TeV Gamma-Ray Astrophysics

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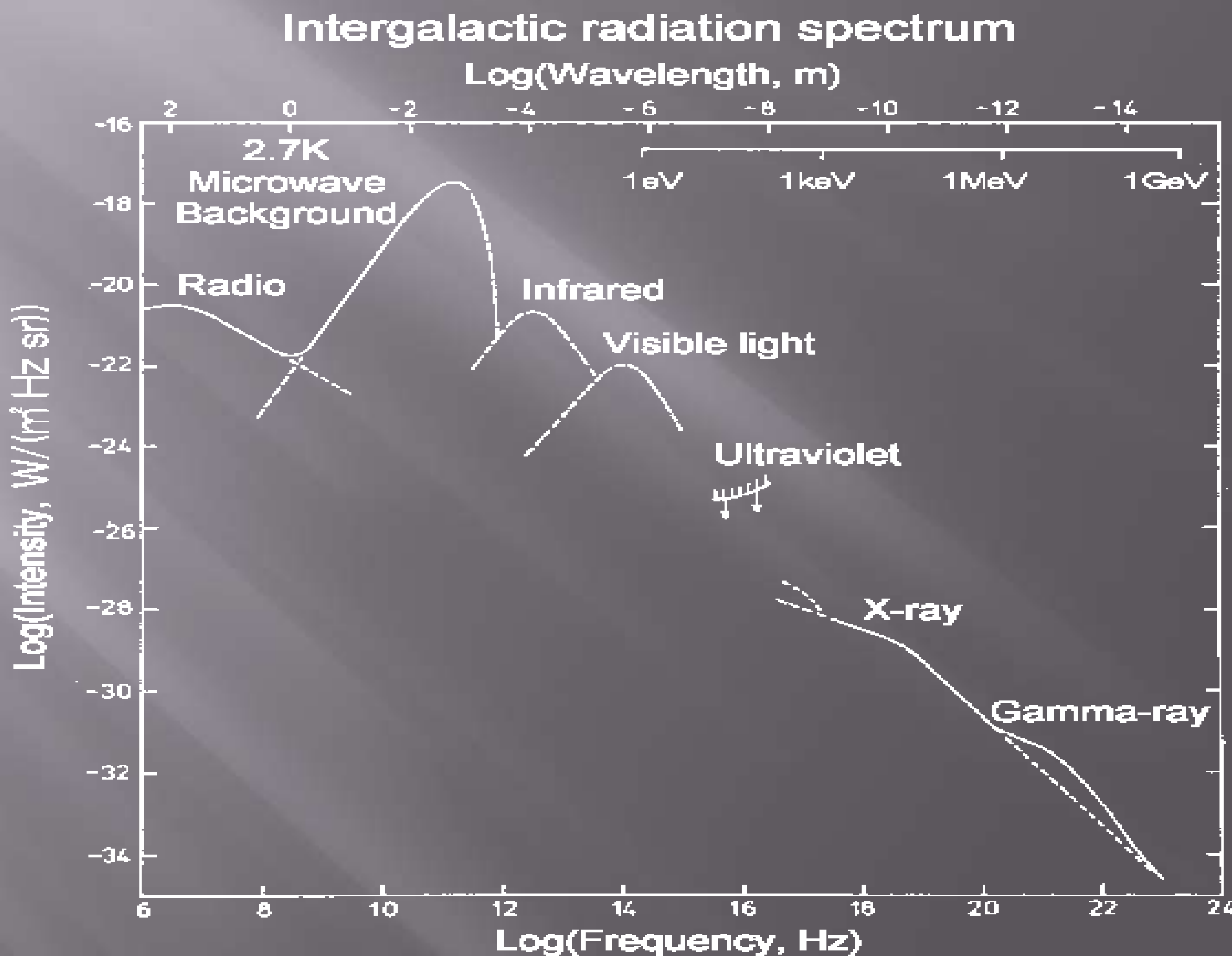
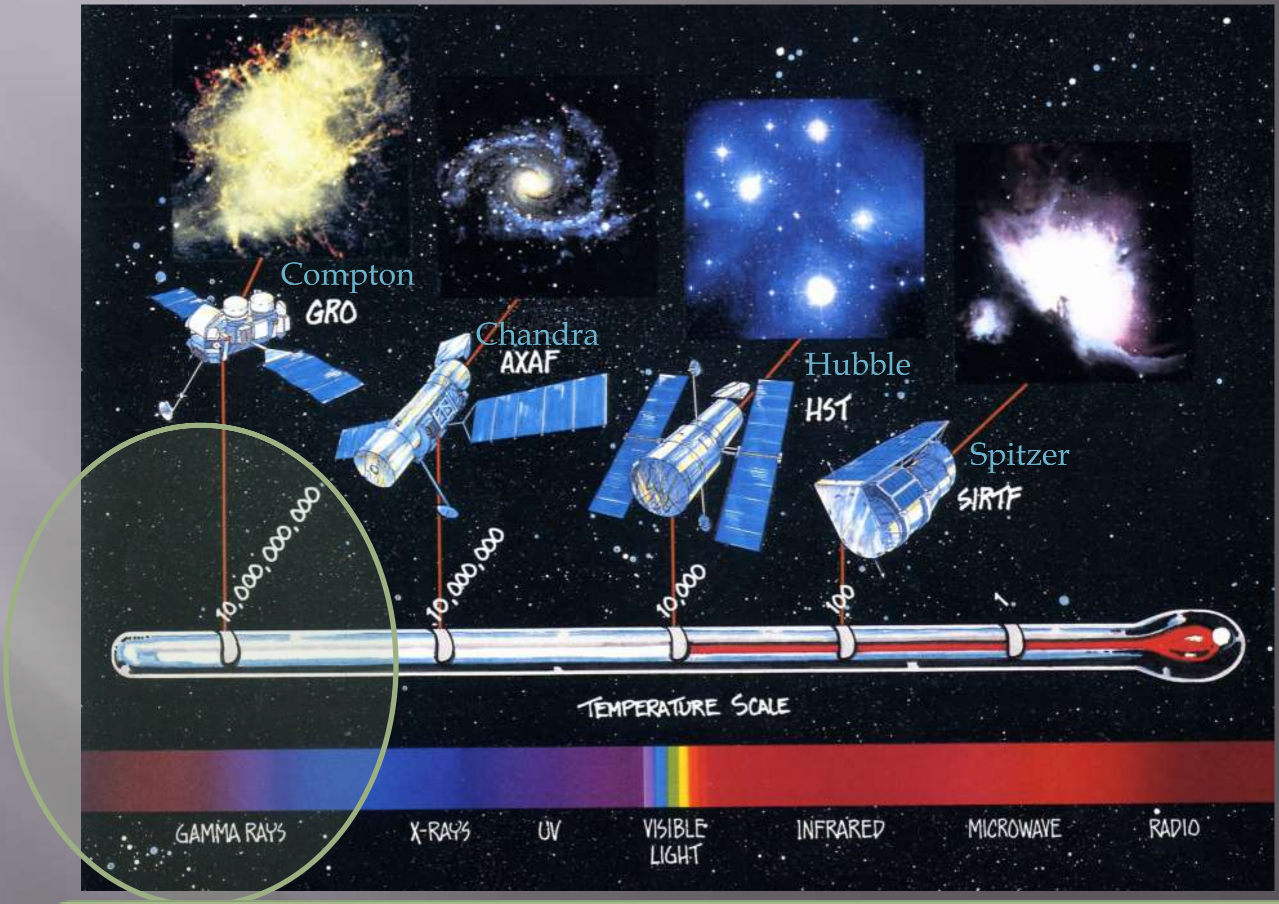
Nagoya GCOE Winter School, Hotel Kintetsu Aquavilla Ise-Shima, February 21, 2009

Interstellar radiation spectrum



Gamma-ray astrophysics



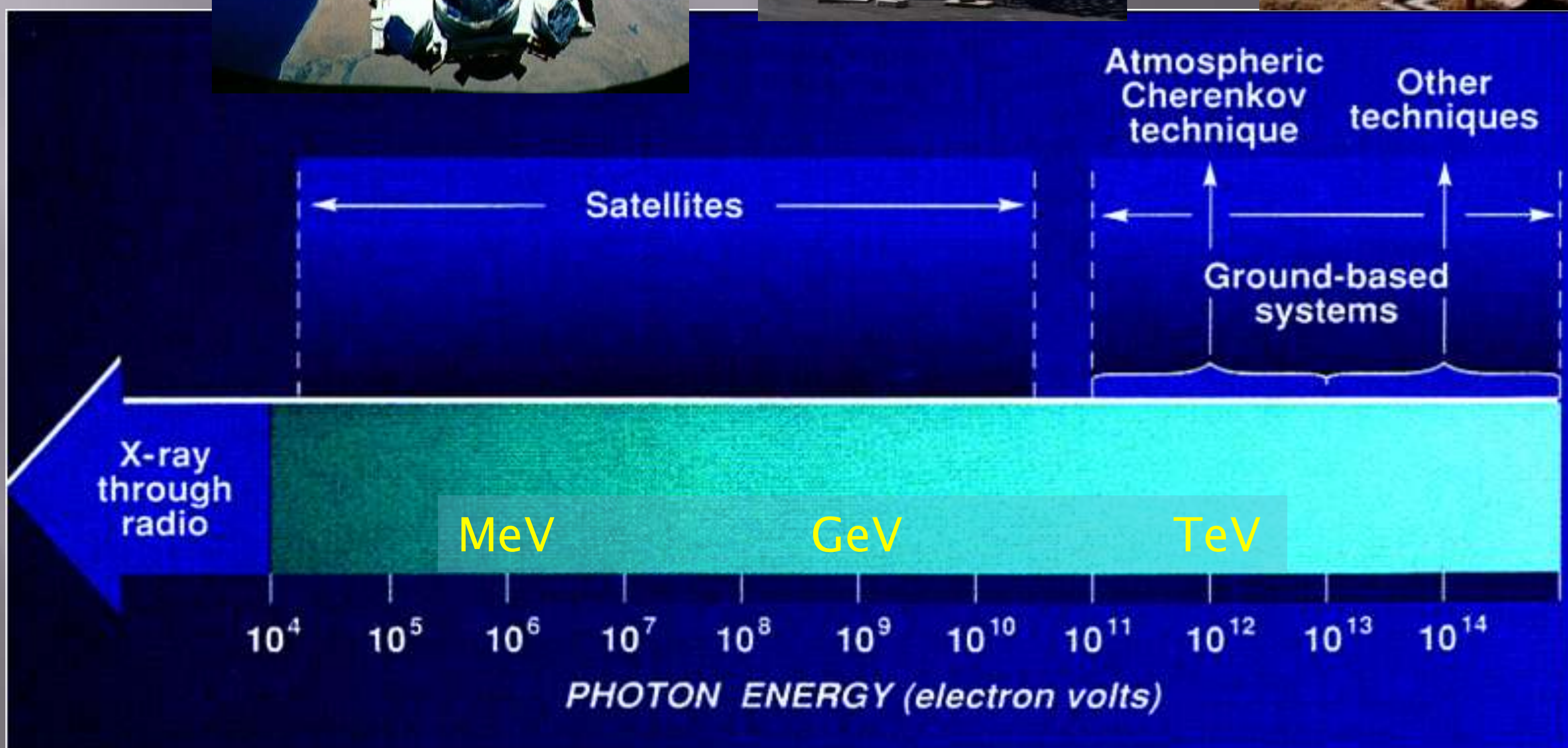
High-energy gamma-rays are emitted by <u>non-thermal</u> processes where one cannot define temperature
↓↑
Elementary process of particle interaction

Gamma-ray spectrum

Compton Gamma-ray Observatory

Whipple Cherenkov Telescope

Tibet ASγ Array

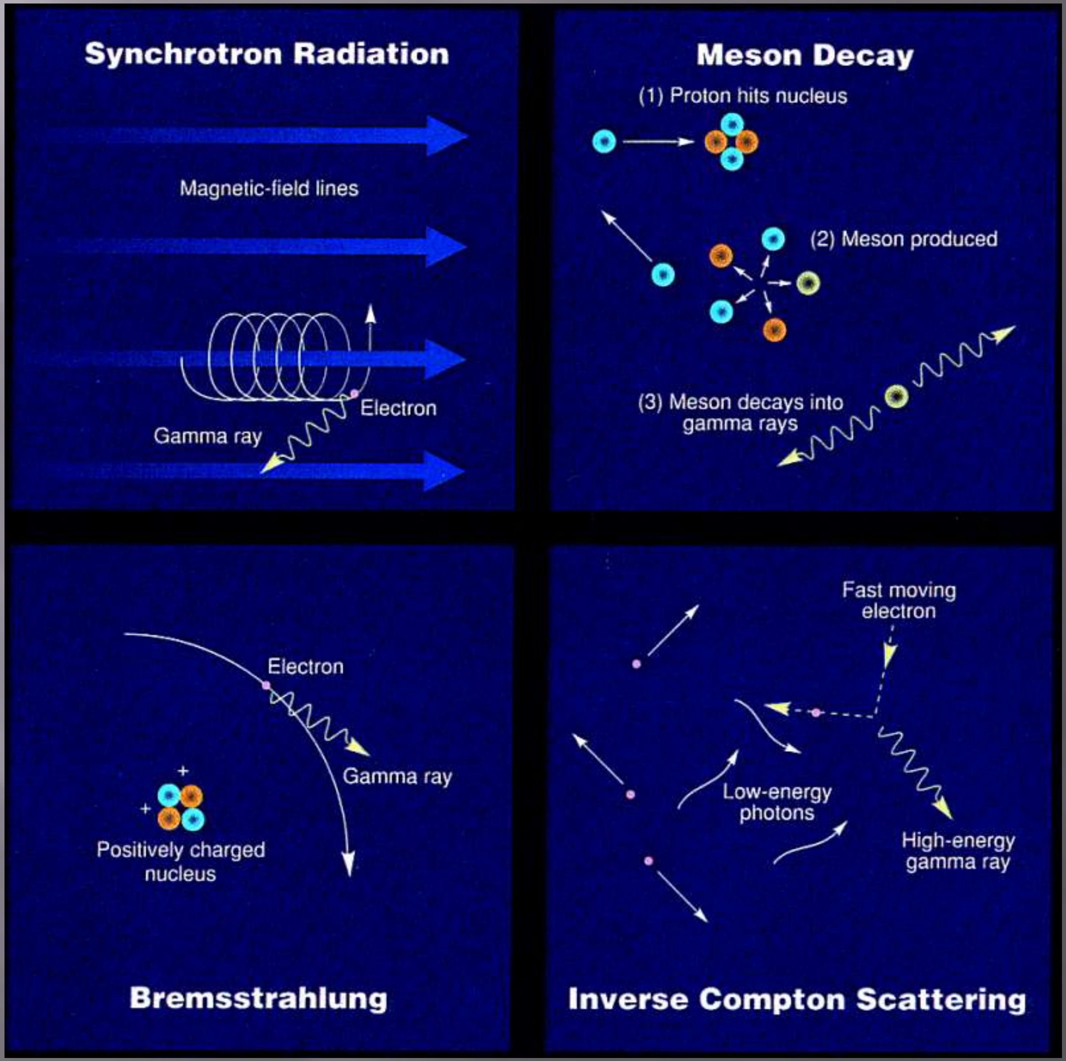


Jelley & Weekes, Sky and Telescope, 1995

Gamma-ray production mechanisms

High energy electron

High energy proton

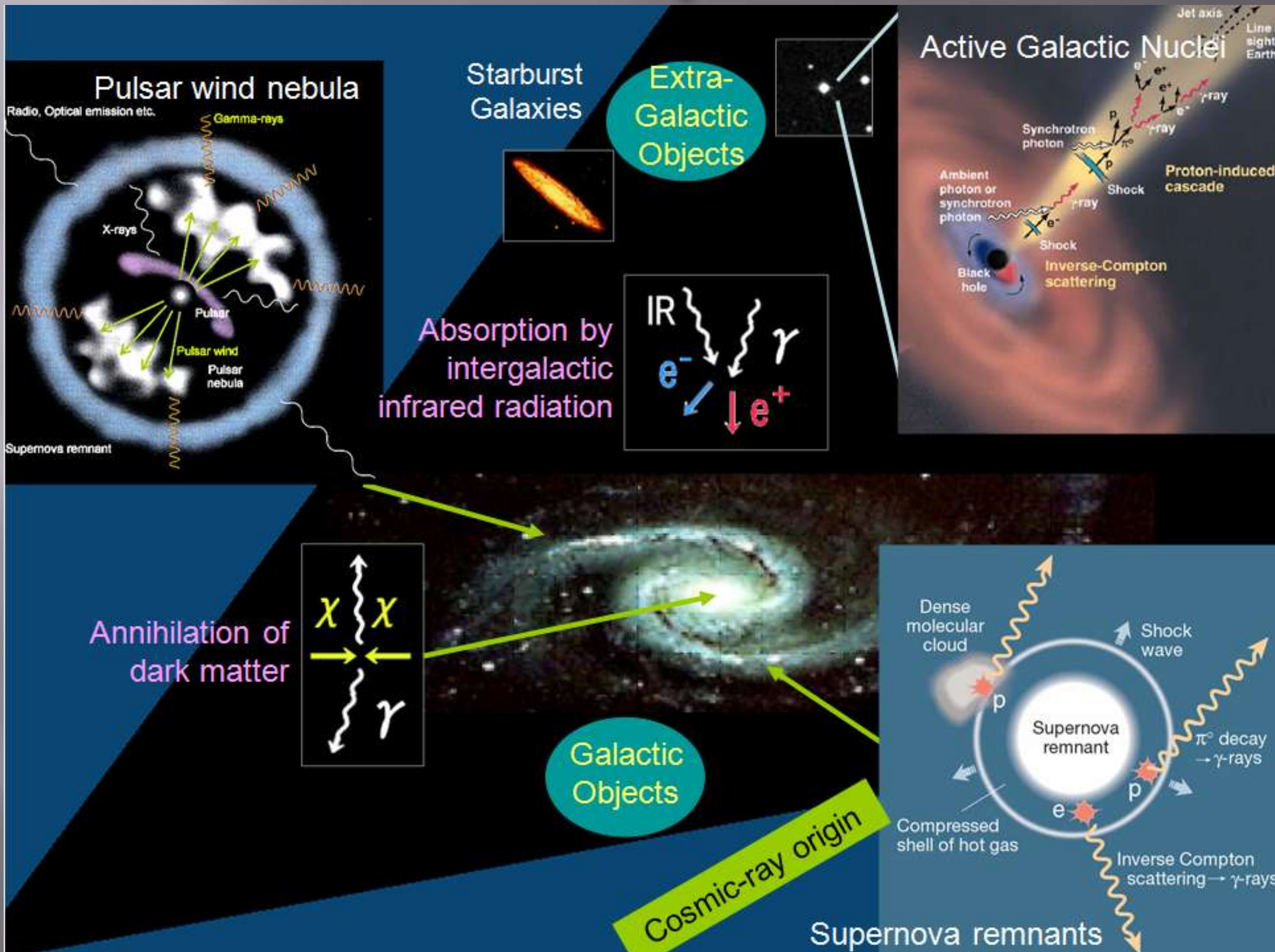


High energy electron

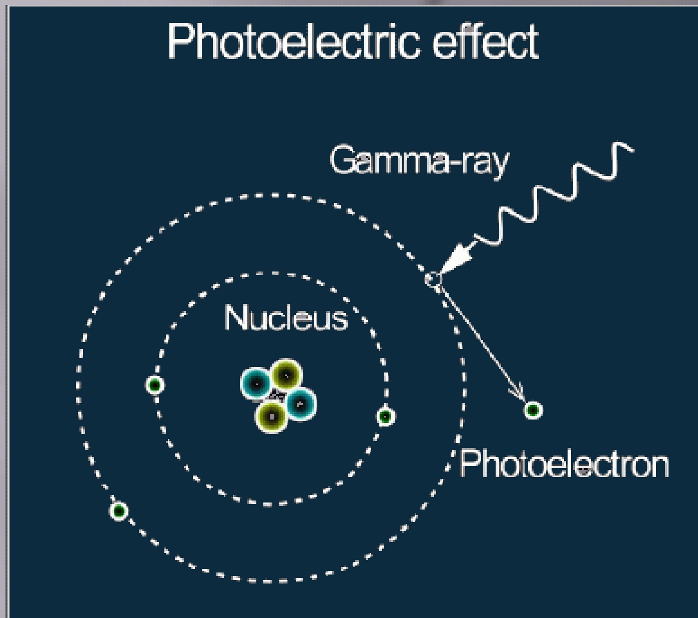
High energy electron

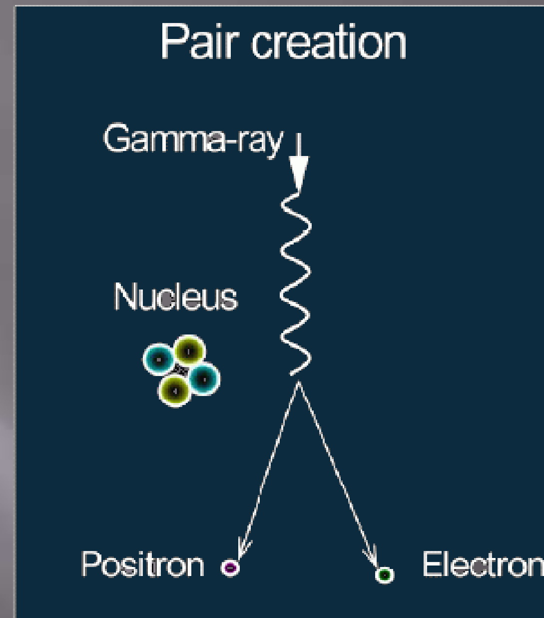
Emission from particles accelerated to high energies by non-thermal processes

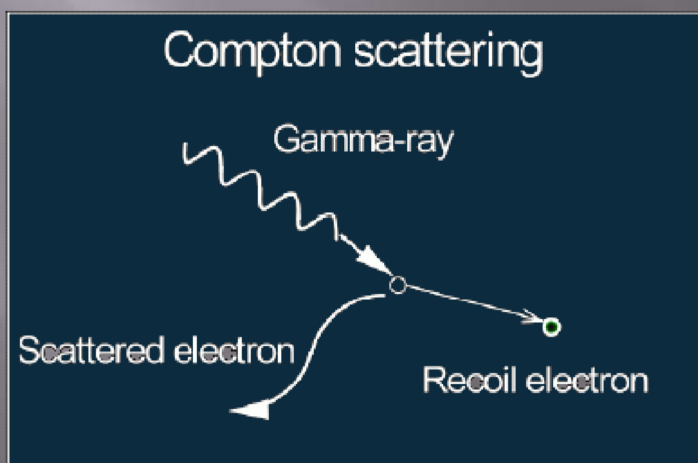
Gamma-ray sources



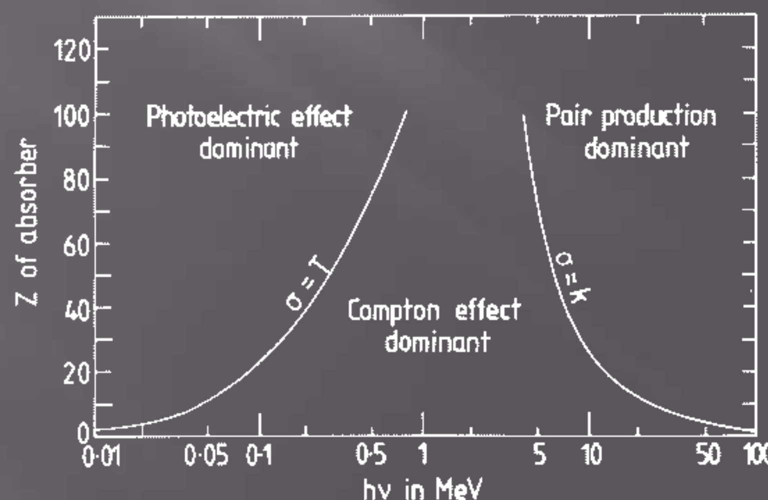
Gamma-ray interaction with matter



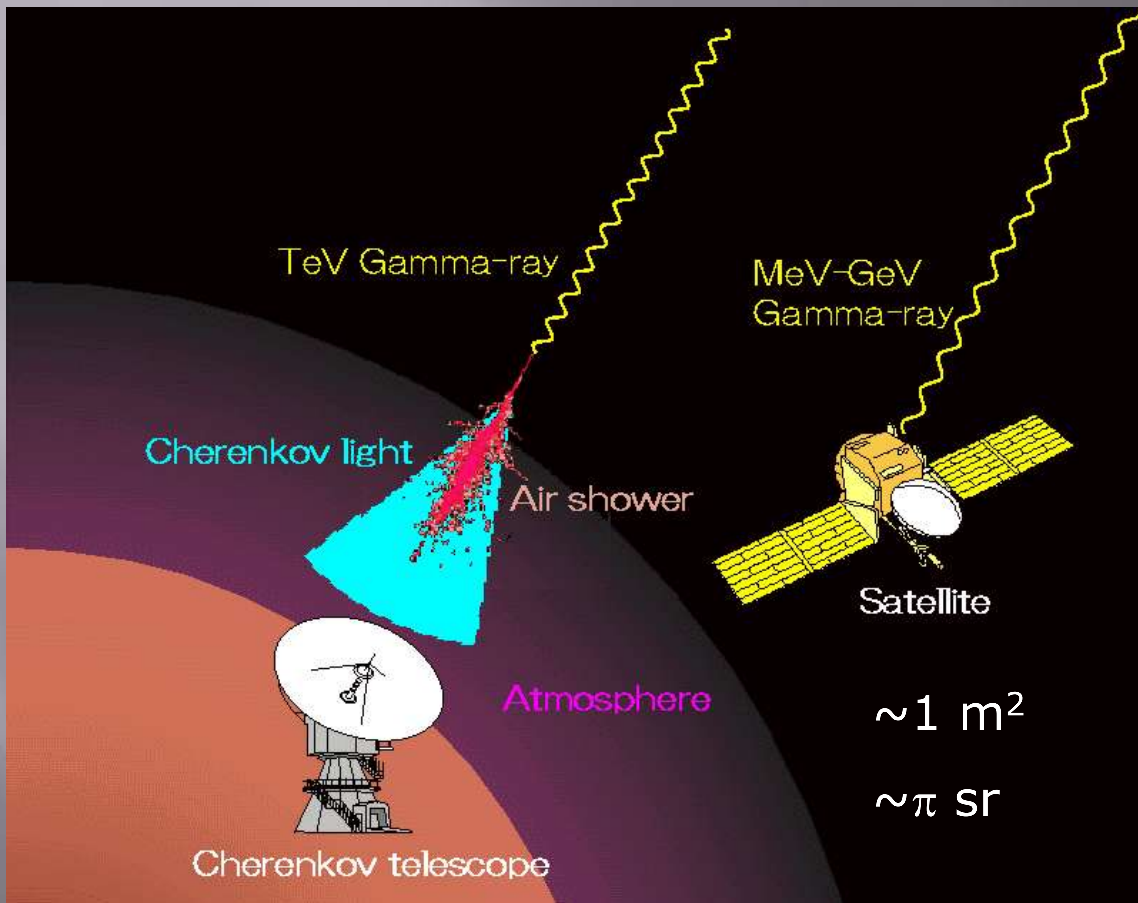




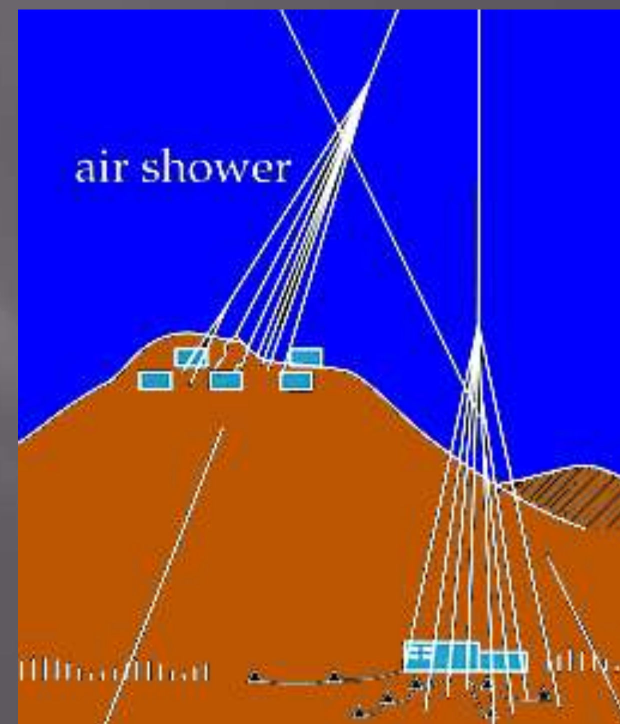
Evans 1955



Detection of gamma-rays



> TeV gamma-rays



$A \sim 10^4 m^2$

$\Omega \sim 10^{-2} sr$

Fermi Gamma-ray Space Telescope (2008 June-)

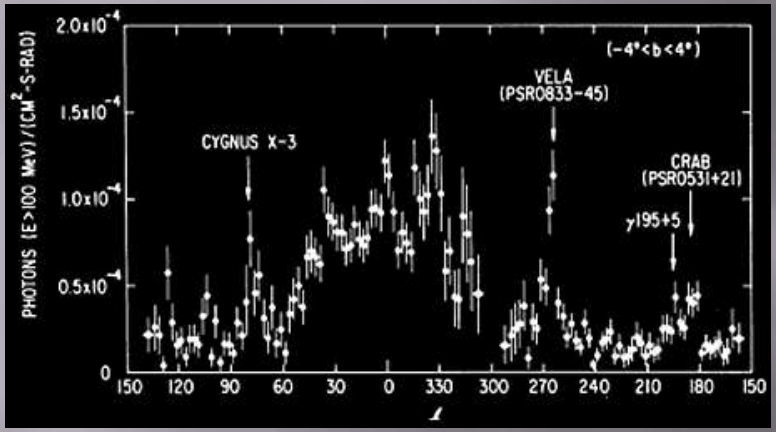
Early history

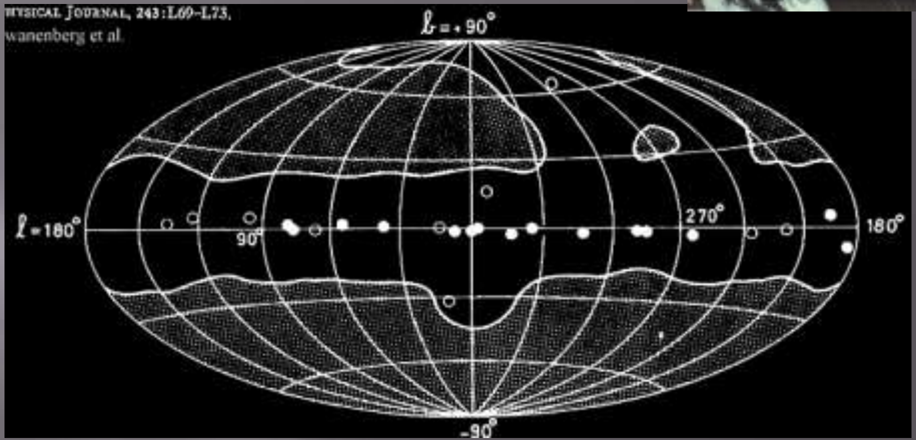
- 1952: S. Hayakawa (Prog.Theo.Phys. 8, 571)
  - π^0 decay gamma-rays during CR propagation
- 1958: P. Morrison (Nuovo Cim. 7, 858)
  - Synchrotron/Bremsstrahlung/ π^0 /de-excitation of nuclei/electron-positron annihilation
  - Sun/Crab/radio galaxy/matter-antimatter annihilation
- 1959: G. Cocconi (7th ICRC, Vol.2, 309)
  - π^0 decay gamma-rays from Crab
- 1960-64: A.E. Chudakov et al.
  - 1.5m$\phi\times$12 in Cremea
  - Flux < 10^{-2} of prediction by Cocconi
- 1968: G.G. Fazio et al.
  - Whipple 10m telescope on Mt. Hopkins
  - 3σ detection of Crab nebula (Fazio et al. 1972 ApJ 175, L117)
- 1972: Launch of SAS-2 satellite

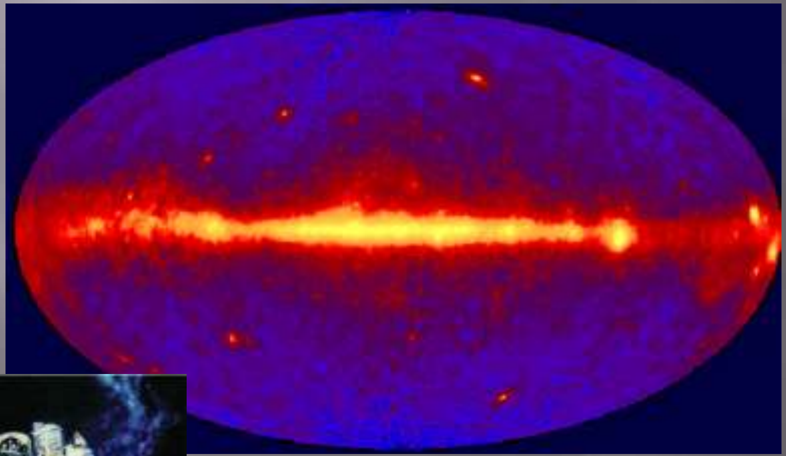
Satellite detectors

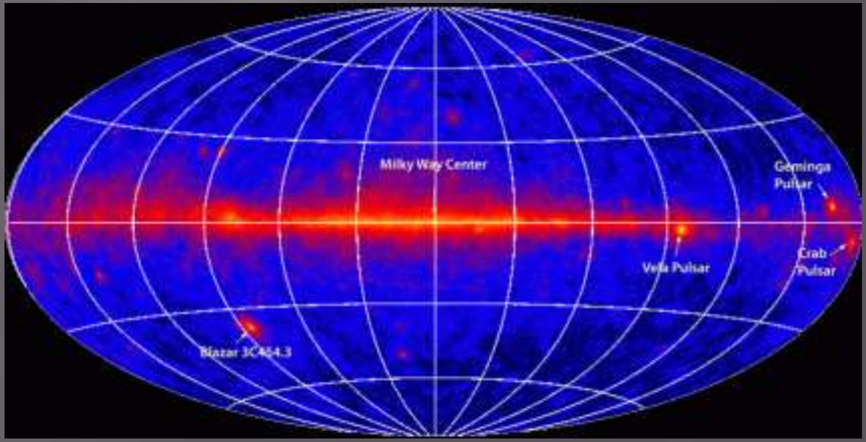
SAS-2 (1973)

COS B (1980)



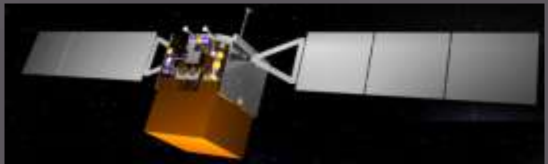






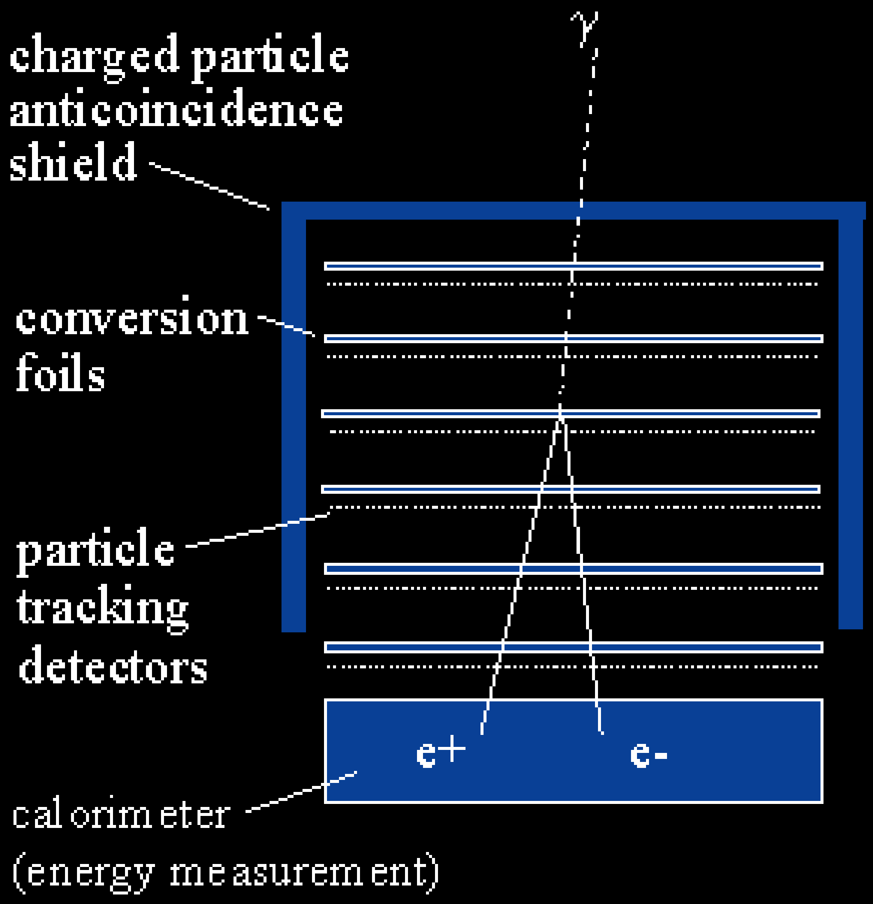
CGRO/EGRET (1996)

Fermi (2008)



From Fermi team

Pair-conversion telescope



- photons materialize into matter-antimatter pairs:

  $$E_\gamma \dashrightarrow m_{e+}c^2 + m_{e-}c^2$$

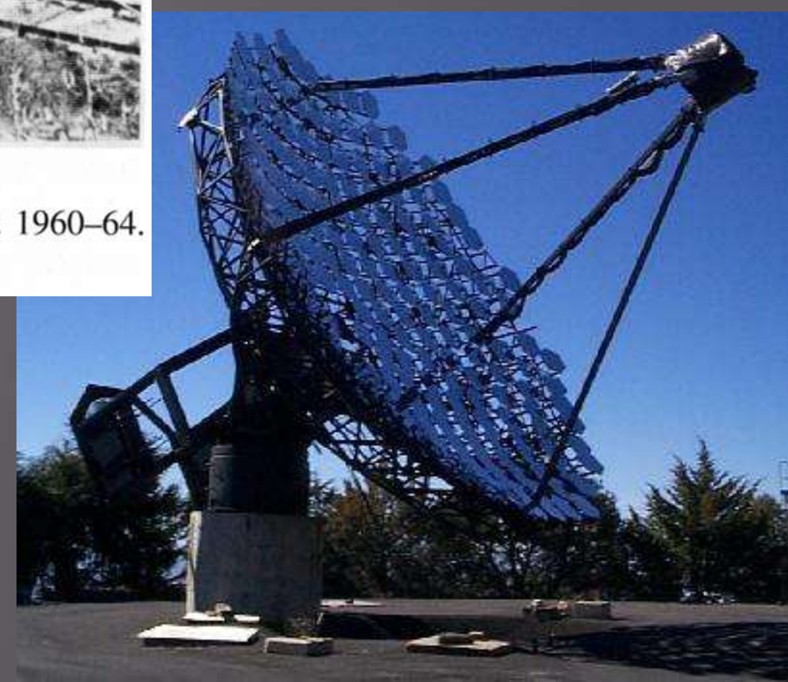
- electron and positron carry information about the direction, energy and polarization of the γ-ray

Early Cherenkov telescopes

Figure 1.2. The Lebedev Institute experiment that operated in the Crimea, *c.* 1960–64. This was the first major VHE gamma-ray telescope. (Photo: N A Porter.)

