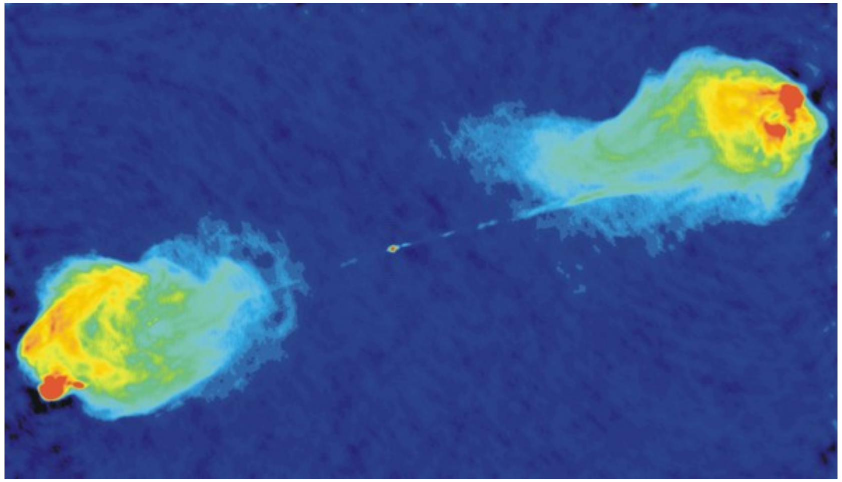
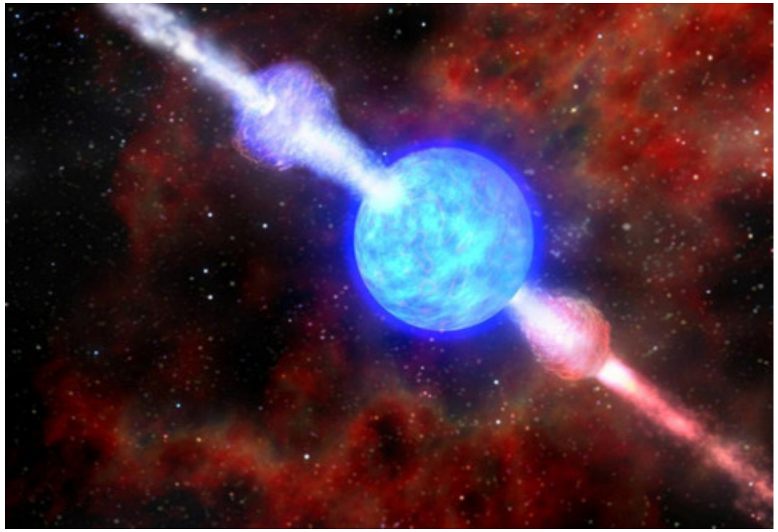
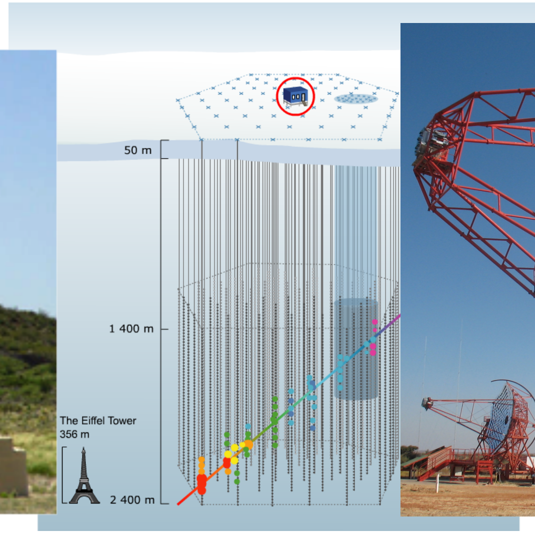
UHECRs: Sources and Acceleration (Propagation)

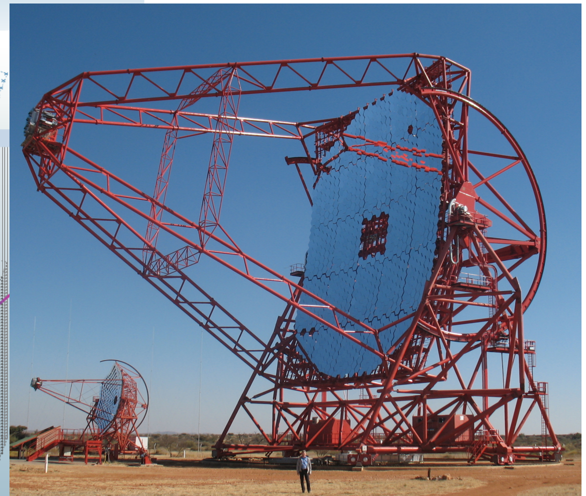
Susumu Inoue (MPP/ICRR)

with help from many collaborators







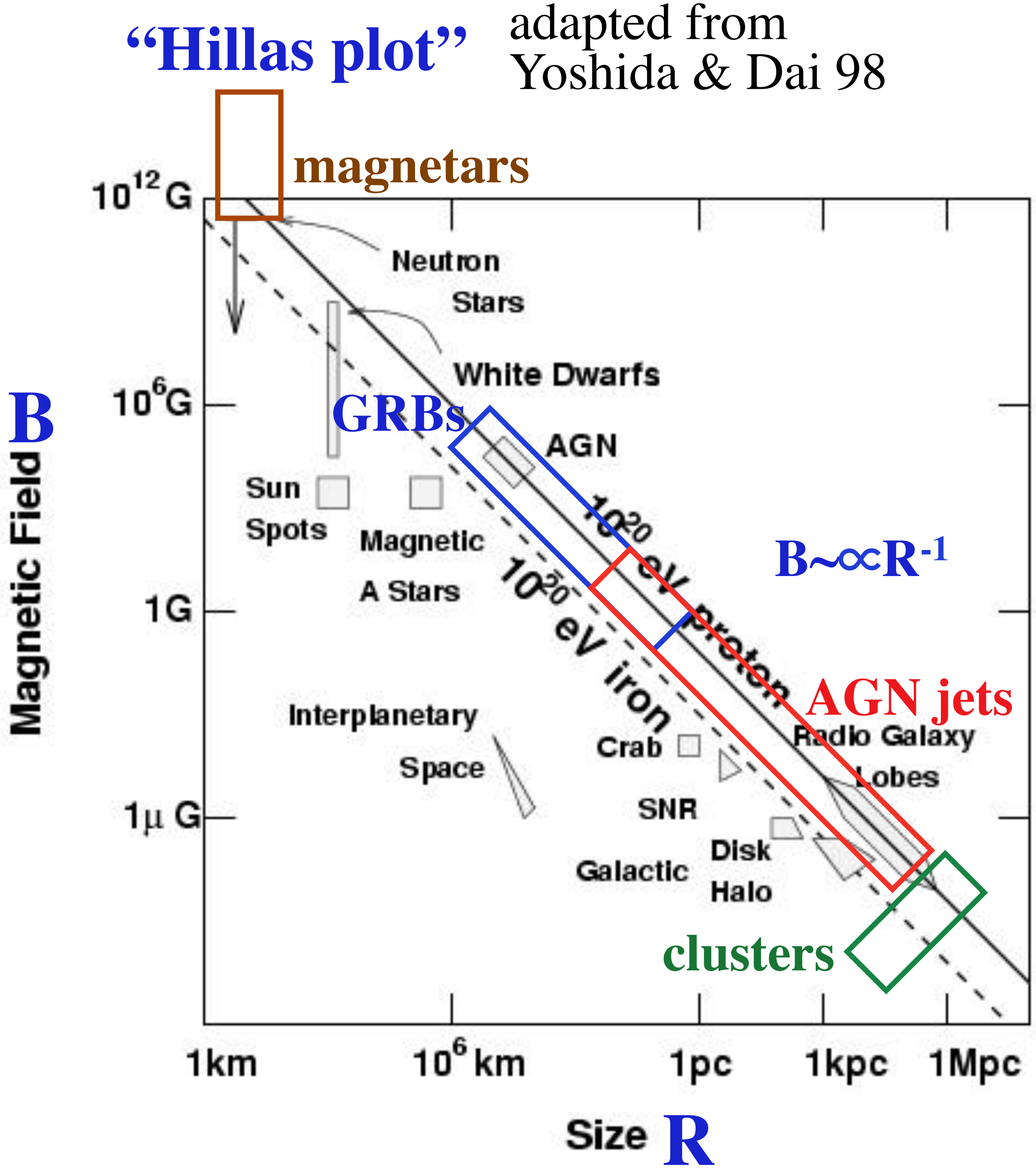


outline

1. general remarks on acceleration, escape, energetics
2. GRBs
   general remarks
   composition issue, nuclear synchrotron gamma-rays
3. AGNs
   general remarks on jets
   possibility of ultra-fast outflows
4. potential importance of UHECRs for IGM/IGMF

Some pieces of advice from having somewhat more experience

UHECR sources: acceleration



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

confinement

E_{max} acceleration vs:

escape

source lifetime

adiab. expansion loss

radiative loss

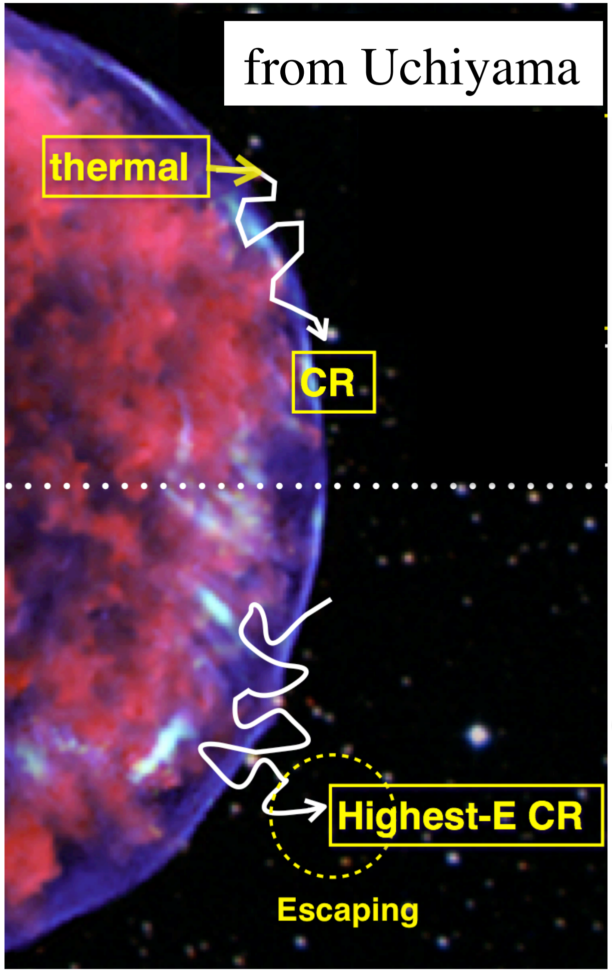
old favorite: AGNs

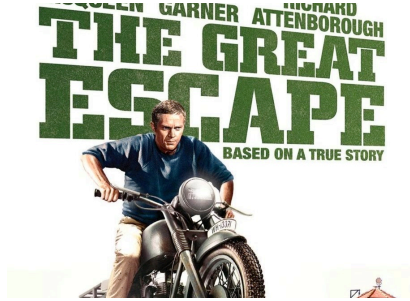
leading contender: GRBs

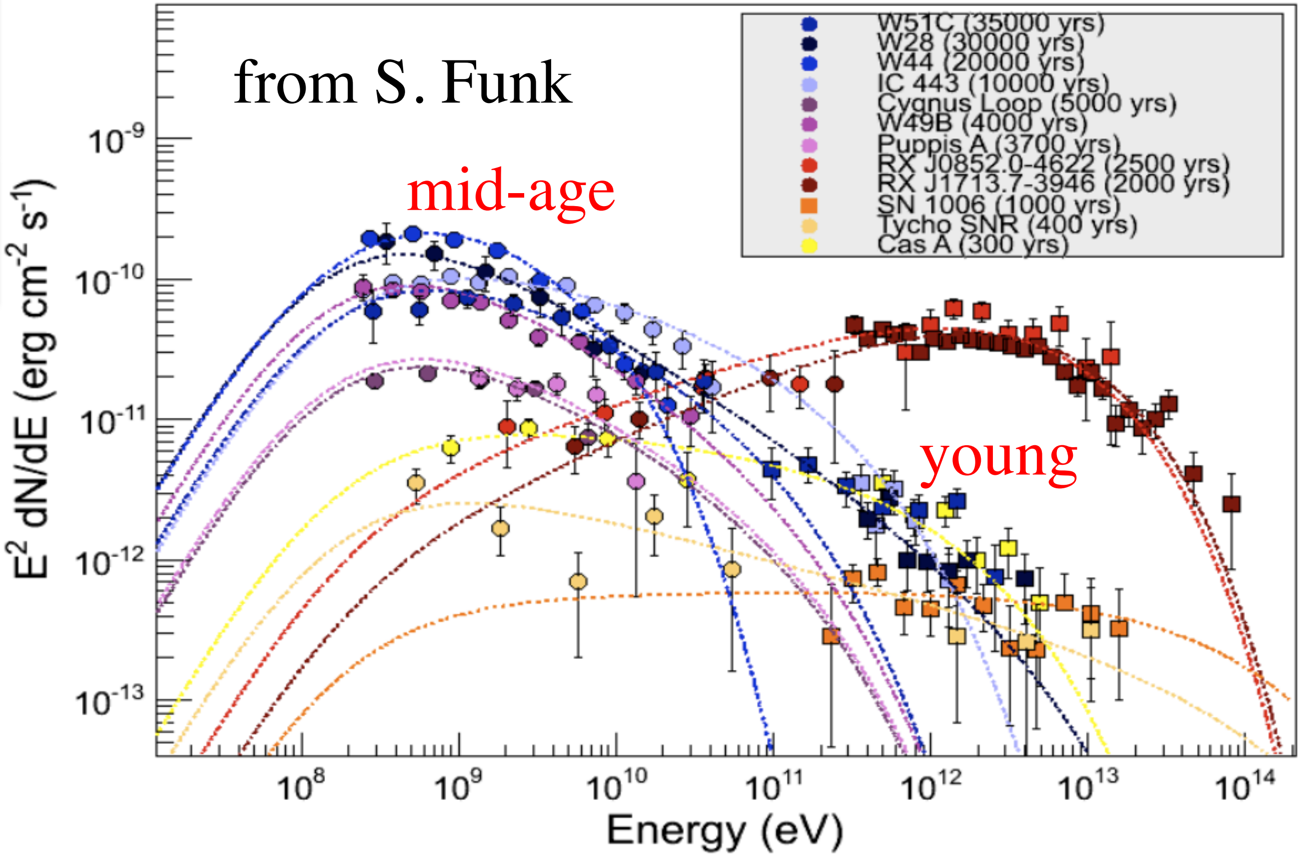
dark horse: magnetars

clusters, etc.

