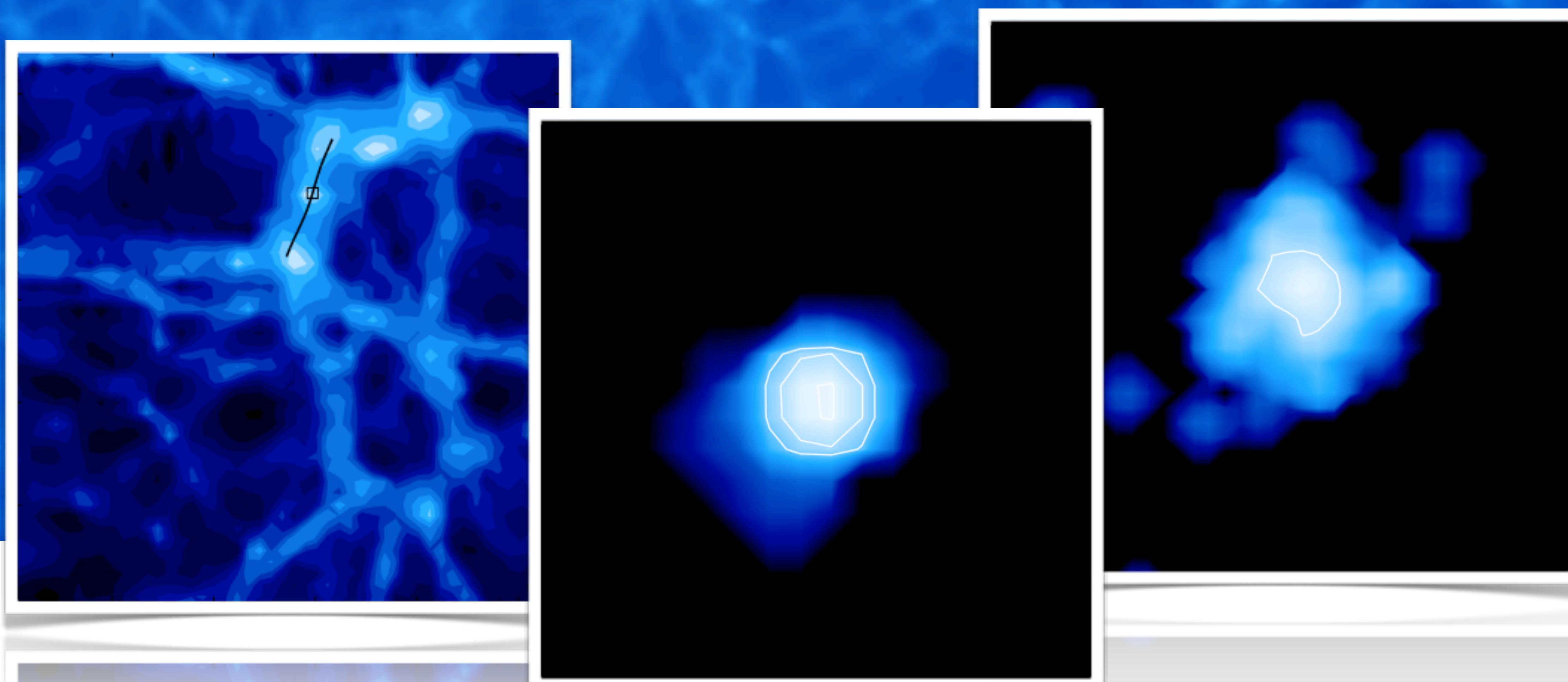
Are signatures of ultrahigh energy cosmic rays detectable in gamma rays?

K.K., D. Allard and M. Lemoine, in prep.



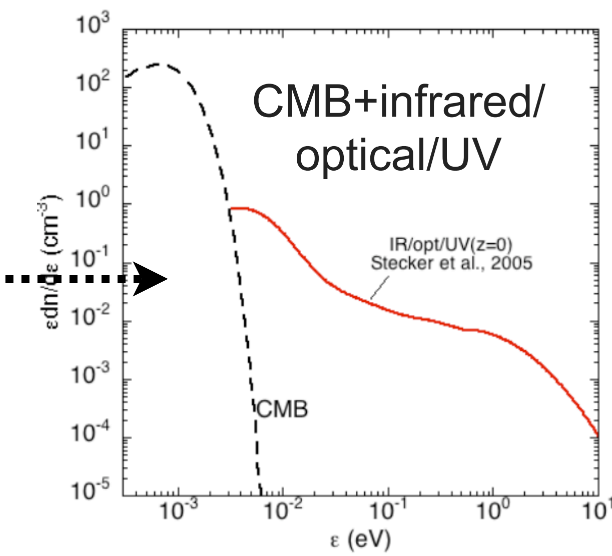
Necessity of multi-messenger Astrophysics

sources?
acceleration
mechanisms?

?

ultrahigh energy cosmic rays

charged particles propagation affected by **extragalactic magnetic fields**



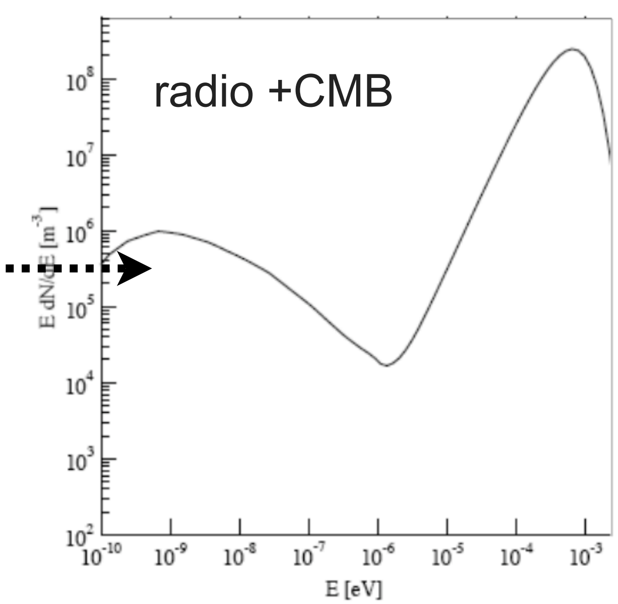
interactions on photonic and baryonic backgrounds

high energy neutrinos

low interaction rate
with matter
need huge detectors

e+, e-

charged particles
propagation affected by **extragalactic magnetic fields**?
to which extent?



synchrotron
Inverse Compton

cascades

X rays, γ rays

observable ?

due to interactions with photon backgrounds,
for E_γ > 100 TeV, **horizon** of a few Mpc

Electromagnetic cascades in magnetic fields

$\gamma\gamma_{bg} \to e^+e^-$ → $e\,\gamma_{bg} \to e\,\gamma$ → ...

pair production — **Inverse Compton**

Protheroe 86
Protheroe & Stanev 93
Aharonian et al. 94

$E_{e,\gamma}$ > 100 TeV:

cascade in Klein Nishina regime (rectilinear propagation)

ends at short distance from source
as energy loss lengths $\lambda_{\gamma\gamma}$, λ_{IC} < 5 Mpc for $E_{e,\gamma} < 10^{18}$ eV

$E_{e,\gamma}$ < 100 TeV:

cascade in Thomson regime - IC emission isotropized

$$\frac{t_{IC}}{t_L} \sim 3\times 10^{-2}\, E_{14}^{-2}\,(1+E_{14}^{3/2})\, B_{-12}$$

$$t_L < t_{IC} \Rightarrow B_{IGM} \gtrsim 3\times 10^{-11}\,\mathrm{nG}$$

if $B_{IGM} > 3\times10^{-11}$G, isotropization of e^{+-} over t_{IC}

homogeneous B case:

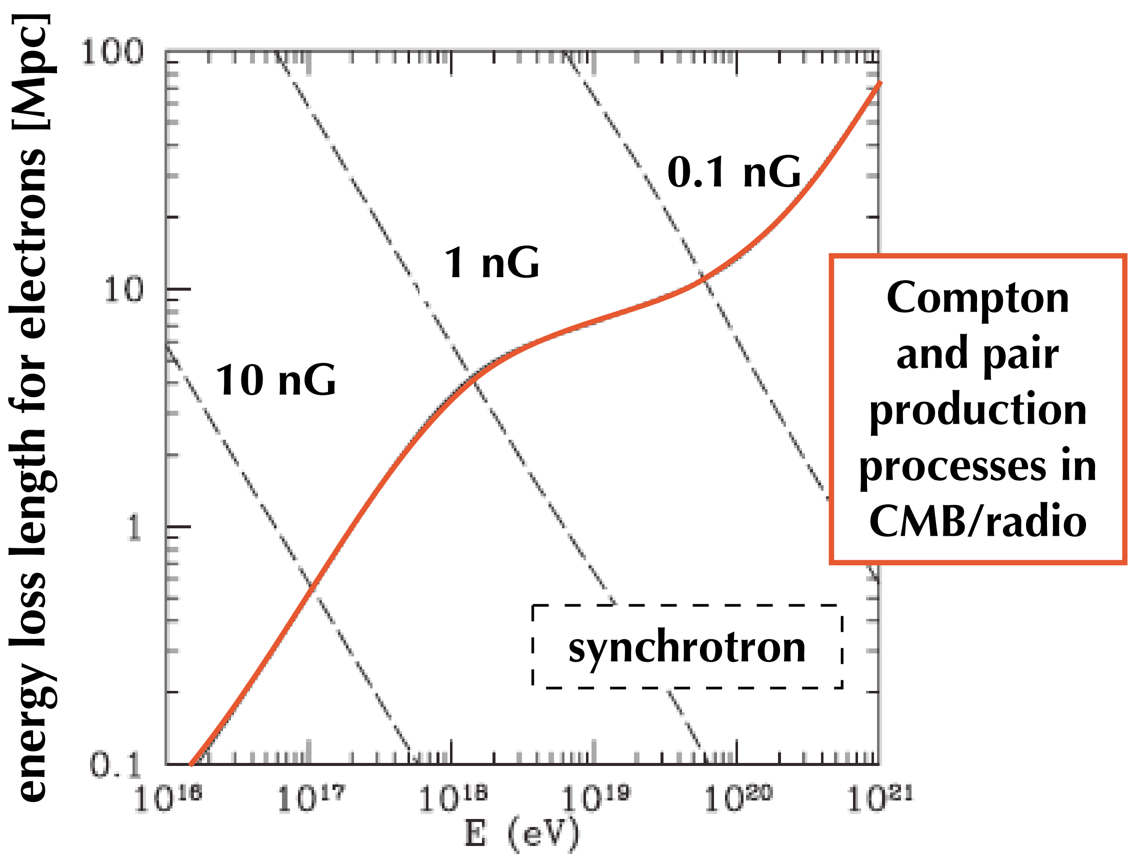
beyond some Mpc, pairs isotropized and photons are up-scattered isotropically by IC
Observed from a distance d, the cascade thus results in

halo of size ~ 30° at d=100 Mpc (for homogeneous B=1 nG)

Flux diluted - not observable with current and upcoming intrument sensitivities.