Telescopes in Crimea

Whipple
10m telescope



Gamma-ray shower vs hadron shower

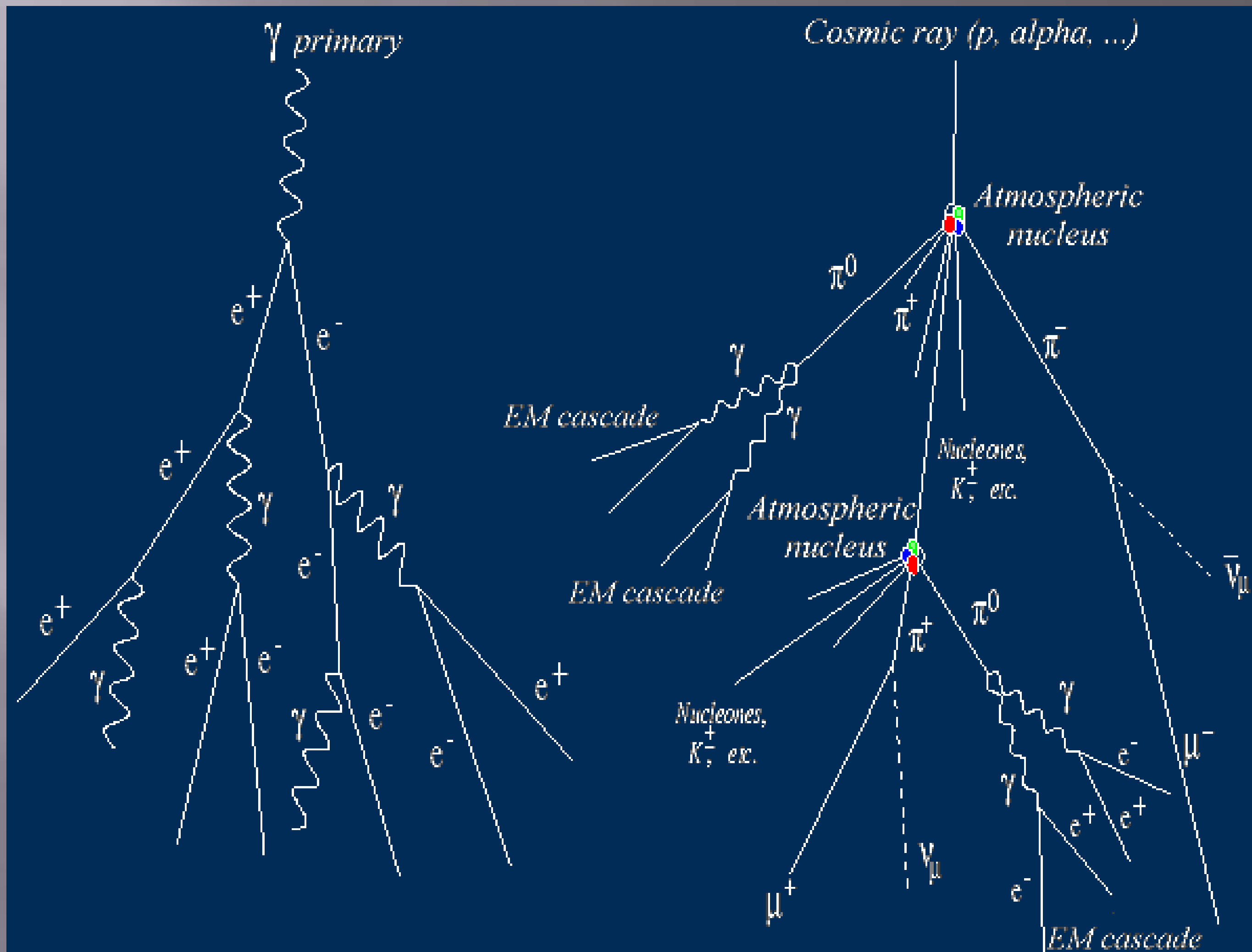
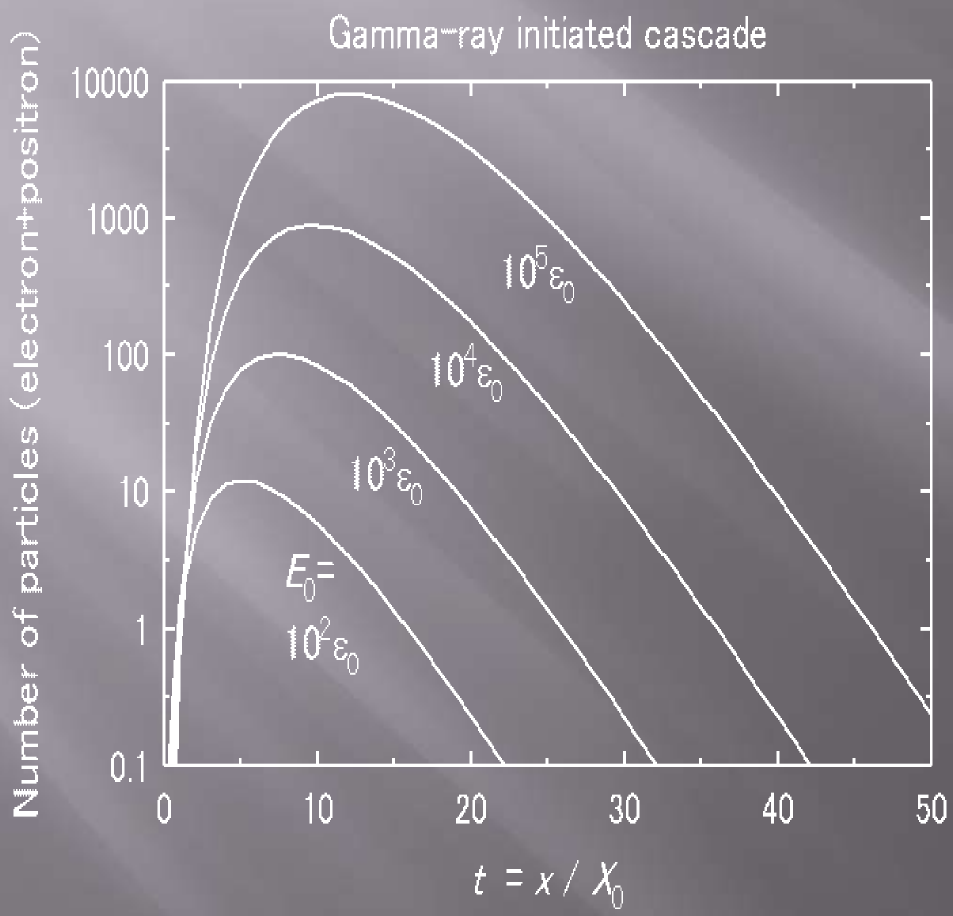
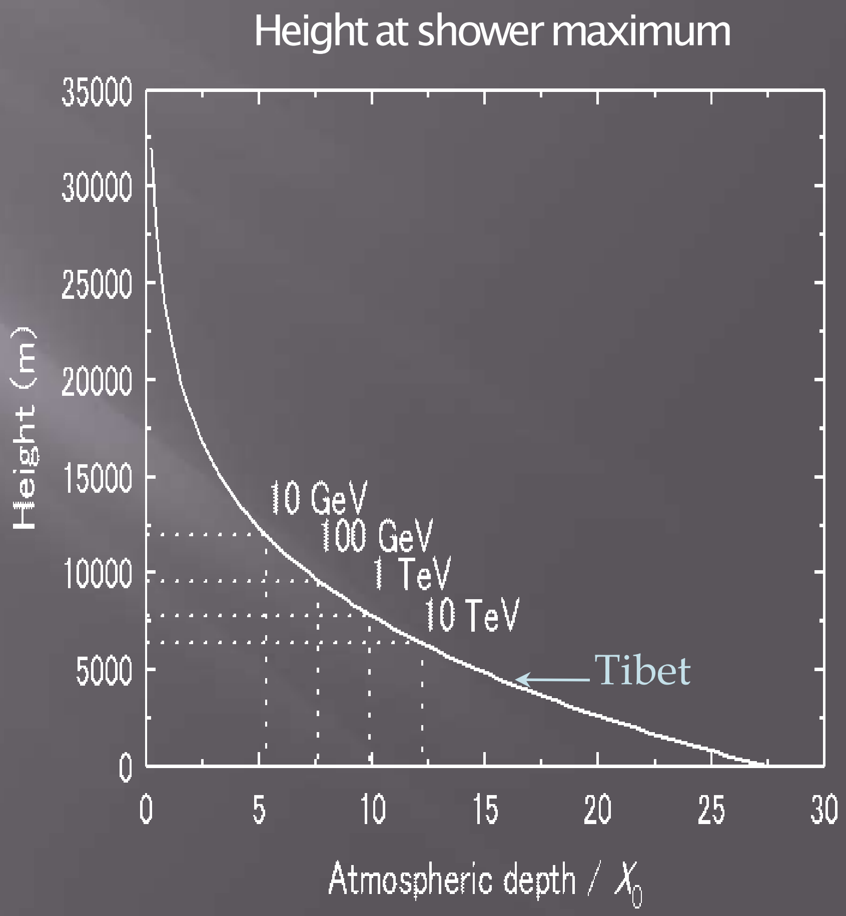


Figure: *Geometric model of emission of Cherenkov radiation for γ-ray and hadron shower.*

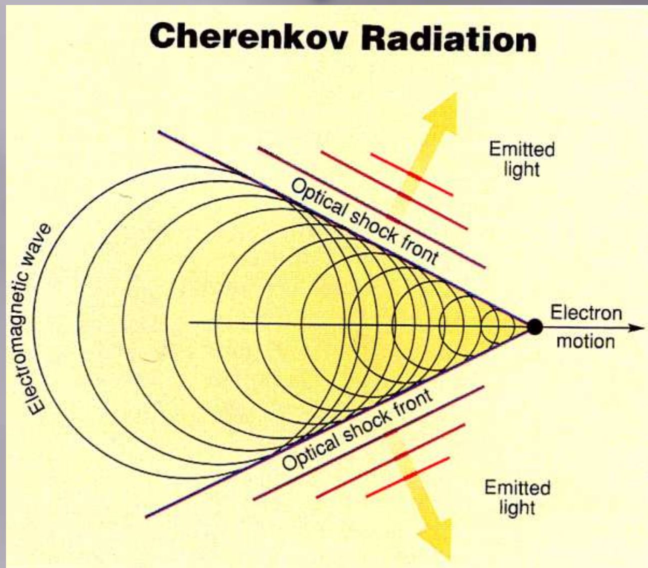
Air shower development

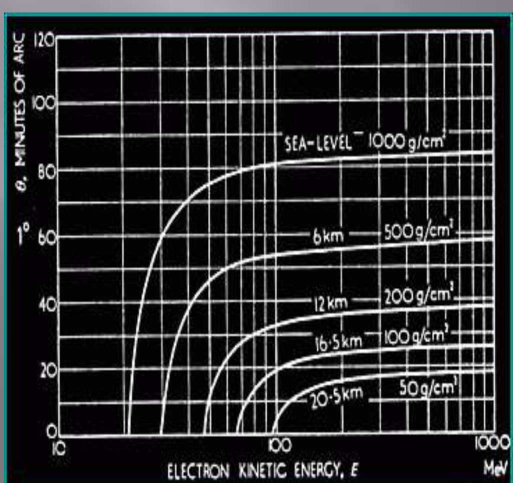




X_0 : radiation length (37 g/cm^2 in air)
ε_0 : critical energy (80 MeV in air)

Atmospheric Cherenkov light





Jelley, 1958

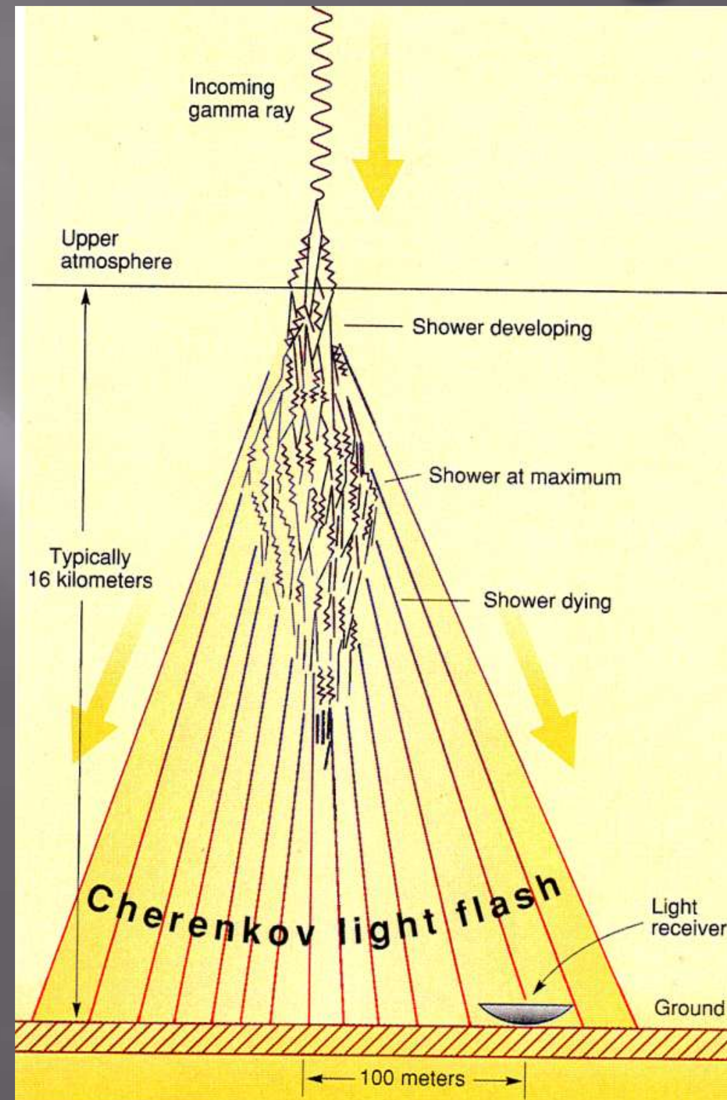
- Cherenkov angle

  $\cos\theta = 1/n\beta$

  $\beta = v/c$

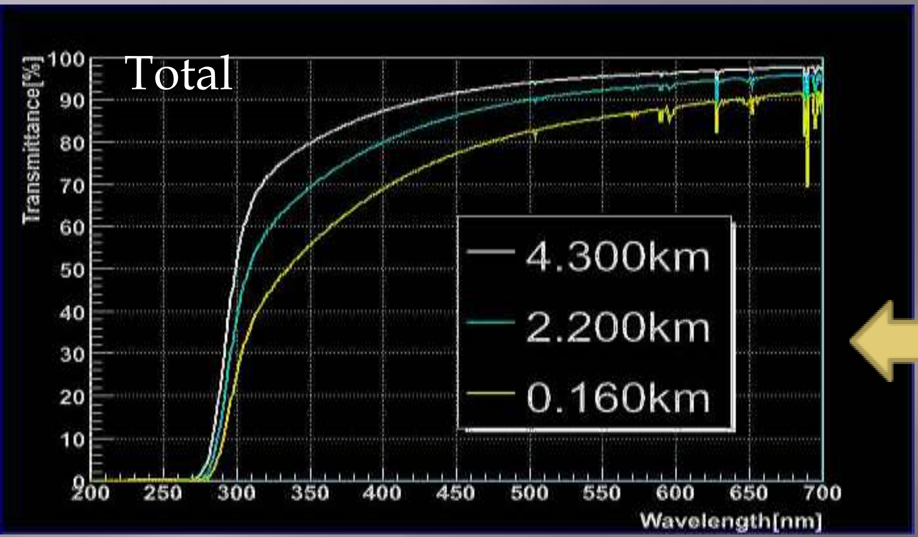
  $n = 1.0003$ (1atm)

  $\Rightarrow \theta = 1.3^{o}$ (sea level)

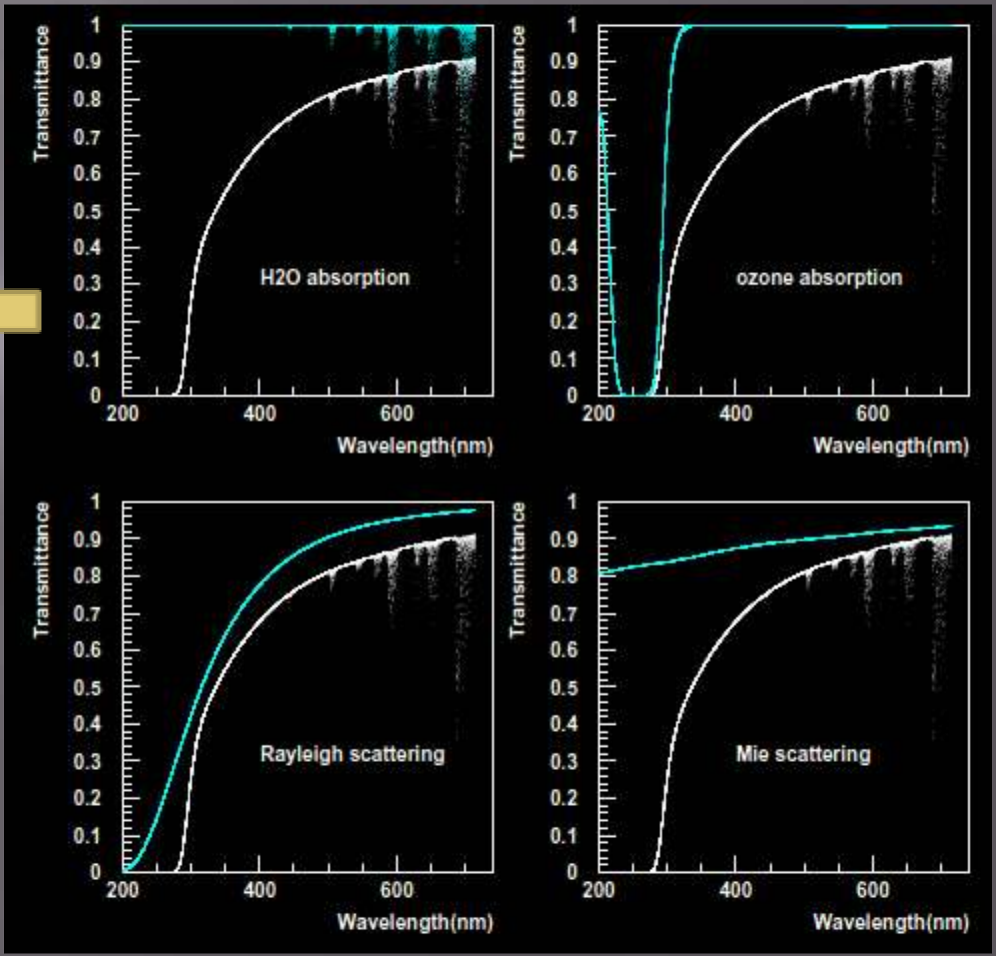


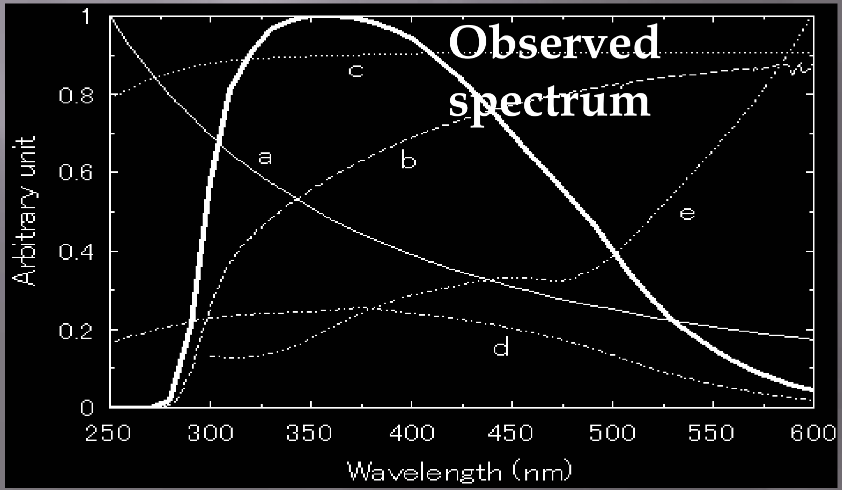
Jelley & Weekes, Sky and Telescope, 1995

Atmospheric transmission



MODRAN4 calculation by M.Yuasa (2006)

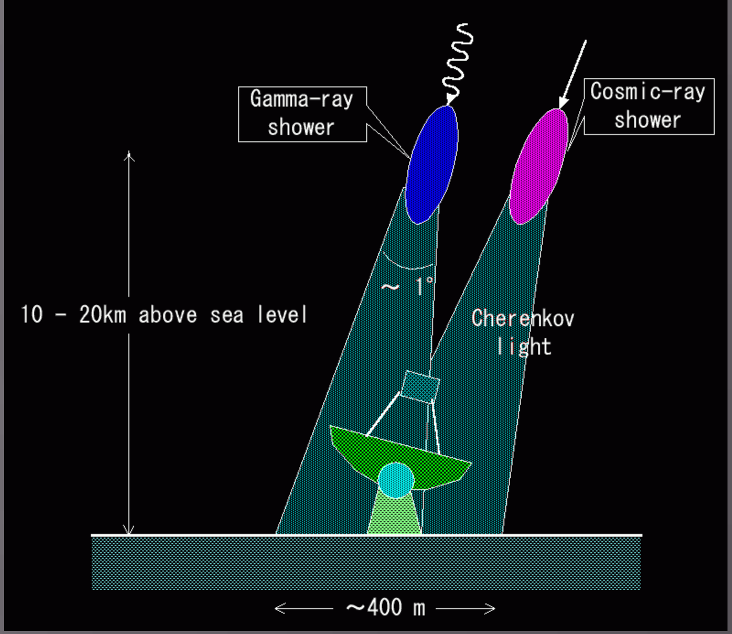




MODRAN4 calculation by H. Tsunoo (2002)

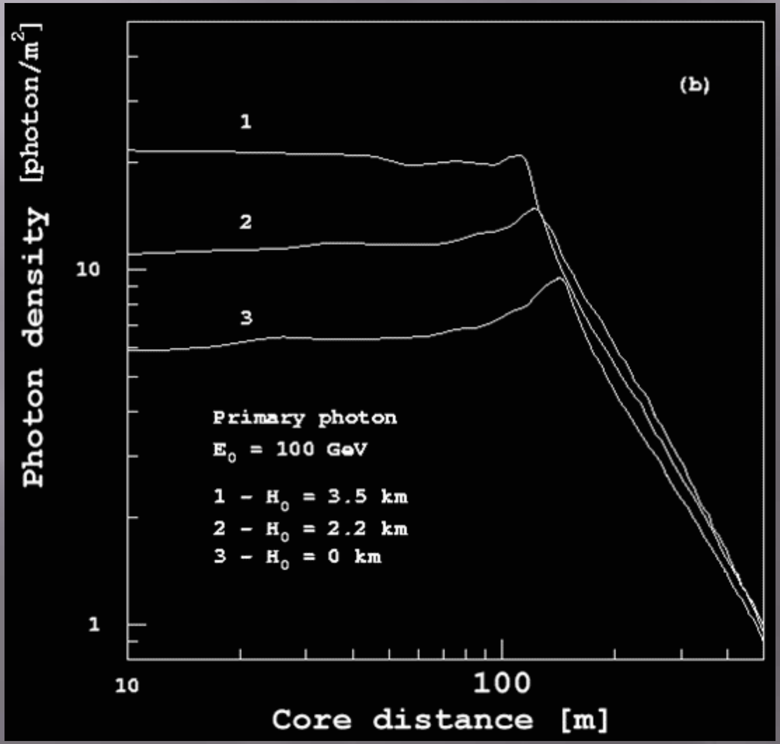
a: Cherenkov, b: transmission, c: mirror, d: QE, e: NSB

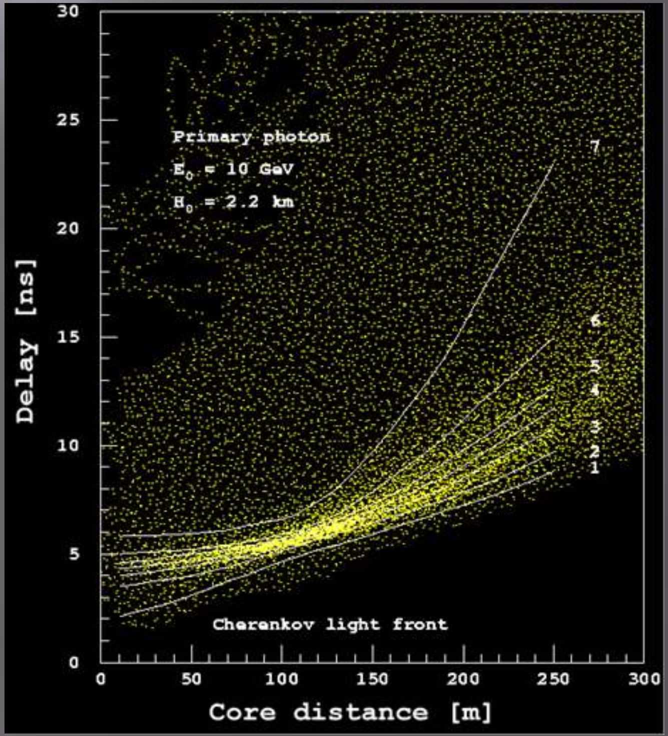
Atmospheric Cherenkov Telescope



Cherenkov light from gamma-ray showers

Lateral distribution & Timing distribution



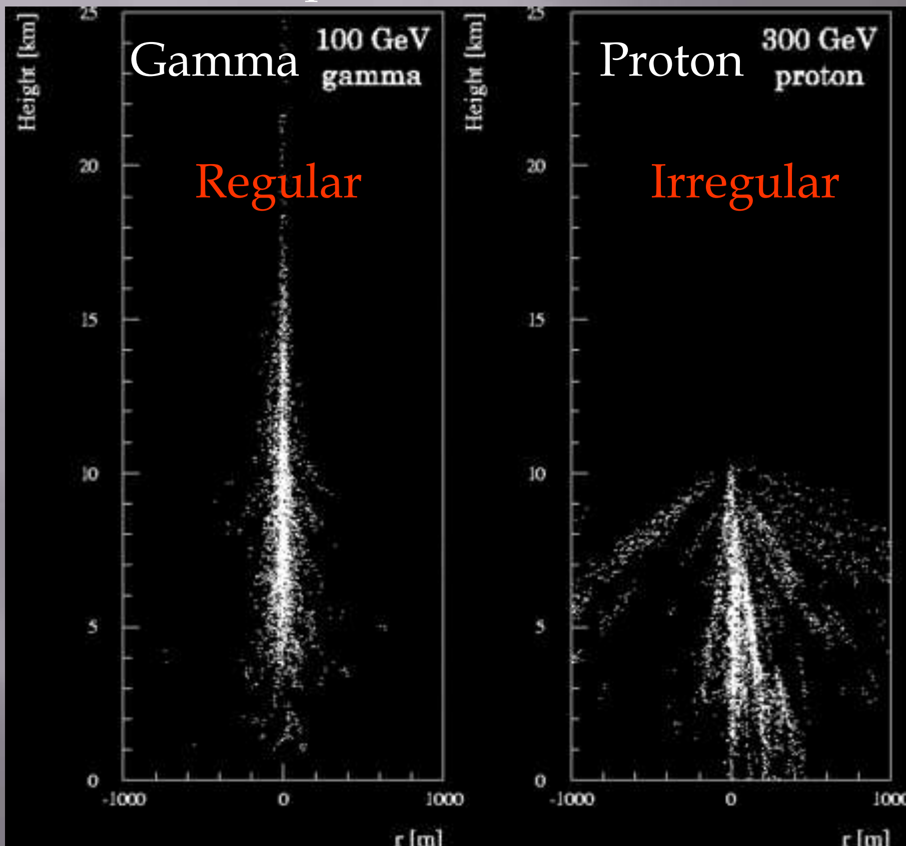


Aharonian & Konopelko 1997

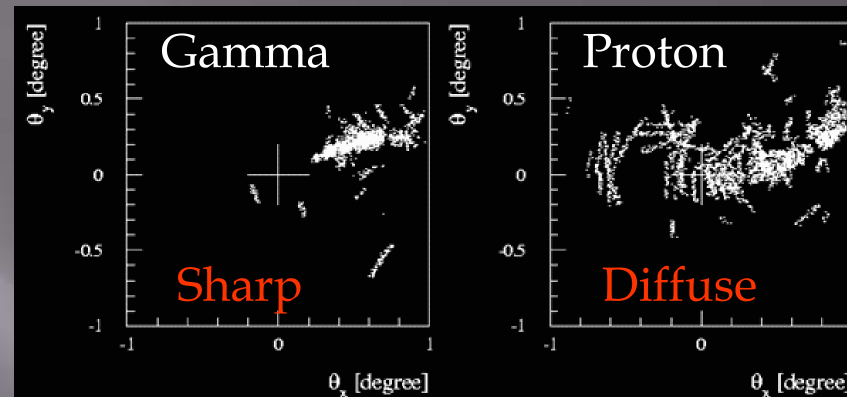
Aharonian et al. 1997

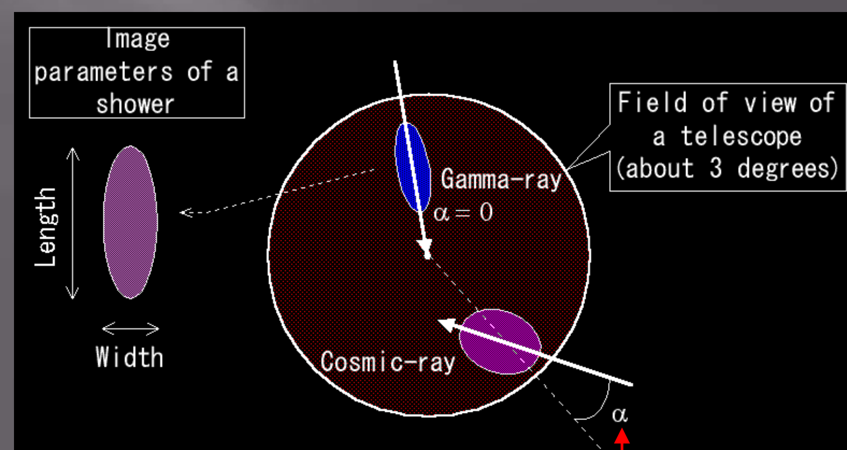
Imaging Atmospheric Cherenkov Telescope

Shower profile



Focal plane image



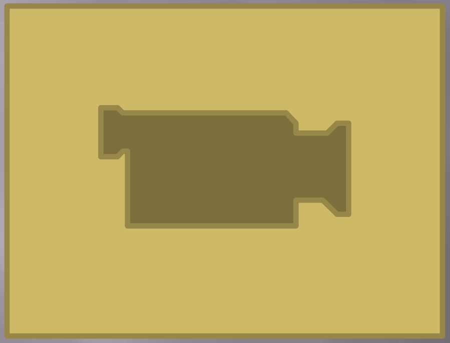


α (image orientation angle)

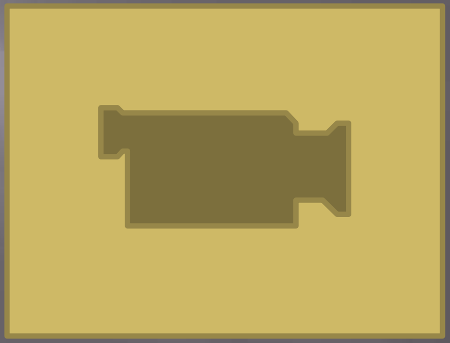
→ Differentiation of gamma-rays from charged cosmic rays

Shower simulation movies

500 GeV Gamma-ray



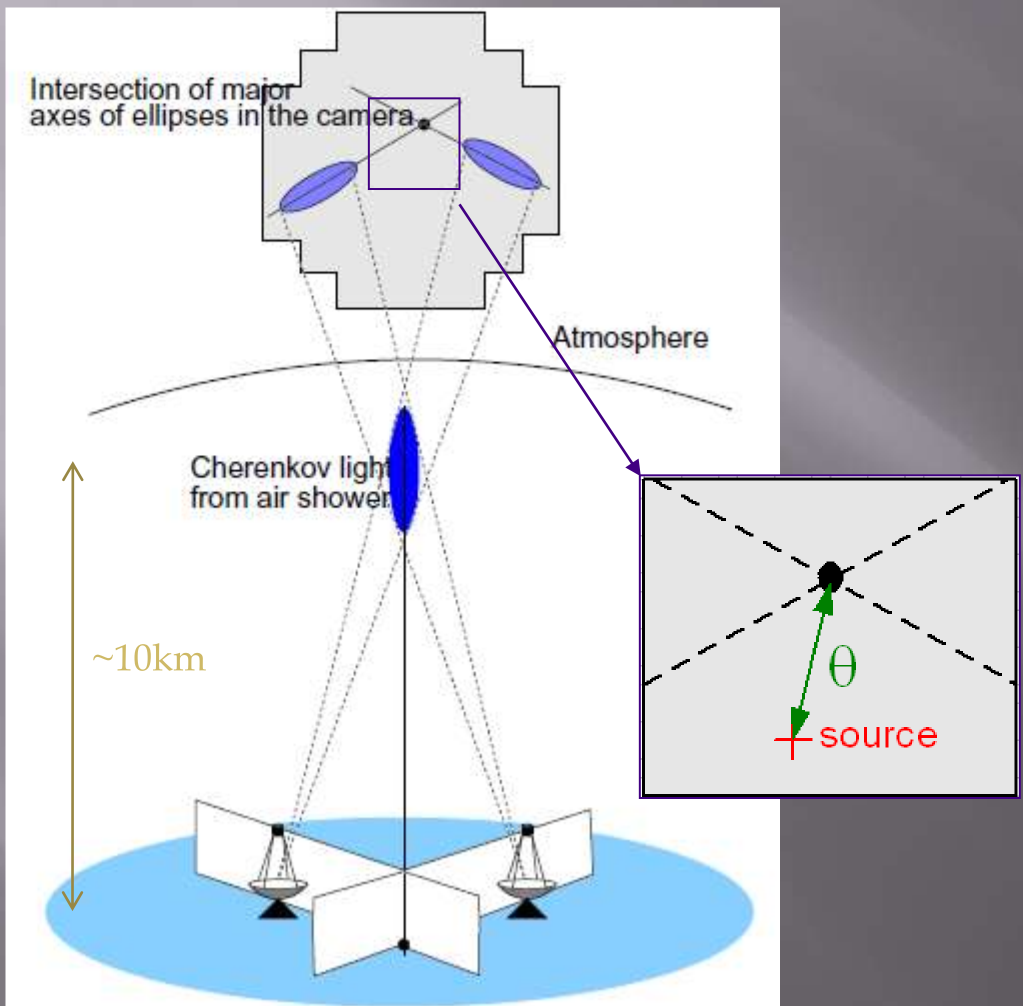
2 TeV Proton



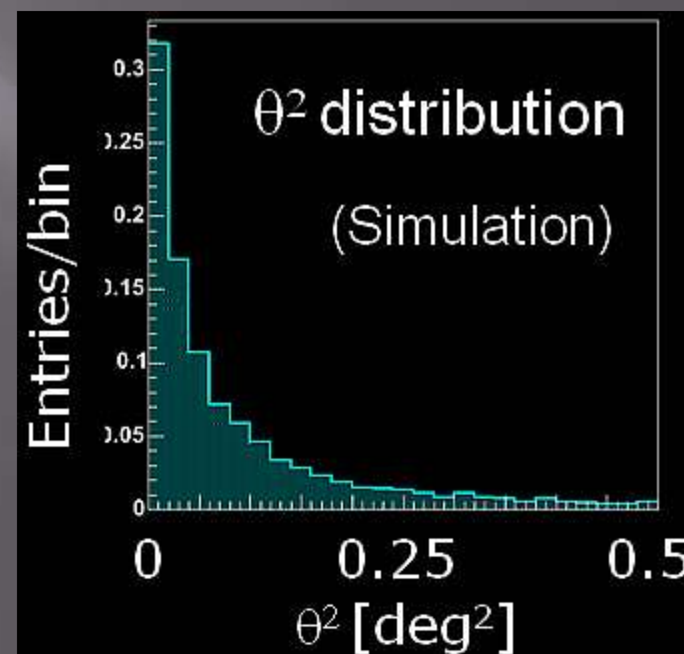
Miguel F. Morales, http://scipp.ucsc.edu/milagro/Animations/AnimationIntro.html

