High Energy Gamma-Rays from GRBs and Clusters induced by UHE Hadrons

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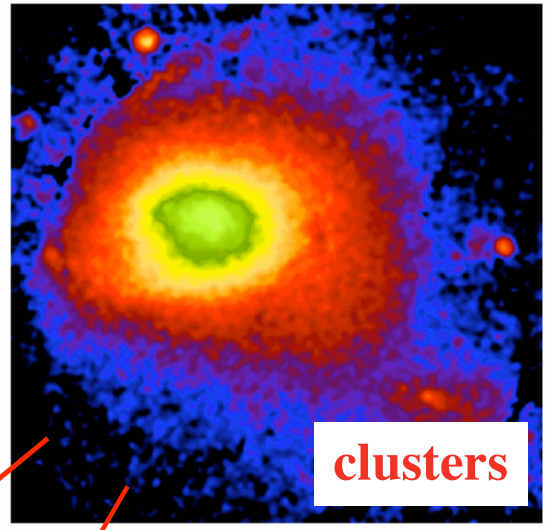


γ

γ

p, Fe?

p, Fe?

outline

1. **introduction**
   radio-loud AGNs vs Auger

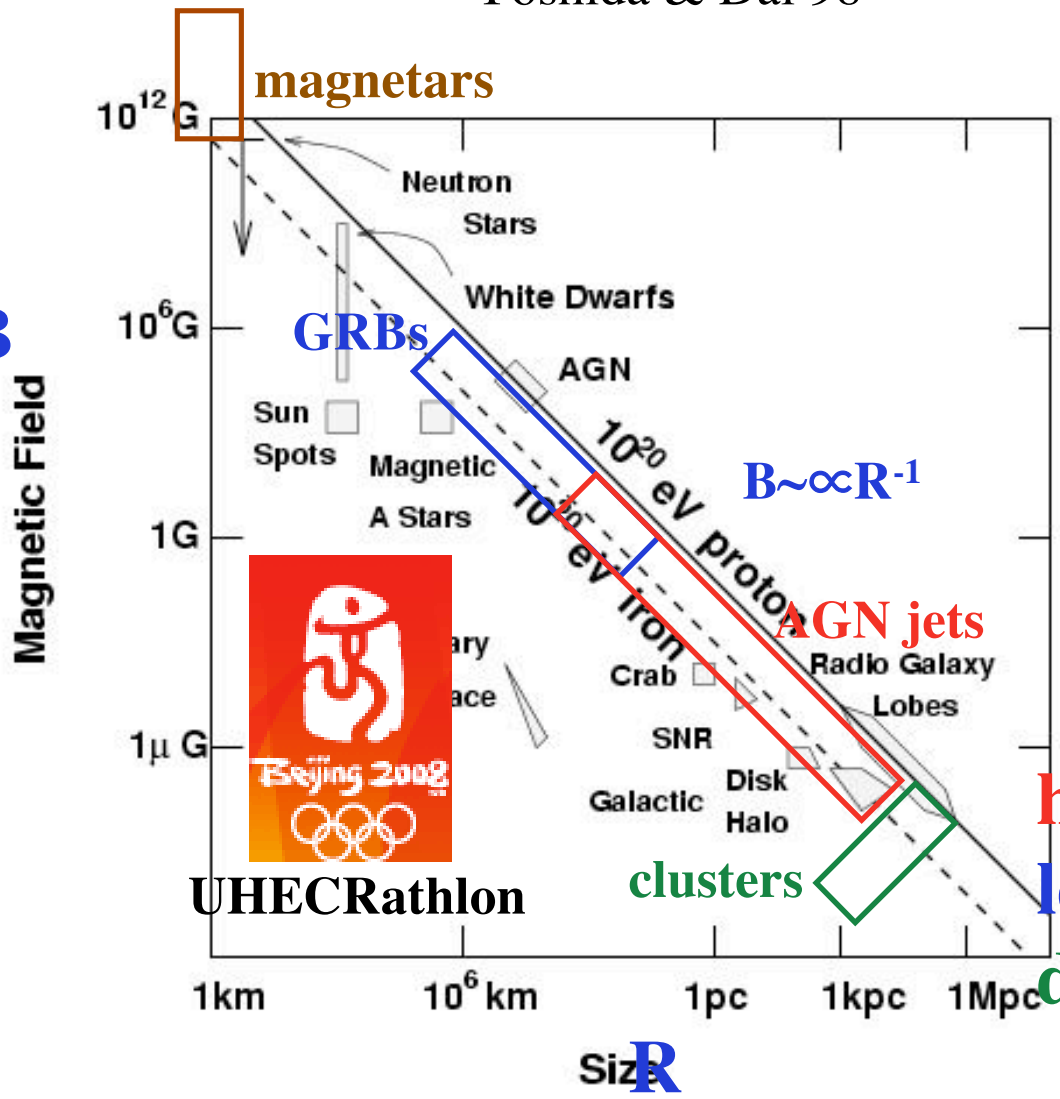
2. **GRBs:**
   proton-induced cascade emission
   proton-dominated GRBs
   UHE nuclei synchrotron

3. **clusters:**
   UHE proton-induced X & γ-rays
   heavy nuclei as UHECRs

review: Inoue, arXiv:0809.3205 (TAUP2007 proceedings)

UHECR sources: acceleration

"Hillas plot" adapted from Yoshida & Dai 98



UHECRathlon

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

confinement

E_{max} acceleration vs:

escape
source lifetime
adiab. expansion loss
radiative loss

heavy favorite: AGNs

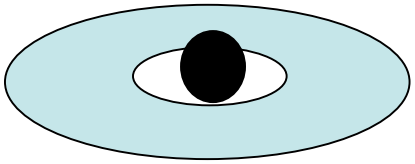
leading contender: GRBs

dark horse: clusters, etc.

upsets do occur…

active galactic nuclei (AGNs)

supermassive black hole
+accretion disk (flow)



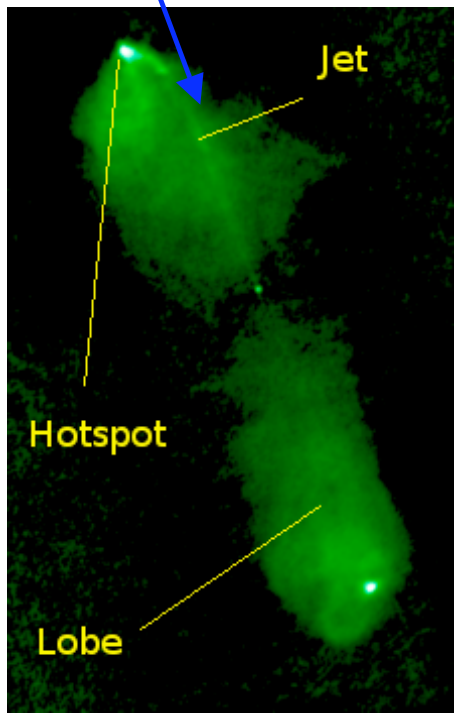
radio-loud
(relativistic jet)

high-
power

~<1%

FR 2
radio
galaxy

GeV blazar

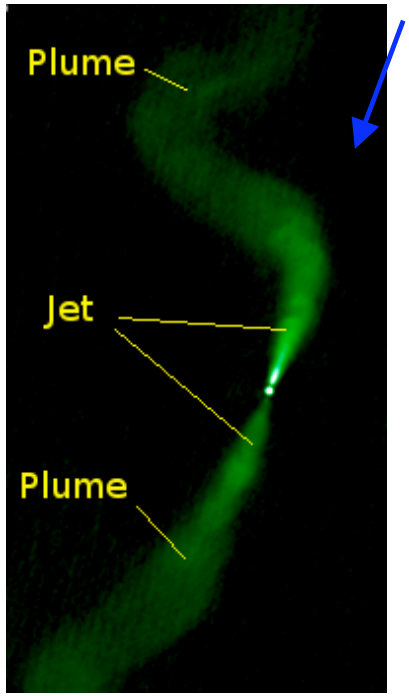


low-
power

~9%

TeV blazar
(BL Lac)

FR 1
radio
galaxy



radio-
quiet
(no jet)

~90%

Seyfert galaxy
radio-quiet quasar

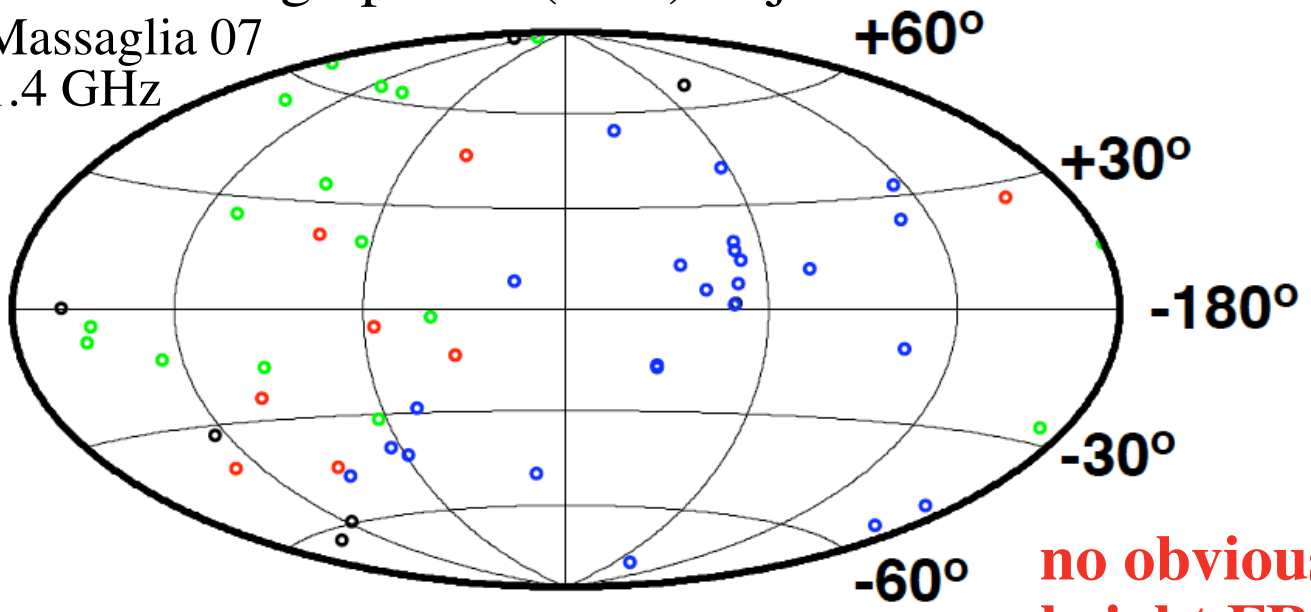
strong nonthermal
emission
=particle acceleration

radio galaxies vs UHECR

Takami, SI, Yamamoto & Sato in prep.

