



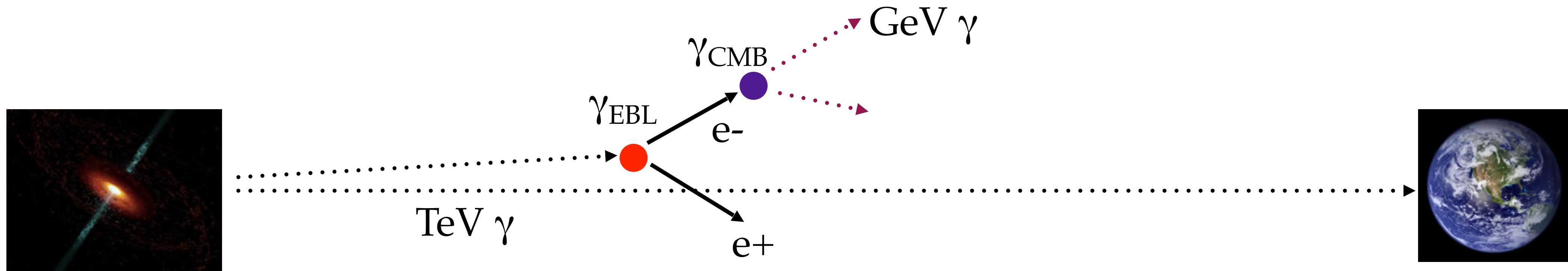
VERITAS Search for Magnetically-Broadened Emission From Blazars



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Probing the Intergalactic Magnetic Field (IGMF)



(Neronov & Semikoz, 2009)

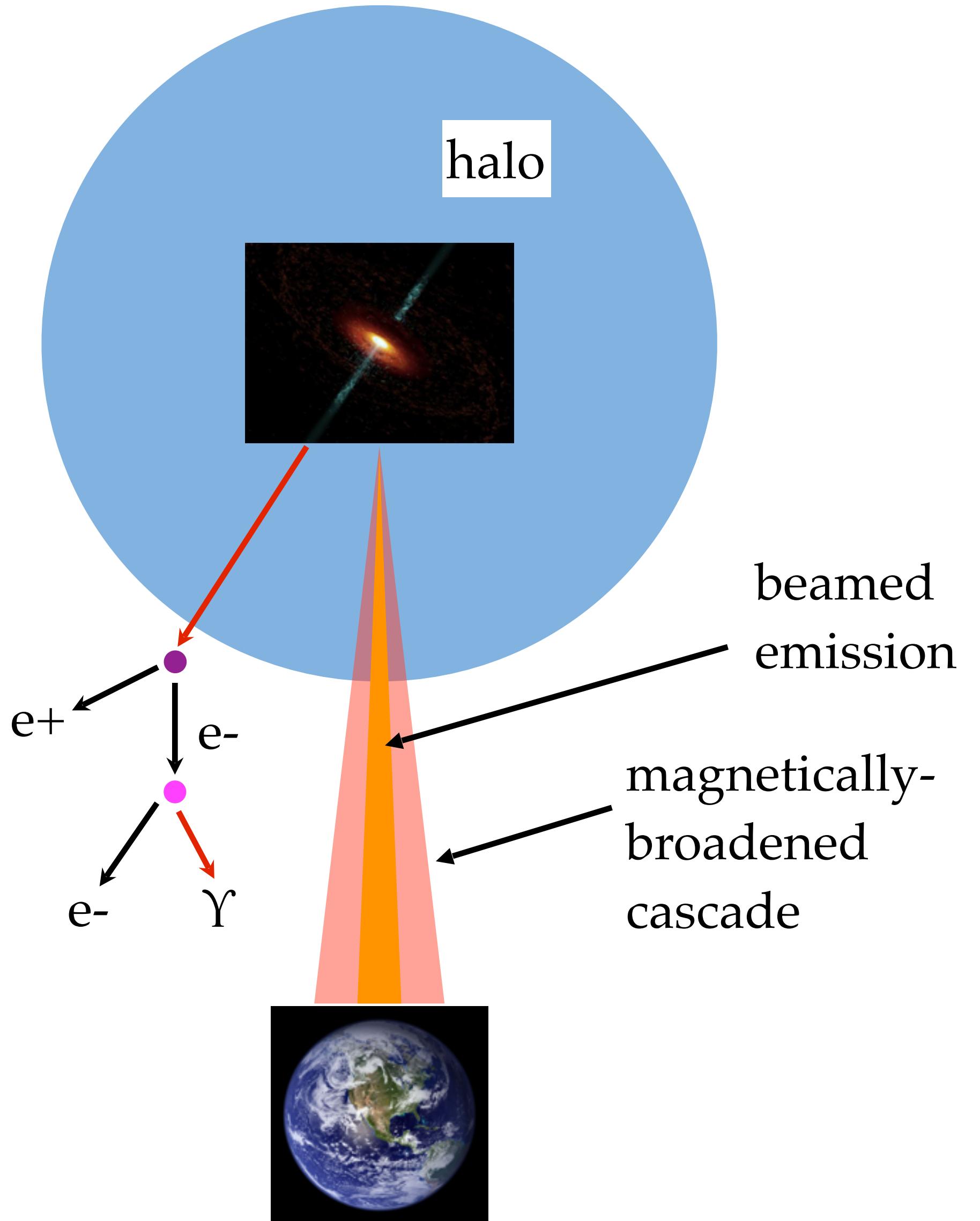
$$E_\gamma = \frac{4}{3} (1 + z_{\gamma\gamma})^{-1} \epsilon \frac{E_e^2}{m_e^2} \approx 0.32 \left(\frac{E_{\gamma_0}}{20 \text{ TeV}} \right)^2$$

ϵ = typical CMB photon energy

$\sim 10 \text{ TeV}$ initial photon $\rightarrow \sim 100 \text{ GeV}$ cascade photon

