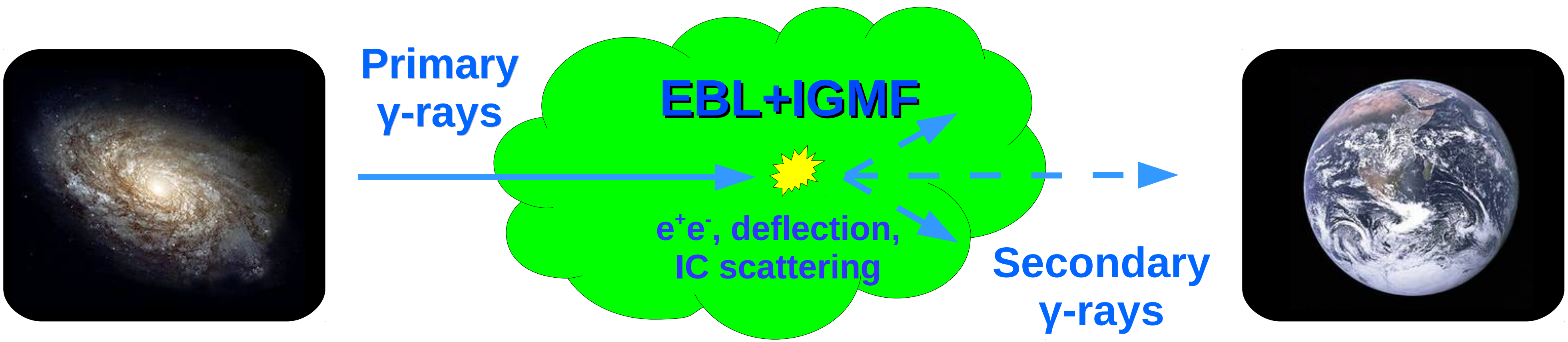
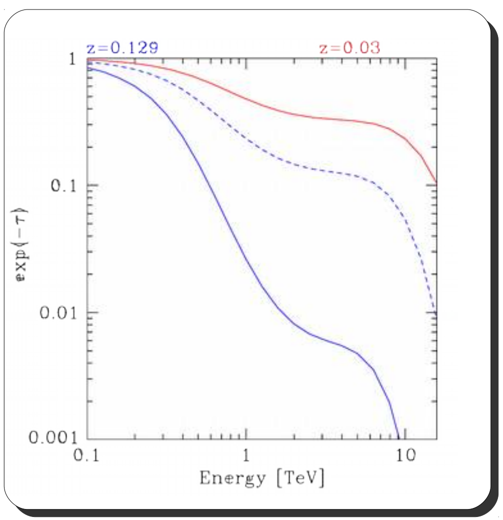
VHE sources and intergalactic magnetic fields

Ievgen Vovk

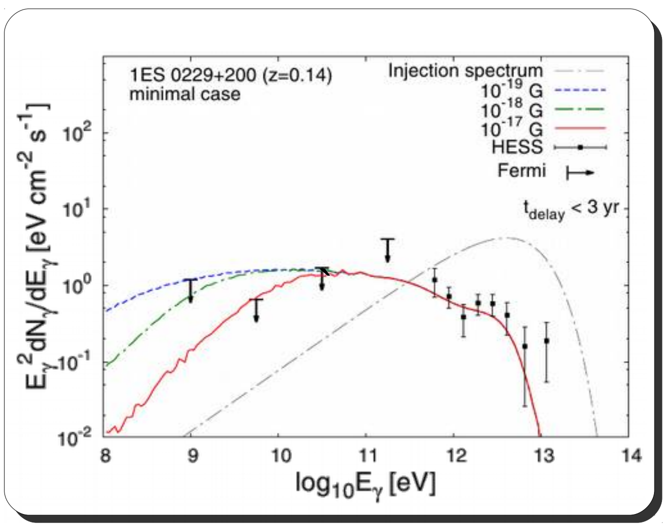
MPI for Physics,
Munich, Germany

Propagation of VHE photons: EBL and IGMF



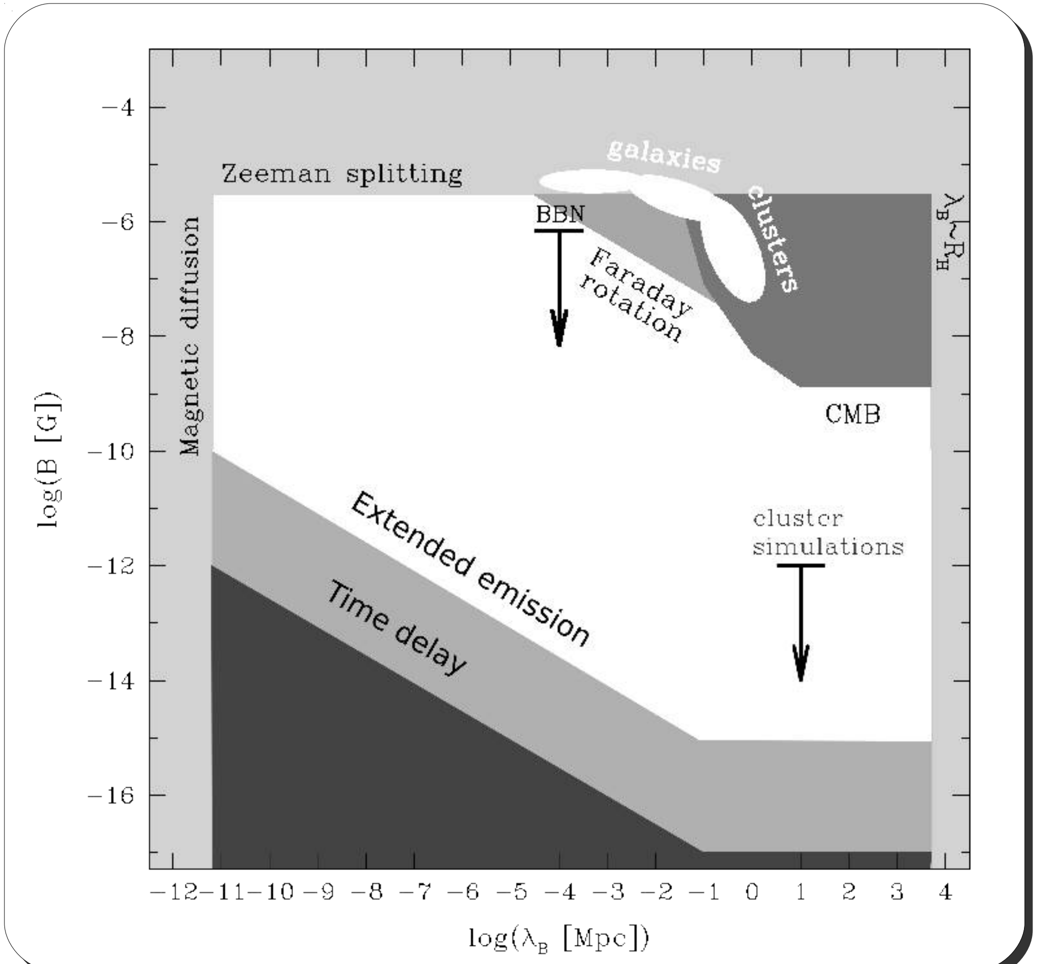


Costamante+ '07



Taylor+ '11

Intergalactic magnetic field



Taylor+ '11

The properties of the IGMF can be represented – in a simplified way – by its strength B and coherence scale λ.

Magnetic diffusion scale < **λ** < Size of the Universe

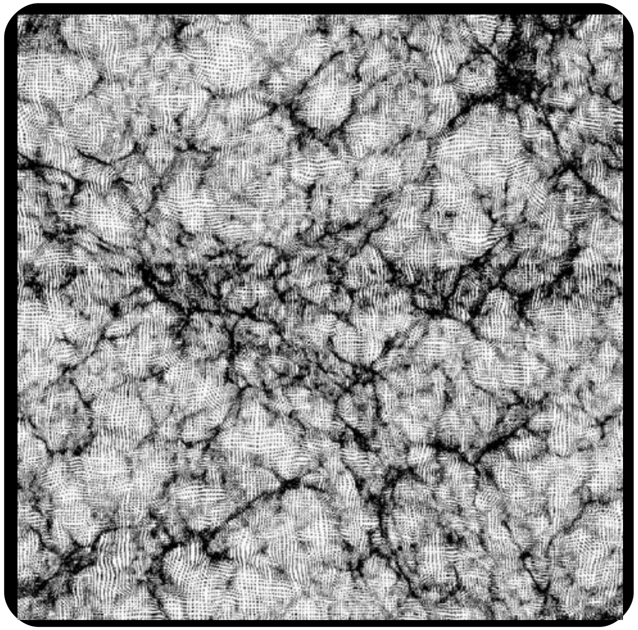
+ additional constraints depending on the nature of the IGMF

The strength B is constrained from the top ($<10^{-9}$ G) by several observational techniques
(Zeeman splitting, Neronov & Semikoz '09, CMB anisotropy, Barrow+ '97, Faradey rotation, Kosowsky & Loeb '96)
Its lower limits ($>10^{-17}$ G) were recently suggested from the gamma-ray data
(Neronov & Vovk '10, Tavecchio+ '10...)