high power (FR2) objects

Massaglia 07
1.4 GHz



radio galaxies (D<75Mpc): black

Auger: blue

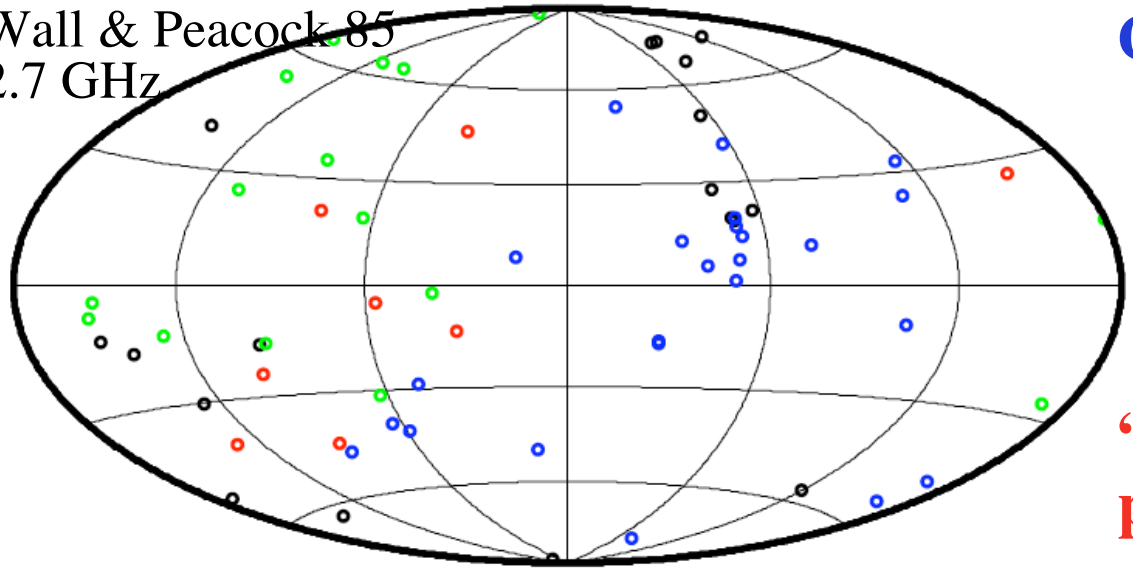
AGASA:
green (>40 EeV)
red (>20 EeV)

no obvious correlations with bright FR2 or 1 radio galaxies

Cen A statistical fluke?

high+low power (FR2+1) objects

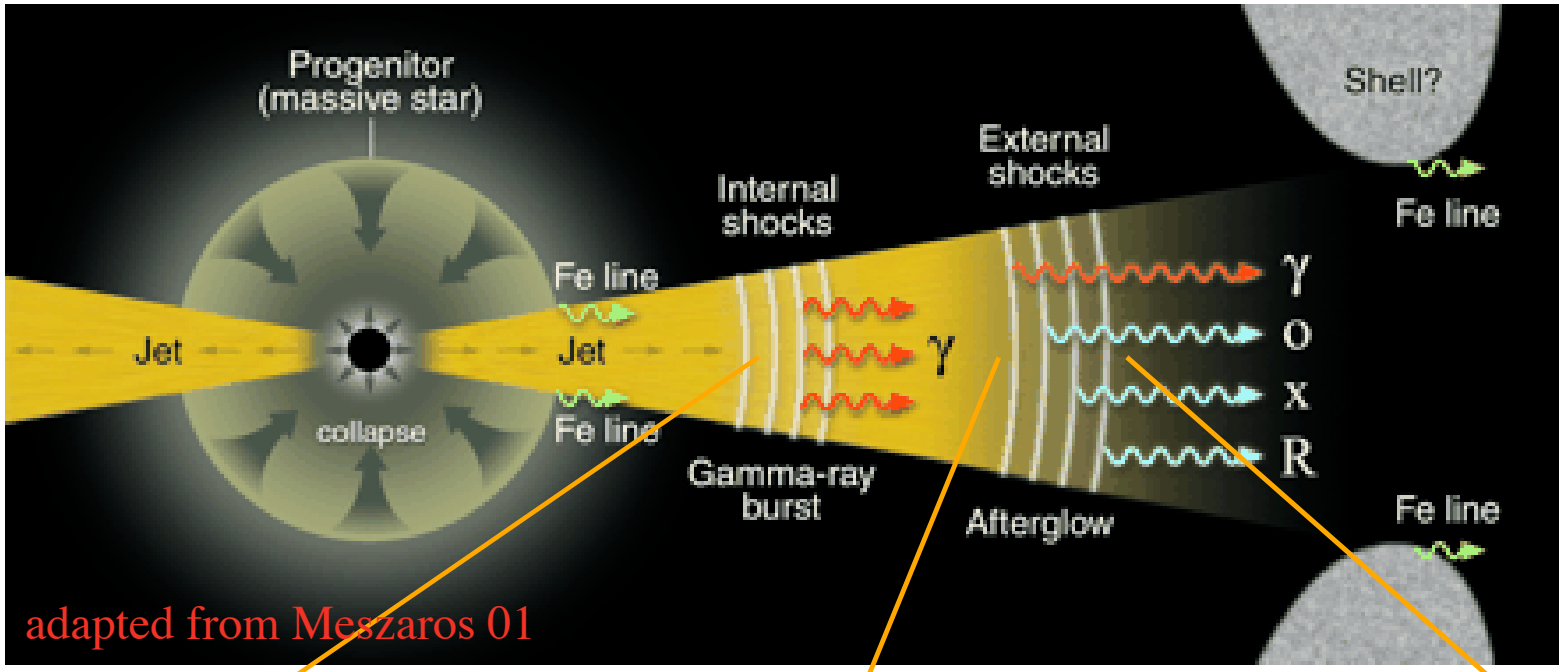
Wall & Peacock 85
2.7 GHz



"simplest" radio-loud AGN picture not confirmed

GRBs: acceleration sites

宇宙最大爆発



Waxman 95
Vietri 95

prompt X-γ emission
internal shocks

$R \sim \Gamma^2 ct_{var} \sim 10^{12}\text{-}10^{16}$ cm
$B \sim 10^{6}\text{-}10^{3}$ 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

$R \sim R_{dec}\text{-}R_{NR} \sim 10^{16}\text{-}10^{18}$ cm
$B \sim 10\text{-}0.01$ G? $>> B_{ISM}$
$\Gamma_{rel} >> 1$

escape nontrivial

accel. nontrivial

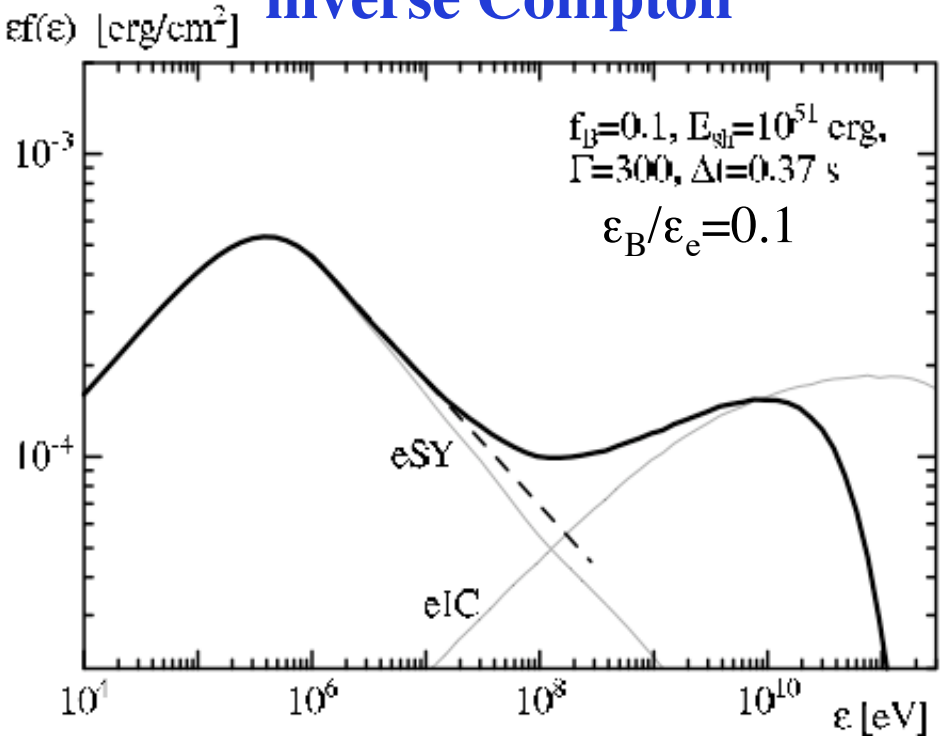
GRB GeV-TeV emission from electrons+protons

