Gamma ray signatures of Ultra High Energy Cosmic Ray accelerators

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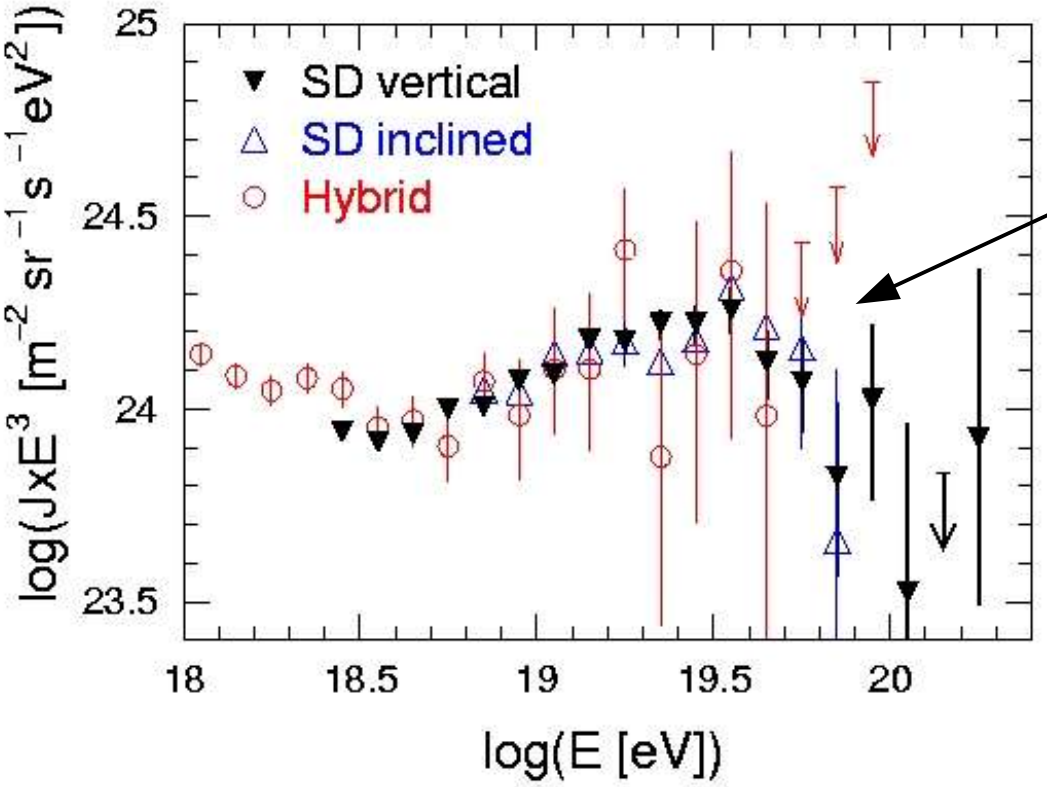
...but moving soon to DIAS, Dublin!

Who is accelerating UHECRs???

(see talk by Angela Olinto)



Hint for a suppression in the spectrum???

AUGER, ICRC2007

- ✔ **extreme sources!** must accelerate up to 10^{20}eV and more!
- ✔ can we do **CR astronomy?** (we don't know...) IGMF basically unknown
- ✔ **AUGER** statistics and better angular resolution...

A new possibility: searching for UHECR accelerators in gamma rays

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

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

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

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

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

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

Interactions with background photon fields and magnetic field

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

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

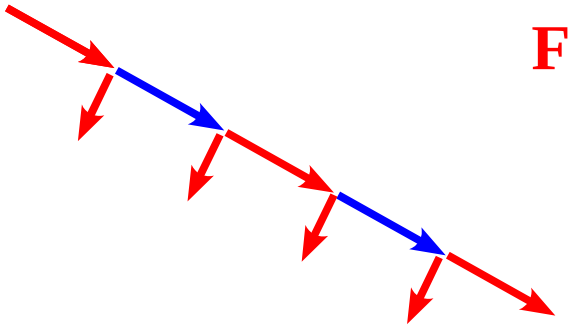
Can we detect these photons?
In which energy band?

Electromagnetic cascade initiated by a UHECR

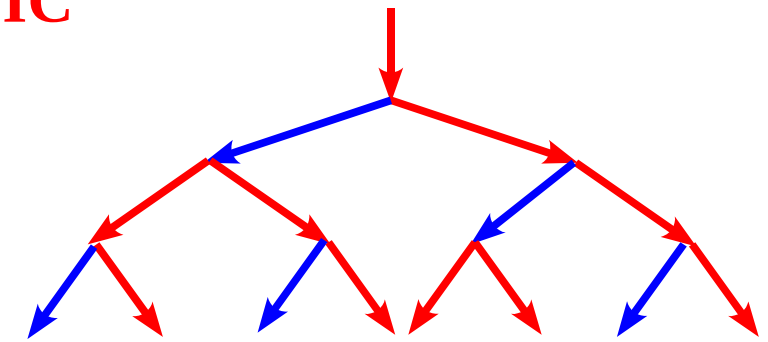
SG and Aharonian, 2005,2007

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

NO MAGNETIC FIELD!!!



Gould & Rephaeli,1978



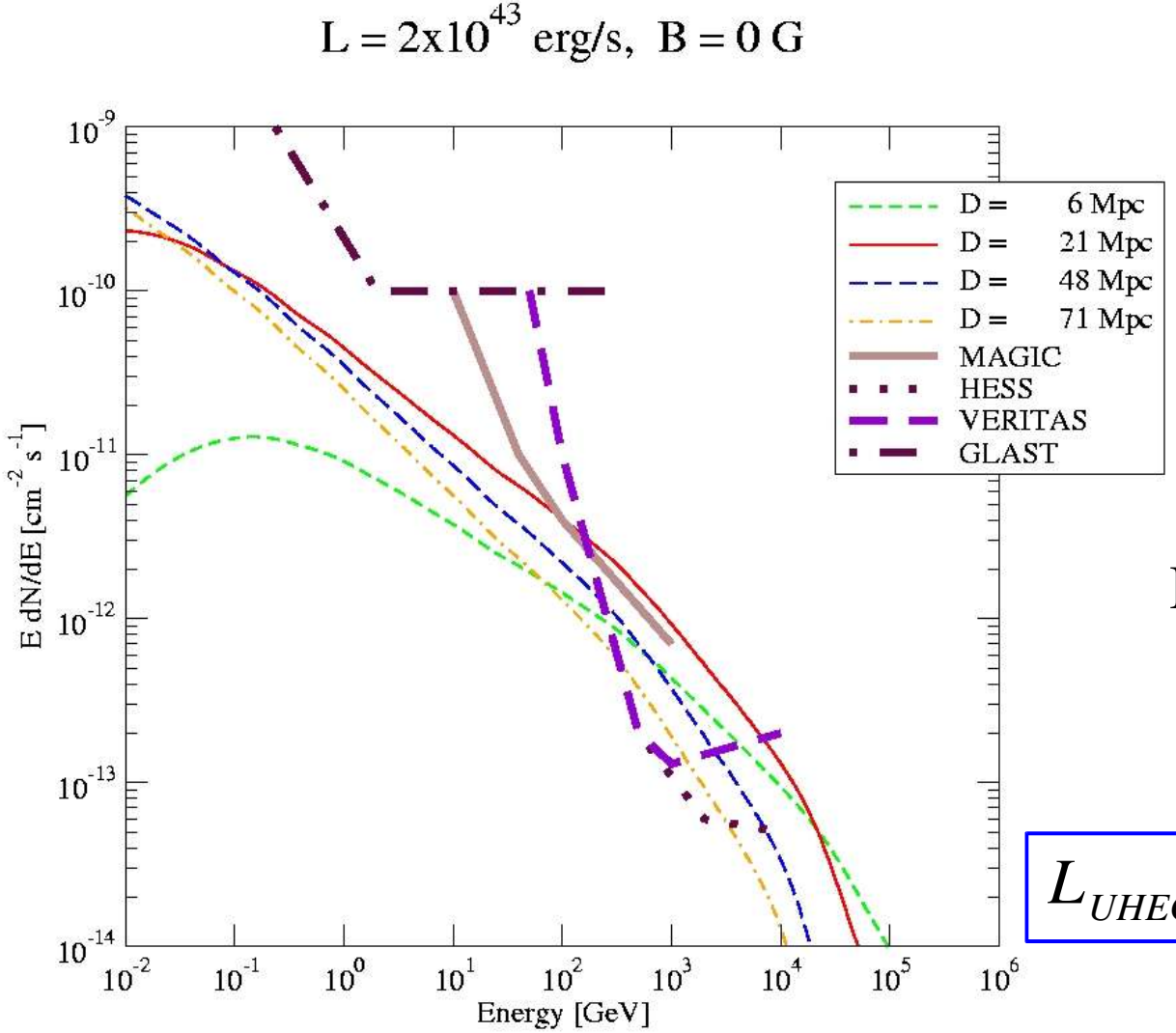
One leading particle!!!

Lots of particles

The case of the unmagnetized Universe

Ferrigno, Blasi and De Marco, 2005

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

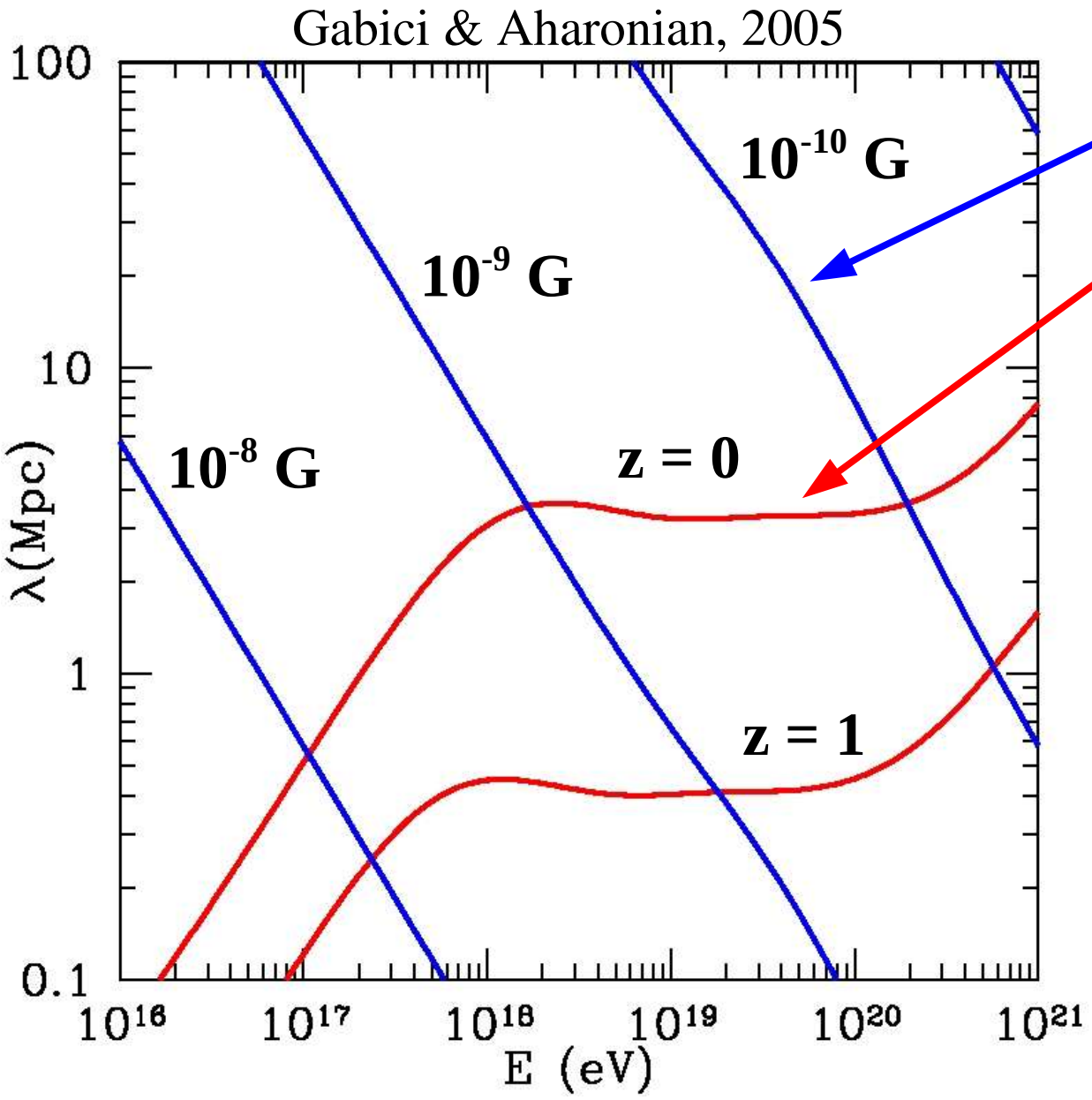


What does "unmagnetized" mean?

