PRELIMINARY RESULTS FOR THE *FERMI* HIGH LATITUDE EXTENDED SOURCE CATALOG

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TeVPa 2017

Columbus, Ohio

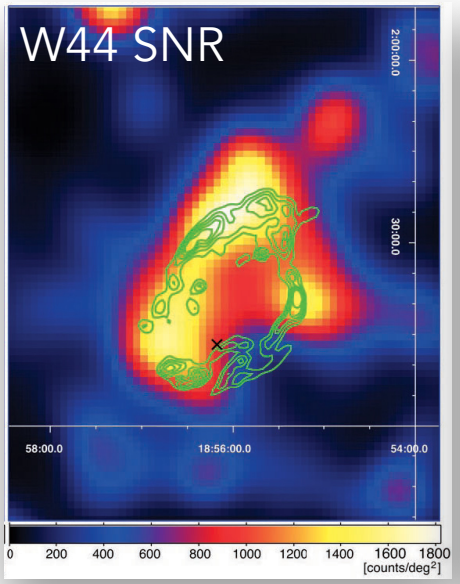
August 9, 2017

Unterstützt von / Supported by

Alexander von Humboldt
Stiftung/Foundation

MOTIVATION

- Observation of extended γ-ray sources probe **acceleration of relativistic particles**
- **Most known extended sources are within Milky Way disk**: supernova remnants (SNRs), pulsar wind nebulae (PWNe), star forming regions (SFRs)



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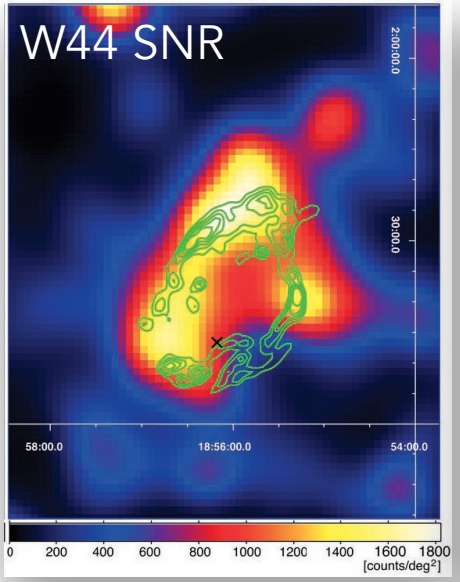
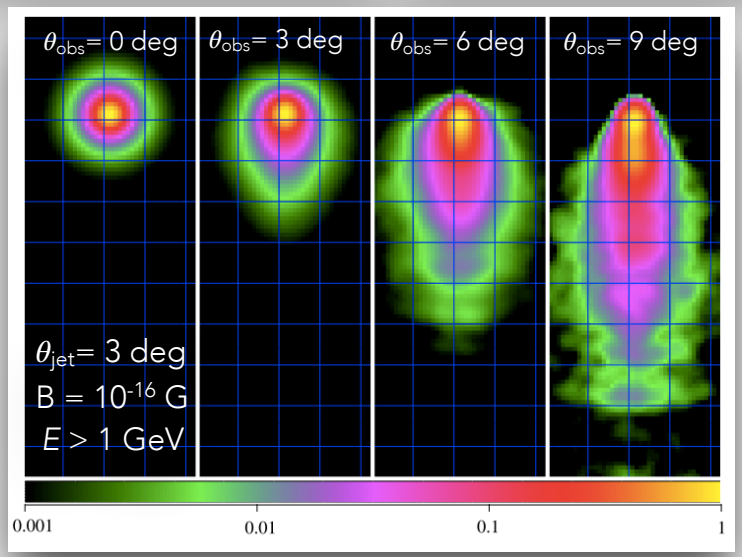
  - **Cascade emission** initiated by γ rays from active galactic nuclei (AGN) → depends on **intergalactic magnetic field (IGMF)**
  - Dark matter annihilation signal from Galactic subhaloes





Neronov et al. (2010)

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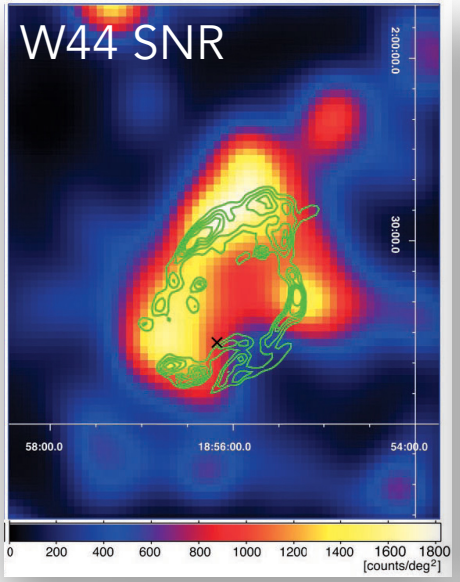
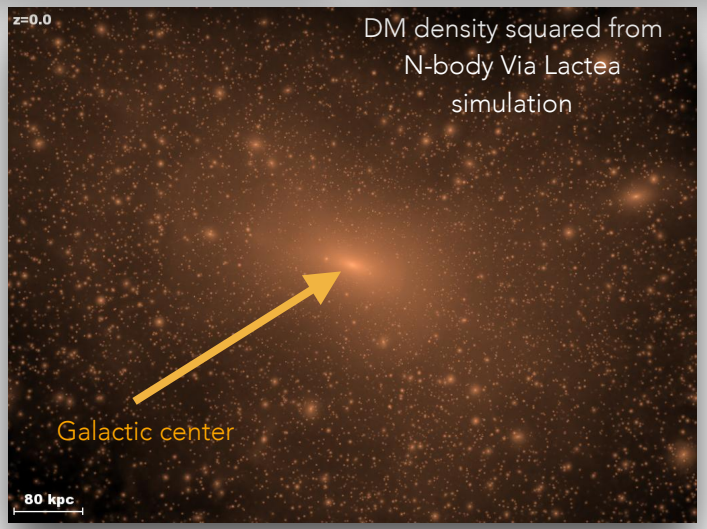
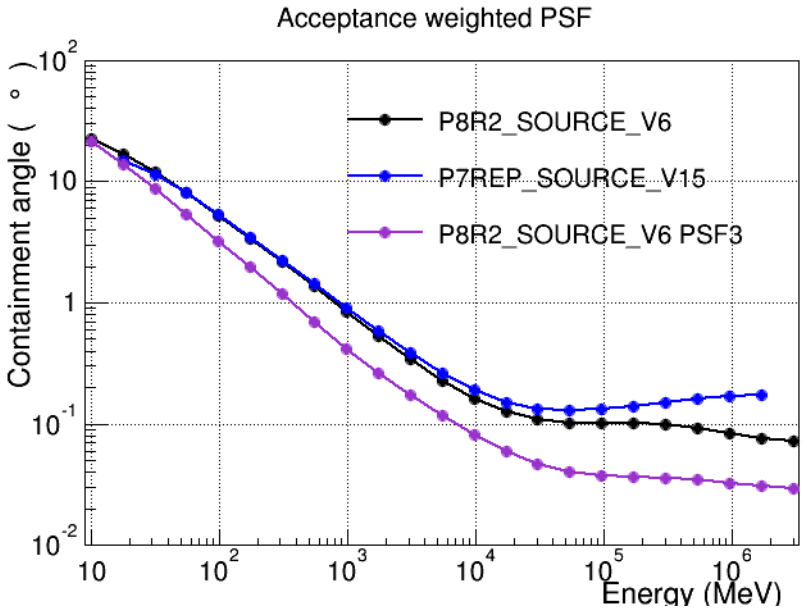
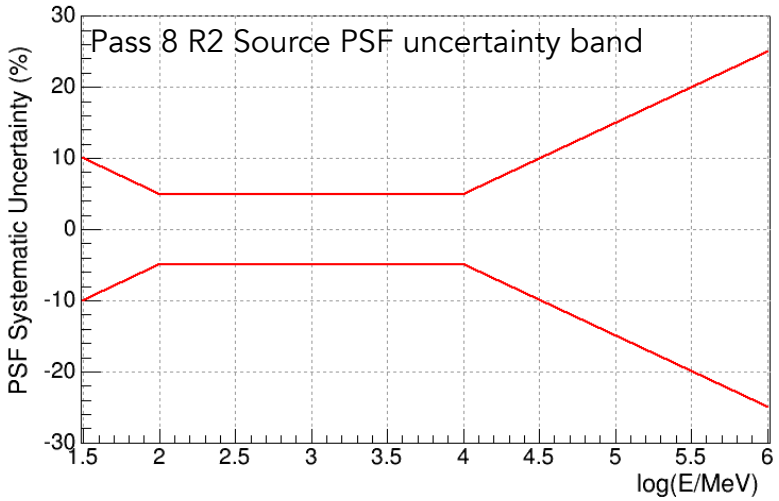