Probing the IGMF: Halos

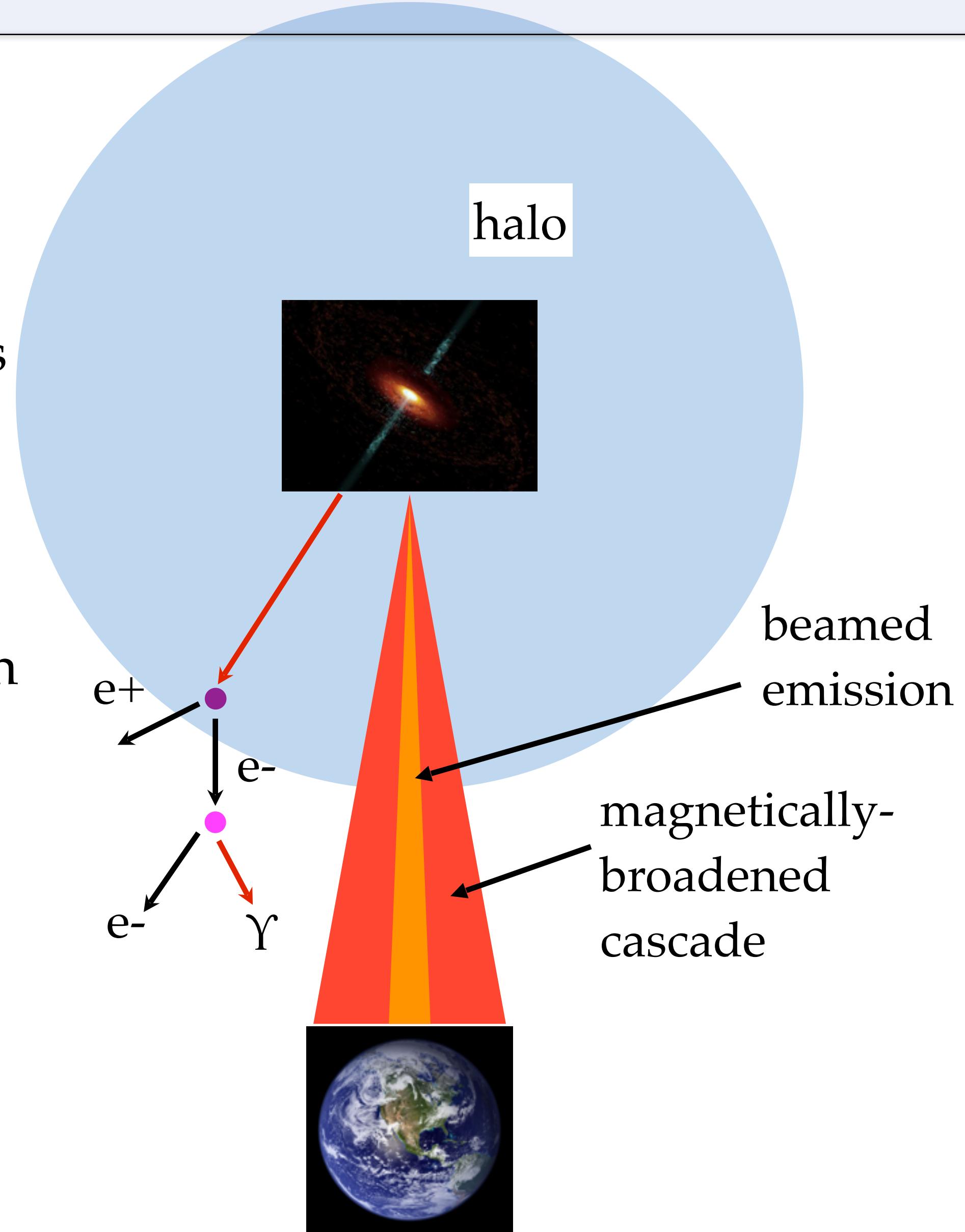
- IGMF strength $10^{-12} \text{ G} < B < 10^{-7} \text{ G}$
- Field strong enough to isotropize majority of e+ / e- pairs
- Secondary emission extremely time delayed
- Flux of secondary emission depends on blazar history
 - Insensitive to exact IGMF strength