EM cascade might be observed @ TeV energies by Cherenkov telescopes

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

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



Synchrotron

Compton-pair production

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

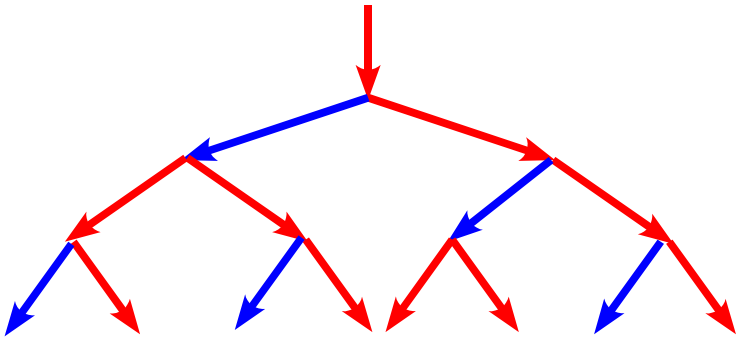
$$E_e = 5\cdot 10^{18}\, E_{p,20}\ \text{eV}$$

The cascade is suppressed if:

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

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) $B \ll B_{ISO} \sim 10^{-12}$ G $\rightarrow$ one-dimensional cascade

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

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

low energy electrons are isotropized, no energy losses

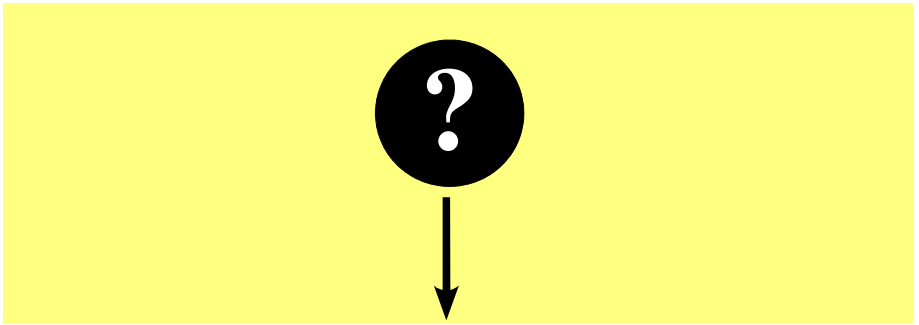
(3) $B \geq B_{syn}$ $\rightarrow$ no cascade