Stereoscopic observation of Cherenkov light

- Angular resolution
  - 0.25deg → 0.1 deg
- Energy resolution
  - 30% → 15%
- Better S/N (no local muons)



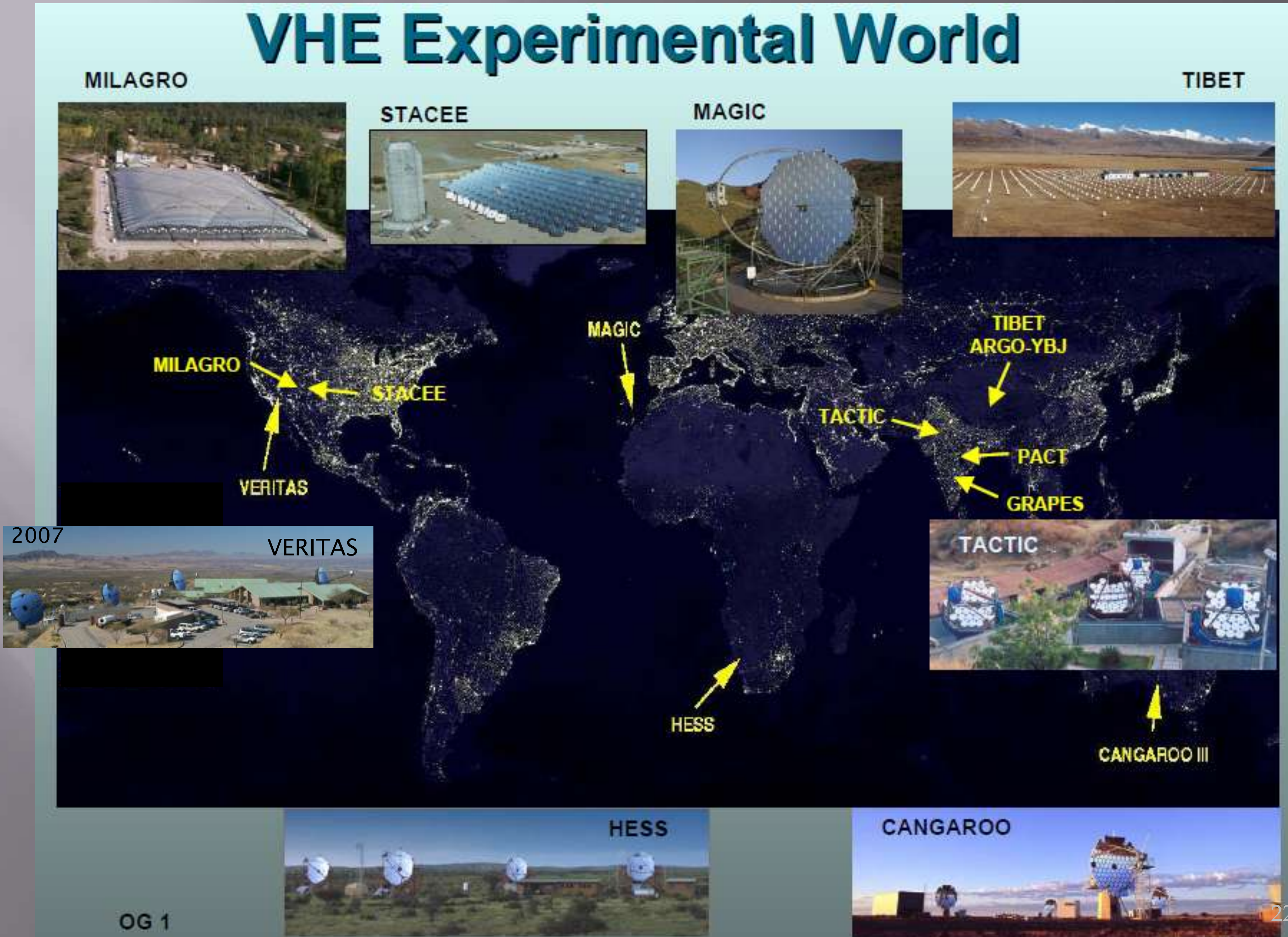
© S.Funk, 2005



Comparison of detection methods

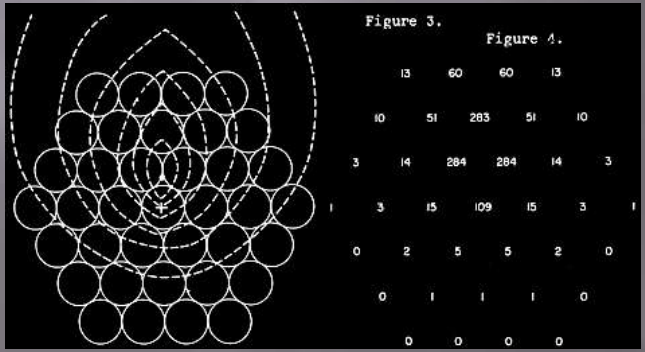
Base	Satellite	Ground	Ground
Gamma-ray detection	Direct (pair creation)	Indirect (atmospheric Cherenkov)	Indirect (shower array)
Energy	< 30 GeV ($\rightarrow$ 100 GeV)	>100 GeV ($\rightarrow$ 50 GeV)	>3 TeV ($\rightarrow$ 1 TeV)
Pros	High S/N Large FOV	Large area Good $\Delta\theta$	24hr operation Large FOV
Cons	Small area High cost	Low S/N (CR bkgd.) *(but imaging overcomes this!)* Small FOV	Low S/N (CR bkgd.) Moderate $\Delta\theta$

Rene Ong, ICRC2005 OG2 rapporteur talk (updated)



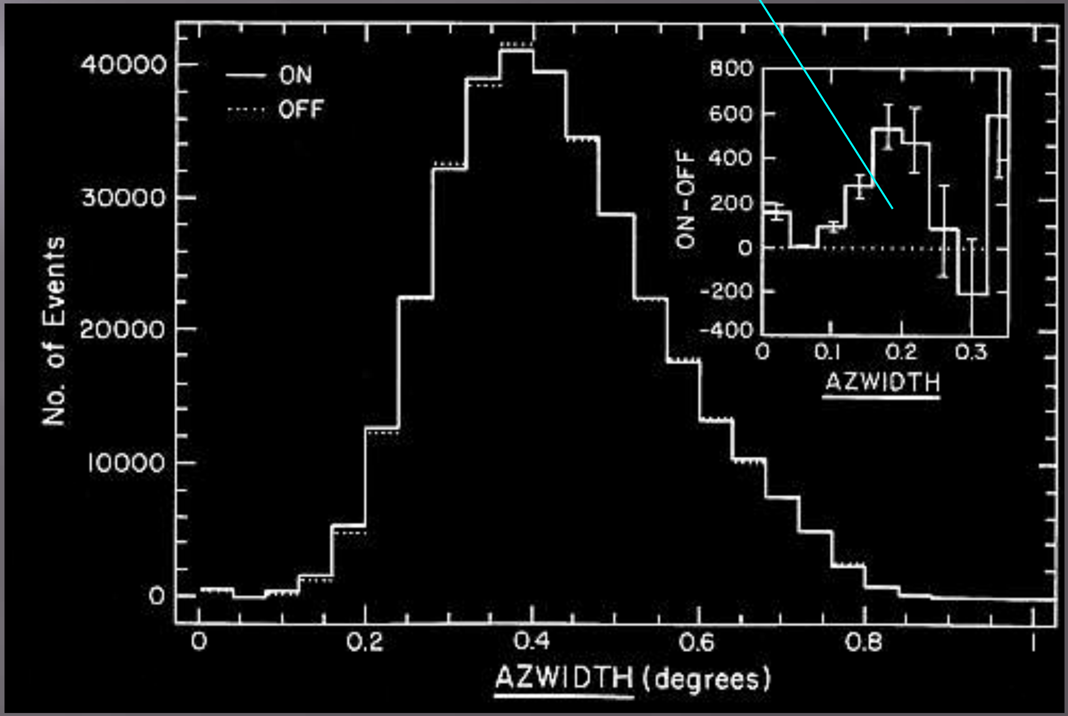
Crab: the first TeV source

Whipple 10m telescope



37ch imaging camera

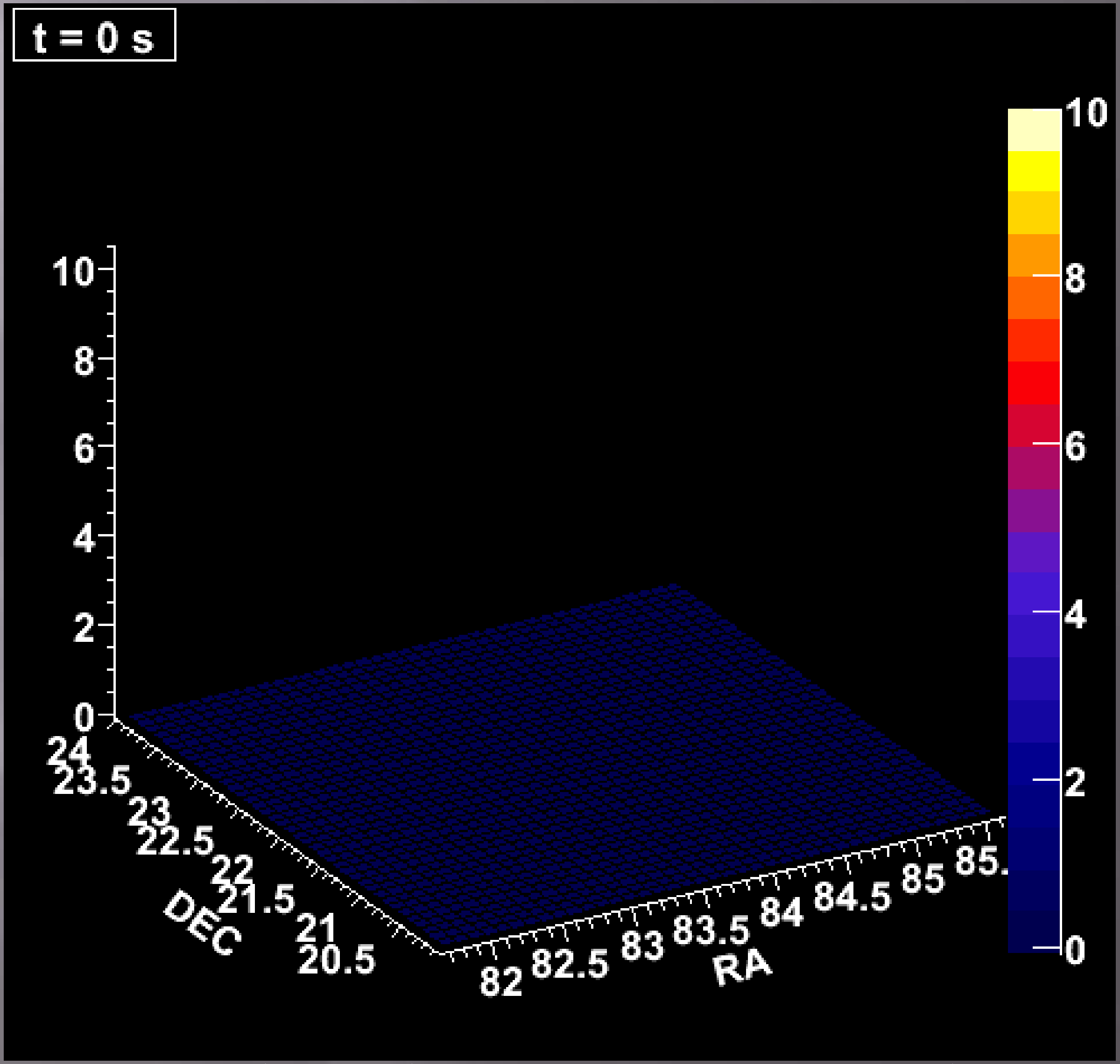
Gamma-ray signal



82hrs, 0.24γ/min

Crab: 2008

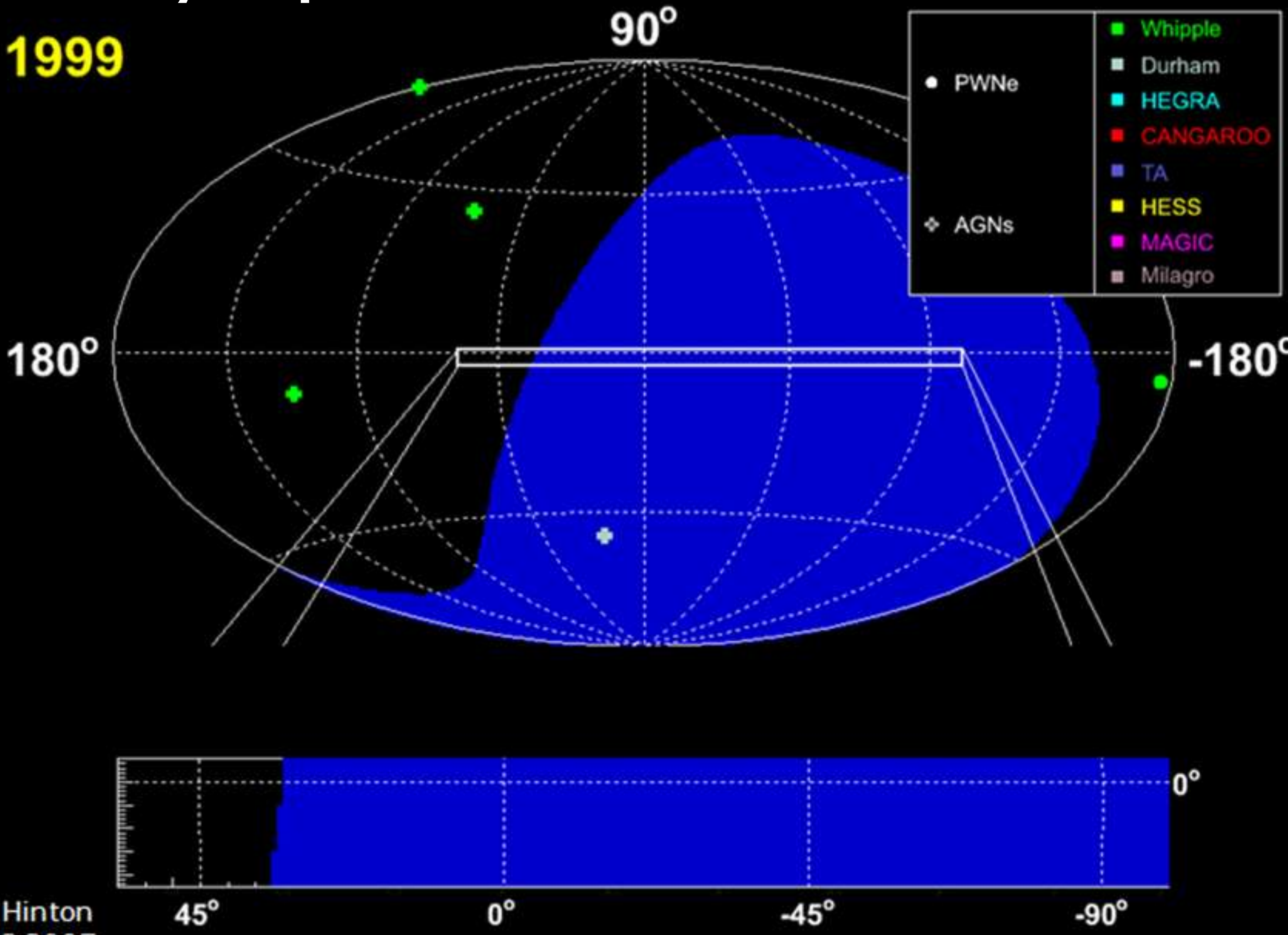
Clock



Signal

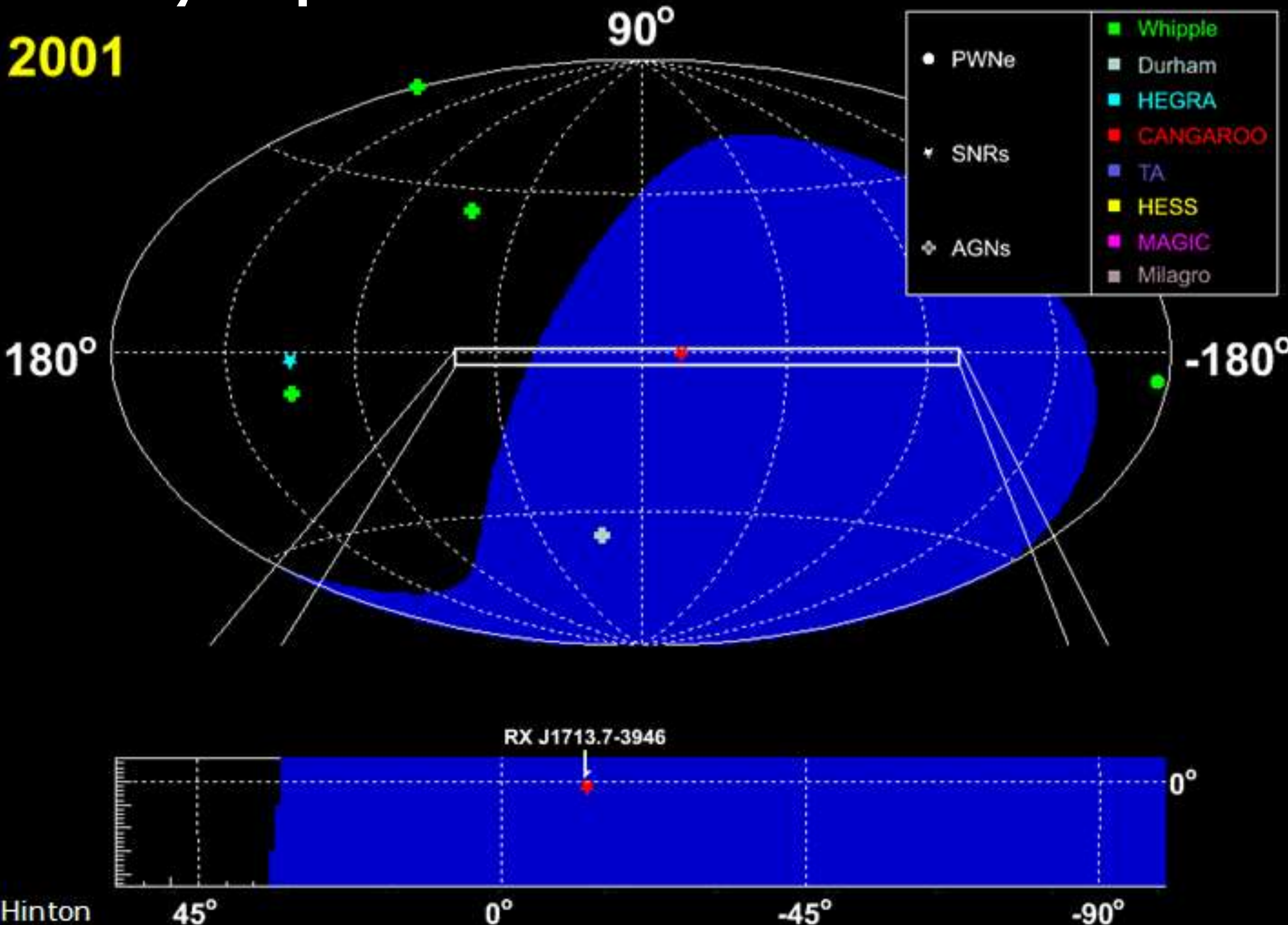
Crab Signal as seen in VERITAS in real time during commissioning

TeV skymap



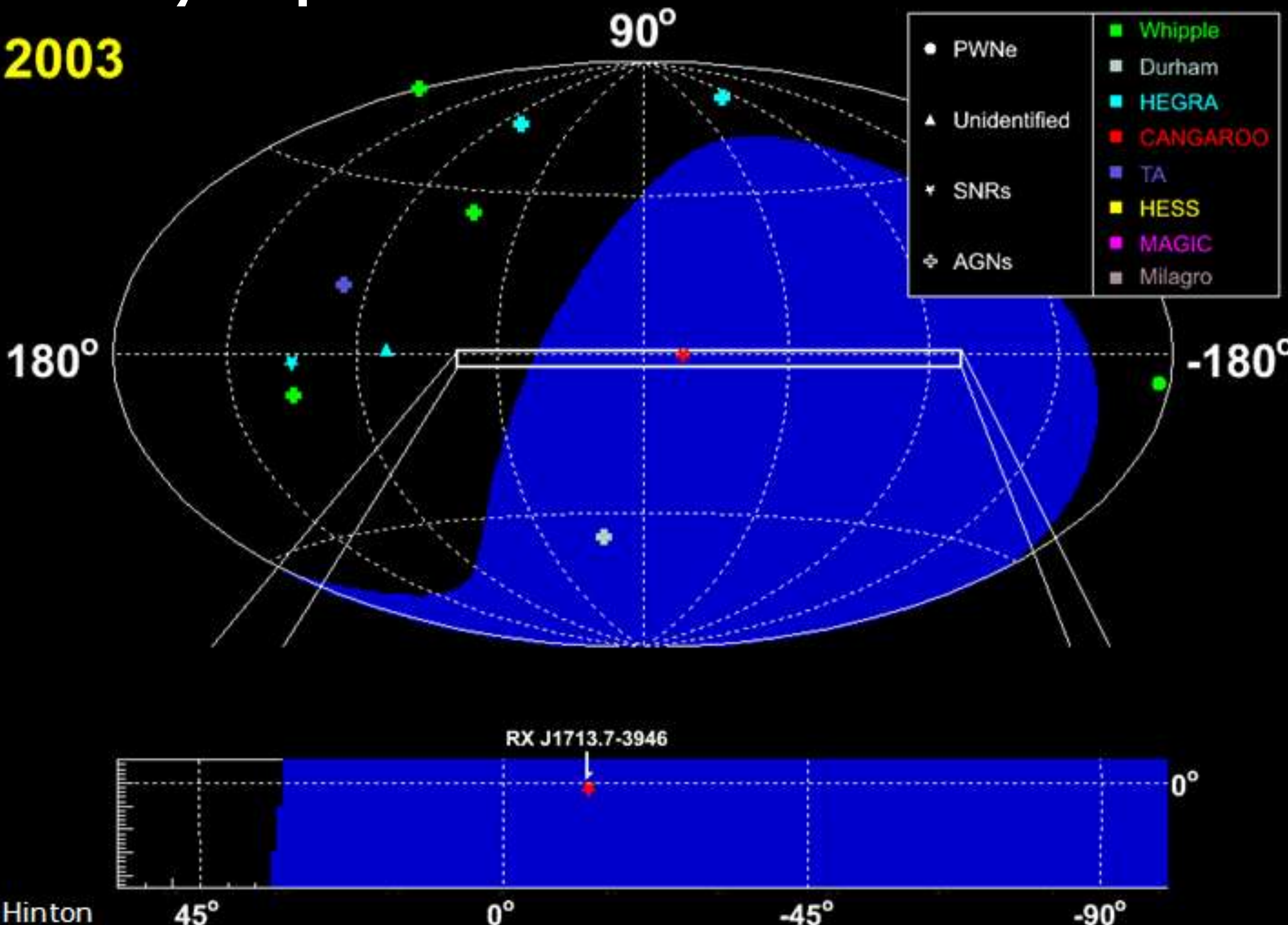
Jim Hinton
ICRC 2007

TeV skymap



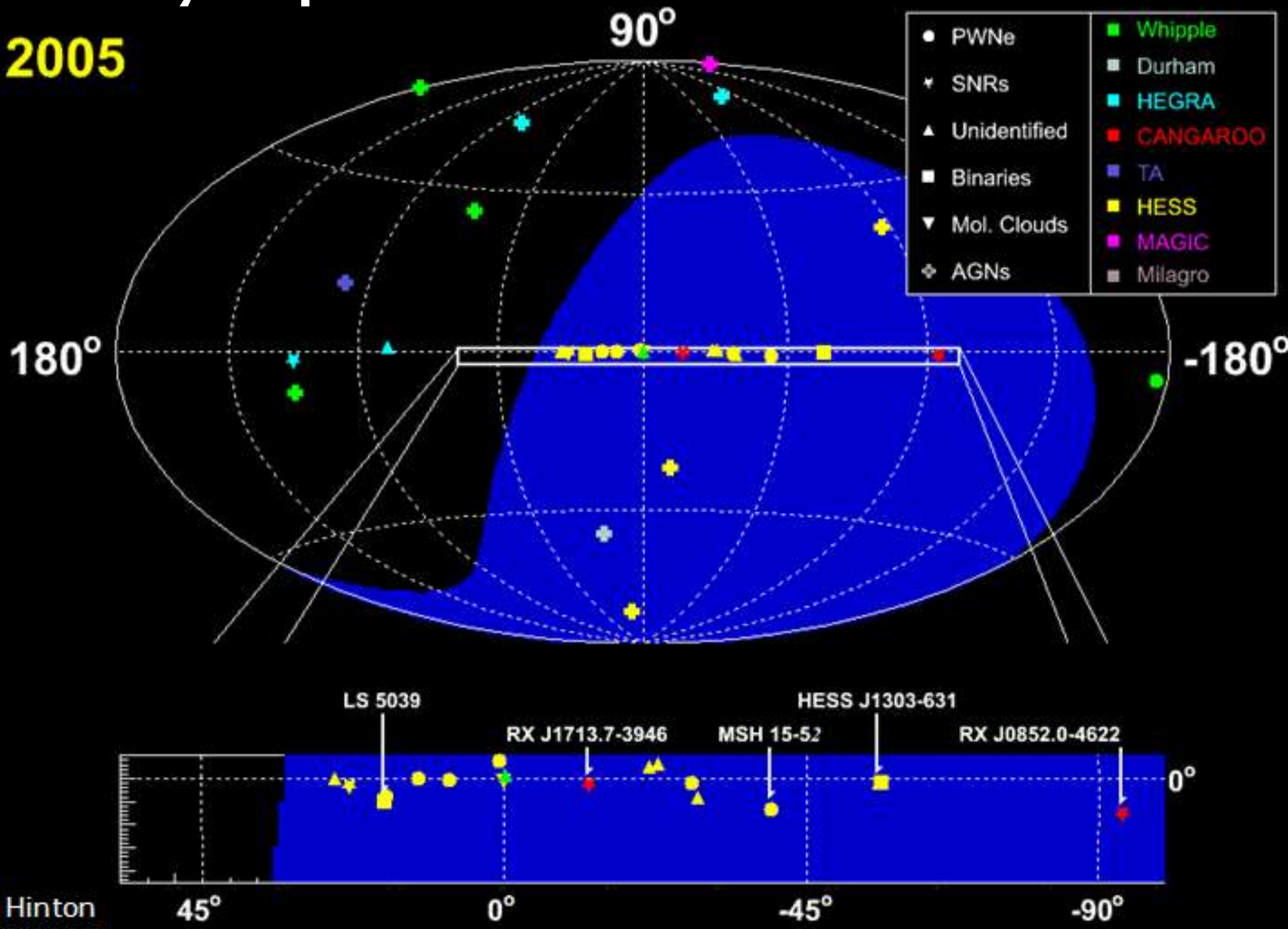
Jim Hinton
ICRC 2007

TeV skymap



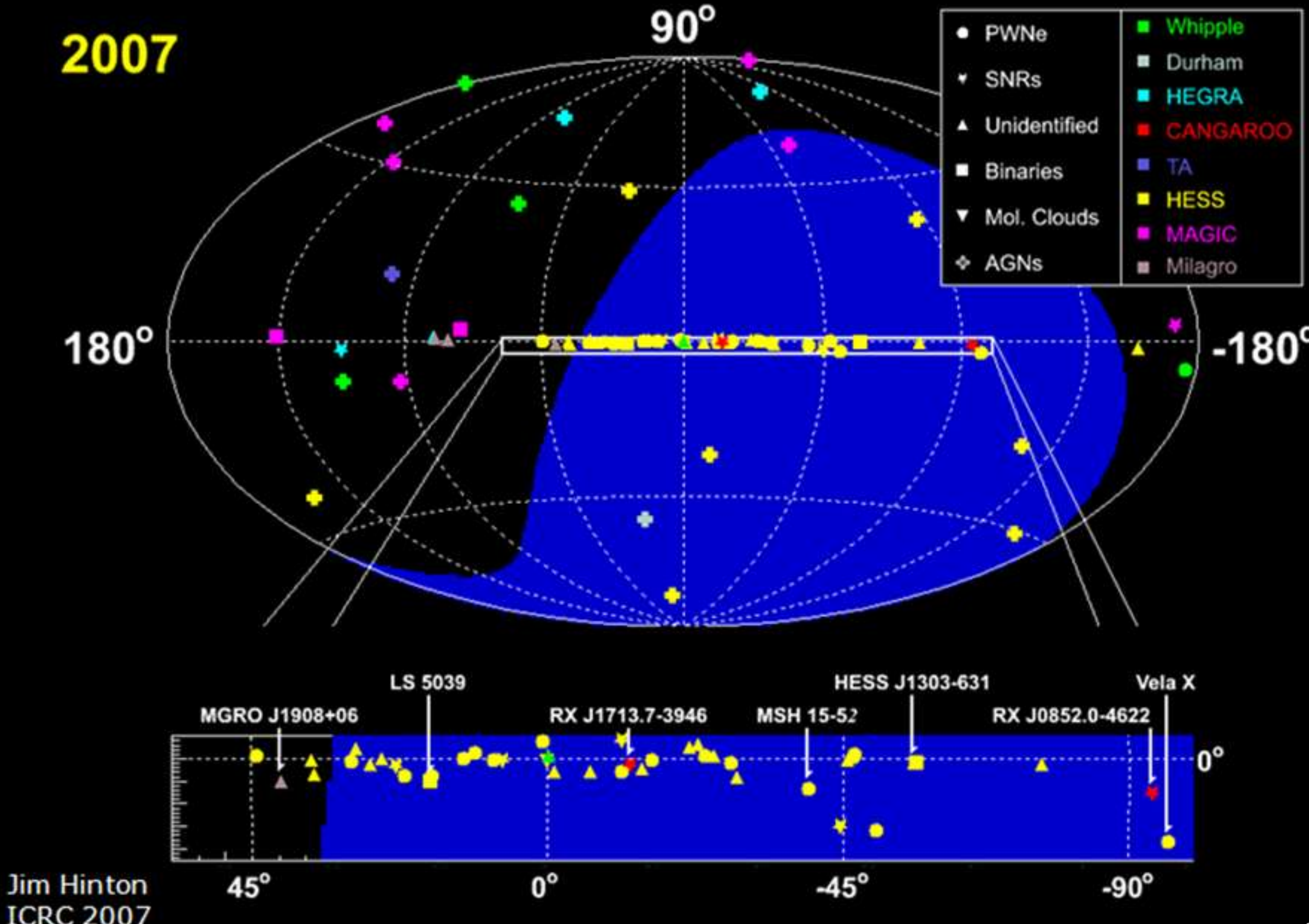
Jim Hinton
ICRC 2007

TeV skymap



Jim Hinton
ICRC 2007

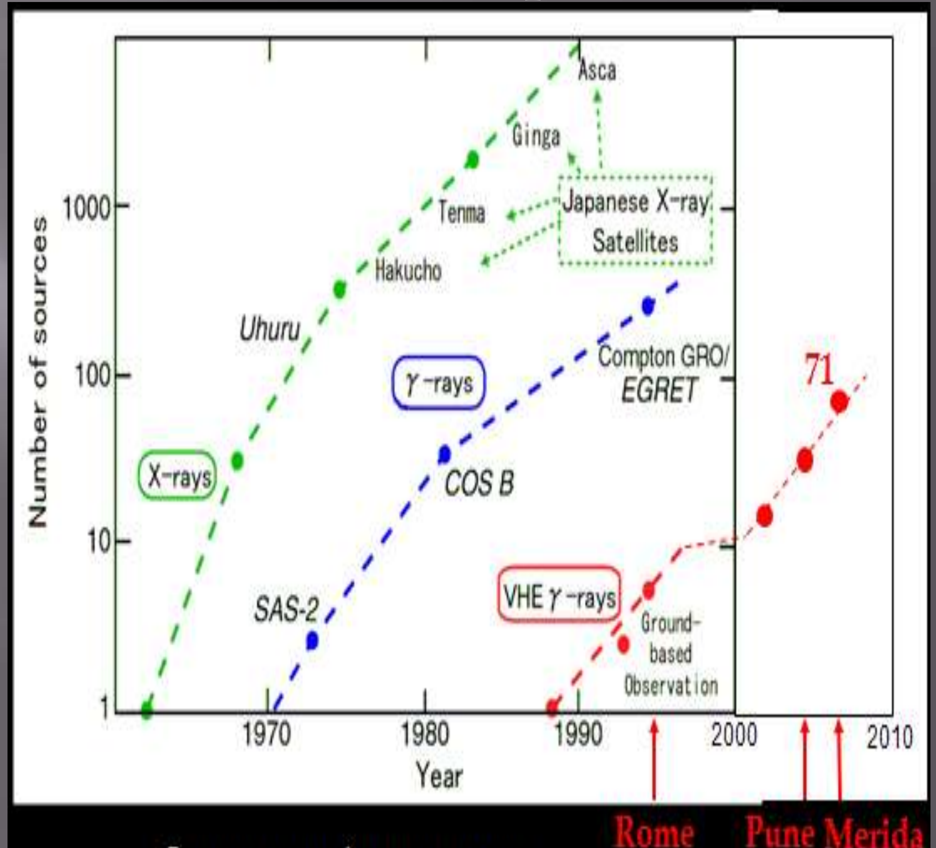
TeV skymap


2007
90°
180°
-180°
PWNe
SNRs
Unidentified
Binaries
Mol. Clouds
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
MGRO J1908+06
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
Vela X
0°
45°
0°
-45°
-90°
Jim Hinton
ICRC 2007

Increase of TeV sources

Class	2003	2005	2007
PWN (Pulsar Wind Nebulae)	*1*	*6*	*18*
SNR (Subernova remnants)	*2*	*3*	*7*
Binary	*0*	*2*	*4*
Diffuse	*0*	*2*	*2*
AGN (Active Galactic Nuclei)	*7*	*11*	*19*
UnId (Unidentified sources)	*2*	*6*	*21*
Total	**12**	**33**	**71!**

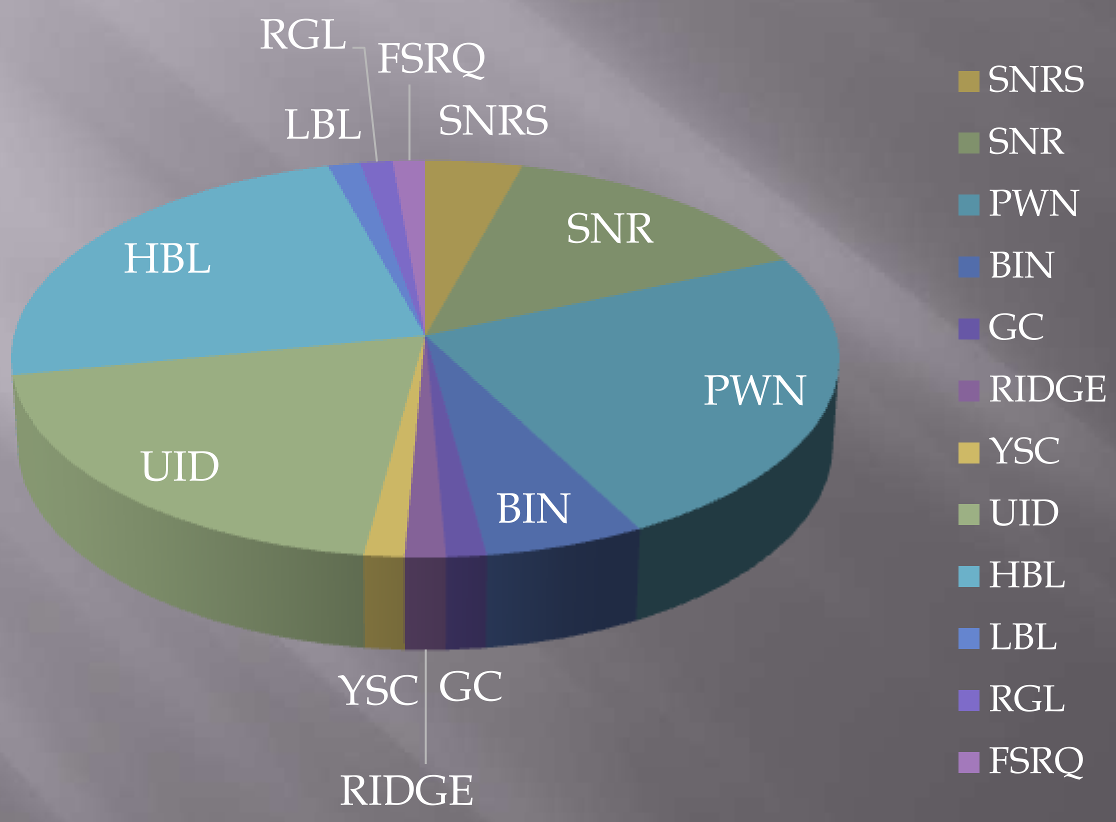
"Kifune plot"