Synchrotron emission from UHE electrons propagating in magnetized environments

Aharonian (2002)
Gabici & Aharonian (2005)



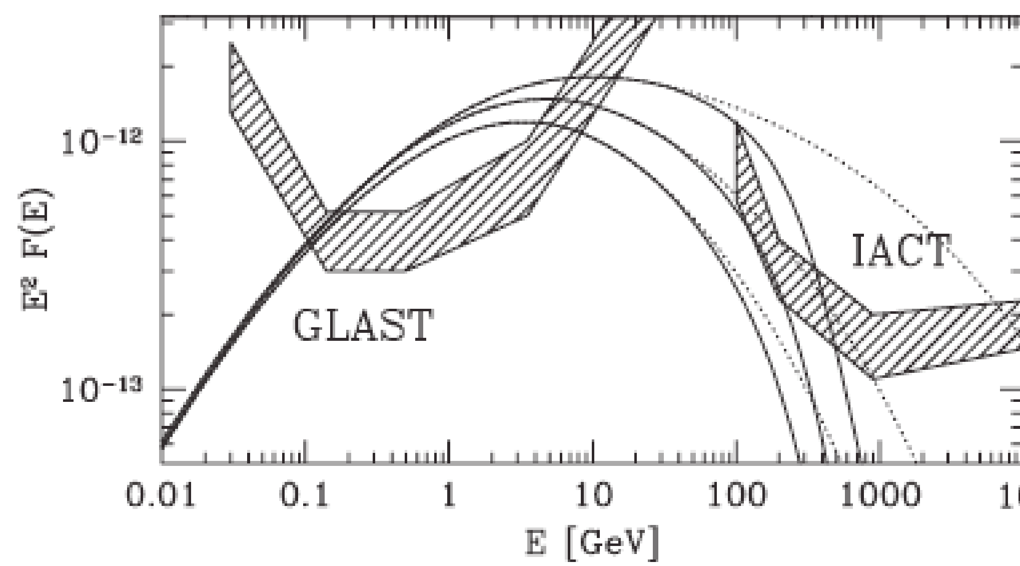
$$x_{syn} \sim 3.8\ \text{kpc} \left(\frac{B}{10\ \text{nG}}\right)^{-2} \left(\frac{E_e}{10^{19}\ \text{eV}}\right)^{-1}$$

$$E_{\gamma,syn} \sim 6.8 \times 10^{10}\ \text{eV} \left(\frac{B}{10\ \text{nG}}\right) \left(\frac{E_e}{10^{19}\ \text{eV}}\right)^{2}$$

$x_{syn} < x_{IC}$

If the magnetic field **close to the source** is at **nanoGauss level**, first generation electrons generated by UHECR propagation cool rapidly emitting **GeV synchrotron photons** and the development of the cascade is strongly inhibited.

source luminosity $L_{19} = 10^{46}$ erg s^{-1}
B = 1 nG over 20 Mpc sphere around source
distance d = 1 Gpc



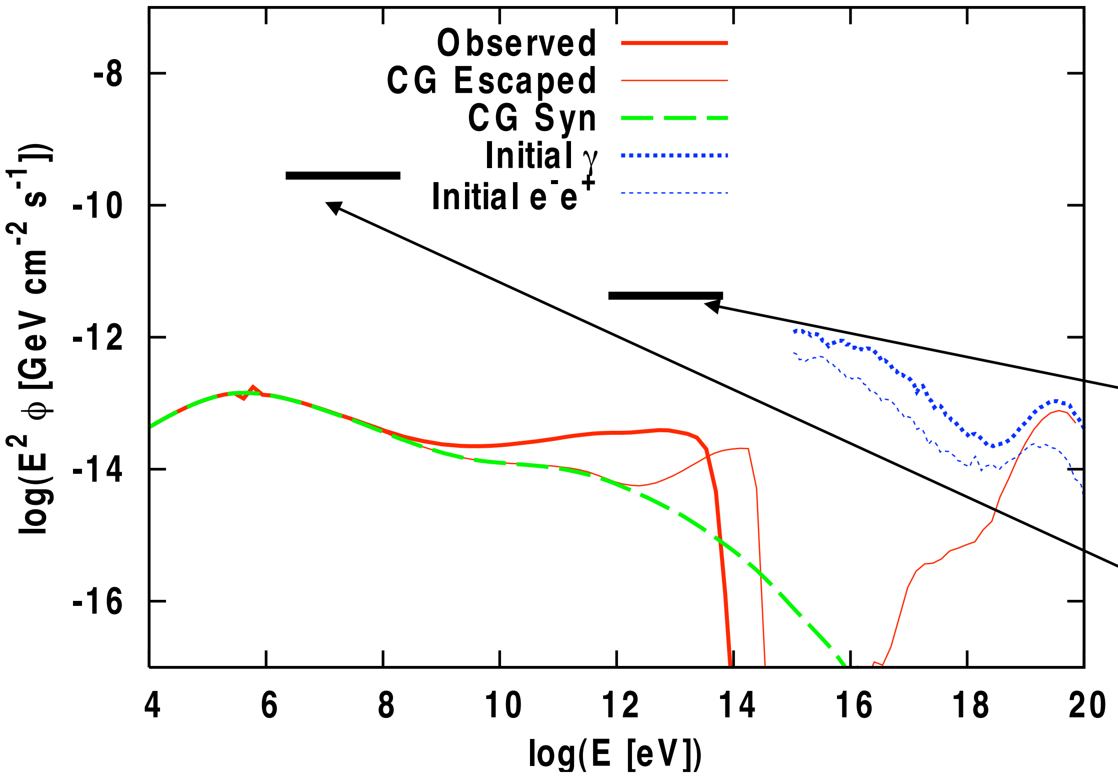
These calculations assume a homogeneous magnetic field and a pure proton composition.
What if the inhomogeneities are taken into account?

Gamma ray emission from a magnetized cluster of galaxies

Armengaud et al. 2006

K.K., D. Allard, K. Murase, J. Aoi, Y. Dubois, T. Pierog, S. Nagataki, 2009

B_{core} = 10 μG
spectral index = 2.3
AGN luminosity for $E_{max} = 10^{20.5}$ eV:
$L_{cr,19} = 10^{42}$ erg s^{-1}



gamma rays from UHECR injected in a cool core cluster, numerical work in a particular cluster model

