42

42 *or*

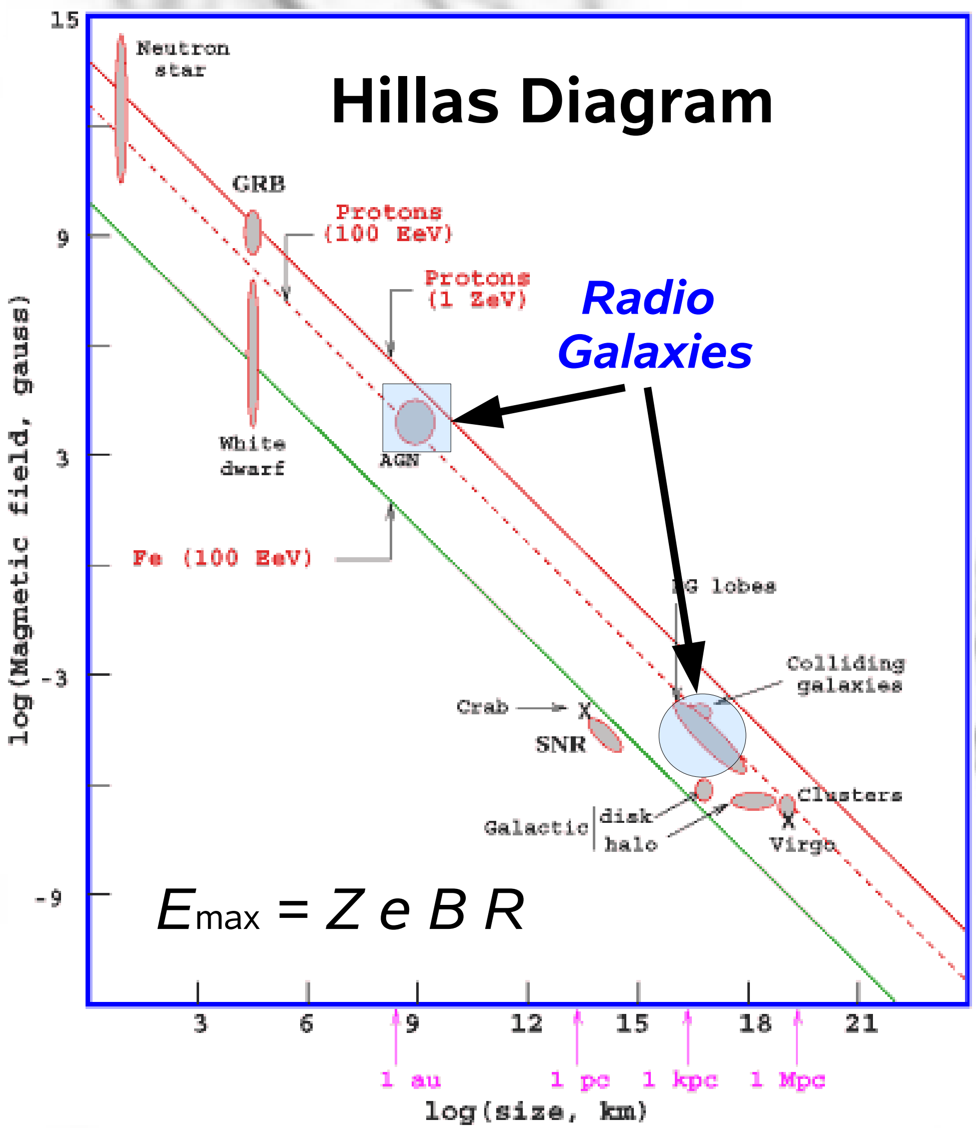
on the usefulness of asking questions....
....before obtaining answers!

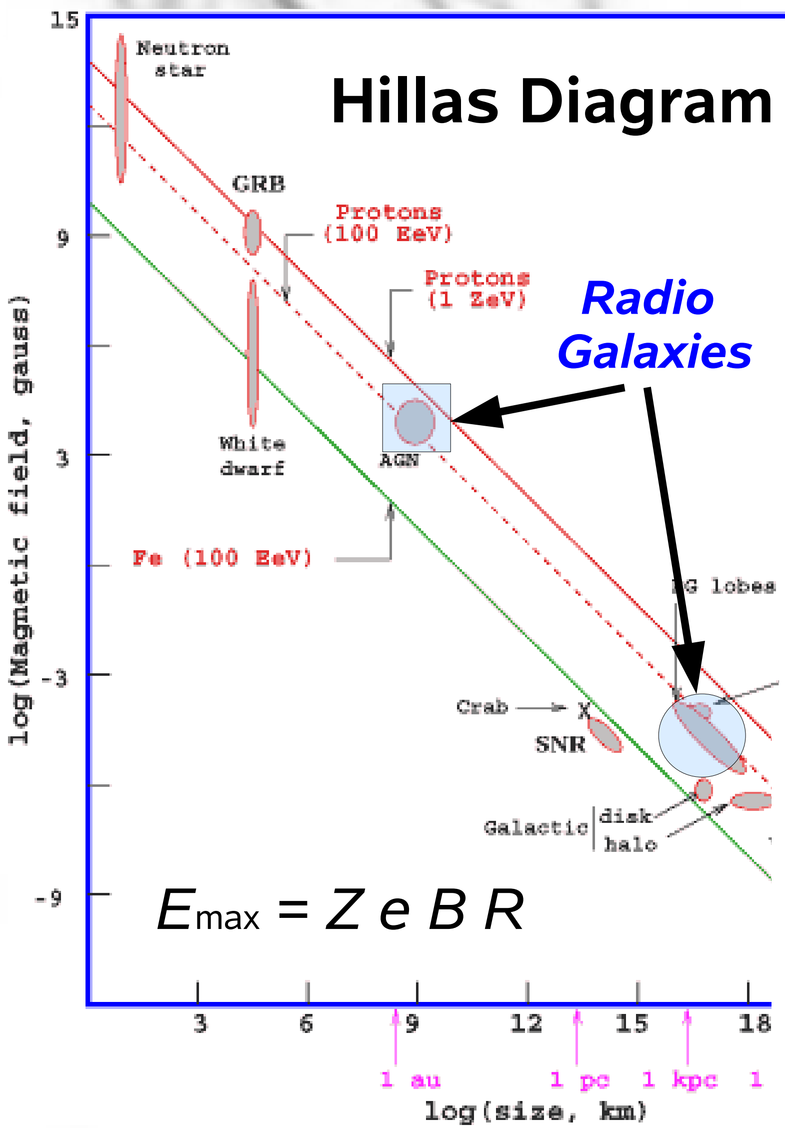
Ultra High Energy Cosmic Rays from Radio Galaxies - revisited -

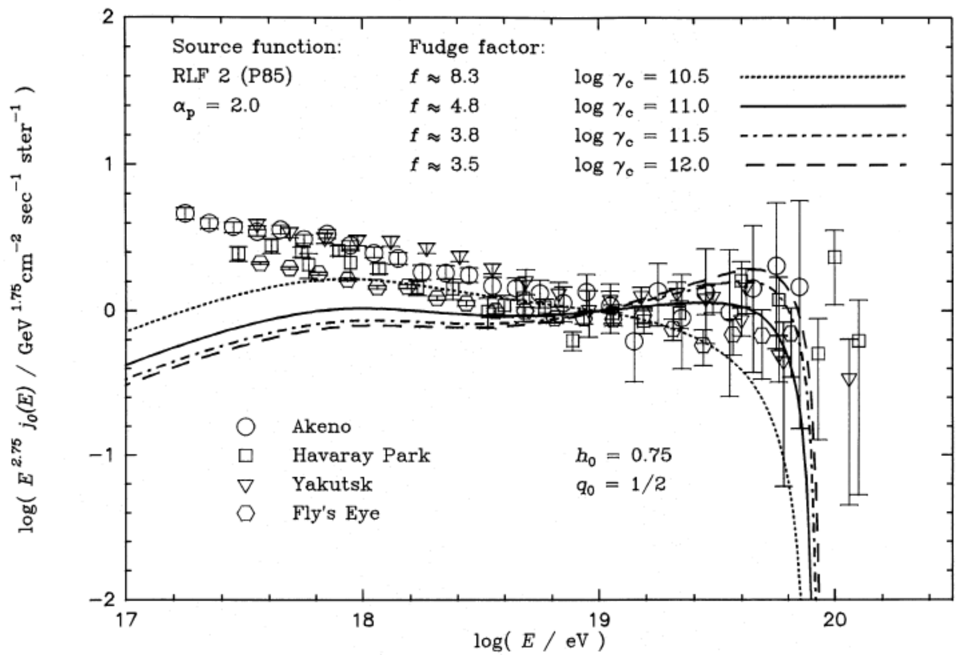
Jörg P. Rachen
Max-Planck-Institute for Astrophysics
Garching, Germany

Why consider radio galaxies?

And why revisit them now?


Hillas Diagram
Neutron star
GRB
Protons (100 EeV)
Protons (1 ZeV)
Radio Galaxies
White dwarf
AGN
Fe (100 EeV)
RG lobes
Colliding galaxies
Crab
SNR
Clusters
Galactic disk halo
Virgo
$E_{max} = Z\, e\, B\, R$
log(Magnetic field, gauss)
15
9
3
-3
-9
3
6
9
12
15
18
21
1 au
1 pc
1 kpc
1 Mpc
log(size, km)





Astron. Astrophys. 272, 161–175 (1993)

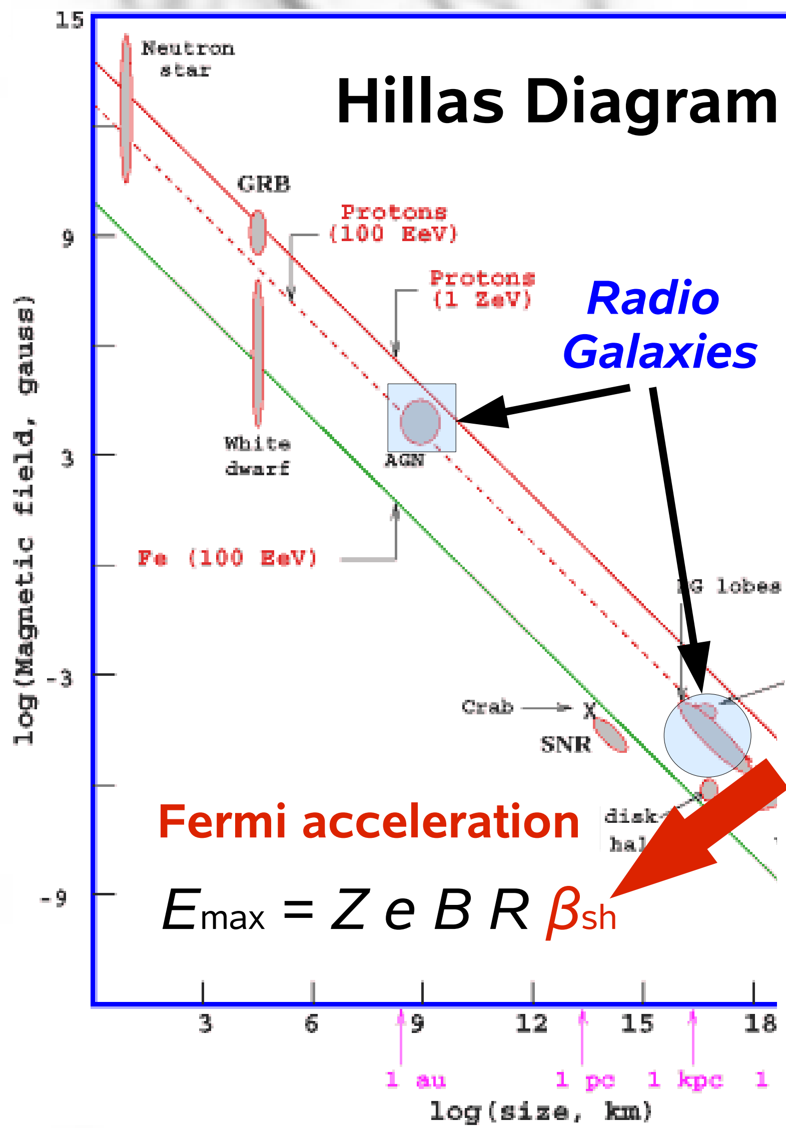
Extragalactic ultra-high energy cosmic rays

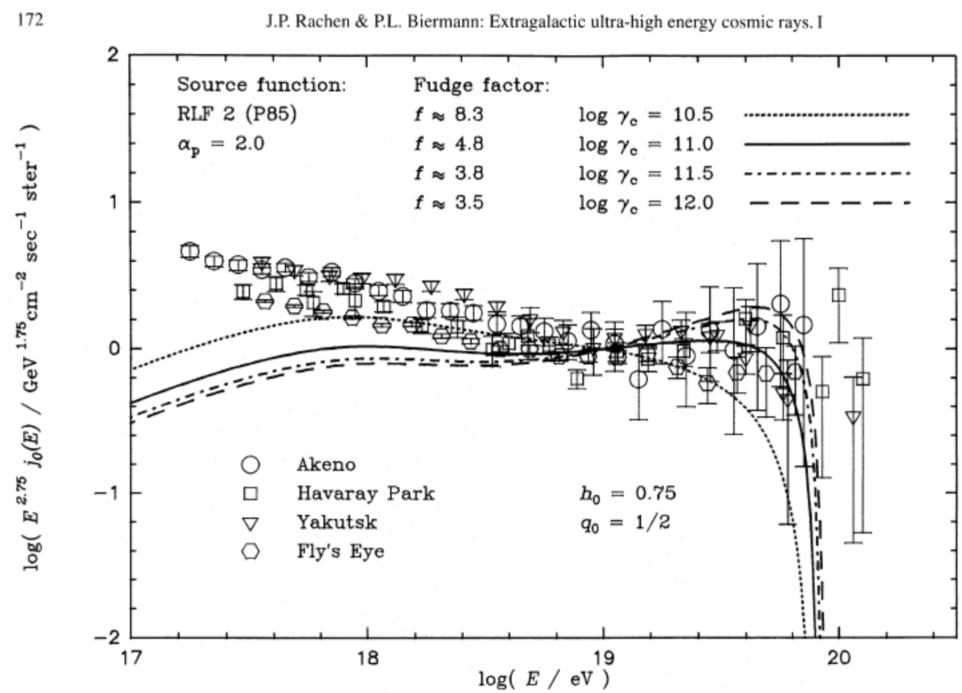
I. Contribution from hot spots in FR-II radio galaxies

