高エネルギーガンマ線天体物理学の近況

森　正樹
東京大学宇宙線研究所

東京大学大学院理学研究科宇宙理論グループセミナー

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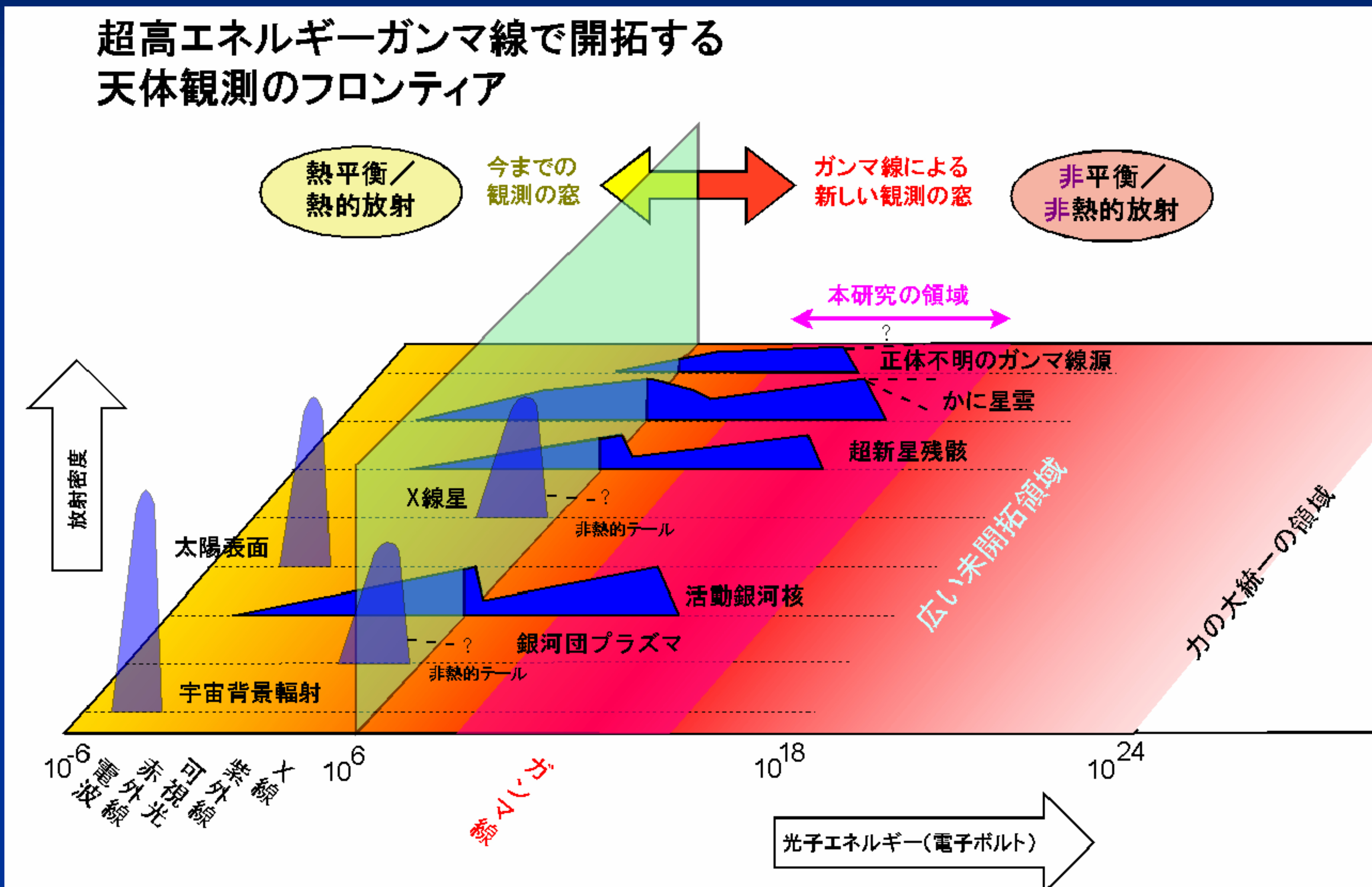
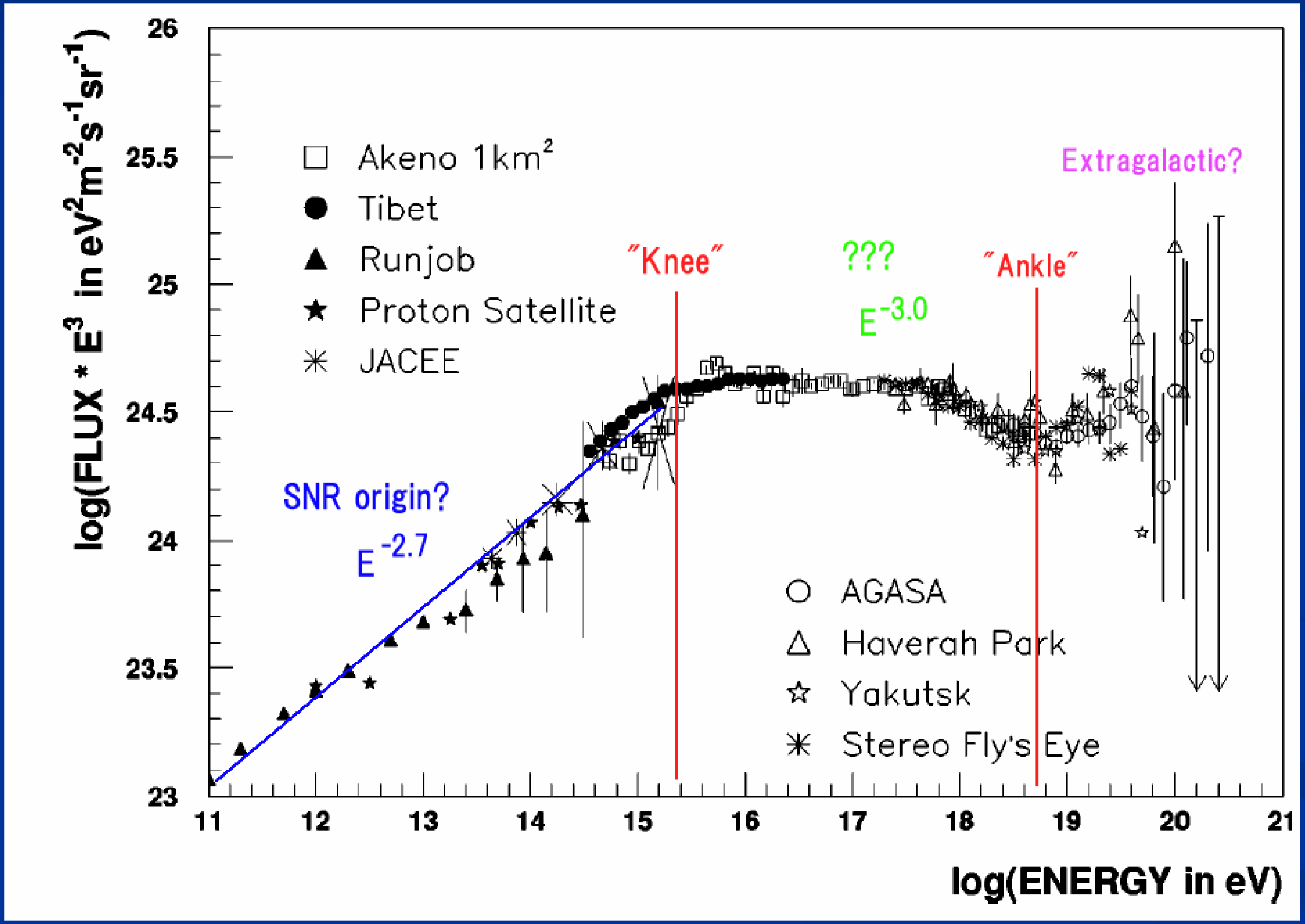
「非熱的宇宙」の統一的理解



宇宙線の起源

Power-law spectrum ↔ non-thermal origin



Nagano & Watson 2000

高エネルギーまで加速された電子または陽子（宇宙線）

↓

ガンマ線の発生

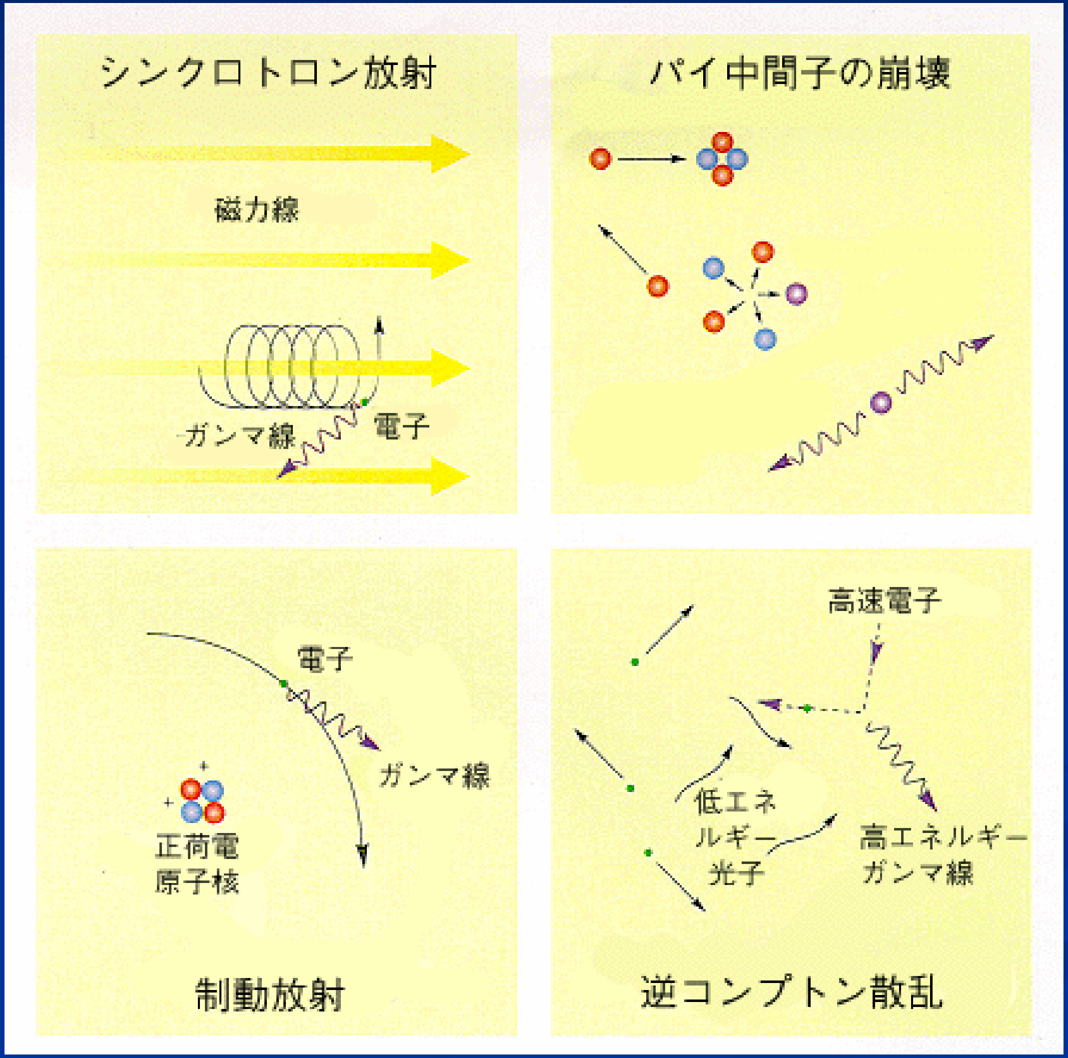
↓

発生源から地球まで直進

ガンマ線の放射機構：非熱的

高エネルギー
電子 ＋ 磁場

高エネルギー
陽子 ＋ 物質

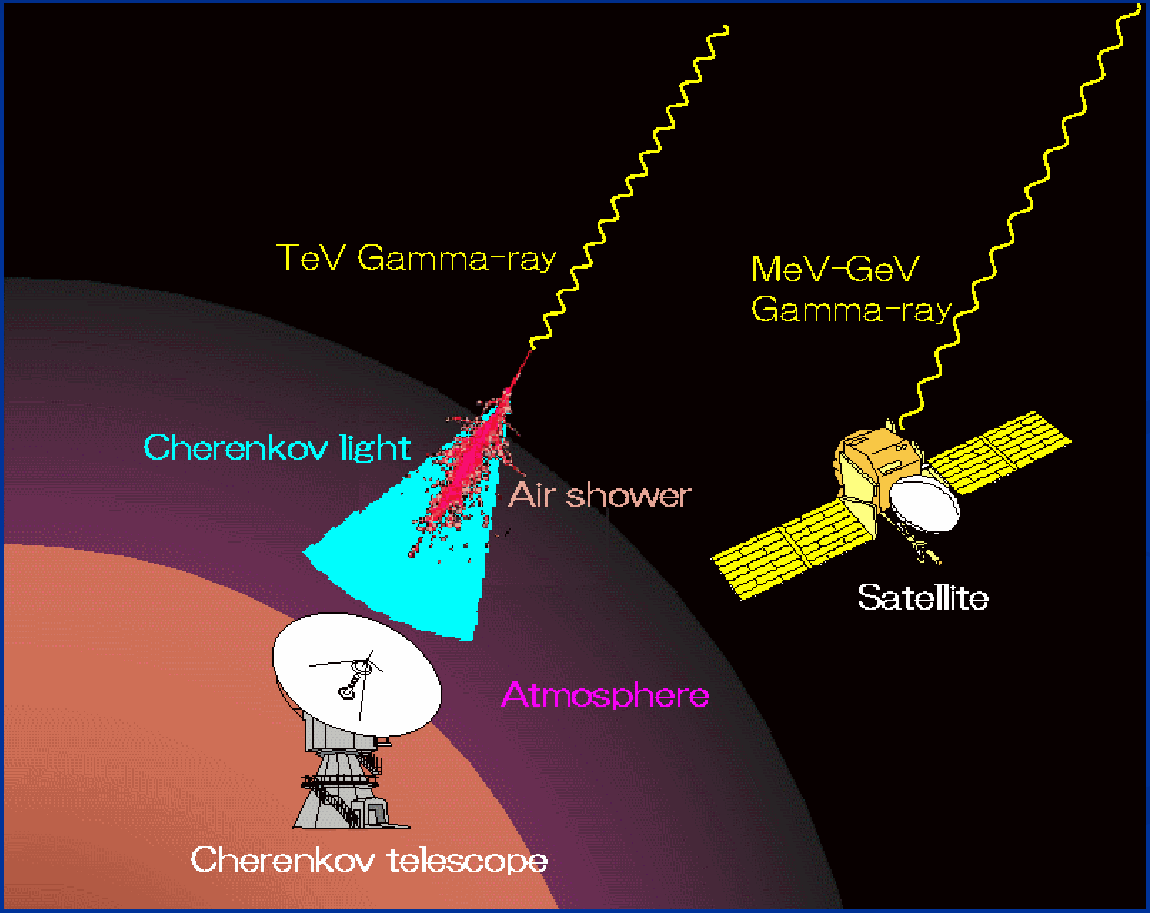


高エネルギー
電子 ＋ 原子
の電場

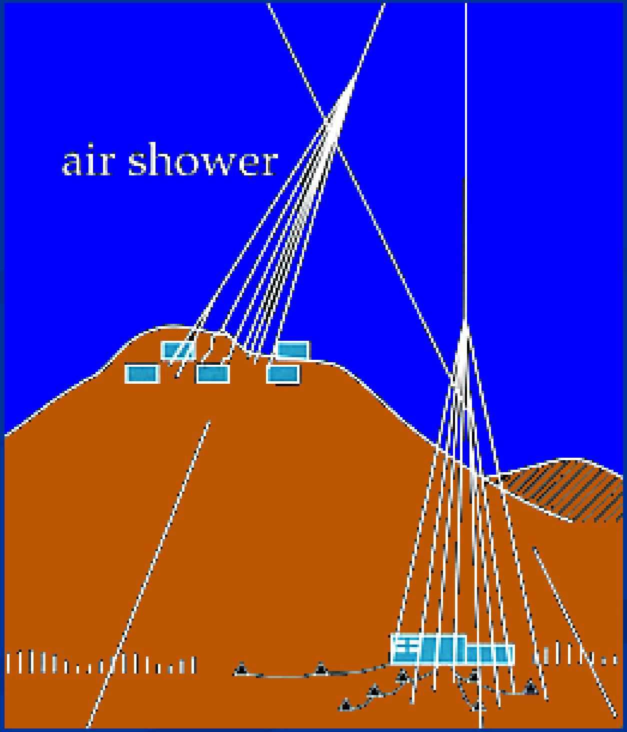
高エネルギー
電子 ＋ 光子場

高エネルギー粒子の存在 ⇐ 粒子加速過程

Detection of gamma-rays (1)



> TeV gamma-rays



大気チェレンコフ望遠鏡

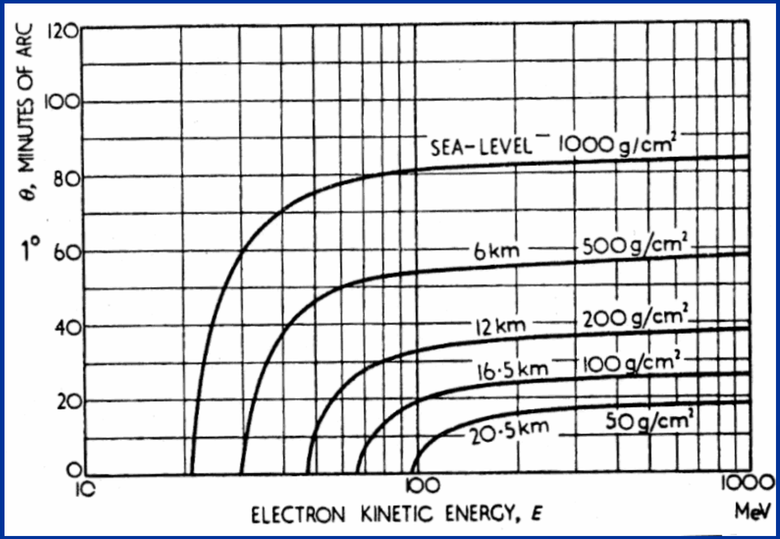
- **チェレンコフ角**

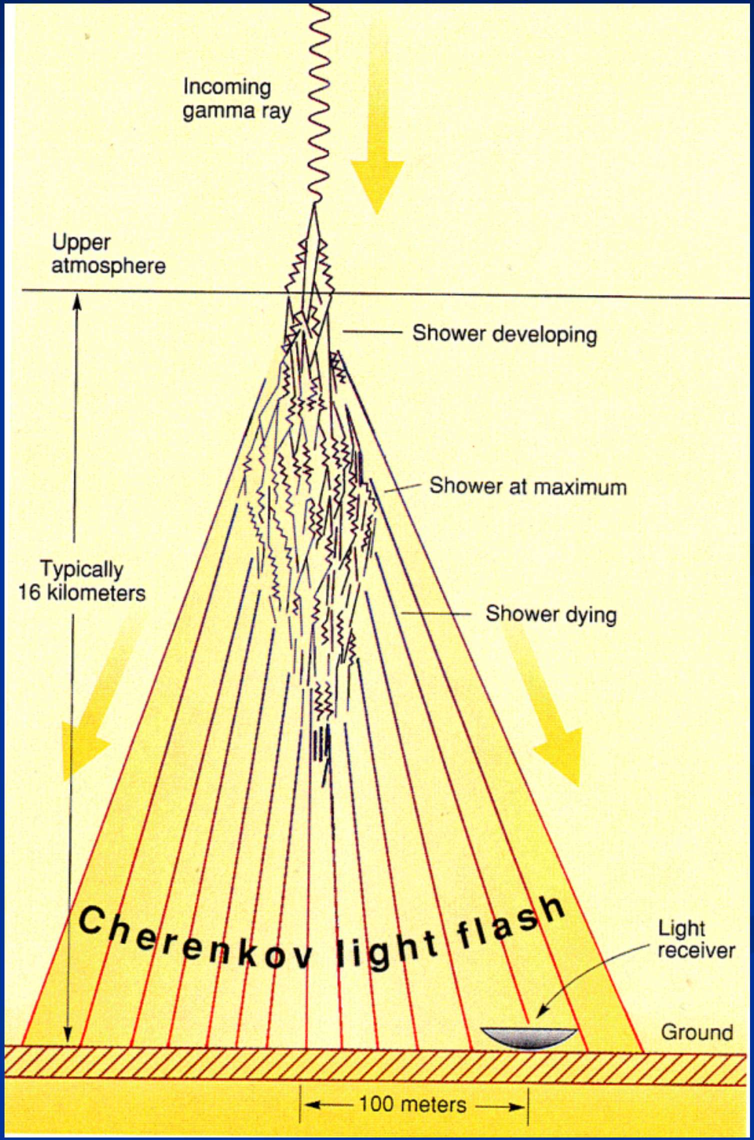
$$\cos\theta = 1/n\beta$$

$$\beta = v/c$$

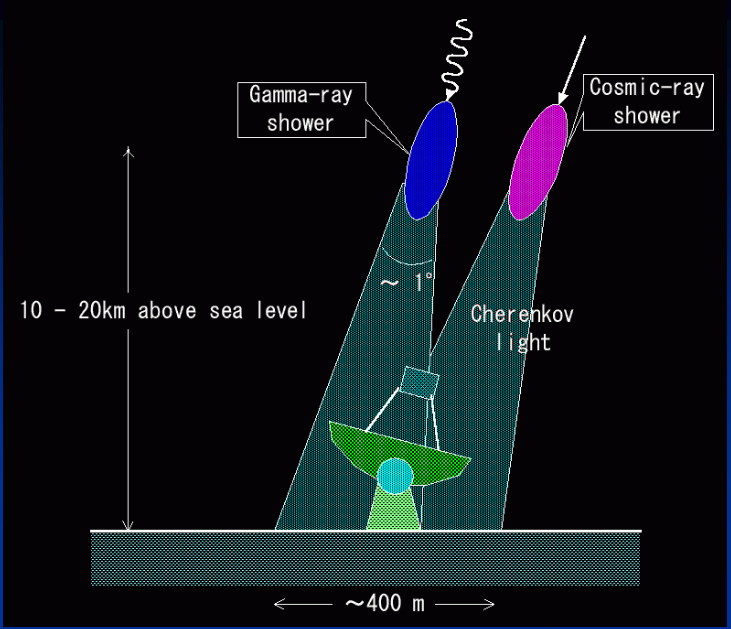
$$n = 1.0003 \text{ (1atm)}$$

$\Rightarrow \theta = 1.3^{o}$ (**地上**)



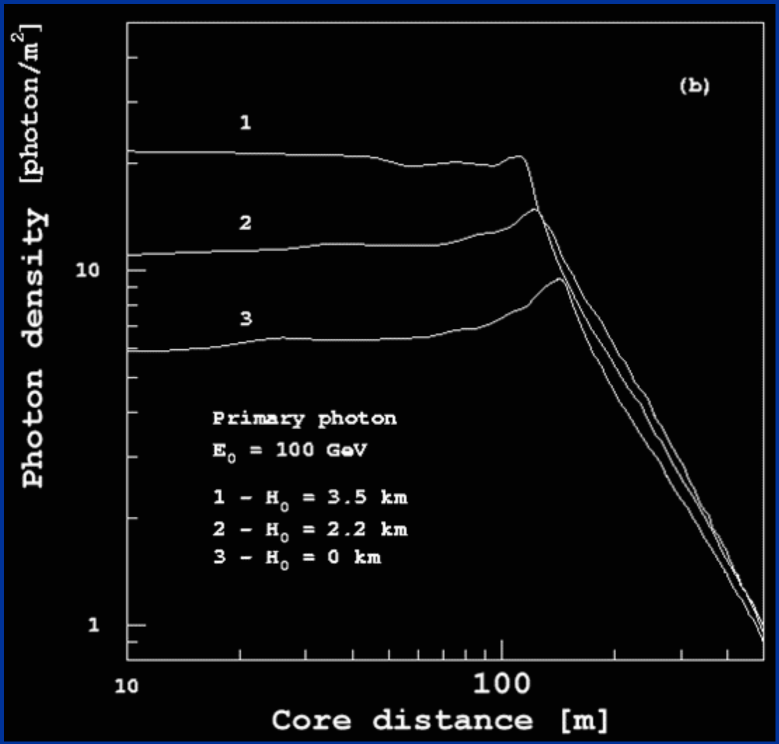


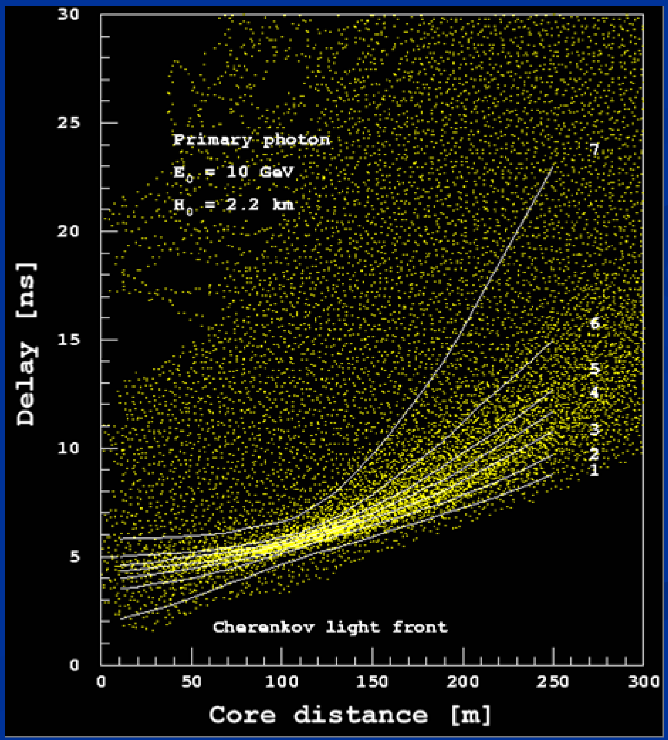
Atmospheric Cherenkov telescopes



Cherenkov light from gamma-ray showers

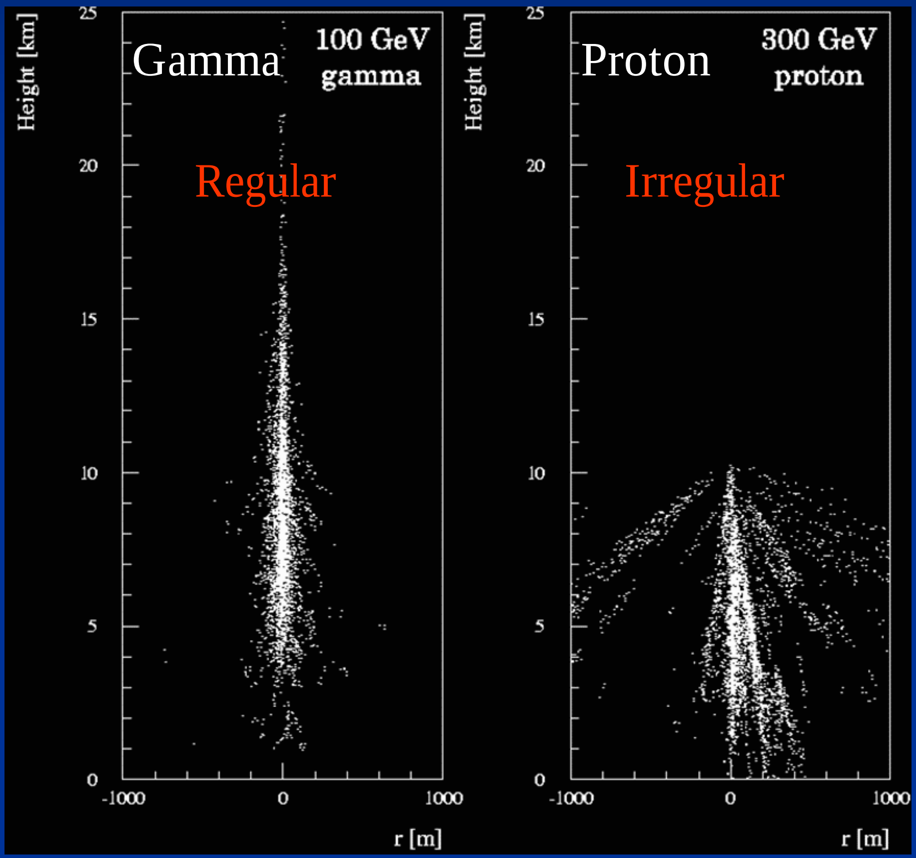
Lateral distribution & Timing distribution



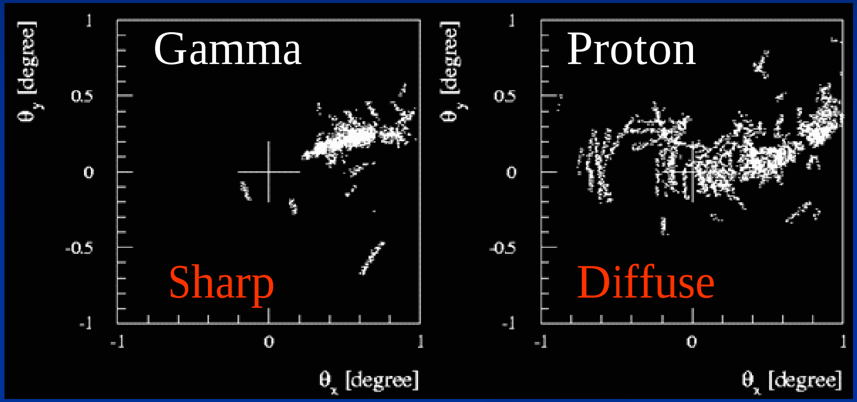


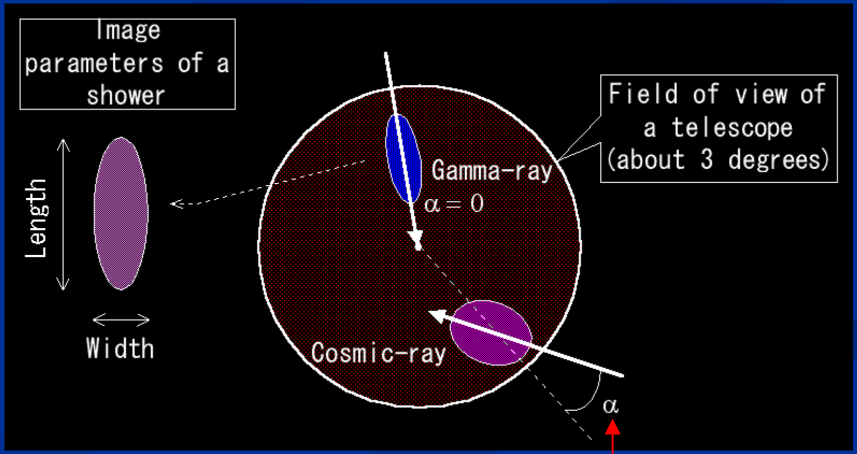
Imaging Cherenkov Telescopes

Shower profile



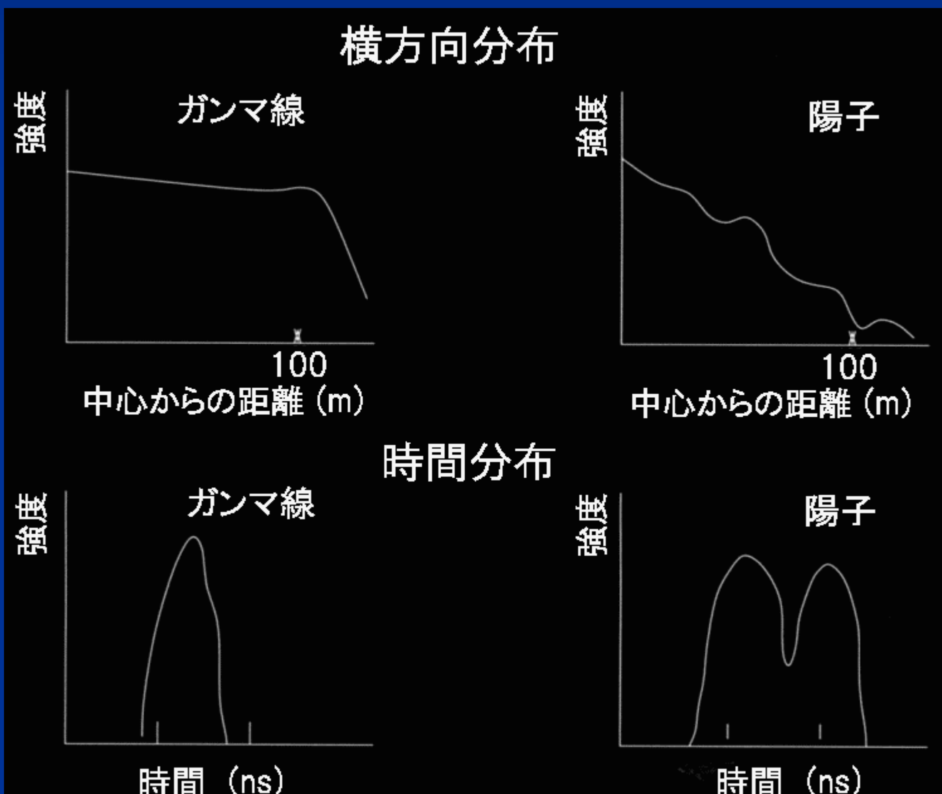
Focal plane image

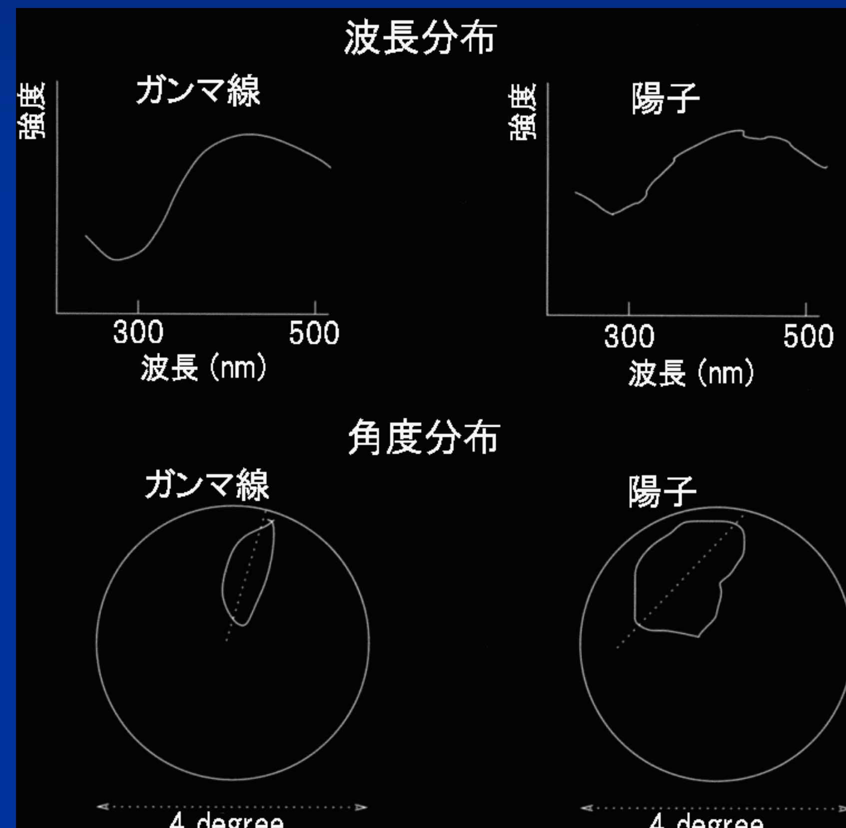




α (image orientation angle)

