EM cascade for constraint on IGMF

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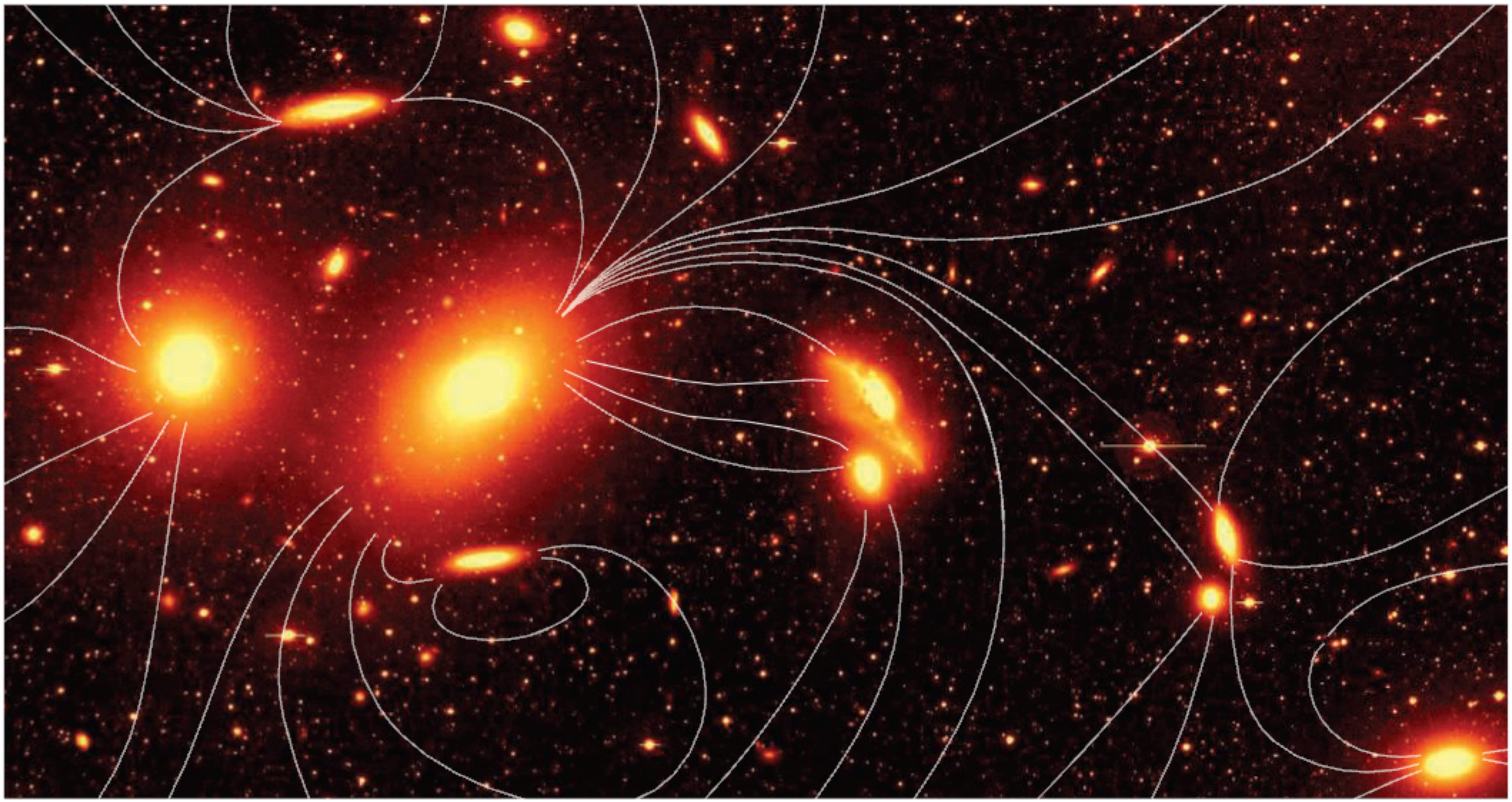
LHAASO collaboration meeting in Kunming

