Intergalactic Magnetic Field Constraints with VERITAS

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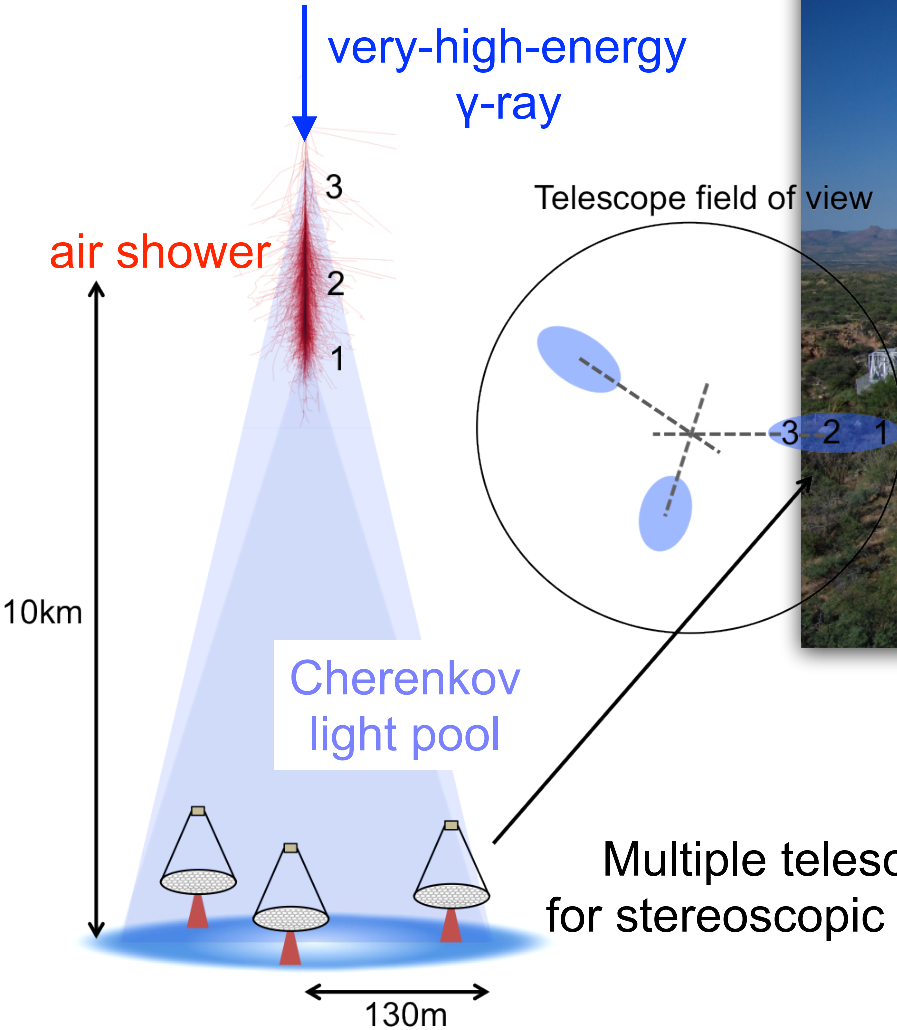
Cosmic Magnetism in Voids and Filaments
2023.01.25

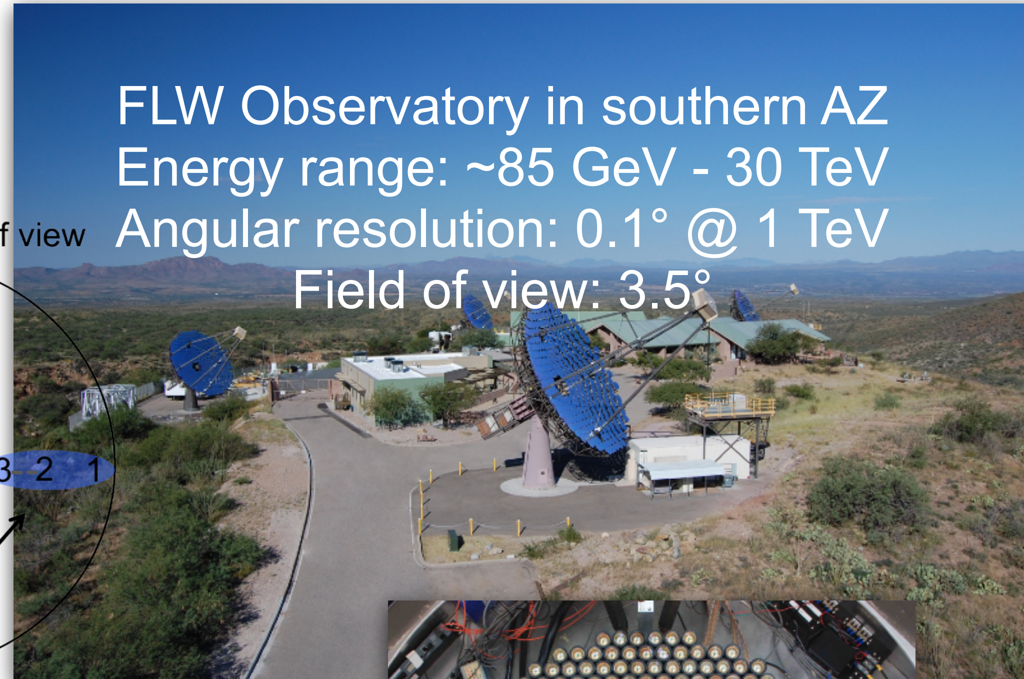
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