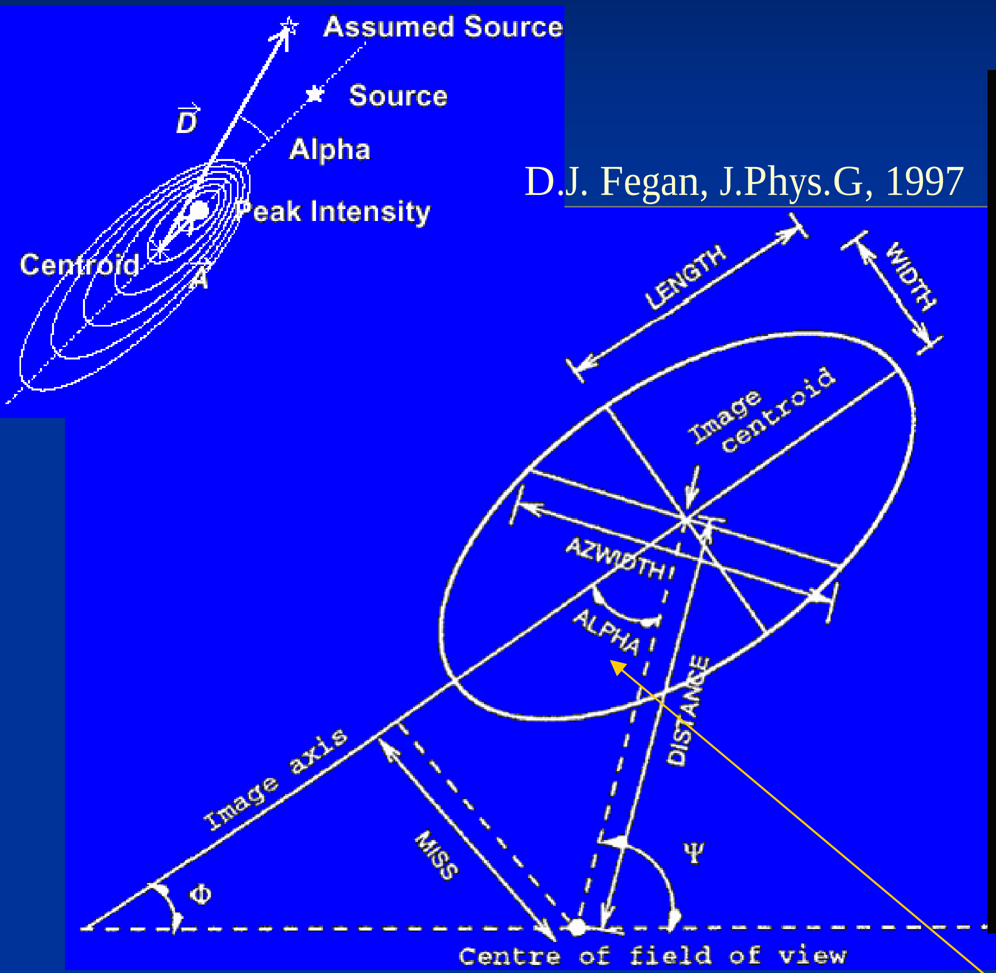
ガンマ線と陽子のチェレンコフ光





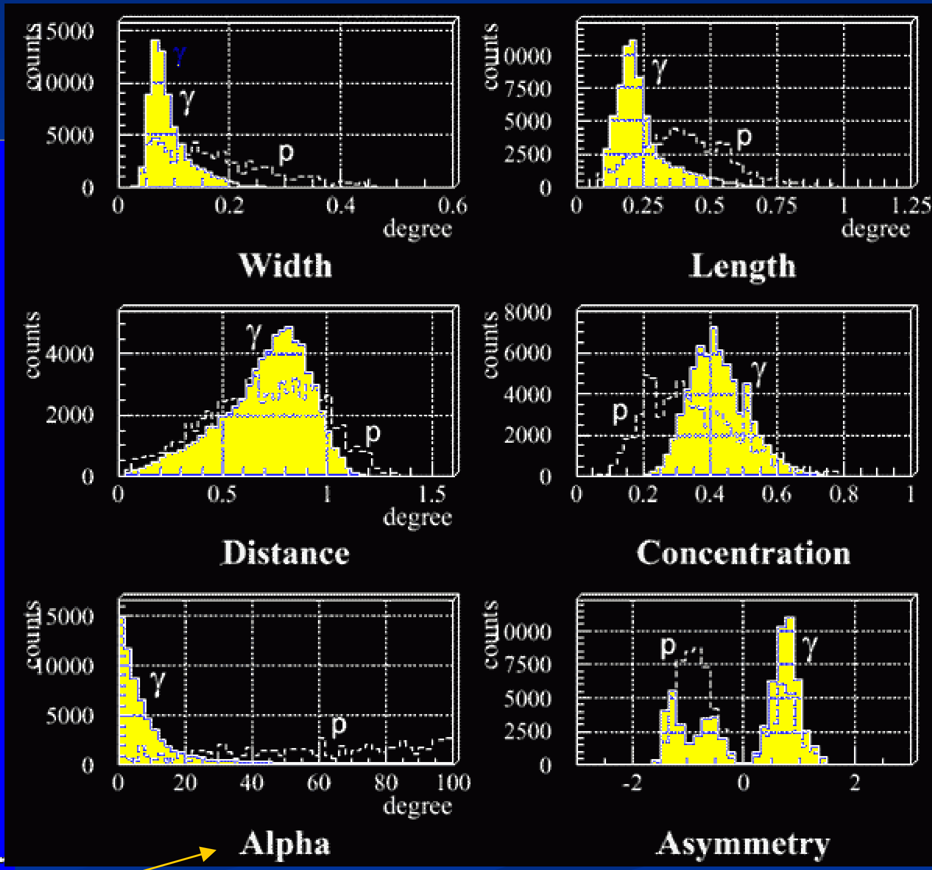
Weekes, “Very High Energy Gamma-ray Astronomy”

Imaging analysis



D.J. Fegan, J.Phys.G, 1997

Distribution of imaging parameters



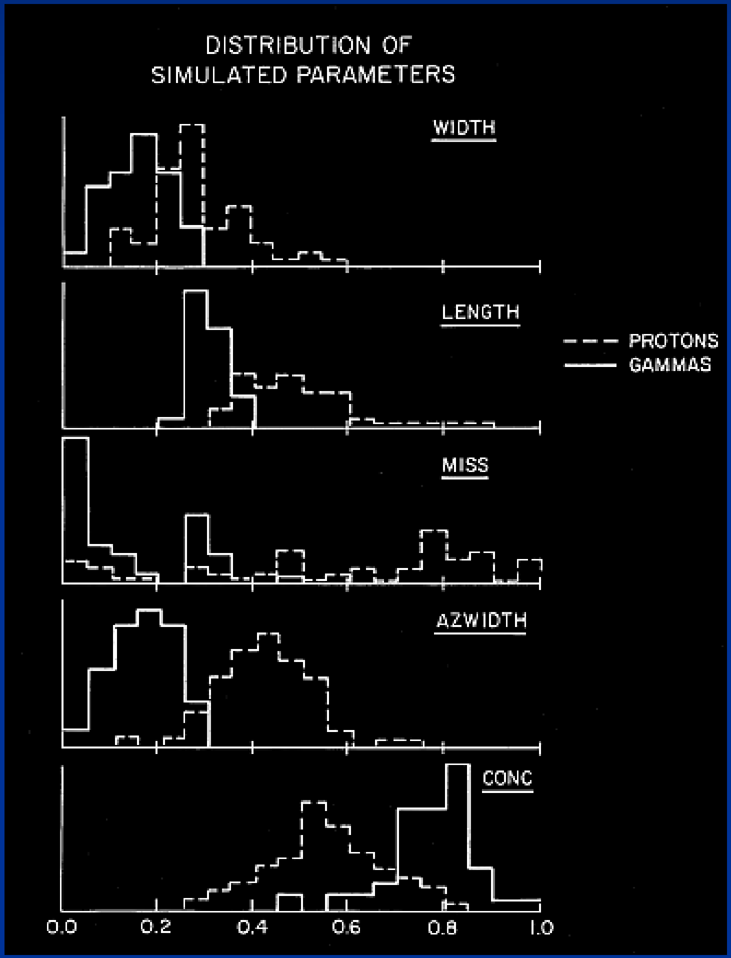
α (image orientation angle)

(Simulation)

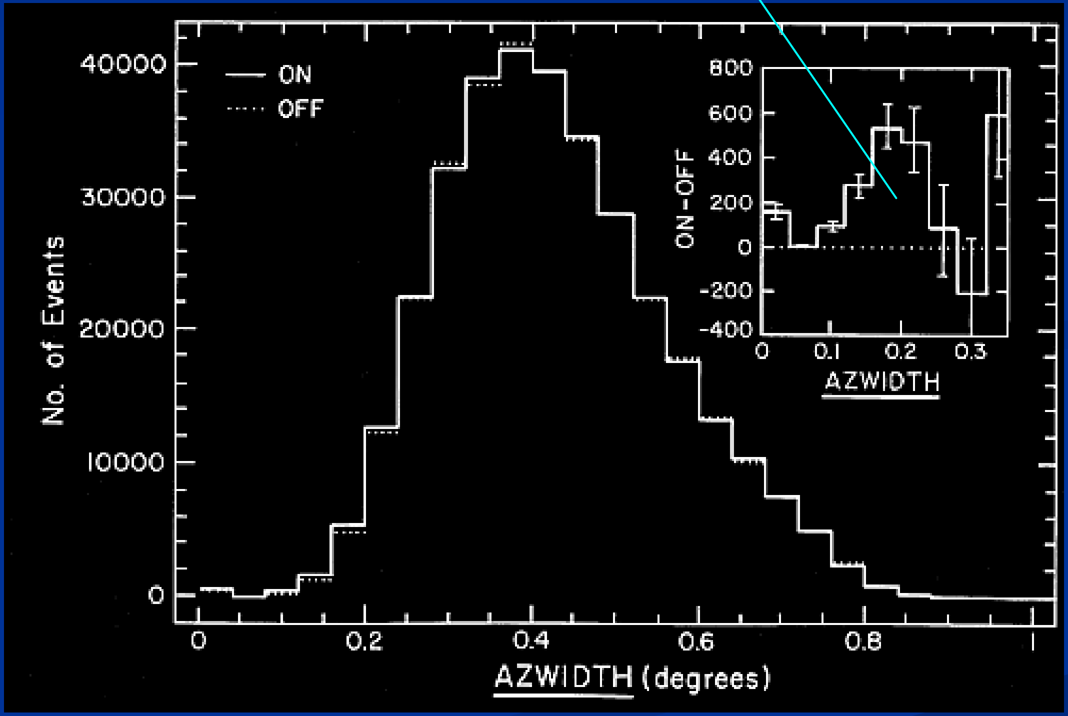
“Image parameters”: A.M. Hillas, 1983 ICRC

“Alpha”: A.V.Plyasheshnikov and G.F.Bignami, N.C. 1985

WhippleによるCrabの検出



ガンマ
線信号

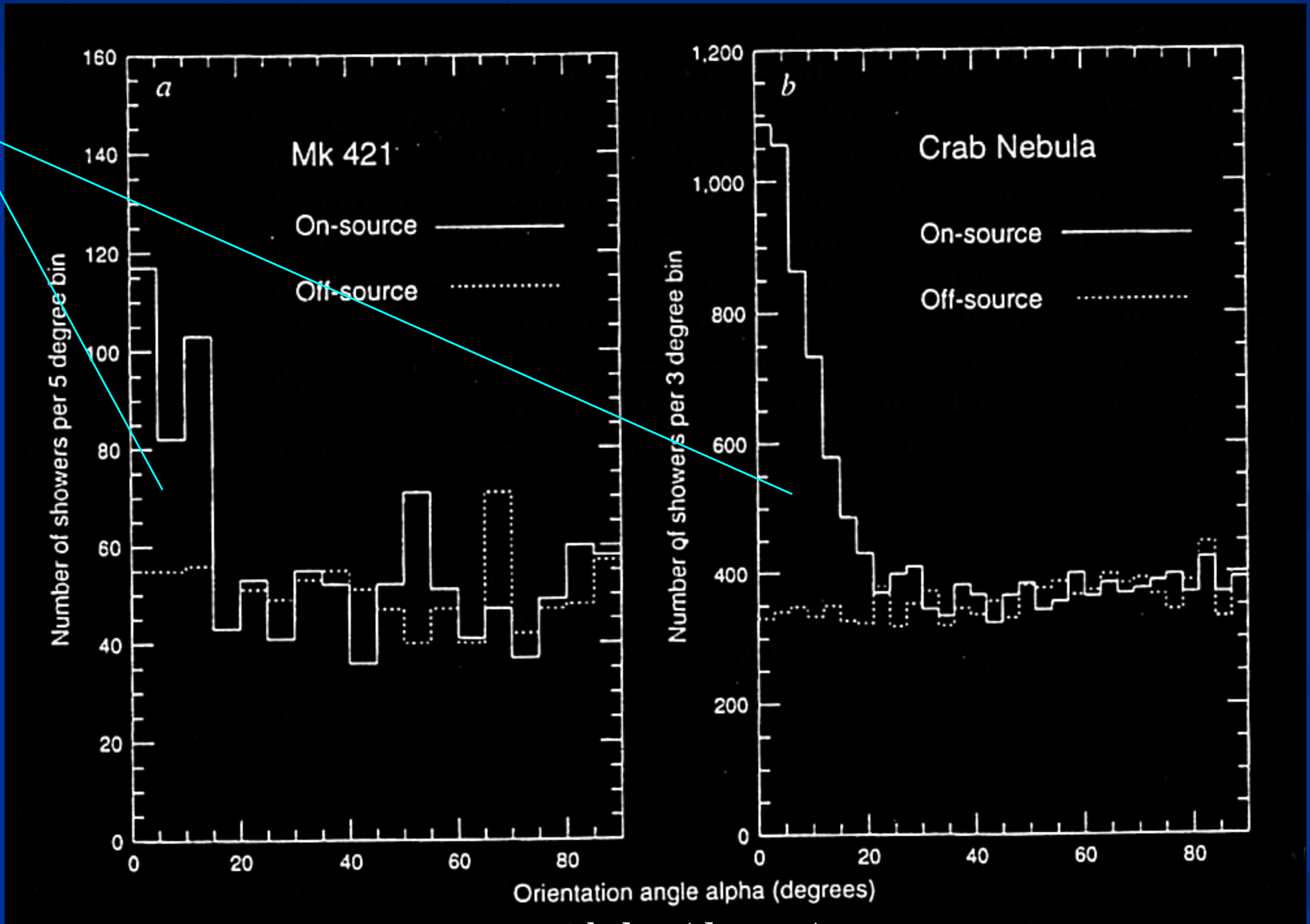


82hrs, 0.24γ/min

Weekes et al. ApJ 342 (1989) 349

WhippleによるMrk421の検出

ガンマ線信号



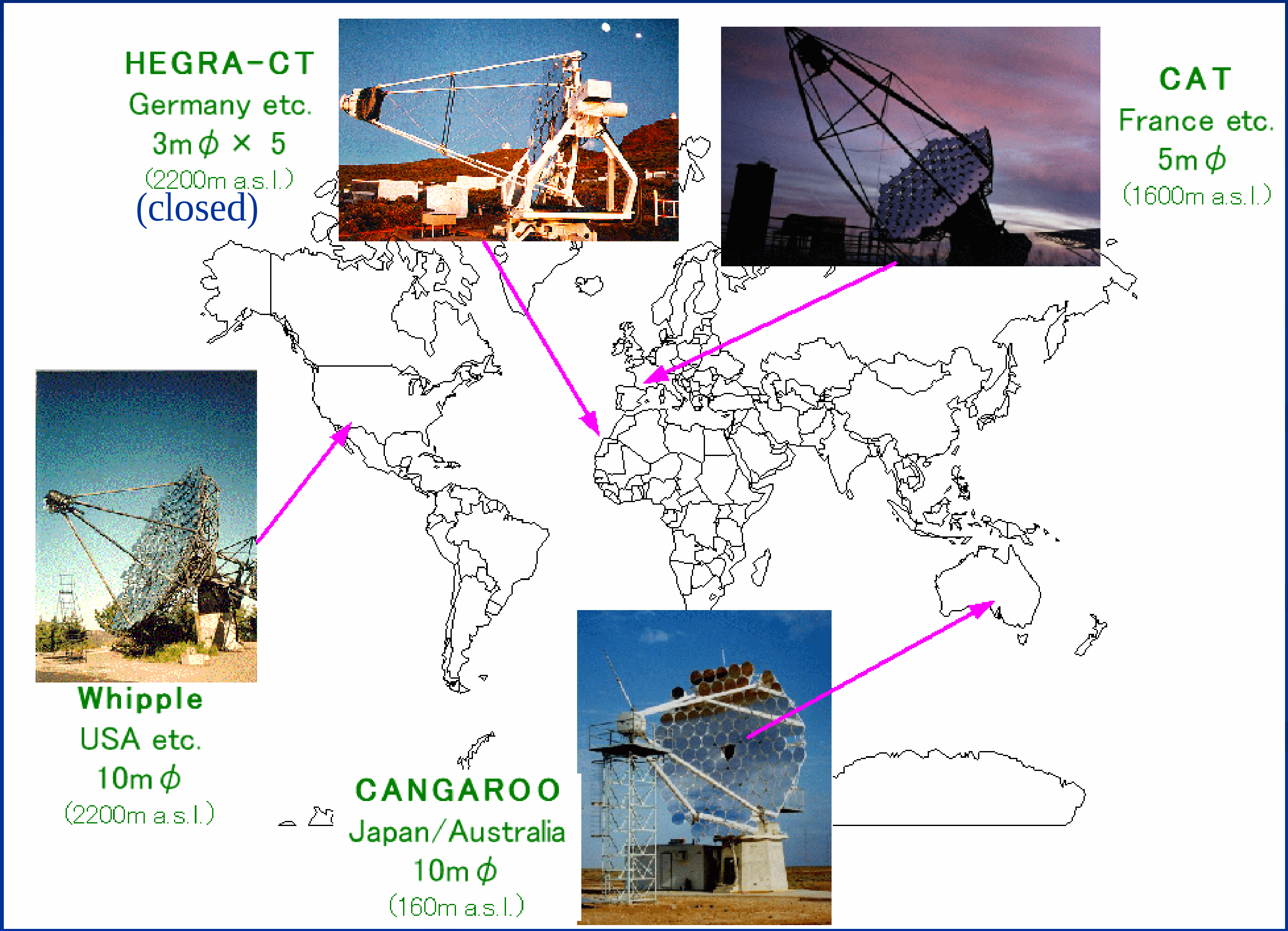
Alpha (degree)

Punch et al. Nature 358 (1992) 477

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



"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)

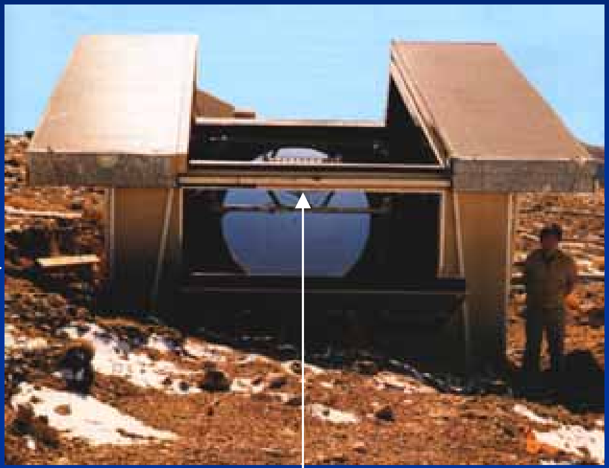
- University of Adelaide
- Australian National University
- Ibaraki University
- Ibaraki Prefectual University
- Kitasato University
- Konan University
- Kyoto University
- Nagoya University
- National Astronomical Observatory of Japan
- Osaka City University
- Shinshu University
- Institute for Space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

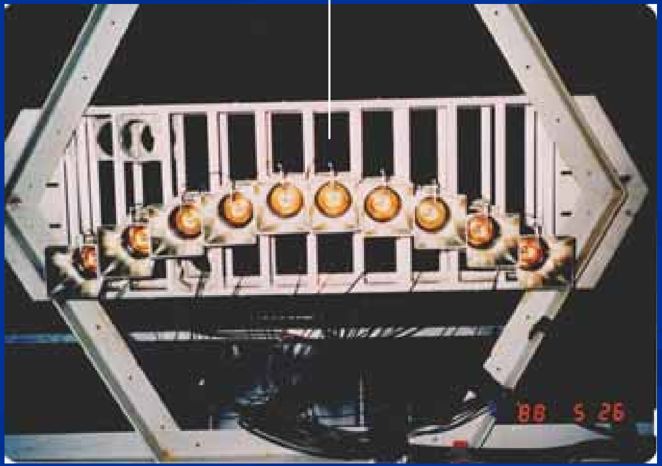
CANGAROO history

- 1987: 超新星1987A
- 1990: 3.8m 望遠鏡
- 1990: 宇宙線研・Adelaide Physics 部局間協定
- 1992: 3.8m 望遠鏡の観測開始
- 1994: パルサー1706-44からのガンマ線検出
- 1998: 超新星残骸1006からのガンマ線検出
- 1999: 7m望遠鏡完成
- 2000: 7m望遠鏡を10mに拡大
- 2001: U.Tokyo-U.Adelaide 大学間協定
- 2002: 10m望遠鏡第2号機、第3号機建設

ニュージーランドでのJANZOS実験

Japan Australia New Zealand Observation of Supernova 1987A





空気シャワー検出器アレイ

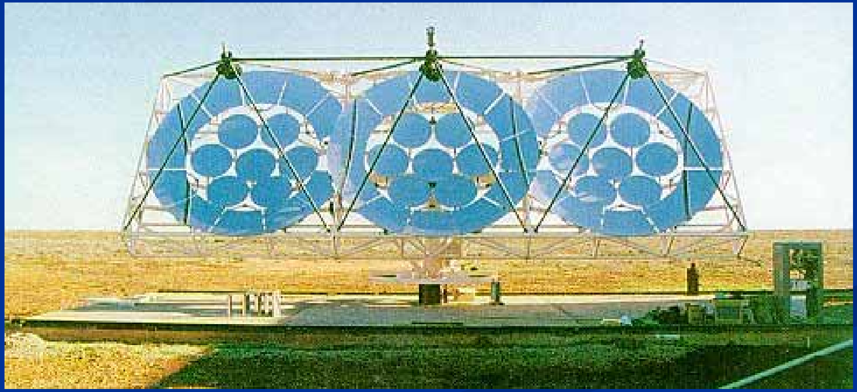
＋

固定型チェレンコフ望遠鏡3台

なぜWoomeraを選んだか？

- ニュージーランド：湿潤、晴天率低
- Woomera:
  - かつてのロケット発射場、立ち入り禁止区域：インフラ整備、サポートセンター
  - アデレード大学によるBIGRAT望遠鏡が稼動

ELDO rocket Launch site in ’60s

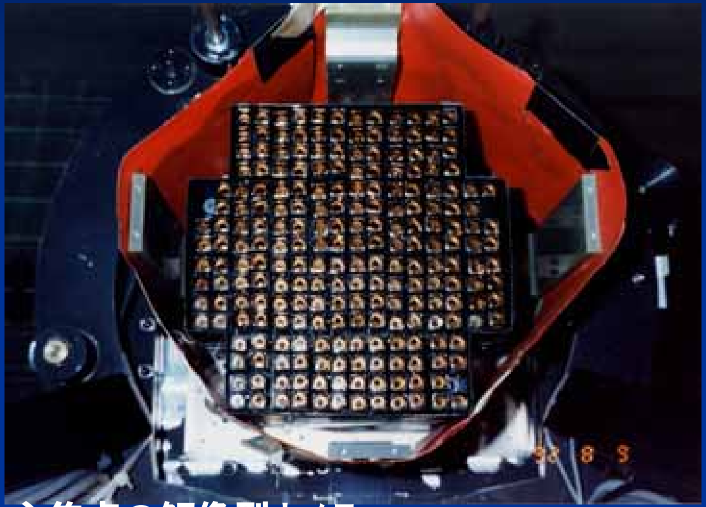


BIGRAT

(BIcentinnial Gamma RAy Telescope)

Woomera

3.8m望遠鏡 (元：月レーザ測距儀)

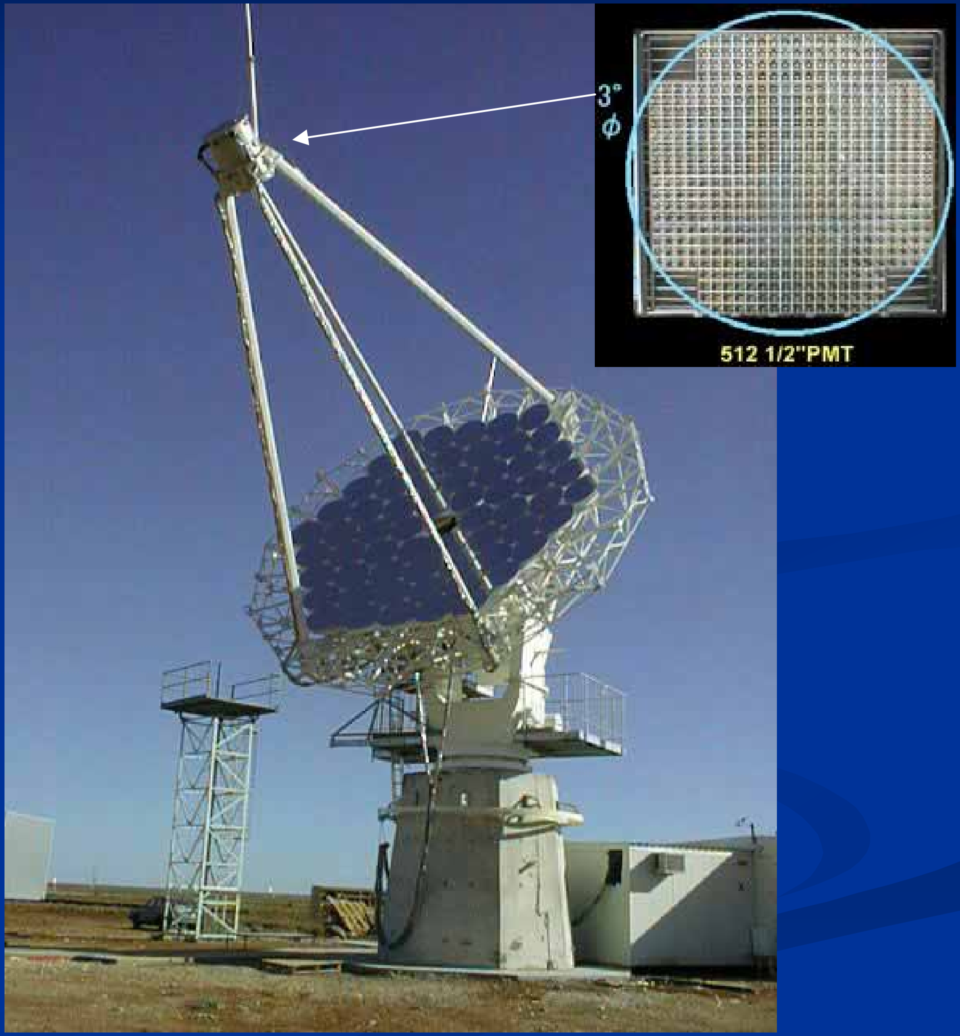


主焦点の解像型カメラ

木舟正 & John Patterson

CANGAROO 7m 望遠鏡

- 1999年3月完成
- 60 x 80cm CFRP主材の小型球面鏡
- 焦点距離8m
- 経緯台式架台
- 552ch解像型カメラ
- 電荷および時間情報を記録する電子回路



(March 1999)

CANGAROO 10m 望遠鏡

- 2000年3月に拡張
- 114 x 80cm CFRP主材の小型球面鏡x 80cm
- 552ch 解像型カメラ
- 電荷測定回路(ADC)追加

(March 2000)

CANGAROO 7m 望遠鏡

CANGAROO 10m望遠鏡で検出した天体

- かに星雲
- パルサー PSR1706-44
- 超新星残骸 SN1006
- 超新星残骸 RX J1713.7-3946
- 活動銀河核（ブレーザー） Mrk421
- 爆発的星形成銀河 NGC253
- 銀河中心 (予備的)
- 超新星残骸 RX J0852.0-4622 (予備的)

Galactic sources: basics

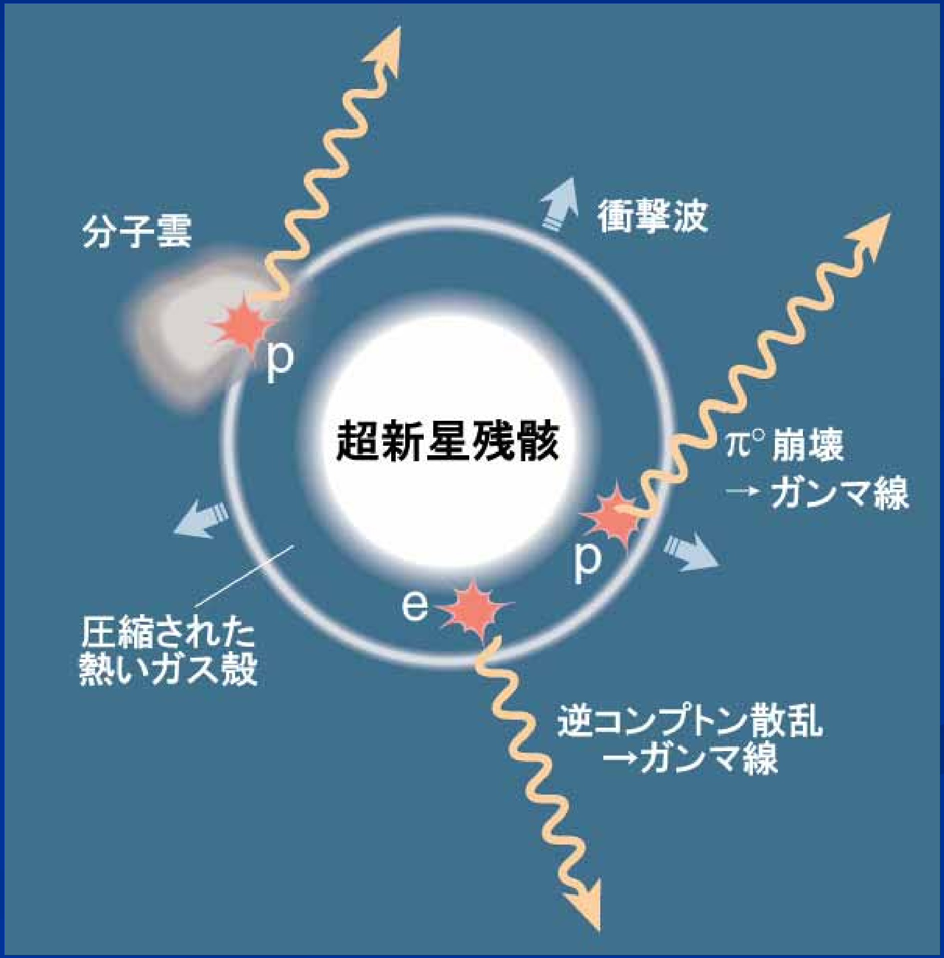
- Supernova remnants = Origin of CR?
  - Energetics – OK (if 10% of E_{SN} goes to CR)
  - Maximum energy – Up to “Knee region”
  - How much of them?
  - Some evidences, which can be ascribed to HE electrons: where are HE protons?
- Pulsar and pulsar wind nebula (plerions)
  - Crab – “The standard candle”
    - 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,…

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)



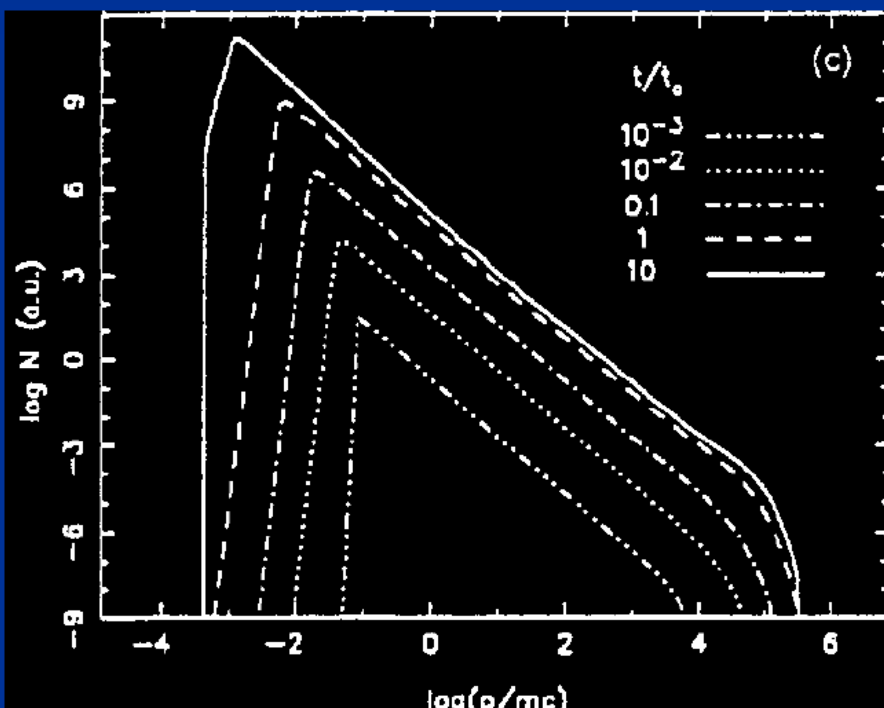
Particle acceleration in SNR

Non-linear kinetic theory

$t_0 = R_0/v_0$; sweep up time

Particle spectrum

Maximum momentum



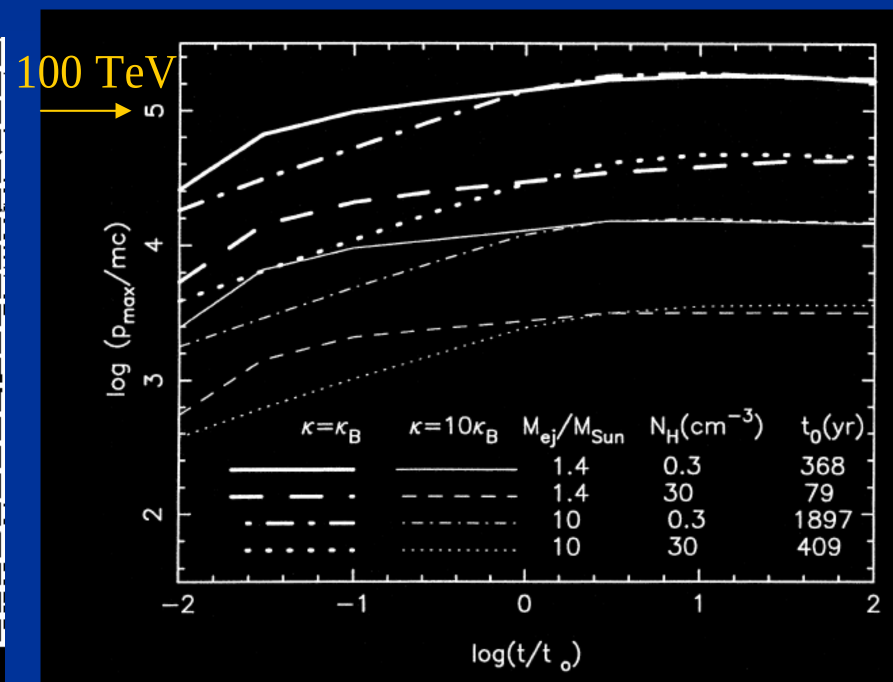


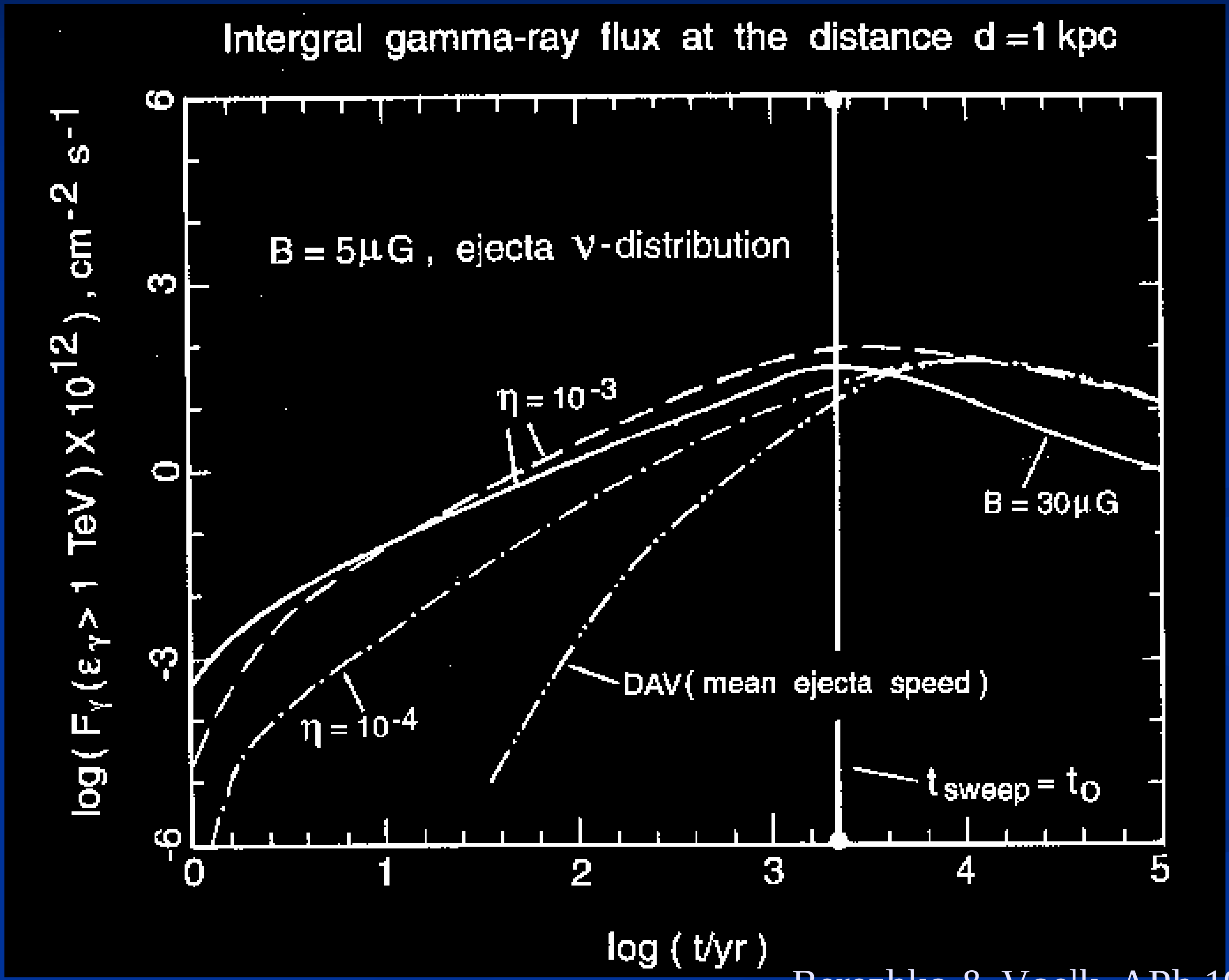
Fig. 2. The maximum CR momentum as a function of time for the same cases as in Fig. 1.

