Searches for Angular Extension in High-Latitude Fermi-LAT Sources

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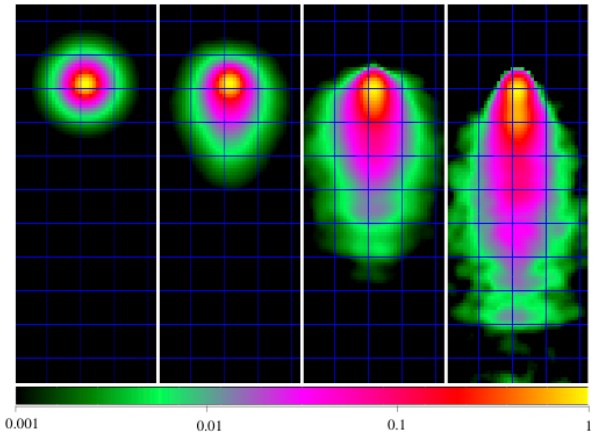
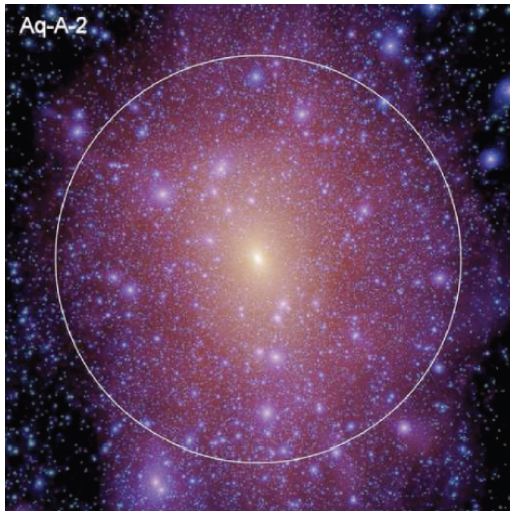
Motivation

- The majority of high-latitude Fermi-LAT sources is observed to have point-like emission consistent with populations of gamma-ray AGN and pulsars

Neronov et al. 2010

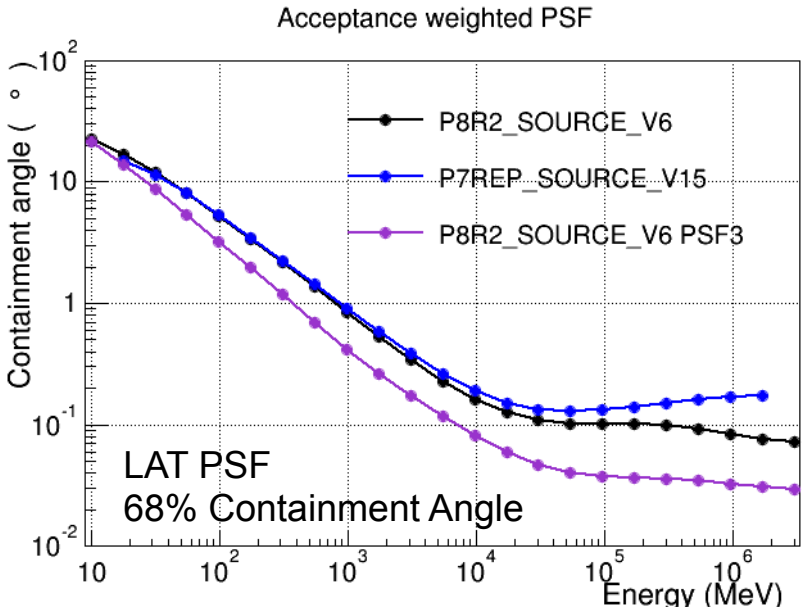


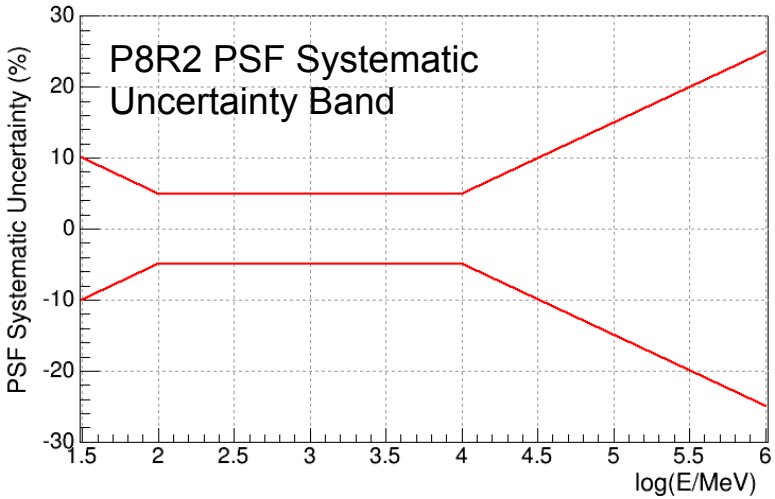
- Detection of angular extension in high-latitude sources has potentially interesting physics implications, e.g.
  - Intergalactic Magnetic Field (IGMF)-induced broadening of pair cascades - “pair halos”
  - Dark matter annihilation or decay in subhalos of the Milky Way



