TeV Gamma Ray Results,
and
Origin of Cosmic Rays

1. (T.C.Weekes : Whipple)
2. Tadashi Kifune : CANGAROO
3. (H.Völk : HEGRA & H.E.S.S.)

Key words:
Galactic Sources, Southern Sky, CANGAROO

Outline of the talk

- Among broad topics of TeV gamma ray astronomy,
  we discuss the relation between TeV gamma rays and cosmic rays
- Advertising and mainly using CANGAROO results

  Collaboration for Gamma Ray Observatory in the Outback
- describe/summarize the present status,

  raising questions,

  how to clarify the “origin of cosmic rays” observationally

late Prof. M. Oda used to say

the Purposes of CR physics & γ-rays

are as follows:

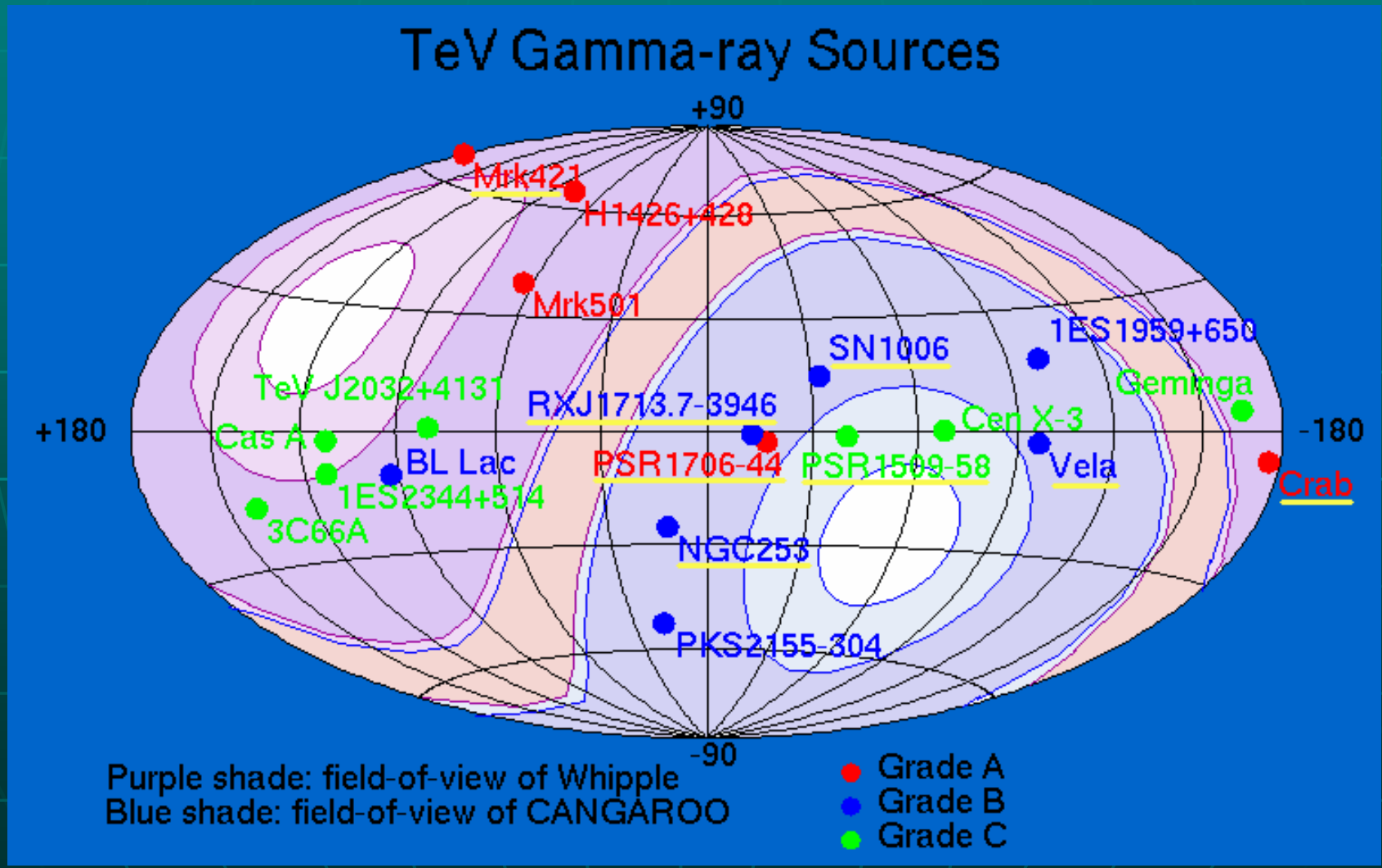
- **Acceleration site ?**
  SNR as likely site of acceleration
- **propagation effect:?**
  confinement in the Galactic disk
  interactions in the (interstellar) space
  to know interstellar matter, 2.7K CMB….
- **Acceleration mechanism / (unkown) particle interaction?**
  Shock Acceleration

Origin of cosmic rays will appear as γ ray source

Gamma-ray emission from Galactic disk (Absorption, Regeneration of γ-rays ….)

Exotic phenomena,
Black hole,
Dark matter, …

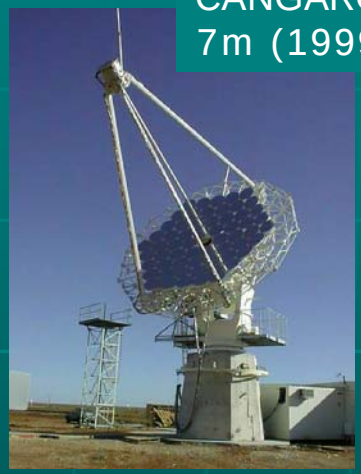
Sites in north and south cooperate to cover all sky



Progress of telescope; CANGAROO as an example

CANGAROO-I
3.8m (1992)

CANGAROO-II
7m (1999)



upgraded

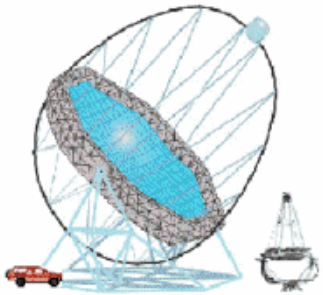
CANGAROO-III
T1 10m (2000)

CANGAROO-III
T1,T2,T3 (2002)

New telescopes are coming…. (next generation IACT)

2004

Large aperture
Multiple telescopes
Lower threshold energy
Stereo observation



MAGIC

VERITAS

HESS

2004

CANGAROO-III

2005
(VERITAS-4)

2003

Results came along a path somewhat "twisted":

(1) Detection of TeV γ-rays from the Crab nebula and then, other pulsar nebulae:

GeV EGRET sources as candidates for TeV γ-rays,

however,

(2) "GeV SNRs": EGRET unID sources associated with SNR such as W28, IC443, W44 .....

Power index of about 2.0 : standard shock acceleration

TeV γ-rays are detected from none of GeV SNRs

(3) "X-ray SNRs":SN1006 etc., not detected by GeV γ-rays

acceleration site other than SNR such as GRB?

- No detection yet on Galactic disk emission,

giving just upper limits

steps for “Origin of Cosmic Rays”

1. Point-like sources of γ-rays from proton?
2. Maximum energy up to knee energy?

Energetics of Cosmic Rays in balance of supply and escape is consistent with SNRs

3. Energetics of TeV point sources consistent with emission from Galactic disk?

Confinement in the Galactic disk: spectral indice of CR and γ-rays ?

4. How many such sources (SNRs) are now active as CR source? :

10^4yrs/50yrs $\sim$ 100?

5. .....

Results : Observation of SNRs

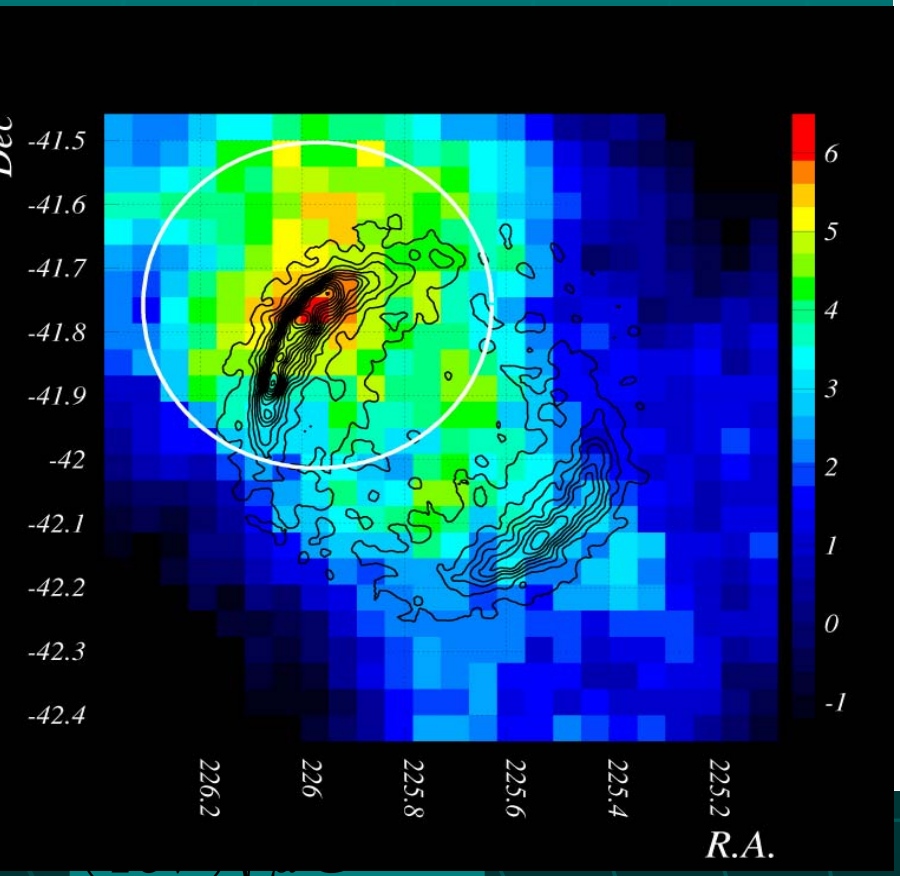
- Three SNRs: SN1006, RXJ1713.7-3946, Cas A,

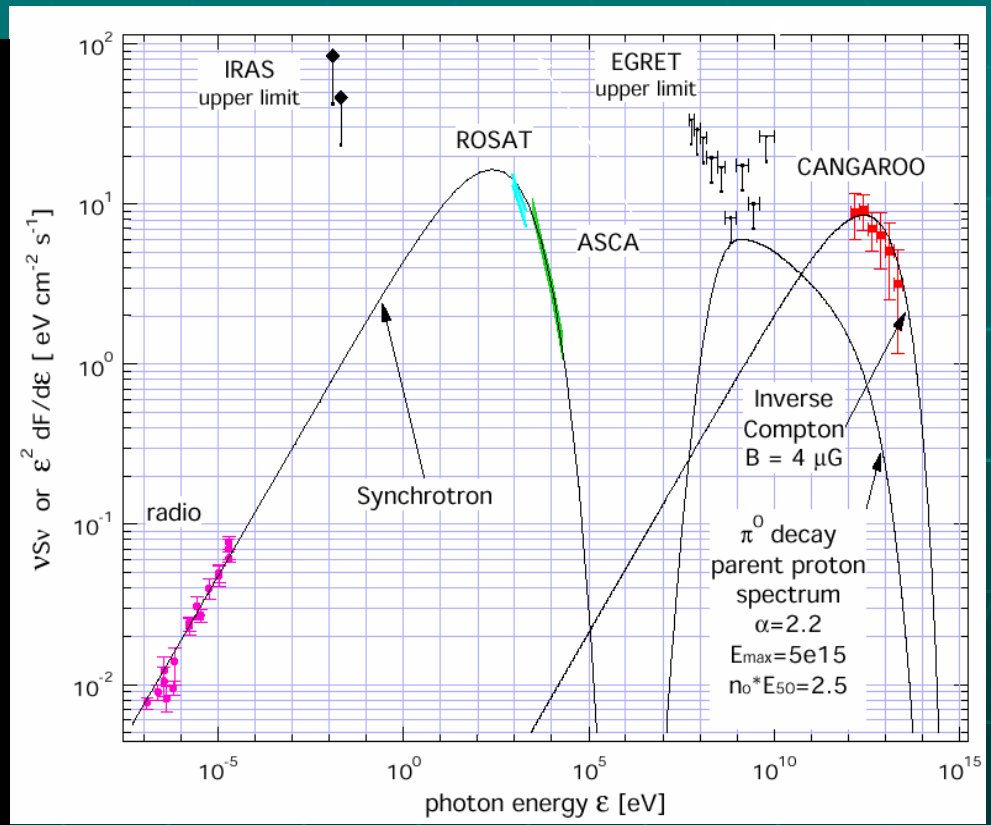
SN1006:

morphology

PSF ~0.25 deg radius.

