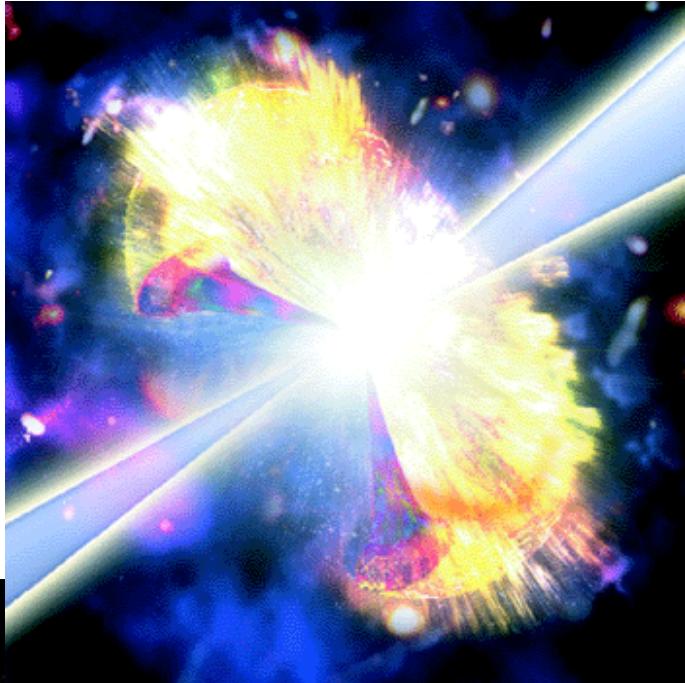
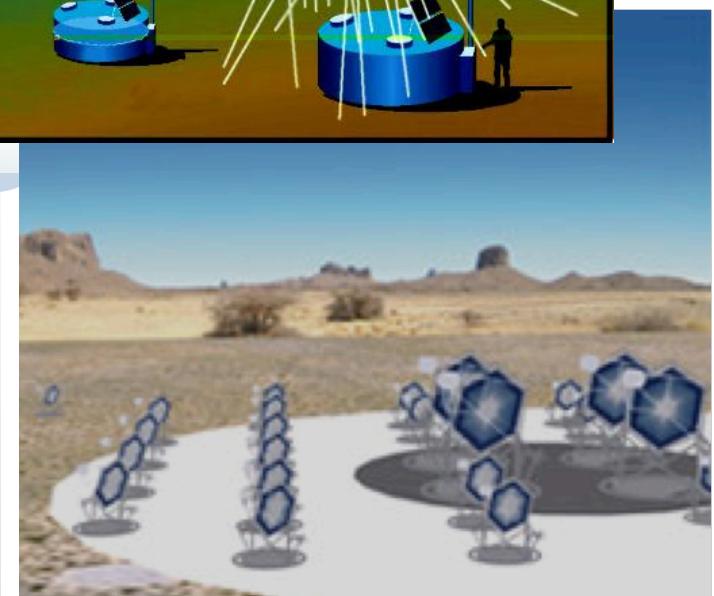
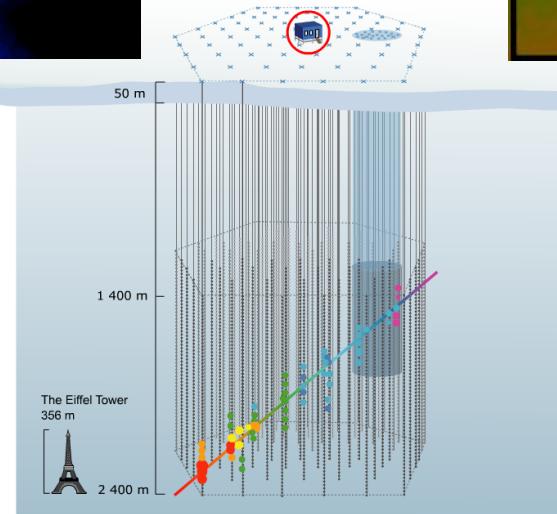
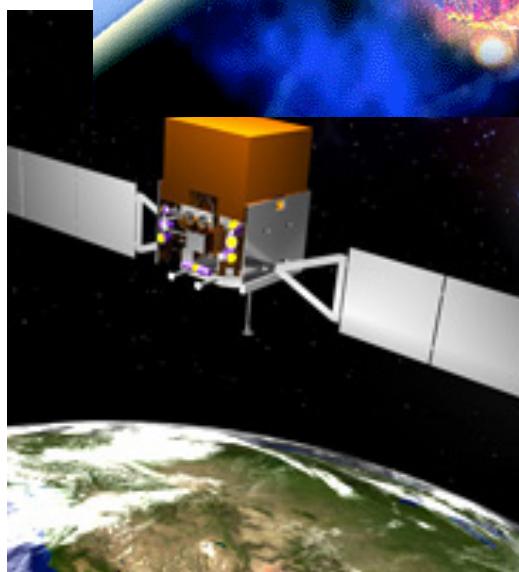
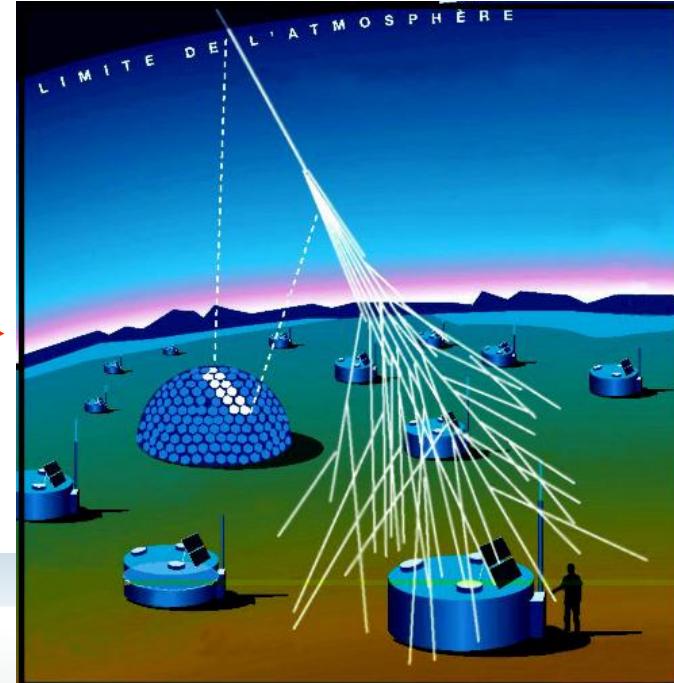


GRBs and UHECRs in the multi-messenger era

Susumu Inoue (ICRR/MPP)
with help from many collaborators



p...Fe
?



outline GRBs and UHECRs

1. observational status of UHECRs
2. acceleration
3. energetics
4. escape
5. tests: CRs, gamma rays, neutrinos
6. use(?)

cosmic vs terrestrial accelerators

$E_{\text{UHECR}} \sim 3 \times 10^{20} \text{ eV} \sim 50 \text{ J}$

kinetic E of fastball

$E_{\text{MT}} \sim 8 \times 10^{20} \text{ eV} (145 \text{ g}, 155 \text{ km/h})$



kinetic E of free kick

$E_{\text{CR7}} \sim 2 \times 10^{21} \text{ eV} (430 \text{ g}, 130 \text{ km/h})$



$E_{\text{LHC}} \sim 7 \text{ TeV}$

\ll

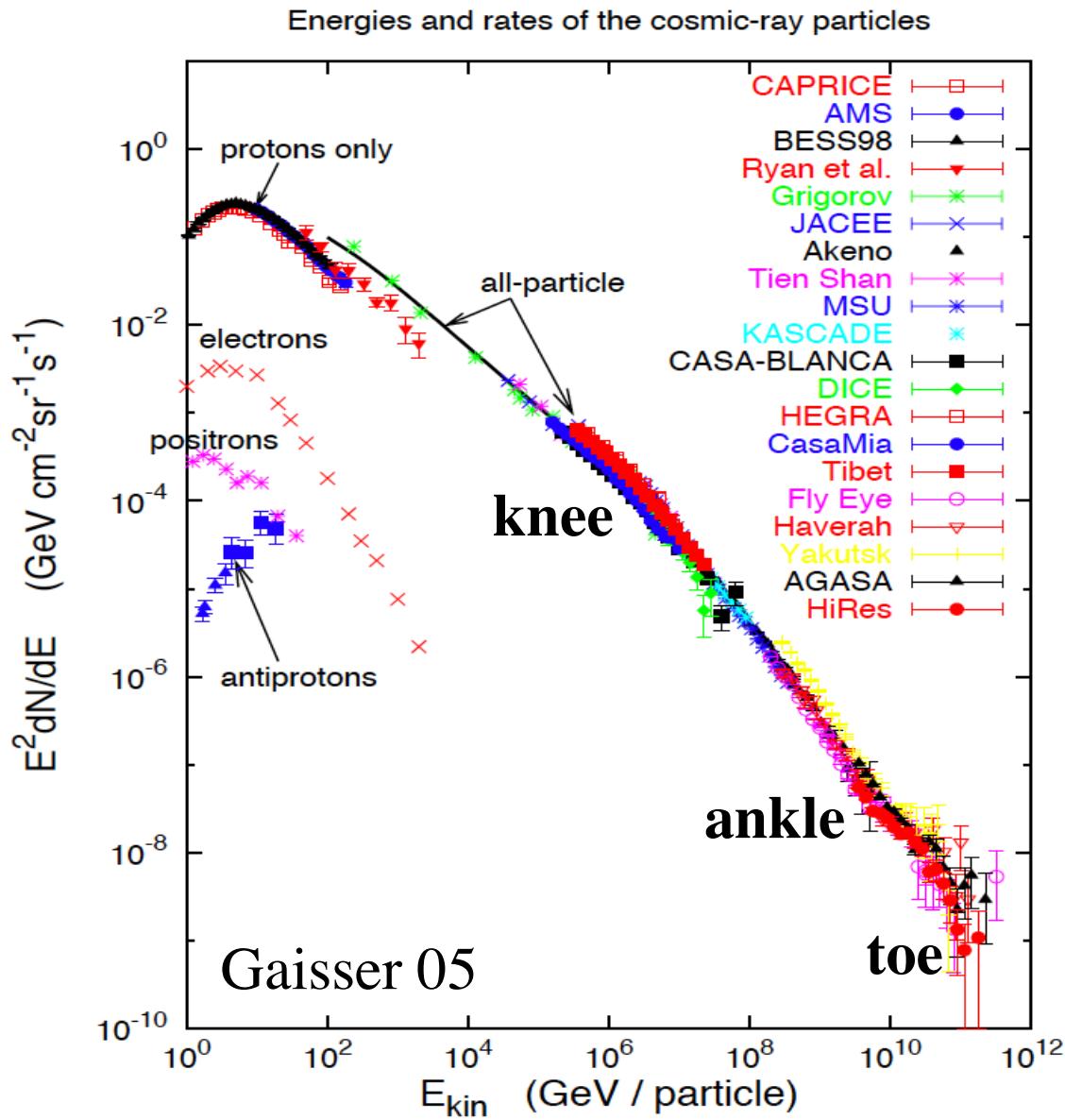
kinetic E of housefly

$E_{\text{fly}} \sim 200 \text{ TeV} (20 \text{ mg}, 7 \text{ km/h})$



1. observational status of UHECRs

observed CR spectrum



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

Galactic SNRs?

likely, but not yet definitive

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

Galactic? no new source?

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

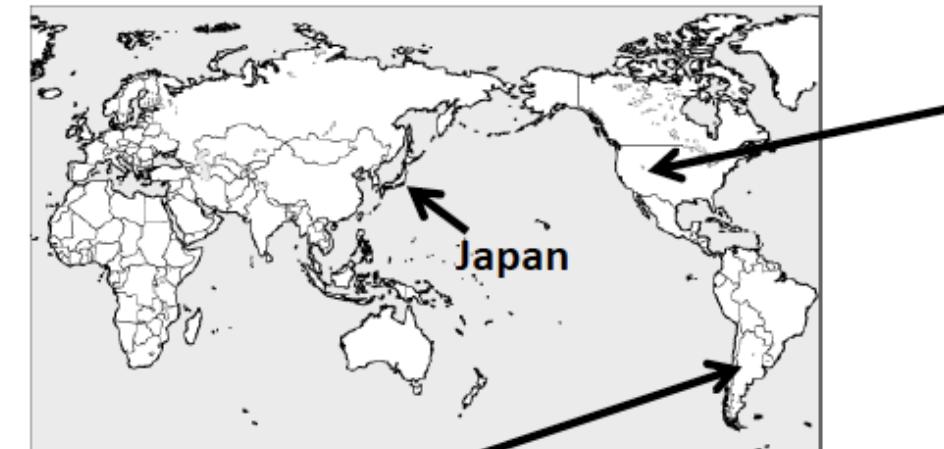
extragalactic: AGNs?

GRBs?

???

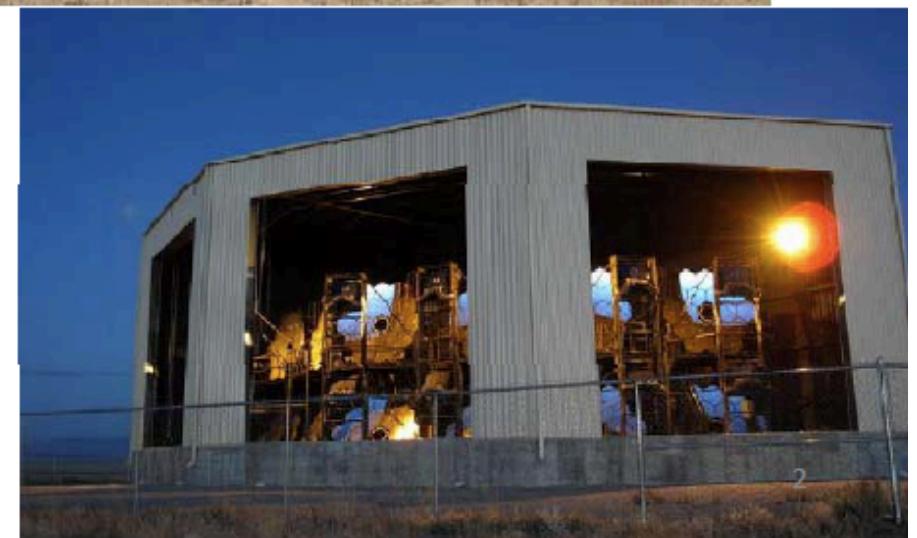
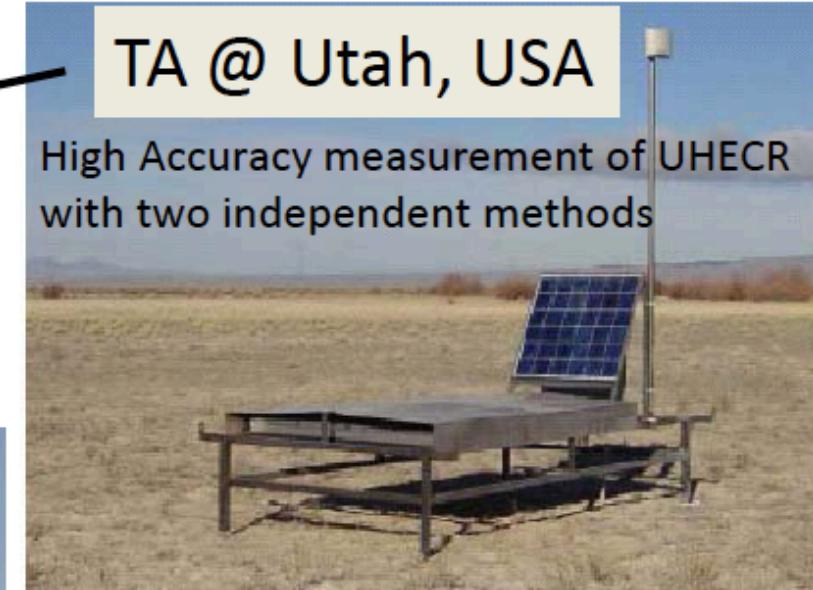
UHECR observatories today: Auger and TA

