TeV Gamma-Ray Astronomy

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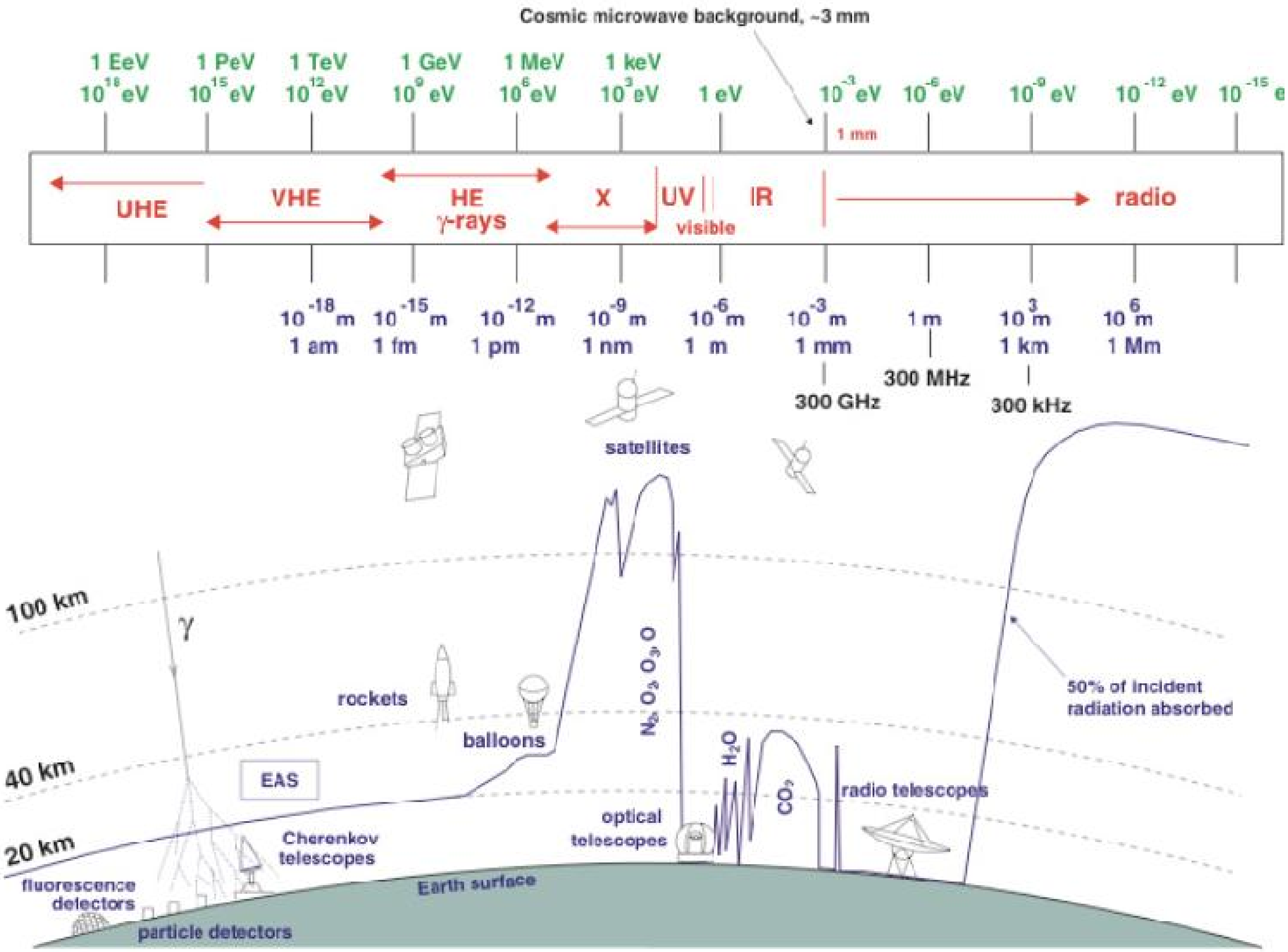


from M. Longair, High Energy Astrophysics (Cambridge University Press, 1992)

The Very High Energy (VHE) domain — 0.1 to ∼100 TeV

VHE/TeV Gamma-rays are the highest energy photons so-far detected

Why study TeV Gamma-Rays?

- Gamma-rays are closely linked to particle acceleration: Particles (hadrons/leptons) accelerated at/in/around an energetic source will interact with surrounding matter and/or EM radiation fields. As a result, non-thermal radiation from radio to gamma-ray energies is produced.

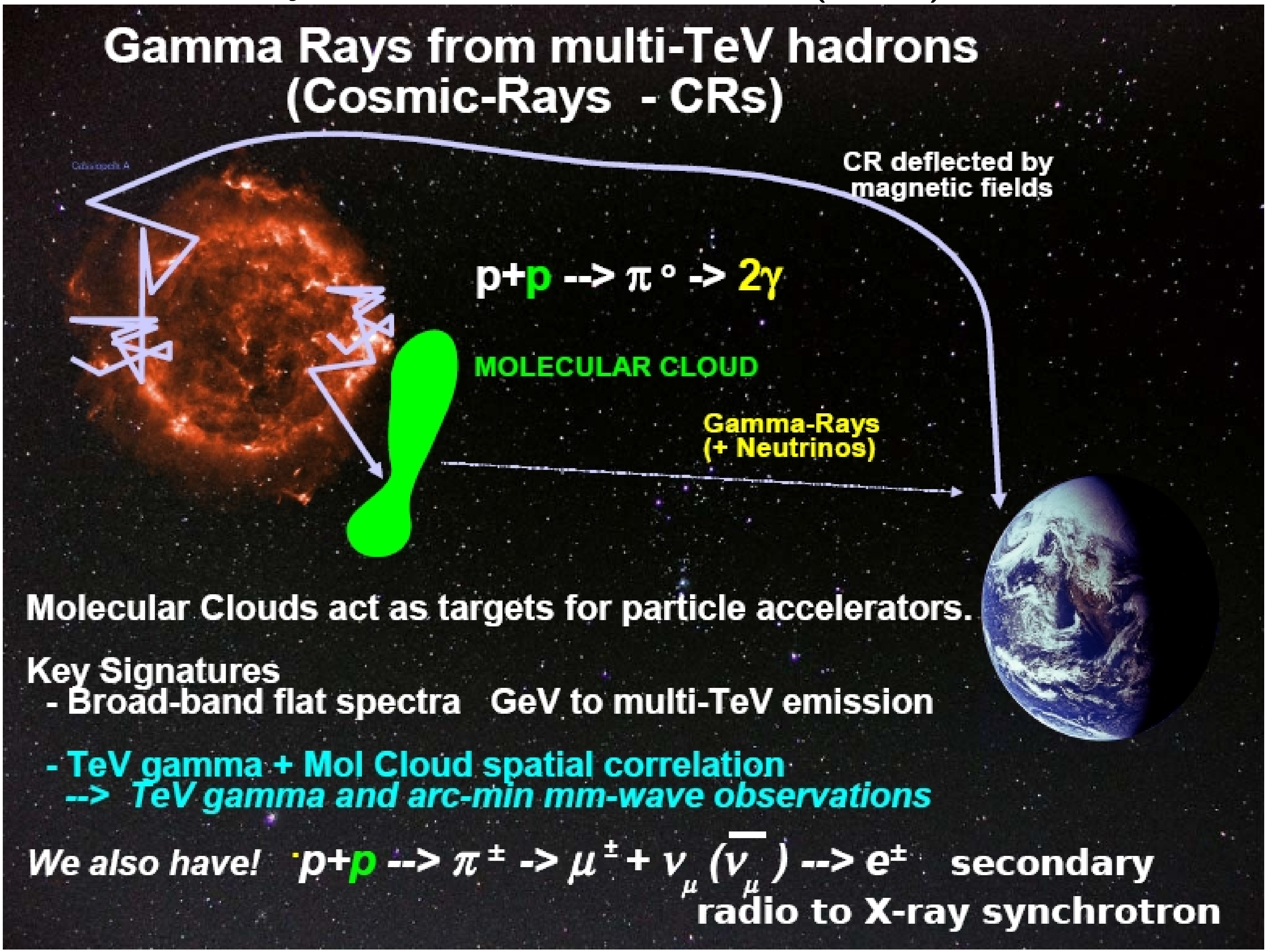
- TeV gamma-rays penetrate relatively freely† through intergalactic and Galactic magnetic fields — they provide a unique window into extreme astrophysical environments (supernova remnants, pulsar environments, black holes & accretion) from parsec to kiloparsec scales. † TeV gamma-ray interaction with soft photon fields imposes a 'gamma-ray horizon' (more on this later).

- Gamma-Rays are therefore **tracers** of particle acceleration and extreme astrophysics: Gamma trajectories are unaffected by magnetic fields, and hence they reveal their production location. **Gamma-rays provide the easiest way to search for and study particle acceleration to extreme energies.**

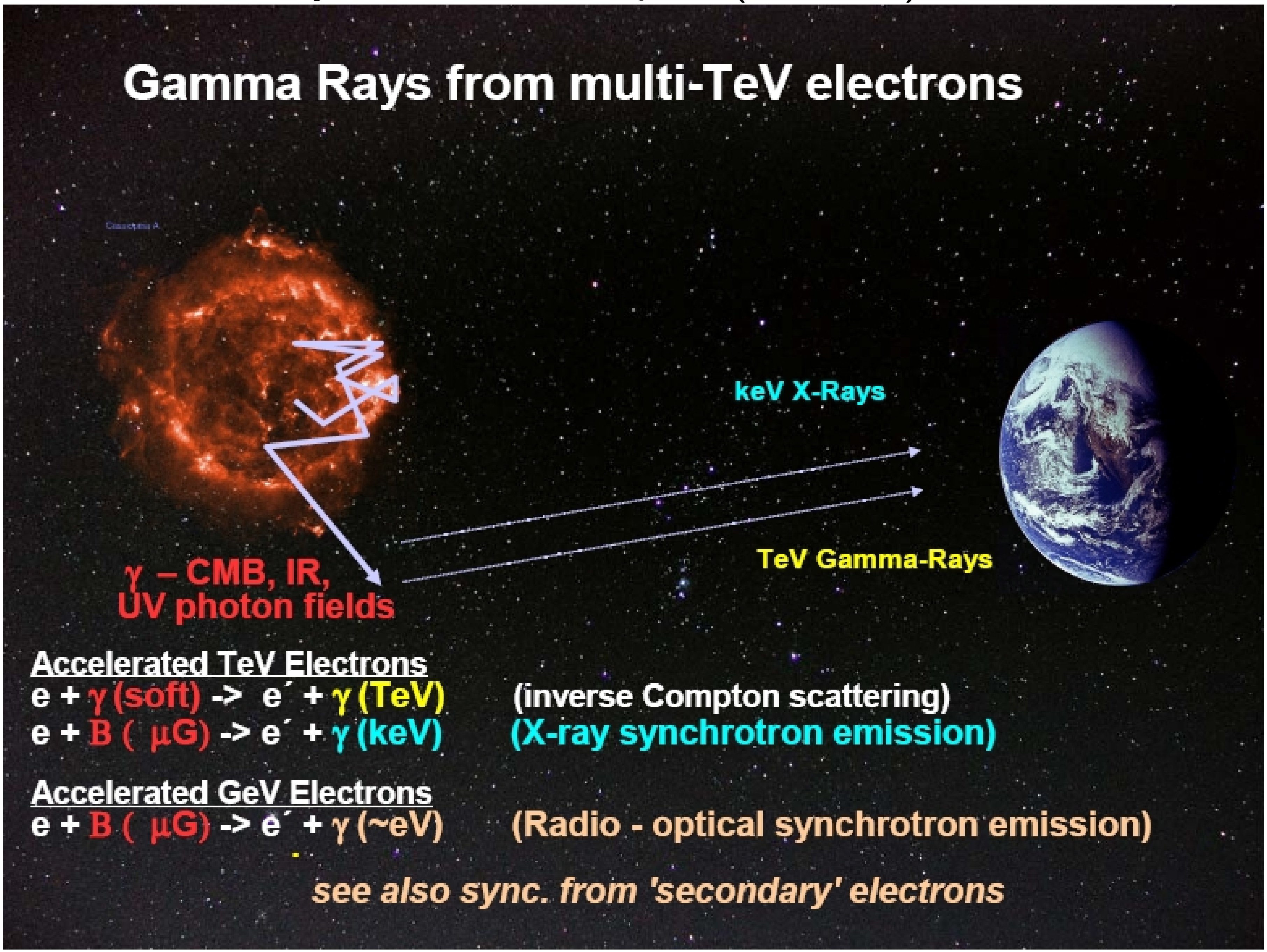
- Cosmic Rays (CRs): Accelerated charged particles propagating throughout the Universe. NOTE: Both hadrons (protons/nuclei) and leptons (electrons) are accelerated in extreme environments. As per common convention, we will refer to *Cosmic-Rays* as accelerated hadrons or protons/nuclei, and refer to accelerated electrons/leptons distinctly.

- KEY ISSUE: The Origin of CRs remains the longest unanswered question in modern astrophysics: It is essentially unanswered since their discovery in 1912, and the search for CR accelerators provided the original impetus for gamma-ray astronomy.
- Spaced-based gamma-ray astronomy up to GeV energies developed in the 1970's (SAS-2) & 1980's (COS-B), and epecially with EGRET (1990's) and in early 2008 — GLAST (we will not cover these instruments specifically here)
- Ground-based TeV gamma-ray detection methods are now finally proven, and highly sensitive (detectable energy fluxes better than 10^{-12} erg cm^{-2} s^{-1}). Results since 2004, especially from H.E.S.S., have been dramatic, and evolved TeV gamma-ray detection into a mainstream astronomical discipline. Clues are emerging as to how various types of objects are able to accelerate particles to $>$TeV energies.
- This course will review TeV gamma-ray astronomy, its motivation, and the key methods. We will review a range of TeV sources (by no means all) and what we know, and what we don't know about them. At the end, we will look into the future of the field.....

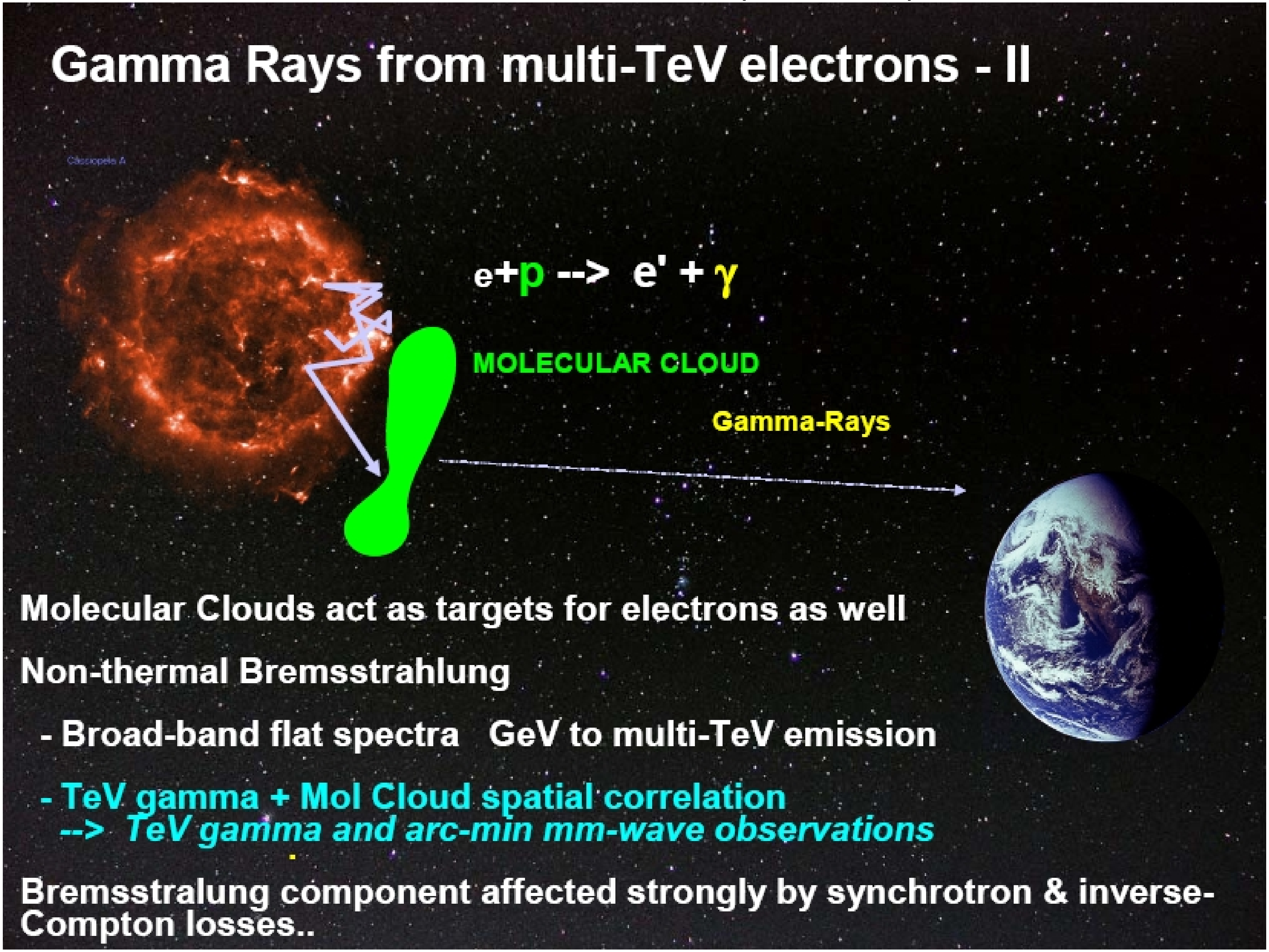
Gamma-Rays as tracers of CR Hadronic (nuclei) Accelerators



Gamma-Rays as tracers of Lepton (electrons) Accelerators



Gamma-Rays as tracers of Lepton (electrons) Accelerators

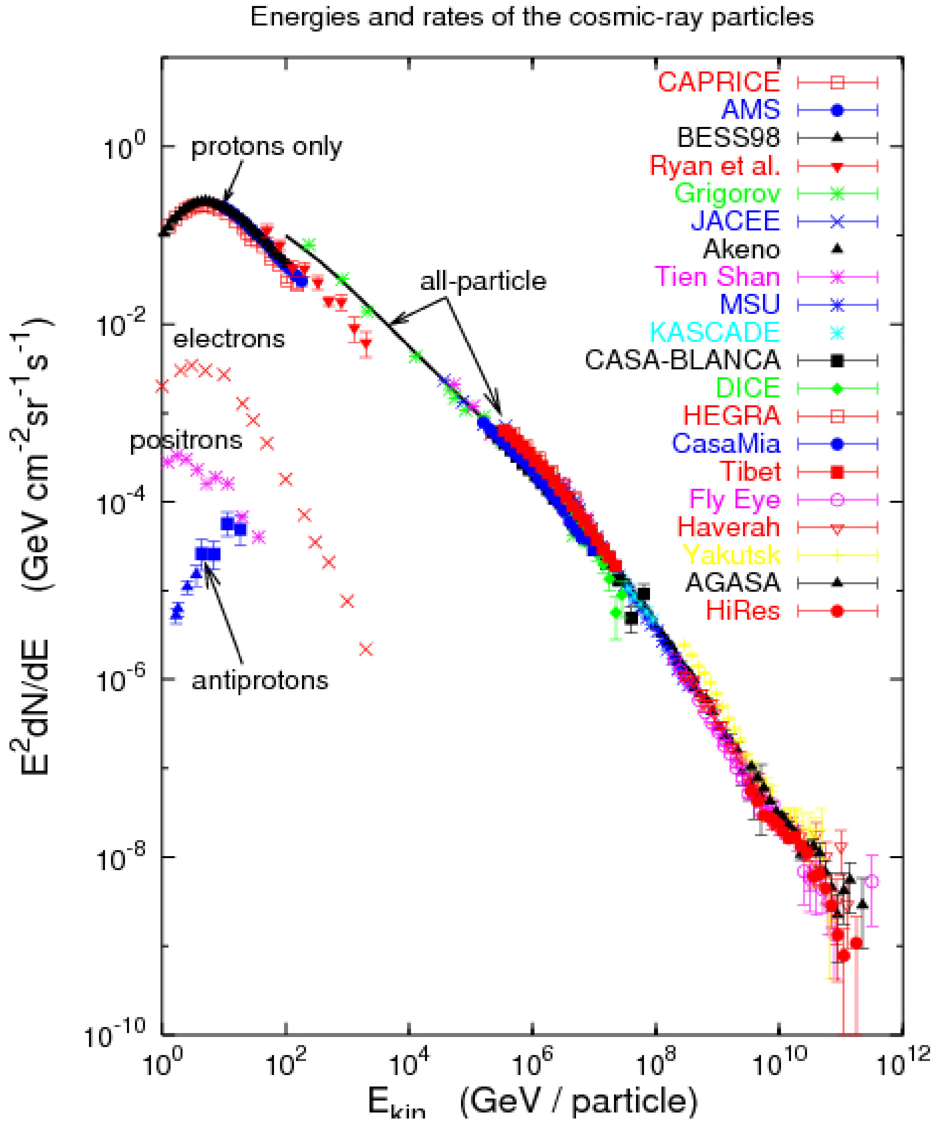


Objectives of TeV Gamma-Ray Astronomy

- Origin of (Galactic) CRs:
  shell-type supernova remnants, molecular clouds, diffuse radiation of the Galactic disk.
- Particle acceleration in stellar winds, wind-wind interactions, wind-ISM interactions: Superbubbles, massive stars, stellar clusters, protostars?
- Physics of particle acceleration/interaction & photon production/transport in magnetised environments: Pulsar wind nebulae, compact binaries, X-ray binaries
- Relativistic flows - Galactic & Extragalactic: Pulsars, pulsar winds, microquasars, small and large scale jets of active galaxies, gamma-ray bursts
- Observational gamma-ray cosmology: Indirect probe of extragalactic background photon fields
- Large-scale accelerators: Clusters of galaxies
- Exotic: Searching for (Cold) dark matter (DM) halos (indirect search) around massive objects

The CR Spectrum

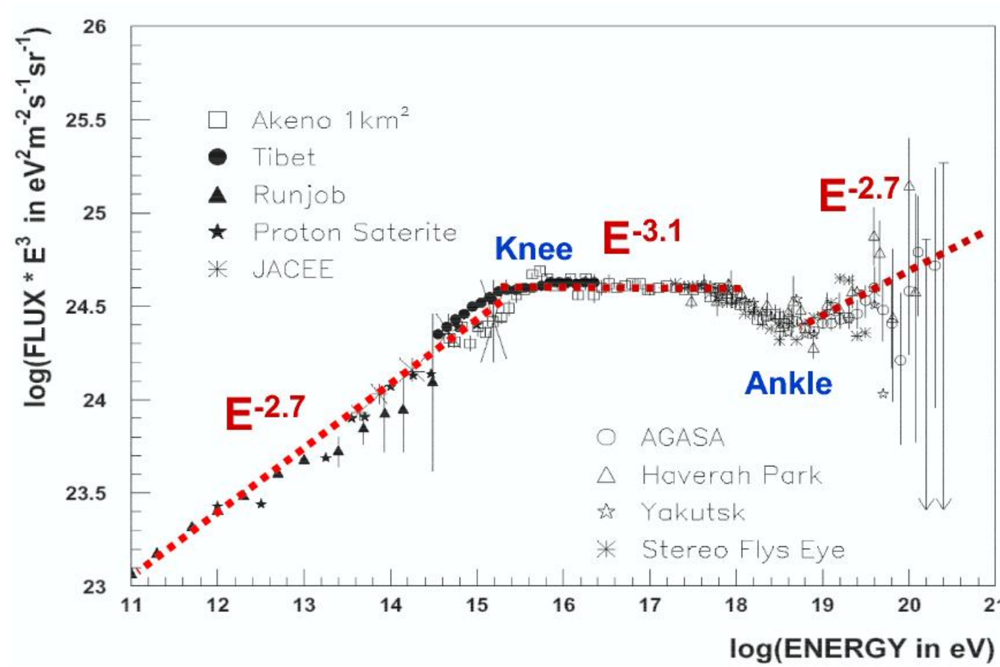
The measured CR spectrum spans *more than 10 decades in energy*



CR measurements; Assembled by Gaisser (Hillas 2006)

Steep power law $F(E) = \dfrac{dN}{dE} \propto E^{-2.7\,\mathrm{to}\,-3.1}$

Indicates a **non-thermal** process as distinct to a thermal (eg. black-body) process.



Hillas (2006) arXiv:astro-ph/0607109

Cosmic Rays: Galactic & Extragalactic

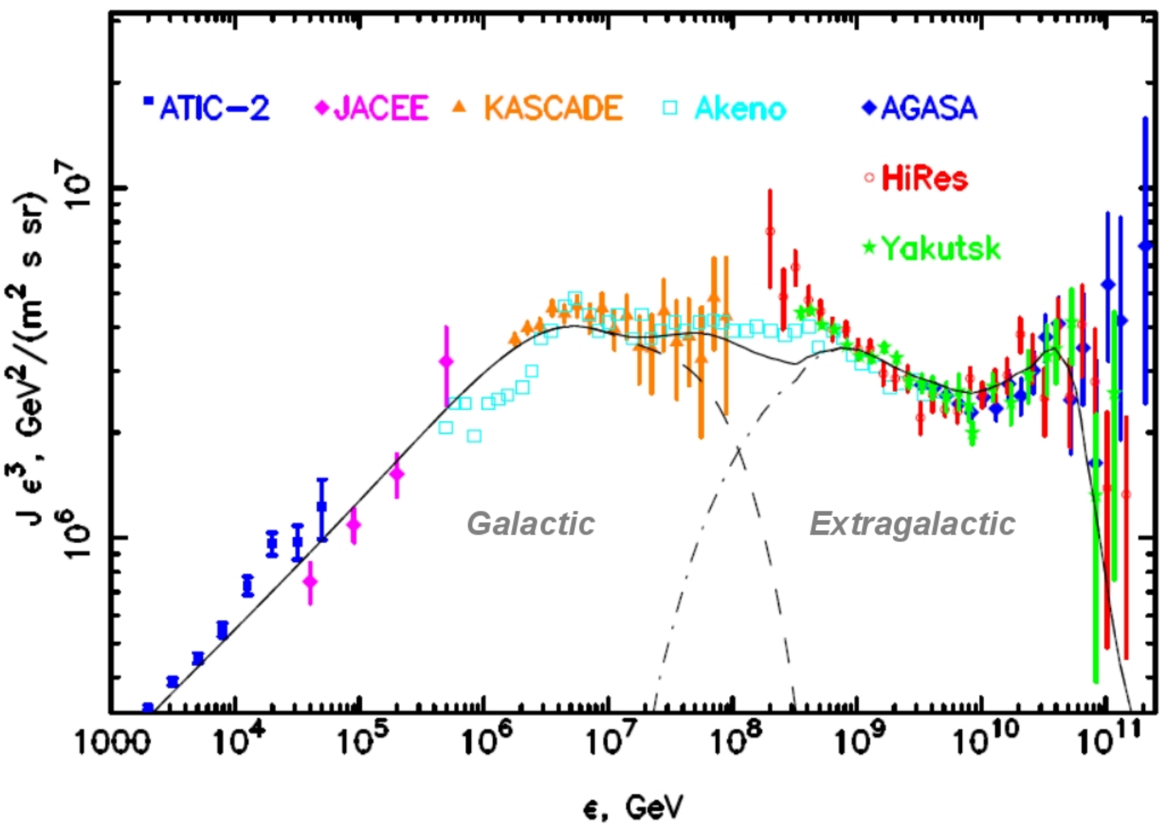
The boundary between 'Galactic' and 'extragalactic' CRs is thought to lie somewhere between the **knee** and **ankle** energies. The CR gyroradius r_g is similar to the Galactic disk thickness h ≈200 pc for $E \approx 10^{17}$ eV CRs.

<u>CR Spectrum at the source:</u>

CRs will lose energy during diffusive transport in our Galaxy. We find that (Leaky-Box model) the measured proton spectrum at Earth $F(E) = Q(E)E^{-\delta}$ for $Q(E)$ the proton spectrum **at the source** and $\delta \approx 0.5$.

Since $F(E) \propto E^{-2.75}$

$\rightarrow Q(E) \propto E^{-2.1}$



CR measurements; Assembled by Voelk et al. (2007)

Galactic Cosmic Rays & SNRs

Ginzburg & Syrovatski (1964) showed that shell-type SNRs could be responsible for Galactic CRs.

- Consider the luminosity L_{CR} of Galactic CRs $L_{CR} = V_D \rho_{CR}/\tau_{esc} \sim 10^{41}$ erg s^{-1}
  for $V_D = \pi R^2 h$ Galactic disk volume ($R = 15$ kpc, $h = 200$ pc)
  $\tau_{esc} \sim 6 \times 10^6$ yr - escape time for CRs in the Galaxy (from diffusion considerations)
- Core-collapse SNR: $10 M_\odot$ at $v \sim 5 \times 10^8$ cm s^{-1}, at SN rate of 1/30 yr
  Galactic SNR kinetic Luminosity L_{SNR} ~few$\times 10^{42}$ erg s^{-1}

  The released gravitational binding energy in a SNR is $\sim 10^{53}$ erg with ~1% in kinetic energy $W_{KE} \sim 10^{51}$ erg (the rest goes into neutrinos)
- Thus SNRs may provide the Galactic CR energetics provided ~10% of their KE (ie. 10^{51} erg) goes into CR production
- Also: Diffusive Shock Acceleration (DSA) provides a CR source flux $Q(E) \propto E^{-2}$, similar to the observed CR spectrum at Earth if we remove diffusive transport losses.

Potential CR Accelerators

CR accelerators need to satisfy the CR luminosity $\sim 10^{41}$ erg s^{-1} (as a population)

Supernova remnants (SNRs): L_{SNR} $\sim$few$\times 10^{42}$ erg s^{-1}; total power $W_{KE} \sim 10^{51}$ erg

Pulsars: Via rotational energy: Pulsar rotational KE $E = I\omega^2/2$. Pulsars spins are slowing down — *spin-down power* $\dot{E} = I\omega\dot{\omega}$ is available for particle acceleration. Typical $\dot{E} \sim 10^{32}$ to $\sim 10^{39}$ erg s^{-1}

Pulsars: Directly via electric fields: Huge potential difference available to accelerate charged particles. Maximum particle energies $E_{max} \approx 8 \times 10^{20} Z(B/10^{13}\mathrm{G})(\omega/3000\mathrm{Hz})^2$ eV

Accretion: Accretion of matter onto black holes: Accretion power $L_{acc} = \epsilon c^2 \dot{M}/2$ for mass transfer rate $\dot{M}$, efficiency 10 to 20%. For $\dot{M} \sim 1M_{\odot}$/yr (AGN black holes) $L_{acc} \sim 10^{46}$ erg s^{-1}. In galactic black hole systems, we can expect $L_{acc} \sim 10^{40}$ erg s^{-1} or thereabouts.

Jets (extragalactic & Galactic scales): associated with matter accretion: Jets can be a very efficient or *lossless* way of transferring energy out of the accretion region to kpc distances.

CR Acceleration: Maximum Particle Energies

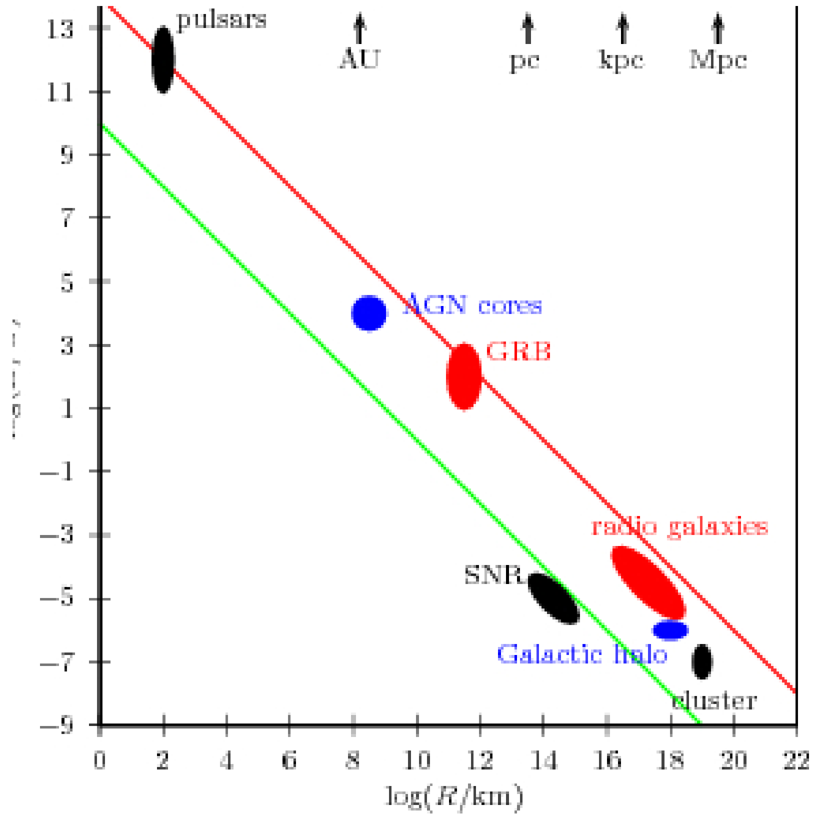
Hillas (1984) showed that the size and magnetic field of the accelerator limits the **maximum particle energies** E_{max} possible under DSA. The CR gyroradius $R_L = E/ZeB$ must be less than R_s, the source size.

$$E_{max} = \Gamma Z e B R_s$$

(Lorentz factor Γ accounts for any relativistic bulk motion)

- Red Line: Protons $E > 10^{21}$ eV
- Green Line: Iron $E > 10^{20}$ eV

Lagage & Cesarsky (1983) – optimistically $E_{max} \sim 10^{14}$ eV (accel. for SNR lifetime).



Bell & Lucek (2001) – strongly amplified B field & diffusion length $\approx R_L$ (Bohm diffusion) ok – higher $E_{max} > 10^{15}$ eV.

See topical review by Hillas (2005) J. Phys.G: 31, p95

Gamma-Ray Production Processes

Hadronic: CRs collide with matter nuclei N:

$p + N \rightarrow N' + \pi^{\circ}\pi^{\pm}$ π in roughly equal numbers

$\pi^{\circ} \rightarrow \gamma\,\gamma$ π°-decay ($E_{\gamma} \sim 0.17 E_p$) $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}\bar{\nu}_{\mu} \rightarrow e^{\pm}$

GeV to TeV gamma-rays result from π°-decay. Charged $\pi^{\pm}$ decay to muons and neutrinos, and thereafter, *secondary* electrons. Secondary electrons provide radio to X-ray emission (synchrotron radiation)

Energy loss rate for protons interacting with a ambient medium of number density n:

$$\boxed{dE_p/dt = (n\sigma_{pp} f c) E_p}$$

where f is the inelasticity for single interactions ($f \sim 0.5$ - Gaisser 1990) and σ_{pp} is the total cross section for the interaction.

Leptonic (Electrons):Inverse Compton (IC) scattering:

TeV electrons will up-scatter soft photon fields (CMB, IR, Optical/UV) to TeV energies

$e^- + \gamma_{soft} \rightarrow e'^- + \gamma_{TeV} \qquad (E_e \sim 20\sqrt{E_\gamma})$

Assuming a monoenergetic soft photon energy ω with number density n_{ph}, the energy loss rate for electrons of energy $E_e = E_e/(m_e c^2)$ is $\boxed{dE_e/dt = \frac{4}{3}\sigma_T c \omega n_{ph} E_e^2}$
for σ_T is the Thompson cross section

Bremsstralung:

High energy electrons will also convert their energy to high energy photons upon scattering in the field of a nucleus (ambient matter) - known as Bremsstralung (*braking*) radiation:
Energy loss rate $\boxed{dE_e/dt = c m_p n_p E_e/X_o}$ for radiation length $X_o = 7/(9 n_p \sigma_o)$,
and σ_o the pair production cross section.

Synchrotron Radiation: Radio to X-rays: Electrons spiralling around magnetic field lines.

TeV electrons — $e^- + B \rightarrow e'^- + \gamma_{keV}$ X-rays
GeV electrons — $e^- + B \rightarrow e'^- + \gamma_{eV}$ radio/opt/UV
Energy loss rate $\boxed{dE_e/dt = \frac{4}{3}\sigma_T c U_B E_e^2}$ for $U_B = B^2/8\pi$ magnetic field energy density

Generally the same electron population will emit both synchrotron and IC emission and thus the two process are competing. The close connection between the synchrotron F_{sync} and IC F_{IC} fluxes can be seen:

$$\frac{F_{IC}}{F_{sync}} = \frac{\dot{E}_{IC}}{\dot{E}_{sync}} = \frac{U_{rad}}{U_B} \qquad \text{for } U_{rad} = \omega n_{ph}$$

In the δ-function approximation for the synchrotron and IC cross sections, and IC scattering of the CMB field (Aharonian et al. 1997) we find that:

$$F_{IC} \sim \frac{F_{sync}}{10(B/10\mu\mathrm{G})^2}$$

Thus, a comparison of the TeV gamma-ray and X-ray synchrotron fluxes can provide an estimate of the magnetic field B in an extreme environment. This highlights the close connection between TeV and X-ray astronomy.

Additional links with radio and X-ray astronomy via synchrotron from directly accelerated electrons, and/or secondary electrons as by-products of CR interactions with matter.

Radiative Cooling Time

Cooling time t is the time taken for a population of particles to radiate all of their energy away: Recall the energy rate $\dot{E} = dE/dt$.

$\boxed{\text{Cooling time } t = E/\dot{E}}$

The cooling time is a useful parameter to understand the relative importance of radiative processes in a high energy particle accelerator. A short cooling time implies fast conversion of particle energy to photon energy, and initially, this process will dominate over other competing process with a longer cooling time. This issue is particularly important for electrons where synctrotron and IC radiation losses often compete. Let's look at cooling times:

Pi-zero decay: $t_{pp} = (n\sigma_{pp} f c)^{-1} \approx 5.3 \times 10^7 (n/\mathrm{cm}^3)^{-1}$ yr
IC scattering: $t_{IC} \approx 3 \times 10^8 (U_{rad}/\mathrm{eV/cm}^3)^{-1} (E_e/\mathrm{GeV})^{-1})$ yr
Bremsstrahlung: $t_{br} \approx 4 \times 10^7 (n/\mathrm{cm}^3)^{-1}$ yr
Synctrotron: $t_{sync} \approx 12 \times 10^6 (B/\mu\mathrm{G})^{-2} (E/\mathrm{TeV})^{-1}$ yr

Gamma-Ray Visibility of Molecular Clouds

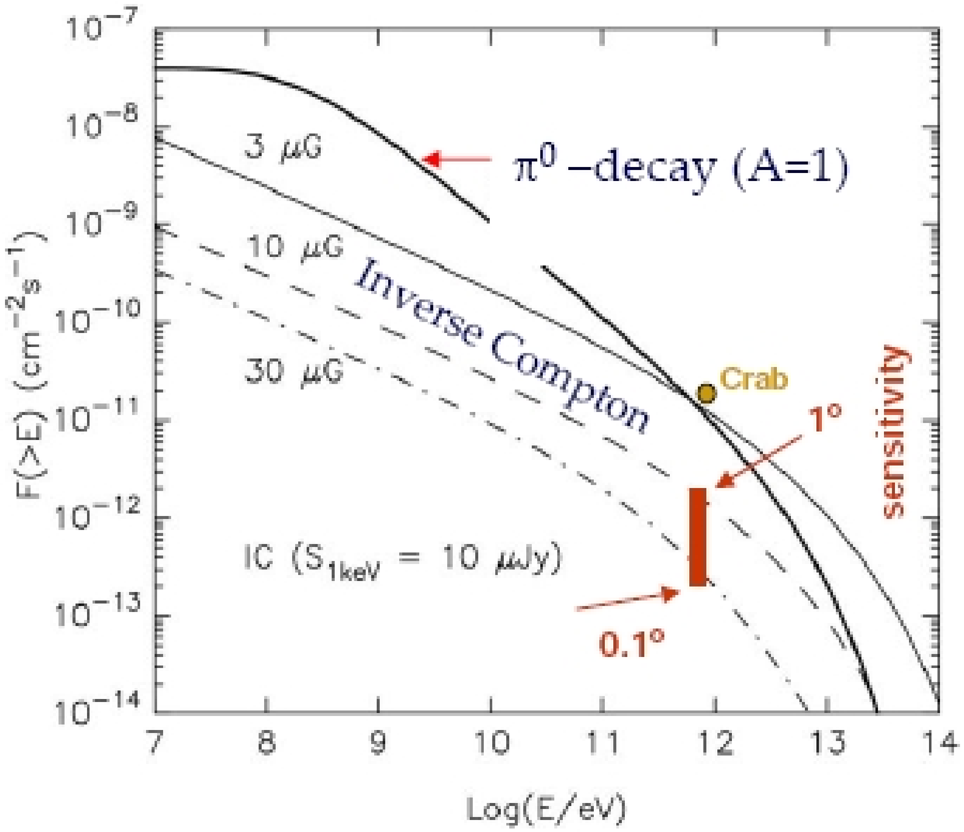
Molecular clouds act as passive targets for CRs as they diffuse through the ISM. The gamma-ray spectrum will closely follow the spectrum of CRs incident on the cloud. The predicted hadronic (integral) TeV gamma-ray flux for an **Earth-like** CR density with spectral index of -2.6 (e.g. as expected after diffusion/transport losses) is (Aharonian 1991):

$$F(\geq E) \approx 3 \times 10^{-13}\ (E/\mathrm{TeV})^{-1.6}\ k(E)\ M_5/d^2_{\mathrm{kpc}} \quad \text{ph cm}^{-2}\ \text{s}^{-1}$$

where $k(E)$ is the CR density enhancement factor above an Earth-like value, M_5 is the cloud mass ($10^5 M_\odot$ units), and d is the distance.

Thus we can use TeV gamma-ray measurements with measurements of cloud masses (from mm/sub-mm obs.) to estimate the CR density. This highlights the close connection between TeV and mm/sub-mm observations

Gamma-Ray Visibility of Shell-Type SNRs



Synchrotron flux $S_{1\mathrm{keV}}$ is fixed at 10μJy.

Drury, Aharonian & Voelk (DAV) 1994 (see also Naito et al. 1994) showed that Shell-Type SNRs could be detectable. They estimated hadronic ($\pi^\circ \rightarrow 2\gamma$) and leptonic IC TeV gamma-ray fluxes. Red area on plot indicates expected TeV telescope flux sensitivty to a 0.1° and 1.0° sized source. The predicted hadronic TeV (integral) gamma-ray flux:

$$F(>E) = 10^{-11}\,A\,(E/\mathrm{TeV})^{-1}\ \mathrm{ph\ cm^{-2}\ s^{-1}}$$

$A = (W_{cr}/10^{51}\mathrm{erg})(n/\mathrm{cm}^{-3})(d/\mathrm{kpc})^{-2}$

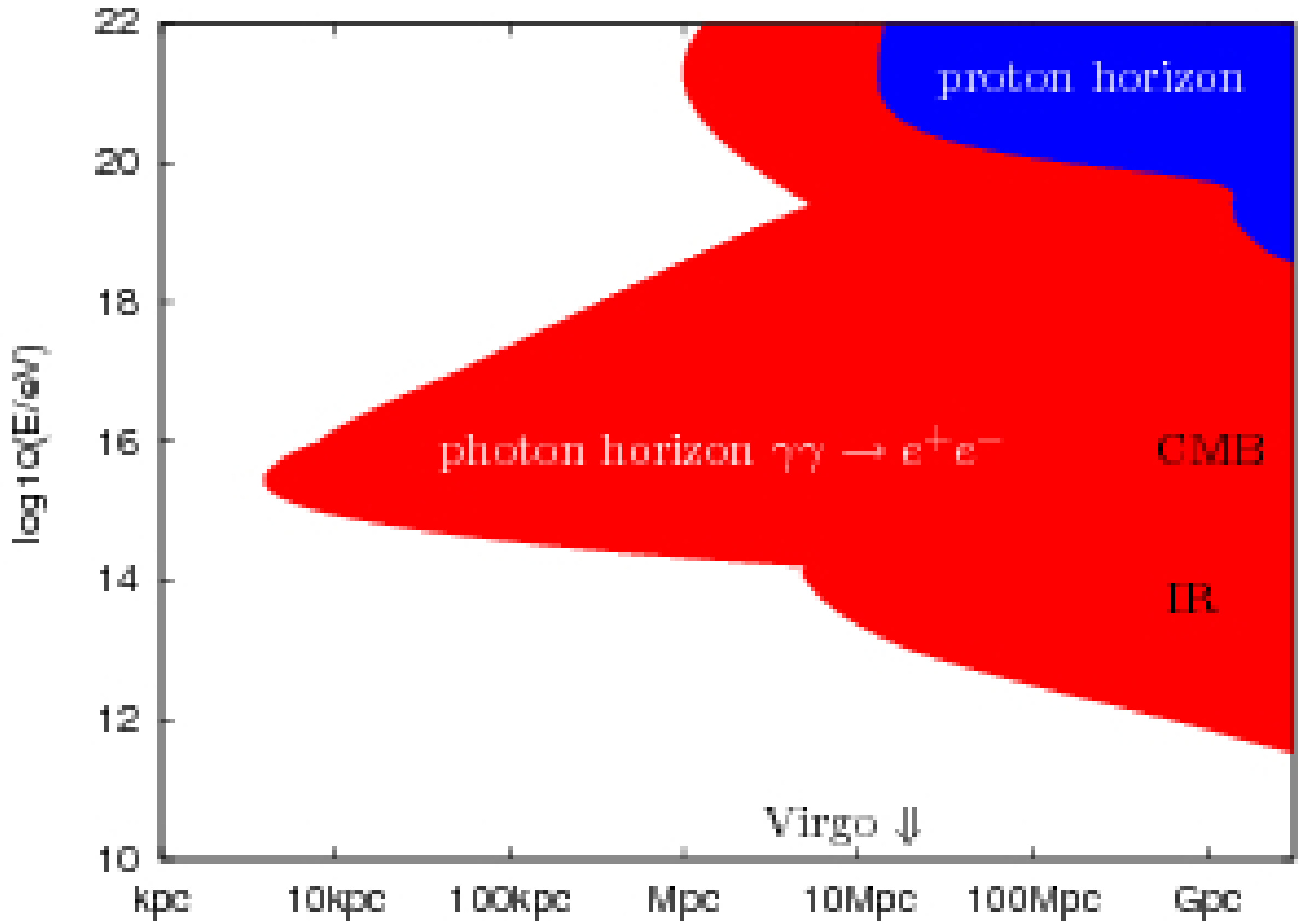
W_{cr} = total energy in accelerated protons

$W_{cr} \sim 10^{50}$ ergs

n = ambient matter density

d = distance

The Gamma-Ray & CR Horizon



The interaction of CRs (protons in above plot) and gamma-rays with intervening radiation and particle fields limits their *horizon*. TeV gamma-ray astronomy is restricted due to pair production ($\gamma \rightarrow e^{\pm}$) but extends to $\sim$Gpc in the TeV regime.

2 Detecting TeV Gamma-Rays

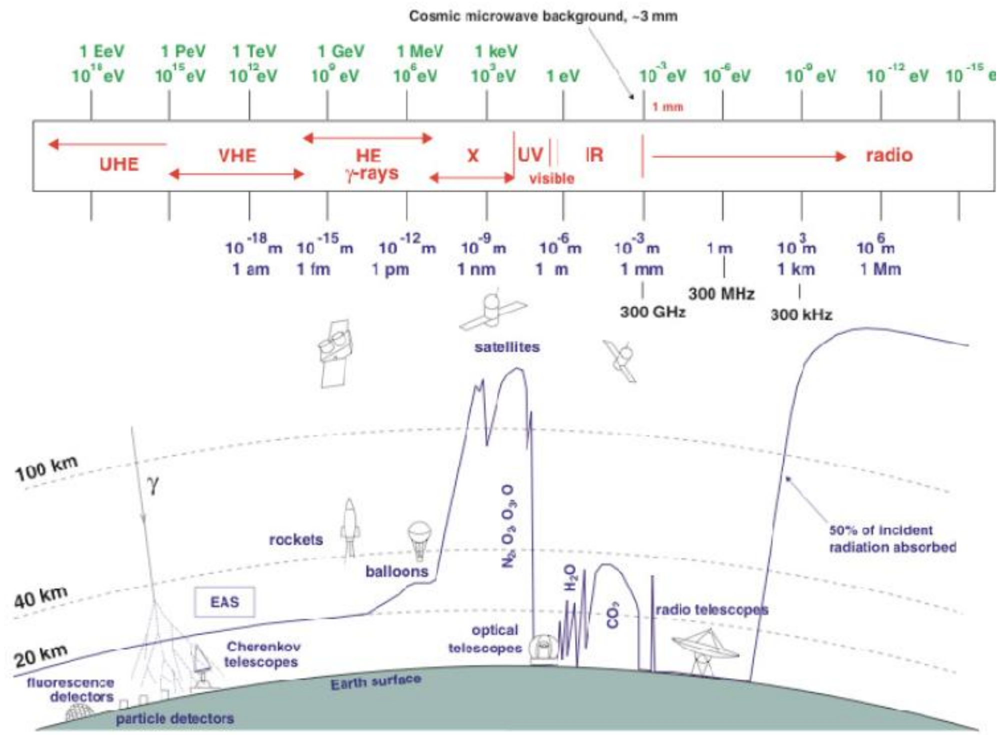
- Satellites only effective for $E \leq 100$ GeV due to size & therefore collection area constraints (max coll. area <few m^2)

- *Fortunately*, gamma-rays will interact with the atmosphere. The interaction length X for gamma/pair production

  $X(\gamma \rightarrow e^- \, e^+) \approx 40$ gm cm^{-2}

  Compare this to the atmosphere 'thickness' $\sim$1030 gm cm^{-2} at sea level.