Probing the IGMF: Magnetically-Broadened Cascades

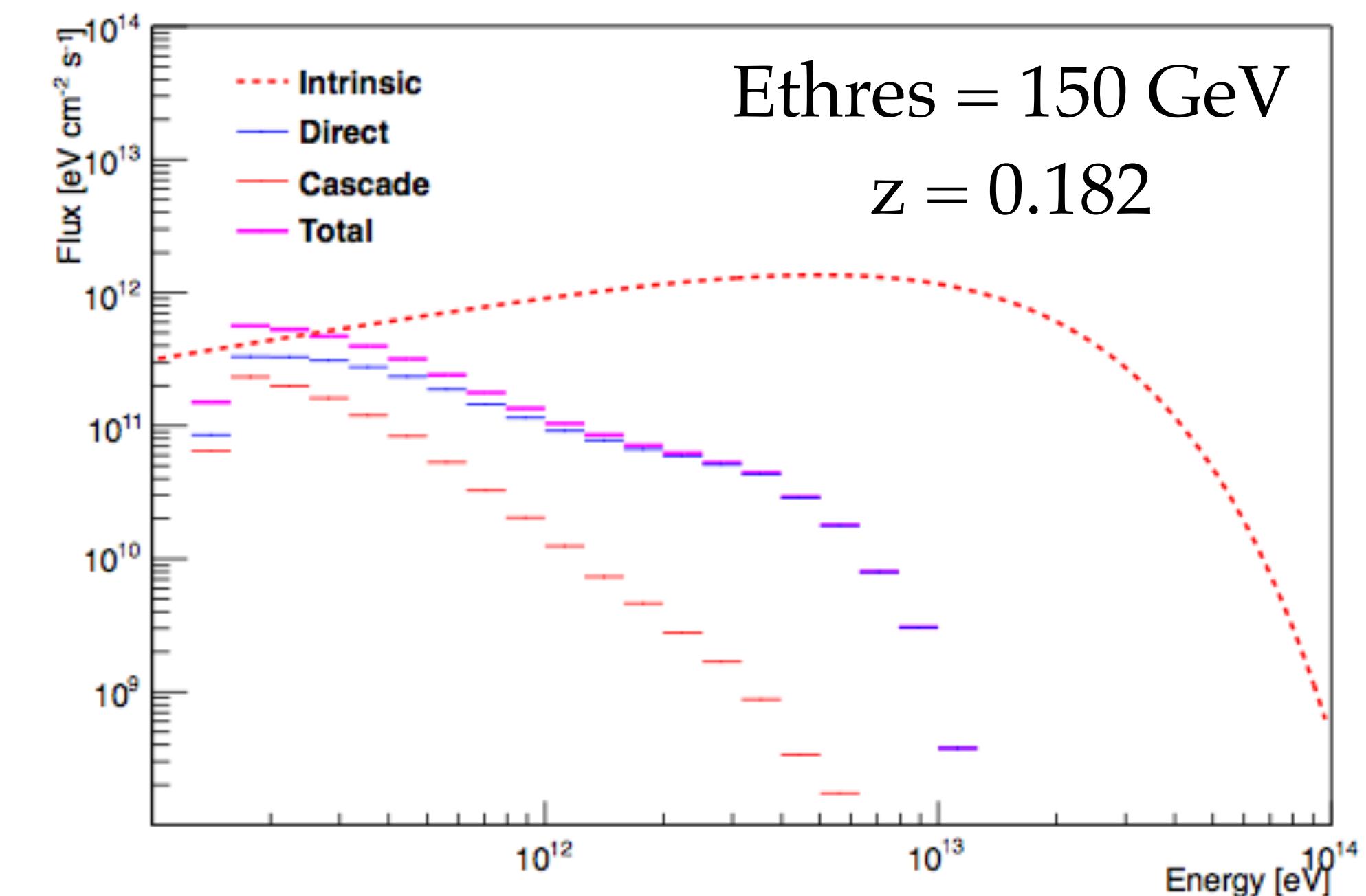
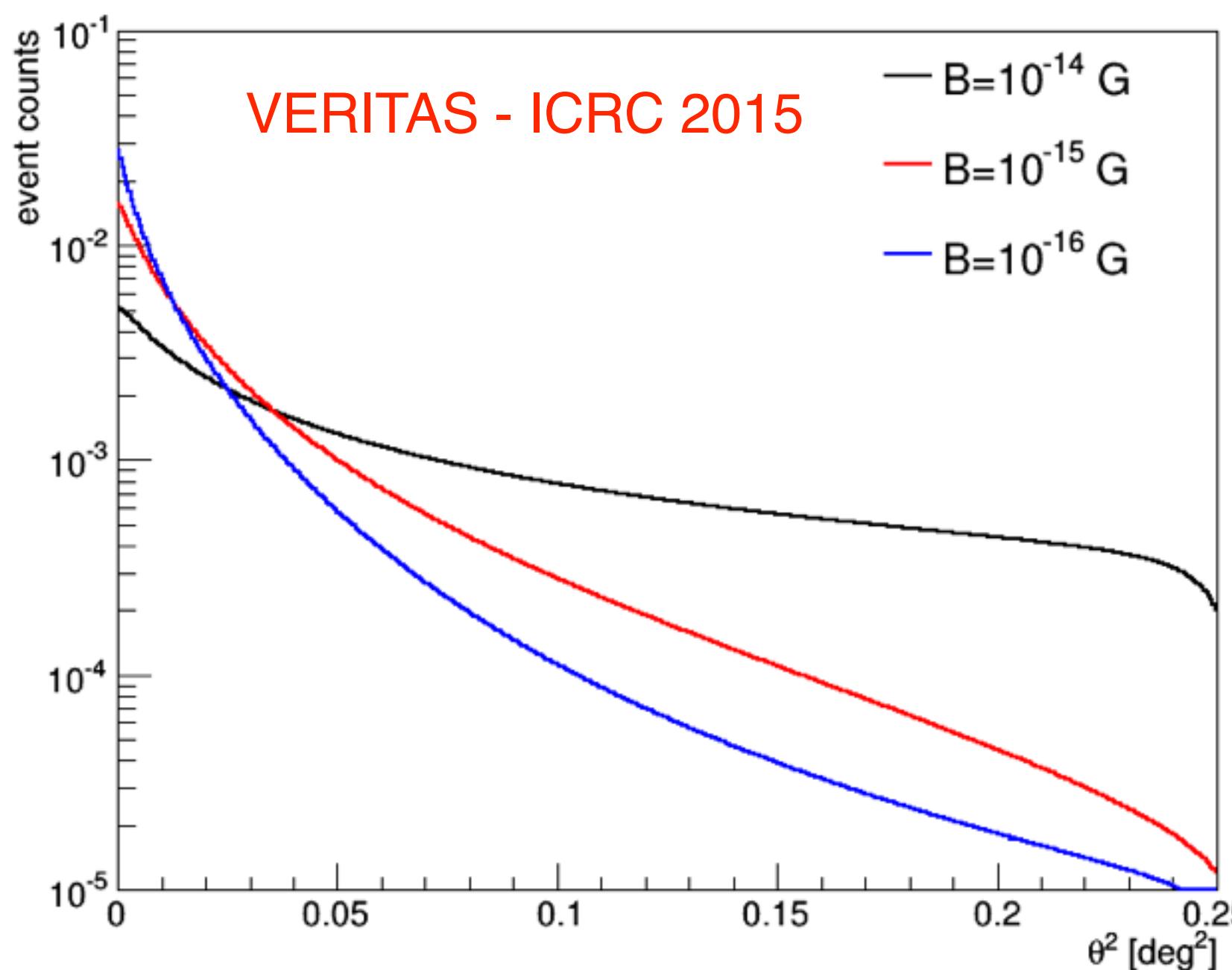
- IGMF strength $10^{-16} \text{ G} < B < 10^{-12} \text{ G}$
- Field not strong enough to isotropize majority of e^+ / e^- pairs
 - Cascade travels with beamed emission
 - Secondary emission slightly time delayed
 - Weaker fields detectable as time delayed secondary emission

Previous studies:
MAGIC: A&A 524, A77 (2010)
H.E.S.S.: A&A, 562, A145 (2014)
Fermi-LAT: Astrophys. J., 765, 54 (2013)