slide from T. Yamamoto



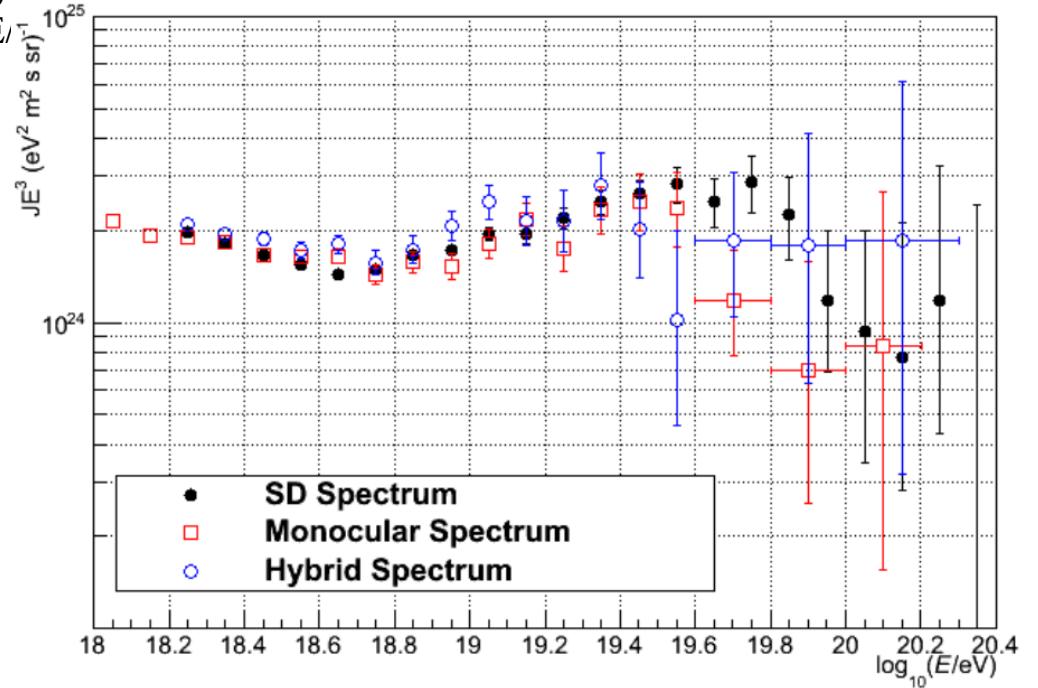
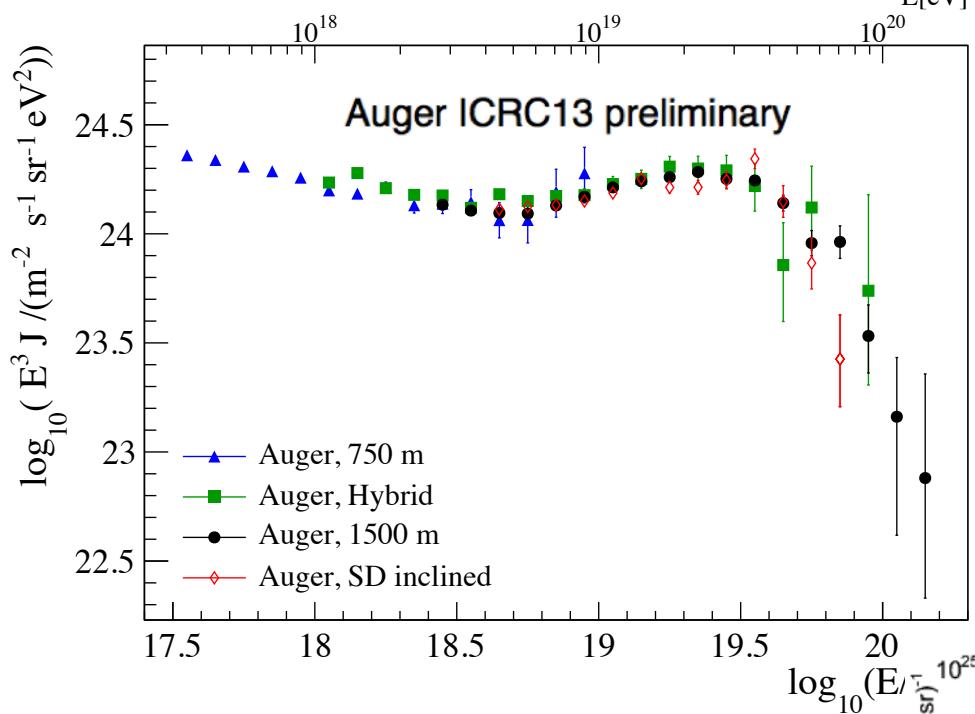
Auger @ Malargüe Argentina

Observe UHECR with Unprecedented Precision



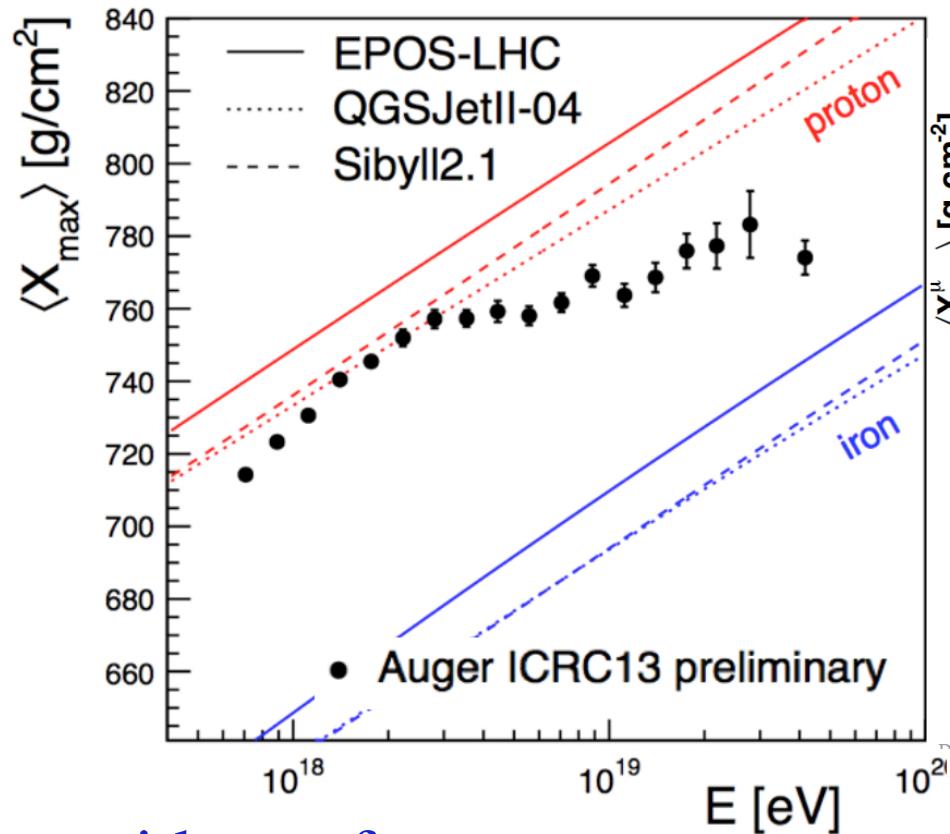
UHECR spectrum: Auger, TA

talks from Rio ICRC 2013

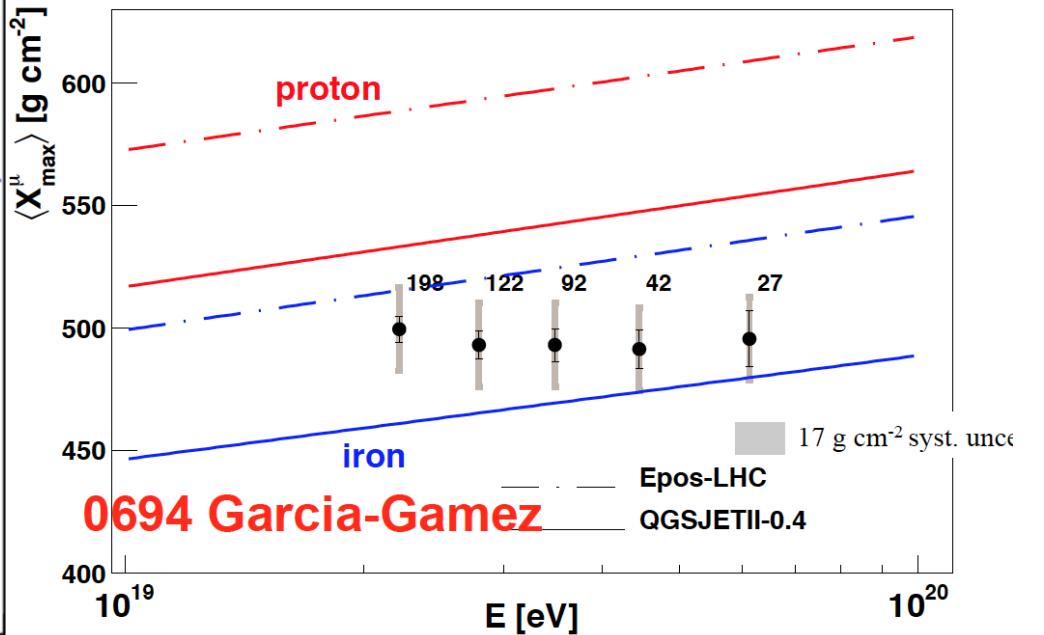


UHECR Xmax (composition?): Auger

Letessier-Selvon
Rio ICRC 2013



Data from 1-January 2004 to 31-December 2011



evidence for:
heavier composition at higher E
or nontrivial hadronic interactions

NB: data from HiRes and TA consistent so far with light
as well as heavy composition
(official conclusion from UHECR12 working group)

UHECR anisotropy: Auger vs TA

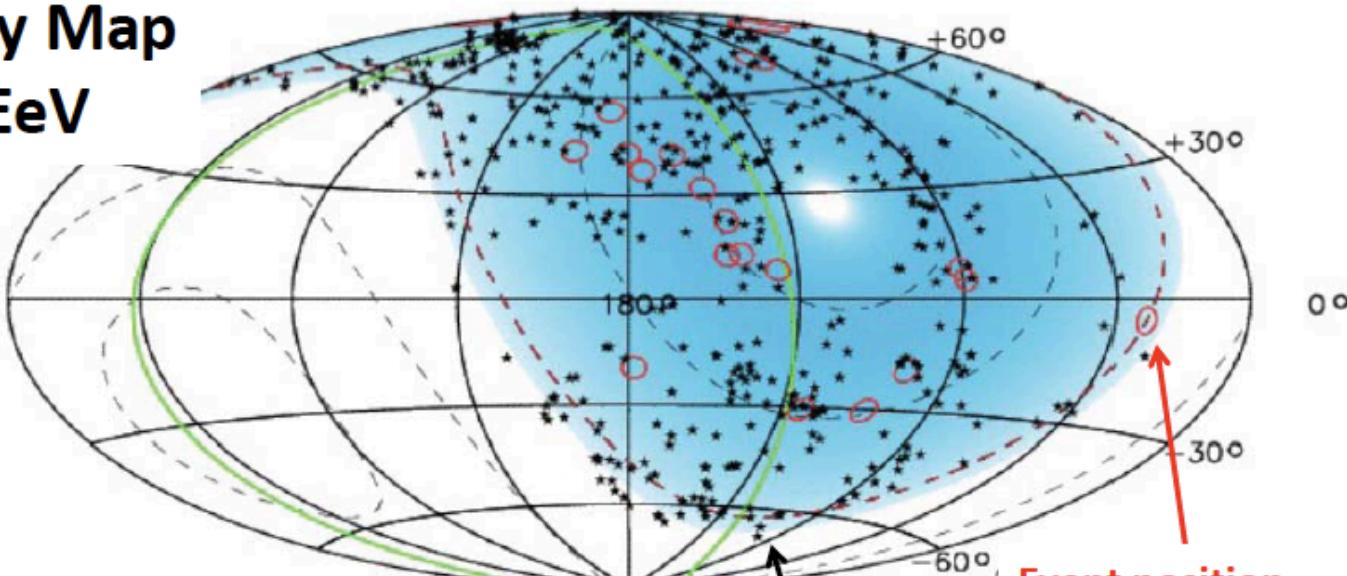
Beijing ICRC 2011
slide from T. Yamamoto

TA Sky Map

E>57EeV

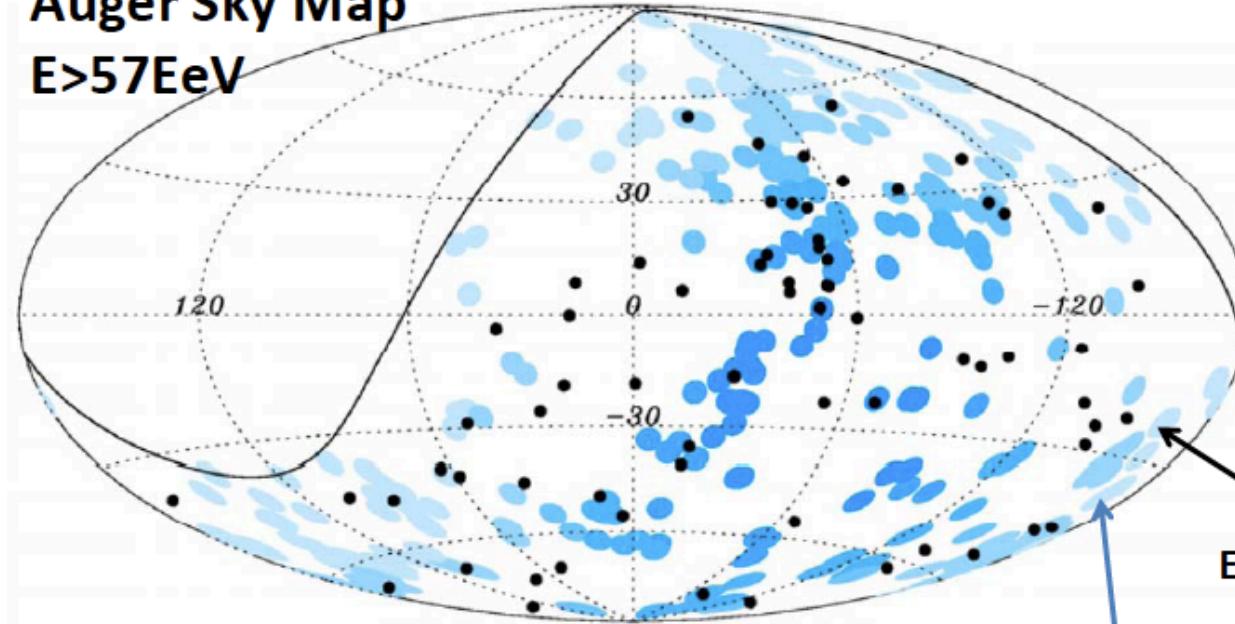
20Events Observed

8Events Correlate
(24%)



Auger Sky Map

E>57EeV



84Events Observed
28Events Correlate
(33%)

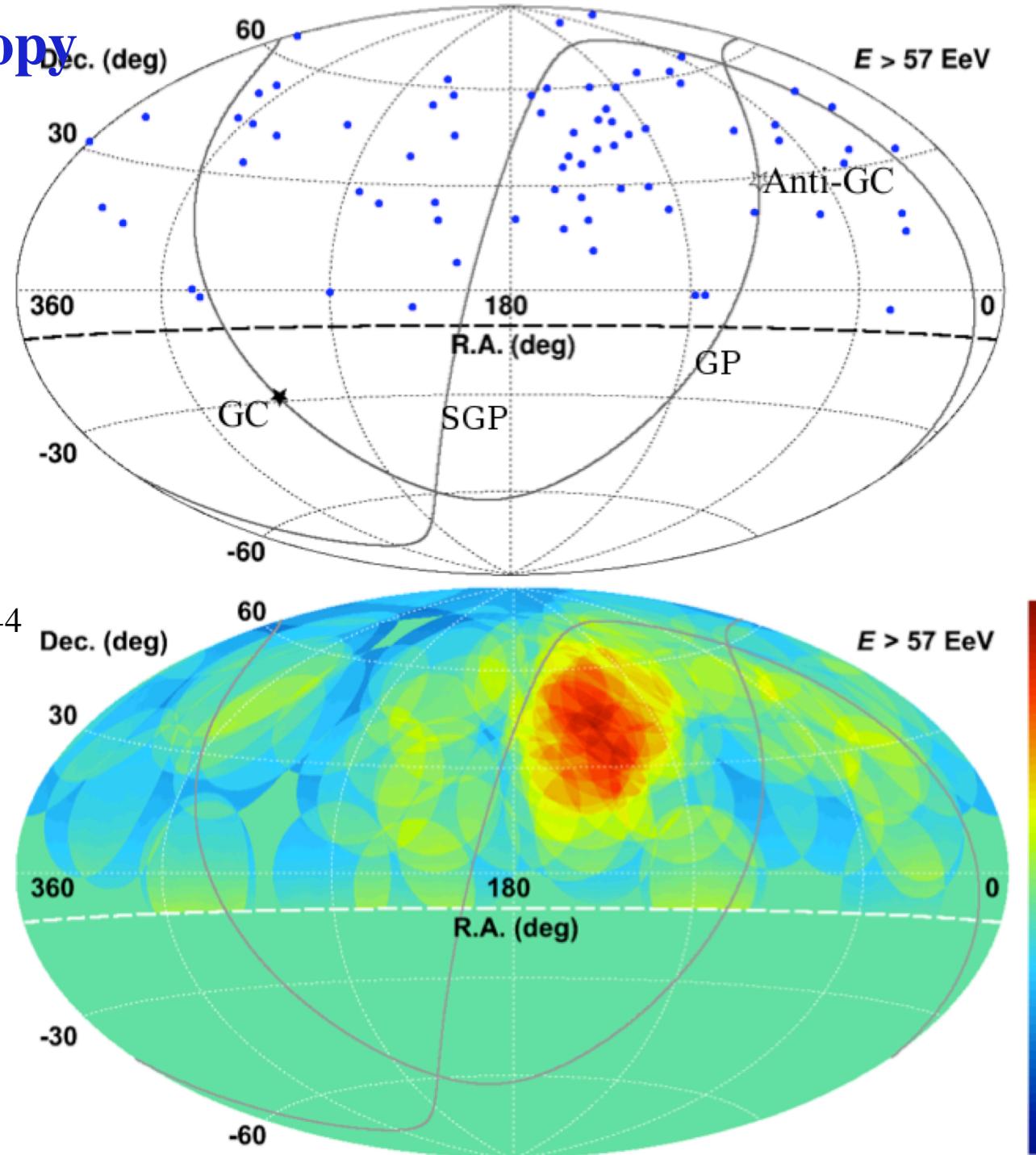
AGN position(3.1° circle)

