超高エネルギーガンマ線による天体物理

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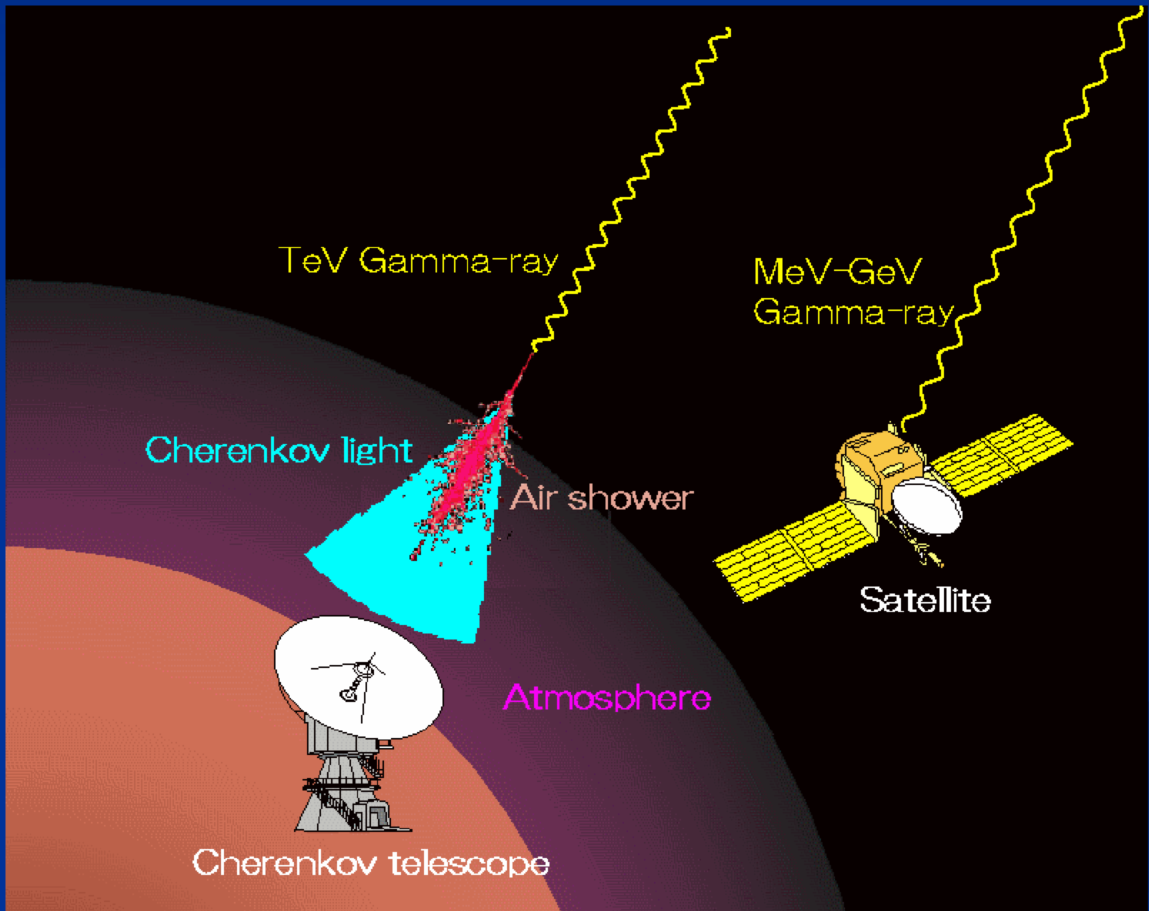
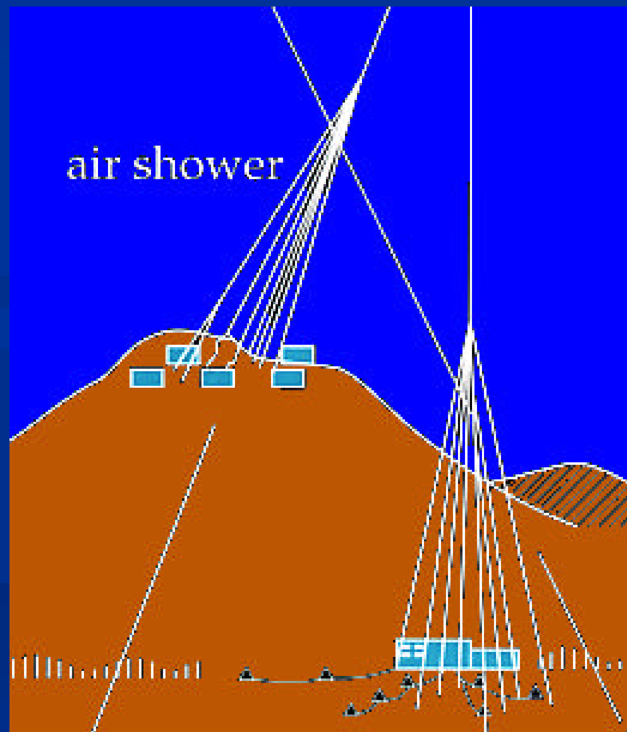
極限エネルギーガンマ線と宇宙線による宇宙像」
研究会, Feb. 18-19, 2004, 甲南大学

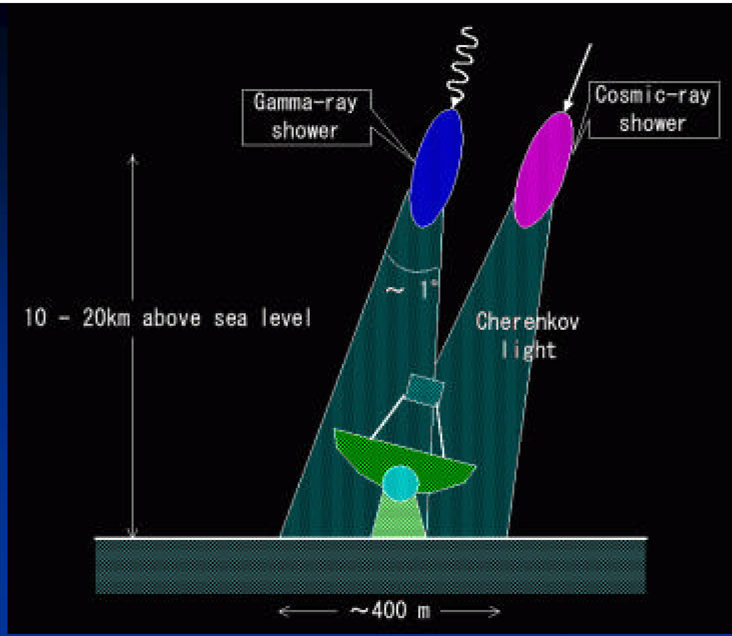
Detection of gamma-rays (1)



> TeV gamma-rays

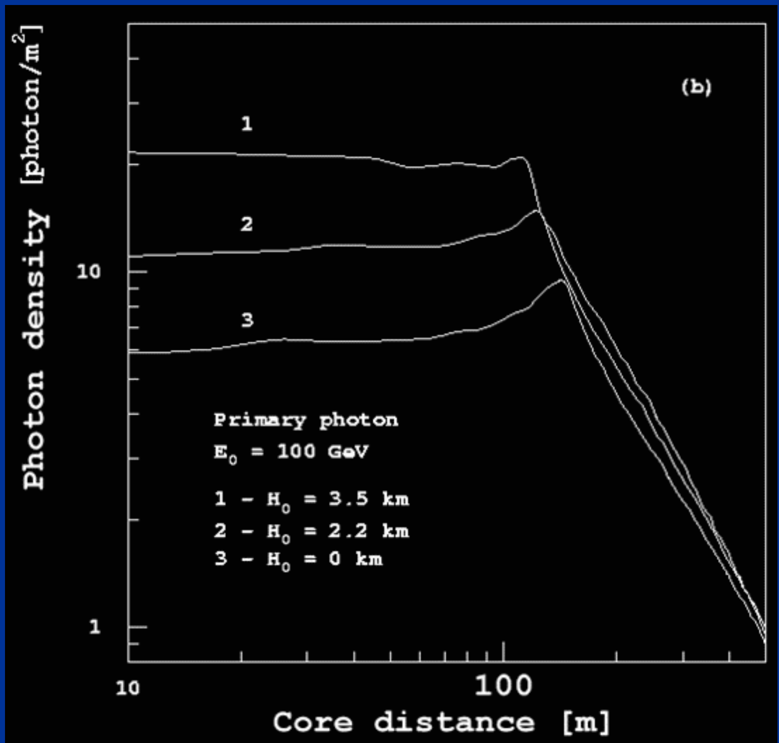


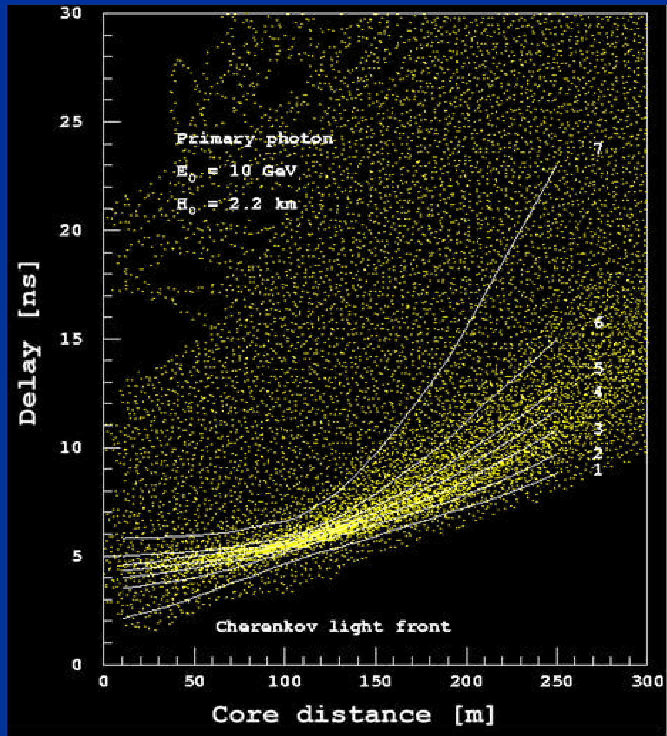
Atmospheric Cherenkov telescopes



Cherenkov light from gamma-ray showers

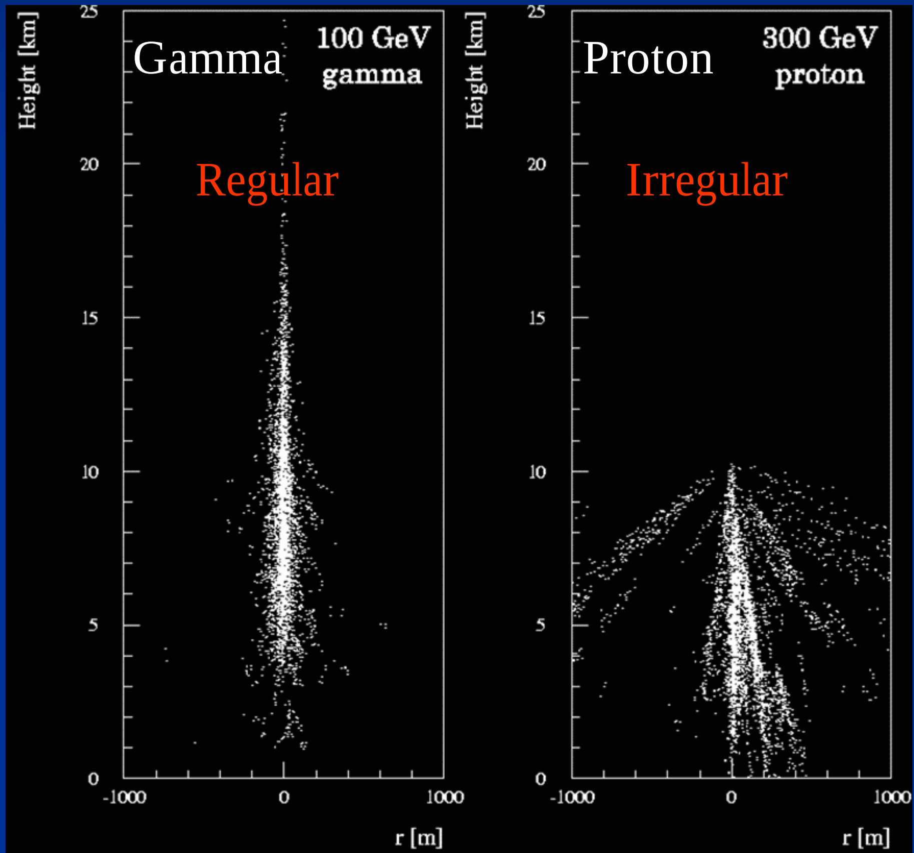
Lateral distribution & *Timing distribution*



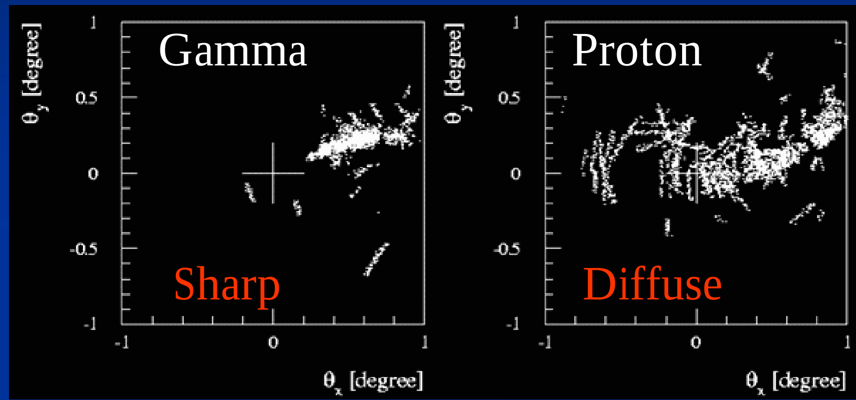


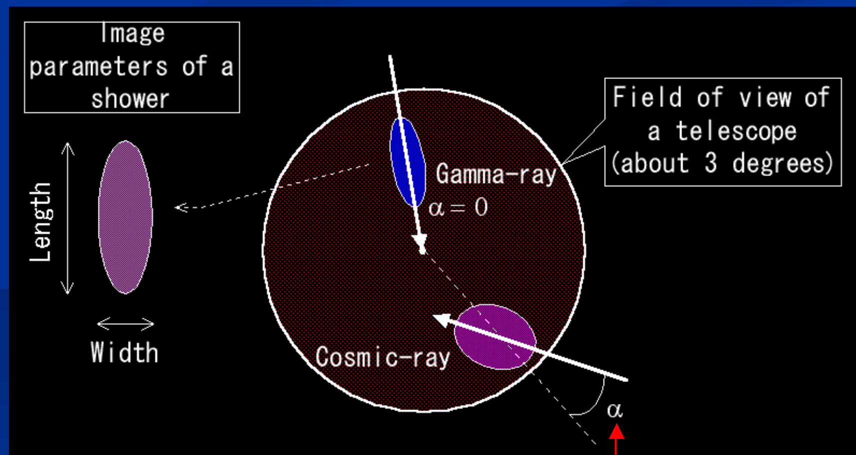
Imaging Cherenkov Telescopes

Shower profile



Focal plane image



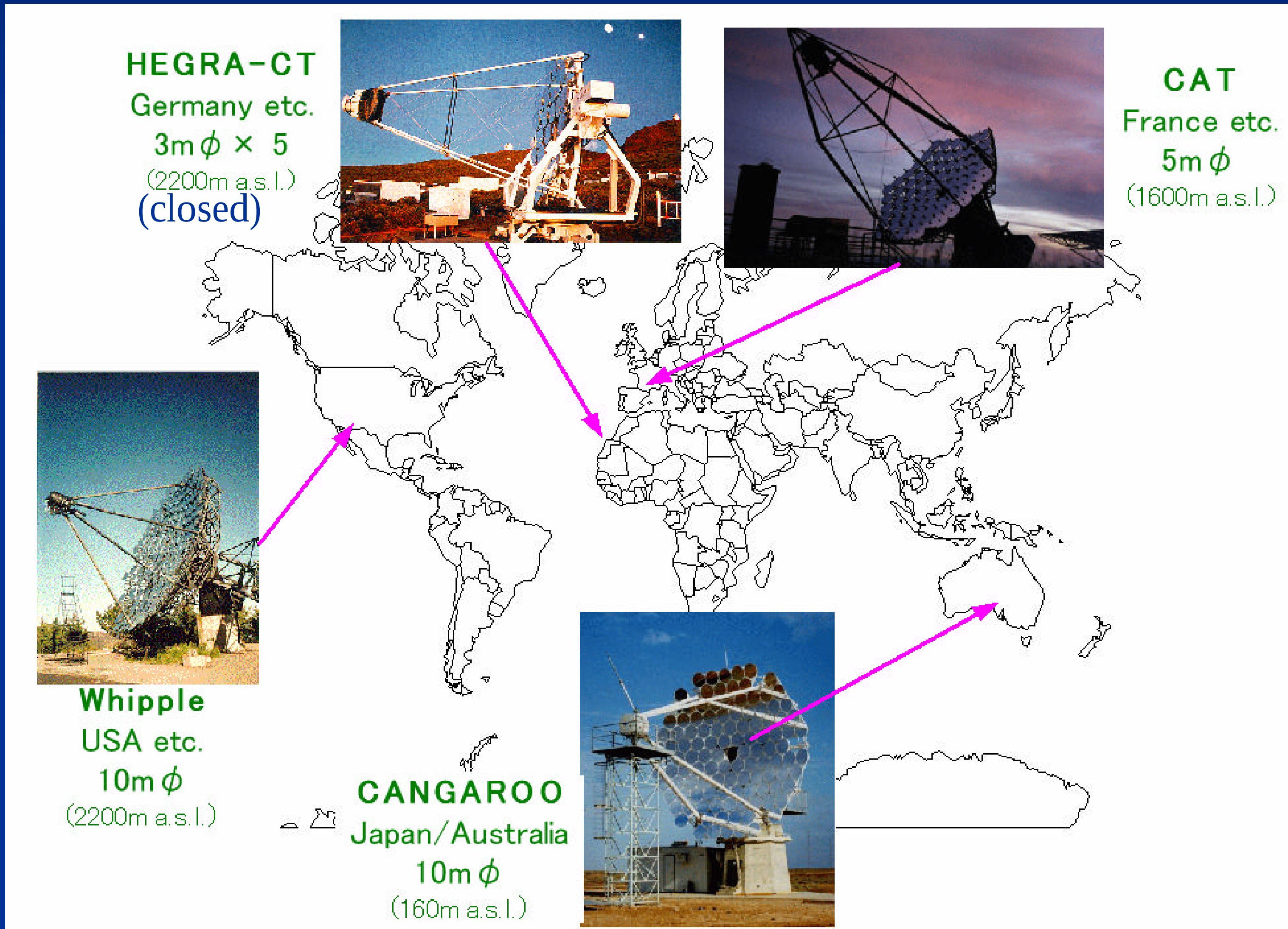


a (image orientation angle)

Detection of gamma-rays (2)

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 $\Delta\theta$

Imaging Cherenkov telescopes in operation



Galactic sources: basics

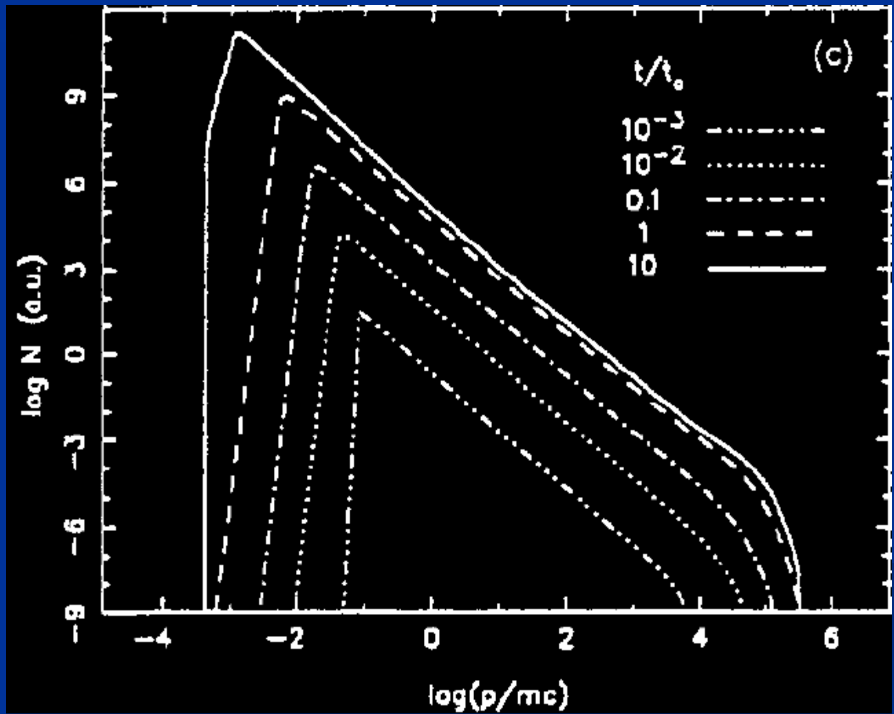
- Supernova remnants = Origin of CR?
  - Energetics – OK (if 10% of E_{SN} goes to CR)
  - Maximum energy – Up to "Knee region"
  - How much of them?
  - Some evidences, which can be ascribed to HE electrons: where are HE protons?
- Pulsar and pulsar wind nebula (plerions)
  - Crab – "The standard candle"
    - Up to a few 10GeV: pulsed+unpulsed
    - Above: unpulsed only
    - - Unpulsed: SSC (Synchrotron-Self-Compton) model
    - - Where is the cutoff?
    - - (Pulsar emission models)
  - Others? Vela, PSR1706-44,…

Particle acceleration in SNR

Non-linear kinetic theory

$t_0 = R_0 / v_0$; sweep up time

Particle spectrum



Berezhko & Voelk, APh 1997

Maximum momentum

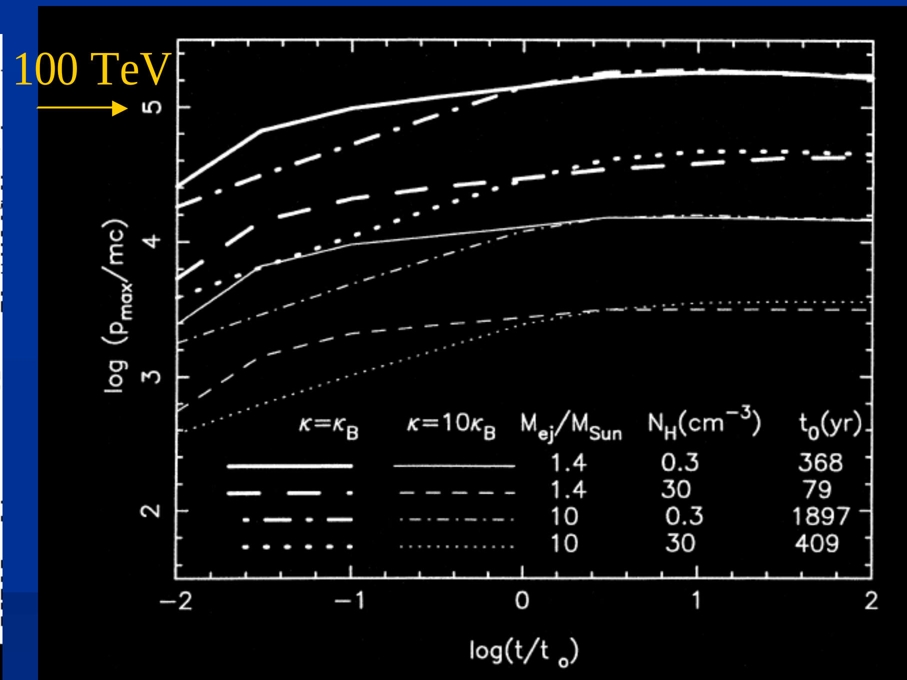
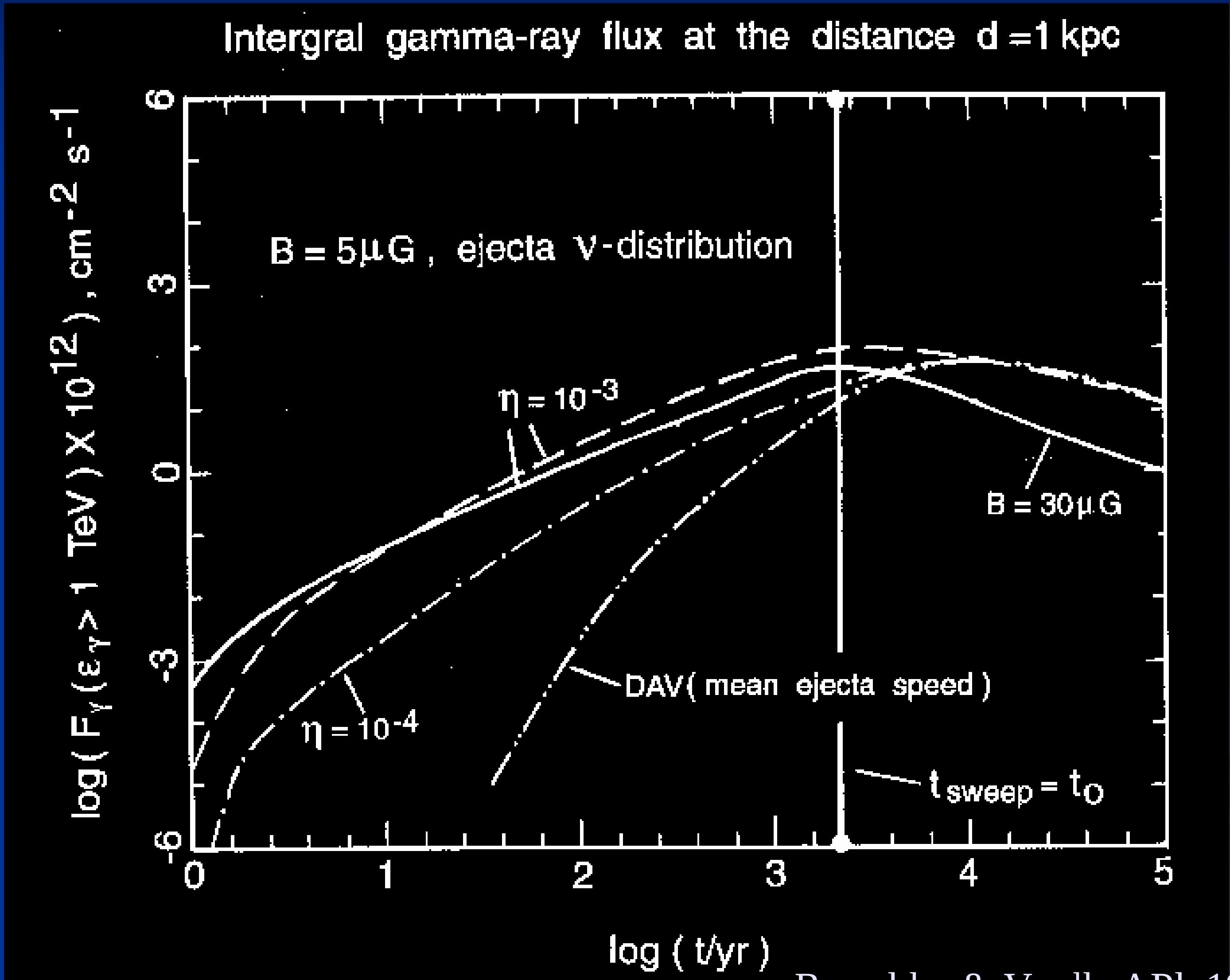


Fig. 2. The maximum CR momentum as a function of time for the same cases as in Fig. 1.

