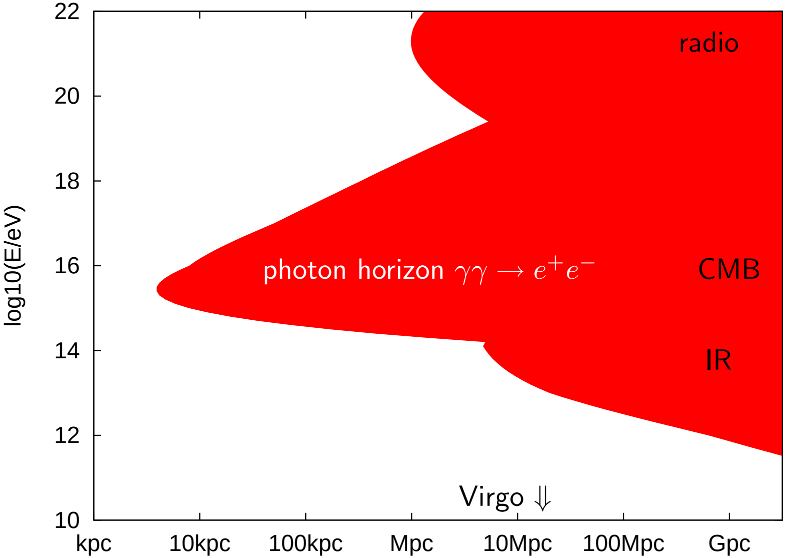
Gamma-rays from CR sources

Michael Kachelrieß

NTNU, Trondheim

TeV gamma-rays from UHECR sources



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- during propagation: “cosmogenic” photons
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  - galactic CR sources
  - GRB:
    - large redshift
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    - for small EGMF: auto-correlation $n_{\rm GRB} \sim \tau \dot{n}_{\rm GRB} < n_{\rm AGN}$

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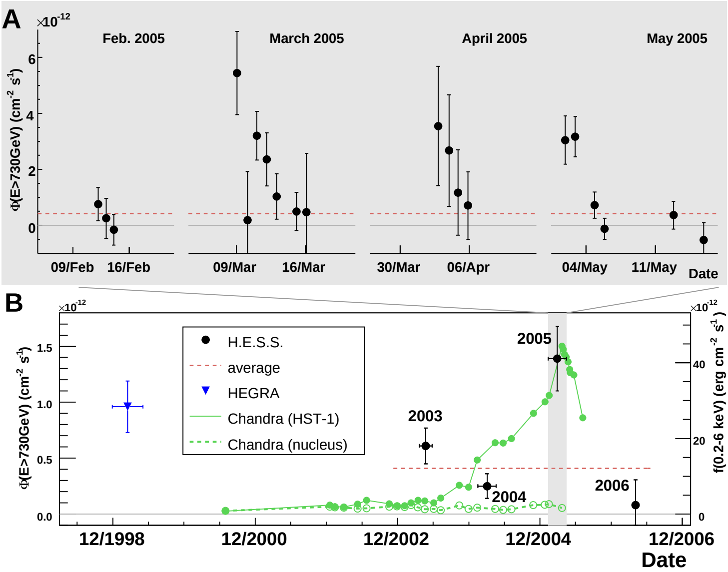
    - for small EGMF: auto-correlation $n_{\rm GRB} \sim \tau \dot{n}_{\rm GRB} < n_{\rm AGN}$
  - AGN:
    - jets: small densities, B
    - core: high B, large UV and IR densities, $\tau_{p\gamma} \sim 1$

HESS observations of M87:



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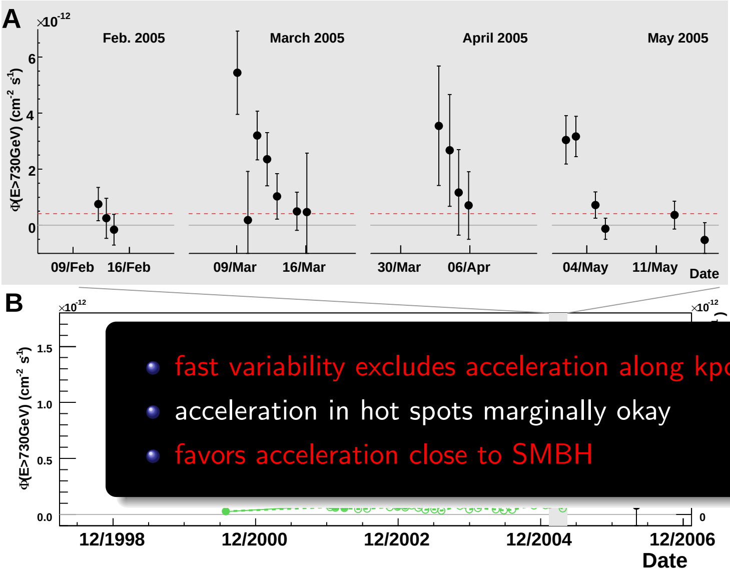
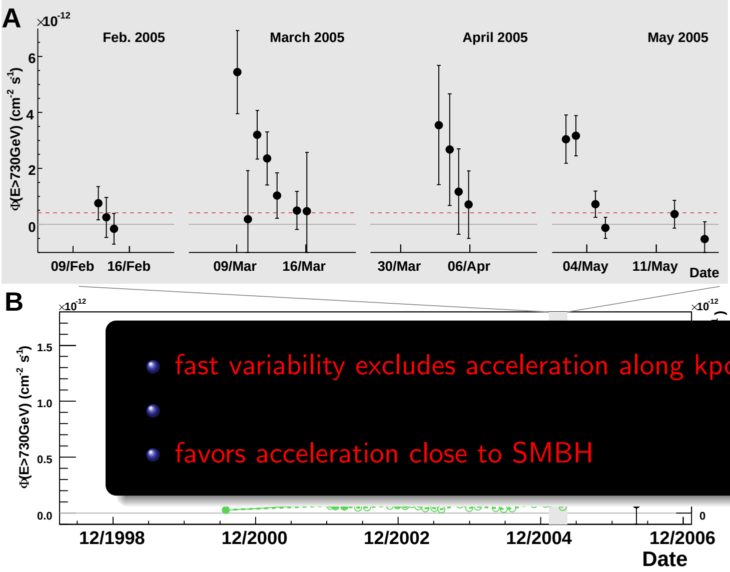


- fast variability excludes acceleration along kpc jet
- acceleration in hot spots marginally okay
- favors acceleration close to SMBH

HESS & Veritas observations of M87:



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Outline of the talk

1. Introduction
2. Gamma-rays produced in UHECR sources
   - How do get multi TeV gamma-rays out off AGN cores: electromagnetic cascades in UHECR sources
3. Cosmogenic fluxes:
   - Cosmogenic neutrino limits from Fermi-LAT
   - Cosmogenic photons: diffuse flux
   - Secondary photons from CR point sources
4. Lower limit on EGMF using gamma-rays
5. Summary

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Multi-messenger astronomy with Cen A?

+ 2 events correlated with Cen A within 3.1°
+ more events close-by [Gorbunov et al. '07, Fargione '08, Rachen '08]
+ general correlation with AGN

– confusion with LSS?
– no confirmation by HiRes
– tension to PAO chemical composition
– $E_{\max}$ for most AGN (incl. Cen A) high enough?

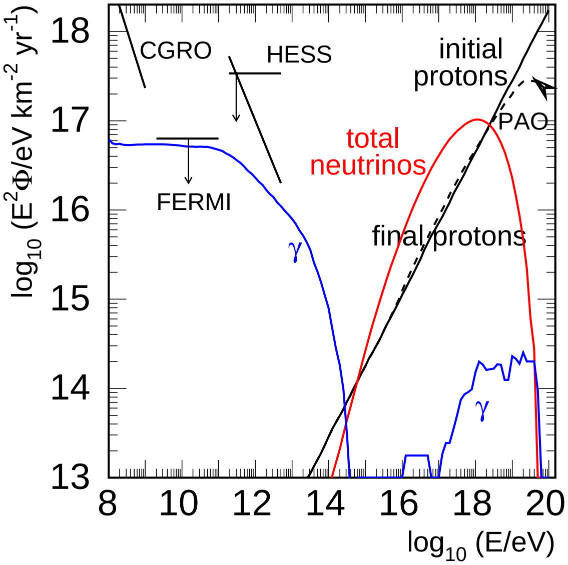
correlations with AGN:

- independent/additional evidence?

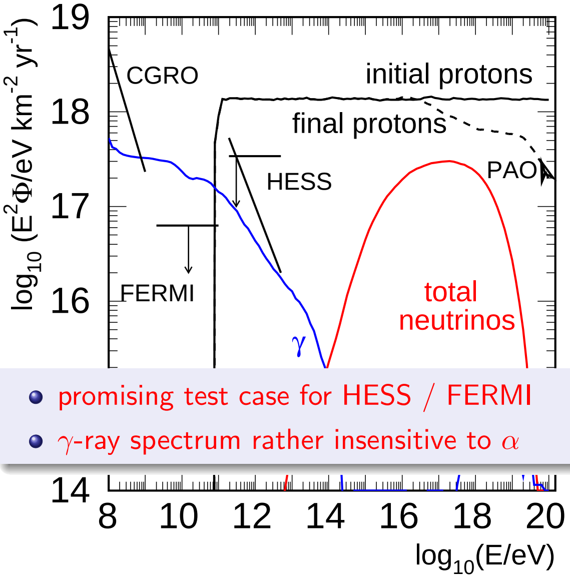
- Cen A closest AGN

⇒ good test case for multi-messenger astronomy: accompanying γ-ray and neutrino fluxes?

