

Lower bound on the extragalactic magnetic field

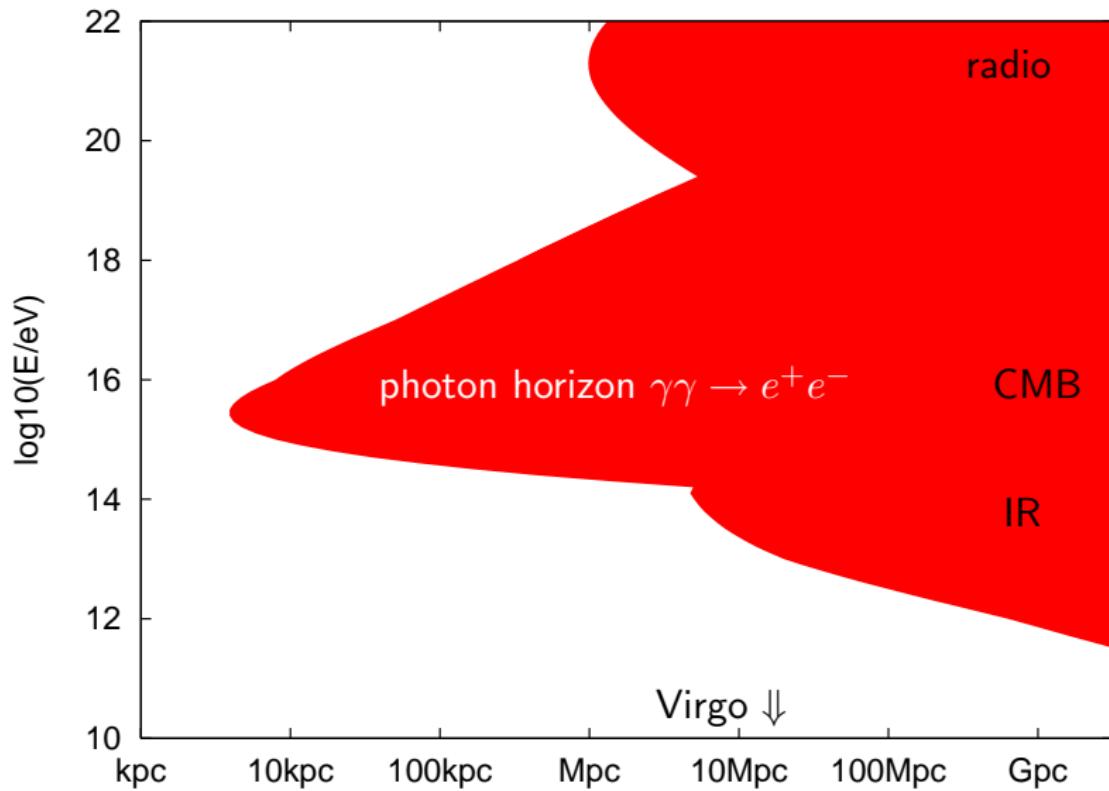
Michael Kachelrieß

NTNU, Trondheim

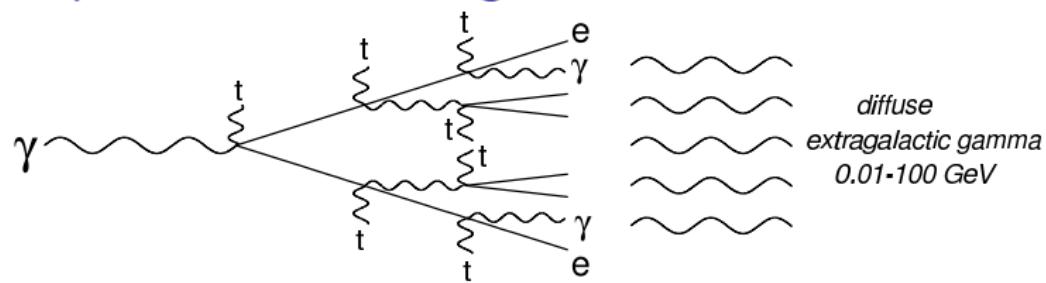
Dolag, MK, Ostapchenko, Tomàs '10

Neronov, Semikoz, MK, Ostapchenko, Elyiv '10

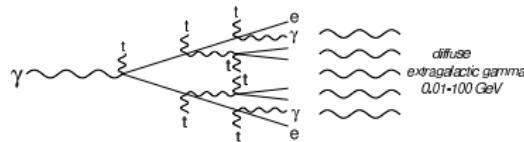
Mean free path of photons



Development of the elmag. cascade:



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- analytical estimate:

[Berezinsky, Smirnov '75]

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

- three regimes:

- Thomson cooling:

$$E_\gamma = \frac{4}{3} \frac{\varepsilon_{\text{bb}} E_e^2}{m_e^2} \approx 100 \text{ MeV} \left(\frac{E_e}{1 \text{ TeV}} \right)^2$$

- plateau region: ICS $E_\gamma \sim E_e$
 - above pair-creation threshold $s_{\min} = 4E_\gamma \varepsilon_{\text{bb}} = 4m_e^2$: flux exponentially suppressed

Gamma-rays and extragalactic magnetic fields (EGMF)

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- Seed required as **input** for EGMF simulations

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 - ▶ synchrotron halo: $\Rightarrow B \sim (0.1 - 1) \mu\text{G}$
 - ▶ Faraday rotation: $\Rightarrow B \sim (1 - 10) \mu\text{G}$

