ガンマ線天体と粒子加速

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宇宙線の超新星残骸起源説

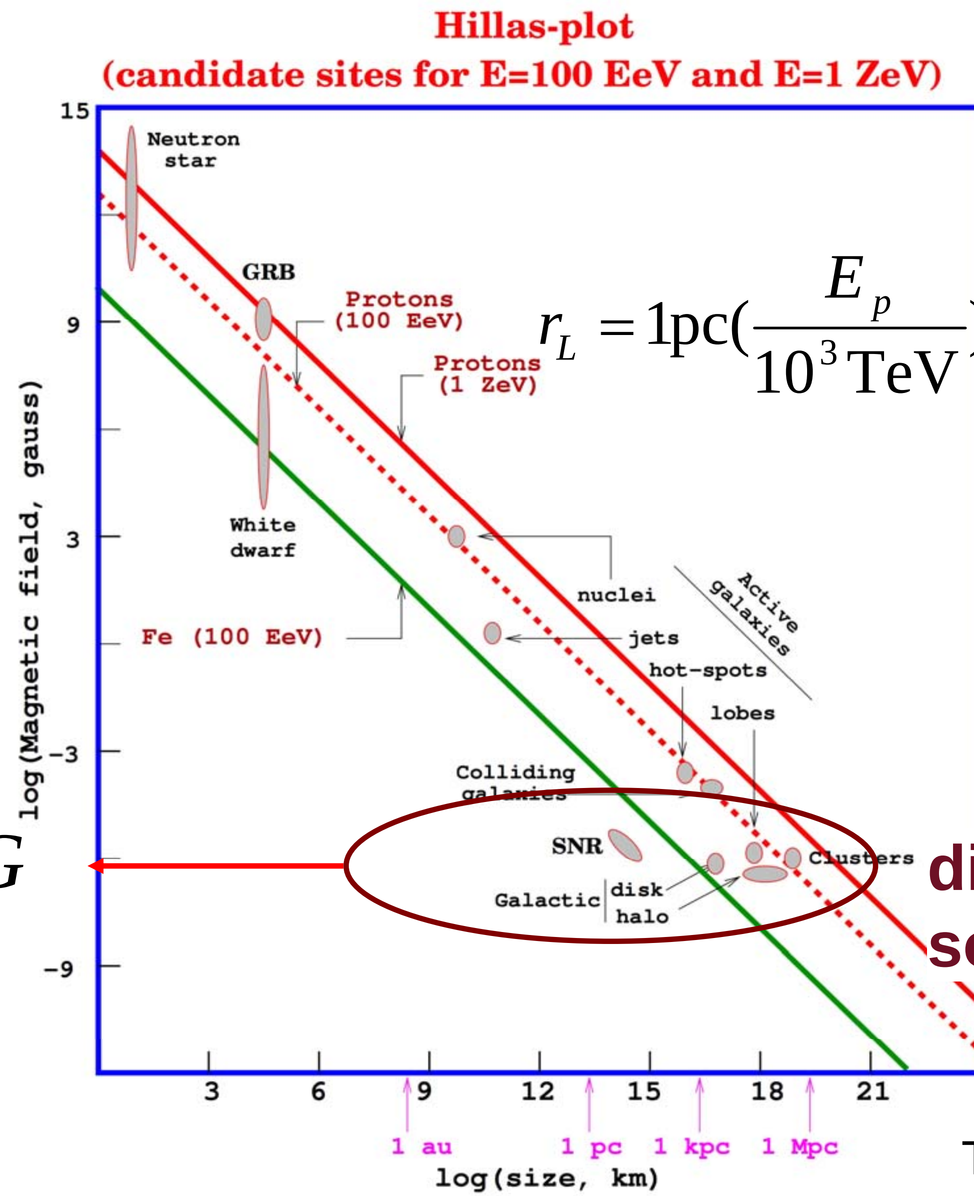
- エネルギー収支

$$L_{CR}=\frac{V_{gal}U_{CR}}{t_{CR,life}}\sim 10^{42}\,\mathrm{erg/s}$$

$$\sim\left(\frac{\mathrm{E_{SN}}}{10^{51}\mathrm{erg}}\right)\left(\frac{\eta}{0.01}\right)\left(\frac{f_{SN}}{1/30\mathrm{yr}}\right)$$

  - 早川・伊藤・寺島、Ginzburg 1950年代
- スペクトル
  - 爆発の爆風⇒周囲の物質と衝撃波⇒衝撃波加速
  - 加速粒子は(ナイーブには)$\propto p^{-2}$のべき乗スペクトル
    - (テスト粒子近似、強い衝撃波M>>1で$p^{-(2+4/M^2)}$)
    - Fermi 1949、…

SNRs on Hillas plot



$$r_L = 1\text{pc}\left(\frac{E_p}{10^3\,\text{TeV}}\right)\left(\frac{B}{1\mu\text{G}}\right)^{-1} < \text{Size}$$

$B = \mu G$

diffuse sources

T. Yoshida

Another Hillas plot

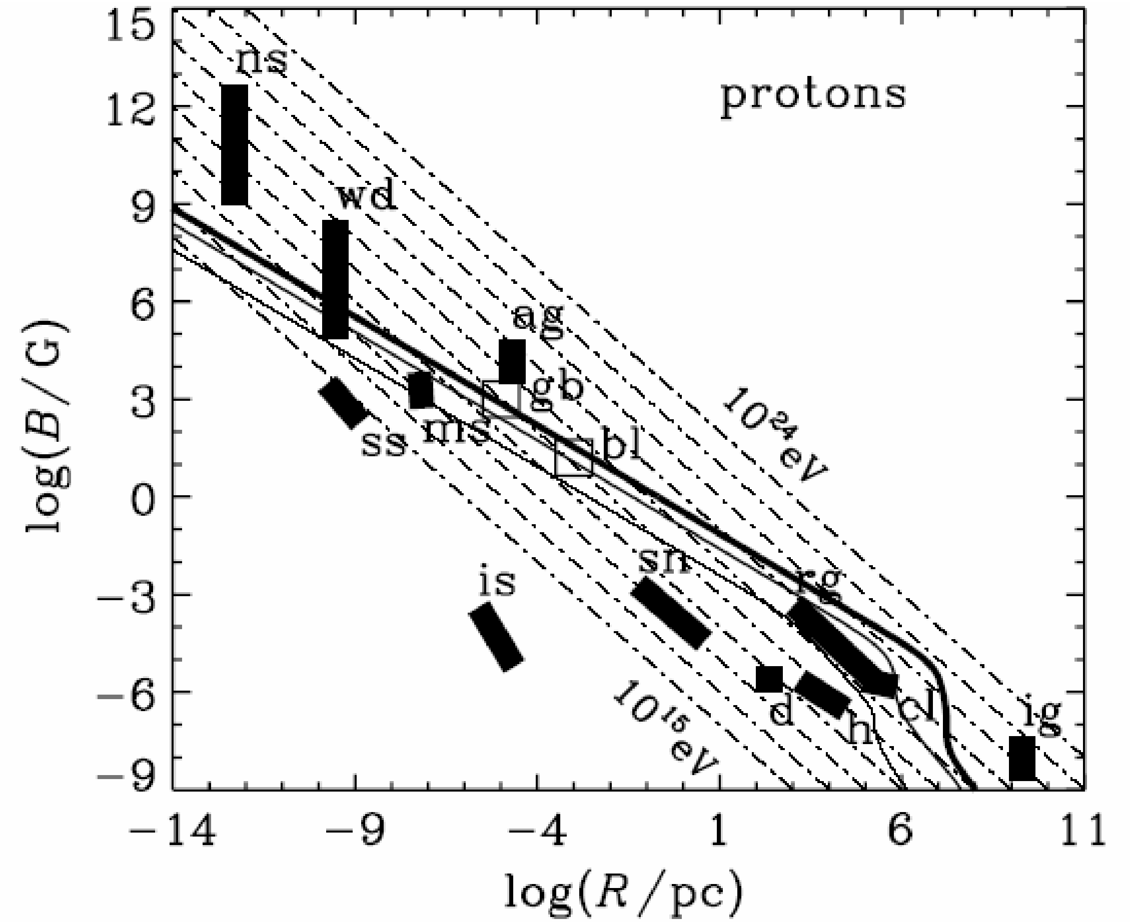


Fig. 6. "Hillas plot" showing (chain curves) magnetic field vs. gyroradius for proton momenta 10^{15}, 10^{16},..., 10^{24} eV/c. The solid curves correspond to those in part Fig. 5(b) such that the parameter space of accelerated particles is to the left of the curve corresponding to the chosen acceleration rate parameter. Typical size and magnetic field of possible acceleration sites (taken from Hillas [22]) are shown for neutron stars (ns), white dwarfs (wd), sunspots (ss), magnetic stars (ms), AGN (ag), interstellar space (is), supernova remnants (sn), radio galaxy lobes (rg), galactic disk (d) and halo (h), clusters of galaxies (cl) and intergalactic medium (ig). Typical jet-frame parameters of the synchrotron proton blazar model [21] and gamma ray burst model [30] are indicated by the open squares labelled "bl" and and "gb".

Protheroe, APh 21, 405 (2004)

SNRからのガンマ線

- 陽子起源 : $p + p \rightarrow \pi^0 (\rightarrow \gamma+\gamma) + X$
  - Input spectrum $\propto E_p^{-a}$
    $\Rightarrow$ output spectrum $\propto E_\gamma^{-a}$ (for $E_\gamma >> m\pi$)

$$flux = \frac{E_{tot} \times \eta_p \times c\sigma_{pp} n_{ISM}}{4\pi d^2}$$

$$= 5 \times 10^{-11} (\frac{\eta_p}{0.1}) n_{ISM} (\frac{d}{3\mathrm{kpc}})^{-2} \ \mathrm{TeV\ cm^{-2} s^{-1}}$$

$$\sigma_{pp} \approx 30\mathrm{mb}$$

$$= 3 \times 10^{-26} \mathrm{cm}^2$$

SNRからのガンマ線

- 電子起源
  - 制動放射 : $e + Z \rightarrow \gamma + e + Z$
    - Input spectrum $\propto E_e^{-a}$
      $\Rightarrow$ output spectrum $\propto E_\gamma^{-a}$
  - 逆コンプトン : $e + h\nu \rightarrow \gamma + e$
    - Input spectrum $\propto E_e^{-a}$
      $\Rightarrow$ output spectrum $\propto E_\gamma^{-(a+1)/2}$

SNRにおける加速のパラメータ

- E_{max} : The maximum energy of accelerated particles
- E_{CR}/E_{SN}: The efficiency of particle acceleration
- B : The magnetic field
- κ : The diffusion coefficient
  (δB) (The magnetic turbulence)
- e/p: The ratio of electrons to protons

SNRからのガンマ線スペクトル

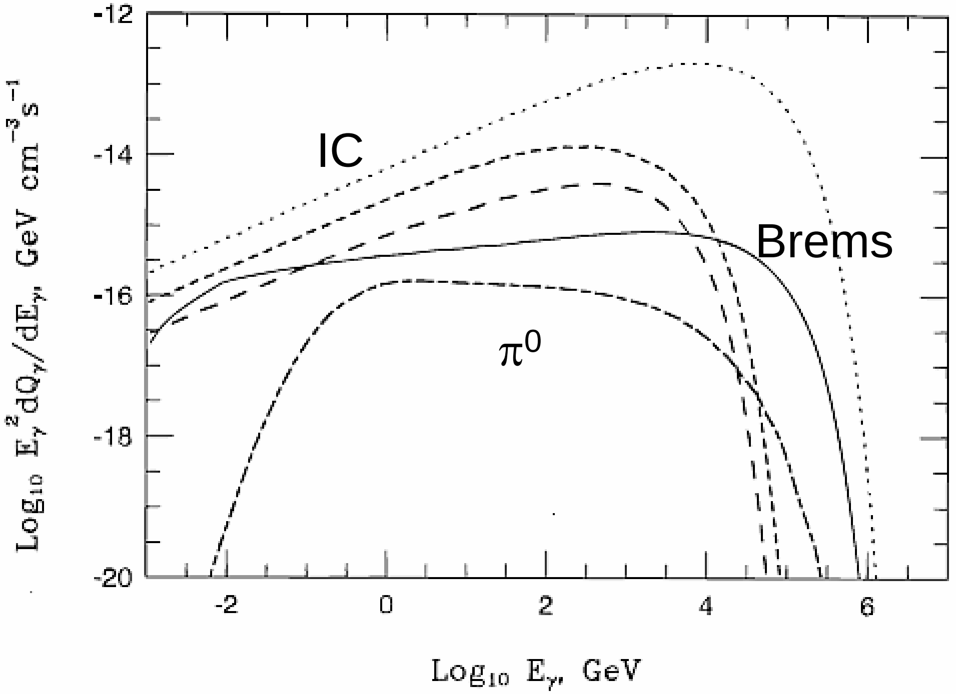


FIG. 3.—Gamma-ray emissivity at IC 443 produced by particles (electrons and protons) with momentum spectrum $dn/dp = p^{-2}$ cm^{-3} (GeV c^{-1})$^{-1}$, interacting with interstellar matter with nucleon number density 1 cm^{-3} and with interstellar (IR/O) and cosmic microwave radiation fields of Fig. 1. *Dot-dashed line*: π^0 production; *solid line*: bremsstrahlung; *long-dashed line*: IC on interstellar (IR/O); *short-dashed line*: IC on infrared radiation at IC 443; *dotted line*: IC on microwave.

