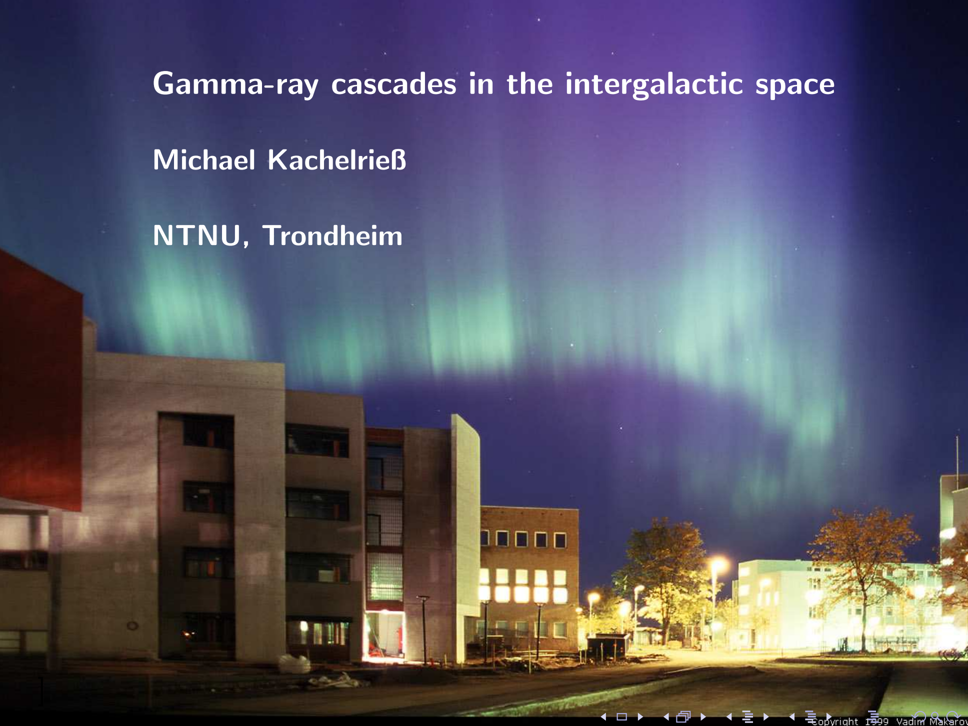
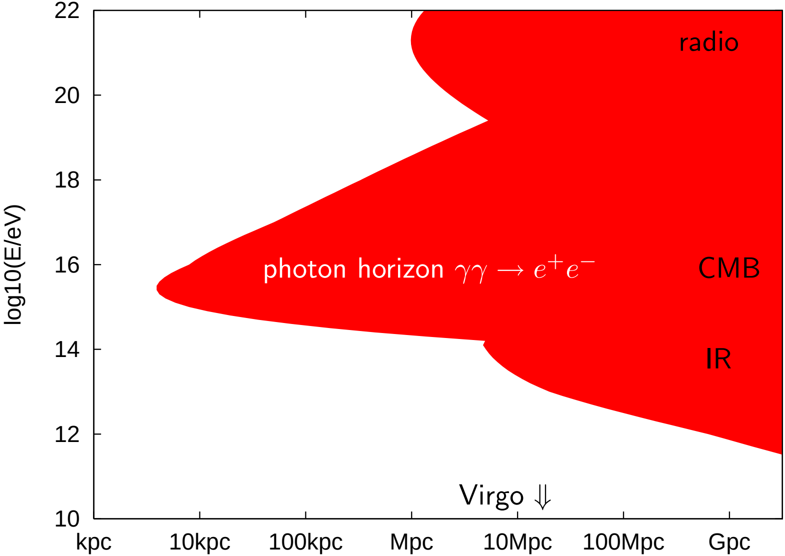
Gamma-ray cascades in the intergalactic space

Michael Kachelrieß

NTNU, Trondheim



Mean free path of photons



Origin of cascade photons:

- UHECRs:
  - Photon and neutrino production relatively tight connected:
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$$p + \gamma_{3K} \to \begin{cases} p + \pi^0 \to p + 2\gamma \\ n + \pi^+ \to p + 2e^\pm + 4\nu \end{cases}$$

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    - ★ connection to UHECRs looser

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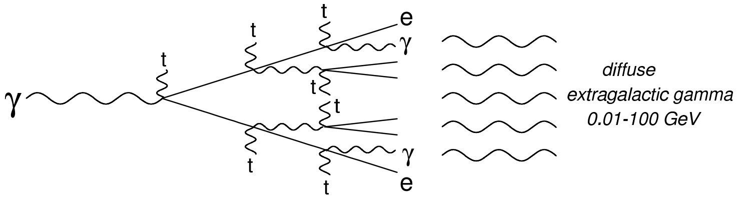