Berezhko & Voelk, APh 2000

Cf. Lagage and Cesarsky 1984

Nuclear gamma-ray flux from SNR



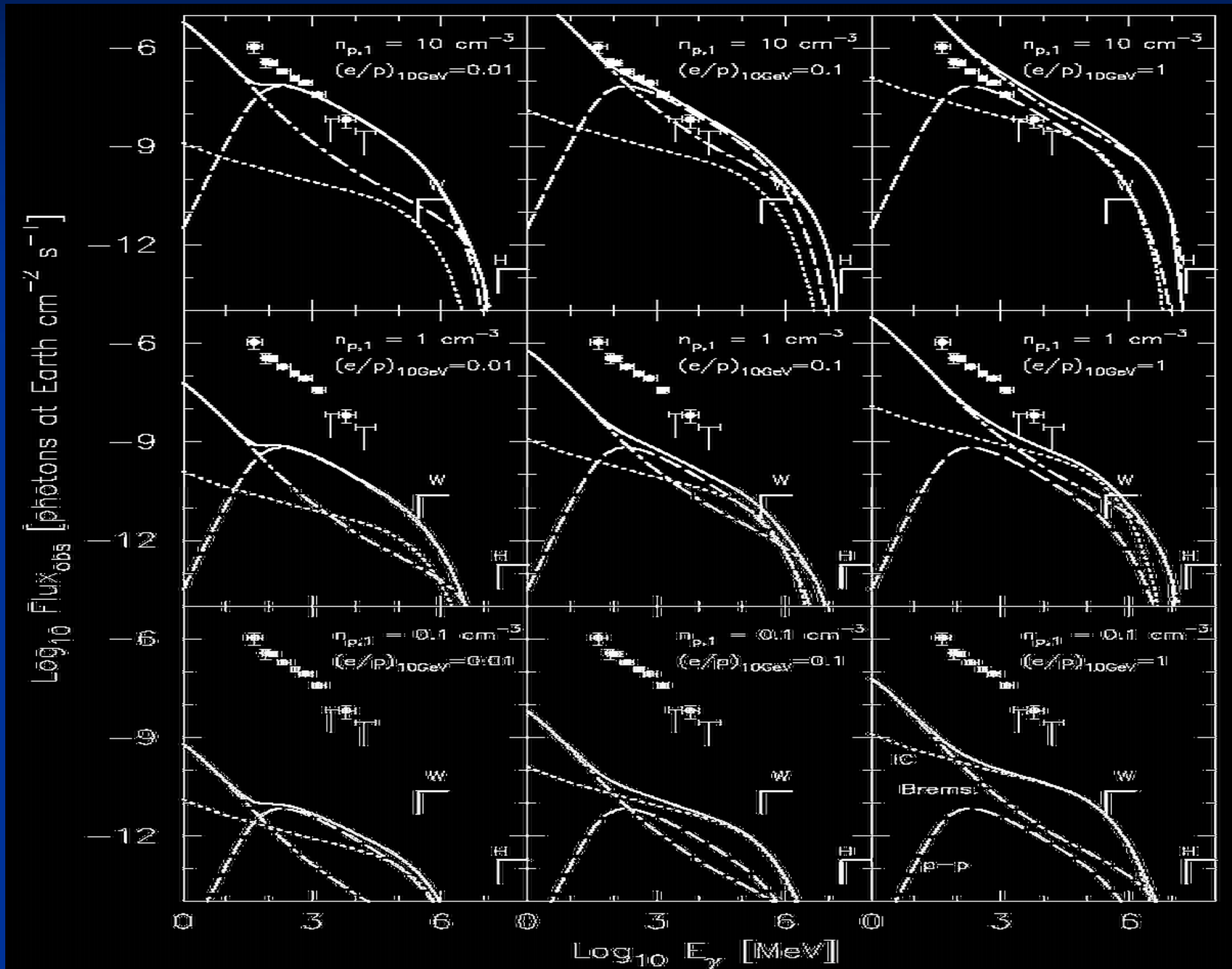
Berezhko & Voelk, APh 1997

Gamma-ray emission from SNR

n=10 cm^{-3}

n=1 cm^{-3}

n=0.1 cm^{-3}



e/p = 0.01 0.1 1

Dot: IC

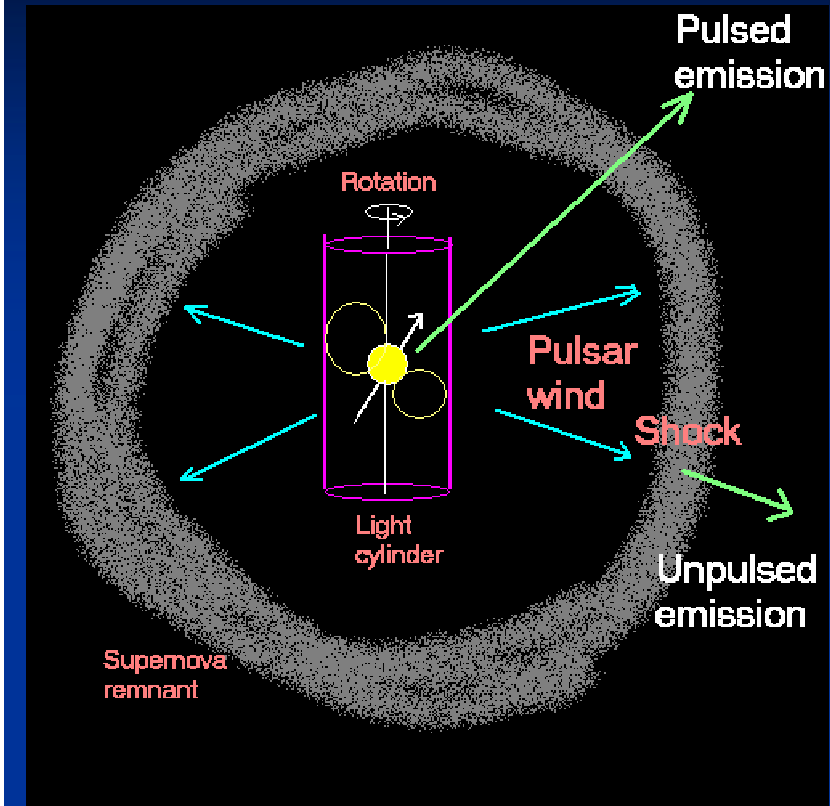
Dash: π^0

Dot-dash:brems

(Data: EGRET IC443)

Baring et al. 1999 ApJ 513, 311

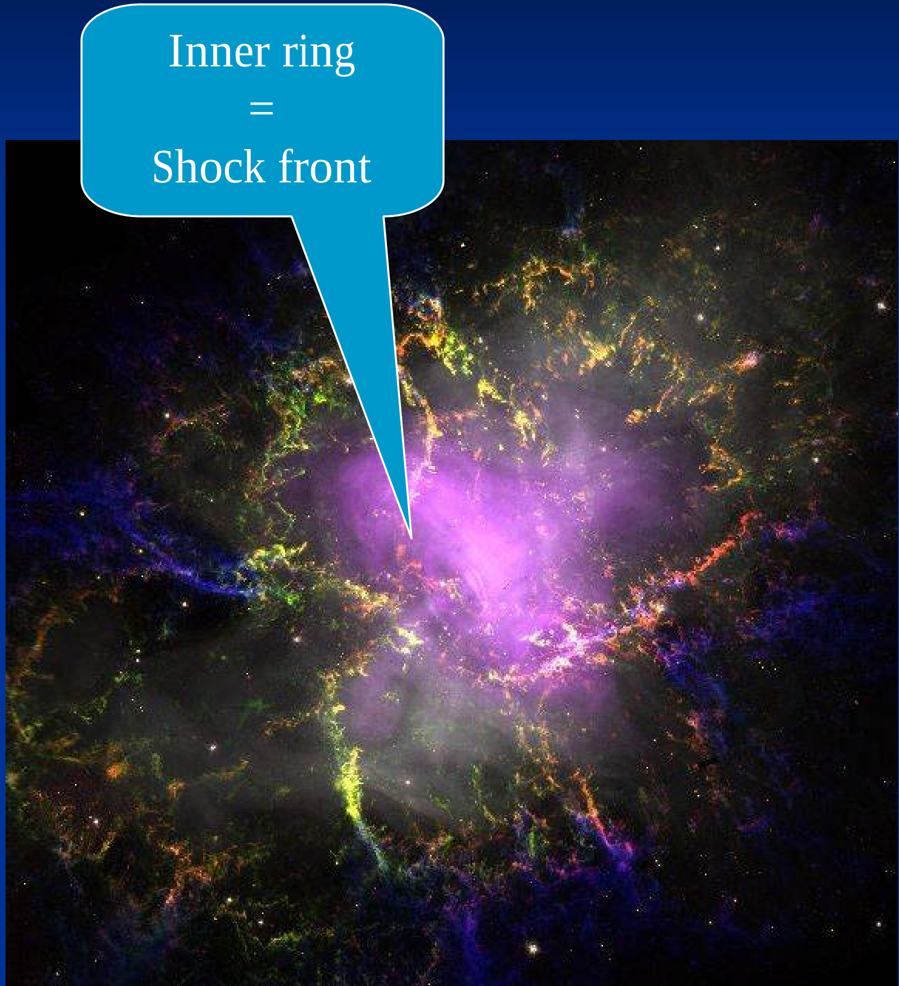
Pulsar nebula



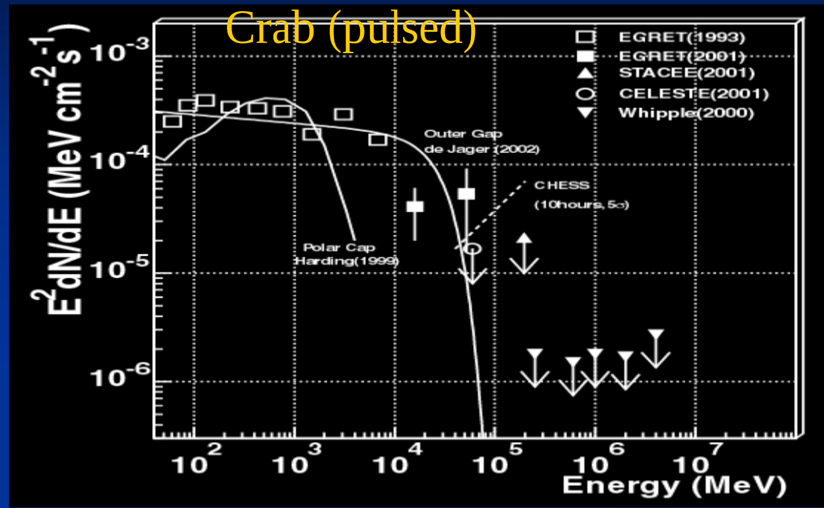
- 周囲のガス圧とバランスするところで衝撃波が形成され、圧縮加熱されたパルサー風がシンクロトロン放射で輝く

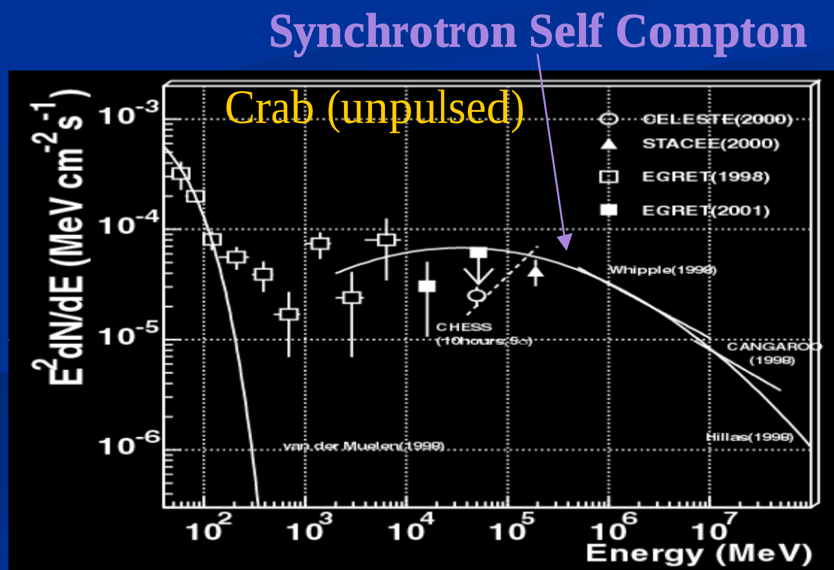
K.Mori, talk at ICRR, Dec 2003

The Crab



Optical + X-ray image



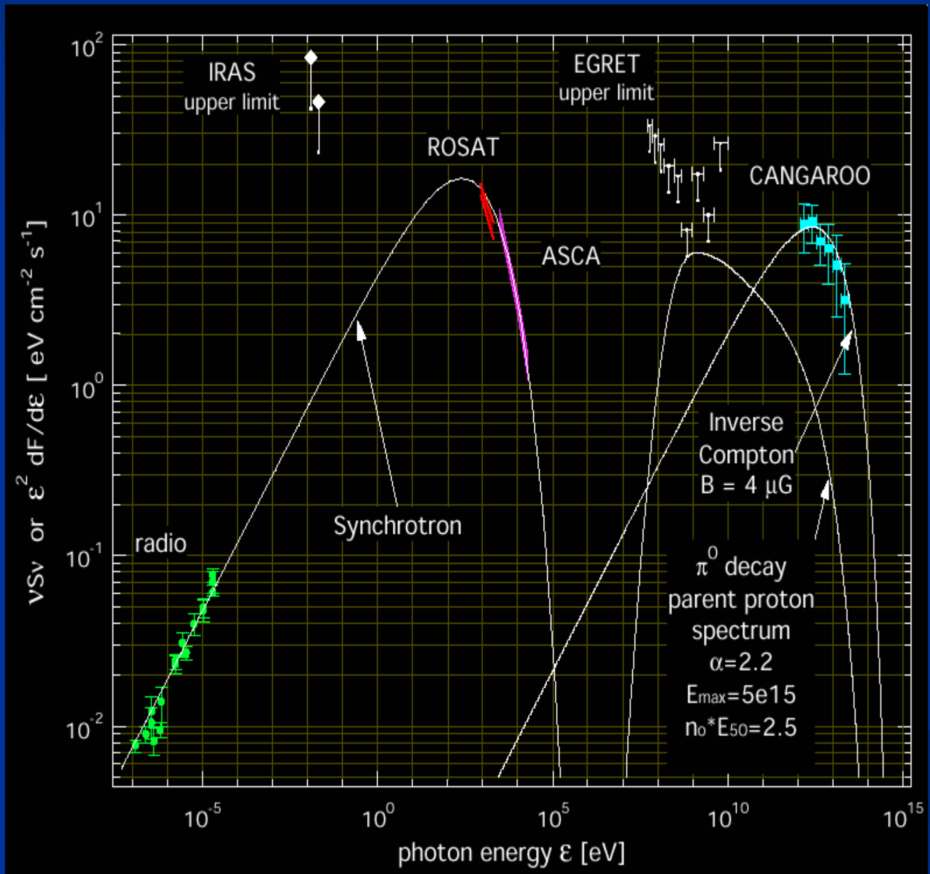


Asahara et al., SPIE 2002

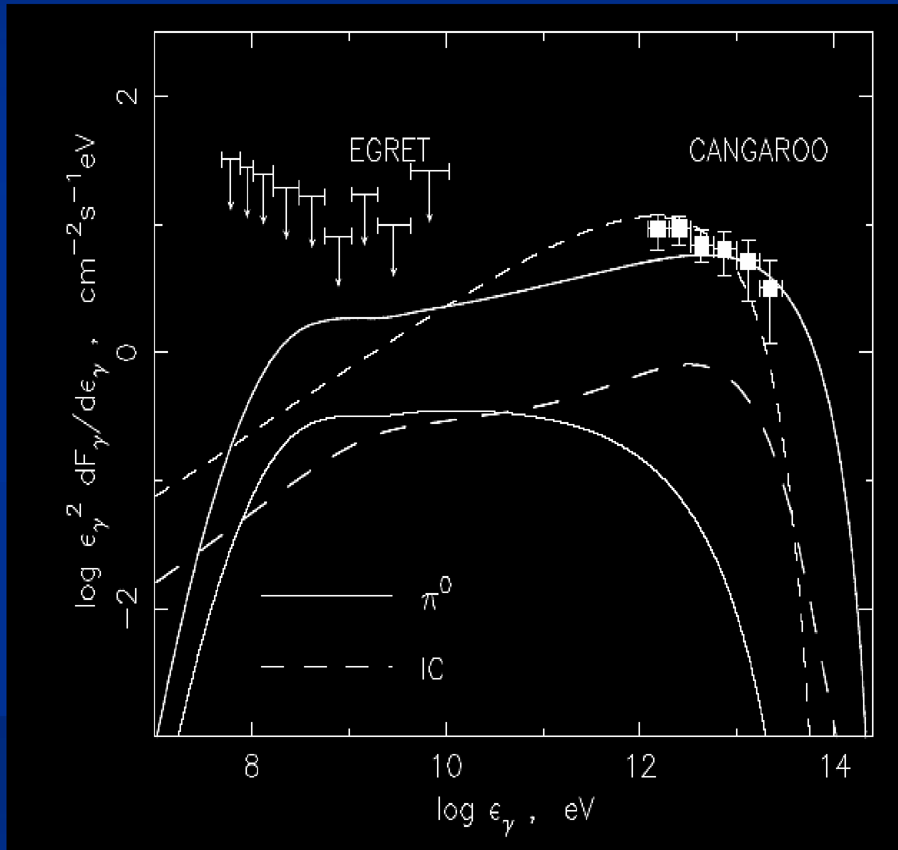
“Known” galactic sources

- Crab “The standard candle”
  - Well established (many observations since 1989)
- Pulsar PSR 1706-44
  - CANGAROO 1995
- Vela pulsar
  - CANGAROO 1997
- Supernova remnant SN1006
  - CANGAROO 1998, HEGRA CT1 2003
- Supernova remnant RX J1713.7-3946
  - CANGAROO 2000, 2002
- Supernova remnant Cas A
  - HEGRA CT system 2001

SN1006 emission mechanism



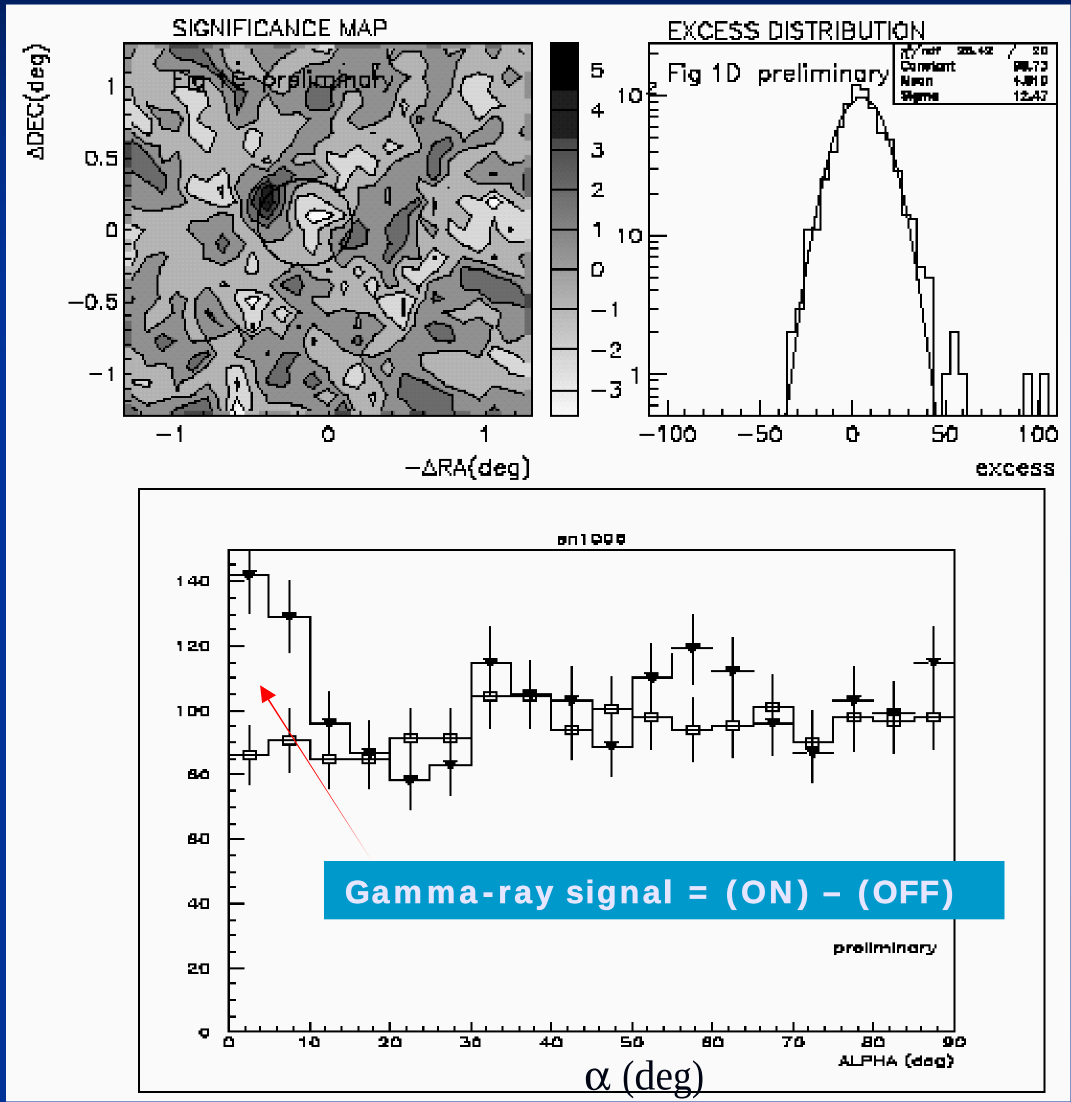
Naito et al. AN 320 (1999)



Voelk et al. AA 396 (2002)

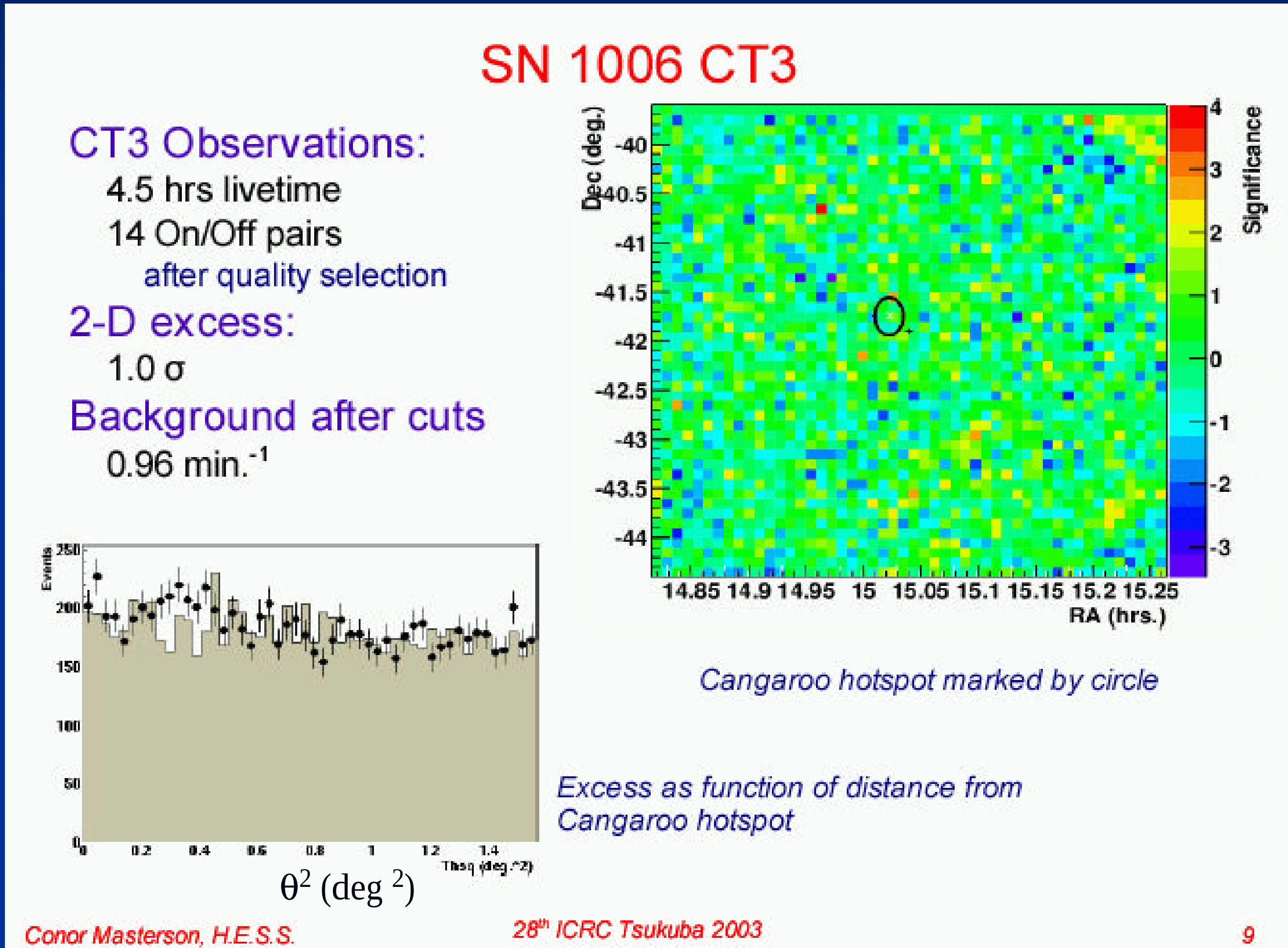
SN1006: HEGRA CT1

- HEGRA CT1
- 219hrs
- >18TeV
- 5σ excess
- Position within 0.1° of CANGAROO hotspot



Vitale et al. 28th ICRC (2003)

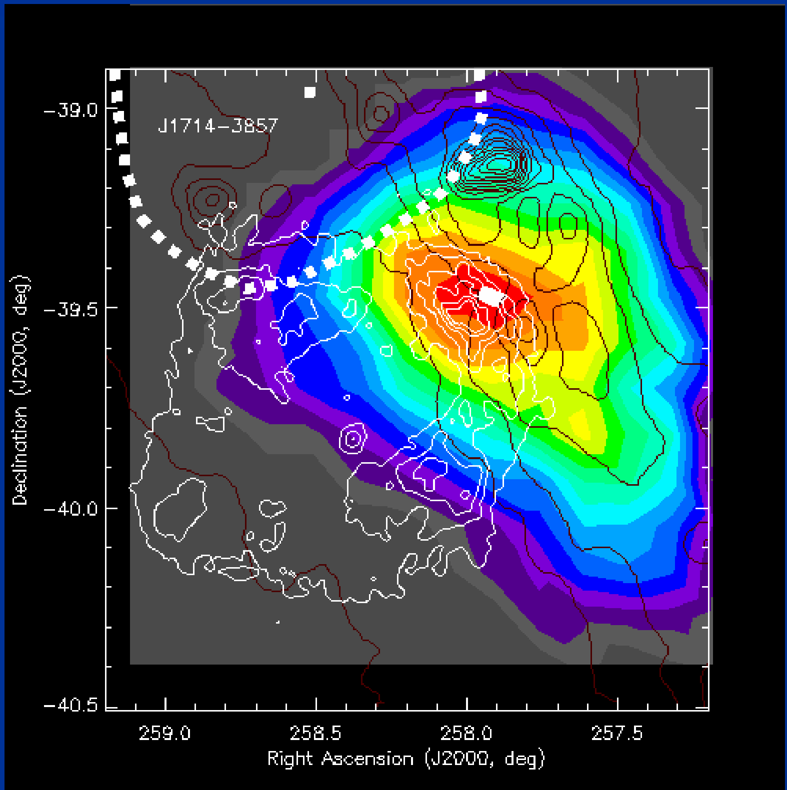
SN1006: H.E.S.S.



