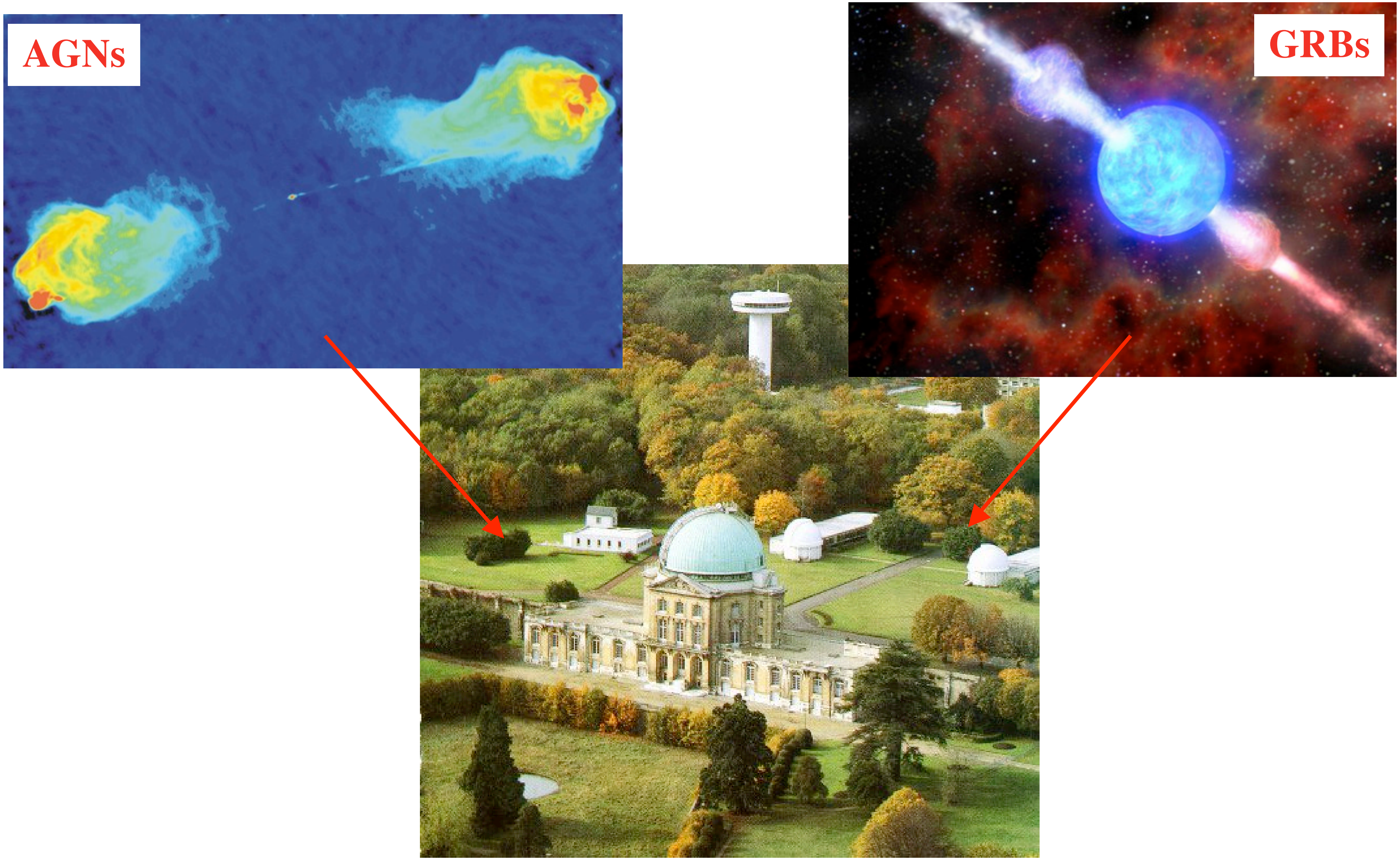
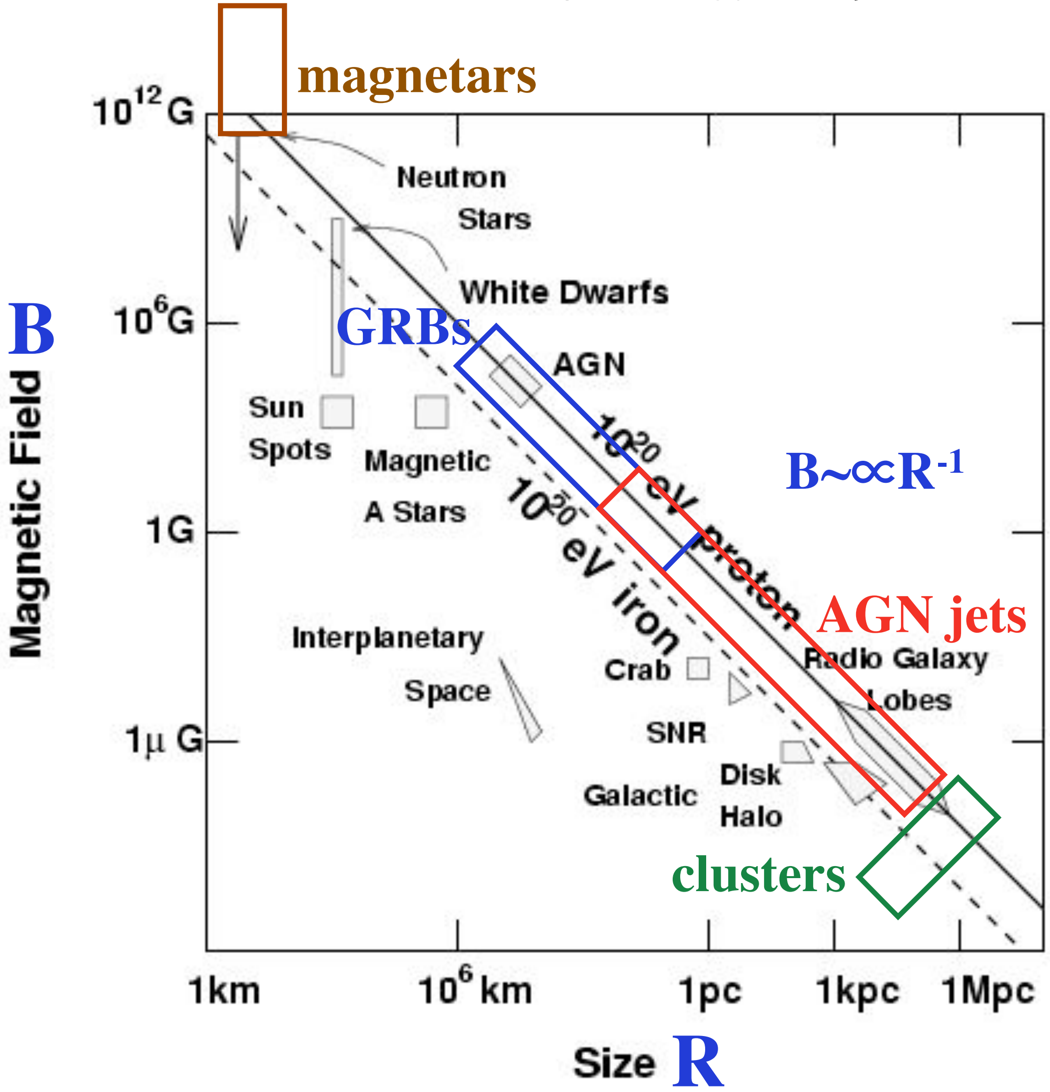
Gamma-Ray Emission from UHECR Accelerators

Susumu Inoue (Kyoto U.)



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

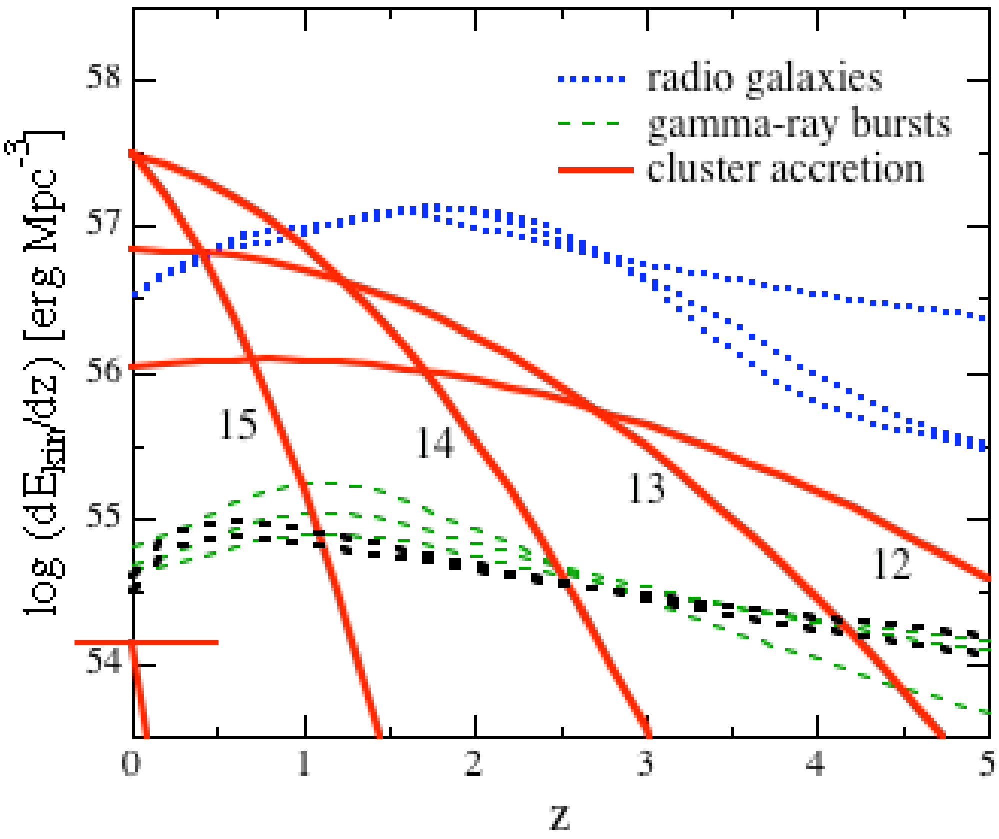
leading contender: GRBs

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

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

Keshet+ 04

UHECR budget @10^{19} eV

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

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

UHECR source composition highly uncertain!

