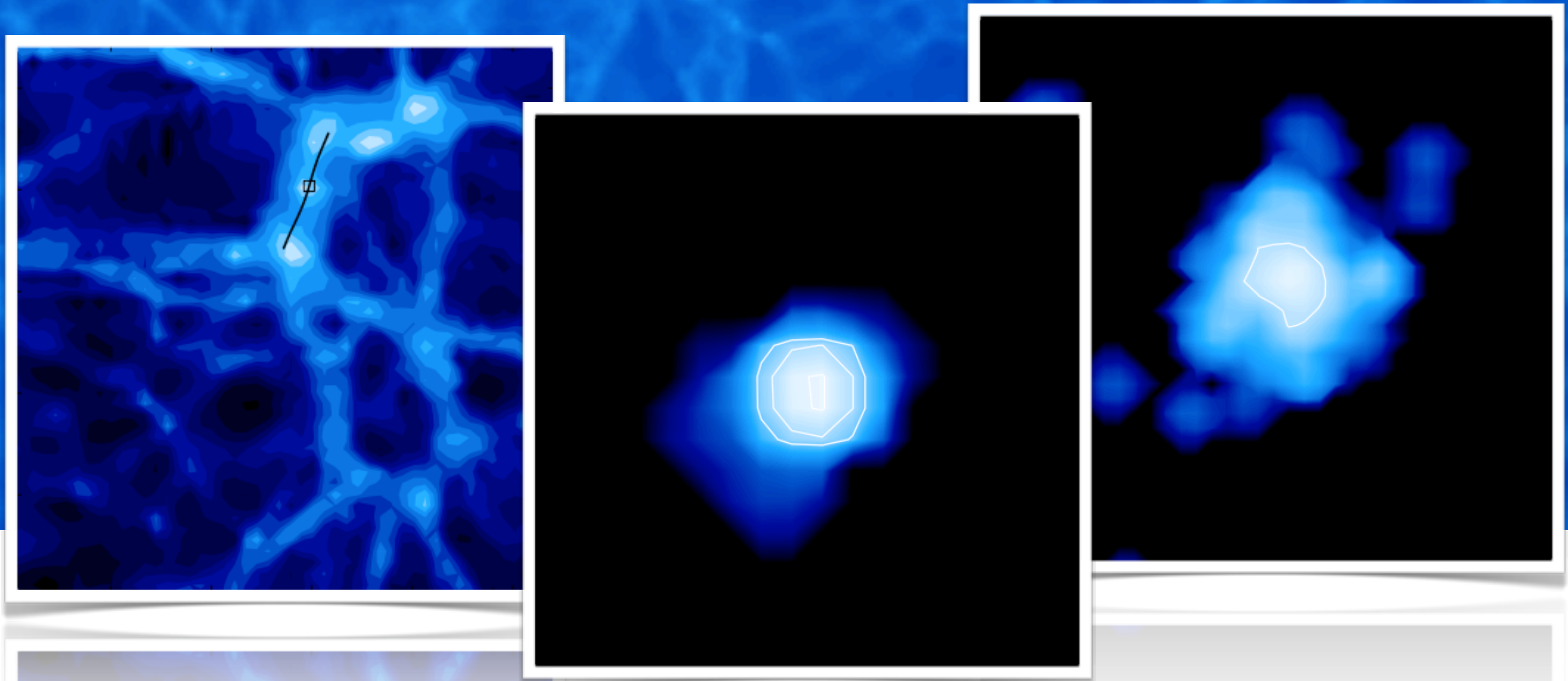
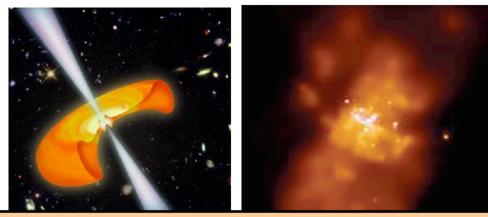
Are signatures of ultrahigh energy cosmic rays detectable in gamma rays?

K.K., D. Allard and M. Lemoine, submitted to A&A



Why do we care about multi-messenger Astrophysics at UHE?



astrophysical sources

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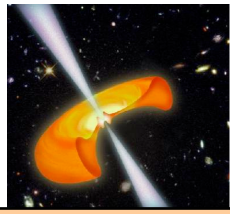

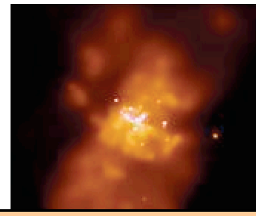

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acceleration (ex. in shocks)

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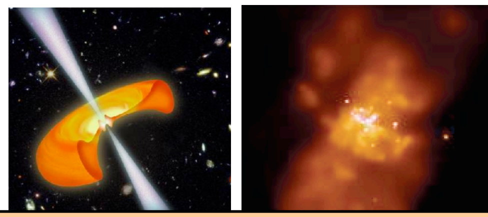

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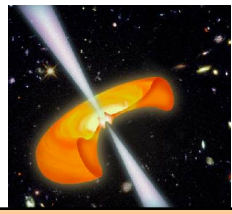

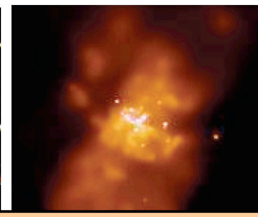

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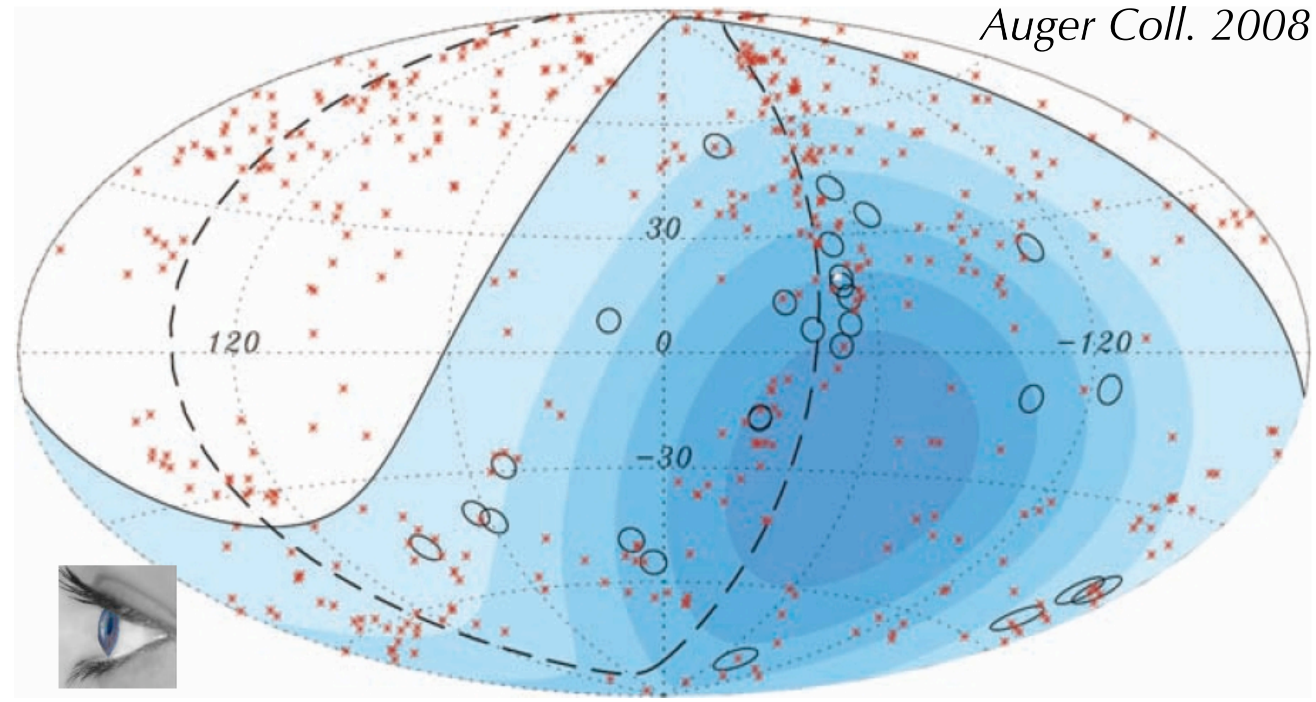

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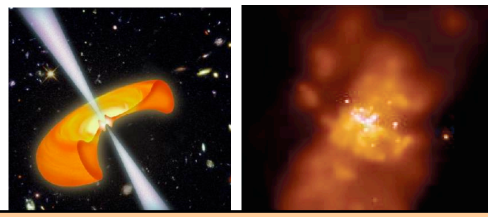

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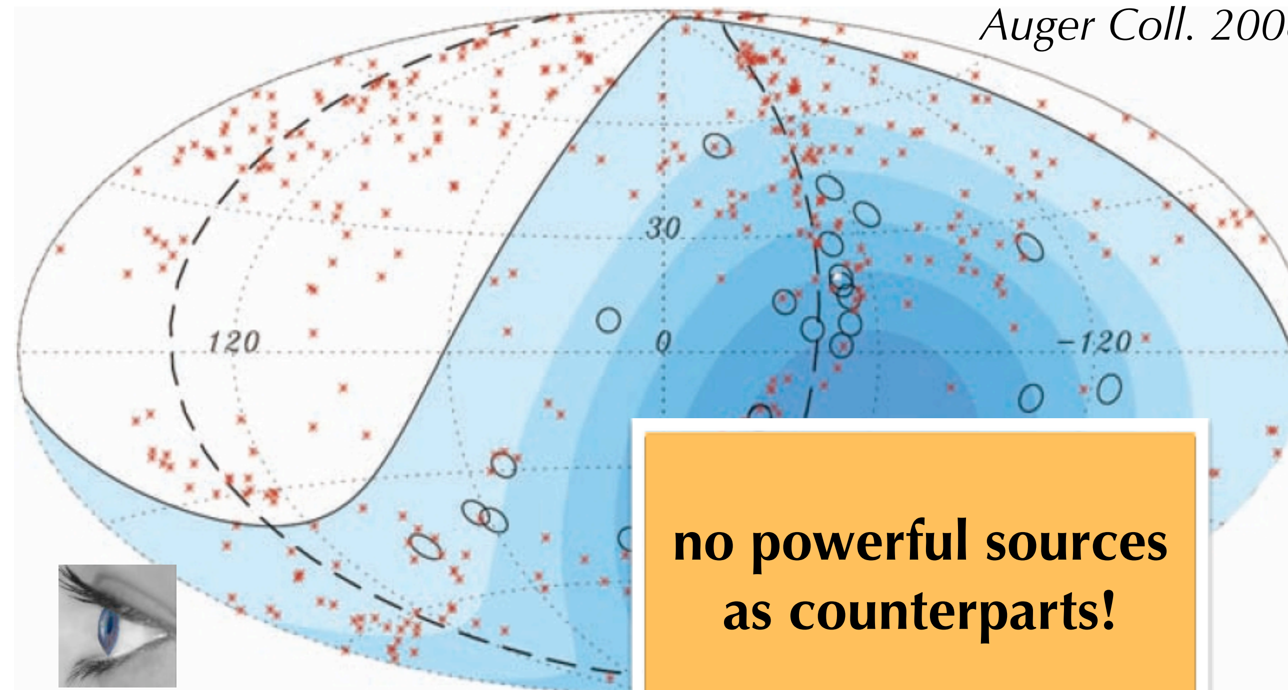

Auger Coll. 2008

no powerful sources
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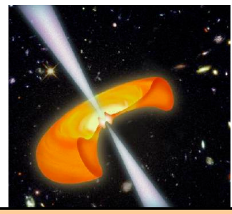

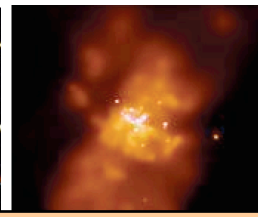

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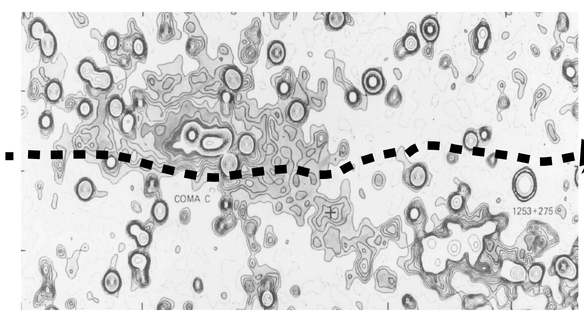

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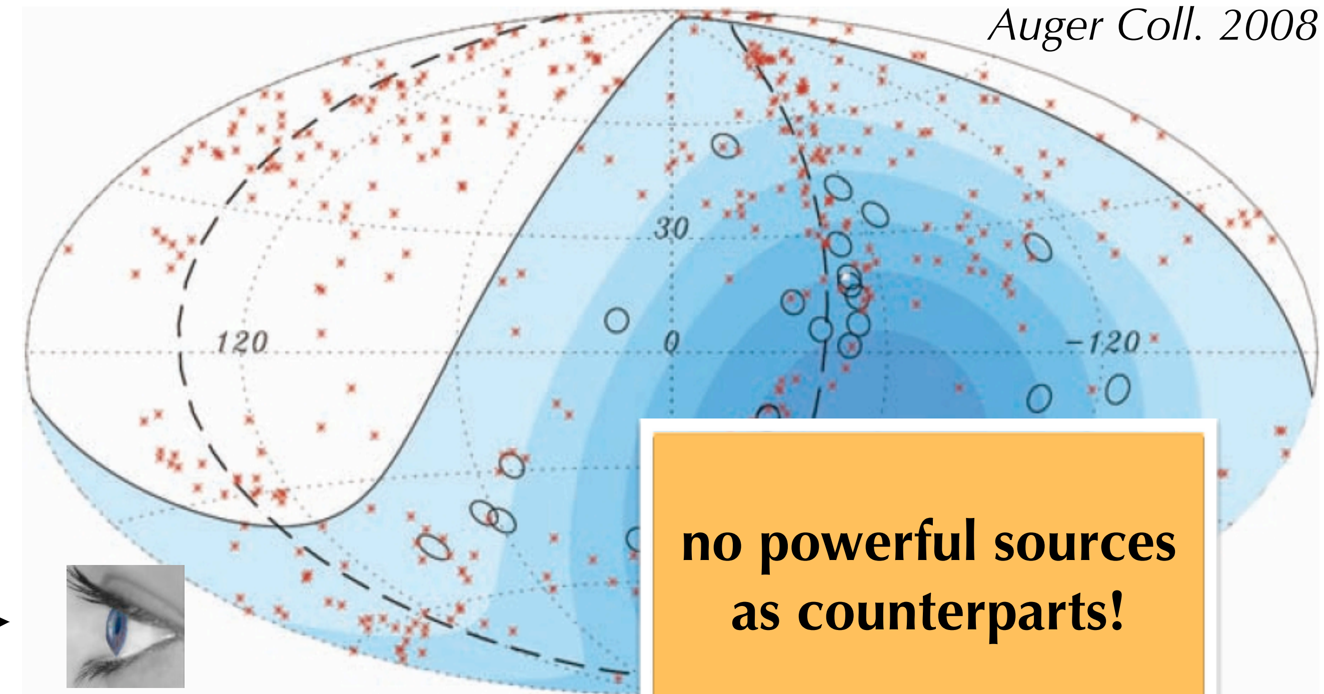

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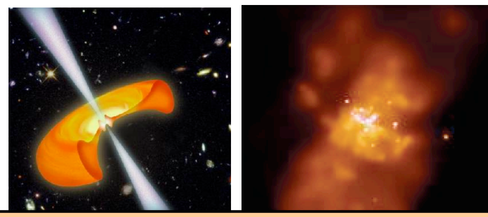

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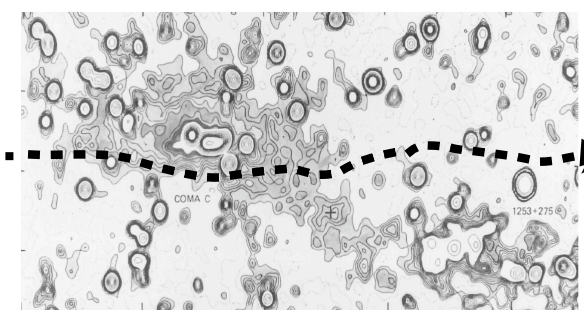