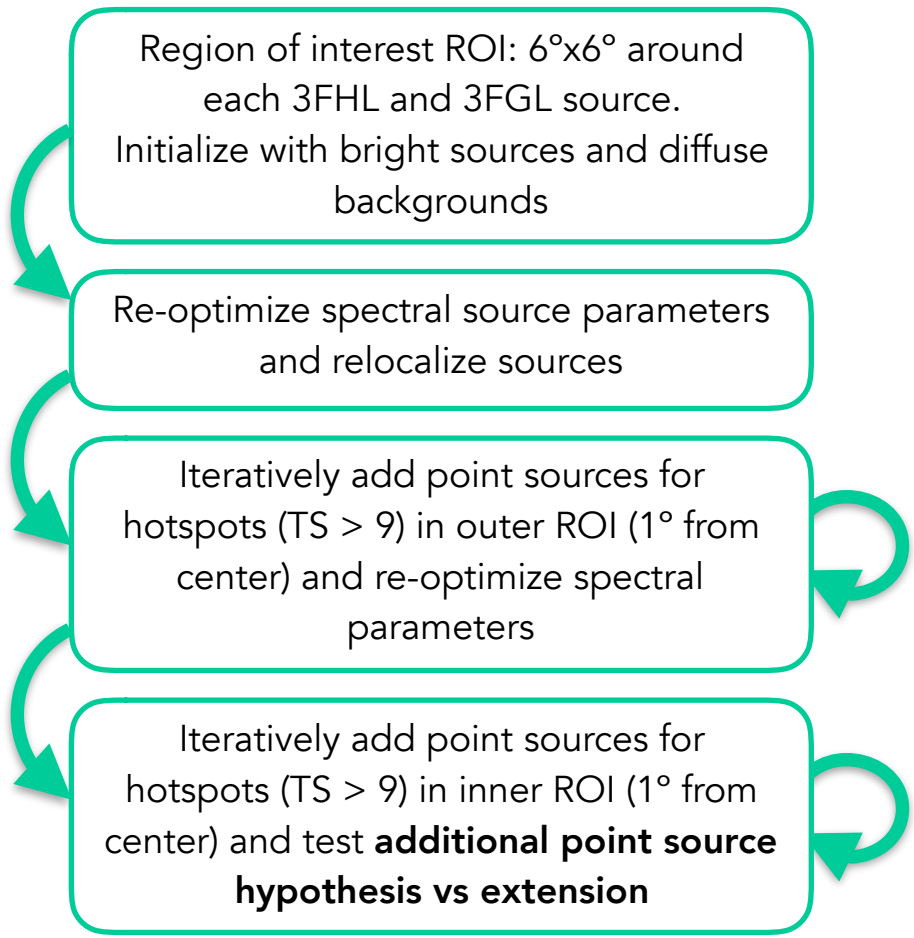
FERMI HIGH LATITUDE EXTENDED SOURCE (FHES) CATALOG

- Search for source extension in high latitude ($|b| > 5°$) sources listed in 3FHL and 3FGL catalogs using *Fermi*-LAT data
- 7.5 years of Pass 8 data between 1 GeV and 1 TeV
- Pass 8 data provides:
  - Increased sensitivity over full LAT energy range
  - Improved PSF above 10 GeV
- FHES excludes known extended sources with large extent / complex morphology (SMC, LMC, Cygnus Loop, Cen A Lobes)





ROI OPTIMIZATION



ROI OPTIMIZATION

Region of interest ROI: 6°x6° around each 3FHL and 3FGL source. Initialize with bright sources and diffuse backgrounds

Re-optimize spectral source parameters and relocalize sources

Iteratively add point sources for hotspots (TS > 9) in outer ROI (1° from center) and re-optimize spectral parameters

Iteratively add point sources for hotspots (TS > 9) in inner ROI (1° from center) and test **additional point source hypothesis vs extension**

Extension models tested:

1. **2D Gaussian** with same spectrum as central point source
2. **Halo**: Point source superimposed with 2D gaussian with power-law spectrum

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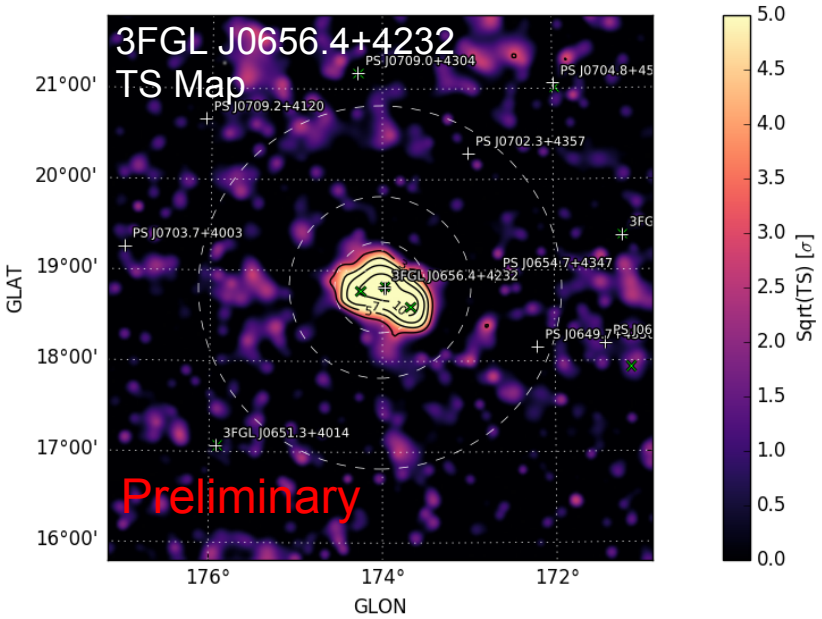

