Gamma ray signatures of UHECR sources

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DIAS, Dublin

MARIE CURIE ACTIONS

Overview of the talk

(1) CR spectrum extends up to extreme energies → $> 10^{20}$ eV

which are the sources of UHECRs? can we do CR astronomy?

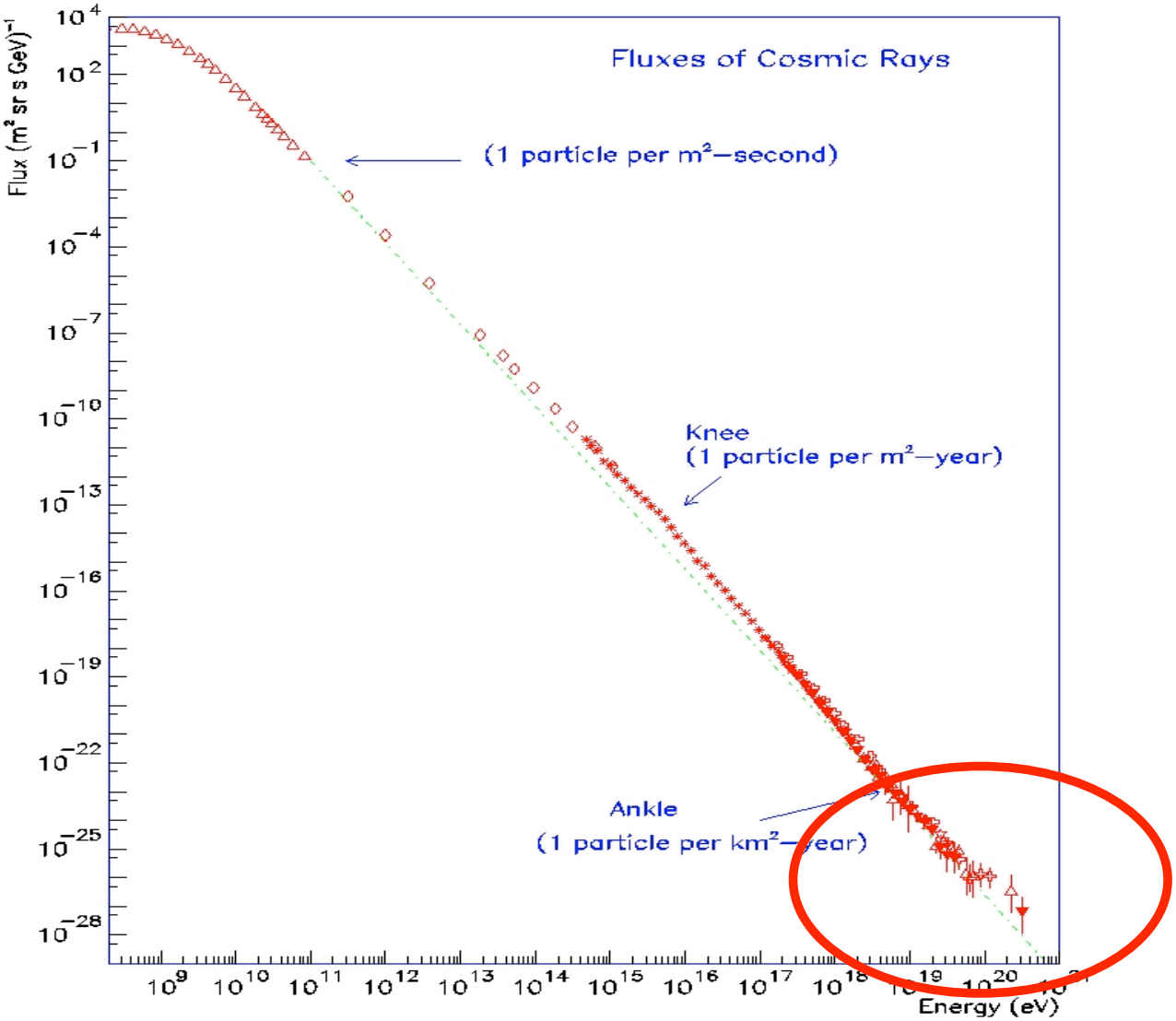
(2) UHECRs need to be accelerated… (generalized Hillas criterium)

if acceleration limited by radiative losses → **GAMMA RAYS**

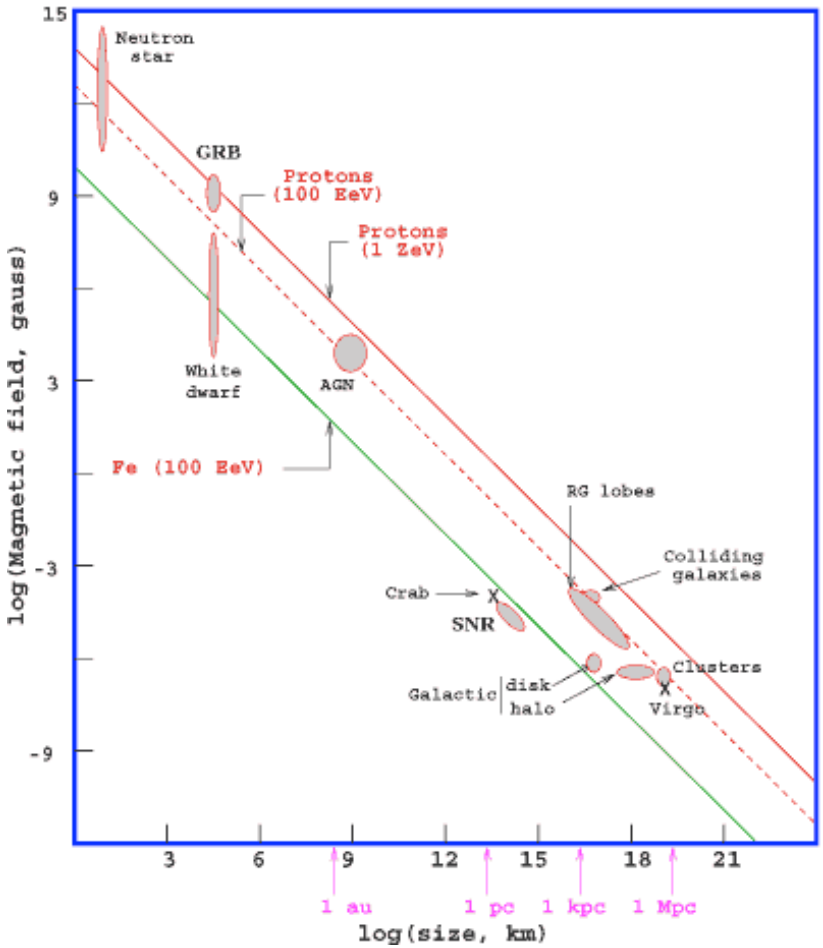
(3) …and have to propagate to the observer

GZK suppression → **GAMMA RAYS (unavoidable!)**

Which are the sources of UHECRs?



Who is accelerating UHECRs?
The Hillas plot



adapted from Hillas (1984)

In order to be accelerated, particles have to be confined in the accelerator

$$2\ R_L(E,B) < L_{acc}$$

$$B(G)L_{acc}(pc) > \frac{0.2}{Z}\left(\frac{E}{10^{20}eV}\right)$$

This is a necessary, but not sufficient condition!
One should consider energy losses!

Both during the acceleration (Aharonian et al., 2002) and the escape from the source (Norman, Melrose & Achterberg, 1995)

In many cases, acceleration of UHECRs MUST be accompained by radiation!

Aharonian et al, 2002; Derishev et al, 2003; Neronov et al, 2005

If you want to accelerate particles you need strong EM field

→ radiative losses may become important

→ radiation is expected to show up at gamma ray energies

BUT…

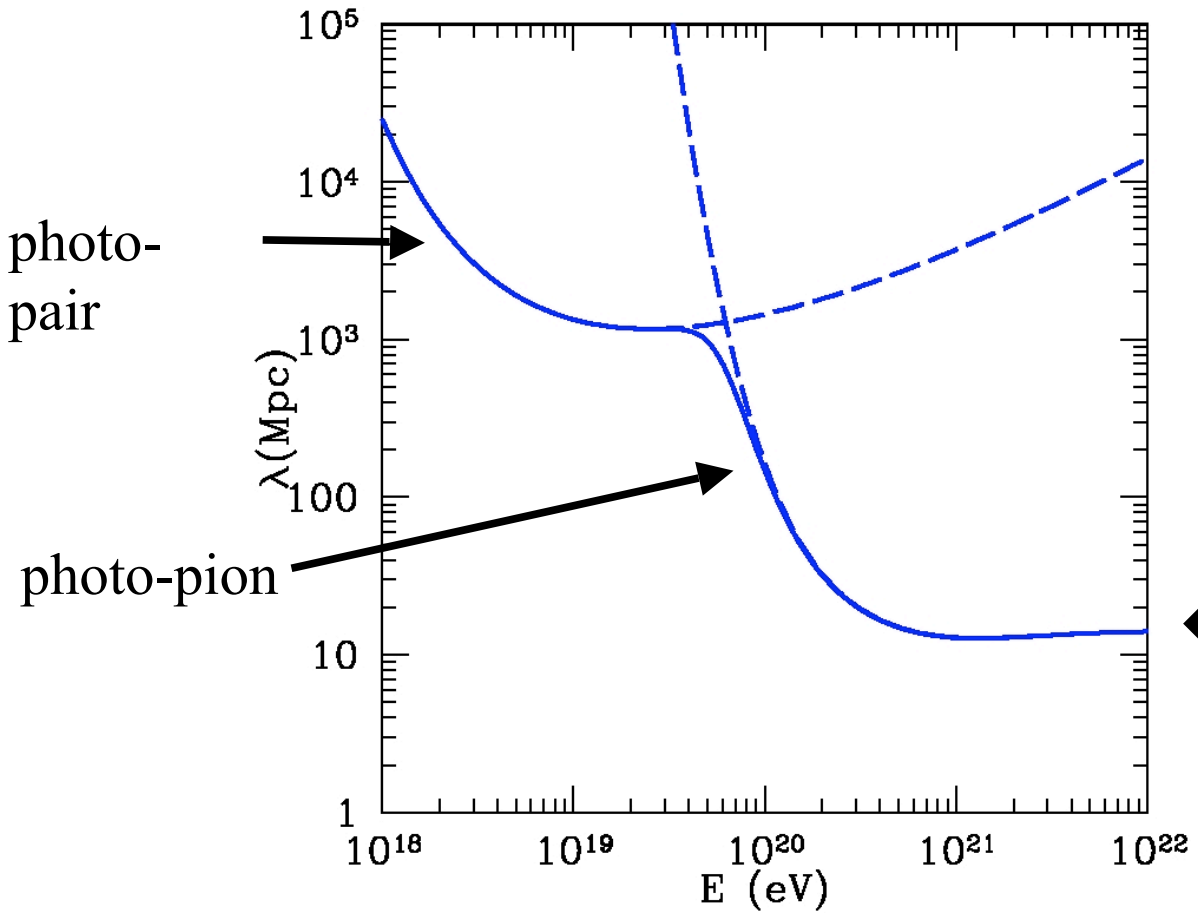
1) Is acceleration limited by energy losses or escape?
2) Which EM energy loss? (synchrotron, curvature…)
3) Are there strong radiation fields within the accelerator? (p-gamma losses)

Need for more detailed studies

Acceleration is not enough: propagation

Two main processes: photo-pion production $p + \gamma_{CMB} \rightarrow p + \pi^0 + \pi^{\pm}$

photo-pair production $p + \gamma_{CMB} \rightarrow p + e^+ + e^-$

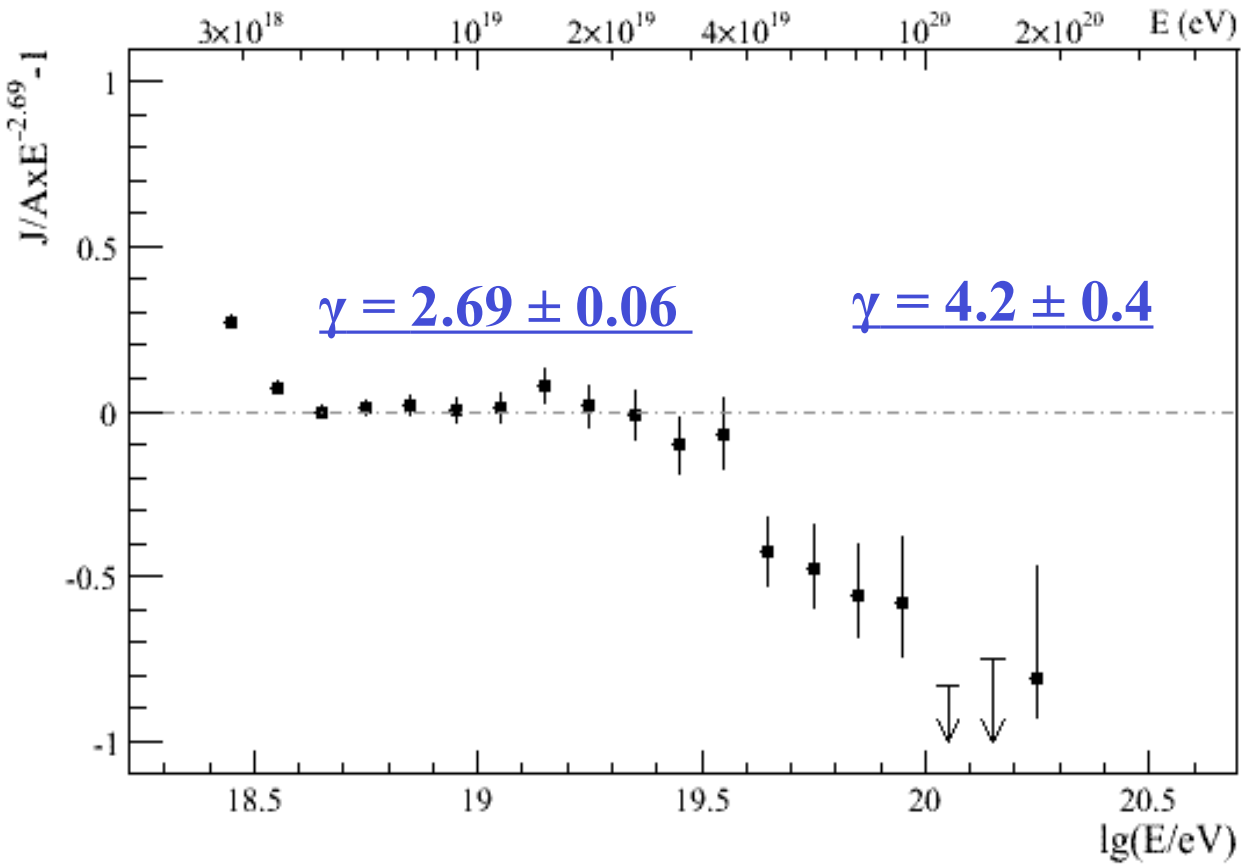


If sources are distributed homogeneously in the Universe we do expect a strong suppression in the CR spectrum at ~10^{20}eV