Diffuse cascade flux:

- analytical estimate: [*Berezinsky, Smirnov '75*]

$$J_\gamma(E) = \begin{cases} K(E/\varepsilon_{\rm X})^{-3/2} & \text{at} \quad E \leq \varepsilon_{\rm X} \\ K(E/\varepsilon_{\rm X})^{-2} & \text{at} \quad \varepsilon_{\rm X} \leq E \leq \varepsilon_{\rm a} \\ 0 & \text{at} \quad E > \varepsilon_{\rm a} \end{cases}$$

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- three regimes:
  - Thomson cooling:

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

  - plateau region
  - above pair-creation treshold $s_{\min} = 4E_\gamma\varepsilon_{\rm bb} = 4m_e^2$: flux exponentially suppressed

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inserting in energy conservation,

$$E_\gamma dn_\gamma = q_e(E_e) dE_e \,,$$

gives

$$J(E_\gamma) \propto E_\gamma^{-3/2}$$

Diffuse flux, analytical estimate for plateau region:

- energy conservation and $N_e/N_\gamma = \text{const.}$

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- to log. accuracy

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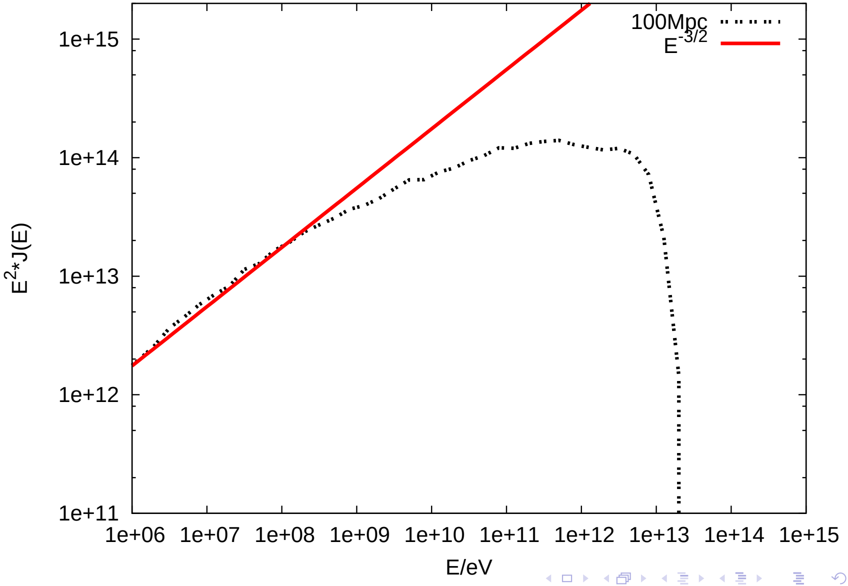
Monte Carlo vs. analytical estimate: single source



