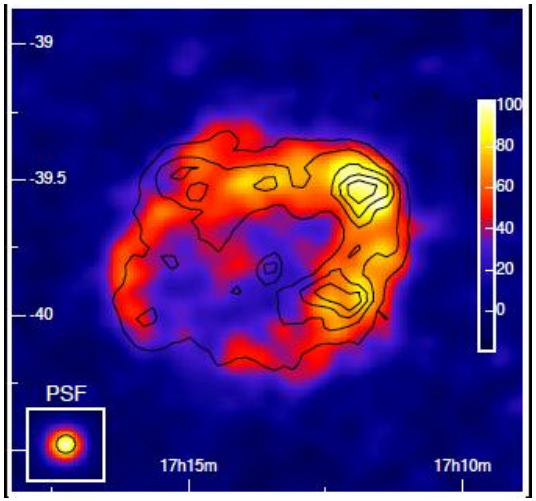
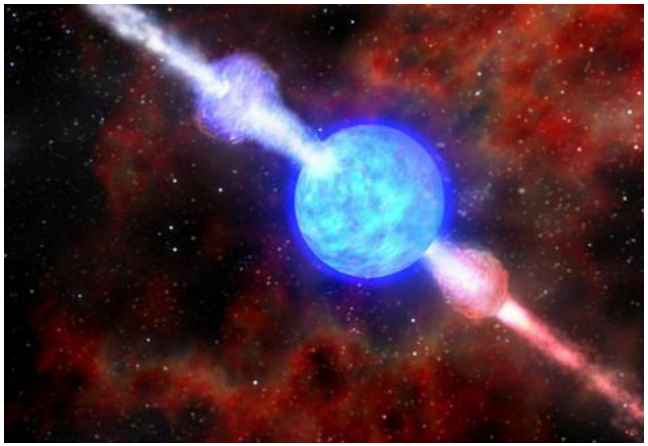
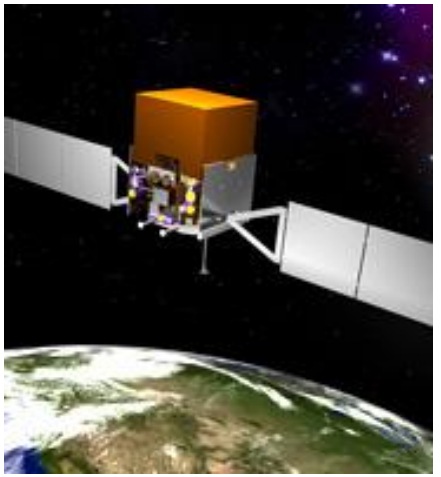
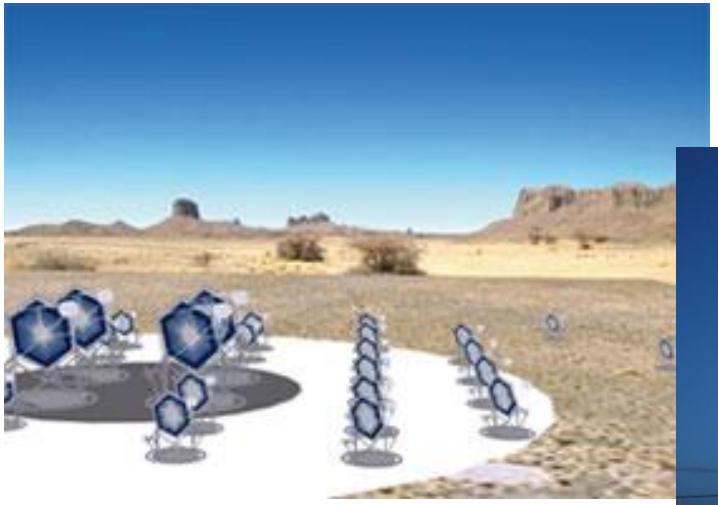
ガンマ線観測からハドロン加速はどこまで押さえられたか

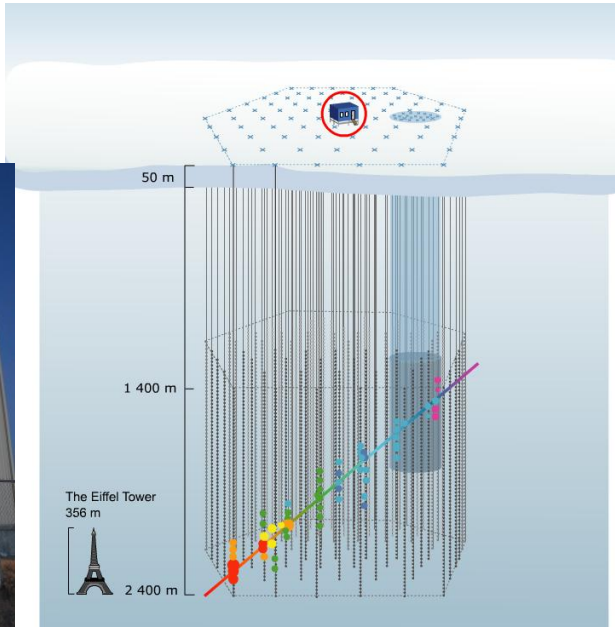
井上 進 （京大理）











outline

0. introduction

1. Galactic CRs: SNRs

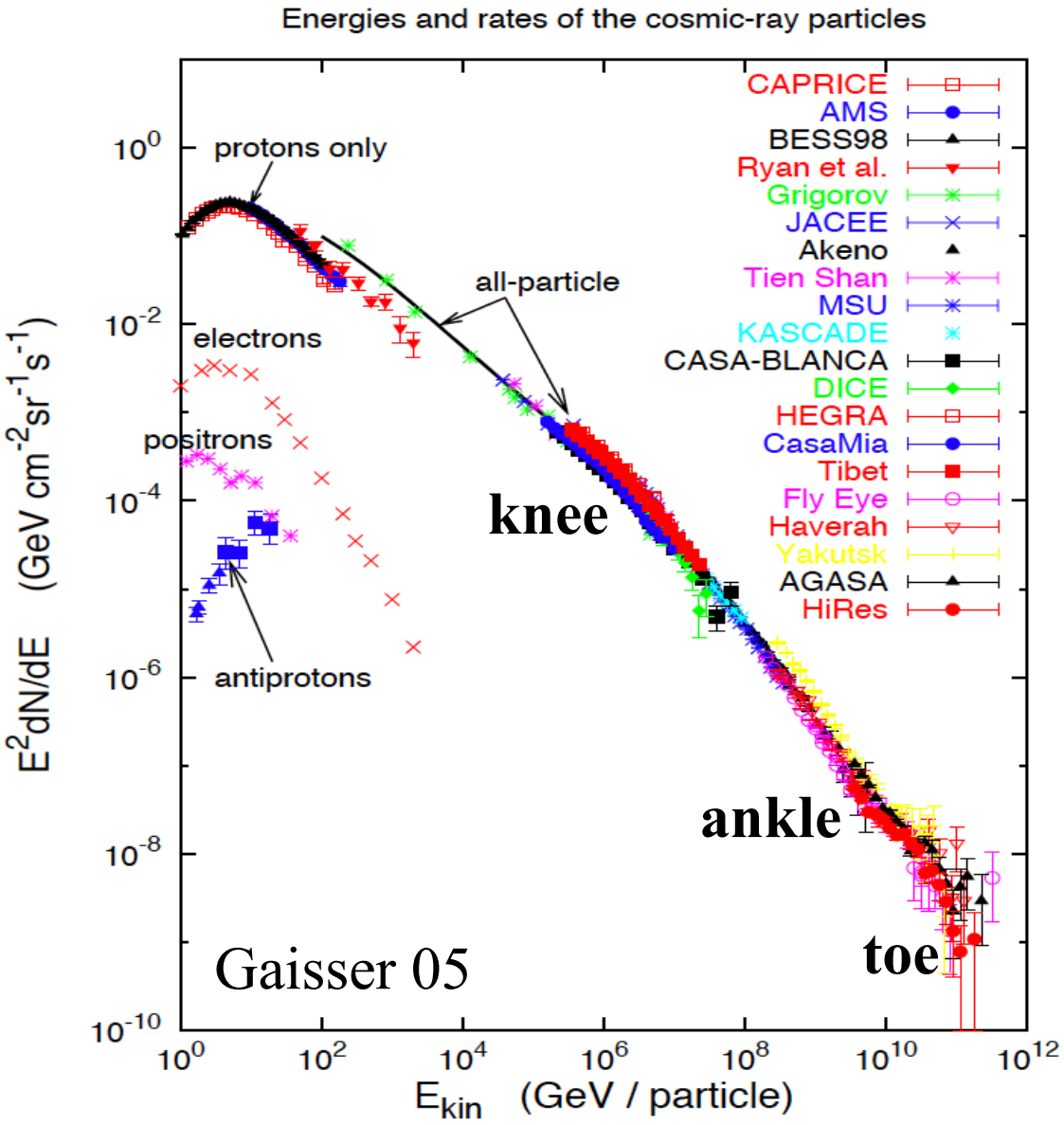
2. UHECRs: AGNs (blazars)
GRB protons
(GRB nuclei)
(cluster nuclei)

3. knee-ankle CRs: clusters

as hadron indicators

gamma-rays:	vs	neutrinos:
easy to detect		not easy to detect
easily contaminated		not easily contaminated
easily absorbed		not easily absorbed

observed CR spectrum



up to knee ($<10^{15\text{-}16}$ eV)

Galactic SNRs?

likely, but not yet definitive

knee-ankle ($10^{15\text{-}16}$-10^{18} eV)

Galactic? no new source?

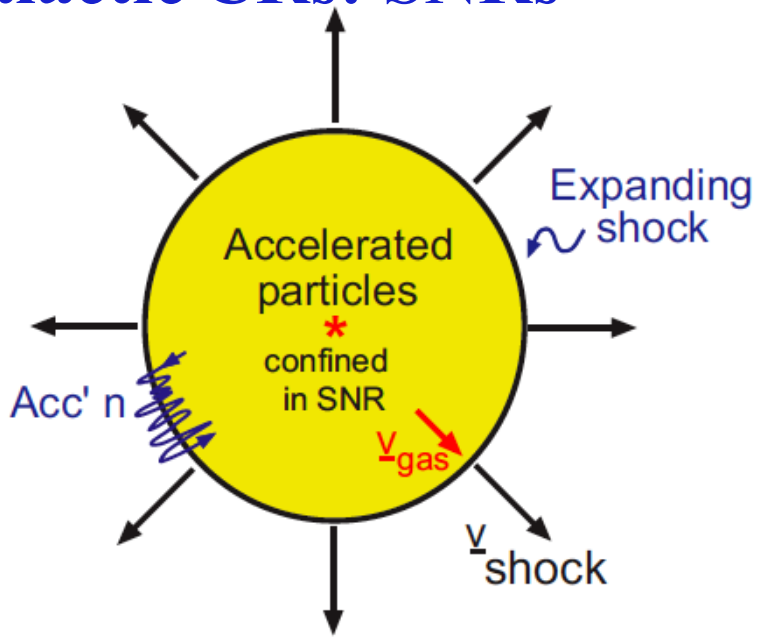
above ankle ($>10^{18}$ eV)

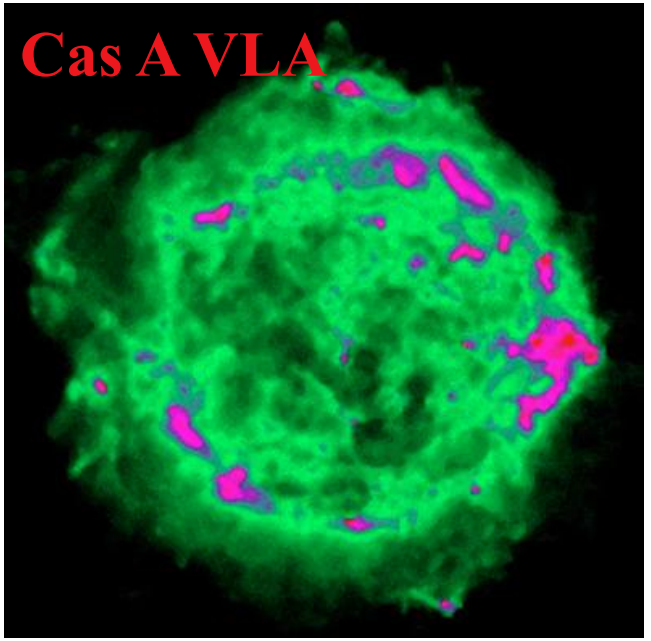
extragalactic: AGNs?

GRBs?

???

Galactic CRs: SNRs





energetics $L_{GCR} \sim 10^{41}$ erg/s$\sim 0.1 \times E_{SN}/t_{SN}$

radio/X evidence for electron acceleration

BUT

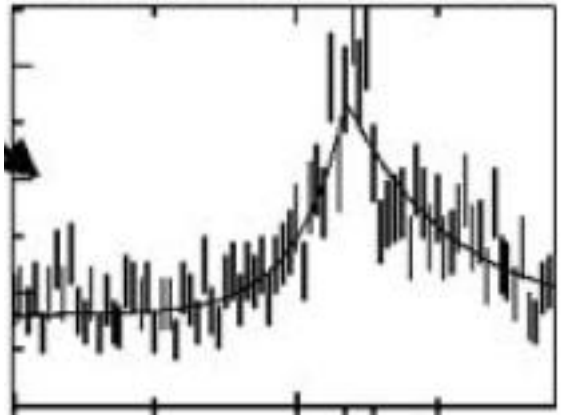
simple theory: $E_{max} \sim v/c\ Z\ e\ B\ (vT)$ Lagage & Cesarsky 83

$< 10^{14}$eV $Z\ v_{5000km/s}{}^2 T_{1000yr} B_{3\mu G} < E_{knee}$

no definitive evidence yet for proton acceleration

SNRs: X-rays in high resolution

Bamba+ 03



shock surfaces ~ very thin filaments
→ B~ few 100 μG

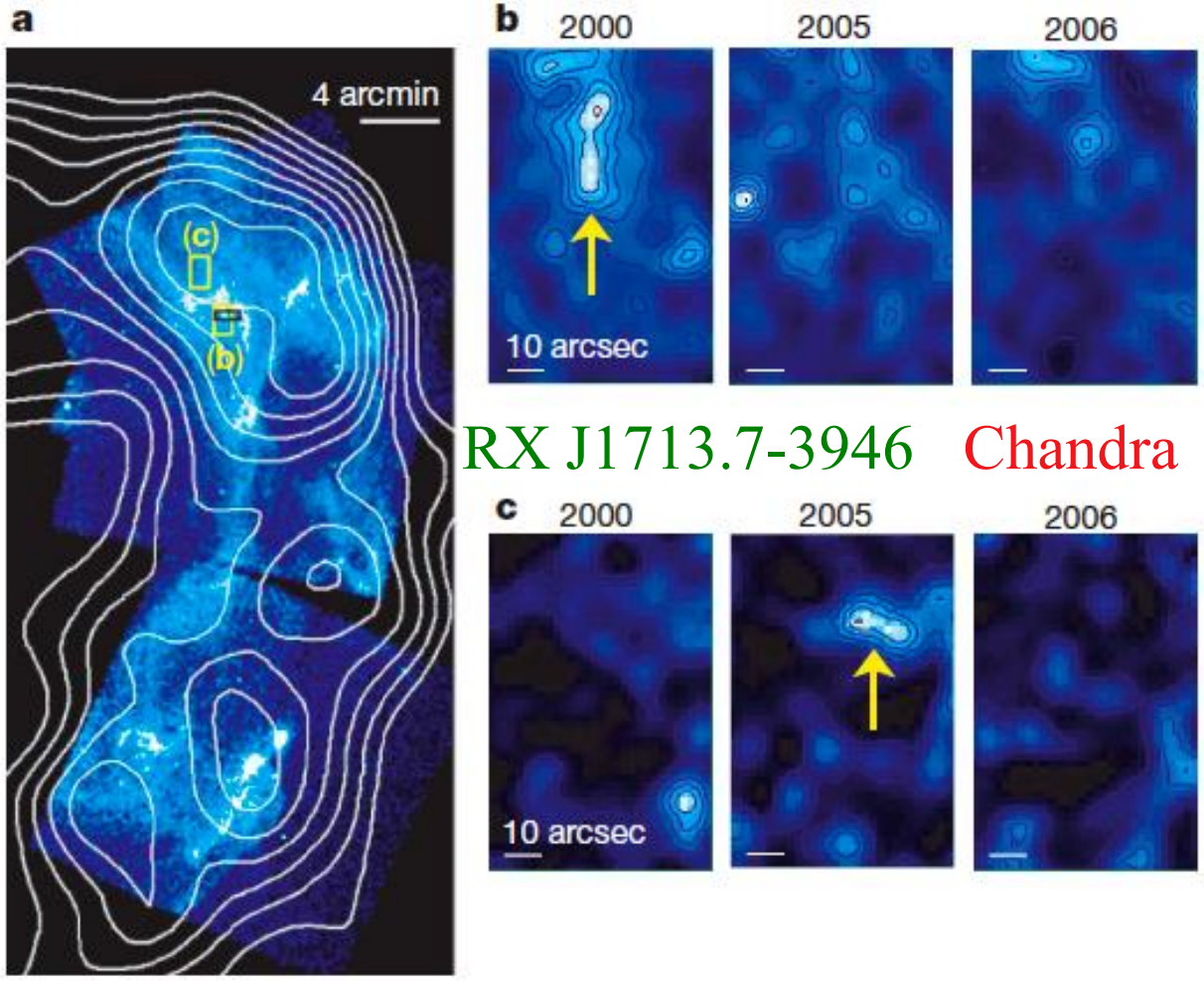
CR B amplification?

Lucek Bell 00, Bell 04

acceleration up to E_{knee}!

SNRs: X-ray variability!

Uchiyama+ 07, Nat 449, 576

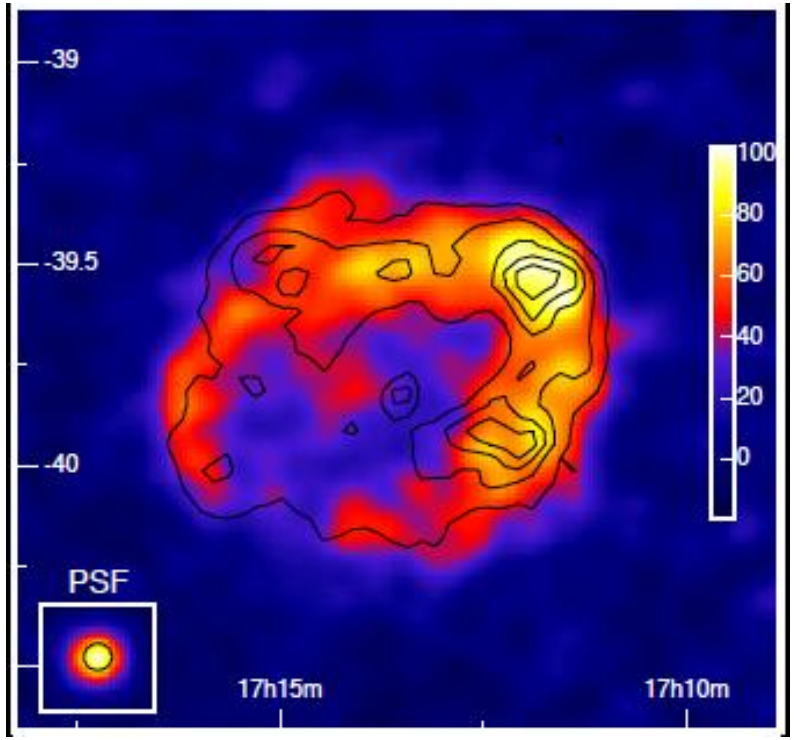


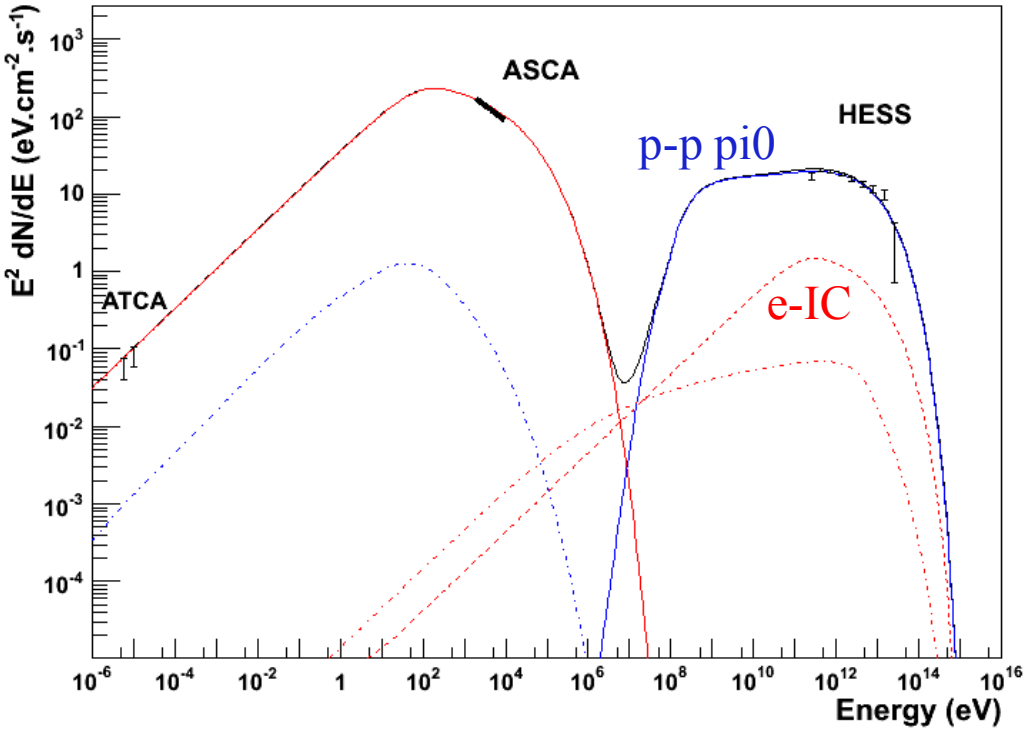
shock surface hot spots
~ yr time scale variability
→ B~1mG!

