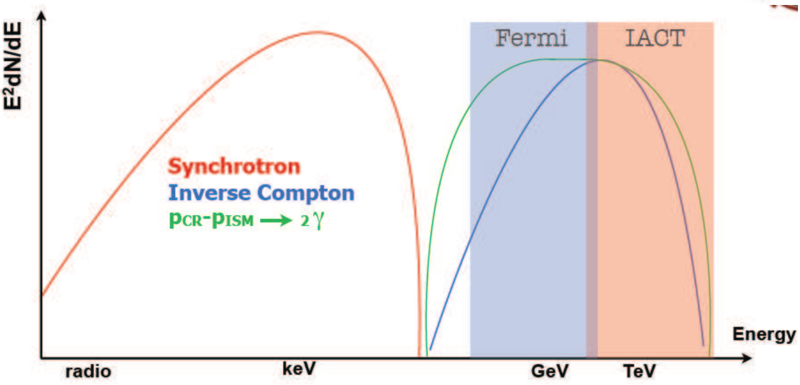
Plan of the lectures: Photons

- Basic observations
- Approaches
- Open questions and possible explanations:
  - Dipole anisotropy
  - Breaks and non-universality of primary nuclei spectra
  - Positron excess
  - Knee and the end of the Galactic CR spectrum

SNR: Leptonic versus hadronic models



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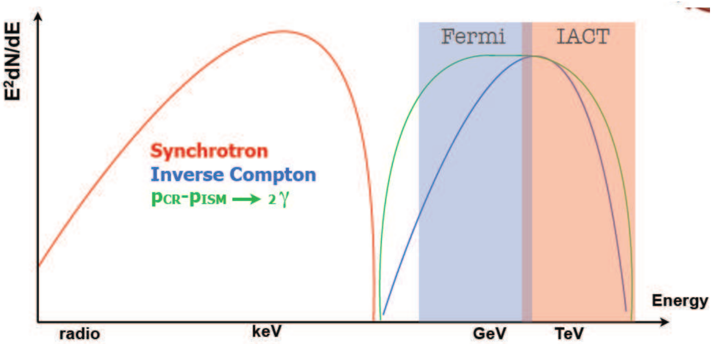
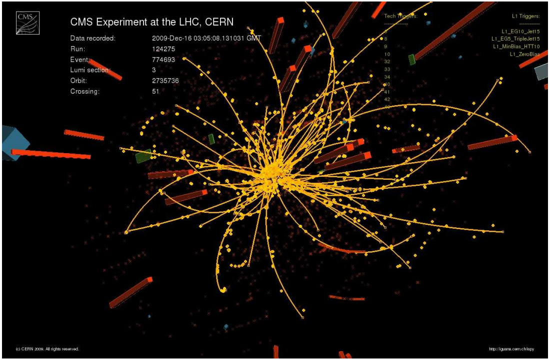


- ICS and π^0 photons differ most below 100 MeV
- combining Fermi and IACT constrains models tightly

The pion peak

- CR scattering on gas or photons: $pp \to$ mesons, baryons $\to e, \gamma, \nu, p$



- the lightest mesons, π^0 and $\pi^\pm$, are produced most often
- decays: $\pi^0 \to 2\gamma$ and $\pi^\pm \to 3\nu + e^\pm$

The pion peak

- $\pi^0 \to \gamma(\boldsymbol{k}_1) + \gamma(\boldsymbol{k}_2)$ at rest:
  - energy conservation: $m_\pi/2 = E_1 = E_2$
  - momentum conservation: $\boldsymbol{k}_1 = -\boldsymbol{k}_2$
  - moving back-to-back

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- π^0 is moving:
  - decay isotropic in rest-frame $\Rightarrow dn/dE_\gamma$ =const.
  - min./max. photon energies

$$E_{\min}^{\max} = \gamma \frac{m_{\pi^0}}{2}(1 \pm \beta) = \frac{m_{\pi^0}}{2}\sqrt{\frac{1 \pm \beta}{1 \mp \beta}}$$

  - geometric mean $\sqrt{E_{\min} E^{\max}} = \frac{m_{\pi^0}}{2}$

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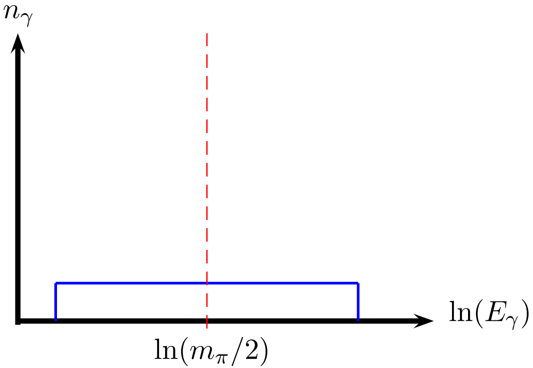

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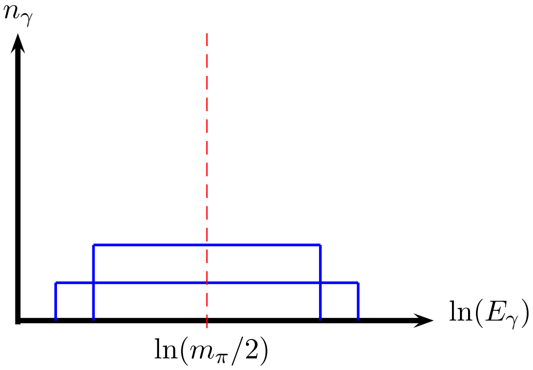