Origin of the IGMF

Cosmological

Fills 100% of the Universe



Astrophysical

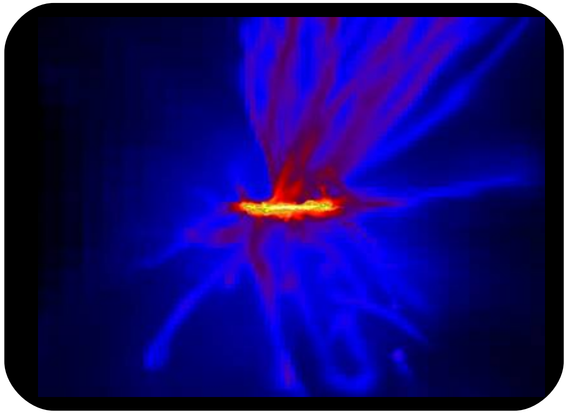
(large z)

Filling factor: unknown

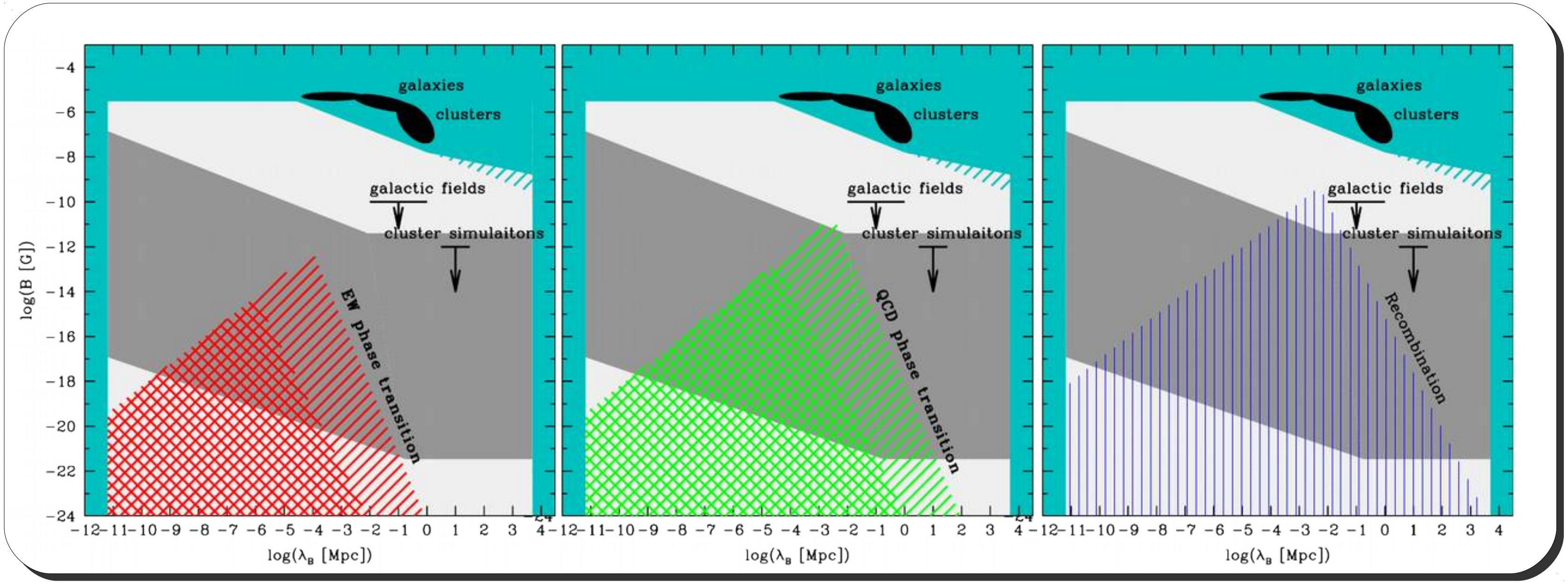
Astrophysical

(small z)

Filling factor: unknown



Cosmological IGMF



Neronov & Semikoz, '09

Magnetic fields produced during different epochs:

- ✔ QCD phase transitions: ~10^{-12}
- ✔ electroweak phase transitions: 10^{-11} G
- ✔ recombination: ~10^{-9} G

Astrophysical IGMF

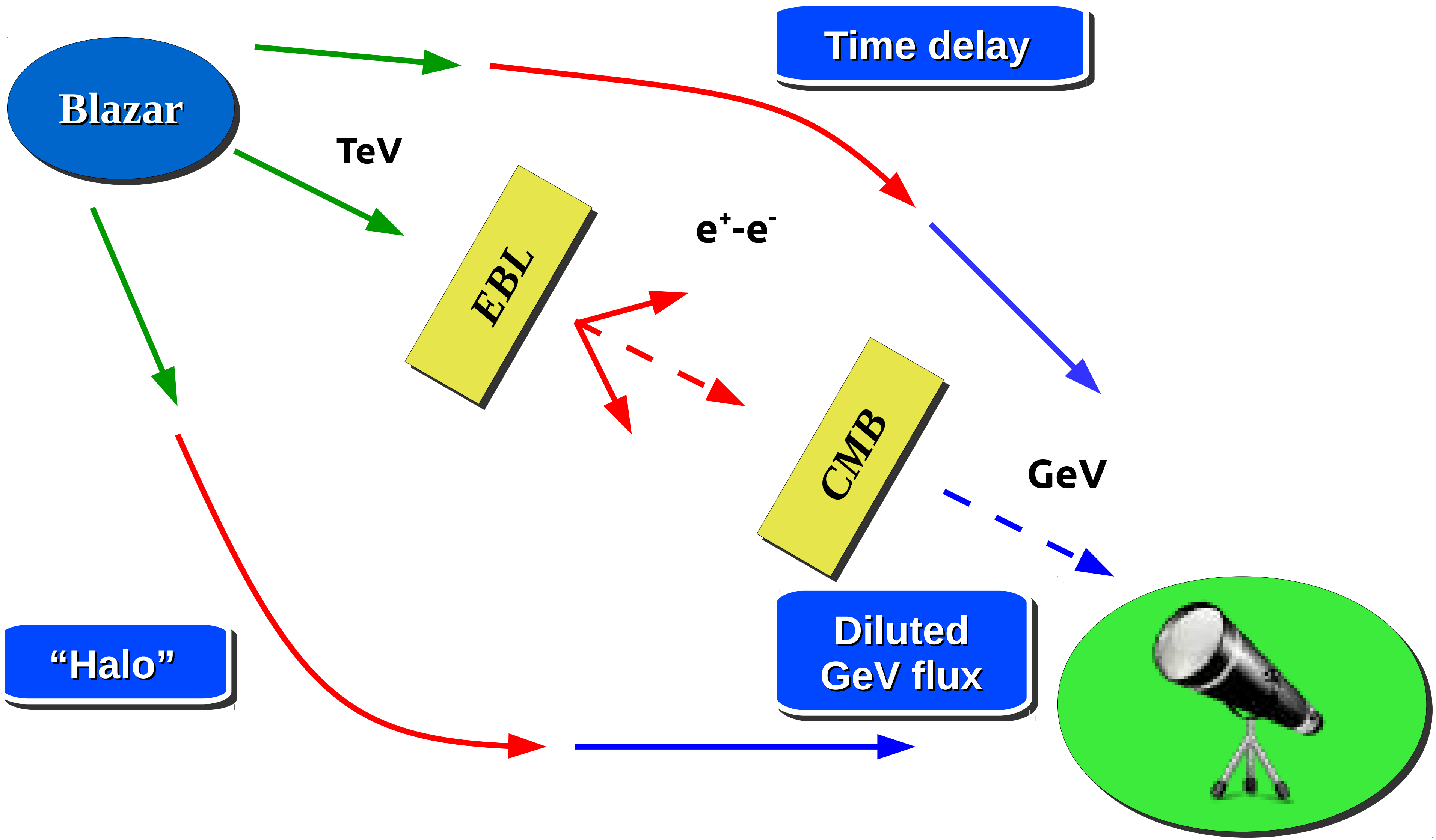
- Vorticity in protogalaxies during the radiation-dominated era can produce fields as strong as 10^{-19}G.
- Biermann battery effect operating in protogalaxies can also lead to the production of $\sim 10^{-17}$ G field on large (megaparsec) scales.
- Stellar evolution (with account for the Biermann battery effect) can also produce a B-field inside the young galaxy.
- AGN are also promising sites for the magnetic field to be born and amplified.

