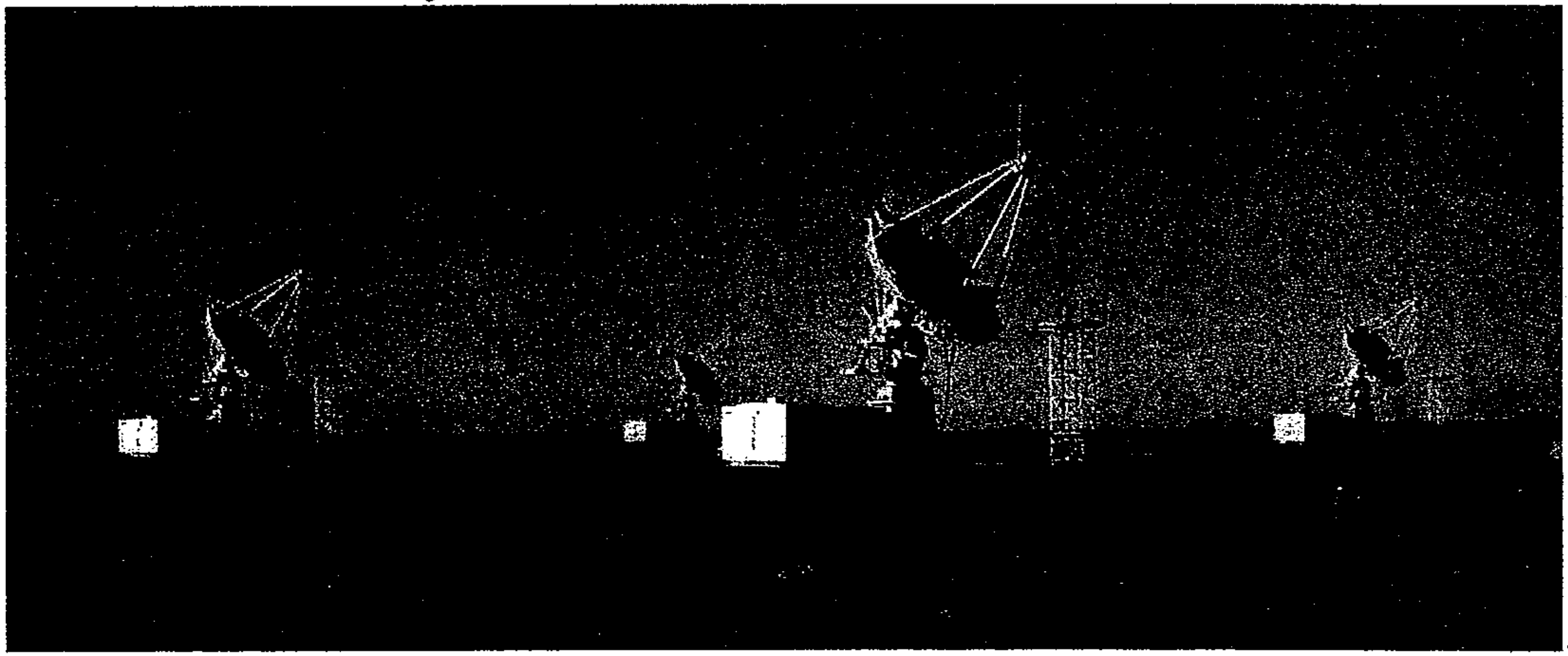
CANGAROO Website http://icrhp9.icrr.u-tokyo.ac.jp

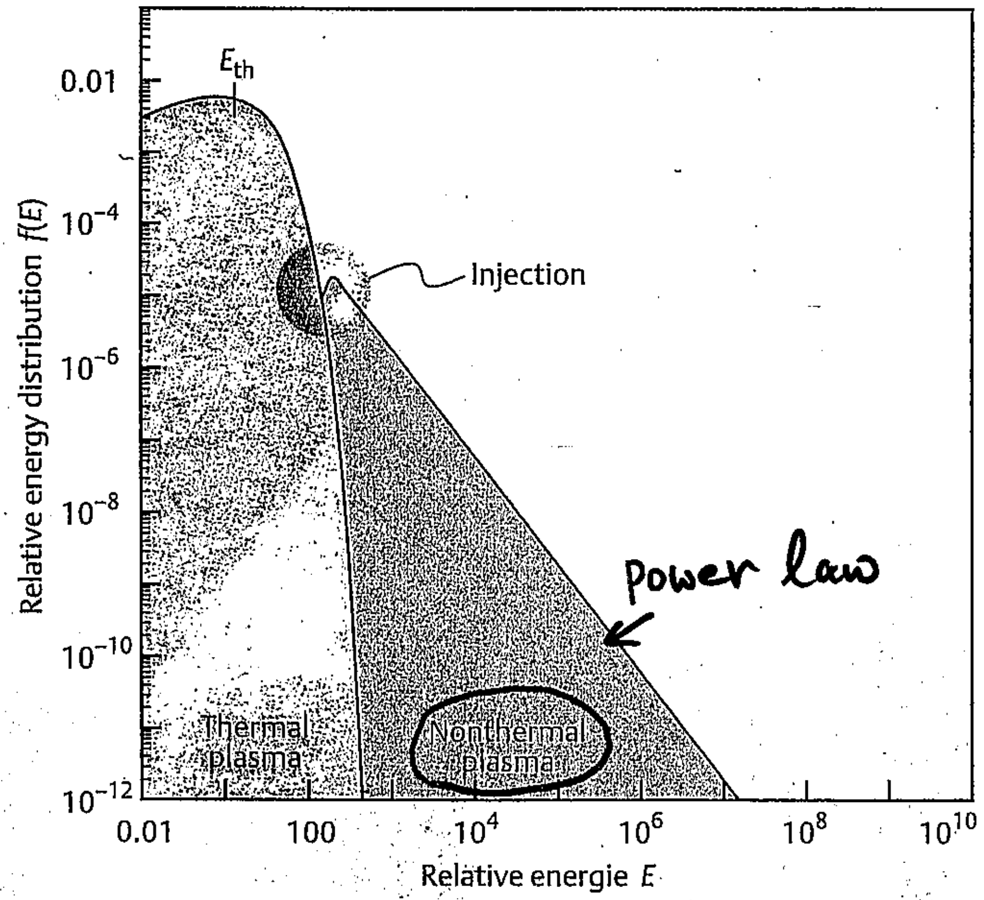
CANGAROO-III

CANGAROO III

- Array of four 10m telescopes(~2004)
- Full Imaging: FOV $>3^{o}$ Angular Res. $\sim 0.1^{o}$
- Energy Threshold: ~100GeV
- Sensitivity : $>5 \times 10^{-13}\ cm^{-2}\ s^{-1}$

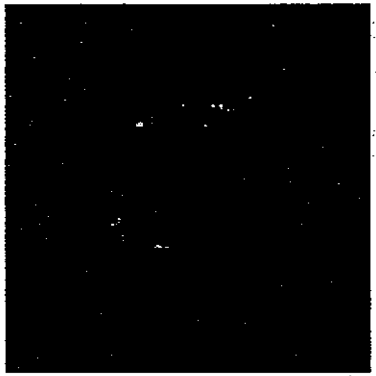


Non-thermal Phenomena in the Universe.

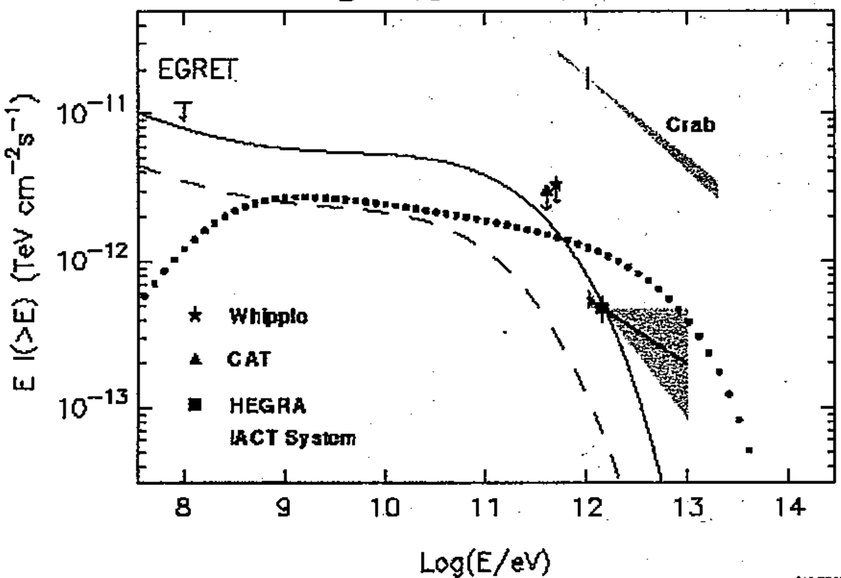


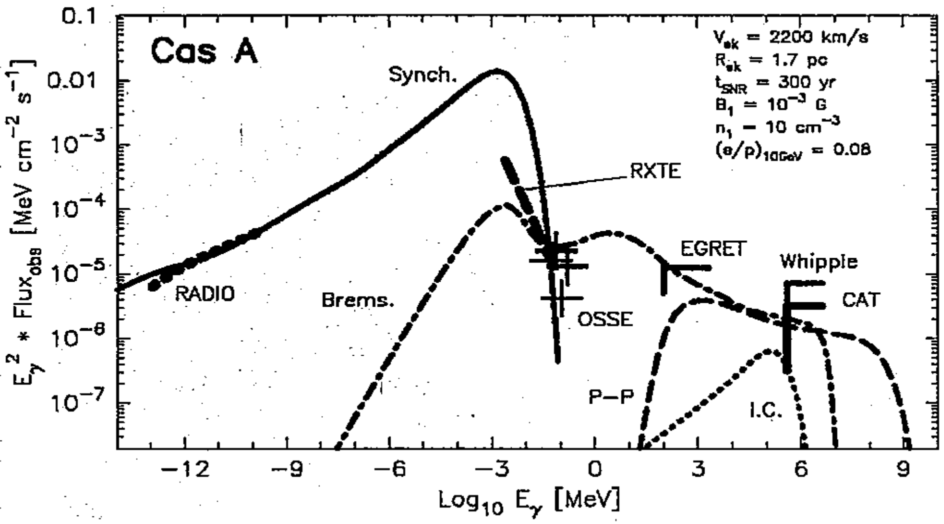
- Particle Acceleration → γ-rays
- Magnetic field
- Dark Matter
-

•Supernova remnant: Cas A (HEGRA)



●HEGRA 2000





rigure 2: *Predictions of the nonlinear diffusive shock-acceleration model from radio to TeV γ-rays as compared to observations (see Ellison et al. (1999) for details and references therein). The present result is shown together with the Whipple upper limit of Lessard (1999).*

Goret et al. 26th ICRC OG2.2.18, 1999

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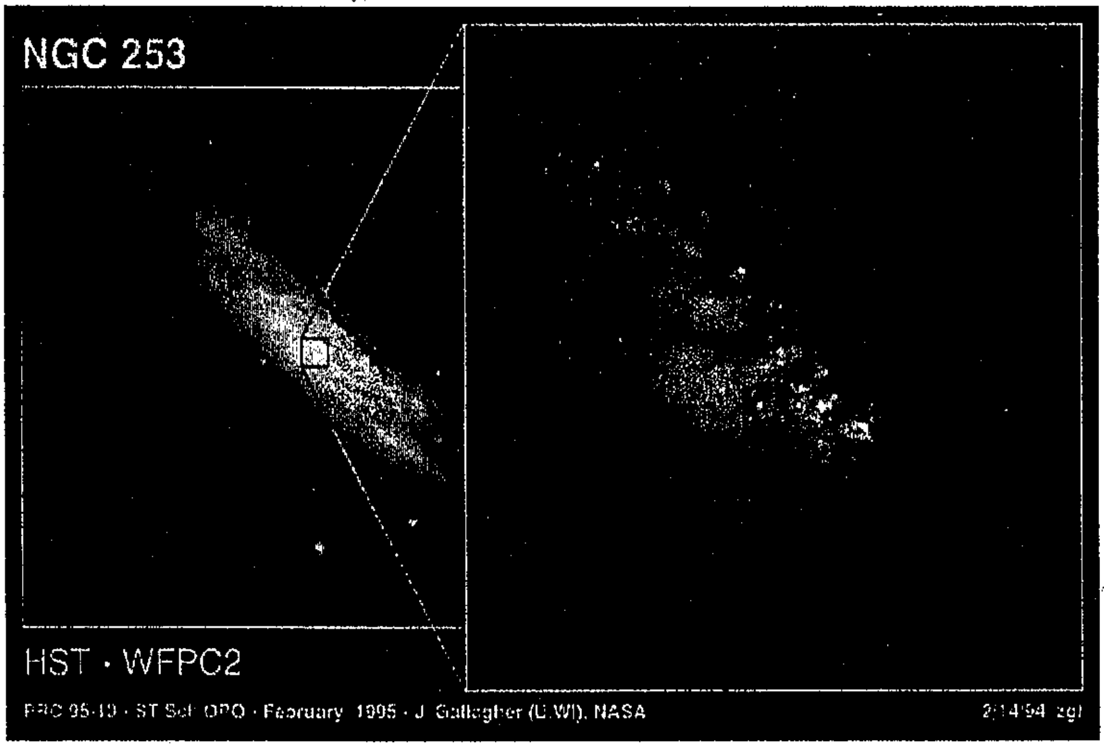
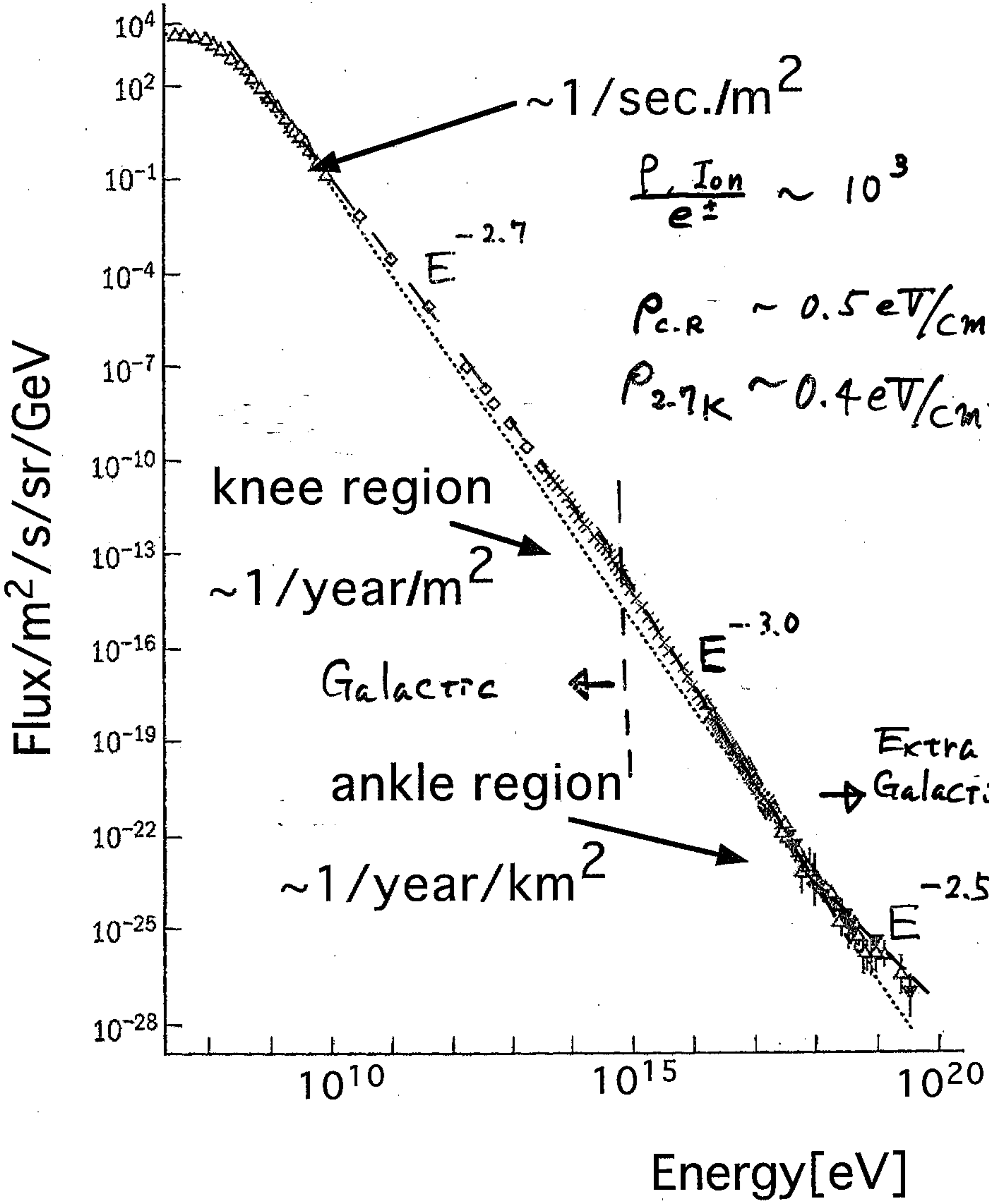
Nearest starburst galaxy