← 10÷20 Mpc

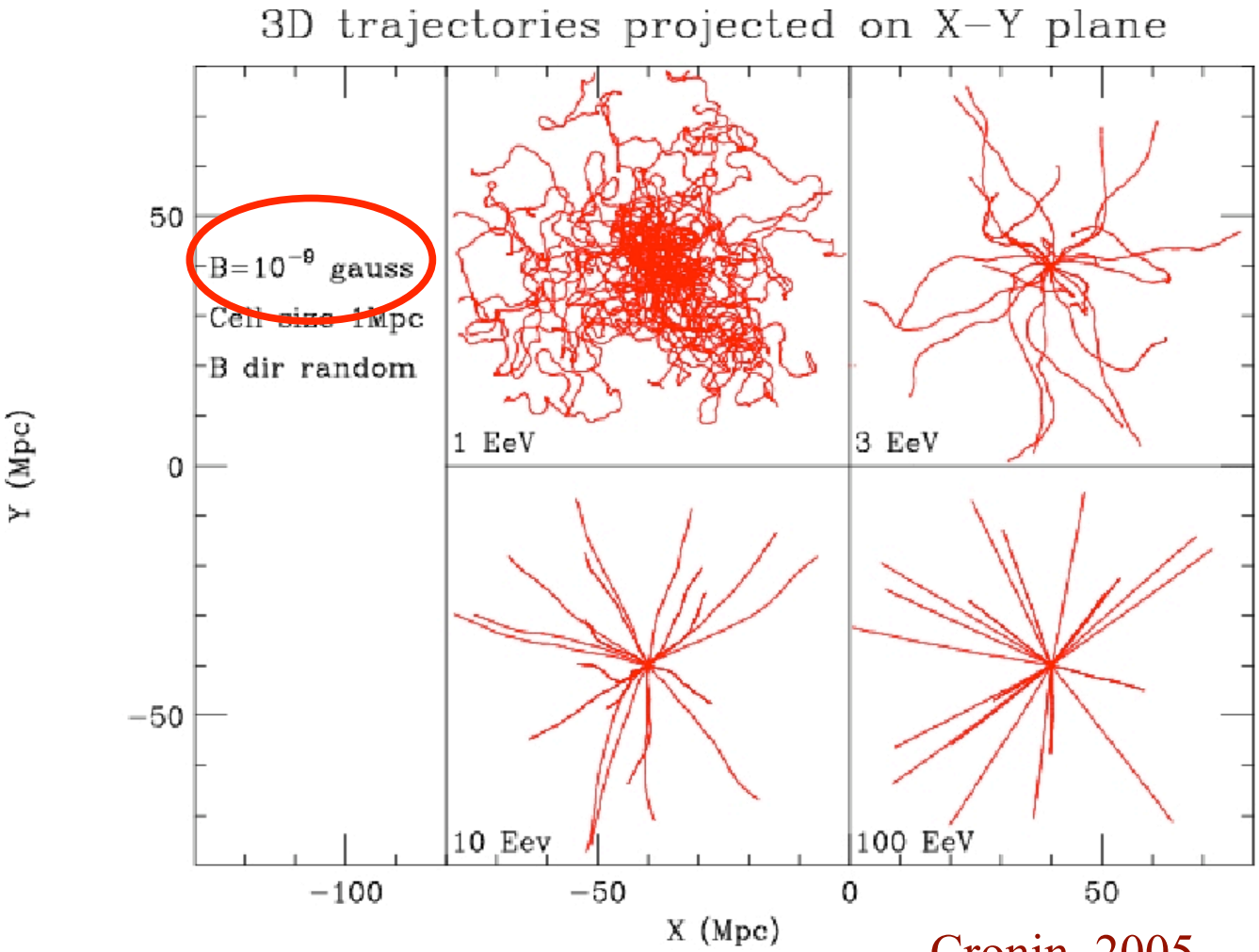
AUGER results

AUGER collaboration, PRL, 2008



Single power law rejected with significance > 6 sigmas

Propagation: the beginning of CR astronomy?

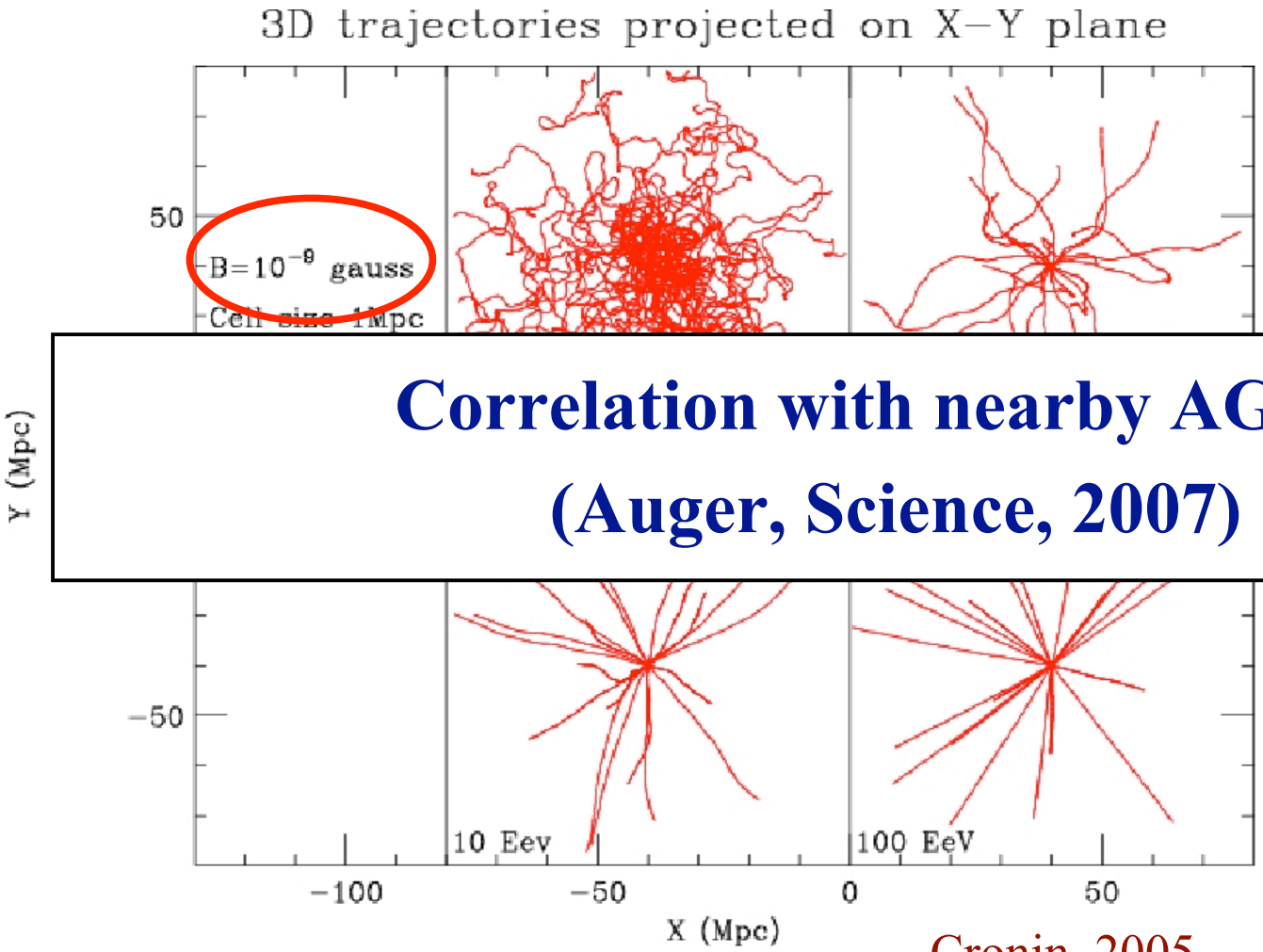


Cronin, 2005

Sigl et al. 2004
Dolag et al. 2005
Das et al. 2008

The value of the intergalactic magetic field is unknown!!!

Propagation: the beginning of CR astronomy?



Correlation with nearby AGNs?

(Auger, Science, 2007)

Cronin, 2005

Sigl et al. 2004
Dolag et al. 2005
Das et al. 2008

The value of the intergalactic magetic field is unknown!!!

A new possibility: searching for UHECR accelerators in gamma rays

Ferrigno et al., 2005; ***SG*** and Aharonian, 2005,2007; Armengaud et al., 2006

$p + \gamma_{CMB} \rightarrow p\ (n) + \text{pions}$

$\pi^0 \rightarrow \gamma + \gamma$

$\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm} + \text{neutrinos}$

$E_{\gamma} = 10^{19}\ E_{p,20}\ \text{eV}$

$E_e = 5 \cdot 10^{18}\ E_{p,20}\ \text{eV}$

Interactions with background photon fields and magnetic field

$e^{\pm} \rightarrow$ Inverse Compton and Synchrotron $\rightarrow \gamma$

$\gamma \rightarrow$ Pair Production $\rightarrow e^{\pm}$

Can we detect these photons?

In which energy band?

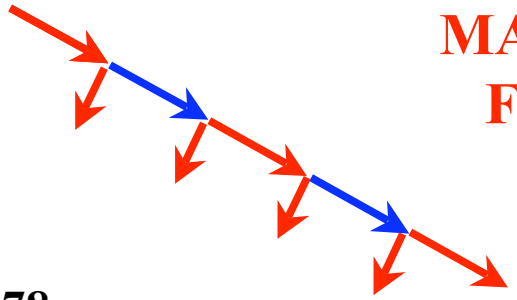
THIS RADIATION IS UNAVOIDABLE!

Electromagnetic cascade initiated by a UHECR

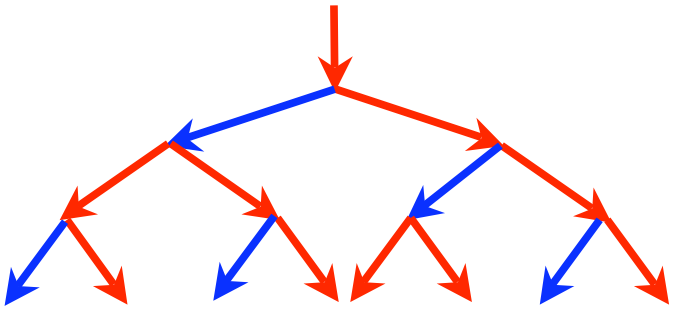
SG and Aharonian, 2005,2007

$\epsilon_b E_{e/\gamma} \gg m^2c^4$: e ➔ γ ➔ e ... $\epsilon_b E_{e/\gamma} \approx m^2c^4$: EM cascade

NO MAGNETIC FIELD!!!



Gould & Rephaeli,1978



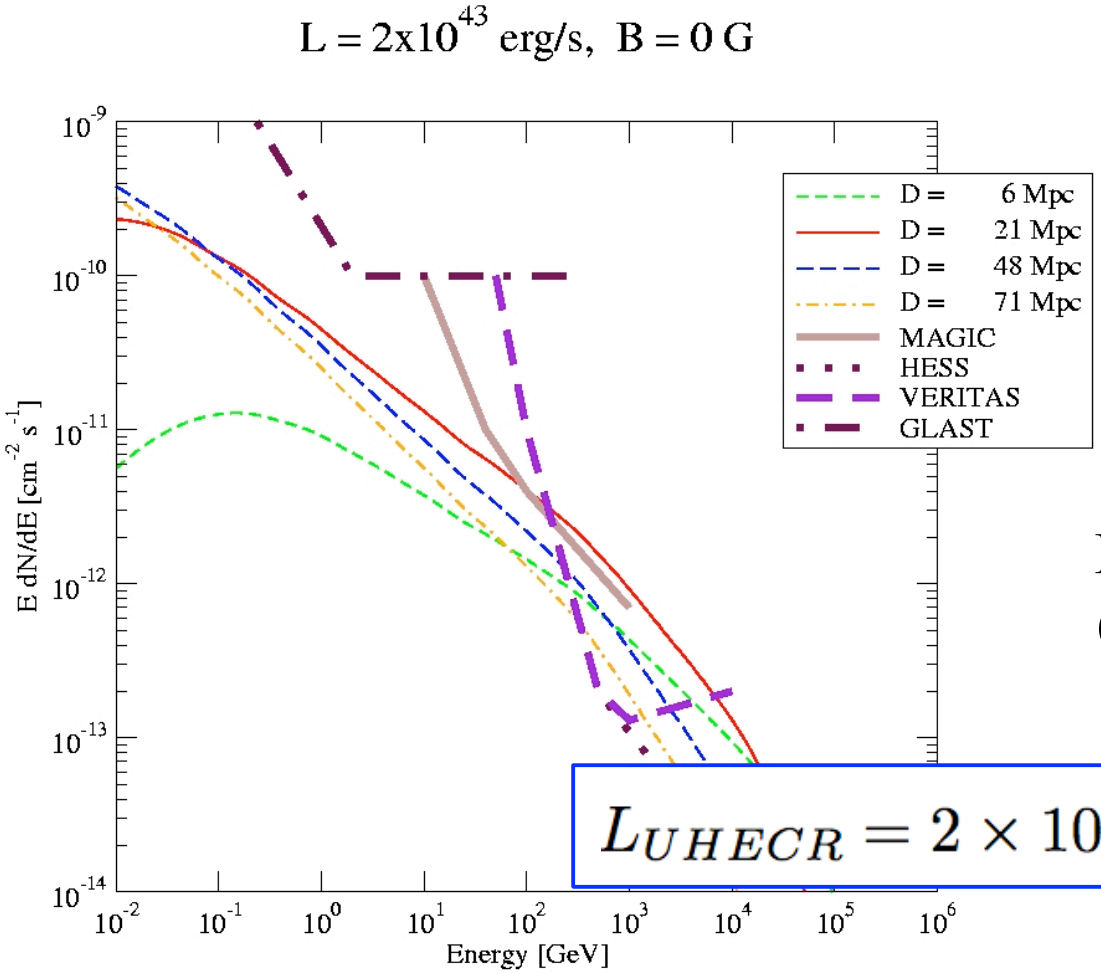
One leading particle!!!

Lots of particles

The case of the unmagnetized Universe

Ferrigno, Blasi and De Marco, 2005

Ideal case: ***B = 0 G*** → one-dimensional cascade (no losses, no deflection)



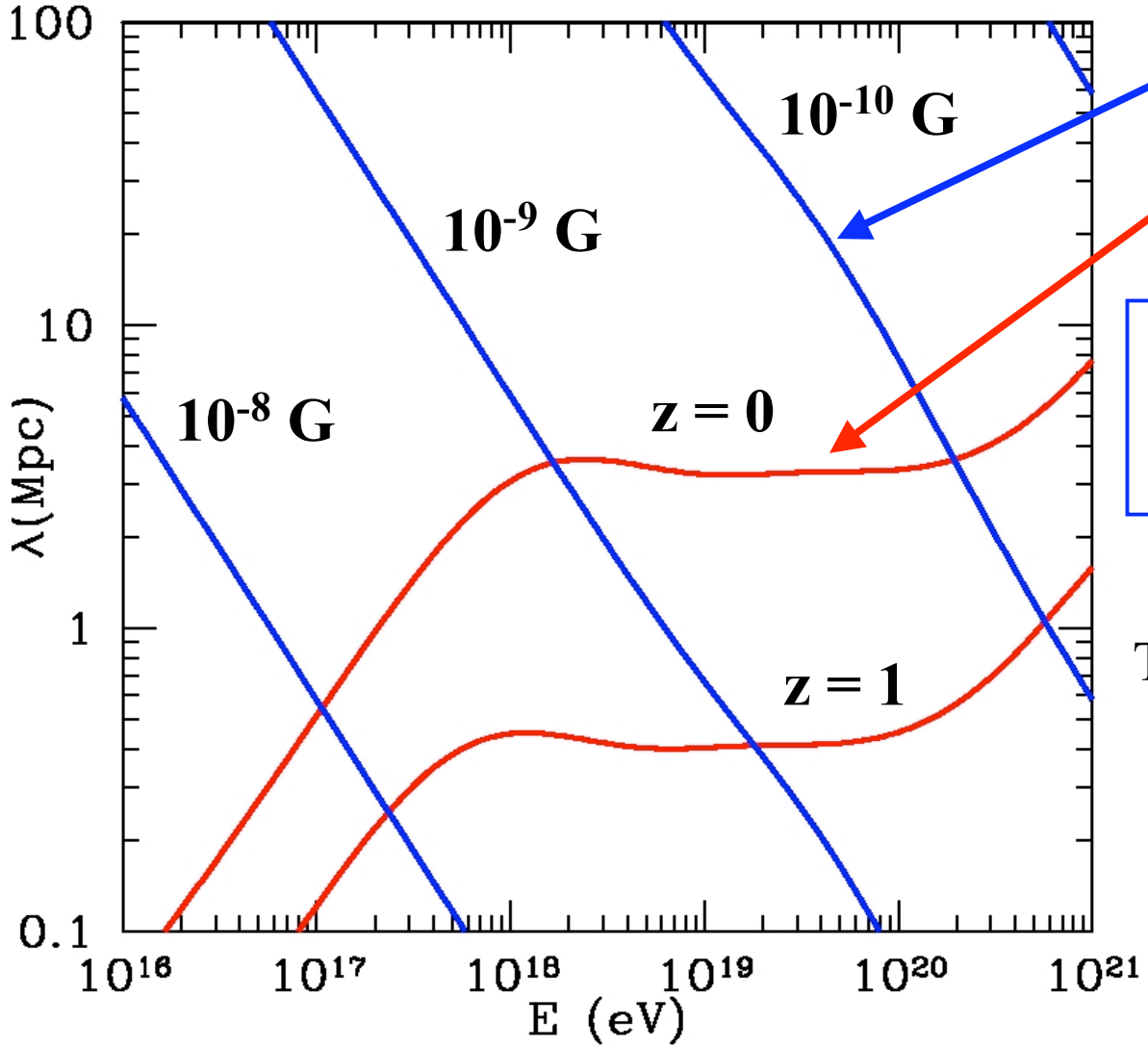
What does "unmagnetized" mean?