(L. M. Widrow, Rev. Mod. Phys. 74, 775 (2002))

- Cosmic-ray-driven currents in young galaxies can also be responsible for the creation of the magnetic fields.

(Miniati F. and Bell A., ApJ, v. 729, I. 1, id. 73 (2011))

Secondary ɣ-ray emission from the electromagnetic cascade



IGMF-induced suppression of the GeV flux

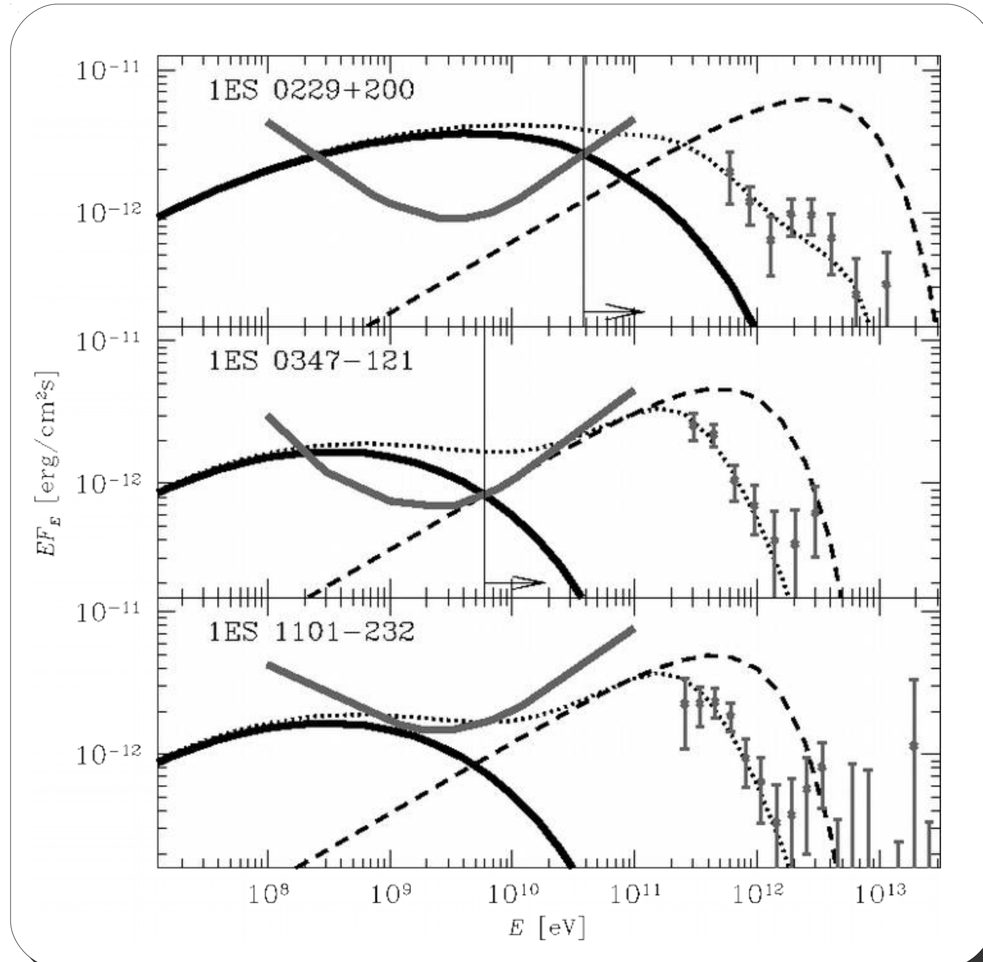
IGMF induces the presence of the extended “halo” around distant AGNs of the size (Neronov & Semikoz '09):

$$\Theta_{\rm ext} \simeq \begin{cases} 0.5^\circ (1+z)^{-2} \left[\frac{\tau_\theta}{10}\right]^{-1} \left[\frac{E_\gamma}{0.1\ {\rm TeV}}\right]^{-1} \left[\frac{B_0}{10^{-14}\ {\rm G}}\right], & \lambda'_B \gg D_e \\ 0.07^\circ (1+z)^{-1/2} \left[\frac{\tau_\theta}{10}\right]^{-1} \left[\frac{E_\gamma}{0.1\ {\rm TeV}}\right]^{-3/4} \left[\frac{B_0}{10^{-14}\ {\rm G}}\right] \left[\frac{\lambda_{B0}}{1\ {\rm kpc}}\right]^{1/2}, & \lambda'_B \ll D_e \end{cases}$$

with $\tau_\gamma = D_\theta / D_\gamma$.

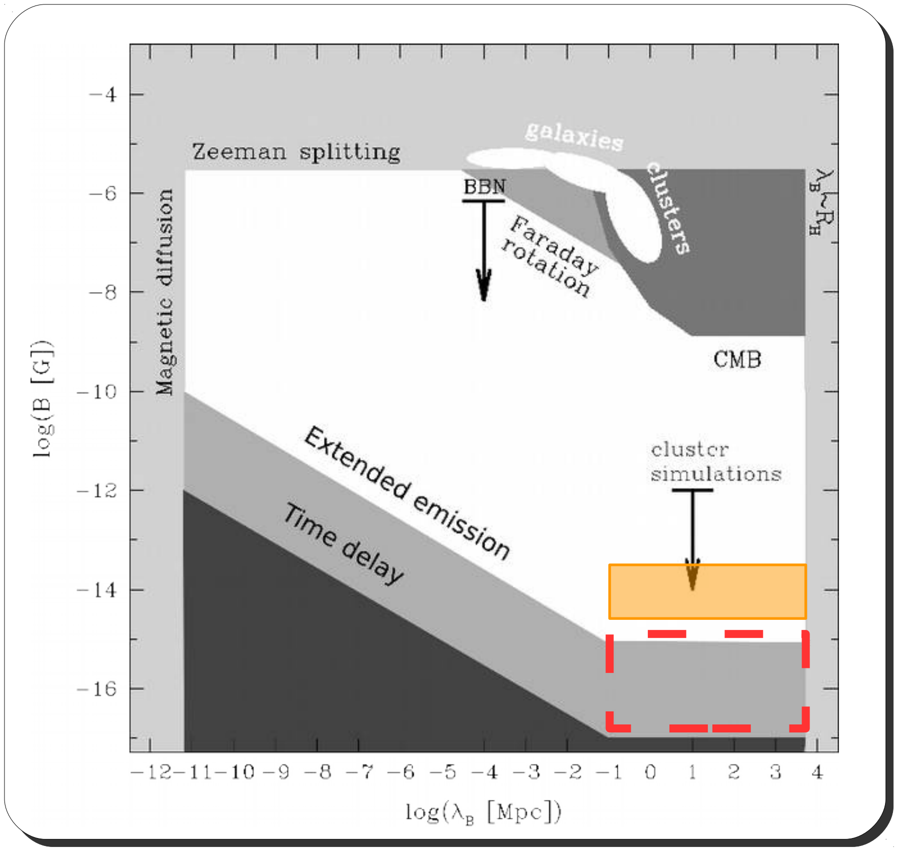
These “halo” remove the flux from the point source AGN in the IGMF-depent way. Observations of the resulting suppression lead to the lower limit of > 3×10^{-16} G (Neronov & Vovk '10, Tavecchio+ '10,11).

This observations also indicate that the IGMF volume filling factor is > 60% (Dolag+ '11).