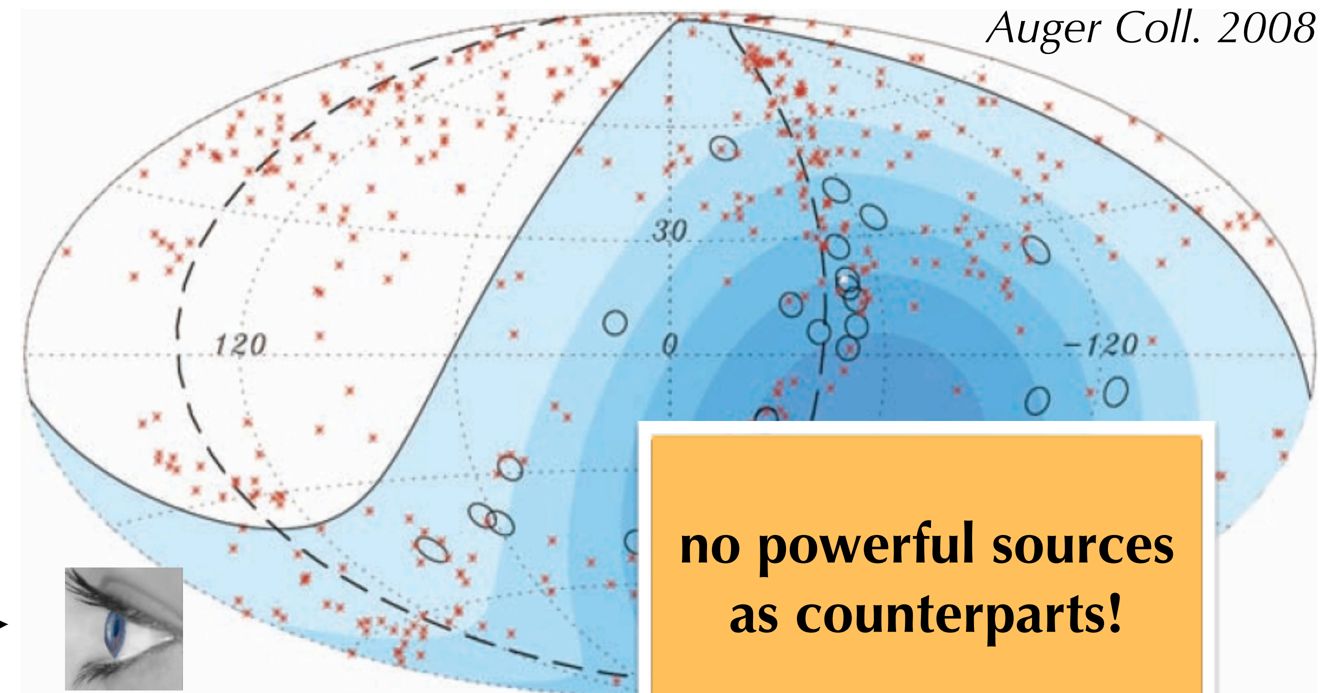

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time delay : temporal decorrelation if transient source

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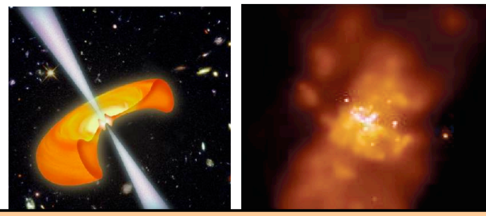

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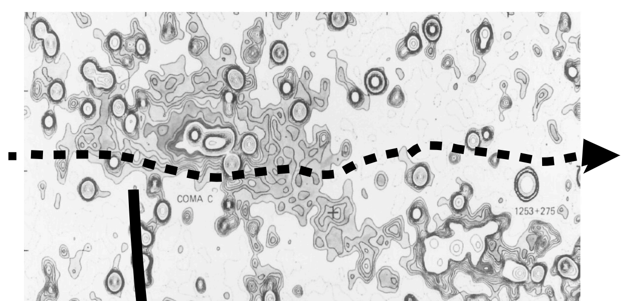

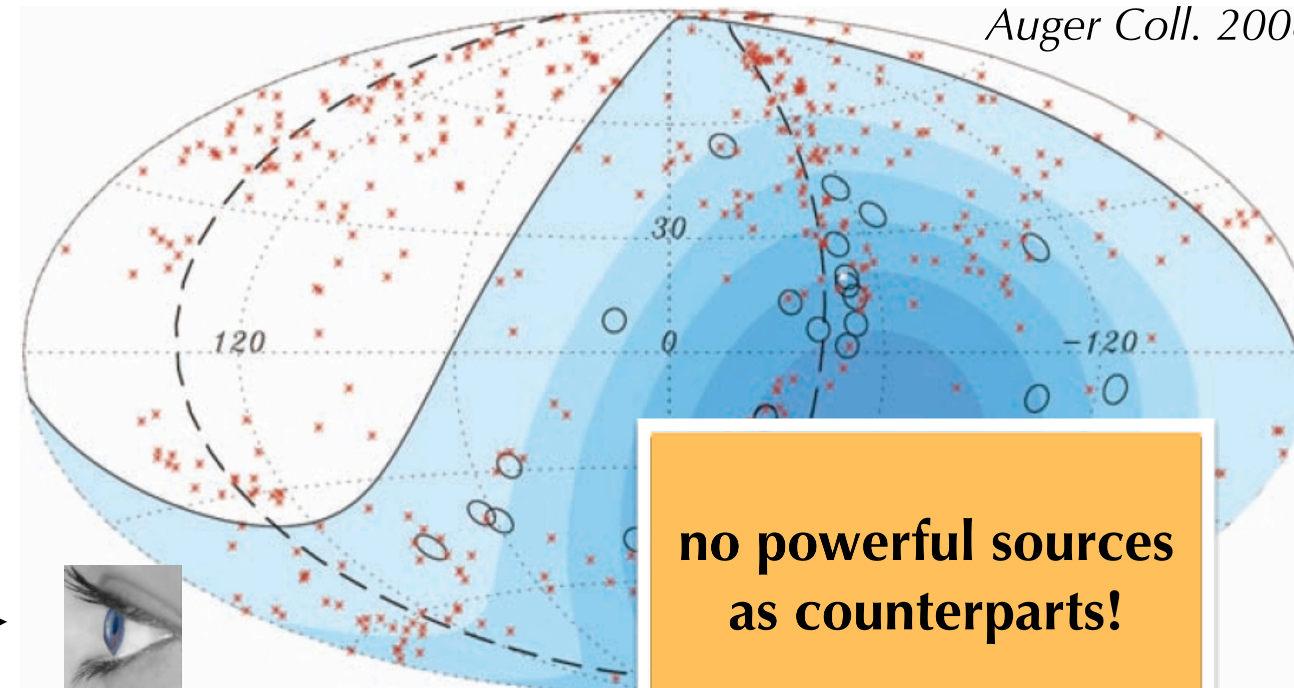

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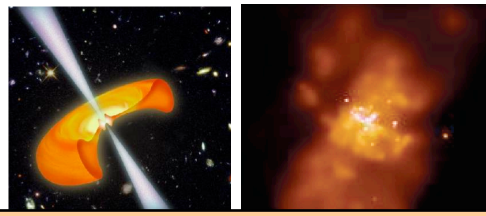

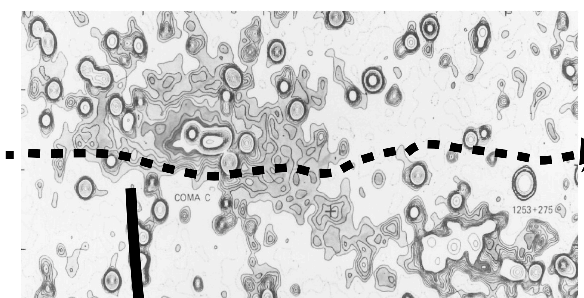

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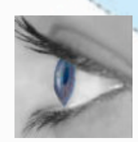

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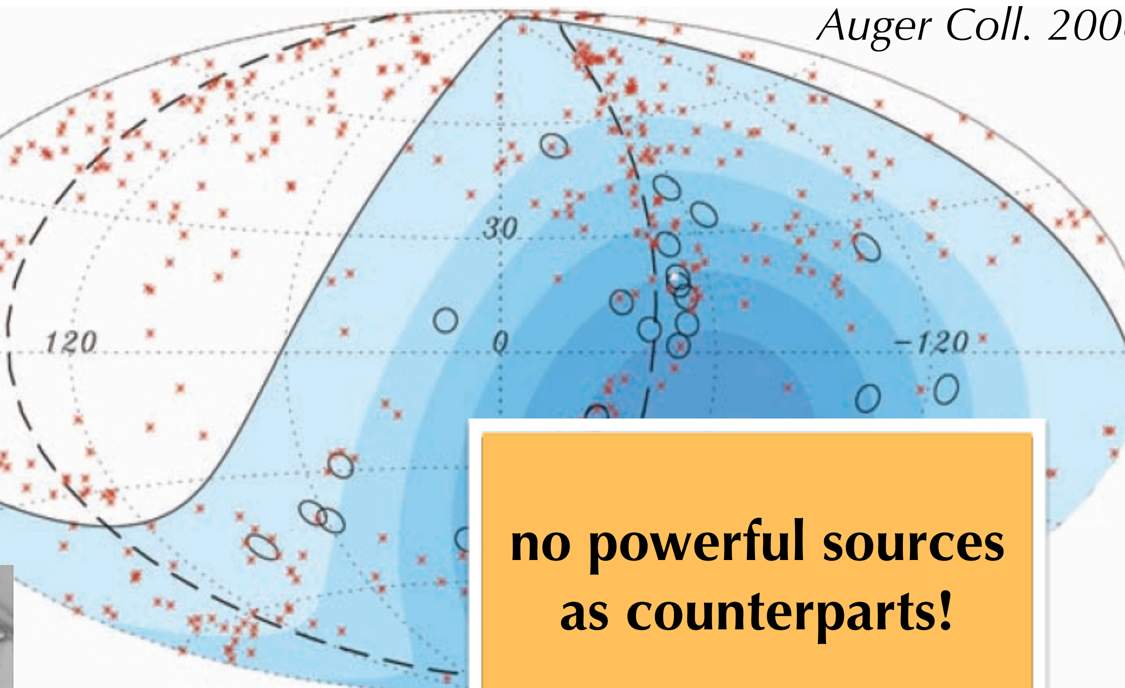

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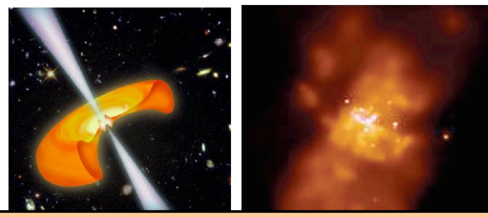

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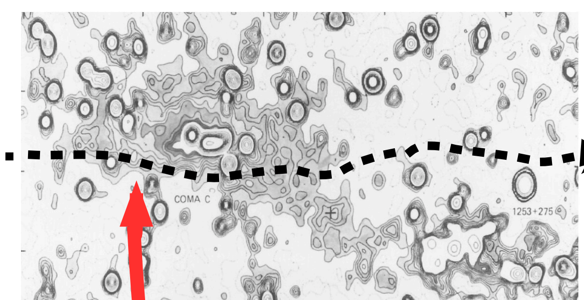

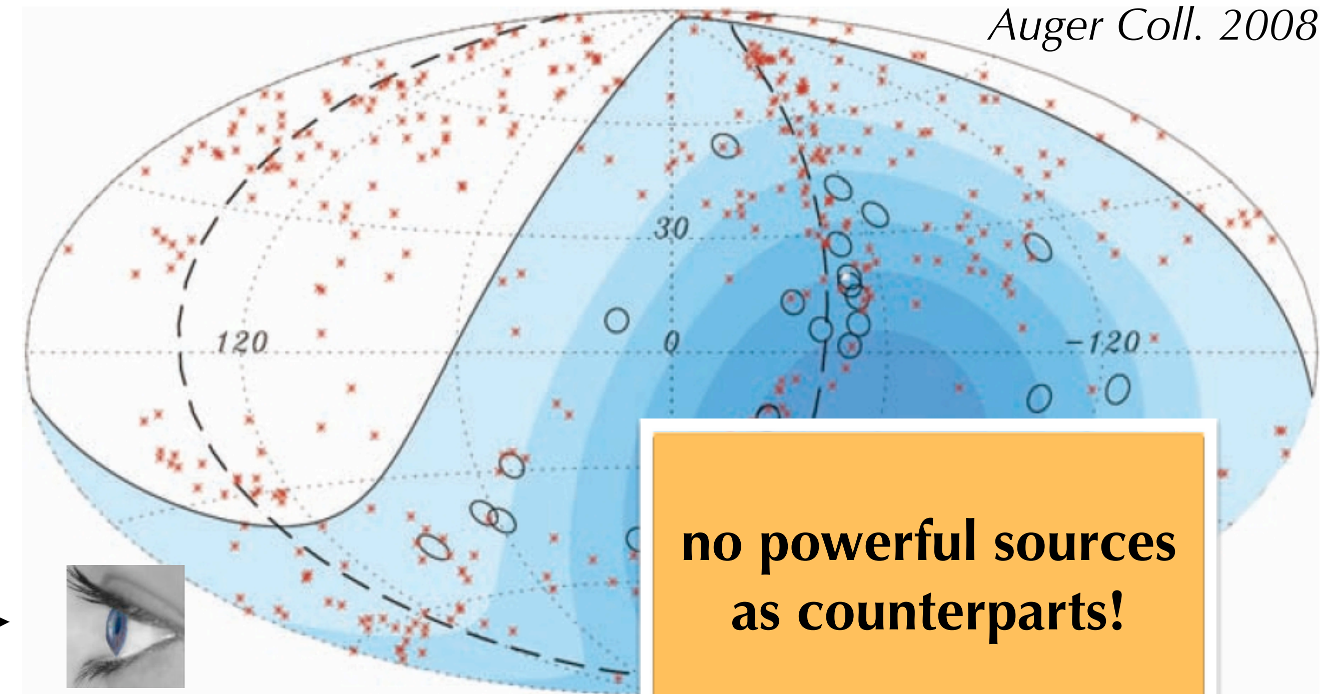

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Fate of gamma rays after their production by UHECRs

CR (10^{20} eV) + γ_{bg} $\longrightarrow$ $\boxed{e^{+-},\ \gamma_{UHE}}$

Cascade in IGM

interactions with radio/CMB photons

$\underbrace{\gamma\gamma_{bg} \to e^+e^-}_{\text{pair production}} \longrightarrow \underbrace{e\gamma_{bg} \to e\gamma}_{\text{Inverse Compton}} \longrightarrow \ldots \quad \underbrace{\gamma_{TeV\text{-}GeV}}_{\text{no more interactions}}$

Synchrotron nearby source

if source environment sufficiently magnetized

$e^{+-} \xrightarrow[\text{B, synchrotron}]{} \underbrace{\gamma_{GeV}}_{\text{no more interactions}}$

γ ray halo of limited extension around source

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Protheroe 86, Protheroe & Stanev 93, Aharonian et al. 94

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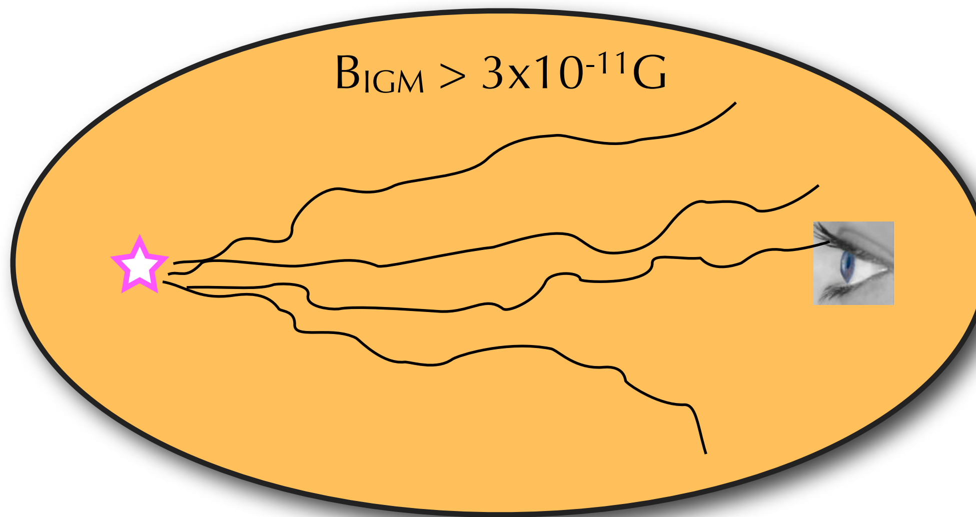

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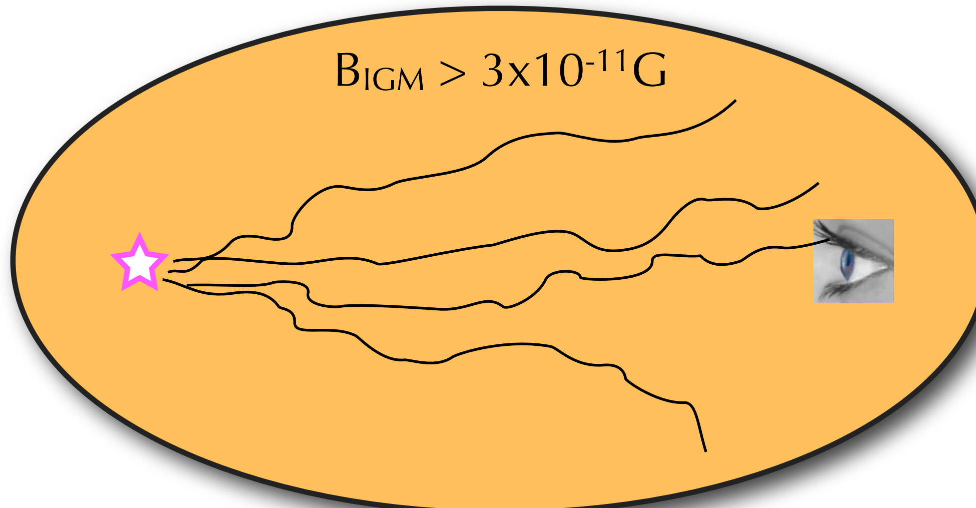