CTA: point source **~ 10^{-11} GeV cm^{-2} s^{-1}**

cluster of R ~ 5Mpc at 100 Mpc: $\theta_{source} \sim 3^{o}$

Fermi: source of some degrees **~ 10^{-9} GeV cm^{-2} s^{-1}**

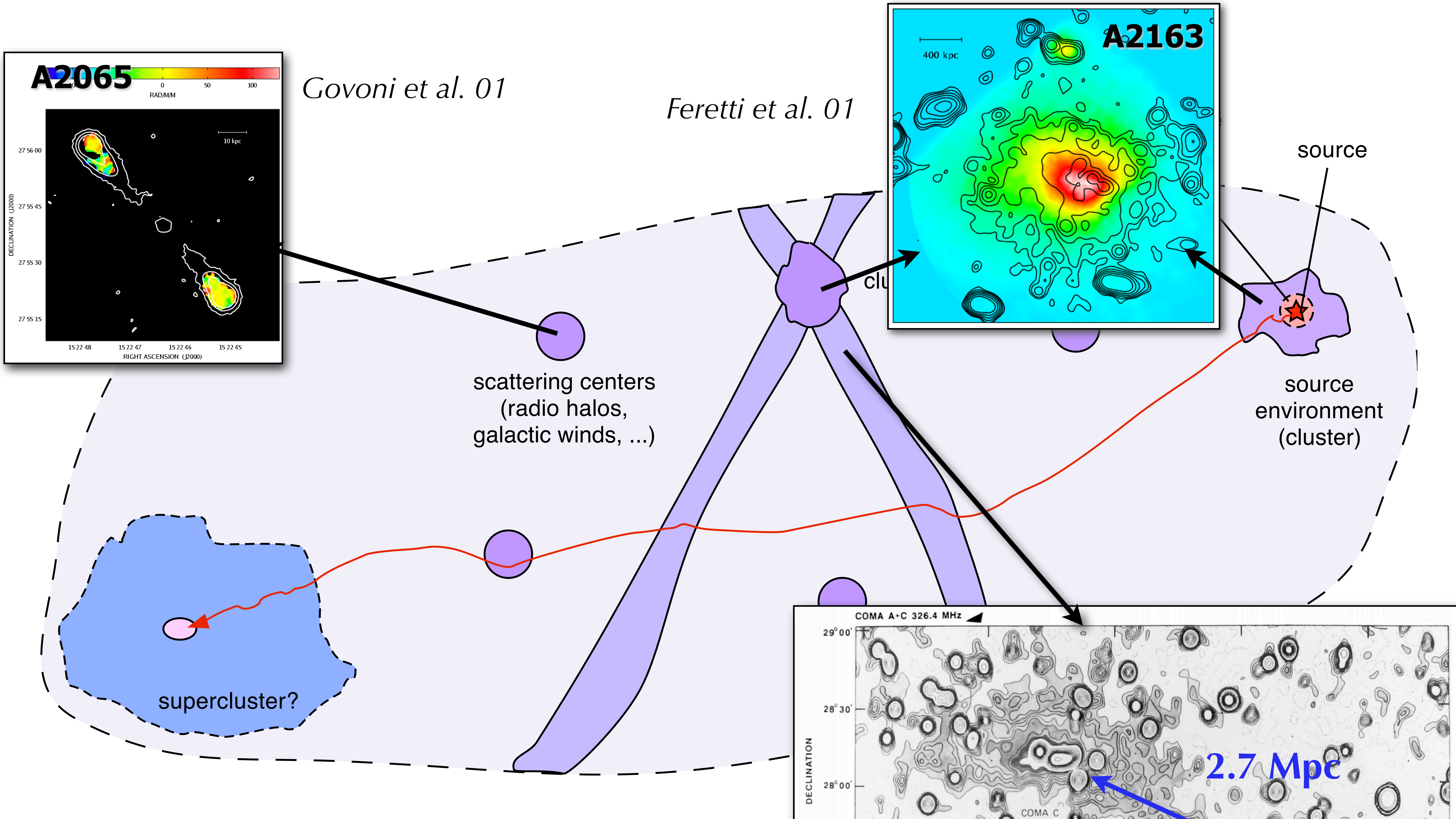
- More general cases?

  magnetic field **structure/intensity changes** (e.g. source in filaments)

- Exceptional cases?

  close-by source (< 30 Mpc)?
  powerful sources?

What do we know about extragalactic magnetic fields?



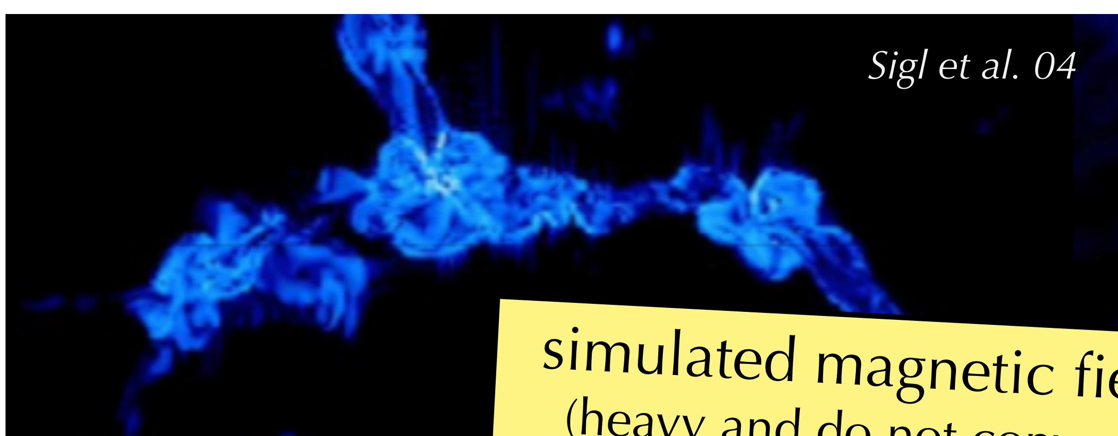
very few observations/measurements of extraGalactic magnetic fields

Modeling extragalactic magnetic fields

theories on the origins...
(that do not really converge)

primordial (inflation, phase transition, reionization...)
or "**astrophysical**": ejection/pollution from galactic winds, AGN jets

use ad-hoc modeling of these origins
+ cosmological simulations
+ MHD equations for evolution of B field coupled to matter



simulated magnetic fields
(heavy and do not converge)

different consequences for cosmic ray propagation:

Sigl/Miniati/Ensslin:
deflections > 10° beyond 10^{20} eV
Dolag/Grasso/Tkachev:
very small deflections (< few degrees)

flexible modeling
(*K.K. & Lemoine 2008*)

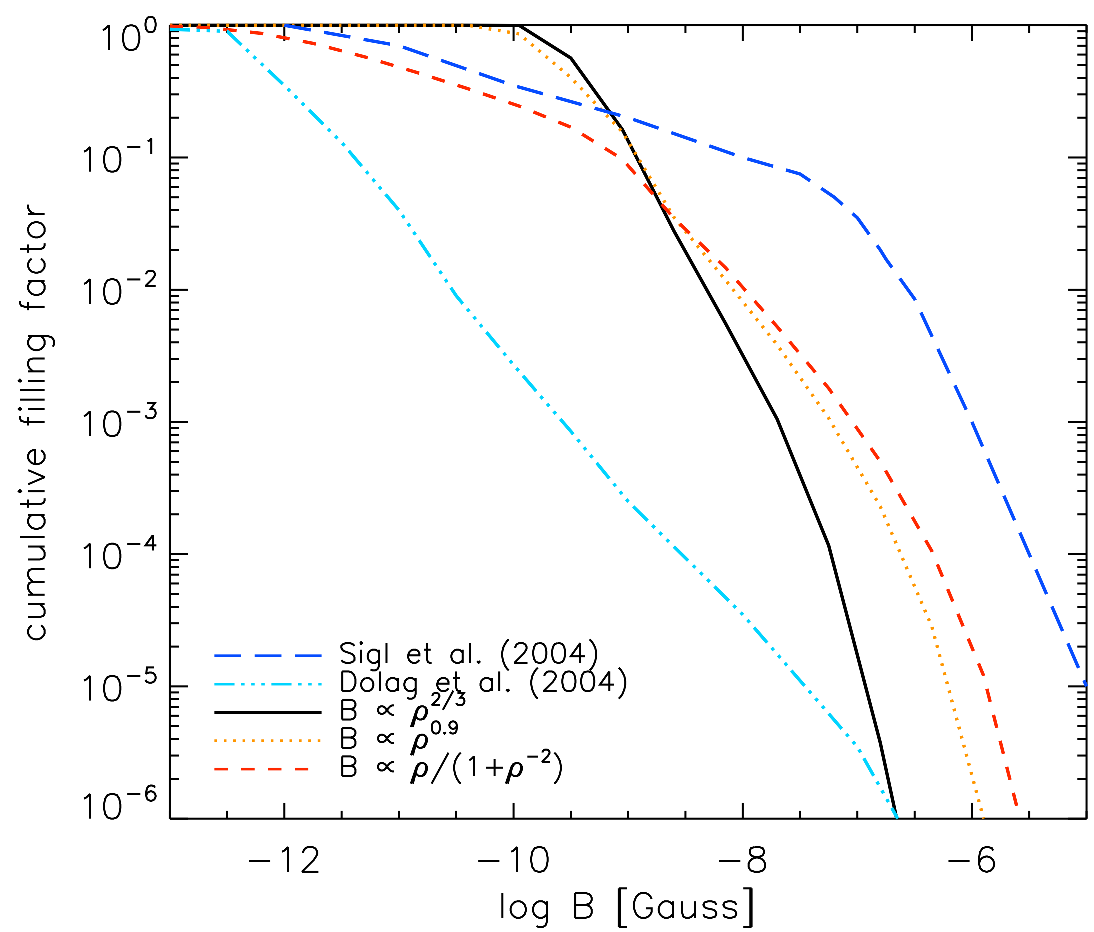
ρ density grid from Dark Matter cosmological simulation