1. matter composition
2. injection into acceleration
3. spallation and/or photodisintegration

Z,A-dependent maximum energy

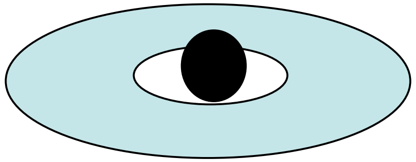
- lifetime or expansion limited (E-independent)
  -> $E_{max} \sim E_{pmax} x Z$ (constant max. rigidity)

- synchrotron loss limited
  -> $E_{max} \sim E_{pmax} x A/Z^{1.5}$

- photodisintegration limited
  -> case by case

active galactic nuclei (AGNs)

supermassive black hole
+accretion disk (flow)



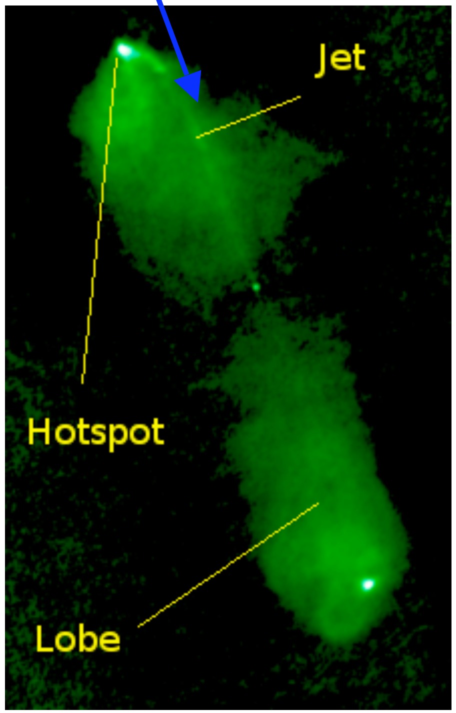
radio-loud
(relativistic jet)

high-
power

~<1%

FR 2
radio
galaxy

GeV blazar

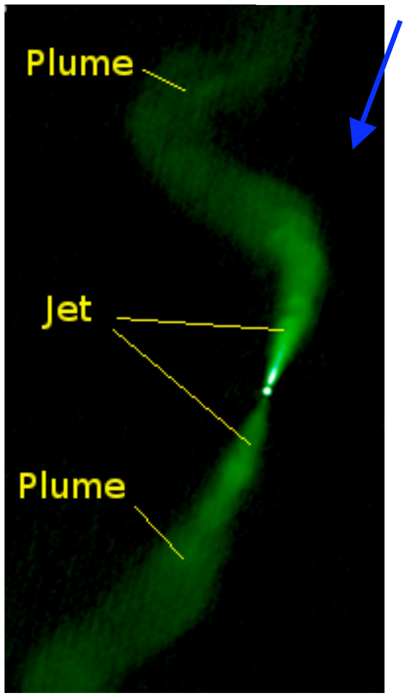


low-
power

~9%

TeV blazar
(BL Lac)

FR 1
radio
galaxy



radio-
quiet
(no jet)

~90%

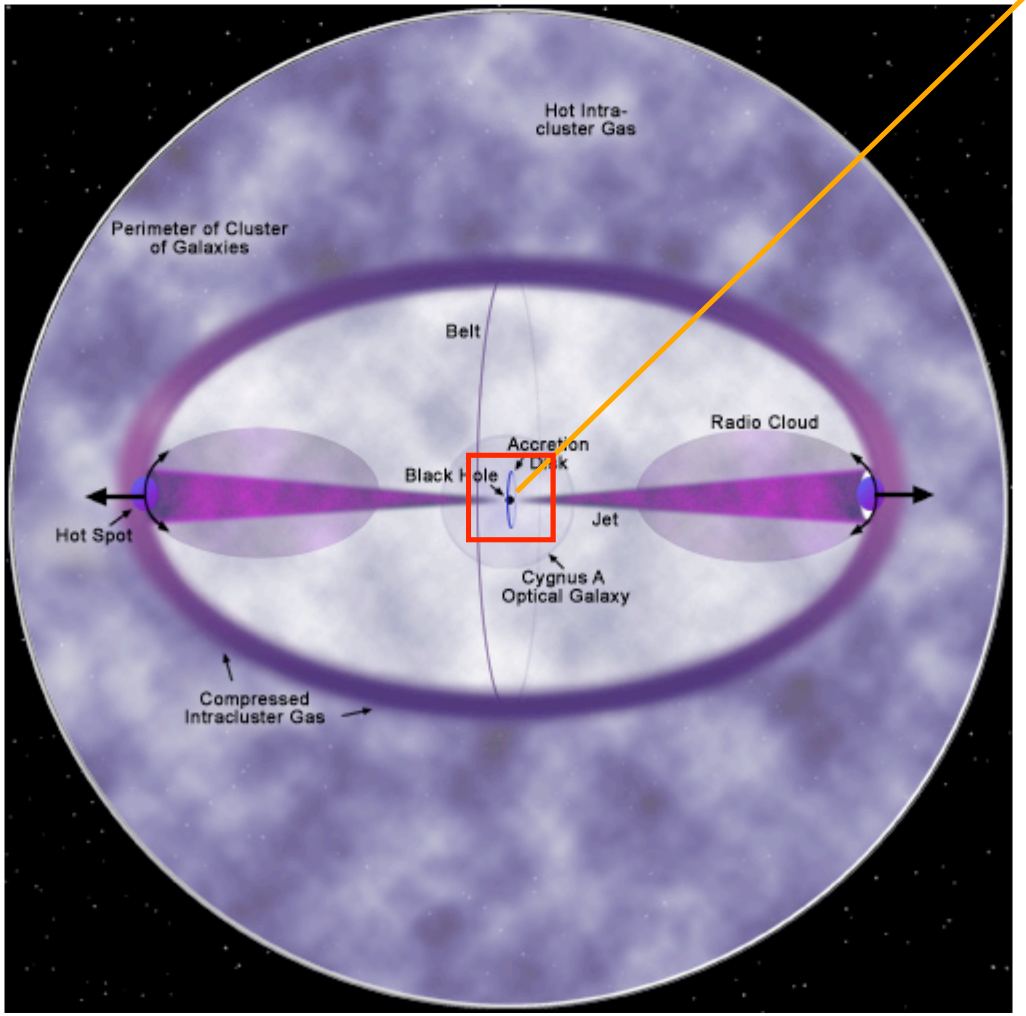
Seyfert galaxy
radio-quiet quasar

strong nonthermal
emission
=particle acceleration

activity timescales
$\sim 10^6$-10^8 yr

AGNs: acceleration sites

radio-quiet+radio-loud AGN



from Chandra webpage

near-nucleus

$R \sim 10^{13}$-10^{14} cm $B \sim 10^4$G?

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

e.g. Boldt & Ghosh 99

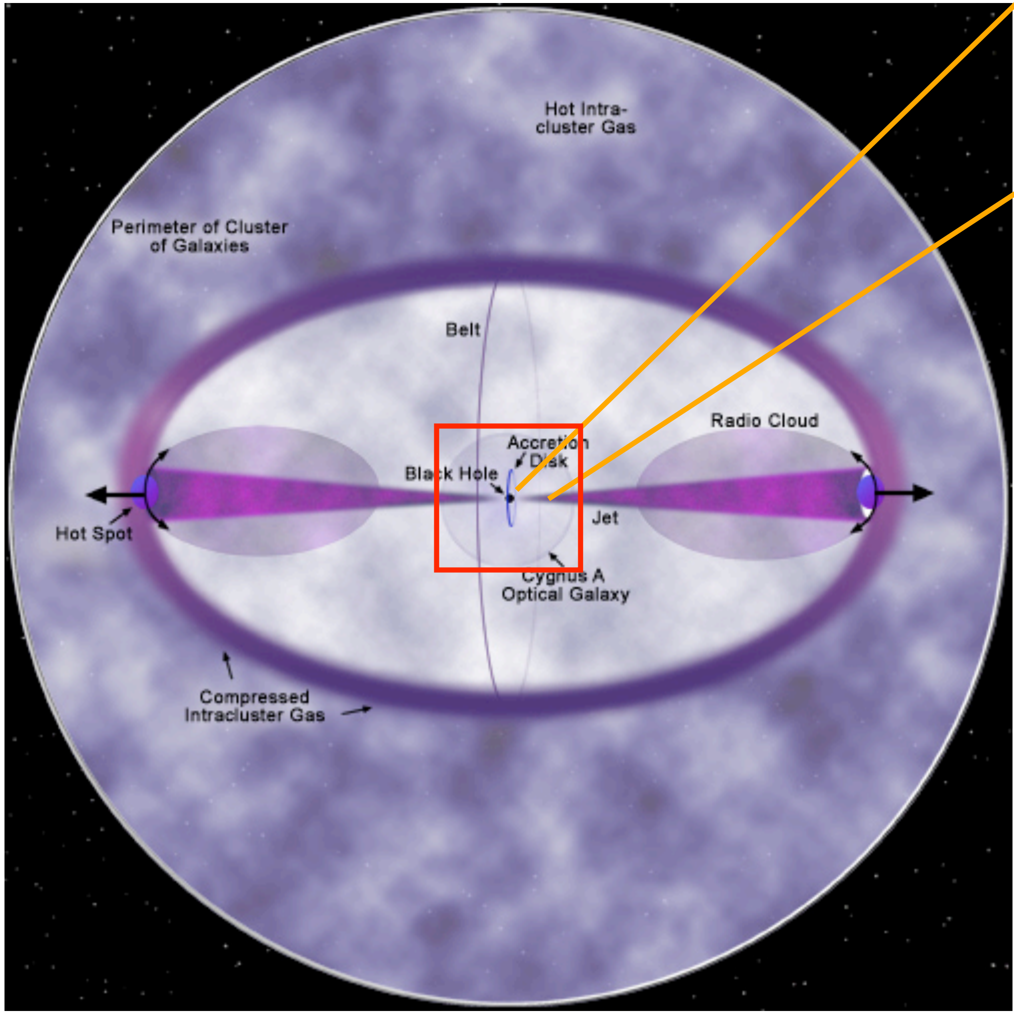
electrostatic acceleration
in BH magnetospheres
of low L objects?

highest E not expected

-> Rieger

AGNs: acceleration sites

low+high power (FR 1+2) radio galaxy



from Chandra webpage

near-nucleus

highest E not expected

inner jet (blazar)

$R \sim 10^{16}$-10^{17} cm $B \sim 0.1$-1G

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

e.g. Mannheim 93

adiabatic loss ->
n conversion escape?