Neronov & Vovk '10

Direct searches for the extended emission



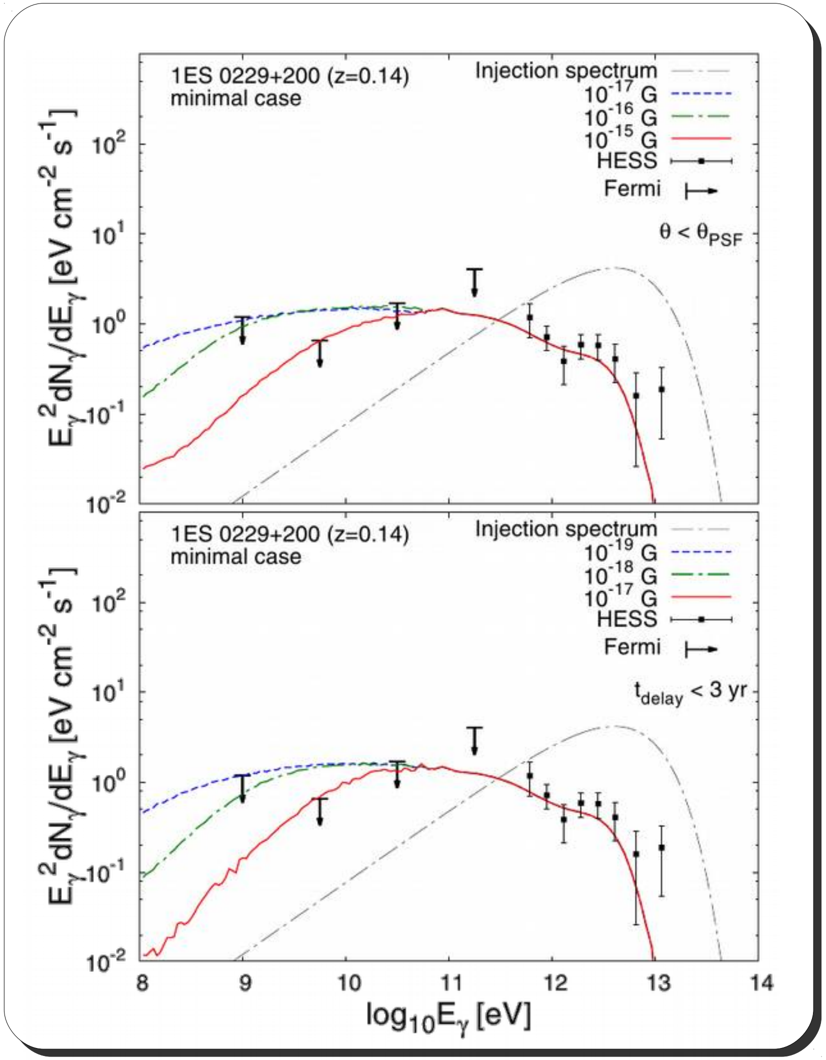
Detection of the extended emission around distant AGN would imply a measurement, rather than limit, of the IGMF.

GeV band (Fermi/LAT)
Ando & Kusenko '10 have claimed the detection in stucking analysis of AGNs, were later disproved by Neronov+ '11, Ackermann+ '13.
Recently Chen+ '14 announced more advanced analysis, claiming a detection of ~1-degree halo.

TeV band (Cherenkov telescopes)
Several attempts were performed (Aharonian+ '01, Aleksic+ '10, Abramowski+ '14), excluding the IGMF range $3\times10^{-15} < B < 3\times10^{-14}$ G.

One should note, that though halo searches are insensitive to the time delay (the halo size does not depend on it), they are very much sensitive to the amount of the absorbed power, which is not always firmly known.

Flux suppression due to the IGMF-induced time delay



Taylor+ '11

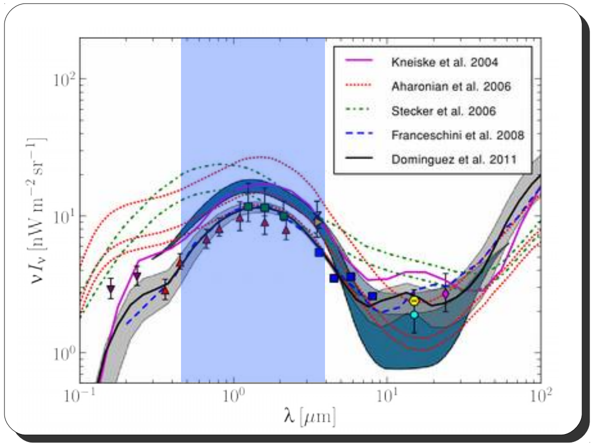
Deflection of electrons by the IGMF leads to longer travel paths, so the secondary emission becomes delayed in time.

The observed absence of the reprocessed emission can be explained in this way, relaxing the lower limit on the IGMF down to $B > 10^{-17}$ G (Dermer+ '11, Taylor+ '11).

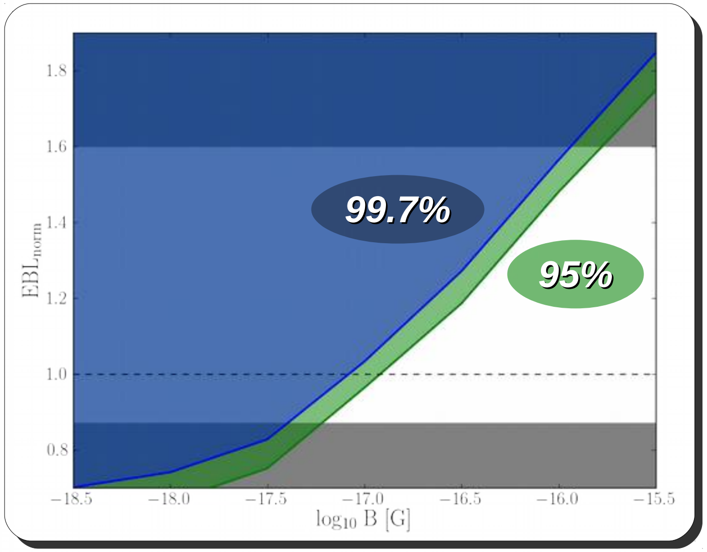
These results are mainly based on observations of 1ES 0229+200, which was assumed to be non-variable in the TeV band (Dermer+ '11). Recent VERITAS observations (Aliu+ '14) suggest that certain variability takes place, suggesting that the limit is a bit lower — $B > 3 \times 10^{-18}$ G.

Further observations are needed to clarify this question.

Combined EBL-IGMF constraint



Orr+ '11



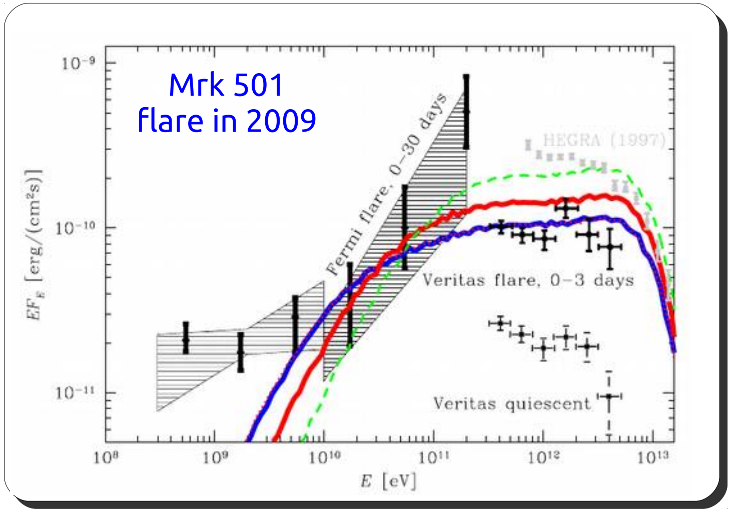
Vovk+ '12

Limits on the IGMF rely on the estimates of the expected reprocessed emission. These estimates rely on the assumed EBL density.

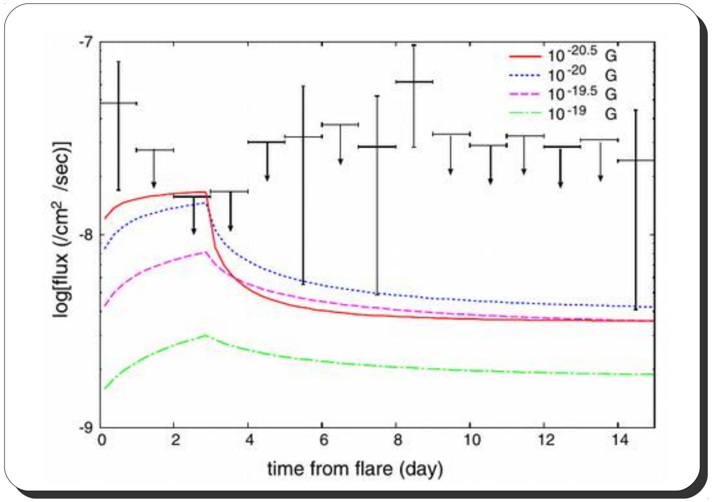
The uncertainty in the EBL density influences the IGMF limits. And other way arround — the estimates of the EBL from the γ-ray data depend on the assumed IGMF.

Vovk+ '12 demonstrated, that the existing uncertainty in the EBL level can push the IGMF limits down to 10^{-18} G.