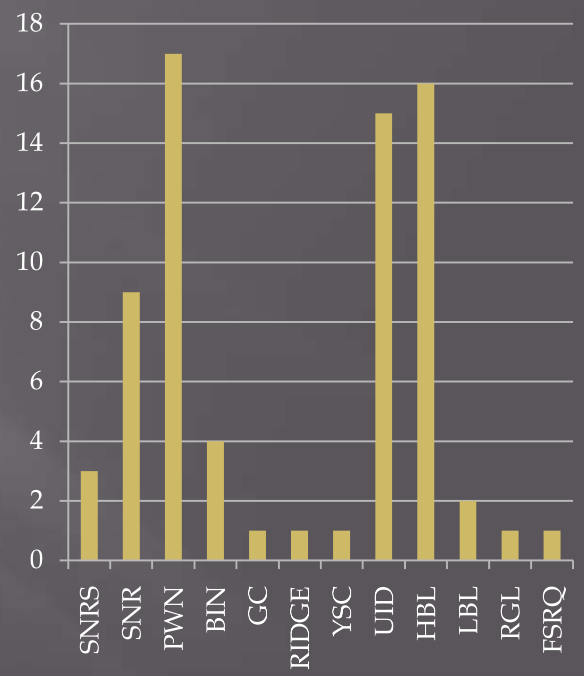


Source count versus year [T. Kifune]

Classified by M. Mori

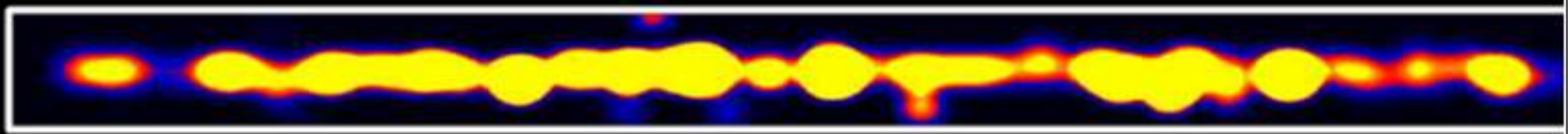
TeV sources classified

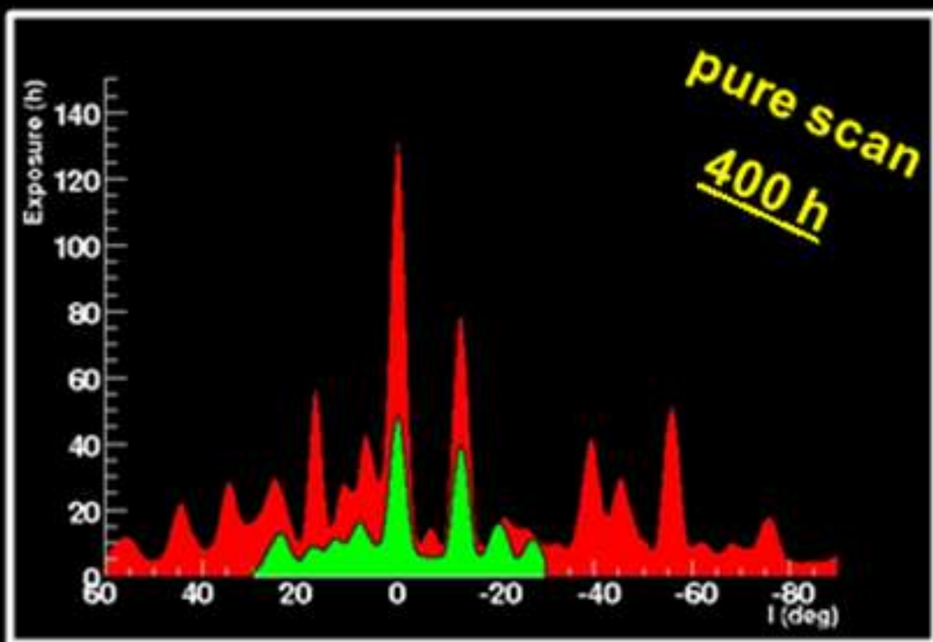




* Borders for SNR/PWN/UnID are vague…

H.E.S.S. Galactic survey

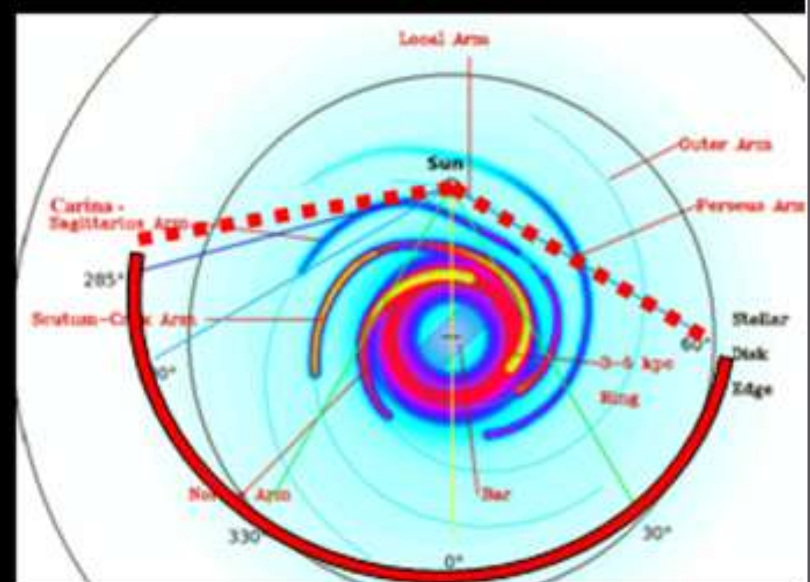




Survey region was extended in the years 2005 - 2007

Hoppe 269

-85° < l < 60°   -2.5° < b < 2.5°



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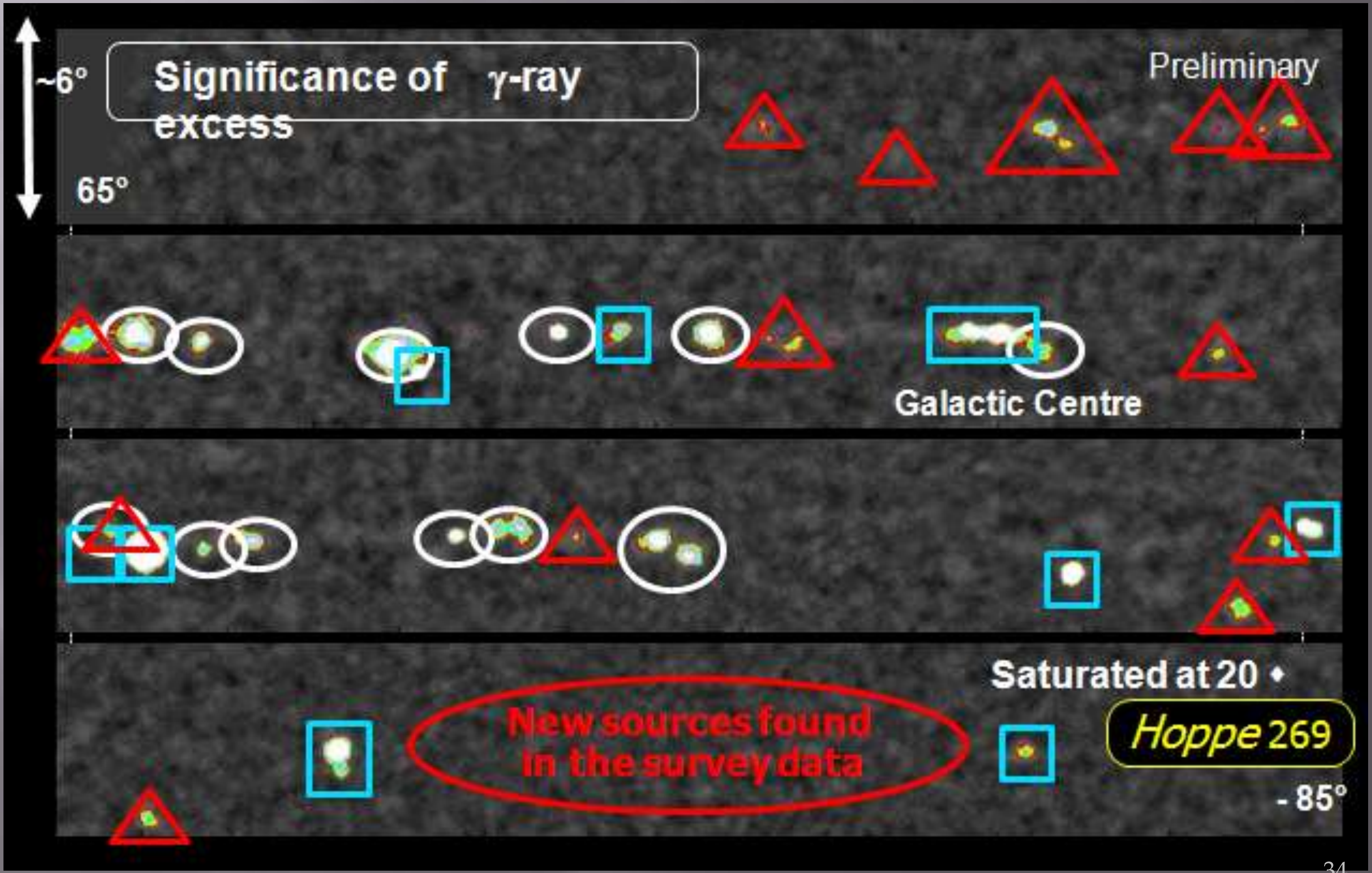
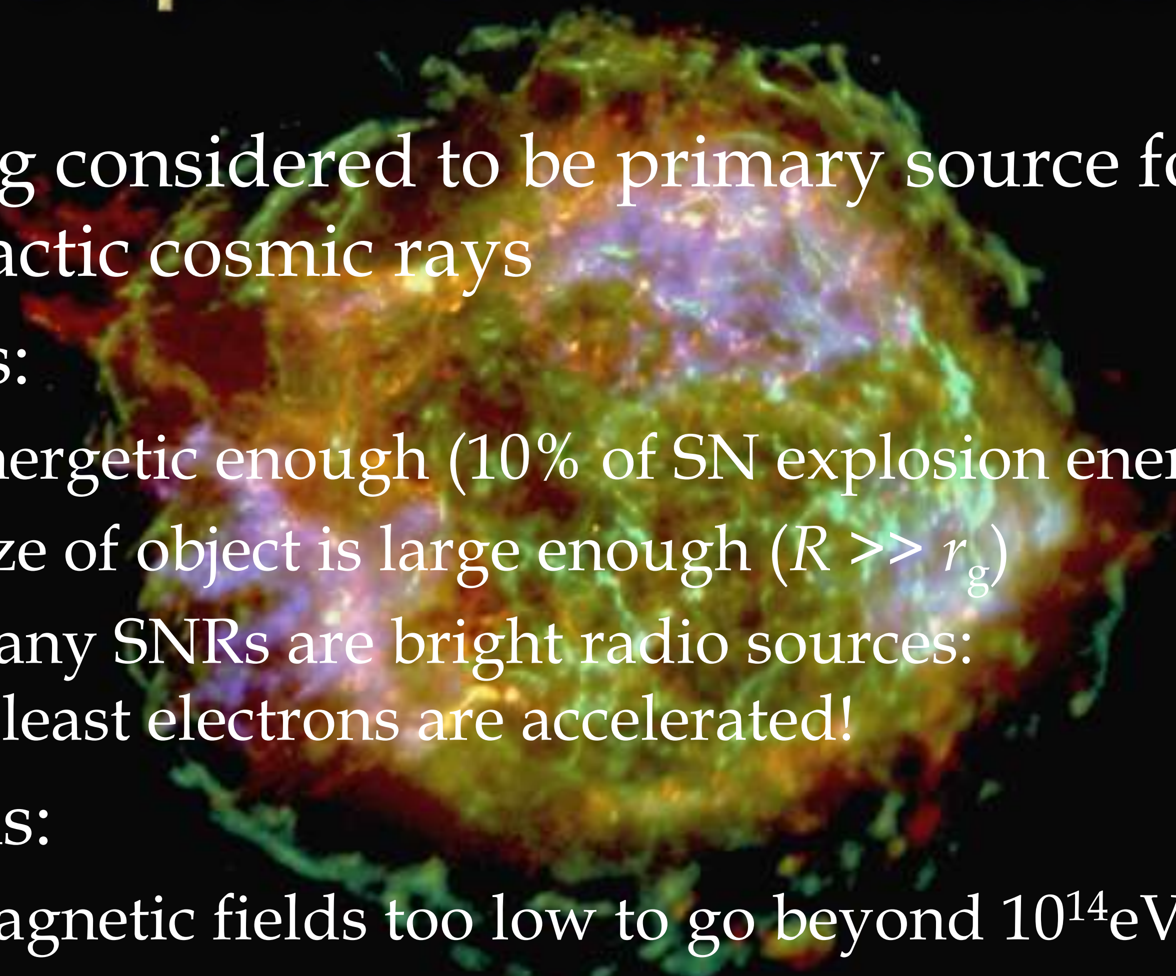


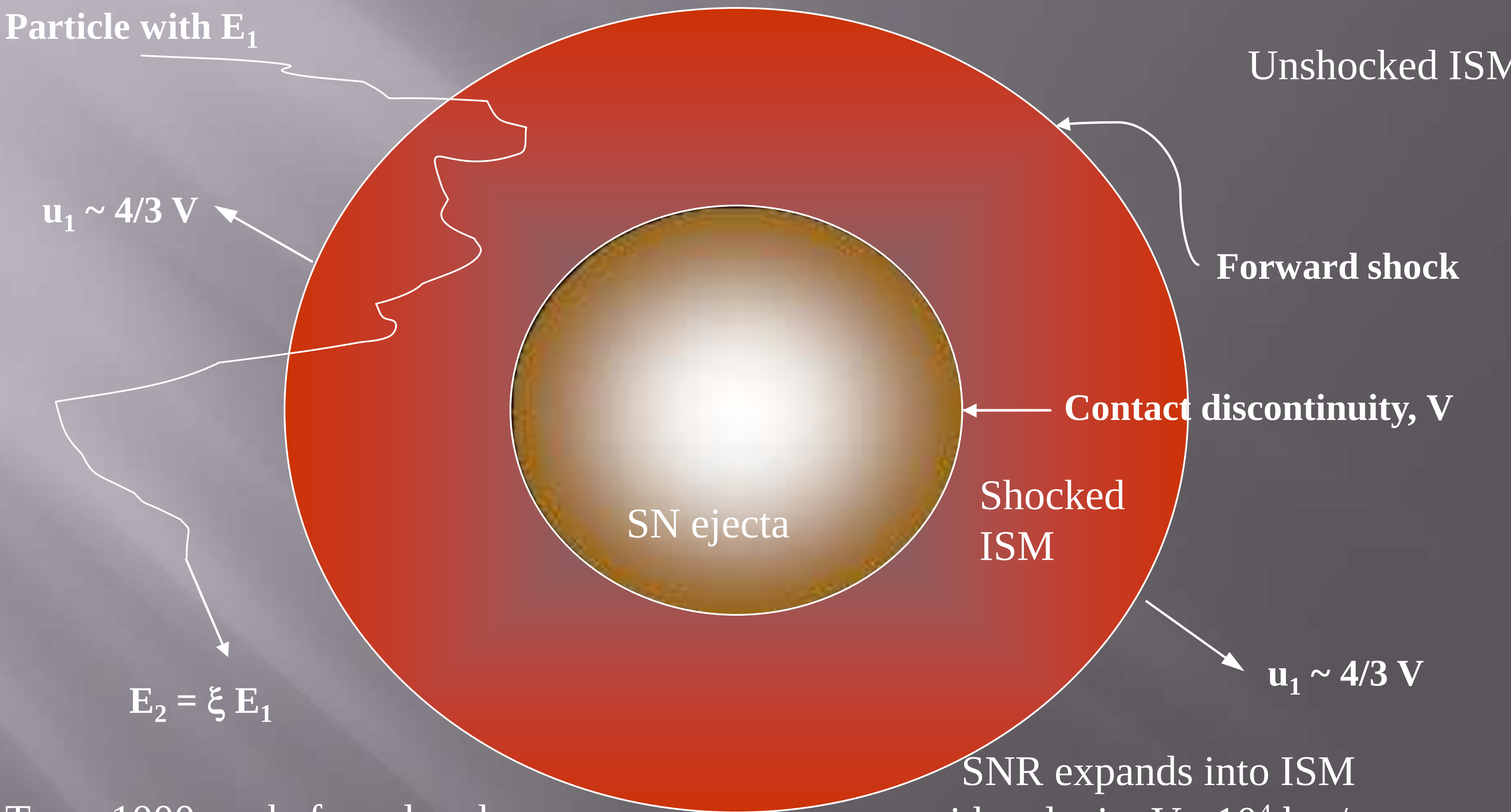
Supernova remnants



- Long considered to be primary source for Galactic cosmic rays
- Pros:
  - Energetic enough (10% of SN explosion energy)
  - Size of object is large enough ($R >> r_g$)
  - Many SNRs are bright radio sources: at least electrons are accelerated!
- Cons:
  - Magnetic fields too low to go beyond 10^{14}eV
  - Additional problem: adiabatic losses

Cas A by Chandra

Supernova blast wave acceleration



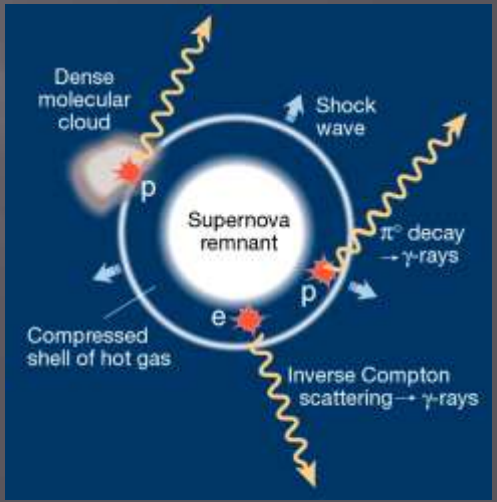
SNR expands into ISM
with velocity V~ 10^4 km/s.
Drives forward shock at 4/3 V

$T_{SN} \sim 1000$ yrs before slowdown
$E_{max} \sim Z \times 100$ TeV

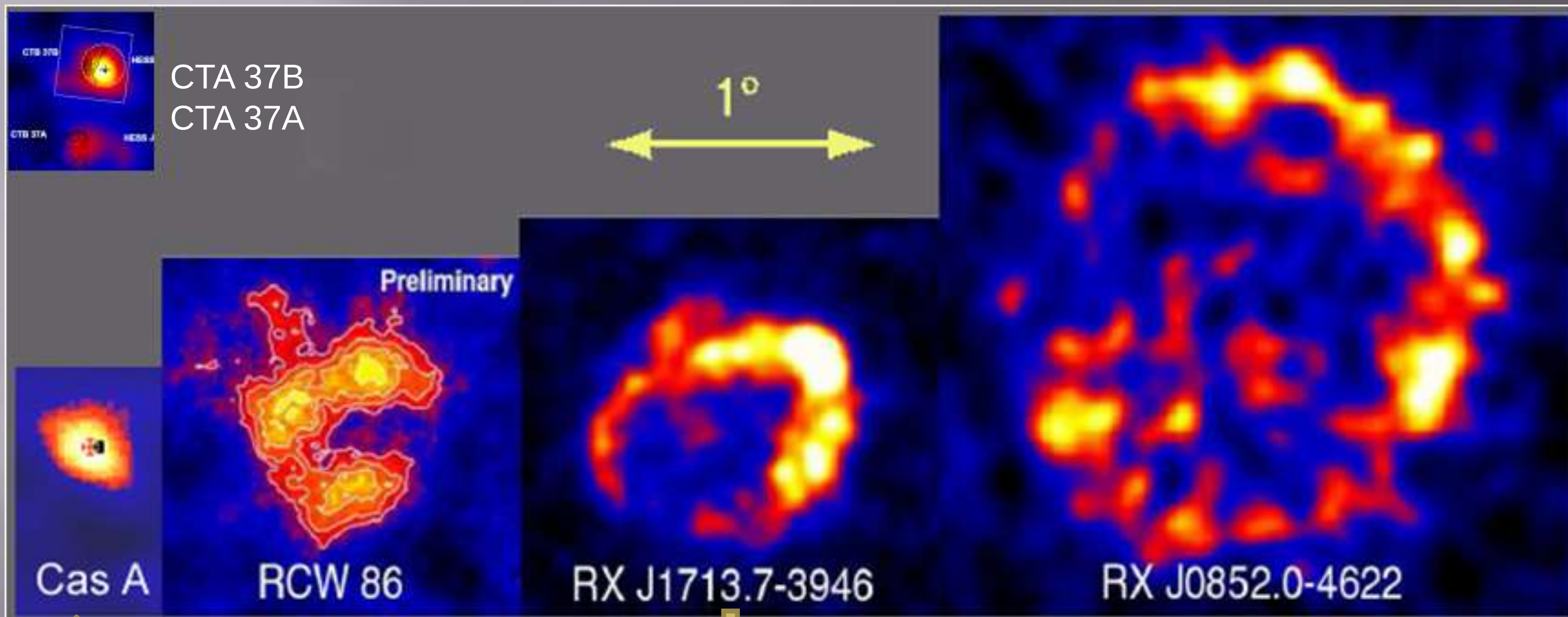
36

Problem of simplest SNR shock model

- Expected shape of spectrum:
  - Differential index $\alpha \sim 2.1$ for diffusive shock acceleration
    - $\alpha_{observed} \sim 2.7$; $\alpha_{source} \sim 2.1$; $\Delta\alpha \sim 0.6$ → $\tau_{esc}(E) \sim E^{-0.6}$
    - $c\,\tau_{esc}$ → T_{disk} ~100 TeV
    - → Isotropy problem
- $E_{max} \sim \beta_{shock}\, Ze \times B \times R_{shock}$
  - → $E_{max} \sim Z \times 100$ TeV with exponential cutoff of each component
  - But spectrum continues to higher energy:
    - → E_{max} problem
- Expect p + gas → γ (TeV) for certain SNR
  - Need nearby target as shown in picture from *Nature* (April 02)
  - Some likely candidates (e.g. HESS J1745-290) but still no certain example
  - → Problem of elusive π^0 γ-rays

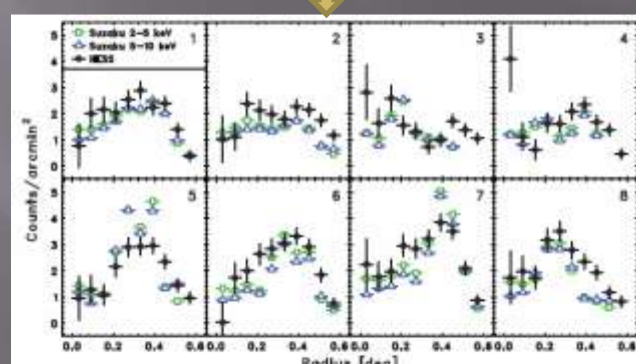


Shell SNRs seen at TeV



Comparable to PSF (0.09°)

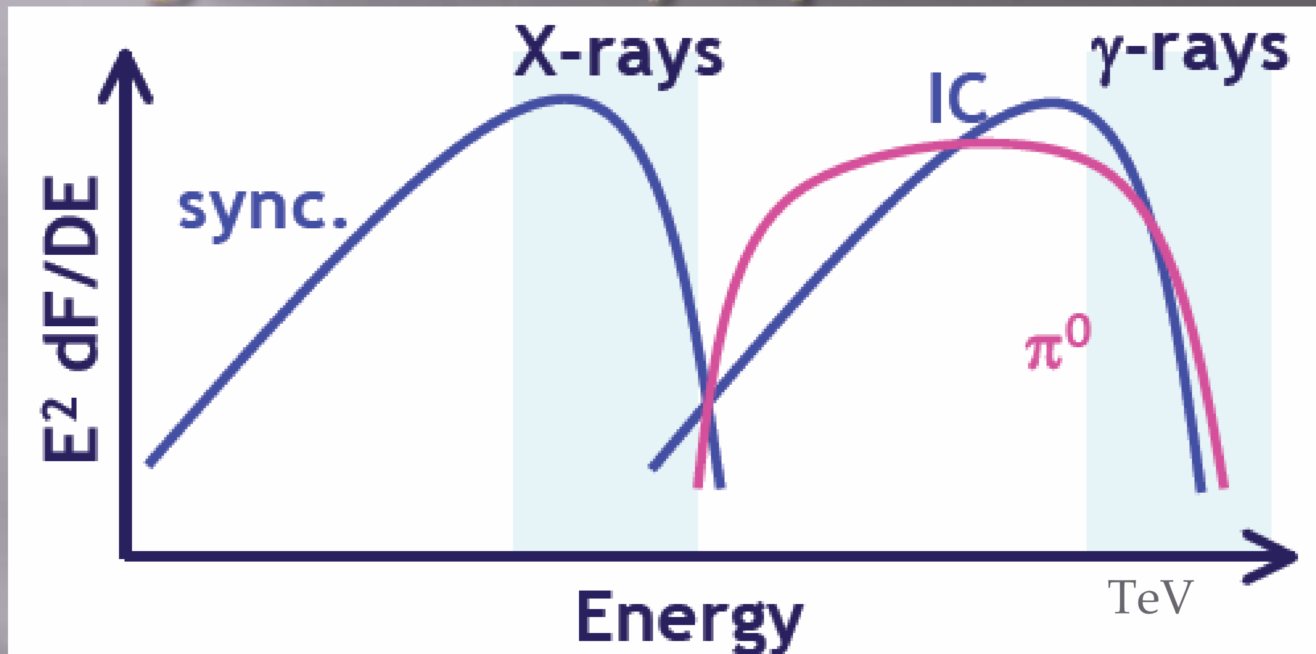
J. Albert et al., A&A 474, 934 (2007)



T.Tanaka, PhD thesis, 2007

Good keV-TeV Correlation!

Accelerated particles and gamma-ray spectrum



©A.Bamba

p/e ratio problem

Proton → Π^0 decay → Flat spectrum above 100MeV

Electron → Synchrotron X-rays → Inverse Compton gamma-rays

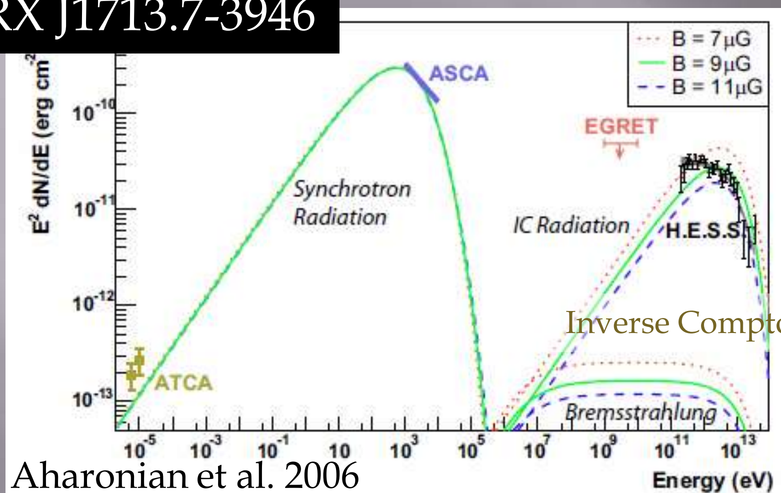
SNR spectrum

Hard power-law + cutoff (?): ~$E^{-2}\exp(-E/E_{max})$

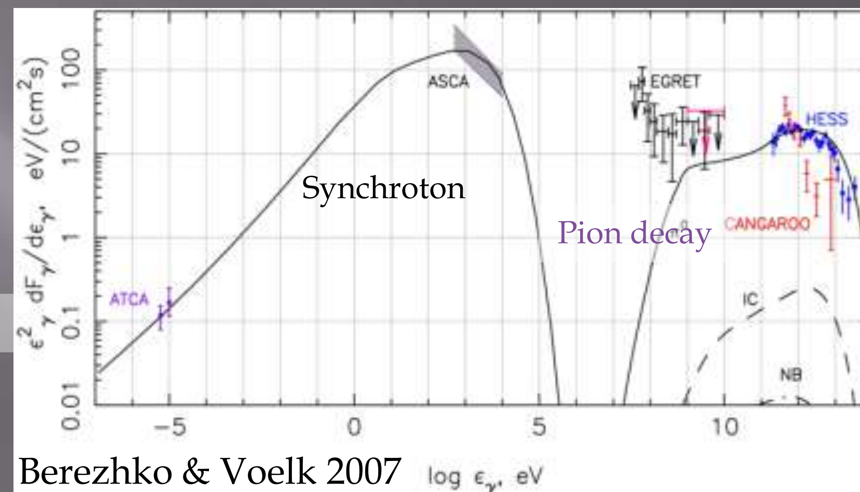
Electron model

Proton model

RX J1713.7-3946

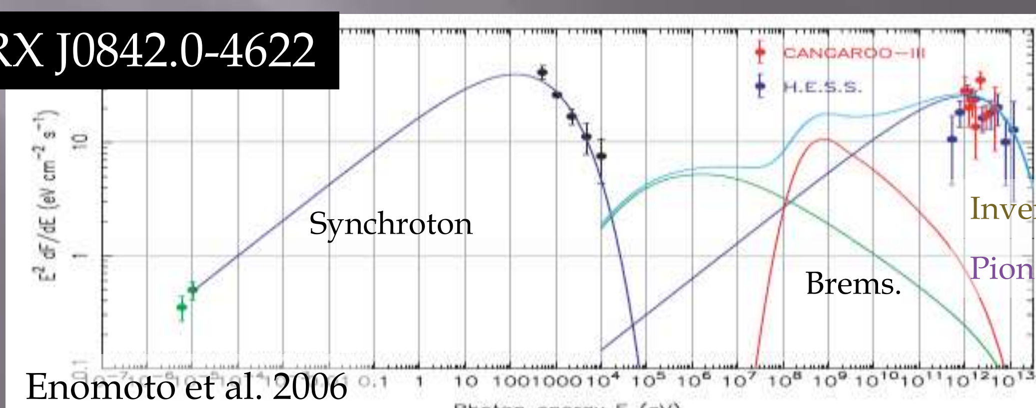


Aharonian et al. 2006



Berezhko & Voelk 2007

RX J0842.0-4622



Enomoto et al. 2006

NO definitive answer for accelerated particles!

D. Ellison et al., ApJ 661 (2007) 879

Identification of particles is not easy

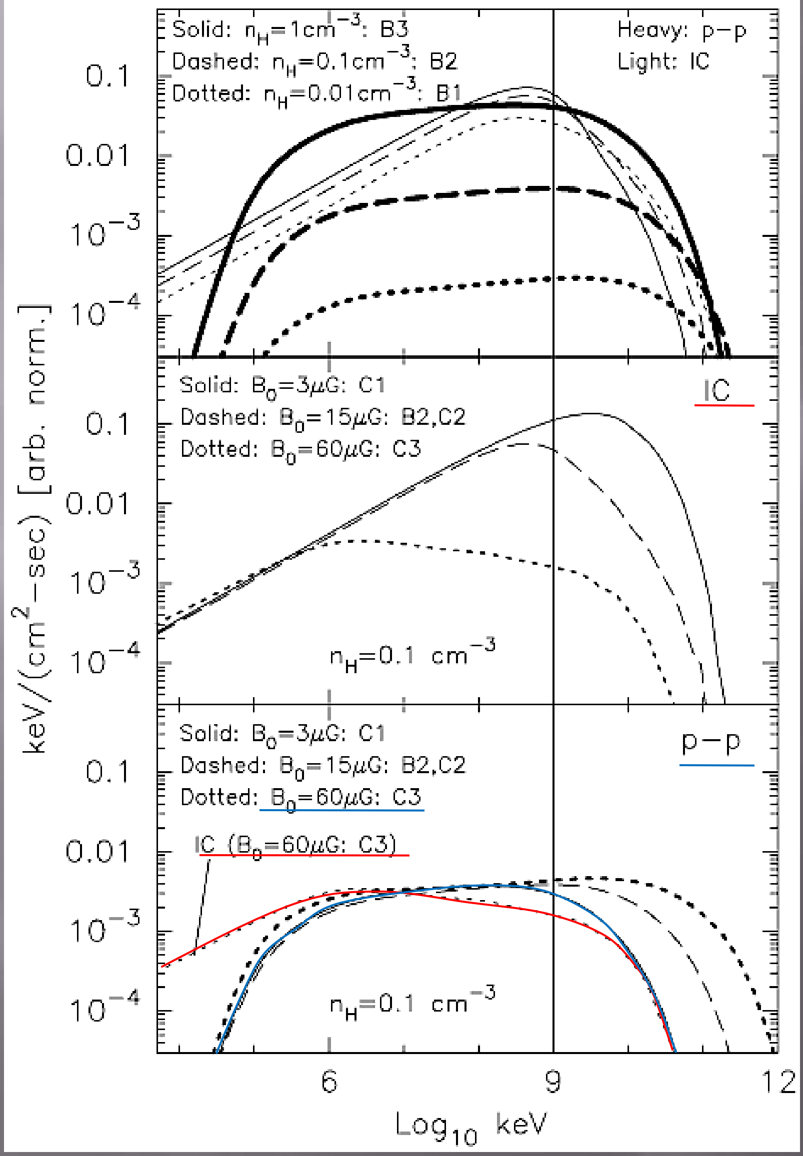


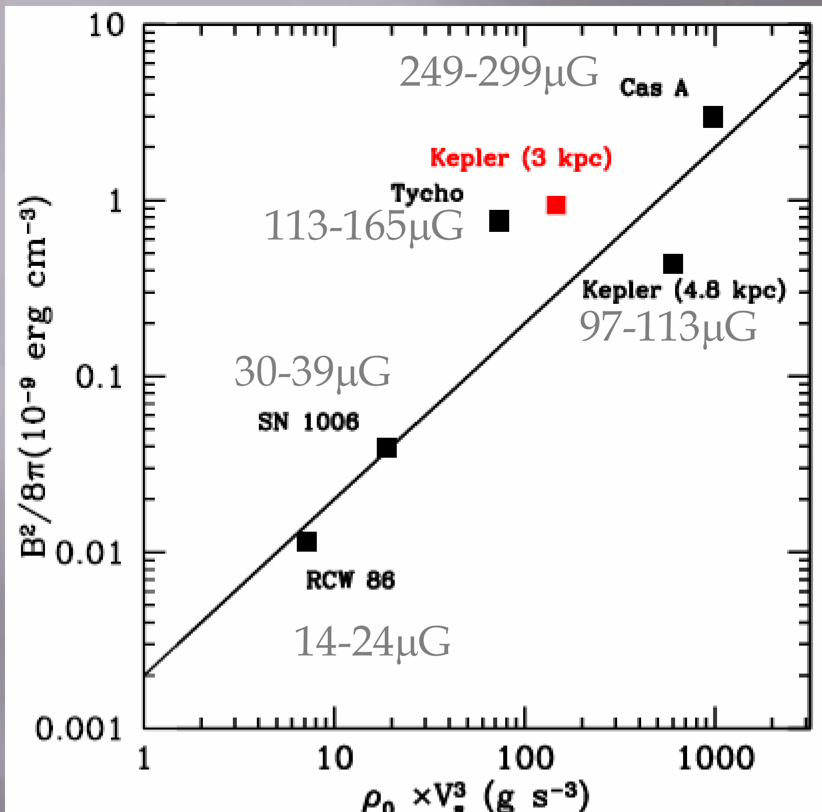
Fig. 12.—Pion-decay and IC emission for a range of n_H and B_0. In the top panel, the heavy curves are pion decay, the light curves are IC, and $\epsilon_{rel} = 36\%$ and $B_0 = 15\ \mu G$ in all cases. The strong dependence of pion decay on ambient density n_H is evident. The middle panel shows IC, and the bottom panel shows pion decay for $n_H = 0.1\ cm^{-3}$, with B_0 varying from 3 μG (*solid curves*) to 15 μG (*dashed curves*) to 60 μG (*dotted curves*). For comparison to the π^0, we show in the bottom panel the IC emission for $B_0 = 60\ \mu G$ (*light dotted curve*). The particle distributions producing the emission in the bottom two panels are those shown in the top panel of Fig. 11.

Difficult in the GeV-TeV region if magnetic field is strong!