Energy spectrum : Consistent with electrons (synchrotron-inverse Compton)
However, protons ? with high magnetic field





Naito et al. Astron. Nach. 320, 1999

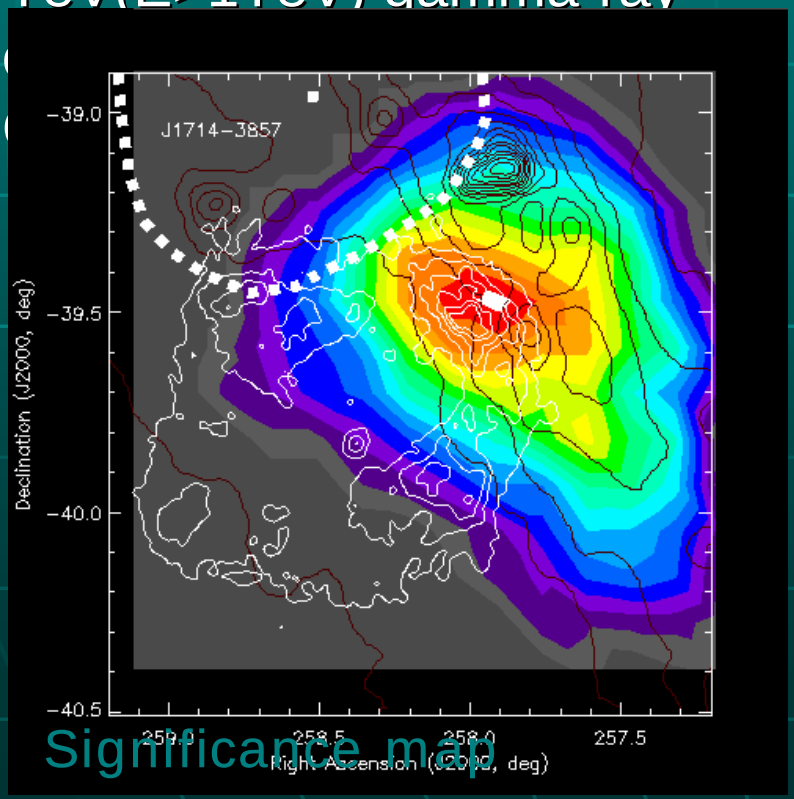
SNR RXJ1713.7-3946

- From the NW rim,

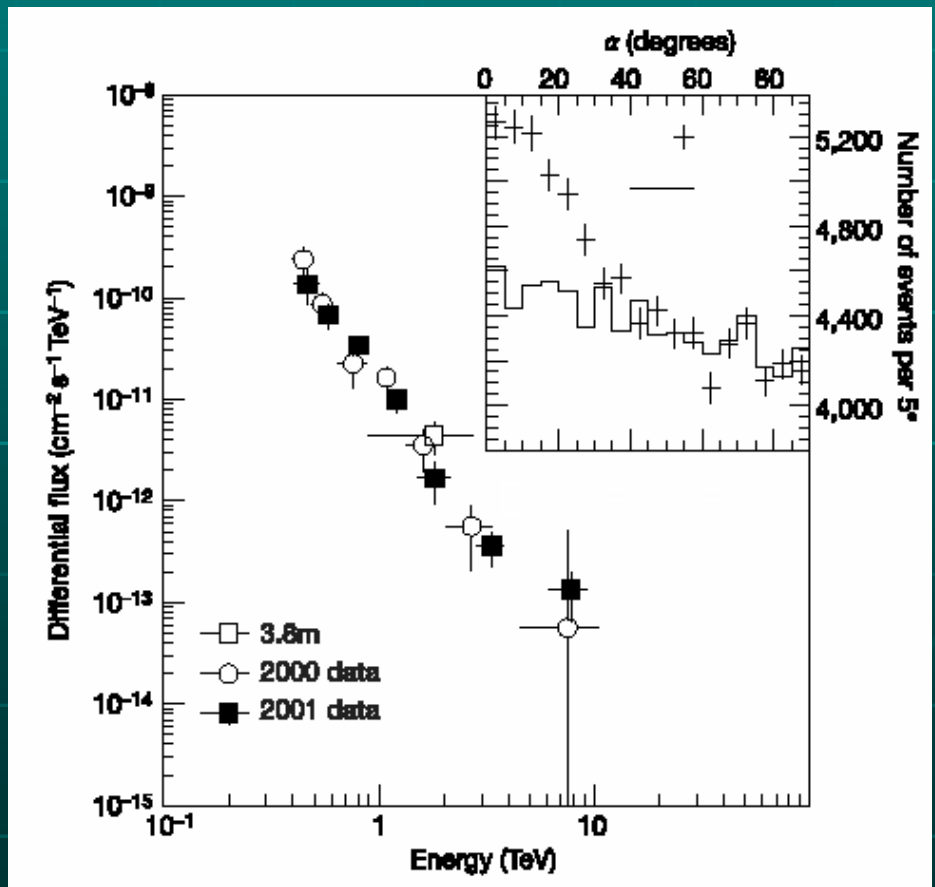
  non-thermal X-ray emission detected with ASCA (Koyama et al.1997),

  TeV(E>1TeV) gamma-ray

Detected with CANGAROO-II at 14σ level in 2000 and 2001

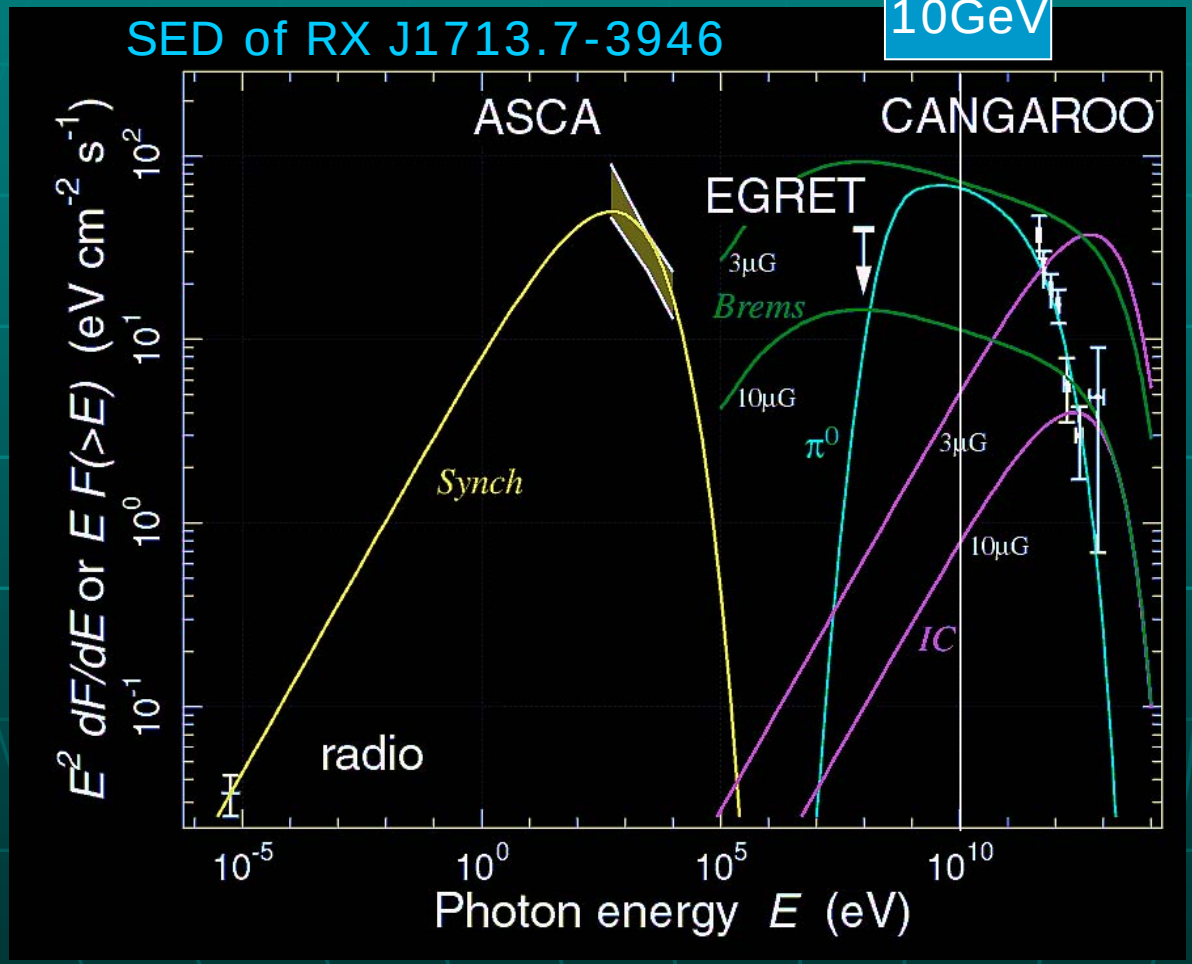


Significance map



Enomoto et al. Nature 2002

Spectral energy distribution of RXJ1713.7-3946



Spectral shape

↓

Leptonic:

[IC, Brems]

or/and

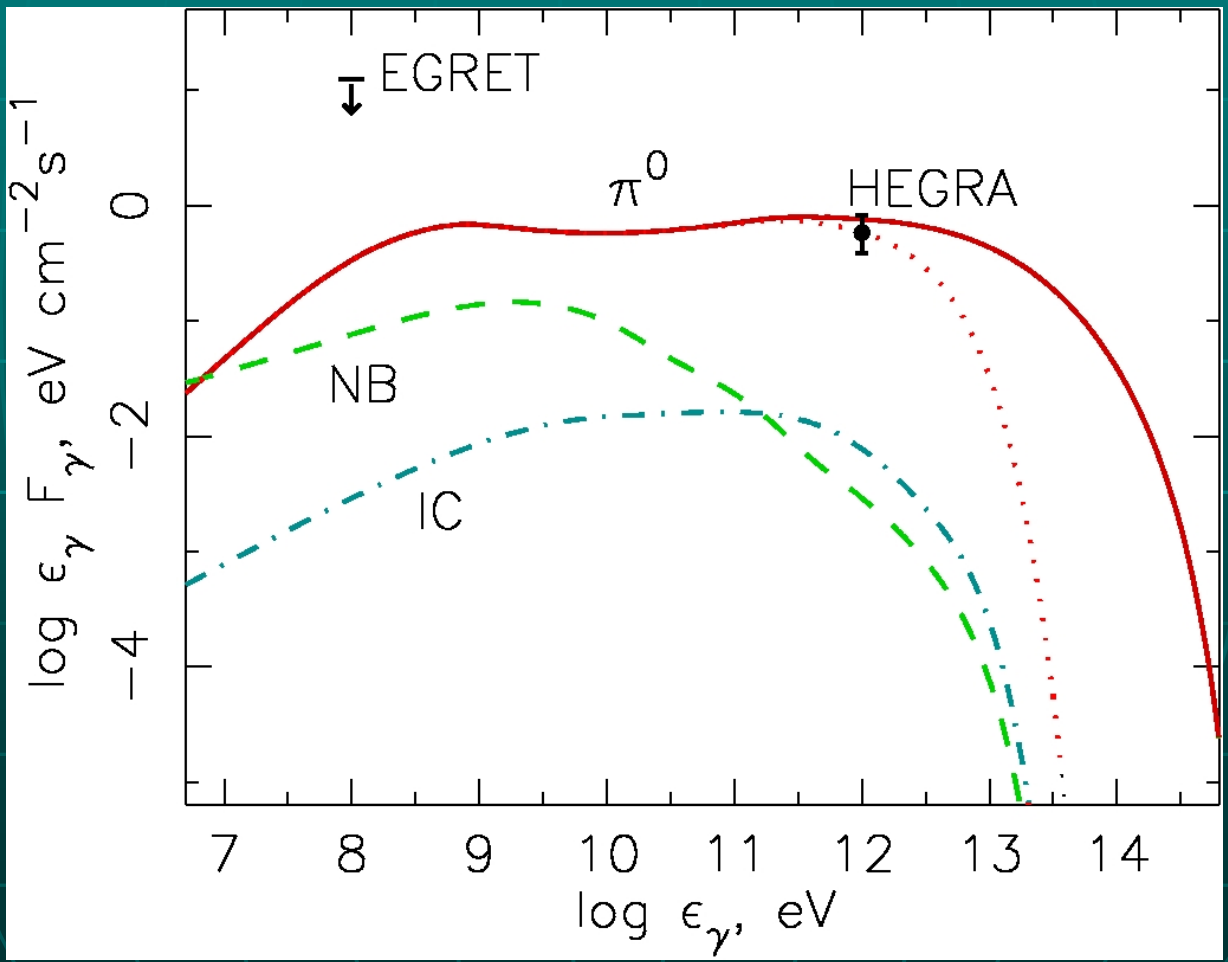
Hadronic:

[π^0]

Enomoto et al. 2002 Nature 416, 823

Cassiopeia A

Deep study led HEGRA to detect Cas A



Results and questions: SNRs

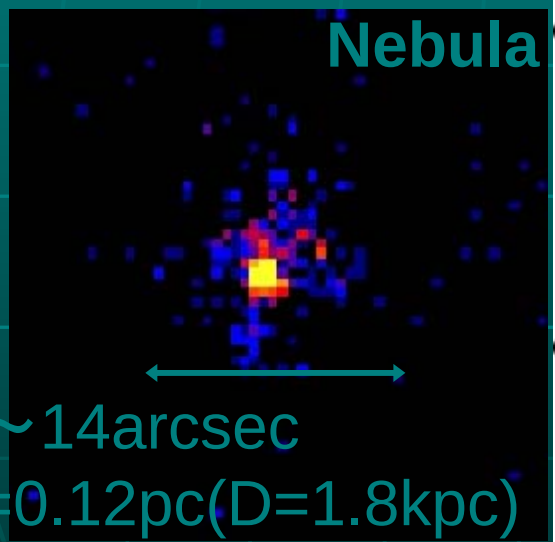
- Three SNRs: SN1006, RXJ1713.7-3946, Cas A,

  Deeper observation for weaker sources

Spectral energy distribution consistent with synchrotron/inverse Compton radiation?