favors p-p π^0 as TeV

SNRs: TeV gamma-ray imaging Aharonian+ 04 Nat., 05, 06

RX J1713.7-3946 (discovered by CANGAROO Enomoto+ 02)



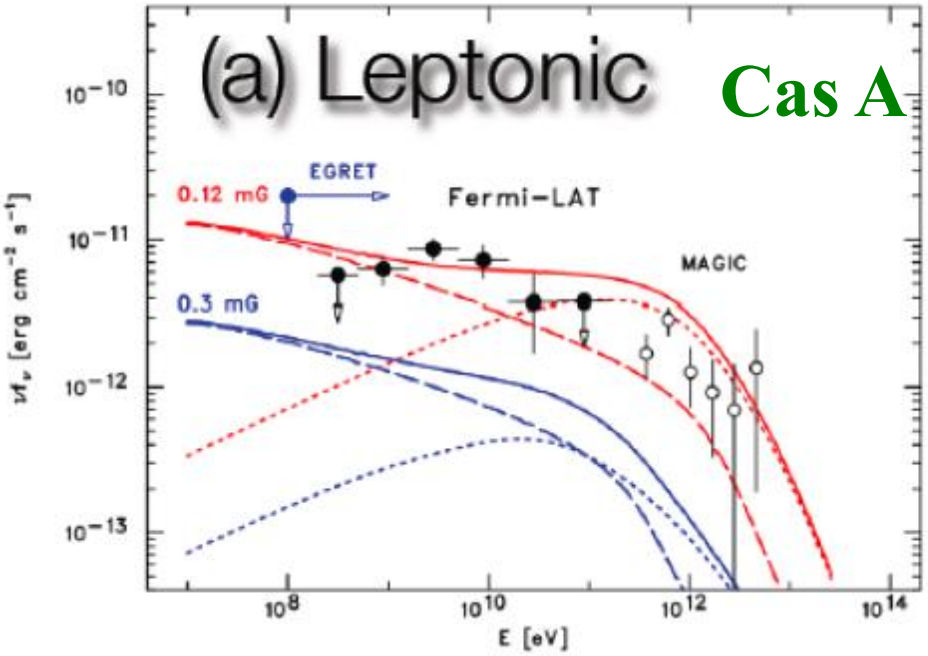


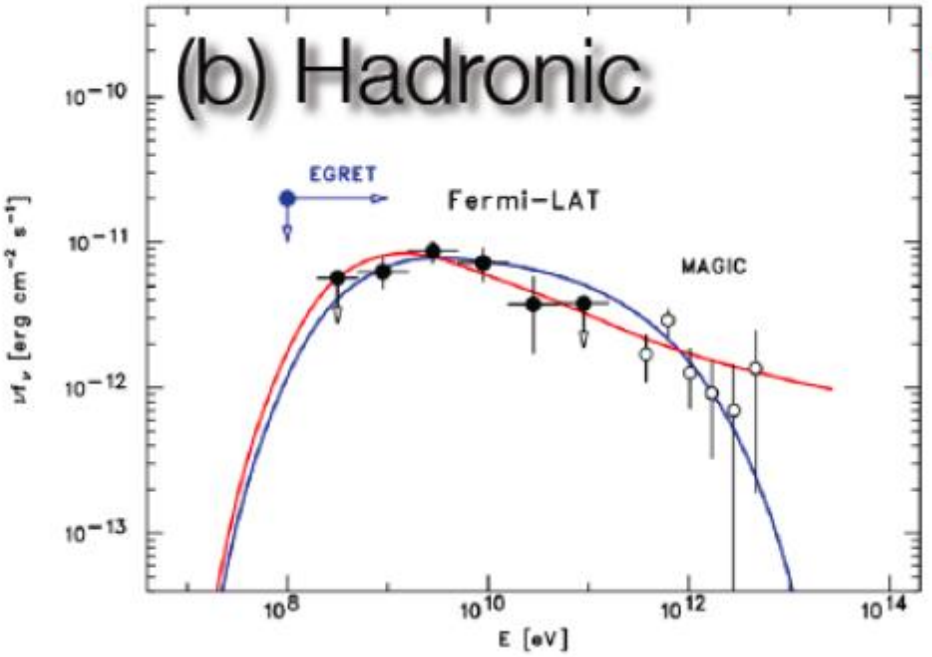
p-p π^0 likely (+some e-IC)?

E_{max}~100 TeV< E_{knee}
later/other SNRs up to E_{knee}?

SNRs: Fermi results

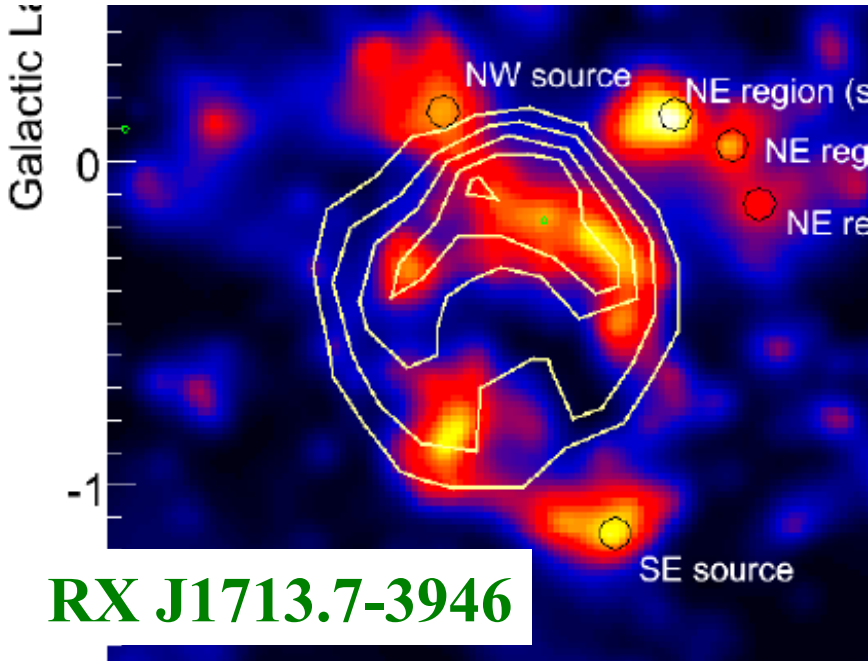
Abdo+ 10 (Funk, Uchiyama)





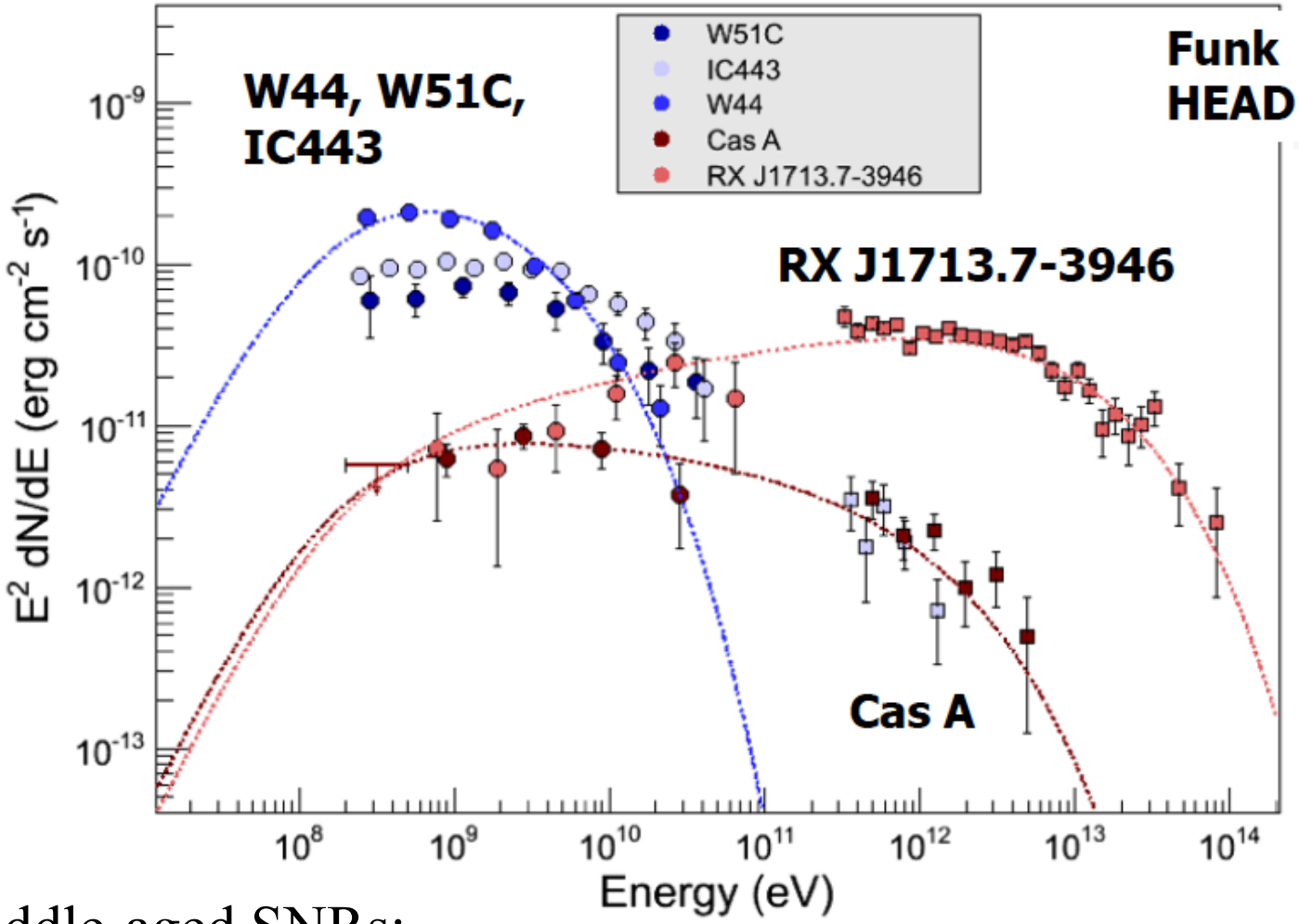
clear detection
clear shell morphology

BUT unclear on π^0 bump…
-> <100 MeV observations
ν observations!



SNRs: Fermi results

young vs middle-aged SNRs

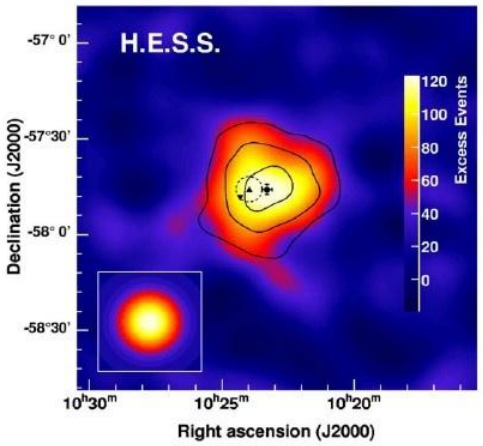


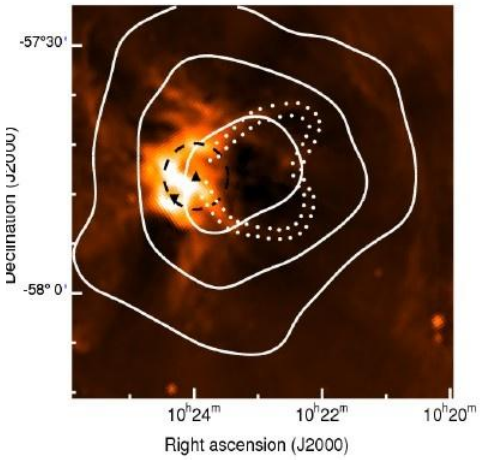
middle-aged SNRs:
1-10 GeV spectral break -> early CR escape?
evidence of interaction with molecular clouds

宇宙線が逃げていく
様子が見えてきた

other Galactic CR source candidates

hints from TeV



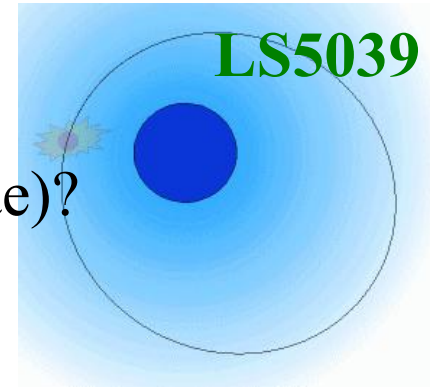


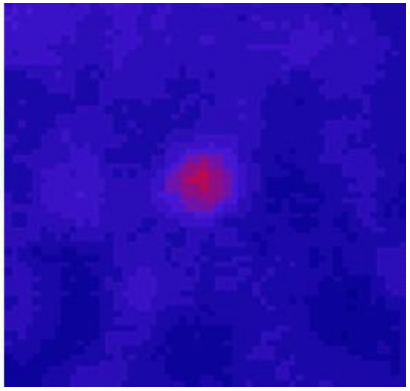
stellar winds Aharonian+ 07

p-p pi0 or e-IC?

pulsar wind nebulae?

γ-ray binaries (microquasars) Aharonian+ 05 Sci., 06
Albert+ 06 Sci.



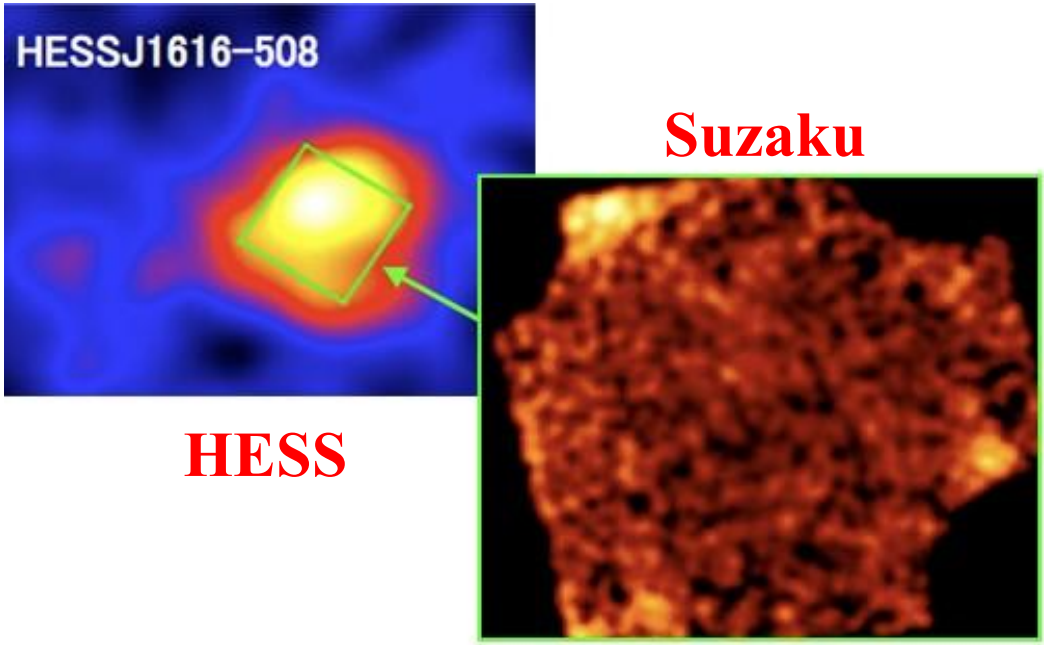


BH (microblazar) or NS (wind nebulae)?

ν source?

Galactic GRBs e.g. Wick, Dermer & Atoyan 04

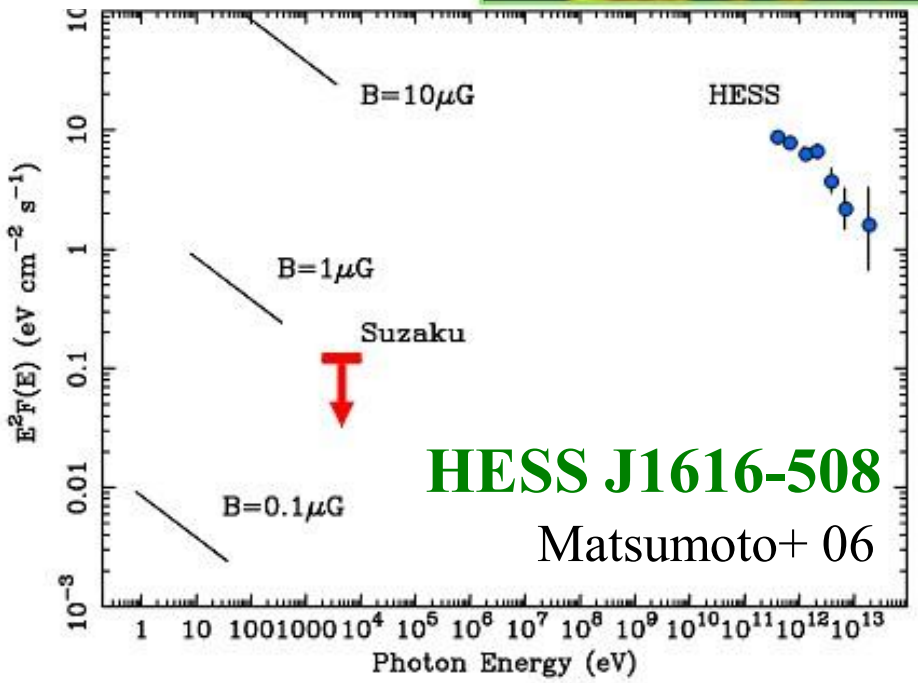
TeV unID sources: dark accelerators!



possibilities

- stellar winds
- offset pulsar nebulae
- old SNRs
- GRB remnants
- photoexcitation of CR nuclei
- dark matter

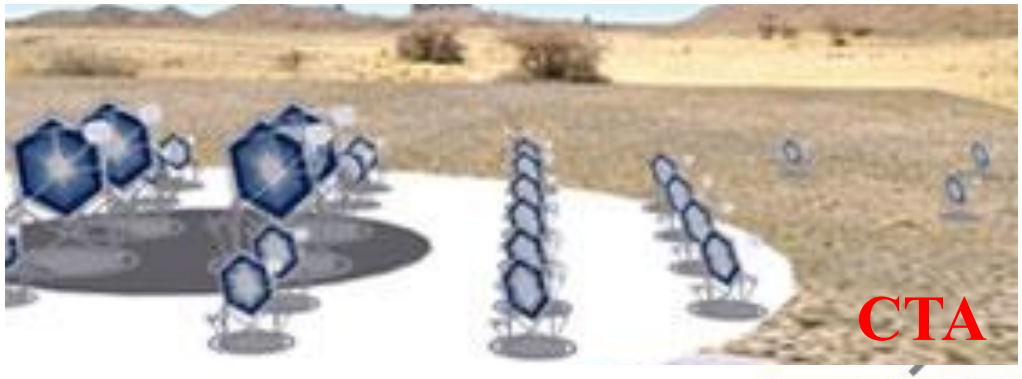
???