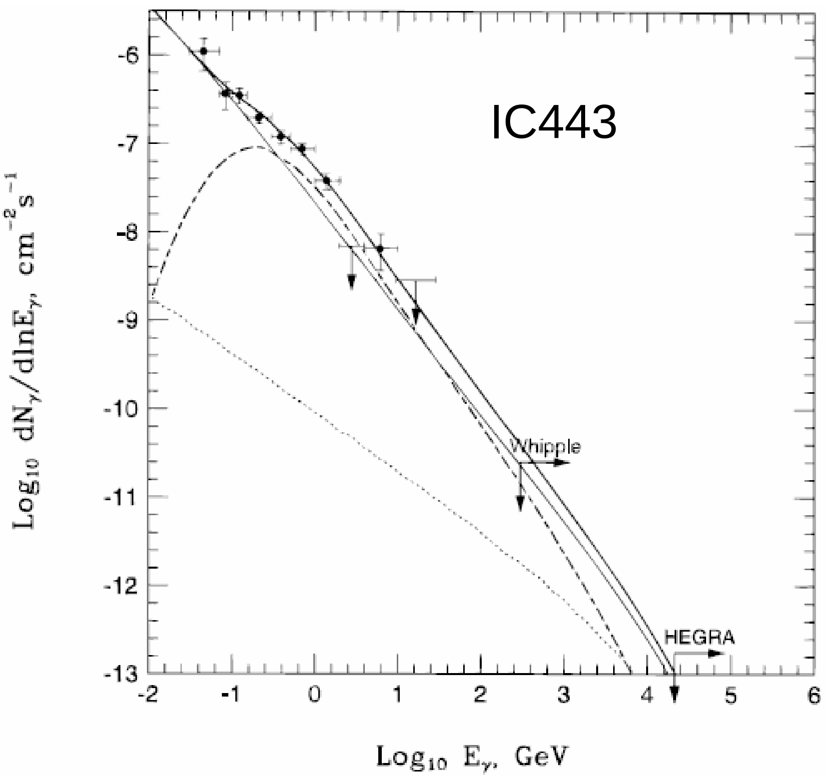
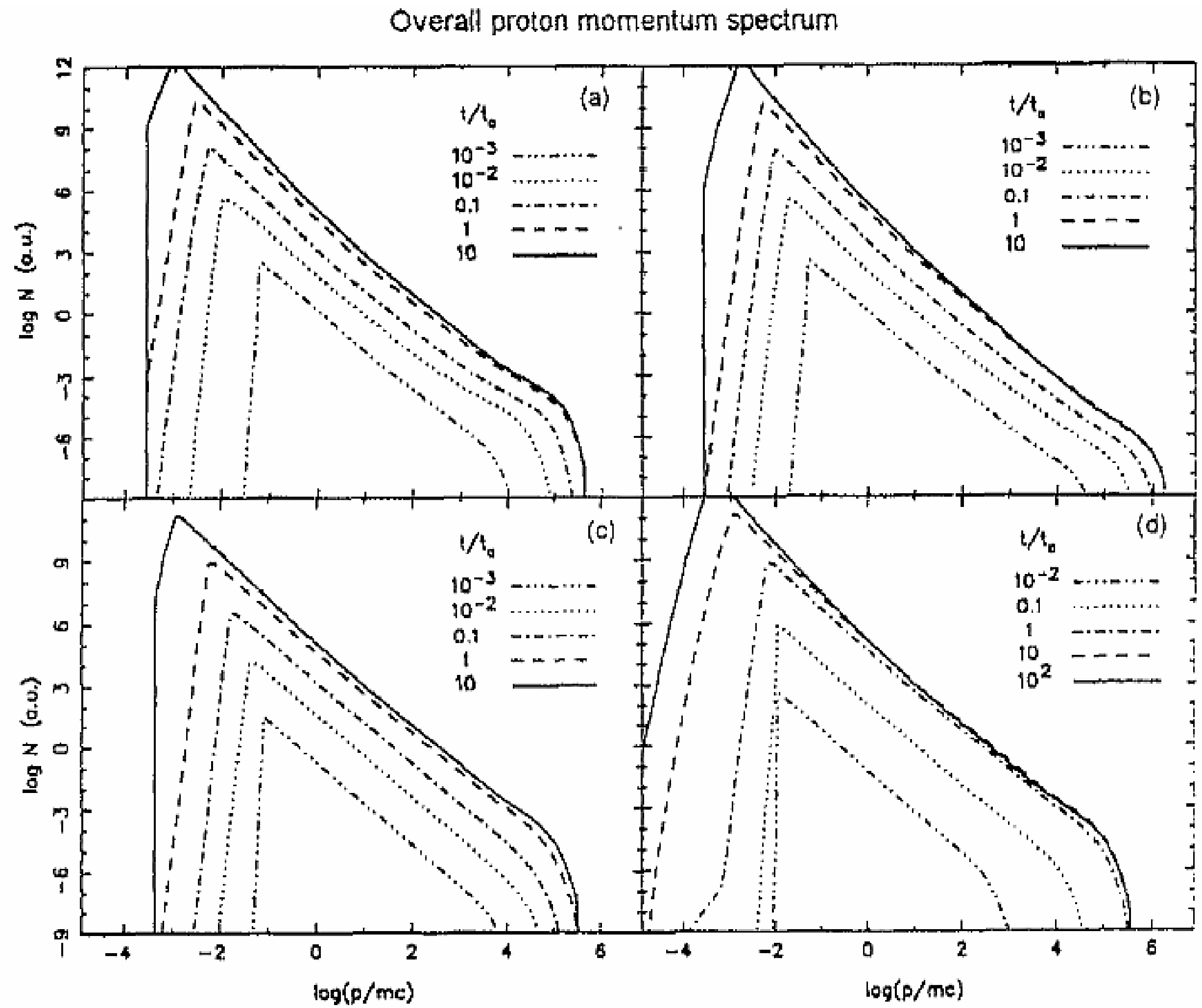


FIG. 4.—Best fit (fit 1) to EGRET observations of IC 443, including upper limits (*thick solid line*). Whipple (Buckley et al. 1997) and HEGRA upper limits (Prosch et al. 1995) are not included in the fits. The small IC contributions from the interstellar and source IR radiation are not shown in this and other fit spectra. Other lines, as in Fig. 3.

Gaisser, Protheroe & Stanev, ApJ 492, 219 (1998)

Nonlinear kinetic theory of shock acceleration in SNR



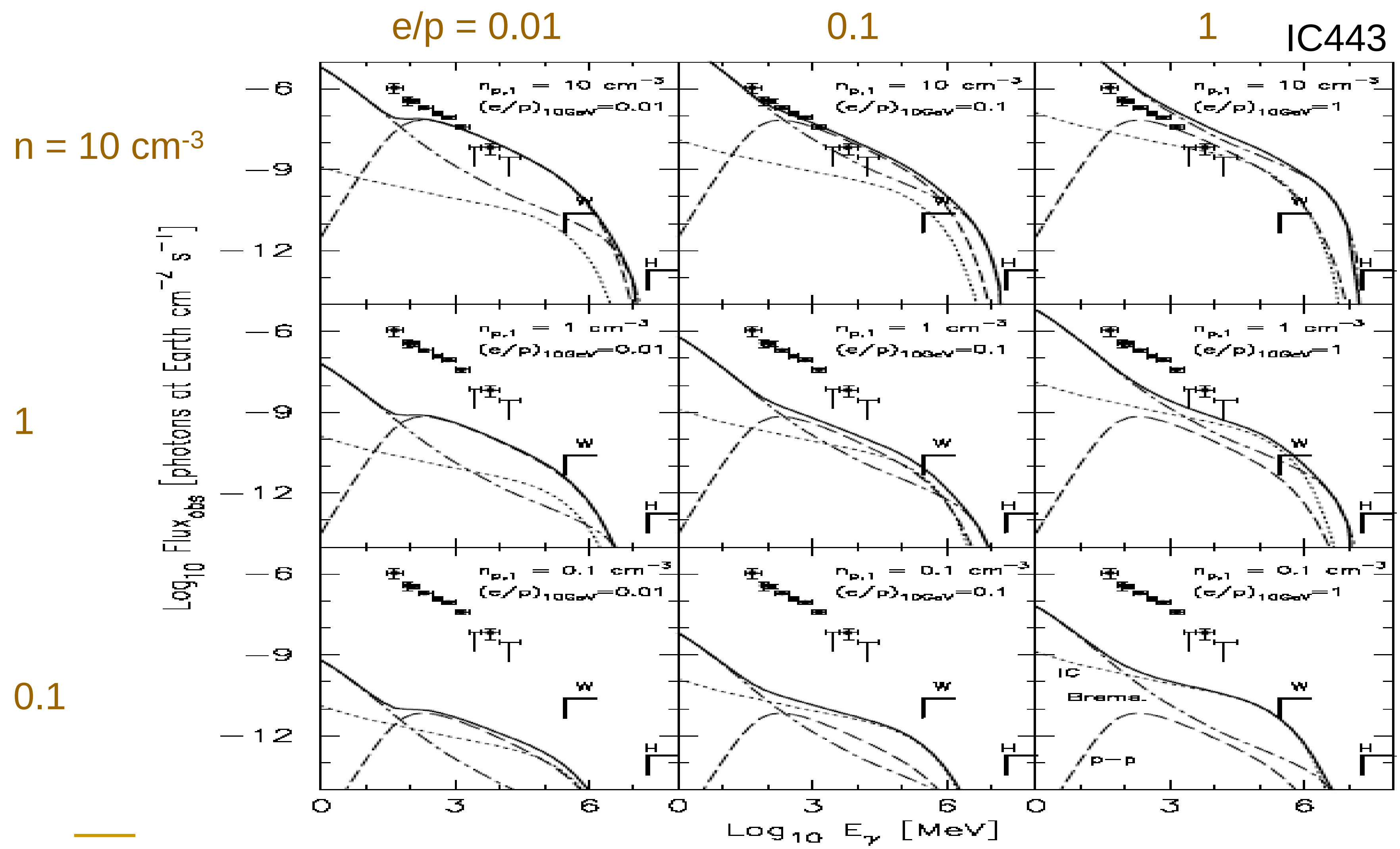
the injection rates $\eta = 10^{-3}$ (a,b) and $\eta = 10^{-4}$ (c,d), ISM magnetic field $B_0 = 5\ \mu G$ (a,c,d) and $B_0 = 30\ \mu G$ (b), the ejecta velocity distribution (13) (a,b,c) and the uniformly moving ejecta (d), expanding in a uniform ISM with number density $N_0 = 0.3\ cm^{-3}$; $t_0 = 1893$ yr.

"Nonlinear" = Back reaction from accelerated particles are taken into account (NOT a test particle approximation)

Efficient acceleration: $\propto p^{-2}$ ($p^{-1.7}$ for $p/mc \gg 10^3$)

Berezhko & Voelk, APh 7, 183 (1997)

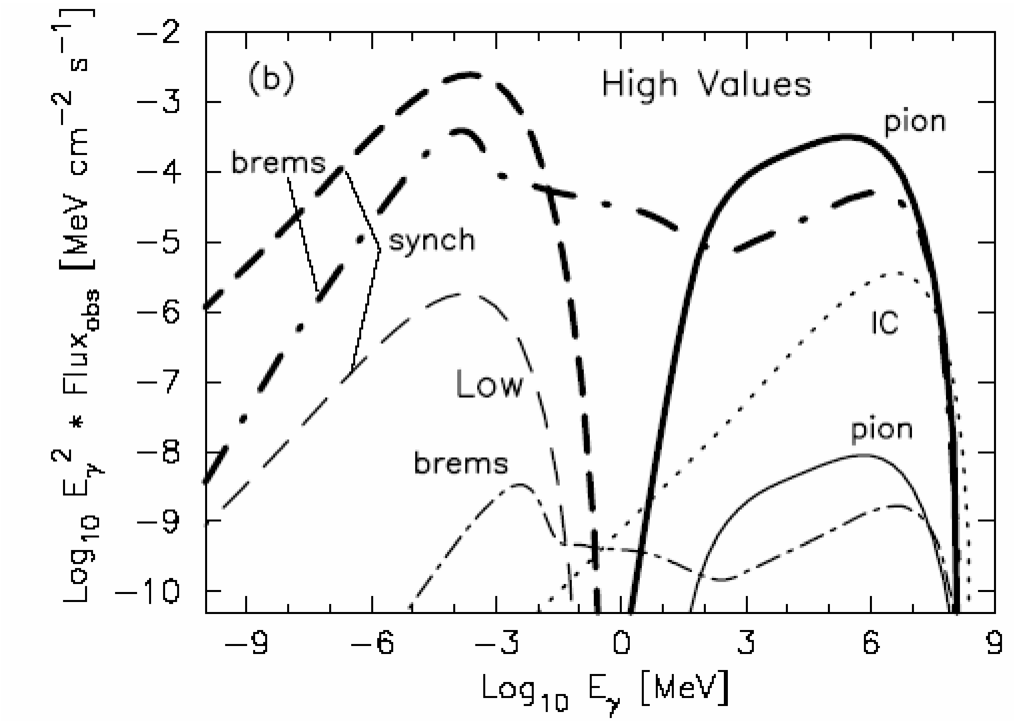
SNRからのガンマ線スペクトル



[With nonlinear effect]

Baring et al., ApJ 513, 311 (1999)

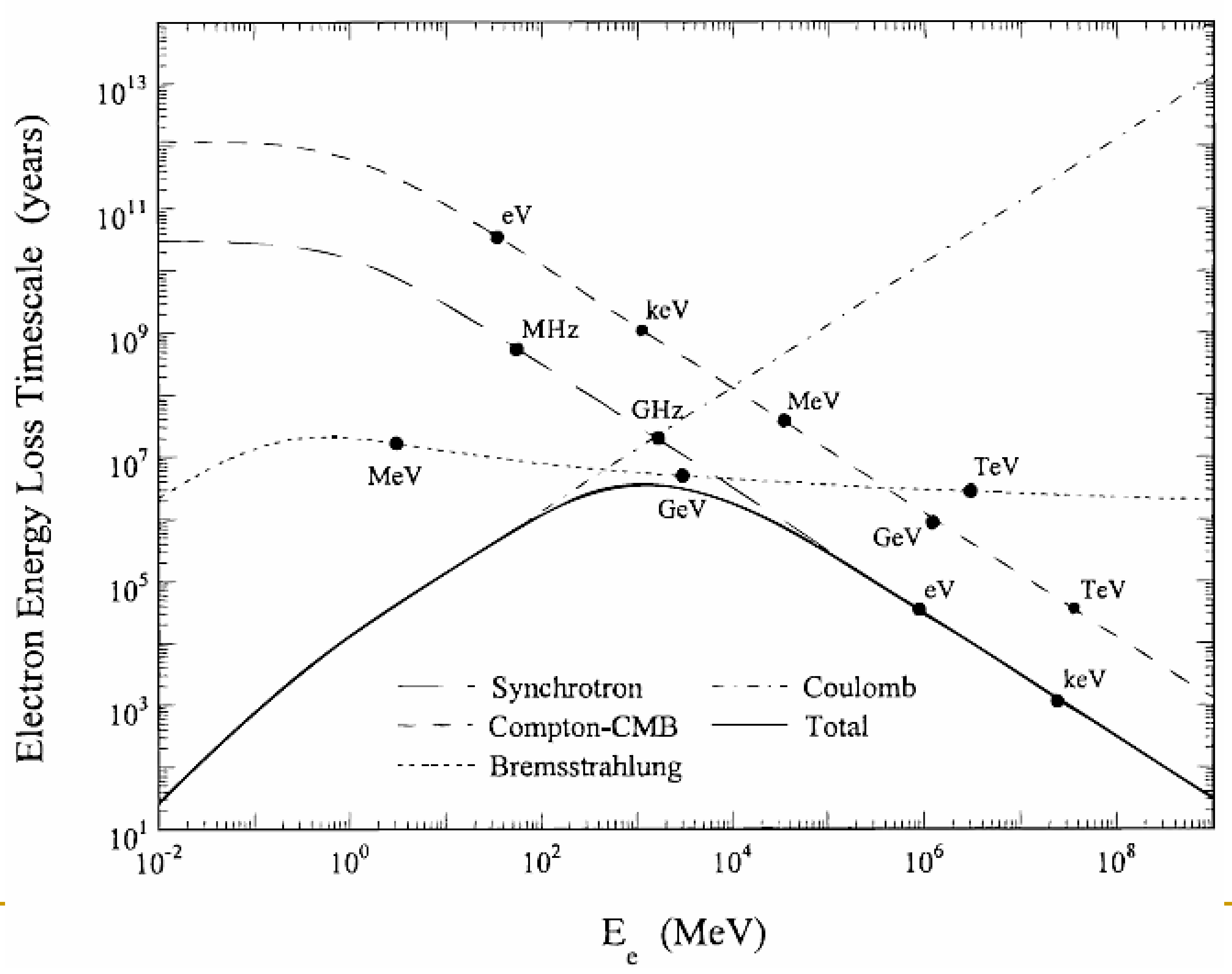
SNRからのガンマ線スペクトル



Parameters	Low	High
		Input Parame
n_{p0} (cm^{-3})[b]	0.01	10
B_0 (μG)	3	30
B_2 (μG)[c]	3	30
t_{snr} (yr)	1000	1000
E_{sn} (10^{51} ergs)......	1	1
M_{ej} ($M_\odot$)	1	5
T_{p0} (K).............	10^4	10^4
T_{e2}/T_{p2}	1	1
$\eta_{inj,p}$[d]	10^{-3}	10^{-3}
$(e/p)_{rel}$	0.03	0.03
η_{mfp}	1	1
α	1	1
n	0	0

