TeVガンマ線による天体物理

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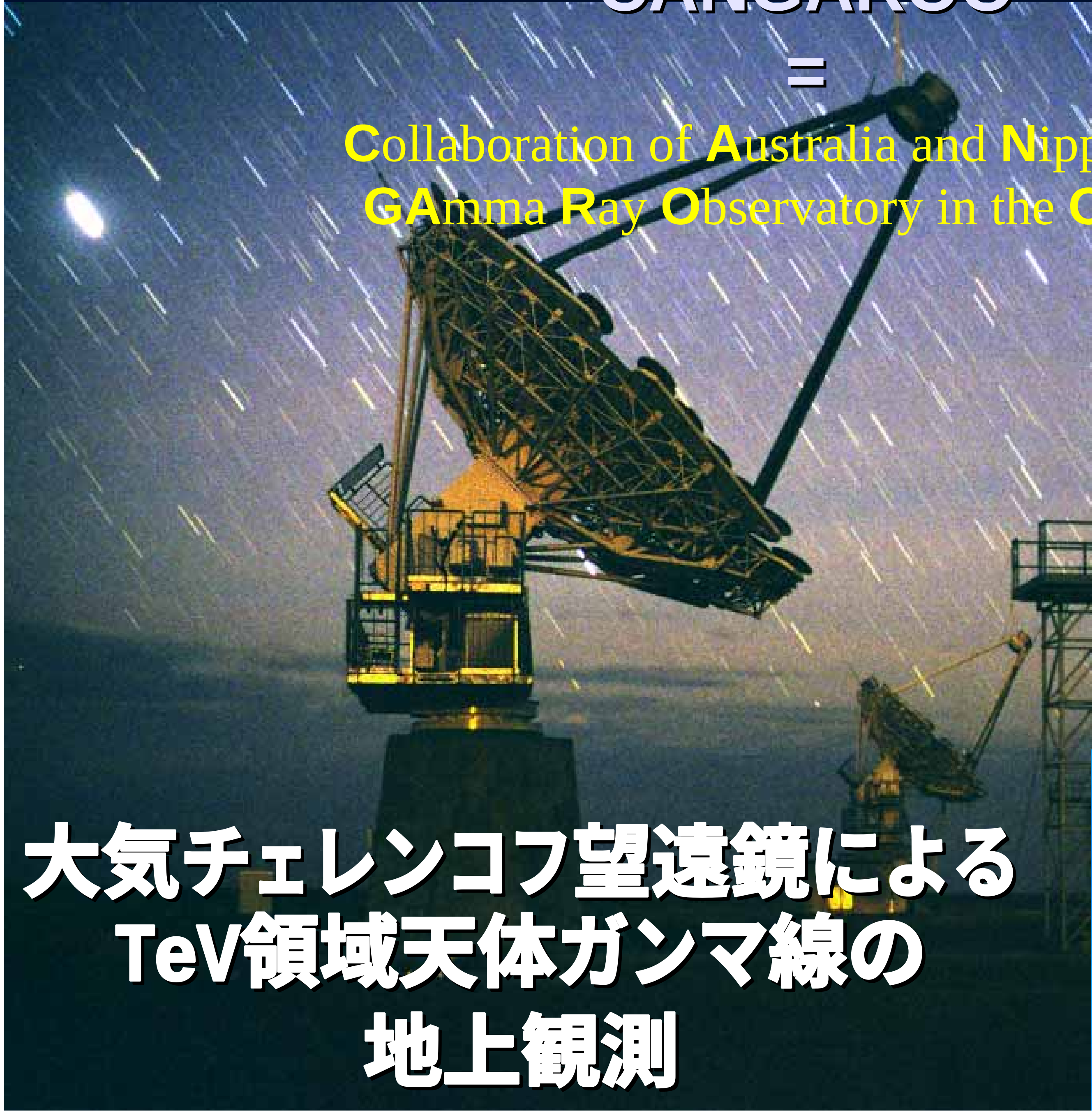
天体ガンマ線の検出法

Base	Satellite	Ground	Ground
Gamma-ray detection	Direct (pair creation)	Indirect (atmospheric Cherenkov)	Indirect (shower array)
Energy	< 30 GeV (→ 100 GeV)	>100 GeV (→ 50 GeV)	>3 TeV (→ 1 TeV)
Pros	High S/N Large FOV	Large area Good Δθ	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 Δθ

“CANGAROO”

=

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



大気チェレンコフ望遠鏡による TeV領域天体ガンマ線の 地上観測

CANGAROO

CANGAROOチーム(日豪共同)

- University of Adelaide
- Australian National University
- Ibaraki University
- Ibaraki Prefectual University
- Kitasato University
- Konan University
- Kyoto University
- Nagoya University
- National Astronomical Observatory of Japan
- Osaka City University
- Shinshu University
- Institute for Space and Aeronautical Science
- Tokai University
- ICRR, University of Tokyo
- Tokyo Institute of Technology
- Yamagata University
- Yamanashi Gakuin University

銀河系内のガンマ線源

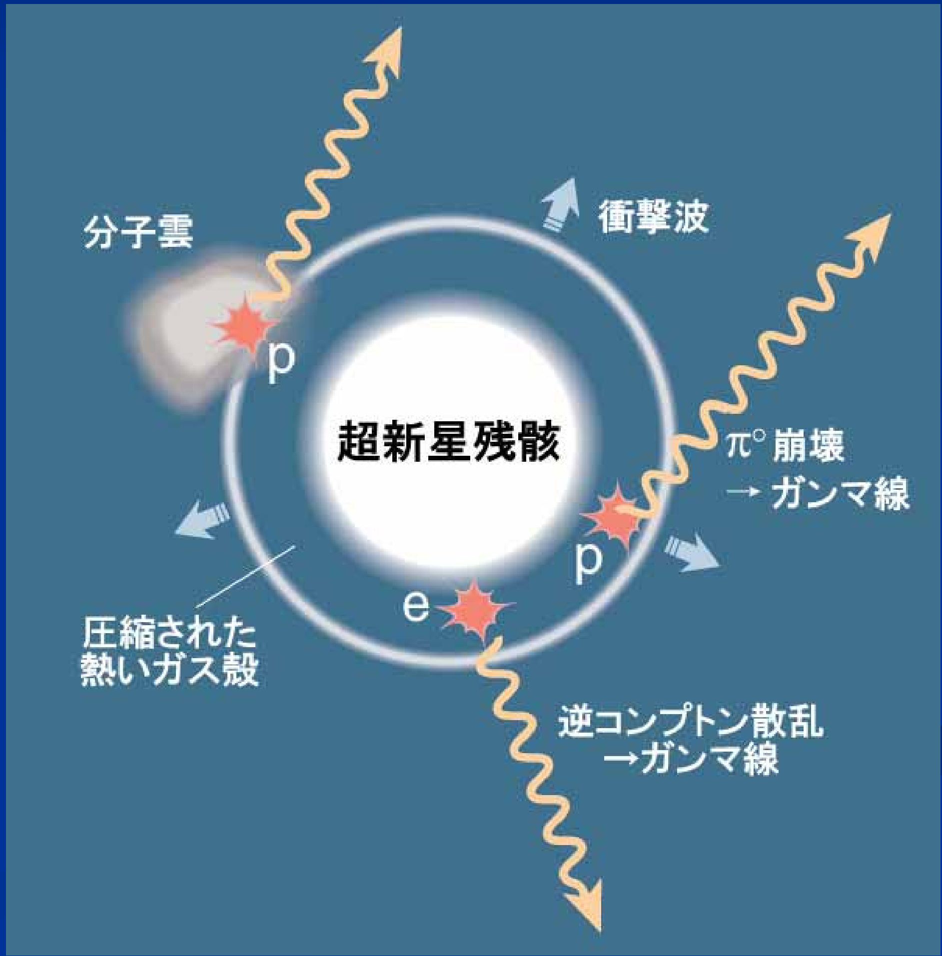
- 超新星残骸 = 宇宙線の起源?
  - エネルギー収支 – OK (if 10% of E_{SN} goes to CR)
  - 最大加速エネルギー – “Knee”領域まで
  - 何個あるか?
  - 高エネルギー電子の存在は確実だが、高エネルギー陽子の証拠はどうか?
- パルサーとパルサー星雲 (plerions)
  - かに星雲 – “The standard candle”
    - Up to a few 10GeV: pulsed+unpulsed
    - Above: unpulsed only
    - - Unpulsed: SSC (Synchrotron-Self-Compton) model
    - - エネルギーのカットオフ?
    - - (Pulsar emission models)
  - Others? Vela, PSR1706-44,…

超新星残骸

Cas A (X線画像)

- 超新星爆発による拡大する爆風⇒ 衝撃波
- 衝撃波による粒子加速
- 周囲の物質との相互作用
  - e + B (シンクロトロン)
  - e + 光子 (IC)
  - p + 物質 (π^0)

  ⇒ ガンマ線放射
- 宇宙線の起源?
(エネルギー学に基づく古くからの議論)



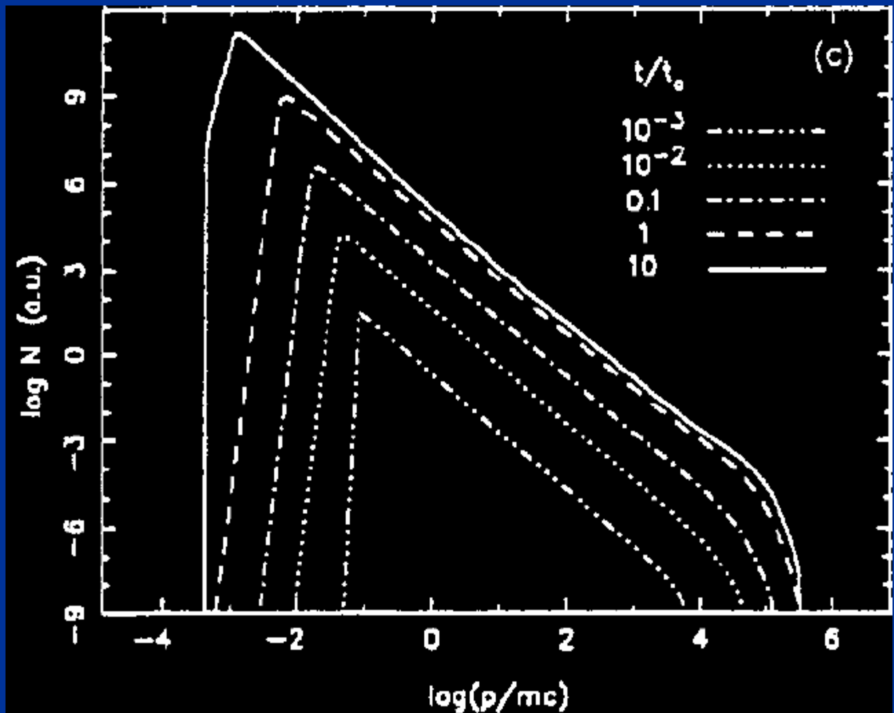
Particle acceleration in SNR

Non-linear kinetic theory

$t_0 = R_0/v_0$; sweep up time

Particle spectrum

Maximum momentum



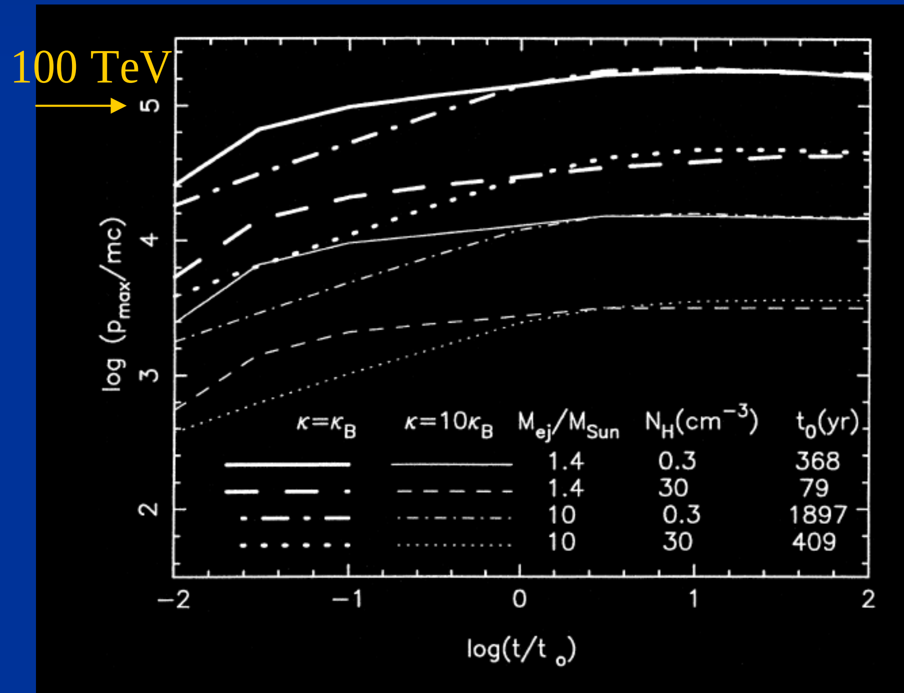


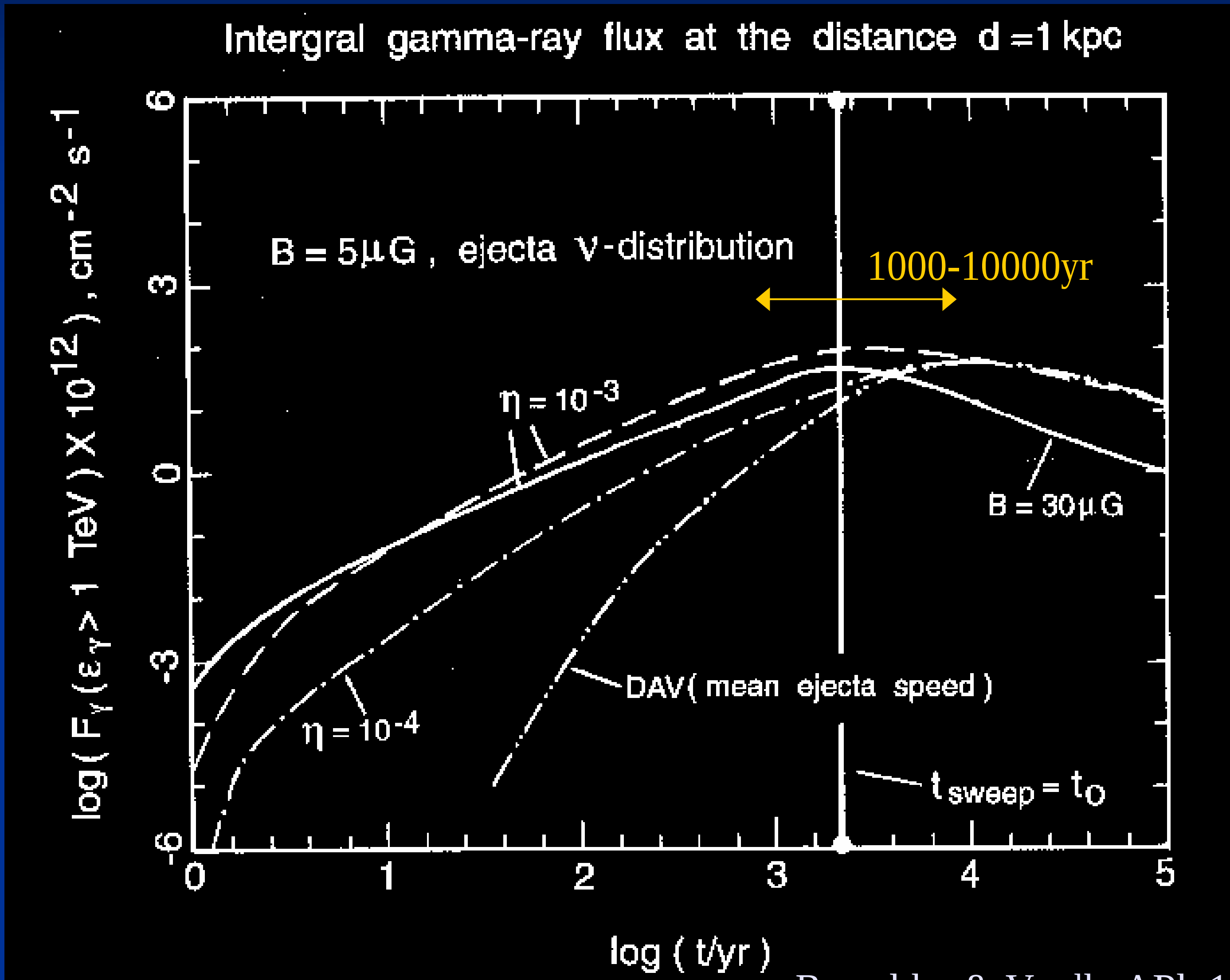
Fig. 2. The maximum CR momentum as a function of time for the same cases as in Fig. 1.

Berezhko & Voelk, APh 1997

Berezhko & Voelk, APh 2000

Cf. Lagage and Cesarsky 1984

Nuclear gamma-ray flux from SNR



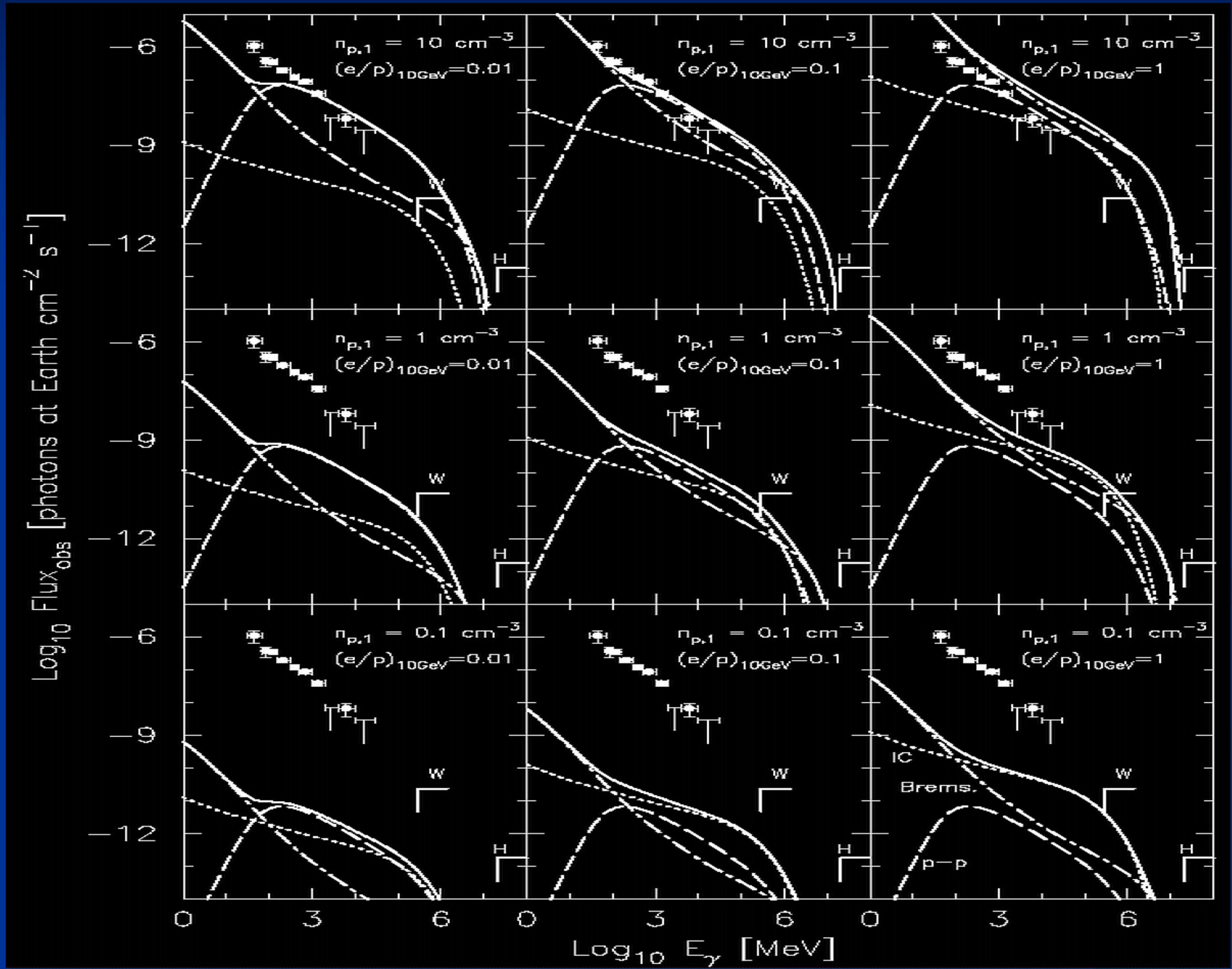
Berezhko & Voelk, APh 1997

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

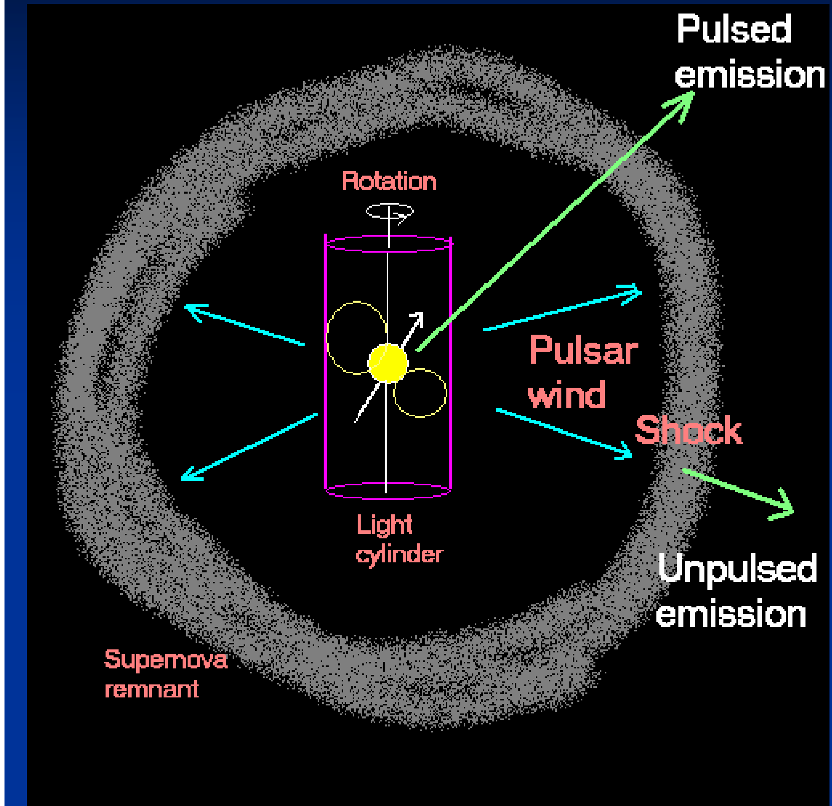
Dash: π^0

Dot-dash:brems

(Data: EGRET IC443)