CR acceleration and escape in SNRs







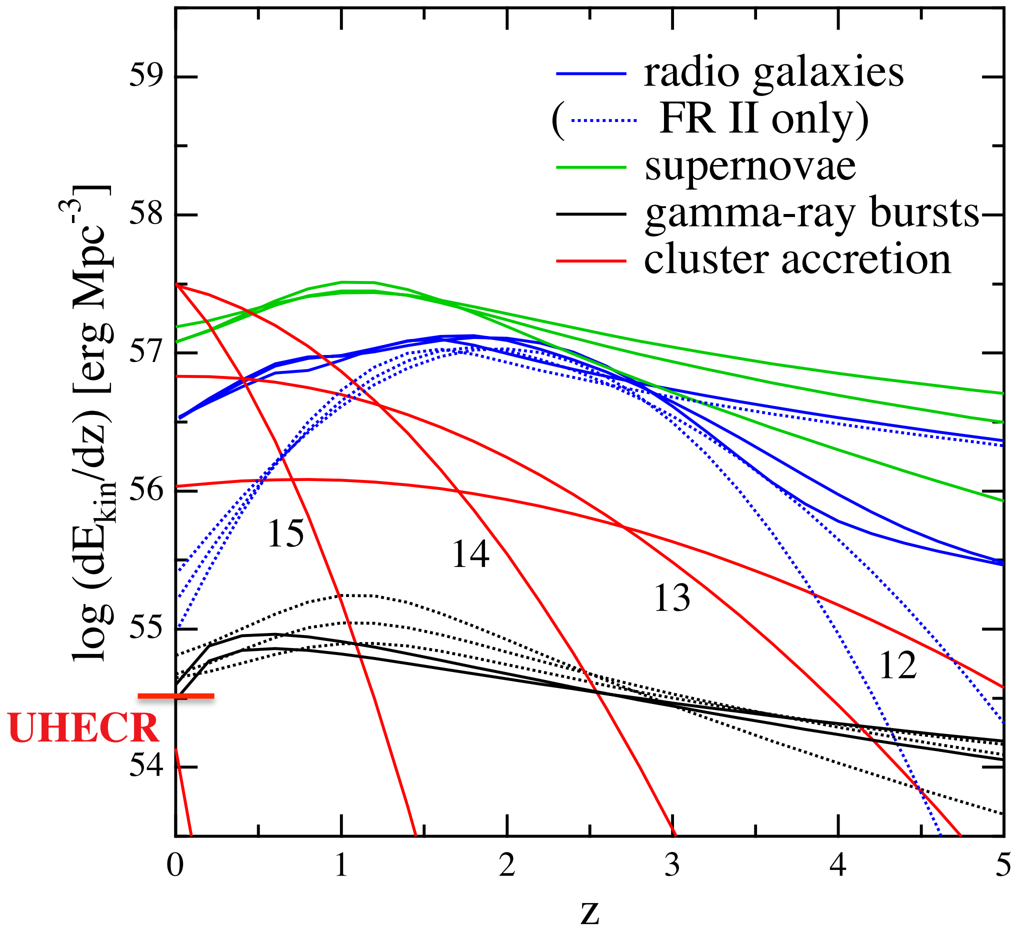
- higher-energy CRs escape earlier -> talks on Friday

- CR spectrum at acceleration ≠ observed

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

$E_{SN}=10^{51}$ erg

cluster accretion

Press Schechter mass function

$L_{acc}(M)\sim0.9\times10^{46}\,(M/10^{15}\,M_{\Theta})^{5/3}$ erg/s

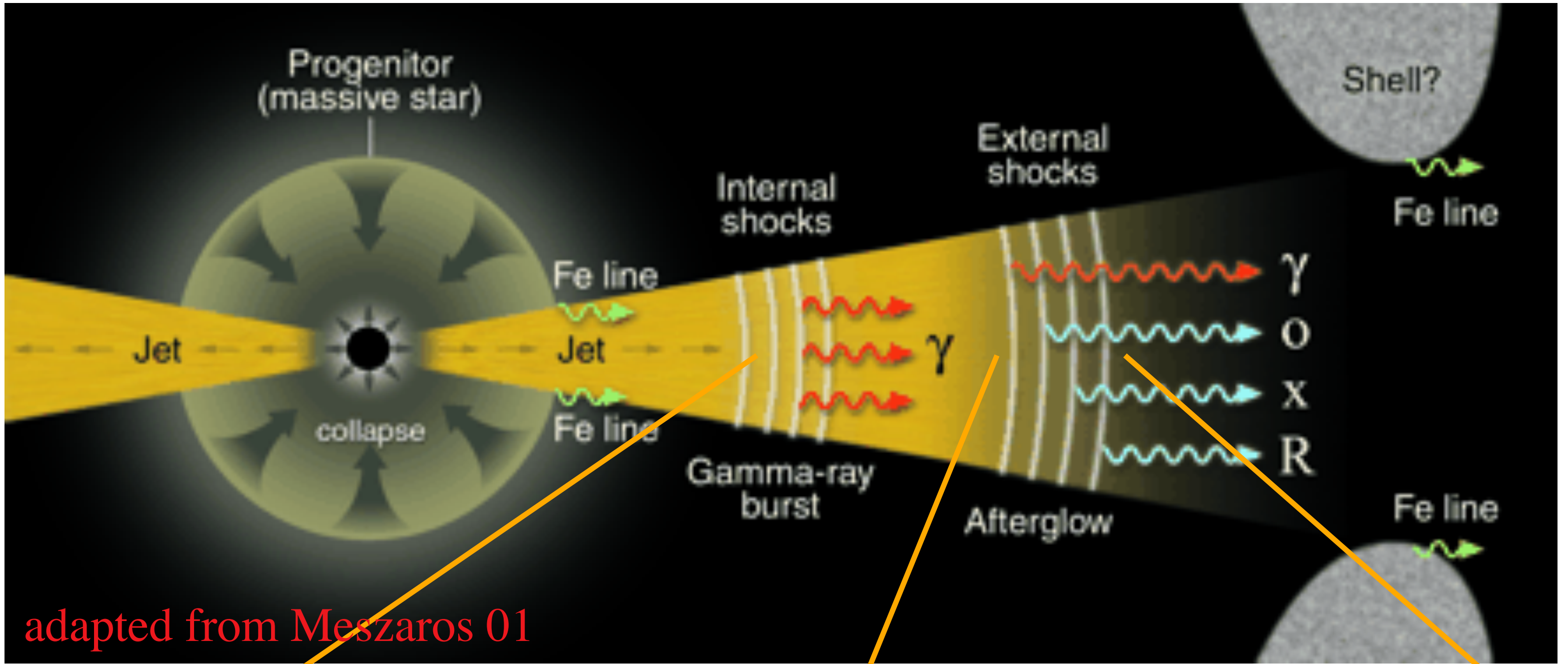
Keshet+ 04

UHECR budget @$10^{18.5}$ eV

$u_{CR}\sim10^{-19}$ erg cm^{-3}

$\sim3\times10^{54}$ erg Mpc^{-3}

GRBs: acceleration sites



Waxman 95
Vietri 95

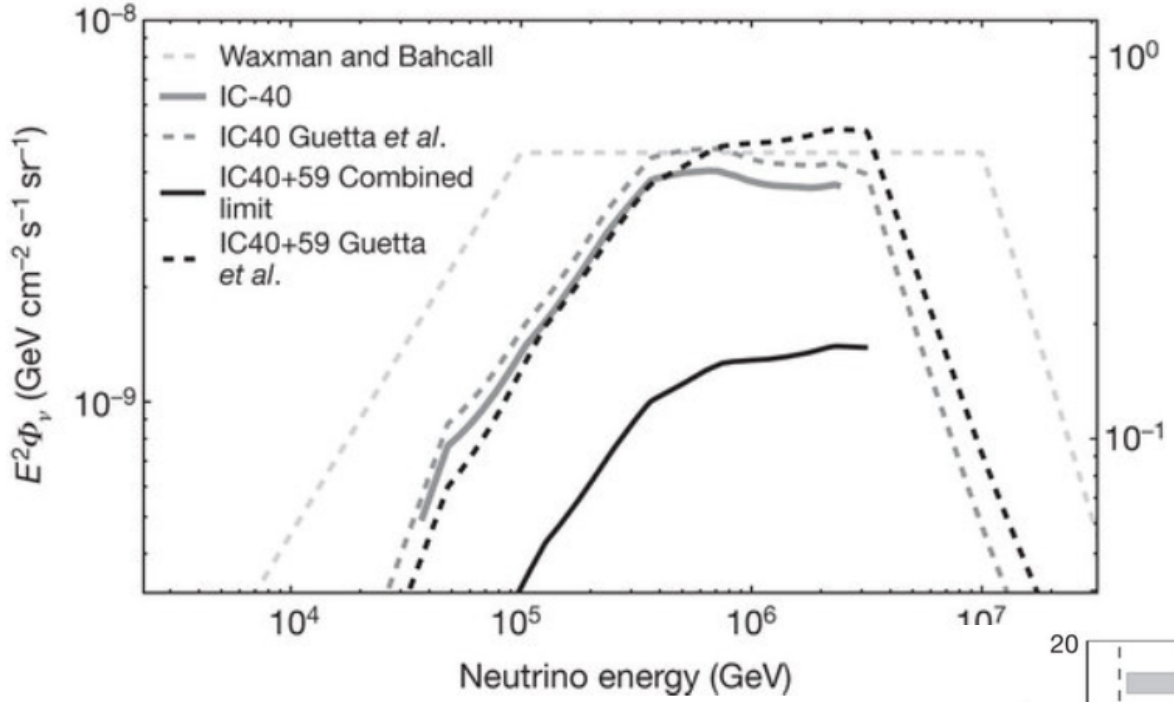
prompt X-γ emission	optical flash, radio flare	radio-IR-opt-X afterglow
internal shocks	**external reverse shock**	**external forward shock**
$R \sim \Gamma^2 c t_{var} \sim 10^{12}$-$10^{16}$ cm	$R \sim R_{dec} \sim 10^{16}$ cm	$R \sim R_{dec}$-$R_{NR} \sim 10^{16}$-10^{18} cm
$B \sim 10^6$-10^3 G	$B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

escape nontrivial **accel. nontrivial**

energetics: stringent requirements -> proton-dominated?