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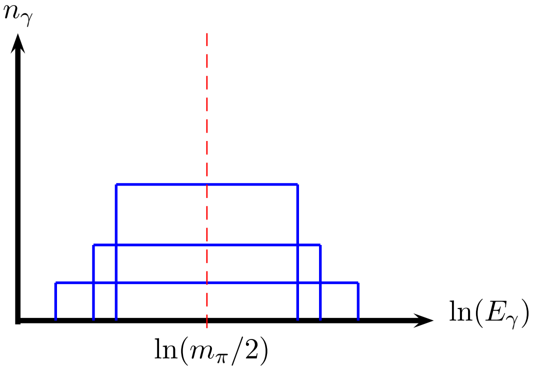

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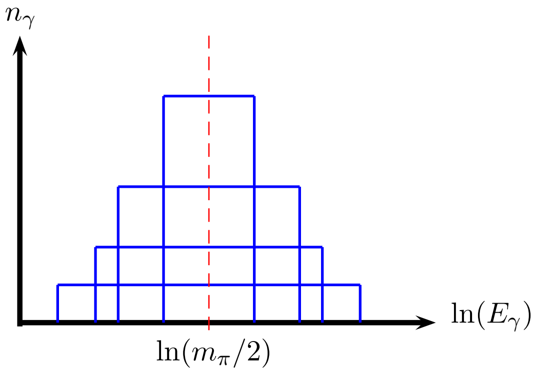

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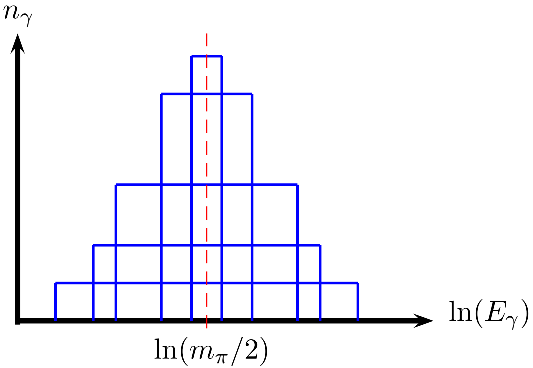

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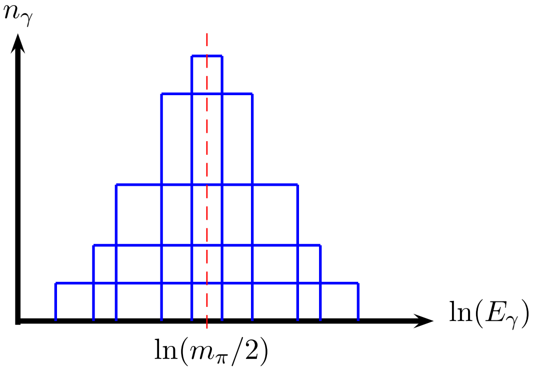
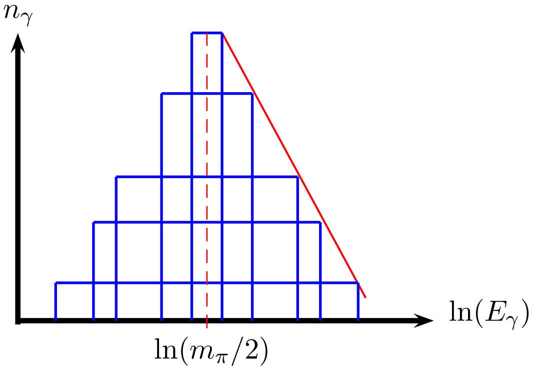


- independent of velocity distribution of pions:

$\Rightarrow$ symmetric photon distribution w.r.t. $m_{\pi^0}/2$

The pion peak: pp interactions



- low threshold & approx. Feynman scaling

$\Rightarrow$ $dN_\gamma/dE \sim dN_{CR}/dE$

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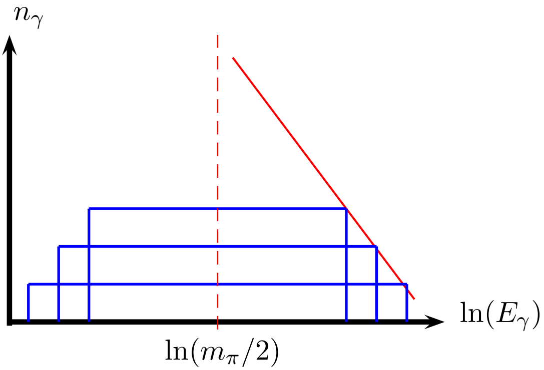

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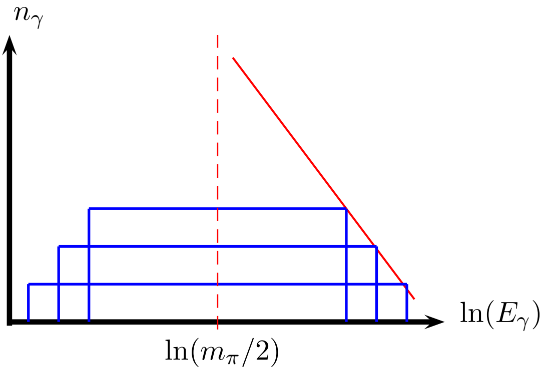