Jörg P. Rachen and Peter L. Biermann

Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, W-5300 Bonn 1, Germany

Received October 9, accepted December 22, 1992





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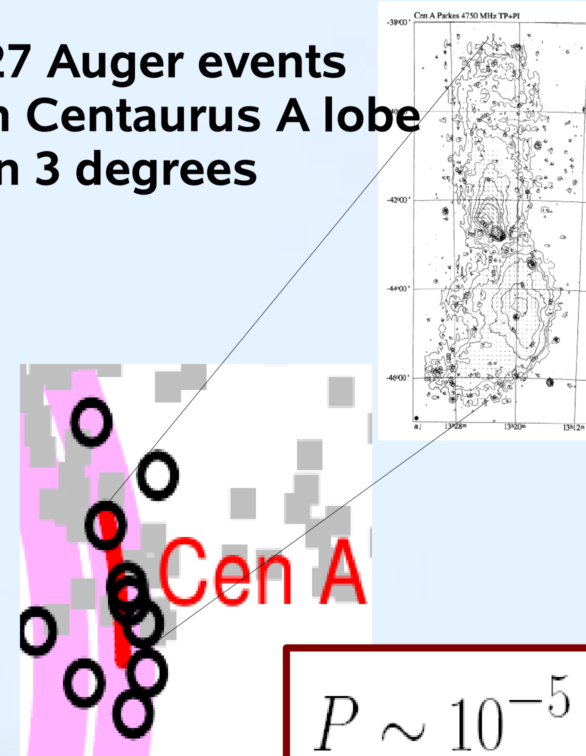
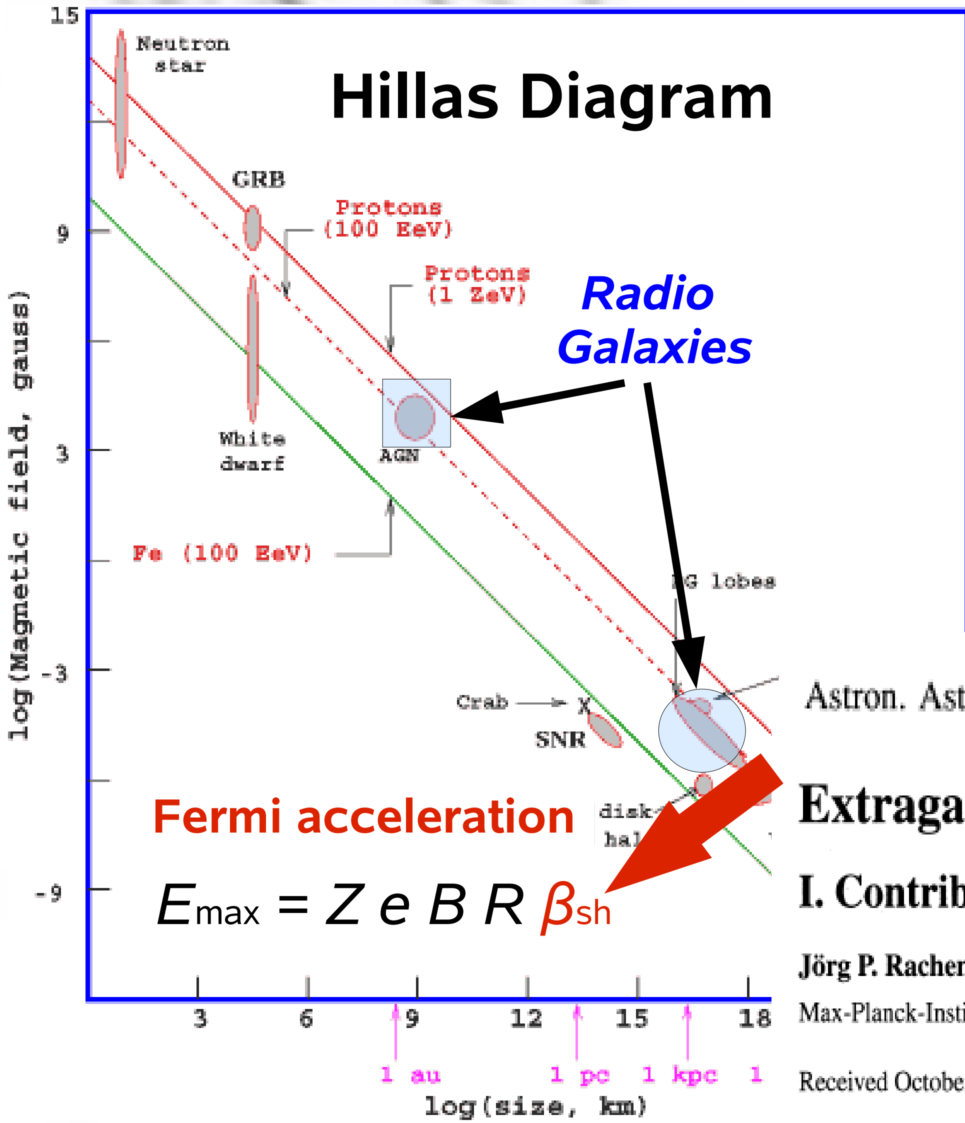
5 of 27 Auger events touch Centaurus A lobe within 3 degrees



$$P \sim 10^{-5}$$

Hillas Diagram



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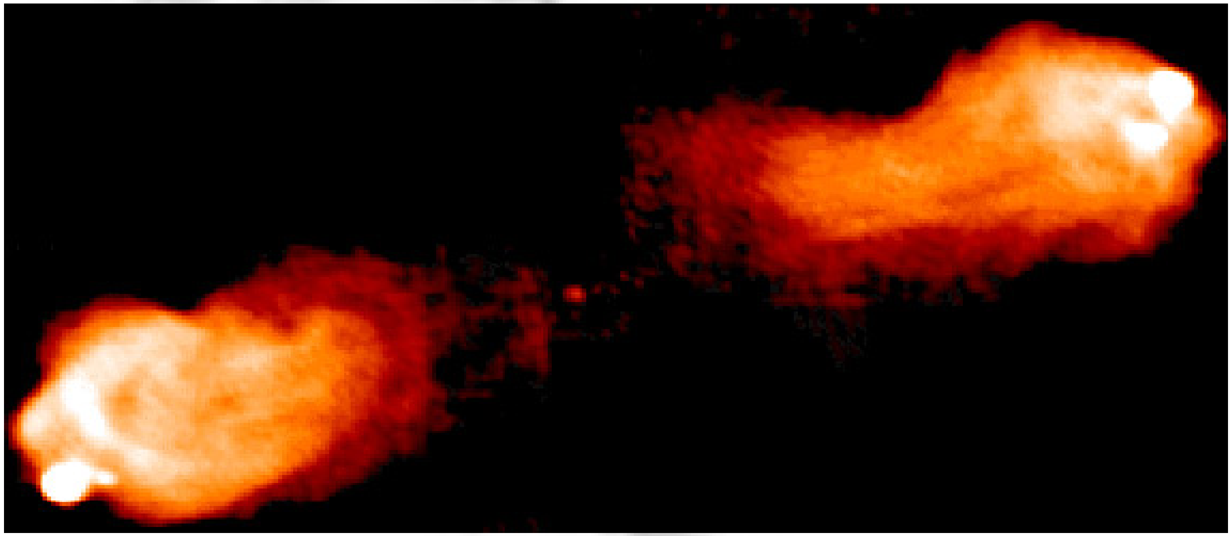
What the hell means FR-II?

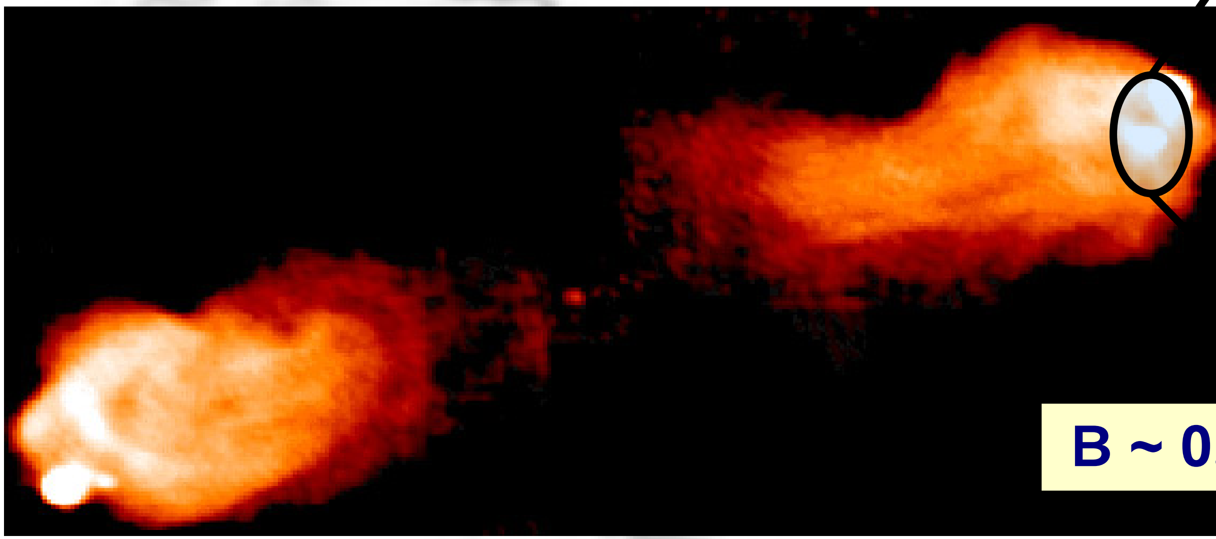
or

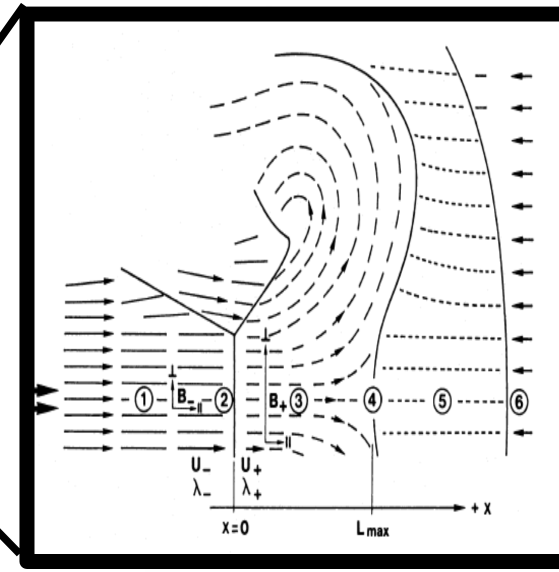
Can all radio galaxies accelerate UHECR?

Fanaroff-Riley Class II (e.g. Cygnus A)

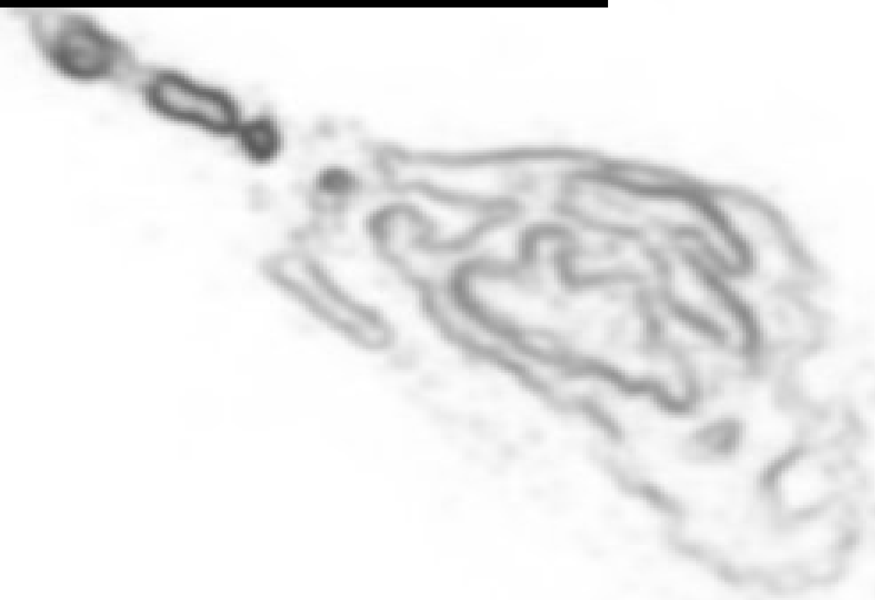


Fanaroff-Riley Class II (e.g. Cygnus A)





B ~ 0.3 mG, R ~ 1kpc, β_{sh} ~ 0.3



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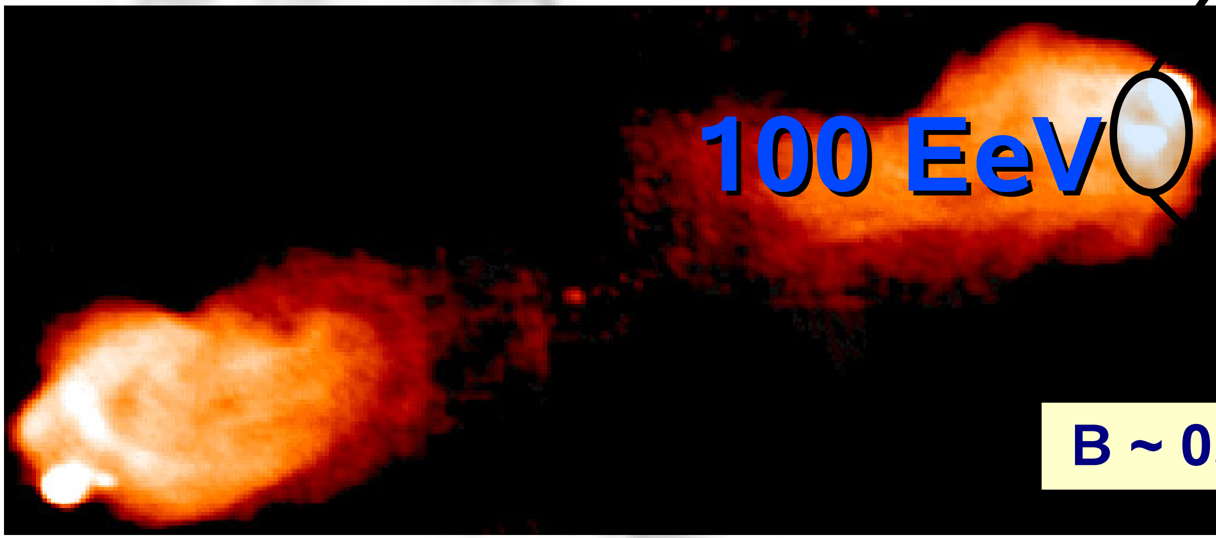
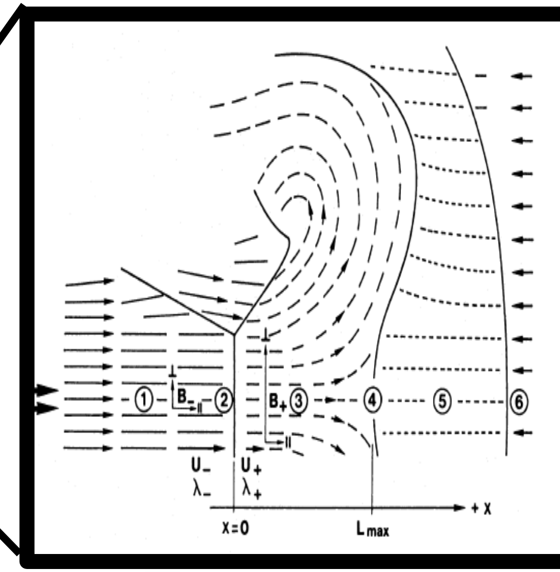
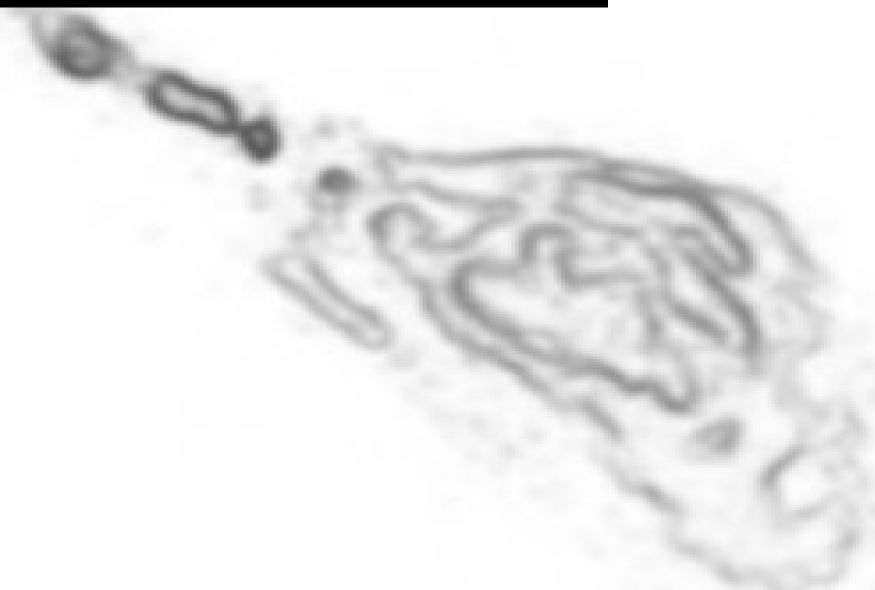
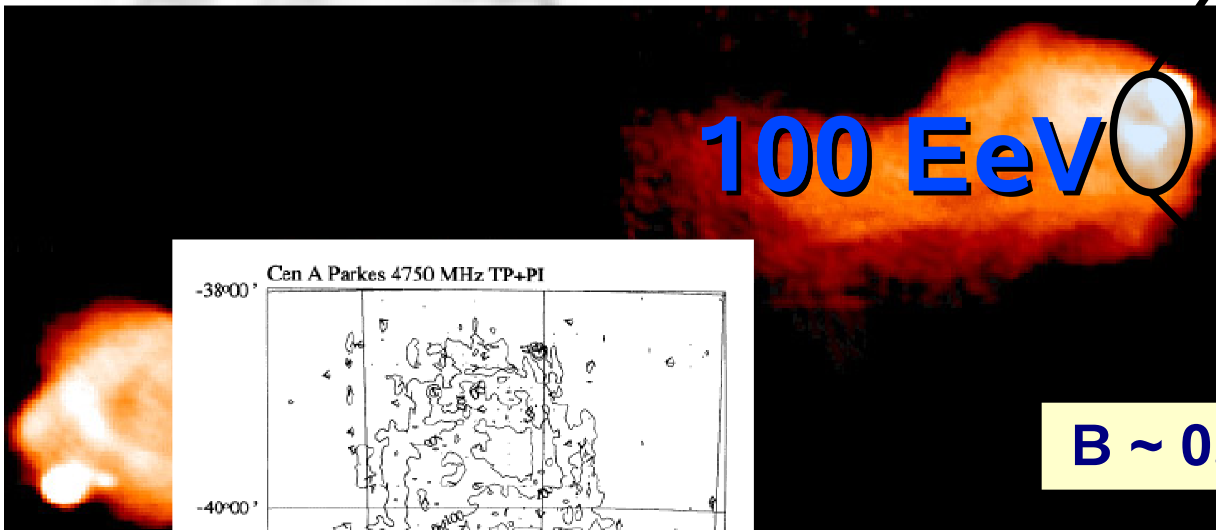