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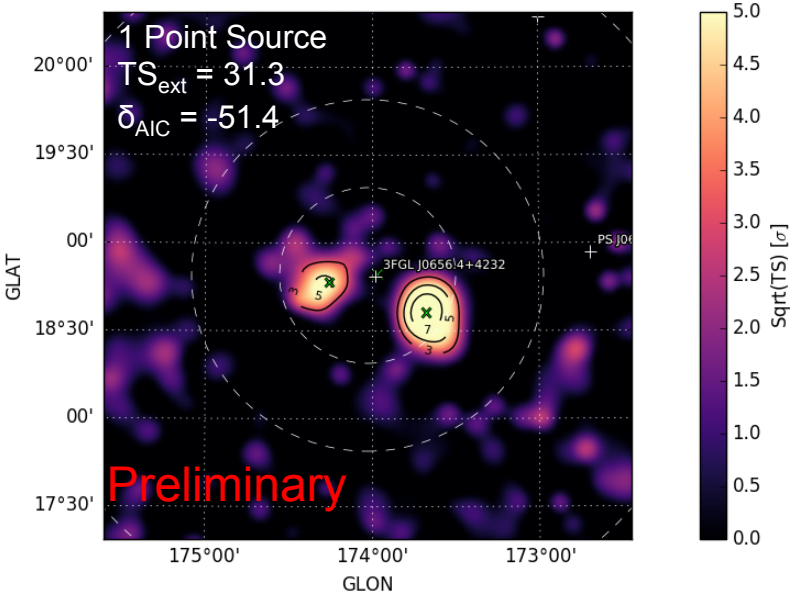

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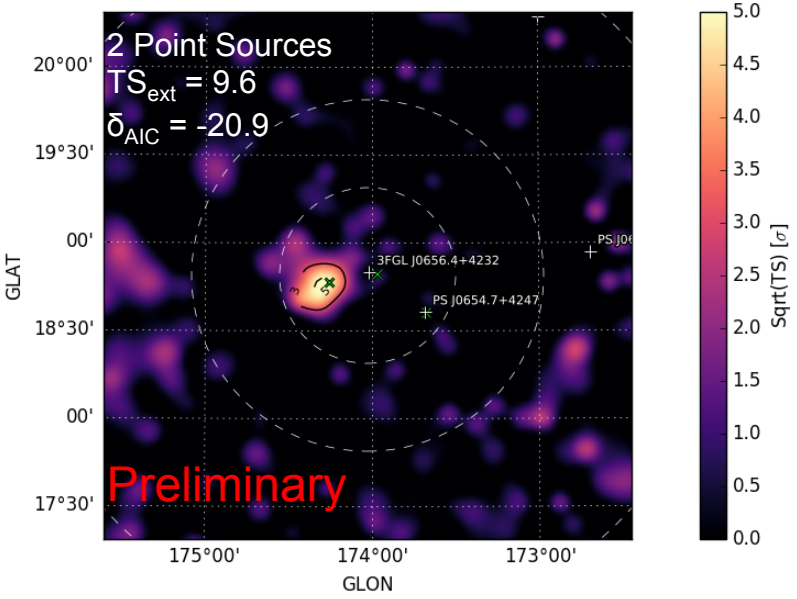

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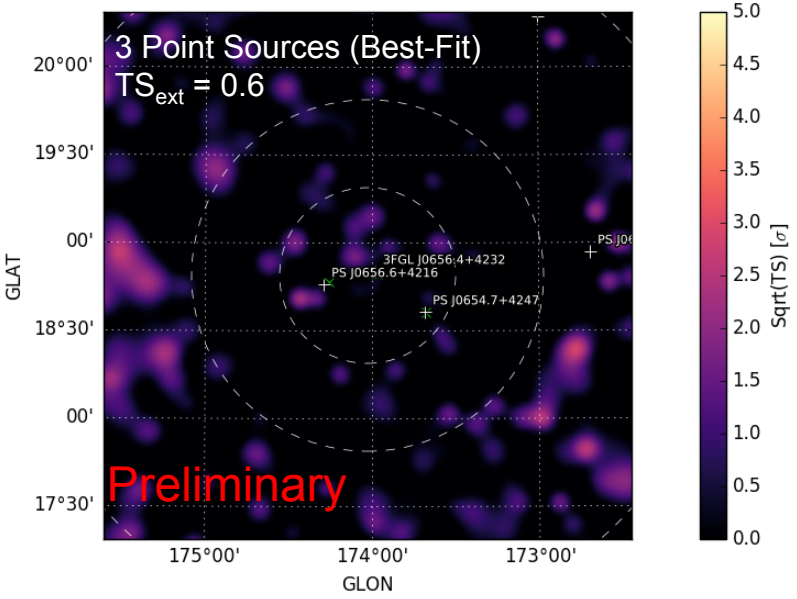
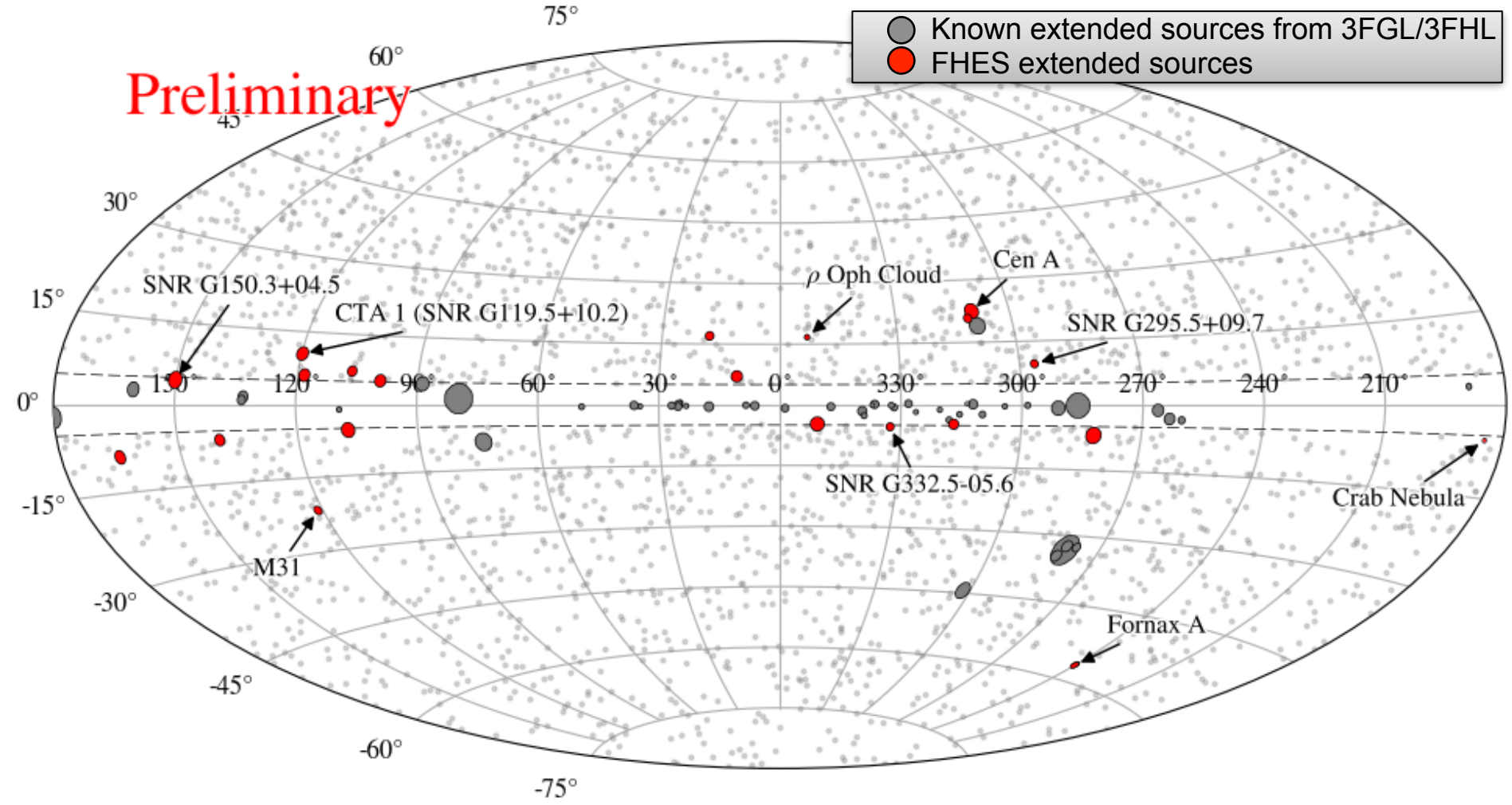