	NGC253		MilkyWay
SNR	3～10倍	⇦	1回/30yr
SFR	100倍	⇦	$1M_{\odot}$/yr
Photon density	100倍	⇦	400/cc
CR energy density	1～100倍	⇦	10^{-12}erg/cm^3

⇨ γ線により観測すべきTarget

Cosmic-Ray Spectrum



$\frac{\rho_{Ion}}{e^{\pm}} \sim 10^3$

$\rho_{C.R} \sim 0.5\, eV/cm^3$

$\rho_{2.7K} \sim 0.4\, eV/cm^3$

Possible Origins of Cosmic Ray

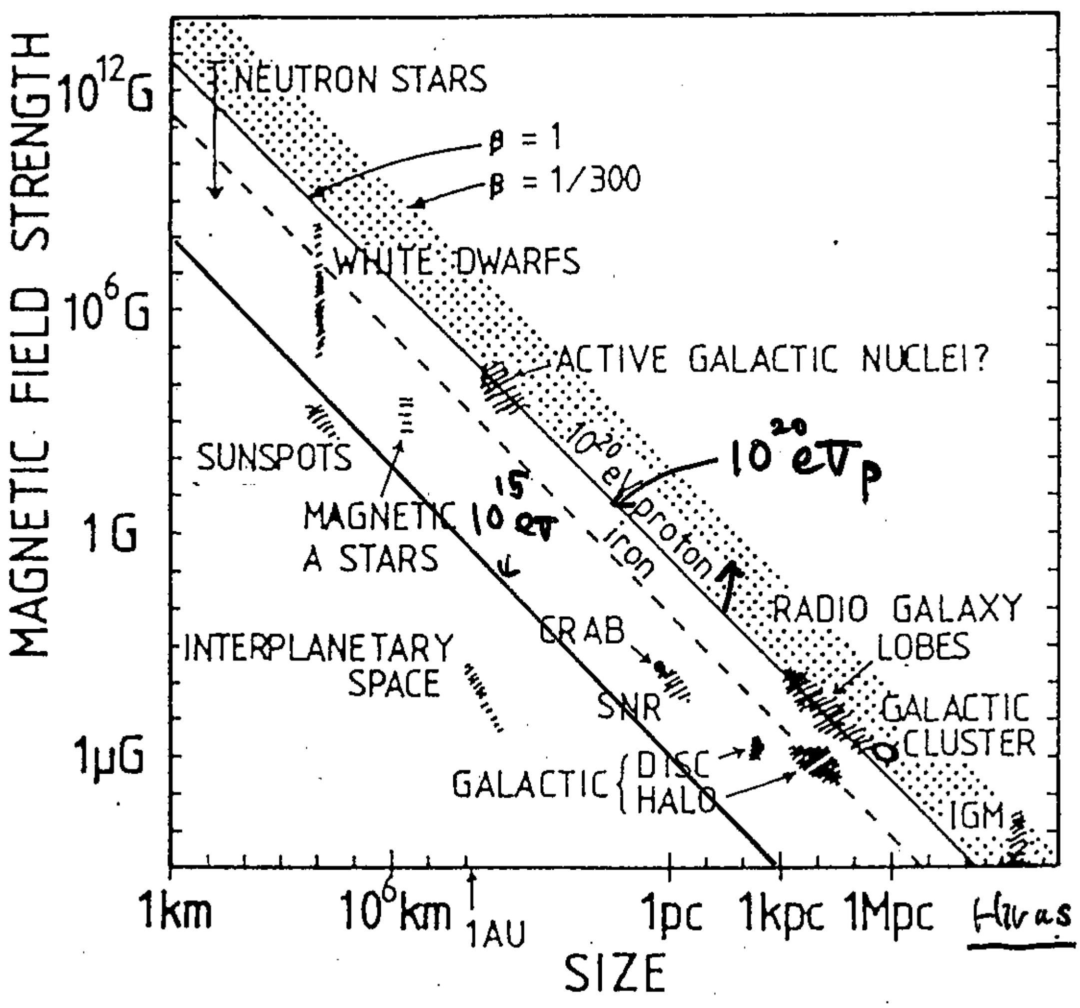
Hillas Ann Rev. A.A (1984)

- Shock Acceleration

$$\left(\frac{E_{max}}{10^{15}\,\mathrm{eV}}\right) \lesssim 0.5\left(\frac{B}{1\,\mu G}\right)\cdot\left(\frac{L}{1\,\mathrm{pc}}\right)\cdot Z\cdot\beta$$

$\beta = \frac{u}{c}$ (u: velocity of shock: $10^3 \sim 10^4$ km/s)

Shock Acc. → Standard Model ?

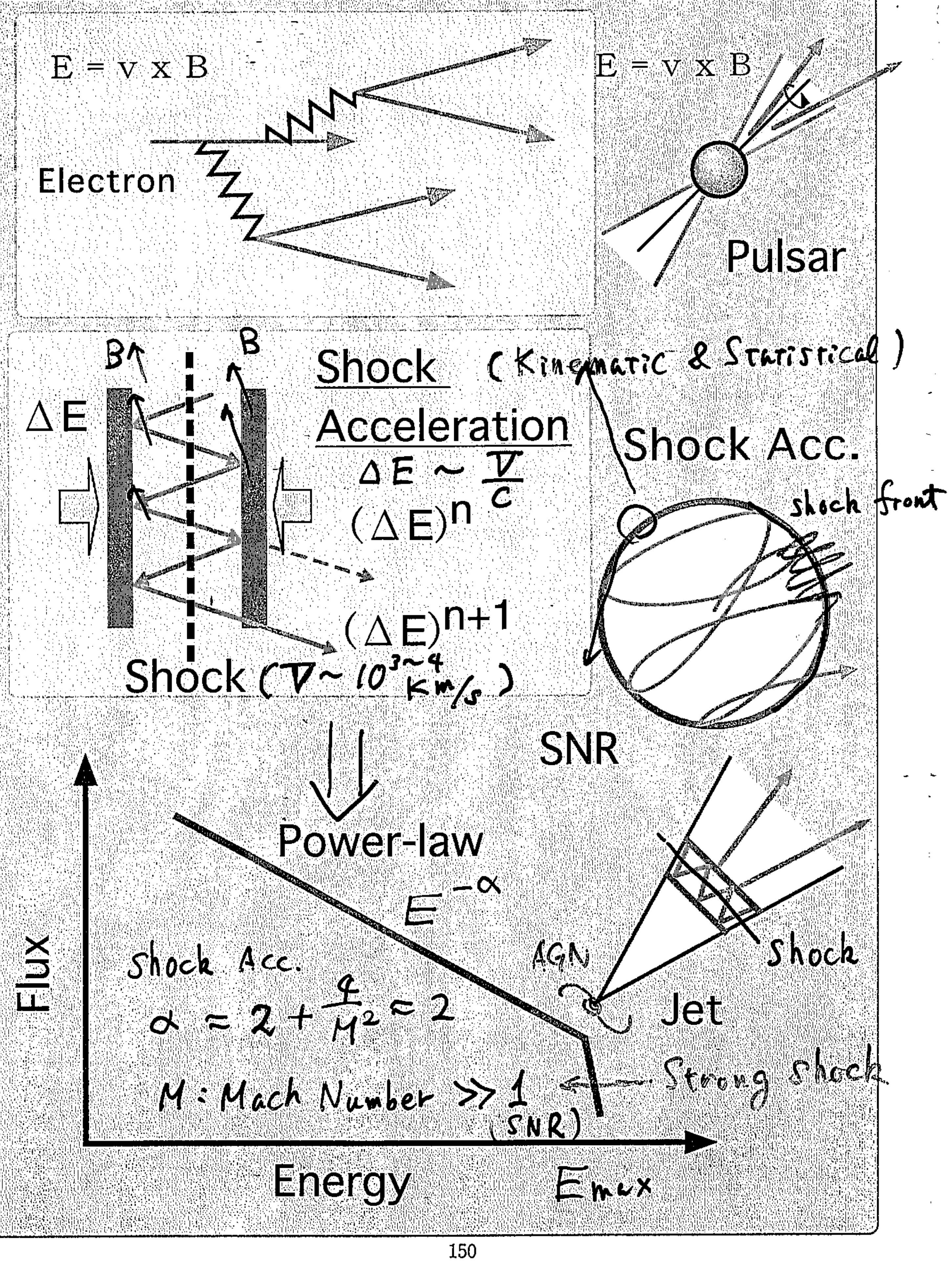


Shock Acceleration in Universe

- Unique Theory for the generation of high energy particles(>>GeV) in very Large Scale
- Simple theory: B, Time, Energy Velocity, n(density),
- $E_{max} \propto B \times$ Size, Power law (index -2~3)
- Widely believed, but Little observational evidences
- Quantitative studies are necessary
- Universe ⟶ Unique laboratory for Shock Acc.

  Rare and Large

Non-thermal Radiation



Mechanism of HEV Gamma Emisson

- HEV Gamma rays from π^0 decay induced by Proton scattering

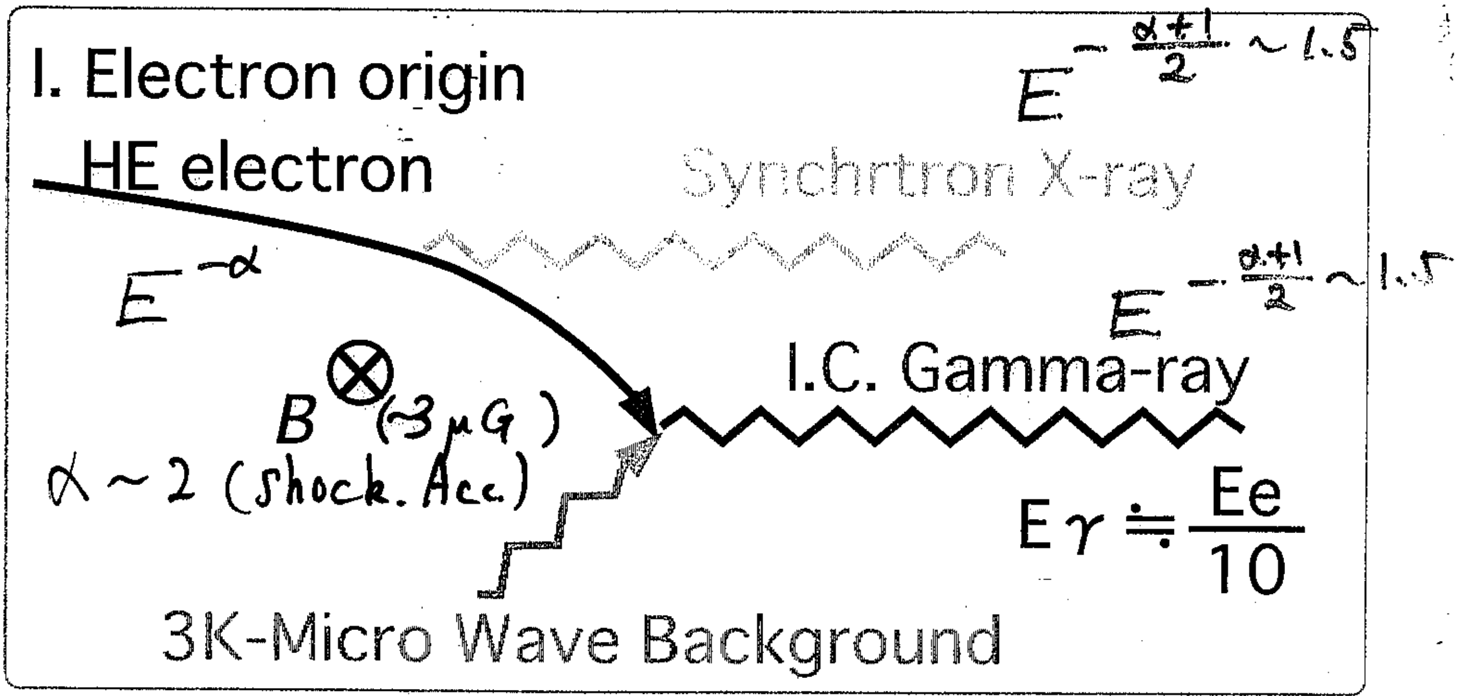
Power index of Gamma-ray spectrum similar to that of progenitor proton
(~2.2 for Shock Acceleration)

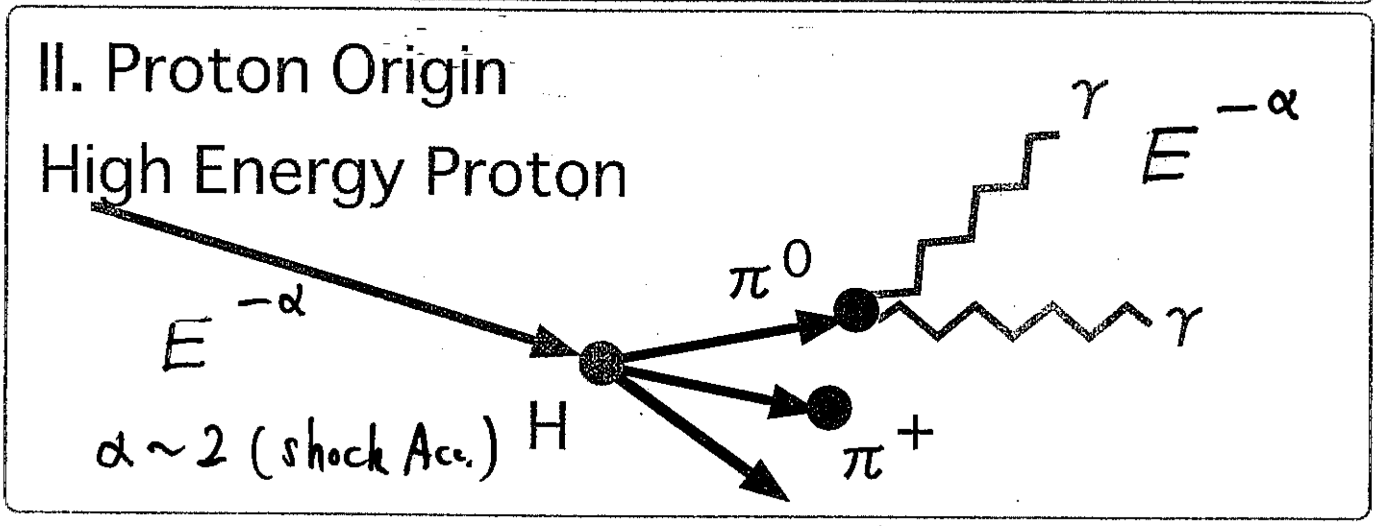
- HEV Gamma rays from Inverse Compton Scattering of HE electrons

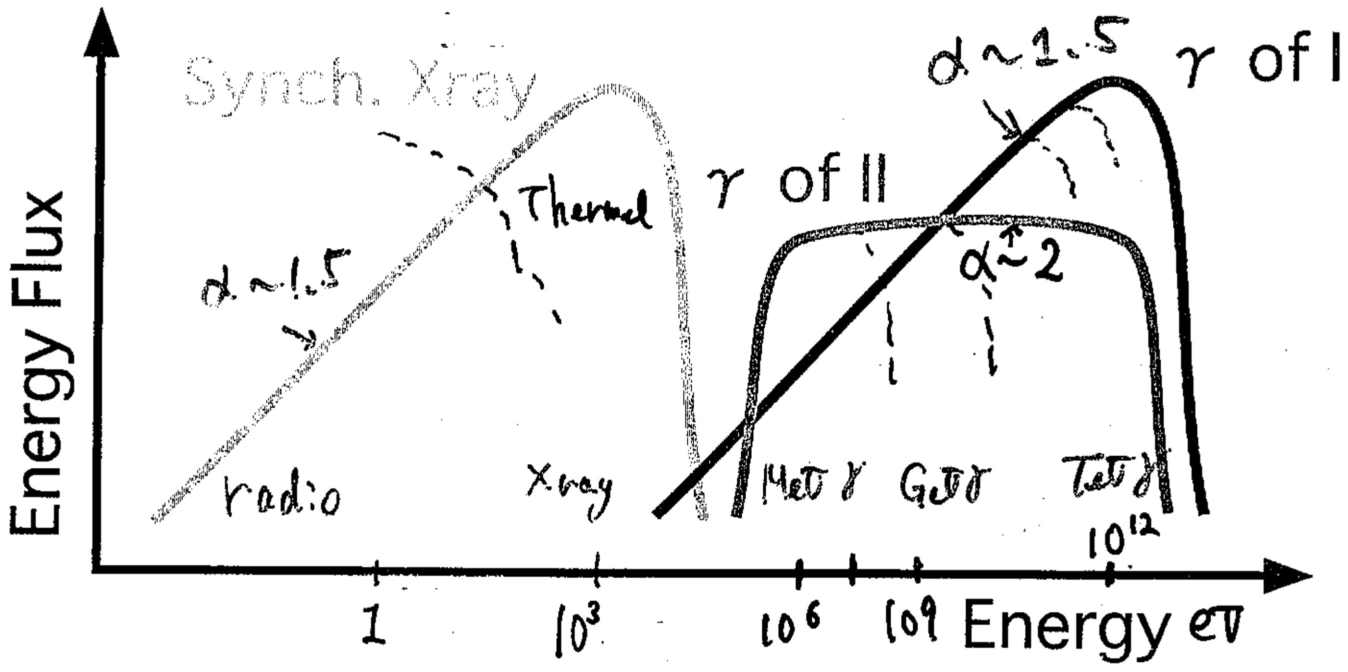
with 2.7K, Infra-red, etc
with Self-Synchrotron photon emitted by HE electrons(SSC)