UHECR anisotropy TA “hotspot”

Abbasi+
arXiv:1404.5890

clustering at
 $E > 57 \text{ EeV}$
20 deg radius circle
5.1 σ significance
chance prob 3.7×10^{-4}

~ 20 deg off SGP
Ursa Major cluster?
(not far from
Coma, Virgo)



recipe for a good CR source

good source =

good accelerator -> good confiner

+ efficient escape, inefficient adiabatic losses

-> good deconfiner

+ inefficient radiative losses

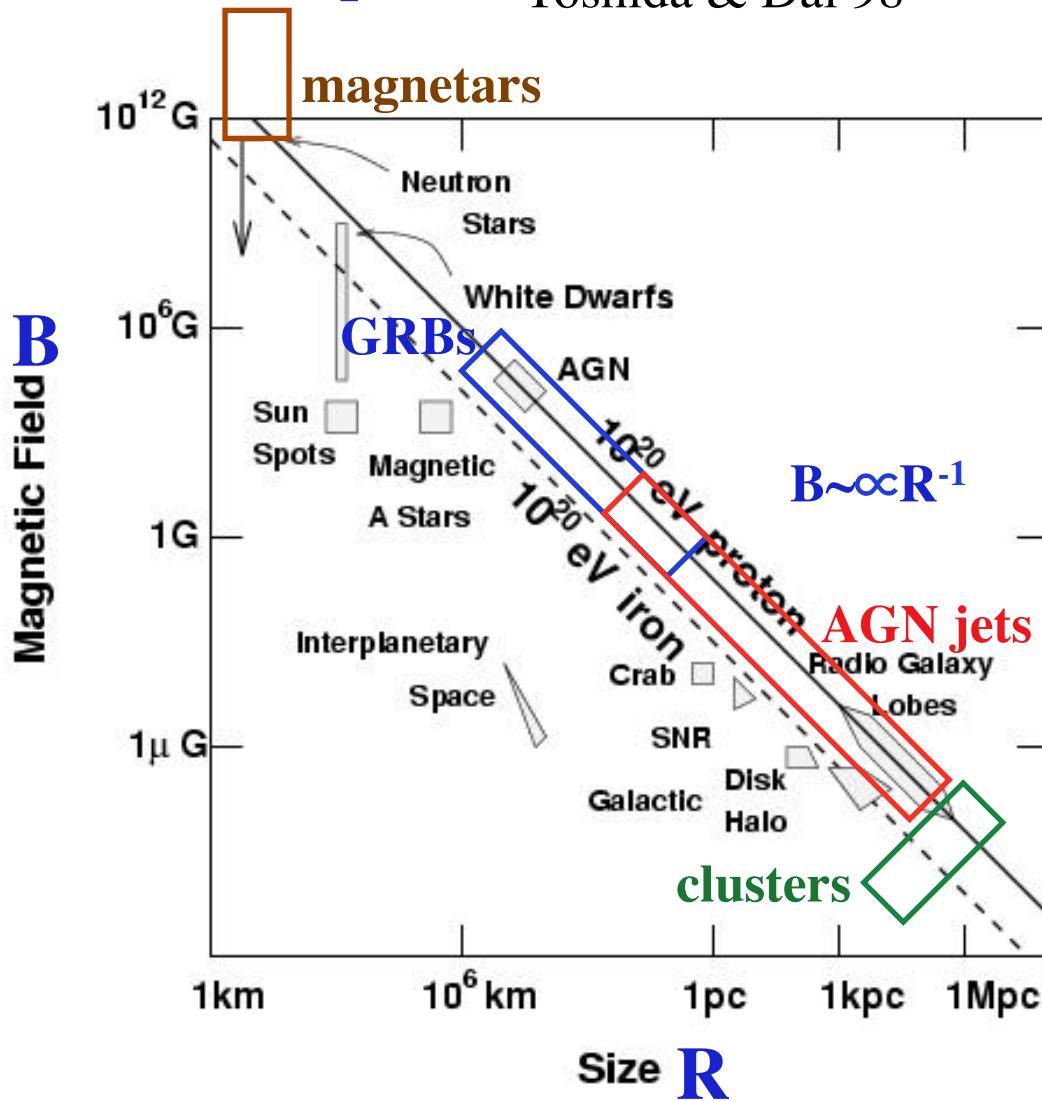
-> no-good radiator of neutrinos/hadronic gamma-rays

2. acceleration

-> Lemoine

UHECR sources: acceleration

“Hillas plot” adapted from Yoshida & Dai 98

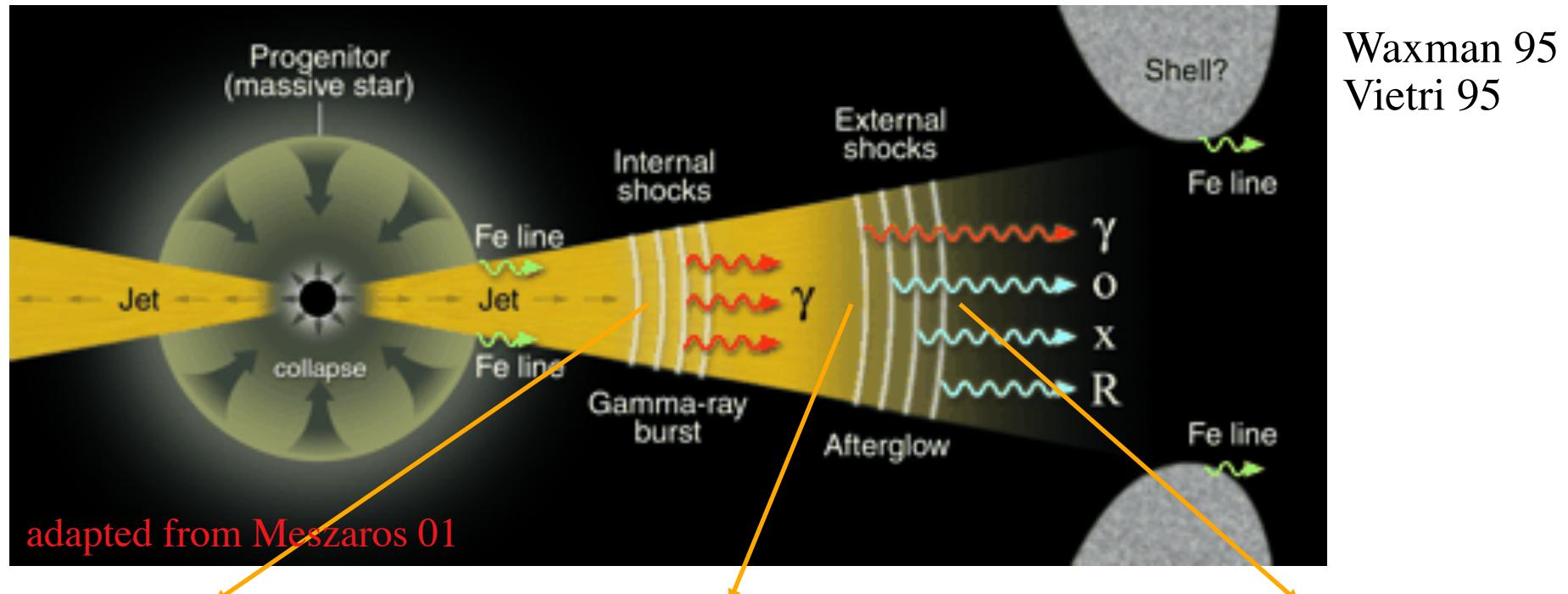


$E \leq ZeBR(v/c)$
confinement

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

old favorite: AGNs
leading contender: GRBs
dark horse: magnetars
clusters, etc.

GRBs: acceleration sites



prompt X- γ emission

internal shocks?

B reconnection?

$$R \sim \Gamma^2 c t_{\text{var}} \sim 10^{12} - 10^{16} \text{ cm}$$

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

$$\Gamma_{\text{rel}} \sim 1$$

escape nontrivial

optical flash, radio flare

external reverse shock

radio-IR-opt-X afterglow

external forward shock

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

$$B \sim 10 \text{ G}$$

$$\Gamma_{\text{rel}} \sim 1$$

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

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

$$\Gamma_{\text{rel}} \gg 1$$

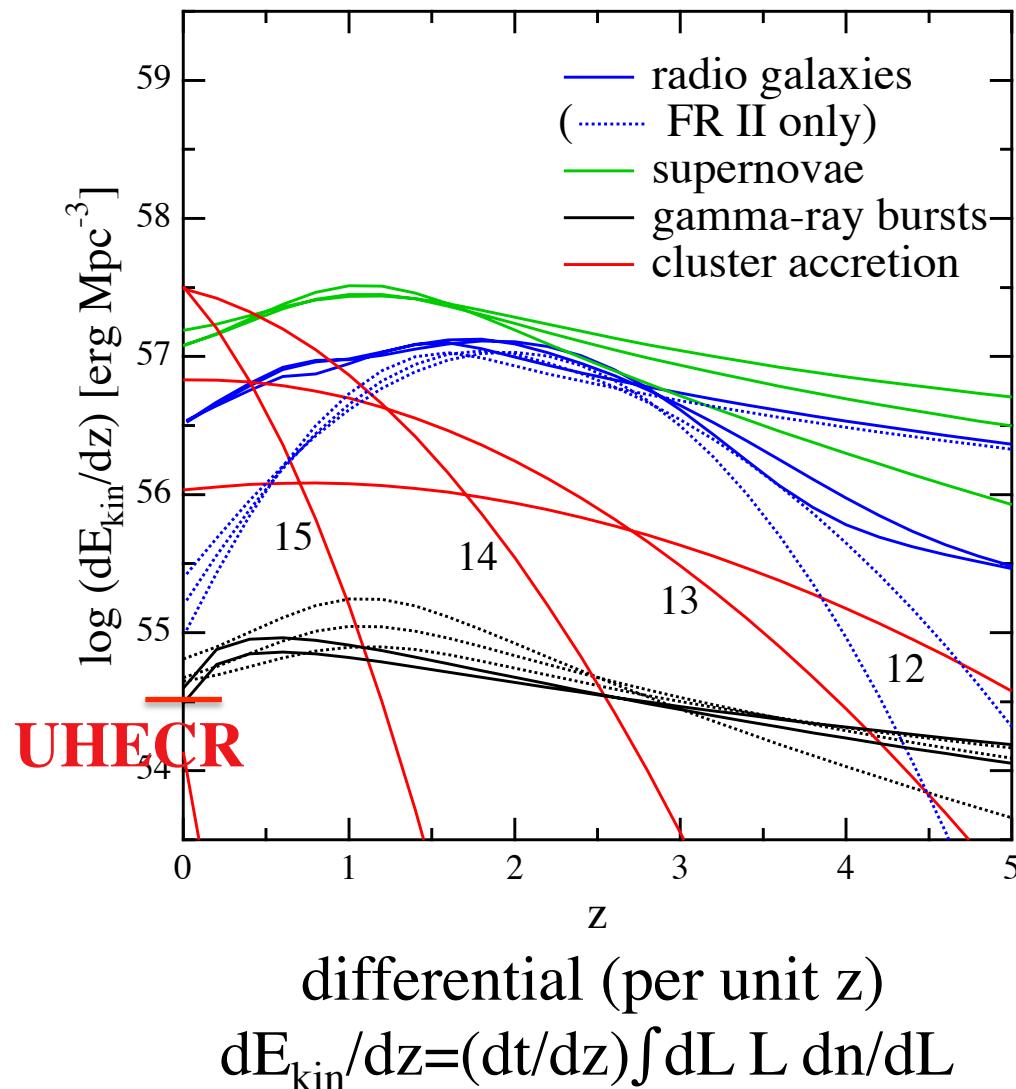
accel. nontrivial

3. energetics

UHECR sources: energy budget

SI, arXiv:0809.3205

kinetic E input into the universe



GRBs

\propto star formation rate

Porciani & Madau 01, Le & Dermer 07

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

UHECR budget @ $10^{18.5}$ eV

$u_{\text{CR}} \sim 10^{-19}$ erg cm⁻³

$\sim 3 \times 10^{54}$ erg Mpc⁻³

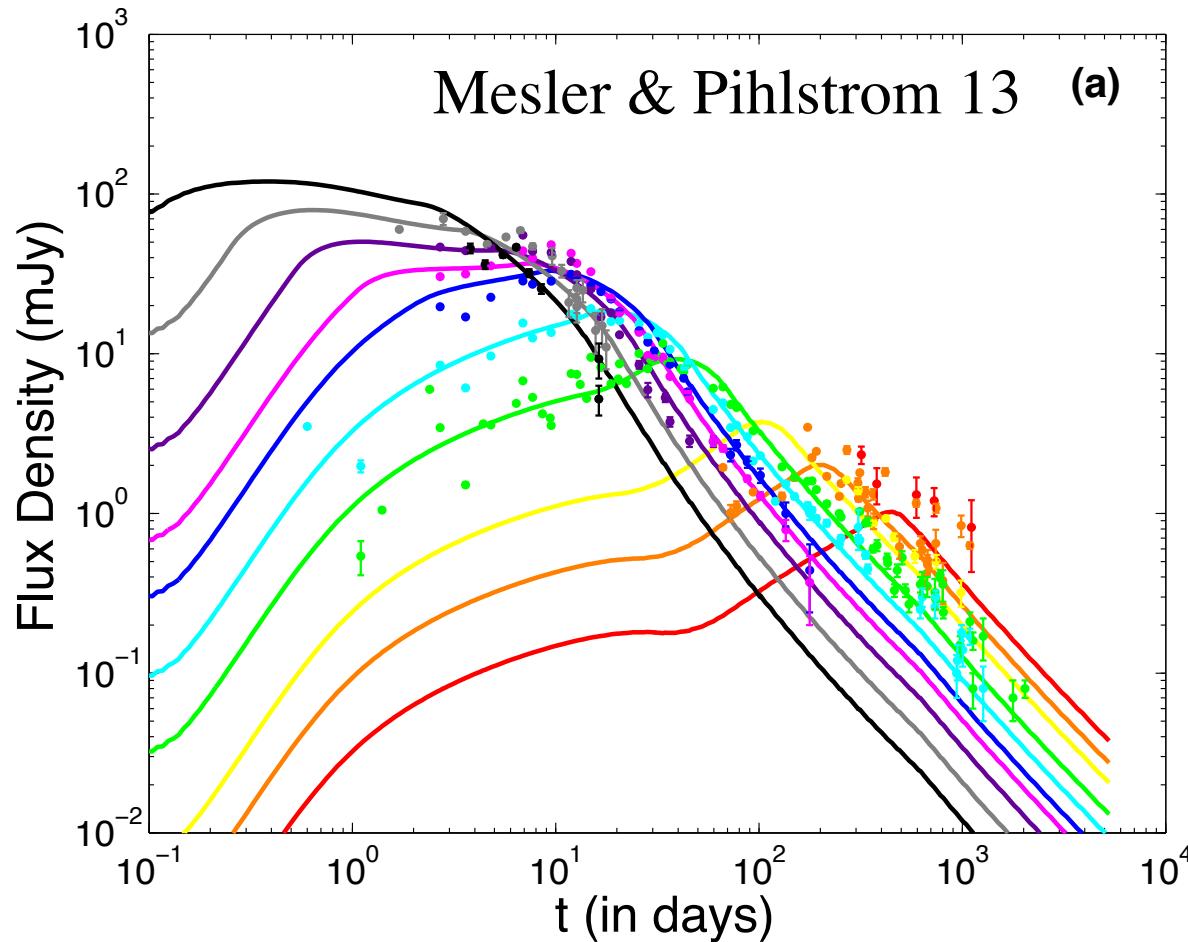
stringent requirements
-> proton-dominated?