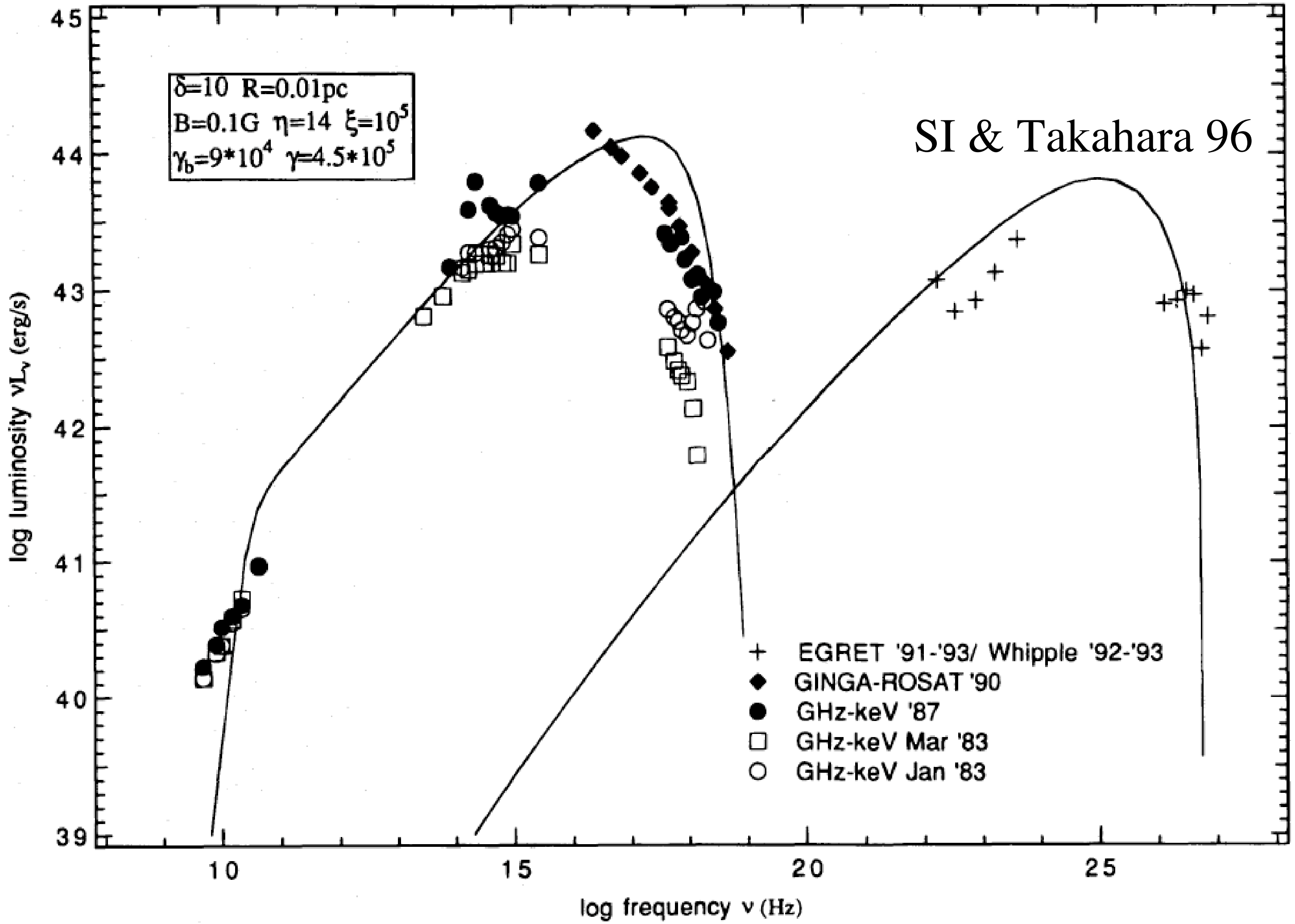
shear-layer acceleration?

accel./escape nontrivial

blazar emission: leptonic interpretation

-> Katarzynski, Stawarz

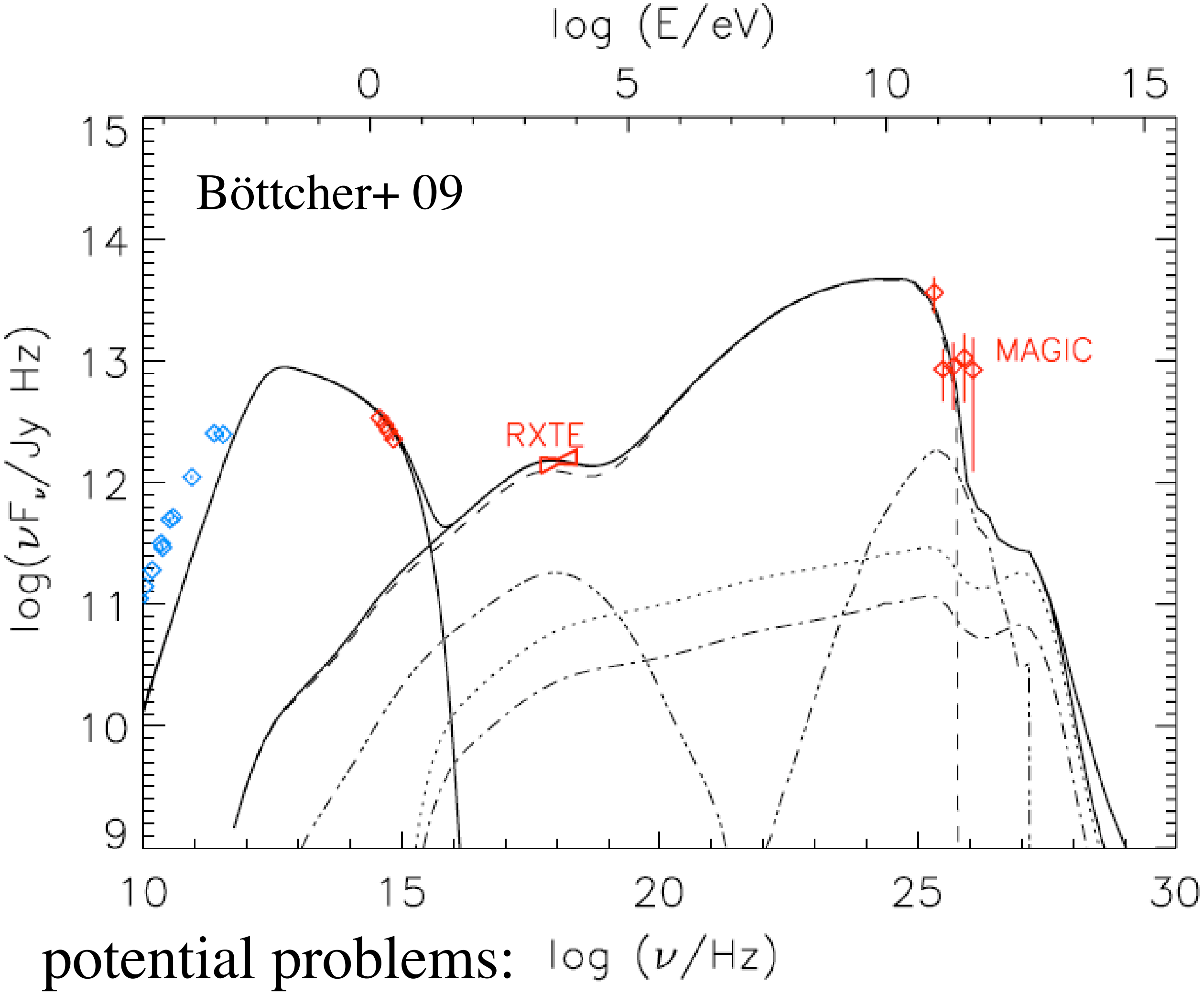
from one-zone modeling:
sub-equipartition B fields
(strongly) sub-Bohm B turbulence -> **UHECRs not expected**



blazar emission: hadronic interpretation

near-equipartition B fields
Bohm-like B turbulence

-> more favorable for UHECRs



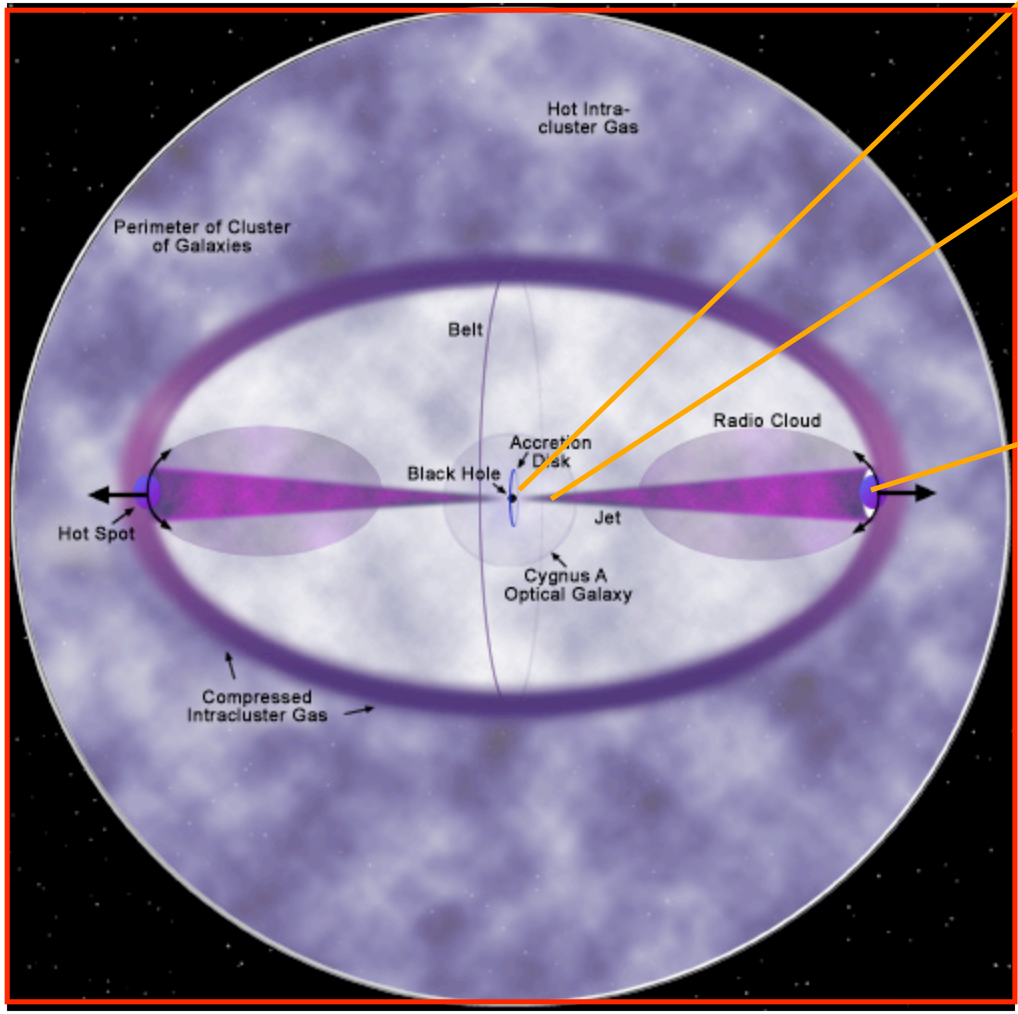
- proton synchrotron
- pγ-induced pair cascade
- muon synchrotron