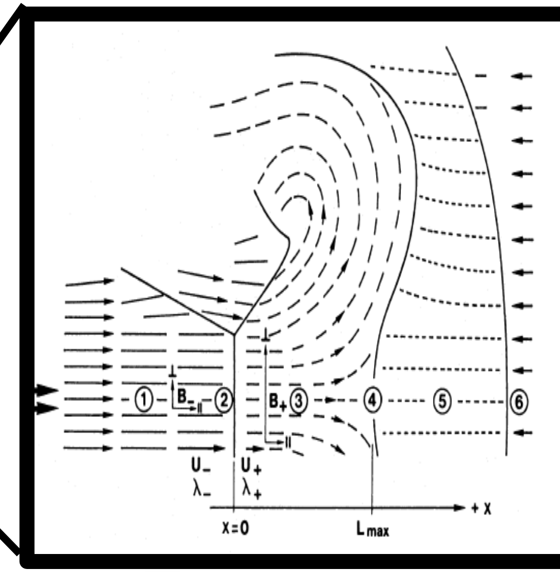


$B \sim 0.3$ mG, $R \sim 1$kpc, $\beta_{sh} \sim 0.3$

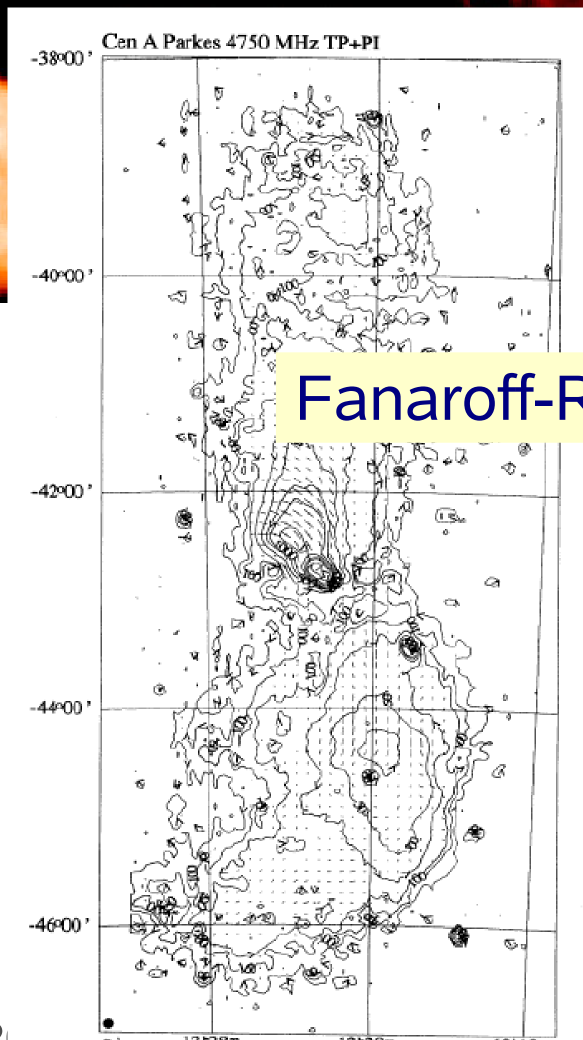


Fanaroff-Riley Class II (e.g. Cygnus A)

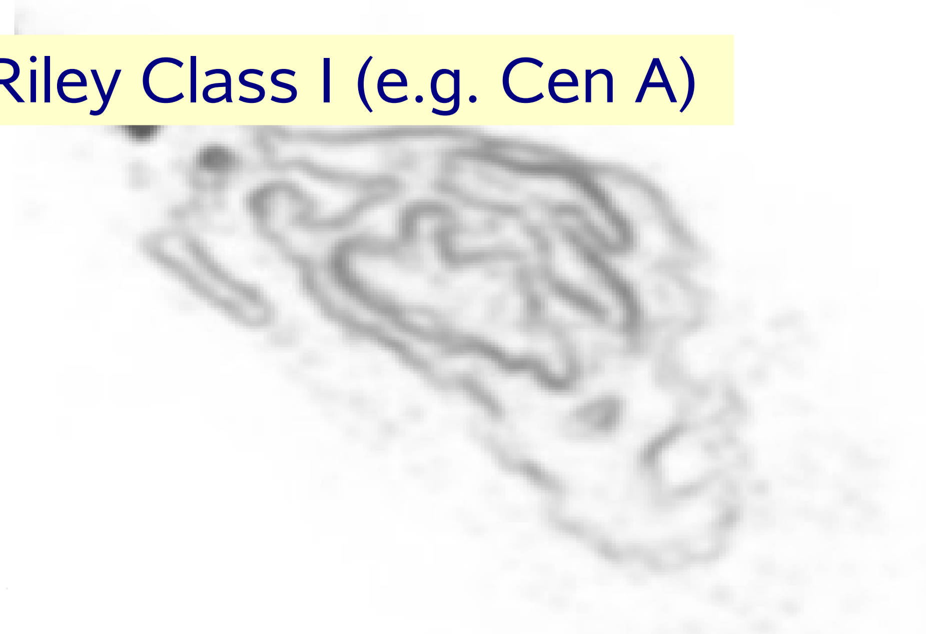




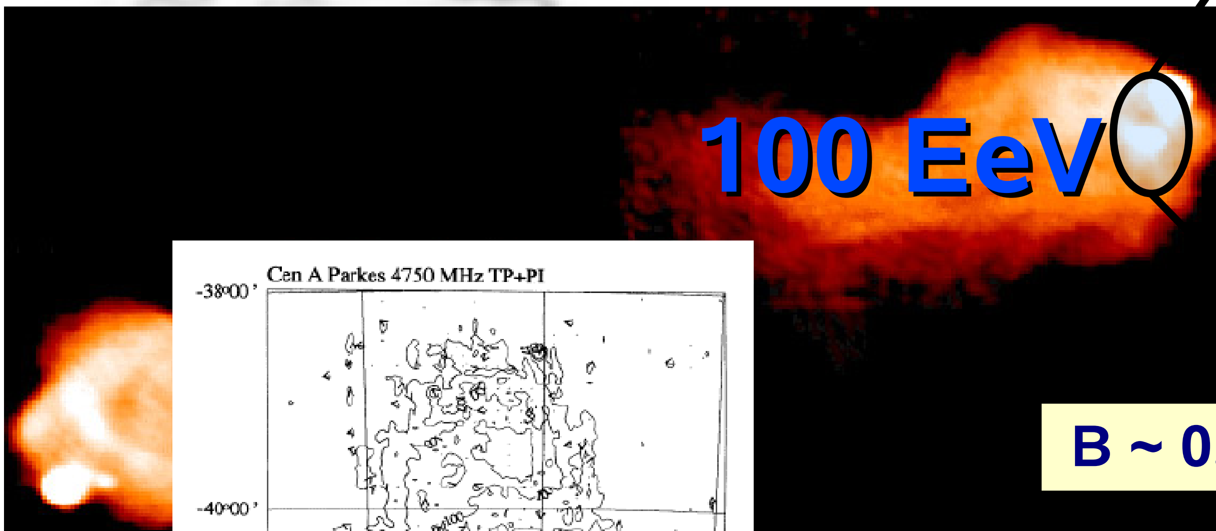
B ~ 0.3 mG, R ~ 1kpc, β_{sh} ~ 0.3

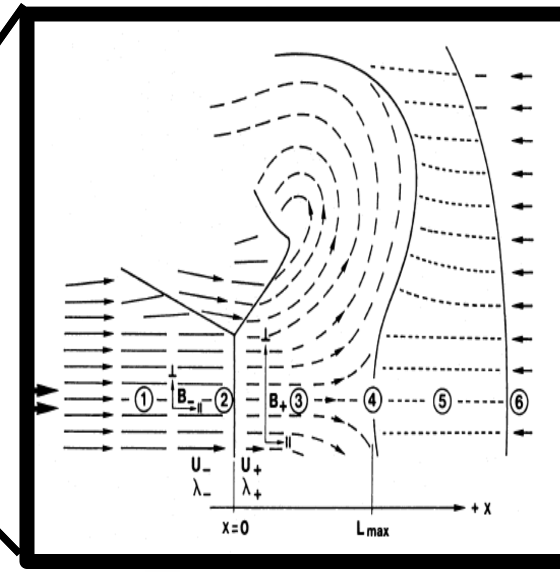


Fanaroff-Riley Class I (e.g. Cen A)

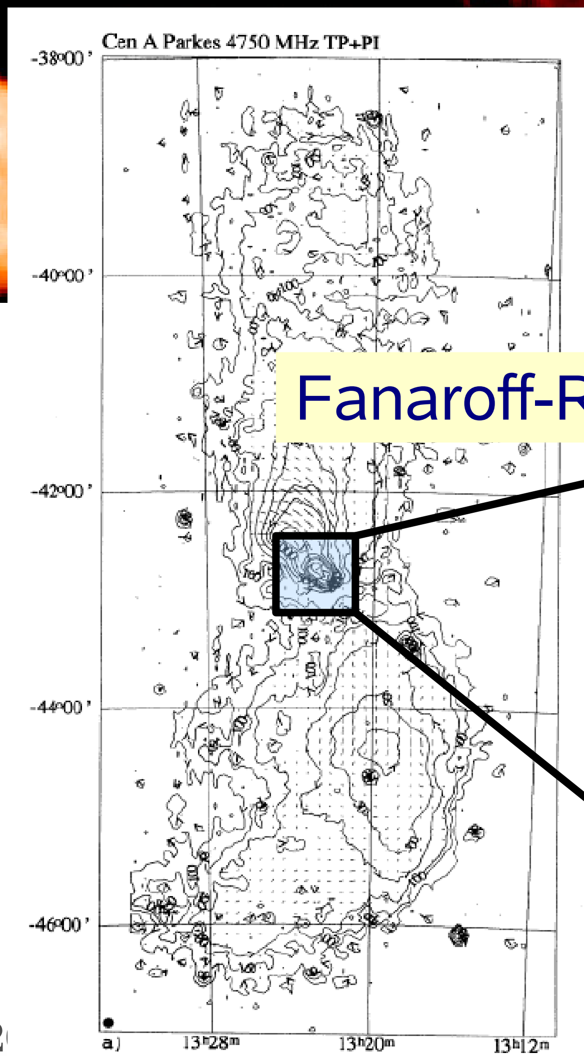


Fanaroff-Riley Class II (e.g. Cygnus A)





B ~ 0.3 mG, R ~ 1kpc, β_{sh} ~ 0.3



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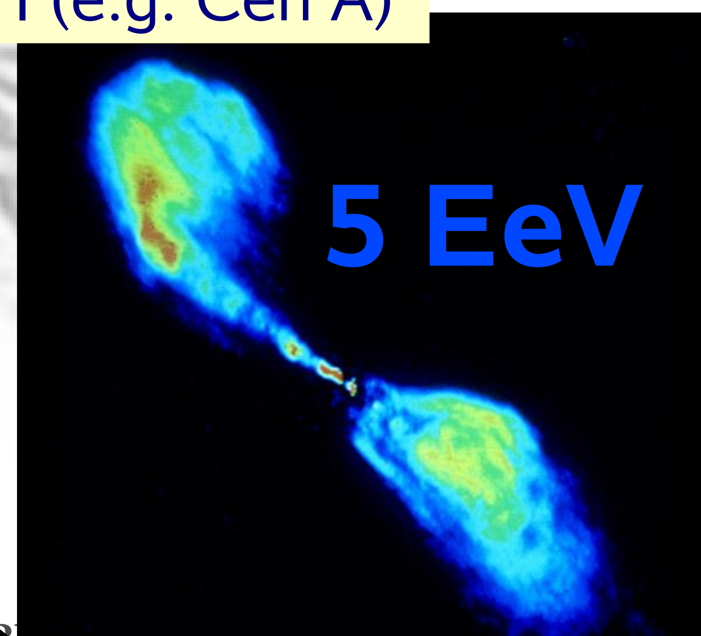
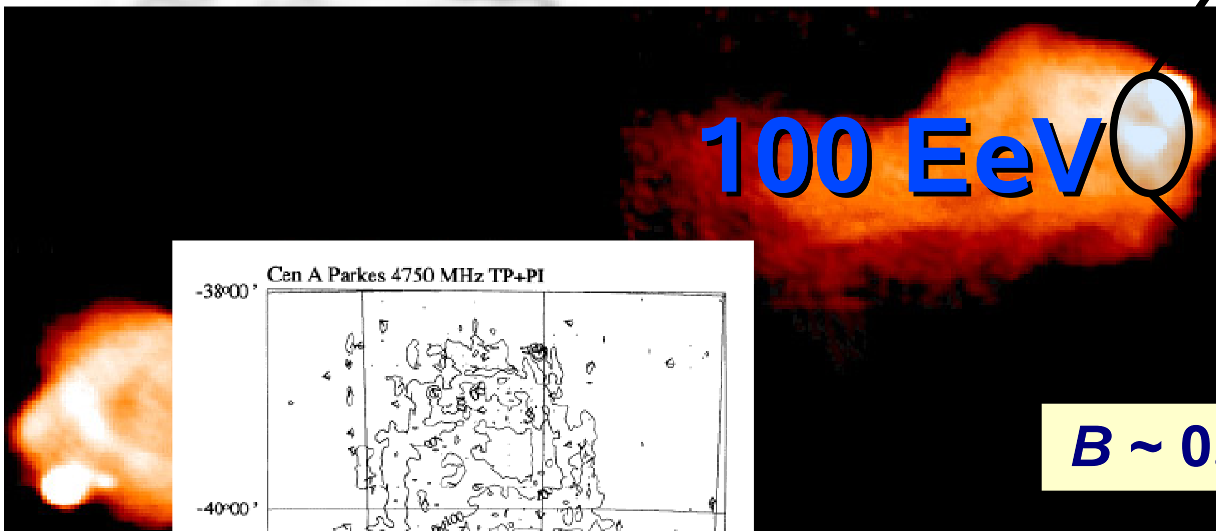
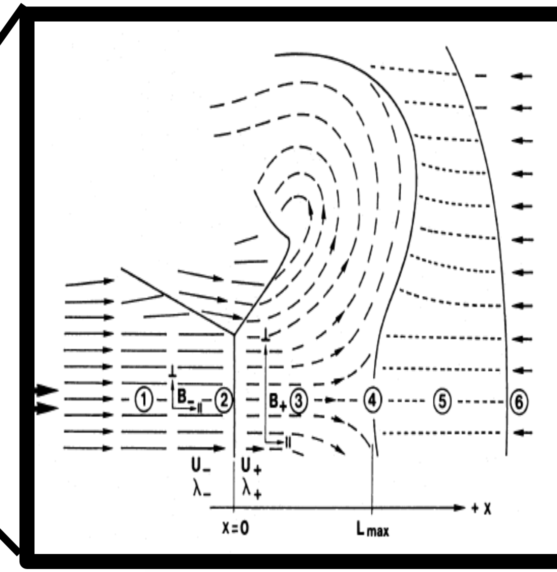