Baring et al. 1999 ApJ 513, 311

Pulsar nebula

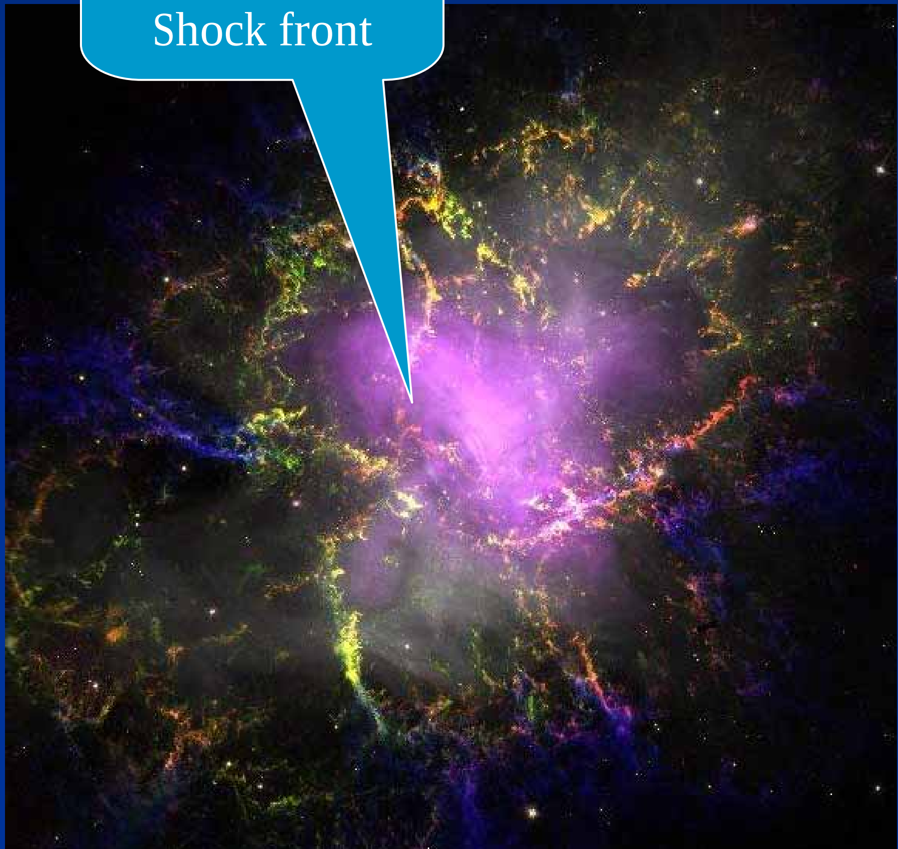


- 周囲のガス圧とバランスするところで衝撃波が形成され、圧縮加熱されたパルサー風がシンクロトロン放射で輝く

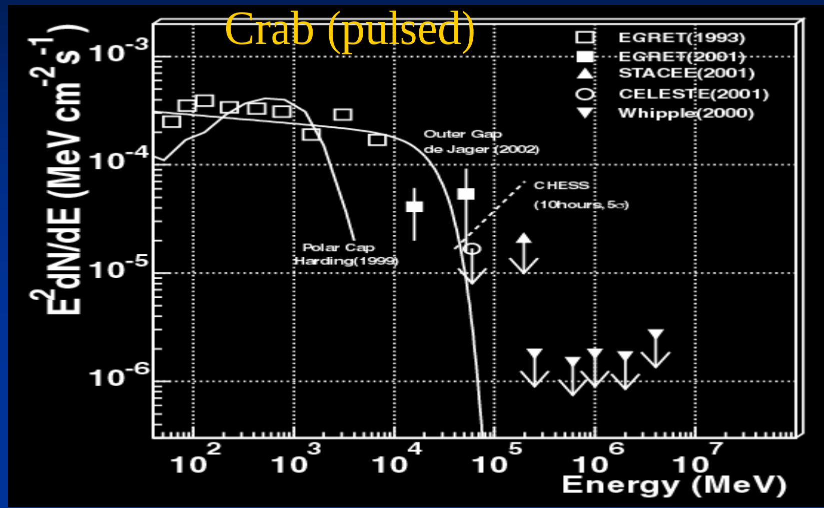
K.Mori, talk at ICRR, Dec 2003

The Crab

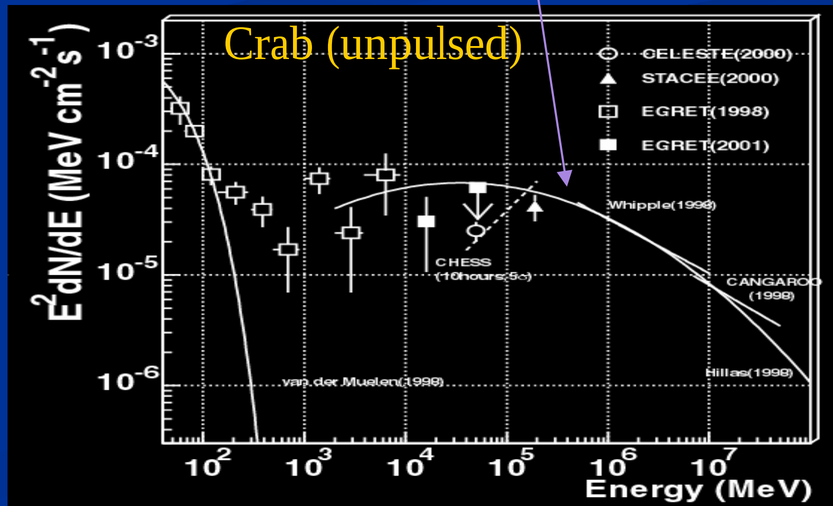
Inner ring
=
Shock front



Optical + X-ray image



Synchrotron Self Compton



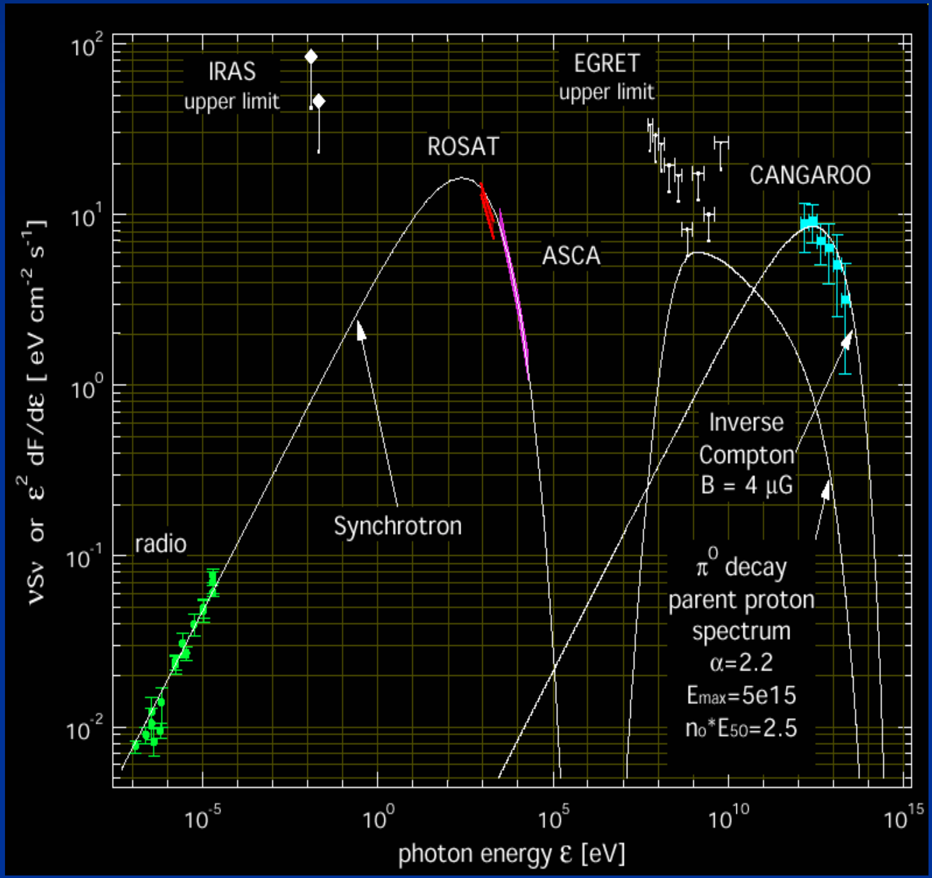
Asahara et al., SPIE 2002

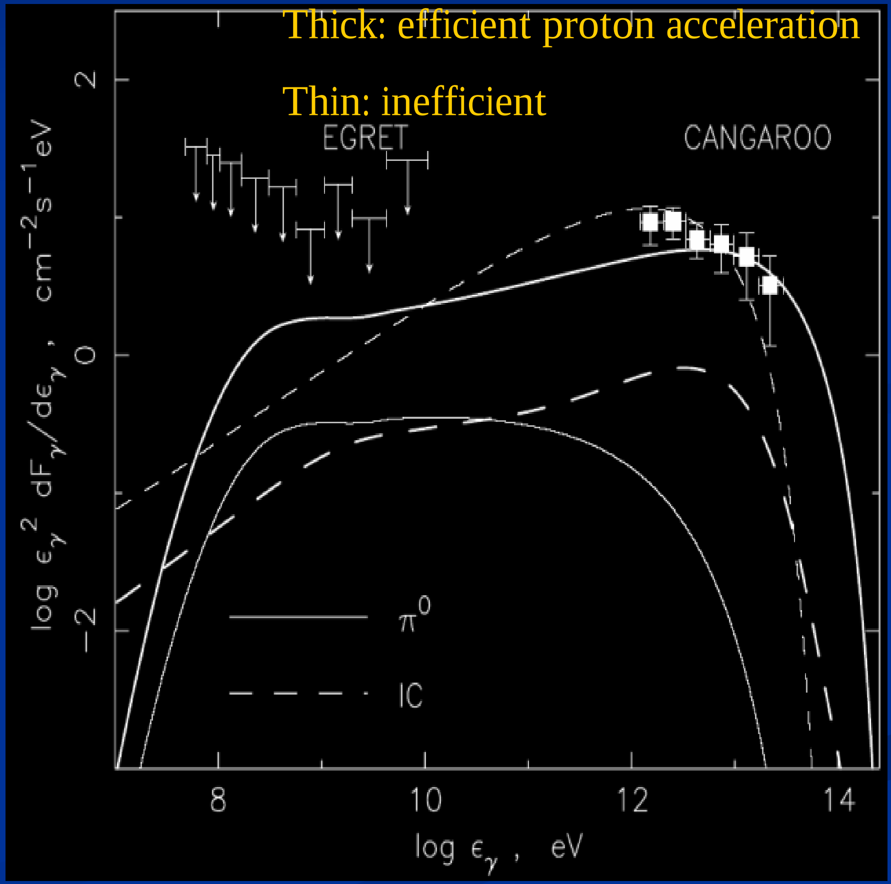
“Known” galactic sources

- 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

Electron origin vs Proton origin

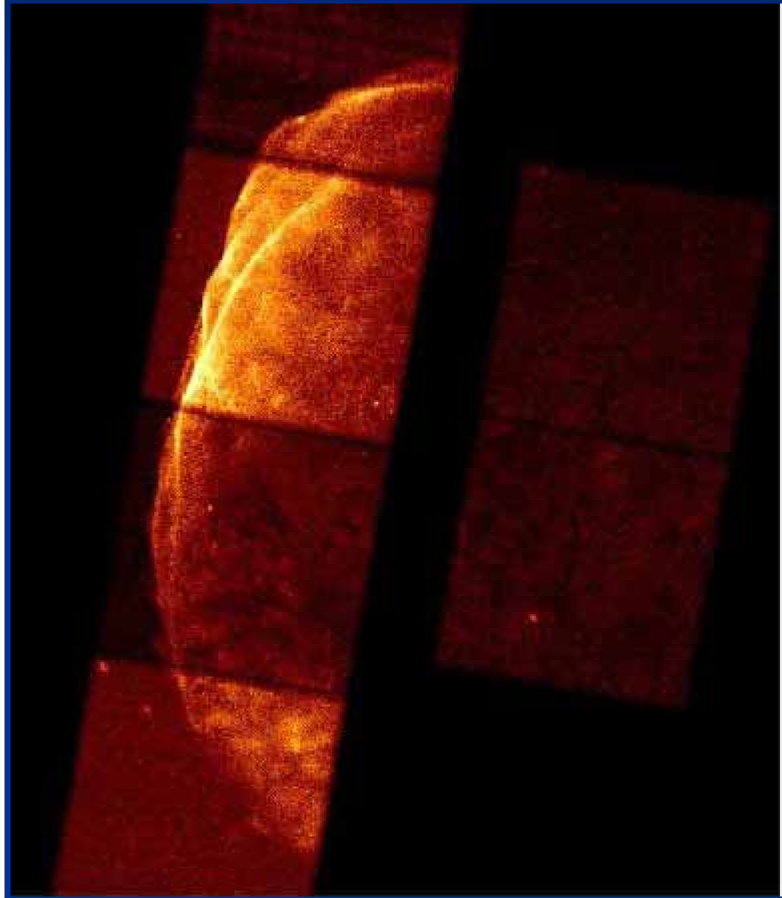




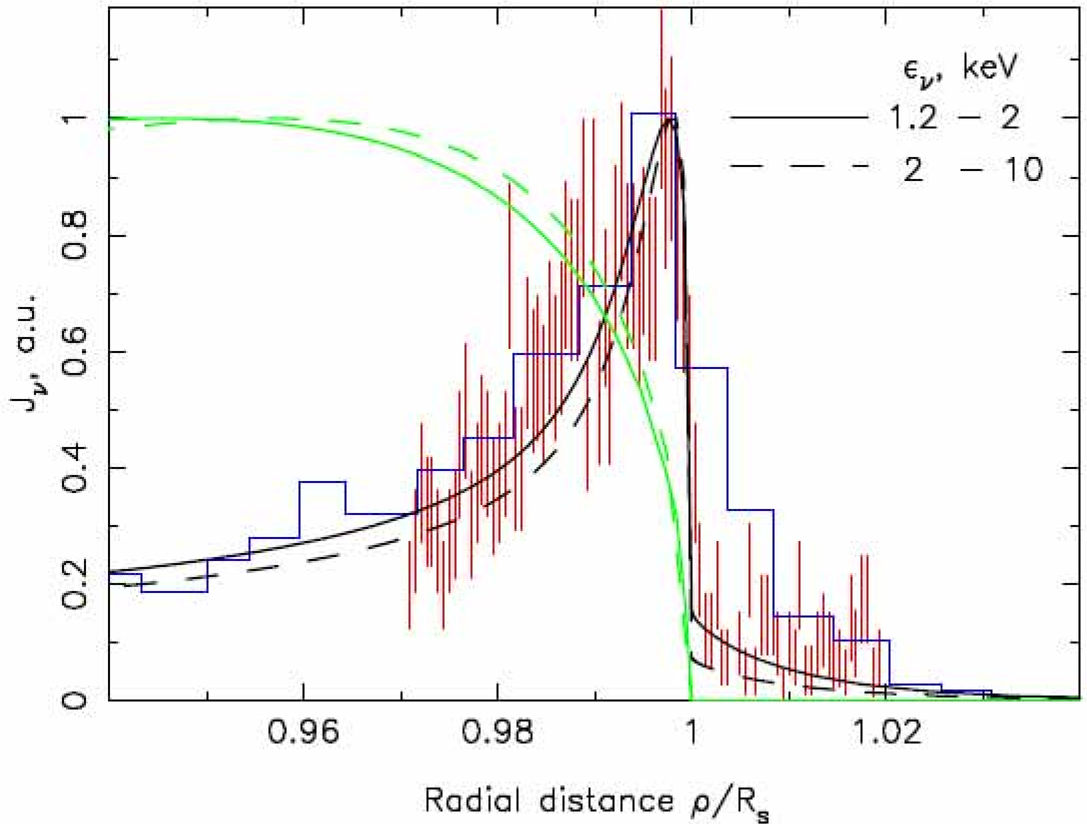
Naito et al. AN 320 (1999)

Berezhko, Ksenofontov and Voelk, AA 395 (2002) 943

SN1006 rim structure



Chandra image



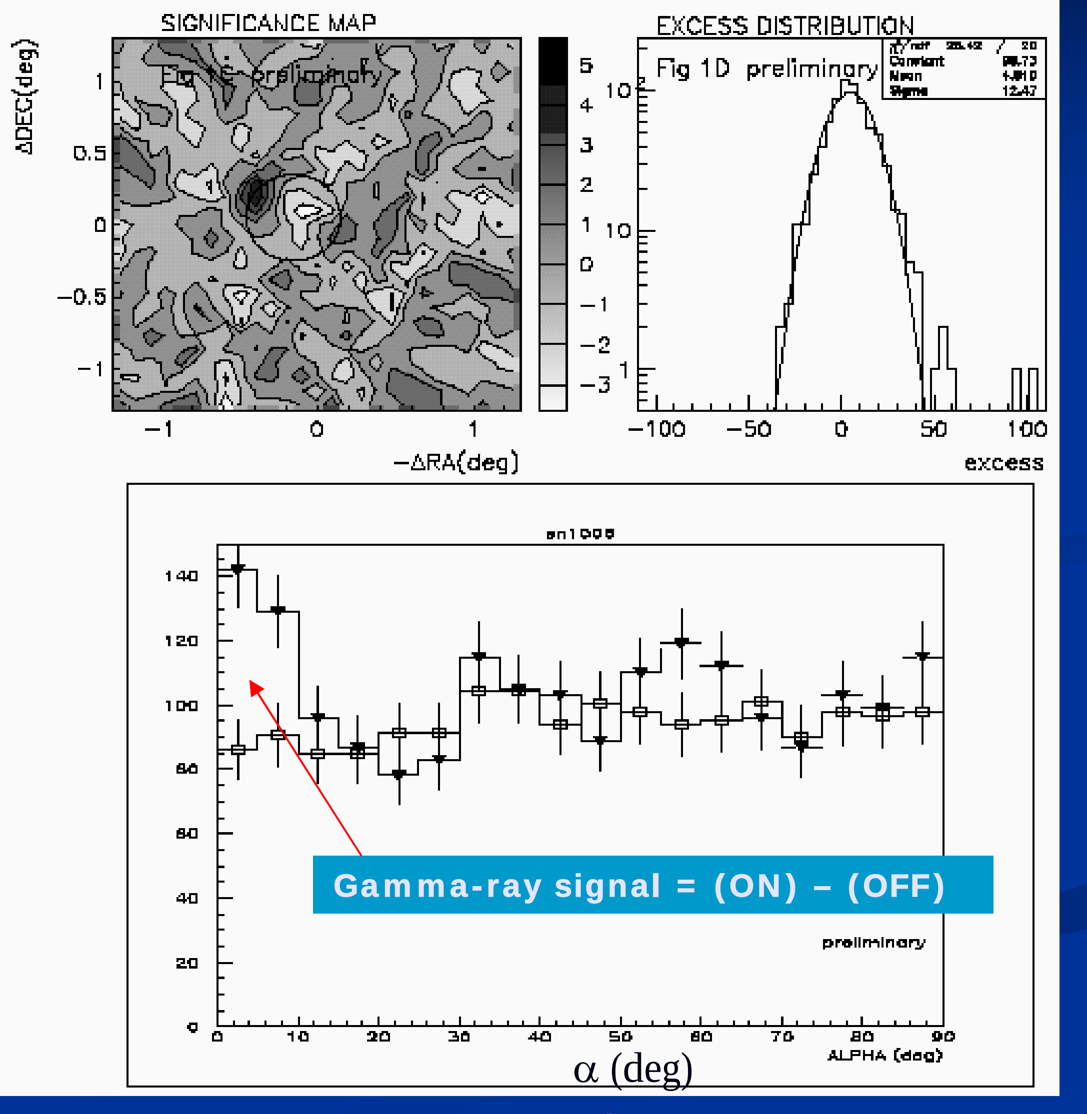
Black: efficient proton acceleration e/p=0.0015

Green: inefficient e/p=0.04

Berezhko, Ksenofontov and Voelk AA 412 (2003) L11

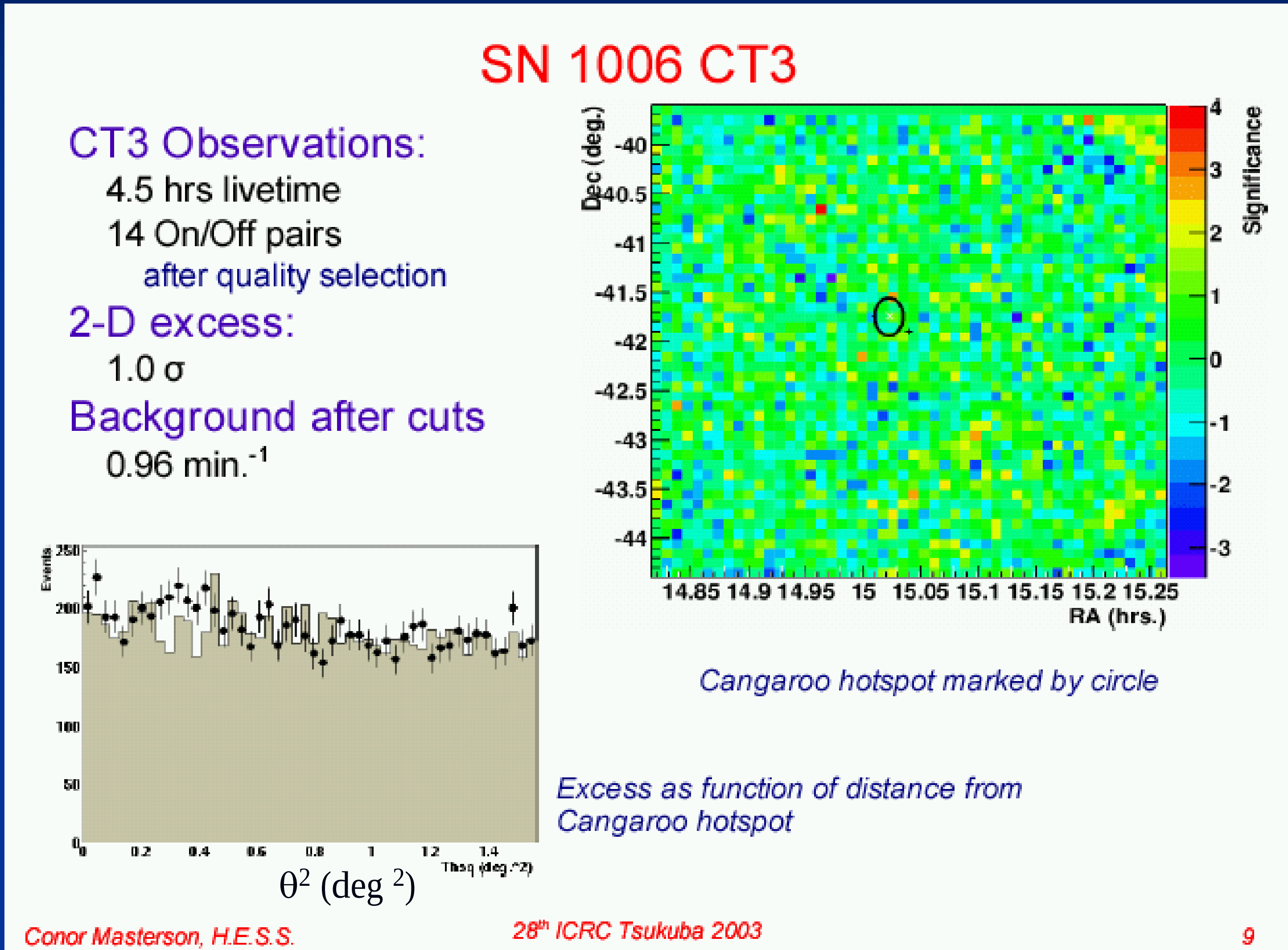
SN1006: HEGRA CT1

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



Vitale et al. 28th ICRC (2003)

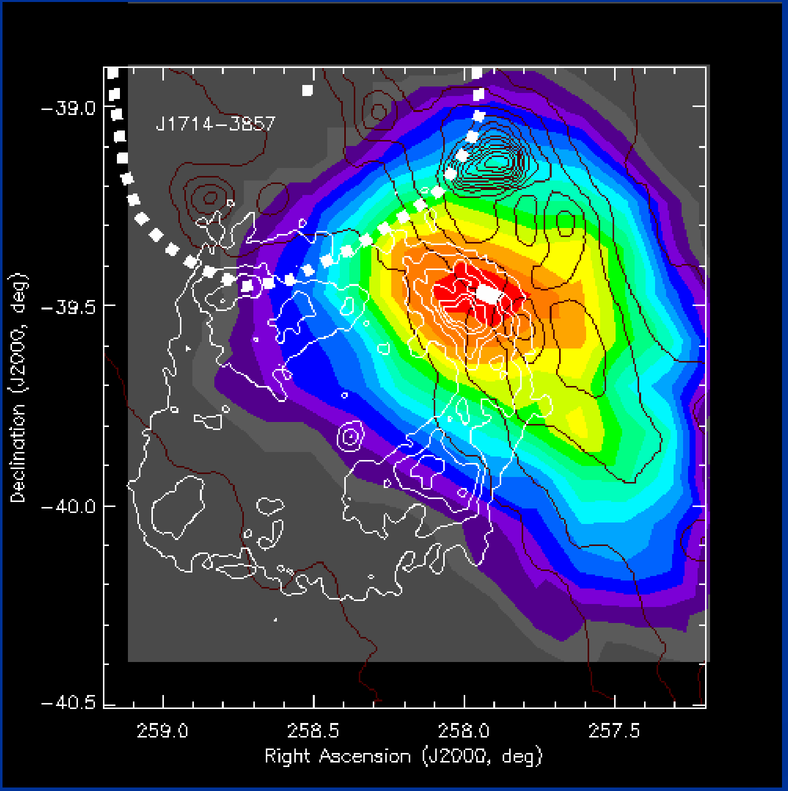
SN1006: H.E.S.S.



Masterson et al., 28th ICRC (2003)

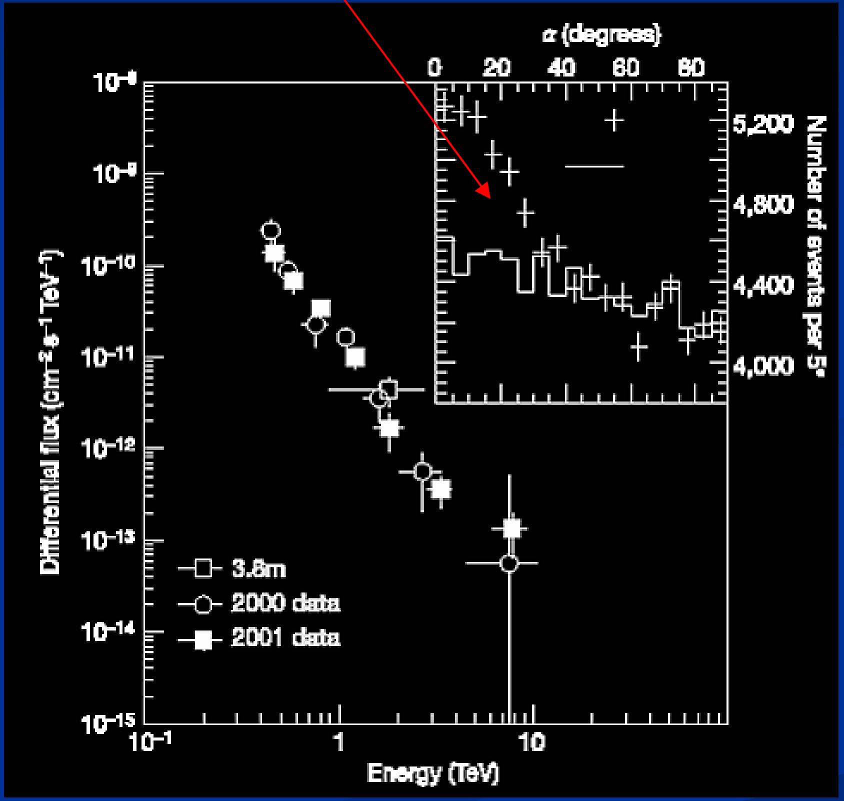
SNR RX J1713.7-3946 (1)

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



Significance map

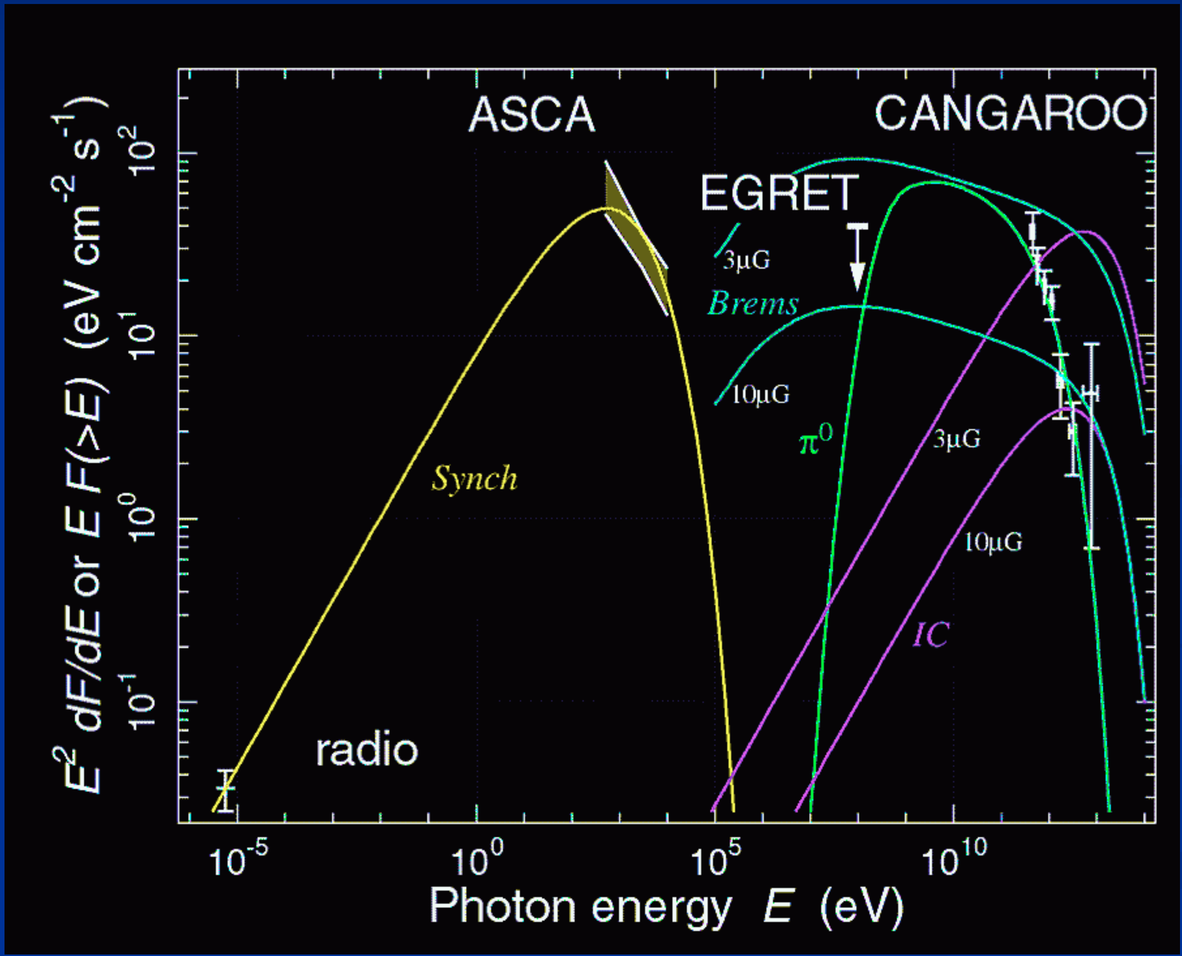
Gamma-ray signal = (ON) − (OFF)



Energy spectrum

Enomoto et al. Nature 416 (2002) 823

SNR RX J1713.7-3946 (2)



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~10^{48}erg ~ $0.001 L_{SN}$

(Fukui et al. PASJ 55, 2003)

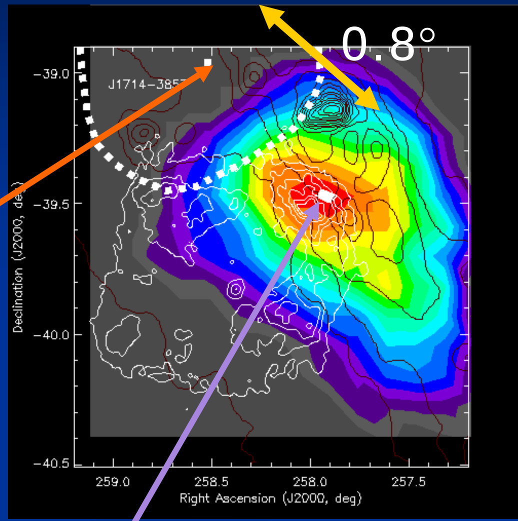
Enomoto et al. Nature 416 (2002) 823

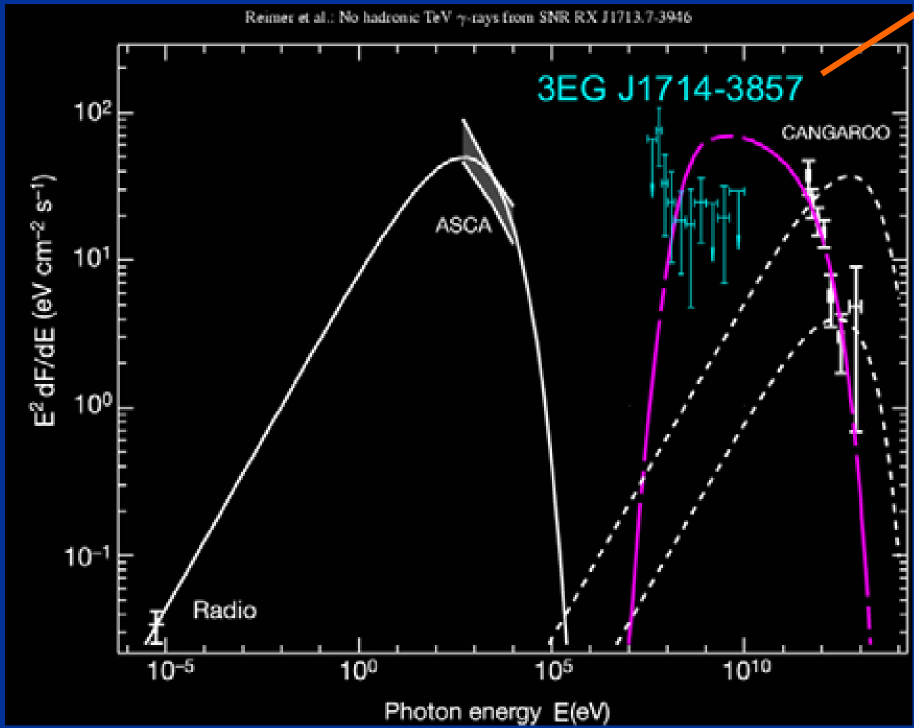
SNR RX J1713.7-3946 (3)