LAT High-Latitude Extension Catalog

- The LAT high-latitude extension catalog is a comprehensive search for angular extension in high-latitude 3FGL sources (|b| > 5 deg) using 7.5 years of Pass 8 data
- Pass 8 data release provides several improvements that increase the sensitivity of the LAT to angular extension
  - Better high-energy PSF (E > 10 GeV)
  - New PSF event type selections
- Catalog Data Selection
  - P8R2_SOURCE class data
  - E = 1-316 GeV
  - Binned likelihood with joint fit to PSF0-PSF2 (evtype=28) and PSF3 (evtype=32) event type selections





Analysis Pipeline

- Analysis performed with Fermi Science Tools and the fermipy package -- https://github.com/fermiPy/fermipy

- Starting from the 3FGL catalog (based on 4 years of P7REP data) we optimize each ROI as follows
  - Refit spectral parameters of 3FGL sources
  - Relocalize 3FGL sources
  - Add new point source (PS) candidates with TS > 9

- Source-finding is performed in two stages
  - 1. Add PS candidates found more than 1 deg from the ROI center
  - 2. Iteratively add PS candidates to the inner ROI (R < 1 deg) while testing for extension until no more sources are found with TS > 9

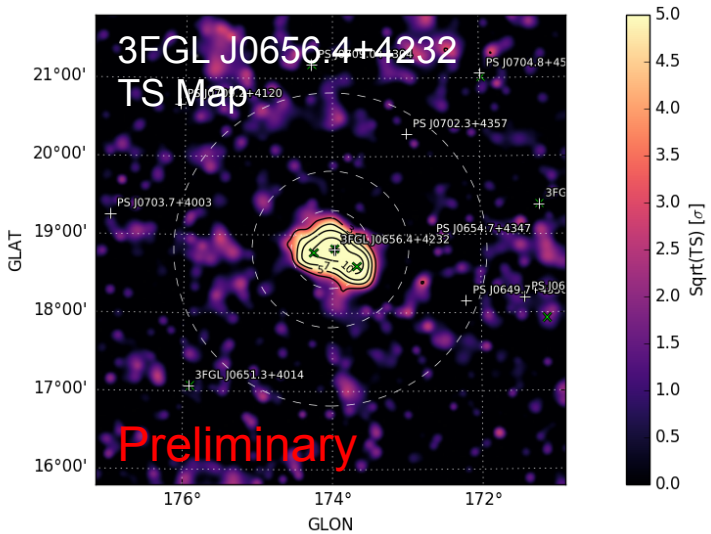
Extension Modeling

- We test each source for extension with a symmetric 2D Gaussian with angular size R_{68} (68% containment radius) from 0 to 1.7 deg

- After each iteration of source finding we evaluate the evidence for extension by testing two hypotheses against a single PS model
  - Extension (TS_{ext})
    - **Spatial Model**: 2D Gaussian
    - **Spectral Model**: Same as 3FGL Source
  - Halo (TS_{halo})
    - **Spatial Model**: 2D Gaussian on top of PS (same position)
    - **Spectral Model**: PowerLaw with free norm and index

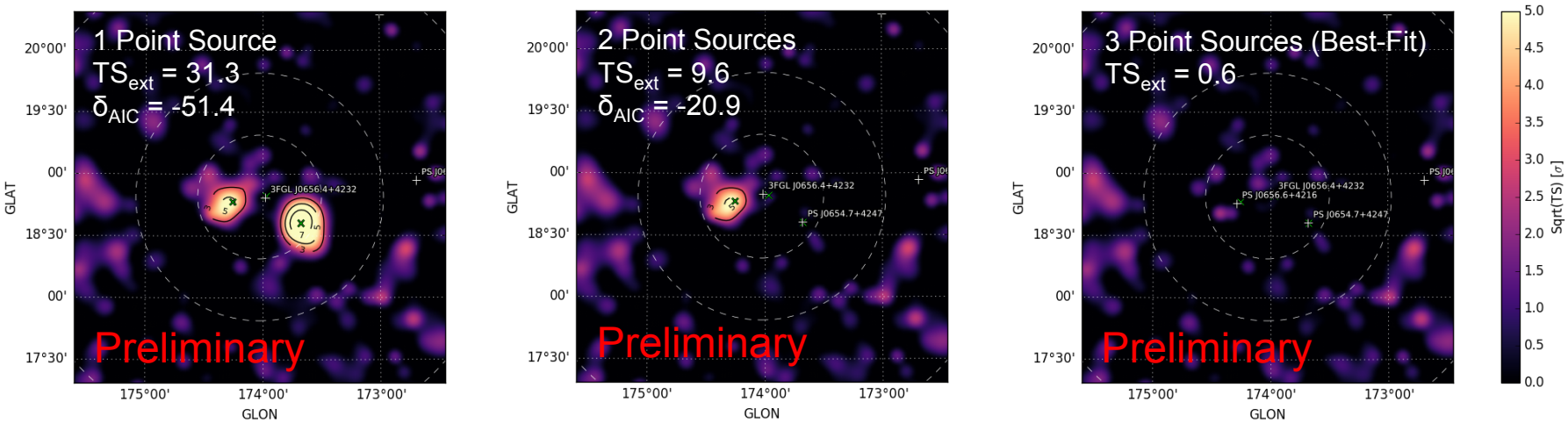
- We additionally extract halo SEDs on a grid of R_{68} values that we use to evaluate the likelihood of cascade models with arbitrary spectra and energy-dependent morphology