B ~ 50 μG, R ~ 1kpc, β_{sh} ~ 0.1

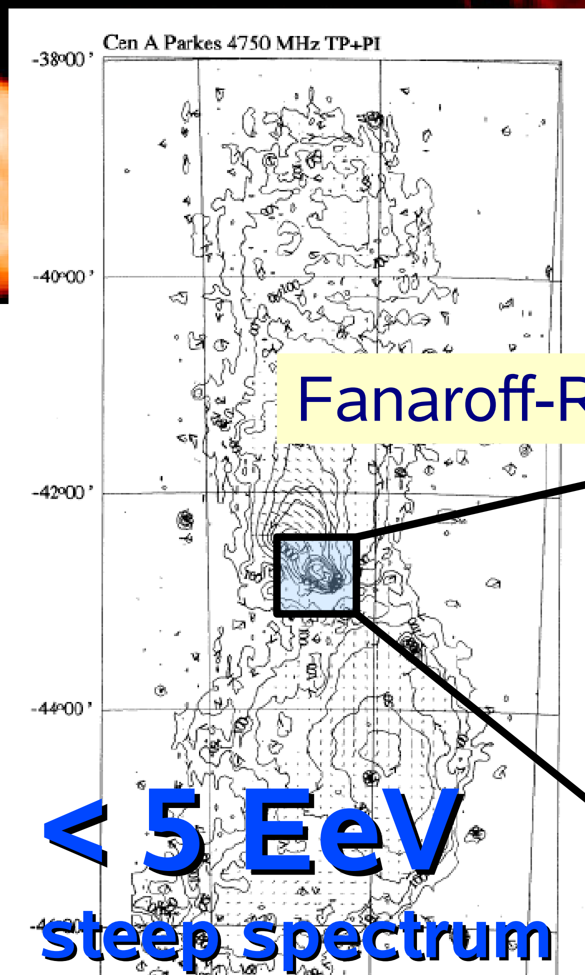
Fanaroff-Riley Class II (e.g. Cygnus A)



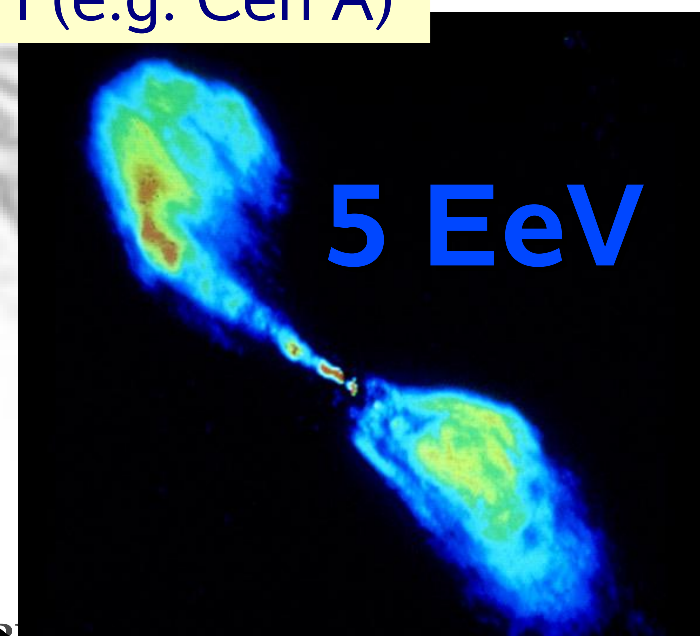
100 EeV



B ~ 0.3 mG, R ~ 1kpc, β_{sh} ~ 0.3



Fanaroff-Riley Class I (e.g. Cen A)



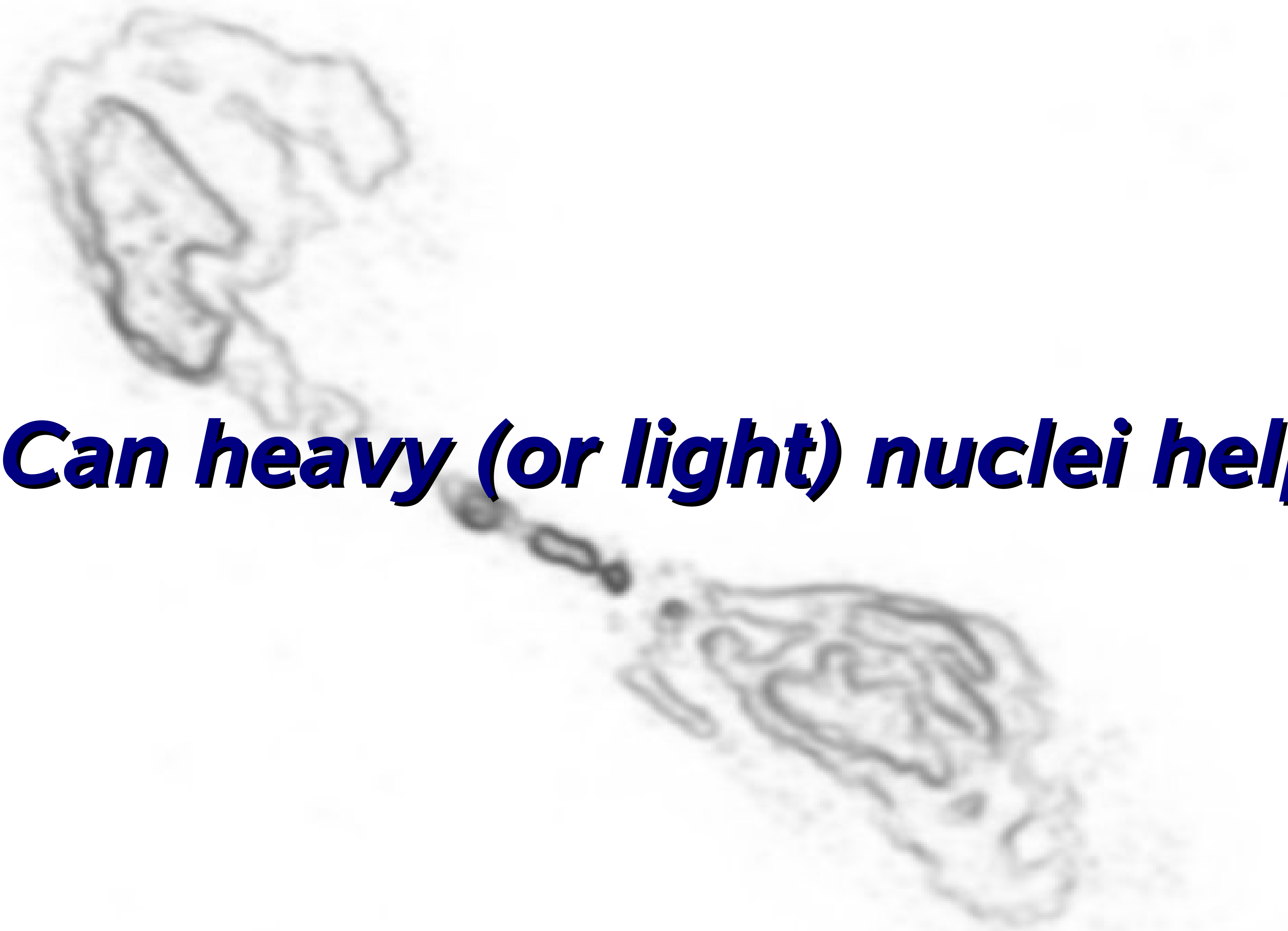
5 EeV

< 5 EeV
steep spectrum

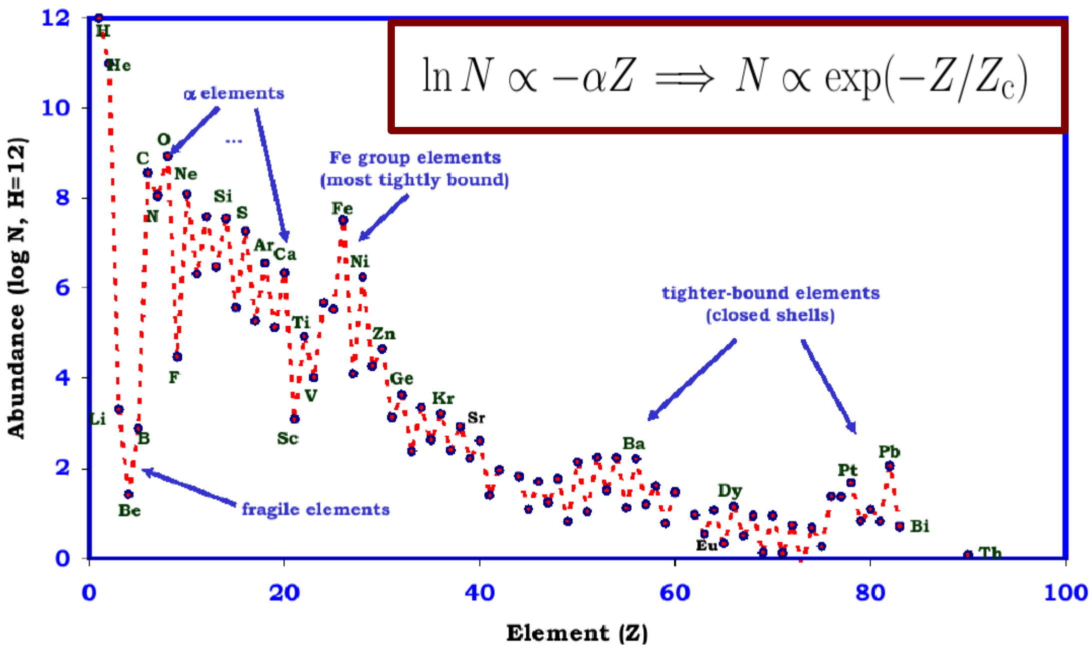
B ~ 10 μG, R ~ 30kpc, β_{alv} ~ 0.02

$\beta_{exp} \ll \beta_{alv}$: *are there shocks at all?*

B ~ 50 μG, R ~ 1kpc, β_{sh} ~ 0.1

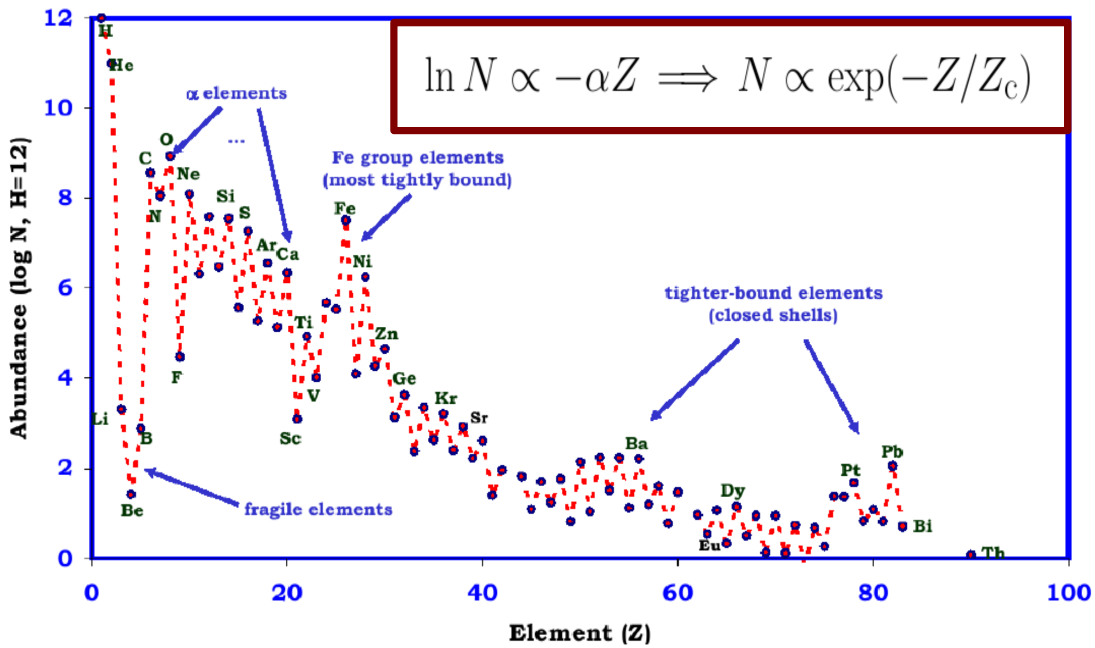


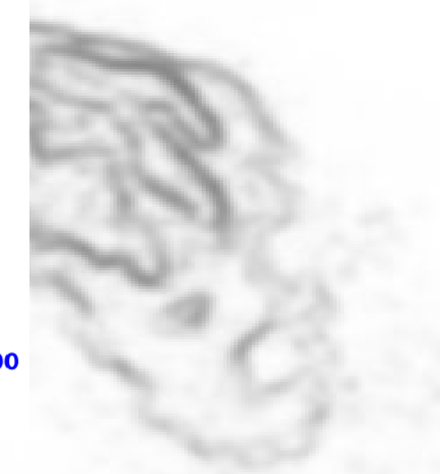
Can heavy (or light) nuclei help?


$\ln N \propto -\alpha Z \implies N \propto \exp(-Z/Z_c)$
α elements
Fe group elements
(most tightly bound)
tighter-bound elements
(closed shells)
fragile elements
Abundance (log N, H=12)
Element (Z)
H
He
Li
Be
B
C
N
O
F
Ne
Si
S
Ar
Ca
Sc
Ti
V
Fe
Ni
Zn
Ge
Kr
Sr
Ba
Eu
Dy
Pt
Pb
Bi
Th
0
2
4
6
8
10
12
0
20
40
60
80
100

$$J_{\rm src}(r,Z) \;\propto\; r^{-s}\exp\left(-\frac{r}{r_{\rm c}}\right)\exp\left(-\frac{Z}{Z_{\rm c}}\right)$$

$$J_{\rm obs}(r,Z) \;\sim\; r^{-s}M(r,z)Z^{-1}\mathcal{C}\left(-\frac{rZ}{r_{\rm c}Z_{\rm c}}\right)$$





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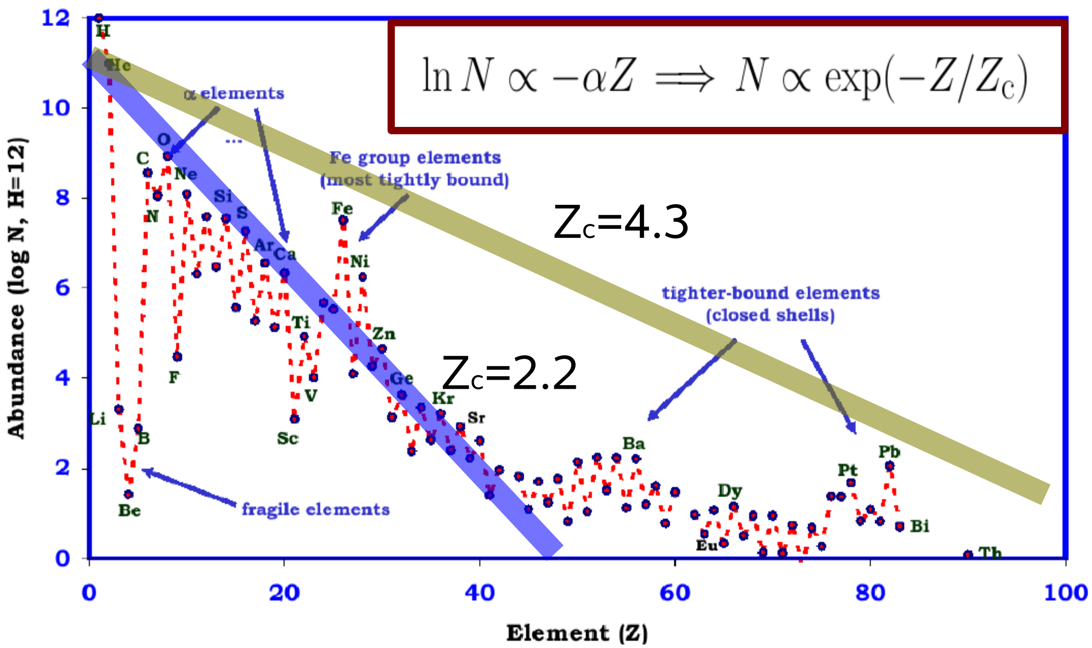