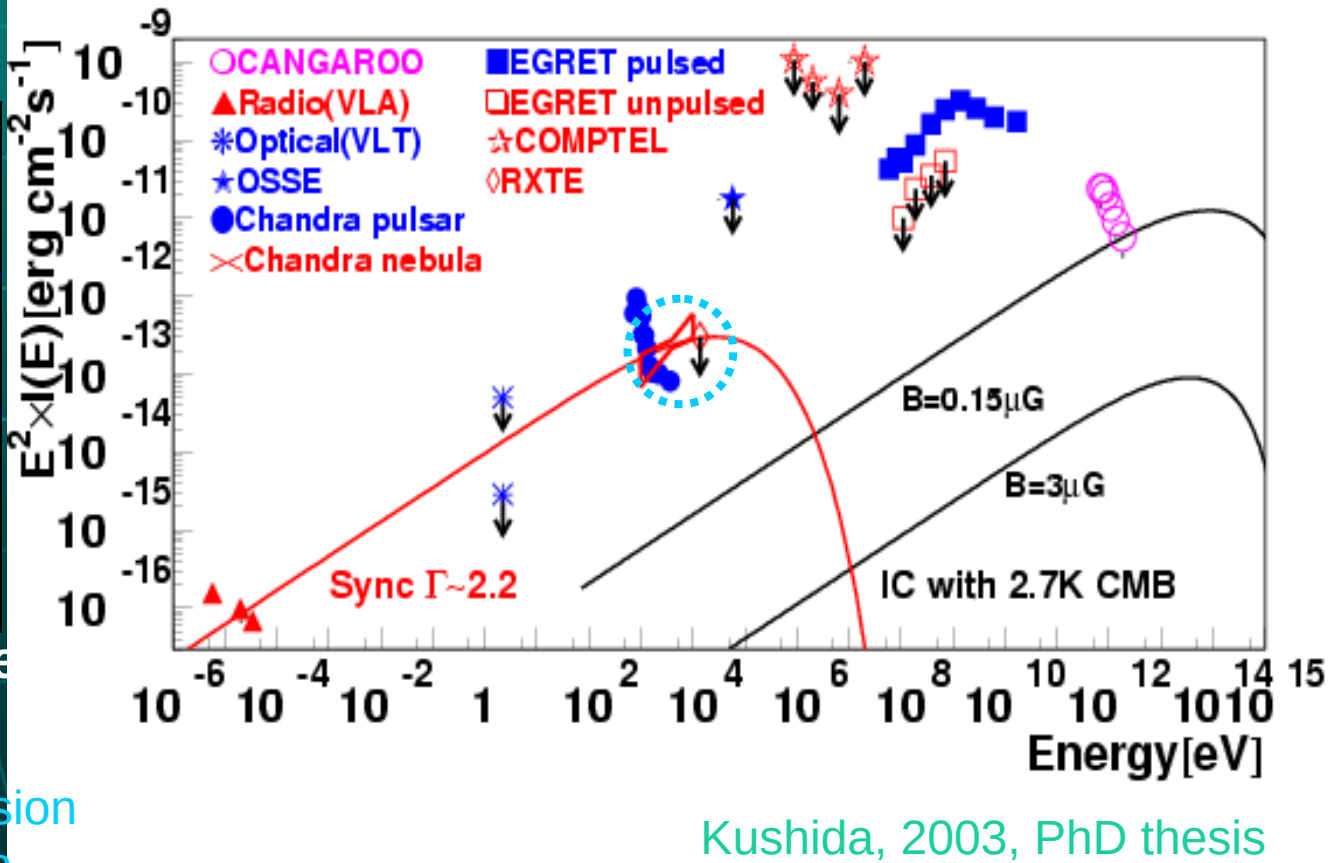
PSR 1706-44: multi-band spectrum

- The peak intensity of detected gamma-ray flux is 10 times stronger than that of X-ray flux from the nebula
- TeV gamma-ray flux is difficult to explain (2.7k CMB) model in Sync-IC



~14arcsec
=0.12pc(D=1.8kpc)

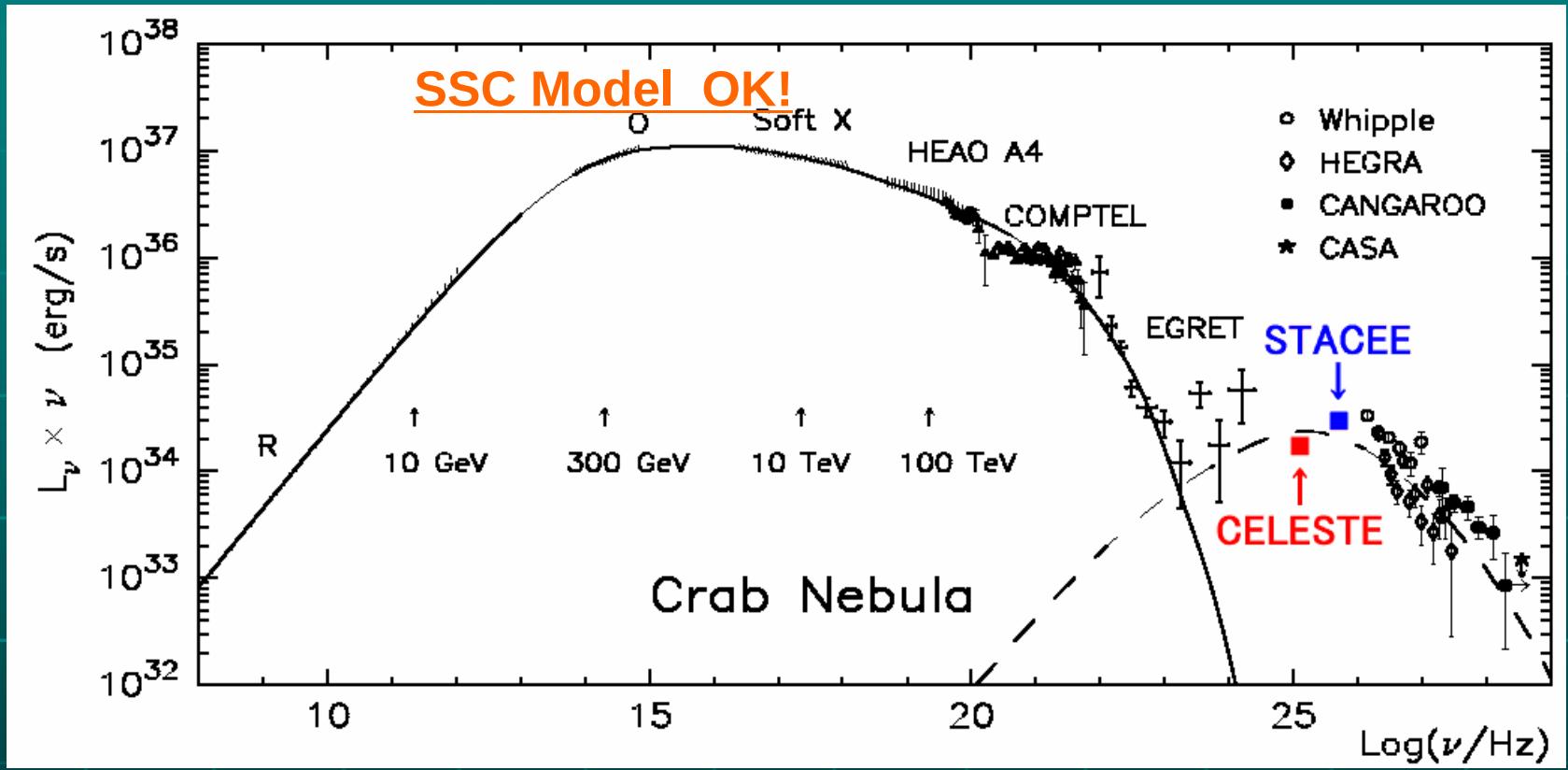
Chandra ACIS Image
(0.7-9 keV)



Kushida, 2003, PhD thesis

Non-thermal X-ray emission detected from the nebula(Gotthelf et al.2002)

Crab nebula(unpulsed) is the standard source for calibration, but not the standard to represent the other TeV sources



the sole SNR/plerion :
"complete" multi wavelength Spectrum
With definite flux in any band.

Max. acceleration energy ?

~20 TeV or >100 TeV

Results and questions: SNRs

- Three SNRs: SN1006, RXJ1713.7-3946, Cas A,
  - Deeper observation for weaker sources

Synchrotron/inverse Compton or π^0 decay?

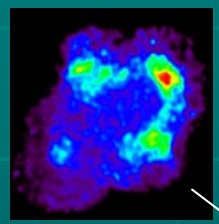
Morphology : mapping of γ-ray emission in comparison with other wavelength

Maximum/cut off energy E_γ of γ-ray spectrum?

No TeV signal from EGRET “SNRs”, implying that the hard GeV spectrum does not extend to TeV band.

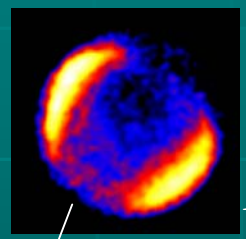
How many sources do we have to visit, before we can rest on sound base?

RX J1713.7-3946 (CANGAROO)



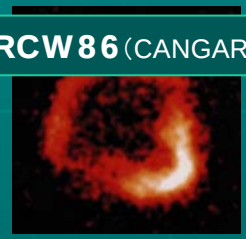
ASCA

SN1006 (CANGAROO)



ASCA

RCW86 (CANGAROO under analysis)



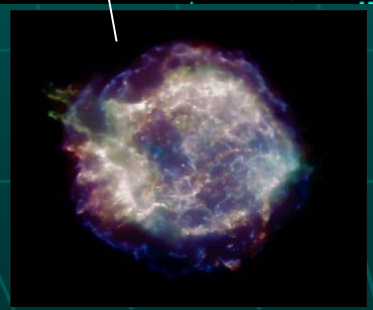
ROSAT

Crab nebula

("Standard candle")

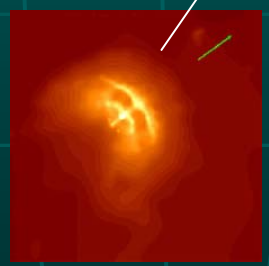
Chandra

・optical



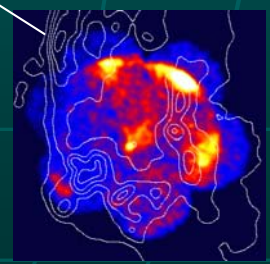
Chandra

Cas A (HEGRA)



Chandra

Vela (CANGAROO)



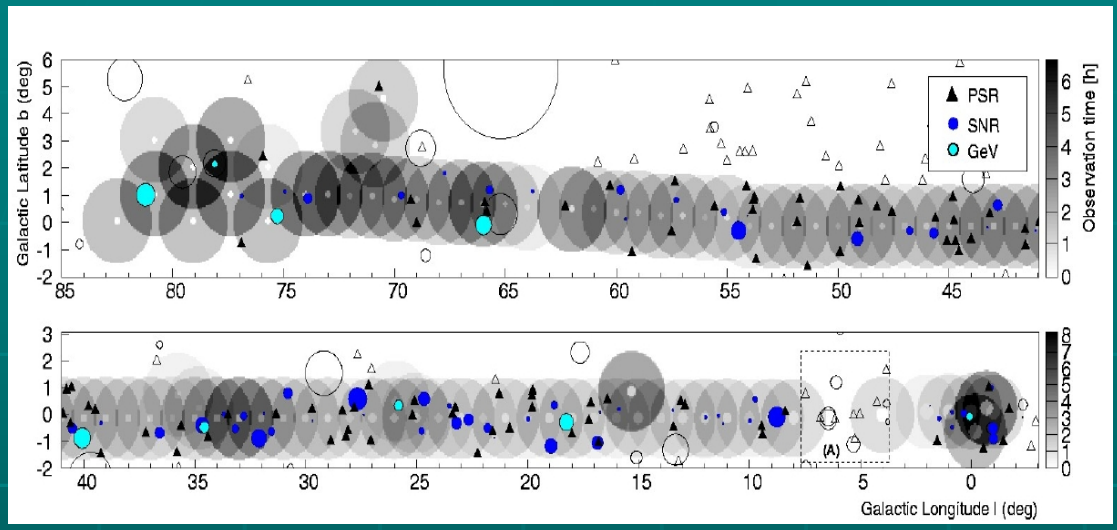
ROSAT

RX J0852-46 (CANGAROO under analysis)

questions stimulate γ-ray study :

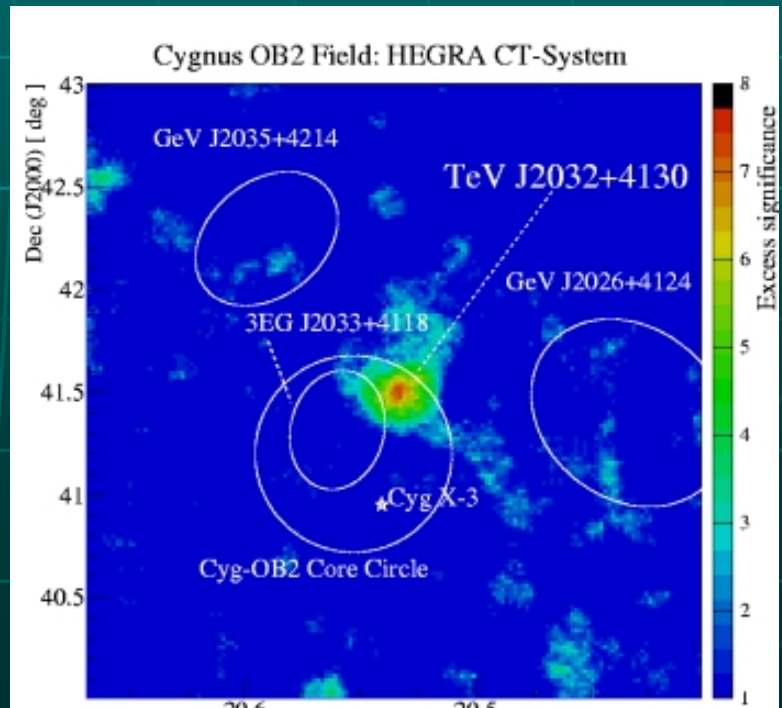
- γ-ray spectra consistent with the CR spectrum below the knee?
- The way how accelerated particles fill the Galactic disk and then escape out of the Galaxy?
- **How** to “observe” acceleration mechanism?
- ……..
- **CR (γ-ray) sources other than SNRs? Other galaxies, blazars and black hole**
- **Transient sources?**
- above **the knee energy 10^{15} eV**
  new sources?
  Extragalactic CRs?