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K.K. et al. 2010

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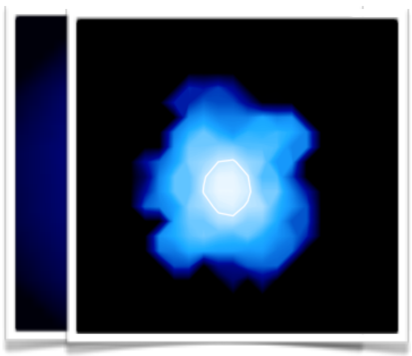

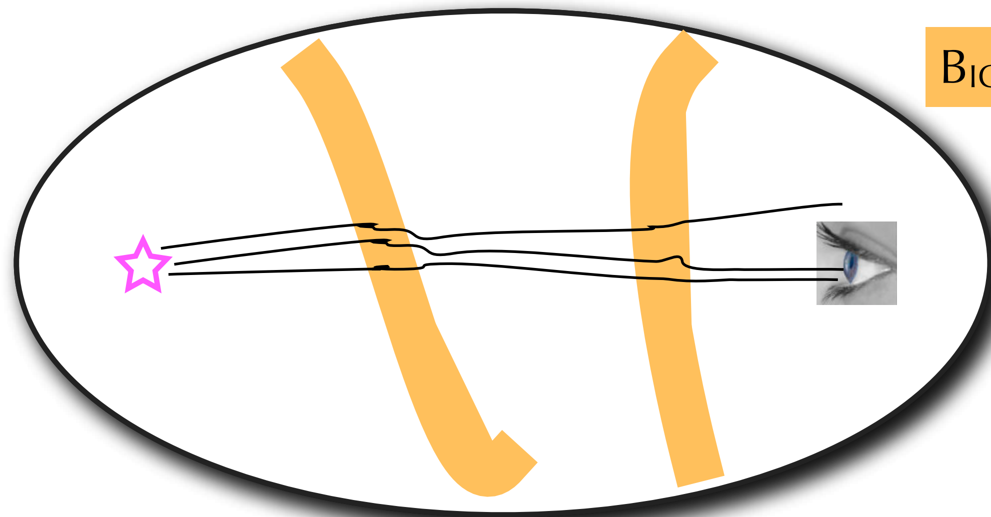

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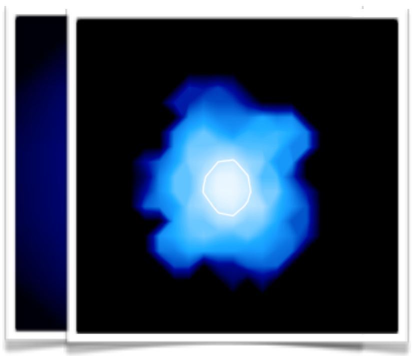

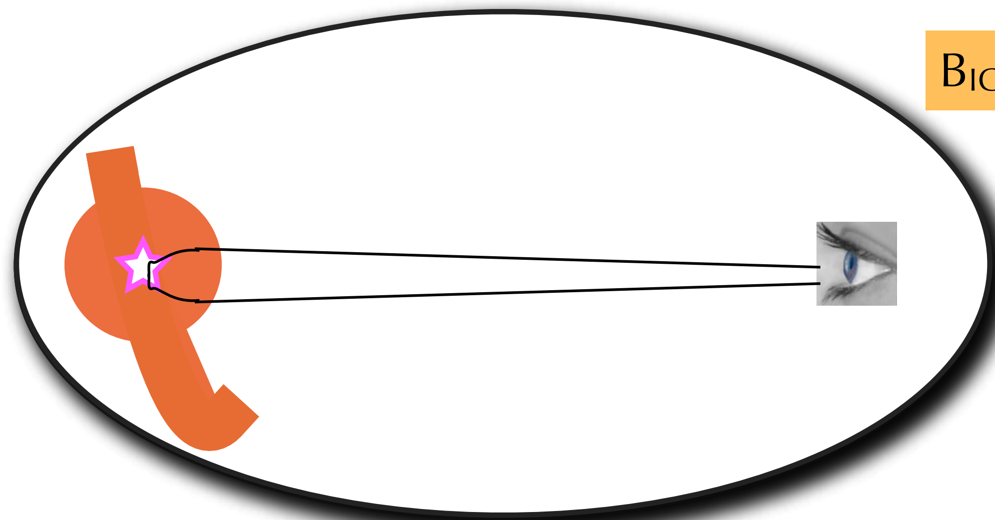

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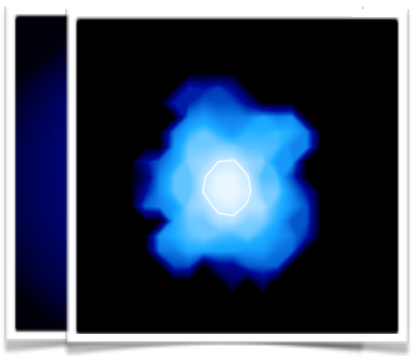

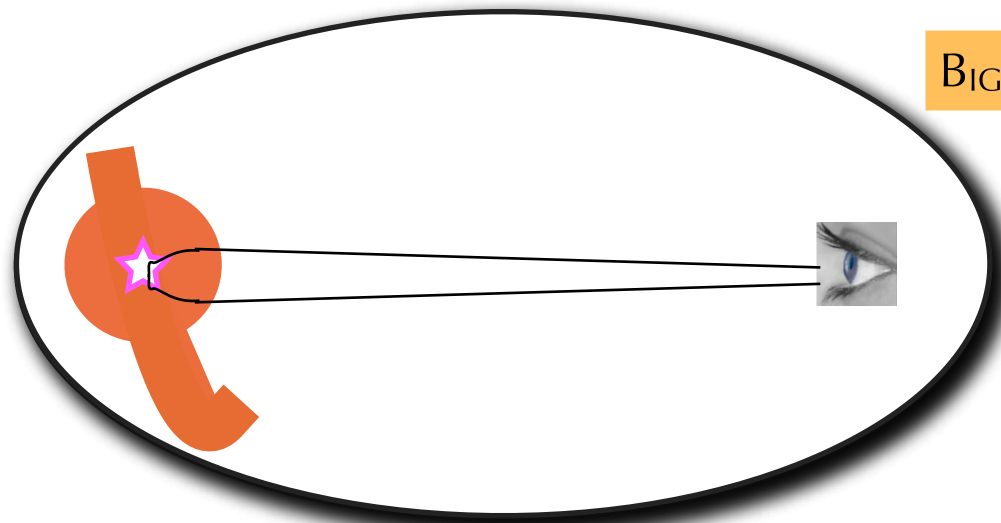

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homogeneous magnetized sphere around source

Gabici & Aharonian 06

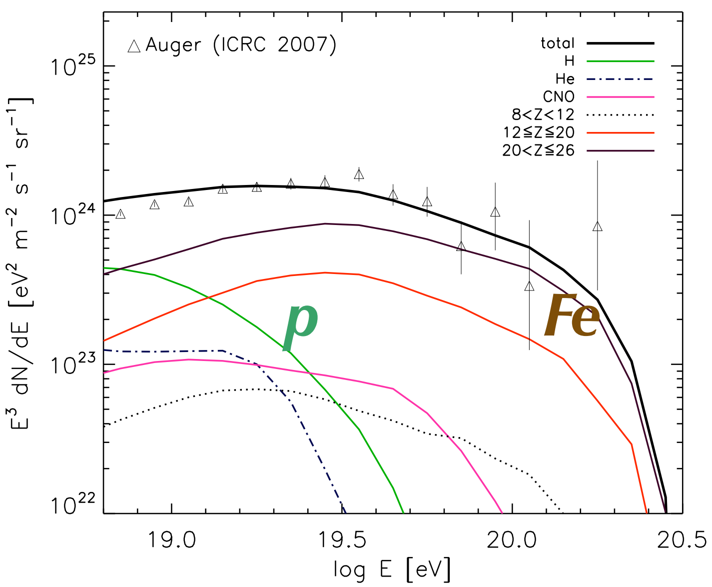
filaments, inhomogeneous B

K.K. et al. 2010

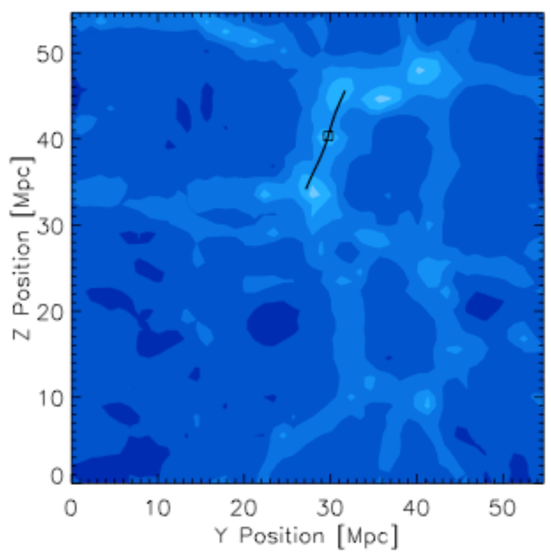
Explore influence of astrophysical parameters on gamma ray signal

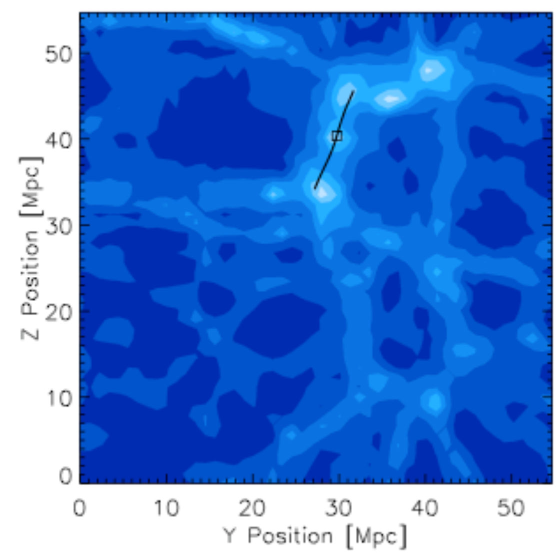
Chemical compositions for UHECR: **protons, Galactic mixed, iron, [mixed + low $E_{p,max}$]**

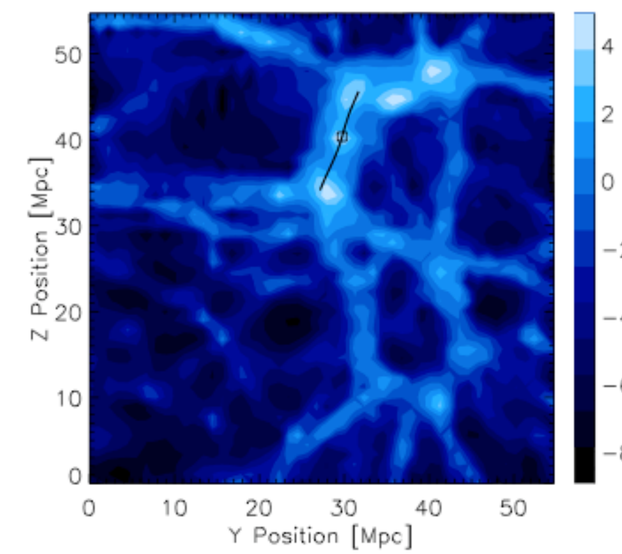
Various extragalactic magnetic field configurations (intensity, contrast, ...)



adapted from Allard et al. 08







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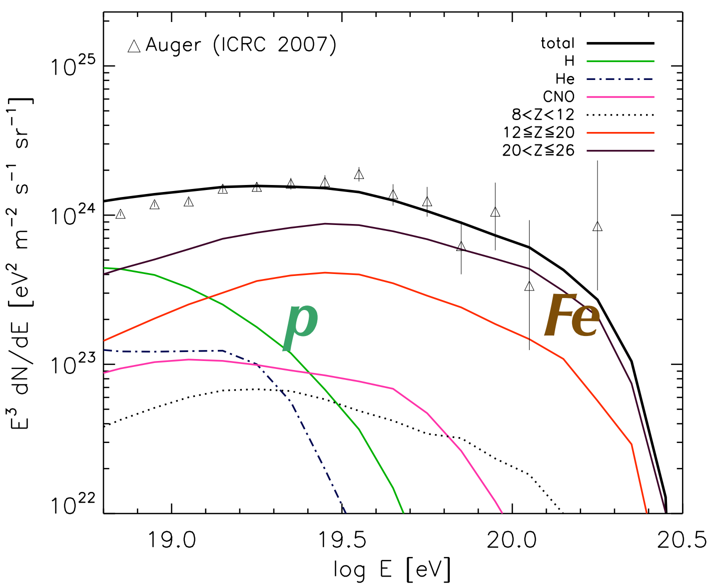

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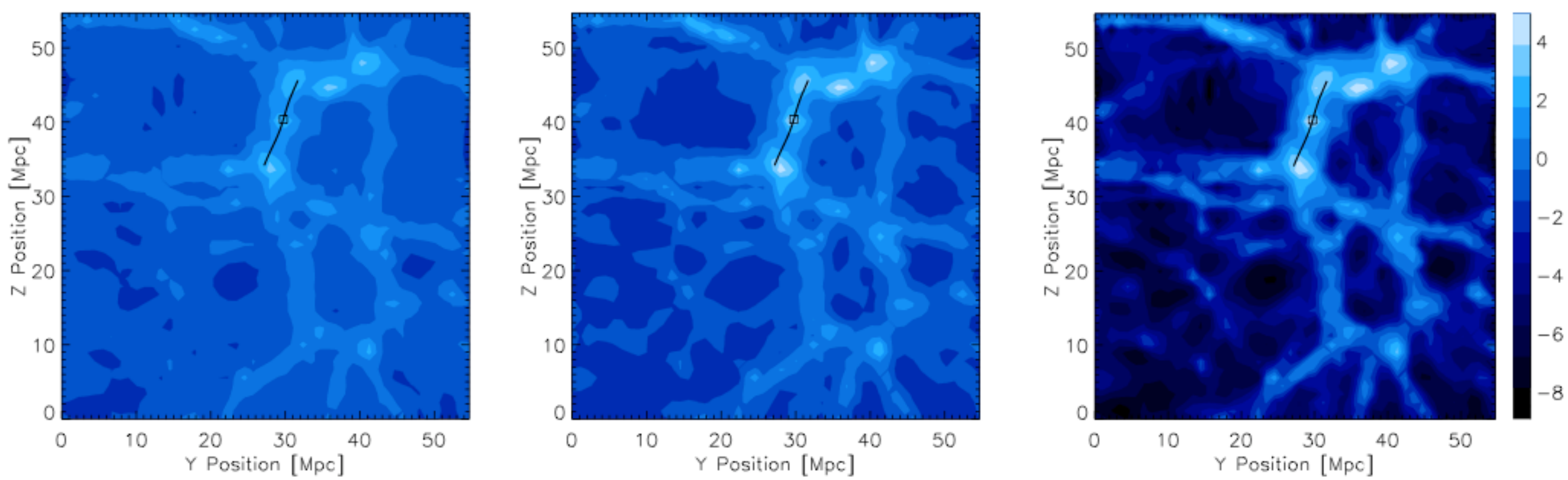


... using a complete propagation and interaction code

K.K. et al. 2009

Propagation in magnetic fields *K.K. & Lemoine 2008a*

Interactions of nuclei with cosmic backgrounds + multimessengers (γ,ν)

Allard et al. 05, **SOPHIA** (*Mücke et al. 1999*), **EPOS** (*Werner et al. 06*), **CONEX** (*Bergmann et al. 07*)