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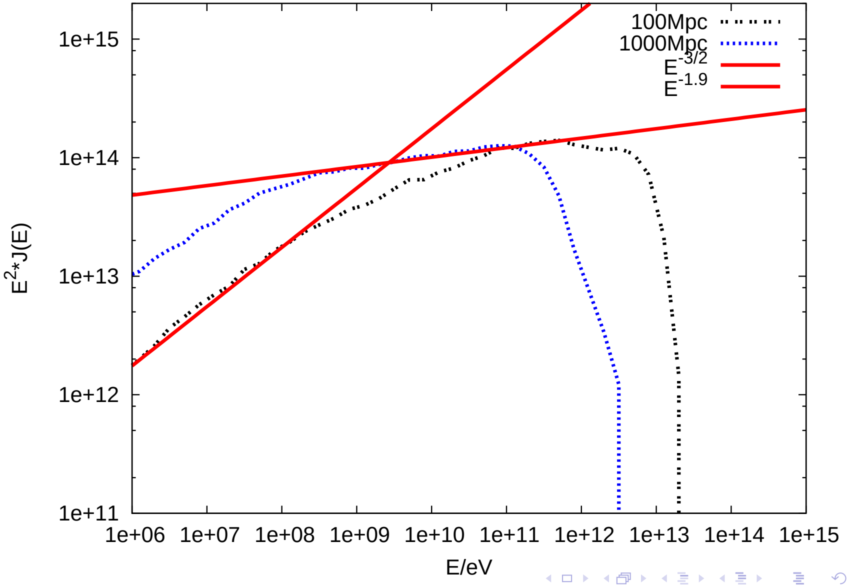
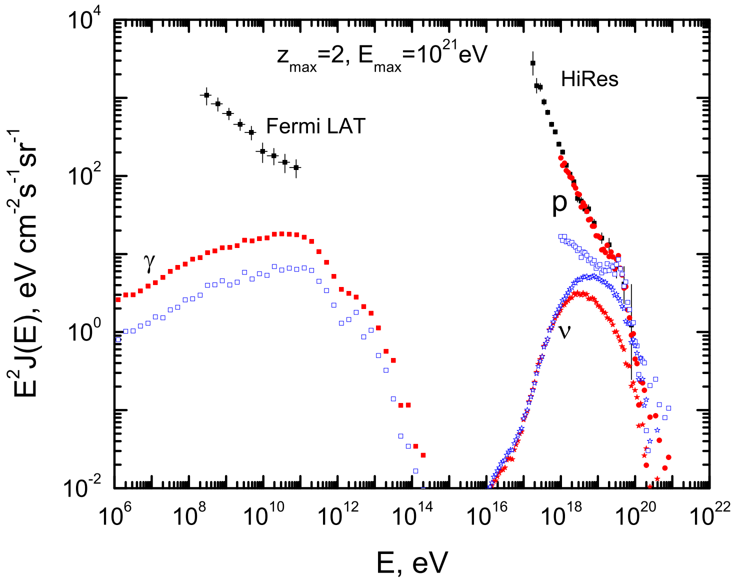


Fermi-LAT vs. UHECR data:

[Berezinsky et al. '10]



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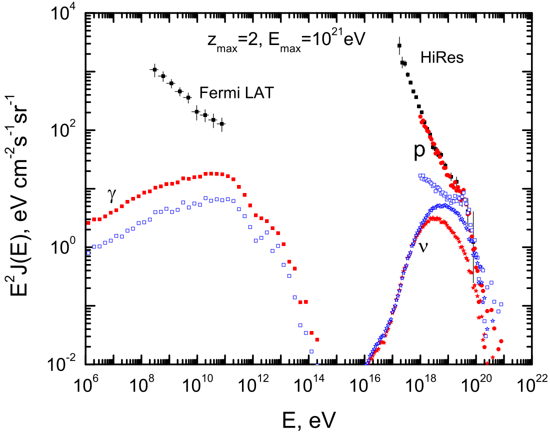

integrating $EJ(E)$ gives bound $\omega_{\rm cas} \lesssim 6 \cdot 10^{-7}\, {\rm eV/cm}^3$

Problems of analytical estimates:

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- diffuse flux: superpositions of different $\tau(l)$
- easy and difficult questions:
  - difficult: tail $J(E, \vartheta)$
  - easy: main flux $J(E, 0)$

Influence of EGMF on diffuse flux:

- elmag. cascade only below critical electron energy $E_{\rm cr}$ defined by

$$\left(\frac{1}{E}\frac{dE}{dt}\right)_{\rm syn} = \left(\frac{1}{E}\frac{dE}{dt}\right)_{\rm IC}$$

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$$\frac{\omega_{\rm cas}^B}{\omega_{\rm cas}} = \frac{\ln(E_{\rm cr}/E_{\rm min})}{\ln(E_{\rm max}/E_{\rm min})}.$$

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- for $E_{\rm max} \sim 1 \times 10^{21}$ eV and $E_{\rm min} \sim 1 \times 10^{9}$ eV,

$$\omega_{\rm cas}^B/\omega_{\rm cas} = 0.78$$

- steeper generation spectrum than -2 $\Rightarrow \omega_{\rm cas}^B/\omega_{\rm cas} \to 1$