mapping:
$$B = f(\rho)$$

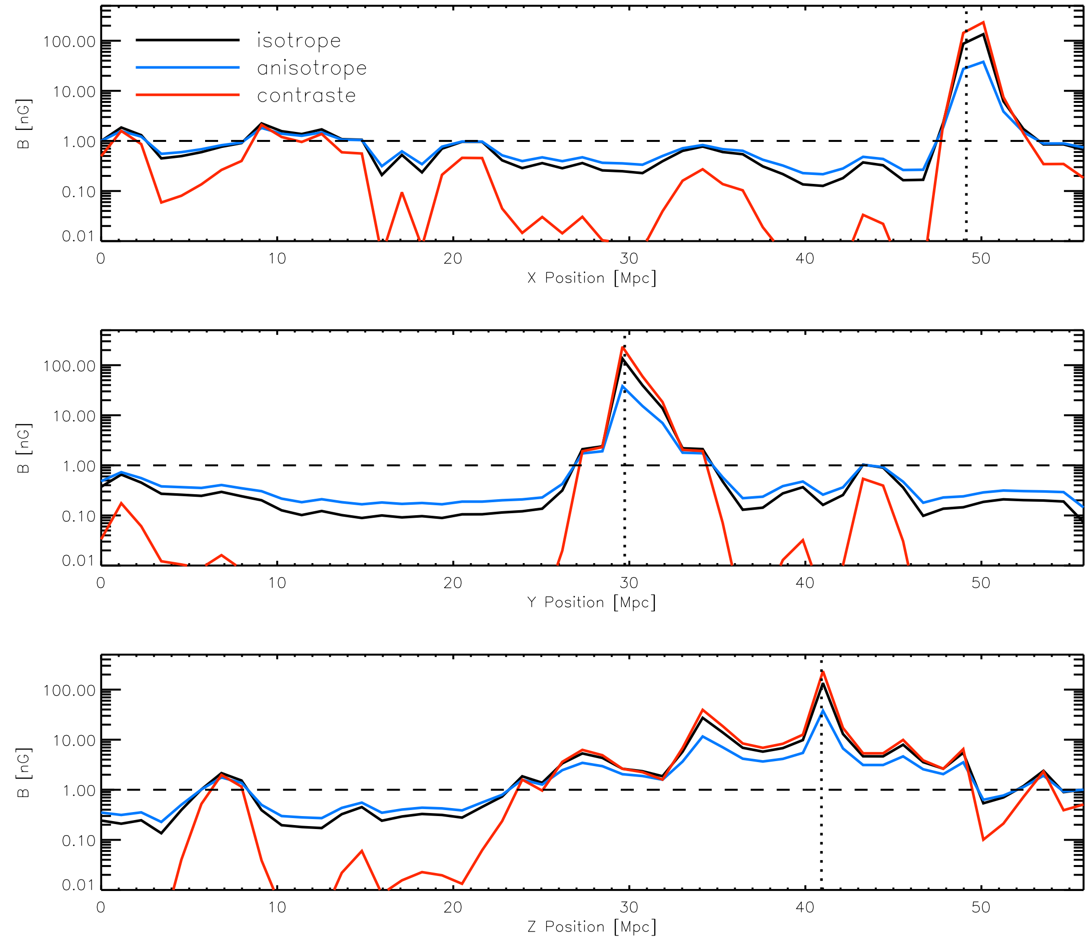
$$f_{\rm ani}(\rho) = \rho^{0.9}$$

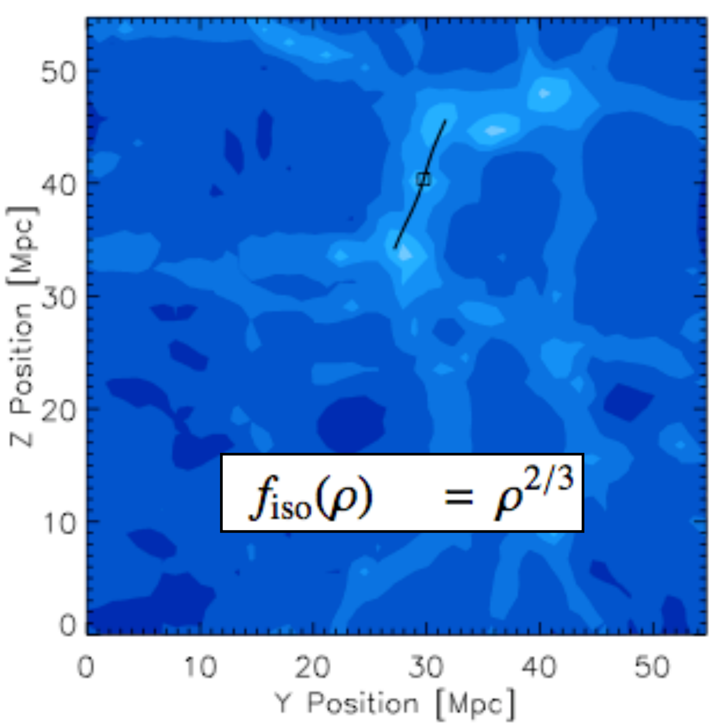
$$f_{\rm iso}(\rho) = \rho^{2/3}$$

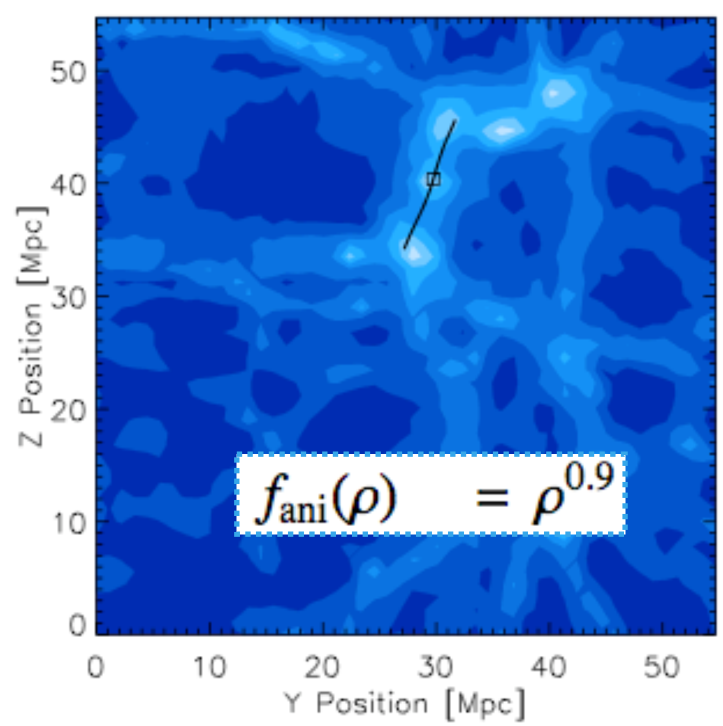
$$f_{\rm contrast}(\rho) = \rho\left[1+\left(\frac{\rho}{\langle\rho\rangle}\right)^{-2}\right]^{-1}$$

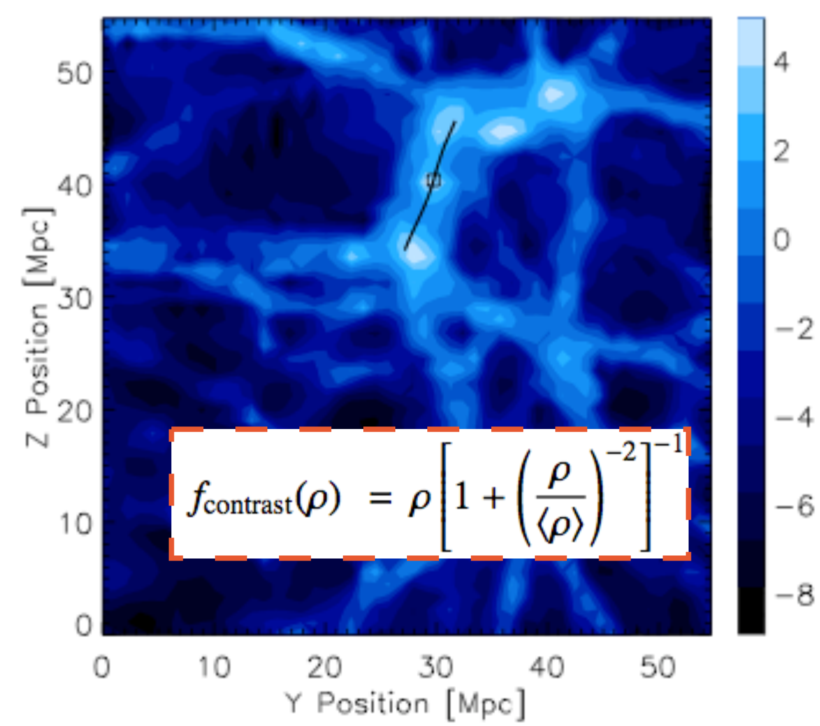


Our modeling of extragalactic magnetic fields







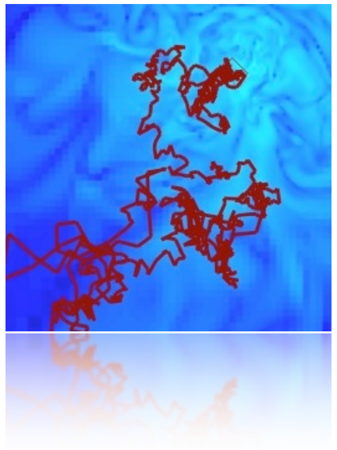


A complete propagation code

K.K., D. Allard, K. Murase, J. Aoi, Y. Dubois, T. Pierog, S. Nagataki, 2009

Propagation in magnetic fields:
fast semi-analytical propagation code that takes into account small-scale turbulence effects (Cellular method, *Kotera & Lemoine 2008a*)

cosmic ray trajectory in magnetic field

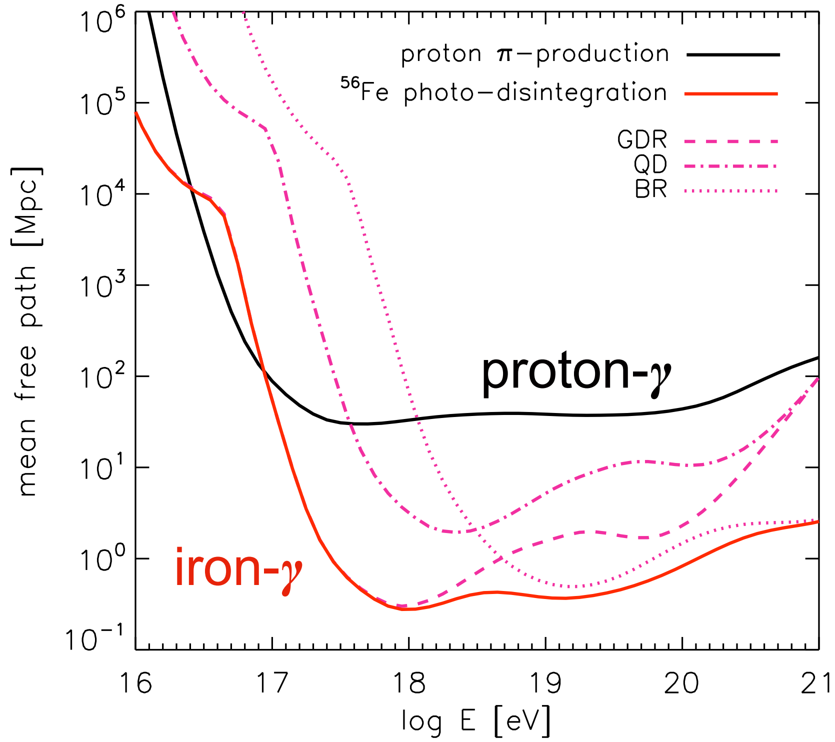


Interactions with nuclei:
γ-N processes and propagation of secondary nucleons (*Allard et al. 05*, and SOPHIA, *Mucke et al. 1999*)

p-N processes: using CONEX, EPOS (hadronic interaction codes to simulate air showers)