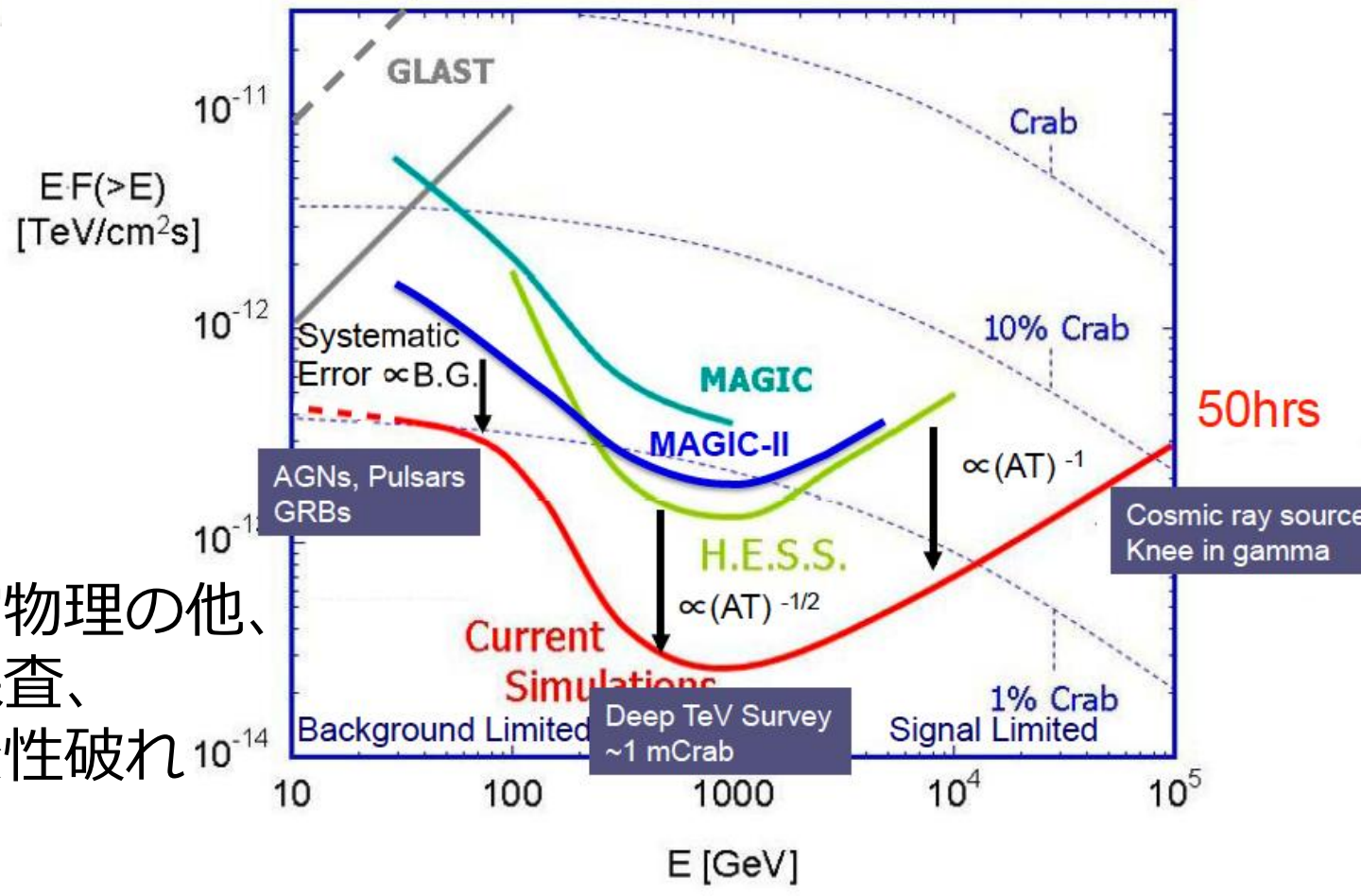


陽子起源、 >~100 TeVまで加速

明確なカットオフの兆候なし
-> knee宇宙線源？

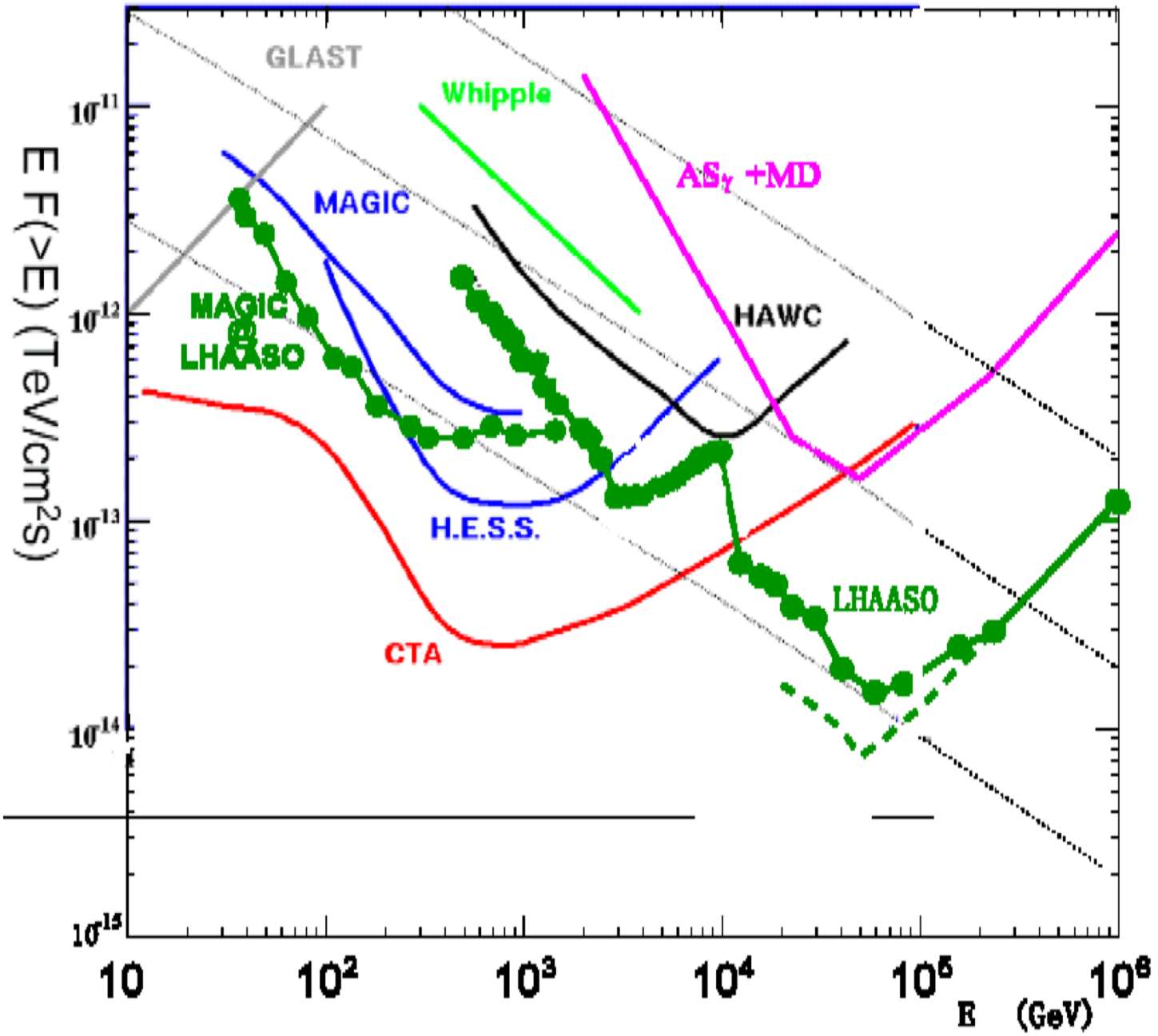
Cherenkov Telescope Array: future of GeV-TeV astronomy



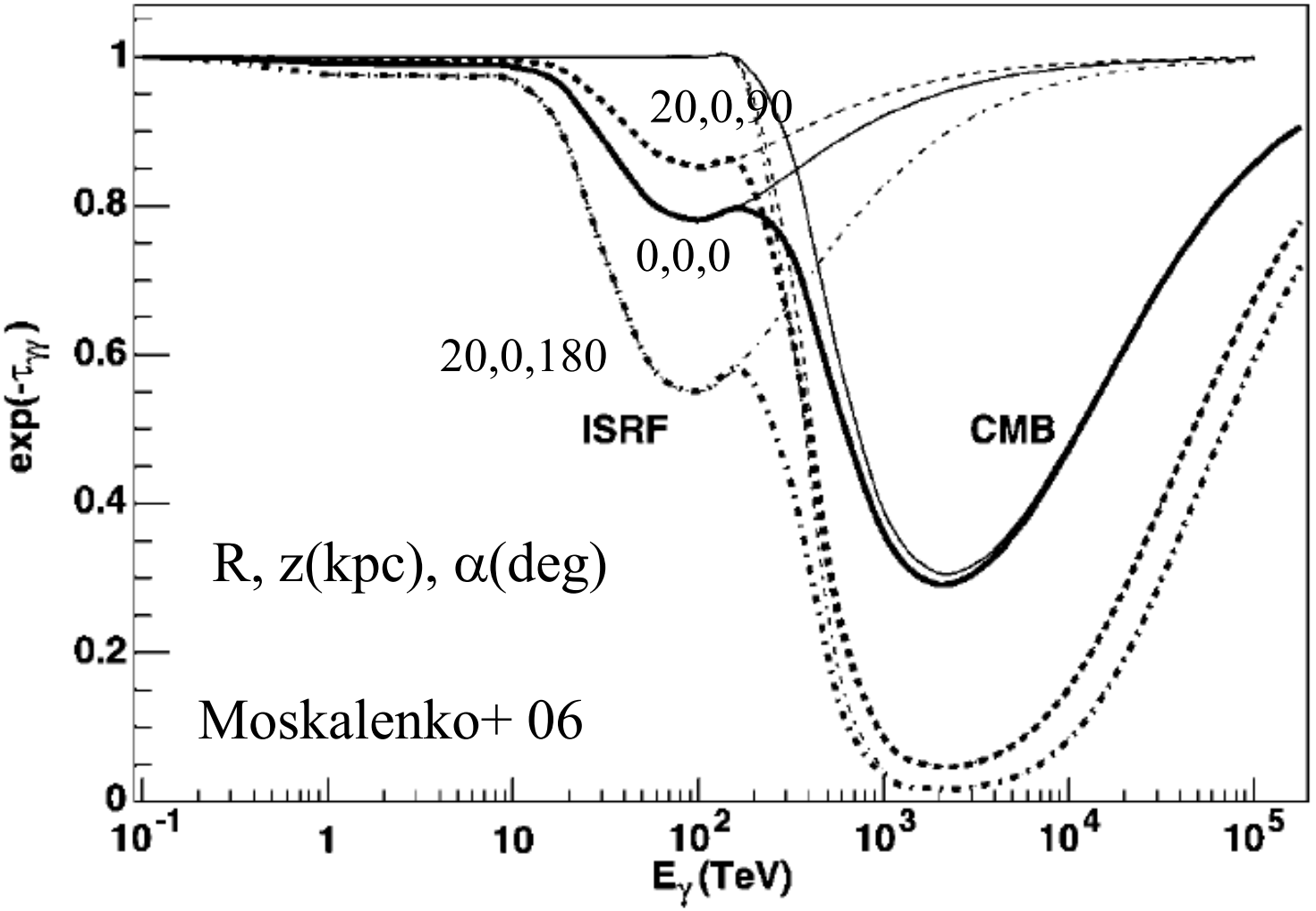


いろいろな宇宙物理の他、
ダークマター探査、
ローレンツ不変性破れ
の検証など

PeVatron search: wide field facilities



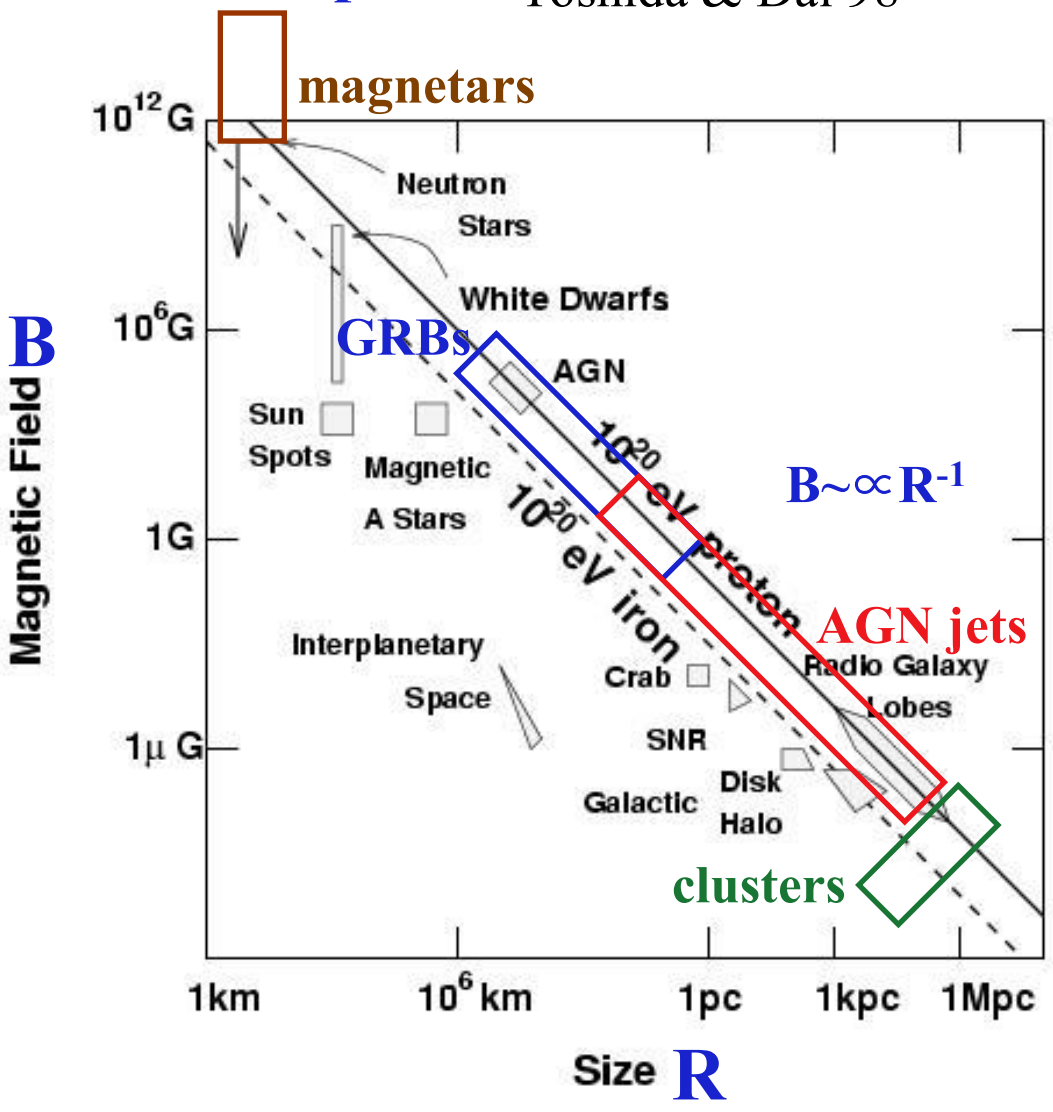
γγ opacity for Galactic interstellar radiation field



additional absorption for < few 100 TeV possible

UHECR sources: acceleration

"Hillas plot" adapted from Yoshida & Dai 98



$E \leqq Ze\ B\ R\ (v/c)$

confinement

E_{max} acceleration vs:
escape
source lifetime
adiab. expansion loss
radiative loss

heavy favorite: AGNs

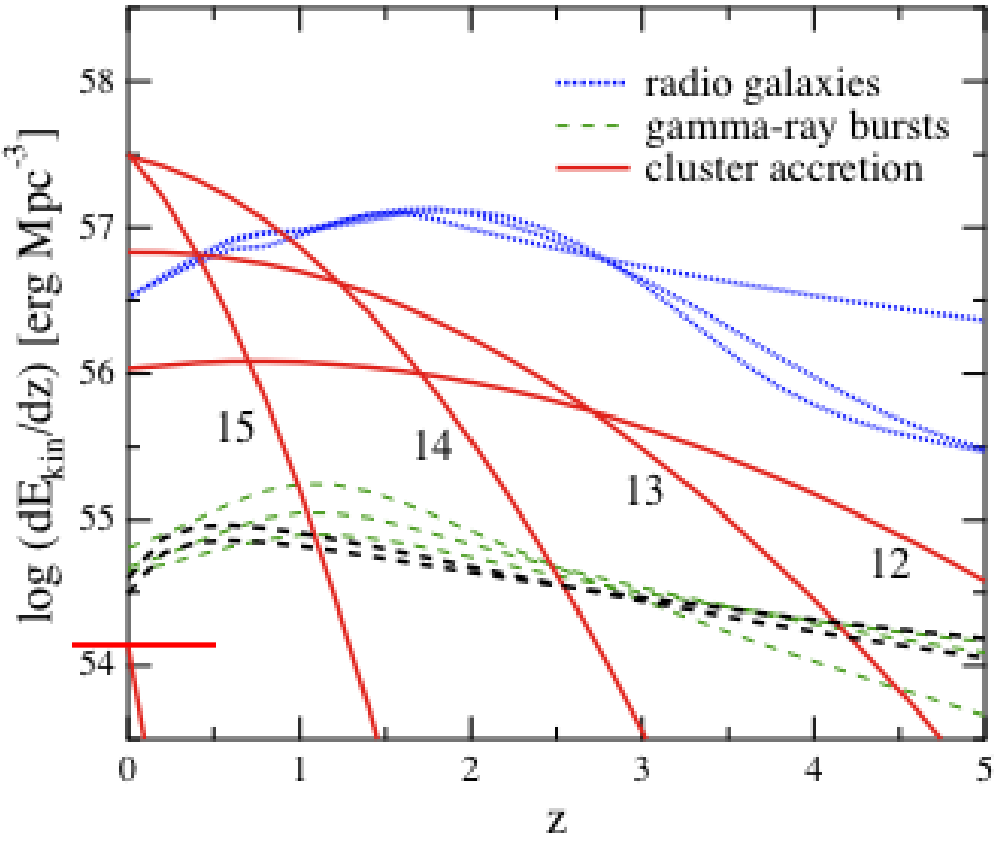
leading contender: GRBs

dark horse: clusters, etc.

UHECR sources: energy budget

SI, arXiv:0809.3205

kinetic E input into the universe



differential (per unit z)

$dE_{kin}/dz=(dt/dz)\int dL\ L\ dn/dL$

AGNs (radio galaxies)

z-dep. LF Willott+ 01

L_{kin}-L_{rad} correlation Rawlings 92

supernovae, GRBs

$\propto$ star formation rate

Porciani & Madau 01, Le & Dermer 07

$E_{GRB}=10^{54}$ erg, indep. of beaming

cluster accretion

Press Schechter mass function

$L_{acc}(M)\sim 0.9\times10^{46}\ (M/10^{15}\ M_{\odot})^{5/3}$ erg/s

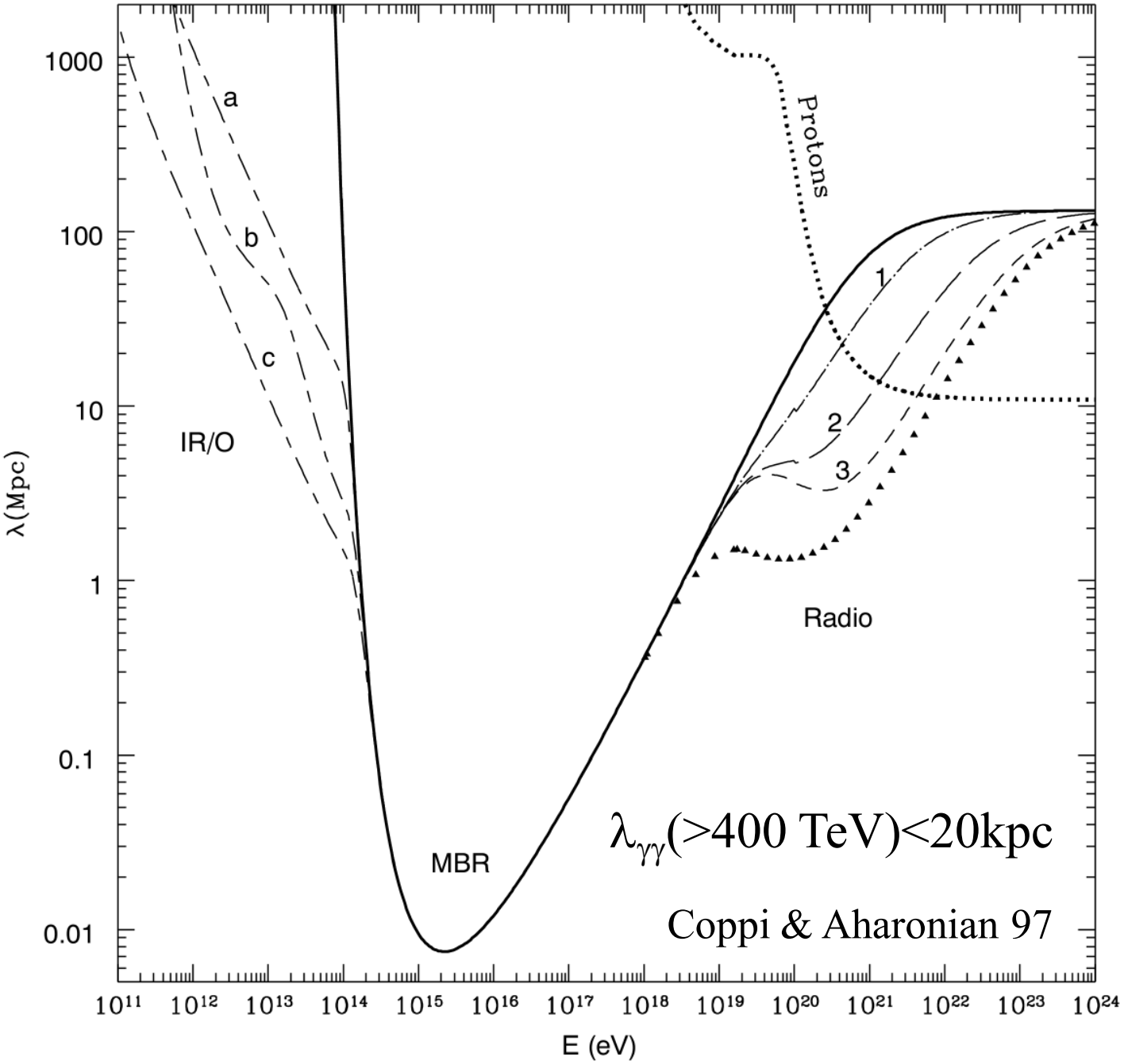
Keshet+ 04

UHECR budget @10^{19} eV

$u_{CR}\sim 3\times10^{-19}$ erg cm^{-3}

$\sim 10^{54}$ erg Mpc^{-3}

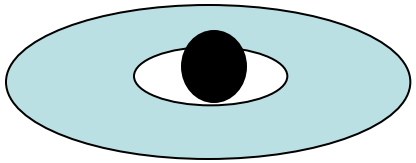
local extragalactic gamma-ray horizon



emission from secondary pairs (pair halos)?