Results for acceleration close to the core: $\alpha = 1.2$

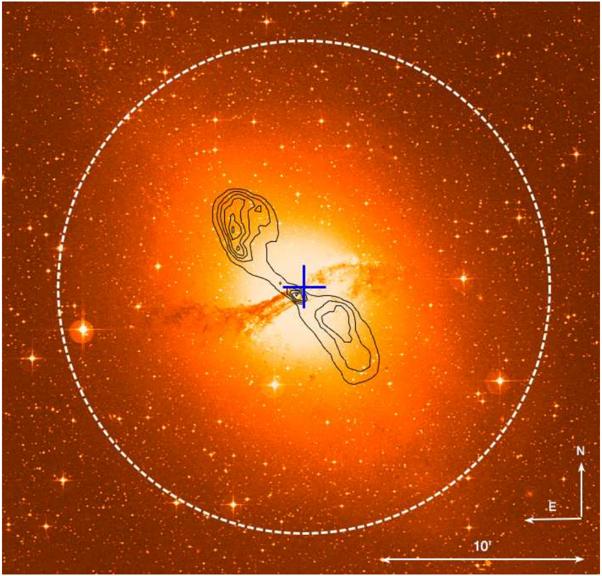


Results for acceleration close to the core: $\alpha = 2$



- promising test case for HESS / FERMI
- γ-ray spectrum rather insensitive to α

HESS observations of Cen A



- no variability

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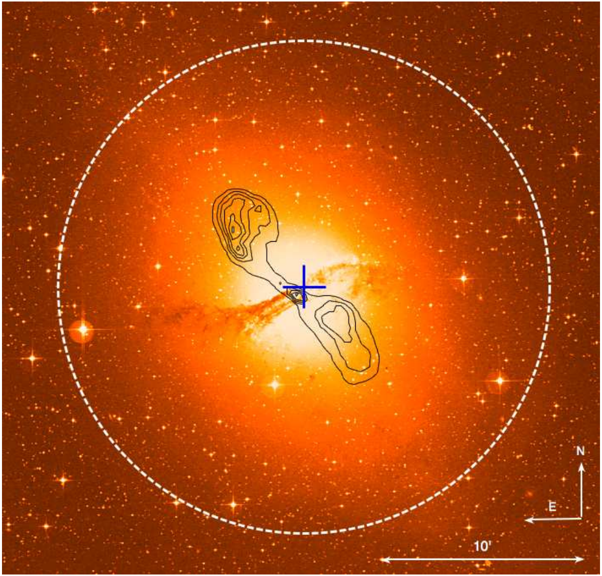

- no variability
- consistent with point source

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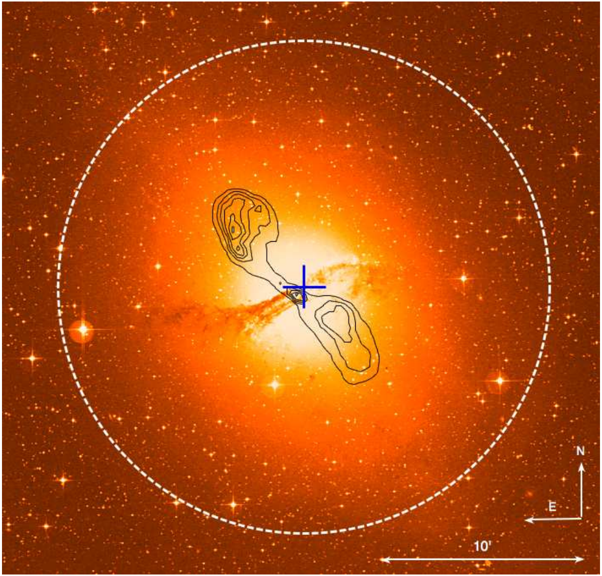
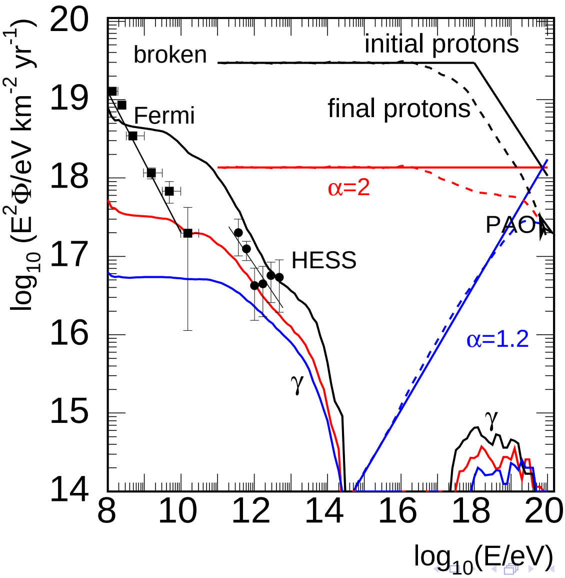


- no variability
- consistent with point source
- HE emission from central region (1'$\simeq$ 1.1 kpc)

Comparison to recent HESS and FERMI observations



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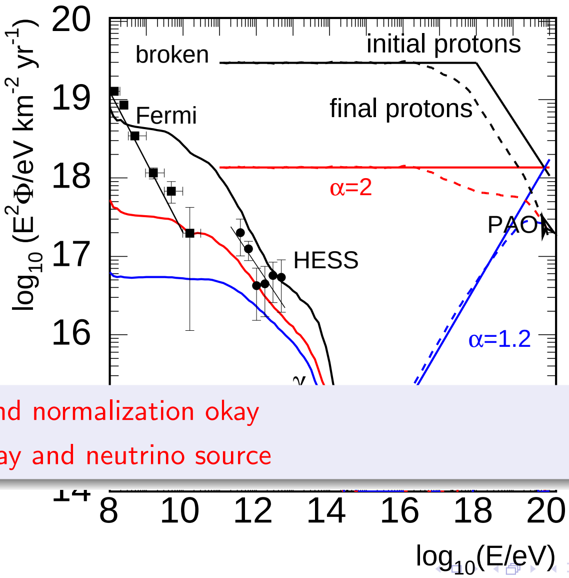
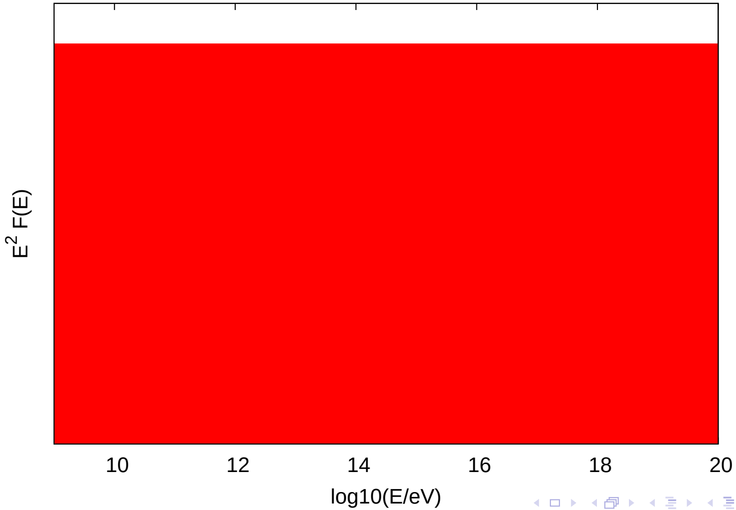


- shape and normalization okay
- TeV γ-ray and neutrino source

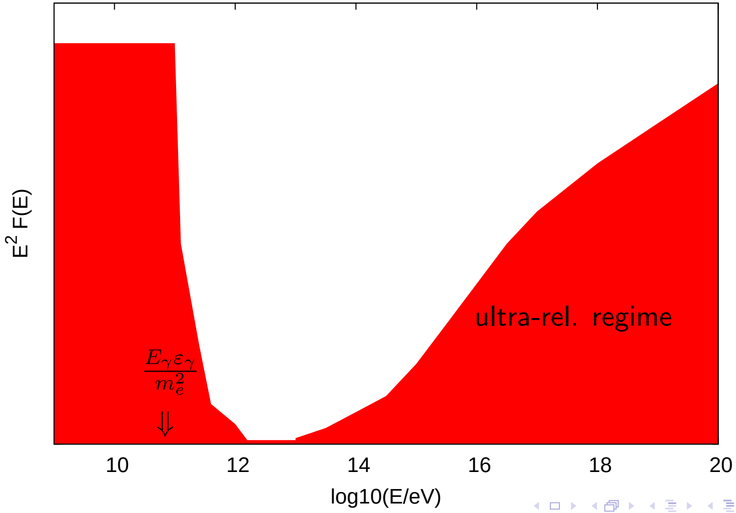
Regenerating TeV photons: a) (isotropic) source