Masterson et al., 28th ICRC (2003)

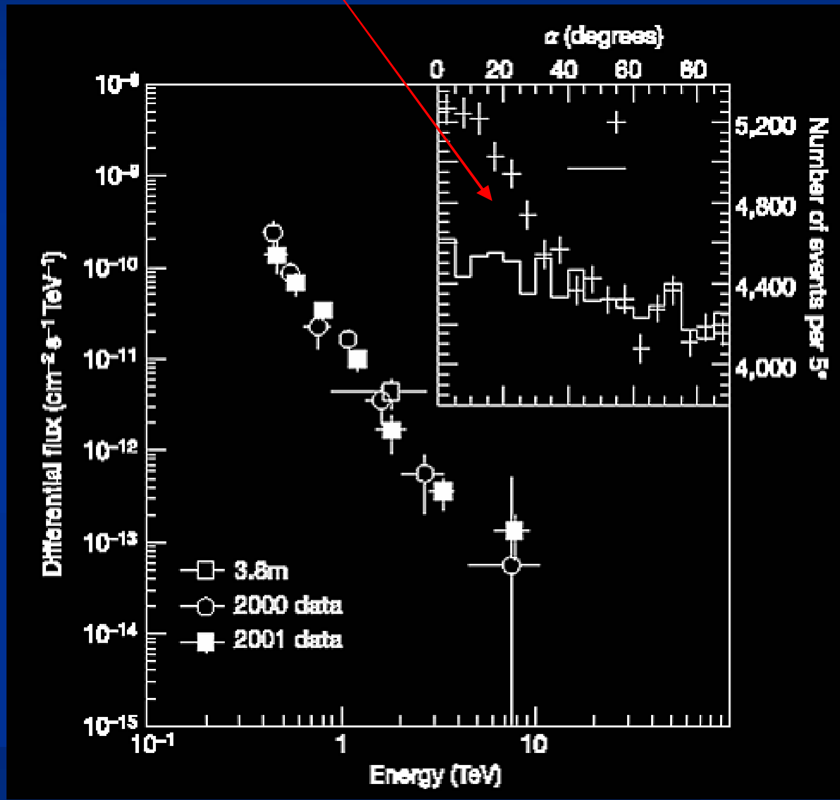
SNR RX J1713.7-3946 (1)

- Detected in X-rays
- Non-thermal X-ray spectrum



Significance map

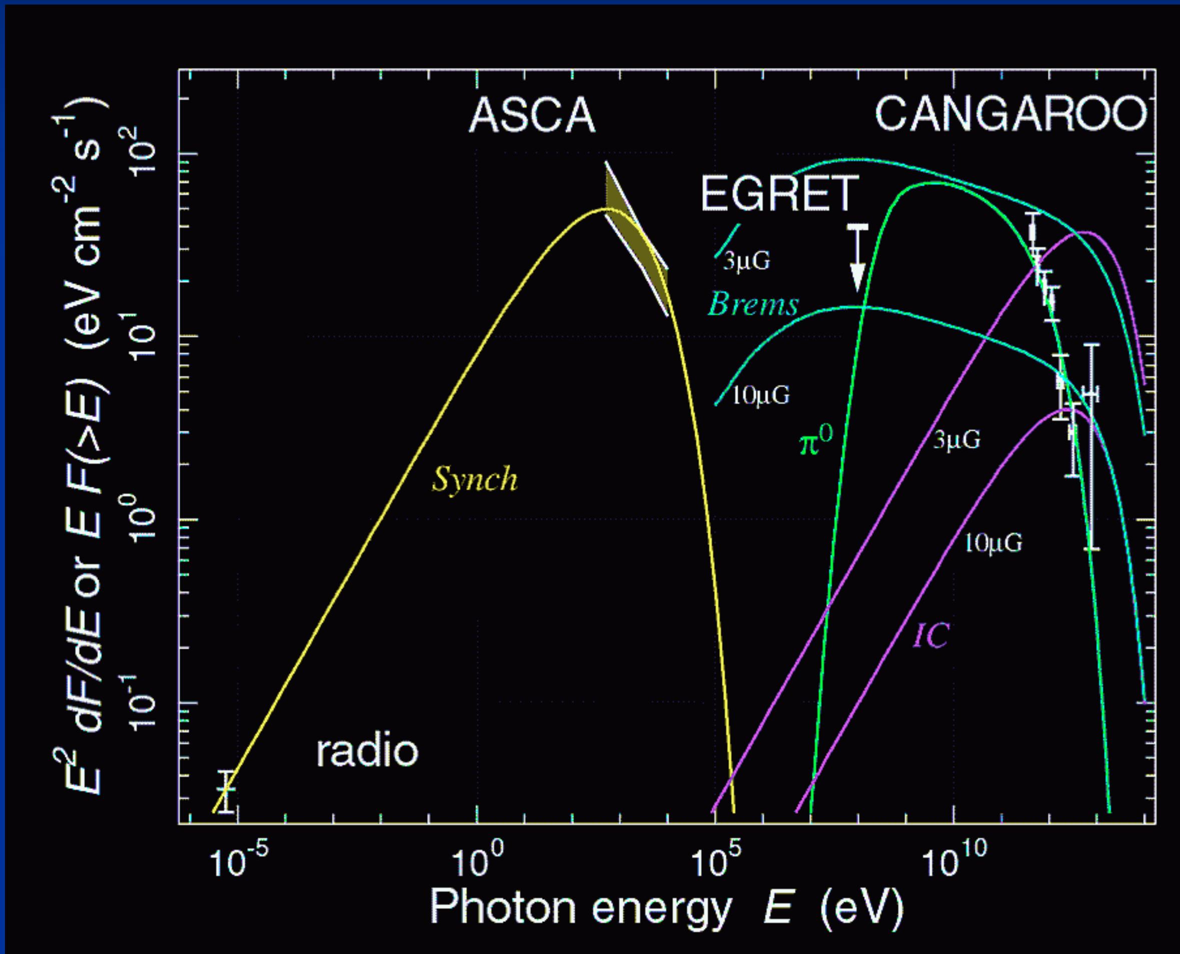
Gamma-ray signal = (ON) – (OFF)



Energy spectrum

Enomoto et al. Nature 416 (2002) 823

SNR RX J1713.7-3946 (2)



Enomoto et al. Nature 416 (2002) 823

Hard to explain by emission from electrons (Brems, IC)

⇒Emission from protons (π^0)?

⇒ Cosmic ray origin?

NANTEN results :

Distance ~ 1 kpc

Age ~ 1600yr

→ $L_p \sim 10^{48}$erg ~ $0.001 L_{SN}$

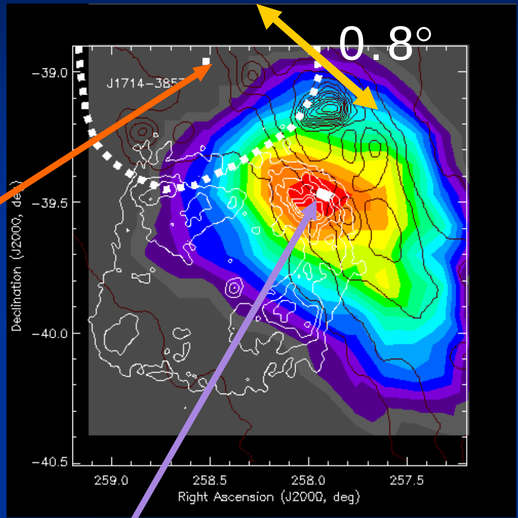
(Fukui et al. PASJ 55, 2003)

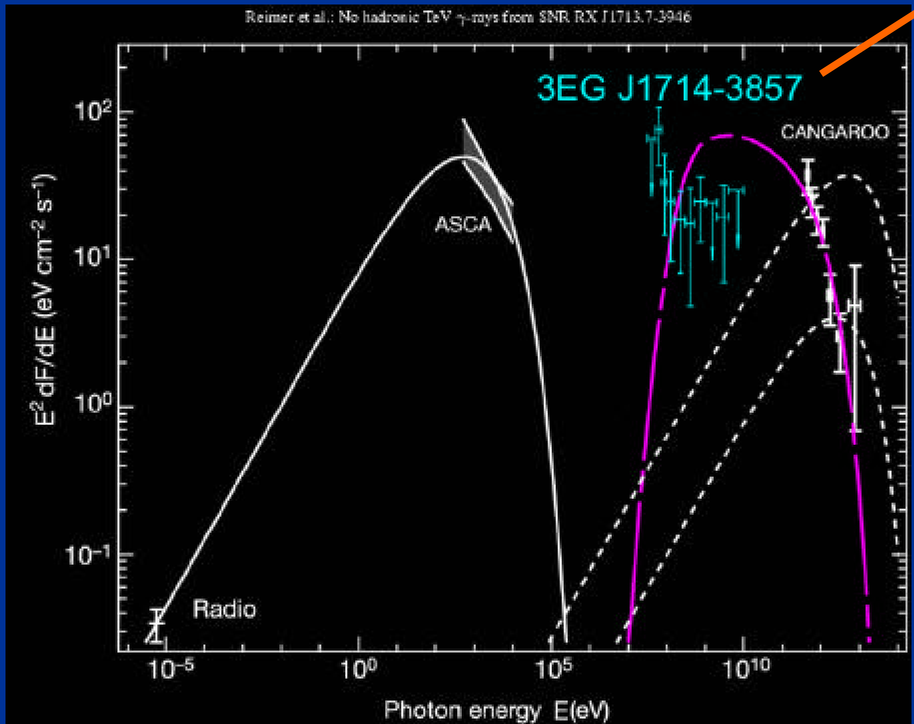
SNR RX J1713.7-3946 (3)

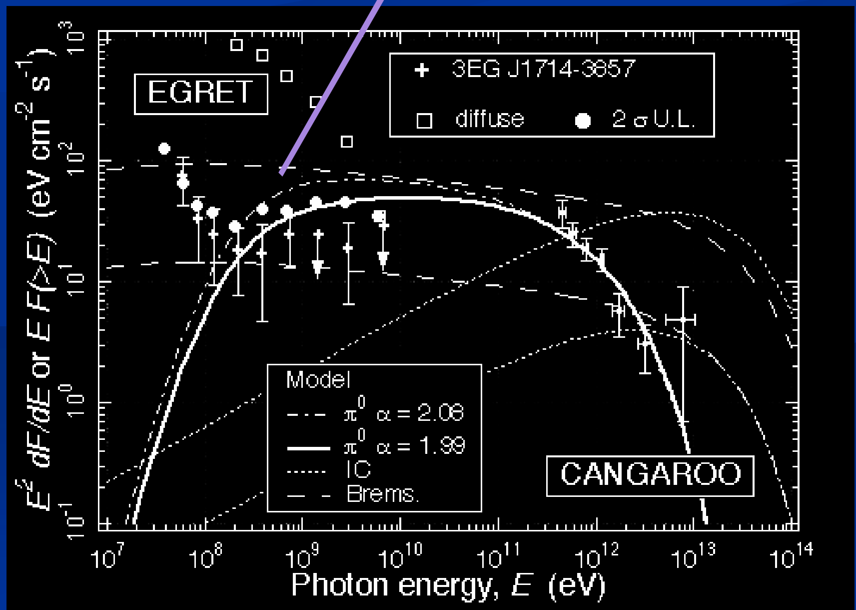
Counter arguments

* Reimer & Pohl, A&A 390 (2002) L43

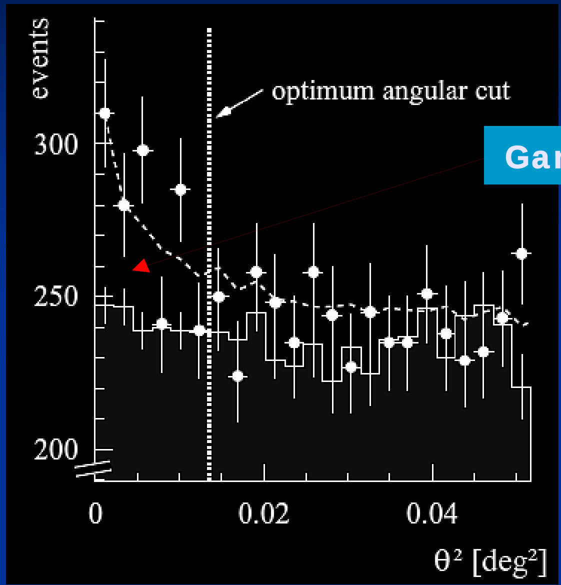
* Butt et al., Nature 418 (2002) 489







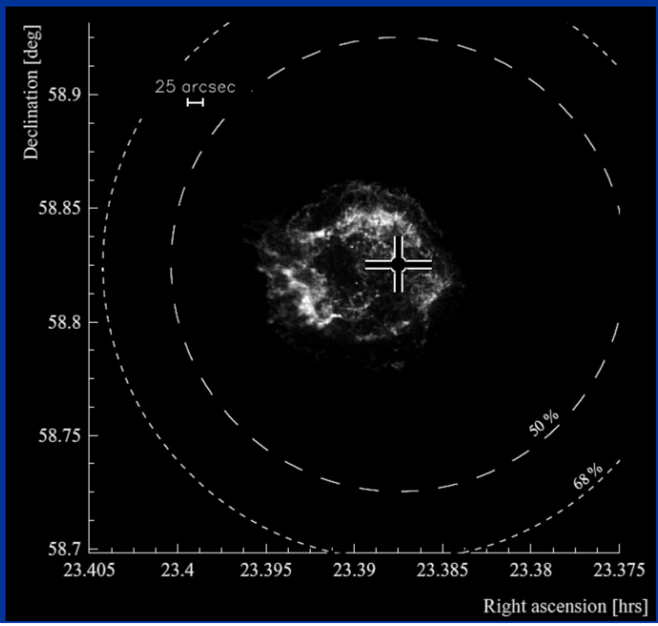
SNR Cas A

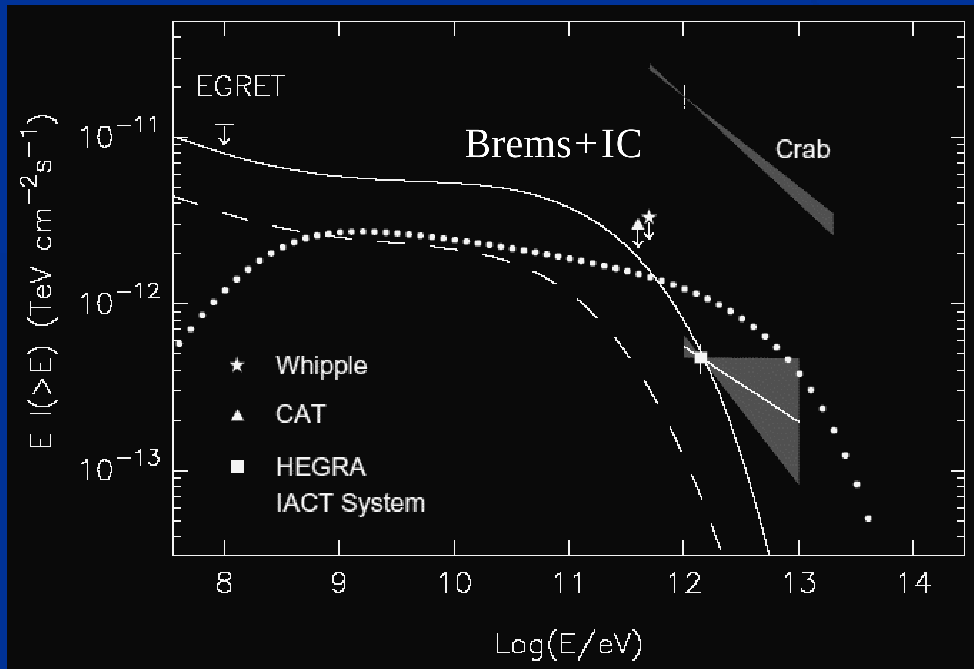


Gamma-ray signal = (ON) – (OFF)

HEGRA-CT system (stereo)

232 hrs

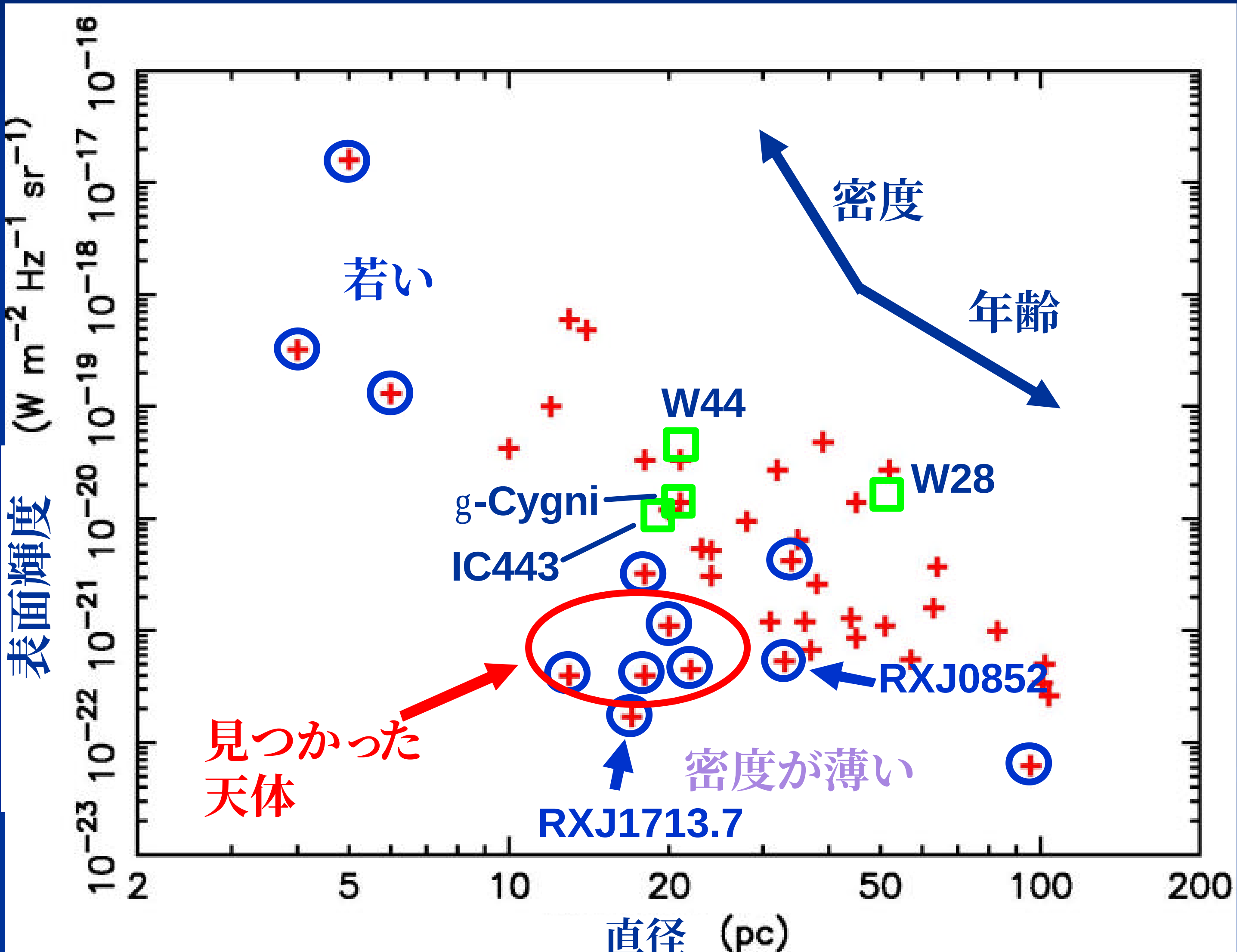




Aharonian et al. A&A 370 (2001) 112

More TeV SNRs?