the development of the cascade is strongly suppressed

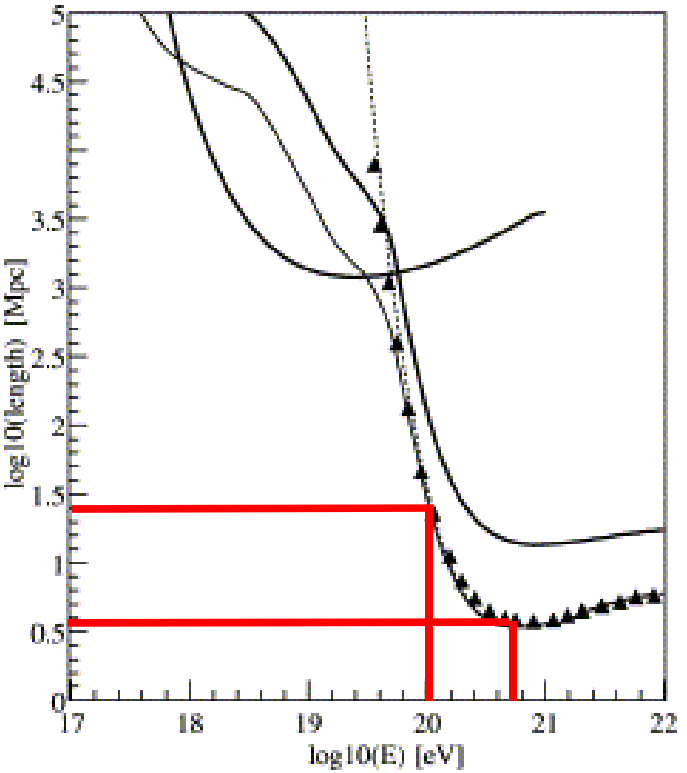
Regime 1: one-dimensional cascade

SG & Aharonian, 2007

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



proton interaction length

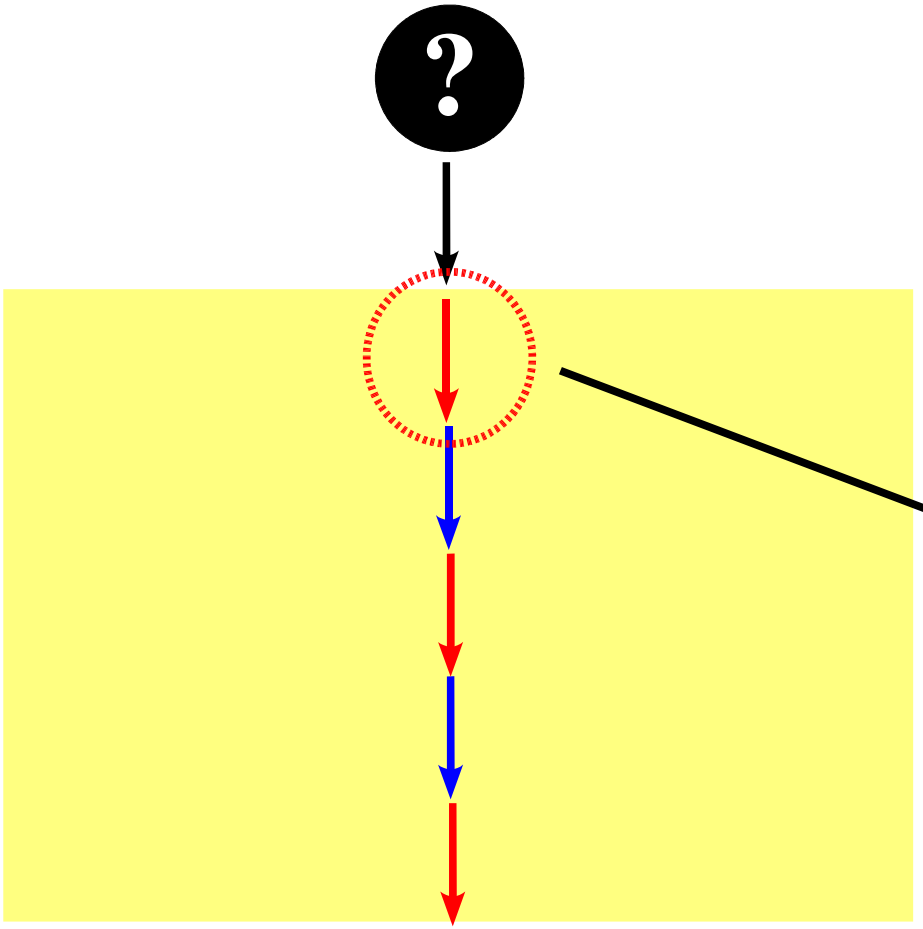


De Marco et al., 2004

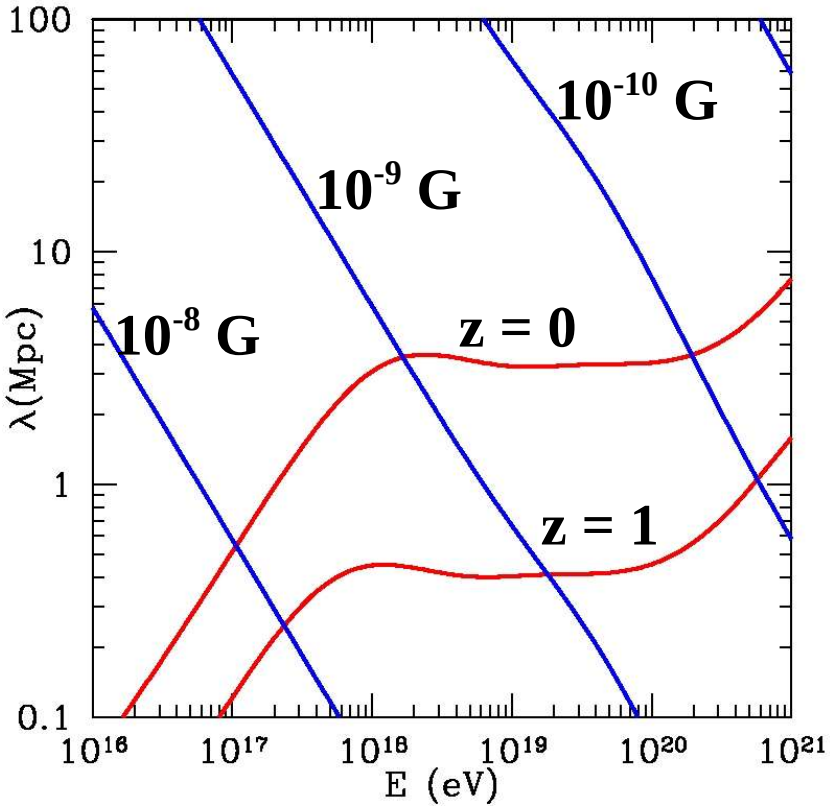
Regime 1: one-dimensional cascade

SG & Aharonian, 2007

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



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

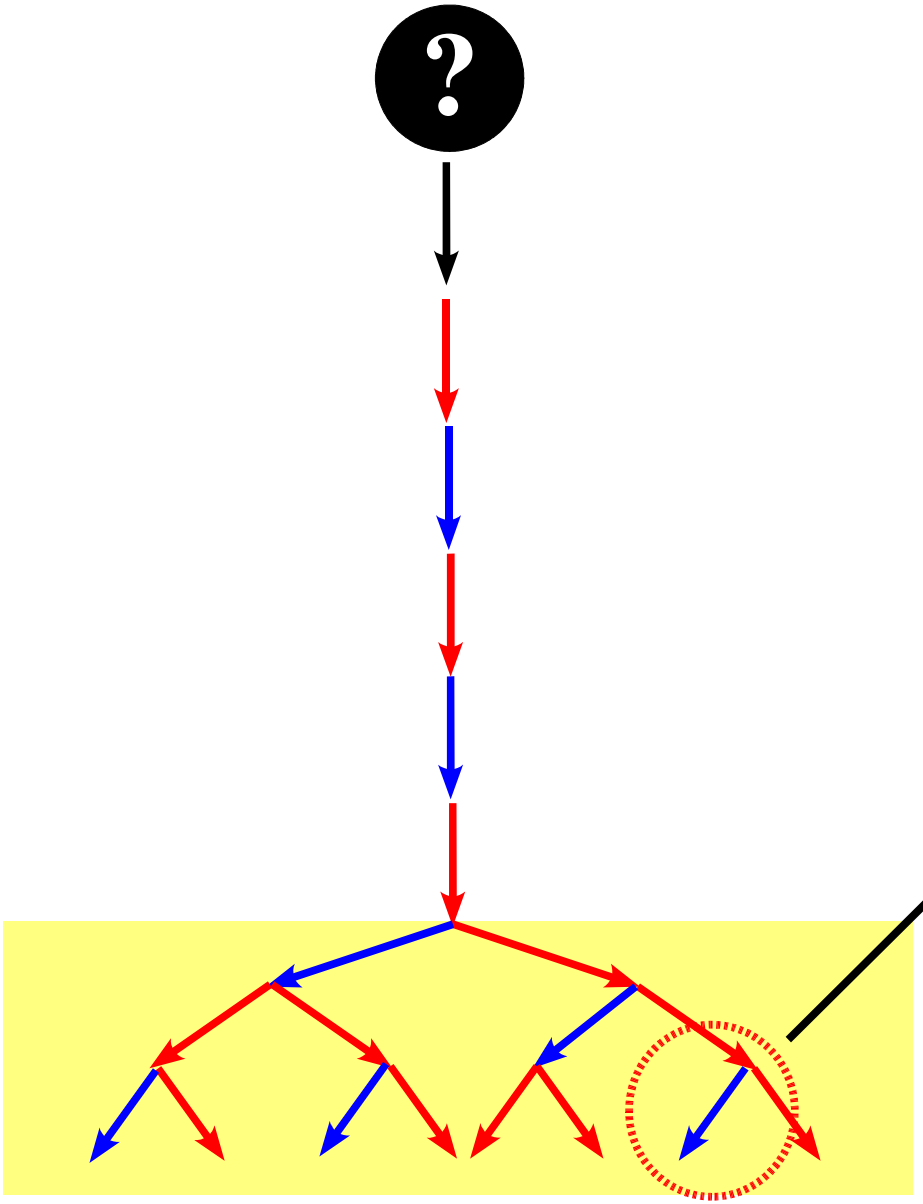


~ 5 – 10 Mpc

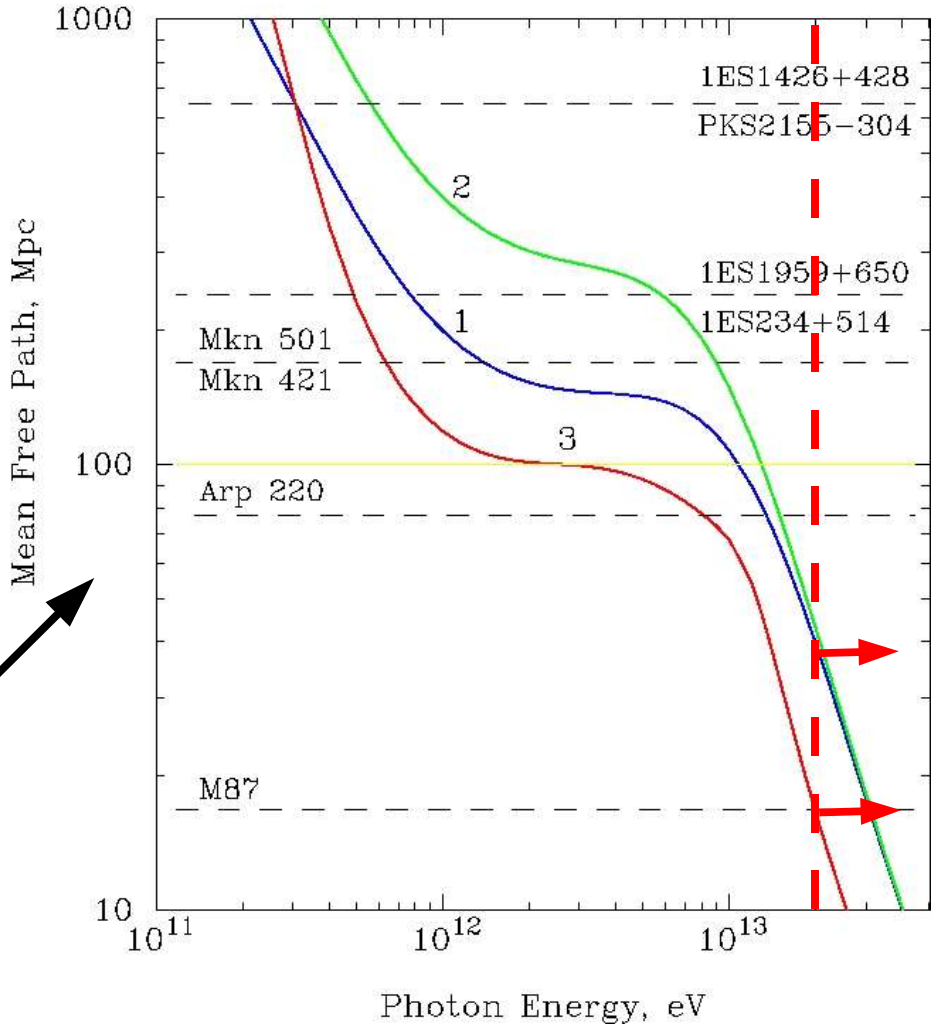
Regime 1: one-dimensional cascade

SG & Aharonian, 2007

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



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

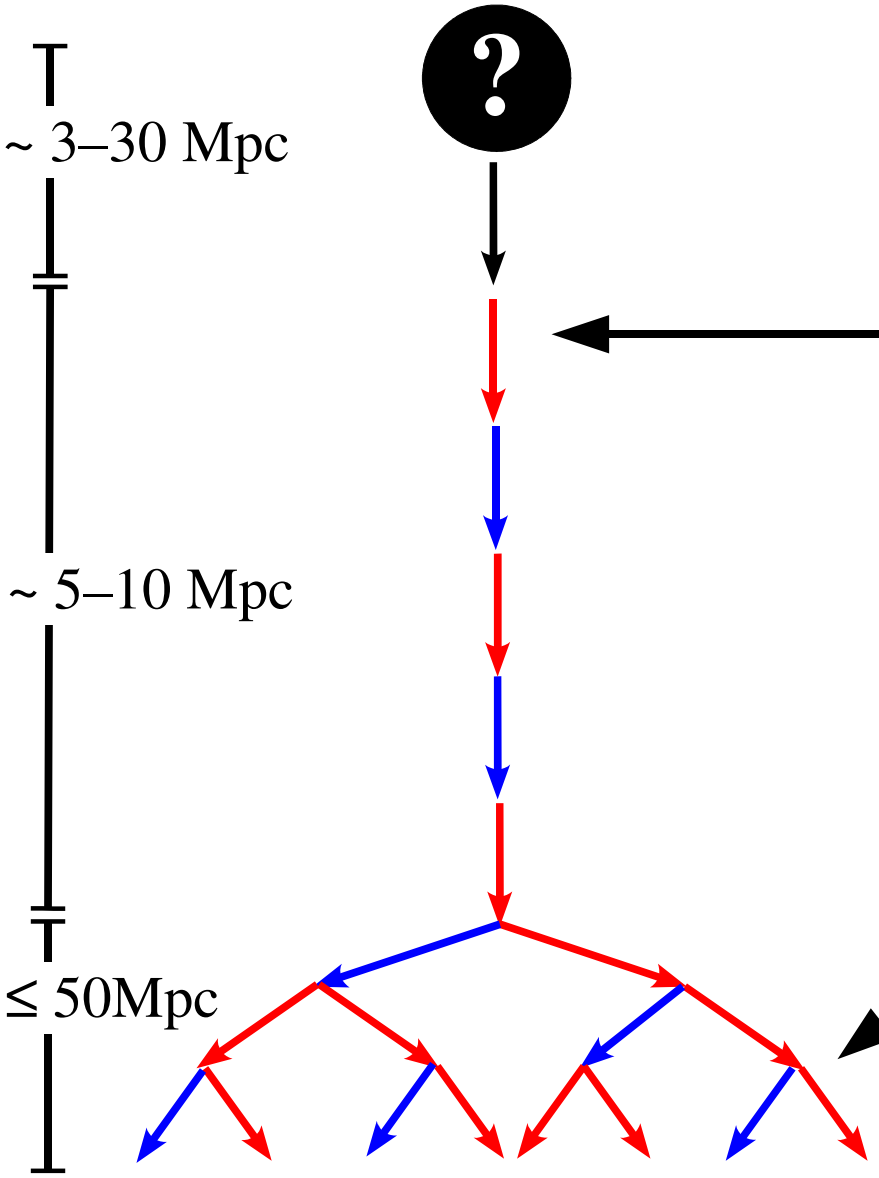


Aharonian, 2001

Regime 1: one-dimensional cascade

SG & Aharonian, 2007

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



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

to avoid energy losses

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

to avoid isotropization

it is a very small magnetic field!

but not ruled out...

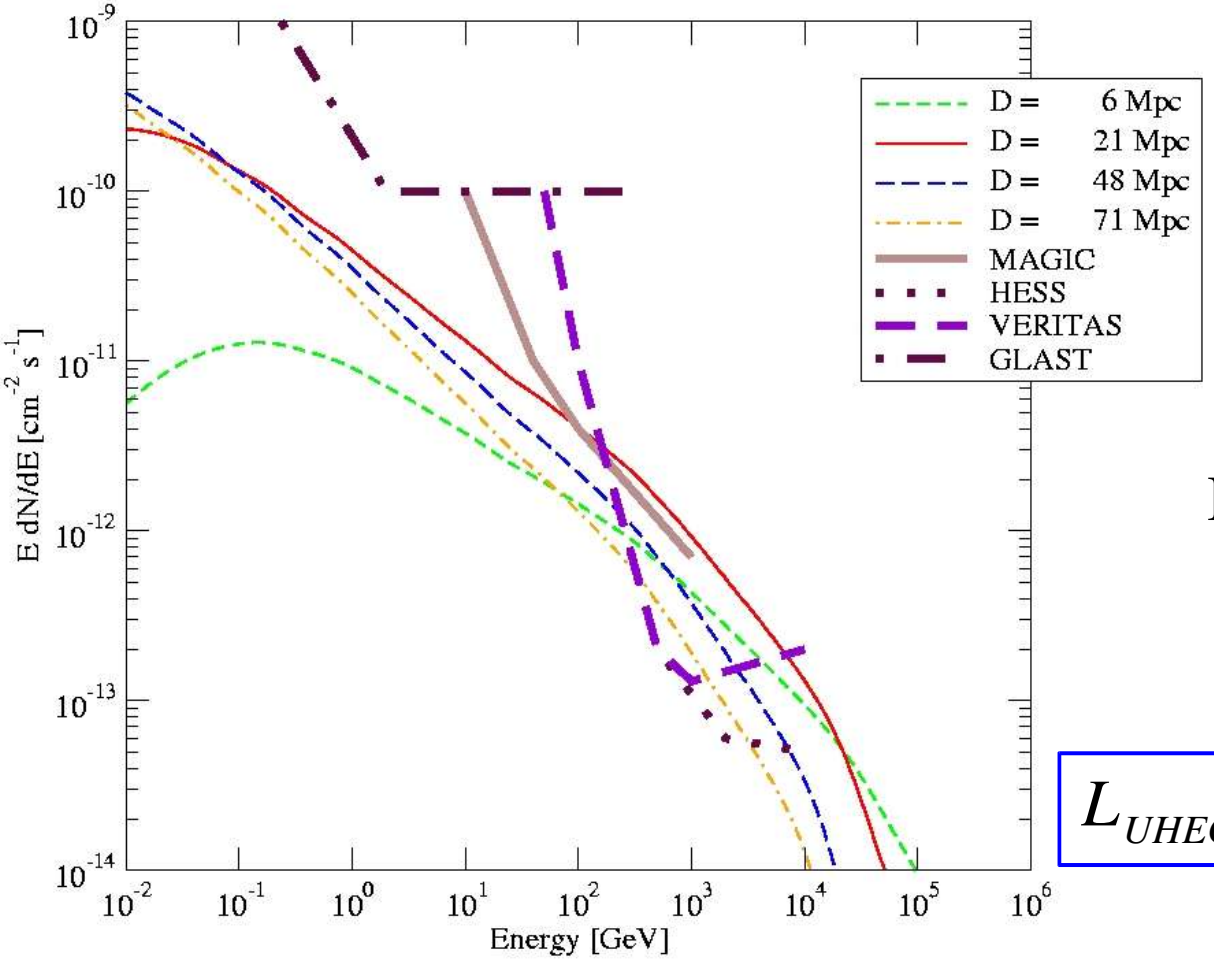
Regime 1: one-dimensional cascade

(Ferrigno, Blasi and De Marco, 2005)

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

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

$L = 2 \times 10^{43}$ erg/s, B = 0 G



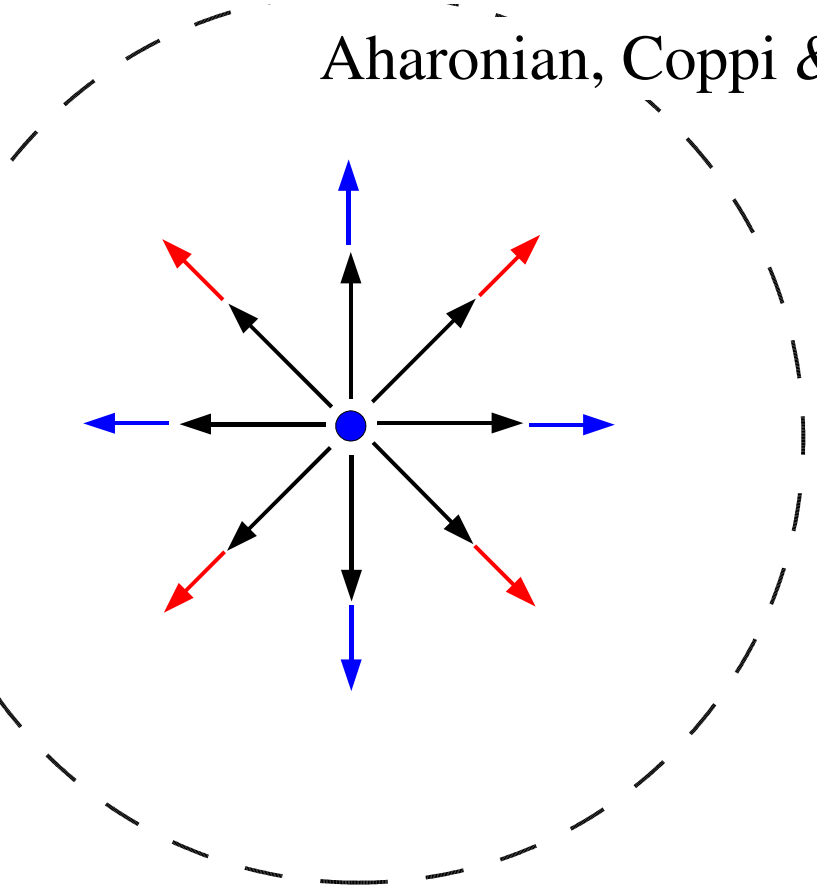
EM cascade might be observed @ TeV energies by Cherenkov telescopes