J. Vink, astro-ph/0601131

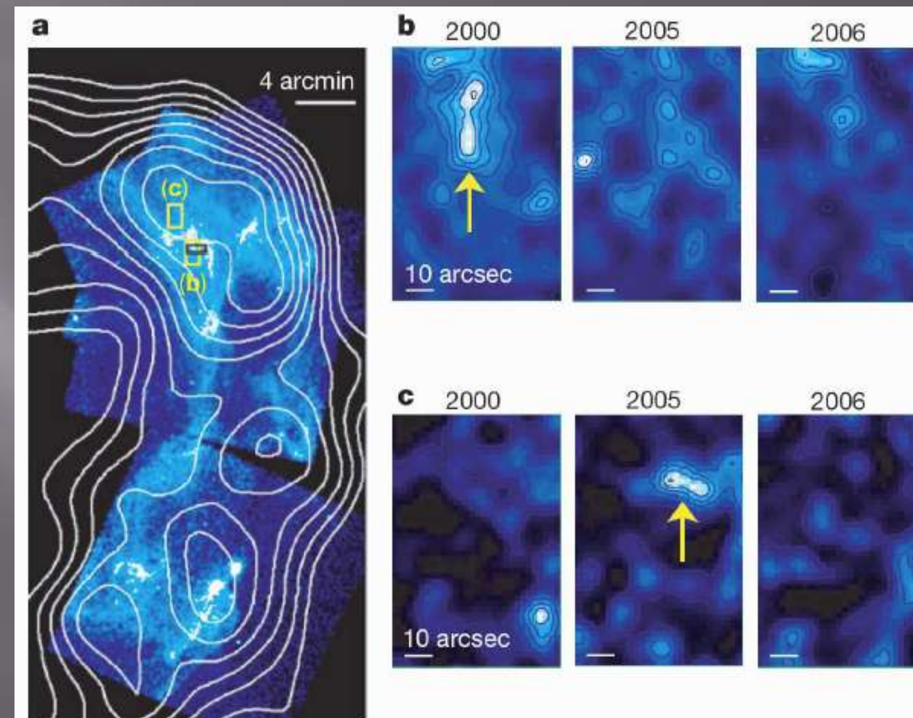
Y. Uchiyama et al., Nature 449, 576 (2007)

Magnetic field in SNR



SNR	Dist kpc	V_s km s^{-1}	n_0 cm^{-3}	width ″	B_{loss} μG	B_{diff} μG
Cas A	3.4	5200	3	0.5	249	299
Kepler	4.8	5300	0.35	1.5	97	113
Tycho	2.4	4500	0.3	2	113	165
SN1006	2.2	4300	0.1	20	30	39
RCW86	2.5	3500	0.1	45	24	14

RX J1713.7-3946 by Chandra

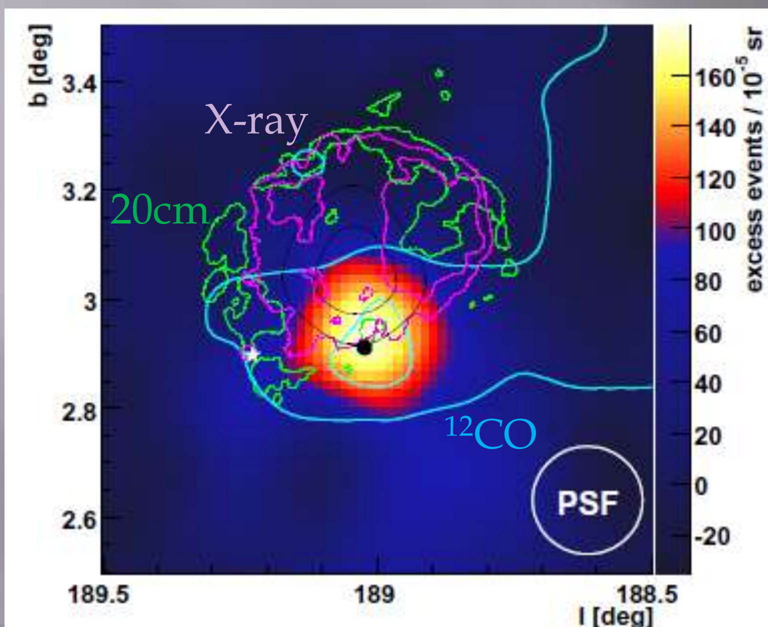


Variation in ~1yr time scale
→ Need > 1mG ! (locally)
→Protons produce TeV gamma-rays!?

Counter arguments: Y.Butt et al. , arXiv:0801.4954

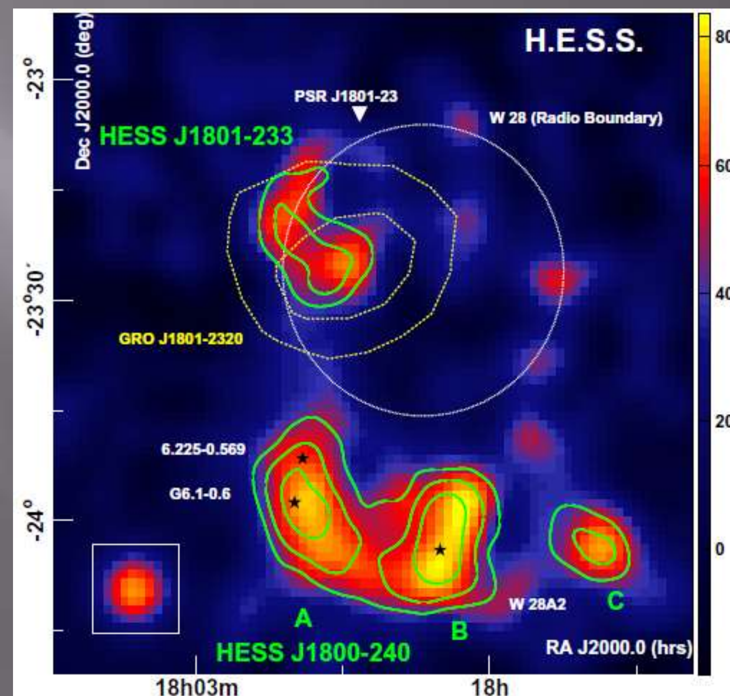
SNRs interacting with clouds?

IC443

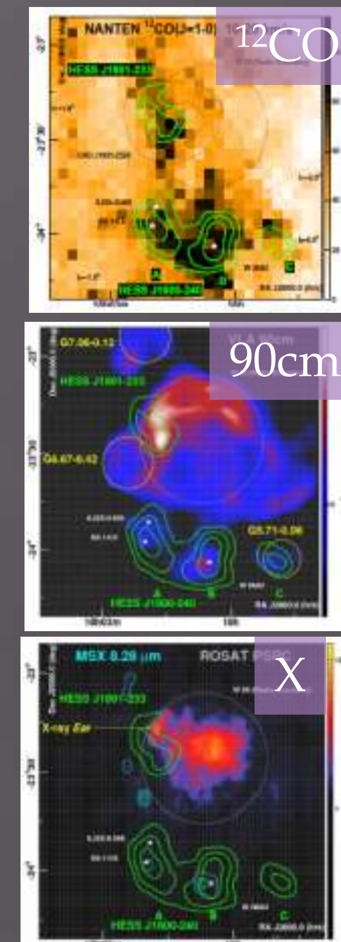


[MAGIC, Albert et al. , ApJ 664, L87,2007]

W28



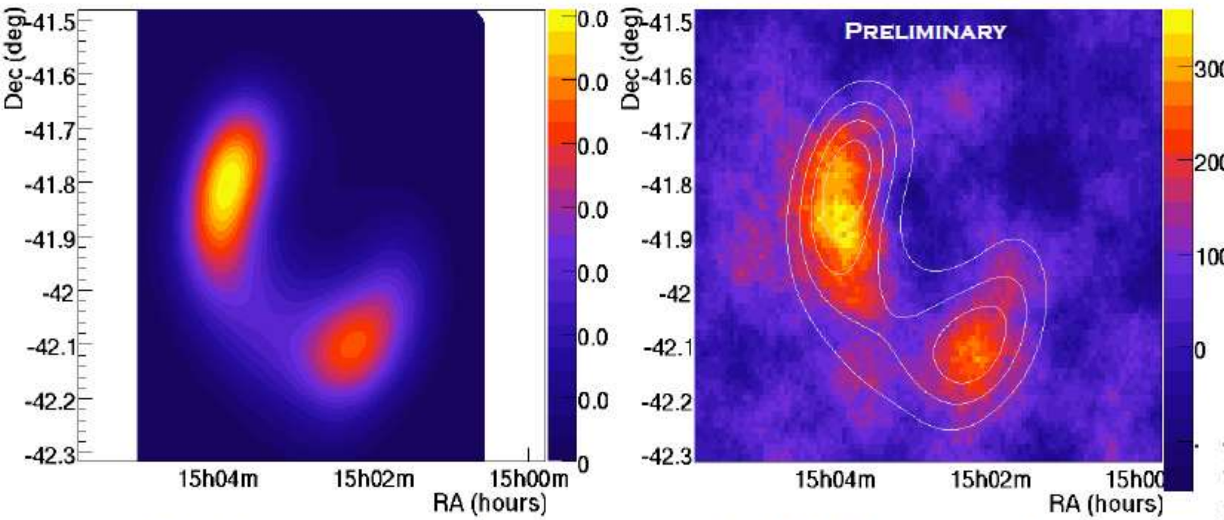
[H.E.S.S., Aharonian et al. , A&A, in press]



Evidence of proton acceleration?

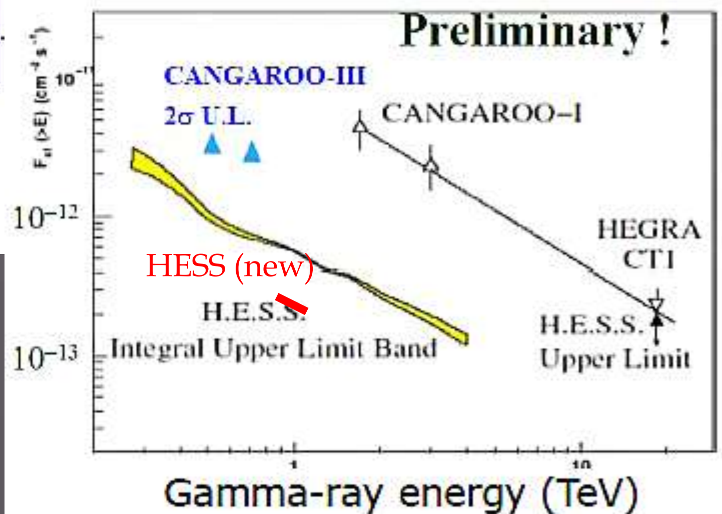
SN1006

Chandra and H.E.S.S. Morphology



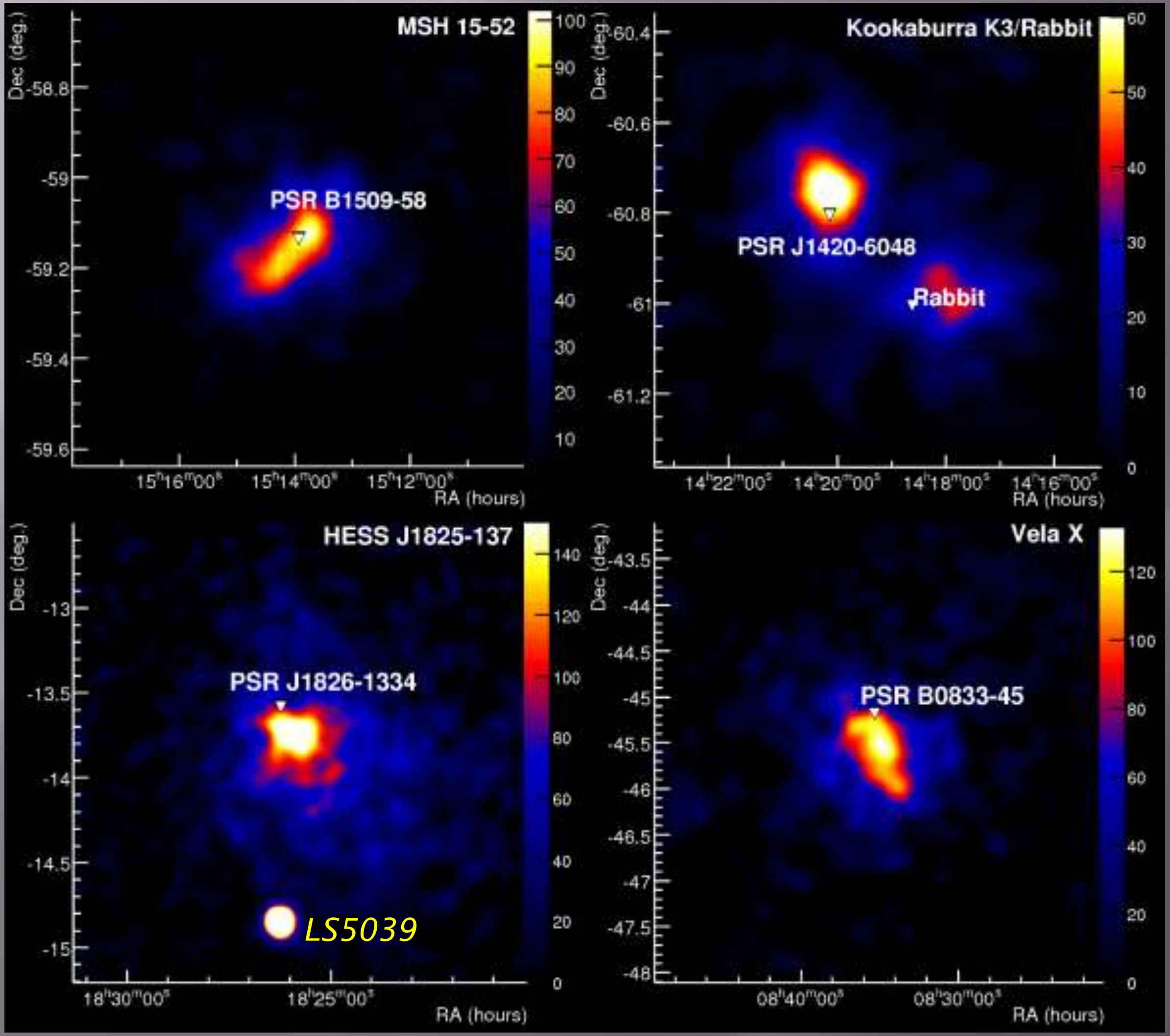
➡ Chandra map smoothed by the H.E.S.S. PSF and oversampled with 0.1°

➡ H.E.S.S. map with Chandra contours



- Independent analysis methods confirm the detection of the NE rim of SN 1006 at about 6 sigma in the region pre-defined in the 2004 H.E.S.S. upper limit paper
- Compatibility with non-thermal X-ray morphology very good
- Given the flux level of ~1% Crab, both leptonic and hadronic scenarios are reasonable

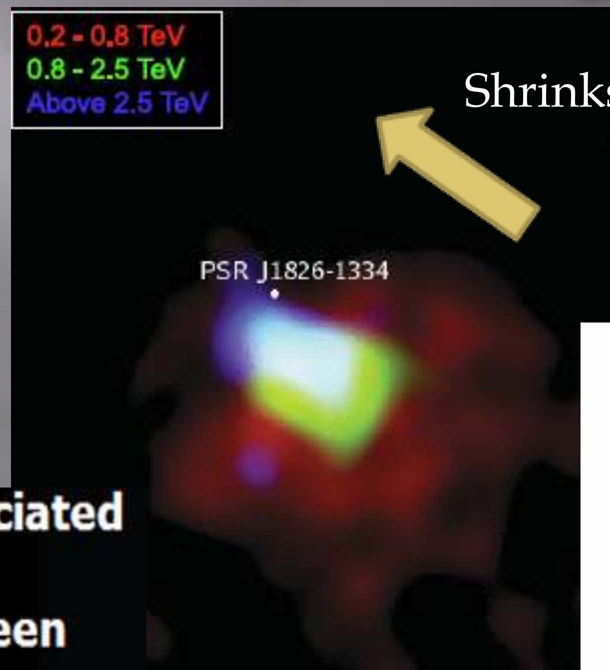
Pulsar nebulae



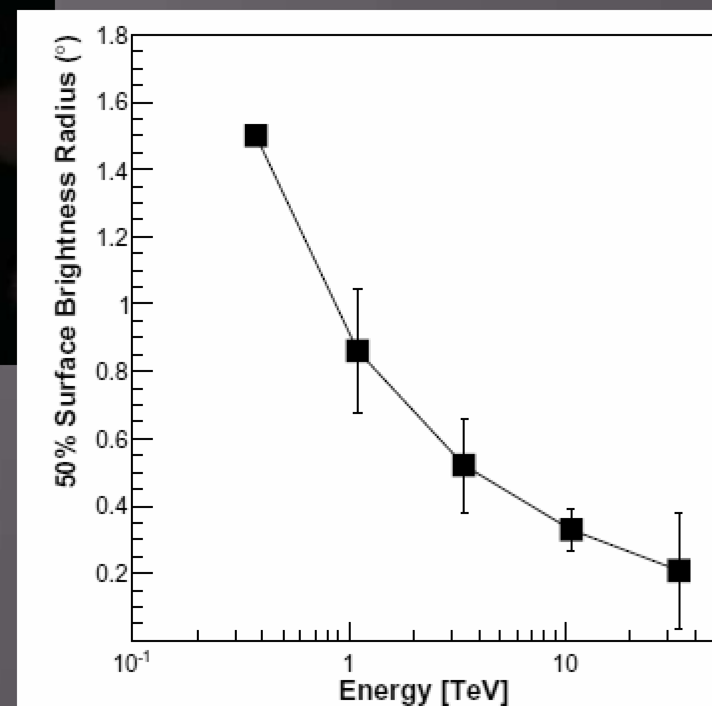
- Major group in Galactic TeV sources
  - 18/71 by Hinton (2007ICRC)
  - Associated with relatively young (<10^5 years) and large spin-down pulsars
- Extended *O*(10pc), displaced from pulsars
- Gamma-rays via inverse Compton by electrons?

S. Funk et al., ICRC 2007

Pulsar nebula: energy-dependent morphology

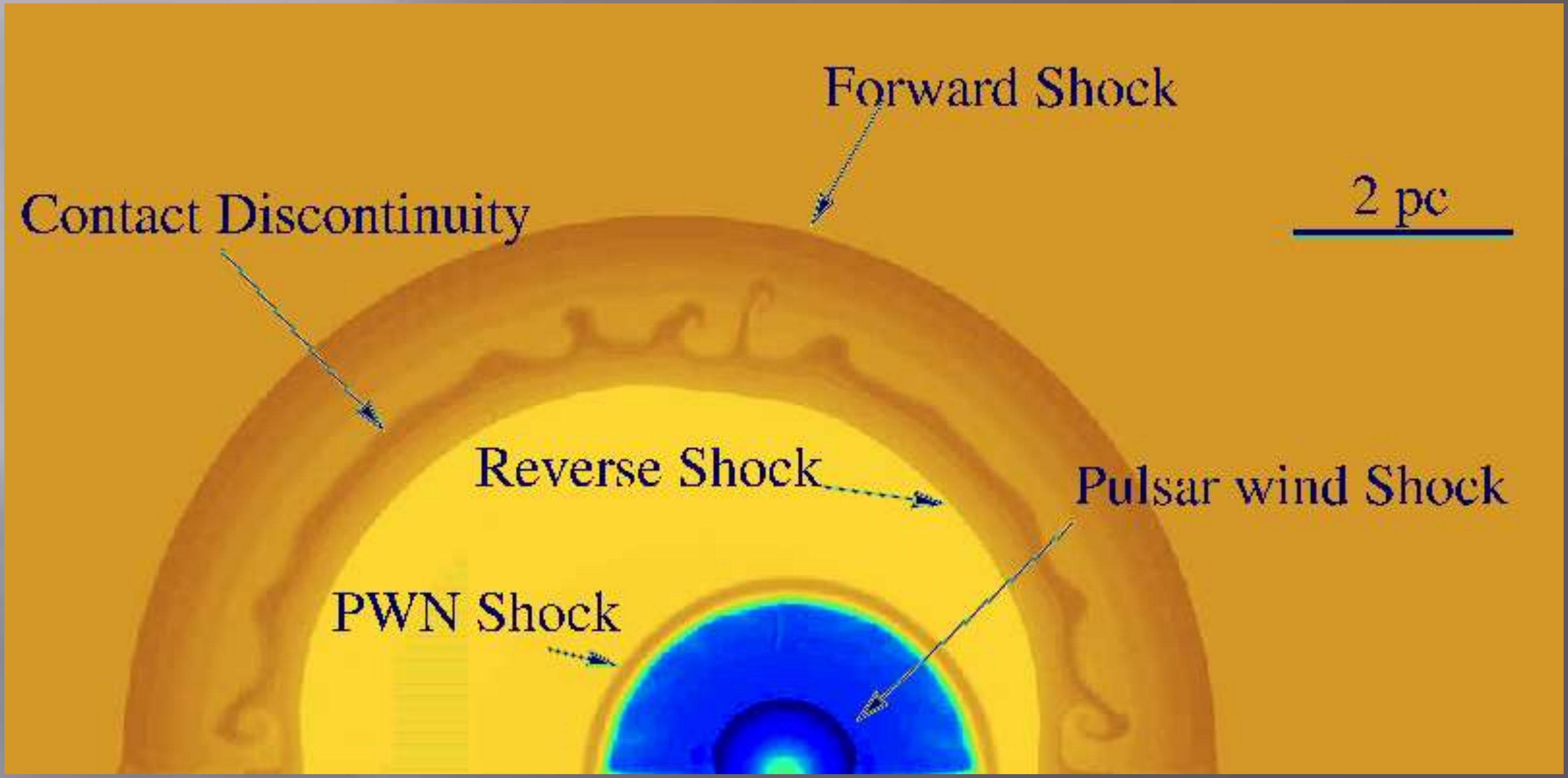


- **HESS J1825-137 associated with energetic pulsar**
- **Spectral steepening seen away from the pulsar**
- **Very likely this is evidence for cooling of electrons in the Nebula**
  - **Seen in several *X-ray* PWN**
- **A first in gamma-ray astronomy!**



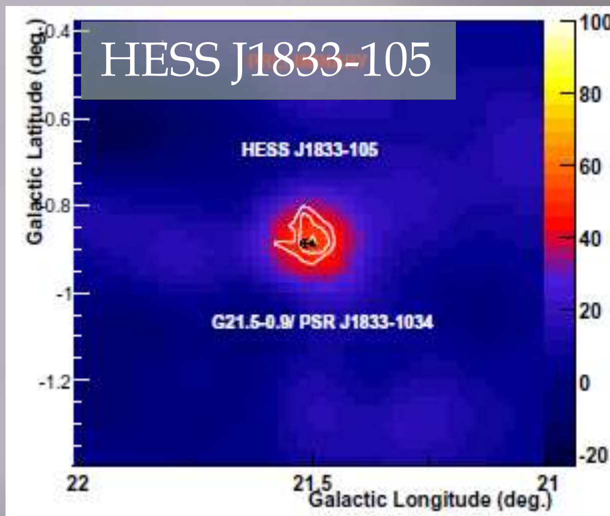
van der Swaluw, Downes, & Keegan 2003

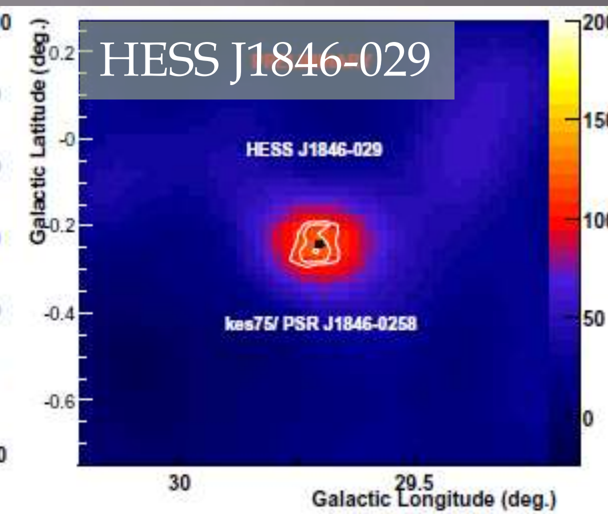
Simulations of Pulsar Wind Nebula



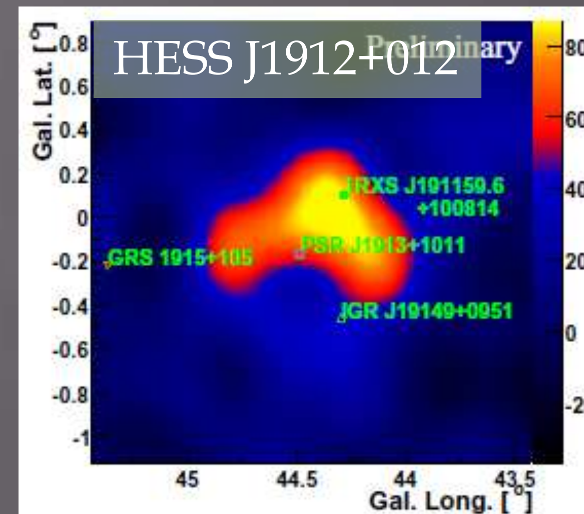
Displacement due to pulsar kick ?

More pulsar nebulae…

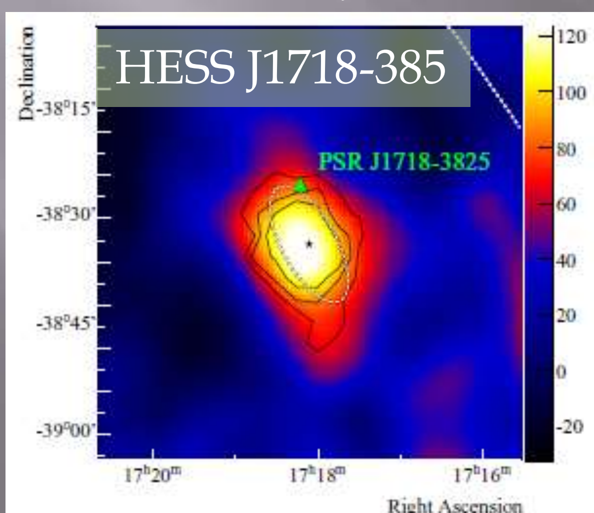




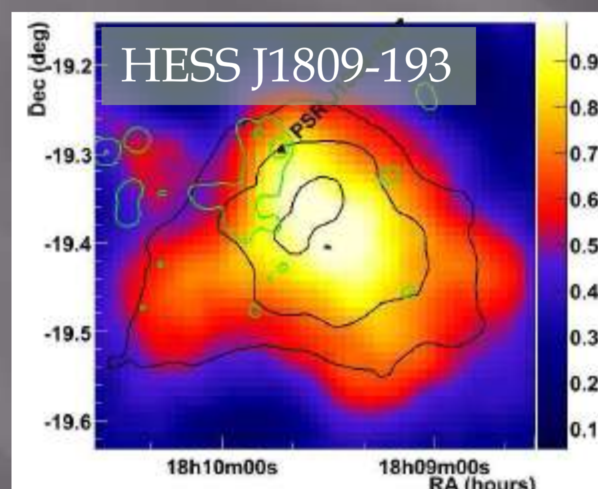
Djannati-Atai et al., ICRC2007



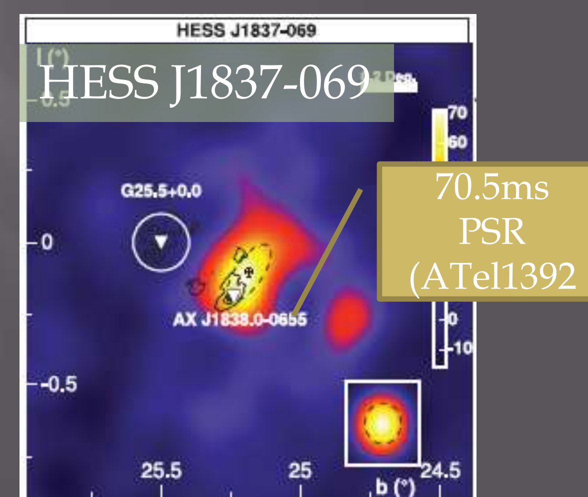
Hoppe et al., ICRC2007



Carrigan et al., ICRC2007



Komin et al., ICRC2007



Aharonian et al. ApJ 777 (2007)

S. Funk, paper 390, 30th ICRC (Merida), 2007

Pulsar nebulae and spin-down luminosity

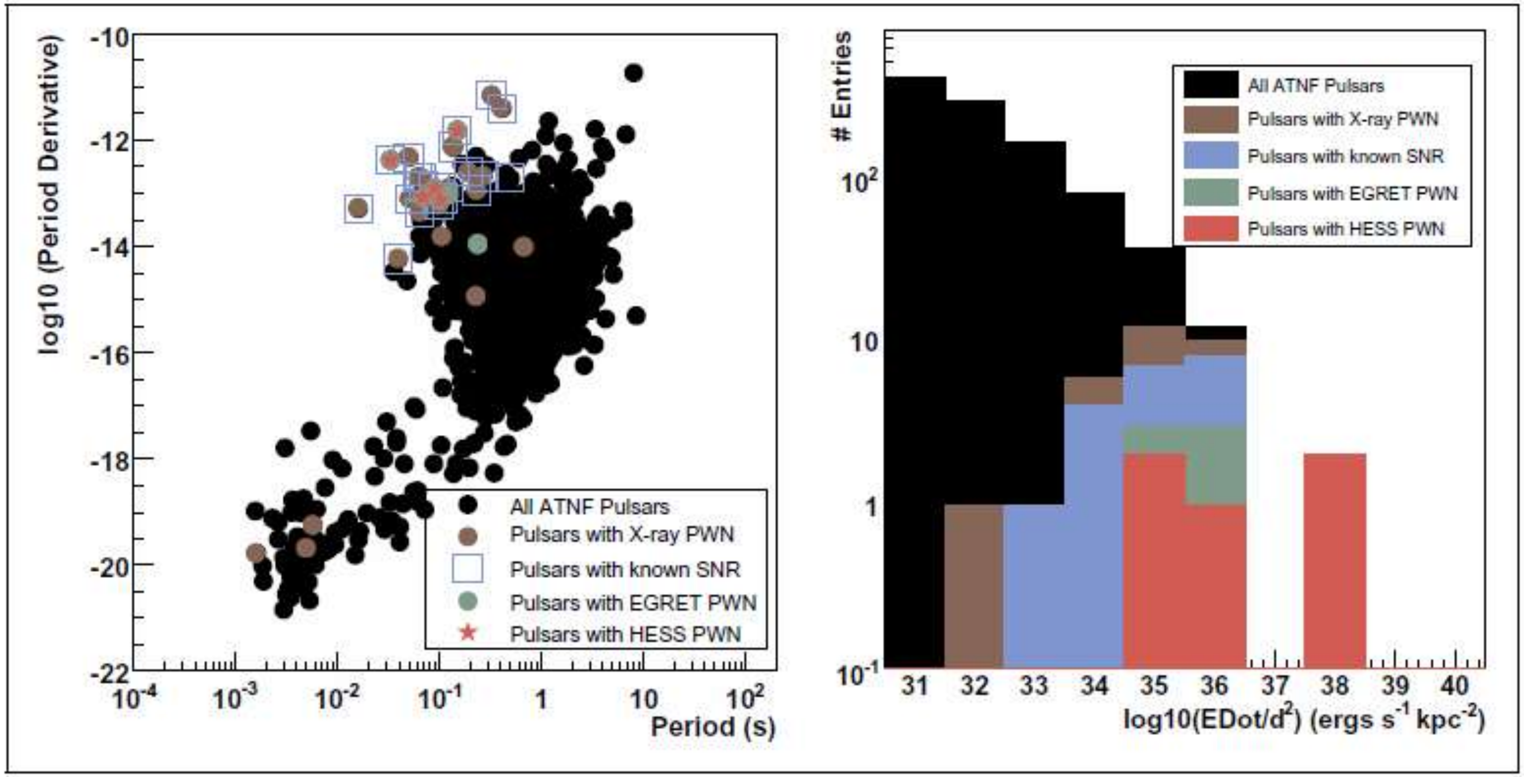
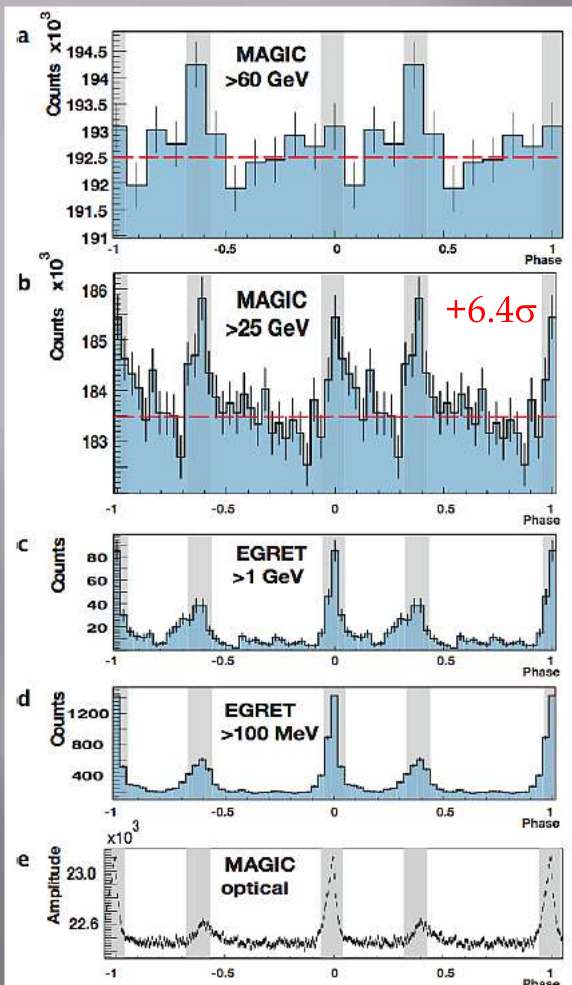


Figure 3: **Top:** $P - \dot{P}$ diagram for pulsars: all ATNF pulsars (black), with detected X-ray PWN (brown), with a known corresponding SNR (blue), potentially associated to an EGRET source (green), associated to a H.E.S.S. VHE PWN (red). **Bottom:** Energy output for the selections used at the top.

MAGIC: Aliu et al., arXiv: 0809.2998

Pulsed emission from Crab



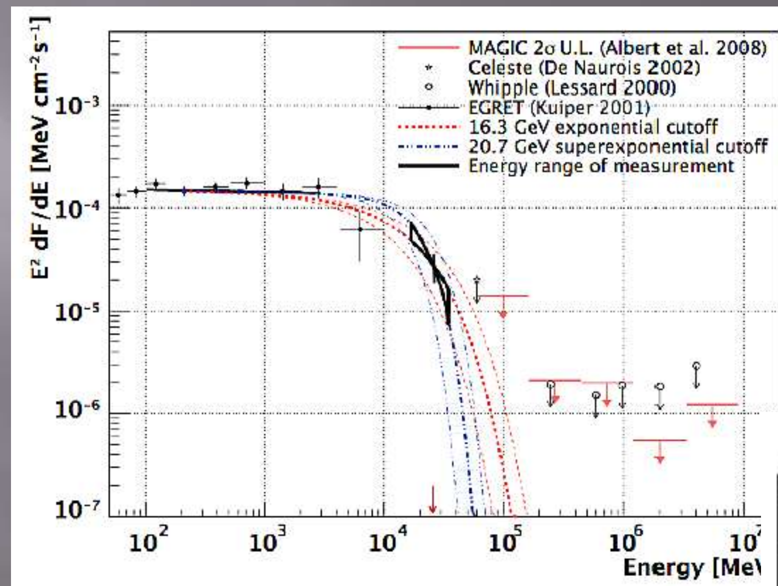
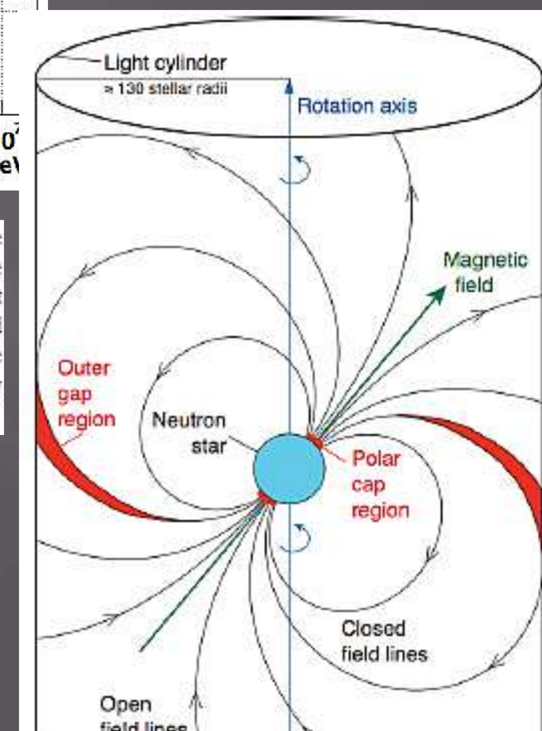


Figure 4: Crab pulsar spectral cutoff. The black flux point indicates the energy range and the statistical error of our flux measurement, assuming an exponential and a super-exponential cut-off. The black crosses on the left represent flux measurements from EGRET (15). The arrows on the right denote upper limits from various previous experiments. The EGRET spectrum has been extrapolated with an exponential (red) and a super-exponential (blue) shape. The coloured bands illustrate the combined statistical and systematic errors and denote the total uncertainty of our measurement, by which the flux point can move to higher or lower energies.