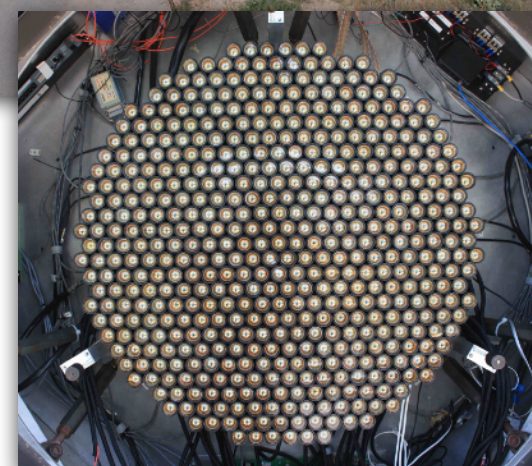
VERITAS Instrument



Multiple telescopes
for stereoscopic imaging

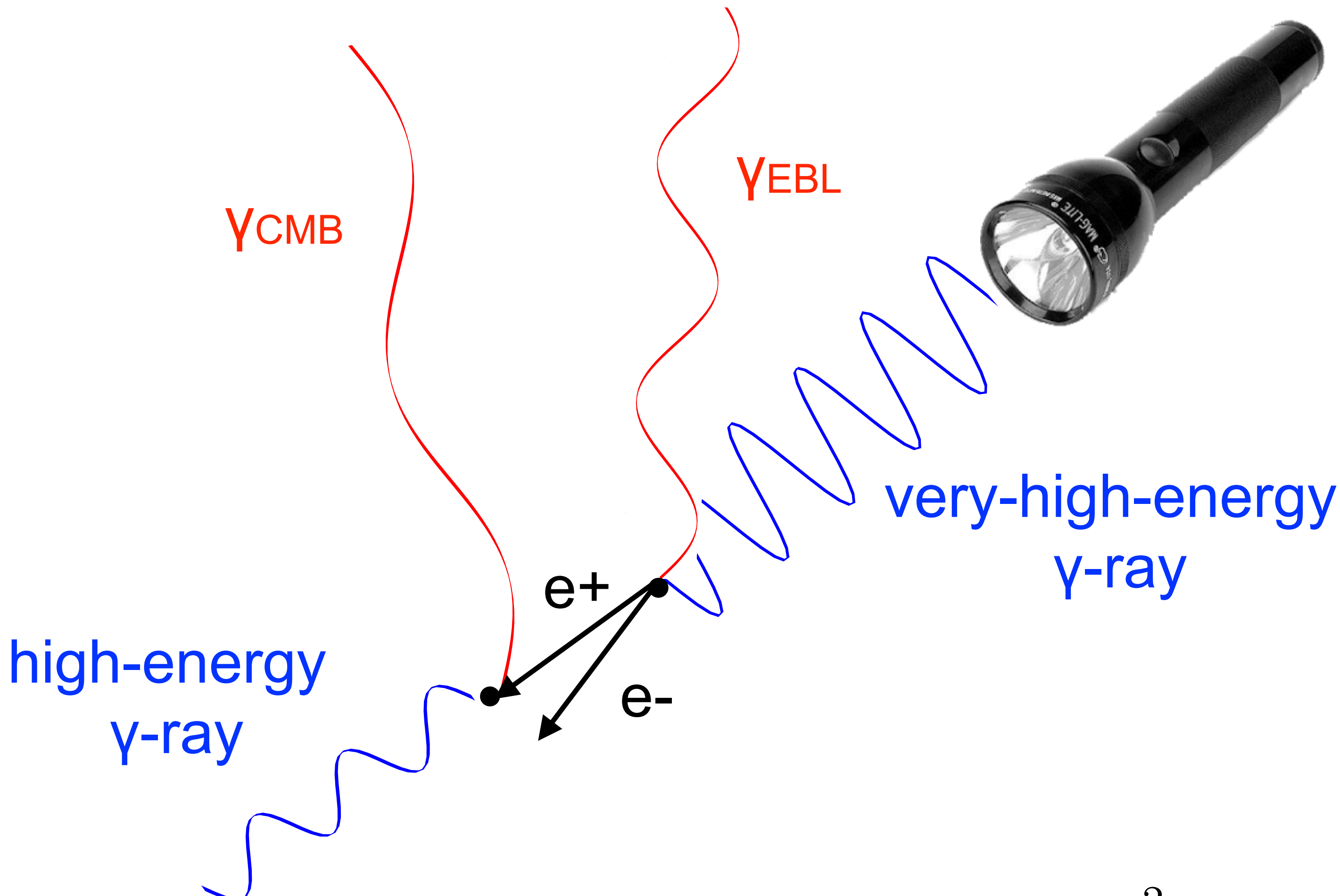
Credit: J. Holder





Photomultiplier tube cameras
for faint & fast signal

Electromagnetic Cascades

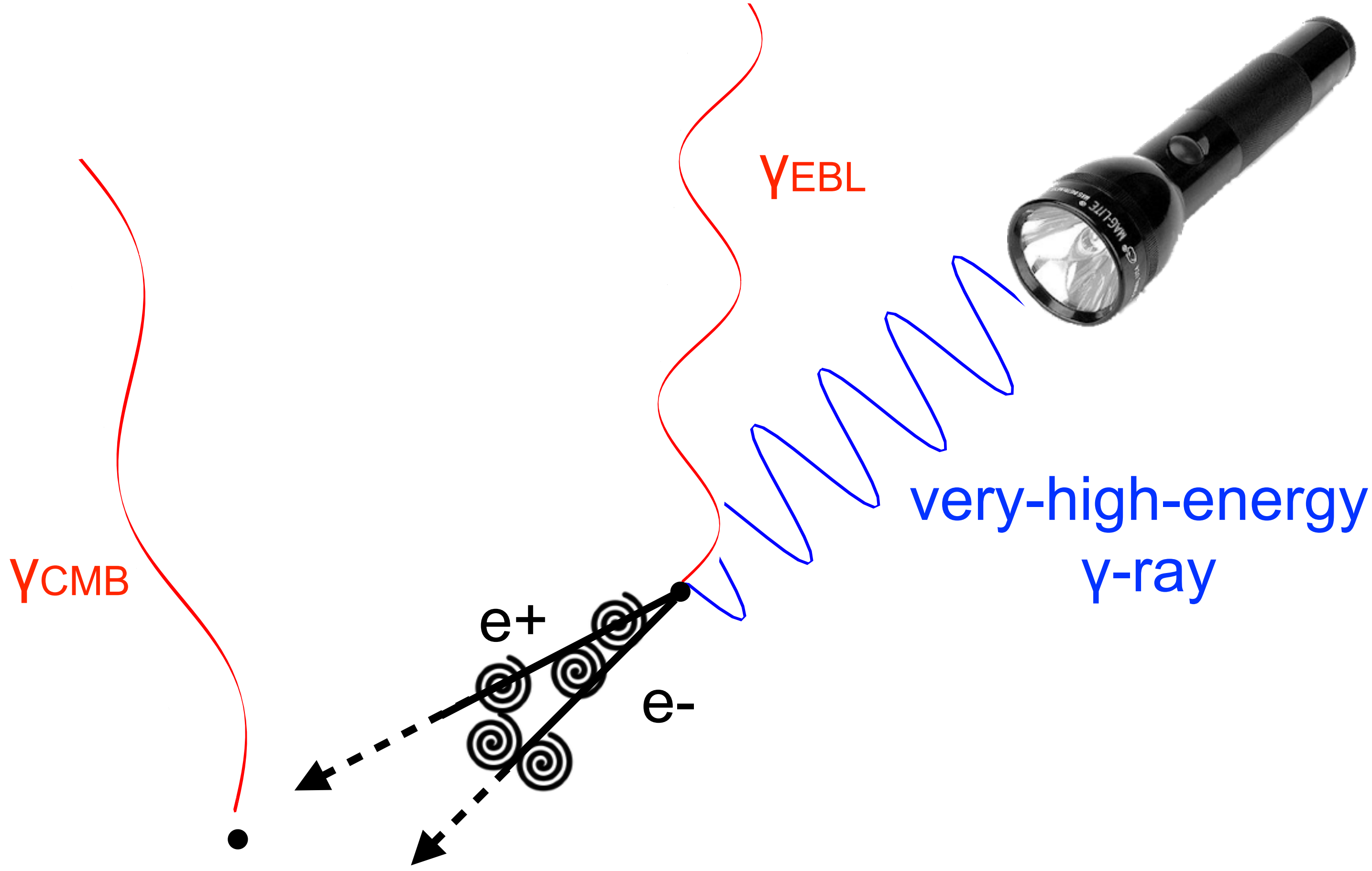


$$E_\gamma = \frac{4}{3}(1+z_{\gamma\gamma})^{-1}\epsilon\frac{E_e^2}{m_e^2} \approx 0.32\left(\frac{E_{\gamma_0}}{20\ TeV}\right)^2$$

ϵ = typical CMB photon energy

~10 TeV initial photon → ~100 GeV cascade photon

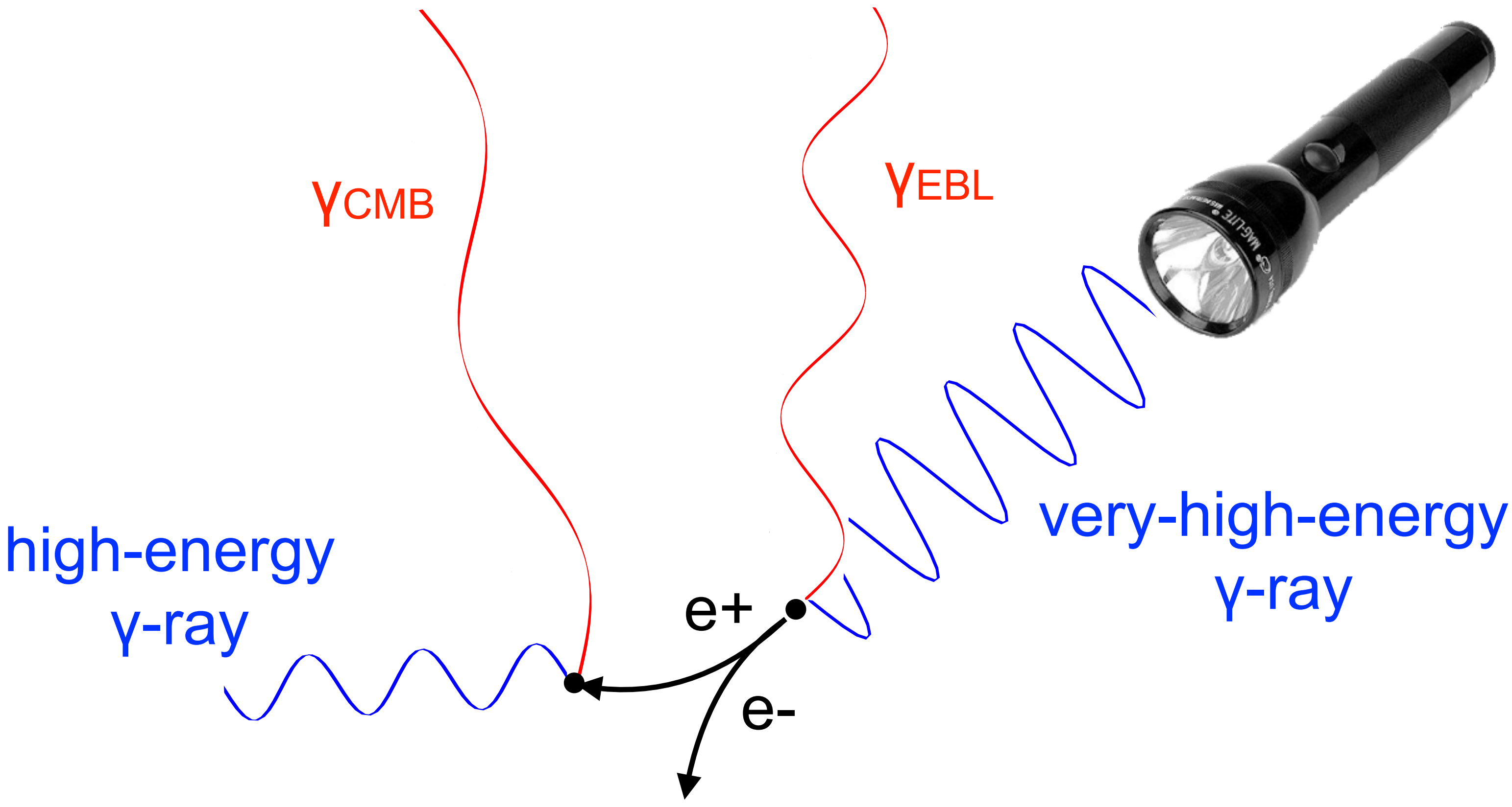
Plasma Beam Instabilities?



Energy loss of e+e- pairs due to plasma instabilities?
Relative cooling timescales determine cascade development

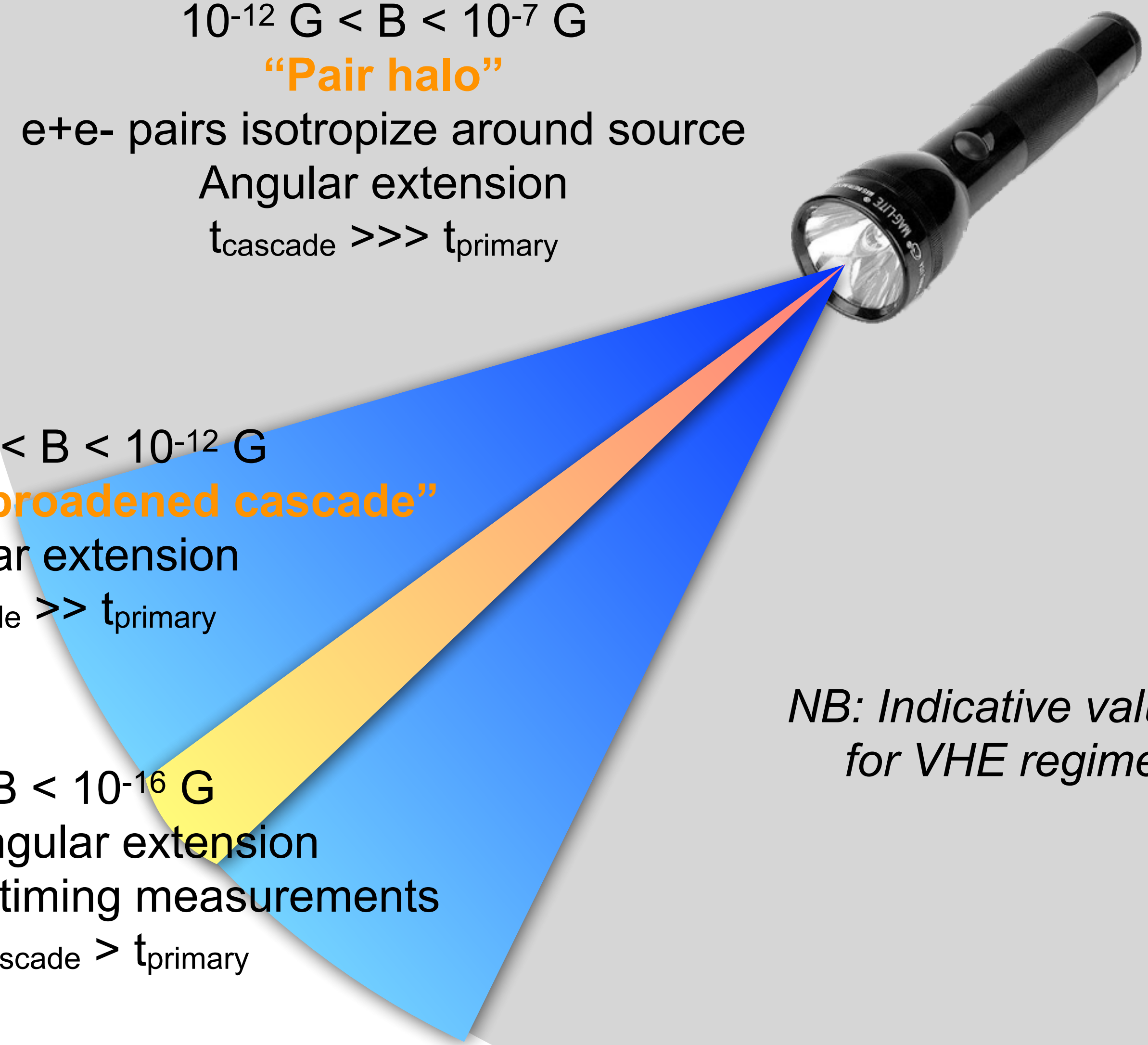
Following results assume inverse-Compton cooling to be dominant effect