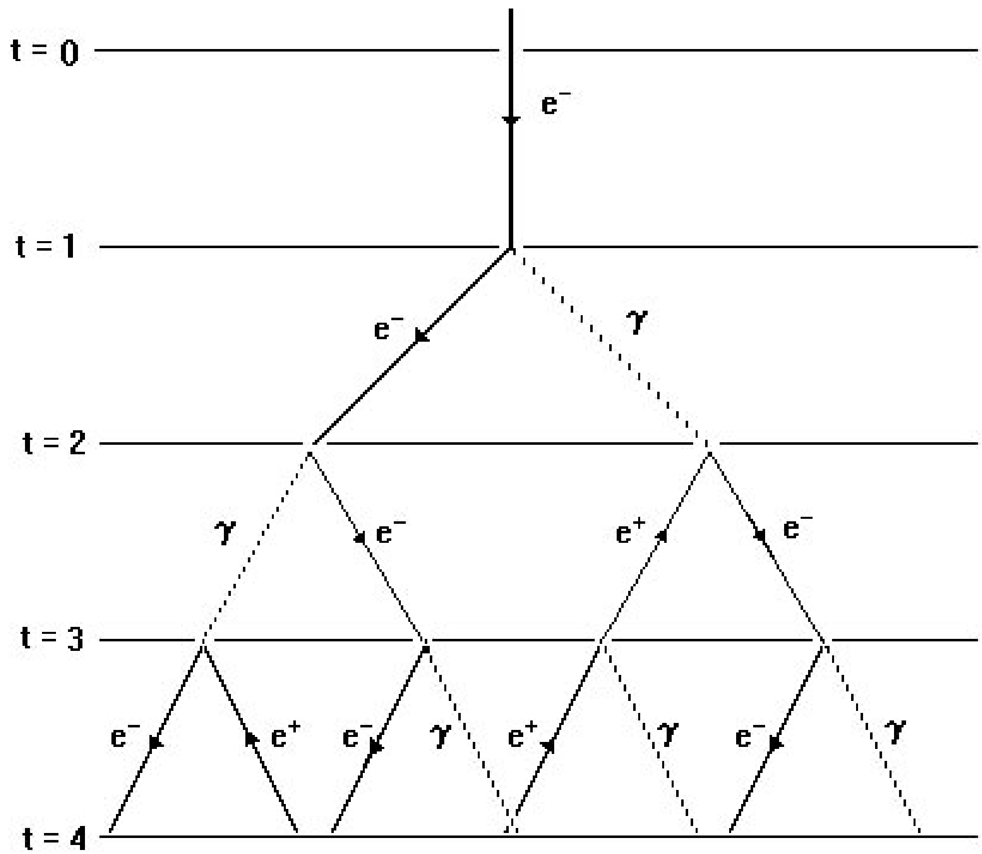
  Thus gamma-rays will not survive to ground level, but will initiate *Extensive Air Showers* (EAS) or cascade of secondary particle/photons



- We can utilise EAS properties to determine the *primary* gamma-ray direction and energy $\rightarrow$ gamma-ray astronomy!

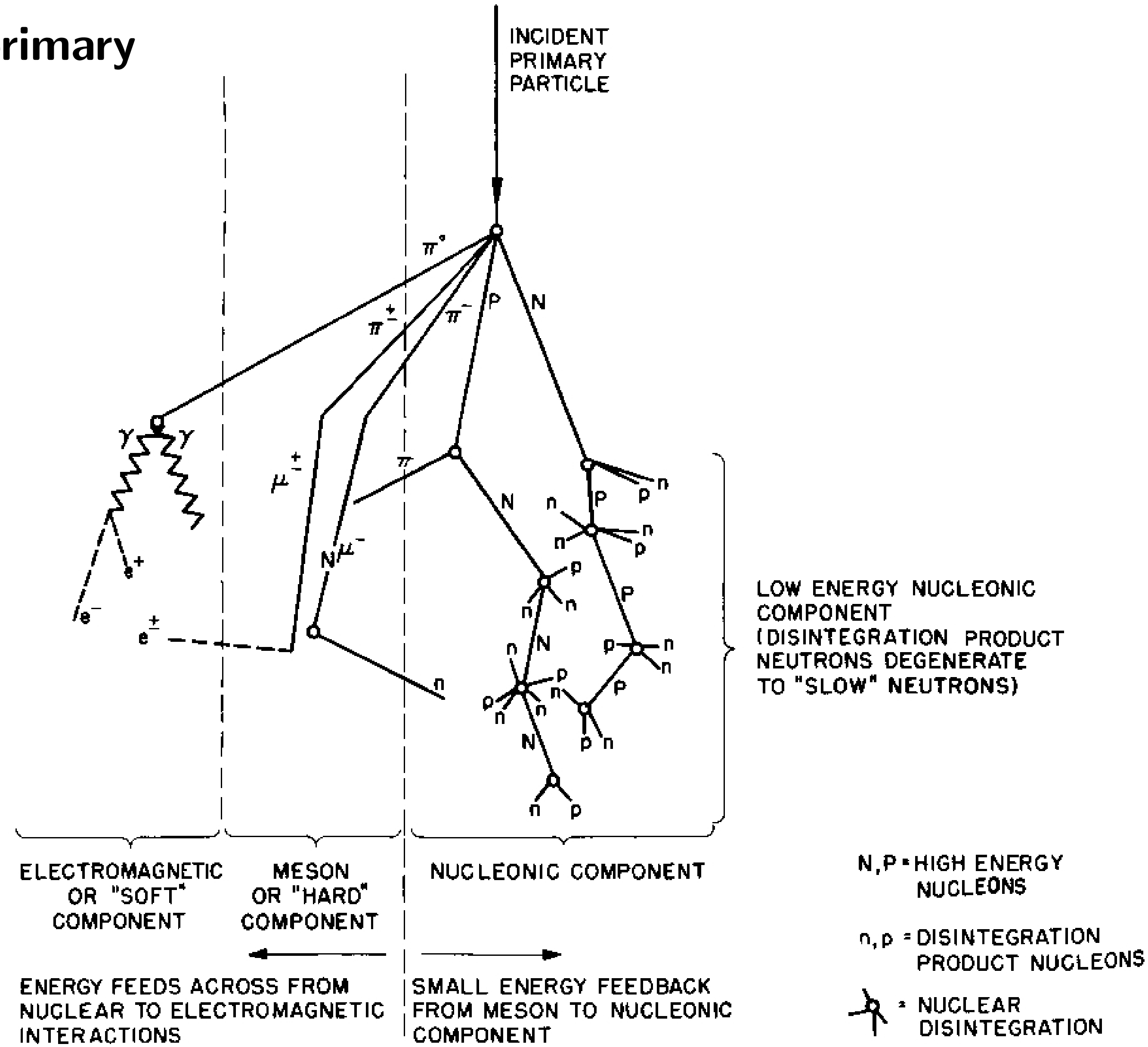
Extensive Air Showers (EAS) - Overview

Gamma-Ray primary (starts with $\gamma \rightarrow e^{\pm}$)



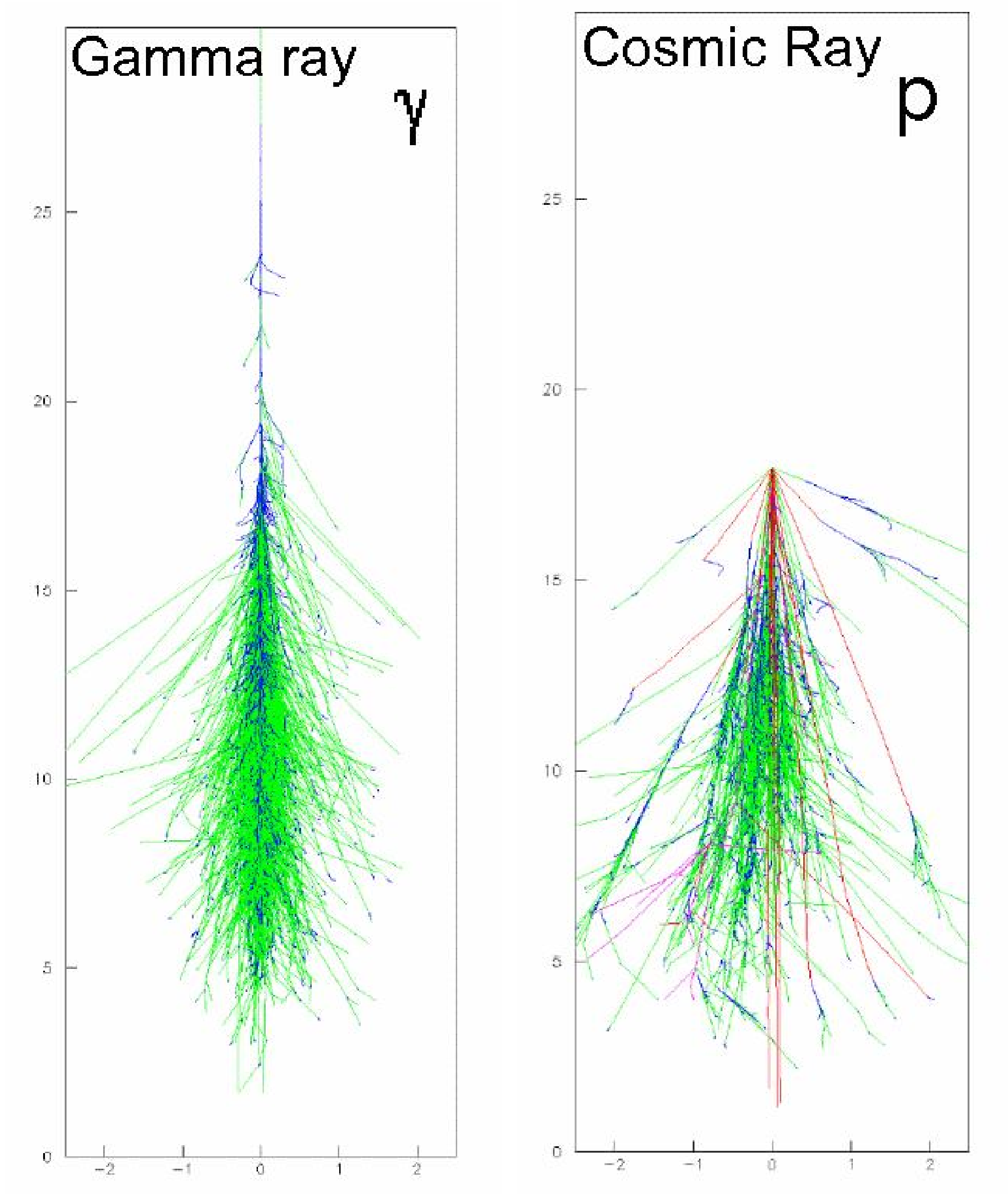
The gamma-ray *primary* will initiate a *cascade* of $e^{\pm}$ and photons, via pair-production and bremsstralung ($e^{\pm} \rightarrow \gamma$) - Electromagnetic EAS. Eventually these processes are dominated by ionisation losses and the cascade dies off.

Cosmic-Ray primary



Schematic Diagram of Cosmic Ray Shower

Simulated particle tracks for gamma-ray and proton EAS (1 TeV energy)



Monte-Carlo simulation of EAS.

Particles are colour-coded:

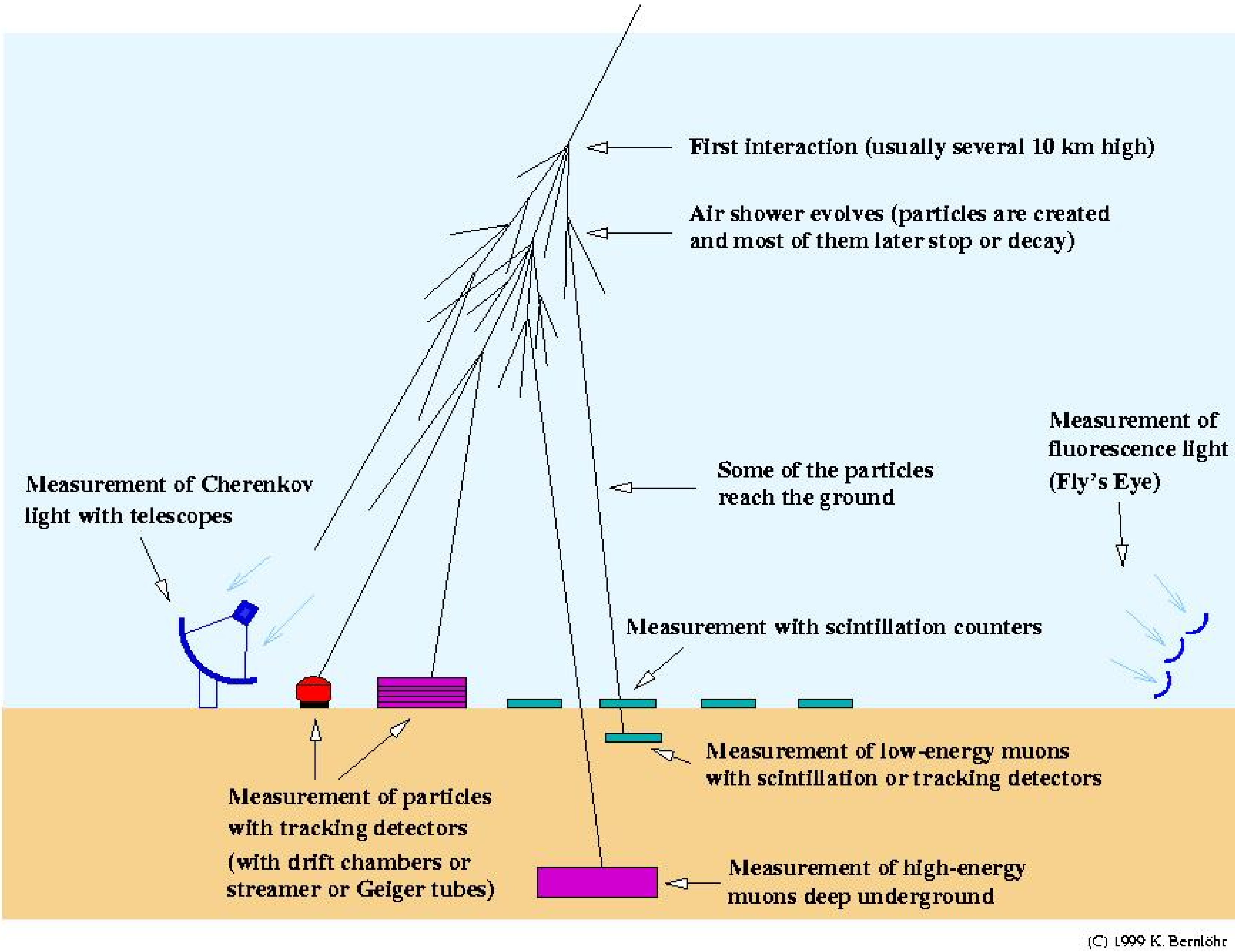
Electrons (blue)

Gamma-rays (green)

Muons (red)

Note the numerous electromagnetic cascades or *sub-showers* in the proton EAS, and the scale of the EAS — distances are in km!

Measuring cosmic-ray and gamma-ray air showers



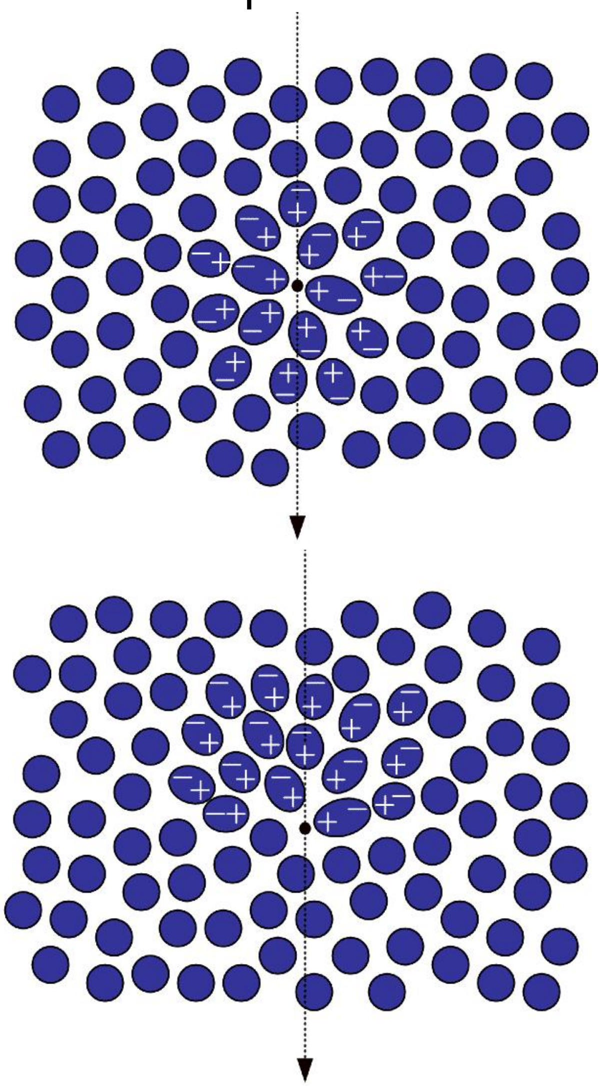
Atmospheric Cherenkov Imaging Technique

Rather than detecting the EAS particles directly (or via Nitrogen fluoroescence), EAS particles will also emit *Cherenkov Radiation*. The optical-UV component of this radiation can be viewed at ground level by telescopes comprising a mirror of sufficient area coupled with a focal plane array of light detectors.

The first such Cherenkov telescopes were used to view the *lateral* distribution of Cherenkov radiation from an EAS. Telescopes have now progressed from single to multi-telescope arrays viewing the *angular* distribution of Cherenkov radiation - known as the Stereoscopic Atmospheric Imaging Technique.

Cherenkov Radiation

Charged particles with speed v faster than the local phase velocity of light ($= c/n$ for the refractive index n of the medium) will emit *Cherenkov radiation*. At any speed the charged particle will polarise the atoms of the medium:

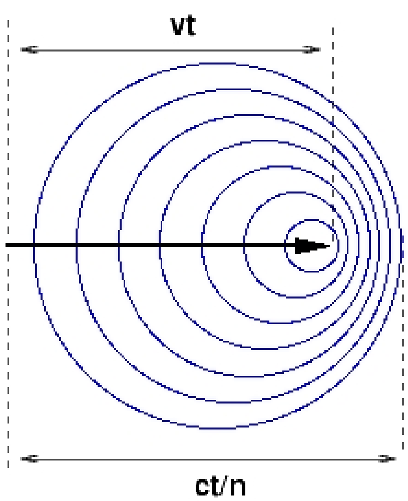


For $v << c$: Induced electric field is symmetric. For v approaching c: A net dipole field is setup. Each track element will emit pulses of e-m radiation which normally destructively interfere.

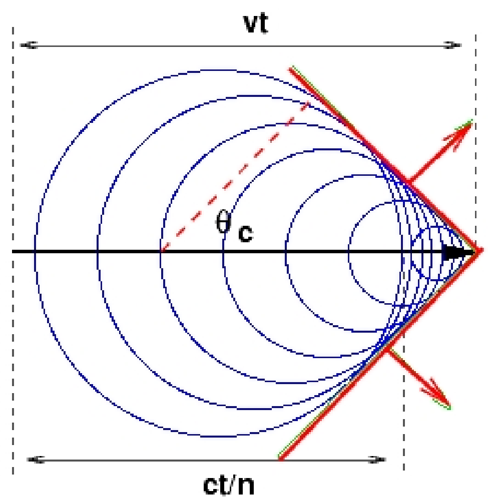
If $v > c/n$ then the e-m pulses can constructively interfere.

Huygens Construction

The Huygens construction for each track pulse or wavelet is shown below.



v < c/n



v > c/n

For a particular angle θ_c, and $v > c/n$ the wavelets form a coherent wave front:

$\cos\theta_c = 1/(\beta n)$ for $\beta = v/c$

$v =$particle speed

For $\beta \rightarrow 1$

(ultra relativistic limit)

$\theta_{c\,max} = \cos^{-1}(1/n)$

Air (sea level)	n=1.00029	$\theta_{c\,max} = 1.3^\circ$
Water	n=1.33	$\theta_{c\,max} = 42^\circ$

In air, $\theta_{c\,max}$ actually varies between 0.5° to 1.3° in going from 15 km altitude to sea level due to the change in refractive index with air density (& hence altitude).

EAS Particle Cherenkov Thresholds

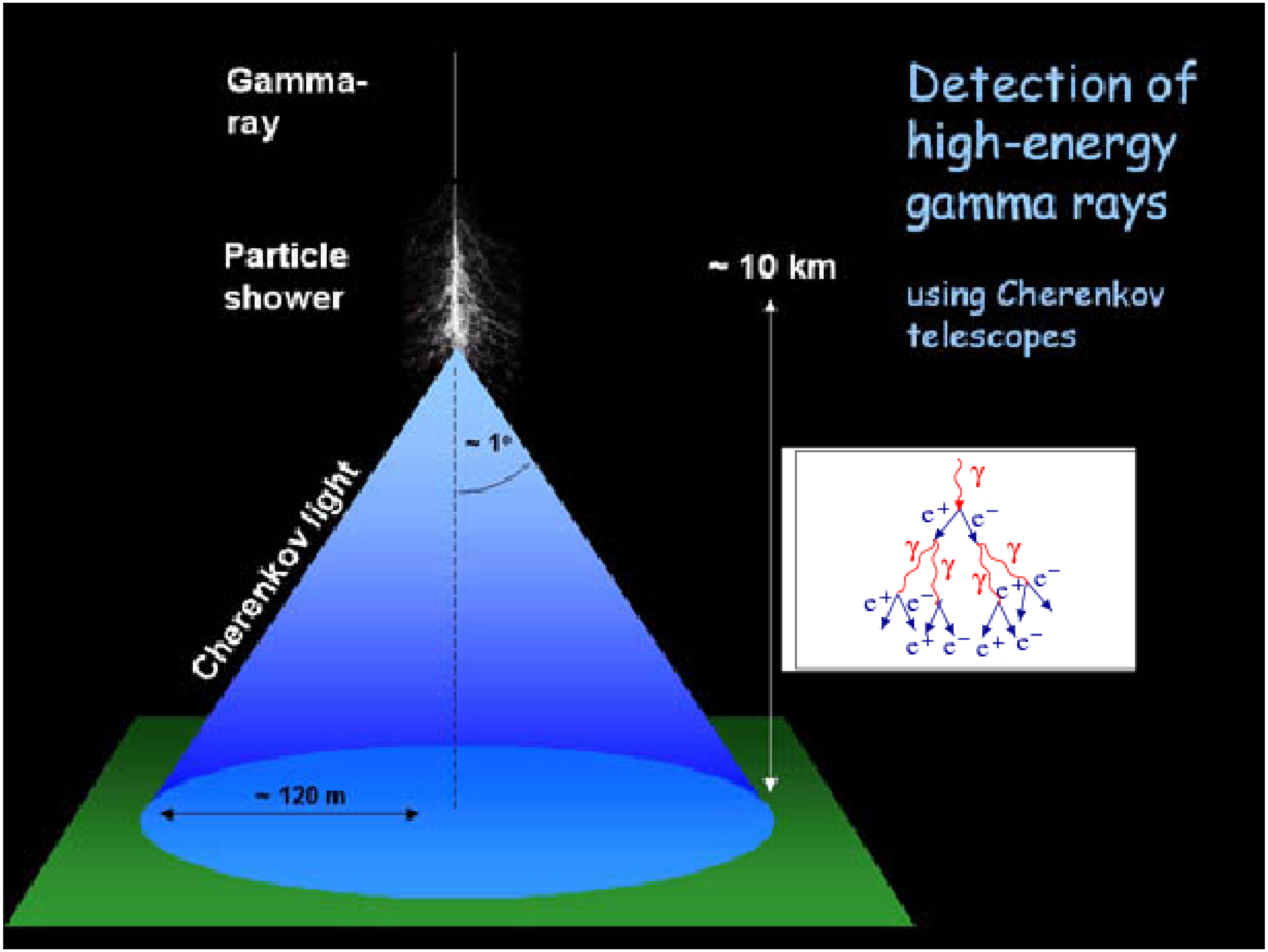
Cherenkov radiation is emitted when particle of reaches speed c/n, giving the critical Lorentz factor:

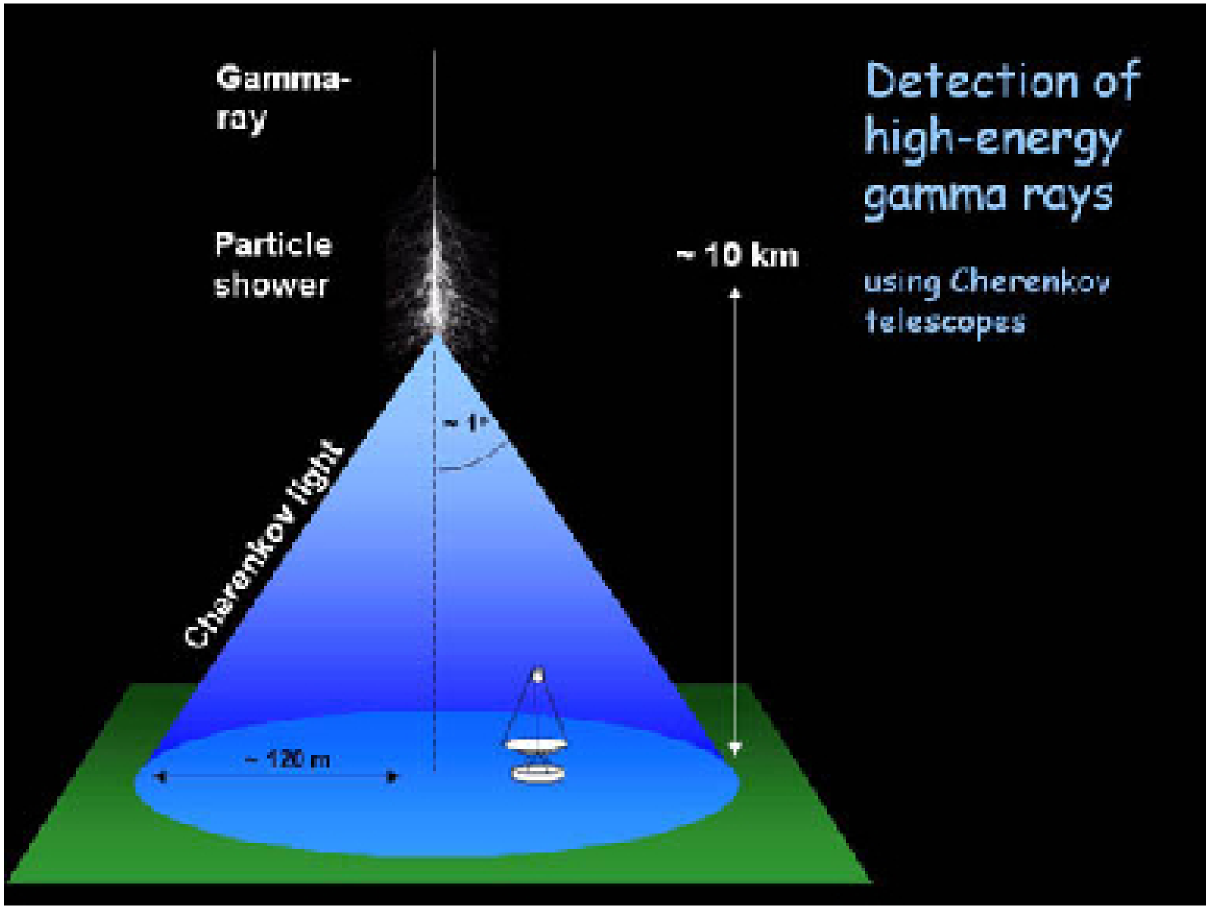
$\gamma_C = 1/\sqrt{(1 - \frac{1}{n^2})}$, where for $n = 1.00029$ (air)
$\gamma_C = 41.53$

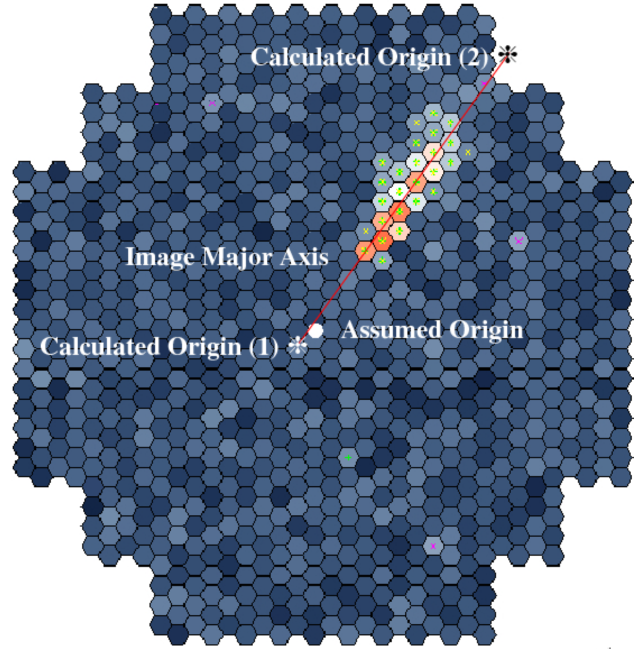
The Cherenkov threshold energy is given by: $E_C = \gamma_C \, E_m$ for rest mass E_m

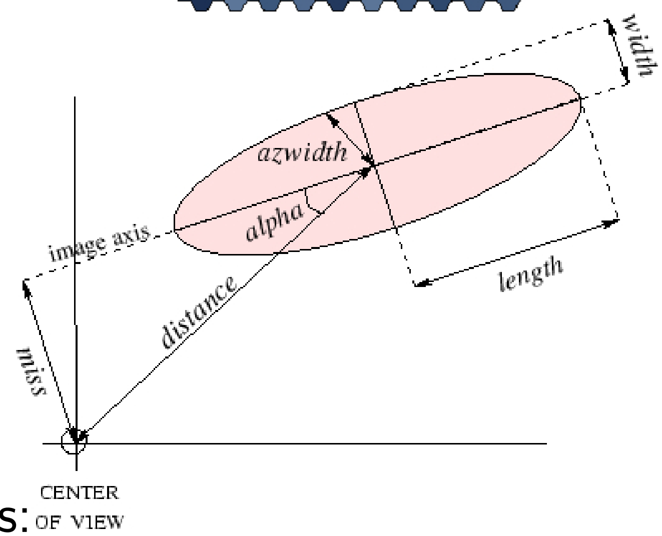
Particle	E_m (MeV)	E_C
$e^{\pm}$	0.511	21 MeV
$\mu^{\pm}$	105.7	4.4 GeV
p	938.3	39 GeV

The Cherenkov radiation from an EAS is expected to come primarily from electrons and muons, and can be emitted by primary Cosmic Rays & Gamma Rays of energy few 10's of GeV and above.


Gamma-ray
Particle shower
Cherenkov light
~ 1°
~ 10 km
~ 120 m
Detection of high-energy gamma rays
using Cherenkov telescopes
γ
e+ e−

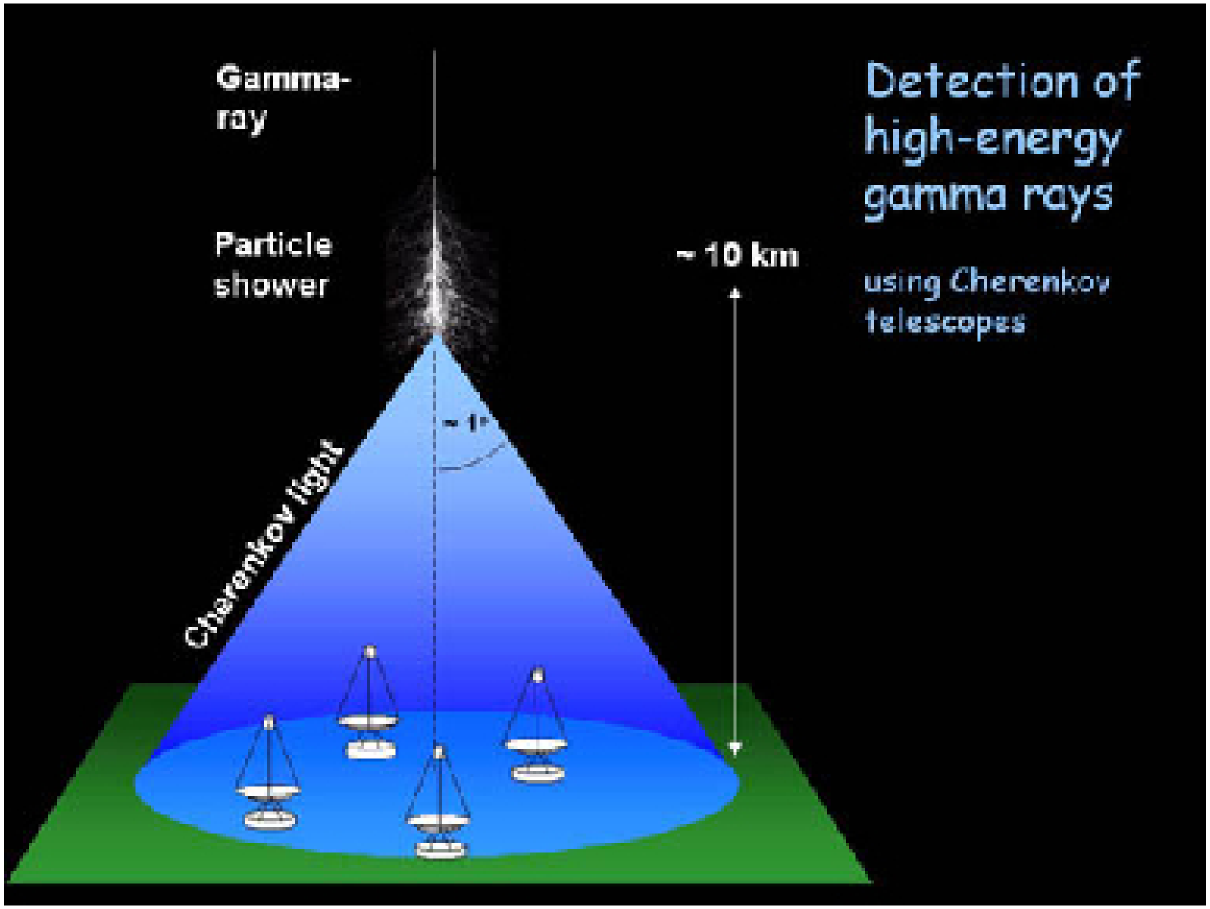


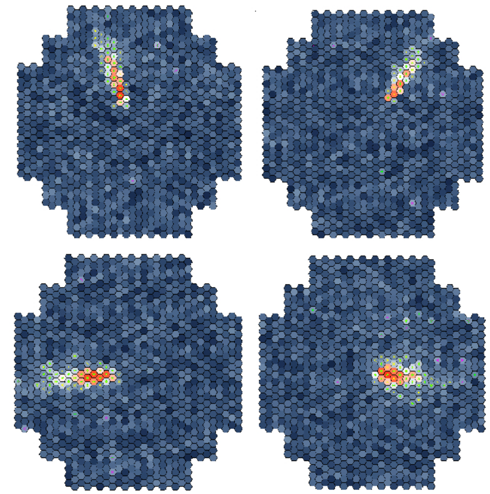


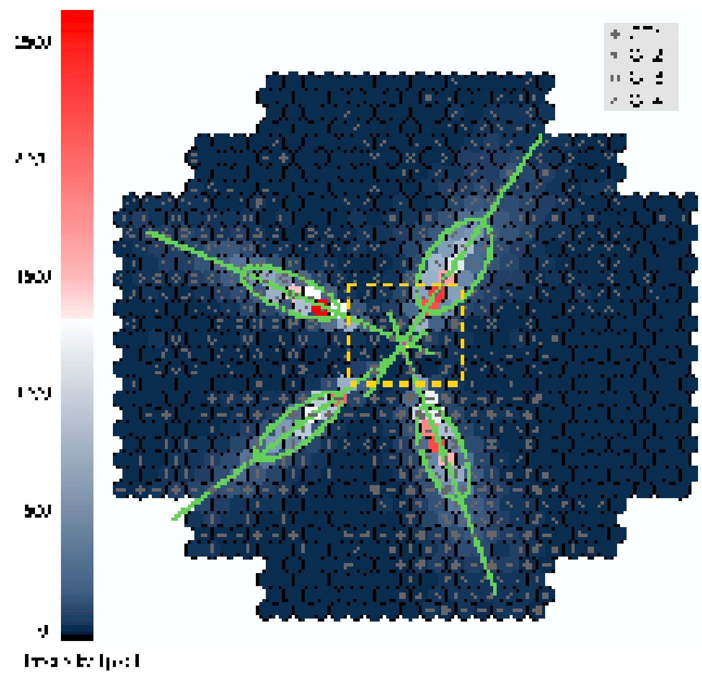


Single Telescope view with Multi-Pixel Detector at Focus:

Angular resolution: $\sigma_\theta \geq 0.1^\circ$ (6 arcmins) $\theta =$ dist. between 'true' and reconstruced direction Energy resolution: $\Delta E/E \geq 0.15$







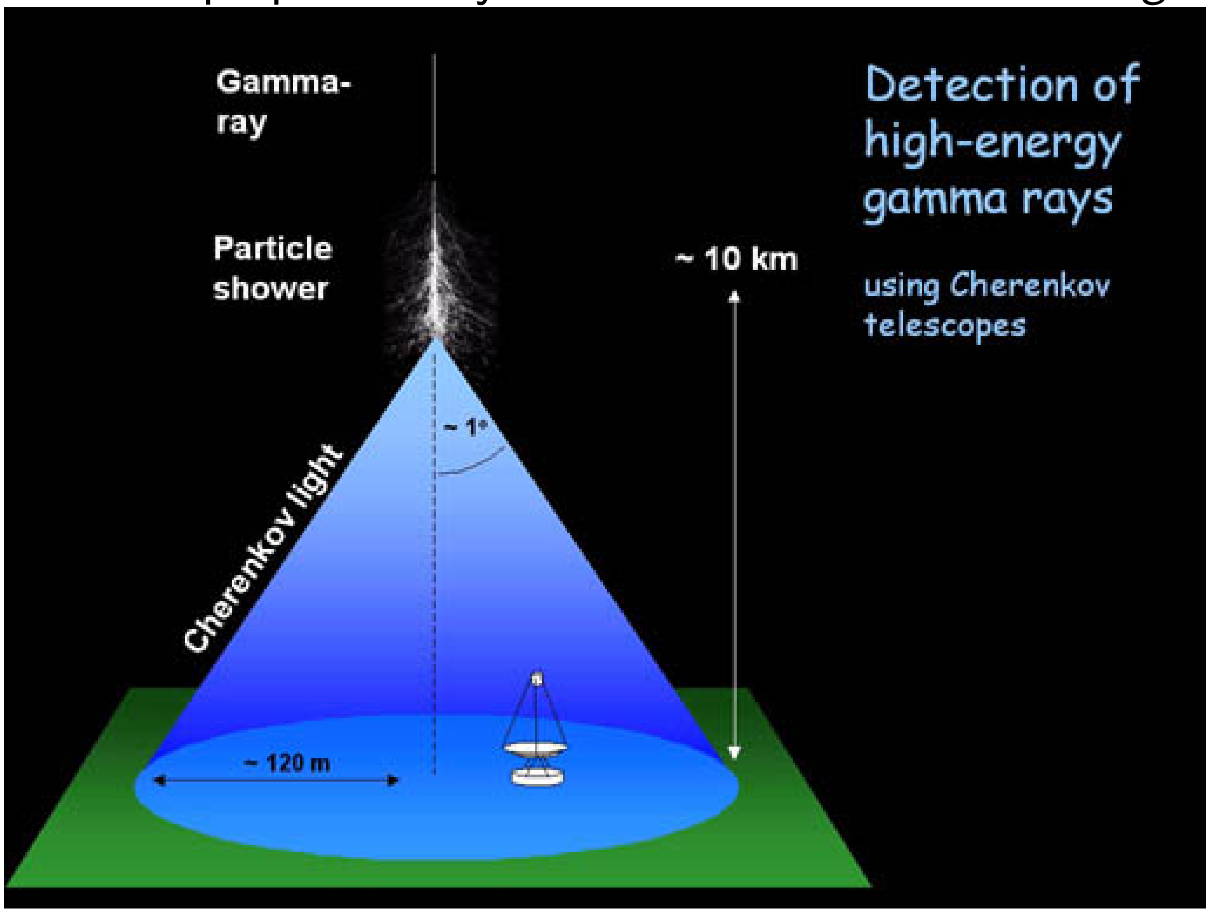
Multi-Telescope view with Multi-Pixel Detectors at Foci:

Stereo reconsruction of arrival direction.

Angular resolution: $\sigma_\theta \leq 0.1^\circ$ Energy resolution: $\Delta E/E \leq 0.15$

Huge Effective Collecting Area

A telescope placed anywhere within the *Cherenkov light pool* will detect the EAS.