- injection spectrum $F_\gamma(E) \propto 1/E^2$



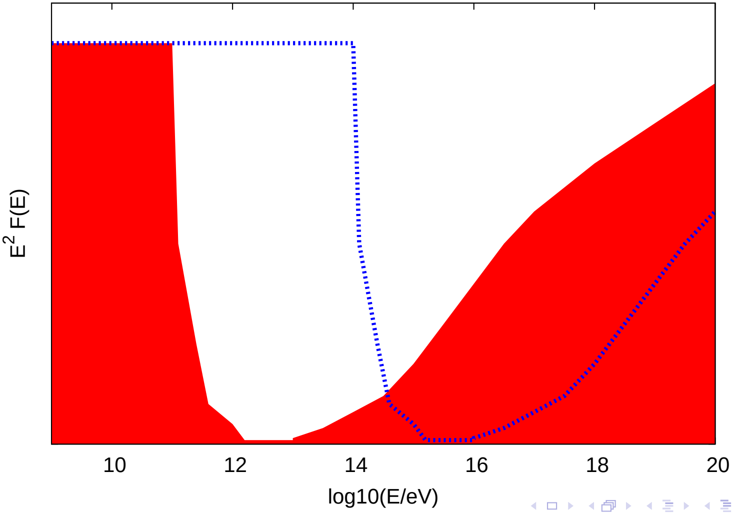
Regenerating TeV photons: a) (isotropic) source

- : thin above 10^{16}eV, ultra-rel. regime



Regenerating TeV photons: b) on EBL

- photons above 10^{14}eV cascade on EBL



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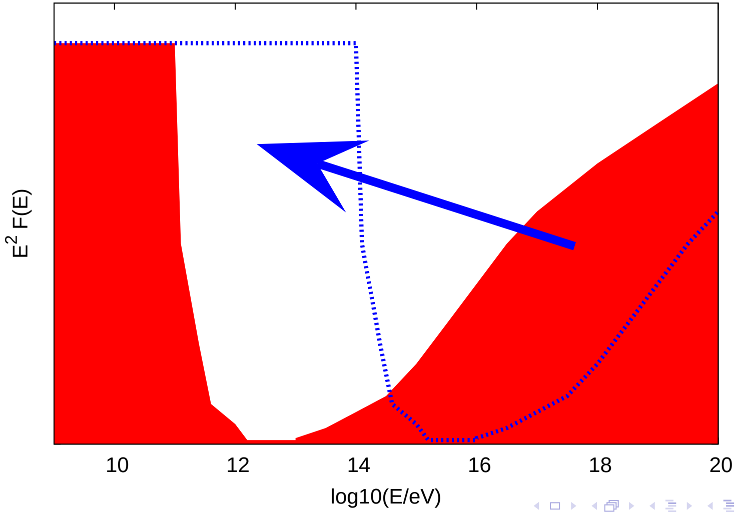

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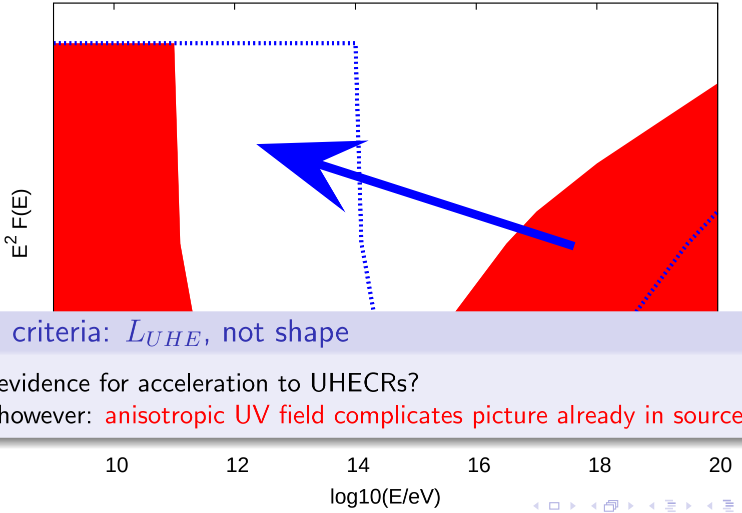
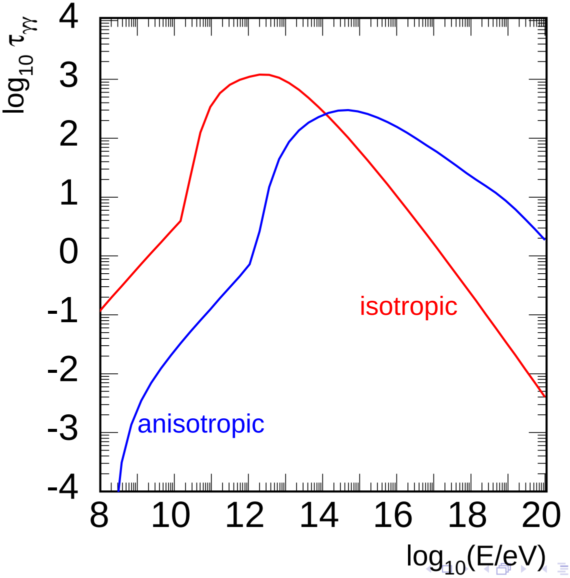


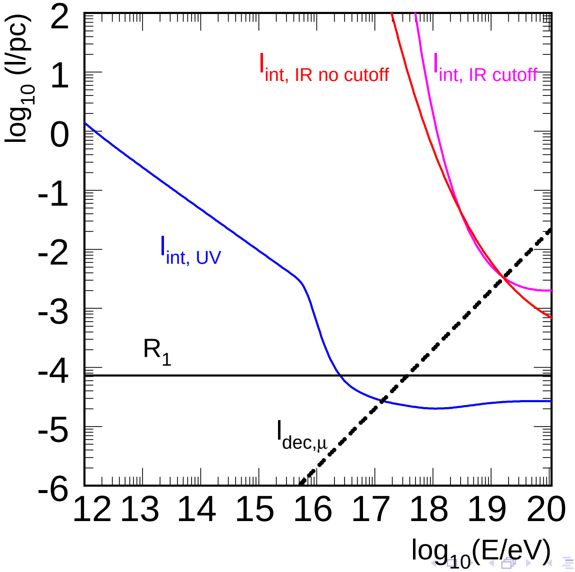
main criteria: L_{UHE}, not shape

- evidence for acceleration to UHECRs?
  however: anisotropic UV field complicates picture already in source

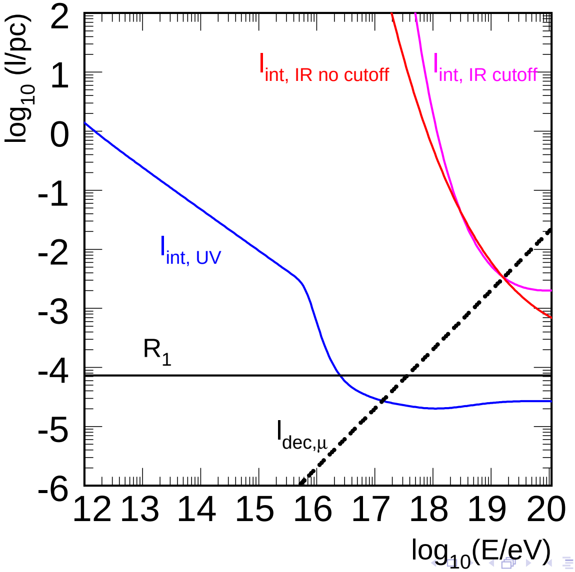
Regenerating TeV photons: collinear regime



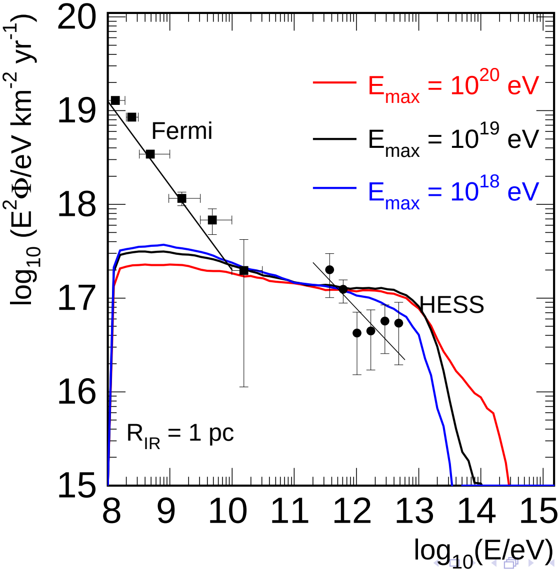
Regenerating TeV photons: decaying muons



Regenerating TeV photons: adding IR



adding IR from a compact source:



Cascade limit for cosmogenic neutrinos

- Photon and neutrino production relatively tight connected:
  - protons:

$$p + \gamma_{3K} \to \begin{cases} p + \pi^0 \to p + 2\gamma \\ n + \pi^+ \to p + 2e^\pm + 4\nu \end{cases}$$

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  - nuclei: $A + \gamma_{3K} \to (A-1) + n \to (A-1) + p + e^- + \nu_e$
  - connection to UHECRs looser