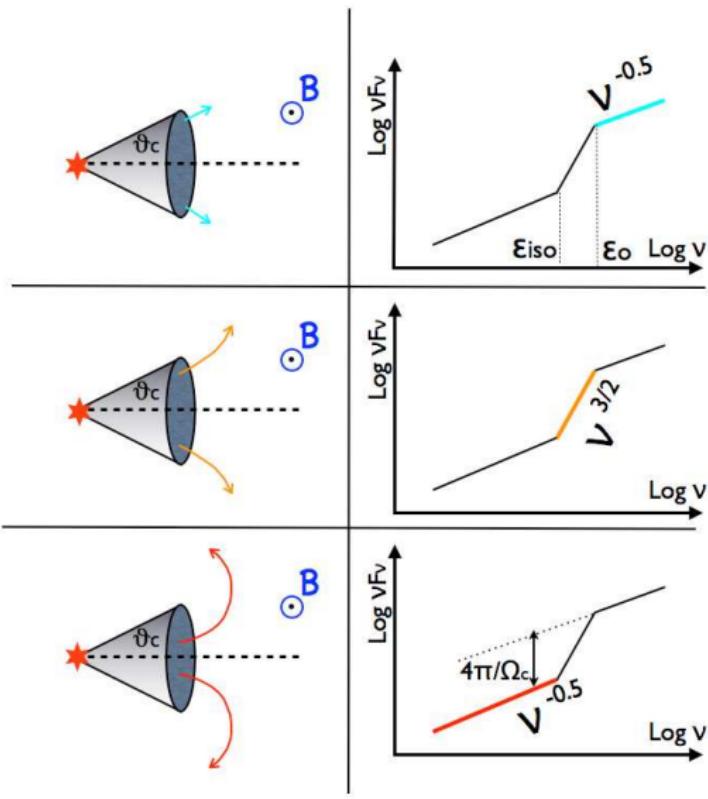
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- Aharonian, Coppi, Völk '94: **Pair halos** around AGNs

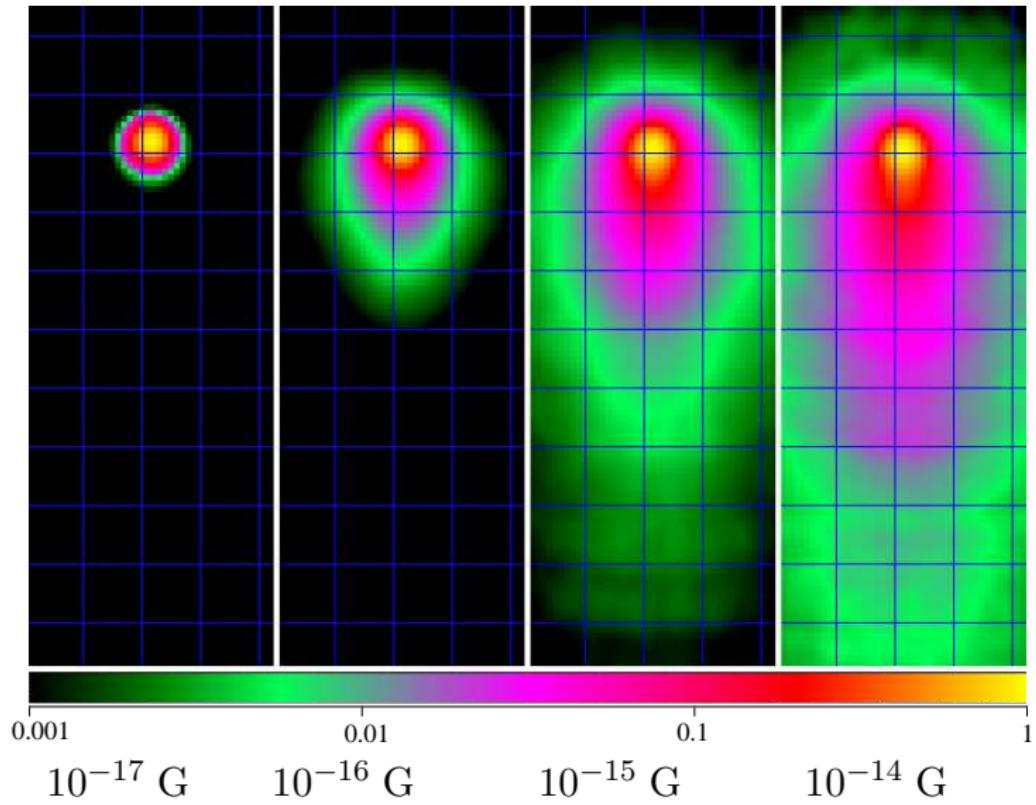
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- Aharonian, Coppi, Völk '94: Pair halos around AGNs
- Plaga '95: **EGMFs deflect and delay cascade electrons**
 \Rightarrow search for delayed “echoes” of multi-TeV AGN flares/GRBs

Influence of EGMF on flux from single source: deflections



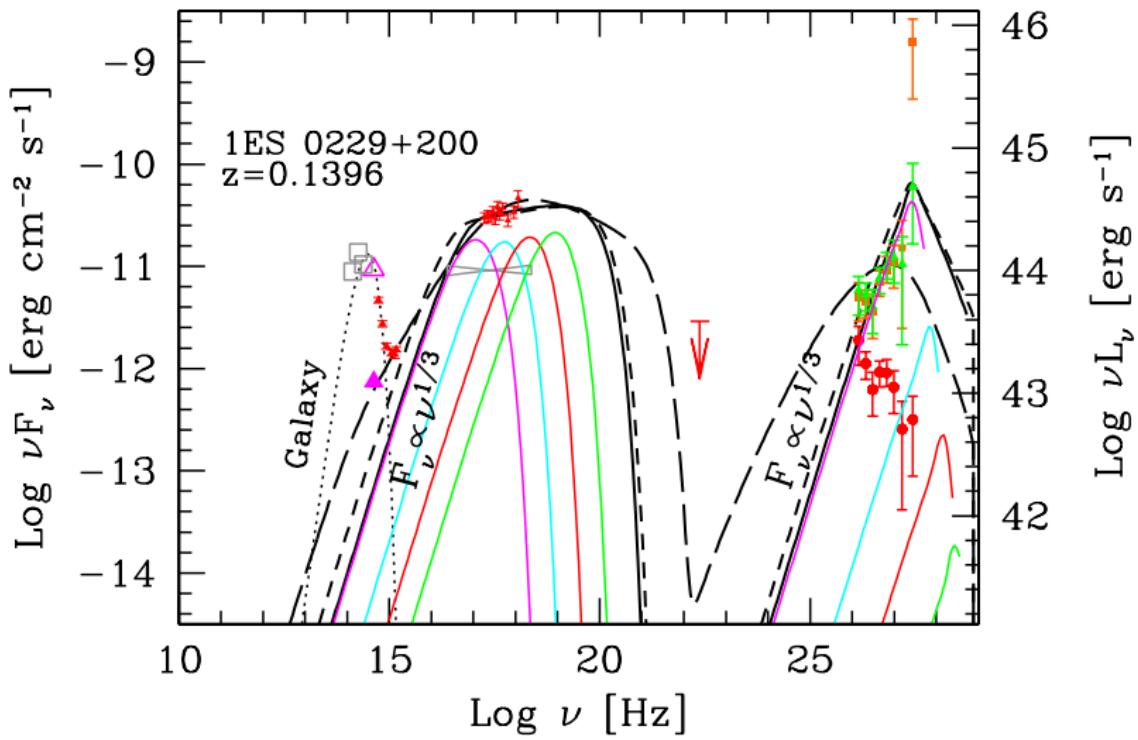
“GeV jets”: B dependence



Lower limit on EGMF:

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

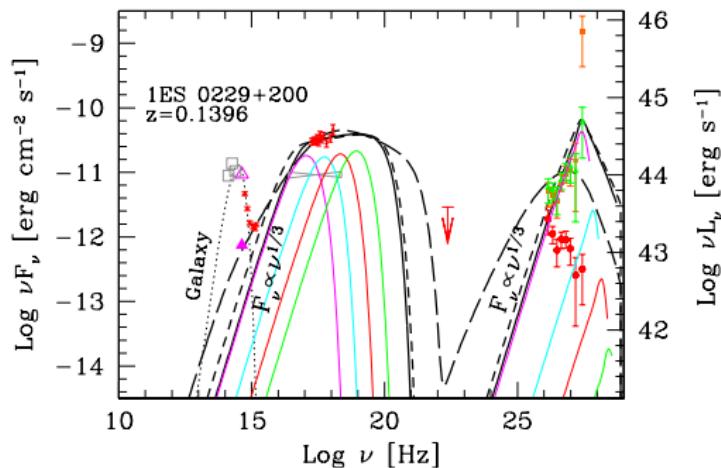
- choose blazar: **large z** , stationary, **low GeV**, high multi-TeV emission



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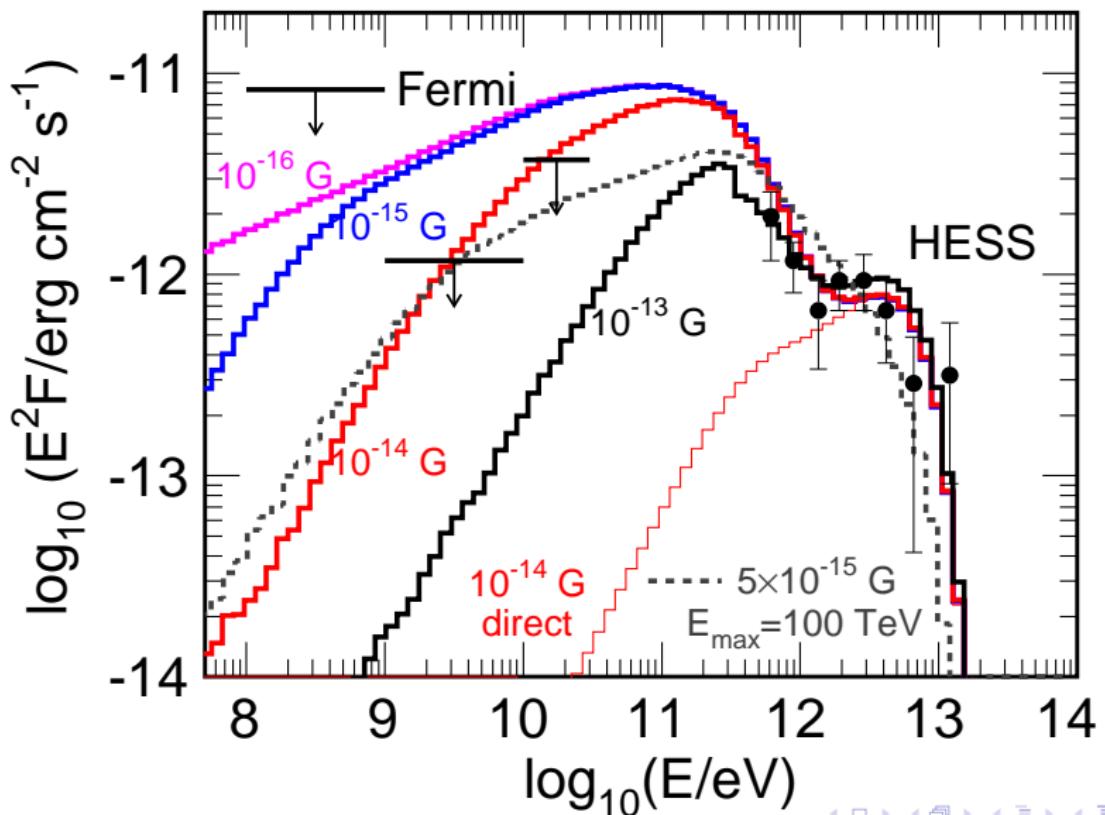
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- TeV photons cascade down:
 - ▶ small EGMF: fill up GeV range
 - ▶ “large” EGMF: deflected outside, isotropized