2017/01/19

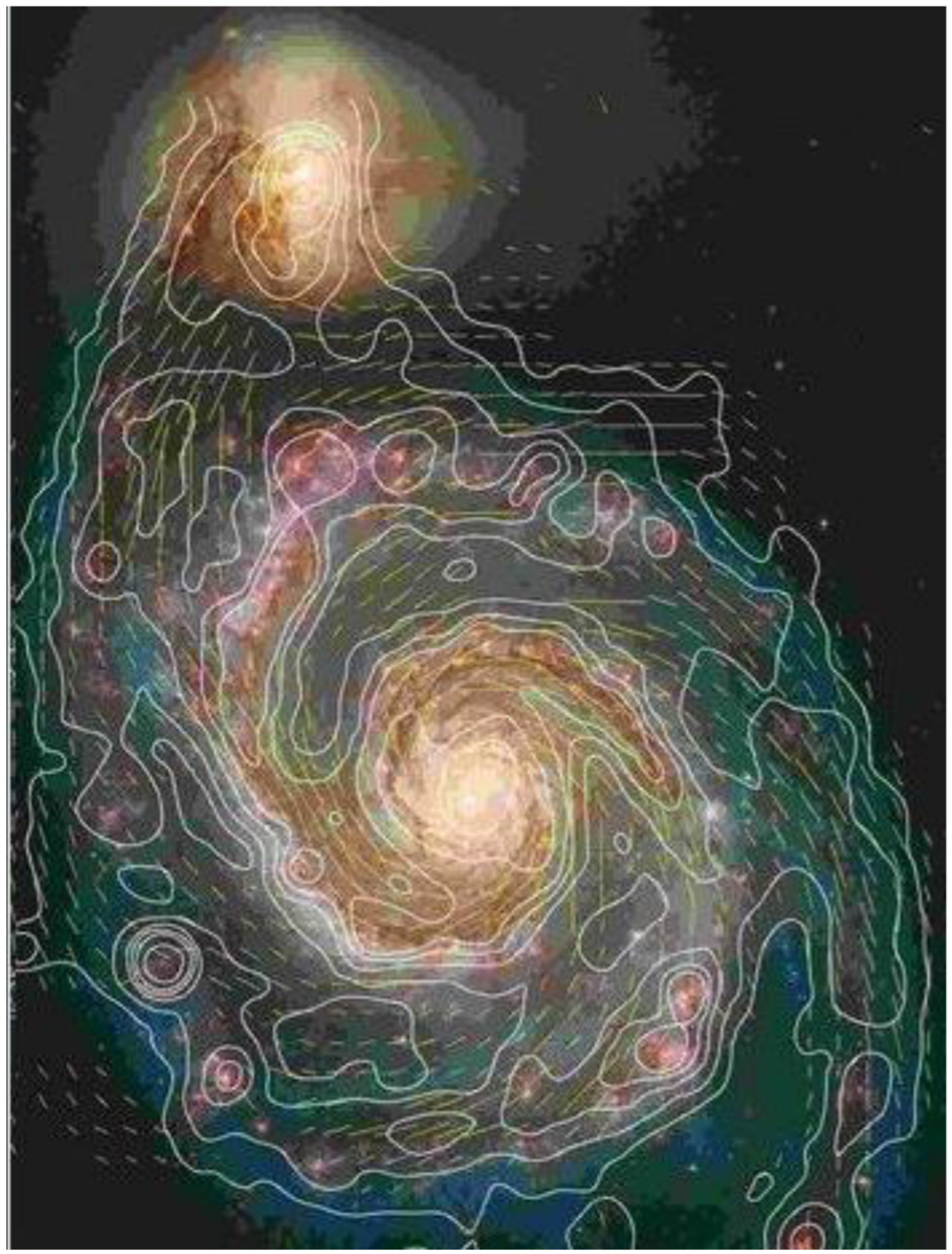
Intergalactic Magnetic Fields



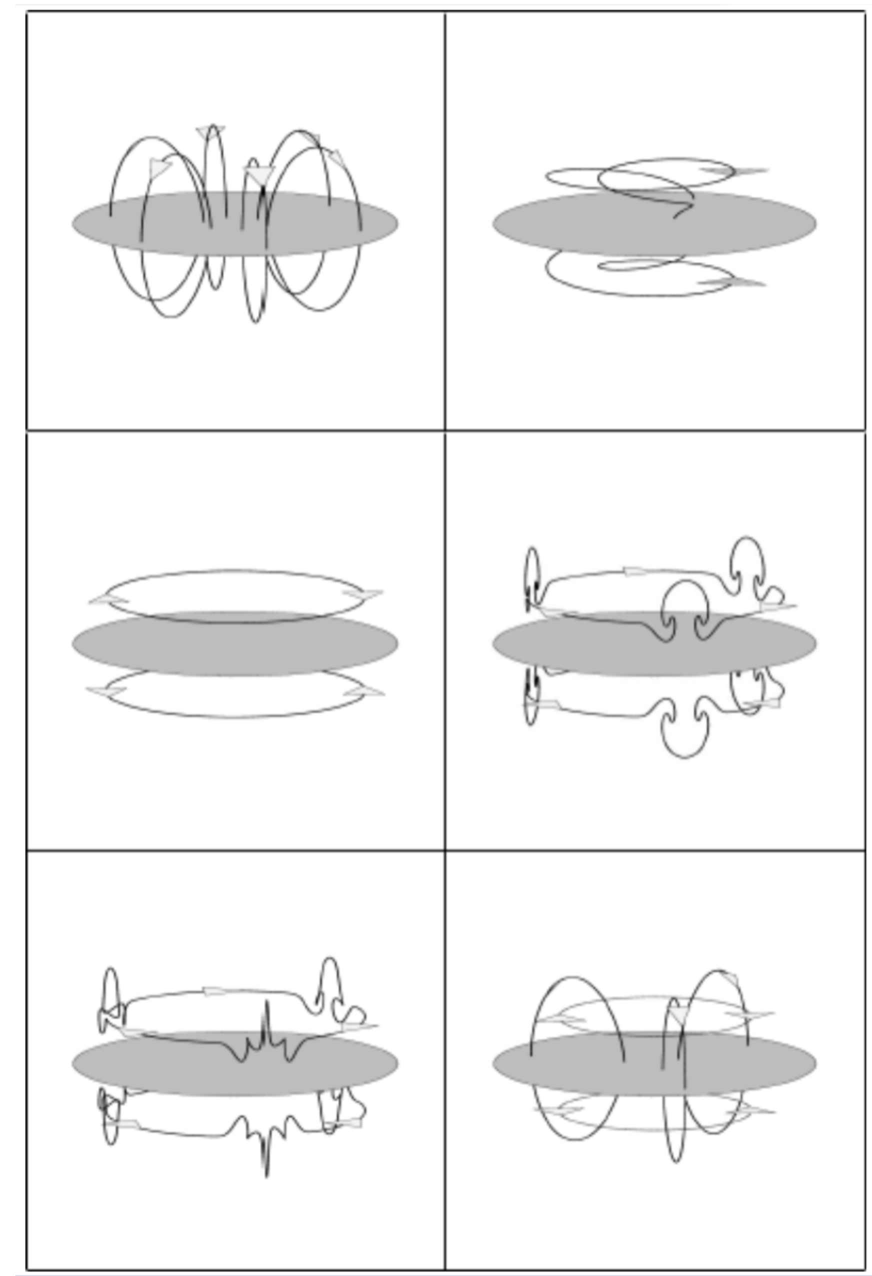
Intergalactic magnetism. The Virgo cluster with one possible configuration of magnetic field lines (artist's impression). [Original Virgo image from (*15*)]