+ can predict **multimessengers**

proton vs iron mean free paths



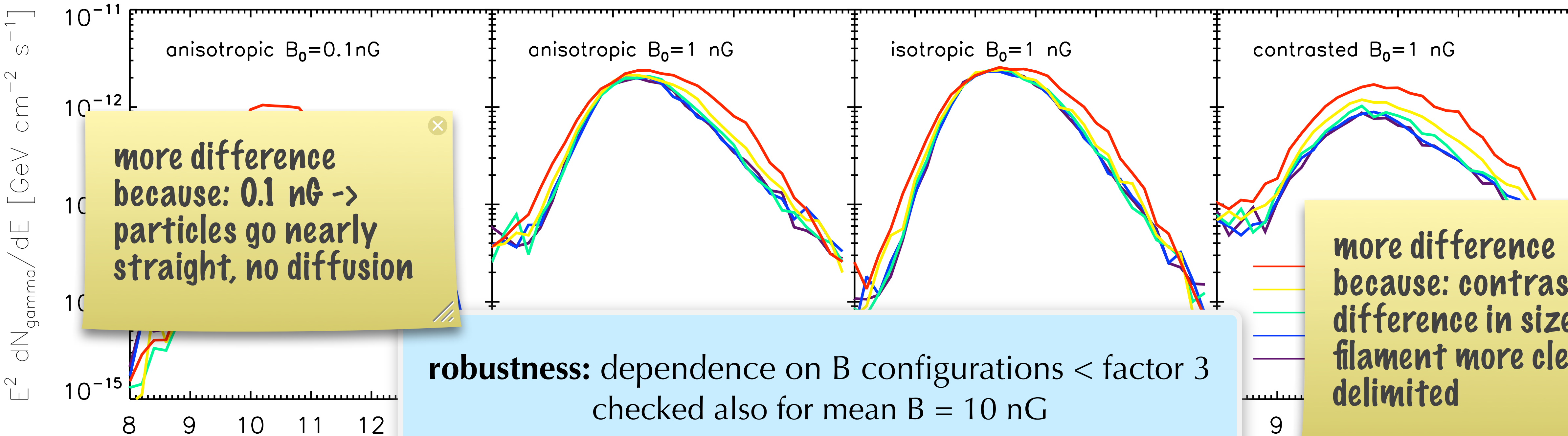
Gamma-ray cascades:
Treated as post-analysis

Effects of inhomogeneous magnetic fields

<B> = 1 nG, spectral index = 2.3

$E_{max} = 10^{20.5}$ eV and $L_{cr,19} = 10^{42}$ erg s^{-1}

distance to observer d = 100 Mpc



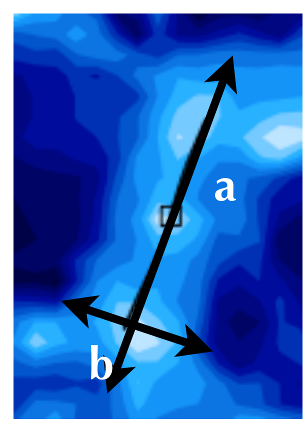
more difference because: 0.1 nG -> particles go nearly straight, no diffusion

more difference because: contrasted -> difference in size of filament more clearly delimited

robustness: dependence on B configurations < factor 3
checked also for mean B = 10 nG

$$t_{\rm syn} < t_{\rm IC} \Rightarrow B_{\rm IGM} \gtrsim 3\,{\rm nG}\,E_{18}^{-3/4}$$

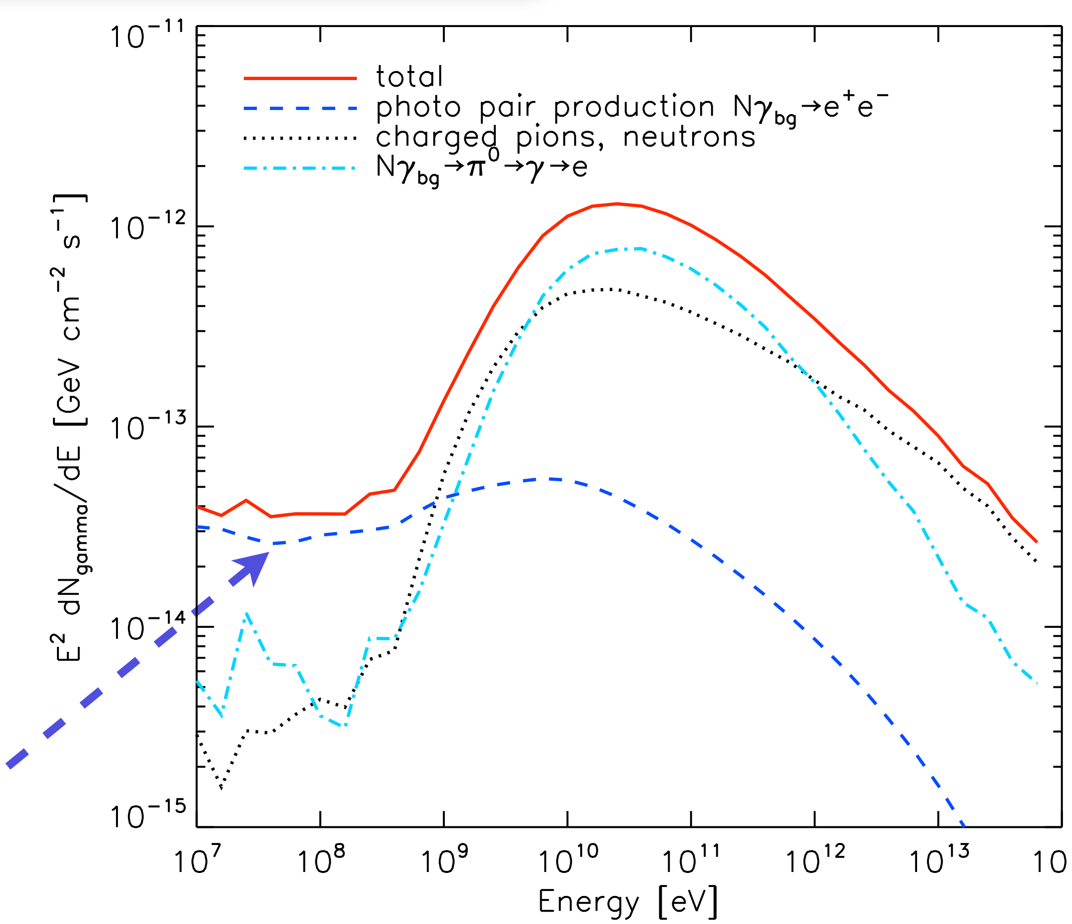
$$\frac{t_{\rm L}}{t_{\rm syn}} > 1 \Longleftrightarrow E_{\rm e} > 2\times 10^{18}\,{\rm eV}\,B_{-8}^{-1/2}$$



The whole structure with B > 3 nG will be illuminated in synchrotron from e^{+-} of E > 10^{18} eV.

At a given energy E_e, F_{along}/F_{ortho} ~ a/b ~ 2, where a and b are the characteristic lengths of the axis of the filament, where the field is B > 3 nG $E_{e,18}$.