EM cascade might be observed @ TeV energies by Cherenkov telescopes

$$L_{UHECR} = 2 \times 10^{43} erg/s \quad \rightarrow \quad d < 100 Mpc$$

What does "unmagnetized" mean?
Part I: energy losses

Gabici & Aharonian, 2005



Synchrotron

Compton-pair production

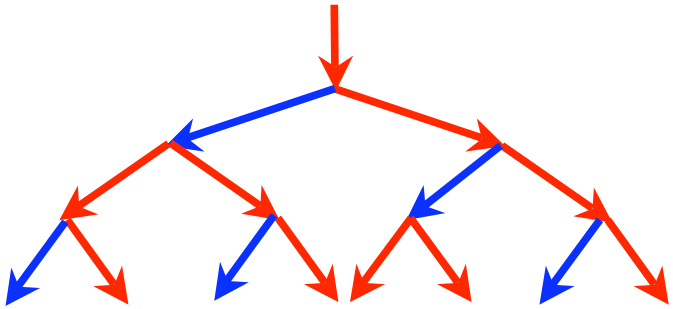
$$E_\gamma = 10^{19}\, E_{p,20}\ \text{eV}$$
$$E_e = 5\cdot 10^{18}\, E_{p,20}\ \text{eV}$$

The cascade is suppressed if:

$$B \geq 10^{-9} G$$

What does "unmagnetized" mean?
Part II: deflection

SG & Aharonian, 2007
Aharonian et al., 1994



⇐ more relevant for lower energies

@ 1 TeV we observe the radiation from:

$$E_e \approx 20 \left(\frac{E_\gamma^{obs}}{TeV}\right)^{1/2} TeV$$

Electrons are ***isotropized*** if they cool in one Larmor time

$$B \geq 10^{-12} \left(\frac{E_\gamma}{TeV}\right) G$$

CAUTION! This is NOT included is the public code CRPropa!(Armengaud et al,2006)

Three different regimes

(1) $B / B_{ISO} \sim 10^{-12}$ G → one-dimensional cascade

the cascade is unaffected by B: no deflection nor energy losses

(2) $B_{ISO} \leq B / B_{syn} \sim 10^{-9}$ G → giant pair halo

low energy electrons are isotropized, no energy losses

(3) $B \geq B_{syn}$ → no cascade

the development of the cascade is strongly suppressed

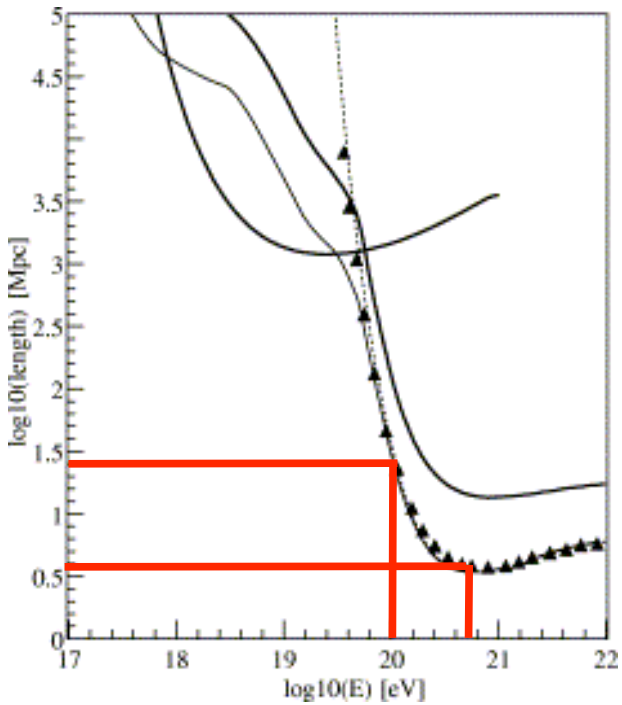
Regime 1: one-dimensional cascade

SG & Aharonian, 2007

$B / B_{ISO} \sim 10^{-12}$ G

?

proton interaction length



De Marco et al., 2004

Regime 1: one-dimensional cascade

SG & Aharonian, 2007

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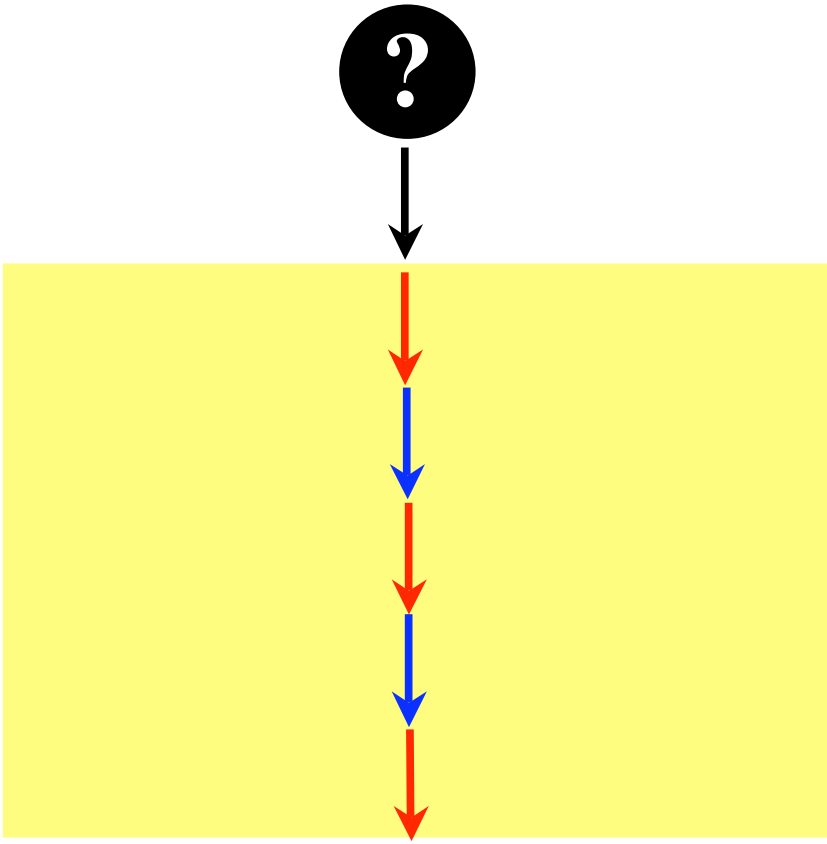
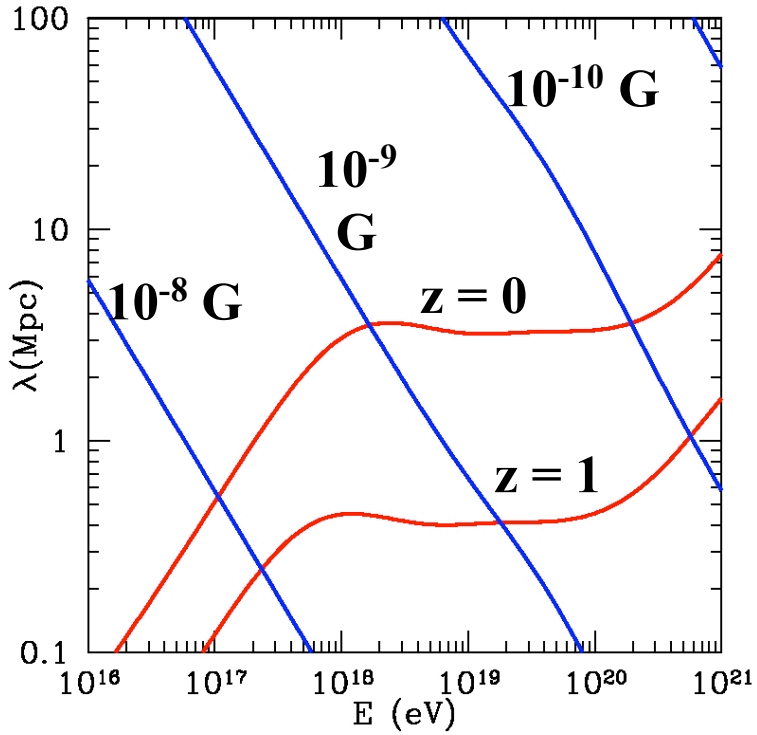


the first generation electron (photon) determines the size of the "Klein-Nishina cascade"

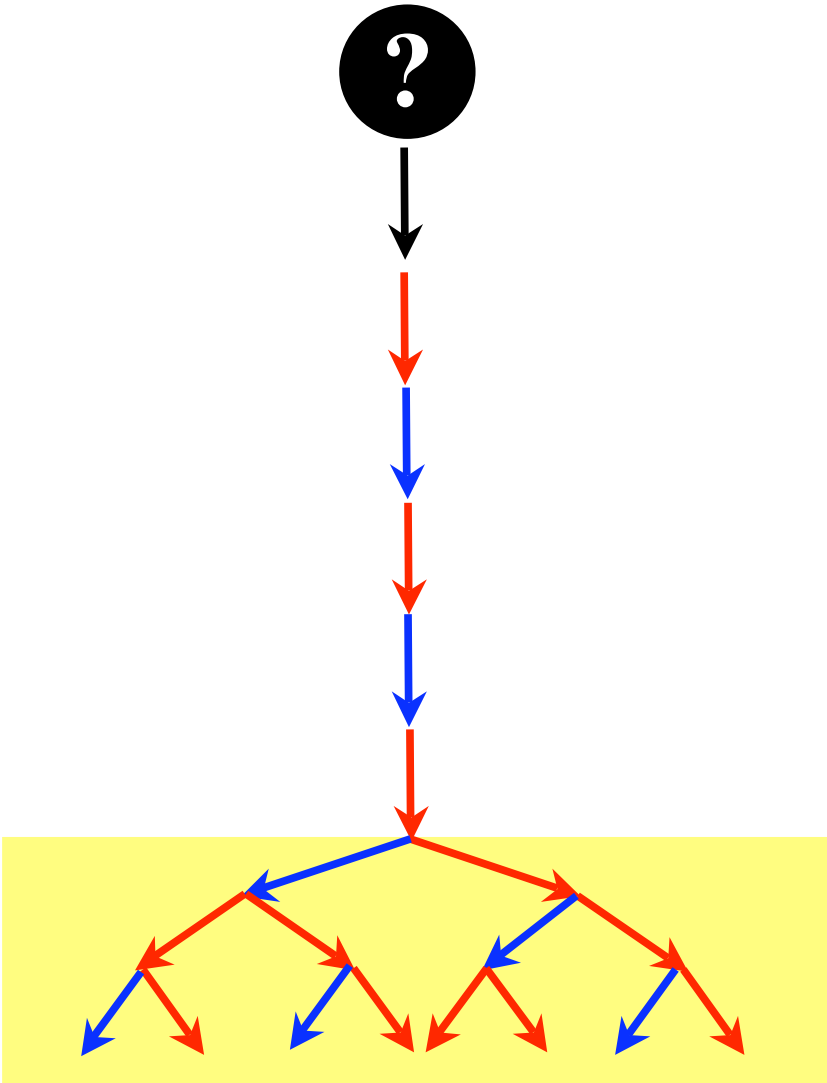


~ 5 – 10 Mpc

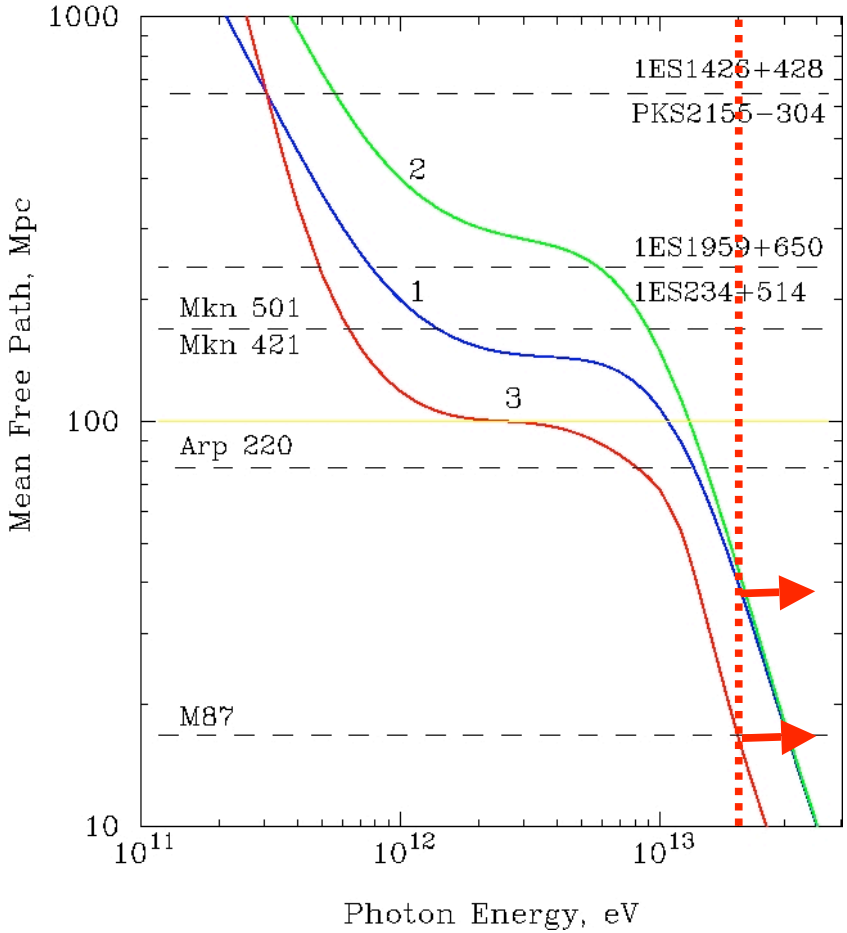
Regime 1: one-dimensional cascade

SG & Aharonian, 2007

$B / B_{ISO} \sim 10^{-12}$ G



the last generation photon determines the size of the "Thomson cascade"