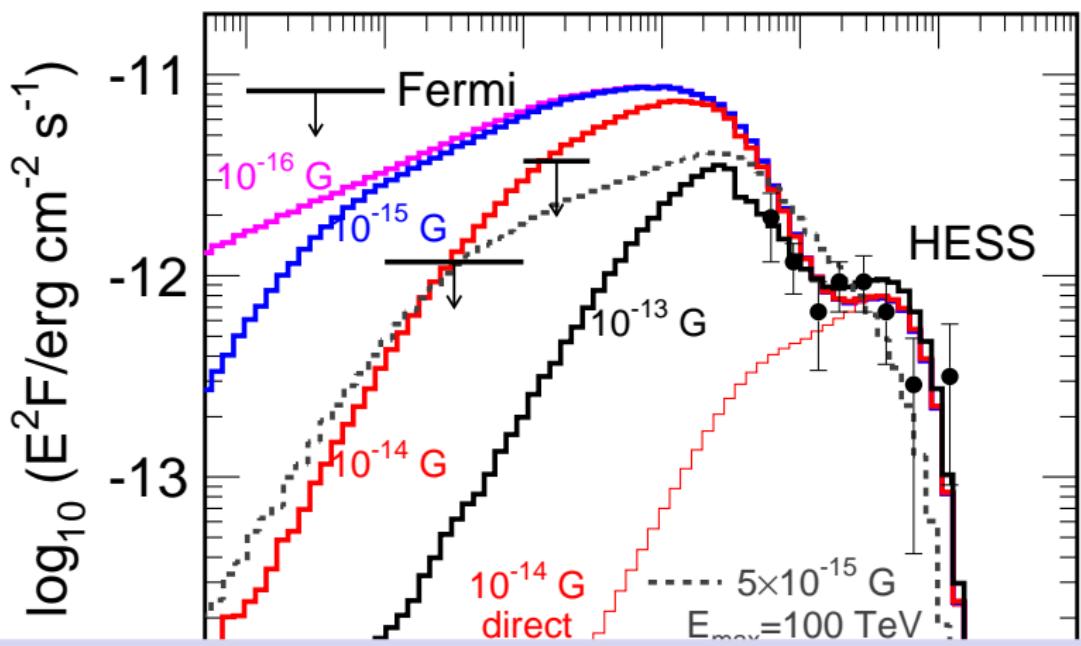
Lower limit on EGMF: uniform field

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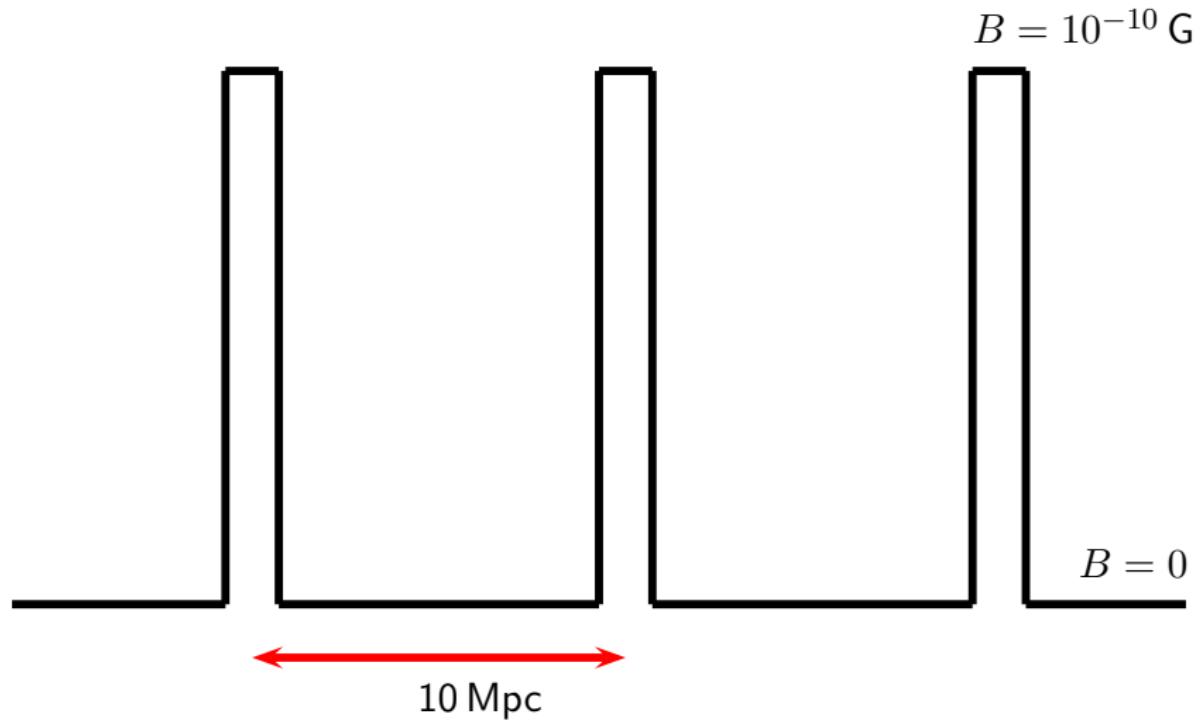


\Rightarrow bound improves as $\lambda^{1/2}$

Lower limit on filling factor:

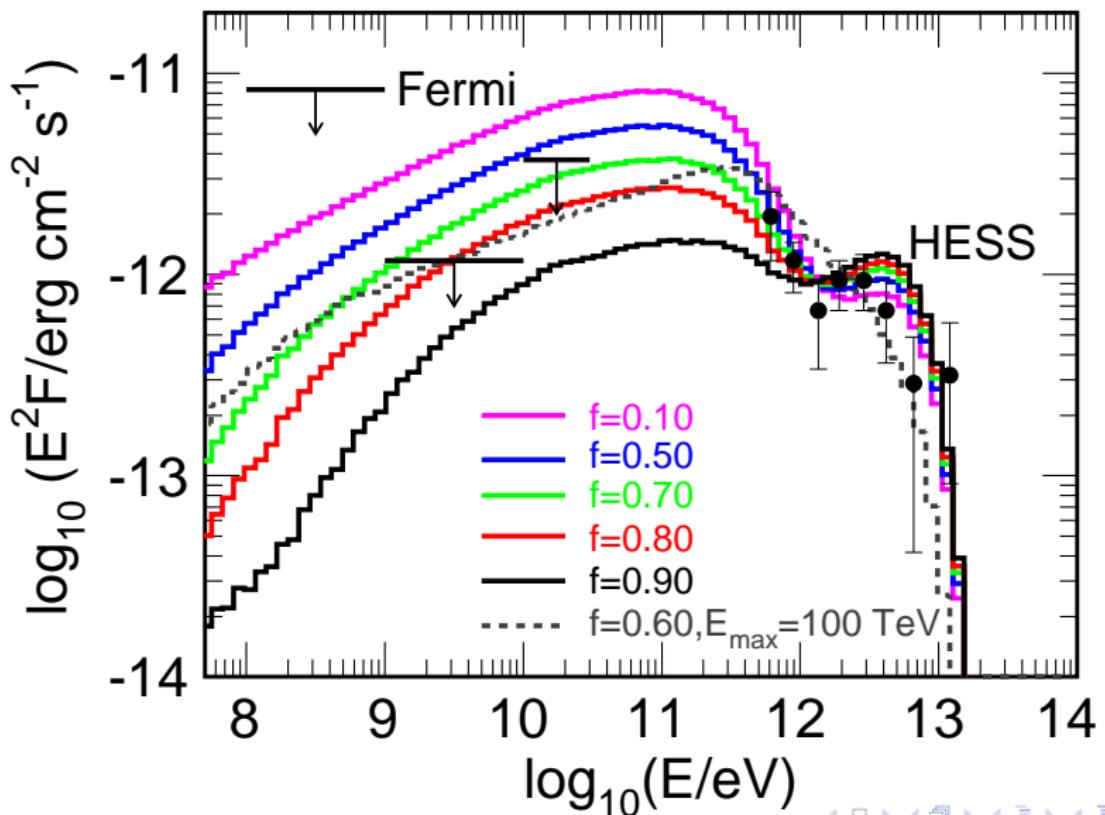
[Dolag et al. '10]