…

potential problems:
sub-hour variability
high jet power

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

$R \sim 10^{21}$ cm $B \sim 1mG$

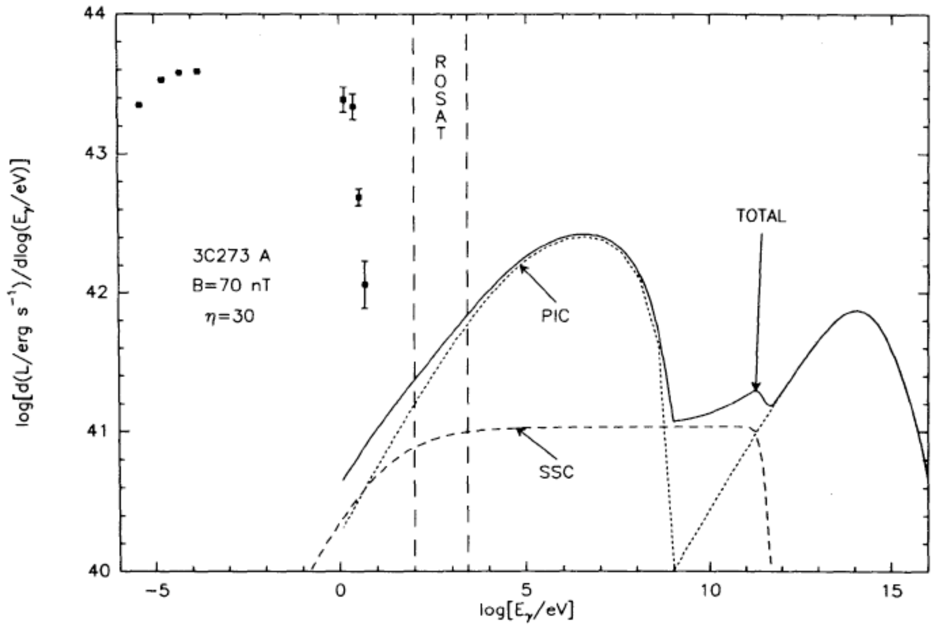
$E_{max} \sim E_{esc} \sim 10^{20-21} eV$

e.g. Rachen & Biermann 93

accel./escape easier

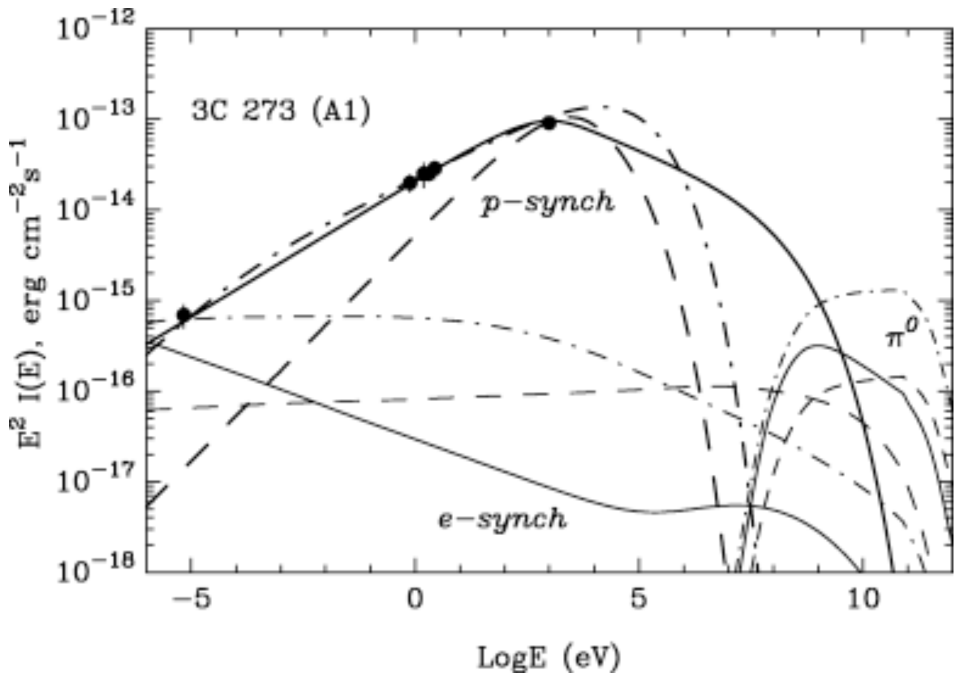
but still nontrivial
escape through cocoon
+contact disc.?