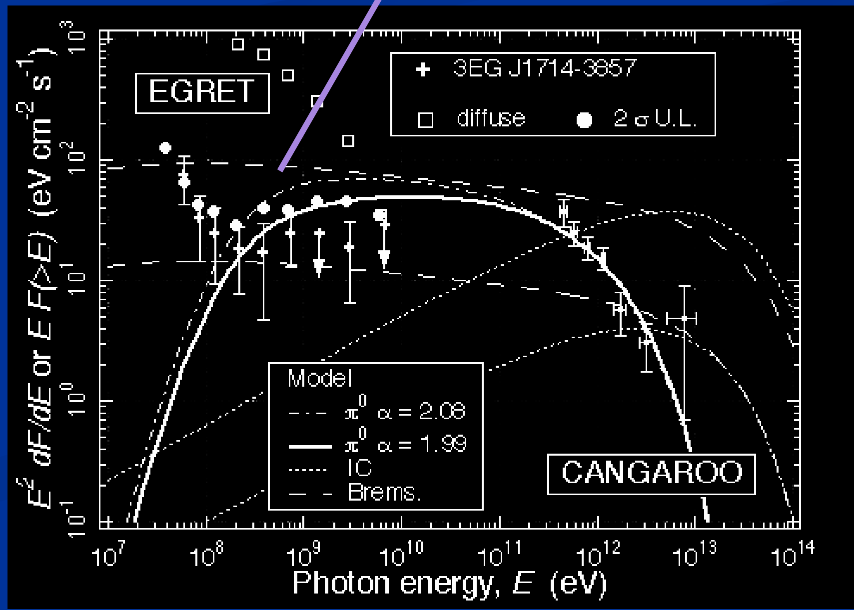
Counter arguments

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

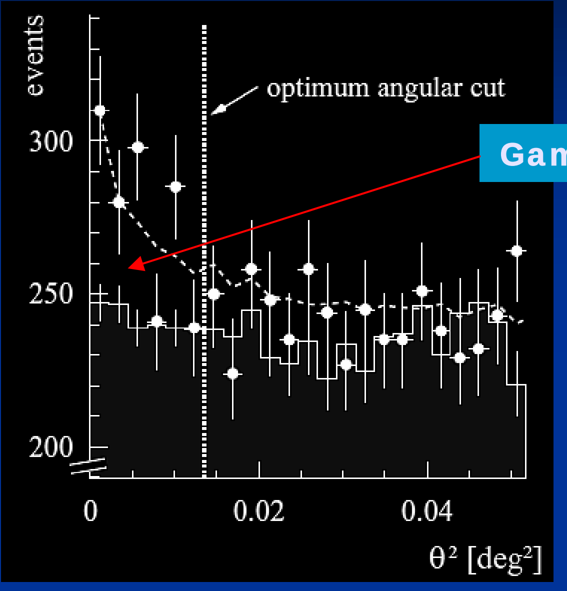
* Butt et al., Nature 418 (2002) 489







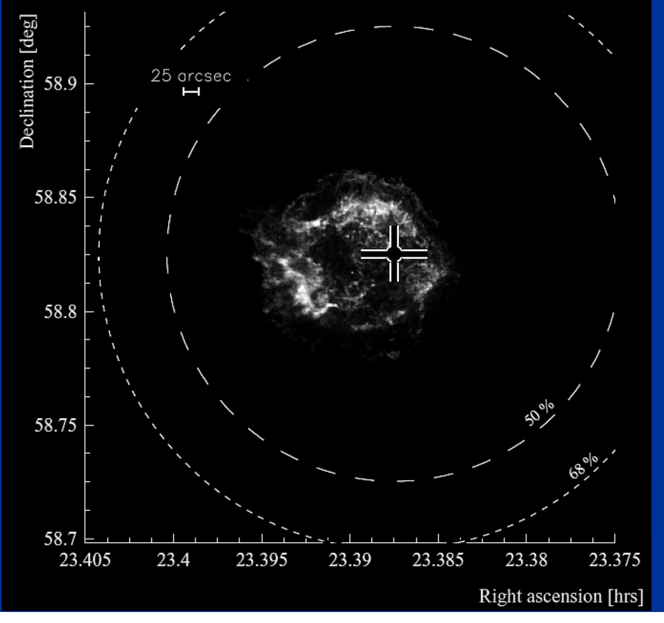
SNR Cas A

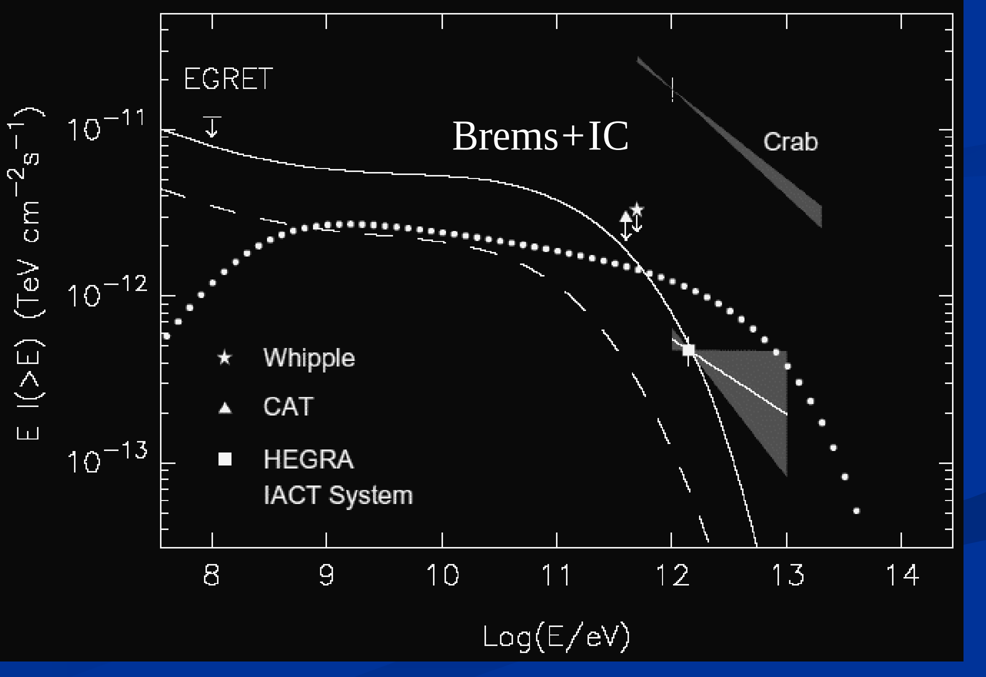


Gamma-ray signal = (ON) – (OFF)

HEGRA-CT system (stereo)

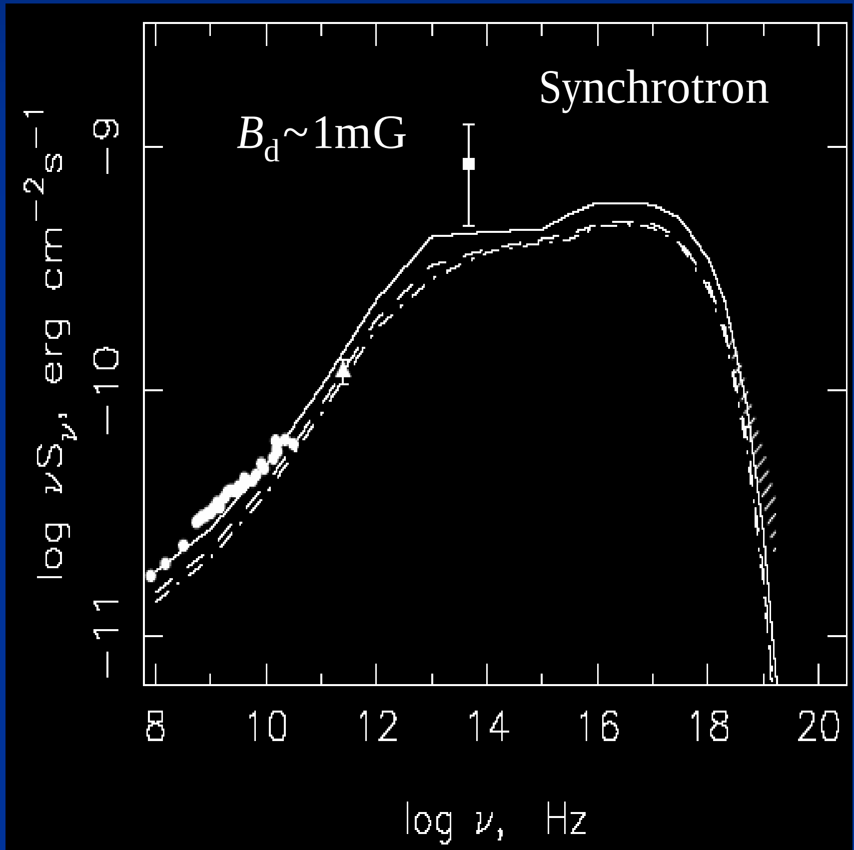
232 hrs

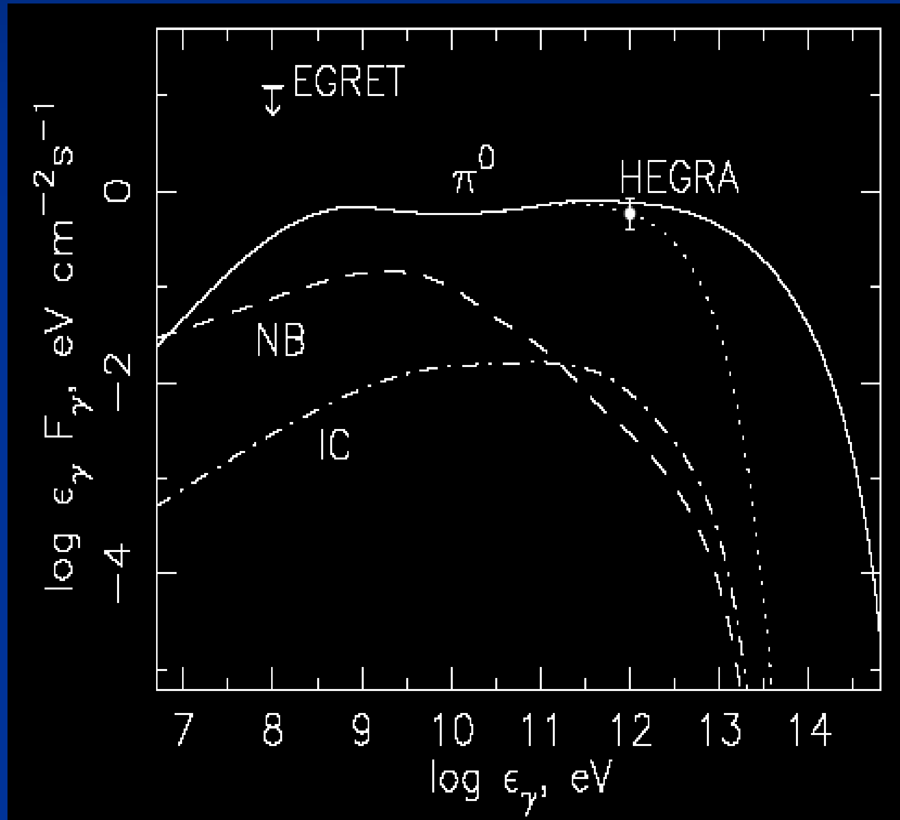




Aharonian et al. A&A 370 (2001) 112

Cas A: proton accelerator?





e/p=0.02

Berezhko et al., AA 400 (2003)

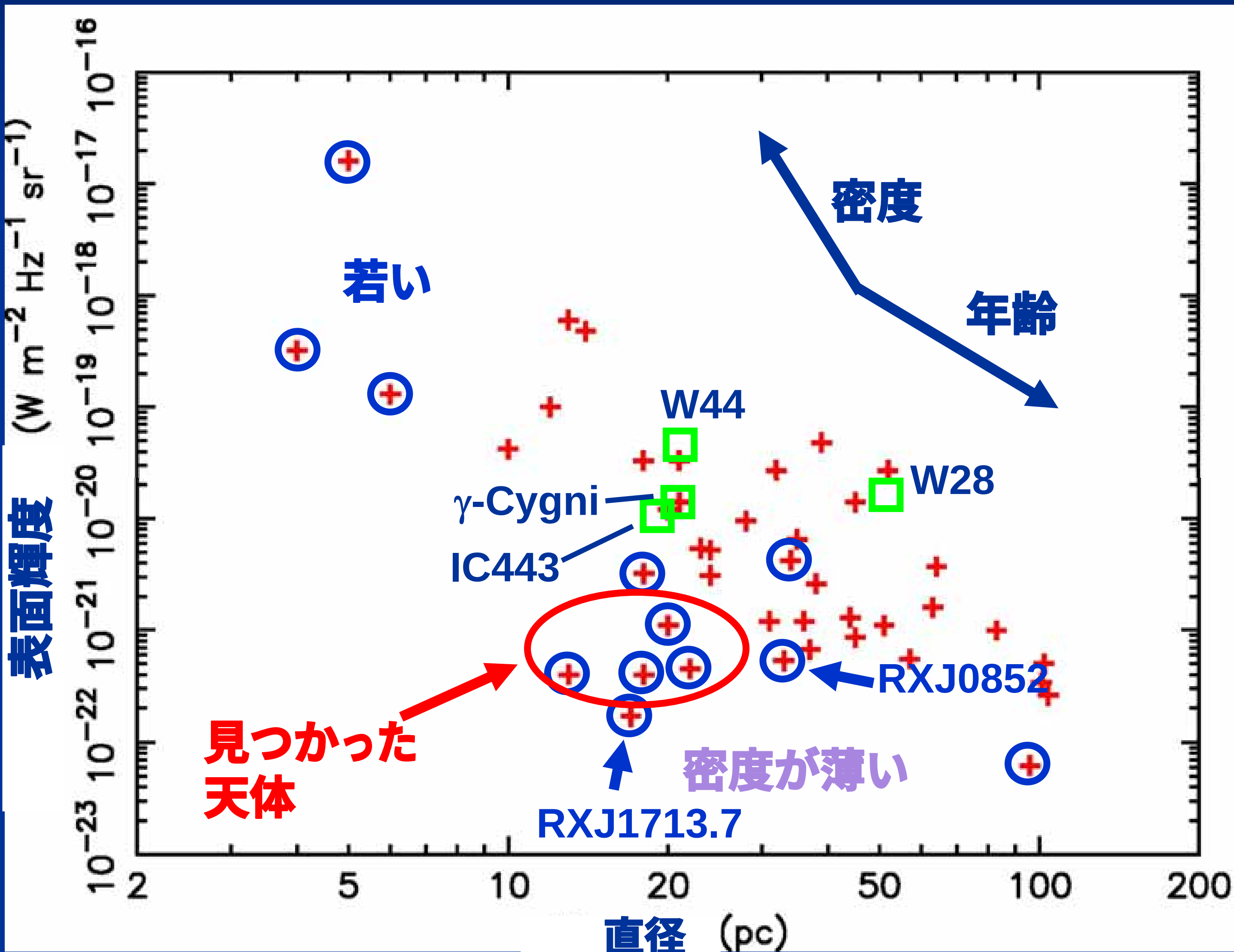
Comparison of SNRs

Name	Distance (kpc)	Age (yr)	Density (cm^{-3})	Mag. field (G)	SN type
SN1006	2.2	1000	0.1-0.3	Several μ (→120 μ)	Ia
RX J1713.7 -3946	1	1600(?)	0.01(amb)- 10(MC)	0.1m- 0.4m	II
Cas A	3.4	320	2-10	0.1m-1m	Ib (masive WR star)

(Various references)

More TeV SNRs?

Ueno, talk in Kyoto, Dec 2003



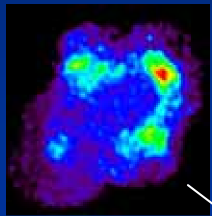
密度が高く
年を取ったもの

シンクロトロンX線
が受からない

EGRET天体

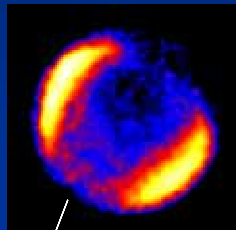
Systematic study of SNRs

RX J1713.7-3946 (CANGAROO)



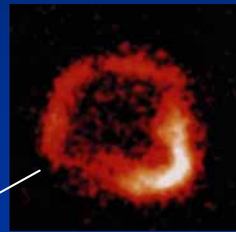
ASCA

SN1006 (CANGAROO)

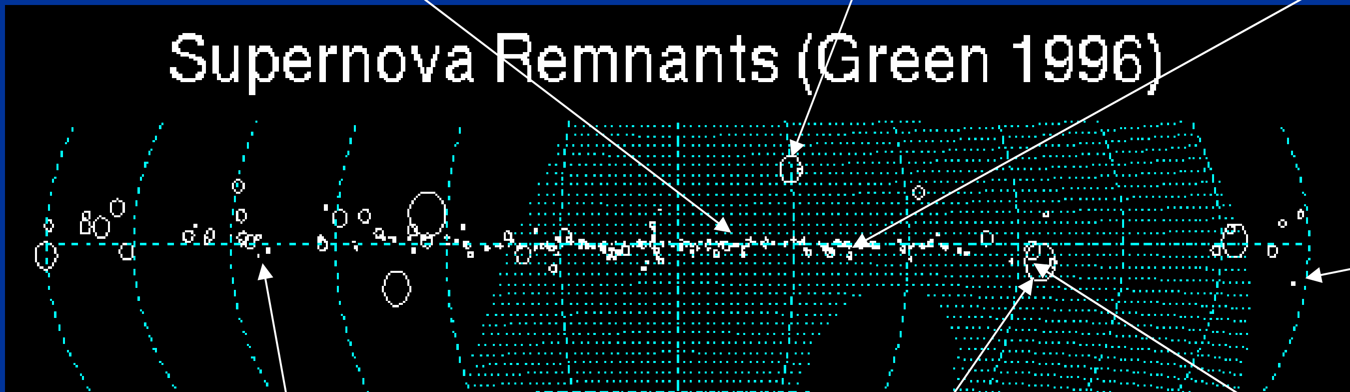


ASCA

RCW86 (CANGAROO under analysis)

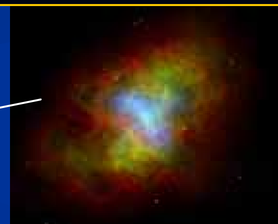


ROSAT



Crab nebula

("Standard candle")

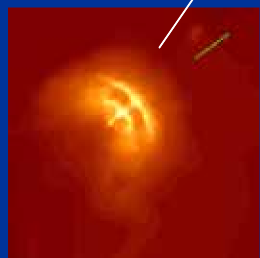


Chandra

• optical

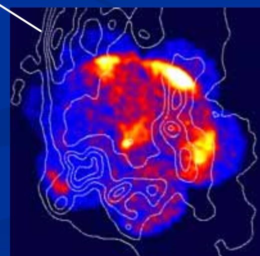
Chandra

Cas A (HEGRA)



Chandra

Vela (CANGAROO)

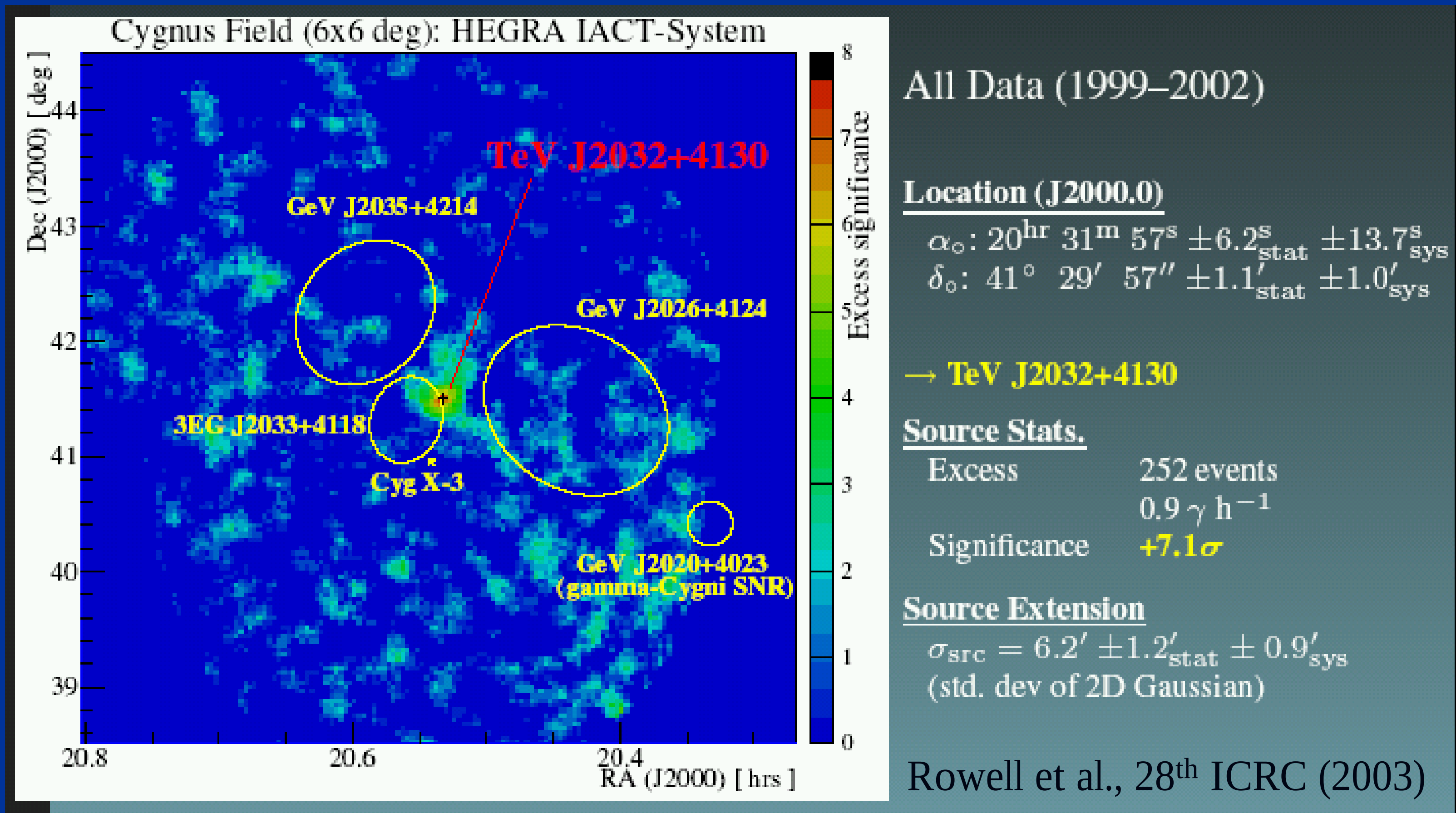


ROSAT

RX J0852-46 (CANGAROO under analysis)

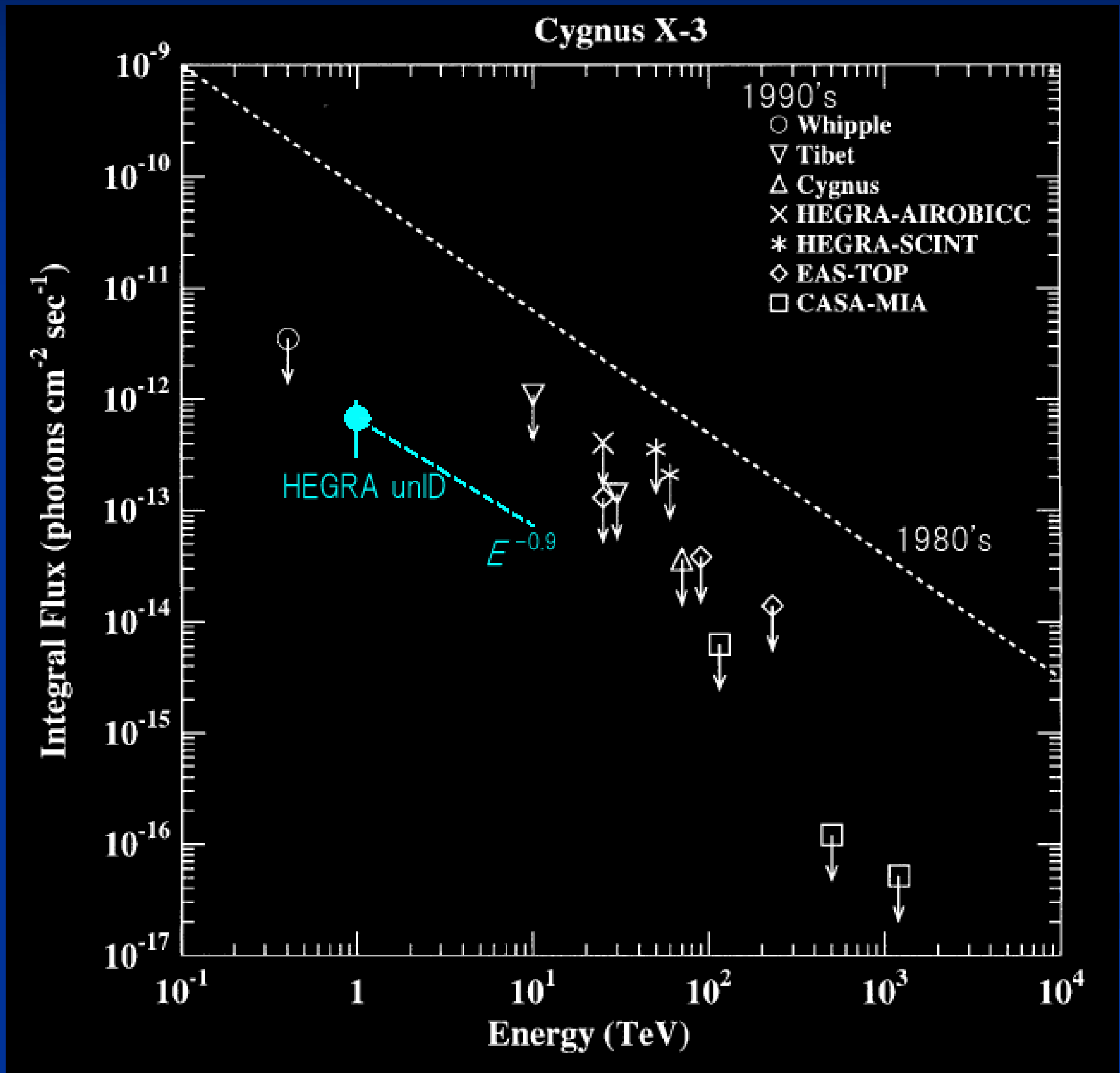
New entry: TeV J2032+4130

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



Rowell et al., 28th ICRC (2003)

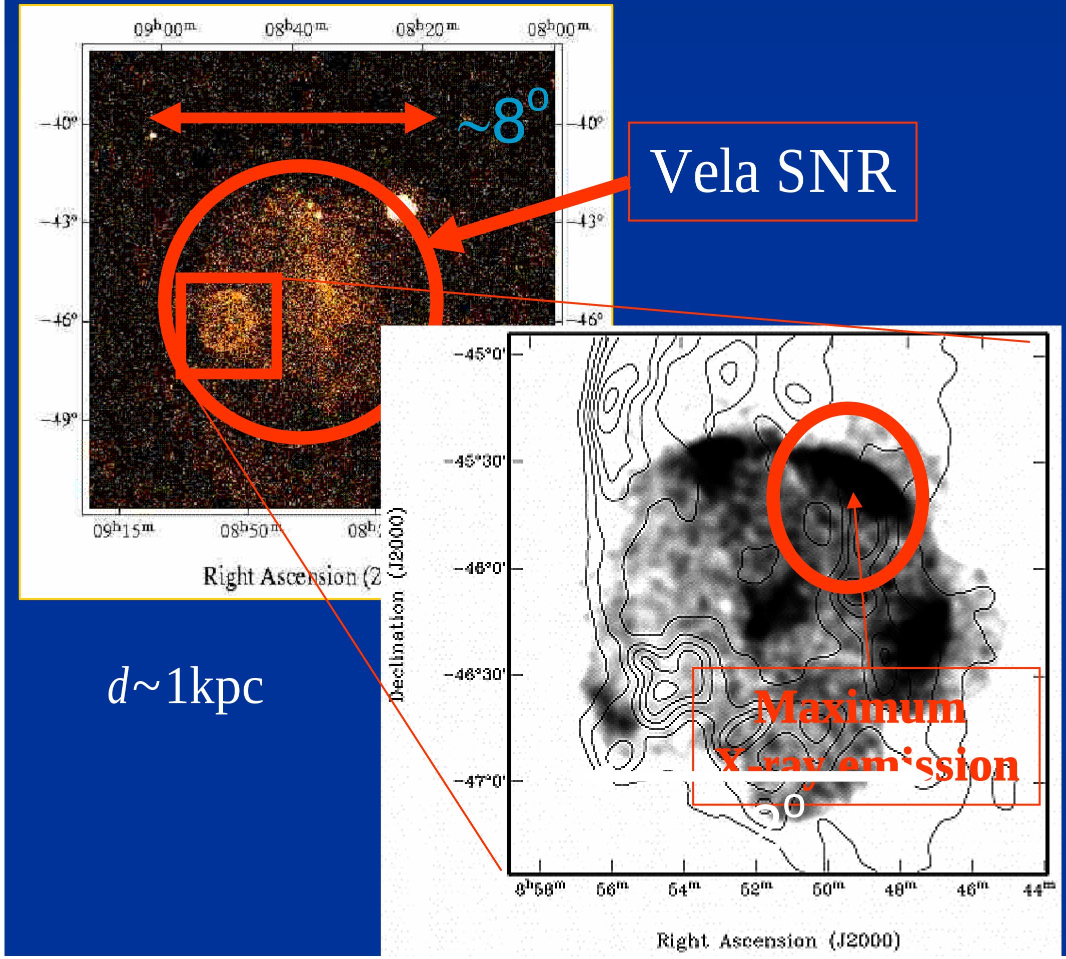
TeV J2032+4130 = Cyg X-3 ???