ROI Optimization



- At each source-finding iteration we add the highest TS PS candidate to the model and compare the likelihood of models with N+1 PS and N PS + extension
- The best-fit model is chosen when no additional PS candidates are found OR extension is preferred over an additional PS according to the Akaike Information Criterion (AIC)

$$\delta_{AIC} = AIC_{N+1\ PS} - AIC_{N\ PS\ +\ ext}$$



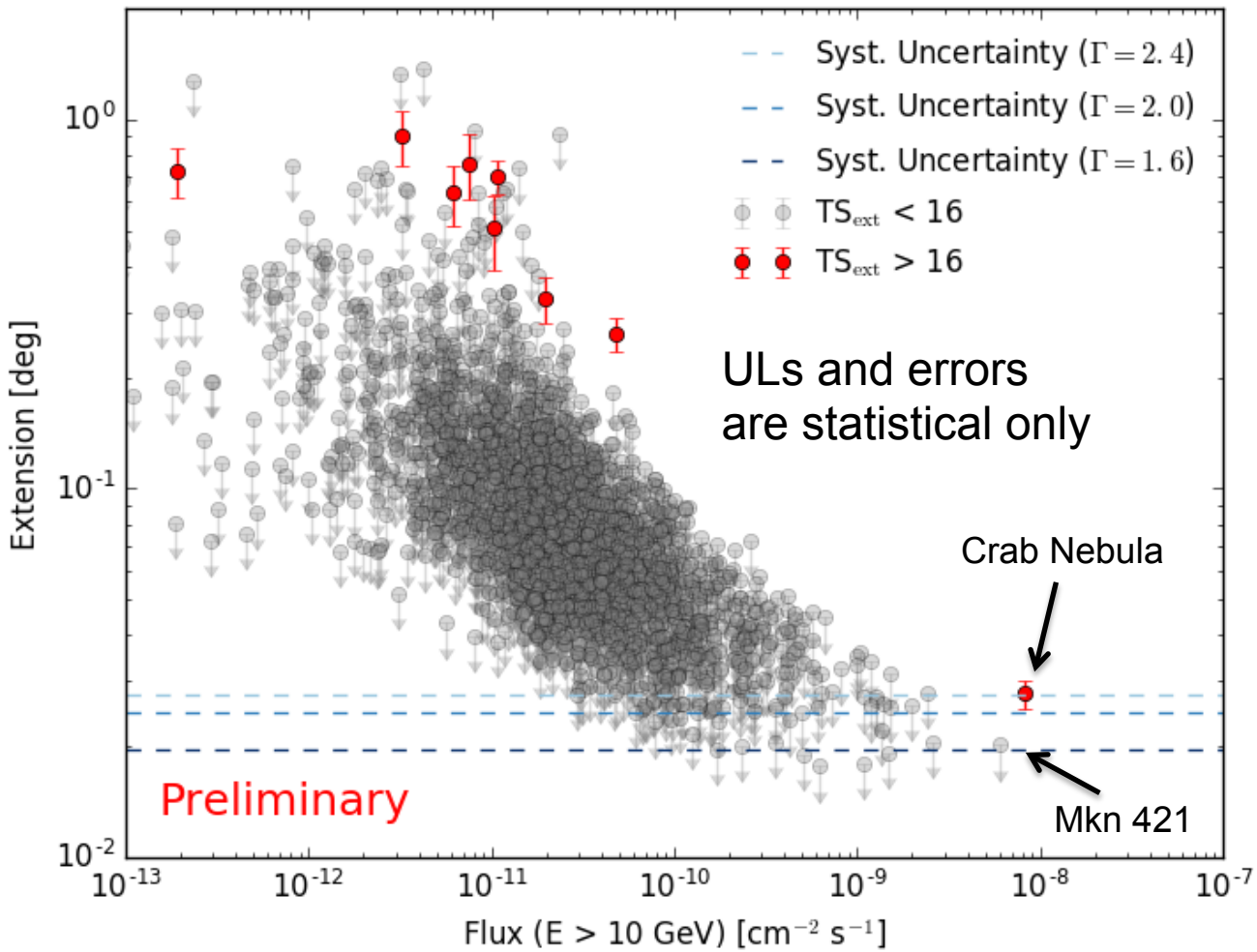
Extended Source Candidates

- High-latitude 3FGL sample contains 2472 objects of which we identify 33 as extended source candidates
  - 10 sources with $TS_{ext} > 16$ and $TS_{halo} > 16$
  - 33 sources with $TS_{halo} > 16$