- 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

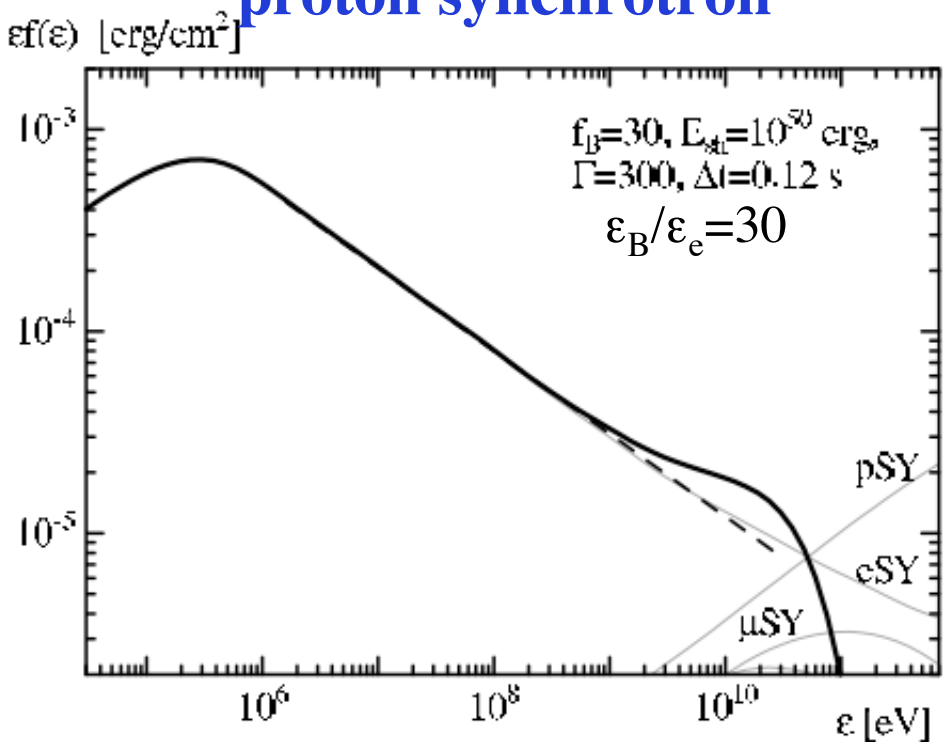
Asano & SI 07

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

inverse Compton



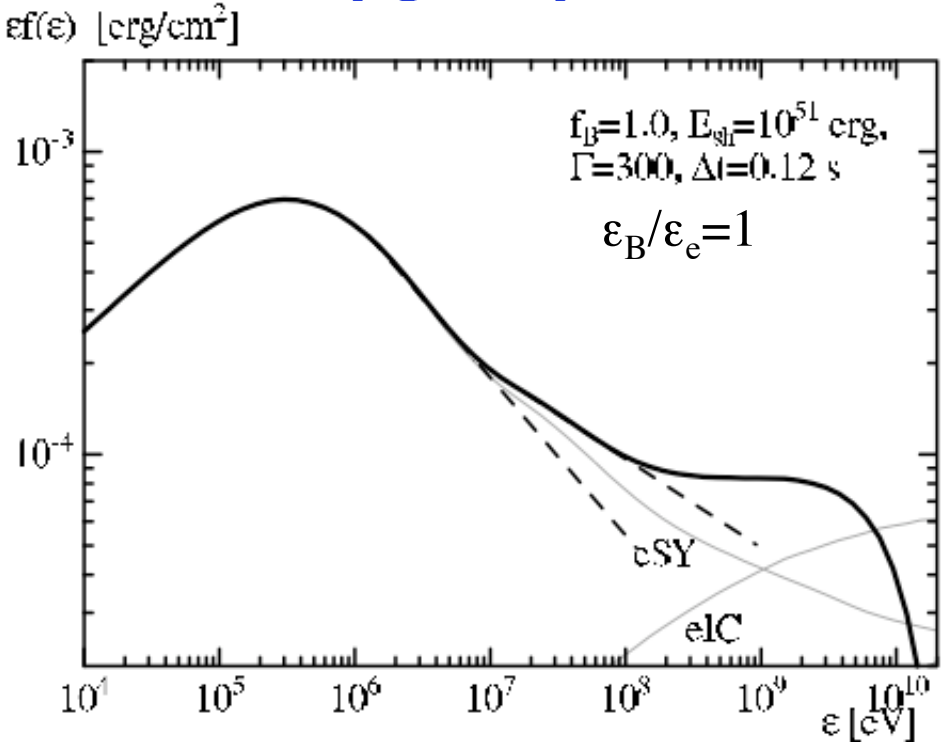
proton synchrotron



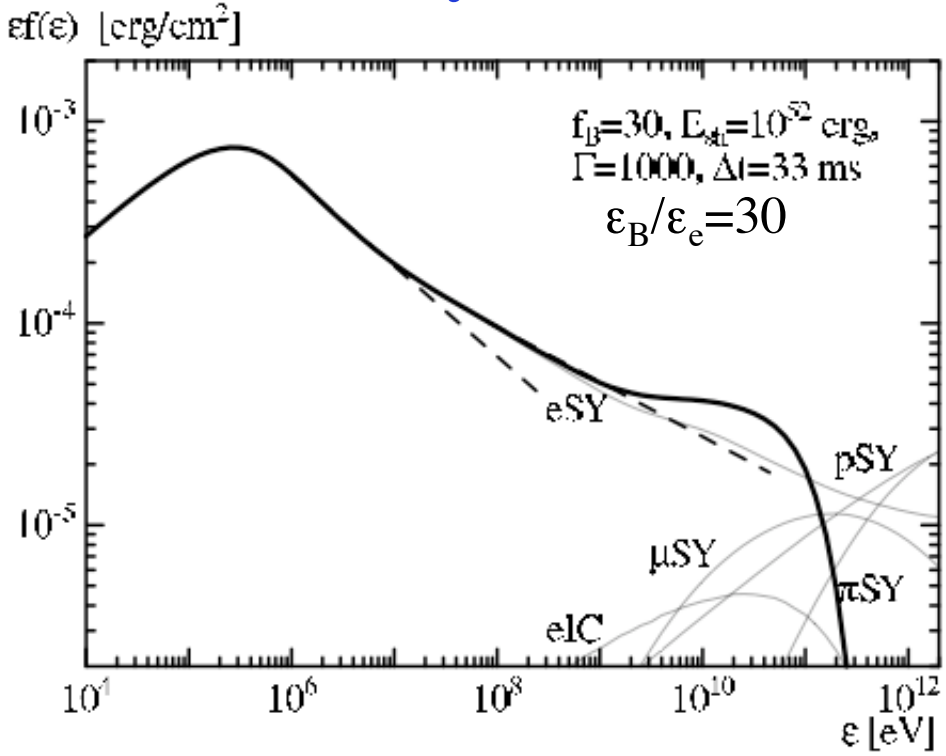
GRB GeV-TeV emission

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

secondary pair synchrotron+



muon synchrotron+



double (multiple) breaks
-> proton signature

Fermi, MAGIC (II), HESS (II), VERITAS, CANG.III …
MILAGRO, ARGO…

post-Swift GRB energetics

- local emissivity $E_p^2 dN_p/dtdE_p$
  ~ 10^{44} erg/yr/Mpc^3 for $E_p > 10^{19}$ eV only, $>10^{44}$ if also at $E_p < 10^{19}$ eV

- post-Swift local GRB rate
  ~ 0.2-1 /yr/Gpc^3 if $\propto$ SFR
  ~ 0.05 /yr/Gpc^3 if stronger z-evol.

Daigne+ 06, Guetta & Piran 07
Le & Dermer 07…

-> required total proton energy/burst (iso. eq.)

$\mathcal{E}_{p,iso} \sim 2\times10^{54}$-$3\times10^{55}$ erg (p=2, $E_p \sim 10^9$-10^{20} eV)

$\mathcal{E}_{e,iso} \sim \mathcal{E}_{\gamma,iso}$(1-$10^4$ keV) ~10^{53}-10^{54} erg

GRBs out of competition?

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$\mathcal{E}_{e,iso}$~$\mathcal{E}_{\gamma,iso}$(1-10^4 keV) ~10^{53}-10^{54} erg

GRBs out of competition?

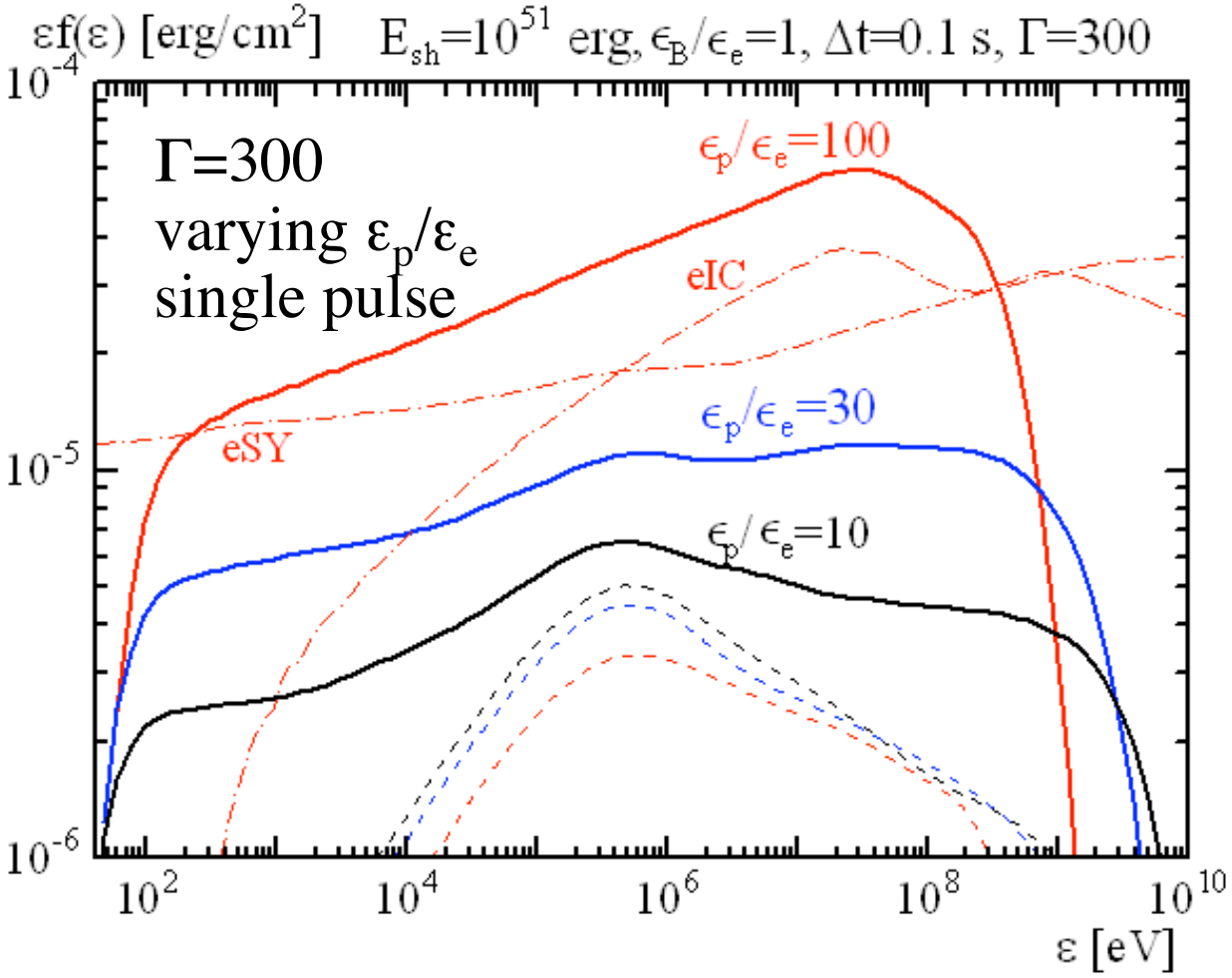
-> p/e ratio $\mathcal{E}_p/\mathcal{E}_e$ >~10-100

proton-dominated GRBs? **加油！**

- central engine poorly understood
- p/e>>1 plausible from shock physics

proton-dominated GRB GeV-TeV effect of pγ-induced pair cascade

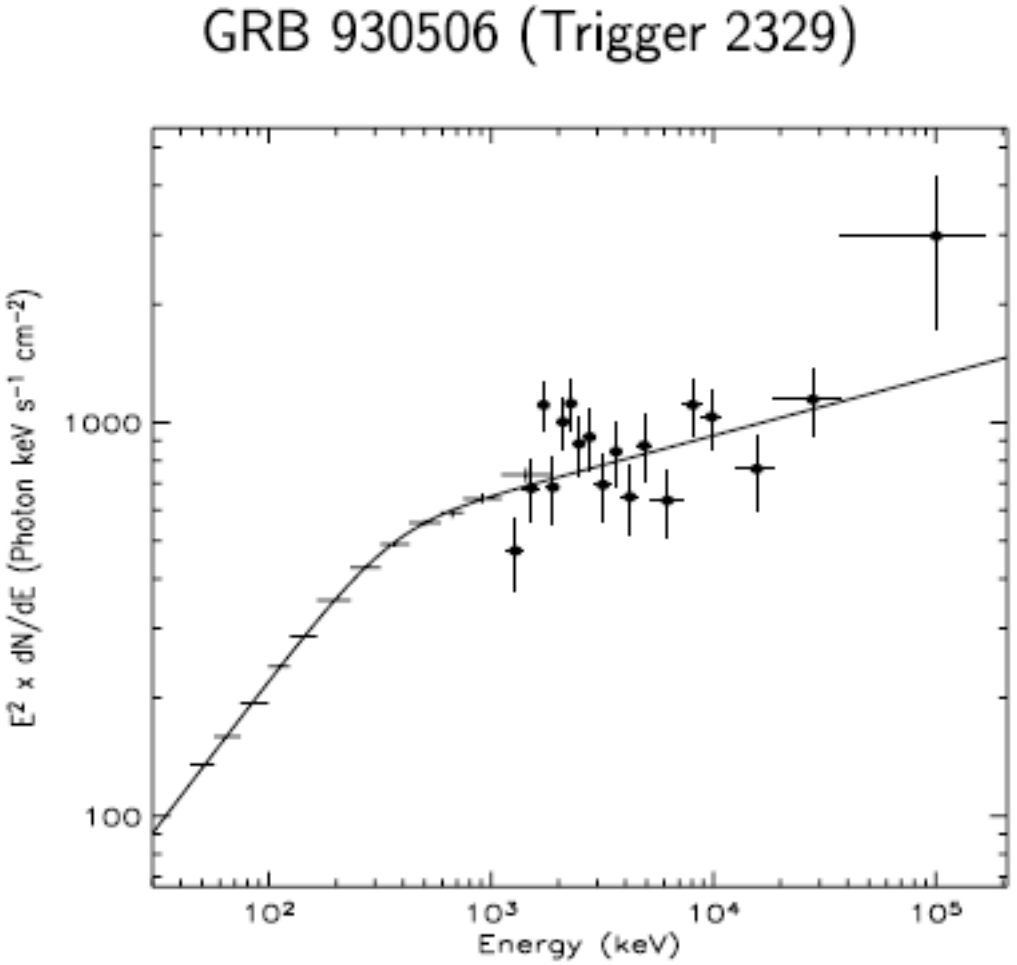
Asano, SI & Meszaros
ApJ, submitted
arXiv:0807.0951



$\varepsilon_p/\varepsilon_e$~<30:
GeV excess
+UV-X excess
from pγ-pair cascade
-> some X-ray rich GRBs?