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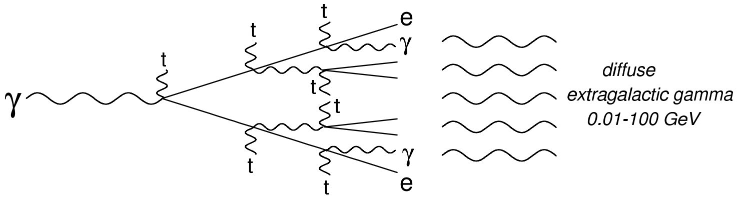
- cascade limit: [Berezinsky, Smirnov '75]

all energy in γ and $e^\pm$ cascades below $\sim 100\,$GeV



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$$J_\gamma(E) = \begin{cases} K(E/\varepsilon_X)^{-3/2} & \text{at} \quad E \le \varepsilon_X \\ K(E/\varepsilon_X)^{-2} & \text{at} \quad \varepsilon_X \le E \le \\ 0 & \text{at} \quad E > \varepsilon_a \end{cases}$$

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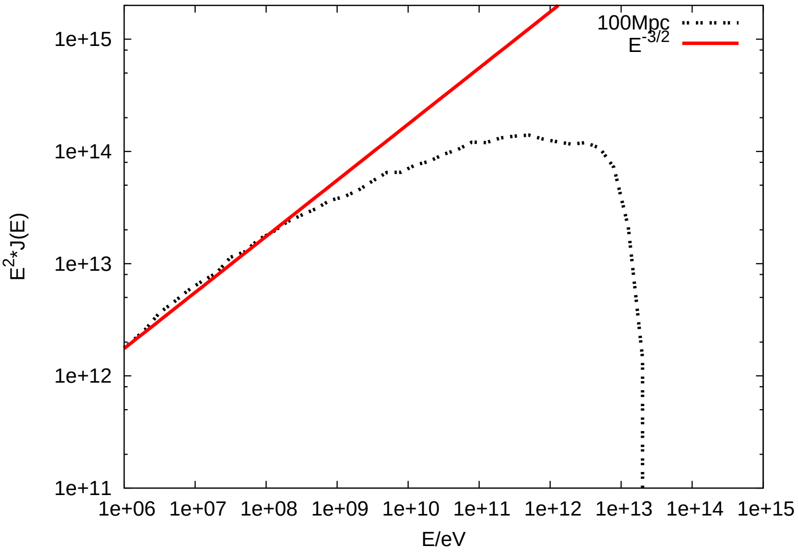
- Fermi-LAT measurement of EGRB:

$$\omega_{\rm cas} > \frac{4\pi}{c}\int_{E_0}^\infty dE\, E I_\nu(E) \geq \frac{4\pi}{c} E_0 I_\nu(>E_0)$$

$$\lesssim 6 \cdot 10^{-7}\,\mathrm{eV/cm^3}$$

Comparison of Monte Carlo and analytical estimate



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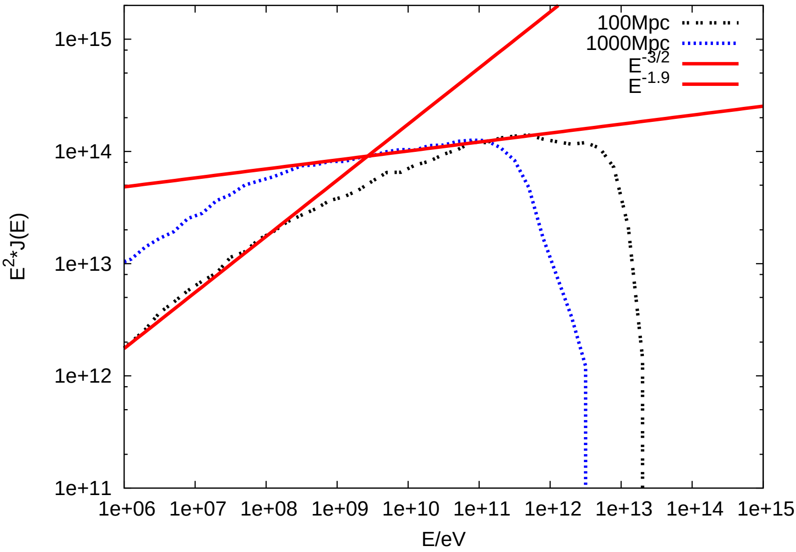
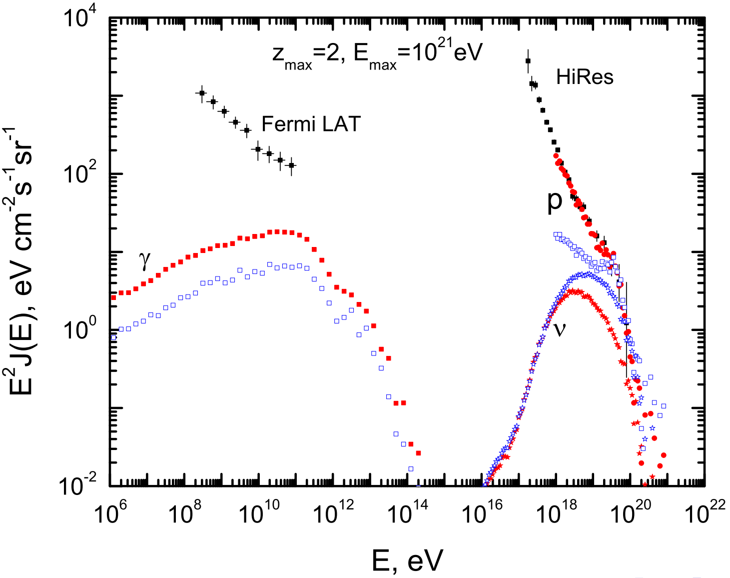


Fermi-LAT vs. UHECR data:

[*Berezinsky et al. '10*]



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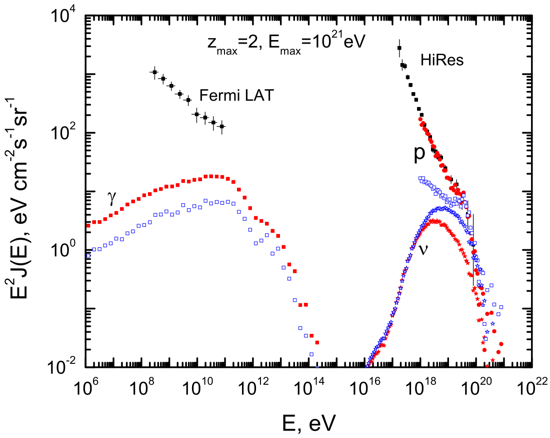

integrating $EJ(E)$ gives bound $\omega_{\text{cas}} \lesssim 6 \cdot 10^{-7}\,\text{eV}/\text{cm}^3$

Cascade limit for cosmogenic neutrinos

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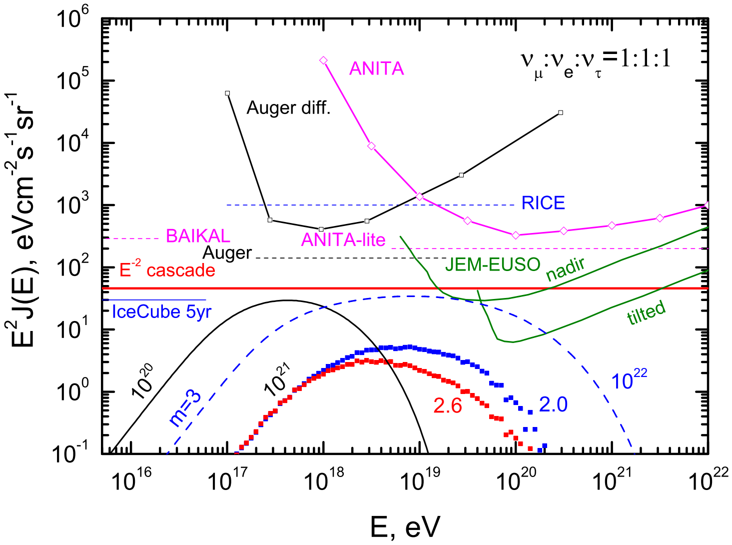
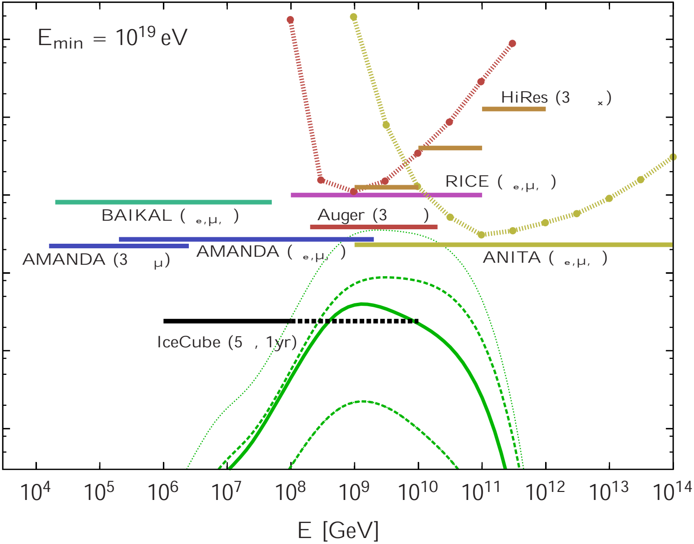