low energy: controlled by B
more confinement -> more pairs -> more gamma

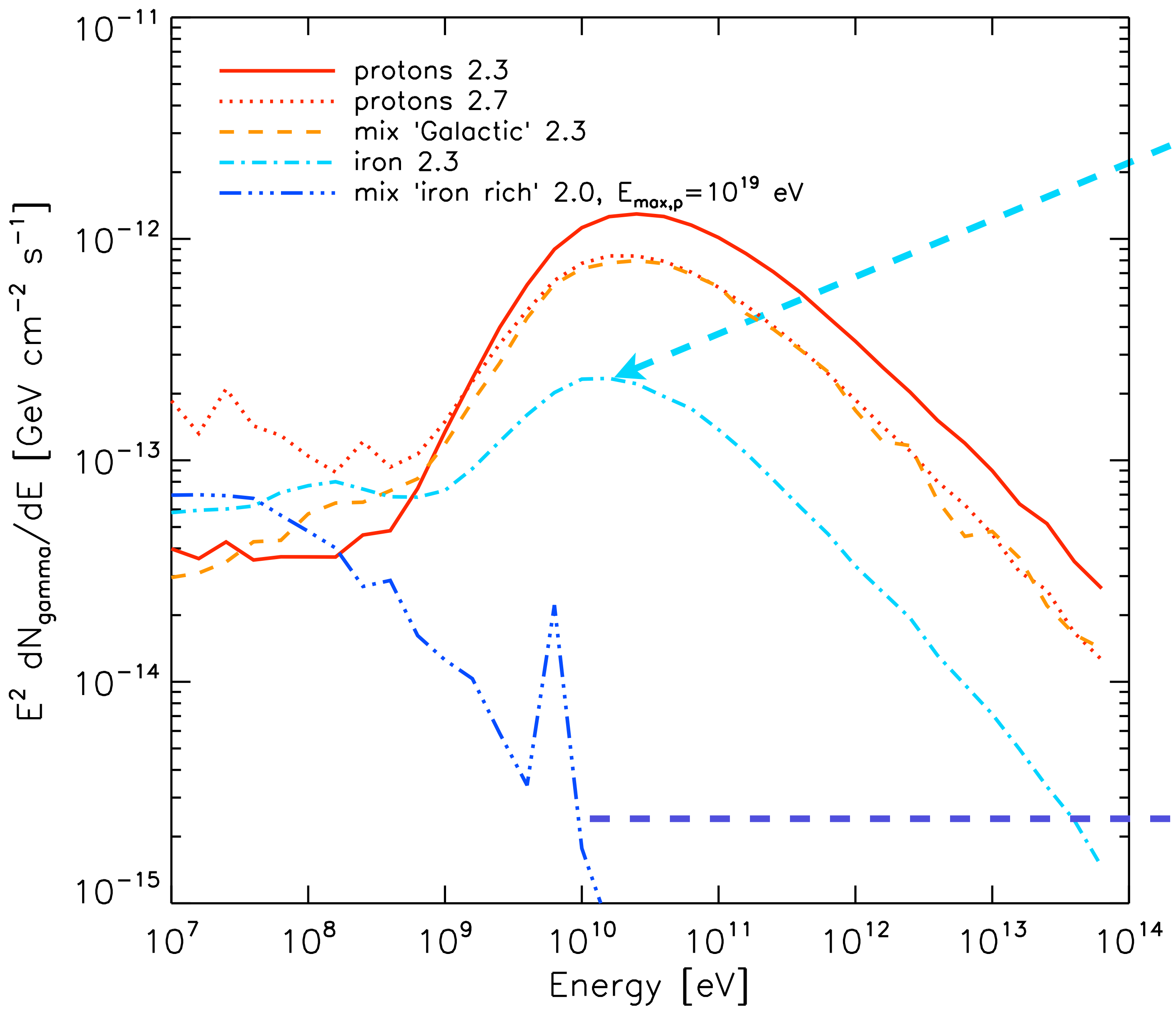


Effects of cosmic ray composition

$\langle B \rangle = 1$ nG, spectral index = 2.3

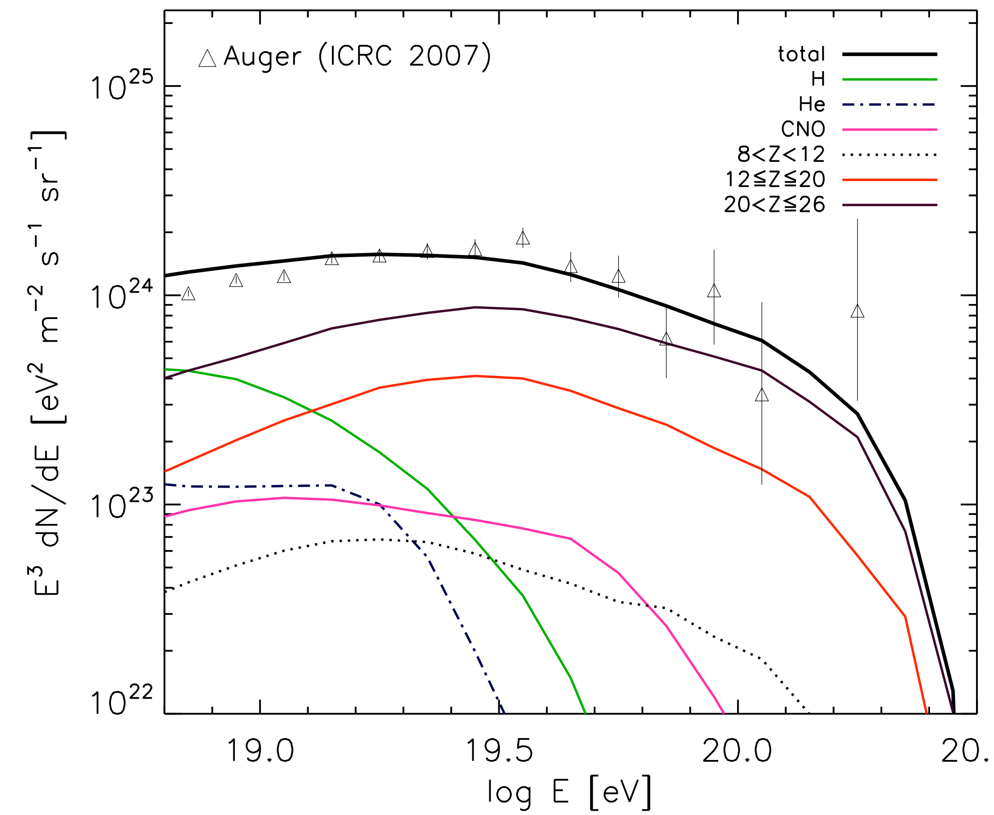
$E_{max} = 10^{20.5}$ eV and $L_{cr,19} = 10^{42}$ erg s^{-1}

distance to observer d = 100 Mpc



For nuclei, flux due to secondary protons. Intensity of flux depends on the rate of particles with

$$E_A/A > E_{p\gamma_{\rm CMB}}$$



adapted from Allard et al. 2008

robustness: dependence on composition < factor 5

Detectability: for average types of sources

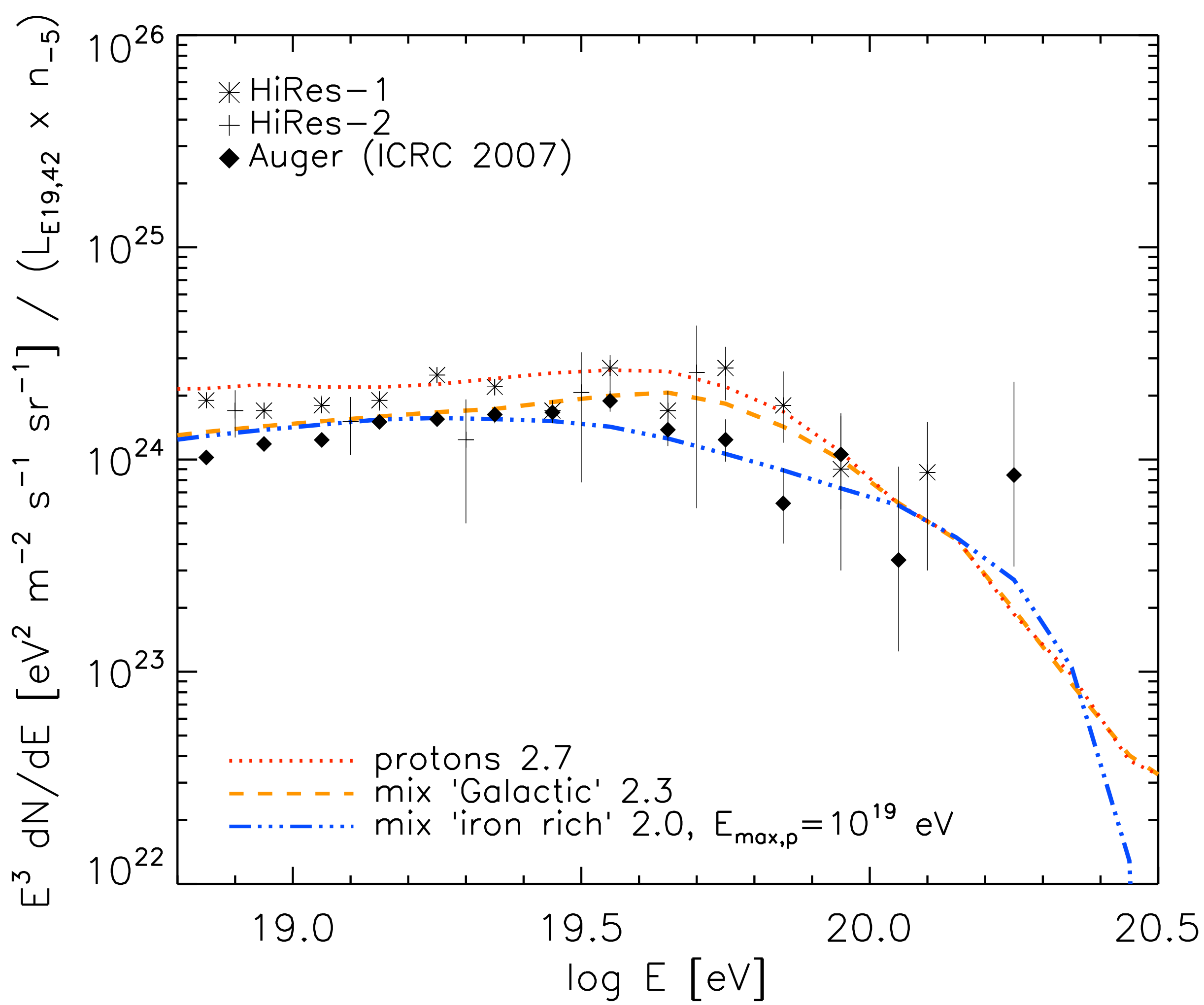
$\langle B \rangle = 1$ nG, spectral index = 2.3