GRB neutrino limits

Abbasi+ 12

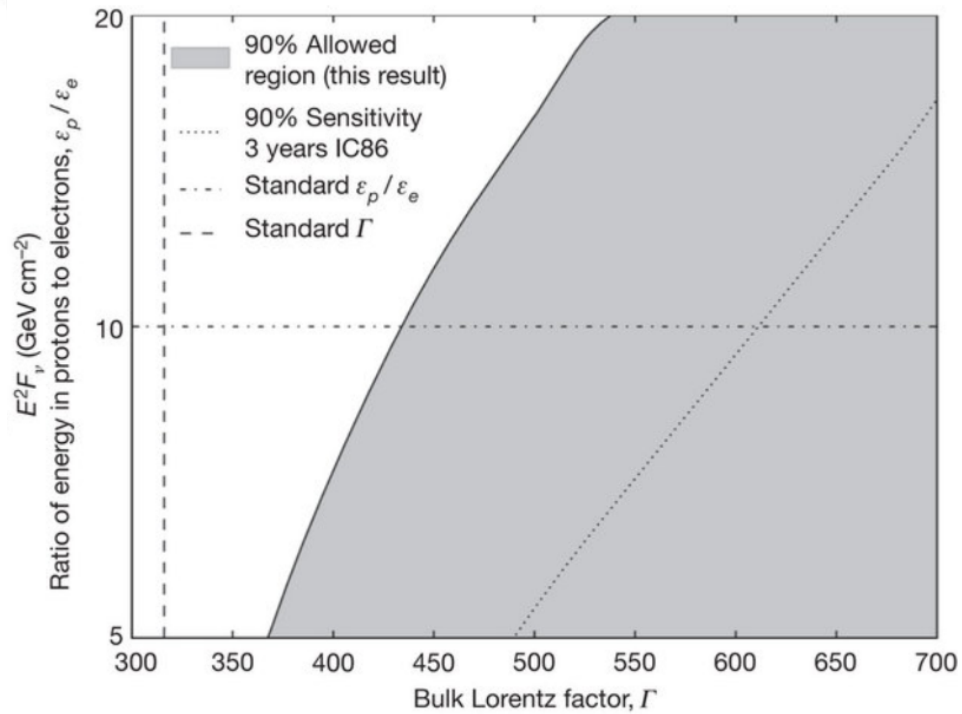


large parameter space not ruled out with large Γ, large R

-> best conditions for UHECR production+escape

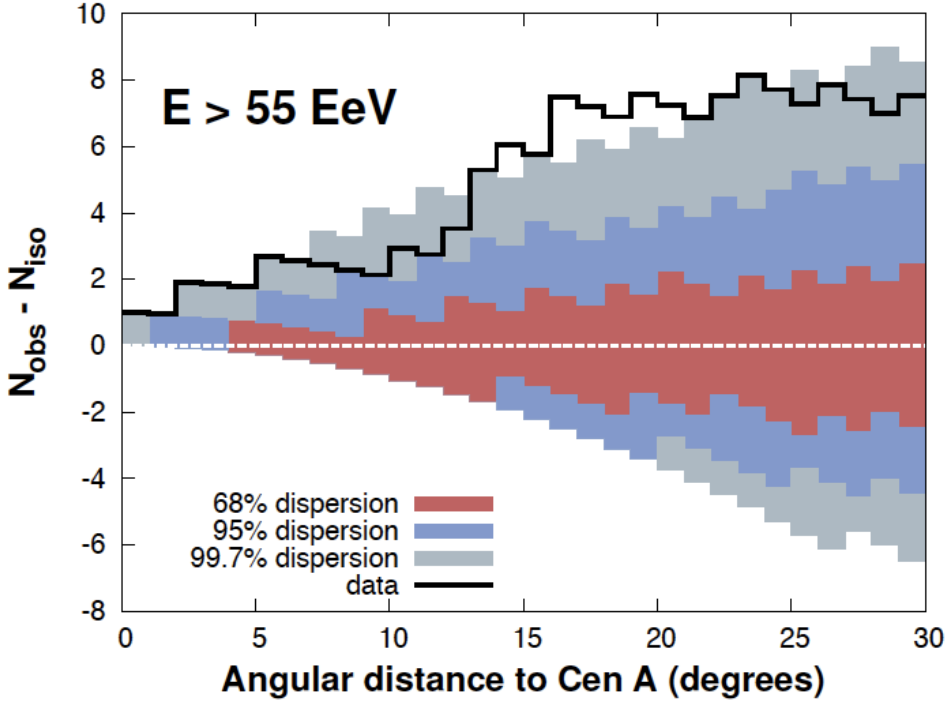
~good conditions for γ-ray escape

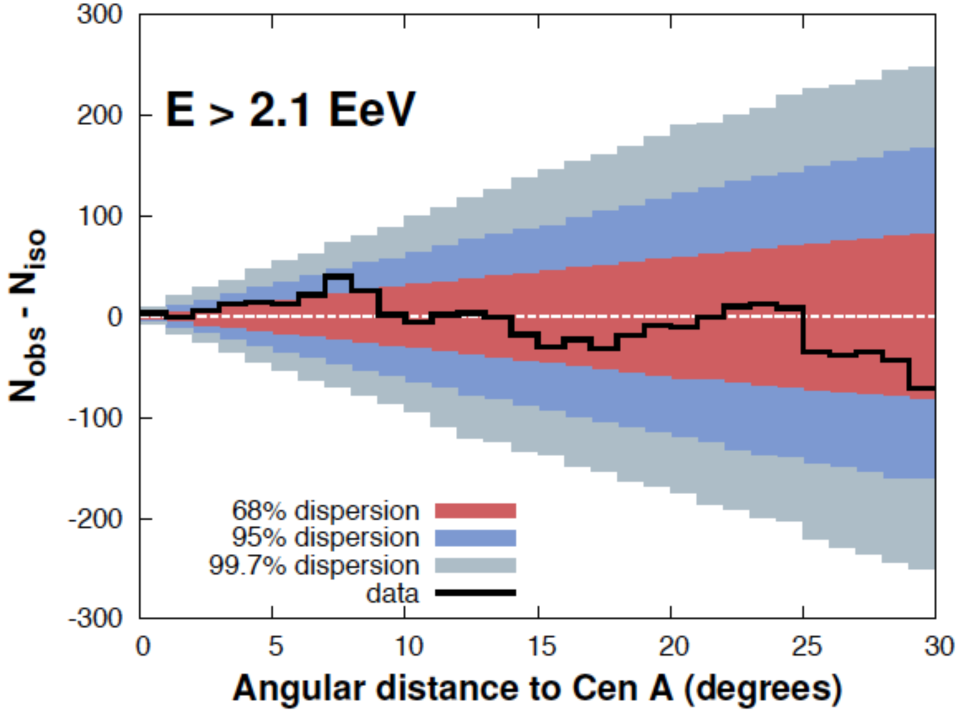
-> Asano



Auger anisotropy: Cen A

Auger 2011 (arXiv:1106.3048)





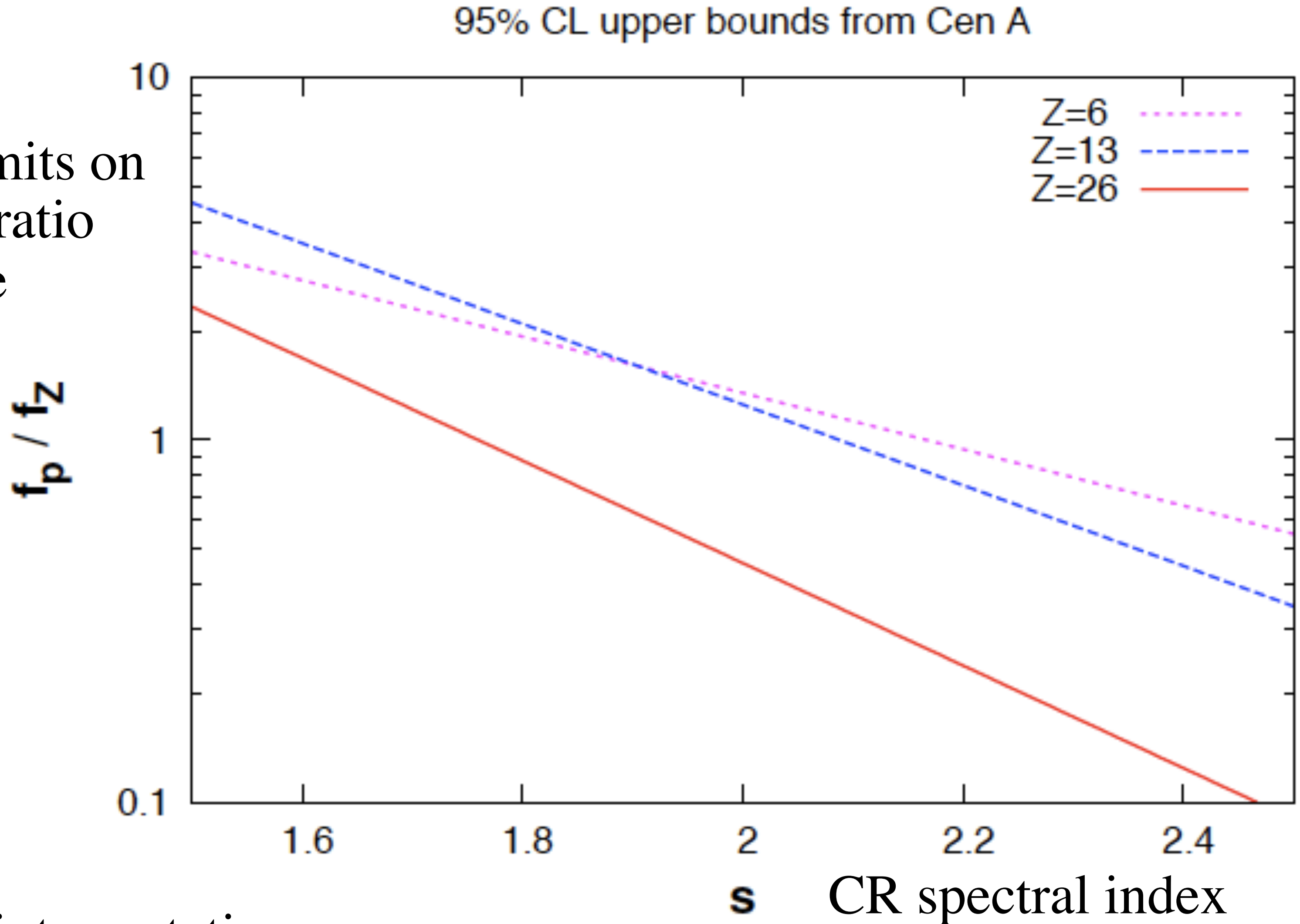
>~3 sigma excess at E>55 EeV
for ~20 deg around Cen A

no corresponding anisotropy
at e.g. E>55/26 EeV

Auger anisotropy implications

Auger 2011 (arXiv:1106.3048)

upper limits on number ratio at source at low E



CR spectral index

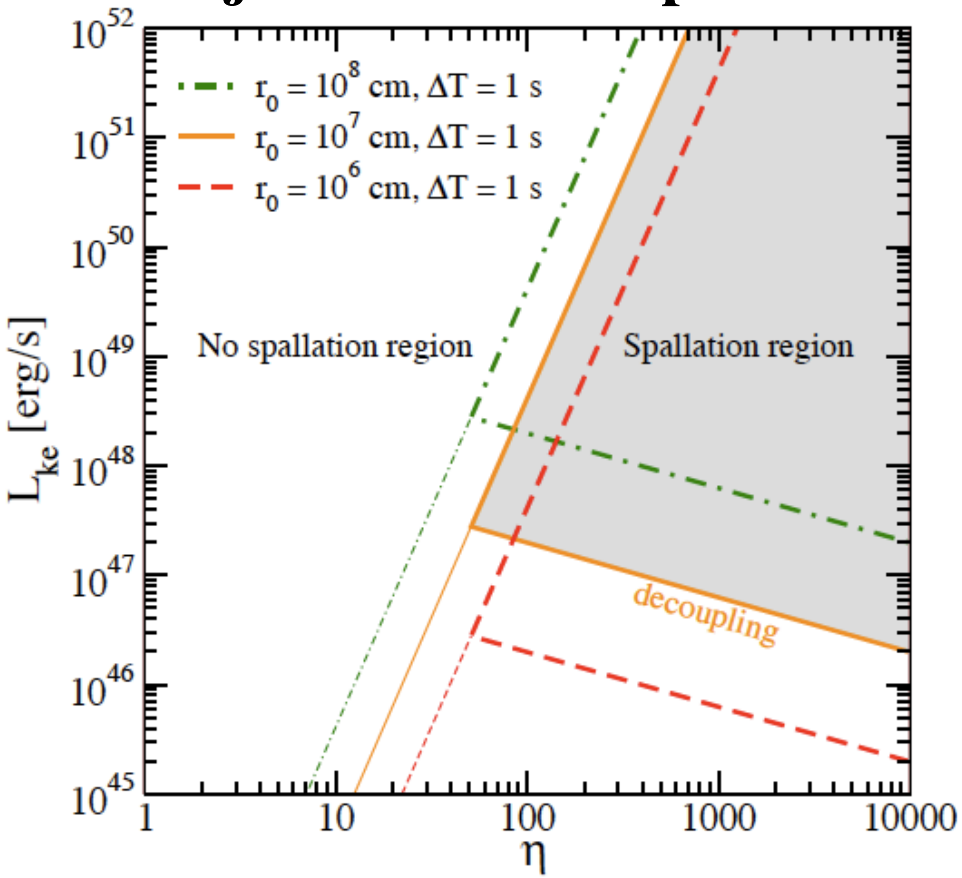
possible interpretations:

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

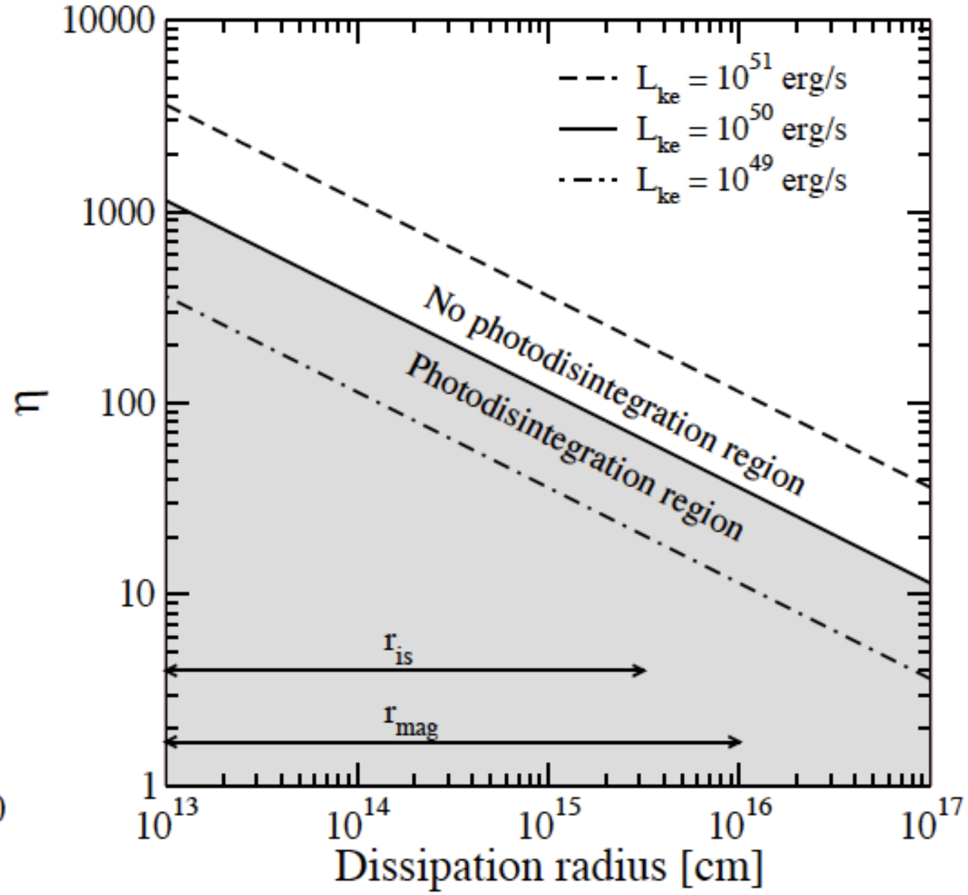
survival of Fe nuclei in GRBs

Horiuchi+ arXiv:1203.0296

jet acceleration phase



dissipation phase



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

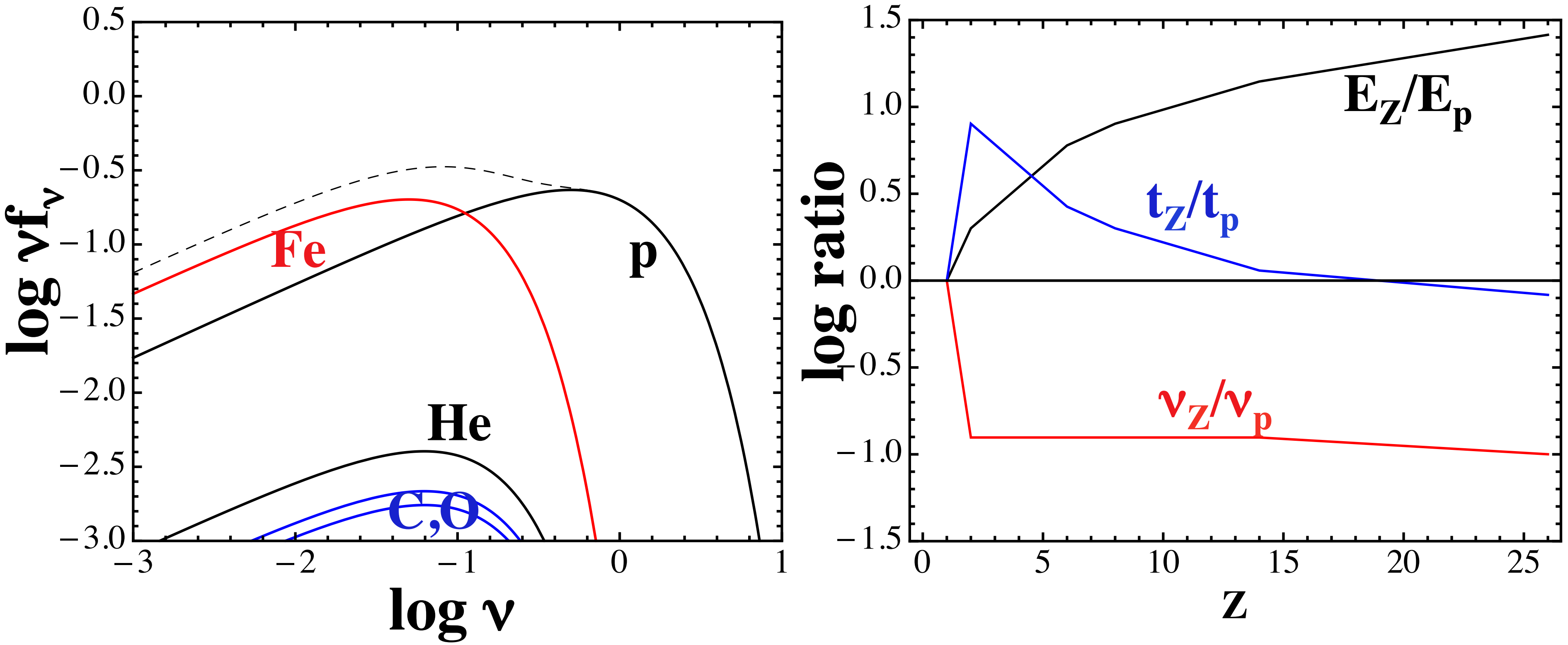
-> Horiuchi

NB: supernovae produce more metals than they destroy

nuclear synchrotron spectra and cooling times

normalize to proton synchrotron spectrum **Inoue, in prep.**

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



abundance at low E: enhanced Fe/H~4

H=0.2, He=0.014, Fe=0.8 (C=3x10^{-3}, O=3.7x10^{-3})

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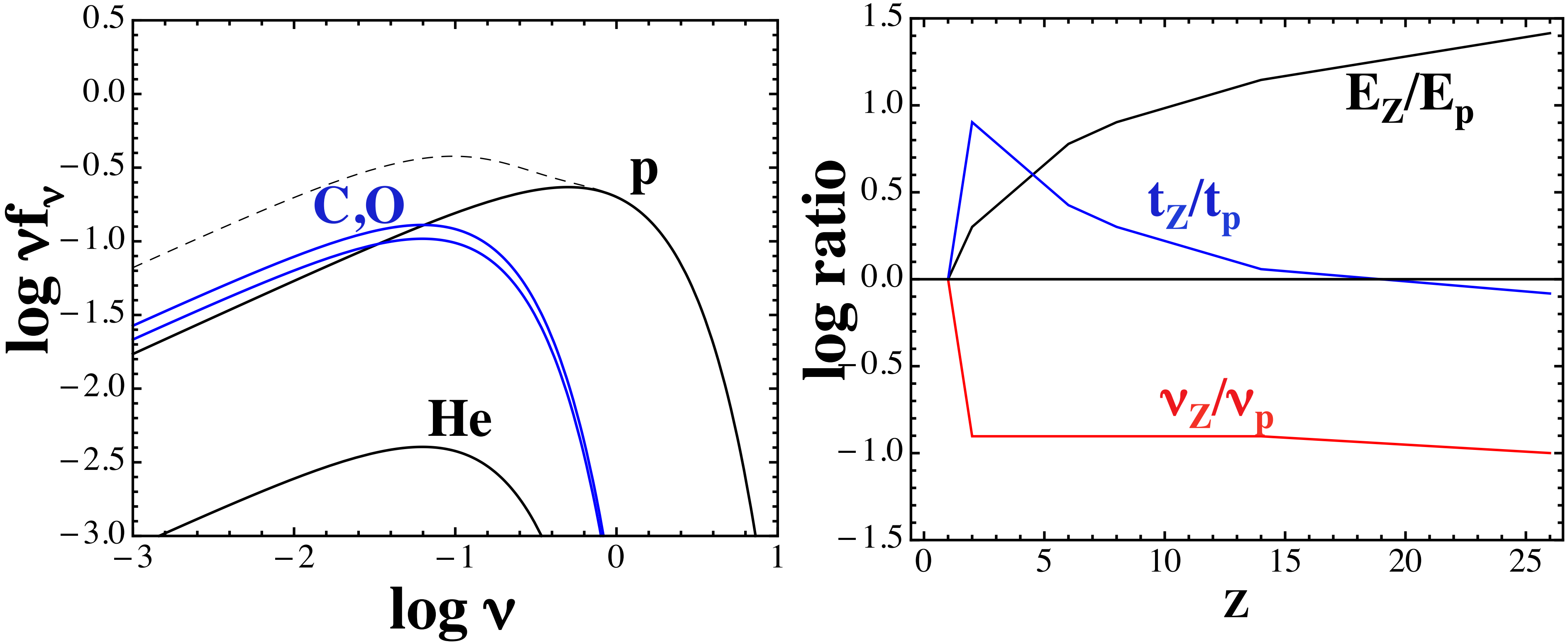


abundance at low E: enhanced C,O/H~4

H=0.2, He=0.014, C=0.22, O=0.28 (Fe=7x10^{-4})

conseil n°1

Don't shy away from new proposals involving newly-recognized concepts/phenomena

e.g. GRBs as UHECR sources Waxman 1995

conseil n°2

Think how important your work might be for your colleagues next door

Do UHECRs tell us something unique and important about their sources?

e.g. GRBs: potential info on central engine
AGN: jet composition

conseil n°2

Think how important your work might be for your colleagues next door

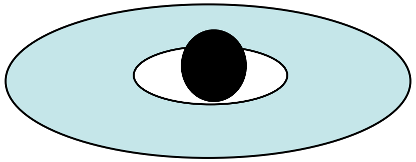
Do UHECRs tell us something unique and important about their sources?

e.g. GRBs: potential info on central engine
AGN: jet composition

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

active galactic nuclei (AGNs)

supermassive black hole
+accretion disk (flow)

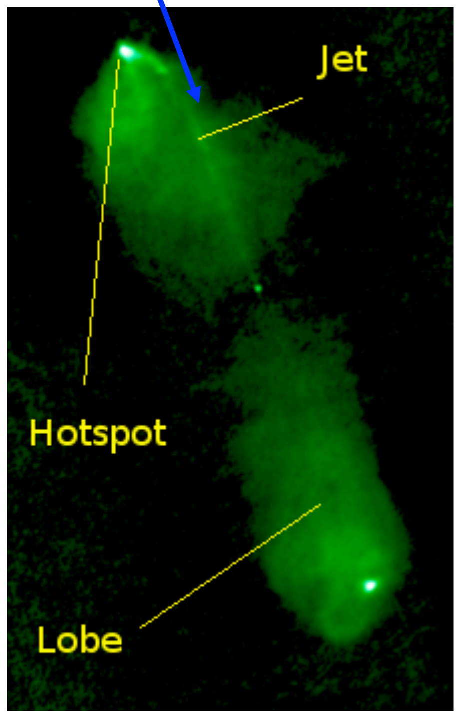


radio-loud
(relativistic jet)

high-
power
~<1%

FR 2
radio
galaxy

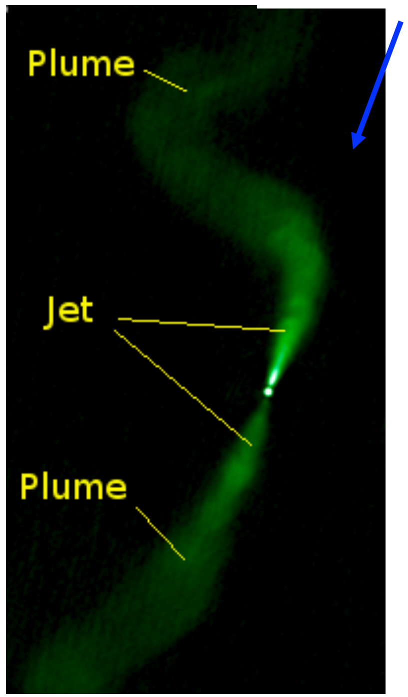
GeV blazar



low-
power
~9%

TeV blazar
(BL Lac)

FR 1
radio
galaxy



radio-
quiet
(no jet)
~90%

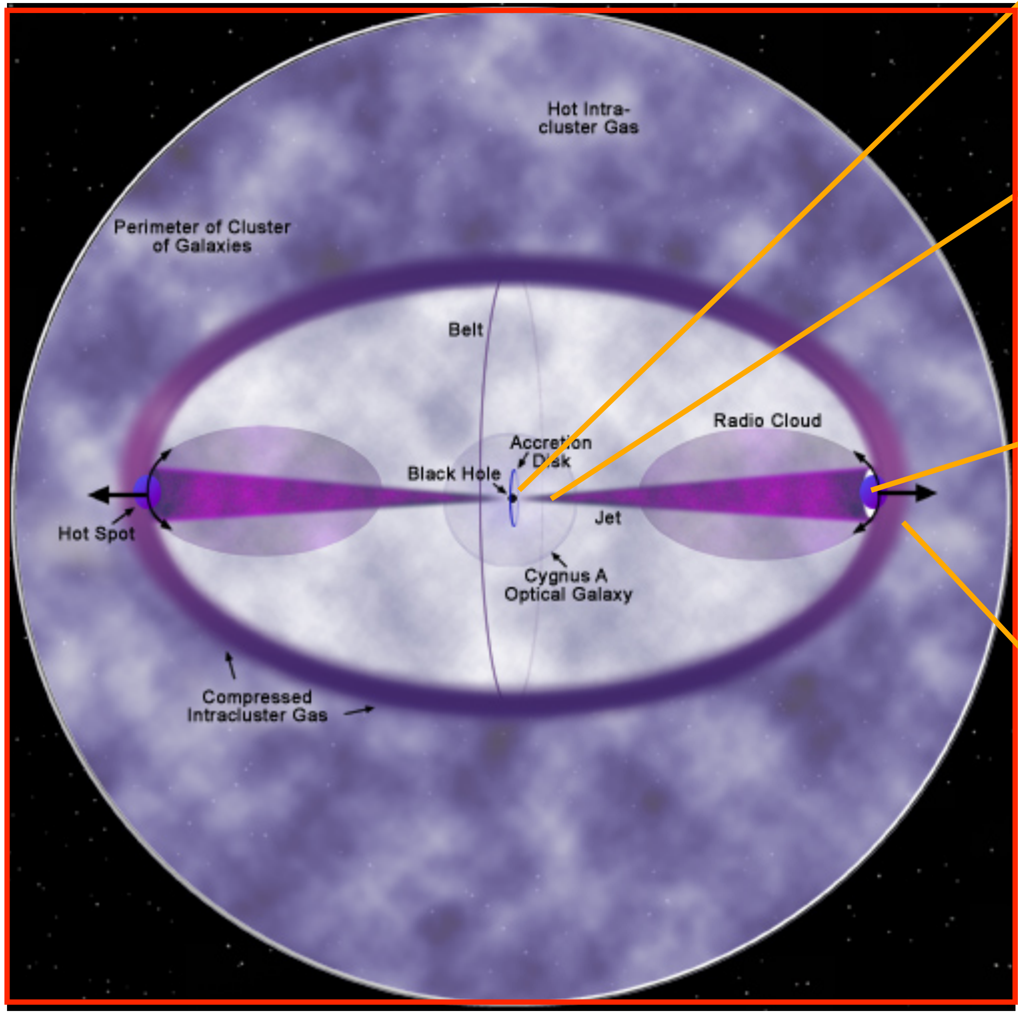
Seyfert galaxy
radio-quiet quasar

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

e.g. Szabo & Protheroe 94

inner jet (blazar)