Berezhko & Voelk, APh 1997

Berezhko & Voelk, APh 2000

Cf. Lagage and Cesarsky 1984

Nuclear gamma-ray flux from SNR



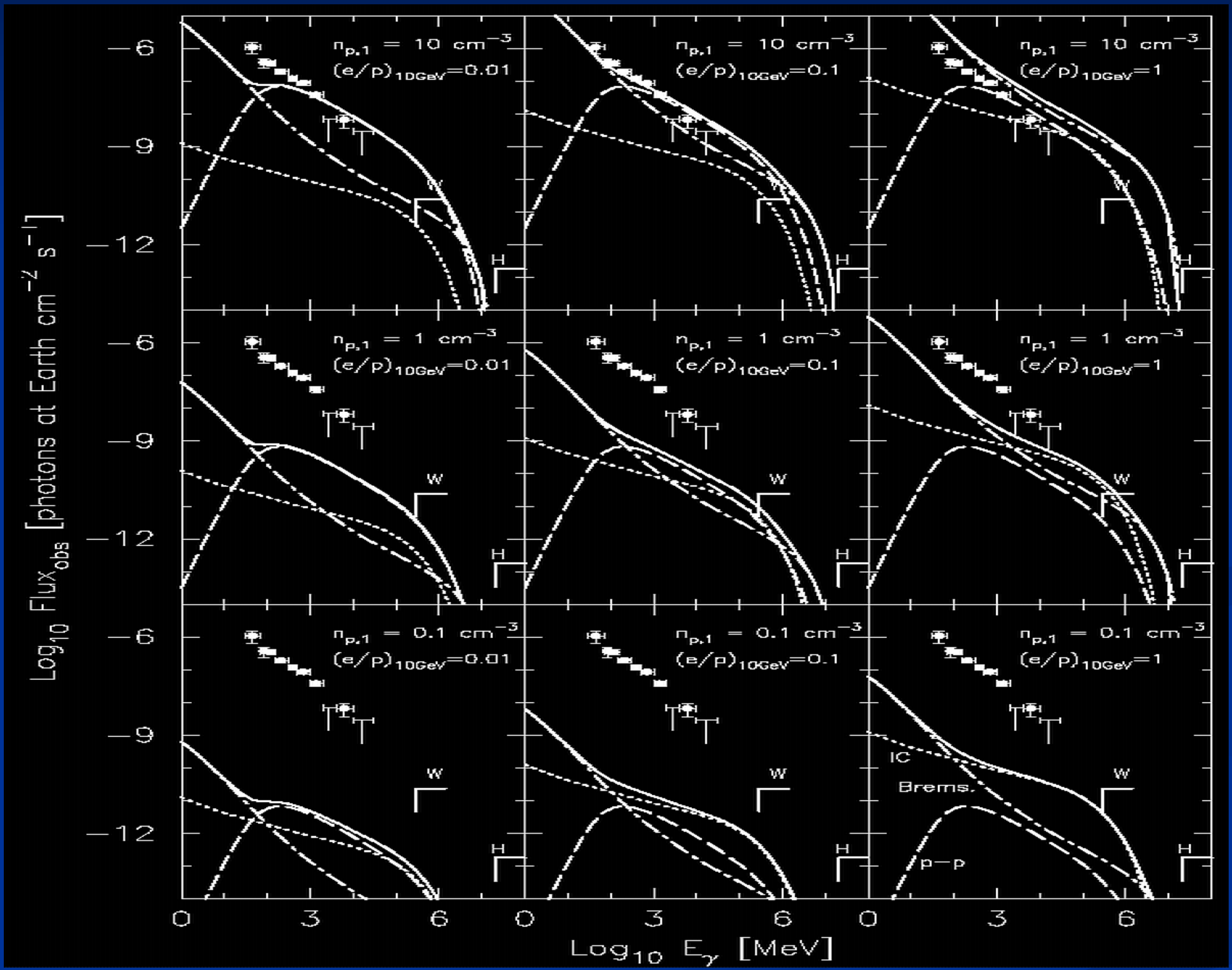
Berezhko & Voelk, APh 1997

Gamma-ray emission from SNR

n=10 cm^{-3}

n=1 cm^{-3}

n=0.1 cm^{-3}



Dot: IC

Dash: π^0

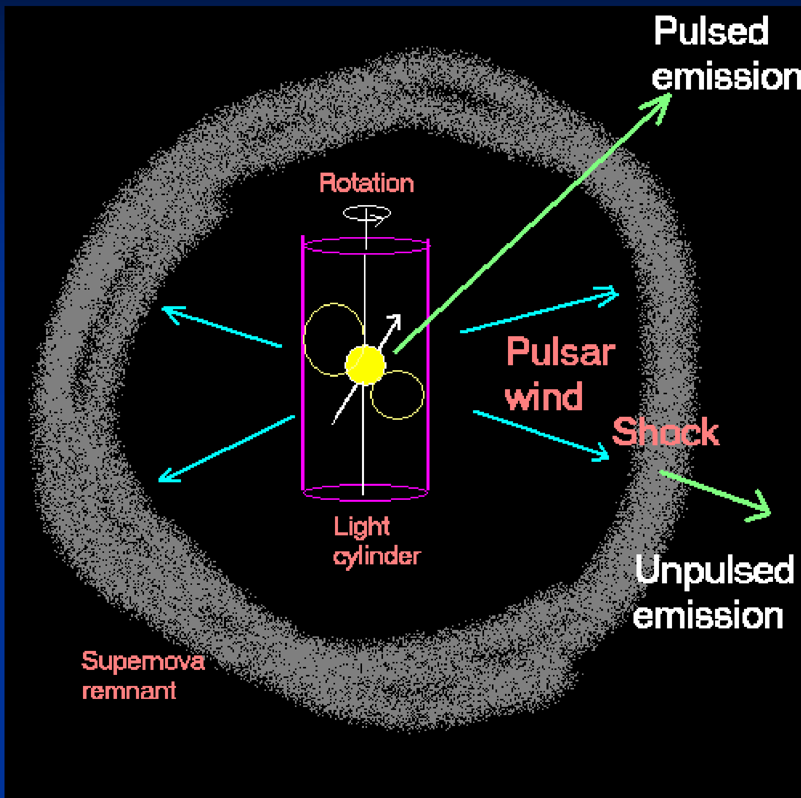
Dot-dash:brems

(Data: EGRET IC443)

e/p = 0.01 0.1 1

Baring et al. 1999 ApJ 513, 311

Pulsar nebula

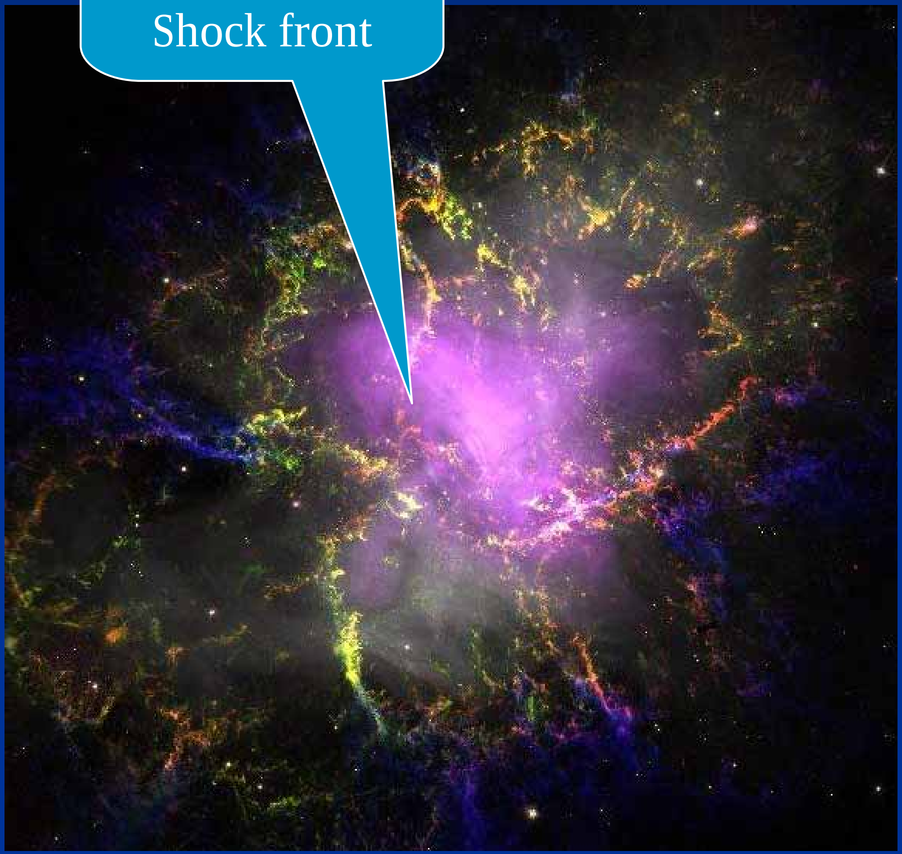


- 周囲のガス圧とバランスするところで衝撃波が形成され、圧縮加熱されたパルサー風がシンクロトロン放射で輝く

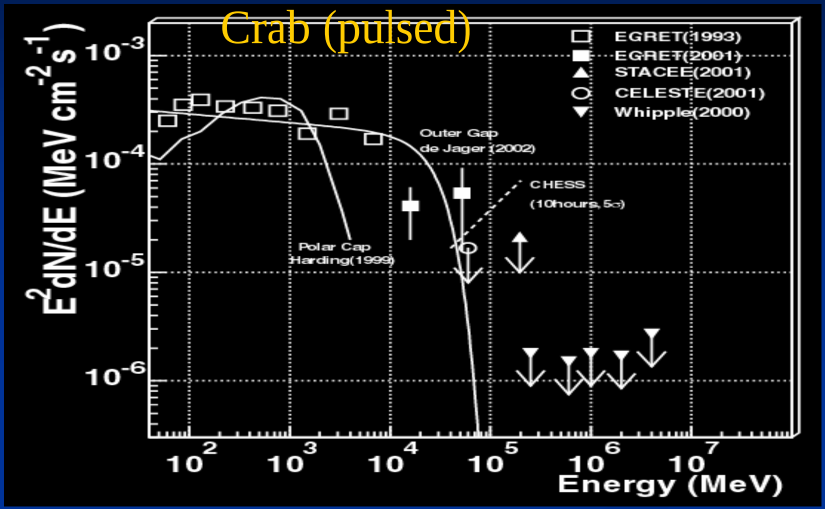
K.Mori, talk at ICRR, Dec 2003

The Crab

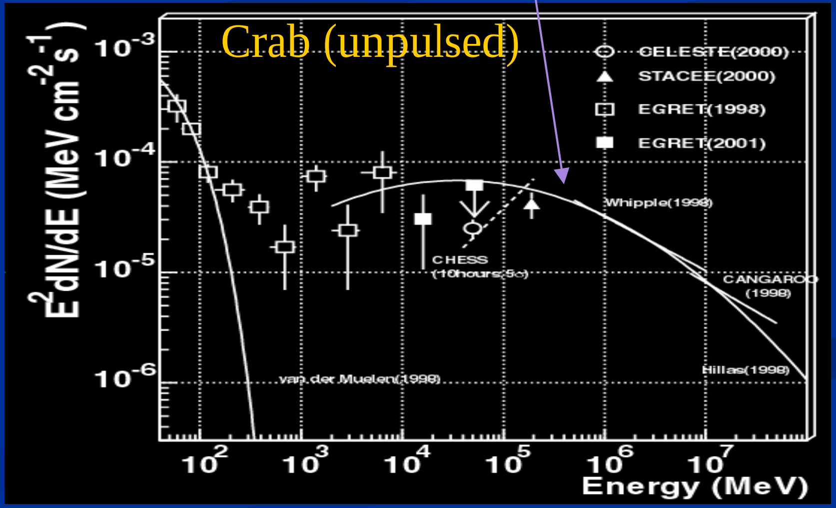
Inner ring
=
Shock front



Optical + X-ray image



Synchrotron Self Compton



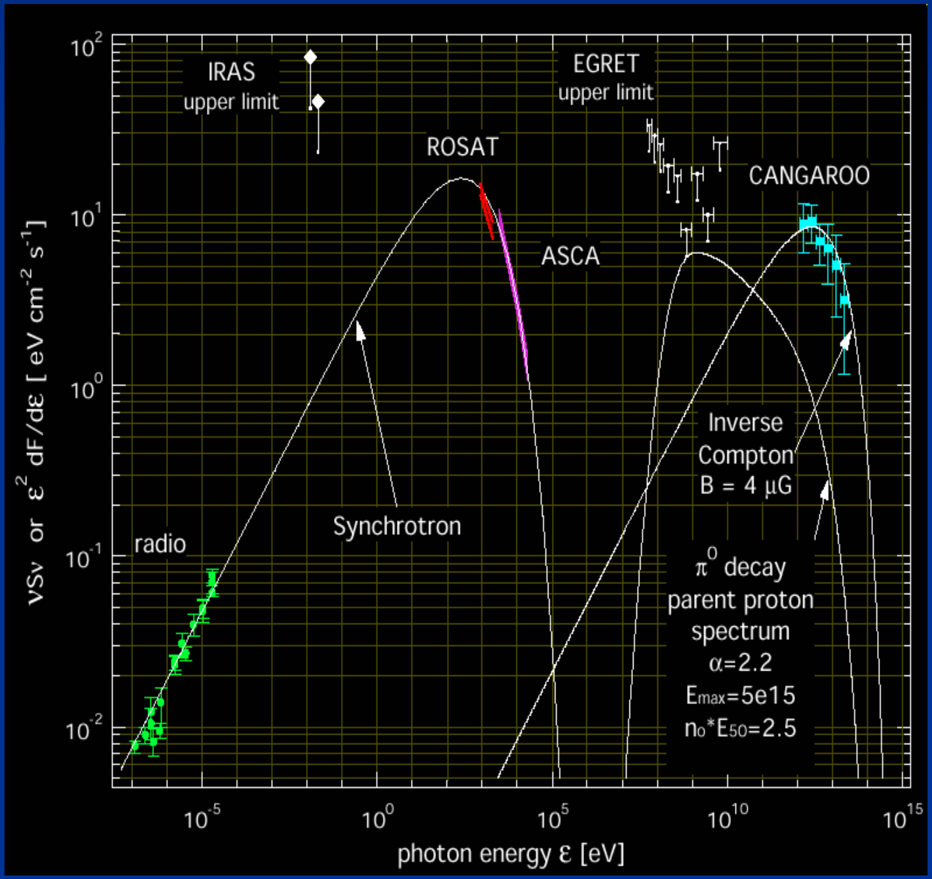
Asahara et al., SPIE 2002

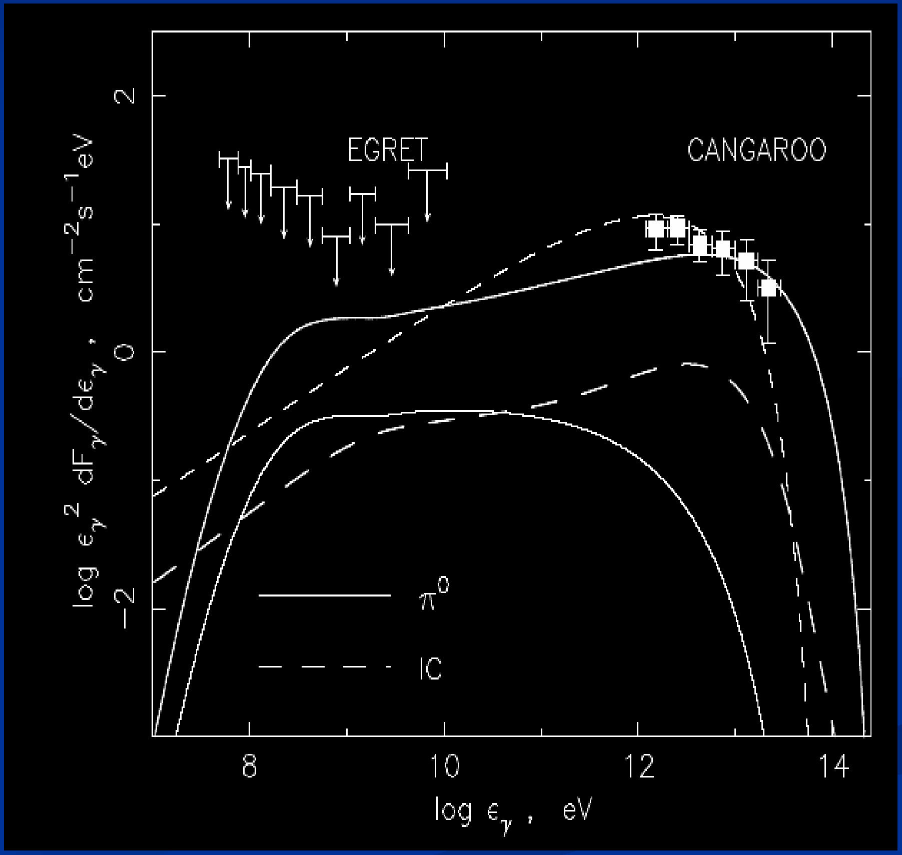
“Known” galactic sources

- 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



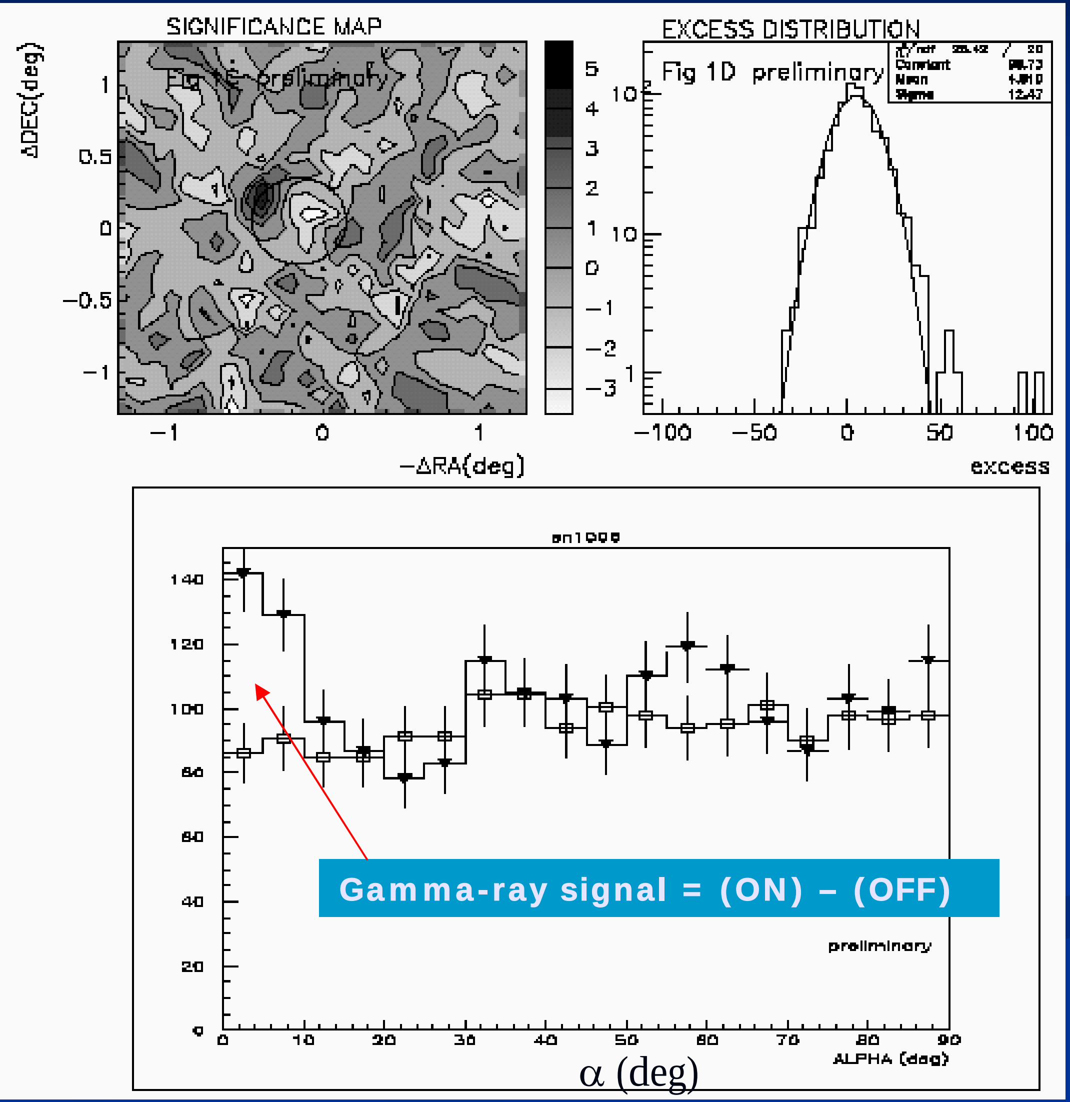


Naito et al. AN 320 (1999)

Voelk et al. AA 396 (2002)

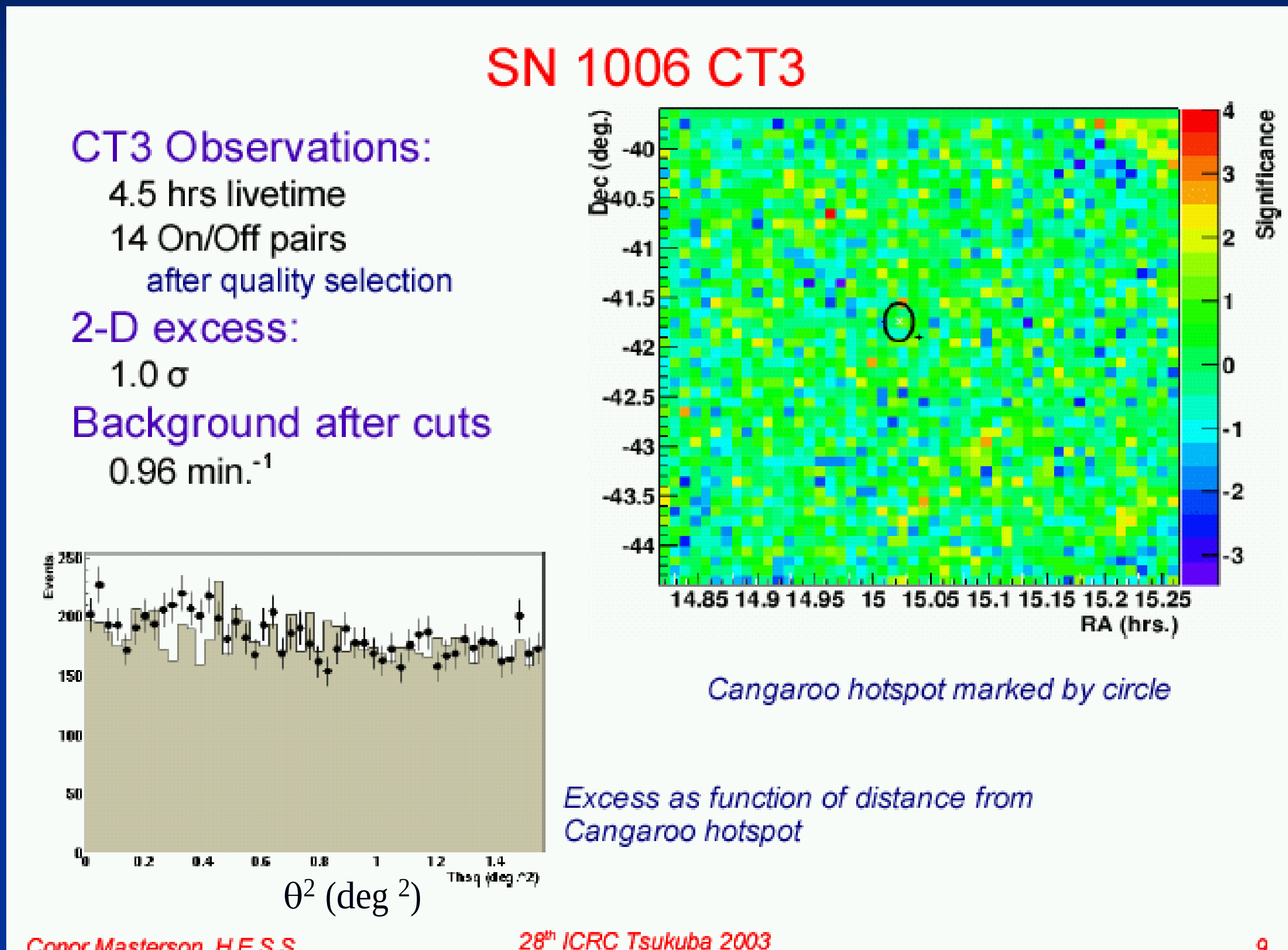
SN1006: HEGRA CT1

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



Vitale et al. 28th ICRC (2003)

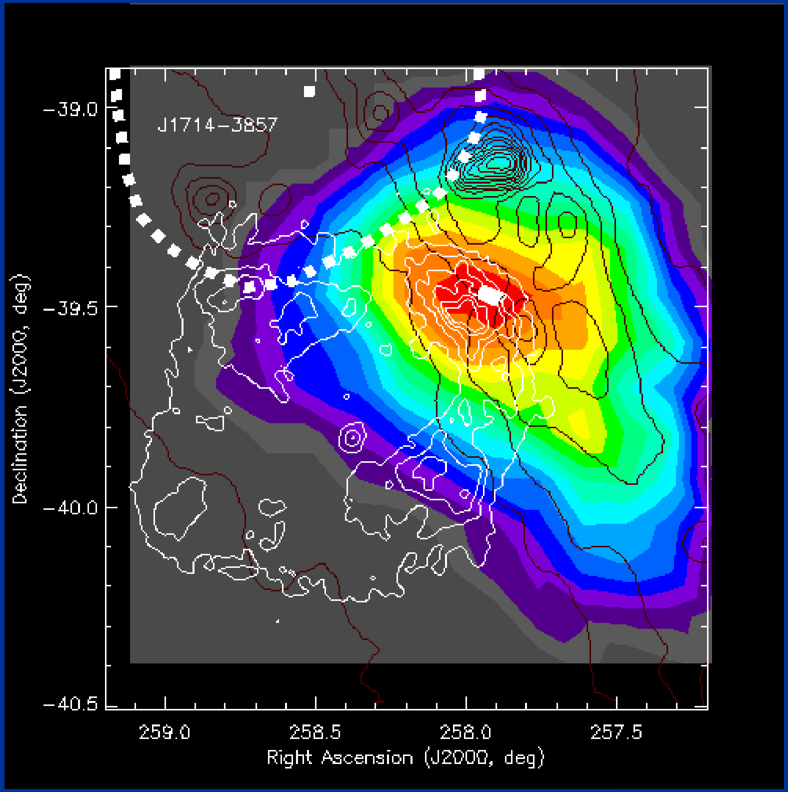
SN1006: H.E.S.S.



Masterson et al., 28th ICRC (2003)

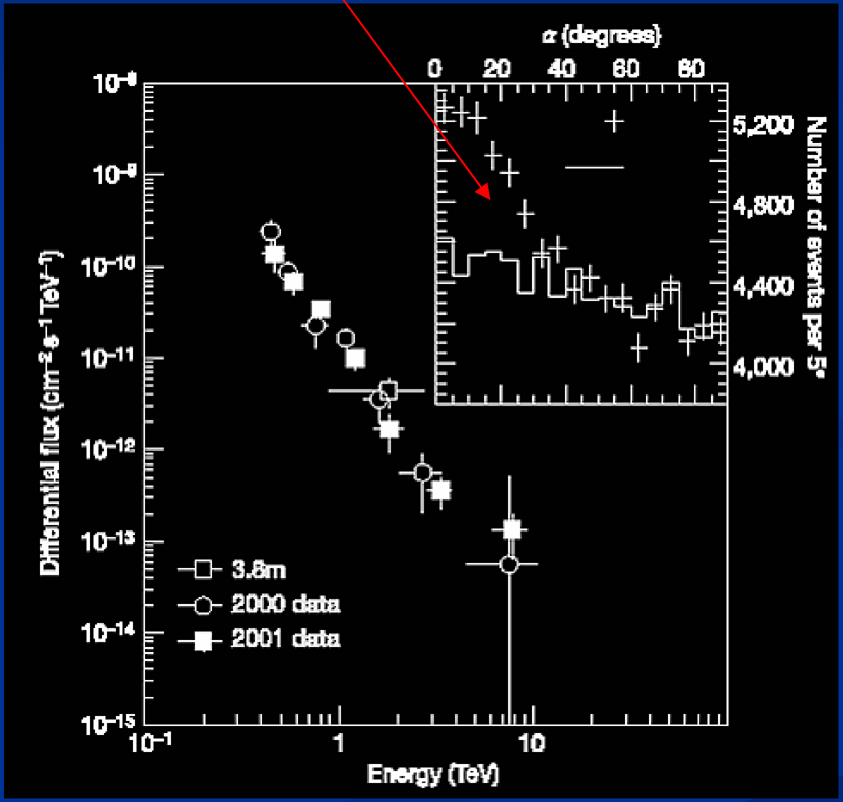
SNR RX J1713.7-3946 (1)

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



Significance map

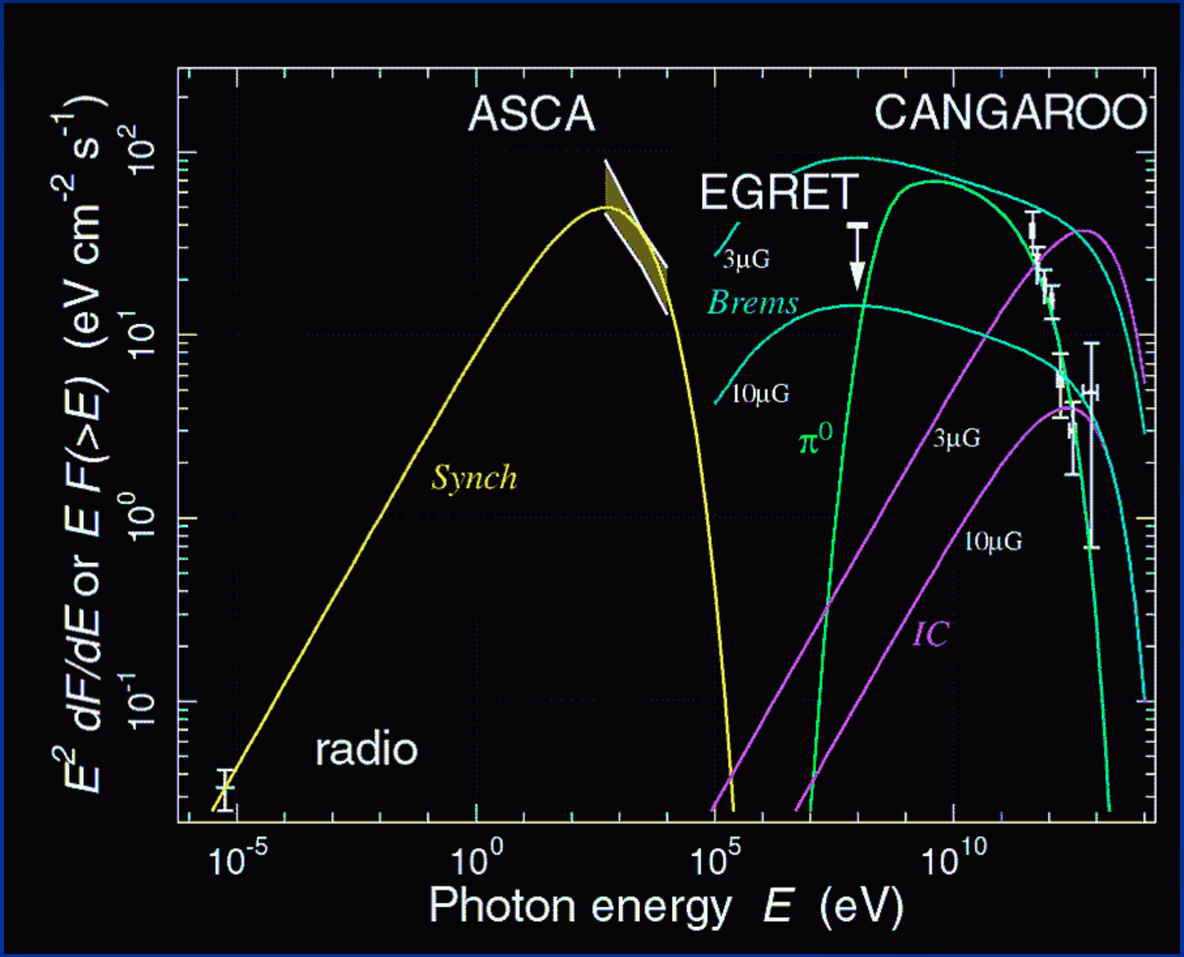
Gamma-ray signal = (ON) – (OFF)



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 ~ $0.001 L_{SN}$

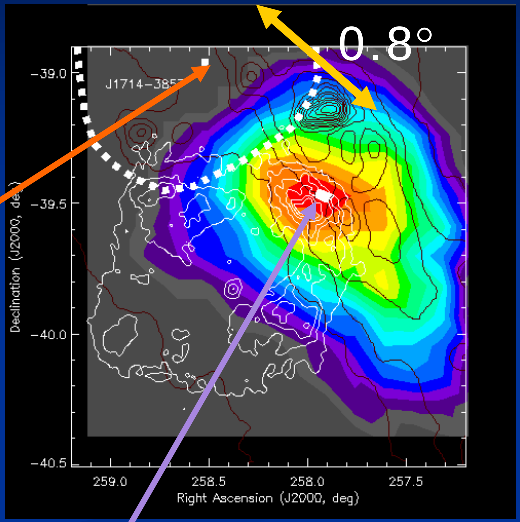
(Fukui et al. PASJ 55, 2003)

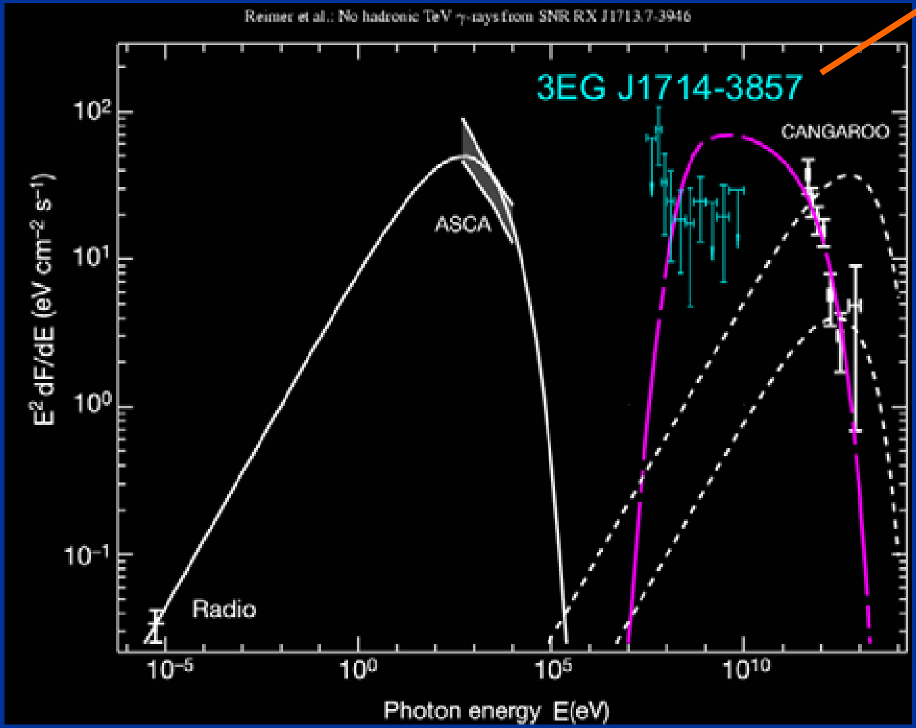
SNR RX J1713.7-3946 (3)