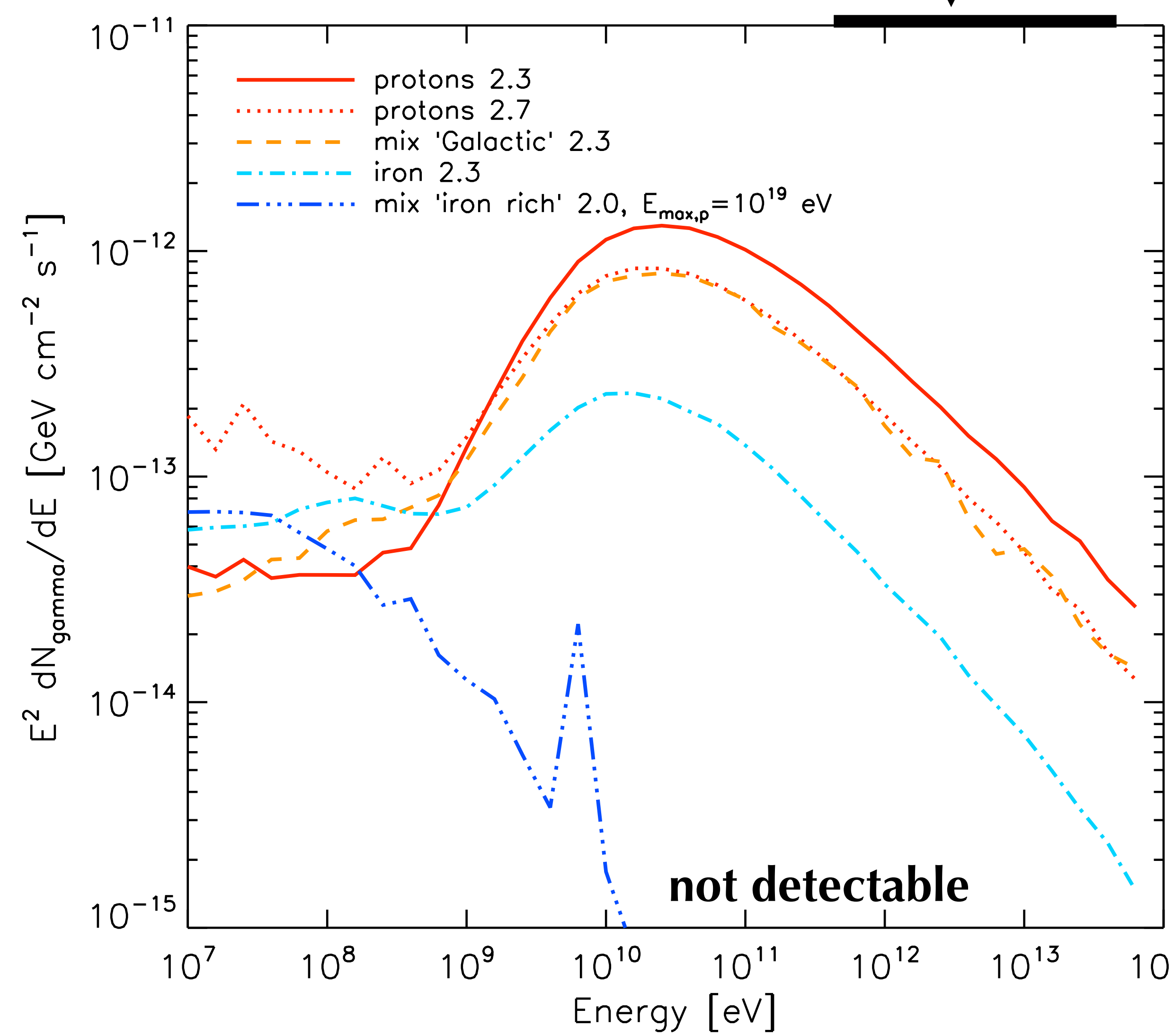
$E_{max} = 10^{20.5}$ eV and $L_{cr,19} = 10^{42}$ erg s^{-1}