Cascade limit for cosmogenic neutrinos

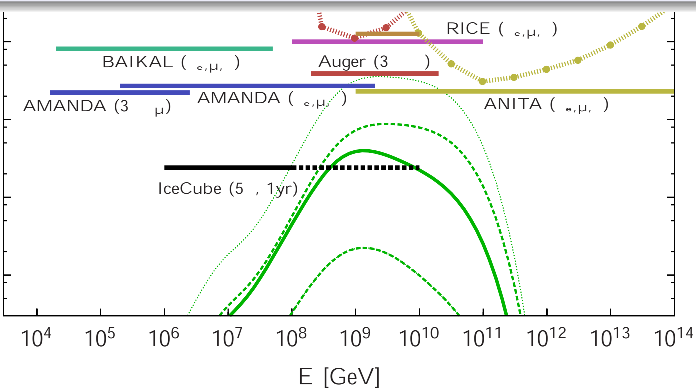
[*Ahlers et al. '10*]



Cascade limit for cosmogenic neutrinos

Main difference: expected IceCube sensitivity

- end of exp. sensitivity for $1/E^2$ flux: 10^{17} vs. 10^{19} eV
- overall sensitivity of IceCube



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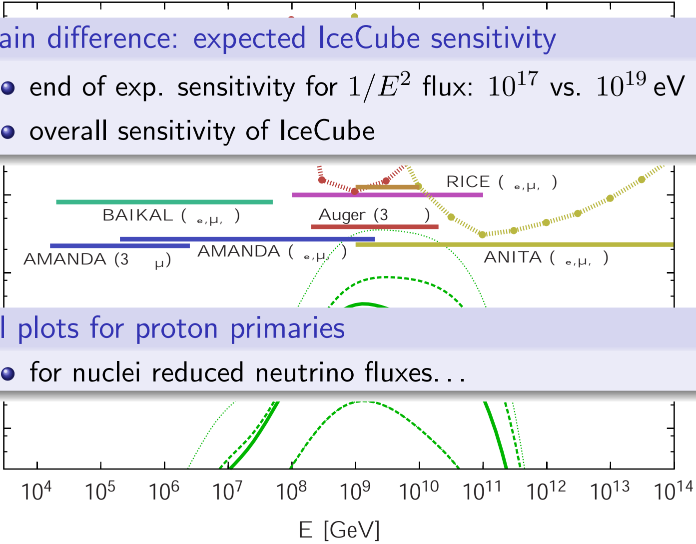

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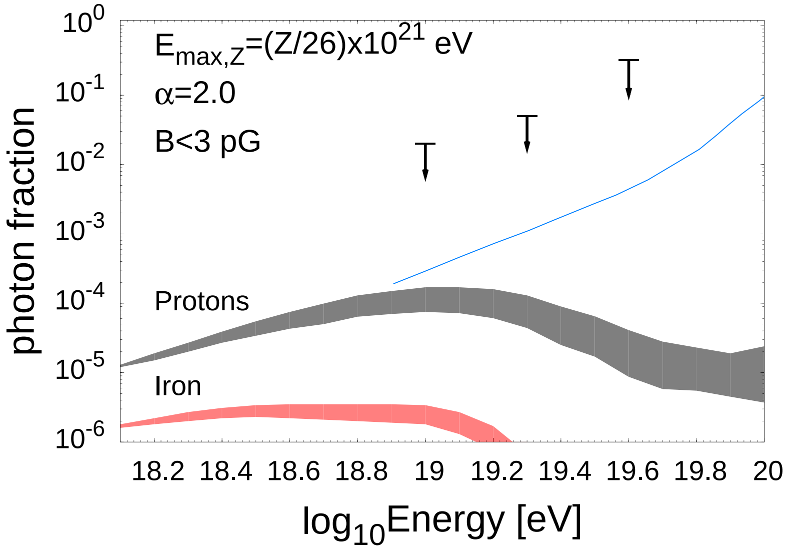
All plots for proton primaries

- for nuclei reduced neutrino fluxes. . .

Cosmogenic photons

[*Hooper, Taylor, Sarkar '10*]



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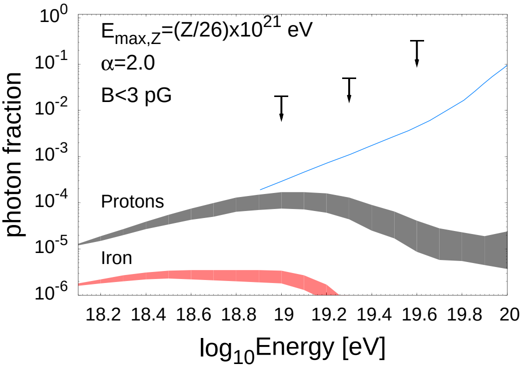
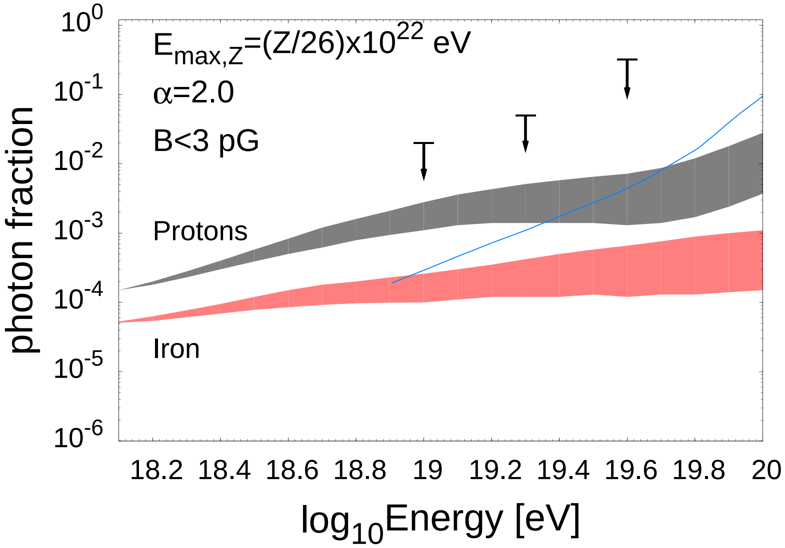


- $A > 1$: photons suppressed by factor 10 compared to protons
- even proton: requires sensitivity improved by ~ 100
- large $E_{\max}$ and small α helps. . .

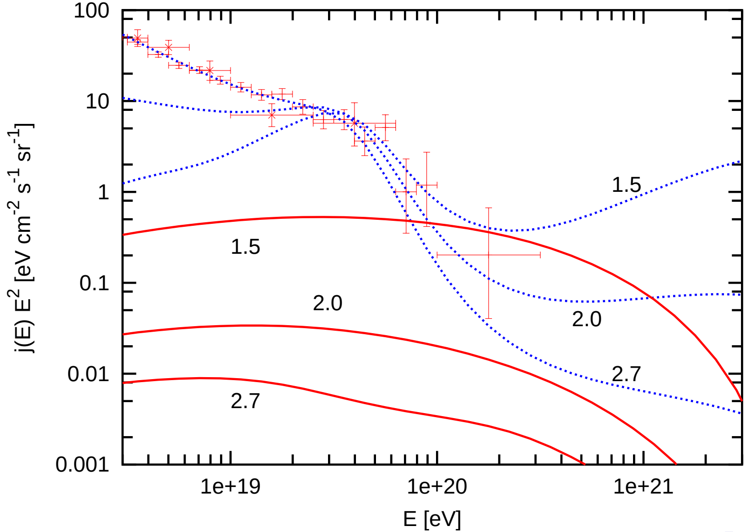
Cosmogenic photons

[*Hooper, Taylor, Sarkar '10*]



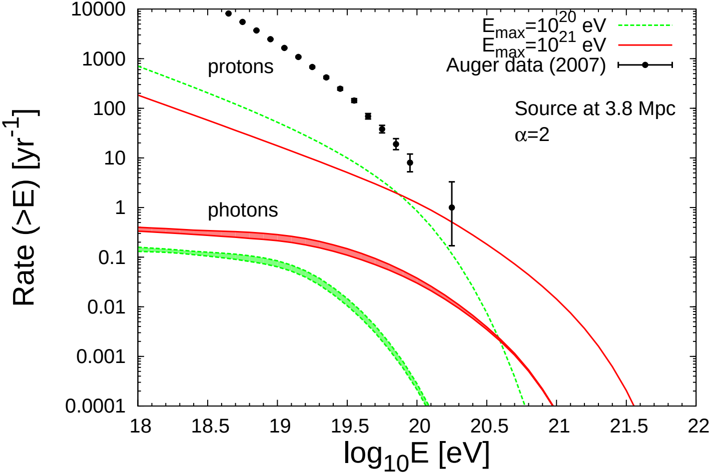
Cosmogenic photons: dependence on α

[Gelmini, Kalashev, Semikoz '05]