Ueno, talk in Kyoto, Dec 2003

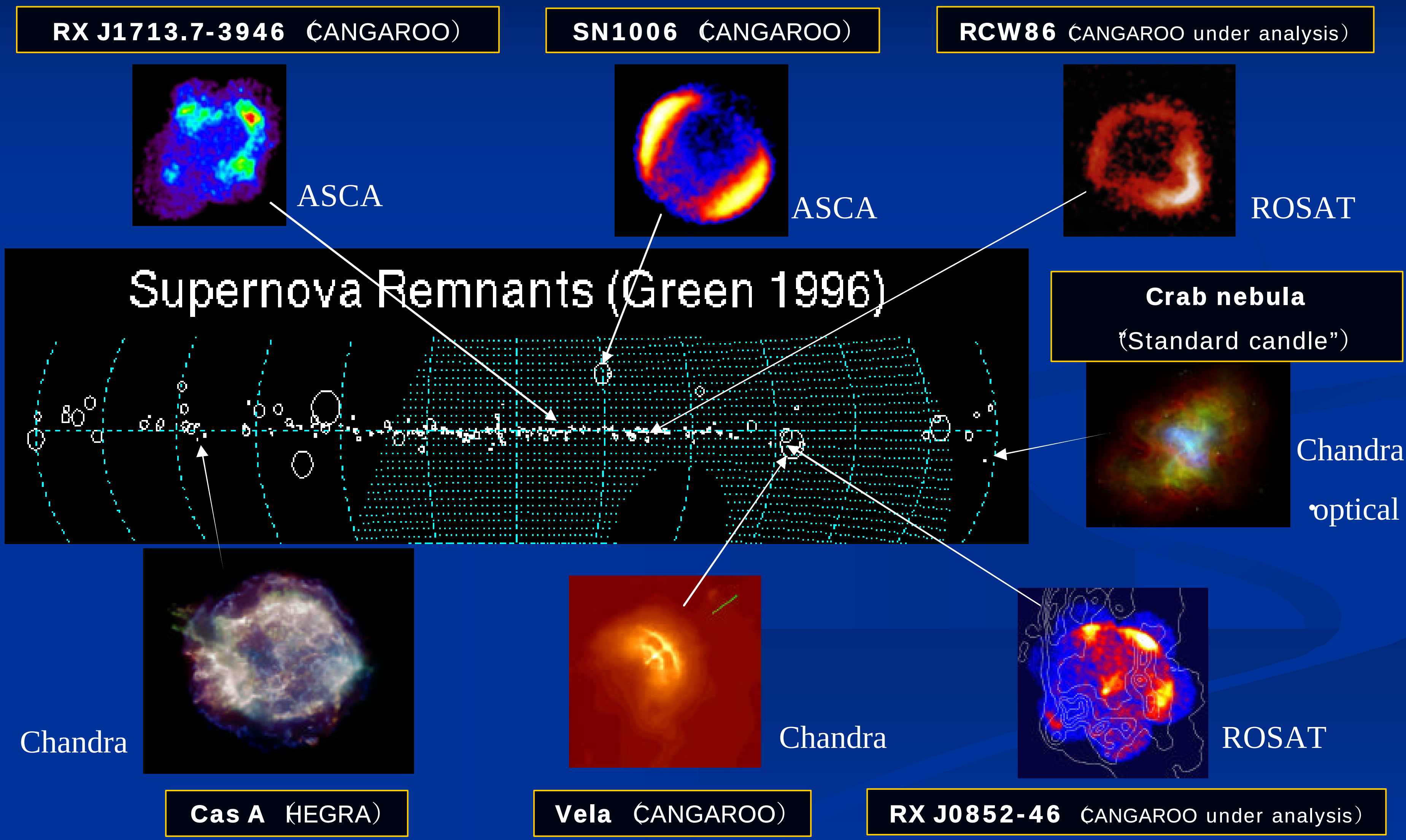


密度が高く
年を取ったもの

シンクロトロンX線
が受からない

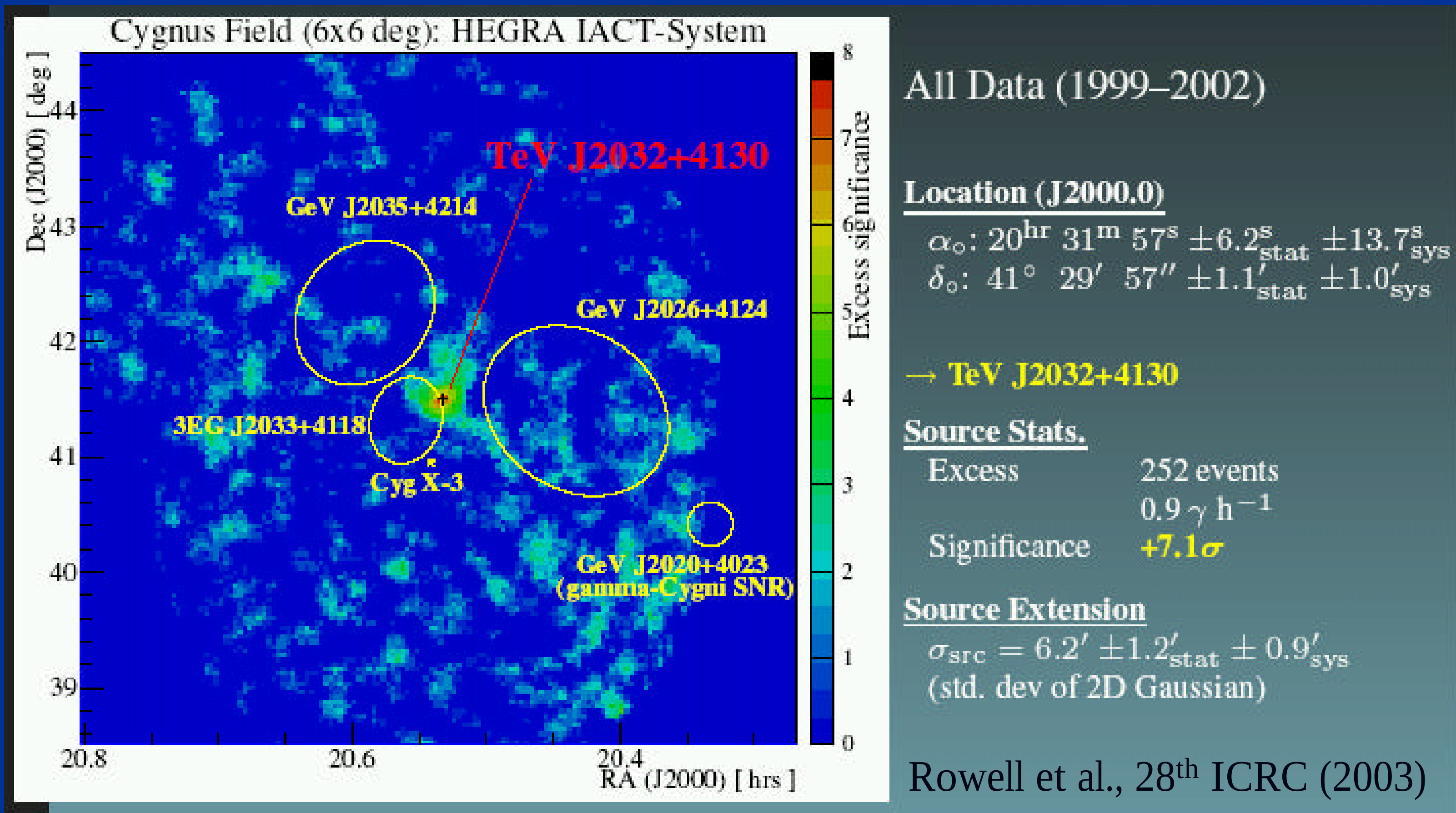
EGRET天体

Systematic study of SNRs



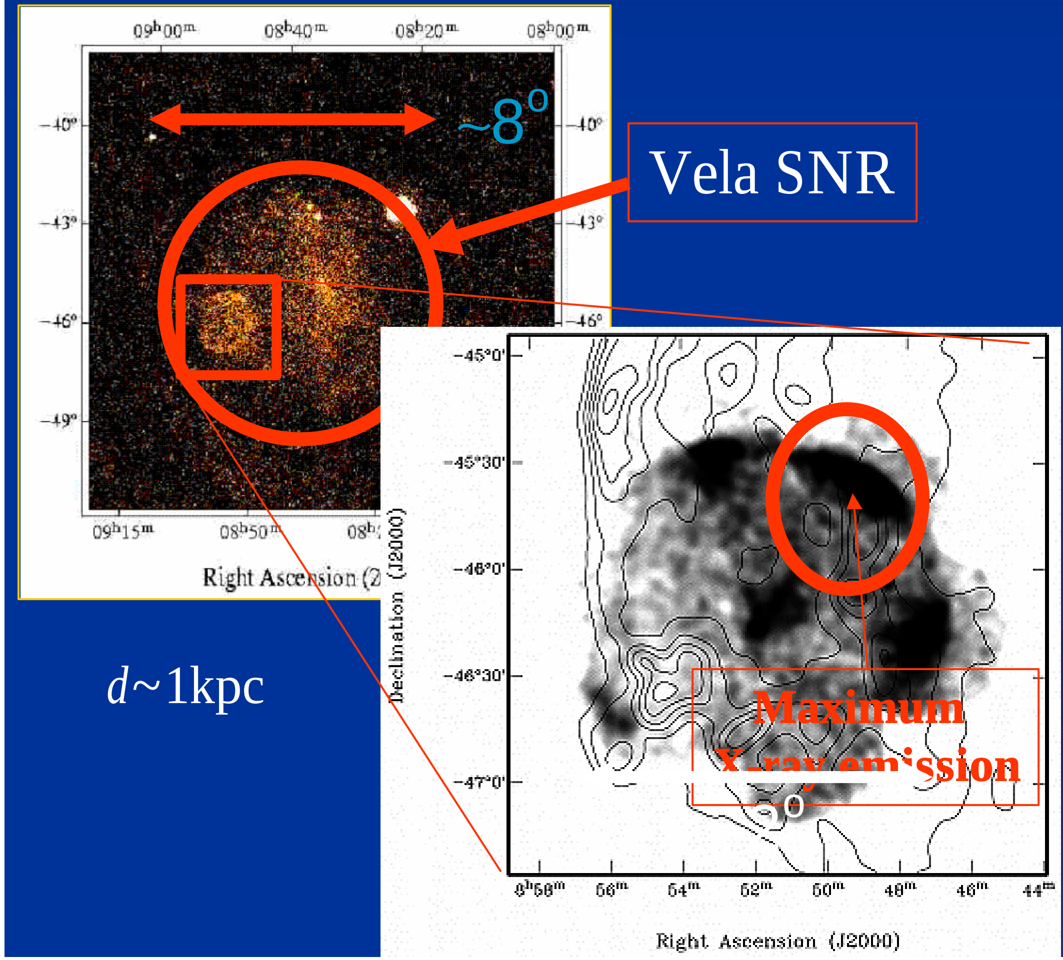
New entry: TeV J2032+4130

- Unidentified TeV source TeV J2032+4130
  - Very hard spectrum $E^{-1.9}$
  - No counterpart in radio or X-rays

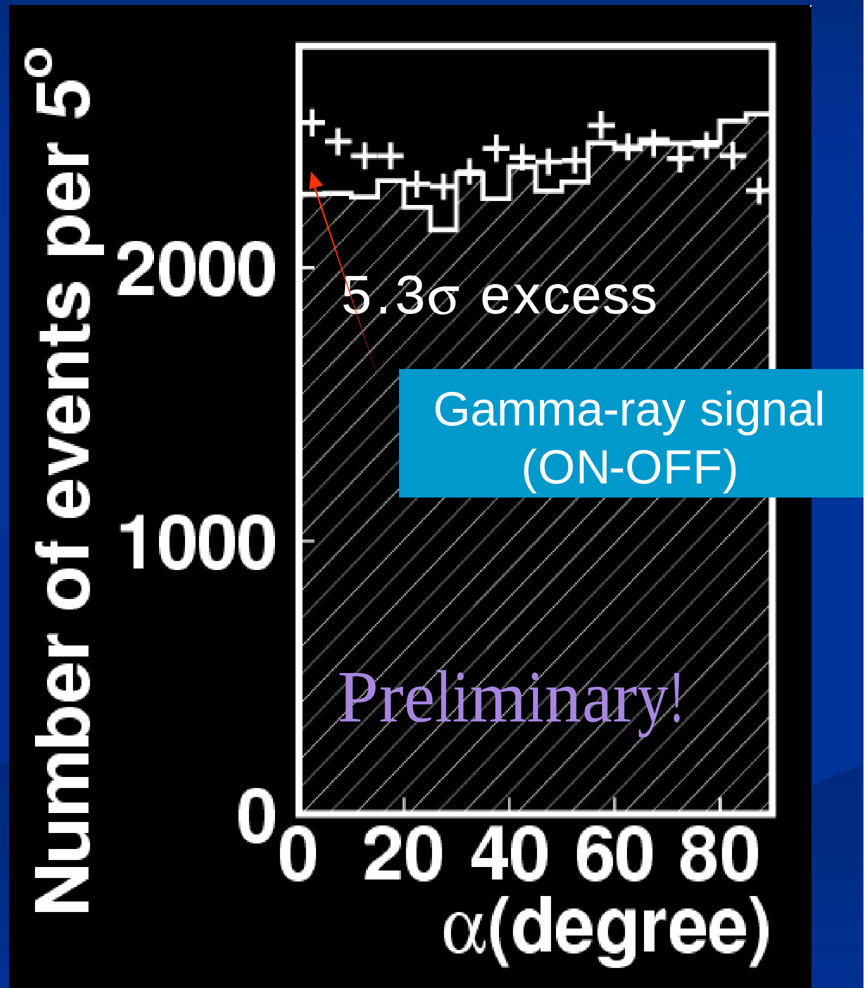


New entry: SNR RX J0852.0-4622

- CANGAROO 10m result



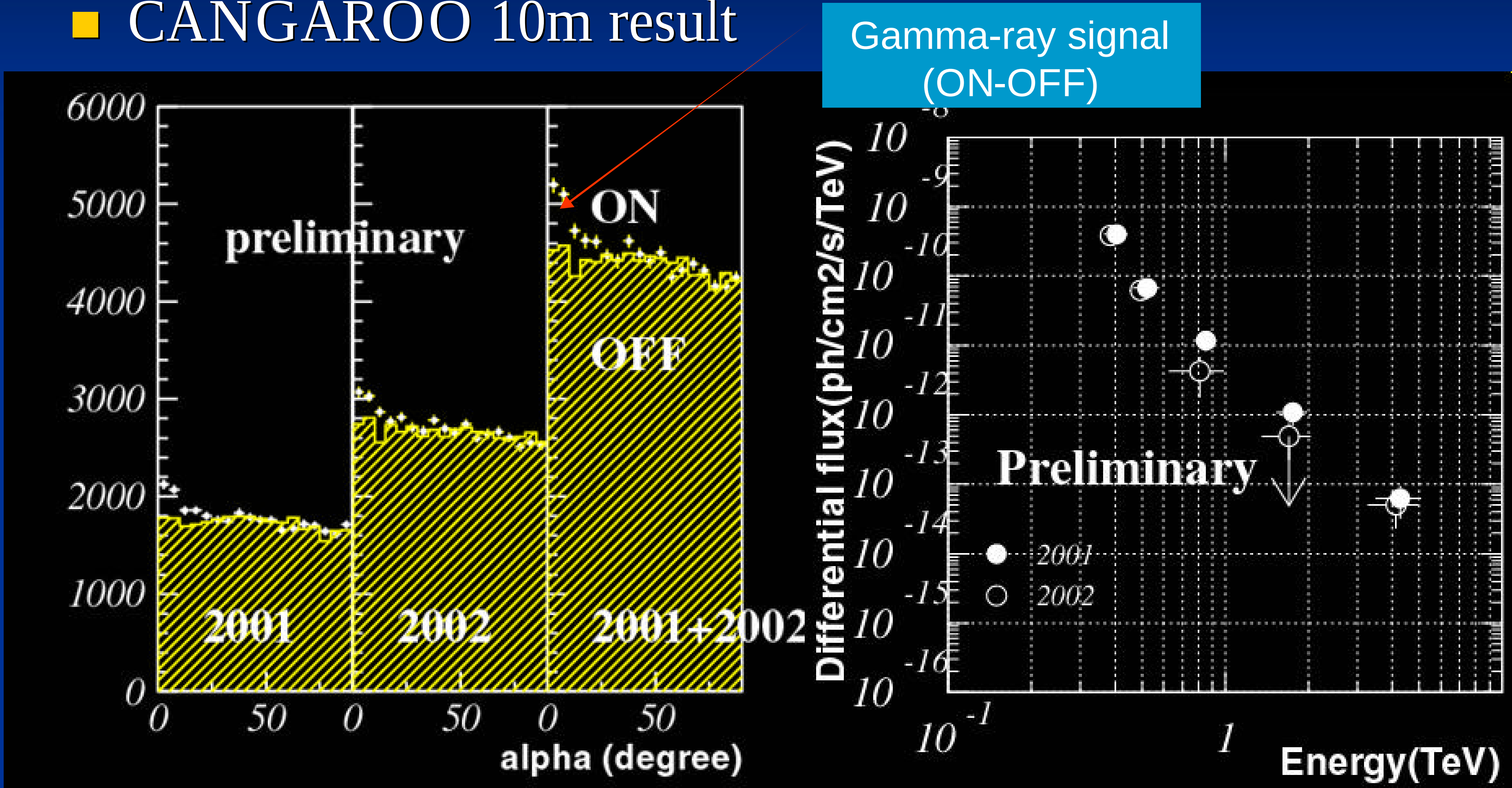
d~1kpc



Katagiri et al., 28th ICRC (2003)

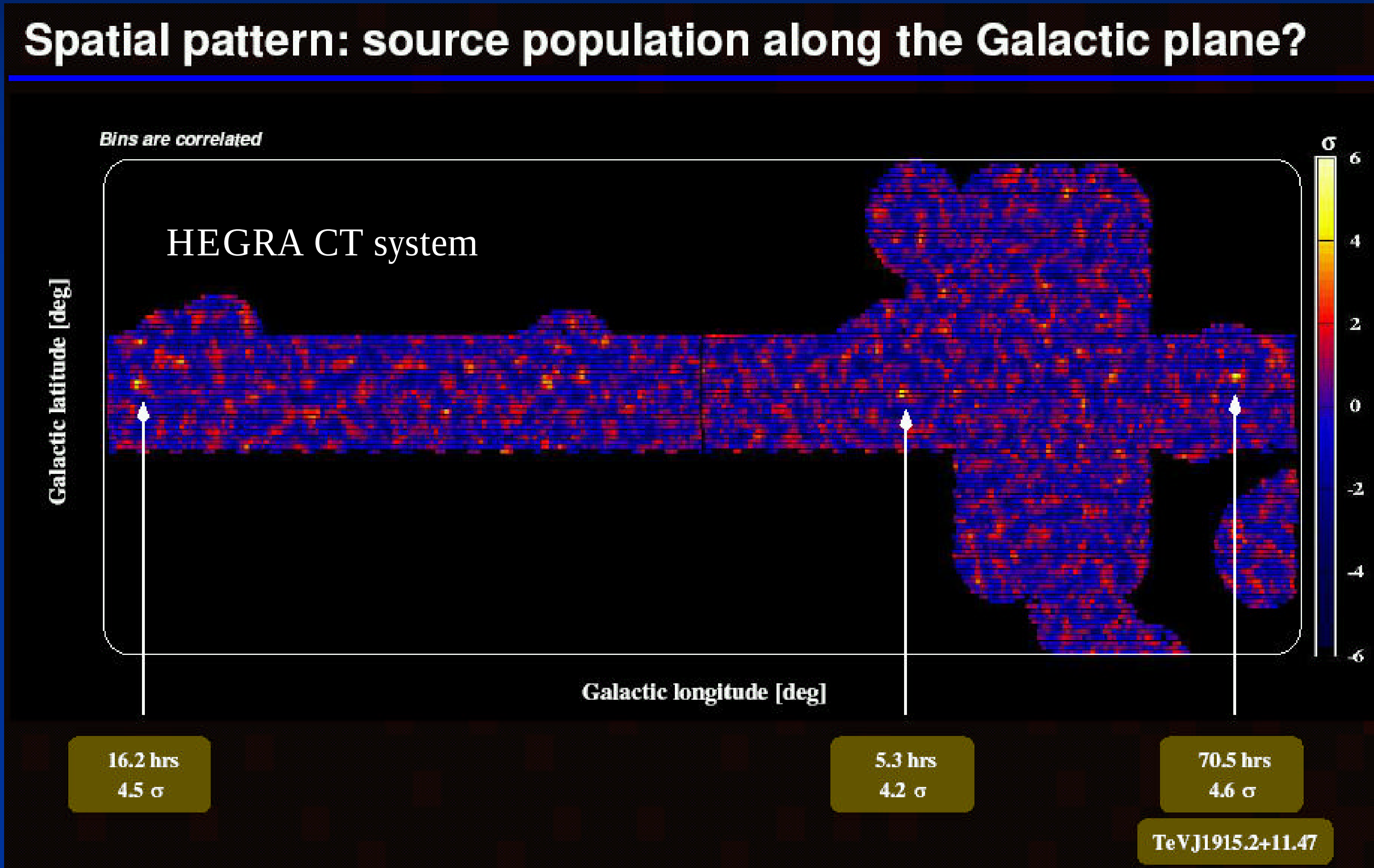
New entry: Galactic center

- CANGAROO 10m result



Tsuchiya et al., 28th ICRC (2003)

Galactic plane survey

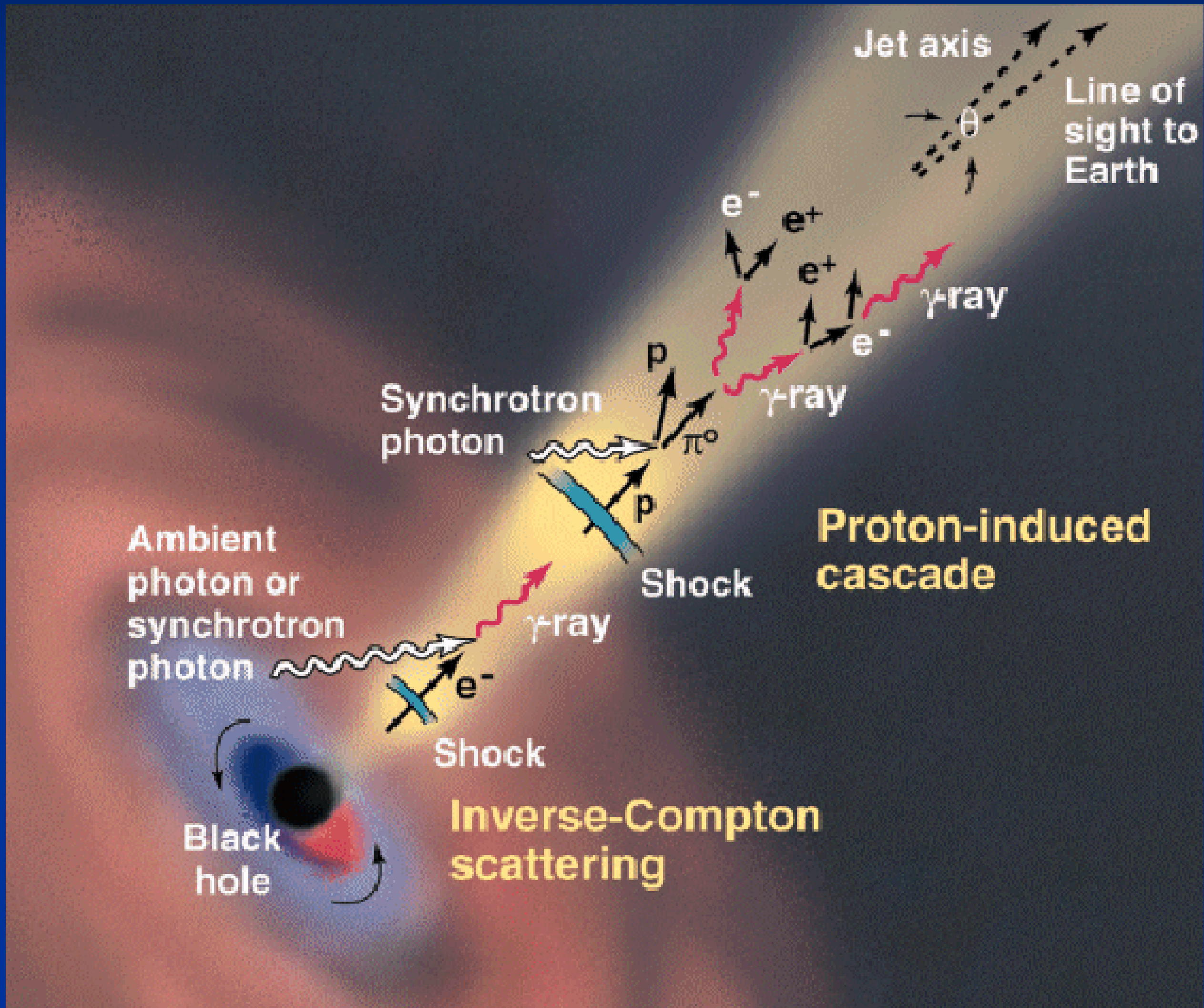


Puehlhofer et al., 28th ICRC (2003)

Extragalactic sources: basics

- Active galactic nuclei
  - Blazars
    - Wide-band spectrum – nonthermal
    - Quasars – LBL (RBL) – HBL (XBL) sequence
    - Leptonic models
      - SSC or EC (External Compton)
    - Hadronic models
      - Proton-initiated cascades
  - Radio galaxy,…
- Gamma-ray absorption by EBL (Extragalactic Background Radiation)
  - Infrared photon field: uncertain
- Center of galaxies
  - Accumulation of dark matter??
- Extragalactic background radiation

Blazars



Beaming factor

$\delta \equiv 1/\Gamma(1-\beta\cos\theta) > 1$

Observed frequency

$n \propto n_0 \delta$

Apparent luminosity

$L \propto L_0 \delta^4$

“Known” extragalactic sources

- Mrk421 (z=0.031)
  - First detection in 1992 [Punch et al. Nature 1992]
  - Flares in 1994, 1996, 2001, 2002-3
- Mrk501 (z=0.034)
  - First detection in 1995 [Quinn et al. ApJ 1996]
  - Large flares in 1997
- 1H1426+428 (z=0.129)
  - First detection in 2001 [Horan et al. 5th Compton 2001]
  - Flares in 2001

Multiwavelength spectra of blazars

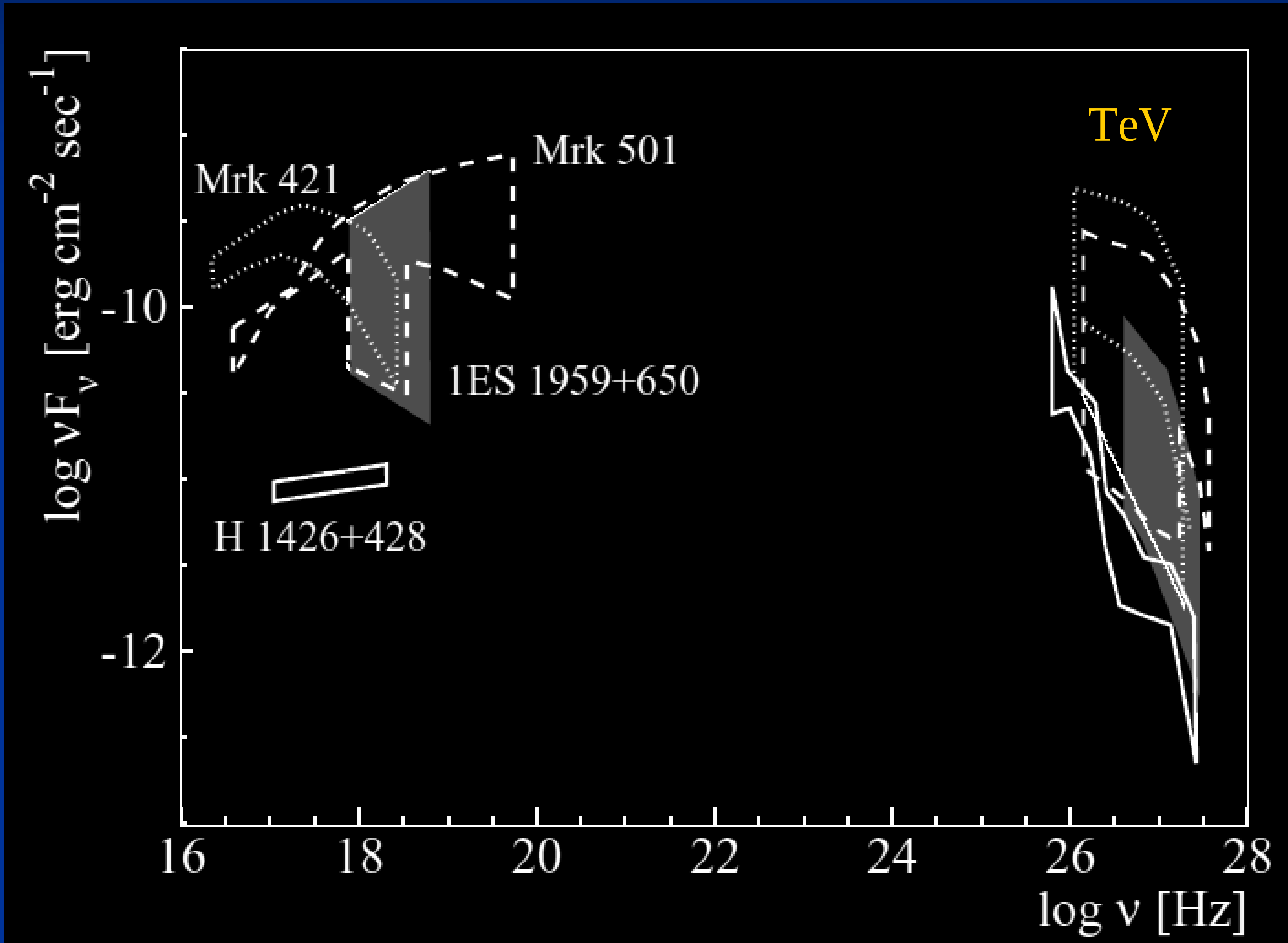
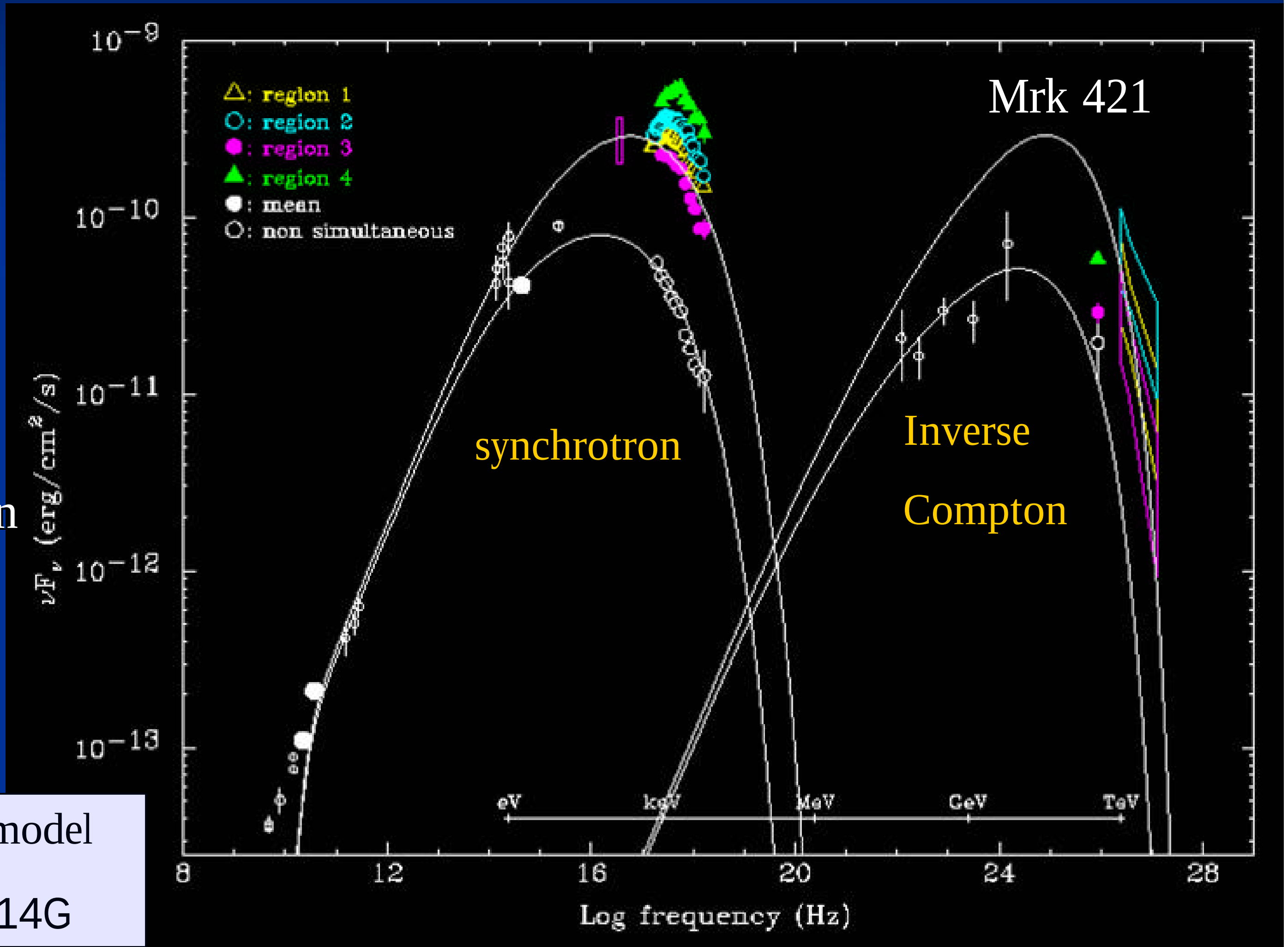


Fig. 1. Simultaneous and non-simultaneous X-ray and TeV γ-ray energy spectra of the 4 TeV blazars with measured TeV γ-ray energy spectra. The regions show the range of values that have been observed with BeppoSAX, RXTE and Cherenkov Telescopes (from ([46])).