Electromagnetic Cascades & IGMF



Magnetic field **deflects** e+e- pairs
Path length to observer **increases**

IGMF Strength Regimes



10^{-12} G < B < 10^{-7} G
"Pair halo"
e+e- pairs isotropize around source
Angular extension
$t_{cascade} >>> t_{primary}$

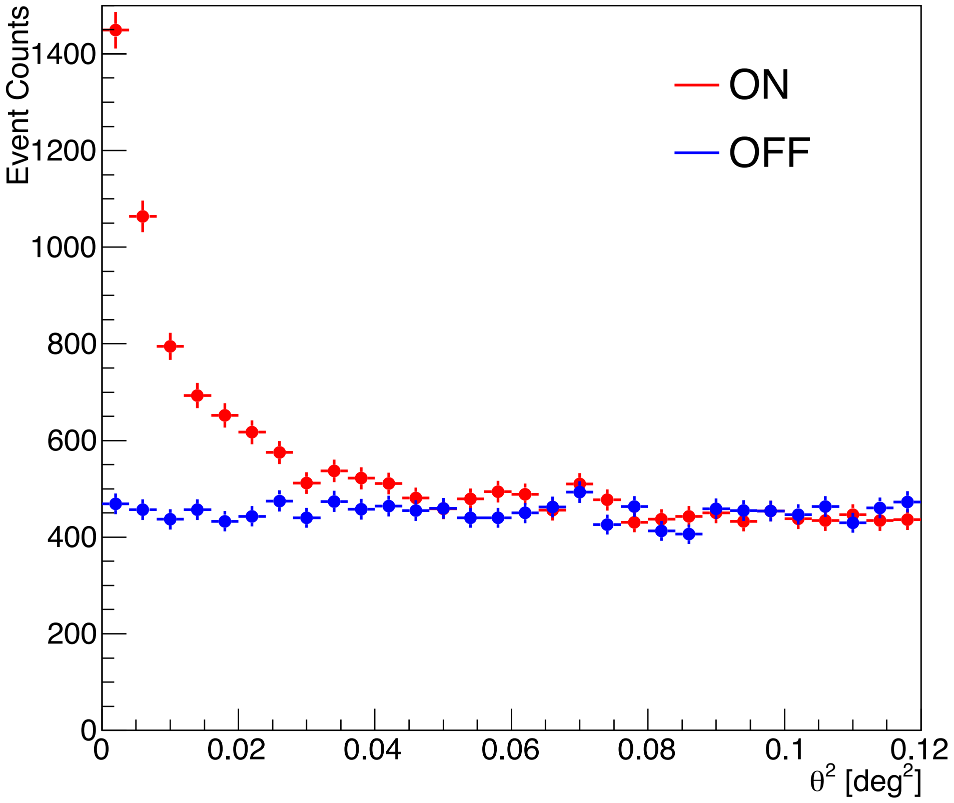
10^{-16} G < B < 10^{-12} G
"Magnetically broadened cascade"
Angular extension
$t_{cascade} >> t_{primary}$

B < 10^{-16} G
No angular extension
Spectral or timing measurements
$t_{cascade} > t_{primary}$

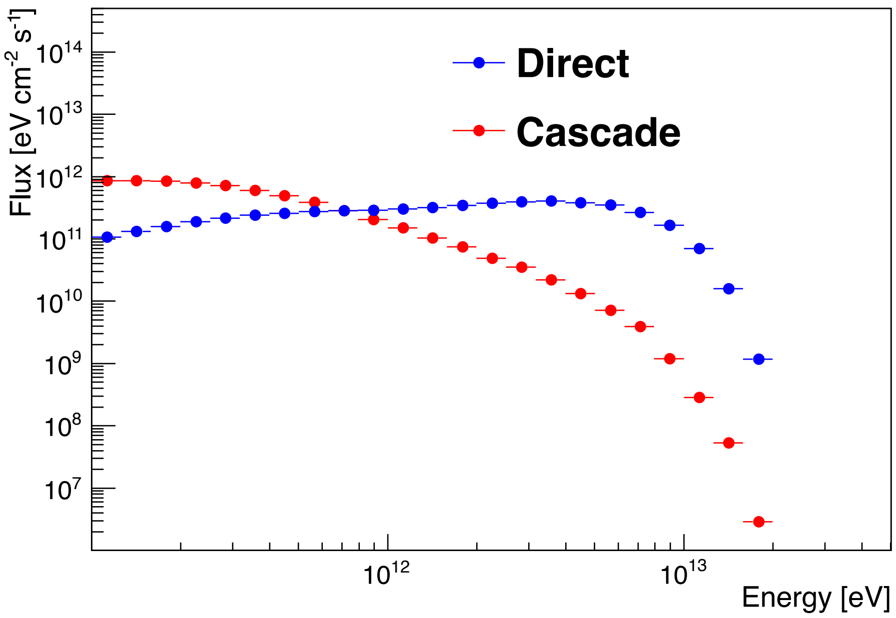
NB: Indicative values for VHE regime

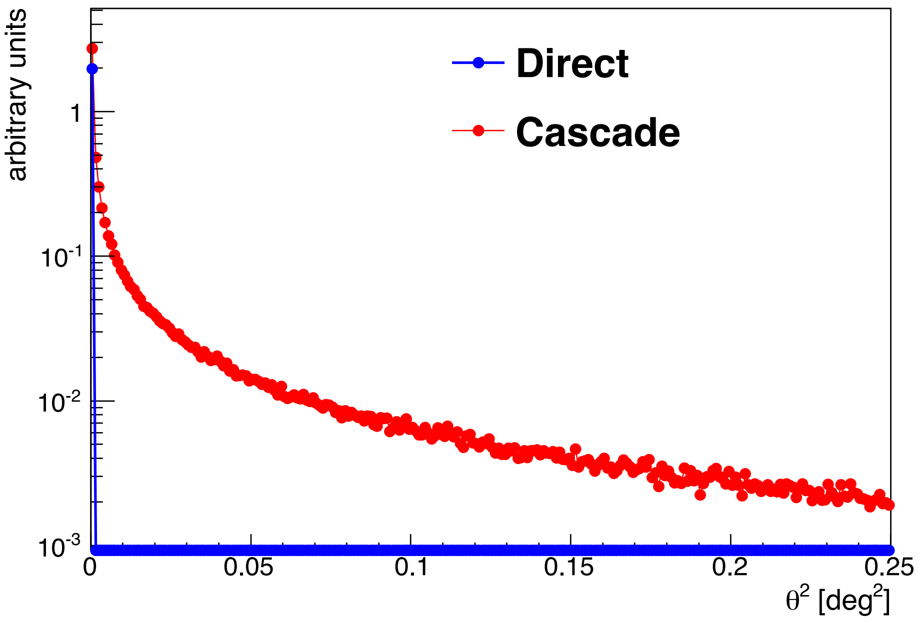
Angular Profile for a Point Source

- Point source
  - Angular profile → θ^2: angular distance between shower arrival direction and source's estimated location
  - Background: flat in θ^2
  - Signal: sharp peak at $\theta^2 = 0$
    - Width → point spread function (PSF)