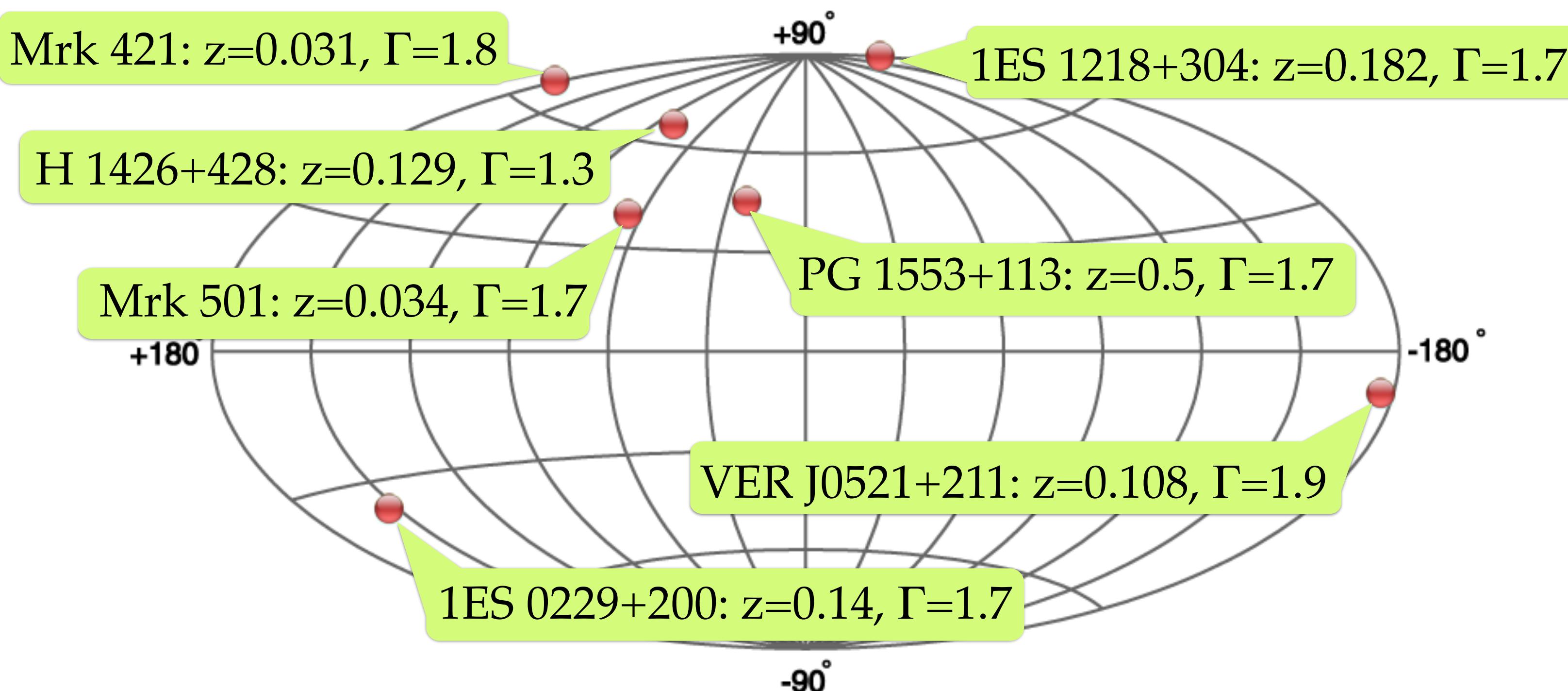
Predicted Angular Profiles

- Predicted angular profile sensitive to
 - Energy of primary γ s (spectral index and cut-off)
 - Source redshift
 - EBL model assumed



- Semi-analytic 3D cascade simulation: *H. Huan and T. Weisgarber. Proc. 32nd ICRC (2011)*
 - Assume EBL model of Gilmore 2012
 - Jet: Doppler factor = 10, viewing angle = 0°
 - Correlation length = 1 Mpc

Source List, Source Properties



Select hard spectrum blazars
Expect greatest sensitivity $z \approx 0.1-0.2$

High energy cut-offs from joint GeV-TeV spectral fits
Range from 0.7 TeV - 10 TeV (for sources w. no evidence for spectral break)

M. Di Mauro et al. Astrophys. J., 786:129 (2014)

The VERITAS Instrument

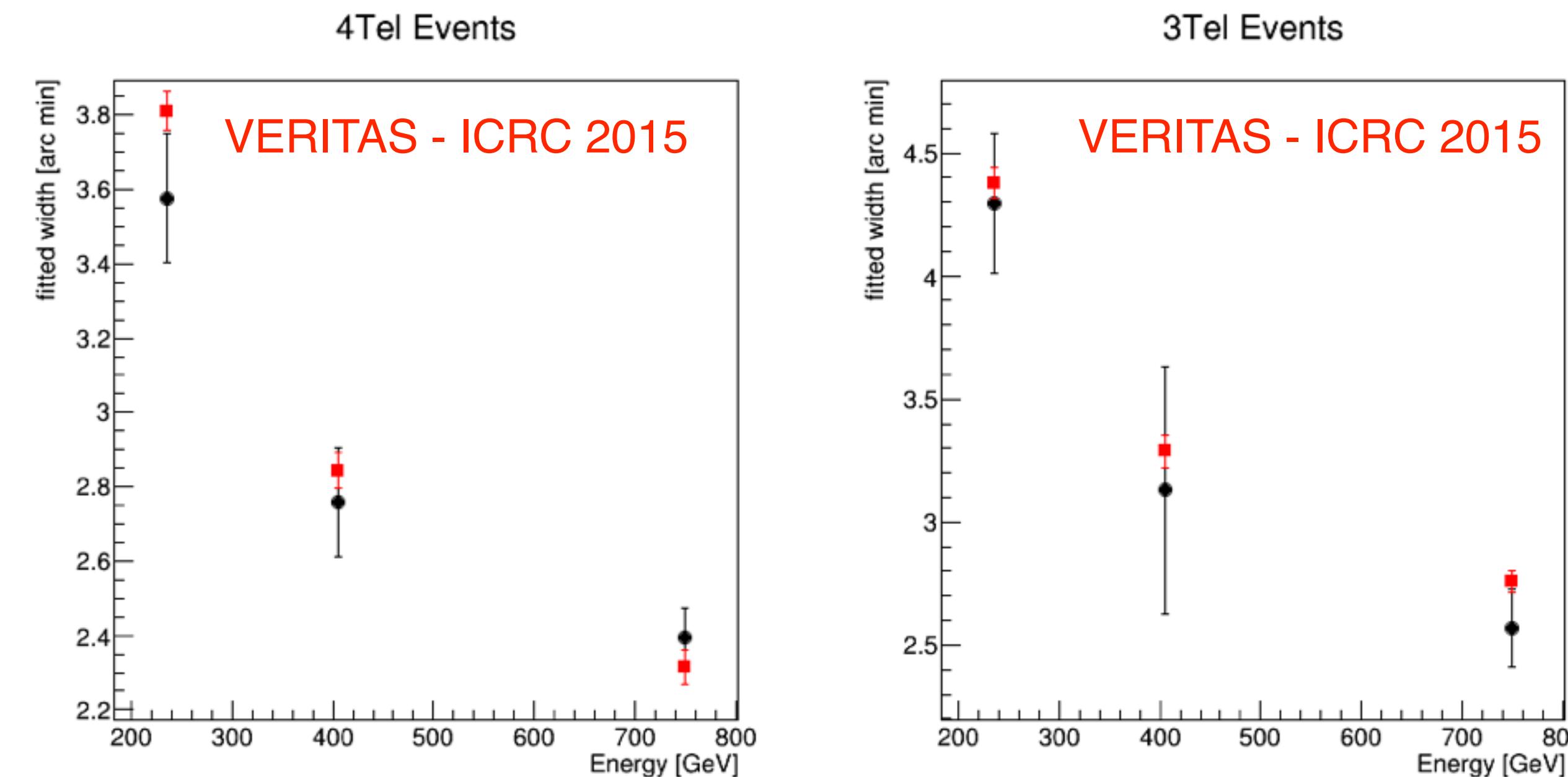


- Four 12m Imaging Atmospheric Cherenkov Telescopes located in southern Arizona
- Energy range: 85 GeV to > 30 TeV
- Energy resolution: 20% at 1 TeV
- Angular resolution: 0.1° at 1 TeV
- Field of view: 3.5°
- Point source sensitivity: 1% Crab in ~ 25 hr