Flatter spectra than those of progenitor electrons
(~1.6 for HE electron:2.2)

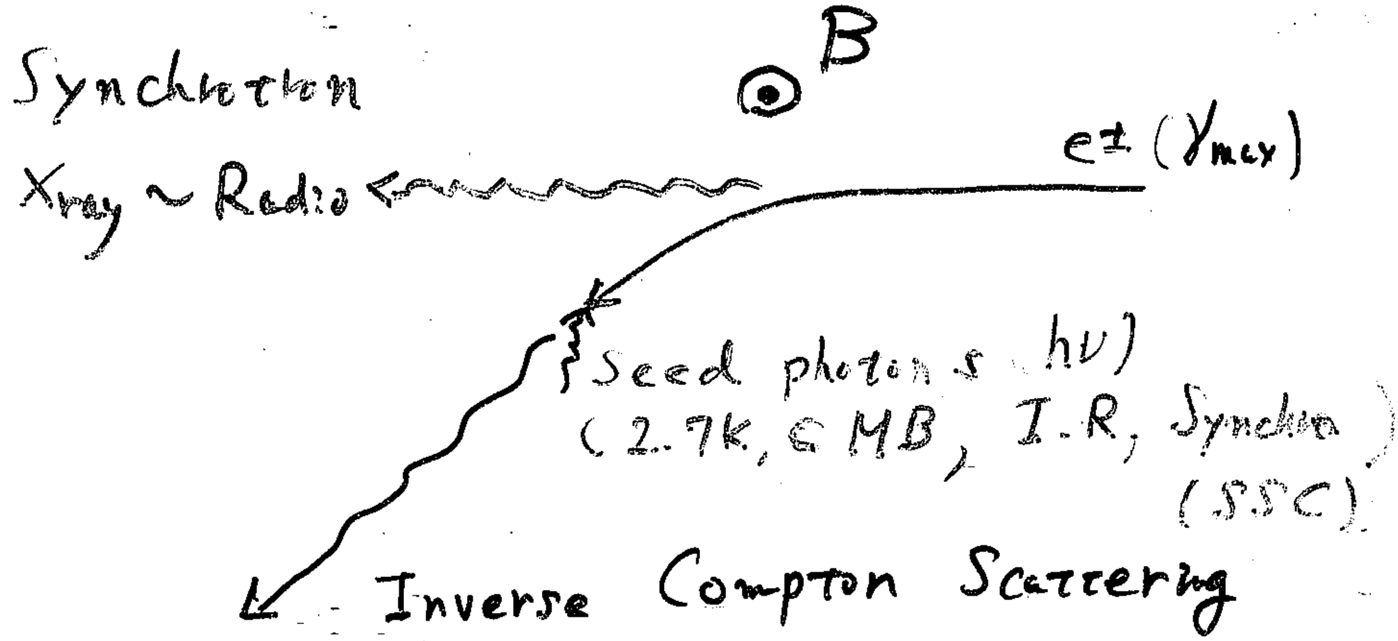
Origin of High Energy Gamma-Ray







Radiation from High Energy $e^{\pm}$



$$-\left(\frac{dE}{dt}\right)_{synchro.} = \frac{4}{3}\sigma_T c \gamma_{max}^2 U_{mag}$$

σ_T : Cross section of Thompthon Scattering

$$U_{mag} = \frac{1}{2\mu_0}B^2$$

$$-\left(\frac{dE}{dt}\right)_{I.C.} = \frac{4}{3}\sigma_T \gamma_{max}^2 U_{rad}$$

$$U_{rad} = (h\nu)$$

$\left(\frac{dE}{dt}\right)_{synchro}$, $\left(\frac{dE}{dt}\right)_{I.C.}$ U_{rad},

observable

⇓

B, γ_{max}. Obtained.

$\int B_{\parallel} dl$

How to find Proton Acceleration Site

- SNR (e, ion plasma), Prelion, AGNs ($e^{\pm}$)
- SNR(Accelerator) ⟶ Molecular Clouds(Target)

  W28, γ-signi,etc GeV γ :yes, TeV γ :No
- Synch. Emission SNRs: SN1006, RXJ1713, etc

  TeV γ :yes mainly e but partially Proton?
- Acceleration Site: Rare or Dense,

  ↕

  Emax, Efficiency, TeV γ Emissivity (p)

  (TeV γ Emissivity (e): 2.7K)
- **<u>10GeV –10TeV Spectrum, 70MeV bump($\pi \rightarrow 2\gamma$)</u>**

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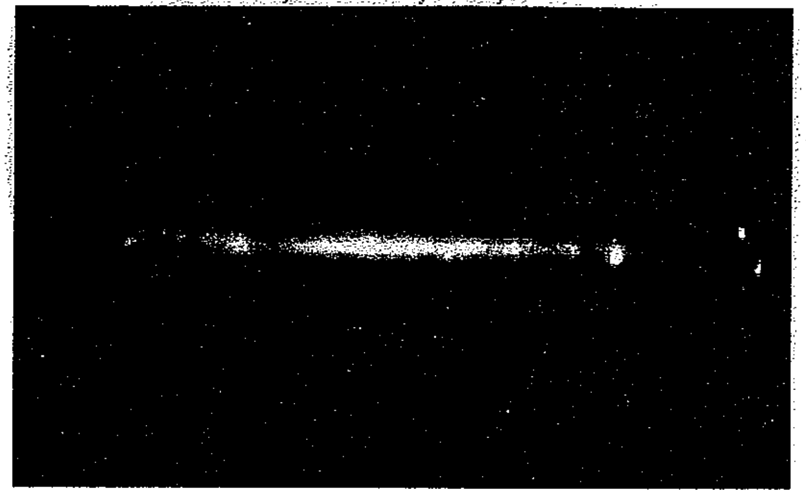
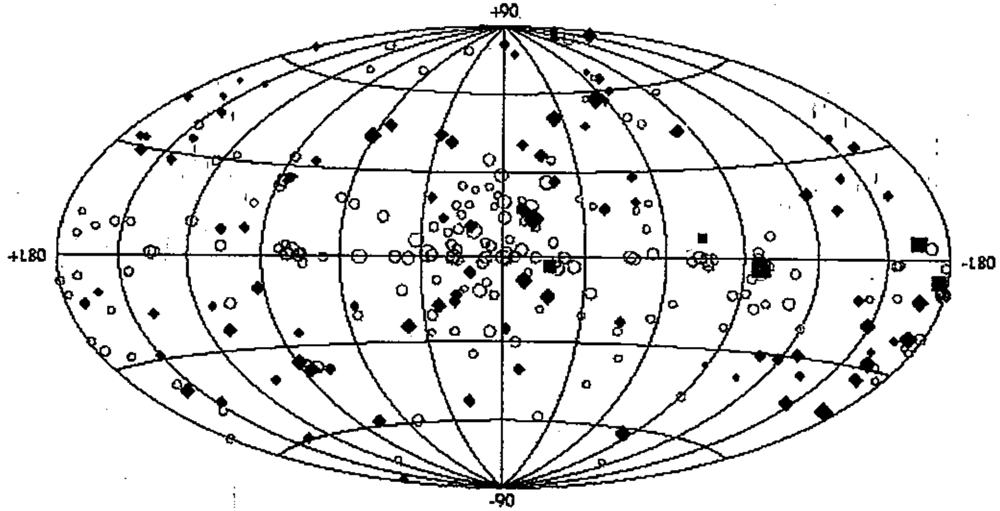
EGRET All Sky Map (E_γ >100MeV)

EGRET All-Sky Gamma Ray Survey Above 100 MeV



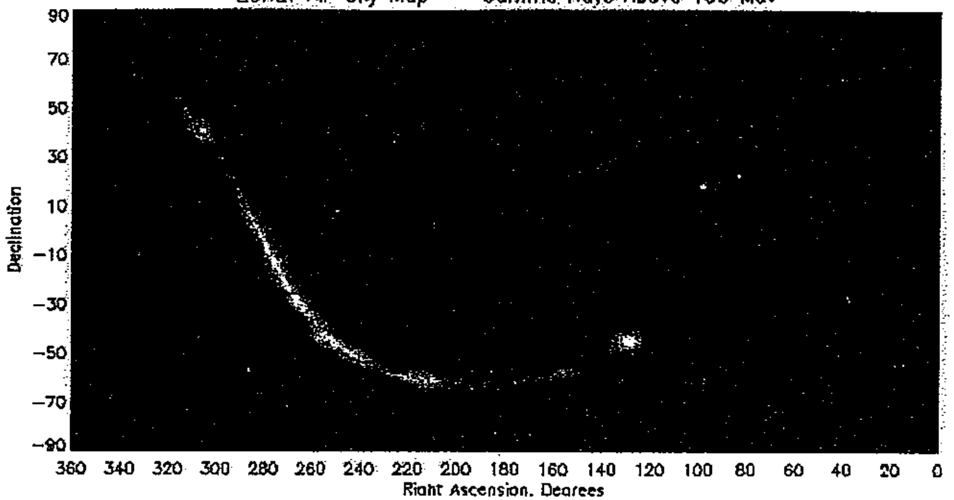
Third EGRET Catalog

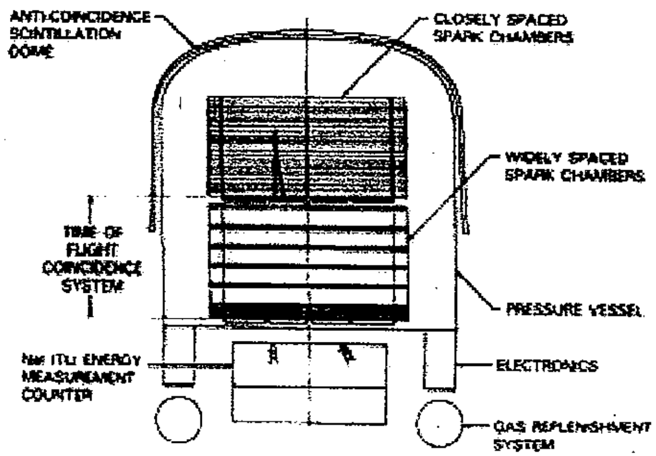
E > 100 MeV

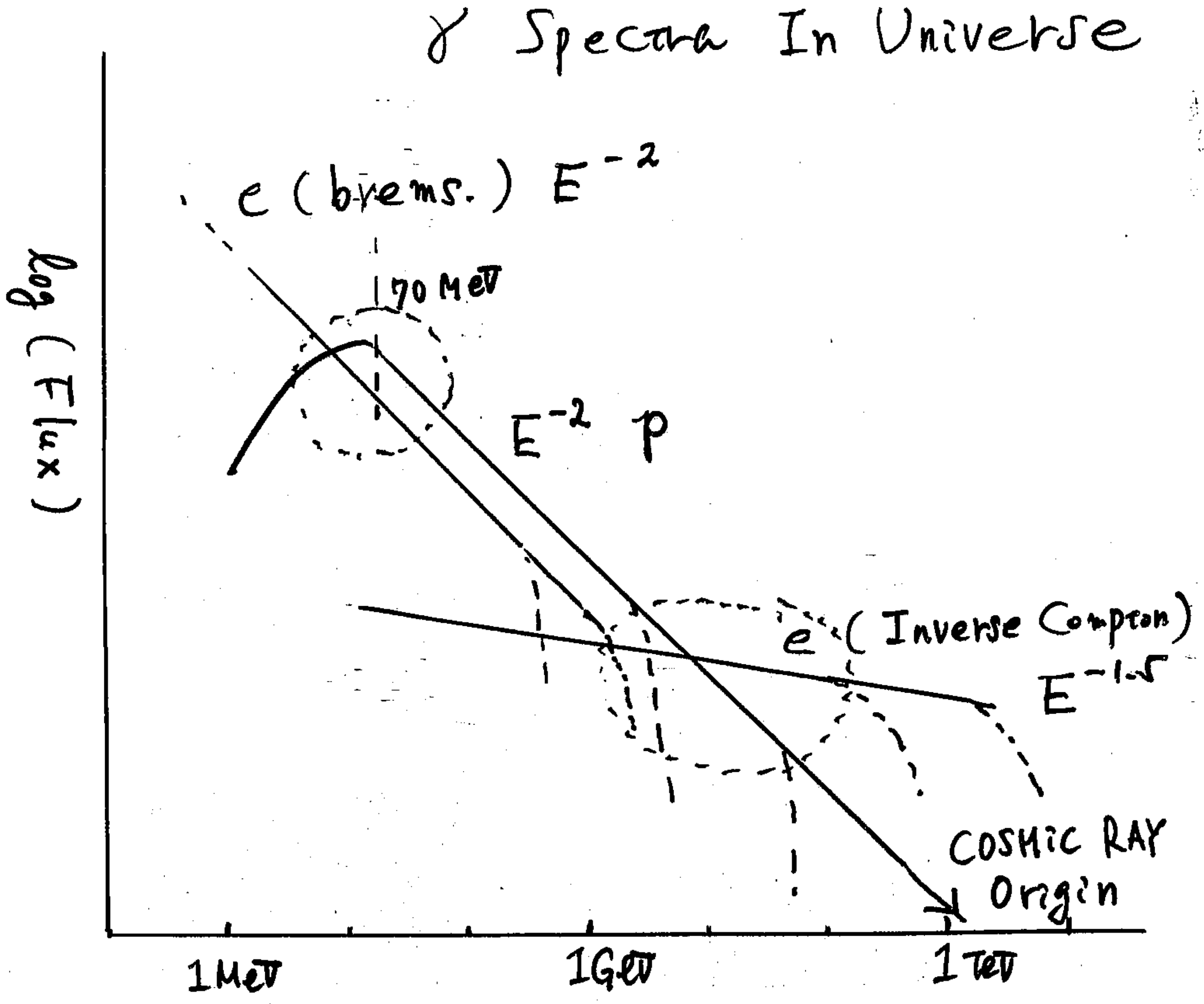


◆ Blazars (+ Cen A)
○ Unidentified EGRET Sources
■ Pulsars
LMC
● Solar FLare

EGRET All-Sky Map — Gamma Rays Above 100 MeV






γ Spectra In Universe
e (brems.) E^-2
70 MeV
E^-2 p
e (Inverse Compton)
E^-1.5
COSMIC RAY Origin
log (Flux)
1MeV
1GeV
1TeV

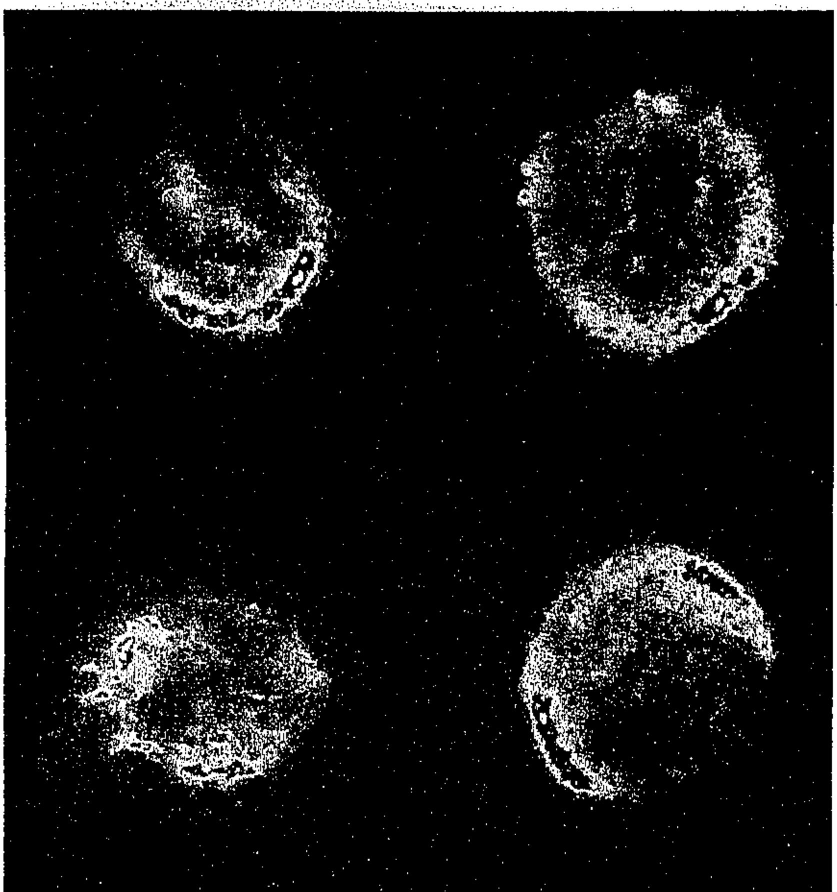
Super Nova Remnant (SNR)