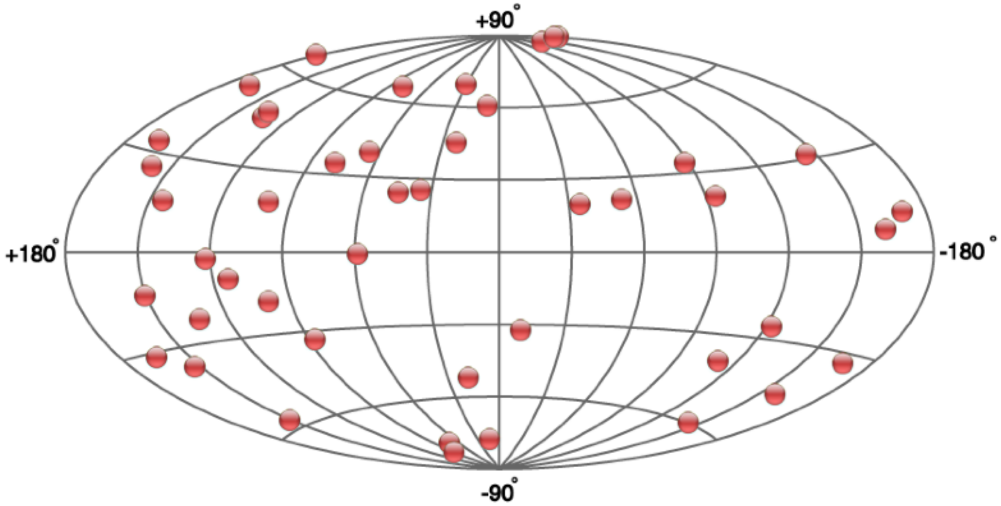
Predicted Energy/Angular Profiles





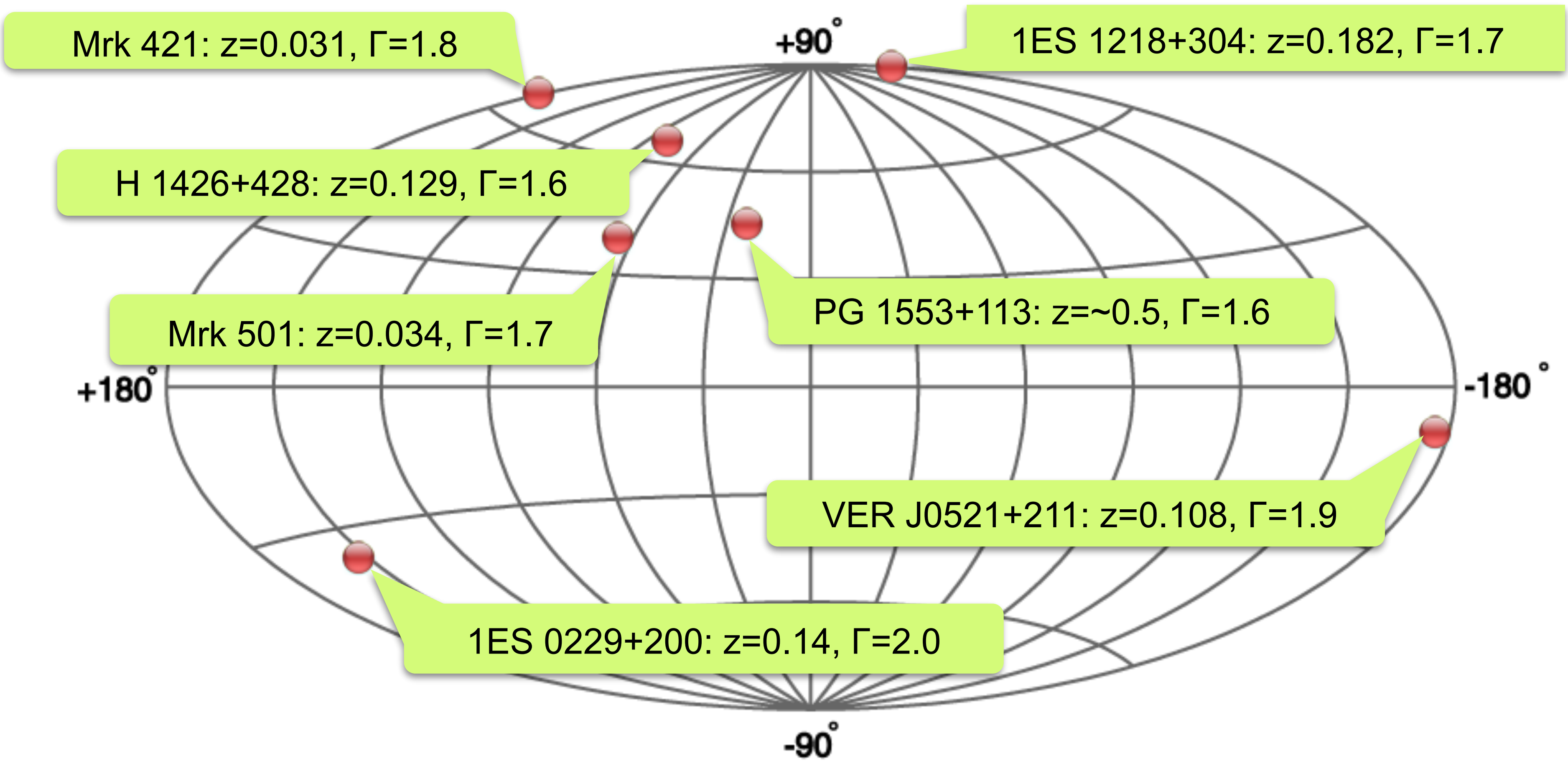
- Semi-analytic 3D cascade simulation from T. Weisgarber
  - Jet: Doppler factor = 10, viewing angle 0°
    - Minimal effect on spectrum above 100 GeV (arXiv:1210.2802)
  - Magnetic field correlation length λ = 1 Mpc
    - Typical choice in literature
    - Results insensitive for λ > inverse Compton cooling length (~100 kpc for 1 TeV gamma rays)

Sources for IGMF Analysis



- Best sources = greatest cascade emission fraction
  - Hard-spectrum blazars (assume 3FGL/3LAC ~ intrinsic index)
  - Emission to multi-TeV energies - HBLs, esp. extreme-HBLs
    - Check for presence of intrinsic cut-off → **1ES 1218+304, 1ES 0229+200 are best sources!**
  - Range of redshifts
    - z = 0.1 - 0.2 is optimal
    - Include near and far sources as cross-check/test redshift dependence in case of detection

Sources for IGMF Analysis



*Note: Mrk 421 and Mrk 501 highly variable in TeV
Remove flaring episodes: spectral variability + direct emission dominates

Maximizing Analysis Sensitivity

Maximize cascade fraction

- Soft cut on image size (integrated charge)
- Cut on maximum energy
- Zenith angle observations < 30°
  - → Energy range: 160 GeV - 1 TeV

Minimize angular resolution

- 4 telescopes operating
- Images in 3 or 4 telescopes
- Distance to shower core < 215 m
- Zenith angle observations < 30°

Simulating Point Sources

Compare source's angular profile against simulated point source

Energy correction

Simulations generated @ $\Gamma=2$

Weight simulation to match energy distribution of excess events

Zenith correction

Simulations generated @ Ze=20°

Derive PSF(Ze) from Crab Nebula data

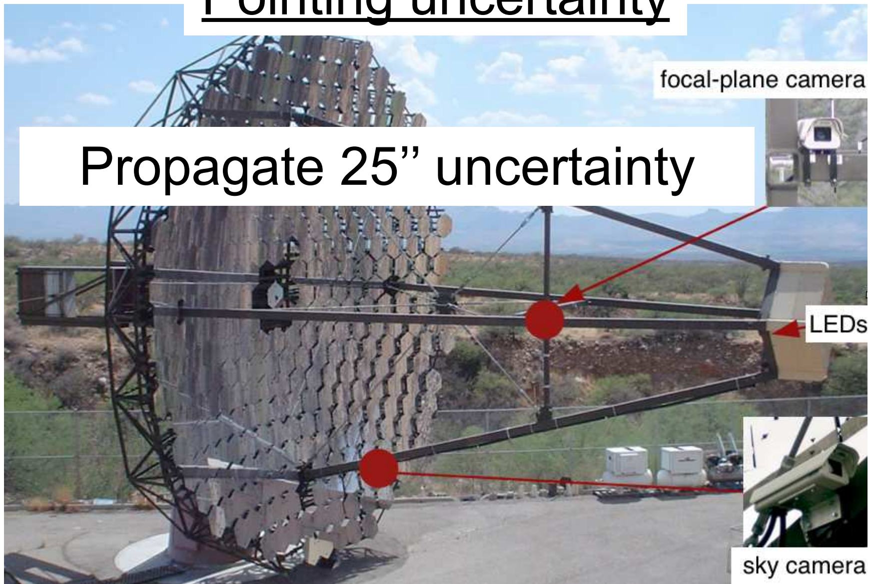
Energy resolution

Propagate 20% uncertainty

Shift simulated energy up and down

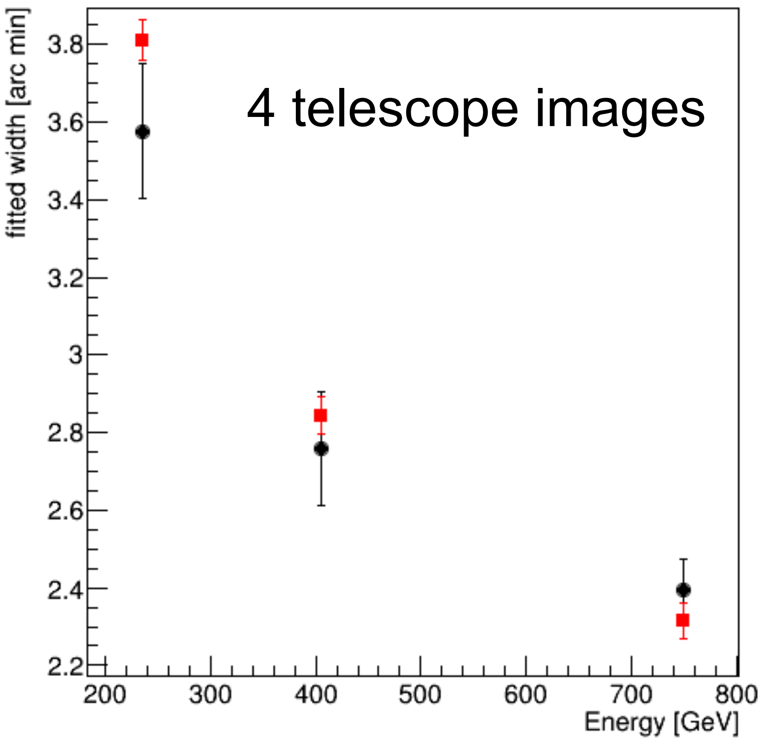
Pointing uncertainty

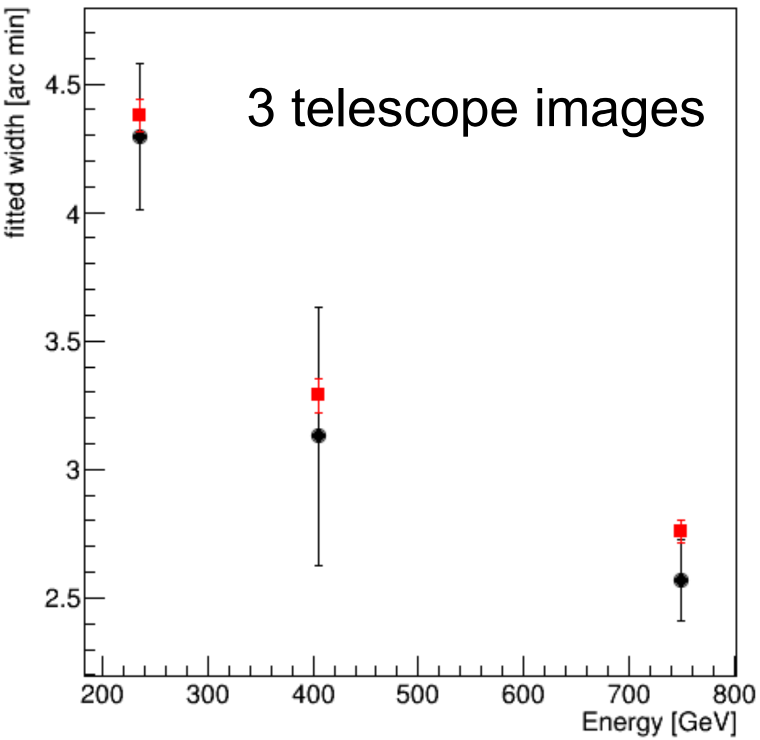
Propagate 25'' uncertainty



Simulating Point Sources: Control Sample

Good agreement between data and simulation on control sample (Mrk 421 high-state observations)