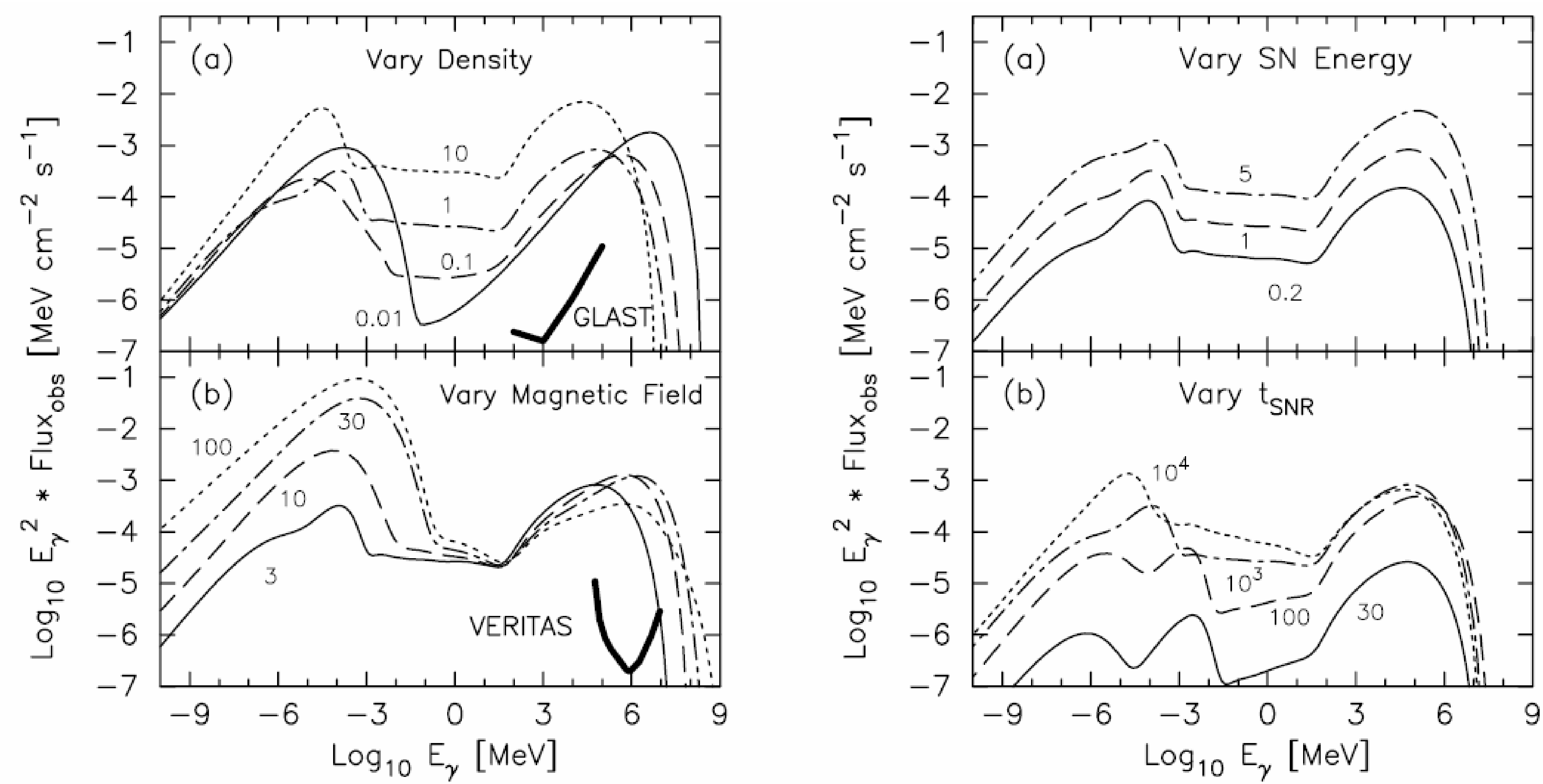
Ellison, Berezhko & Baring, ApJ 540, 292 (2000)

電子のエネルギー損失時間



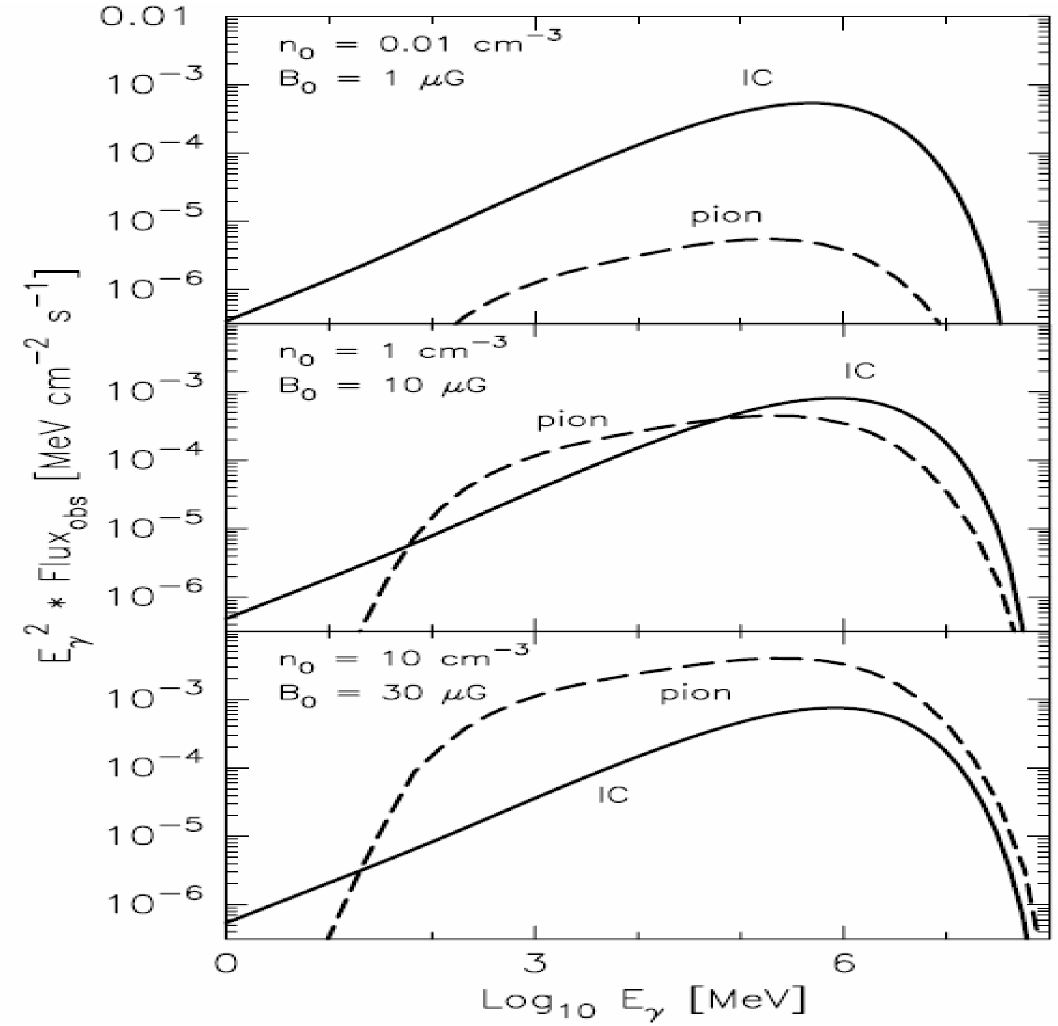
Sturner et al., ApJ 490, 619 (1997)

SNRからのガンマ線スペクトル



Ellison, Berezhko & Baring, ApJ 540, 292 (2000)

SNRからのガンマ線スペクトル



Ellison, Berezhko & Baring, ApJ 540, 292 (2000)

GeV SNRs

Estimated Cosmic Ray Density in the Vicinity of Four Supernova Remnants Which Exhibit Gamma-Ray Emissions

Name (1)	n cm^{-3} (2)	d kpc (3)	M_C 10^{59} H-atoms (4)	Eq. (5) $E_{51}=1$, $\nu=0.01$ 10^{-8} cm^{-2} s^{-1} (5)	Eq. (6)[a] 10^{-8} cm^{-2} s^{-1} $\omega_{CR}=1$ (6)	Observed 10^{-8} cm^{-2} s^{-1} (7)	ω_{CR}[b] (8)
W28	1.3[c]	1.8[d]	36[e]	0.18	0.22	55.9 ± 6.6	254
W44	2.4[f]	3	285[g]	0.12	0.62	50.0 ± 8.0	81
γ Cygni	1.1[f]	1.8	104[h]	0.15	0.65	126.5 ± 6.9	195
IC 443	0.37[f]	1.5	59[i]	0.07	0.52	50.0 ± 3.9	96

[a] M_{SNR} is derived from the product of the spherical supernova remnant volume and the local interstellar medium density.

[b] The value of ω_{CR} is inferred from the observed intensity and Eq. (6).

[c] From Pollock 1985.

[d] From Goudis 1976.

[e] From Wooten 1981.

[f] Derived from the three-dimensional matter distributions calculated for the work reported by Bertsch et al. 1993.

[g] From Wooten 1977.

[h] From Cong 1977 as reported in Pollock 1985.

[i] From CO observations (Cornett, Chin & Knapp 1977).

ω_{CR}: J_{CR}(SNR)/ J_{CR}(solar neighborhood)

~150 ↔ E_{acc}~10^{50}erg ~0.1 E_{SN}

陽子起源と考えて矛盾はない。

Esposito et al., ApJ 460, 821 (1996)

TeV: Whipple upper limits

Buckley et al., AA 329, 639 (1998)

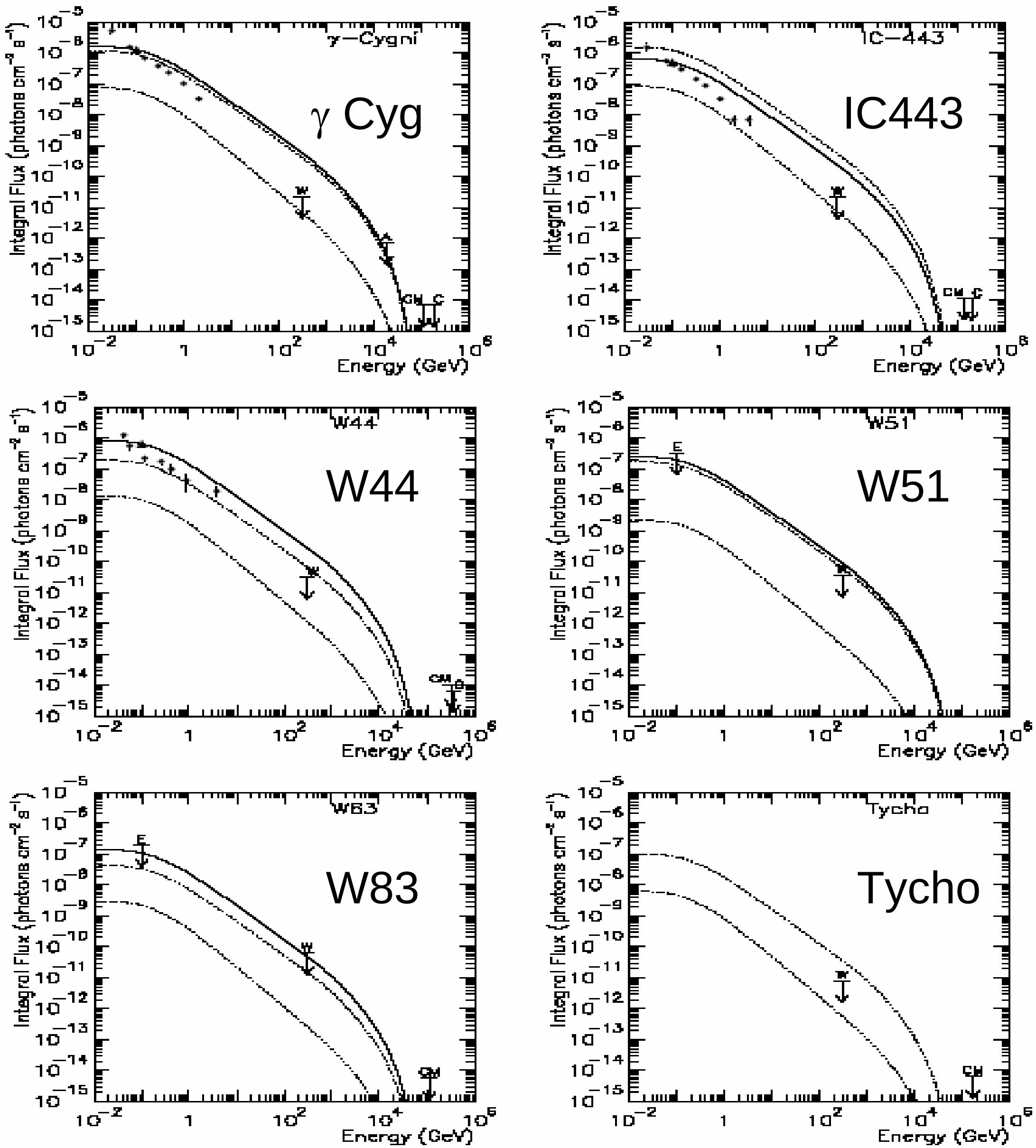
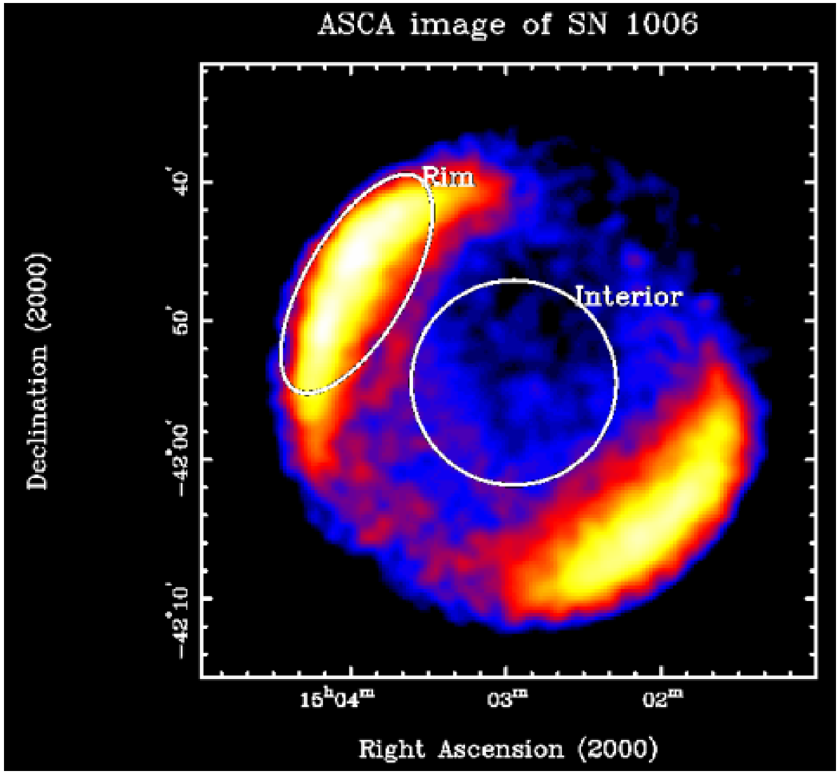
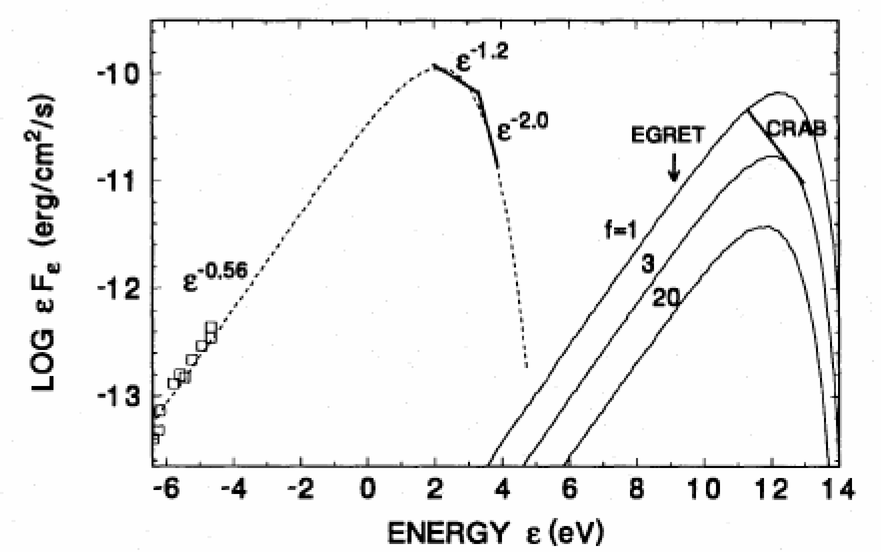


Fig. 8. Whipple upper limits (W) shown along with EGRET integral fluxes (filled triangles), integral spectra (filled circles) and approximate flux upper limits from Esposito et al. (1996) (E). These are compared to extrapolations from the EGRET integral data points (solid curves), as well as a conservative estimate of the allowable range of fluxes from the model of Drury et al. (1994) (dashed curves). Also shown are CASA-MIA upper limits (CM) from Borione et al. (1995), CYGNUS upper limits (C) from Allen et al. (1995), and the AIROBICC upper limit (A) from Prosch et al. (1996)