- model filaments by a top-hat:



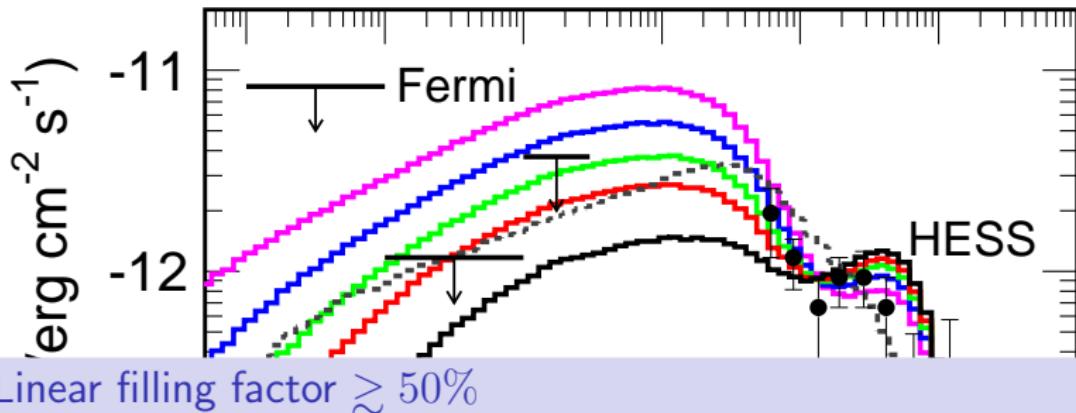
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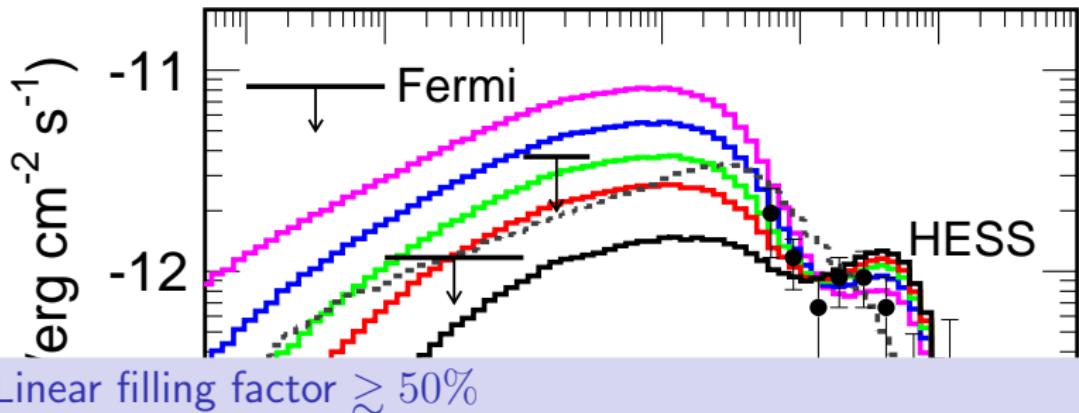
Linear filling factor $\gtrsim 50\%$

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

$$\log_{10}(E/\text{eV})$$

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- \Rightarrow electrons are created “everywhere” and feel B only close to interaction point

$$\log_{10}(E/\text{eV})$$

How to create EGMFs in voids?

- **primordial fields:**
 - ▶ inflation
 - ▶ phase transitions (QCD, electroweak)
 - ▶ reionization

- **astrophysical** (require seed fields):
 - + outflows from AGNs, dwarf galaxies

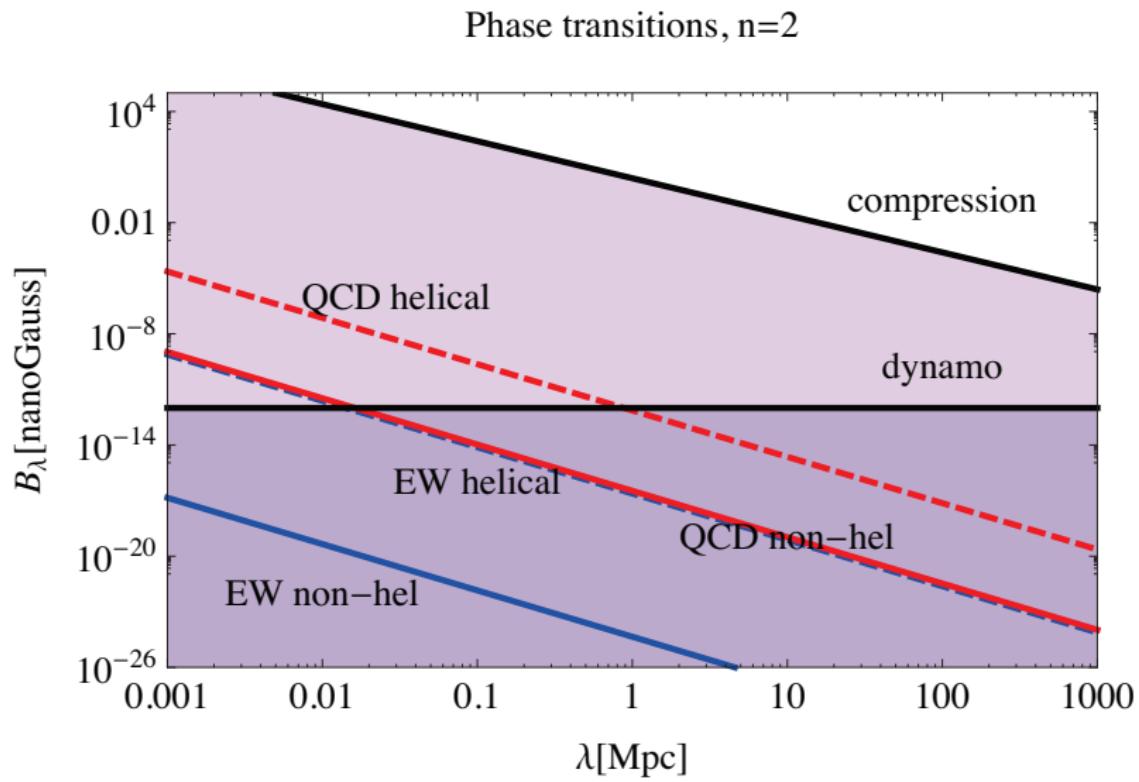
How to create EGMFs in voids?