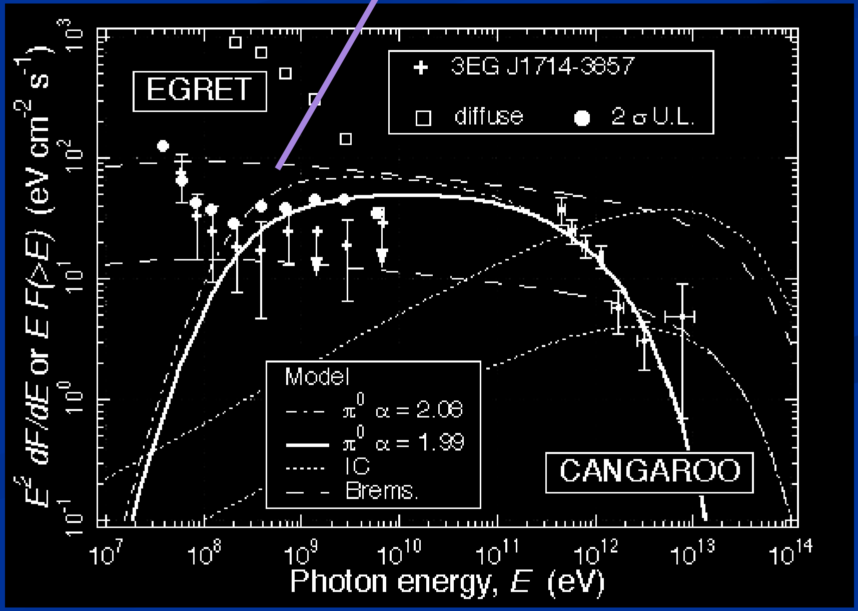
Counter arguments

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

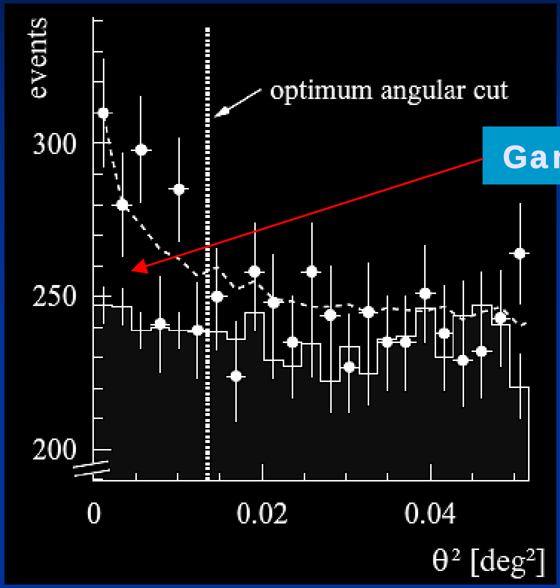
* Butt et al., Nature 418 (2002) 489







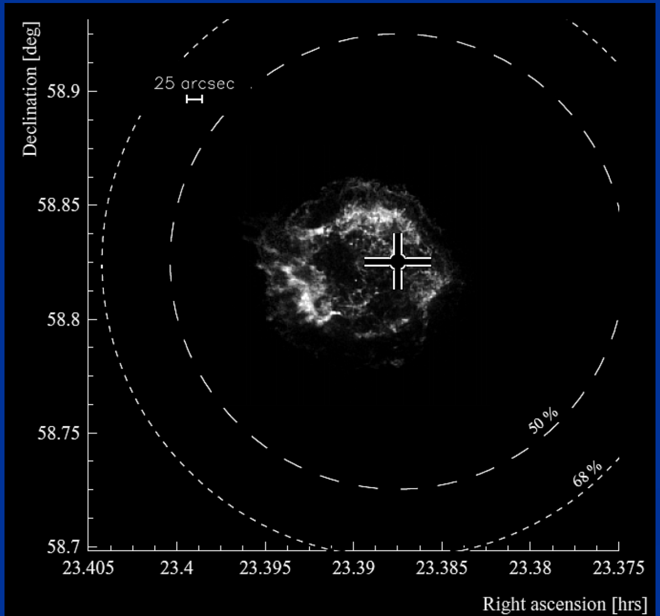
SNR Cas A

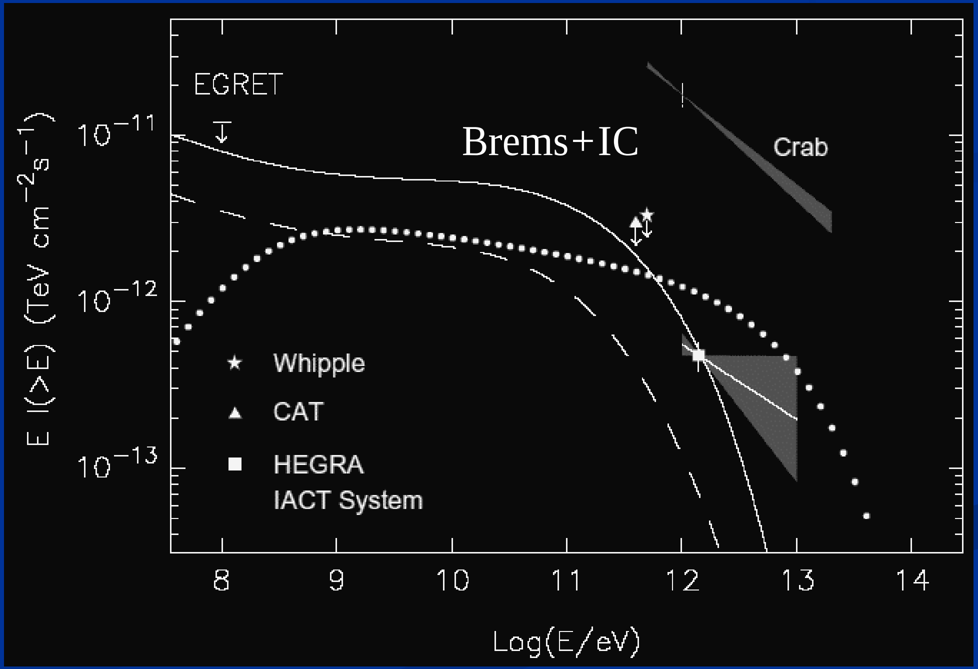


Gamma-ray signal = (ON) – (OFF)

HEGRA-CT system (stereo)

232 hrs

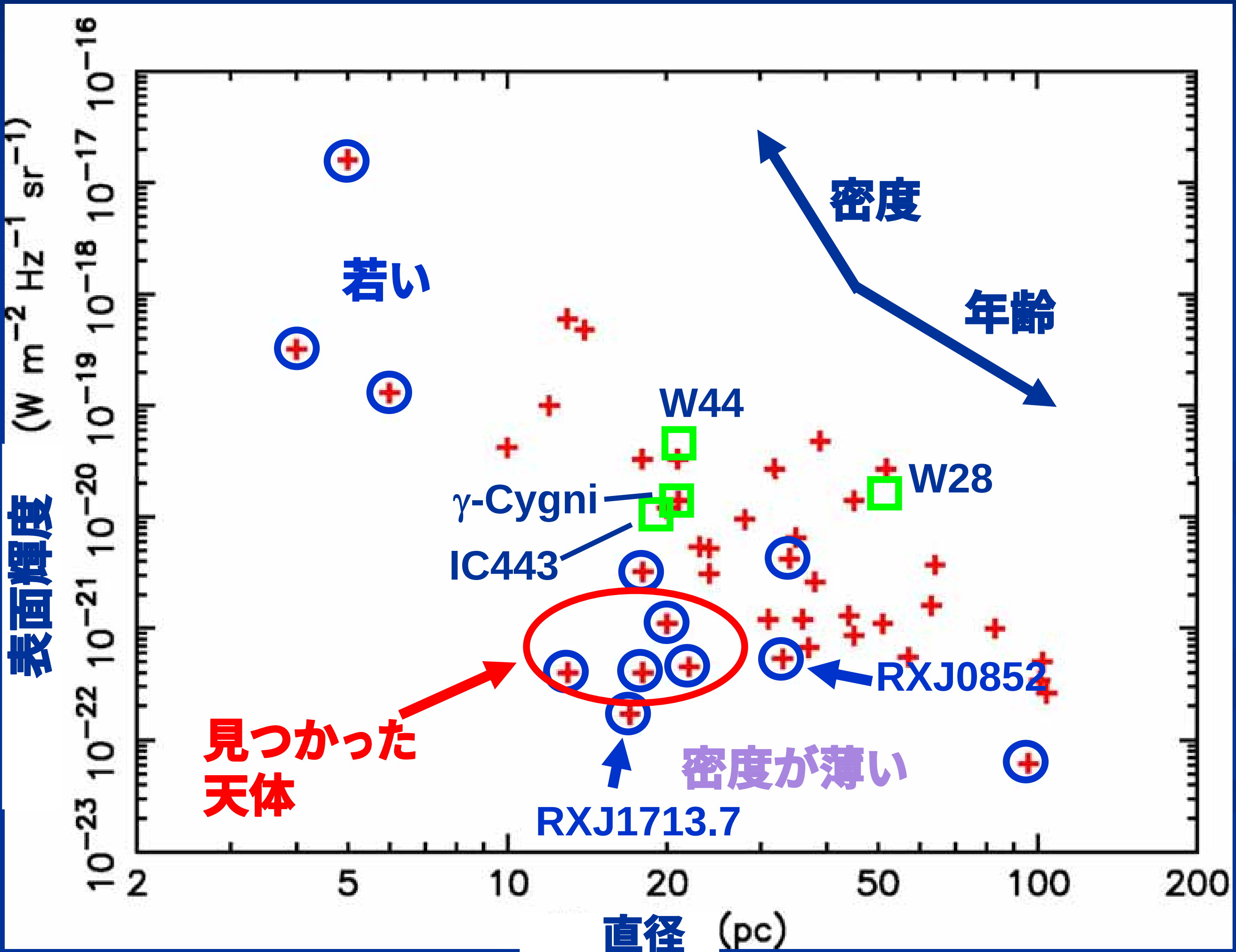




Aharonian et al. A&A 370 (2001) 112

More TeV SNRs?

Ueno, talk in Kyoto, Dec 2003

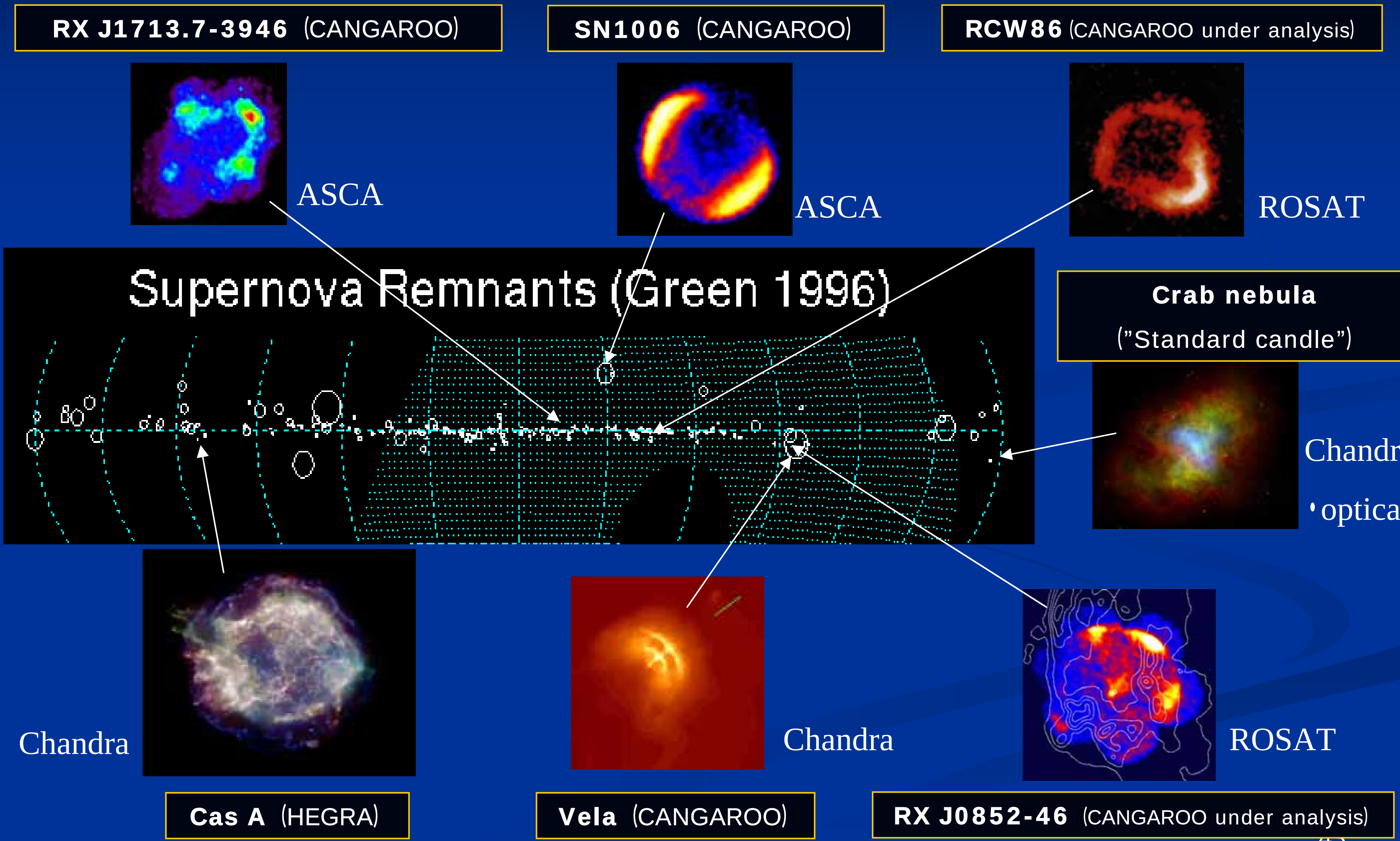


密度が高く
年を取ったもの

シンクロトロンX線
が受からない

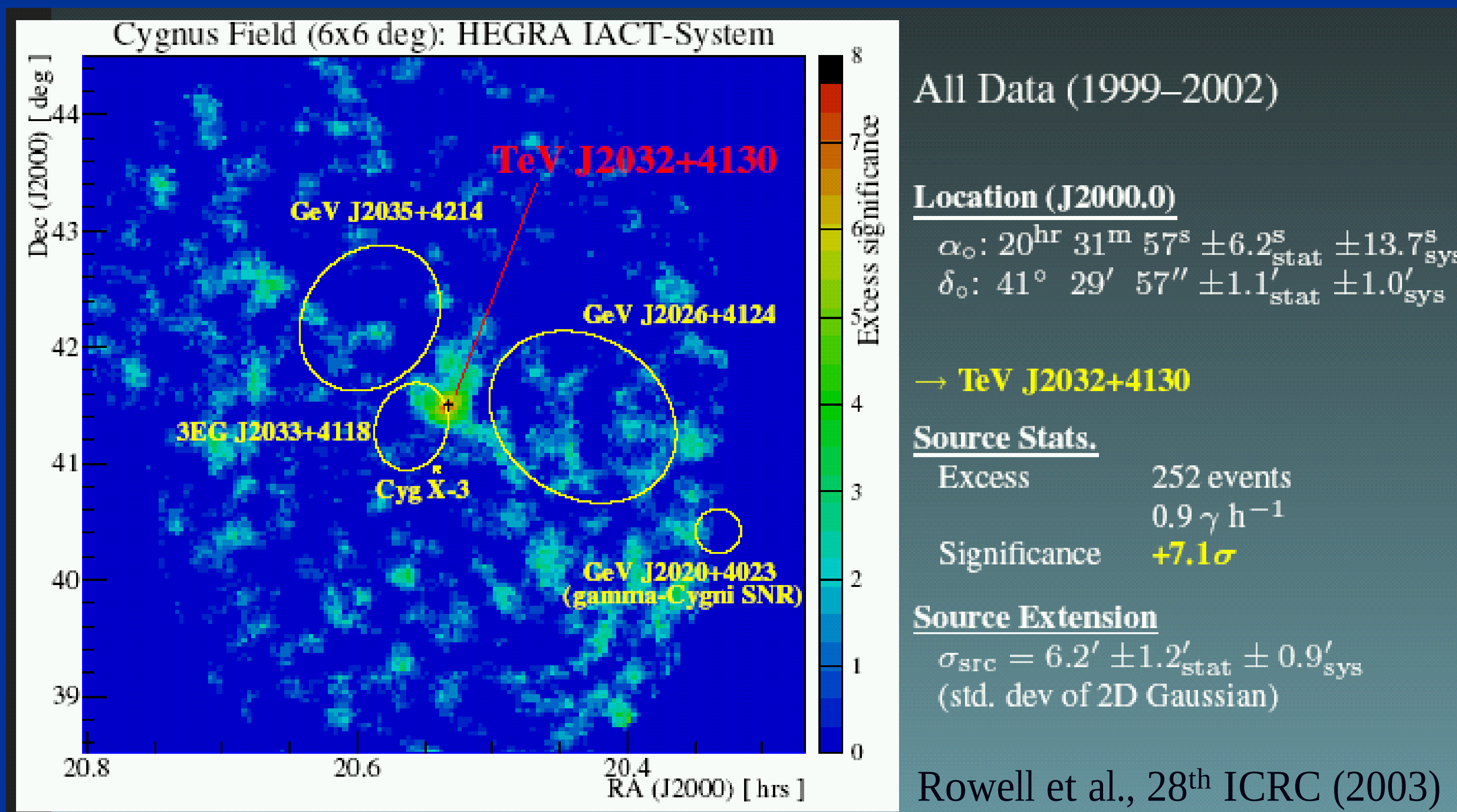
EGRET天体

Systematic study of SNRs



New entry: TeV J2032+4130

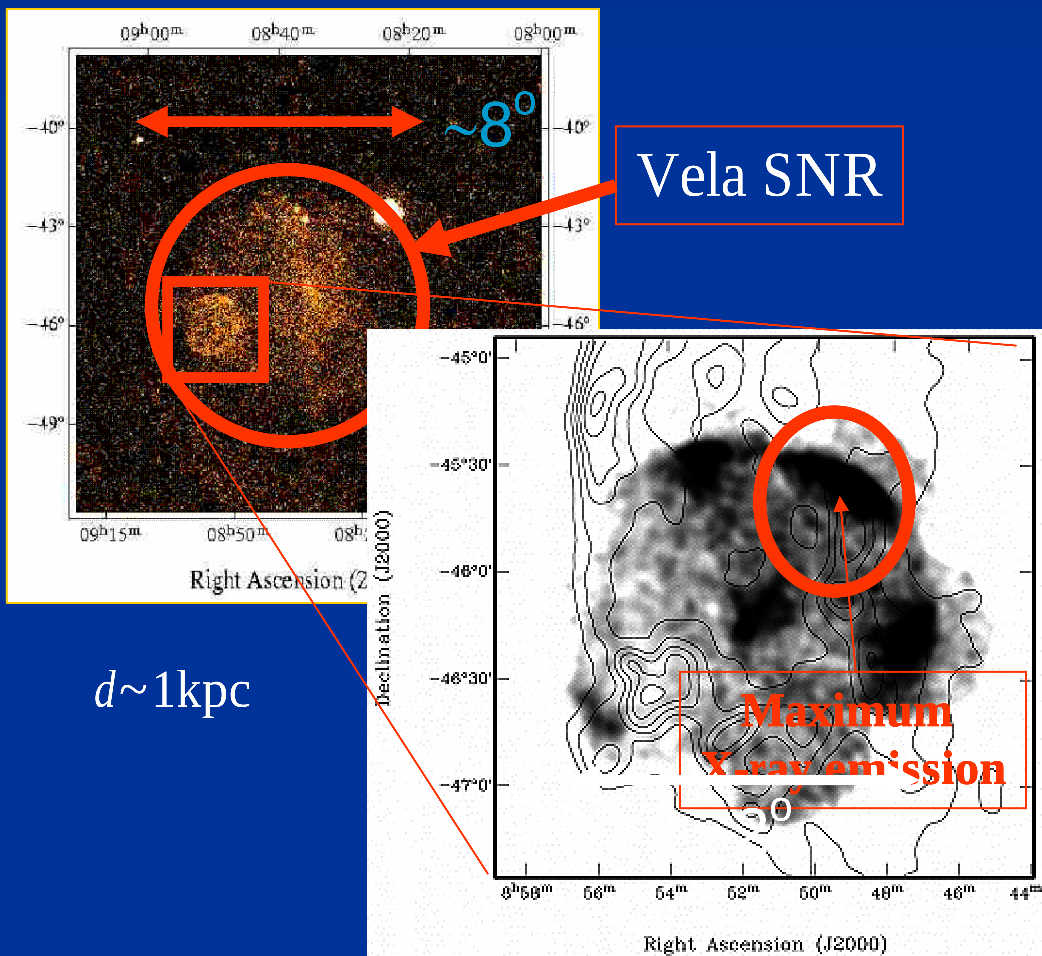
- Unidentified TeV source TeV J2032+4130
  - Very hard spectrum $E^{-1.9}$
  - No counterpart in radio or X-rays



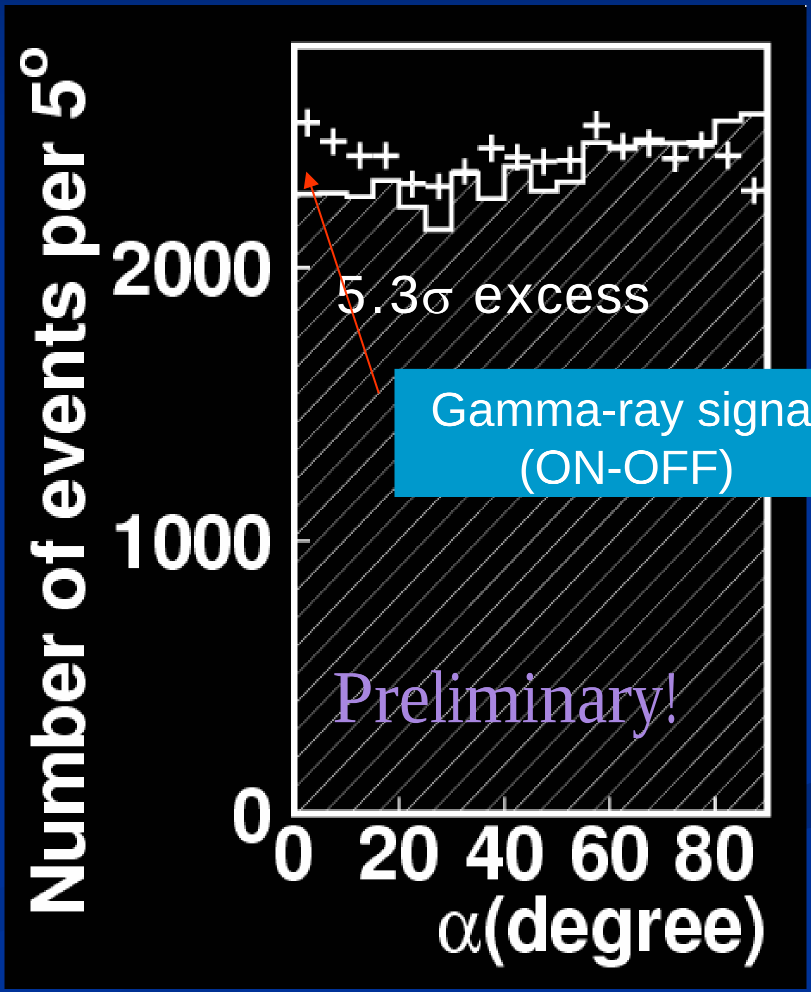
Rowell et al., 28^{th} ICRC (2003)

New entry: SNR RX J0852.0-4622

- CANGAROO 10m result

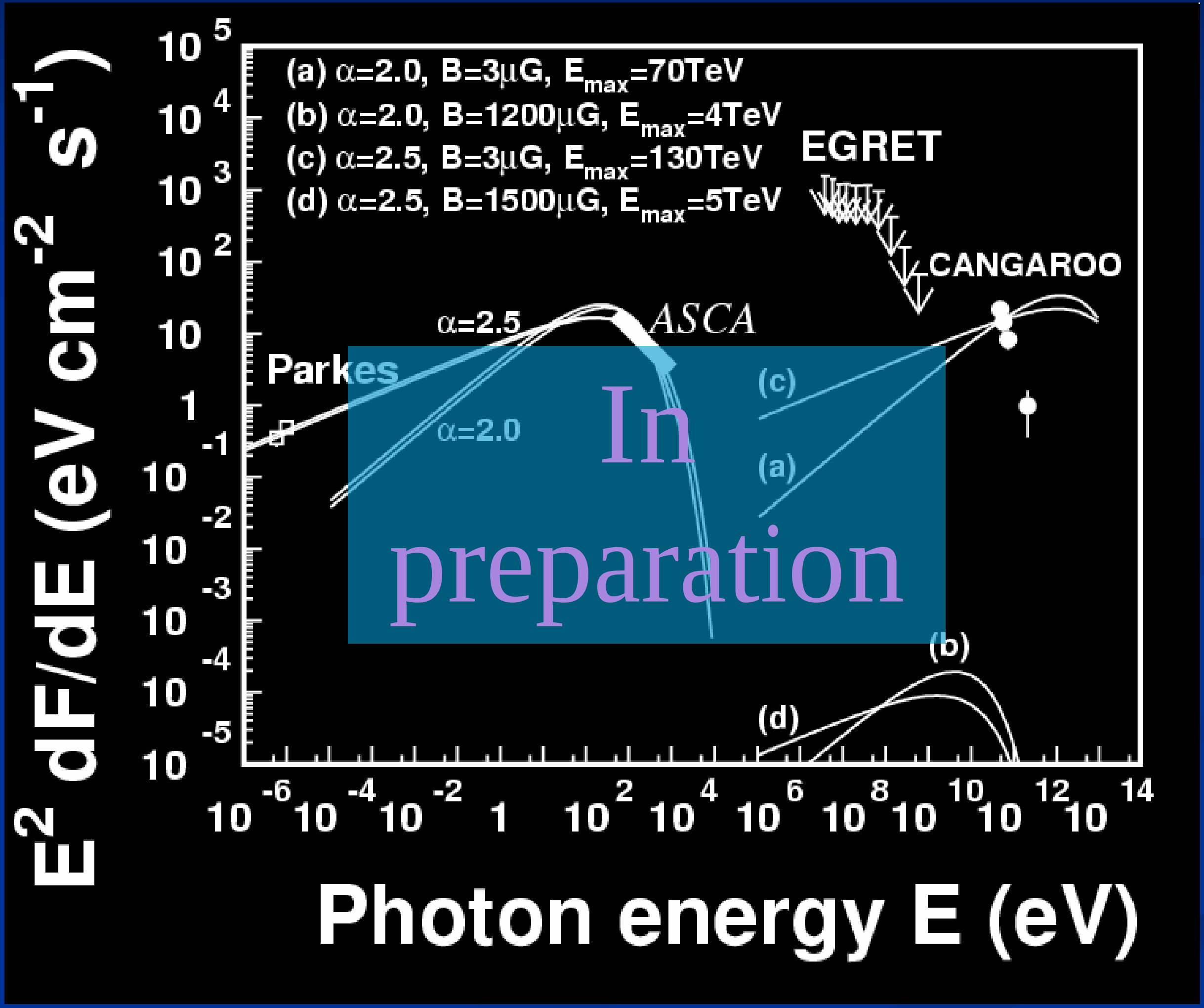


d~1kpc



Katagiri et al., 28th ICRC (2003)

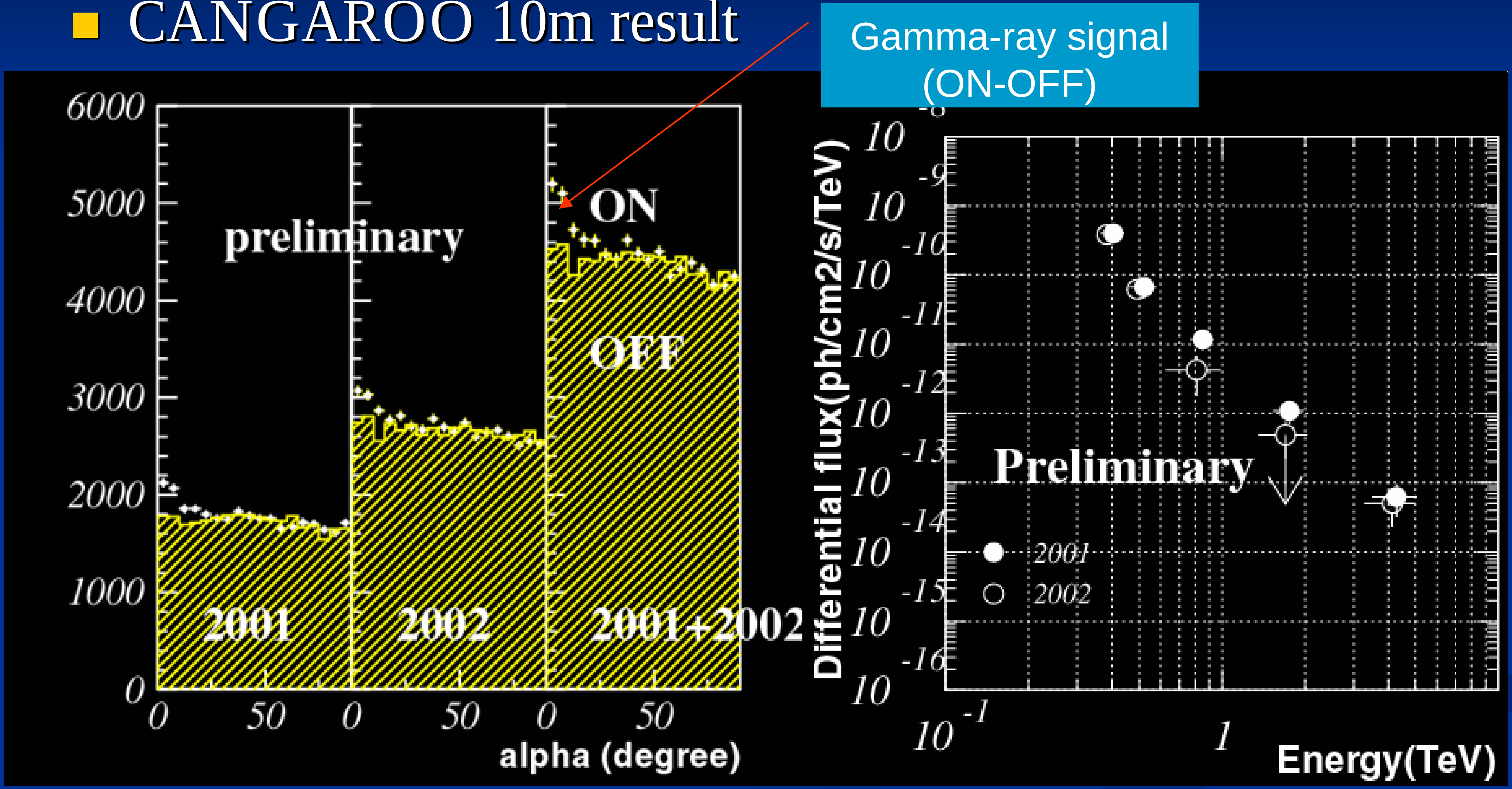
SNR RX J0852.0-4622: IC emission?



Katagiri, Ph.D. thesis (2004)

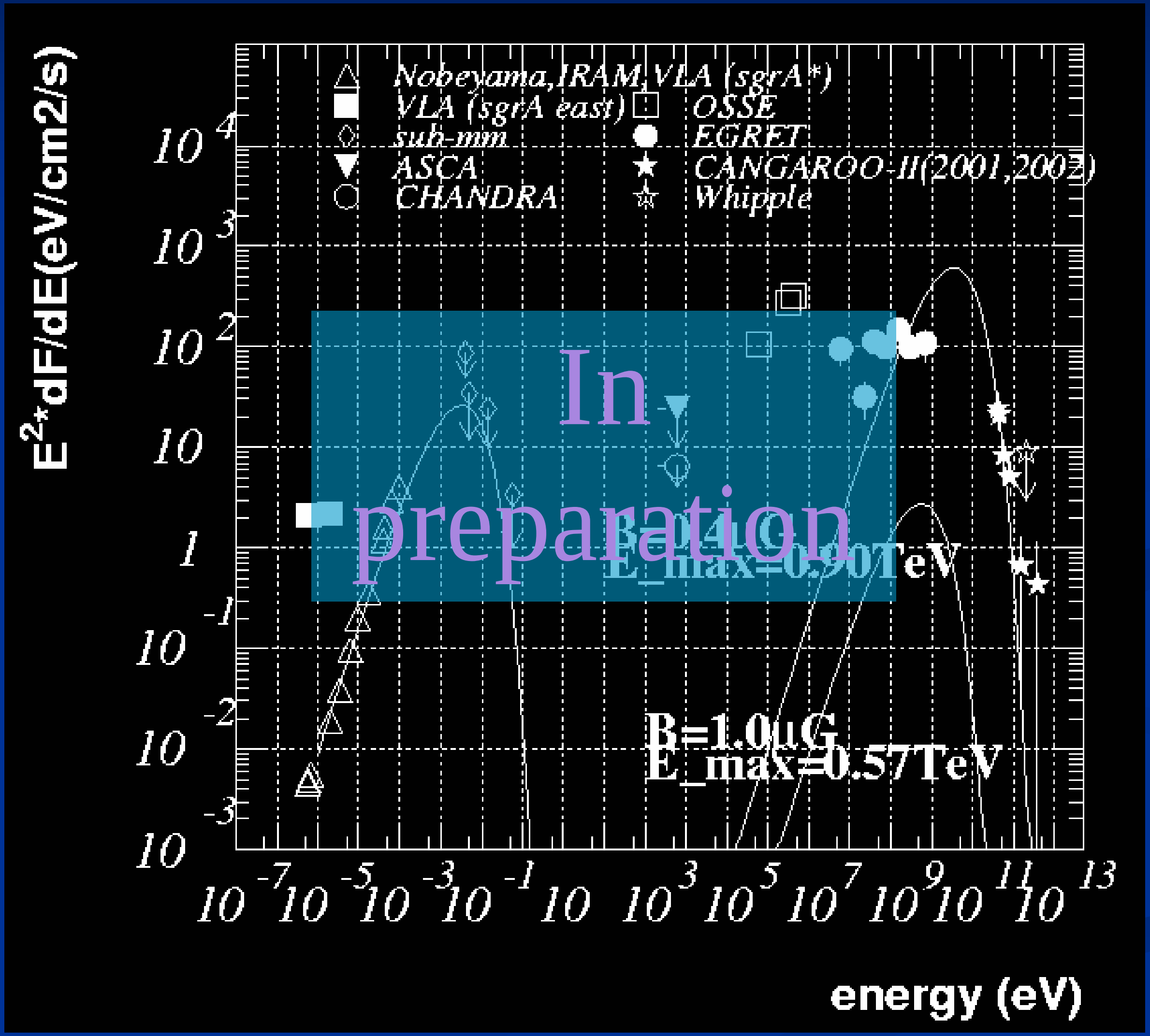
New entry: Galactic center

- CANGAROO 10m result



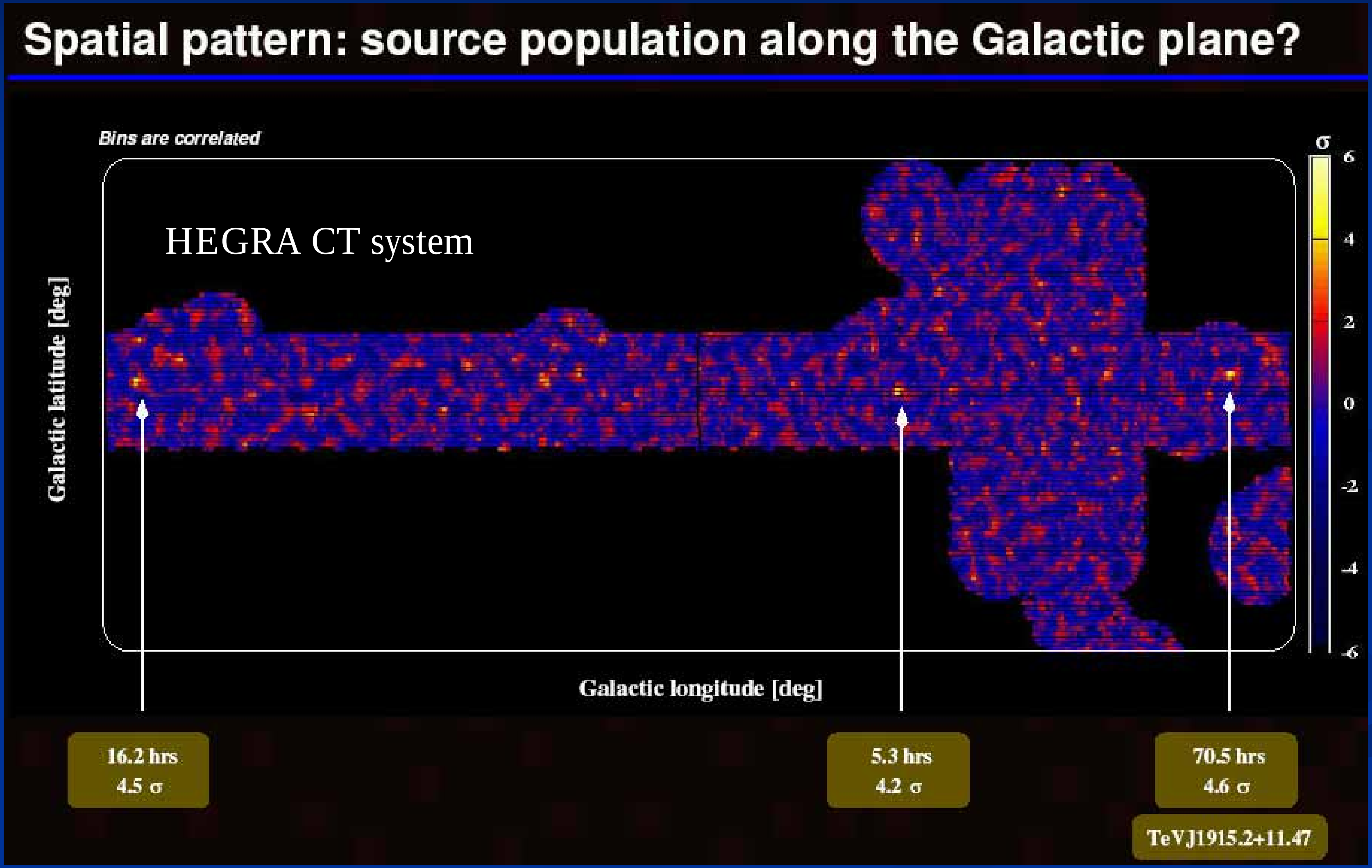
Tsuchiya et al., 28th ICRC (2003)

Galactic center: IC emission?