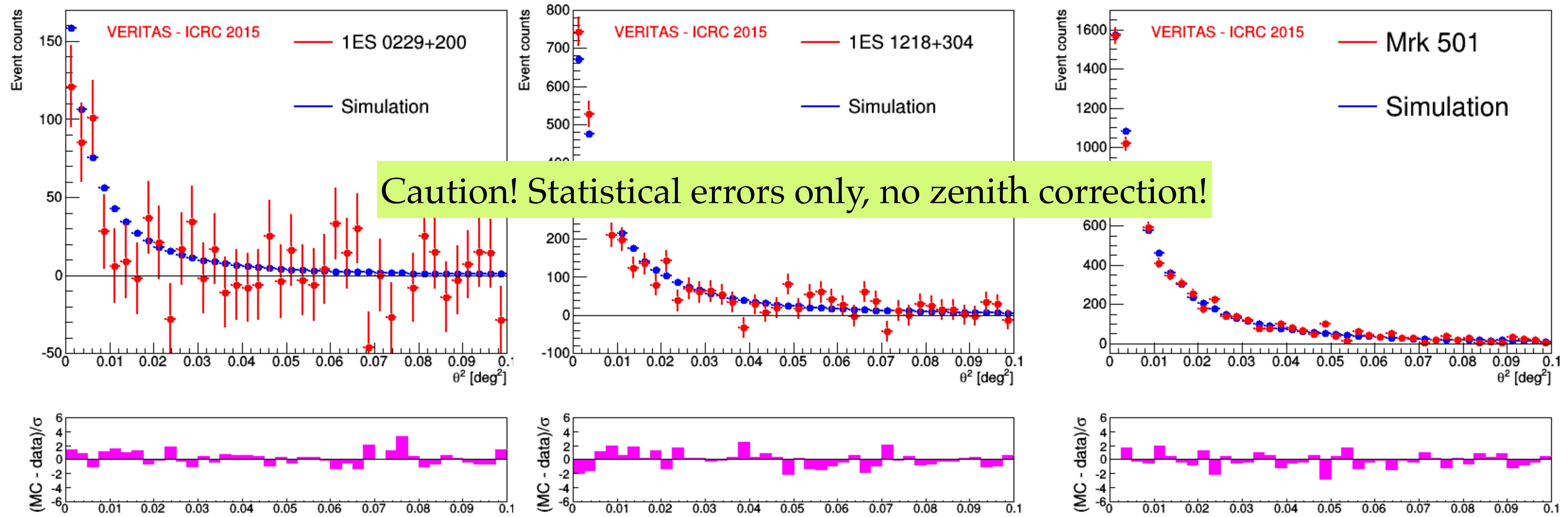


Simulating Point Sources

- Compare source's angular profile against a point source
- PSF depends on: Energy, Zenith angle of obs., Azimuthal angle of obs., Number of telescope images, Night sky background level
- Need use simulated point sources, but need to be convinced that simulation has it right!
- Data control sample: Mrk421 high state