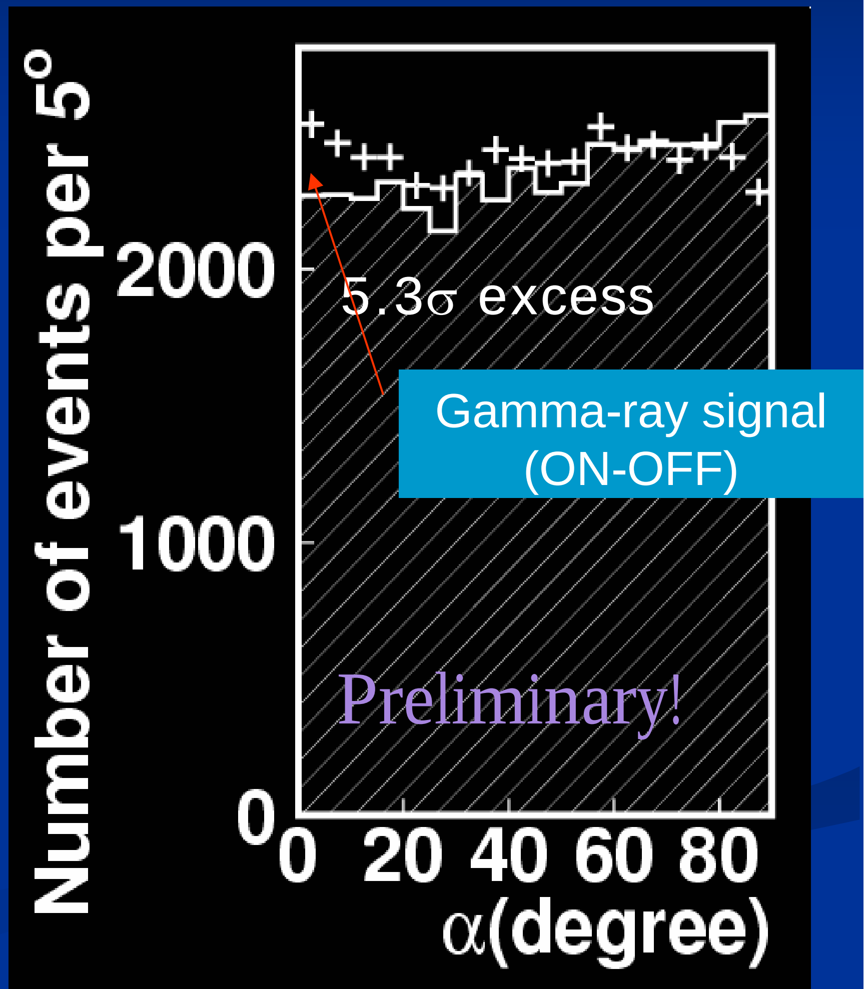
Ong, Phys. Rep. 305 (1998)

New entry: SNR RX J0852.0-4622

- CANGAROO 10m result



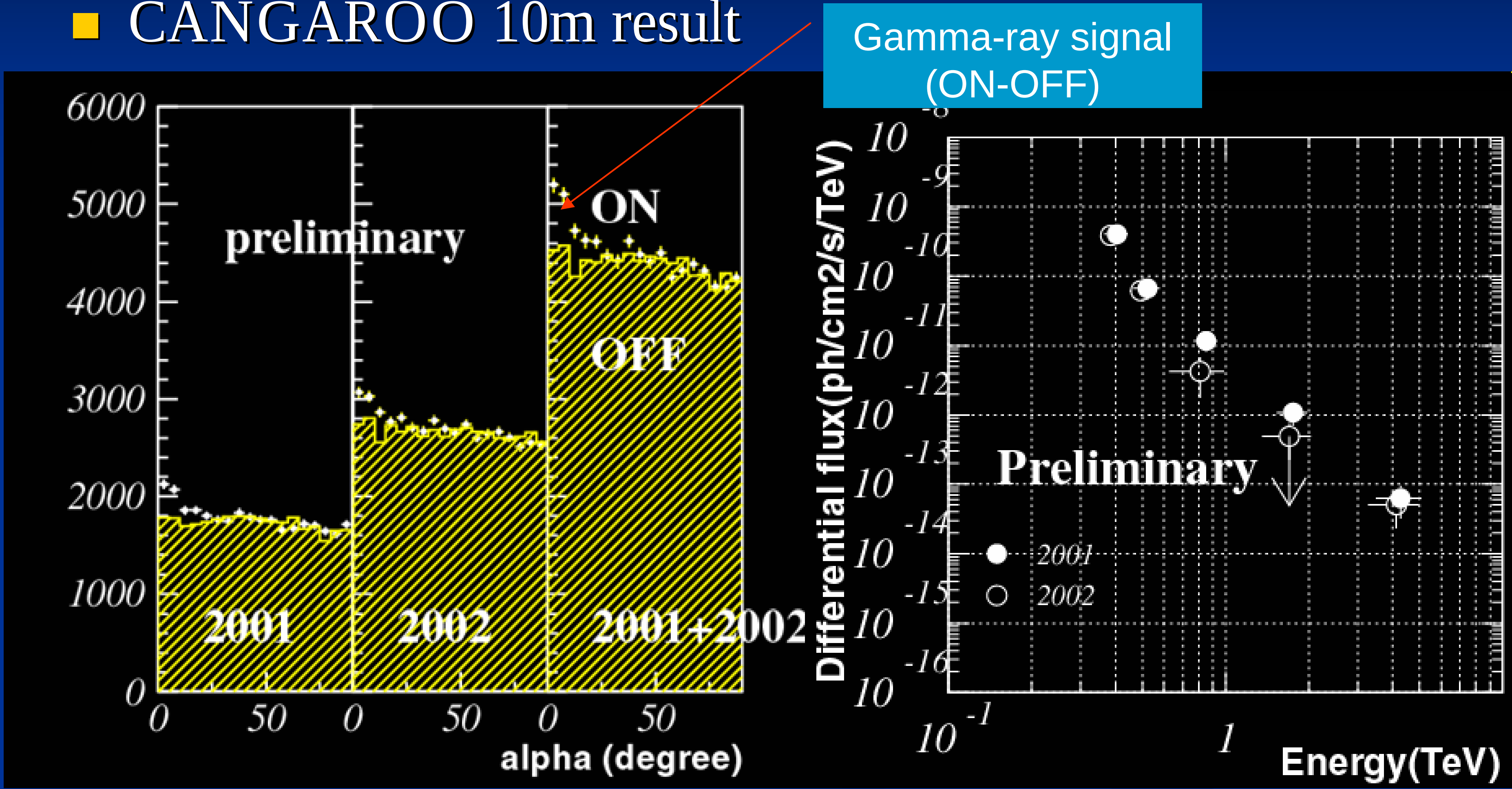
d~1kpc



Katagiri et al., 28th ICRC (2003)

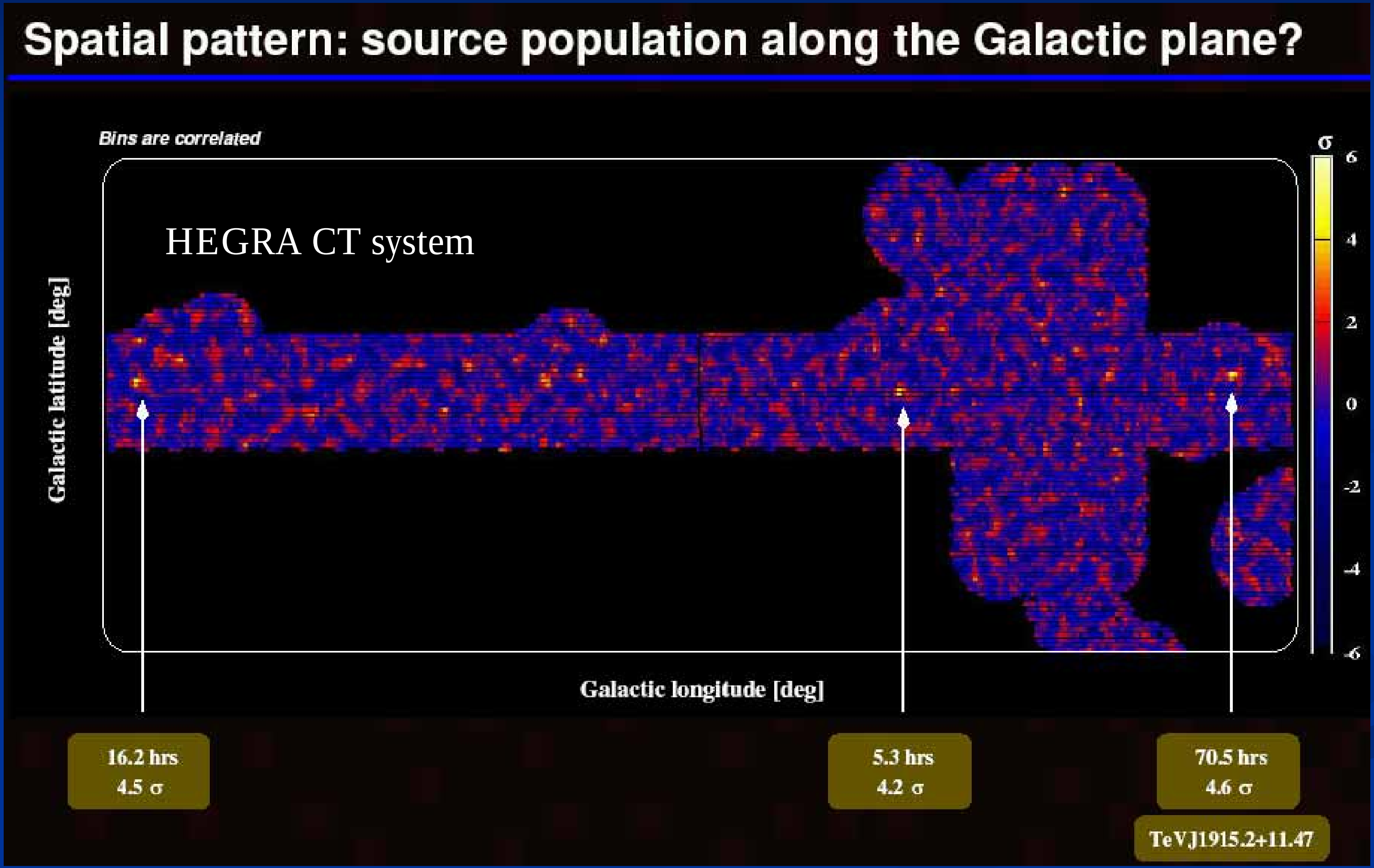
New entry: Galactic center

- CANGAROO 10m result



Tsuchiya et al., 28th ICRC (2003)

Galactic plane survey

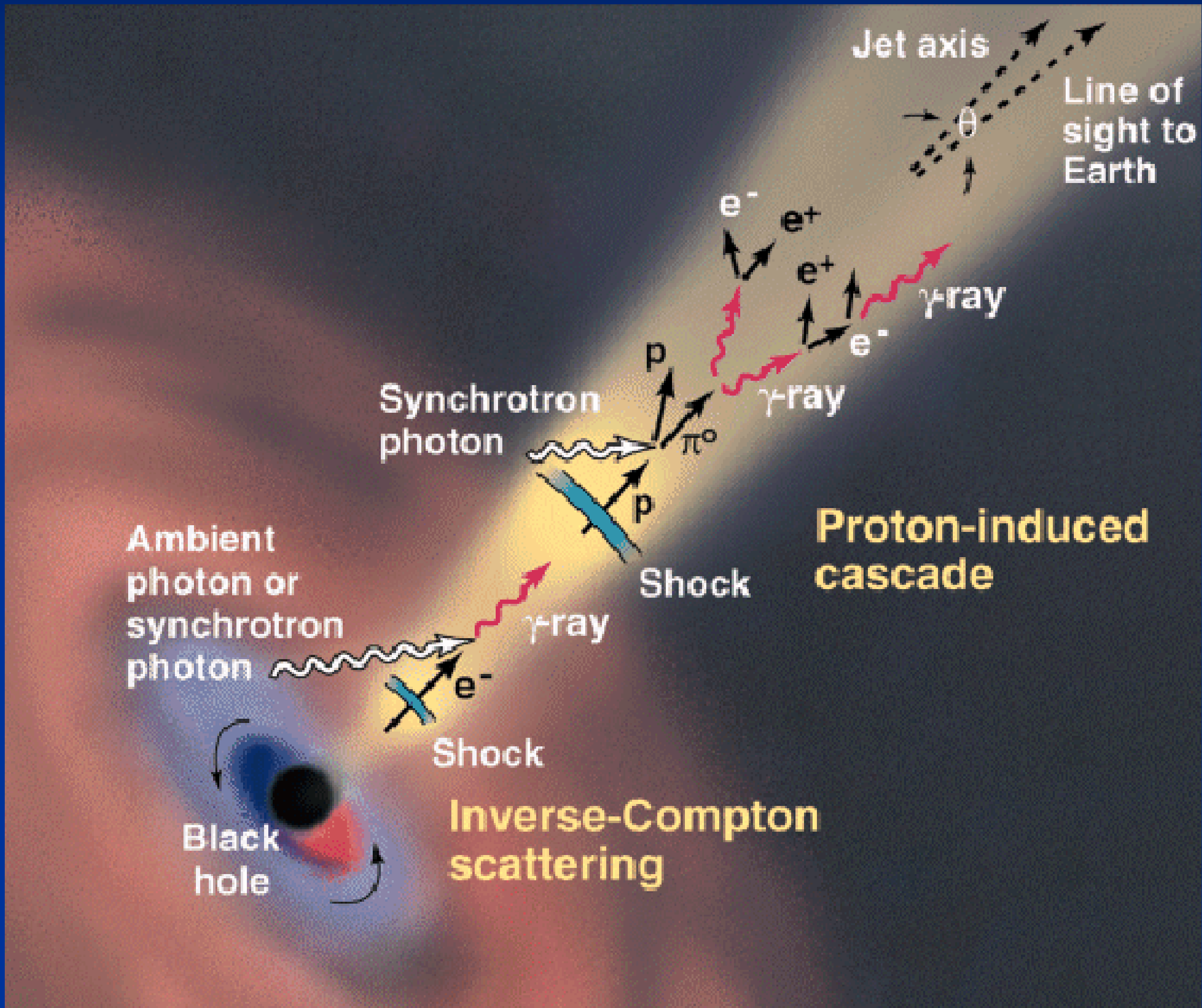


Puehlhofer et al., 28th ICRC (2003)

銀河系外のガンマ線源

- 活動銀河核(AGN)
  - 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,…
- 銀河系外背景放射(EBL: Extragalactic Background Radiation)による吸収
  - 背景赤外線量の不確定性
- 銀河の中心
  - Accumulation of dark matter??
- 銀河系外ガンマ線背景放射

Blazars



Beaming factor

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

Observed frequency

$\nu \propto \nu_0 \delta$

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

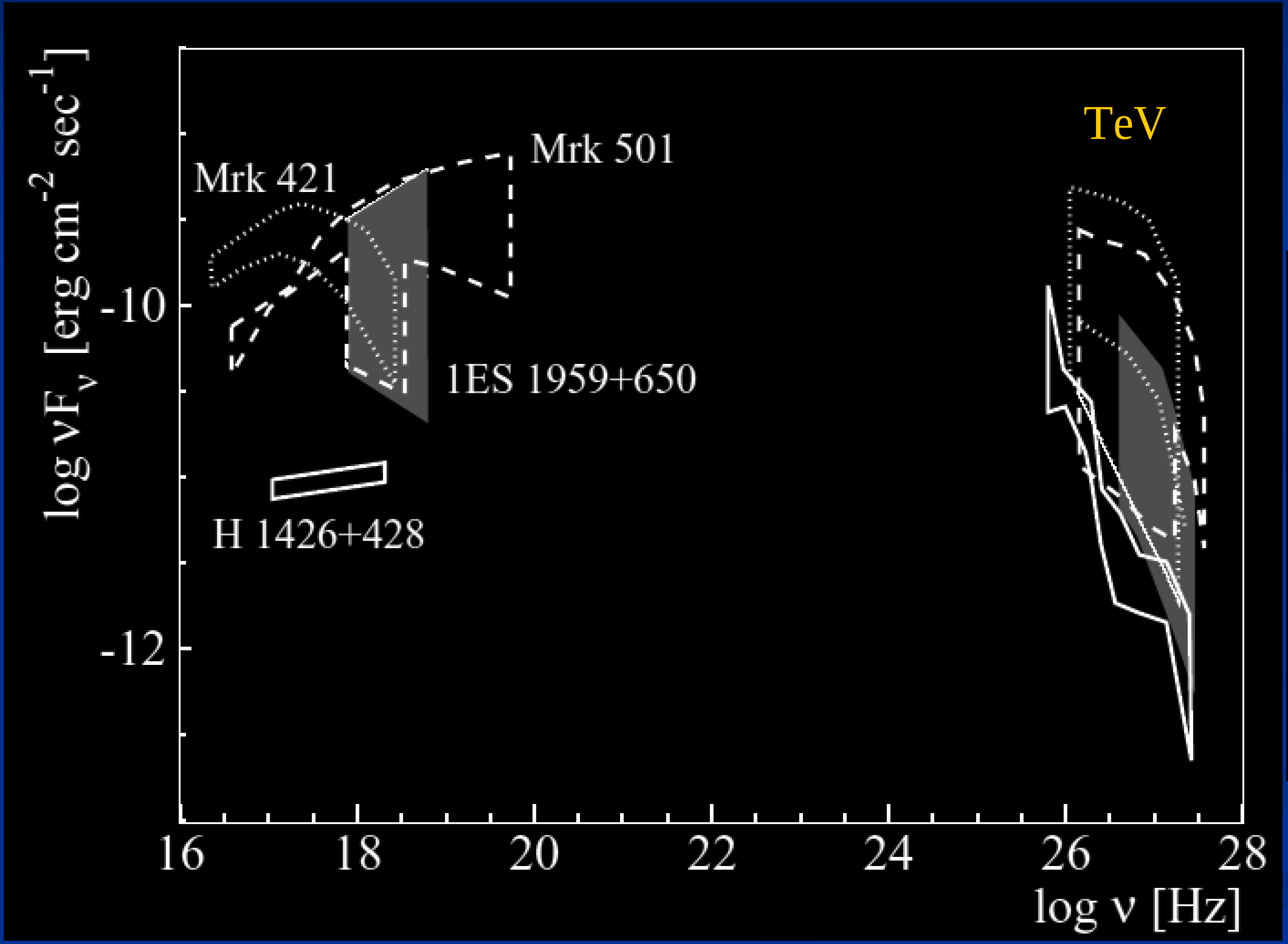
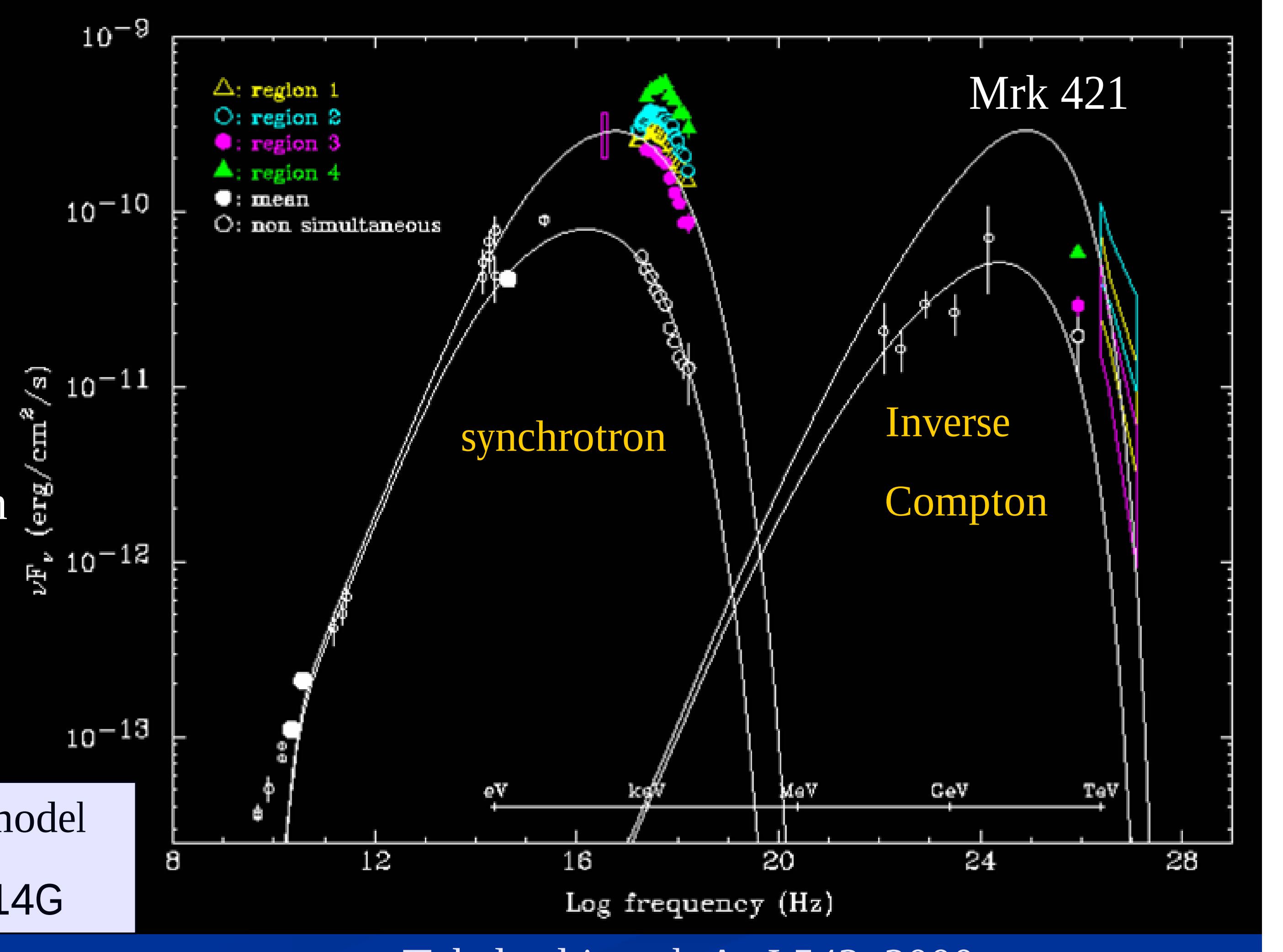


Fig. 1. Simultaneous and non-simultaneous X-ray and TeV γ-ray energy spectra of the 4 TeV blazars with measured TeV γ-ray energy spectra. The regions show the range of values that have been observed with BeppoSAX, RXTE and Cherenkov Telescopes (from ([46])).

Krawczynski, astro-ph/0309443

Synchrotron Self-Compton model (1)

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



One-zone SSC model

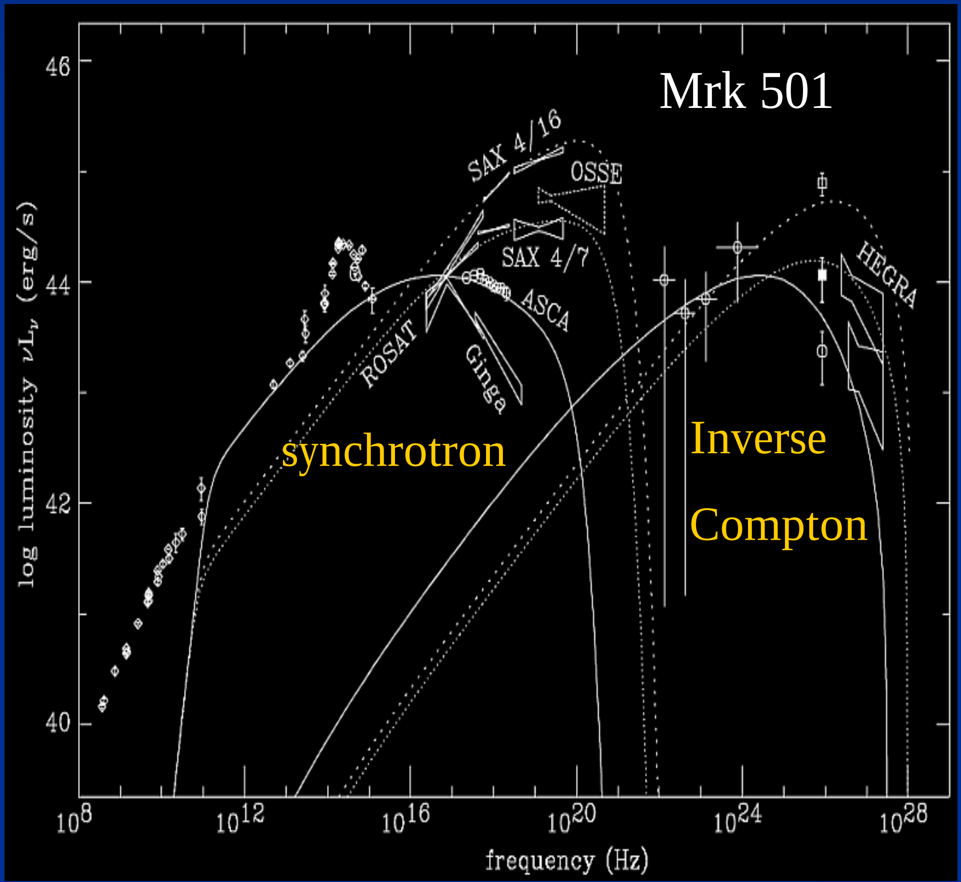
δ =14, B=0.14G

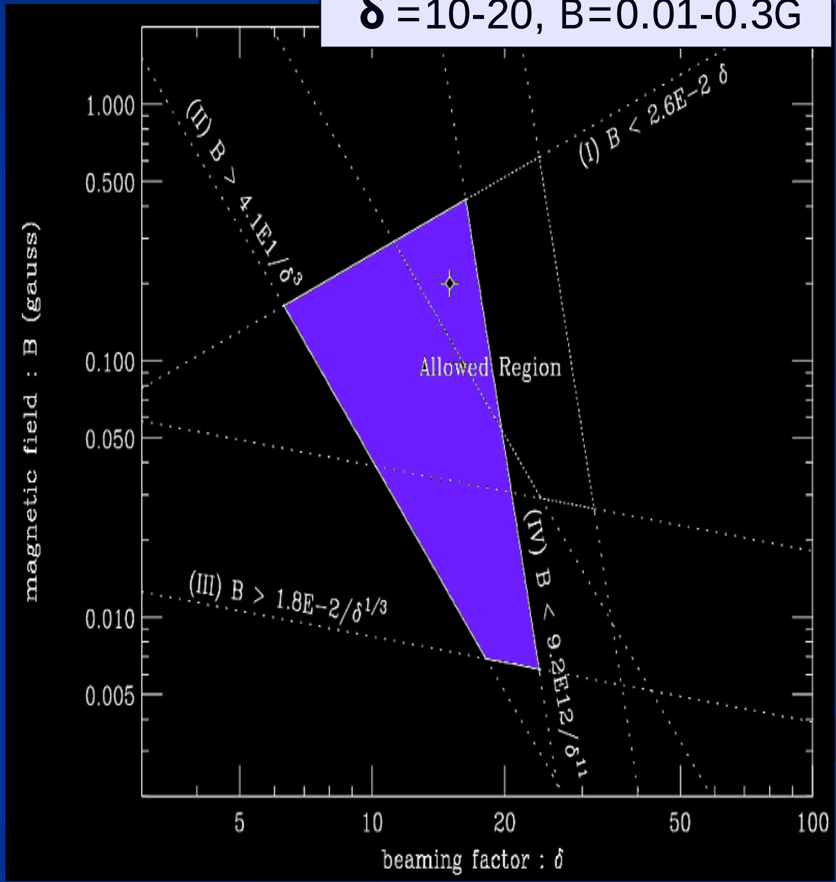
Takahashi et al. ApJ 542, 2000

Synchrotron Self-Compton model (2)