GRB energetics: radio afterglow calorimetry

late time radio afterglow after non-relativistic transition

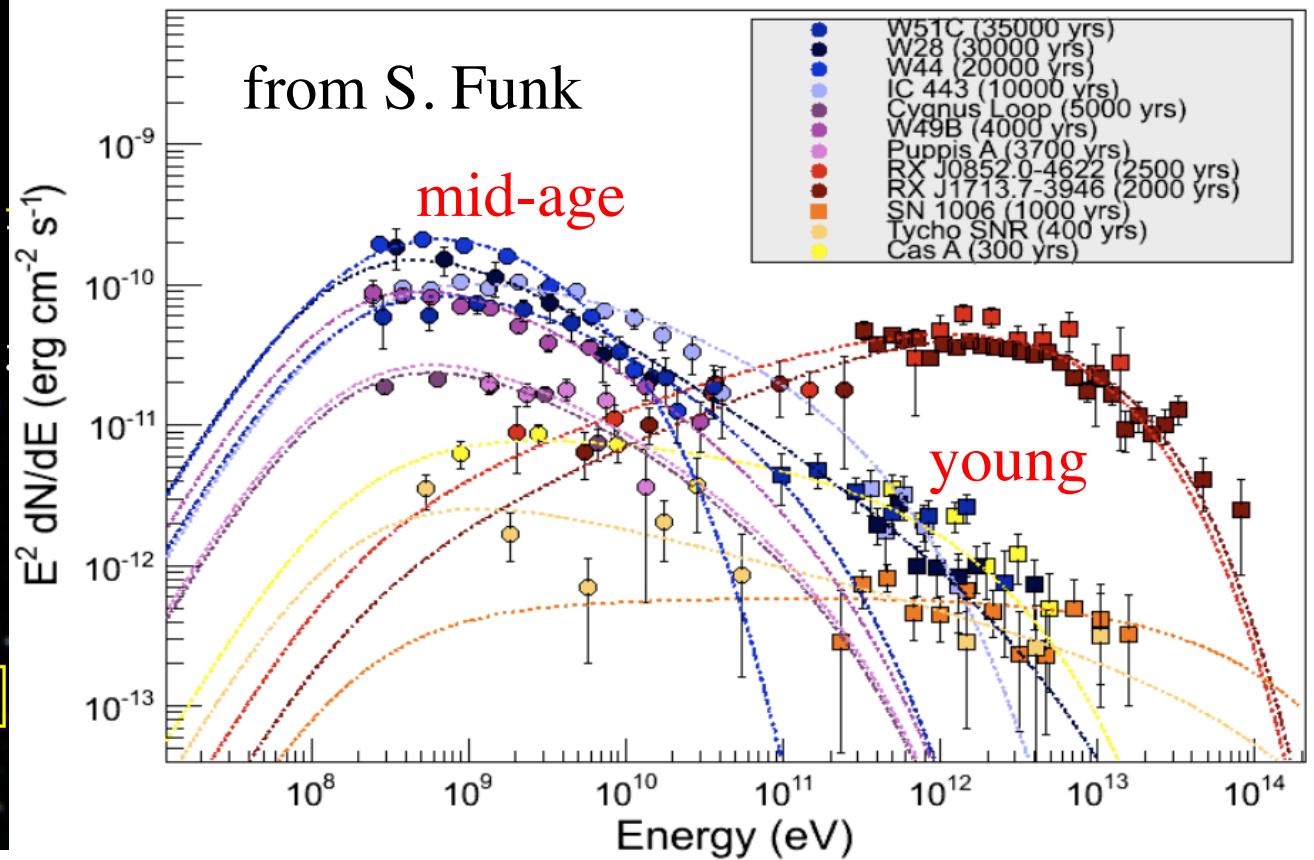
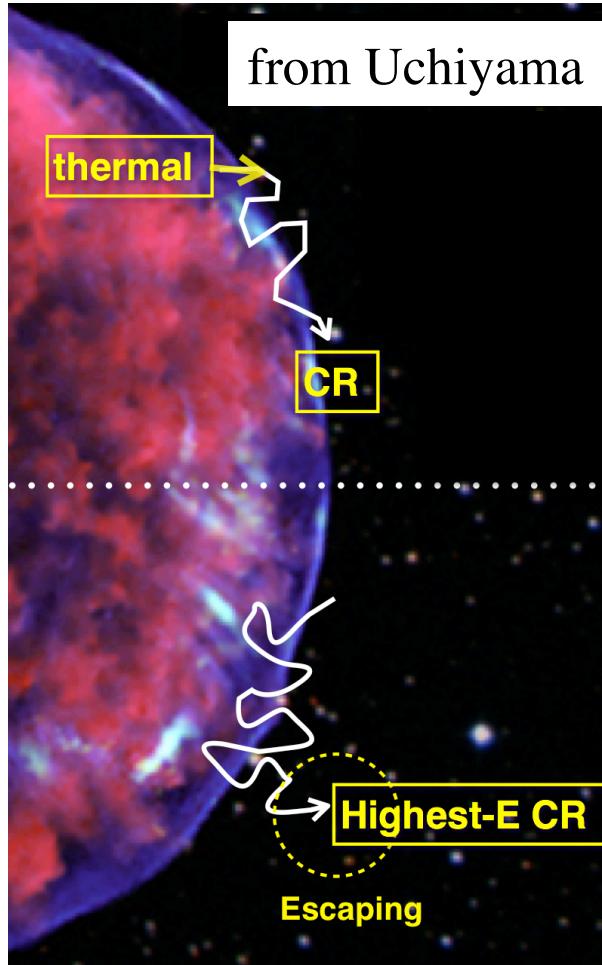
-> total beaming-corrected blastwave energy

GRB 030329 -> $E \sim 10^{51}$ erg



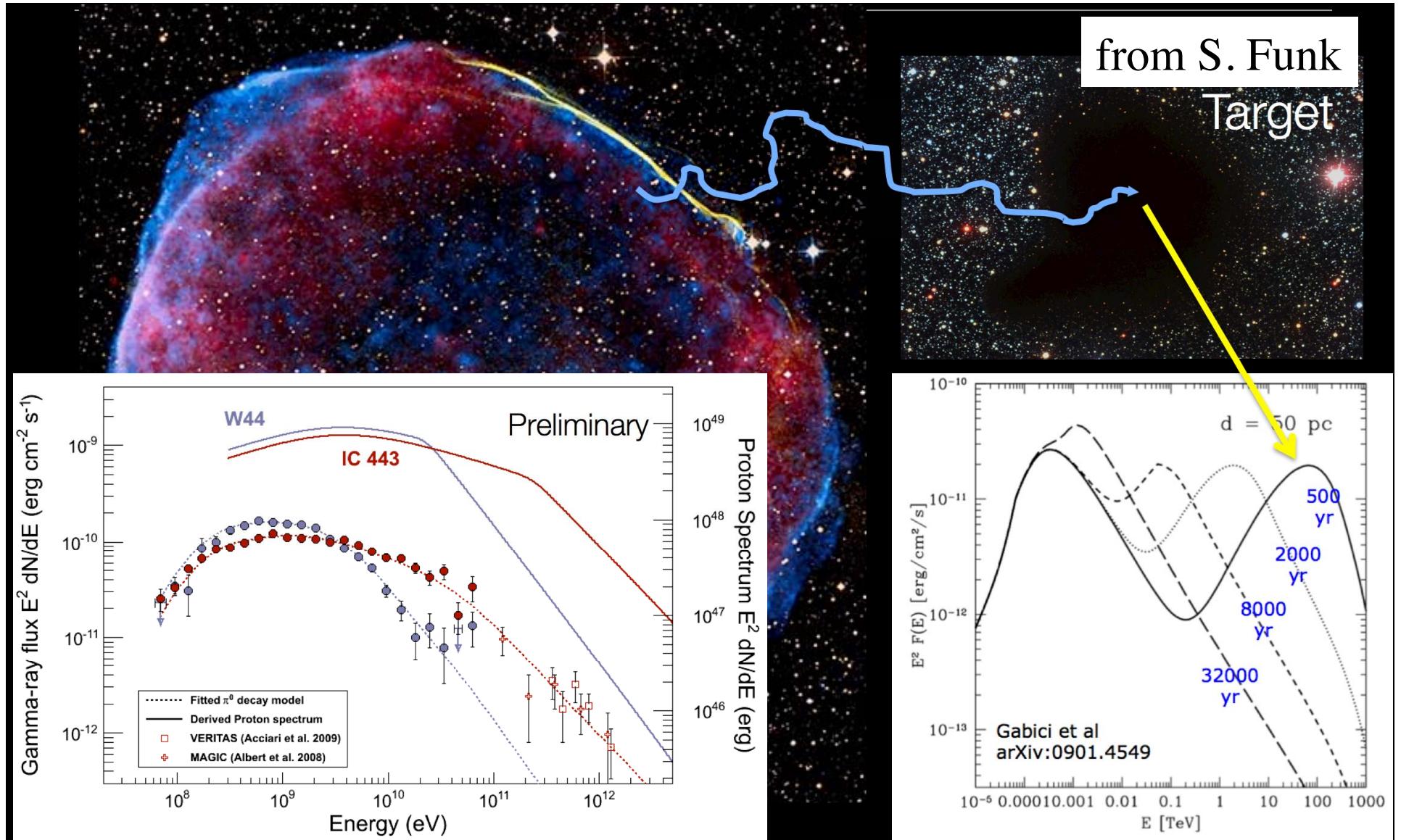
4. escape

CR acceleration and escape in SNRs



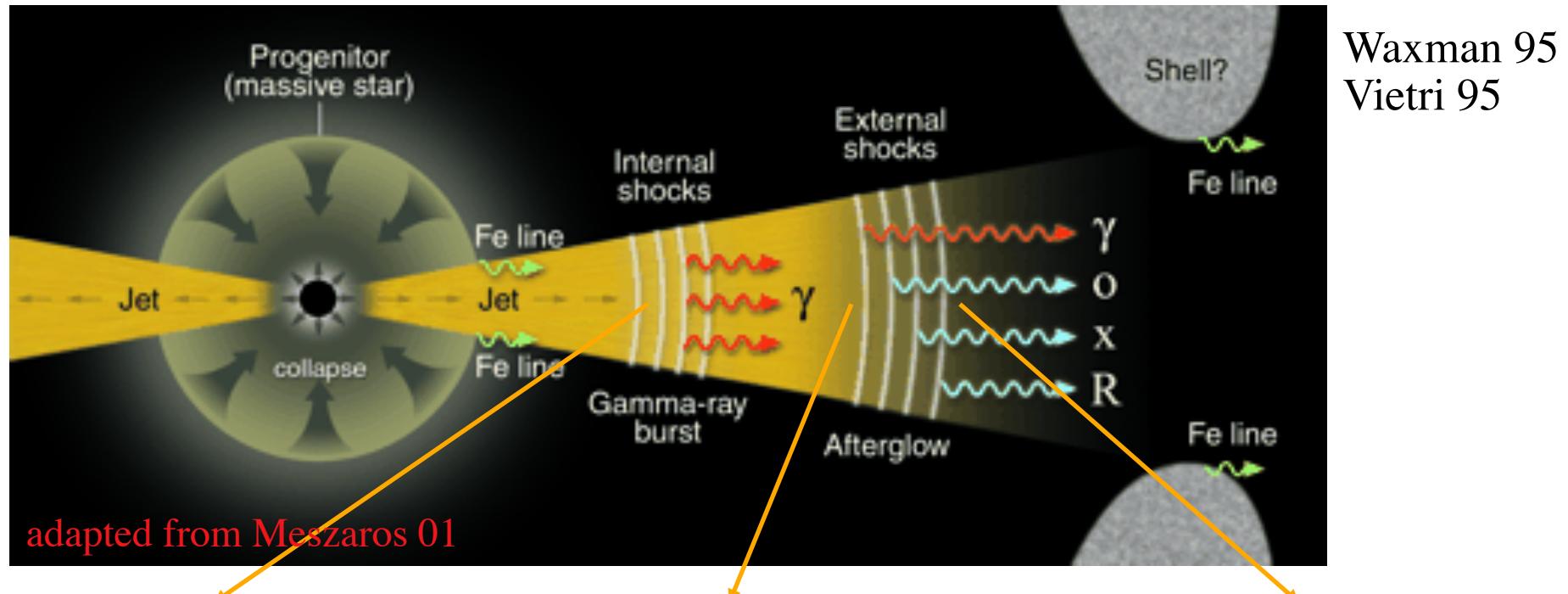
- higher-energy CRs likely escape earlier
- CR spectrum at acceleration \neq observed
- energy losses of CRs small

confined and escaping CRs in SNRs



similar expectation for relativistic forward shocks
Katz, Meszaros & Waxman 2010

GRBs: acceleration sites



prompt X- γ emission

internal shocks?

B reconnection?

$$R \sim \Gamma^2 c t_{\text{var}} \sim 10^{12} - 10^{16} \text{ cm}$$

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

$$\Gamma_{\text{rel}} \gg 1$$

accel. nontrivial

5. tests: CRs, gamma-rays, neutrinos

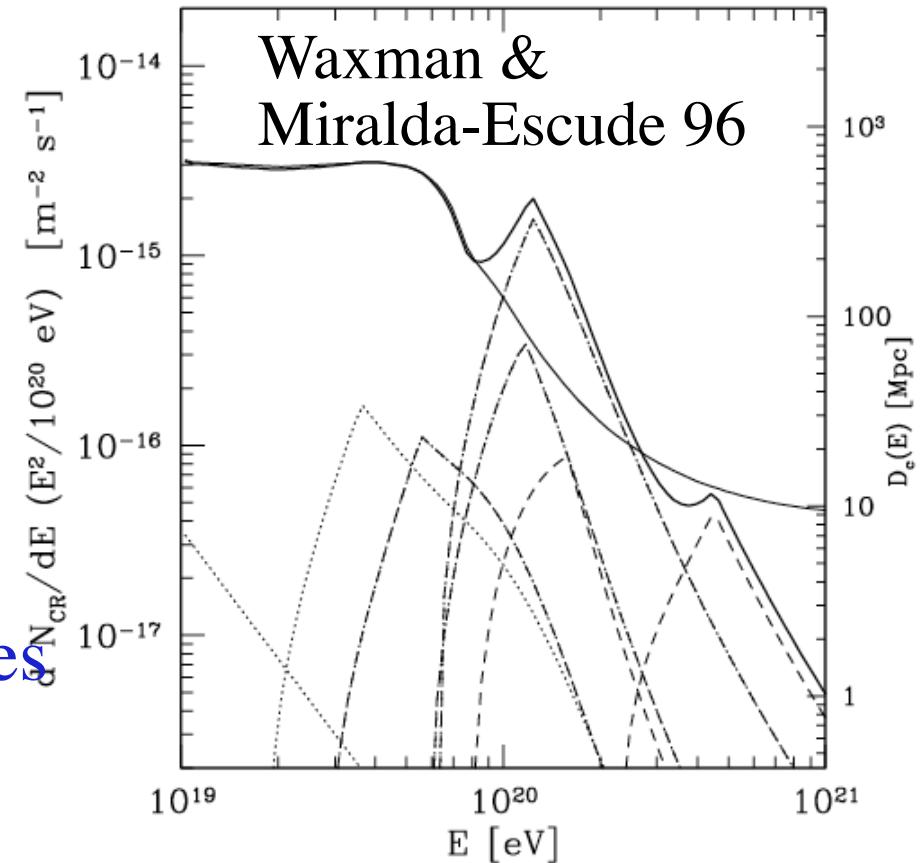
-> Murase, Allard, Bustamante, Petropoulou...

GRBs as UHECR sources: diagnostics

time delay

$$t(E_p, D) \sim \theta^2 D / 4c$$
$$\sim 10^7 \text{ yr } E_{p, 20}^{-2} D_{100\text{Mpc}}^2 l_{\text{Mpc}} B_{-8}^{-2}$$

CR spectra of individual sources
narrow at given time?