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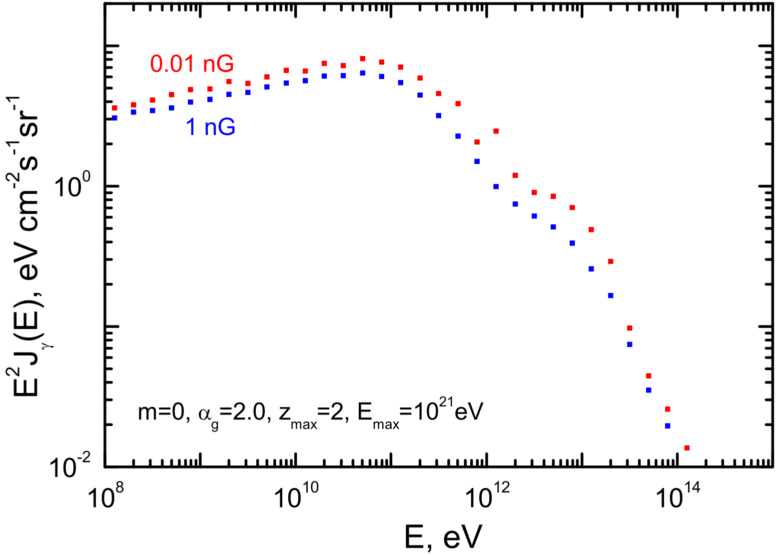

Influence of EGMF on flux from single source: deflections

- deflection of electrons:

$$\vartheta \sim \frac{l_{\rm cool}}{R_L} \propto E_e^{-2}$$

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$\Rightarrow$ cooling regime: transition from

$$J(E) \propto E^{-1.5} \to E^{0.5} \to E^{-1.5}$$

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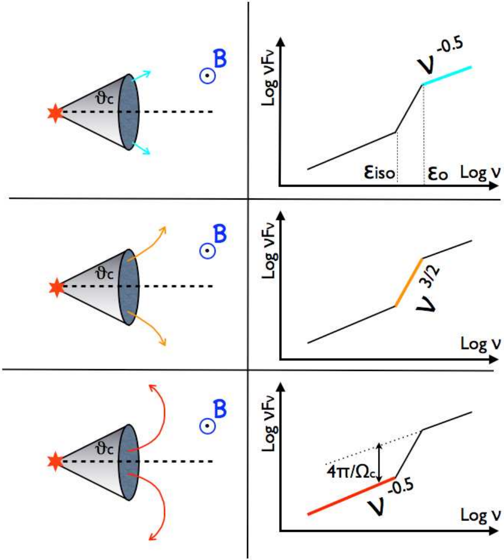

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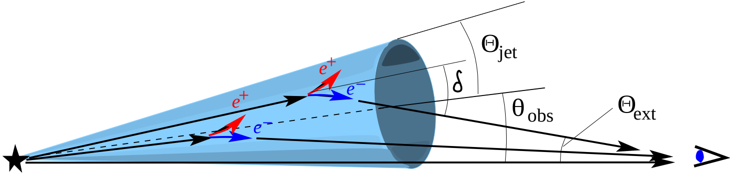

- probability for misalignement $p \propto \vartheta_{\rm obs}$ ⇒ most blazars viewed with $\vartheta_{\rm obs} \sim \vartheta_{\rm jet}$

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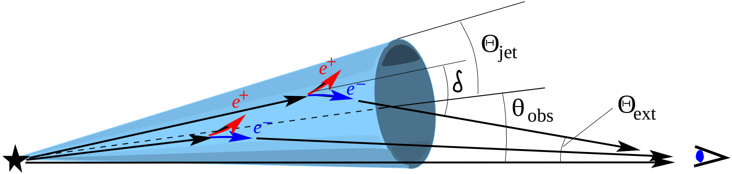

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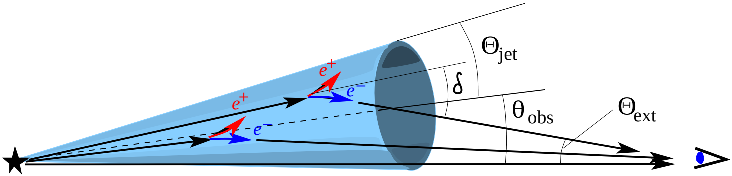

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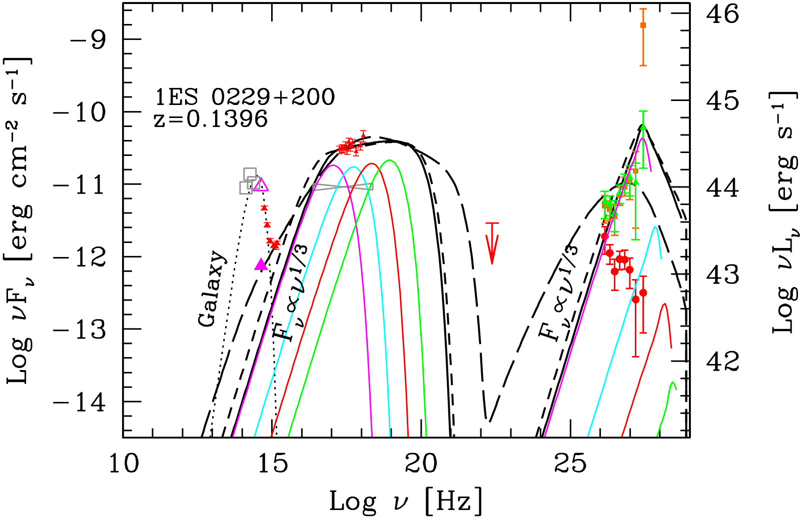
$\Rightarrow$ time-delay is function of ϑ,