One-zone SSC model

δ =10-20, B=0.01-0.3G

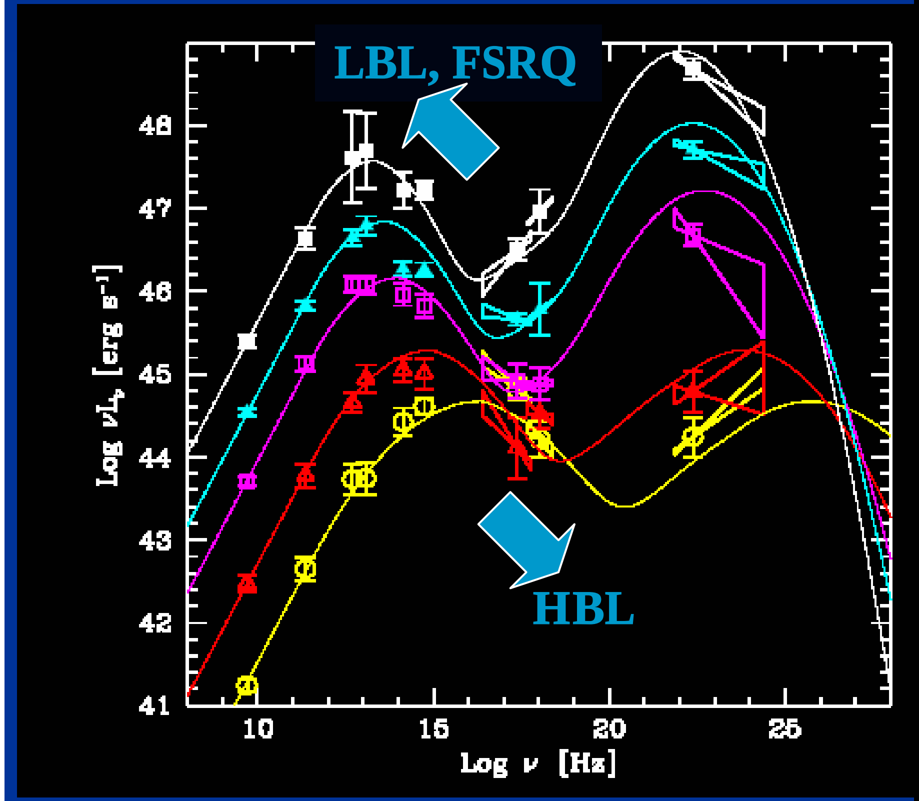


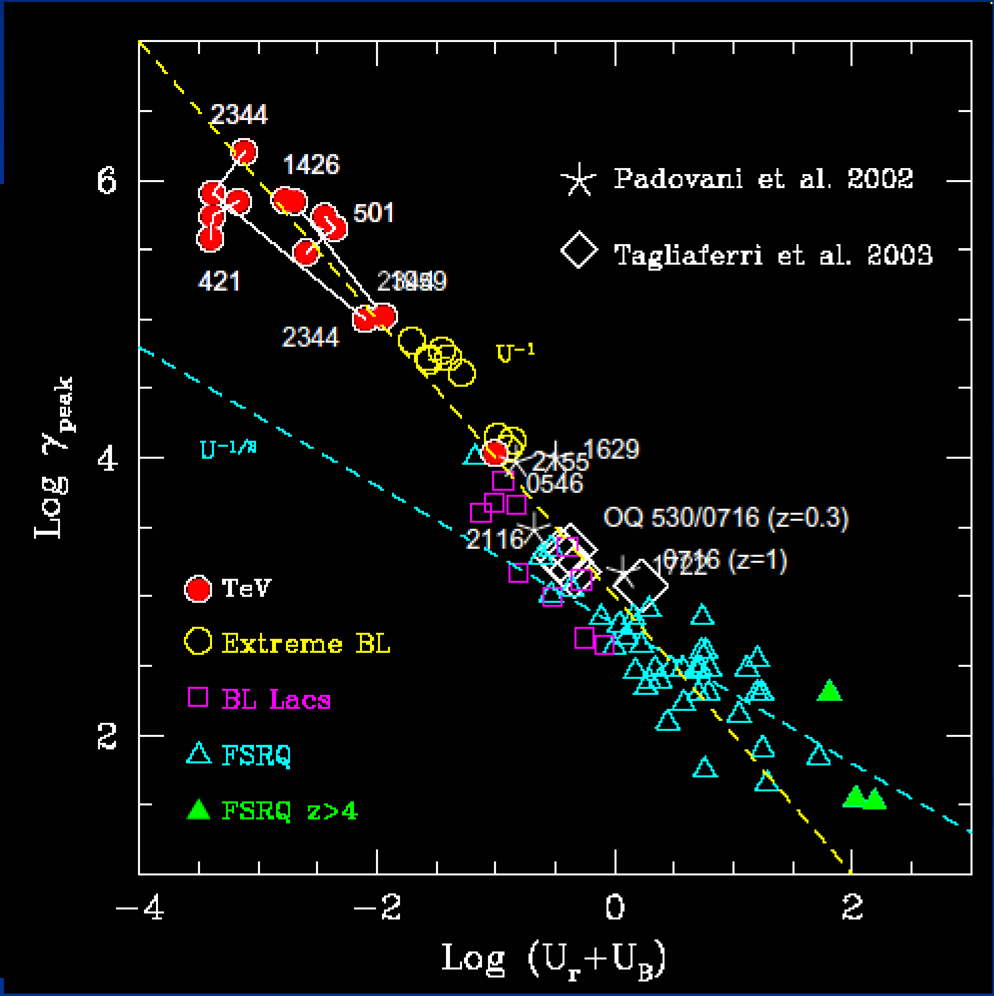


Kataoka et al. ApJ 514 (1999) 138

Blazar sequence & SSC model

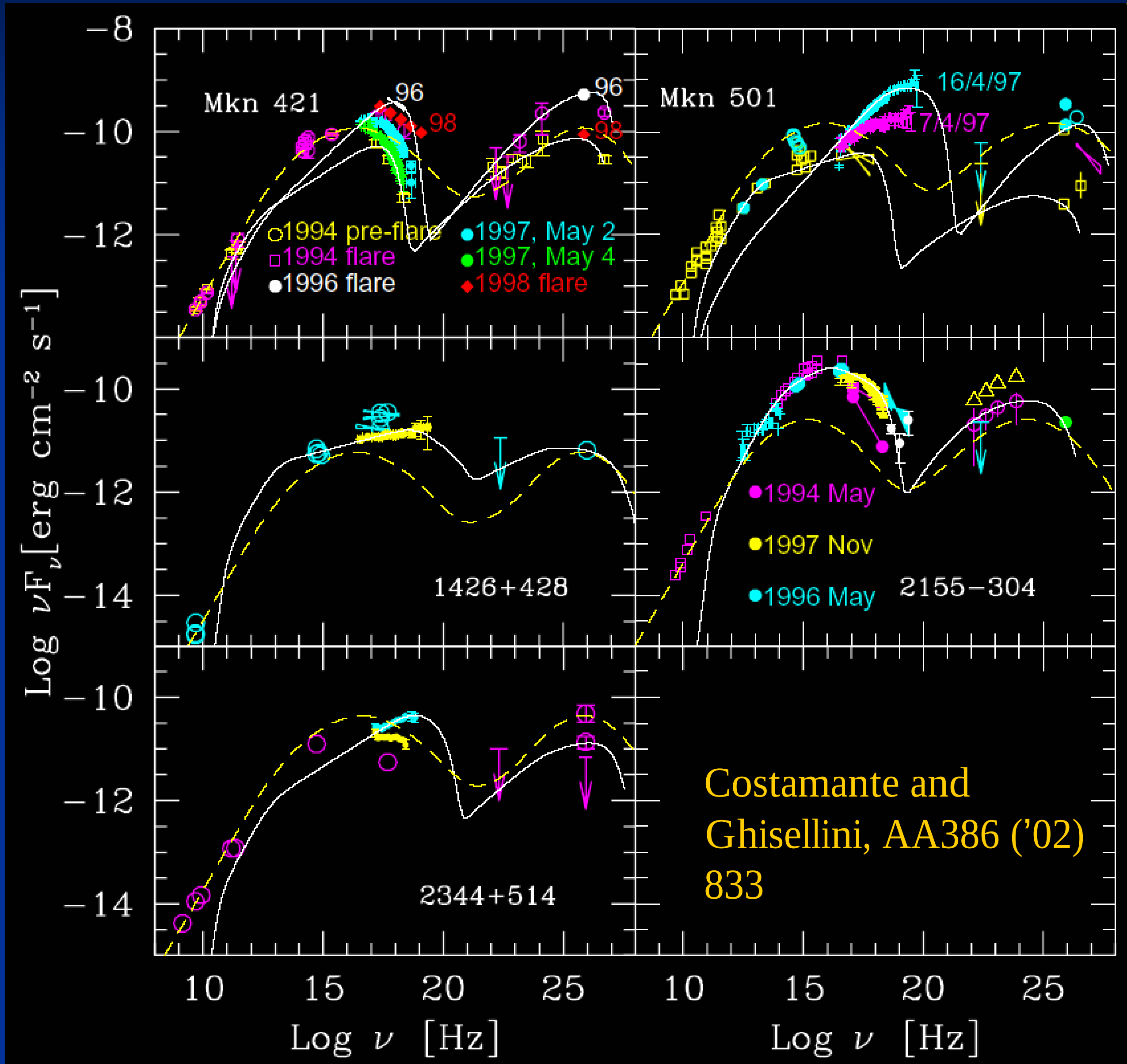
- $(\nu f_\nu)_{synch} \sim (\nu f_\nu)_{IC}$





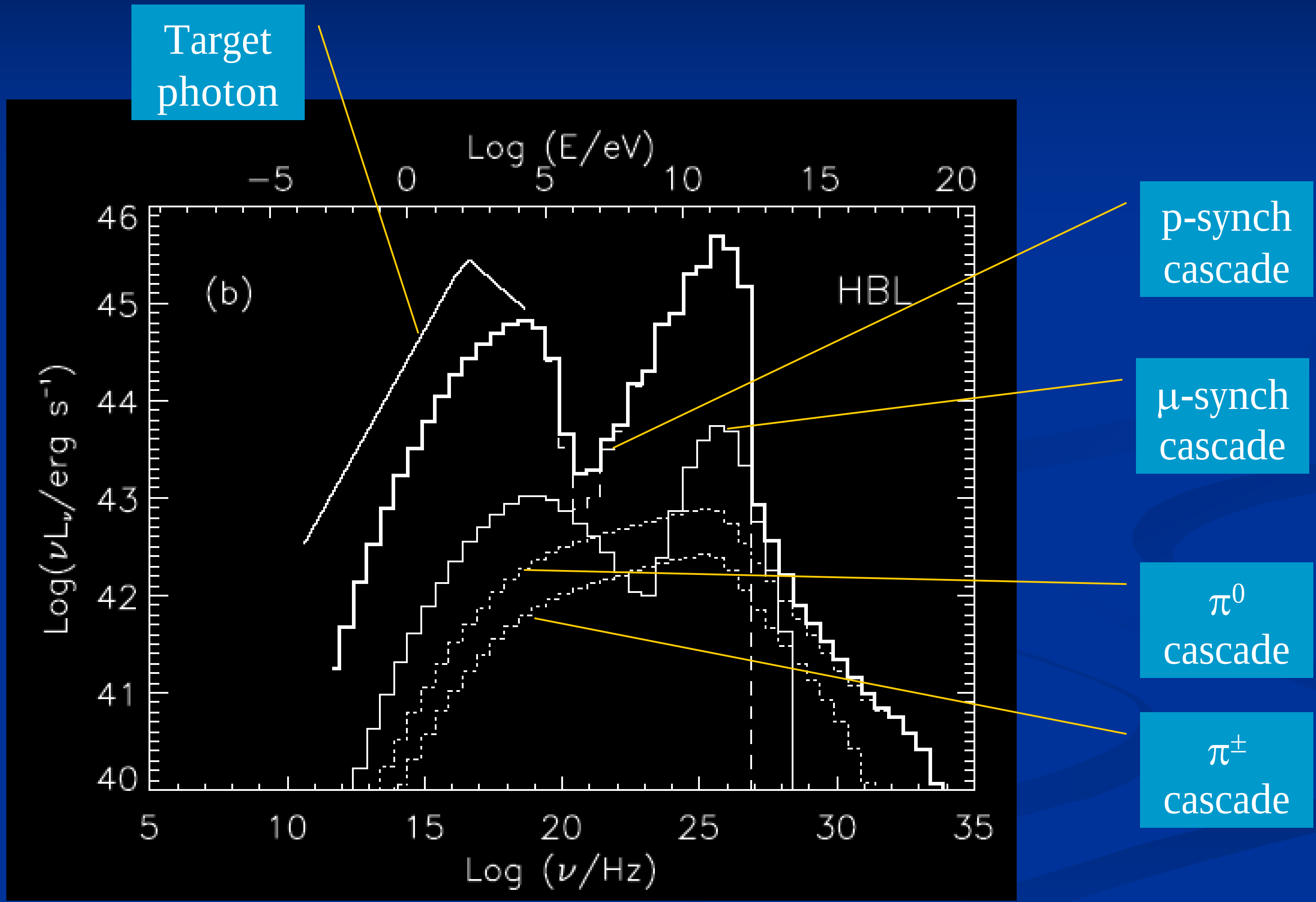
Ghisellini, astro-ph/0308526

SED of TeV blazars



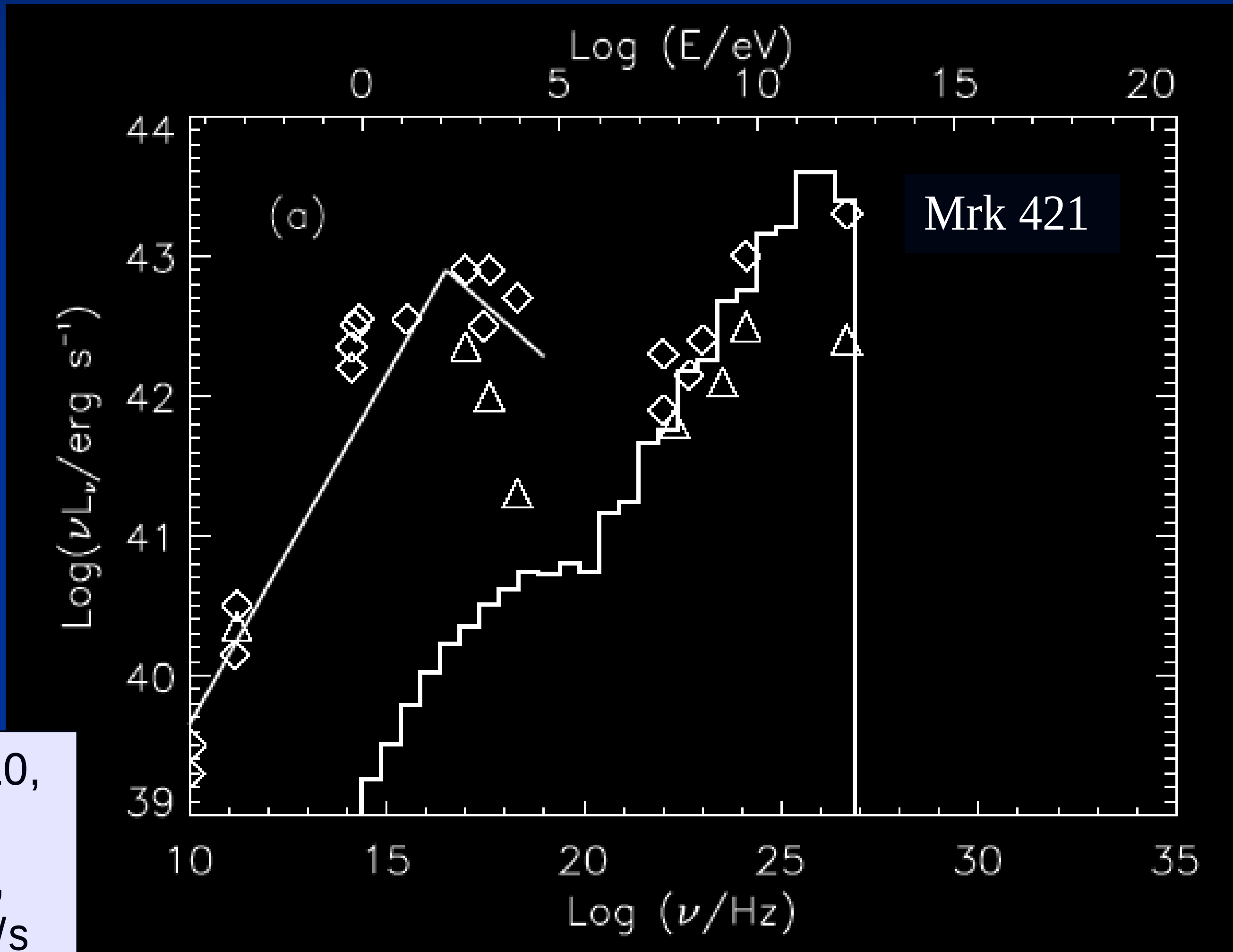
Costamante and Ghisellini, AA386 ('02) 833

Synchrotron proton blazar model (1)



Muecke et al. APh 18, 2003

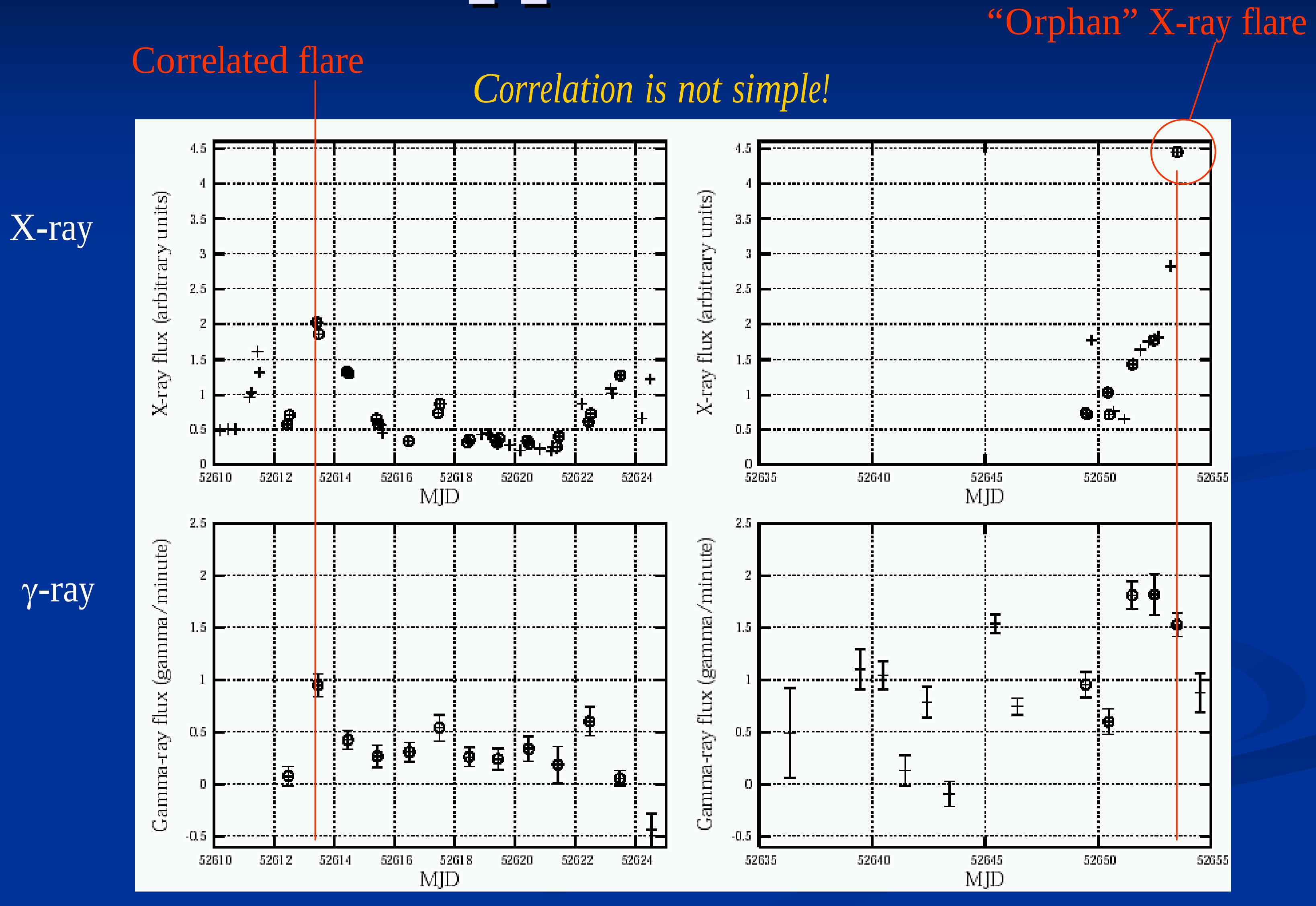
Synchrotron proton blazar model (2)



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

Muecke et al. APh 18, 2003

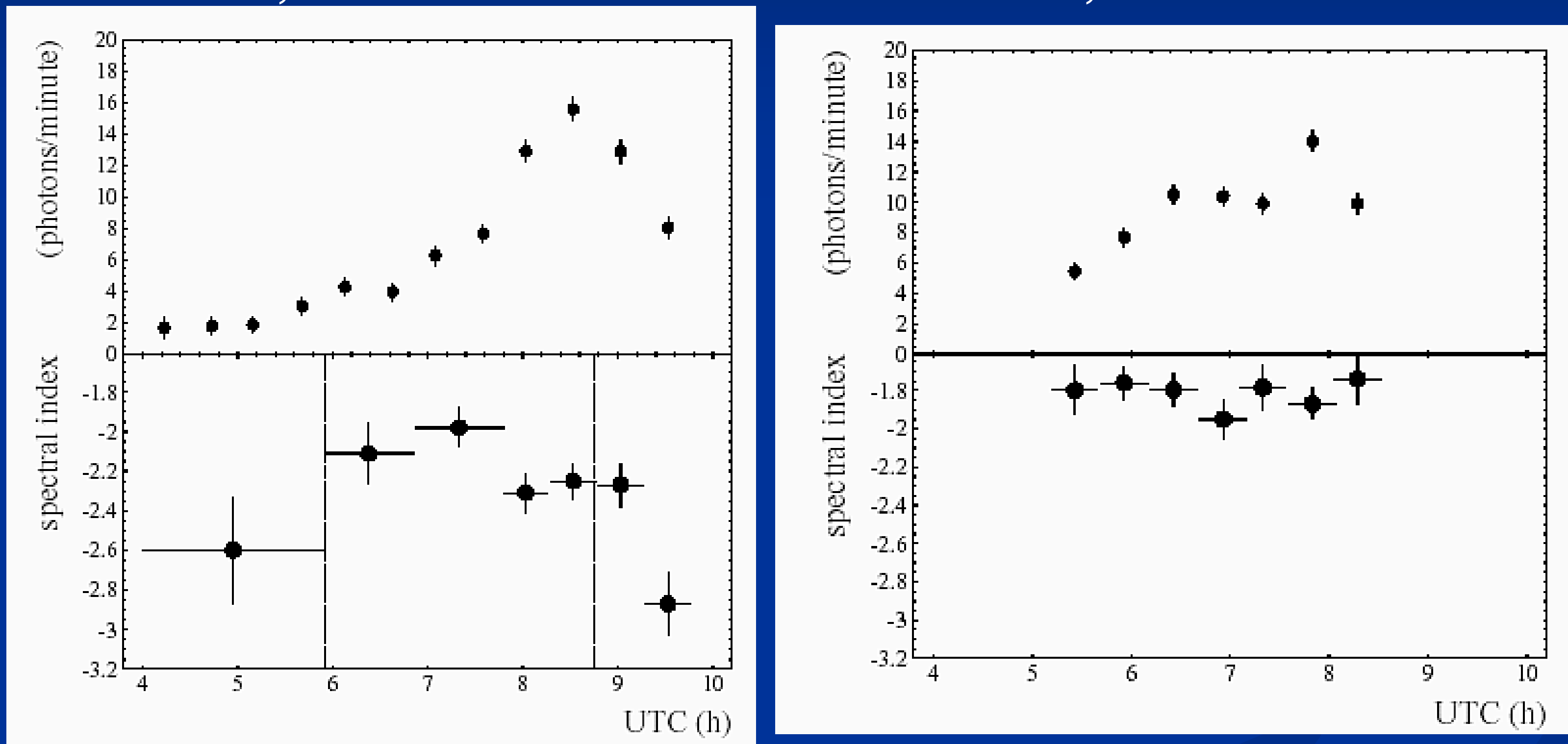
Mrk421: Whipple Flare Dec02-Jan03



Rebillot et al. 28th ICRC (2003)

Mrk421: Whipple Hourly variability

Mar 19, 2001 Mar 25, 2001

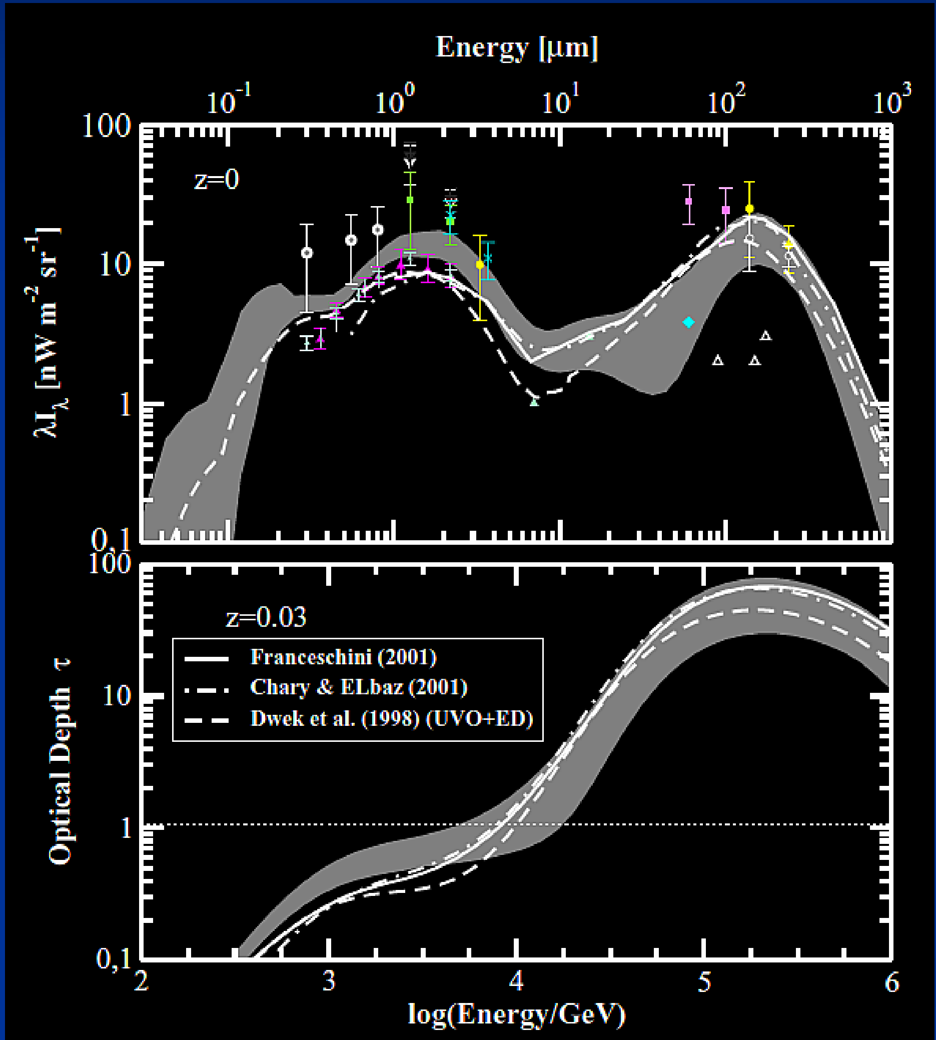


Harder for stronger ↔ Constant slope

Why this difference?

Krennrich et al., 28th ICRC (2003)

TeV gamma-ray absorption on EBL (1)



Kneiske et al., AA 413 (2004) 807

EBL (Extragalactic Background Light)

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

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

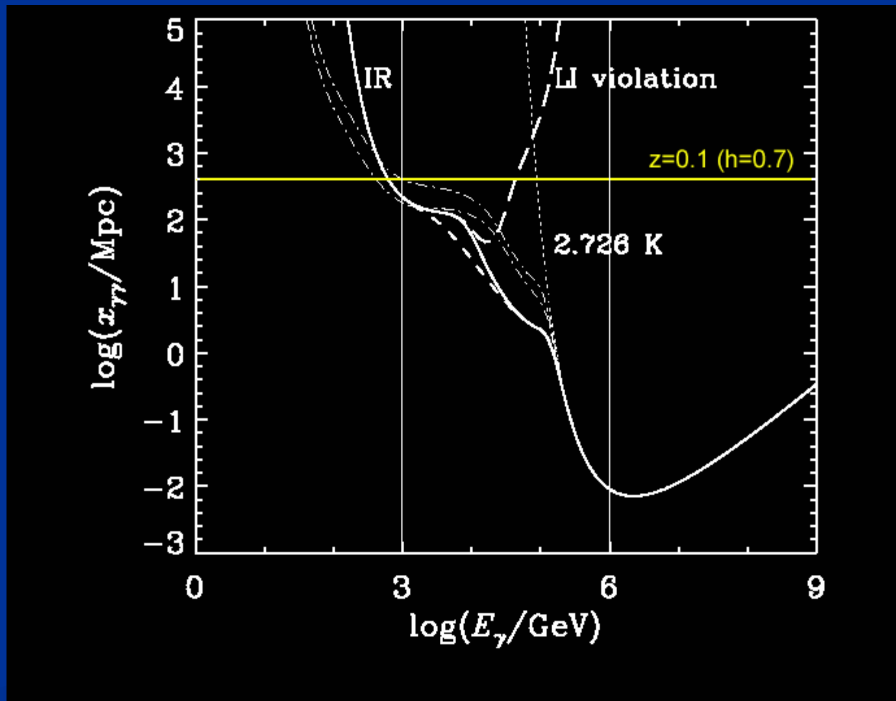


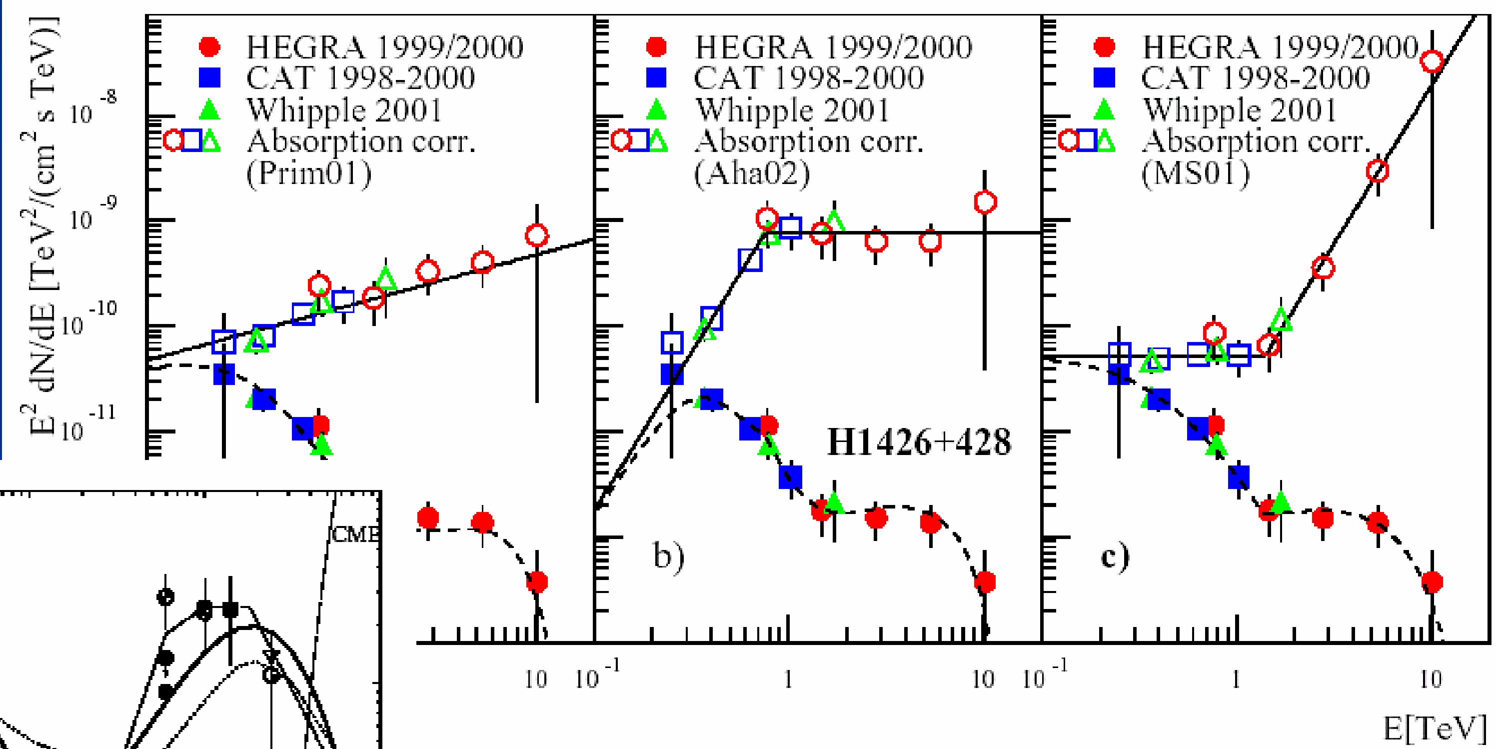
Figure 2: Mean free path for photon-photon pair production in the infrared–microwave background radiation. The curves correspond to those in Fig. 1 except that the effect of Lorentz Invariance violation discussed in Section 4 is shown by the long dashed curve.