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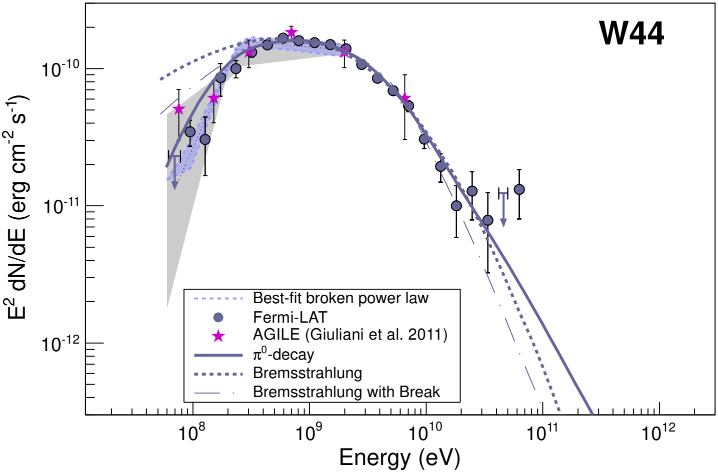
- change for interacting nuclei A:
  - suppressed by $A^{1-\alpha}$

Observing the π^0 bump in SNR W44:



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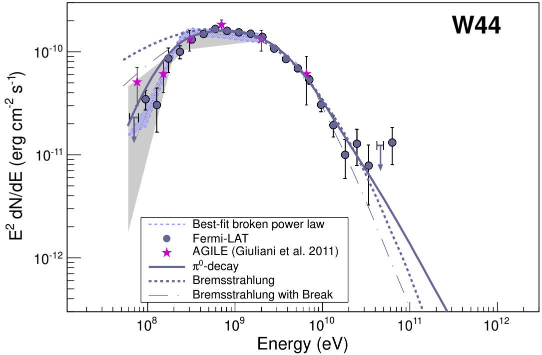
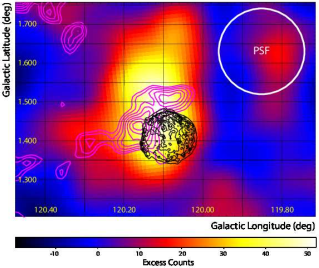
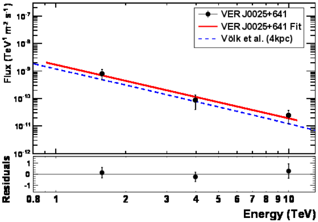


- strong evidence for proton acceleration

Tycho observations by VERITAS





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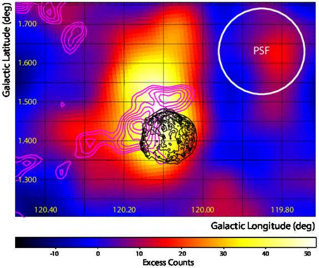

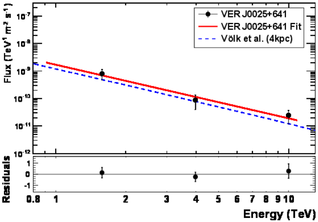

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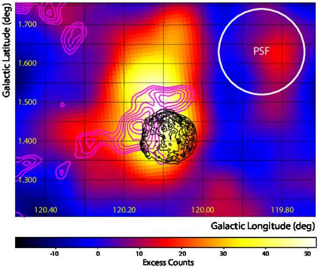

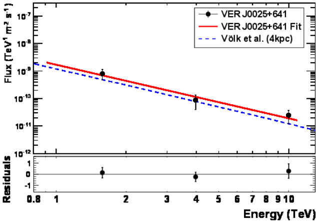

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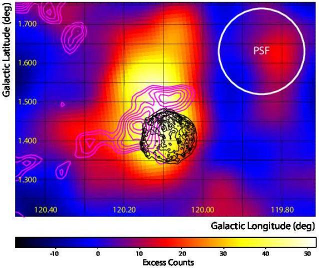

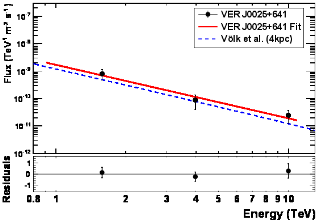

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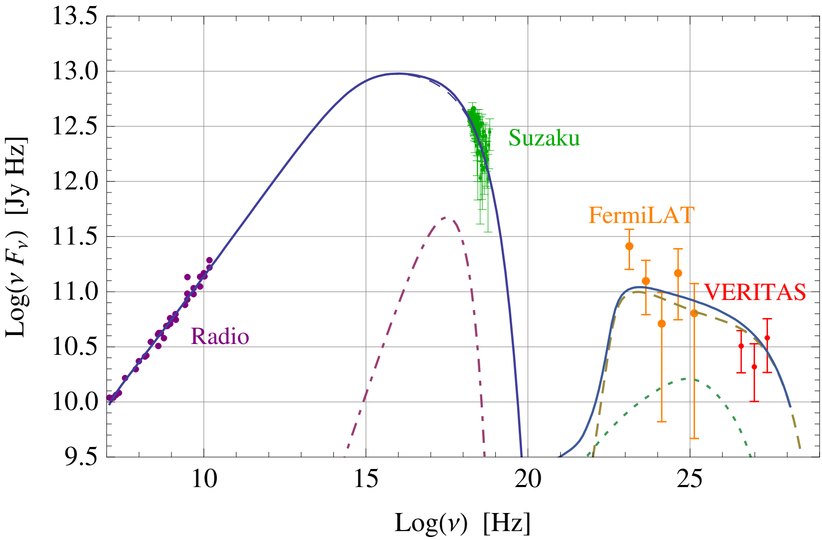
electrons with $E > 50\,$TeV

Tycho: Leptonic versus hadronic models

[Morlino, Capriolo '11]