Galactic disk scanned by HEGRA

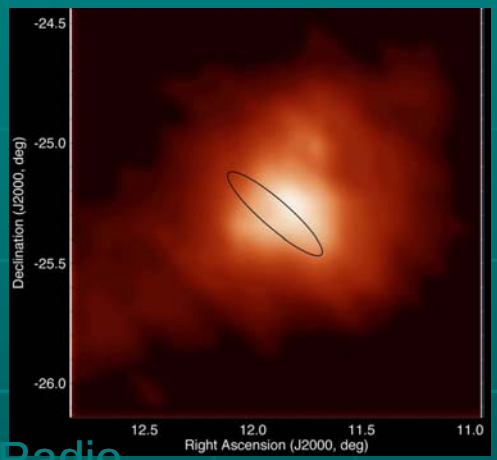


Unidentified source
With a hard
energy spectrum

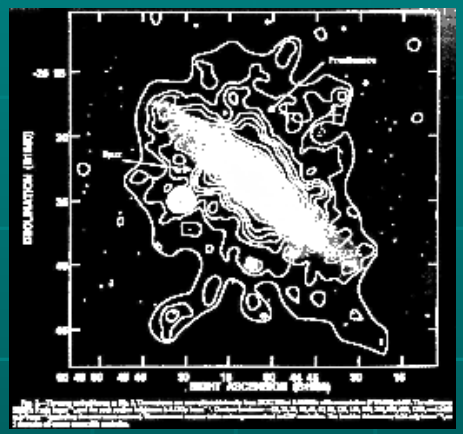
in Cygnus region

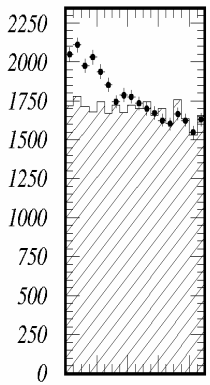


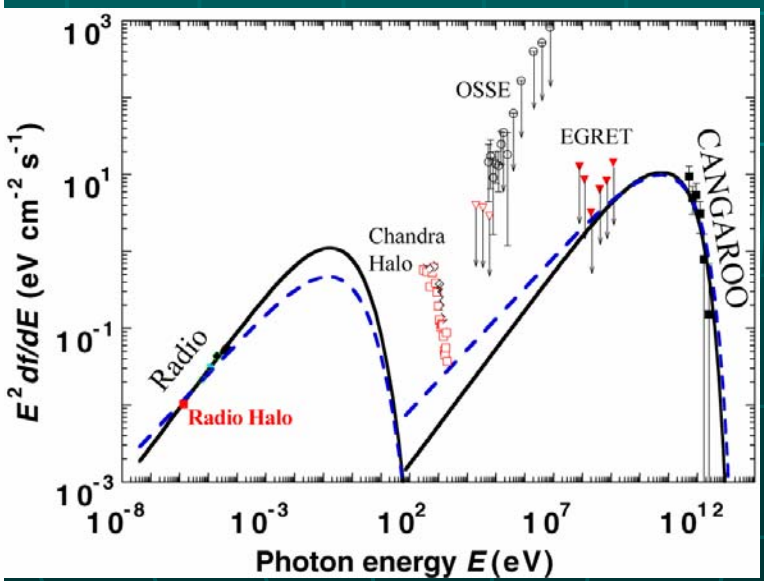
Star burst galaxy NGC253



Radio

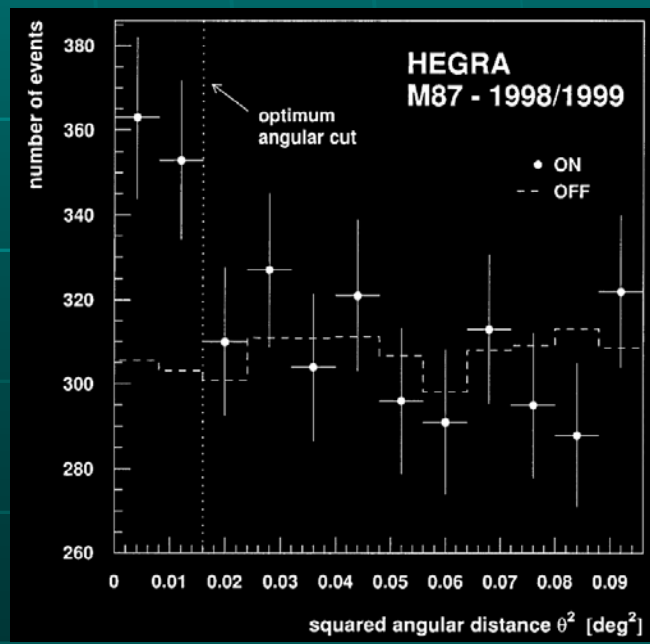






Radio galaxy M87

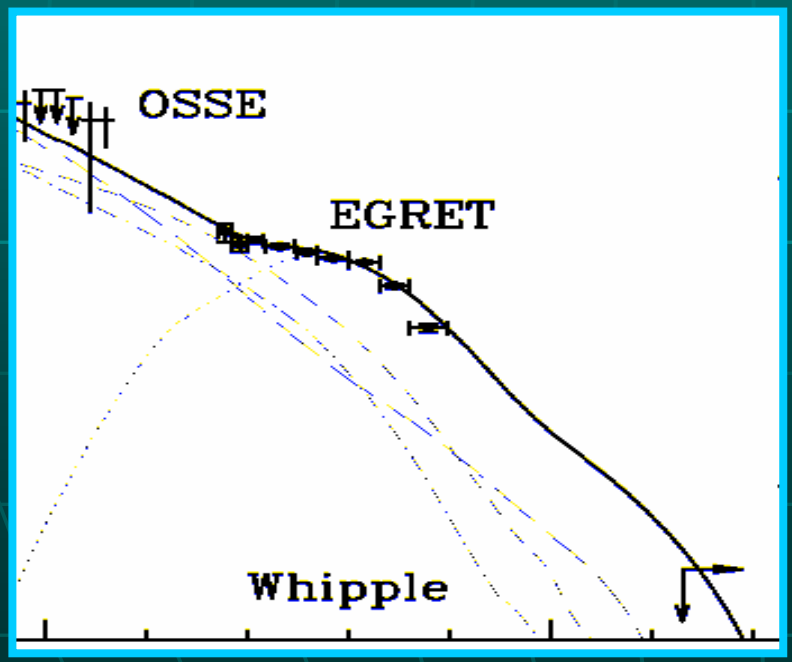
HEGRA
4σ excess

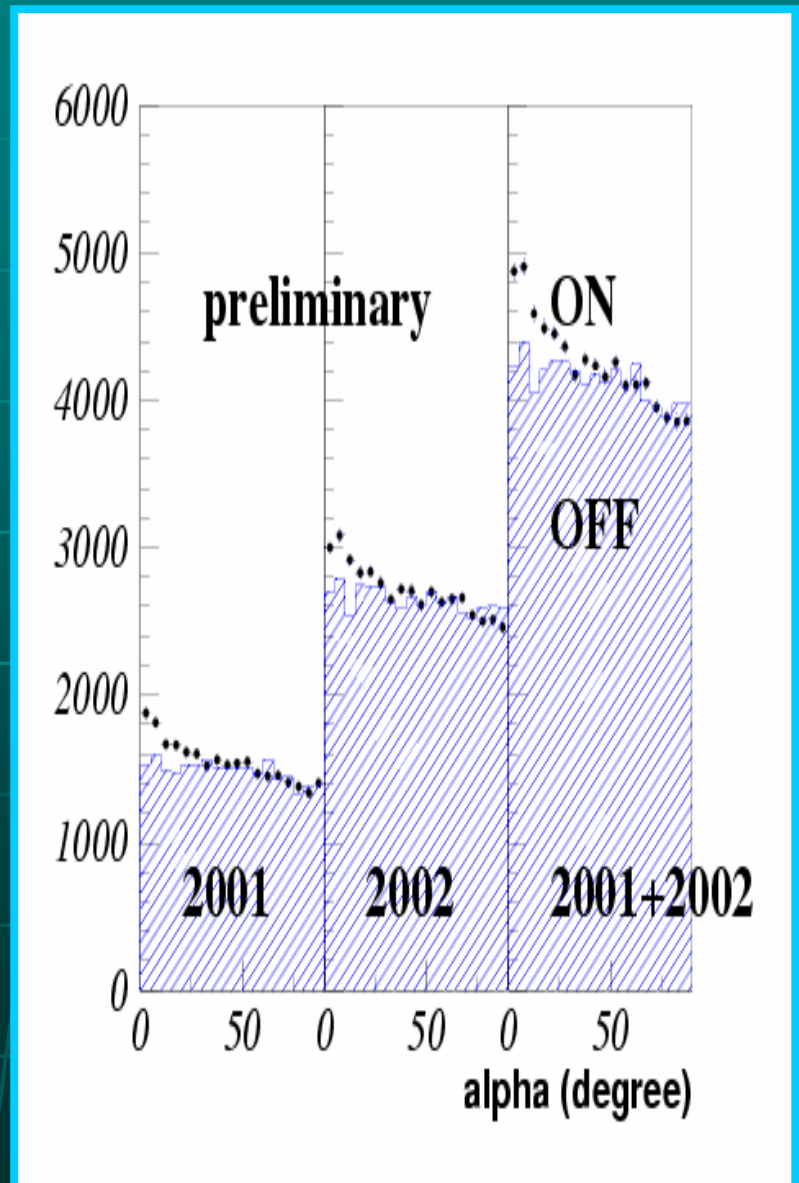


Aharonian et al. 2003 AA 403, L1

Galactic Center ?

- Cangaroo: 7σ, 20+50hrs (20hrs: stereo now taking) point-like,
- Whipple: 2.4σ, 16hrs
  >2TeV





Summary 1

- So far three SNRs (against 100 ≈ $10^{4\sim5}$yrs/50yrs)
  - **How peculiar/standard they are?**
    - E_{acc} up to 10^{15}eV?
- two galaxies
  - **How peculiar/standard the Galactic CRs are?**
    - Disk emission?
    - Normal galaxies by deeper observation
  - **γ-ray observation extends CR physics to extragalactic space**

Summary 2

- **We are just beginning to answer for "Origin of cosmic rays"**

  1. having (almost) found "point-source γ-rays" from hadrons,

     the site of accelerating hadronic CRs

     It is, however, necessary to collect data at higher E_γ and of detailed γ-ray morphology of fine mapping

  2 Still a long way to go, but the right one we are taking. Further investigation which should follow :

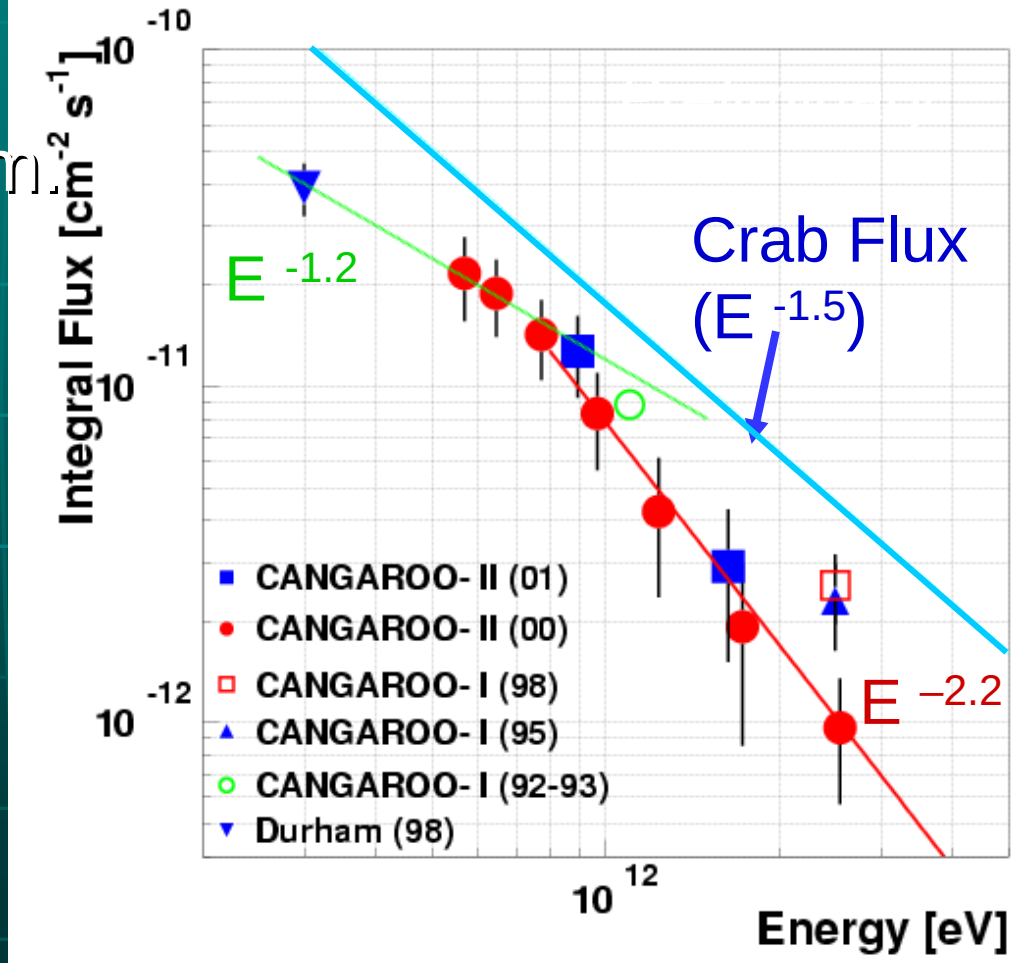
  Transport/Propagation effects,

  Acceleration mechanism, and so on …….

