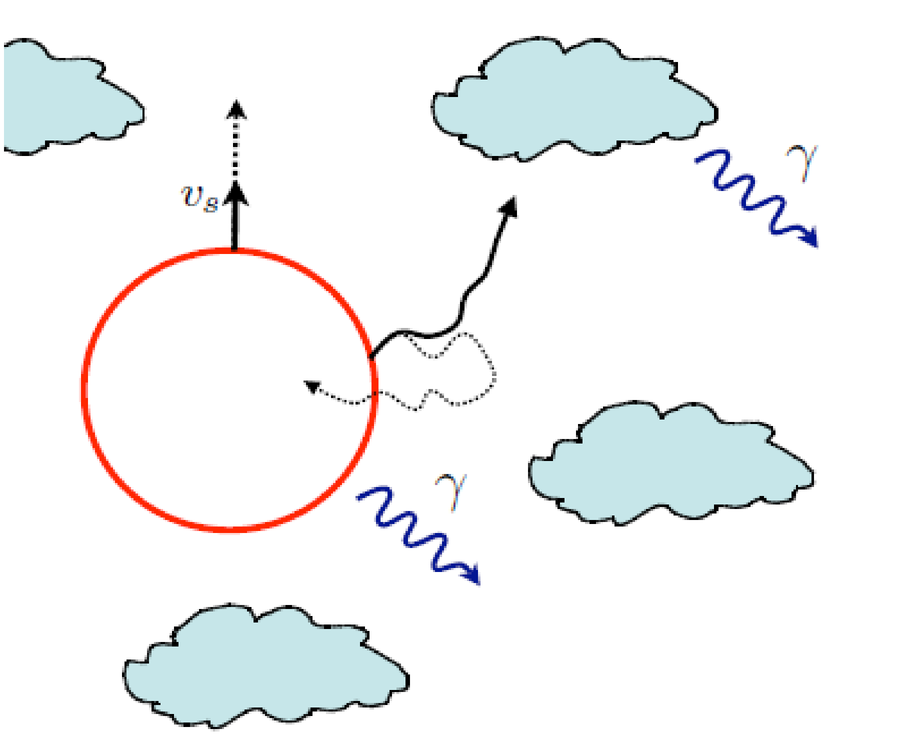


VERITAS Sky Survey (07-09):

- N. Hemisphere – Cygnus arm.
- 115h + 55h follow-up; done before
  improvements to sensitivity.
- ~3% Crab (99%) for E > 200 GeV.
- Discovery of VERJ2019, detection of TeV2032+4130



γ-ray astronomy and cosmic rays (CR)



Both SNR and surrounding molecular clouds emit gammas

Molecular Clouds, sites of star formation

dense -> n ~ 100 cm^{-3}

massive -> Mass up to 10^6 $M_\odot$

$$L_\gamma \approx \sigma\, c \int dV\, n_{CR}\, n_{ISM} \propto M_{cl}$$

Gamma rays from escaping particles:

Aharonian & Atoyan, 1996 (**CR accelerator**)

Gabici & Aharonian, 2007 (**SNRs**)

Follow up papers:

Torres et al, 2008

Rodriguez-Marrero et al, 2008

Gabici et al, 2009

No escape of particles in observations yet

CR in the vicinity of the shock are scattered by irregularities in the magnetic field. In the linear theory, these irregularities consist of Alfven waves generated by the CR themselves as they diffusively drift through the plasma upstream of the shock. If $U_{\rm a}$ is the energy density of the Alfven waves and $P_{\rm cr}$ is the CR pressure, then the growth and advection of $U_{\rm a}$ in the shock rest frame (the inertial frame in which the shock is at rest) obeys the equation

$$\frac{\partial U_{\rm a}}{\partial t} + u\frac{\partial U_{\rm a}}{\partial x} = v_{\rm a}\frac{\partial P_{\rm cr}}{\partial x}, \qquad (1)$$

$$\left(\frac{\Delta B}{B}\right)^2 = M_{\rm a}\frac{P_{\rm cr0}}{\rho u^2},$$

Bell 1987; Falle & Giddings 1987), $P_{\rm cr0} \sim \rho u^2$, and $M_{\rm a}$ is necessarily greater than 1, implying that the magnetic field is amplified non-linearly. Naive application of this relation gives $\Delta B/B \gg 1$ for parameters typical of young supernova remnants. A shock moving at $10^4\,{\rm km\,s^{-1}}$ into a medium containing 1 proton $\rm cm^{-3}$ and a magnetic field of 3×10^{-6} G has an Alfven Mach number of $M_{\rm a} = 1500$. A naive application of equation (2) suggests an increase in the magnetic field energy by a factor of 1000. The conclusion is first that the linear theory breaks down and secondly that it is at least possible that the magnetic energy density close to the shock is much greater than that in the undisturbed upstream plasma.

$$\frac{\partial f}{\partial t} = \frac{D}{R^2}\frac{\partial}{\partial R}R^2\frac{\partial f}{\partial R} + \frac{\partial}{\partial E}(Pf) + Q$$

Here $f \equiv f(E,R,t)$, is the distribution function of particles at instant t and distance R from the source; $P = -(dE/dt)$ is the continuous energy loss rate , $Q \equiv Q(E,R,t)$ is the source function; $D \equiv D(E)$ denotes the diffusion coefficient which is assumed to be independent of R and t, i.e. a homogeneous quasi-stationary medium surrounding the source is supposed.

Recently we have obtained a simple Green's function solution to Eq.(1) for an arbitrary injection spectrum $f_{\rm inj}(E)$ of accelerated particles, $Q(E,R,t) = N_0 f_{\rm inj}(E)\delta(\mathbf{R})\delta(t)$, energy losses $P(E)$ and diffusion coefficient $D(E)$ (Atoyan et al. 1995). In the particular case of power-law injection spectrum, $f_{\rm inj} = E^{-\alpha}$, and power-law diffusion coefficient, $D(E) \propto E^{\delta}$, in the energy

$$f(E,R,t) \approx \frac{N_0\, E^{-\alpha}}{\pi^{3/2}\, R_{\rm dif}^3}\ \exp\left(-\frac{(\alpha-1)t}{\tau_{\rm pp}} - \frac{R^2}{R_{\rm dif}^2}\right).$$

Here

$$R_{\rm dif} \equiv R_{\rm dif}(E,t) = 2\sqrt{D(E)\,t\,\frac{\exp(t\delta/\tau_{\rm pp})-1}{t\delta/\tau_{\rm pp}}}\,.$$

$$F_\gamma = \frac{M_{\rm cl}}{m_{\rm p}}\frac{q_\gamma}{4\pi d^2}\,,$$