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

Regime 2: giant pair halo

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

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



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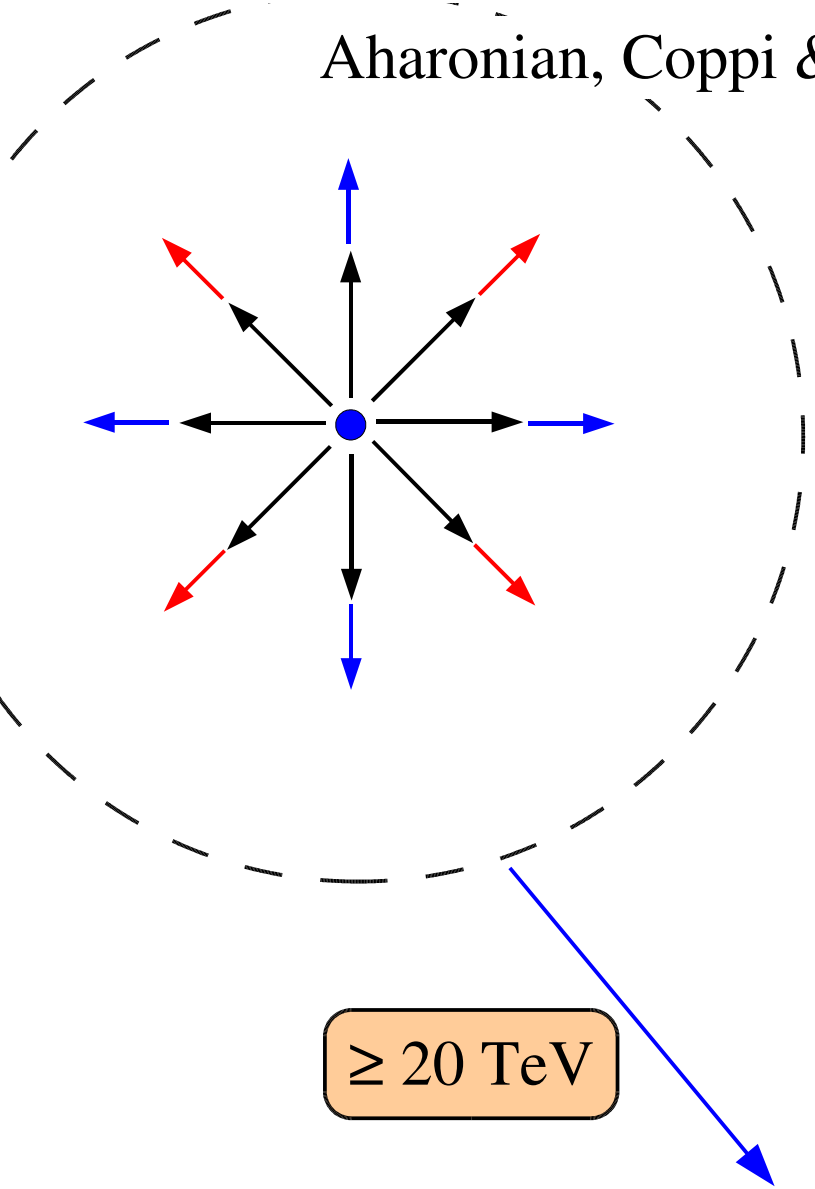

≥ 20 TeV

Regime 2: giant pair halo

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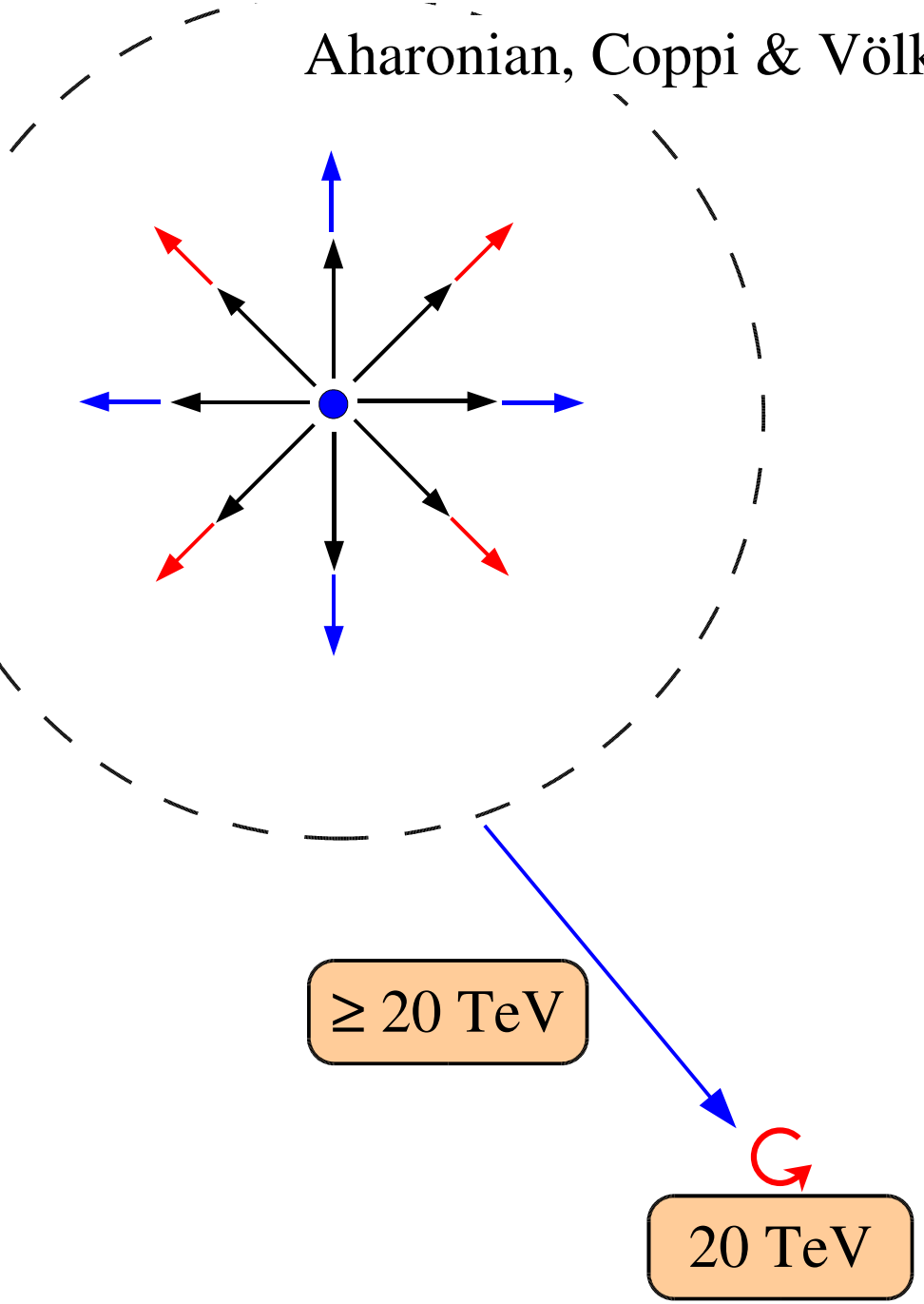

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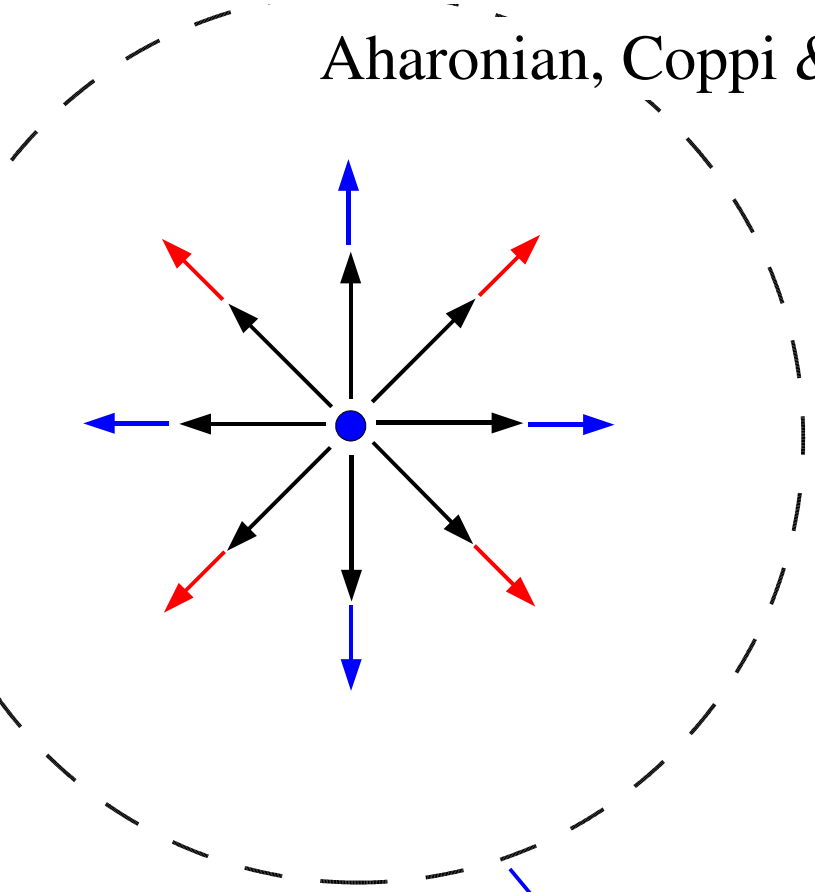
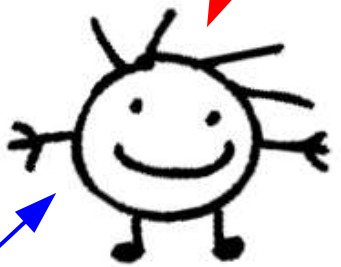




you (observer)

1 TeV

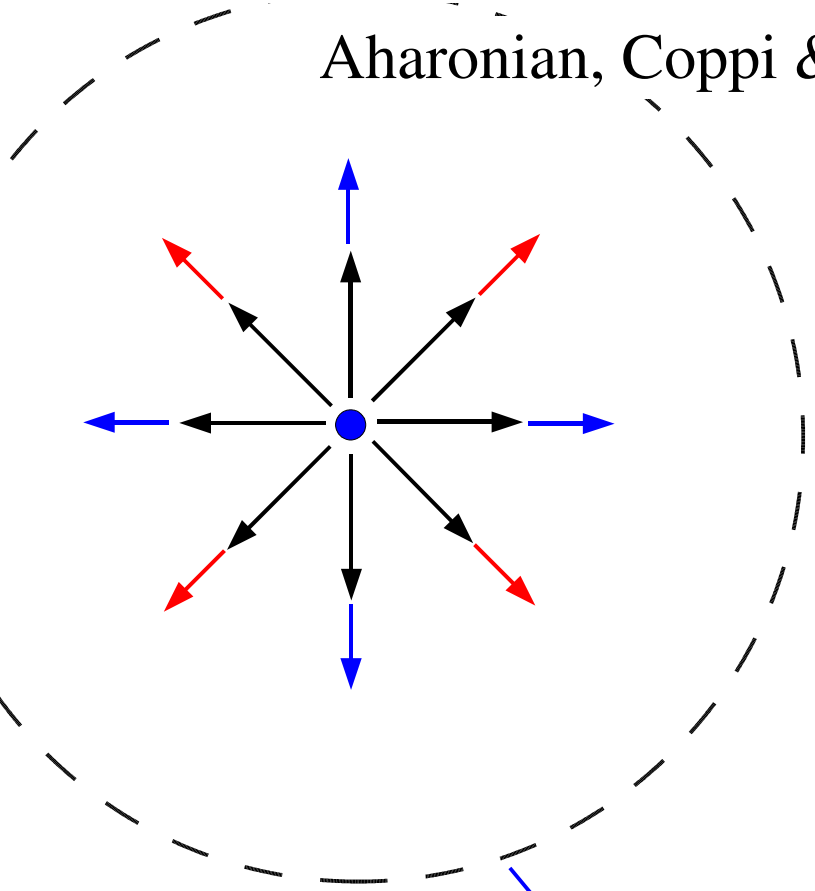
≥ 20 TeV

20 TeV

Regime 2: giant pair halo

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

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



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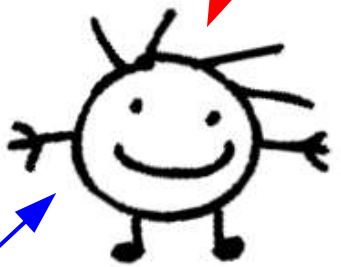