Source/Simulated Point Source Agreement: Part I



Systematic Uncertainties & Zenith Correction

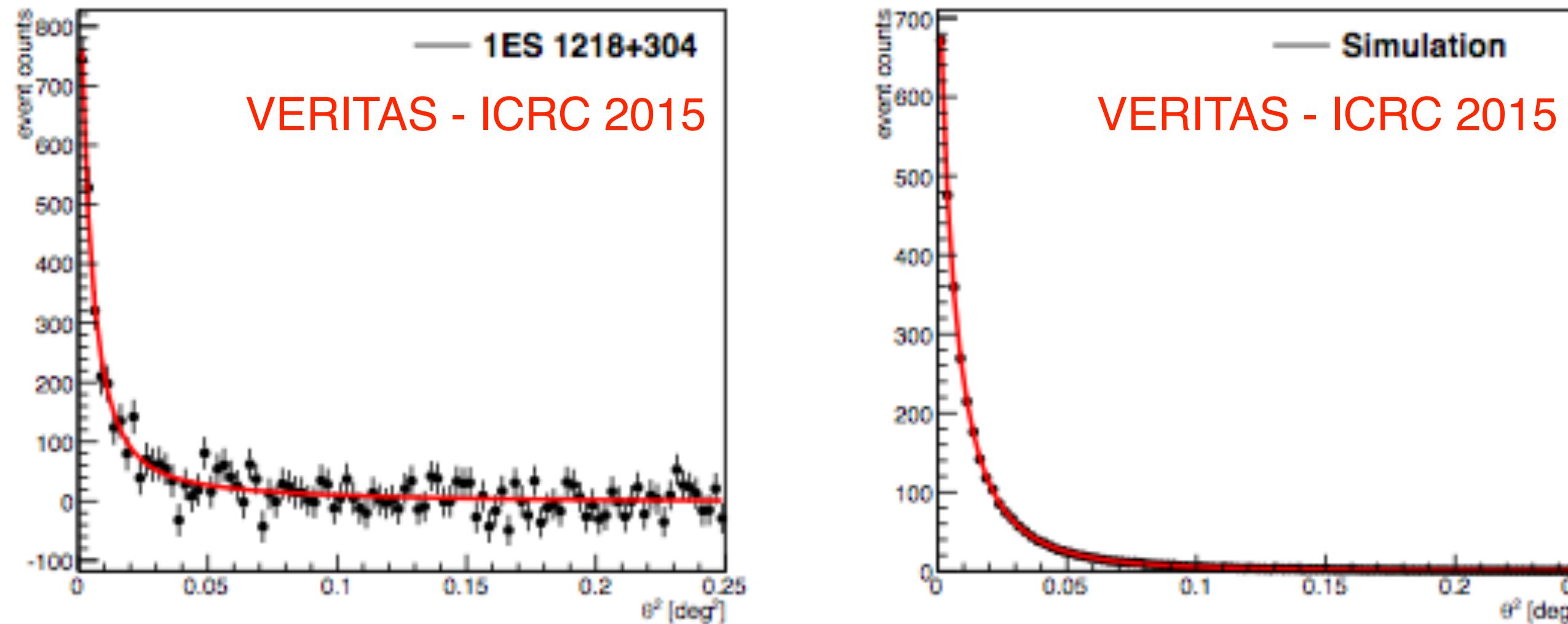
Mispointing: propagate 25" uncertainty

Energy resolution: propagate 20% uncertainty

Zenith correction: derive $PSF(Ze)$ from Crab data



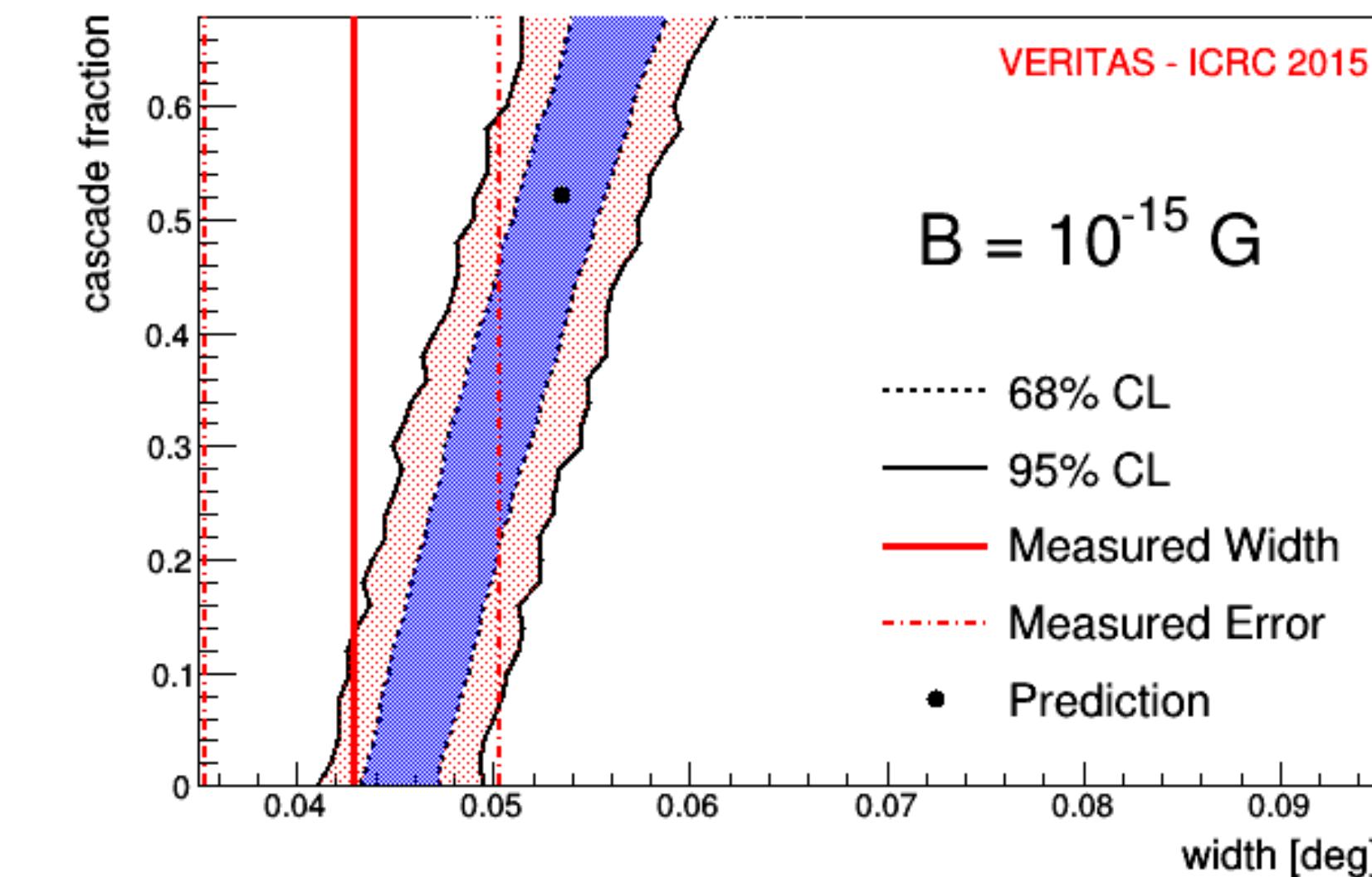
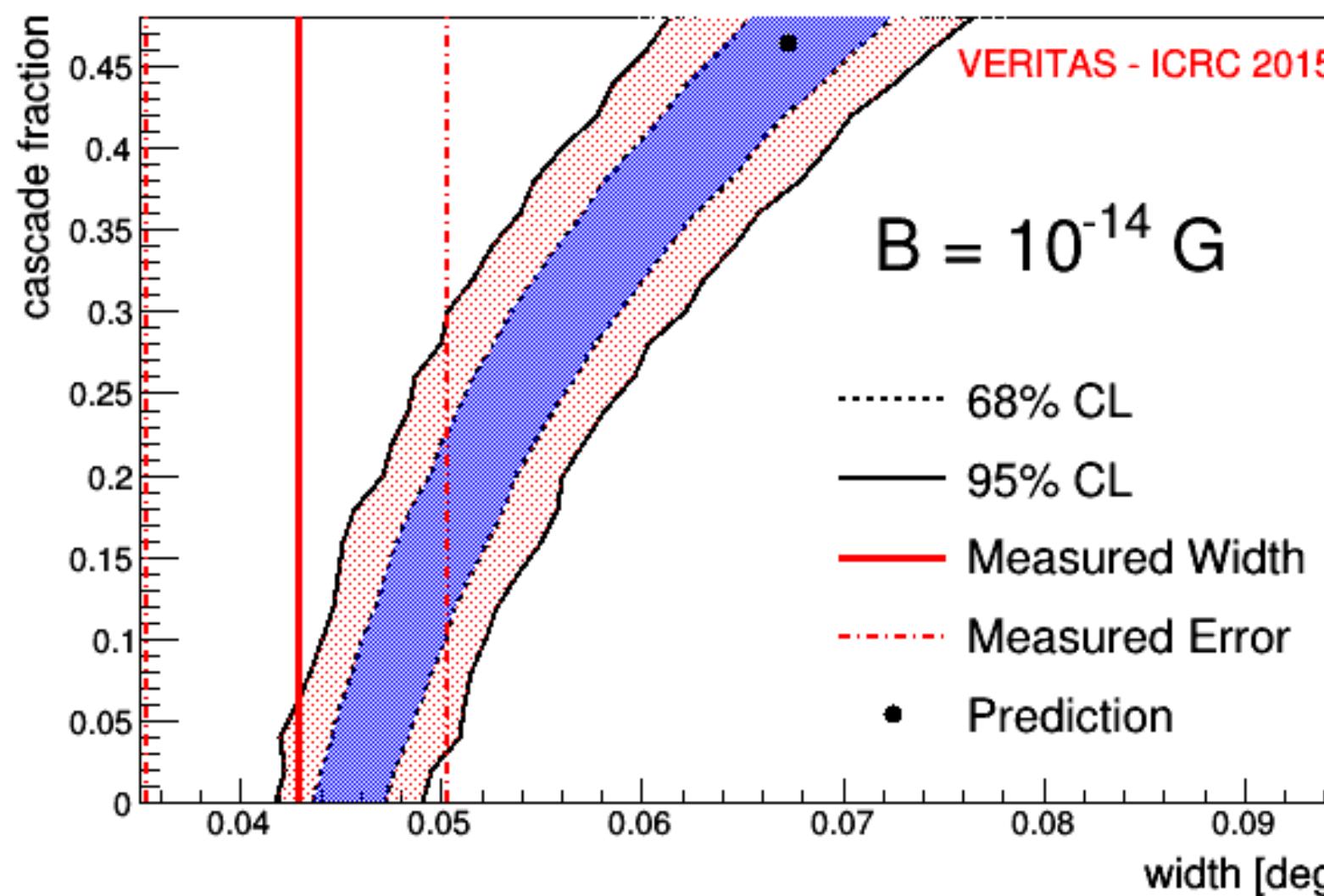
Source/Simulated Point Source Agreement: Part II