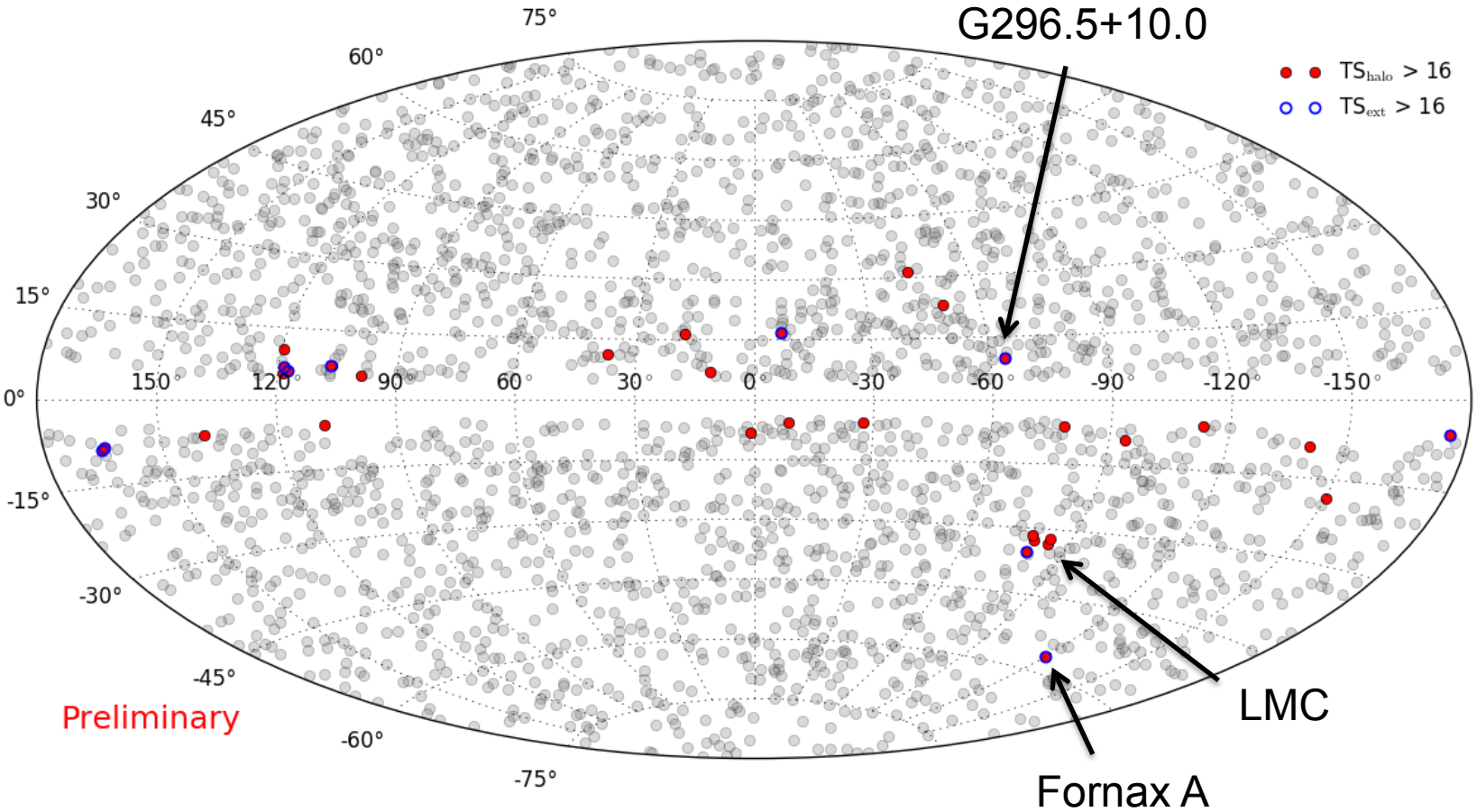
- Known extended sources not included in the 3FGL
  - New LMC components (Ackermann et al. 2015)
  - Fornax A (Ackermann et al. 2016)
  - G296.5+10.0 (Acero et al. 2016)

- Majority of candidates are unassociated sources with 0.5-1 deg scale extension and $|b| < 20$ deg
  - Latitude distribution suggests Galactic origin
  - May be associated with residuals in the Galactic diffuse model