hot spots: UHECR-induced emission



pγ pair cascade

Mannheim+ 91



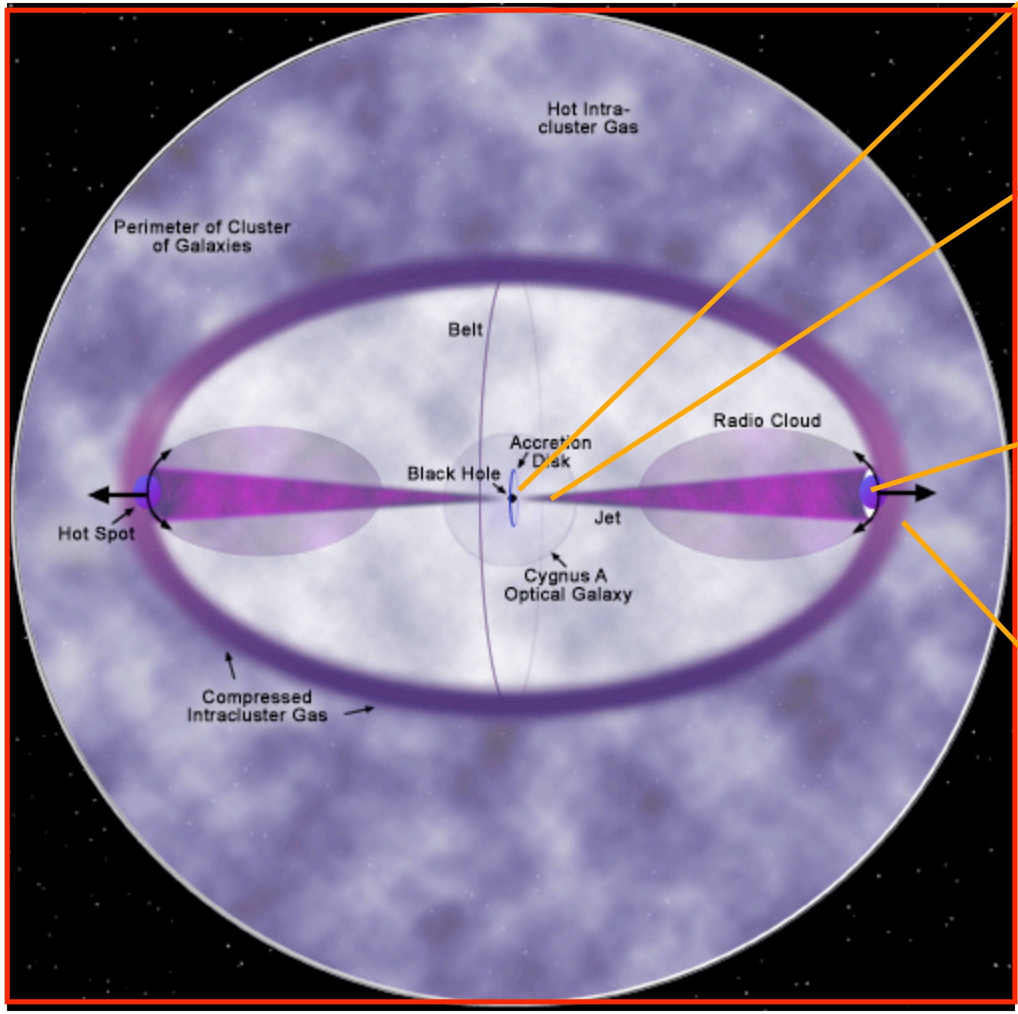
proton synchrotron

Aharonian 02

generally not strong,
but worth reconsideration
for CTA

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

$R \sim 10^{21}$ cm $B \sim 1$mG

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

accel./escape easier

bow shock

$R \sim 10^{23}$ cm $B \sim 0.1$mG

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

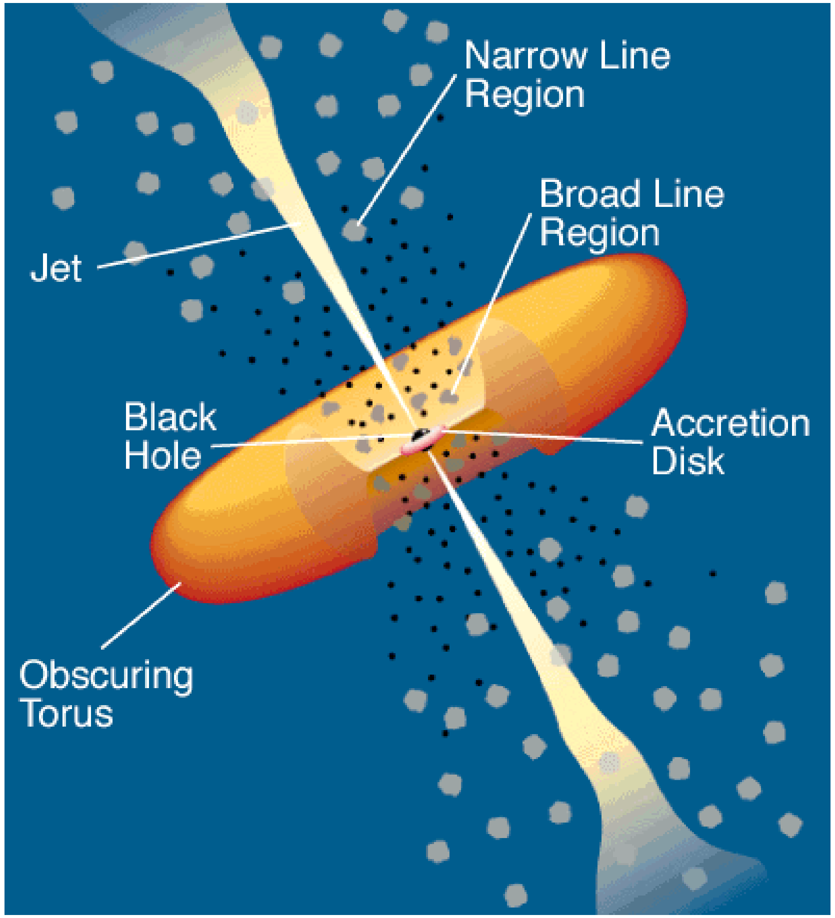
Berezhko 08

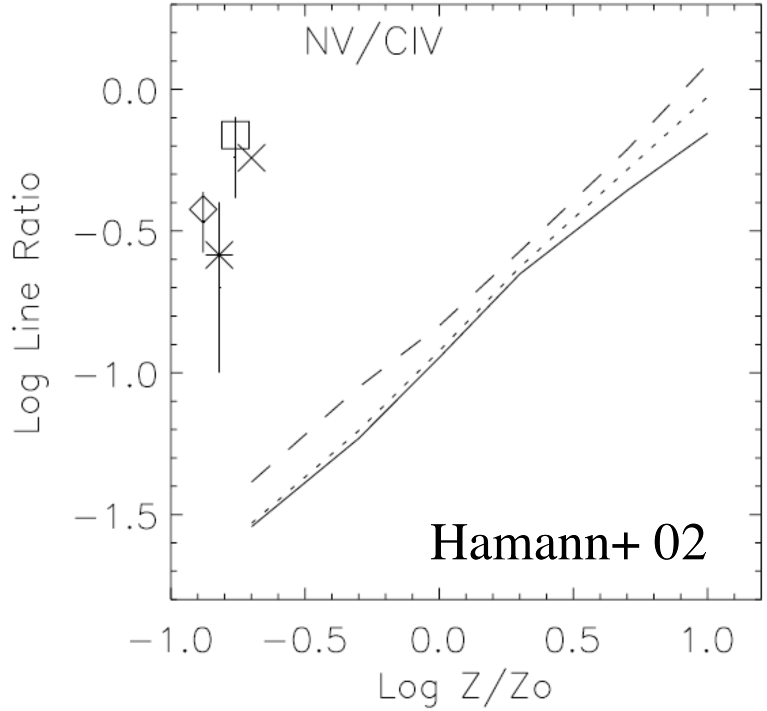
accel. nontrivial

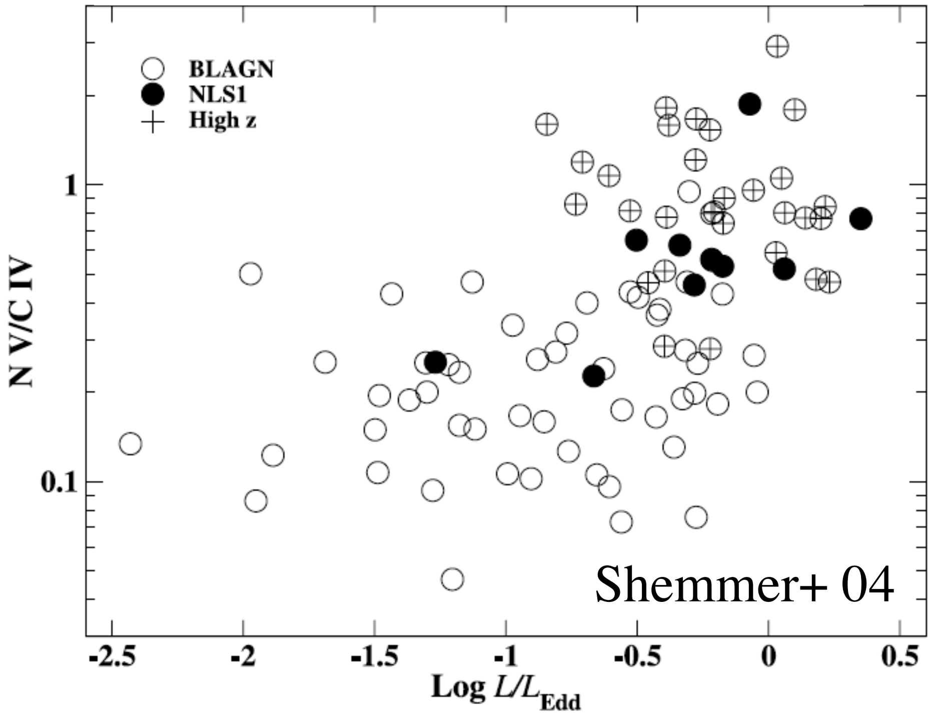
OK IF B field amplified
escape easiest

UHECR source composition for AGNs?

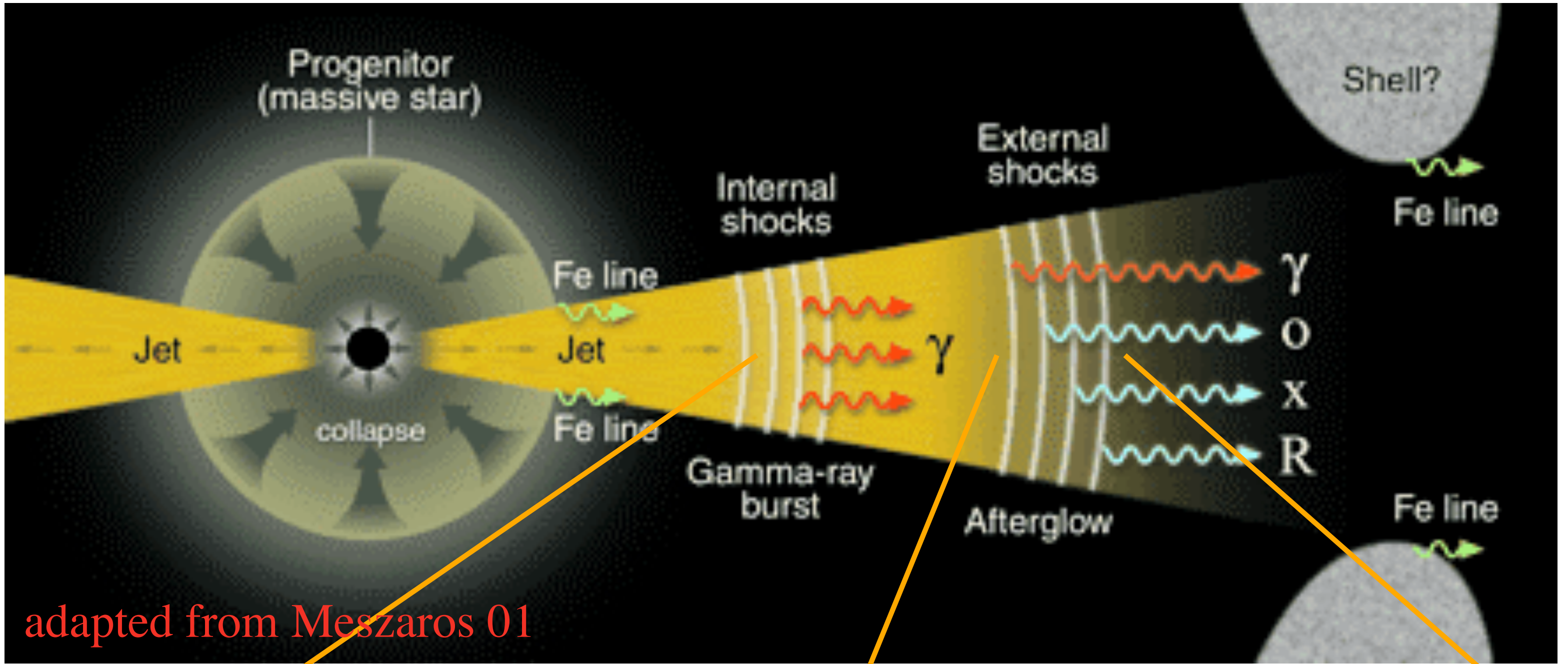
abundance in broad line region (<pc)
~10-30x solar
probably also for accreting matter







GRBs: acceleration sites



Waxman 95
Vietri 95

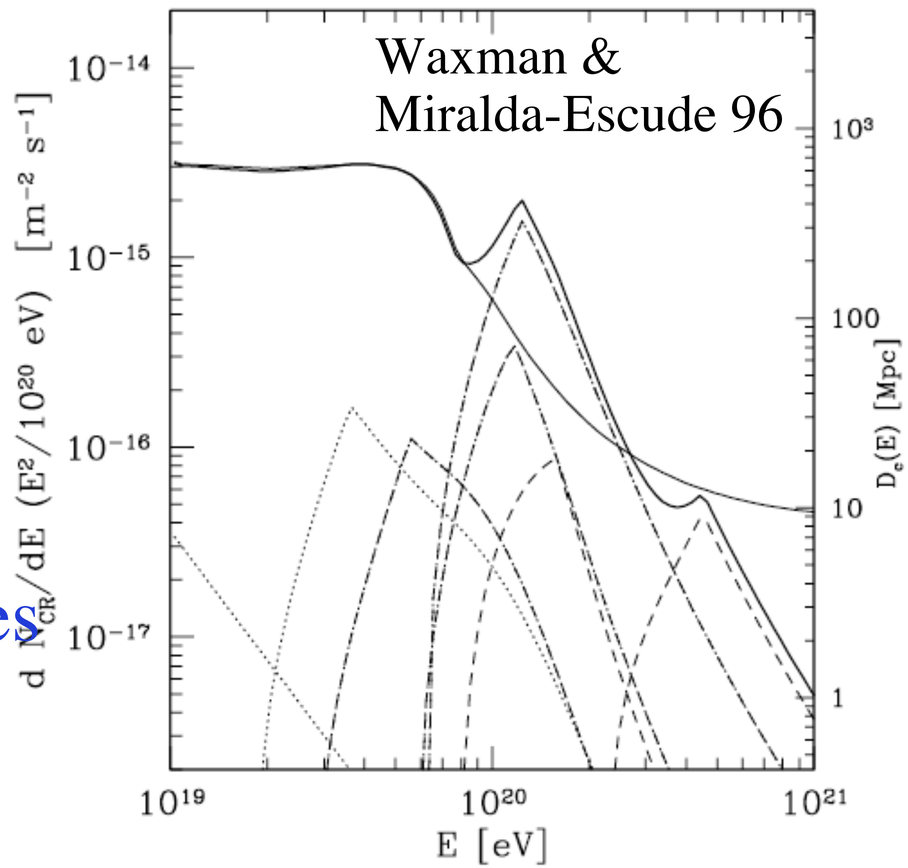
prompt X-γ emission	optical flash, radio flare	radio-IR-opt-X afterglow
internal shocks	**external reverse shock**	**external forward shock**
$R \sim \Gamma^2 c t_{var} \sim 10^{12}\text{-}10^{16}$ cm	$R \sim R_{dec} \sim 10^{16}$ cm	$R \sim R_{dec}\text{-}R_{NR} \sim 10^{16}\text{-}10^{18}$ cm
$B \sim 10^6\text{-}10^3$ G	$B \sim 10$ G	$B \sim 10\text{-}0.01$ G? $>> B_{ISM}$
$\Gamma_{rel} \sim 1$	$\Gamma_{rel} \sim 1$	$\Gamma_{rel} >> 1$