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

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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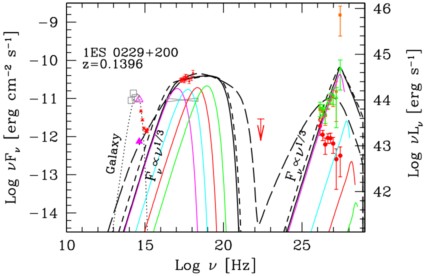

- TeV photons cascade down:
  - small EGMF: fill up GeV range
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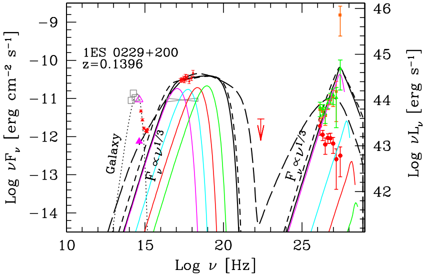

- TeV photons cascade down:
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- open questions:
  - influence of EGMF structure?
  - time-dependence for flaring sources?

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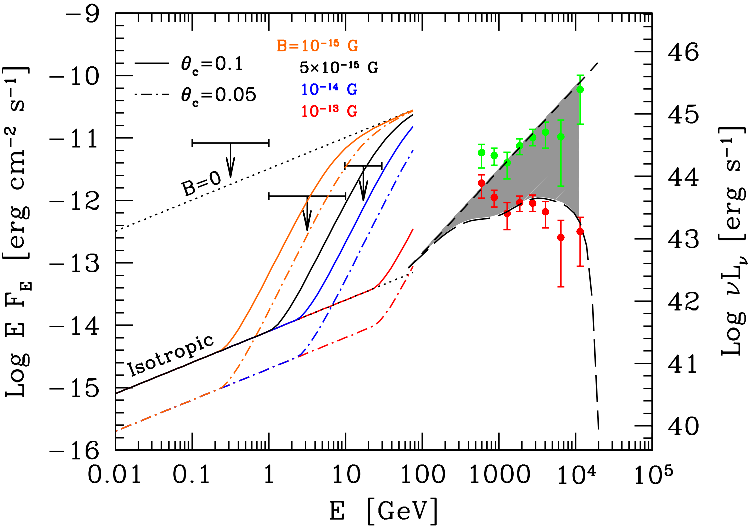

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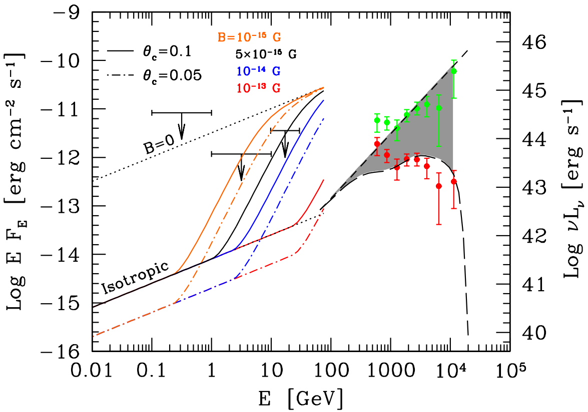

- $B \gtrsim 10^{-15}$ G
- some dependence on $\vartheta_{\rm jet}$
- no simulation of elmag. cascade with B

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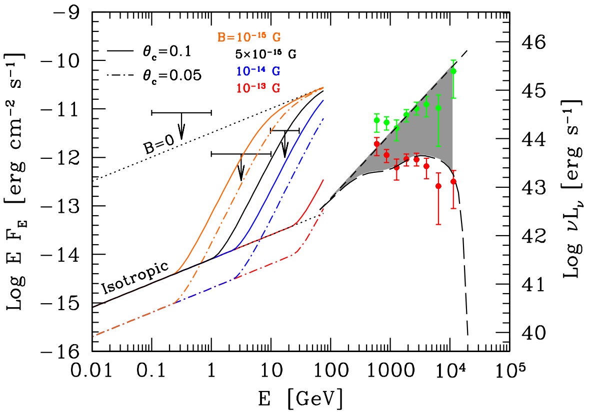