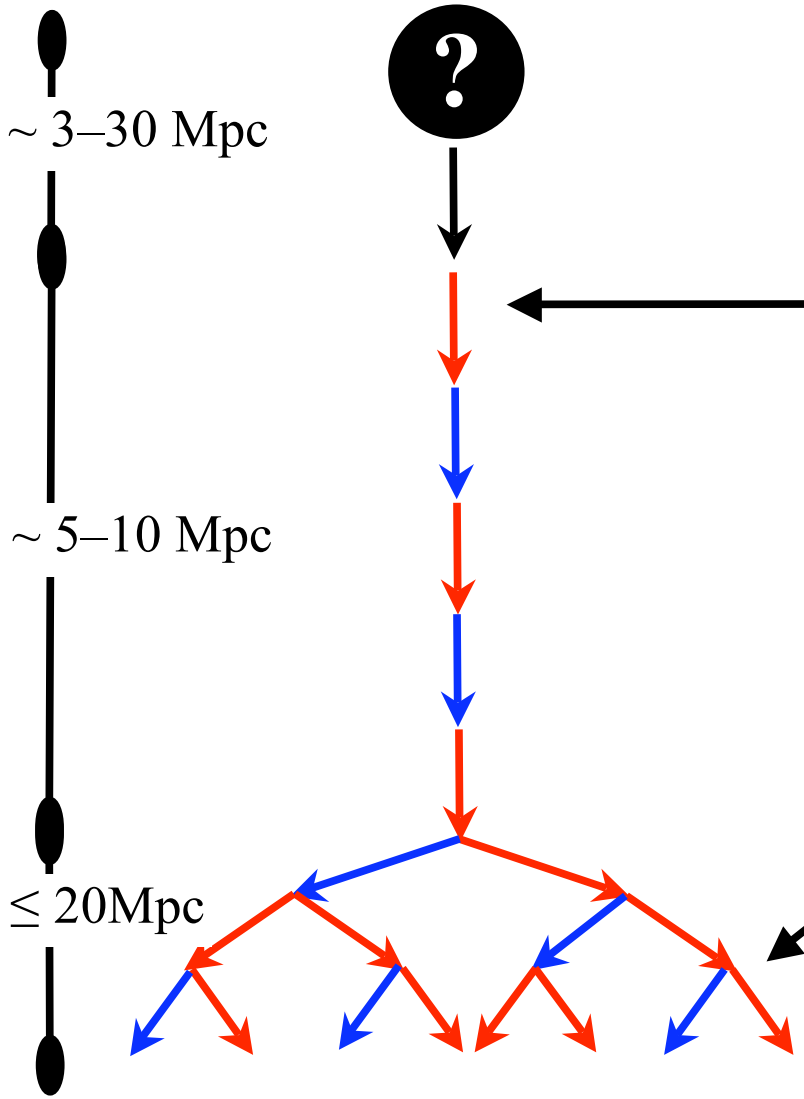


Aharonian, 2001

Regime 1: one-dimensional cascade

SG & Aharonian, 2007

$B / B_{ISO} \sim 10^{-12}$ G



$$B \ll 10^{-9} G$$

to avoid energy losses

$$B \ll 10^{-12} G$$

to avoid isotropization

it is a very small magnetic field!

but not ruled out...

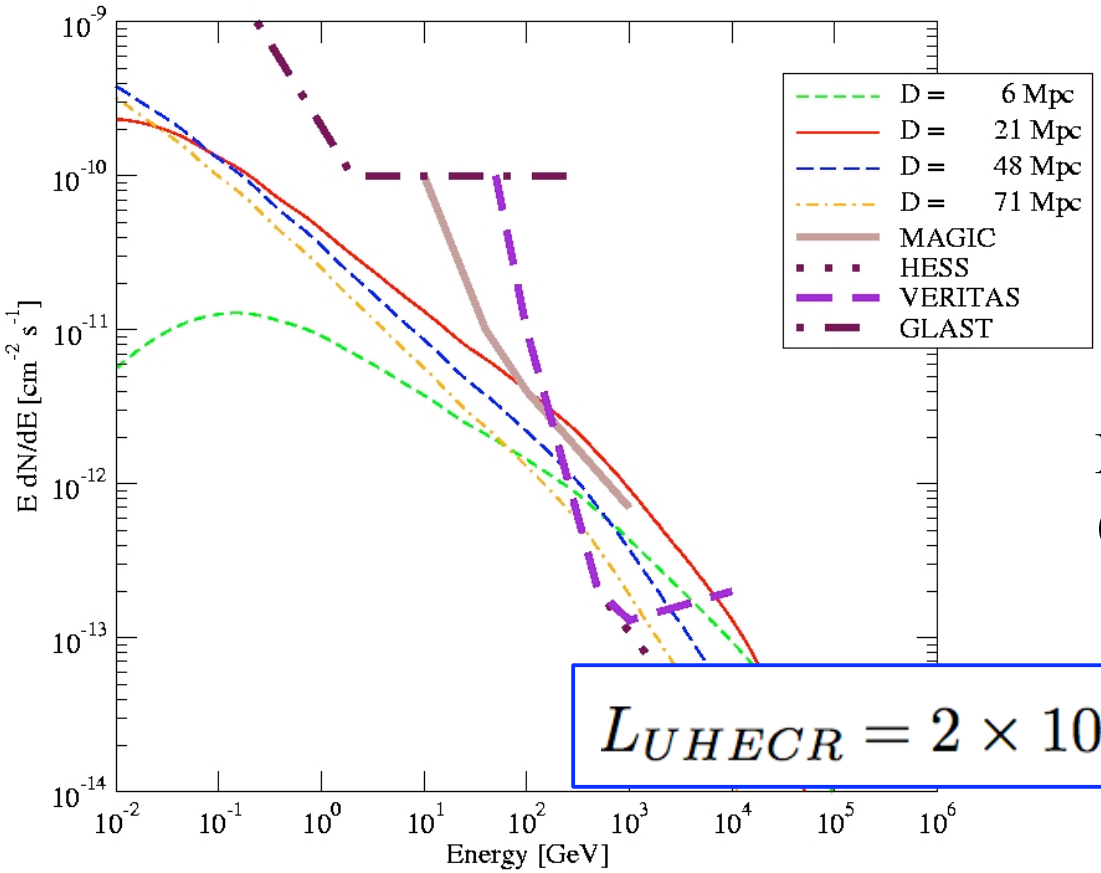
Regime 1: one-dimensional cascade

(Ferrigno, Blasi and De Marco, 2005)

$B / B_{ISO} \sim 10^{-12}$ G

Ideal case: ***B = 0 G*** → one-dimensional cascade (no losses, no deflection)

$L = 2x10^{43}$ erg/s, B = 0 G



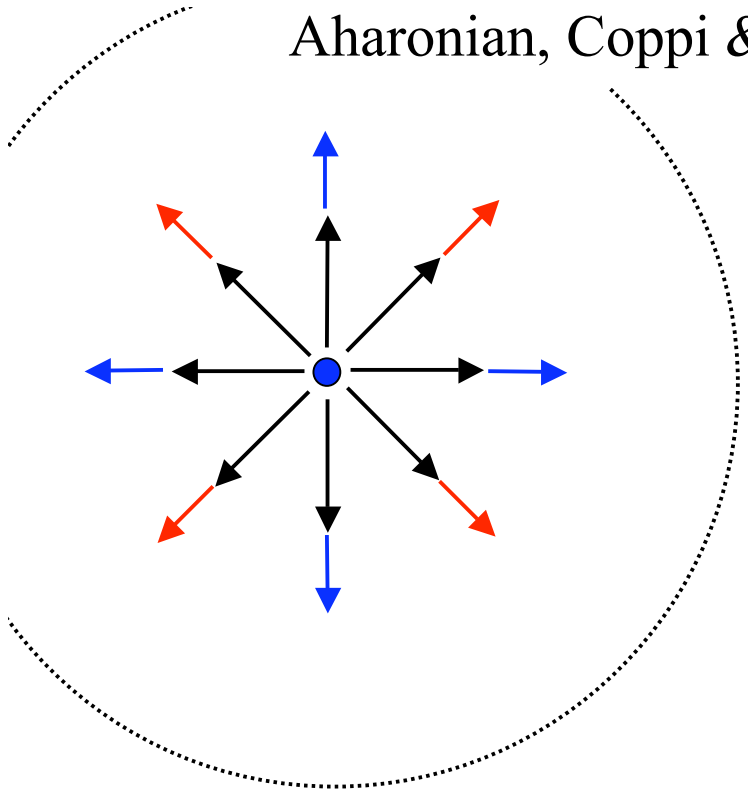
EM cascade might be observed @ TeV energies by Cherenkov telescopes

$$L_{UHECR} = 2 \times 10^{43} erg/s \quad \rightarrow \quad d < 100 Mpc$$

Regime 2: giant pair halo

$B_{ISO} \leq B / B_{syn} \sim 10^{-9}$ G

Aharonian, Coppi & Völk, 1994; ***SG*** & Aharonian, 2007



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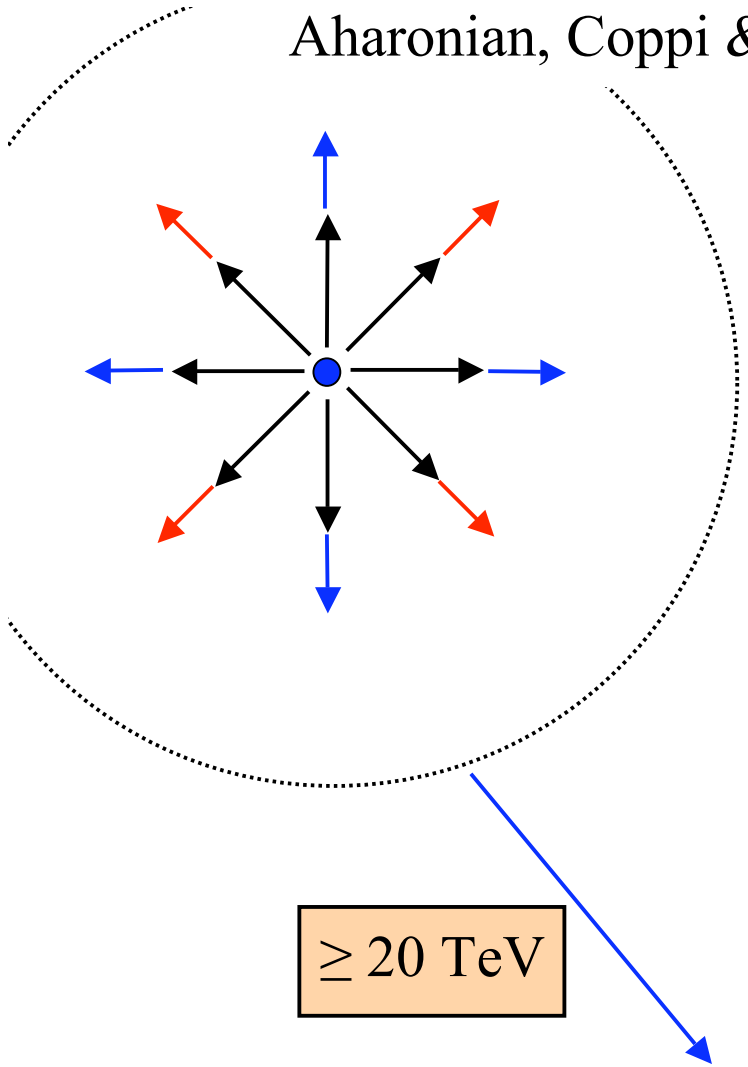

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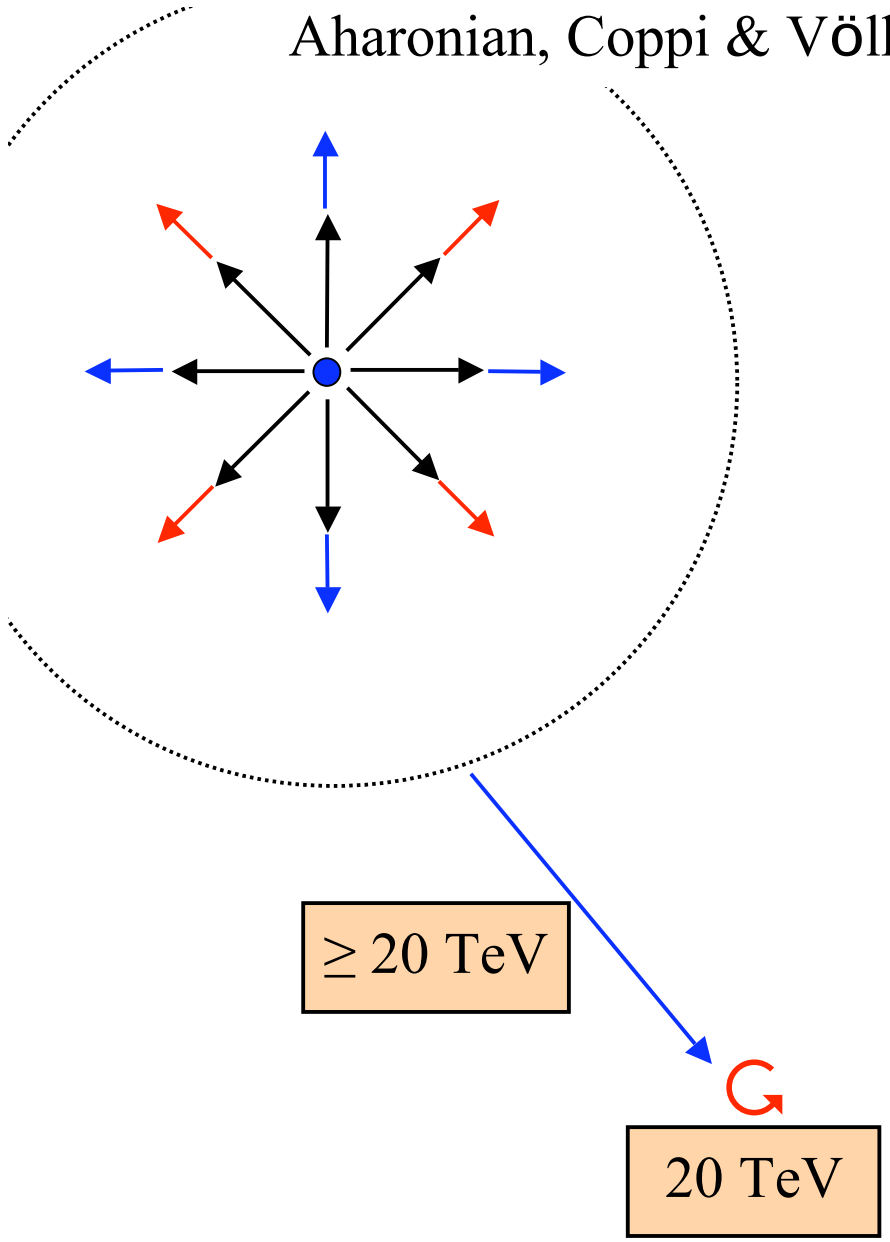