The light pool can extend to to 1 km in radius for higher $\geq 10^{13}$ eV energies. **Thus the effective collection area A_{eff} can reach values $A_{eff} \sim 1$ km^2.**

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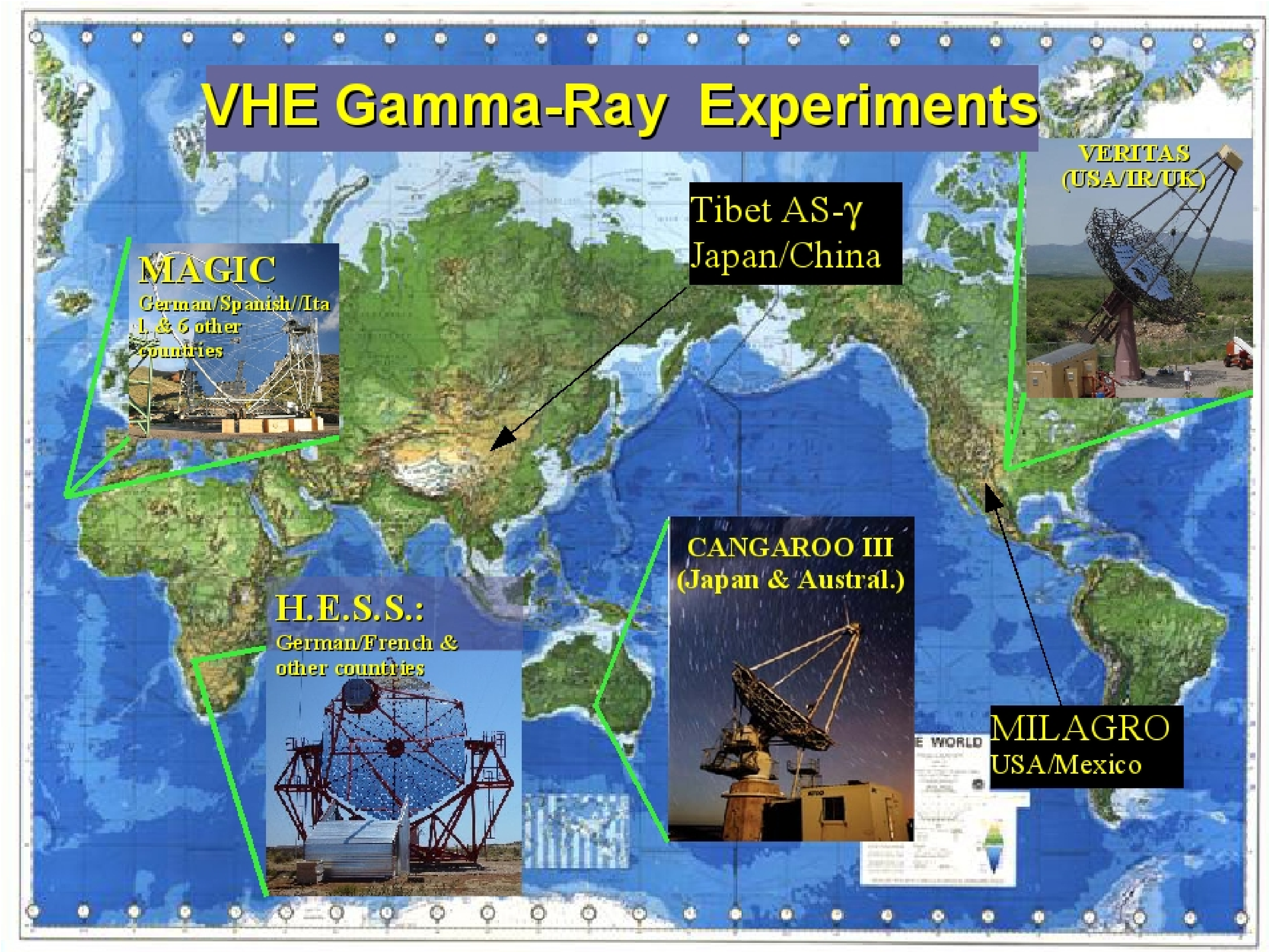
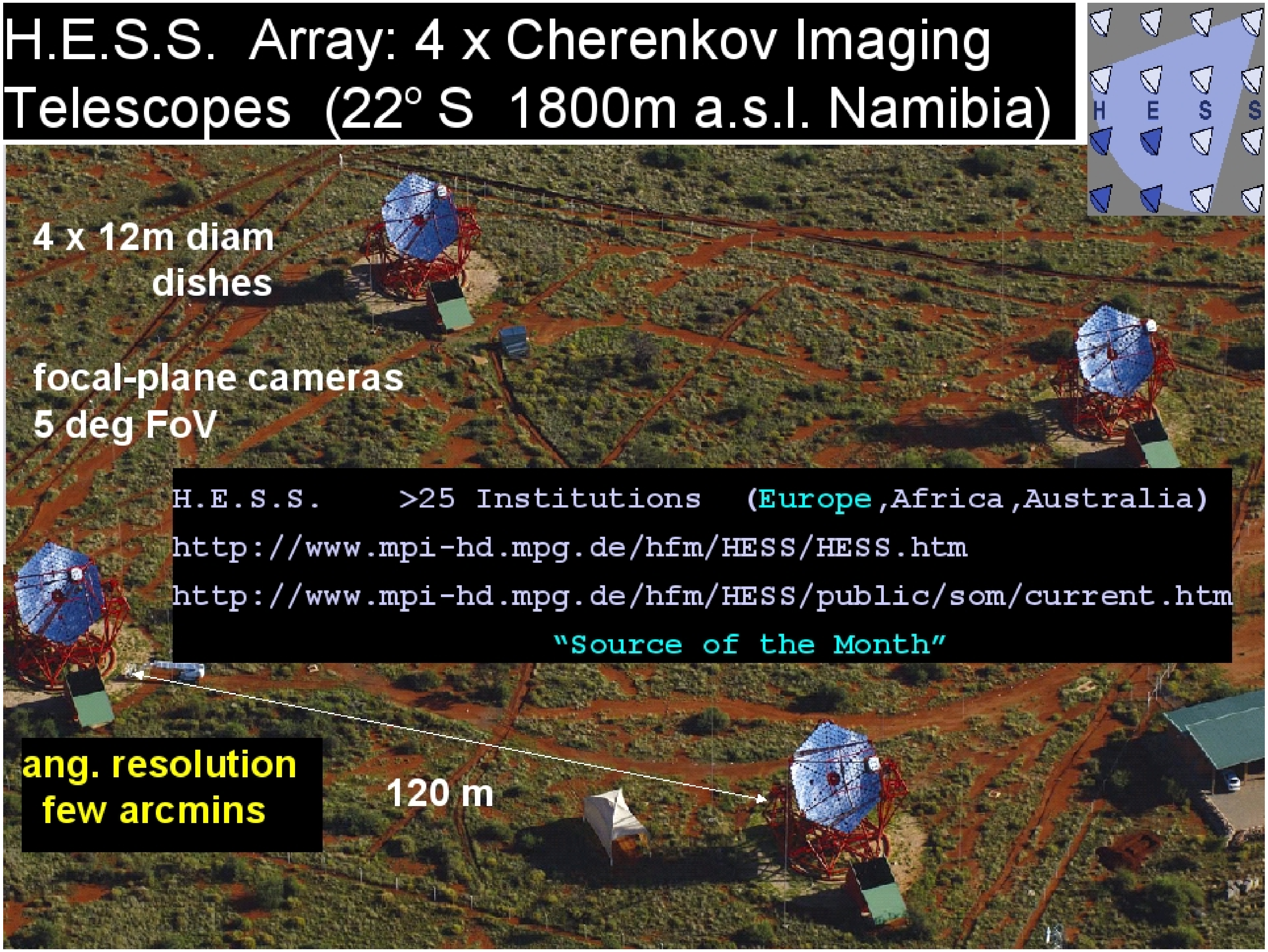


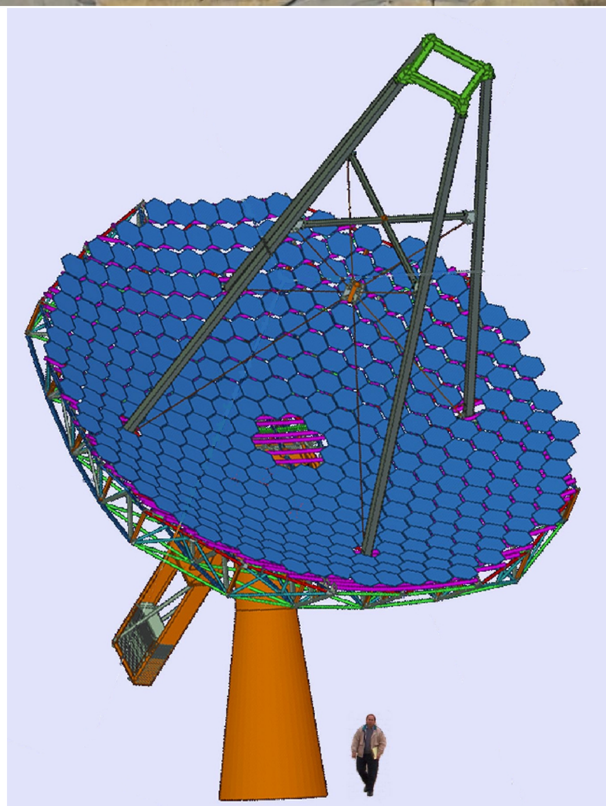
VHE Gamma-Ray Experiments
VERITAS
(USA/IR/UK)
Tibet AS-γ
Japan/China
MAGIC
German/Spanish//Ita
l. & 6 other
countries
CANGAROO III
(Japan & Austral.)
H.E.S.S.:
German/French &
other countries
MILAGRO
USA/Mexico

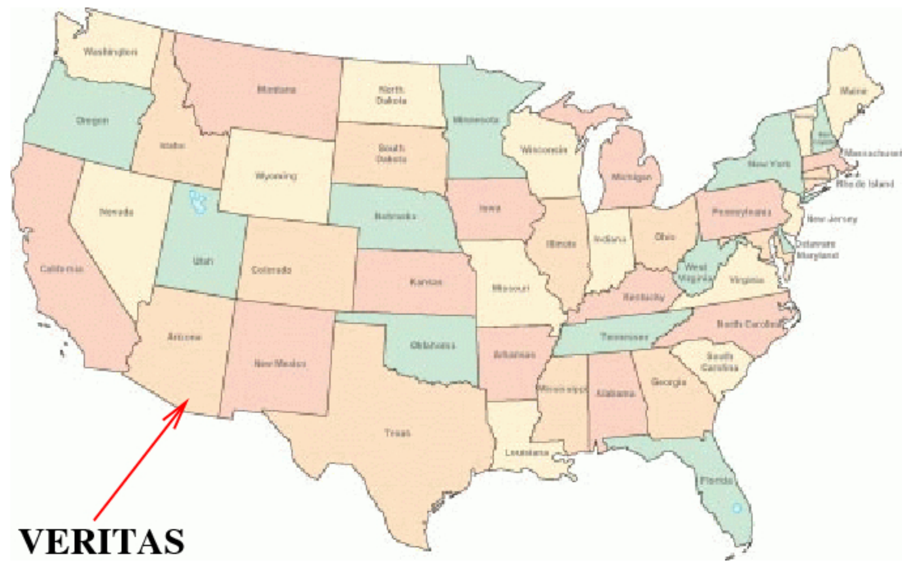


HESS-II 30 metre telescope under construction at the centre

VERITAS

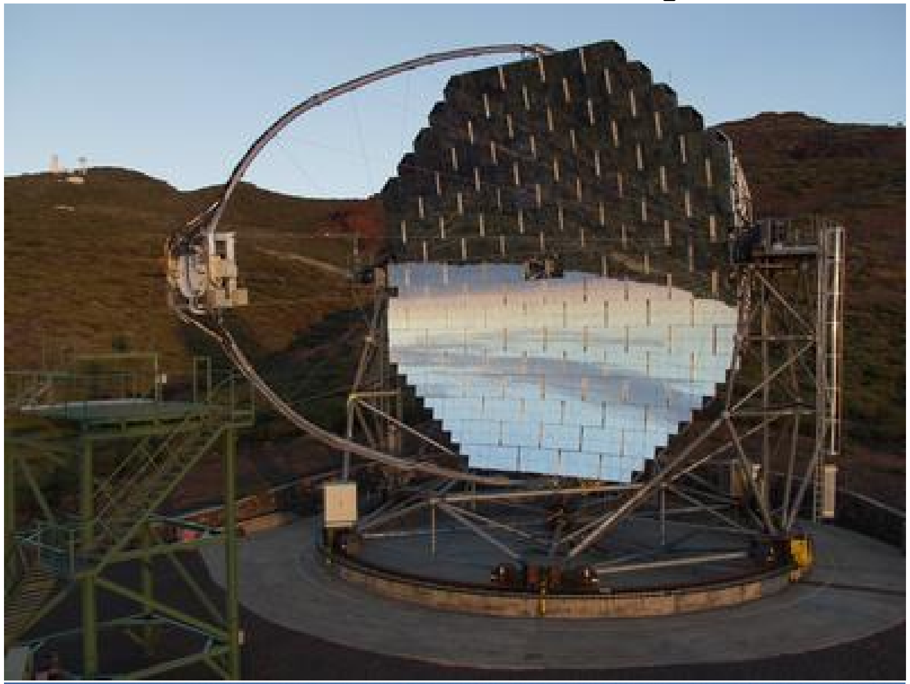
Very **E**nergetic **R**adiation **I**maging **T**elescope **A**rray **S**ystem `http://veritas.sao.arizona.edu/`





MAGIC/MAGIC-II

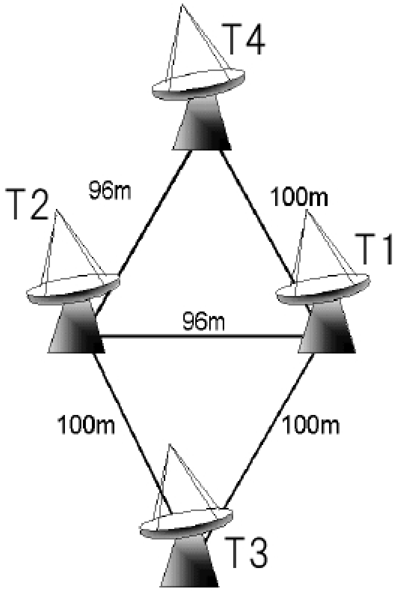
http://wwwmagic.mppmu.mpg.de/

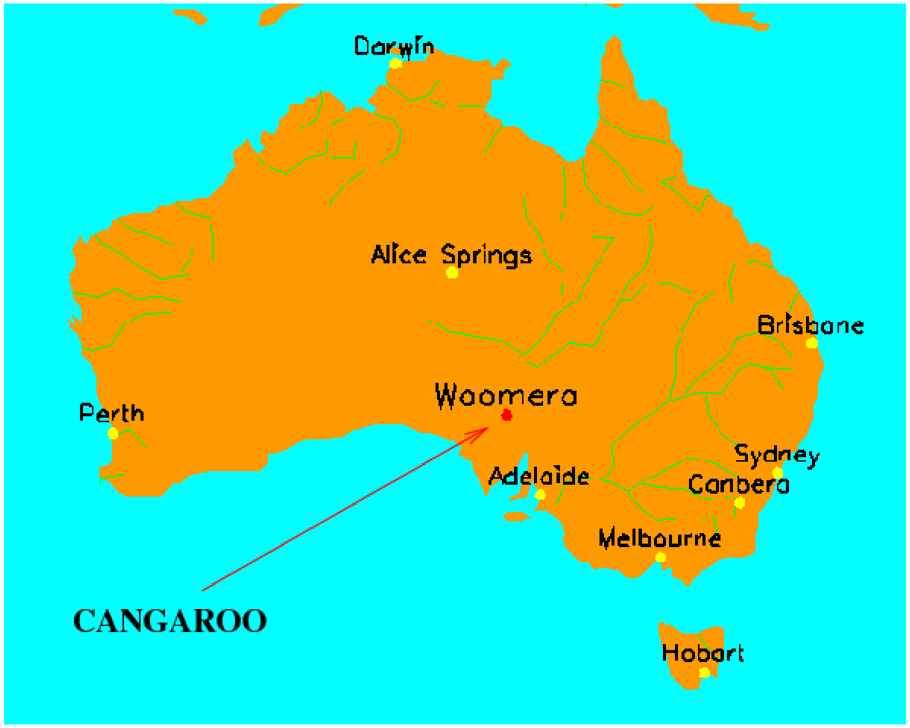


CANGAROO-III

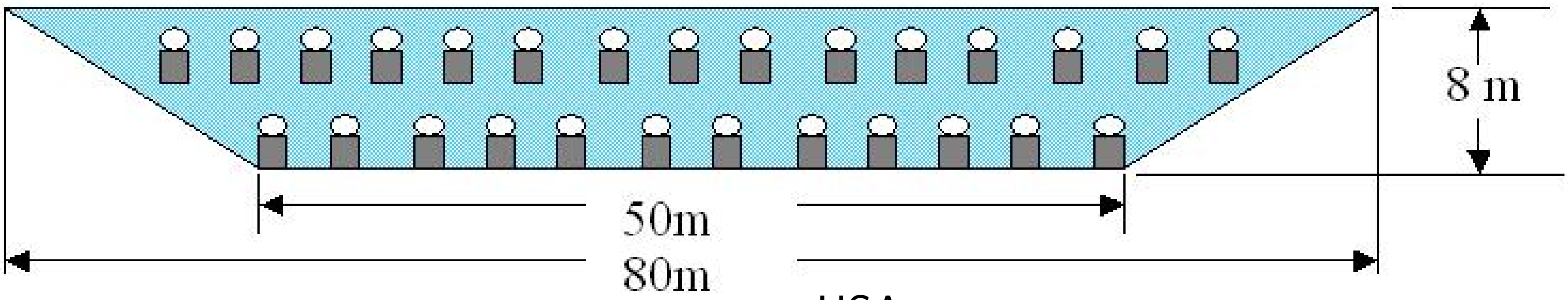
Collaboration between **A**ustralia and **N**ihon for a **GA**mma **R**ay **O**bservatory in the **O**utback

`icrhp9.icrr.u-tokyo.ac.jp/c-iii.html`

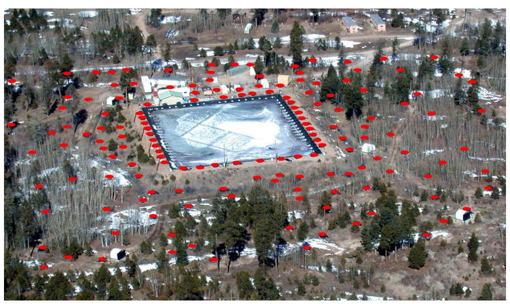




MILAGRO - An EAS Particle Detector



USA

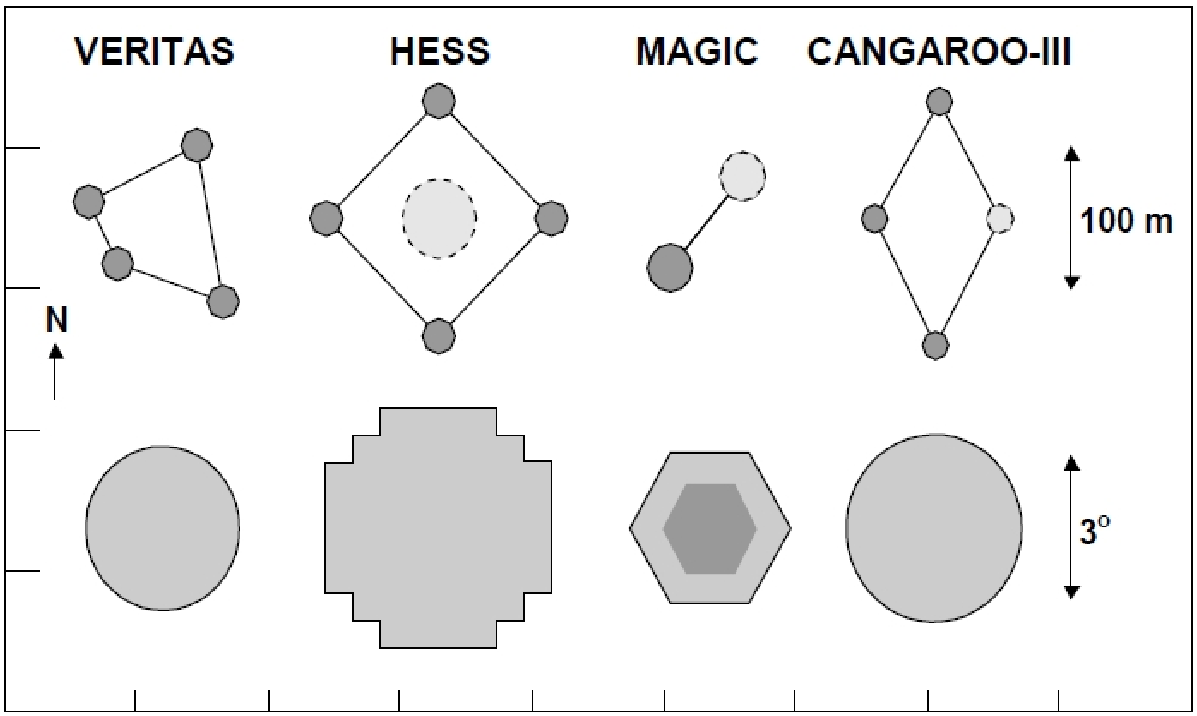


- Large Water pond with two layers of PMTS
- Detection of EAS particles via Cherenkov in water
- **Key benefit: 2π sr FoV - All Sky Monitor**
- PMTs 450 (top) 273 (bottom)
- 5000 m^2
- 2630 m a.s.l.
- **2002: Complete with outriggers**
- `http://umdgrb.umd.edu/cosmic/milagro.html`

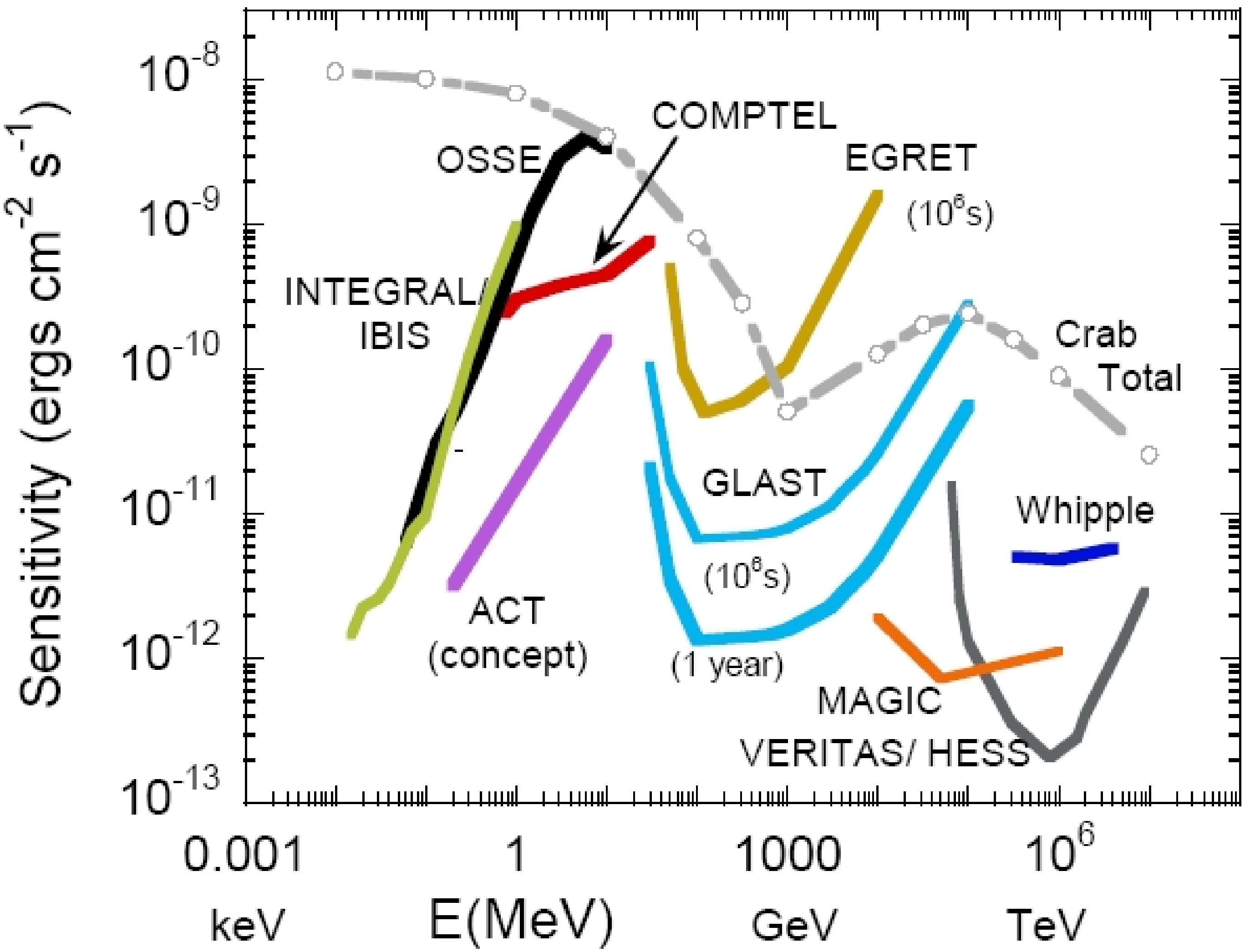
TeV Cherenkov Imaging Telescopes: Overview

from Hinton New J. Phys. *in press* arXiv:0803.1609

Instrument	Lat. (°)	Long. (°)	Alt. (m)	Tels.	Tel. Area (m^2)	Total A. (m^2)	Pixels	FoV (°)	Thresh. (TeV)	Sensitivity (% Crab)
H.E.S.S.	-23	16	1800	4	107	428	960	5	0.1	0.7
VERITAS	32	-111	1275	4	106	424	499	3.5	0.1	1
MAGIC	29	18	2225	1	234	234	574	$3.5^{\dagger}$	0.06	2
CANGAROO-III	-31	137	160	3	57.3	172	427	4	0.4	15
Whipple	32	-111	2300	1	75	75	379	2.3	0.3	15
Shalon	43	77	3338	1	11.2	11.2	144	8	0.8	*
TACTIC	25	78	1300	1	9.5	9.5	349	3.4	1.2	70
HEGRA	29	18	2200	5	8.5	43	271	4.3	0.5	5
CAT	42	2	1650	1	17.8	17.8	600	$4.8^{\dagger}$	0.25	15



TeV Telescope Performance vs. Others



Space-based et al. — typically 1 Ms or 1 yr

H.E.S.S. et al. — $\geq 5\sigma$ detection after 50 h observation

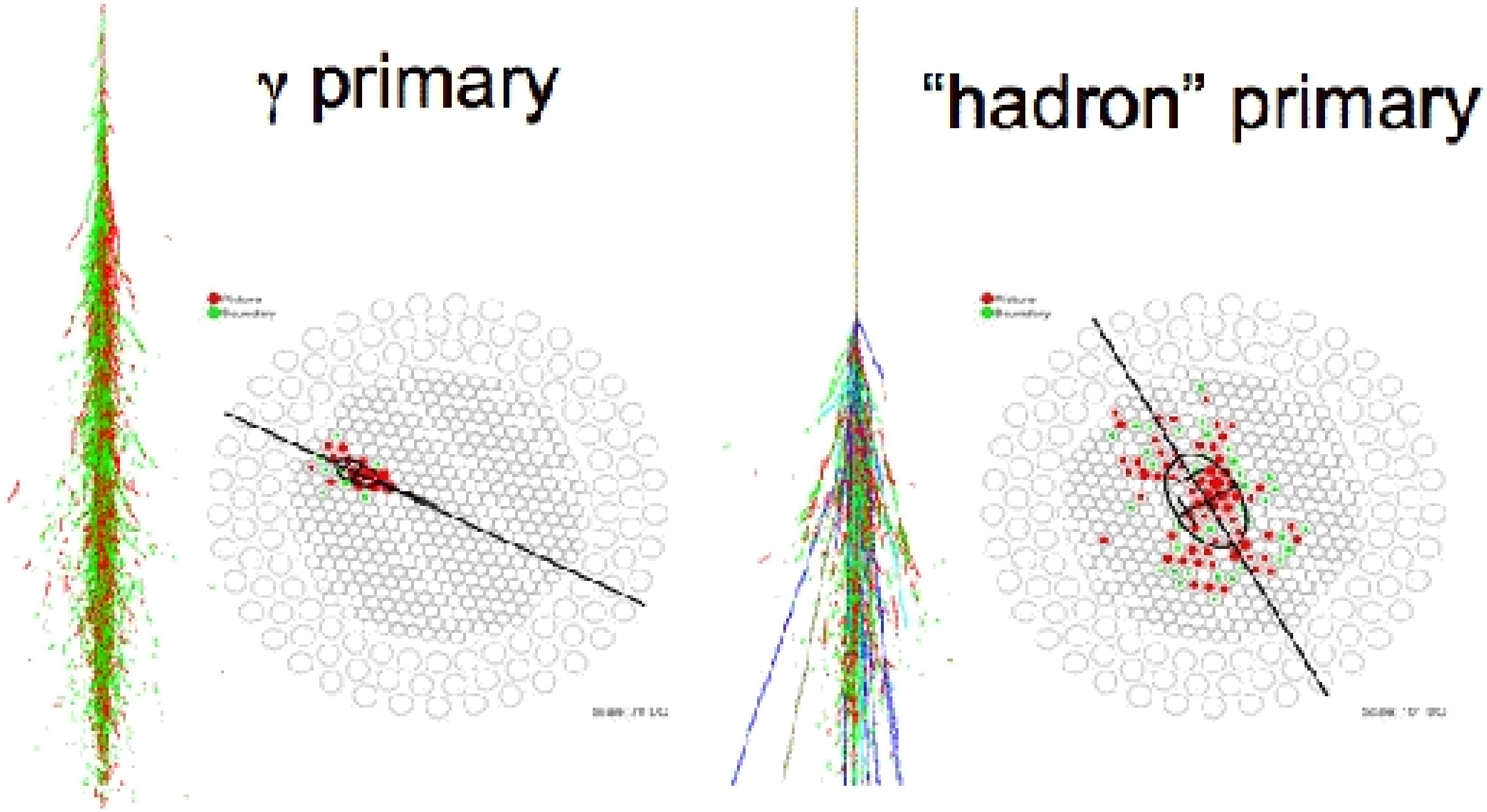
Gamma-Ray & CR Cherenkov Image Discrimination

The dominant event type in a Cherenkov imaging telescope originates from CRs. CR events comprise the **background** events, and typically outnumber gamma-ray events by a factor 1000 or more. We therefore need to *reject* CRs without rejecting too many gamma-rays.

We can exploit:

1. The **shape** of the Cherenkov images: Gamma-ray and CR EAS are quite different. CR EAS will have additional, nucleonic components; making them more ragged and less uniform than gamma-ray EAS (as we saw earlier).
2. The **direction** of the Cherenkov images: In the majority of cases we are searching for localisd gamma-ray sources above the *isotropic* background of CRs. The reconstructed arrival direction can therefore be used to reject CR events outside a particular source region.

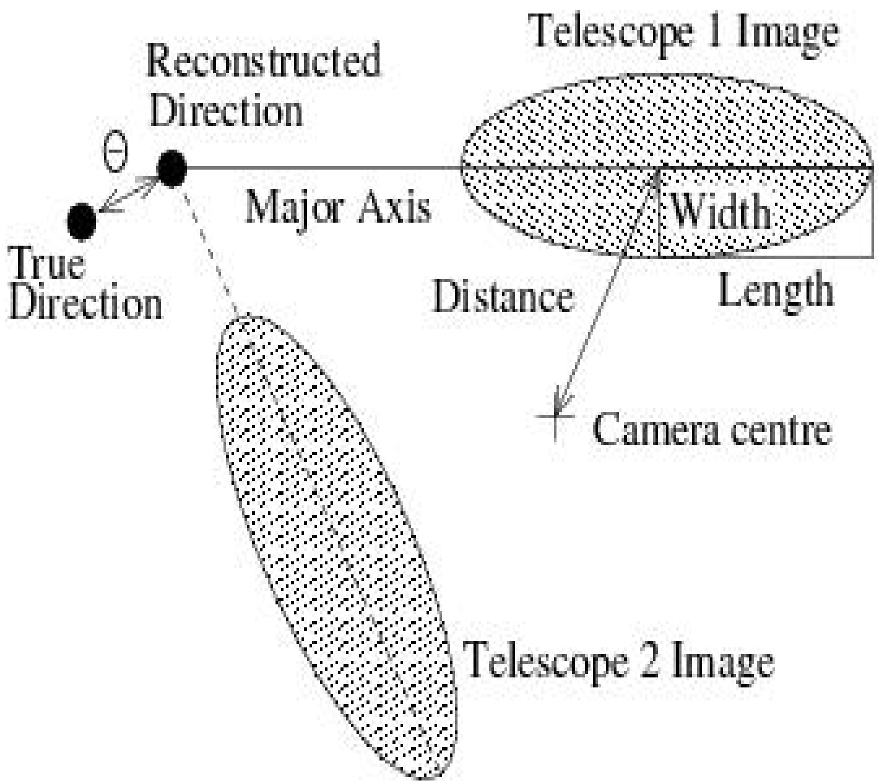
Simulated Cherenkov photons in the focal plane of a telescope

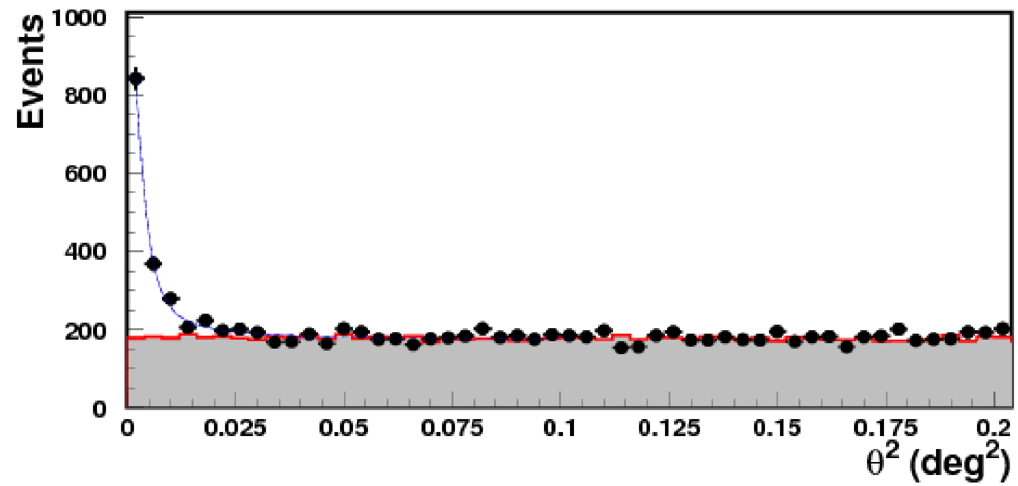


Note the irregular shape of the hadron Cherenkov image, compared to the gamma-ray image.

CR Background Rejection: Direction

$\theta =$ angular distance between reconstructed and true/nominal position



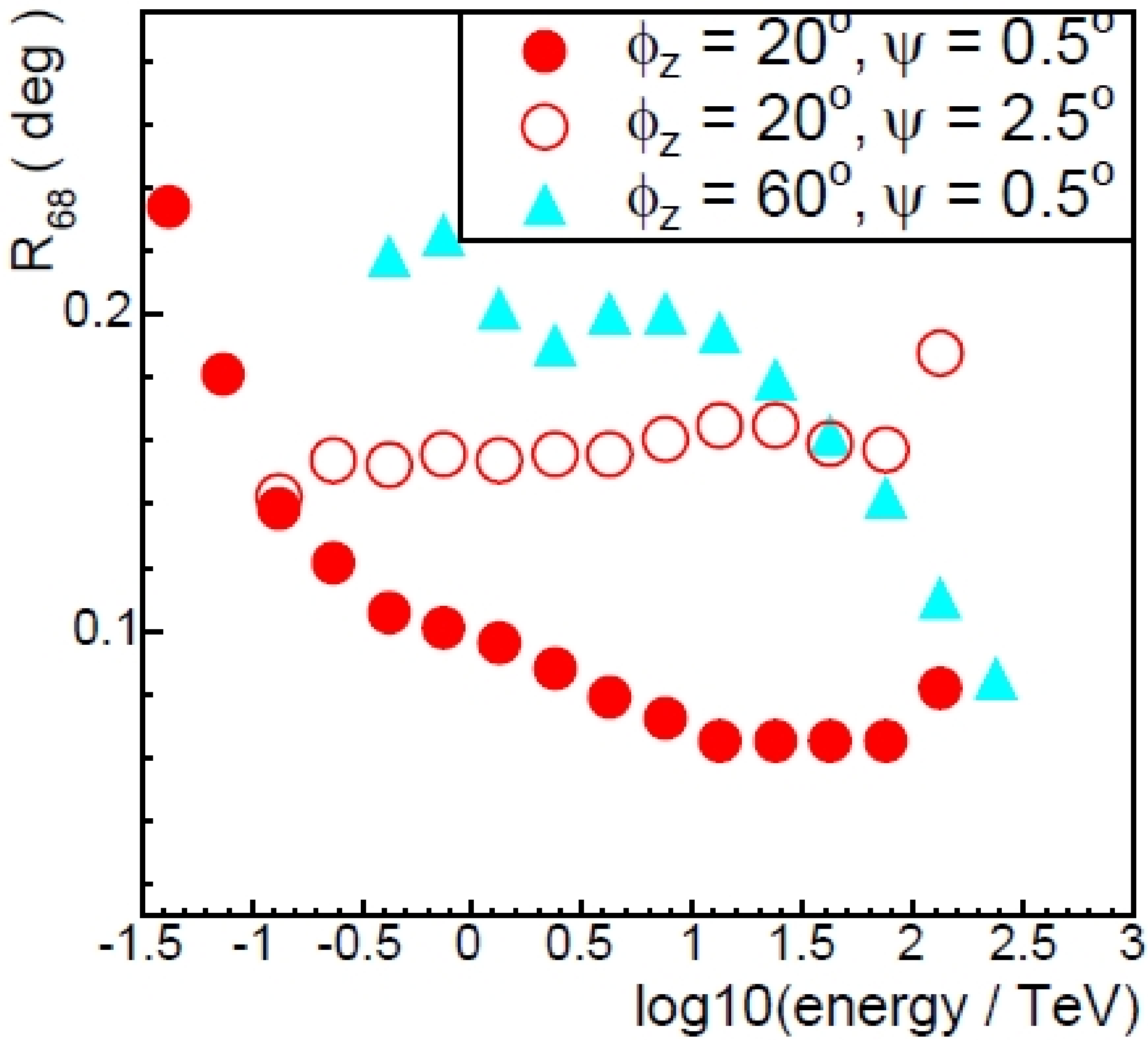


θ^2 plot (black points) for the Crab Nebula (H.E.S.S. data). The *isotropic* CR background is indicated by the red line.

Direction reconstruction:

- Intersection of pairs of major-axes (Hofmann et al. 1999)
- Full MC max-likelihood fit (de Naurois 2006)

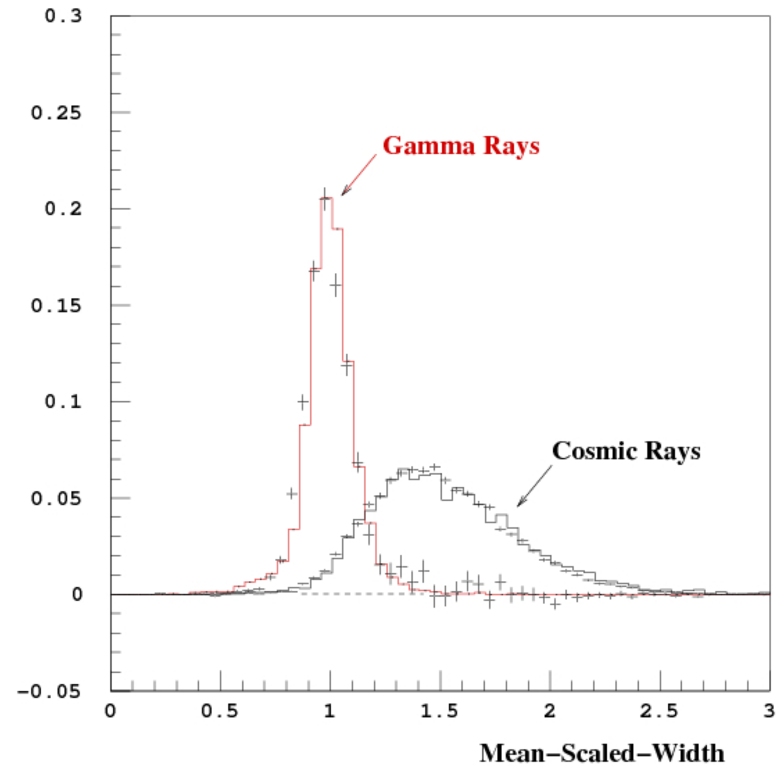
Direction: Angular Resolution (H.E.S.S.)



H.E.S.S. angular resolution R_{68} (radius containing 68% of events for a point-like source) vs. Log(energy). Results for different zenith ϕ_z and offset angles Ψ with respect to the camera centre are shown (D.Berge 2006 - PhD thesis).

CR Background Rejection: Shape

HEGRA $\bar{w}$ Konopelko et al. 1999 Astropart. Phys. 10, 275



Mean-Scaled-Width $\bar{w}$

- *width* w (from Hillas 1985)
- *length* l (from Hillas 1985)

Other methods:

χ^2 (LeBohec et al. 1997 – CAT) & max. likelihood comparison with EAS models (e.g. H.E.S.S. de Naurois 2006)

$\boxed{\bar{\boldsymbol{w}} < \mathbf{1.1}}$ (HEGRA $\bar{\boldsymbol{w}}$)

Acceptances (for gamma-ray & CRs):

$\boldsymbol{\kappa_\gamma > 0.5}$

$\boldsymbol{\kappa_{\mathrm{CR}} < 0.01}$

For telescopes $i = 1...N$:

$$\boxed{\bar{w} = \frac{1}{N}\sum_{i}^{N}\frac{w_i}{w_{e,i}}} \qquad \text{(HEGRA)}$$

$w_{e,i}$ - expected *width* vs. (size,impact,zenith)

HESS $\bar{w}$ slightly different.

Gamma-Ray Source Detection

1. First apply image *shape* cuts (eg. $\bar{w} < 1.1$) to all events.

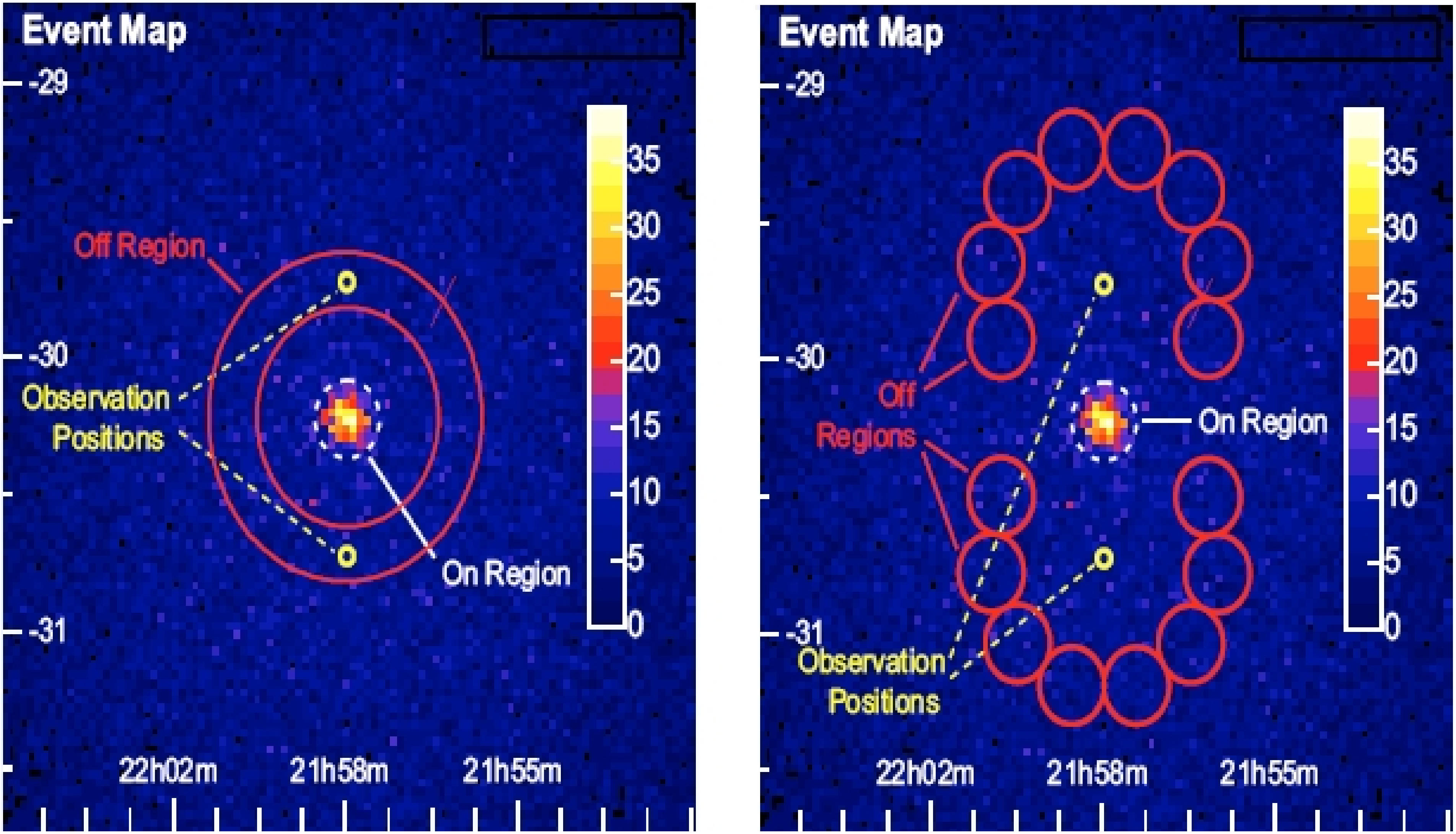
2. Reconstruct arrival directions and use test position in the field of view as the 'true or nominal direction.

ON & OFF Statistics:

$N_{\rm on}$ = events within a region (circle) of radius θ <some value (based on PSF)
$N_{\rm off}$ = events within non-overlapping regions (Ring/Reflected models – Berge et al. 2006) see also (*Template* model eg. Rowell 2003).

Solid angle ratio of ON/OFF region $= \alpha$ Excess counts $s = N_{\rm on} - \alpha N_{\rm off}$

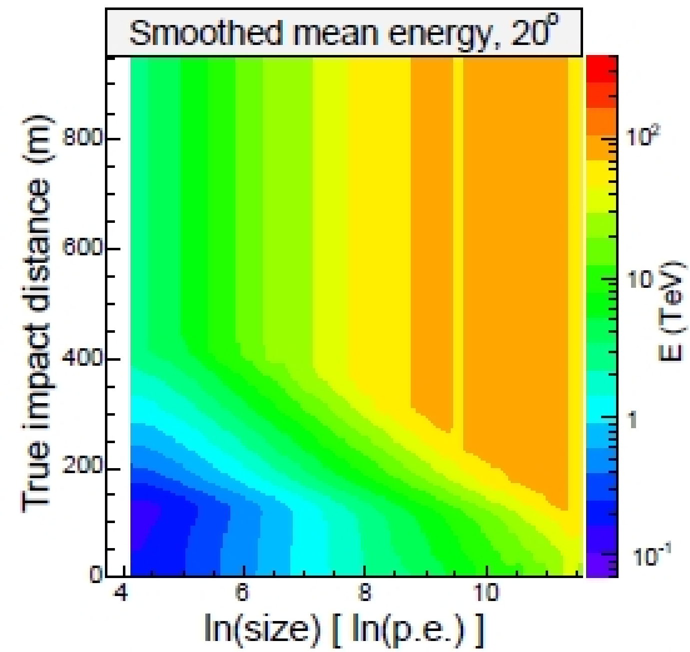
Statisical significance S follows the methods of Li & Ma (1983)



These plots show binned events (real H.E.S.S. data) and illustrate two types of CR background estimation techniques: (Left) Ring Bkg (Right) Reflected bkg

Gamma-Ray Energy Reconstruction

The number of Cherenkov photons (photoelectron *size* in the camera) vs. impact parameter (distance to EAS core) for an image is an accurate measure of the primary photon/particle energy. The Gamma-Ray energy can be reconstructed from a lookup table of energy vs. *size* and impact parameter, and averaged over n telescopes.



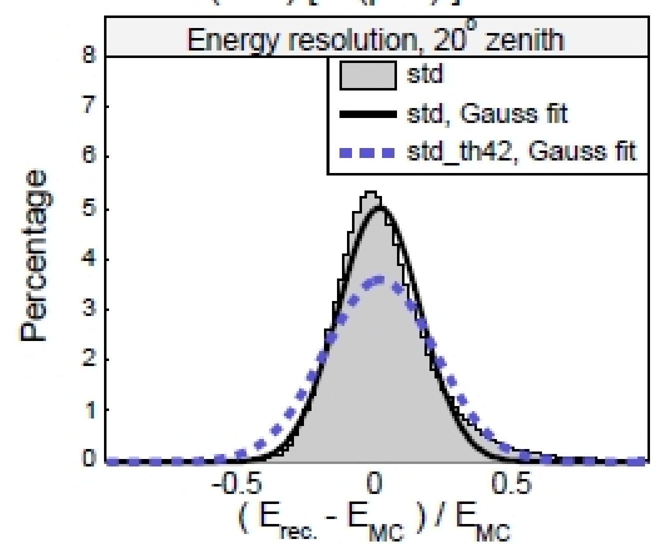


Figure: Top: Energy vs. ln(*size*) and impact parameter; (Bottom) Energy resolution. From D.Berge PhD thesis 2006.

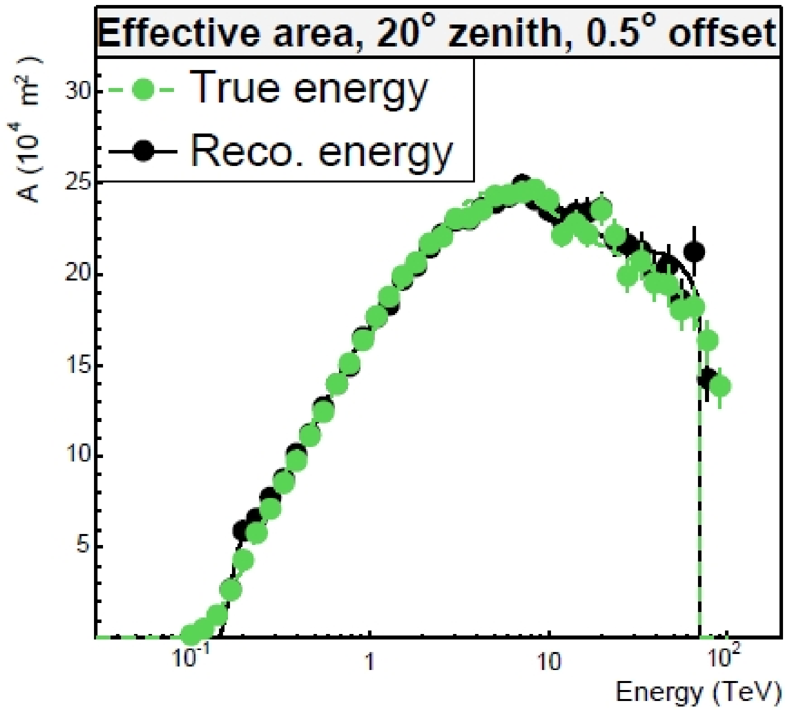
$\mathrm{E_{MC}}$ - true energy; $\mathrm{E_{rec}}$ - reconstructed energy

($\mathrm{E_{MC}}$ - $\mathrm{E_{rec}}$) / $\mathrm{E_{MC}}$ 'RMS' $\leq$20%

Gamma-Ray Energy Spectra Reconstruction

Gamma-ray spectra are calculated in a similar way to ON, OFF statistics but within energy bins:

$N_{\rm on} \rightarrow N_{\rm on}(E)$; $N_{\rm off} \rightarrow N_{\rm off}(E)$



Effective collection ares for HESS (after standard cuts). From D.Berge PhD thesis 2006.

Gamma-Ray Differential Flux:

$$F(E) = \frac{N_\gamma(E)}{dA\,dt\,dE} = \frac{N_{\rm on}(E)}{A(E)\,dt\,dE} - \alpha\frac{N_{\rm off}(E)}{A(E)\,dt\,dE}$$

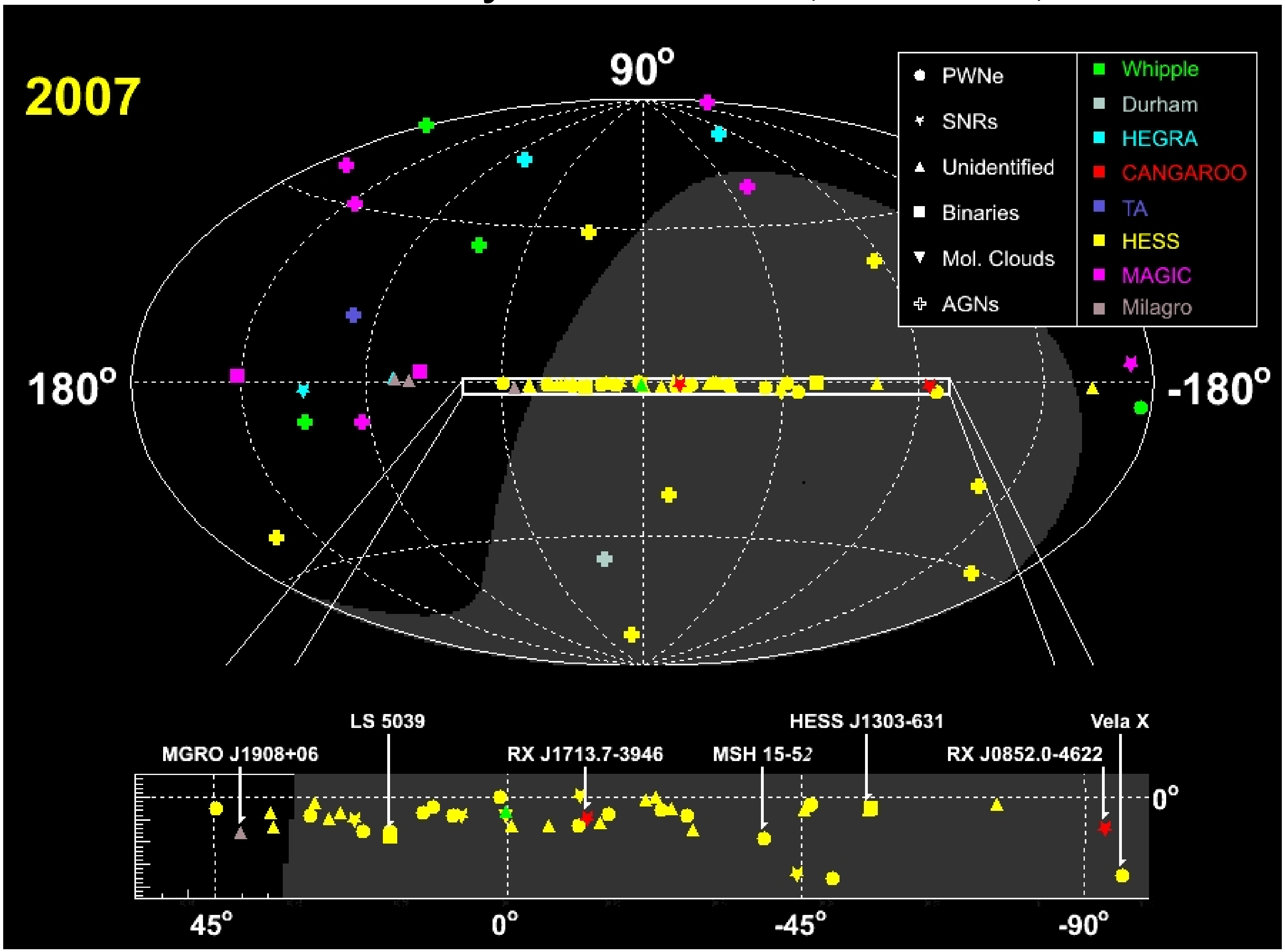
Units: photons cm^{-2} s^{-1} TeV^{-1}

$A(E)$ = Effective Collection Area of the Detector. HESS $A_{max} \sim 0.25$km^2 (7 TeV)

Other methods: Forward-folding (Piron et al.)