Krawczynski, astro-ph/0309443

Synchrotron self-Compton model

- Synchrotron + inverse Compton model works well
  → $e^{\pm}$ origin (SSC: Synchrotron Self Compton)

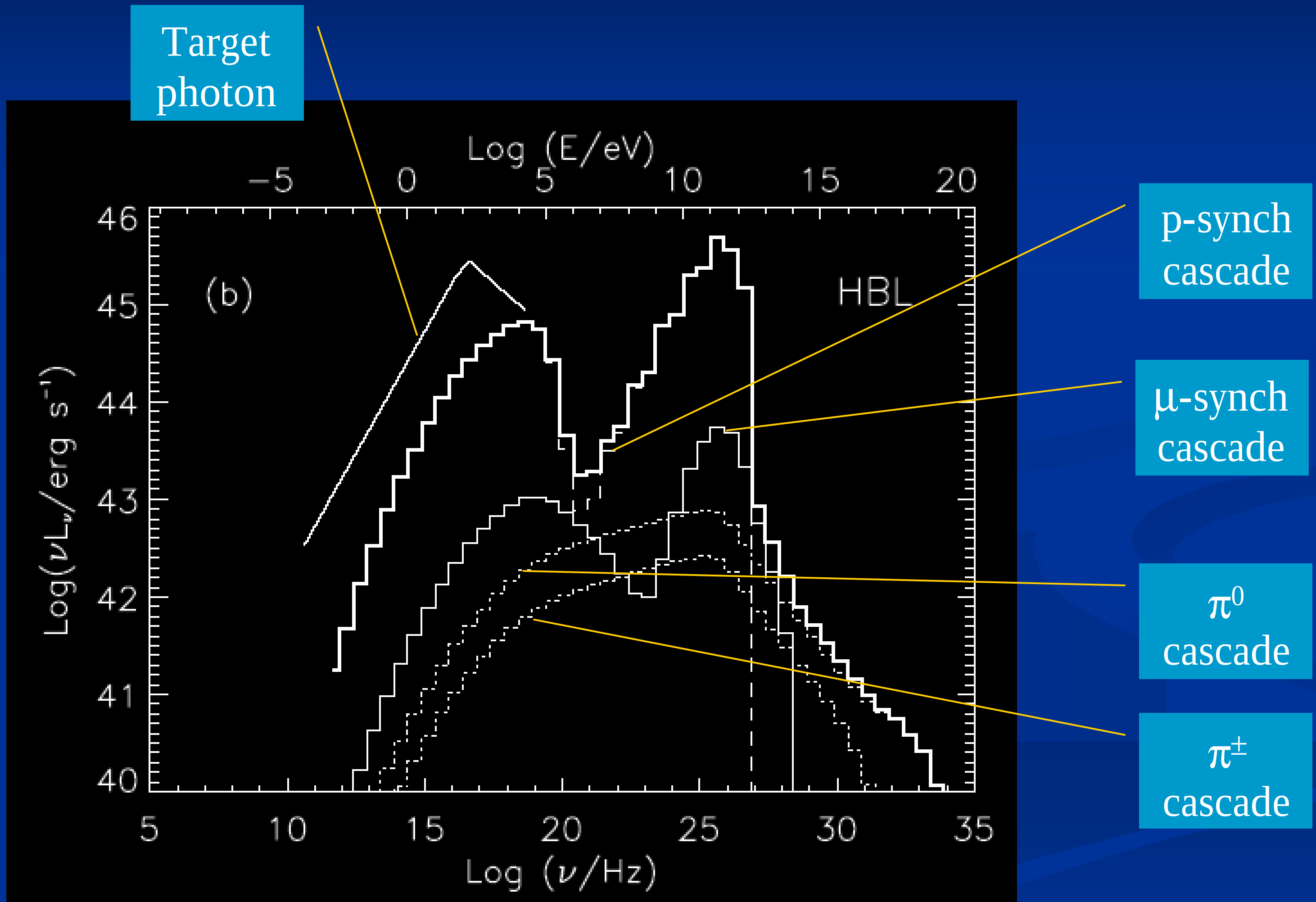


One-zone SSC model

δ =14, B=0.14G

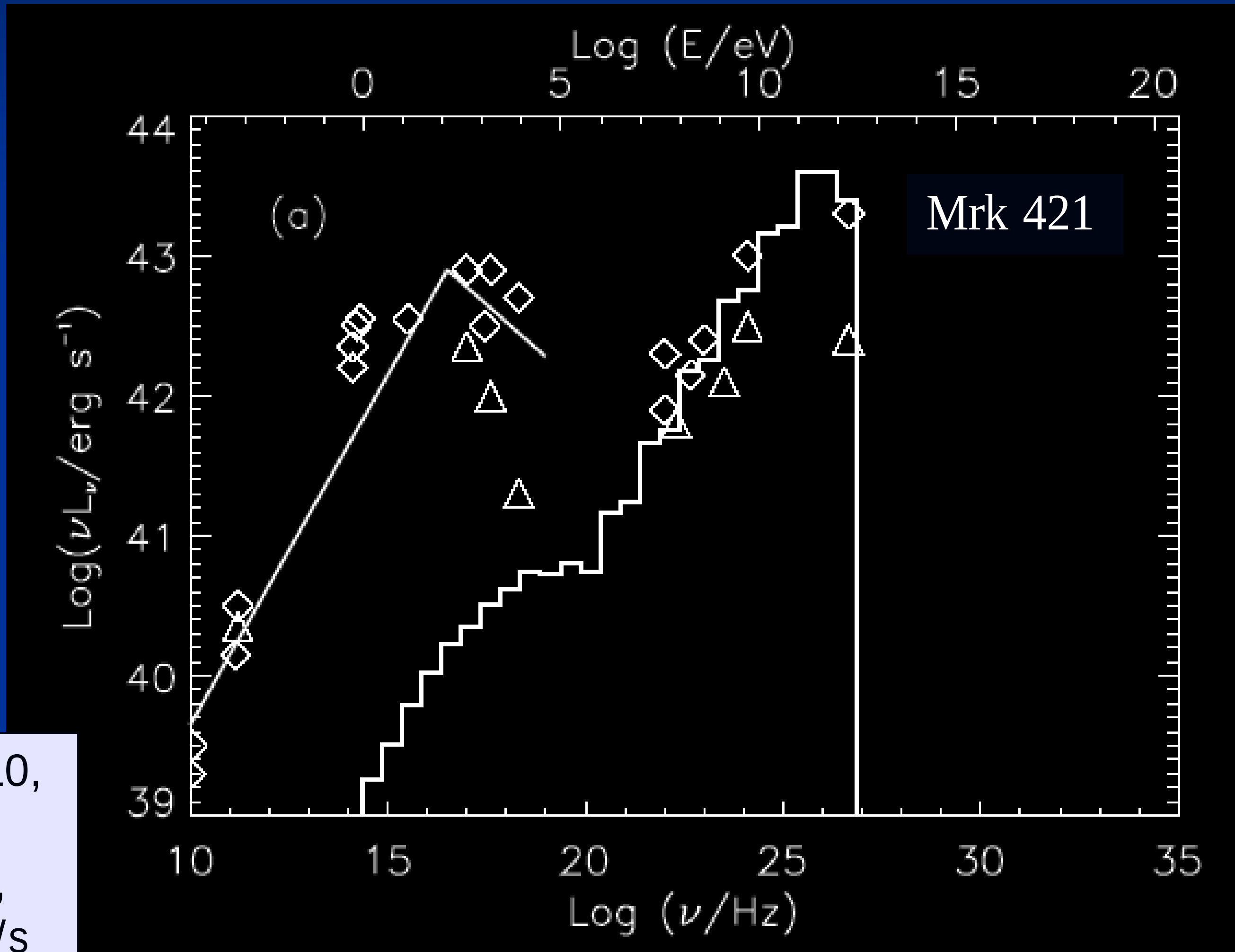
Takahashi et al. ApJ 542, 2000

Synchrotron proton blazar model (1)



Muecke et al. APh 18, 2003

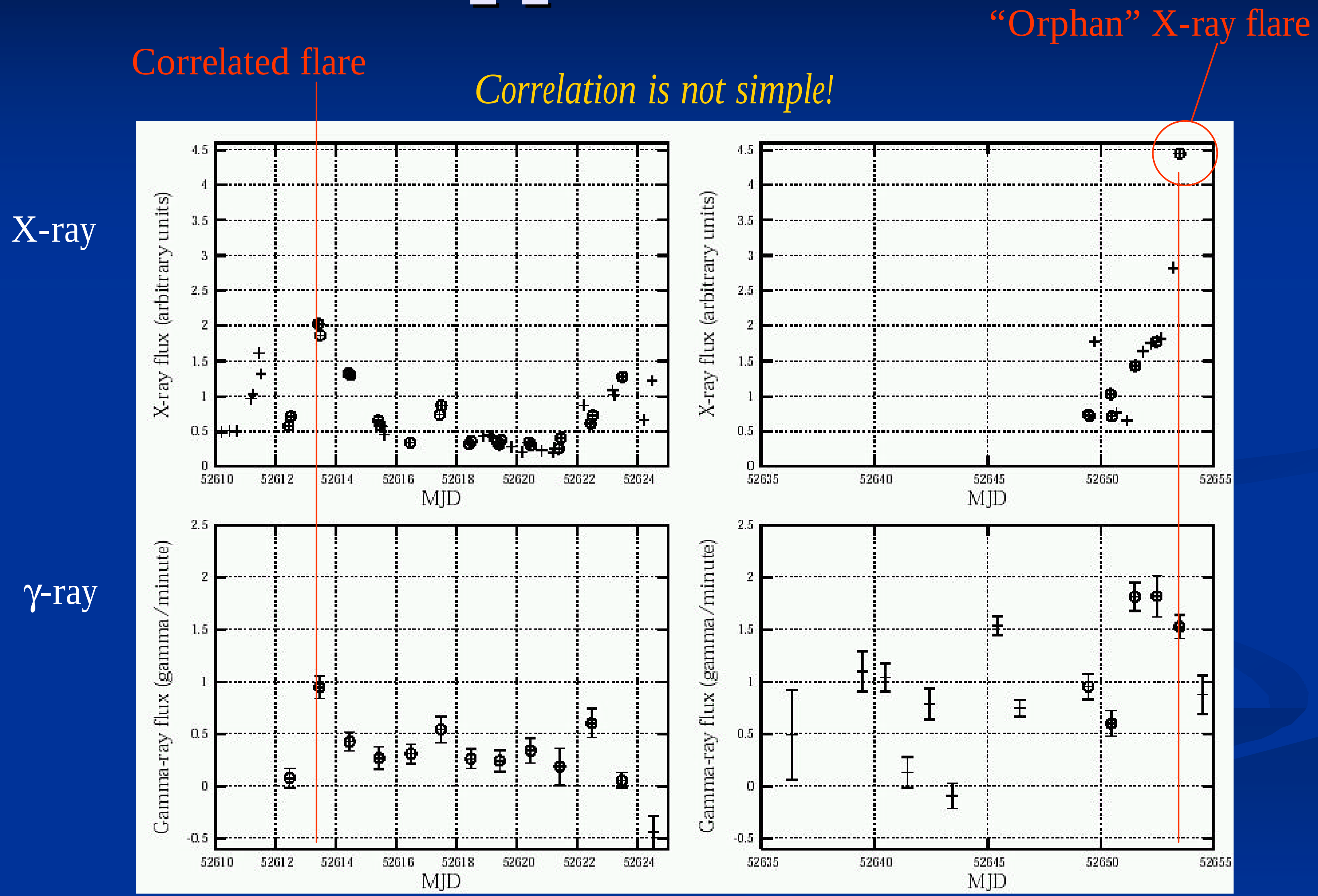
Synchrotron proton blazar model (2)



$dF/dE \propto Ep^{-2}$, δ=10,
B=30G,
$\gamma_{max,p}=4\times10^{10}$,
$L_{jet}=9\times10^{44}$erg/s

Muecke et al. APh 18, 2003

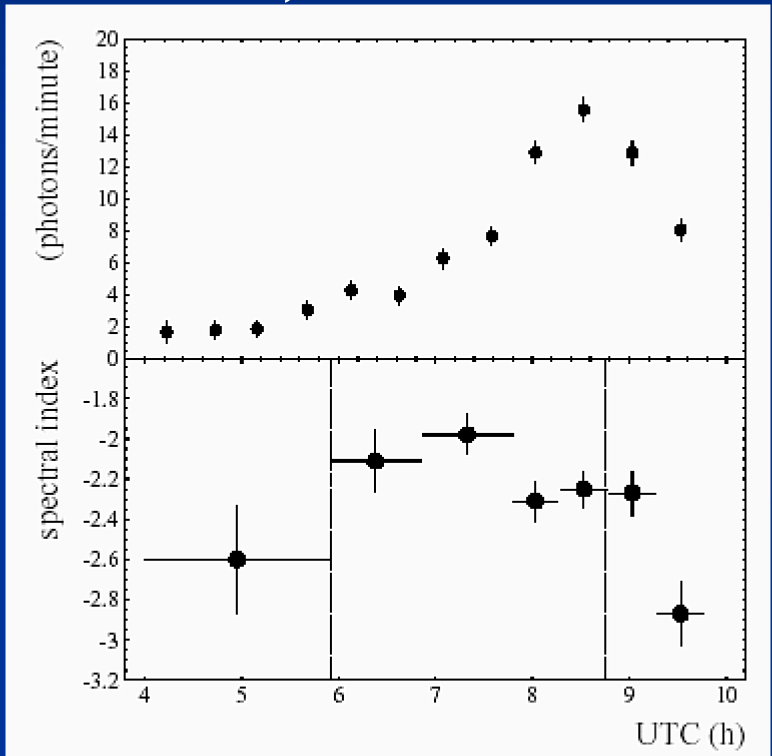
Mrk421: Whipple Flare Dec02-Jan03



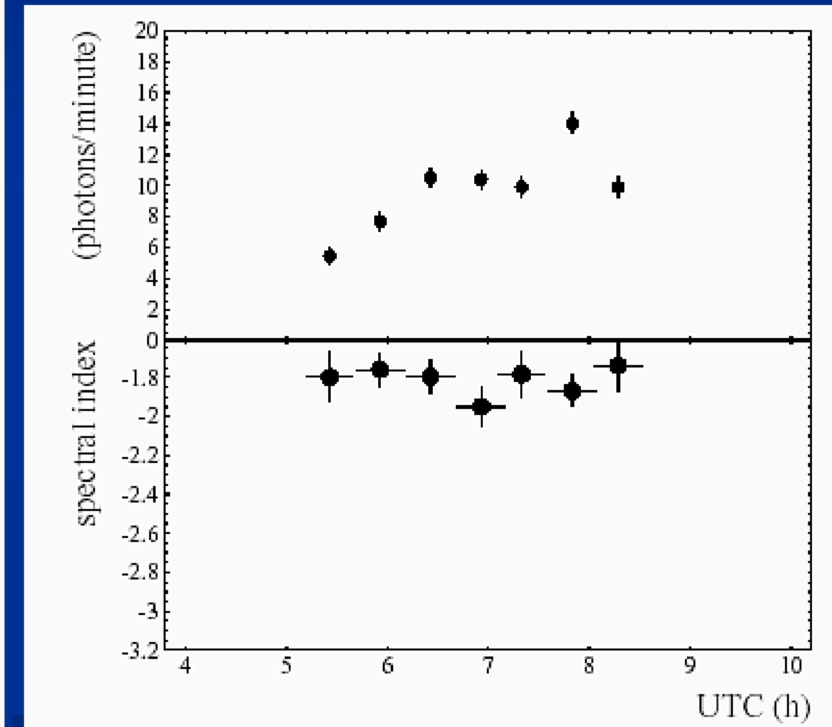
Rebillot et al. 28th ICRC (2003)

Mrk421: Whipple Hourly variability

Mar 19, 2001



Mar 25, 2001

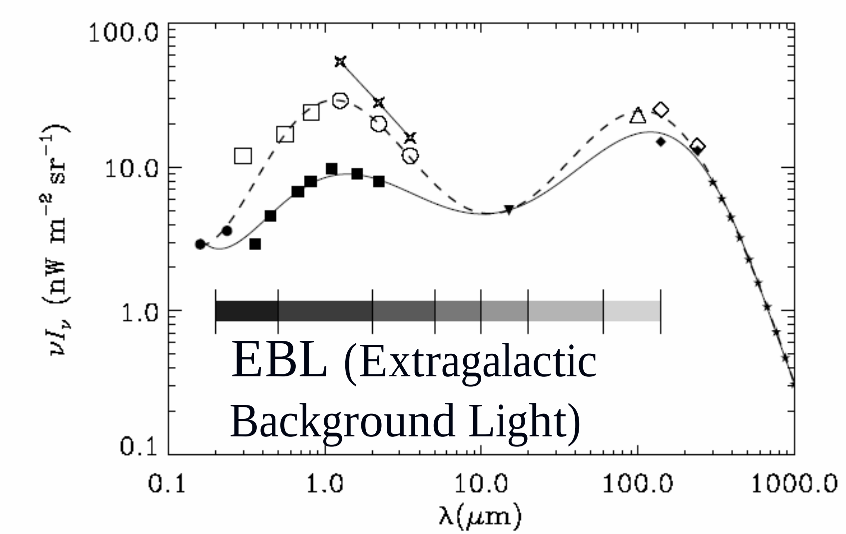


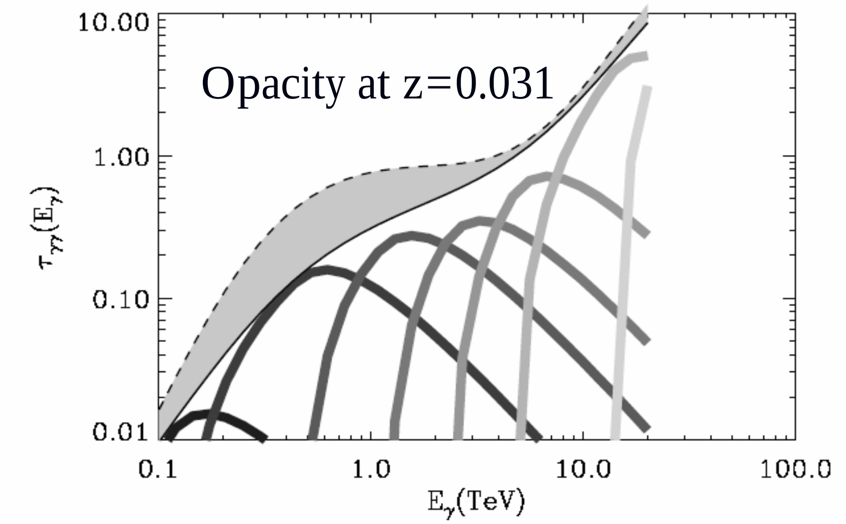
Harder for stronger ↔ Constant slope

Why this difference?

Krennrich et al., 28th ICRC (2003)

TeV gamma-ray absorption on EBL (1)





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

Mean free path for $e^{+}e^{-}$ pair production

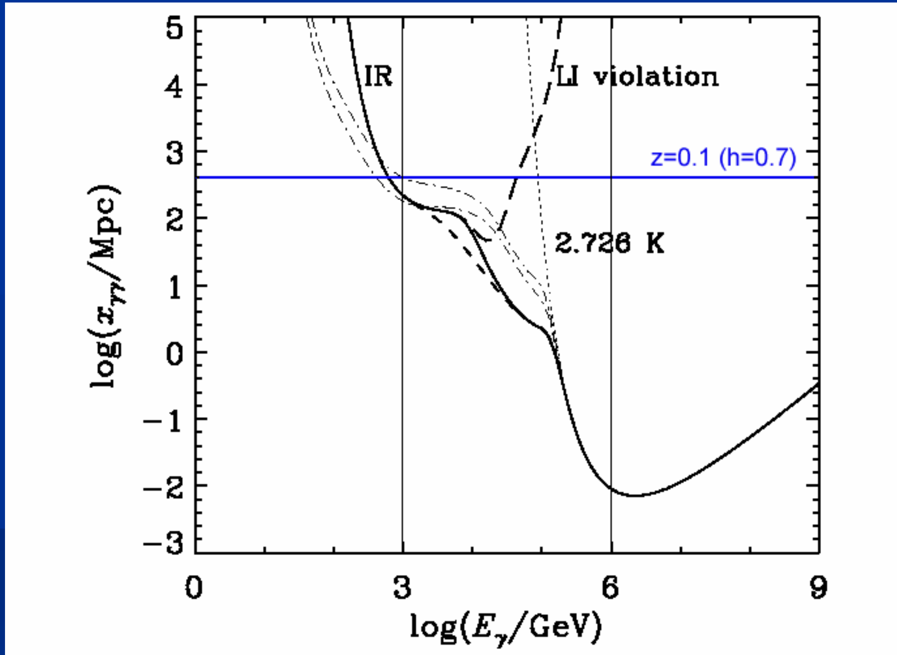


Figure 2: Mean free path for photon-photon pair production in the infrared–microwave background radiation. The curves correspond to those in Fig. 1 except that the effect of Lorentz Invariance violation discussed in Section 4 is shown by the long dashed curve.