① Shell type (Ia) → No pulsar, B.H.
SN1006, Tycho, -- a few/100 years

② II → pulsar or B.H. Crab, Vela --
$\lesssim$ 1/100 years pulsar/nebula

← Radio Image
Tycho

Xray Image
(Einstein)



Tycho Kepler

CAS.A SN1006

Origin of Cosmic Ray

- Energetics of Galactic Cosmic Rays($<10^{16}$ eV)

  Required Energy Supply $\sim 10^{40}$ erg/s

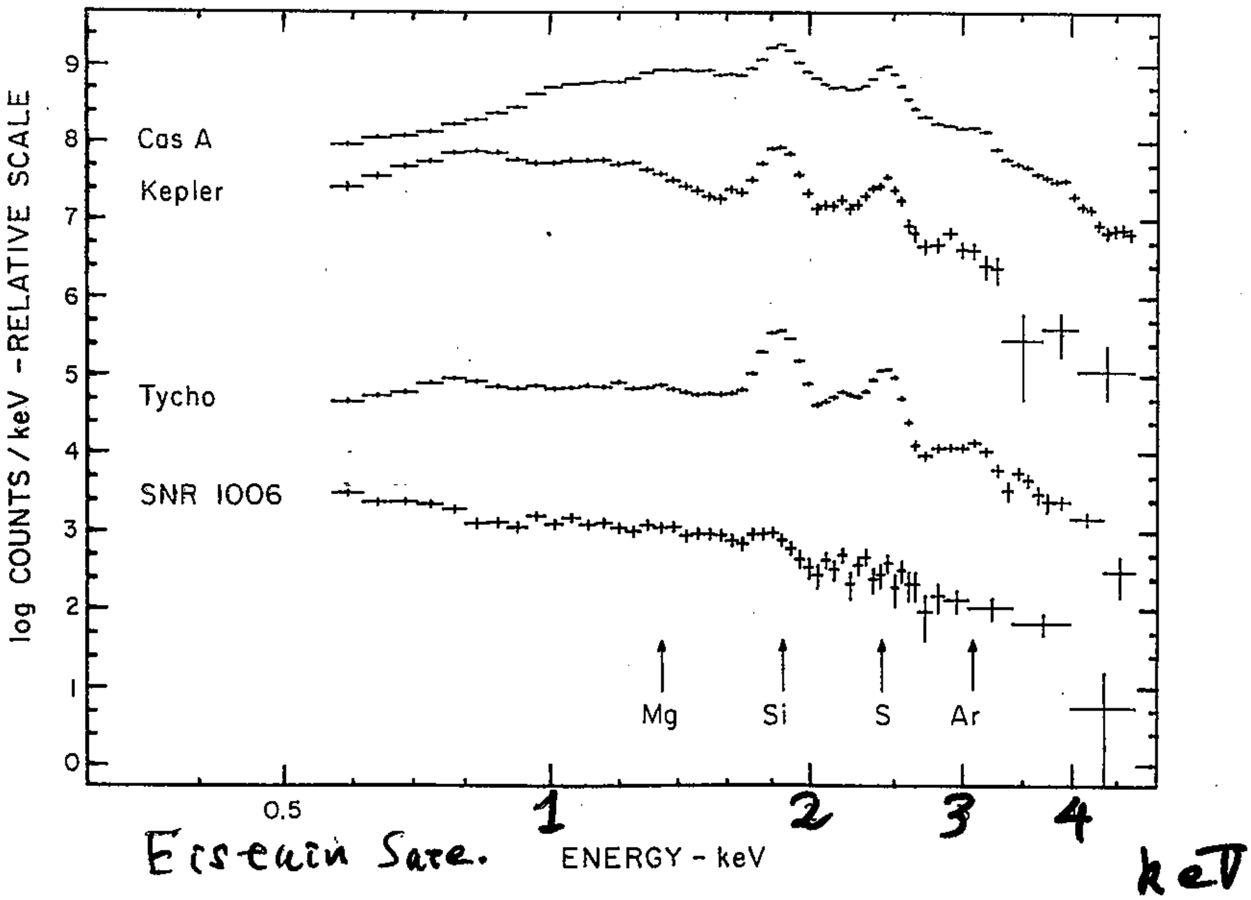
  Unique Candidate SNR $E_{max} < \sim 10^{15}$ eV
- ExtraGalactic Origin($>10^{16}$ eV) $E_{max} \sim 10^{20}$ eV
- Spectrum -2.5 ~ -3.0 in 10^{9} eV ~ 10^{20} eV

  Shock Acceleration
- Proton Acceleration

Xray Spectra from SNRs

① Thin Thermal Plasma heated by shock.
→ Emission peaks.

② Synchrotron Xrays ?
↓
evidence of High energy particles



Eisteuin Sare.

SN 1006 ASCA Xray Image

Hard XRay GIS

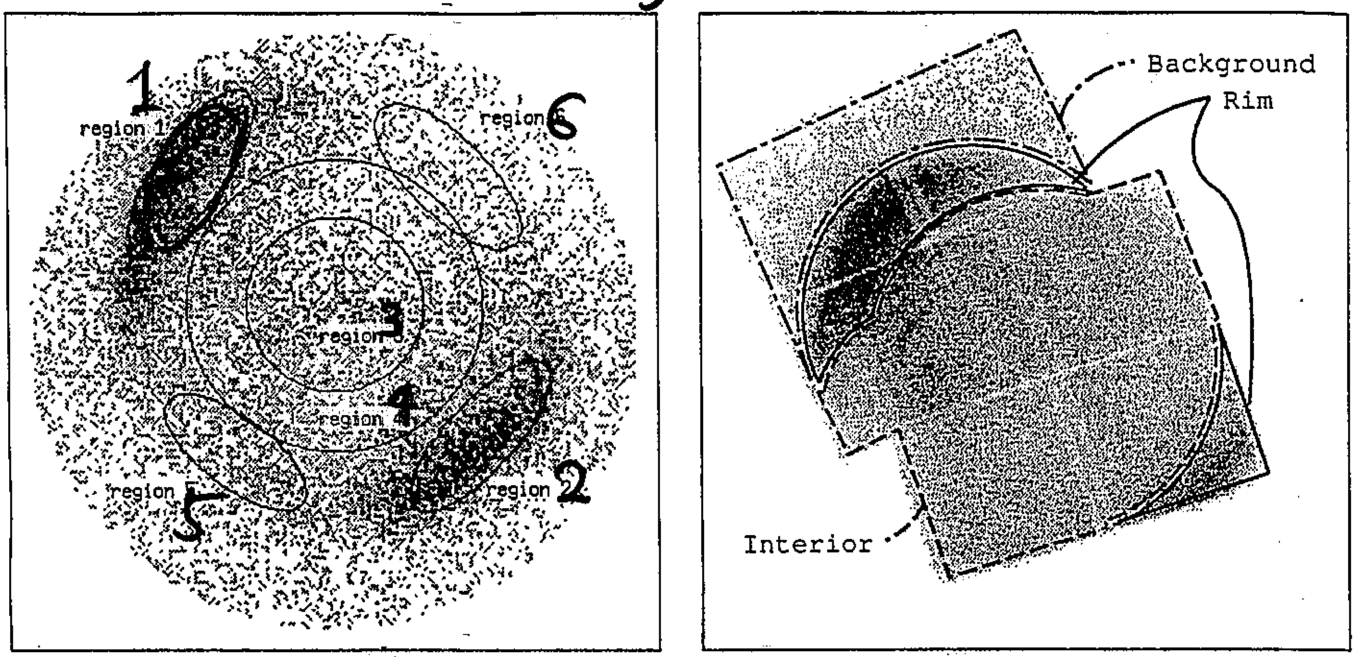
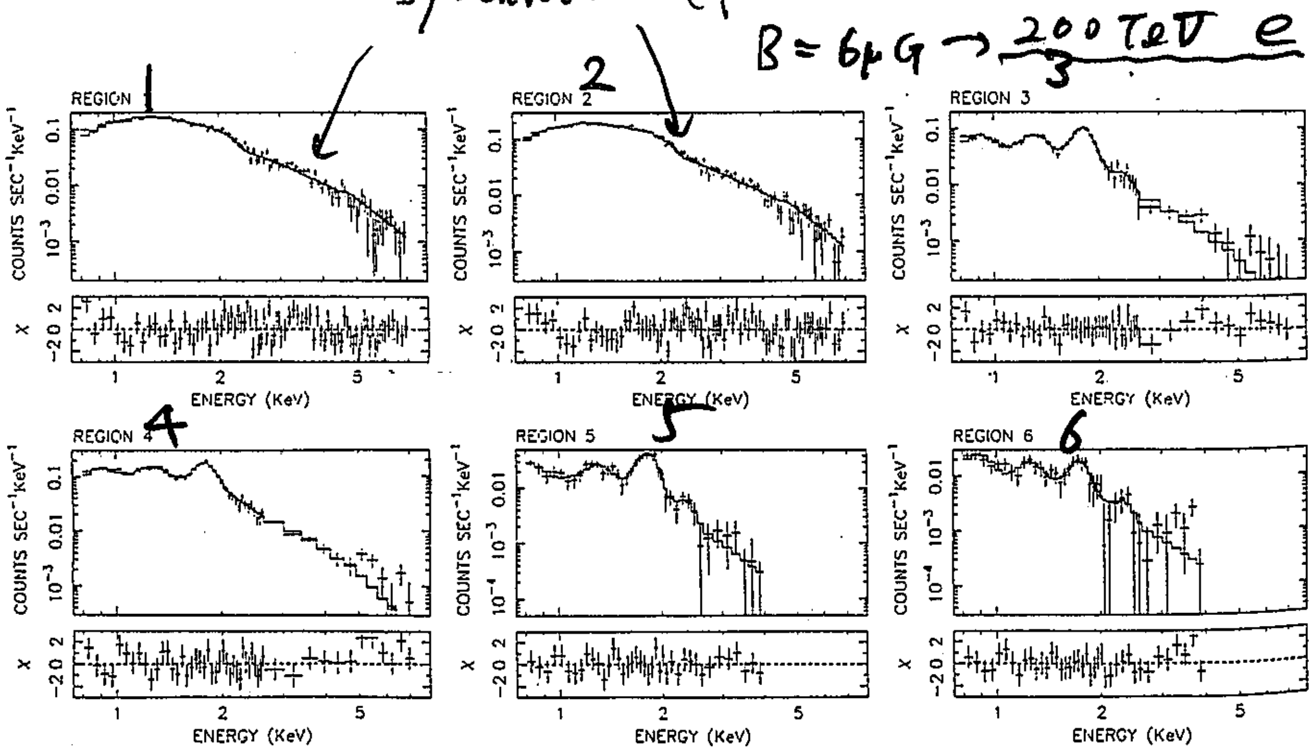


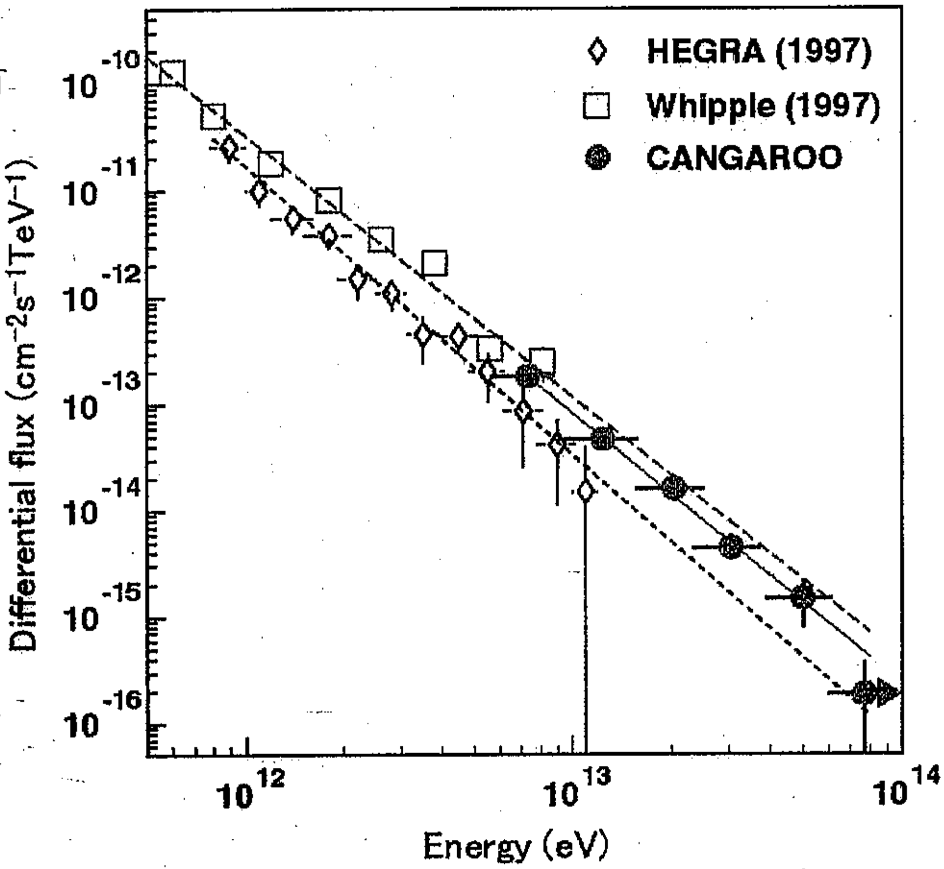
図 1: GIS2 で得られた SN 1006 のイメージ (左) とSIS 全データによるイメージ (右)。



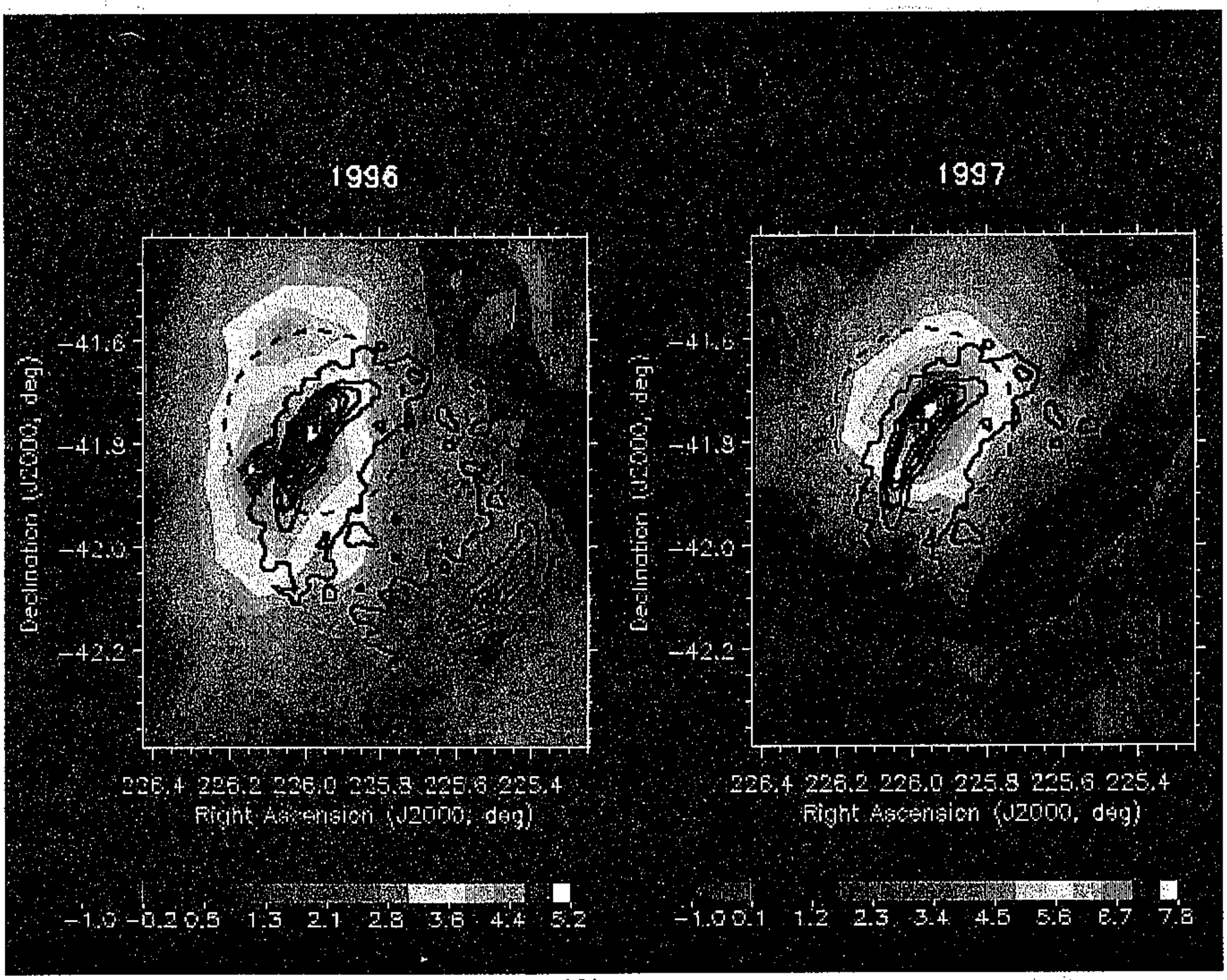
1, 2, → rim

主な解析結果

Crab



HEGRA (1997)
Whipple (1997)
CANGAROO
Differential flux (cm^{-2}s^{-1}TeV^{-1})
Energy (eV)