FHES SOURCES



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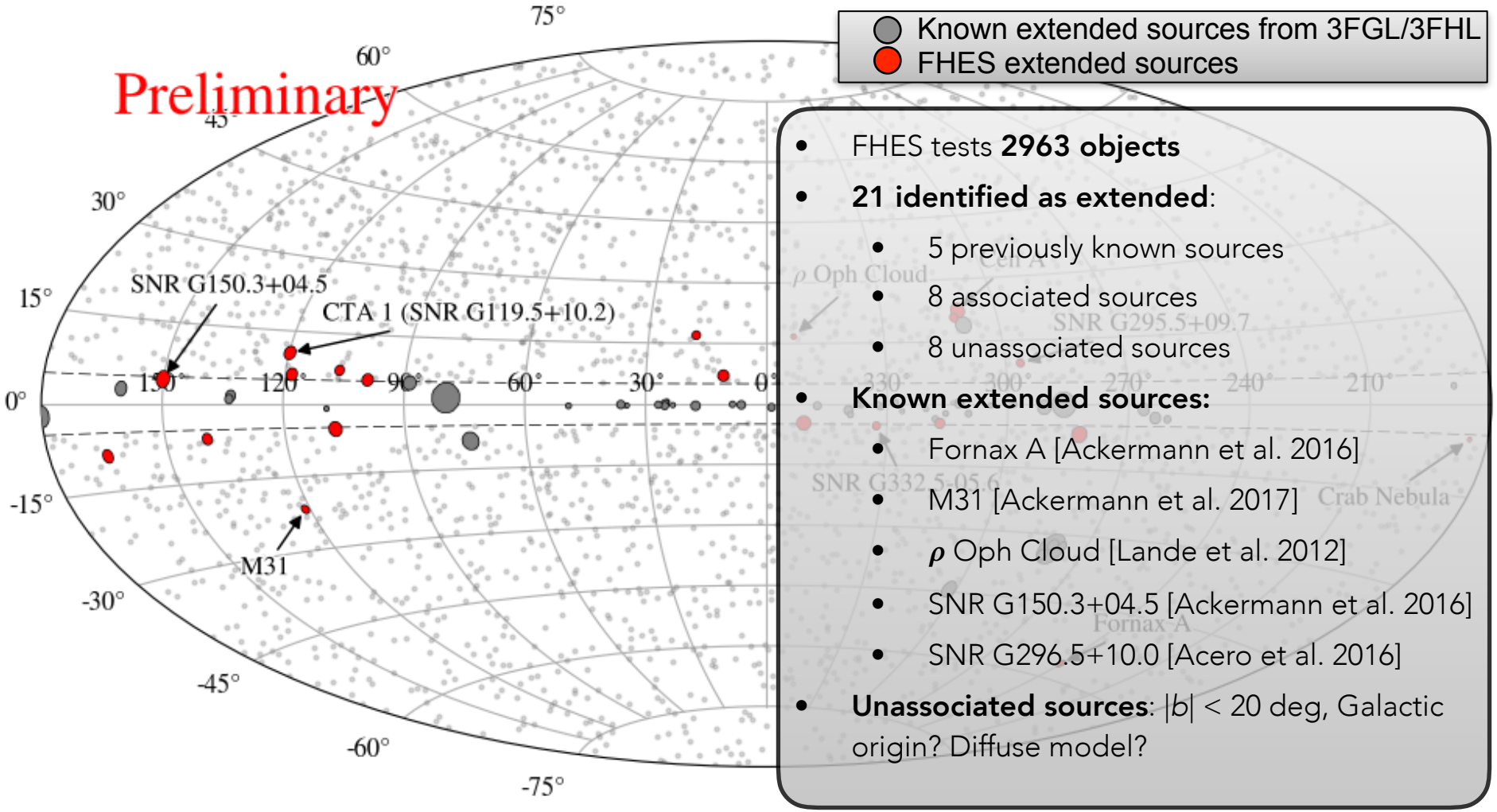
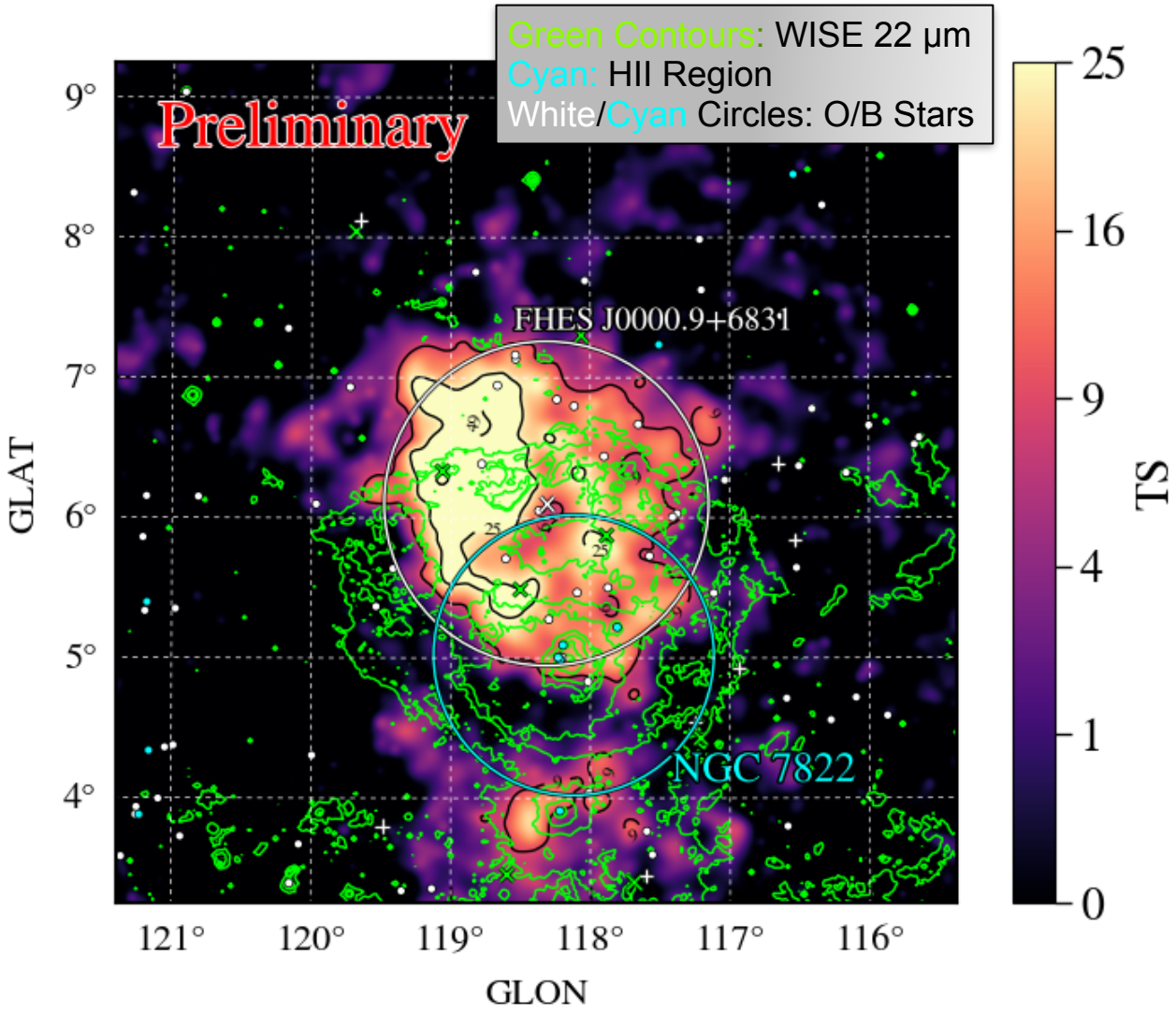