Tsuchiya, Ph.D. thesis in preparation (2004)

Galactic plane survey

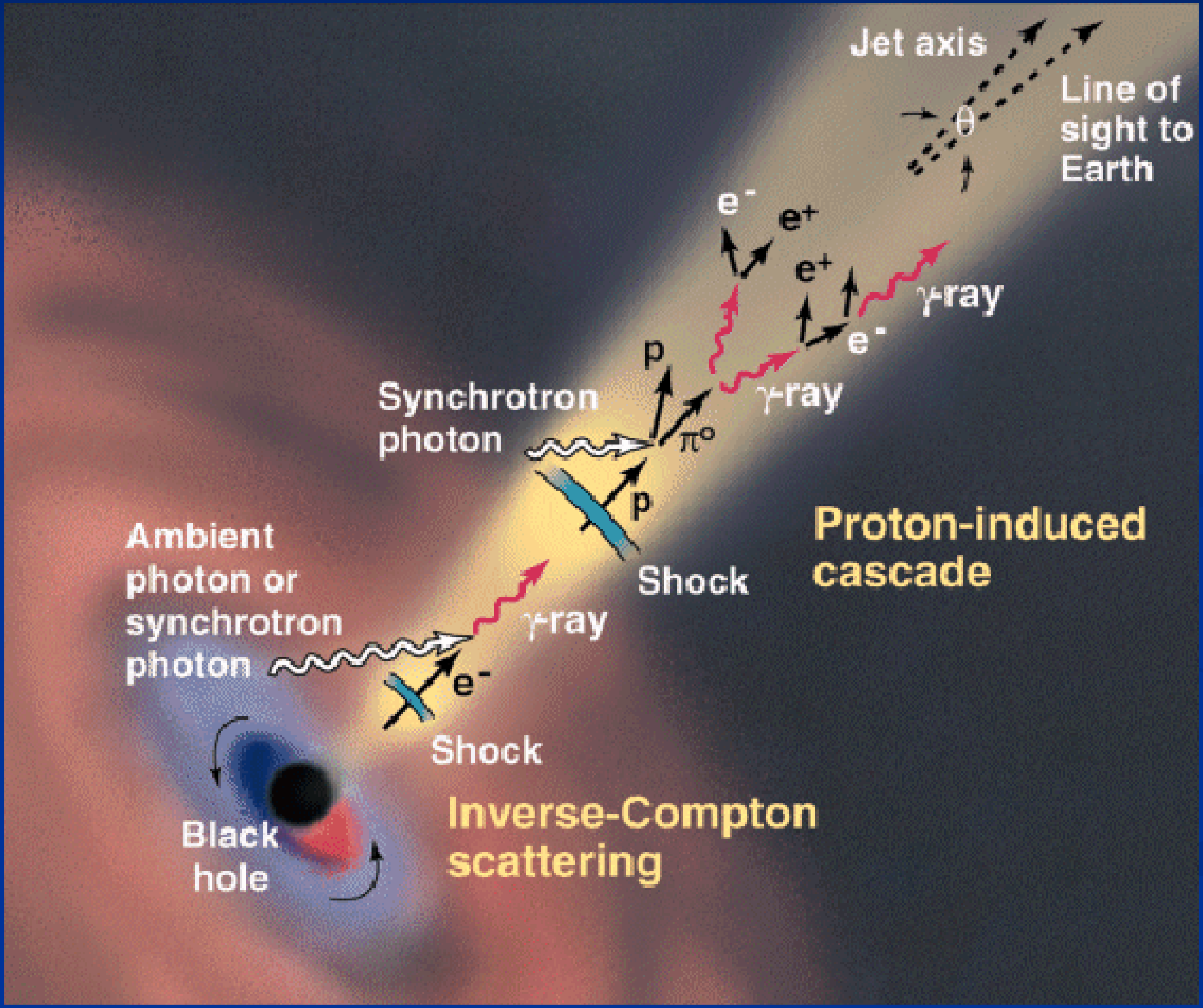


Puehlhofer et al., 28th ICRC (2003)

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

$\nu \propto \nu_0 \delta$

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

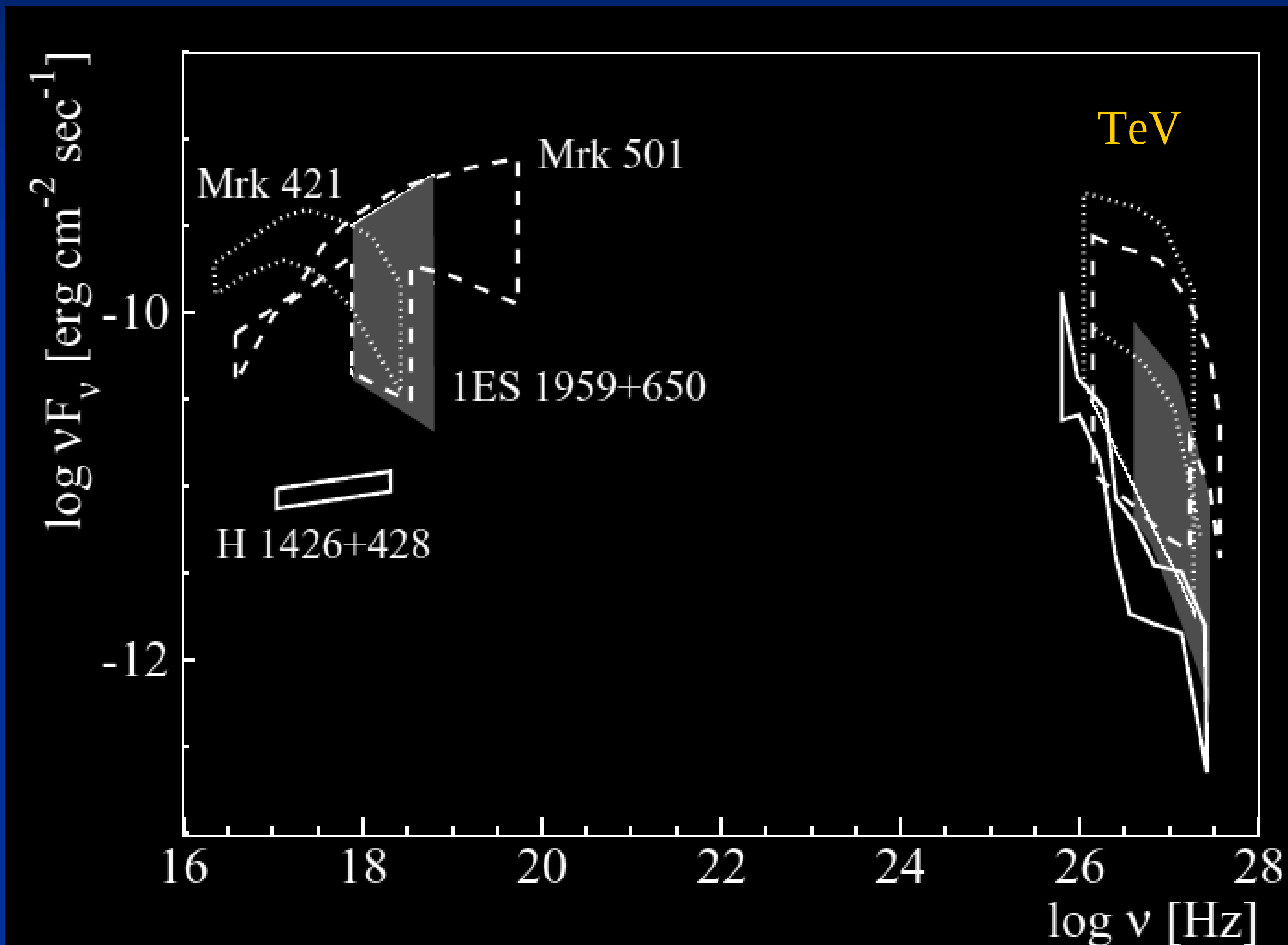
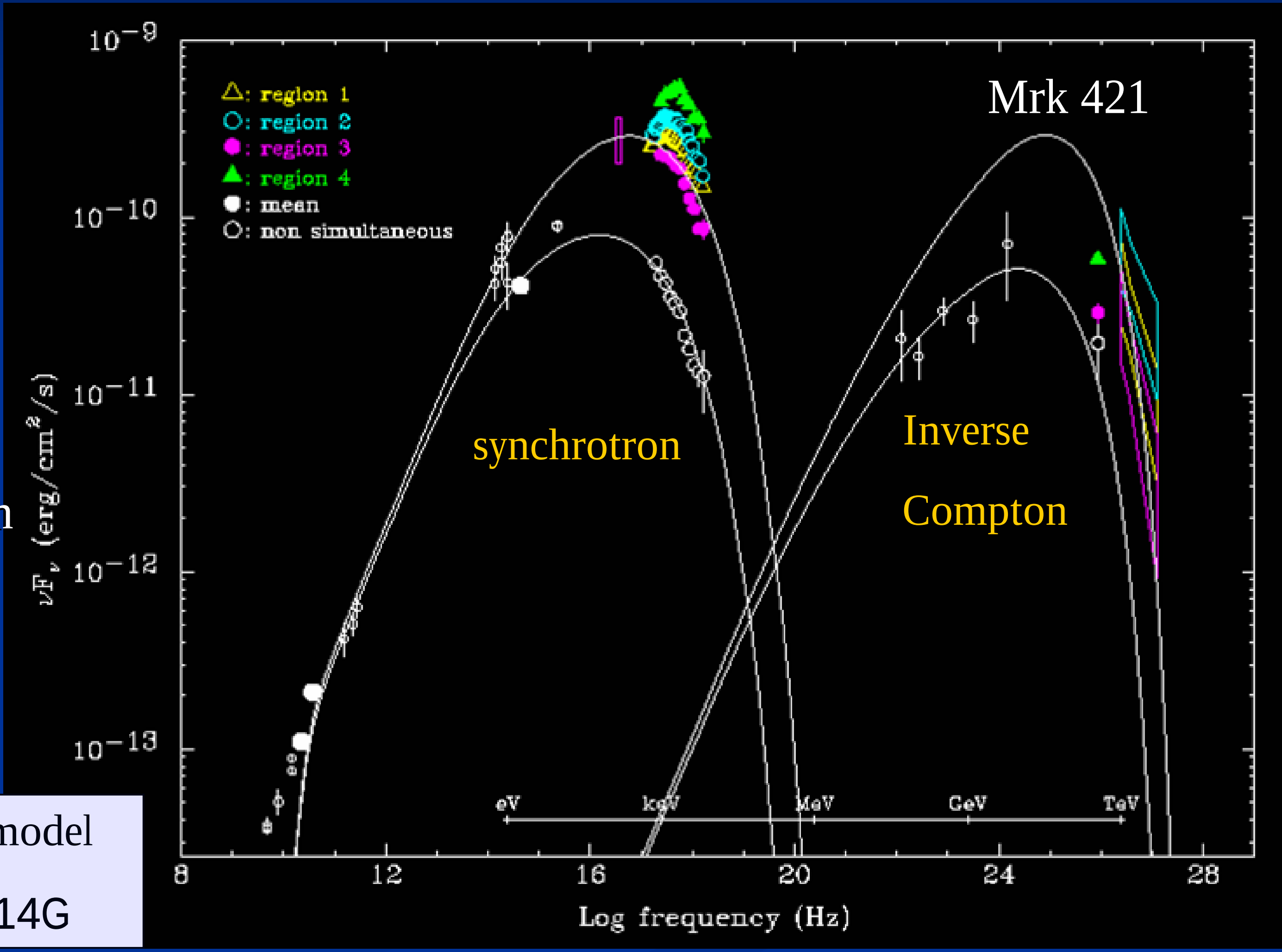


Fig. 1. Simultaneous and non-simultaneous X-ray and TeV γ-ray energy spectra of the 4 TeV blazars with measured TeV γ-ray energy spectra. The regions show the range of values that have been observed with BeppoSAX, RXTE and Cherenkov Telescopes (from (46)).

Krawczynski, astro-ph/0309443

Synchrotron Self-Compton model

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



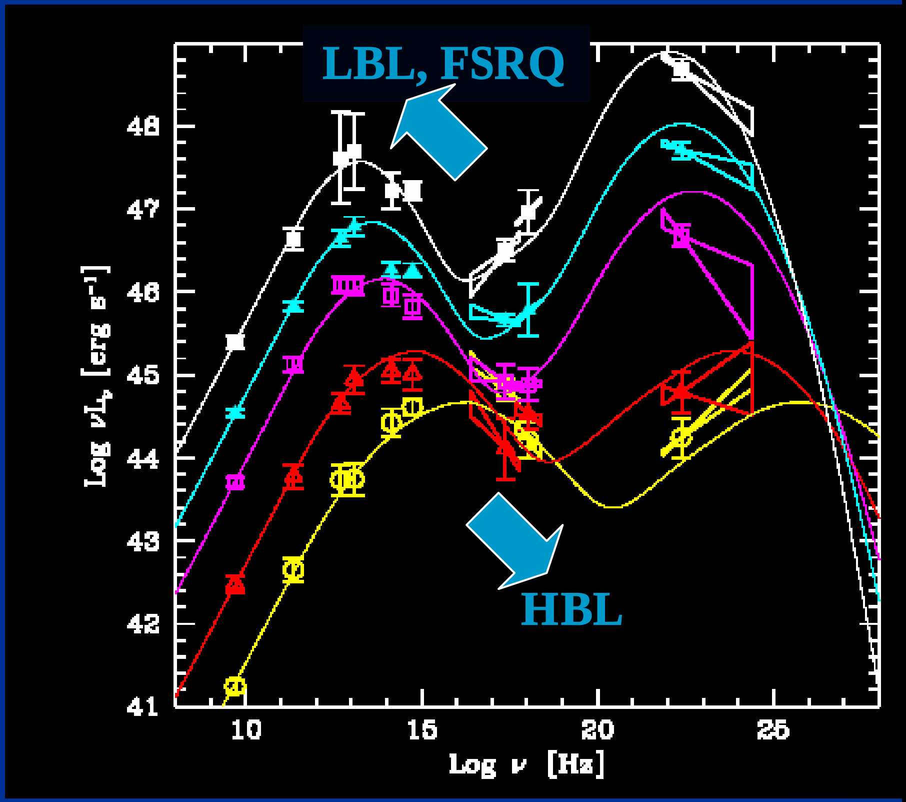
One-zone SSC model

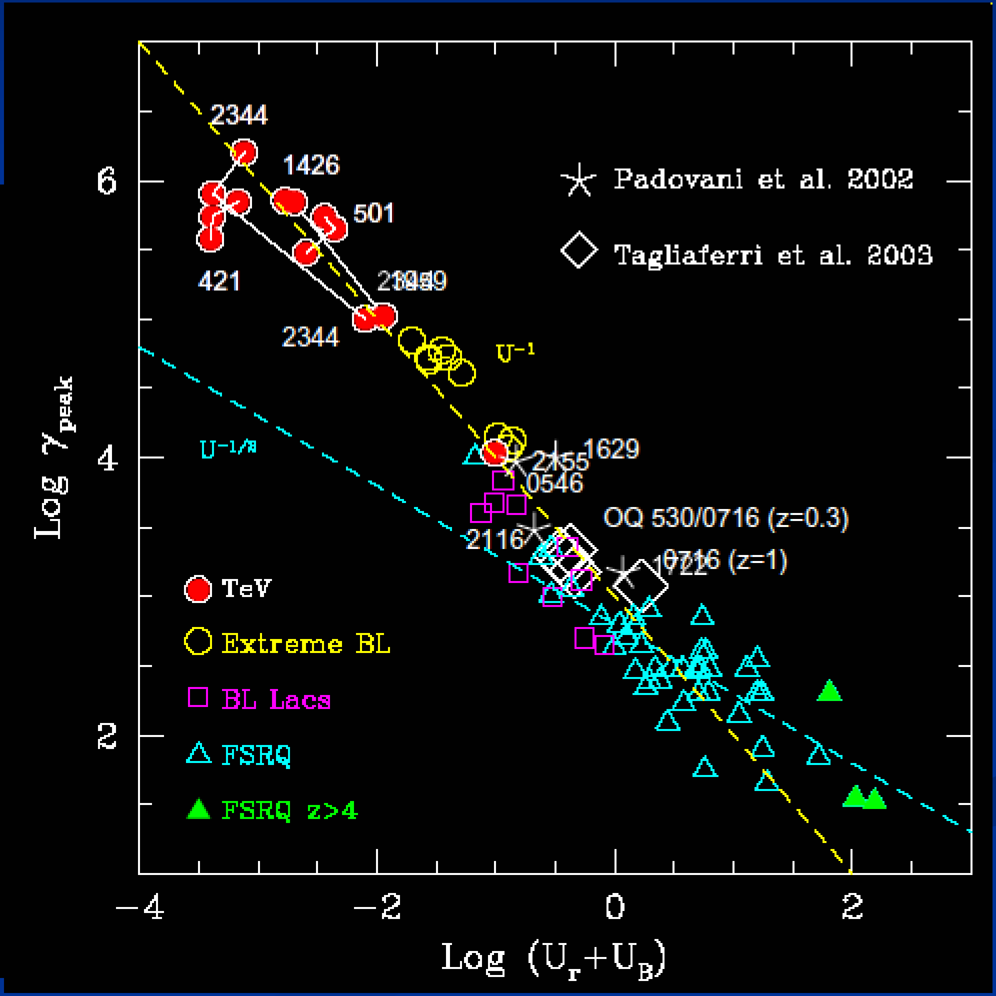
δ =14, B=0.14G

Takahashi et al. ApJ 542, 2000

Blazar sequence & SSC model

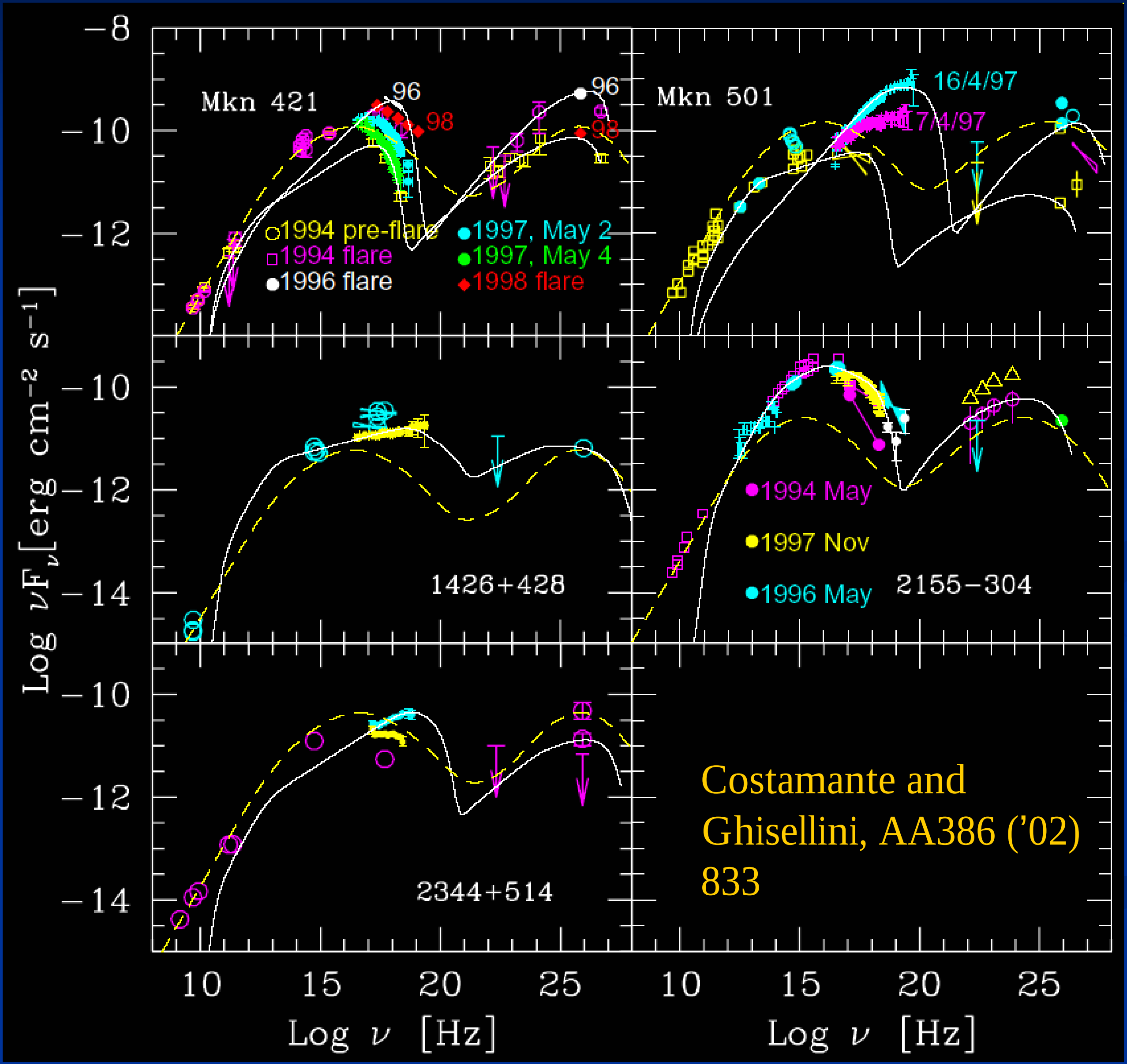
- $(\nu f_\nu)_{synch} \sim (\nu f_\nu)_{IC}$





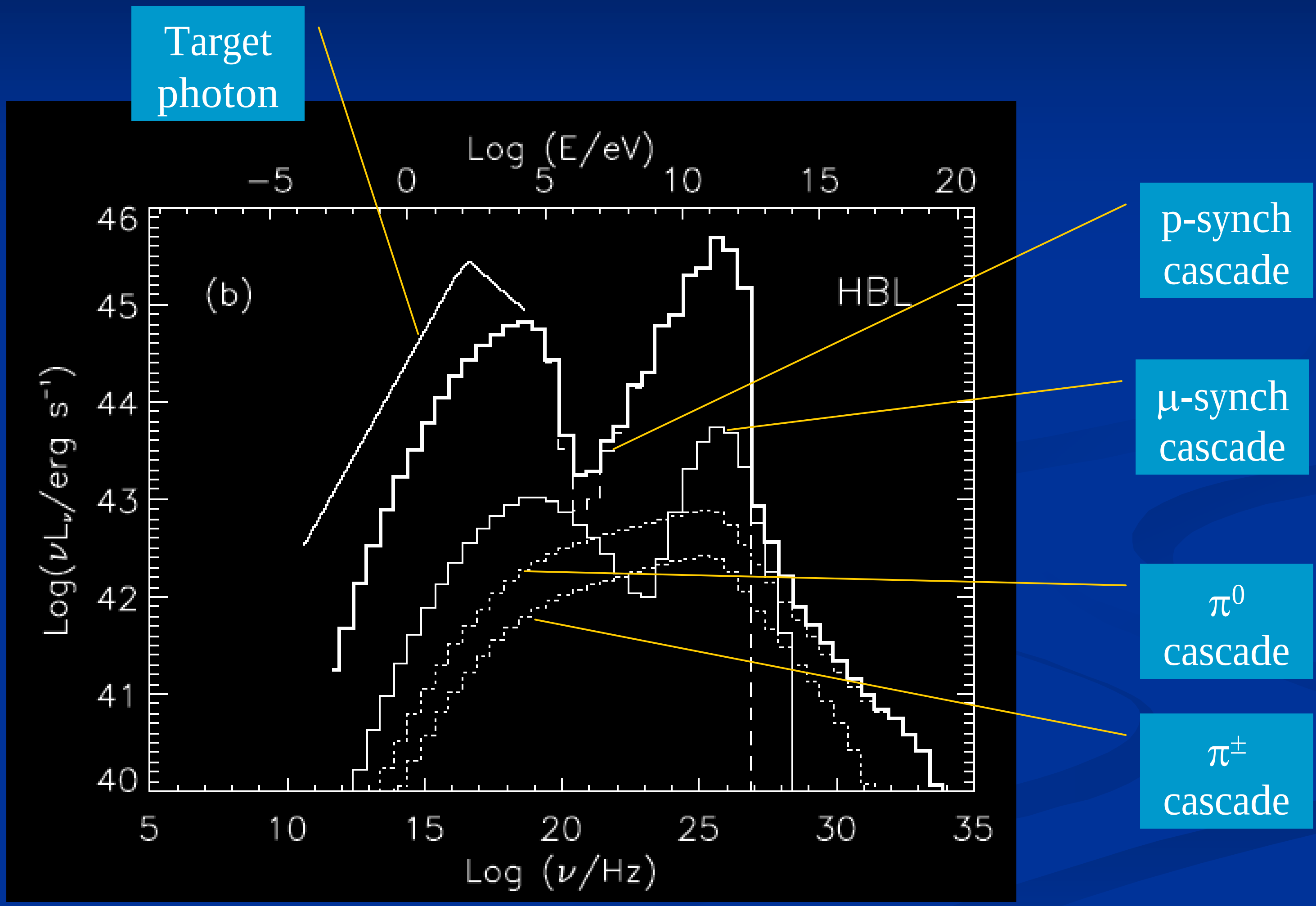
Ghisellini, astro-ph/0308526

SED of TeV blazars



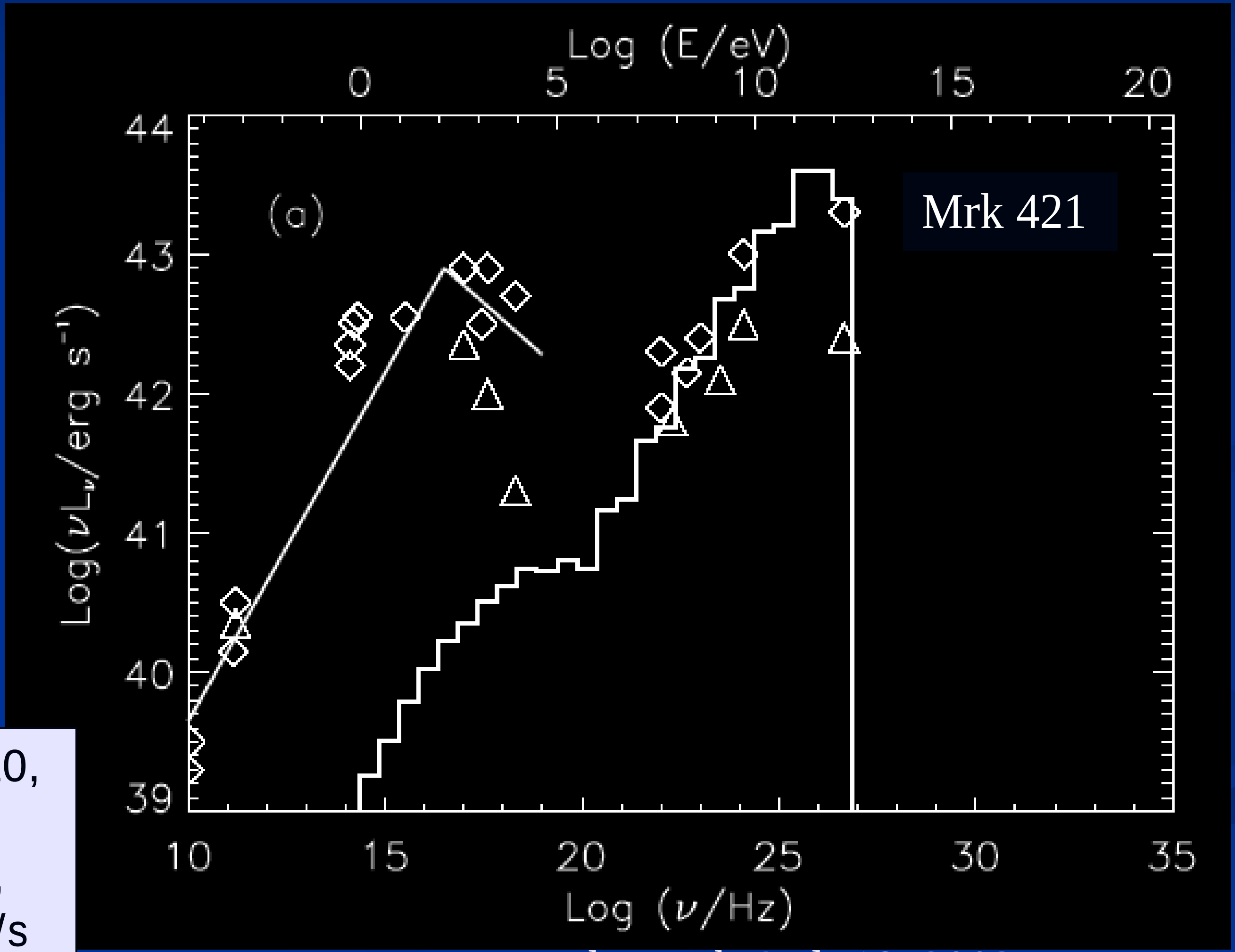
Costamante and Ghisellini, AA386 ('02) 833

Synchrotron proton blazar model (1)



Muecke et al. APh 18, 2003

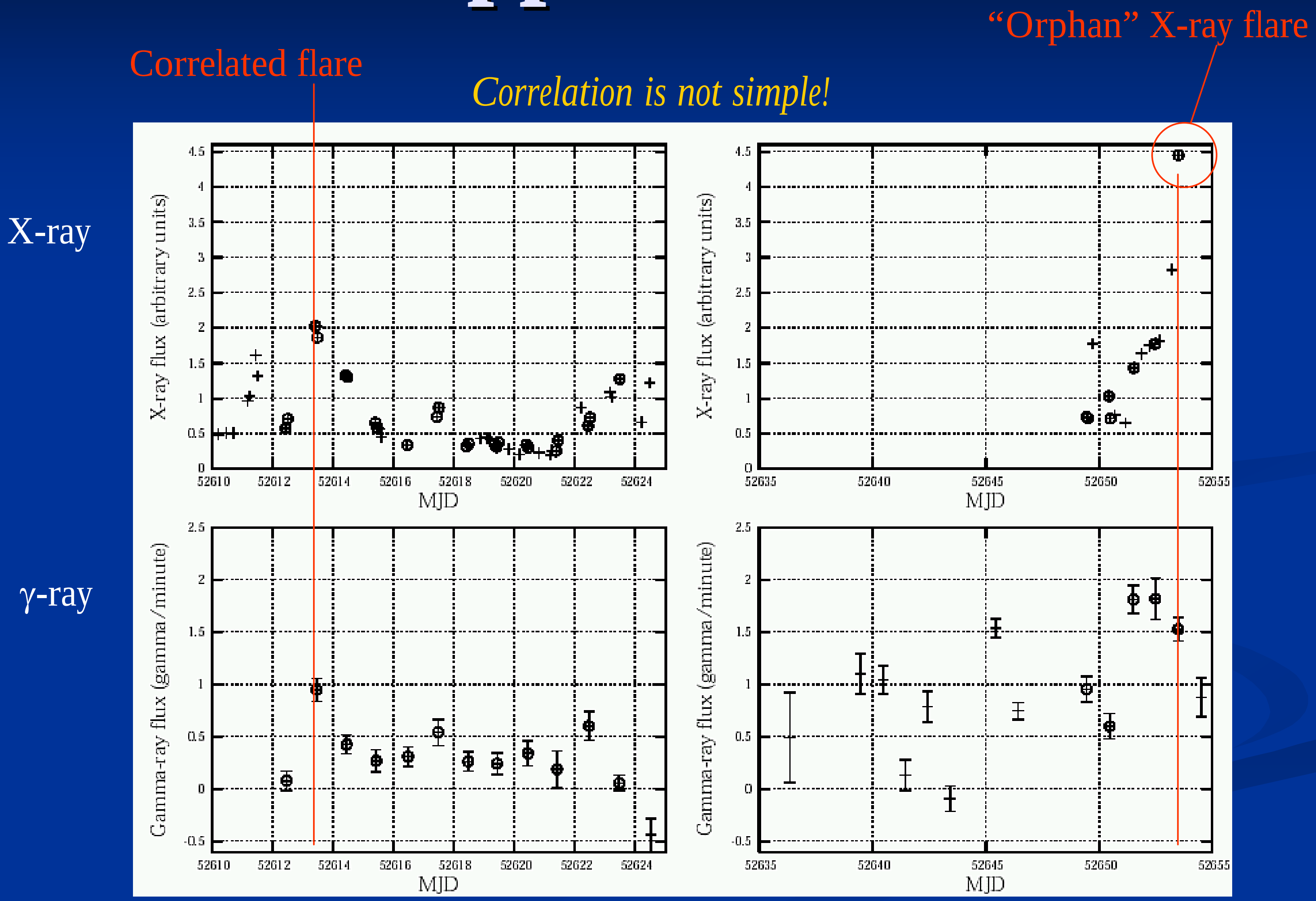
Synchrotron proton blazar model (2)



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

Muecke et al. APh 18, 2003

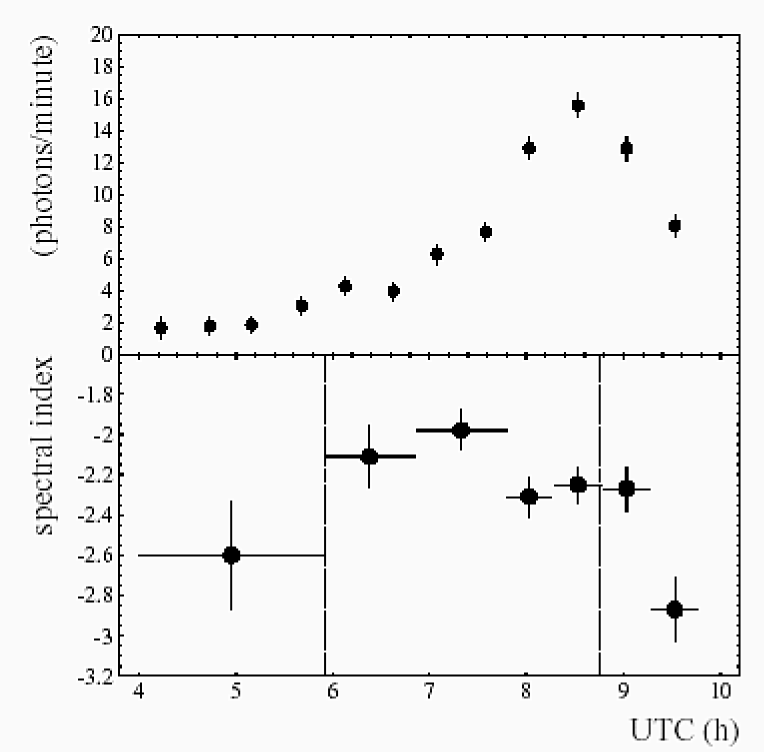
Mrk421: Whipple Flare Dec02-Jan03



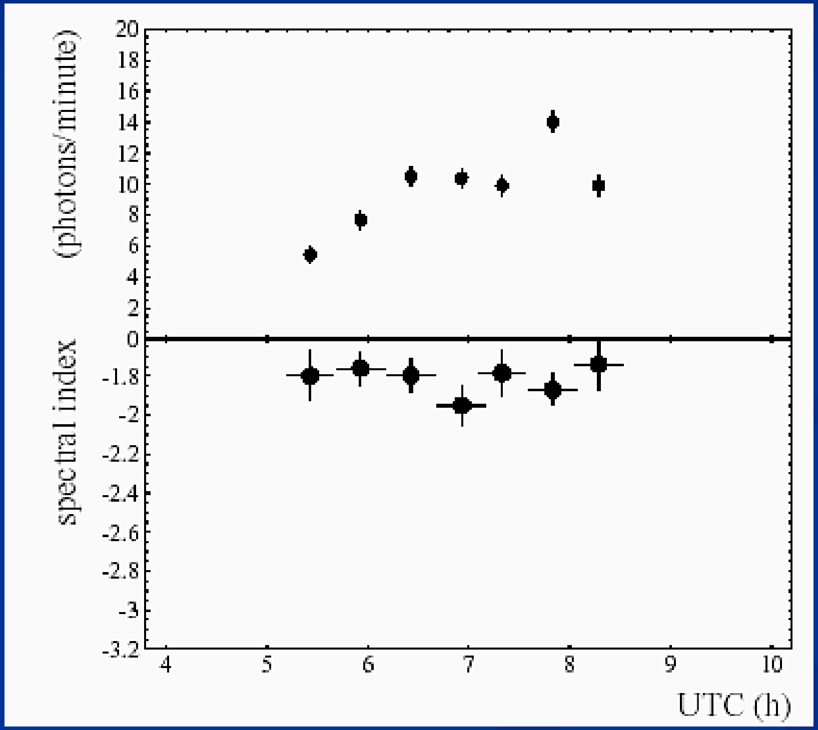
Rebillot et al. 28th ICRC (2003)

Mrk421: Whipple Hourly variability

Mar 19, 2001



Mar 25, 2001

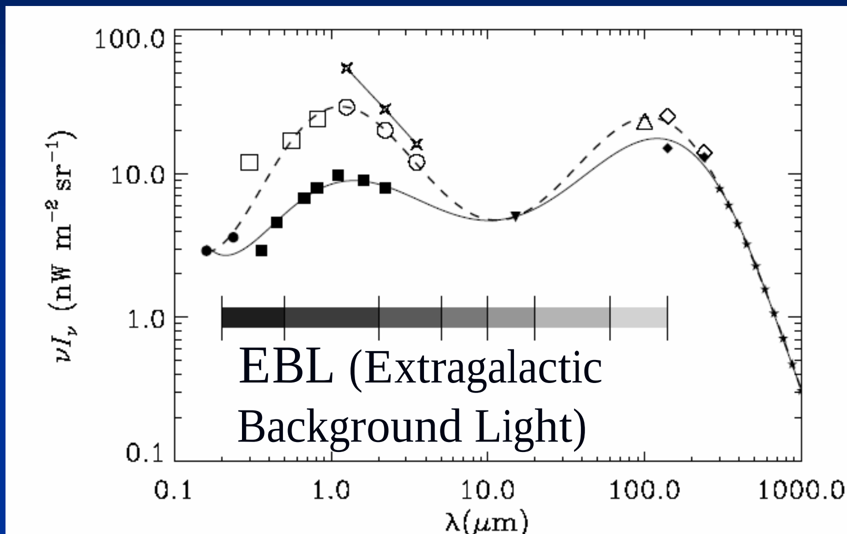


Harder for stronger ↔ Constant slope

Why this difference?