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

accel./escape nontrivial

e.g. Mannheim 93

hot spot

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

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

accel./escape easier

e.g. Rachen & Biermann 93

bow shock

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

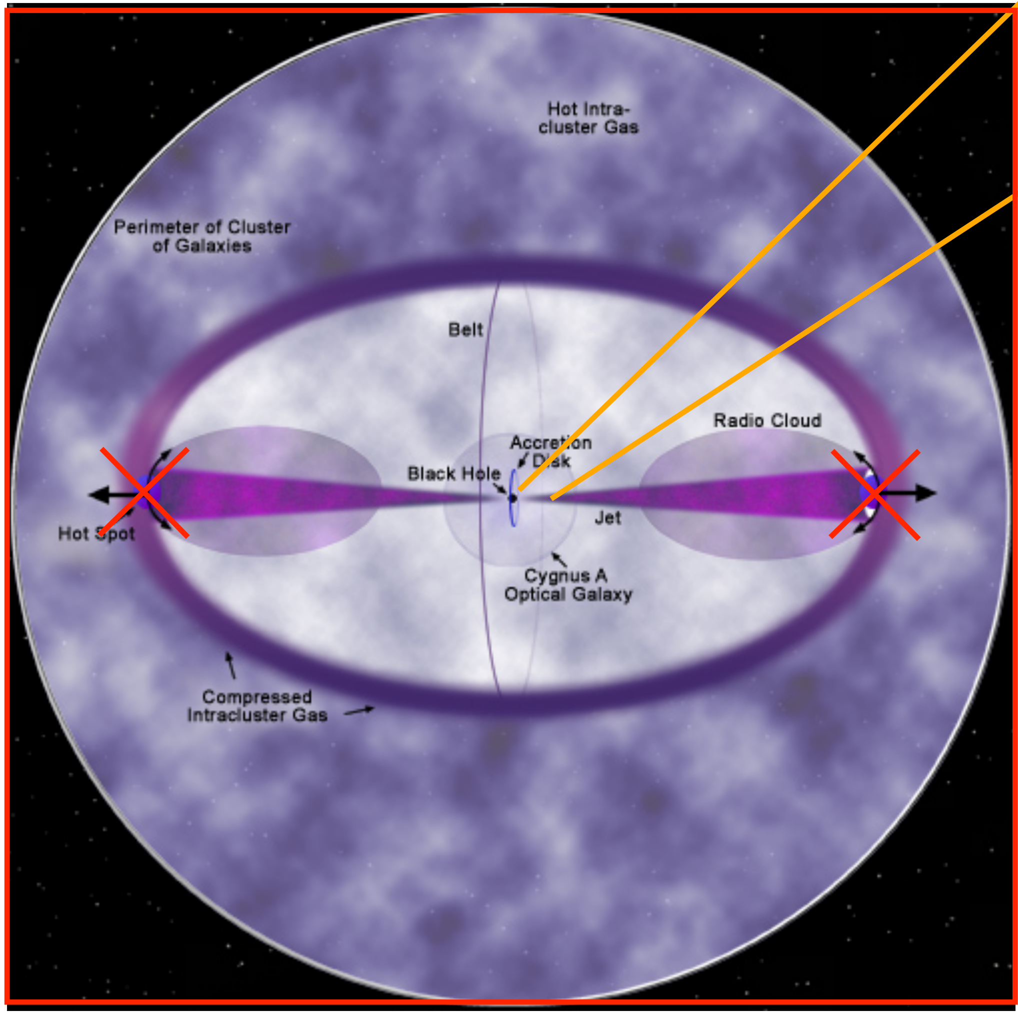
$E_{max} \sim E_{esc} \sim 10^{20}$ eV

accel. nontrivial

Berezhko 08

AGNs: acceleration sites

low power (FR 1) radio galaxy



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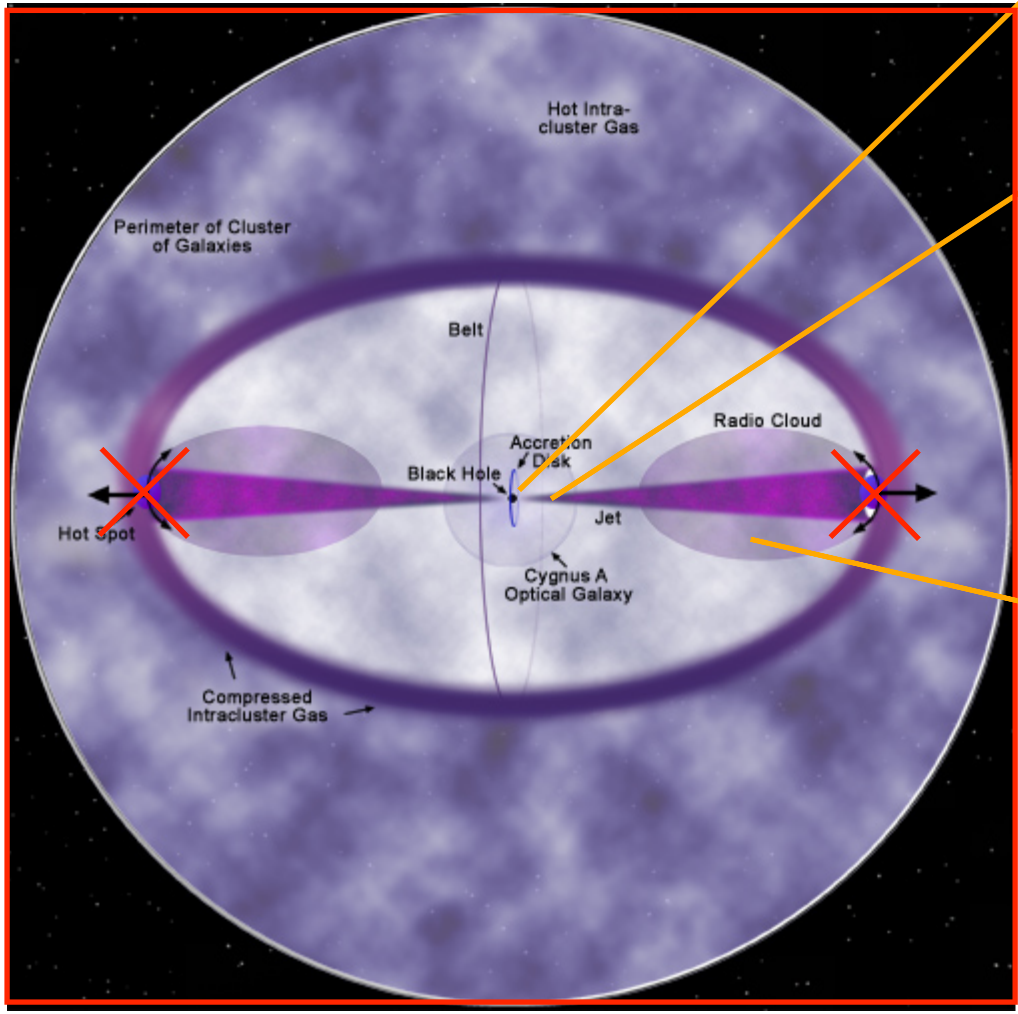

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e.g. Mannheim 93

diffuse lobe?

c.f. diffuse GeV from Cen A, Fermi bubble

-> Stawarz
Cerruti
Becherini

ultra-fast outflows (UFOs) in AGN

blue-shifted X-ray absorption lines

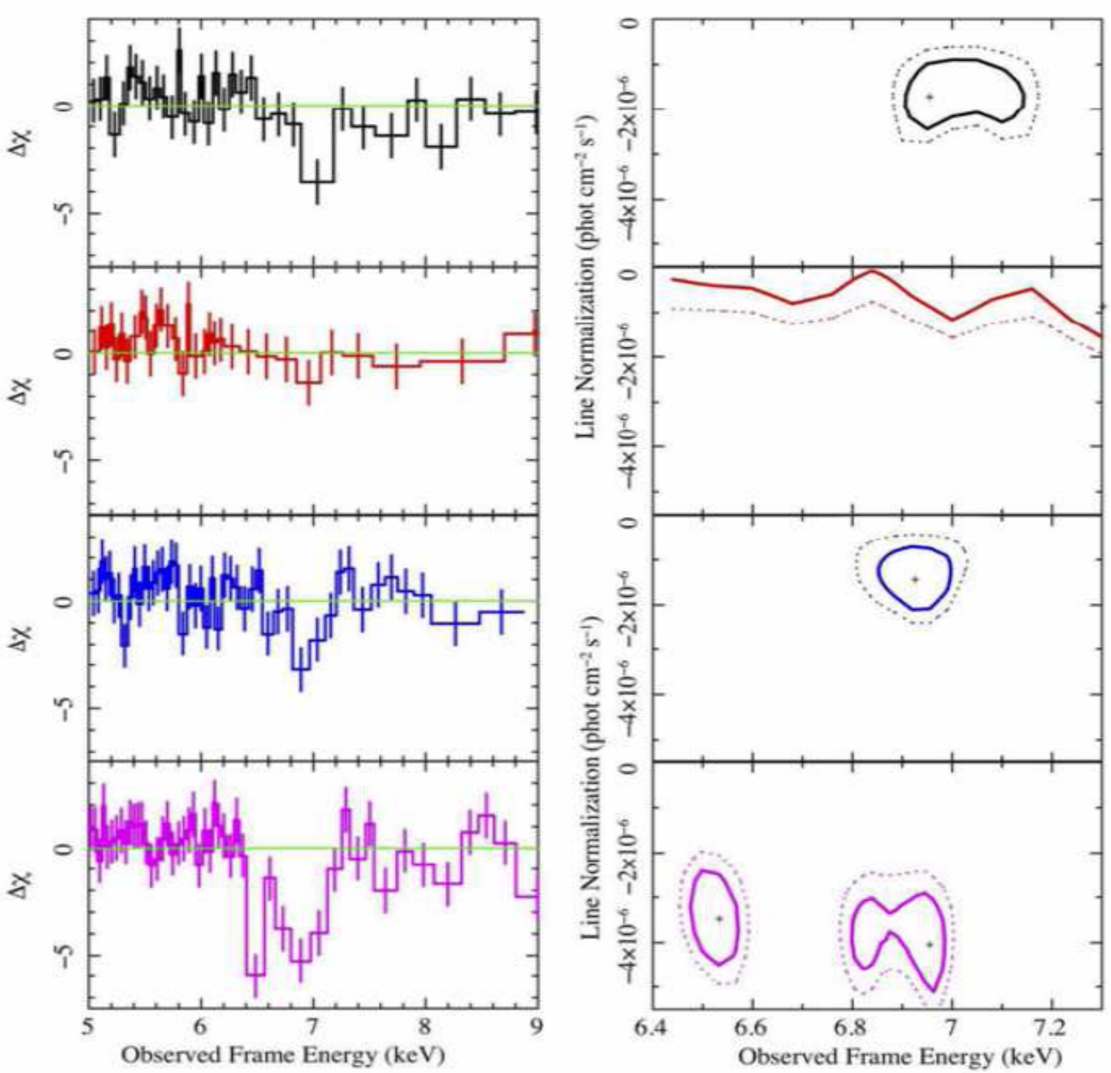
- fast outflow: v~0.05-0.3c
- variable: t_{var}>~ks
- highly ionized: Fe XXV/XXVI, $\xi_i \sim 10^3 - 10^6$ erg s^{-1} cm
- high column density: $N_H \sim 10^{22} - 10^{24}$ cm^{-2}
- ~40 % of all AGNs, both radio-quiet/radio-loud

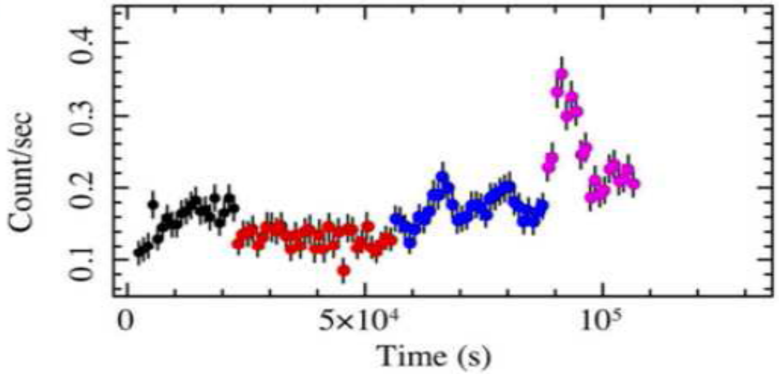
-> R~0.0003-0.03 pc (~10^2-10^4 Rs)