3 Overview of the TeV Sky

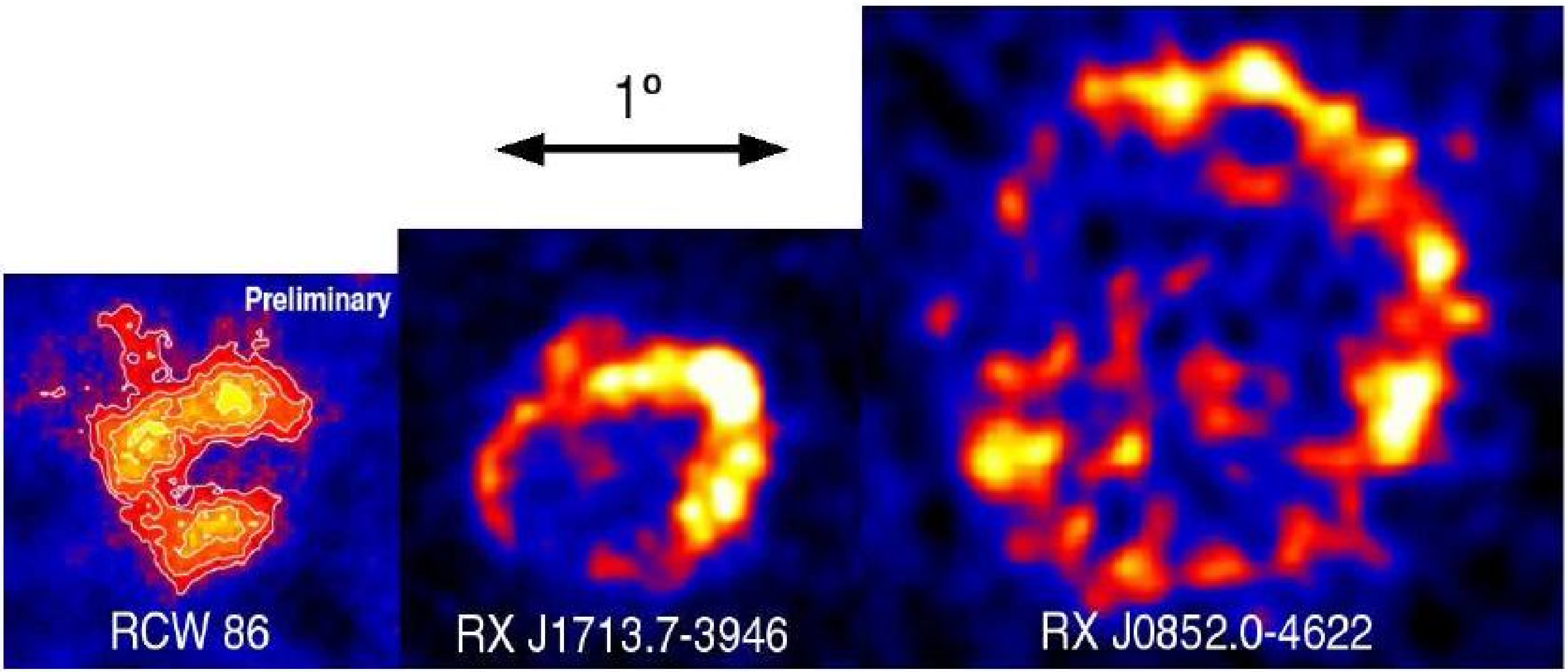
The TeV Sky - 2007 Jim Hinton (ICRC 2007 Mexico)



4 Supernova Remnants (SNRs)

Shell-Type Supernova Remnants

Observations motivated originally by CR acceleration. Since H.E.S.S., detailed TeV morphology and spectral studies, as well as comparisons with multiwavelength data are now possible.



from Hinton 2007 30th ICRC (Mexico); 2008 arXiv:0803.1609

Also: SN 1006; Cas-A

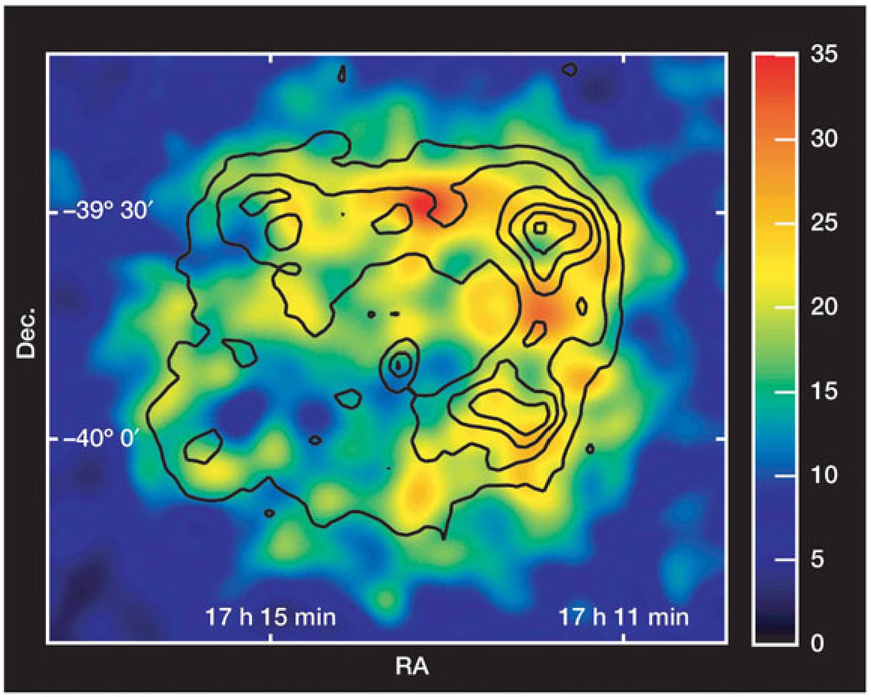
RX J1713.7$-$3946: Resolved in TeV Gamma-Rays (H.E.S.S.)

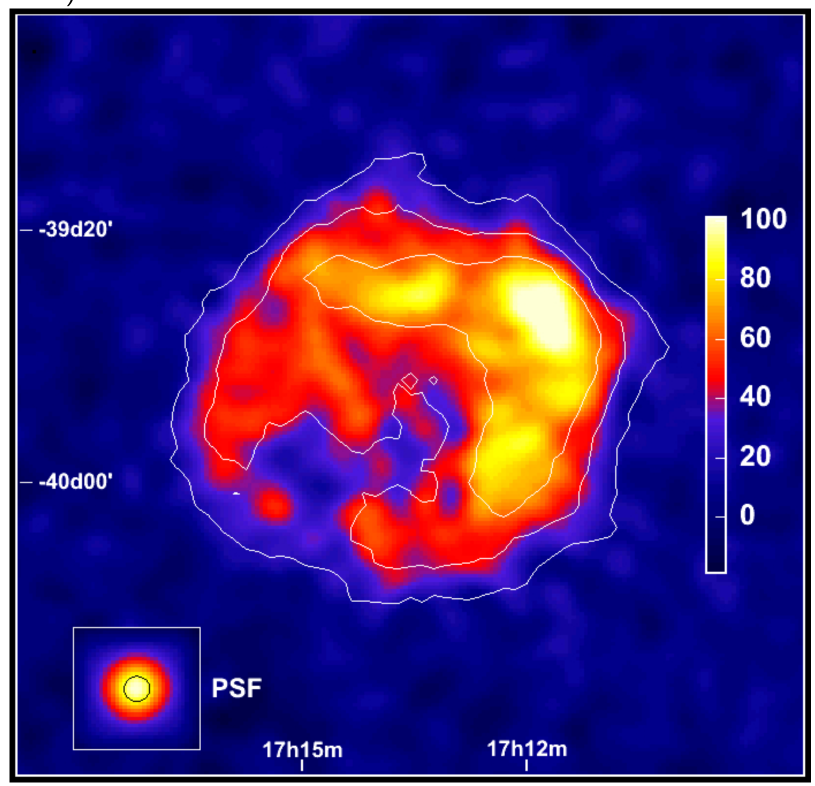
- TeV emission first detected CANGAROO-I, CANGAROO-II

(Muraishi et al. 1999, Enomoto et al. 2002 Nature 416, 823).

- Shell-like structure ($E > 0.8$ TeV) discovered by H.E.S.S.

(Aharonian et al. 2004 Nature 432, 75, Aharonian et al. 2006, Aharonian et al. 2007)



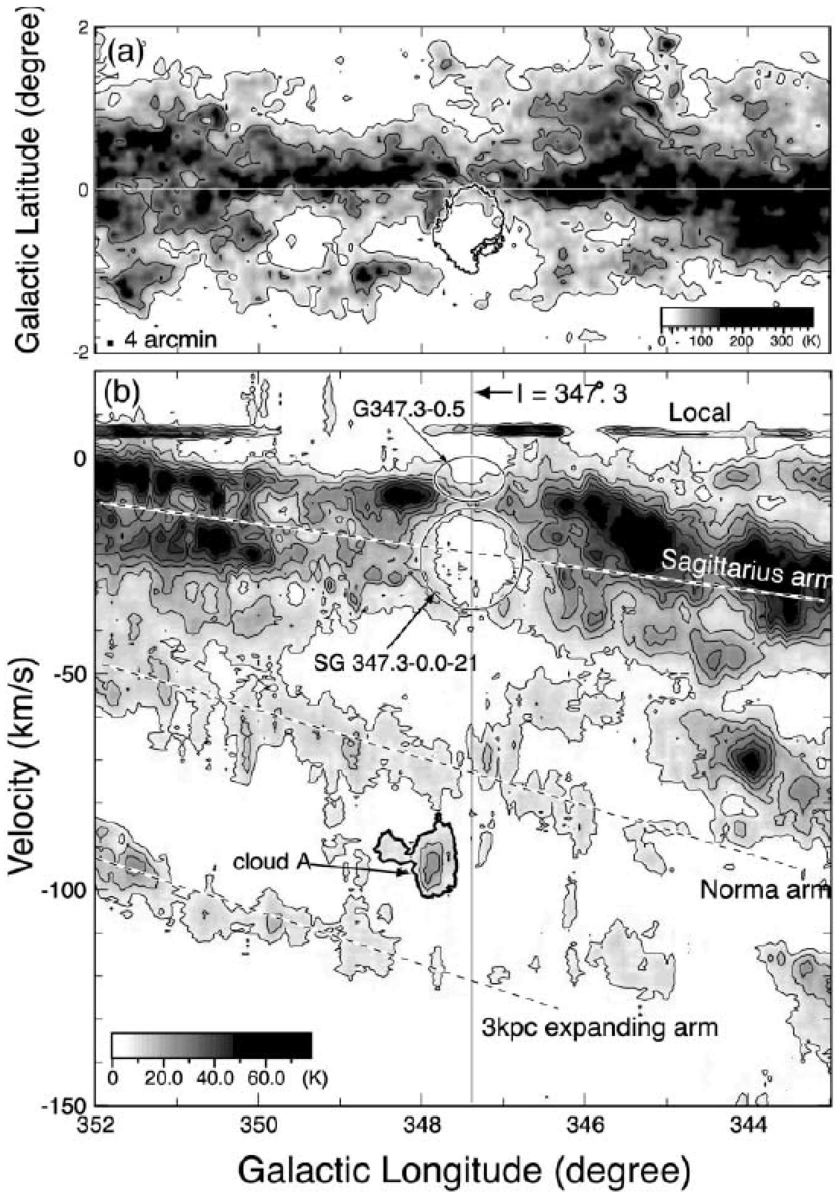


Left: 2003 Image; **Right:** 2003–2005 data image

Black contours: ASCA 1–3 keV X-ray emission (Uchiyama et al. 2002 PASJ 54, L73)

- Proof of multi-TeV particle accel. in SNRs.

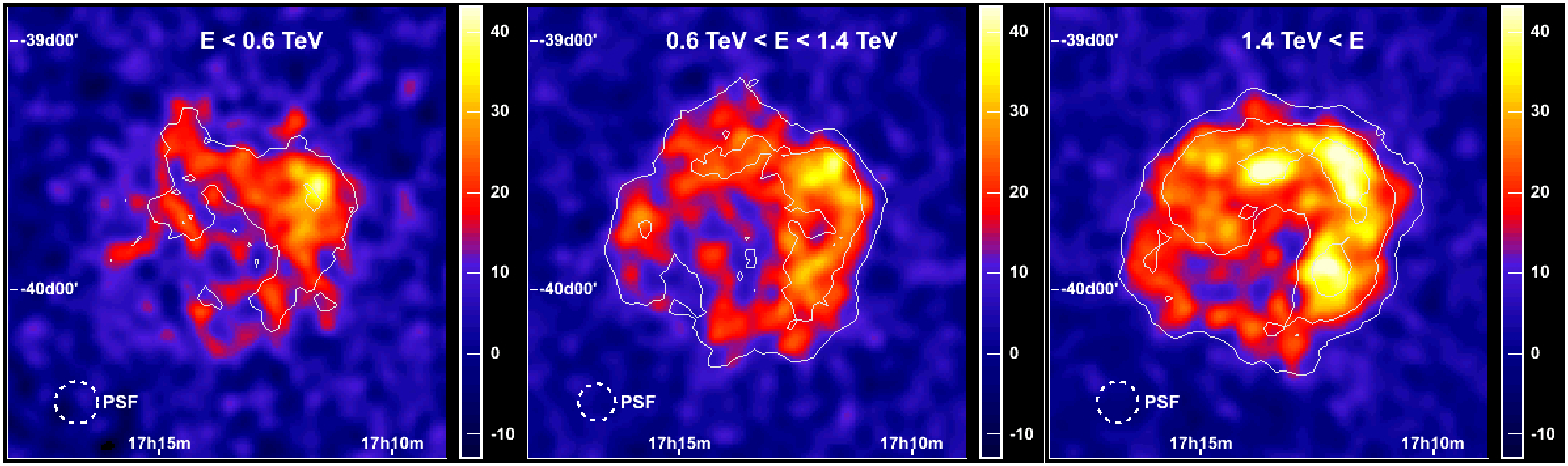
RX J1713.7 (G 347.3−0.5) Distance & Age



NANTEN ^{12}CO(J=1-0) image from Moriguchi et al. 2005

- ^{12}CO(J=1-0) NANTEN Observations reveal a molecular *void* likely blown out by G 347.3−0.5 at $V_{\rm lsr} = -12$ to -3 km/s or $\boxed{\boldsymbol{d \sim 1}\ \textbf{kpc}}$.
- Compare to earlier estimate $d \sim 6$kpc based on association with Cloud A (Slane et al. 1999).
- SG 347.3−0.0-21 (d ∼3 kpc) is a supershell (1.5° diam) possibly blown out by an OB-assocation and/or distant SNRs.
- Wang et al. 1997 suggest guest star of AD 393 in Scorpius is the projenitor. Age is therefore ∼**1600 yr**.

RX J1713.7 Morphology vs. Energy (H.E.S.S.)

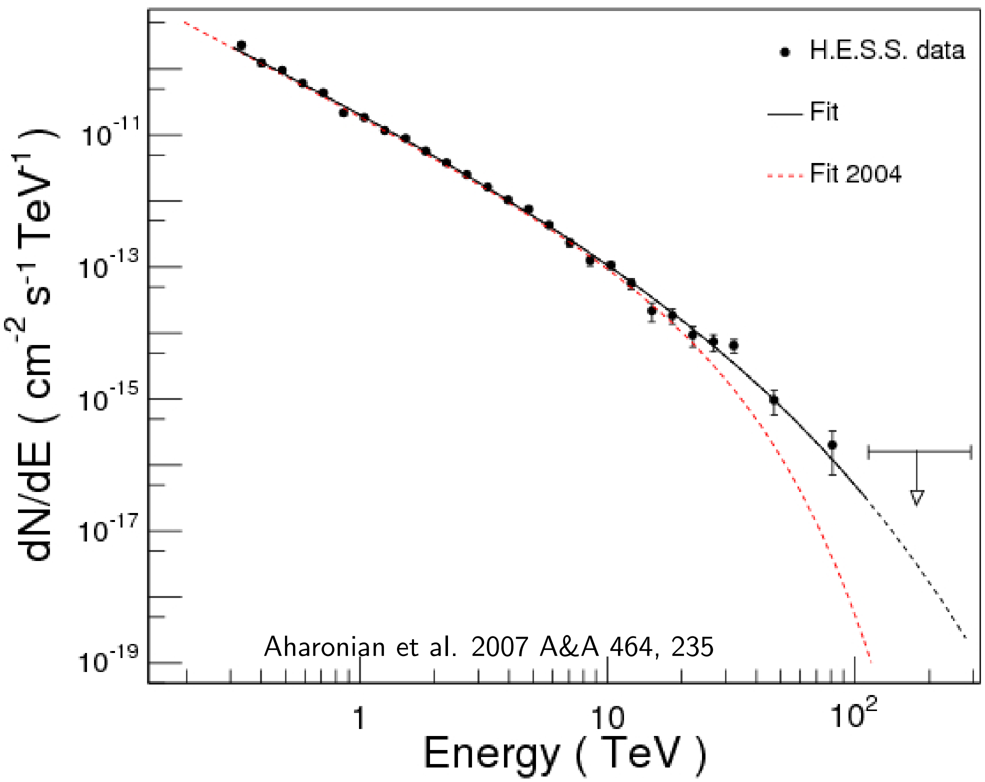


No change in morphology with energy & TeV spectral index Γ ($F(E) \sim NE^{-\Gamma}$) consistent throughout the SNR. The H.E.S.S. point spread function (PSF) is indicated.

H.E.S.S. PSF — 4.2 arcmin $\rightarrow$ 1.2 pc at $d = 1$ kpc.

Also: TeV emission and morphology appears steady.

RX J1713.7 TeV Energy Spectrum (H.E.S.S.)



- Pure power-law ruled out (χ^2/ν = $145.6/25$)
- Good fit: Power law + weak exponential cutoff:

$$F_\gamma(E) = \frac{dN}{dE} = I_o E^{-\Gamma} \exp(-(E/E_c)^\beta)$$

  Detailed functional form derived by Kelner et al. 2006 for π°-decay. Other curved functions also well fit.

- Significant (+4.3σ) flux point at 33 TeV (+2.5σ at 47 TeV; +1.5σ at 81 TeV)

RX J1713.7 Maximum Particle Energies & Total Energetics

The highest energy TeV γ-ray flux point (at $E_\gamma = 30$ TeV) can be used to infer upper limits on the parent particle energies. The parent particles can be: (1) Protons and/or (2) Electrons

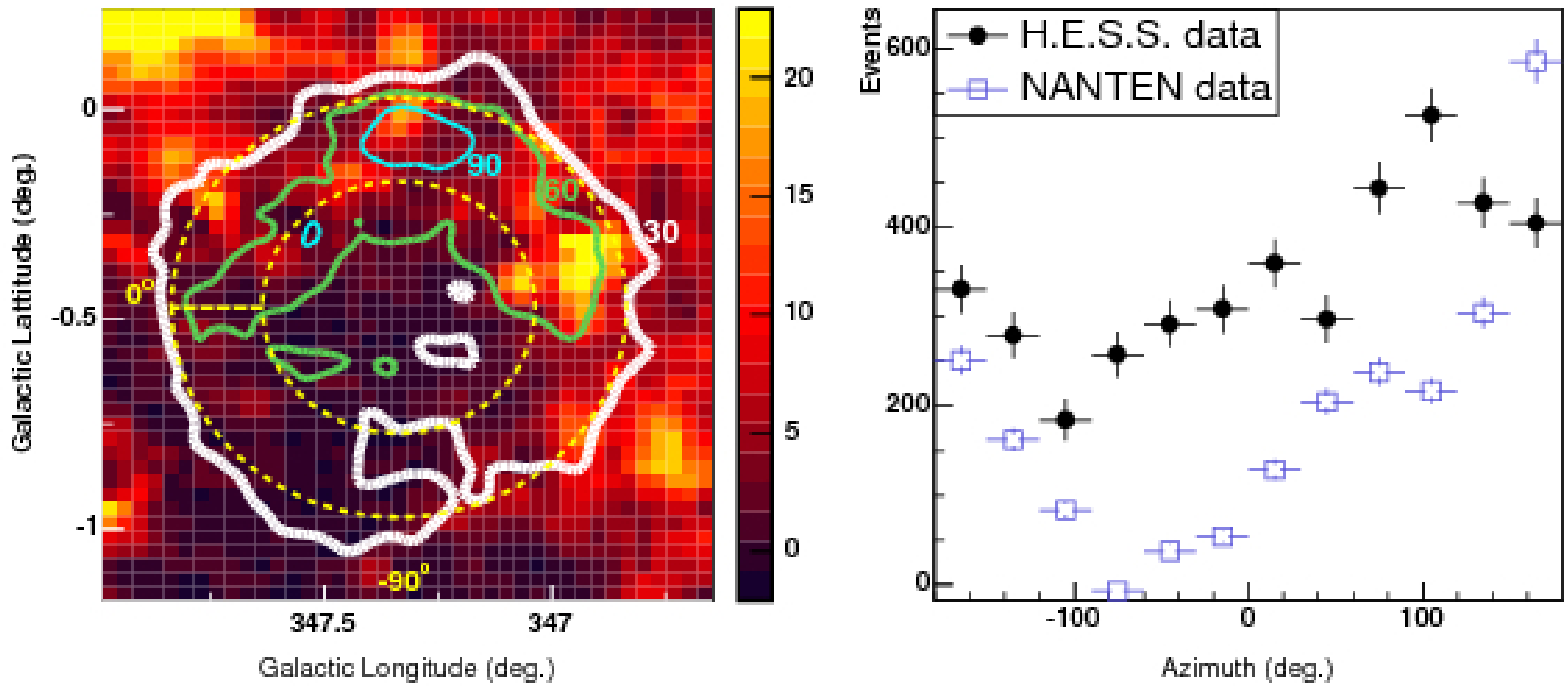
1. Protons: TeV emission from π°-decay. Max. proton energy $E_p \sim E_\gamma/0.17$ ~200 TeV.
2. Electrons: TeV emission from Inverse-Compton scattering of the CMB. Thompson scattering regime, max. electron energy $E_e \sim 20\sqrt{E_\gamma}$ ~110 TeV;

Thus particle acceleration in excess of 100 TeV is inferred from the TeV spectrum.

TeV Gamma-ray luminosity — $L_\gamma = 1.602 \times 4\pi d^2 \int E^2 F(E)\, dE$

$L_\gamma \sim 10^{34}$ erg s^{-1} (0.2–40 TeV; $d = 1$ kpc)

RX J1713.7 H.E.S.S. and NANTEN ^{12}CO(J=1-0)



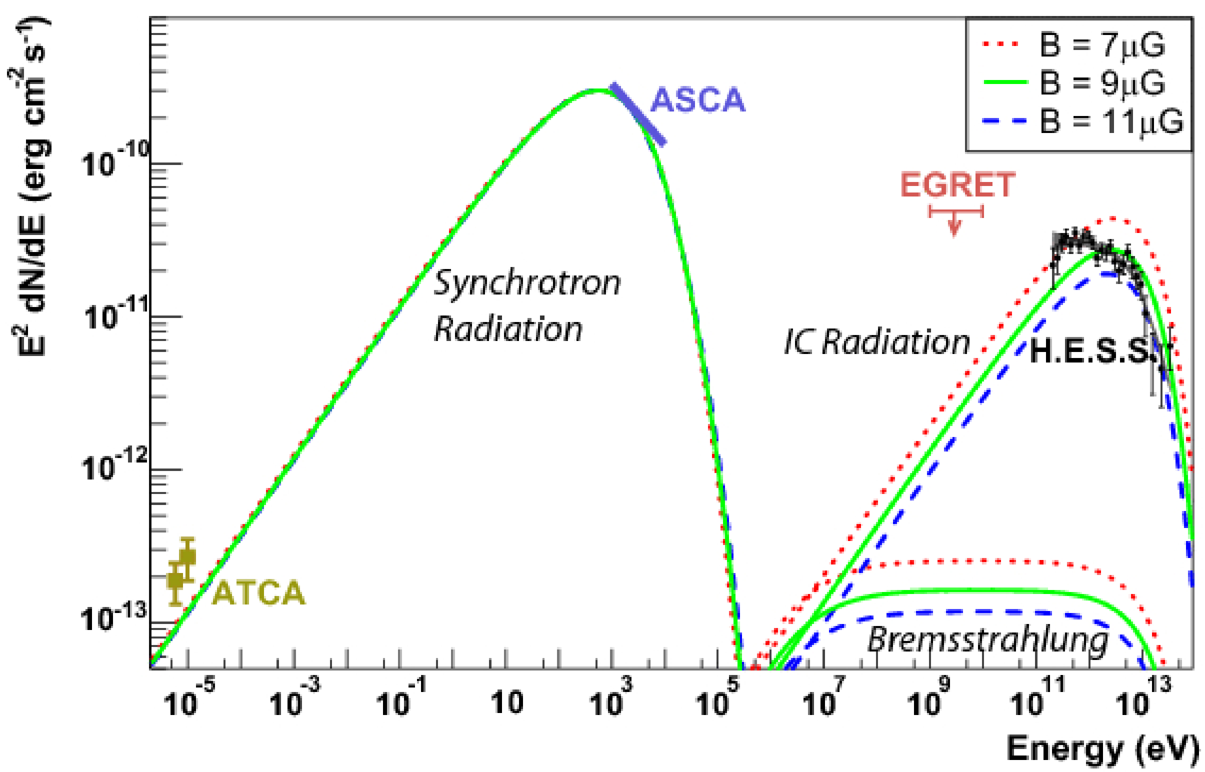
Left: NANTEN ^{12}CO(J=1-0) image (K km/s) $V_{\rm lsr}$-11 to -3 km/s (0.4 to 1.5 kpc) with H.E.S.S. contours

Right: Variation of ^{12}CO(J=1-0) intensity & TeV emission vs. azimuth in ring covering RXJ1713 shell (yellow circle)

Molecular cloud densities $n \sim 300$ cm^{-3} towards the NW, and $n \leq 1$ cm^{-3} towards the SNR centre (ave. ~1 cm^{-3}. Observations at ^{12}CO(J=3-2) transition also suggest some SNR/molecular cloud interaction (warmer gas) along the W boundary (Moriguchi et al. 2005).

RX J1713.7: Leptonic Interpretation

Aharonian et al. 2006



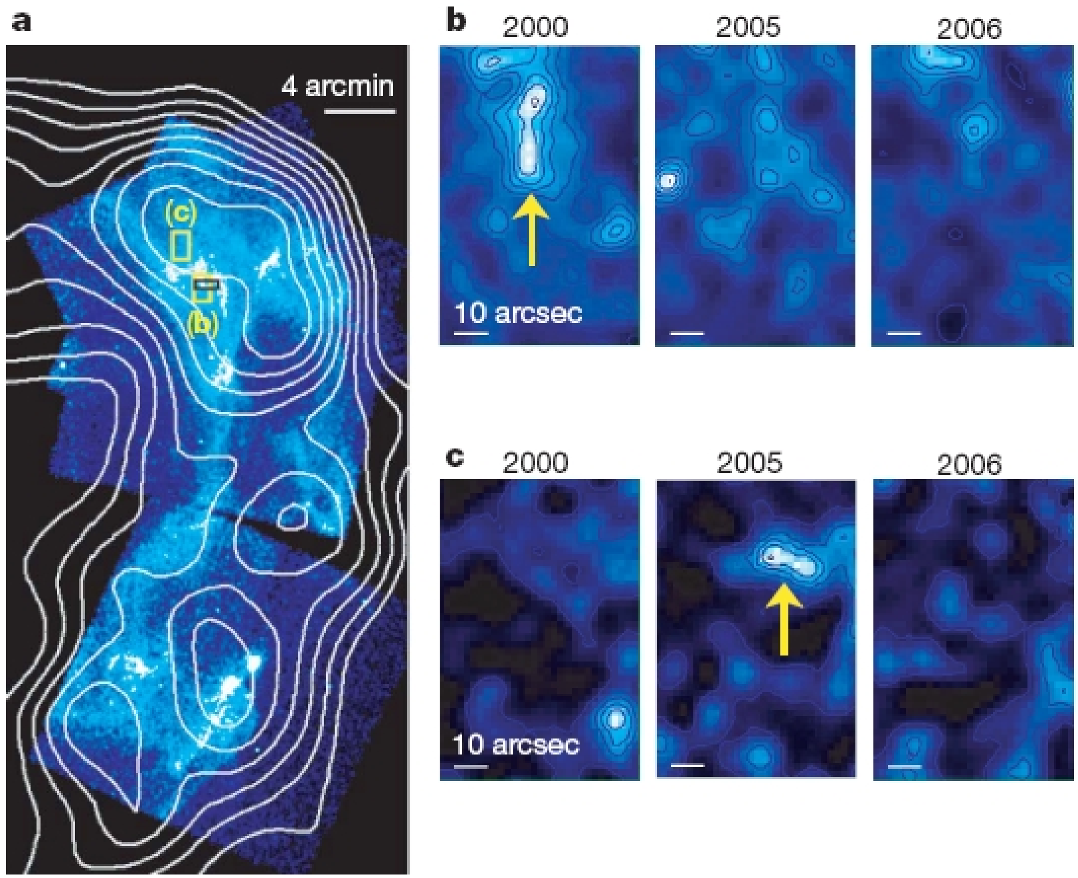
$d = 1$ kpc; Age $= 1000$ yr

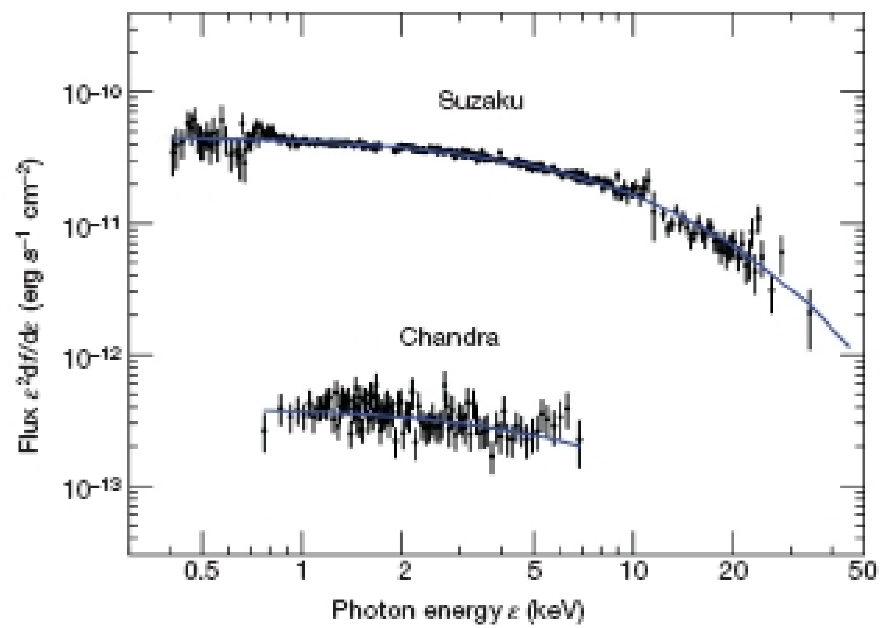
Electron spectrum: $Q_e(E) = Q_0 E^{-2} \exp(-E/100\mathrm{TeV})$
See also Porter et al. 2007

- Inverse-Compton (IC) TeV γ components from seed photons: Optical:IR:CMB $=$ 0.5:0.05:0.25 eV cm^{-3}
- Recall: IC $F_\gamma \sim F_x/B^2$ comparisons: Constrains B value to narrow range $\sim 10\mu$G.
- DSA theory: $B \sim RB_{ISM}$ is compressed by the shock. Recall compression ratio $R \sim 4$ — suggest $B \geq 10\mu$G for $B_{ISM} \sim 3\mu$G.

RX J1713.7: Magnetic Field

Uchiyama et al. 2007 Nature





Variations in arc-second-scale X-ray (Chandra) output on year timescales & non-thermal spectrum to 30 keV.

Also seen in Cas-A X-rays (Uchiyama et al. 2008)

Electron acceleration timescale under DSA (photon energy ϵ):

$t_{acc} \approx \eta(\epsilon/\mathrm{keV})^{0.5}(B/\mathrm{mG})^{-1.5}(v_s/3000\mathrm{kms}^{-1})^{-2}$ yr

$v_s \sim 3000$ km s^{-1} shock speed; $\eta \sim 1$ Bohm diffusion (max accel. rate)

Electron cooling timescale ($t = E/\dot{E}$) under synchrotron emission: (electron energy E):

$t_{synch} \approx 12(B/\mathrm{mG})^{-2}(E/\mathrm{TeV})^{-1}$ yr

Implies $B \sim$ mG in compact regions where variation occurs.

Max proton energy E_p after time t: $E_p \approx 1(B/\mathrm{mG})(t/100\mathrm{yr})$ PeV

$\rightarrow$ PeV hadron acceleration.

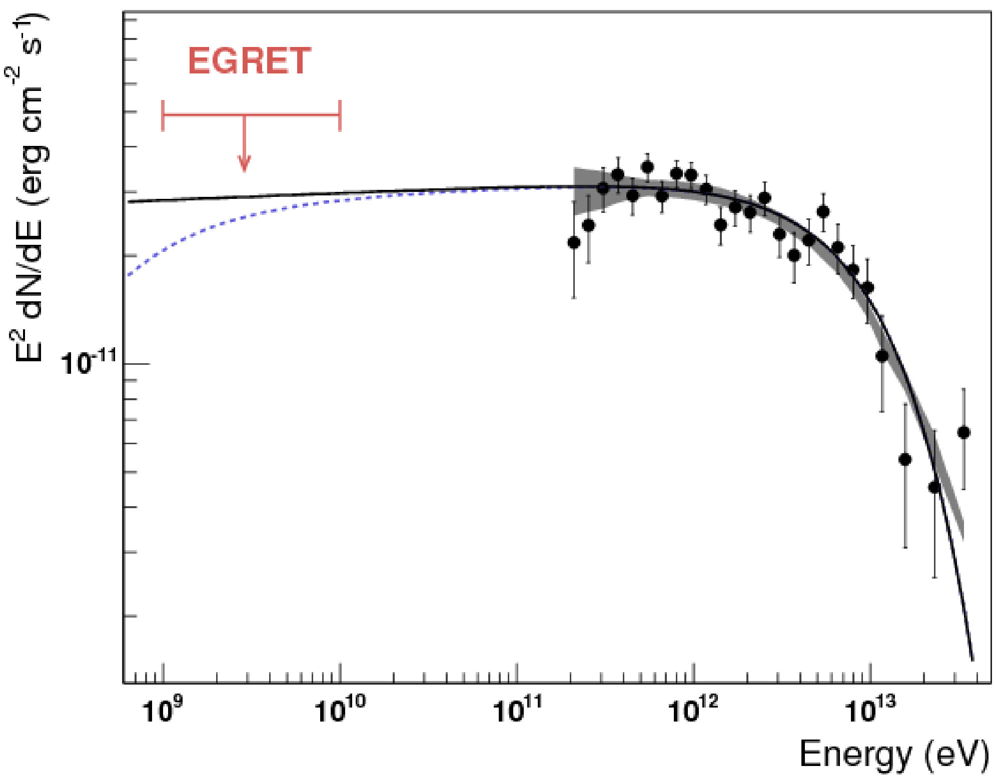
Probably $B \sim 100\mu$G over large scale rim regions $\rightarrow$ strong reduction in leptonic TeV gamma-rays.

Non-thermal X-ray spectrum from Suzaku to 30 keV $\rightarrow$50 TeV electrons.

Note: High $B \sim 100\mu$G fields also suggested by arc-second X-ray filaments earlier observed by Chandra (very short electron cooling length — Völk et al. 2006, Vink et al. 2007).

RX J1713.7: Hadronic Interpretation

Aharonian et al. 2006



See also Voelk et al. 2006, 2007

- Assume average ambient density $n = 1$ cm^{-3}
  (also $d = 1$ kpc)
- π°-decay detailed kinematic calcuation suppresses the GeV flux in the EGRET region. Fit using functional form from Kel'ner et al.
  .
- Good match to H.E.S.S. data.
- Relatively insensitive to B field

RX J1713.7 Proton Energetics

Assume a hadronic origin for the TeV gamma-ray emission. We can estimate the total energy required in the form of accelerated protons W_p via:

$W_p \approx t_{pp}\, L_\gamma$

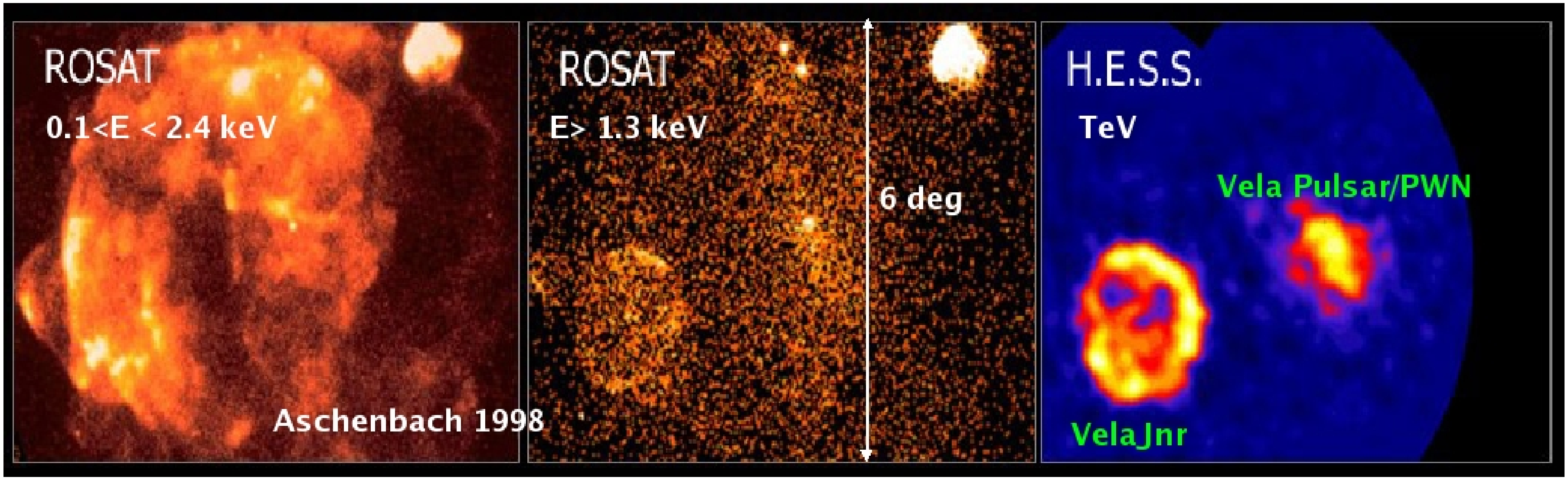
where t_{pp} is the characteristic cooling time of protons under the $p + p \to \pi^\circ \to 2\gamma$ process, and n is the density of ambient matter. We set $n = 1$ cm^{-3} based on NANTEN and X-ray measurements.

Thus $W_p \approx 10^{49}$ erg. However H.E.S.S. covers only 0.2 to 40 TeV, implying proton energies ∼2 to 400 TeV. We can extrapolate the proton energetics to cover 1 GeV to 400 GeV, ie. the entire CR spectrum assuming the various spectral fits to the TeV gammma-ray spectrum (the proton spectral shape will follow) and obtain:

$\boxed{W_p \approx (0.1\,\mathrm{to}\,0.3)\ \times\ 10^{51}\ \text{erg}}$

This appears consistent with the SNR origin of Galactic CRs (ie. 10–30% of SNR KE 10^{51} erg converted to CRs). Thus, a hadronic origin might be favoured.

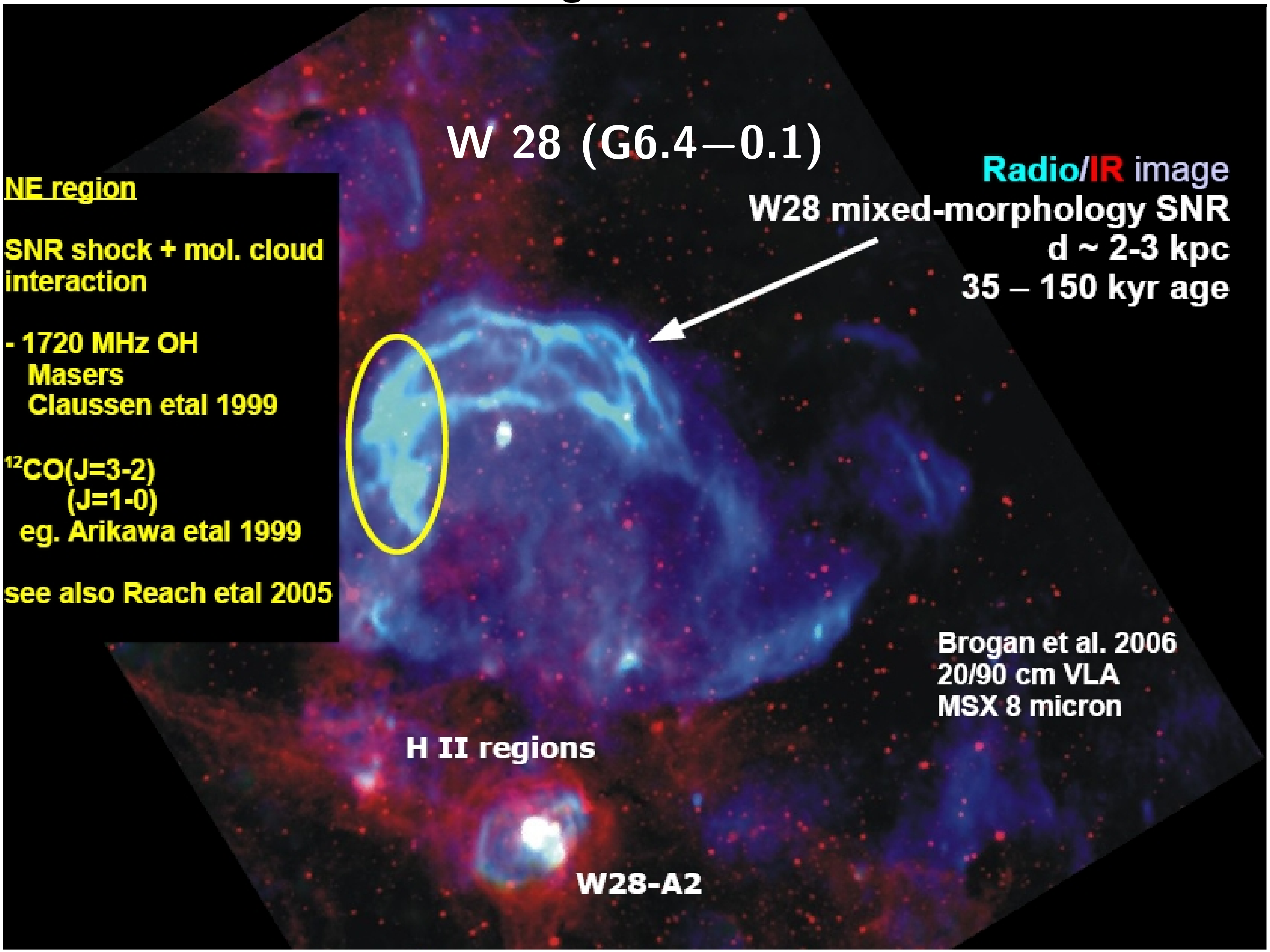
RX J0852.0−4622 (VelaJnr)



A new SNR in the Vela SNR region was discovered in hard(er) X-ray with ROSAT.
This SNR, RX J0852.0−4622 is also known as VelaJnr — Note the image scale.
VelaJnr (and the PWN associated with the Vela Pulsar) was also later detected in TeV γ-rays with H.E.S.S.

See Aharonian et al. A&A 2005 437, pL7 & ApJ 2007 661, p236 for more details.

SNRs Interacting with Molecular Clouds



Tracing SNR and Molecular Cloud Interactions

- SNR shock interacts with adjacent molecular cloud
- Shocked cloud material forms downstream
- OH 1720 MHz masers formed in shocked material (requires warm gas $\geq$25 K and high density $n \geq 10^5$ cm^{-3})
- **OH 1720 MHz masers are an ideal tracer of SNR/Mol. cloud interaction**
- In many cases: Zeeman splitting gives $|B|$ $\leq$few mG
- Crutcher 1999 $|B| \propto \mathrm{density}^{0.5}$

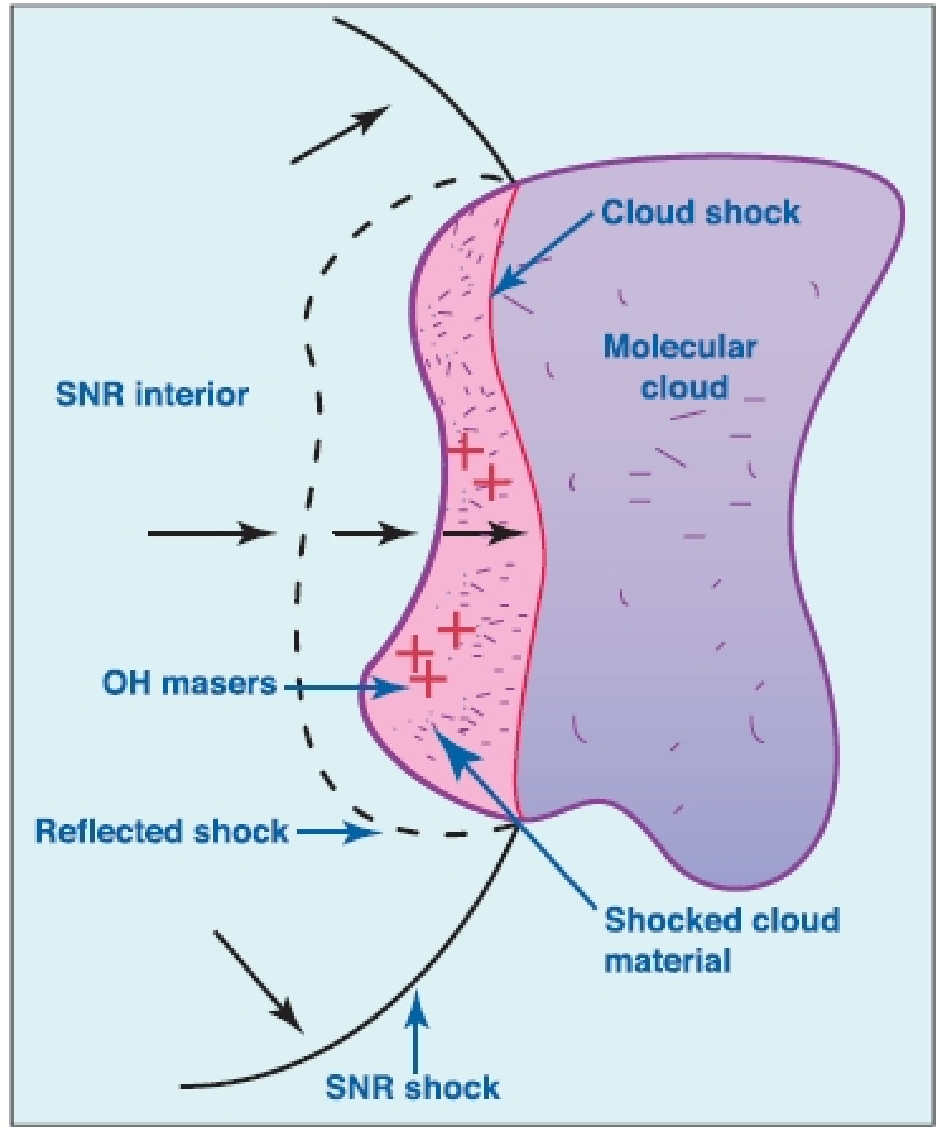


Fig. 1. Schematic of an expanding supernova remnant (SNR) interacting with an adjacent molecular cloud. Black arrows indicate velocity.