Catching the time-delayed emission



Neronov+ '12



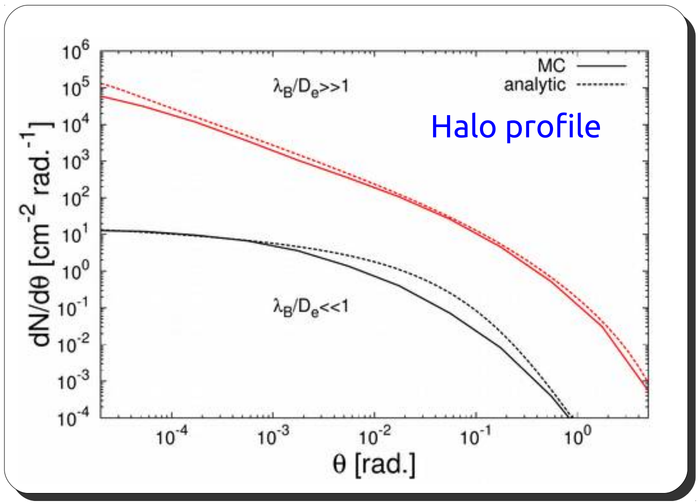
Takahashi+ '12

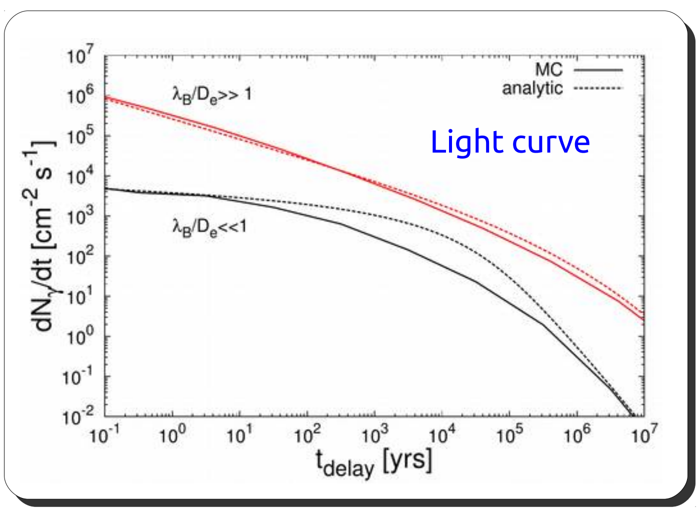
Bright TeV flares give a chance to measure the IGMF through the time-delayed cascade emission. In principle, this approach can allow to detect IGMF as weak as 10^{-20} G.

The investigation of the unusually hard spectrum of the Mrk 501 flare in 2009 suggested the presence of IGMF close to the lower limits (10^{-17} G; Neronov+ '12).

The searches of the corresponding low energy time-delayed flare “echo” did not reveal it, presumably due to the high-level of the stady-state emission of Mrk 501 and insufficient brightness of the flare.

Correlation length of IGMF





Neronov+ '13

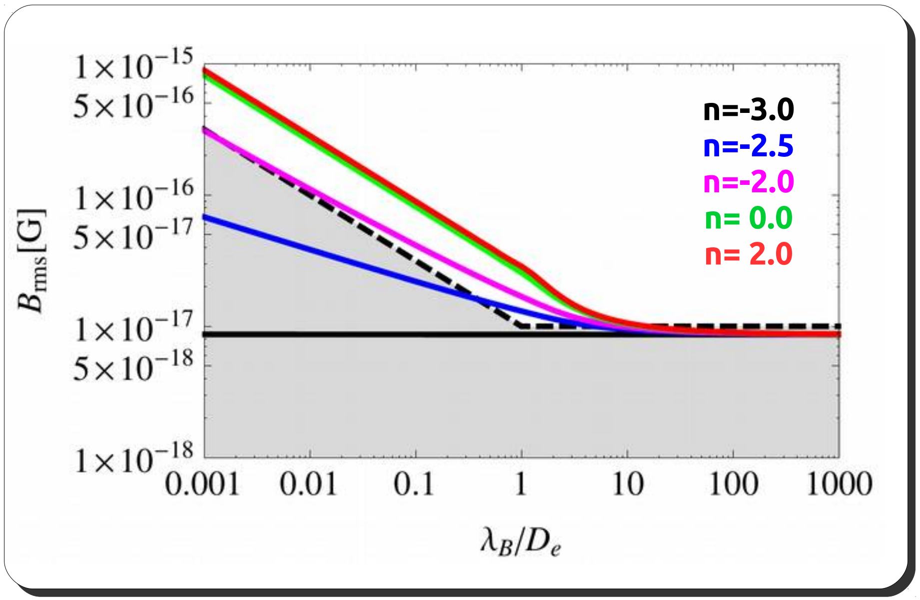
Correlation length is another key parameter of the IGMF, though more difficult to infer than its strength.

Correlation length of IGMF defines the deflection mode of particles (simple or diffusion in angle) and, thus, affects the shape of the produced halo.

The change of the deflection mode $\lambda > D_e$ to $\lambda < D_e$ with the energy would allow to estimate the correlation length.

Similar information can be infered from the light cuves, if the time delayed emission would be clearly identified.

IGMF power spectrum



Deflection angle:

$\delta = D_e / R_L$ $\quad \lambda \gg R_L$ $\quad$ homogeneous field

$\delta = \sqrt{D_e \lambda} / R_L$ $\quad \lambda \ll R_L$ $\quad$ diffusion in angle

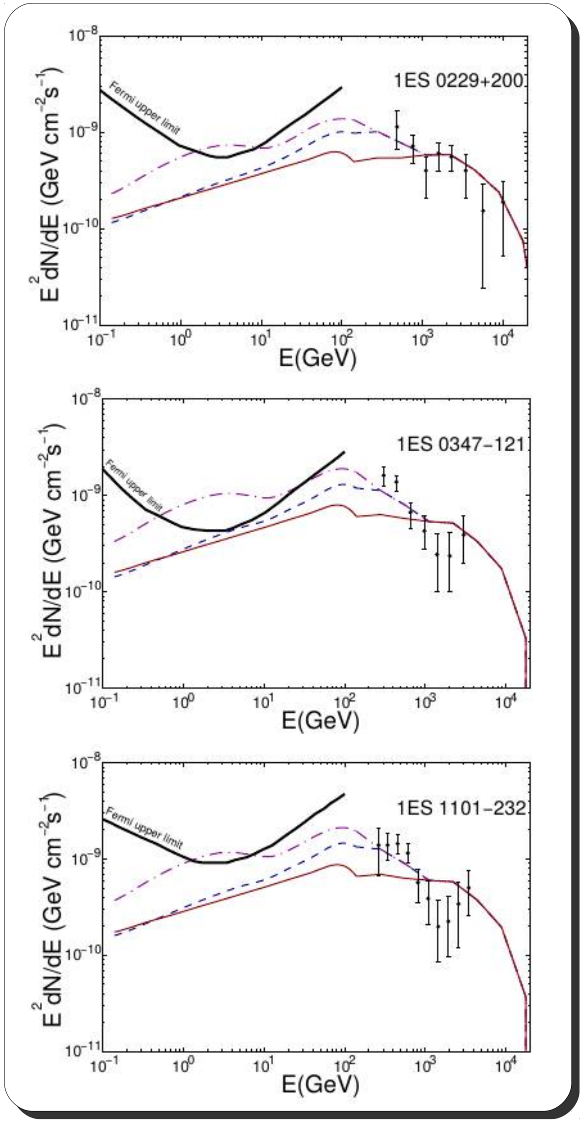
However, the particle does not necessarily make a random walk, if one takes into account the spectrum of the magnetic field

$$P_B(k) \sim k^n$$

This question was addressed by Caprini & Gabici '15, who pointed out that the limit on the IGMF depends on the its assumed spectrum. For n=-3 the constraint at $\lambda << D_e$ becomes as weak as for $\lambda >> D_e$.

This may be important for constraining the IGMF production mechanisms, predicting $\lambda < 0.1$ Mpc.

UHECR-induced cascades and IGMF



Essey+ '11

Despite the fact that the flaring activity of AGNs can be used to detect the IGMF-associated time delay, certain VHE object demonstrate surprisingly low variability.

A possible explanation: their emission mechanisms are different from the other, flaring sources. For instance, the detected TeV emission can be an outcome of the electromagnetic cascade, initiated by the Ultra High Energy Cosmic Rays (UHECRs), produced in these sources (Essey+ '11, Essey & Kusenko '11).

Though the mean free path of UHECRs is different from gamma-rays, the development of the cascade is sensitive to IGMF.
Too strong IGMF would isotropise the cascade and suppress the TeV emission.
Too low IGMF would cause the overprediction of the GeV fluxes.

Under this assumption, the limits become (Essey+ '11):

$$10^{-17}\ \mathrm{G} < B < 10^{-14}\ \mathrm{G}$$

Plasma instabilities and the secondary cascade development

The discussed IGMF constraints stem from the non-detection of the expected secondary IC emission from the electromagnetic cascades.
An alternative possibility to explain these observations is to assume that the cascade power is dissipated differently then via IC emission in gamma rays.