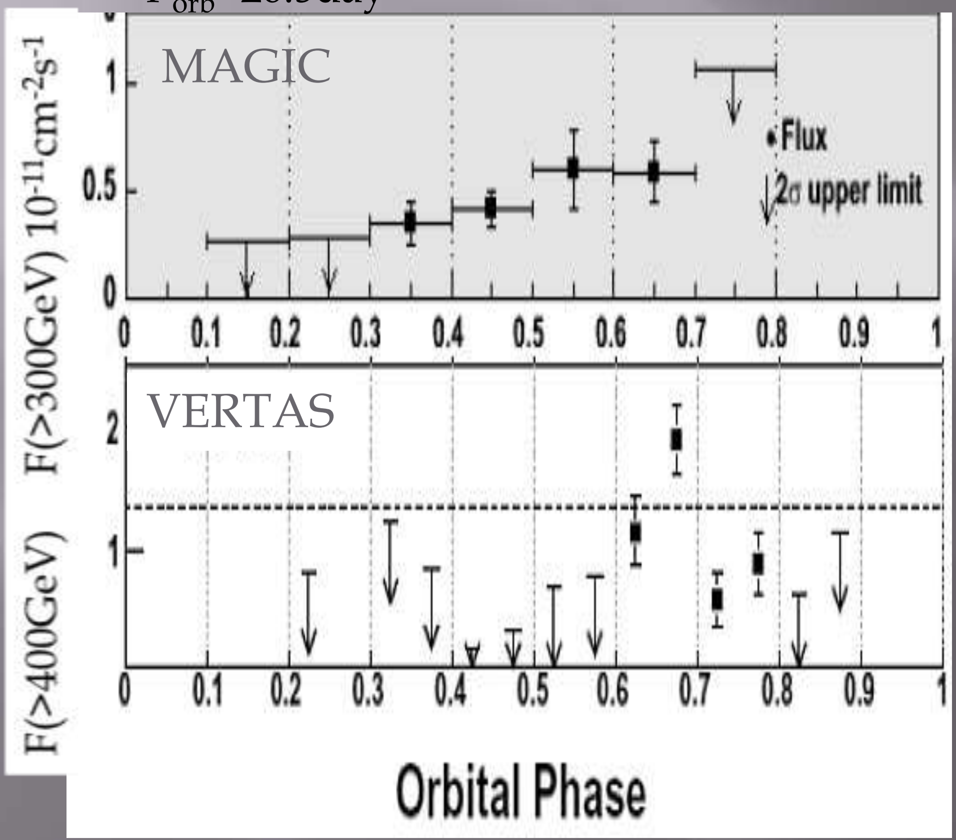
→Favors *outer-gap* model rather than *polar-cap* model



Gamma-ray binaries

LSI +61 303 (VERITAS/MAGIC)

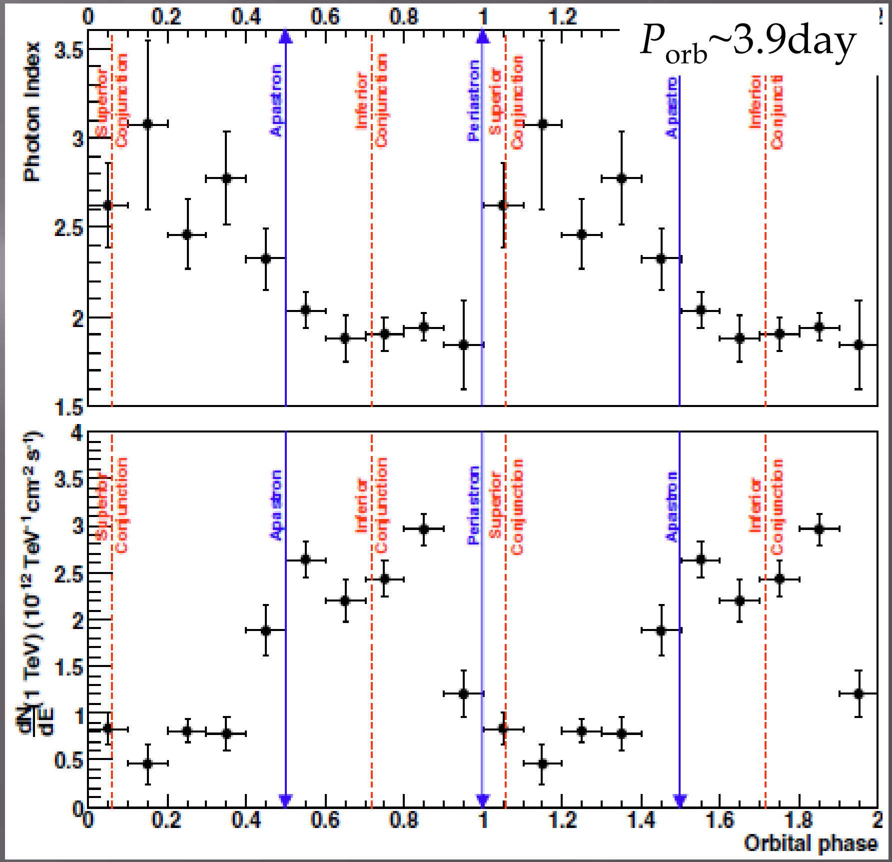
P_{orb}~26.5day



J. Albert et al., Science 312, 1771 (2006)
V.A. Acciari et al., arXiv:0802.2363

LS 5039 (H.E.S.S.)

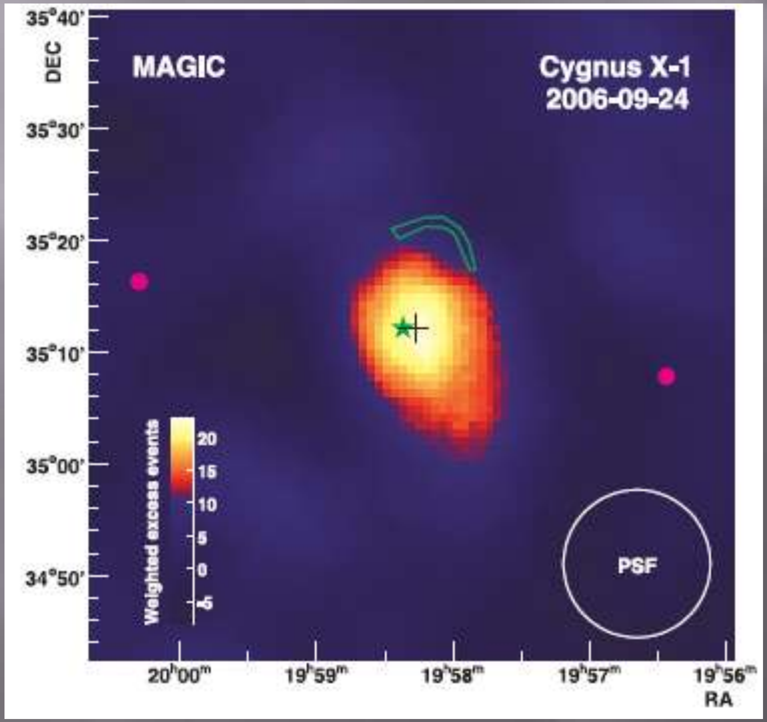
P_{orb}~3.9day

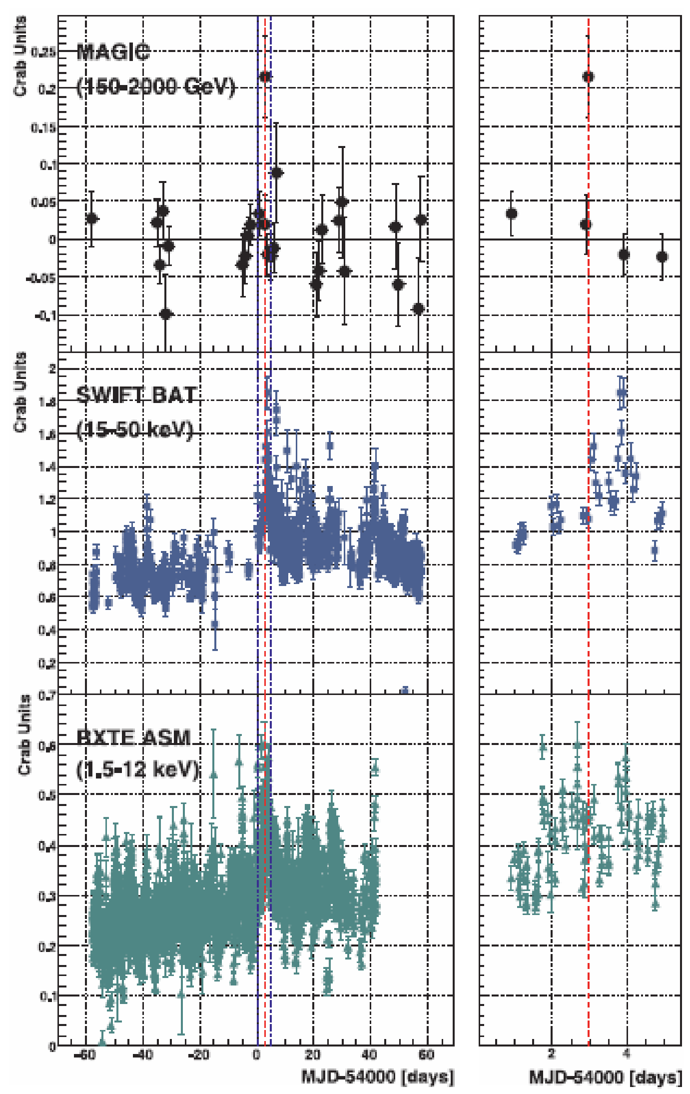


F. Aharonian et al., A&A 460 (2006) 743

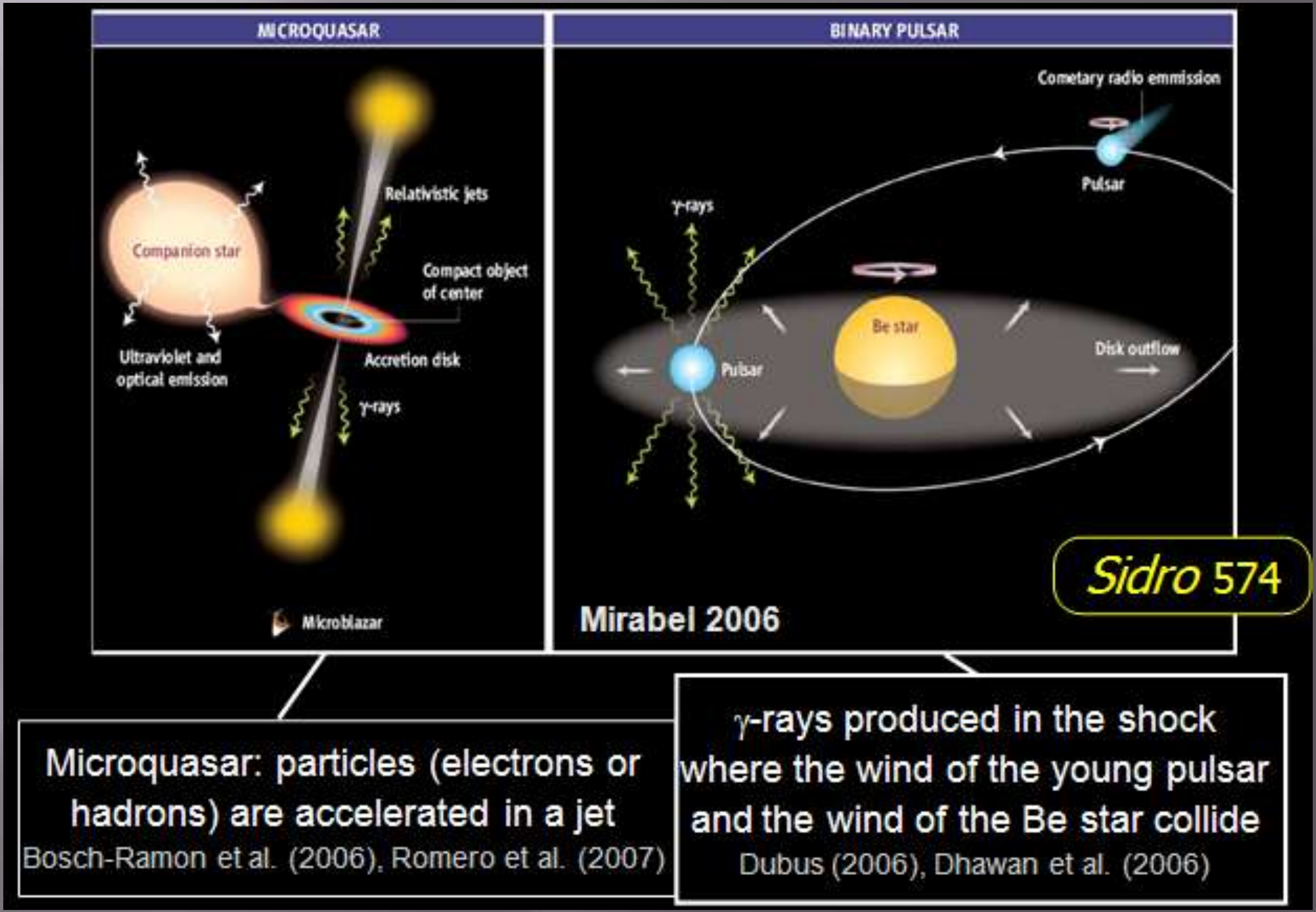
Gamma-ray binary : Cyg X-1

- Black hole binary: M_{BH}~21$M_\odot$, $M_\star$~30$M_\odot$
- Relativistic jet v>0.6c: "microquasar"
- MAGIC 40hr obs.
- 4.9σ seen in one 79 min. time slice
- Estimated significance: 4.1σ after correction for statistical trials





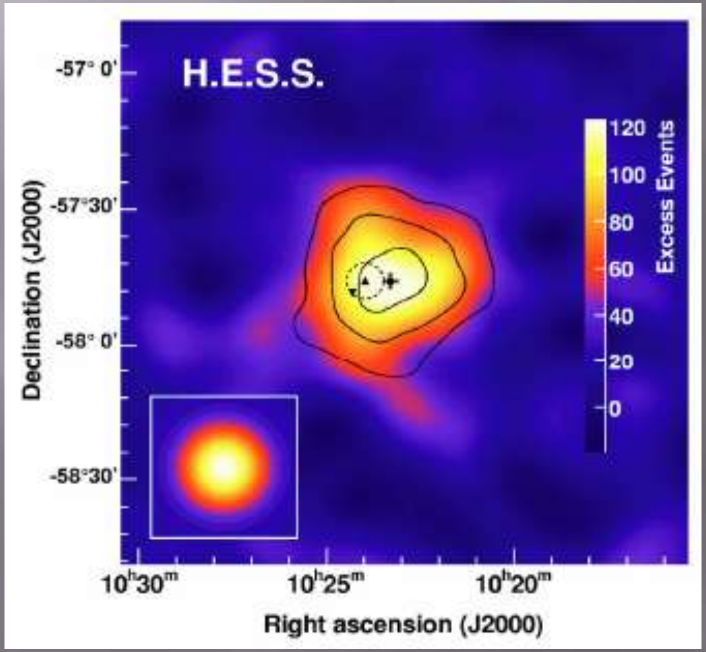
Emission from binaries

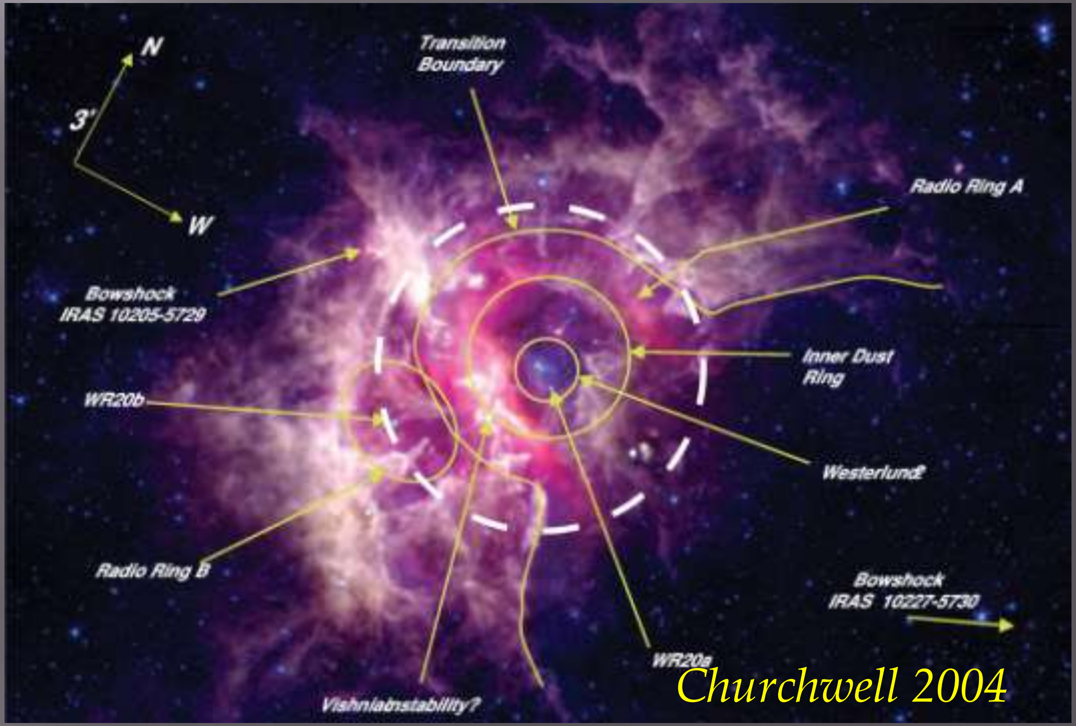


Aharonian et al., A&A 467, 1075 (2007)

Stellar cluster Westerlund 2

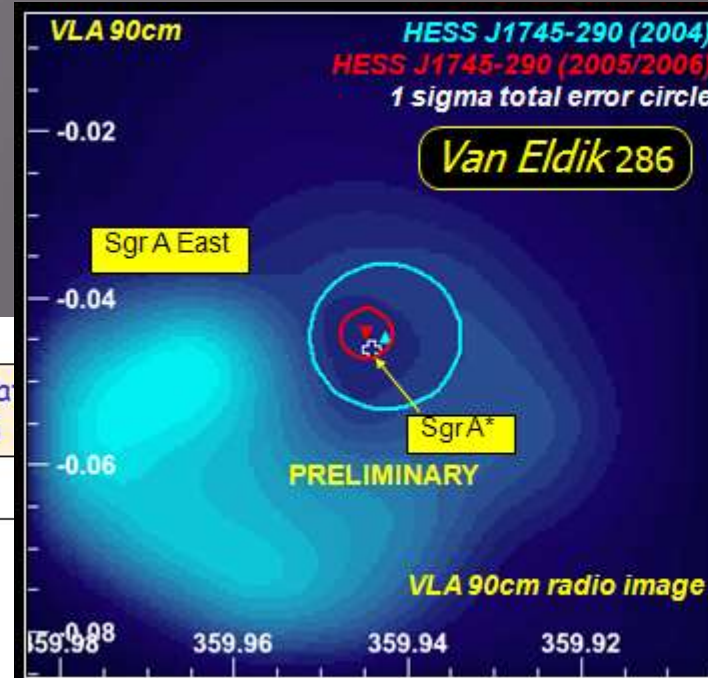
- Young open stellar cluster
  - Dozen O-stars
  - Two Wolf-Rayet stars (~$80M_{\odot}$ each)!
- Extended gamma-ray emission covering (but offset from) Westerlund 2 by HESS
- Due to collective effects of stellar winds in the cluster?
- A new source class?





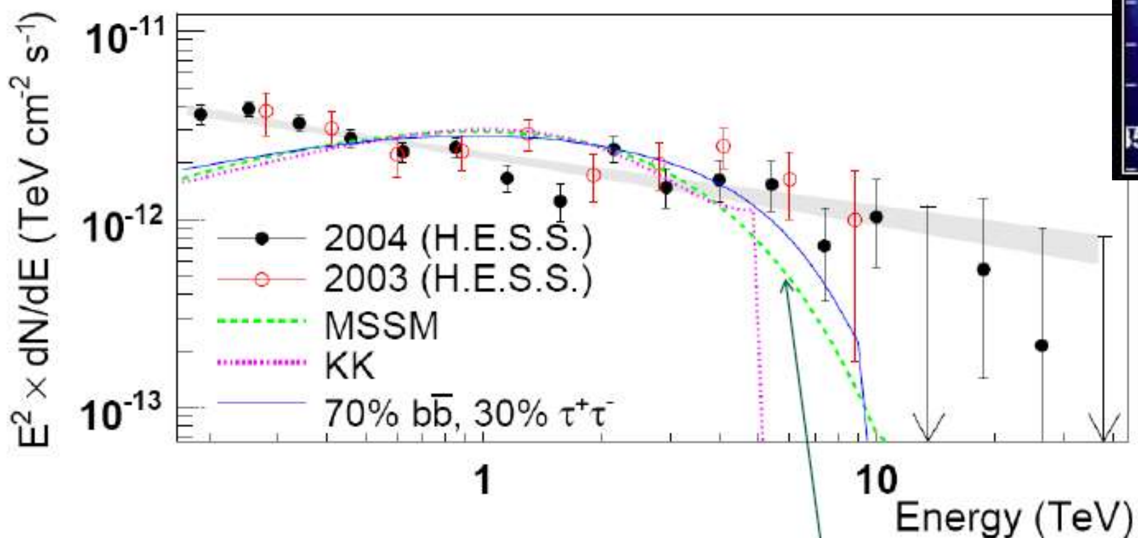
Van Eldik et al., ICRC 2007

Galactic center ≈ Sgr A*



HESS data 2003-2004 towards galactic centre. (We await 2005-6 data eagerly...)

MAGIC (2006) da[ta] agree with HESS



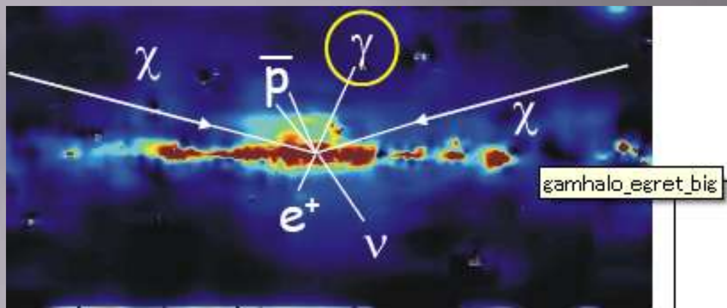
Steady (time-independent) spectrum, pointlike within HESS angular resolution, could be Moore cusp instead of NFW?

But: Probably too high energy (and wrong shape of spectrum) for WIMP annihilation explanation

Shape of these curves uncertain, depends on QED corrections and fragmentation of 5-10 TeV jets. LHC should give important input here.

Energy spectrum is *not* consistent with dark matter annihilation signal!

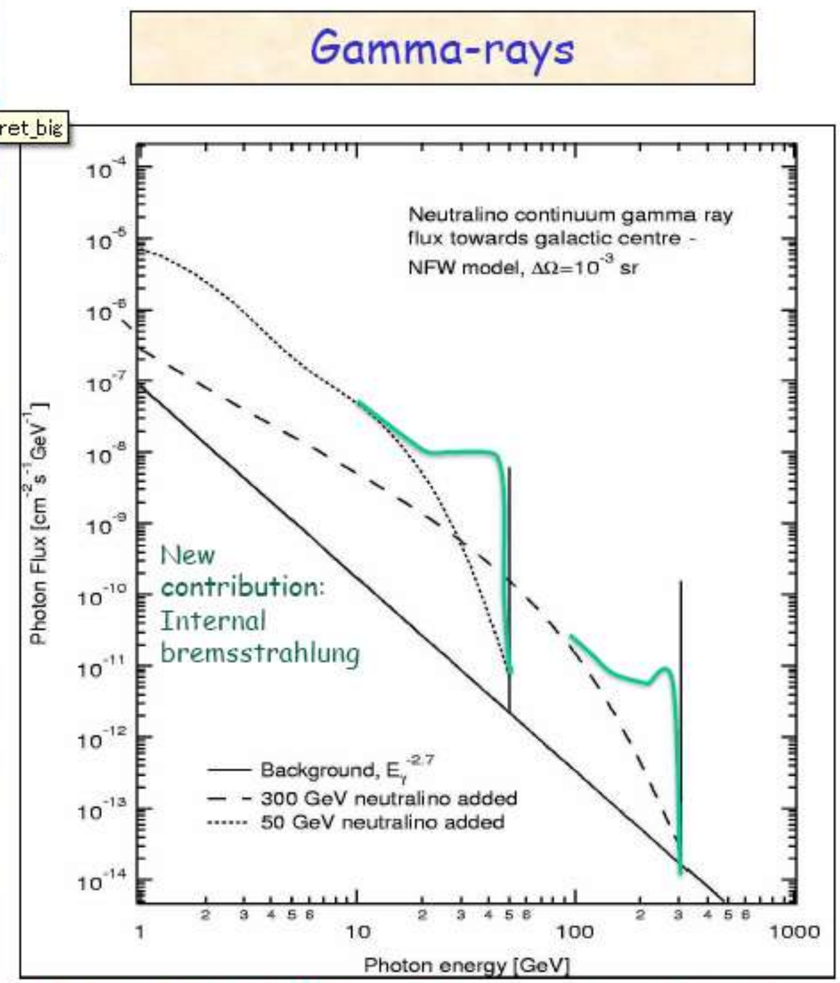
Gamma-ray signal from DM annihilation at the Galactic center



Indirect detection through γ-rays.
Three types of signal:

- Continuous from π^0, K^0, ... decays and
- Monoenergetic line and
- Internal bremsstrahlung from QED process.

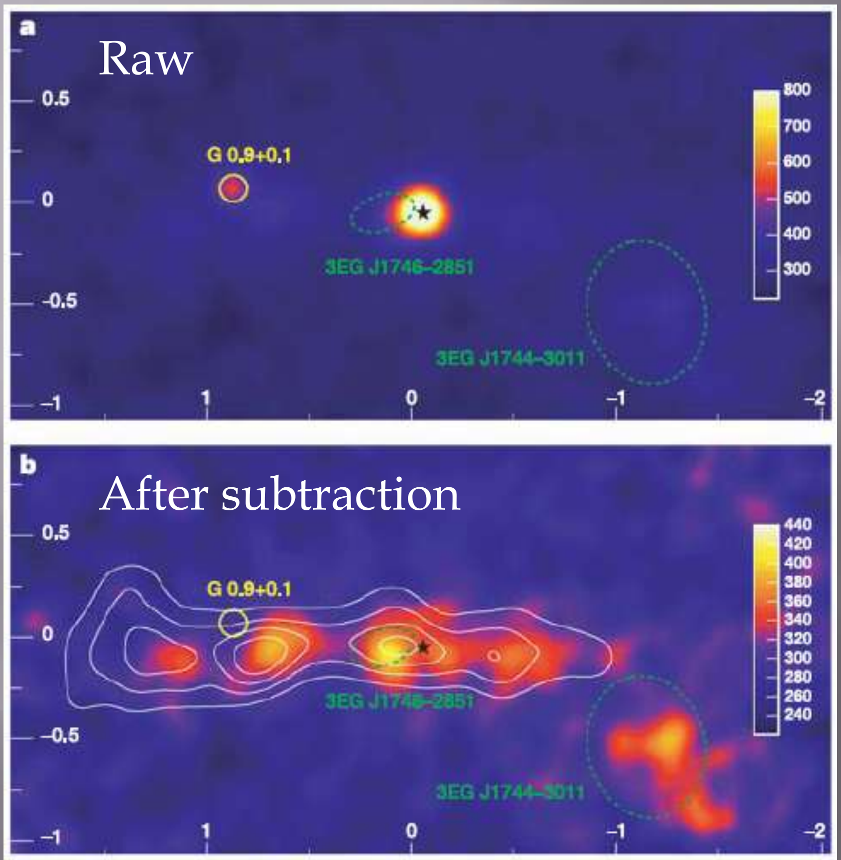
Enhanced flux possible thanks to halo density profile and substructure (as predicted by CDM)
Good spectral signatures!
Unfortunately, large uncertainties in the predictions of absolute rates

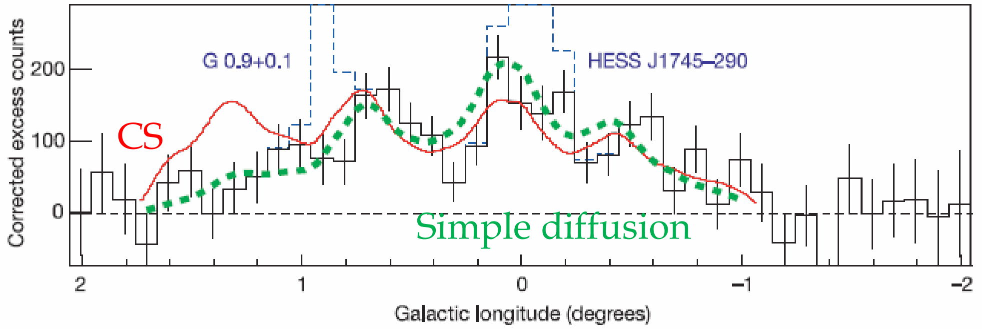


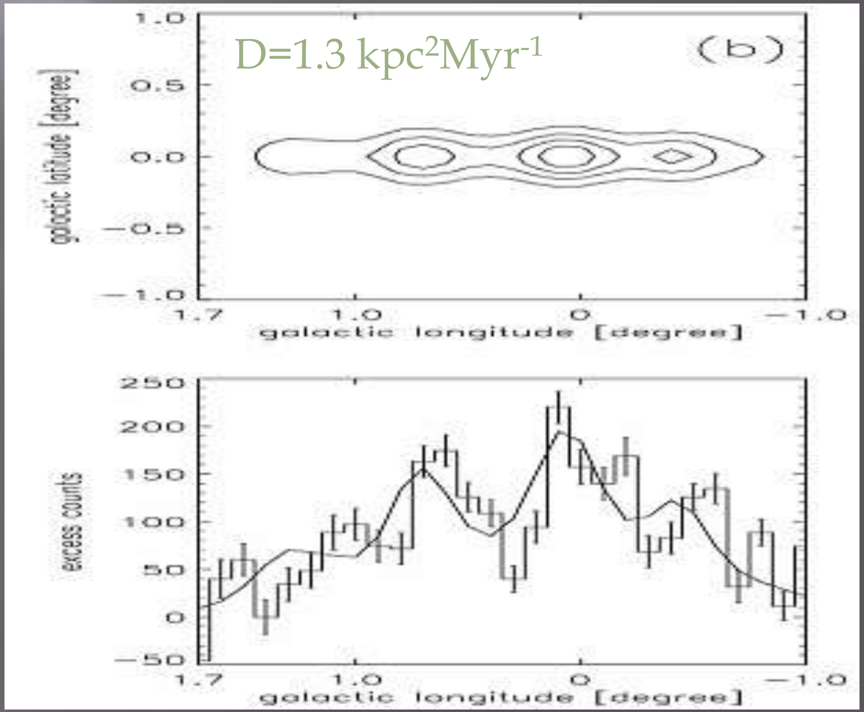
L.B., P.Ullio & J. Buckley 1998   T. Bringmann, L.B., J. Edsjö, 2007

F. Aharonian et al., Nature 439, 695 (2006)

Galactic center ridge





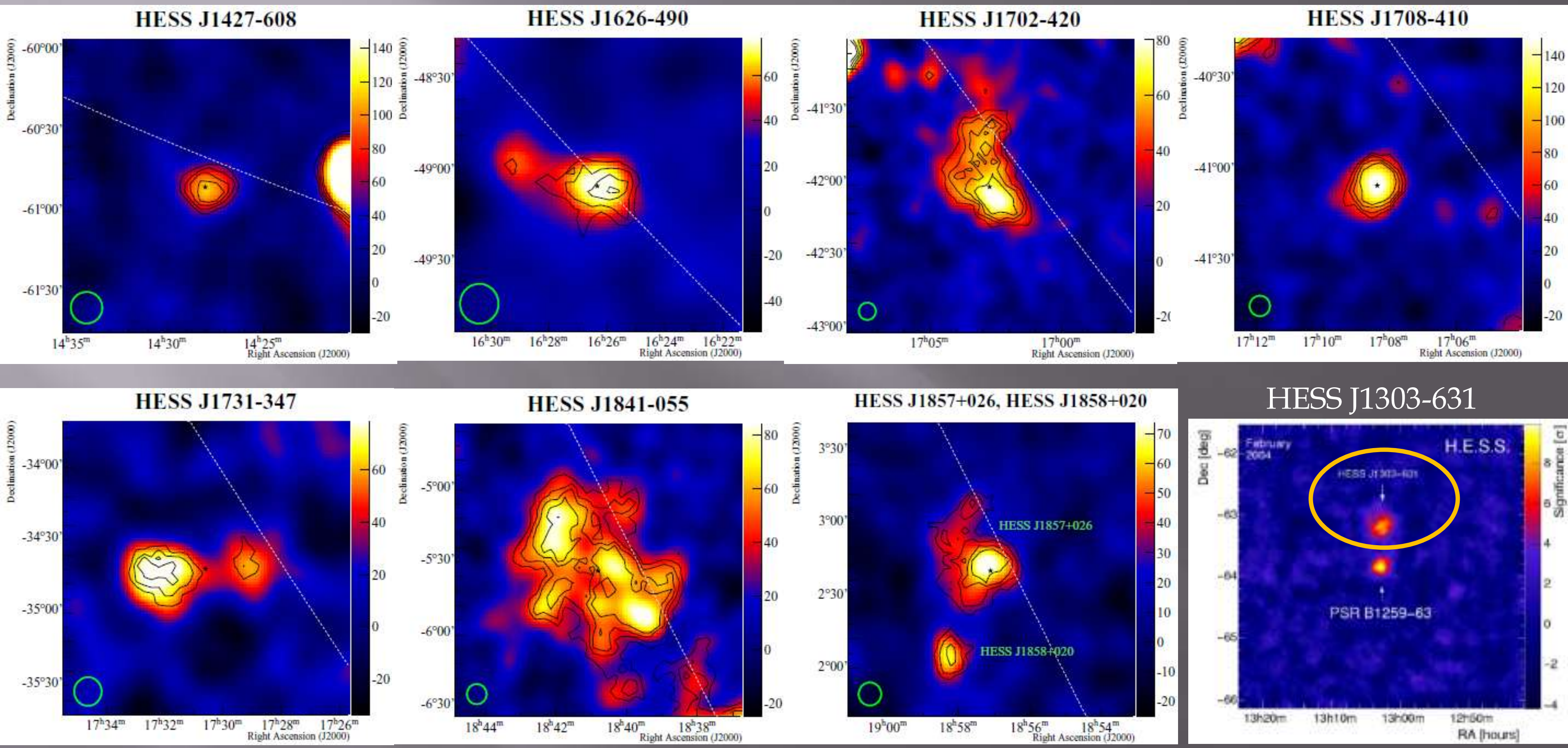


Spectrum is harder than CR spectrum!

Diffusion model by Busching et al. ApJ 656, 841 (2007)

F. Aharonian et al., A&A 477, 353 (2008)

Unidentified HESS sources

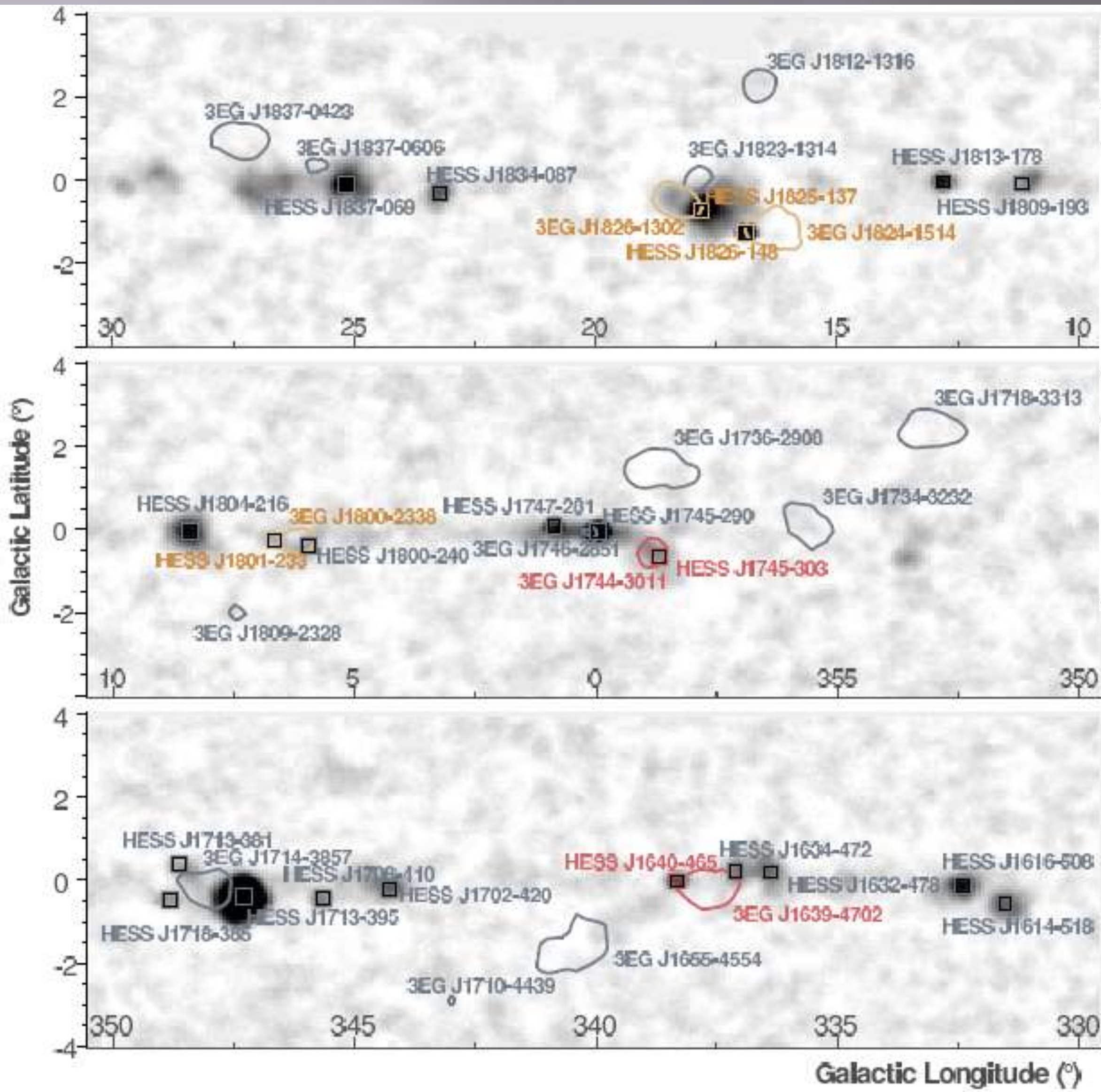


F. Aharonian et al., A&A 442, 1 (2005)

Two types:
1) No compelling counterparts
2) Dark in other wavelengths

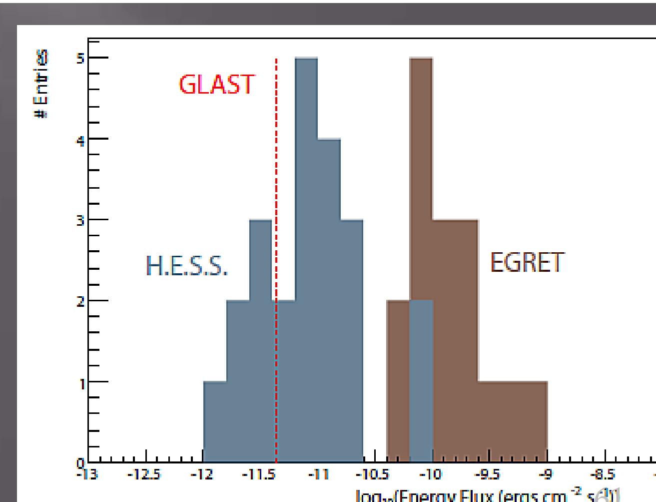
Funk et al., arXiv:0710.1584v1

TeV-GeV relation?