- Next generation telescope "improves answers", hopefully
- What remains for further efforts:
  - Transient sources with wider field of view
  - γ-rays of higher energies

PSR 1706-44

- P=102ms
- Large spindown lum.
  logL(erg/s)=36.5
- D=1.8(2.4~3.2)kpc
- TeV emission detected with Durham and CANGAROO-I
- Observed with CANGAROO-II in 2000 and 2001

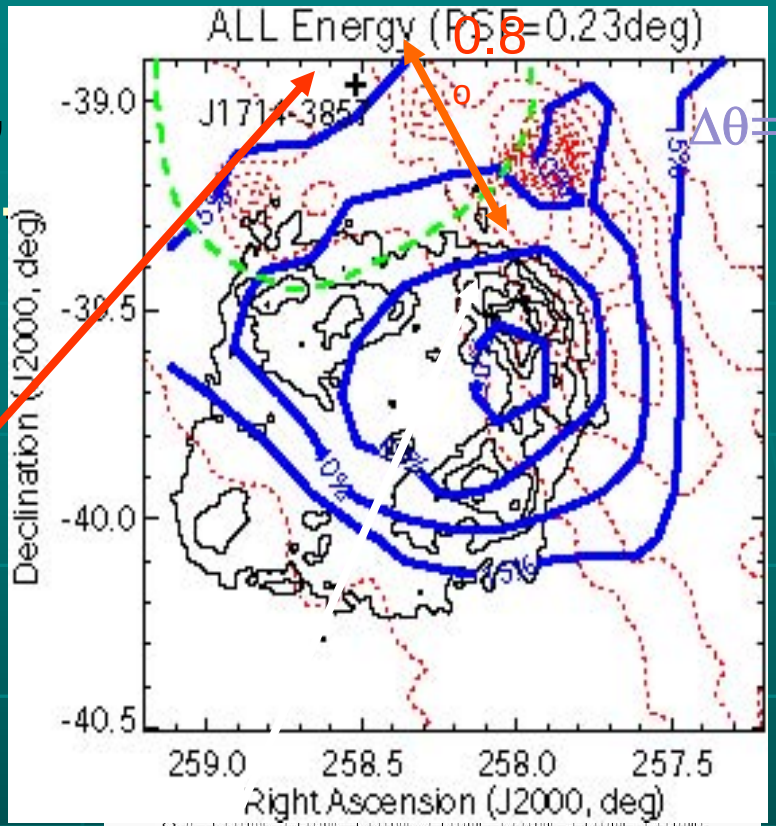


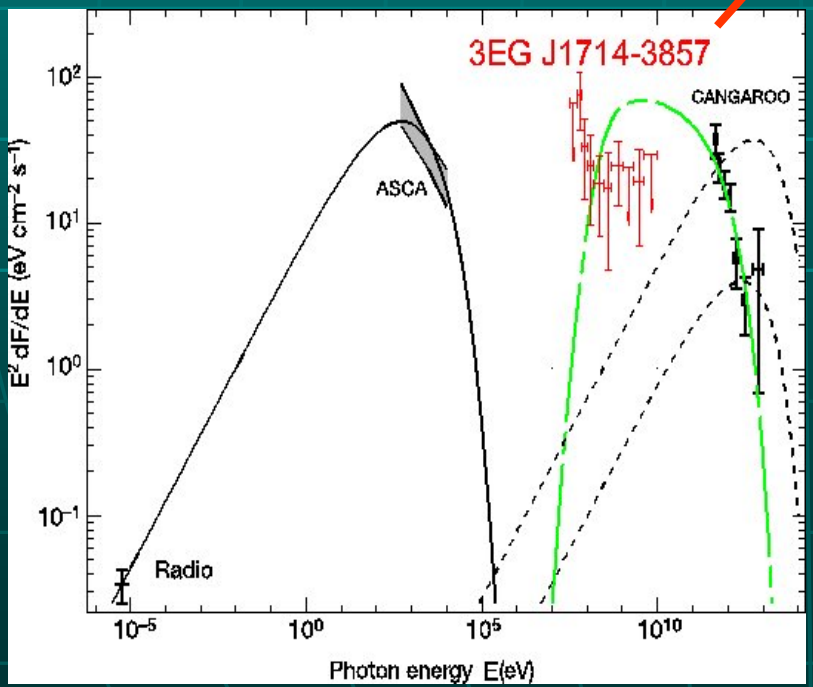
Kushida et al. in preparation

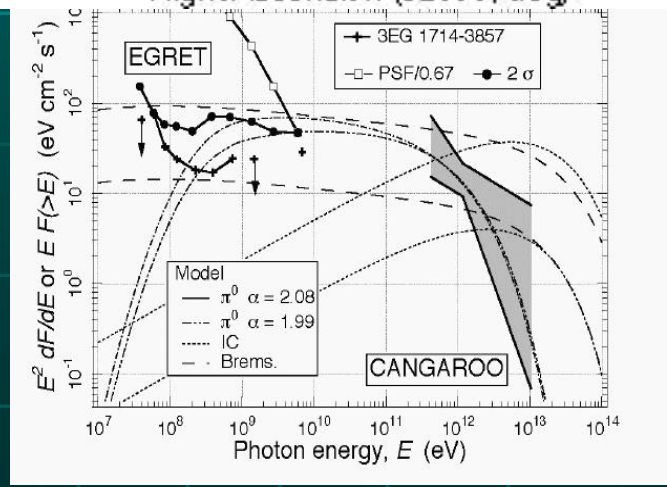
Nearby molecular clouds, EGRET source and so on….

O.Reimer & M.Pohl A&A, 390, L43, 2002
M.Butt et al., Nature 418, 489, 2002

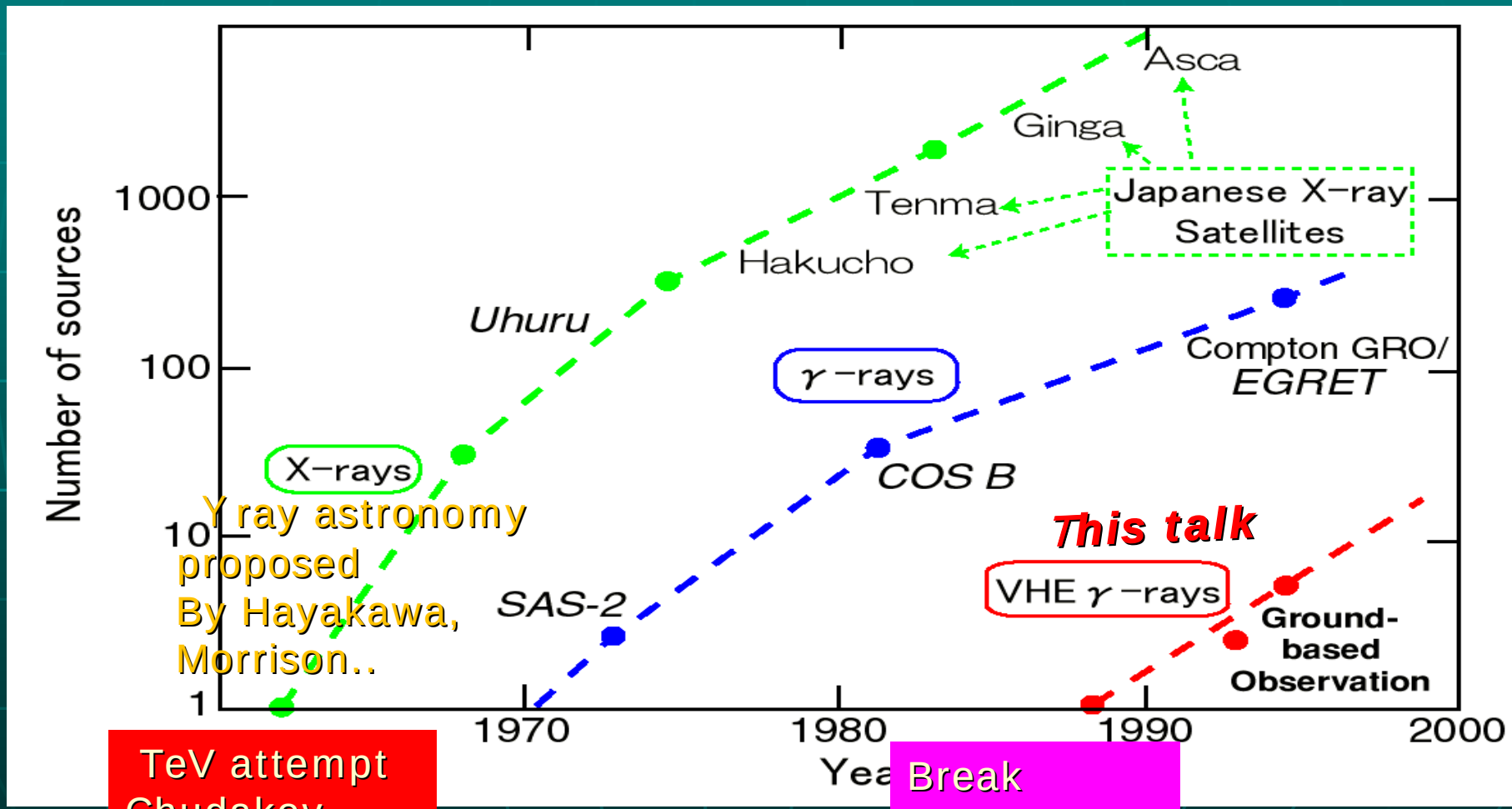
Discussions a lot







A decade of years, since TeV window was opened.

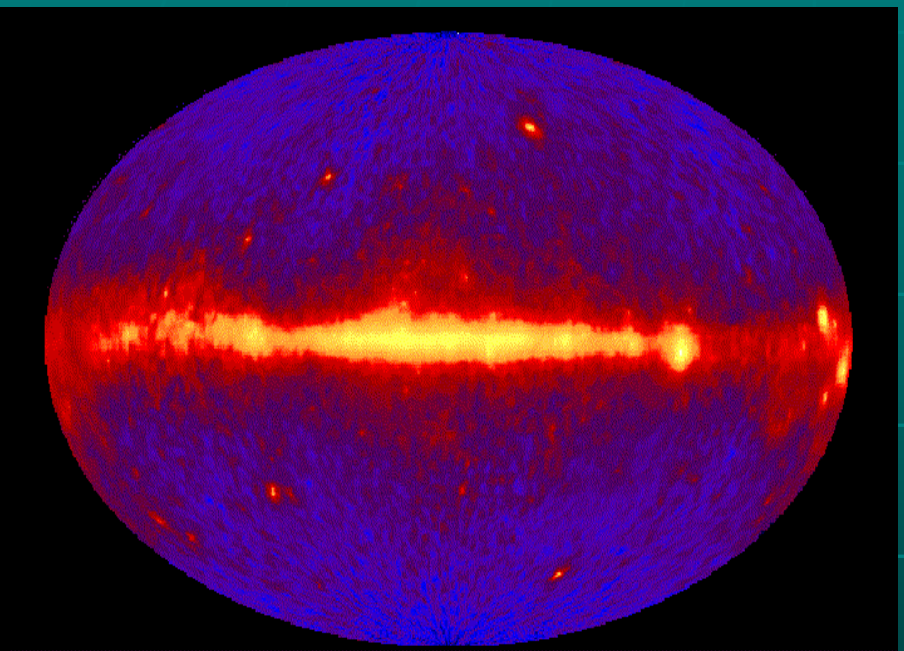


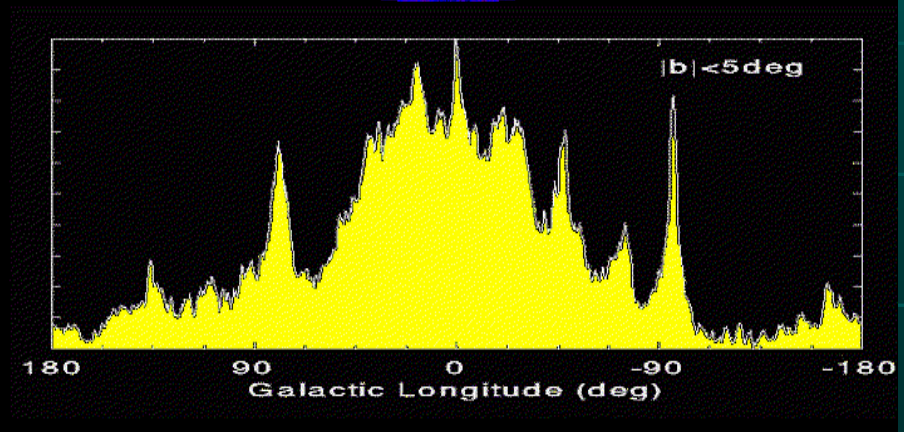
TeV γ-ray sources and "Grade"

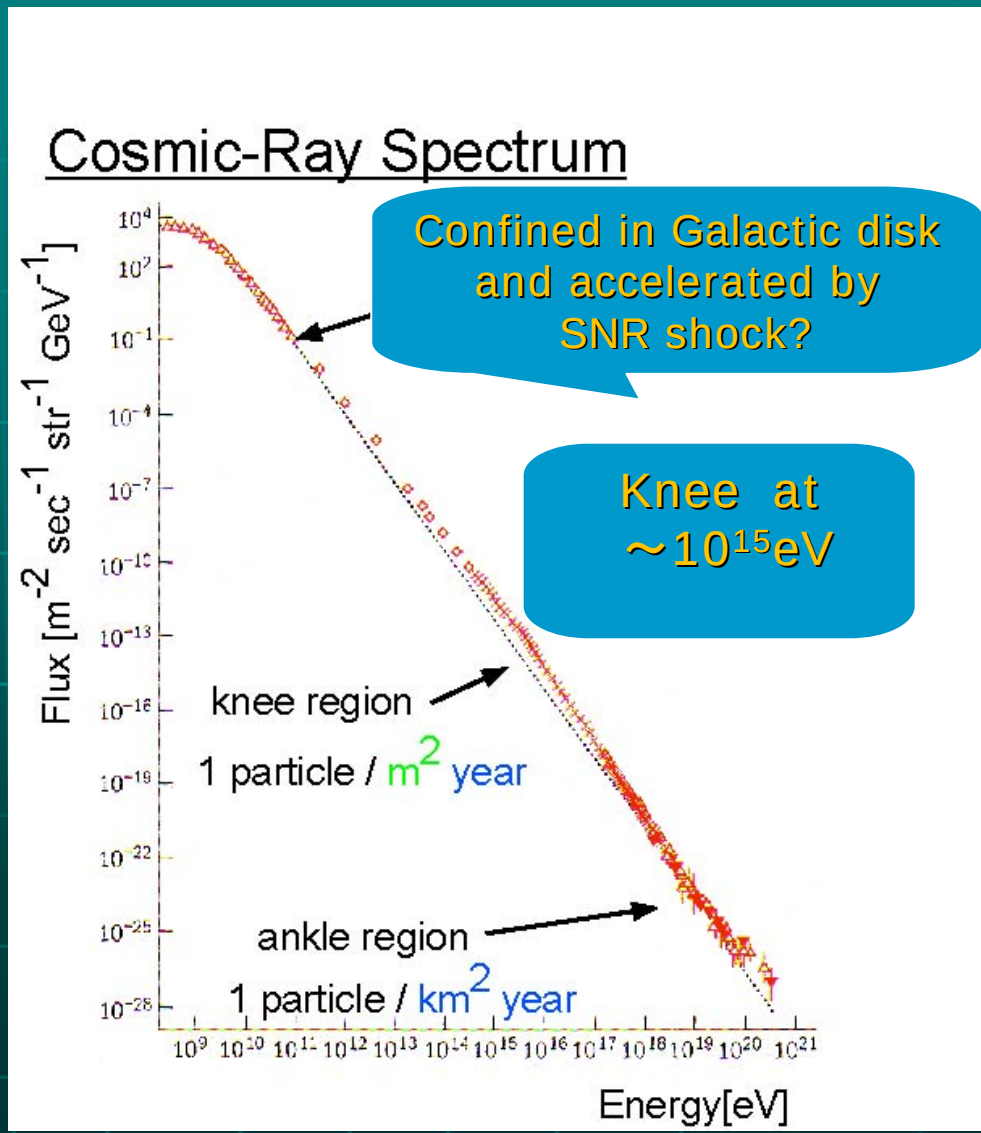
Type	A	B	C
Pulsar nebulae	2	1	1
SNR		3	more to join.....
X-ray binaries			1?
UnID		1	
Others			2 (GC...)
Blazars	4	1	2
galaxies		1 (NGC253)	1(M87)
GRB			1
Total	6	7	About 10