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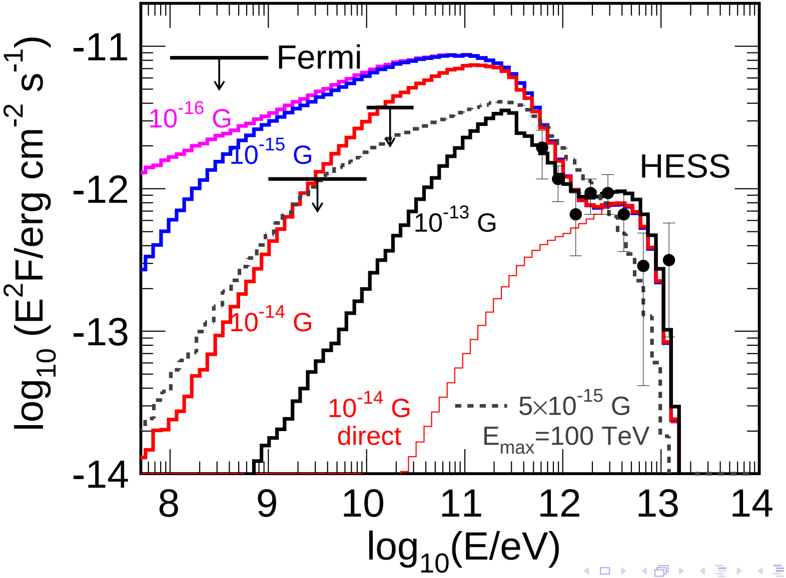
Lower limit on EGMF: uniform field

[*Dolag et al. '10*]



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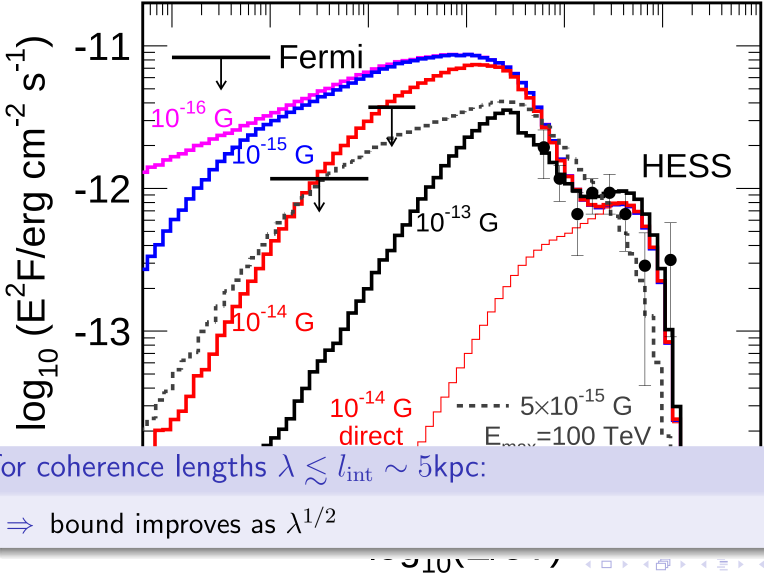


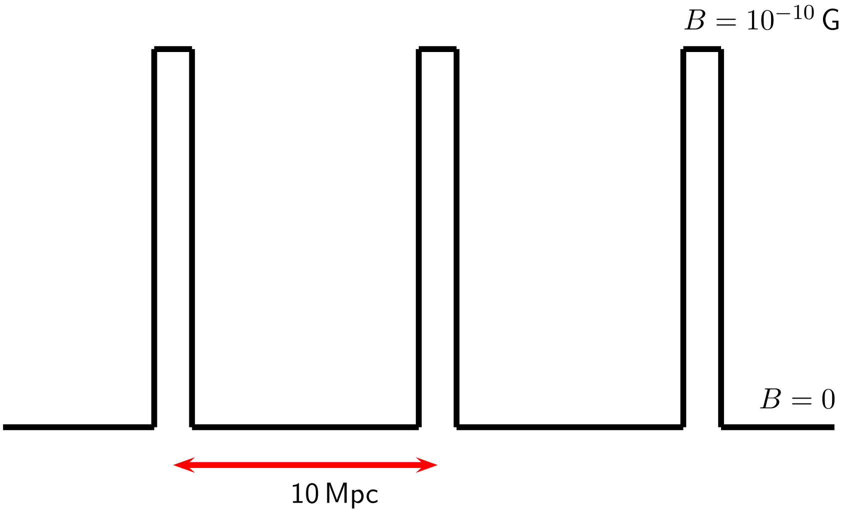
for coherence lengths $\lambda \lesssim l_{\rm int} \sim 5$kpc:

$\Rightarrow$ 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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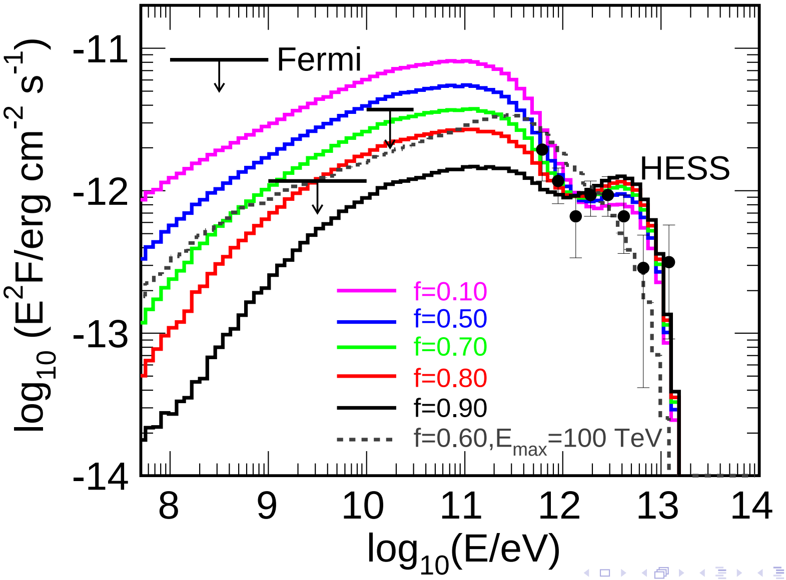

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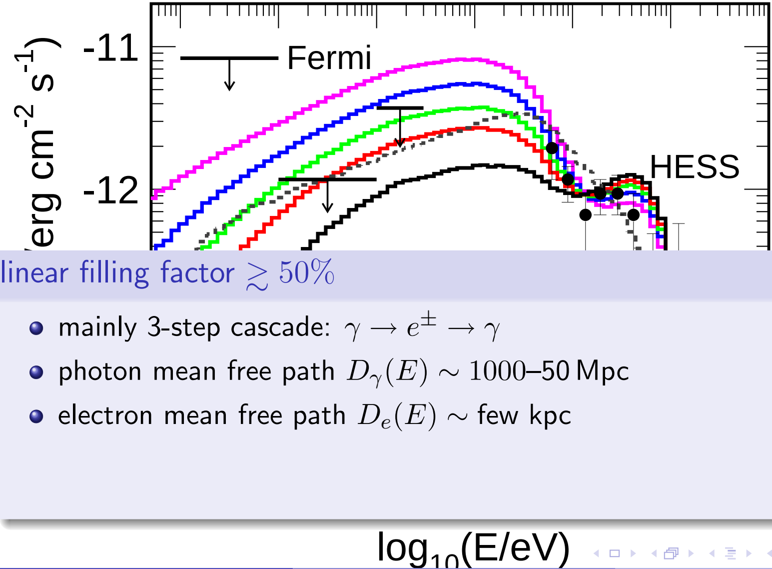

linear filling factor $\gtrsim 50\%$

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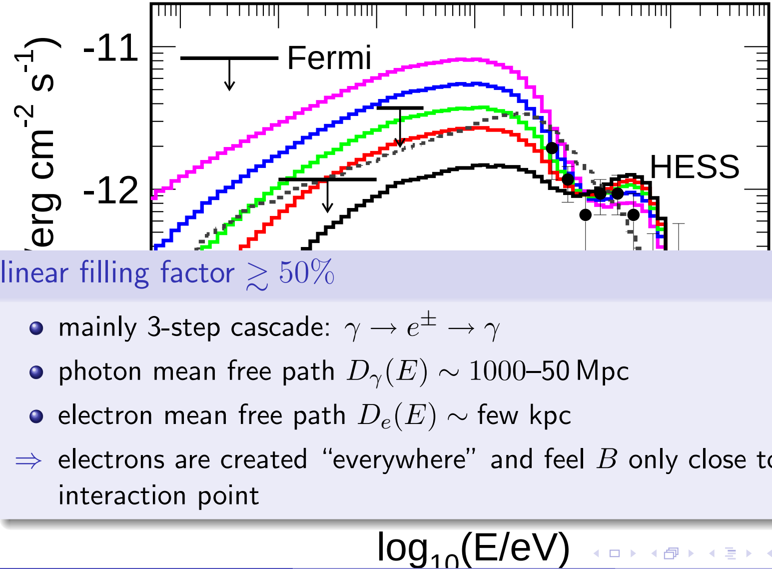