- primordial fields:
 - ▶ inflation
 - ▶ phase transitions (QCD, electroweak)
 - ▶ reionization **too weak**

- astrophysical (require seed fields):
 - + outflows from AGNs, dwarf galaxies
 - outflows **collimated**
 - $B > 0$ and $B = 0$ **plasma does not mix**
 - contamination with **heavy elements**

Expectation for “causally” generated fields:

[Caprini, Durer, ...]



Primordial magnetic fields:

- for a Gaussian field

$$\langle B_i(k) B_j^*(k') \rangle = \delta(k - k') \left[(\delta_{ij} - \hat{k}_i \hat{k}_j) S(k) + i \varepsilon_{ijk} k^l H(k) \right]$$

energy density $\rho = 4\pi \int_0^\infty k^2 S(k)$

helicity density $h = 4\pi \int_0^\infty k H(k)$

- characterized by B_λ and coherence length L_c

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- ▶ analyticity & finite $\rho \Rightarrow B_\lambda \sim B_0 (L_c/\lambda)^{5/2}$

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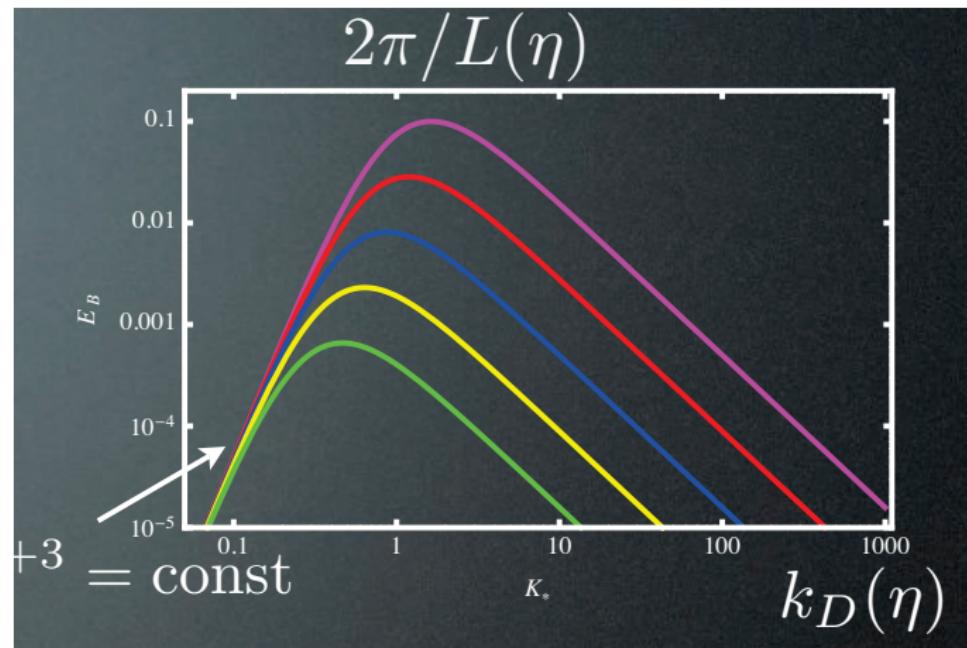
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- how are fields evolving after creation?

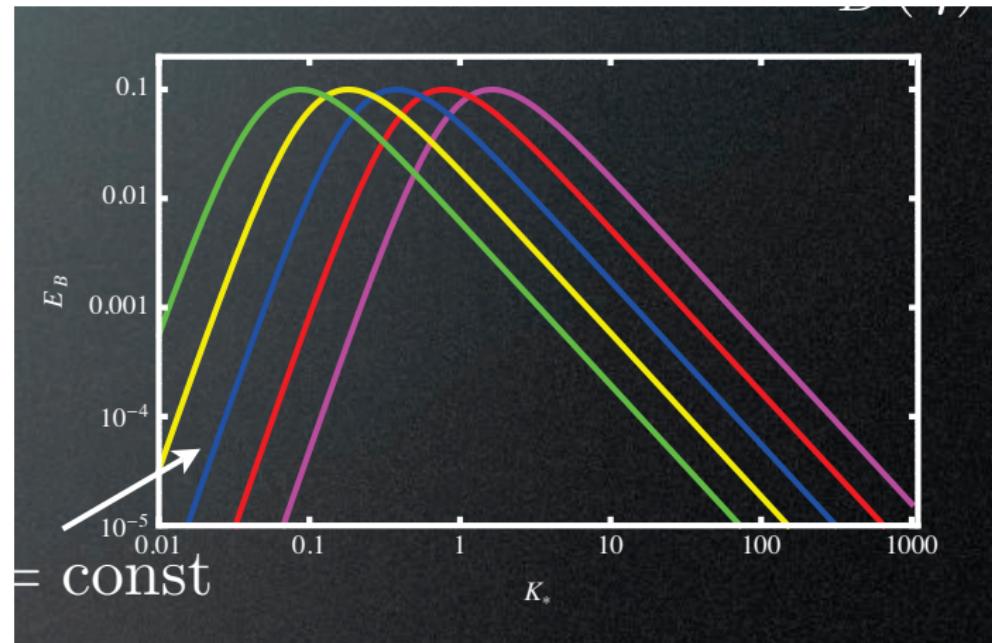
Evolution of primordial magnetic fields:

- non-helical fields: damped above k_D , below $B \propto 1/a^2$



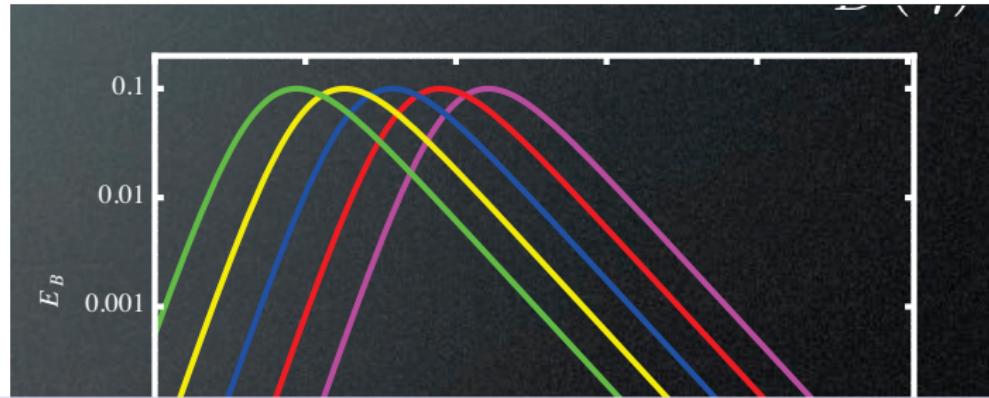
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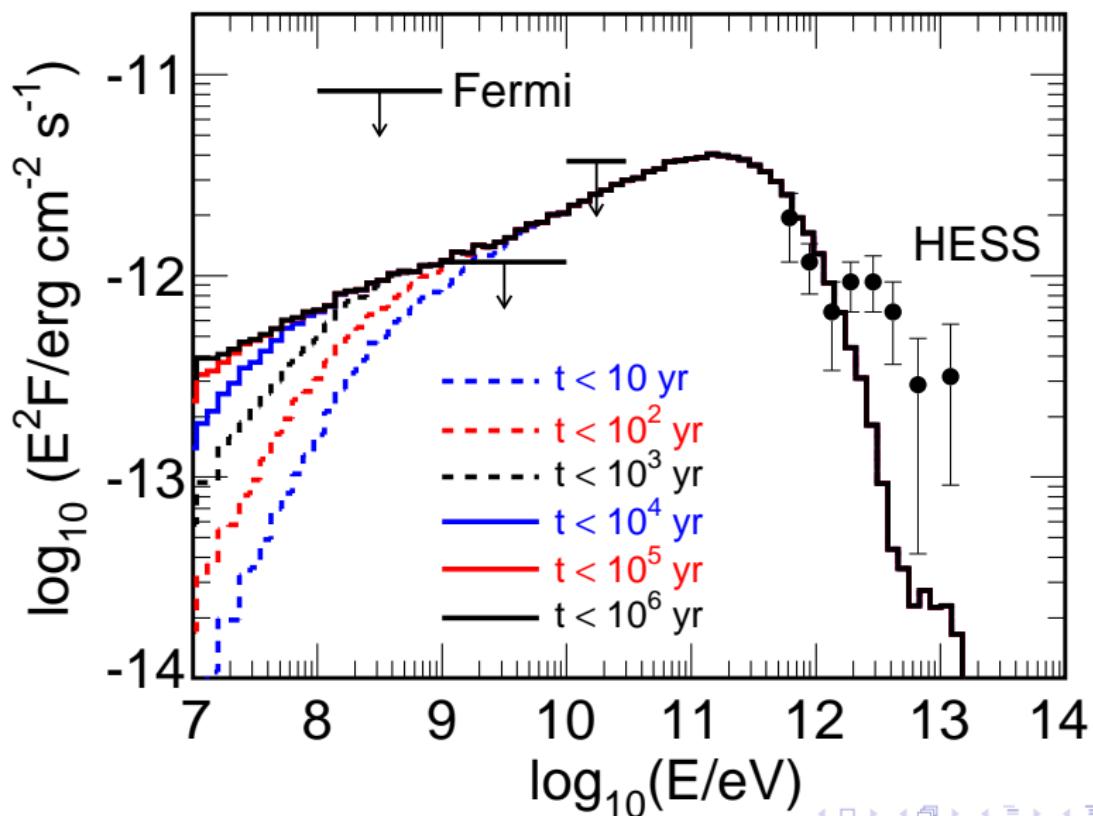
Picture assumes “static” large scale tail $B_\lambda \propto \lambda^{-5/2}$:

- ▶ interaction with turbulent fluid generates $B_\lambda \propto \lambda^{-3/2}$
- ⇒ fields from phase transitions could be strong enough

Summary

- Fermi non-observation of TeV blazars requires EGMF
 - ⇒ quantitative conclusions:
 - ▶ sure: large filling factor $f \gtrsim 0.5$
 - ▶ bound on EGMF: depends on assumed Δt , $B \gtrsim 10^{-17} \text{ G}$
- can be improved by more/longer simultaneous observations
- limit ⇒ detection: CTA?
- suggests primordial origin: phase transition or inflation?

Time dependence for flaring source: $B \gtrsim 10^{-17}$ G



EGMF in voids already observed?

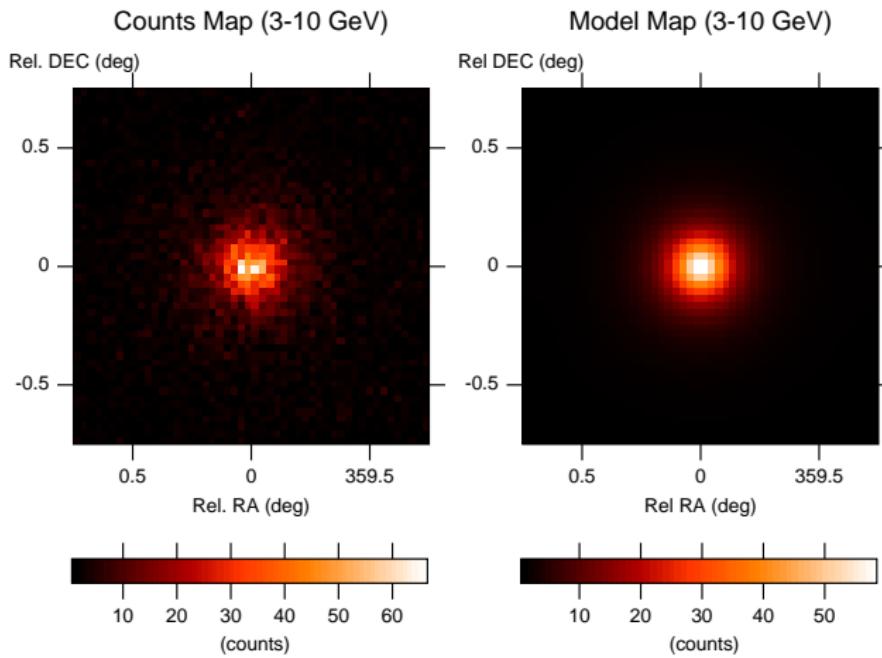
[*Ando, Kusenko '10*]