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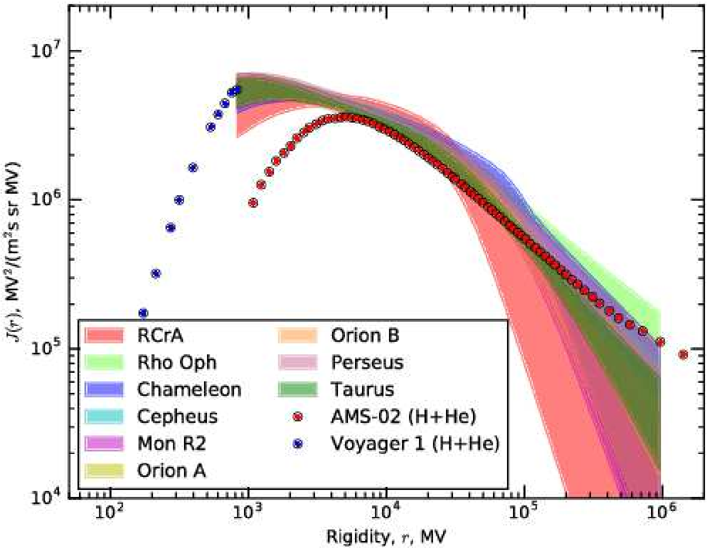
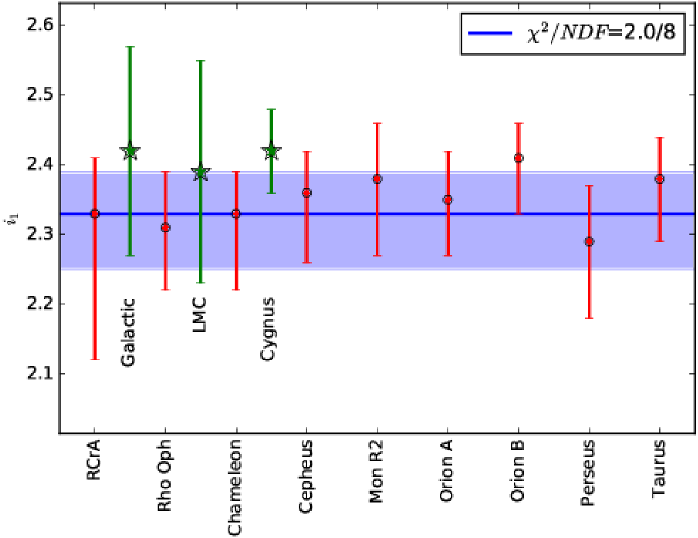
- ill-posed problem, fit instead physically motivated trial functions
- (broken) power-laws

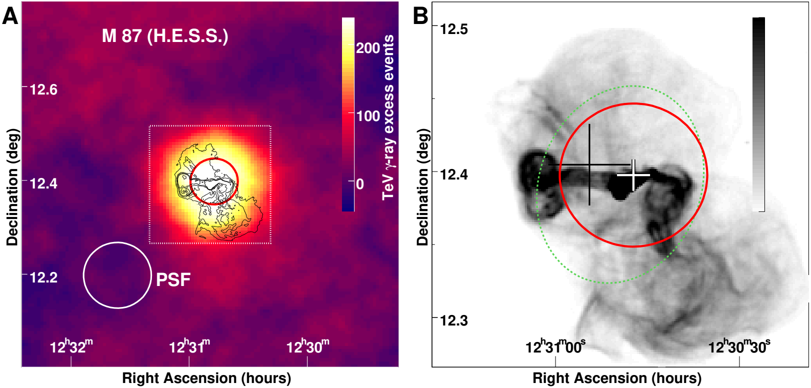
$I_{CR}(E)$ from molecular clouds,



$I_{CR}(E)$ from molecular clouds, below break



HESS observations of M87:



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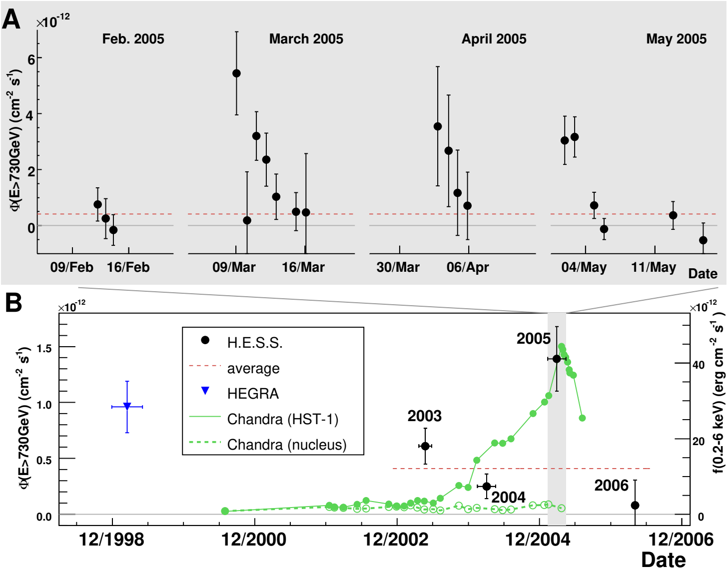