$\varepsilon_p/\varepsilon_e$~100:
- pγ-pair cascade totally dominant! nonlinear in $\varepsilon_p/\varepsilon_e$
- both pair syn.+IC
- high E_{pk}~10-100MeV
-> seen by EGRET TASC?

high E_{peak} GRBs already observed?



Kaneko+ 08

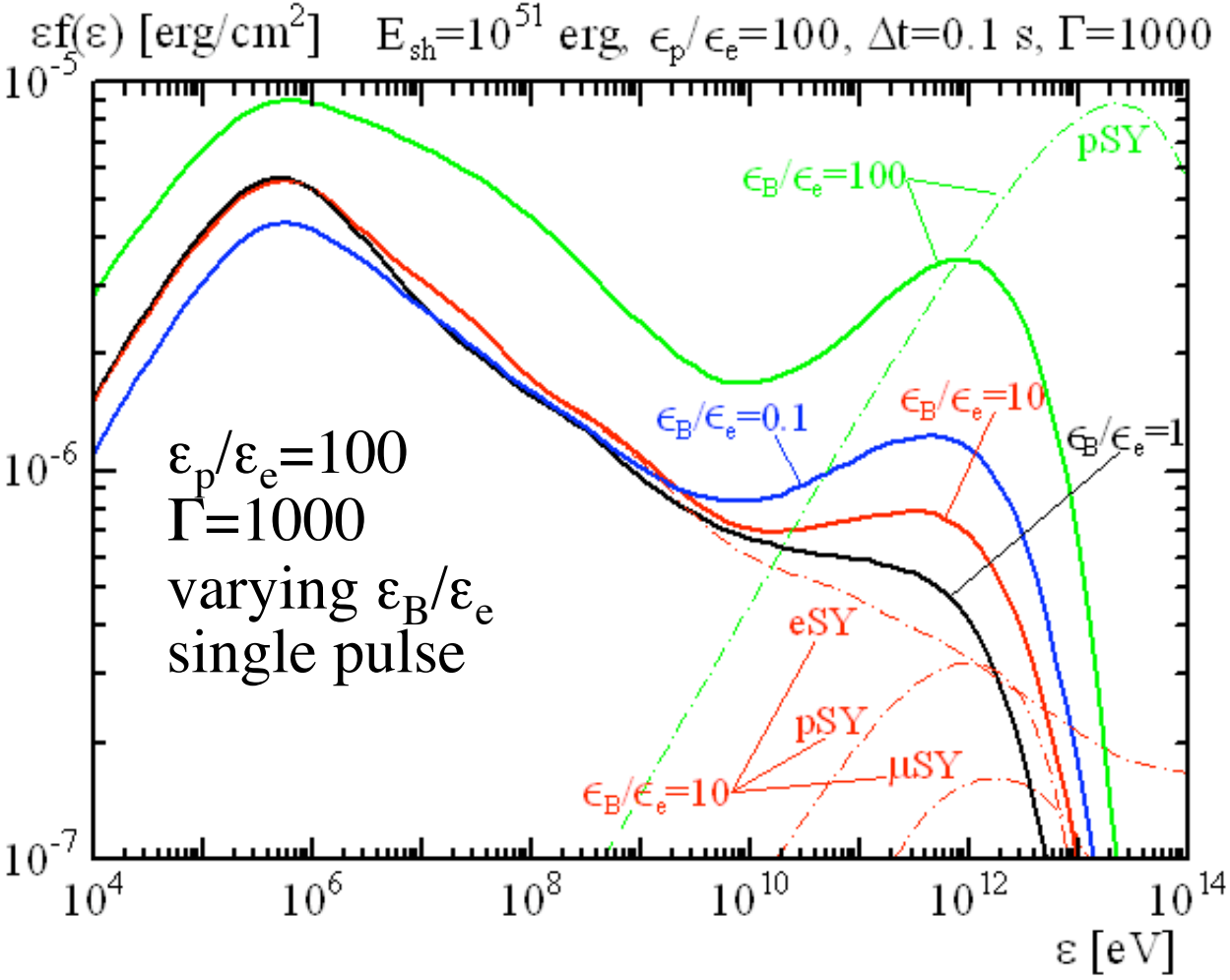
reanalysis of
EGRET TASC data

GRB with E_{peak} >170 MeV

+ few others with
high-energy excess

more to be found by
GLAST, AGILE?

proton-dominated GRB GeV-TeV
B dependence: proton synchrotron or secondary IC



TeV spectral bump

low $\varepsilon_B/\varepsilon_e$~<1:
secondary IC
weaker for higher B

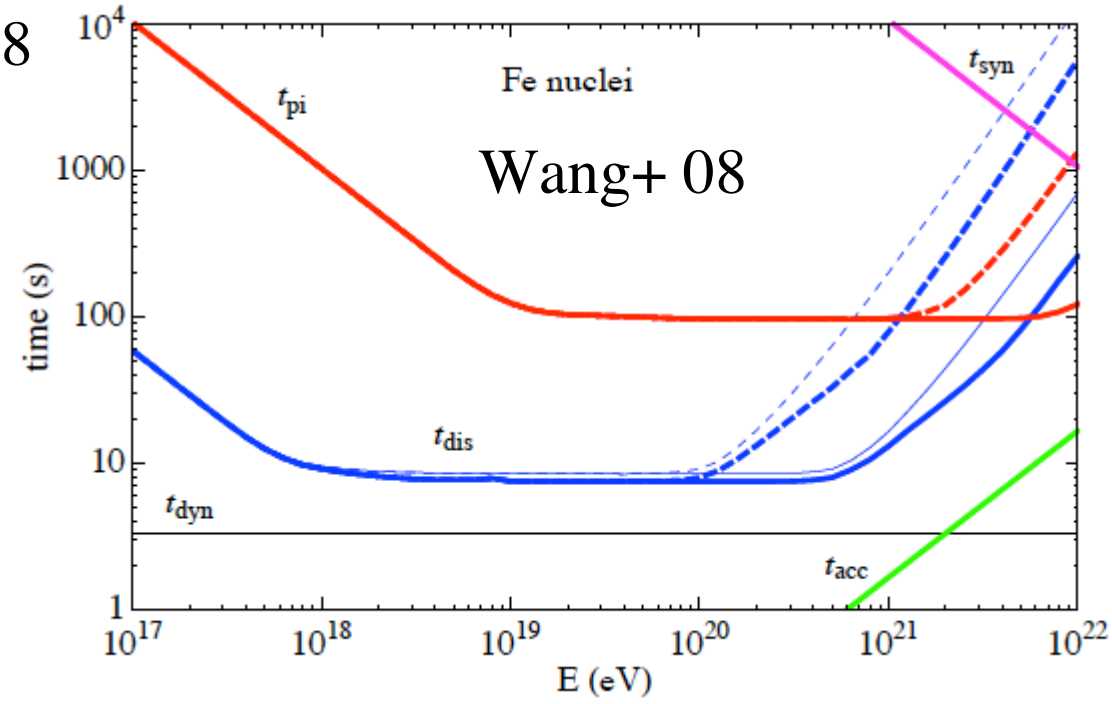
high $\varepsilon_B/\varepsilon_e$>~10:
proton synchrotron
stronger for higher B

highest $\varepsilon_B/\varepsilon_e$~100
luminous proton sync.
+γγ cascade

-> detectable by
e.g. MAGIC to z>~1?

acceleration/survival of heavy nuclei in GRBs

Anchordoqui+ 07, Wang+ 08
Murase+ 08, Dermer 08…

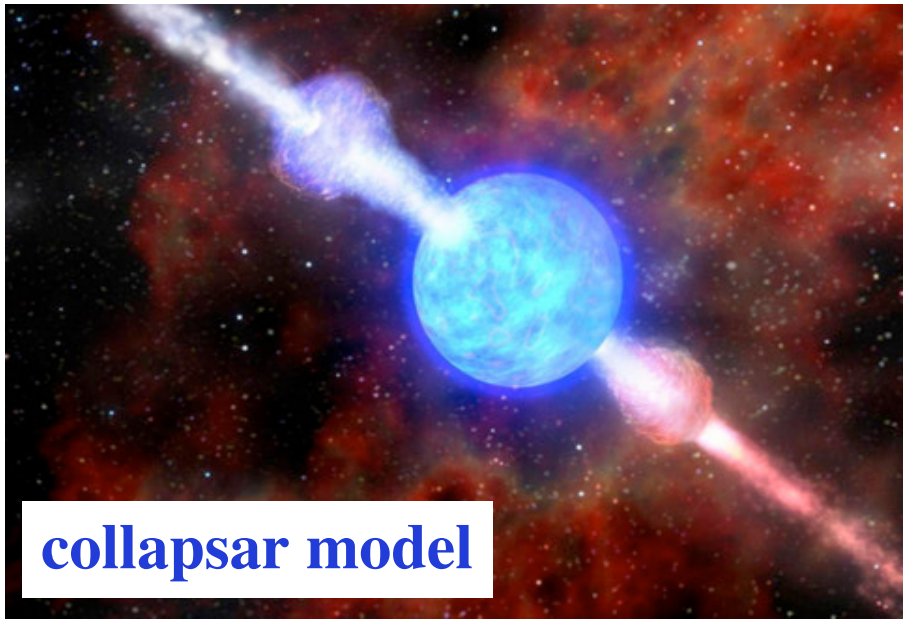


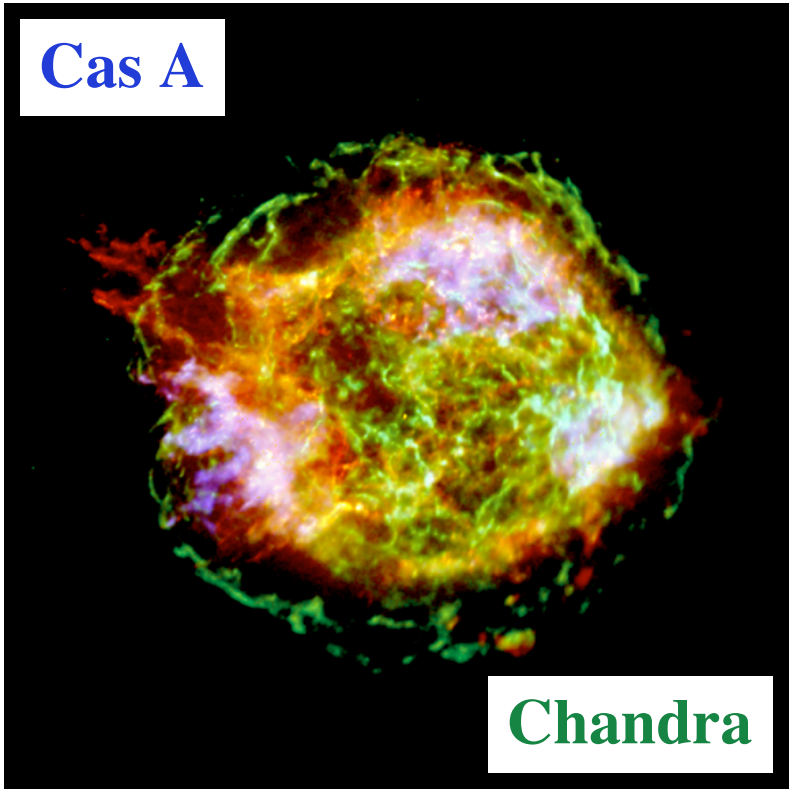
synchrotron from UHE nuclei

Inoue, in prep.