Secondary photons from CR point sources

- for $d <$ few $\times 10$ Mpc: UHE photons survive [*Taylor et al. '09*]



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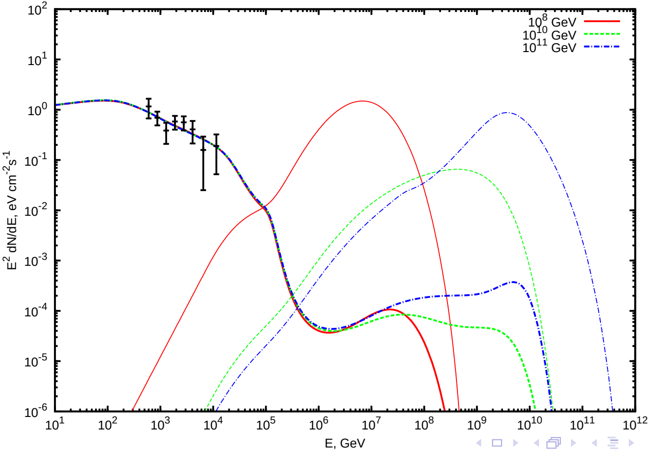
Secondary photons from CR point sources

- for $d <$ few $\times 10$ Mpc: UHE photons survive [*Taylor et al. '09*]
- larger distance: UHE photons cascade down in TeV range [*Essey et al. '10*]
  - universal shape, depending only on EBL and z



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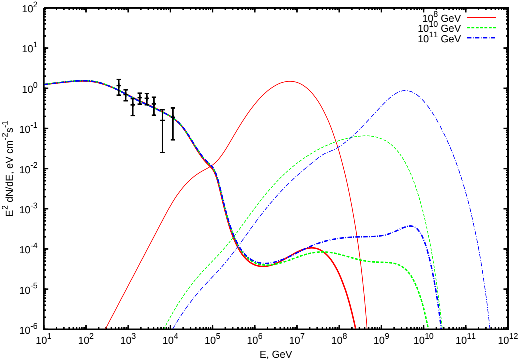

  - large luminosities $L_{\rm eff} \sim 10^{47} - 10^{49}$erg/s in UHECR
  - relatively small EGMFs in voids, $B \lesssim 10^{-14}$ G

Gamma-rays and extragalactic magnetic fields (EGMF)

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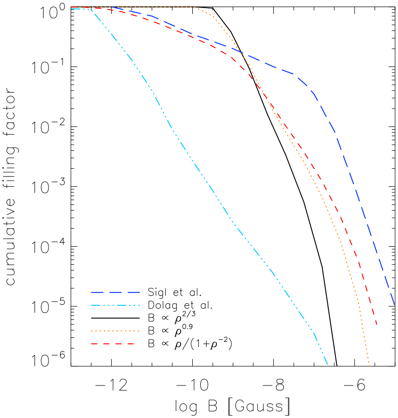

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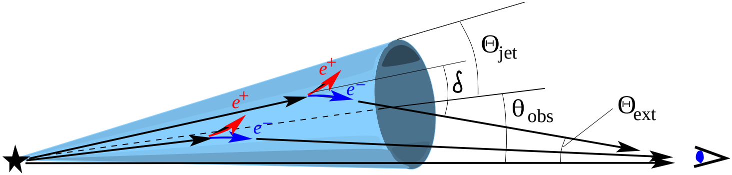
- Plaga '95: EGMFs deflect and delay cascade electrons

$\Rightarrow$ search for delayed "echoes" of multi-TeV AGN flares/GRBs

Observer misaligned with jet:

[*Neronov et al. '10*]



- probability for misalignement $p \propto \vartheta_{\rm obs}$ ⇒ most blazars viewed with $\vartheta_{\rm obs} \sim \vartheta_{\rm jet}$

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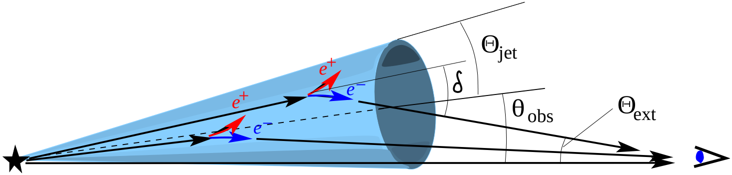

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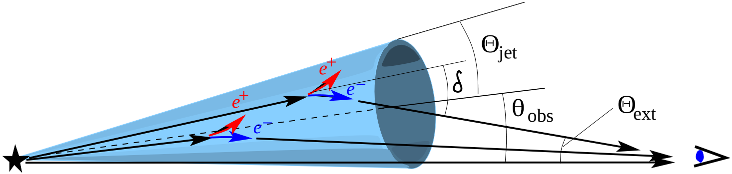

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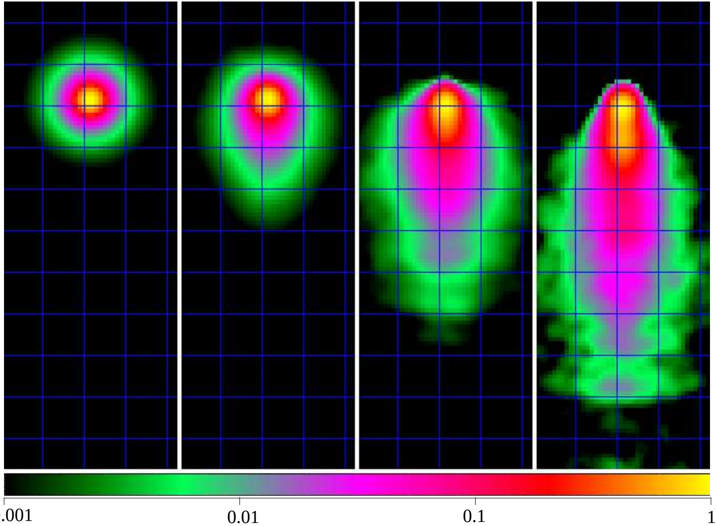
$\Rightarrow$ halos are not symmetric

$\Rightarrow$ time-delay is function of ϑ,

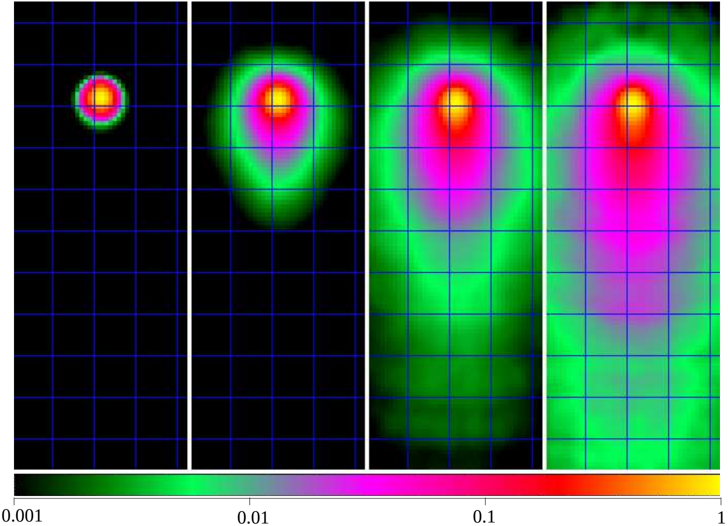
$$T_{\rm delay}(\vartheta) \sim 3 \times 10^6 \text{yr} \left[\frac{(\vartheta_{\rm obs} + \Theta_{\rm jet})}{5^\circ}\right] \left[\frac{\vartheta}{5^\circ}\right]$$

Asymmetric halos around TeV blazars (“GeV jets”):



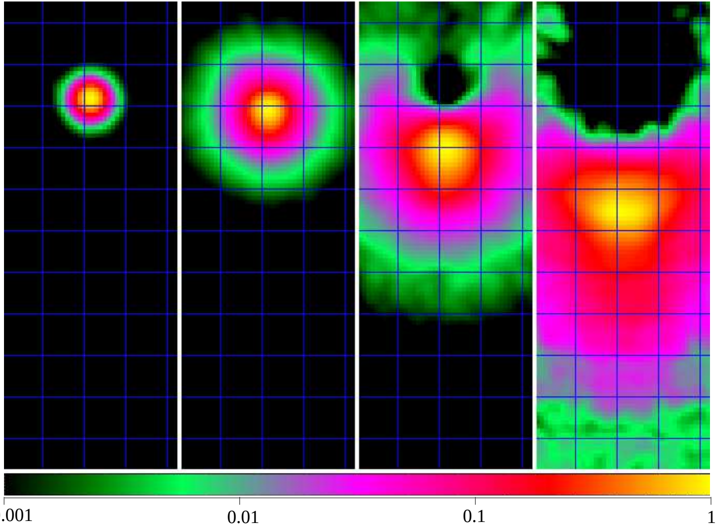
$\vartheta_{\rm obs} = 0°$ $\vartheta_{\rm obs} = 3°$ $\vartheta_{\rm obs} = 6°$ $\vartheta_{\rm obs} = 9°$