- FHES tests **2963 objects**
- **21 identified as extended**:
  - 5 previously known sources
  - 8 associated sources
  - 8 unassociated sources
- **Known extended sources:**
  - Fornax A [Ackermann et al. 2016]
  - M31 [Ackermann et al. 2017]
  - *ρ* Oph Cloud [Lande et al. 2012]
  - SNR G150.3+04.5 [Ackermann et al. 2016]
  - SNR G296.5+10.0 [Acero et al. 2016]
- **Unassociated sources**: $|b| < 20$ deg, Galactic origin? Diffuse model?

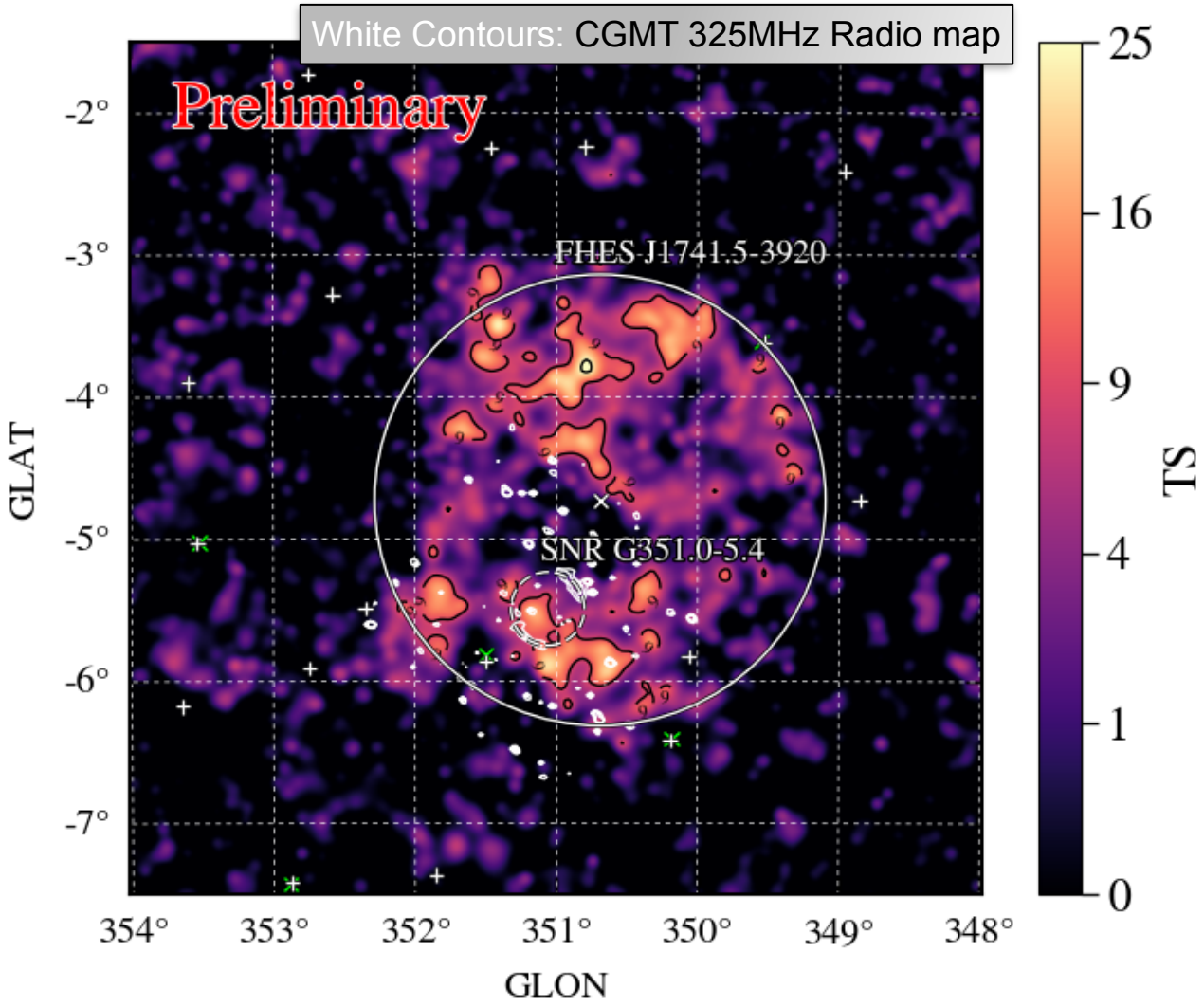
STAR FORMING REGIONS

- 3 FHES sources tentatively associated with SFRs
- Possibly analogous to other ɣ-ray detected SFRs, e.g. Cygnus Cocoon [Ackermann et al. 2011]
- Detections might also be due to mis-modeling of Galactic diffuse emission → under investigation