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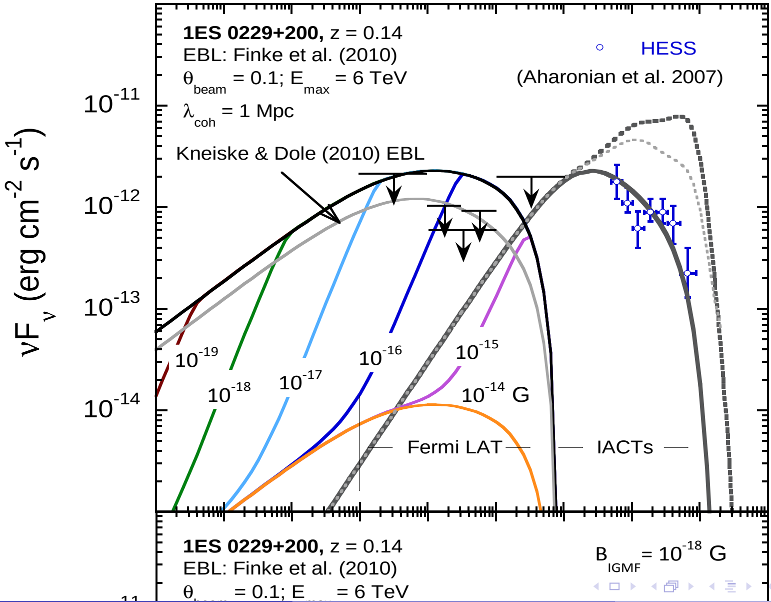
$\Rightarrow$ electrons are created "everywhere" and feel B only close to interaction point

Effect of time-delay

[*Dermer et al. '10*]



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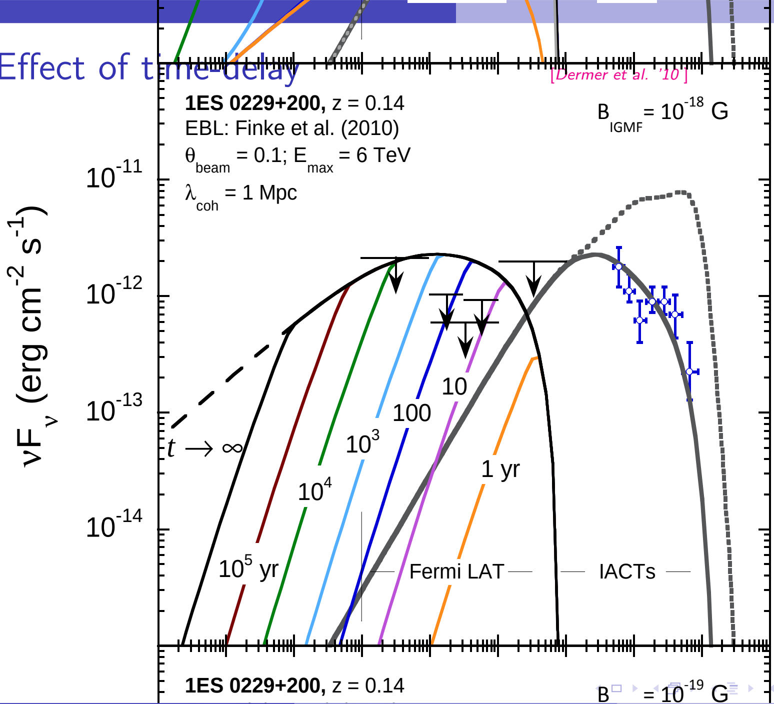

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1×10^6 yr	(0.1–10)GeV
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- for $\tau \sim 100\,$yr: lower limit on B weakens only by a factor 10, to $B = \mathcal{O}(10^{-16}\,\mathrm{G})$

Summary

- Fermi non-observation of TeV blazars requires EGMF

$\Rightarrow$ quantitative conclusions:

  - sure: large filling factor $f \gtrsim 0.5$
  - bound on EGMF: depends on assumed Δt

- can be improved by more/longer simultanous observations
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