Krennrich et al., 28th ICRC (2003)

TeV gamma-ray absorption on EBL (1)



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

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

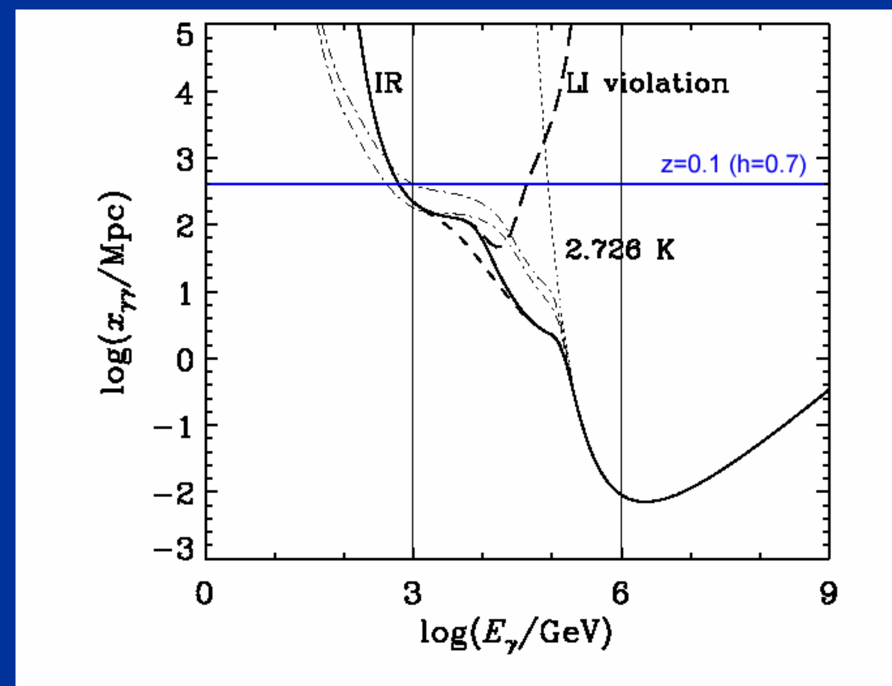
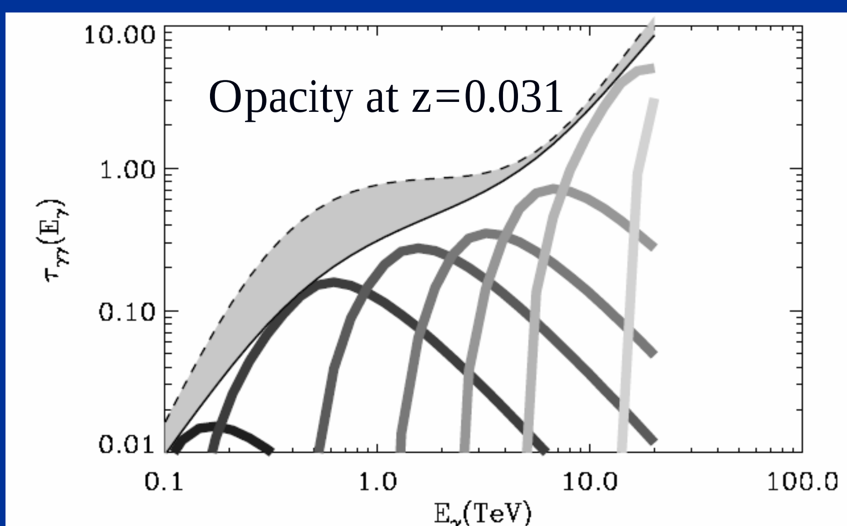


Figure 2: Mean free path for photon-photon pair production in the infrared–microwave background radiation. The curves correspond to those in Fig. 1 except that the effect of Lorentz Invariance violation discussed in Section 4 is shown by the long dashed curve.



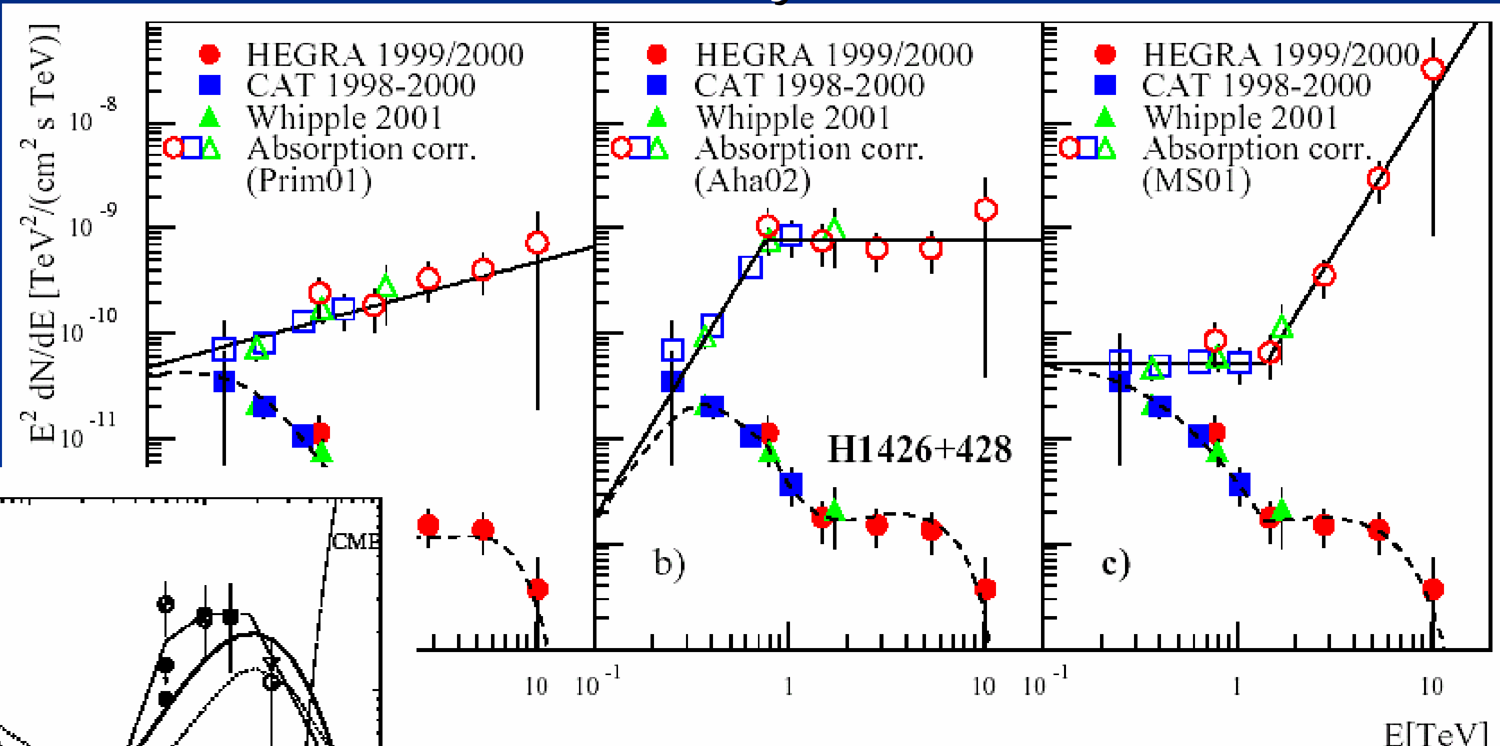
Dwek, "Universe Viewed in Gamma-rays", Kashiwa, 2002

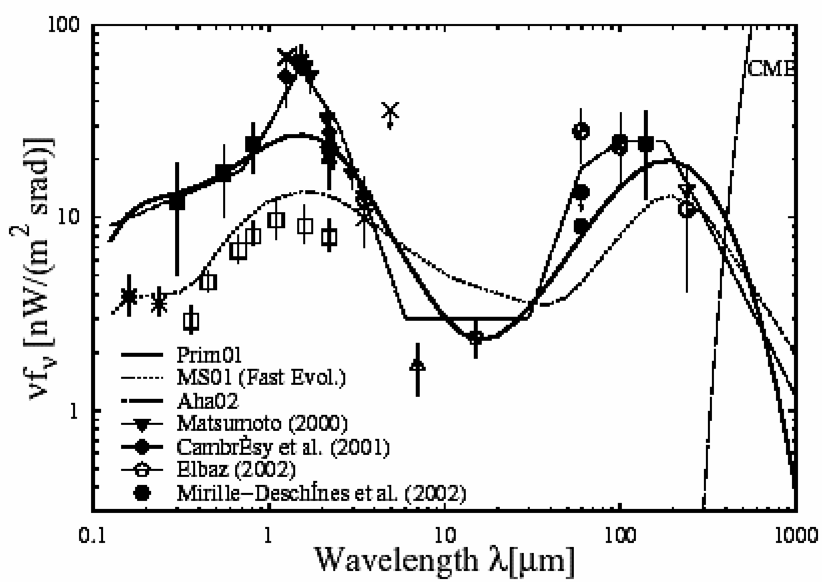
Protheroe et al. astro-ph/0005349

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

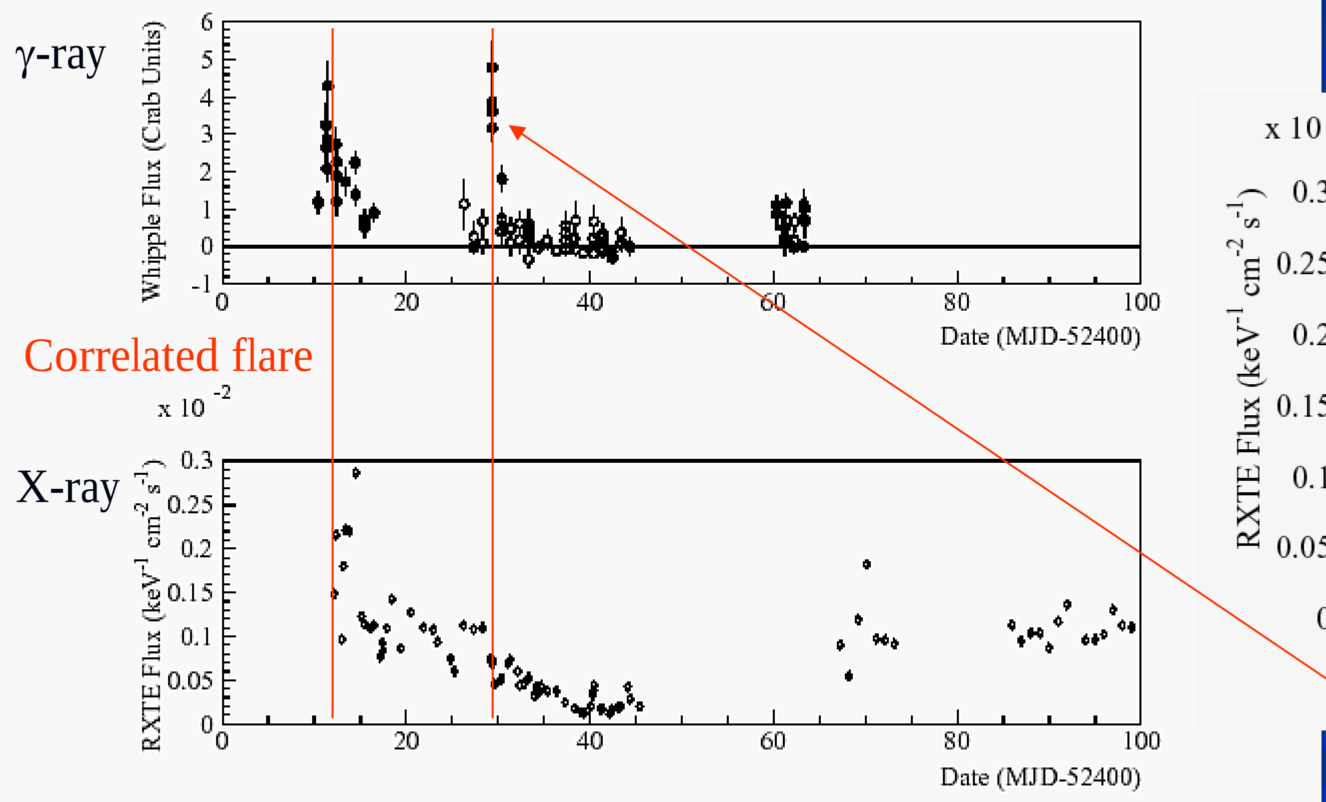
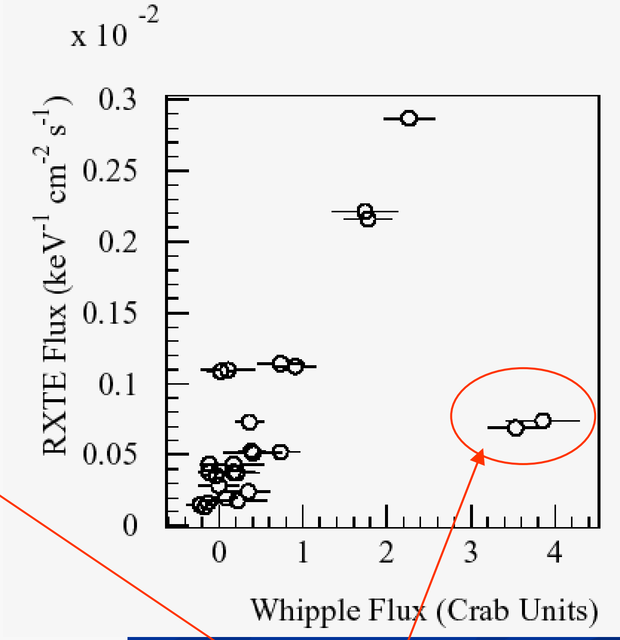


Fig. 1. The Whipple (top) and RXTE (bottom) light curves for 1ES1959+650 in May-July 2002. The filled Whipple points correspond to > 3 σ detections. The RXTE data are from [6].



"Orphan" gamma-ray flare

Holder et al. 28th ICRC (2003)

PKS 2155-304

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

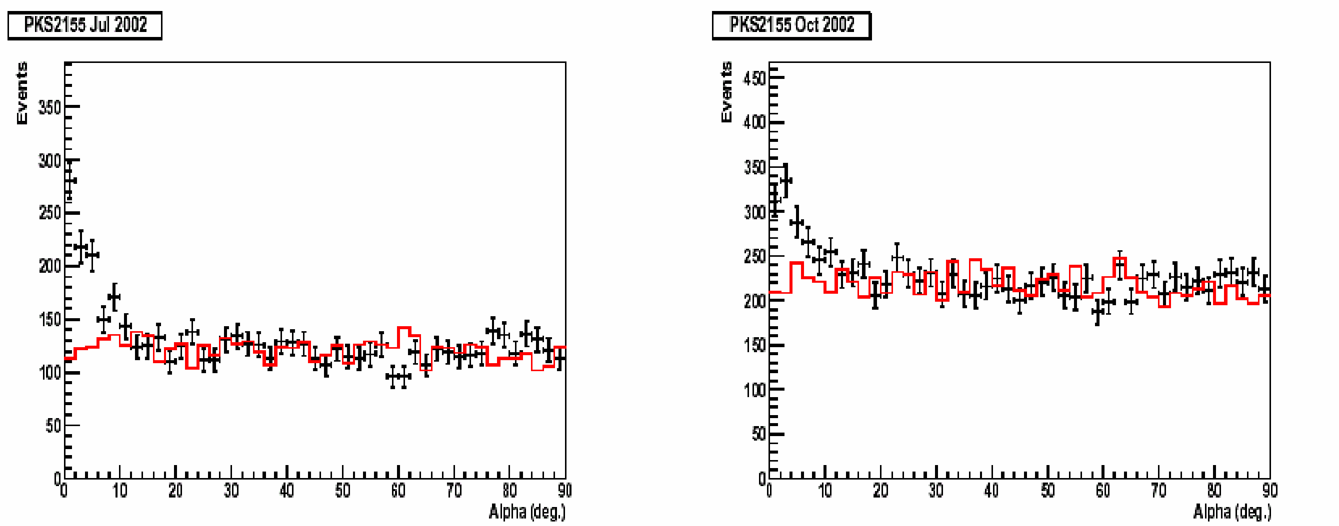
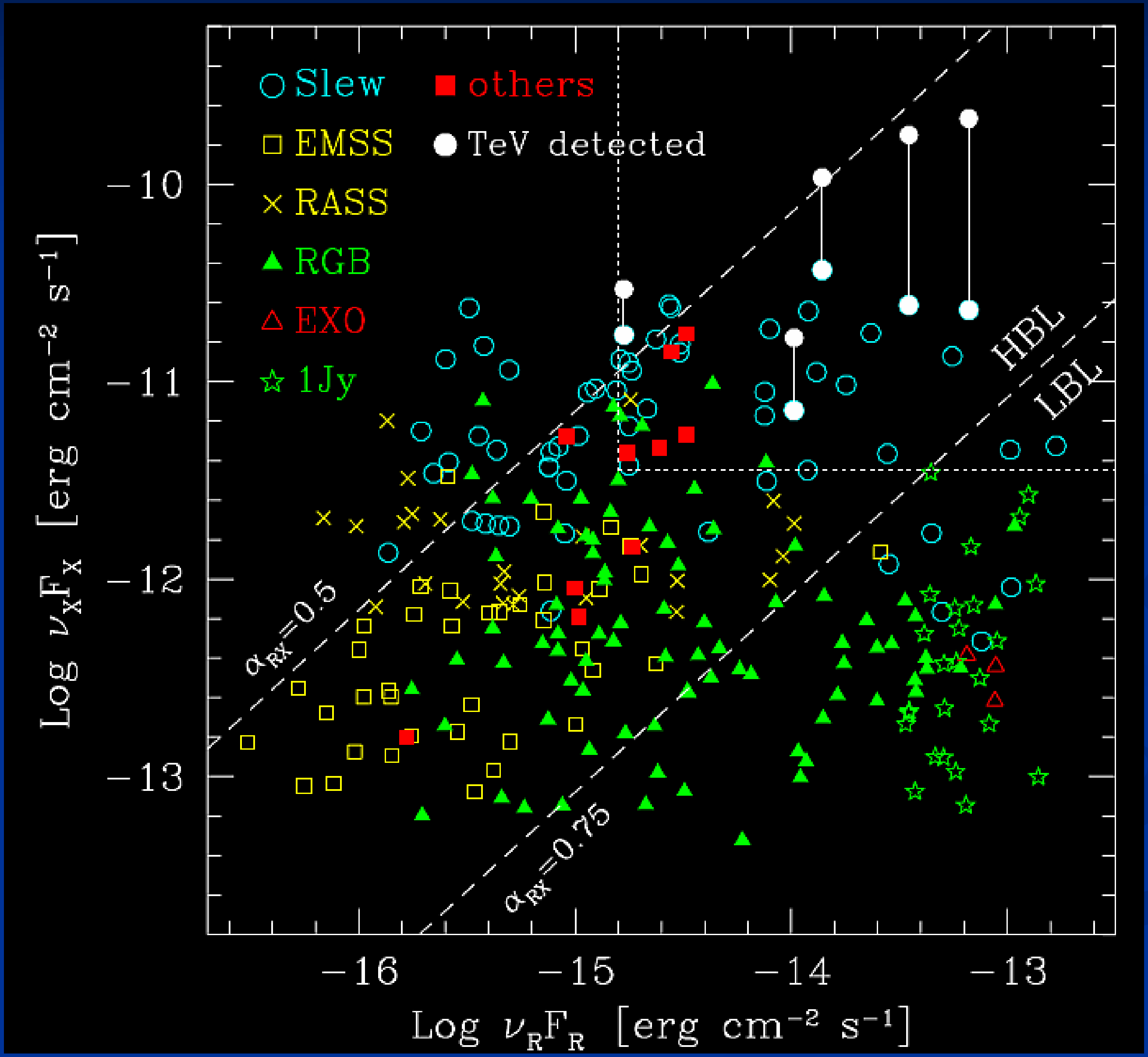


Fig. 1. The pointing angle α-plot of PKS 2155-304 observations for July (left panel) and October (right panel) 2002. The OFF-source distributions have been normalised to the control region between 30° and 90°.

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?

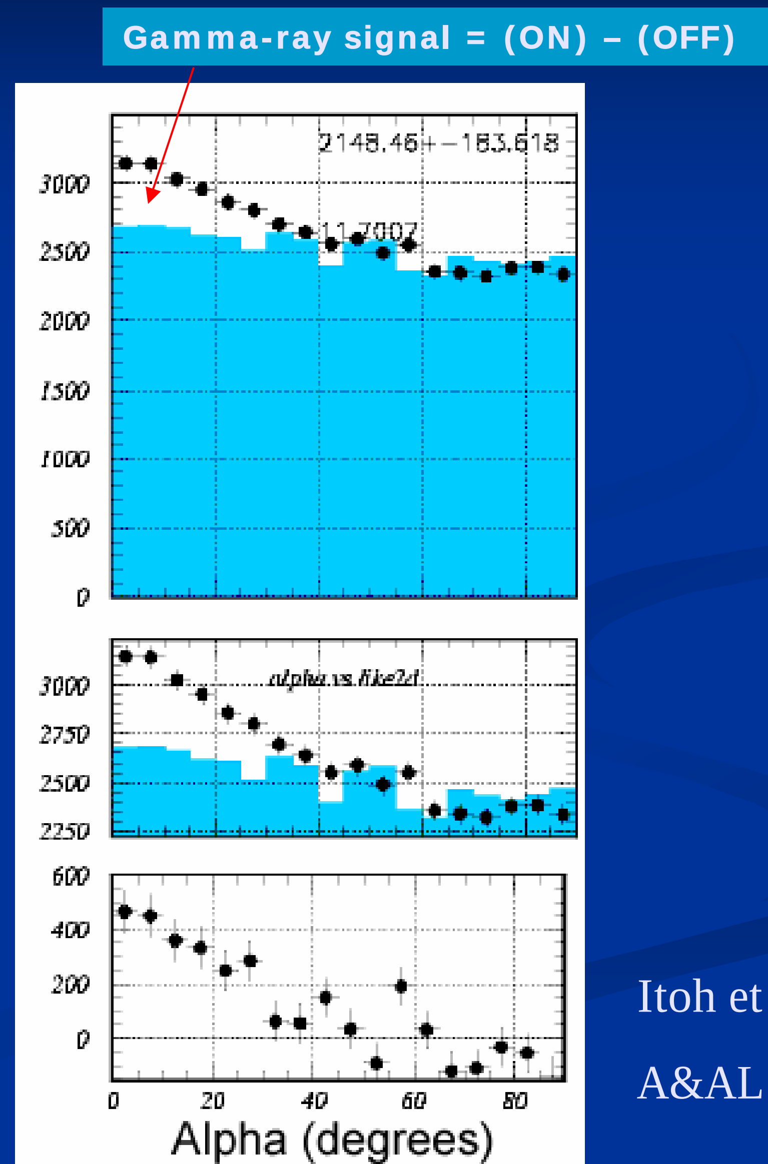


Costamante and Ghisellini A&A 384 (2002) 56

New entry: NGC253 (1)

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

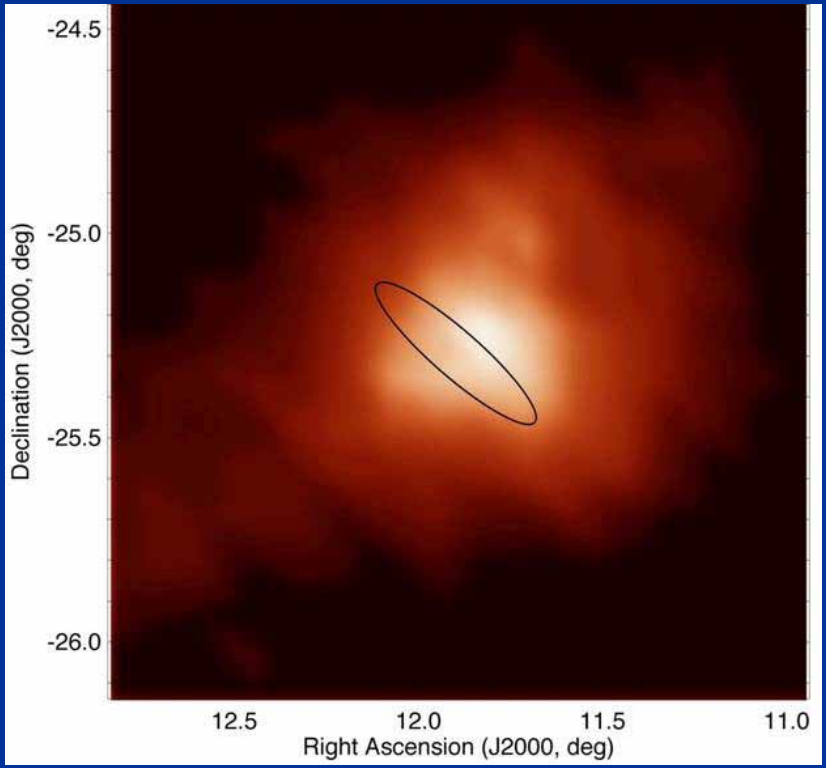
Optical image



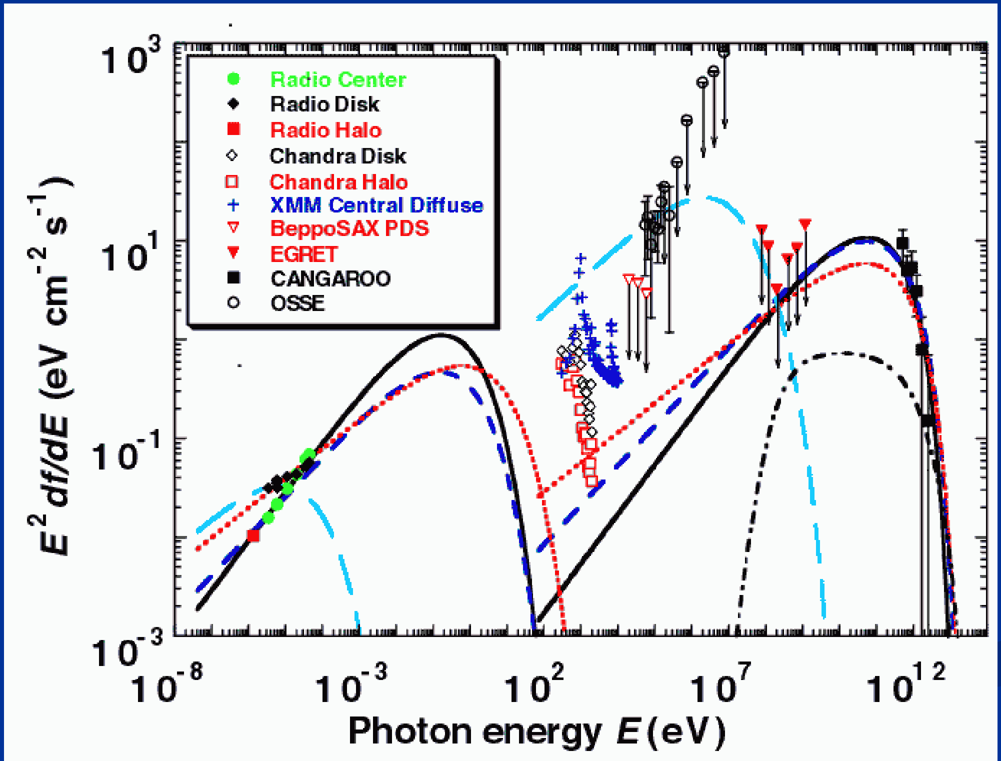
Itoh et al. A&AL (2002)

New entry: NGC253 (2)

- Extended halo?



Significance map by CANGAROO



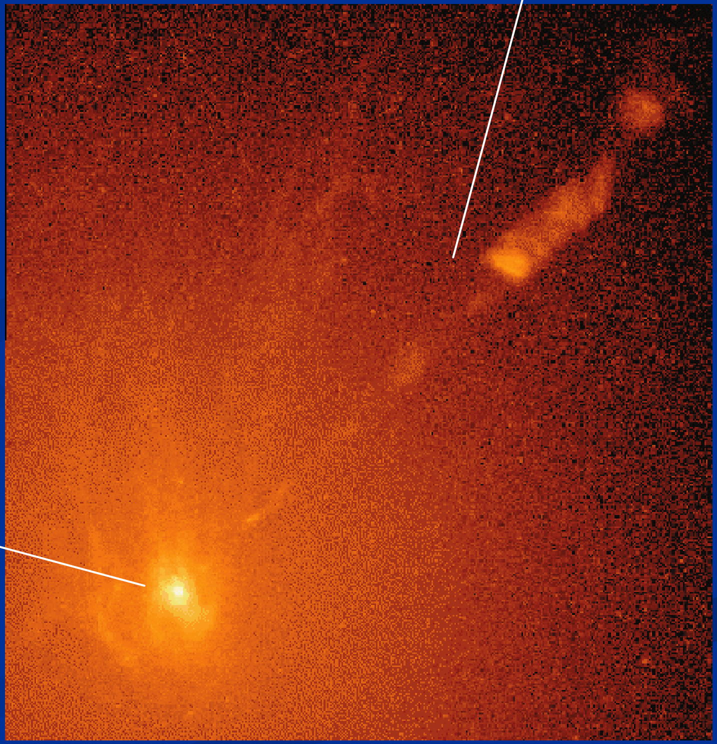
Itoh et al. ApJ (2003)

New entry: M87 (1)

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

Jet

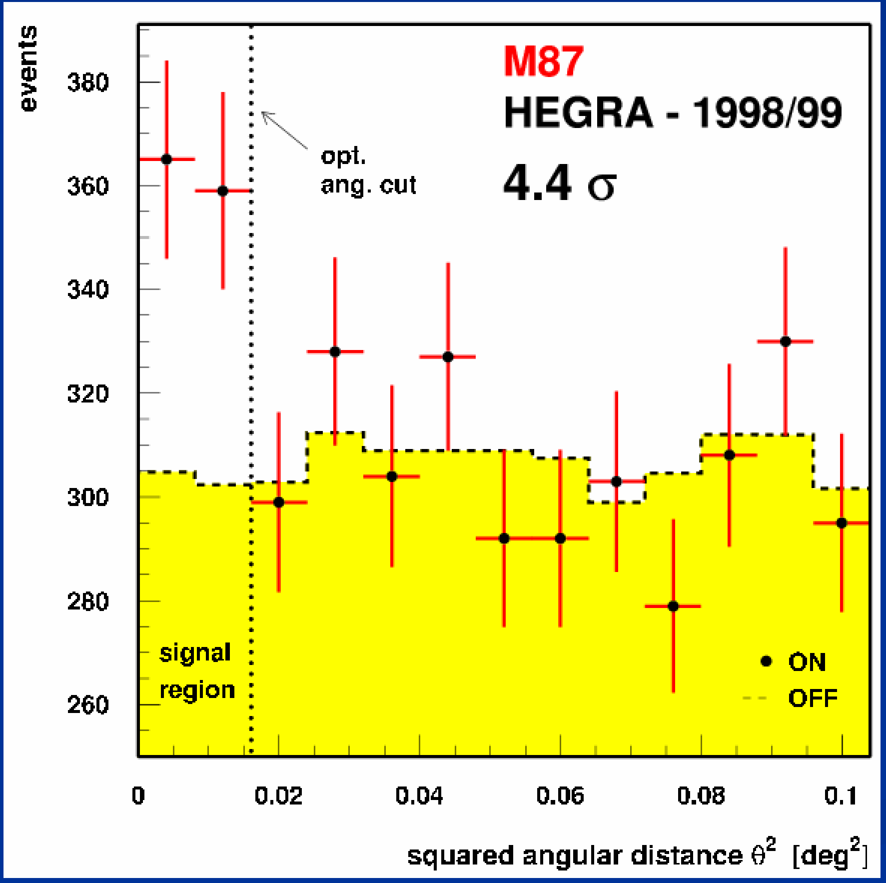
AGN
~$10^9 M_\odot$ B.H.