High energy electrons in SN1006 suggested TeV gamma-rays via IC process

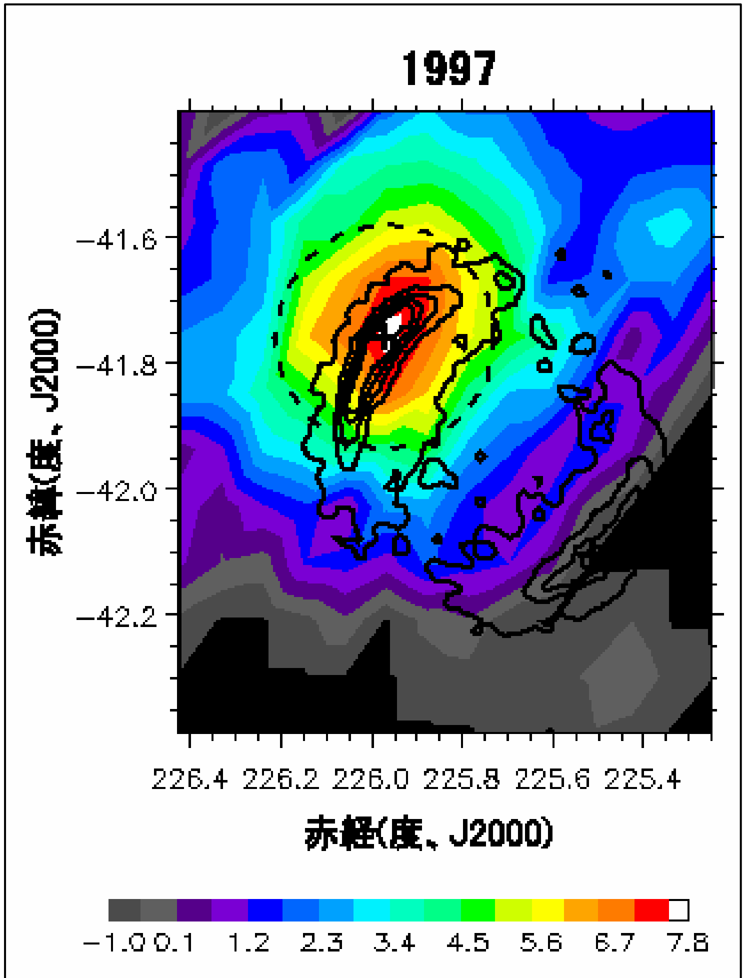


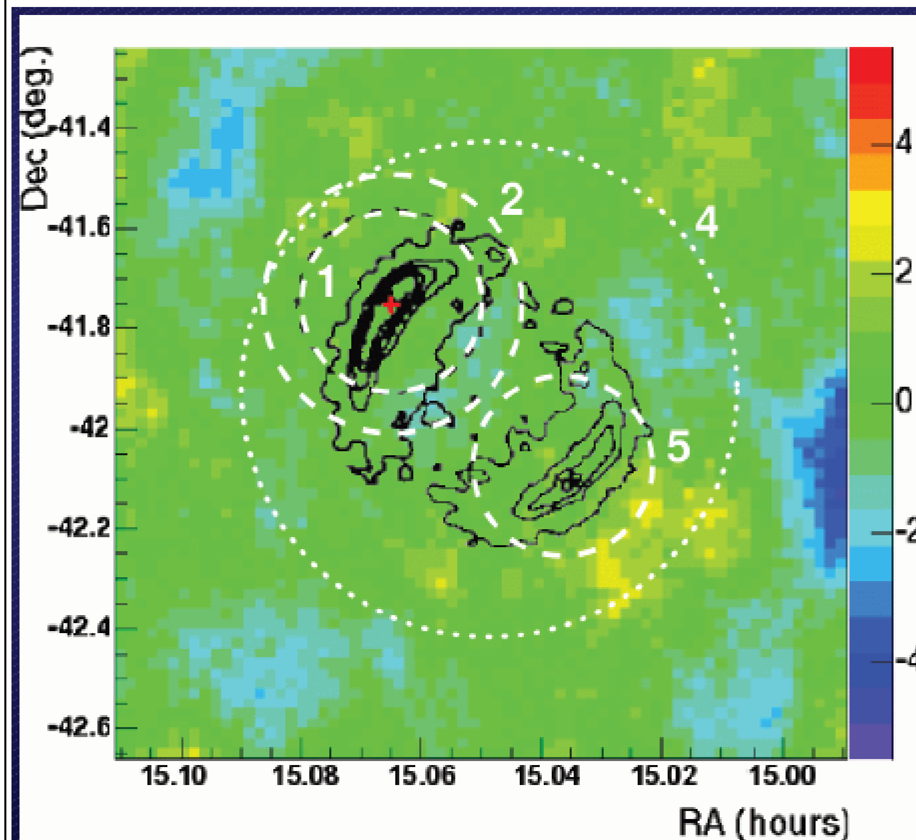
Koyama et al., Nature 378, 255 (1995)



Mastichiadis and de Jager, AA 311, L5 (1996)

超新星残骸:SN1006

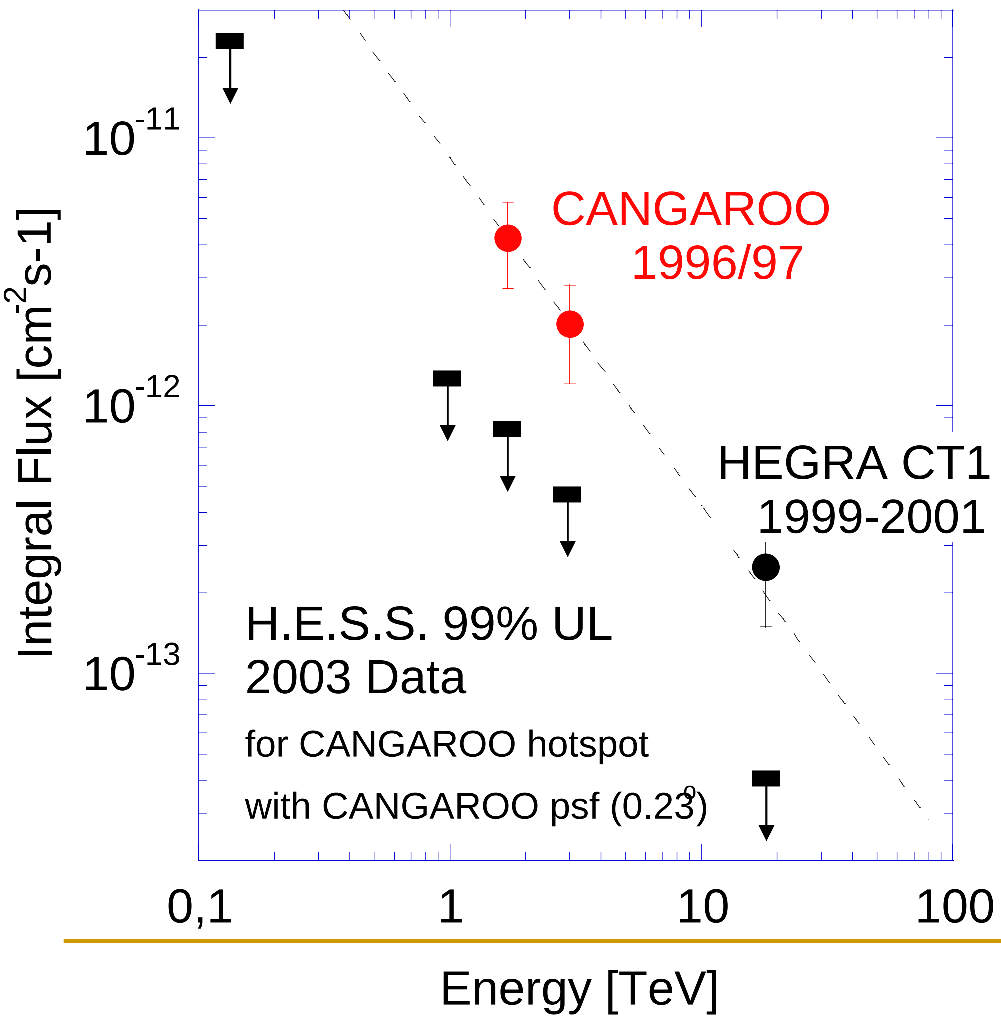




CANGAROO-I (Tanimori et al., 1998)

HESS (Hofmann, Gamma 2004)

SN1006のスペクトル



Time dependence ?

- Size of SNR ~50 LY
- But small scale shocks < 1 LY (Chandra)
- Need O(mG) fields to cool electrons quickly enough

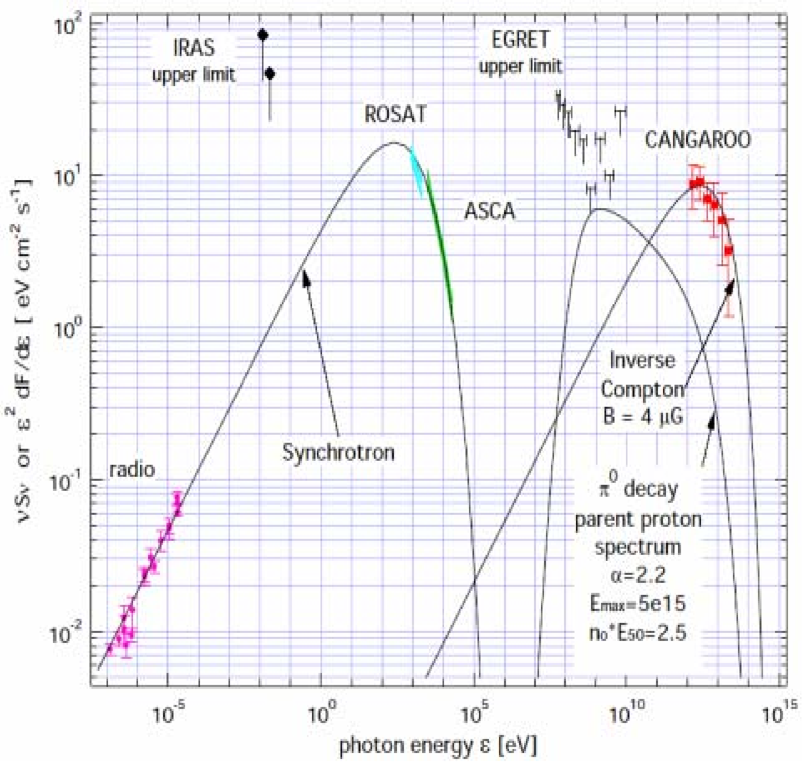
Problem with theory ?

(Berezhko, Völk)

- Fields > 100 μG reduce IC below limit
- Density < 0.1 cm^{-3} reduces π^o component below limit

Hofmann, Gamma2004

SN1006 spectrum: TeV flux smaller?



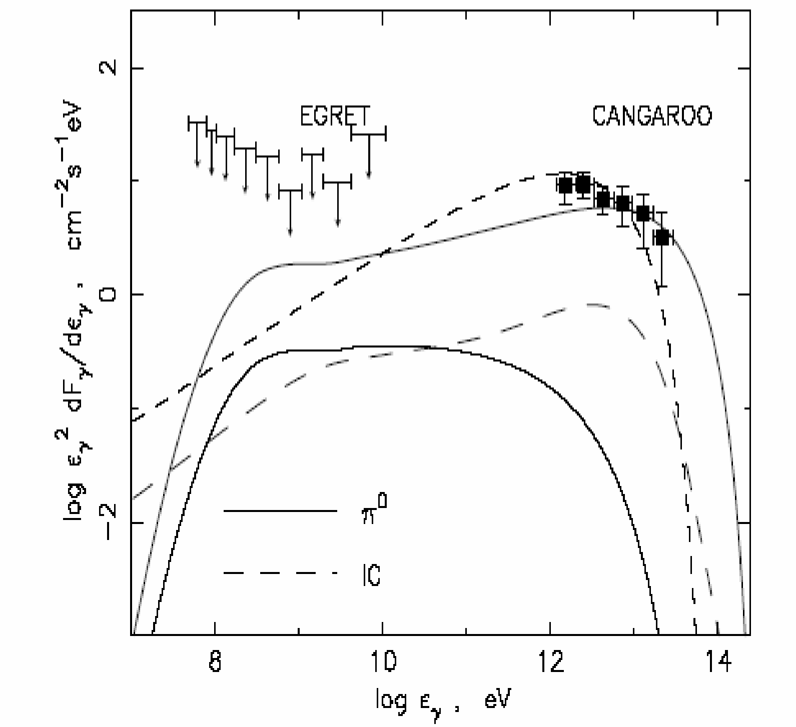
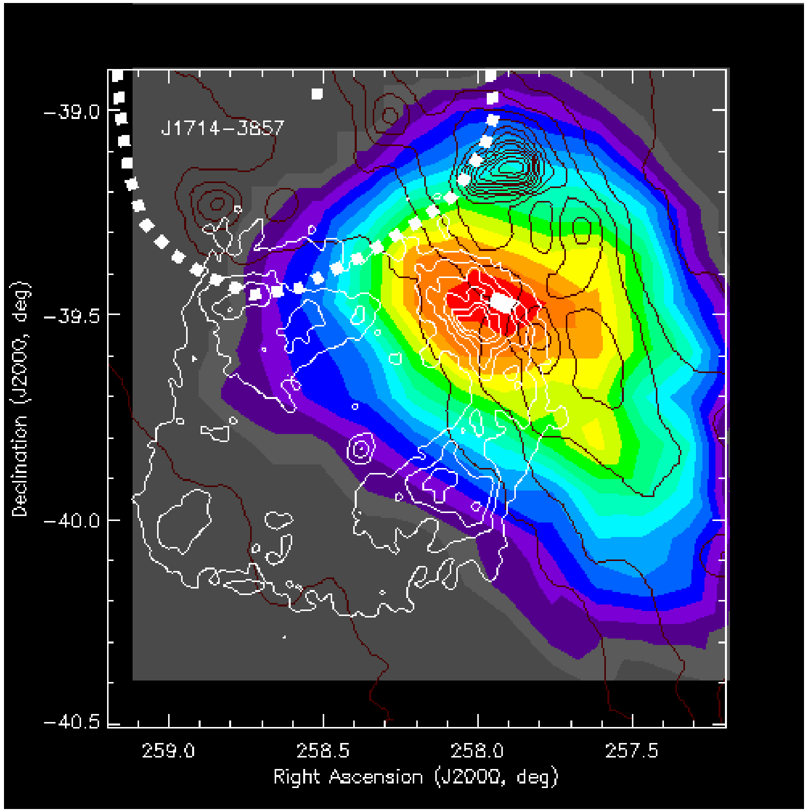


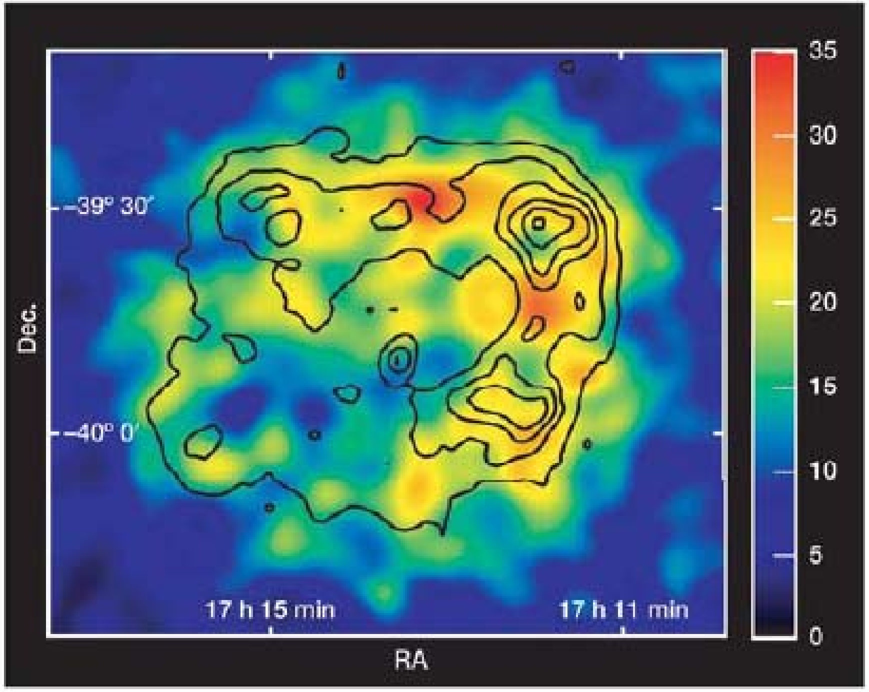
Fig. 5. Differential π^0-decay (*solid lines*) and IC (*dashed lines*) γ-ray energy fluxes as a function of γ-ray energy for the same cases as in Fig. 2. The recent differential high energy γ-ray energy flux data (Tanimori et al. 2001) and EGRET upper limits (Naito et al. 1999) are also shown.