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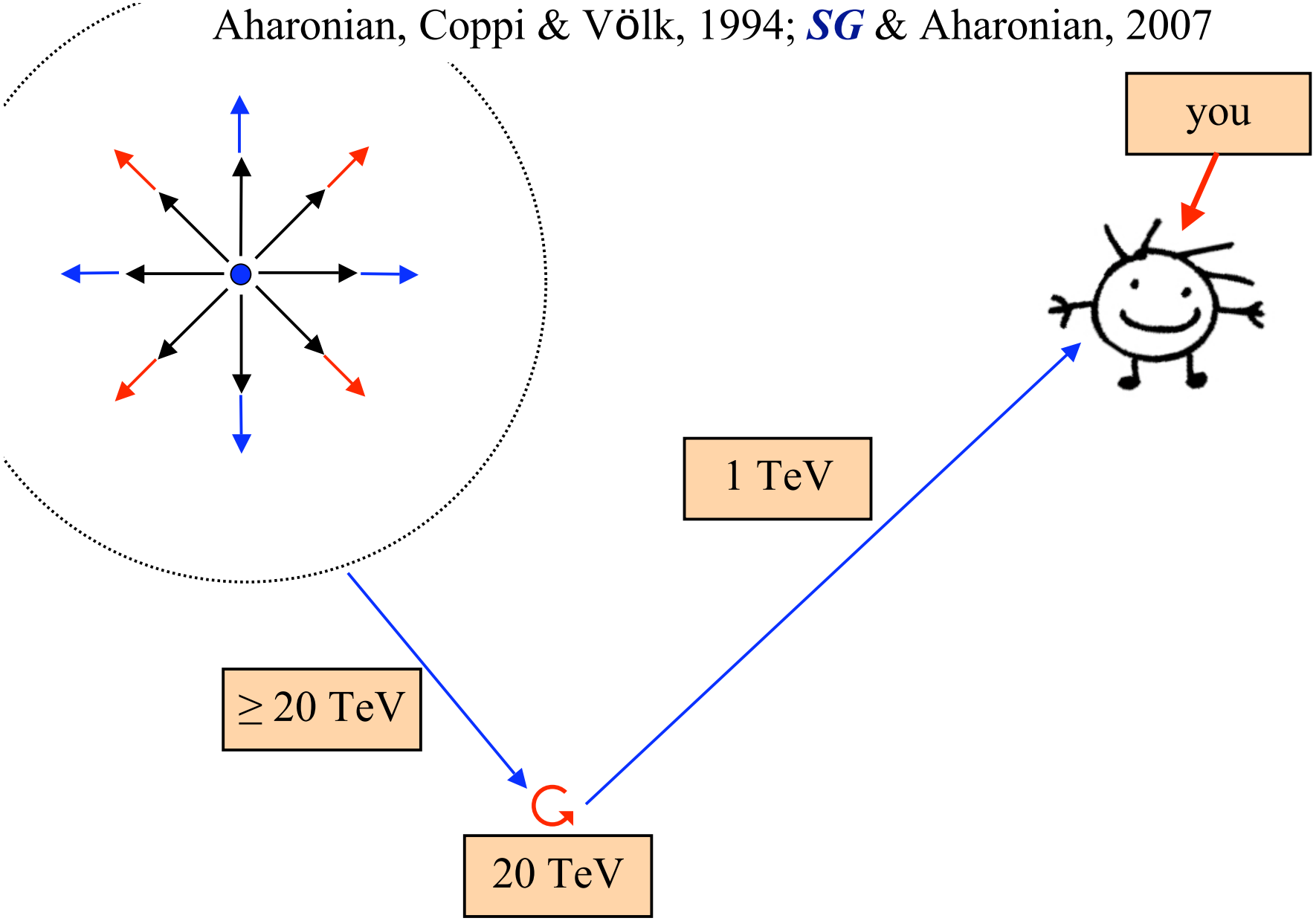

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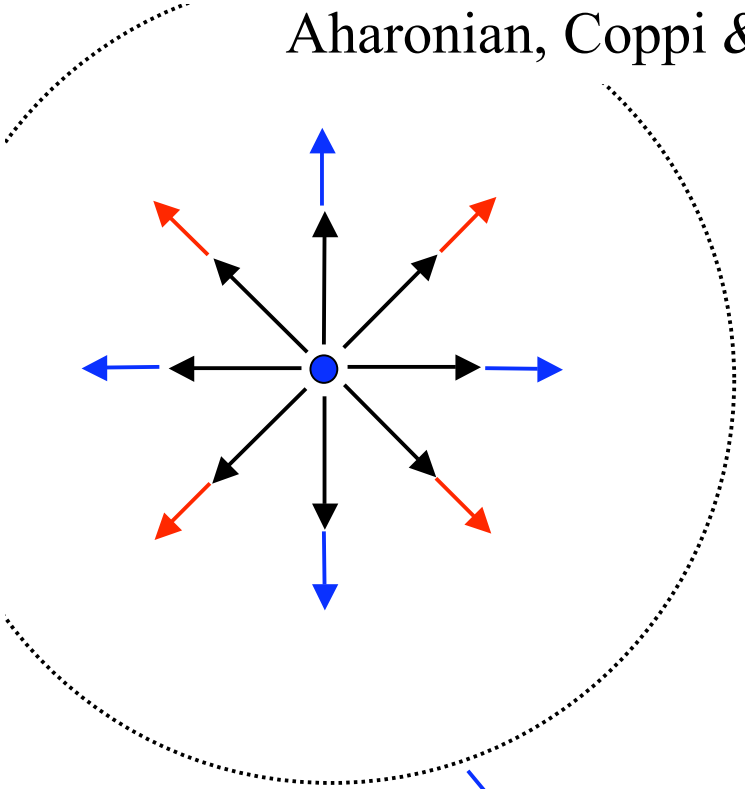
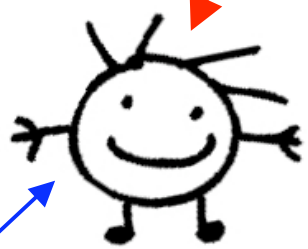




you

1 TeV

conservative (!!!)
estimate of the halo size

$\geq$ 20 TeV

$$\vartheta_h \geq 10^o \left(\frac{l_{halo}}{20Mpc}\right)\left(\frac{D}{100Mpc}\right)^{-1}$$

G

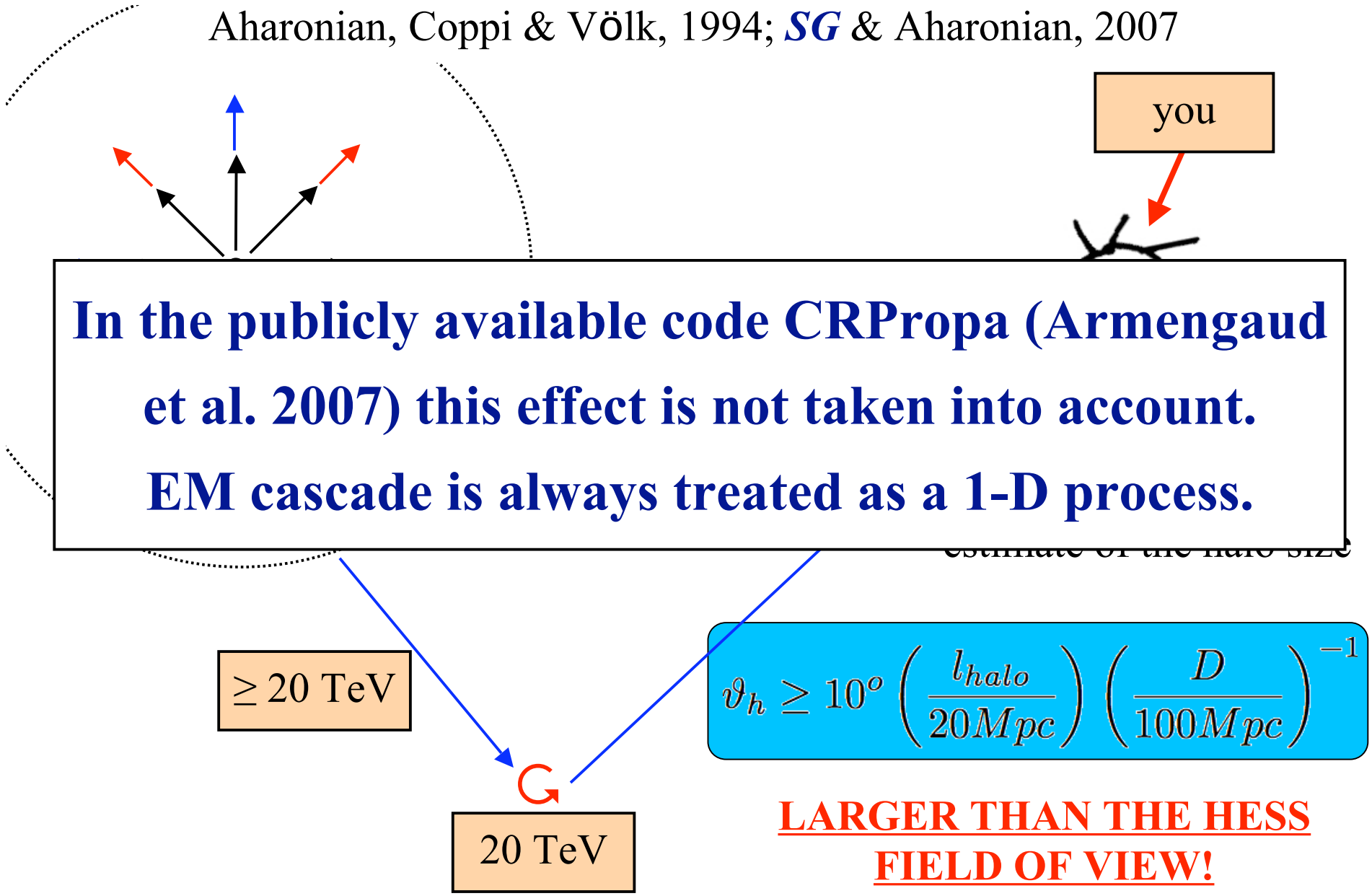
20 TeV

LARGER THAN THE HESS FIELD OF VIEW!

Regime 2: giant pair halo

$B_{ISO} \leq B / B_{syn} \sim 10^{-9}$ G

Aharonian, Coppi & Völk, 1994; ***SG*** & Aharonian, 2007



In the publicly available code CRPropa (Armengaud et al. 2007) this effect is not taken into account. EM cascade is always treated as a 1-D process.

$$\vartheta_h \geq 10^o \left(\frac{l_{halo}}{20Mpc}\right)\left(\frac{D}{100Mpc}\right)^{-1}$$

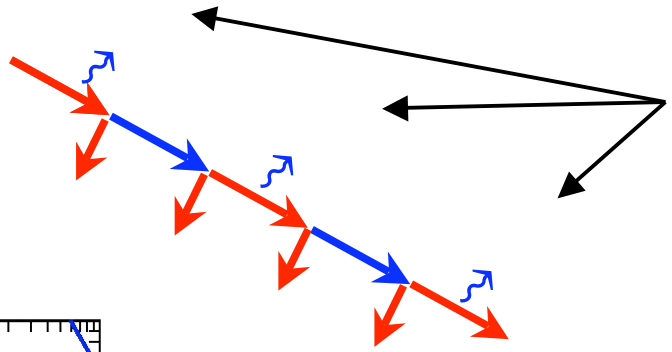
LARGER THAN THE HESS FIELD OF VIEW!

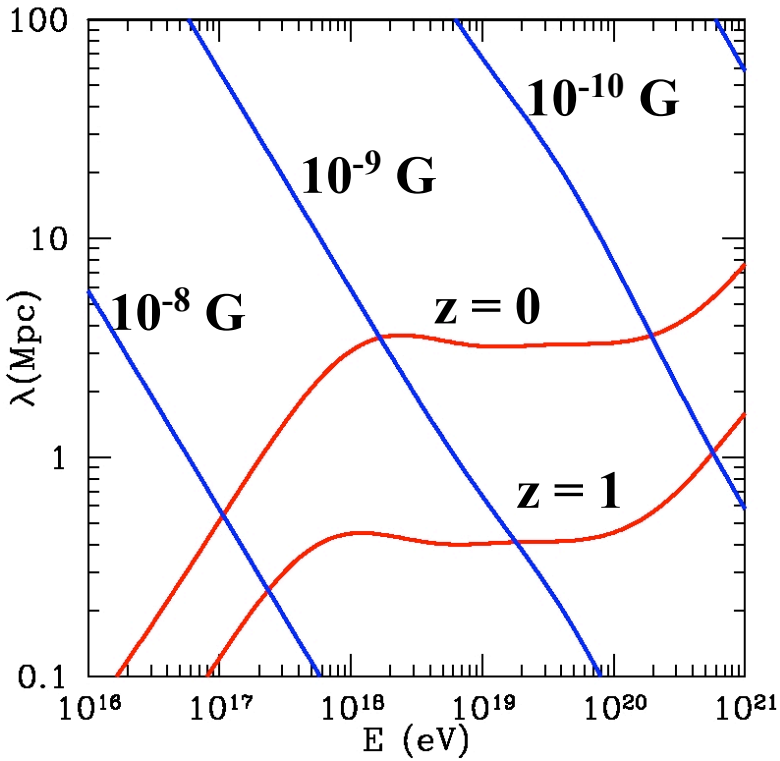
Regime 3: synchrotron gamma ray emission

SG and Aharonian, 2005,2007

$B \geq B_{syn} \sim 10^{-9}$ G

If a ~nG magnetic field is present, the cascade is suppressed at its first (one particle) step!



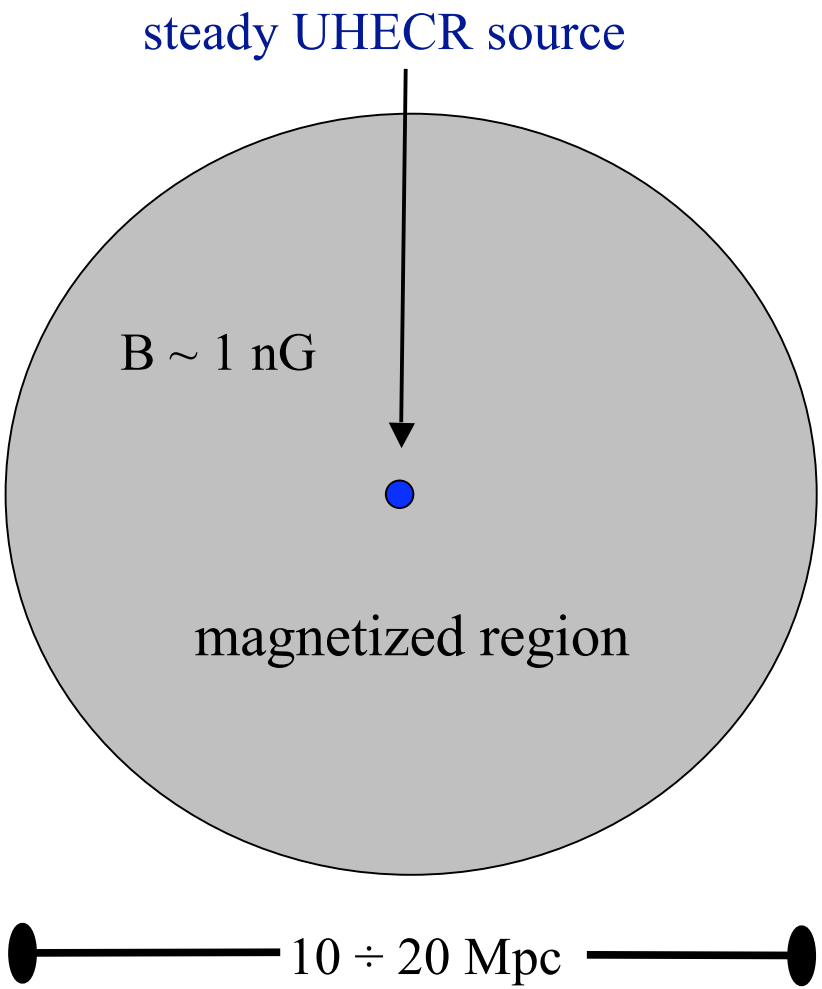


$$E_{syn} \sim 2\left(\frac{B}{nG}\right)\left(\frac{E}{10^{19}eV}\right)^2 GeV$$

GLAST energy range!!!