active galactic nuclei (AGNs)

supermassive black hole
+accretion disk (flow)



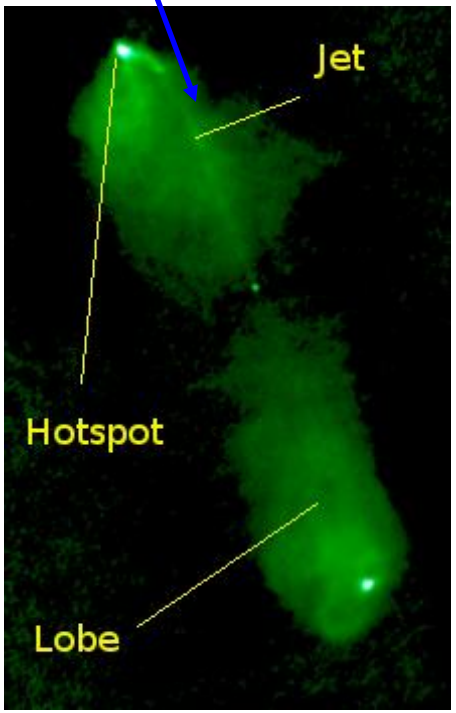
radio-loud
(relativistic jet)

high-
power

~<1%

FR 2
radio
galaxy

GeV blazar

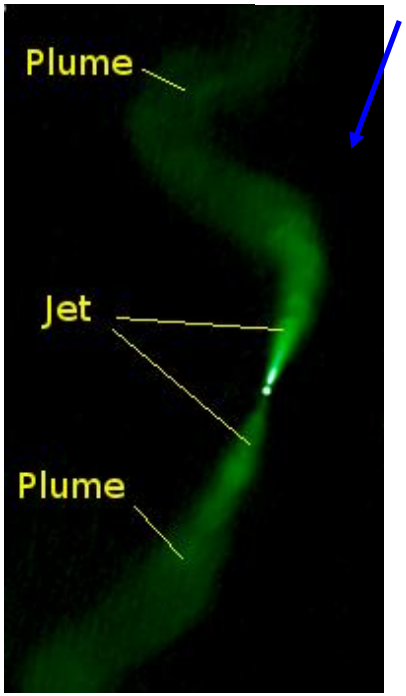


low-
power

~9%

TeV blazar
(BL Lac)

FR 1
radio
galaxy



radio-
quiet
(no jet)

~90%

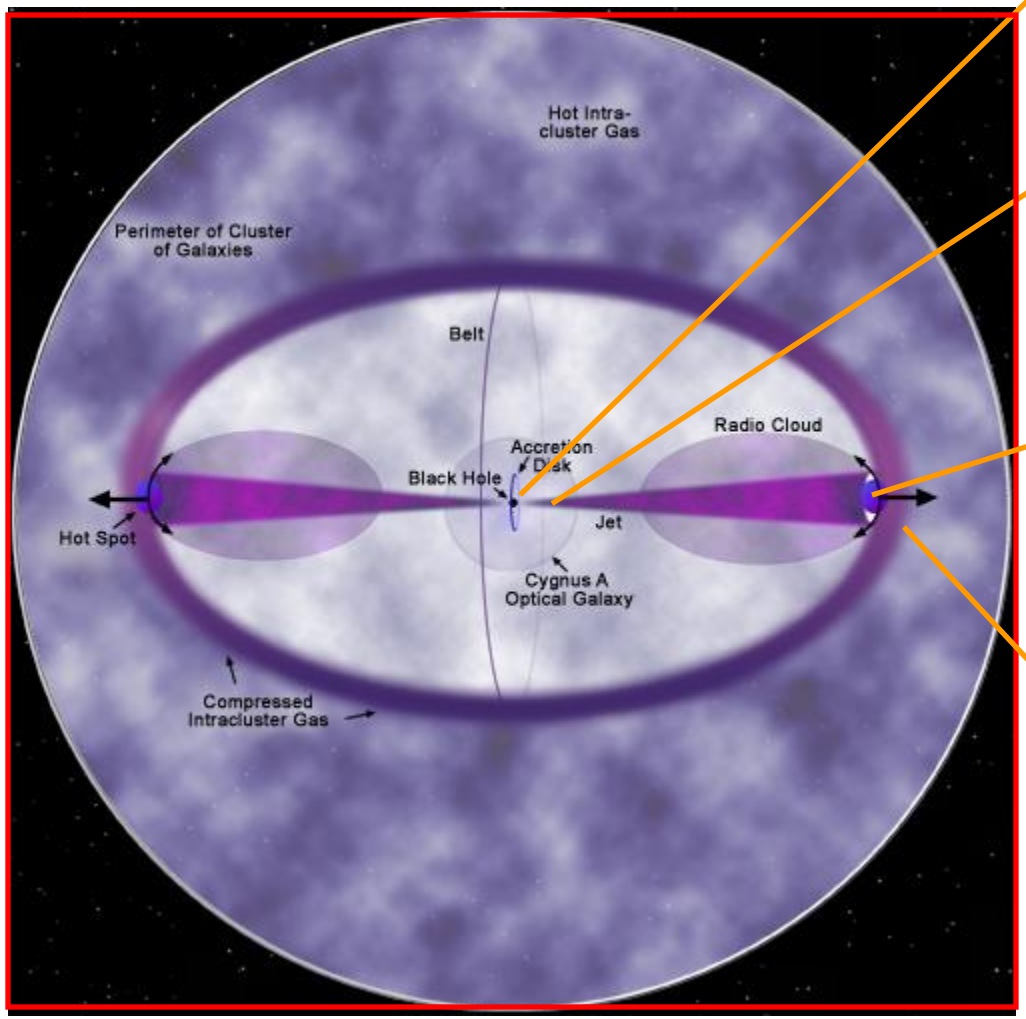
Seyfert galaxy
radio-quiet quasar

strong nonthermal
emission
=particle acceleration

activity timescales
~10^6-10^8 yr

AGNs: acceleration sites

high power (FR 2) radio galaxy



from Chandra webpage

near-nucleus

highest E not expected

inner jet (blazar)

$E_{max} \sim E_{p\gamma} \sim < 10^{20}$eV

accel./escape nontrivial

hot spot

R~10^{21} cm B~1mG

$E_{max} \sim E_{esc} \sim 10^{20\text{-}21}$eV

accel./escape easier

bow shock

R~10^{23} cm B~0.1mG

$E_{max} \sim E_{esc} \sim 10^{20}$eV

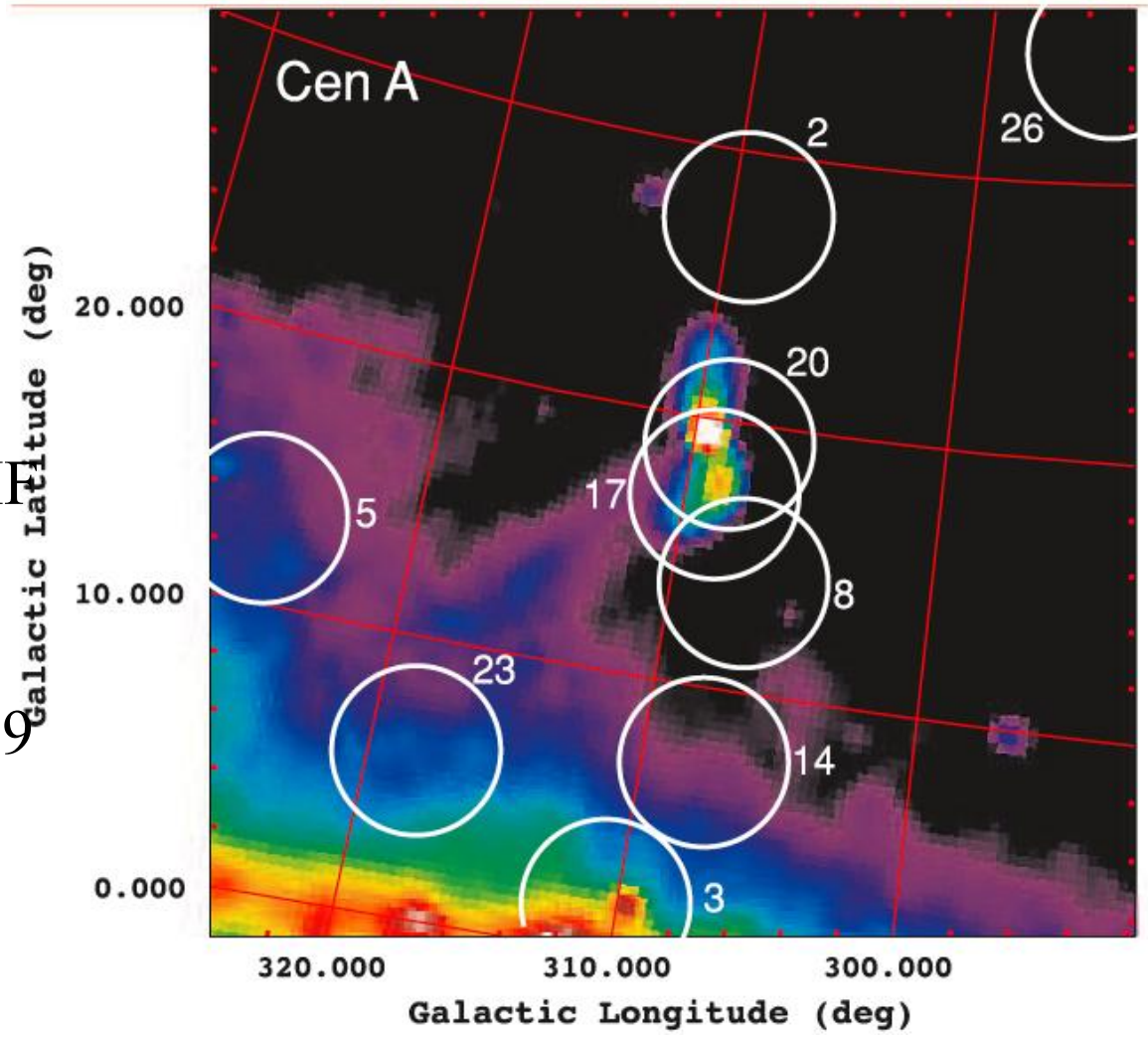
Berezhko 08

accel. nontrivial

Cen A

Cen A excess events:
UHECR (nuclei)
accelerated in jet core
-> escape along jet
-> deflected by lobe MF
+deflected by Galactic MF

c.f. Rachen 08
Lemoine & Waxman 09



Moskalenko+ 09

proton blazar model

Mannheim 93, etc

$e^- + B \rightarrow e^- + \gamma_{LE}$

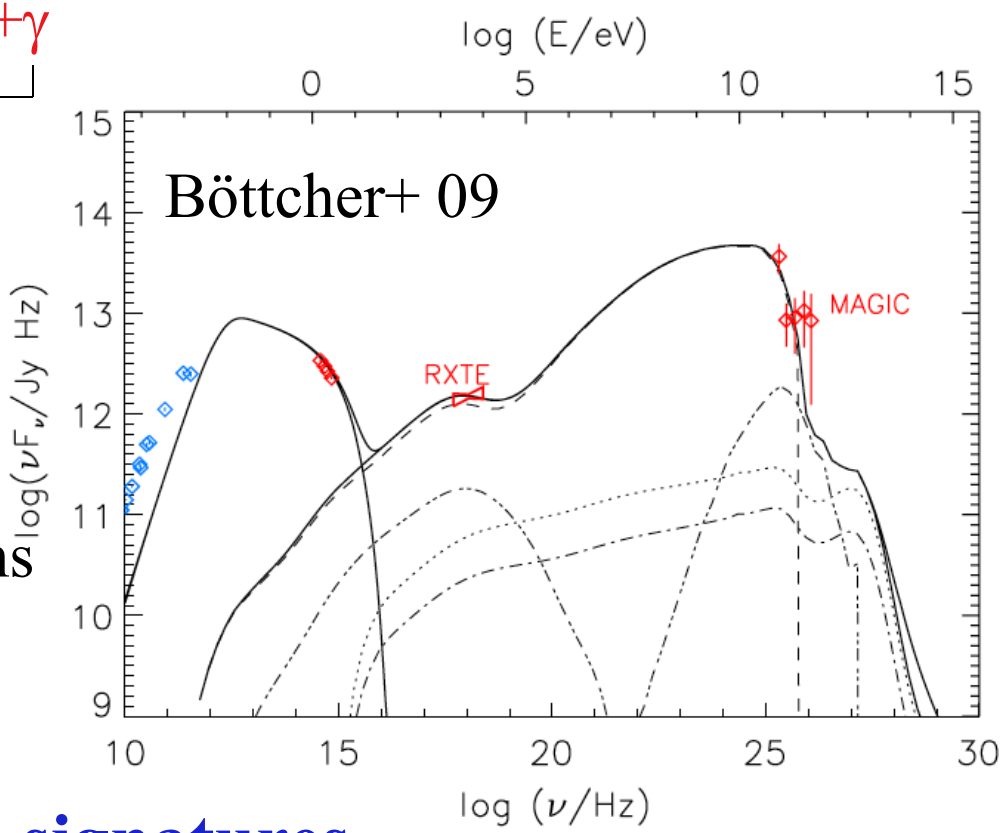
$p + \gamma_{LE} \rightarrow N + \pi^0, \pi^{+-}$ $\quad \pi^0 \rightarrow 2\gamma$ $\quad \pi^{+-} \rightarrow e^{+-} + 3\nu$

$\gamma + \gamma_{LE} \rightarrow e^+e^-$

$e^+e^- + B \rightarrow e^+e^- + \gamma$

proton-induced cascade

$p + B \rightarrow p + \gamma$ proton synchrotron



difficulties

1. poor fit to broadband spectra?
2. $t_{p\gamma}$ too long(?) to explain
   <day timescale X-TeV correlations
   subminute TeV variability

however:
can we still see UHE proton signatures mixed with leptonic emission?

leptonic+hadronic emission model

Cerruti, Zech, SI & Boisson, in prep.

leptonic model of Katarzynski, Sol & Kus 01

- one zone synchrotron+SSC
- electron spectrum: phenomenological broken power-law
- internal $\gamma\gamma$ pair absorption

hadronic processes

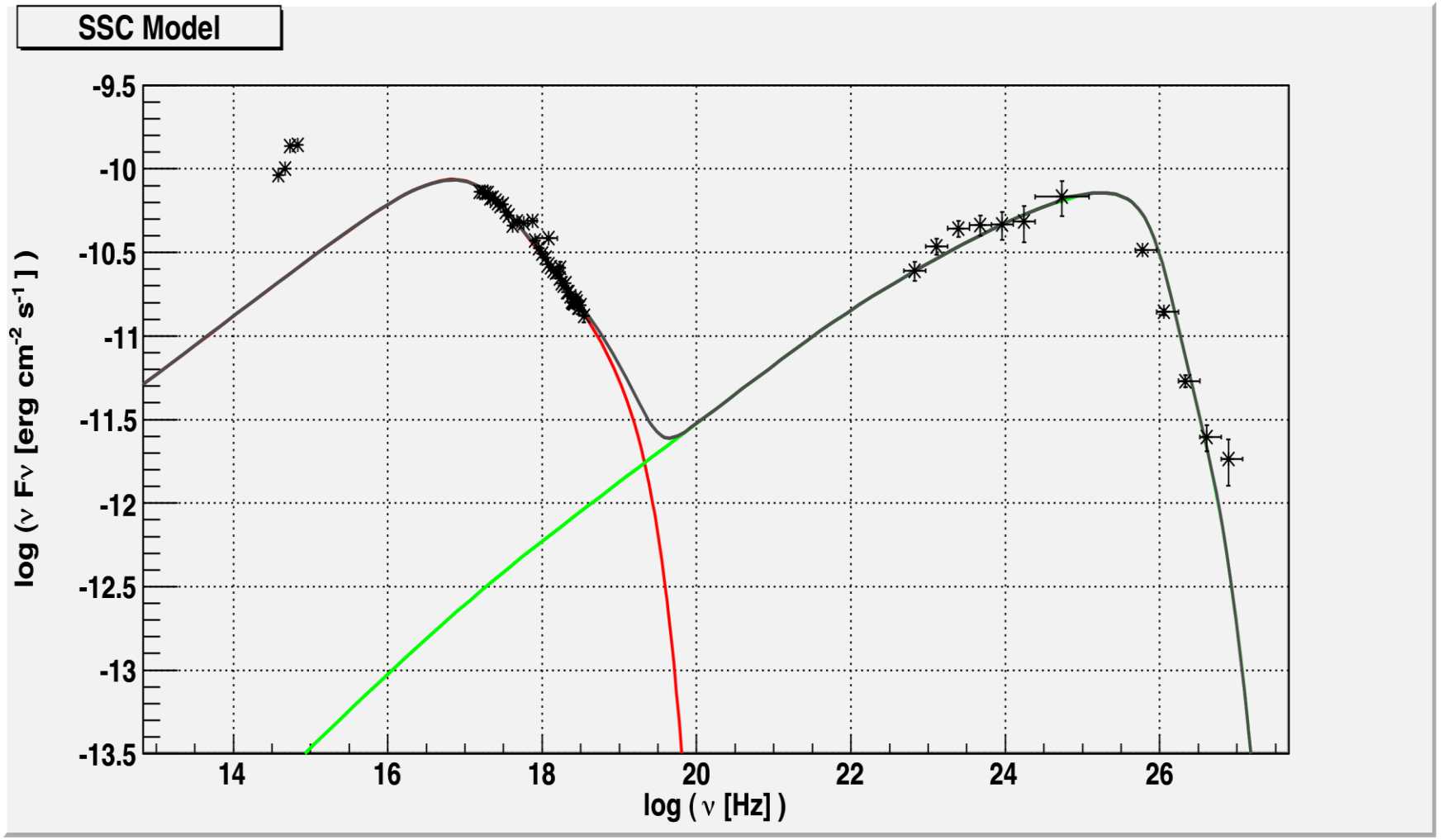
- proton synchrotron
- photomeson interactions (SOPHIA)
- syn+IC emission secondary pairs

(- Bethe-Heitler pair production)
(- muon synchrotron)