Durrer, 2006, Science

Galactic Magnetic Fields

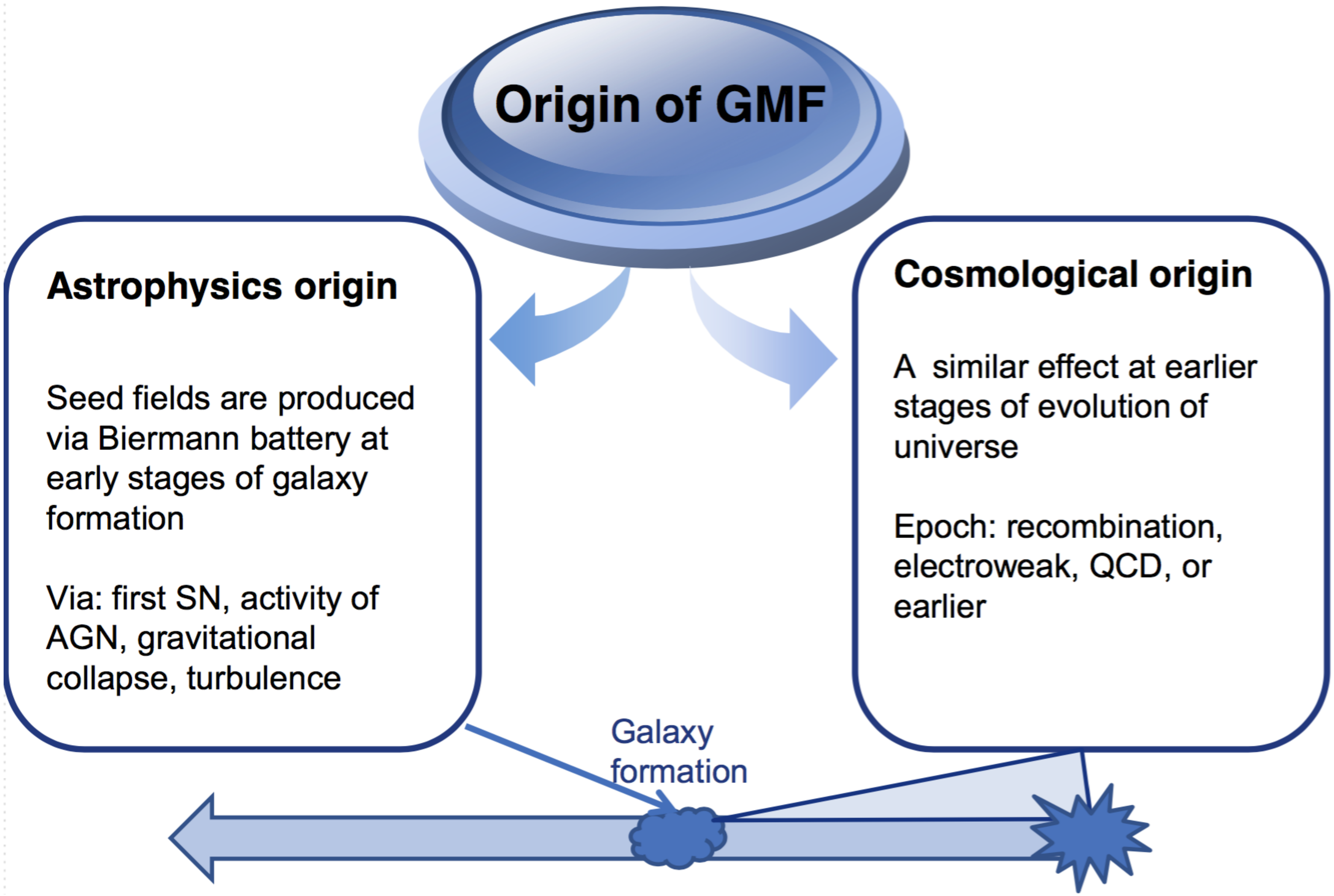


GMF strength: ~10 muG

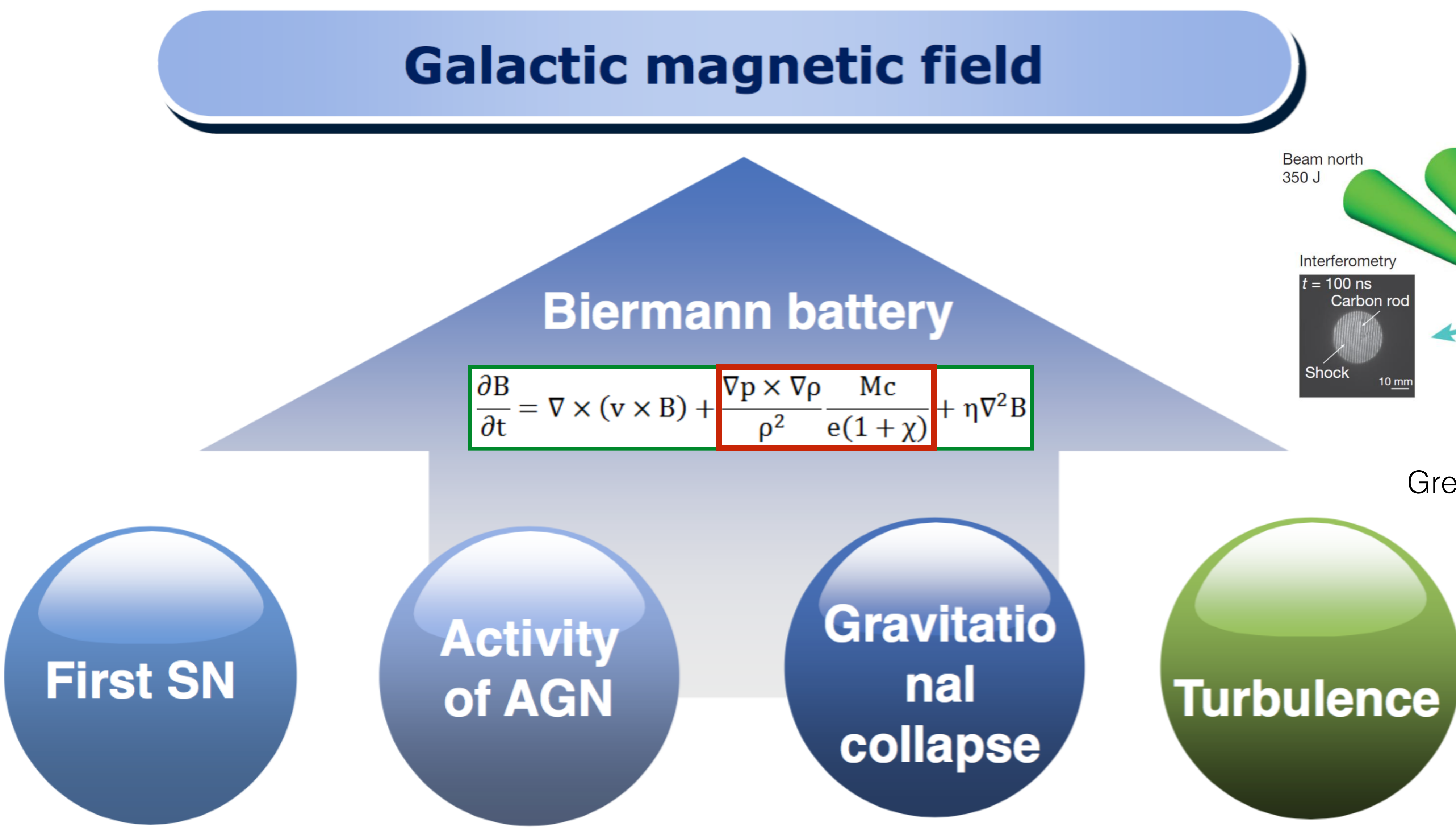


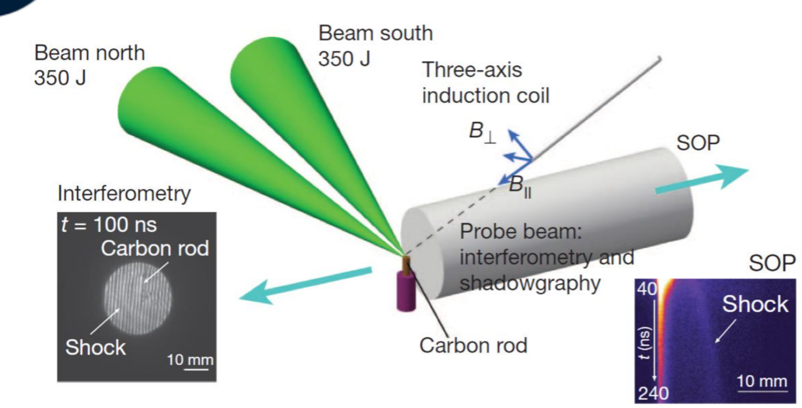
Widrow, 2002, Rev. Mod. Phys.

GMF Origin


Origin of GMF
Astrophysics origin
Seed fields are produced via Biermann battery at early stages of galaxy formation
Via: first SN, activity of AGN, gravitational collapse, turbulence
Cosmological origin
A similar effect at earlier stages of evolution of universe
Epoch: recombination, electroweak, QCD, or earlier
Galaxy formation