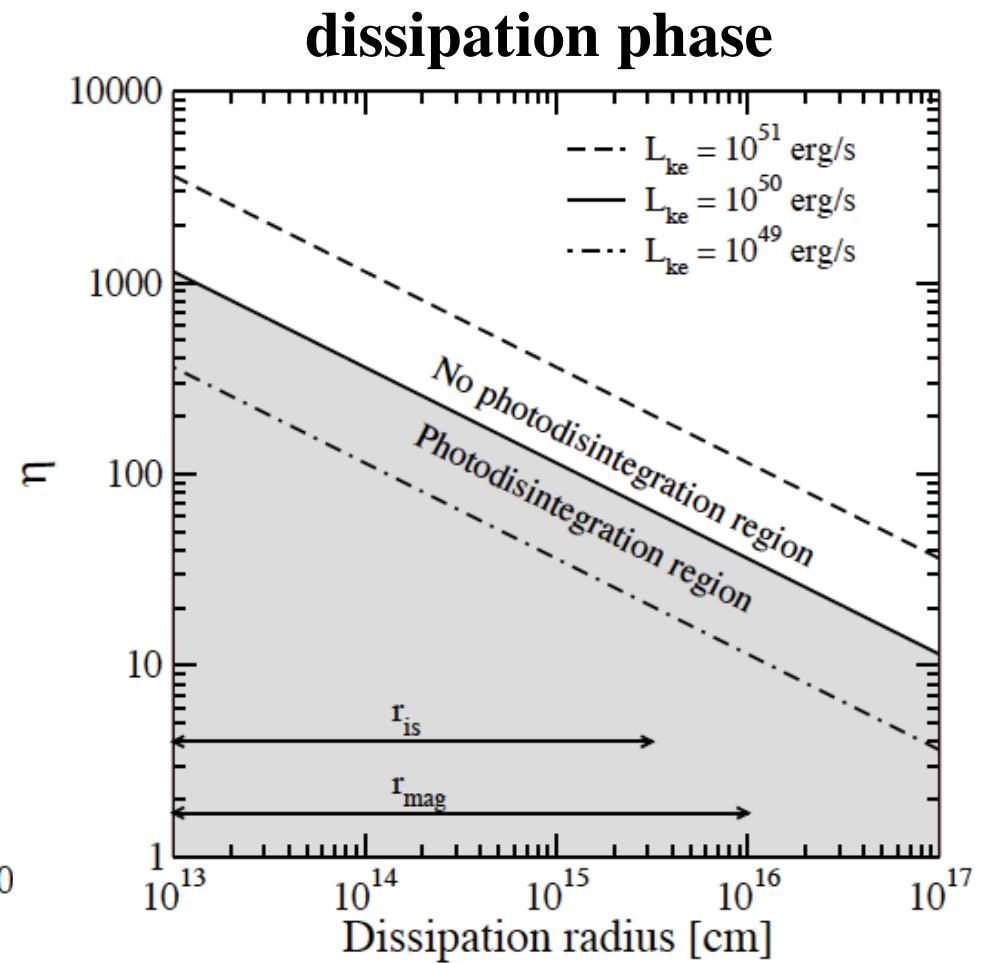
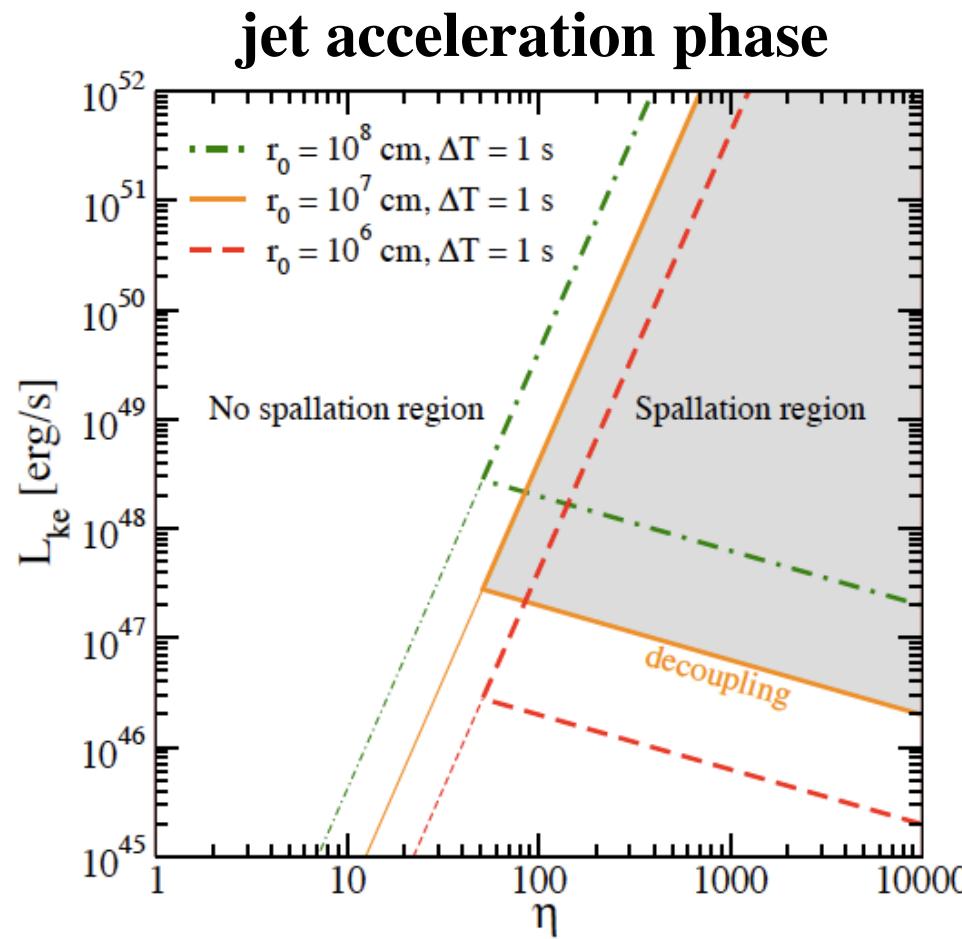


maybe unlikely with realistic luminosity function

Takami & Murase 12

survival of Fe nuclei in GRBs

Horiuchi+ 12

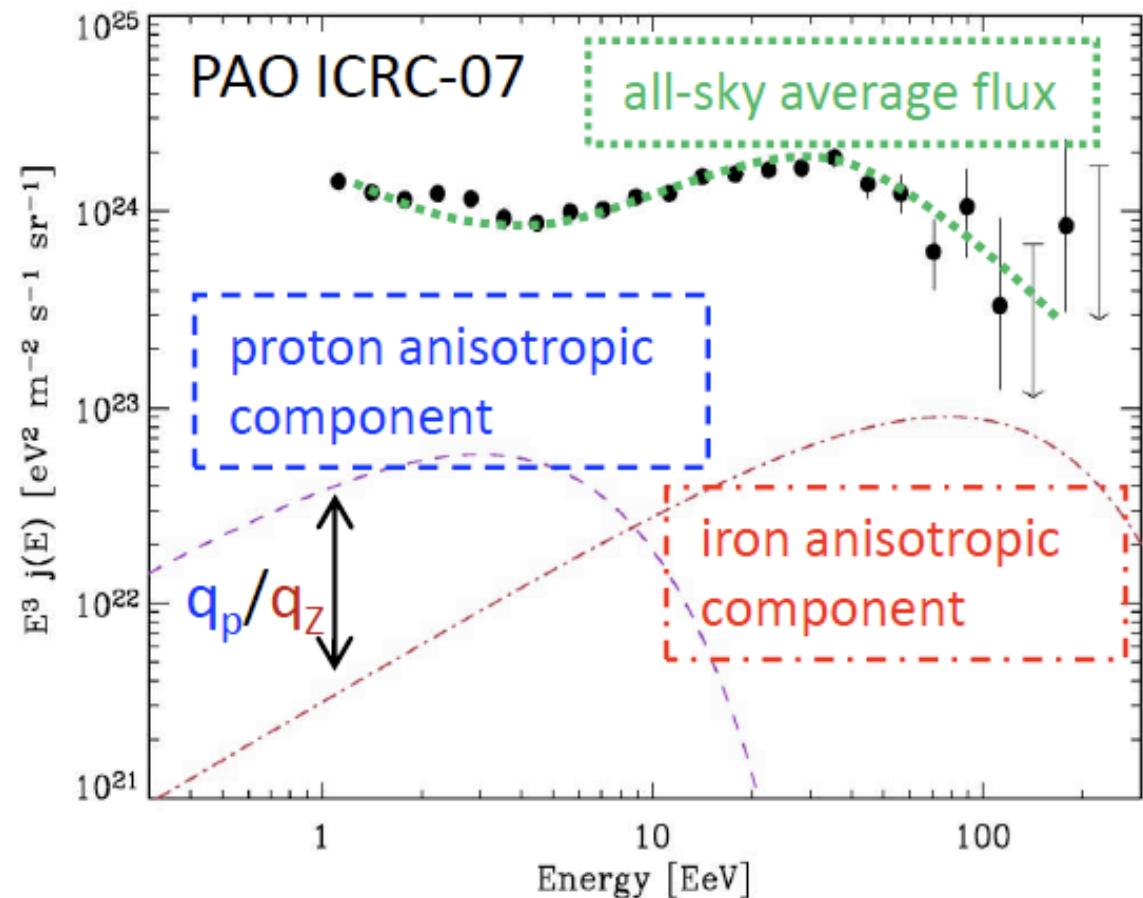


Fe may survive destruction throughout the processes of jet formation, shock formation and particle acceleration in GRBs

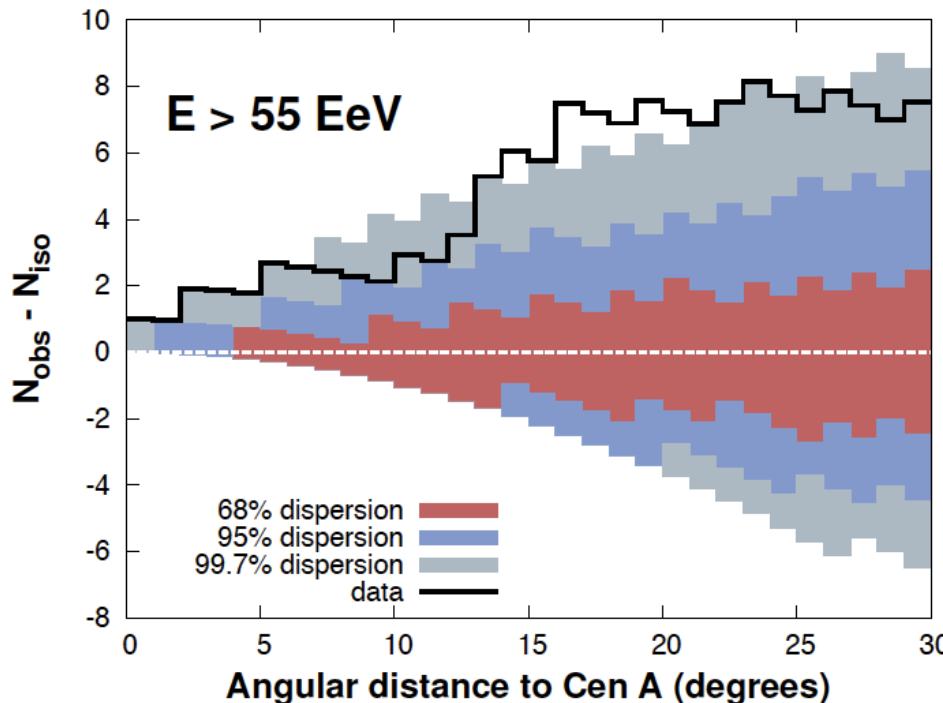
UHECR composition vs low-energy anisotropy

Lemoine & Waxman 09

If heavy nuclei with Z produce anisotropy at E :
protons produce anisotropy at E/Z stronger by
 $p/nuclei$ abundance ratio at source

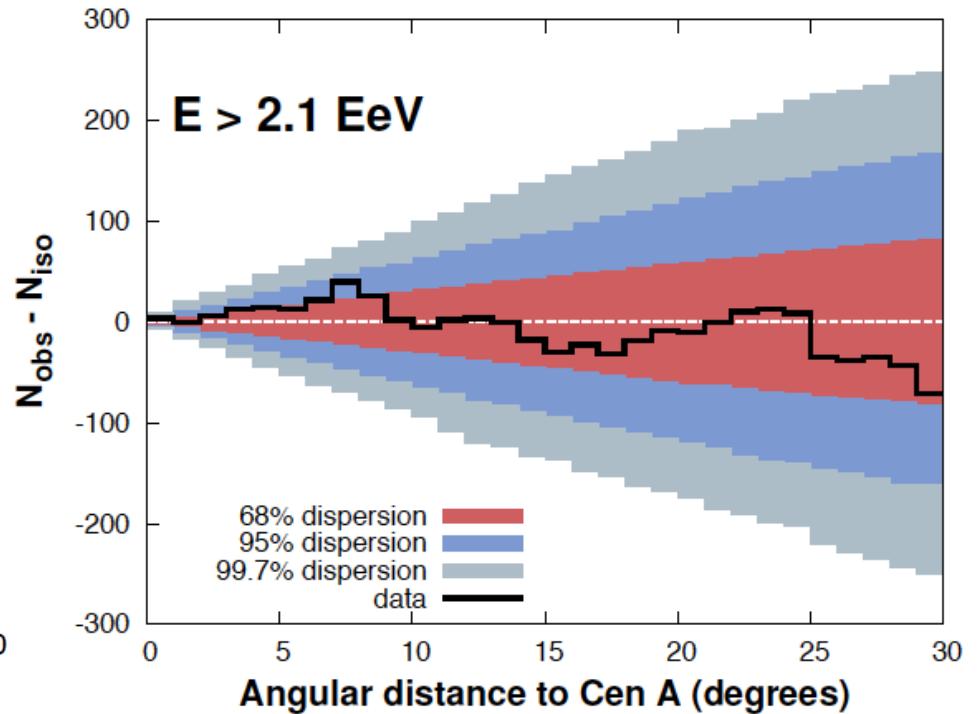


Auger anisotropy: Cen A



$>\sim 3$ sigma excess at $E > 55 \text{ EeV}$
for ~ 20 deg around Cen A

Auger 2011 (arXiv:1106.3048)

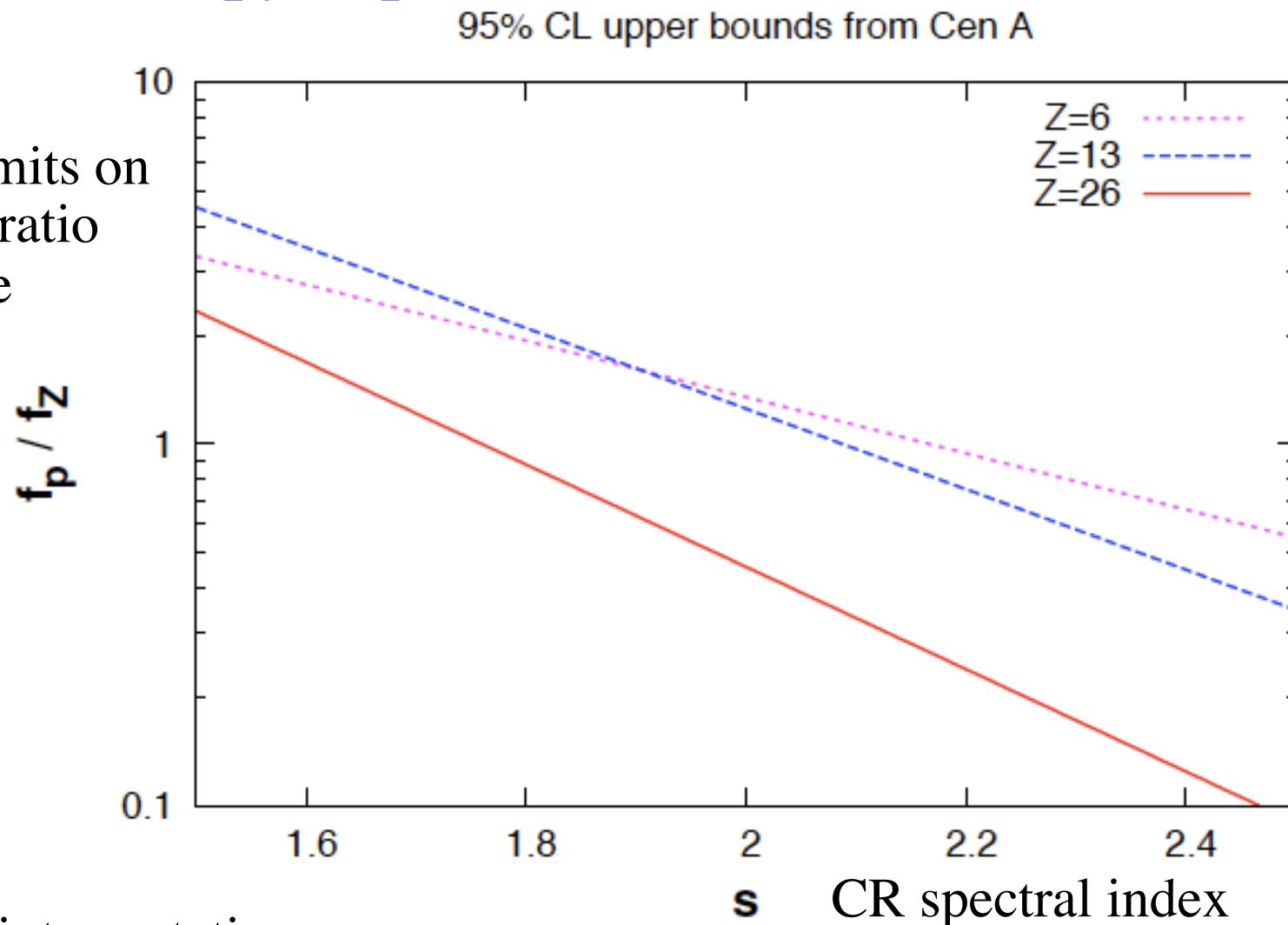


no corresponding anisotropy
at e.g. $E > 55/26 \text{ EeV}$

Auger anisotropy implications

Auger 2011 (arXiv:1106.3048)

upper limits on
number ratio
at source
at low E

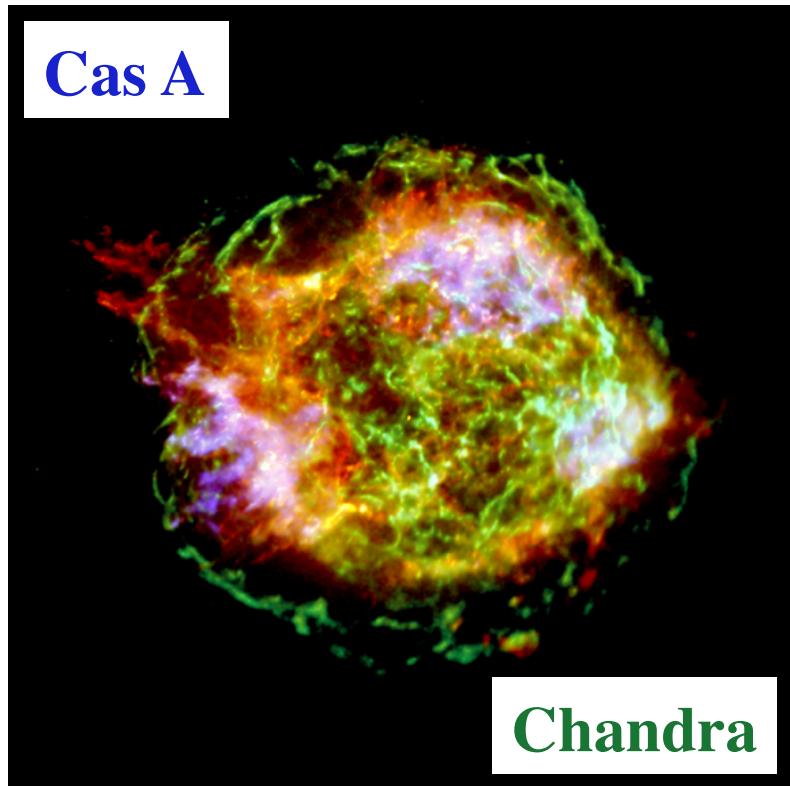


possible interpretations:

- nuclei strongly overabundant compared to protons: $\text{Fe/H} \sim 0.5-10$
- Auger anisotropy at $E > 55 \text{ EeV}$ not significant
- heavy nuclei not dominant at highest E (Xmax evol. from hadronic inter.)