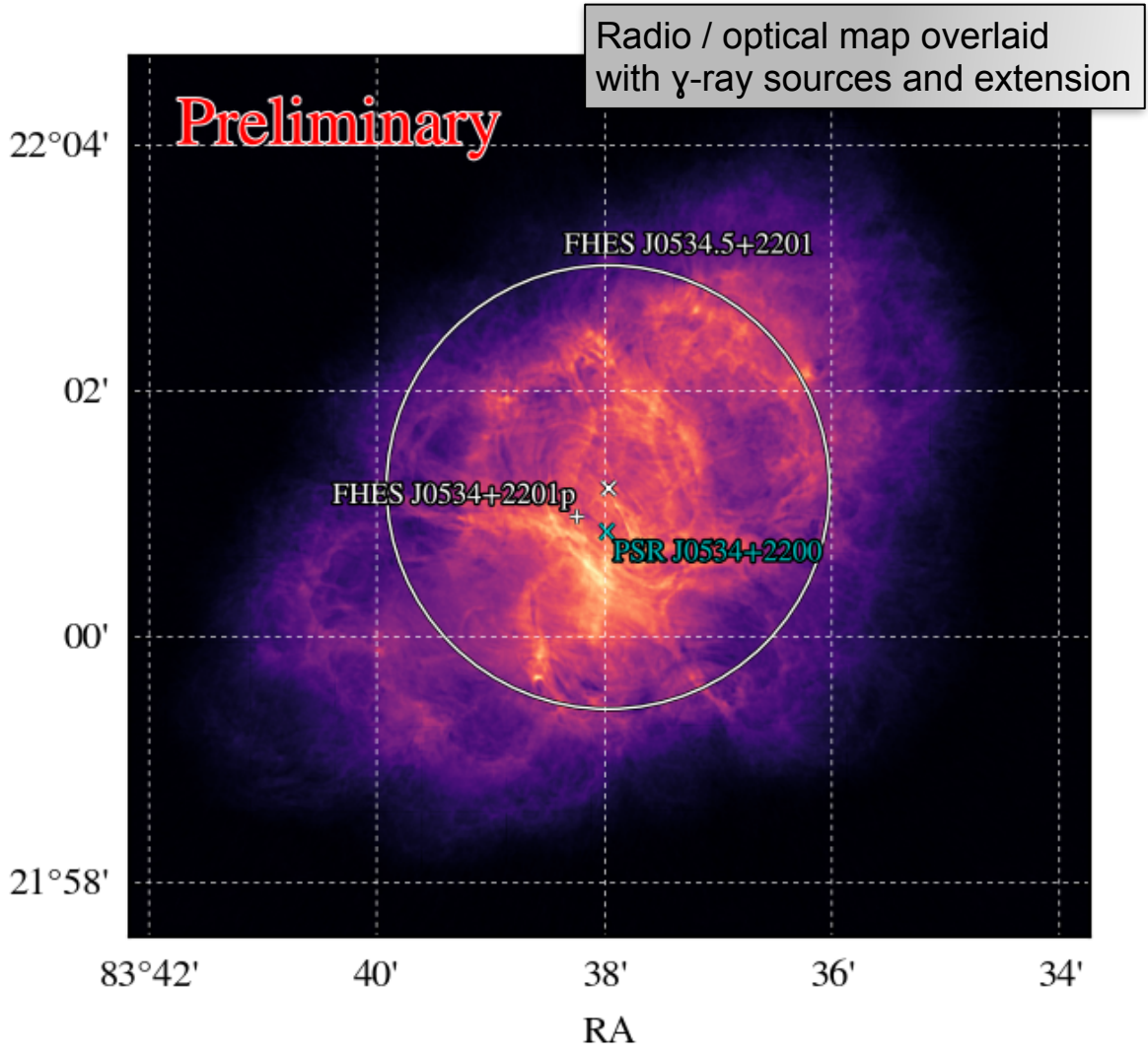
SUPERNOVA REMNANT CANDIDATES

- FHES J1741.5-3920: unassociated FHES source
- Identify as a possible shell-type SNR candidate
  - Large angular extent (D~3 deg) best-fit with a uniform disk
  - Hard spectral index (Γ~1.8)
- Matches position and morphology of ɣ-ray source reported in [Araya 2016]
- Encompasses radio-detected SNR G351.0−5.4
- Similar in morphology and spectral characteristics to SNR G150.3+04.5 (first detected in the 2FHL)



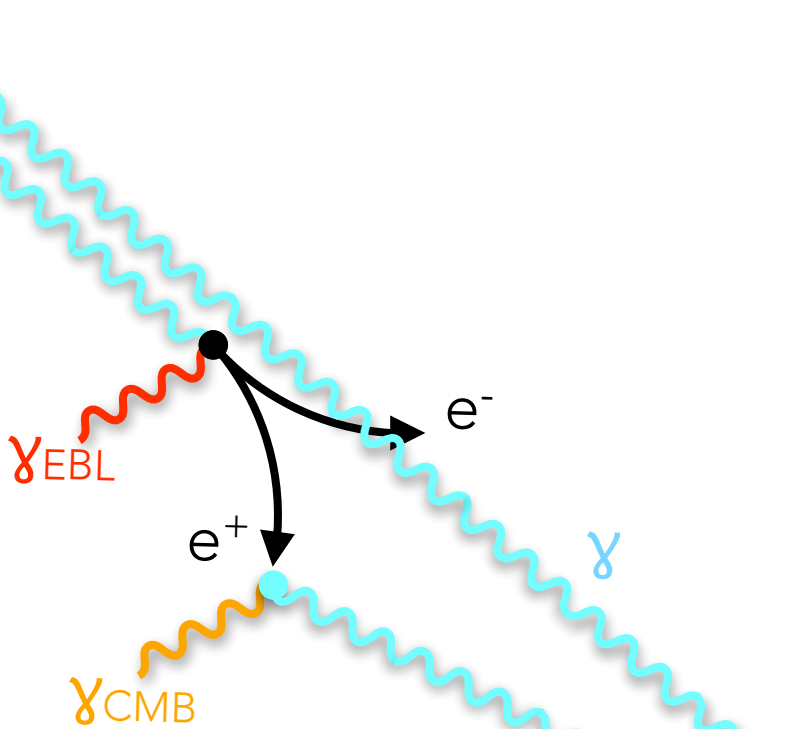
THE CRAB NEBULA

- Detected extension (68% confidence):
  r_{68} = 0.03°± 0.003°
  in Inverse Compton component
- Extension evidence falls below detection threshold when systematic uncertainties of the PSF are considered (TS_{ext} drops from 42 to 9)
- However: no extension observed in individual AGN with comparable flux above 10 GeV (e.g. Mkn 421)
- Consistent with recent HESS results [Holler et al. 2017]:
  $r_{68} = 0.022° \pm 0.001°_{stat} \pm 0.003°_{sys}$