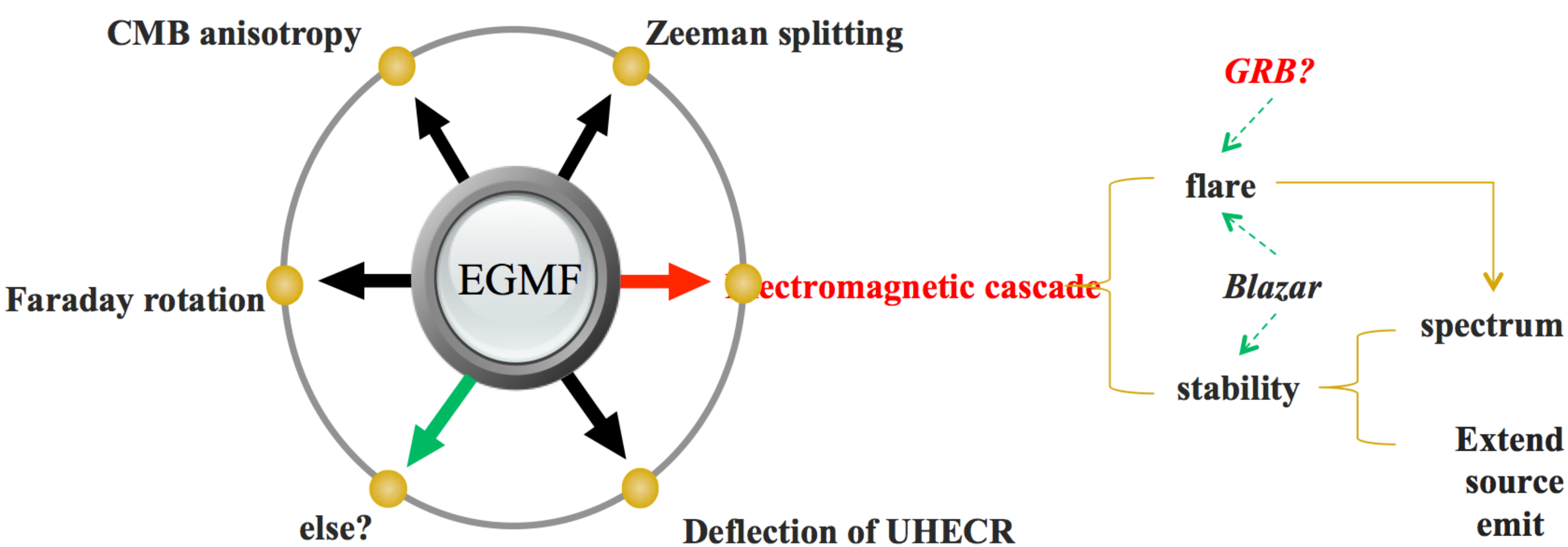
Astrophysical Origin



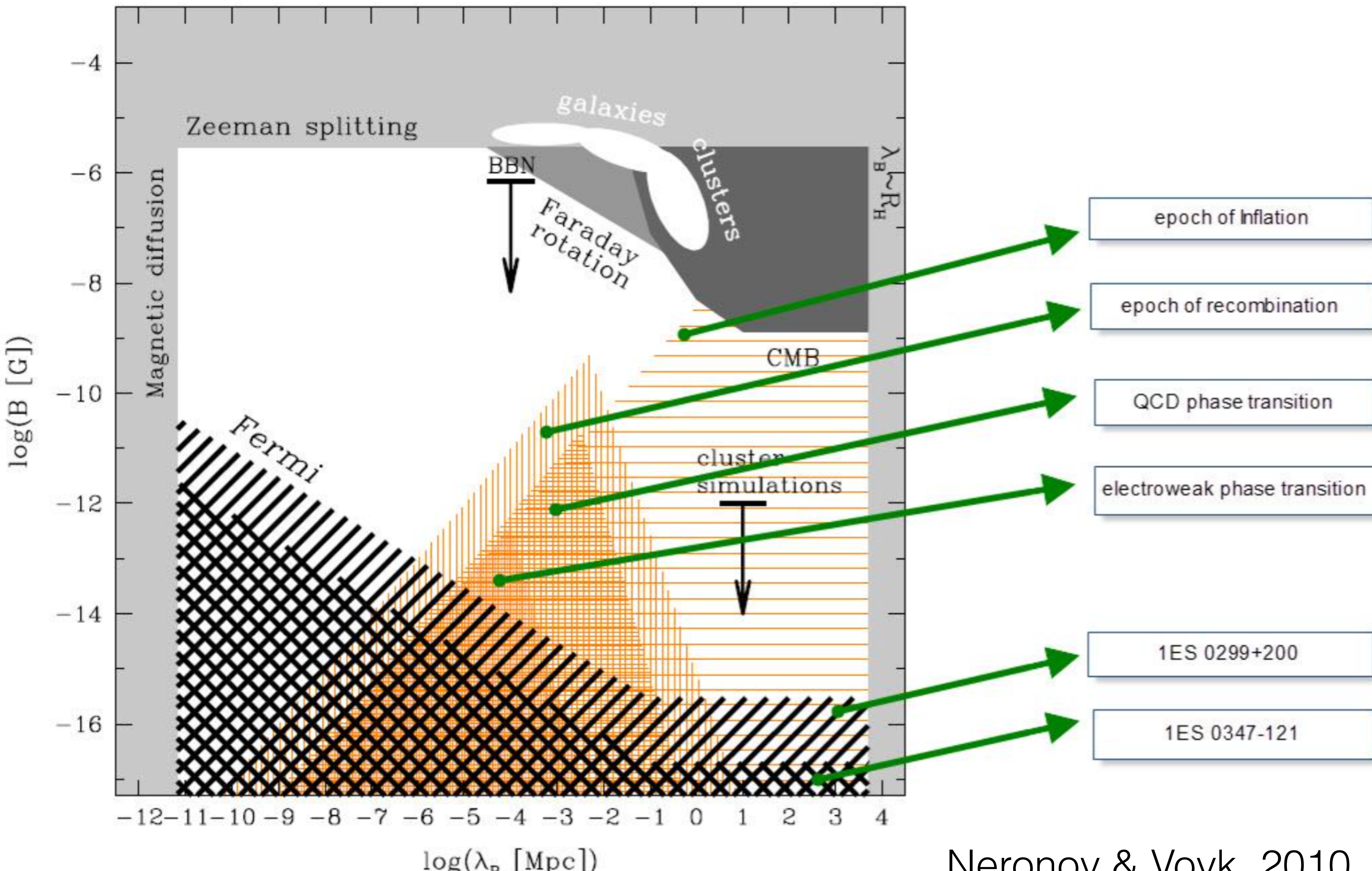


Gregori et al. 2012, Nature

How to Constrain IGMF

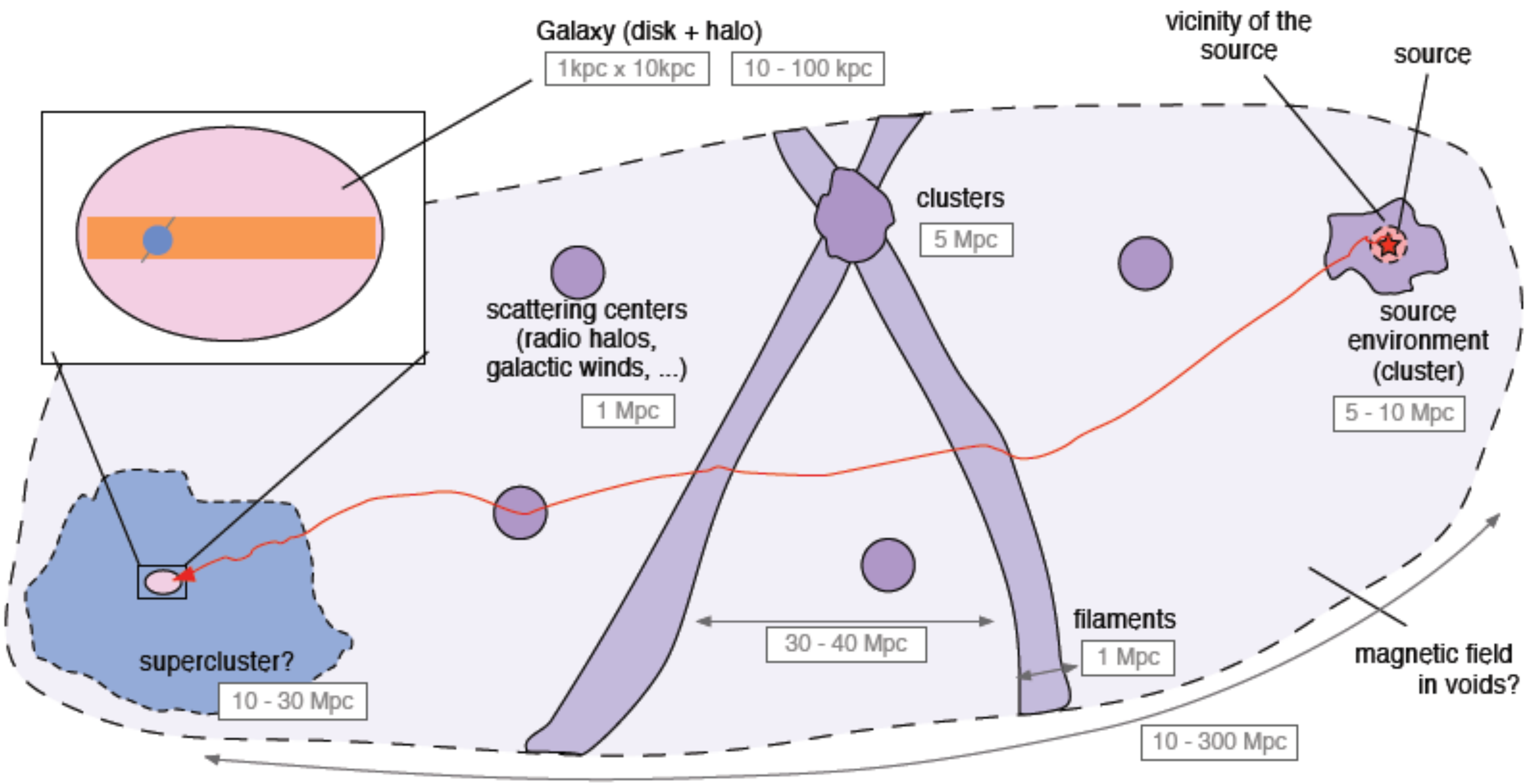


Constraint on IGMF



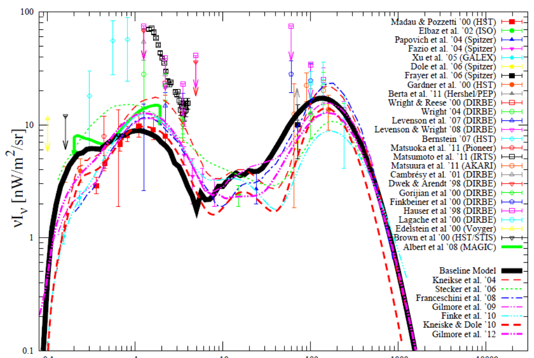
Neronov & Vovk, 2010, Science

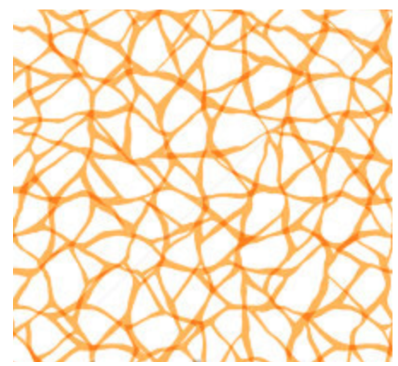
Charged Particles in IGM



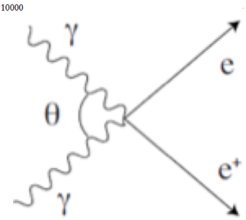
Kotera & Olinto, 2010, ARA&A

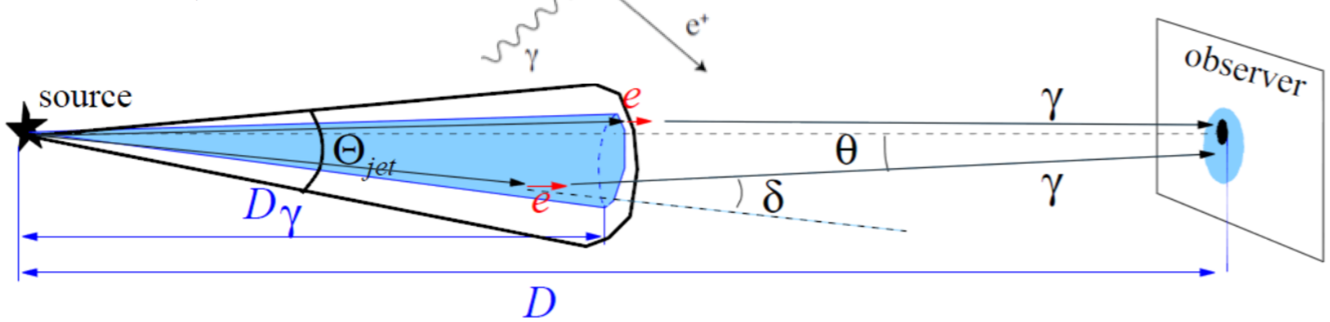
EM Cascade



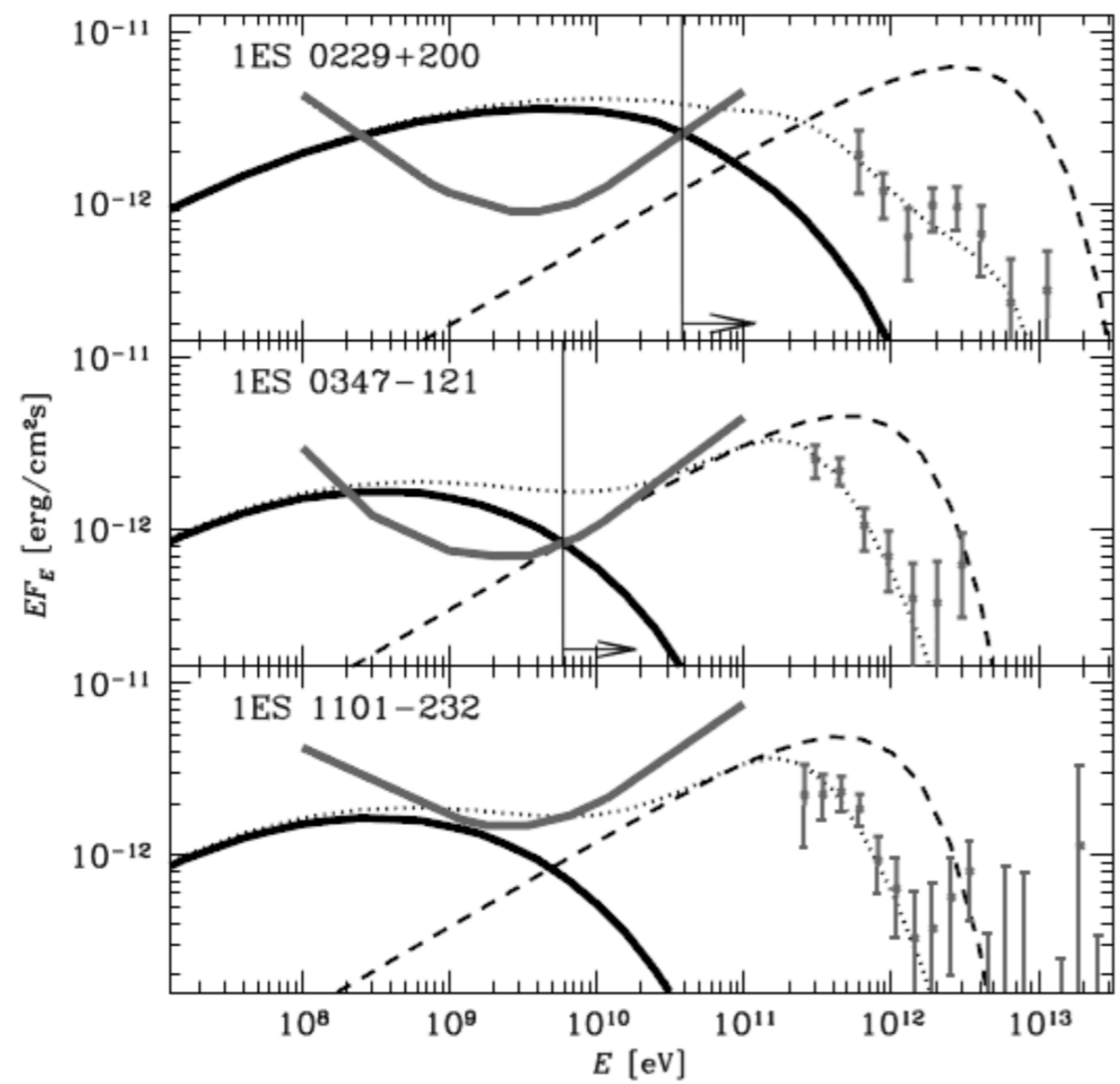


$E'_\gamma \epsilon' \gtrsim 2(m_e c^2)^2$





$$B \geq B_{PSF} \simeq \begin{cases} 6 \times 10^{-17} \tau \left(\frac{E_{\gamma,min}}{10 GeV}\right) G \; (\lambda_B > D_e) \\ 8 \times 10^{-16} \tau \left(\frac{E_{\gamma,min}}{10 GeV}\right)^{\frac{3}{4}} \left(\frac{\lambda_B}{1 kpc}\right)^{-\frac{1}{2}} G \; (\lambda_B < D_e) \end{cases}$$



Neronov & Vovk, 2010, Science

Unified Model

Time delay and extended halo for constraints on the intergalactic magnetic field

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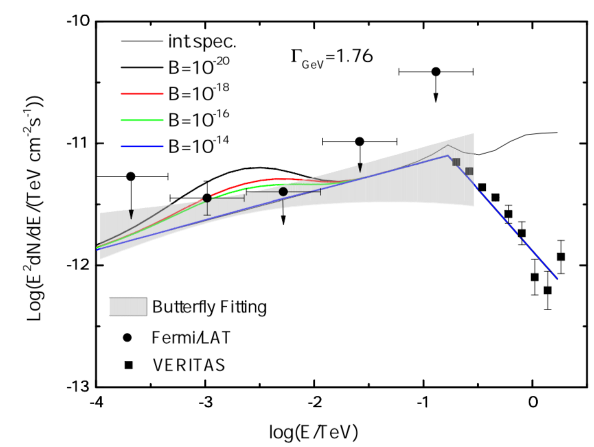
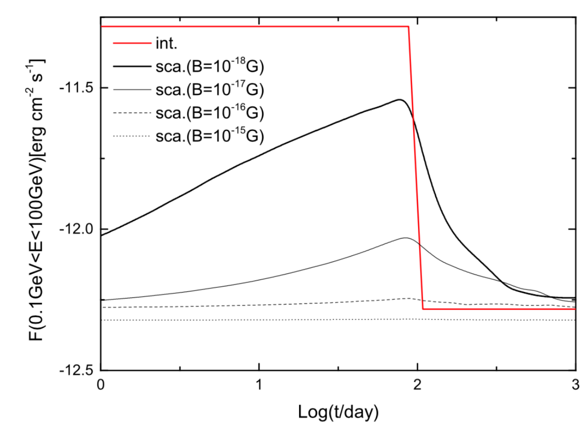
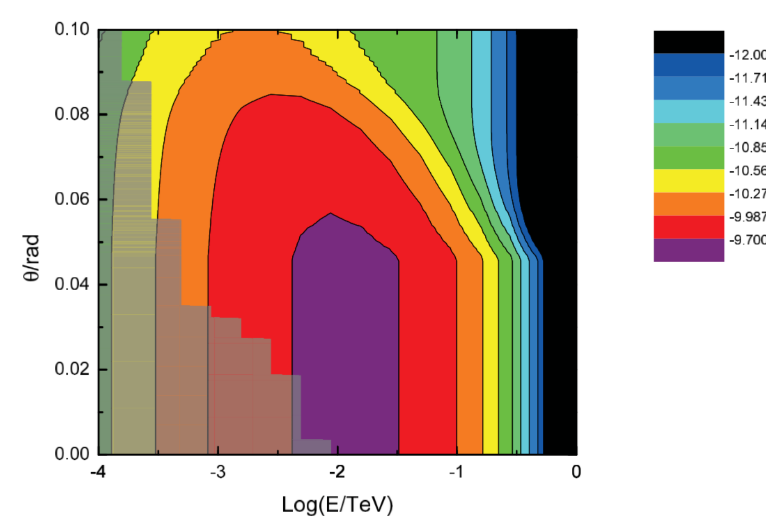
Abstract Primary gamma rays emitted from extragalactic very-high-energy (VHE) sources, such as blazars, will generate cascade radiation in intergalactic space with a scale of $\sim$ 100 Mpc, for $z \sim 0.1$ and $E_\gamma \sim 1$ TeV. These cascades proceed through electron-positron pair production and inverse Compton (IC) scattering in the cosmic background radiation fields, mainly cosmic microwave background (CMB) radiation and extragalactic background light in the voids of the universe. The existence of an intergalactic magnetic field (IGMF) would deflect paths of electron-positron pairs that scatter CMB photons, causing some observable effects, such as time delay, an extended halo, and a spectral change. Here we reanalyze the diffusion of an electron jet deflected by IGMF and propose a unified semi-analytical model. By using publicly available data from the Fermi/LAT detector and contemporaneous TeV observations, we find that the cascade photon flux is not significantly affected by the IGMF strength for non-variable blazars when the IGMF is weaker than $\sim 10^{-16}$ G. This result is clearly different from previous works that analyzed the extended halo and time delay separately for non-variable blazars and flaring blazars. By applying our model to two extreme blazars (1ES 0229+200 and 1ES 1218+304), we obtain the IGMF lower limit of order $\gtrsim 10^{-13} \sim 10^{-14}$ G in the non-variable case, which is a stronger constraint on the IGMF strength than previous works ($\gtrsim 10^{-16} \sim 10^{-18}$ G), and $\gtrsim 10^{-18} \sim 10^{-19}$ G in the case of flaring blazars. Furthermore, we study the light curves and extended halo of the cascade photons by considering the effects of the IGMF.

Key words: gamma rays: general — galaxies: magnetic field — galaxies: individual (1ES 0229+200, 1ES 1218+304)