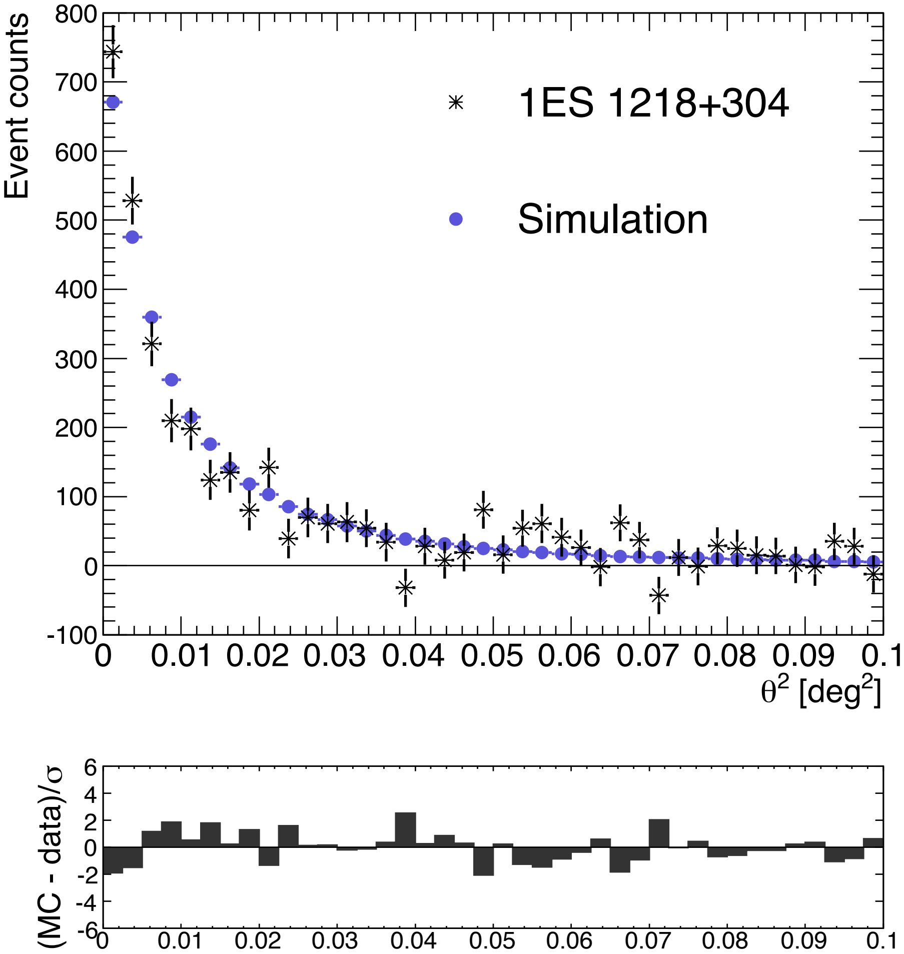




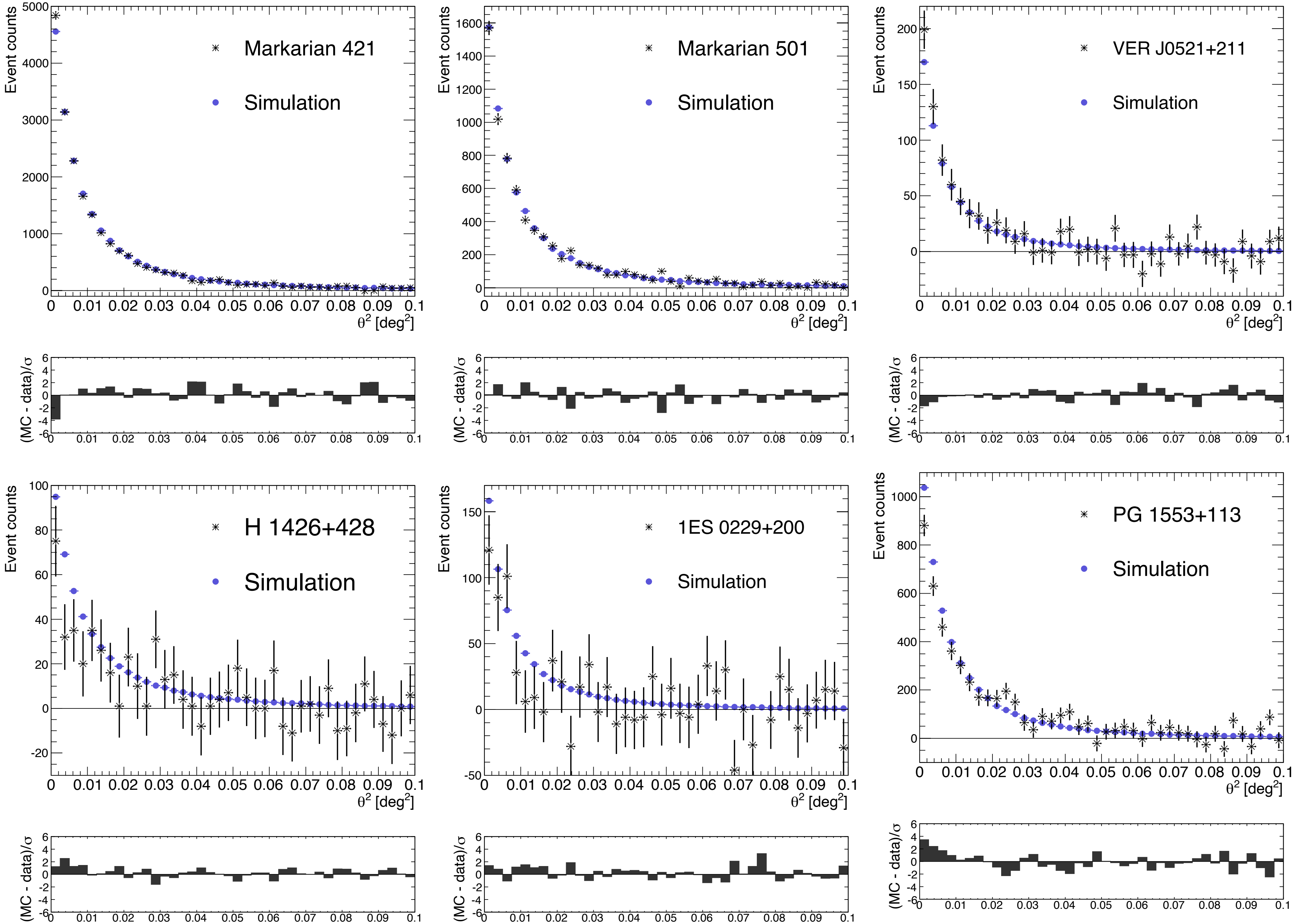
Red = simulations
Black = data

Comparing Sources & Simulated Sources

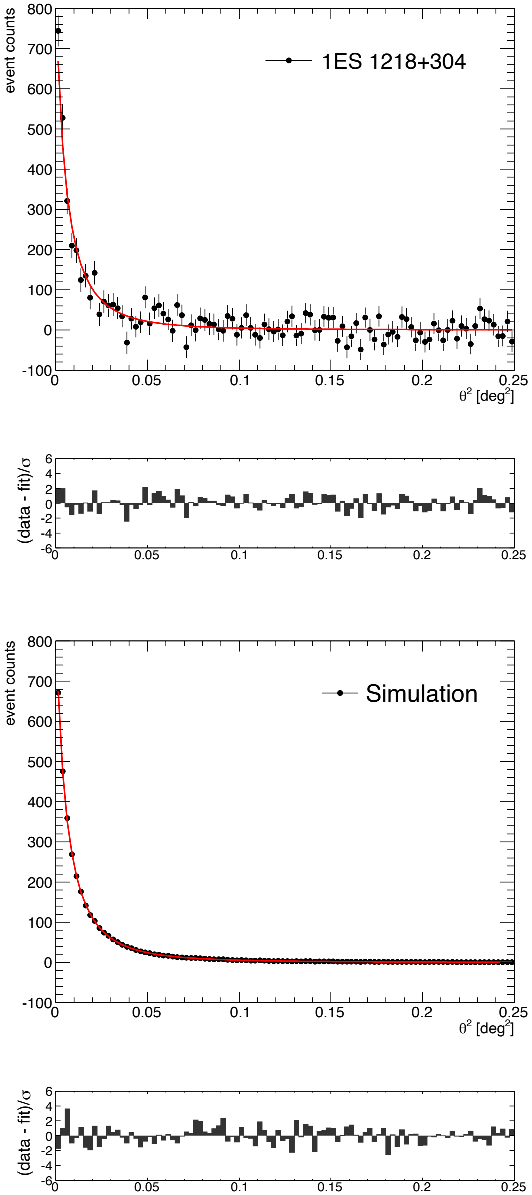
- Histogram residuals
  - 2 histogram test
  - Only one marginal p-value
  - Does not account for zenith correction, systematic uncertainties