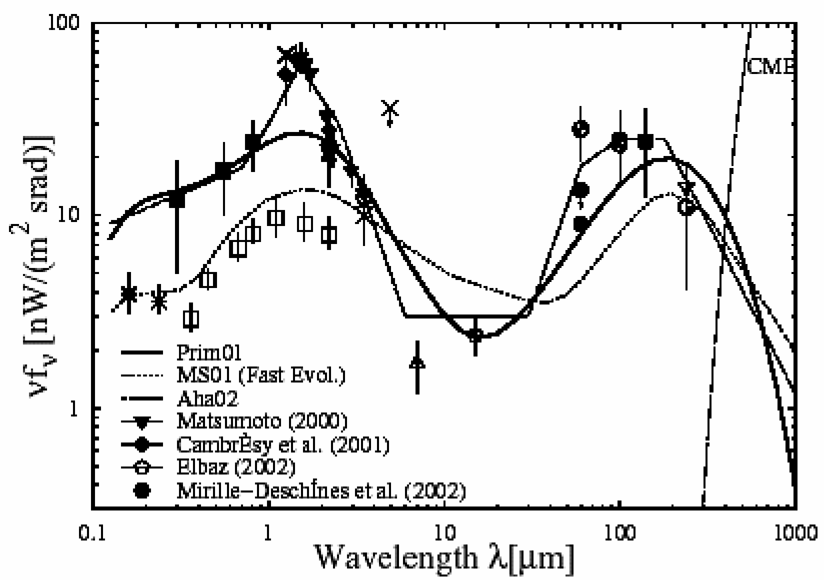
Protheroe & Meyer, PL B493 (2000) 1

TeV gamma-ray absorption on EBL (2)

- H1426+428: HEGRA CT system

z=0.129

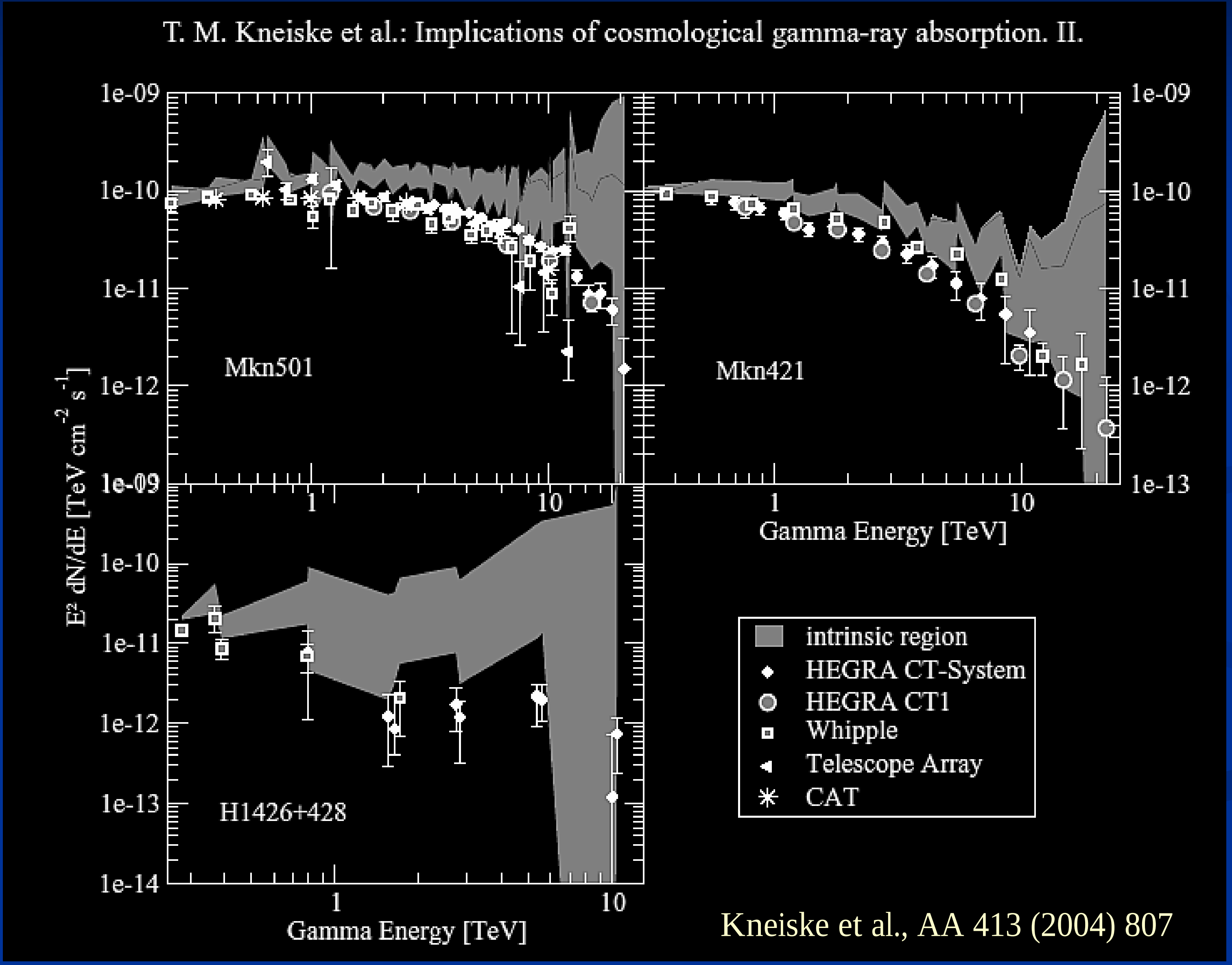




EBL (Extragalactic Background Light) ⟺ Intrinsic spectrum

Horns et al., 28th ICRC (2003)

TeV gamma-ray absorption on EBL (3)

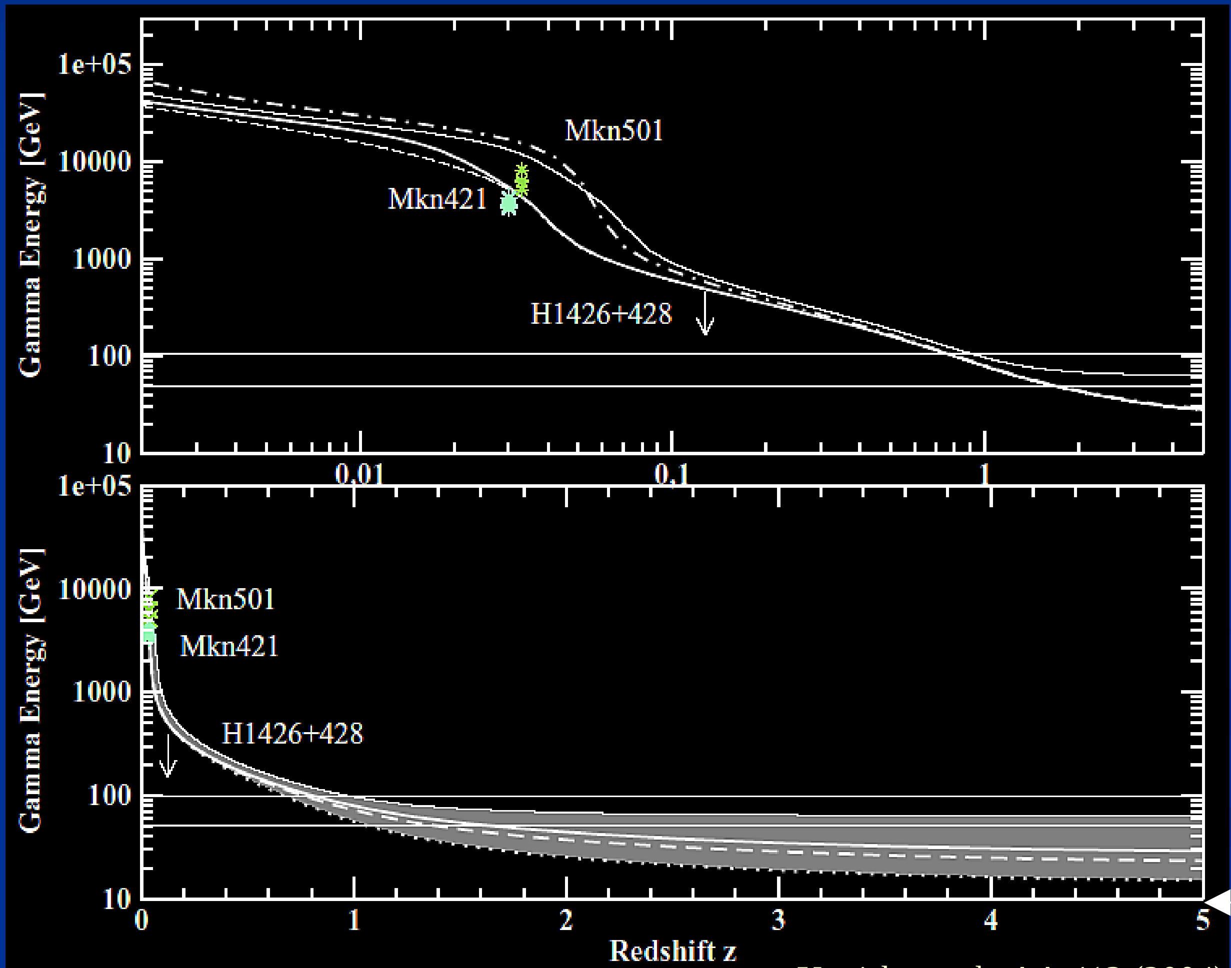


Kneiske et al., AA 413 (2004) 807

Fazio-Stecker relation

Fazio and Stecker, Nature 226 (1970) 135

- Gamma-ray horizon (cutoff) due to the metagalactic radiation field



Kneiske et al., AA 413 (2004) 807

10GeV photons can probe the whole Universe!

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

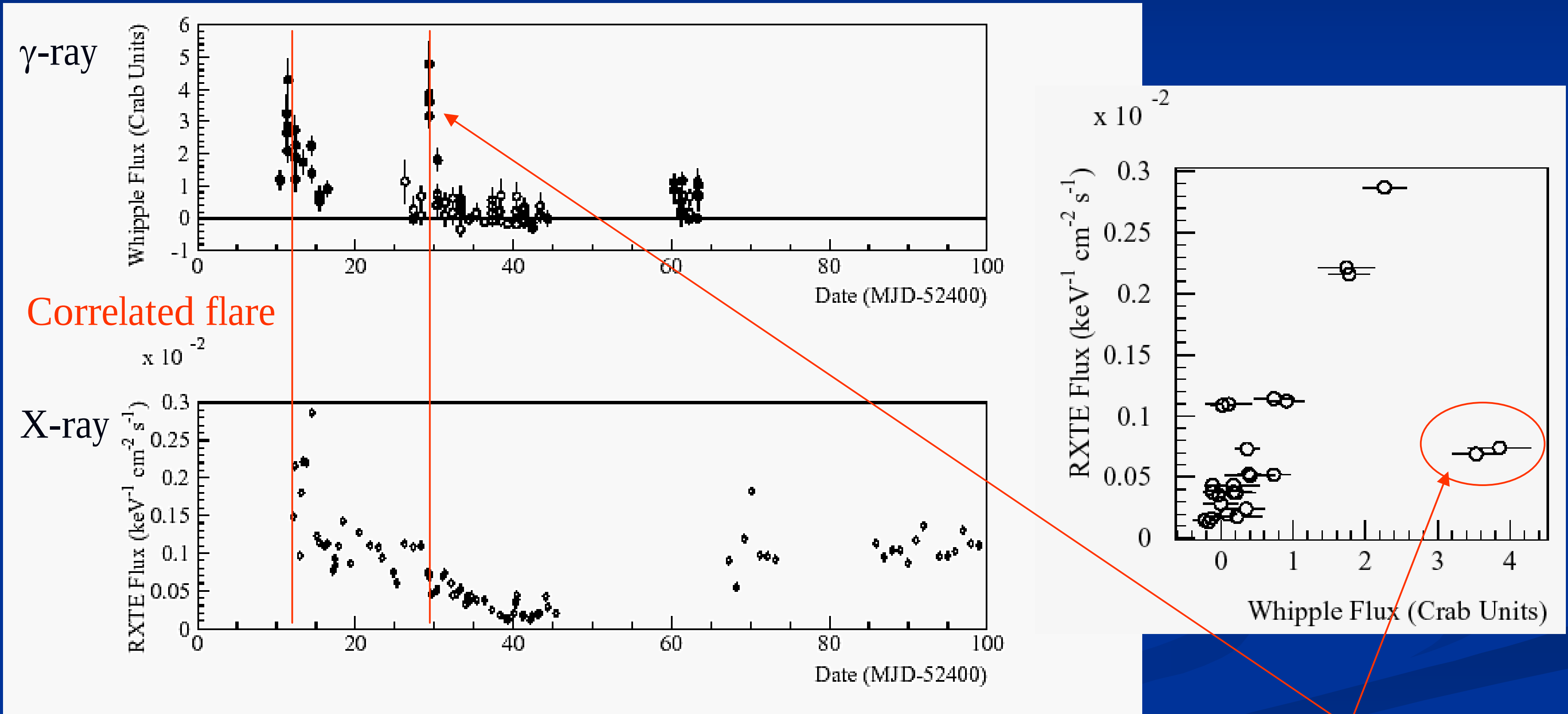


Fig. 1. The Whipple (top) and RXTE (bottom) light curves for 1ES1959+650 in May-July 2002. The filled Whipple points correspond to $> 3\ \sigma$ detections. The RXTE data are from [6].

Holder et al. 28th ICRC (2003)

PKS 2155-304

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

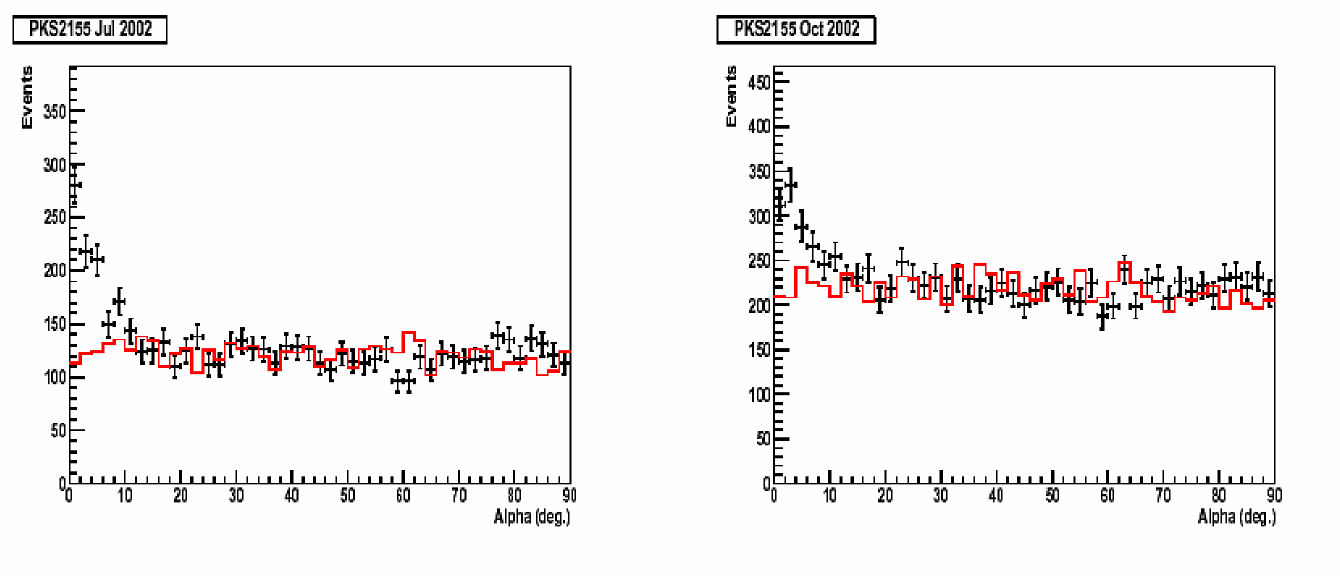
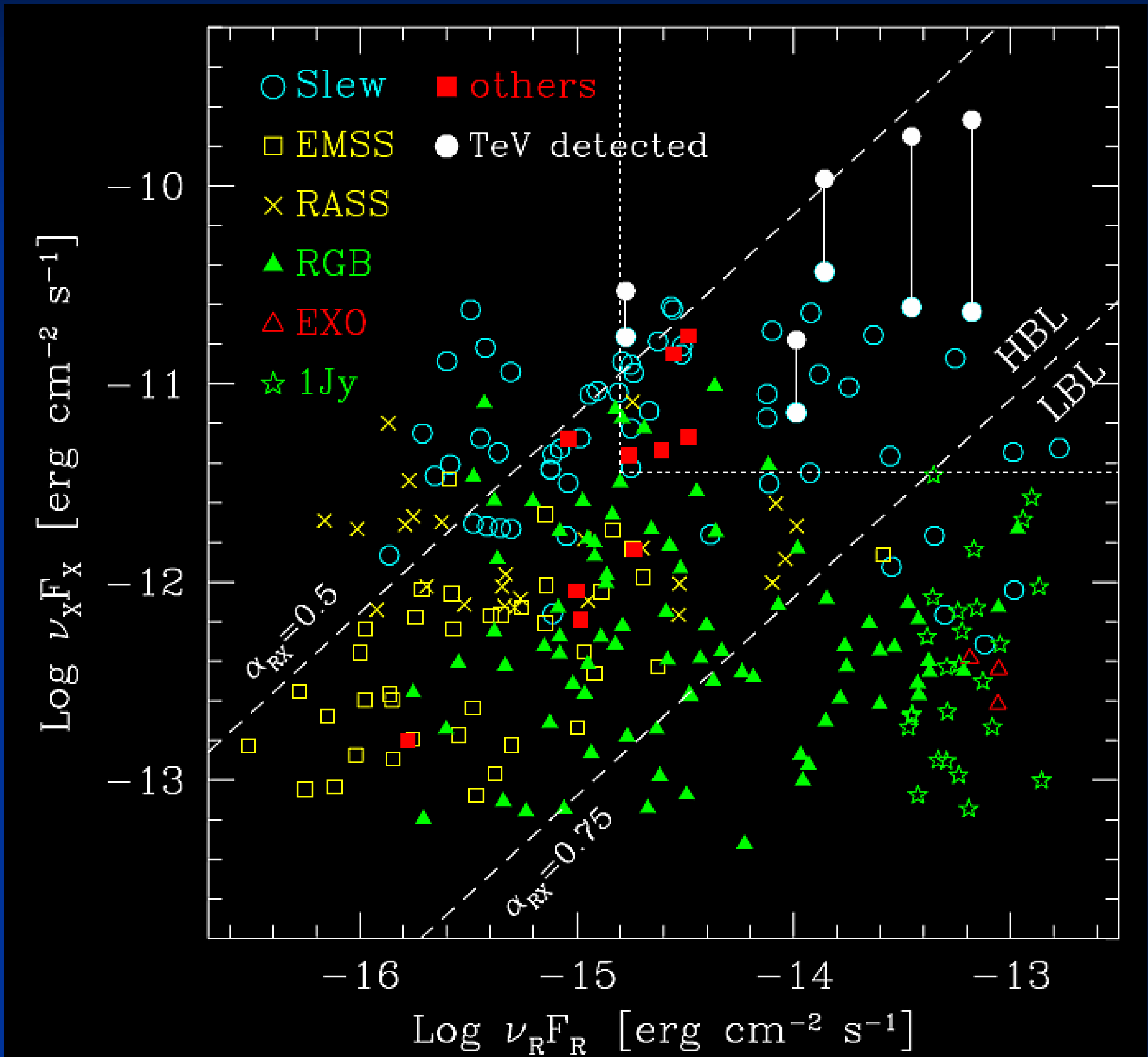


Fig. 1. The pointing angle α-plot of PKS 2155-304 observations for July (left panel) and October (right panel) 2002. The OFF-source distributions have been normalised to the control region between 30° and 90°.

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

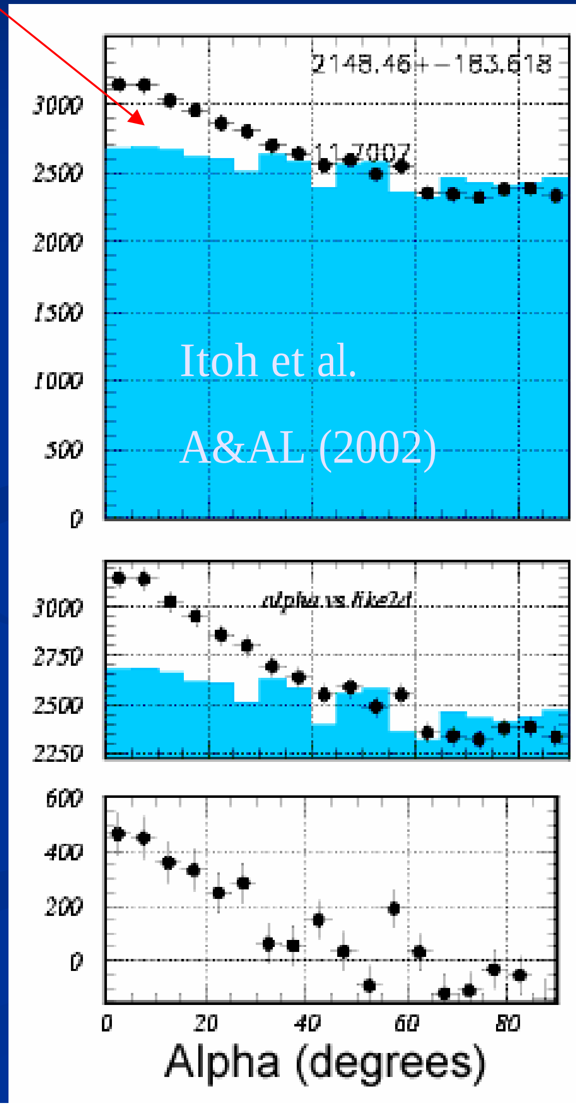
New entry: NGC253 (1)

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

Optical image

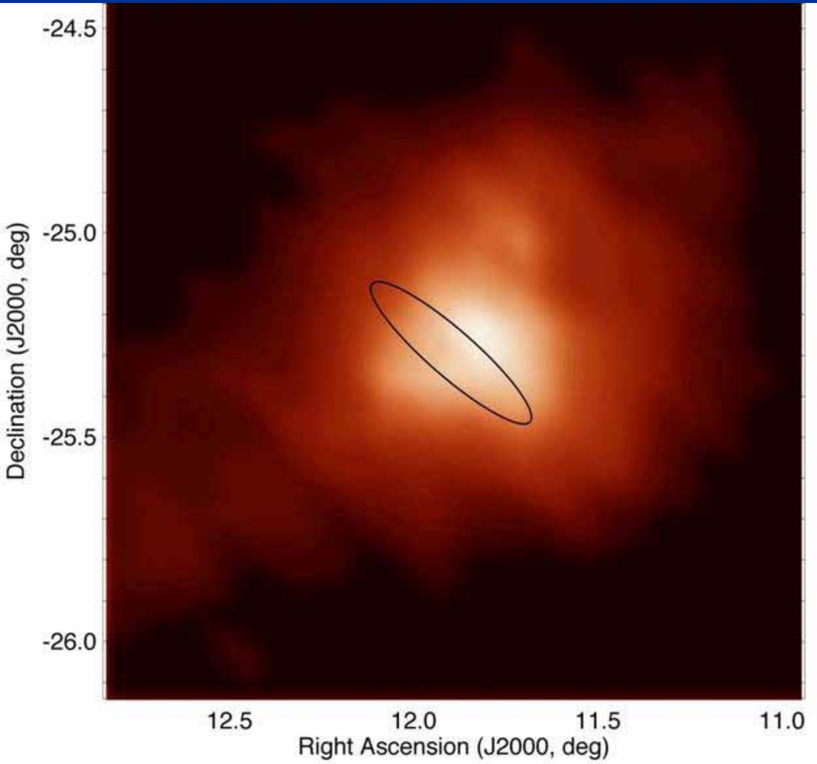
	SB region	Milky Way
SFR	10 -10^2	~3 M_o yr^{-1}
Proton density	10^2-10^5	~1 cm^{-3}
Age of SB region	10^7-10^8	~10^{10} yr^{-1}
Size of SB region	0.1-1.0	~50 kpc
B field	10-10^2	~3 μG

Gamma-ray signal = (ON) – (OFF)

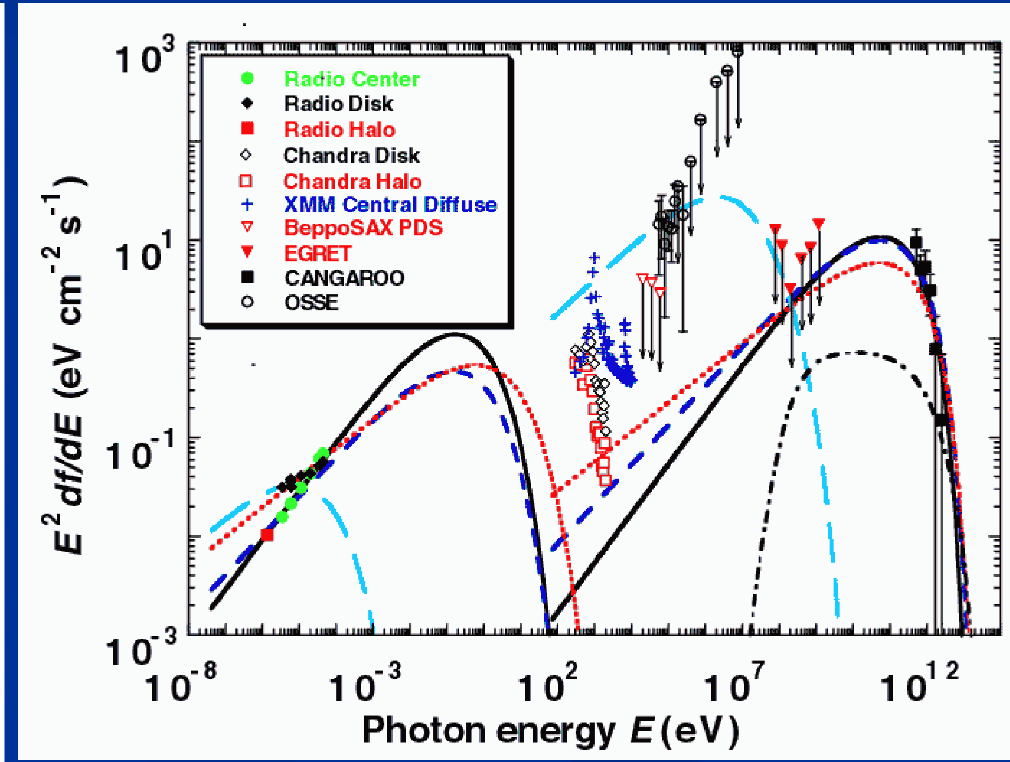


New entry: NGC253 (2)

- Extended halo?



Significance map by CANGAROO



Itoh et al. ApJ (2003)

Starburst galaxies observed by Whipple

Table 1. Observed sources.