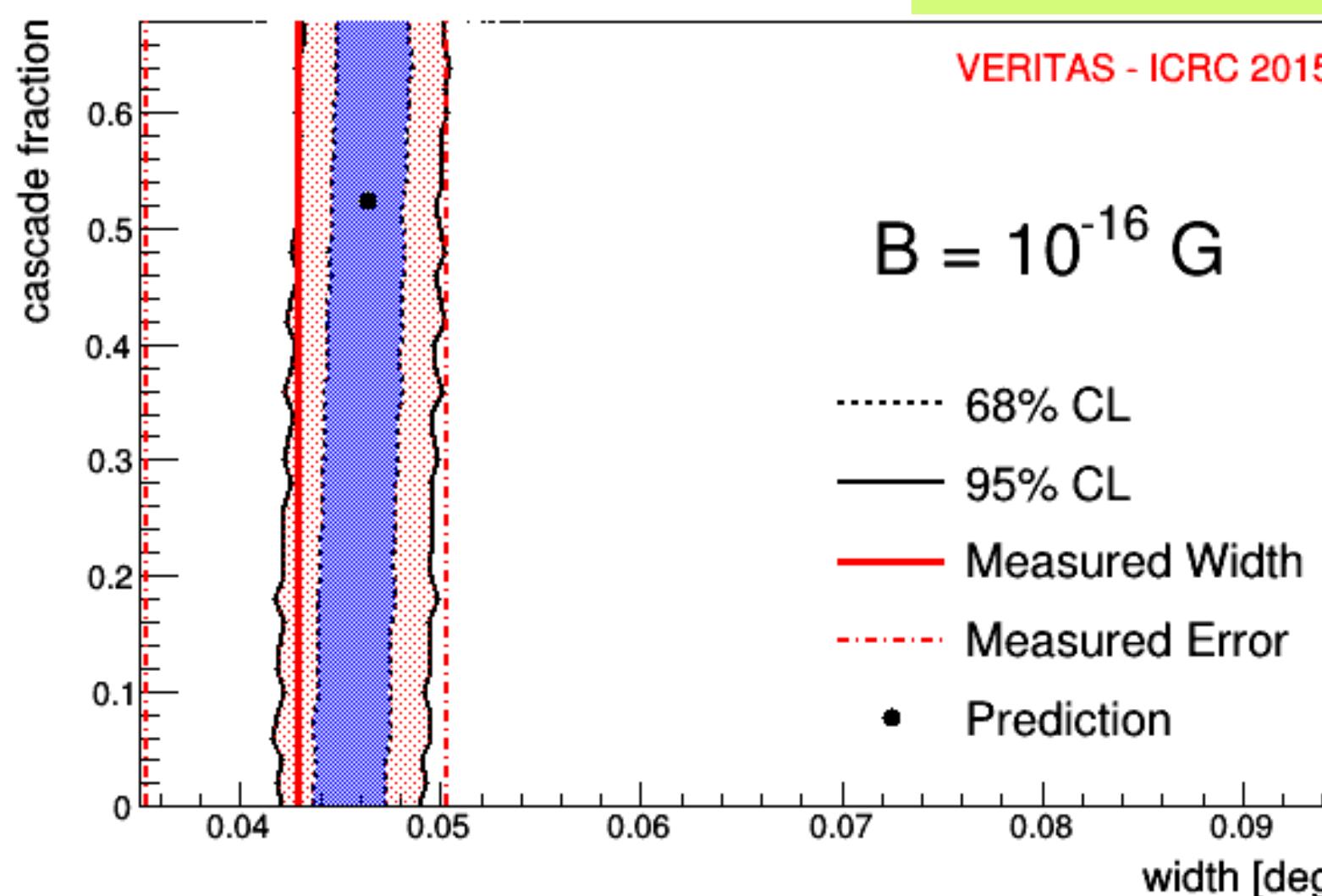
	$w_{data} \pm \sigma_{stat}$	$w_{sim} \pm \sigma_{stat} \pm \sigma_{syst}$
Mrk 421	$0.0483^\circ \pm 0.0004^\circ$	$0.0484^\circ \pm 0.0002^\circ \pm 0.0009^\circ$
Mrk 501	$0.0503^\circ \pm 0.0008^\circ$	$0.0481^\circ \pm 0.0003^\circ \pm 0.0007^\circ$
1ES 0229+200	$0.0429^\circ \pm 0.0075^\circ$	$0.0461^\circ \pm 0.0003^\circ \pm 0.0011^\circ$
H 1426+428	$0.0591^\circ \pm 0.0109^\circ$	$0.0547^\circ \pm 0.0003^\circ \pm 0.0014^\circ$
VER J0521+211	$0.0428^\circ \pm 0.0004^\circ$	$0.0451^\circ \pm 0.0002^\circ \pm 0.0012^\circ$
1ES 1218+304	$0.0468^\circ \pm 0.0020^\circ$	$0.0507^\circ \pm 0.0003^\circ \pm 0.0007^\circ$
PG 1553+113	$0.0558^\circ \pm 0.0021^\circ$	$0.0521^\circ \pm 0.0002^\circ \pm 0.0011^\circ$