"GeV jets": B dependence



10^{-17} G $\quad 10^{-16}$ G $\quad 10^{-15}$ G $\quad 10^{-14}$ G

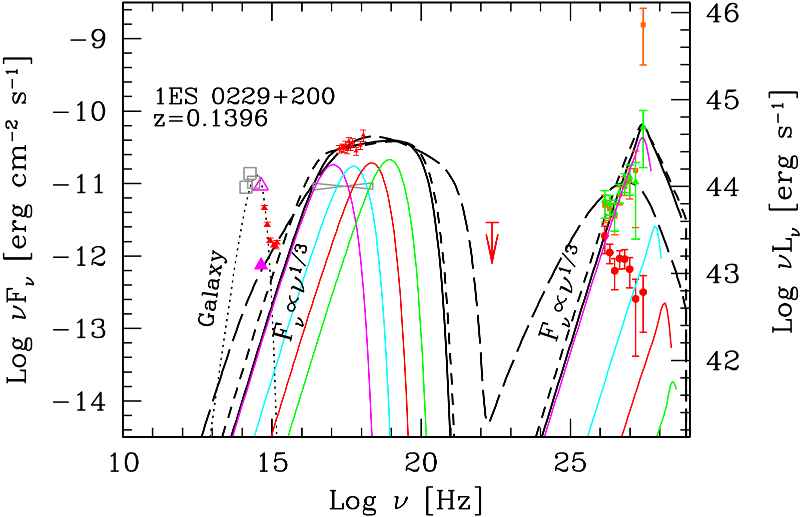
"GeV jets": time dependence of flares



$0 < T_{\rm delay} < 10^5$ yr $\quad$ 3×10^6 yr$< T_{\rm delay} < 10^7$ yr

Lower limit on EGMF:

- choose blazar: large z, stationary, low GeV, high multi-TeV emission



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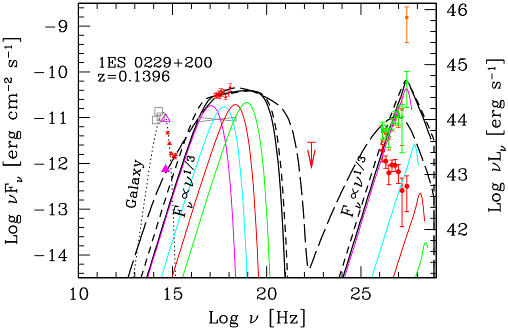
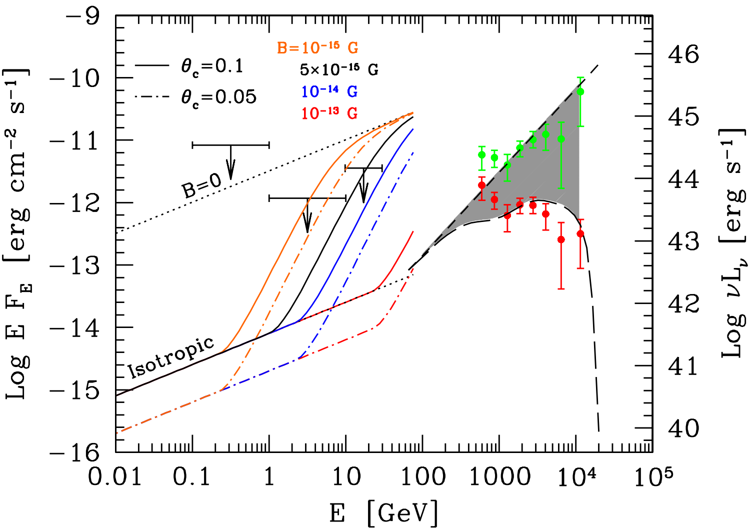


- TeV photons cascade down:
  - small EGMF: fill up GeV range
  - "large" EGMF: deflected outside, isotropized

Lower limit on EGMF:

[F. Tavecchio et al. '10, A. Neronov, I. Vovk '10]



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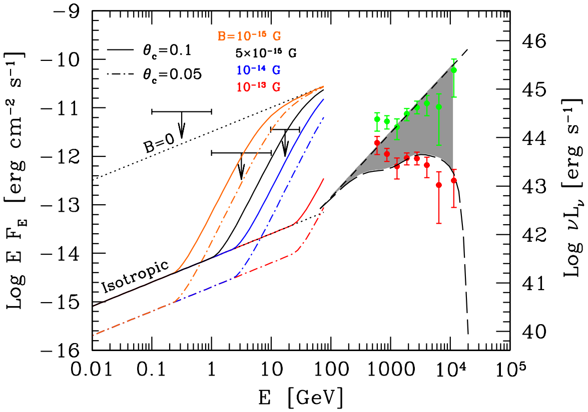

- $B \gtrsim 10^{-15}$ G
- some dependence on $\vartheta_{\rm jet}$

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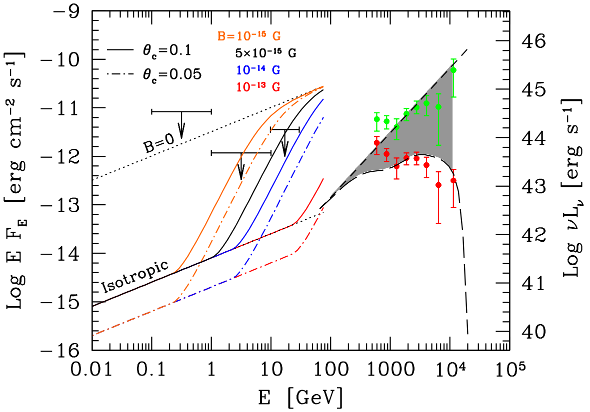
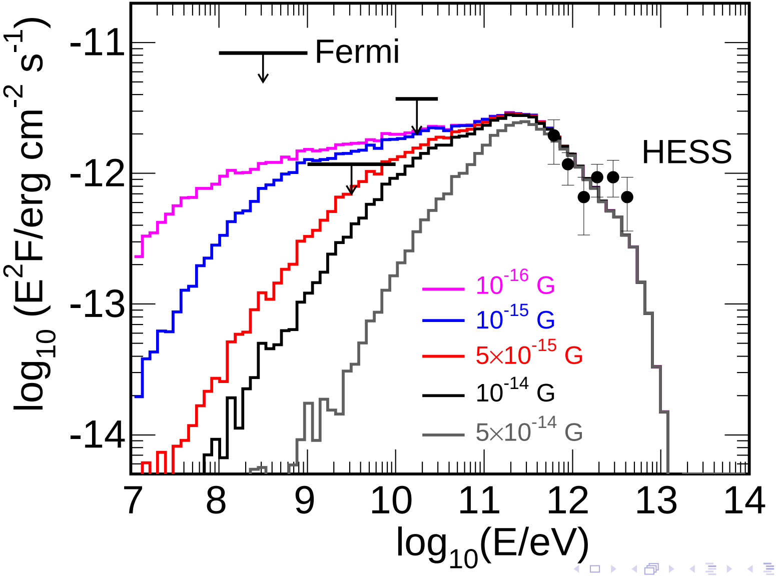


- $B \gtrsim 10^{-15}$ G
- some dependence on $\vartheta_{\rm jet}$
- no simulation of elmag. cascade with B
- what happens for structured B?

Lower limit on EGMF:

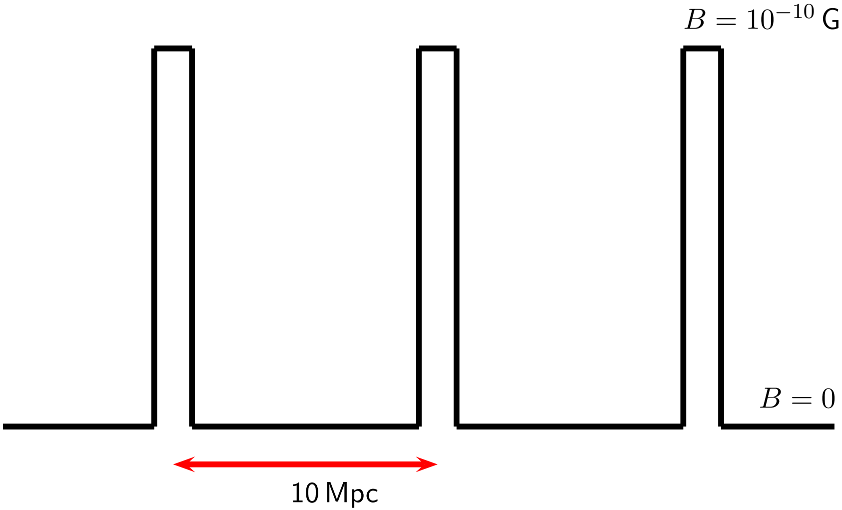
[*MK, Ostapchenko, Tomàs*]



Lower limit on filling factor:

[*MK, Ostapchenko, Tomàs '10*]

- model filaments by a top-hat:



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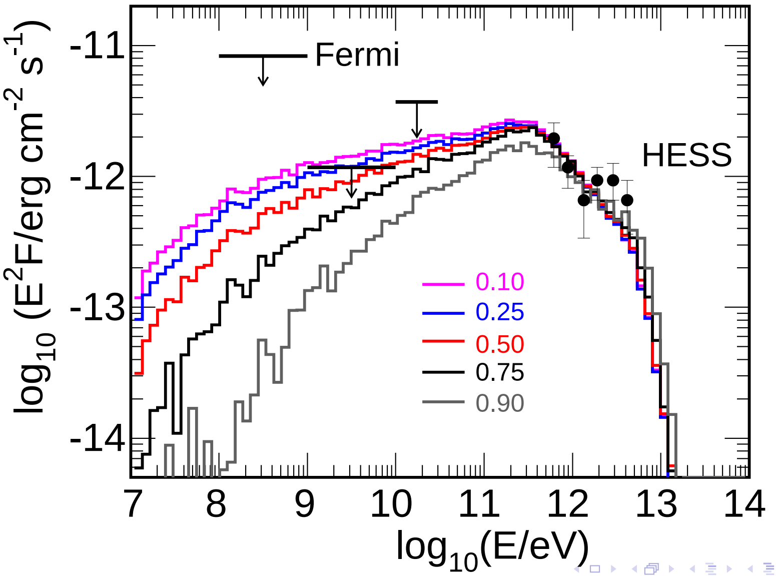

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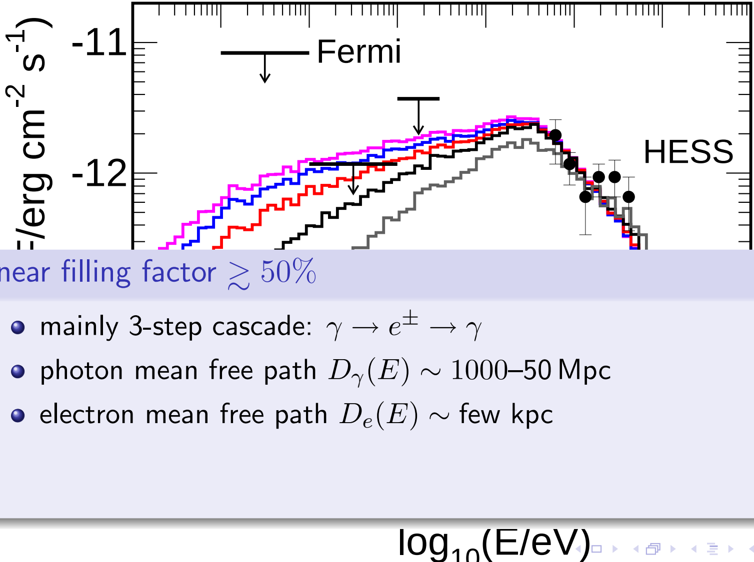

linear filling factor $\gtrsim 50\%$

- mainly 3-step cascade: $\gamma \to e^{\pm} \to \gamma$
- photon mean free path $D_\gamma(E) \sim 1000$–$50\,$Mpc
- electron mean free path $D_e(E) \sim$ few kpc

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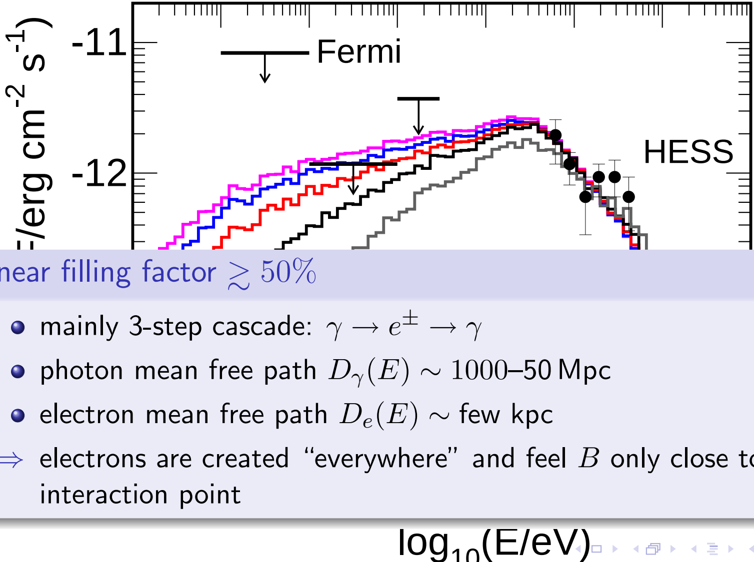

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$\Rightarrow$ electrons are created "everywhere" and feel B only close to interaction point

EGMF in voids already observed?

[Ando, Kusenko '10]

- stack 170 brightest AGN

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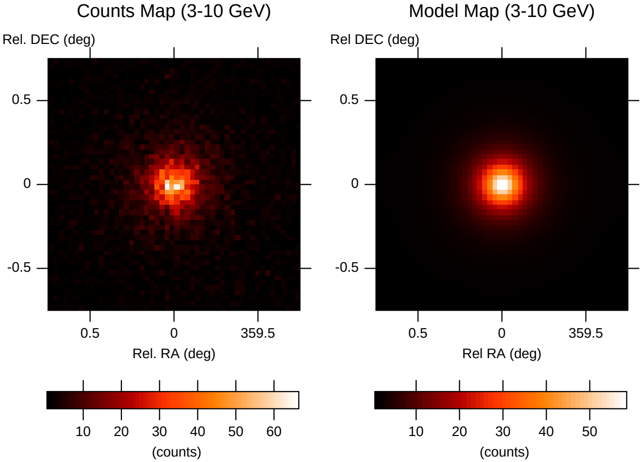

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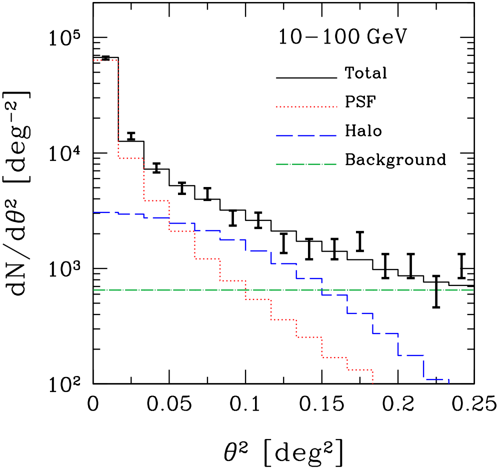

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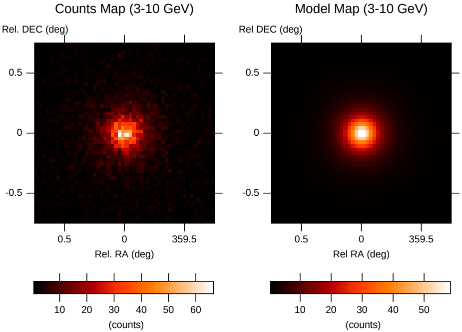

⇒ explained by

$$B \sim 10^{-15}\ \mathrm{G}\,(\lambda_B/1\ \mathrm{kpc})^{-1/2} \qquad \text{and} \qquad \lambda_B < 10 - 100\ \mathrm{kpc}$$

EGMF in voids already observed?

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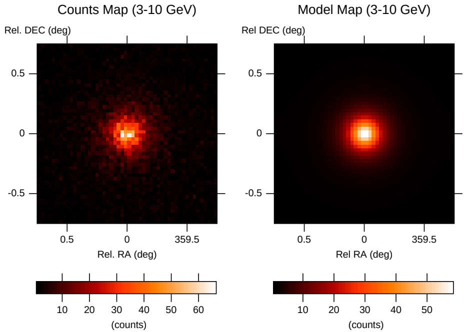
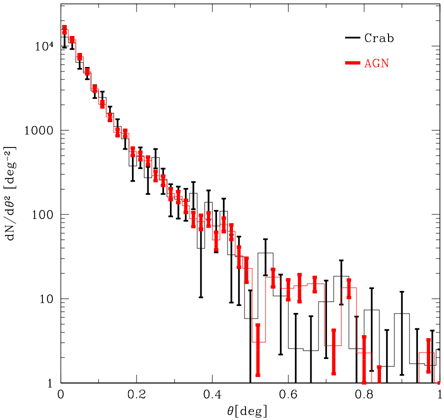


- lower limit $B \gtrsim 5 \times 10^{-15}$ G requires $\lambda_B \lesssim 0.1$ kpc

EGMF already observed? Probably not. . .

[*Neronov et al.* '10]

- point source Crab shows the same "halo" as stacked AGN:



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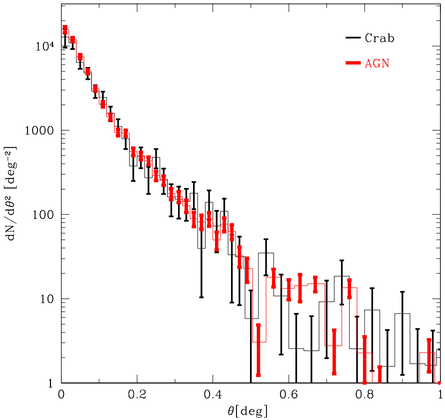

- tail of PSF wrong (?), difference between "front" and "back" photons

Summary

- multi-TeV photons from AGN cores require
  - photons in KN regime
  - HE muons

⇒ hadronic models

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- secondary photons:
  - chemical composition
  - TeV sources ??
- cascade limit from Fermi data reduced by factor ~ 7
- lower limit on EGMF in voids $B \gtrsim 10^{-15}$ G