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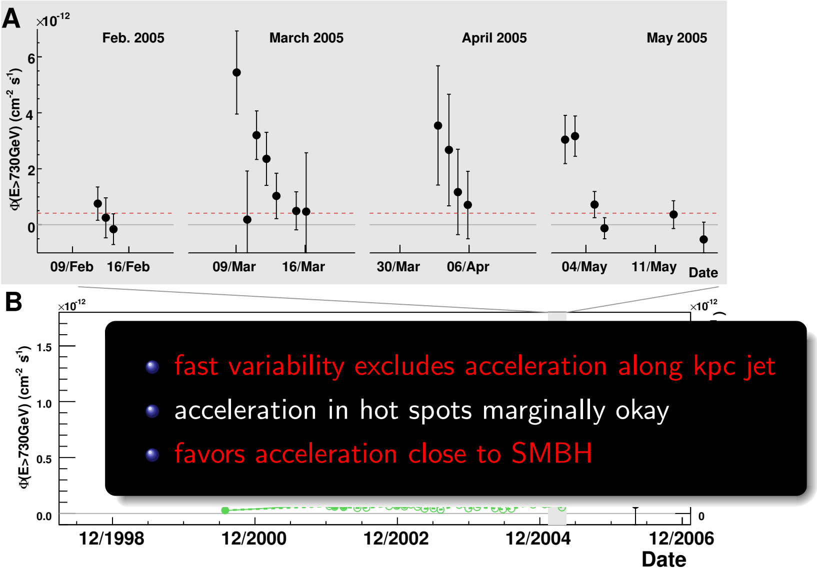
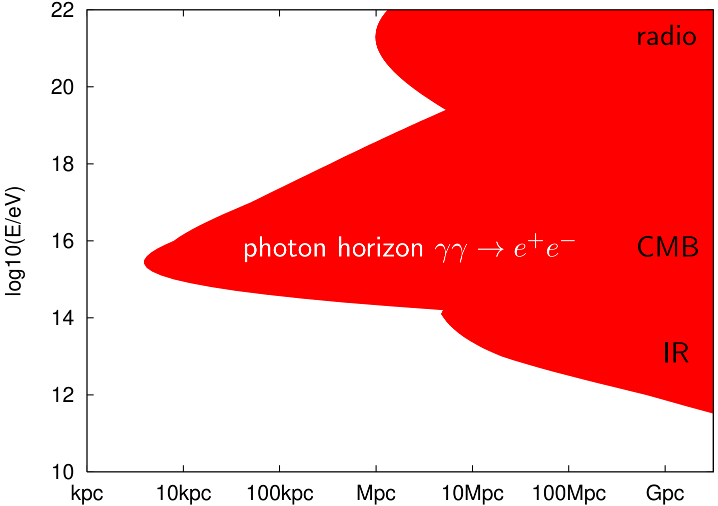
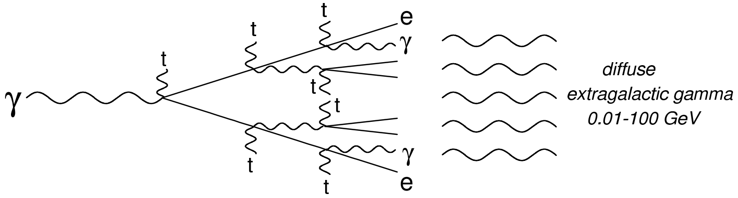


- fast variability excludes acceleration along kpc jet
- acceleration in hot spots marginally okay
- favors acceleration close to SMBH

Photon horizon



Development of the elmag. cascade:



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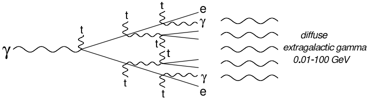

- analytical estimate: *[Strong '74, Berezinsky, Smirnov '75]*

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

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

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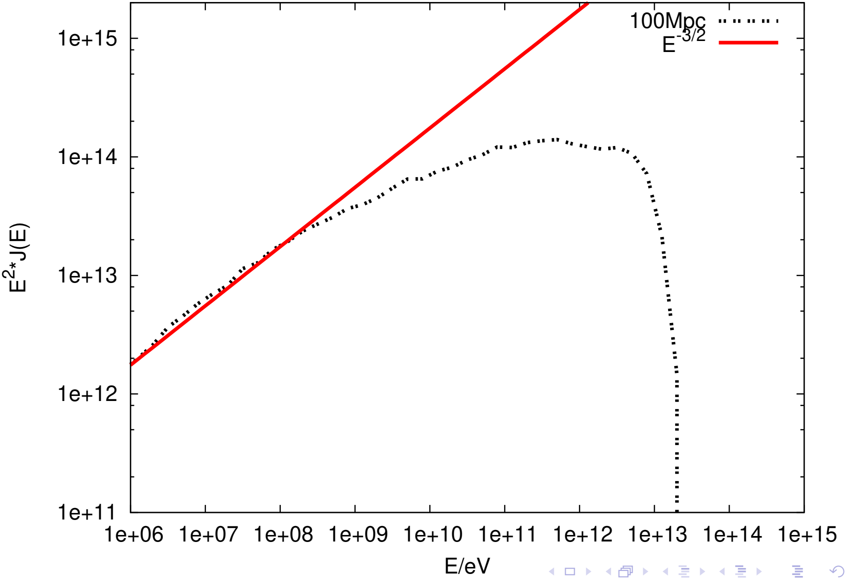