Gamma-ray cascades

Synchrotron component

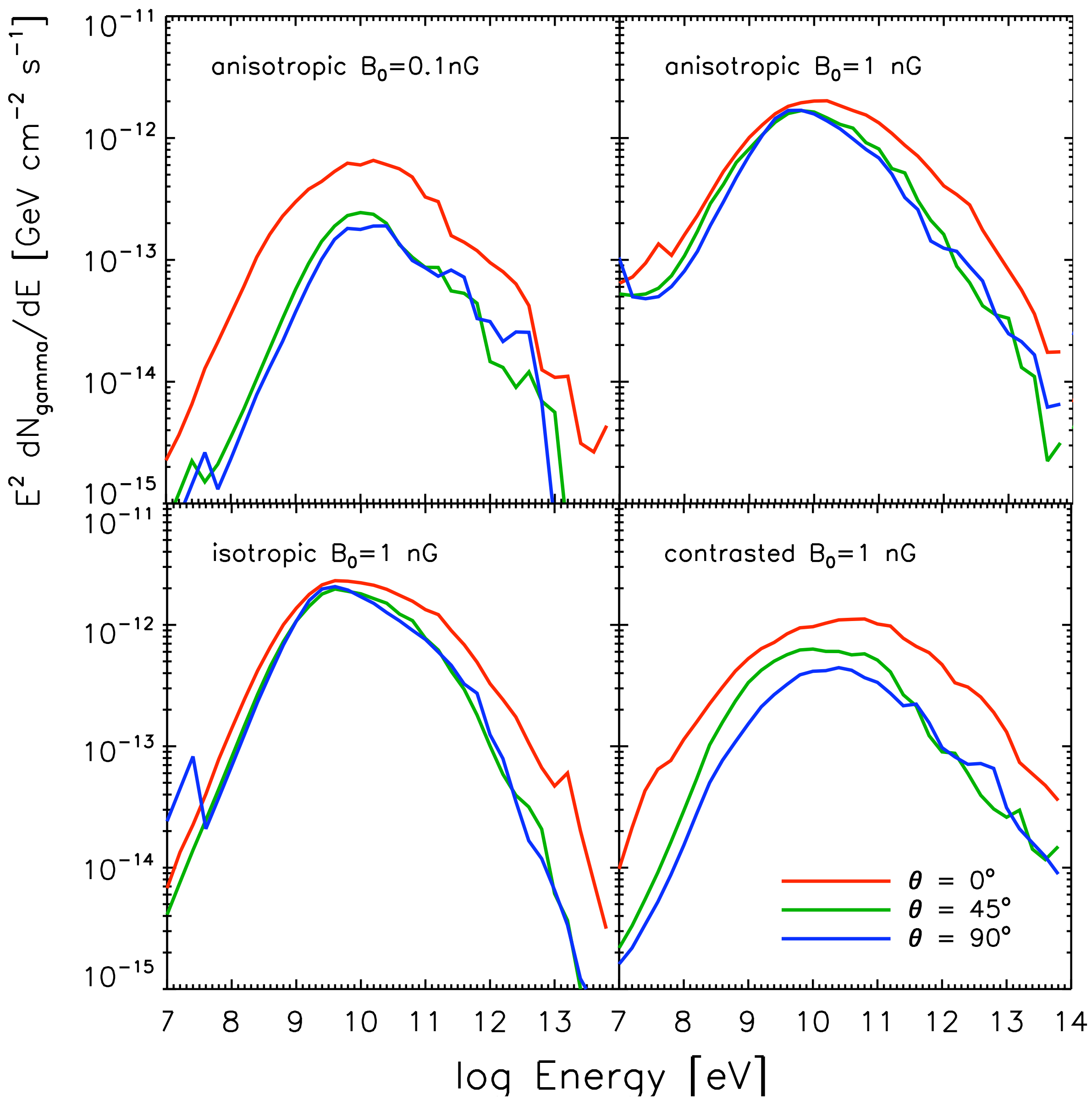
+ cascaded component: flux x a few

$L_{cr}(E>10^{19}$ eV$) = 10^{42}$ erg s^{-1}

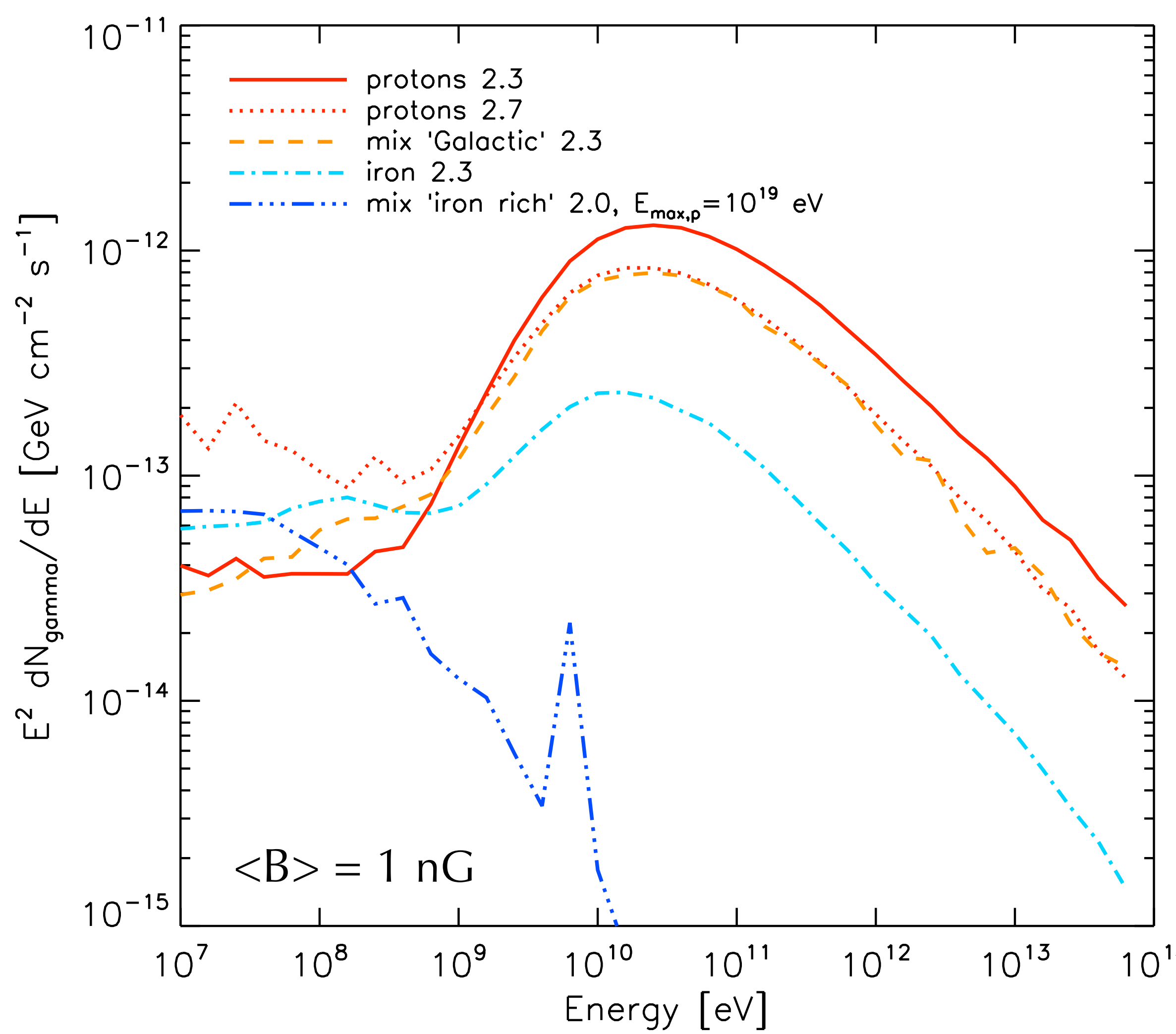
average type of source: fits Auger spectrum for **$n_{sources} = 10^{-5}$ Mpc^{-3}**

distance to observer d = 100 Mpc

$E_{max} = 10^{20.5}$ eV, spectral index = 2.3



Extragalactic magnetic field configurations



Chemical compositions of primary UHECR

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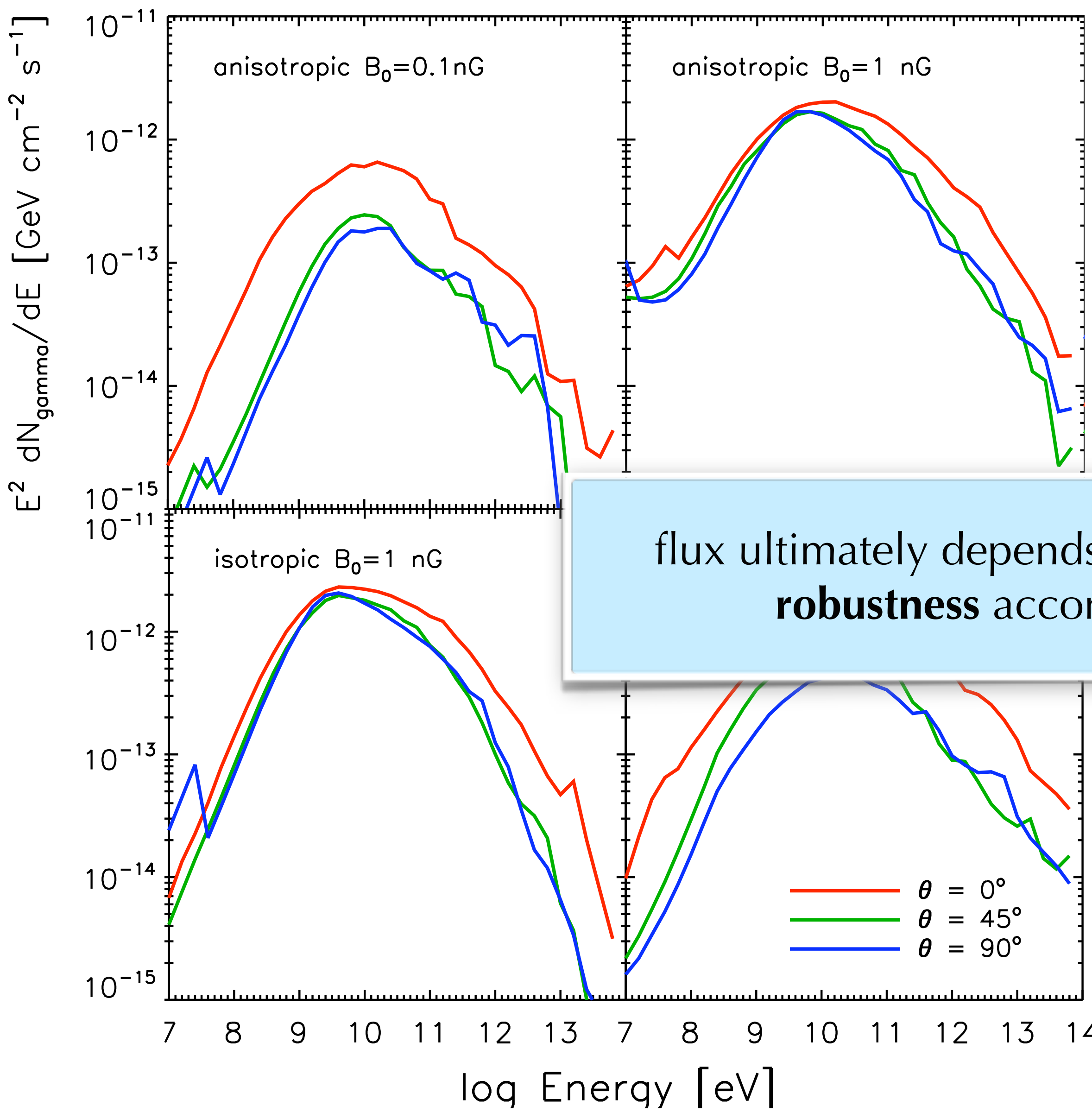
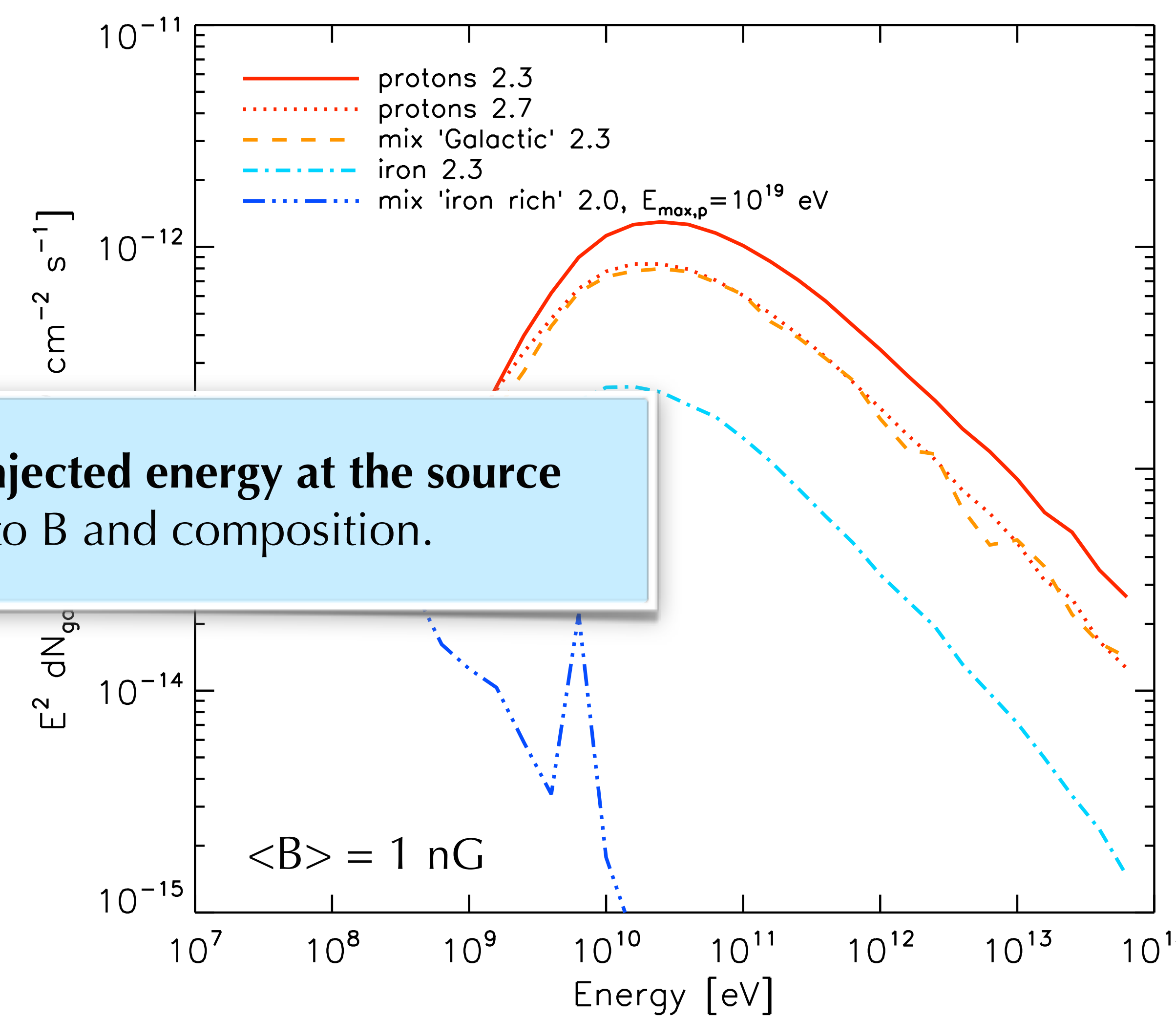




flux ultimately depends on **injected energy at the source**
robustness according to B and composition.