Summary on radio lobes

- **Hot spots in FR-II radio galaxies can produce UHECR at >40 EeV, but**
  - *sources are too rare (nearest FR-II at 100 Mpc)*
  - *incompatible wit Auger event distribution*
- **Lobes in FR-I radio galaxies (like Centaurus A) can produce UHECR only up to a few EeV**
  - *not enough to explain Auger events*
  - *the giant lobes do not contribute as accelerators, as there are no or only weak shocks (Kronberg et al. 2004)*
- **Inclusion of nuclei (He-Fe) with a realistic abundance distribution effectively shift the maximum energies only by a factor of ~3**
  - *not enough to save the case for FR-I lobes*

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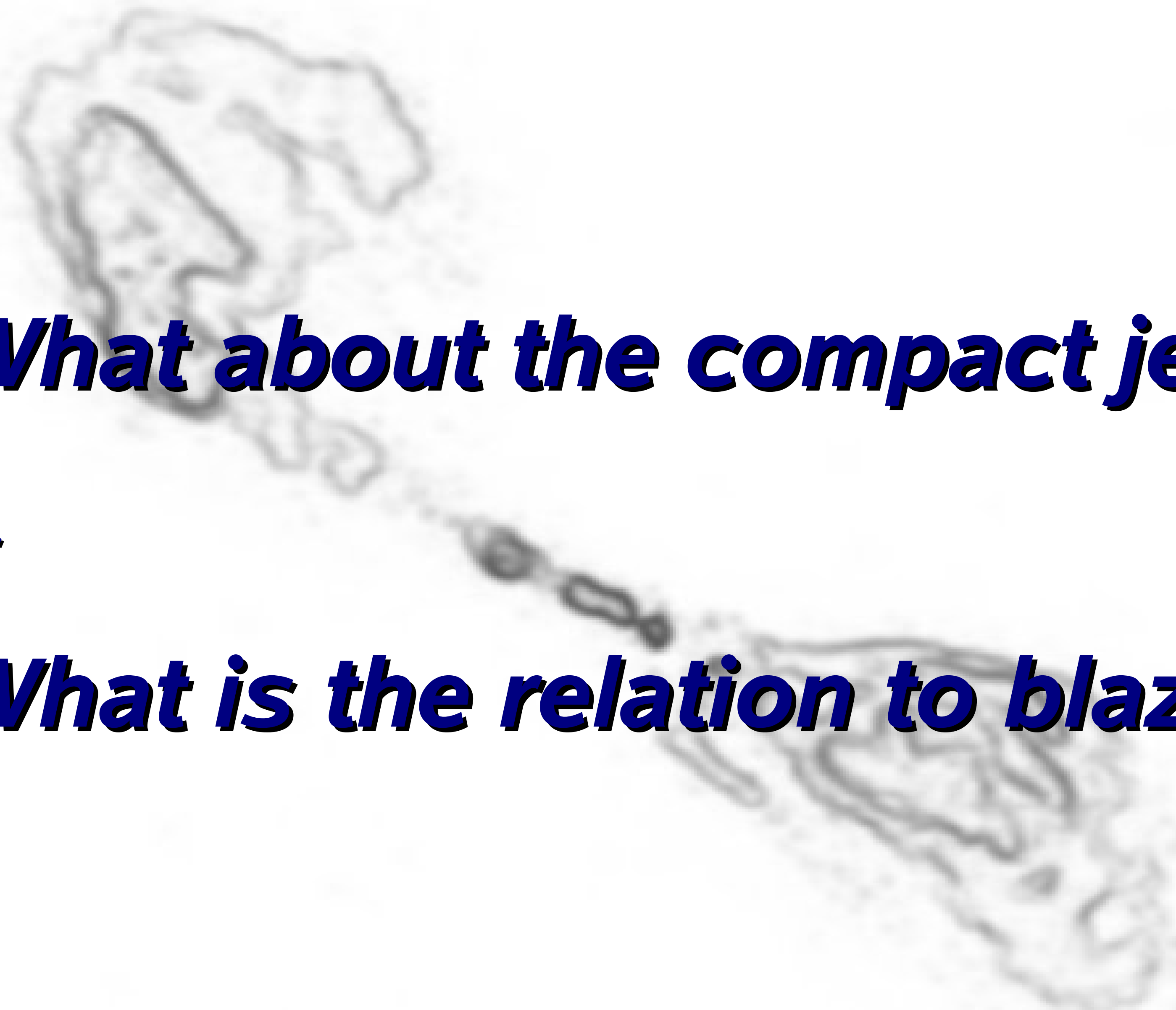
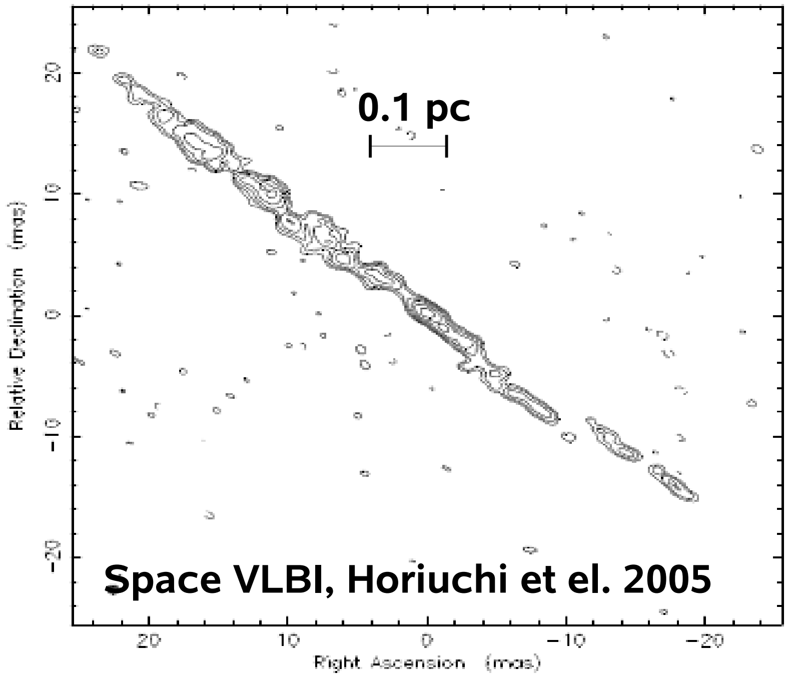


What about the compact jet?

or

What is the relation to blazars?

The „blazar“ zone of Cen A



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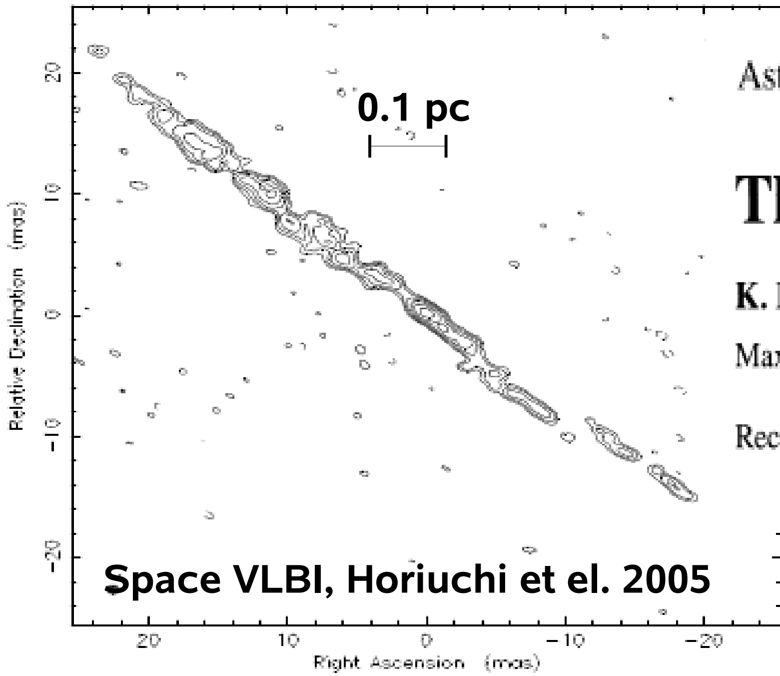
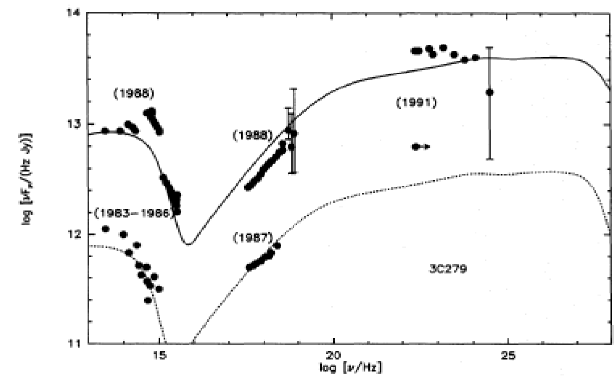


Space VLBI, Horiuchi et el. 2005

K. Mannheim:



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The proton blazar

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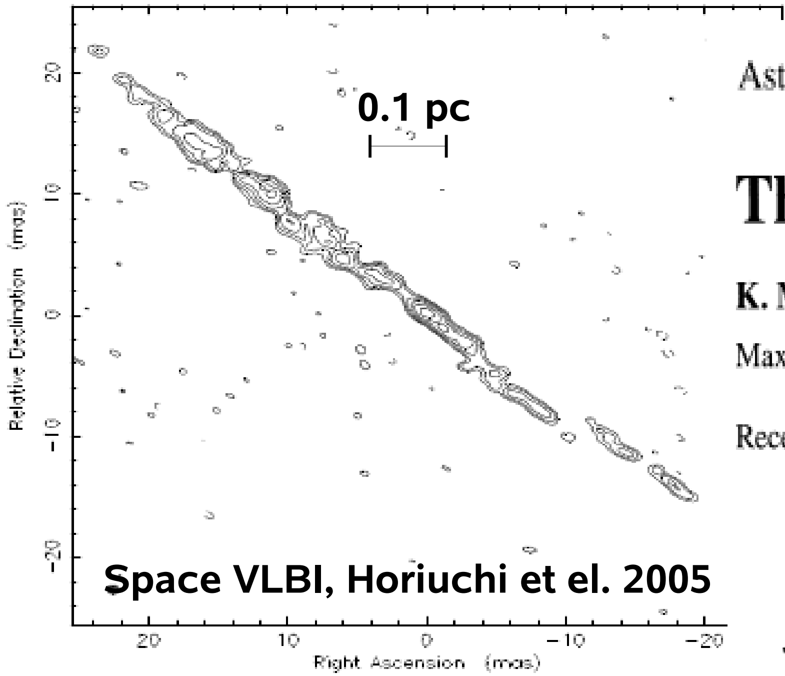
Received July 8, accepted September 8, 1992

The „blazar“ zone of Cen A



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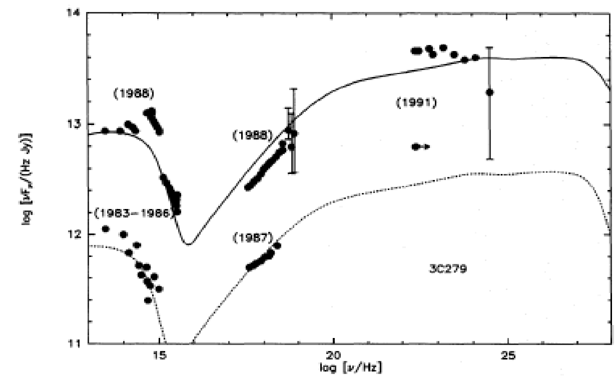

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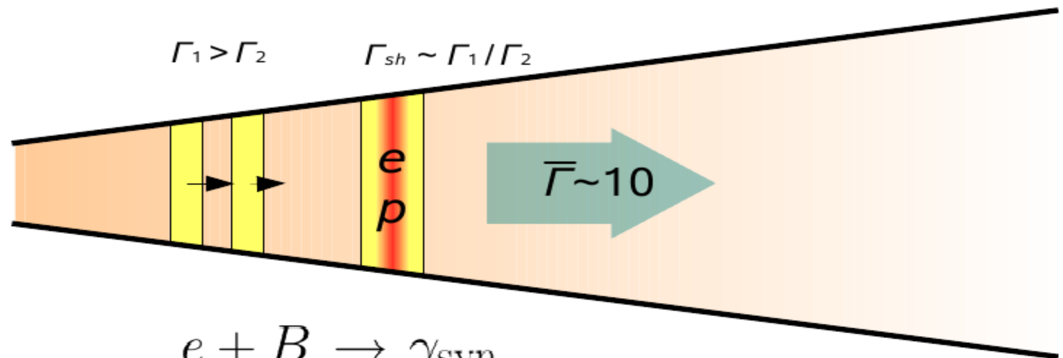
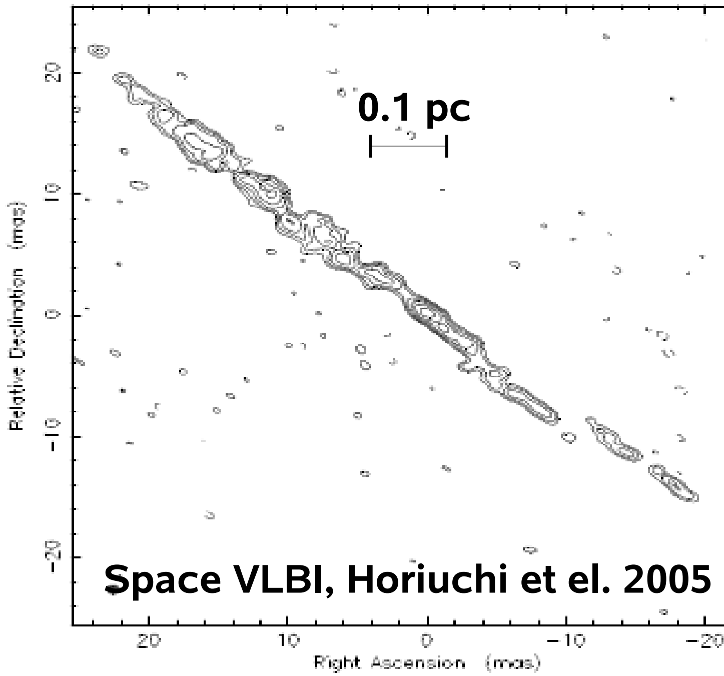


$$e + B \longrightarrow \gamma_{\rm syn}$$

$$p + \gamma_{\rm syn} \longrightarrow \begin{cases} p + \pi^0 \longrightarrow \gamma\text{-rays} \\ n + \pi^+ \longrightarrow \text{UHECR} + \nu \end{cases}$$

The „blazar“ zone of Cen A



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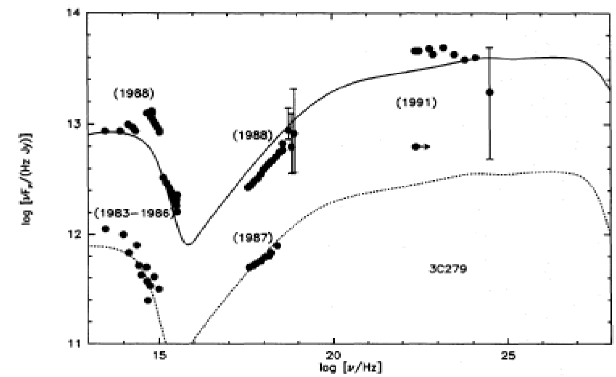
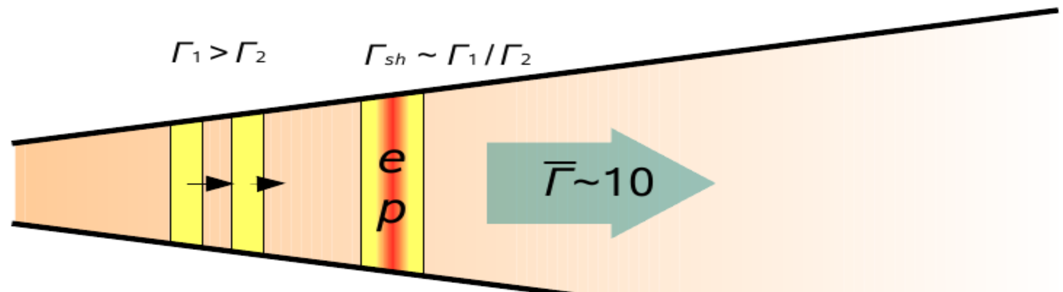
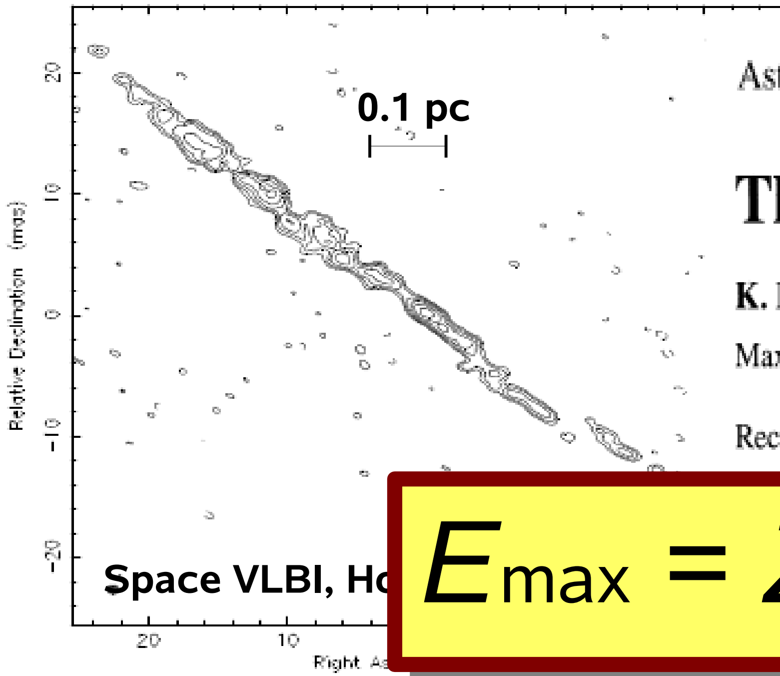




Baryonic blazar beams contain energetic photons, neutrinos and neutrons with comparable luminosities.