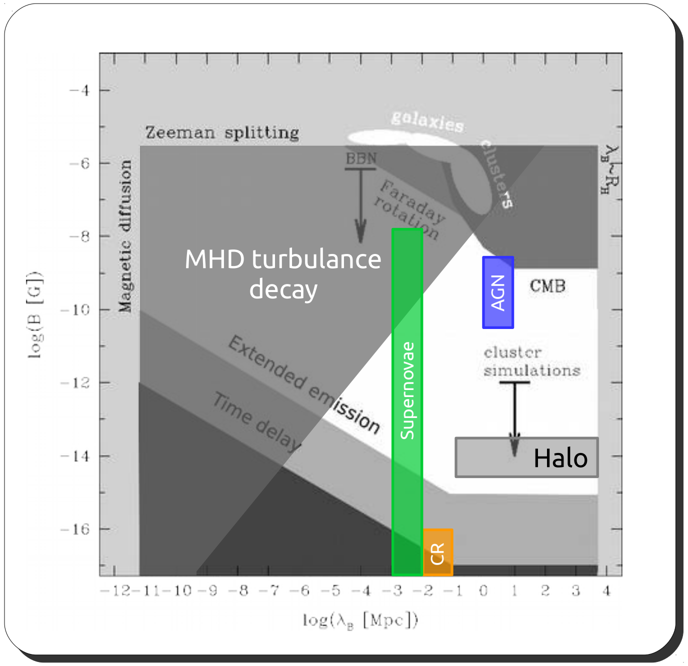
Chang+ '12 and Broderick+ '12 suggested that this power can be dissipated via the plasma instabilities during the cascade development, leading to a strong suppression of the gamma-ray emission.

Miniati & Elyiv '12 considered the back reaction of the beam perturbations on the instability growth rate and concluded that the non-linear Landau damping and large-scale plasma inhomogenioutities should stop the development of the instabilities.

Schlickeiser+ '12 also considered the non-linear case with the back reaction and concluded that for certain beam densities (similar to those expected for the "IGMF" blazars) half of the initial power is transferred to the turbulance.

Overall, the role of the instabilities in the cascade development is not completely clear. Further investiagations are clearly needed.

General picture and opened questions



Miniati & Bell '11
Furlanetto & Loeb '01
Bertone+ '06

IGMF can be produced by various mechanisms and gamma-ray measurements start to constrain some of them. This gives opens interesting possibilities for the studies of the history of the Universe.

Opened theoretical questions:
Gamma-ray or CR cascades?
Importance of the instabilities?

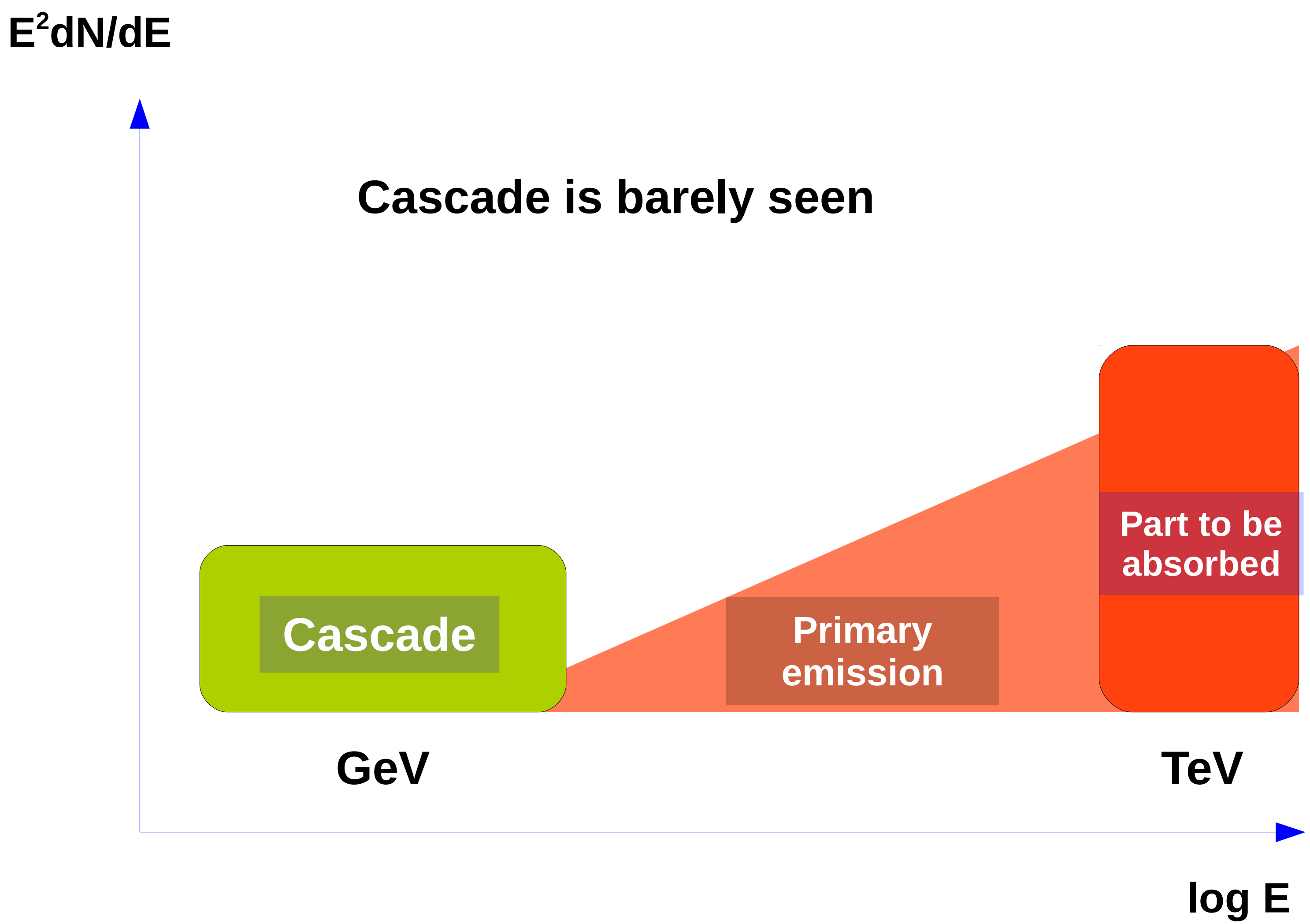
Observational issues:
For weak IGMF (< 10^{-16} G) a characteristic time delay can be deteceted. For stronger IGMF we should rather look for halos. Both are not detected so far.

Coherence length of IGMF?

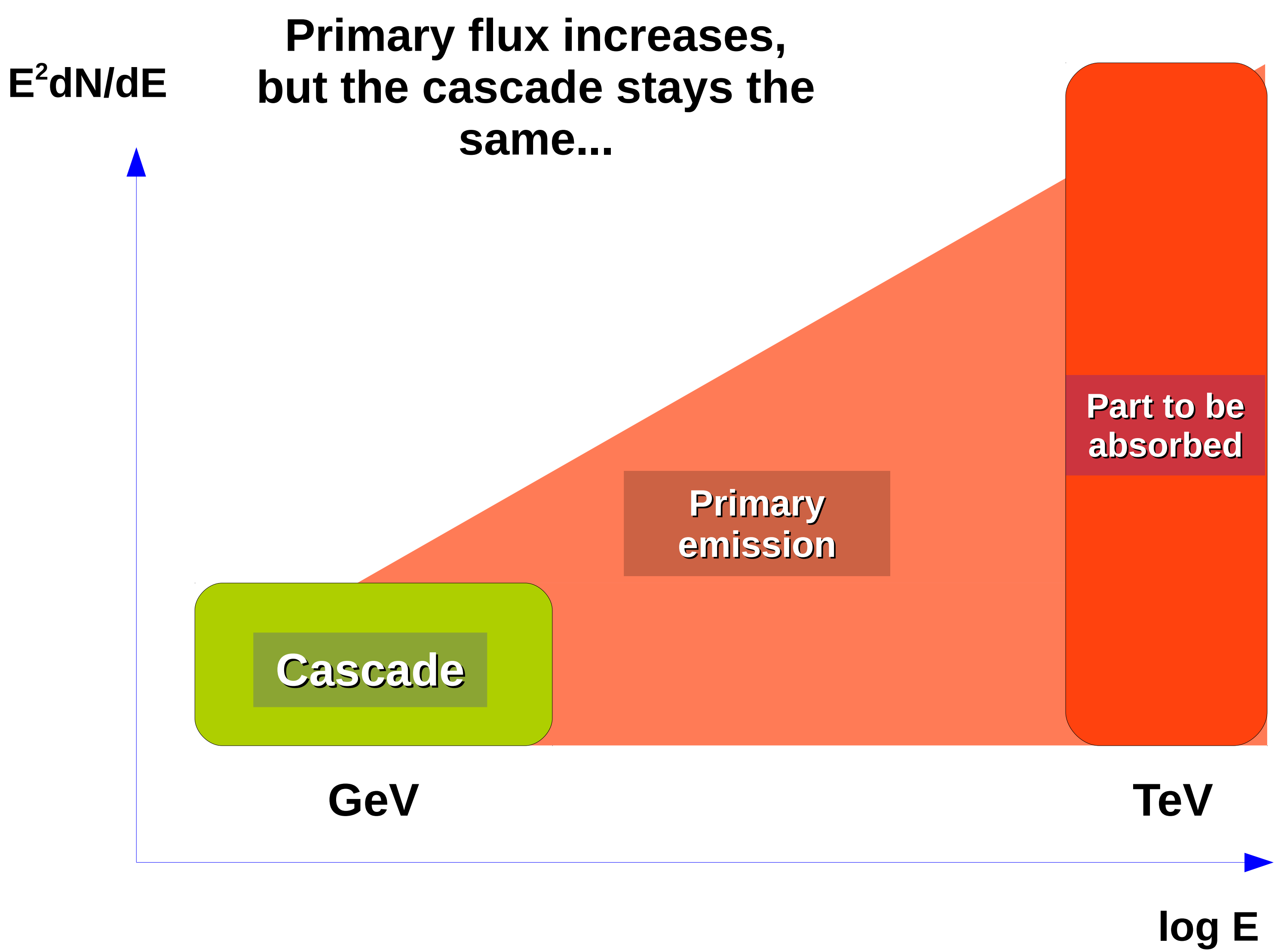
IGMF at larger reshifts (z~1)?