-> M~0.01-1 M_{sun}/yr, L_{kin}~0.01-1 L_{edd}

-> broad opening angle, independent of relativistic jet

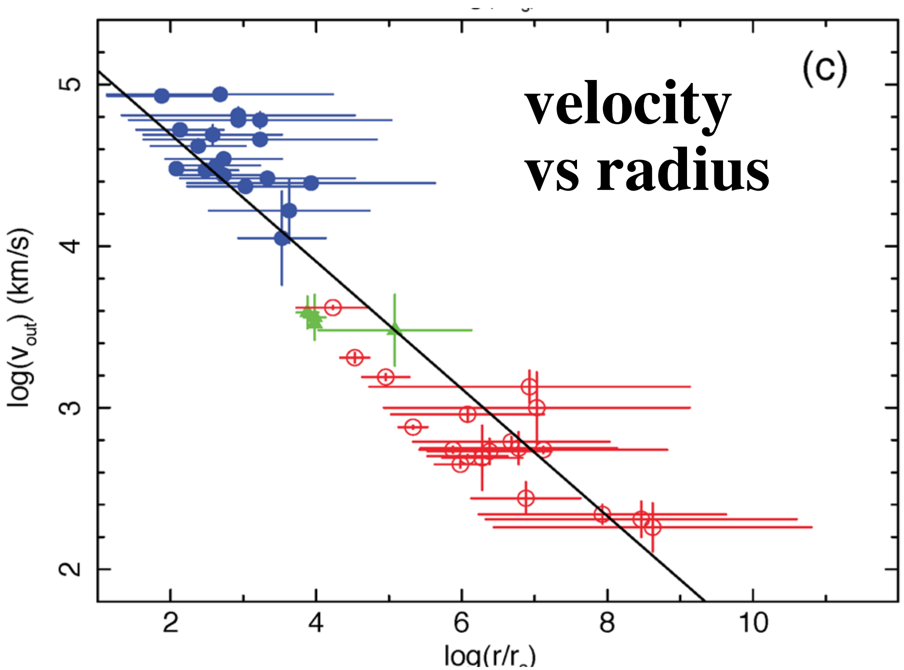
ultra-fast outflows (UFOs) in AGN

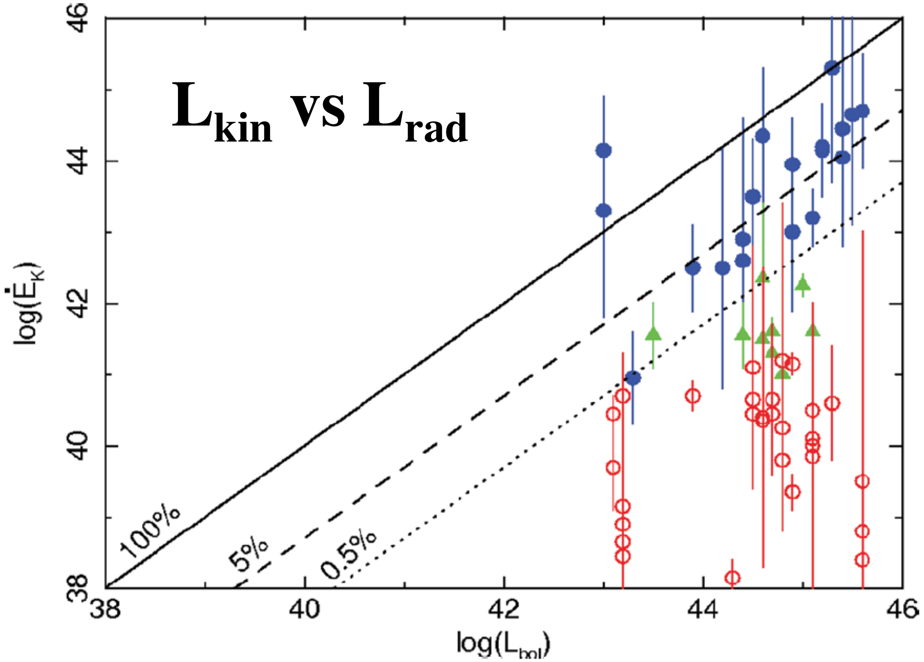




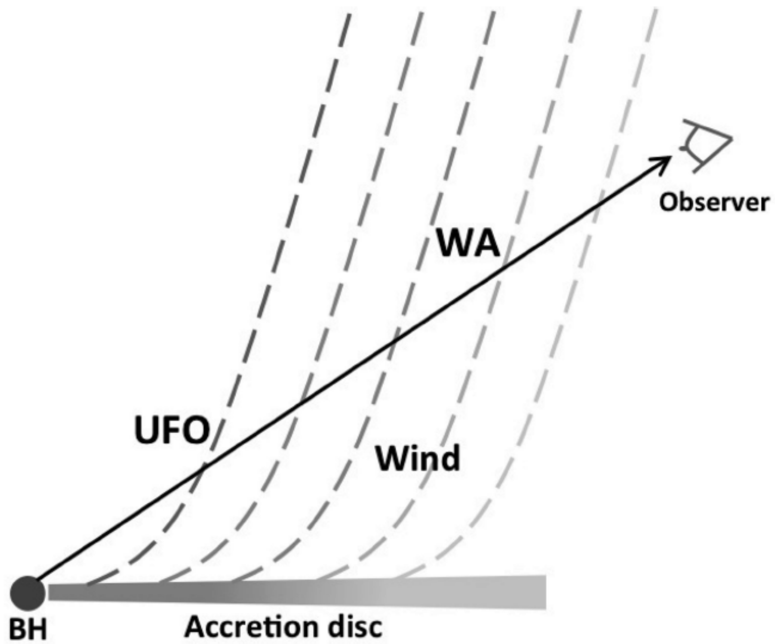
Giustini+ 11

ultra-fast outflows (UFOs) in AGN

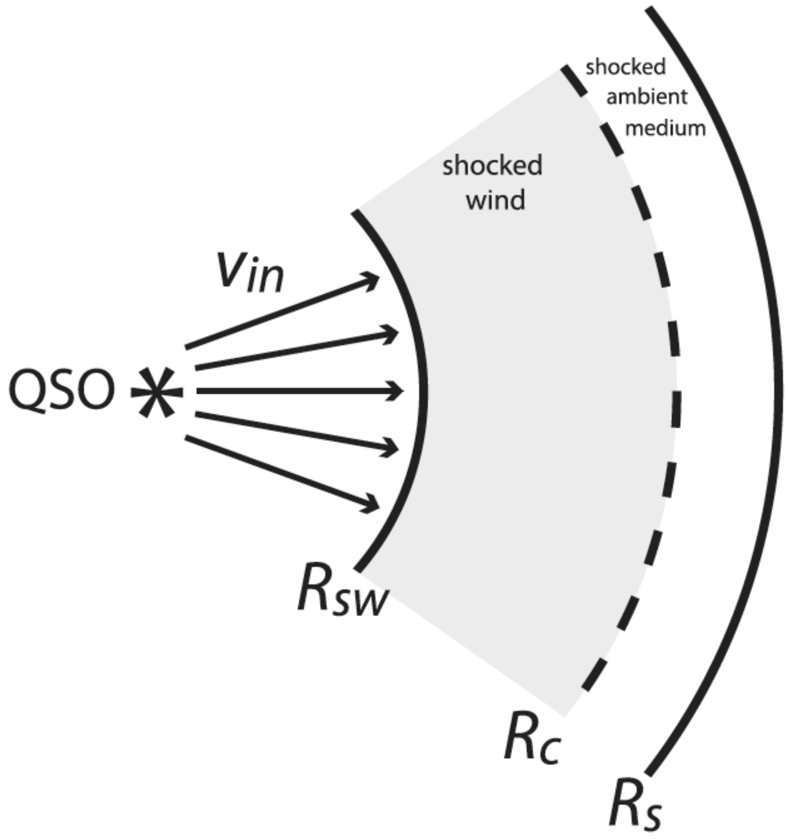




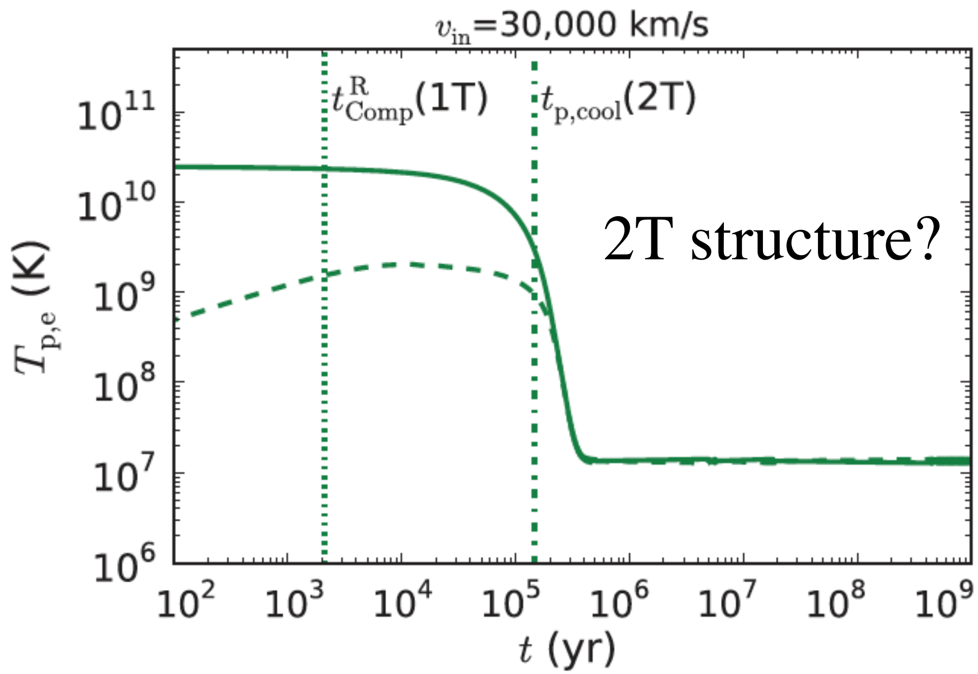
Tombesi+ 13



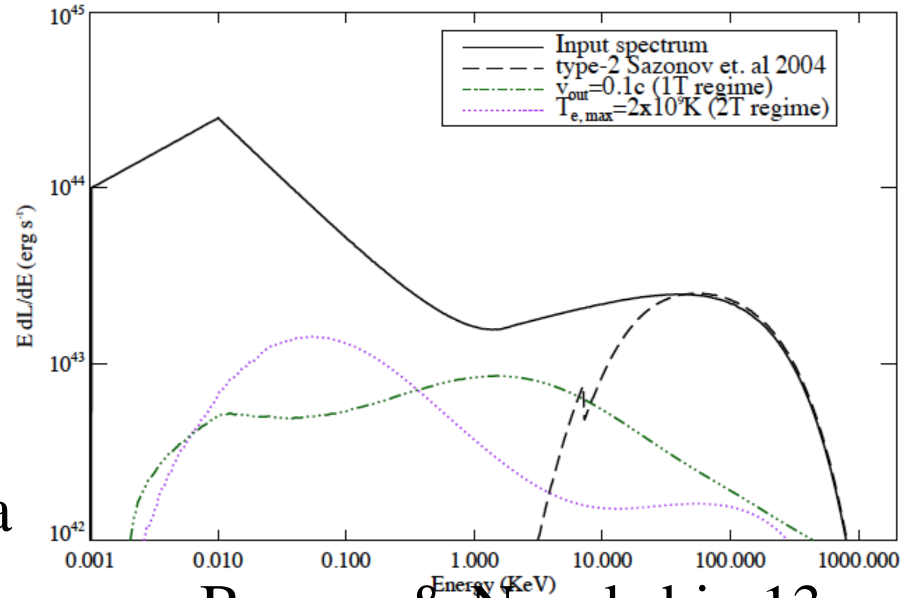
UFO external shock



Faucher-Giguere & Quataert 12



2T structure?



Bourne & Nayakshin 13

Compton upscattered X-rays from shocked thermal plasma potentially observable

UFO shocks: electron & proton acceleration **SI+, in prep.**

$M_{BH}=10^8\ M_{sun}$, $v_{out}=0.1c$, $L_{kin}=10^{45}$ erg/s ~ $0.1\ L_{edd}$

$B_{eq}{}^2/8\pi=\varepsilon_B\ L_{kin}/4\pi\ R^2\ v_{out}$

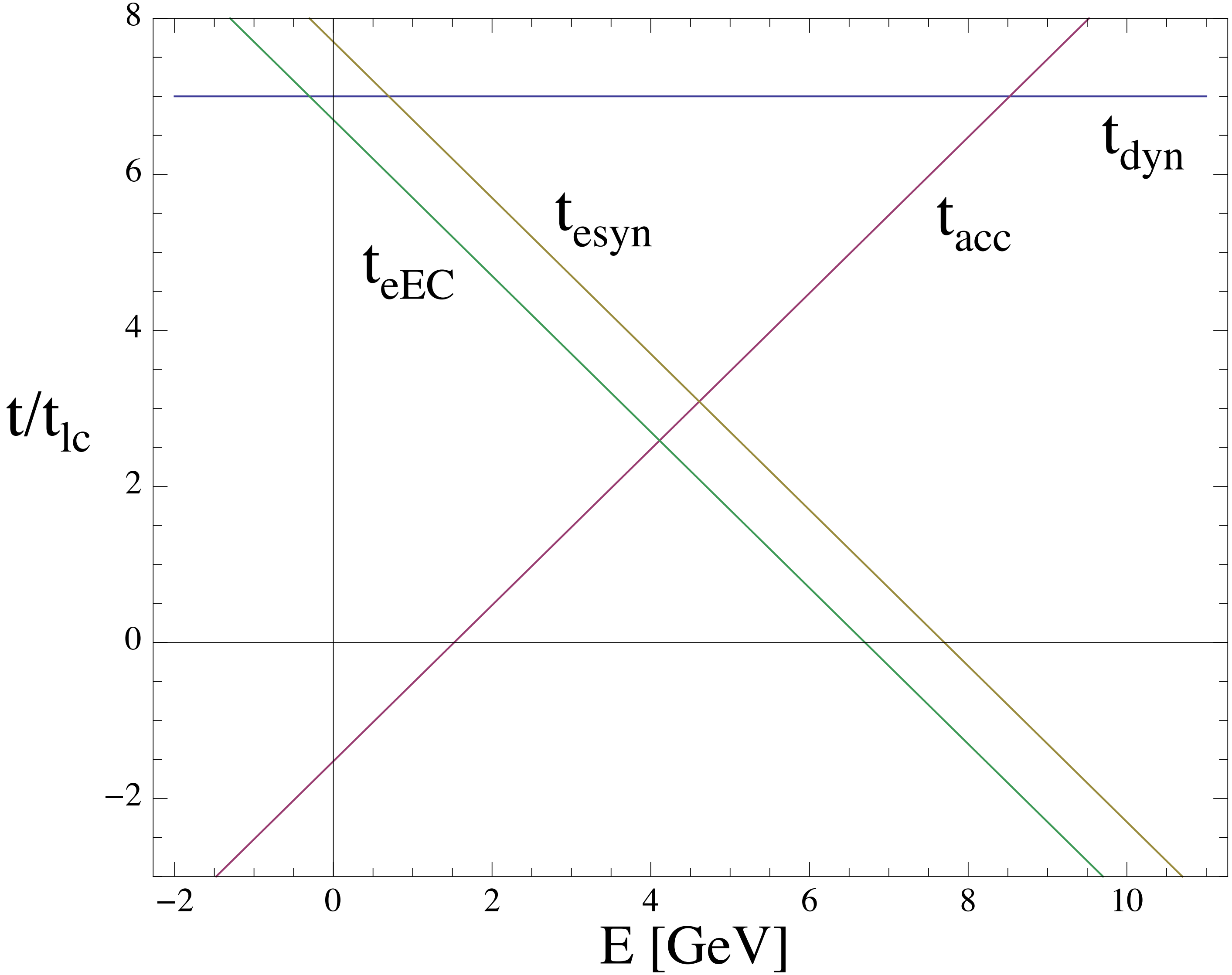
$t_{dyn}=R/v_{out}$, $t_{lc}=R_s/c=500$ s
$t_{acc}\sim 10\ (v_s/c)^{-2}\ E/ceB$

electron loss
$t_{esyn}=3\ m_e{}^2c^3/4\sigma_T u_B E_e$
$t_{eIC}=3\ m_e{}^2c^3/4\sigma_T u_{ph} E_e$

proton loss
$t_{pp}=(\kappa_{pp}\sigma_{pp}n_p c)^{-1}$
$t_{p\gamma} \propto \int \kappa_{p\gamma}(x)\sigma_{p\gamma}(x)x\ dx \int n_{ph}(x)dx)^{-1}$ $x=h\nu/m_e c^2$