Gamma rays are a probe for cosmic rays
SNR as likely site of acceleration

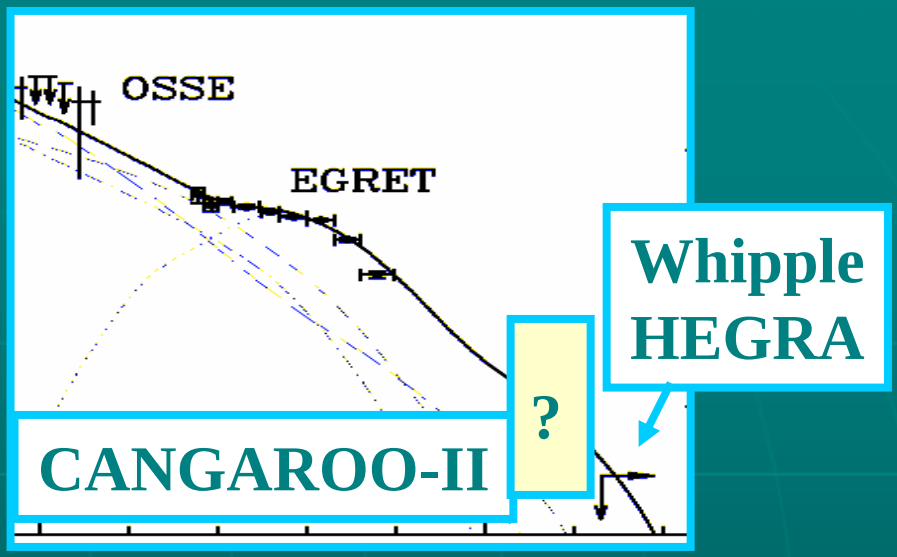
Disk emission: by EGRET
100MeV: $< E\gamma <$ about 10 GeV







Very High Energy Gamma-rays from the Galactic Center

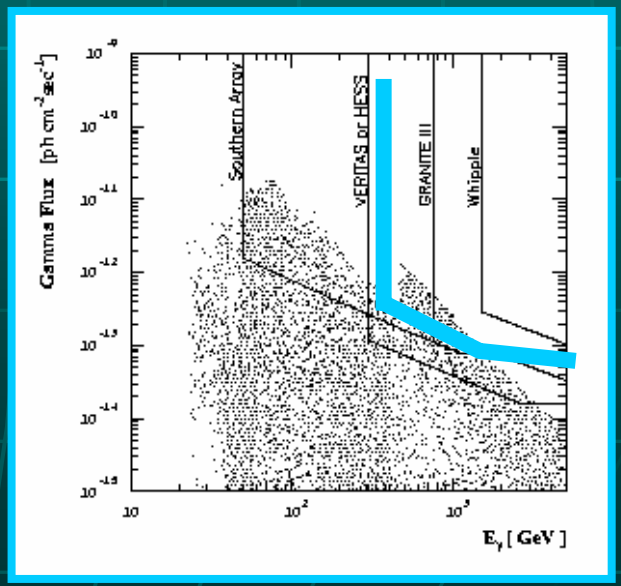


- SNR

  Inverse Compton emission

  or pi0 gamma-rays?
- Massive black hole
- Cold dark matter

  the cusp around the galactic center → annihilation

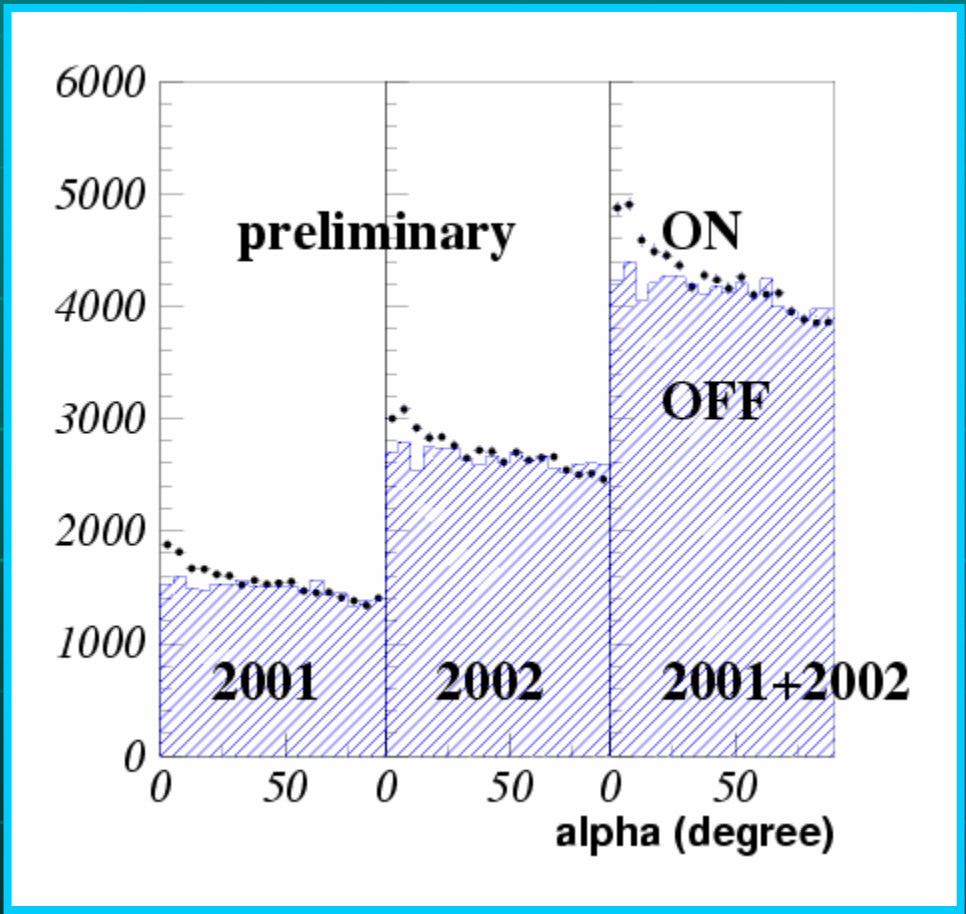


Bergstrom et al (1997)

Alpha distributions with Likelihood analysis

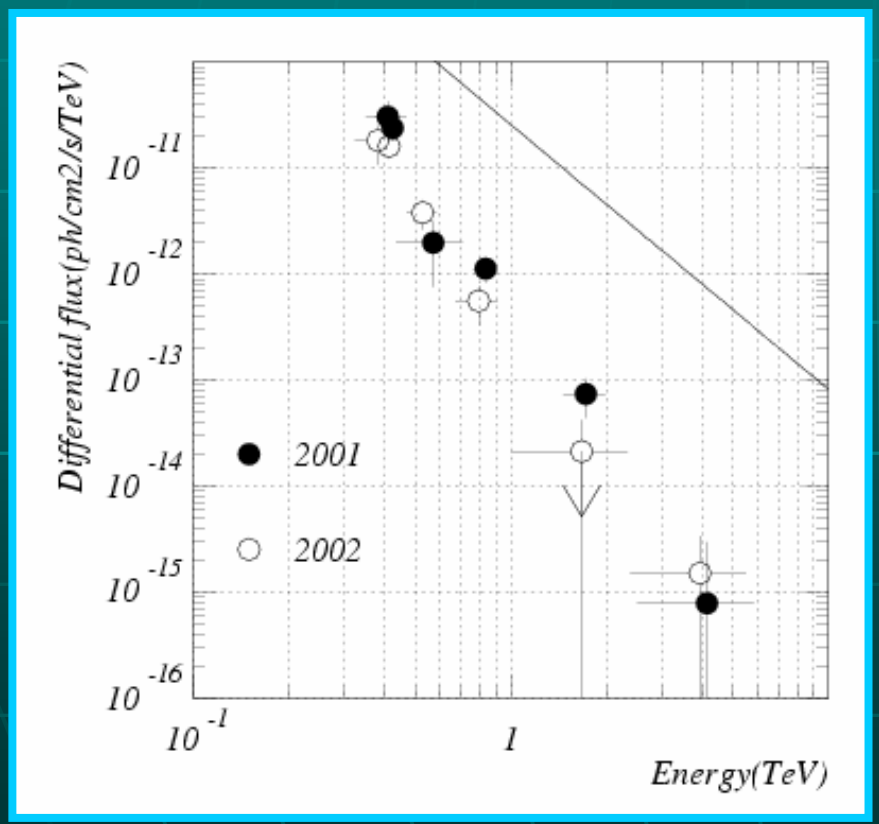
0.25<Distance<1.2
E-ratio cut <0.25
0.4<Likelihood ratio<1.0
Alpha <15

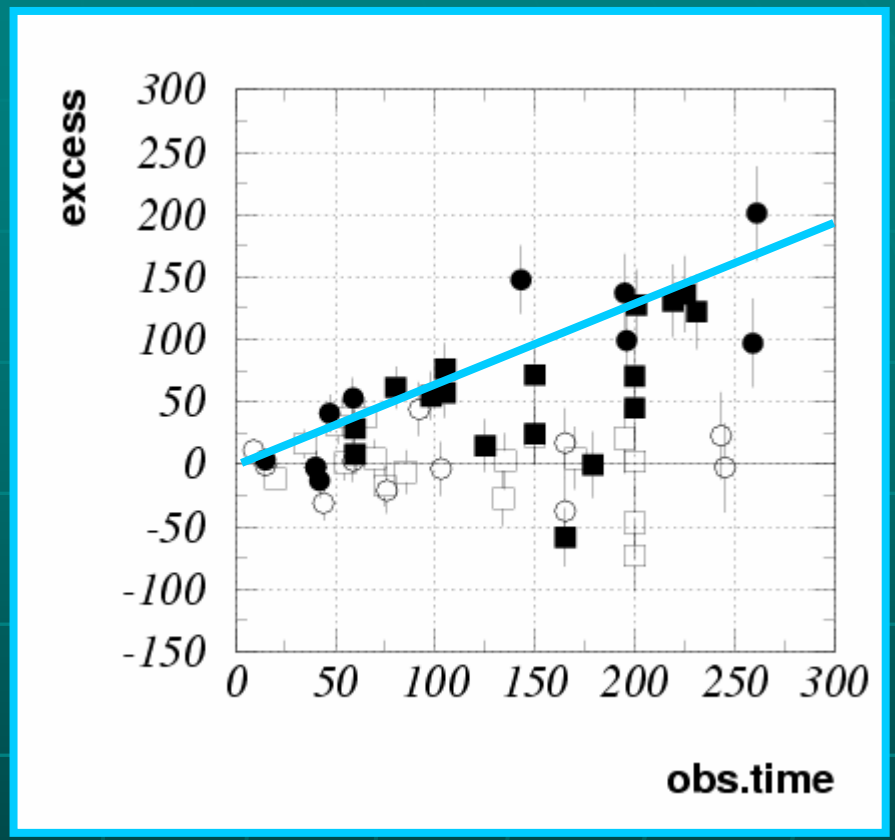
Gamma-ray signals from the galactic center



Differential Flux

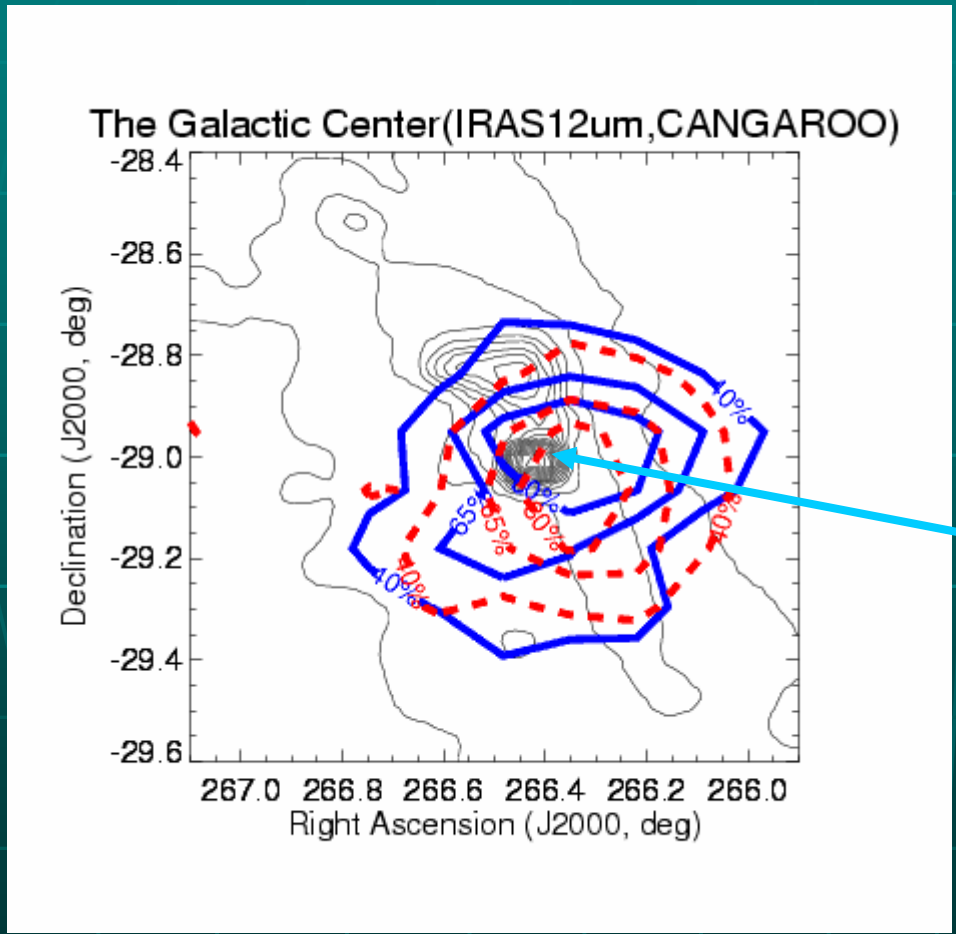
Preliminary results !