Wardle & Yusef-Zadeh 2002 Science 296, 2350

TABLE 3. Summary of OH (1720 MHz) maser detections in SNRs.

Galactic Name	Common Name	SNR Type	No. Masers	V_{LSR} (km s^{-1})	D (kpc)	Ref.[c]
	CND	-	2	132.4	8.5 [a]	1
G0.0+0.0	Sgr A East	S	8	+58.1	8.5 [a]	1
G1.05−0.1	Sgr D SNR	S	1	−2	8.5 [a]	2
G1.4−0.1		S	2	−2.3	8.5 [a]	2
G6.4−0.1	W28	S	41	+10.4	3.0	3
G16.7+0.1		C	1	+20.0	2.2/14.1	this work
G21.8−0.6	Kes69	S	1	+69.3	11.2	this work
G31.9+0.0	3C391	S	2	+107.6	7.2	4
G34.7−0.4	W44	C	25	+45.0	3.0	3
G49.2−0.7	W51C	S	2	+70.4	6.0	this work
G189.1+3.0	IC443	S	6	−4.6	1.5 [b]	3
G337.0−0.1	CTB33	S	3	−70.4	11.0	4
G348.5+0.1	CTB37A	S	10	−56.2	11.3	4
G349.7+0.2		S	5	+15.8	22.4	4
G357.7+0.3		S	5	−36	8.5 [a]	2
G357.7−0.1		S	1	−12.4	11.8	4
G359.1−0.5		S	6	−4.4	8.5 [a]	5

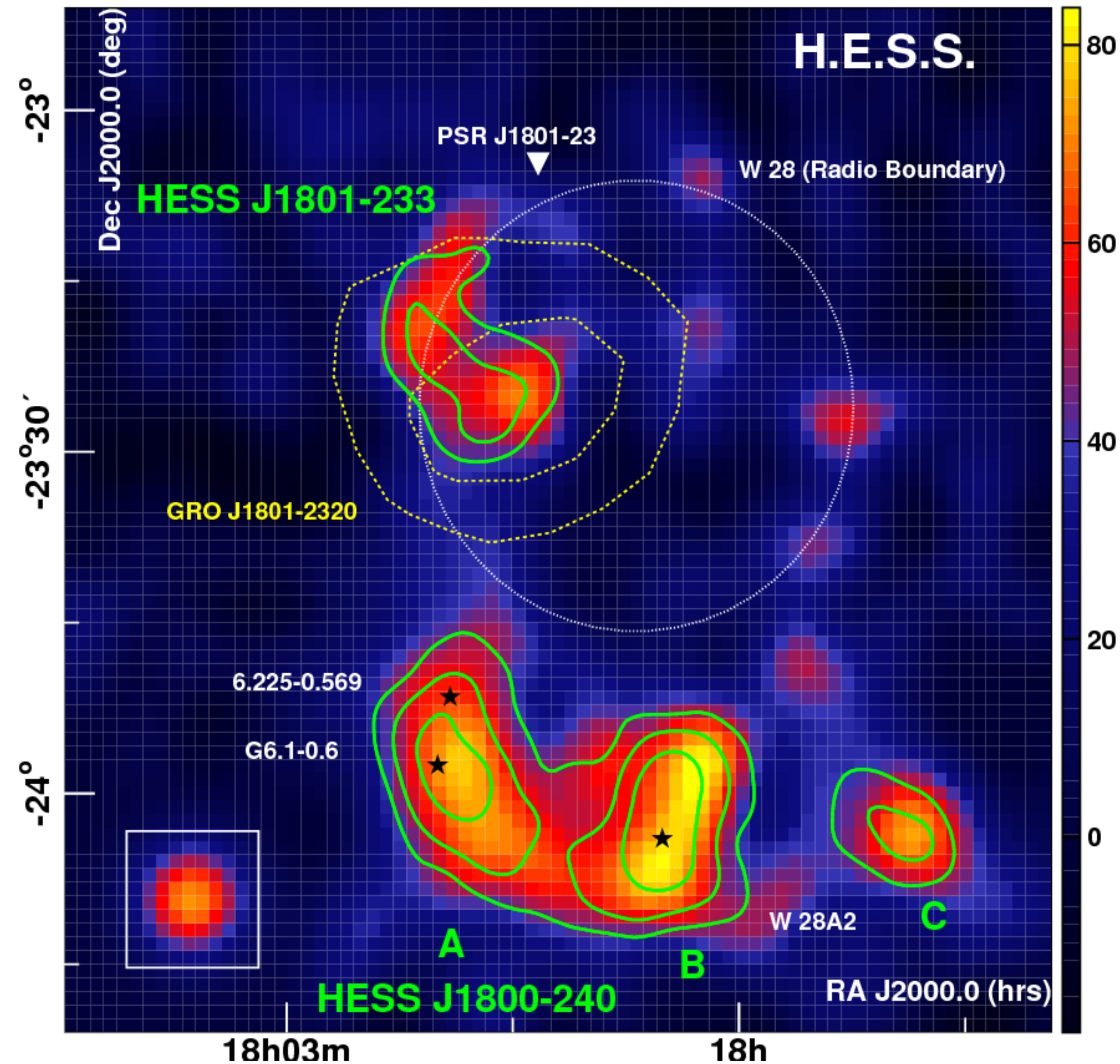
[a]Galactic Center distance assumed 8.5 kpc
[b]Distance from Fesen (1984)
[c]Refs: 1. Yusef-Zadeh et al. (1996), 2. Yusef-Zadeh et al. (1997), 3. Claussen et al. (1997), 4. Frail et al. (1996), 5. Yusef-Zadeh et al. (1995)

SNRs associated with 1720 MHz OH masers (Green et al. 1997 Astron. J. 114, 2058)

CTB 37A (HESSJ1714-385), G359.1−0.5 (HESSJ1745-303) & IC 443 also TeV sources!

(Aharonian et al. 2008,2008; Albert et al. 2007)

W 28 in TeV γ-rays with H.E.S.S.



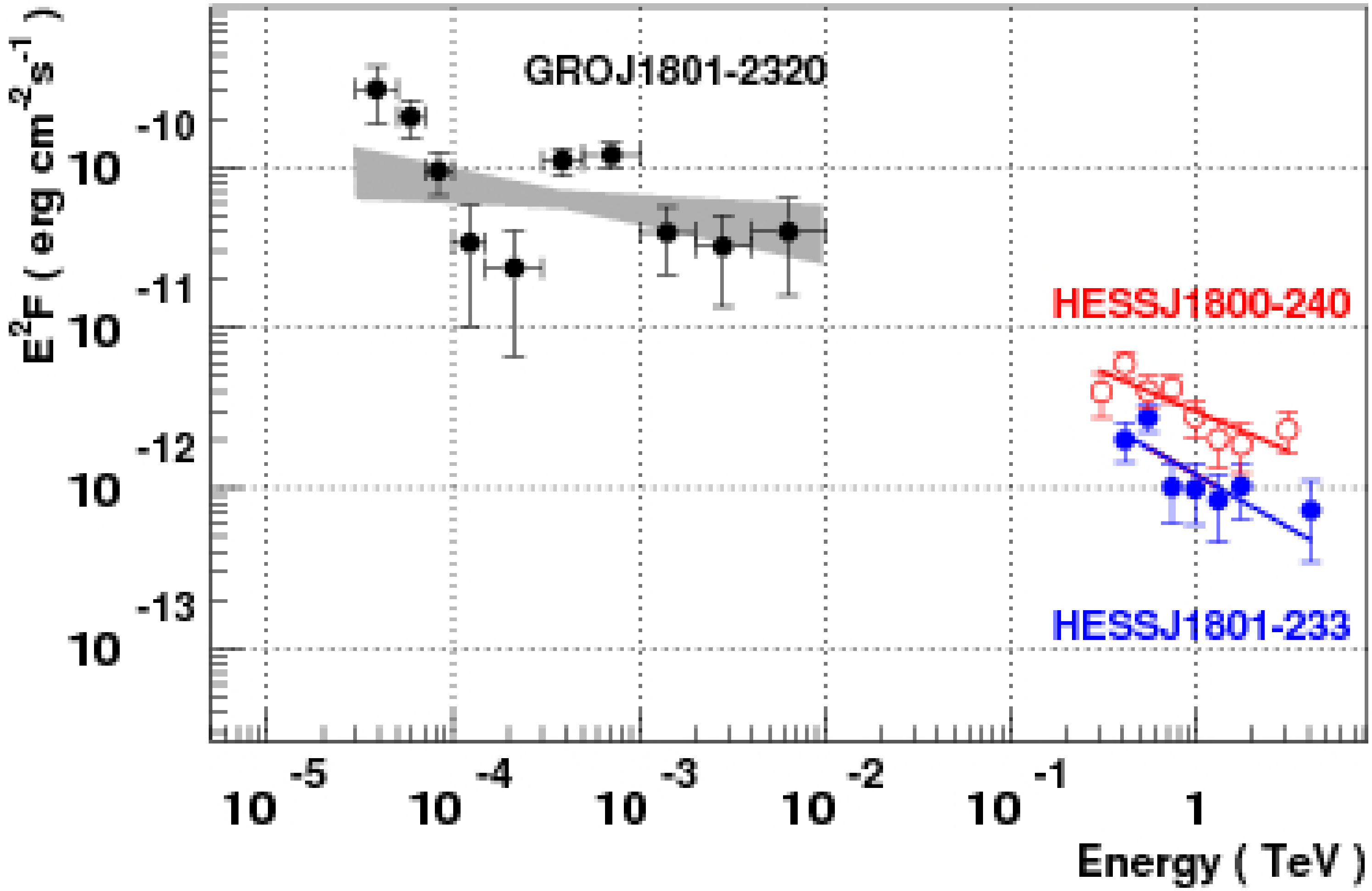
H.E.S.S. TeV image (colour scale) – Aharonian et al. 2008

Several sources in the W 28 field.
HESSJ1801-233 – NE region
HESSJ1800-240 – Complex of 3 sources at S edge of SNR.

Spectra:
$F(E) \sim E^{-\Gamma}$ for Γ=2.3 to 2.7

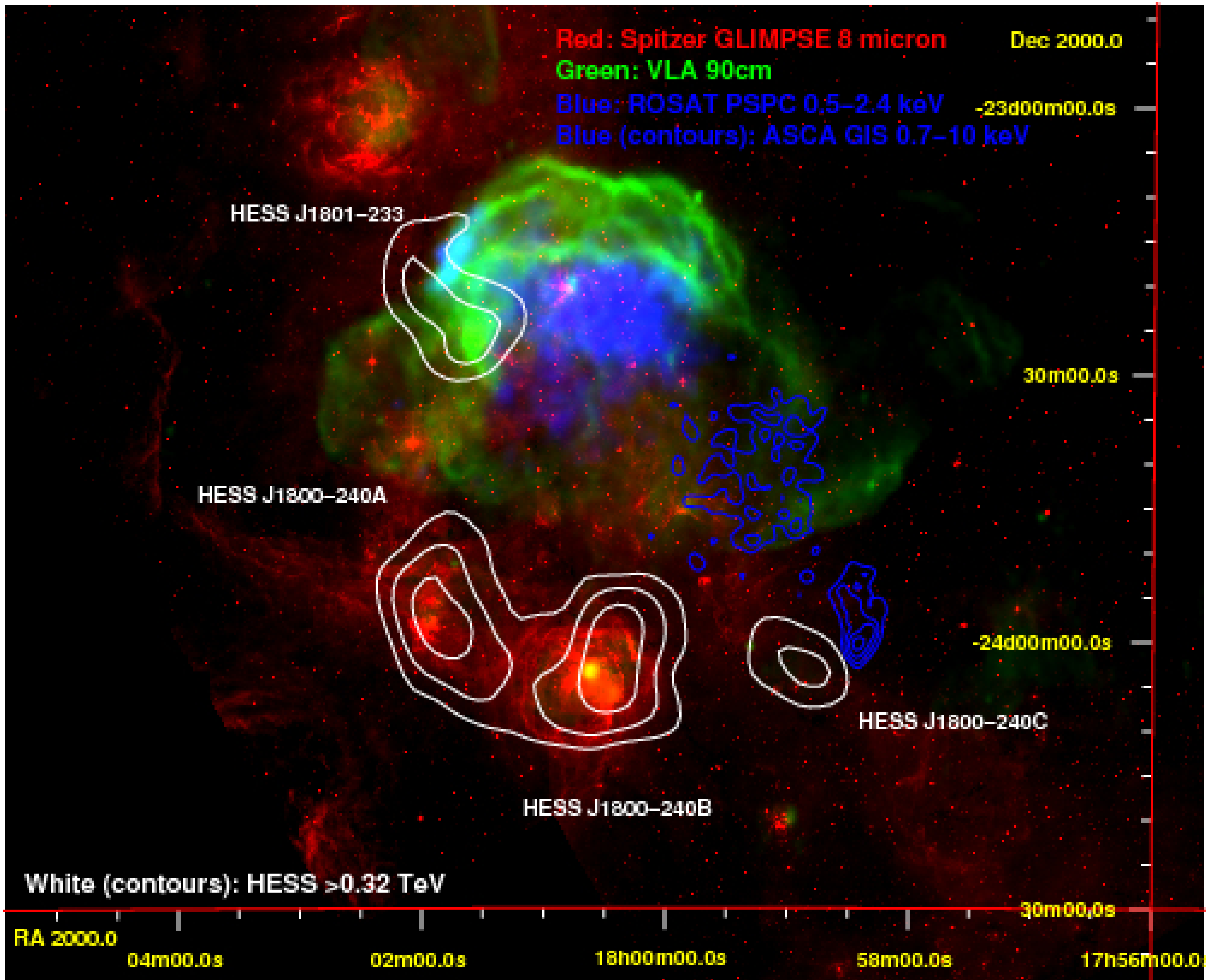
TeV luminosities $L_\gamma \sim 10^{33}$ erg s^{-1} (for $d = 2$ kpc)

W 28 TeV Spectra

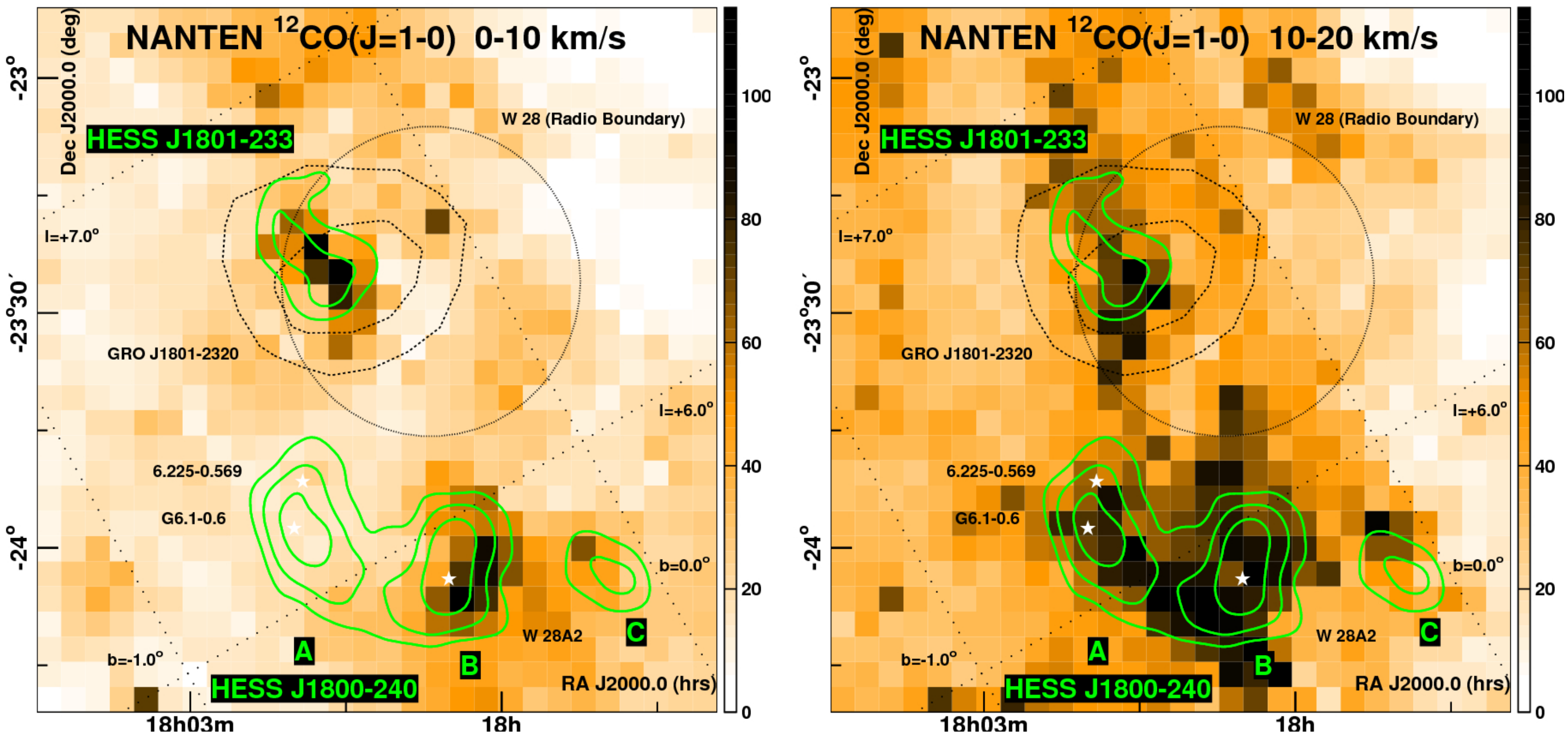


HESSJ1801-233 (NE region); HESSJ1800-240 (Sum of HESSJ1800-240A, B & C)

EGRET GeV & H.E.S.S. TeV spectra may be connected


Red: Spitzer GLIMPSE 8 micron
Green: VLA 90cm
Blue: ROSAT PSPC 0.5–2.4 keV
Blue (contours): ASCA GIS 0.7–10 keV
Dec 2000.0
-23d00m00.0s
30m00.0s
-24d00m00.0s
30m00.0s
HESS J1801−233
HESS J1800−240A
HESS J1800−240B
HESS J1800−240C
White (contours): HESS >0.32 TeV
RA 2000.0
04m00.0s
02m00.0s
18h00m00.0s
58m00.0s
17h56m00.0s

W 28 H.E.S.S. & NANTEN ^{12}CO(J=1-0)

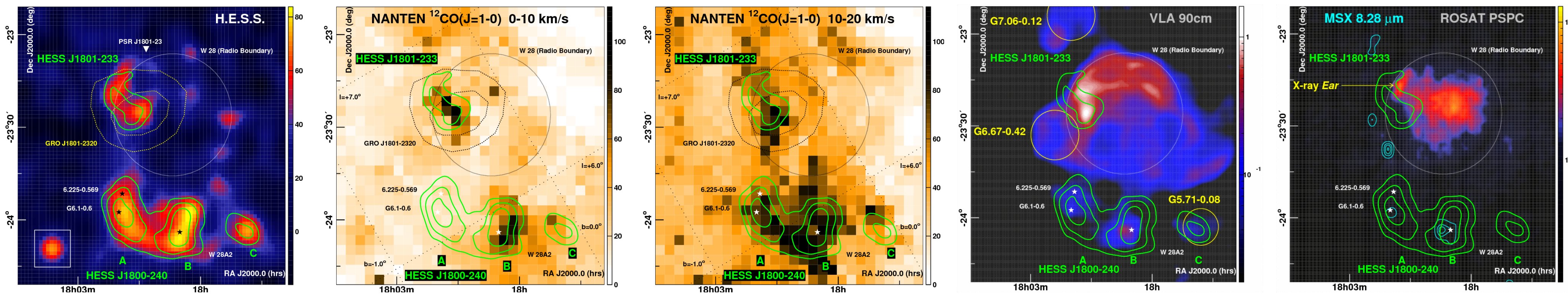


d ~0 to 2.5 kpc $\qquad$ d ~2.5 to 4 kpc

Very good TeV and molecular cloud spatial association → indication for hadronic origin. However, there are several cloud velocity components present. Are the clouds all connected or are projection effects apparent?

Also : We may not expect perfect TeV/MolecularCloud correlation due to E-dependent diffusion (Gabici & Aharonian 2007).

W 28 Field TeV Sources – CR Density



Assume TeV emission is due to CRs:

Estimate CR density $k_{\rm CR}(E)$ enhancement

Recall:

$F(\geq E) \approx 3 \times 10^{-13}(E/{\rm TeV})^{-1.6}\, k_{cr}\, M_5/d^2_{\rm kpc}$ ph cm^{-2} s^{-1}

Implied CR density factor $k_{\rm CR}$ (above Earth-like values) ∼10 to 30.

TeV Source	$V_{\rm LSR}$ (km s^{-1})	d (kpc)	$^{\dagger}M$	$^{\ddagger}n$	$^{\S}\mathbf{k}_{\rm CR}$
HESS J1801−233	0-25	2.0	0.5	1.4	**13**
HESS J1801−233	0-12	2.0	0.2	2.3	**32**
HESS J1801−233	13-25	4.0	1.1	0.6	**23**
HESS J1800−240	0-20	2.0	1.0	1.0	**18**
HESS J1800−240A	12-20	4.0	1.0	0.7	**28**
HESS J1800−240B	0-12	2.0	0.4	2.3	**18**
HESS J1800−240B	12-20	4.0	1.5	1.2	**19**

† Cloud mass $\times 10^5\ M_\odot$

‡ Cloud density $\times 10^3$ cm^{-3}

§ Cosmic-ray density enhancement, $k_{\rm CR}$ above the local value required to produce the $E > 1$ TeV TeV γ-ray emission (using Eq.10 of Aharonian 1991)

W 28 Field TeV Sources - Potential Counterparts & Interpretation

W 28:

W 28 s old age$\sim 10^5$ yr may also favour a hadronic TeV interpretation (Yamazaki et al. 2007) due to electron cooling. The required CR densities vs. typical SNR energetics seem plausible. Zeeman splitting of OH masers in NE region (Hoffman et al. 2005) $|B|$ $\approx$0.75 mG!

Additional SNRs:

Radio surveys (e.g. Brogan et al. 2006) reveal several additional SNRs in the field.

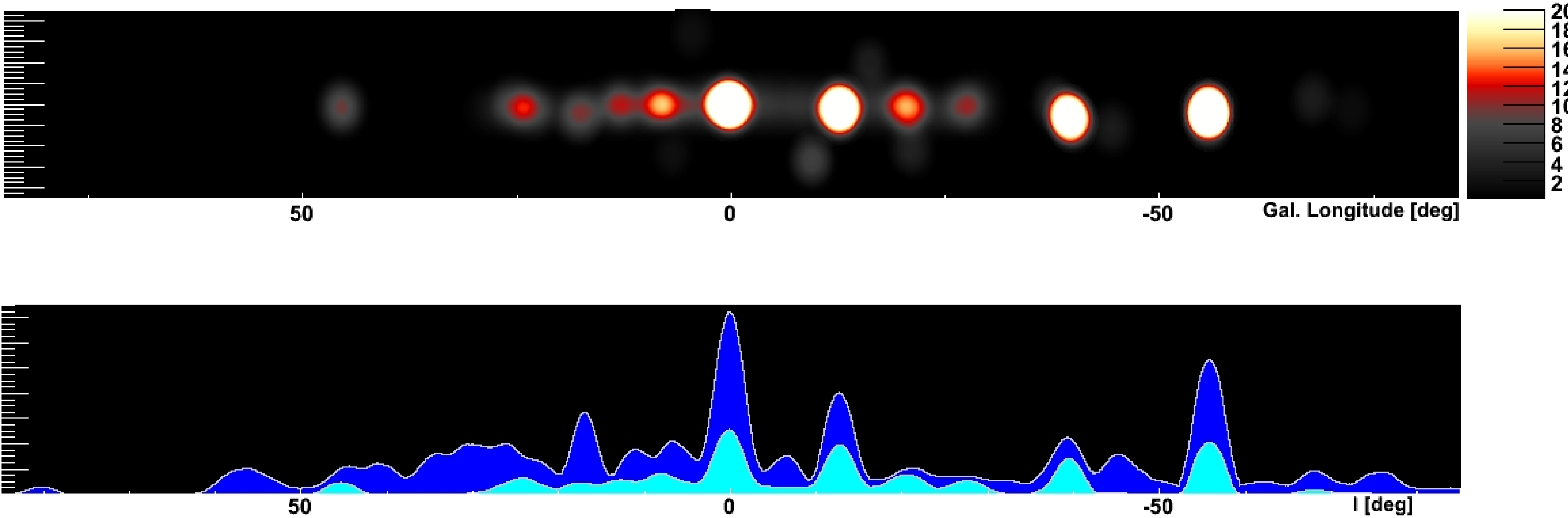
HII regions:

In particular the ultra-compact HII region W 28-A2 may be a counterpart to HESS J1800-240B. W 28-A2 exhibits strong bipolar molecular outflows (protostellar) and may have contributed $\sim 10^{46}$ erg to the region during 10^3 to 10^4 yr (e.g. Sollins et al. 2004). Additionally, protostellar winds speeds $\sim$1000 km s^{-1}. Protostars as CR accelerators (eg. Araudo et al. 2007)

More detailed observations to study the dynamics of the molecular clouds are required to accurately estimate the hadronic component of the TeV emission.

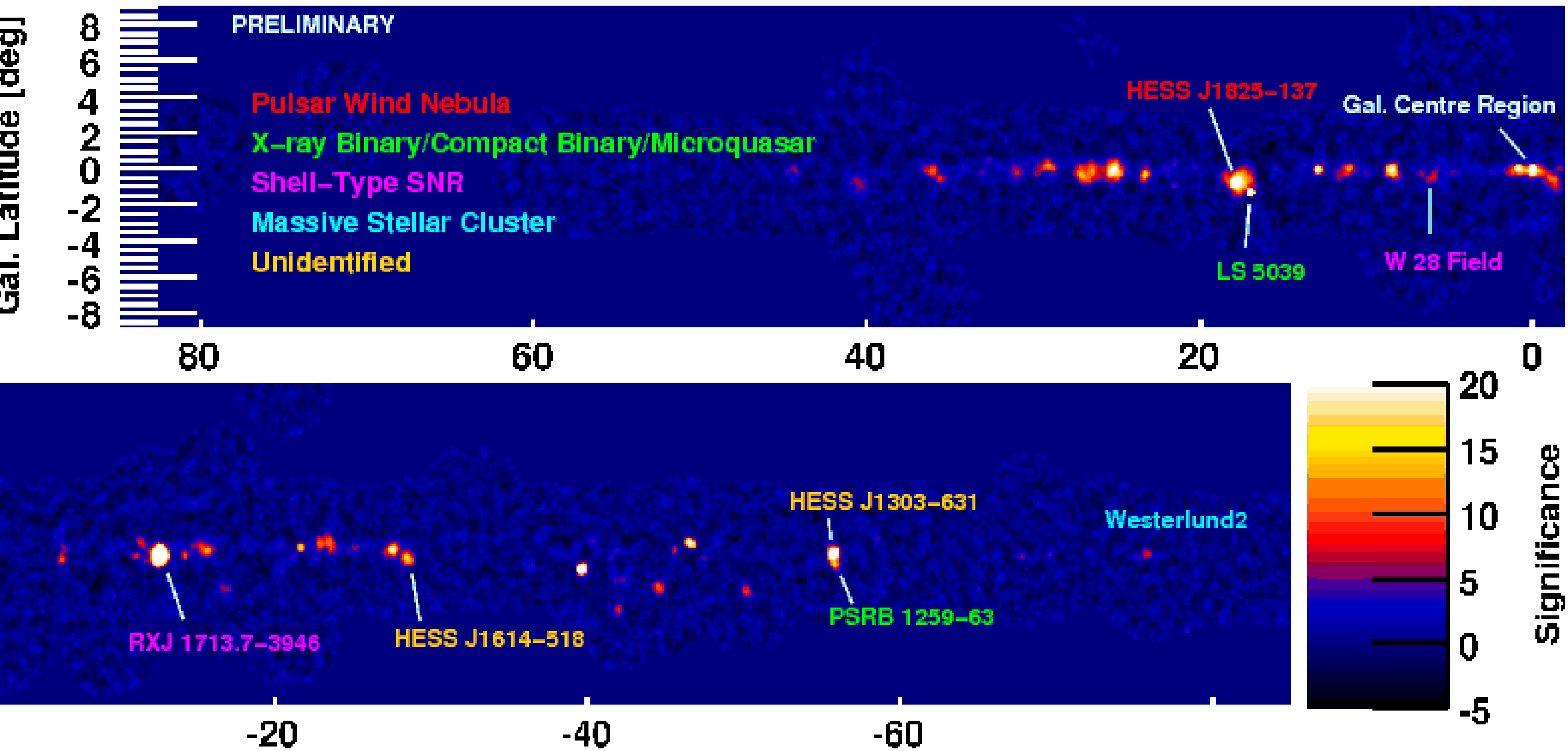
5 Galactic Plane Surveys

H.E.S.S. Surveys of the Southern Galactic Plane (to early-2008)

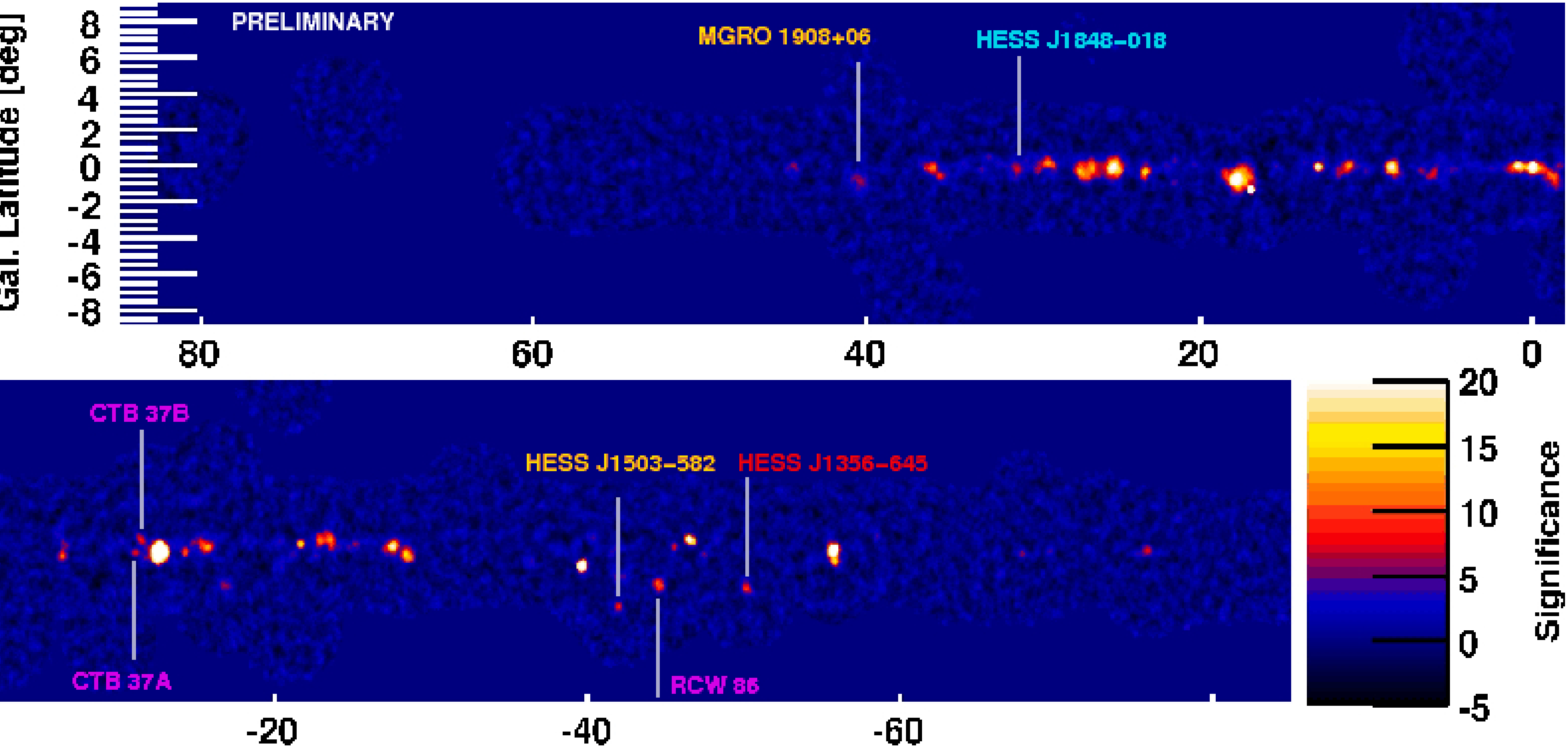


H.E.S.S. Exposure Maps of the Galactic Plane [hr] - Chaves et al. 2008

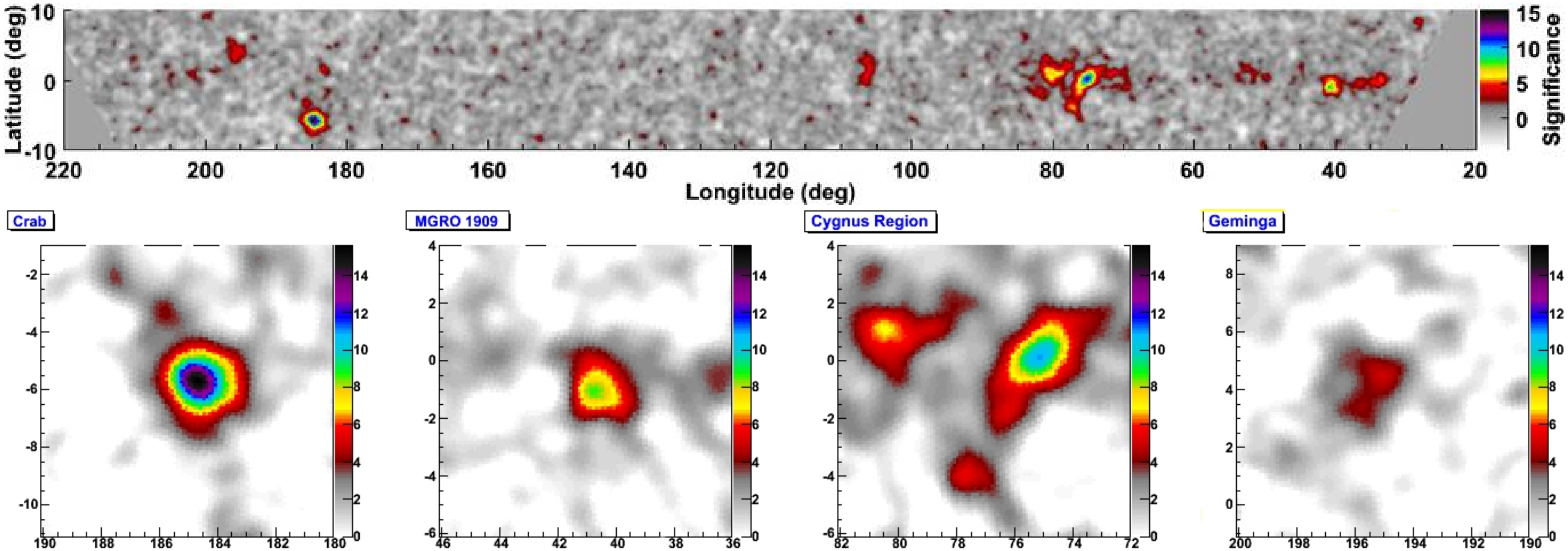
H.E.S.S. 2008: Bright & Some Key Sources



H.E.S.S. 2008: New Sources



MILAGRO Northern Galactic Plane Survey



Abdo et al. 2007 ApJ 664, L91

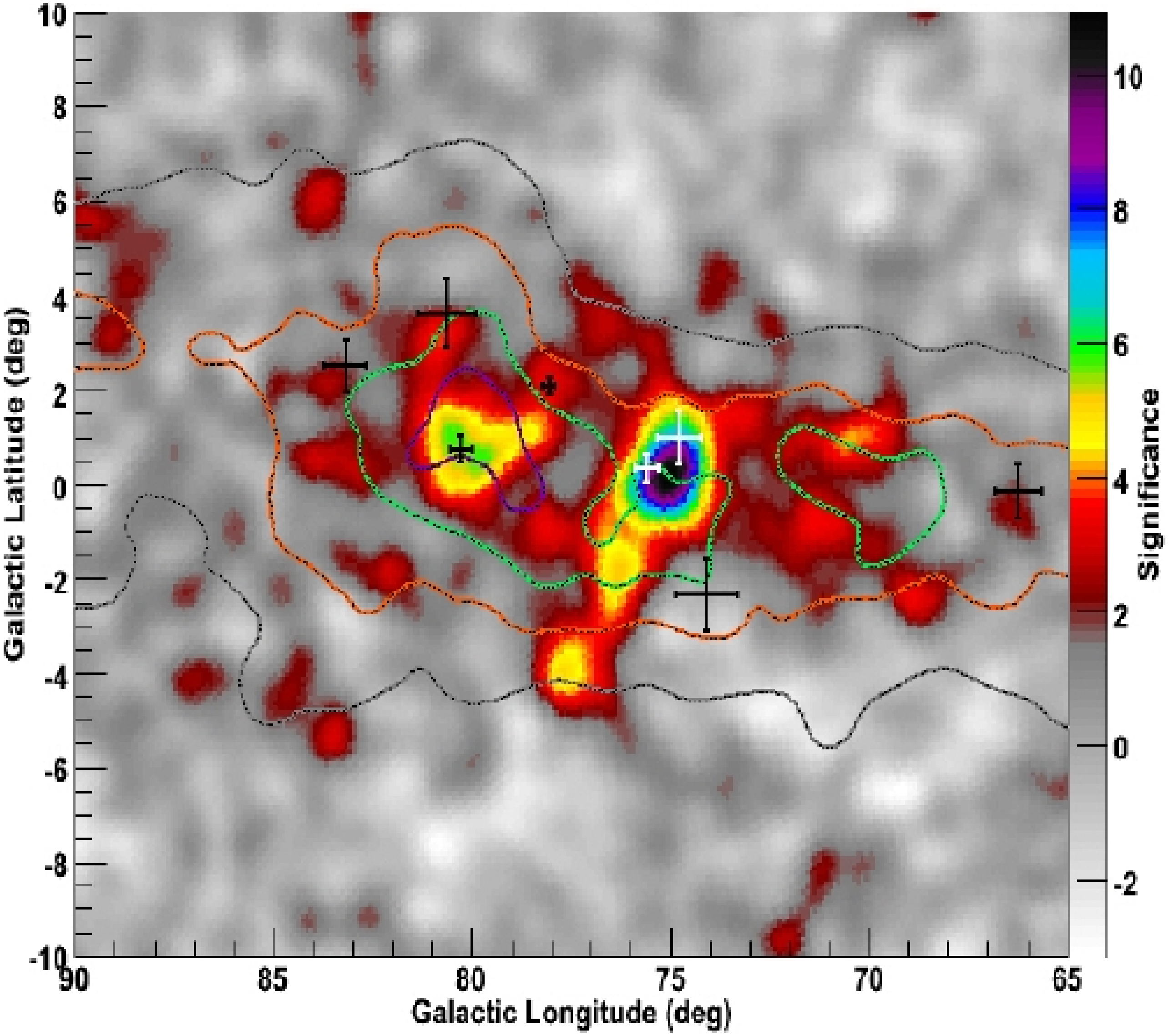
The MILAGRO Water Chernkov Detector has also revealed new TeV sources in along the northern Galactic Plane. Several are well-known objects such as the Crab, the Cygnus Region and possibly Geminga (γ-ray-bright pulsar). Some sources are **unidentified**.

Prelim Energy spectra (Hüntermeyer et al. 2008 AIP Conf. Ser. in press):

MGRO J1908+06 - $dN/dE = 8.19 \times 10^{-12} E^{-1.62} \exp(E/20\mathrm{TeV})$ ph cm^{-2} s^{-1} TeV^{-1}

MGRO J2019+37 - $dN/dE = 1.58 \times 10^{-11} E^{-2.55} \exp(E/100\mathrm{TeV})$ ph cm^{-2} s^{-1} TeV^{-1}

MILAGRO: The Cygnus Region in TeV Gamma-Rays



Abdo et al. 2007 ApJ 658, L33

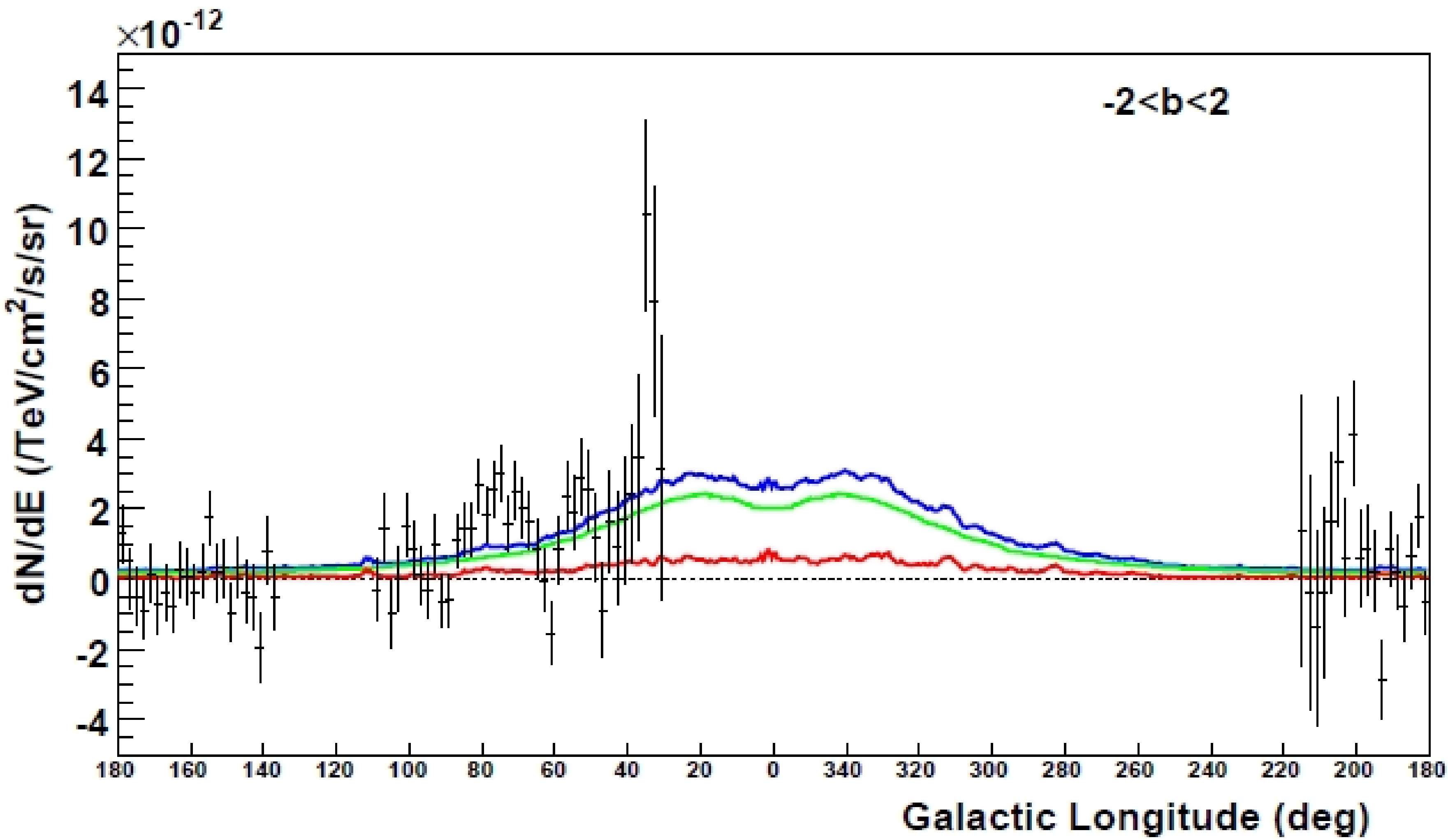
Contours of matter density from HI (Kalberla et al. 2005) & CO (Dame etal 2001) surveys

The Cygnus region is one of most active massive star formation sites. MILAGRO has detected diffuse $E > 10$ TeV emission from this region.

NOTE: MILAGRO angular resolution is $\sim 0.5^\circ$.

TeV emission is not clearly correlated with matter density. Higher resolution studies (e.g. with VERITAS) are necessary to resolve this issue.

MILAGRO: Diffuse Emission – North Galactic Plane

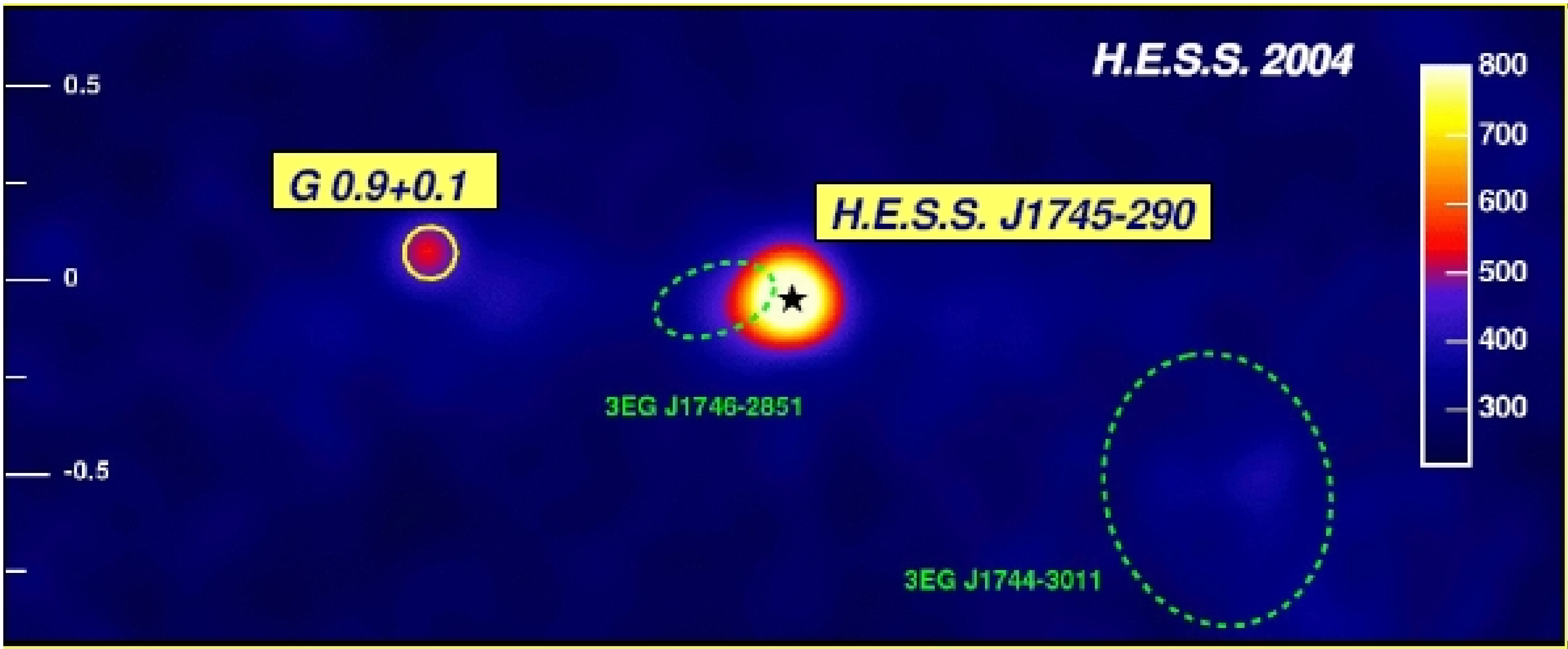


Abdo et al. 2008 ApJ *in press*

MILAGRO Galactic plane emission after discrete source subtraction (black points) compared to optimised GALPROP prediction (red - π-decay; green - inverse-Compton; blue - total)

6 Galactic Centre Region

Galactic Centre Region in TeV γ-Rays



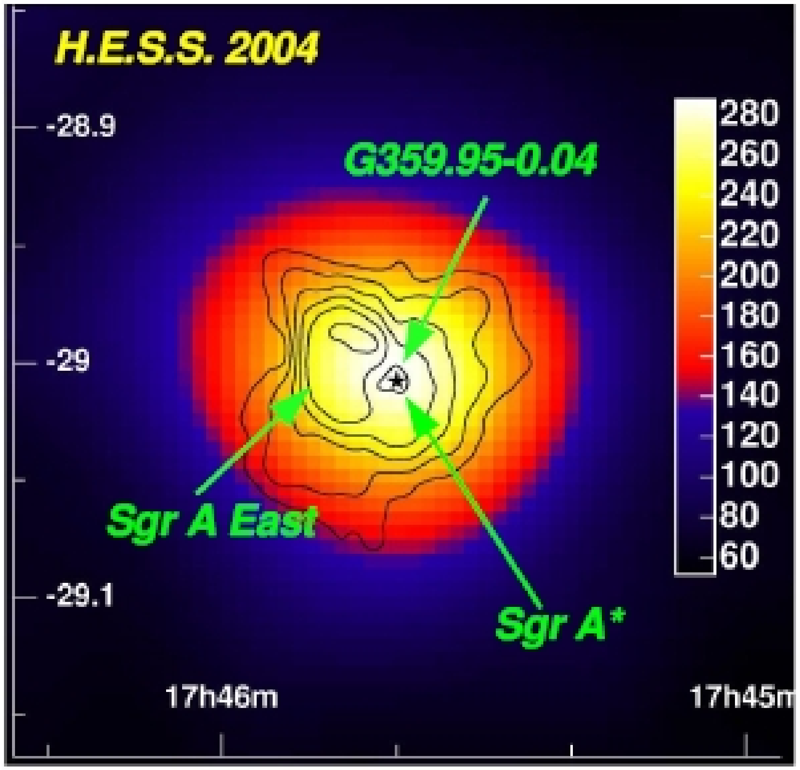
H.E.S.S. TeV image: Aharonian et al. 2004, vanEldik et al. 2007

Two TeV sources — HESS J1745−290 — G 0.9+0.1 (SNR)

HESS J1745−290 was discovered earlier by CANGAROO-II (Tsuchiya et al.) & Whipple (Kosack et al.)