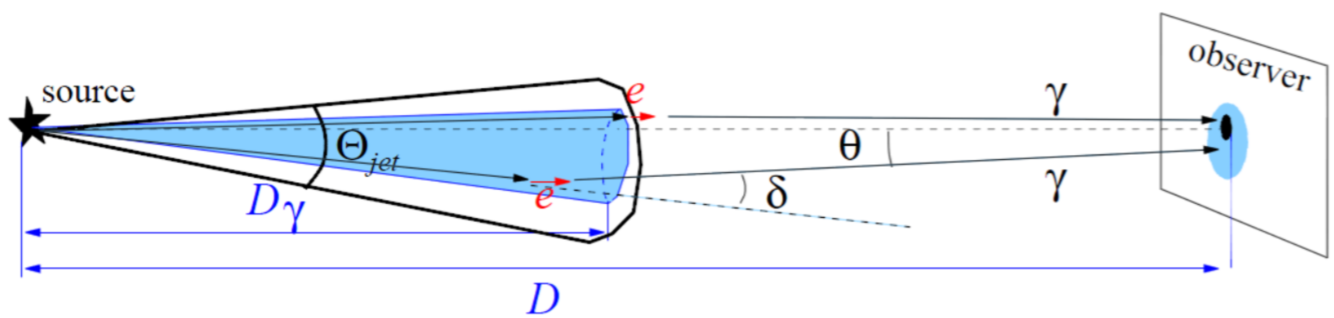


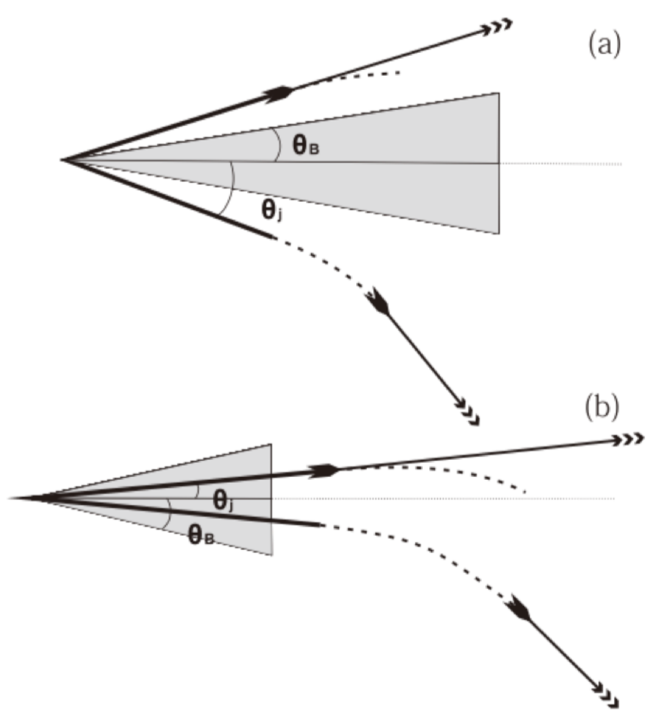
Basic Physical Process

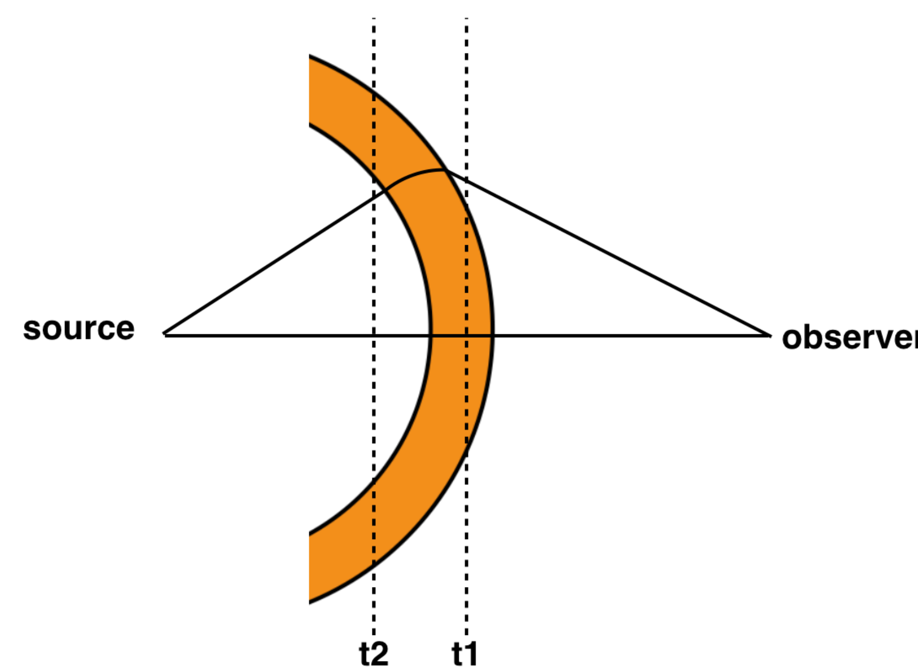
- Pairs have Lorentz factors: $\gamma_{\rm e} = E'_\gamma/2m_{\rm e}c^2 \approx 10^6(1+z)(E_\gamma/{\rm TeV})$
- Cascade photon energy: $\sim \gamma_{\rm e}^2\bar{\epsilon}' \simeq 0.63(E_\gamma/1{\rm TeV})^2\,{\rm GeV}$
- IC cooling timescale: $\Delta t_{\rm IC} \approx (1+z)\dfrac{t_{\rm IC}}{2\gamma_{\rm e}^2} \approx 40{\rm s}(1+z)^{-3}(\gamma_{\rm e}/10^6)^{-1},$
- Deflection delay: $\Delta t_B \approx (1+z)\dfrac{\lambda_{\gamma\gamma}\theta_B^2}{2c}\left(1-\dfrac{\lambda_{\gamma\gamma}}{D}\right) = (1+z)\dfrac{1}{\eta}\dfrac{\lambda_{\gamma\gamma}\theta_{\rm e}^2}{2c},$
- Deflection angle: $\theta_B \approx \begin{cases} \lambda_{\rm IC}/r_{\rm L} & \text{if } \lambda_{\rm IC} < \lambda_{\rm coh}, \\ \sqrt{\lambda_{\rm coh}/\lambda_{\rm IC}}\,\lambda_{\rm IC}/r_{\rm L} & \text{if } \lambda_{\rm IC} > \lambda_{\rm coh}, \end{cases}$

Time-dependent Spectra

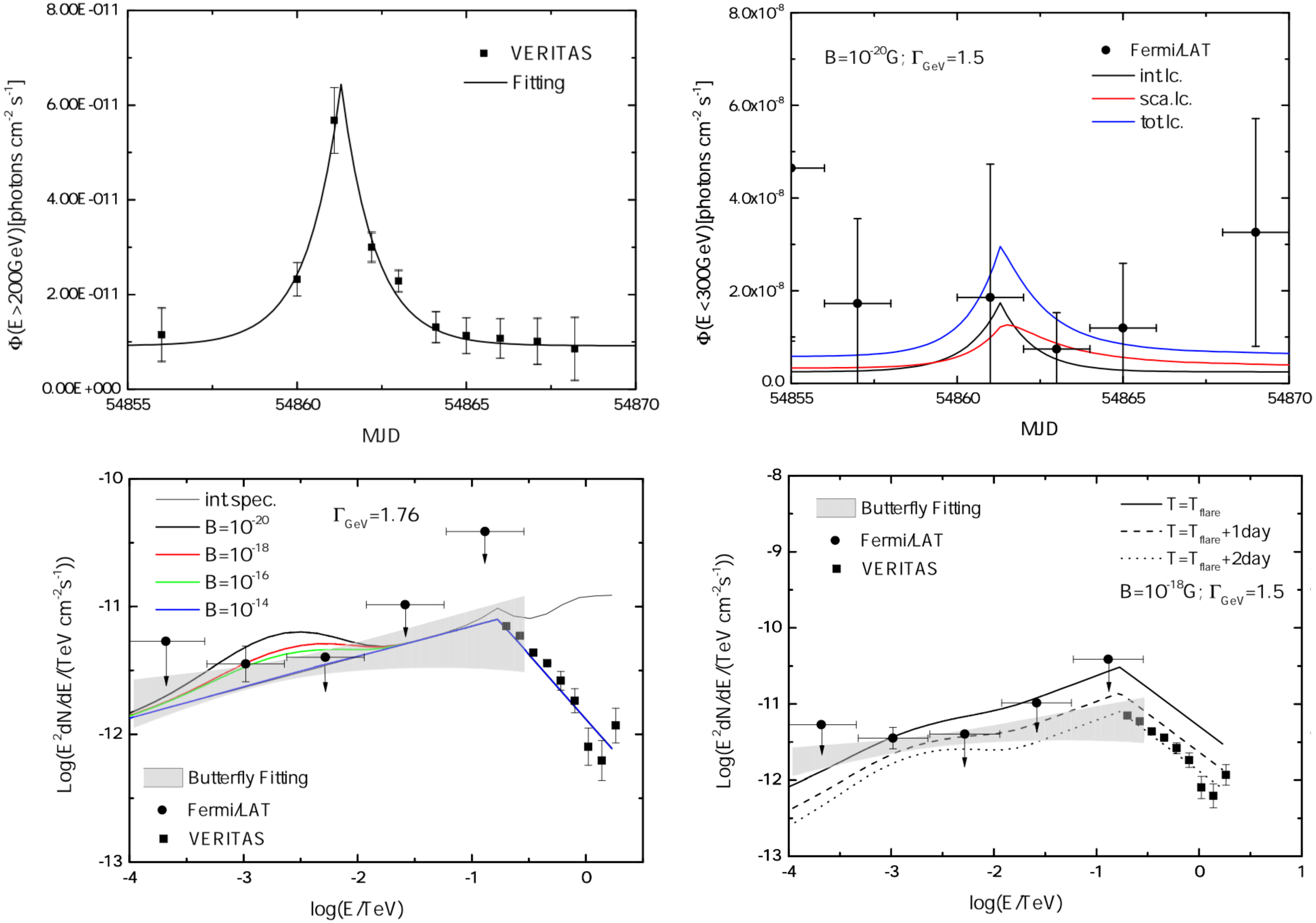
$$\frac{dN_\gamma^{\rm SC}}{dE_\gamma^{\rm sc}}(t) = \int d\gamma_{\rm e} \int_0^{\max(\theta_j,\theta_B)} \left(\frac{dN_{\rm e}}{d\gamma_{\rm e}}(t-\Delta t_B)\right)\left(\frac{dN_{{\rm e},\epsilon}}{dtdE_\gamma^{\rm sc}}\right)\frac{dt}{d\theta}d\theta,$$