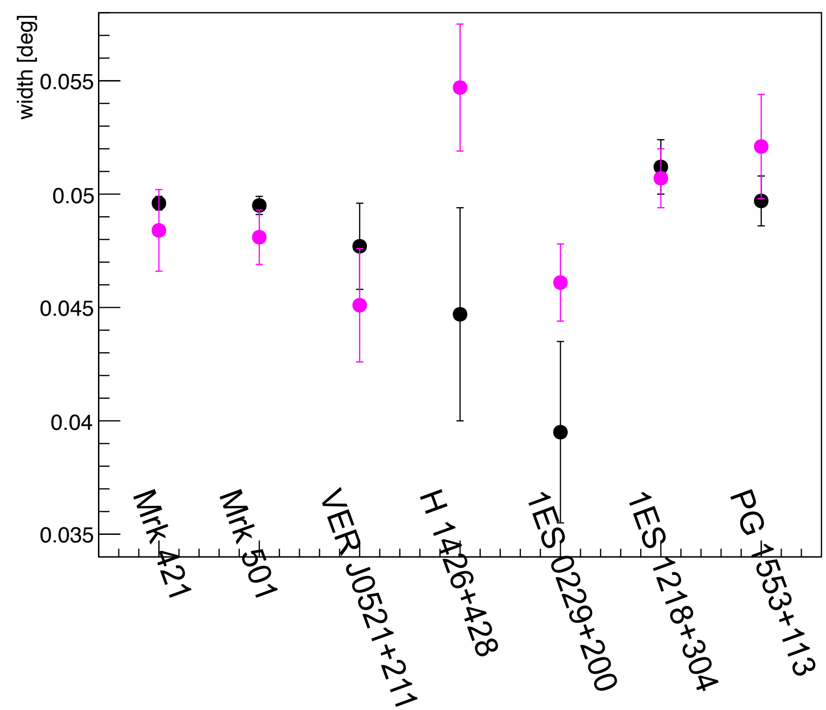
Restricted θ^2 range to show detail
Residuals calculated for $\theta^2 < 0.25$ deg^2


Markarian 421
Simulation
Markarian 501
Simulation
VER J0521+211
Simulation
H 1426+428
Simulation
1ES 0229+200
Simulation
PG 1553+113
Simulation
Event counts
θ^2 [deg^2]
(MC - data)/σ

Source/Simulated Point Source Agreement



- Fit angular profiles
  - Empirical function
  - Check agreement of widths



No significant tension
No trend

Cascade Fraction Limits → IGMF Limits

IGMF strength B = 1 x 10^{-16} - 1 x 10^{-13} G, 13 values

Generate toys at different cascade fractions (f_c)

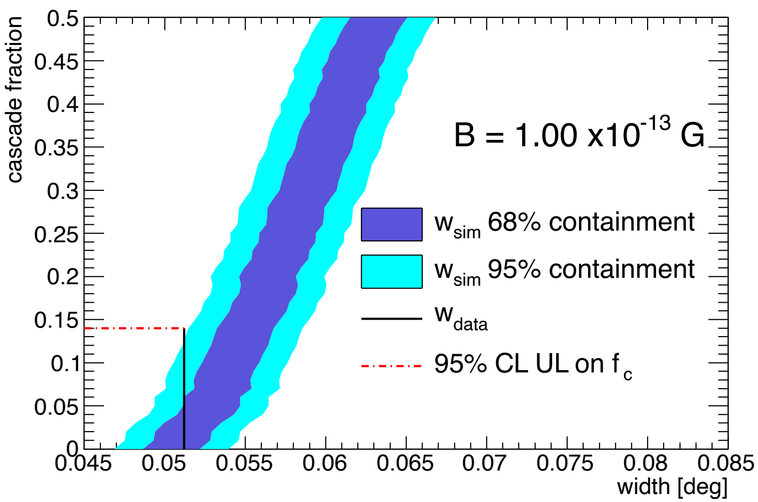
Primary emission + Cascade emission

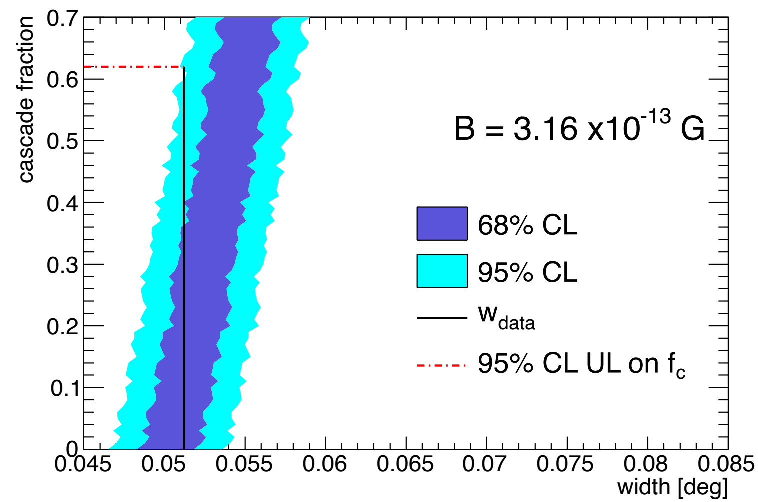
$(1 - f_c)$ PSF + f_c (PSF conv. w. cascade model)

PSF: from simulated point source

cascade model: from cascade sims

Set 95% CL upper limits on f_c





Cascade Fraction Limits → IGMF Limits

IGMF strength B = 1 x 10^{-16} - 1 x 10^{-13} G, 13 values

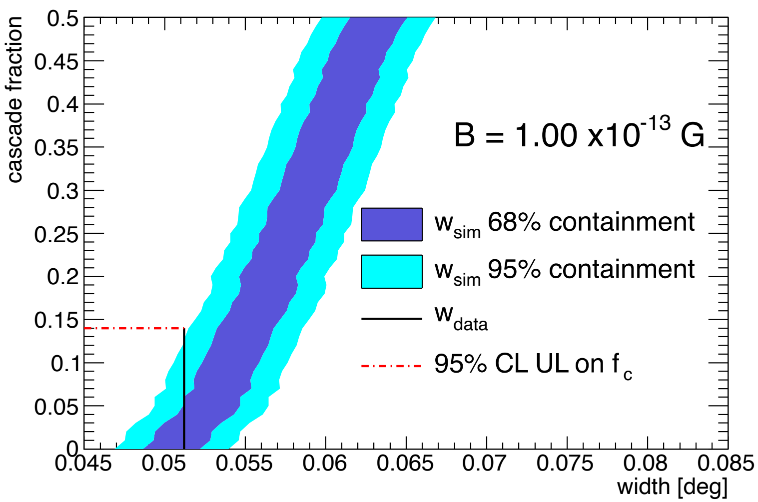
from s
point

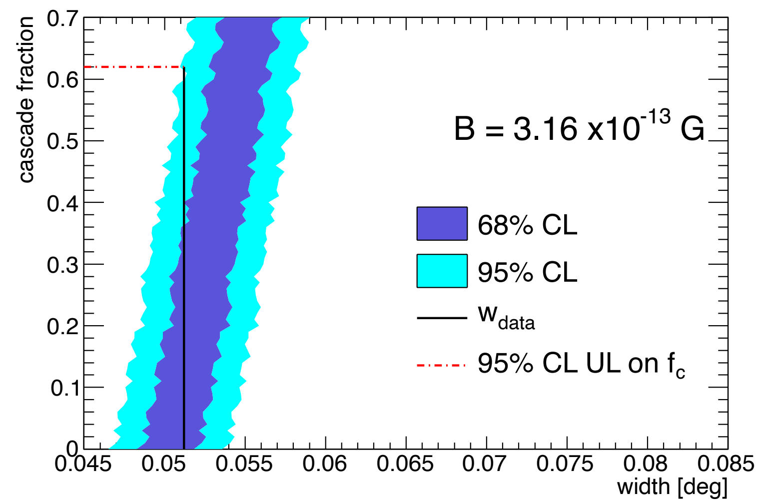
Predicted cascade fraction must be sufficiently large & statistical uncertainties sufficiently small to constrain f_C