EBL: Kneiske+04 best fit model

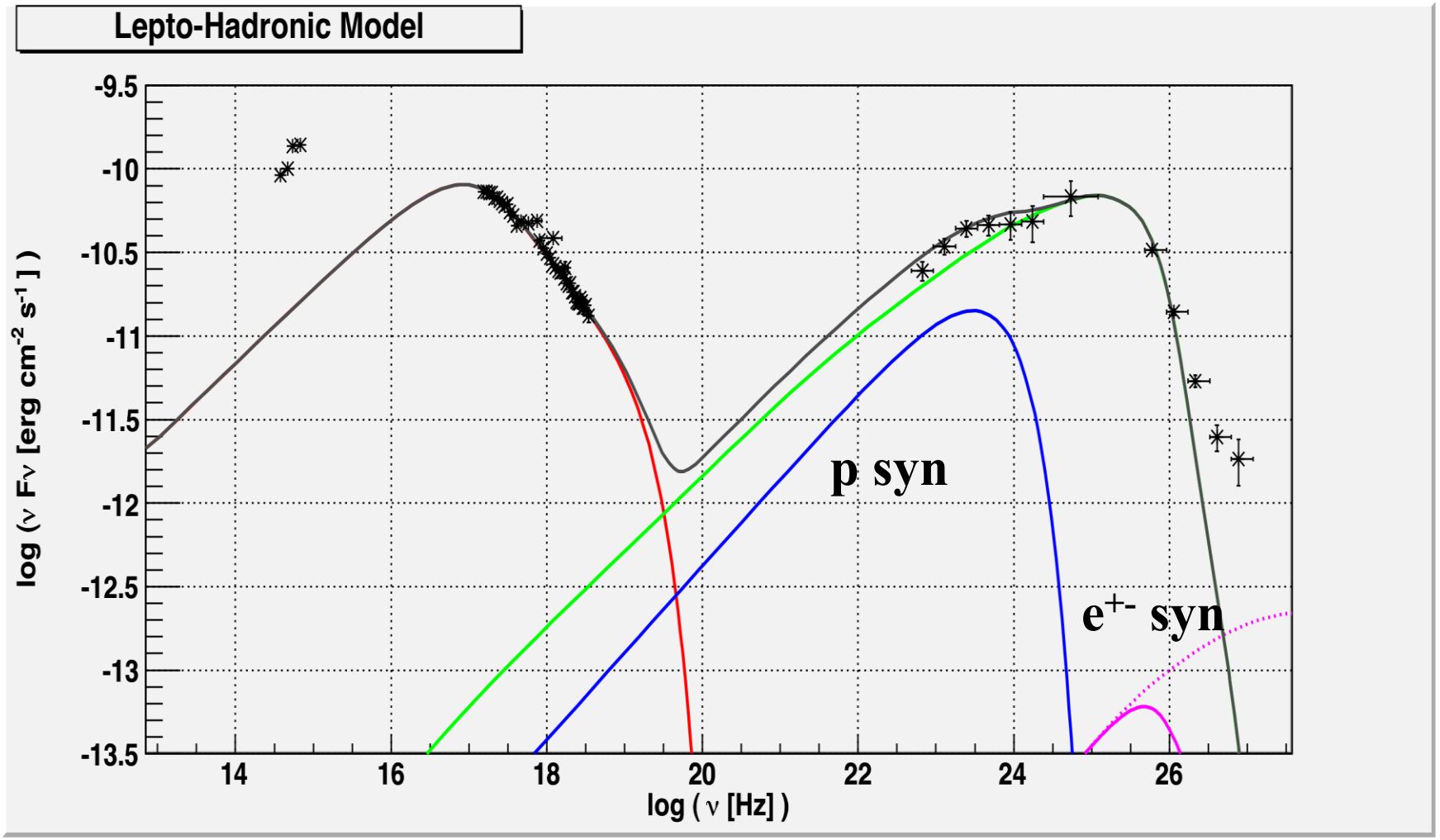
compare with PKS 2155-304 2008 simultaneous data
HESS, Fermi, RXTE, ATOM Aharonian+ 09

leptonic emission model



δ=32, B=0.018 G, R=4.7x10^{16} cm^{2}

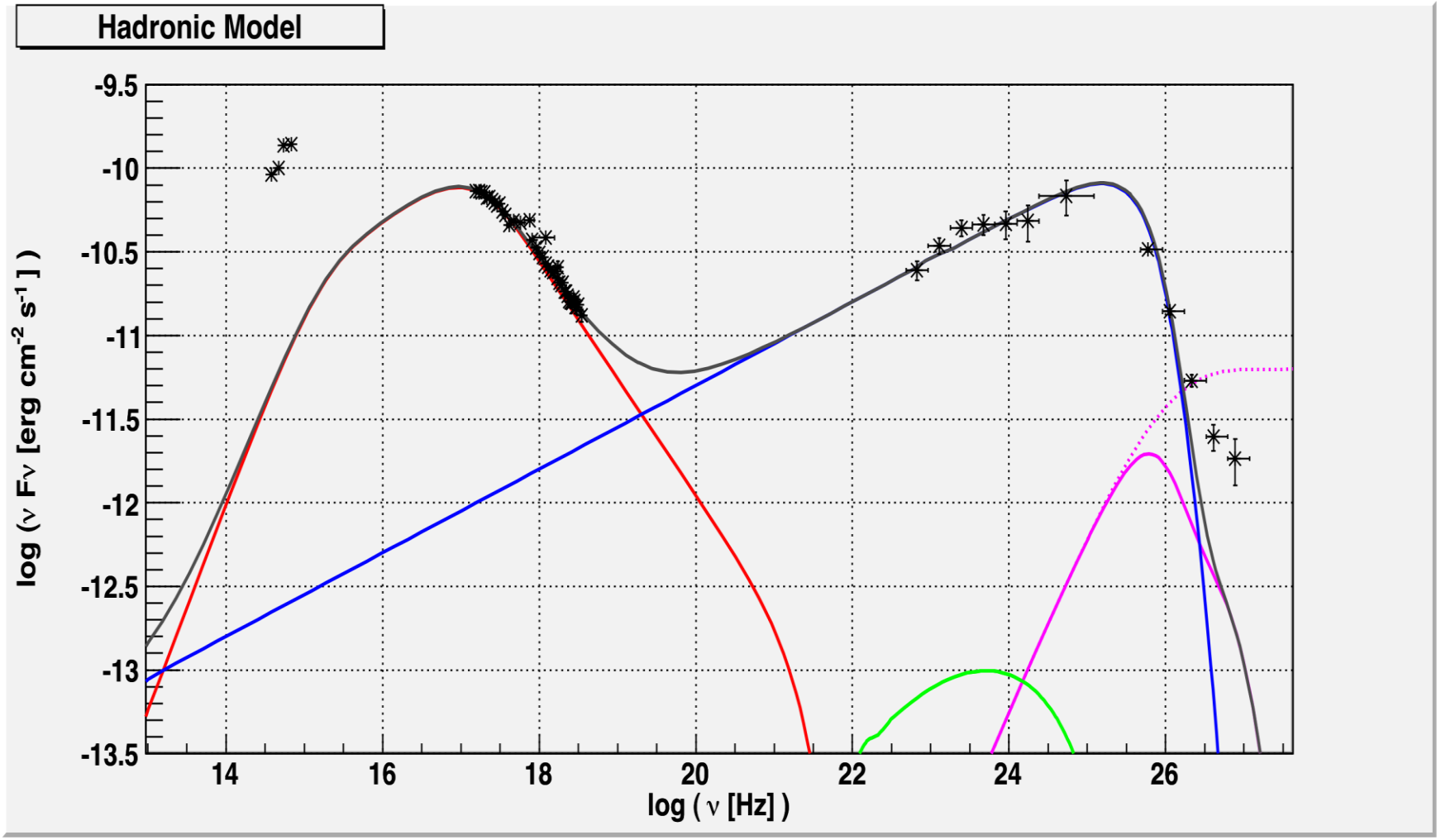
leptonic+hadronic emission model



δ=25, B=0.25 G, R=5.2x10^{15} cm^2, U_p/U_e=1

GeV “feature”~ p sync? test with variability

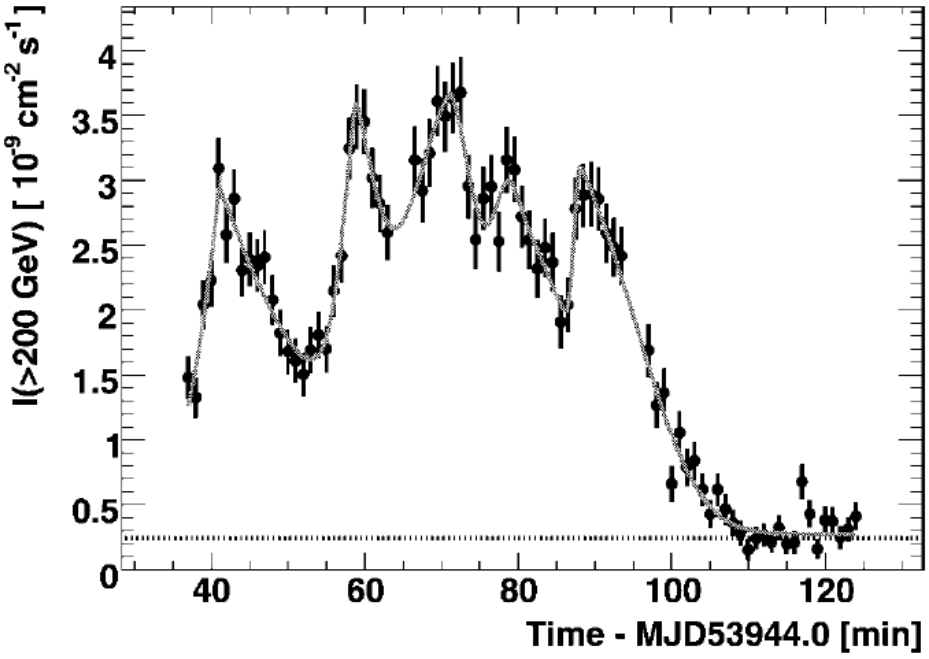
hadronic emission model



δ=20, B=70G, R=1.0x10^{15} cm^2, U_p/U_e=10^4

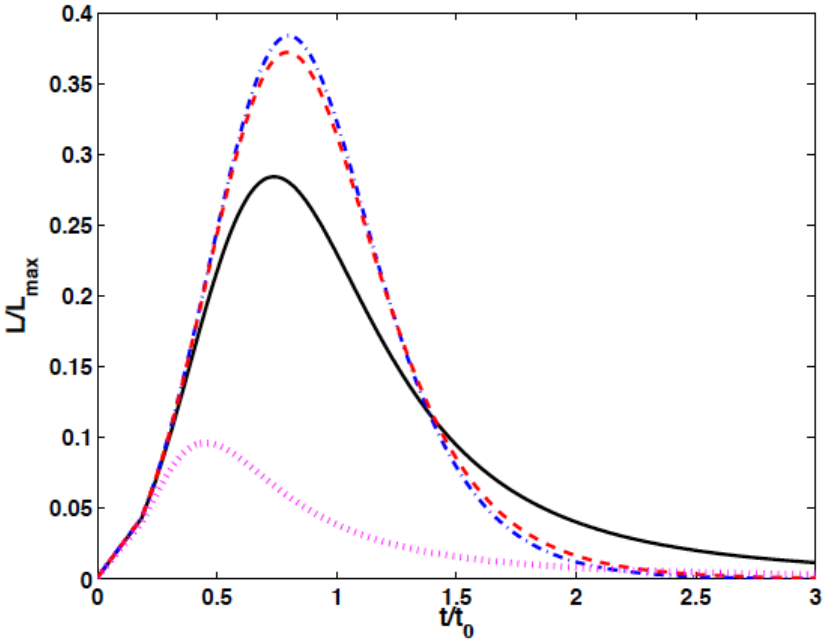
TeV "excess"~ pγ cascade? test with variability

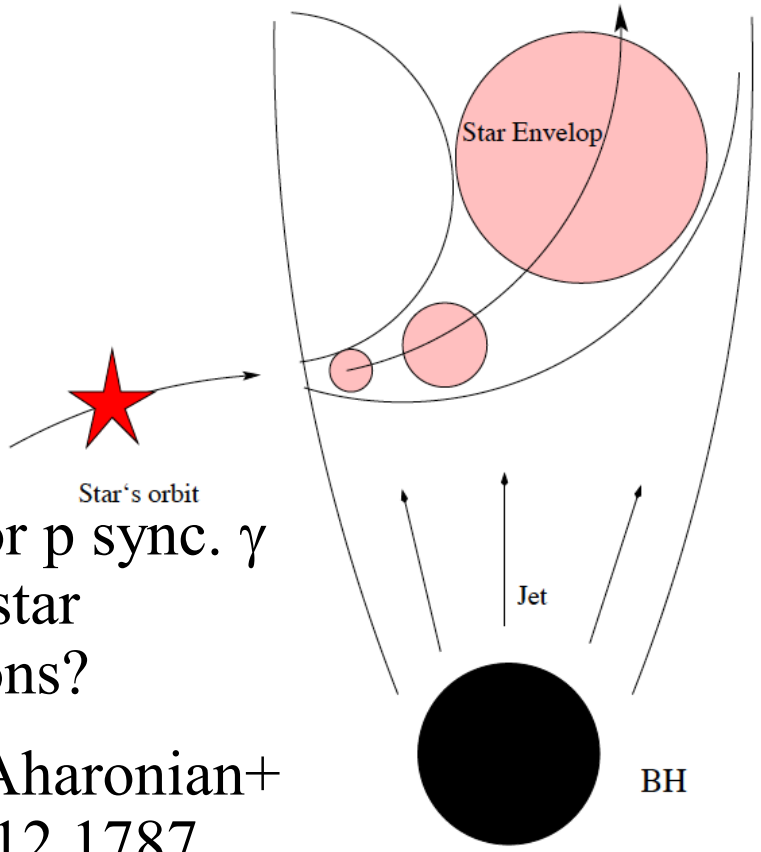
short timescale flare from jet-star interaction?



Aharonian+ 06

HESS observations of min timescale flare in PKS 2155-304

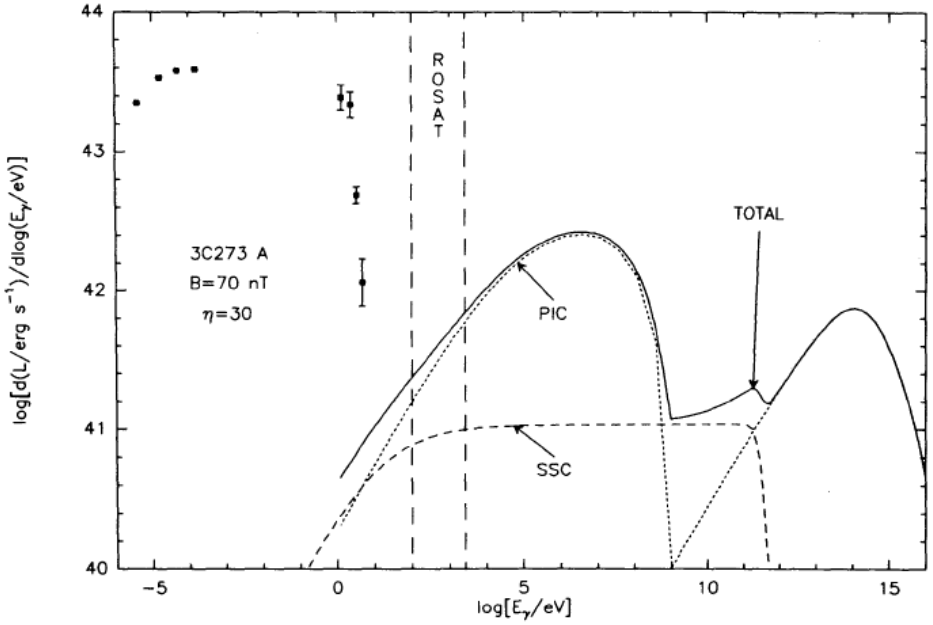




p-p and/or p sync. γ from jet-star interactions?