Excess vs Observation time for each runs

Significance Map

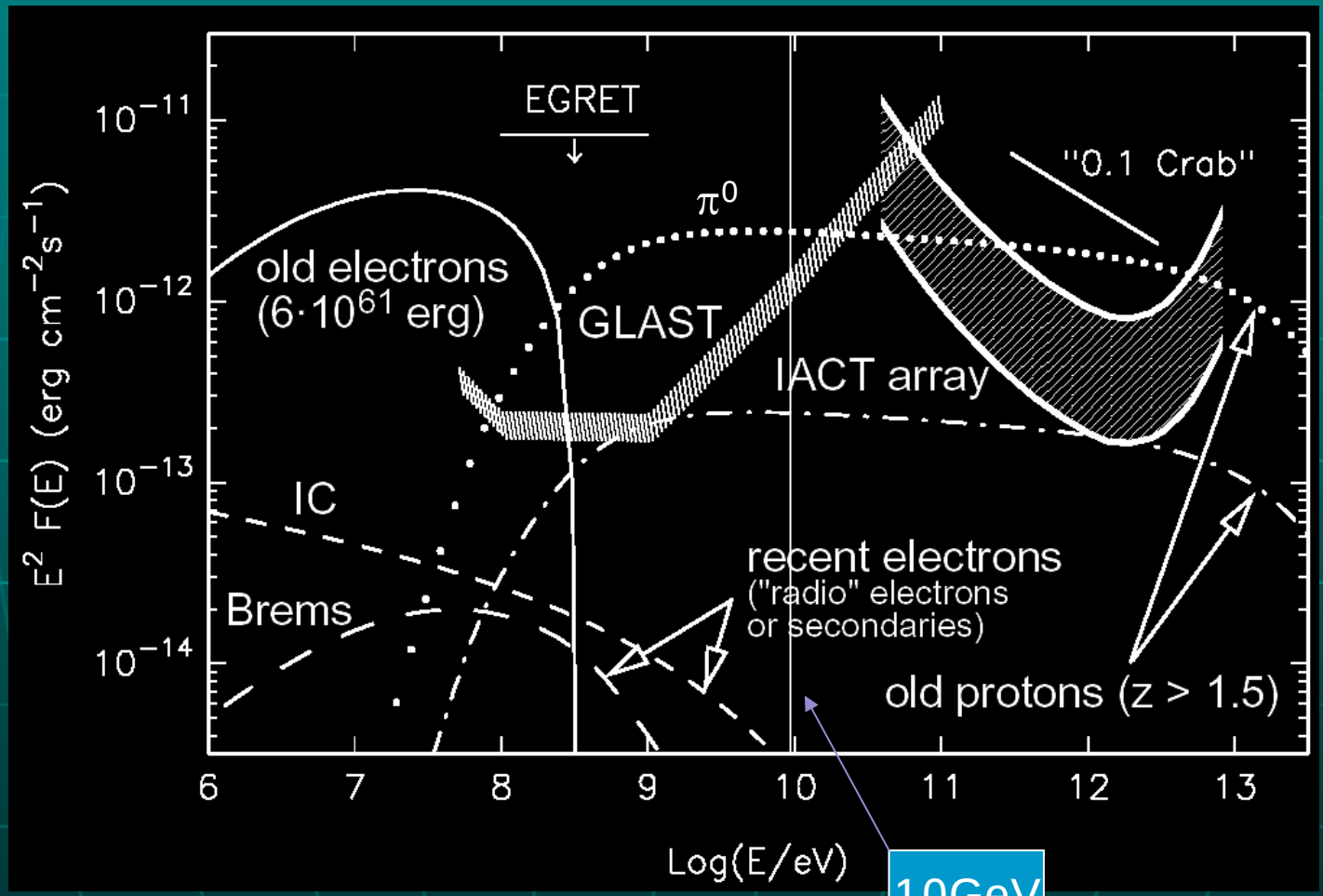


Red dot : 2001 data
Blue line : 2002 data
Black solid : IRAS

Preliminary results !

Very High energy gamma-rays from the Galactic Center

Coma cluster



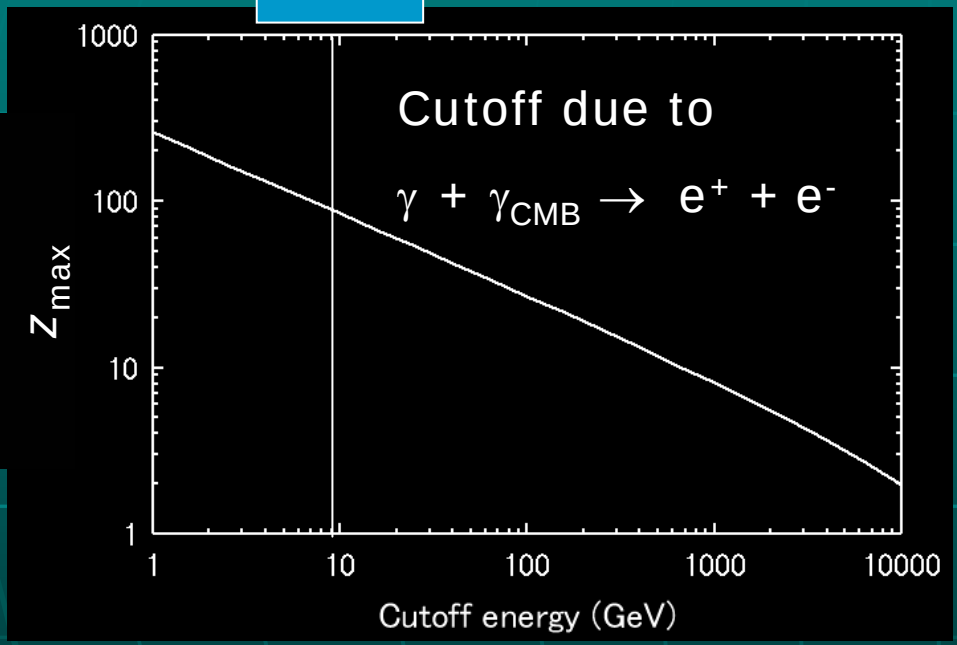
$B = 1\mu G$

$W_p = 3x10^{62}/3x10^{61}$ ergs

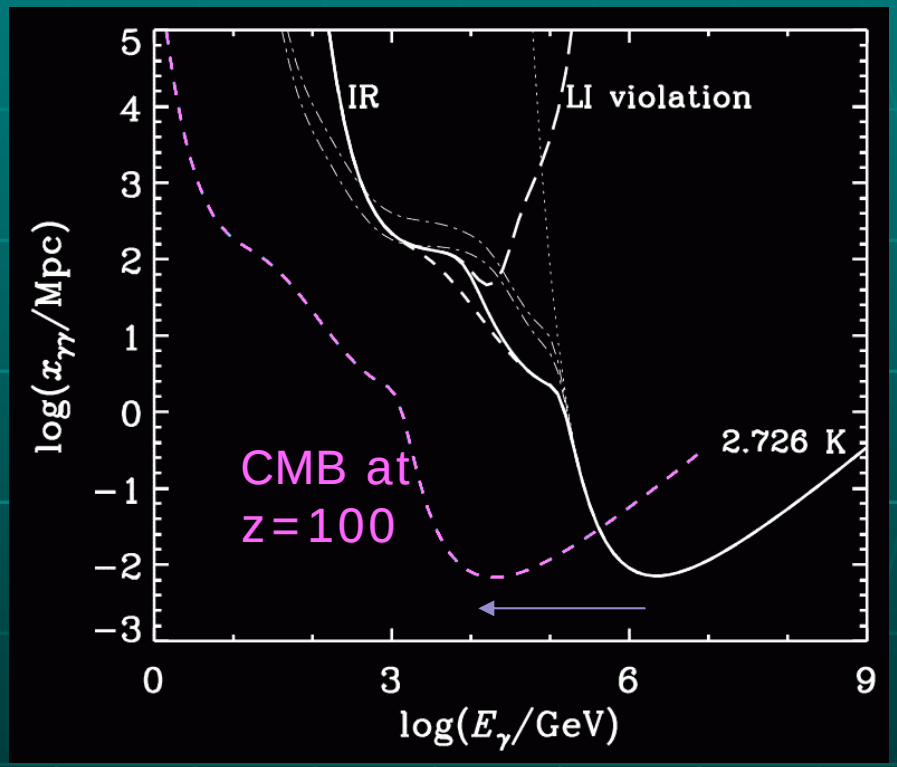
Atoyan and Voelk 2000 ApJ 535, 45

Cosmological gamma-ray horizon

10GeV



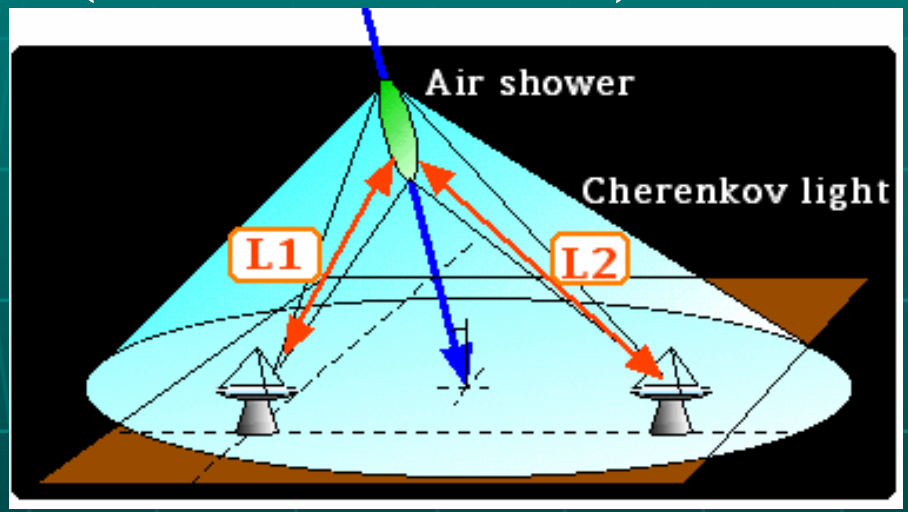
Fazio & Stecker 1970 Nature 226, 135

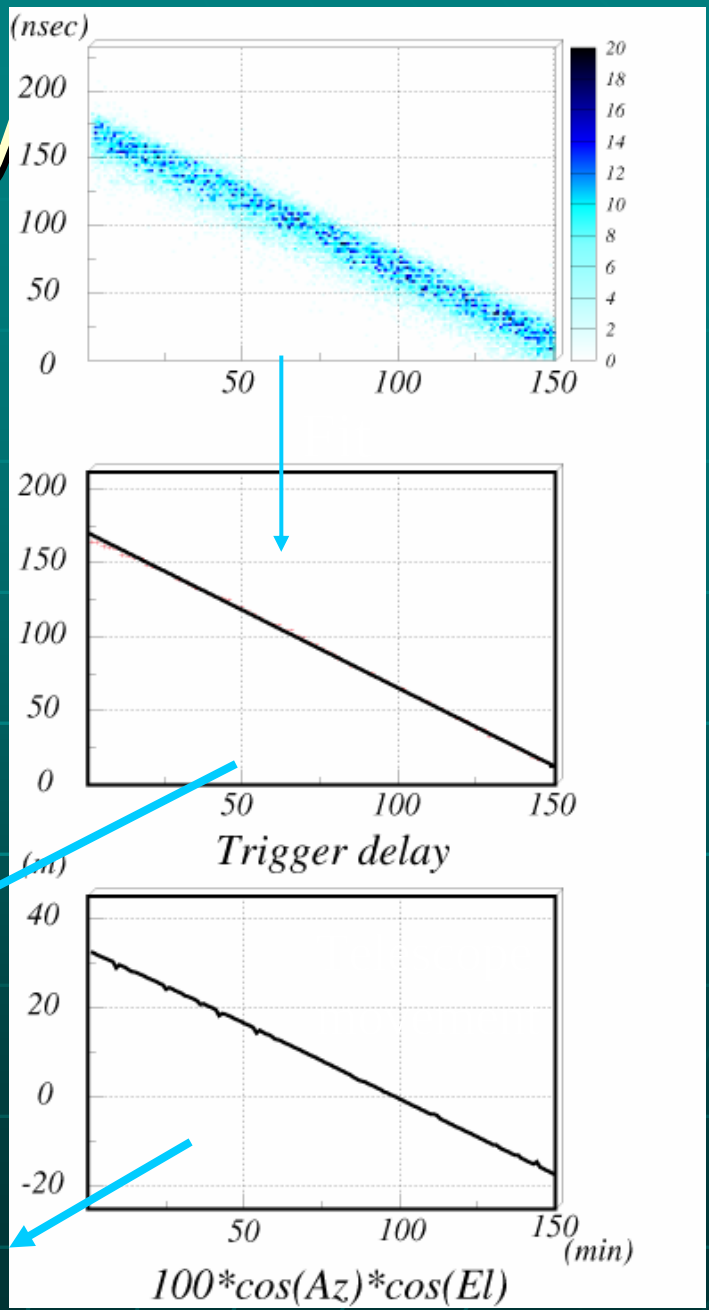


10 GeV gamma-rays can explore the Universe up to z=100!

Stereo Analy

Trigger Delay time
(measured with TDC)