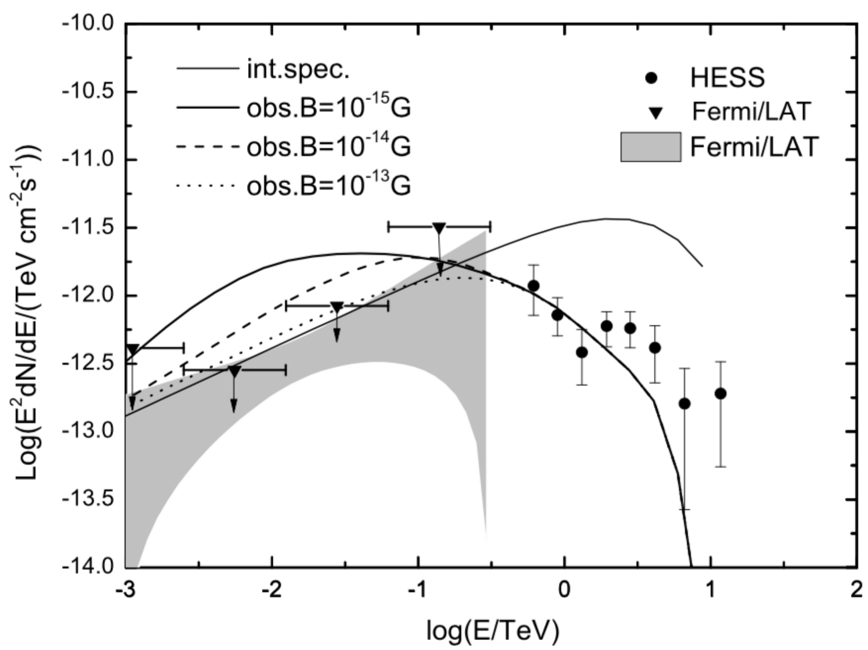




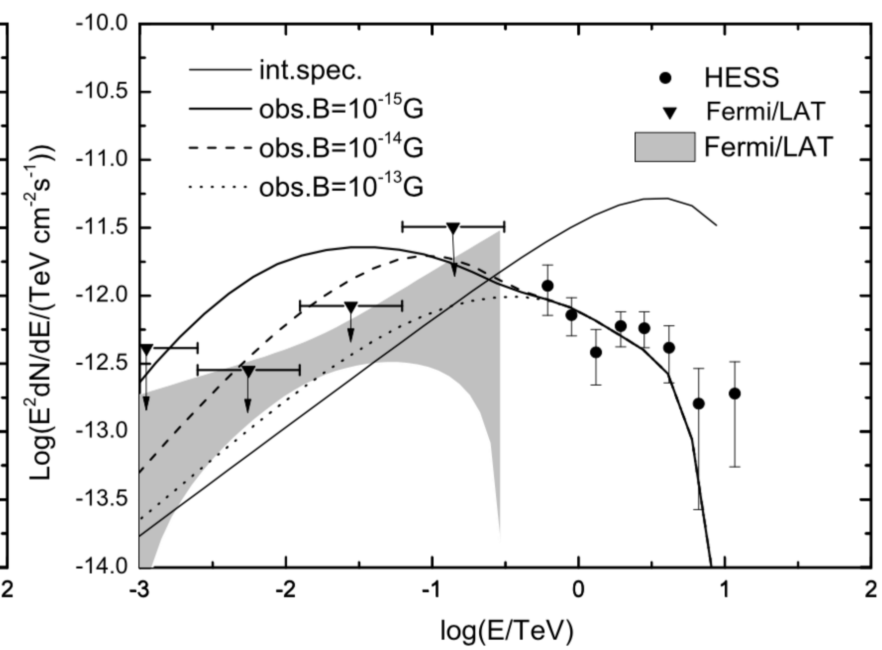
1ES 1218+304


VERITAS
Fitting
Φ(E>200GeV)[photons cm⁻² s⁻¹]
MJD
B=10⁻²⁰G; Γ_GeV=1.5
Fermi/LAT
int lc.
sca.lc.
tot lc.
Φ(E<300GeV)[photons cm⁻² s⁻¹]
MJD
int spec.
B=10⁻²⁰
B=10⁻¹⁸
B=10⁻¹⁶
B=10⁻¹⁴
Γ_GeV=1.76
Butterfly Fitting
Fermi/LAT
VERITAS
Log(E²dN/dE/(TeV cm⁻²s⁻¹))
log(E/TeV)
Butterfly Fitting
Fermi/LAT
VERITAS
T=T_flare
T=T_flare+1day
T=T_flare+2day
B=10⁻¹⁸G; Γ_GeV=1.5
Log(E²dN/dE/(TeV cm⁻²s⁻¹))
log(E/TeV)

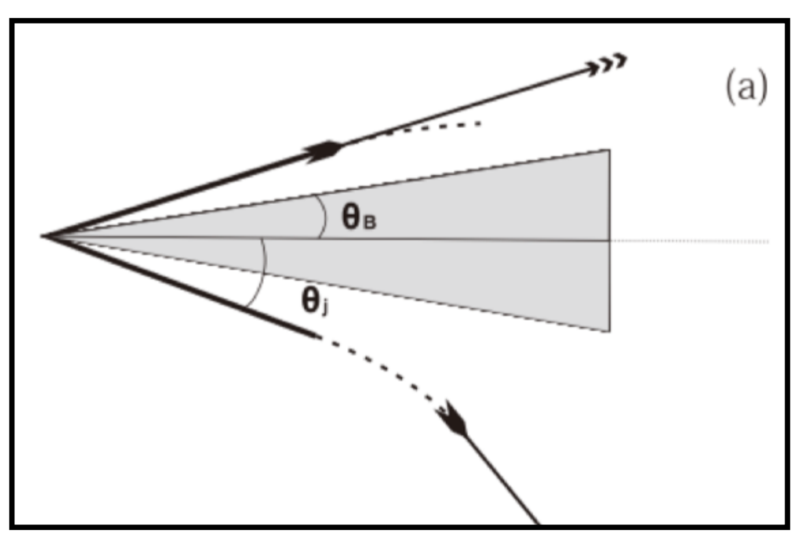
1ES 0229+200



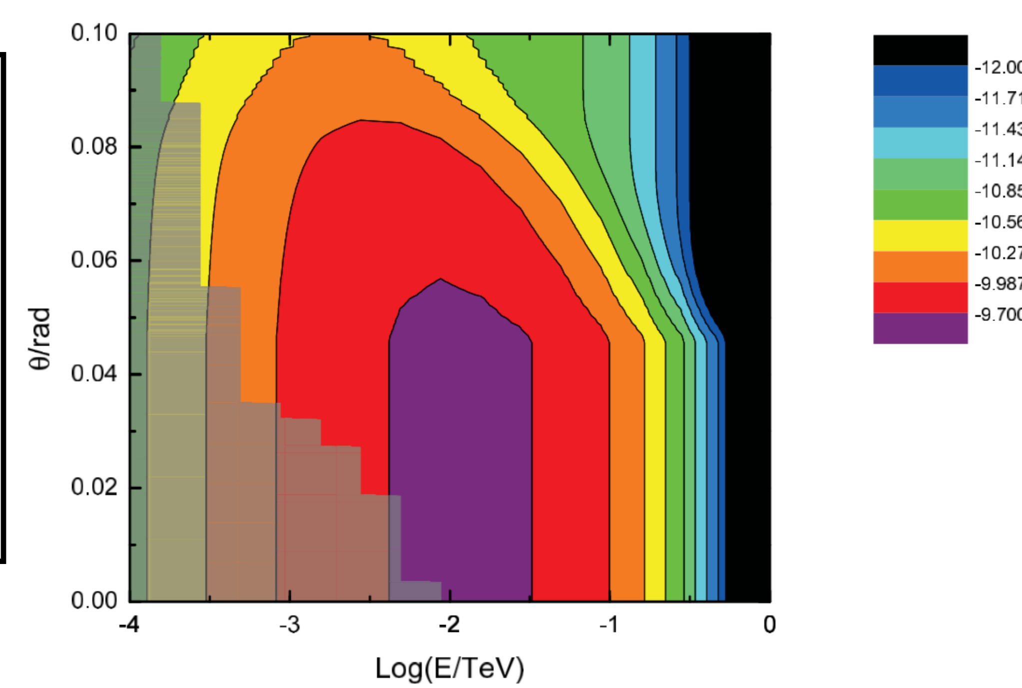
int.spec.
obs.B=10^-15G
obs.B=10^-14G
obs.B=10^-13G
HESS
Fermi/LAT
Fermi/LAT
Log(E^2dN/dE/(TeV cm^-2s^-1))
log(E/TeV)



int.spec.
obs.B=10^-15G
obs.B=10^-14G
obs.B=10^-13G
HESS
Fermi/LAT
Fermi/LAT
Log(E^2dN/dE/(TeV cm^-2s^-1))
log(E/TeV)