Extragalactic magnetic field configurations

Chemical compositions of primary UHECR

Synchrotron component

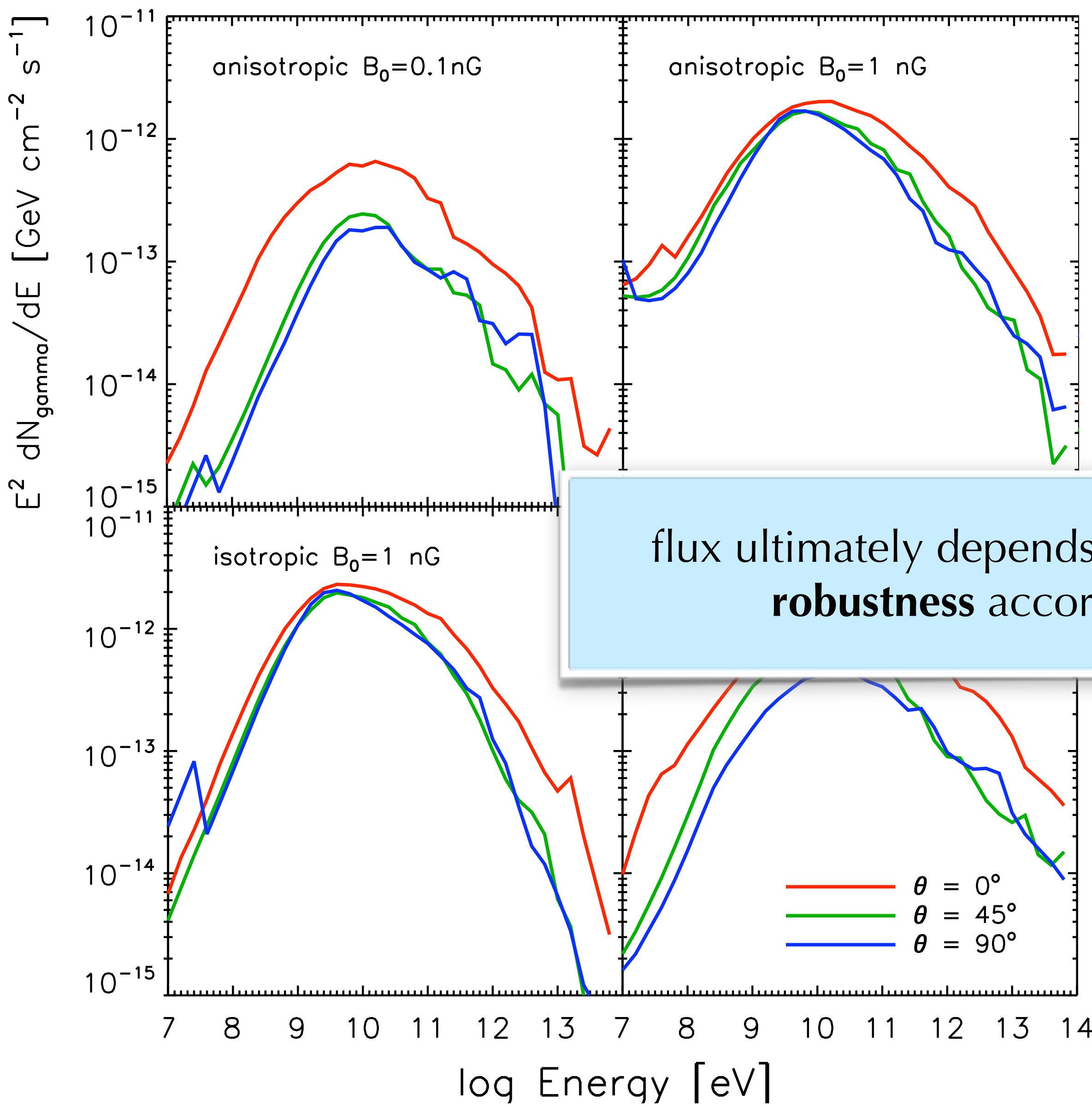
+ cascaded component: flux x a few

$L_{cr}(E>10^{19}$ eV) = 10^{42} erg s^{-1}

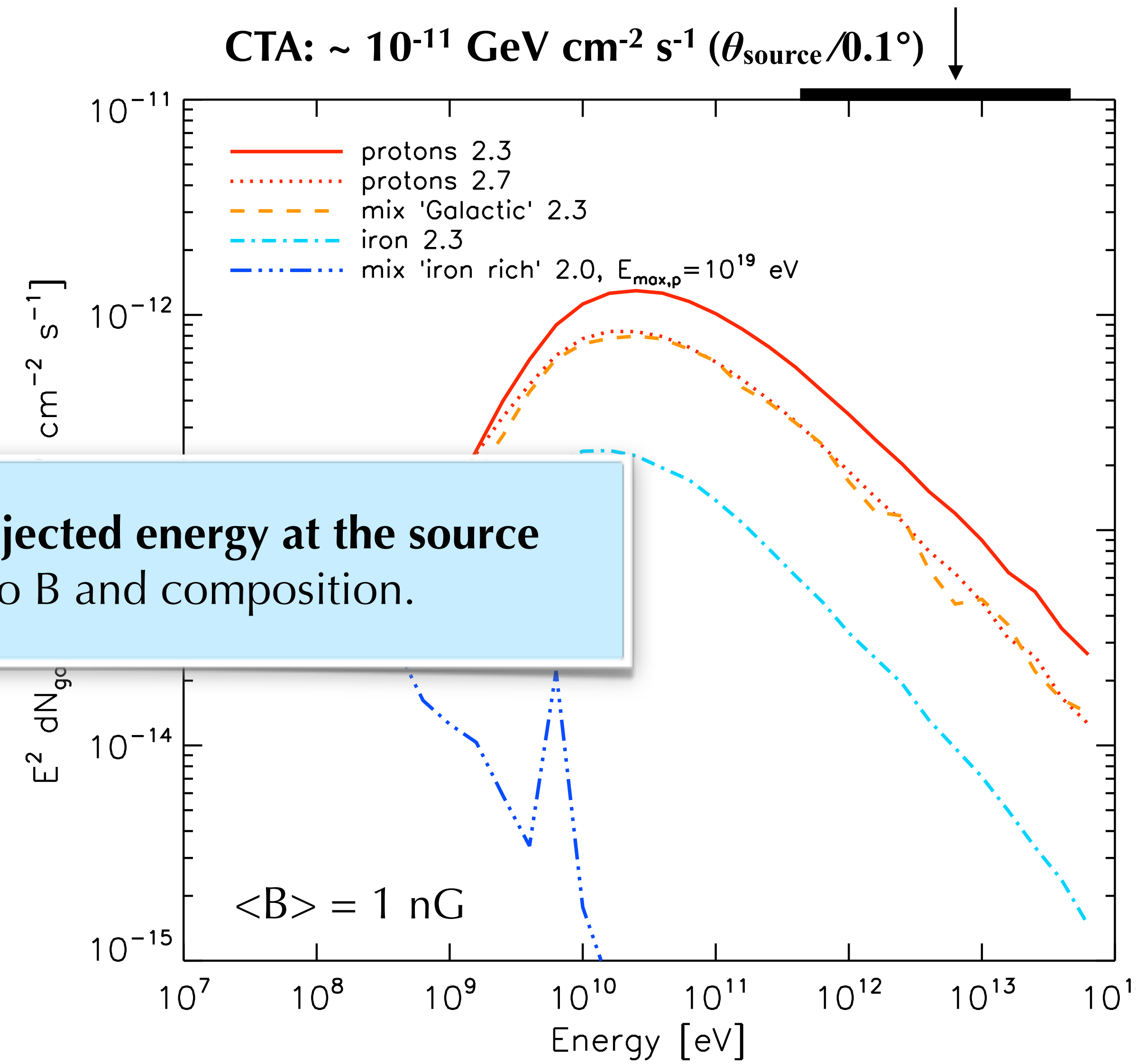
average type of source: fits Auger spectrum for **$n_{sources}$ = 10^{-5} Mpc^{-3}**

distance to observer d = 100 Mpc

$E_{max} = 10^{20.5}$ eV, spectral index = 2.3



CTA: ~ 10^{-11} GeV cm^{-2} s^{-1} (θ_{source}/0.1°)



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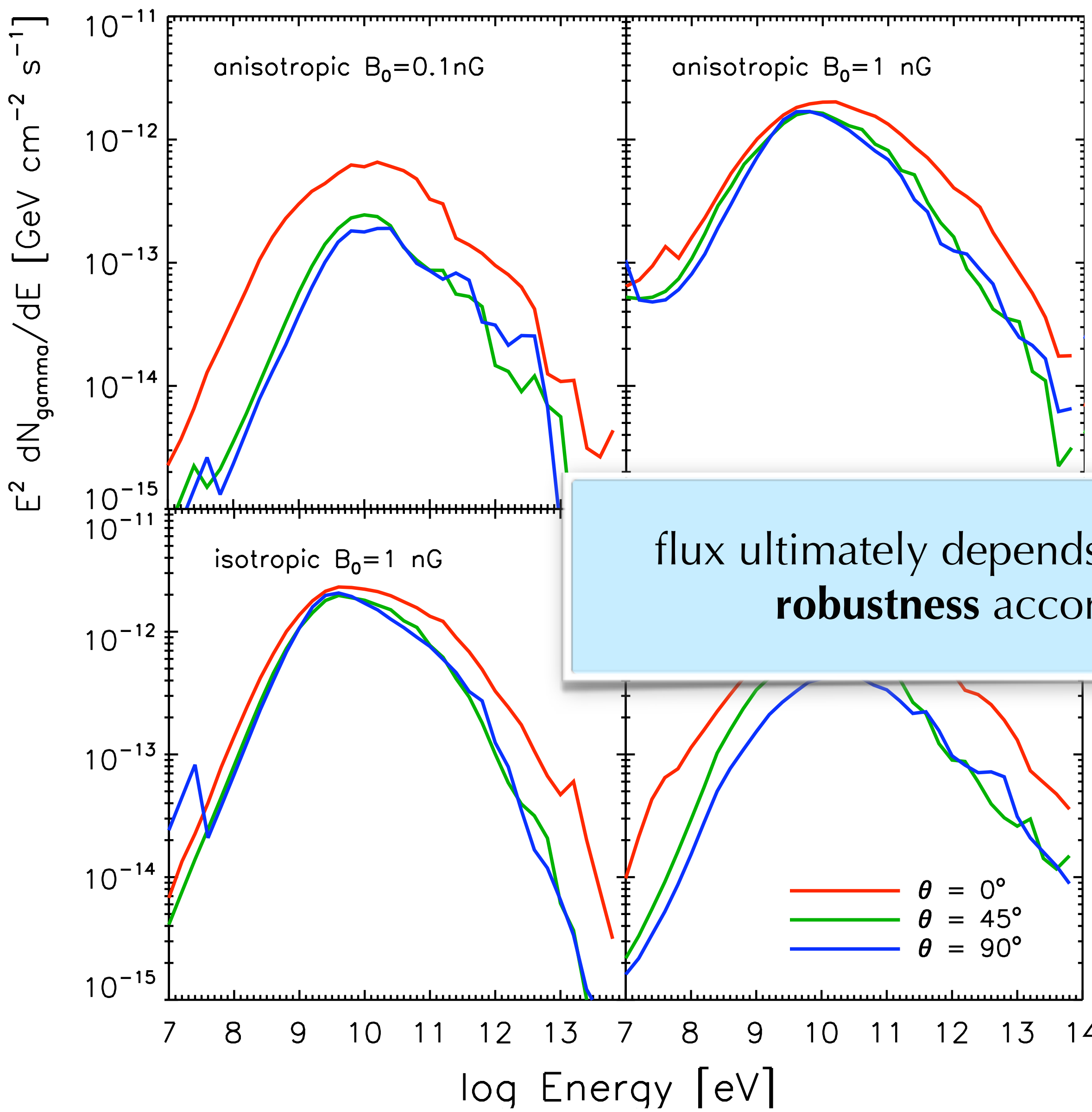

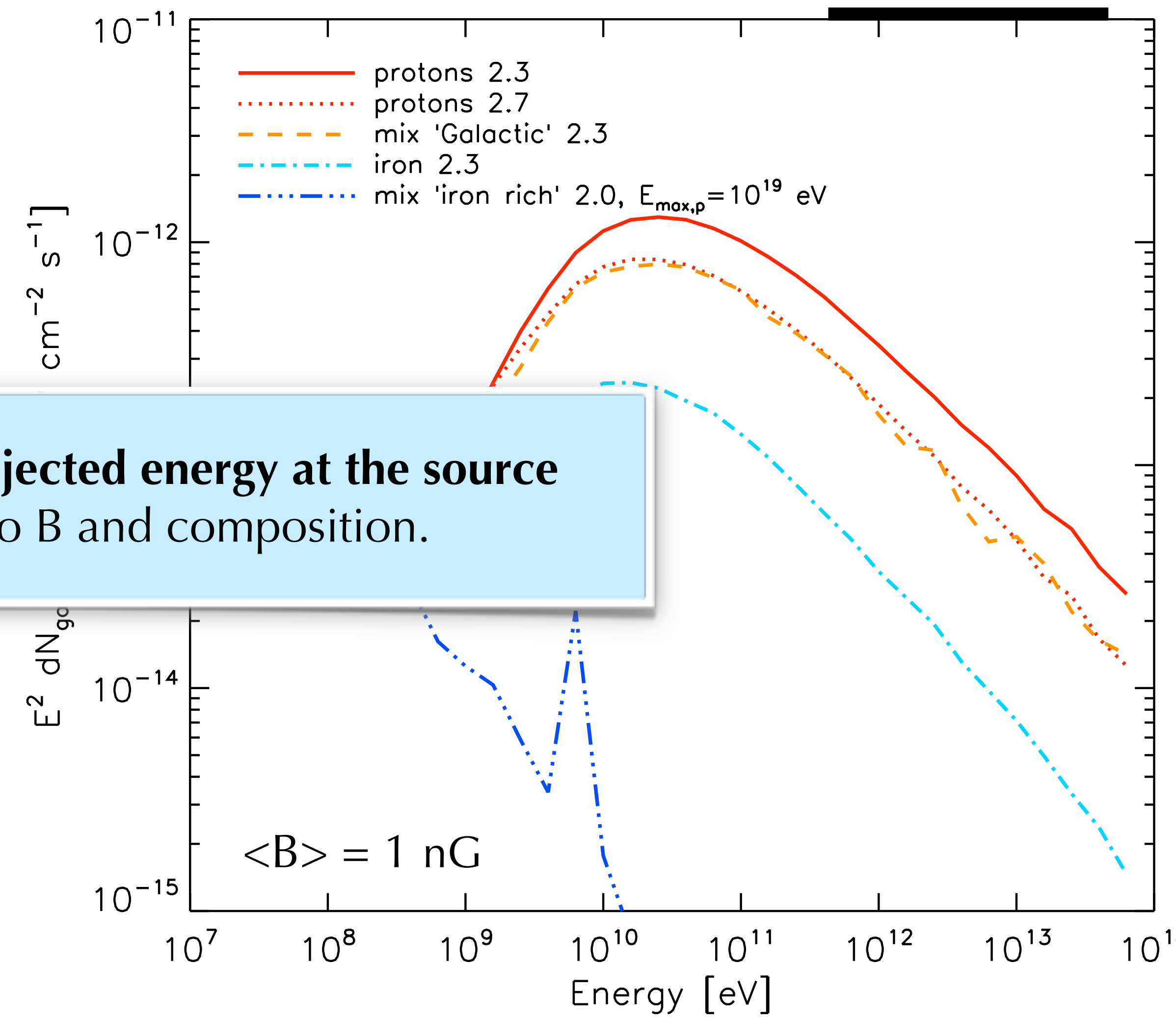

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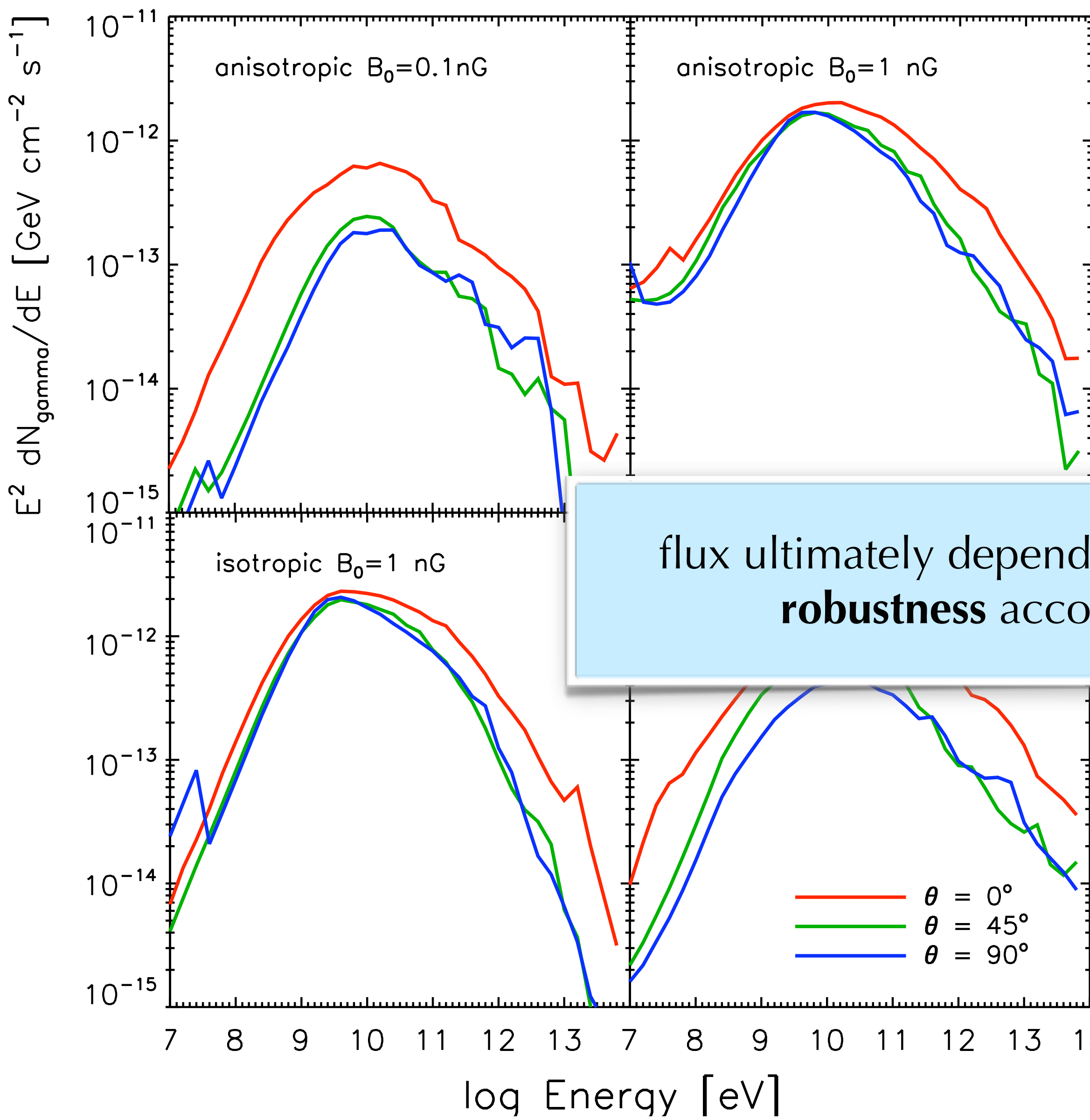
distance to observer d = 100 Mpc

$E_{max} = 10^{20.5}$ eV, spectral index = 2.3

detectable only if:
- particularly powerful source (rare)
- close-by source (Cen A?)