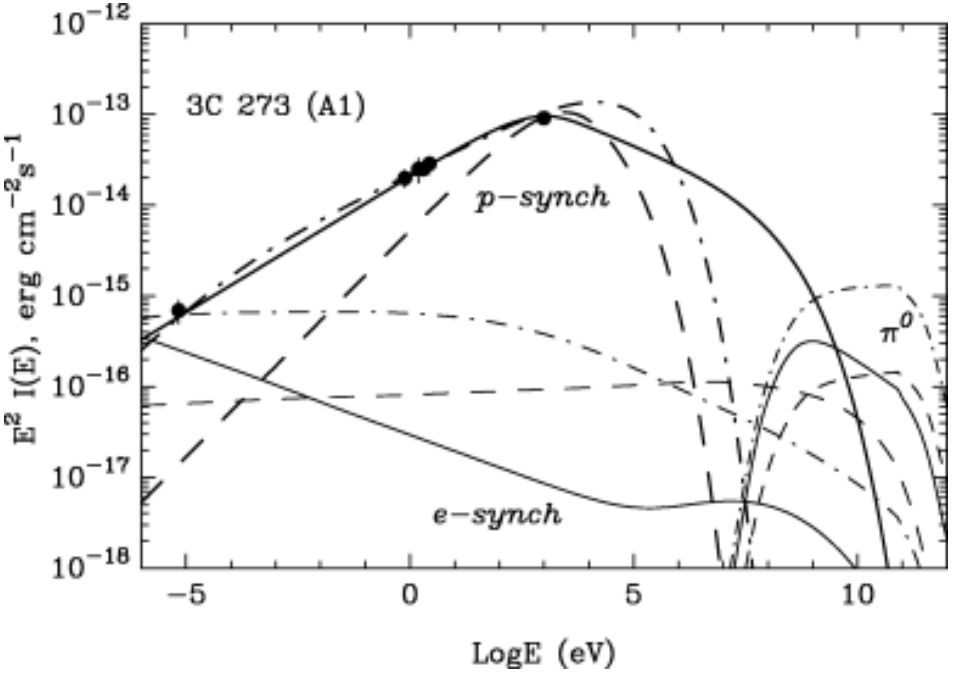
Barkov, Aharonian+ arXiv:1012.1787

hot spots: UHECR-induced emission



pγ pair cascade

Mannheim+ 91

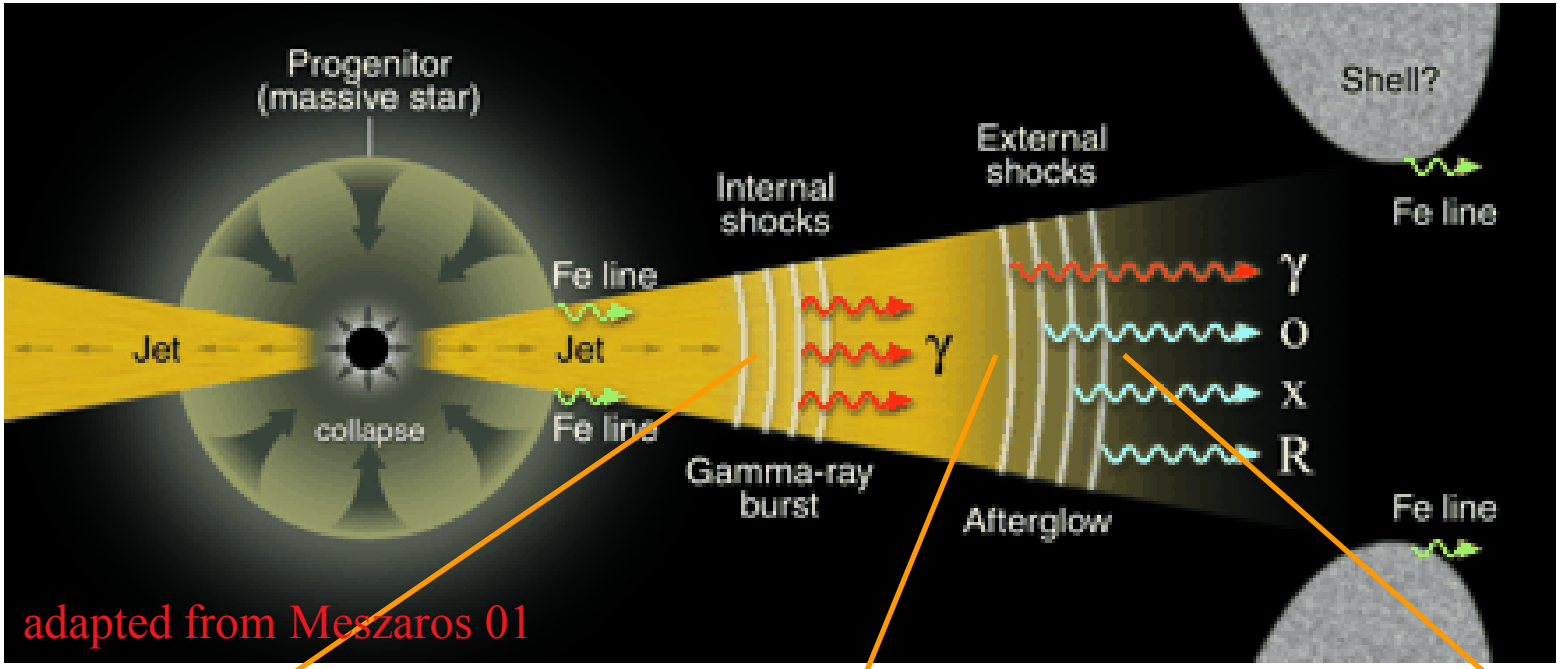


proton synchrotron

Aharonian 02

generally not strong,
but worth reconsideration
for CTA

GRBs: acceleration sites



Waxman 95
Vietri 95

prompt X-γ emission

internal shocks

$R \sim \Gamma^2 ct_{var} \sim 10^{12}$-$10^{16}$ cm

$B \sim 10^{6}$-10^{3} G

$\Gamma_{rel} \sim 1$

optical flash, radio flare

external reverse shock

$R \sim R_{dec} \sim 10^{16}$ cm

$B \sim 10$ G

$\Gamma_{rel} \sim 1$

radio-IR-opt-X afterglow

external forward shock

$R \sim R_{dec}$-$R_{NR} \sim 10^{16}$-10^{18} cm

$B \sim 10$-0.01 G? $>> B_{ISM}$

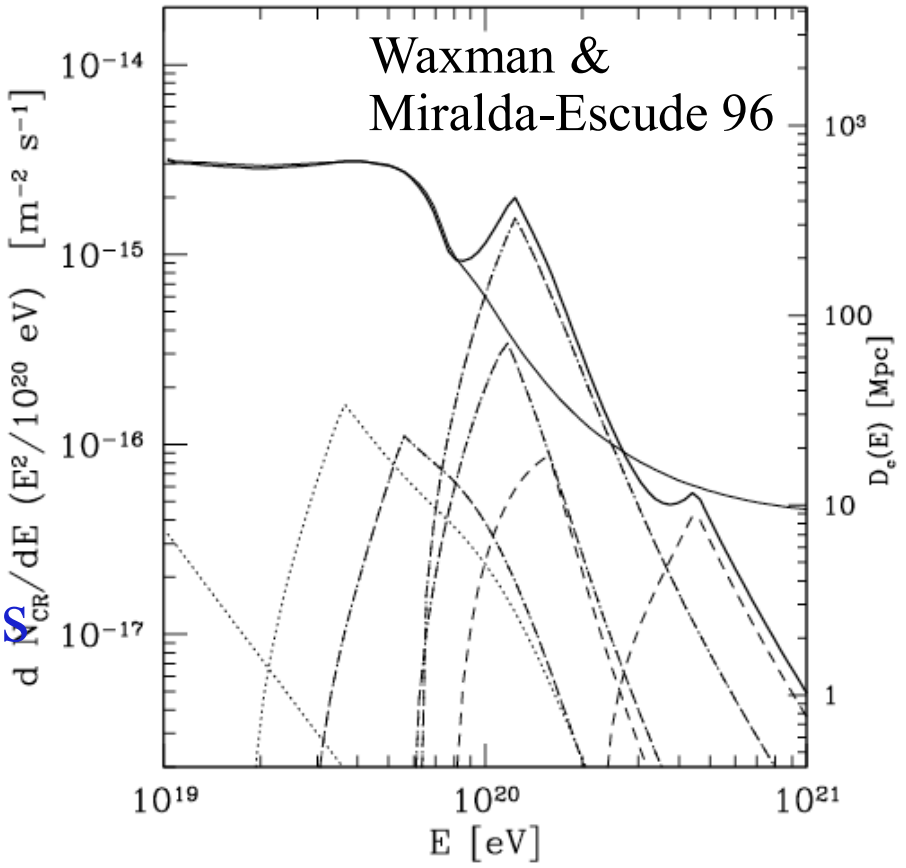
$\Gamma_{rel} >> 1$

GRBs as UHECR sources: diagnostics

time delay

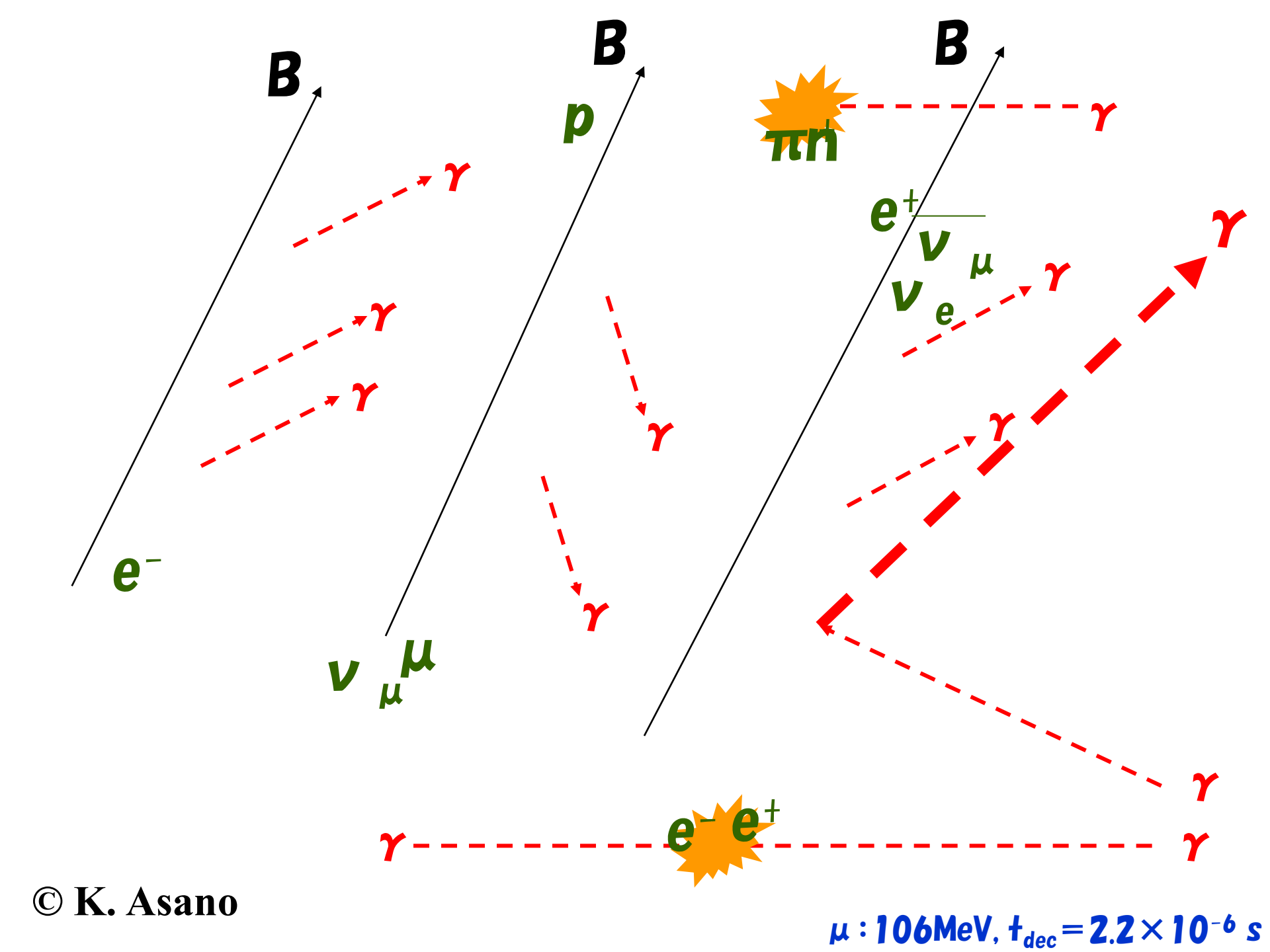
$t(E_p,D) \sim \theta^2 D/4c$

$\sim 10^7$ yr $E_{p,20}^{-2}\, D_{100\mathrm{Mpc}}^{2}\, l_{\mathrm{Mpc}}\, B_{-8}^{2}$



CR spectra of individual sources narrow at given time?
-> need large statistics

secondary neutral (gamma & neutrino) signatures essential to identify sources



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μ : 106MeV, $t_{dec} = 2.2 \times 10^{-6}$ s

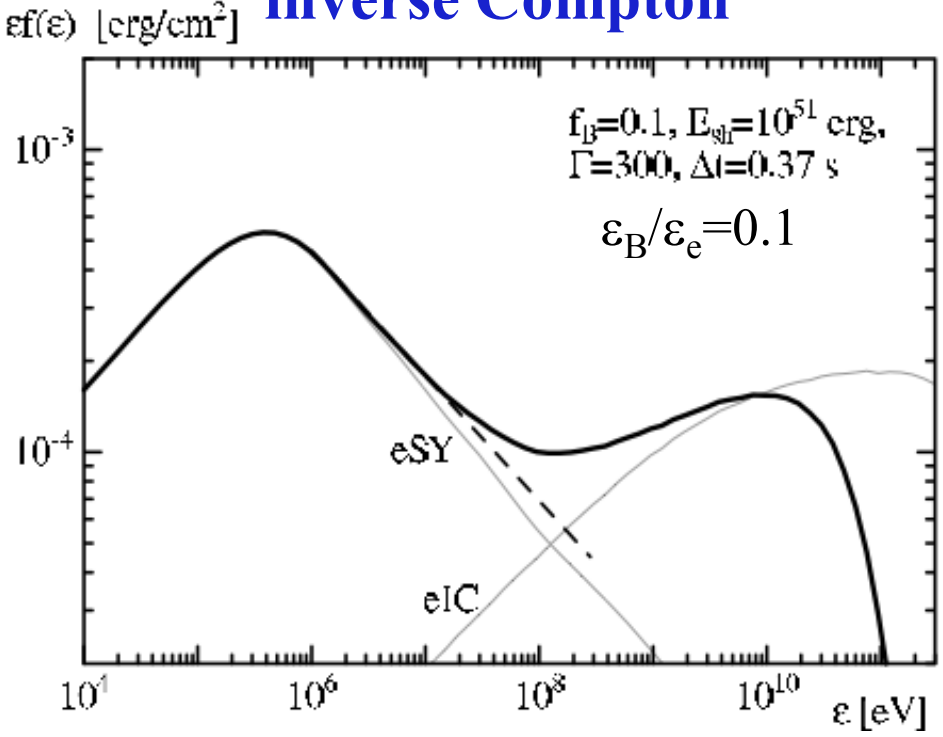
GRB GeV-TeV emission from electrons+protons

- electrons+protons acceleration in internal shocks (prompt phase)
- pair cascading, pγ interactions, various radiative processes…
- parameters: pulse energy E_{sh}, pulse timescale Δt, Γ, $f_B=u_B/u_e$
  fix E_{pk}=300 keV, β=2.5, assume $u_p=u_e$, p_p=2
- fluence spectra, z=0.1, no intergalactic γγ

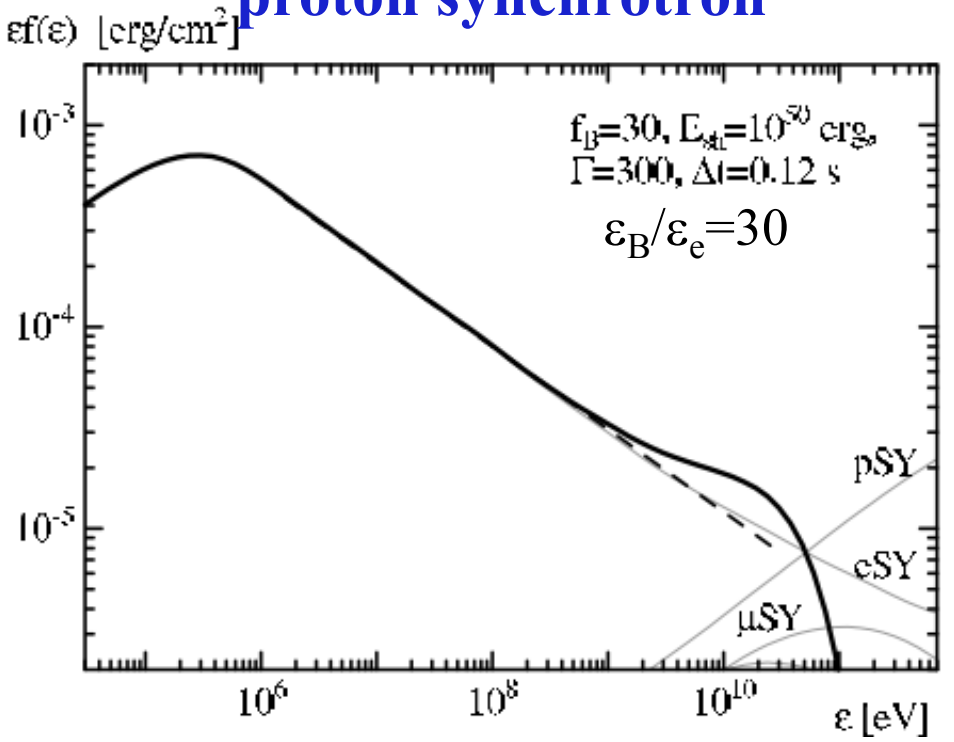
Asano & SI 07

$\varepsilon_p/\varepsilon_e$ =1 (proton-electron equip.) $E_{\gamma,iso}$ =10^{53} erg

inverse Compton



proton synchrotron

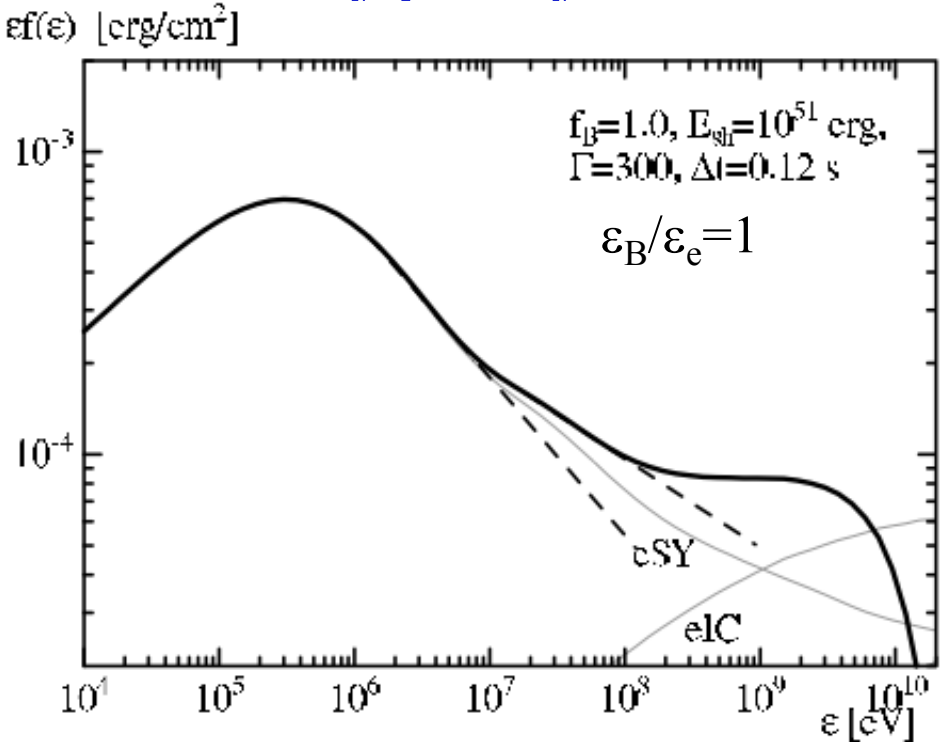


GRB GeV-TeV emission

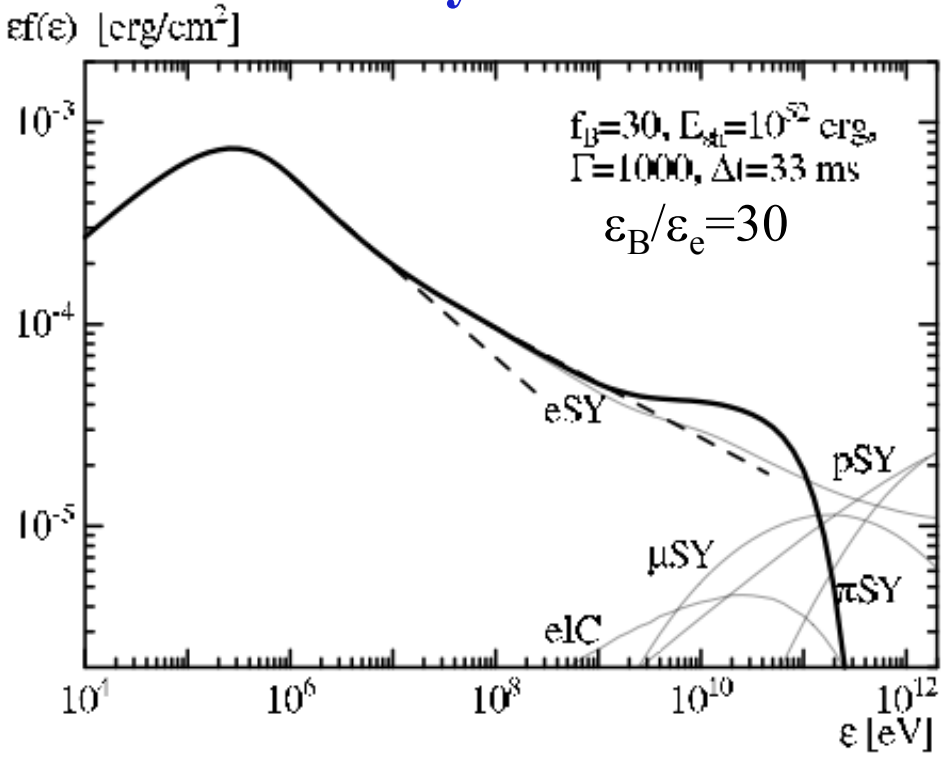
Asano & SI 07

$\varepsilon_p/\varepsilon_e = 1$ (proton-electron equip.) $E_{\gamma,iso} = 10^{53}$ erg