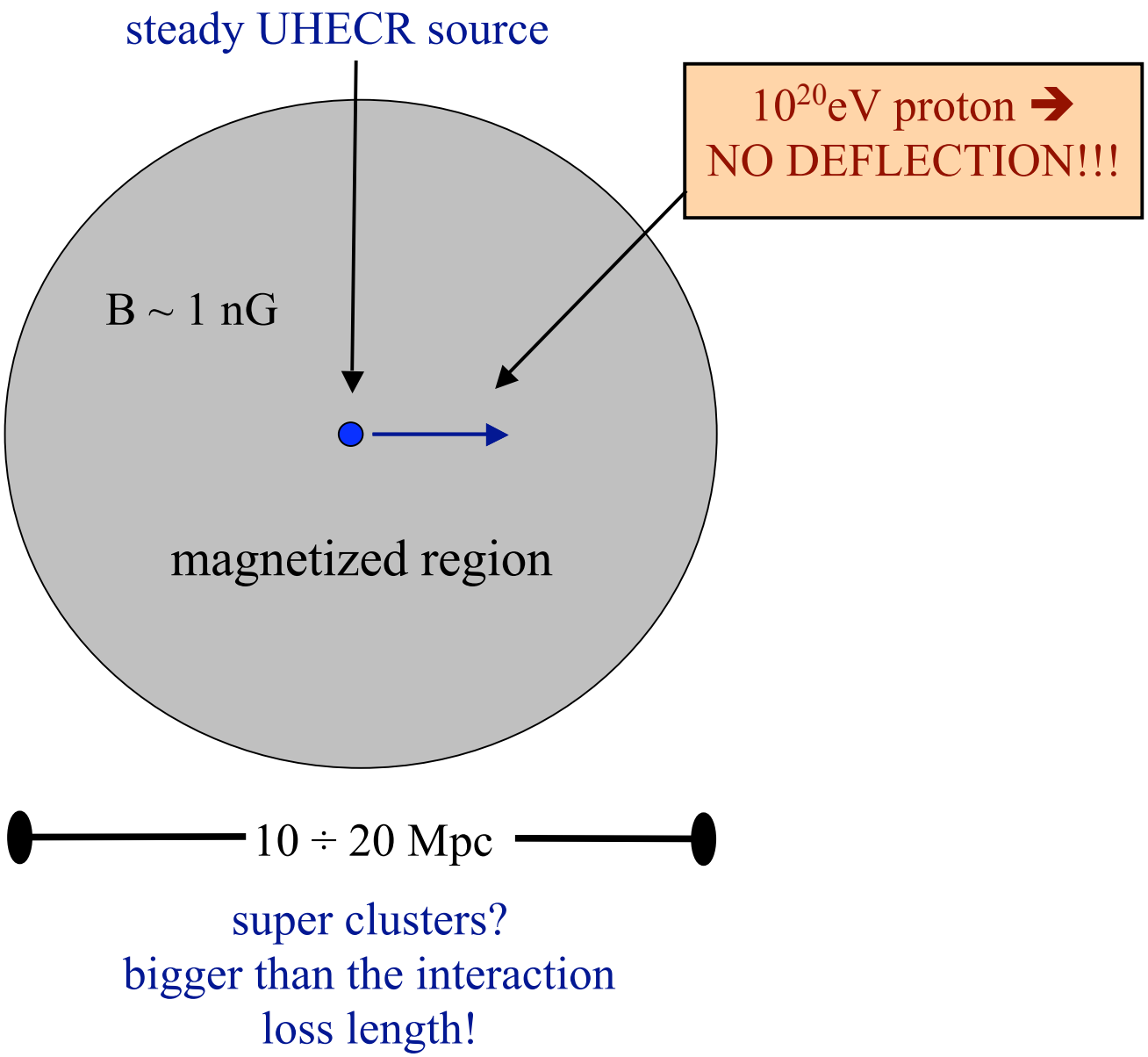
Gabici & Aharonian, 2005

New way to identify UHECR sources!



super clusters?
bigger than the interaction
loss length!

New way to identify UHECR sources!



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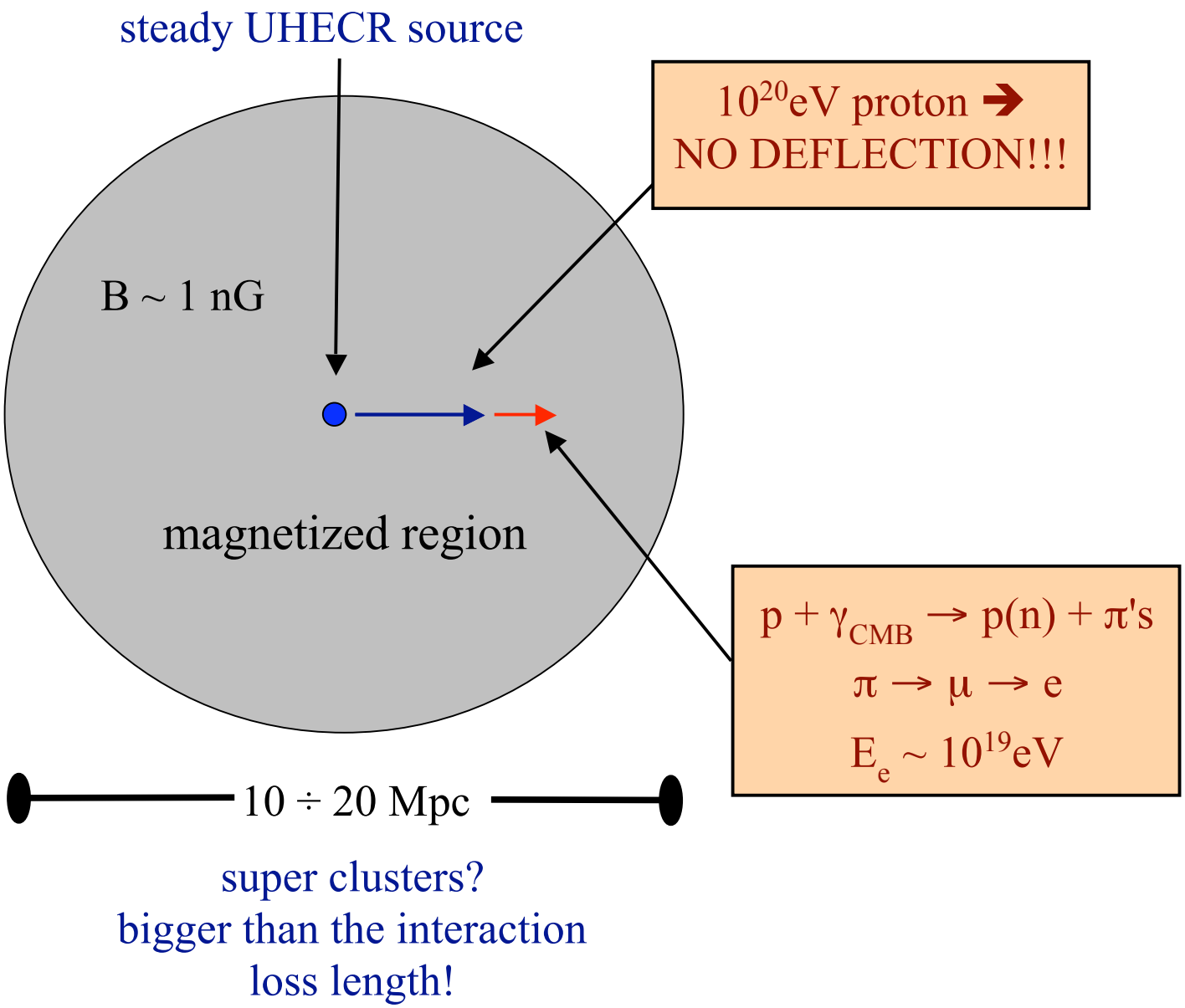

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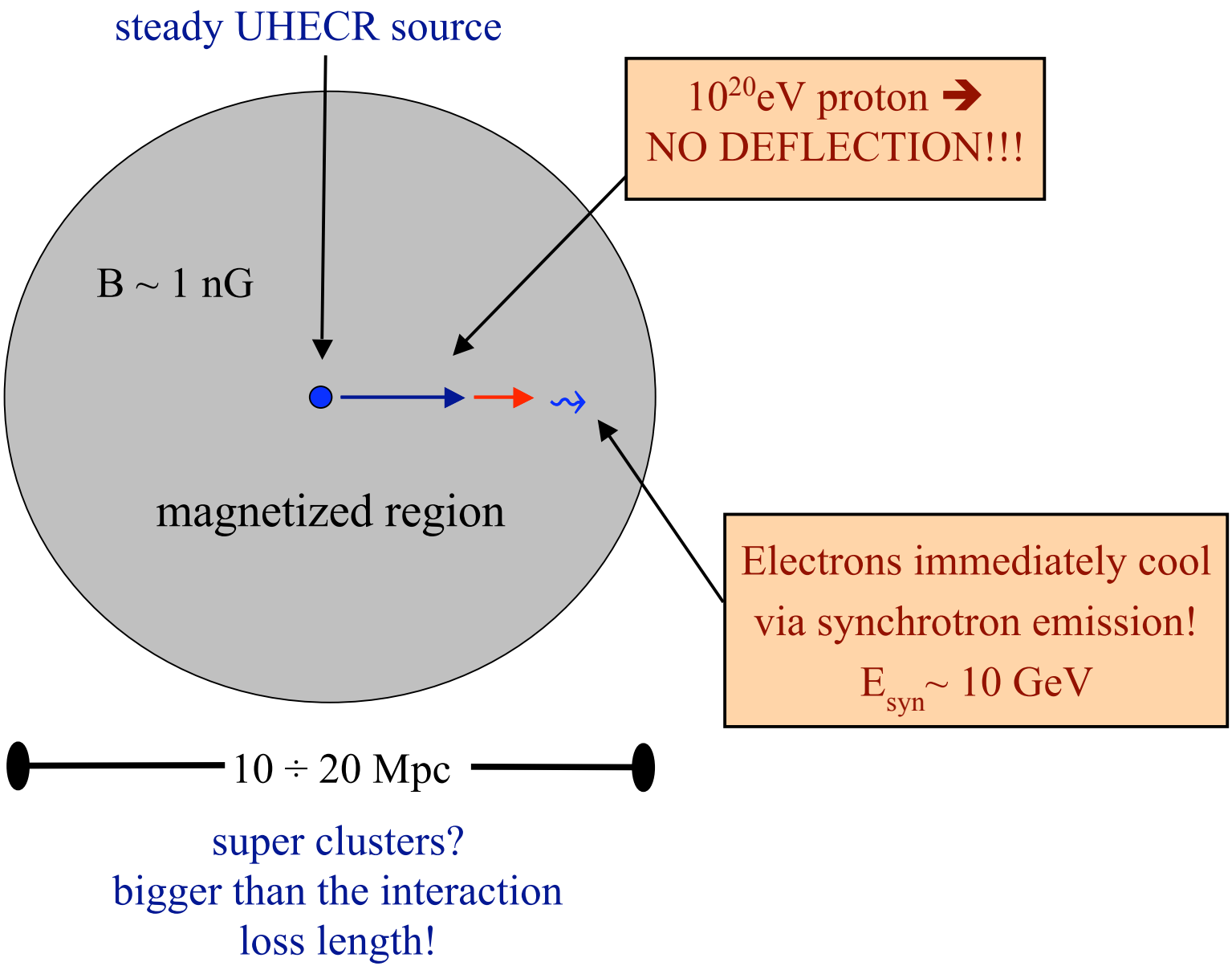

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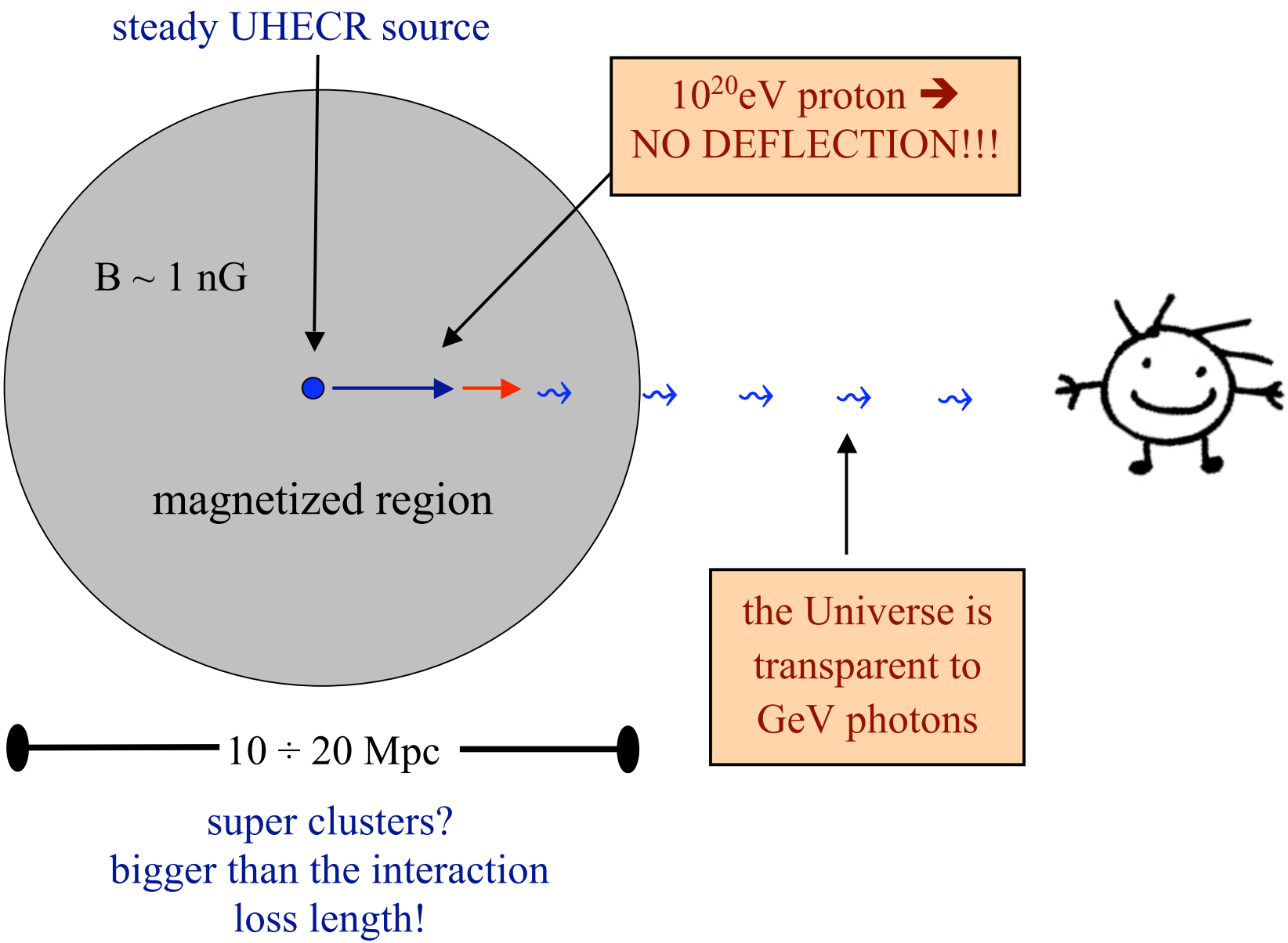