HESS J1745−290 - Power law spectra $\Gamma = 2.25$ up to ~ 20 TeV - STEADY over 5 yrs!

Counterparts to HESS J1745−290



H.E.S.S. TeV closeup of HESS J1745−290 with VLA 90 cm contours

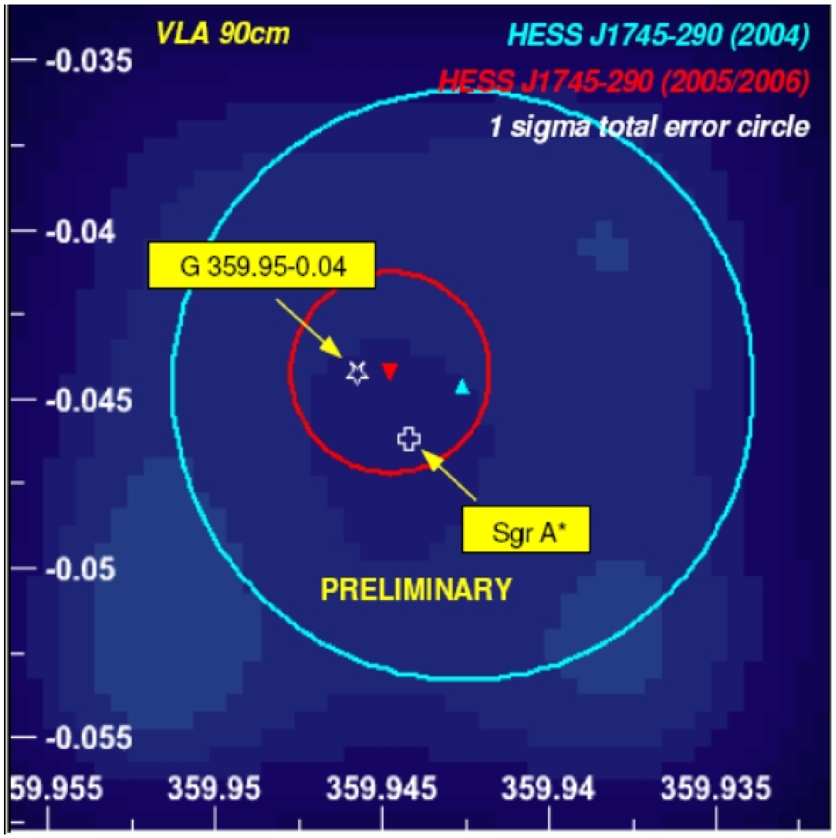
Sgr A East: Very energetic SNR or superbubble with radio shell-like extension.

Sgr A*: Radio source at the Galactic centre — A supermassive black hole powered system?

Dark Matter: A pure DM origin is ruled out by the very wide spectrum (expect turnover in pure KK and neutralino decay signals)

H.E.S.S. systematic pointing uncertainties were improved from 20 arcsec (2004) to 6 arcsec (2005/2006).
$\longrightarrow$ rules out Sgr A East.

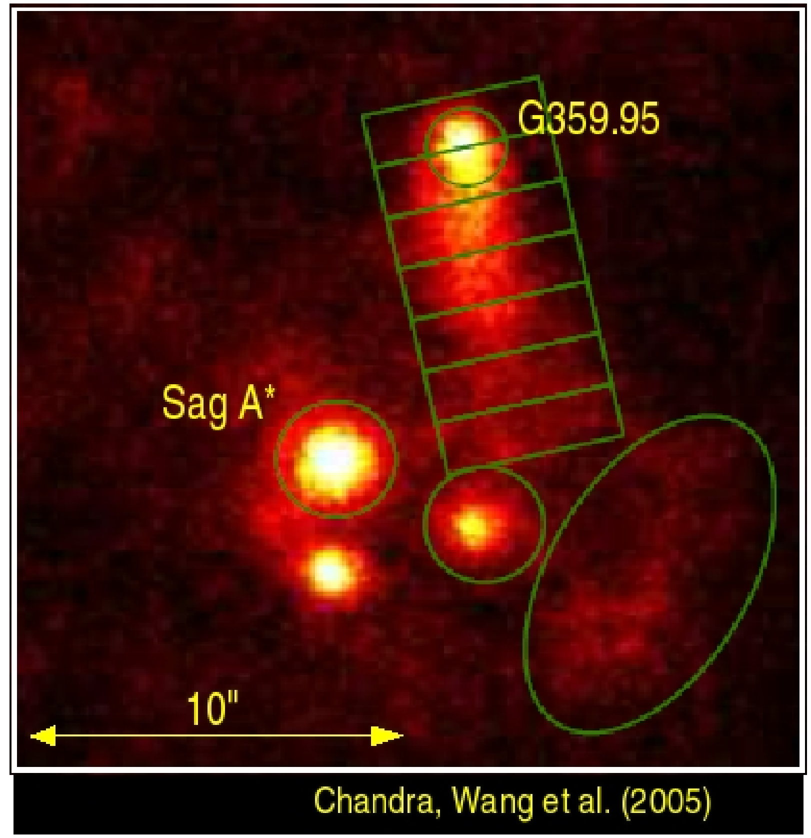
Counterparts to HESS J1745−290 - II



VLA Radio Image:

Blue - 2004 position/error

Red - 2005/2006 position/error



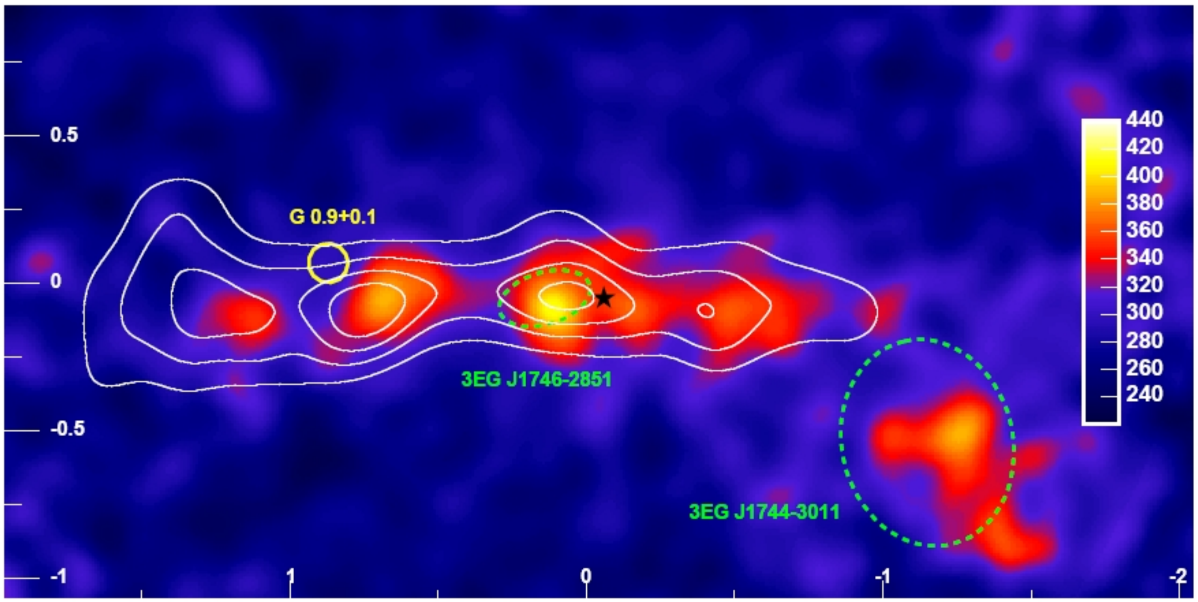
Chandra discovery of new PWN G359.95. Unfortunately too close to Sgr A* rule out TeV connection....

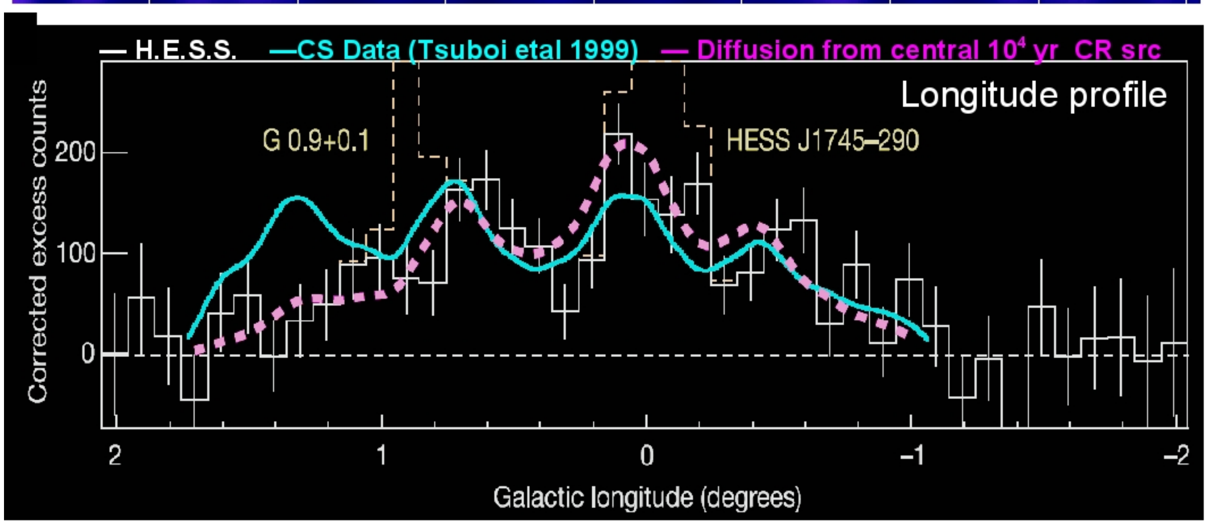
PWN origin for HESS J1745−290 (Hinton & Aharonian 2007)

Molecular Clouds: Galactic Ridge TeV Emission

Aharonian et al (2005) Nature 439, 695

Subtract HESSJ1745−290 & G 0.9+0.1 emission





Diffuse TeV emission seen towards Galactic Ridge. Spatial correlation with molecular gas (CS line)

$|l| < 0.8^\circ$ $|b| < 0.3^\circ$
$M \sim 1.7$ to $4.4 \times 10^7 M_\odot$

Single, central CR accelerator may be the source $F(E) \sim E^{-\Gamma}$ $\Gamma = 2.5 \pm 0.07$

No change in Γ throughout TeV region.

Diffusion coeff:

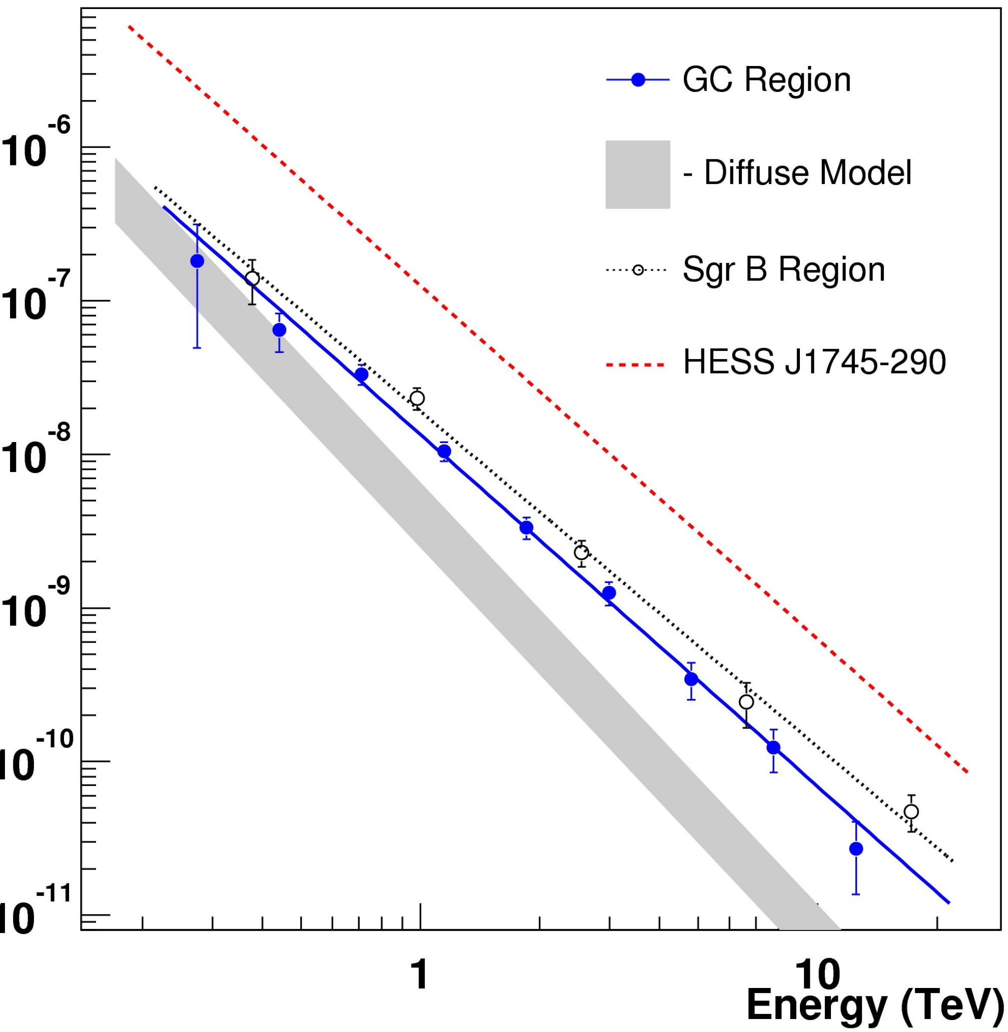
$D_{\rm fewTeV} = \eta \times 10^{30}$ cm^2 s^{-1}; $\eta \leq 1$

Diffusion timescale:

$t = 3000(\theta/1^\circ)^\circ/\eta$ yr

Molecular Clouds: Galactic Ridge TeV Spectrum

Aharonian et al. (2005) Nature 439, 695



Compare the TeV spectrum (GC-Region) with expected flux F from *local CRs* interacting with dense molecular clouds (Aharonian 1991) (grey shaded area)

$F(\geq E) \approx 3 \times 10^{-13} (E/\mathrm{TeV})^{-1.6}\, k(E)\, M_5/d^2_{\mathrm{kpc}}$ ph cm^{-2} s^{-1}

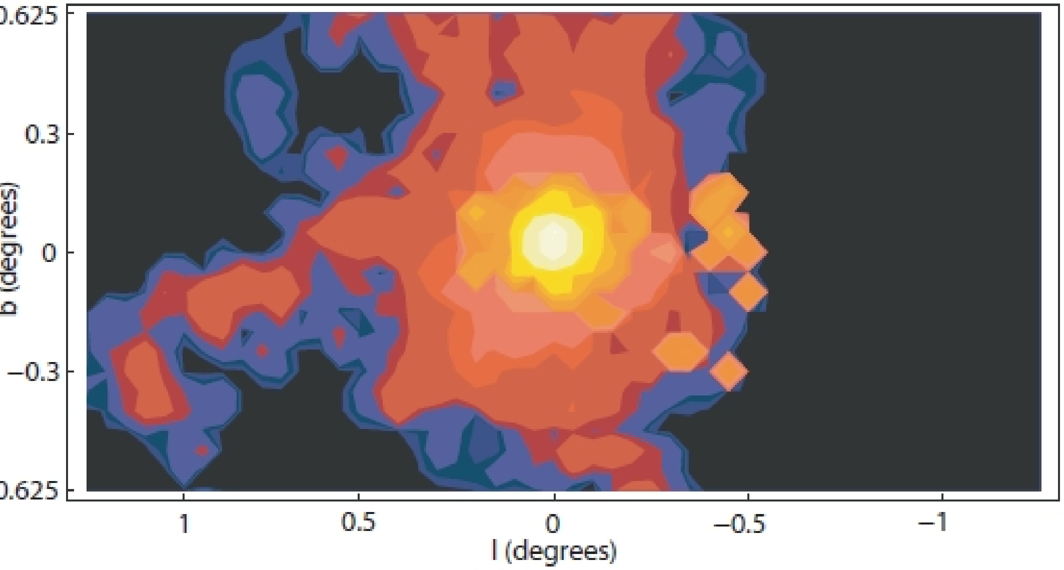
$k = 1$ for Earth-like CR fluxes

$k \sim 4$ to 10

→ CR flux in Gal. Centre Region ~ 4 to $10\times$ the Earth-like CR flux.

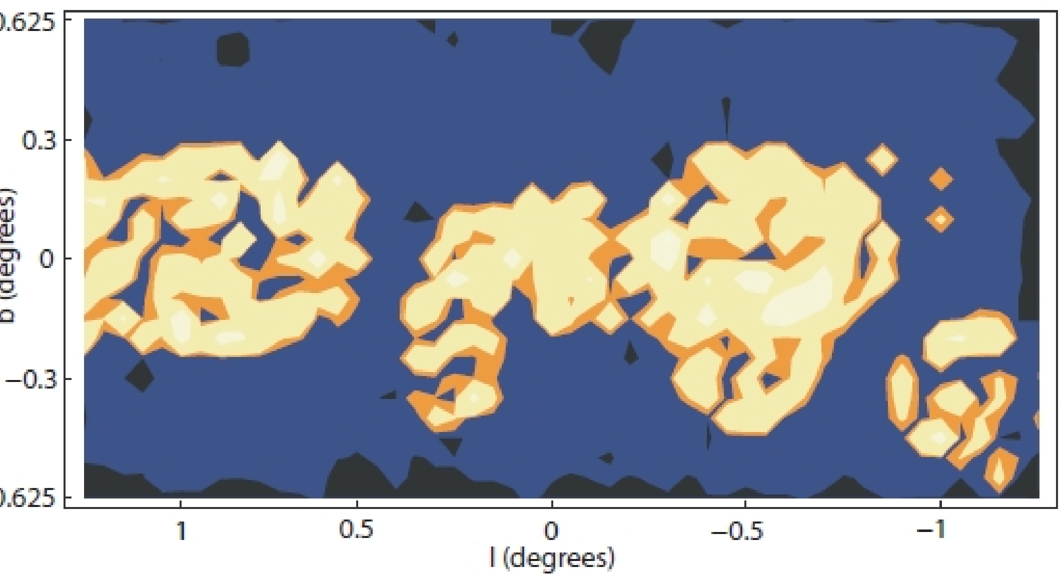
Molecular Clouds: CR Propagation/Acceleration

Wommer et al. 2008 MNRAS 387, 987



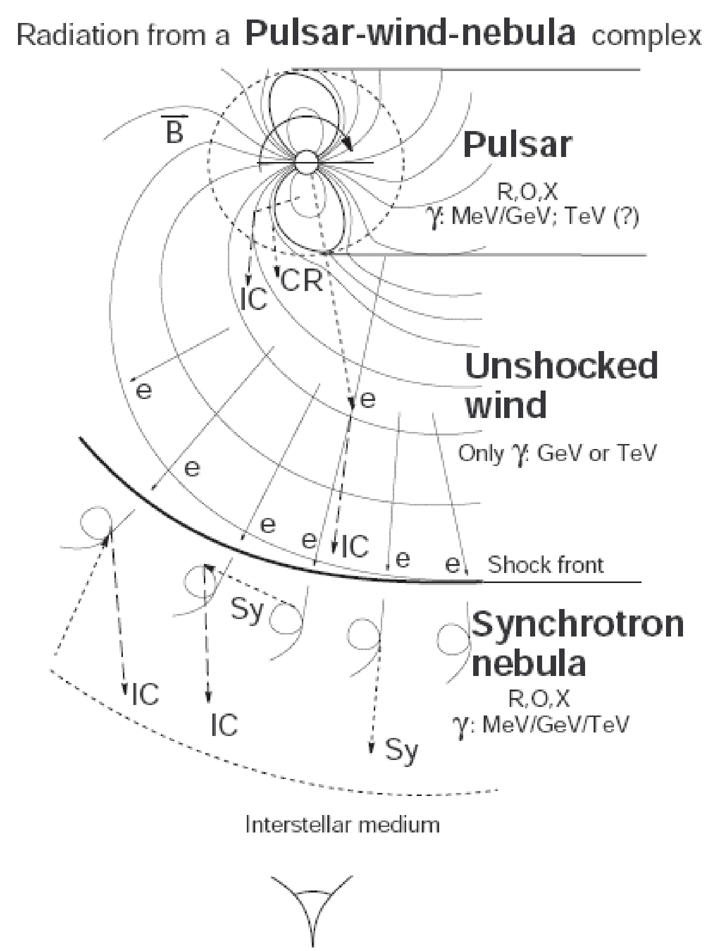
Following individual particles through Mol. Clouds (3D model). 10μG B-field (Kolmolgorov turbulence)

Top: Cosmic-Rays injected at Galactic Centre



Bottom: Cosmic-Rays accelerated between clouds via 2nd order Fermi process (off the turbulent B-field).
See also Crocker et al. 2007, Protheroe et al. 2008 (Models for the Sgr B molecular cloud)

7 Pulsar Wind Nebulae (PWN)

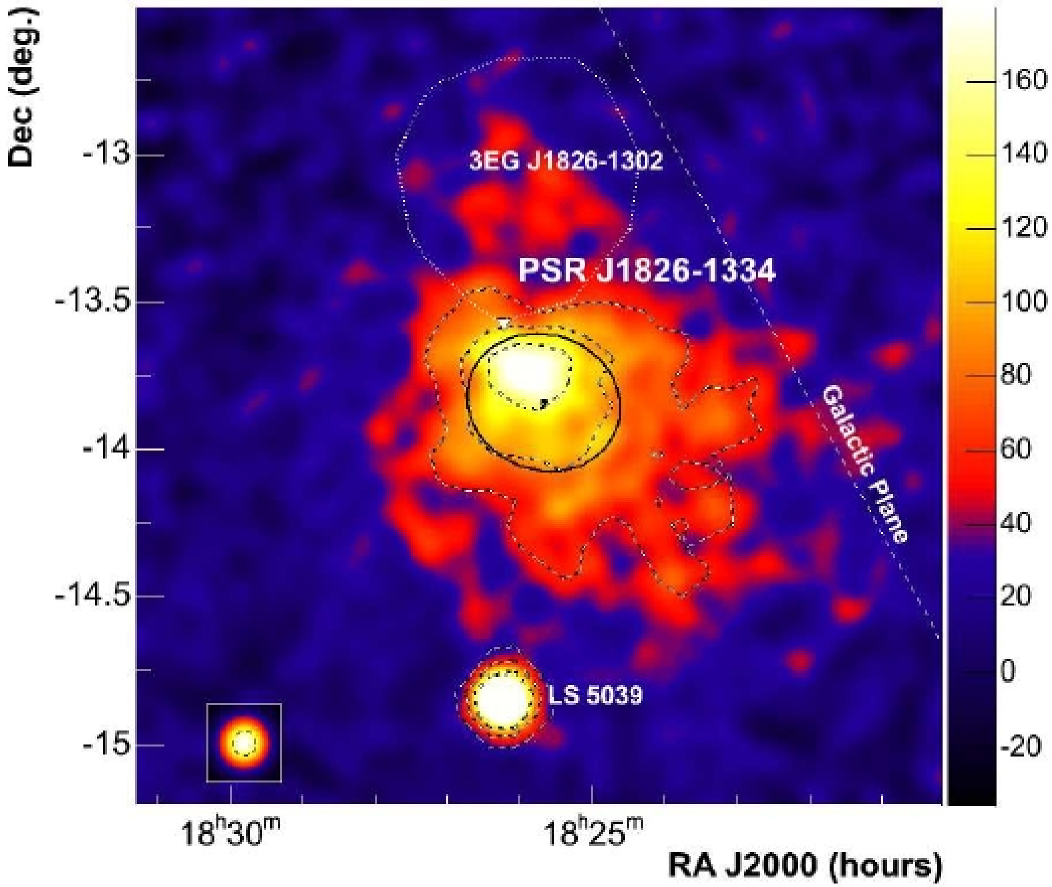


Powered by rotational energy of pulsar. Recall the *spin-down power* $\dot{E} = I\omega\dot{\omega}$

$\dot{E} \sim 10^{32}$ to $\sim 10^{39}$ erg s^{-1}

Pulsar wind & ISM pressure balance leads to a termintion shock, where particles may be accelerated. (figure - Aharonian & Bogovalov 2003)

HESS J1825−137



H.E.S.S. TeV image: Aharonian et al. 2006

Large (degree-scale) asymmetric PWN detected by H.E.S.S. (survey 2004).

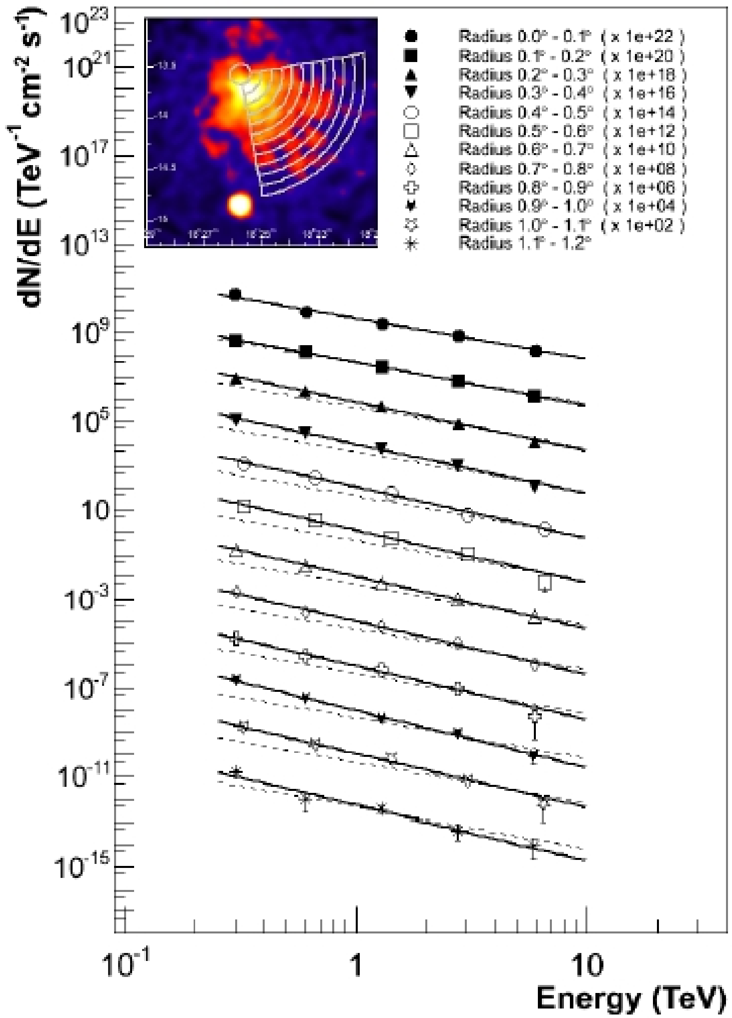
Pulsar: Period - 101 ms;

$\dot{E} = 3 \times 10^{36}$ erg s^{-1}

Age - 20 kyr

d ~4 kpc

HESS J1825−137 - Spectral Evolution



A softening of the energy spectrum can be seen with increasing distance from the pulsar. This is evidence of a leptonic origin since electrons will rapidly cool (lose energy) in the magnetised environment. Suggests pulsar is the energy source.

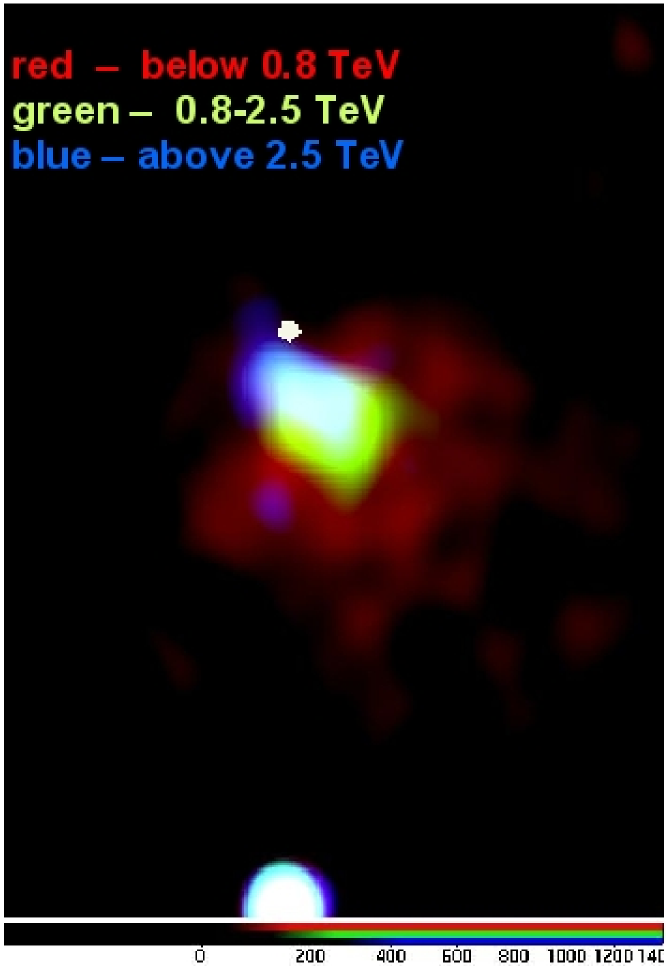
Electron lifetime (IC & Synch. losses):

$t_{Sy+IC} = 3.1 \times 10^5 (U_r/\mathrm{eV cm}^{-3})^{-1} (E_e/\mathrm{TeV})^{-1}$ yr

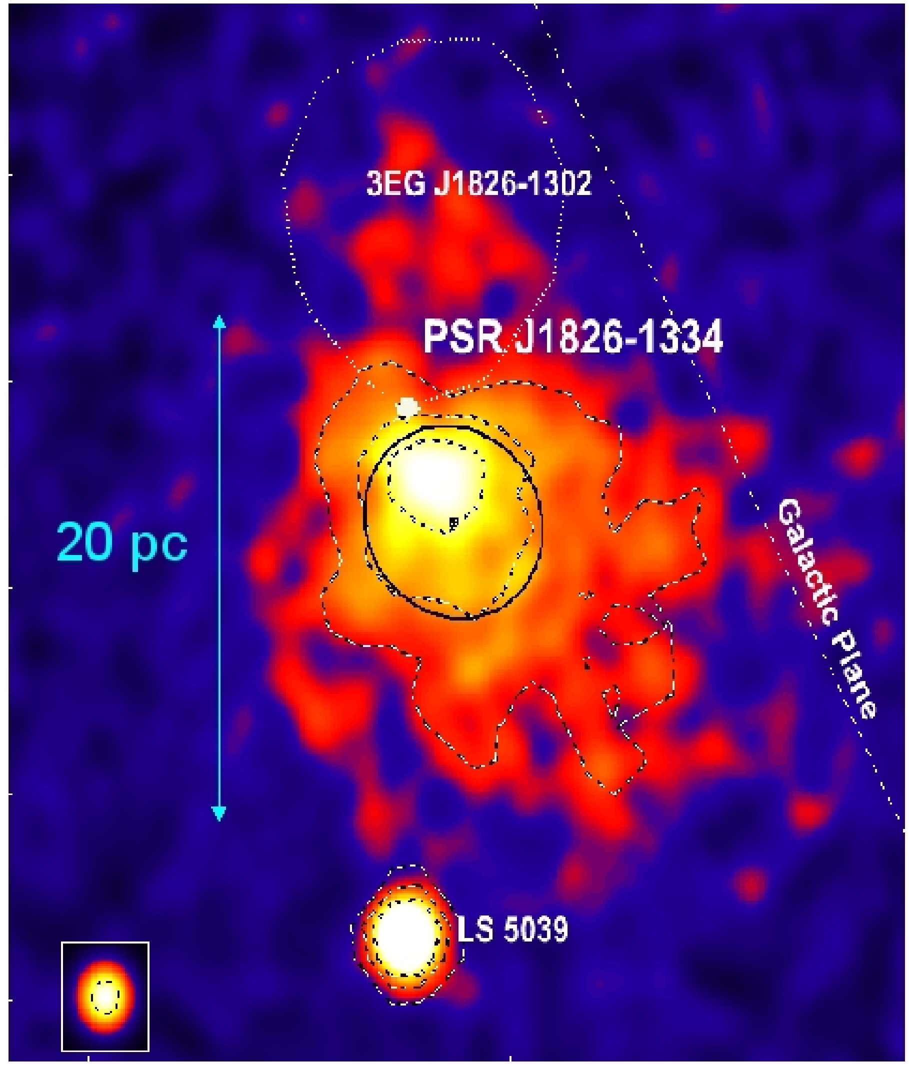
for U_r = soft photon density + mag. field density.

We find that $t_{Sy+IC} <$ Age even for modest $B \sim 6\mu$G

Dotted line - Spectrum at the compact core/pulsar region.

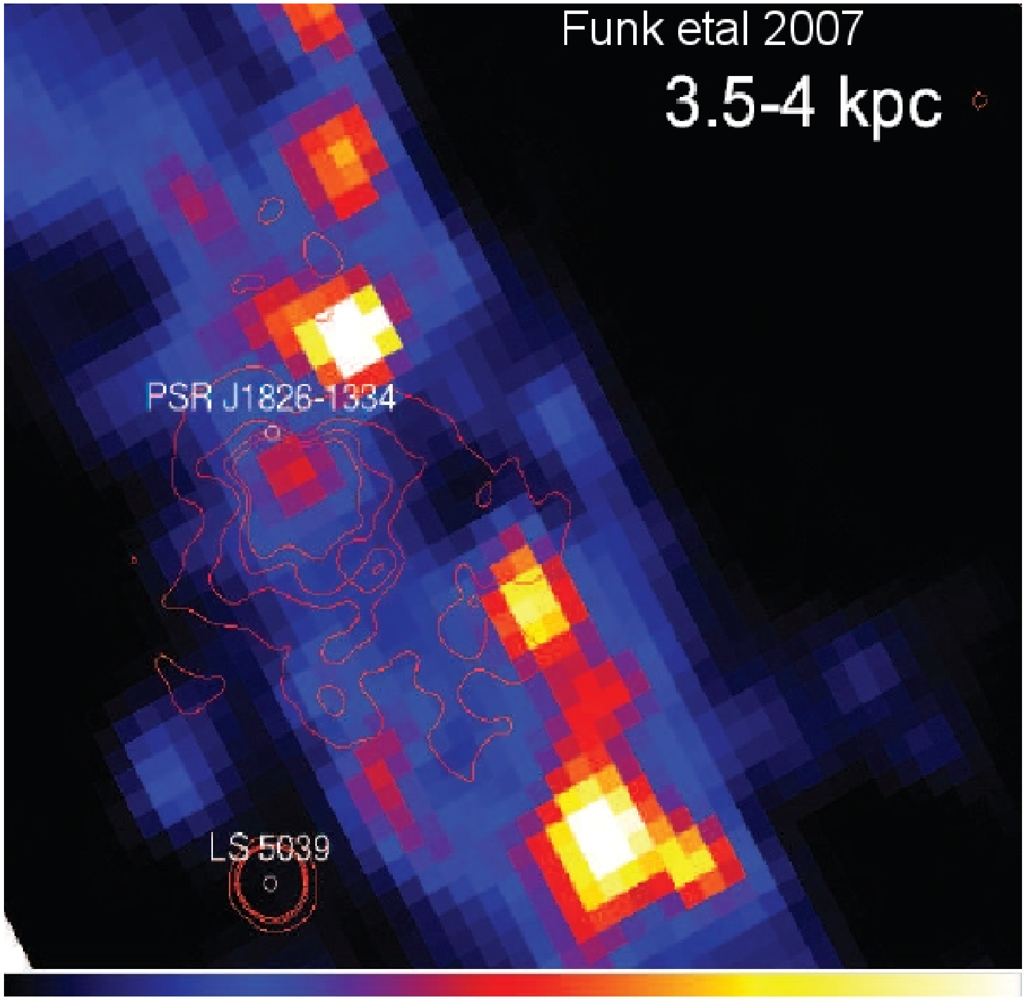


red – below 0.8 TeV
green – 0.8-2.5 TeV
blue – above 2.5 TeV
0
200
400
600
800
1000
1200



3EG J1826-1302
PSR J1826-1334
20 pc
Galactic Plane
LS 5039

HESS J1825−137 - Why Asymmetric?



Answer:

Dense molecular cloud at N edge.

PWN 'crushed' or distorted by SNR reverse shock after interaction with molecular cloud.

see eg. Blondin et al. 2001, Gaensler et al. 2003, van derSwaluw et al. 2004

A common feature in many TeV PWN.

H.E.S.S. Pulsar Population Studies in TeV PWN

Look at fraction of pulsars detected (via PWN) vs. pulsar spin-down power $\dot{E}$

Wenig et al. 2008; Carrigan et al. 2007

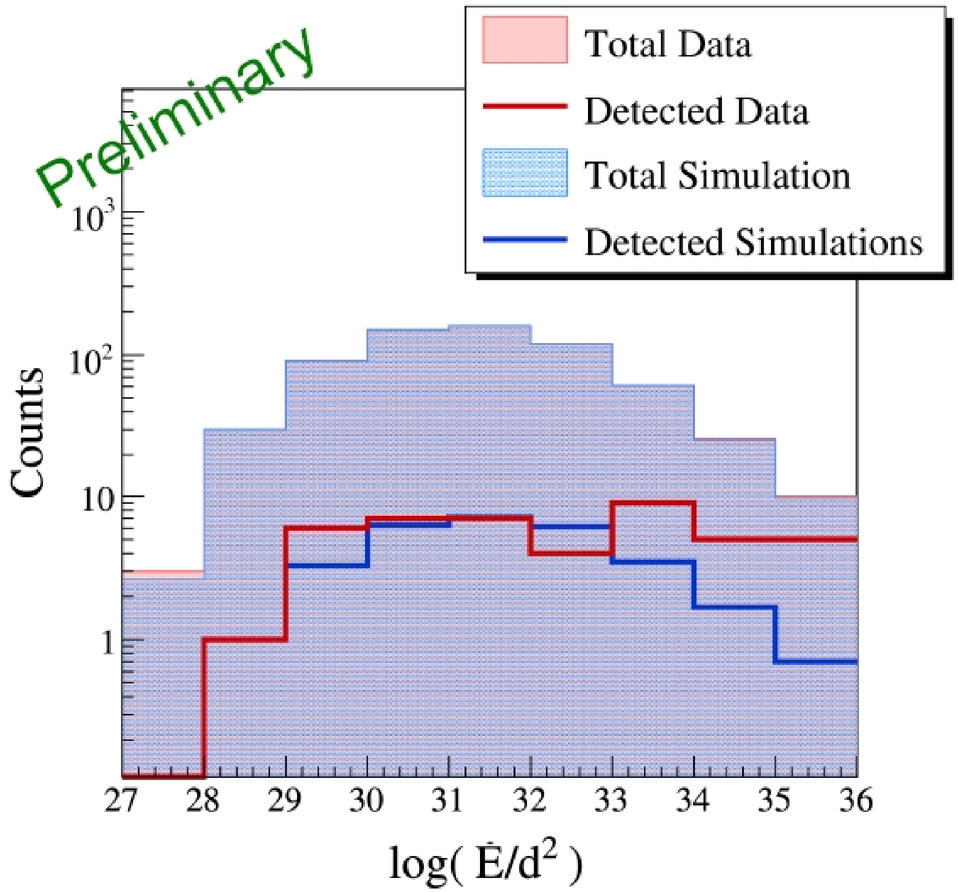


Figure 4: log(Ė/d²) distribution of all (filled) and detected (line) PWNe for data (red) and MC (blue).

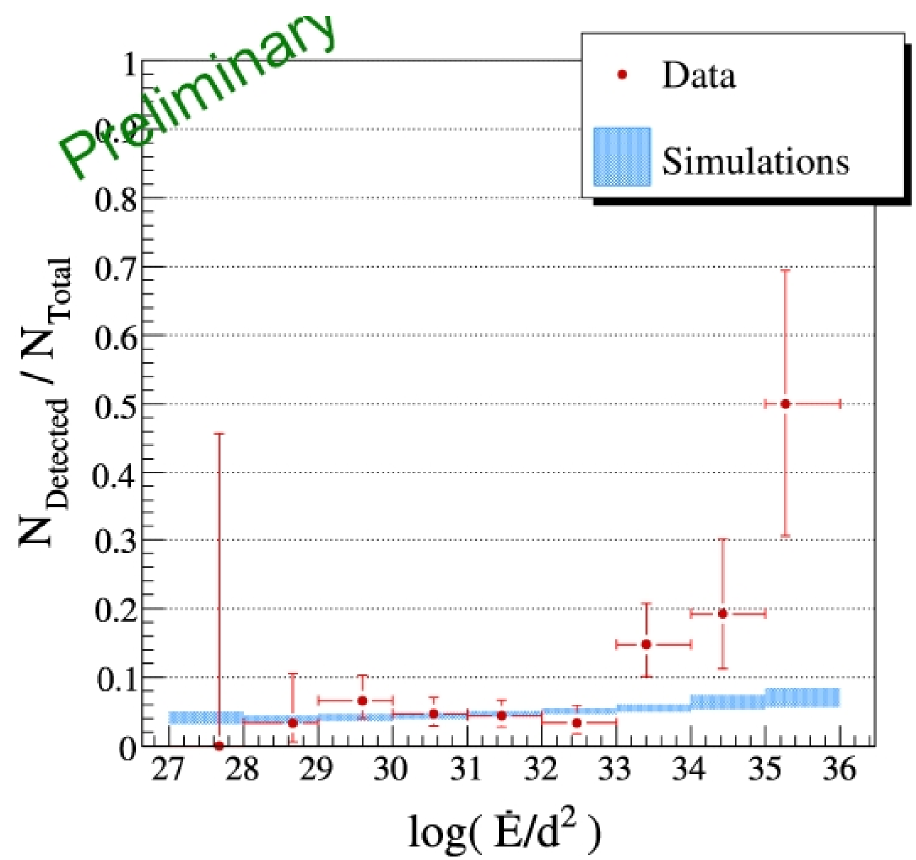


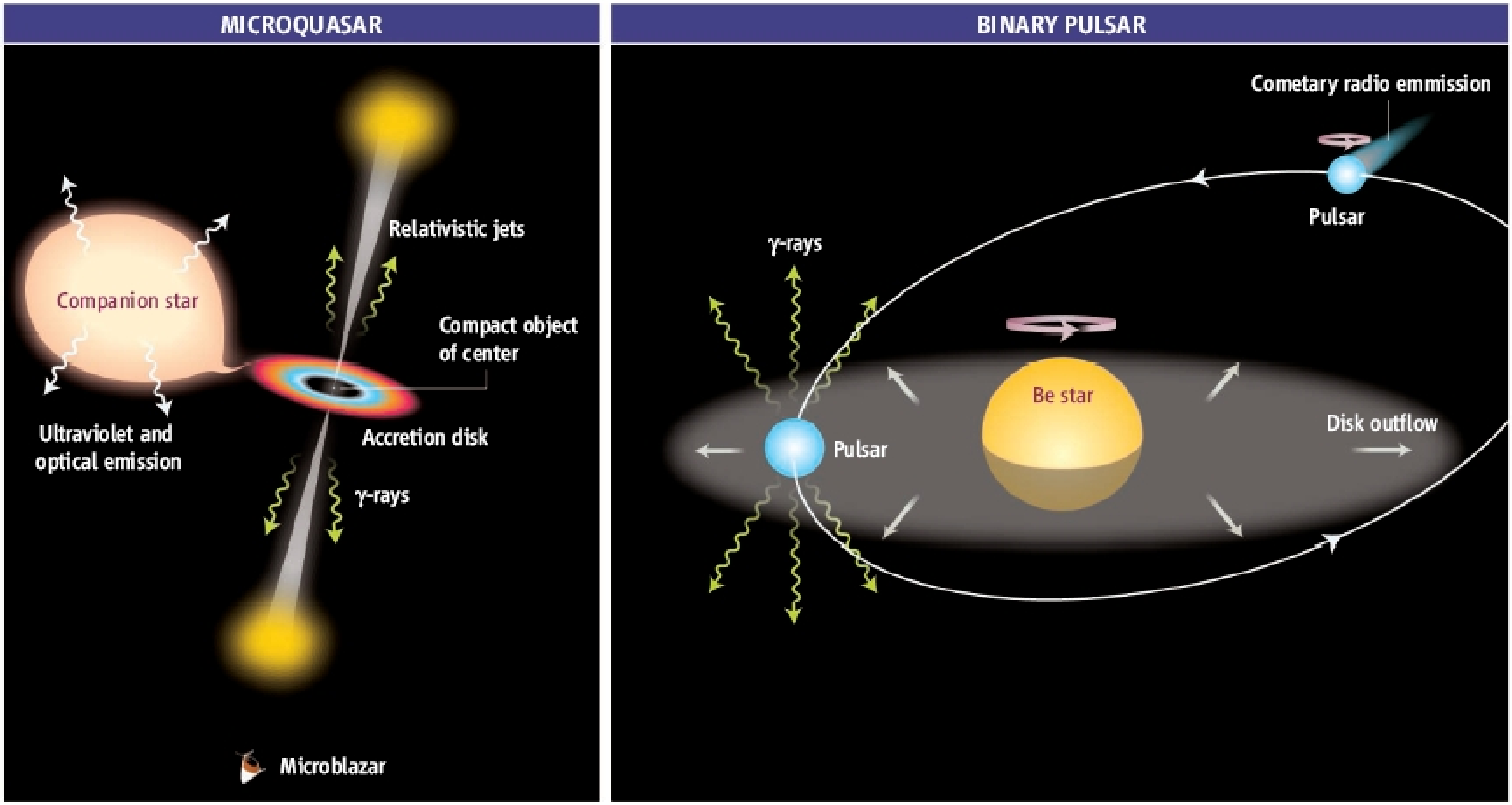
Figure 5: ratio of detected over all PWNe for the data (red) and the simulation (blue).

Conclusion:

Fraction ~50% of pulsars with $\dot{E} > 10^{35}$ erg s^{-1} are TeV sources!

8 Microquasars & Binary Pulsars

Microquasars are a subset of X-ray Binaries (XRB)



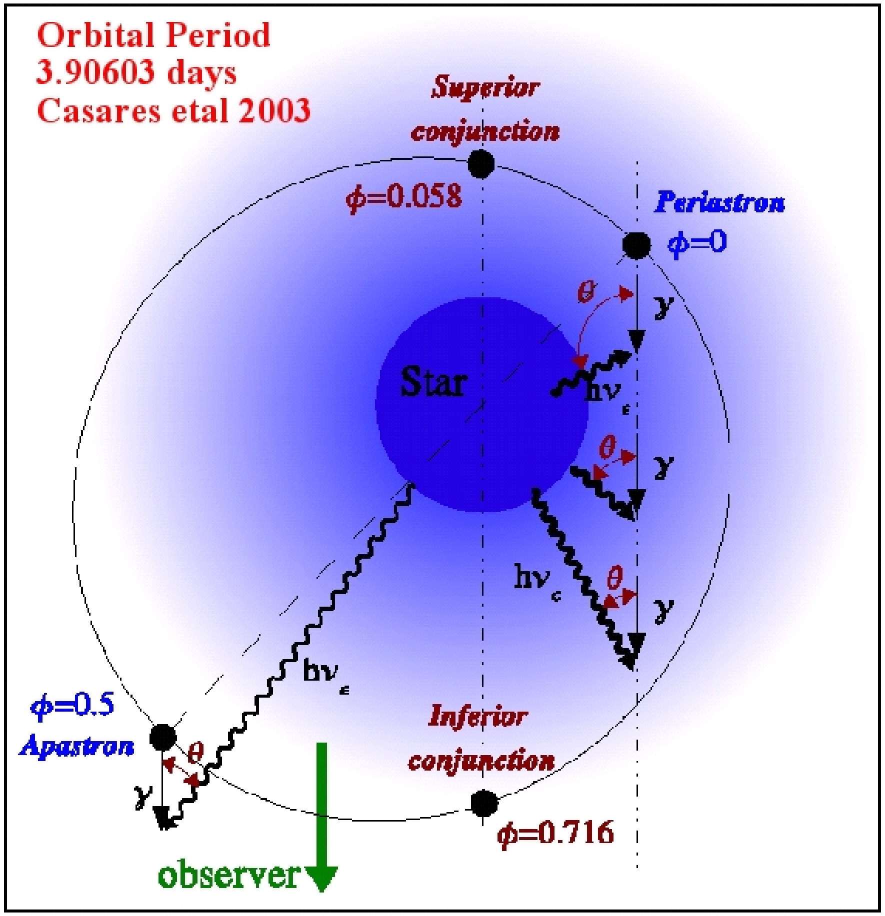
Mirabel 2006

TeV Microquasars: LS 5039, LSI+61°303, Cyg X-1?