secondary pair synchrotron+



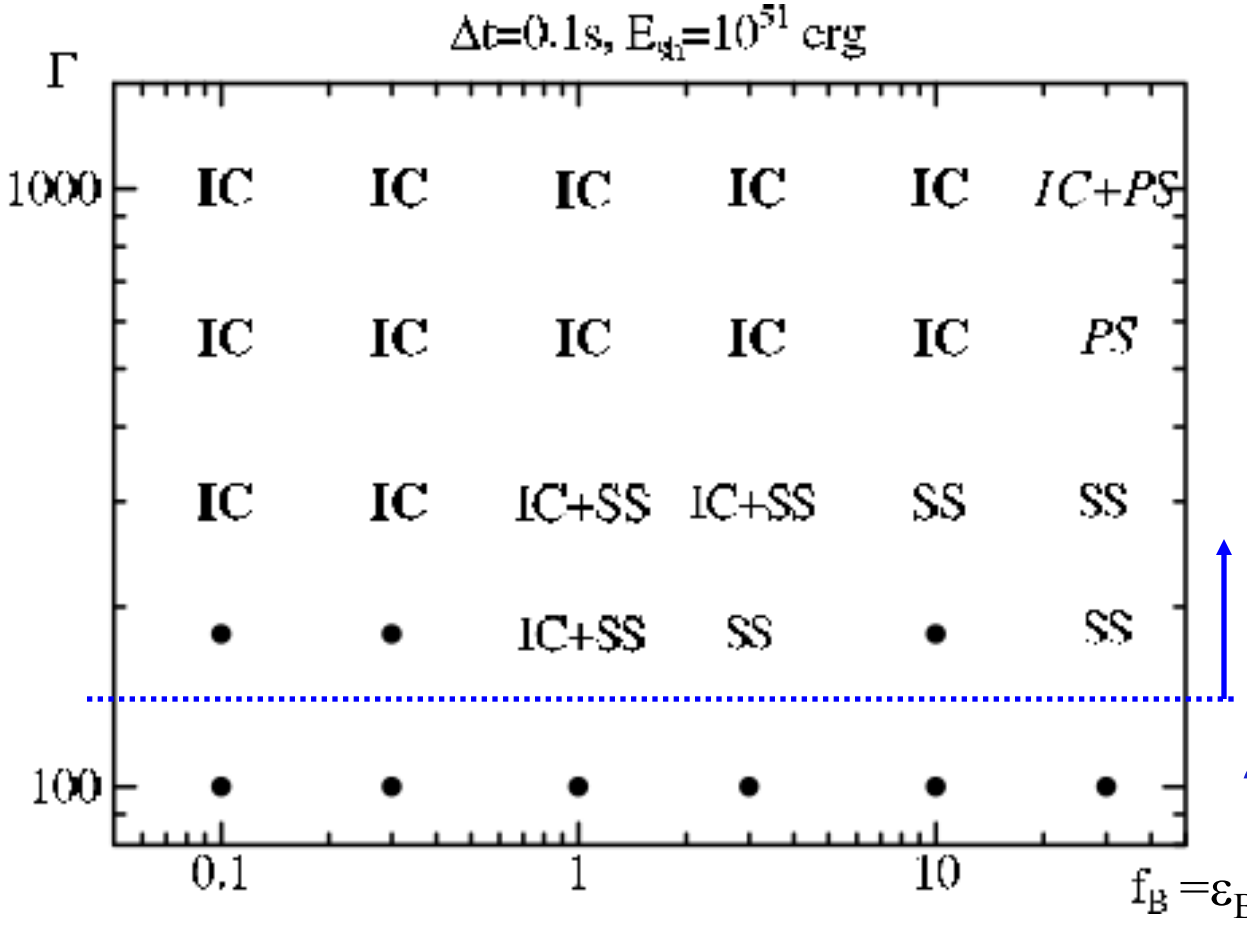
muon synchrotron+



double (multiple) breaks
-> proton signature

Fermi, Cerenkov telescopes…

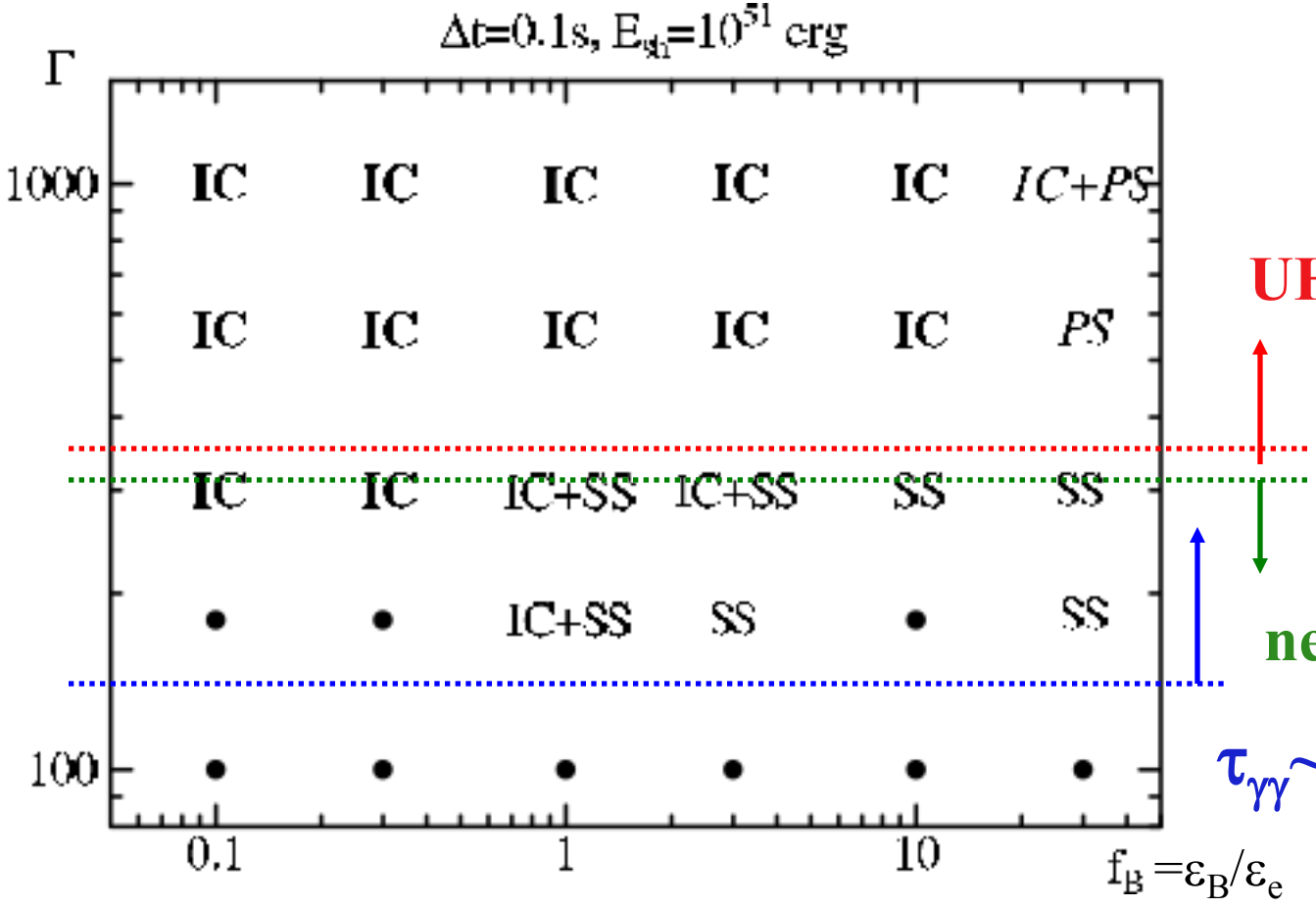
GRB GeV-TeV



$\tau_{\gamma\gamma} \sim n_g R \sigma_{\gamma\gamma} < 1$

proton-induced γ components require $\varepsilon_B/\varepsilon_e > 1$

GRB GeV-TeV - UHECR - neutrino connection



UHECR escape

$\tau_{exp} < \tau_{p\gamma} \sim n_\gamma R \sigma_{p\gamma}$

n conversion

$\tau_{exp} > \tau_{p\gamma}$

neutrino emission

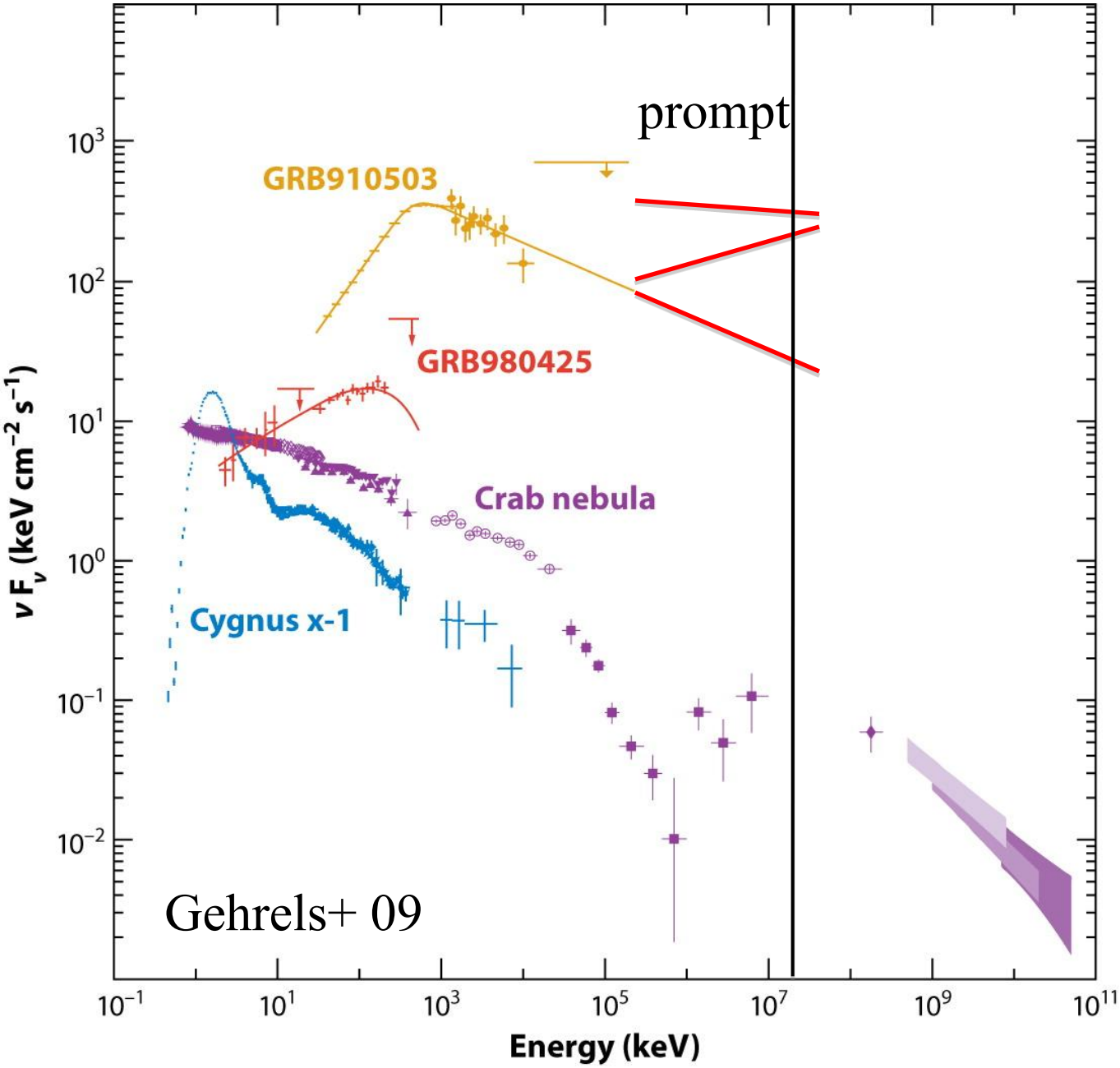
$\tau_{\gamma\gamma} \sim n_\gamma R \sigma_{\gamma\gamma} < 1$

proton-induced γ components: $\varepsilon_B/\varepsilon_e > 1$

$\Gamma_{UHE} > \sim 300\ (\Delta t/0.1s)^{-0.3} (E/10^{51} erg)^{0.5}$

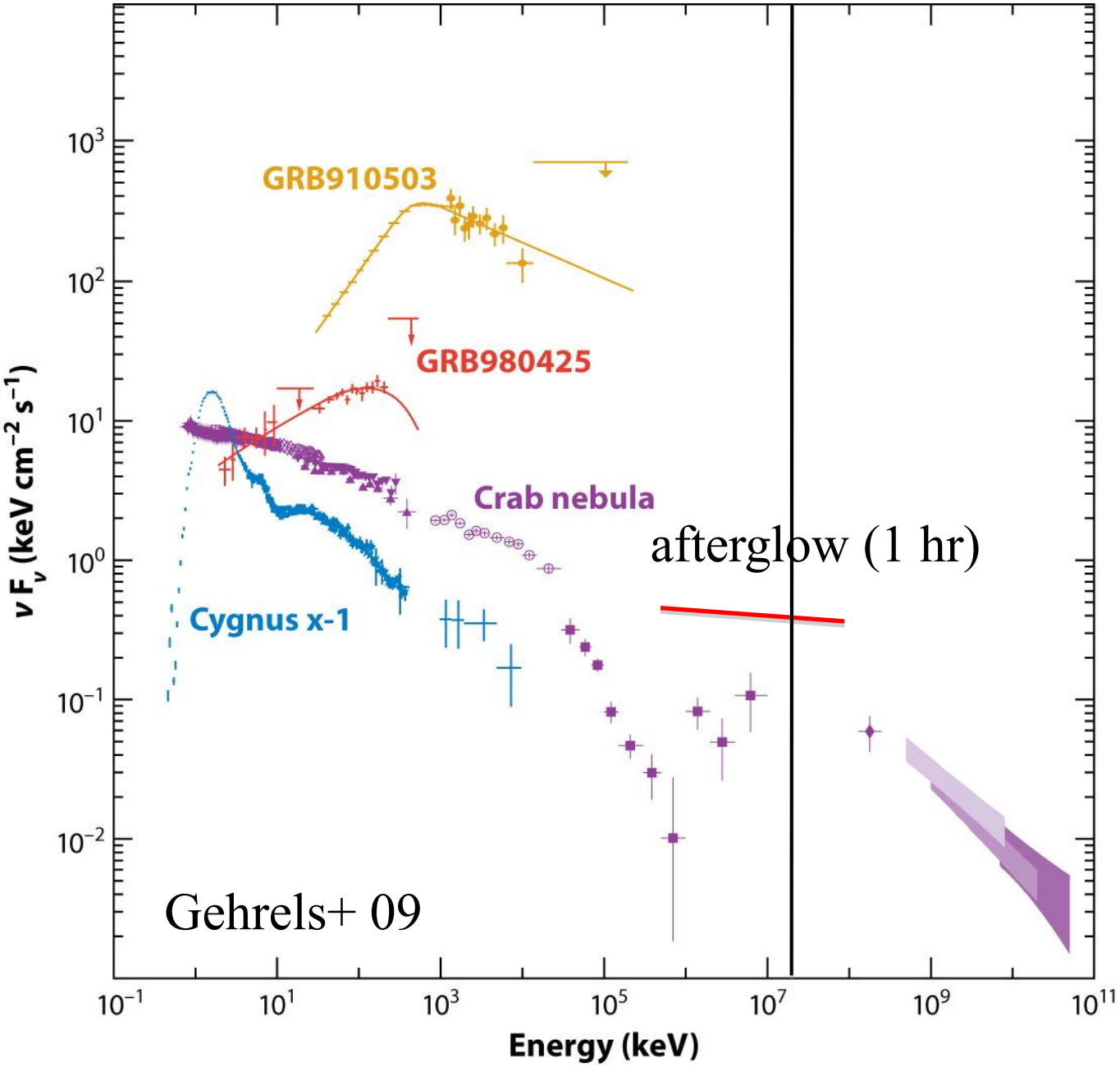
GeV-TeV (inc. IC) : $\tau_{\gamma\gamma} < 1$ -> $\tau_{exp} < \tau_{p\gamma}$ efficient UHECR escape

GRBs: Fermi results



- prompt GeV in bright GRBs
- MeV extension at least to 10-30 GeV
- excess hard compt. for brightest GRBs
- both long (few 100s), short (few s)

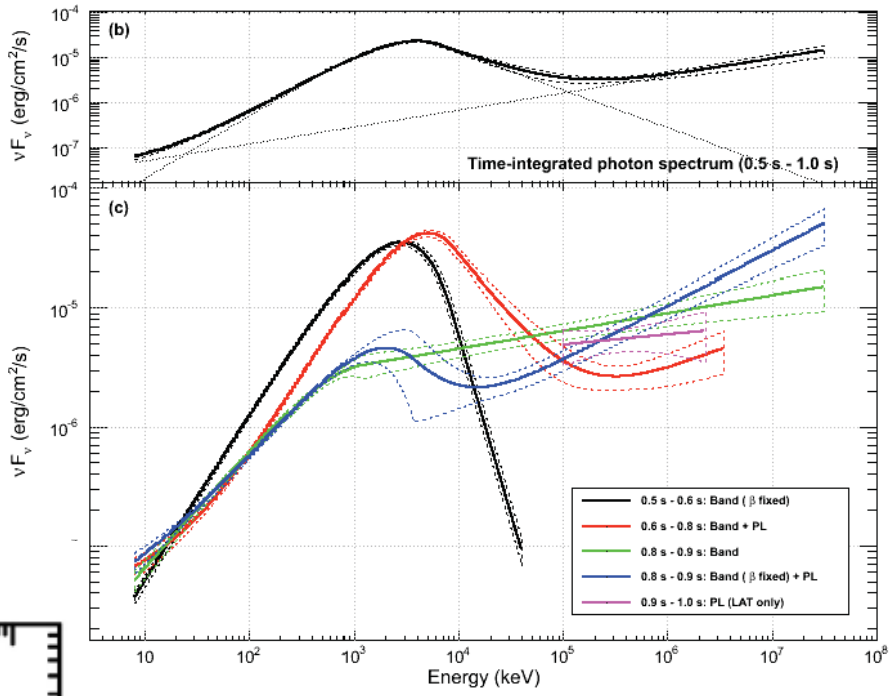
GRBs: Fermi results

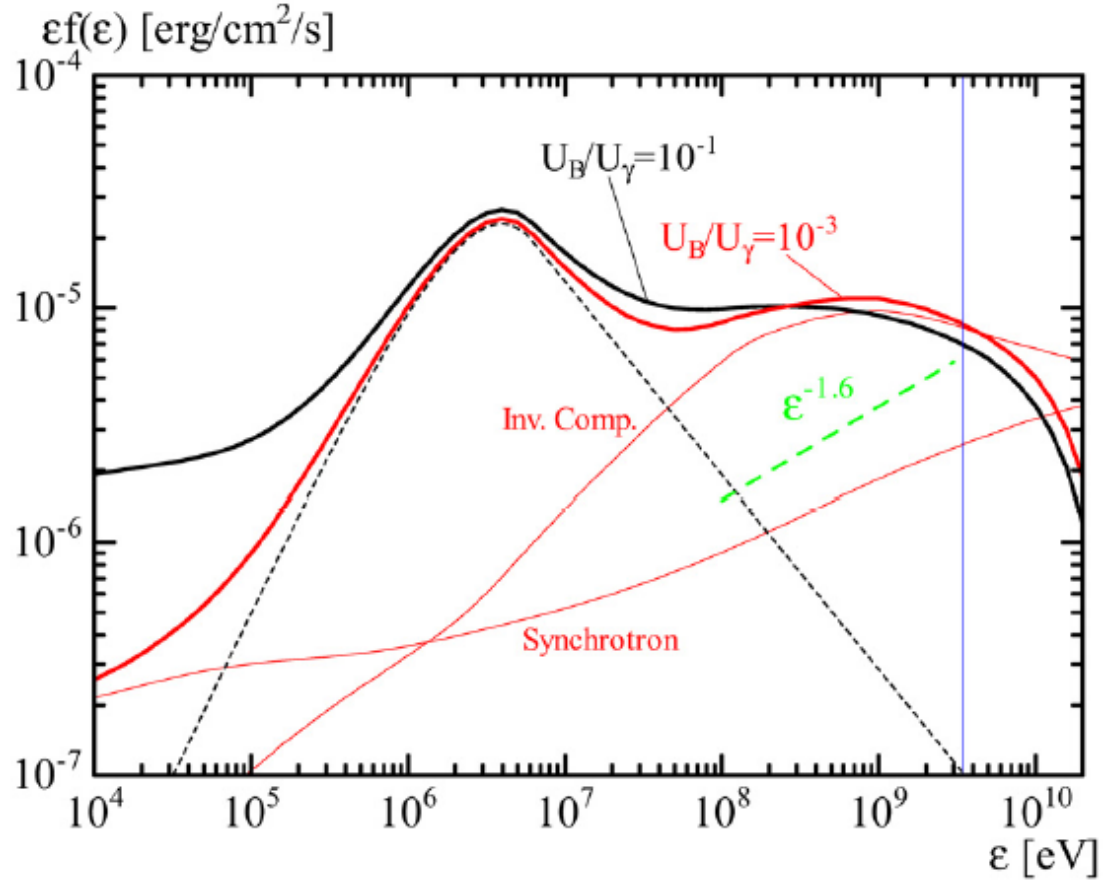


- GeV afterglow up to few ks
  $\propto$ $t^{-1.2}$-$t^{-1.5}$
- consistent with most GRBs having GeV prompt+afterg.
- BUT physics unclear due to low GeV photon statistics