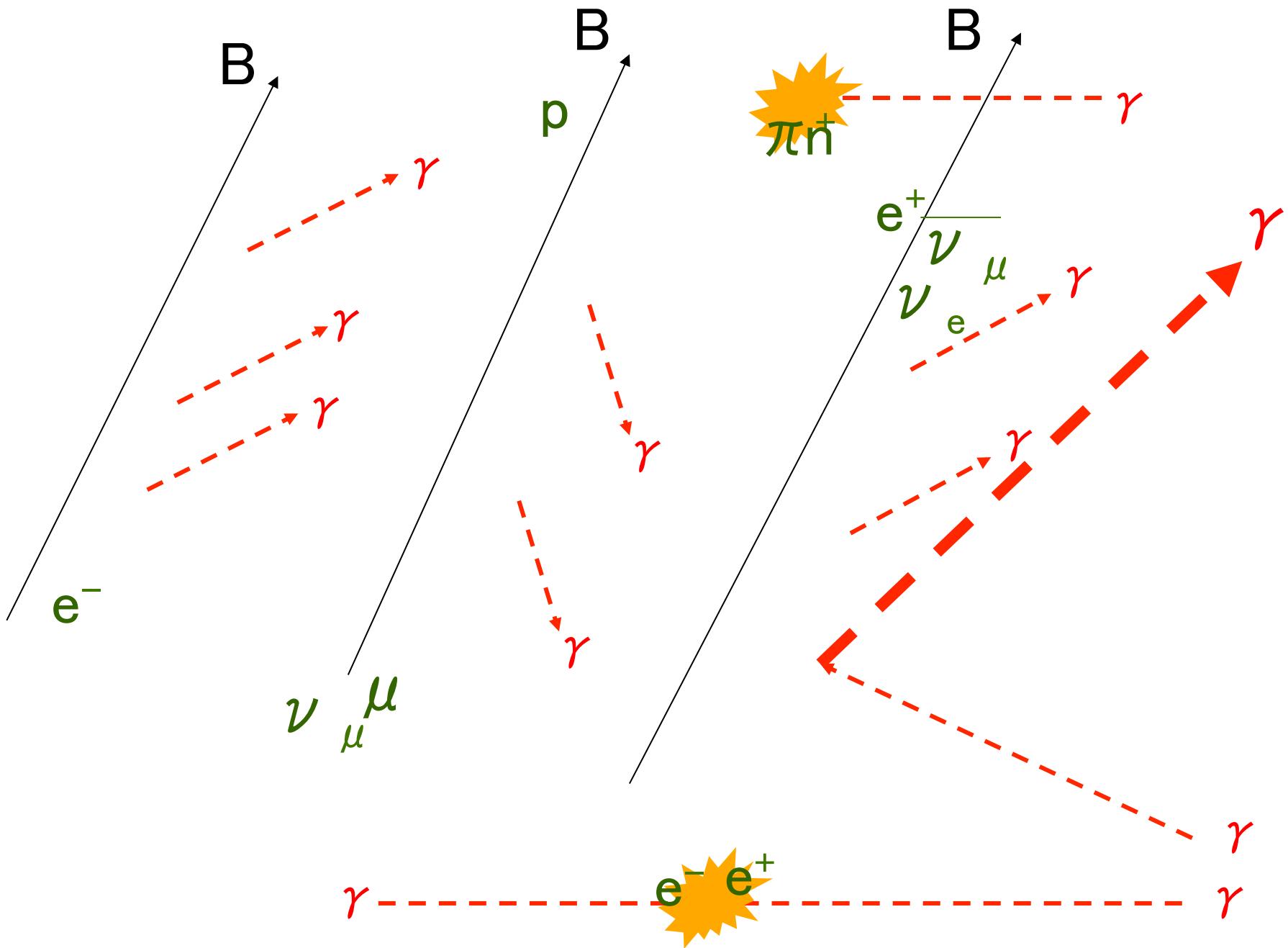
composition of metal-rich clumps in young SNRs case of Cas A

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...



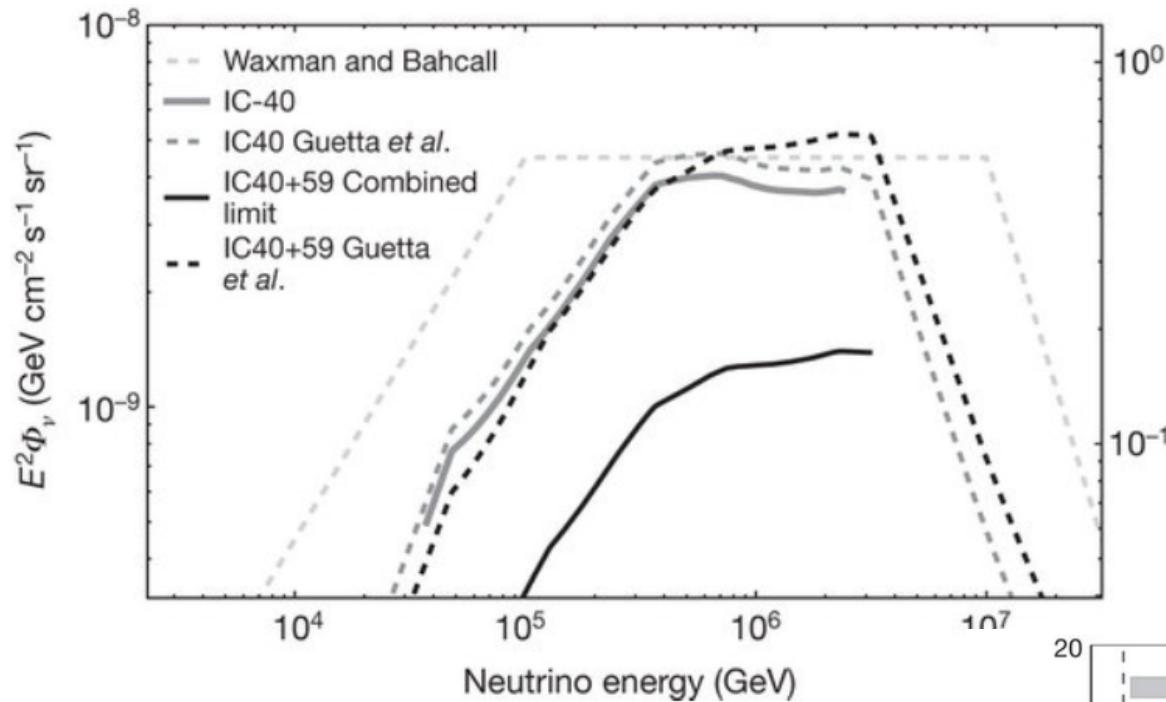
© K. Asano

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

GRB neutrino limits

Abbasi+ 12

-> Murase

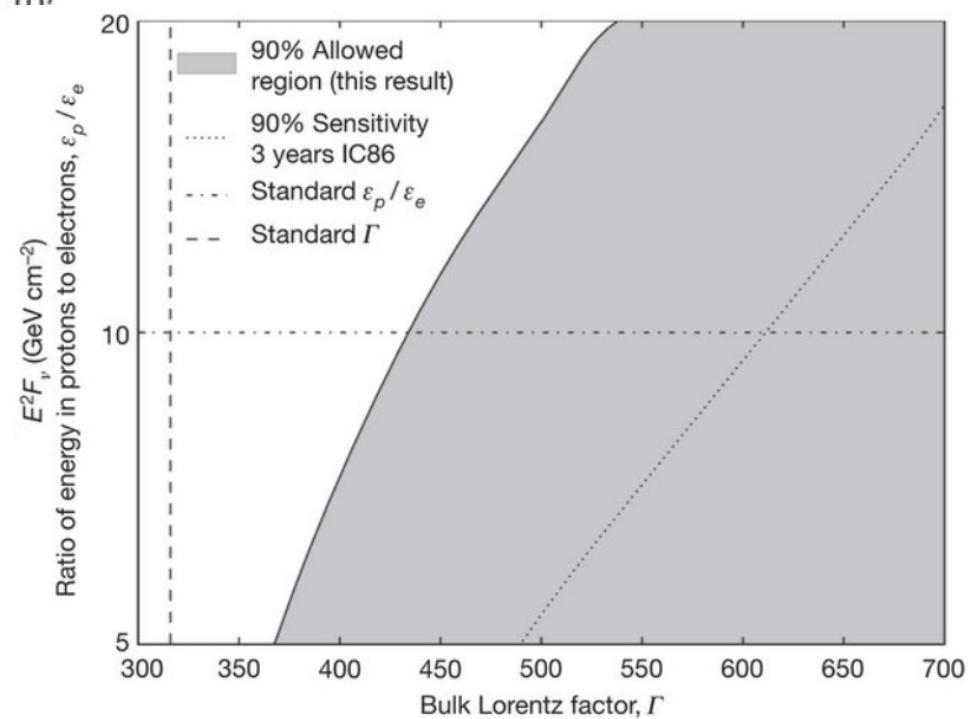


large parameter space not ruled out
with large Γ , large R

-> better conditions for UHECR
production+escape

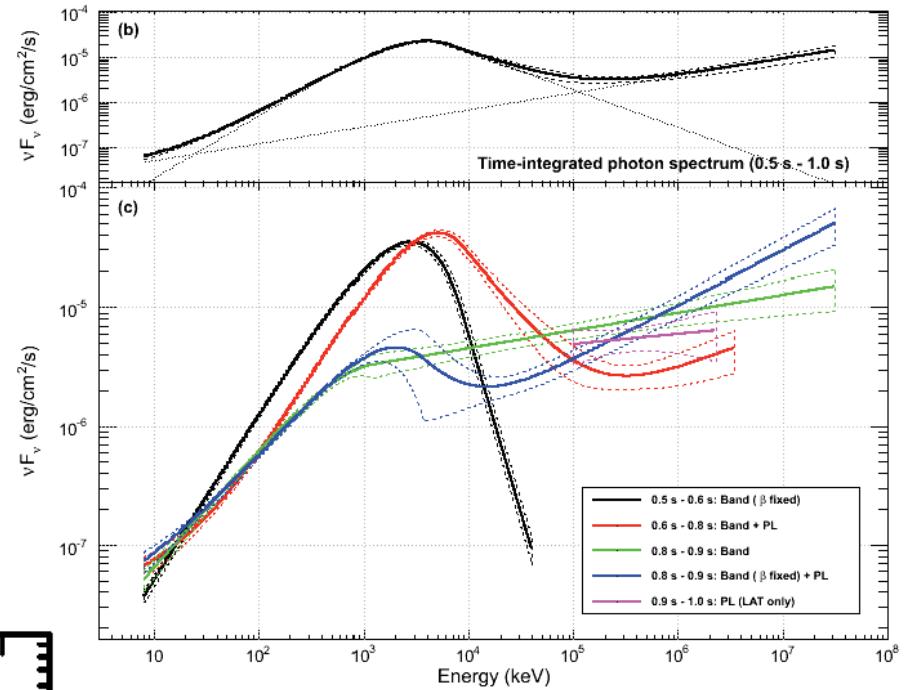
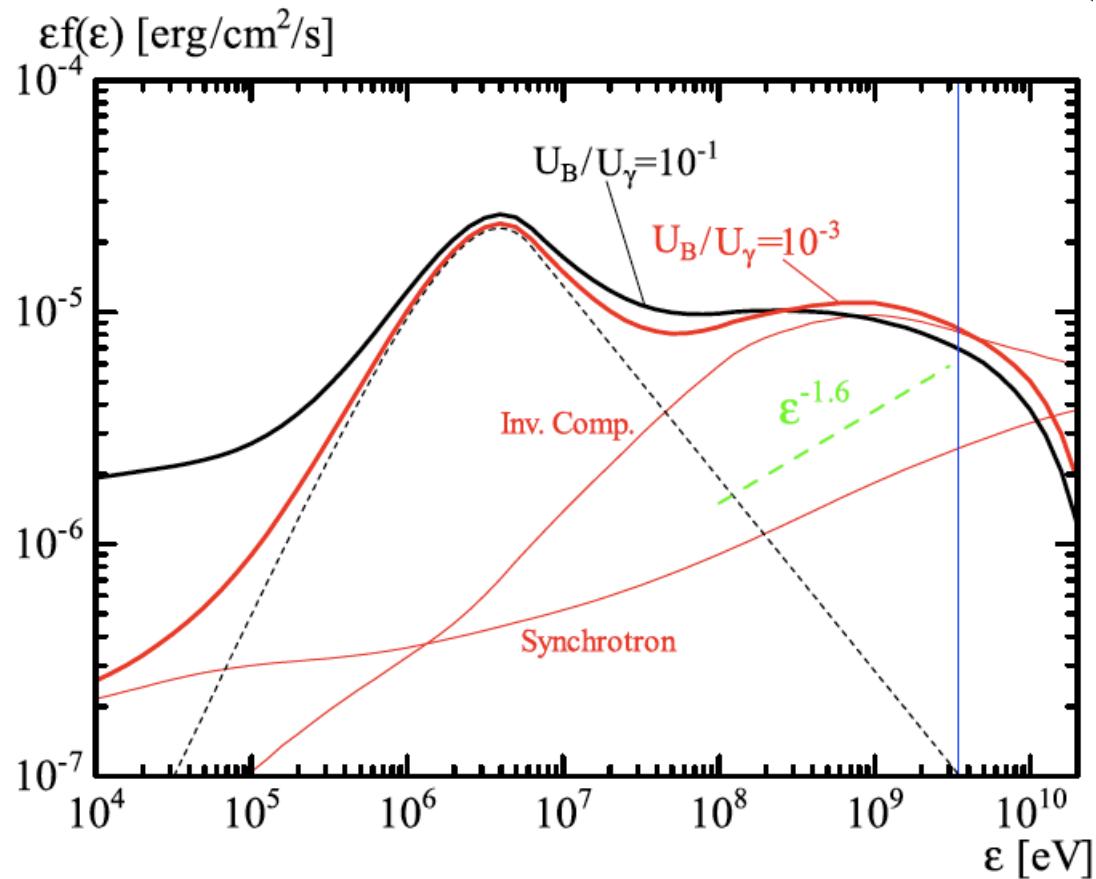
~better conditions for γ -ray escape

non-detection hardly rules out
(in some senses even supports)
GRB origin of UHECRs