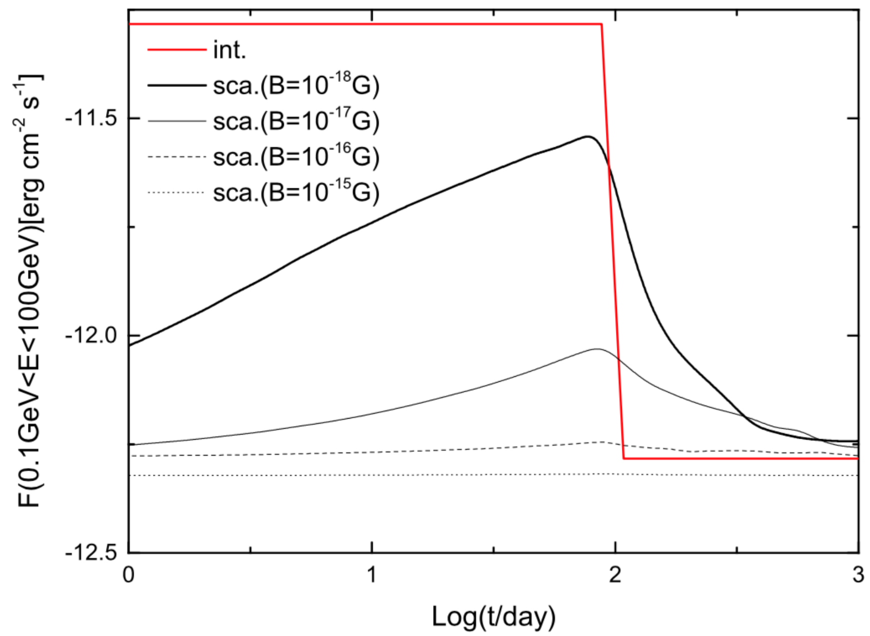


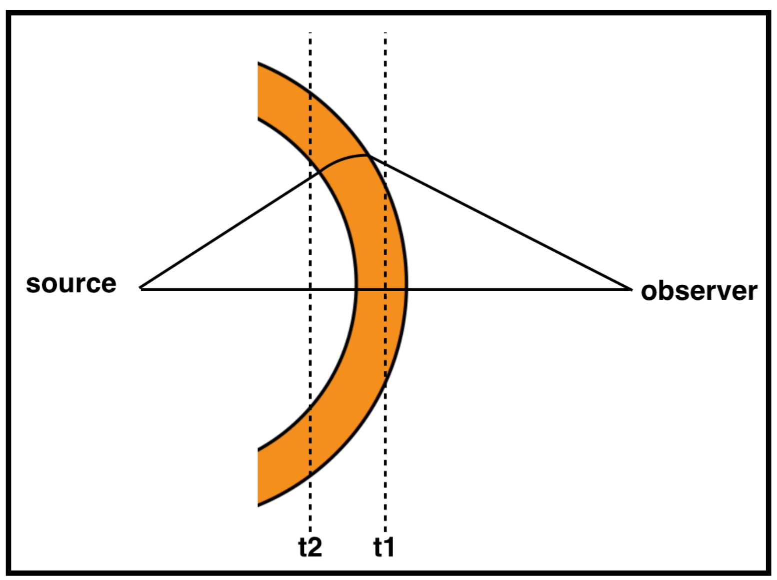
(a)
θB
θj

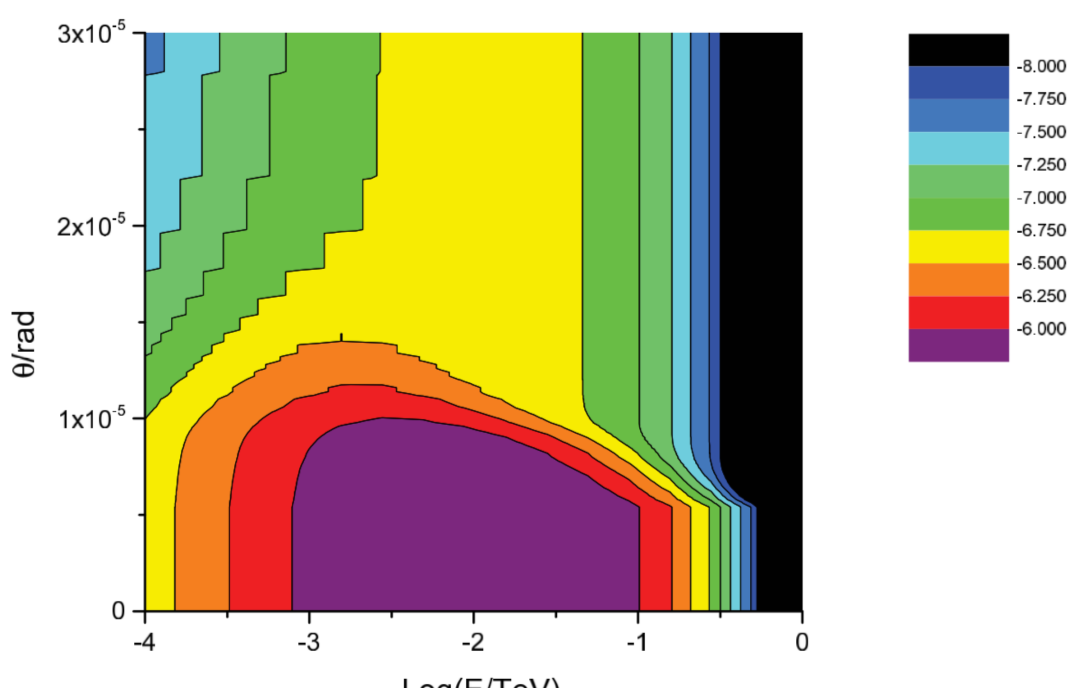


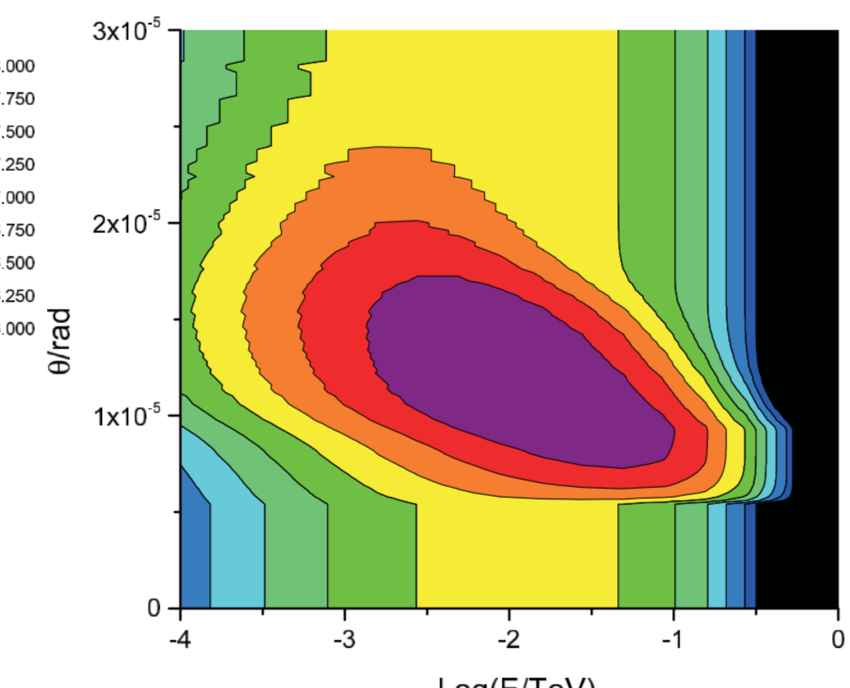
θ/rad
Log(E/TeV)
-12.00
-11.71
-11.43
-11.14
-10.85
-10.56
-10.27
-9.987
-9.700

Extreme Blazar Flare



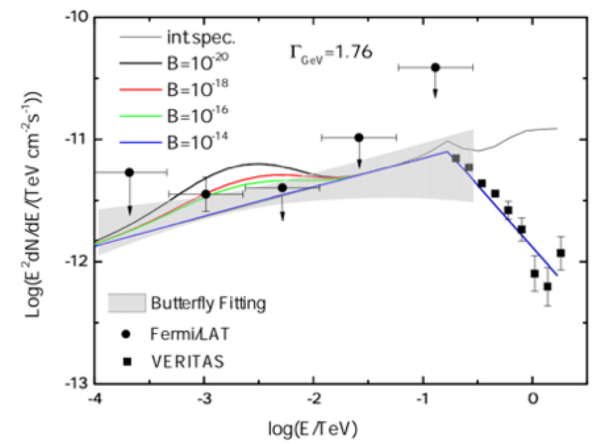


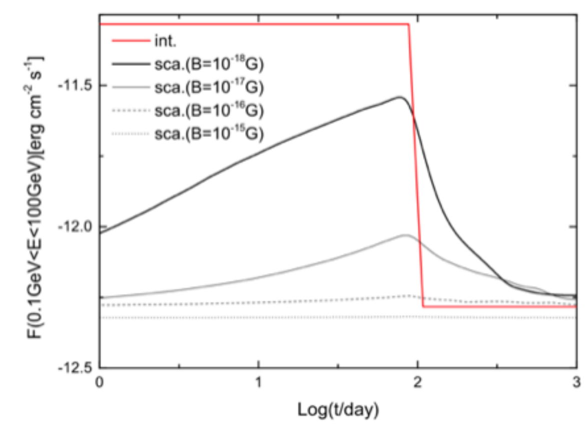


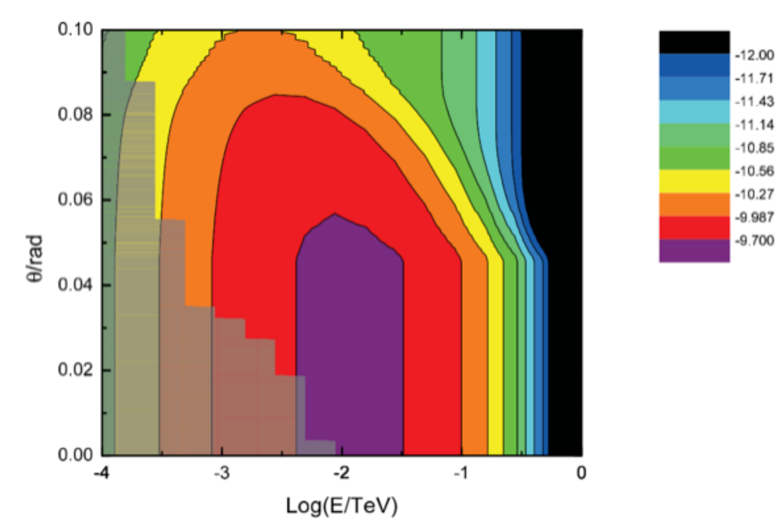


Summary

- Observation properties:
    1. Spectral change
    2. Time Delay
    3. Extended halo
- More stringent constraint on the IGMF
    A. Jet opening-angle correction
    B. Light curve analysis







Thank You!