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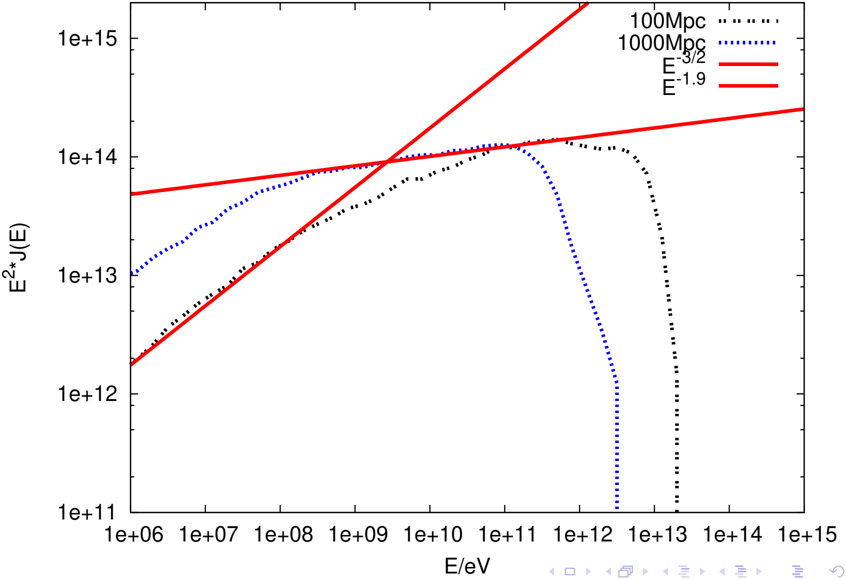

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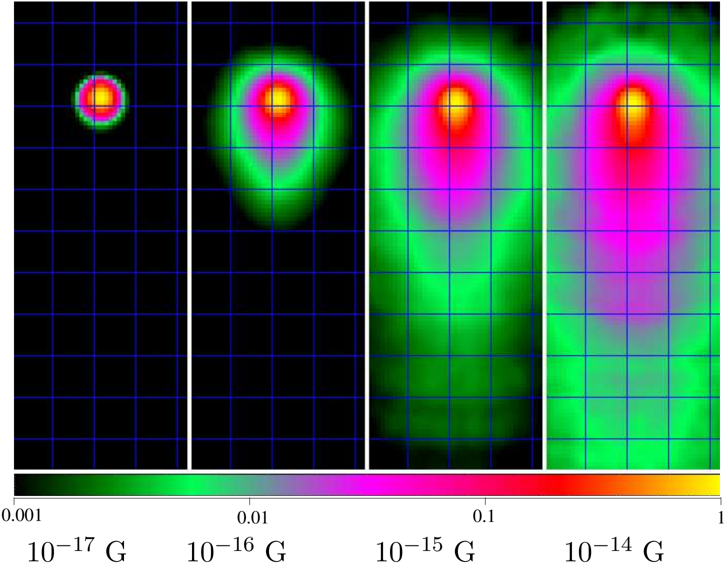
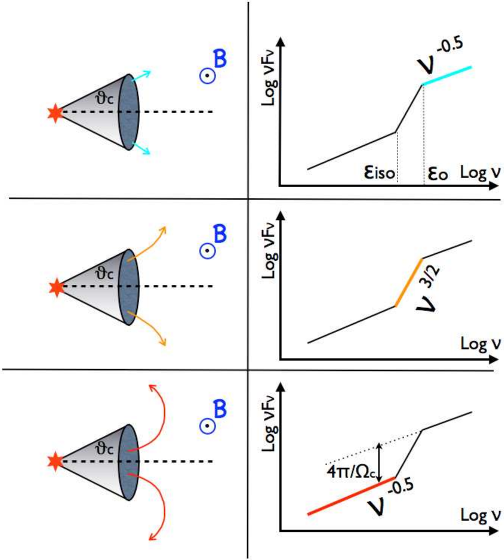
- d'Avezac, Dubus and Giebels '07: non-observation of TeV blazars in Fermi gives lower limit on EGMF

"GeV jets": B dependence



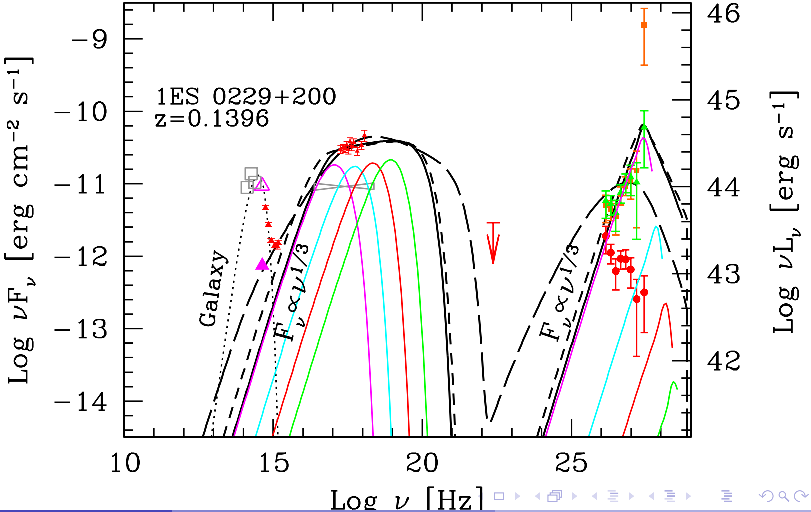
Influence of EGMF on flux from single source: deflections