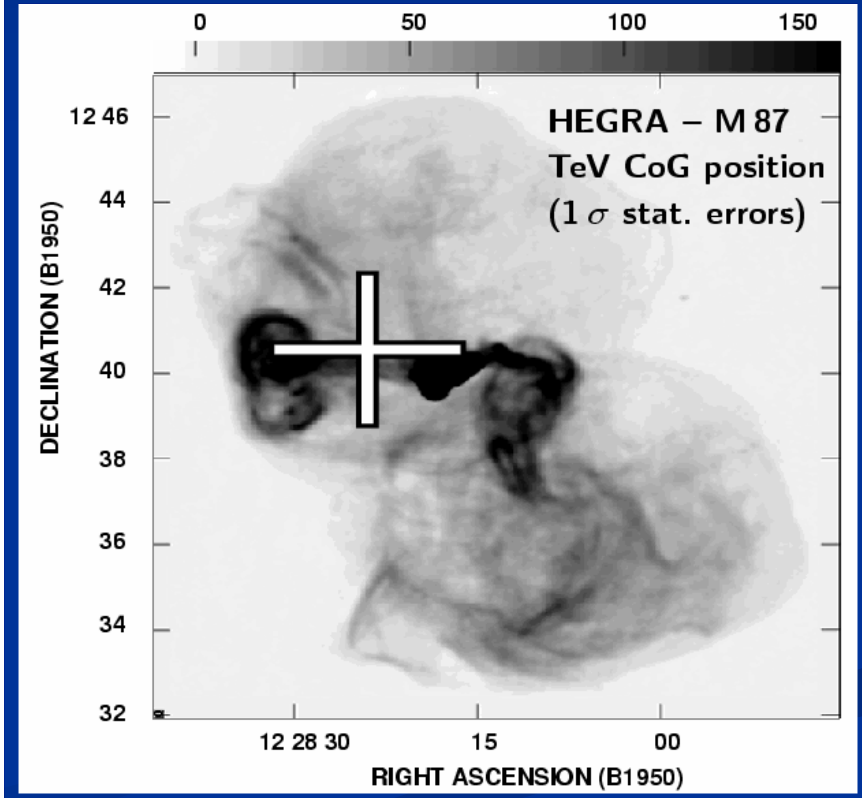


Optical image

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

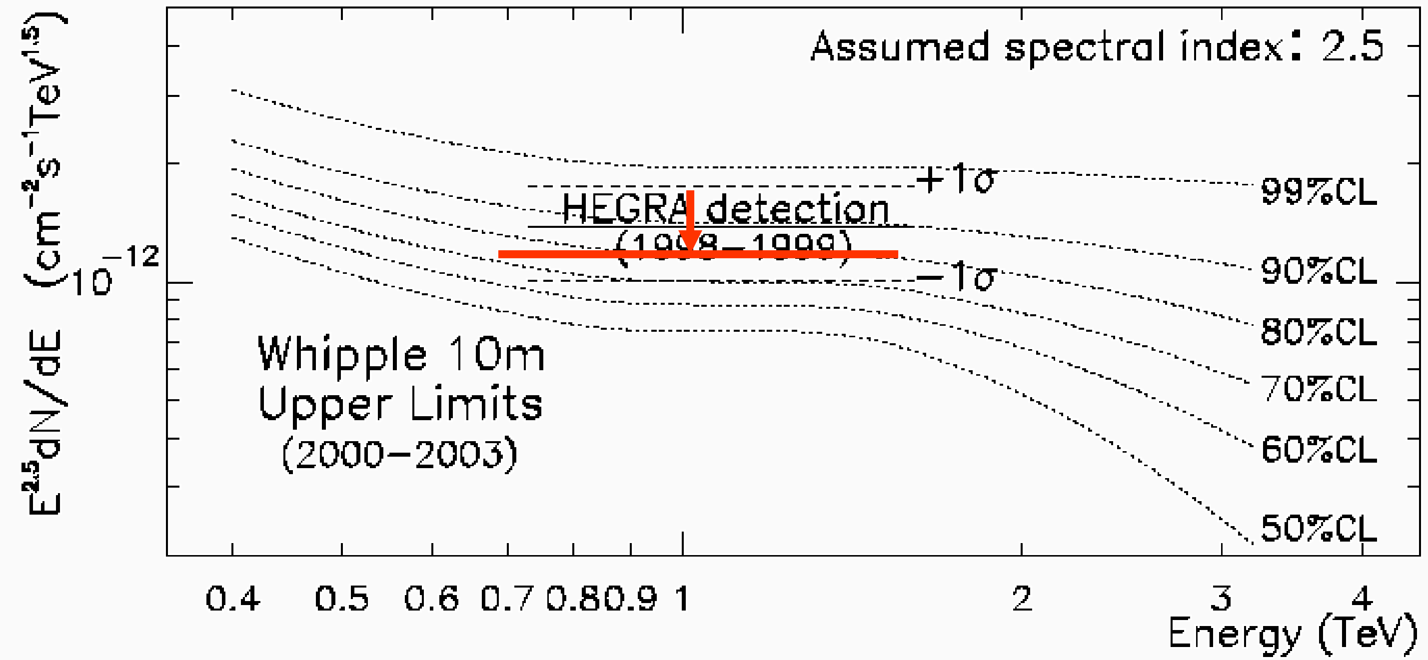
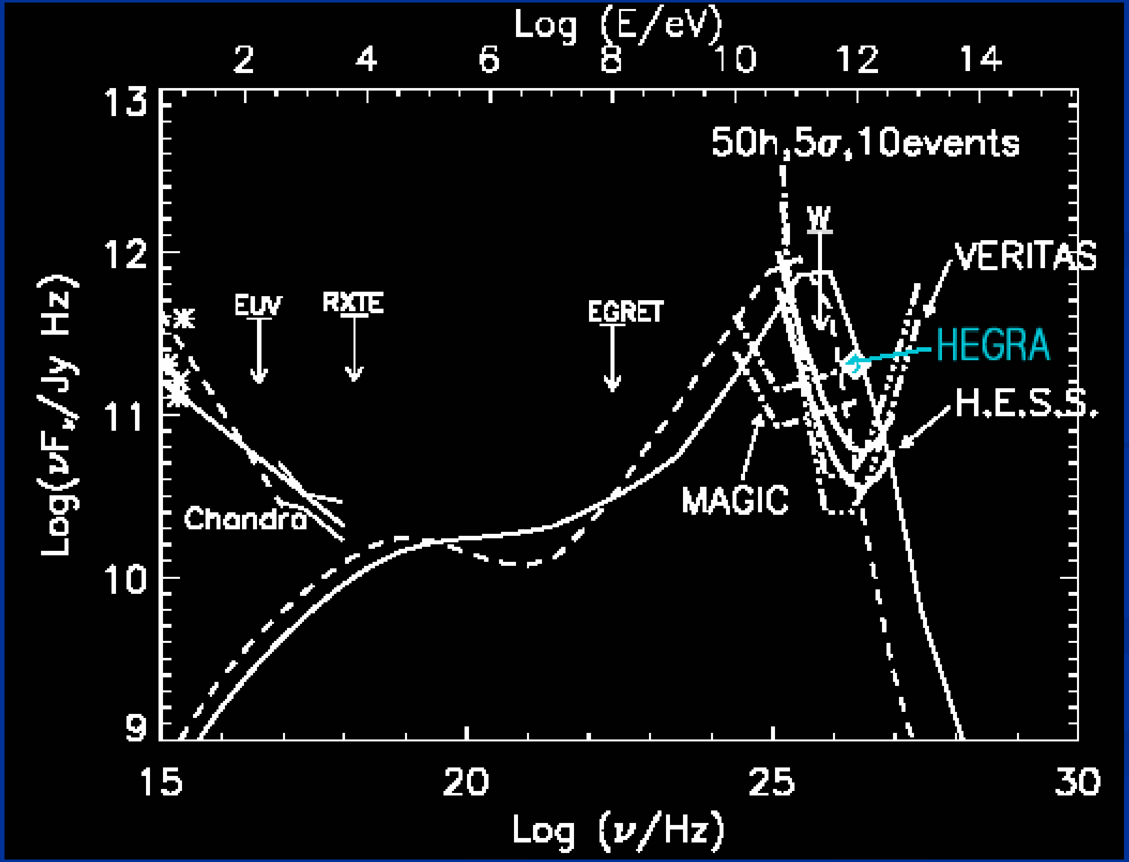


Fig. 1. The Whipple 10-m upper limit on the differential flux from M87 compared to the detection by HEGRA under the assumption that the spectrum ca be described by a power law of index 2.5.

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



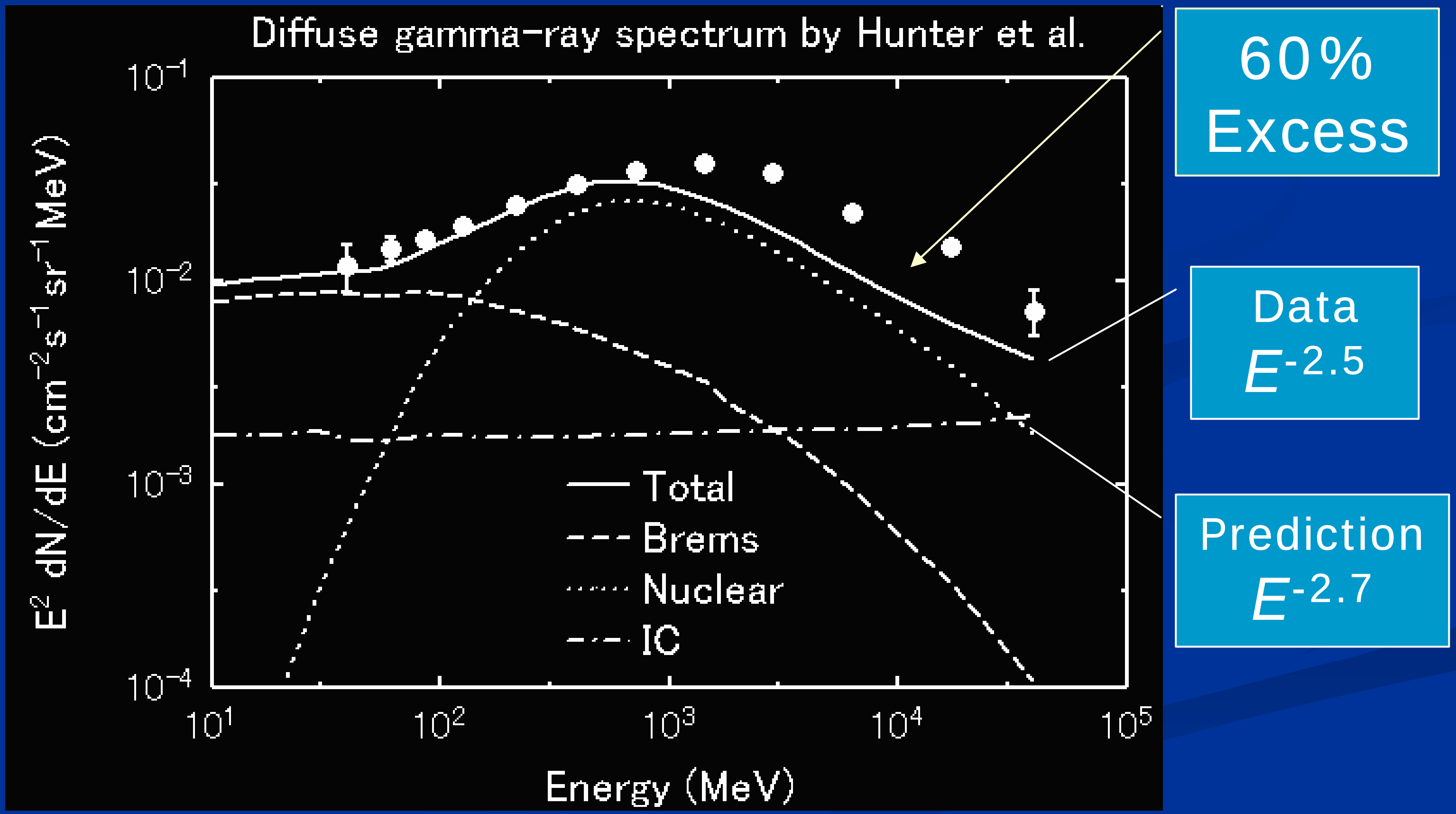
$L_{jet} \sim 3 \times 10^{43} erg/s$

$B \sim 30G$

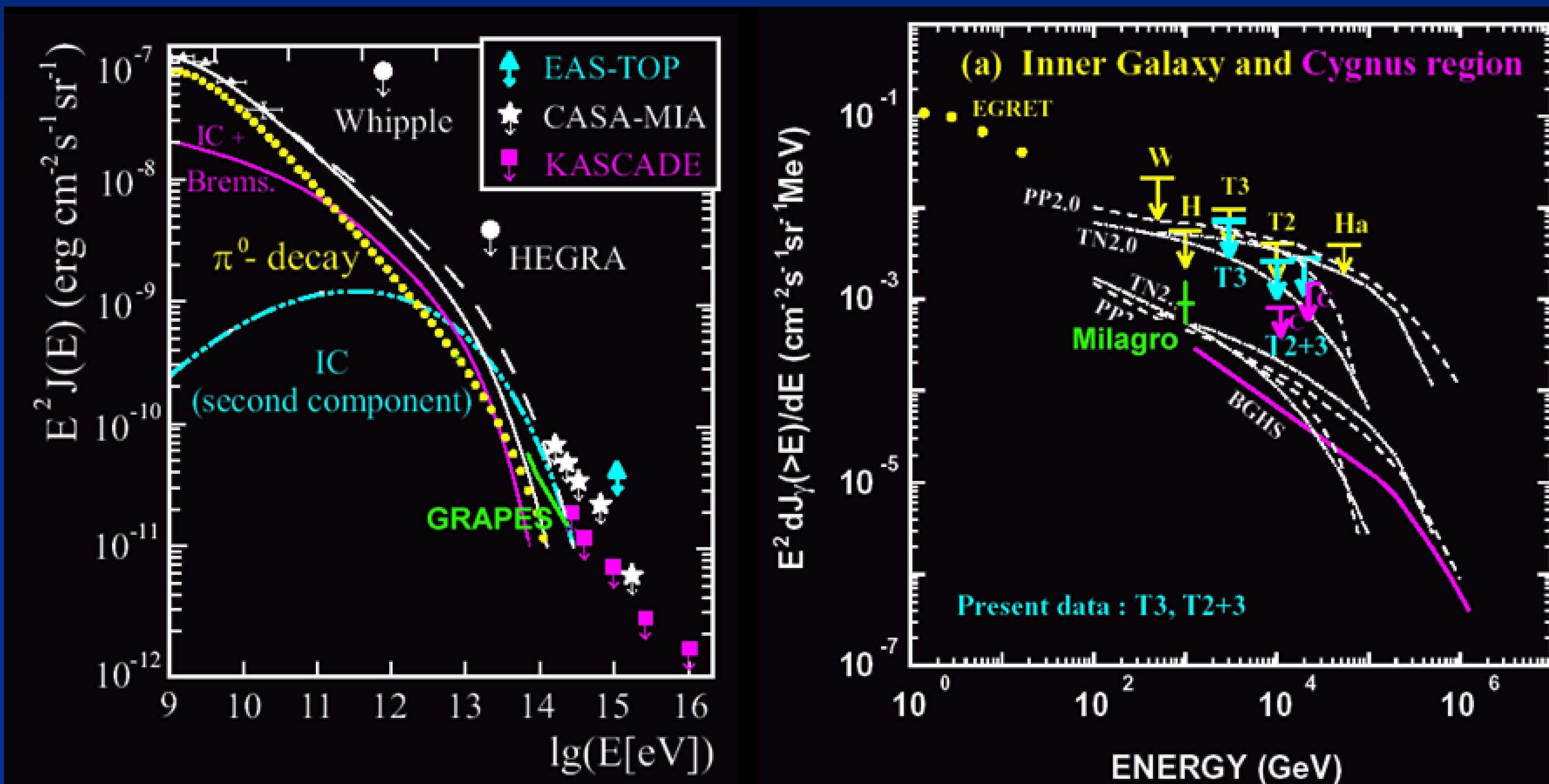
Reimer, Donea & Protheroe, APh 19 ('03) 559

Galactic diffuse gamma-rays (1)

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



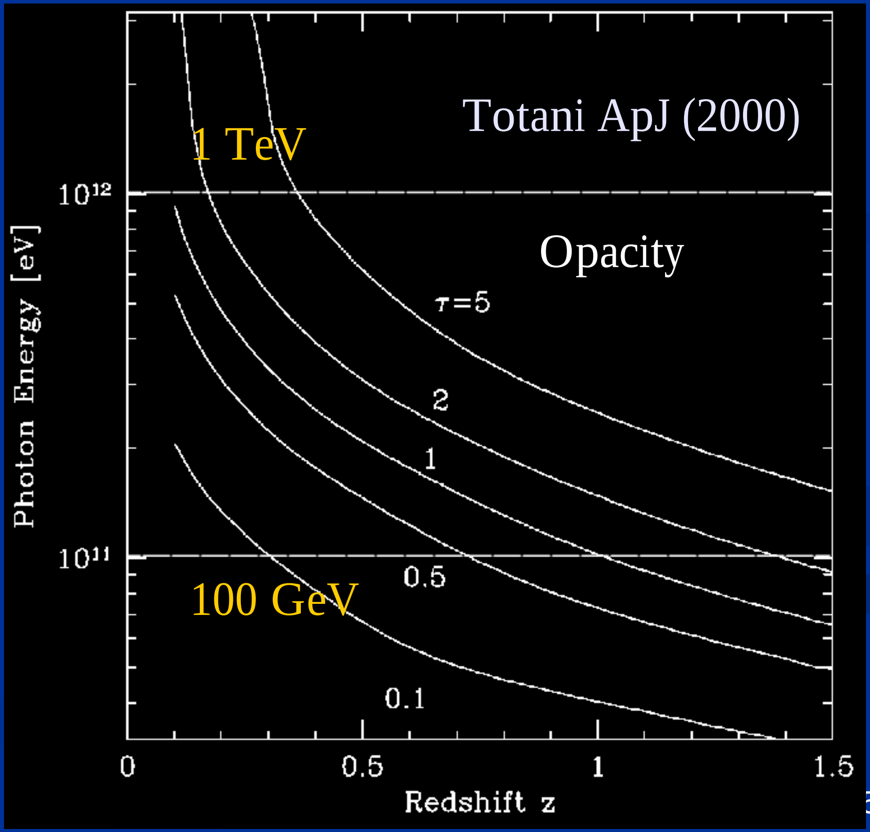
Galactic diffuse gamma-rays (2)

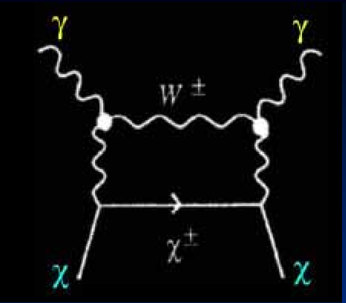


Summary by Mori, ICRC2003

Gamma Ray Bursts

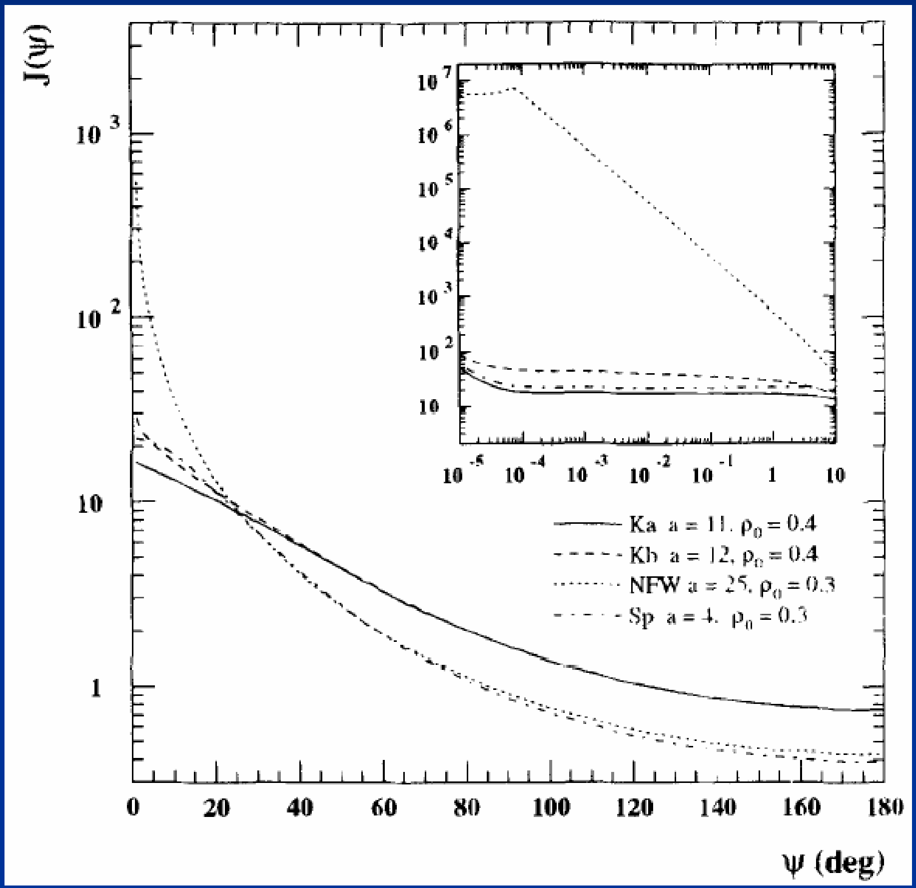
- Ground-based experiments?
  - TeV gamma-rays (afterglow)
    - MAGIC a few per year expected
  - Air shower rate
    - Tibet-III
  - Single particle rate
    - GRAND
    - ARGO-YBJ
    - Tibet-III
- Need fast and precise GRB alerts!

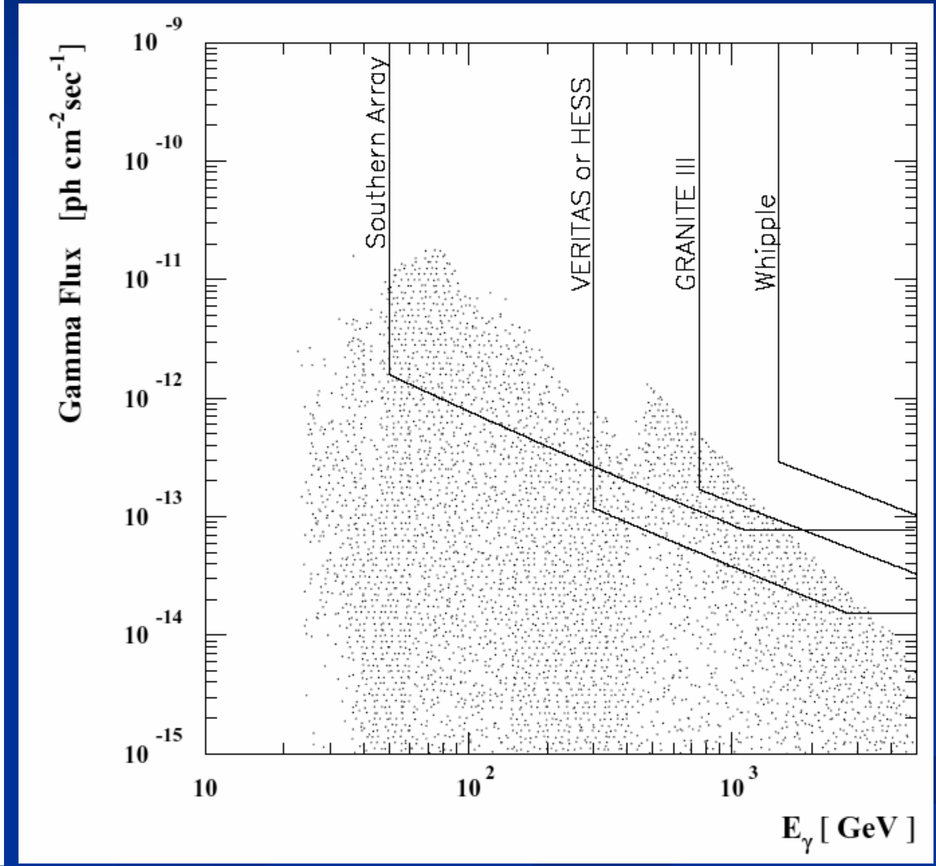




Dark matter annihilation at the Galactic Center

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





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

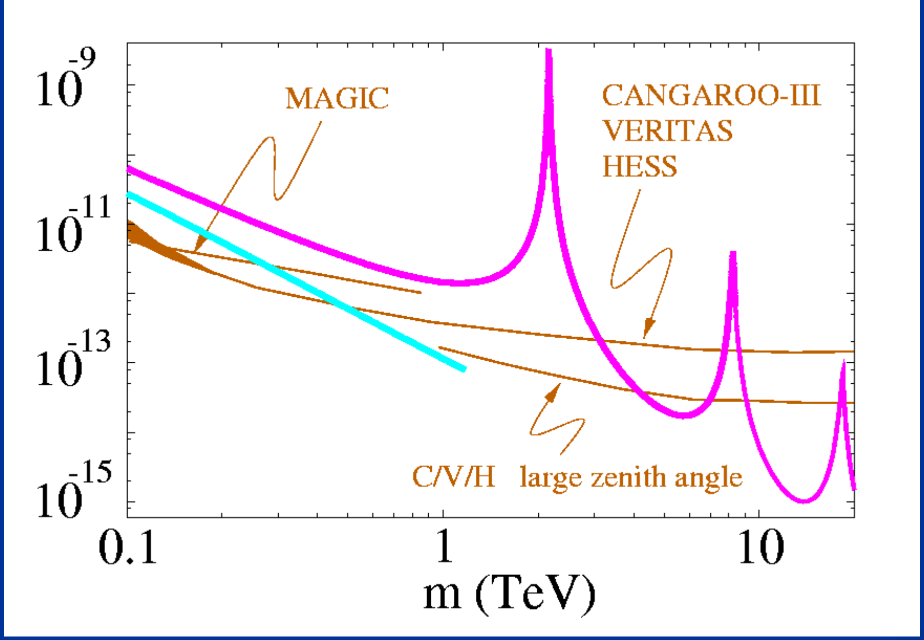
Bergstroem et al., APh 9 (1998) 137

Explosive dark matter annihilation

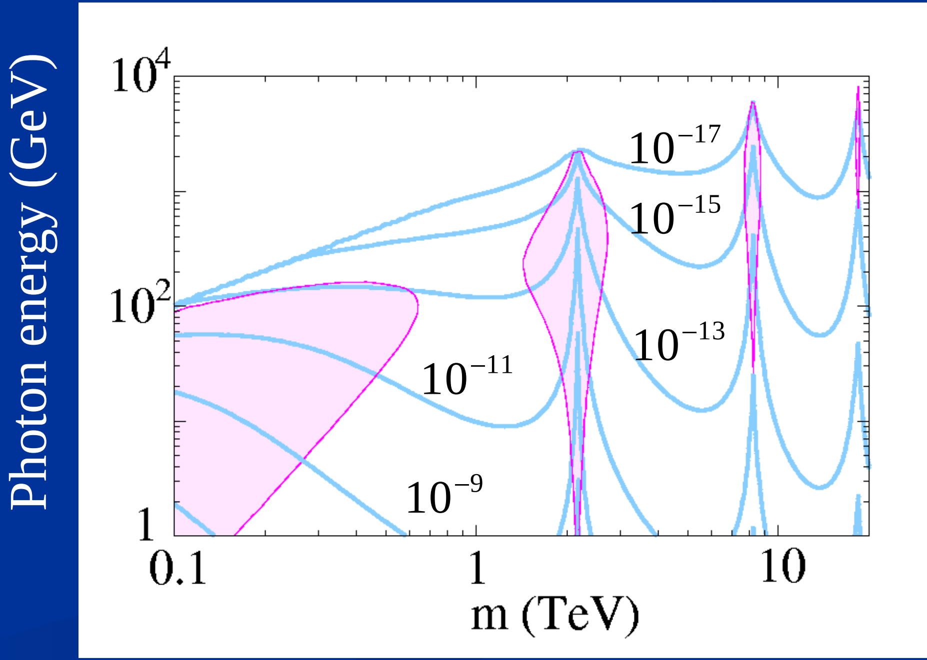
"Explosive annihilation" by non-perturvative effect

Line (Galactic center, J=500)

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

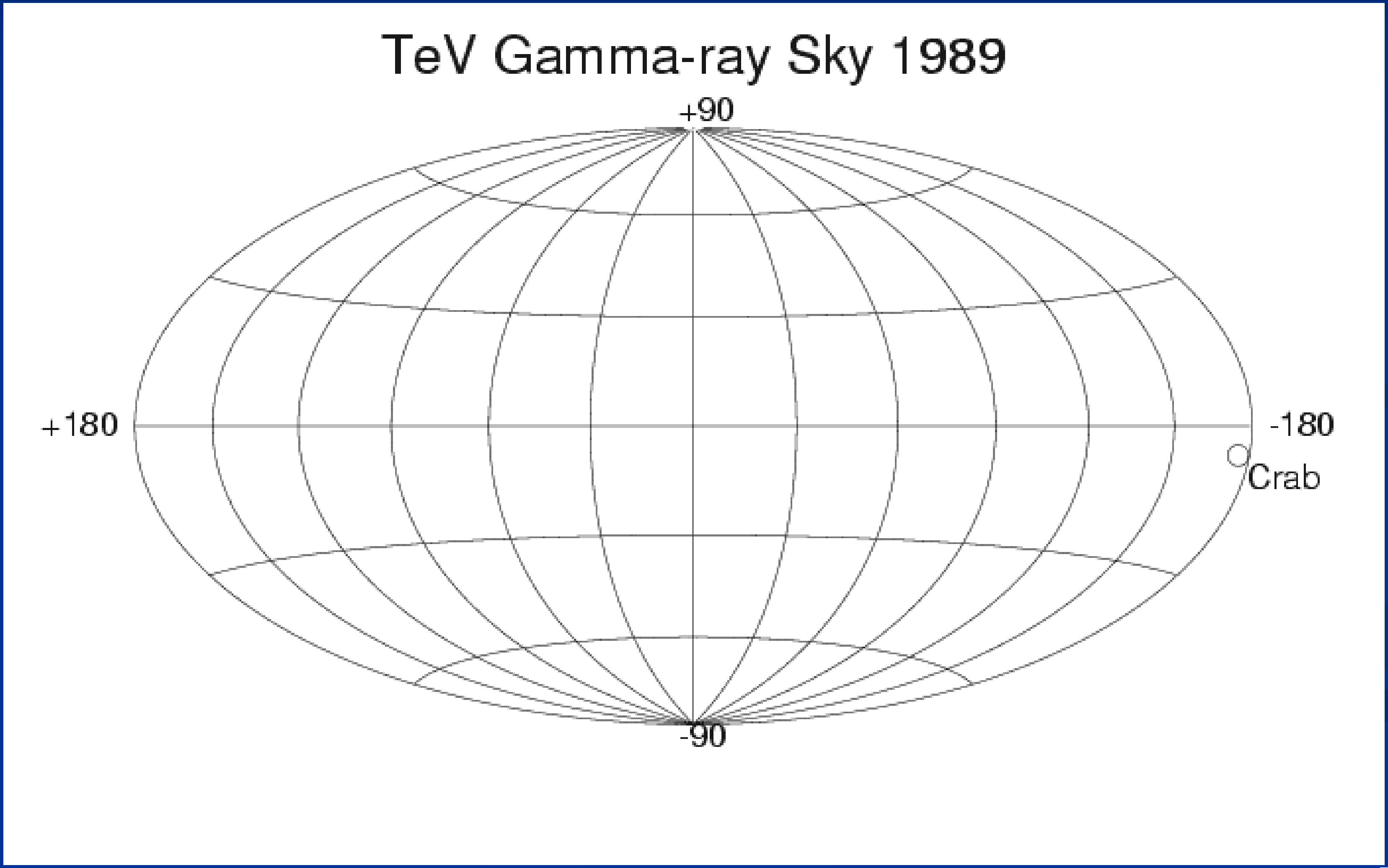


Continuum (Galactic center, J=500)



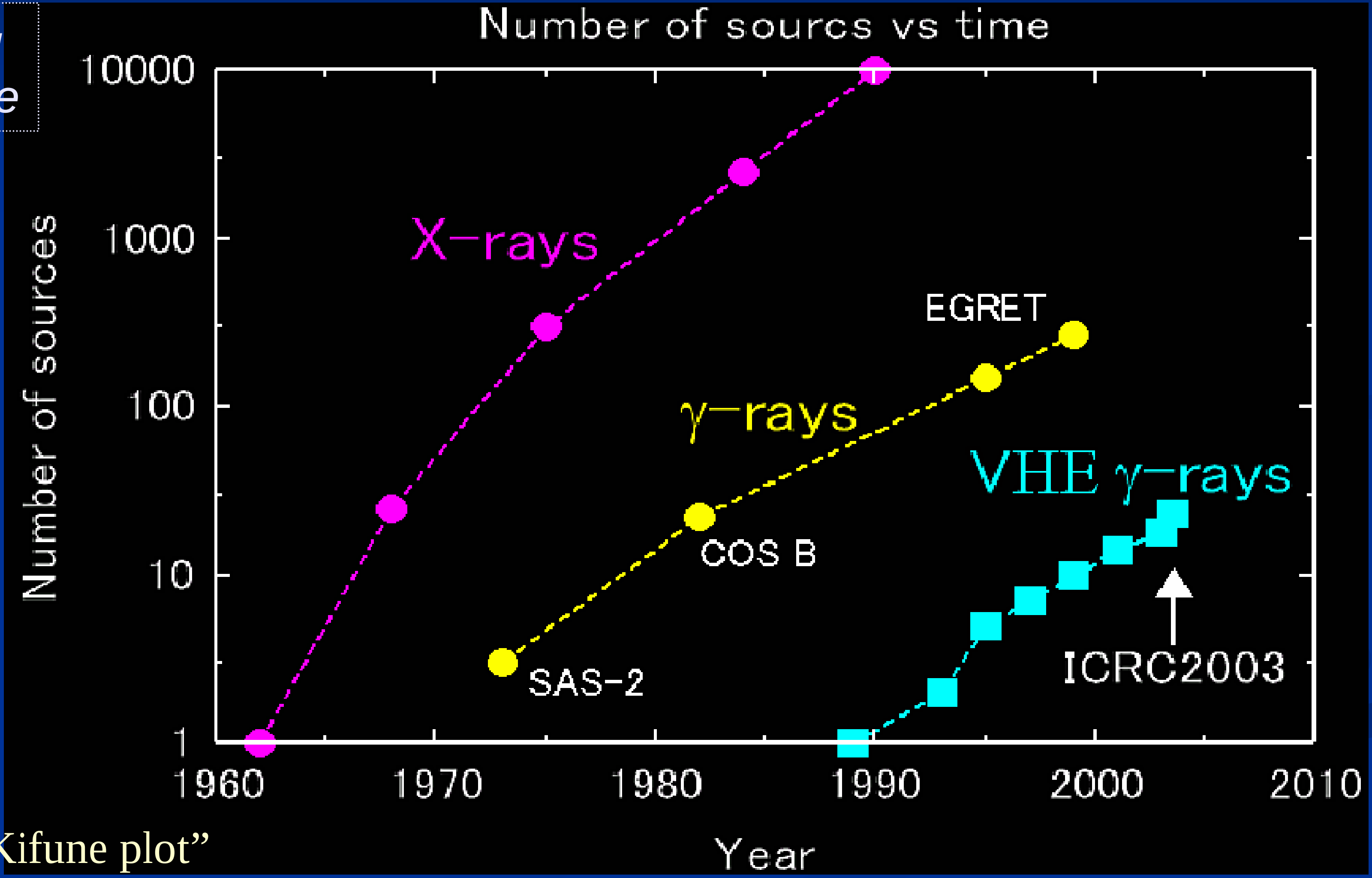
Hisano, Matsumoto, Nojiri PRL 92 (2004)