hadronic interpretation ($p\gamma$ -induced cascade) Fermi GRB 090510

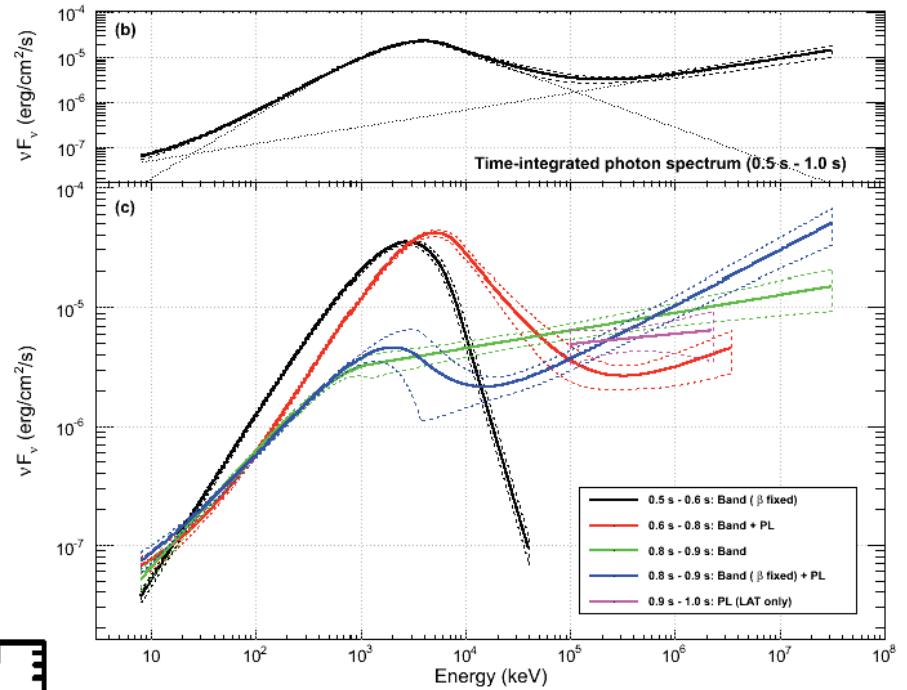
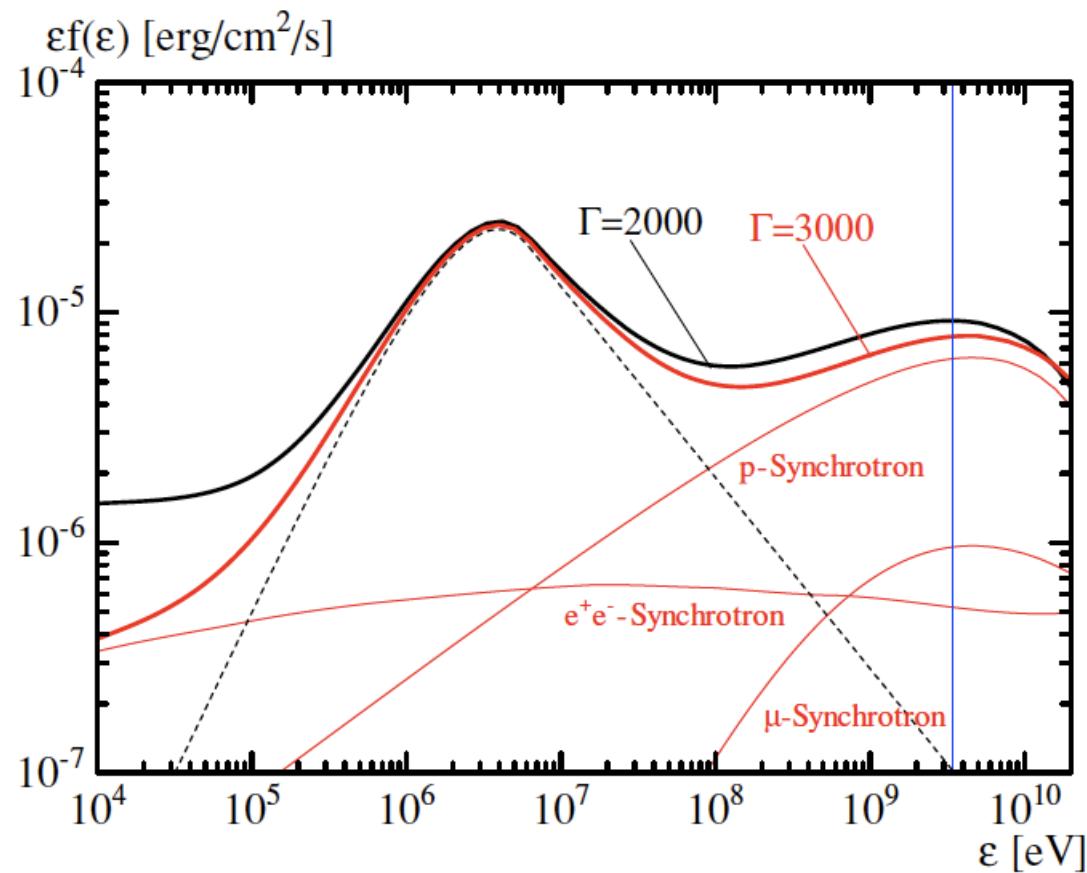
Asano+ 09



$$\begin{aligned}
 R &= 10^{14} \text{ cm} \\
 \Gamma &= 1500 \\
 U_B/U_\gamma &= 0.001-0.1 \\
 L_p/L_\gamma &= 30-200
 \end{aligned}$$

hadronic interpretation (proton synchrotron) Fermi GRB 090510

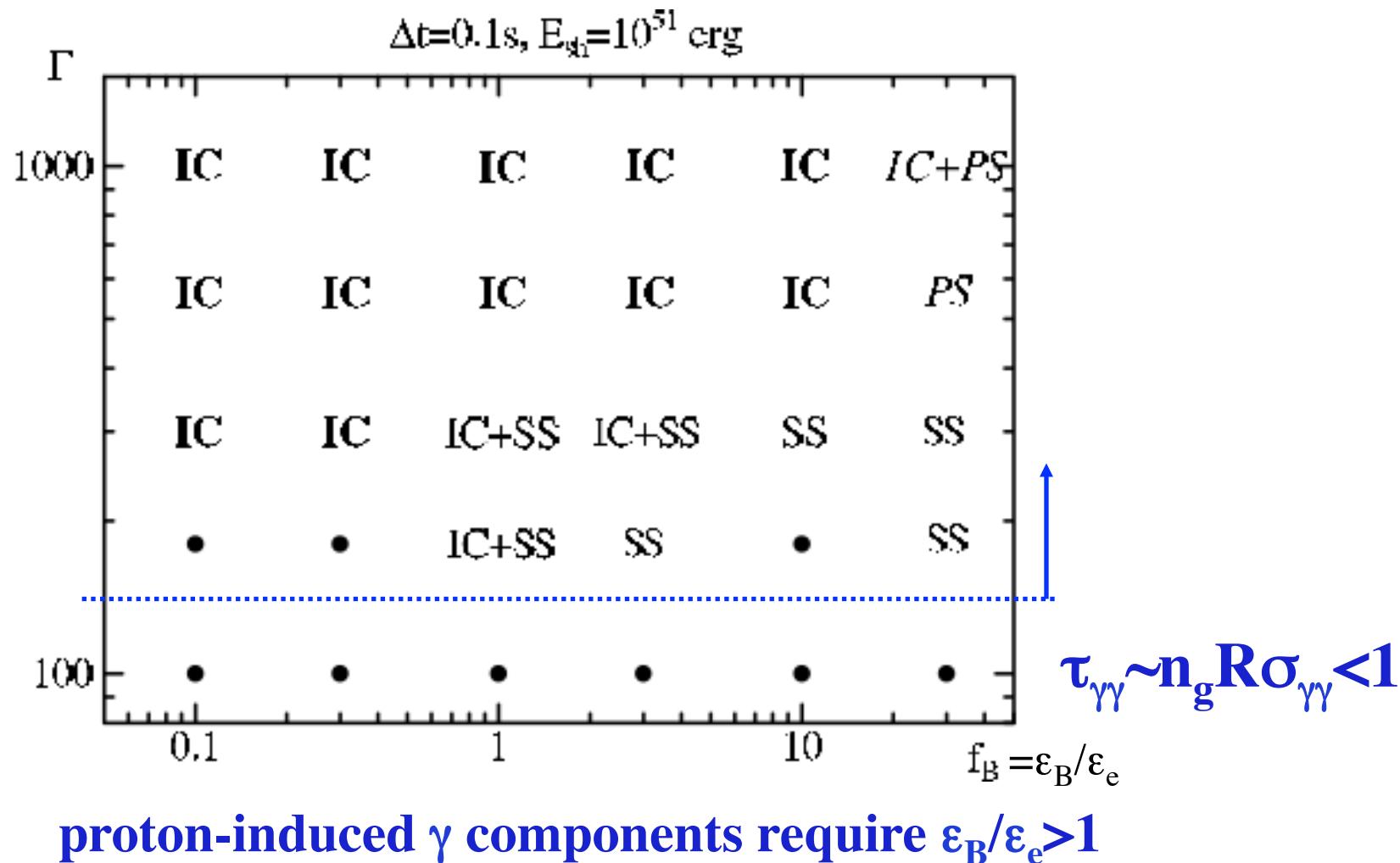
Asano+ 09



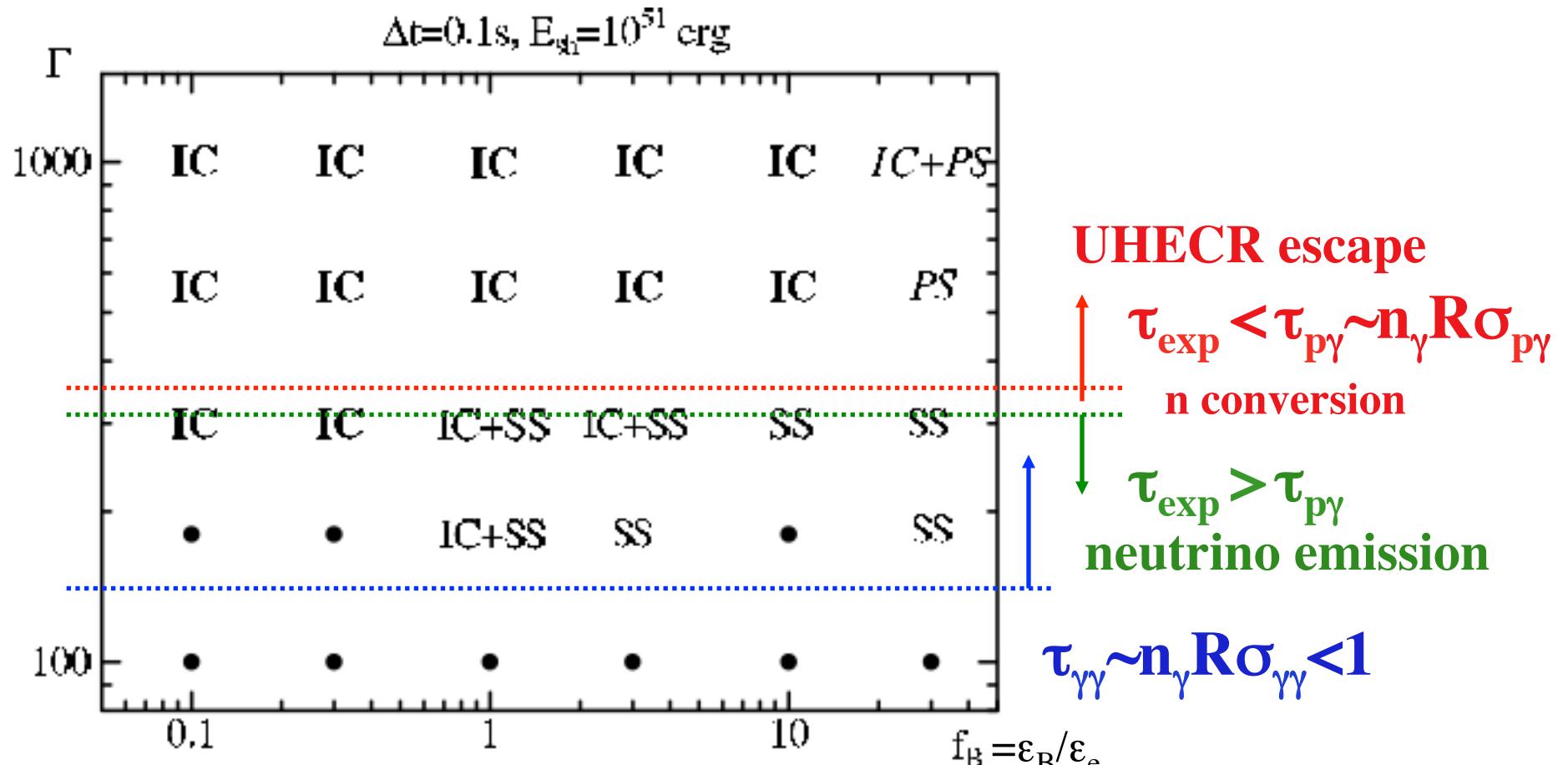
$$\begin{aligned} R &= 10^{14} \text{ cm} \\ \Gamma &= 2000-3000 \\ U_B/U_\gamma &= 200-300 \\ L_p/L_\gamma &= 100-300 \end{aligned}$$

GRB GeV-TeV

Asano & SI, 2007



GRB GeV-TeV - UHECR - neutrino connection



proton-induced γ components: $\epsilon_B/\epsilon_e > 1$

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

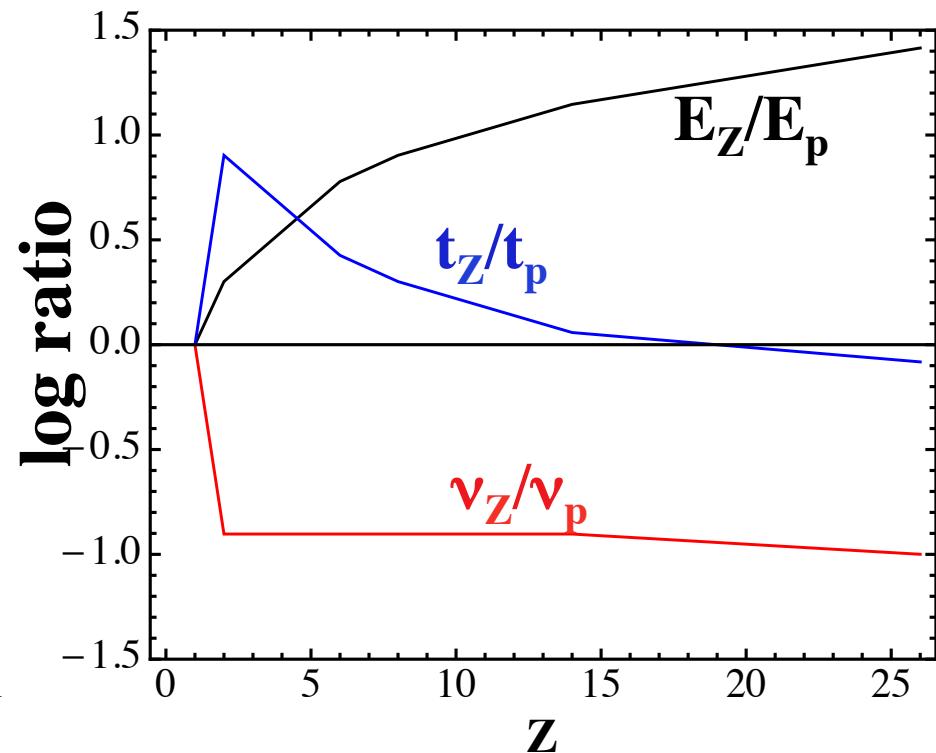
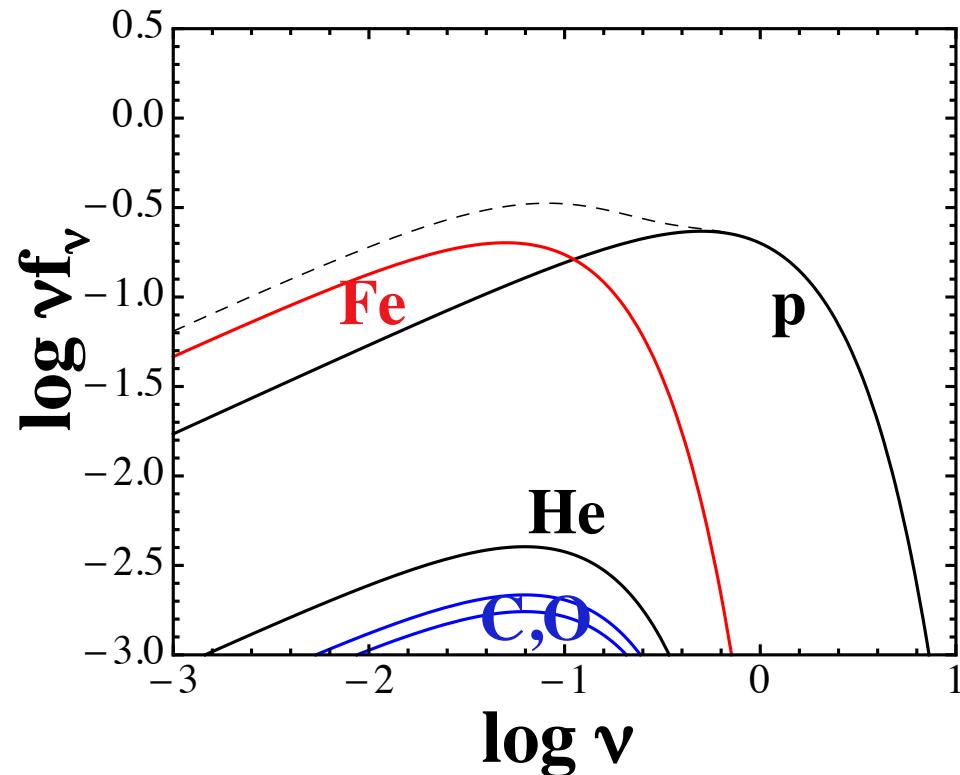
GeV-TeV (inc. IC) : $\tau_{\gamma\gamma} < 1 \rightarrow \tau_{\text{exp}} < \tau_{p\gamma}$ efficient UHECR escape

nuclear synchrotron spectra and cooling times

normalize to proton synchrotron spectrum

Inoue, in prep.