Extended Candidates

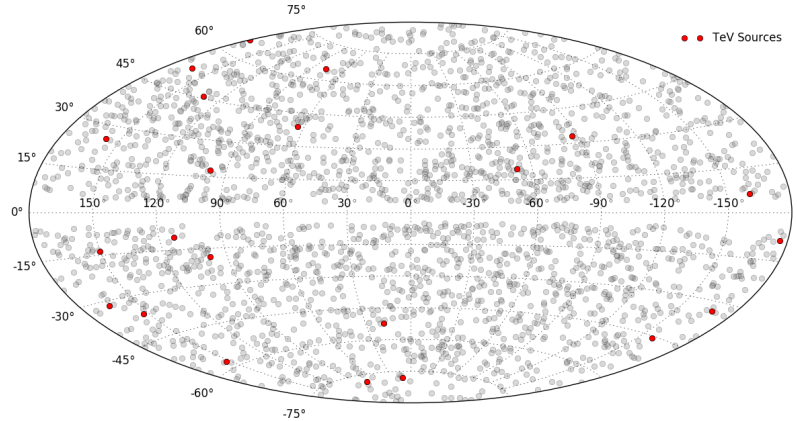


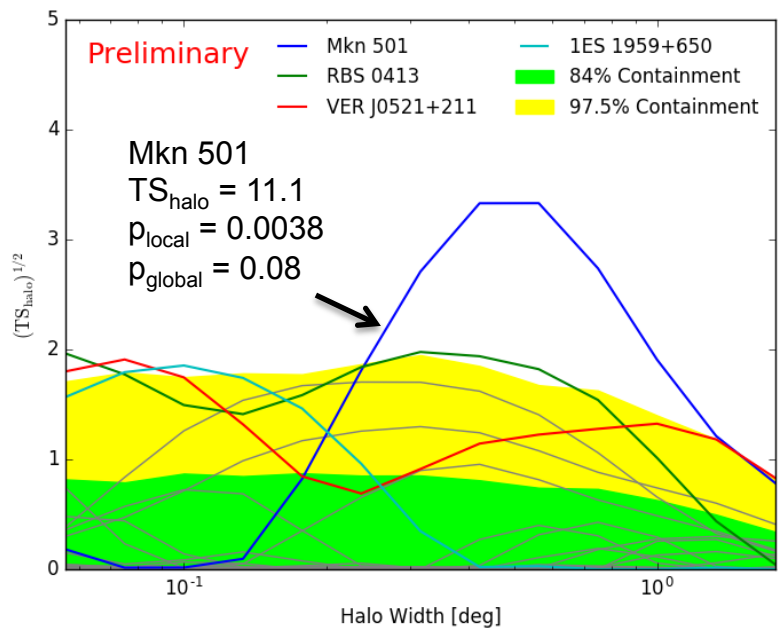
Extended Candidates



TeV-Selected Sources

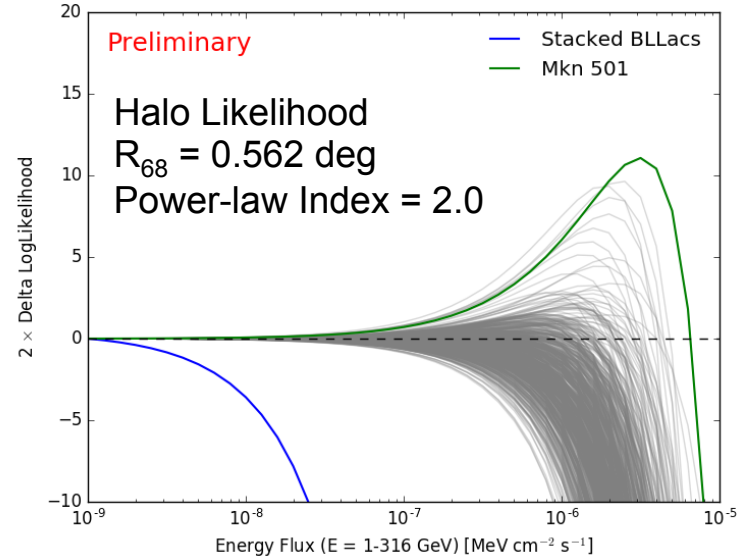
- Sources with strong TeV emission provide the best prospects for detection of pair cascades
- We consider a sample of 22 objects with well-characterized TeV spectra (IACT observations by H.E.S.S., VERITAS, MAGIC)
- No evidence for extended emission is found – expectation bands for TS_{halo} derived from sample of 650 BL Lac objects
- Largest excess observed for Mkn 501 (BL Lac at z = 0.034)
  - TS_{halo} = 11.1 for R_{halo}=0.5 deg
  - Consistent with expectations from BL Lac control sample (p_{global} = 0.08)

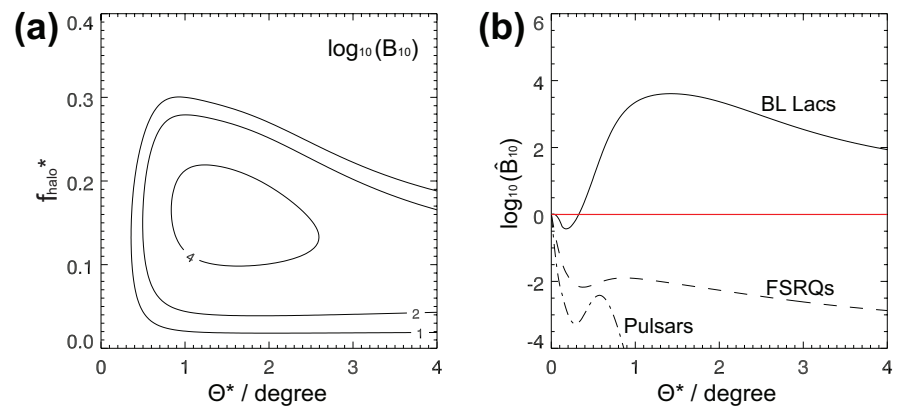




Stacking Analysis

- We use a stacking analysis to test for evidence of extended emission in different source populations (BL Lac, FSRQ, etc.)
- Chen et al. 2015 have claimed evidence for extended emission in a sample of 24 HSP BL Lacs drawn from the 1FHL
- Stacking is performed by summing the log-likelihood profiles for a given object sample and population model
  - Halo with fixed size (R_{68}) and constant fractional amplitude (f_{halo})
  - Halo with fixed size (R_{68}) and constant absolute flux (F_{halo})
  - Extension with fixed angular size