1 TeV

conservative (!!!)
estimate of the halo size

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

≥ 20 TeV

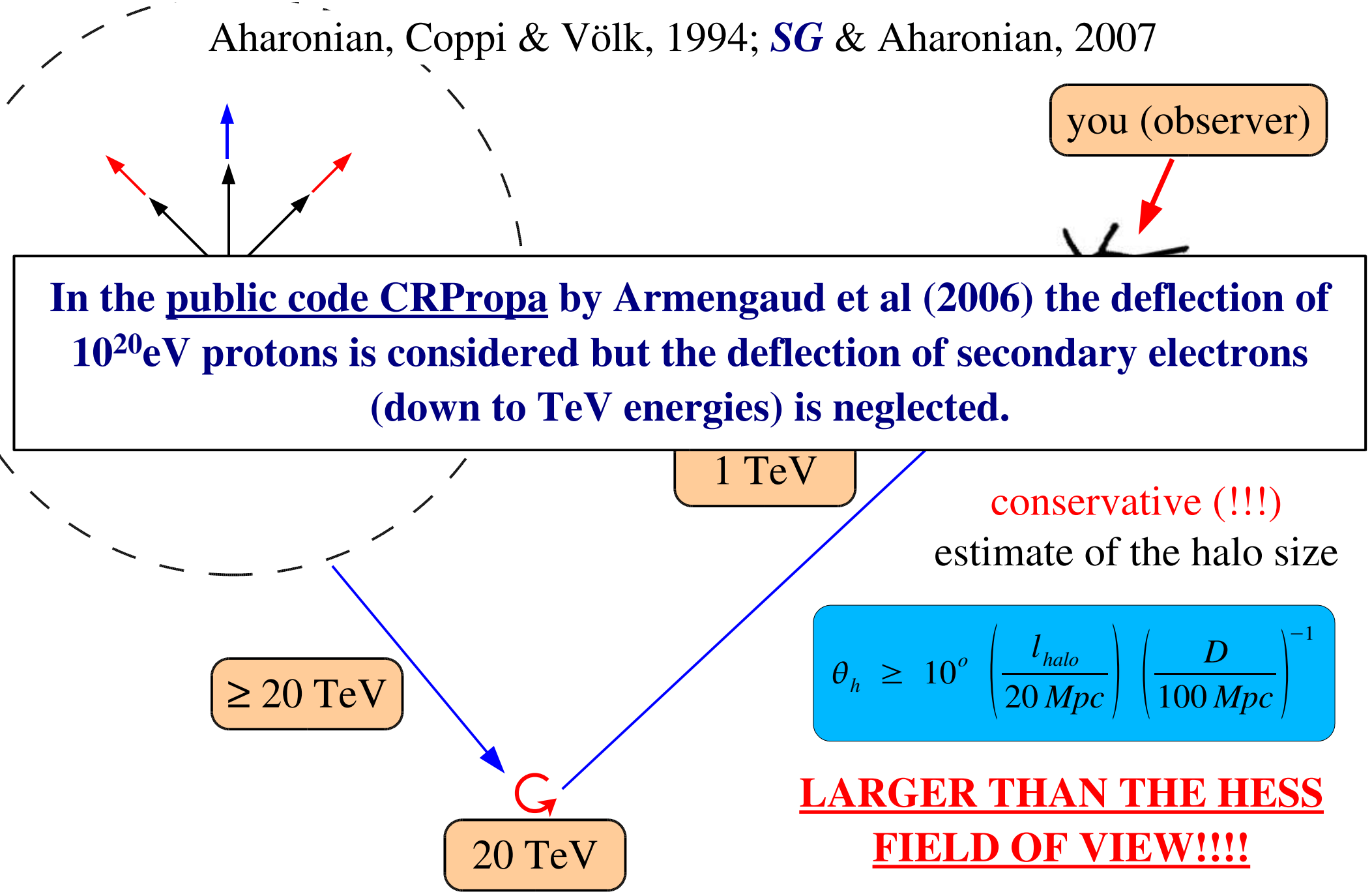
20 TeV

LARGER THAN THE HESS FIELD OF VIEW!!!!

Regime 2: giant pair halo

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

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



conservative (!!!)
estimate of the halo size

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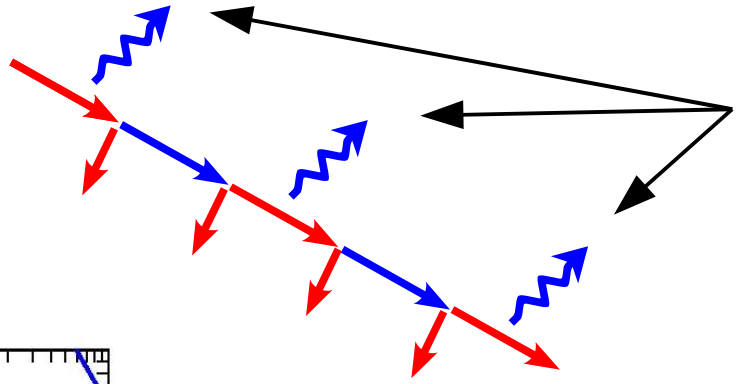
LARGER THAN THE HESS FIELD OF VIEW!!!!

Regime 3: synchrotron gamma ray emission

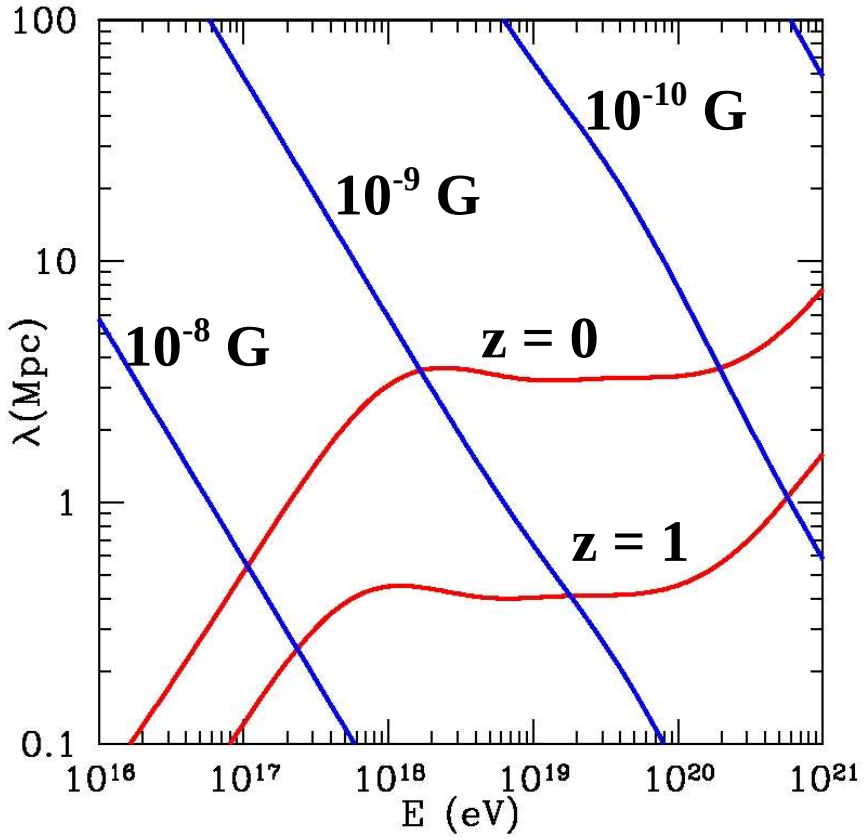
SG and Aharonian, 2005,2007

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

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



synchrotron photons

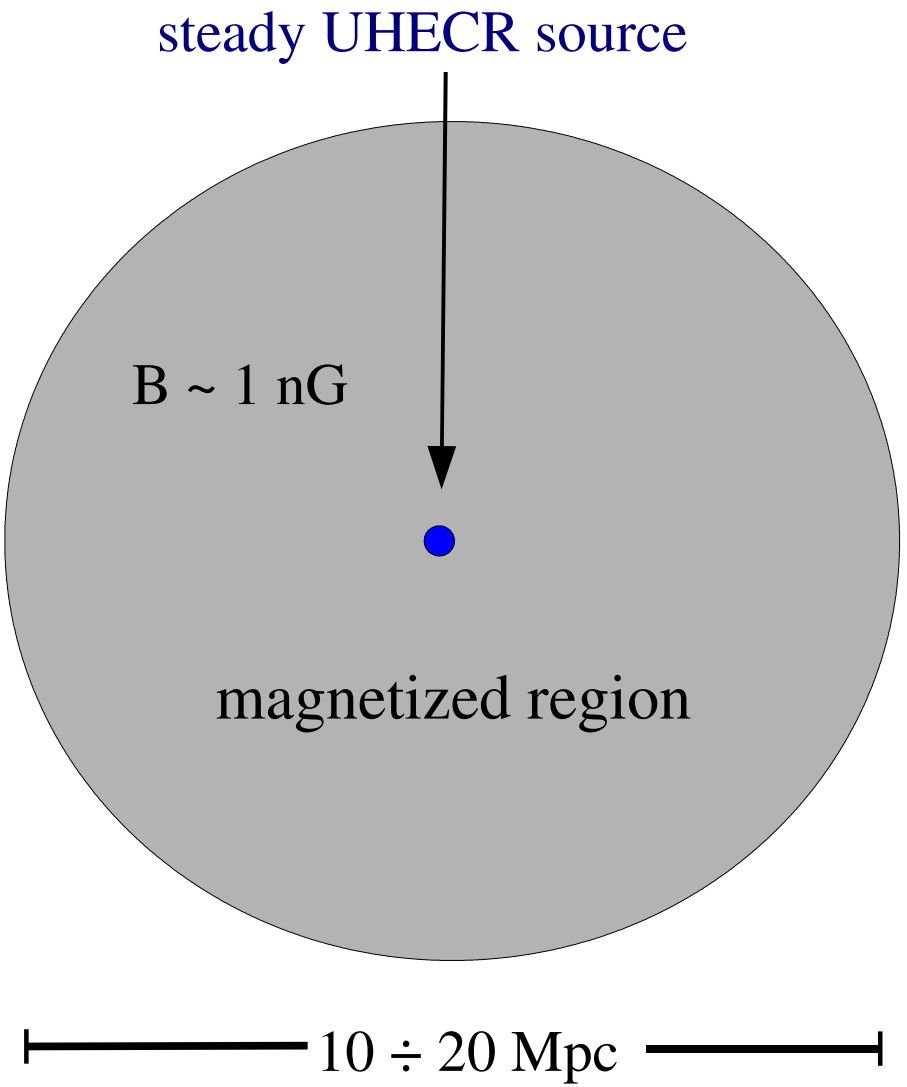


$$E_{syn} \sim 2 \left(\frac{B}{nG}\right) \left(\frac{E}{10^{19} eV}\right)^2 GeV$$

GLAST energy range!!!

⇦ Gabici & Aharonian, 2005

New way to identify UHECR sources!



super clusters?
bigger than the interaction
loss length!

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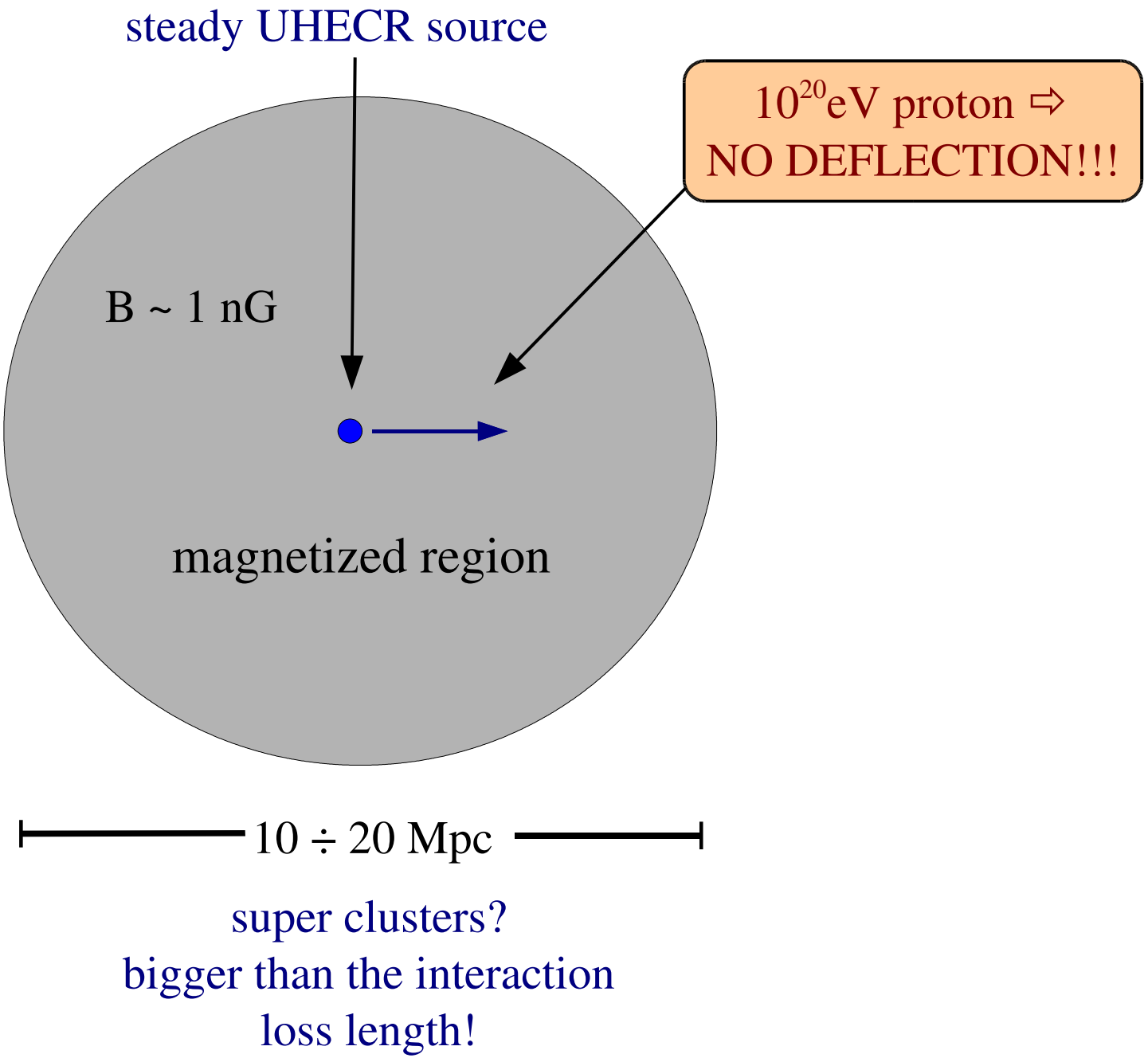