The „blazar“ zone of Cen A



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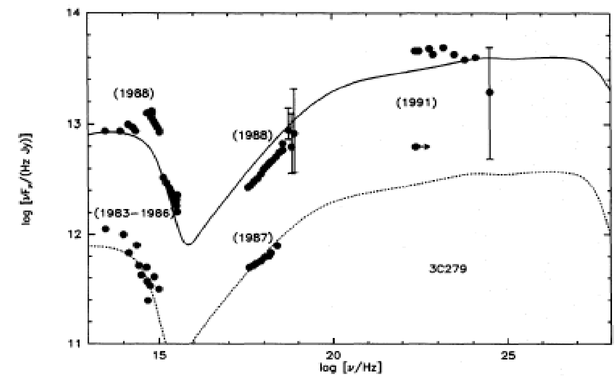
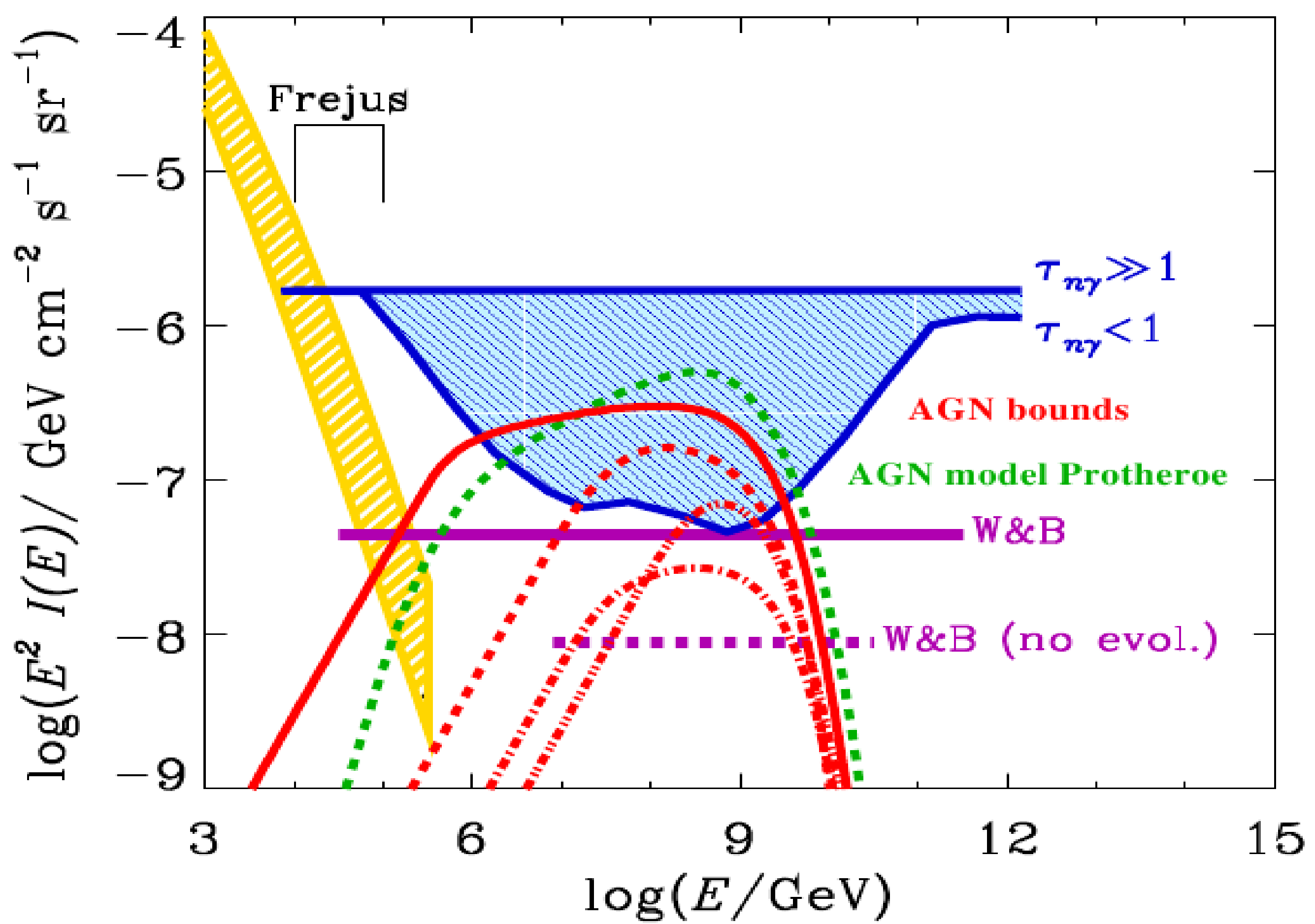


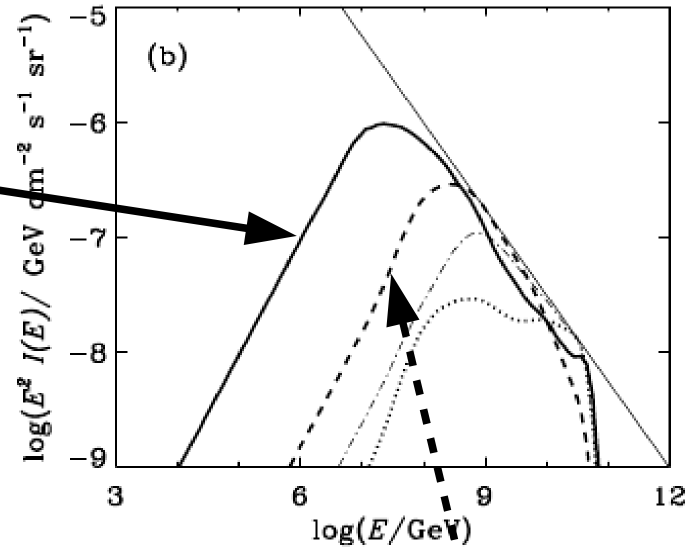
$$E_{max} = Z\, e\, B\, R\, \beta_{sh}\, \Gamma_{jet}$$

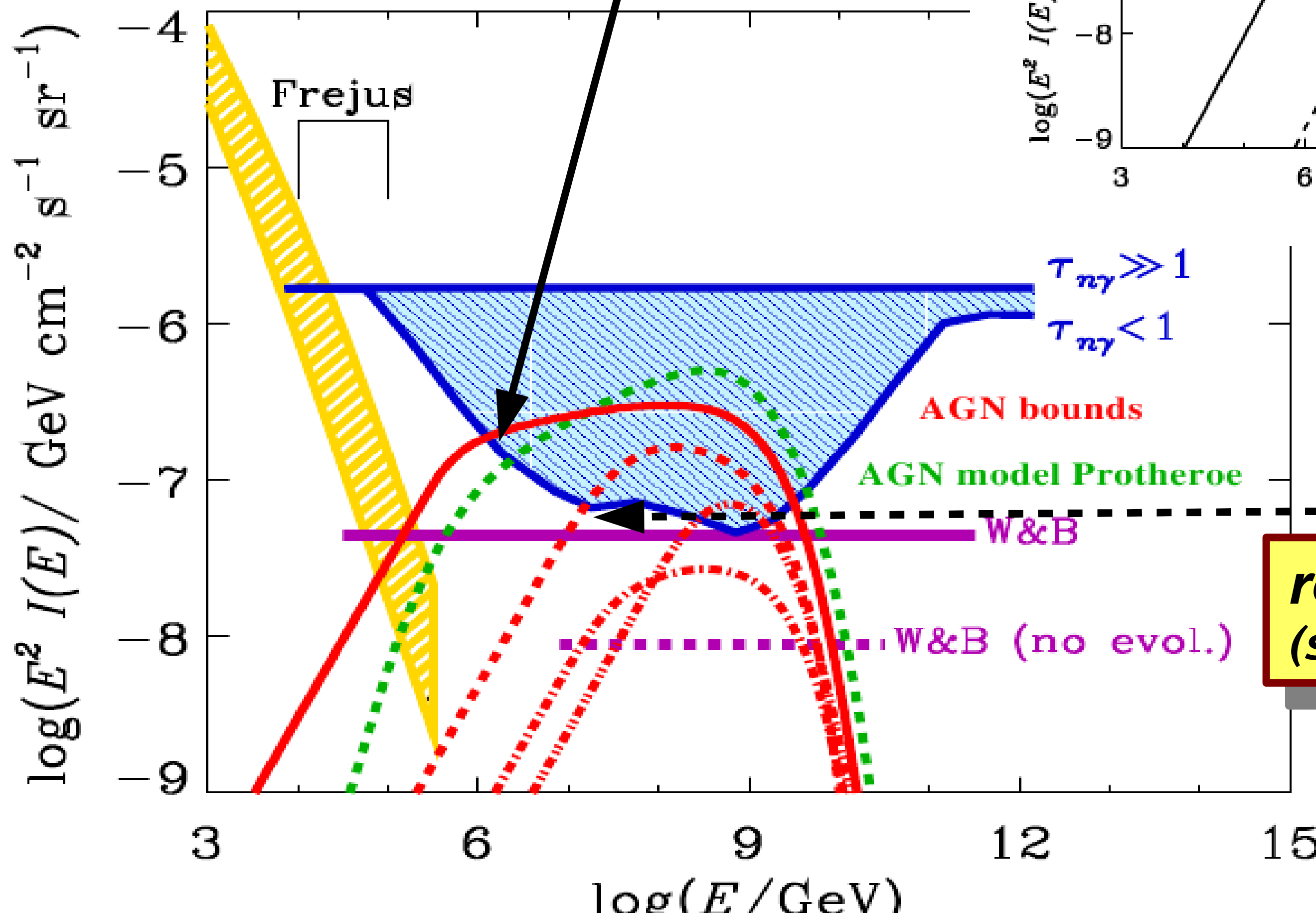
Baryonic blazar beams contain energetic photons, neutrinos and neutrons with comparable luminosities.



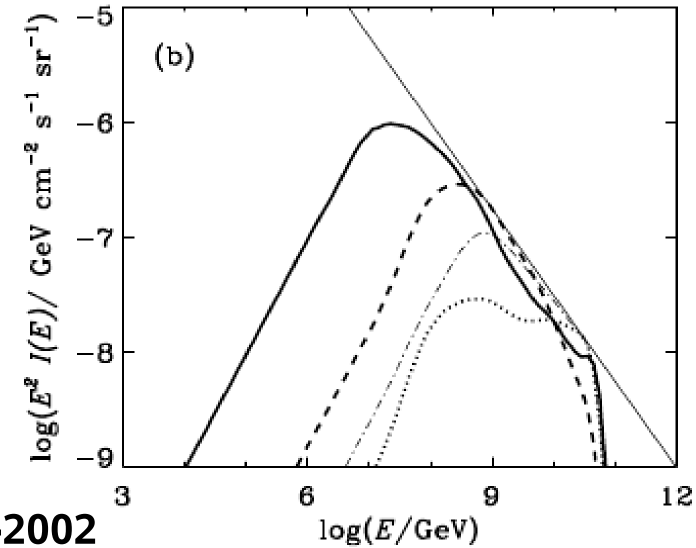
Frejus
$\tau_{n\gamma} \gg 1$
$\tau_{n\gamma} < 1$
AGN bounds
AGN model Protheroe
W&B
W&B (no evol.)
$\log(E^2\, I(E)/\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}})$
$\log(E/\mathrm{GeV})$
−4
−5
−6
−7
−8
−9
3
6
9
12
15

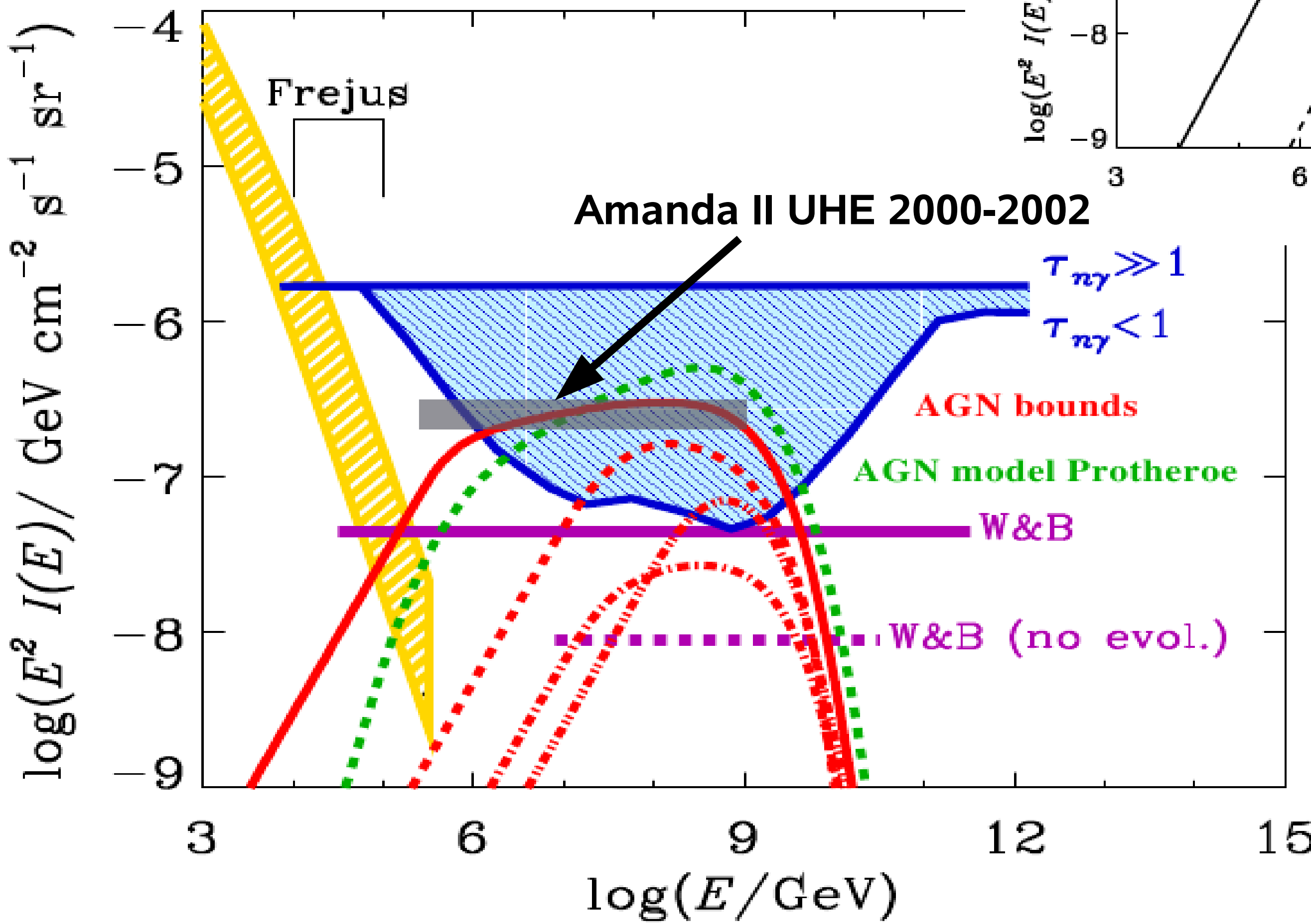
maximum model = upper bound
(produces EGRB and UHECR)





realistic AGN model
(still produces UHECR)