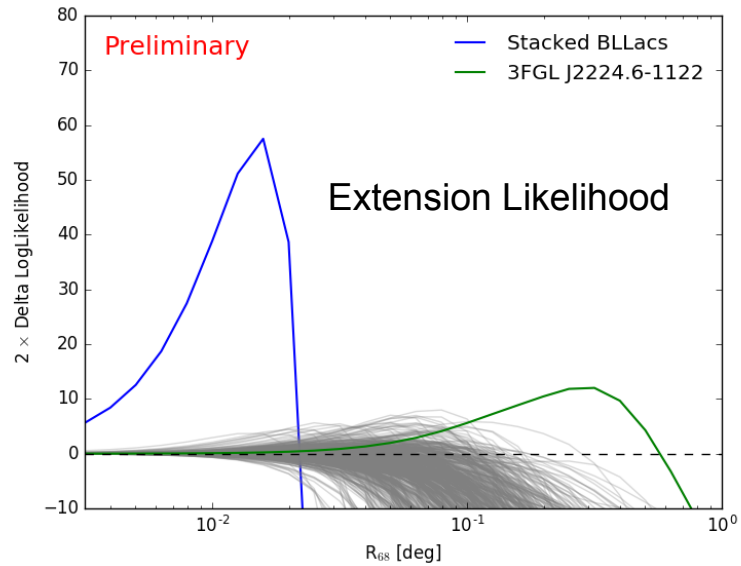




Chen et al. 2015

Stacking Results

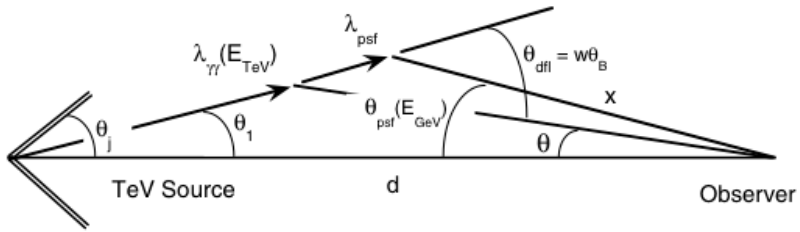
- No evidence for a halo component in any of the samples tested
- PSR and BL Lac samples both show evidence for extension
  - R_{68} = 0.02-0.03 deg
  - Angular size is consistent with extension induced by PSF systematic uncertainty

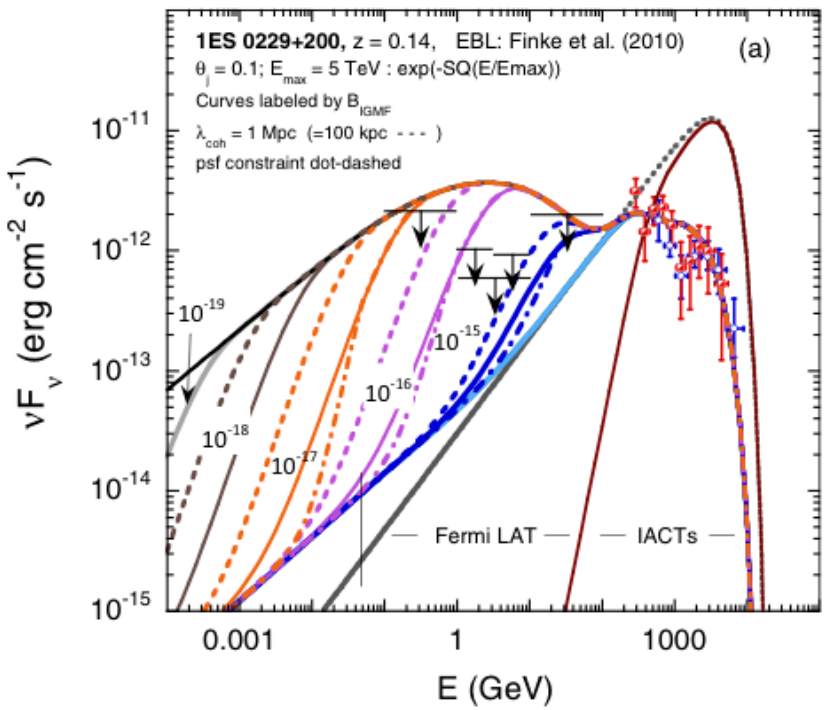


Sample	N_{obj}	TS_{ext}	TS_{halo} (const. fractional amplitude)
Chen et al. 2015	24	0.5	0.0
TeV-Selected AGN	22	9.1	2.5
BL Lac	648	57.6	1.8
FSRQ	444	12.9	1.9
PSR (excluding Crab PSR)	87	21.7	10.8
BCU	498	0.7	0.0
Unassociated	503	0.0	0.7

Constraining the IGMF with TeV Blazars

- Pair production of TeV photons produces cascades which are deflected by the IGMF
- Amplitude and angular size of the cascade component carries information about the IGMF strength (B_{IGMF}) and coherence length scale (L_{coh})
- Absence of GeV emission in TeV Blazars has been used to set strong constraints on IGMF (see e.g. Neronov and Vovk 2010, Tavecchio et al. 2011, Dermer et al. 2011, Finke et al. 2015)