photon energy $\nu_{syn} \propto E^2 Z/A^3$
power $P_{syn} \propto E^2 Z^4/A^4$
loss time $t_{syn} \propto E^{-1} A^4/Z^4$

UHE nuclei composition at GRB?





unmixed O, Si, Fe clumps!

fiducial assumption:
abundance at low E=Galactic CR source at fixed E/A
H=1, He=0.07, C=3x10^{-3}, O=3.7x10^{-3}, Si= 7x10^{-4}, Fe=7x10^{-4}

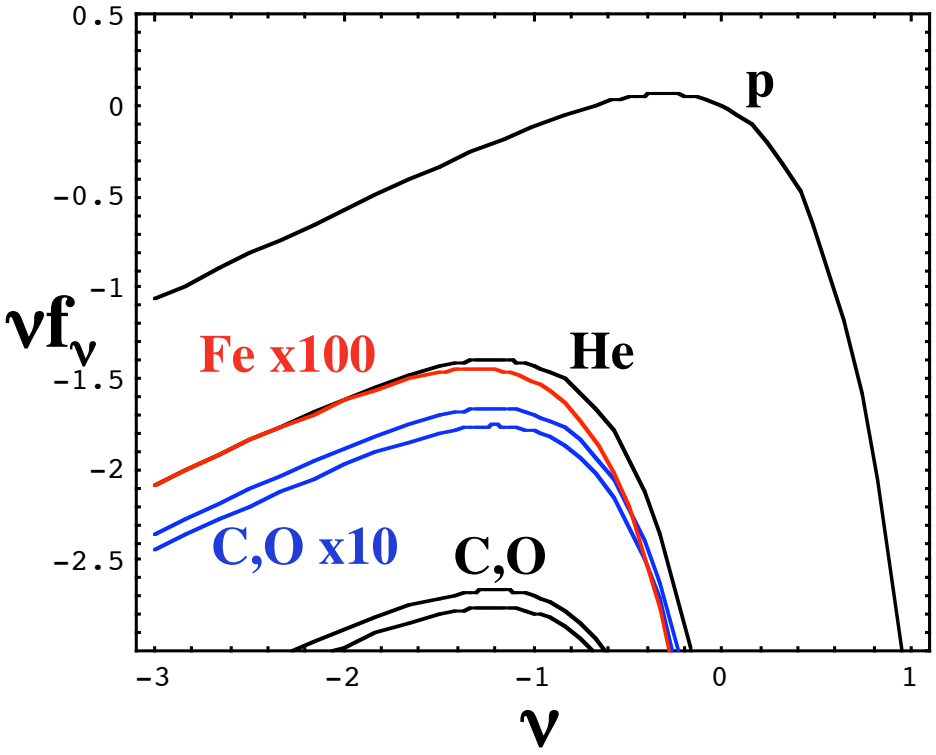
caveat: metals may be highly enhanced in GRBs!

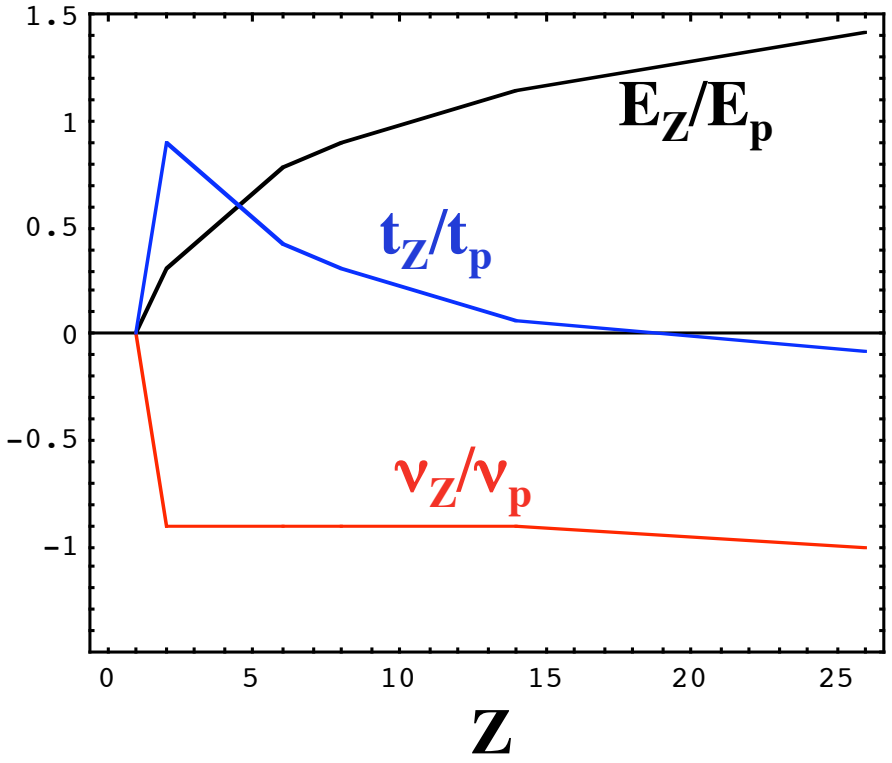
nuclear synchrotron spectra

Inoue, in prep.

normalize to proton synchrotron

expansion limited case $t_{acc}(\propto Z)=t_{dyn}$ $E_Z \propto Z$, $\nu_Z \propto Z^3/A^3$, $t_Z \propto A^4/Z^5$





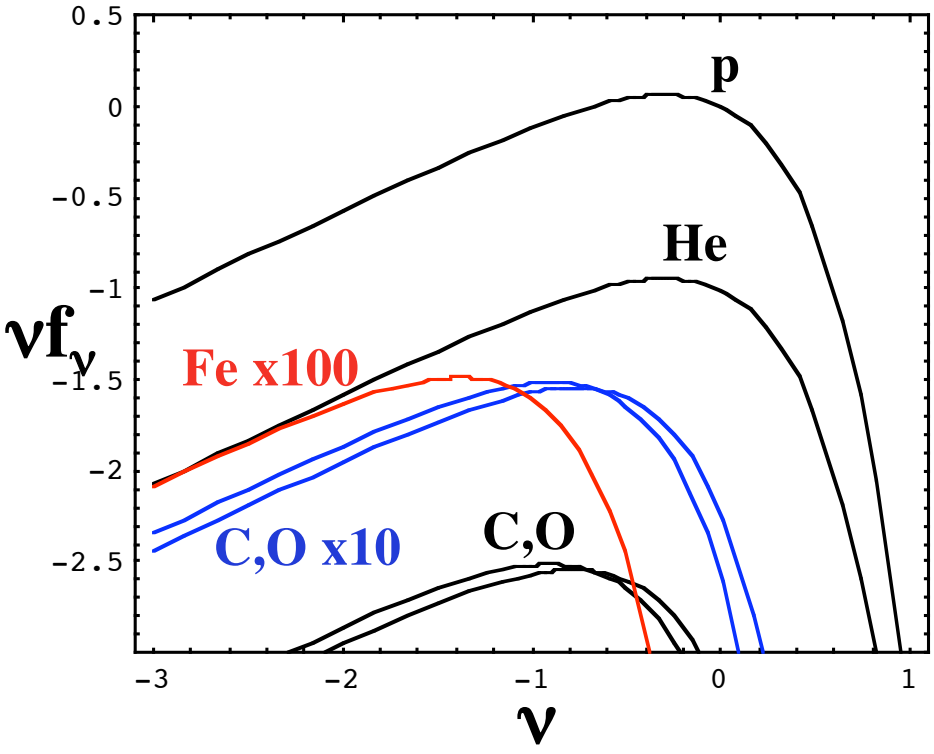
p dominant, but t_{syn} shorter -> late appearance of He?

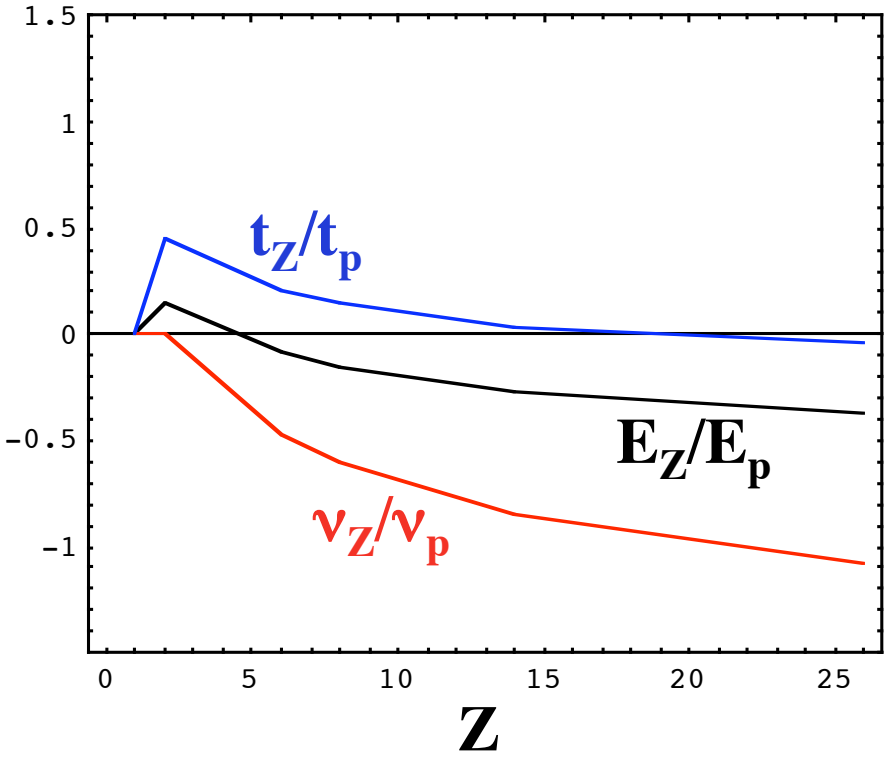
pure CO or Fe different E_{peak}, t_{syn}

nuclear synchrotron spectra

synchrotron limited case $t_{acc}(\propto Z)=t_{syn}(\propto A^4/Z^4)$ **most relevant**