GRBs as UHECR sources: diagnostics

time delay

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

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



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

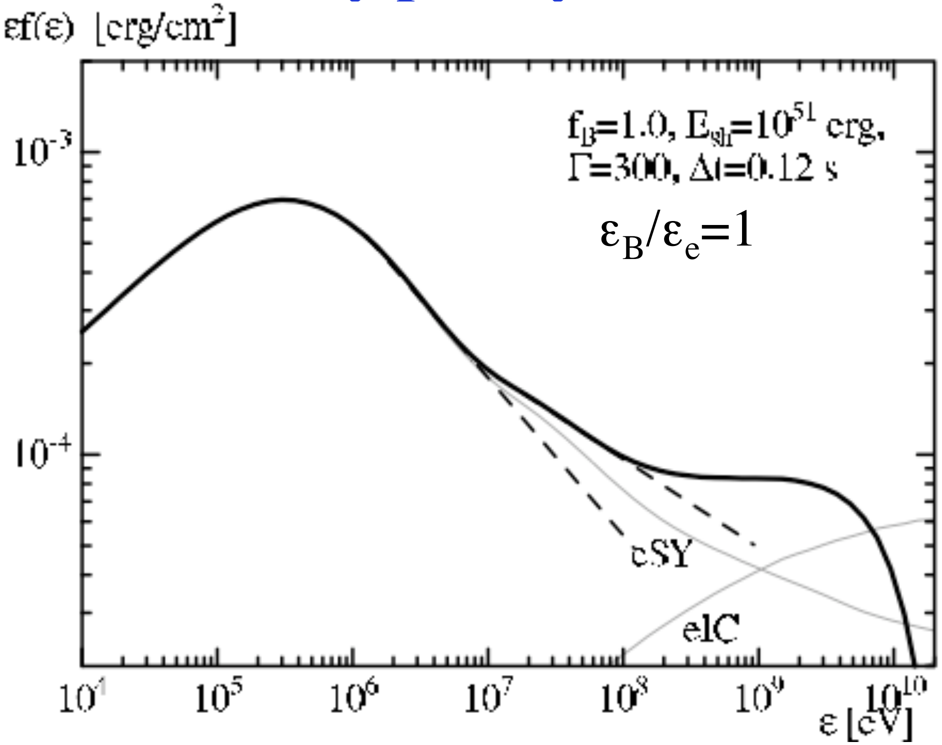
secondary neutral (gamma & neutrino) signatures essential to identify sources

GRB GeV-TeV emission

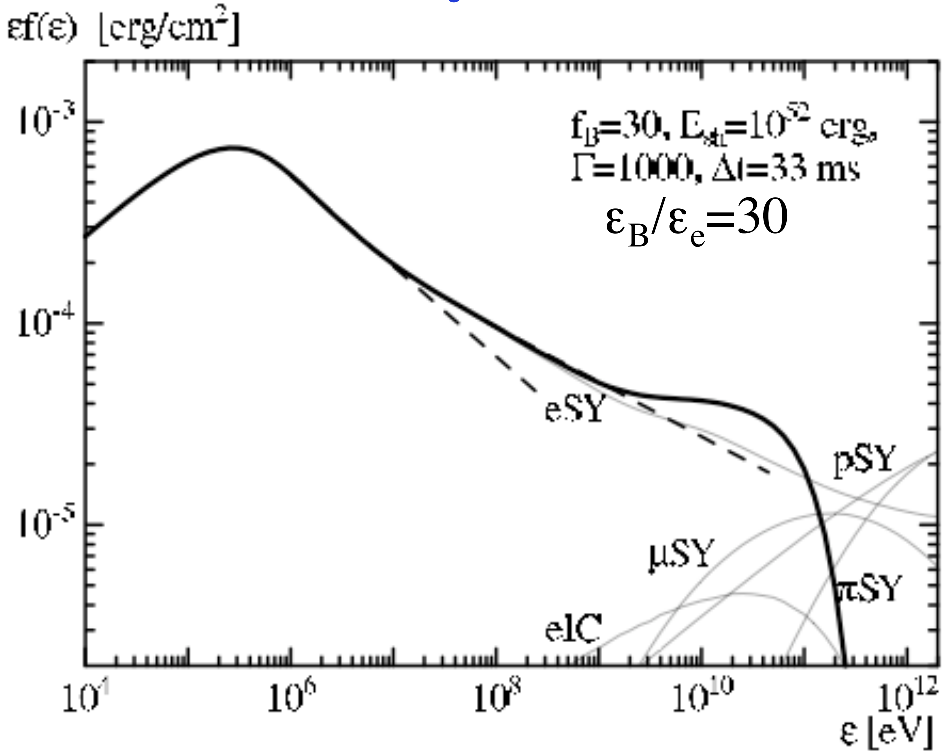
Asano & SI 07

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

secondary pair synchrotron+



muon synchrotron+



double (multiple) breaks
-> proton signature

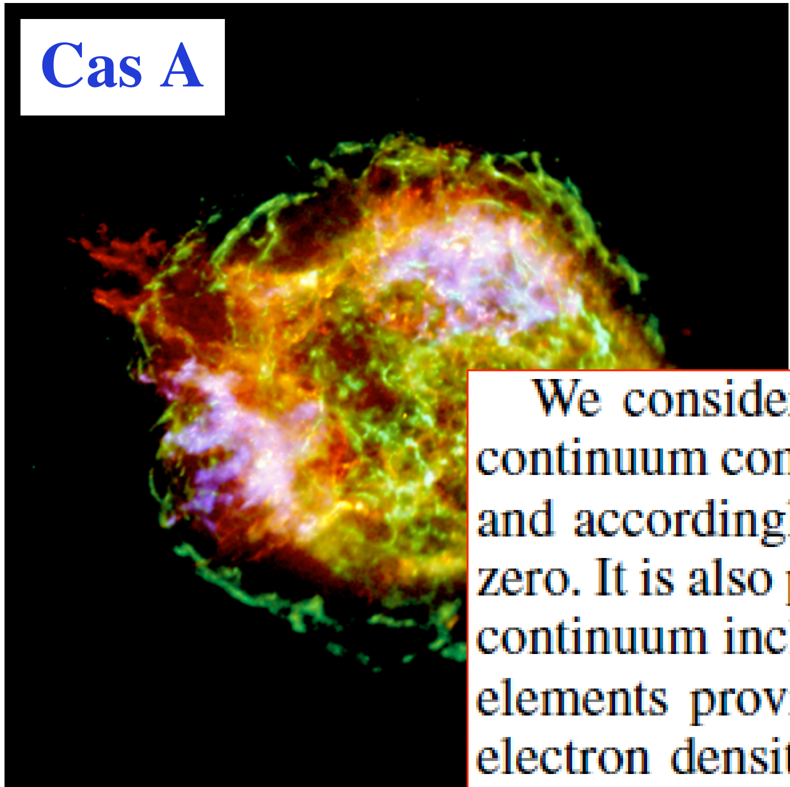
Fermi, Cerenkov telescopes…

-> see Asano's talk

proton-dominated case   **Asano, SI & Meszaros 09**

UHECR source composition for GRBs?
case of Cas A

SN IIb (H layer nearly stripped), 300 years after explosion



O, Si, Fe-rich clumps!