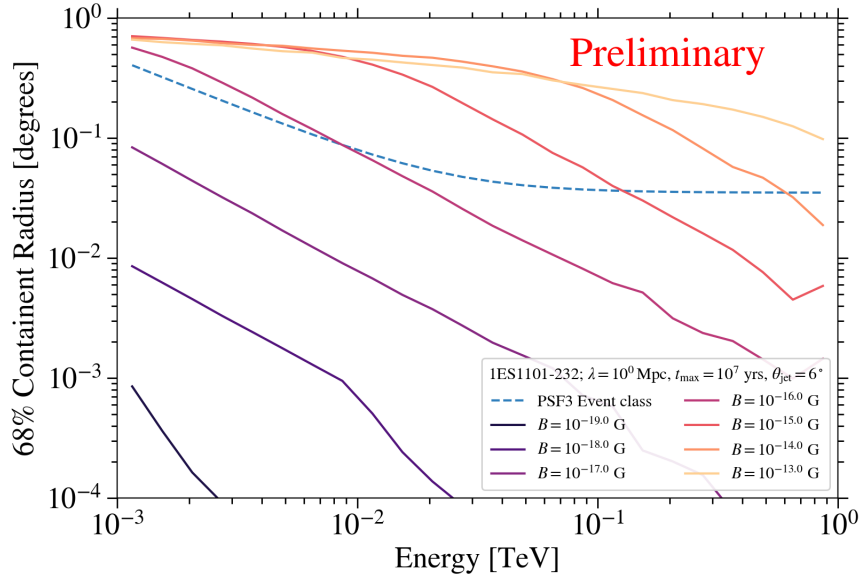
SEARCH FOR CASCADE EMISSION

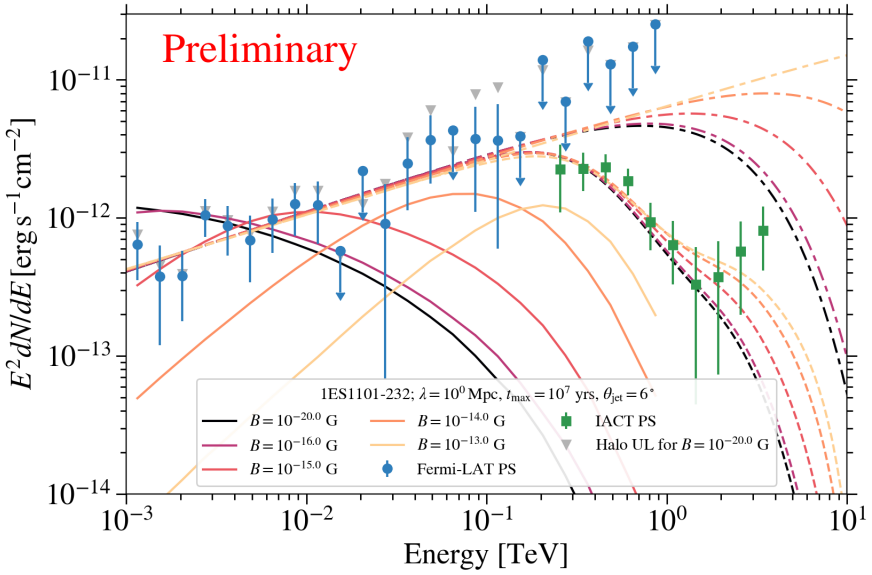
- **FHES results used to search for electromagnetic cascade**
- Cascade induced through γ-ray absorption on EBL and inverse Compton scattering of CMB photons [Protheroe & Stanev 1993]
- **Signal depends on intergalactic magnetic field (IGMF; strength + coherence length) as it deflects electron-positron pairs**
- **Expected: excess at GeV energies (low IGMF), halo around AGN (high IGMF), time-delayed emission** [Aharonian et al. 1994, Plaga 1995]
- Absence of spectral signature used to set lower limits on IGMF strength [e.g. Neronov & Vovk 2010, Tavecchio et al. 2011, Taylor et al. 2011, Finke et al. 2015]



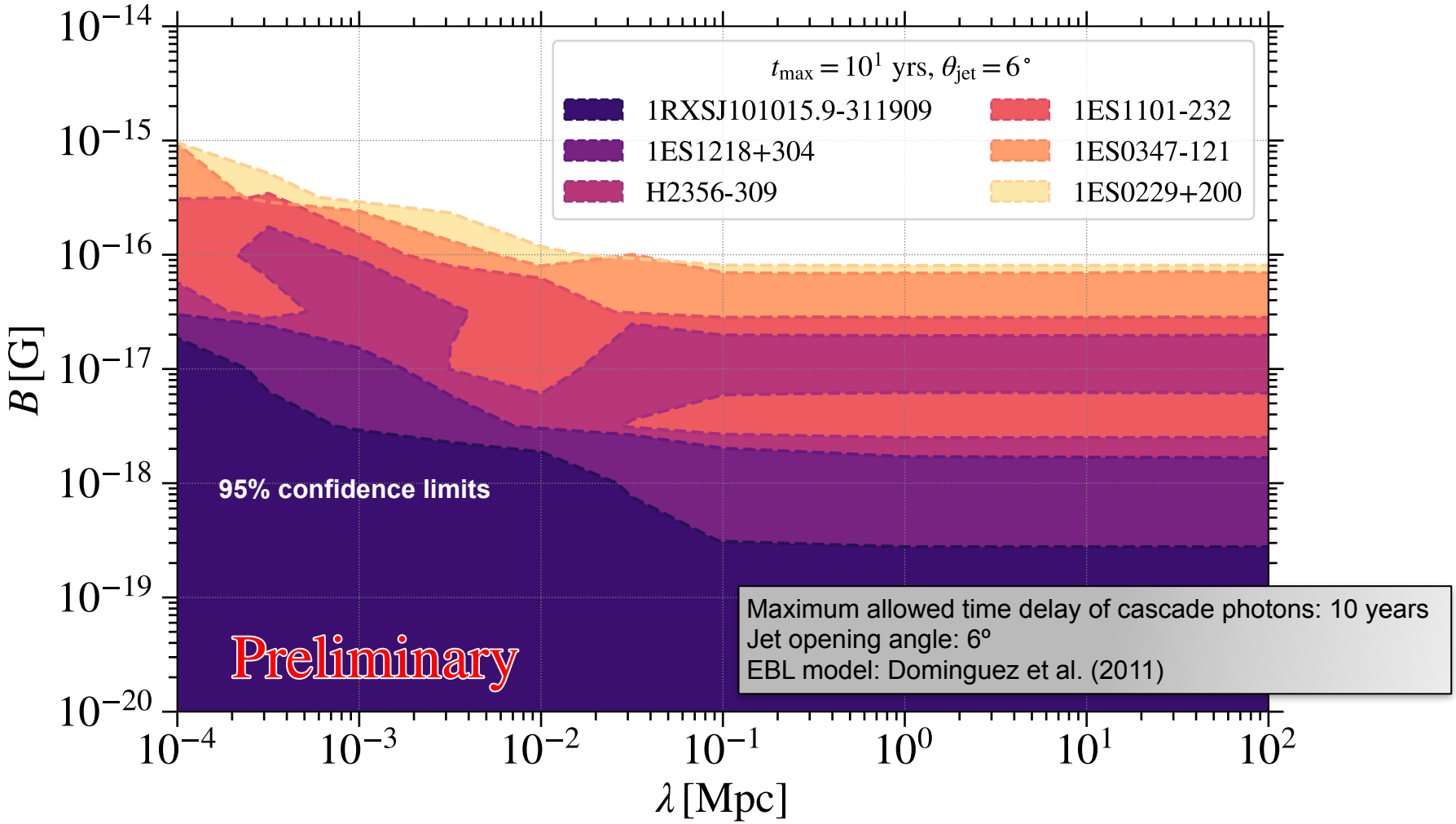
NO EXTENSION FOUND

- **No extension found in FHES in individual or stacked sources**
- Considered sources: extragalactic or high latitude
  (|b| > 20°) sources
- We set limits on IGMF using:
  - A sample **of TeV detected blazars** with data from Cherenkov telescopes and FHES
  - **ELMAG Monte Carlo code** [Kachelrieß et al. 2012] to model the cascade emission
  - **Combined fit:**
    1. Fermi point source (from FHES)
    2. Halo flux and extension (from FHES)
    3. TeV point source (from Cherenkov Telescopes)