(b)
log(E^2 $I(E)$/ GeV cm^{-2} s^{-1} sr^{-1})
log(E/GeV)


Frejus
Amanda II UHE 2000-2002
$\tau_{n\gamma} \gg 1$
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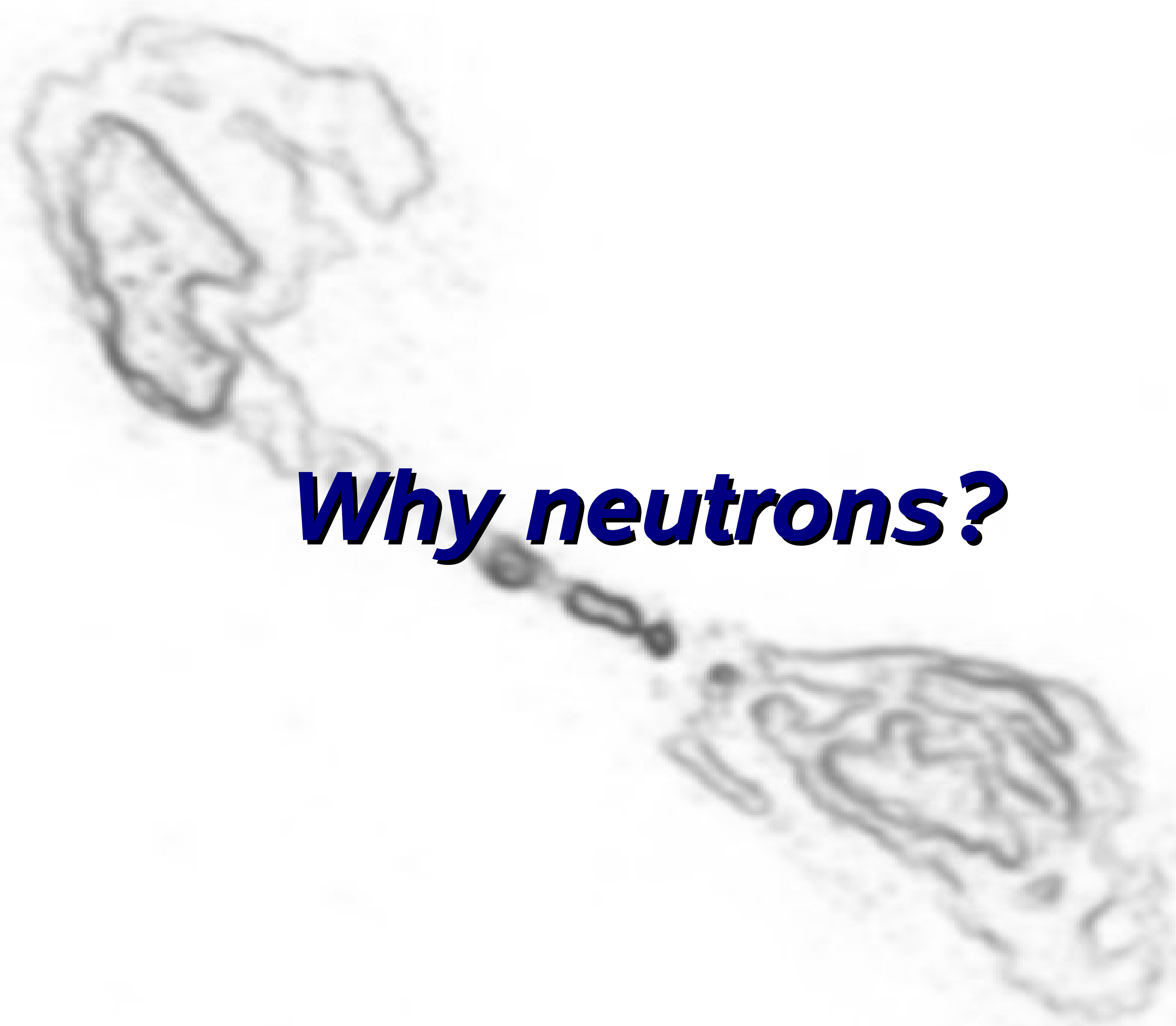
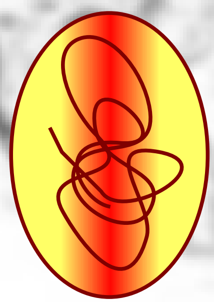
AGN bounds
AGN model Protheroe
W&B
W&B (no evol.)
log(E^2 $I(E)$/ GeV cm^{-2} s^{-1} sr^{-1})
log(E/GeV)

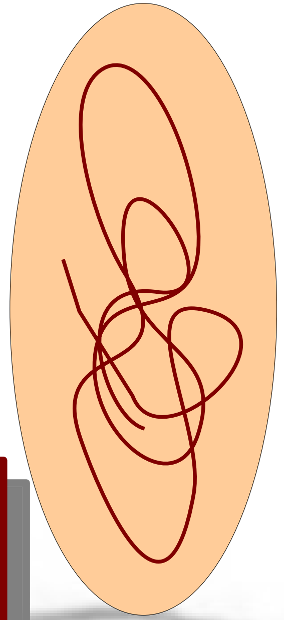


Why neutrons?

adiabatic losses (dE = -p dV)



$$E \propto R^{-1}$$

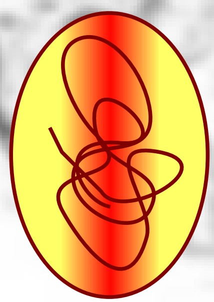


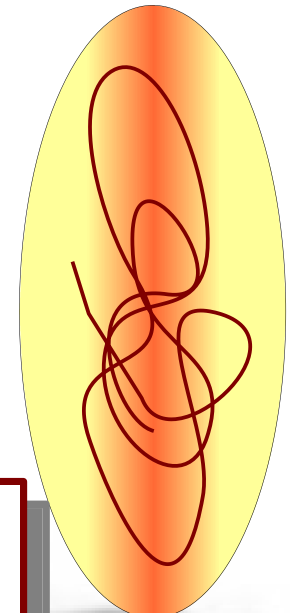
$$B \propto R^{-\alpha} \quad (1 \leq \alpha \leq 2)$$

$$E_{max} = Z\, e\, B_{esc}\, R_{acc}\, \beta_{sh}\, \Gamma_{esc}$$

expansion with continous acceleration

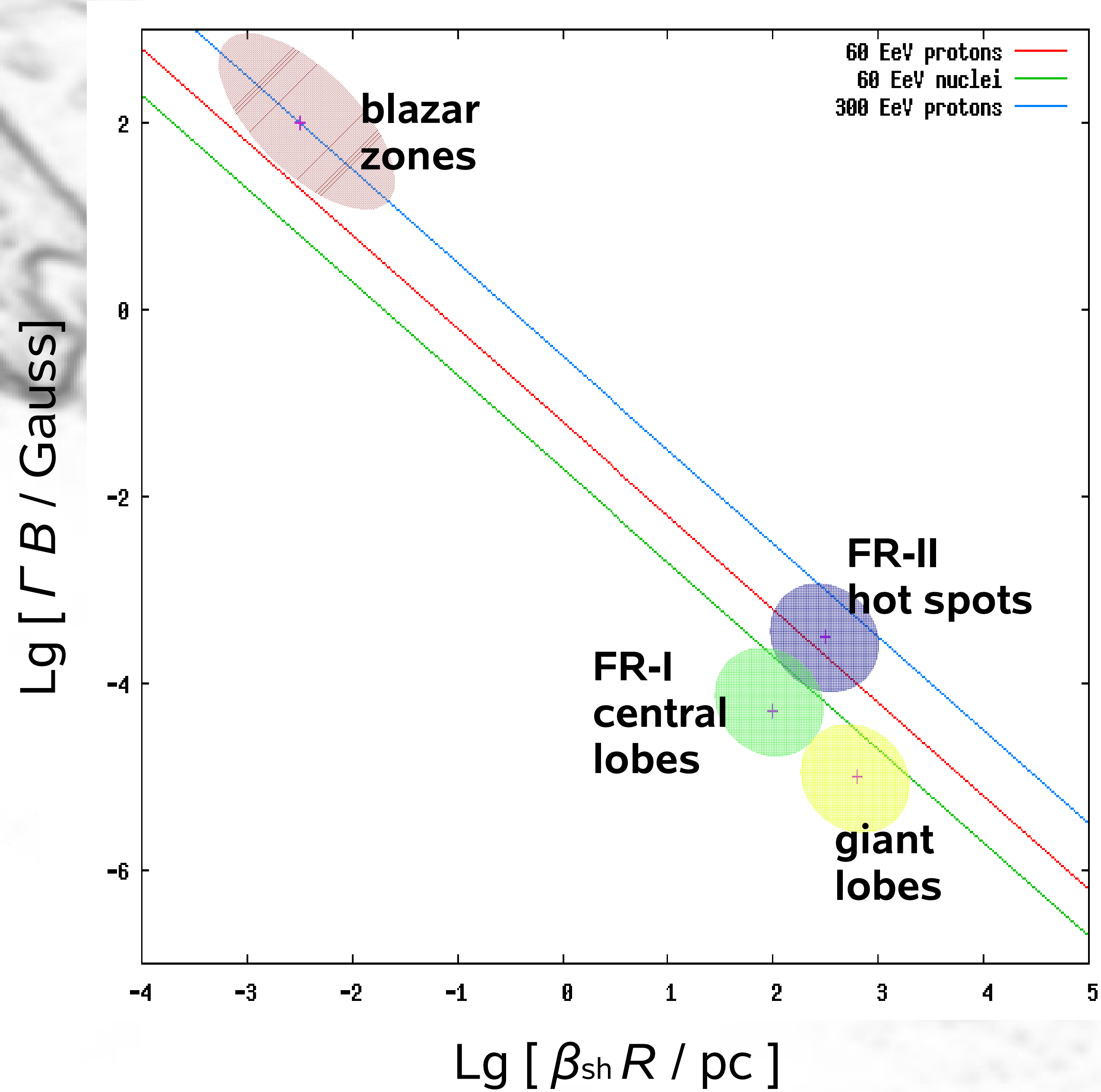
$$E \propto RB$$

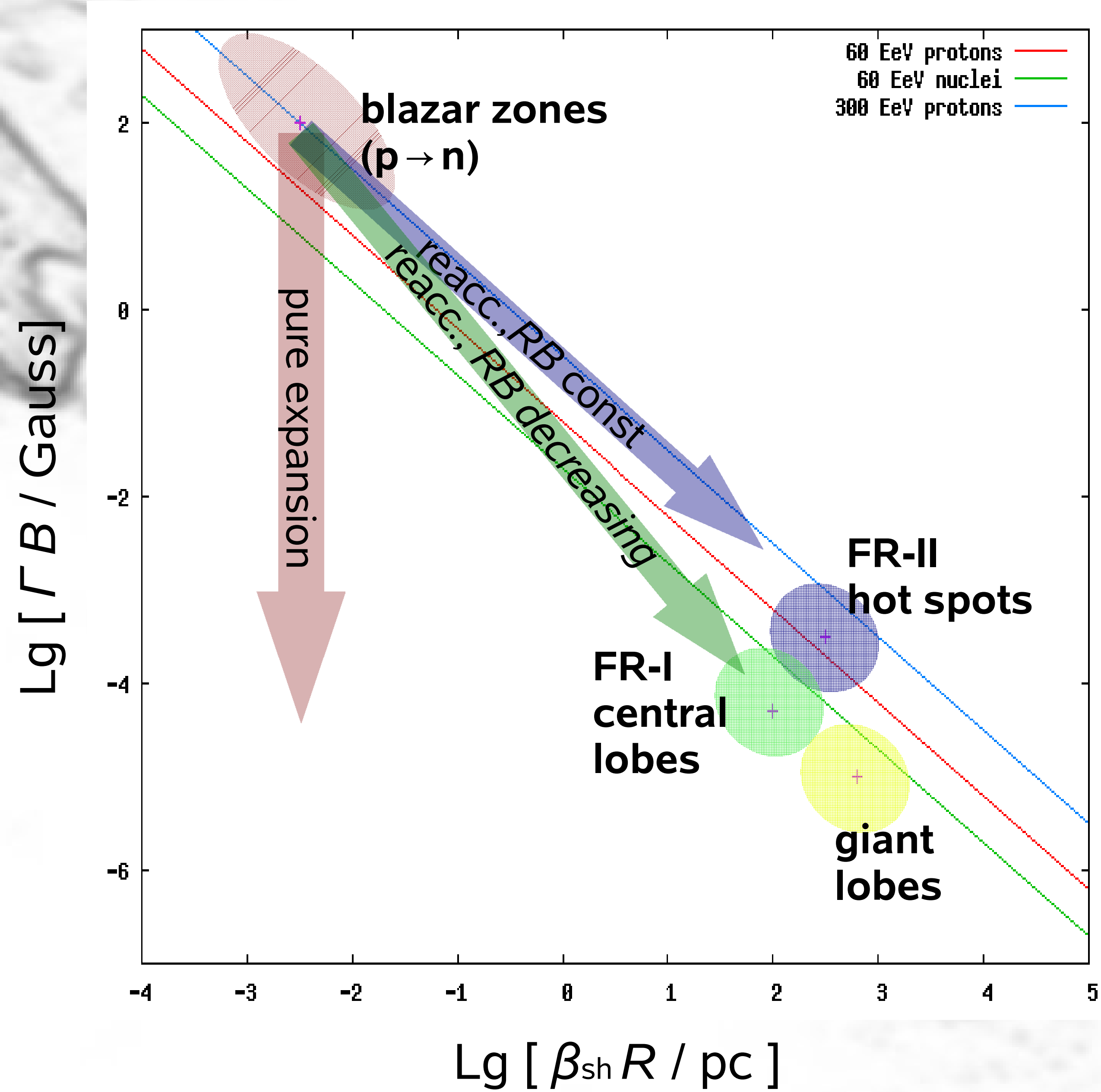


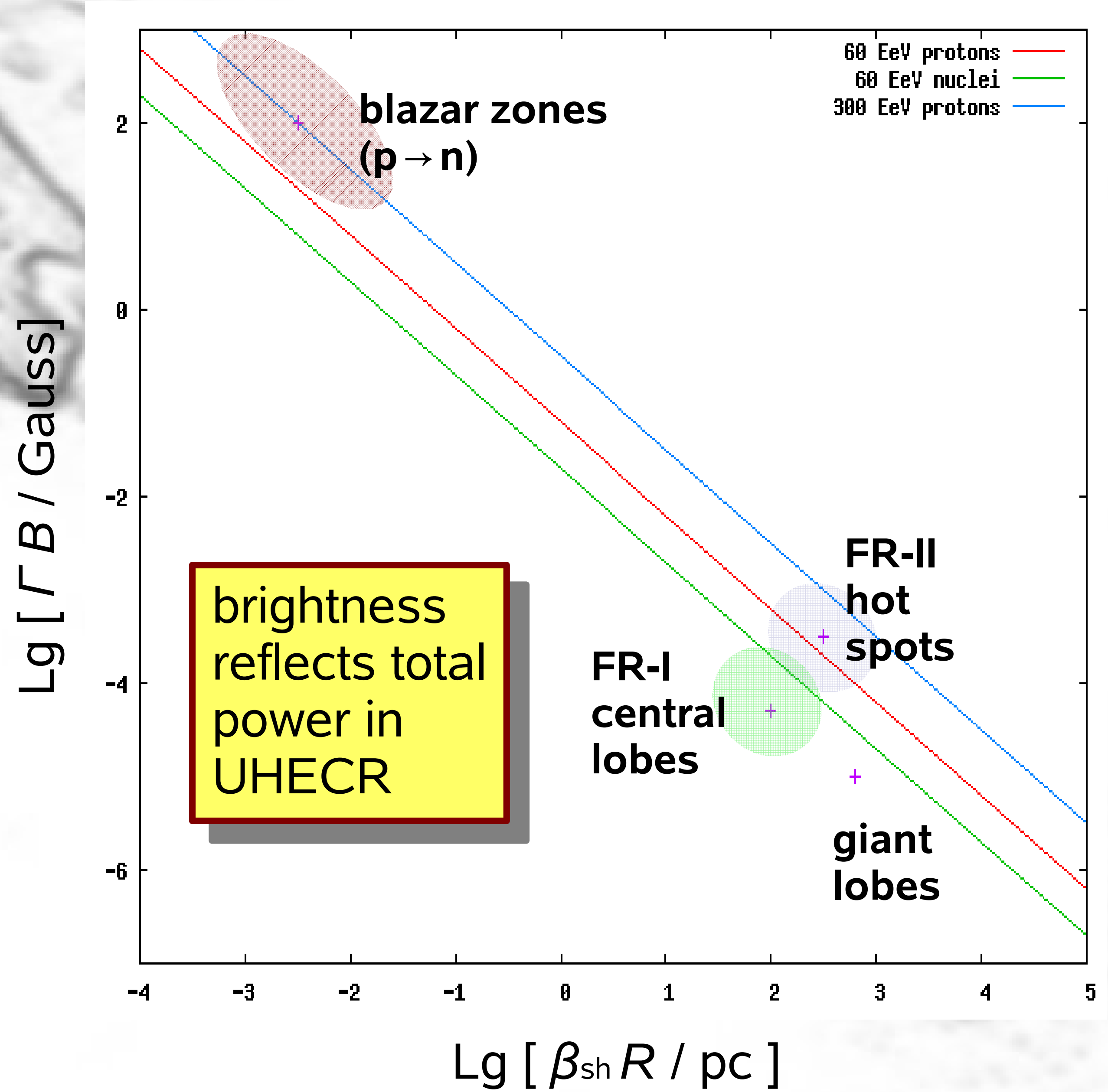


$$B \propto R^{-\alpha} \quad (1 \leq \alpha \leq 2)$$

$$E_{max} = Z\, e\, B_{esc}\, R_{esc}\, \beta_{sh}\, \Gamma_{esc}$$


60 EeV protons
60 EeV nuclei
300 EeV protons
blazar zones
FR-II hot spots
FR-I central lobes
giant lobes
Lg [Γ B / Gauss]
Lg [βsh R / pc]
2
0
-2
-4
-6
-4
-3
-2
-1
0
1
2
3
4
5