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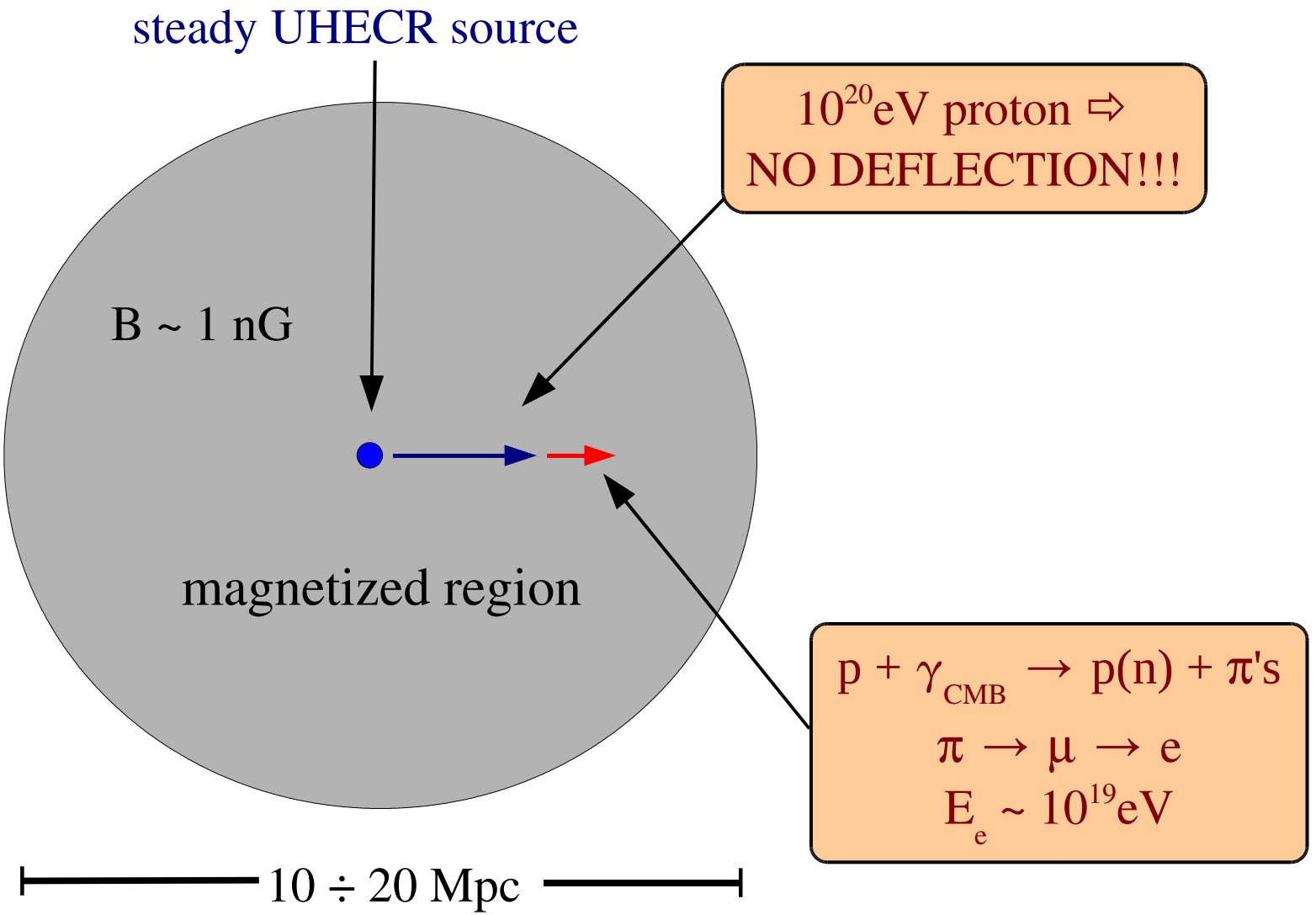

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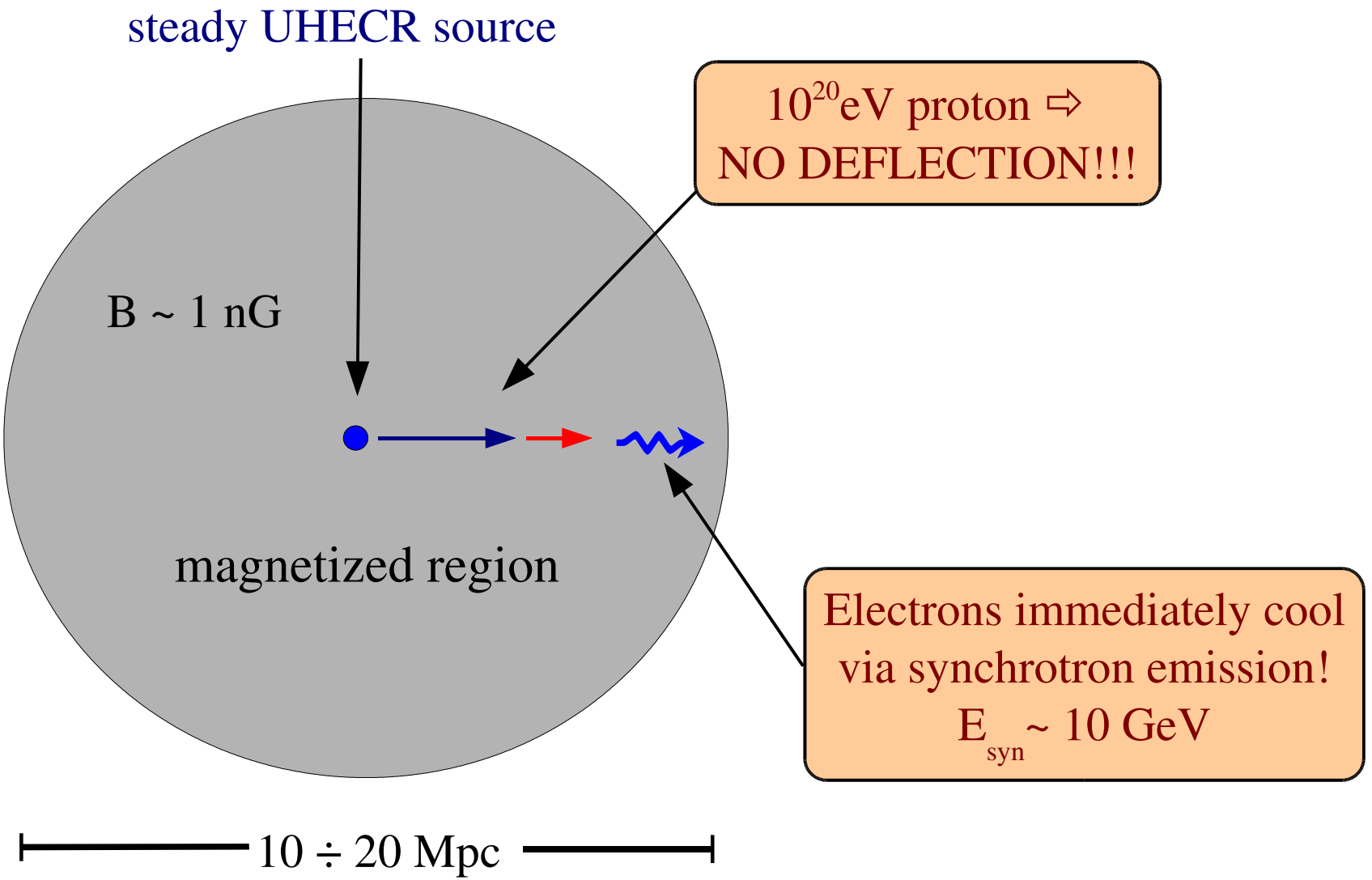

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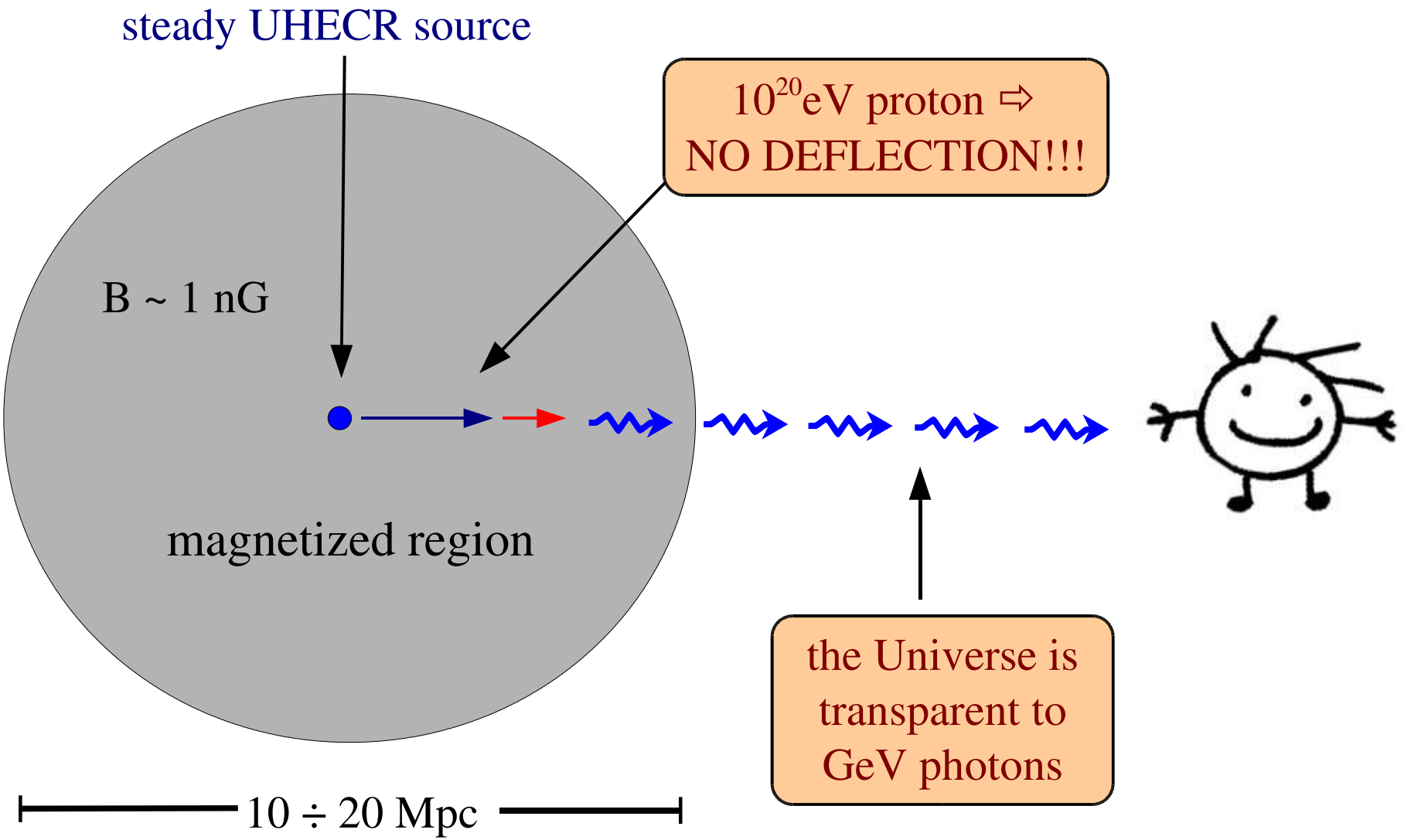