Dermer et al. 2011

IGMF Modeling Analysis

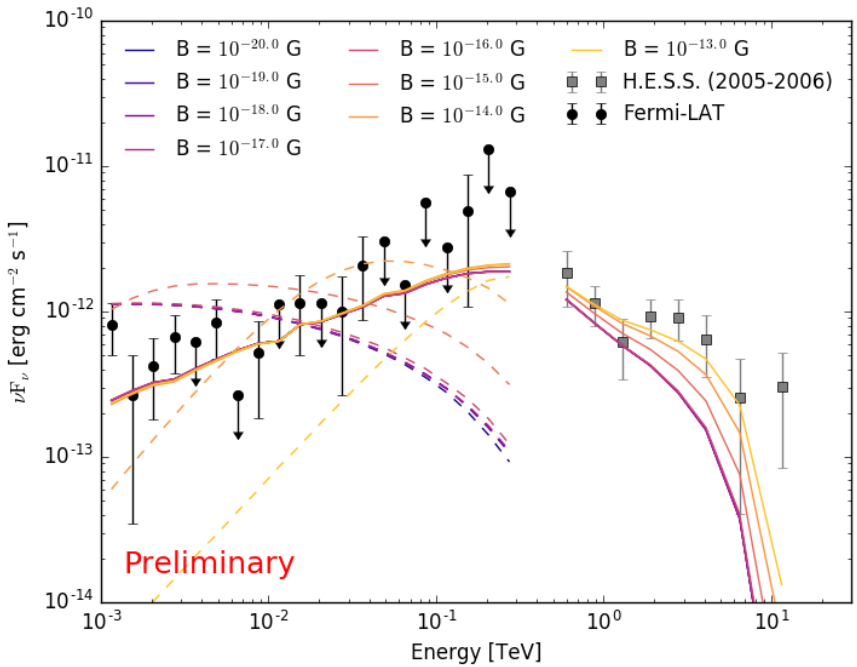
- IGMF analysis focuses on sources with well-measured TeV spectra from IACT observations
- Cascade model calculation performed with ELMAG MC simulation package (Kachelrieß et al. 2012)
- Input source parameters
  - Redshift
  - Jet opening angle (1-10 deg)
  - Activity time scale (10 yr – 10 Myr)
  - EBL Model (Dominguez et al. 2011)
  - Observation Angle (fixed to 0)
- IGMF constraints derived from joint GeV (morphology + spectrum) and TeV (spectrum-only) likelihoods

$$\ln L(B, L_{coh}) = \ln L_{casc,GeV} + \ln L_{prim,TeV} + \ln L_{prim,GeV}$$

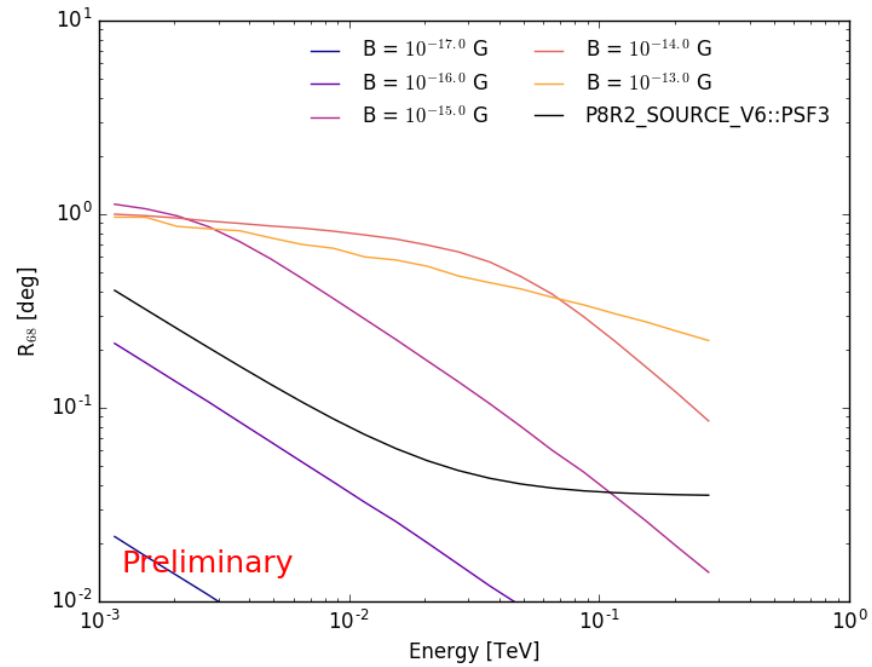
- For each point in the IGMF parameter space (B and L_{coh}) we fit for the parameters of the primary injection spectrum modeled as a power law with an exponential cutoff

IGMF Constraints: 1ES 0229+200

Primary and Cascade Flux



Cascade Angular Size (68% containment)

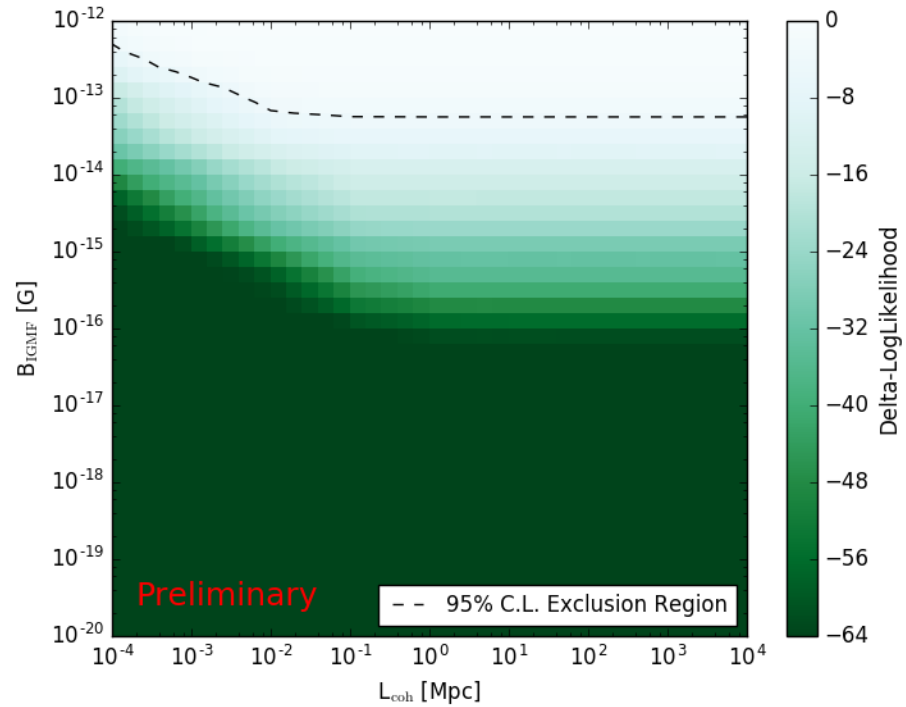


TeV Spectrum: 1ES 0229+200 (HESS 2005-2006)
Jet Angle: 6 deg
T_{max} = 10 Myr
z = 0.14
L_{coh} = 1 Mpc