$n_{sources} = 10^{-5}$ Mpc^{-3}

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

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

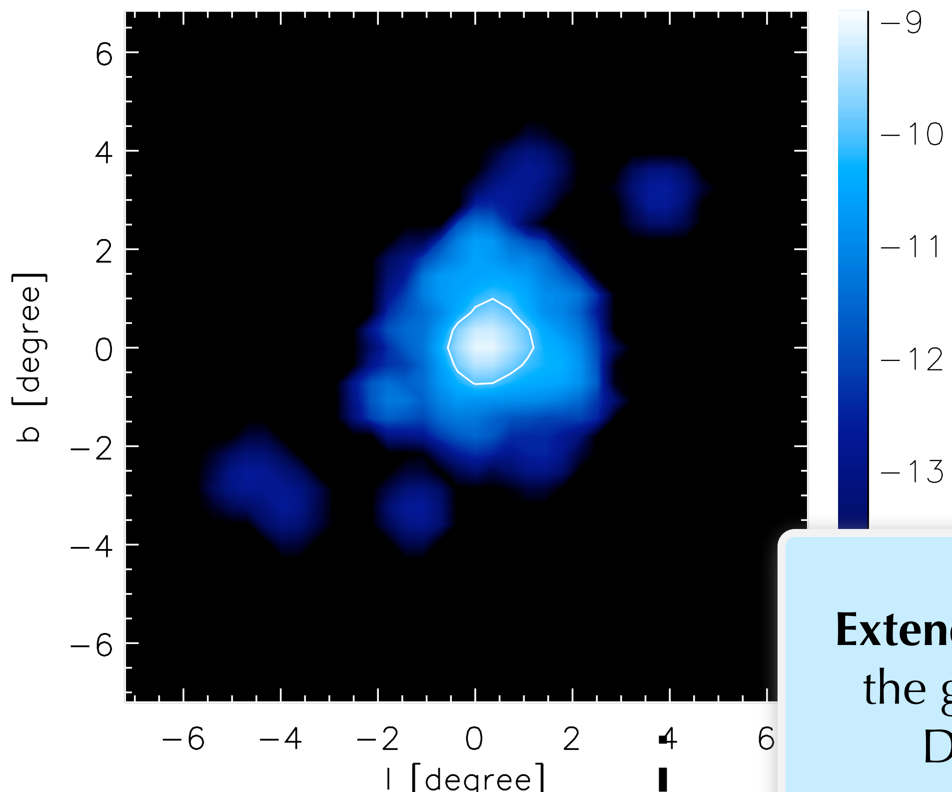




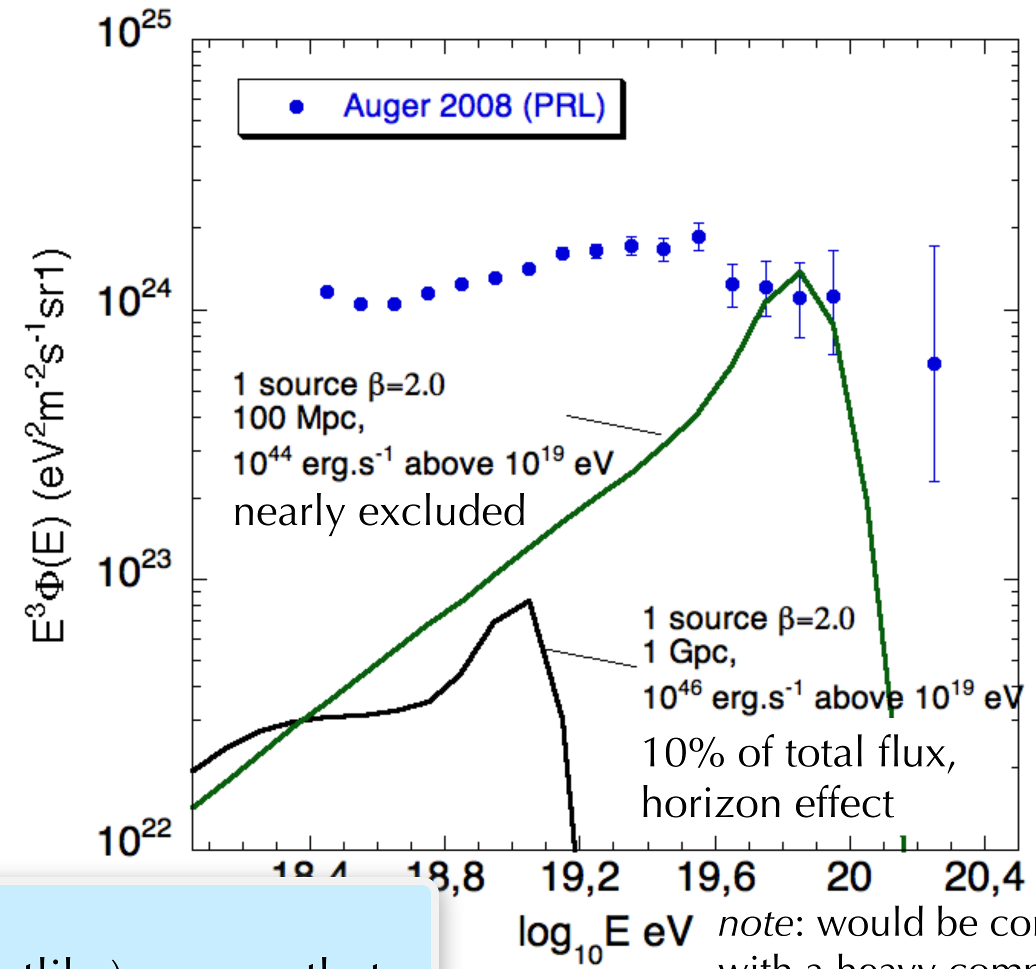
distance to observer d = 100 Mpc

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

Detectability:
case of particularly powerful sources

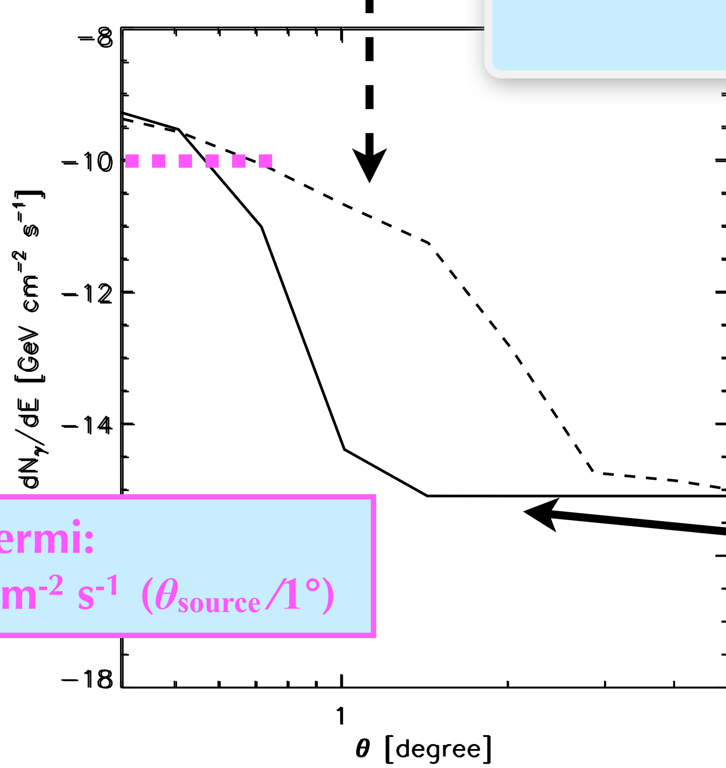


$L_{cr,19} = 10^{44}$ erg s^{-1}
d = 100 Mpc



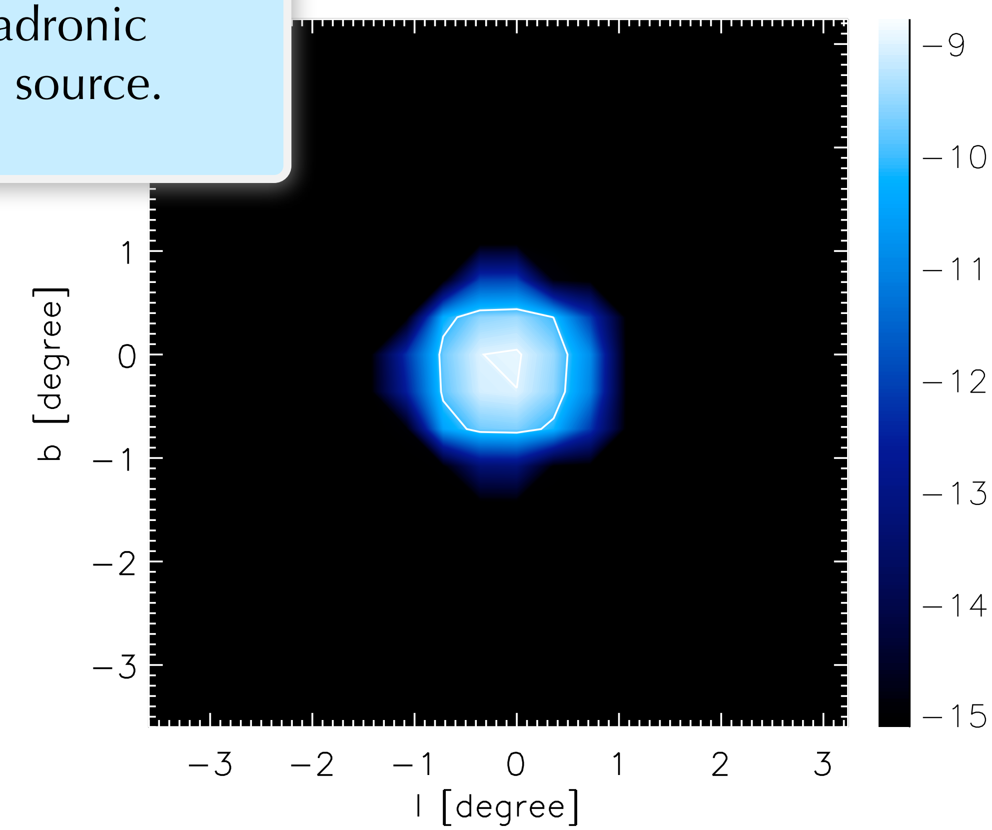
note: would be consistent with a heavy composition at UHE (Auger?)

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



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

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



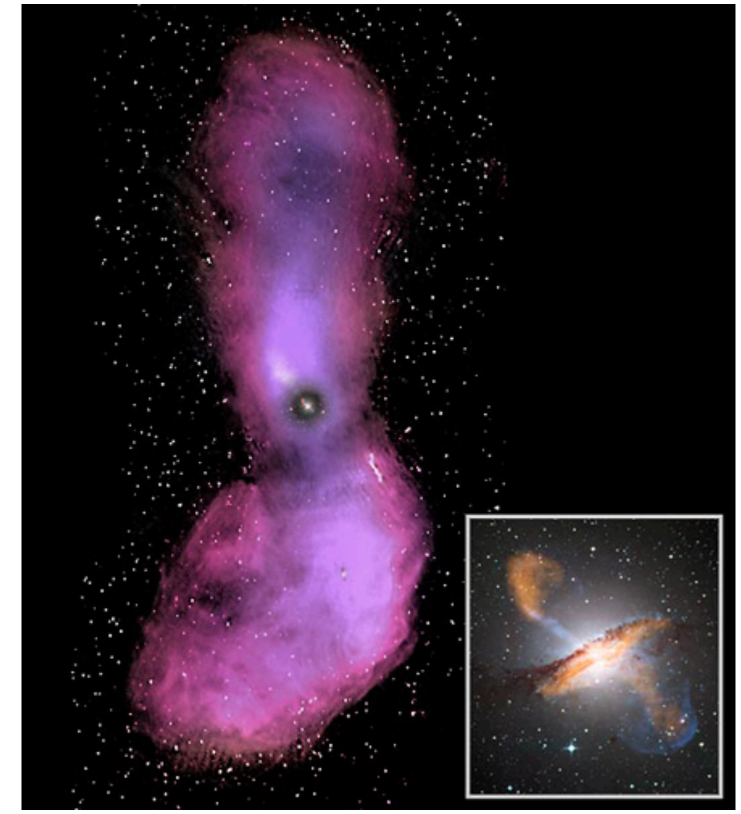
Detectability:
case of a close-by source, Cen A

to detect propagation signatures, extended and strong magnetic field necessary

-> **lobes of Cen A?**

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

Cuoco & Hannestad 08



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

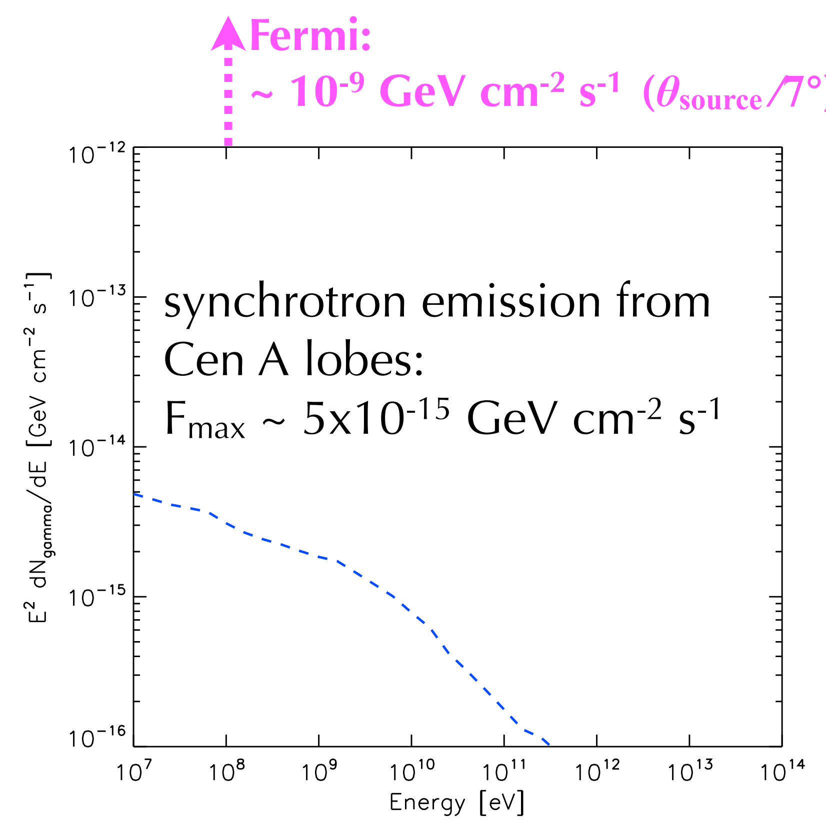
↘ due to limited extension ($R_{lobe} \sim 100$ kpc), production of e^{+-} decreased compared to [cluster+filament] case of $\mathbf{f > \Delta t_{cluster,B\sim0.1\mu G} / \Delta t_{lobe} \sim 10}$

↘ $R_{lobe} < R_{filament}$: less pion production -> flux loss of factor **~ 10**

↘ assuming $L_{cr,19} \sim 10^{39}$ erg s^{-1}, flux decreased of factor **~ 10^3** (according to average sources)

↗ proximity ($d_{CenA} \sim 3.8$ Mpc) -> flux increased of $\mathbf{(d_{CenA}/d_{100Mpc})^2 \sim 625}$

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**

Conclusions

K.K., D. Allard, M. Lemoine, in prep.

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 ~1°**
  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