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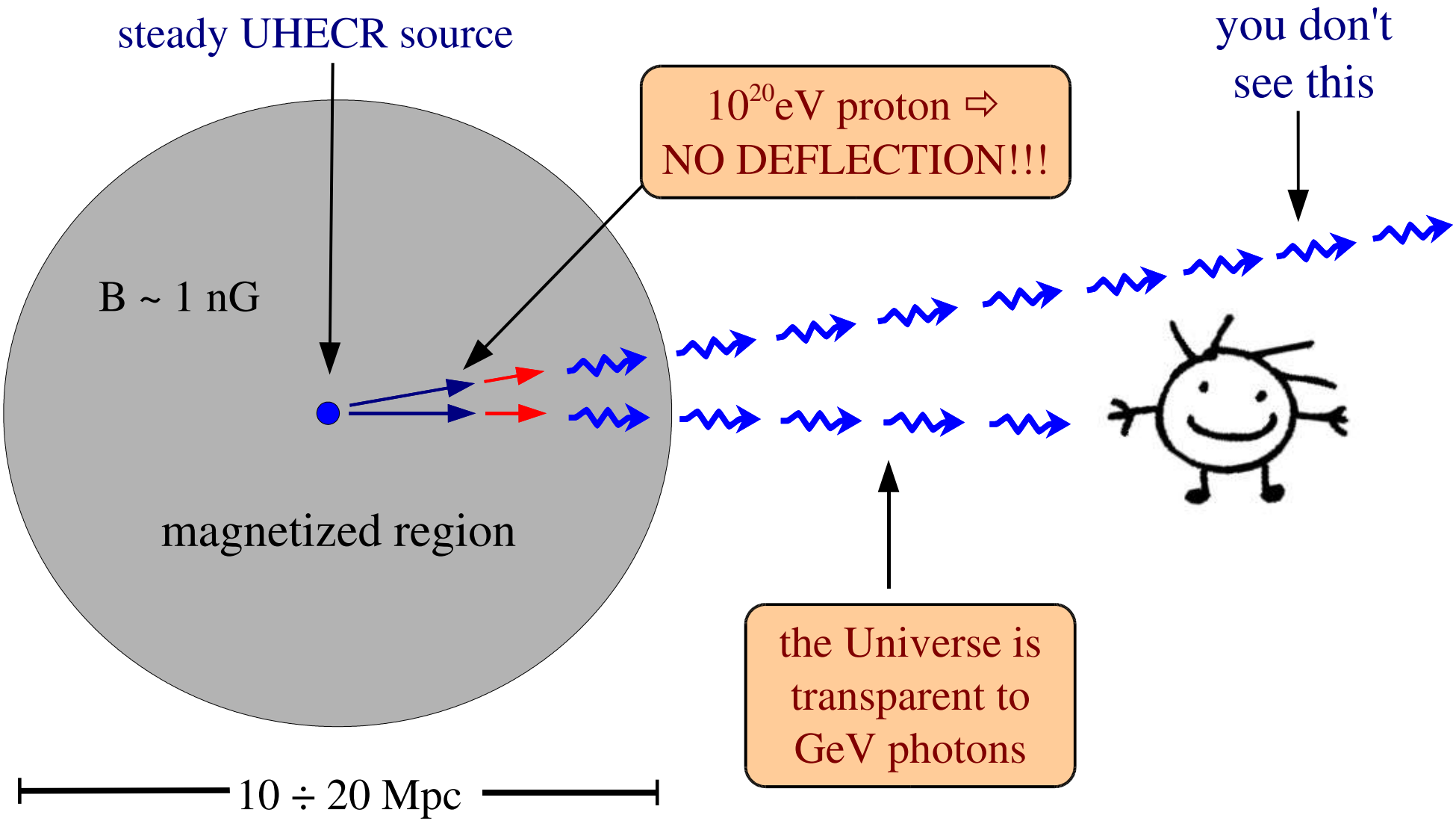

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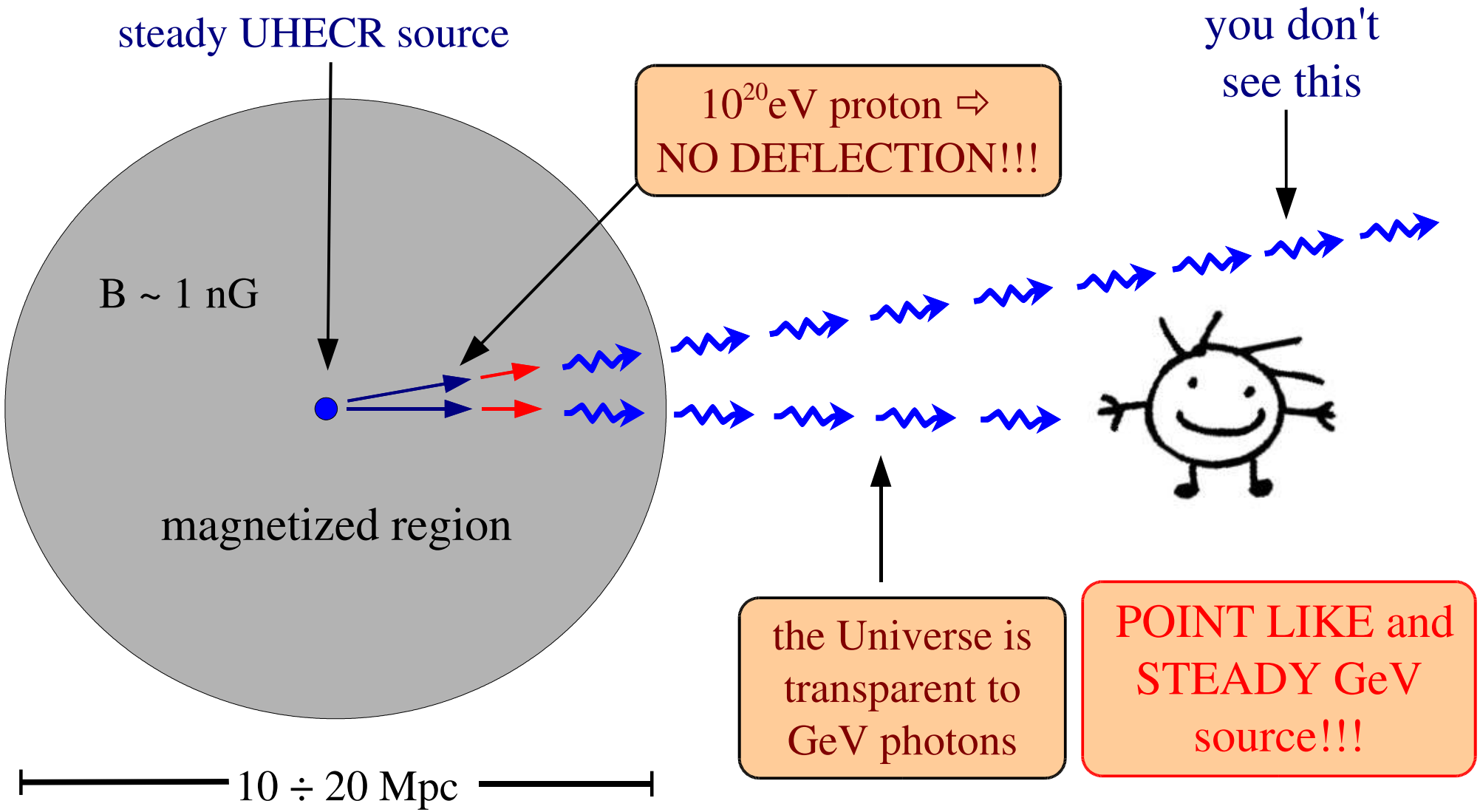

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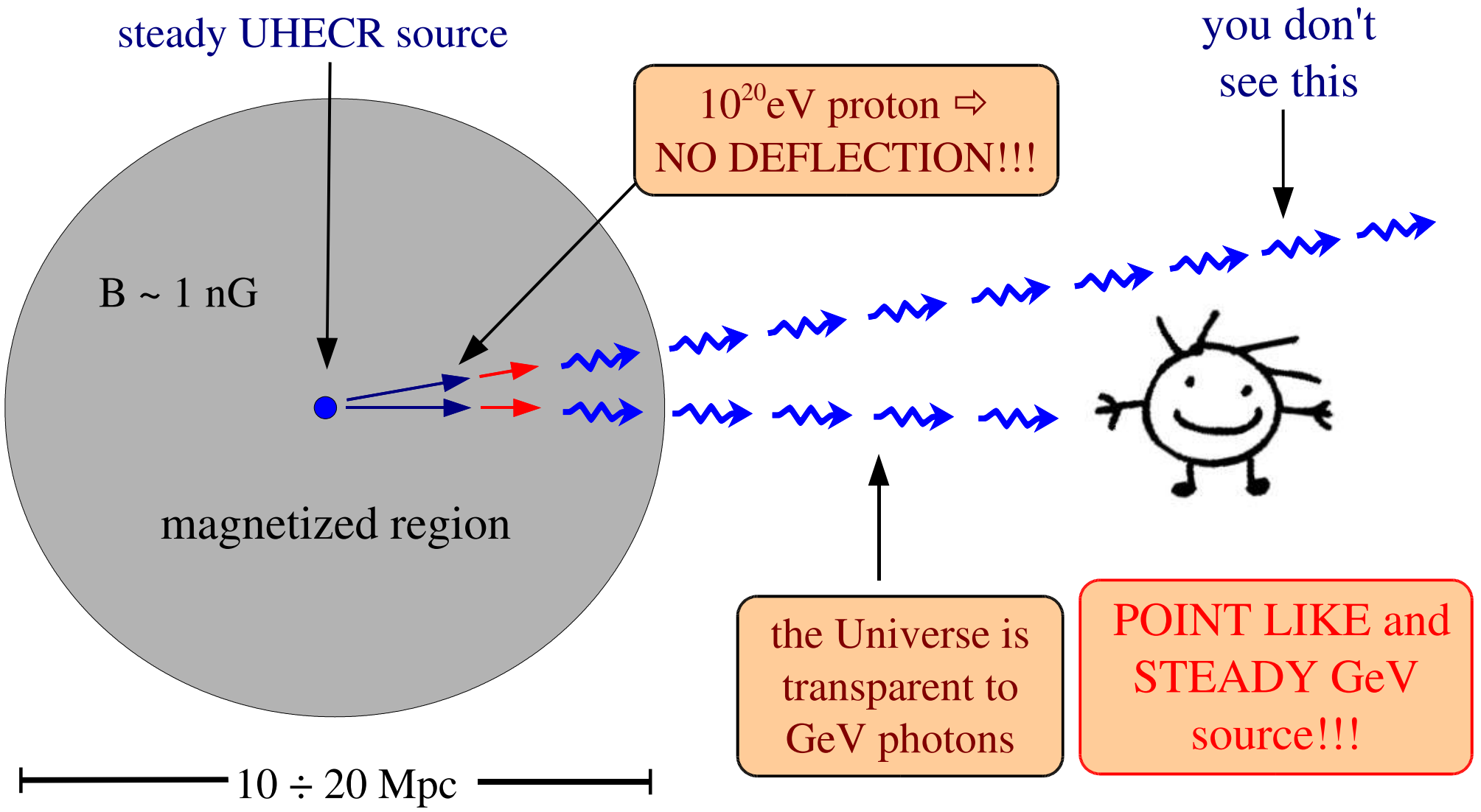
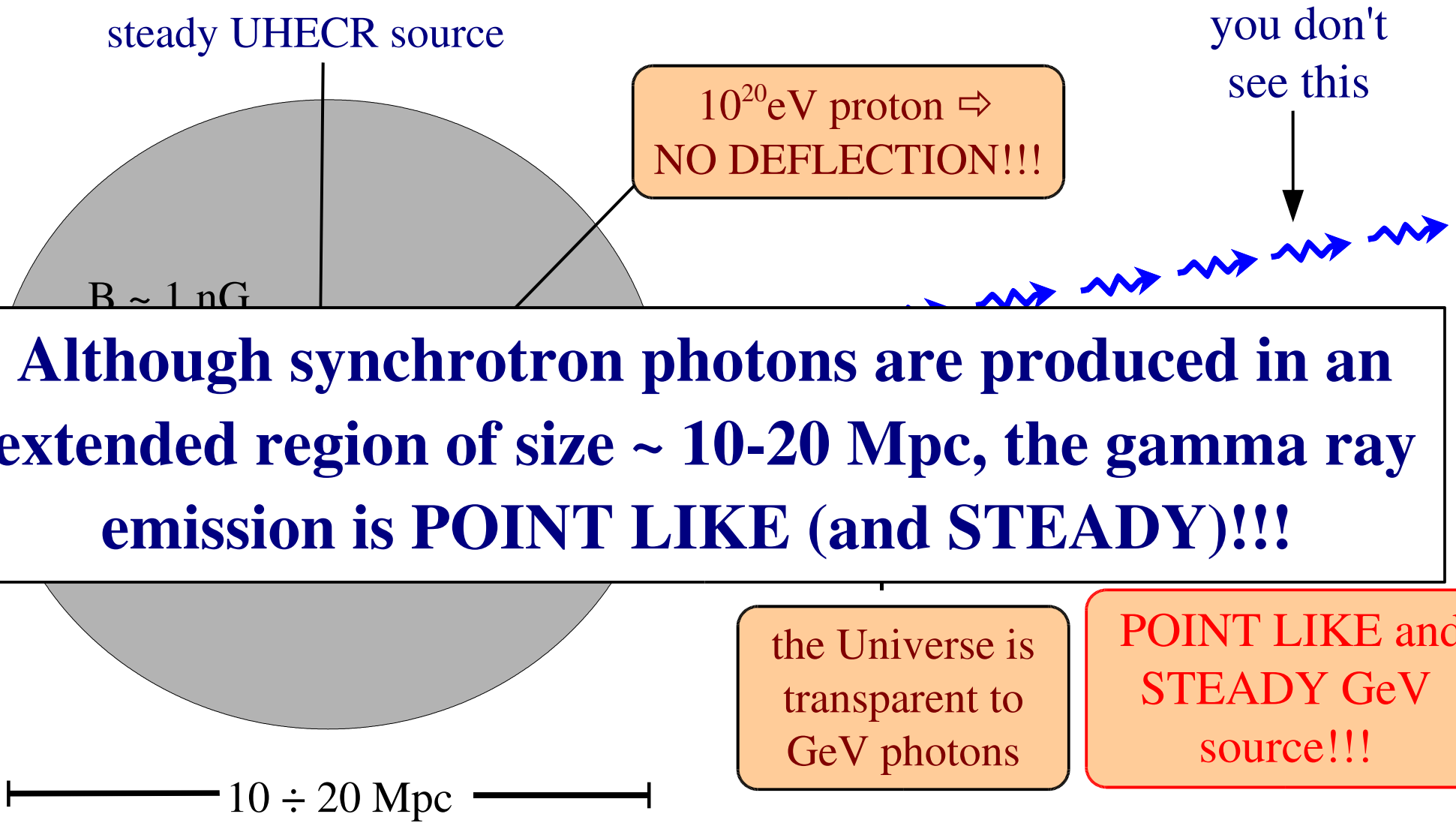


UHE neutrinos ⇨ $E_\nu^2 F_\nu \sim 1 \frac{EeV}{km^2\, yr}$ @ $E_\nu = 5 \cdot 10^{18}\, eV$ ANITA, AUGER?