60 EeV protons
60 EeV nuclei
300 EeV protons
blazar zones
(p → n)
reacc.,RB const
reacc., RB decreasing
pure expansion
FR-II
hot spots
FR-I
central
lobes
giant
lobes
Lg [Γ B / Gauss]
Lg [βsh R / pc]
2
0
-2
-4
-6
-4
-3
-2
-1
0
1
2
3
4
5


60 EeV protons
60 EeV nuclei
300 EeV protons
blazar zones
(p → n)
FR-II
hot
spots
FR-I
central
lobes
giant
lobes
brightness reflects total power in UHECR
Lg [Γ B / Gauss]
Lg [βsh R / pc]
2
0
-2
-4
-6
-4
-3
-2
-1
0
1
2
3
4
5

Summary on compact jets

- **If the gamma ray emission of blazars is of hadronic origin, blazars are the most favoured sources of UHECR**
  - *can easily reach energies of > 300 EeV even for protons, due to (mildly) relativistic shocks and relativistic beaming*
  - *The same physics applies all FR-I radio galaxies (like Centaurus A)., i.e. sources are numerous and there is plenty of power*
- **Cosmic rays escape from blazars in collimated neutron beams**
  - *transport of protons to larger scales suffers from adiabatic losses*
  - *UHECR nuclei are supressed by photodisintegration in the source and by adiabatic losses*
  - *model makes predictions for diffuse neutrino flux*

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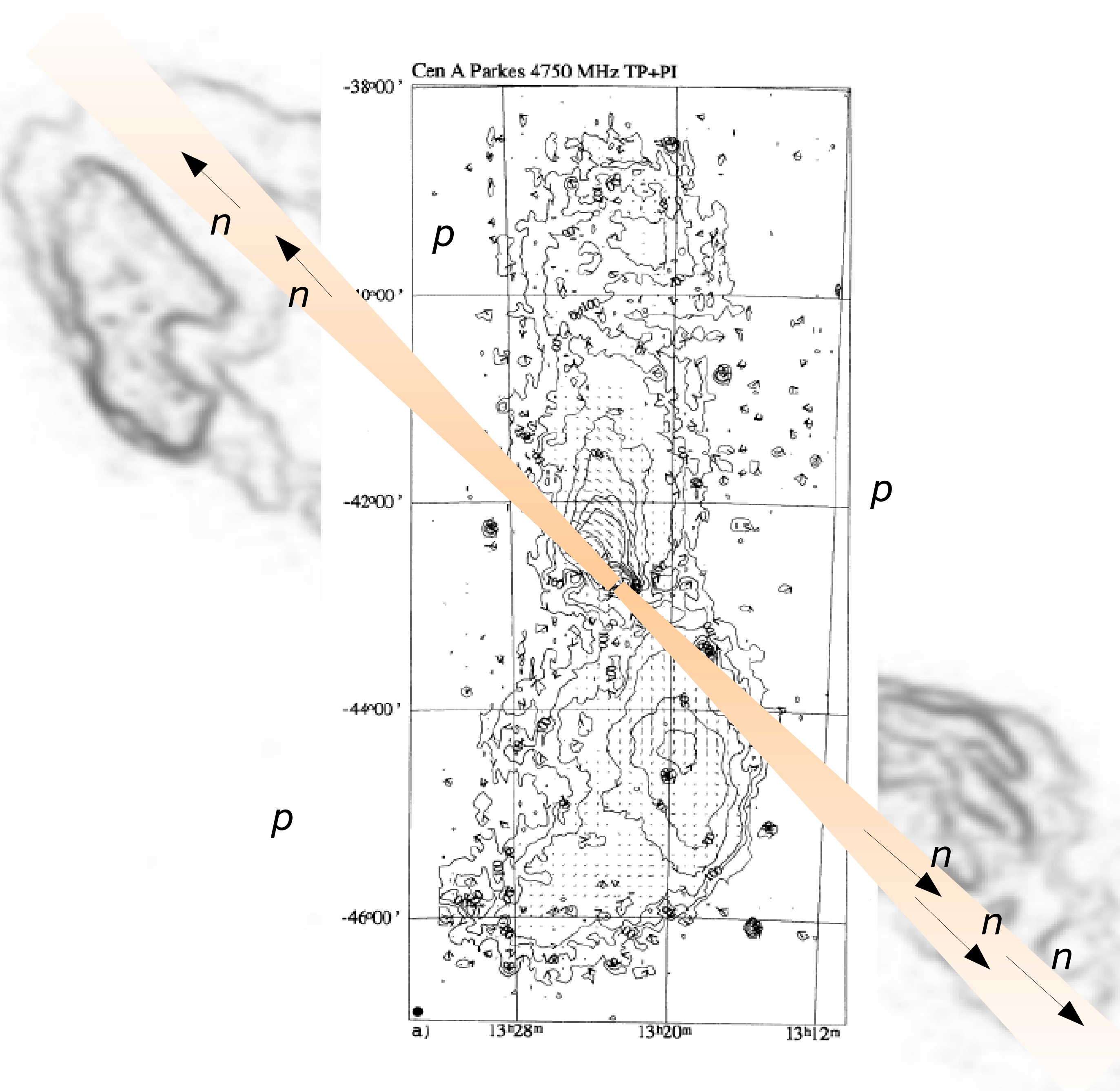
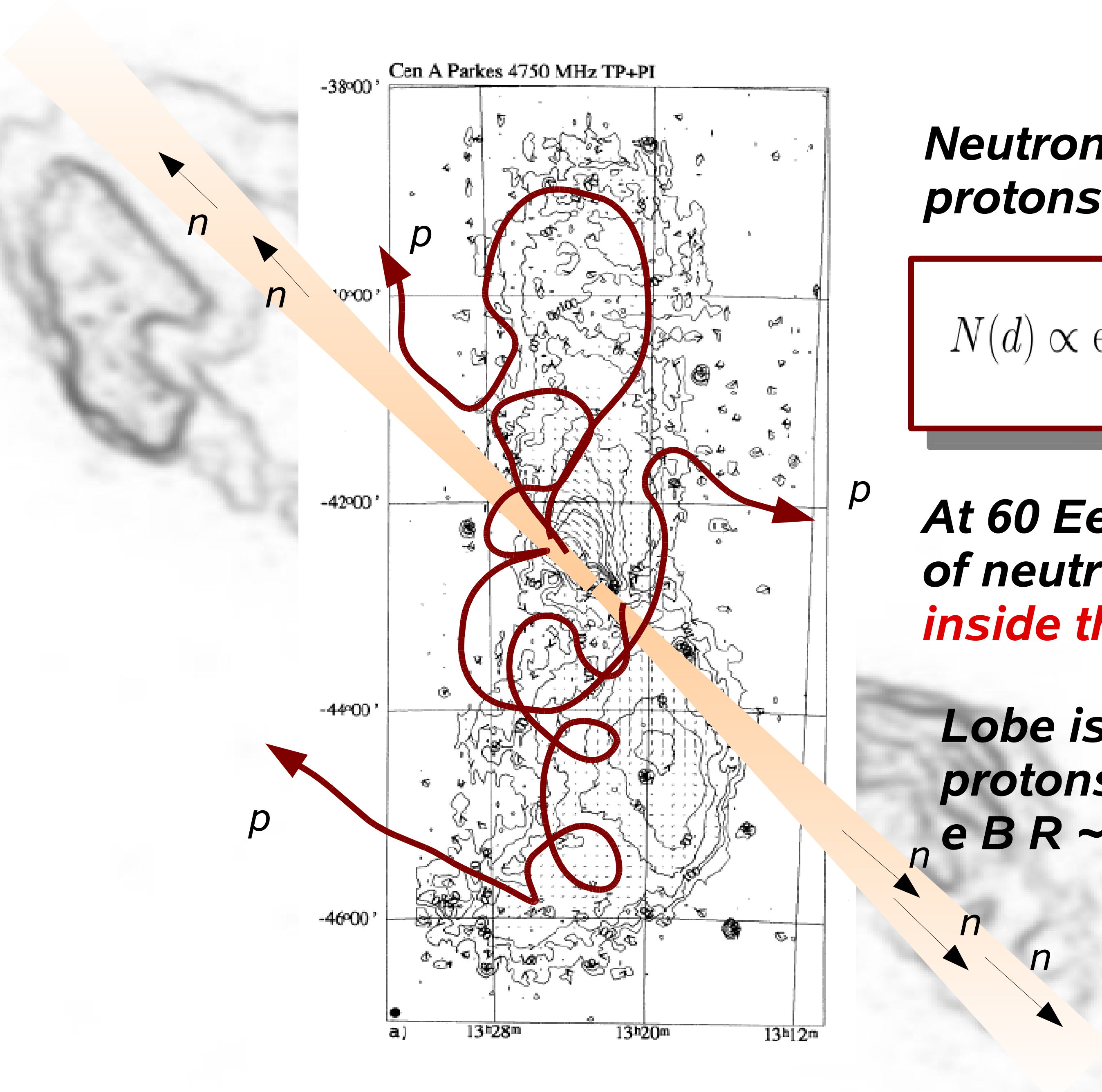

Cen A Parkes 4750 MHz TP+PI
-38°00'
-40°00'
-42°00'
-44°00'
-46°00'
a)
13h28m
13h20m
13h12m
p
p
p
n
n
n
n
n



Neutrons decay to protons following:

$$N(d) \propto \exp\left(-\frac{d}{c\tau(E)}\right)$$

At 60 EeV, ~15% of neutrons decay *inside the lobe*

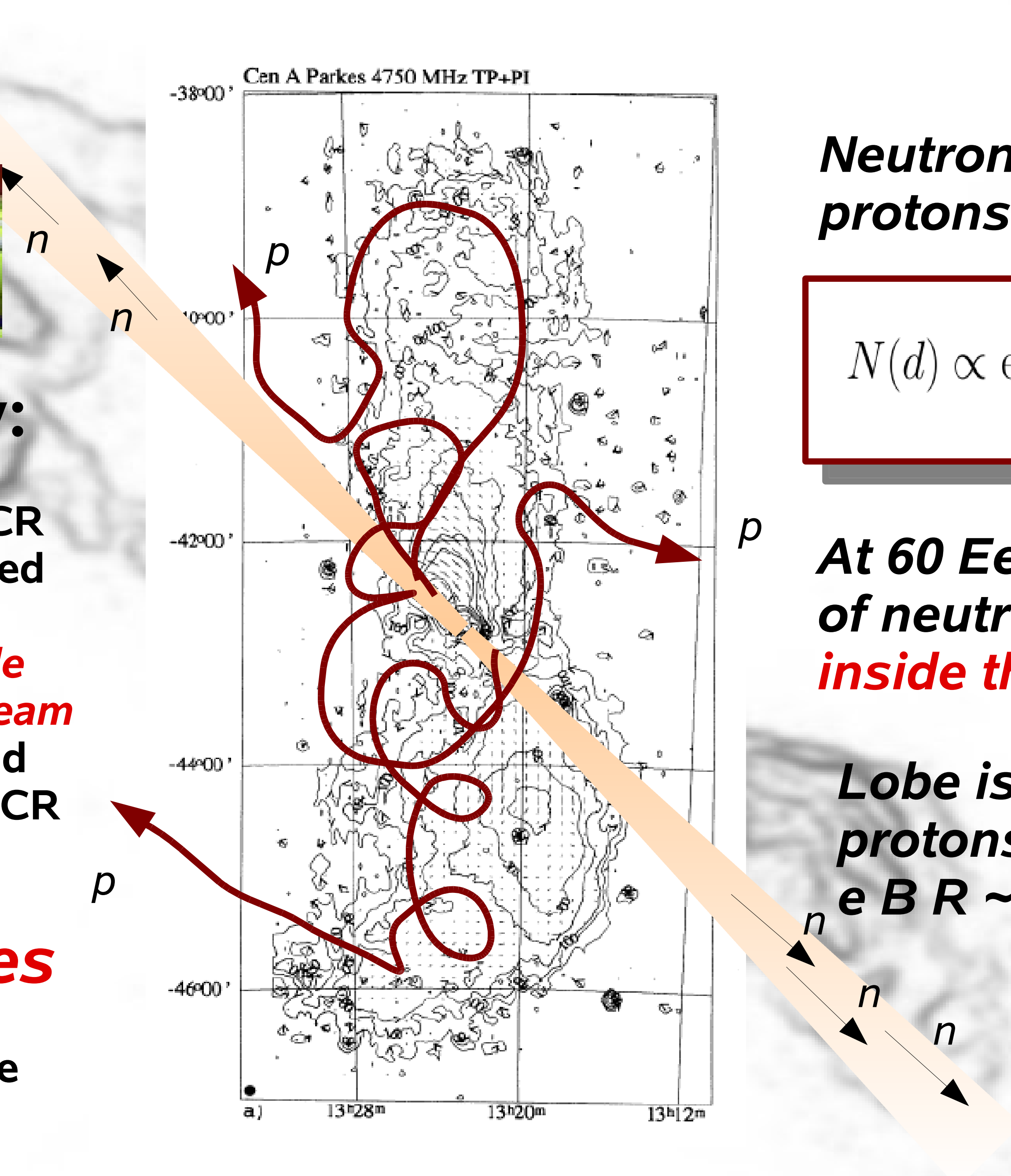
Lobe isotropises protons up to e B R ~ 100 EeV

Corollary:

An alien UHECR detector located at 3.4 Mpc distance *inside the neutron beam* of Cen A would receive a UHECR flux

1000 times

higher than we do!



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Summary of questions:

- *Is there a correlation of arrival directions with predictions for radio loud AGN (considering source power, orientation, possible deflection by other objects, realistic models for cosmic magnetic fields….)?*
- *Is the composition of cosmic rays up to 100 EeV consistent with (almost) pure proton composition?*
- *Is there a diffuse neutrino flux around 1 EeV about a factor of 3 above the Waxman-Bahcall bound (with evolution)?*
- *Is there a way to really distinguish hadronic and inverse Compton gamma ray emssion from blazars in simultaneous multifrequency observation campains?*