Naito et al., AN 320, 205 (1999) Berezhko et al., AA 395, 943 (2002)

超新星残骸:RX J1713.7-3946

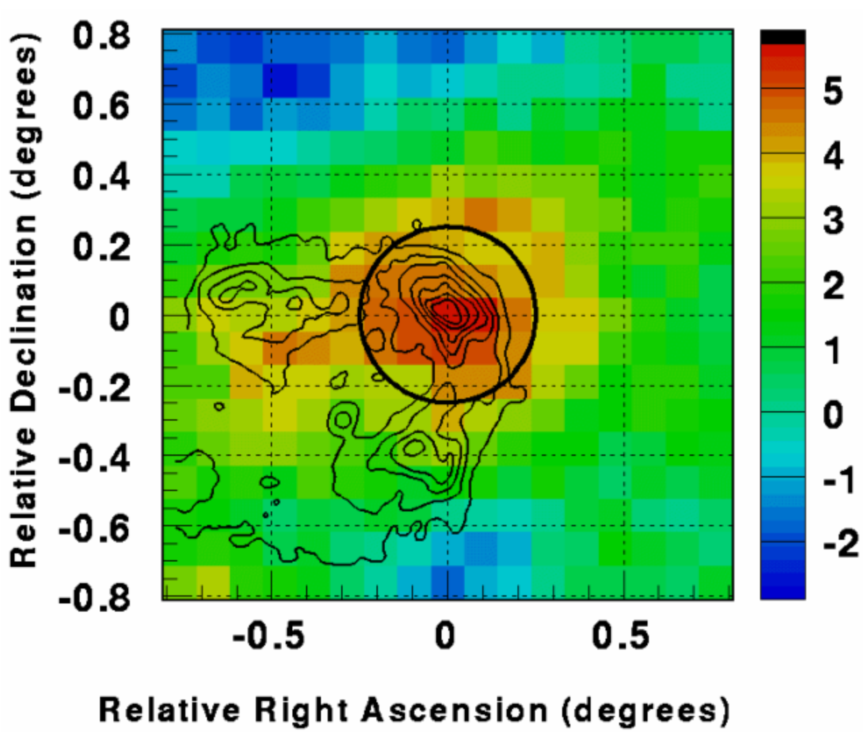


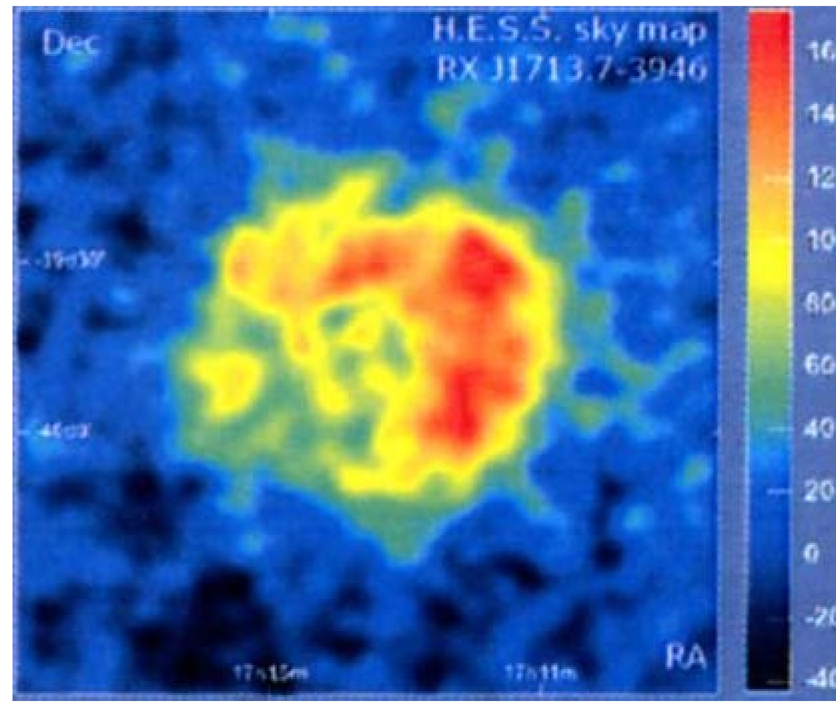
CANGAROO-II (Enomoto et al., 2002)



HESS 2003 (Nature, 432, 75 (2004))

超新星残骸：RX J1713.7-3946

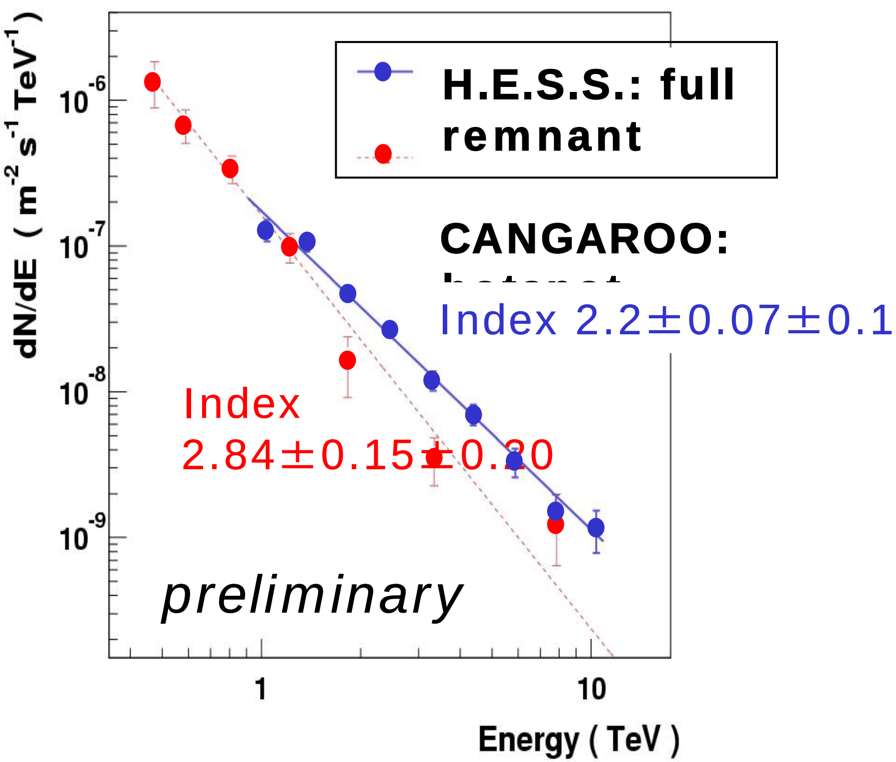




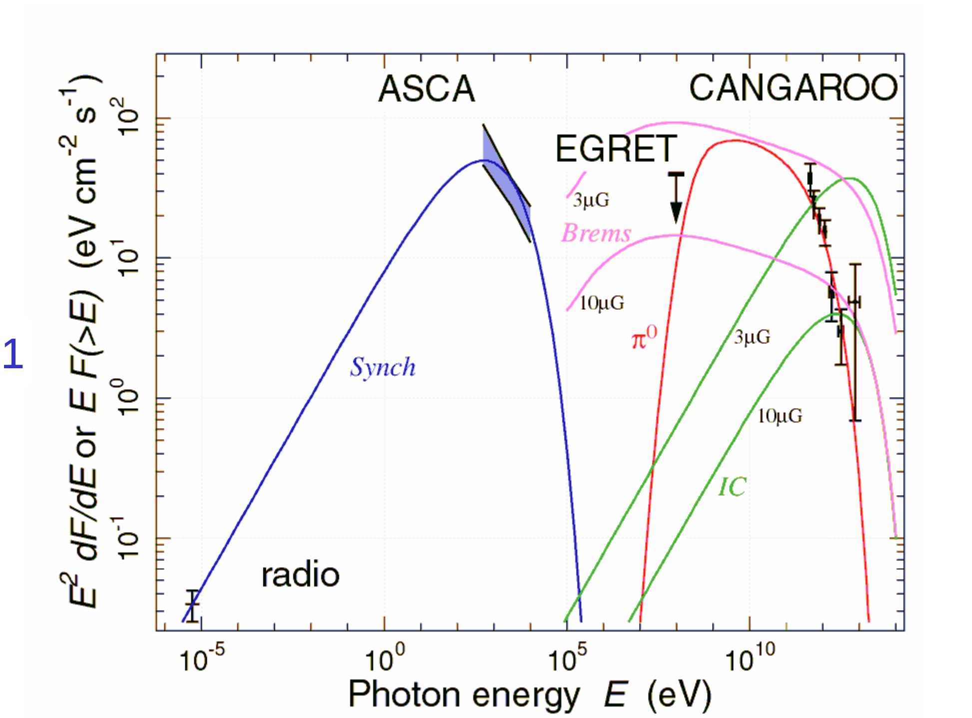
CANGAROO-I (Muraishi et al., 2000)

HESS (Texas symposium 2004)

RX J1713.7-3946のスペクトル

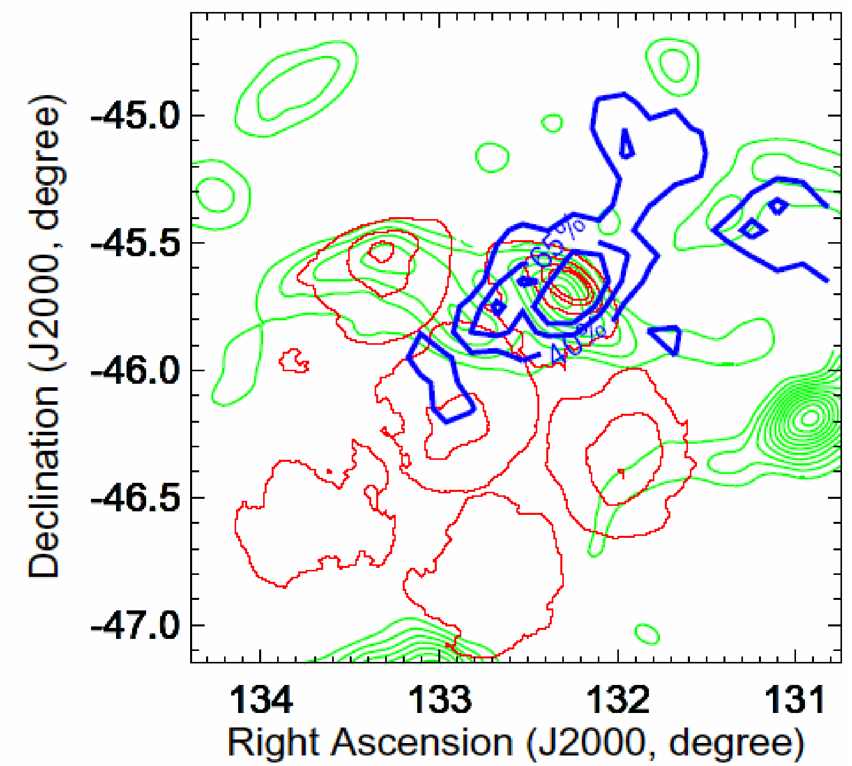


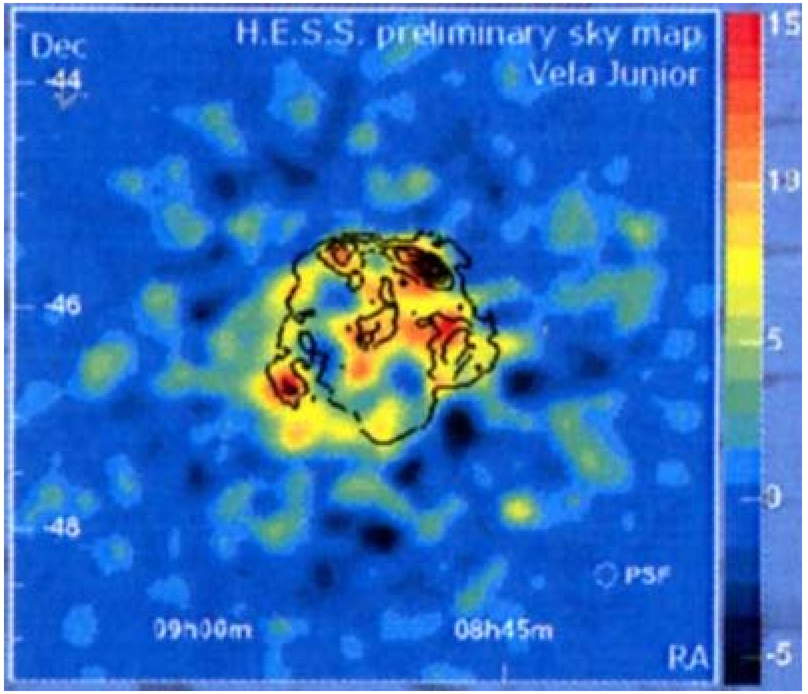
Hofmann, Gamma2004



CANGAROO-II (Enomoto et al., 2002)

超新星残骸:RX J0852.0-4622





CANGAROO-II (Katagiri et al., 2004)

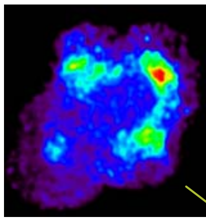
HESS (Texas symposium 2004)

TeV SNRの比較

SNR	位置(l,b)	距離	年齢	周囲
SN1006	（327.6, 14.6）	2.2kpc	1000yr	B~μG
RXJ1713	（347.3, -0.5）	1kpc	~2000yr?	分子雲 B~mG?
RXJ0852	(266.2, -1.2)	~0.5kpc	500-1100yr	Vela SNR B~mG?