The TeV duty cycles of the used AGNs are, perhaps, observationally, the most important question.

The effect of time delay

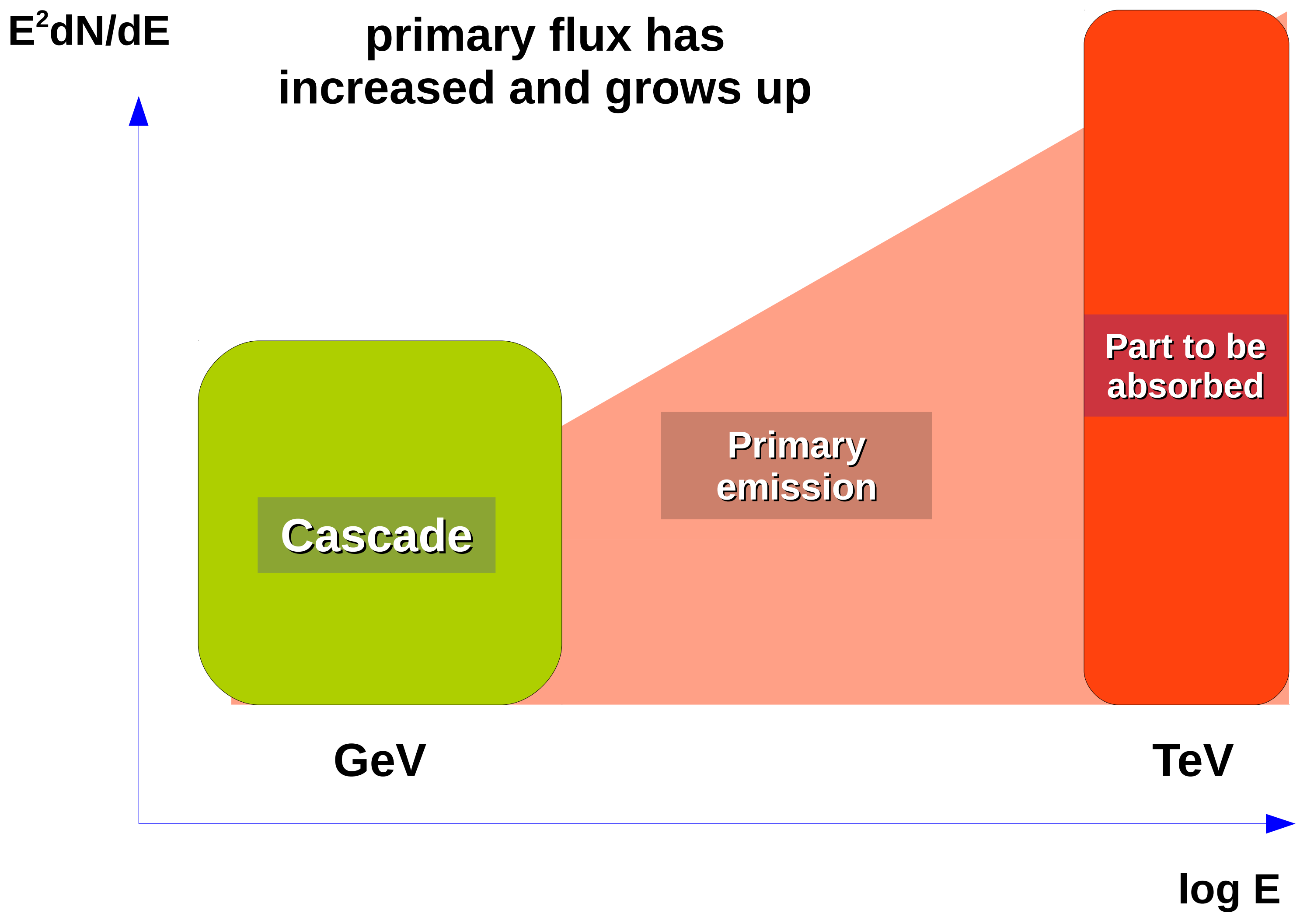


The effect of time delay



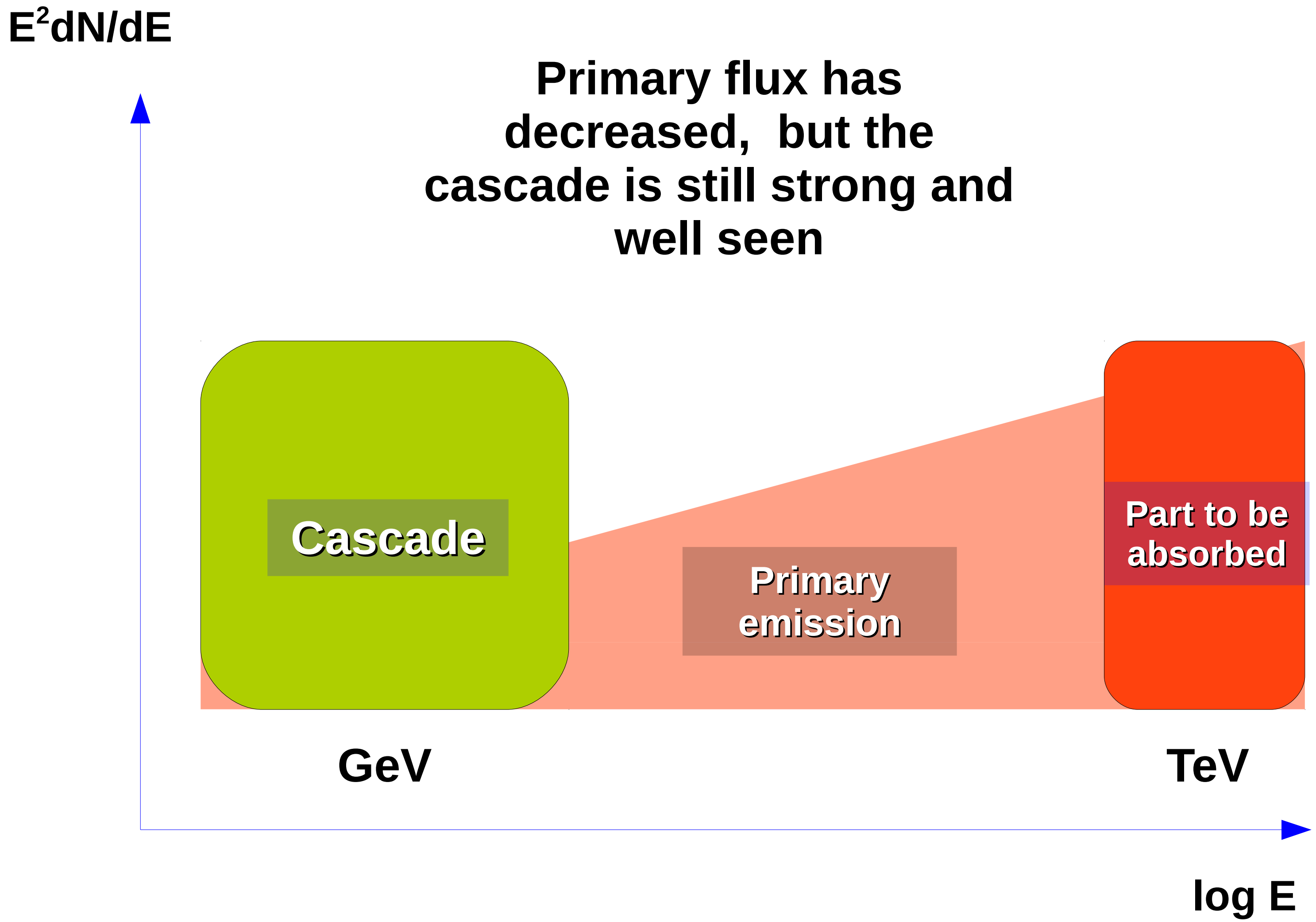
The effect of time delay

Cascade “realizes” that primary flux has increased and grows up