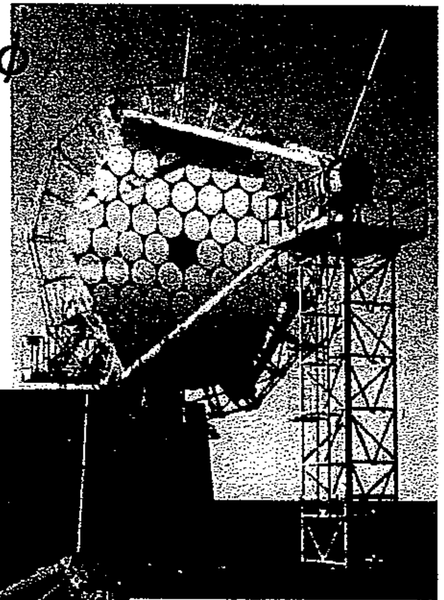
1996
1997
Declination (J2000, deg)
Right Ascension (J2000, deg)

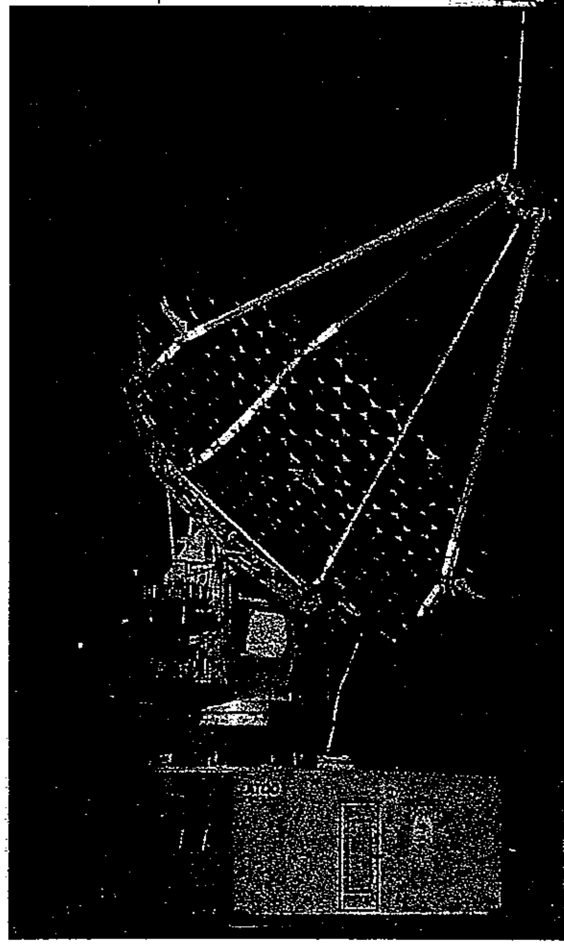
CANGAROO III

The first 10m telescope

	10m telescope
Focal length	8m Prabola
80cm CFRP mirrors	114 (57m²)
Number of PMTs	552 (1/2") FOV ~ 3°
Electronics	TDC(0.5ns) & ADC (All PMTs)
Point image size	0.20° (FWHM) (0.15° ,7m ϕ)

1999 7m ϕ





2000 10m ϕ

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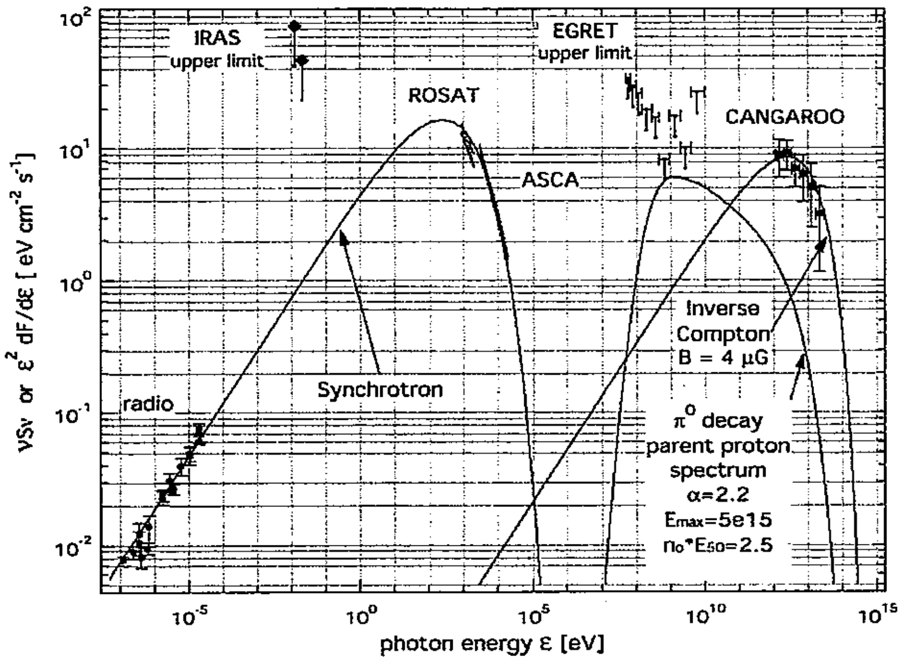
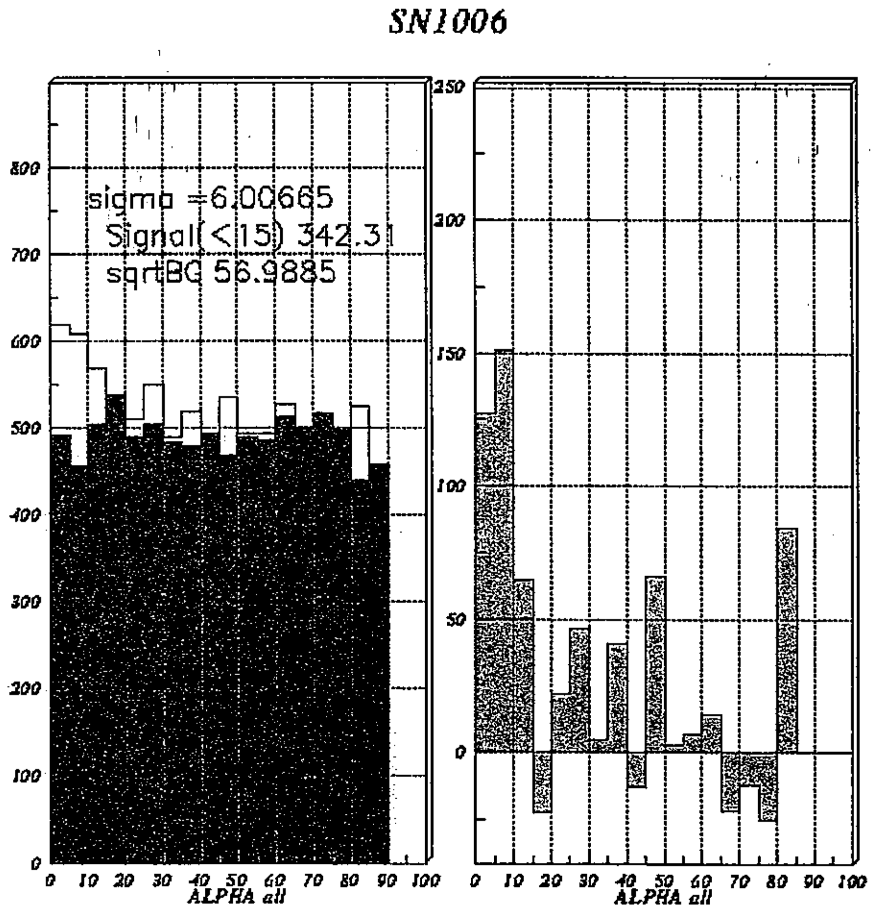
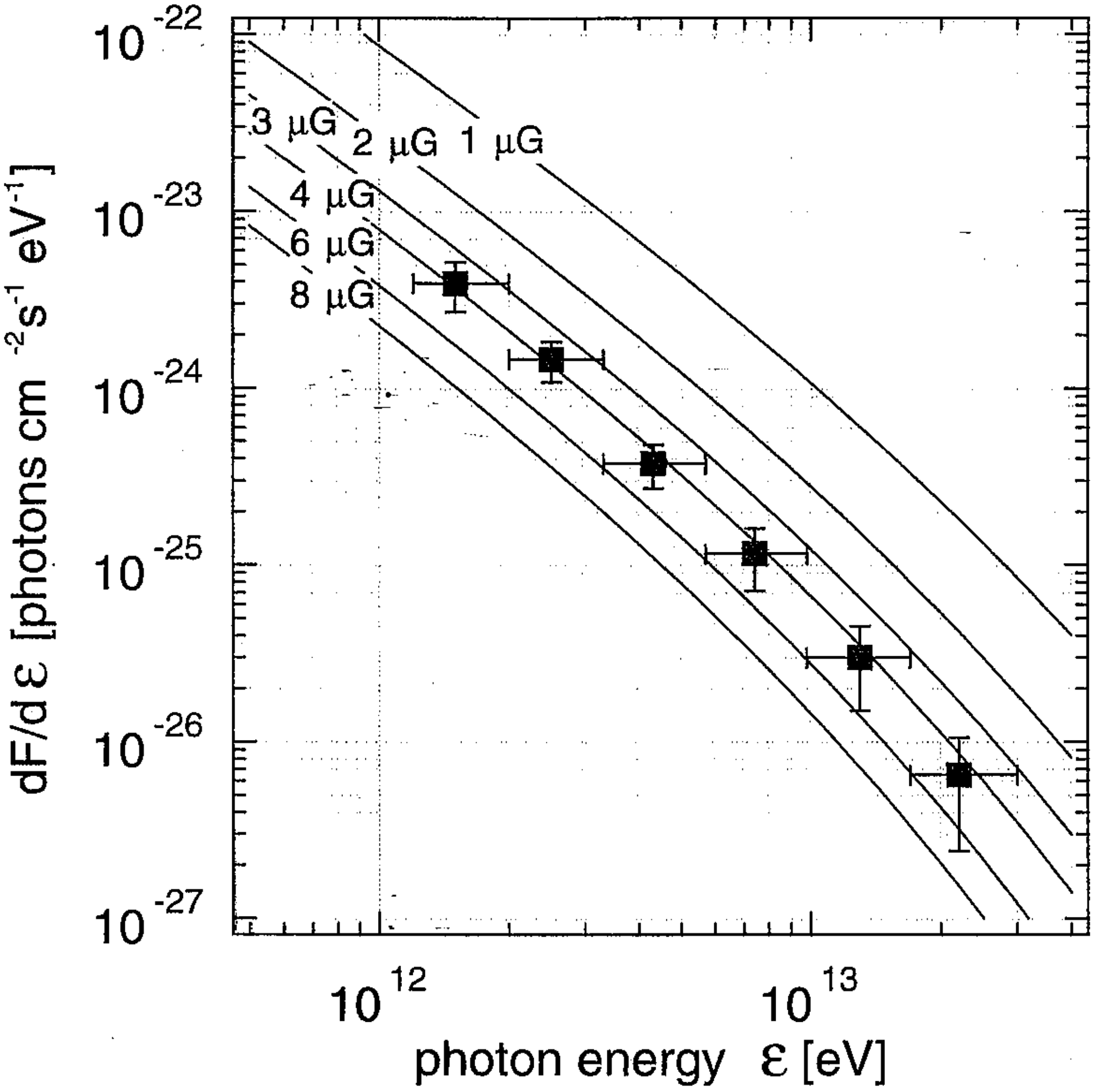
SNR: SN1006(CANGAROOIII) Preliminary !





- No protons?
- B ~ 4 μG
- Synch.+ IC with 2.7k

SN 1006
TeV γ Flux



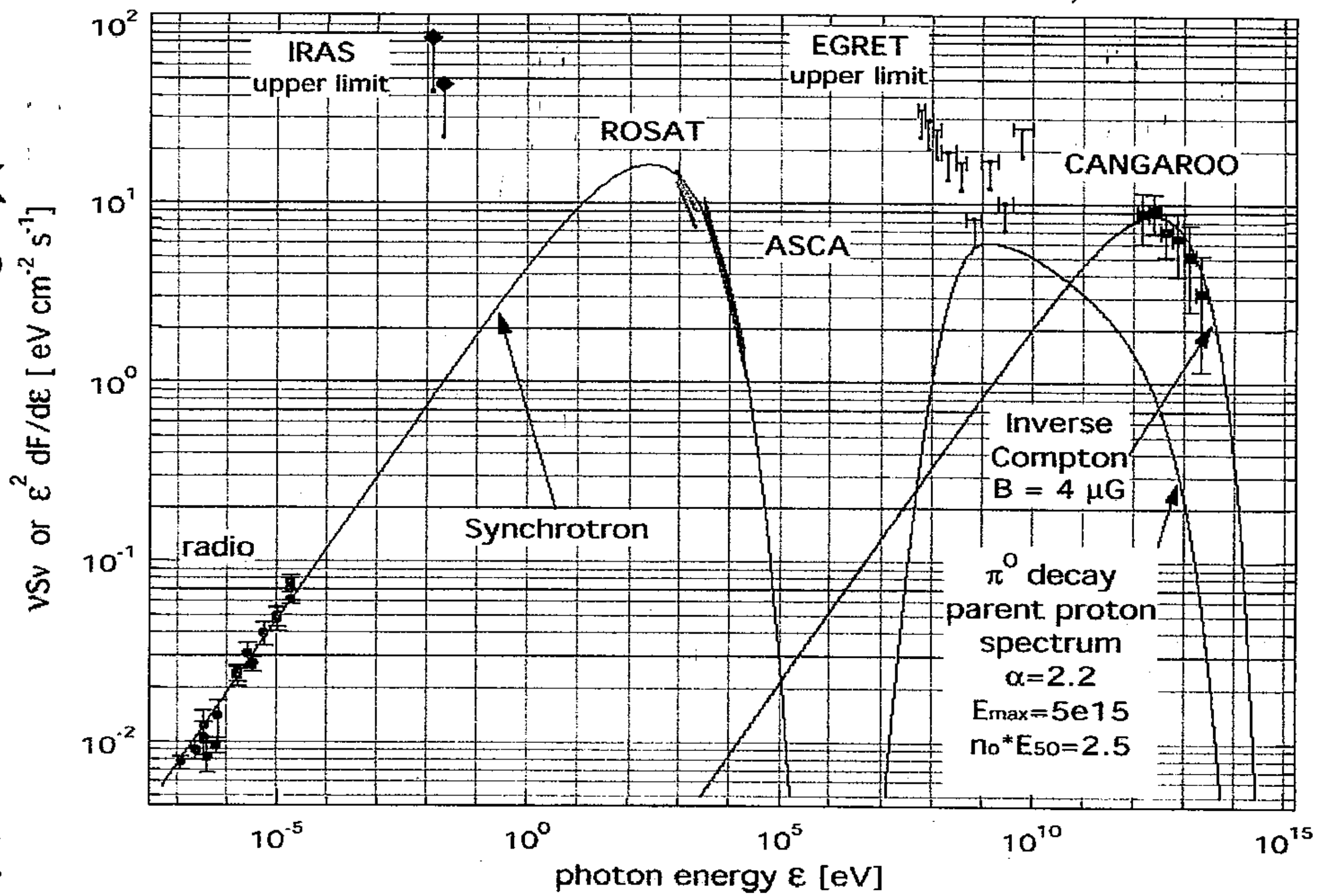
$$J(E) = (1.1 \pm 0.4 \pm 0.6) \times 10^{-11} \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-2.3 \pm 0.2 \pm 0.1} \quad \mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