Largest tensions 2.0σ (Mrk 501) and 1.9σ (1ES 1218+304)

Model-dependent Limits



Most constraining source: 1ES 0229+200



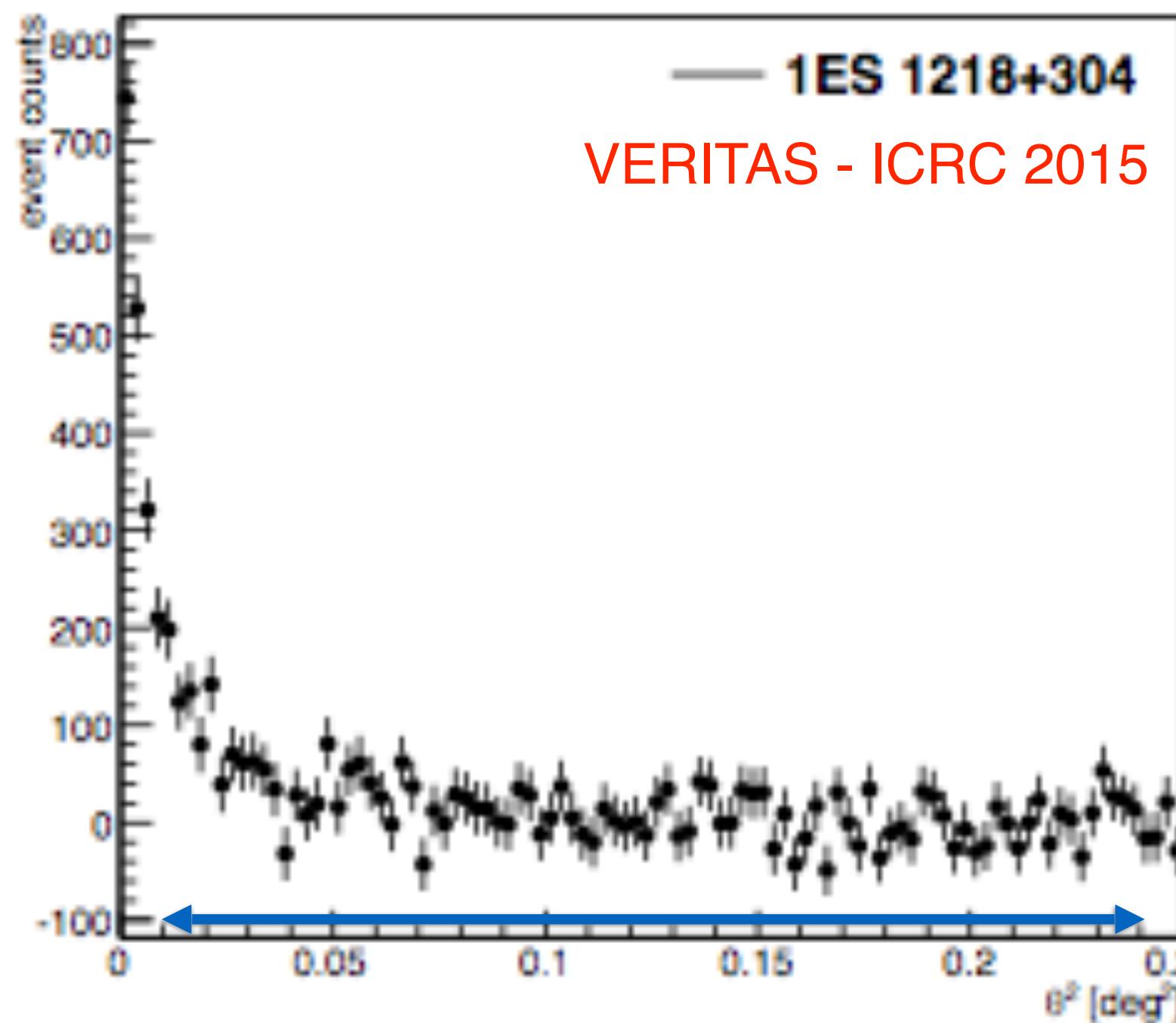
$B = 10^{-14} \text{ G}$ $< 0.18 @ 68\% \text{ CL}$
 $< 0.35 @ 95\% \text{ CL}$

$B = 10^{-15} \text{ G}$ $< 0.36 @ 68\% \text{ CL}$
 $< 0.78 @ 95\% \text{ CL}$

$(5.0\text{--}10.0)\times10^{-15} \text{ G}$ excluded @ 95% CL
(Note: for regime of field strengths considered)



Model-independent Limits on Flux from Extended Emission



$$excess = \int_{0.01}^{0.24} \theta_{Source}^2 - \int_{0.01}^{0.24} \theta_{SIM}^2$$

	99% $CL(\Gamma)$	99% $CL(\Gamma + 1)$
	[$10^{-12} cm^{-2} TeV^{-1} s^{-1}$]	[$10^{-12} cm^{-2} TeV^{-1} s^{-1}$]
Mrk 421	0.62	0.50
Mrk 501	2.69	2.16
1ES 0229+200	0.64	0.58
H 1426+428	1.23	1.18
VER J0521+211	0.20	0.17
1ES 1218+304	0.58	0.46
PG 1553+113	1.83	1.48

Conclusions.

- Search for extended emission on a large sample of hard-spectrum blazars
 - Range of redshifts
 - Model-independent limits set on flux due to extended emission
 - $(0.17\text{--}2.69) \times 10^{-12} \text{ cm}^{-2}\text{TeV}^{-1}\text{s}^{-1}$
 - Model-dependent limits set
 - Best limits from 1ES 0229+200
 - Exclude IGMF strengths $(5.0\text{--}10.0) \times 10^{-15} \text{ G}$ at 95% CL