Fermi: ~ 10^{-10} GeV cm^{-2} s^{-1} (θ_{source}/1°)

CTA: ~ 10^{-11} GeV cm^{-2} s^{-1} (θ_{source}/0.1°)



flux ultimately depends on **injected energy at the source**
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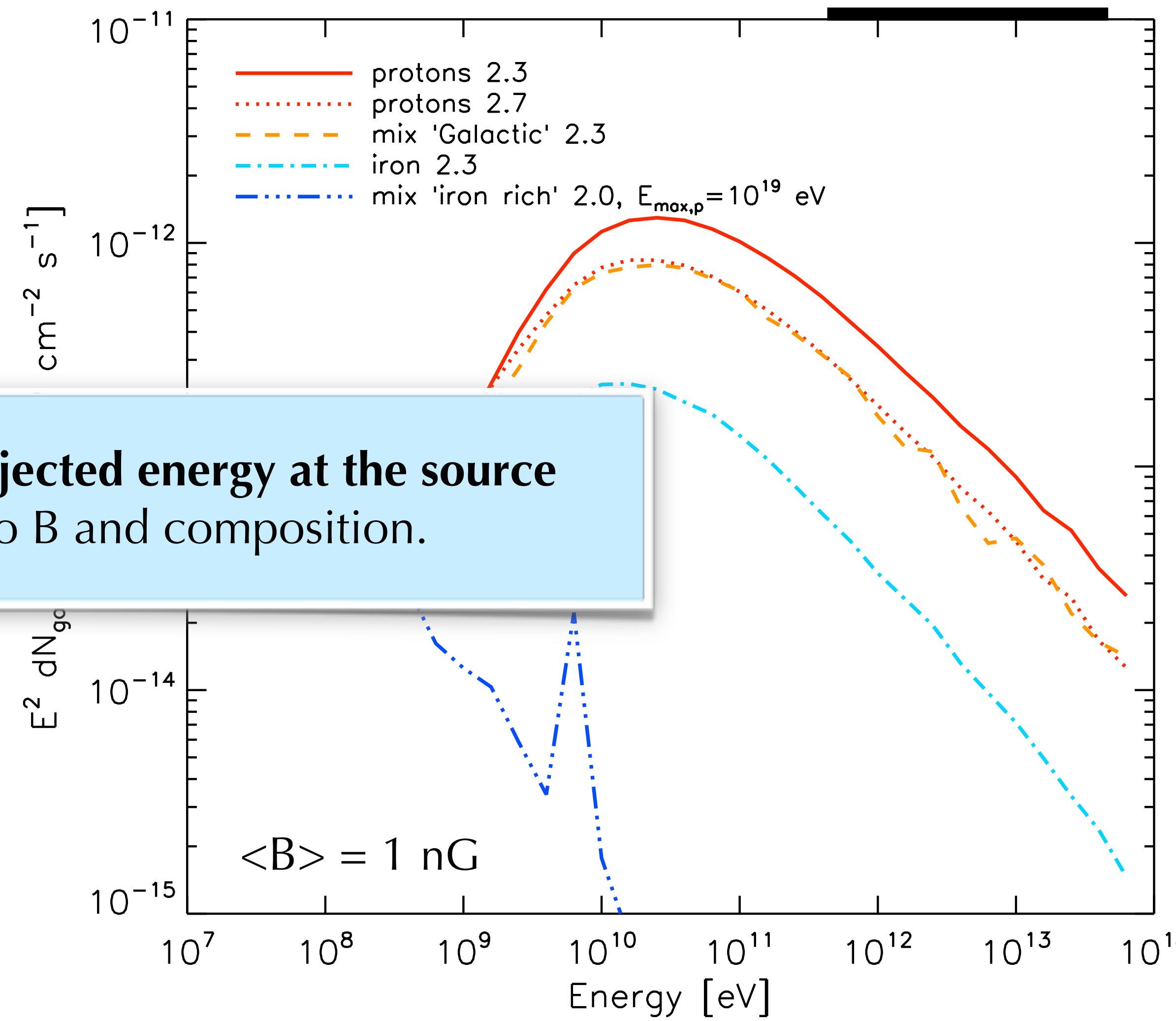
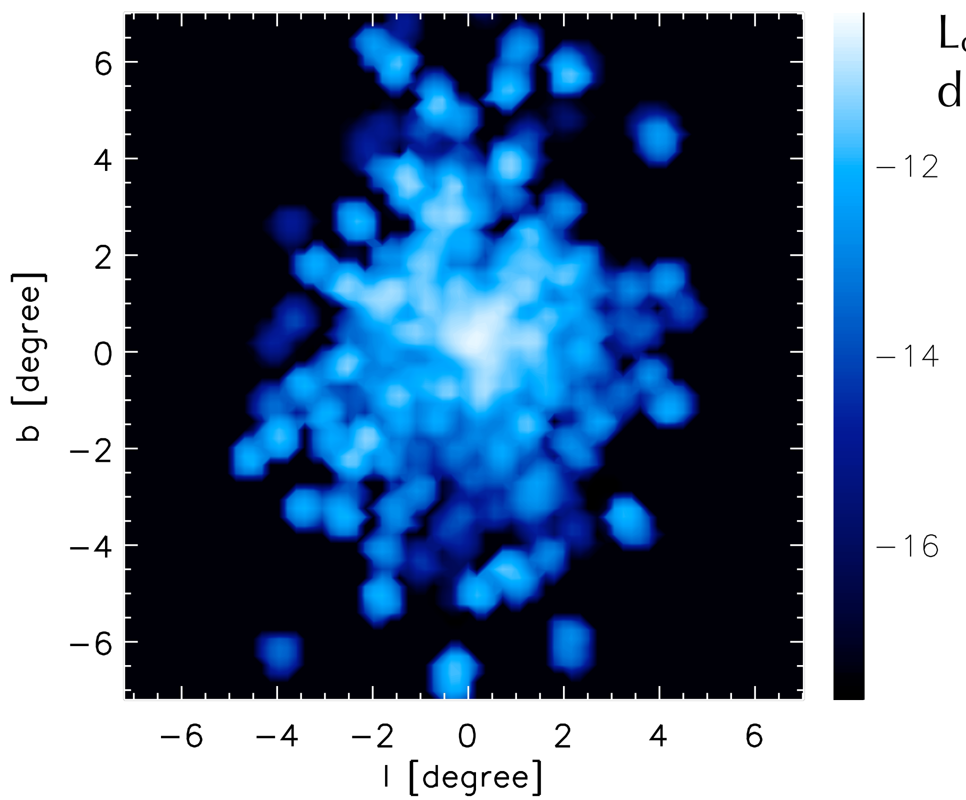


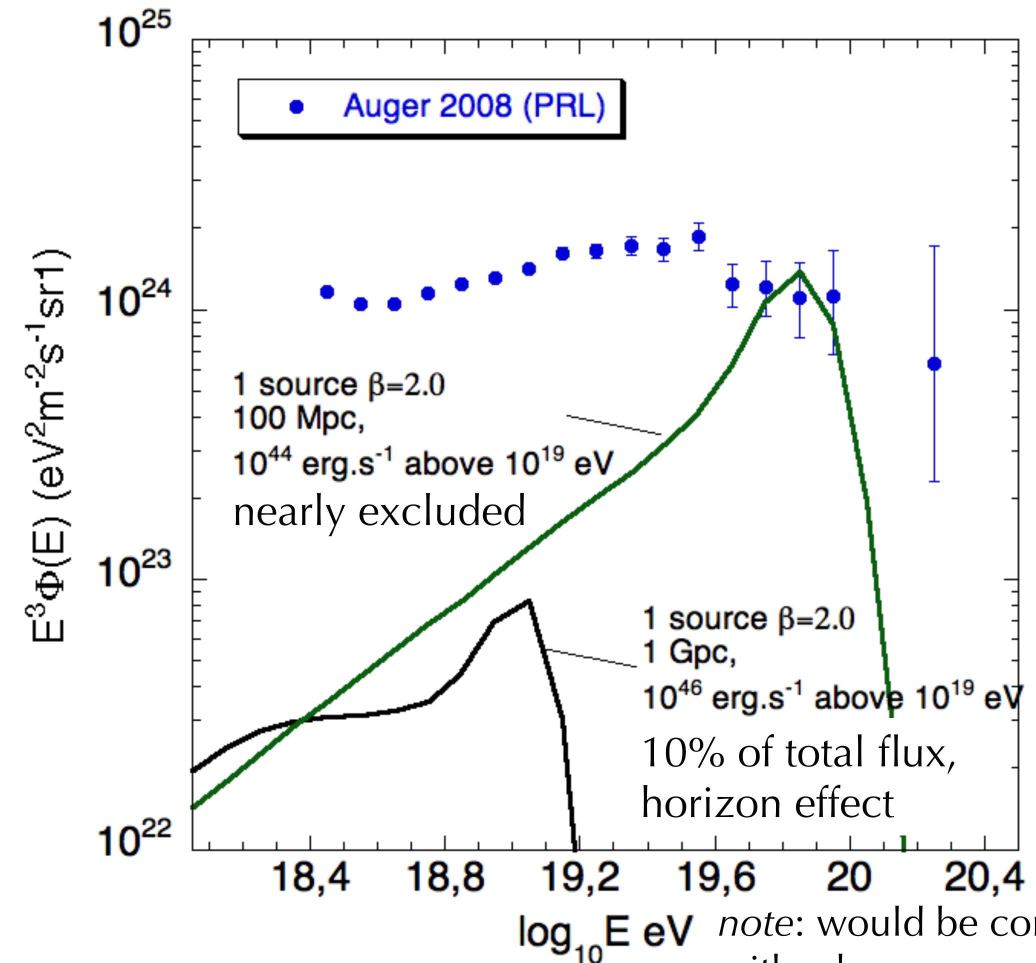
Extragalactic magnetic field configurations

Chemical compositions of primary UHECR

Case of particularly powerful sources

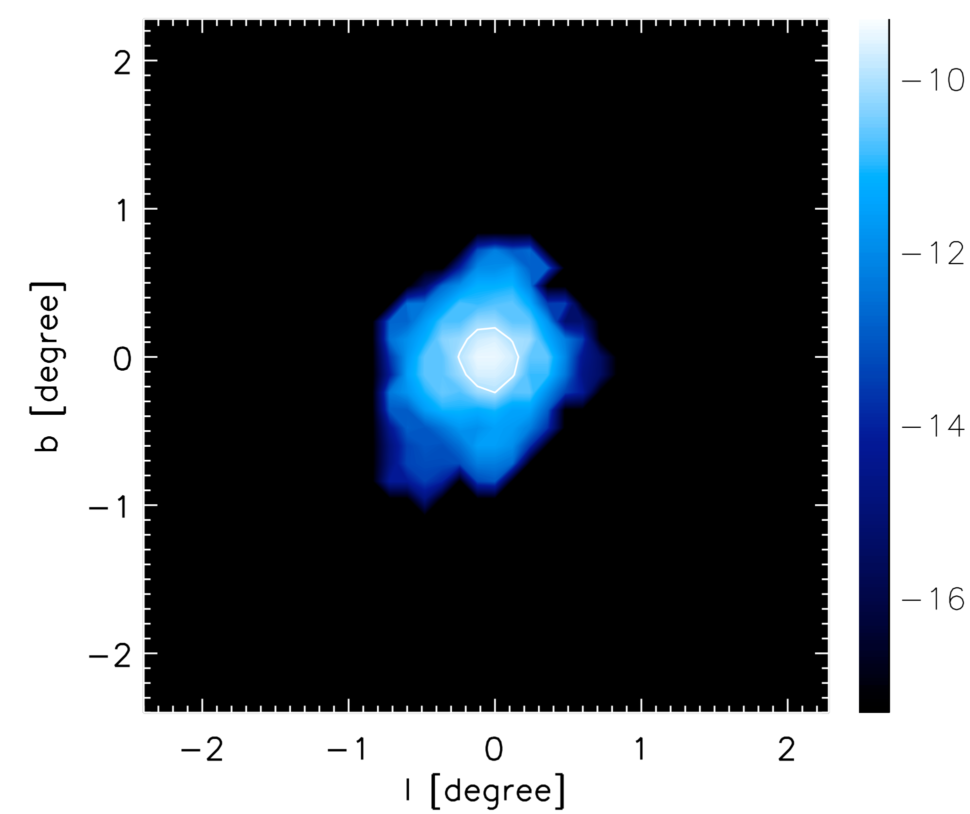


$L_{cr,19} = 10^{44}$ erg s^{-1}
d = 100 Mpc

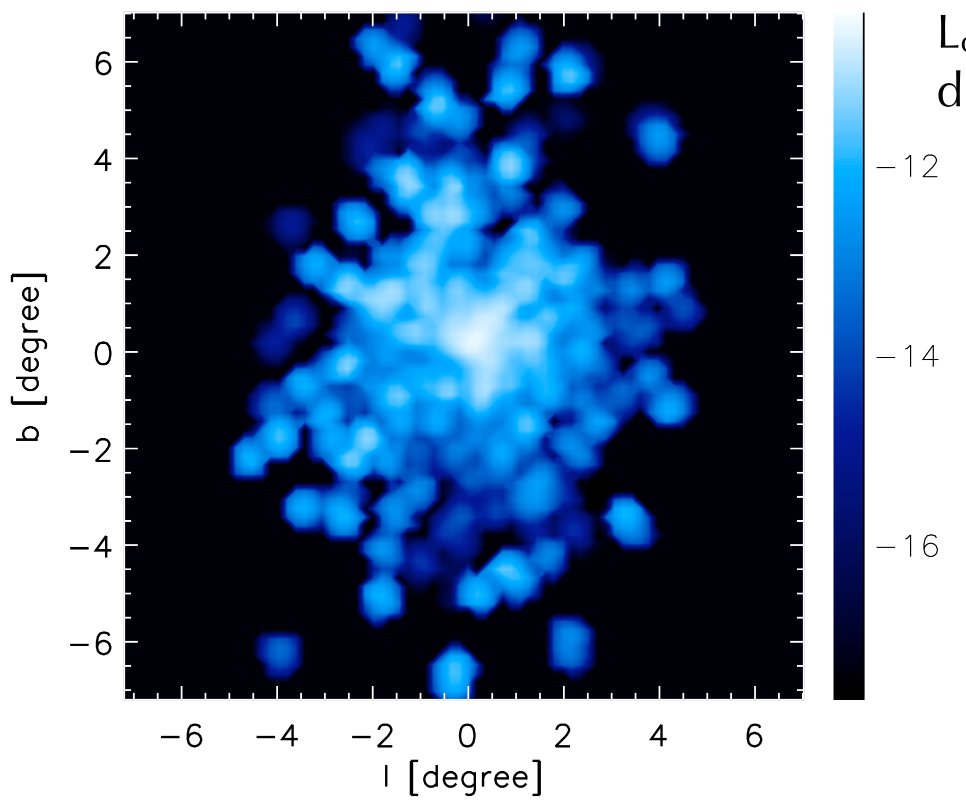


note: would be consistent with a heavy composition at UHE (Auger?)