$E_Z \propto A/Z^{1.5}$, $\nu_Z \propto A/Z^2$, $t_Z \propto A^2/Z^{2.5}$



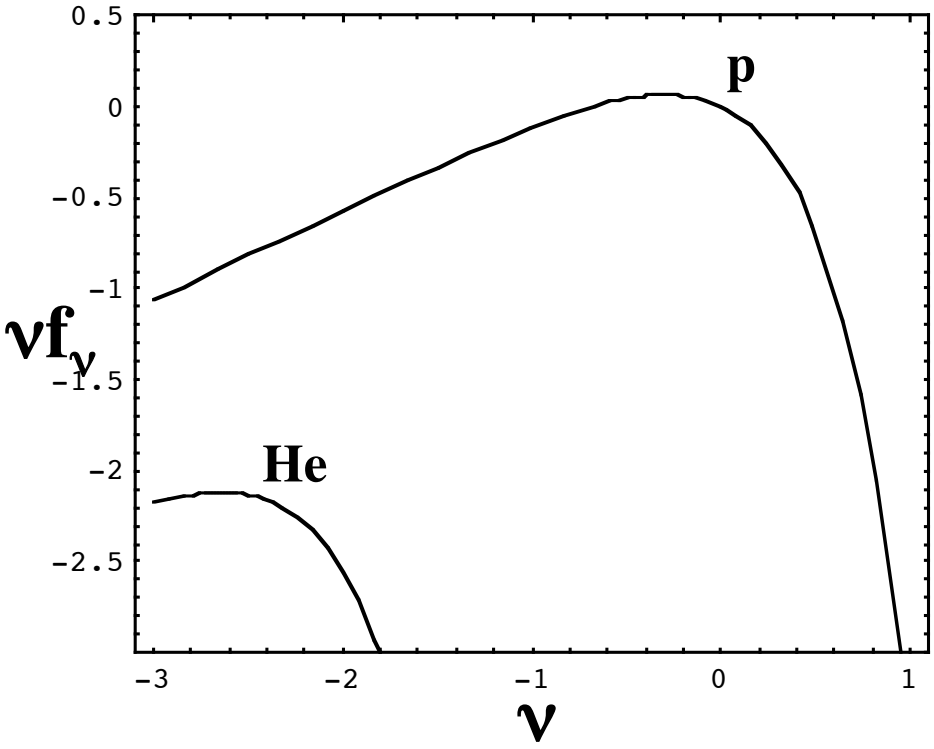


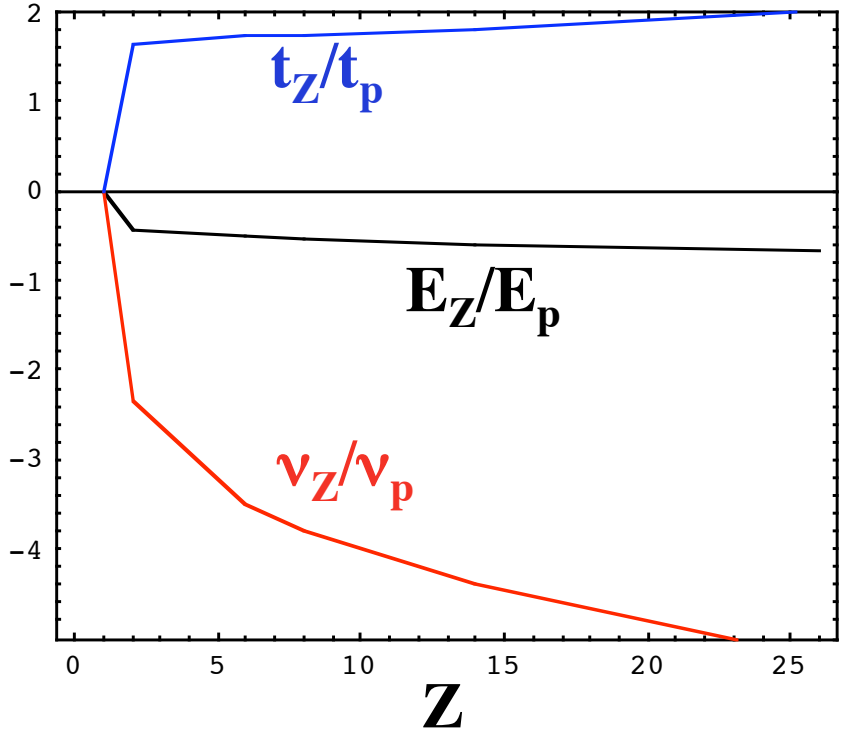
nuclear synchrotron spectra

photodisintegration limited case $t_{acc}(\propto Z)=t_{dis}(\propto\sim A^{1.2})$

depends on low E spec.

$E_Z\propto Z/A^{1.2}$, $\nu_Z\propto Z^3/A^{5.4}$, $t_Z\propto A^{5.2}/Z^5$





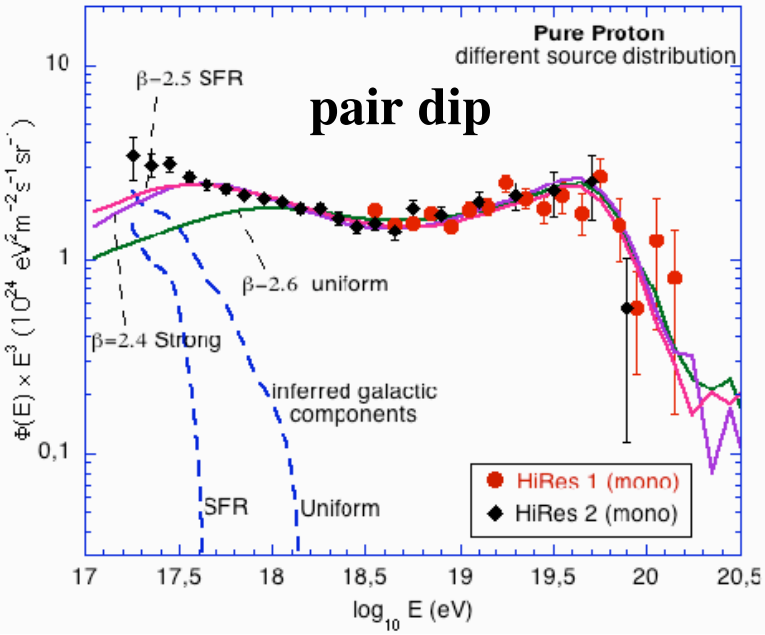
implications

He observable -> crucial for interpretation of UHECR ankle

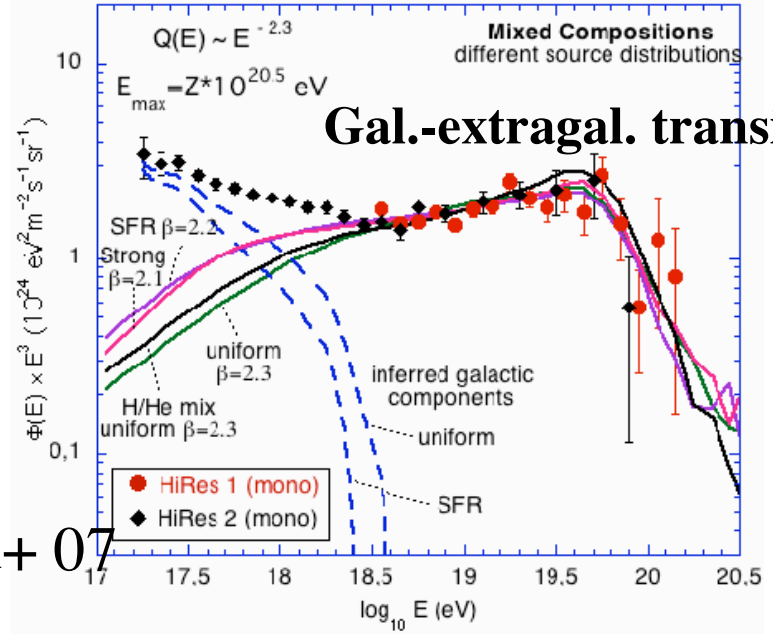
C,O,Si,Fe… may be observable
if highly enhanced and/or protons cool faster

unique probe of UHE nuclei acceleration in GRBs!

He/p<0.10 required!

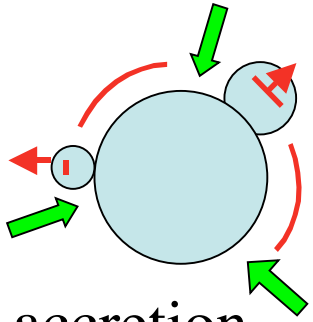


Allard+ 07



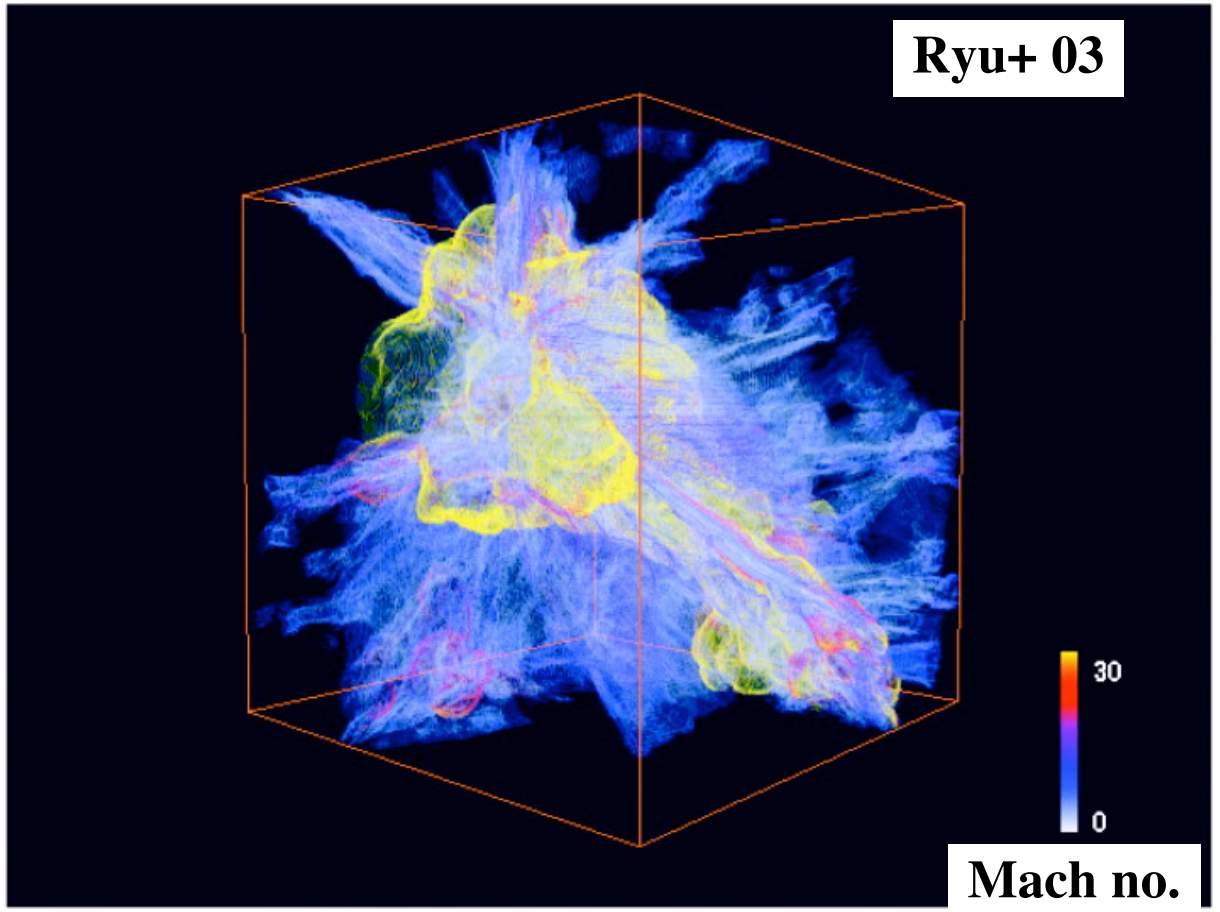
cluster accretion shocks

宇宙最大天体



accretion
(minor merger)

strong (high $\mathcal{M}$) shock
-> hard spectra,
high efficiency



accretion power

$L_{acc}(M)=f_{gas}GM\dot{M}/R_s$

$\sim 10^{46}$ erg/s $(M/10^{15}\ M_\Theta)^{5/3}$

massive clusters ($\sim 10^{15}\ M_\Theta$)