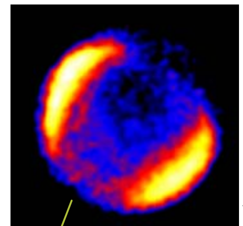
SNRの系統的観測

RX J1713.7-3946（CANGAROO/HESS）



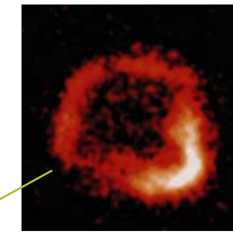
ASCA

SN1006（CANGAROO）

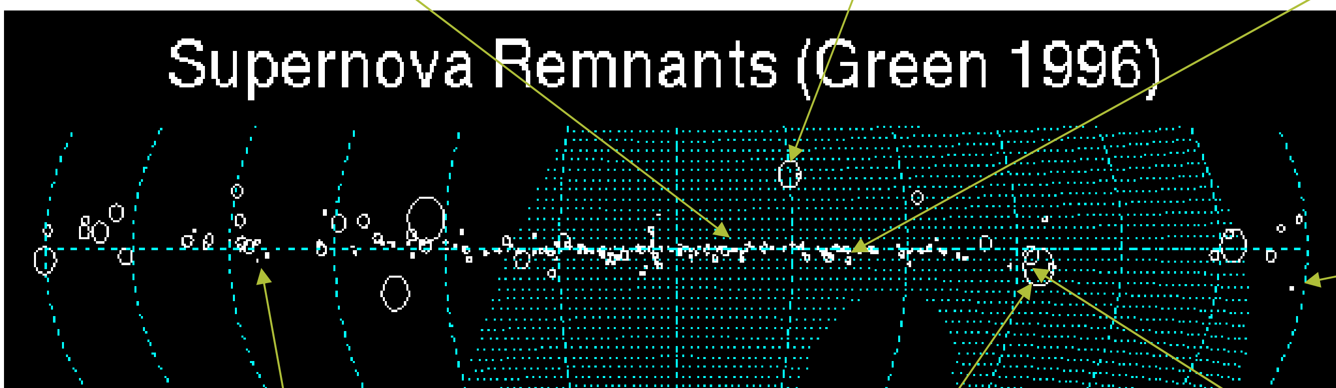


ASCA

RCW86（CANGAROO under analysis）

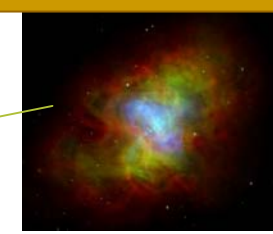


ROSAT



Crab nebula

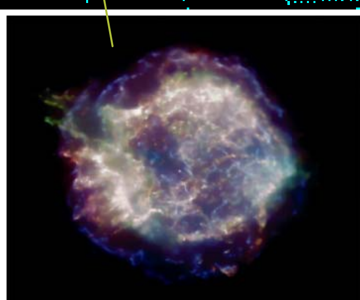
（”Standard candle”）



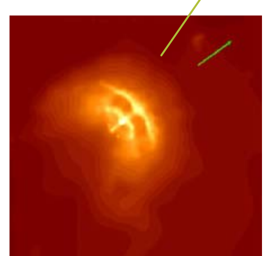
Chandra

・optical

Chandra

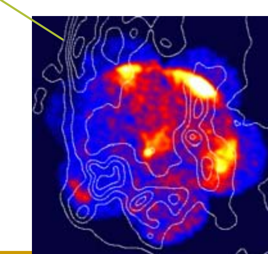


Cas A（HEGRA）



Chandra

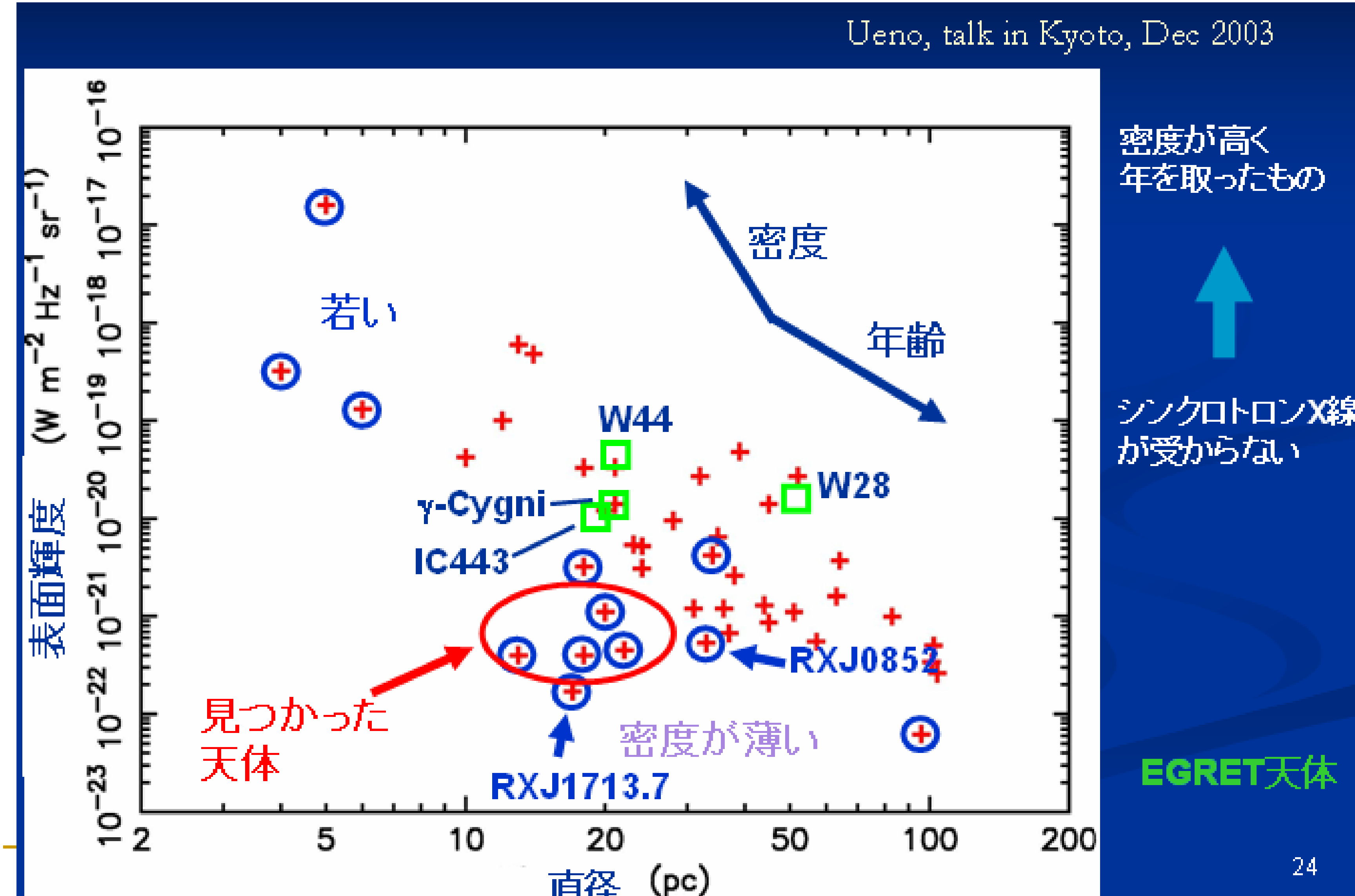
Vela（CANGAROO）



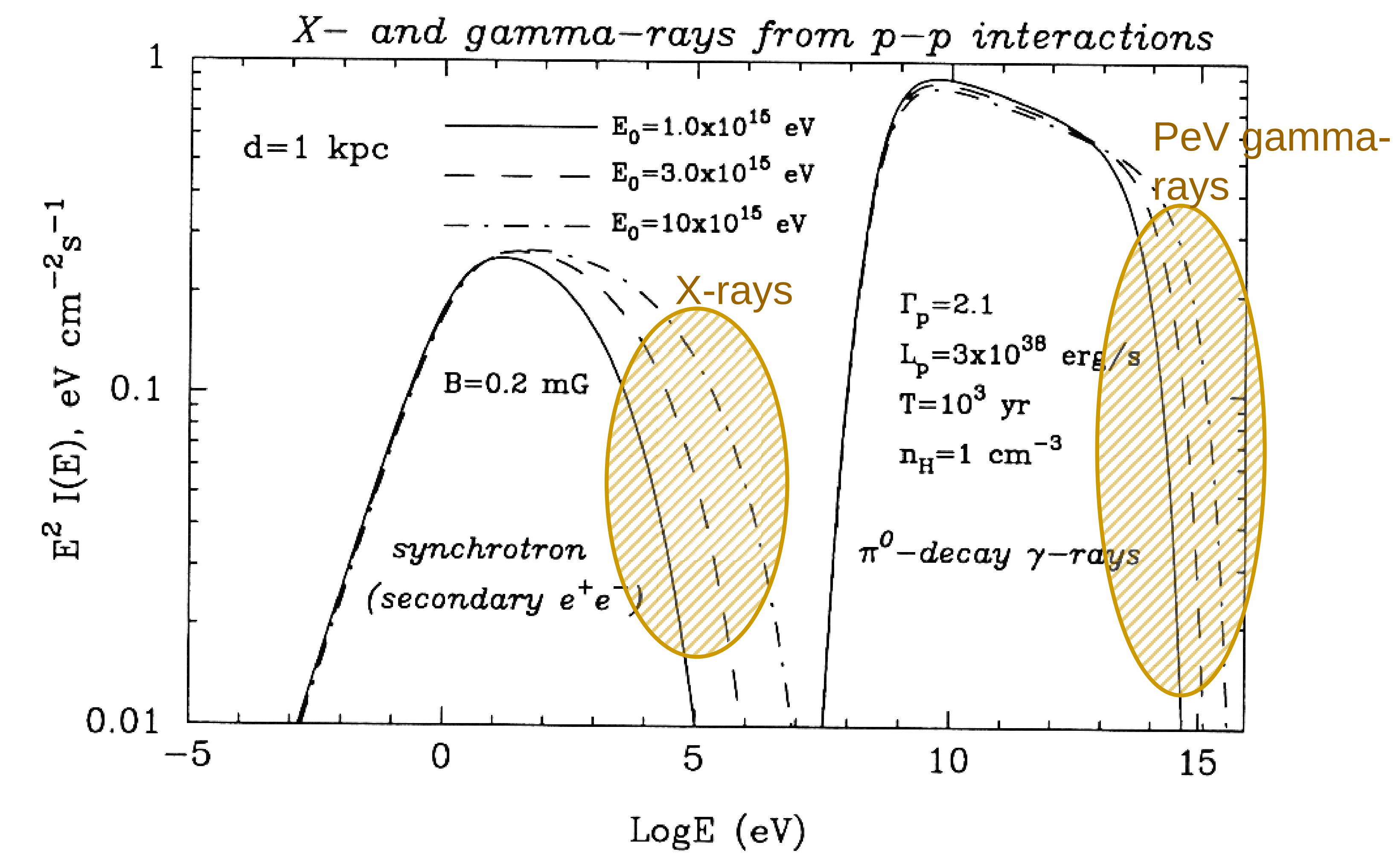
ROSAT

RX J0852-46（CANGAROO/HESS）

More TeV SNRs?



PeV SNRs?



Aharonian, VHE Cosmic Gamma Radiation (2004)

衝撃波加速の最大エネルギー

- Lagage and Cesarsky (AA 125, 249, 1983)

  Plane-wave approximation

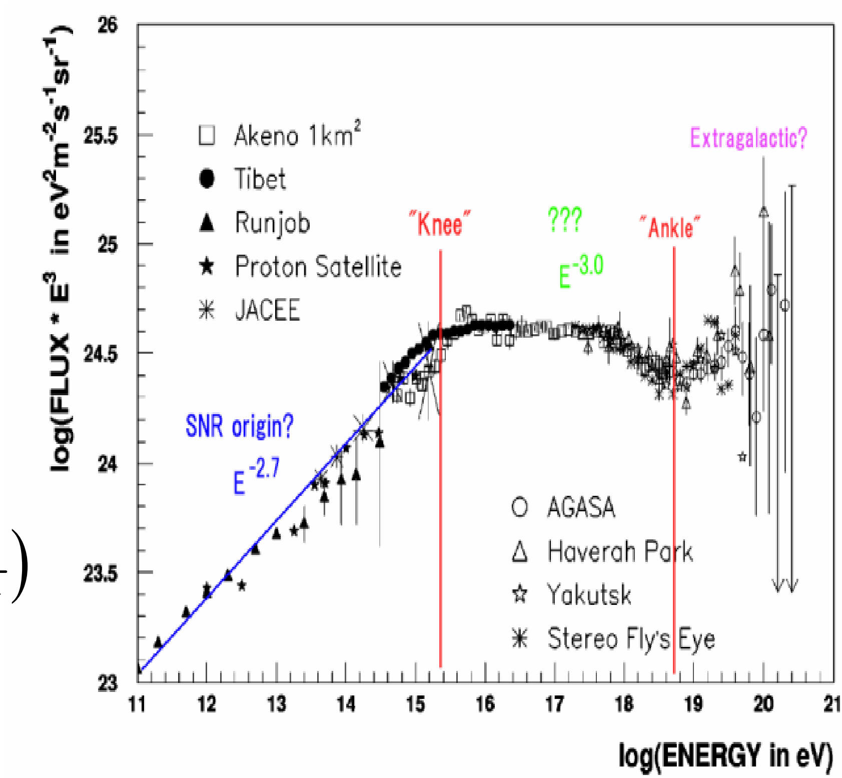
  $E_{max} = Z \times 10^{14}$ eV

- Berezhko (APh 5, 367, 1996)

  Non-linear modification of shock

  $E_{max} = Z \times 10^{15}$ eV

  $$\times \left(\frac{E_{SN}}{10^{51}\,\mathrm{erg}}\right)^{1/2} \left(\frac{M}{10 M_{sun}}\right)^{-1/6} \left(\frac{N_p}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1/3} \left(\frac{B}{3\mathrm{mG}}\right)$$



⇒「Knee」まで届く?!

宇宙線スペクトルはOKか？

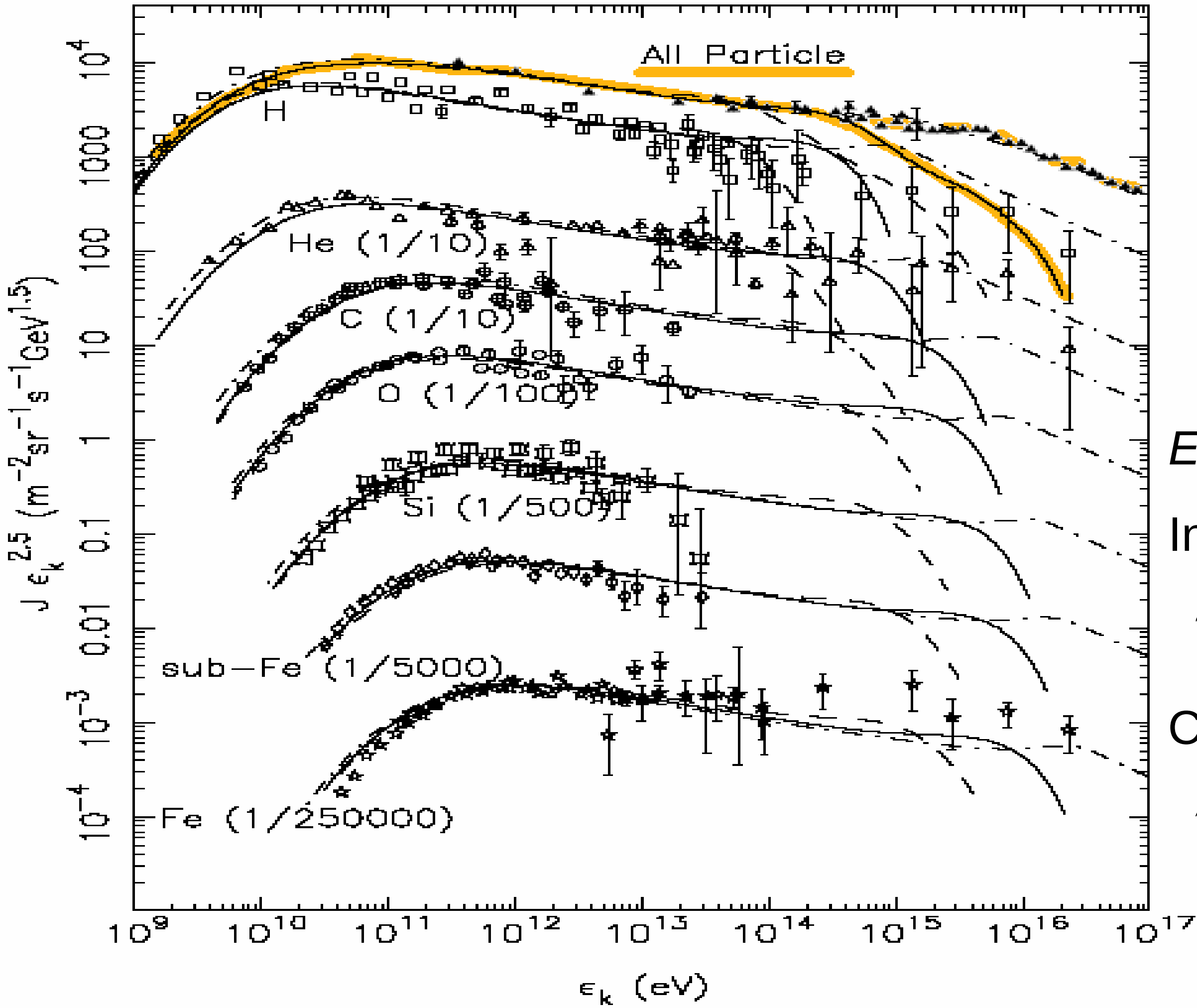


Figure 1. CR intensity near the Earth as function of the kinetic energy. Experimental points are taken from Shibata (1995). Solid (dashed) lines correspond to calculation for hot (warm) ISM with injection rate $\eta = 10^{-4}$. Dot-dashed lines correspond to hot ISM with magnetic field $B_0 = 12\ \mu G$ and $\eta = 5 \times 10^{-4}$.