TeV Binary Pulsar: PSR B1259−63

LS 5039, LSI+61°303 could fall into both categories - often called Compact Binaries

LS 5039 High Mass X-ray Binary System



Aharonian et al. 2006

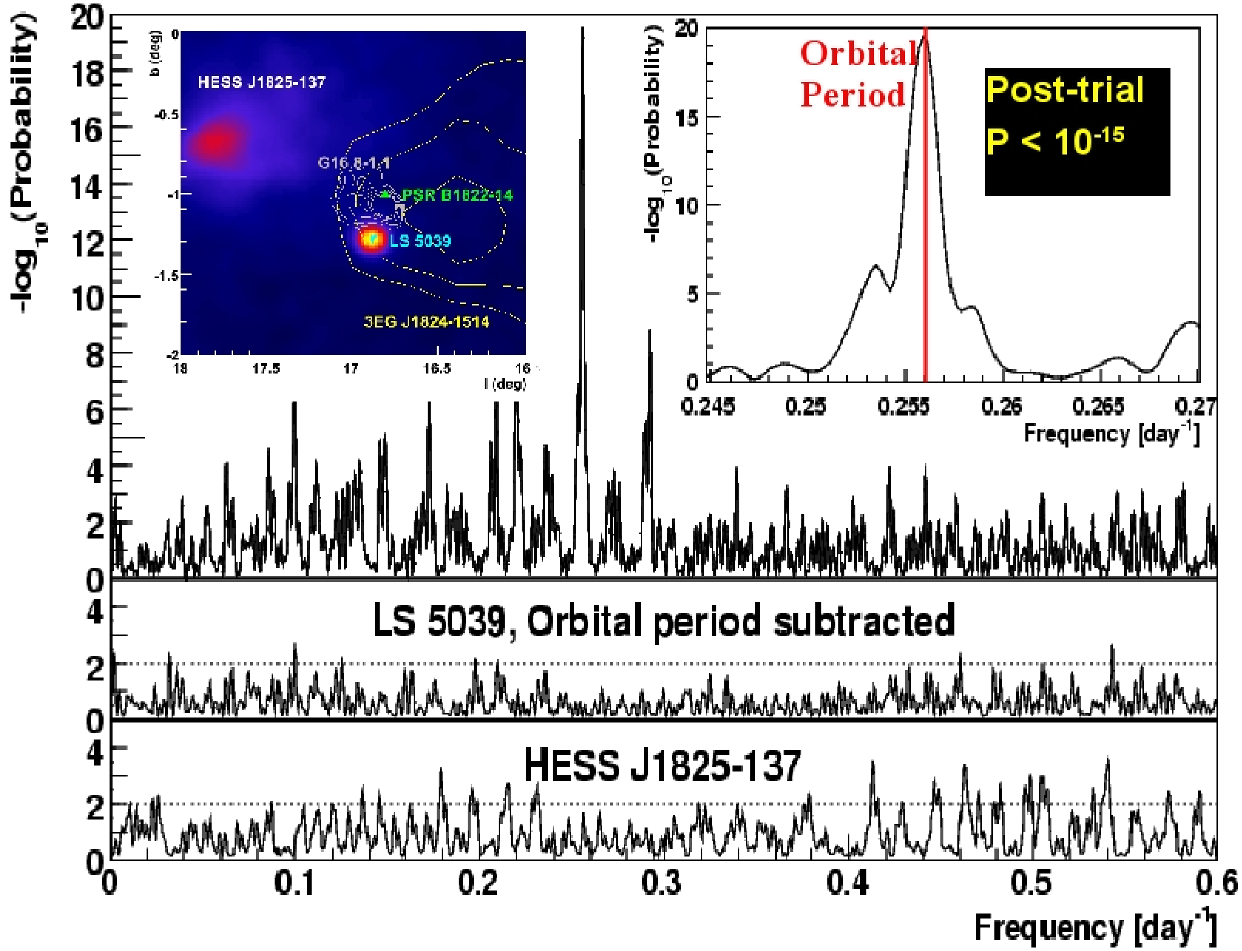
O-star: 25 $M_{\odot}$; Compact object $M \sim 3.7 M_{\odot}$ (large uncertainties)

θ - angle between TeV γ-ray and UV photon.

Dense optical/UV field from O-star (10^{14} ph cm^{-3}). Absorption of TeV γ-rays (from compact object) absorbed via pair production ($\gamma\gamma \rightarrow e^{\pm}$) (e.g. Moskalenko 1995, Protheroe & Stanev 1997). The absorption is **orbital-phase dependent**, due to angular dependence in the pair production cross-section threshold, and density of Opt/UV photons – suggests orbital phase modulation of the TeV gamma-ray signal (e.g Dubus 2005). Additional issues such as changing particle acceleration conditions could also occur (Aharonian et al. 2006)

LS 5039 TeV Orbital Phase Modulation

Aharonian et al. 2006



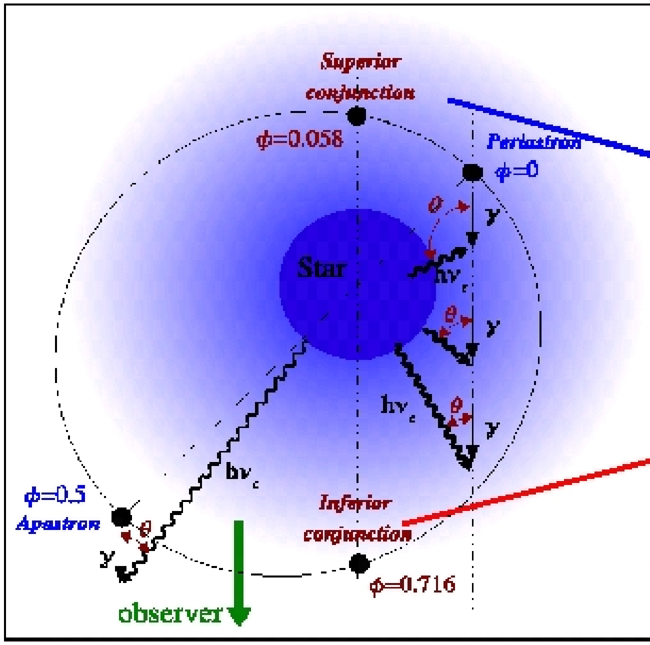
Aharonian et al. 2006

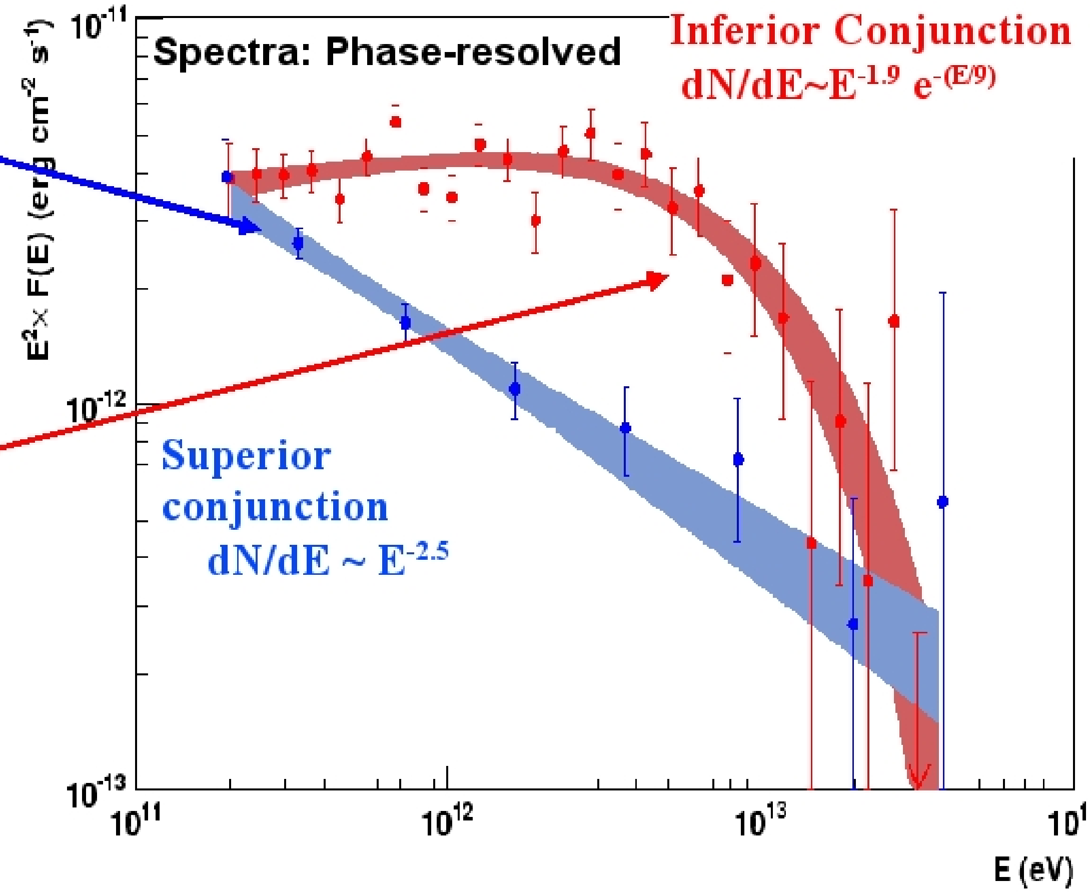
Lomb-Scargle test (Scargle 1982) strong evidence for periodicty is seen.

First time to see orbital periodicity at gamma-ray energies.

Constrain much of the TeV source region with $\sim$1 AU of the compact object.

LS 5039 Phase-Resolved TeV Spectrum



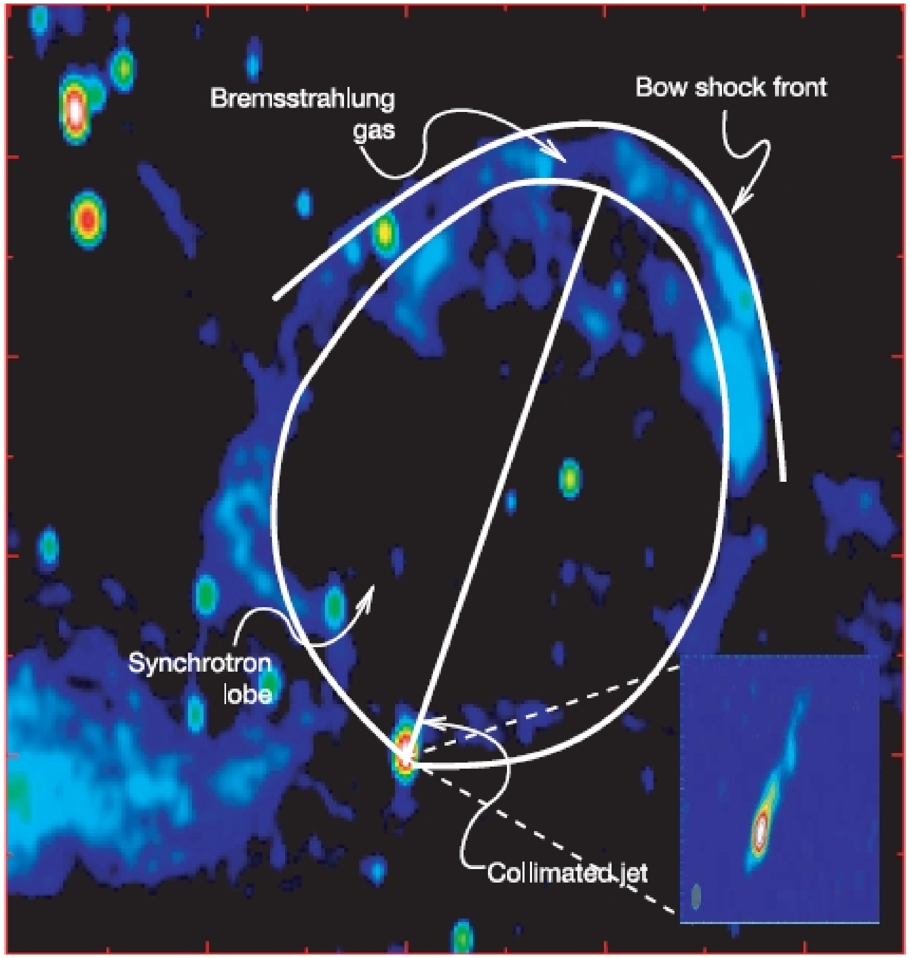


Absorption threshold $E_\gamma \sim \dfrac{2(m_e c^2)^2}{\epsilon(1-\cos\theta)}$ for $\epsilon \sim 10$ eV UV photon ave. energy.

Expect modulation at 200 GeV - *but not seen!*

Needs additional effects - $\gamma\gamma/e^{\pm}$ cascades, angular-dependence in IC X-section (Khangulyan et al. 2007)

Cyg X-1: A Black Hole Microquasar



Gallo et al. 2005 Nature

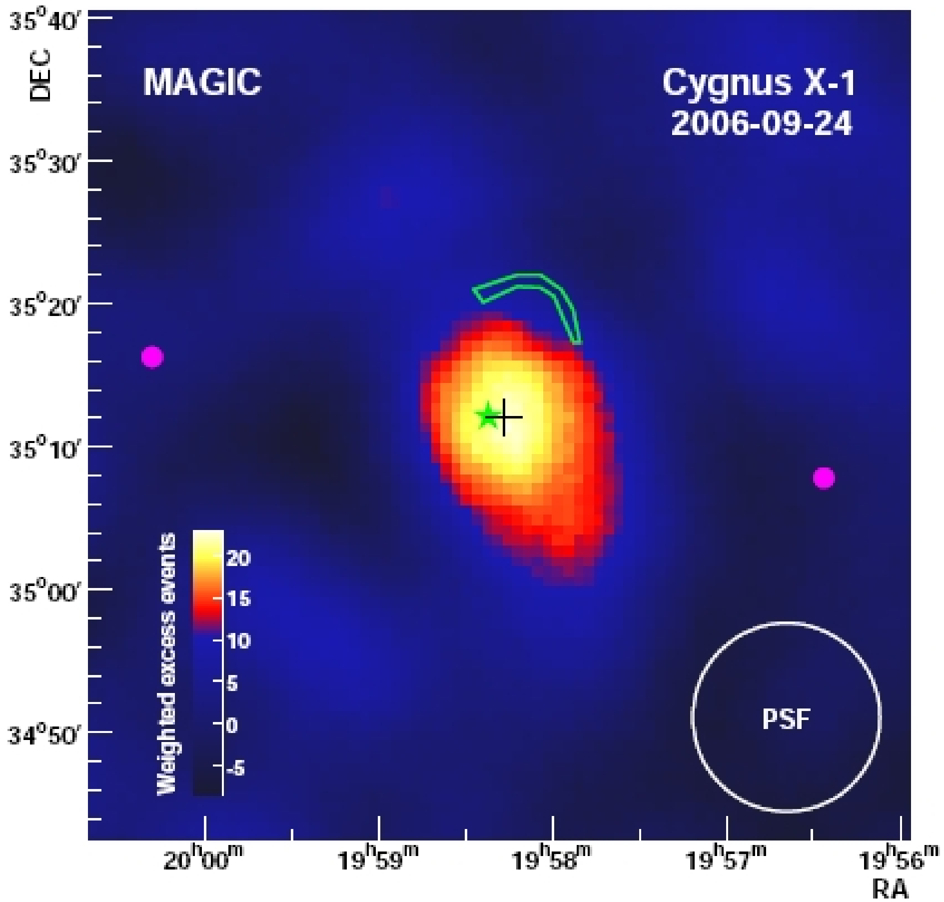
- Compact object 21± 8 $M_\odot$ Black Hole
- 40$\pm 10 M_\odot$ O9.7 massive compansion
- Circular orbit – period 5.6 days
- Inclination angle 25 to 65°

Gallo et al. 2005 found a radio (1.4 GHz) *bow-shock* from the northern jet (**2nd example of Galactic jet interaction (after SS-433)**.

Bow-Shock Energetics: $10^{36\,\mathrm{to}\,37}$ erg s^{-1}
Jet Energetics: $10^{36\,\mathrm{to}\,37}$ erg s^{-1} !

Cyg X-1: A TeV flare

Albert et al. 2005 ApJ



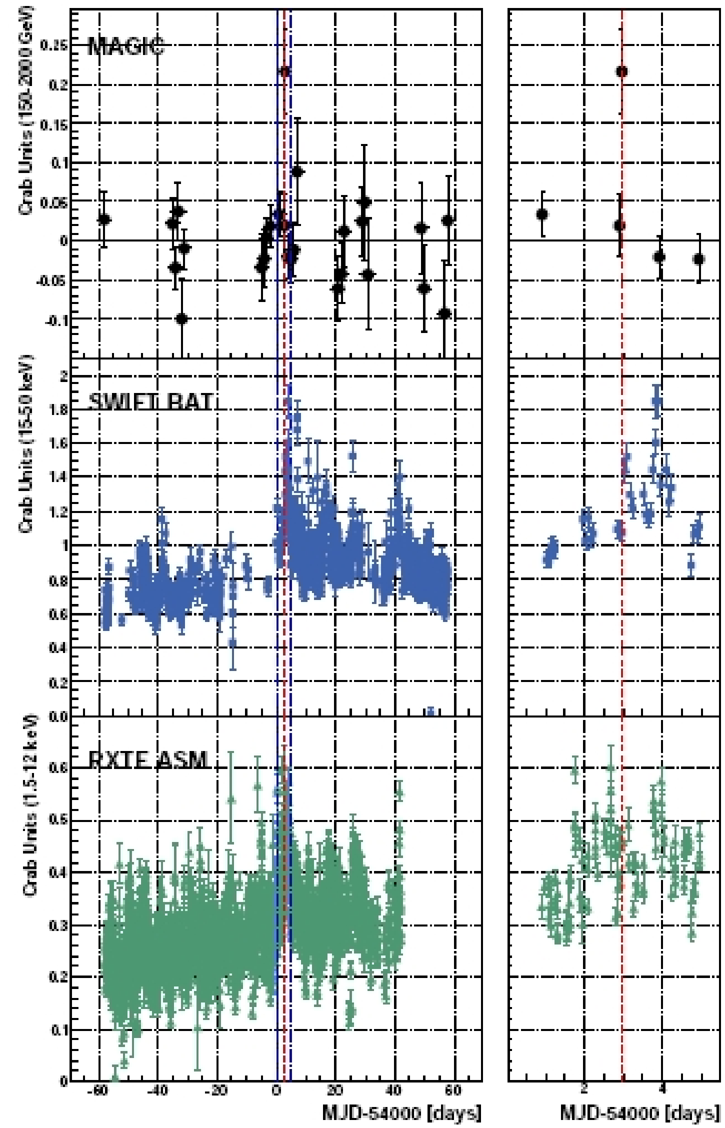


FIG. 4.— From top to bottom: MAGIC, *Swift*/BAT and *RXTE*/ASM measured fluxes from Cygnus X-1 as a function of the time. The left panels show the whole time spanned by MAGIC observations. The vertical, dotted blue lines delimit the range zoomed in the right panels. The vertical red line marks the time of the MAGIC signal.

TeV Flare 24 Sept 2006

MAGIC 0.15 to 2 TeV; Swift 15-50 keV; RXTE-ASM 1.5 to 12 keV

TeV flare before hard X-ray (Swift) flare!

9 Stellar Clusters & Massive Stars

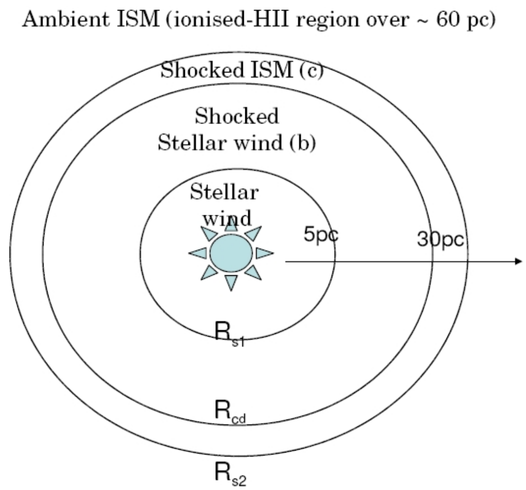


Figure1 O7 star @ 1 Myr

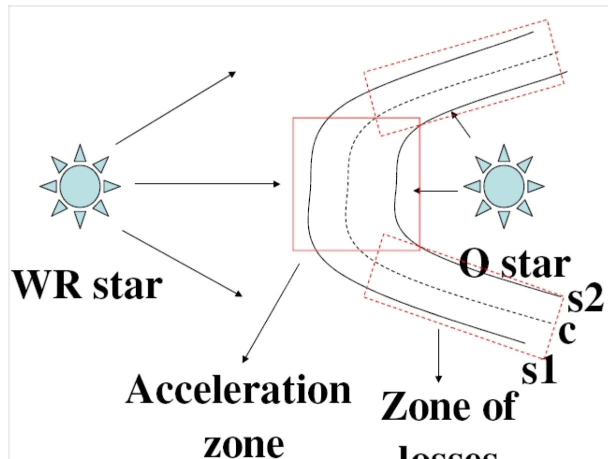


Figure 2: wind-wind collision

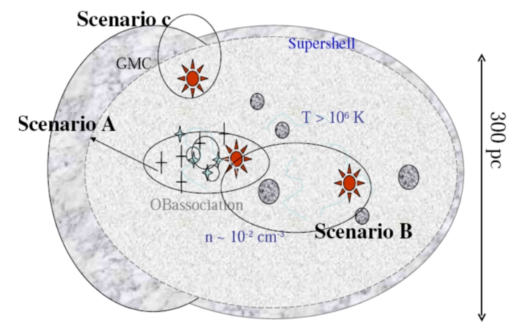


Figure 3: Collective star winds/ shell scenario

Images from Marcowith et al. 2007

Kinetic luminosities $L_w = \frac{1}{2}\dot{M}v_\infty^2$ of massive (O,B,Wolf-Rayet) stars $\rightarrow$ potential multi-TeV CR accelerators. Eg. B-star with typical mass loss rate $\dot{M} \sim 10^{-7}M_\odot$ yr^{-1} and terminal wind velocities $v_\infty \sim 1000$km s^{-1} yields $L_w \sim 10^{36}$ erg s^{-1}.

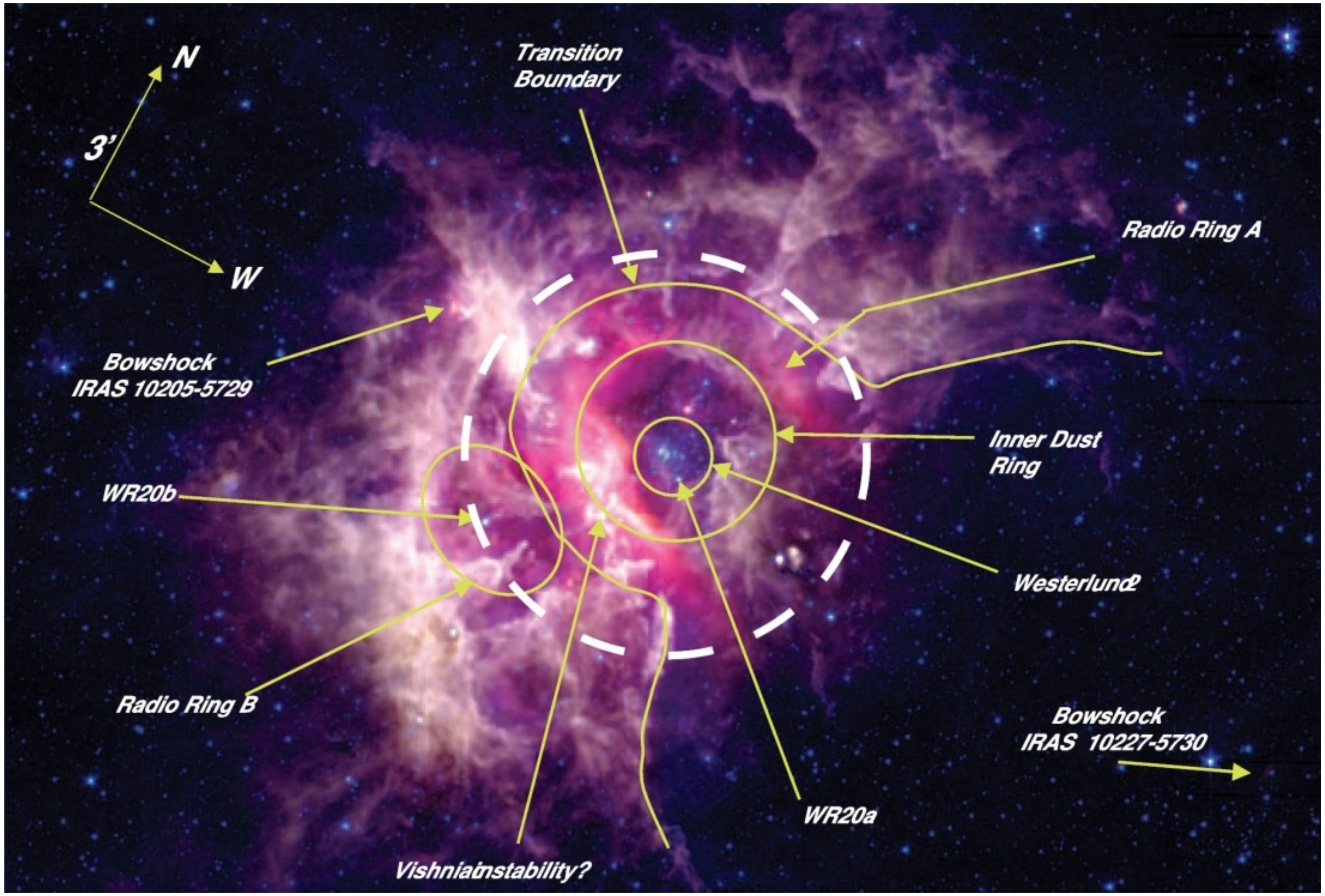
Several scenarios for particle acceleration may be possible:

1. Termination shocks in single stars

2. Colliding winds from binary stars

3. Collective effects from a cluster of massive stars. Only in recent years have they attracted serious attention. But early theory (Montmerle 1979; Cassé & Paul 1980; Völk & Forman 1982).

Massive Cluster — Westerlund-2

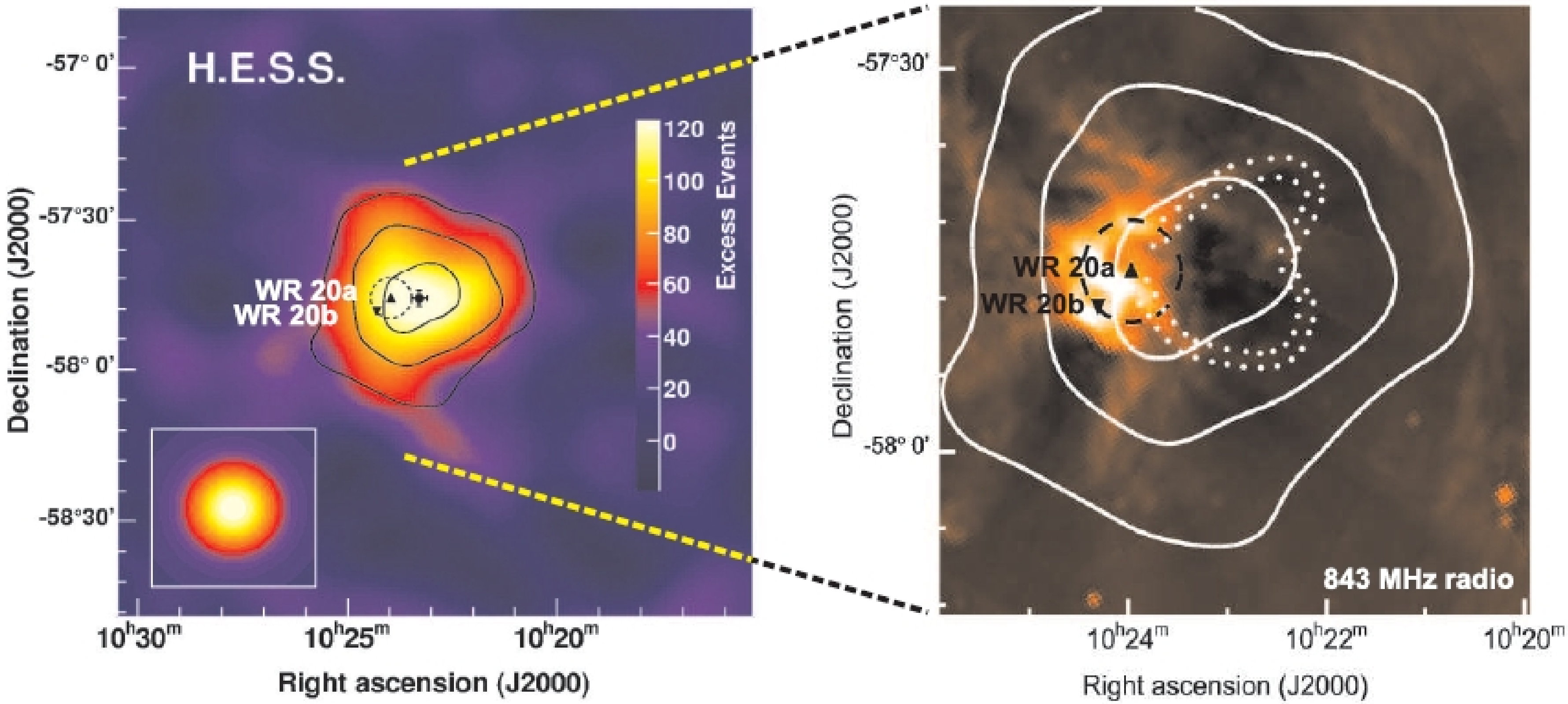


Optical/IR Image Churchwell 2004

Westerlund-2: Young (< 4Myr) massive stellar cluster: 2 Wolf-Rayet members (WR 20a, WR20b)

Associated with HII complex RCW 49.

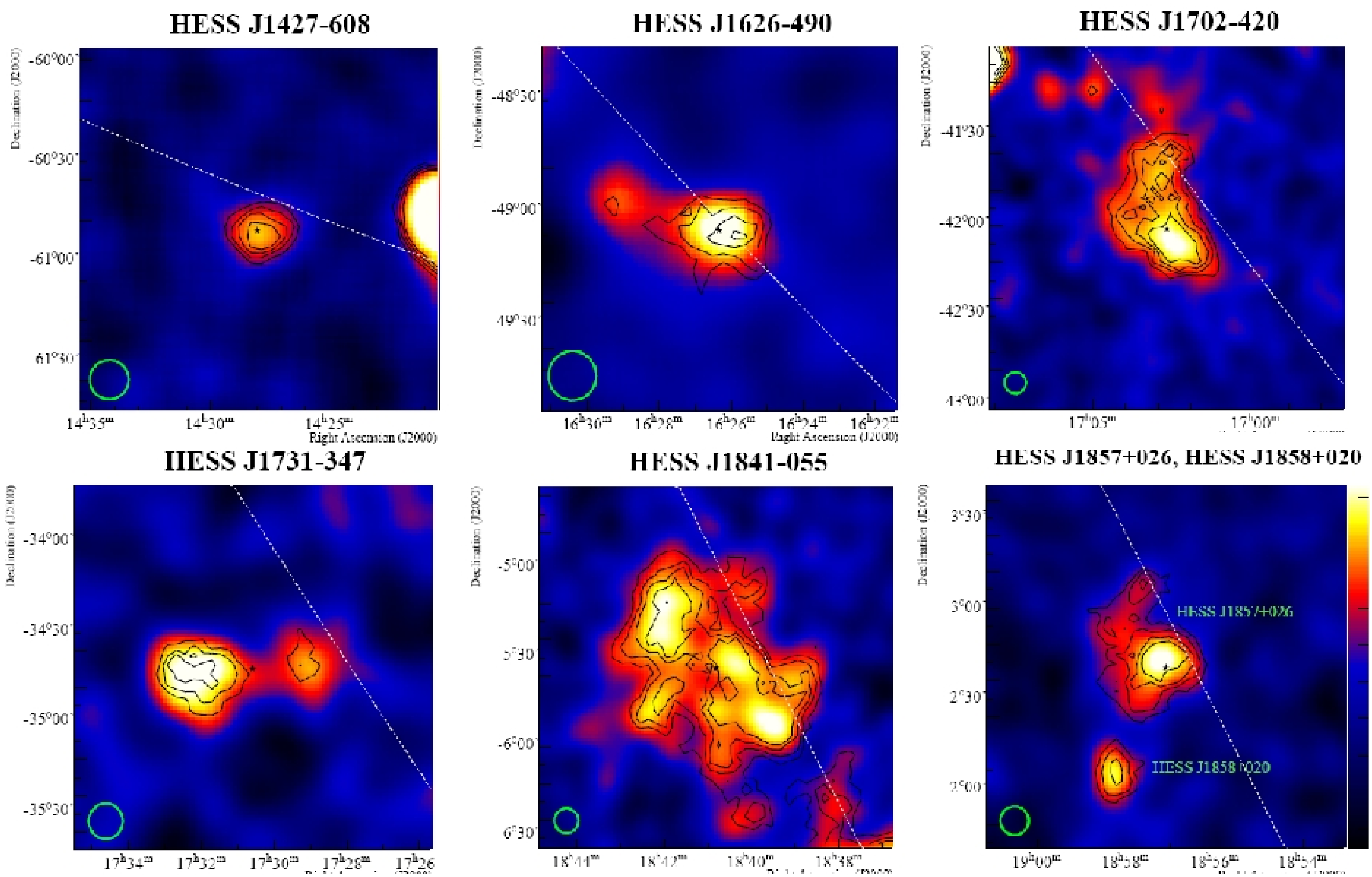
HESS J1023−575 (Westerlund-2)



(left) H.E.S.S. TeV Image Aharonian et al. 2007; (Right) Molongolo Radio Churchwell 2004

TeV Source (slightly extended) detected towards centre of Westerlund-2. Not possible to discern origin as from single star(s), or collective effects.

10 Unidentified TeV Sources

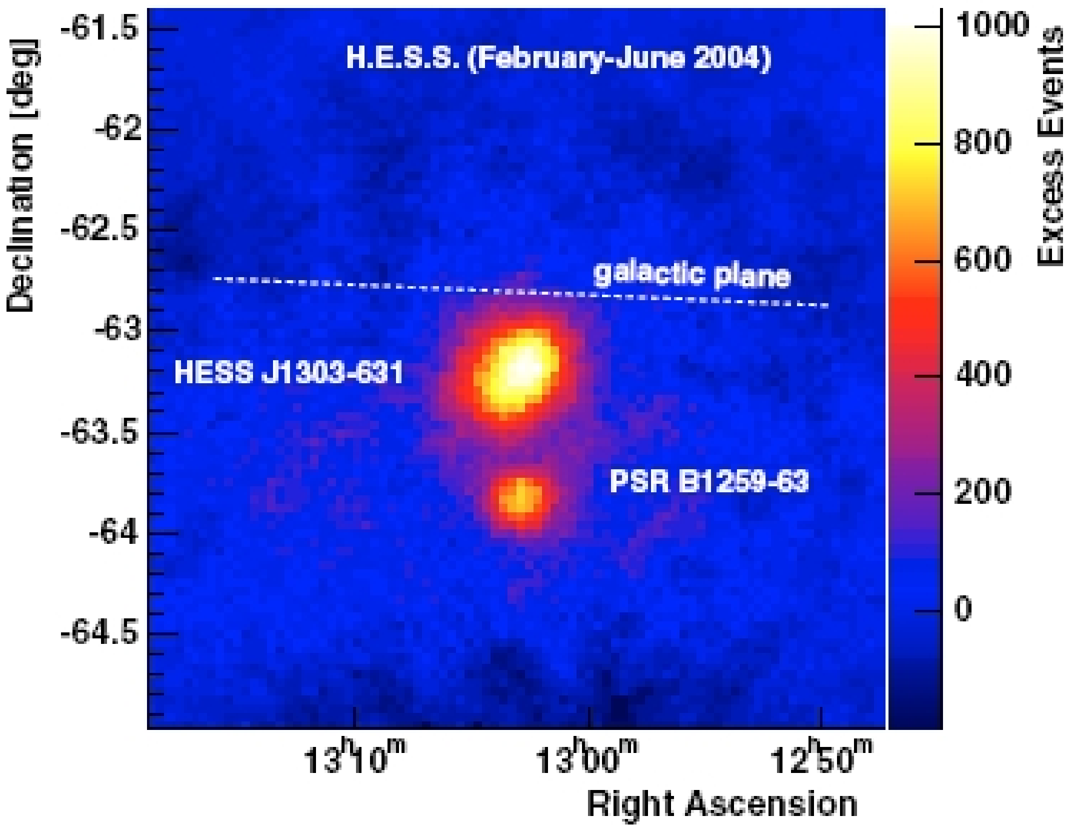


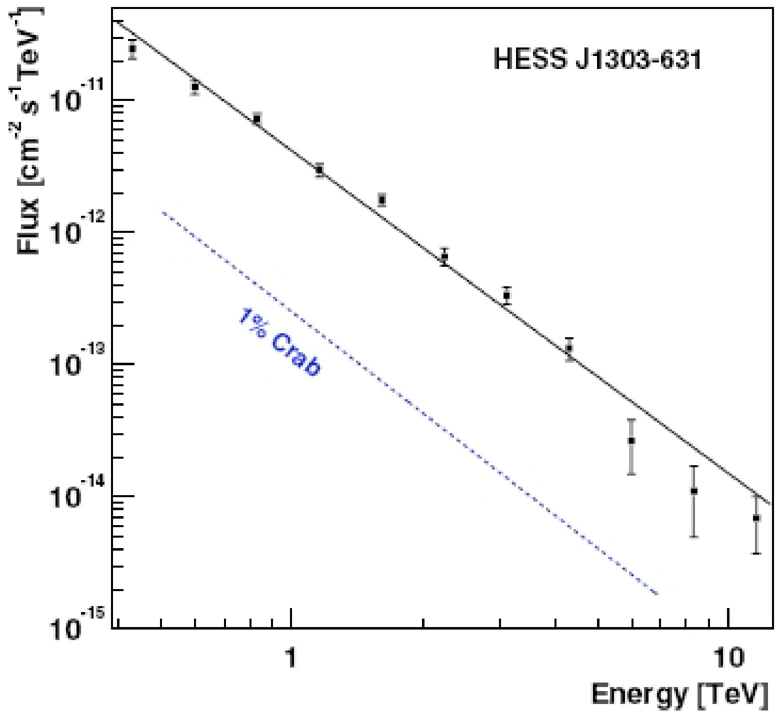
Several unidentified TeV sources from H.E.S.S. surveys (2007)

One of the largest groups of TeV sources now. Encourages multiwavelength followup.

HESS J1303−631

Aharonian et al. 2005 A&A 439, 1023





HESS J1303−631 discovered 0.5° N of PSR B1259−63.

Extended source (0.16°) with spectral index $\Gamma = 2.44$

HESS J1303−631 – Associated with Cen OB1?

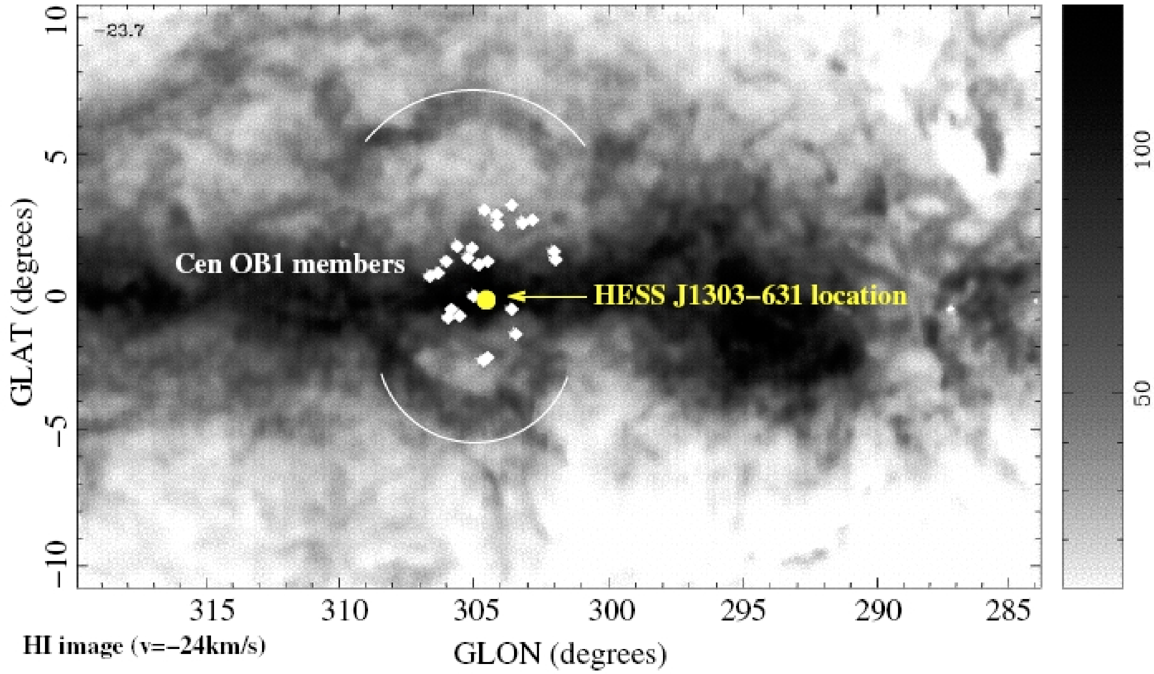


Fig. 7. H I image (∼35° × 20°) at $v = -24$ km s^{-1} of the shell GSH 305+01−24 (McClure-Griffiths et al. 2001). The member stars of Cen OB1, location of HESS J1303-631 and approximate outer boundaries of GSH 305+01−24 are indicated.

Cen OB1 ($d \sim 2.5$ kpc.) but TeV d unknown.

<u>Cen OB1:</u> $\sim$ 20 O,B stars + WR star.

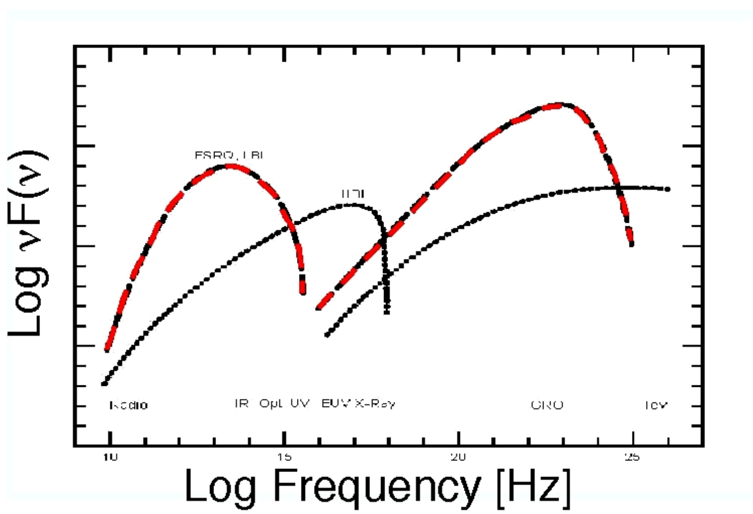
Total KE lum. $> 10^{37}$ erg s^{-1}; Energy source for HI supershell GSH 05.1+01-24 (compare $L_\gamma \sim 10^{34}$ erg s^{-1} at 2.5 kpc) (McClure-Griffiths et al.)