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)!!!

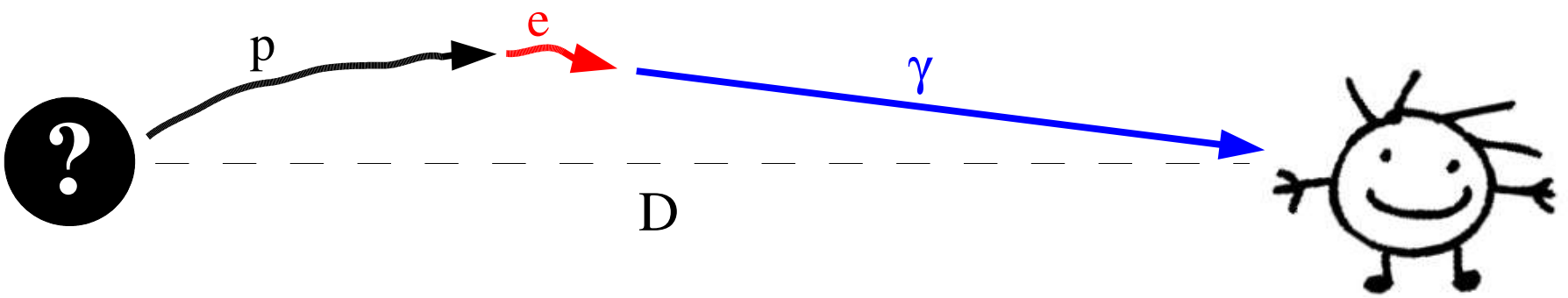
the Universe is transparent to GeV photons

POINT LIKE and STEADY GeV source!!!

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

Quantitative estimates: angular size

SG and Aharonian, 2005,2007



for B = 1 nG

$$\theta_{syn} \approx \left(\theta_p + \theta_e\right)\left(\frac{l_p}{D}\right) \approx \textit{frac of degree}$$

@ 100 Mpc

comparable with the GLAST angular resolution!

GLAST $\rightarrow$ D $\gtrsim$ 100 Mpc

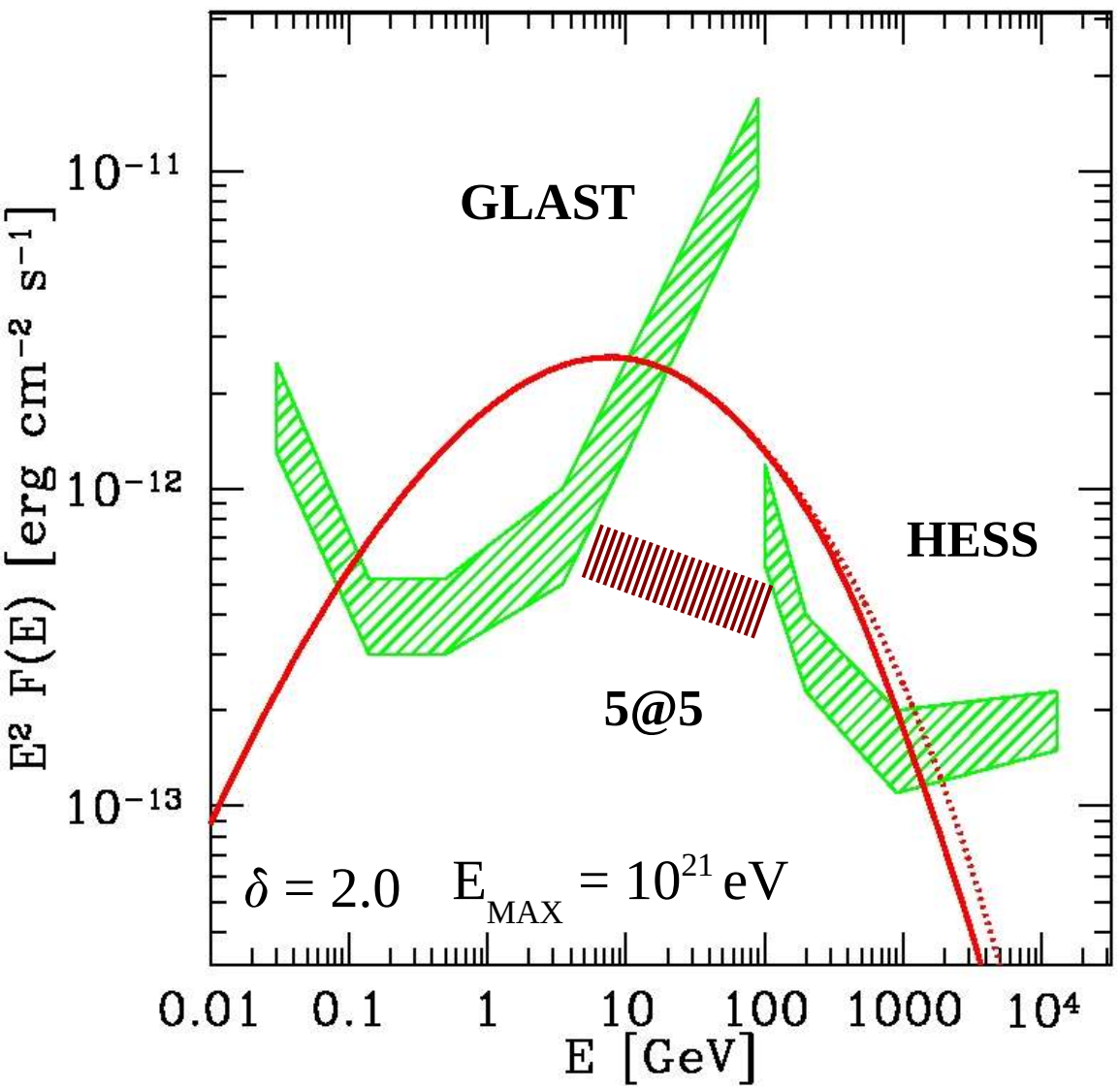
HESS $\rightarrow$ D $\gtrsim$ 1 Gpc

HESS large field of view $\rightarrow$ 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:

$$L_{UHECR} > 8\,10^{43} \div 2\,10^{44} \left(\frac{D_L}{100\,Mpc} \right)^2 \frac{erg}{s}$$

$$\delta = 2.0 \div 2.3$$

Beaming can reduce the energy by a factor:

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

AGN Jets

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

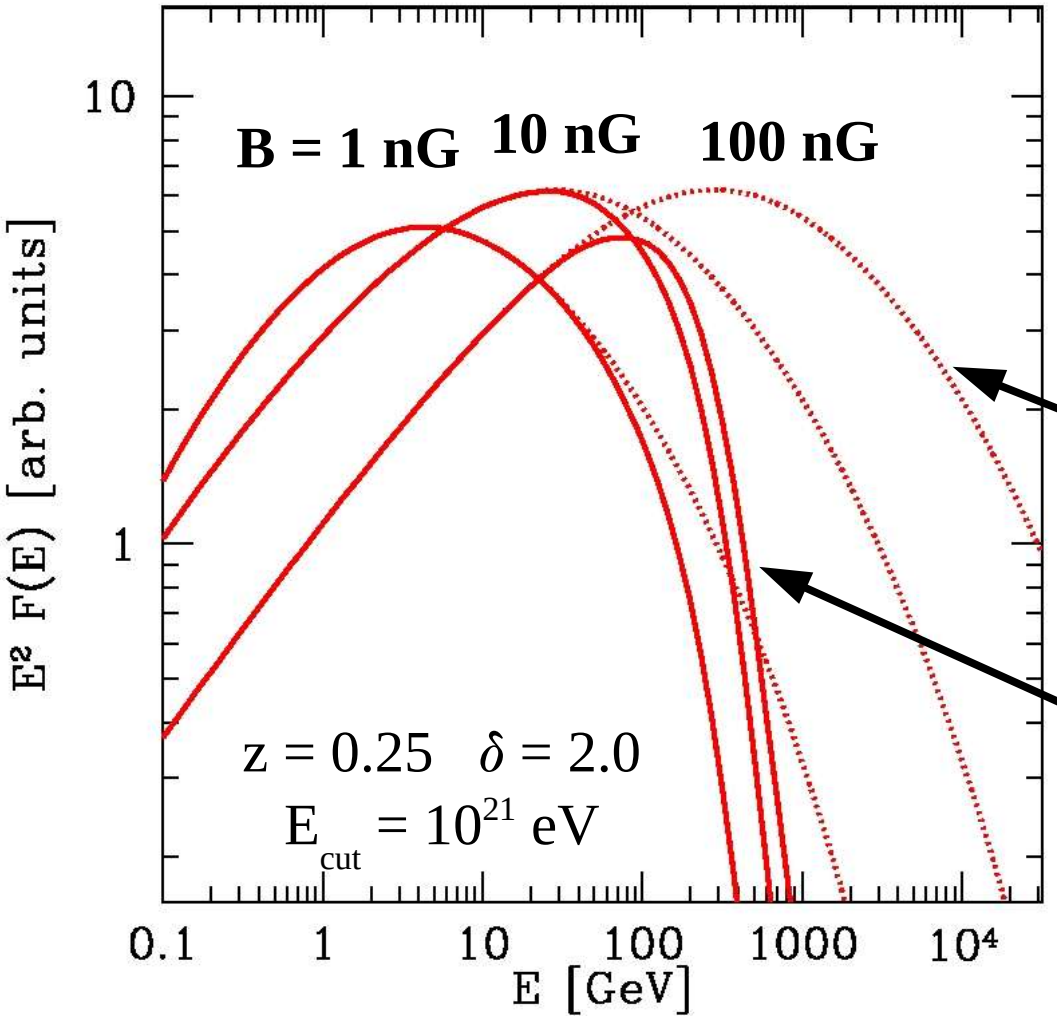
Ghisellini&Celotti,2001

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

The effect of the magnetic field

B << 0.5 nG

no synchrotron!



B >> 50 nG

ABSORPTION!

close source
HESS!

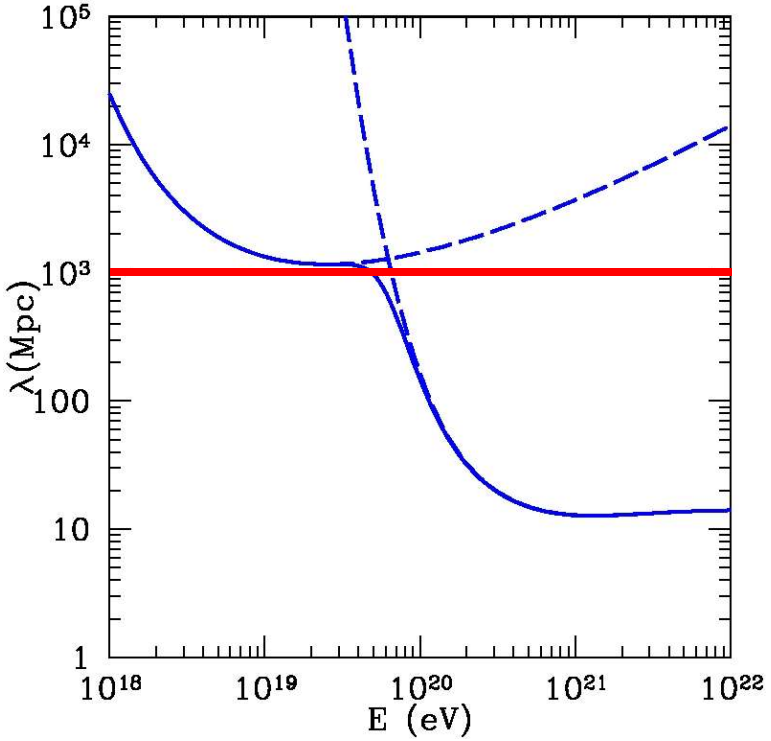
distant source
ABSORPTION!

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

$$\theta_p \approx 10^o \left(\frac{B}{5\,10^{-10}\,G}\right)\left(\frac{E}{5\,10^{19}\,eV}\right)^{-1}$$

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

Detectability condition:

$$L_{UHECR} > 10^{44}\left(\frac{D}{1\,Gpc}\right)^2\left(\frac{\theta_b}{10^o}\right)\frac{erg}{s}$$

Conclusions

- ✔ UHECR sources: still a mystery
- ✔ CR astronomy? → Intergalactic magnetic field basically unknown!
- ✔ An exciting possibility: gamma ray counterparts
- ✔ Three different scenarios:

(1) $B \ll 10^{-12}$ G → 1D cascade — $2\ 10^{43}$ erg/s @ 100 Mpc @ TeV

(2) 10^{-12} G $\leq B \ll 10^{-9}$ G → giant pair halo — **UNDETECTABLE!**

(3) $B \geq 10^{-9}$ G → no cascade — ***BUT SYNCHROTRON!!!***

point like & steady emission - 10^{44} erg/s @ 100 Mpc @ GeV-TeV's

- ✔ Coincidence between CRs and γ 's depending on deflection