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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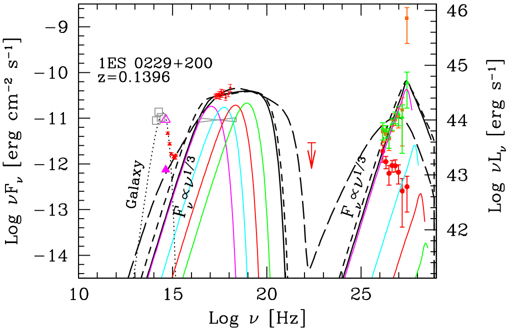
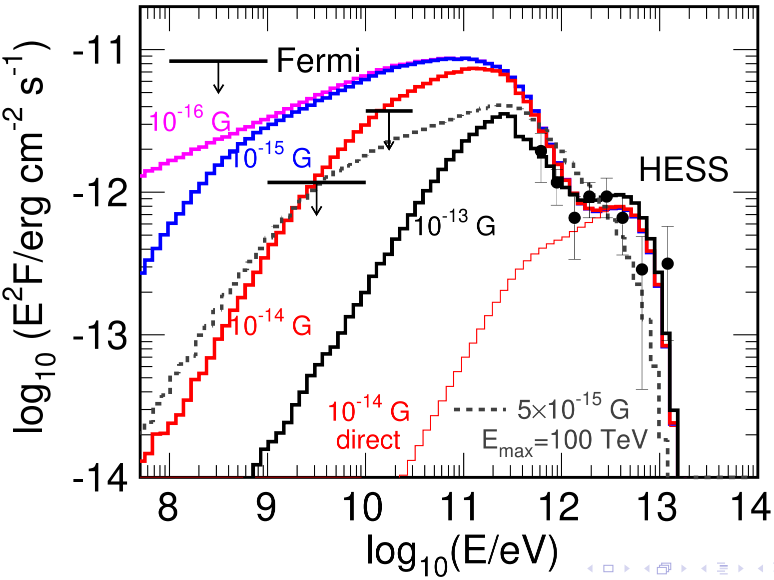


- TeV photons cascade down:
  - small EGMF: fill up GeV range
  - "large" EGMF: deflected outside, isotropized

Lower limit on EGMF: uniform field

[*Dolag et al. '10*]



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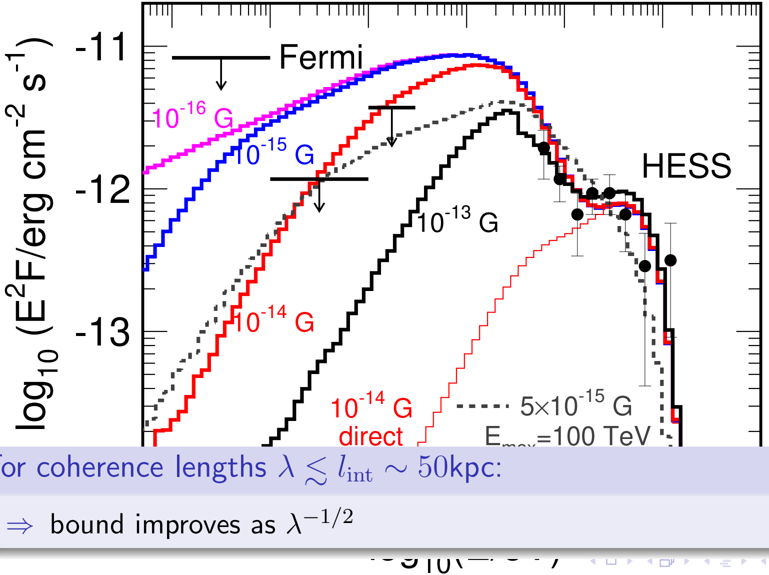


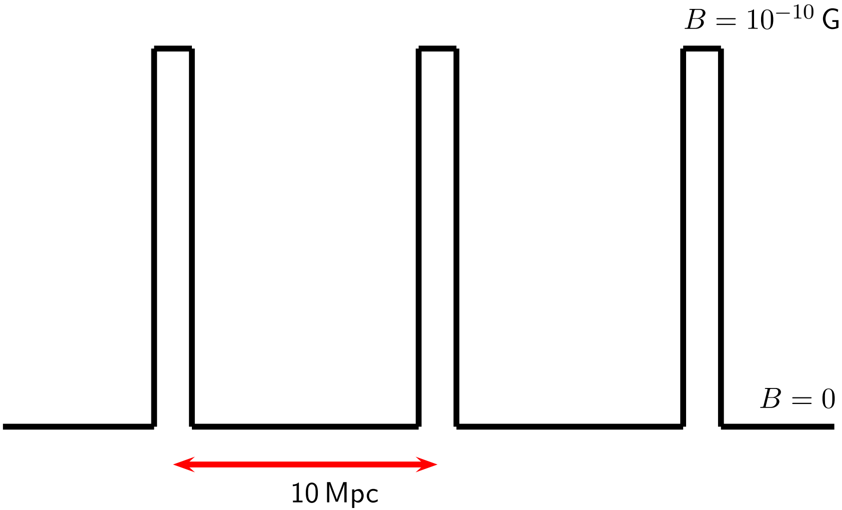
for coherence lengths $\lambda \lesssim l_{\rm int} \sim 50\text{kpc}$:

$\Rightarrow$ 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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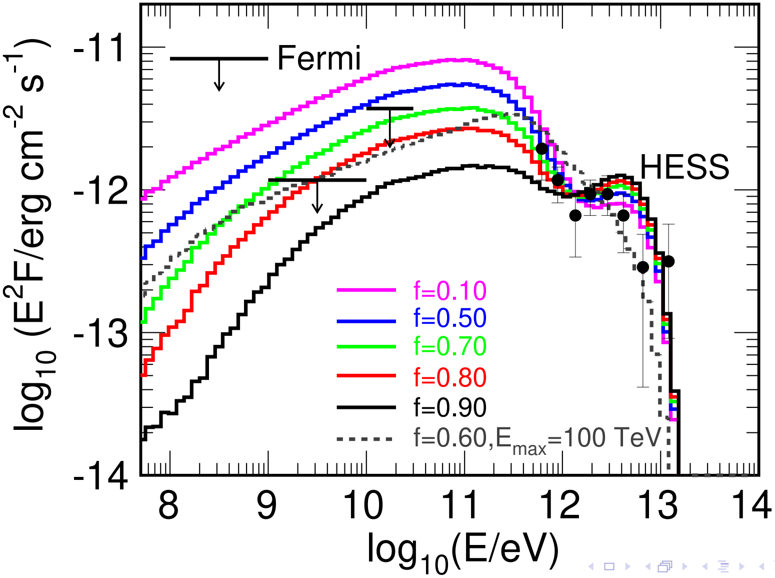

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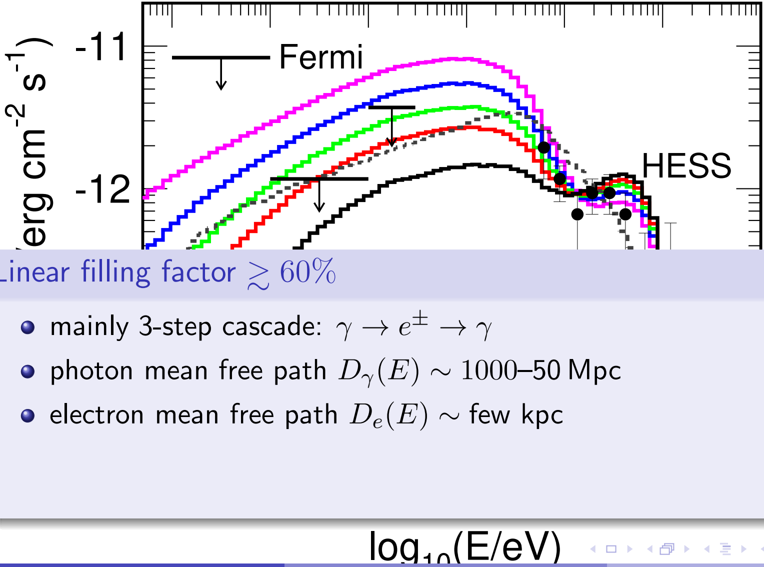

Linear filling factor $\gtrsim 60\%$

- 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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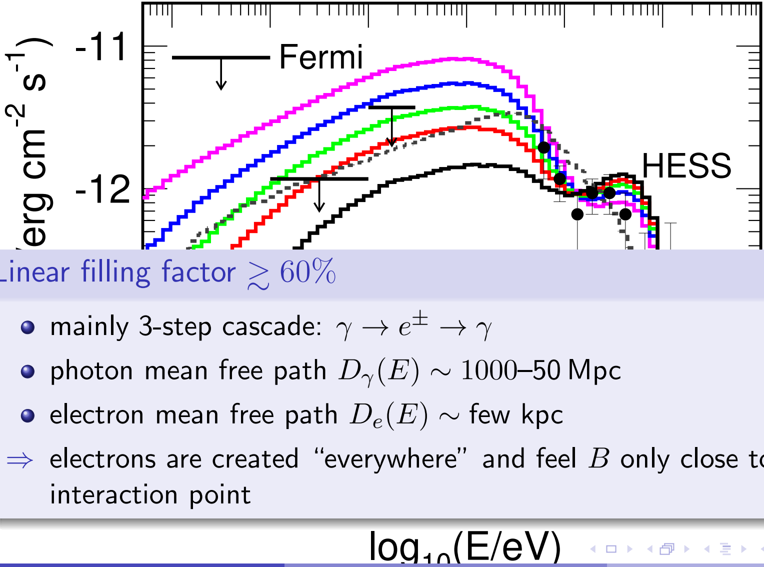

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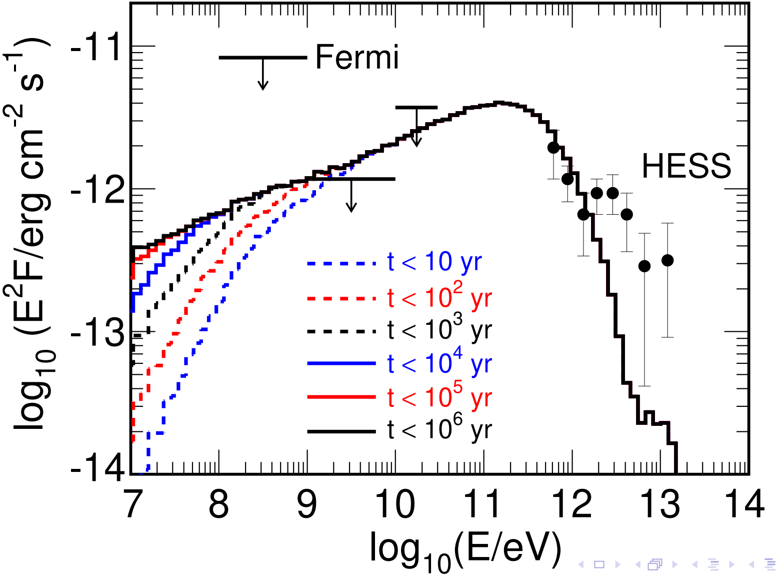
$\Rightarrow$ electrons are created "everywhere" and feel B only close to interaction point

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



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- question: competive with ICS under realistic conditions?
- not decided yet