E_{SN}=10^{51}erg

Injection rate

$\eta=10^{-4}$ (5×10^{-4})

CR residence time

$\tau(R) \propto R^{-\alpha}$ with α=0.7-0.8

Berezhko, SSRv 99, 295 (2001)

他のガンマ線源と粒子加速

- 活動銀河核
  - Hadronic or leptonic
- 銀河中心
  - Dark matter origin??
- パルサー星雲
  - かに星雲、PSR1259-63/SS2883
- 未同定TeV天体
  - J2032+41、J1303-63
- 銀河団、…

AGN: hadronic vs leptonic

- Hadronic
  - SSC (Synchrotron-Self-Compton)
    $\Rightarrow$ X-ray と TeV は相関
  - 短時間変動
- Leptonic
  - Proton-synchrotron + proton-cascade

- BUT absorption by IR $\Rightarrow$ intrinsic spectrum modified…

X線とTeVの相関:SSCモデル

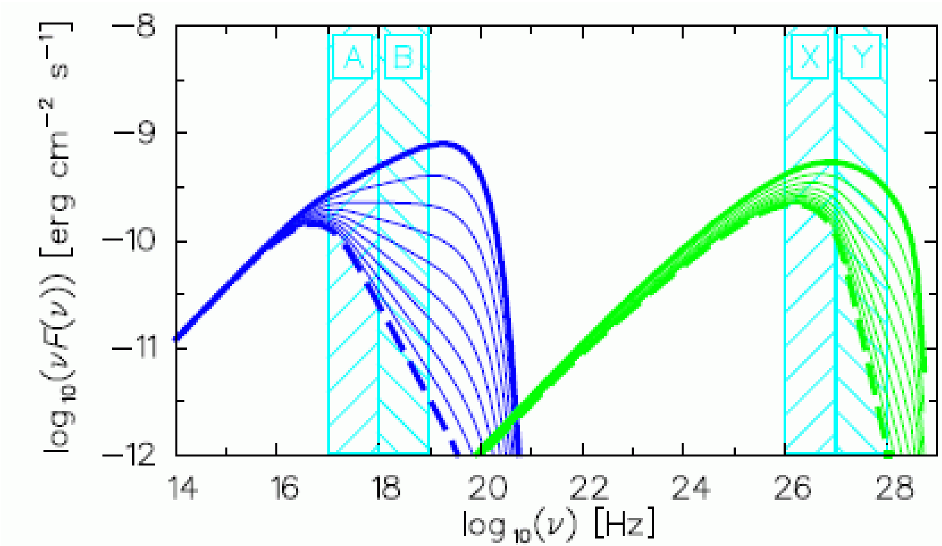
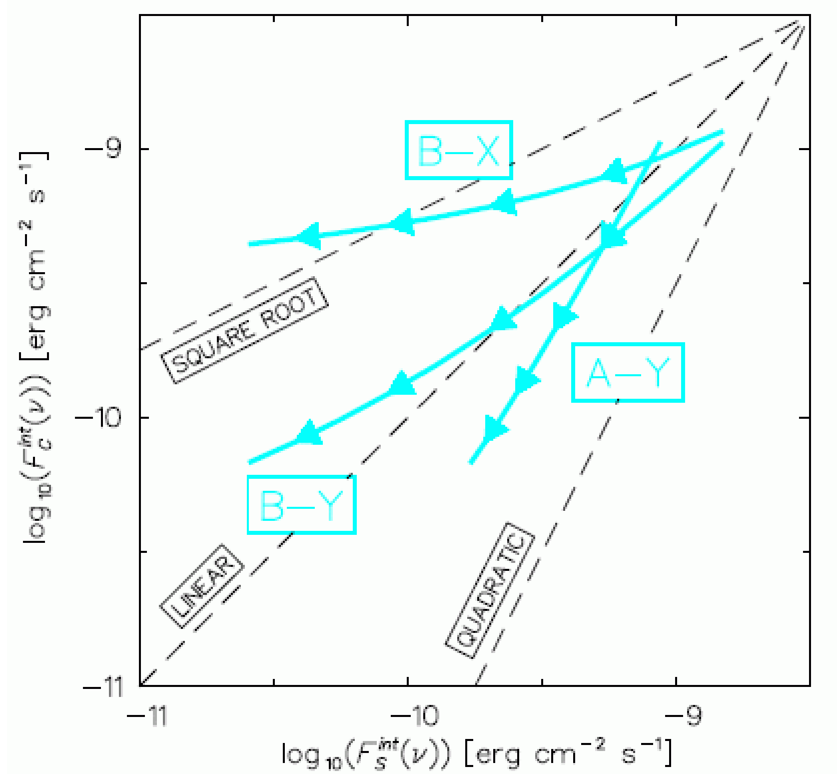
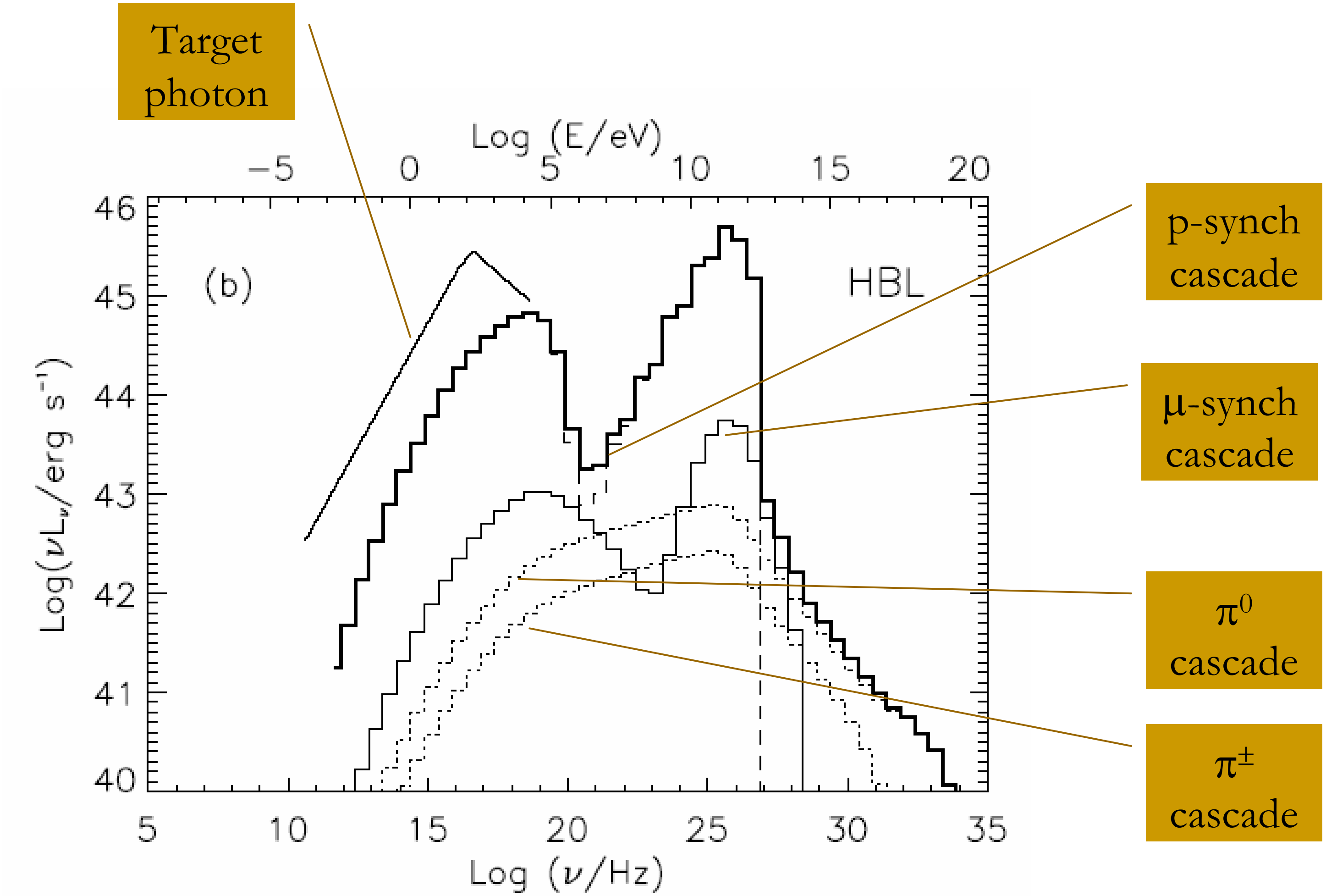


Fig. 5. The upper panel shows the evolution of the SSC emission of the source where only the slope n_2 of the high energy part of the electron spectrum was modified during the simulation. To calculate the correlations presented in the lower panel we selected the same spectral bands as in the previous modeling. Thin lines in the lower panel show a template for the correlations.



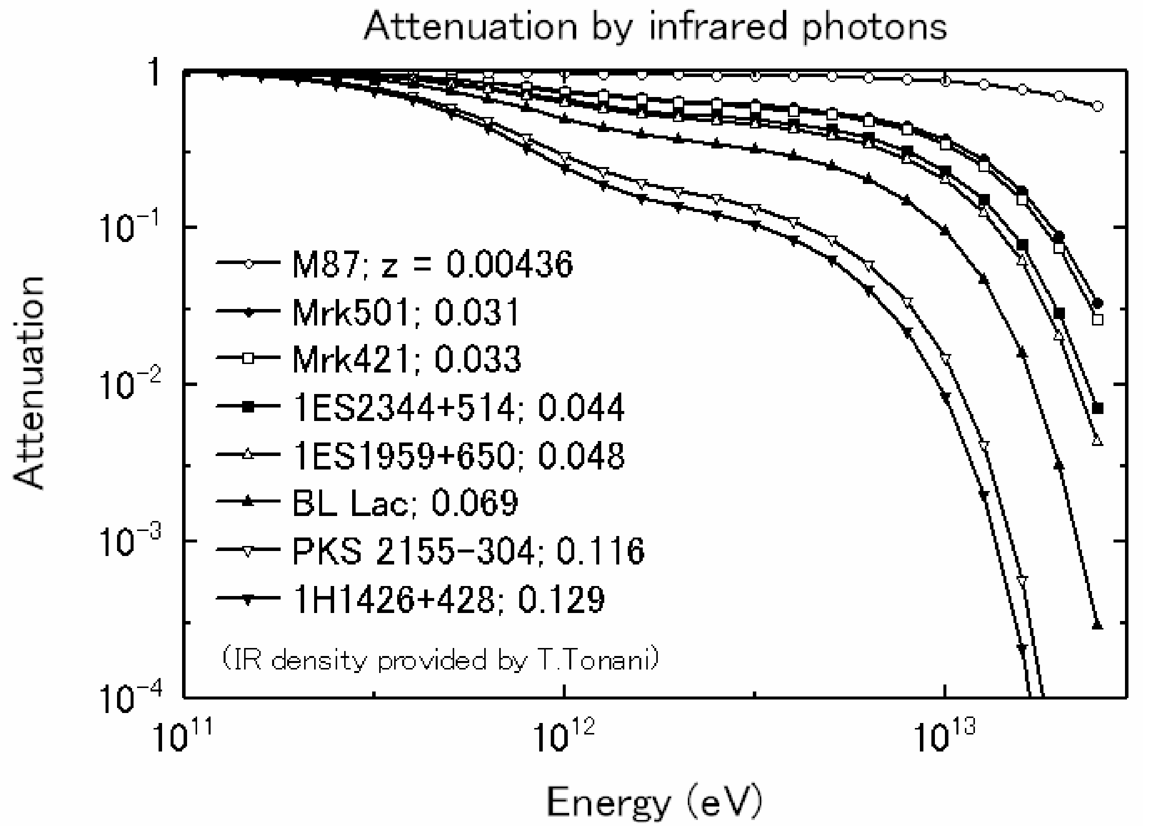
Katarzynski et al., astro-ph/0412405

Synchrotron proton blazar model



Muecke et al. APh 18, 2003

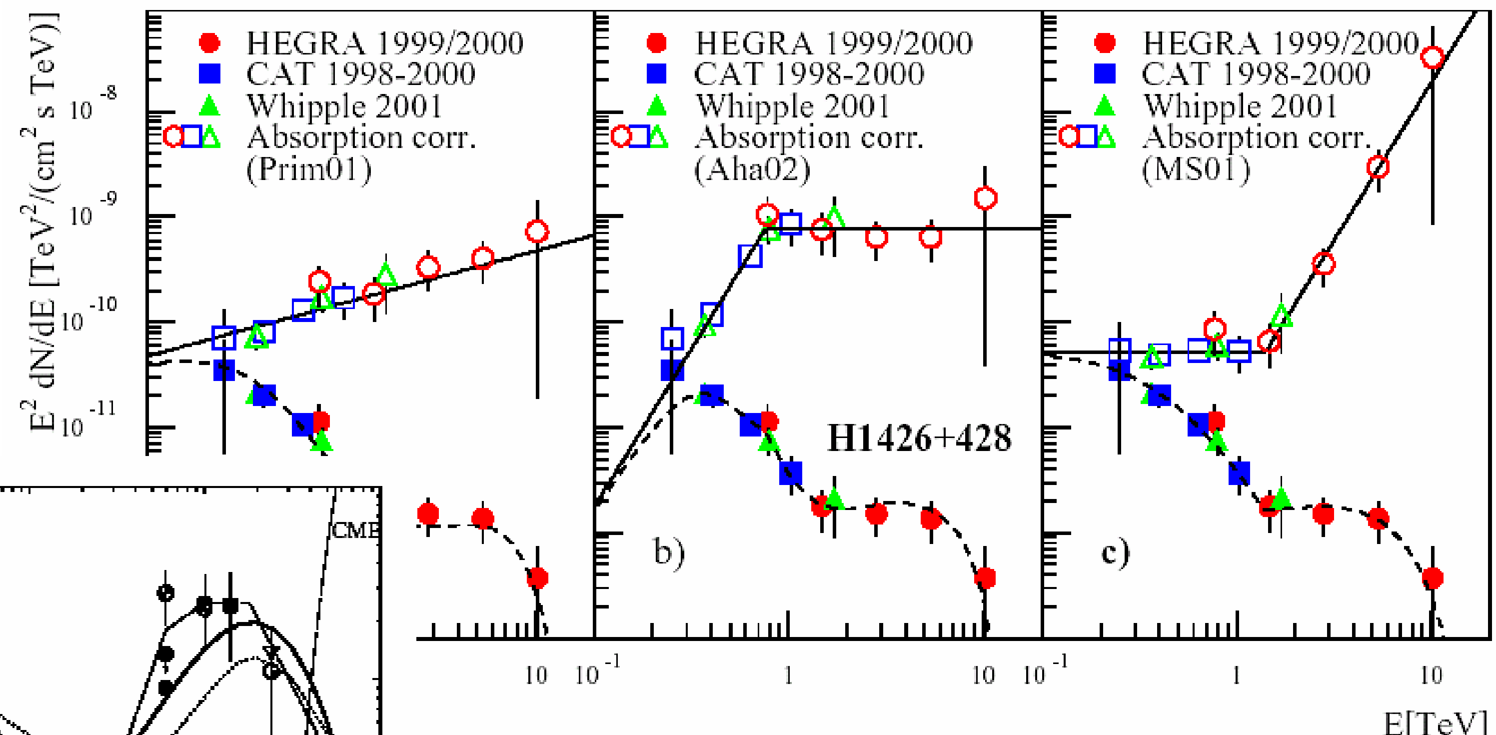
銀河間赤外線による吸収

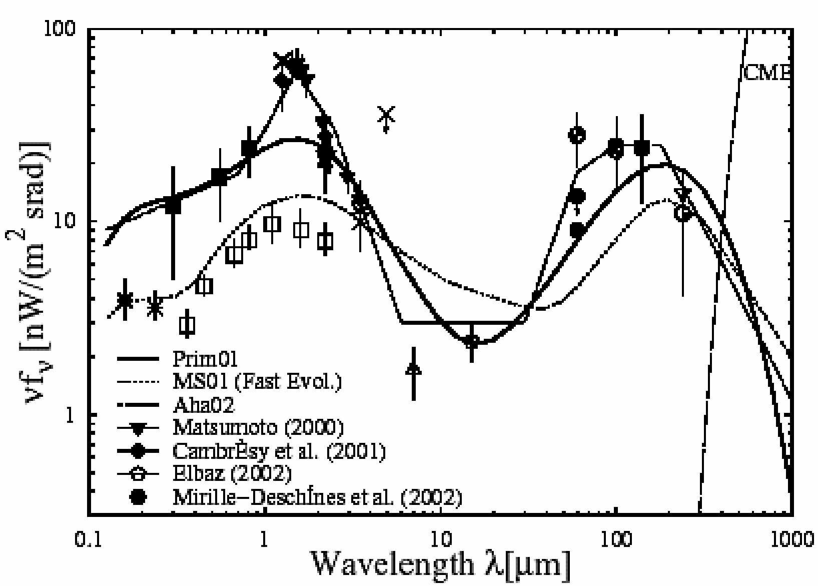


H1426+426の例

- H1426+428: HEGRA CT system

z=0.129





EBL (Extragalactic Background Light) ⟺ Intrinsic spectrum

Horns et al., 28th ICRC (2003)