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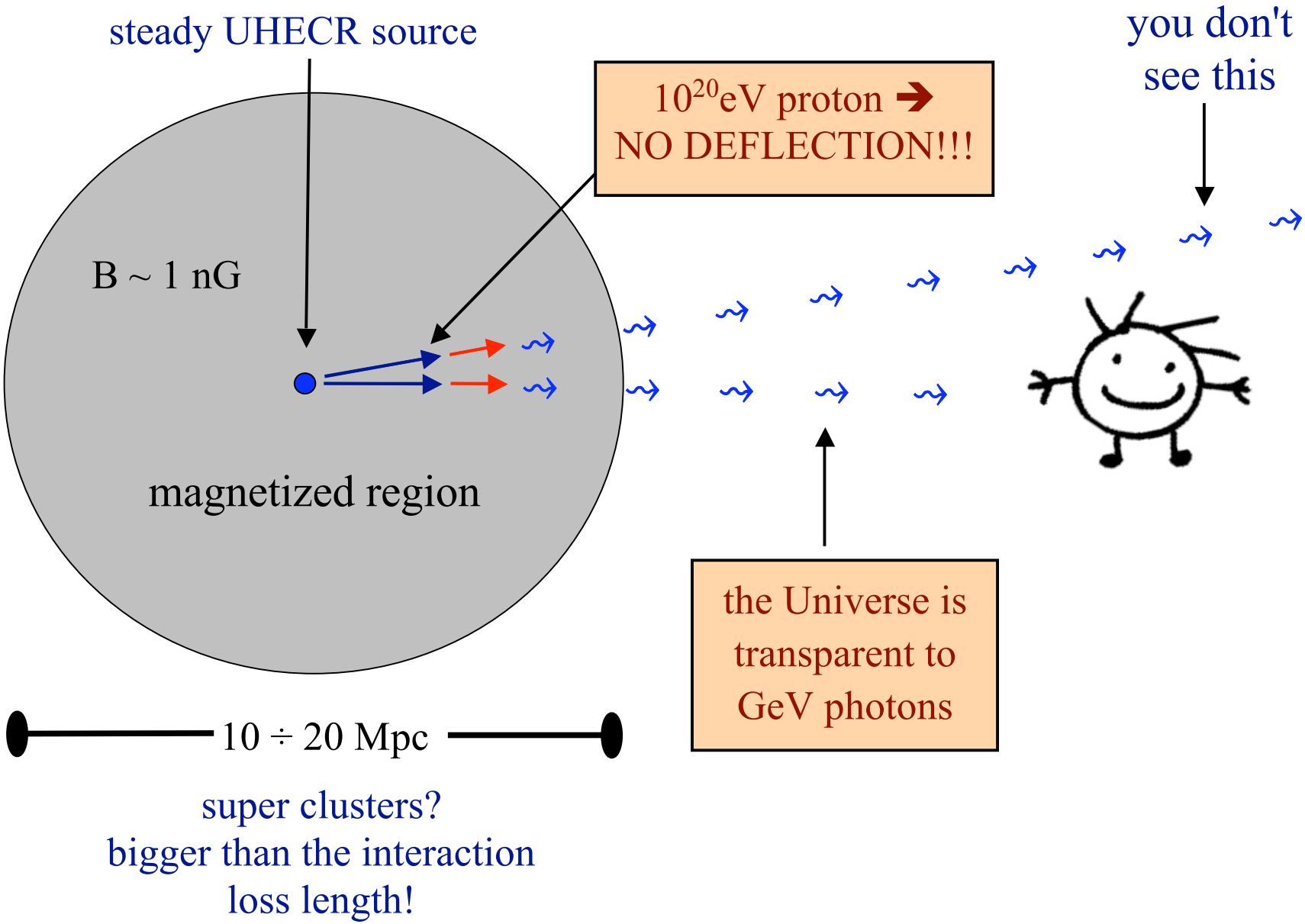

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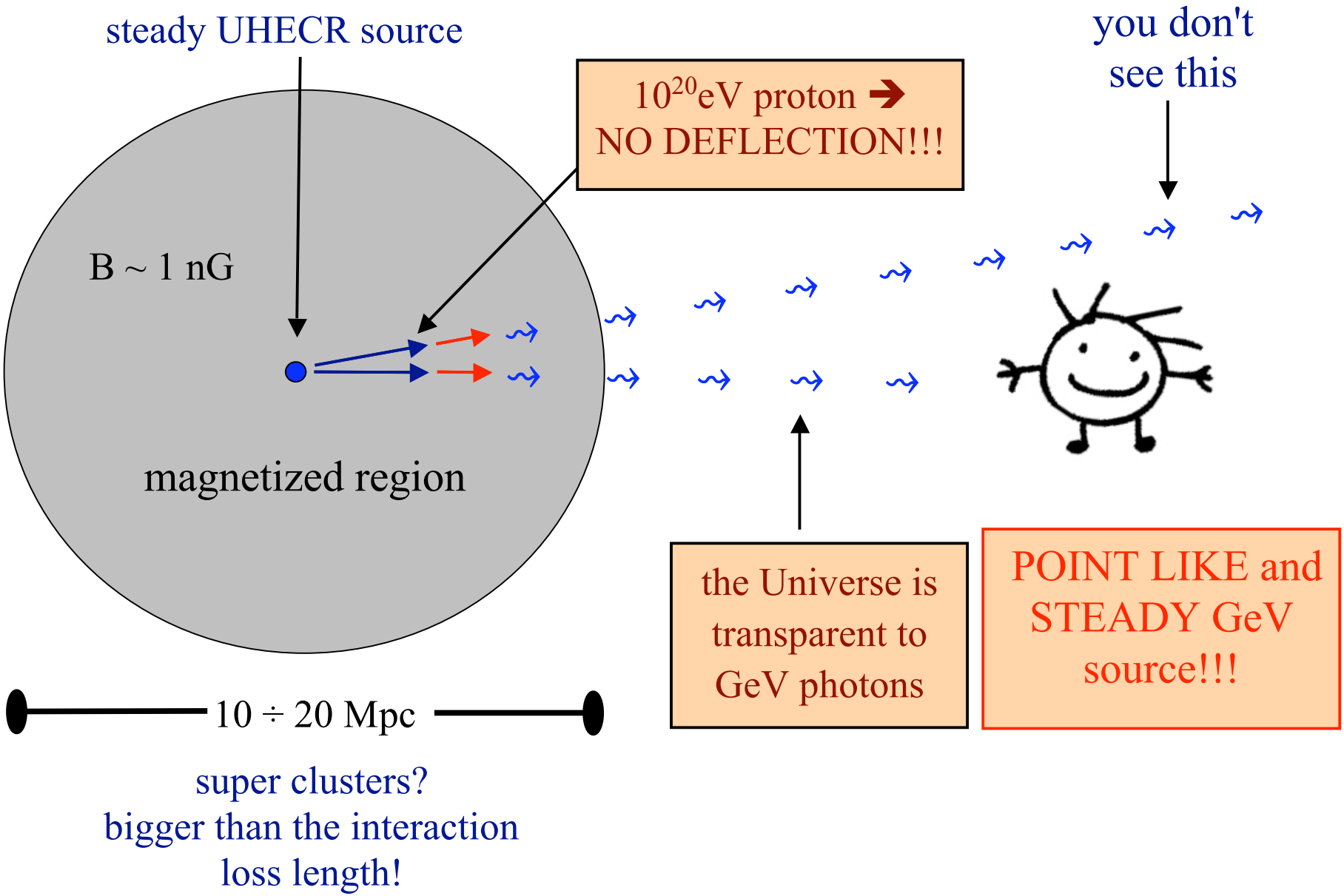

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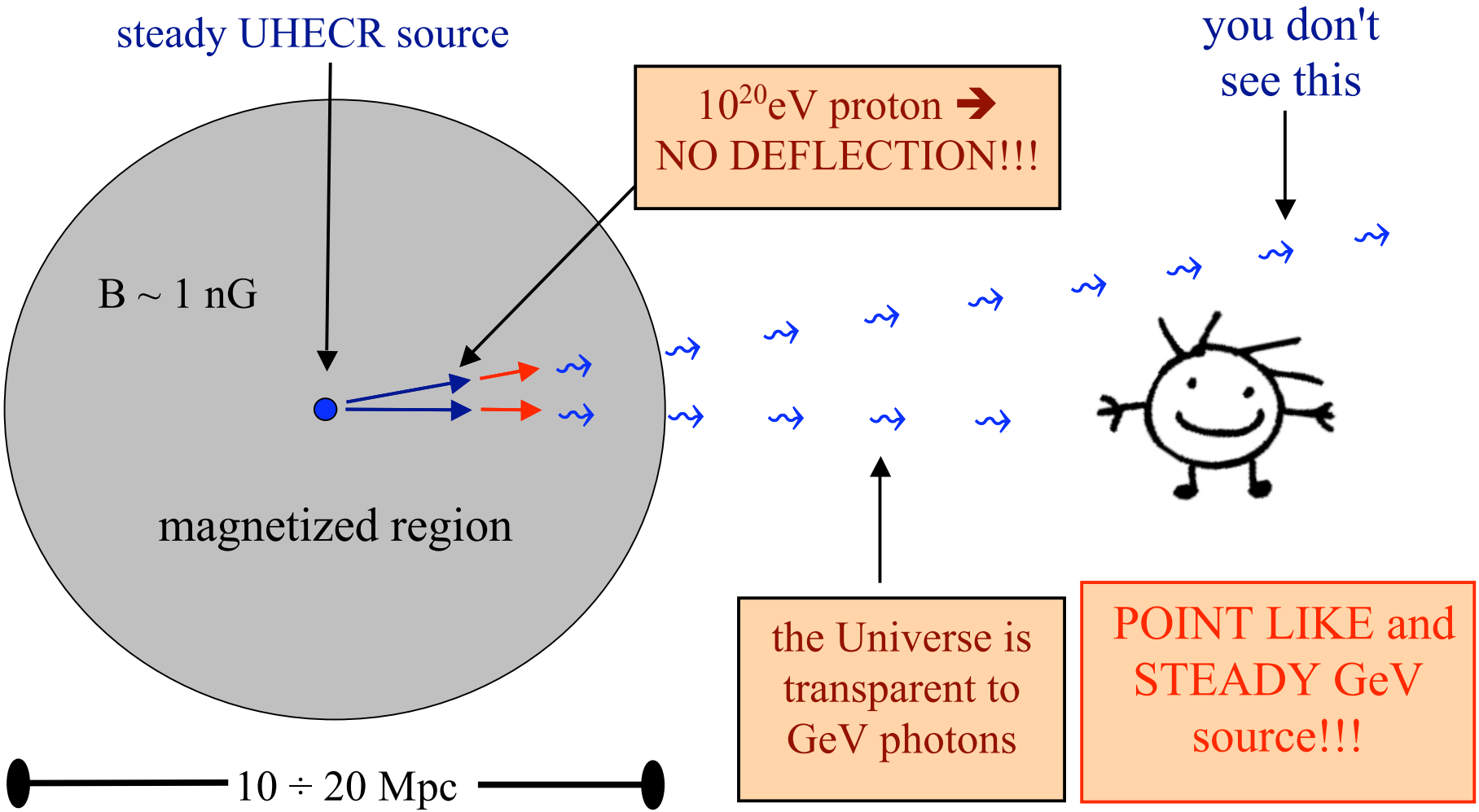
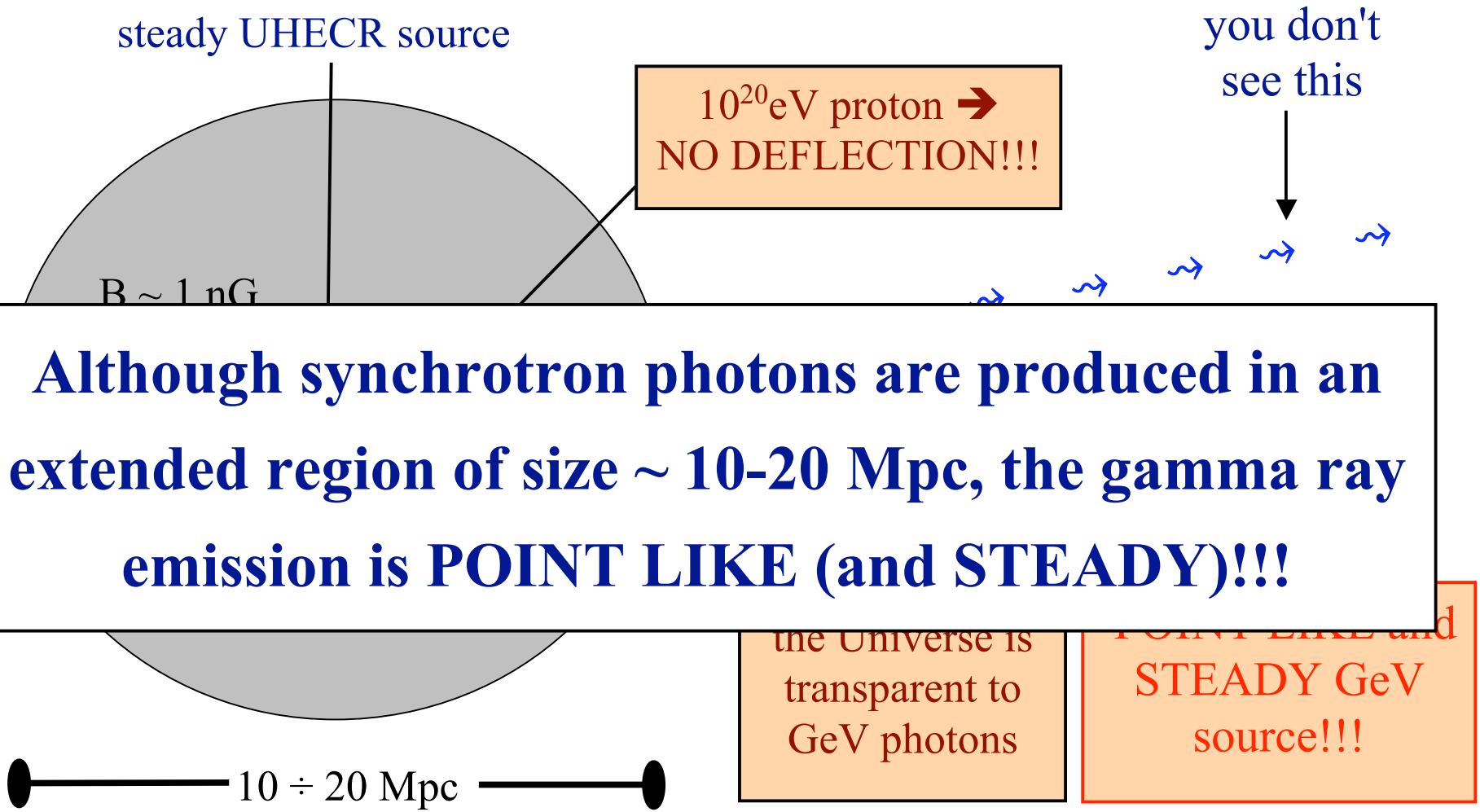


UHE neutrinos ⇨ $E_\nu^2 F_\nu \sim 1 \; \frac{EeV}{km^2 yr} \quad @E_\nu = 5 \times 10^{18} eV$ AUGER?

New way to identify UHECR sources!