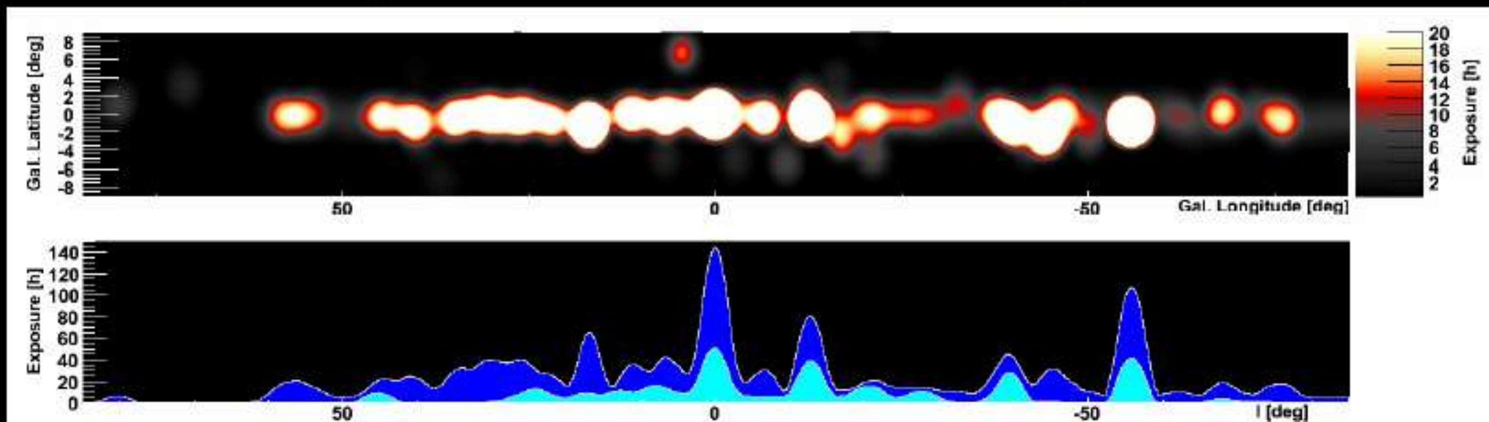
Coincident sources

EGRET source	VHE γ-ray source	Potential Counterpart
	Within the H.E.S.S. GPS	
3EG J1639–4702	HESS J1640–465	G338.3–0.0 (SNR/PWN)
3EG J1744–3011	HESS J1745–303	
3EG J1800–2338	HESS J1801–233	W28 (SNR)
3EG J1826–1302	HESS J1825–137	G18.0–0.7 (PWN)
3EG J1824–1514	HESS J1826–148	LS 5039 (Binary)
	Outside the H.E.S.S. GPS	
3EG J0241+6103	MAGIC J0240+613	LSI +61 303 (Binary)
3EG J0617+2238	MAGIC J0616+225	IC443 (SNR/PWN)
3EG J0634+0521	HESS J0632+058	Monoceros
3EG J1420–6038	HESS J1420–607	Kookaburra (PWN)



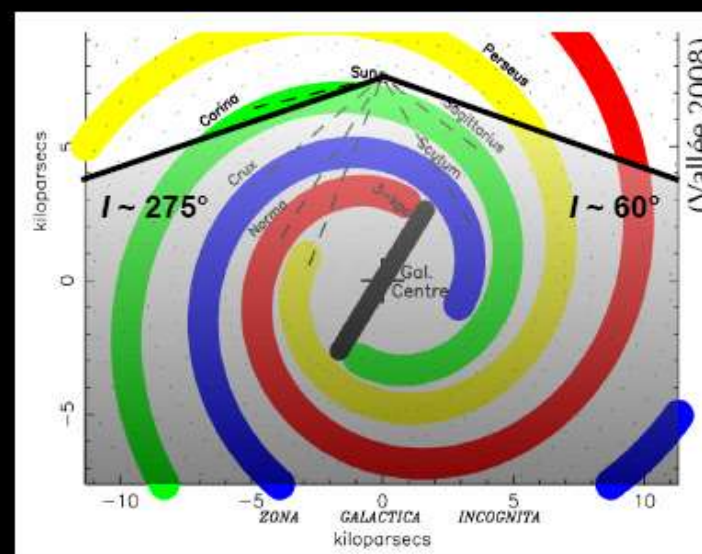
Extended H.E.S.S. survey

Acceptance-corrected Exposure

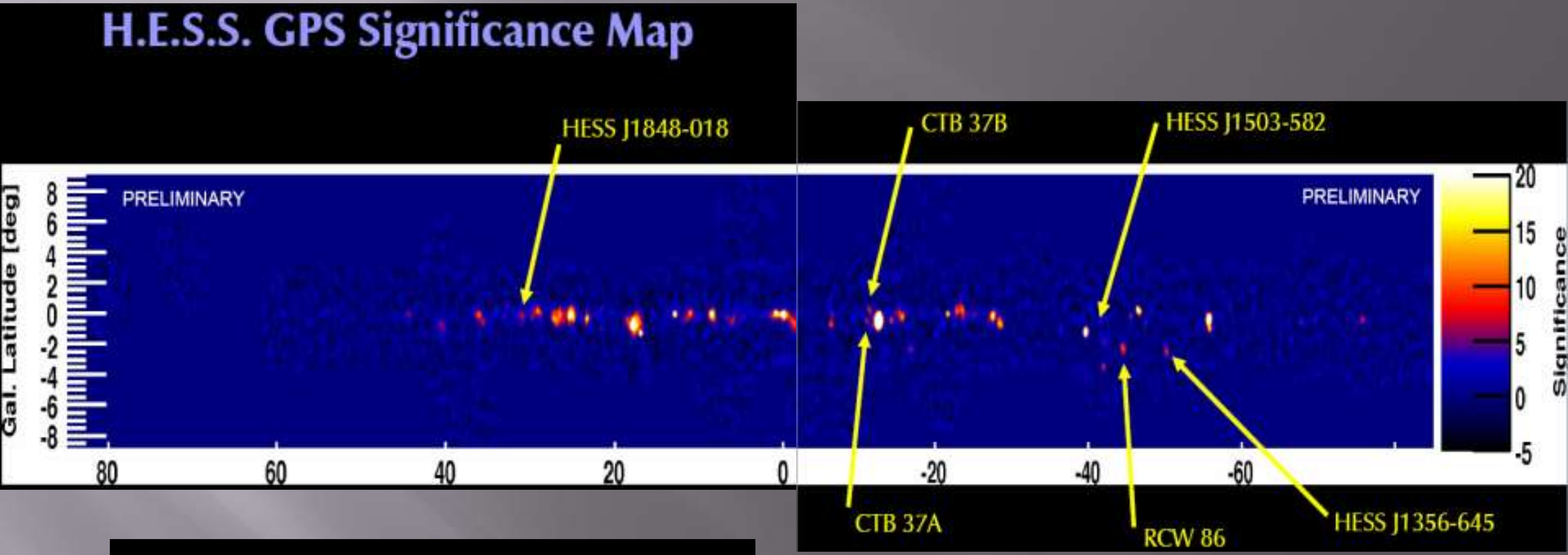


Extended H.E.S.S. GPS

- **-85° < *l* < 60°**
- -3° < *b* < 3°
- Scan mode: **400** h
- Detected **50+ Galactic sources** of VHE gamma-rays
- ICRC 2007, DPG 2008, Gamma08



H.E.S.S. galactic plane survey



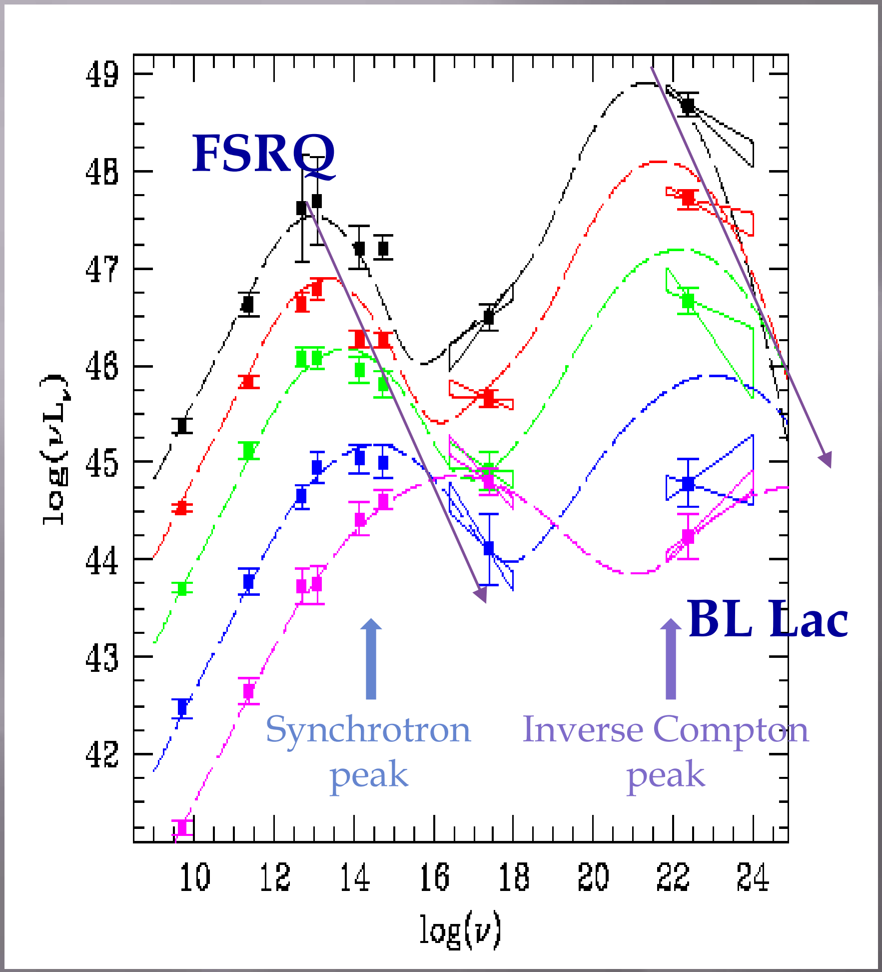
- HESS J1714-385 (SNR CTB 37A)
- HESS J1713-381 (SNR CTB 37B)
- HESS J1442-623 (SNR RCW 86)
- HESS J1356-654 (Offset PWN)
- HESS J1503-582 (FVW?)
- HESS J1848-018 (SFR W 43, WR 121a?)
- HESS J1849-000 (PWN)

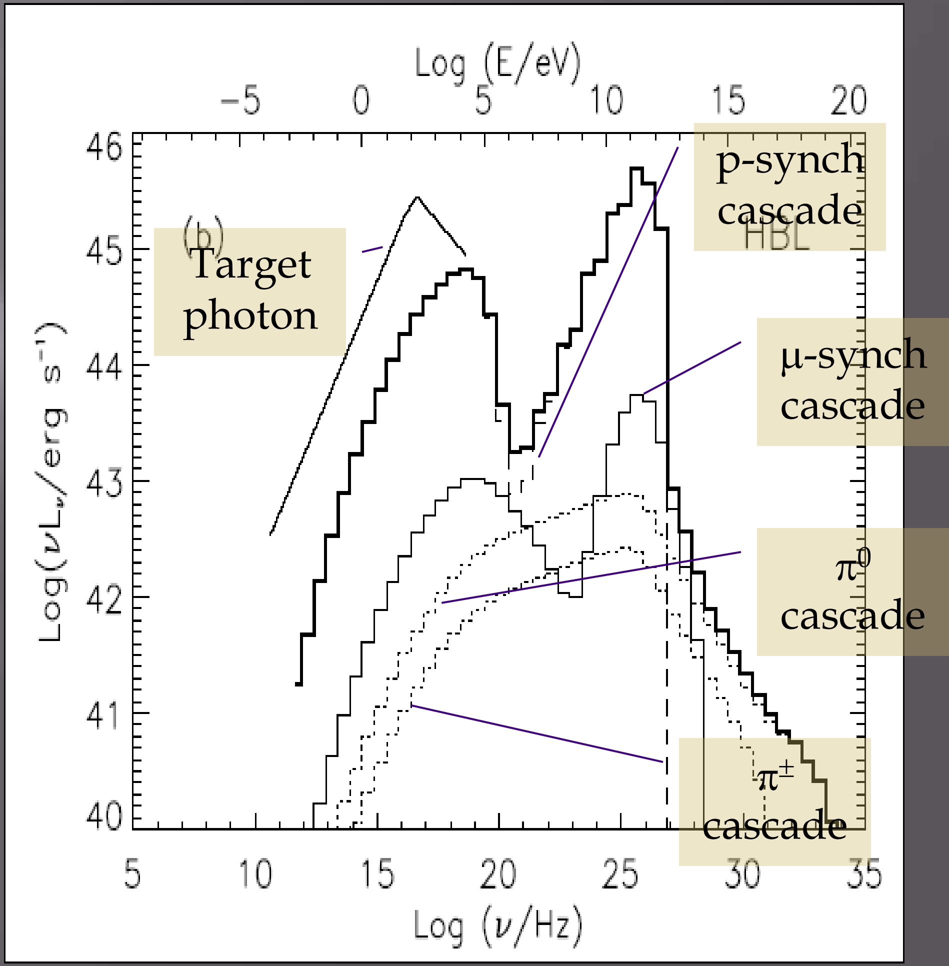
Extragalactic TeV sources

	Name	Discovered	Year	z	Contributions
	M 87	HEGRA	2003	0.004	VERITAS-Colin, HESS-Beilicke, MAGIC-
	Mrk 421	Whipple	1992	0.031	MILAGRO-Smith, VERITAS-Fegan, +
	Mrk 501	Whipple	1996	0.034	TACTIC-Godambe, MAGIC-Paneque, +
	1ES 2344+514	Whipple	1998	0.044	MAGIC-Wagner
→	**Mrk 180**	**MAGIC**	**2006**	**0.046**	**MAGIC-Mazin**
	1ES 1959+650	TA	2002	0.047	MAGIC-Hayashida
→	**BL Lac**	**MAGIC**	**2006**	**0.069**	**MAGIC-Hayashida**
→	**PKS 0548-322**	**HESS**	**2006**	**0.069**	**HESS-Superina**
	PKS 2005-489	HESS	2005	0.071	HESS-Costamante
	PKS 2155-304	Durham	1999	0.116	HESS-Punch, CANGAROO-Sakamoto, +
	H 1426+428	Whipple	2002	0.129	VERITAS-Krawczynski
→	**1ES 0229+200**	**HESS**	**2007**	**0.140**	**HESS-Raue**
	H 2356-309	HESS	2005	0.165	HESS-Costamante
	1ES 1218+304	MAGIC	2005	0.182	MAGIC-Hayashida
	1ES 1101-232	HESS	2005	0.186	HESS-Puelhofer
→	**1ES 0347-121**	**HESS**	**2007**	**0.188**	**HESS-Raue**
→	**1ES 1011+496**	**MAGIC**	**2007**	**0.212**	**MAGIC-Mazin**
→	**PG 1553+113**	**HESS/MAGIC**	**2005**	**?**	**MAGIC-Wagner, HESS-Benbow**
→	**3C 279**	**MAGIC**	**2007**	**0.536**	**MAGIC-Teshima**

8 new AGN

Emission from AGNs





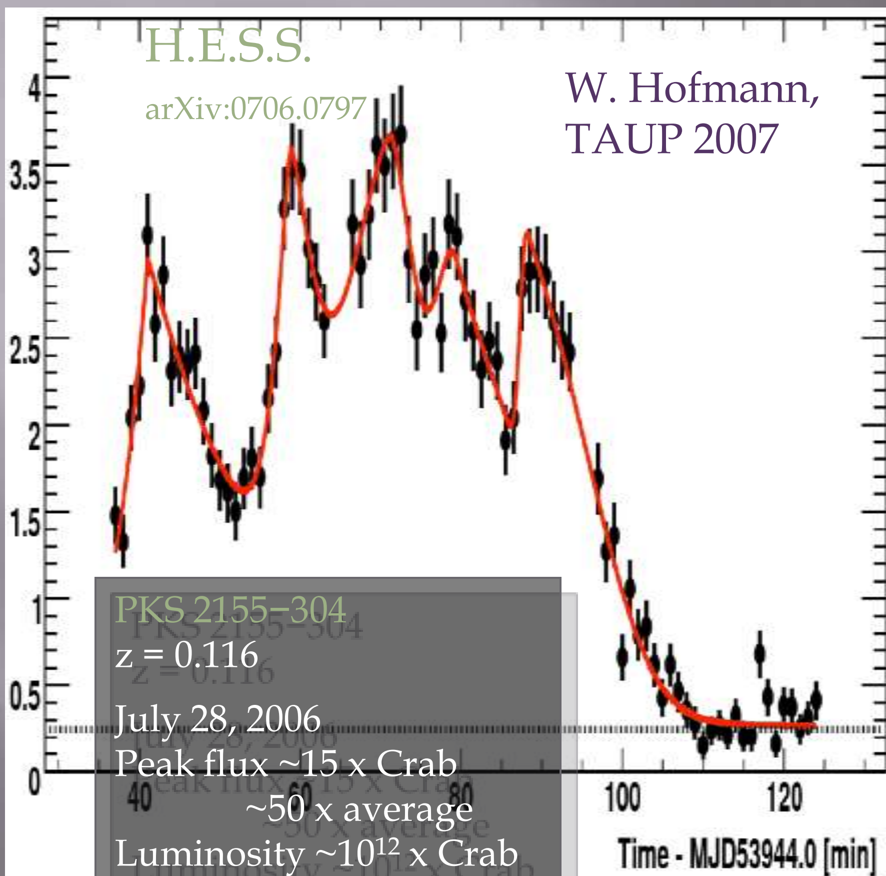
Electron model

Fossati et al. 1998

Proton model

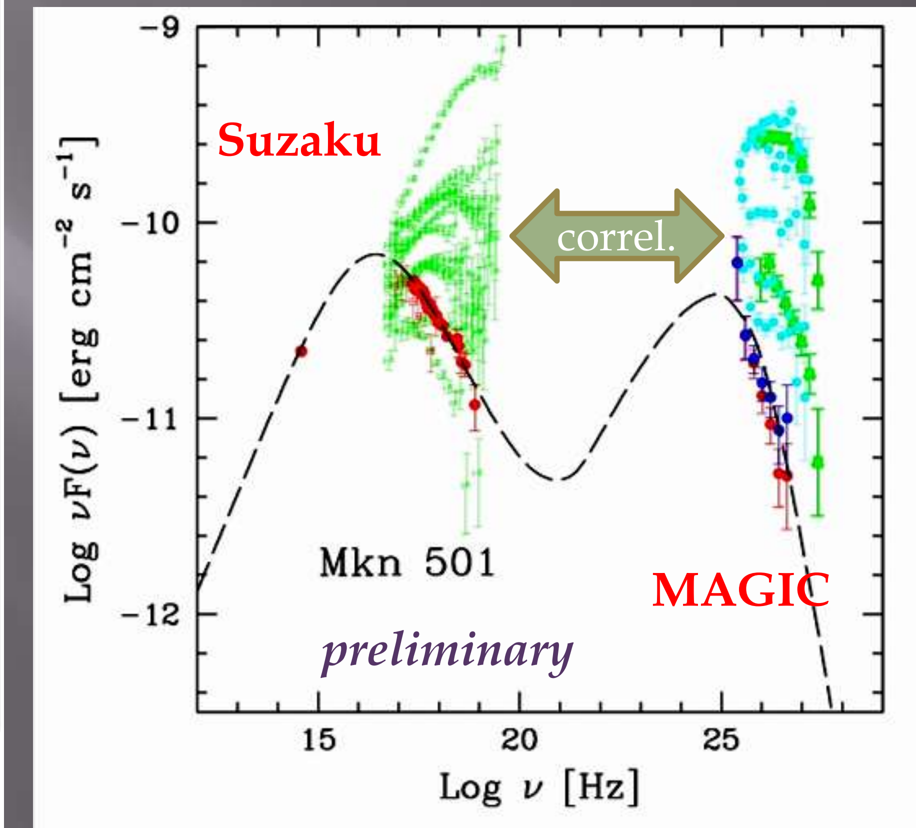
Muecke et al. APh 18, 2003

Fast time variation



PKS 2155−304
z = 0.116
July 28, 2006
Peak flux ~15 x Crab
~50 x average
Luminosity ~10^{12} x Crab
Doubling times
67, 116, 173, 178 ±50 s

$R_{BH}/c \sim 1...2 \cdot 10^4$ s



M. Hayashida, ICRC 2007

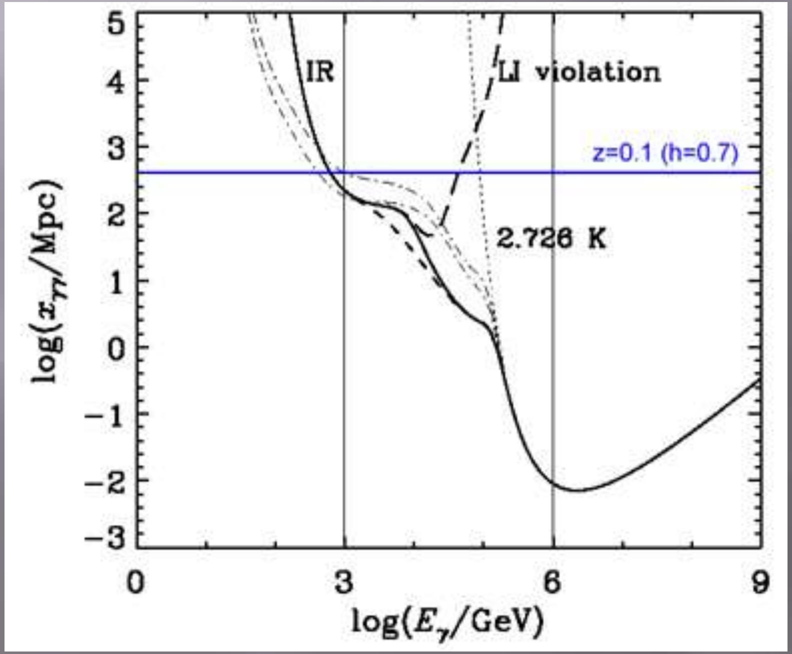
Fast variation ↔ Acceleration site & mechanism

Absorption by IR background

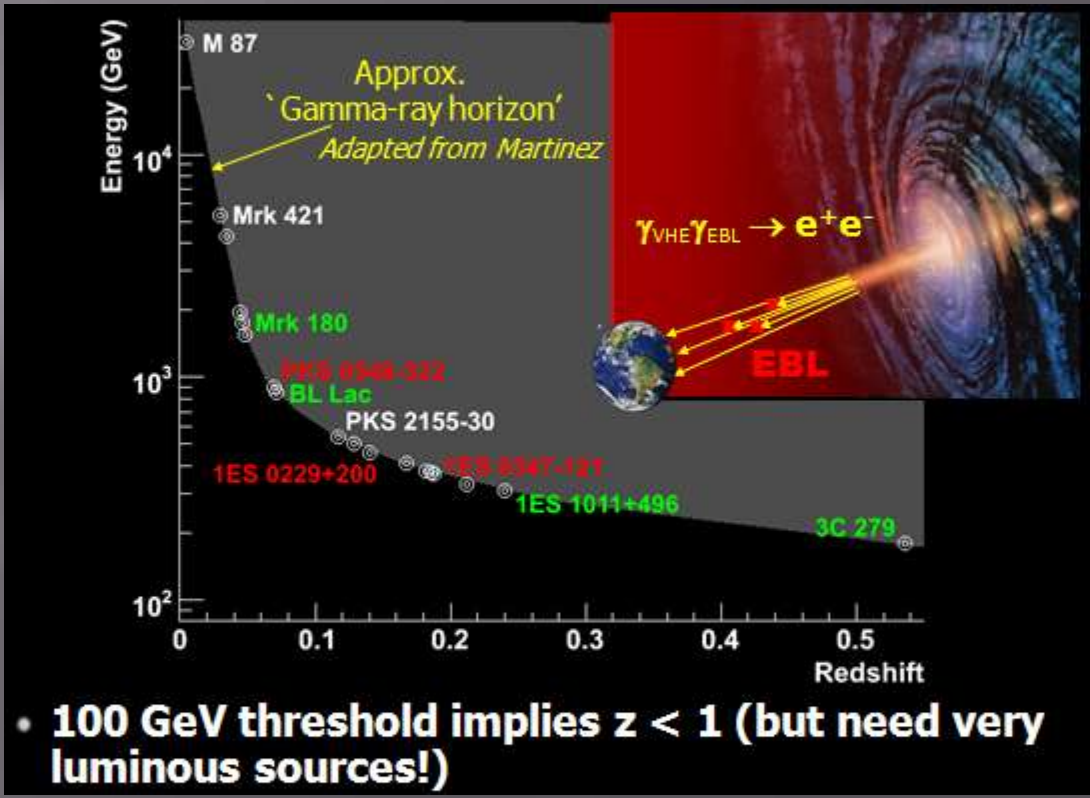
Observed spectrum is affected by integalactic absorption!

$$\gamma_{TeV} + \gamma_{IR} \rightarrow e^+ + e^-$$

Mean free path for e^+e^- pair production



Protheroe & Meyer, Phys.Lett. B493 (2000) 1

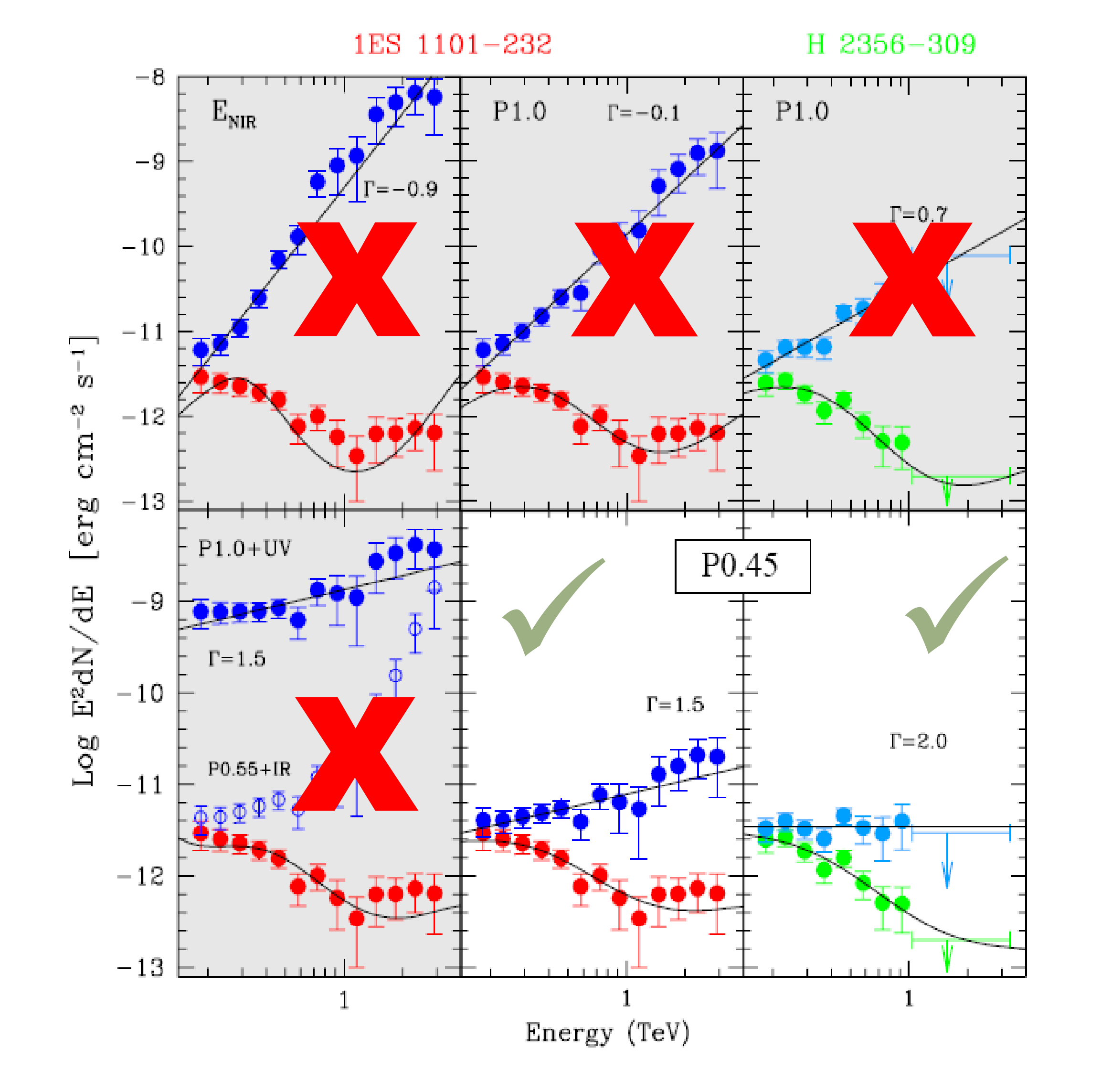


Jim Hinton, rapporteur talk, ICRC 2007

We cannot discriminate source spectrum and intergalactic absorption!

H.E.S.S.: Aharonian et al., Nature 440, 1018 (2006)

Unfolding source spectra

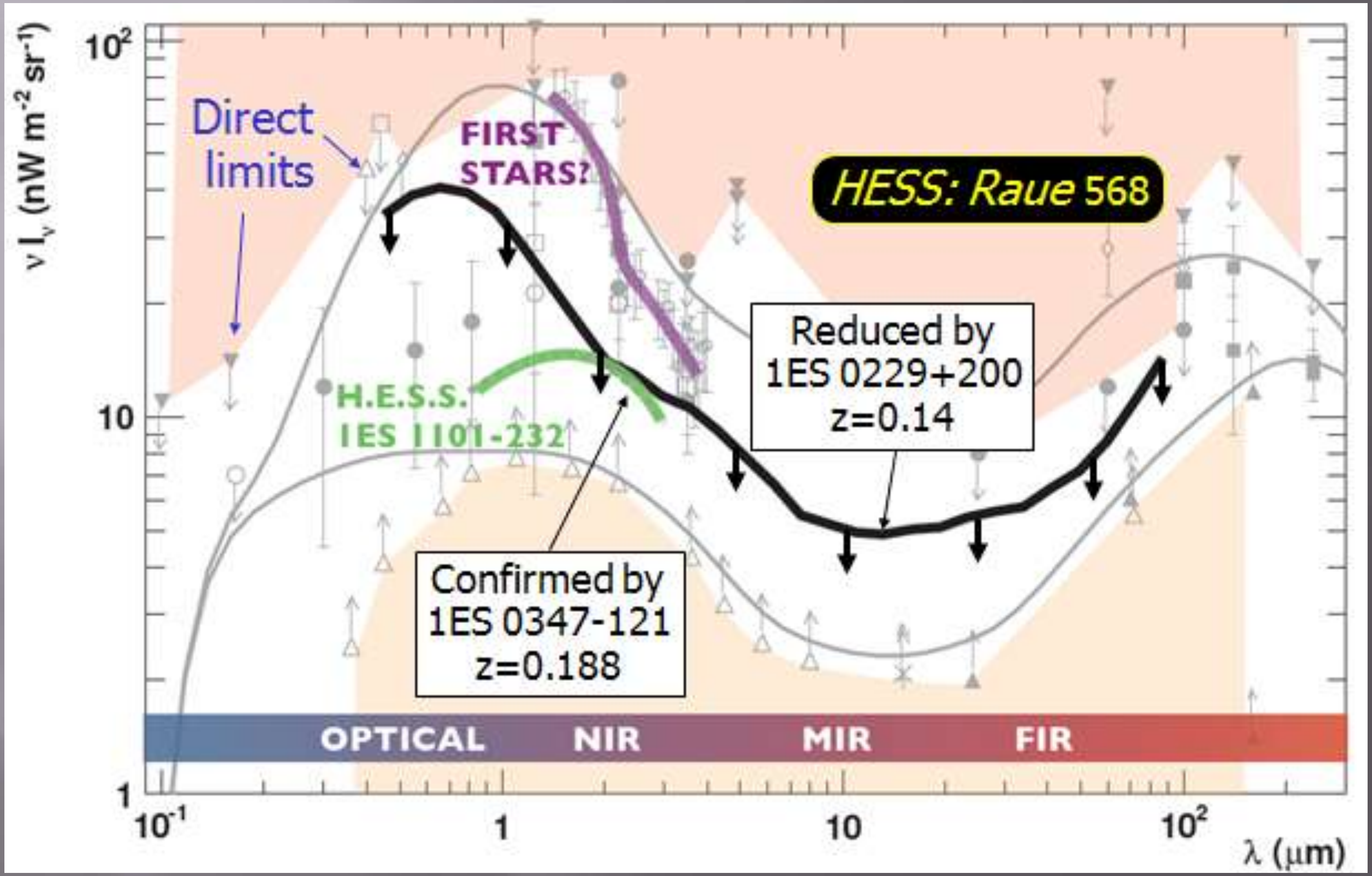


Assume not harder than $E^{-1.5}$

Some models can be rejected

Raue, ICRC 2007

Background IR intensity limited by TeV observations



Upper limits: fluctuation/direct measurements
Lower limits: source counts

MAGIC: Science 320, 1752 (2008)

3C279 at z=0.538

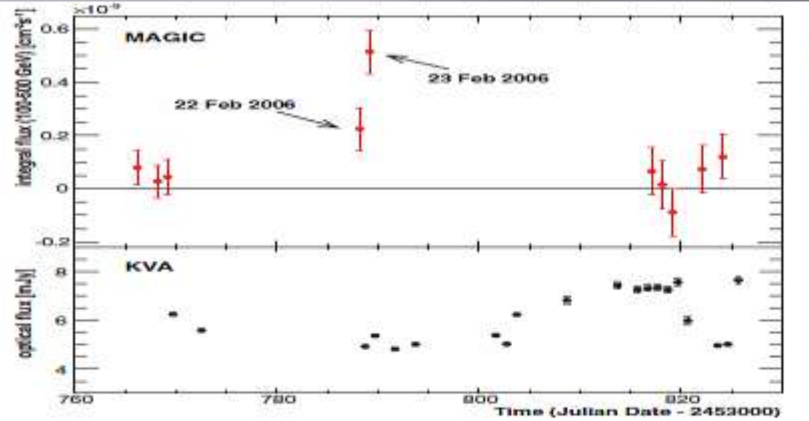


Fig. 1. Light curves. MAGIC (top) and optical R-band data (bottom) obtained for 3C 279 from February to March 2006. The long-term baseline for the optical flux is at 3 mJy.