$$B = 4 \pm 1\ \mu G$$

SNR: SN1006 – Shock Acceleration

- Synch.+ IC with 2.7k
- No protons?
- B ~ 4 μG

Naito et al. Astron. Nach. 320, 1999



$$\left(\frac{E_{max}}{1\,TeV}\right)\sqrt{\frac{B}{1\mu G}} = 101$$

$\frac{dN}{N} = \propto E^{-\alpha}$ $\alpha = 2.2$

$E_{max} \sim 60$ TeV

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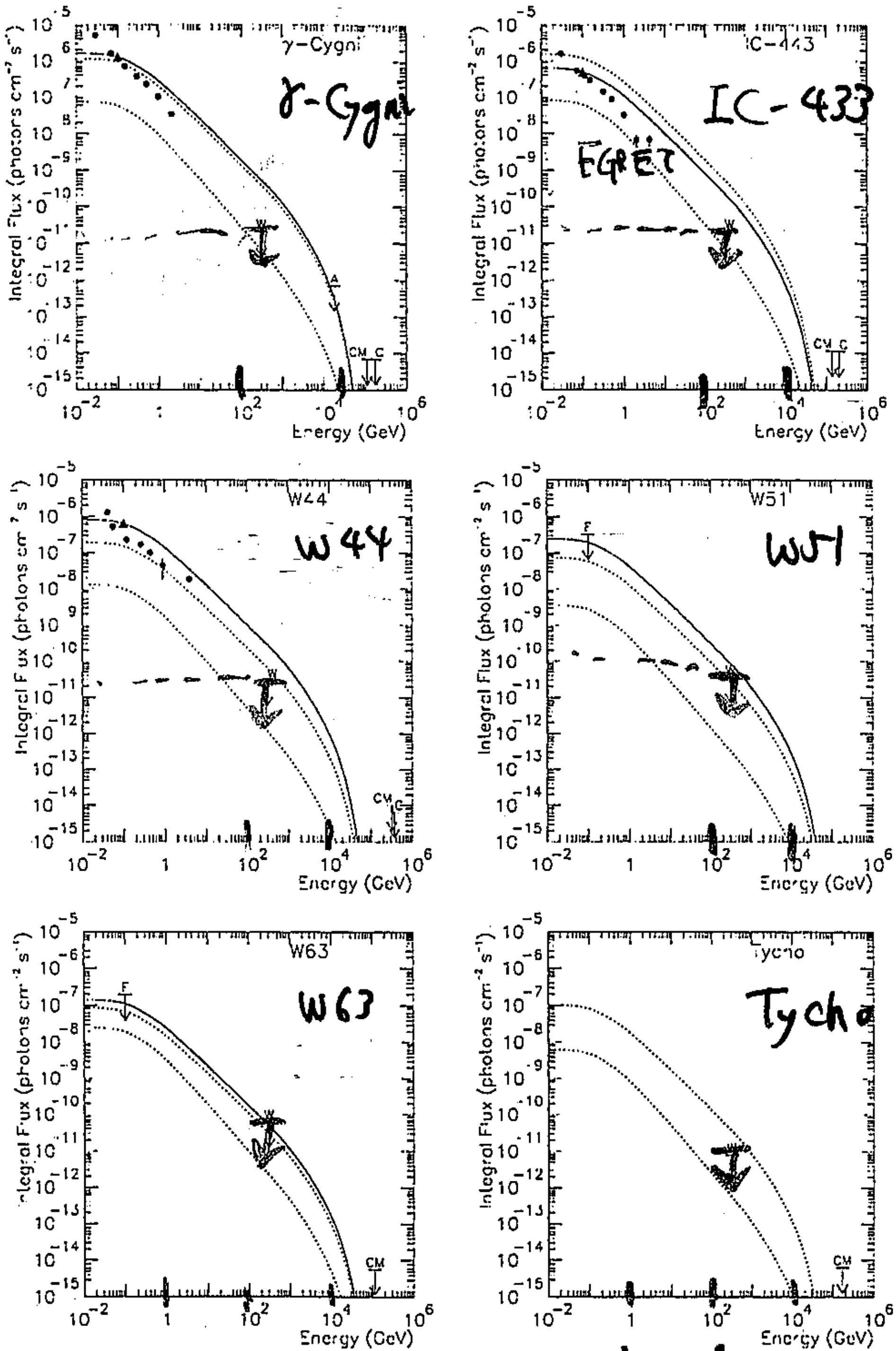
Whipple Observations of SNRs

Buckley et al. (1997)

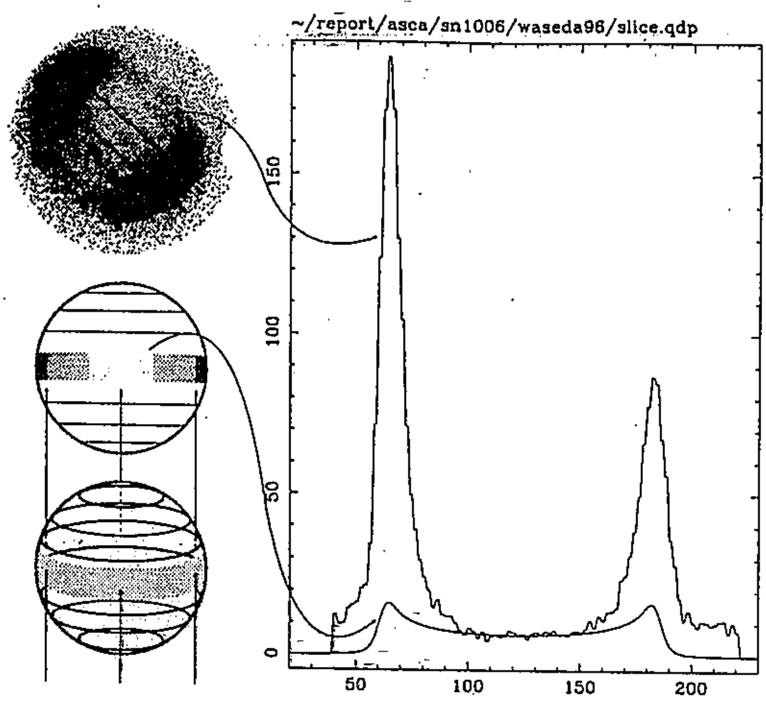


10^1 10^2 10^4 GeV

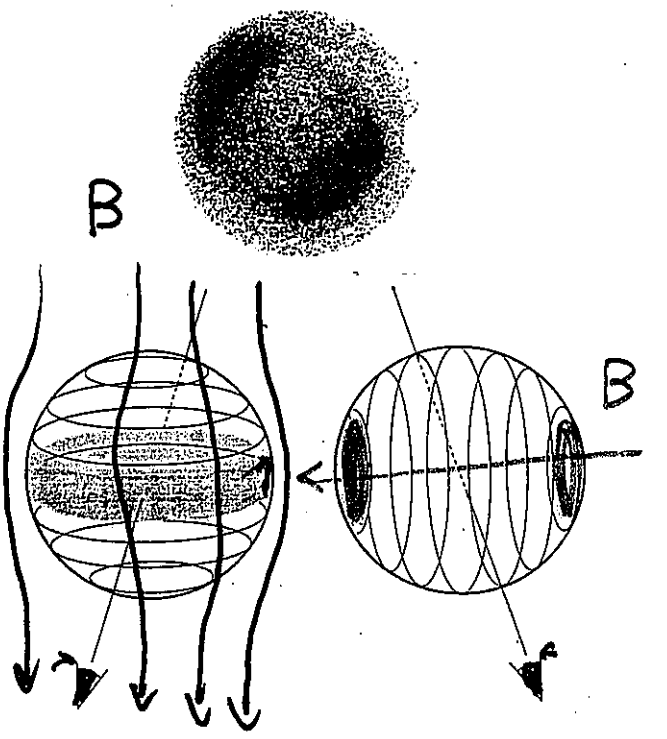
10^1 10^2 10^4 GeV

$E_\gamma < 1 \sim 2 \times 10^{-11}\ cm^{-2} s^{-1}$ @ 300 GeV

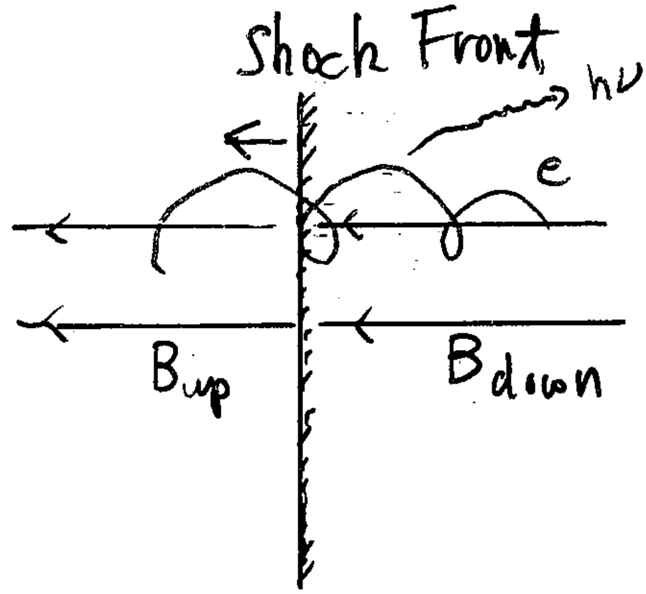
Direction of Magnetic Field



From. M. OZAKI D-thesis



Perpendicular (oblique-shock)   parallel-shock



Parallel Shock

$I_{synch.}(h\nu) \propto n_e.$

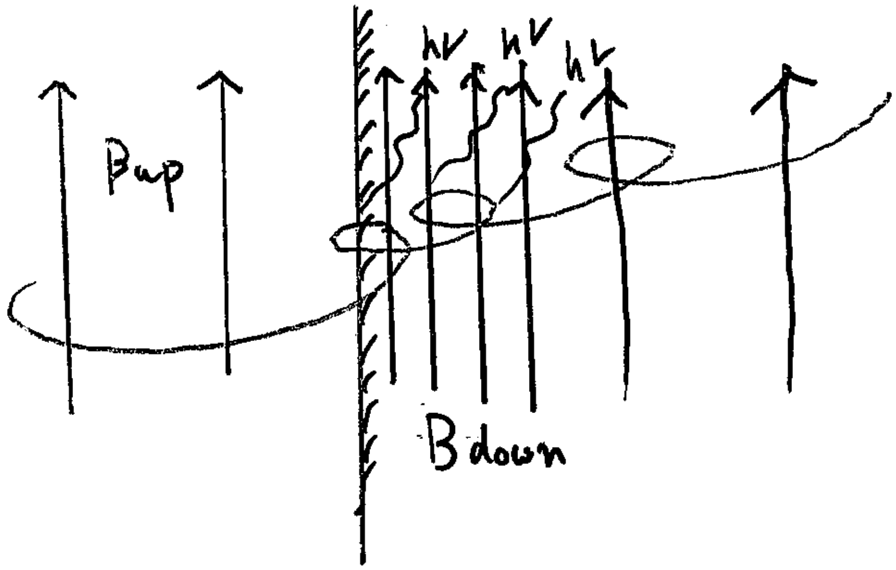
$I_{I.C}(h\nu) \propto n_e.$

$E_{exp}^{max} \lesssim 100\,TeV$

$B_{up} \sim B_{down}$

$\left(-\frac{dE}{dt}\right)_{synch} \propto B^2$

Oblique Shock



<u>More Efficient</u>

× 10 ~ 100

$I_{synch}(h\nu) \propto B^2$

$I_{I.C}(h\nu) \propto n_e$

$4B_{up} \sim B_{down}$

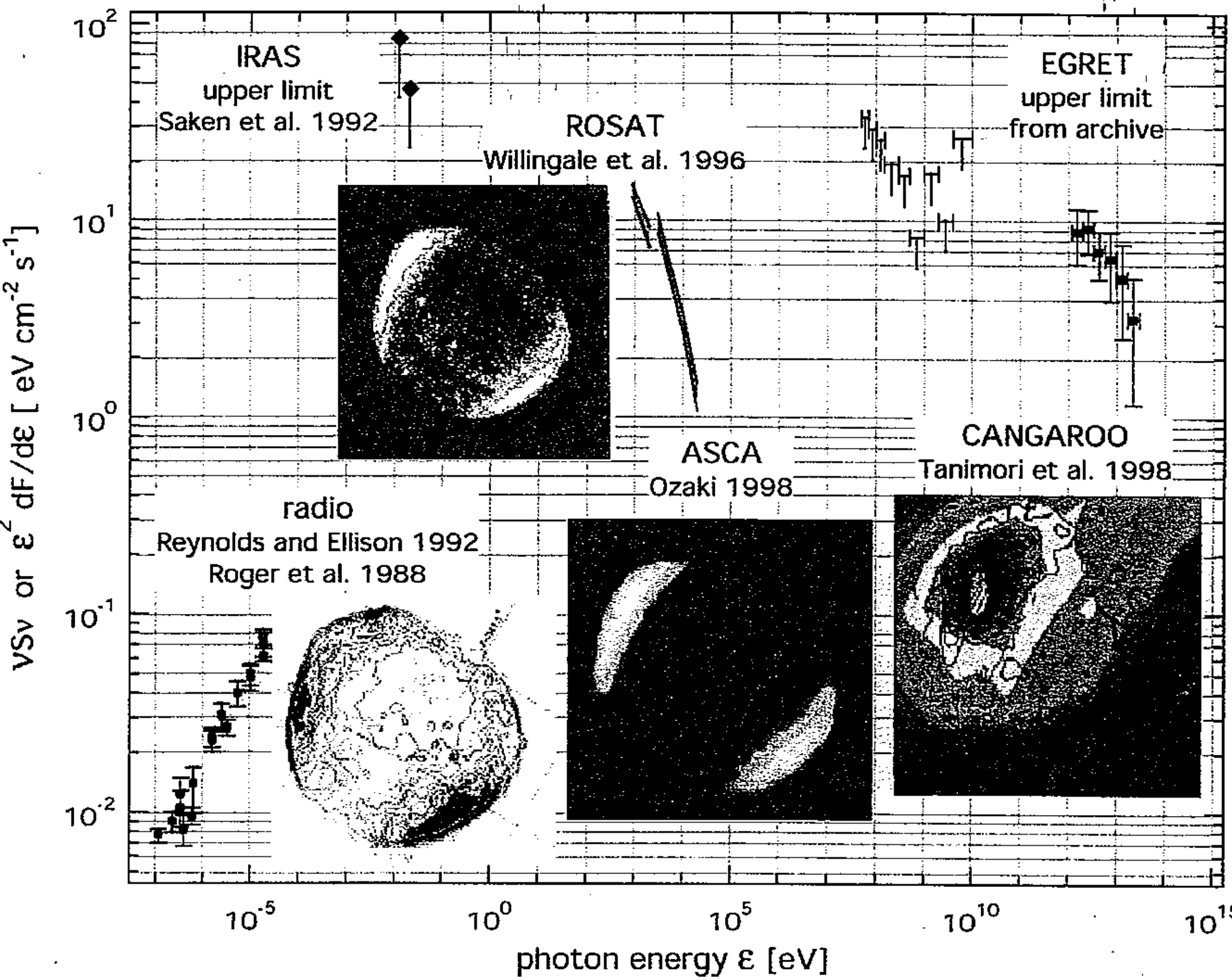
In NE Rim $\quad B_{down} \sim 4\,\mu G \rightarrow B_{up} \sim 1 \text{ or } 4\,\mu G$

X-ray-Distribution $\approx$ TeV-Distribution

/ $\quad$ Parallel ??

Supernova remnant: SN1006 (CANGAROO)

- Synch. X-ray (ASCA)
- AD1006
- Rare Density



T. Naito

TeV γ 線から何がわかったか!

① $\underline{B = 4\,\mu G}$

② $E_{max\_e} \lessapprox \underline{50\,\mathrm{TeV}}$

$(E_{max\_p} \lesssim 3 \times 10^{14}\,\mathrm{eV})$

③ $u_e \sim 1.1 \times 10^{-10}\,\mathrm{erg\,cm^{-3}}$ @ $r_{SNR} = 7.4\,\mathrm{pc}$

$u_B = \frac{B^2}{8\pi} \sim 6.4 \times 10^{-13}\,\mathrm{erg\,cm^{-3}}$ ◎ $\underline{u_e \gg u_B}$

$\frac{N_p}{N_e} < 0.03 \left(\frac{n_p}{\mathrm{cm^3}}\right)^{-1} \rightarrow \frac{u_p}{u_e} < 50 \left(\frac{n_p}{\mathrm{cm^3}}\right)^{-1}$

④ 拡散係数 $D = \eta R_L \frac{c}{3}$

$\underline{\eta \sim 0.5}$ (地球周辺 $\eta = 1 \sim 500$)

高効率 → 斜め衝撃波?