“Evolution” of the TeV gamma-ray sky



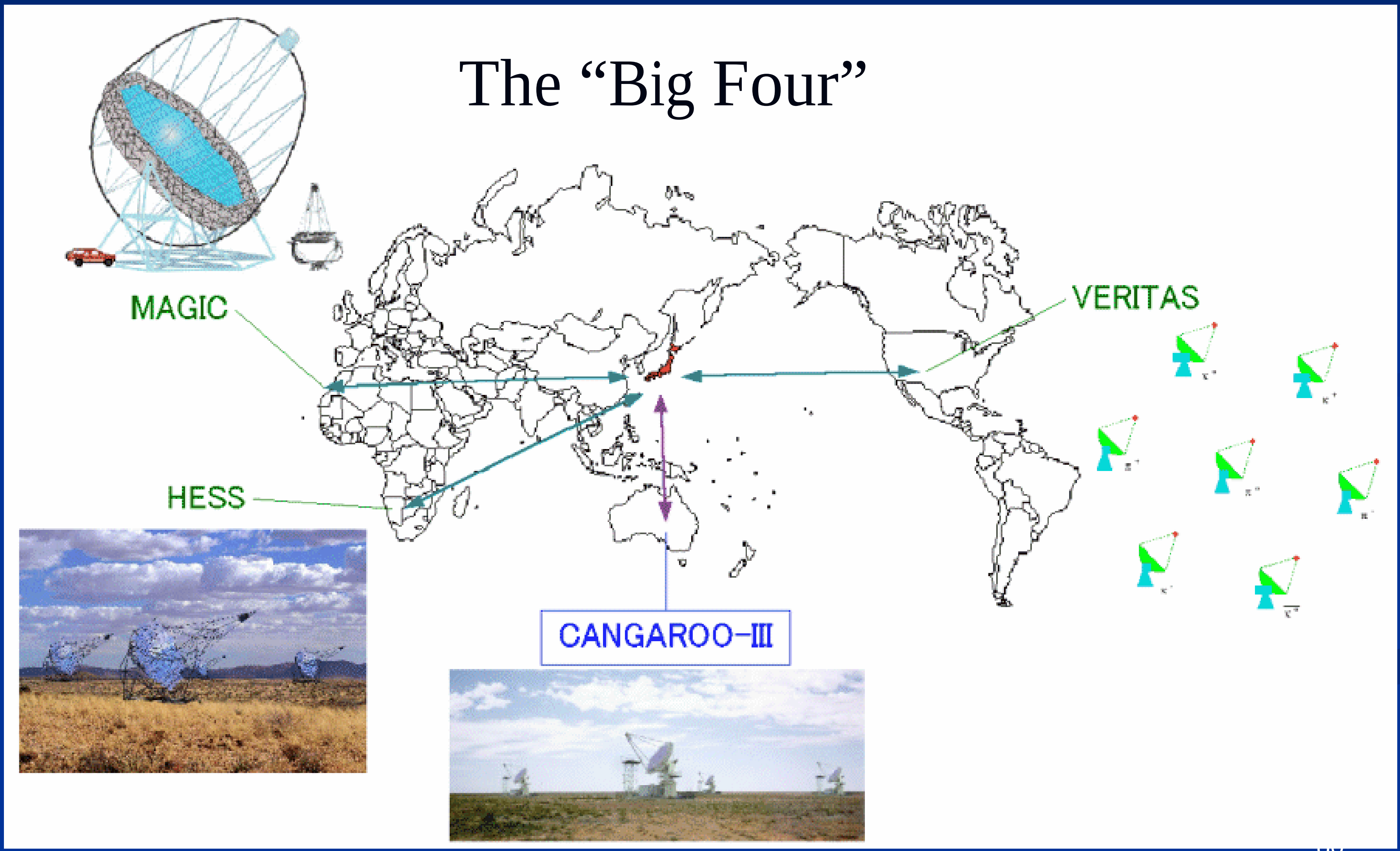
“Evolution” in number of objects

Log scale



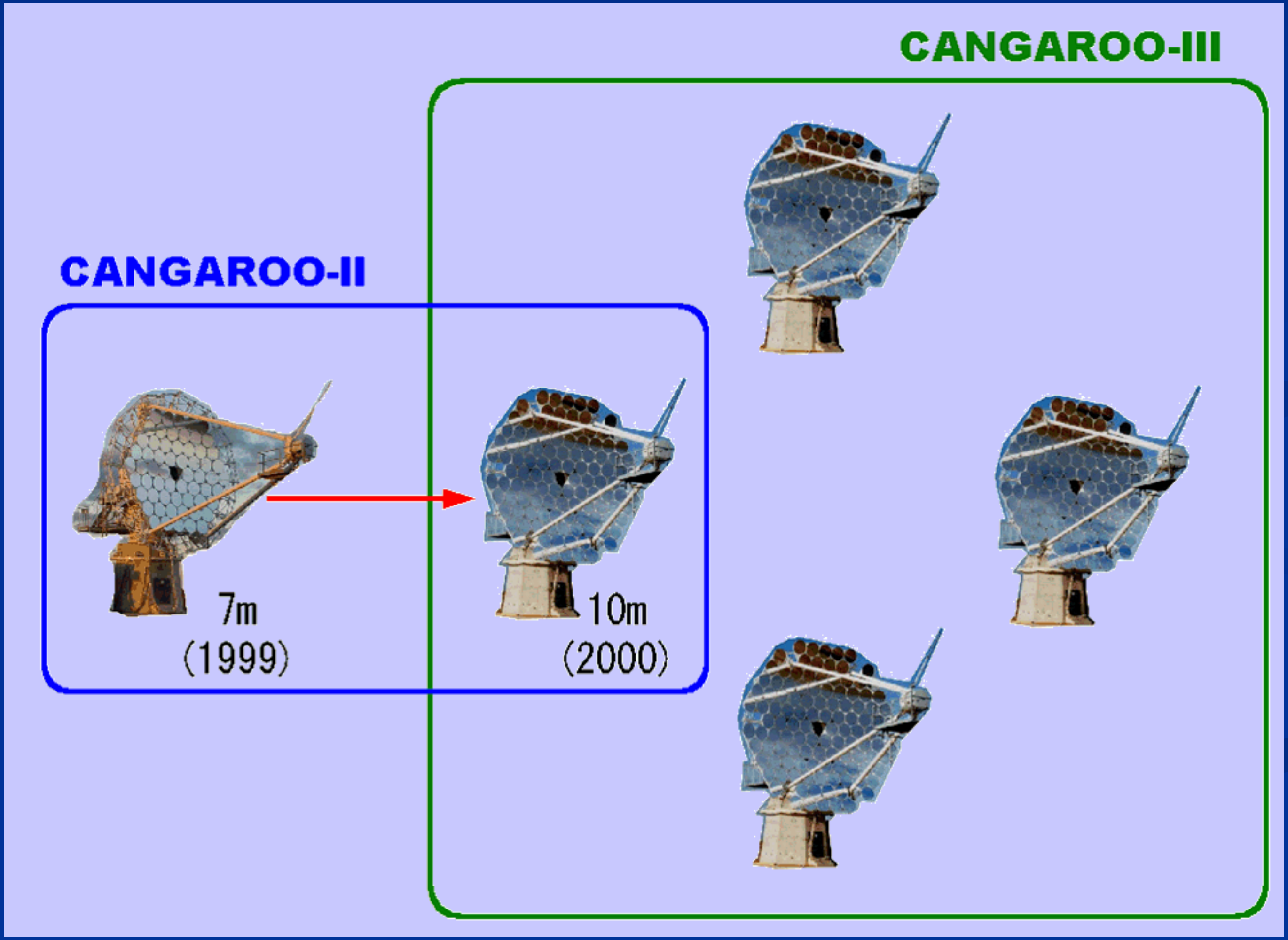
“Kifune plot”

New Cherenkov telescopes



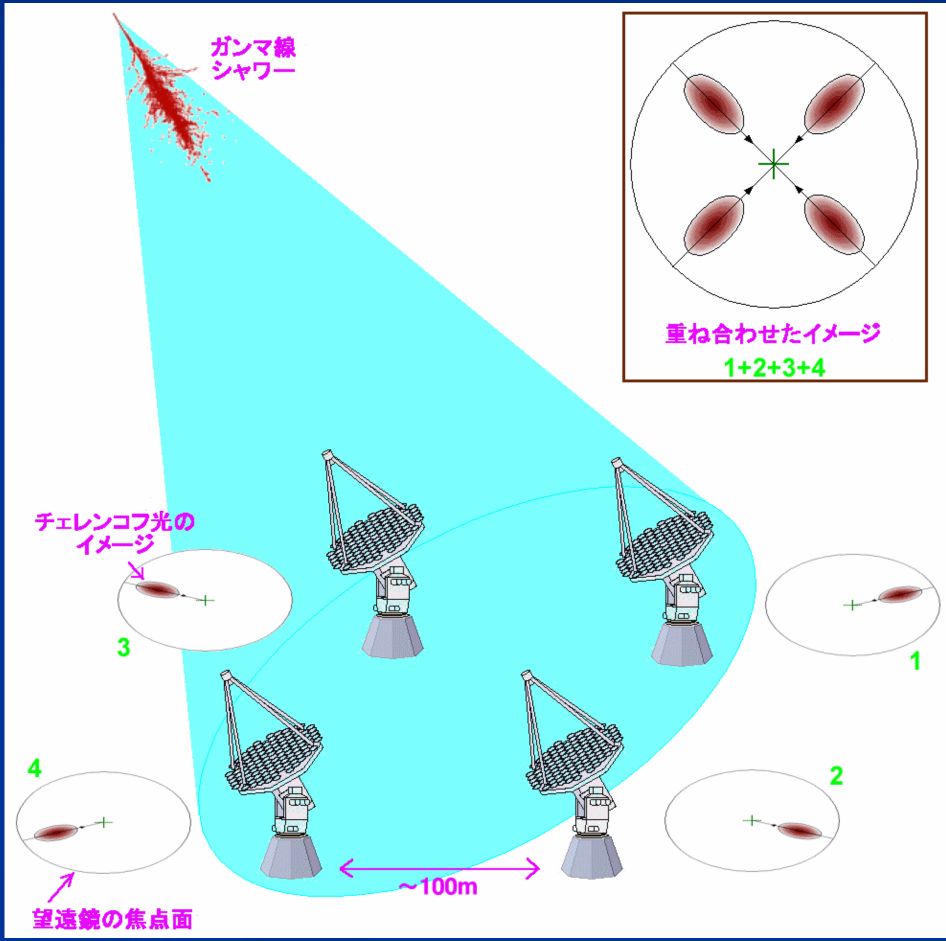
CANGAROO-III project

- 10m 望遠鏡4台のアレイ (2004年3月完成予定)



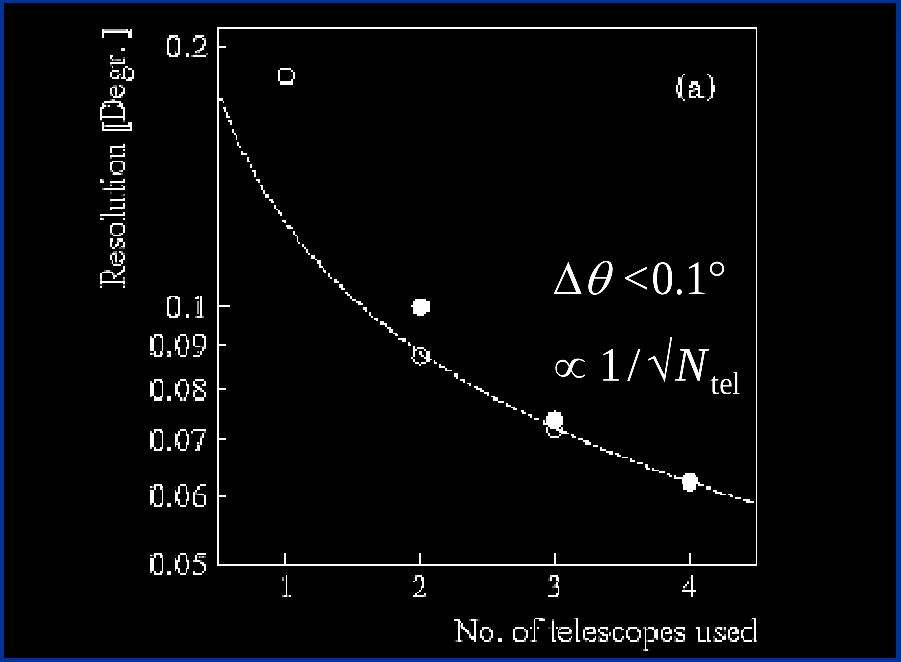
チェレンコフ光のステレオ観測

- チェレンコフ光の「円盤」: 直径~300m、厚さ~1m
- ステレオ観測 ⇒ シャワーまでの距離の情報
- 角度分解能の向上
- エネルギー分解能の向上



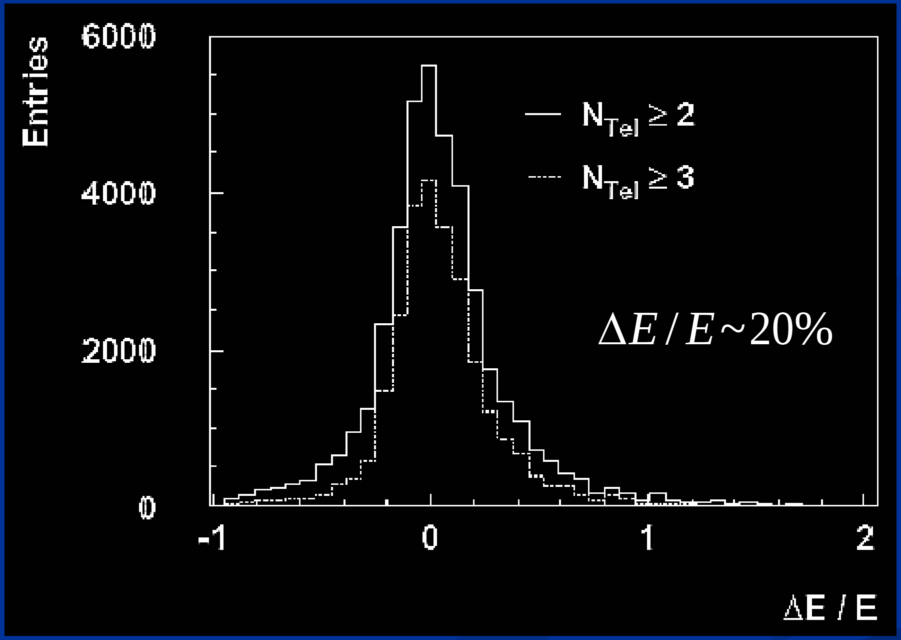
ステレオ観測のメリット

角度分解能



Hofmann et al. APh 12 (1999) 135

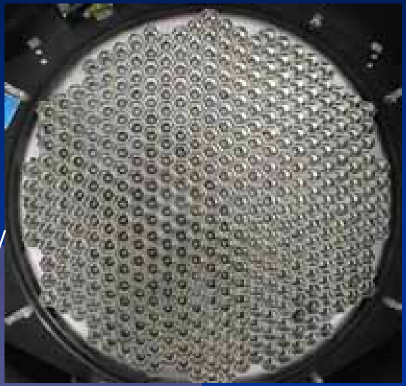
エネルギー分解能



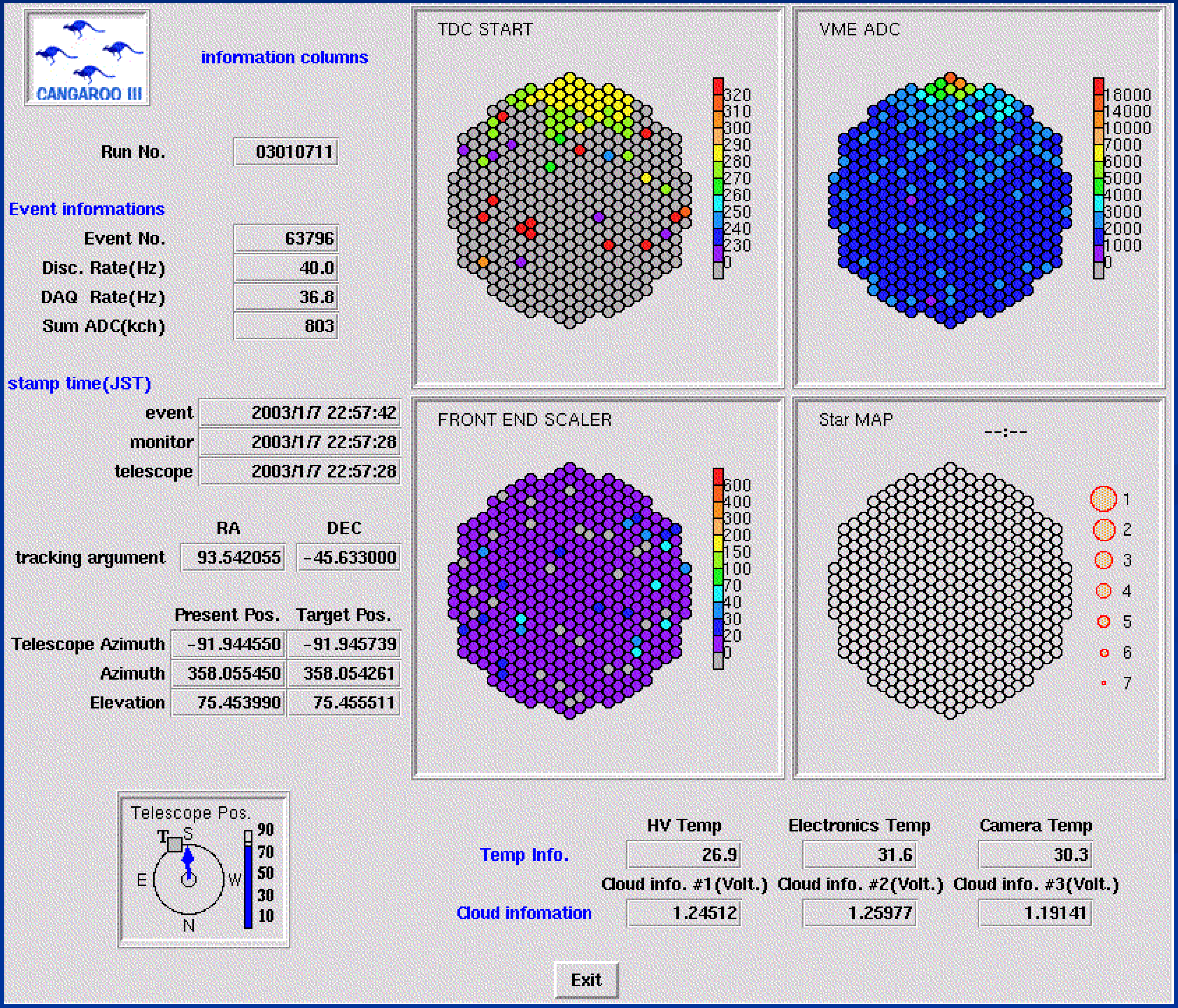
Mrk501: Aharonian et al. A&A 342 (1999) 69

10m望遠鏡2号機

- 2002年完成、12月から稼動開始
- 改良型小型球面鏡
- 427ch解像型カメラ
- 高速型電荷および時間情報回路



2号機で観測したイベント例



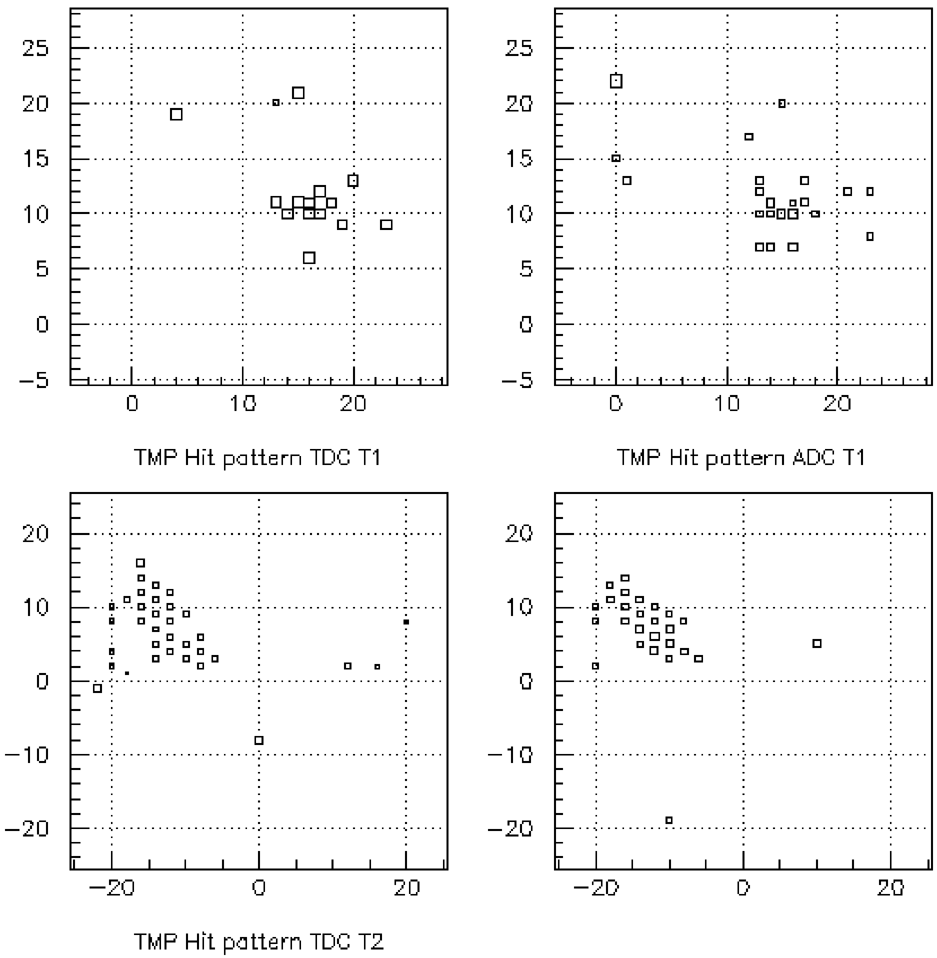
TDC ADC

Scaler Star

ステレオイベント例

T1 TDC

T1 ADC



T2 TDC

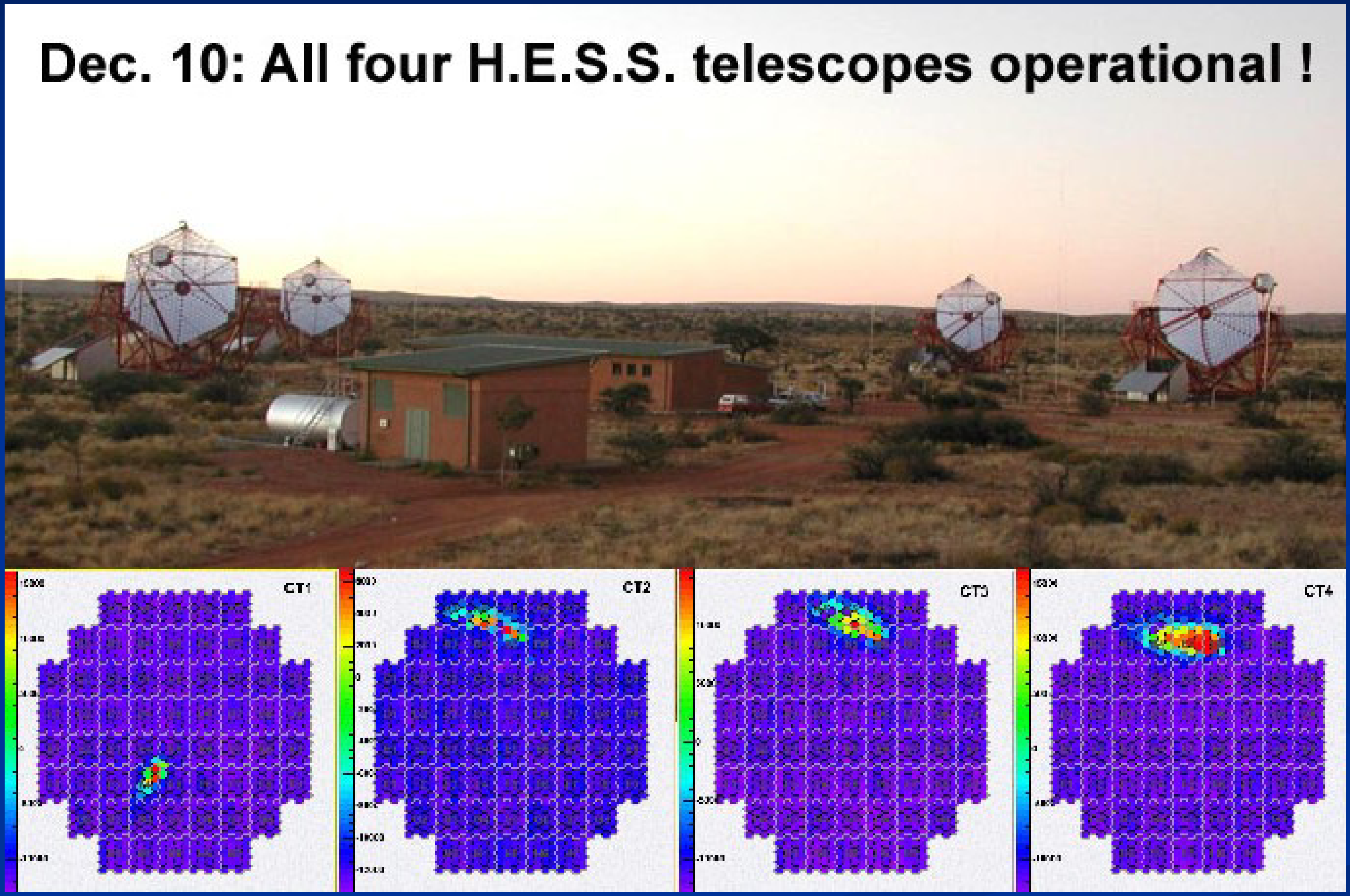
T2 ADC

CANGAROO-III: completion in 2004

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

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

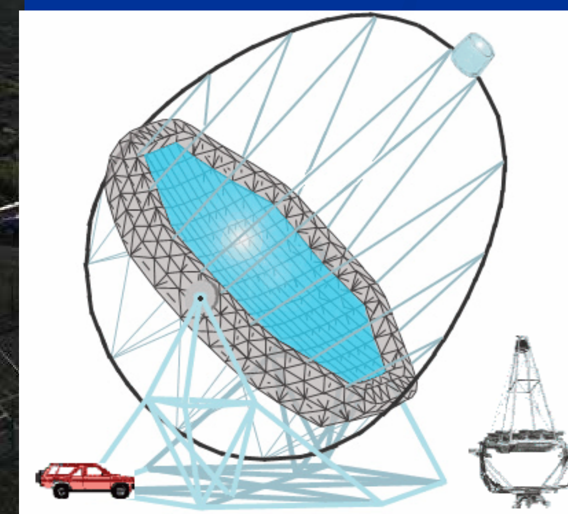
H.E.S.S.: completion in 2003



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

Max Planck Inst., Heidelberg, etc.

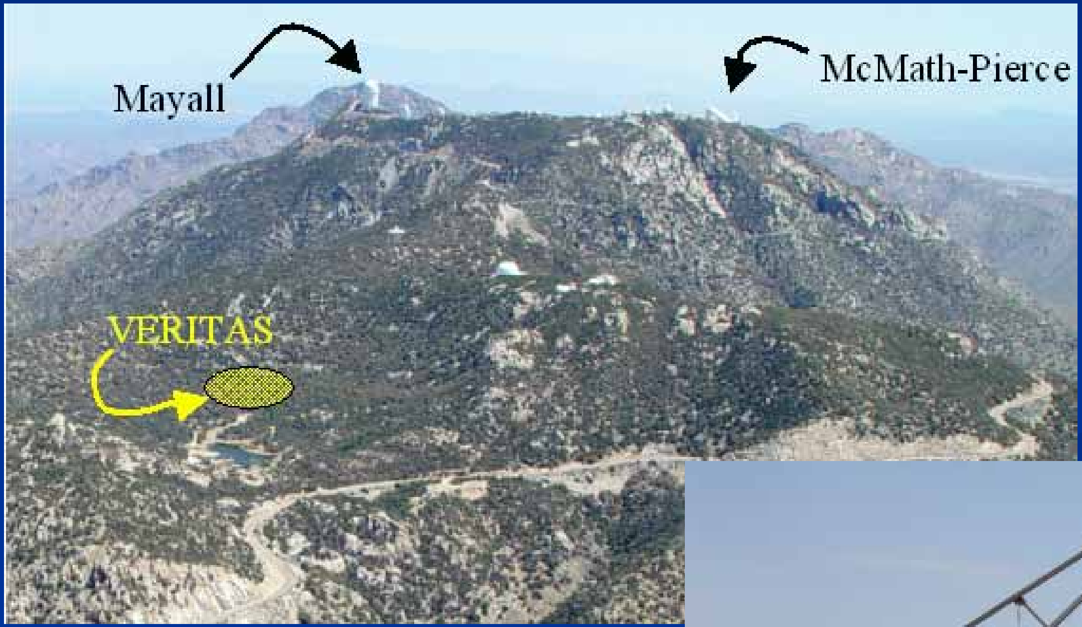
MAGIC: completion in 2003



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)

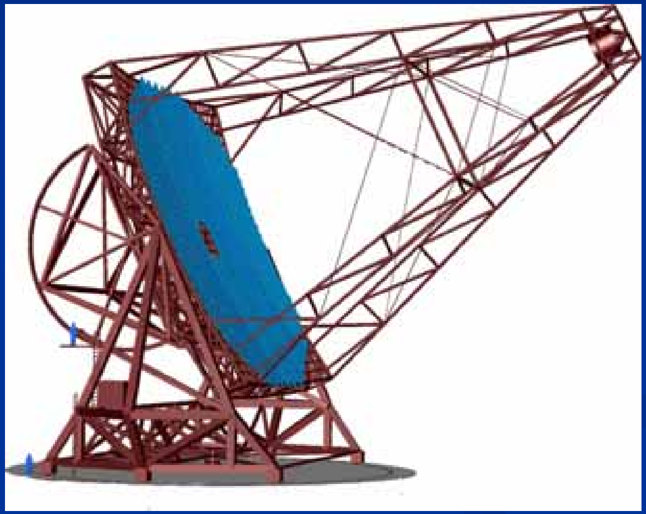
Oct 2005: Completion of Phase I: 4 telescope array

Oct 2007: Completion of Phase II: 7 telescope array

4^{th} generation concepts

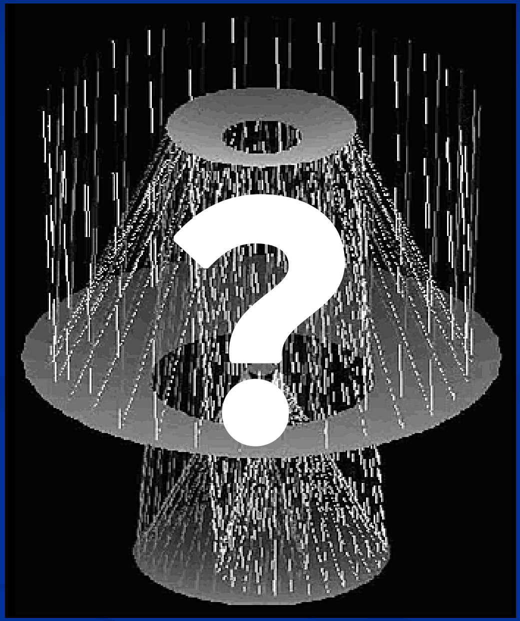
ECO-1000 project

MPI Physics etc.



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

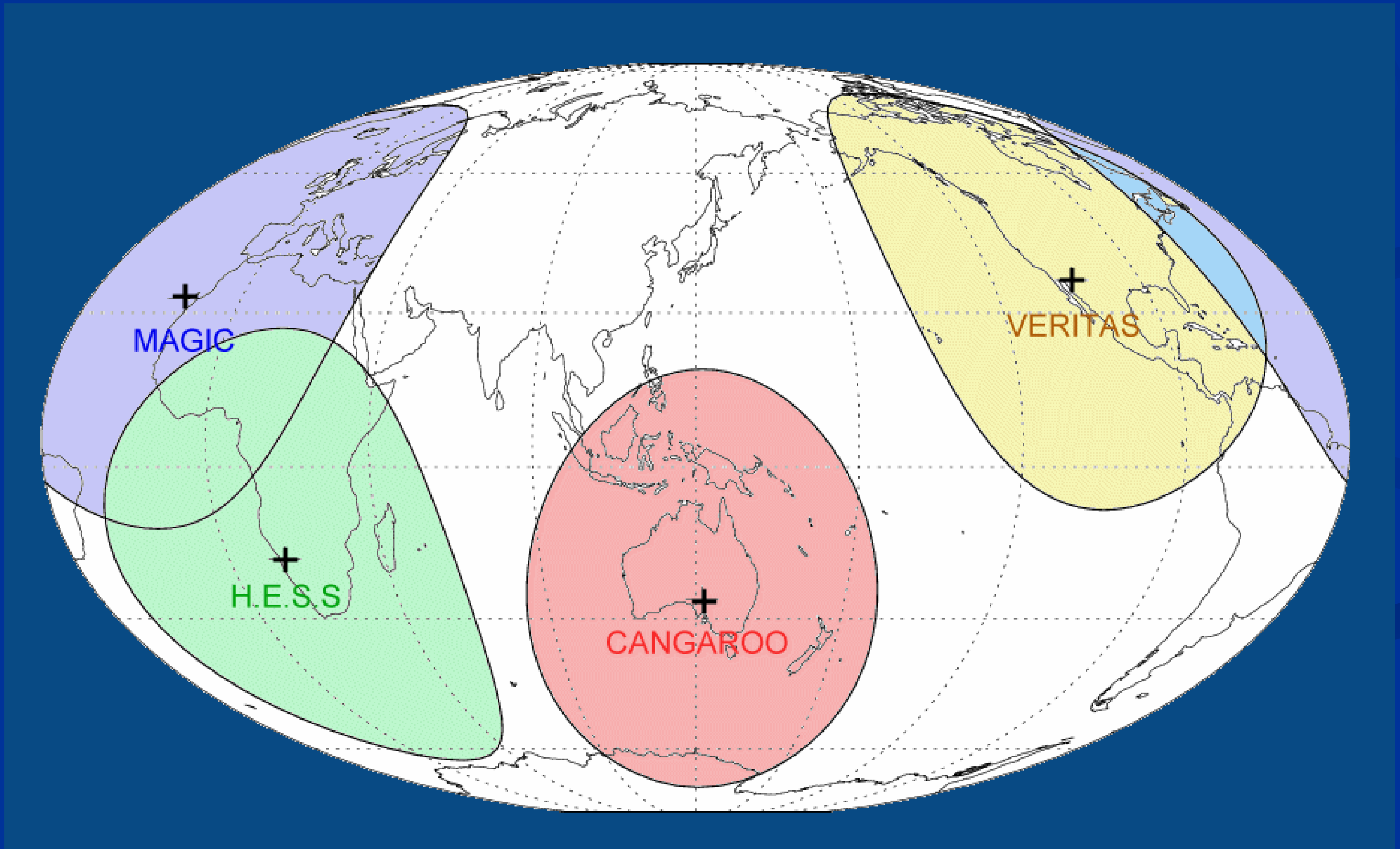
MPI Nuclear Physics etc.



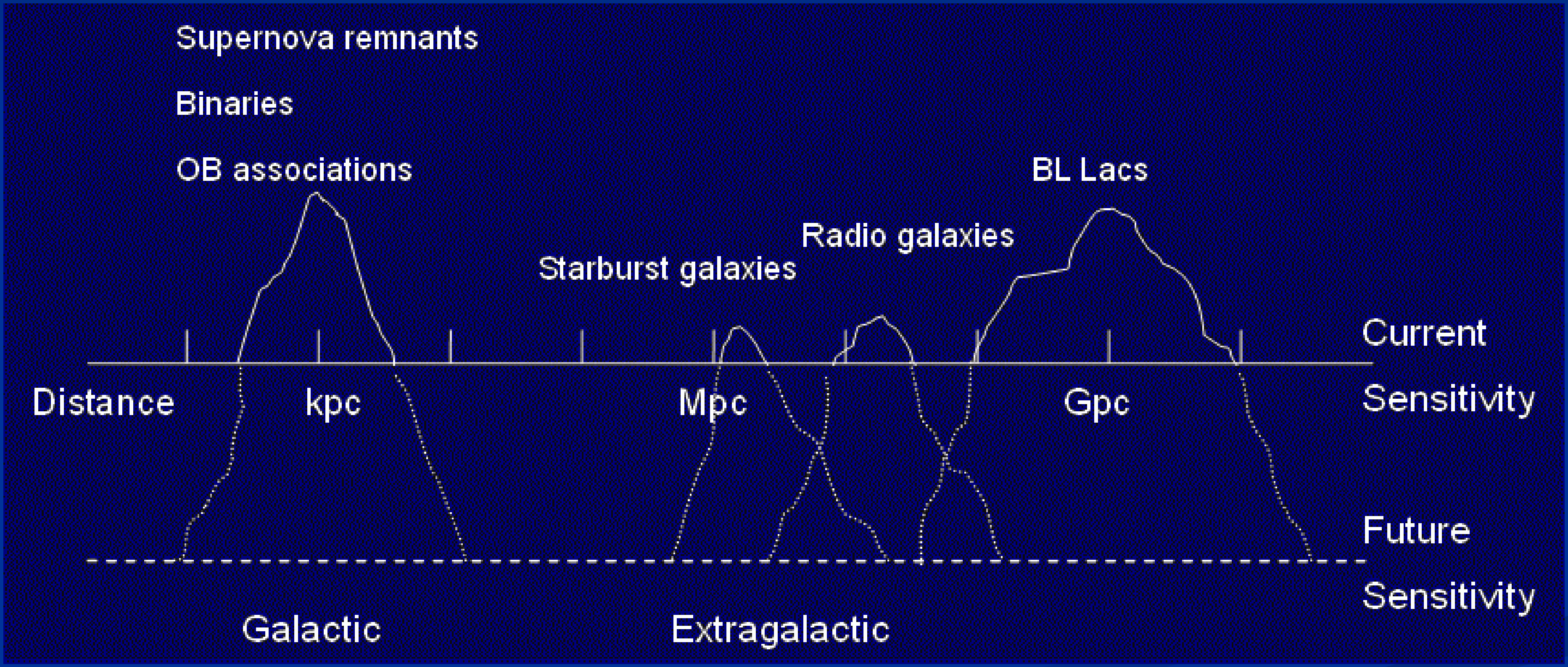
SuperCANGAROO 30m?

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 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.
- There are some evidences of SNR origin of cosmic rays.
- The “third generation” Cherenkov telescopes are about to increase sensitivity – more fun!