IGMF Constraints: 1ES 0229+200

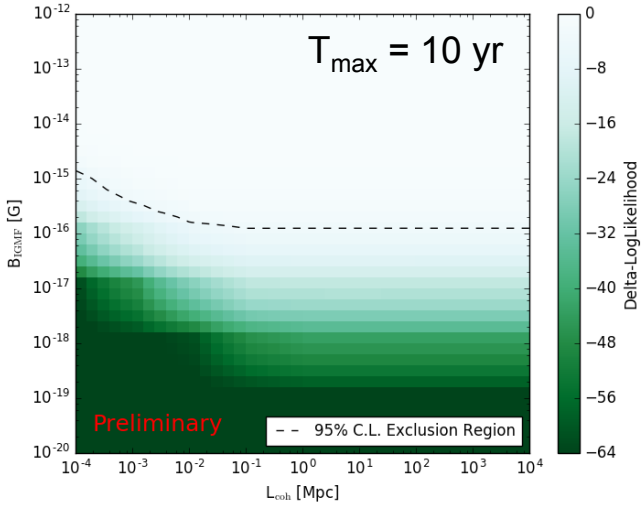
- IGMF exclusion region defined by condition $\ln L_{IGMF}(B_{IGMF},L) - \ln L_{null} < -3.0$ where L_{null} is the likelihood for the no cascade hypothesis (equivalent to high IGMF model)

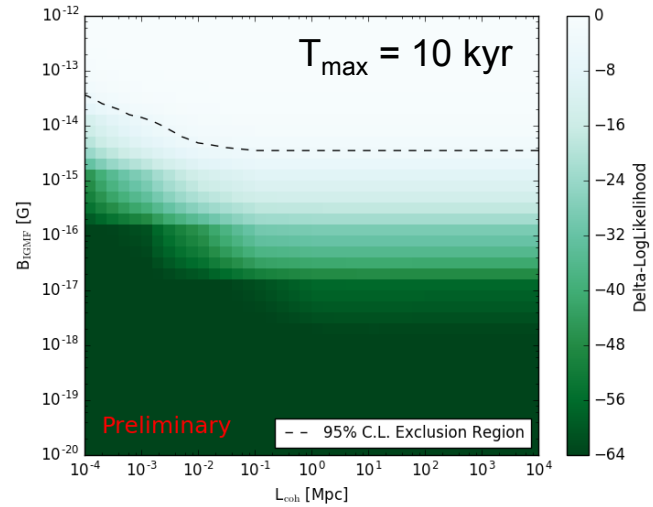
- In the optimistic scenario (T_{max} = 10 Myr) we derive a lower limit $B_{IGMF} > 10^{-13}$ G



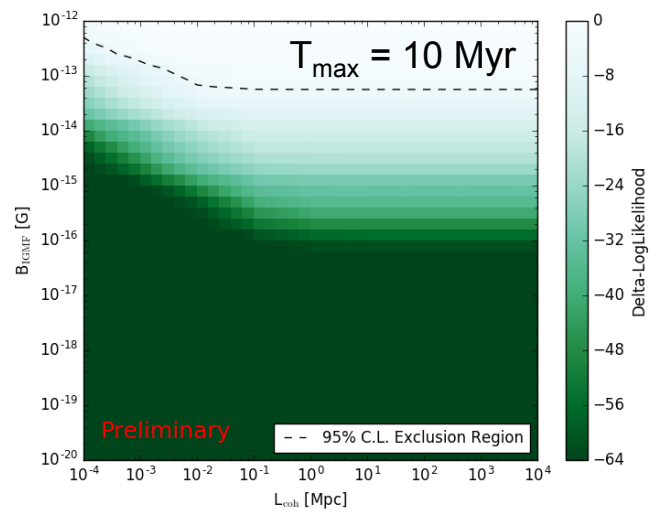
TeV Spectrum: 1ES 0229+200 (HESS 2005-2006)
Jet Angle: 6 deg
T_{max} = 10 Myr

IGMF Constraints vs. Activity Time





- Activity time scale is the dominant factor in determining the constraining power of the analysis
- Using the most conservative time-scale (10 yr) weakens limits by 3 orders of magnitude



Summary

- No evidence for extended emission in extragalactic source populations
  - No detection in TeV-selected AGN, BL Lacs, or unassociated source samples
  - Detection in 1FHL sample claimed by Chen et al. is not confirmed

- Joint GeV-TeV analysis of TeV-selected Blazars sets lower limits on B_{IGMF} depending on what is assumed for the source activity timescale
  - $B_{IGMF} > 10^{-13}$ G (active for ~10 Myr)
  - $B_{IGMF} > 10^{-16}$ G (active for ~10 yr)

- Ongoing Work
  - DM subhalo interpretation (testing compatibility with DM spectra)
  - Exploration of additional sample selection criteria