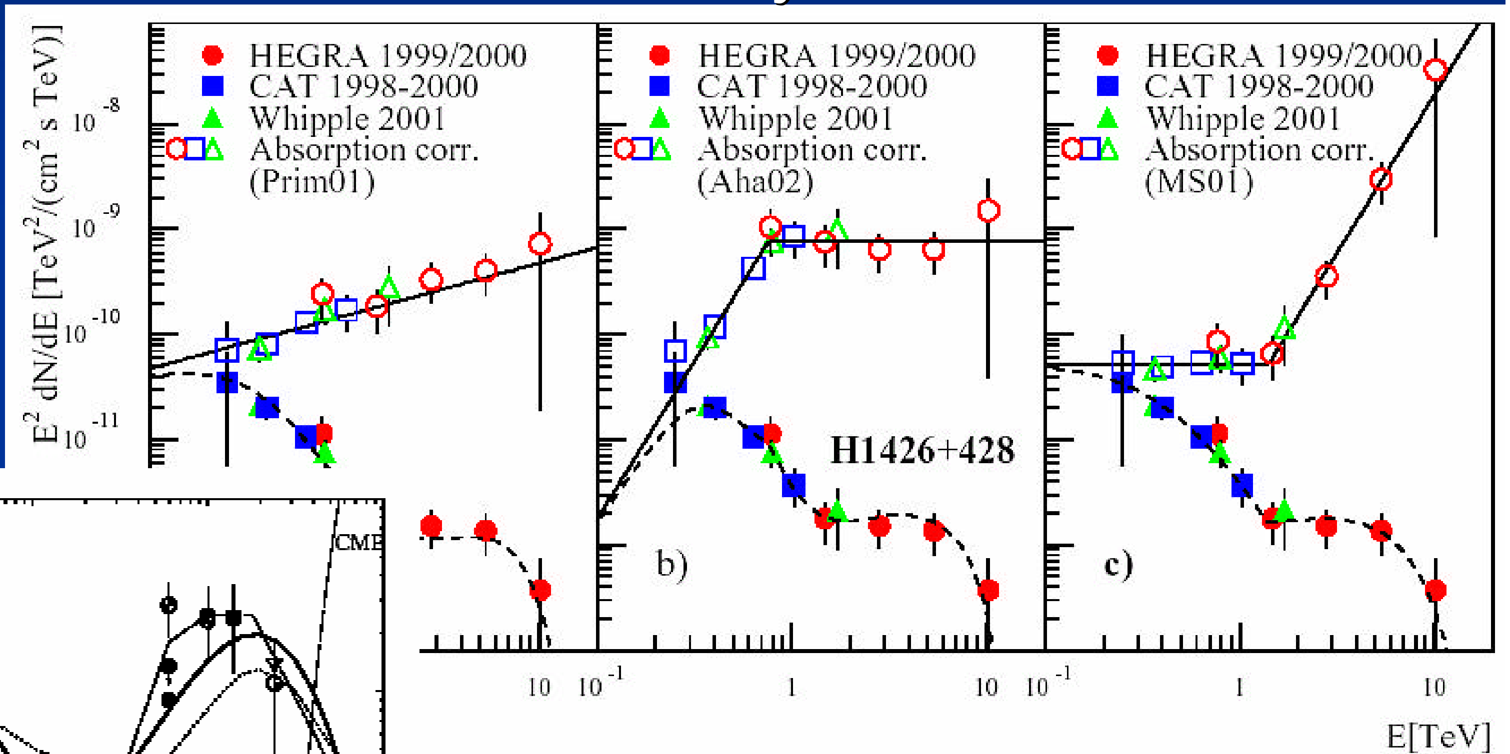
Dwek, "Universe Viewed in Gamma-rays", Kashiwa, 2002

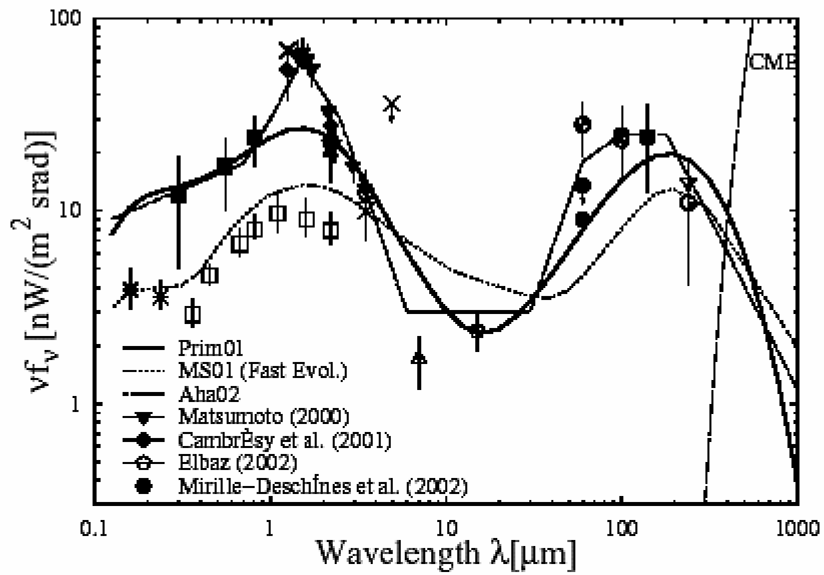
Protheroe et al. astro-ph/0005349

TeV gamma-ray absorption on EBL (2)

- H1426+428: HEGRA CT system

z=0.129





EBL
(Extragalactic
Background Light)

Intrinsic
spectrum

Horns et al., 28th ICRC (2003)

Confirmed extragalactic sources

- 1ES1959+650 (Blazar, z=0.048)
  - Utah 7TA detection [Nishiyama et al. 1999ICRC] 3.9σ
  - Large Flare in 2002
    - HEGRA CT system [Aharonian et al. 2003A&A]
    - HEGRA CT1 [Tonello et al. 28th ICRC 2003]
    - Whipple [Holder 2619]
- 1ES2344+514 (Blazar, z=0.044)
  - Whipple detection [Catanese et al. 1998ApJ]
  - HEGRA CT system [Tluczykont et al. 28th ICRC 2003] 4.4σ
- PKS2155-304 (Blazar, z=0.116)
  - Durham Mark6 detection [Chadwick et al. 1999ApJ]
  - CANGAROO [Nakase et al. 28th ICRC 2003] upper limit, 2000-2001
  - H.E.S.S. [Djannati-Atai et al., 28th ICRC 2003] detection >6σ, 2002

1ES1959+650: Whipple May-July 2002

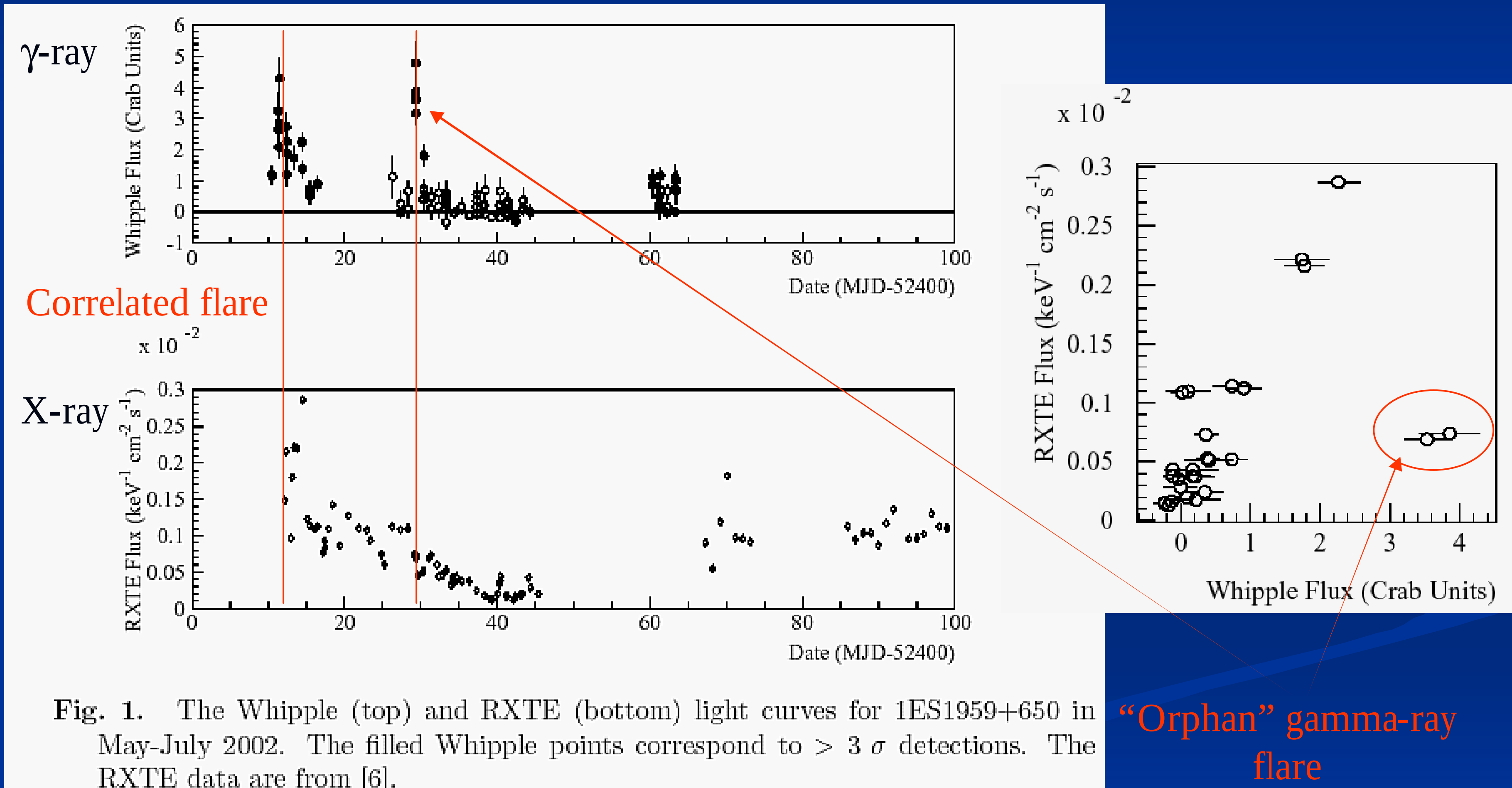


Fig. 1. The Whipple (top) and RXTE (bottom) light curves for 1ES1959+650 in May-July 2002. The filled Whipple points correspond to $> 3\ \sigma$ detections. The RXTE data are from [6].

Holder et al. 28th ICRC (2003)

PKS 2155-304

- H.E.S.S. (single telescope)

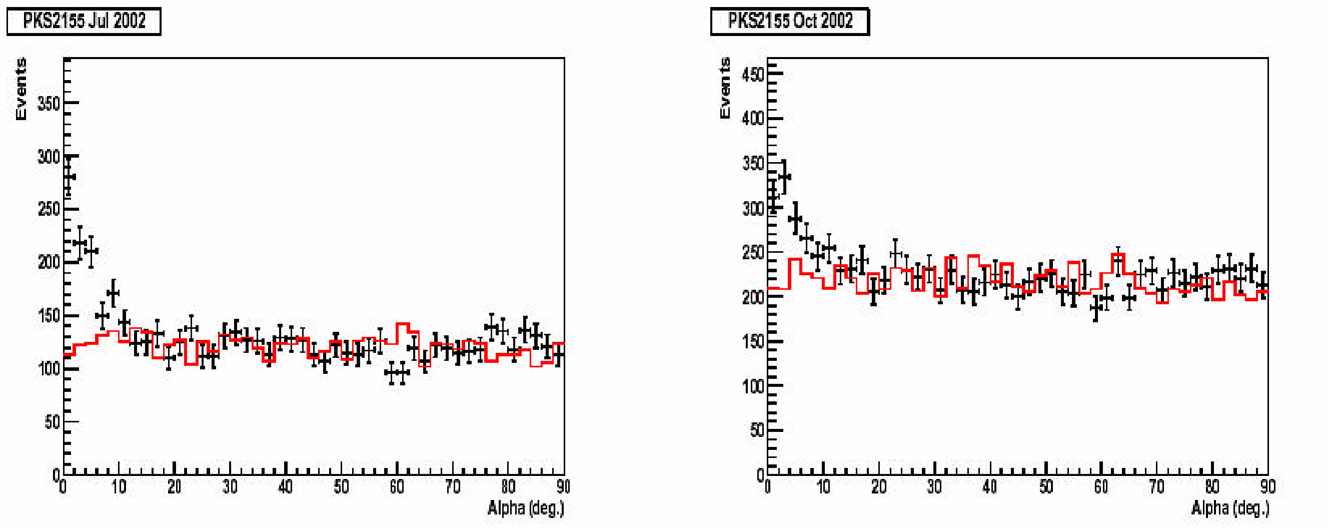
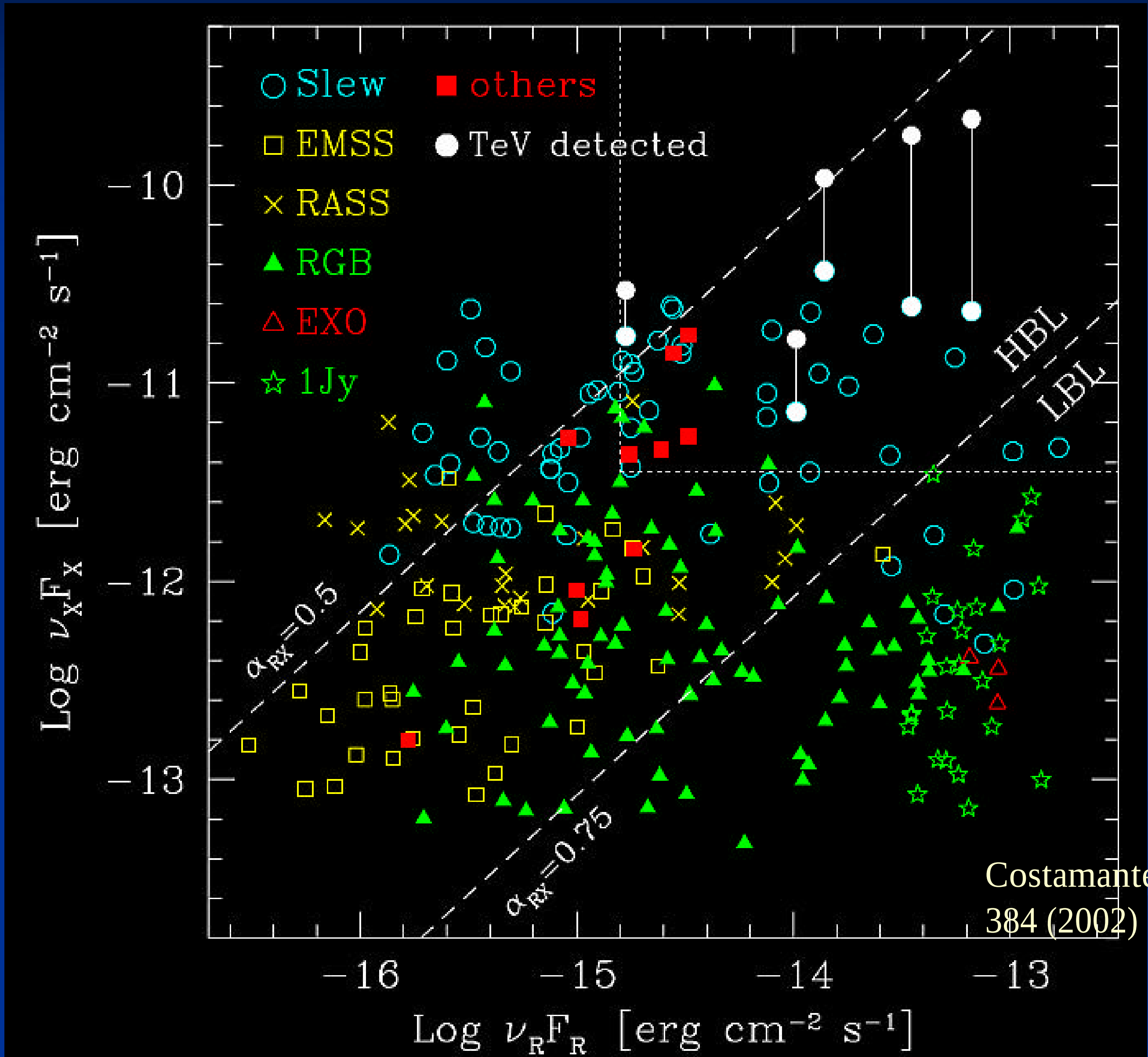


Fig. 1. The pointing angle α-plot of PKS 2155-304 observations for July (left panel) and October (right panel) 2002. The OFF-source distributions have been normalised to the control region between 30° and 90°.

PKS2155	T_{live} (h)	Non	Noff	Excess	γ/min	Significance
Jul 2002	2.2 h	1029	625	404	3.1	9.9 σ
Oct 2002	4.7	1444	1107	337	1.2	6.6 σ

Djannati-Atai et al, 28th ICRC (2003)

TeV blazar population?

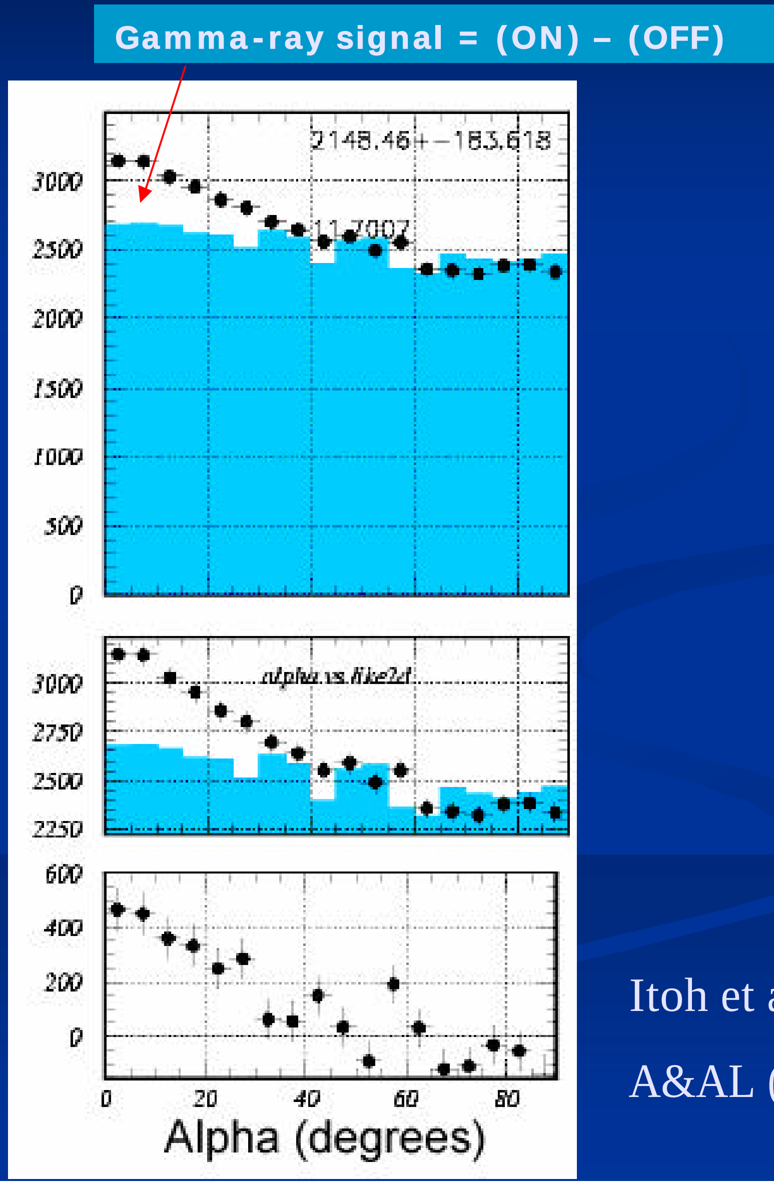


Costamante and Ghisellini A&A 384 (2002) 56

New entry: NGC253 (1)

- Nearby spiral galaxy (2.4Mpc)
- Starburst activity ⇔frequent SNe

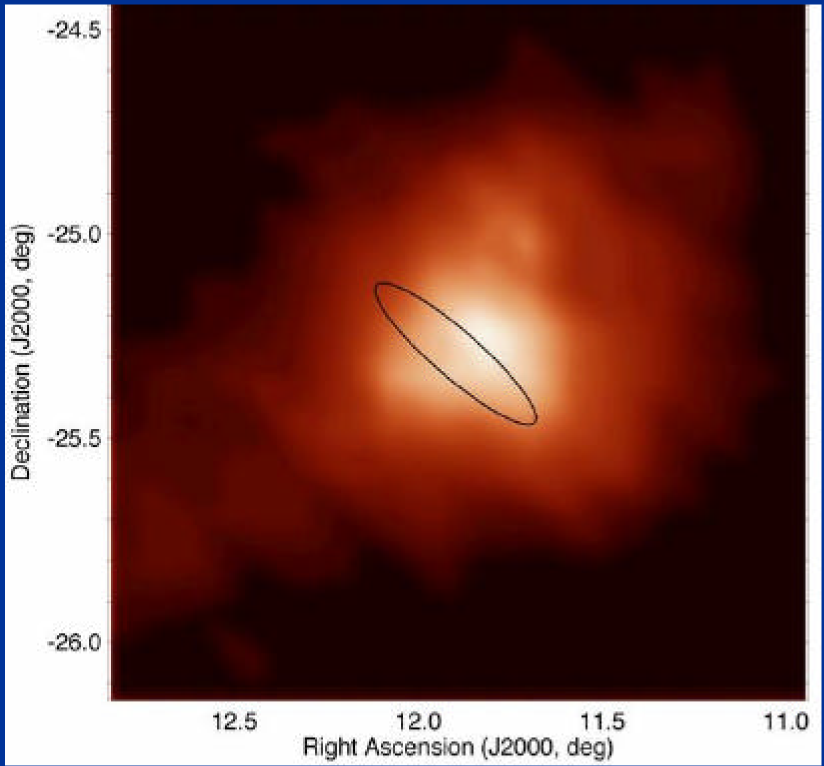
Optical image



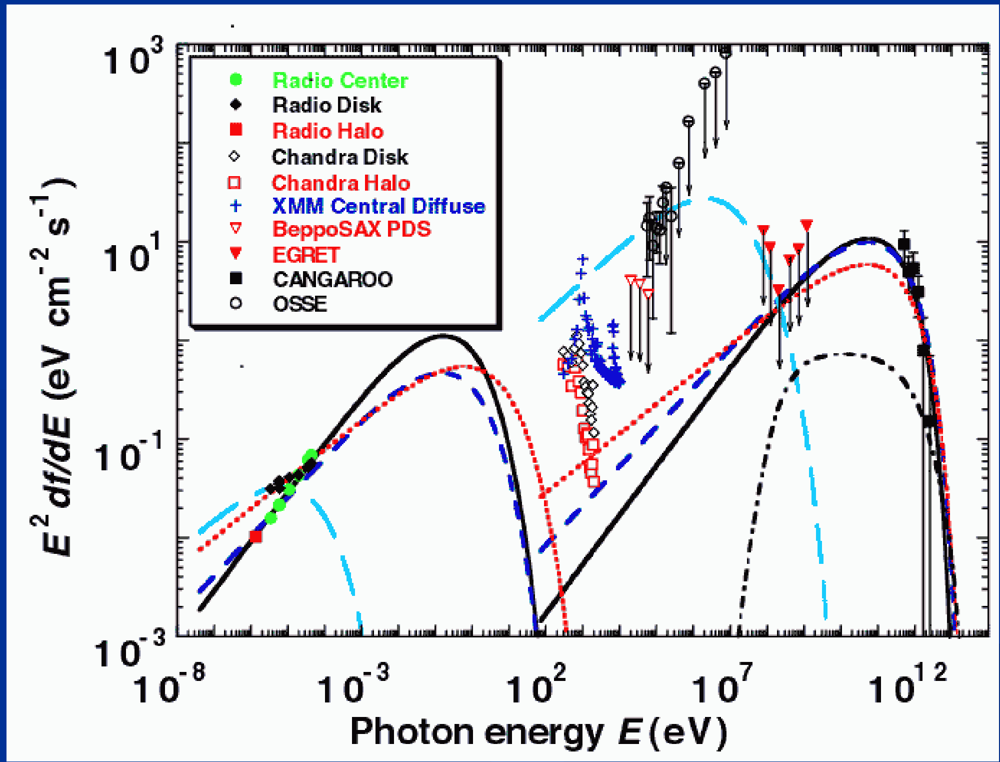
Itoh et al. A&AL (2002)

New entry: NGC253 (2)

- Extended halo?



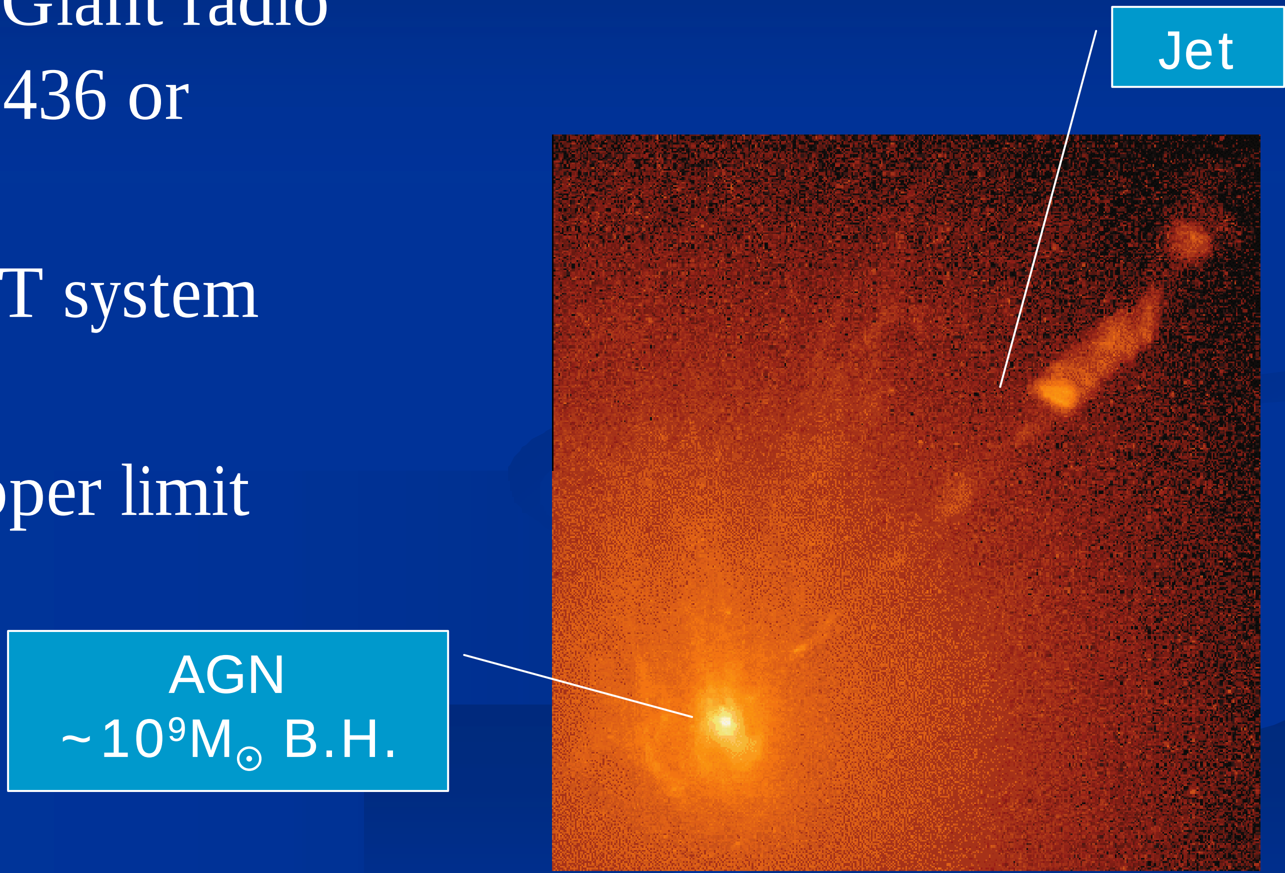
Significance map by CANGAROO



Itoh et al. ApJ (2003)

New entry: M87 (1)

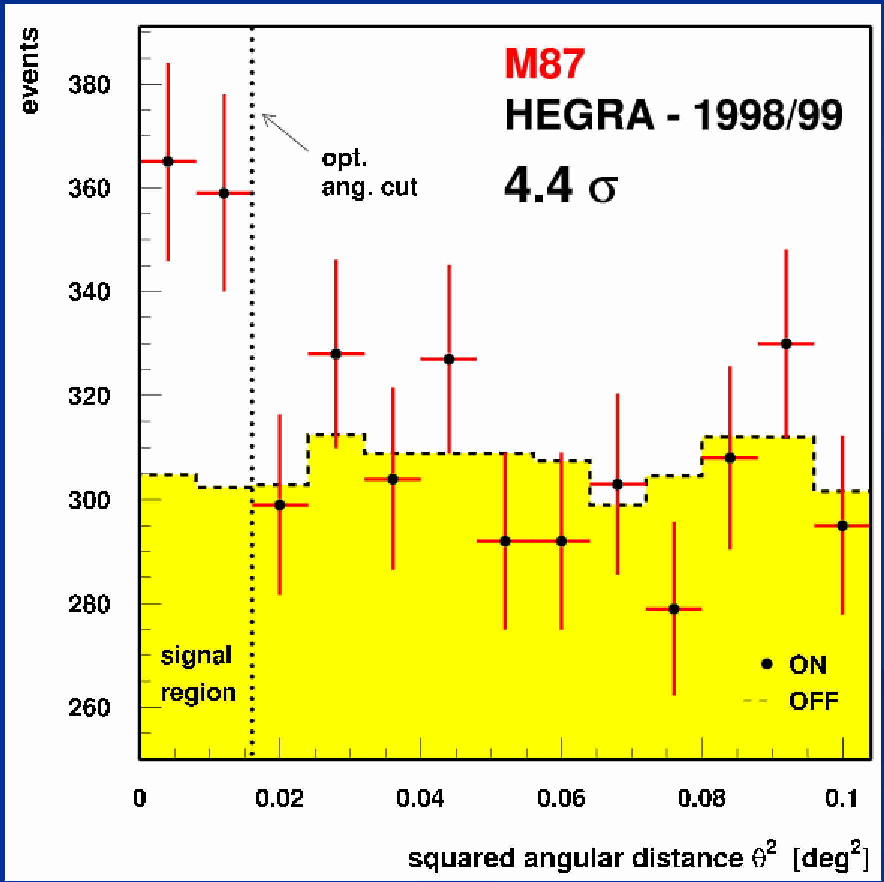
- M87 (Vir A, Giant radio galaxy, z=0.00436 or 16Mpc)
  - HEGRA CT system detection
  - Whipple upper limit