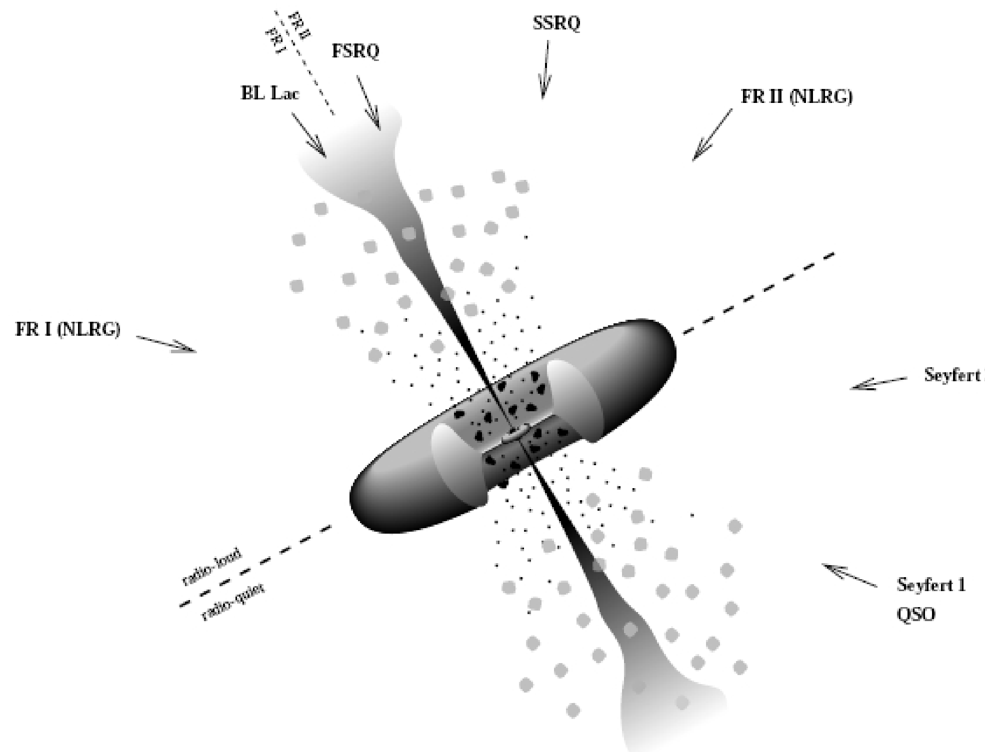
Origin of TeV emission?:

- Coalsack ($d \sim 175$ pc; no star formation)
- Pulsars (none with sufficient $\dot{E}$)
- SNR (no evidence)...BUT Atoyan et al. 2005 suggested a GRB-remnant.
- Stellar-wind interactions in Cen OB1:
- CO survey (Bronfman et al. 1989) no clear overlap

11 Active Galactic Nuclei (AGN)

- The jet is pointing towards us!
- Doppler boosting radiation
  $E_{obs} \sim \delta E_{intrinsic}$
- Fast variability (minute timescales)
- Constraints on interstellar photon fields
- TeV gamma-rays from inverse-Compton (SSC & external-Compton)
- Optical to X-rays from synchrotron





TeV AGN List: early 2007

Name	Type	Redshift	Signif.	Discovered
			***: >10	
M 87	FR I	0.004	***	HEGRA
Mrk 421	BL Lac	0.031	***	Whipple
Mrk 501	BL Lac	0.034	***	Whipple
1ES 2344+514	BL Lac	0.044	***	Whipple
Mrk 180	BL Lac	0.046	5.5	MAGIC
1ES 1959+650	BL Lac	0.047	***	TA
BL Lac	BL Lac	0.069	5.1	MAGIC
PKS 0548-322	BL Lac	0.069	5.8	HESS
PKS 2005-489	BL Lac	0.071	***	HESS
PKS 2155-304	BL Lac	0.116	***	Durham
H 1426+428	BL Lac	0.129	7.5 / 5	Whipple
1ES 0229+200	BL Lac	0.14	6.6	HESS
H 2356-309	BL Lac	0.165	***	HESS
1ES 1218+304	BL Lac	0.182	9 / 6.4	MAGIC
1ES 1101-232	BL Lac	0.186	***	HESS
1ES 0347-121	BL Lac	0.188	***	HESS
1ES 1011+496	BL Lac	0.212	***	MAGIC
PG 1553+113	BL Lac	?	***	HESS/MAGIC
3C 279	FSRQ	0.536	~8 (trials?)	MAGIC

From 2008:

S5 0716+714 $z=0.310$ +7sig BL-Lac (LBL) MAGIC

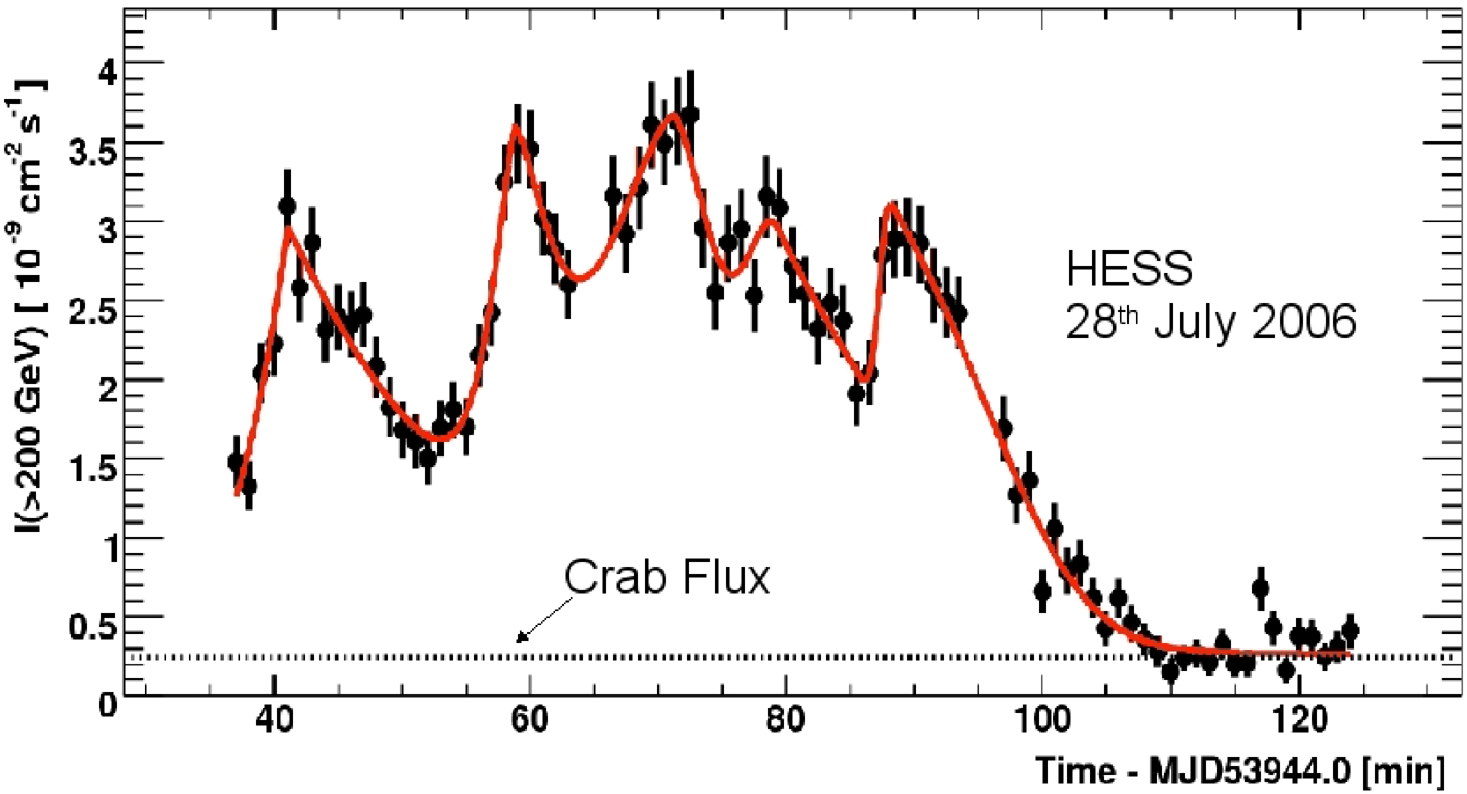
W Comae $z=0.102$ +6sig BL-Lac (IBL) VERITAS

1ES 0806+524 $z=0.138$ +6sig BL-Lac (HBL) VERITAS

RGB J0152+017 $z=0.080$ +7sig BL-Lac (HBL) HESS

PKS 2155−304 (z=0.116) Huge Flare

Aharonian et al. 2007 664, L71



July 28, 2006 Flare   Peak flux 15× Crab $L_\gamma \sim 10^{12}\times$ Crab   Min. timescale $\Delta t \sim 173$ s

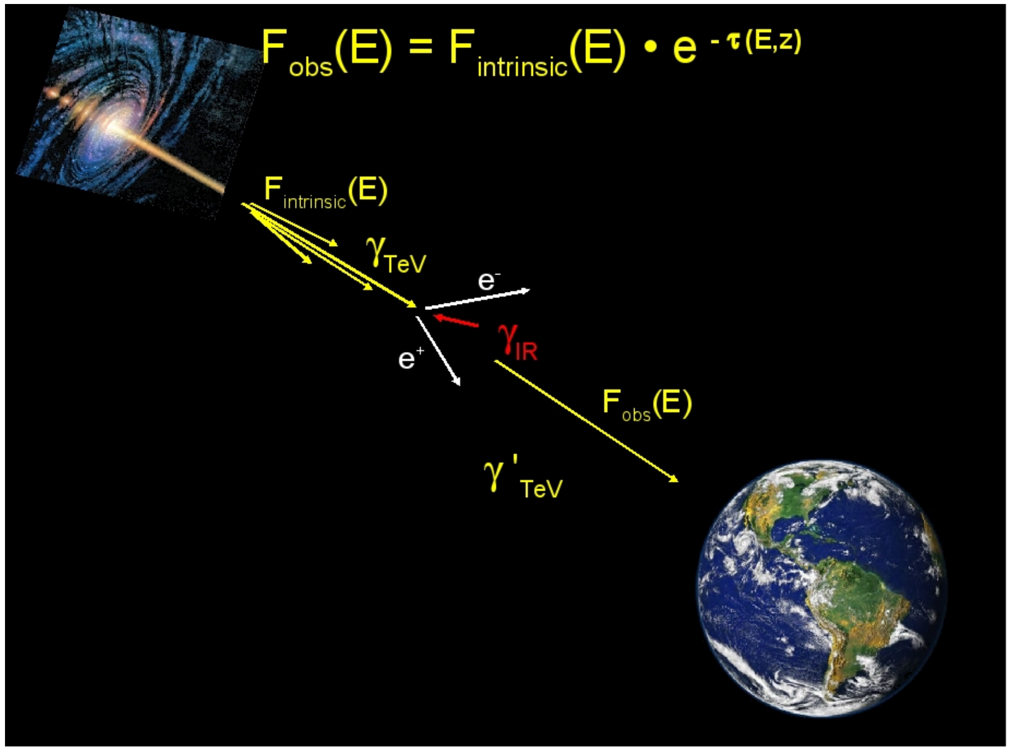
Causality arguments constrain source size $R_{src} < c\,\Delta t\,\delta/(1+z)$

Jet Doppler factor: $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$ for θ viewing angle to the jet and $\beta = v/c$. If BH is responsible then $R_{src} > R_s$ (Schwarzschild radius $= 2GM/c^2$): Solve for δ, where $M \sim 10^9 M_\odot$

Doppler factor $\delta > 60$ to 100! Similar to GRBs!

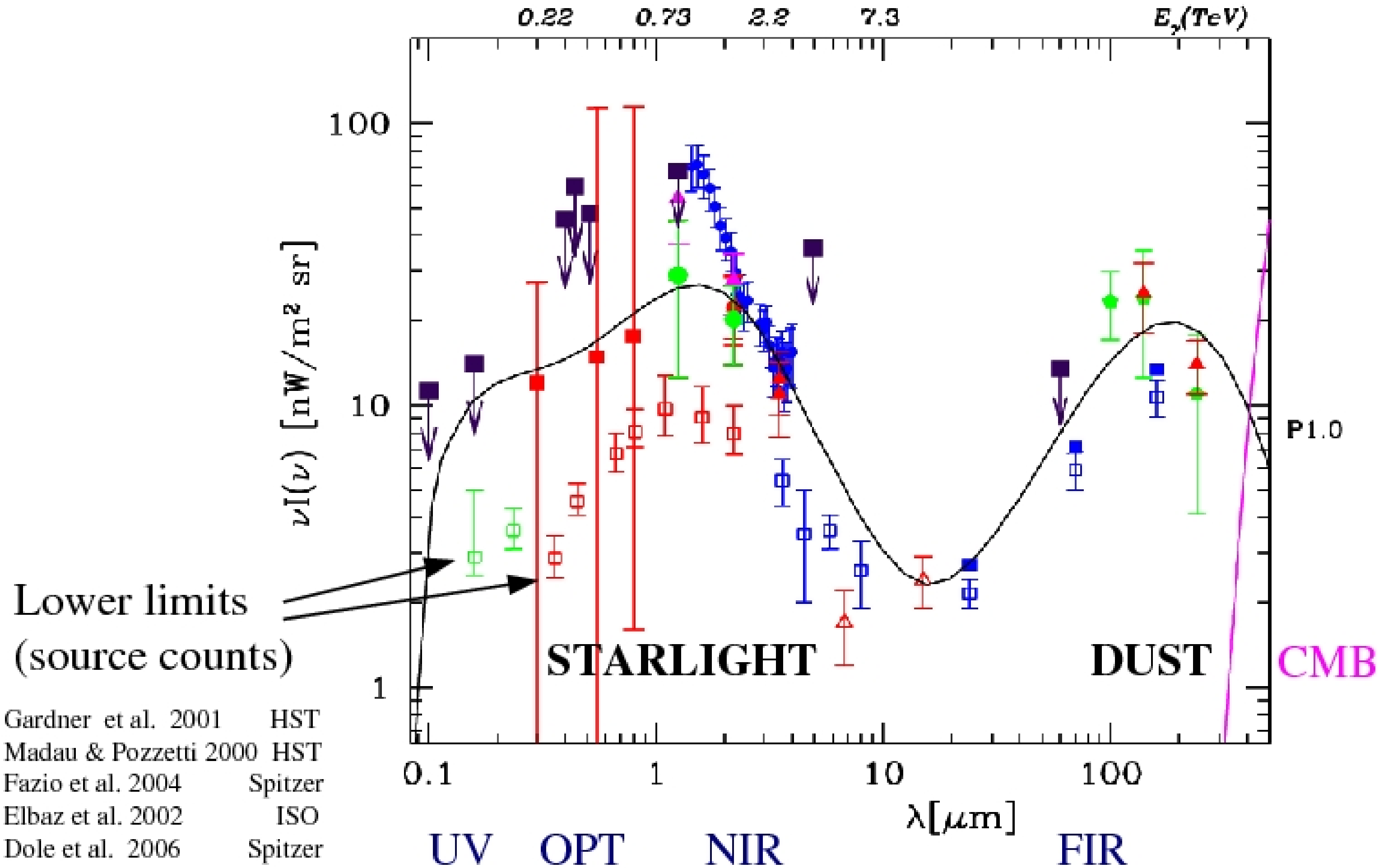
TeV Gamma-Rays & Extragalactic Background Light (EBL)

0.1 to 10 TeV Gamma-Rays interact with 0.1 to 10μm (IR and optical) radiation (EBL) via pair production ($\gamma + \gamma \rightarrow e^{\pm}$). This will redistribute gamma-ray energies to lower values.



TeV AGN spectra can be used to indirectly probe/measure the EBL.

Extragalactic Background Light: the SED



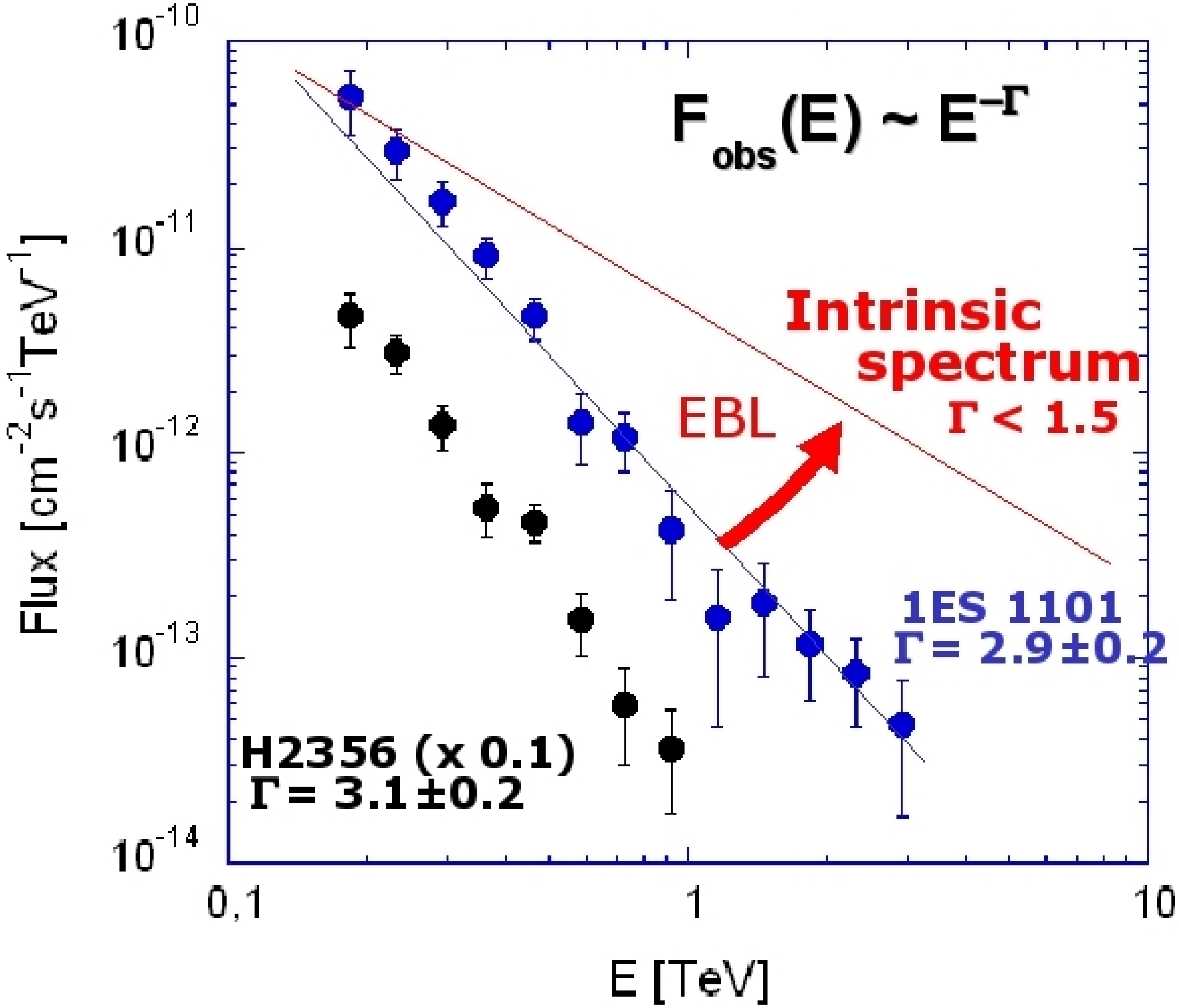
EBL measurements: Compiled by L. Costamante

Upper scale: TeV photon energies for peak pair prod. cross-section

EBL reflects Universe activity: stellar evolution, first stars..but it has been poorly constrained.

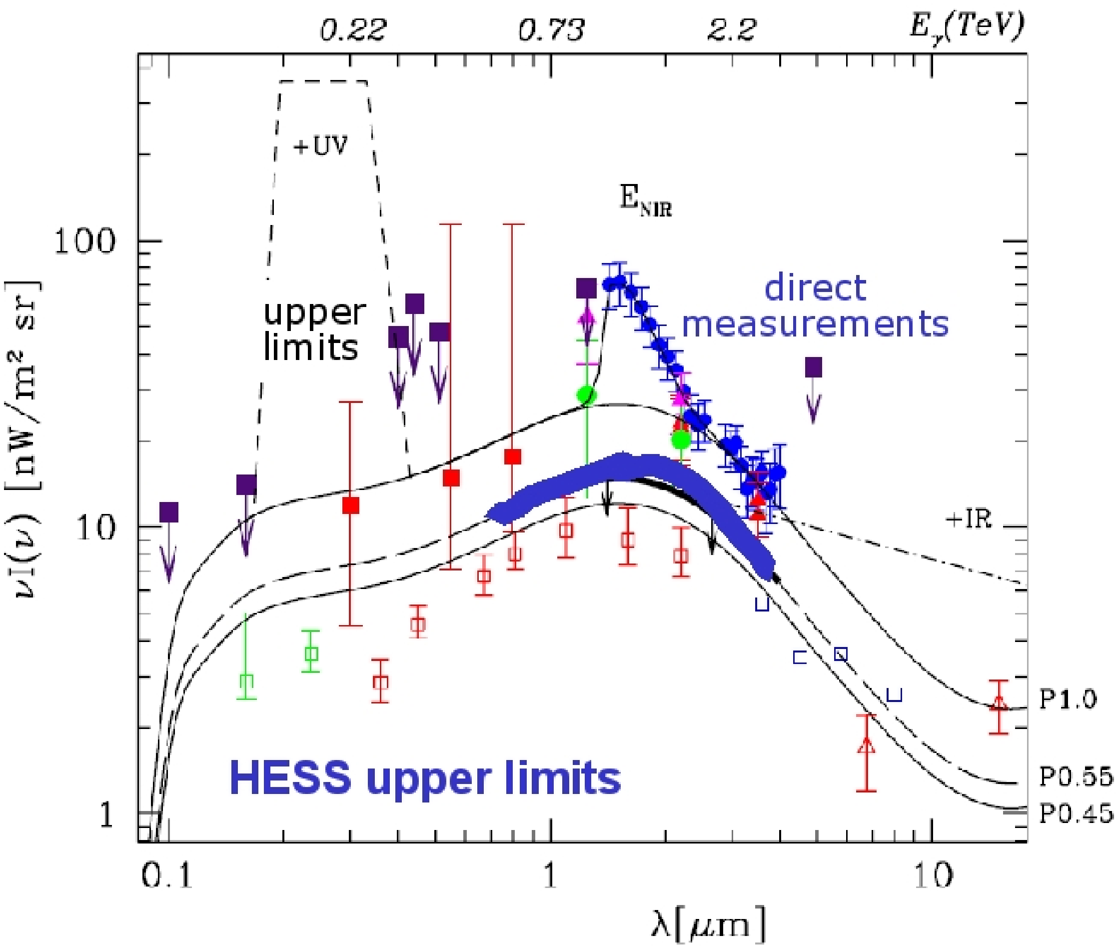
Decoupling the EBL Absorption

We can 'de-absorb' observed spectra to obtain instrinsic spectra $F_{\mathrm{intrinsic}}$. Apply limit on intrinsic spectral index $\Gamma > 1.5$ as implied by shock DSA and inverse-Compton theory (Electrons with $\Gamma = 2$ (DSA) & IC in the Thompson regime): Then, an upper limit on the EBL is obtained:



EBL Upper Limits from H.E.S.S. TeV Observations

e.g. Aharonian et al. 2006



EBL upper limit from HESS obs. of 1ES 1101−232 (z=0.186) & H 2356−309 (z=0.165)

More Recent EBL Constraints

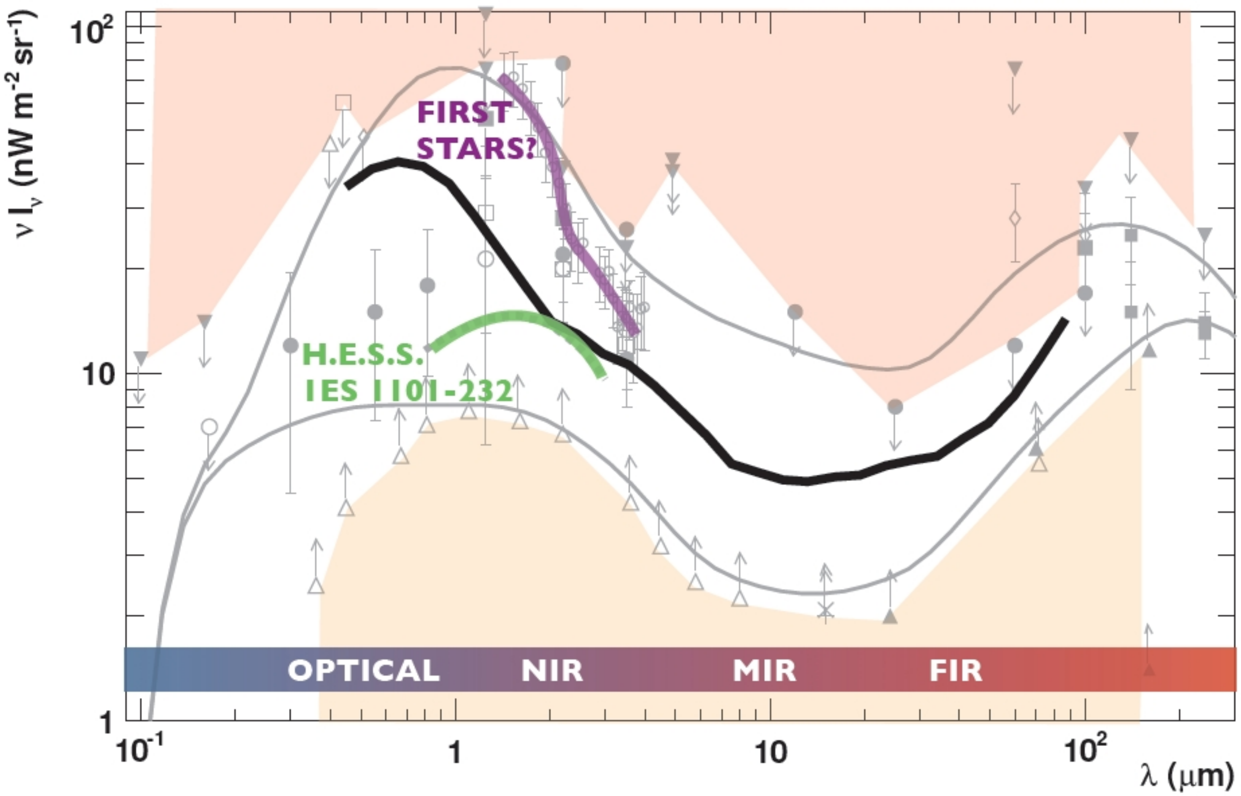
e.g. Raue et al. 2007; Mazin et al. 2007, Pühlhofer et al. 2007

Additional limits from some more distant Blazars:

1ES 0347−121 (z=0.188)

1ES 0229+200 (z=0.14)

Extend EBL constraint to 10μm regime.



Giant Radio Galaxy M 87

Famous nearby radio galaxy

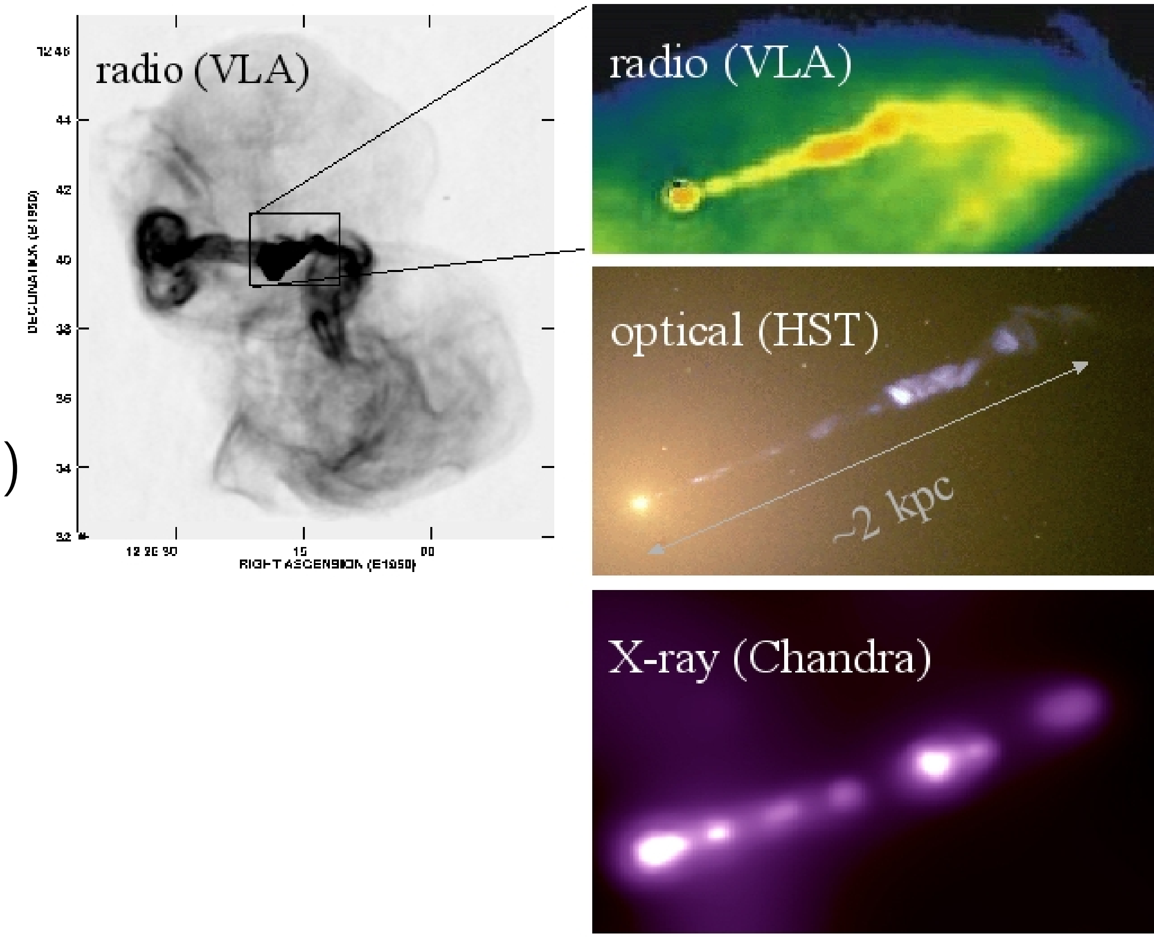
$d \sim 16$ Mpc

Jet angle $\sim 30^\circ$

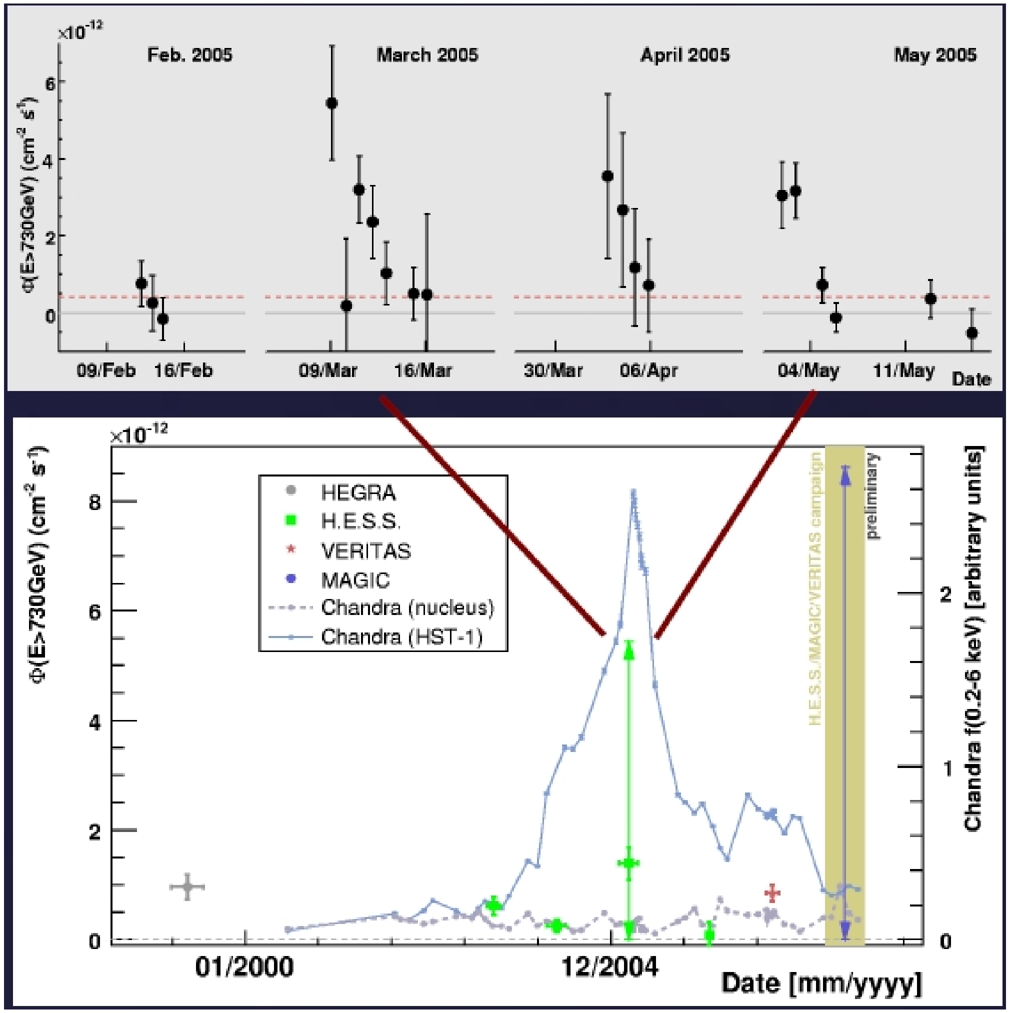
First TeV detection by HEGRA
(Aharonian et al. 2001).
H.E.S.S. observed day-scale variability
(Aharonian et al. 2006 Science 314, 1424)

VERITAS & MAGIC detections
(2007,2008)

Key Questions concern the emission location and its relation to the core and/or jet features.

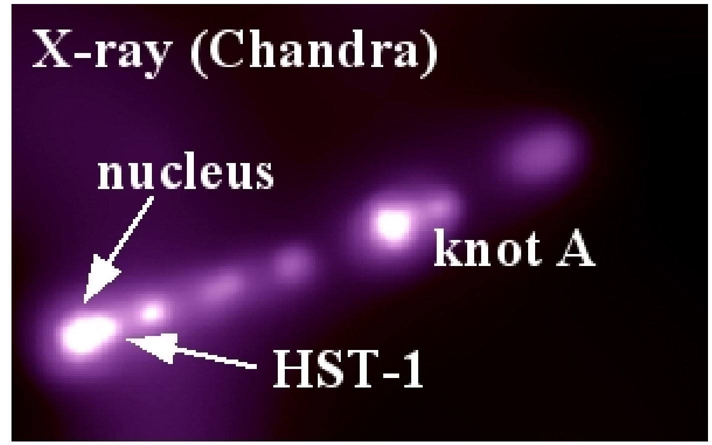


M 87 Variability



Results compilation Beilicke et al. 2008:

HESS/MAGIC/VERITAS campaign



Day-scale variability constrains TeV source size $R_{TeV} < 5\delta R_s$. This rules out knot A and most likely HST1 (HST1 is ~ 65 pc from the core), if the central black hole is the engine.

12 Additional Topics

Galactic:

- MAGIC: Pulsed emission from the Crab (finally!)
- Globular clusters (indirect Dark Matter searches)

ExtraGalactic:

- AGN 'pair-halos' ($\gamma \rightarrow e^{\pm}$): probe B fields
- LMC & SMC surveys (great opportunity to study nearby galaxies)
- Dwarf Galaxies (indirect Dark Matter searches)
- Starburst galaxies (v.active CR acceleration)
- Galaxy Clusters (CR acceleration $>$PeV energies)
- Gamma Ray Bursts (campaigns by all TeV telescopes - no detections)

CR Studies:

- CR electrons (our local $<$ kpc environment)
- CR Composition (CR Fe spectrum)
- Cherenkov radiation from primary particles (Fe possible)

13 Future Directions in TeV Gamma-Ray Astronomy

H.E.S.S. II

30 metre diameter telescope at the centre of H.E.S.S. array is now under construction.

Improved sensitivity at E$\sim$100 GeV (stereo with H.E.S.S.).

Lower threshold to $E \leq$50 GeV (stand-alone)

Astrophysics: A focus is likely on AGN, pulsars, gamma-ray bursts and synergy with GLAST.

MAGIC-II

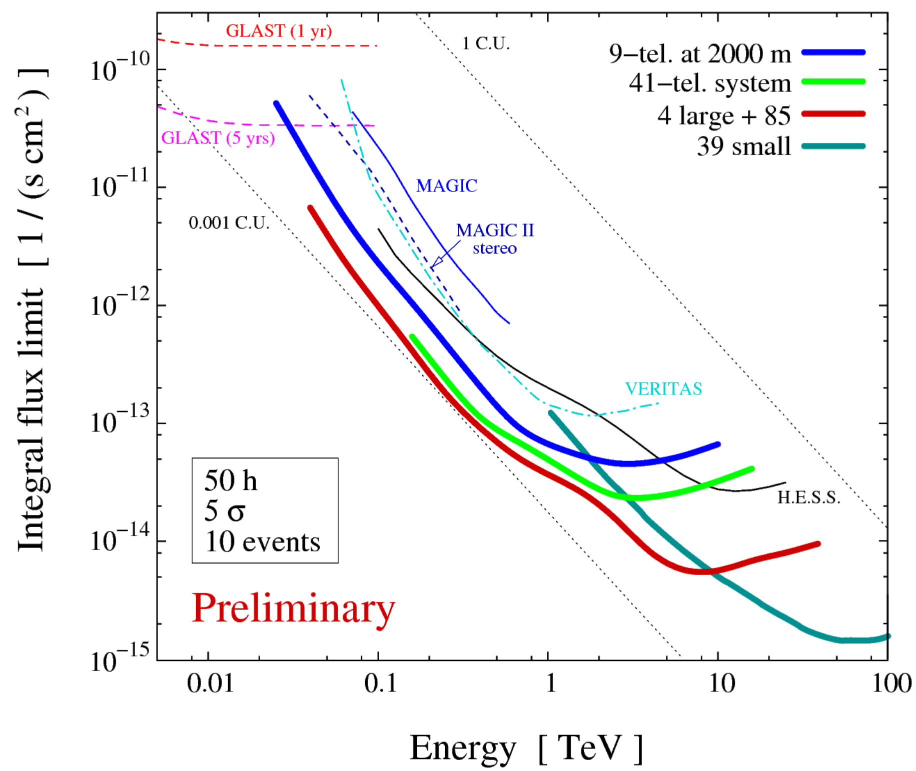
MAGIC-II is a second telescope 80 m from MAGIC-I. I will have some improvements (etc. mirrors, larger FoV camera) but the key benefit will be sterescopy.

MAGIC-II is currently under construction

CTA

Cherenkov Telescope Array

CTA is a large-scale European effort to realise an array of $>$100 telescope of varying sizes.



Bernloher et al. 2008

`http://www.mpi-hd.mpg.de/hfm/CTA/` 10x better sensitivity ∼10 GeV - ∼100 TeV.

AGIS — USA White Paper

USA-based initiative to map out the future direction of the field.

This has led to the AGIS collaboration:

Advanced **G**amma **R**ay **I**maging **S**ystem

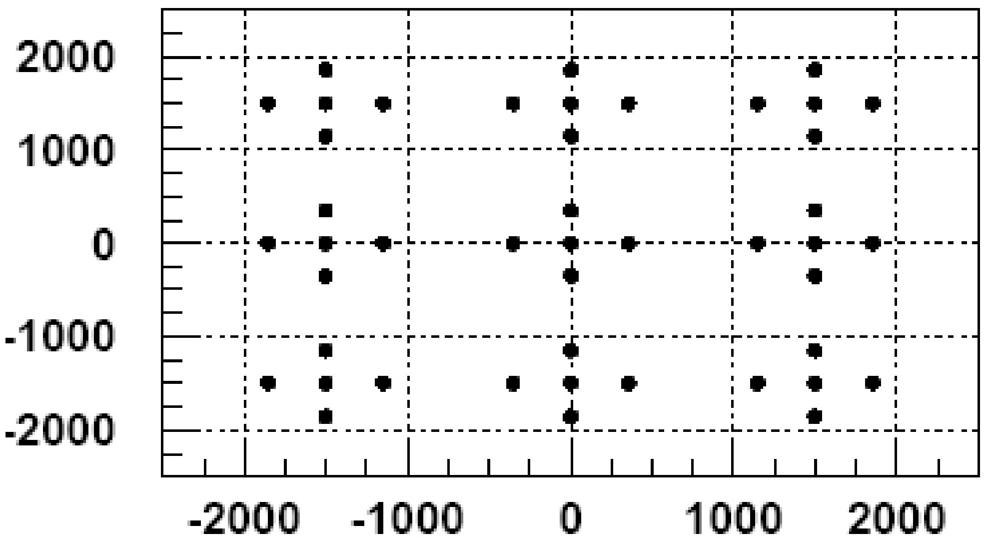
http://gamma1.astro.ucla.edu/agis/index.php/Main_Page

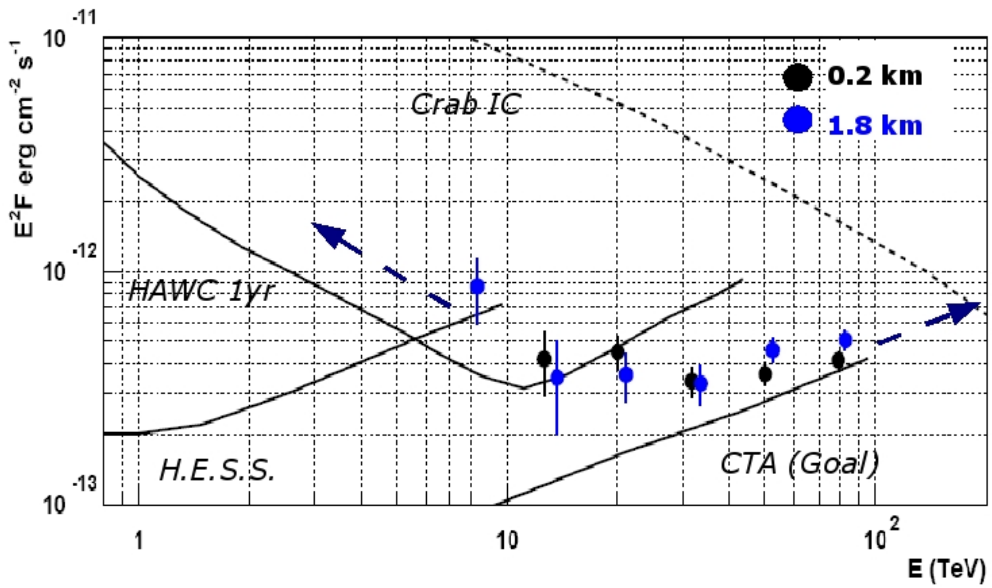
Several new technologies are being investigated, especially ultra-wide field optics (Vassiliev et al. 2006, 2008) for excellent sky survey coverage.

TenTen - High Collection Area for E >10 TeV

Rowell et al. 2007, 2008

High collection area & sensitivity in the 10 to >100 TeV regime. Need 10 km^2 collection areas. TenTen = 10 km^2 above 10 TeV. For E >10 TeV, *much easier to separate hadronic & leptonic processes.*





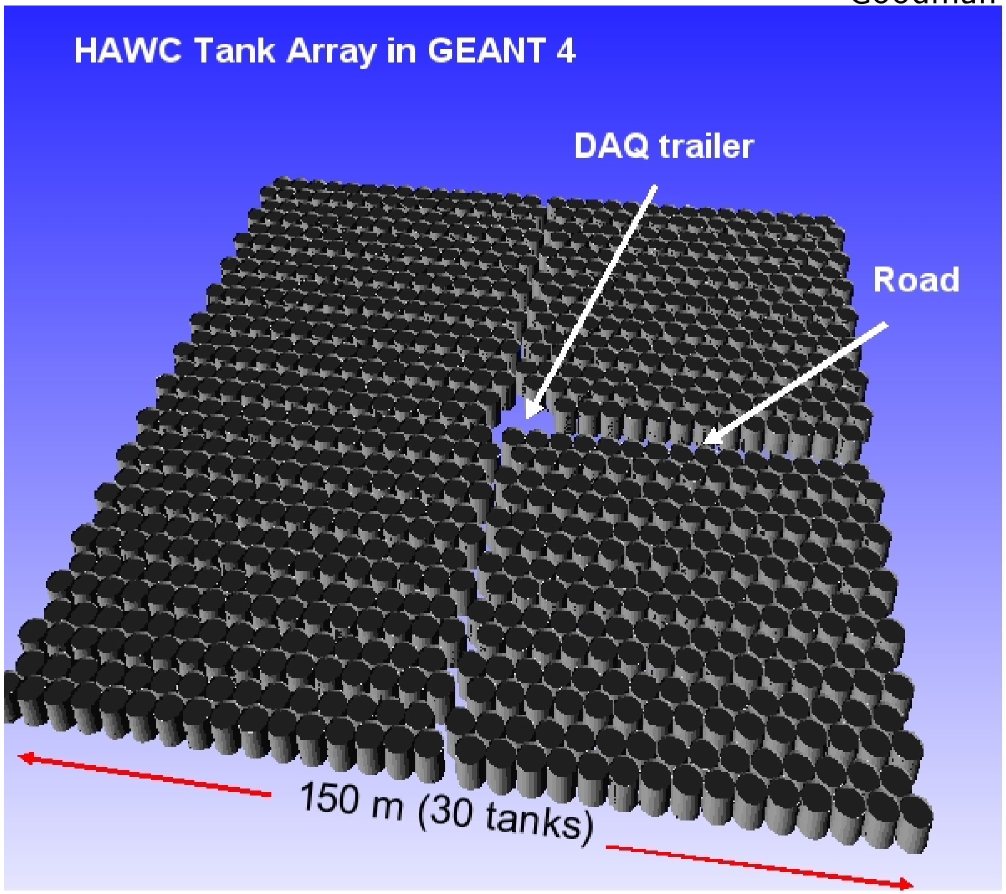
Example layout of 45 telescopes (scale in metres): Prelim sensitivity vs. site altitude for a **point** source

TenTen design (prelim.):

Array of <50 telescopes; Mirror area/size 10-30 m^2; Field of view (8-10deg); Telescope spacing L>200 m Sea-level Australian sites attractive due to better collection area & sensitivity vs. > 1800m sites, especially for extended sources.

HAWC - Water Cherenkov Array at High Altitude

Goodman et al. 2008



Array (900) of water Cherenkov tanks at Sierra Negra 4100 m. >10x more sensitive than MILGARO

14 Summary

TeV gamma-ray astronomy is a vibrant new field. Results from the past few years have dramatically expanded the TeV universe as flux sensitivities have reached $\sim 10^{-13}$ erg cm^{-2} s^{-1}, not far from current X-ray detectors.

A range of Galactic sources are now detected at TeV energies, most of them related to various stages of stellar evolution. Indeed until recently, Galactic TeV sources were mostly linked to aspects of stellar death (SNRs, pulsars..). Recent TeV detections of stellar clusters/massive stars and possibly HII regions, may bring the focus to earlier epochs of stellar evolution. Thus, a wider range of astrophysical topics beckons.

On the extragalactic front, the jet-powered blazars (with jets aimed at us) are the dominant TeV source. Rapid flaring and the constraints on the extrgalactic background light are major topics. Both of these observational tasks require multiwavelength programmes.

The next step in TeV detectors will be large-scale multi telescope arrays aiming to be 10 times more sensitive than current instruments. Several options are under discussion of varying degrees of complexity and scale that would see construction in the next 10 years. Extensions to H.E.S.S., MAGIC, and MILAGRO are underway and promise many new results.

15 Further Reading & Some References

Cosmic-Rays & CR Acceleration

Can diffusive shock acceleration in supernova remnants account for high energy Galactic cosmic-rays? A.M Hillas (2005) Journal of Physics G: Nuclear and Particle Physics 31, p95

Cosmic-Rays and Particle Physics T.K. Gaisser (Cambridge University Press 1990)

Lecture Notes on High Energy Cosmic Rays M. Kachelriess (2008) ariXiv:0801.4376

Gamma-Ray Production/Absorption Processes

`http://www.mpe.mpg.de/r̃od/gamma-ray_processes.ps`

TeV Gamma-Ray Results & Instruments

Gamma Ray Astronomy J. Hinton (2007) Rapporteur at the 20th International Cosmic-Ray Conference, ariXiv:0712.3352

Gamma-Ray, Neutrino & Gravitational Wave Detection G. Rowell (2007) Rapporteur at the 20th International Cosmic-Ray Conference, ariXiv:0801.3886

Telescope websites for publication lists & latest results

`http://www.mpi-hd.mpg.de/hfm/HESS/HESS.htm` (H.E.S.S.)

`http://www.mpi-hd.mpg.de/hfm/HESS/public/HESS_catalog.htm` (H.E.S.S. source catalogue **with links to references**)

`http://tevcat.uchicago.edu/` (TeVCat – a TeV/TeV catalogue)

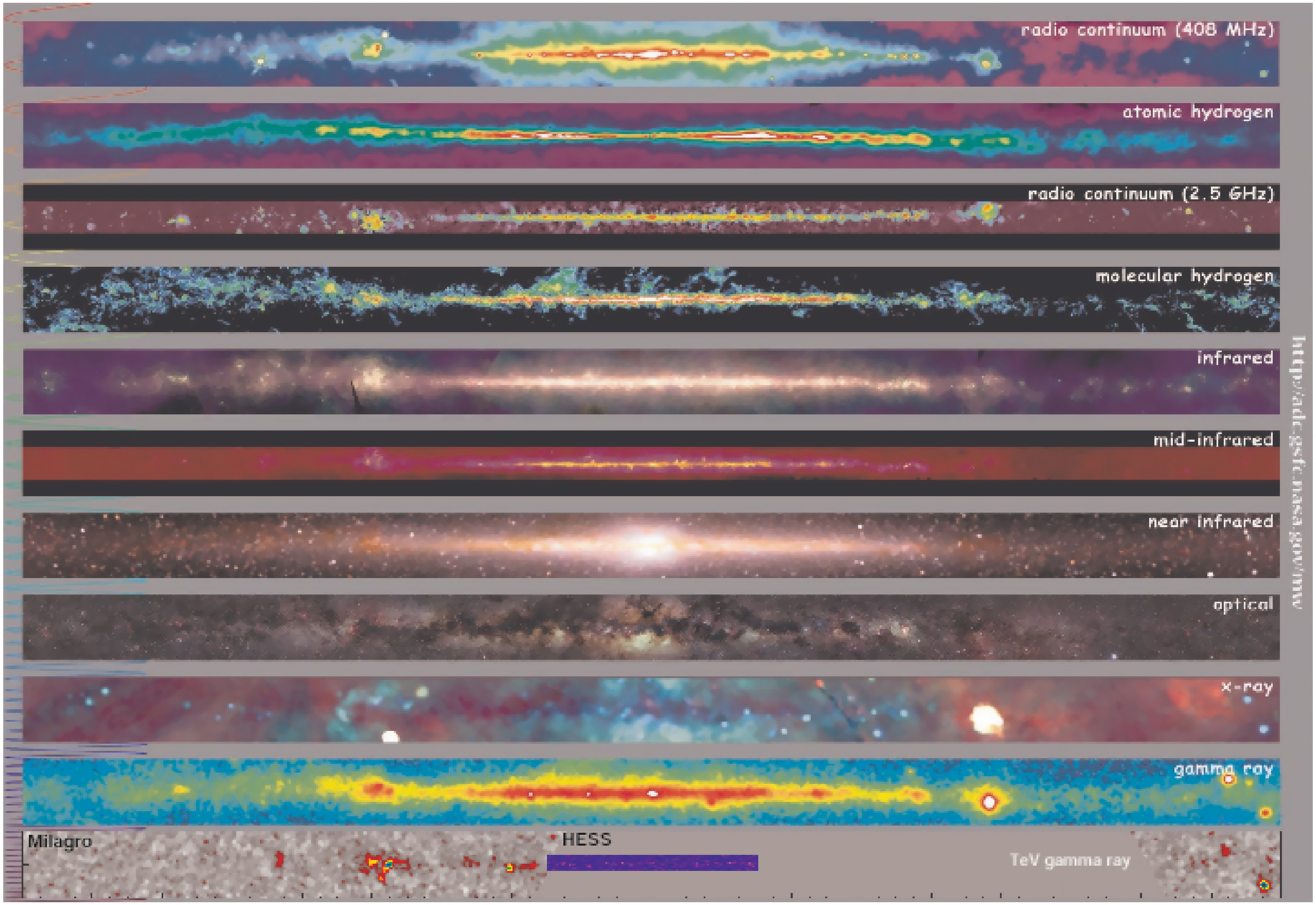
`http://veritas.sao.arizona.edu/` (VERITAS)

`http://wwwmagic.mppmu.mpg.de/` (MAGIC)

`http://umdgrb.umd.edu/cosmic/milagro.html` (MILAGRO)

Most recent conference Heidelberg Gamma-Ray Symposium 2008

`http://www.mpi-hd.mpg.de/hd2008/pages/news.php`



VHE γ-rays: A New Window on the Sky

Thankyou to Jose and the organisers for the invitation....