-1.0515 ±0.02 ns/min

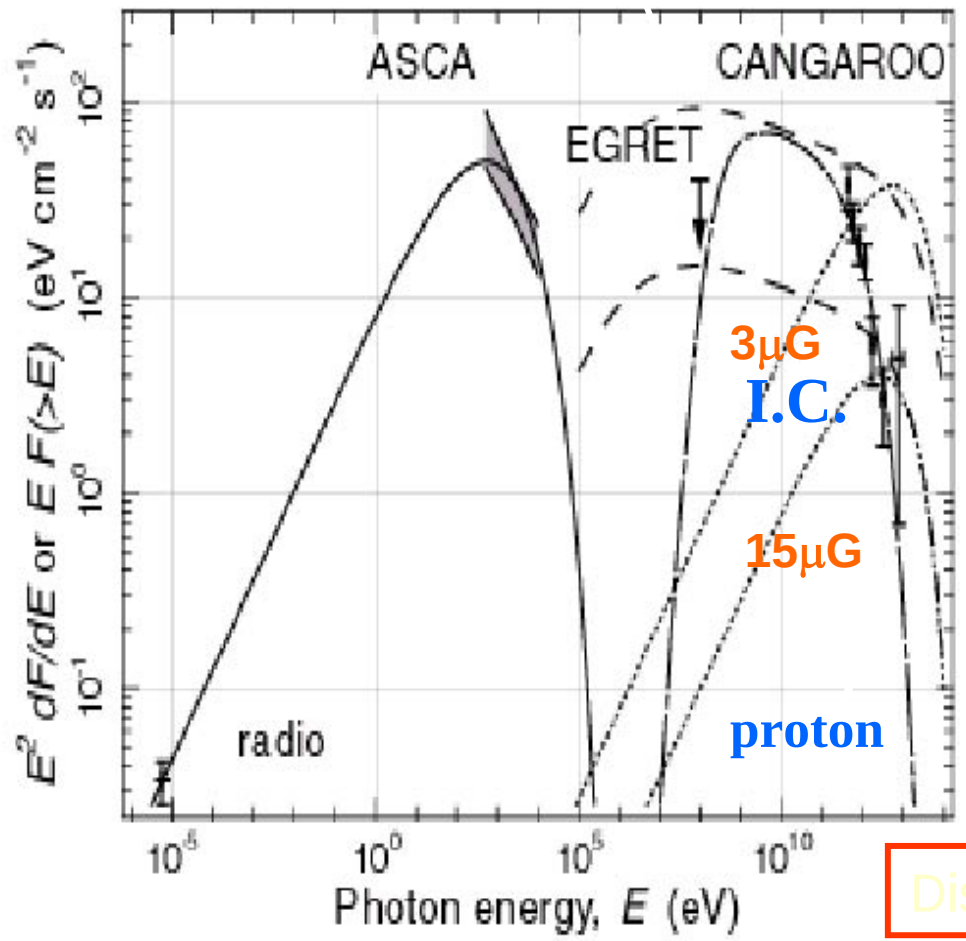
÷ C (light speed)

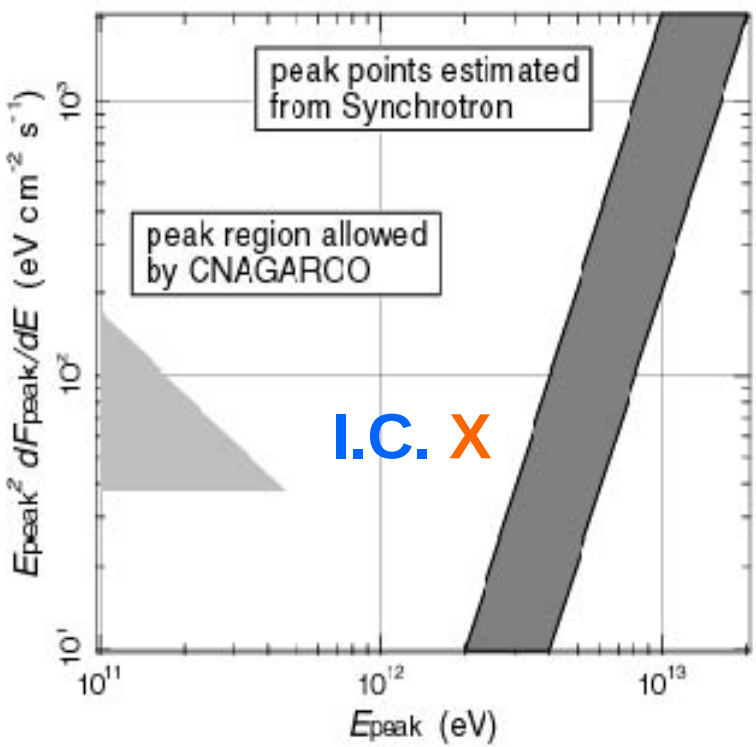
-1.105 ns/min ← -0.331 m/min

RXJ1713: Multi wavelength spectrum with Proton Model

Nature 416, 823 (2002)

Bremsstrahlung



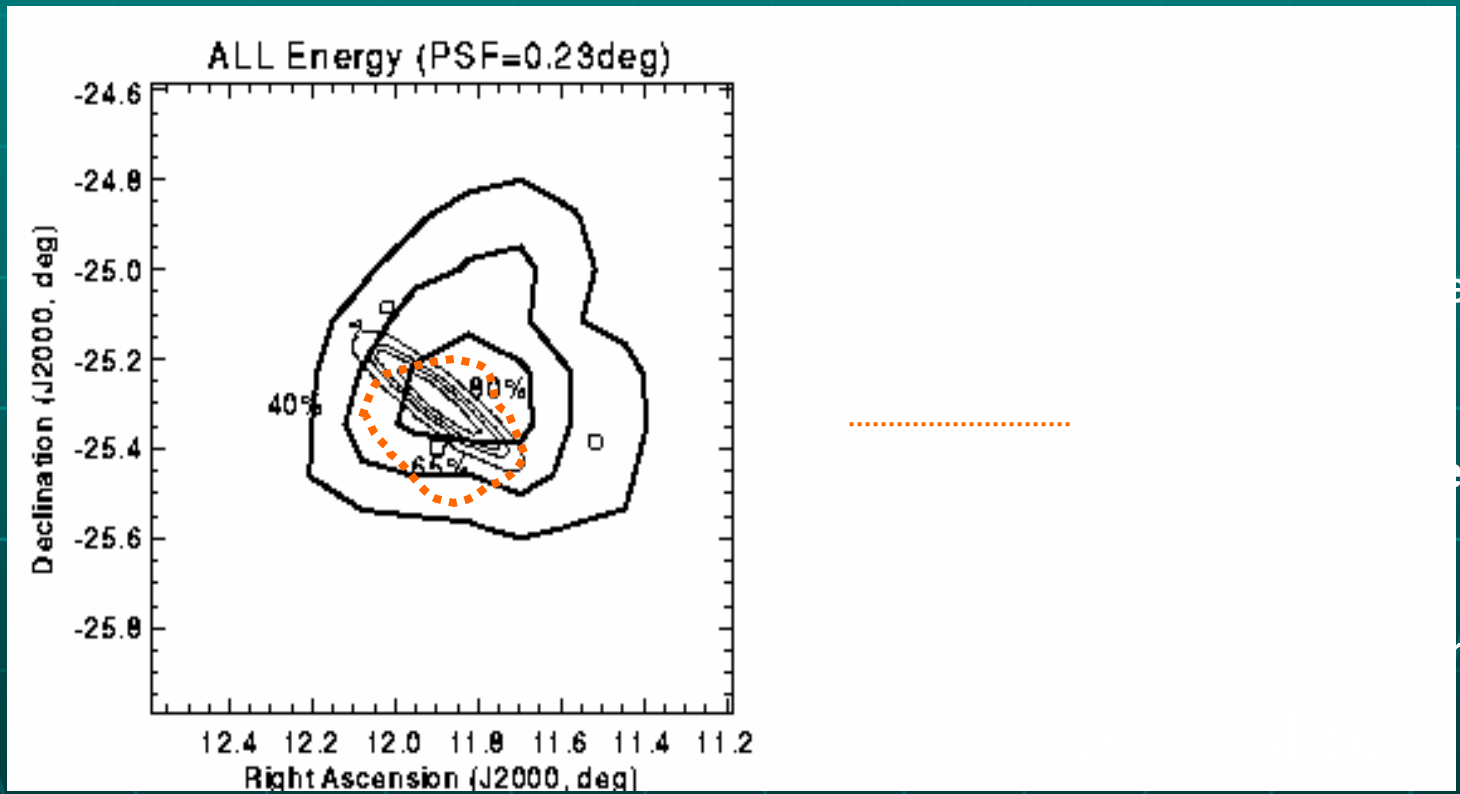


Bremsstrahlung X

from X-ray spectrum

Dist. 6kpc ->~10 times of the Crab

Significance Map



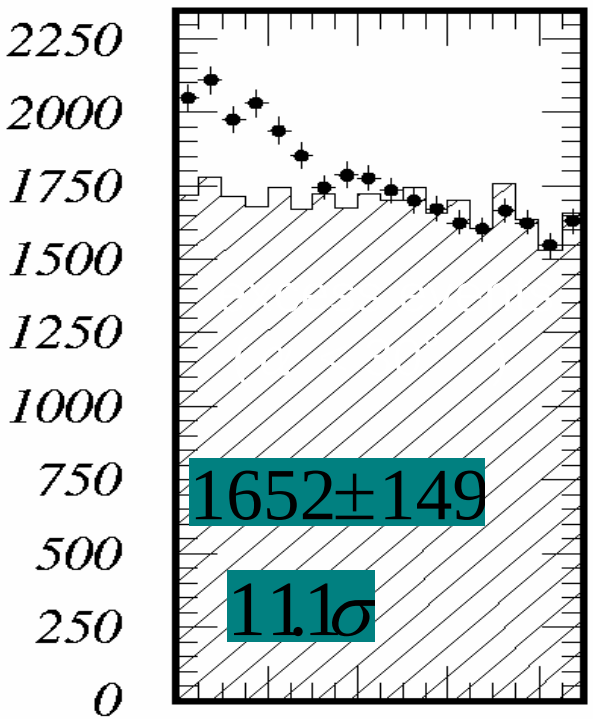
Declination (J2000,deg)

Right Ascension (J2000,deg)

α distribution

ON

OFF



- The γ-ray emission is clearly more extended than PSF

QuickTimeý Ç²
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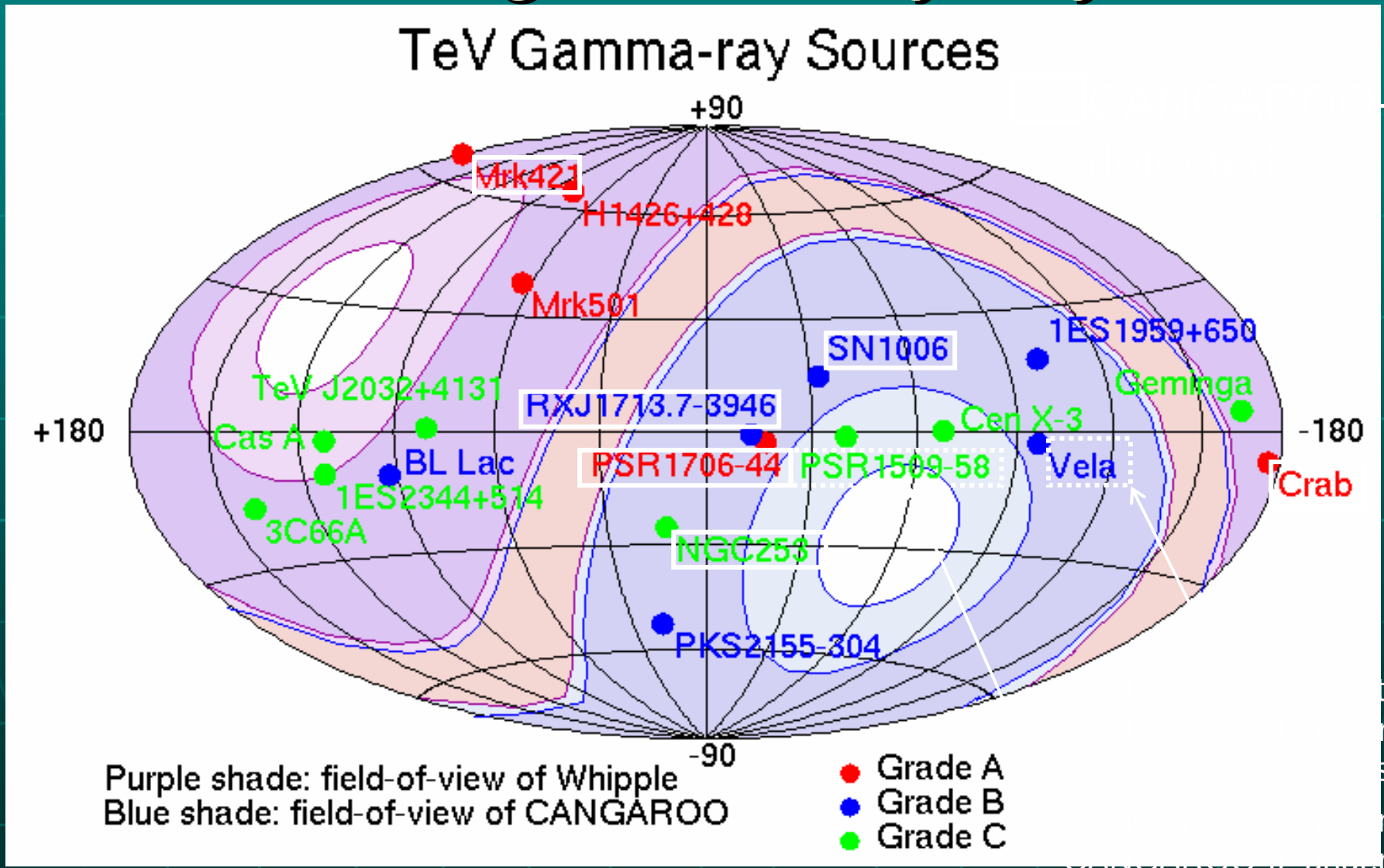
TeV gamma-ray sky



analysis