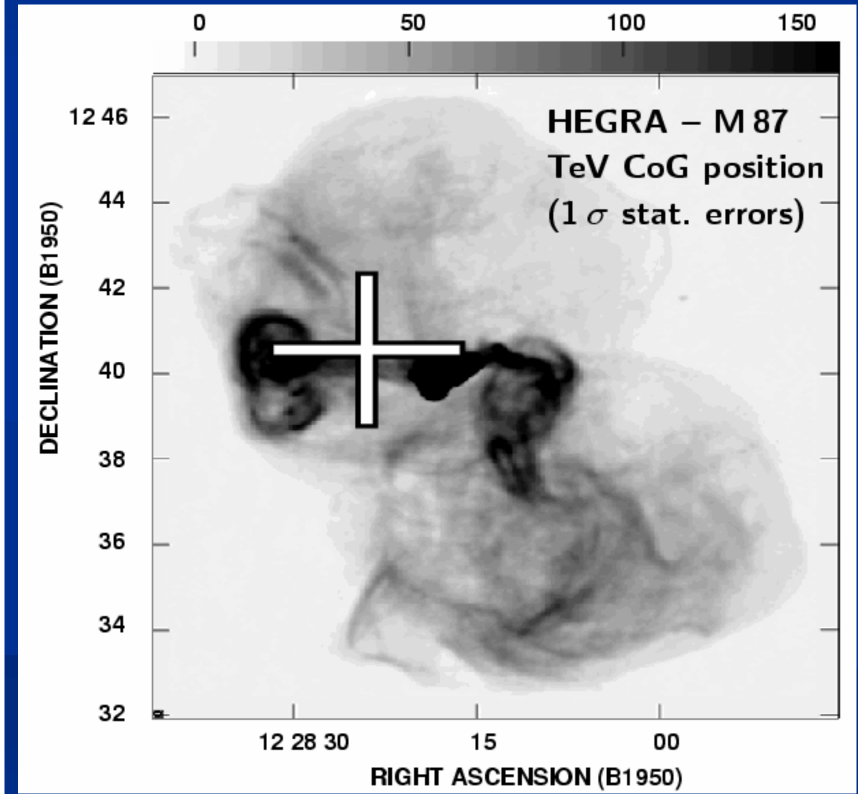


Optical image

New entry: M87 (2)

- M87: HEGRA CT system 1998-1999 4.4σ





Goetting et al. 28th ICRC (2003)

New entry: M87 (3)

- M87: Whipple 2000-2001 2.4σ, 2002-2003 no excess

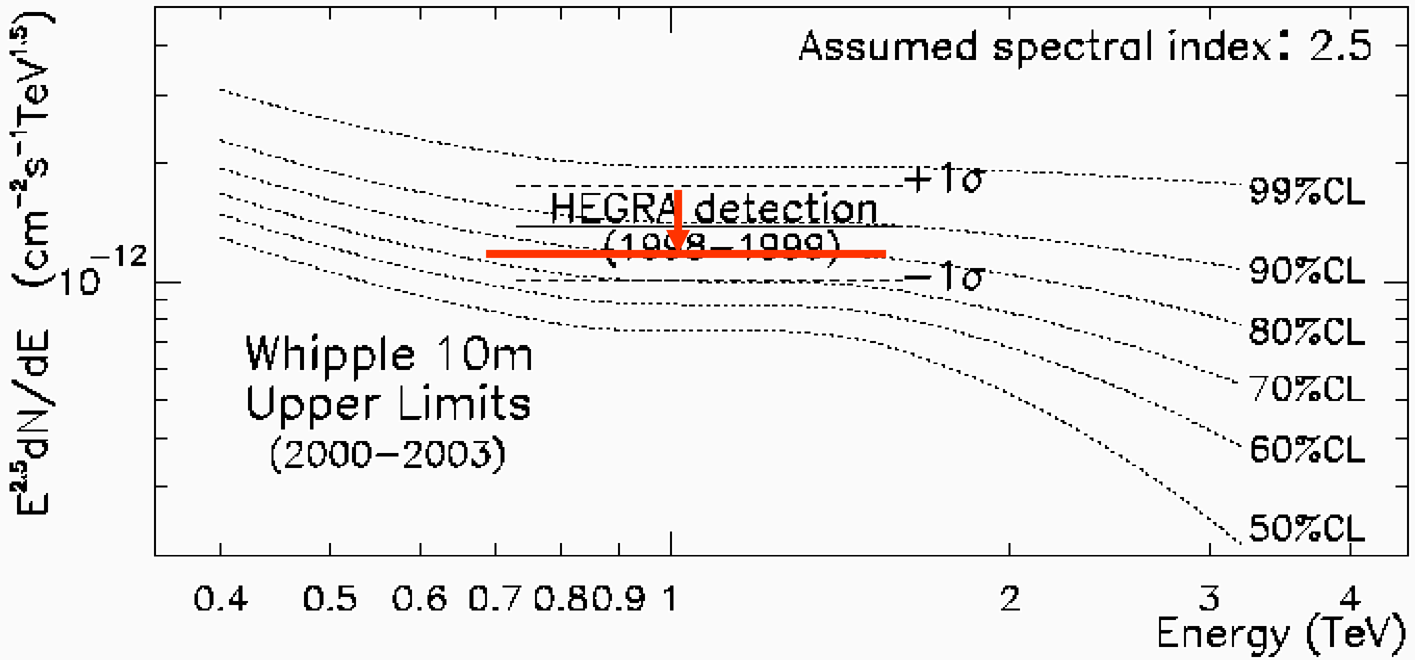
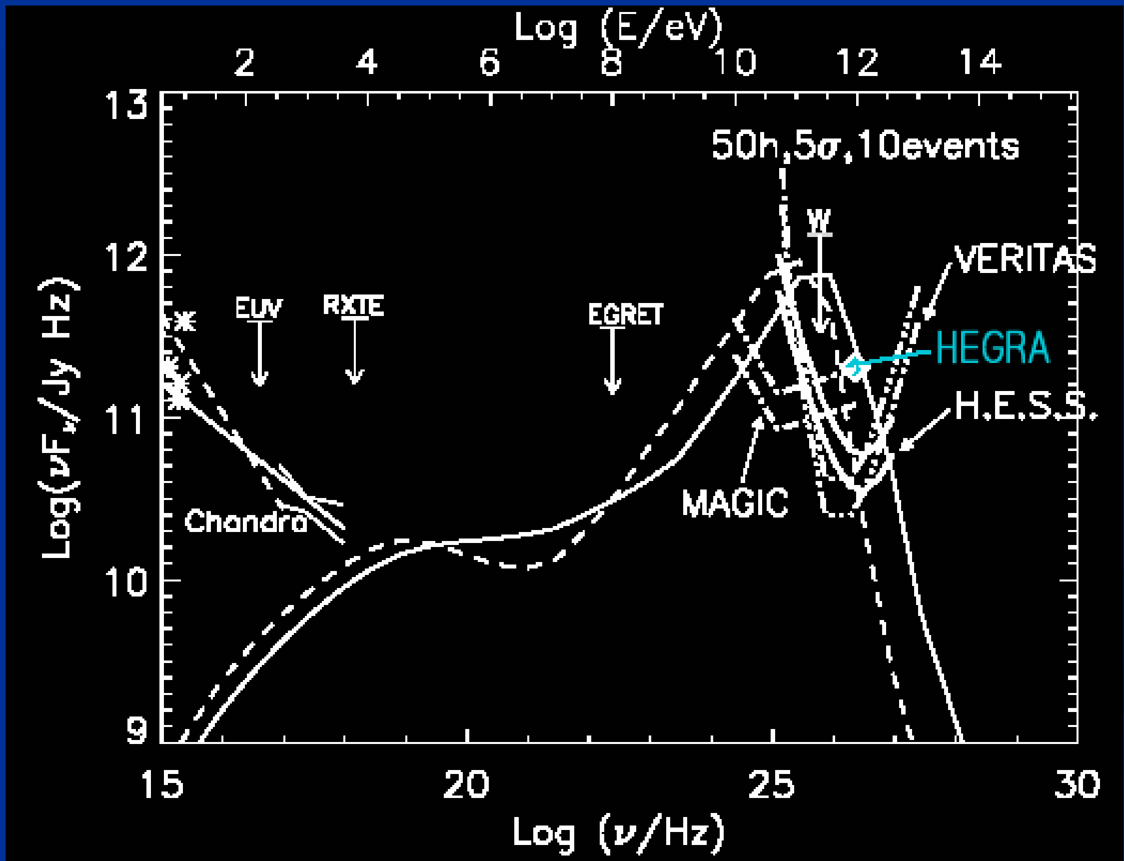


Fig. 1. The Whipple 10-m upper limit on the differential flux from M87 compared to the detection by HEGRA under the assumption that the spectrum ca be described by a power law of index 2.5.

LeBohec et al., 28th ICRC (2003)

M87 models

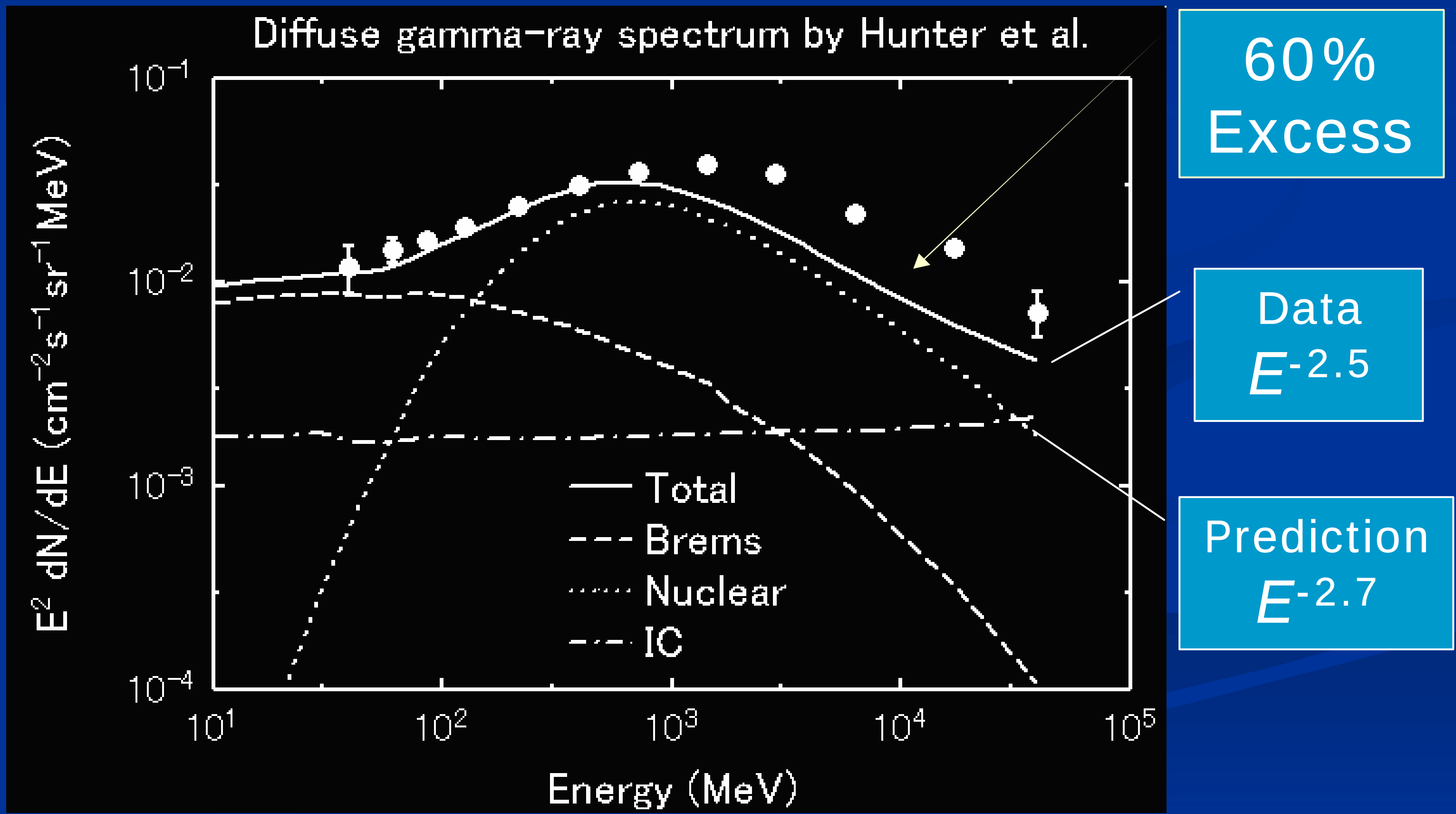
- Inverse Compton by electrons Bai & Lee 2001 ApJ
- Misaligned 'synchrotron proton blazar' model



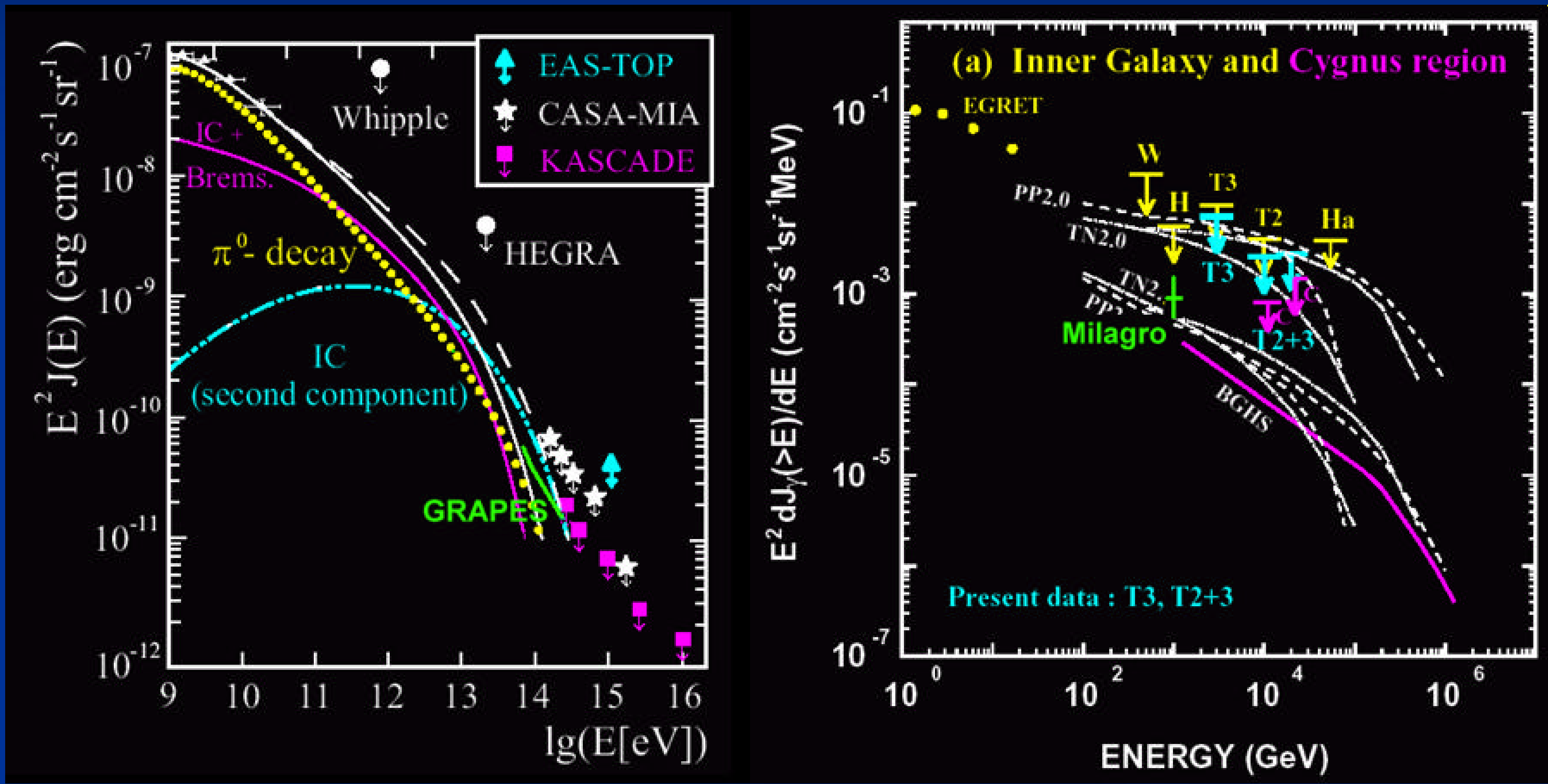
Reimer 2003 ICRC

Galactic diffuse gamma-rays (1)

- EGRET "GeV bump" (Hunter et al. ApJ 1997)



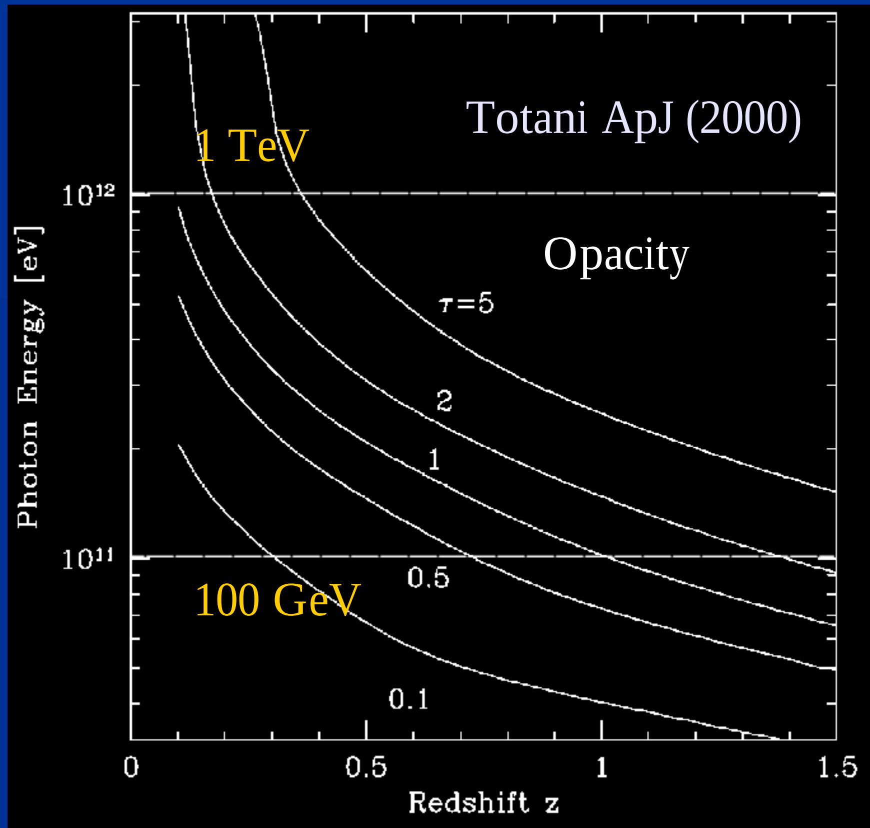
Galactic diffuse gamma-rays (2)

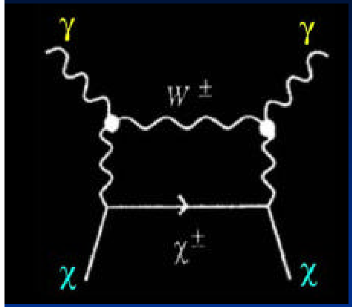


Summary by Mori, ICRC2003

Gamma Ray Bursts

- Ground-based experiments?
  - TeV gamma-rays (afterglow)
    - MAGIC a few per year expected
  - Air shower rate
    - Tibet-III
  - Single particle rate
    - GRAND
    - ARGO-YBJ
    - Tibet-III
- Need fast and precise GRB alerts!





Dark matter annihilation

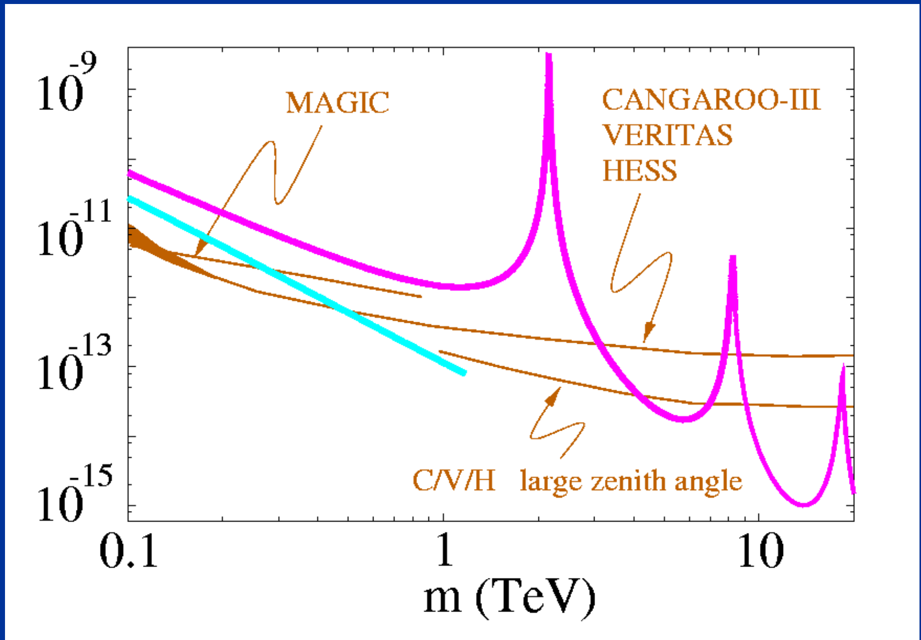
Signal enhancement due to `cusp' structure toward the center?

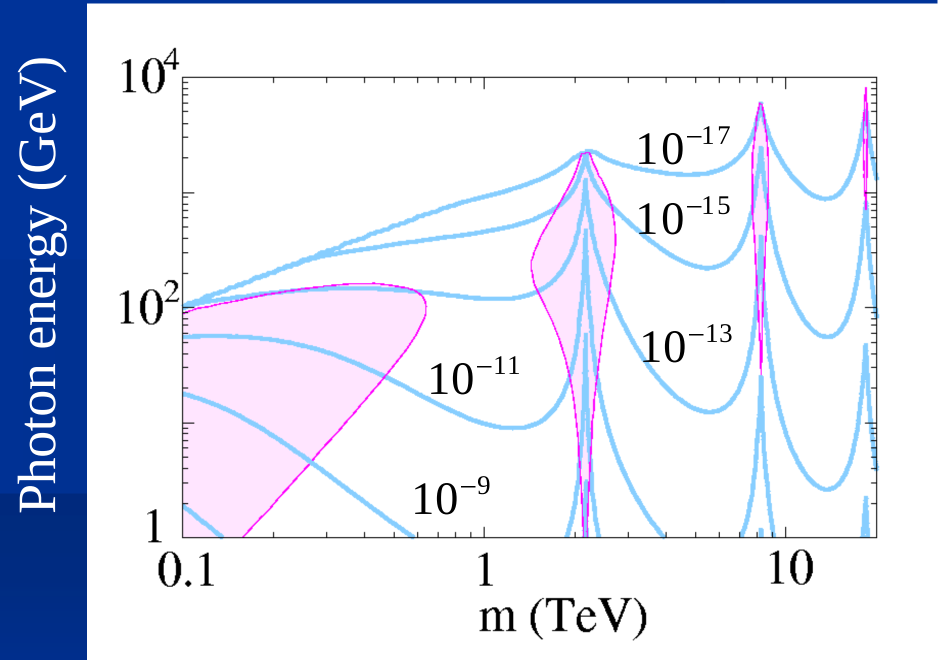
"Explosive annihilation" by non-perturvative effect

Line

Continuum

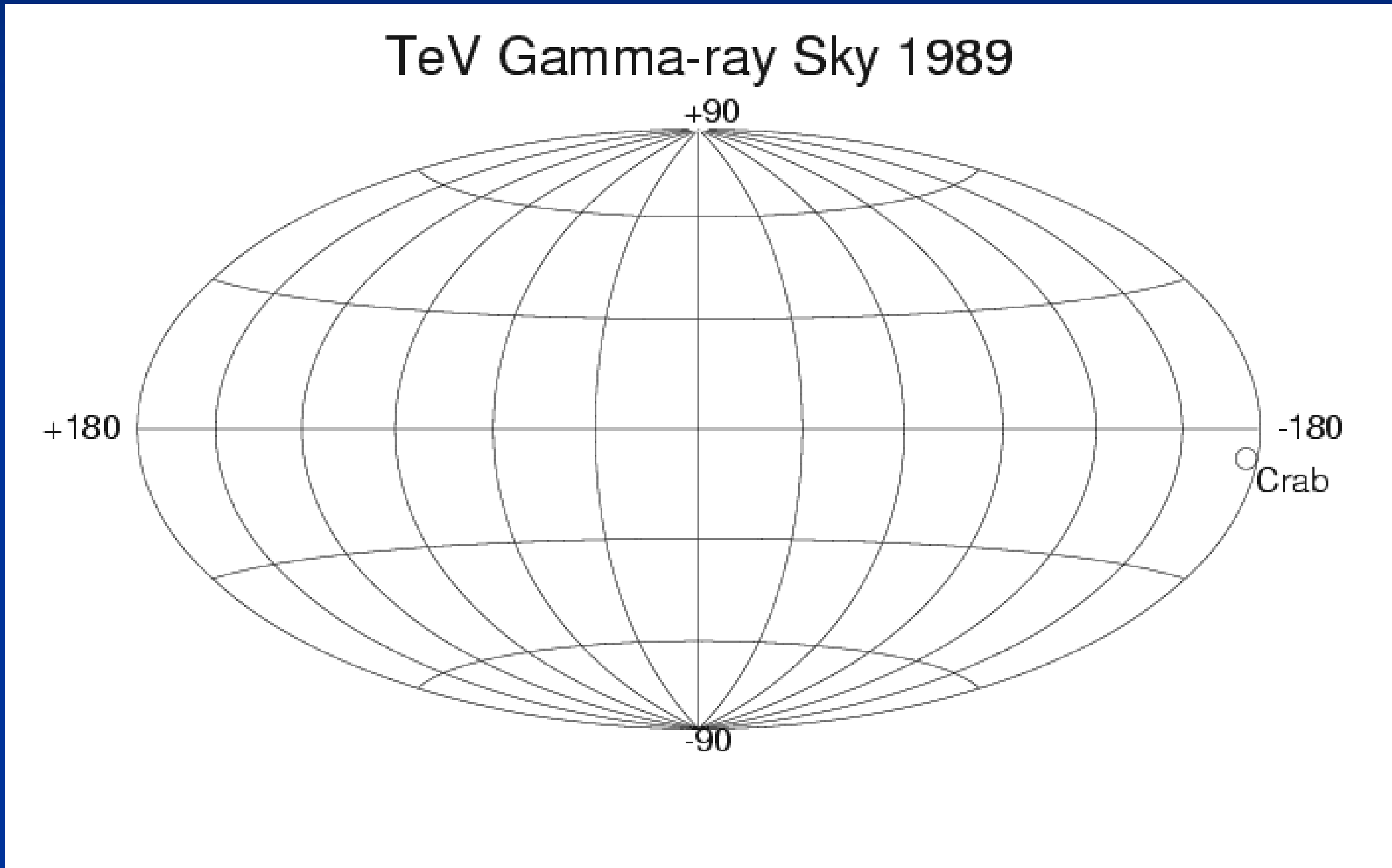
Flux (cm^{-2}sec^{-1}) $\Delta\Omega = 10^{-3}$