Minimum f_C ~10%

Best constraints derived from 1ES 1218+304

sims

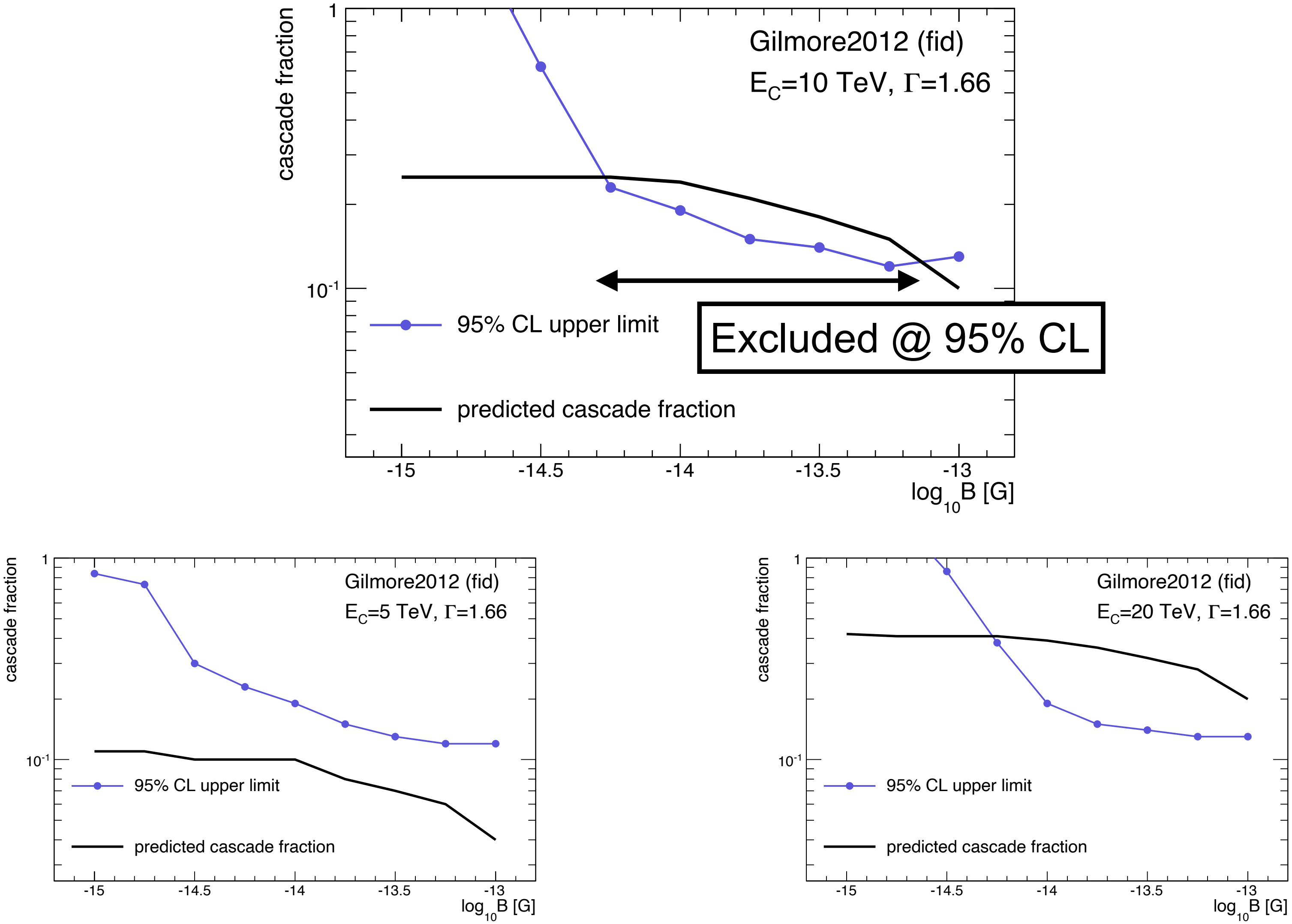




Sensitivity to Assumptions on Spectra

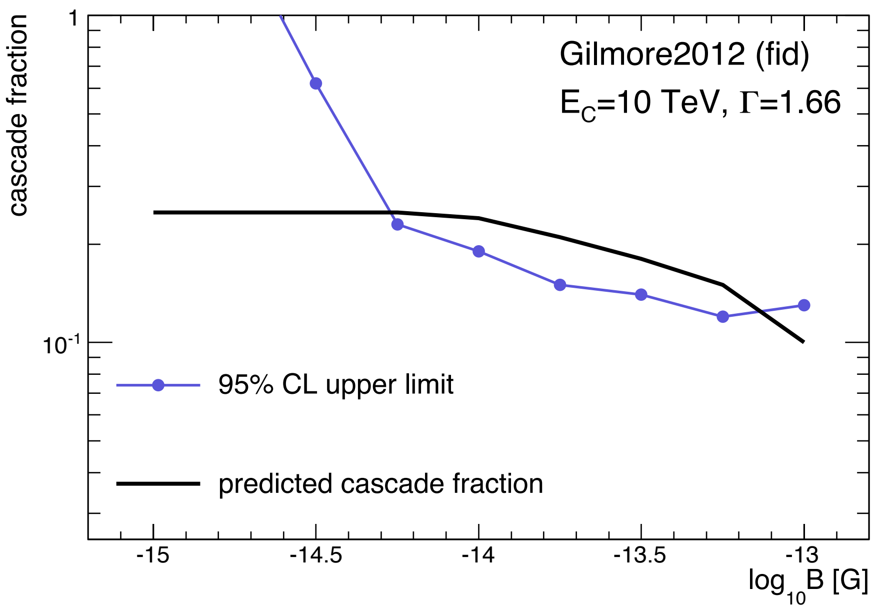
- Consider impact on predicted f_c and f_c upper limit of
  - EBL model
    - From Gilmore 2012 (arXiv:1104.0671, fiducial model) & Franceschini 2008 (arXiv:0805.1841)
  - Intrinsic spectrum
    - Assume spectral index Γ = 1.660, based on Fermi measurement
      - Does not account for possible variability on longer timescales
      - Consider Γ = [1.460, 1.660, 1.860]
    - Assume intrinsic spectrum described by exponentially cut-off power law
      - No cutoff in VERITAS spectrum != no cutoff
      - Highest energy spectral point @ 4 TeV
      - E_c = [5, 10, 20] TeV

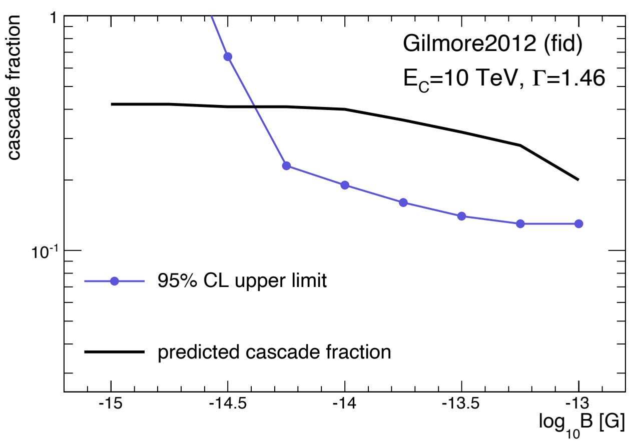
IGMF Limits: Impact of Spectral Cutoff

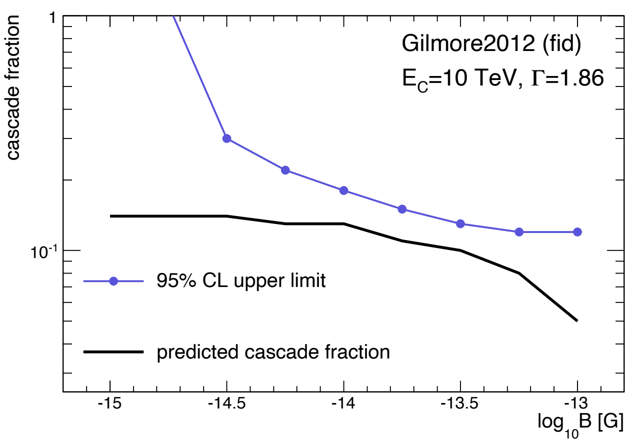


Spectral cutoff at lower energy → no constraints

IGMF Limits: Impact of Spectral Index

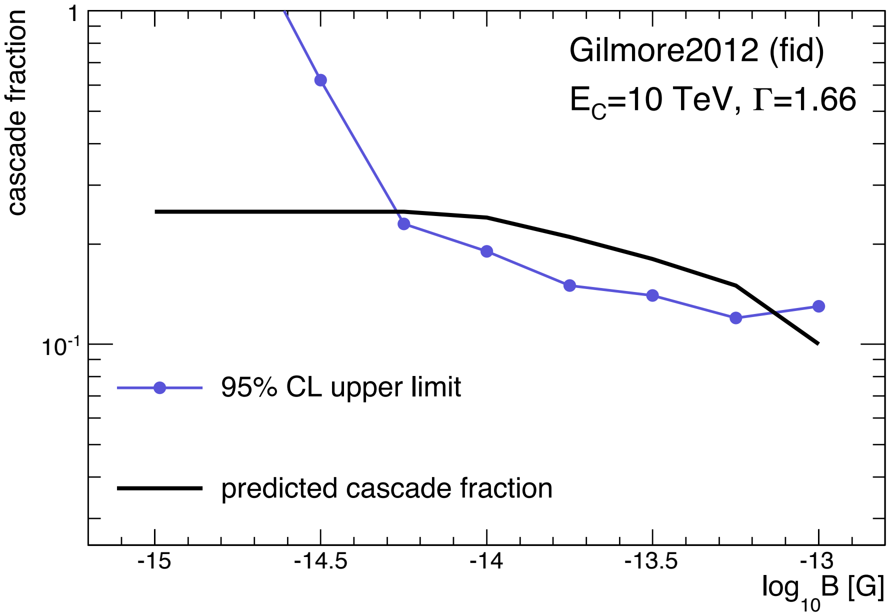


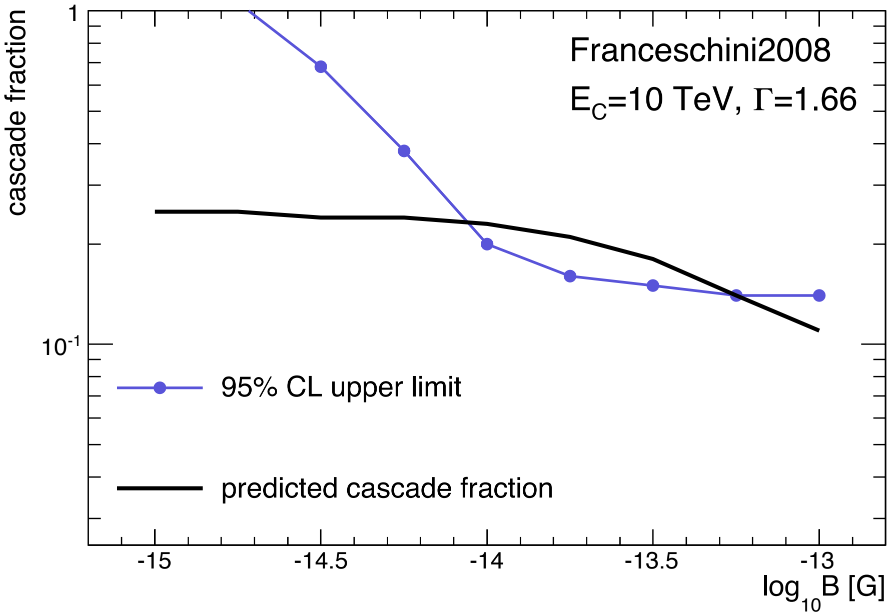




Softer spectral index → no constraints

IGMF Limits: Impact of EBL Model

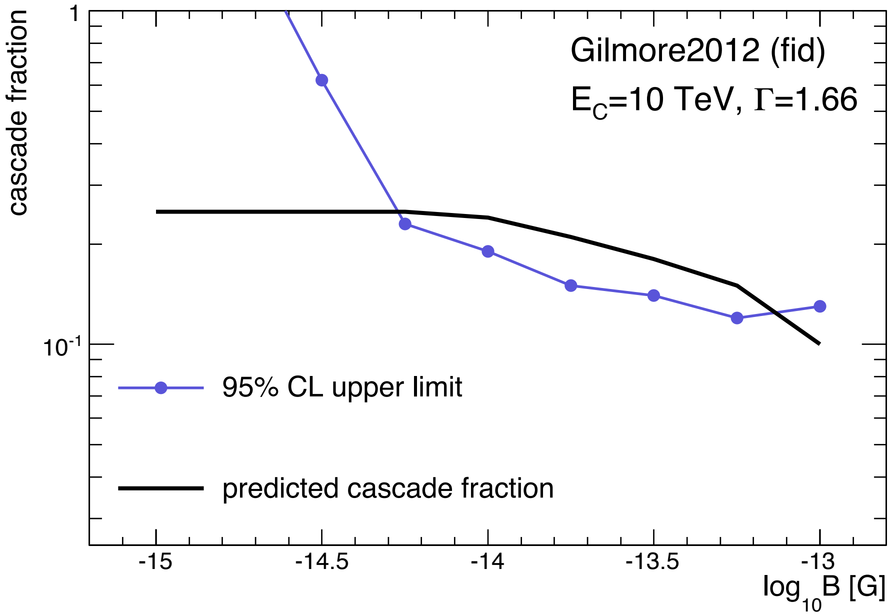




Larger region excluded for Gilmore 2012 fiducial model than for model of Franceschini 2008

5.5×10^{-15} - 7.4×10^{-14} G (Gilmore 2012 fiducial)
versus
9.1×10^{-15} - 5.6×10^{-14} G (Franceschini 2008)