⇓

$E_{max\text{-}p} \rightarrow \gtrsim 10^{15}\,\mathrm{eV}$

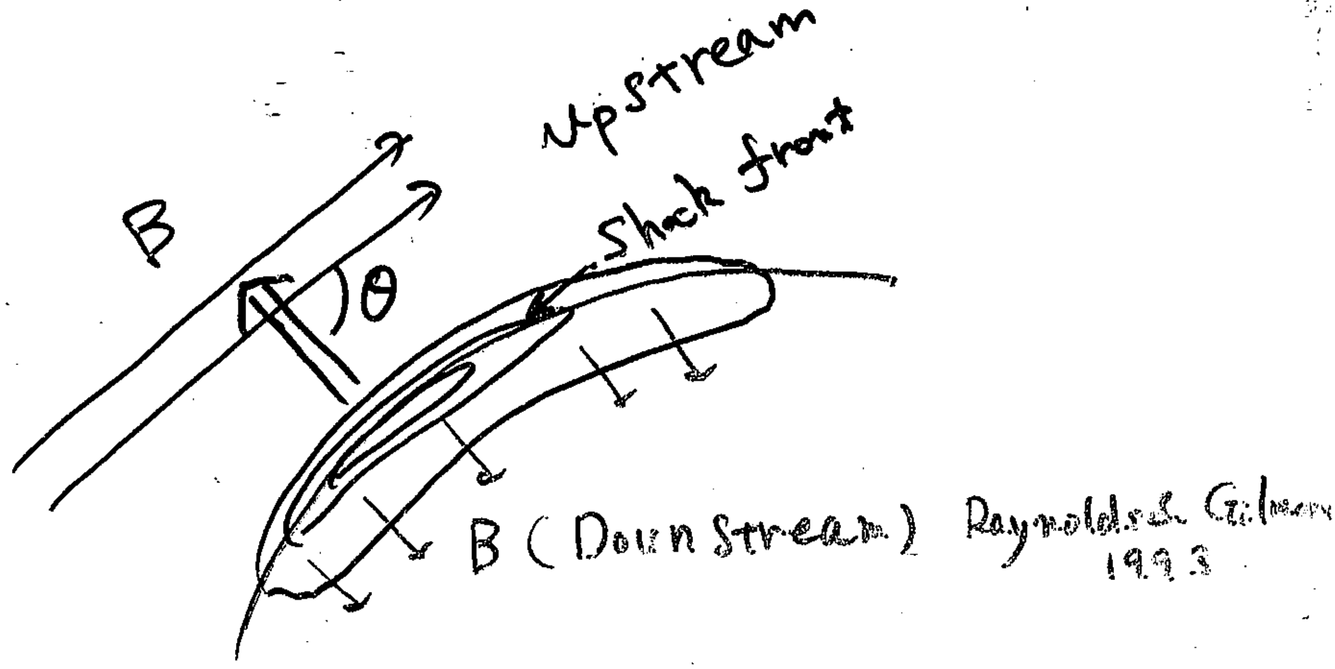
⑤ $\frac{\int E_e\,dt}{E_{tot}} \sim 1\%$

⇓

$\frac{\int E_e\,dt + \int E_p\,dt}{E_{tot}} >$ a few %

Perpendicular OR Parallel Schock?

(with O. de Jager)



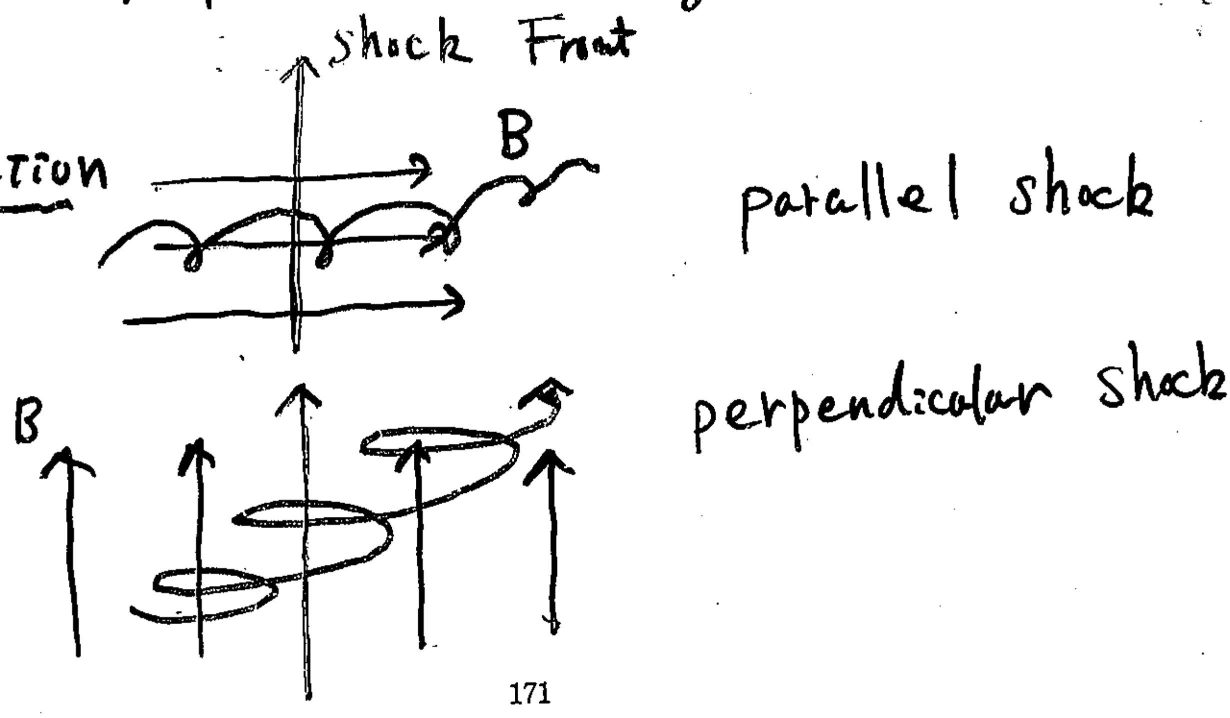
$\theta \simeq 90^\circ$ (Raynolds 1996) → Perpendicular + efficient

⇓

Jokipii 1997

Perpendicular shock high Gain ≫ Parallel

④ X Ray Polarization



Diffusive Shock Acceleration (1978~)

- Unique & Relevant Theory for H. E. particle Acceleration in Universe (E > GeV)

SNR → Simple Case of D. S. Acc.

$$\frac{E_{SNR}}{10^{51}\,erg},\quad \frac{M}{M_\odot},\quad \frac{n_{ISM}}{1\,cm^3},\quad \frac{B_{ISM}}{3\mu G}\quad \frac{t_{age}}{10^3\,years}$$

$$E_{max} \propto A\cdot\left(\frac{B}{3\mu G}\right)\cdot\left(\frac{t_{age}}{10^3\,years}\right)\left(\frac{V_{shock}}{3000\,km/s}\right)^2 \,TeV$$

V : 1000 ~ 5000 km/s　　B_{ISM}: 3 ~ 10 μG

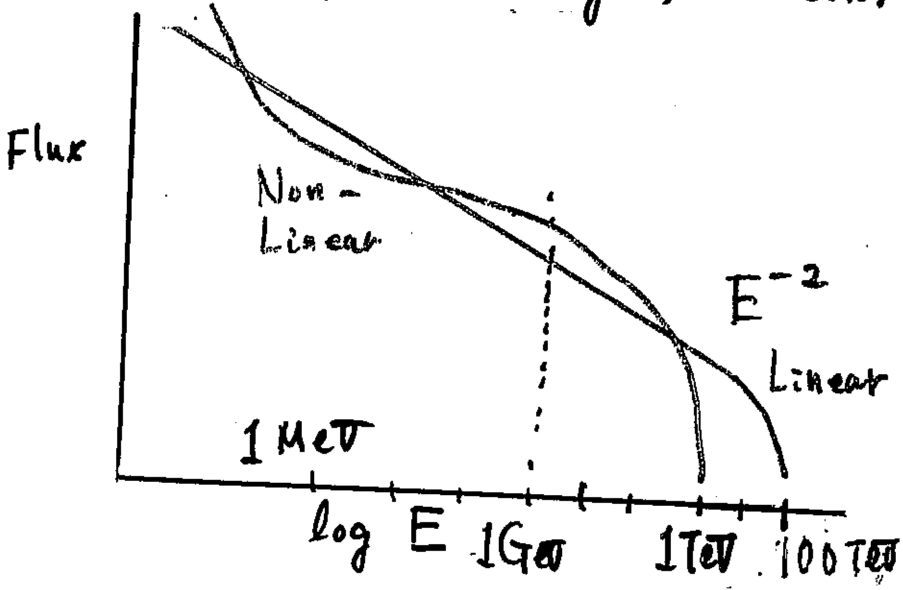
t_{age} ~ 10^3 years　　A : 10 ~ 100

$$E_{max} \sim 10^2 - 10^3\,TeV\,!$$

- Non-Linear Effect (Baring et. al 1997)

Linear : Pressure (gas) >> $P_{c.R.}$ → $P_{gas} \sim P_{c.R.}$

⇓



$E_{max} \propto n^{-\alpha}$

$\alpha > 0$

$E_{max} < 1\,TeV : n > 1\,cm^{3}$

$E_{max} \sim 100\,TeV : n < 0.1\,cm^{3}$

Possibility of TeV γ Detection from SNRs

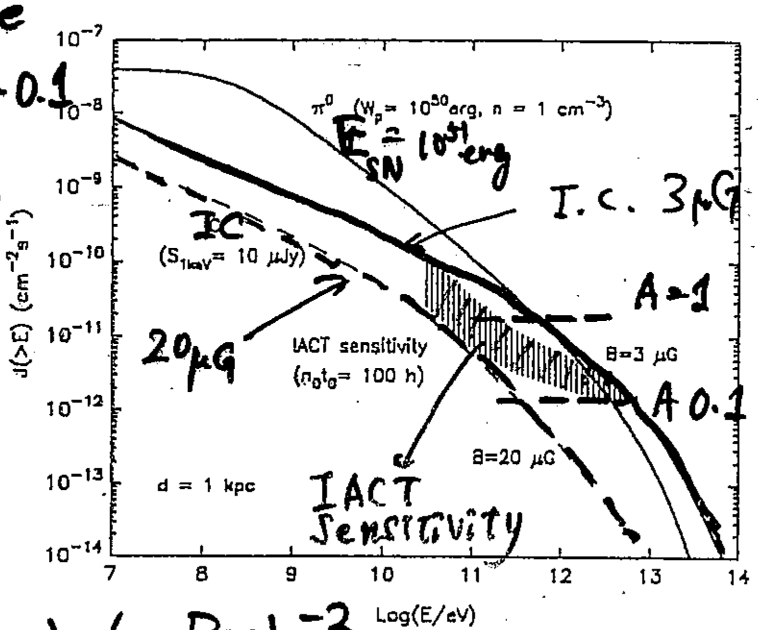
$$J_\gamma(>E) = 10^{-11} A \left(\frac{E}{1\,\text{TeV}}\right)^{-1} \text{photons/cm}^2\text{s}$$

Present IACTs $A \gtrsim 0.1$

- γ from π^0 $A \sim 10 \cdot \theta \cdot \left(\frac{E_{SN}}{10^{51}\text{erg}}\right)\left(\frac{n}{1\,\text{cm}^3}\right)\left(\frac{d}{1\,\text{kpc}}\right)^{-2}$

θ: Efficiency of Particle Acc. in SNR: $\theta \sim 0.1$

Typical SNR @ $d \sim 3$ kpc
↓
$A \sim 0.1$! Marginal



- I.C. γ $A = 1\left(\frac{S_{1\,\text{keV}}}{10\,\mu\text{Jy}}\right)\left(\frac{B_{ISM}}{3\,\mu\text{G}}\right)^{-2}$

$S_{1\,\text{keV}}$: Energy flux of Synchrotron Xray @ 1 keV.

B_{ISM}: Magnetic field in I. S. M.

SN1006 $S_{1\,\text{keV}} = 20\,\mu\text{Jy}$ $B_{ISM} \sim 4\,\mu\text{G}$

<u>$A \sim 1$</u>

Possibility & Type of Young SNRs

SNR	n (cm^{-3})	E_{SN} (erg)	d (kpc)	A_{π^0}	Syn. X	B_{ISM} (μG)	t_{age} (year)	Radio
γ-Cygni	5	10^{51}	1.5	2	Th	10<		Bright
IC 443	10	$2\cdot10^{50}$	1.5	0.9	Th+Sy.	500 μG	~1200	Br.
CAS. A	30	10^{51}	3.4	3	Th+Sy	10^3? μG	~350	Br.
Tycho	1	$2\cdot10^{50}$	2.3	$4\cdot10^{-2}$	Th.	-	400	Br.
SN1006	0.4	$5\cdot10^{50}$	1.8	$6\cdot10^{-2}$	Sy. Dominant	4 μG	1000	Dark
RXJ1713-44	<0.1	?	3~6	$<10^{-3}$	Sy. D.	~3 μG	10^3~10^4	Da.
RXJ0852-46	<1	~10^{50}	0.2	>1	Sy D.	~3 μG	~700	Da.

Upper SNRs (1) Dense, (2) Radio Bright, (3) Large B_{ISM},

D. S. Acc. ⇒ Good Target for TeV γ from π^0

Non-Linear ⇒ $E_{max} \lesssim$ TeV

Lower SNRs (1) Sparse, (2) Radio Dark, (3) Syn. X ray Dominant, (4) Low B_{ISM}

Non-Linear ⇒ $E_{max} \gtrsim 10$ TeV

TeV γ from I.C. Dominant

also Proton exists! → $A_{\pi^0} \ll 1$

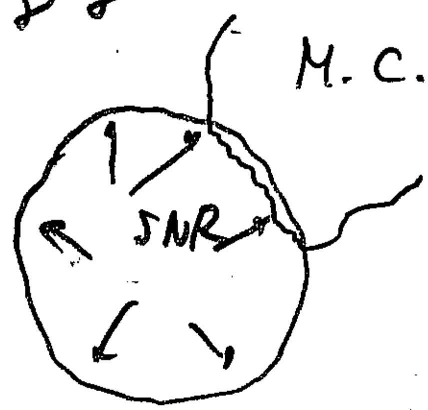
TeV γ-rays from SNRs

① SNR ⊕ Molecular Cloud

Accelerator → Target

$$p + A \to \pi^0 + X, \quad \pi^0 \to \gamma\gamma$$

$n_p \gtrsim 100$ Atoms/cm^3



- EGRET, Whipple, ...

IC 443, γ-Cigni, W44, W28,

◎ Baring et al. Astro-ph/9810158

- $n_p > 1$ Atom/cm^3 → non-liner shock → $E_{max} \lesssim$ TeV
- $t_{acc} \lesssim 300$ years → $E_{max} \lesssim$ TeV

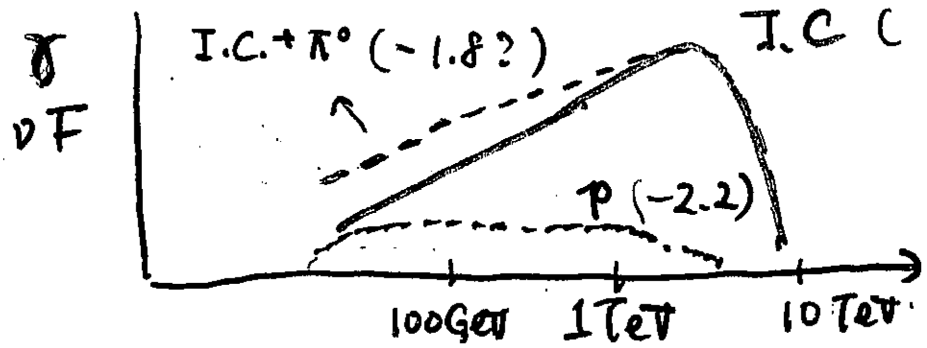
② Low Density SNR (SN1006, RXJ1713-39...)

- $n_p < 1$ Atom/cm^3 → $E_{max} \lesssim 100$ TeV

However,

e → Xray - Synchrotron, 2.7 K CMB. I.C. ← observable (But Only TeV Region)

p → little target ?