Source	Distance (Mpc)	P density (cm^3)	B field (μG)	Size of SB (kpc)	Age of SB region (10^6yrs)
M82	$\sim$3.5	$\sim 10^4$	$\sim$25	$\sim$0.1	$\sim$30
M81	$\sim$3.5	$\sim 10^2$	$\sim$37	$\sim$5	$\sim$30
IC342	$\sim$3.0	$\sim 10^4$	$\sim$75	$\sim$1	$\sim$10
NGC3079	$\sim$16	$\sim 10^3$	$\sim 10^5$	$\sim$1	$\sim$30
MilkyWay	-	$\sim$1	$\sim$3	-	$\sim 10^4$

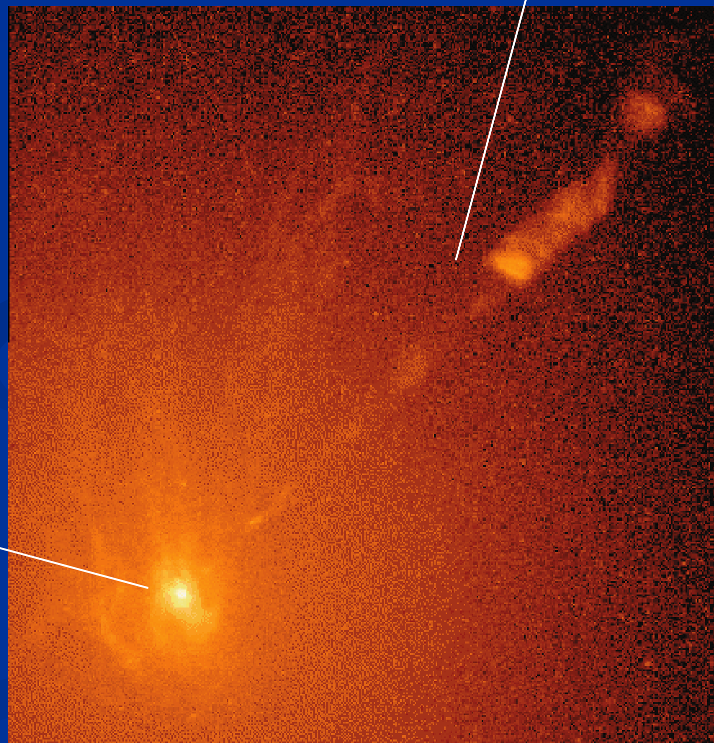
Table 2. A summary of the observations. The flux upper limits are preliminary and correspond to 650 GeV photons, which provide a maximum detection rate of the telescope for observations at 35 degree zenith angle.

Source	Exposure (sec)	Typical zenith (degree)	2 σ upper limit (photon cm^{-2} s^{-1})
M82	29753	38	8.84×10^{-12}
M81	36507	38	7.05×10^{-12}
IC342	22604	37	7.17×10^{-12}
NGC3079	36468	26	1.58×10^{-11}

Nagai et al., ICRC2003

New entry: M87 (1)

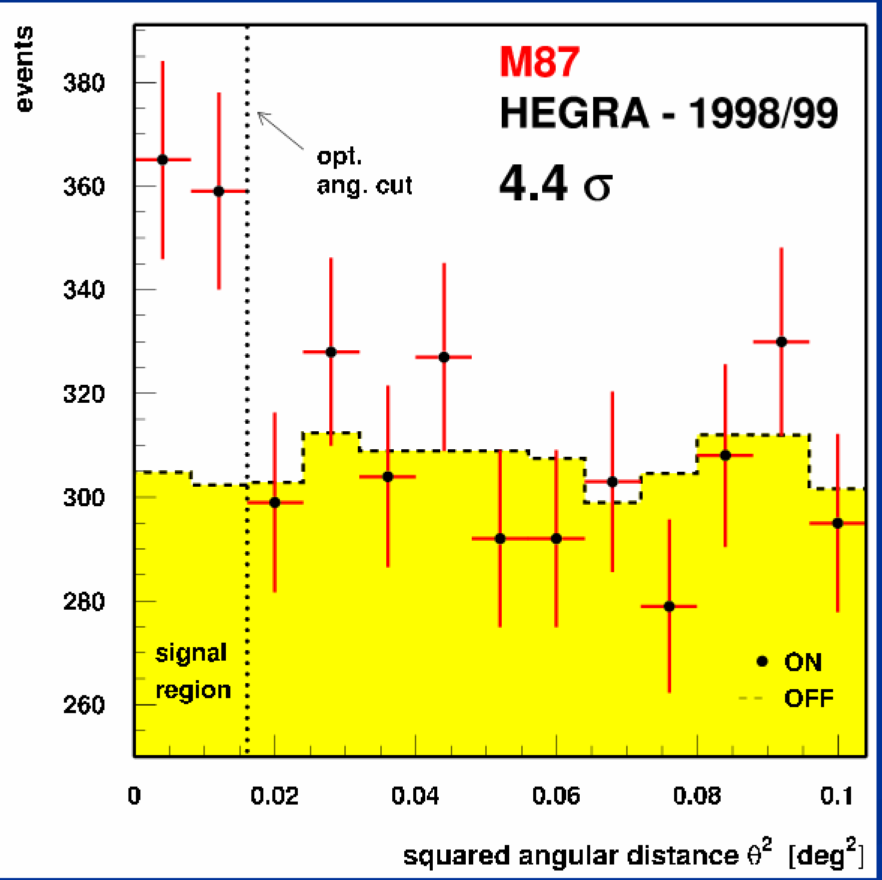
- M87 (Vir A, Giant radio galaxy, z=0.00436 or 16Mpc)
  - HEGRA CT system detection
  - Whipple upper limit

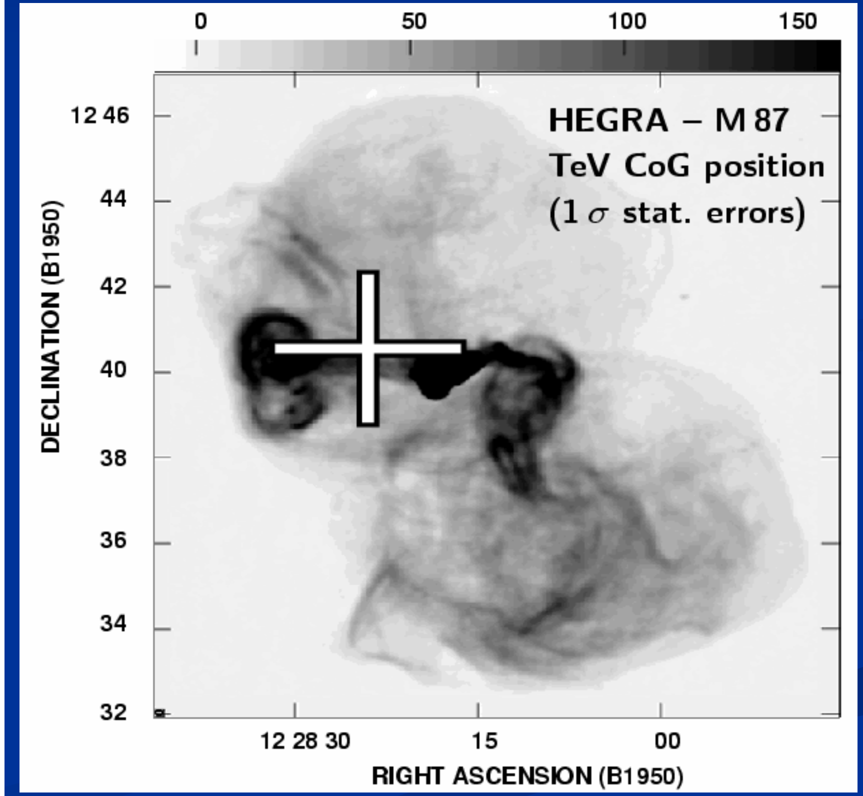


Optical image

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

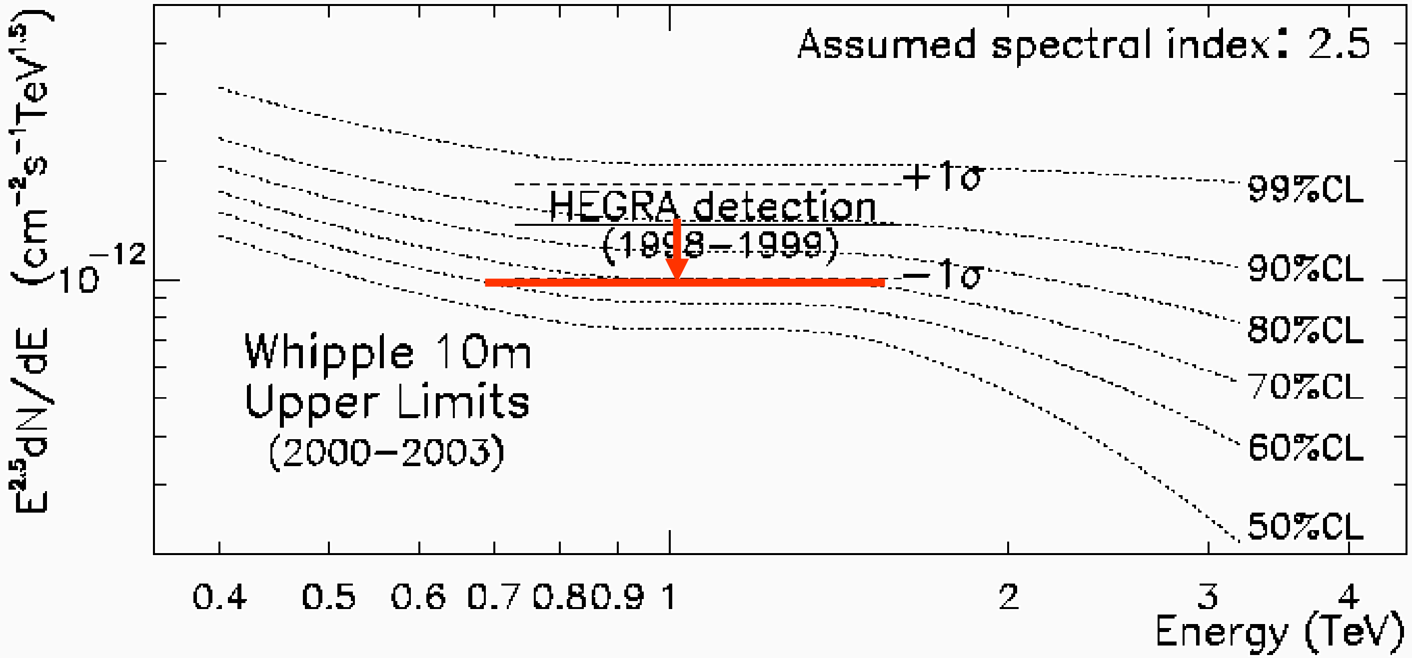
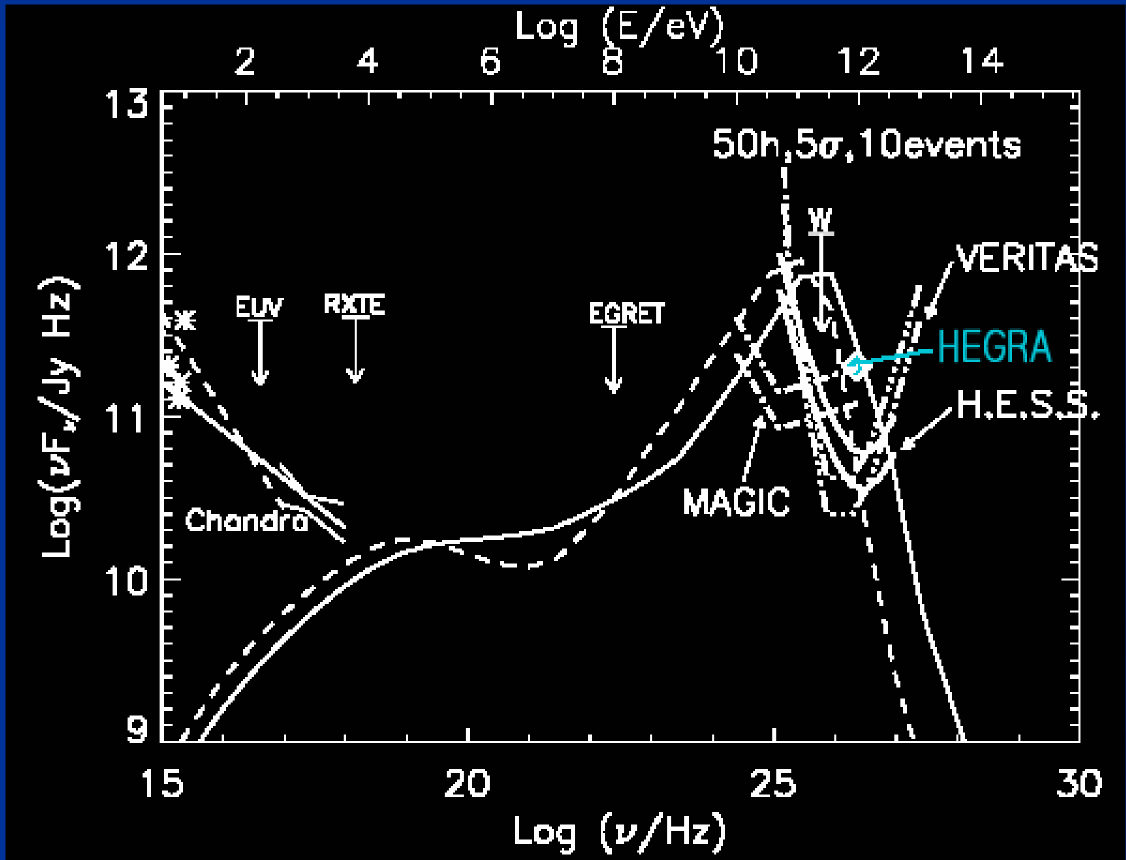


Fig. 1. The Whipple 10-m upper limit on the differential flux from M87 compared to the detection by HEGRA under the assumption that the spectrum ca be described by a power law of index 2.5.

LeBohec et al., 28th ICRC (2003)

M87 models

- Inverse Compton by electrons $L_{synch} \sim 3 \times 10^{42} erg/s$
  - Bai & Lee, ApJ549('01); Stawarz, Sikora & Ostrowski, ApJ597('03)
- Misaligned 'synchrotron proton blazar' model



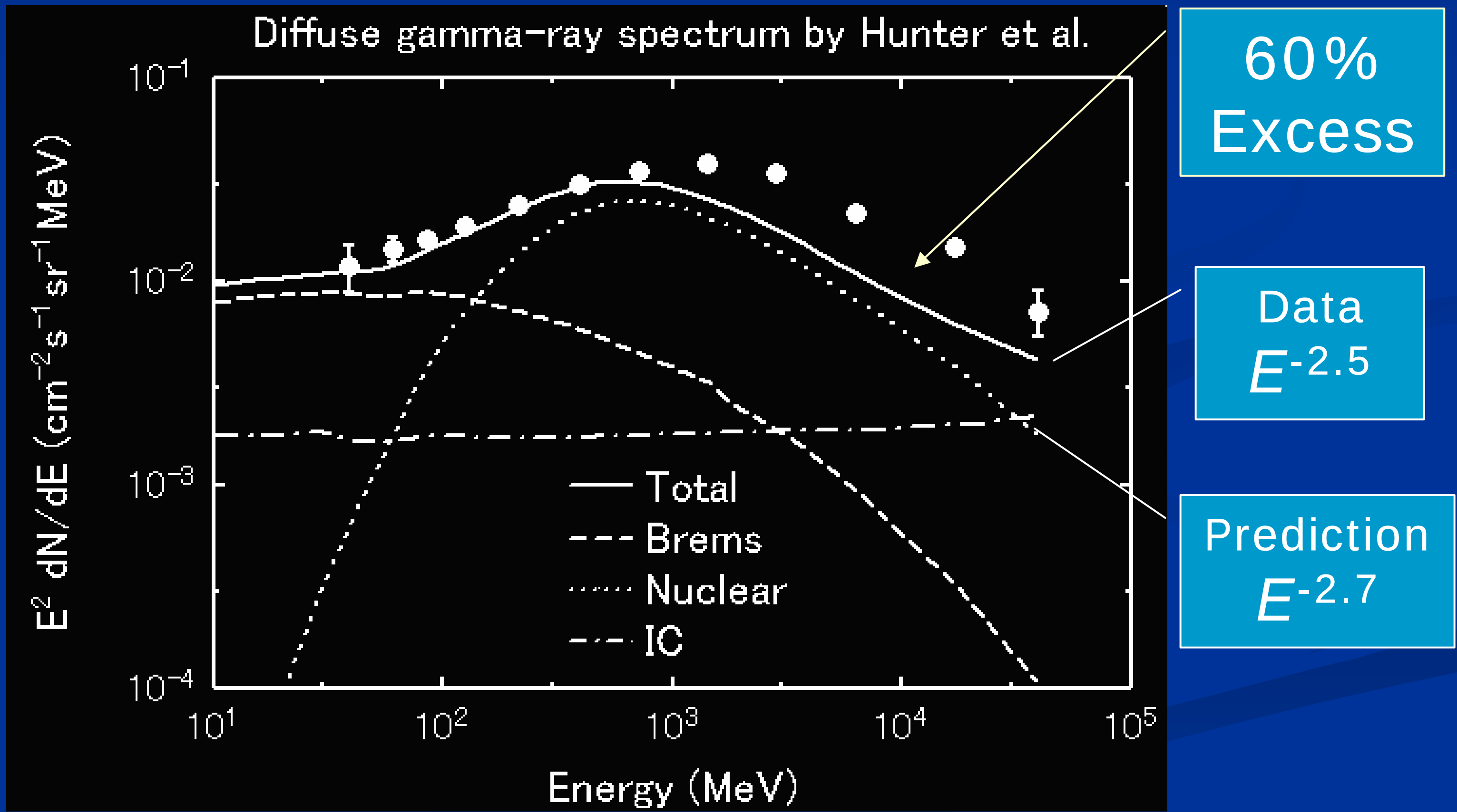
$L_{jet} \sim 3 \times 10^{43} erg/s$

$B \sim 30G$

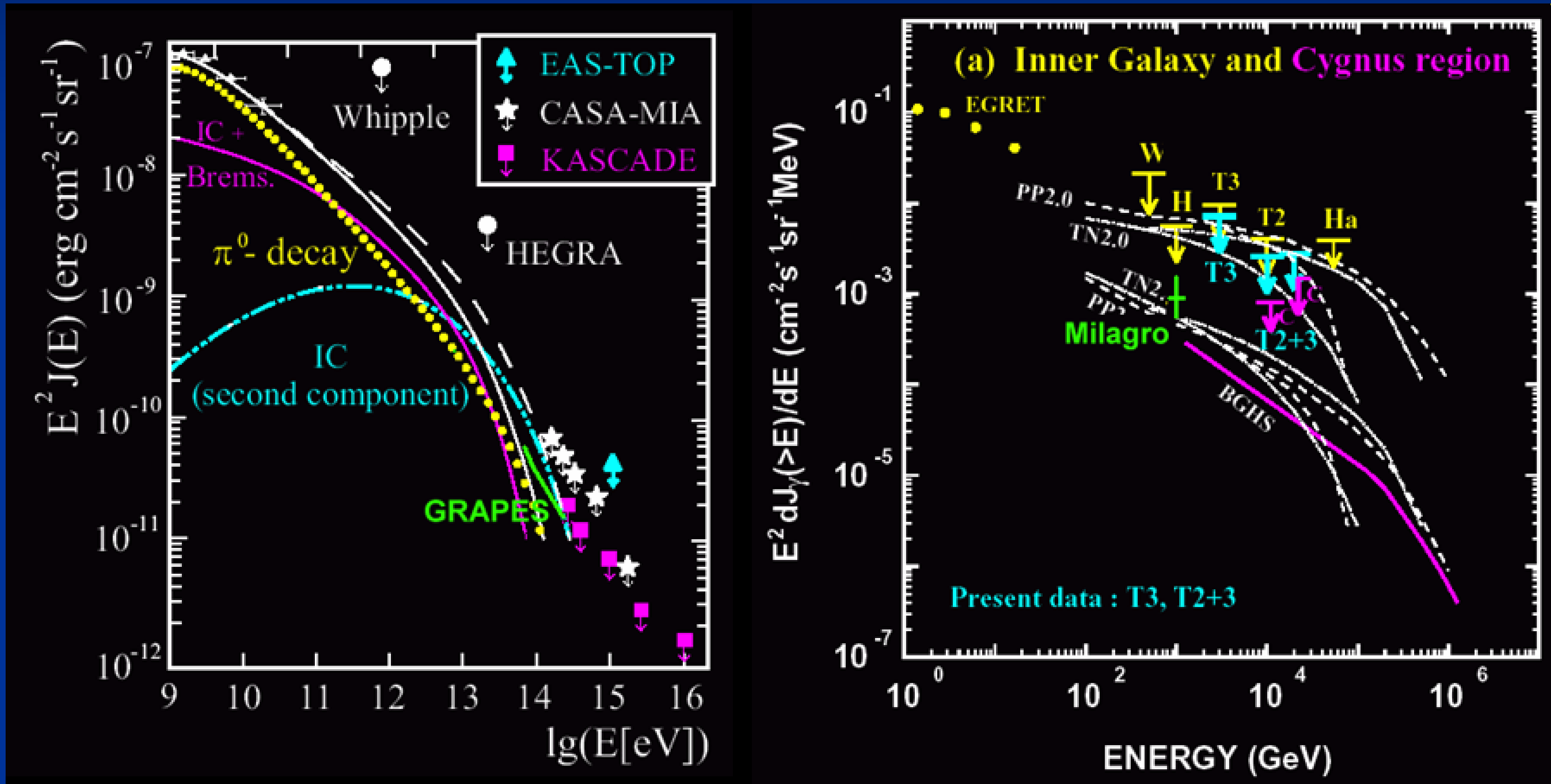
Reimer, Donea & Protheroe, APh 19 ('03) 559

Galactic diffuse gamma-rays (1)

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



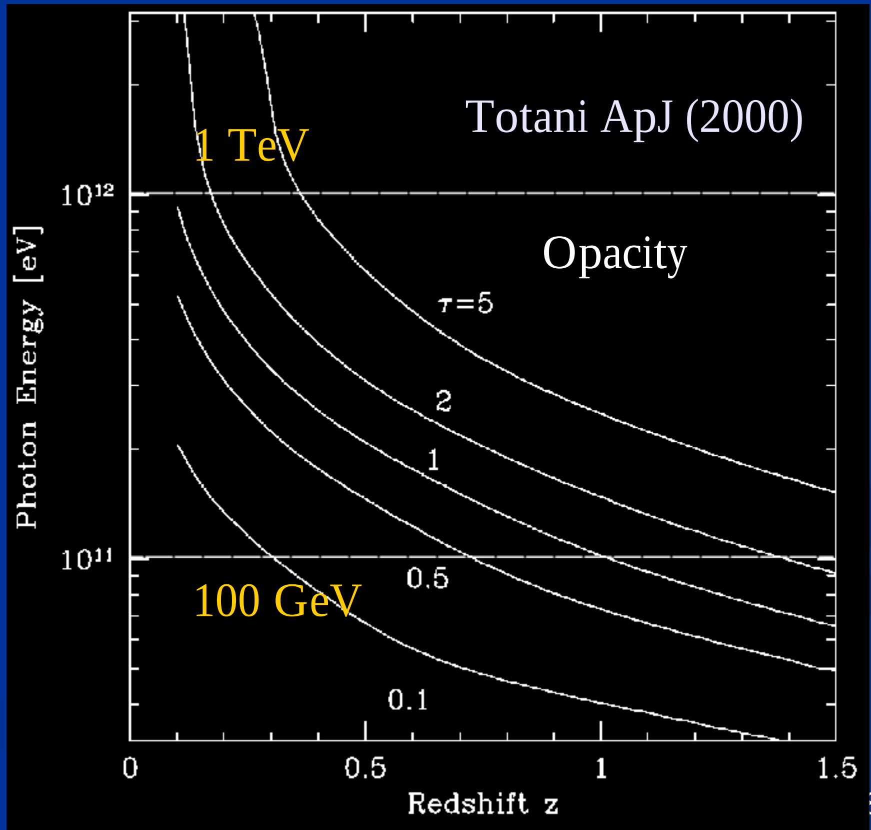
Galactic diffuse gamma-rays (2)

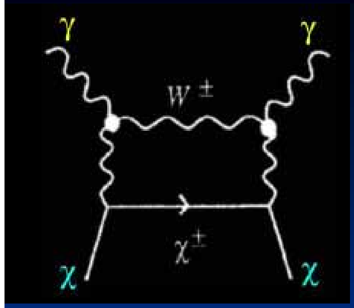


Summary by Mori, ICRC2003

Gamma Ray Bursts

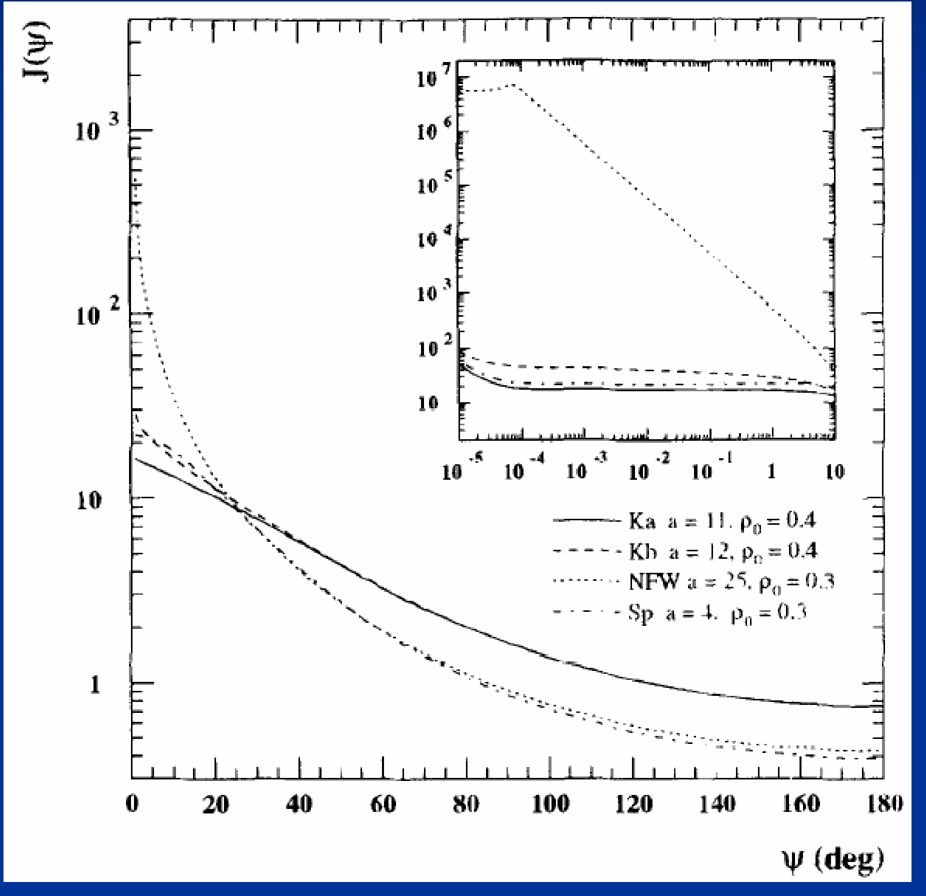
- Ground-based experiments?
  - TeV gamma-rays (afterglow)
    - MAGIC a few per year expected
  - Air shower rate
    - Tibet-III
  - Single particle rate
    - GRAND
    - ARGO-YBJ
    - Tibet-III
- Need fast and precise GRB alerts!