hadronic emission model: GRB 090510

Asano+ 09





$R=10^{14}$ cm

$\Gamma=1500$

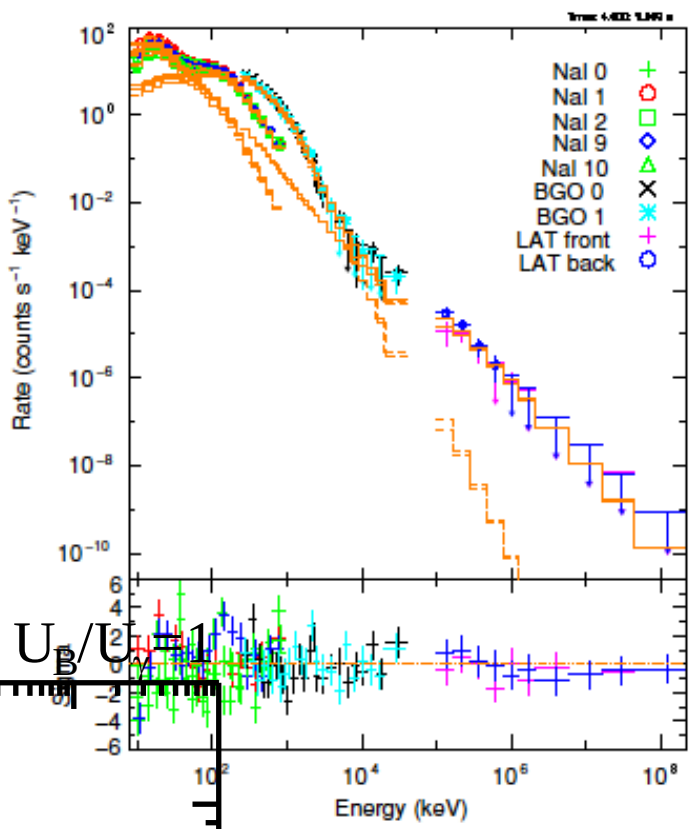
$U_B/U_\gamma=0.001$

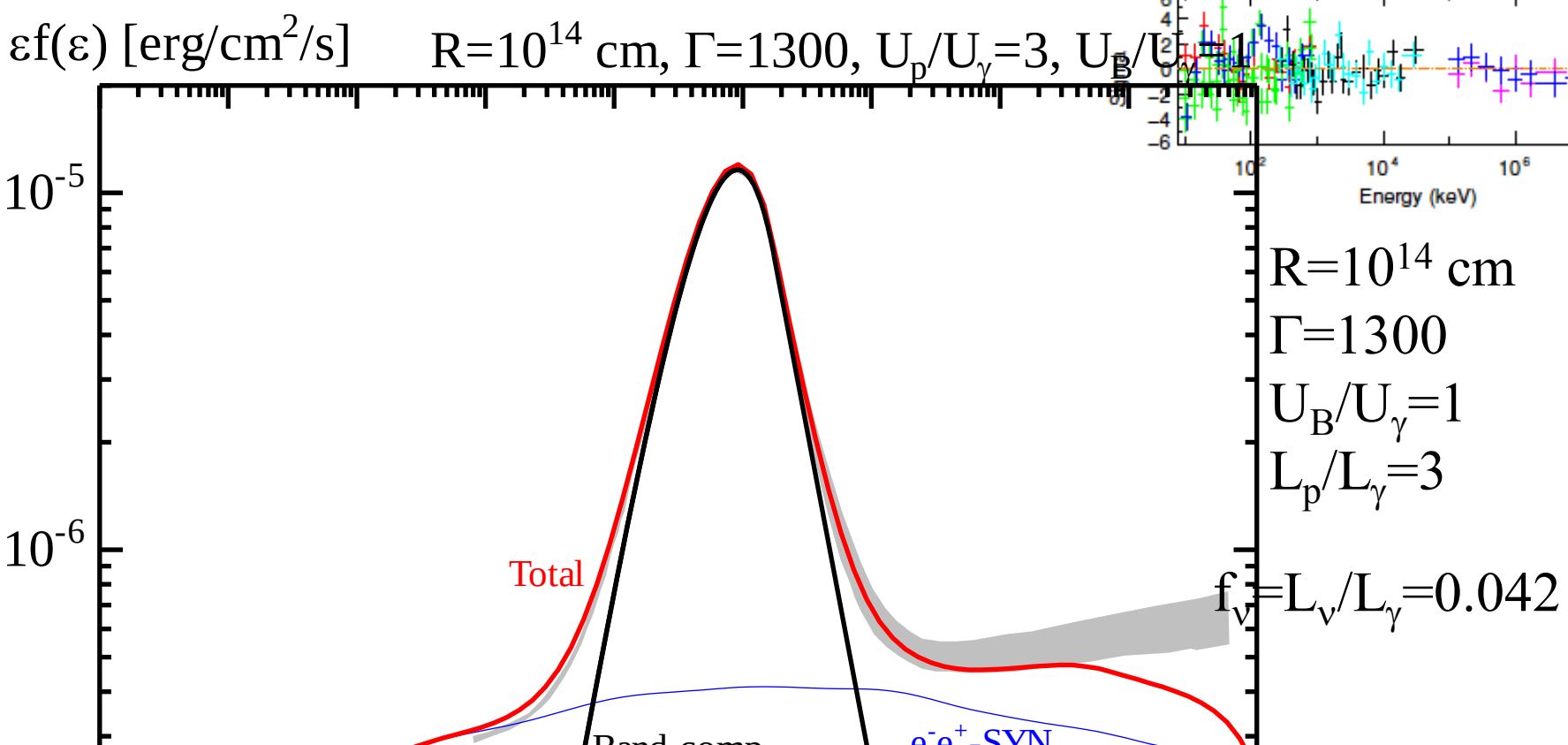
$L_p/L_\gamma=200$

$f_\nu=L_\nu/L_\gamma=0.40$

hadronic emission model: GRB 090902B

Asano, SI & Meszaros 10





R=10^{14} cm

Γ=1300

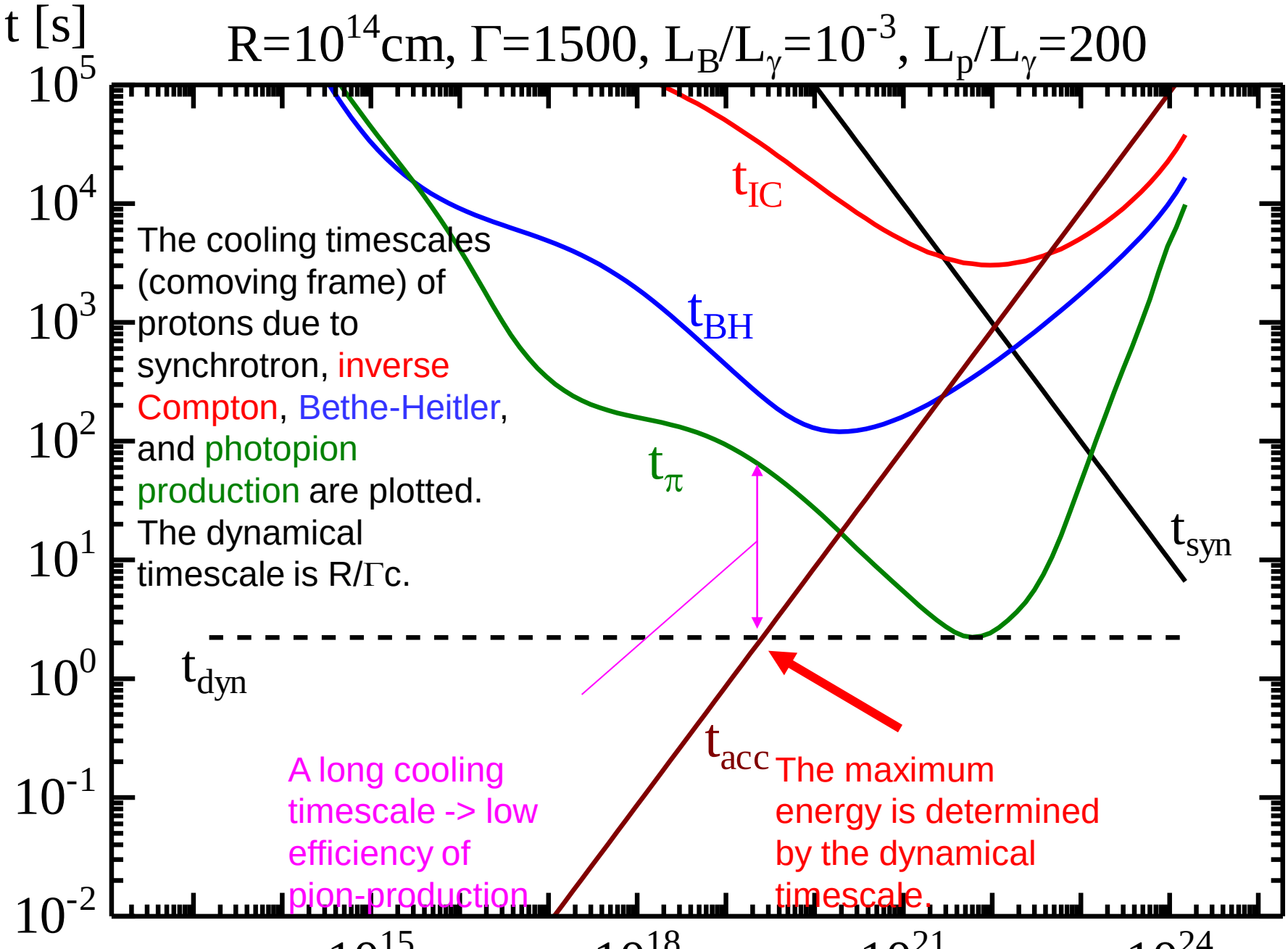
U_B/U_γ=1

L_p/L_γ=3

$f_\nu=L_\nu/L_\gamma$=0.042

hadronic process timescales

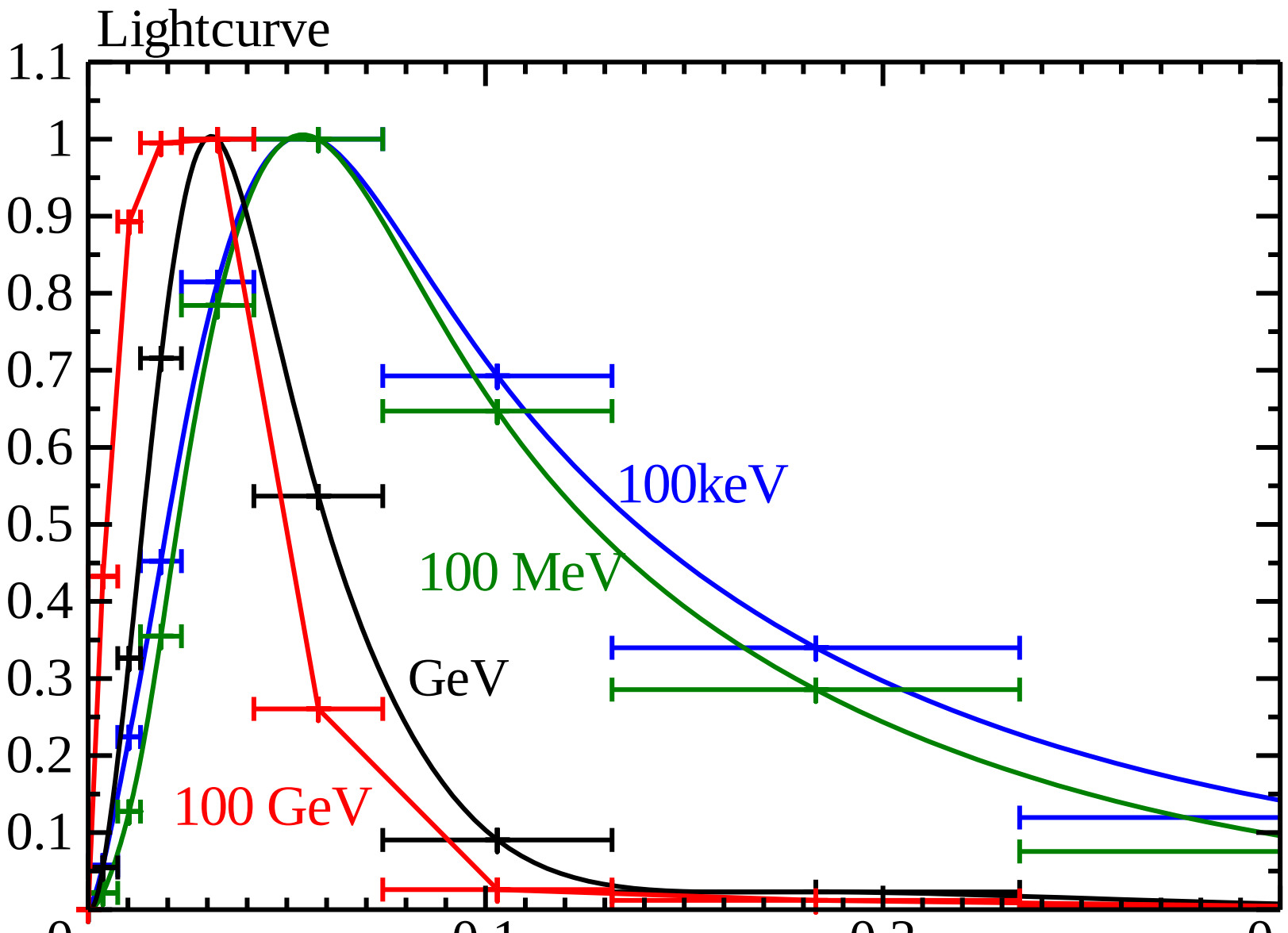
courtesy Asano



light curve modeling

courtesy Asano

currently leptonic only



CTAによるGRB観測

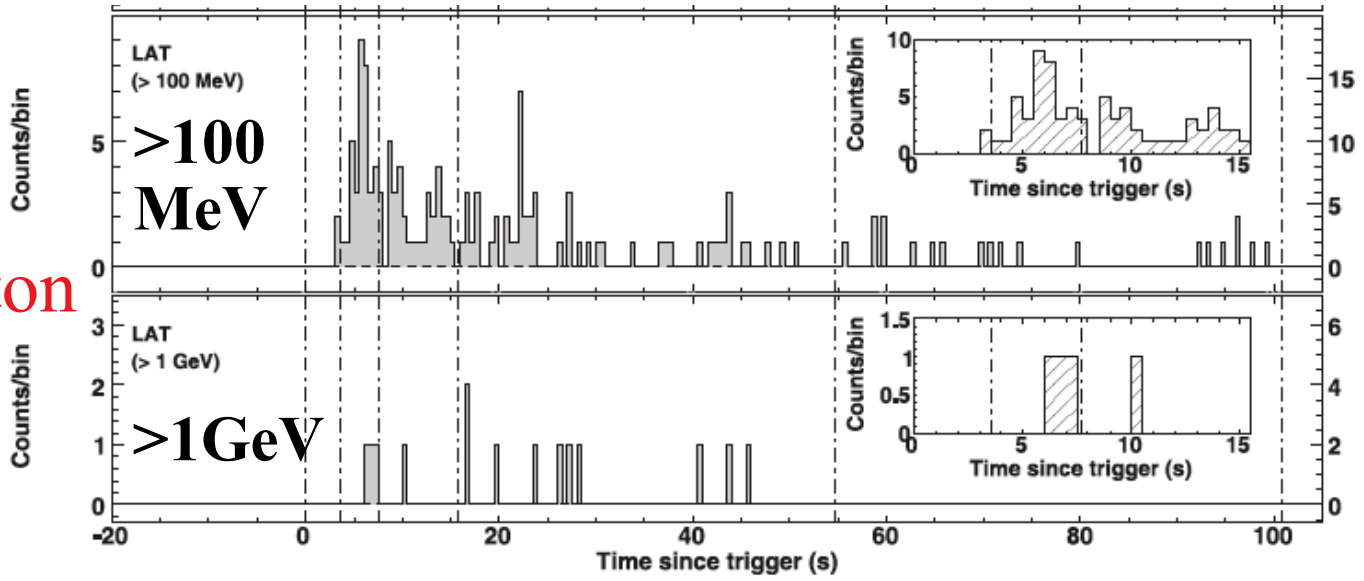
1. 10 GeVに迫るエネルギー閾値 (<<現行IACT)
-> 宇宙背景放射光 (EBL) によるγγ吸収を受けにくい

2. 高速指向性能：180deg/20sec for LST (MAGIC2と同等)
-> long GRBの即時放射中に観測開始

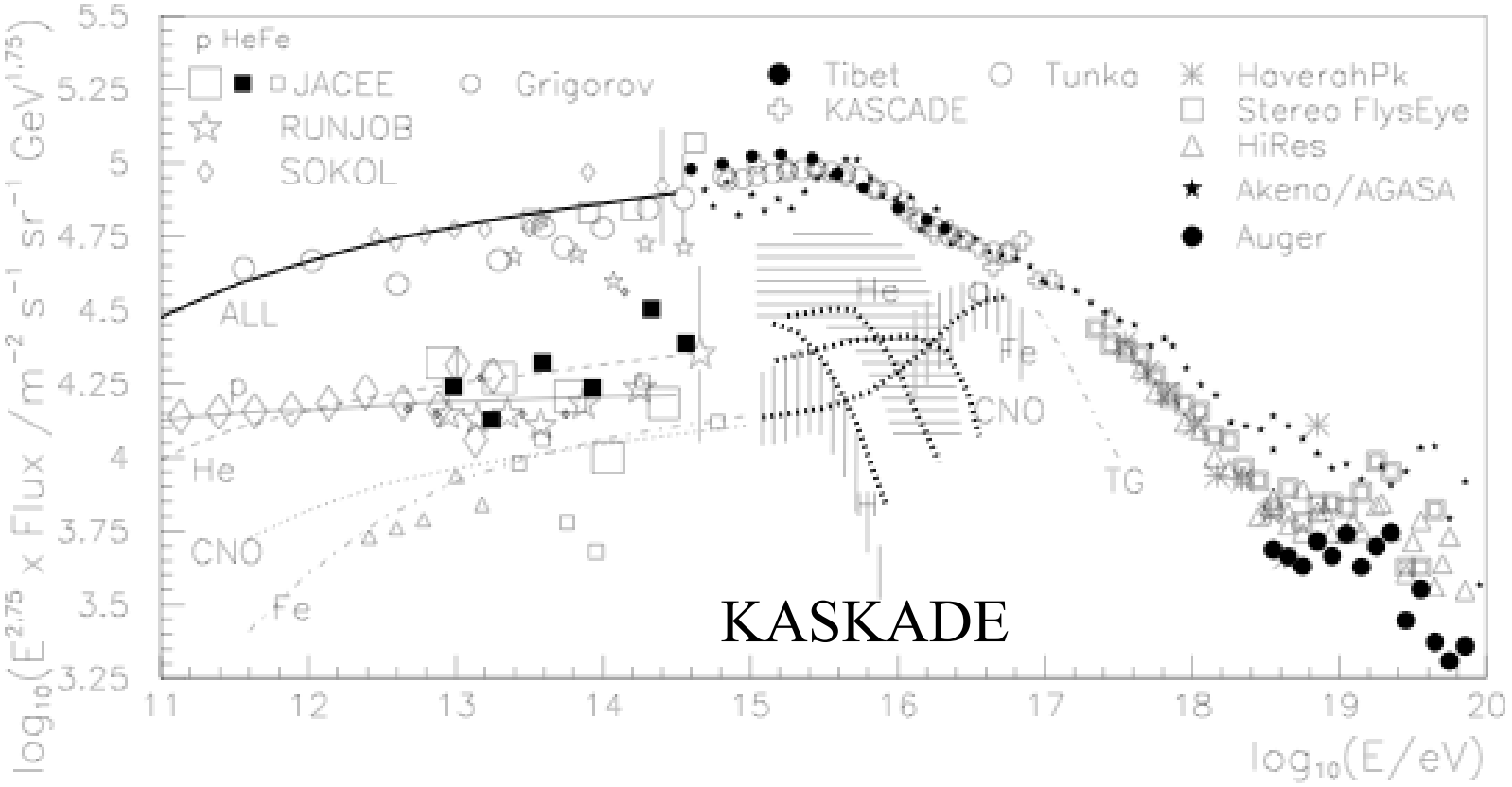
3. 莫大な有効面積：>$10^4 m^2$@30GeV (Fermiの1万倍)
-> 圧倒的な光子統計、詳細なスペクトル・時間変動の情

> 10 GeV photon
Fermi数発 ->
CTA 数万発！

Fermi LAT GRB 080916C Abdo+ 09



Galactic CRs: knee-ankle region

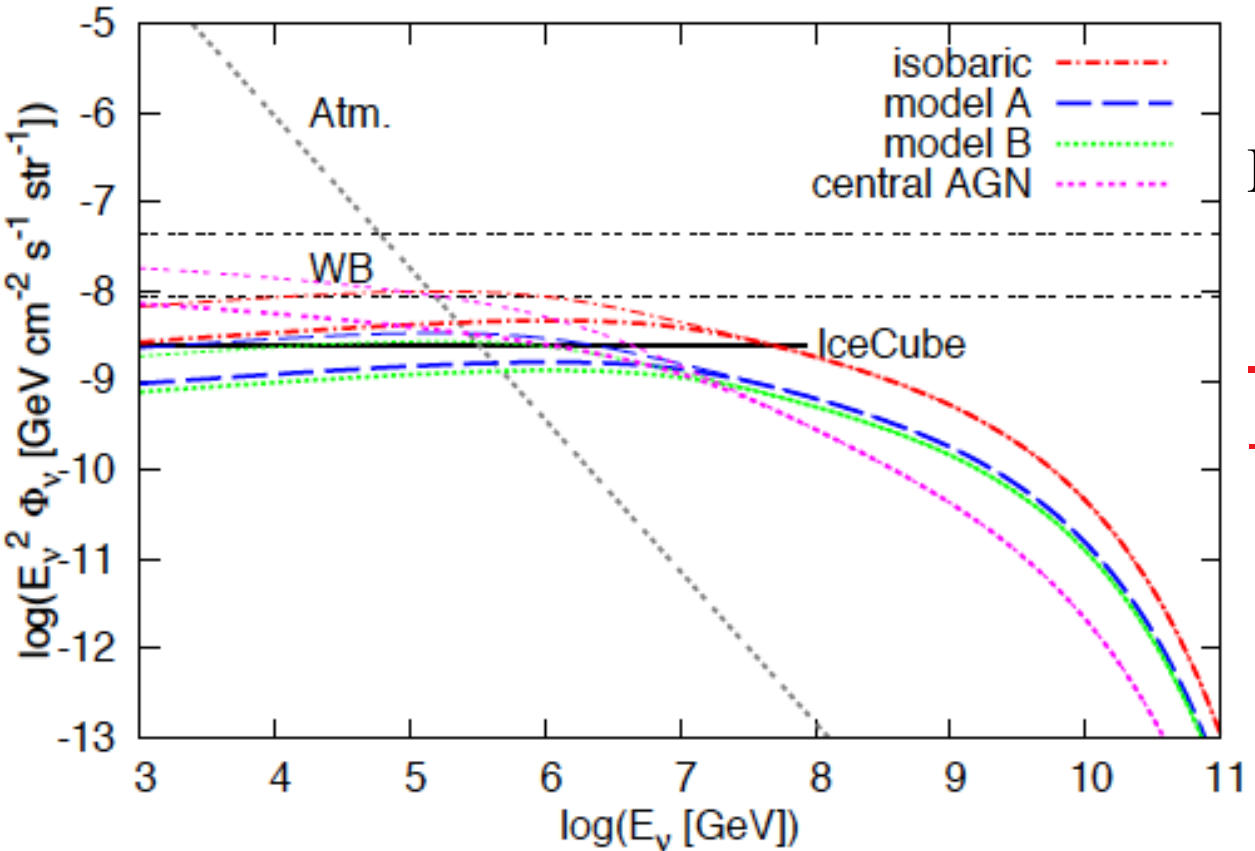


SNRs in stellar winds? multiple SNRs in OB associations
Galactic wind termination shocks?
cluster merger/accretion shocks?
low-energy extension of UHECR spectra (no new source)?

knee-ankle CRs from clusters and p-p neutrinos

$p_{CR}+p_{ICM} \rightarrow \pi^0, \pi^{+-}$ $\quad \pi^{+-} \rightarrow 2\nu_\mu, \nu_e$

Berezinsky+ 97
Colafrancesco & Blasi 98



Murase, SI, Nagataki 08

- promising for IceCube
- probe of PeV CR confinement
(difficult with γ due to γγ horizon)

IceCube-40 limit Abbasi+ arXiv:1012.2137

Catalog	N Sources	Model	p-value	ν_μ Sensitivity	ν_μ Upper Limit	$\nu_\mu + \nu_\tau$ Sensitivity	$\nu_\mu + \nu_\tau$ Upper Limit
Milagro Sources	17	E^{-2}, Uniform	0.32	$\Phi^{90} = 9.0$	$\Phi^{90} = 12.3$	$\Phi^{90} = 15.8$	$\Phi^{90} = 24.5$
	6	6 SNR Assoc.[a]	[c]			SF = 2.9	SF = 7.2
Starburst Galaxies	127	E^{-2}, $\propto$ FIR Flux	–	$\Phi^{90} = 33.1$	$\Phi^{90} = 33.1$	$\Phi^{90} = 58.6$	$\Phi^{90} = 58.6$
Clusters of Galaxies	5	Model A[b]	0.78			SF = 8.4	SF = 7.8
		Model B[b]				SF = 14.4	SF = 12.0
		Isobaric[b]				SF = 13.2	SF = 13.2
		Central AGN[b]				SF = 6.0	SF = 6.0

まとめ

系内宇宙線源

SNR（長年最有力）
X線観測　-> 磁場増幅
GeV-TeV　-> ハドロンっぽいが未確定　　ニュートリノで決定
宇宙線逃げる様子が見え

超高エネルギー宇宙線源

系外以外はまだまだ不明
blazar GeV-TeV: 一部／全部ハドロン解釈もまだあり？
GRB GeV: ハドロン解釈も充分可能
-> 今後時間変動から識別　　ニュートリノで決定打

knee-ankle宇宙線　　ニュートリノのみ？

宇宙線　ああガンマ線
ニュートリノ
~~TAや~~ ~~ああ~~CTA　IceCube（Tibet等も）