$L_{cr,19} = 10^{46}$ erg s^{-1}
d = 1 Gpc



Case of particularly powerful sources



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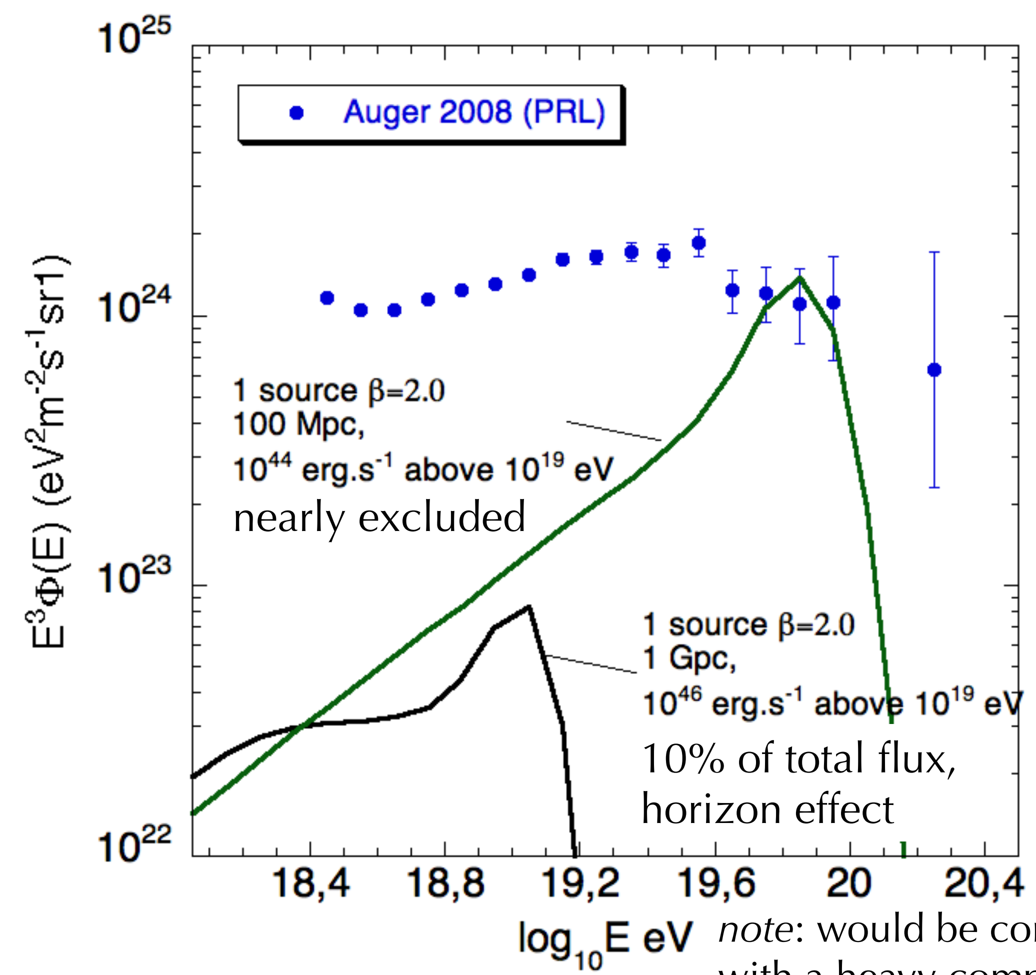
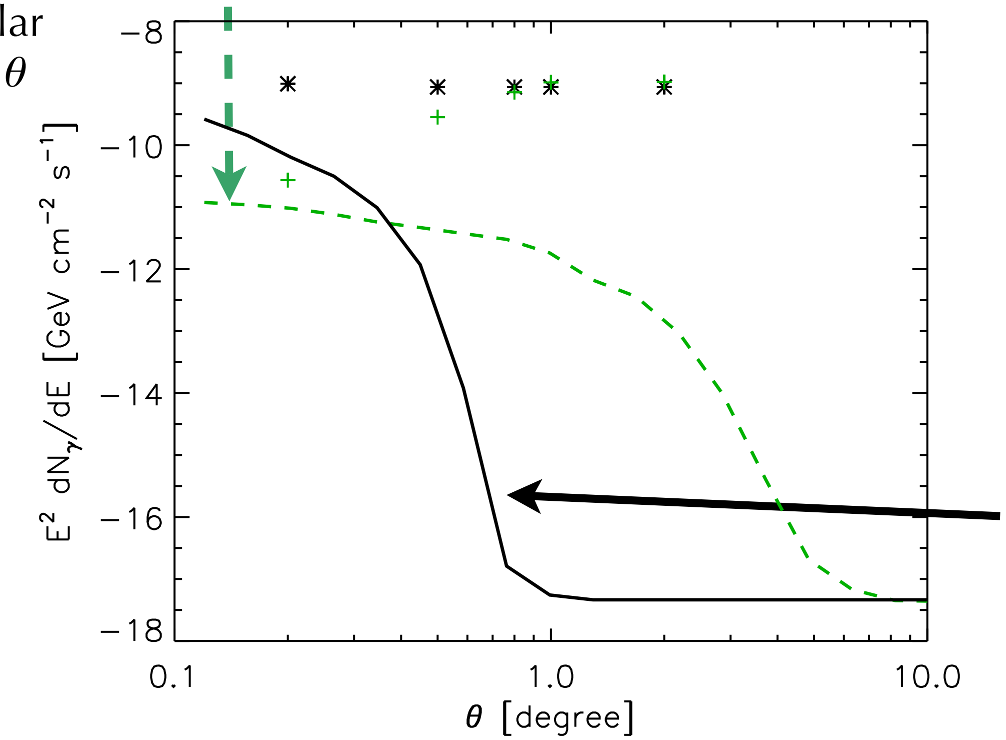


note: would be consistent with a heavy composition at UHE (Auger?)

* + flux integrated up to angular extension θ



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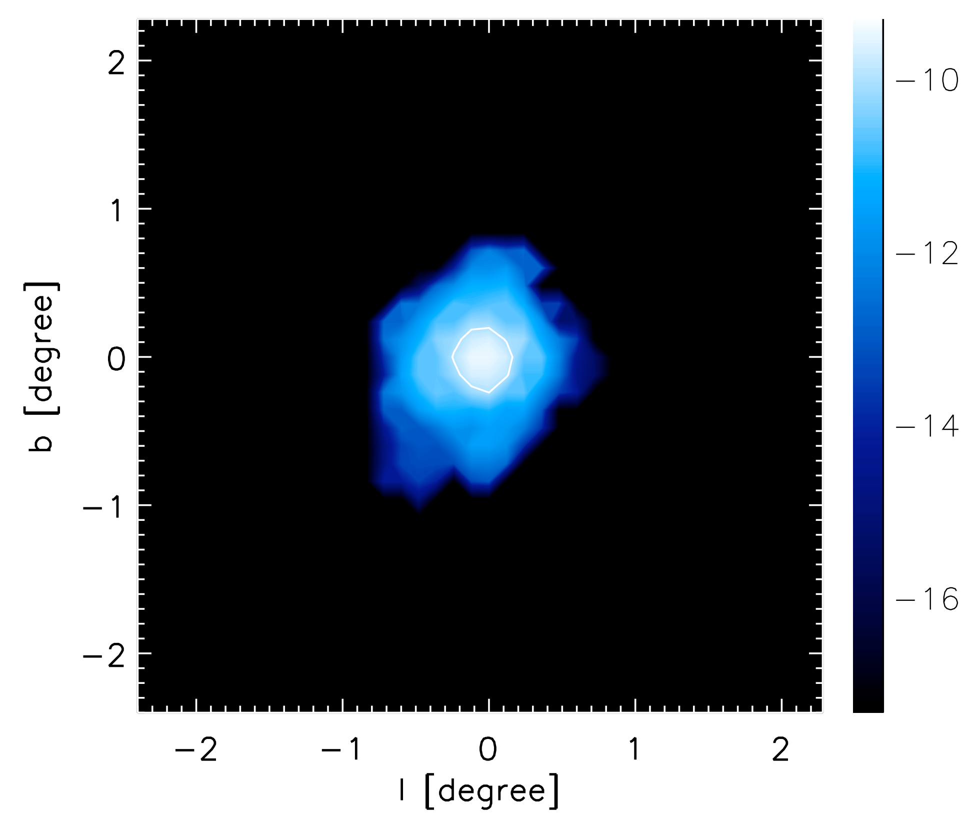

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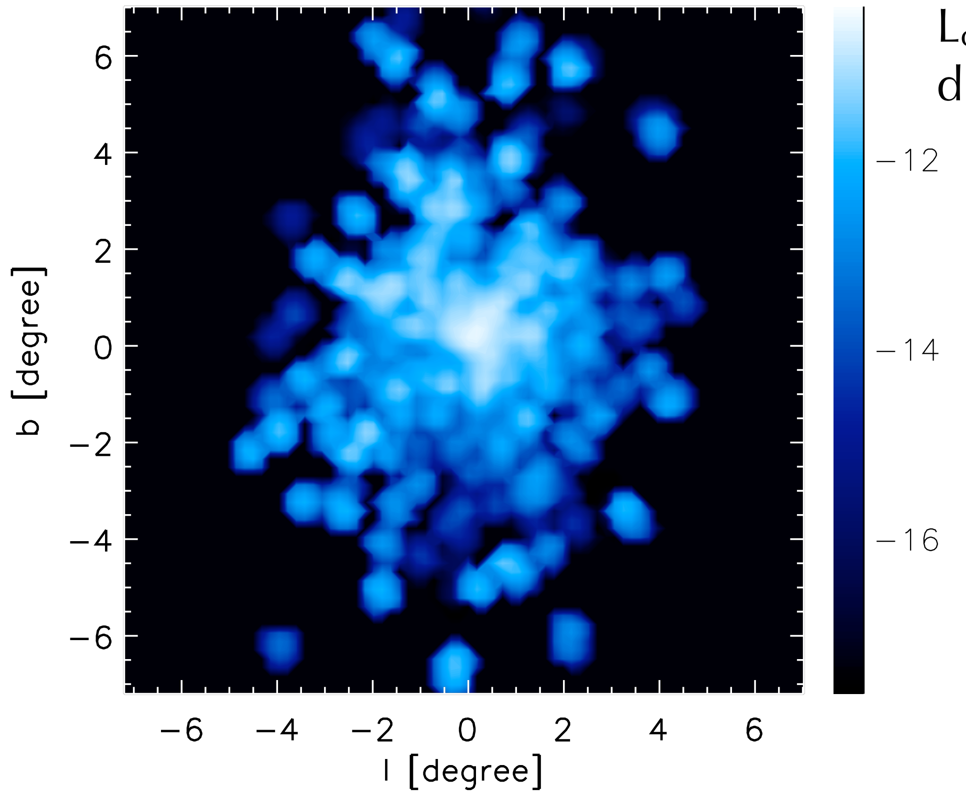

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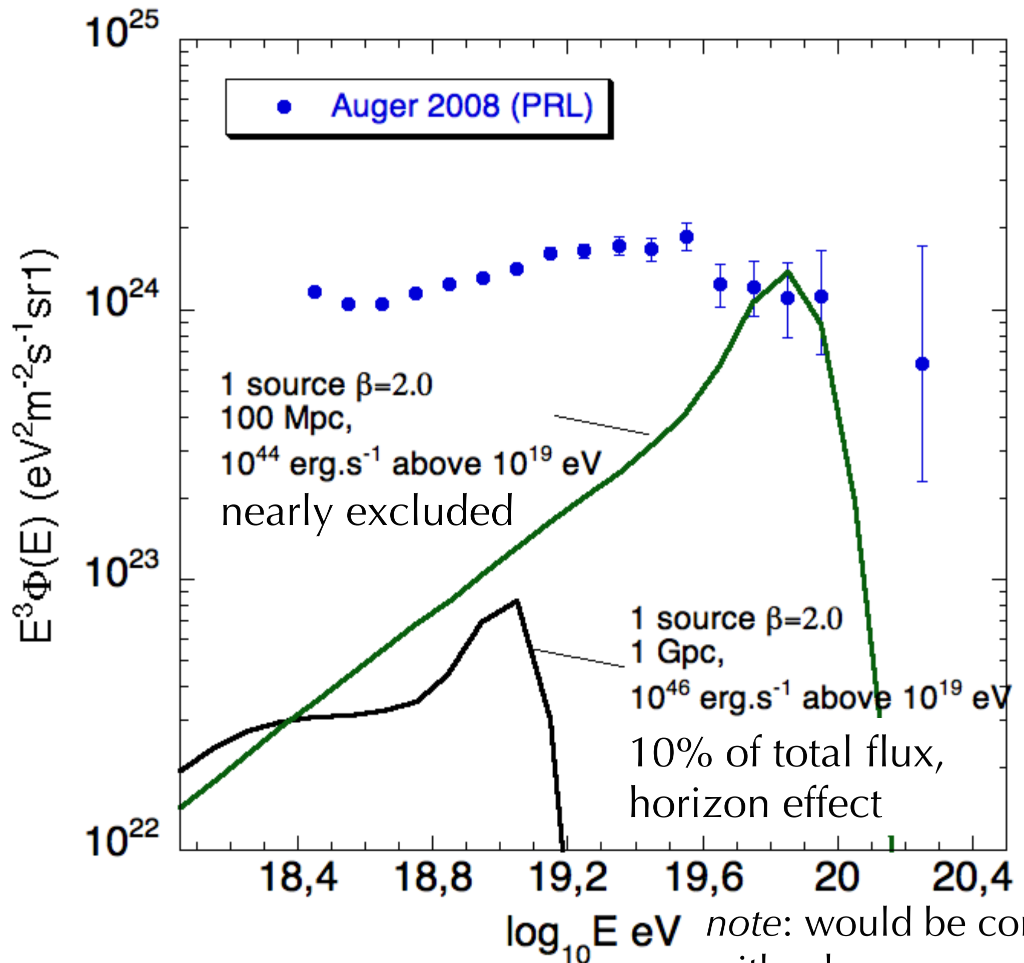

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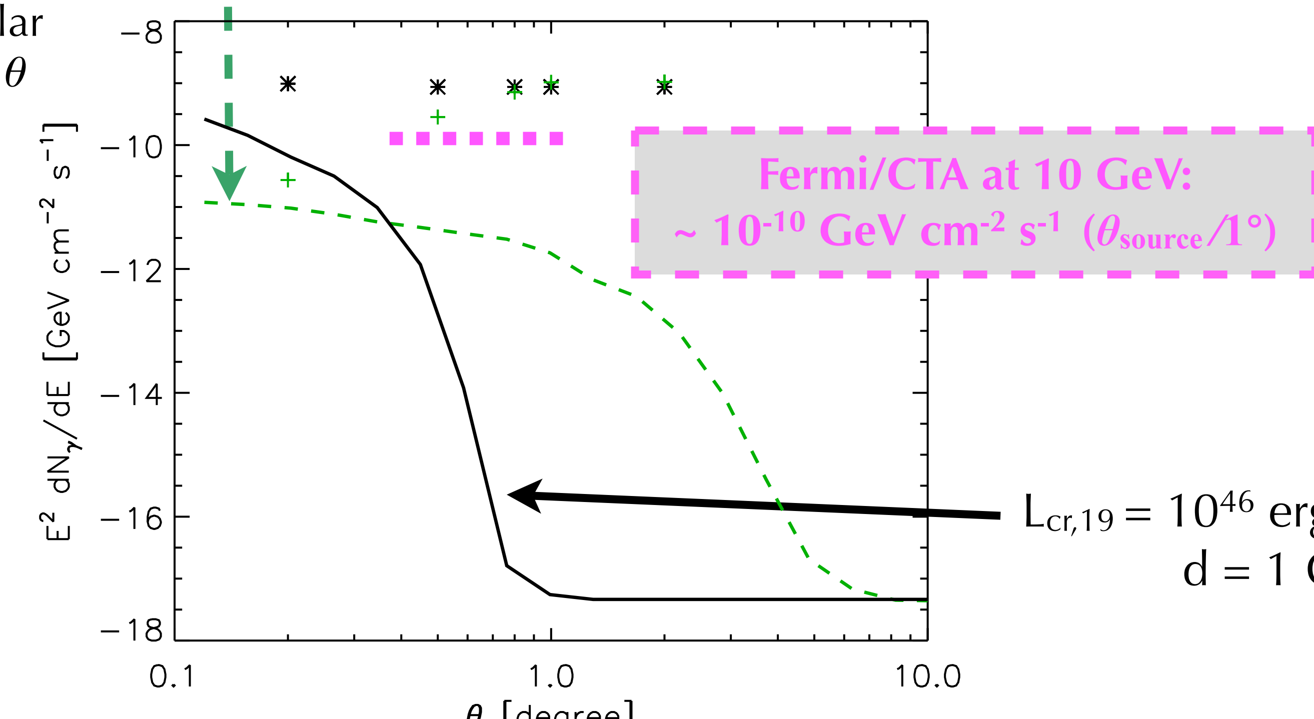

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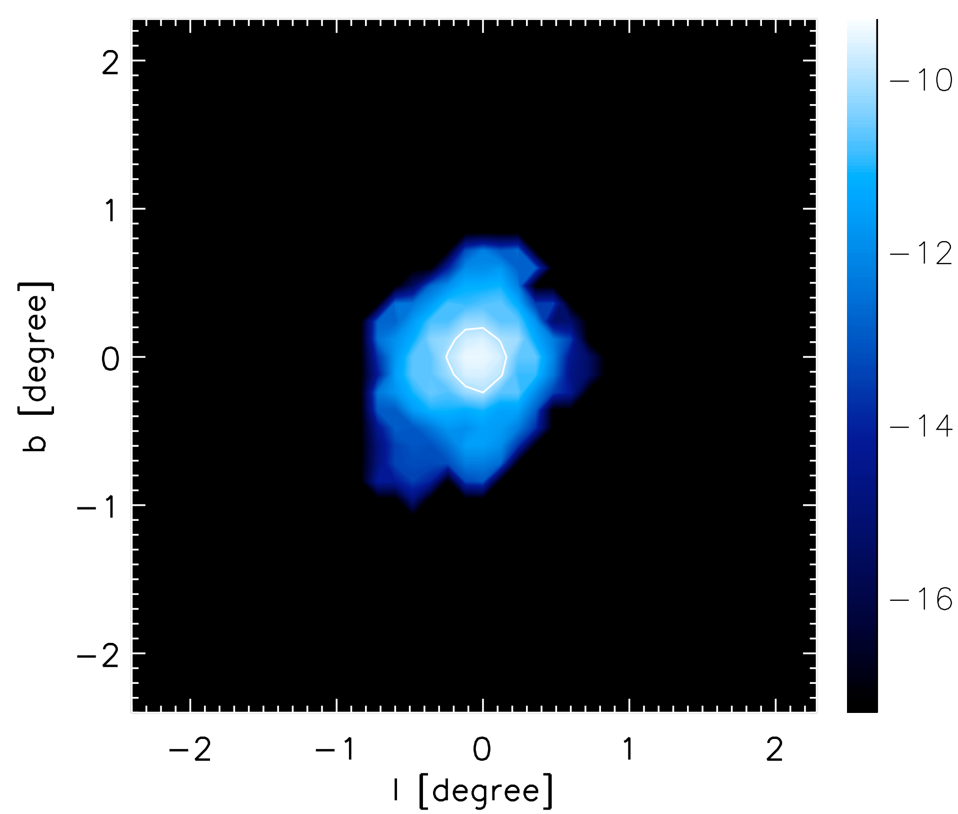
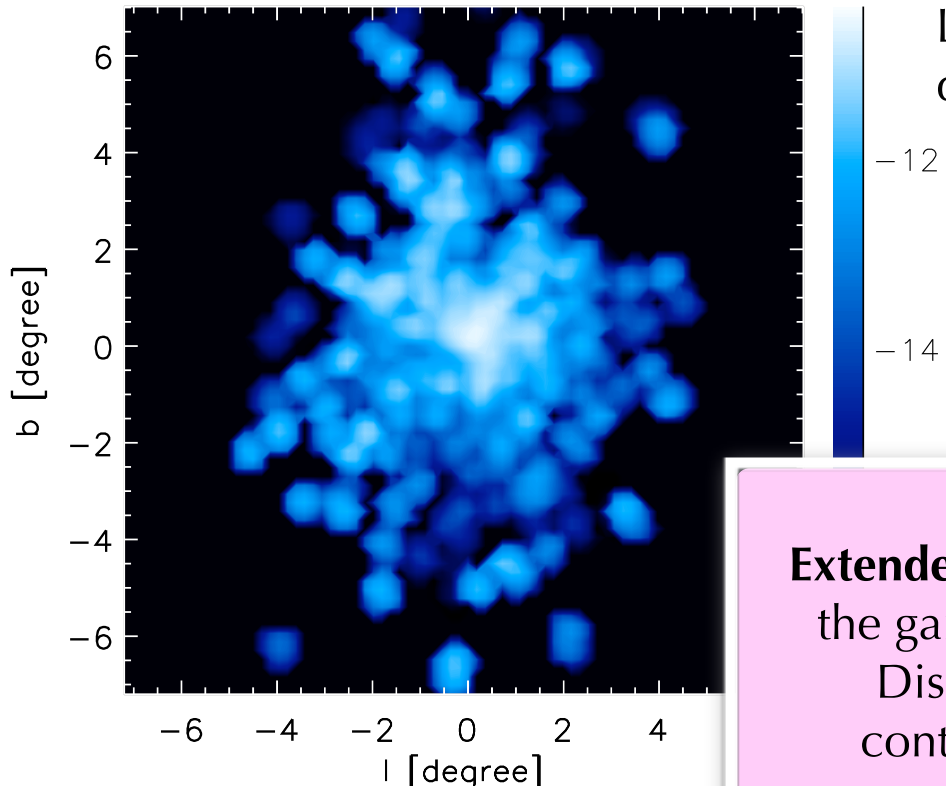
d = 1 Gpc