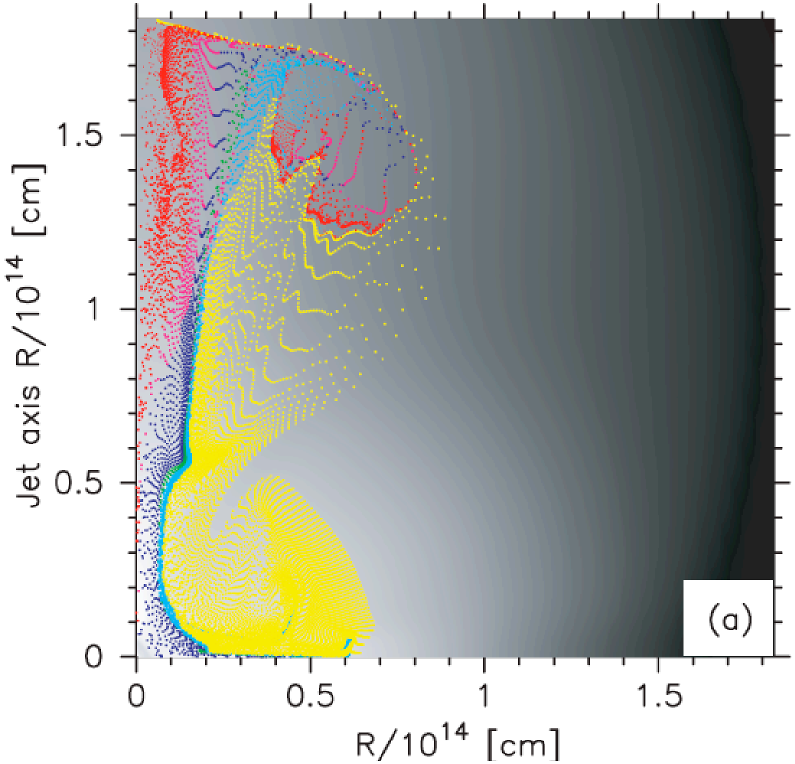
$n_A > n_H$

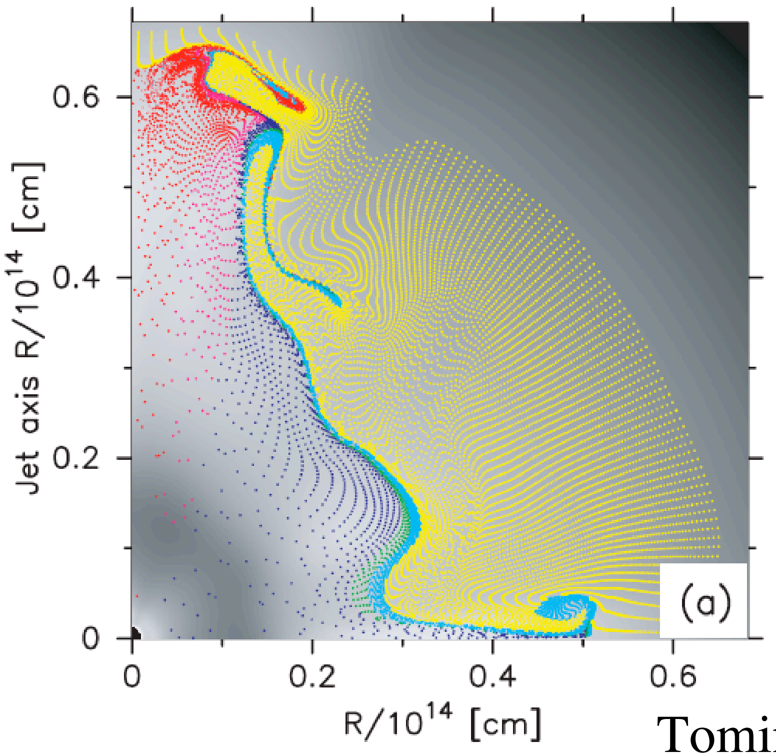
Hwang & Laming 03, 09; Hwang+ 04…

We consider ejecta regions only. We then assume that the continuum comes mainly from ionized O and heavier elements, and accordingly set the abundances of the lighter elements to zero. It is also possible to model the spectra with a light element continuum including H and He. The assumption of which light elements provide the continuum does affect inferences about electron densities and masses in the knot. While some H and He are certainly present in the remnant given its Type IIb classification, the Cas A progenitor exploded at only $4\,M_\odot$ (Young et al. 2006), so it should have lost most of the gas in its outer layers. Moreover, the regions we select are taken to be enriched in heavy elements by instabilities during the explosion.

UHECR source composition for GRBs?

favored progenitor: SN Ic (H+He layer totally stripped)
jet propagates through star and entrains matter (mainly CO+heavier)





Tominaga 09

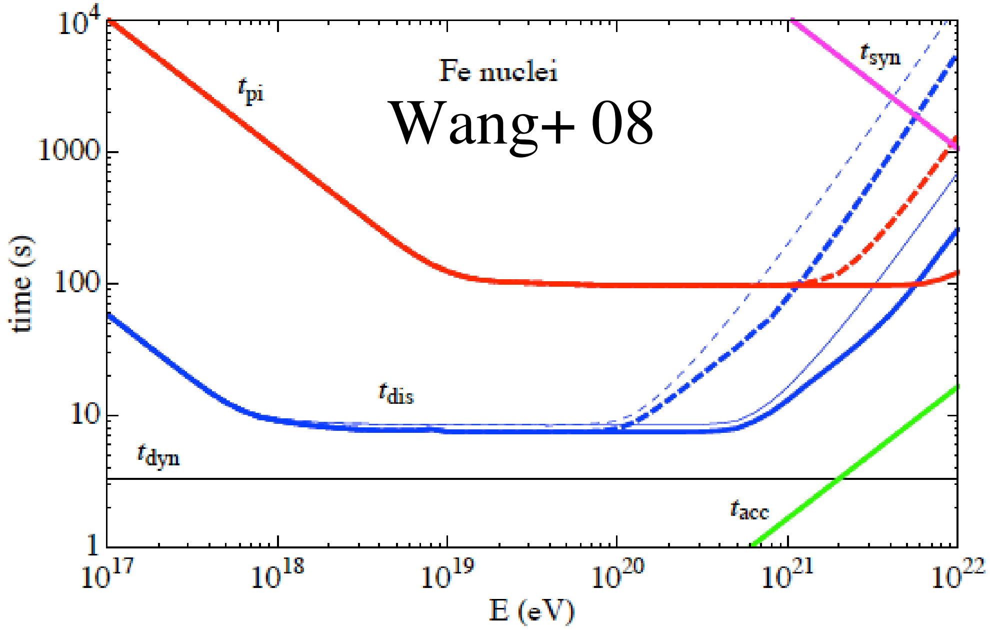
Figure 4. Density structure (background gray scale) and the positions of the mass elements at $t = 10^5$ s for (a) model A and (b) model B. Color of the marks represents the abundance of the mass element (H: yellow, He: cyan, O+C: green, O+Mg: blue, Si: magenta, and Fe: red). Size of the marks represents the origin of the mass element (the jet: dots, and the shocked stellar mantle: filled circles).

photodisintegration/spallation?
-> depends on nature of jet and entrainment

metals may possibly be highly enhanced in GRB jets!

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 $t_{syn} \propto E^{-1} A^4/Z^4$

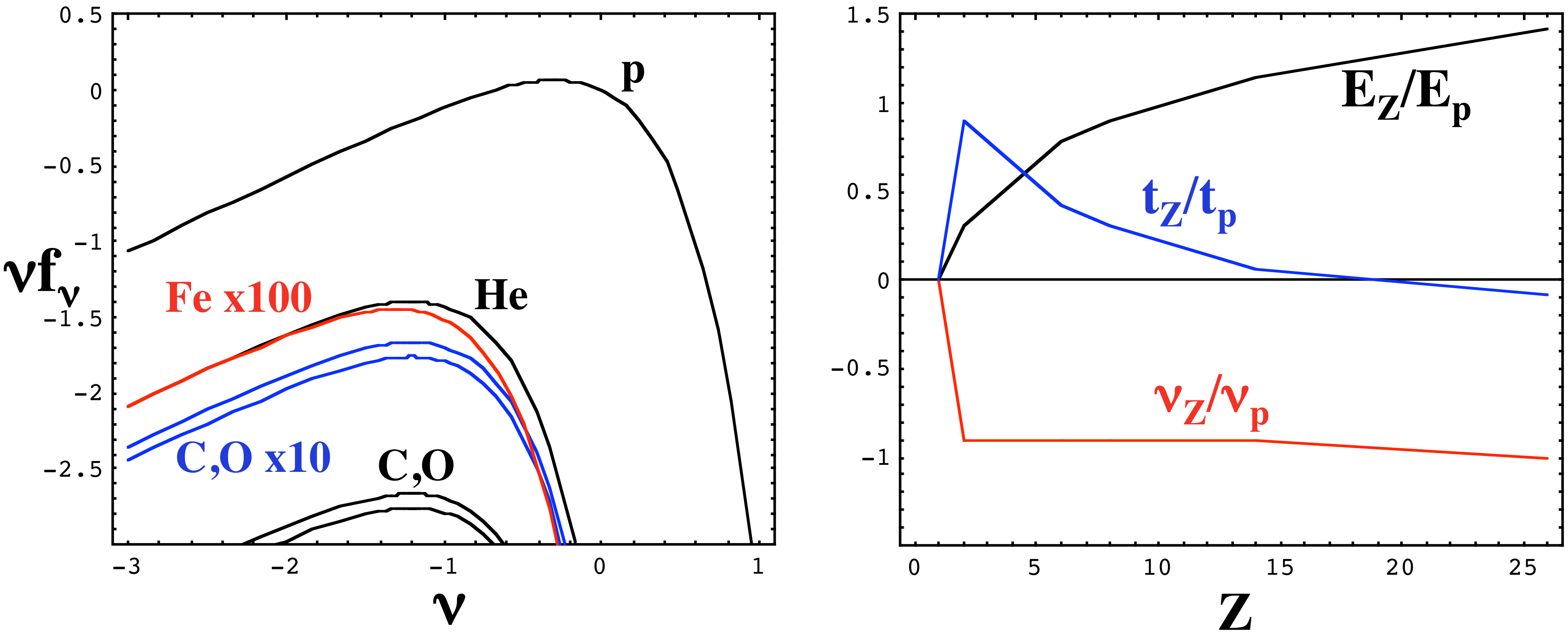
fiducial assumption:
abundance at low E=Galactic CR source at fixed E/A
H=1, He=0.07, C=3×10^{-3}, O=3.7×10^{-3}, Si= 7×10^{-4}, Fe=7×10^{-4}

nuclear synchrotron spectra

Inoue, in prep.

normalize to proton synchrotron

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



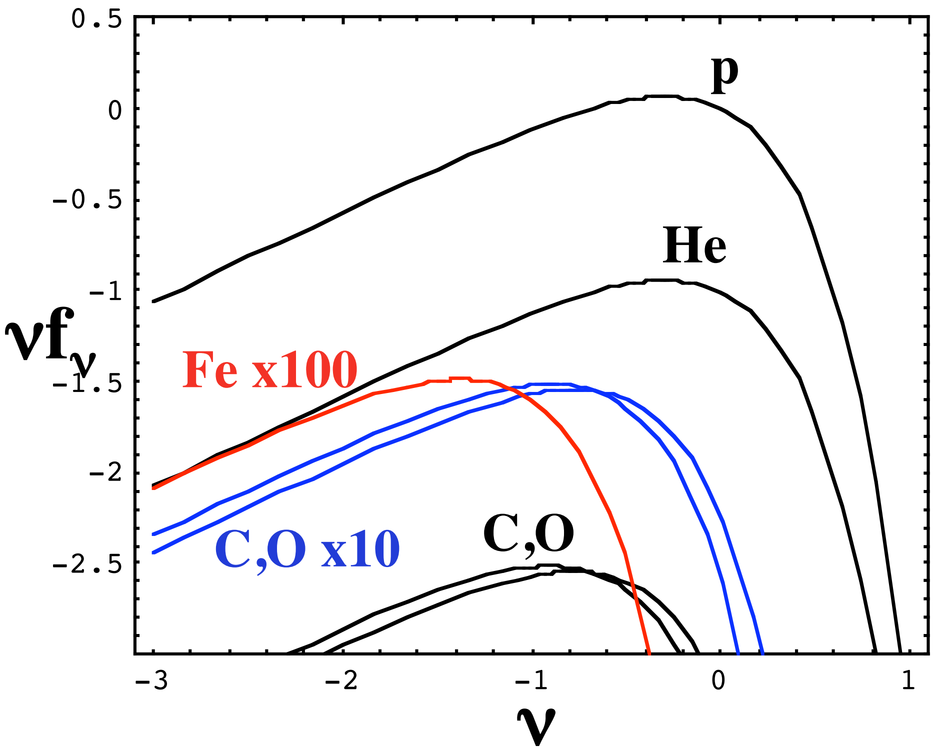
p dominant, but t_{syn} shorter -> late appearance of He?