- stack 170 brightest AGN

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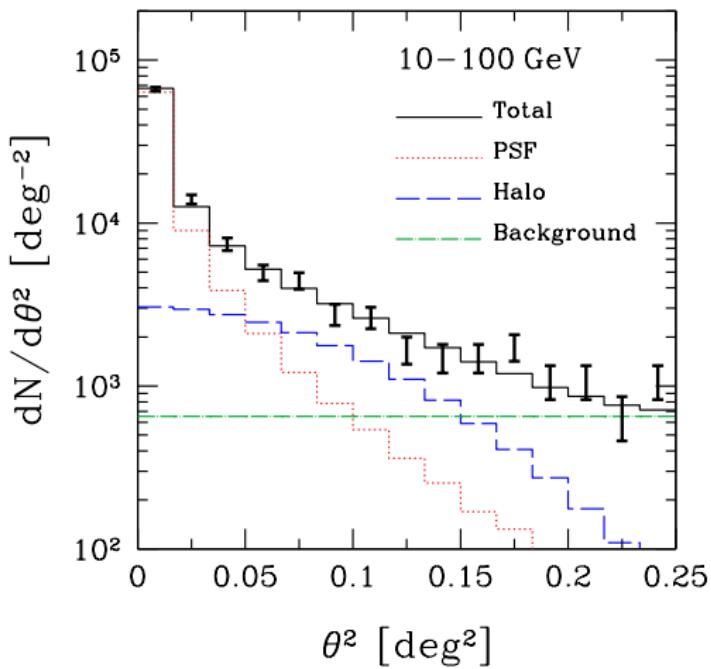
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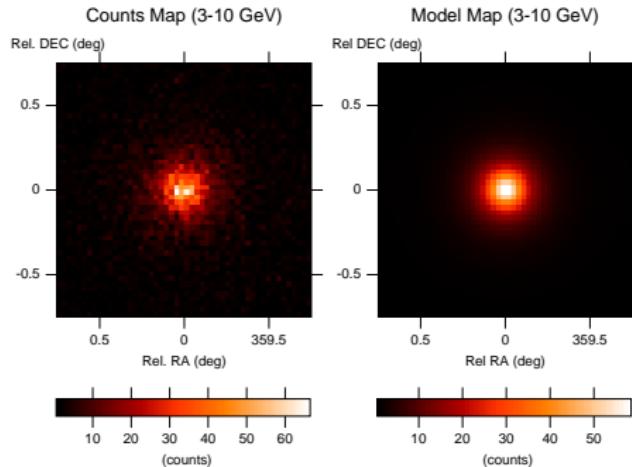
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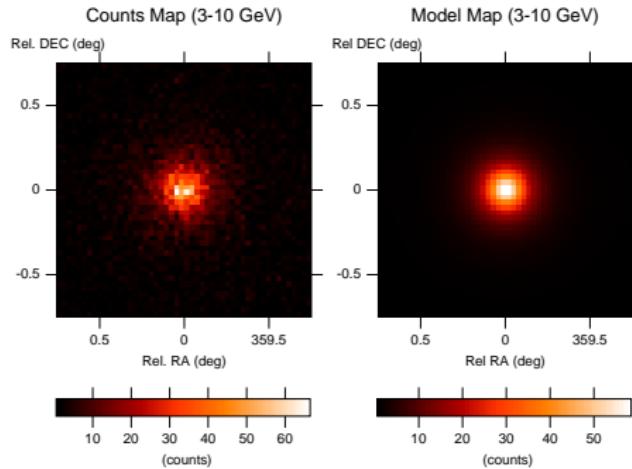
⇒ explained by

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

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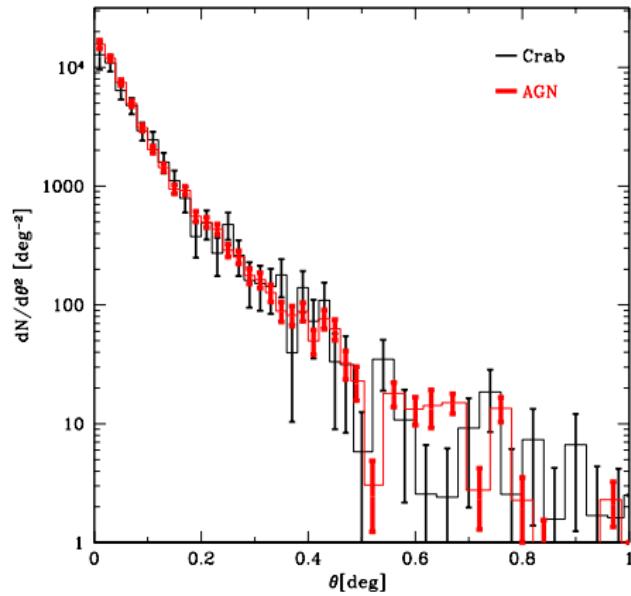


- lower limit $B \gtrsim 5 \times 10^{-15}$ G requires $\lambda_B \lesssim 0.1$ kpc

EGMF already observed? Probably not... . . .

[Neronov et al. '10]

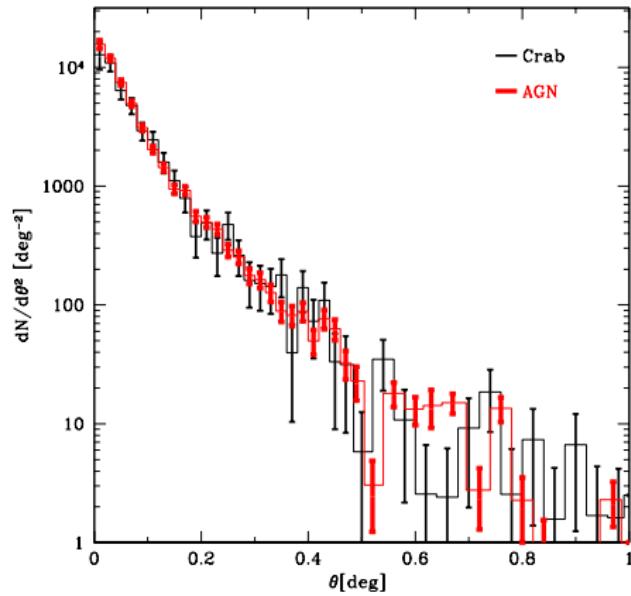
- point source Crab shows the same “halo” as stacked AGN:



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