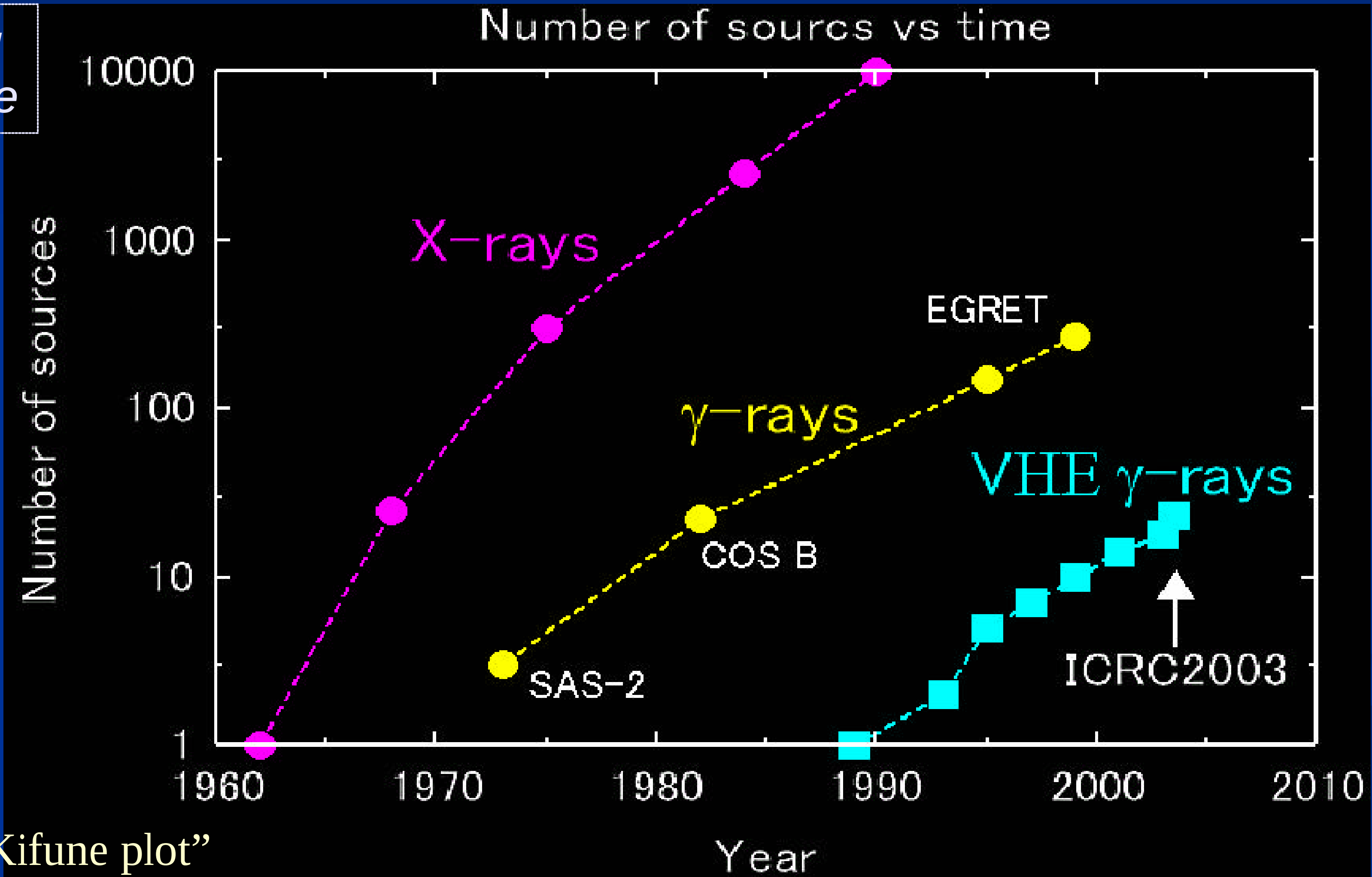
Hisano, Matsumoto, Nojiri PRL 92 (2004)

“Evolution” of the TeV gamma-ray sky



"Evolution" in number of objects

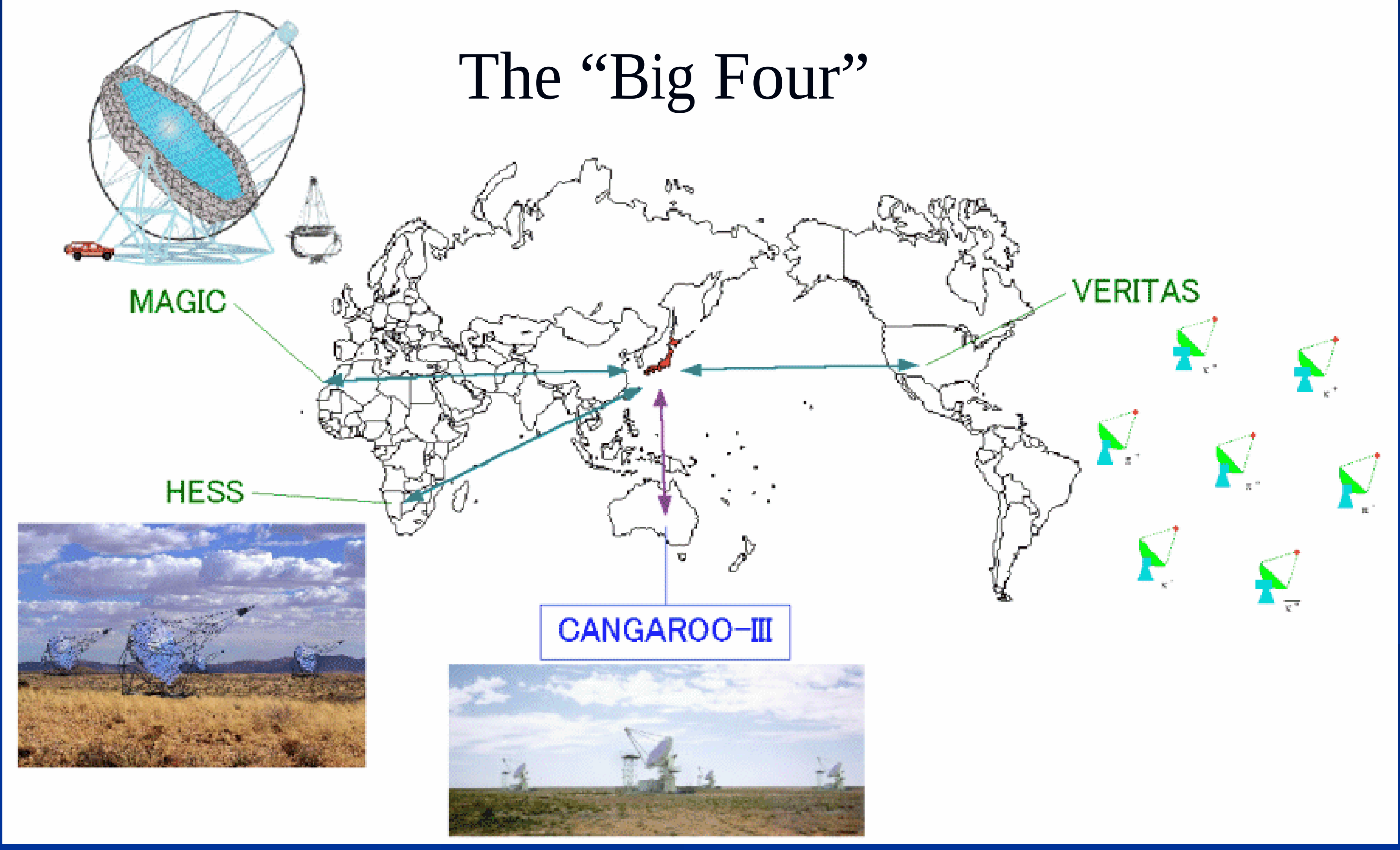
Log scale



"Kifune plot"

New Cherenkov telescopes

The “Big Four”

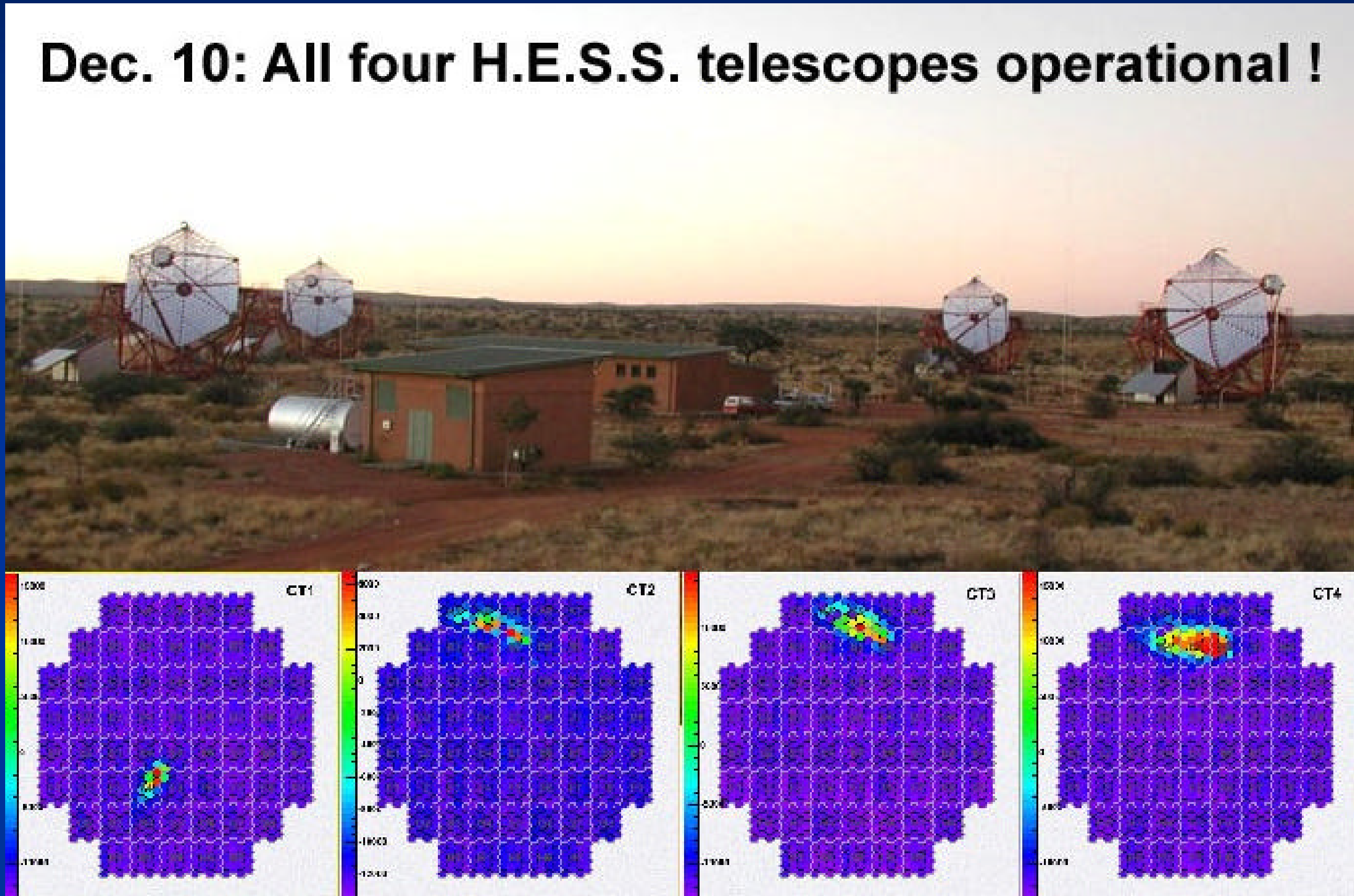


CANGAROO-III: completion in 2003

Four 10m telescopes (3 completed) in Woomera, Australia

ICRR, Univ.Tokyo, Kyoto Univ., Univ. Adelaide etc.

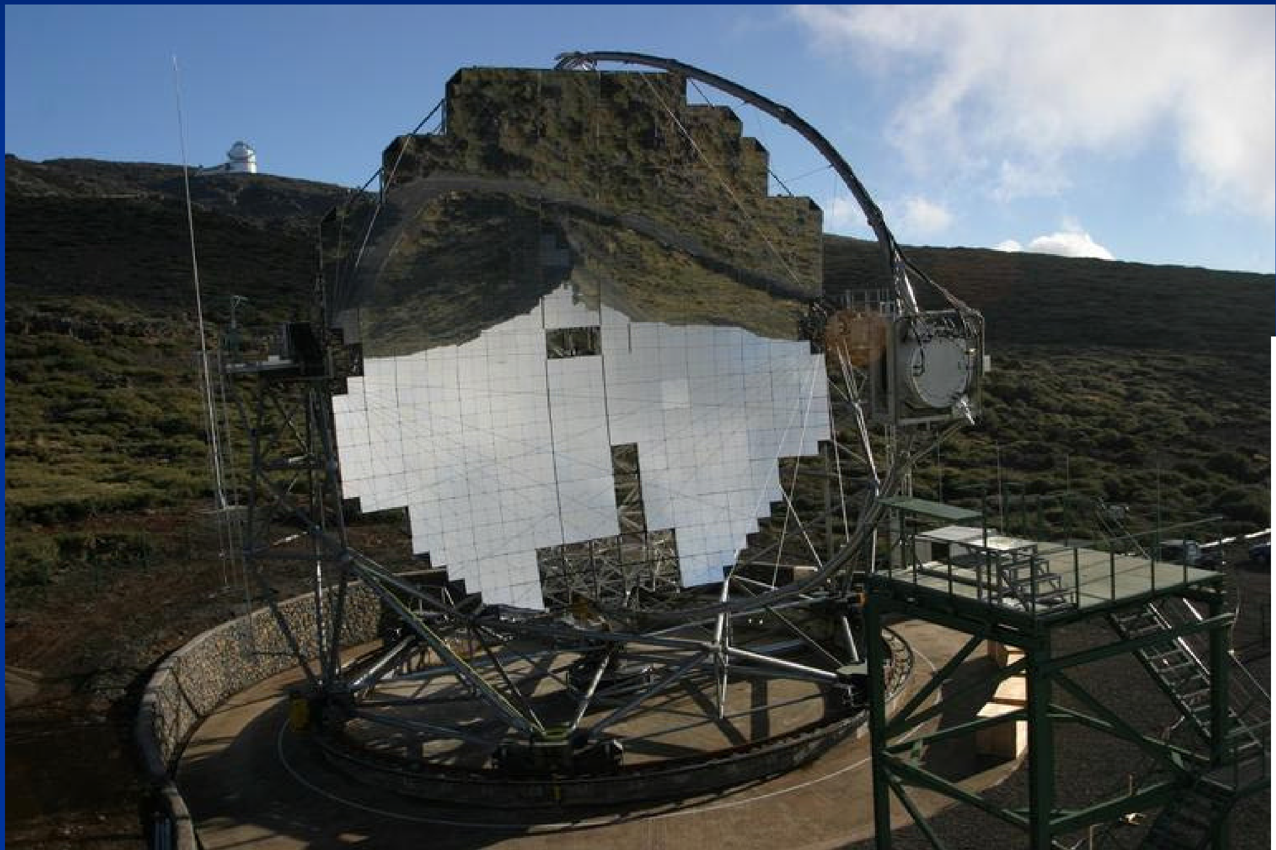
H.E.S.S.: completion in 2003

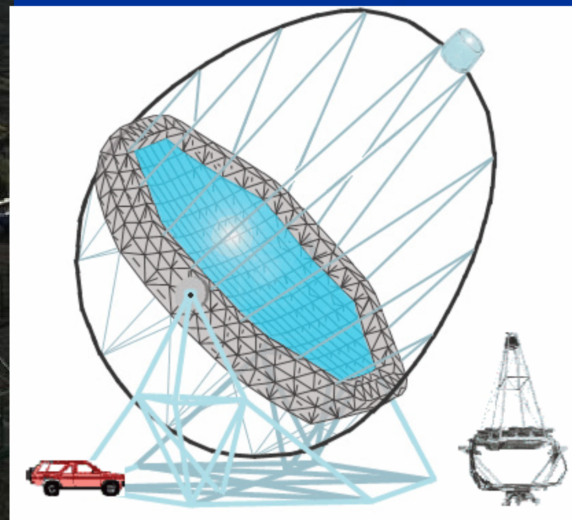


Four 12m telescopes (2 completed) in Namibia, Africa

Max Planck Inst., Heidelberg, etc.

MAGIC: completion in 2003

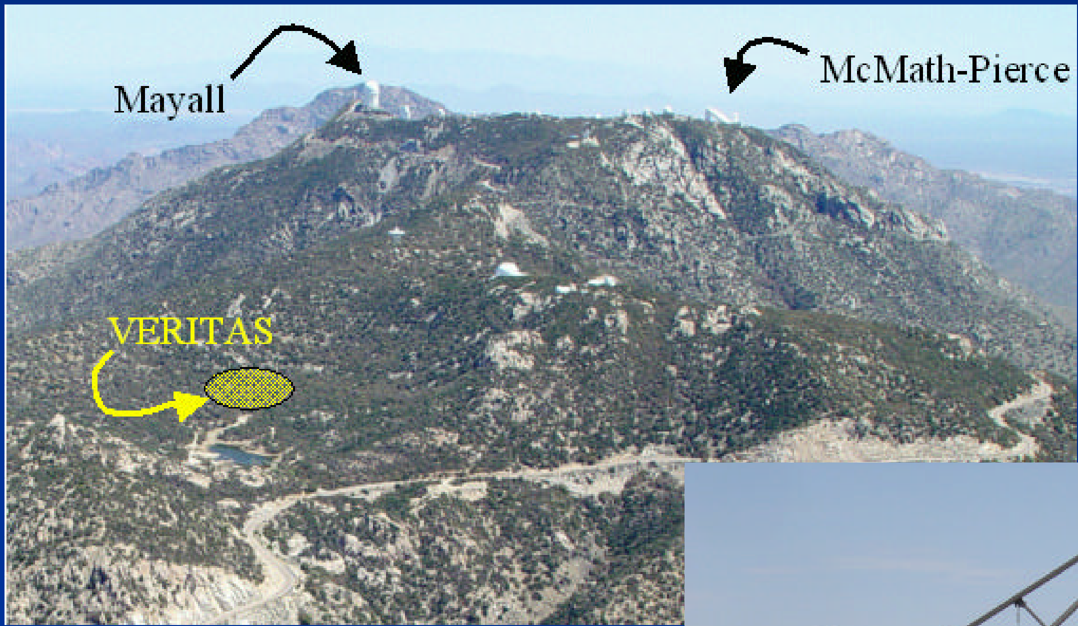




One 17m telescope in Canary Island

Max Planck Inst., Munich, etc.

VERITAS: VERITAS-4 by 2005, then -7



New site: Horseshoe canyon, Kitt Peak, Arizona

Smithonian Inst. etc.

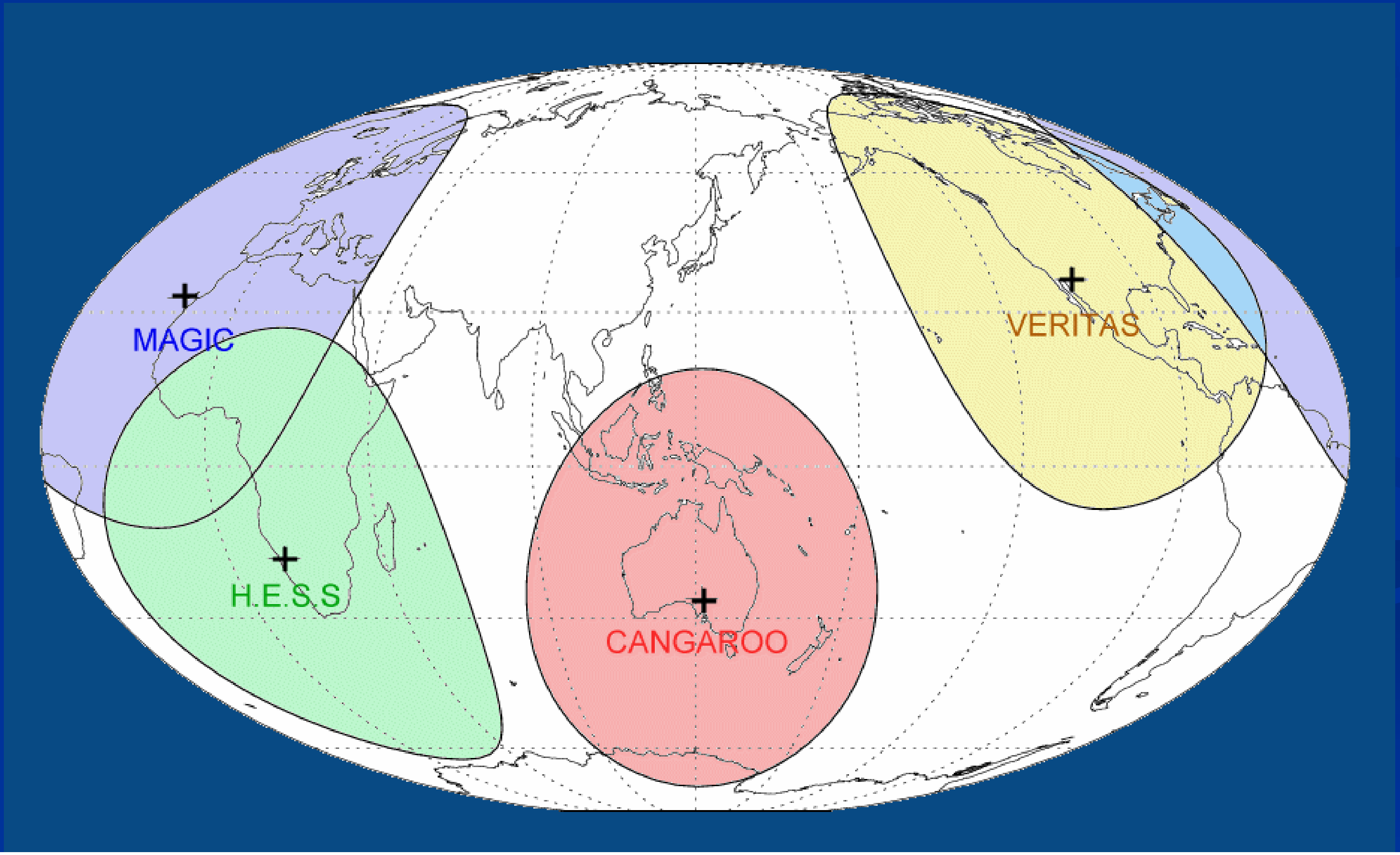
Prototype (Aug ’03)

Oct 2005: Completion of Phase I: 4 telescope array

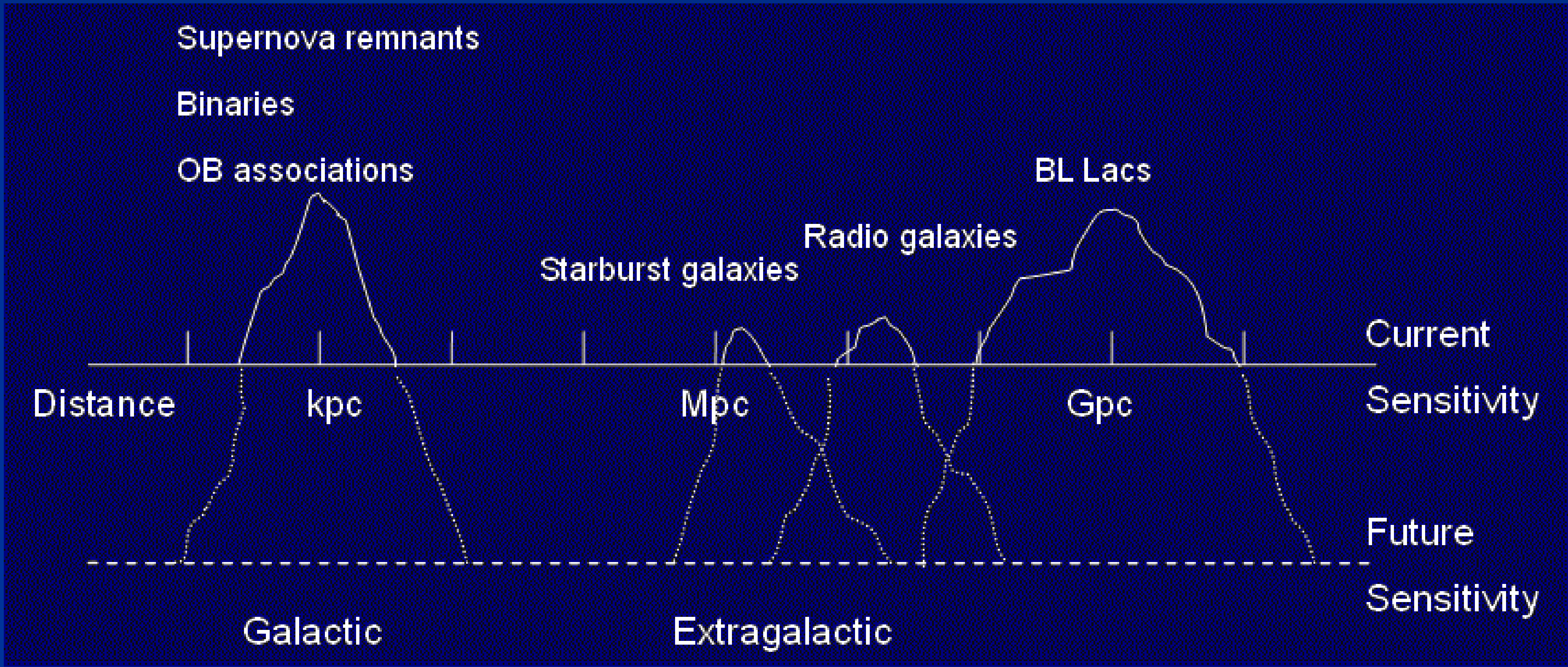
Oct 2007: Completion of Phase II: 7 telescope array

International coordination

- Monitoring of time-variable objects (e.g. blazars)
- Multiwavelength observation campaign



Tips of the Icebergs in the TeV Universe



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Summary

- Very high energy sources may contain large varieties, including both galactic and extragalactic objects.
- TeV gamma-ray astronomy is becoming an indispensable field of astronomy.
- The “third generation” Cherenkov telescopes are about to increase sensitivity – more fun!