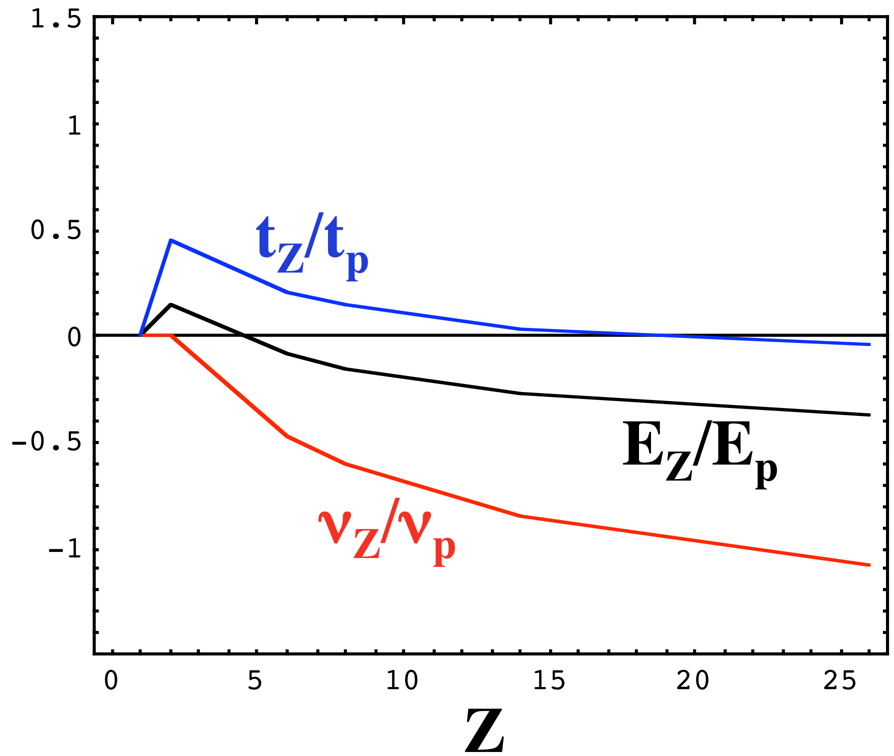
pure CO or Fe different E_{peak}, t_{syn}

nuclear synchrotron spectra

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

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



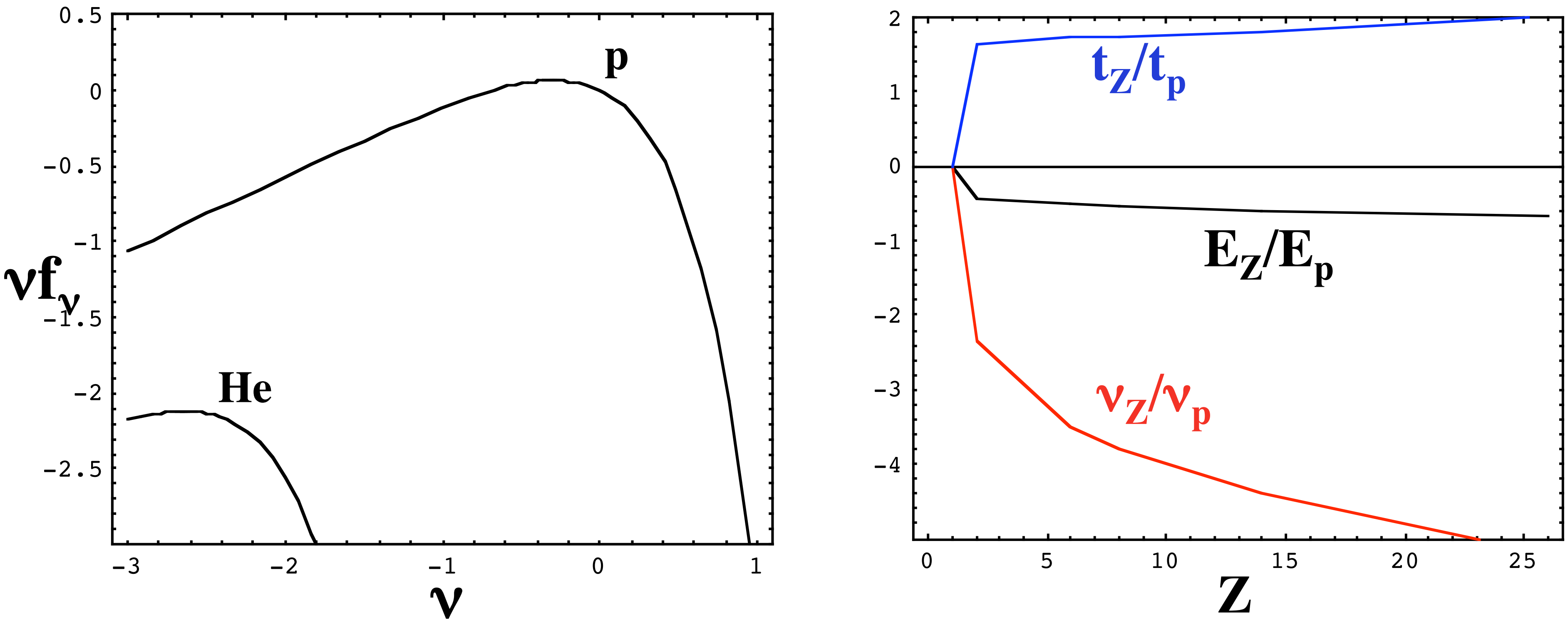


nuclear synchrotron spectra

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

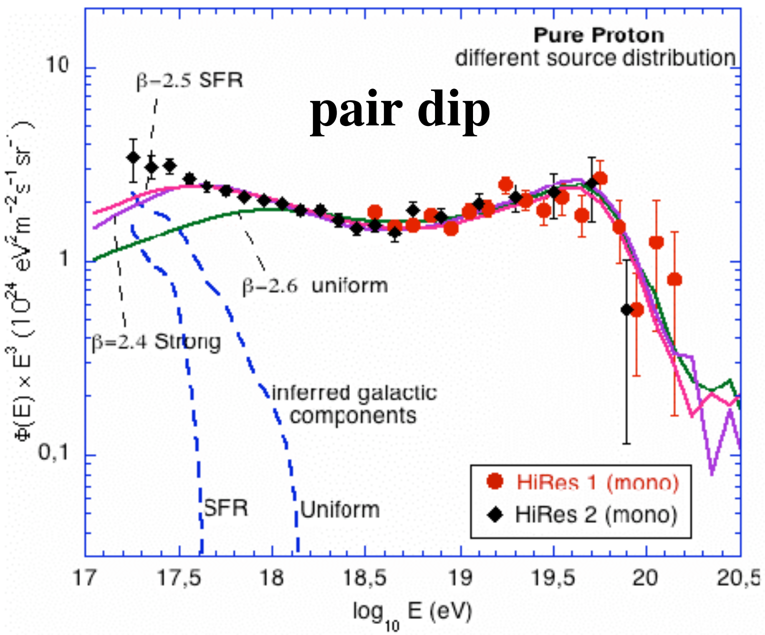
He observable -> crucial for interpretation of UHECR ankle

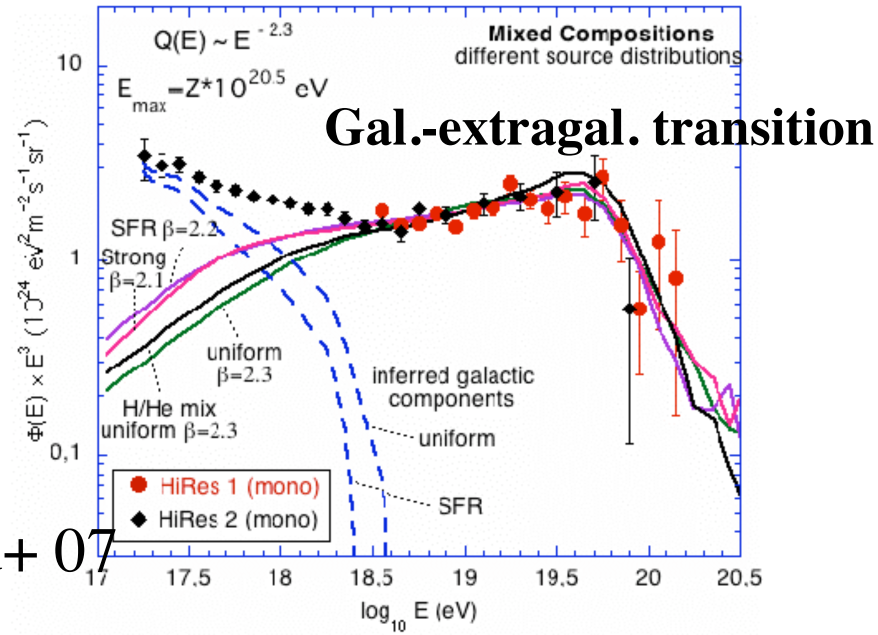
C,O,Si,Fe… may be observable
if highly enhanced and/or protons cool faster

unique probe of UHE nuclei acceleration in GRBs

possibly also for blazars?

He/p<0.10 required!





Allard+ 07

summary gamma-rays from UHECR accelerators

AGNs

number of potential acceleration sites

blazar region: if emission leptonic, unfavorable for UHECRs
if emission hadronic, OK

hot spots: favorable for UHECRs but hadronic emission not strong

UHECR composition:
uncertain but heavy nuclei may be moderately enhanced

GRBs

internal or external reverse shocks:
pγ cascade or p synchrotron GeV-TeV

UHECR composition:
uncertain but possibly mainly heavy nuclei with little p+He

synchrotron GeV-TeV from UHE nuclei possibly observable
under certain conditions