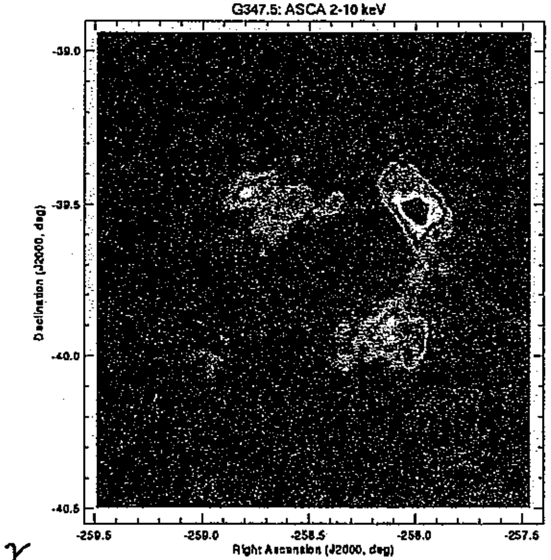


◎ Radio → DARK

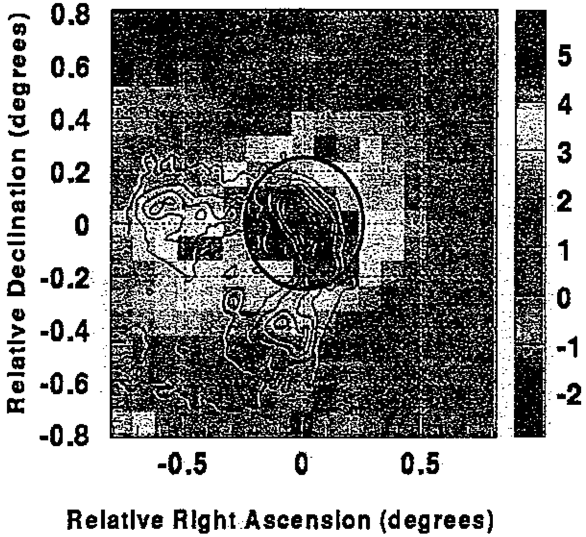
◎ Xray - Bright

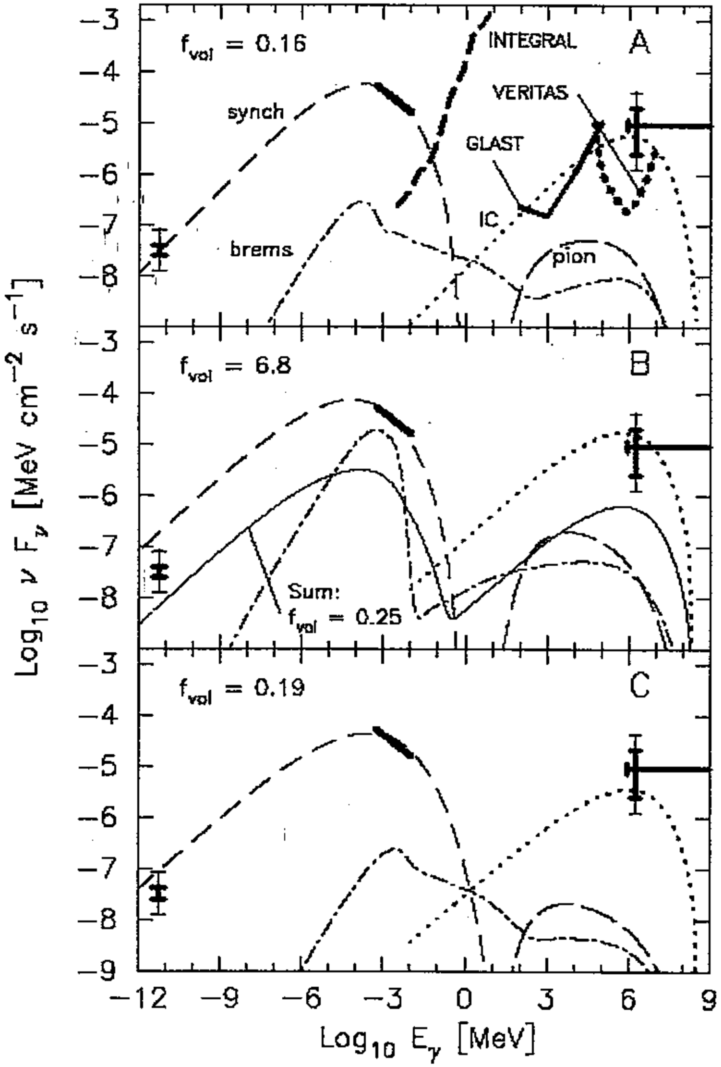
Supernova remnant: RXJ1713

Synch. Xray(ASCA)



TeV-γ



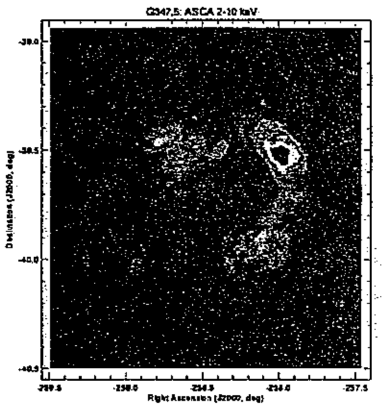


Ellison et al 2001

Morphology of TeV γ

Supernova remnant: RXJ1713

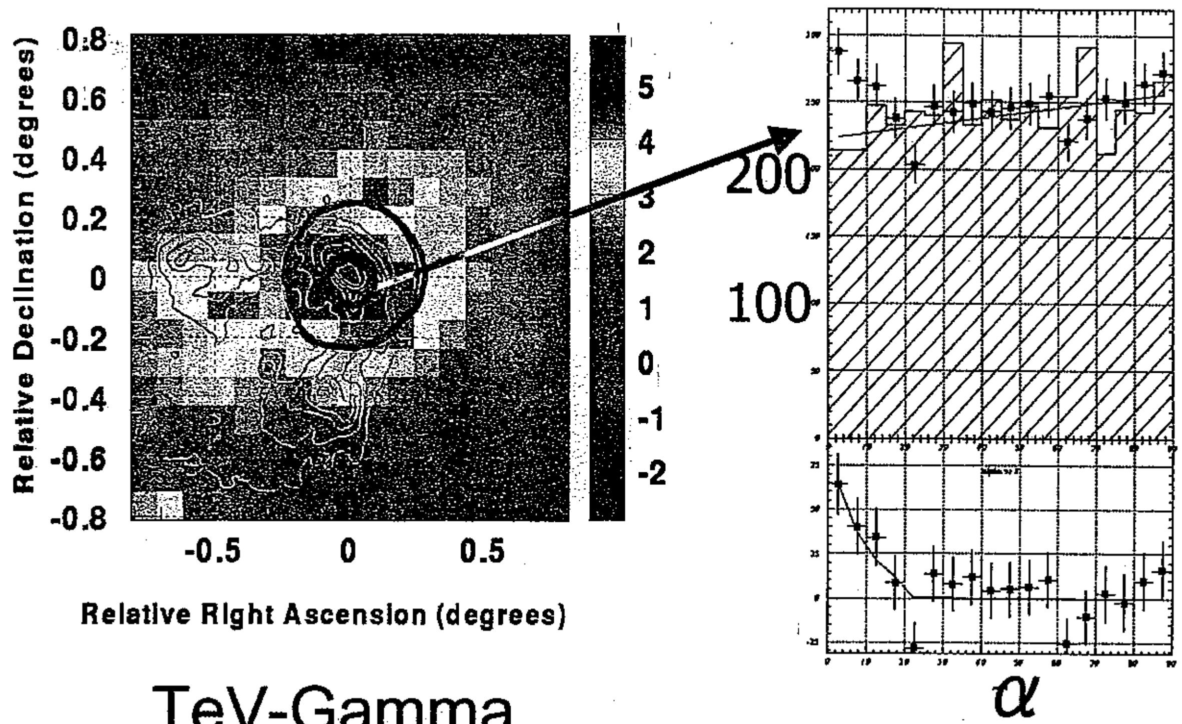
CANGAROO III



RXJ1713.7-3946

Synch. X-ray Emission(ASCA)

Tomida, Ph.D., 1999



TeV-Gamma

3.8m Tele. Δθ~0.2°

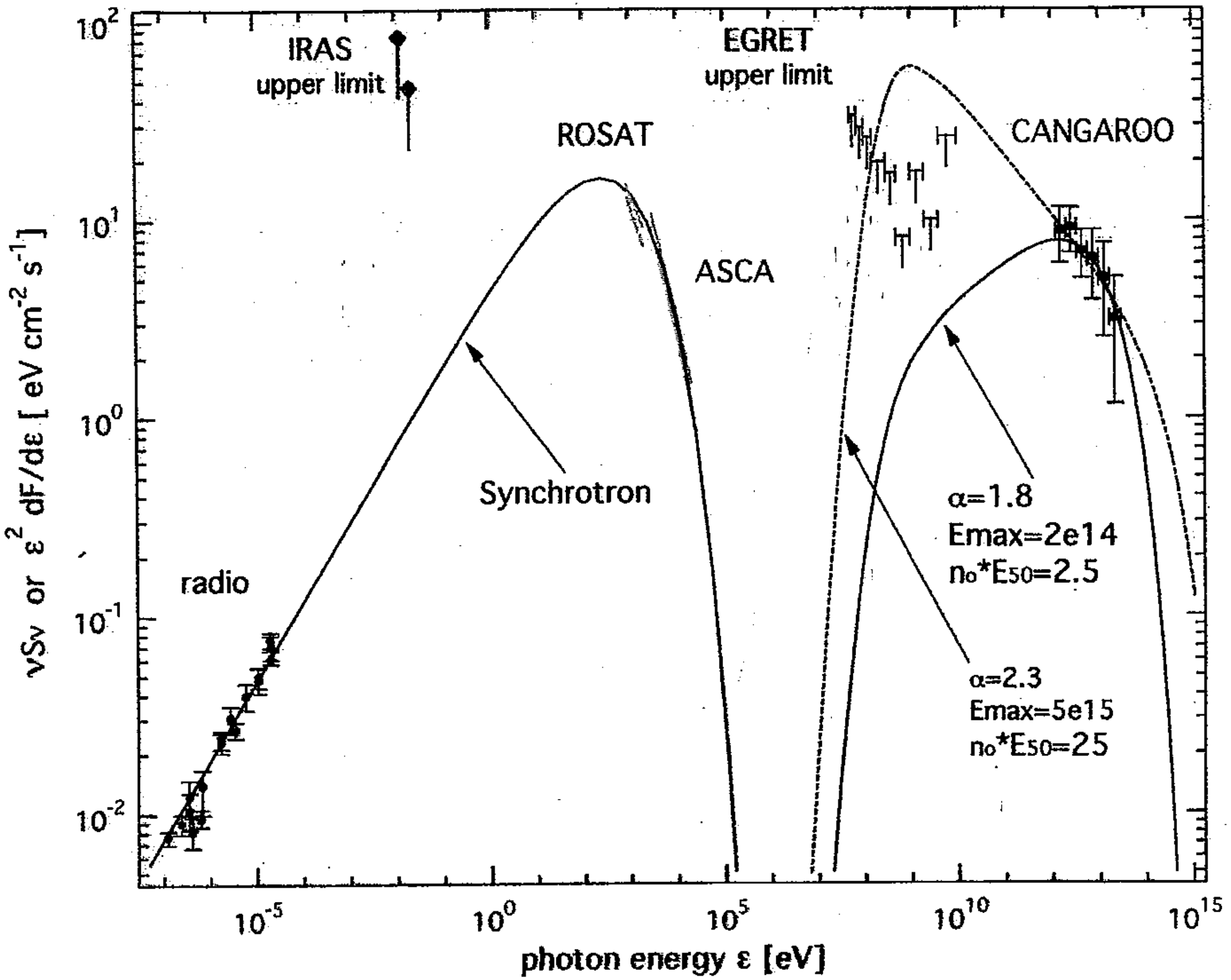
Muraishi et al., A&Ap 354, 2000

7m Tele. 1999 (16hours)

Preliminary

Stereo Δθ≲0.1°

π⁰ decay model



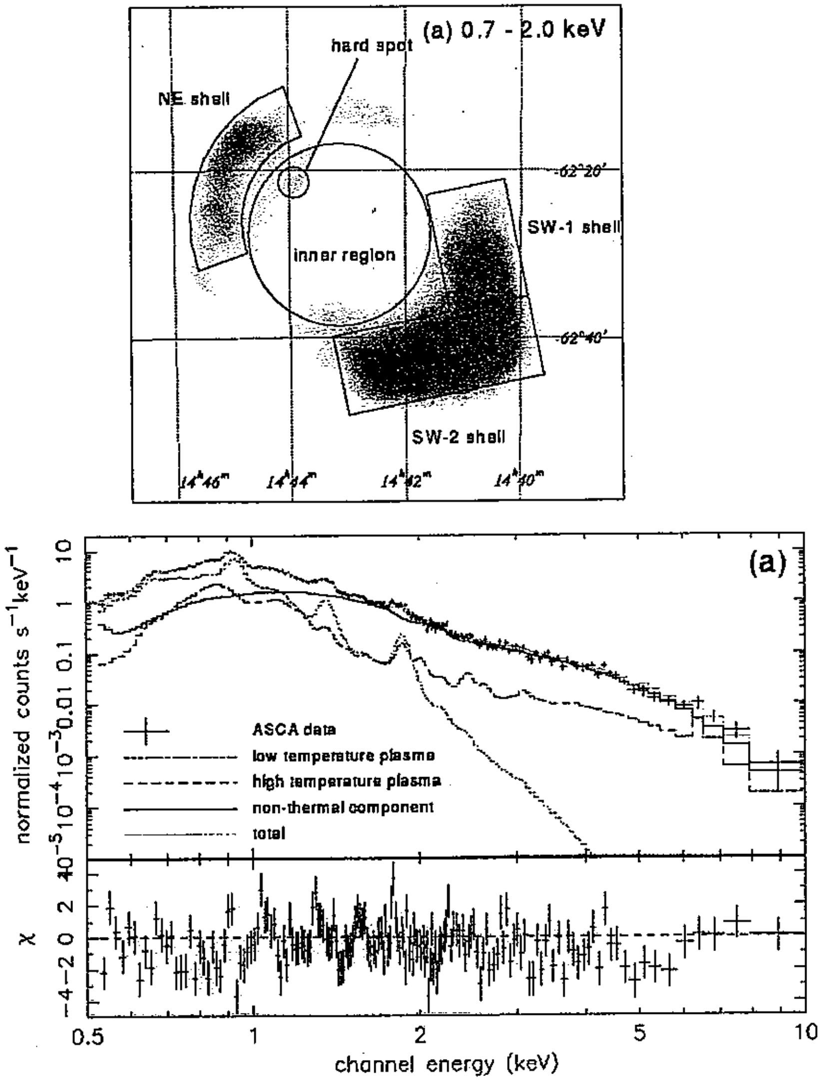
$\alpha_p = 1.8$

proton total energy

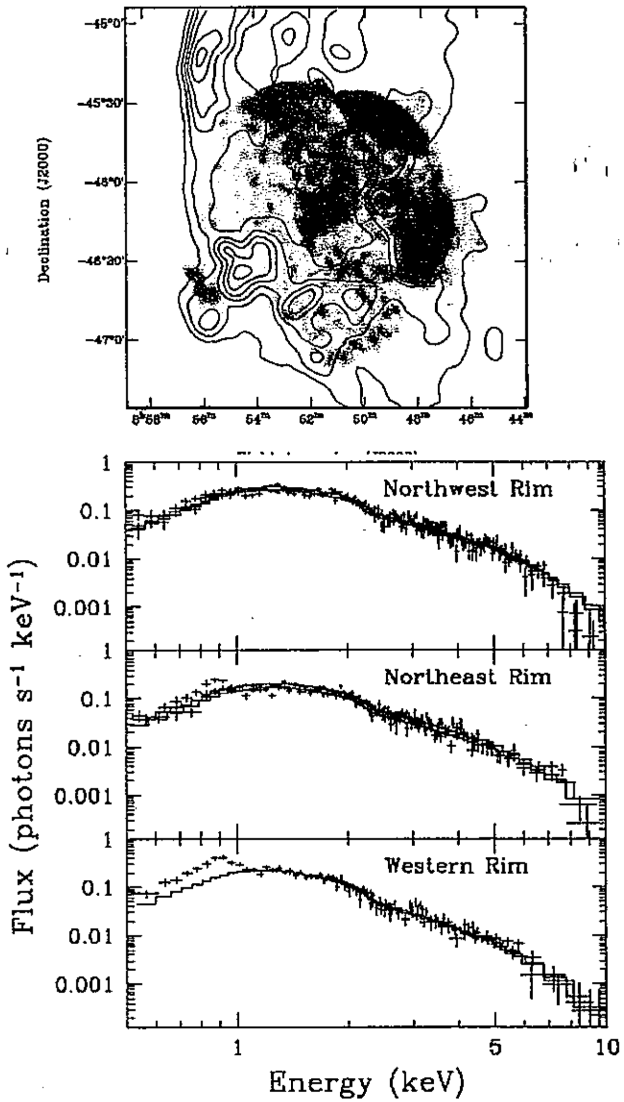
$E_{tot} = 2.5 \times 10^{50}$ erg

$\sim E_{SN}$

X-ray Synchrotron SNRs



Bamba et al. 2000



Slane et al. 2001