$L\sim 10^{46}$ erg/s

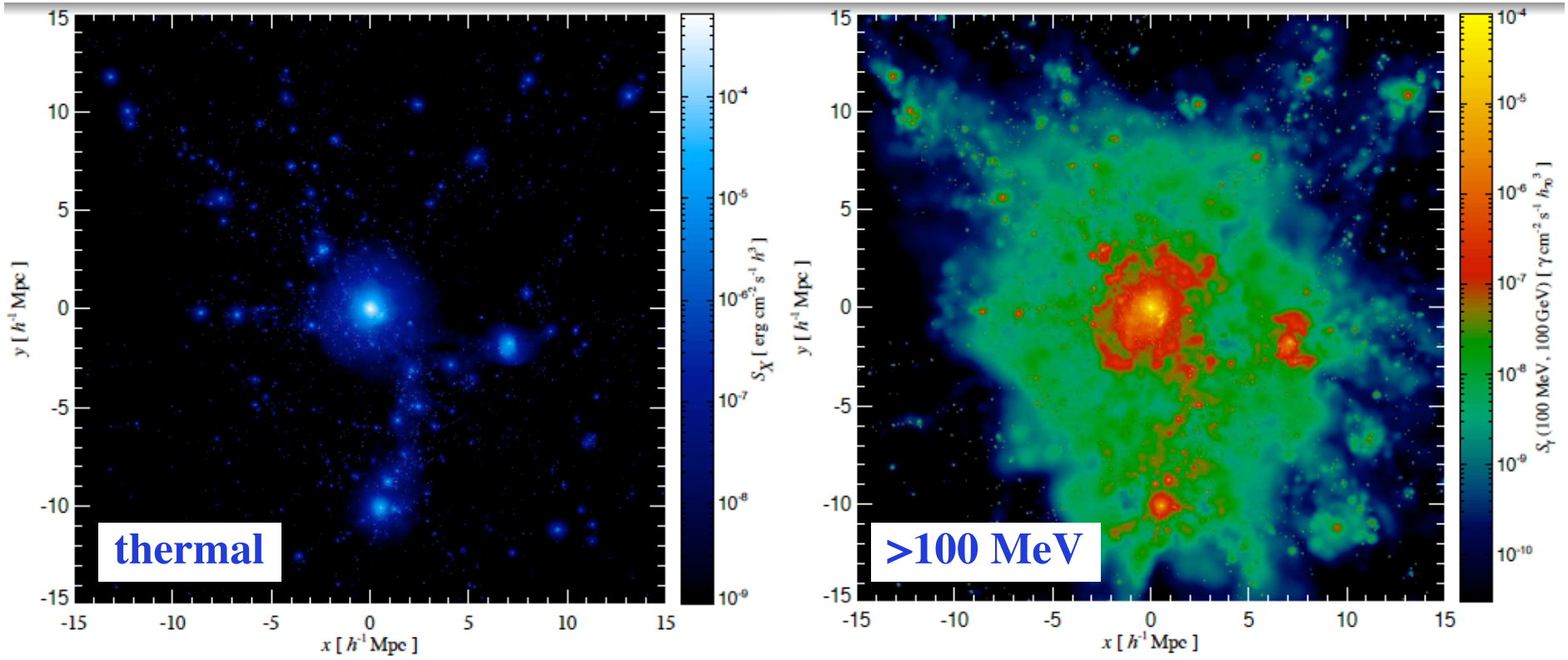
$n\sim 10^{-6}$ Mpc^{-3}

$P\sim 10^{40}$ erg s^{-1}Mpc^{-3}

expected high energy emission from clusters

- primary electron IC — traces shock — $t_{IC} << t_{shock}$ — e.g. Waxman & Loeb 00, Totani & Kitayama 00
- LE proton p+p->π_0 — traces gas — $t_{loss}, t_{conf} >> t_H$ — e.g. Völk et al. 96, Berezinsky et al. 97

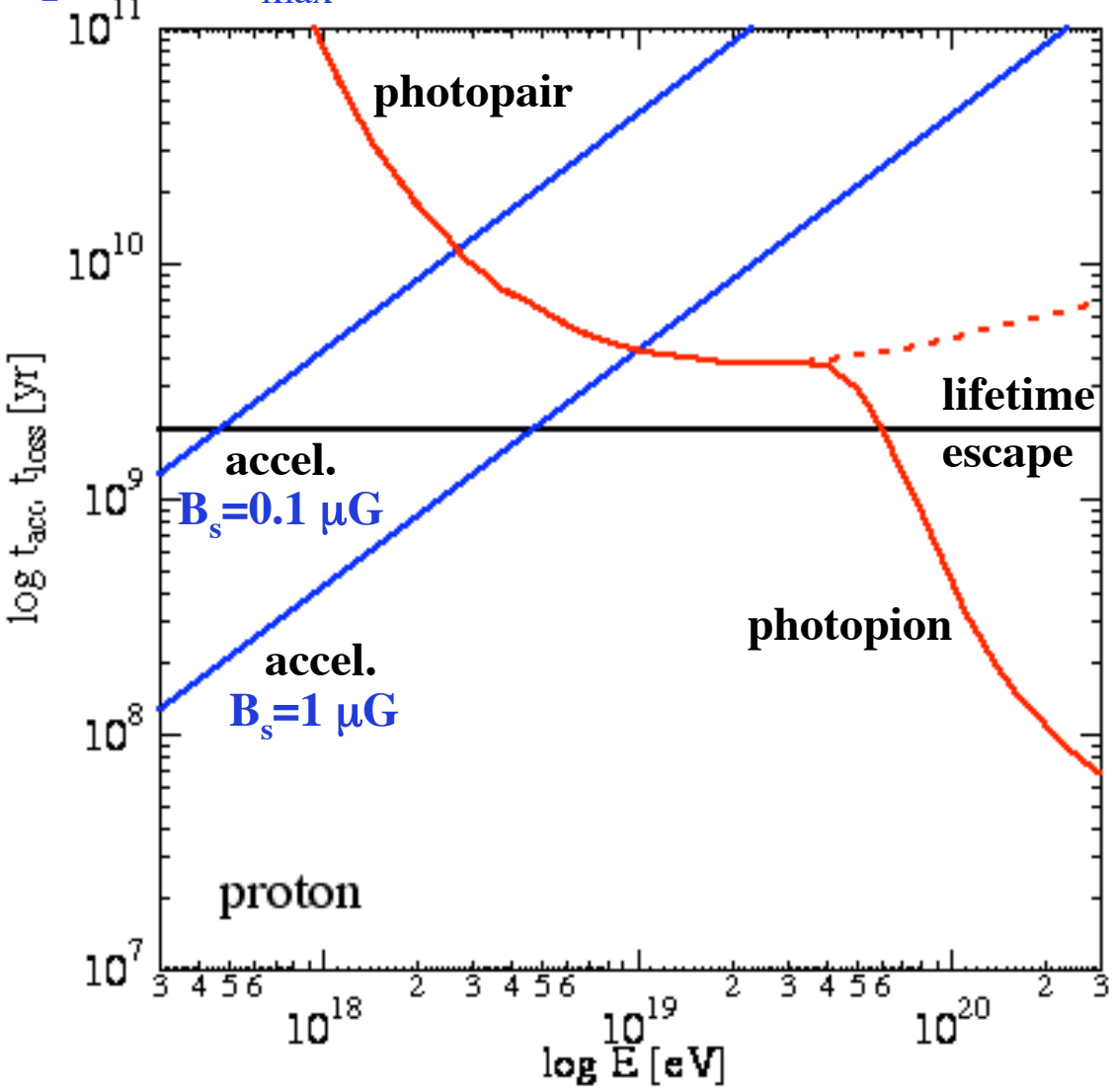
Pfrommer+ 08 assume p=2, ξ_e=0.01



UHE proton acceleration at accretion shocks

e.g. SI, Aharonian & Sugiyama 05

proton E_{max} accel. vs CMB losses, lifetime



c.f. Kang, Rachen & Biermann 97

Coma-like cluster
$M=2\times10^{15}\ M_\odot$

shock radius, velocity, etc.
R_s~3.2 Mpc
V_s~2200 km/s
$B_{s,eq}$~ 6 μG

Bohm limit shock accel. time
$t_{acc}=(20/3)\ \eta\ r_g c/V_s^2$
η~1 (c.f. SNR observations)

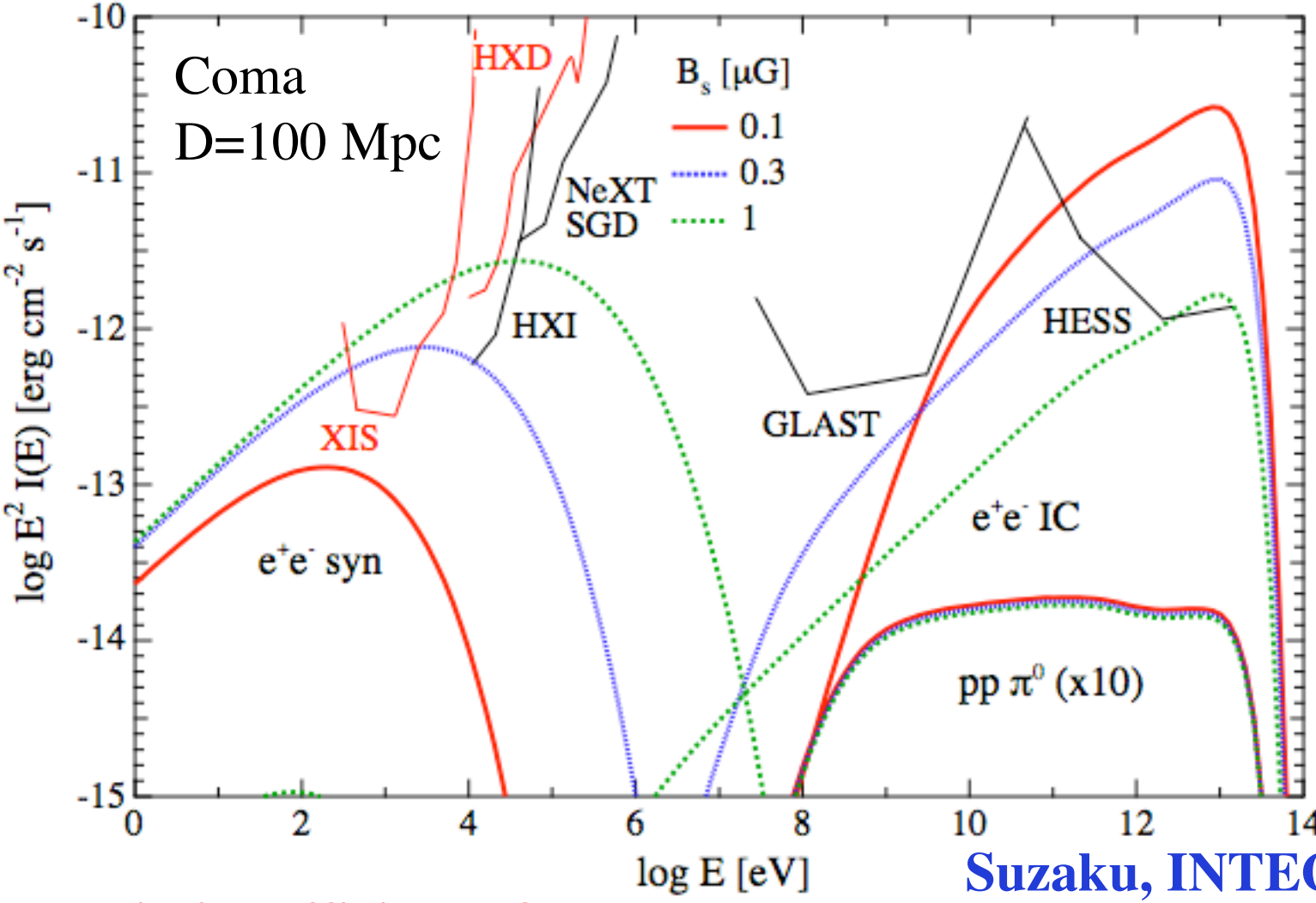
shock lifetime(?)
t_{sl}~R/V~2 Gyr < t_{adiab}~6 Gyr