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



abundance at low E: enhanced Fe/H~4

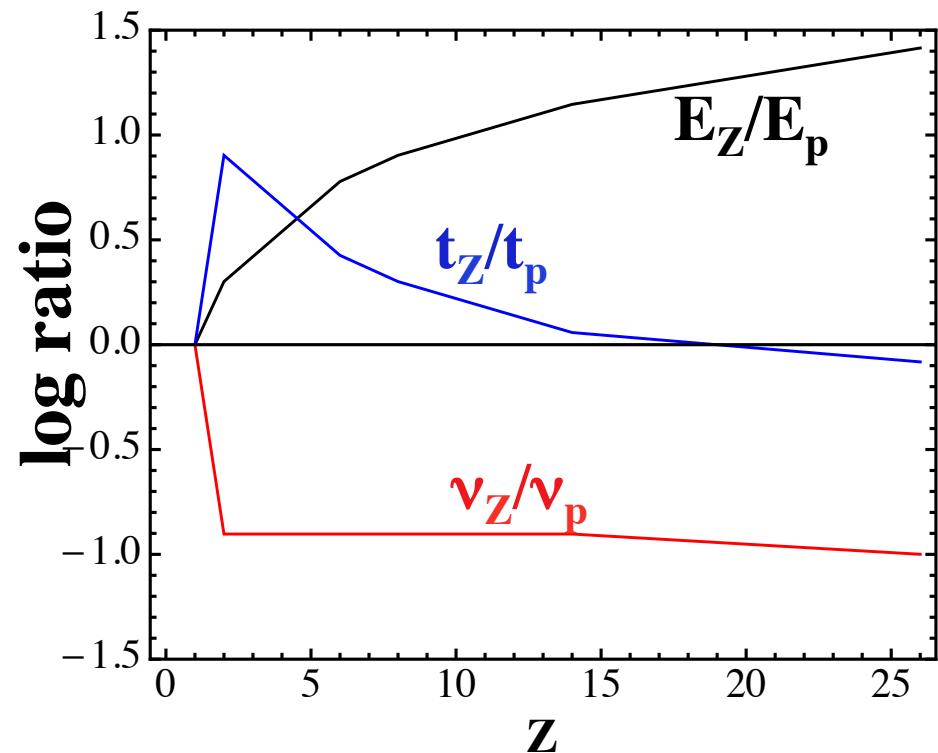
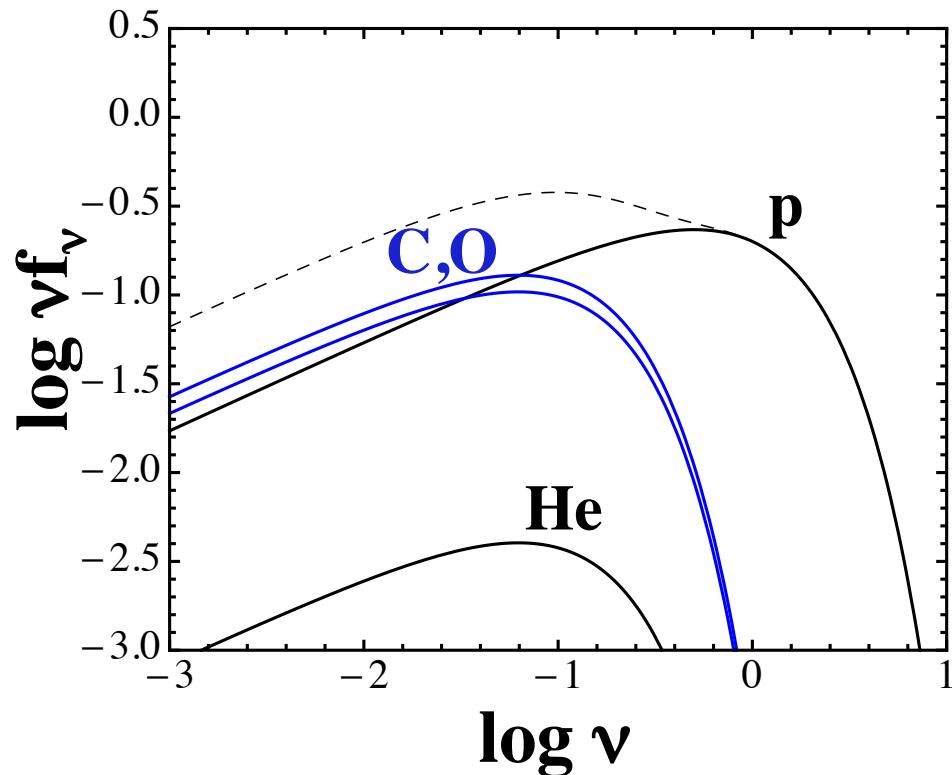
H=0.2, He=0.014, Fe=0.8 (C=3x10⁻³, O=3.7x10⁻³)

nuclear synchrotron spectra and cooling times

normalize to proton synchrotron spectrum

Inoue, in prep.

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



abundance at low E: enhanced C,O/H~4

H=0.2, He=0.014, C=0.22, O=0.28 (Fe=7x10⁻⁴)

6. use?

**use of UHECRs:
do they tell us something unique and important
about their sources?**

i.e. besides confirmation of Hillas condition

use of UHECRs:

**do they tell us something unique and important
about their sources?**

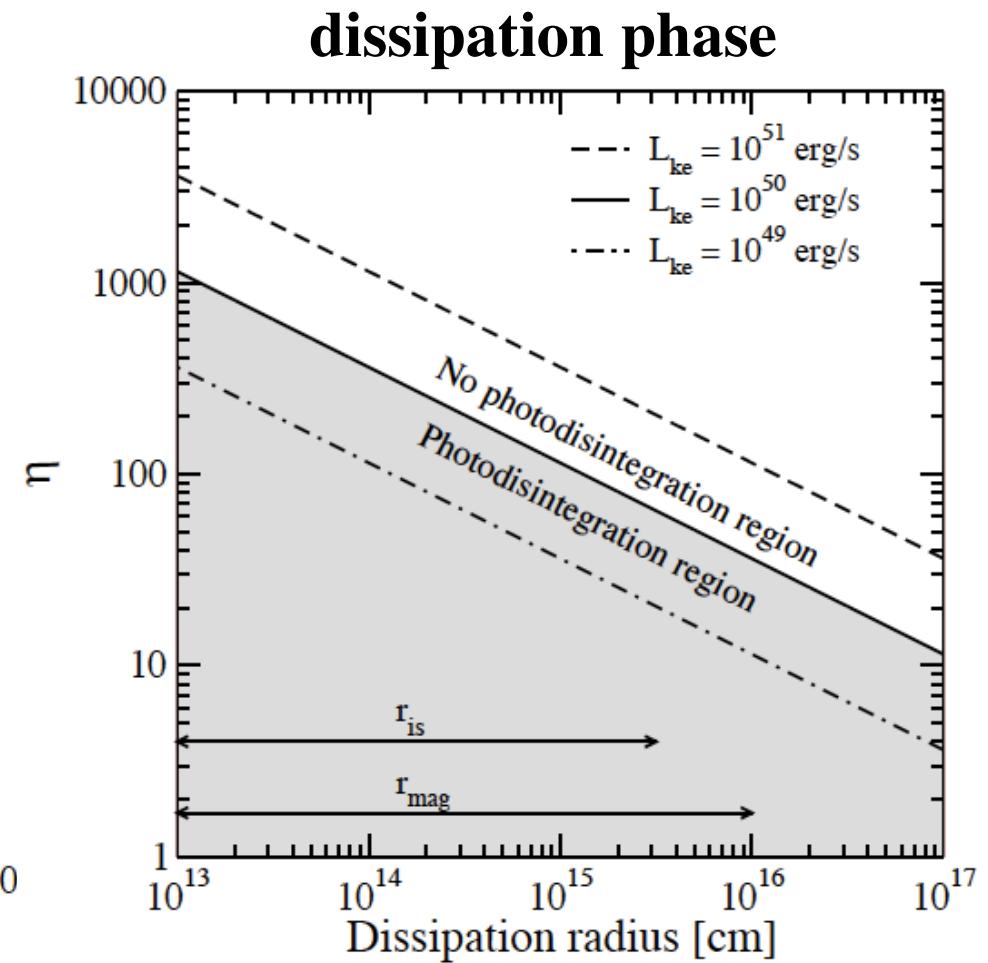
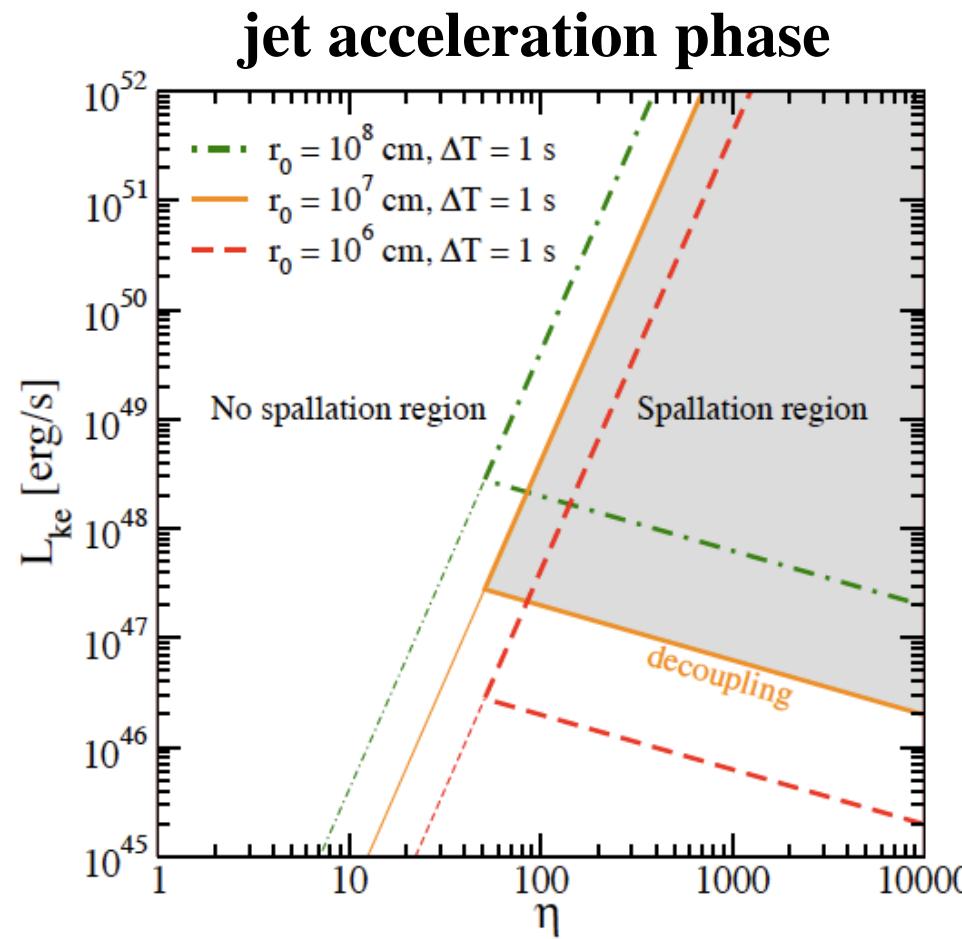
i.e. besides confirmation of Hillas condition

Ask not what you can do for CRs,
ask what CRs can do for you!



survival of Fe nuclei in GRBs

Horiuchi+ 12



Fe may survive destruction throughout the processes of jet formation, shock formation and particle acceleration in GRBs

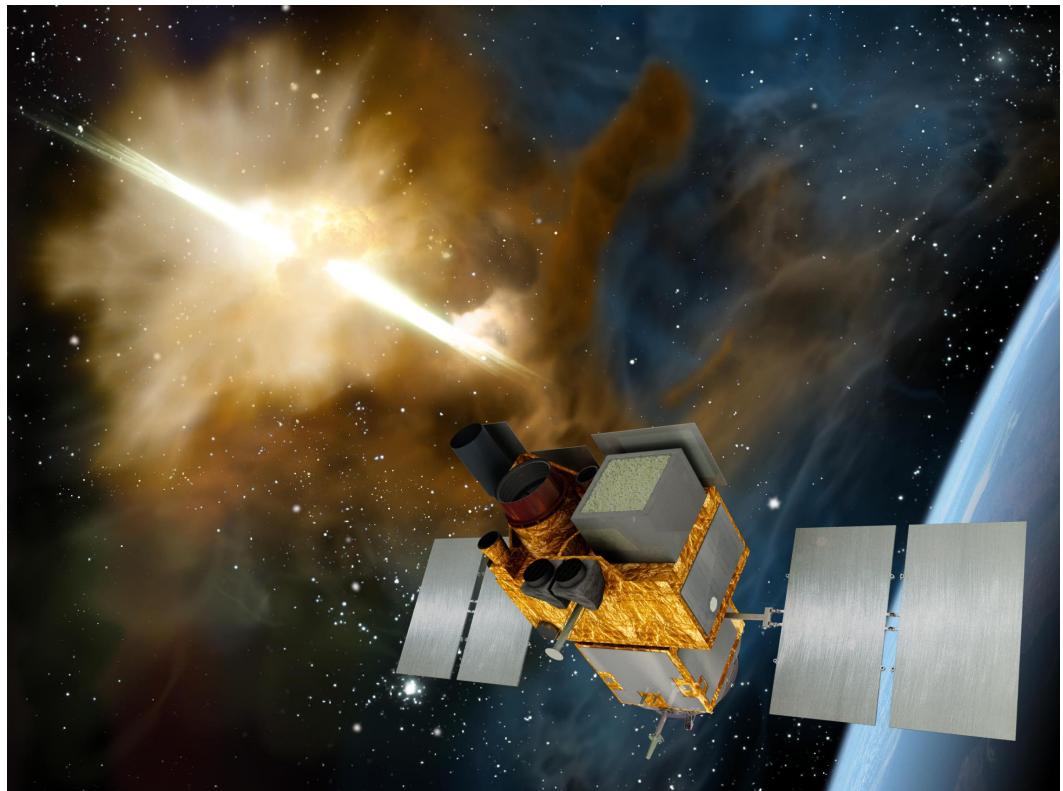
heavy-dominant composition \rightarrow magnetic acceleration favored?

summary GRBs as origin of UHECRs

- one of few realistic candidates for UHECR sources
but energetics remain a challenge
- if confirmed, heavy composition provides some support
but identification via CRs more difficult
- neutrino and gamma-ray tests crucial
but non-detections not decisive
(IceCube limits hardly rule them out)
- need to think more about escape processes, potential use?

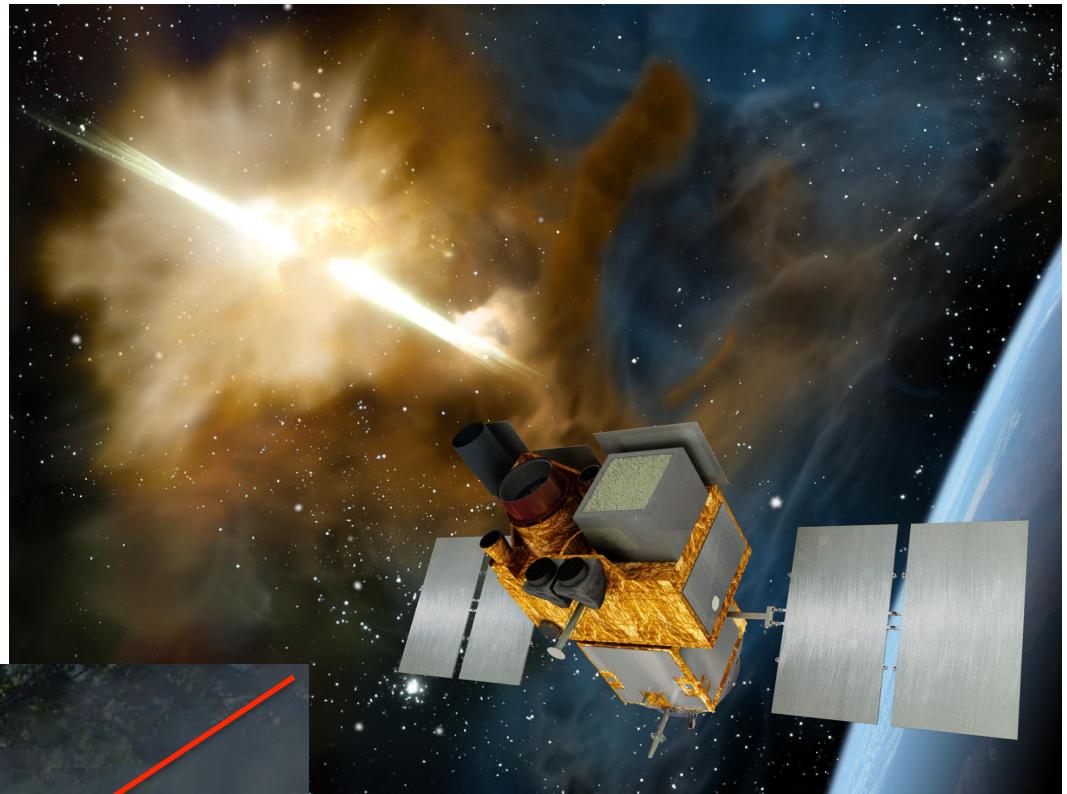
final remark

Allez SVOM!



final remark

Allez SVOM!



Mais pas de la grève,
s'il vous plaît...