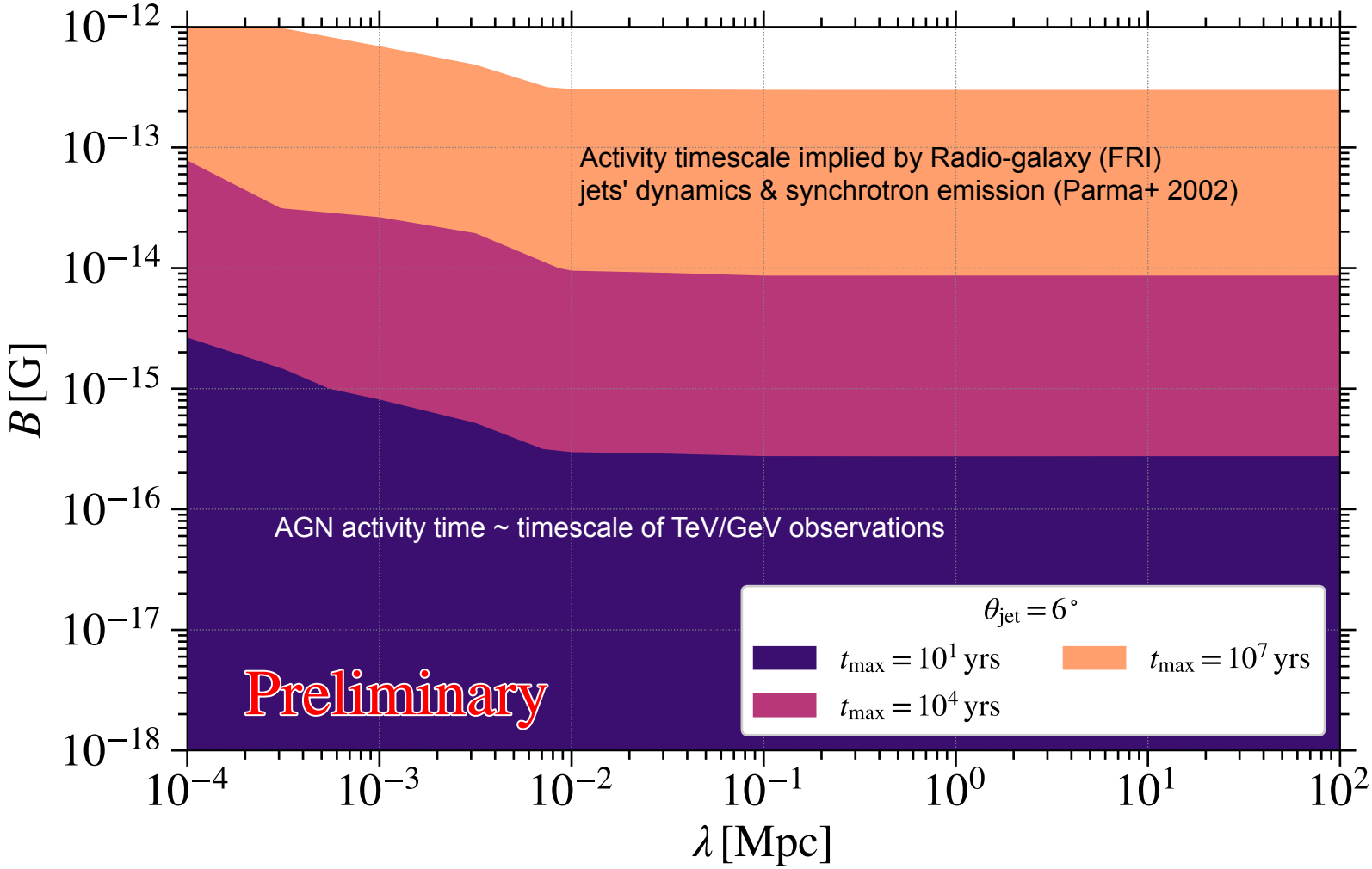




LIMITS ON THE IGMF



COMBINED LIMITS ON THE IGMF



SUMMARY & CONCLUSIONS

- **FHES: first catalog of extended sources at $|b| > 5°$ containing also upper limits on extension for point sources**
- **Found 21 extended sources:**
  - 16 new extended sources
  - Three sources tentatively identified with star forming regions
  - Eight unassociated sources at low Galactic latitudes
  - Found extension of the Crab $\mathbf{r_{68} = 0.03° \pm 0.003°}$, however, not significant if systematic PSF uncertainties are taken into account
- **No evidence for extended emission in extragalactic source populations**
- Joint GeV-TeV analysis of TeV-selected blazars sets **lower limits on B_{IGMF}** depending on assumption of source activity timescale
  - **$B_{IGMF} > 3 \times 10^{-13}$ G (active for ~10 Myr)**
  - **$B_{IGMF} > 3 \times 10^{-16}$ G (active for ~10 yr)**
- Even for 10 yr activity time scale, lower limits improved by ~3 orders of magnitude compared to Finke et al. (2015)

BACK UP

BLAZAR SAMPLE FOR IGMF LIMITS

- TeV detected blazars used to set limits on IGMF

Source	z	R.A. [°]	Dec. [°]	3FGL name	3FGL var. index	Experiment	Obs. Period
1ES 1312-423	0.105	198.76	-42.61	J1314.7-4237	45.0	HESS	2004-2010
RGB J0710+591	0.125	107.63	59.14	J0710.3+5908	55.5	VERITAS	2008-2009
1ES 0229+200	0.14	38.20	20.29	J0232.8+2016	49.2	HESS	2005-2006
1RXS J101015.9-311909	0.143	152.57	-31.32	J1010.2-3120	86.3	HESS	2006-2010
						VERITAS	2009-2012
H 2356-309	0.165	359.78	-30.63	J2359.3-3038	41.0	HESS	2004
						HESS	2005
						HESS	2006
1ES 1218+304	0.182	185.34	30.18	J1221.3+3010	92.5	VERITAS	2007
						VERITAS	2008-2009
1ES 1101-232	0.186	165.91	-23.49	J1103.5-2329	36.5	HESS	2004-2005
1ES 0347-121	0.185	57.35	-11.99	J0349.2-1158	44.3	HESS	2006
1ES 0414+009	0.287	64.22	1.09	J0416.8+0104	55.8	HESS	2005-2009

DETAILS ON IGMF SIMULATION

- We model the cascade emission with the ELMAG MC simulation package (Kachelrieß et al. 2012) using the following input parameters
  - Redshift (taken from optical spectroscopy)
  - 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

$$\ln \mathcal{L}(B, \lambda) = \ln \mathcal{L}_{\mathrm{halo,\,GeV}} + \ln \mathcal{L}_{\mathrm{point,\,TeV}} + \ln \mathcal{L}_{\mathrm{point,\,GeV}}$$

- For each point in the IGMF parameter space (B,λ) we fit for the parameters of the primary injection spectrum modeled as a Power Law with an exponential cutoff