UFO external shock

R=10 pc -> B_{eq}~0.03 G, n_p~0.5 cm^{-3}

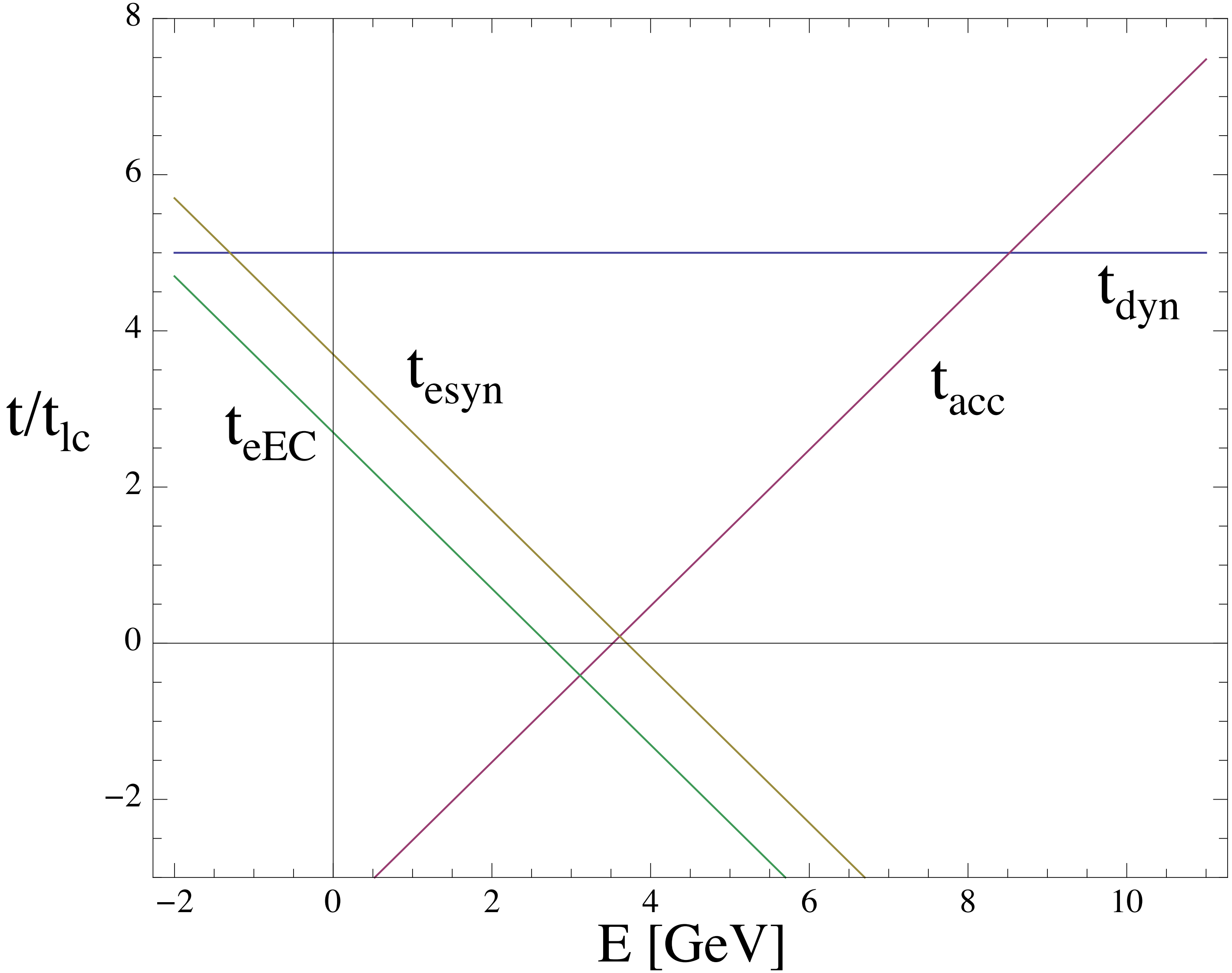


electrons up to ~10 TeV, cooling for ~<GeV

protons up to ~10^{18} eV (Fe up to ~3×10^{19} eV)

UFO external shock

R=0.1 pc -> B_{eq}~3 G, n_p~5x10^3 cm^{-3}

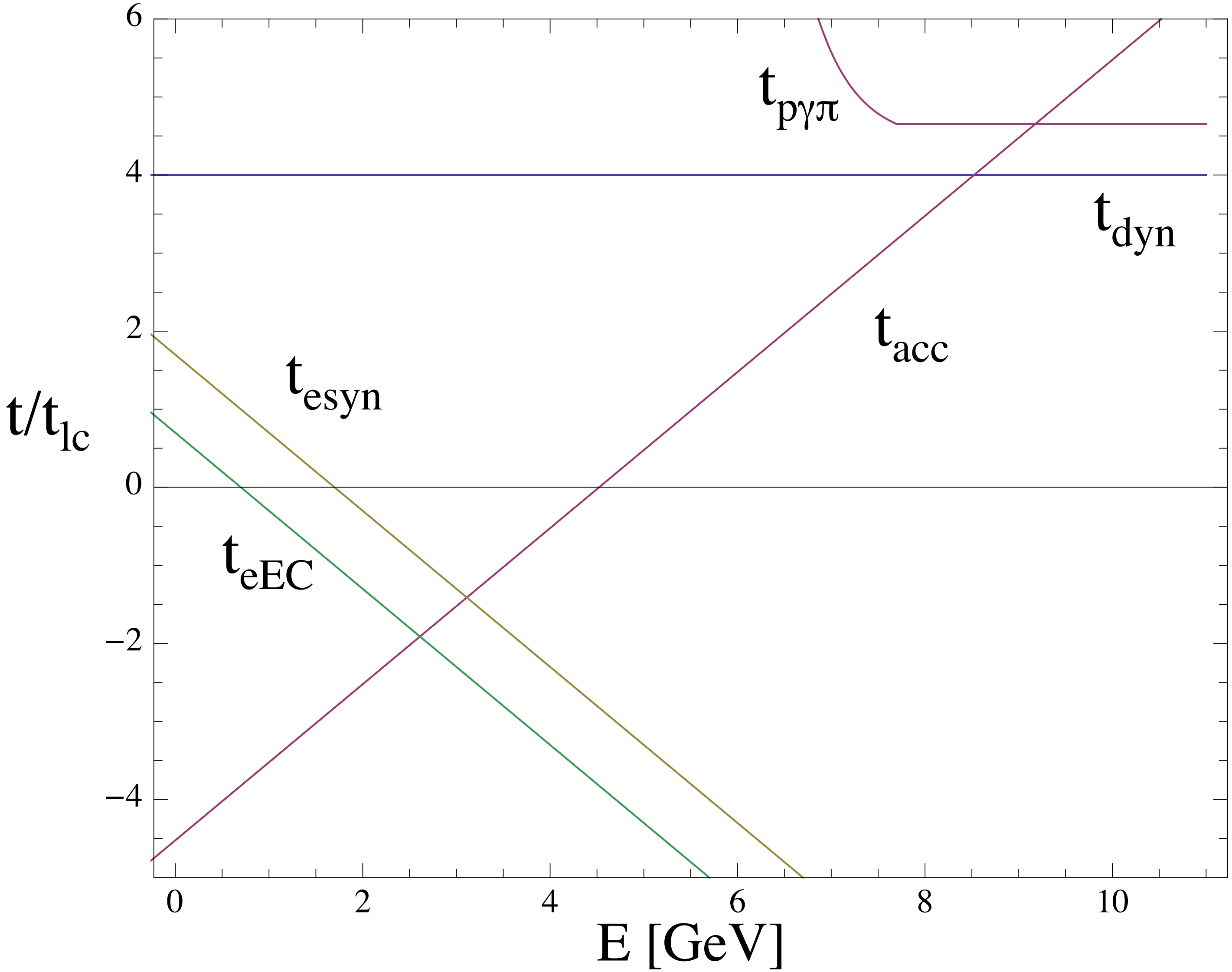


electrons up to ~1 TeV, cooling for ~<10 MeV NB: γγ

protons up to ~10^{18} eV (Fe up to ~3x10^{19} eV)

UFO internal shocks?

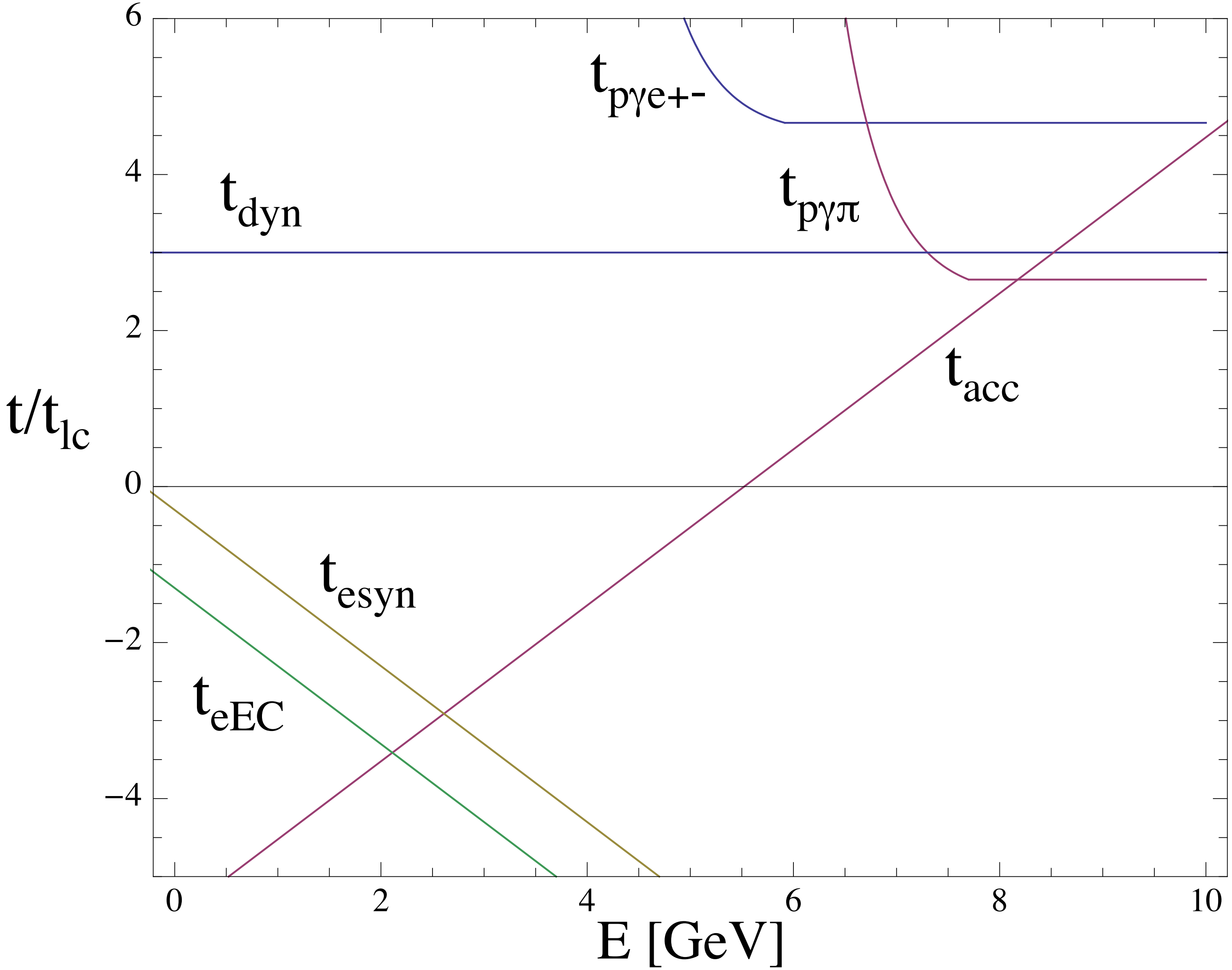
R=0.01 pc -> B_{eq}~30 G, n_p~5x10^5 cm^{-3}



electrons only to ~< GeV NB: internal photons, γγ

protons up to ~10^{18} eV, photomeson non-negligible

UFO internal shocks? R=0.001 pc -> B_{eq}~300 G, n_p~5x10^7 cm^{-3}



electrons only to ~100MeV NB: internal photons, γγ

protons up to ~10^{16} eV, limited by photomeson -> ν,n

potential consequences of near-nucleus $p\gamma$ interactions: revival of old ideas

Kazanas & Protheroe 83, Zdziarski 86, Sikora+87, Rudak+ 89, Begelman+ 90
Mannheim & Biermann 89, Stecker+91, Atoyan 92, Szabo & Protheroe 92…

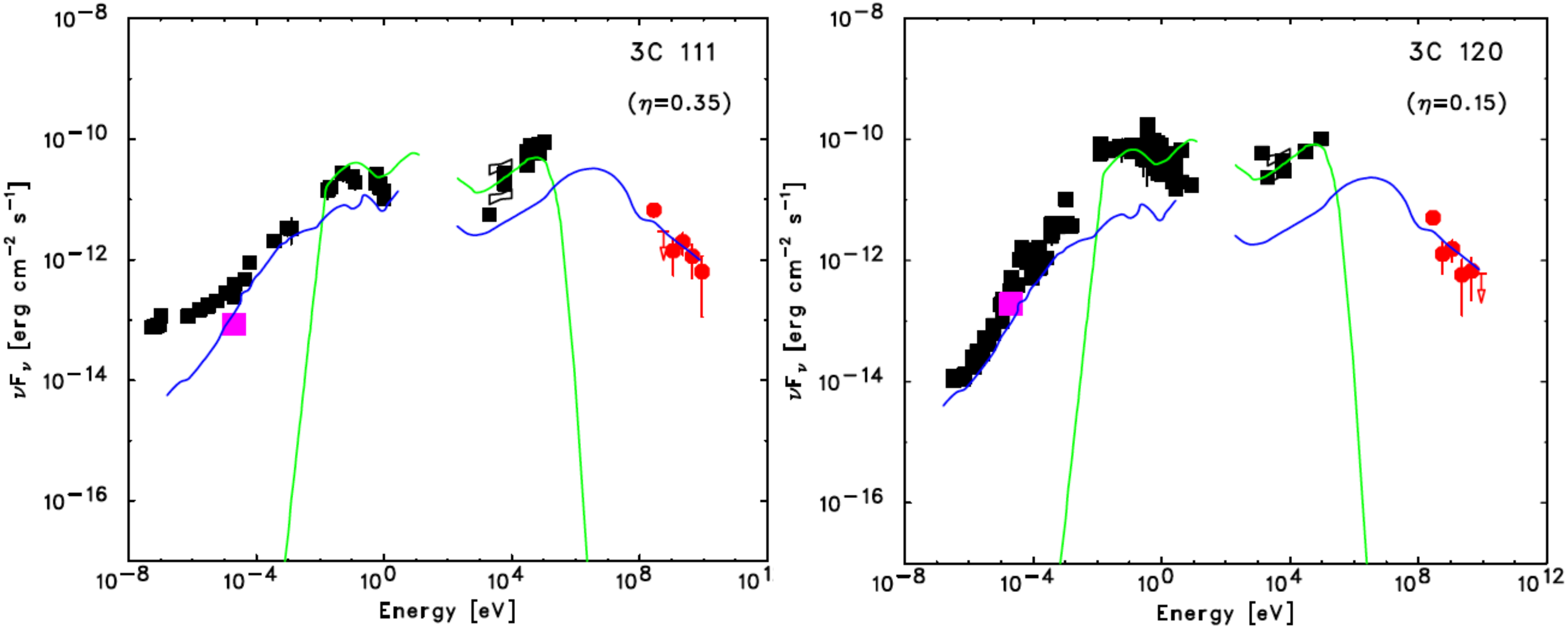
no UHECRs, no GeV-TeV emission but:

- non-thermal X/MeV emission
- TeV-PeV neutrino emission <-> IceCube results?
  -> broad-line region from neutrino-heated stars?
- TeV-PeV neutron injection
  -> decay back to protons within 1-100 pc, CR-driven wind?
  -> mass loading of jets?

radio-loud AGNs with UFOs

Kataoka+ 11

2/18 broad-line radio galaxies detected at GeV

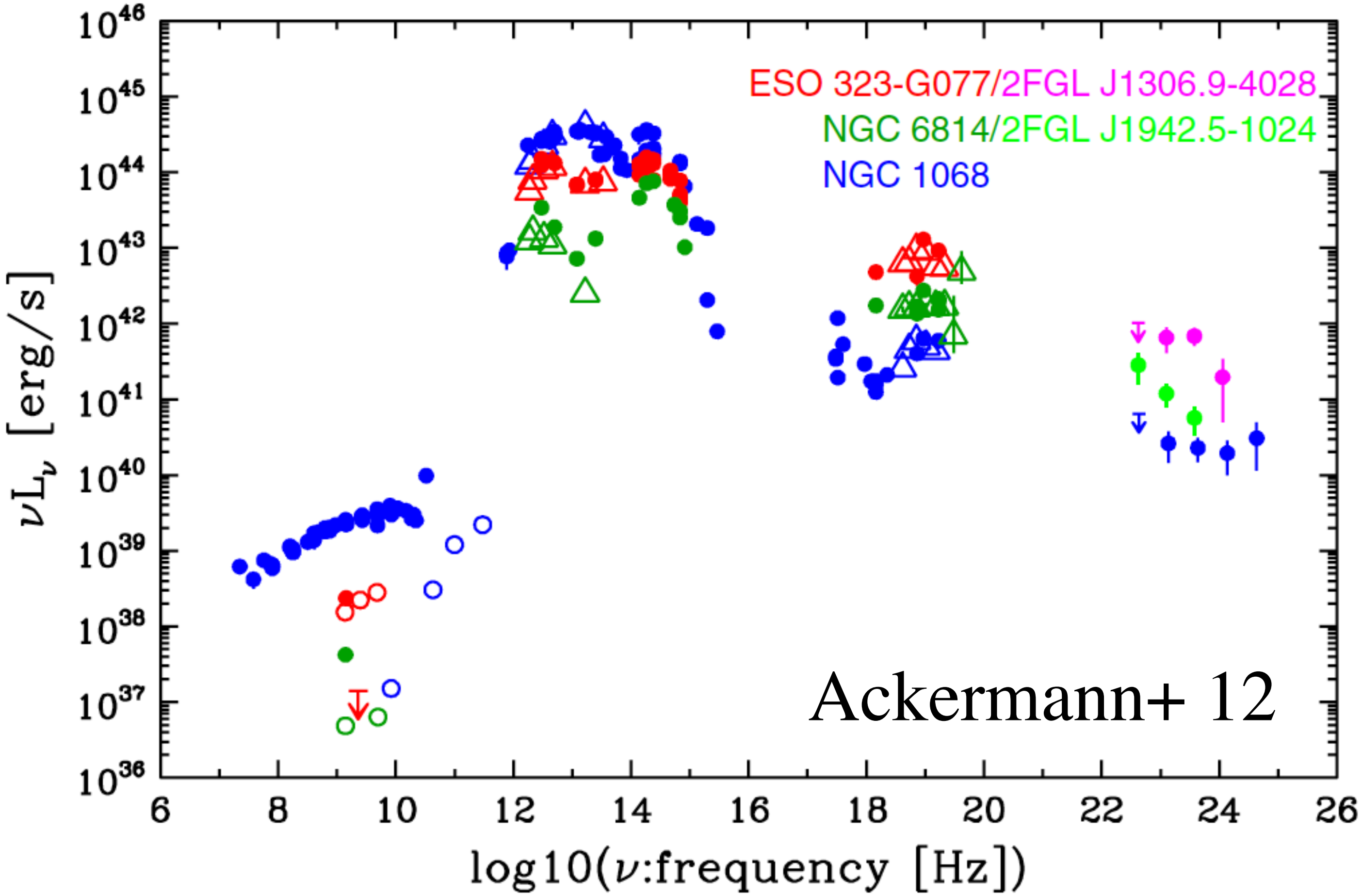


stronger than average core radio emission

-> jet emission at intermediate viewing angle?

3/5 broad-line radio galaxies found to have UFOs

radio-quiet AGN with UFO   ESO 323-G77



2/120 Seyferts with GeV association -> chance coincidence?

correlation with Auger UHECR event   Nemmen+ 10, Jiang+ 10

UFO as UFO?   but low radio -> UHECR cascade?

other possibilities

- hypernovae -> Wang
- dormant black holes
- magnetars -> Fang
- pulsars
- starburst galaxies
- Galactic wind (Fermi bubble)
- cluster shocks -> Keshet

…

conseil n°3

Think how important your work might be for your colleagues down the hall or in the next building (or even neighbors around your home)

Do UHECRs play an important role in the Universe?

c.f. GeV CRs

- ionization/heating -> feedback on star formation
- CR-driven Galactic wind? -> feedback on star formation
  -> metal ejection/heat input into ICM/IGM
- heating of cluster cool cores?

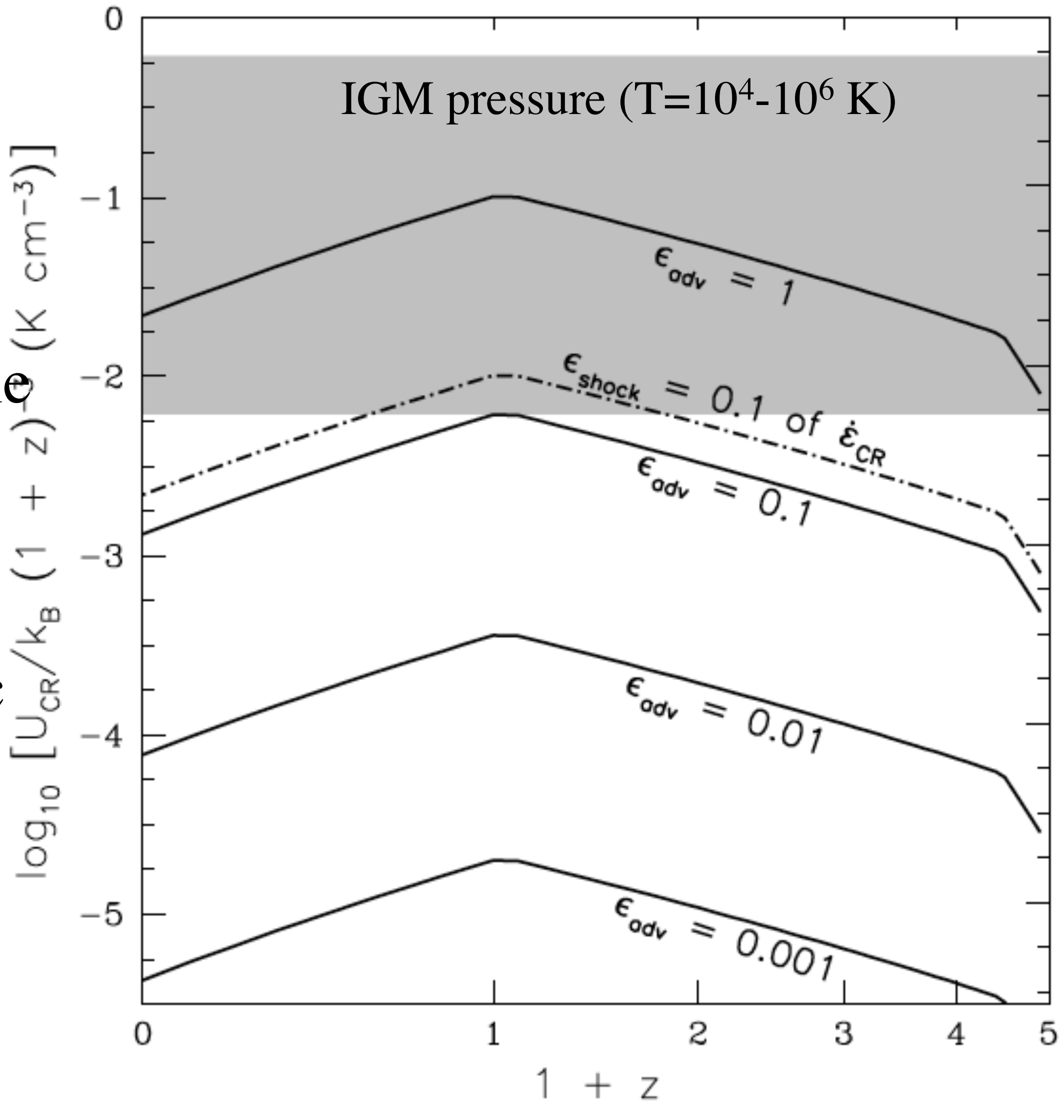
GeV CRs in the IGM

Lacki arXiv:1304.6142

escape into IGM via advection by galactic winds and/or diffusion

->

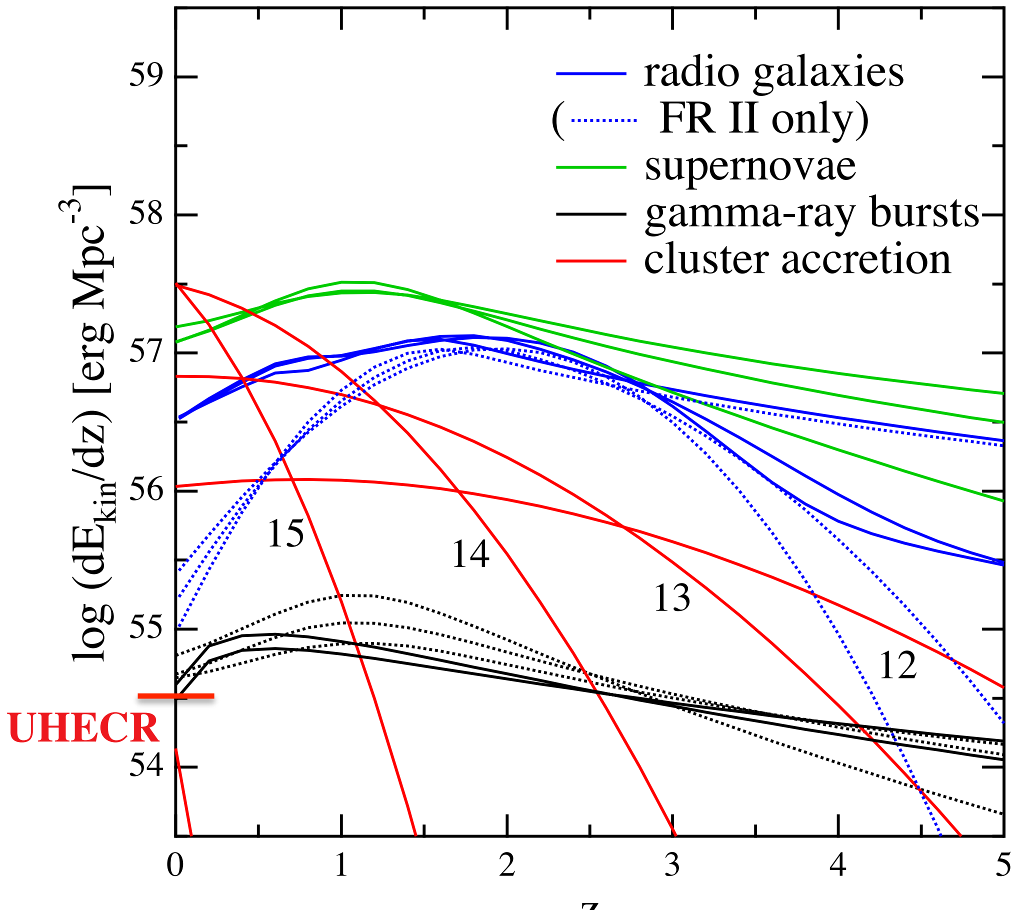
- pressure potentially comparable to diffuse IGM (T~10^4K) greater at z>~1?
- CR streaming limited by sound velocity, reach ~100 kpc
- potential generation of IGMF B>~10^{-13} G



UHECR sources: energy budget

SI, arXiv:0809.3205

kinetic E input into the universe



differential (per unit z)

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

CR energy density in IGM

$u_{CR,GeV}=3\times10^{-18}$ erg cm^{-3}

$u_{CR,EeV}=10^{-19}$ erg cm^{-3}

only factor ~30 lower

$r_g\sim1$ Gpc E/EeV$(B/10^{-12}\,G)^{-1}$

$u_{CR,EeV}>>u_{B,IGM}$

as long as $B<10^{-10}$ G

$u_{CR,EeV}\sim<u_{T,IGM}$ at z~1?

NB: if $B_{IGM}\propto(1+z)^2$,

$r_g\propto(1+z)^{-2}$

summary

conseil n°1

Don't shy away from new proposals involving newly-recognized concepts/phenomena

conseil n°2

Think how important your work might be for your colleagues next door

conseil n°3

Think how important your work might be for your colleagues down the hall or in the next building (or even neighbors around your home)