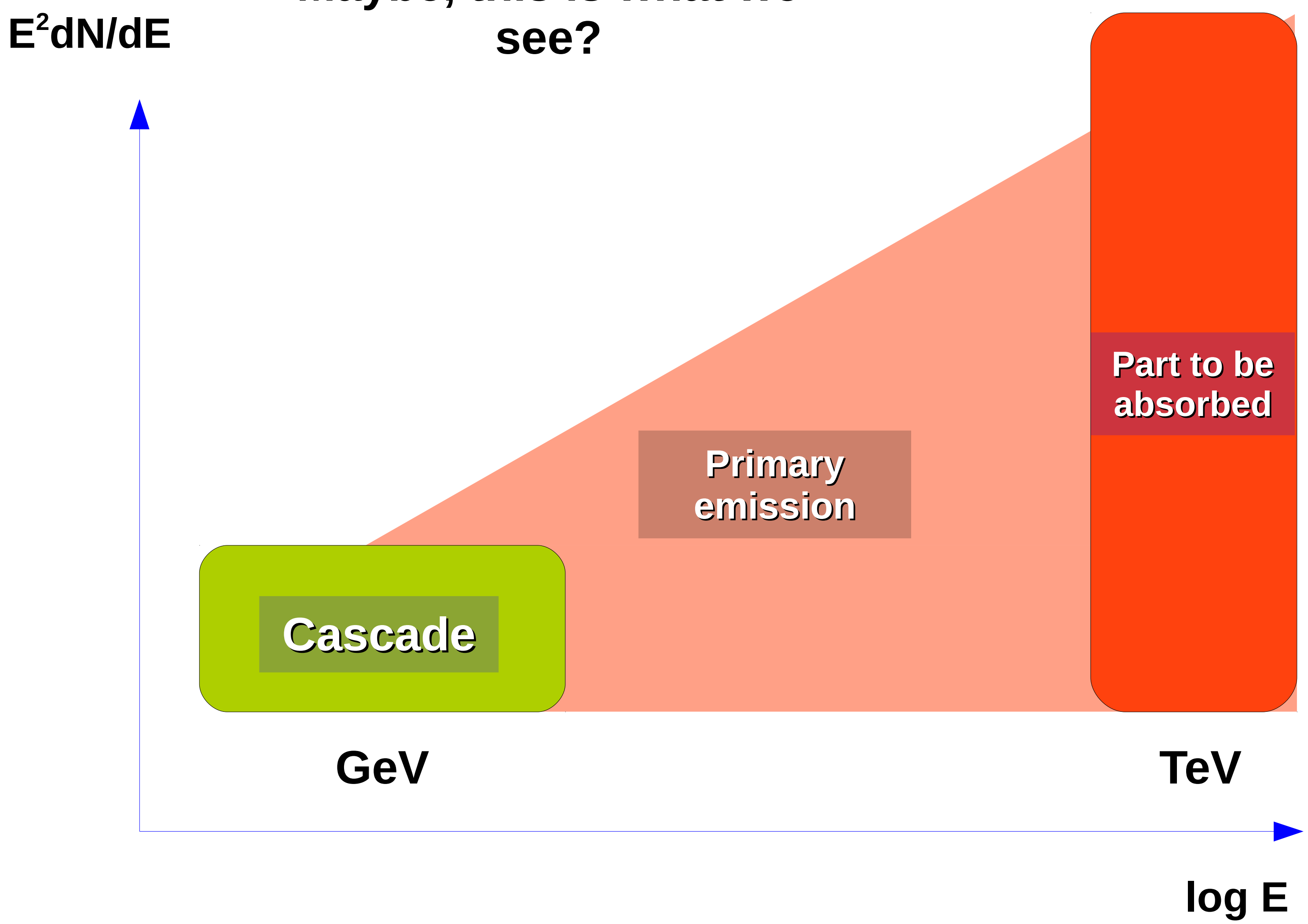
The effect of time delay

Primary flux has decreased, but the cascade is still strong and well seen



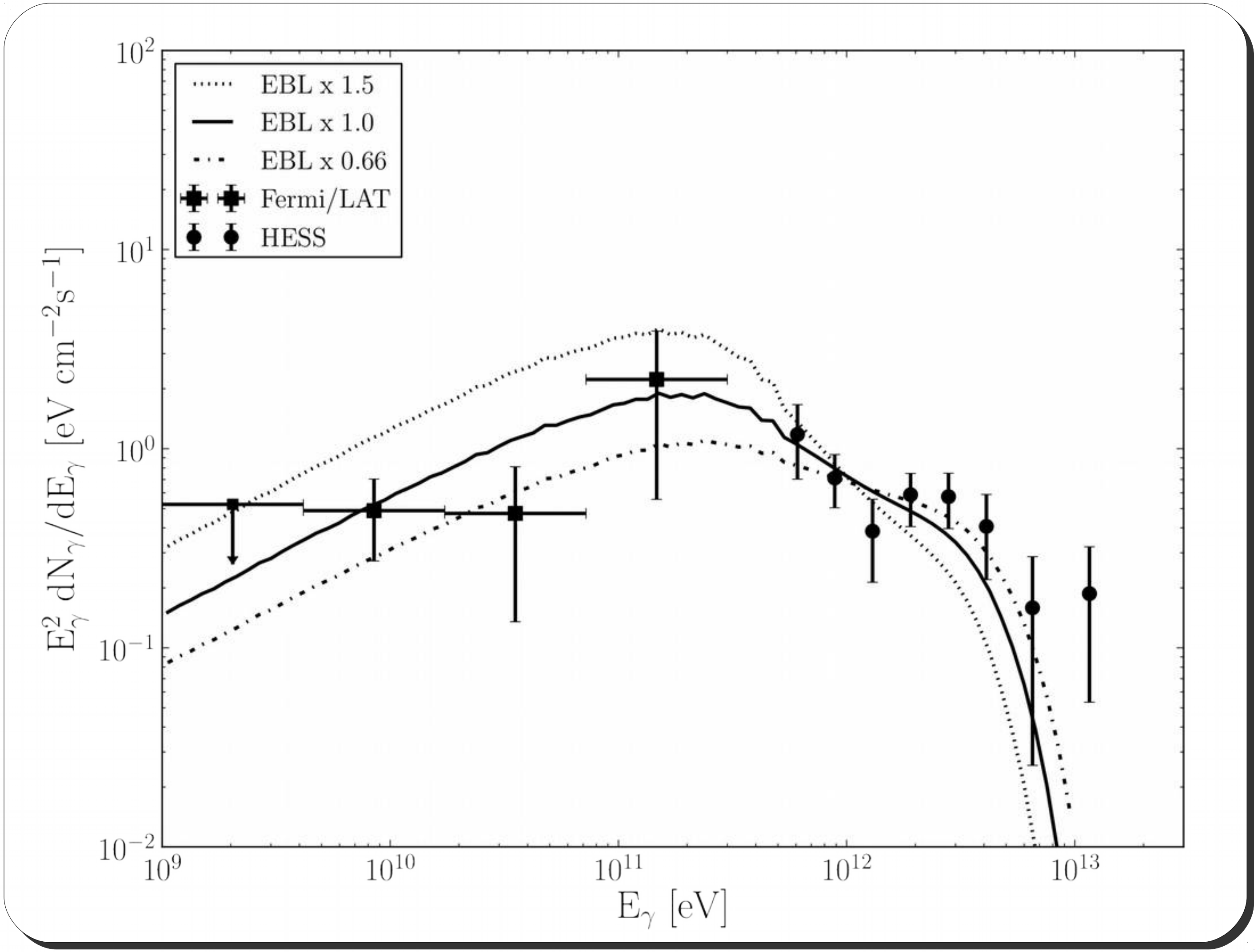
The effect of time delay

Maybe, this is what we see?



Supplementary slides

Effect of the variation of EBL



Vovk+ '12