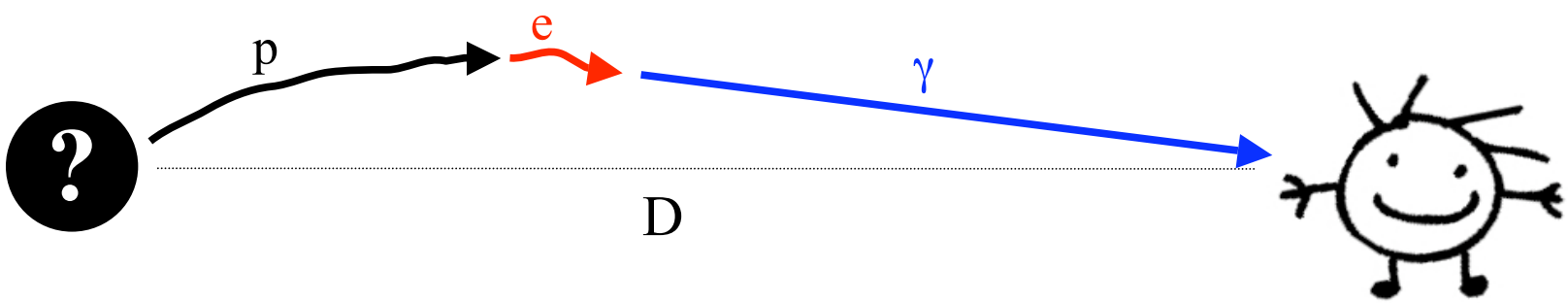


Although synchrotron photons are produced in an extended region of size ~ 10-20 Mpc, the gamma ray emission is POINT LIKE (and STEADY)!!!

UHE neutrinos ⇨ $E_\nu^2 F_\nu \sim 1 \; \frac{EeV}{km^2 yr} \quad @E_\nu = 5 \times 10^{18} eV$ AUGER?

Quantitative estimates: angular size

SG and Aharonian, 2005,2007



for B = 1 nG $\vartheta_{syn} \approx (\vartheta_p + \vartheta_e)\left(\frac{l_p}{D}\right) \approx 0.5^o$ @ 100 Mpc

comparable with the GLAST angular resolution!

GLAST ➔ D ≥ 100 Mpc

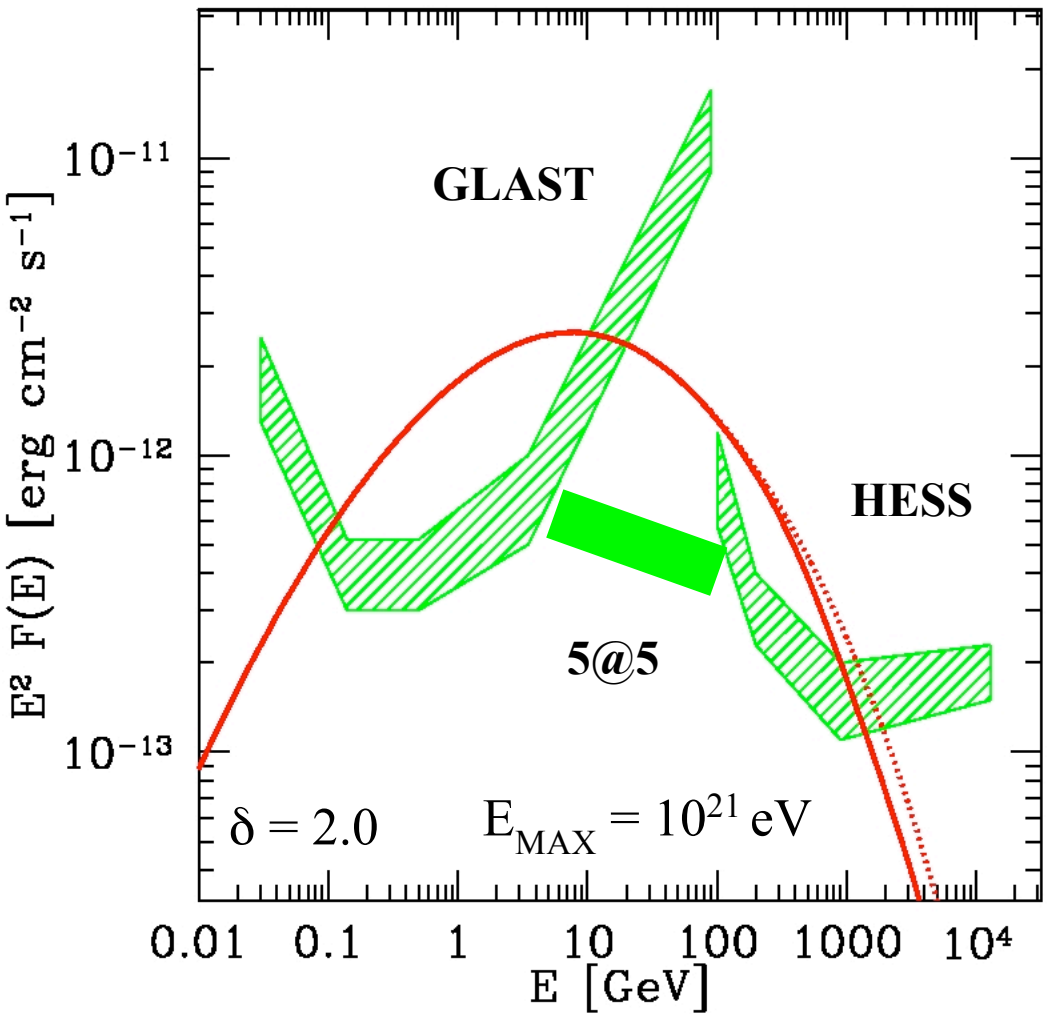
HESS ➔ D ≥ 1 Gpc

HESS large field of view ➔ imaging of closer sources?

Quantitative estimates: total energy

SG and Aharonian, 2005,2007

D=100Mpc B = 1nG L_{UHECR}=2 10^{44} erg/s



Condition for detectability:

$$L_{UHECR} > 10^{44} \left(\frac{D}{100Mpc}\right)^2 \frac{erg}{s}$$

$$\delta \approx 2.0 \div 2.3$$

Beaming can reduce the energy by a factor:

$$f_b = \frac{4\pi}{\omega} \sim 100 \left(\frac{\vartheta}{10^o}\right)^{-1}$$

AGN Jets

$$E_{jet} \sim 10^{47} \div 10^{48} erg/s$$

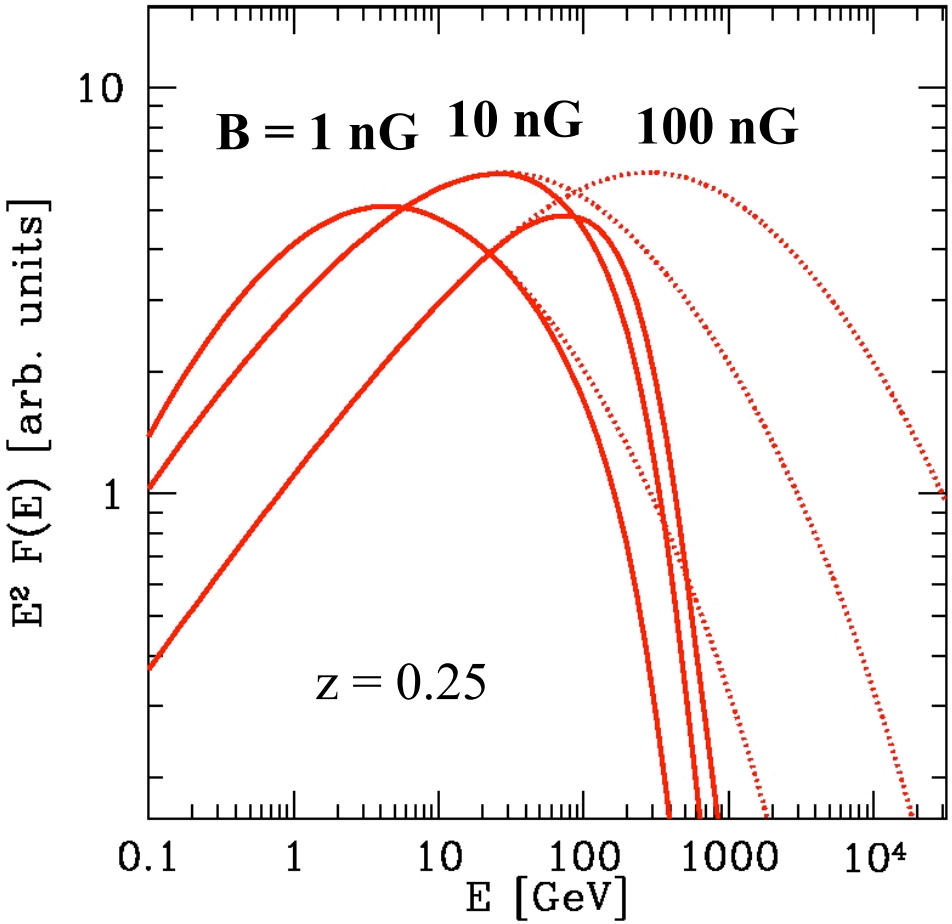
Ghisellini&Celotti,2001

If the source is bursting (e.g.GRB) this does not work! (time spread of the signal)

Can we constrain the magnetic field?

B << 0.5 nG

no synchrotron!



B >> 50 nG

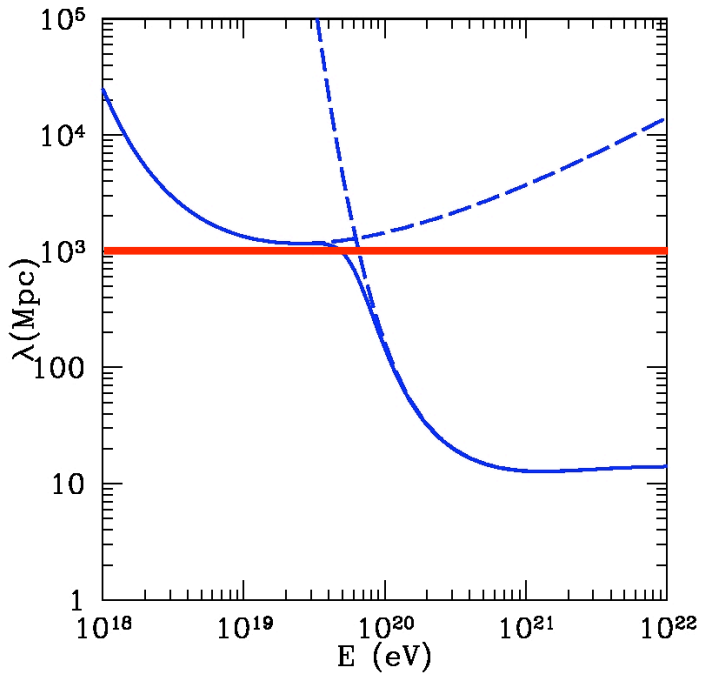
ABSORPTION!

If the field is in the range 0.5 – 50 nG the formation of the synchrotron source seems to be UNAVOIDABLE

Speculation: detecting sources outside the horizon

SG and Aharonian, 2005,2007

Extremely powerful accelerator @ a Gpc or more...



no CR above ~ 5 10^{19} eV ➔ energy losses

no CR below ~ 5 10^{19} eV ➔ deflection

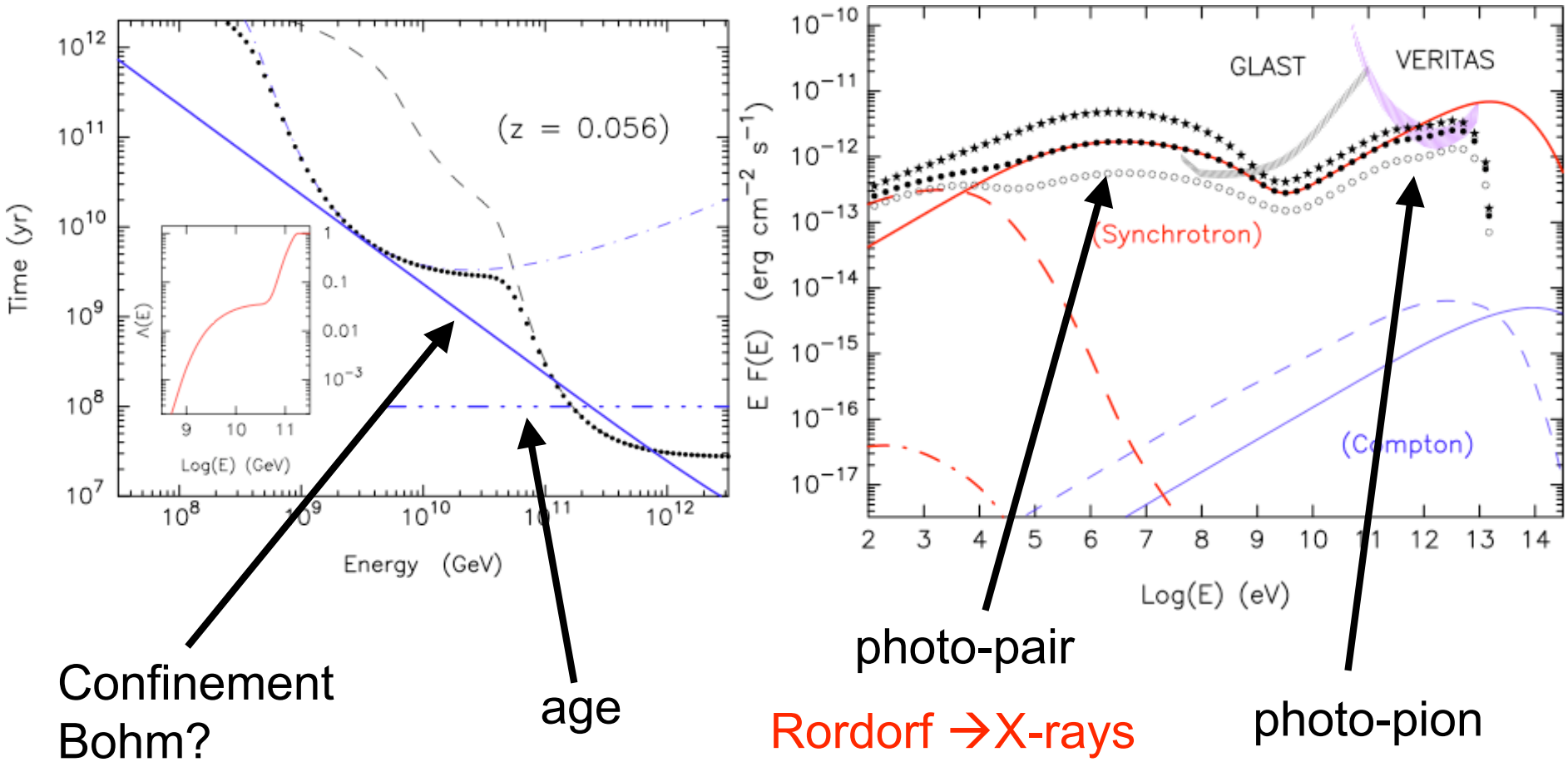
Point-like and steady sources without counterparts might be accelerators of UHECRs located outside the CR-horizon!!!

Detectability condition: $L_{UHECR} > 10^{44} \left(\frac{D}{Gpc}\right)^2 \left(\frac{\vartheta_b}{10^o}\right) erg/s$

Variations: confinement in a cluster of galaxies

Rordorf et al, 2004; Atoyan&Dermer, 2008

CygA: 4 10^{46} erg/s in CRs, B = 20 μG, photo-pair production included



Conclusions

☑ Which are the sources of UHECRs? Can we do CR astronomy?

☑ Gamma ray expected both during UHECR **acceleration** and **propagation**

☑ Gamma rays from propagation are **UNAVOIDABLE!!!**

(1) $B / B_{ISO} \sim 10^{-12}$ G → one-dimensional cascade

TeV point sources → Cherenkov telescopes

(2) $B_{ISO} \leq B / B_{syn} \sim 10^{-9}$ G → giant pair halo

very extended TeV sources → detection very difficult

(3) $B \geq B_{syn}$ → no cascade

GeV/TeV point like or (reasonably) extended → FERMI/Cherenkov