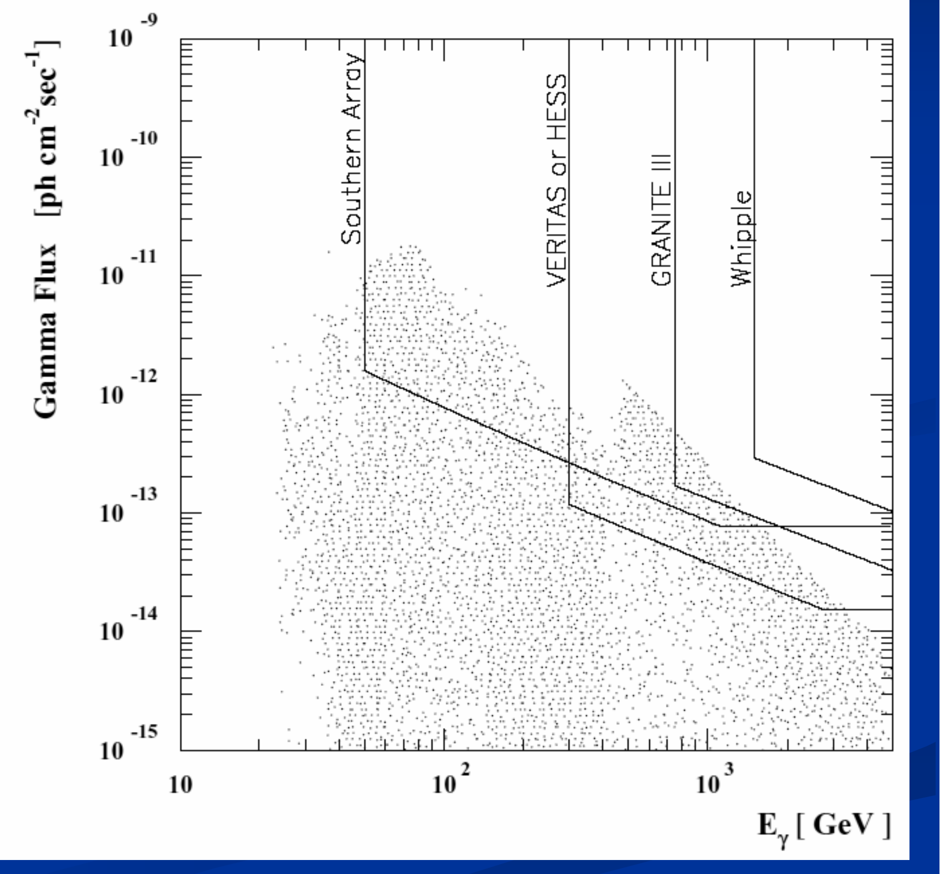




Dark matter annihilation at the Galactic Center

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





$$J(\Psi) = \frac{1}{R\rho_0^2}\int_{\mathrm{line-of-sight}} \rho^2(\ell)d\ell(\Psi)$$

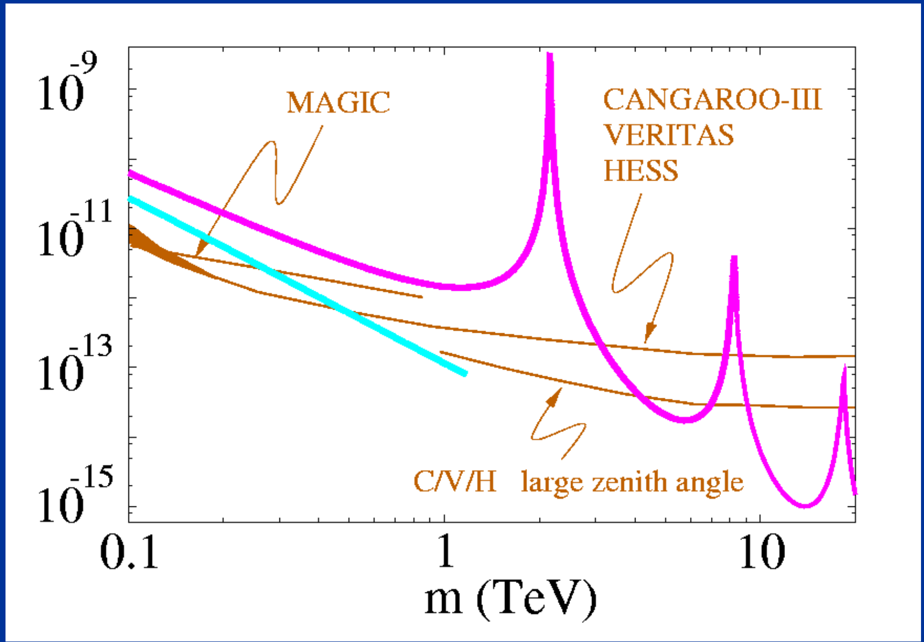
Bergstroem et al., APh 9 (1998) 137

Explosive dark matter annihilation

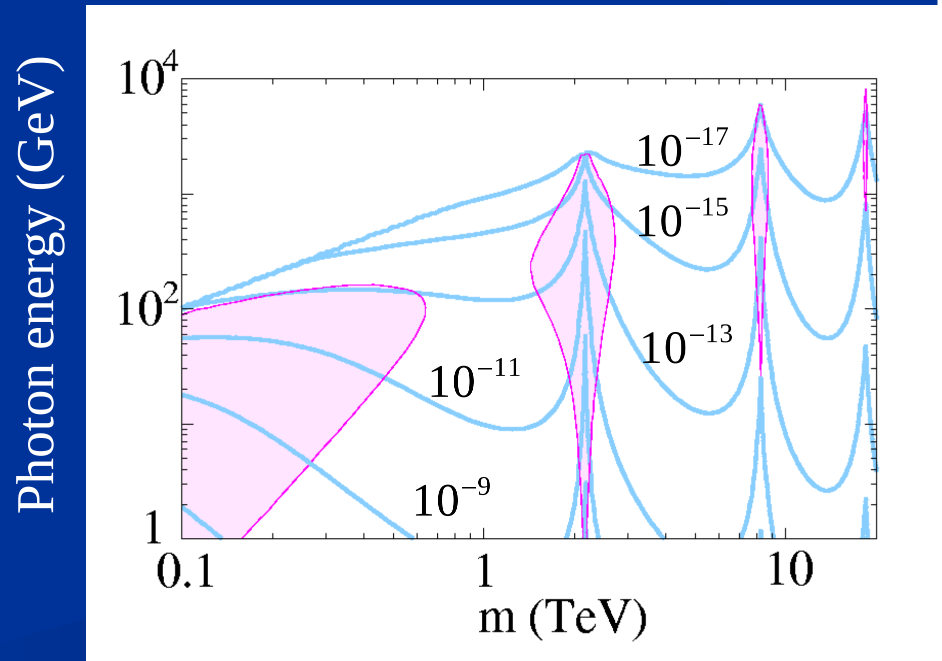
"Explosive annihilation" by non-perturvative effect

Line (Galactic center, J=500)

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

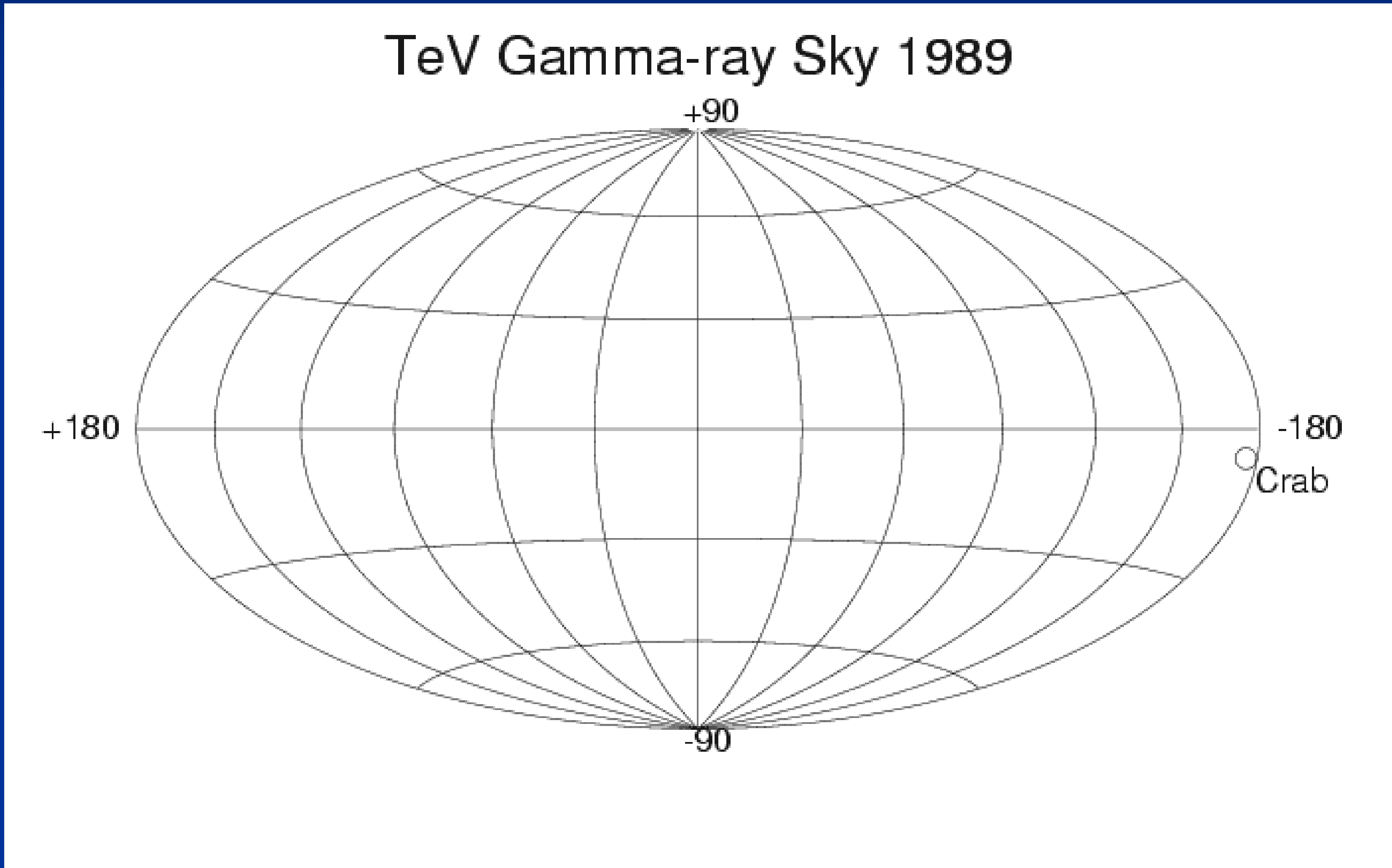


Continuum (Galactic center, J=500)



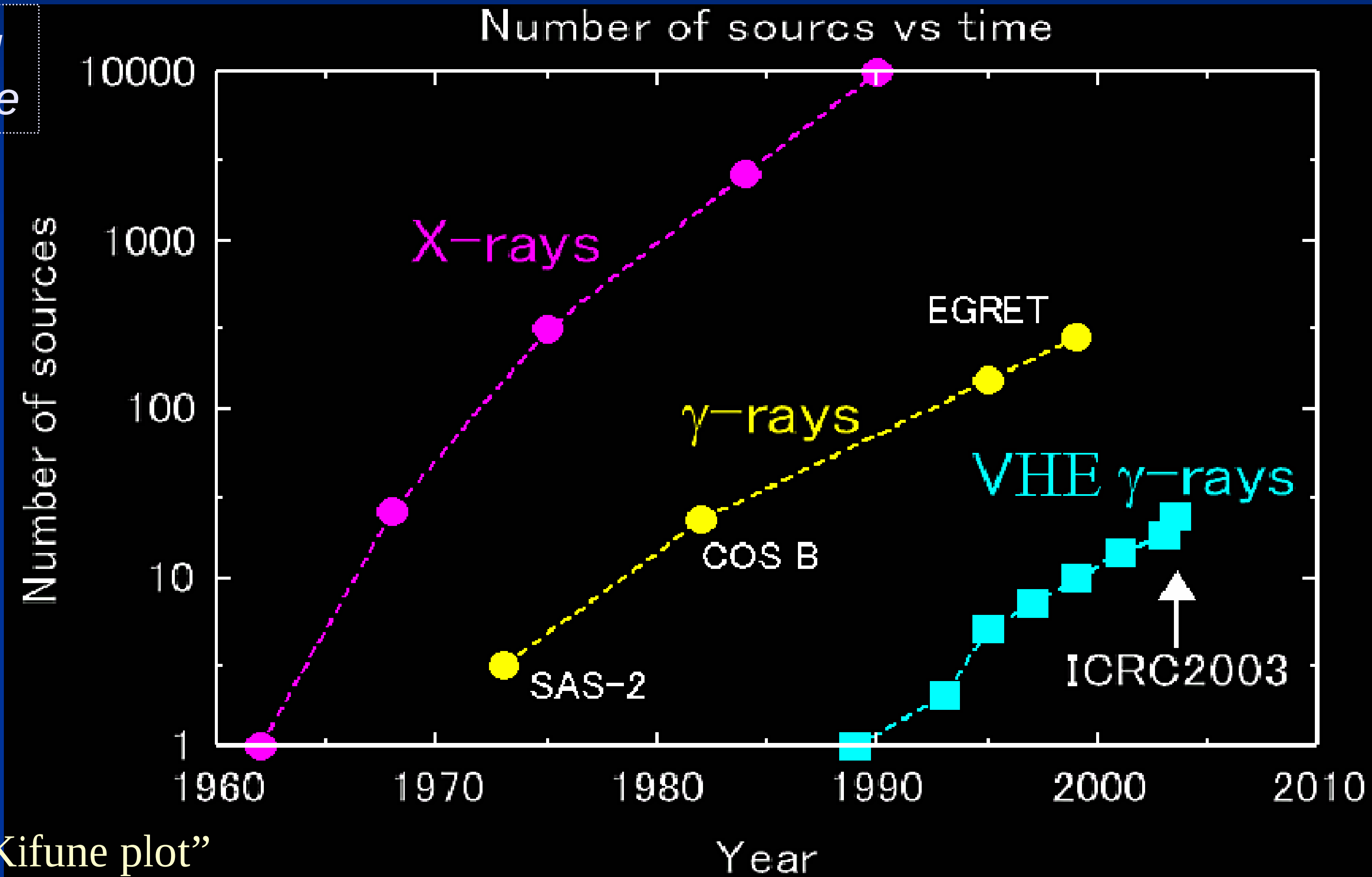
Hisano, Matsumoto, Nojiri PRL 92 (2004)

"Evolution" of the TeV gamma-ray sky



“Evolution” in number of objects

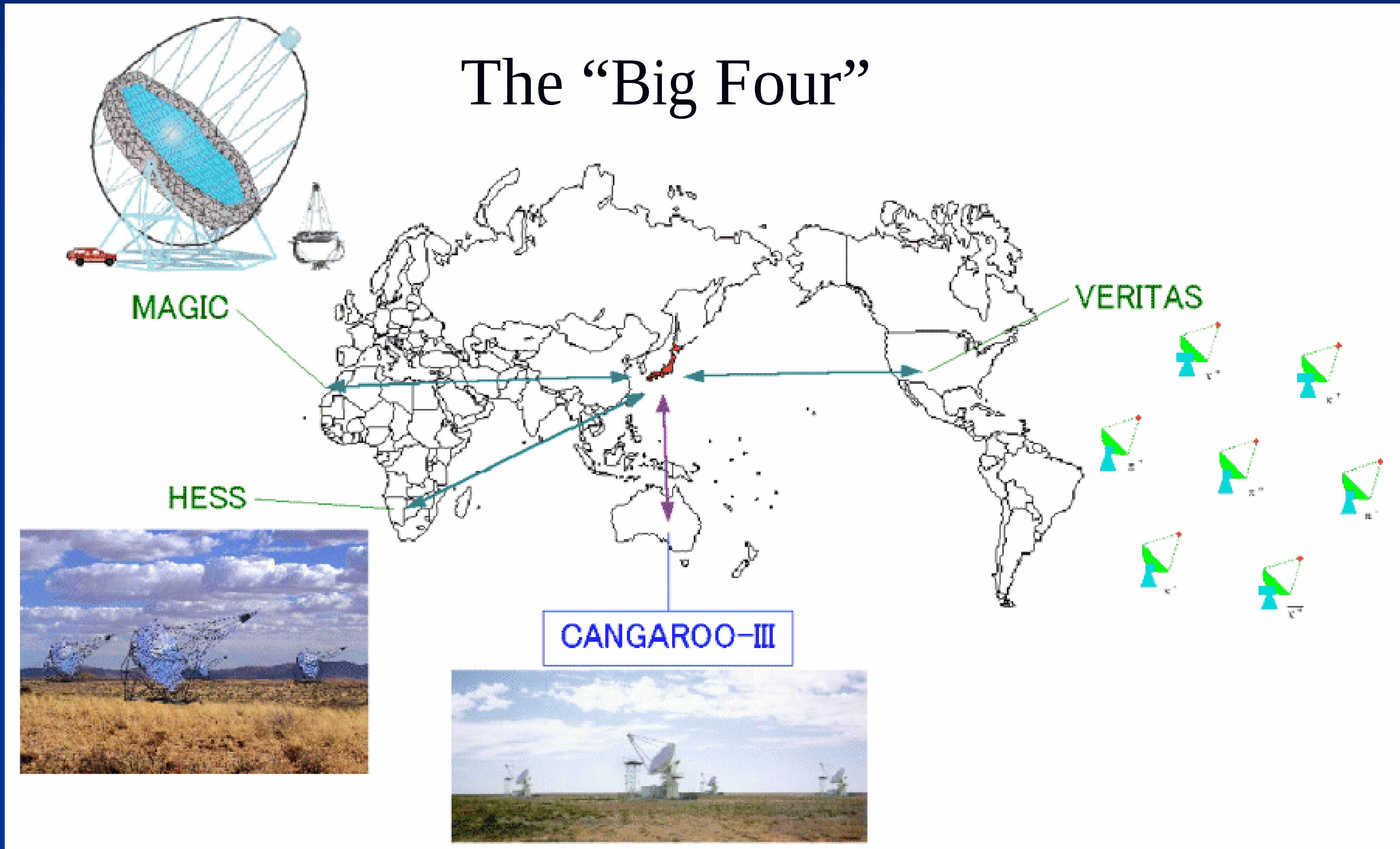
Log scale



“Kifune plot”

©Rene Ong 2002

New Cherenkov telescopes

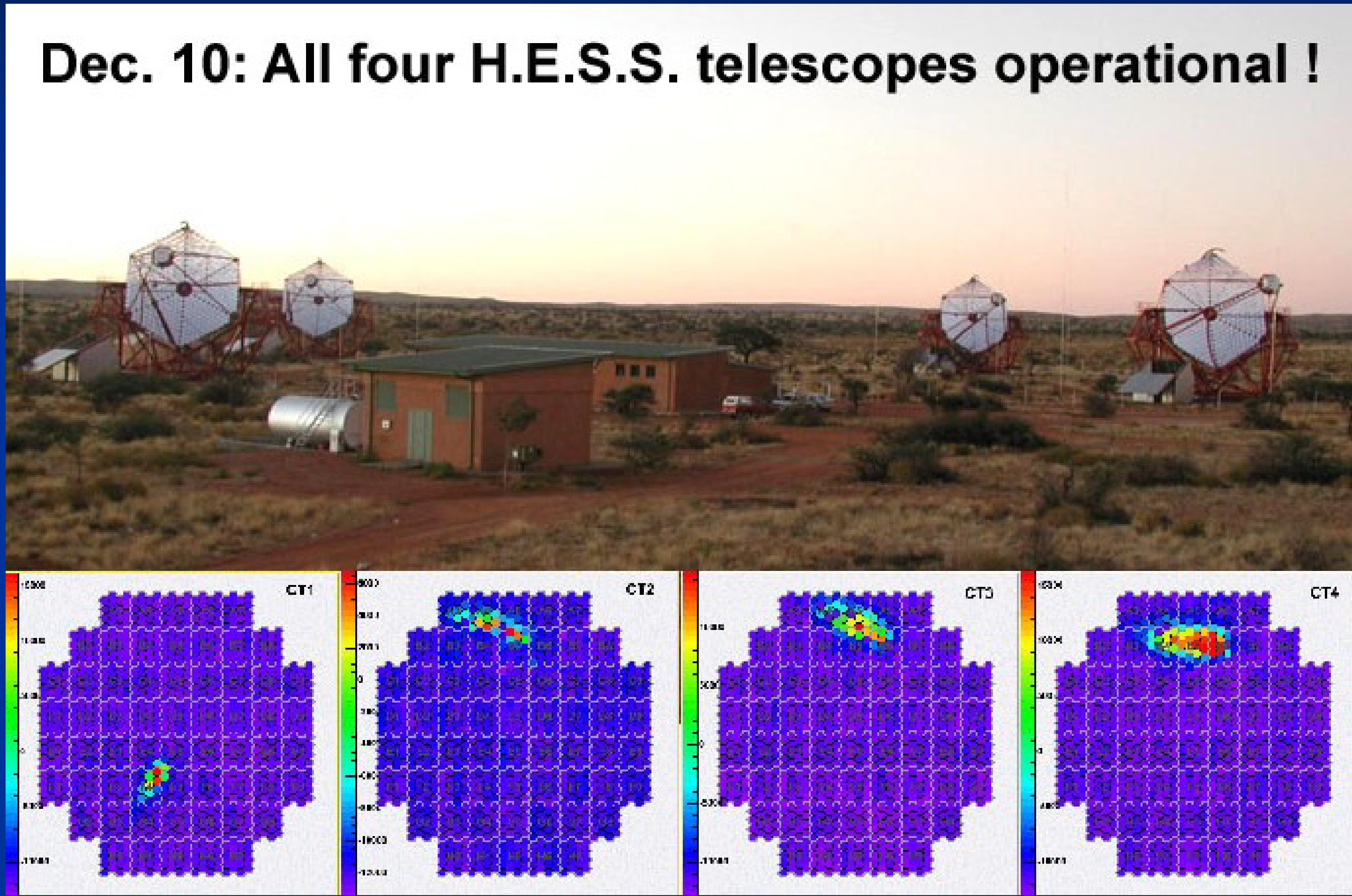


CANGAROO-III: completion in 2004

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

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

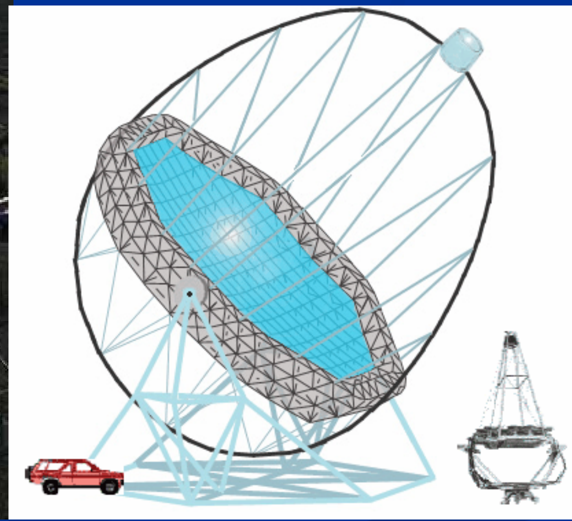
H.E.S.S.: completion in 2003



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

Max Planck Inst., Heidelberg, etc.

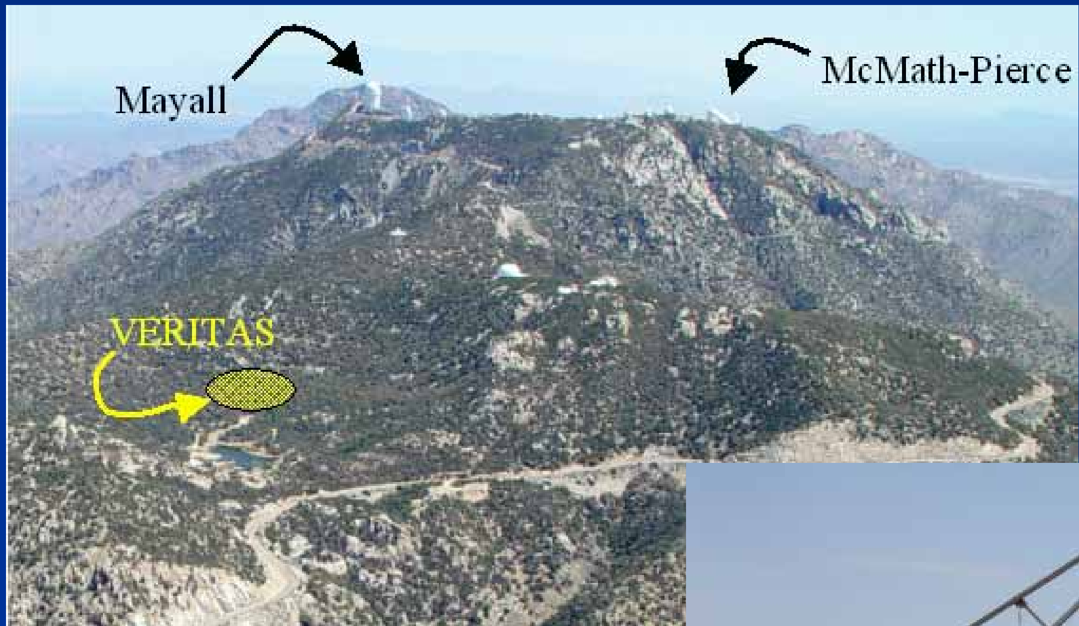
MAGIC: completion in 2003



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)

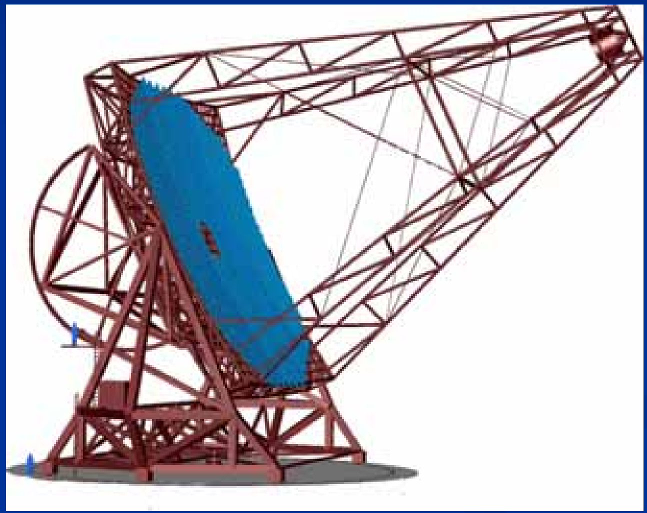
Oct 2005: Completion of Phase I: 4 telescope array

Oct 2007: Completion of Phase II: 7 telescope array

4th generation concepts

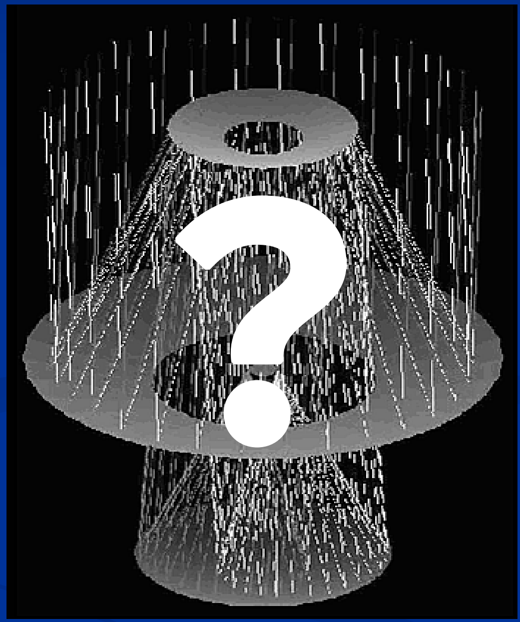
ECO-1000 project

MPI Physics etc.



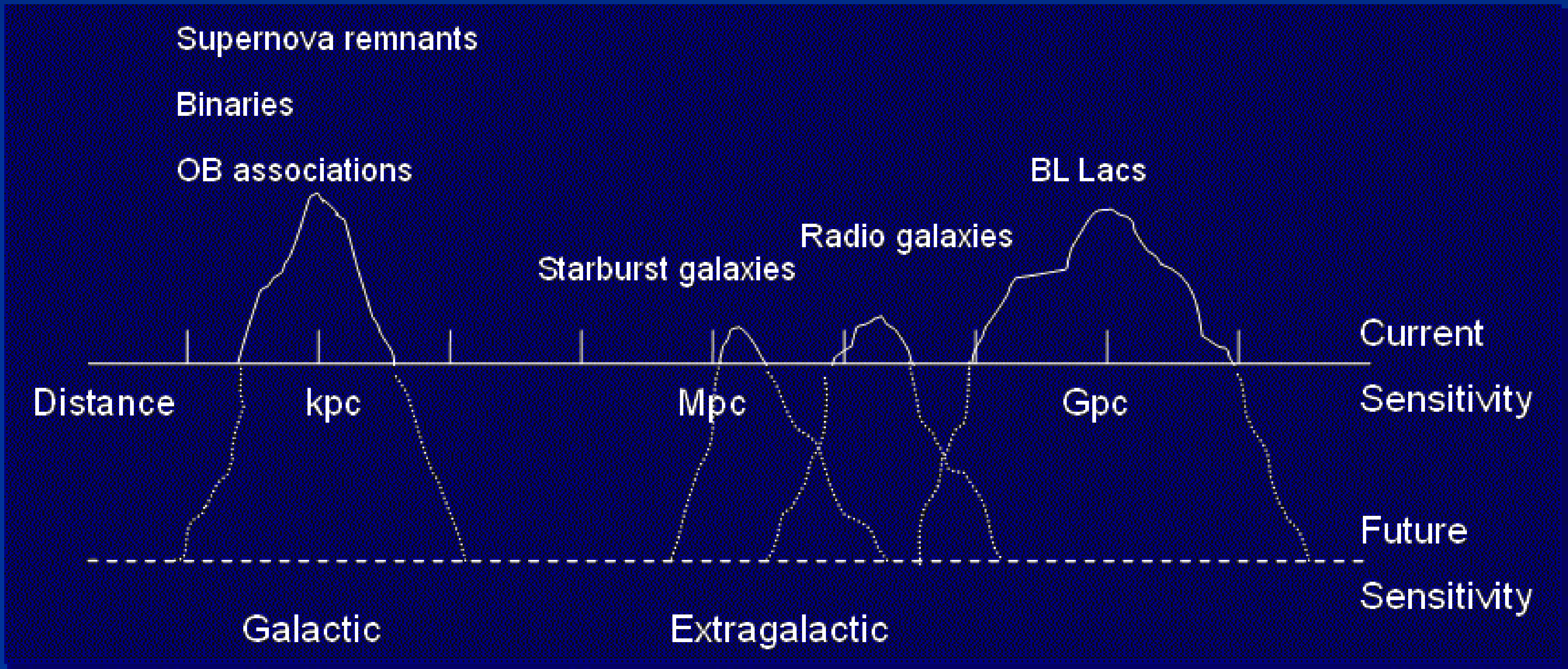
28m telescope at the center of H.E.S.S.

MPI Nuclear Physics etc.



SuperCANGAROO 30m?

Tips of the Icebergs in the TeV Universe



Summary

- Very high energy gamma-rays are probing non-thermal, violent Universe.
- TeV gamma-ray astronomy is becoming an indispensable field of astronomy.
- Very high energy sources may contain large varieties, including both galactic and extragalactic objects, which means particle acceleration is a common phenomenon.
- There are some evidences of SNR origin of cosmic rays, but still there is no unambiguous identification of hadrons. More examples and detailed wide-band observations are necessary!
- The “third generation” Cherenkov telescopes are about to increase sensitivity – more fun!