$E_{p,max}$~10^{18}-10^{19} eV

UHE proton-induced hard X+γ emission from clusters

$p(10^{18}eV) + \gamma_{CMB} \rightarrow p + e^+e^- (10^{15}eV)$ **SI, Aharonian, Sugiyama 05**

$e^+e^- + B(\sim\mu G) \rightarrow keV$, $e^+e^- + \gamma_{CMB} \rightarrow TeV$ Kelner & Aharonian 08



- large radiative efficiency from protons

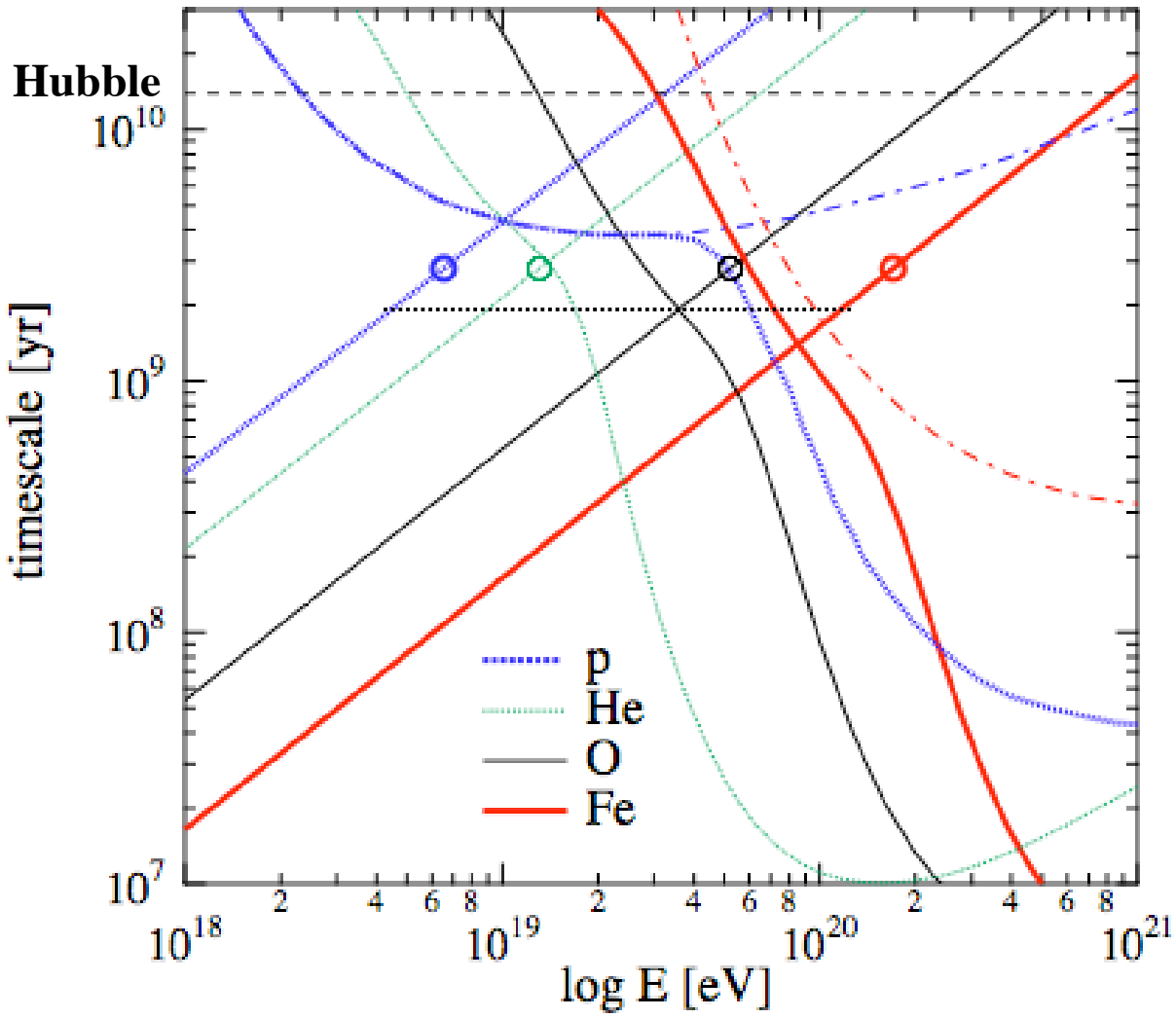
- hard (Γ~-1.5) spectrum + rollover

Suzaku, INTEGRAL?
NeXT
Cerenkov telescopes

nuclei from cluster accretion shocks as UHECRs

SI, Sigl, Miniati & Armengaud, astro-ph/0701167

E_{max} acceleration vs CMB losses, lifetime



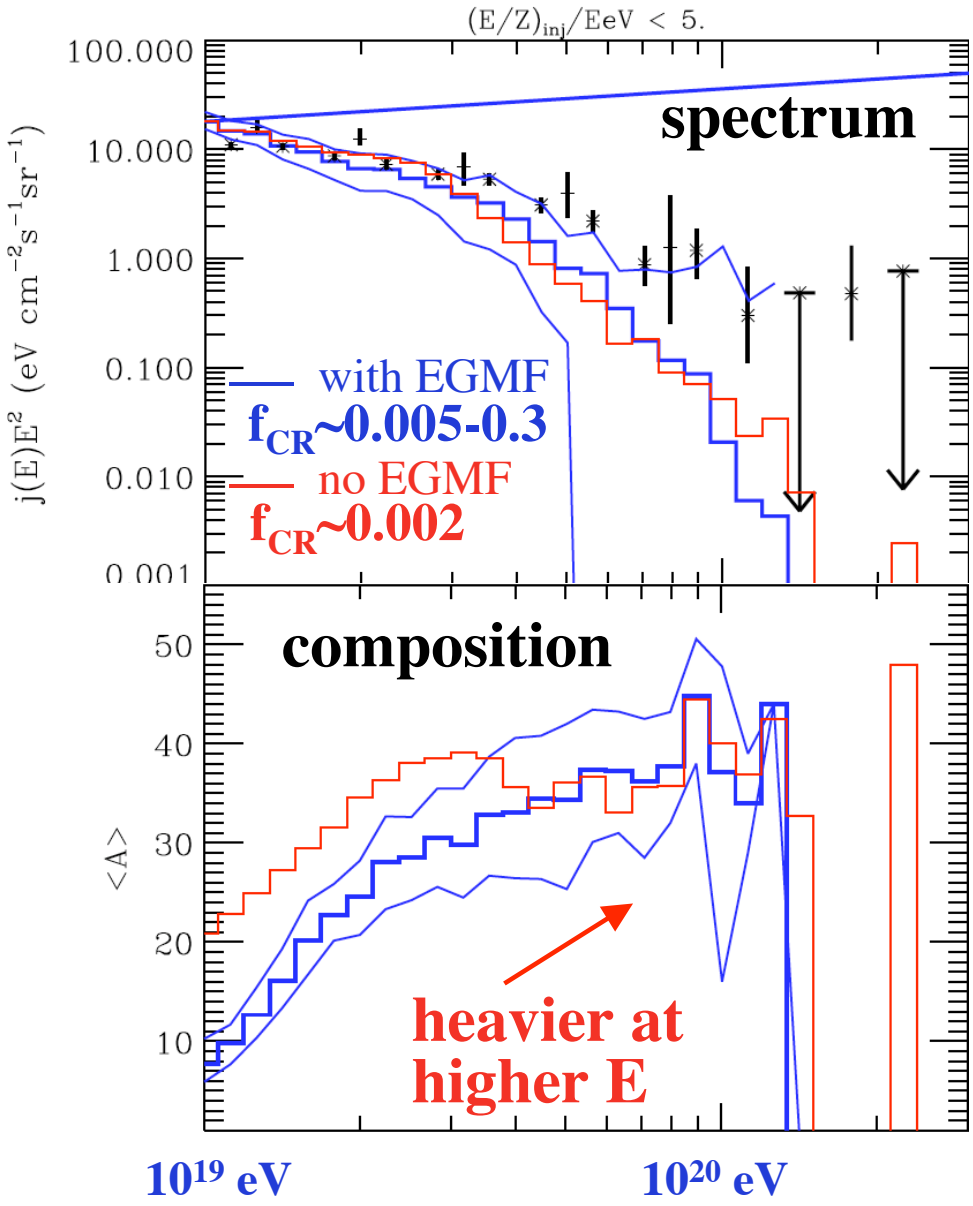
加油！

heavy nuclei E_{max}

for $B_s \sim 1$ μG

$E_{Fe,\,max} \sim 10^{20}$ eV

nuclei from clusters as UHECRs



confirmed by X_{max}?

may work if:
- B_s~1 μG, Bohm (fully turbulent)
- source Fe/p Galactic CR-like
- "right" Galactic+extragal. B field

summary gamma-rays in relation to UHECR sources

GRBs

UHE protons induce pγ cascade or p synchrotron GeV-TeV

p-dominated GRBs as UHECR sources?
can induce high E_{peak}

UHE nuclei induce Z synchrotron GeV-TeV

cluster accretion shocks

UHE protons induce hard X-rays + TeV gamma-rays from photopairs

heavy nuclei as UHECR sources?

summary gamma-rays in relation to UHECR sources

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p-dominated GRBs as UHECR sources?
can induce high E_{peak}

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cluster accretion shocks

UHE protons induce hard X-rays + TeV gamma-rays from BH pairs

heavy nuclei as UHECR sources?

Who will win UHECR gold?