IGMF Limits: Impact of Flux Variability



Predicted cascade fraction based on observed VERITAS flux
Larger flux in the past → larger cascade fraction in present day
Smaller flux in the past → smaller cascade fraction in present day

No constraints possible if average differential flux at 1 TeV <70% observed value

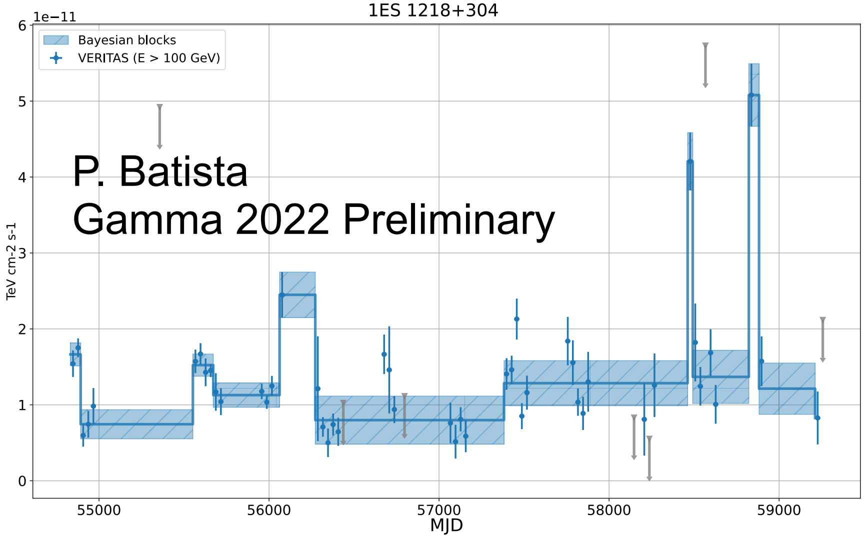
Conclusions & Outlook

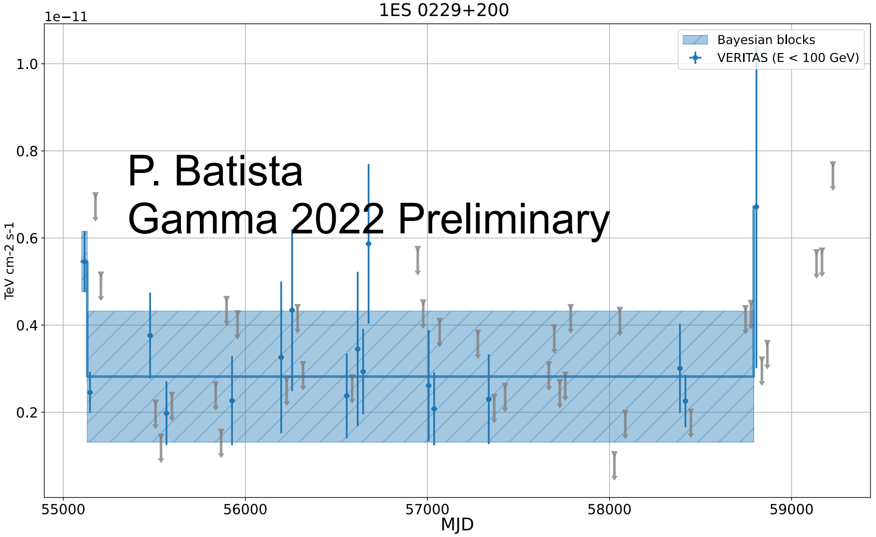
- Conclusions
  - VERITAS rules out band of IGMF strengths around 10^{-14} G
    - Assuming correlation length $\lambda = 1$ Mpc
    - Strong dependence on assumed intrinsic spectral properties
    - Weak depedence on EBL model
  - Results probe IGMF in voids
    - First pair production >10 Mpc from source for 10 TeV gamma rays

- Outlook
  - Updated information on spectral indices in Fermi range (4LAC) - affect assumptions on intrinsic spectra
    - 1ES 1218+304: $\Gamma = 1.660 \pm 0.038 \rightarrow 1.71 \pm 0.02$
    - 1ES 0229+200: $\Gamma = 2.025 \pm 0.150 \rightarrow 1.78 \pm 0.11$
  - Updated EBL models

Outlook

- More data
  - ~60 hours → ~180 hours on 1ES 1218+304 and 1ES 0229+200
    - Majority taken after camera upgrade → lower energy threshold
  - …although with significant flares in recent 1ES 1218+304 data

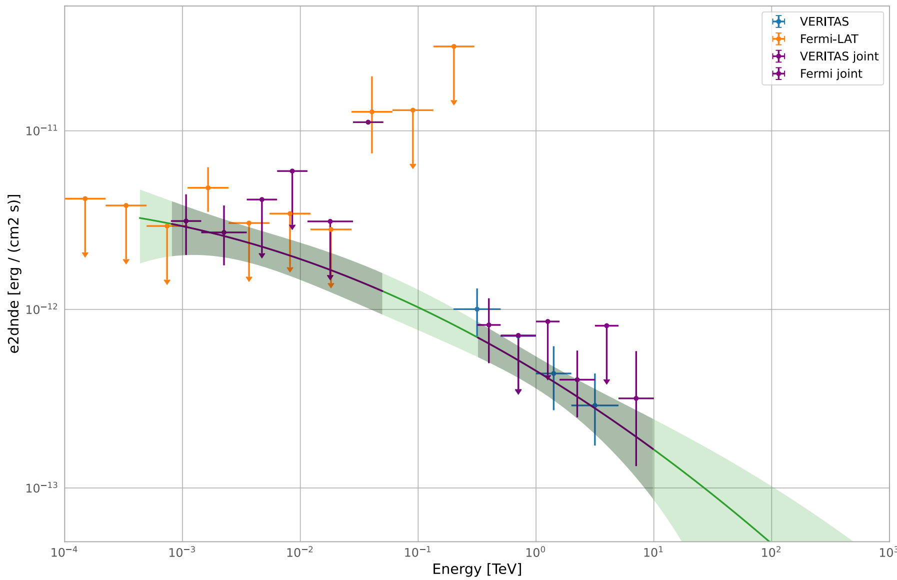




Outlook

- We know that spectral measurements are more powerful!
  - e.g. Fermi-LAT + archival very-high-energy spectra (arXiv:1804.08035)

- The next step could be event-level fits with data from Fermi-LAT, VERITAS, H.E.S.S. and MAGIC with gammapy

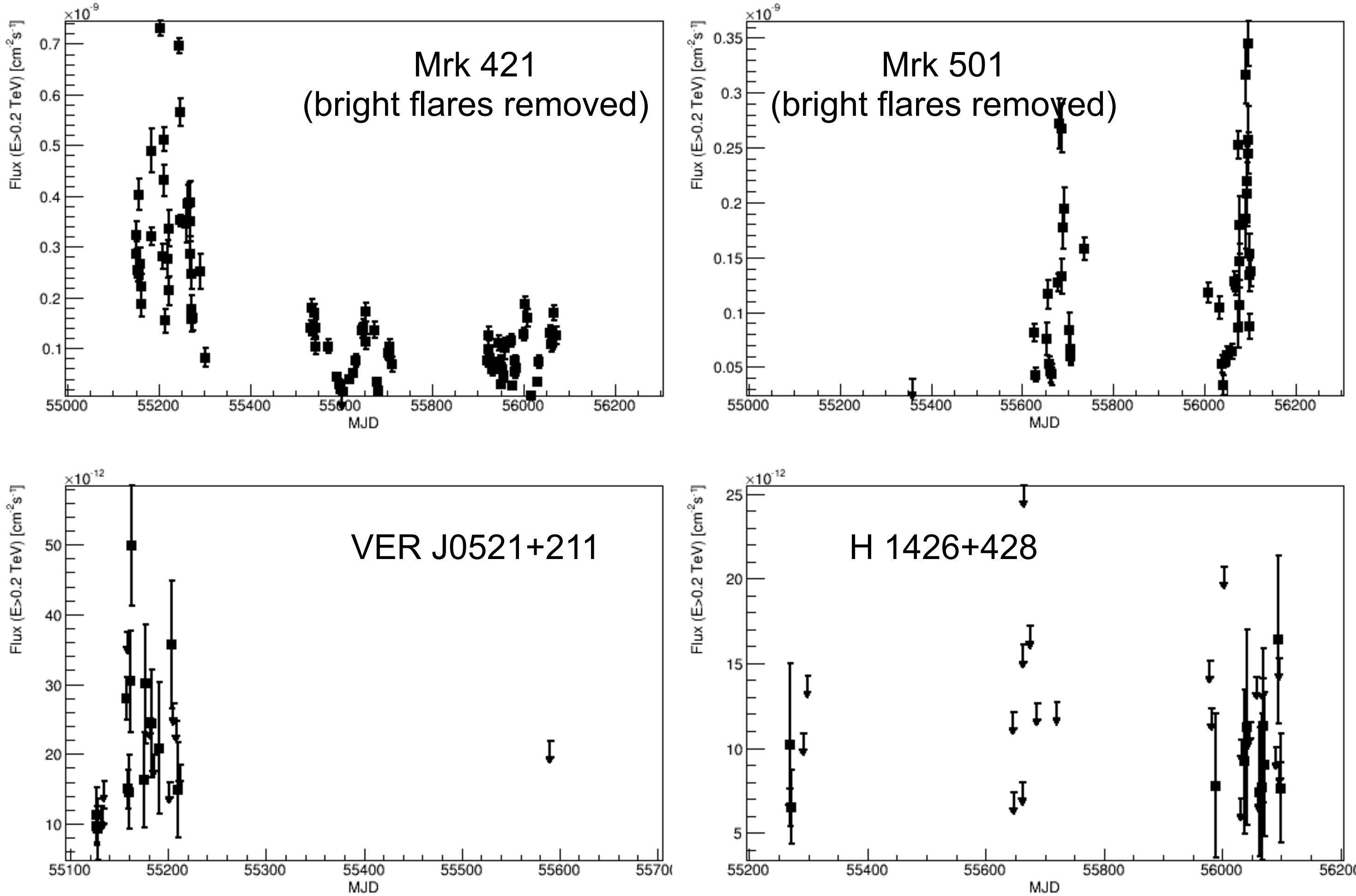


Thanks!

doi:10.3847/1538-4357/835/2/288

Backup

Lightcurves



Lightcurves