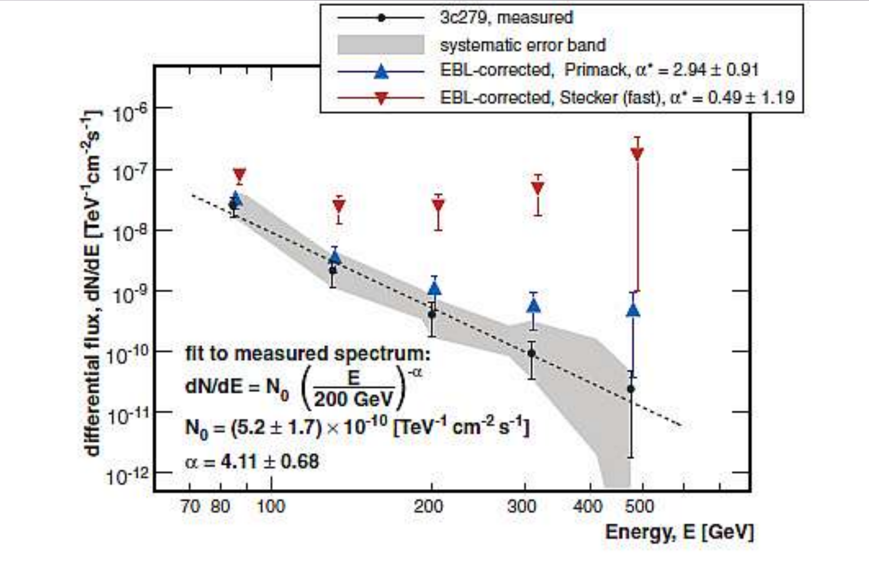
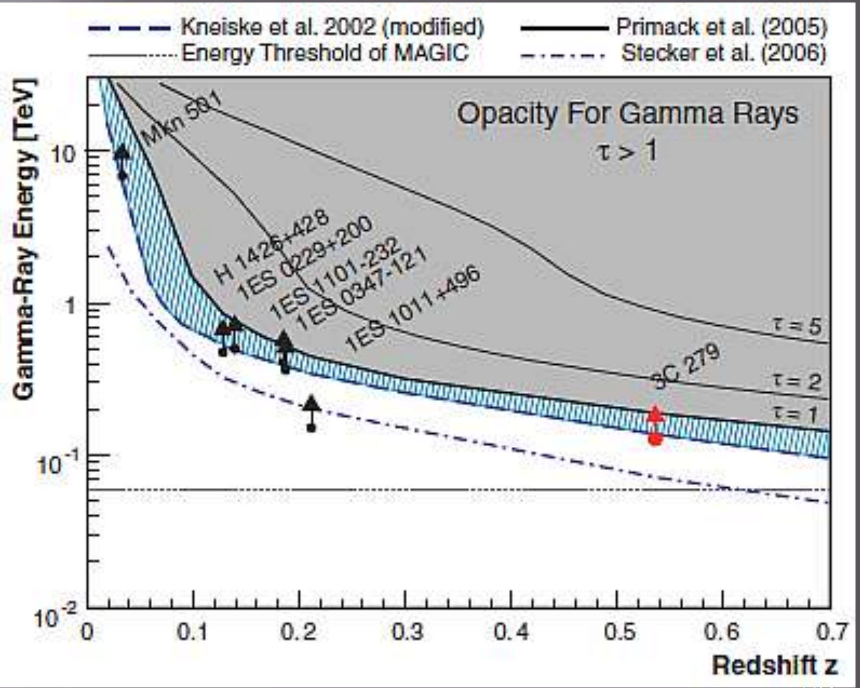


Fig. 2. Spectrum of 3C 279 measured by MAGIC. The gray area includes the combined statistical (1σ) and systematic errors, and underlines the marginal significance of detections at high energy. The dotted line shows compatibility of the measured spectrum with a power law of photon index $\alpha = 4.1$. The blue and red triangles are measurements corrected on the basis of the two models for EBL density, discussed in the text.

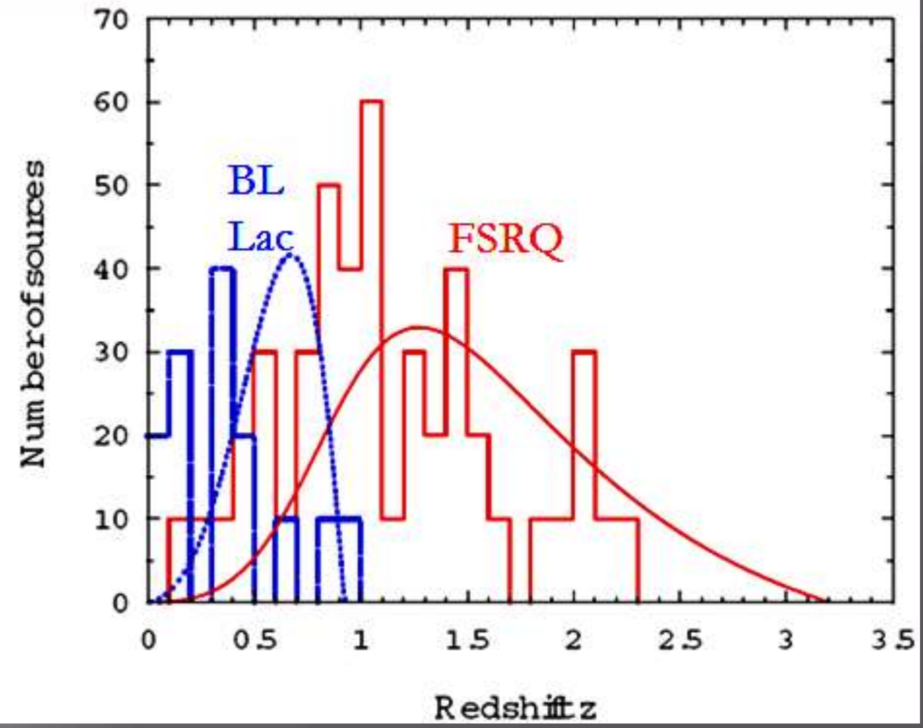


Redshift distribution of blazars

Model Fit to Blazar Redshift Distribution

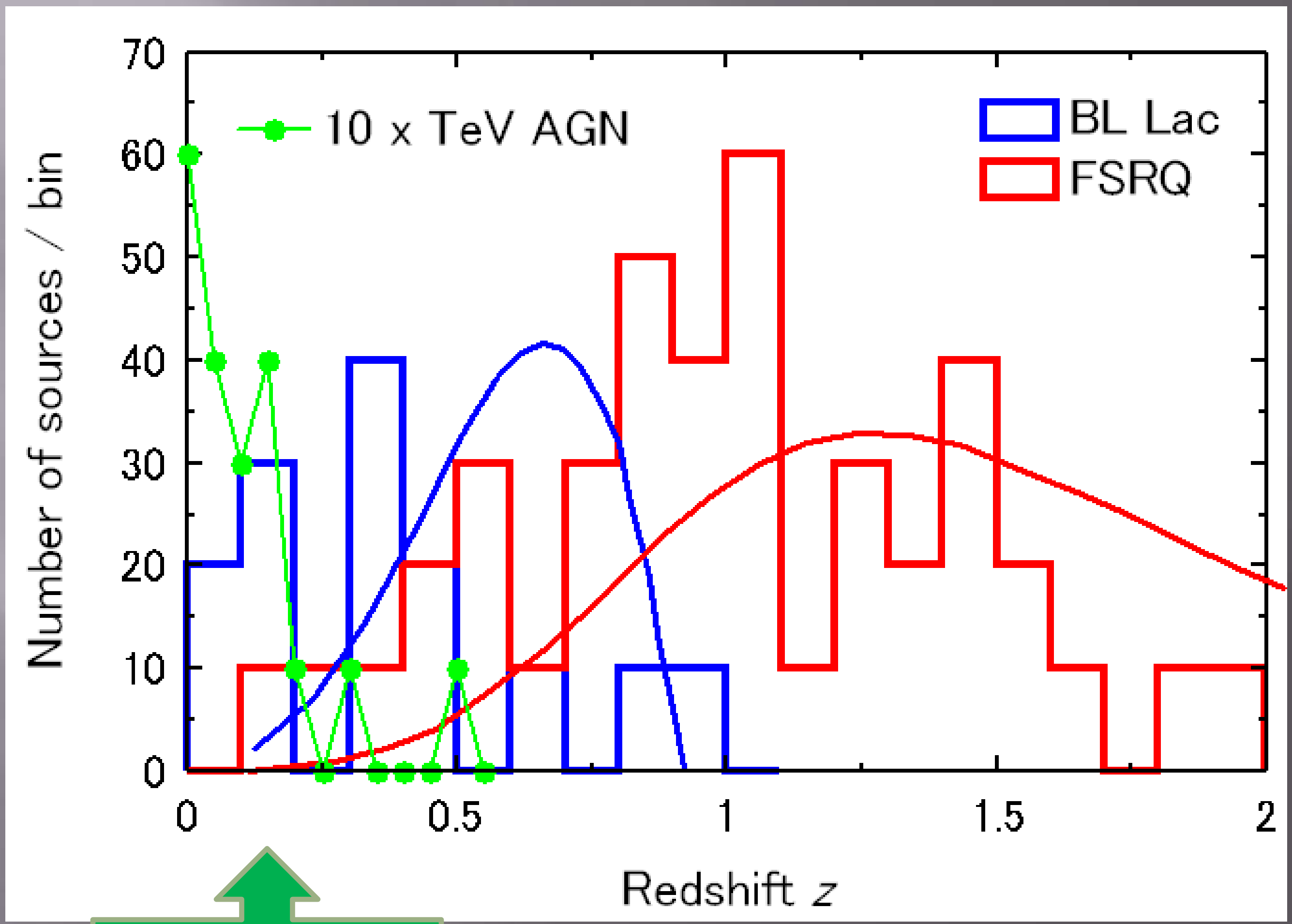
Fit parameters for the FSRQs are Γ = 8 and comoving directional luminosity l = 10^{40} ergs sr^{-1} s^{-1}; EC statistics

Fit parameters for the BL Lacs are Γ = 5 and l = 10^{42} ergs sr^{-1} s^{-1}; syn/SSC statistics



C. Dermer, GLAST LAT AGN Science Group meeting, March 4, 2006

Redshift distribution of blazars

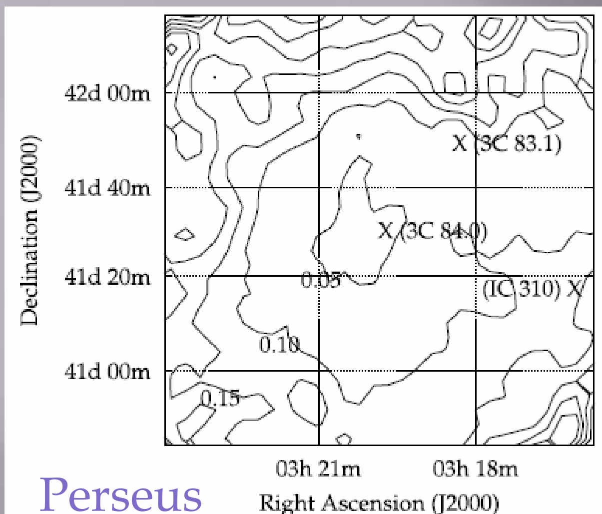


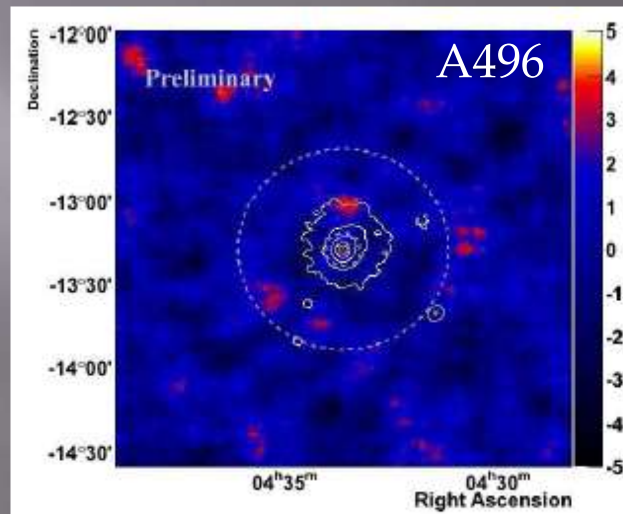
10×TeV AGN

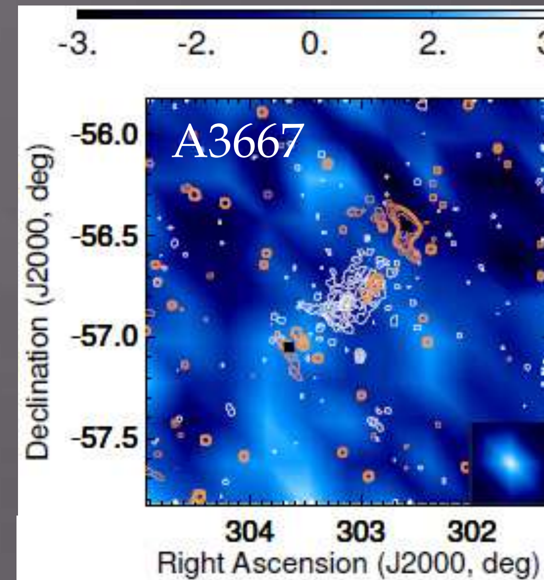
More AGNs as energy threshold goes lower!

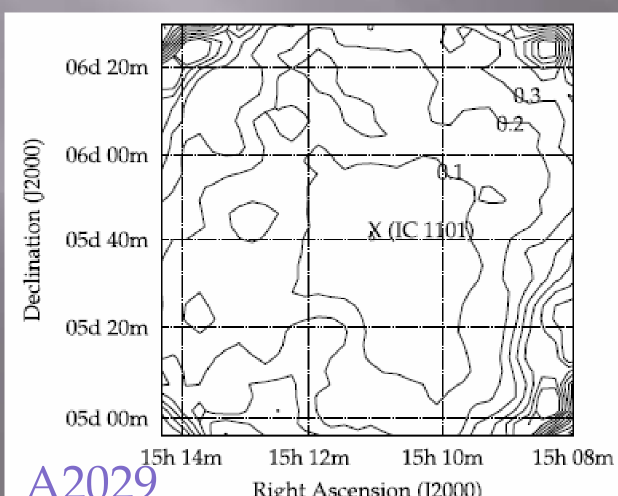
Clusters of galaxies: upper limits

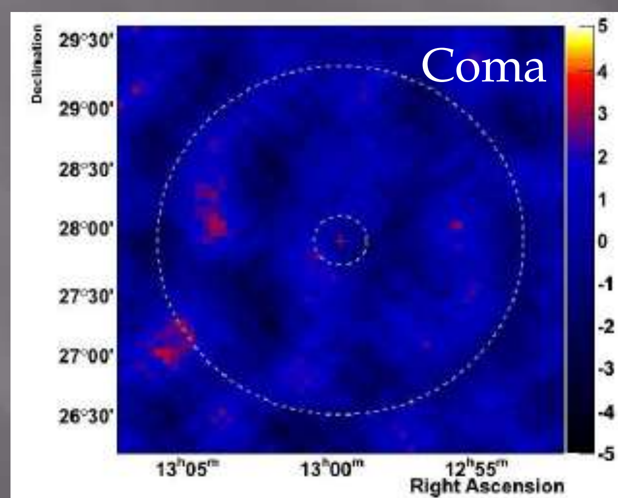
H.E.S.S.: Domainko et al., ICRC2007

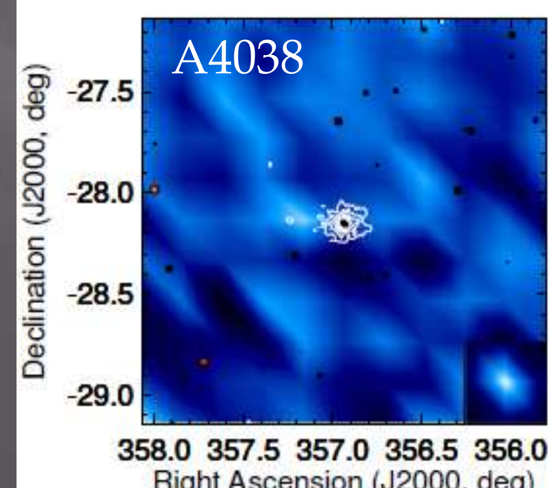












Whipple: Perkins et al., ApJ 644, 148 (2006)

CANGAROO-III: Kiuchi et al., ICRC2007

Air shower arrays

Tibet ASγ (Japan-China, 4300m a.s.l.)

Milagro (US+, 2630m a.s.l.)

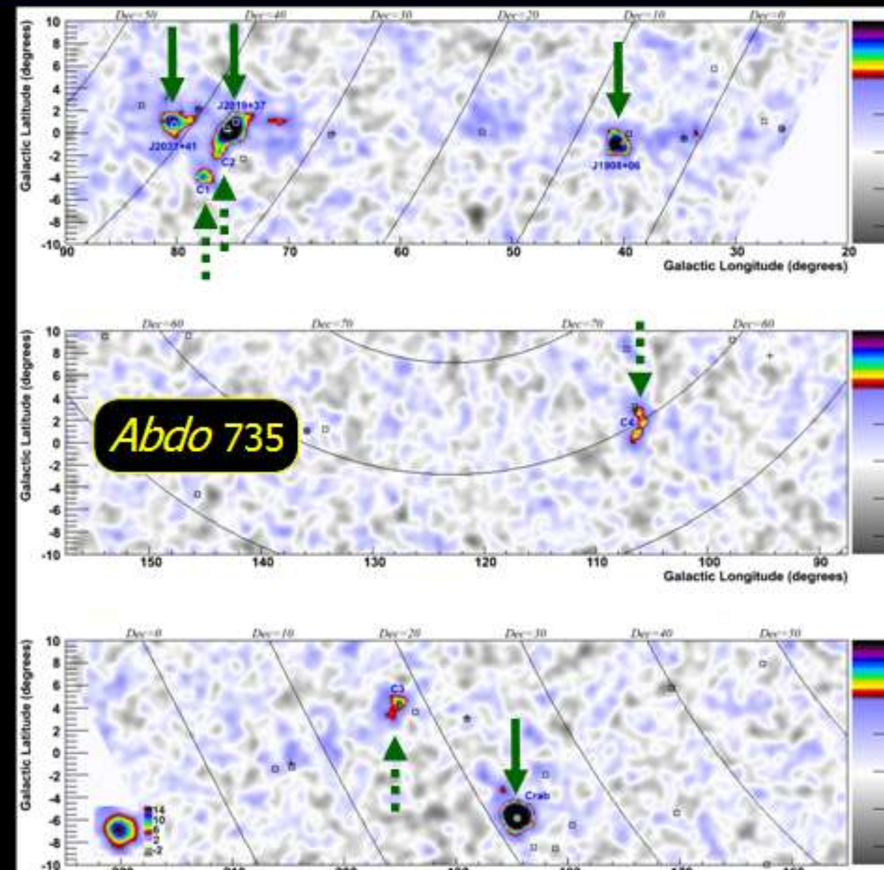
Atmospheric Cherenkov Telescopes	Extensive Air Shower Arrays
Energy Range .05-50 TeV	Energy Range 0.1-100 TeV
Area > 10^4 m^2	Area > 10^4 m^2
Background Rejection > 99%	Background Rejection > 95%
Angular Resolution 0.05°	Angular Resolution 0.3° - 0.7°
Energy Resolution ~15%	Energy Resolution ~50%
Aperture 0.003 sr	Aperture > 2 sr
Duty Cycle 10%	Duty Cycle > 90%
High Resolution Energy Spectra	Unbiased Complete Sky Survey
Precision Study of Known Sources	Extended Sources
Source Location & Morphology	Transient Objects (GRB's)
Deep Surveys of Limited Regions of Sky	Multi-Wavelength/Messenger Observations

Air shower arrays : results

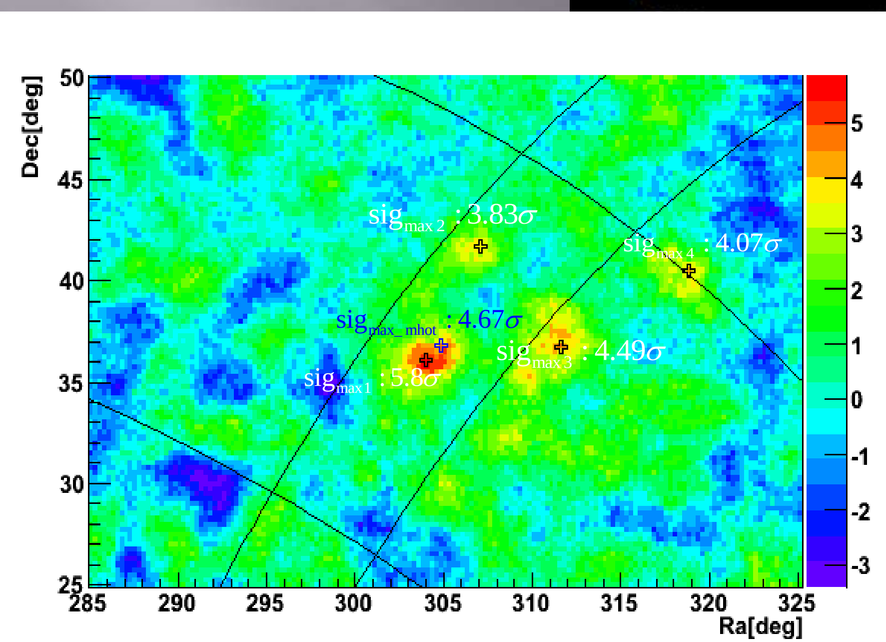
Milagro Sources and Candidates

- 7 year map
- γ/hadron cut raises median energy to 20 TeV
- 3 new sources significant post trials

ard



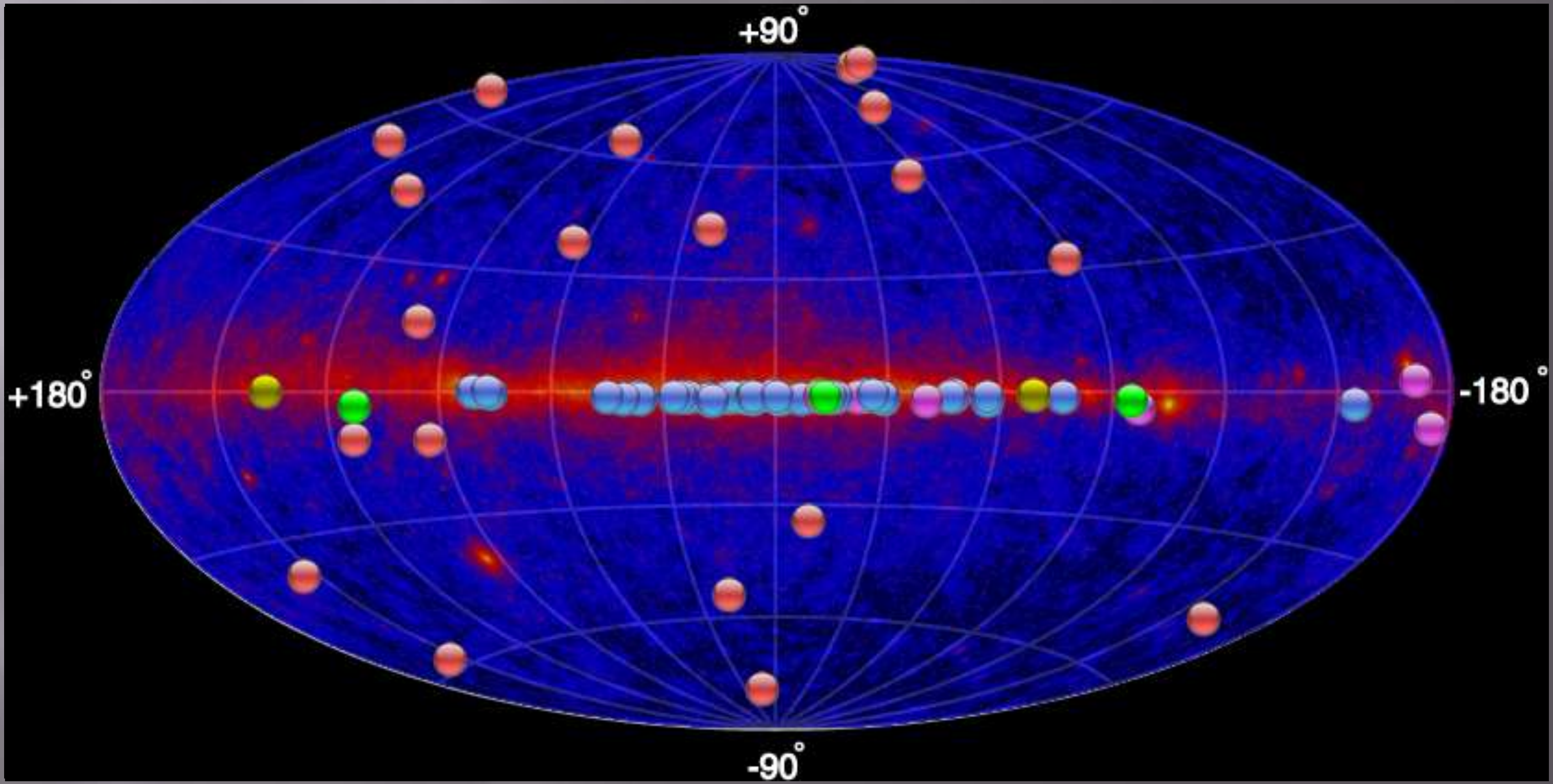
Abdo, ICRC 2007



Wang, ICRC 2007

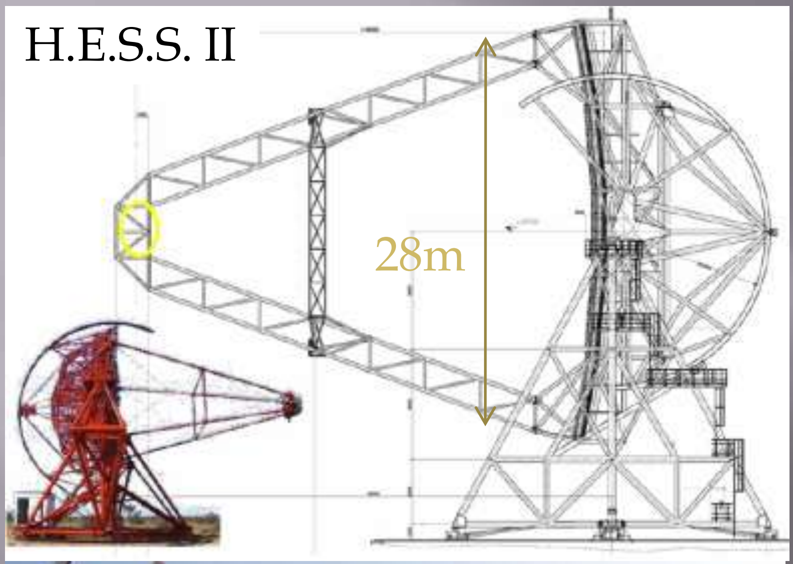
http://tevcat.uchicago.edu

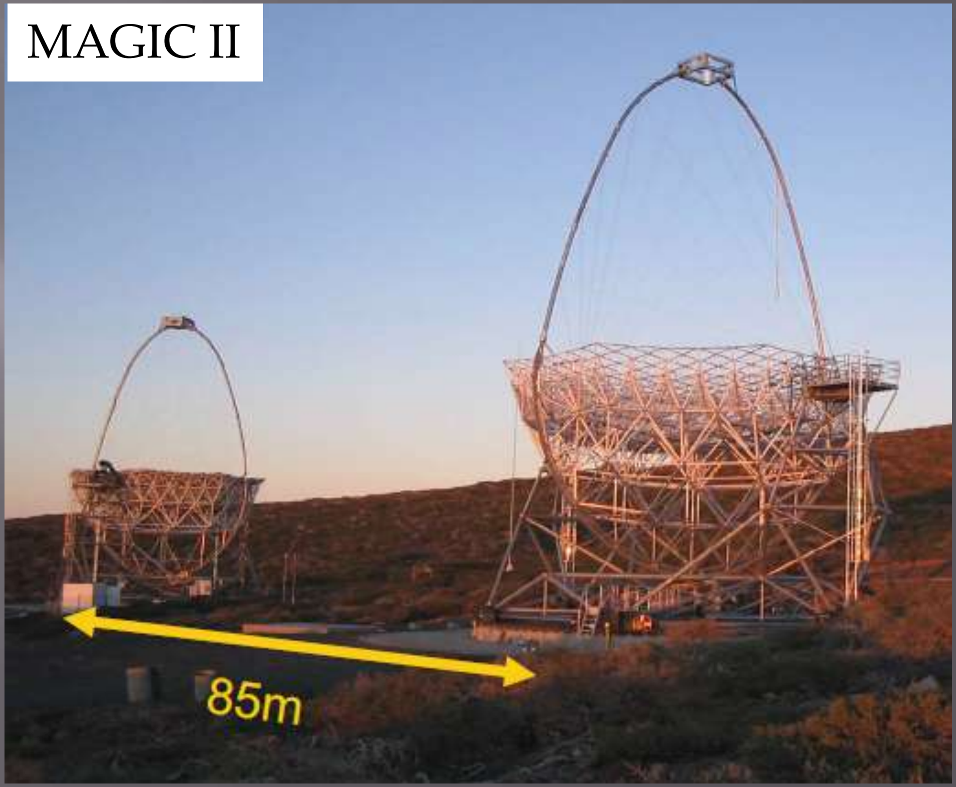
Gamma-ray skymap



(background: Fermi Gamma-ray Space Telescope Firstlight data [>100 MeV])

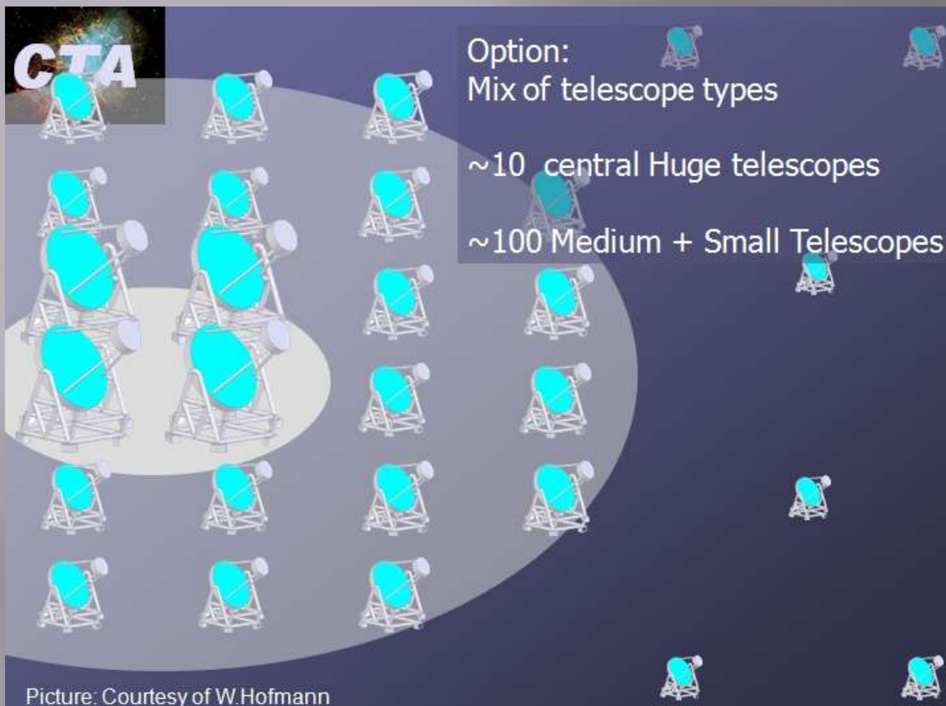
Under construction



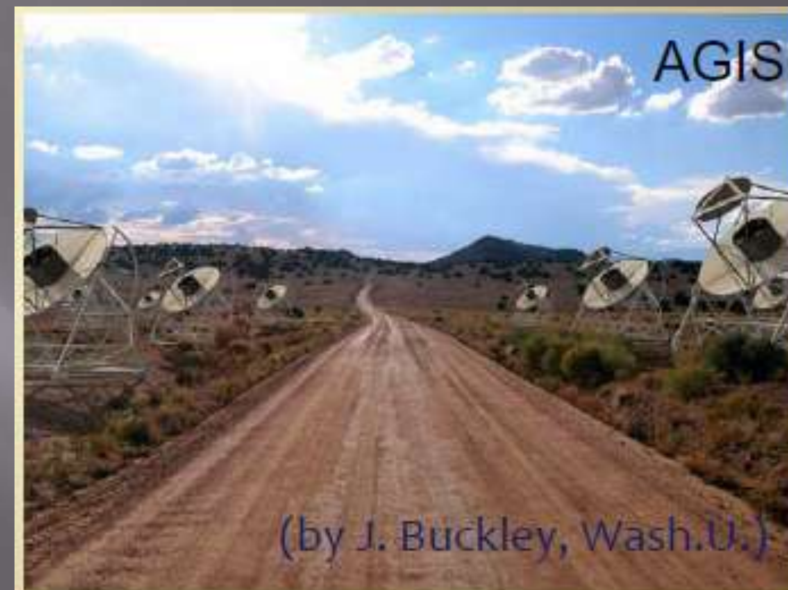


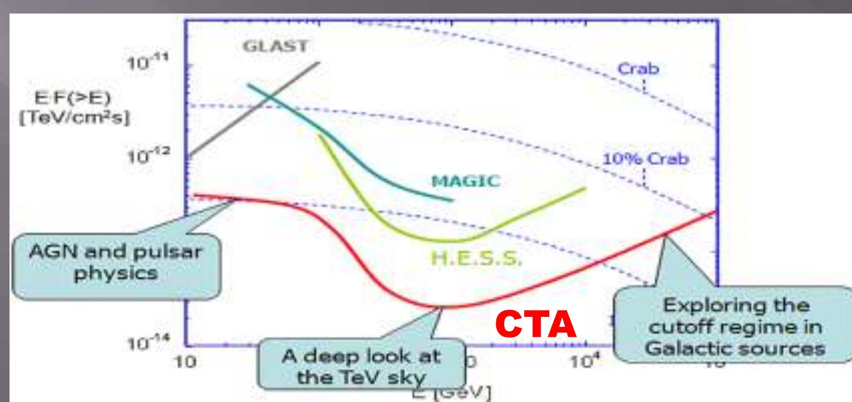
Future projects

CTA (Cherenkov Telescope Array): EU++

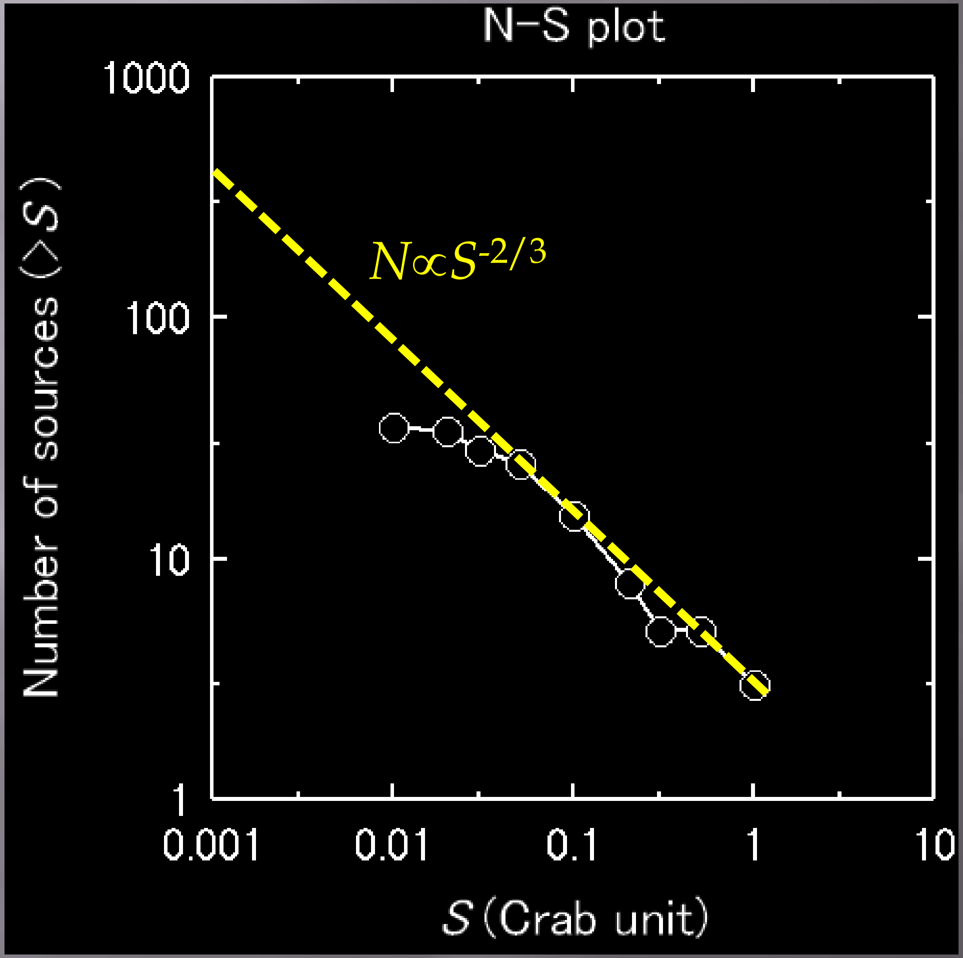


AGIS (Advanced Gamma-ray Imaging System): USA++





log N-log S relation



Data: H.E.S.S. catalog

×2 (North/South)
↓
1000 TeV sources
if mCrab!

Summary

- High energy window of the Universe is now open!
  - Additional 2-3 decades of the photon spectrum
  - Wider variety of sources than expected
    $\rightarrow$ *Cosmic accelerators are ubiquitous!*
  - Much work left to understand their physics
  - Also: cosmology, fundamental physics
- Hoping to detect other class of sources…
  - Pulsars
  - Star-forming galaxies, mergers
  - Dwarf galaxies and dark matter
  - Ultraluminous IR galaxies
  - Clusters of galaxies
  - Gamma-ray bursts

Thank you!

CANGAROO-III telescopes, Woomera, South Australia