Case of particularly powerful sources



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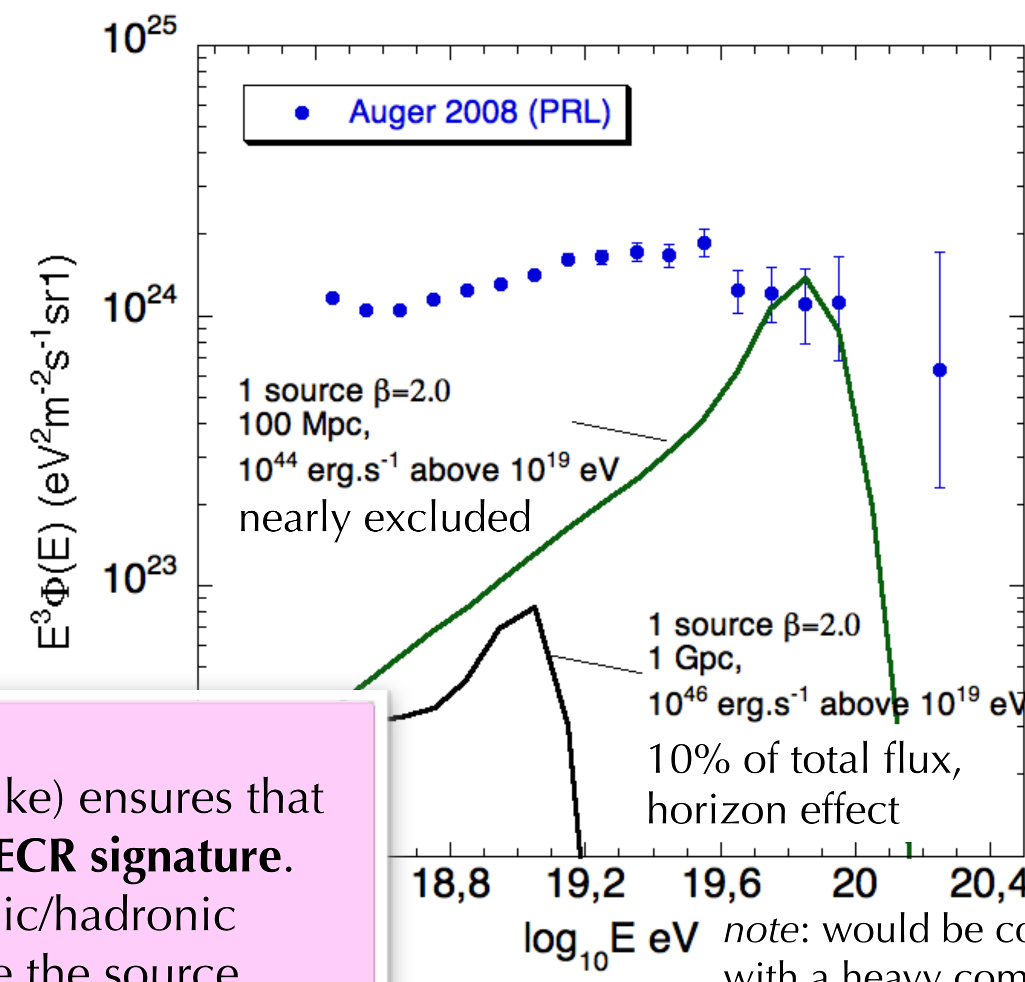
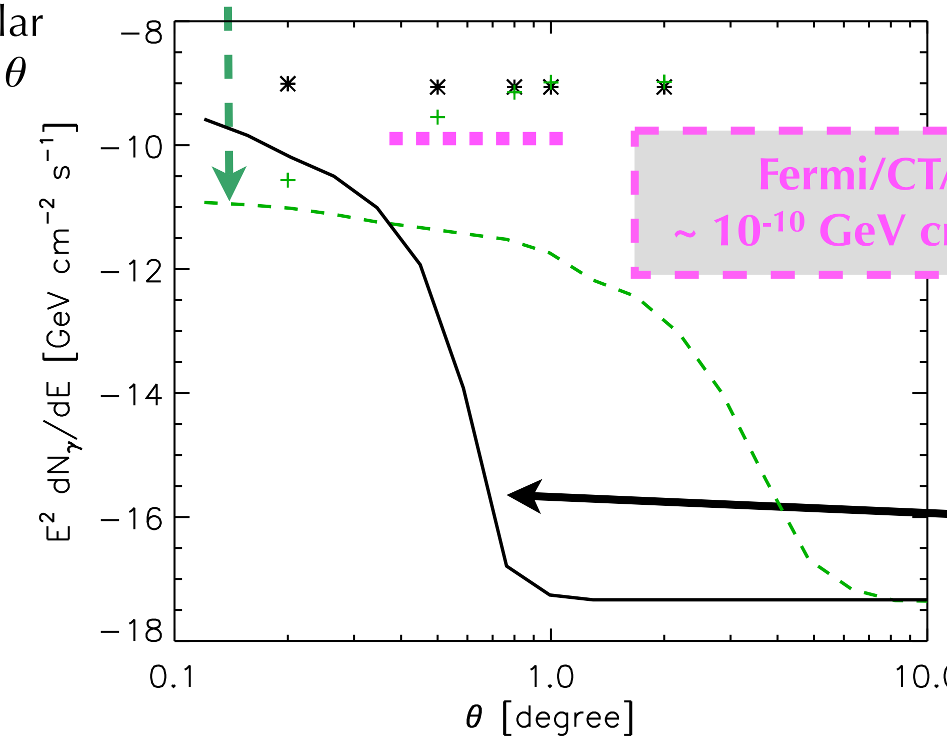
d = 100 Mpc



note: would be consistent with a heavy composition at UHE (Auger?)

Extended emission (NOT pointlike) ensures that the gamma emission is an **UHECR signature**. Distinguishable from leptonic/hadronic contribution produced inside the source.

* + flux integrated up to angular extension θ



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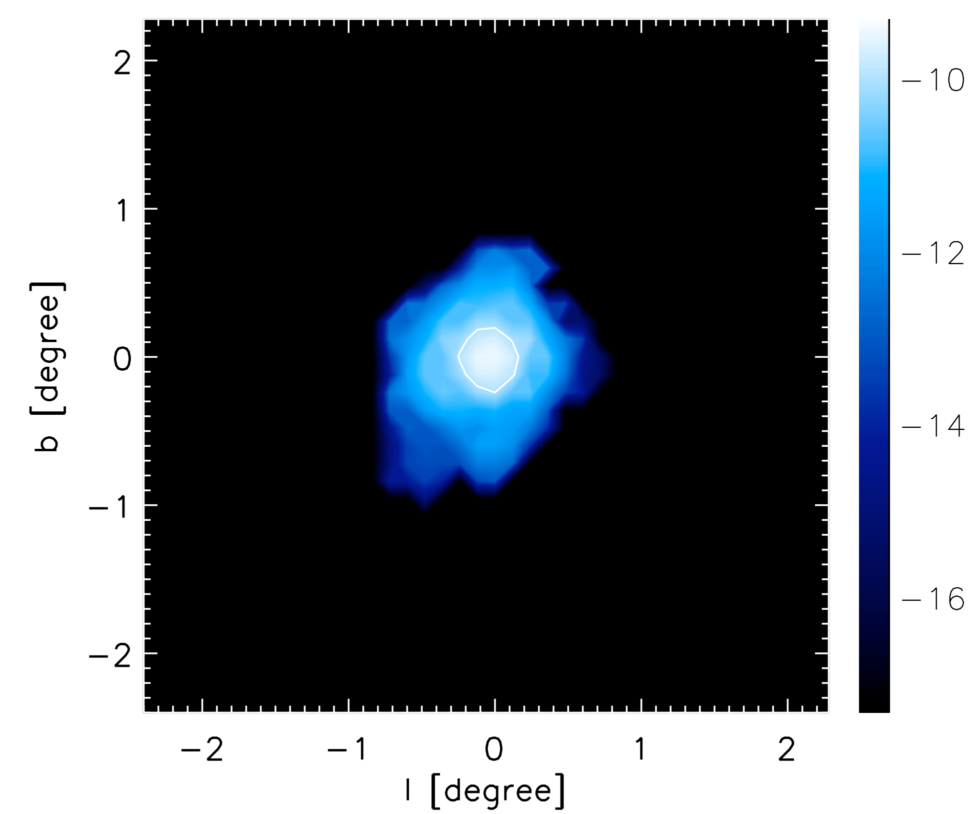


Case of close-by sources: Cen A

for synchrotron emission:
extended and strong magnetic field necessary

-> **lobes of Cen A?**

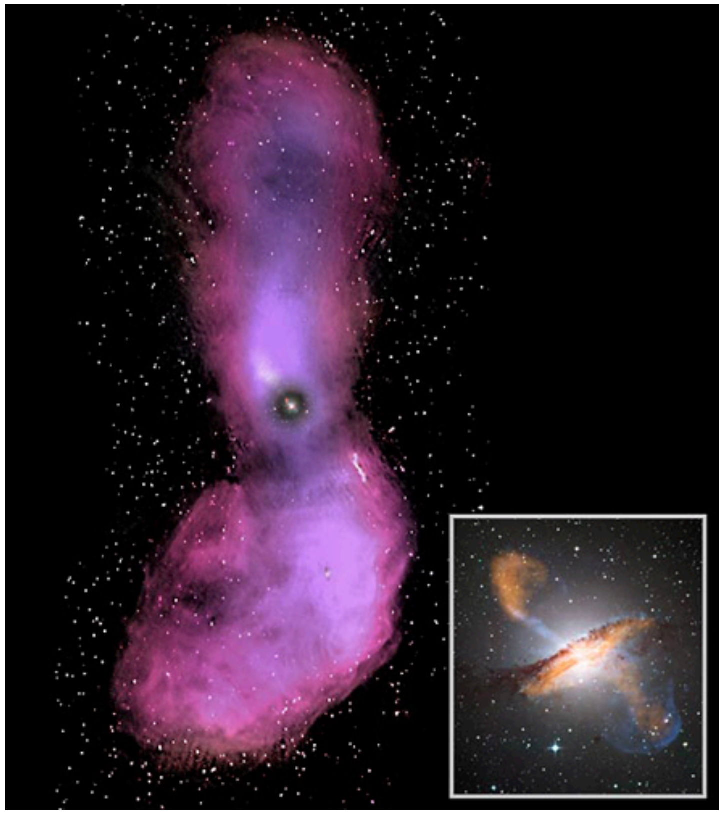
$B_{\rm lobes} \sim 1\ \mu$G, $l_{\rm coh} \sim 20$ kpc, $R_{\rm lobe} \sim 100$ kpc, $L_{\rm cr,19} \sim 3\times10^{39}$ erg s^{-1}

7 degrees in the sky -> sensitivity loss of $\boldsymbol{\theta_{\rm source}/\theta_{\rm PSF} \sim 7}$

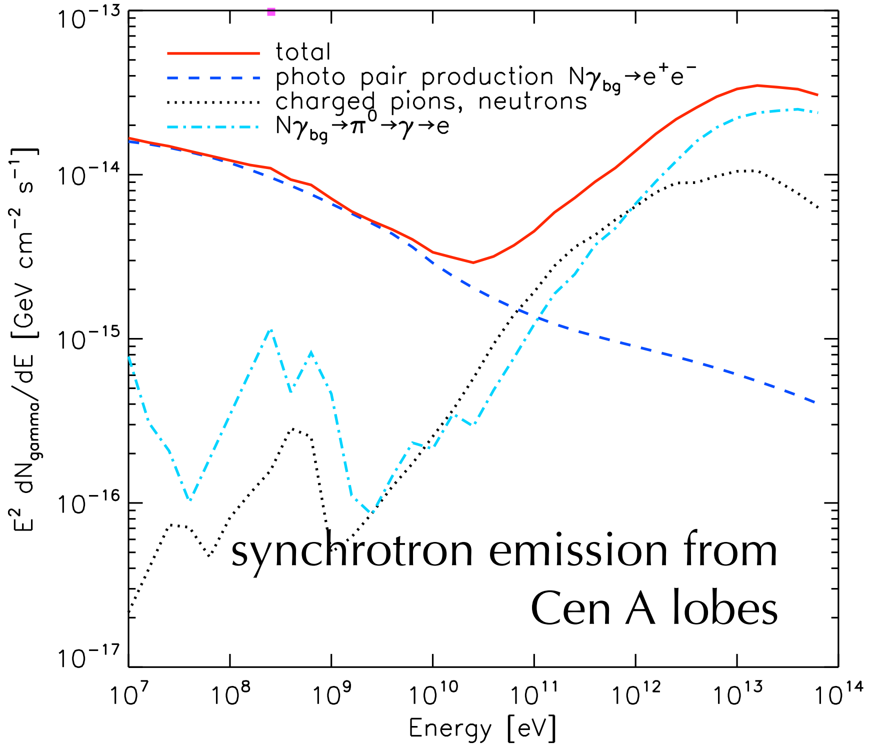
$$F_{\rm lobe,10\,TeV} \sim \left(\frac{d_{\rm Cen\,A}}{d_{\rm fil}}\right)^{-2} \frac{L_{\rm CenA}}{10^{42}\,{\rm erg/s}} \frac{R_{\rm lobe}}{5\,{\rm Mpc}} F_{\rm fil,10\,GeV}$$

total decrease of factor ~ 10^3 compared to average sources -> hardly observable

UHE photons could be detectable with Auger *Taylor et al. 09*
expected rate of $>10^{19}$ eV photons from Cen A,
assuming it is responsible for 10% of the 6×10^{19} eV flux: **0.2–0.3 events/yr**



Fermi:
~ 10^{-9} GeV cm^{-2} s^{-1} ($\theta_{\rm source}/7°$)



Are signatures of UHECR detectable in gamma rays?

K.K., D. Allard, M. Lemoine, submitted to A&A

We studied the detectability of UHECR signatures in gamma rays, taking into account major astrophysical constraints:

- source environment
- magnetic configuration in the Universe
- types of emission: EM cascade, synchrotron emission
- UHECR composition
- source luminosity
- observed UHECR spectrum

Flux ultimately depends on **injected energy at the source** (robust according to B, composition, ...).

Our conclusions on detectability:

- average type of sources not observable by current and upcoming instruments (2 orders of magnitude)
- powerful sources:
  $L_{19}=10^{44}$ erg s^{-1} at 100 Mpc **at limit of observed CR spectrum**, would produce a **detectable γ halo of ~2°**
  $L_{19}=10^{46}$ erg s^{-1} at 1 Gpc produce **10% of observed CR spectrum**, and a **detectable γ halo of fract. of deg.**
  Note: **halo = clear signature of UHECR**
- close-by sources: Cen A
  synchrotron radiation due to injection of UHECR in lobes not observable
  UHE emission potentially observable with Auger if Cen A is responsible for 10% of the 6×10^{19} eV flux