銀河間赤外線量のUpdate

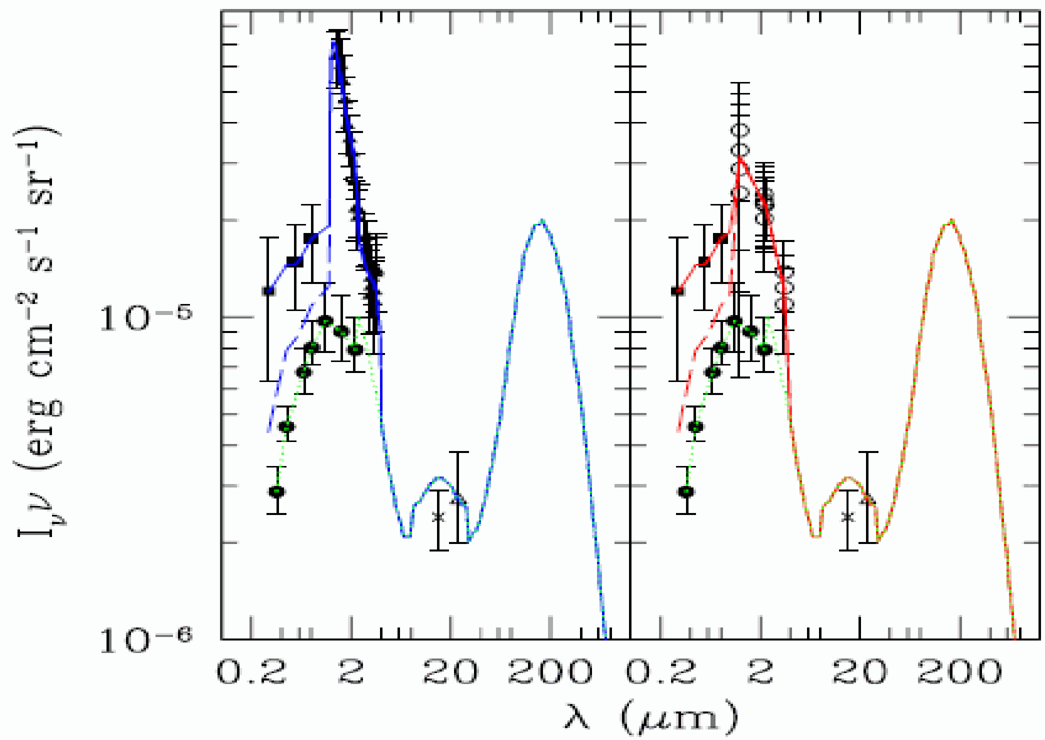


Figure 3. EBL data and corresponding models. **Left panel:** MK1 (*dashed line*), MK2 (*solid line*). The MK data are represented with *filled triangles*.**Right panel:** DW1 (*dashed line*), DW2 (*solid line*). The DW data are represented with *open circles*. In both the two panels are shown: C1 (*dotted line*), data from Bernstein et al. (*filled squares*), Madau & Pozzetti (*filled circles*), Elbaz et al. (*cross*) and Papovich et al (*open triangle*).

※銀河間赤外線量の測定は難しい※

Mapelli et al., astro-ph/0410615

H1426+426のUpdate

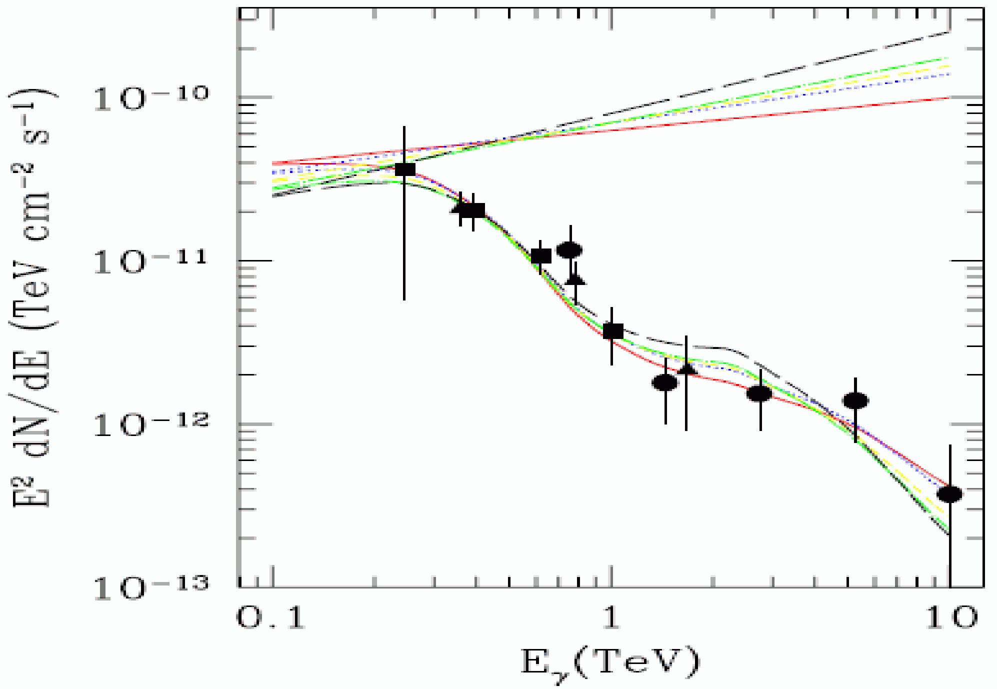
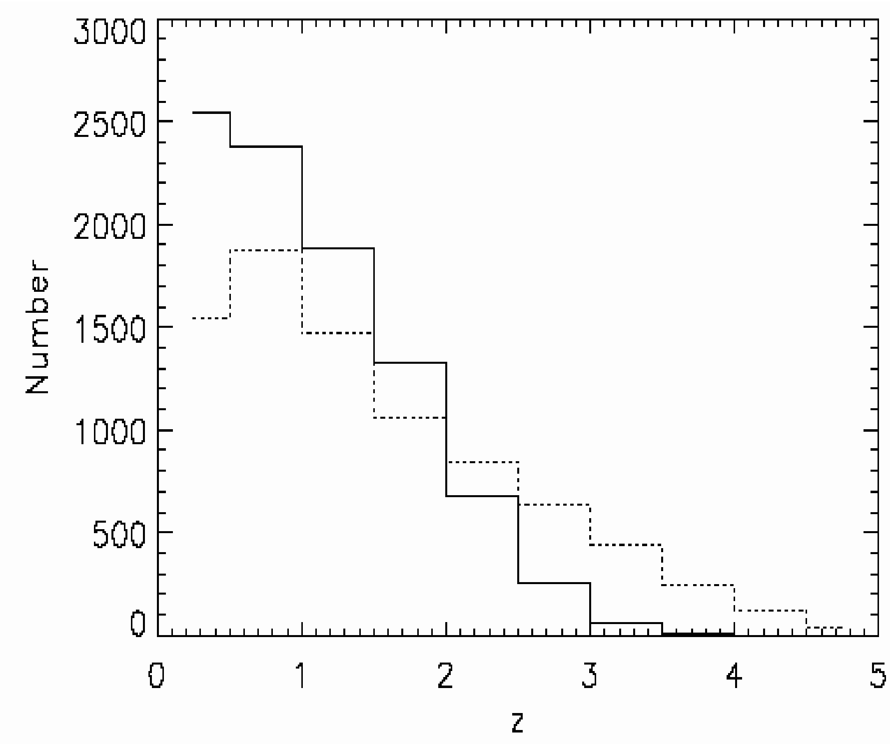


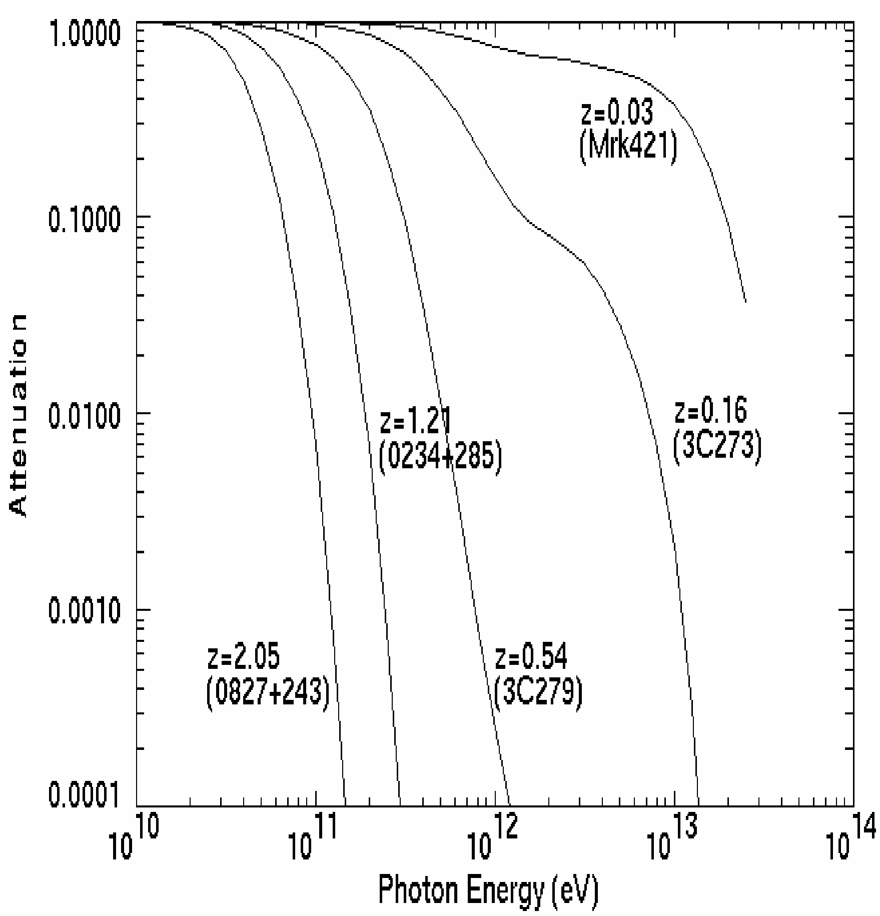
Figure 7. Fit of the H 1426+428 spectrum. We have assumed an EBL model given by: (a) optical background (0.3-1.2 μm): Madau & Pozzetti 2000; (b) near infrared background (1.2-4. μm): DIRBE (Wright 2001) with the ZL model of Wright & Reese (2000); (c) middle and far infrared background : model of Totani & Takeuchi (2002). The model of Totani & Takeuchi for the MIRB and the FIRB has been rescaled in the 8–30 μm range assuming different values of the EBL at 24 μm, in particular assuming: 2.7 (*solid line*), 3.0 (*dotted line*), 3.3 (*short dashed line*), 3.5 (*dot-dashed line*) and 3.8 (*long dashed line*) nW m^{-2} sr^{-1}. The observational data reported here are from CAT 1998-2000 (*filled squares*), Whipple 2001 (*filled triangles*), HEGRA 1999-2000 (*filled circles*).

Mapelli et al., astro-ph/0410615

GLAST database: a finding chart

- GLAST will detect thousands of blazars…





Chen et al., astro-ph/0402152

(IR density by T.Totani)

銀河団からのガンマ線

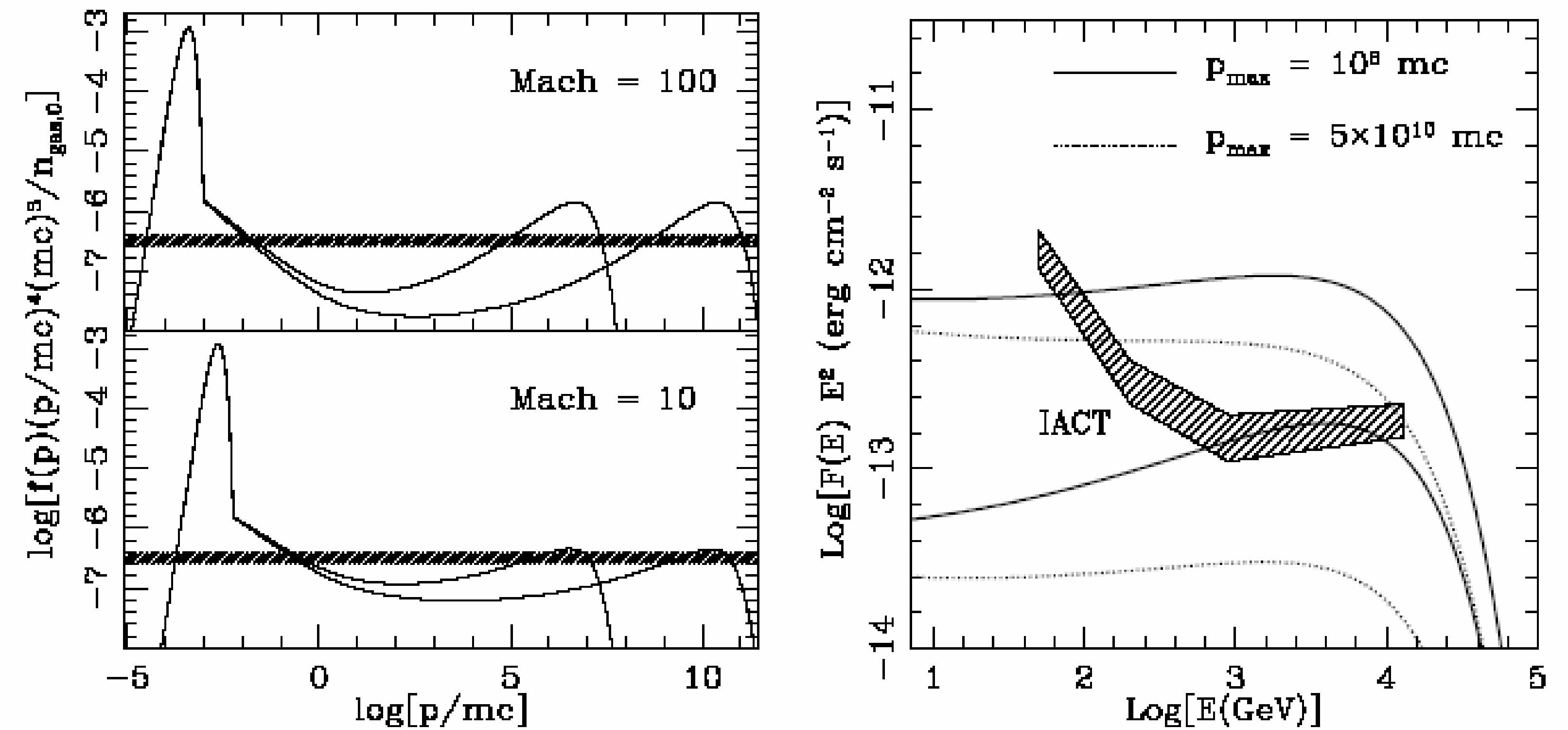


FIGURE 2. **Left panel:** Spectra of protons accelerated at the accretion shock of a Coma–like cluster. The horizontal line represents the result of the linear theory (see text). **Right panel:** Gamma ray fluxes for a Coma–like cluster compared with the HESS sensitivity for point sources. The external temperature is assumed to be $10^6 K$ (two upper curves) or $10^4 K$ (two lower curves).

Shocks in ICM: ~1000km/s, ~1Mpc, ~μG, 10^4-10^6K

Gabici and Blasi, astro-ph/0411028

Summary

- 「宇宙線の超新星残骸起源説」
  - 宇宙線源の一つとしてはTeVガンマ線の観測で確立
  - 加速のパラメータの特定にはまだまだ先がある
    - E_{max}, e/p ratio, power-law index, …
    - ⇒「Knee」まで延びているかは定かではないが…
- 他にも多種多様な加速天体！
  - 活動銀河核、銀河中心、パルサー星雲、…
  - 銀河団？