Fermi Gamma-ray Space Telescope

The Second Fermi All-sky Variability Analysis Catalog

Matteo Giomi, Rolf Bühler, Dan Kocevski, Marco Ajello for the Fermi LAT collaboration


Rolf Bühler


Dan Kocevski

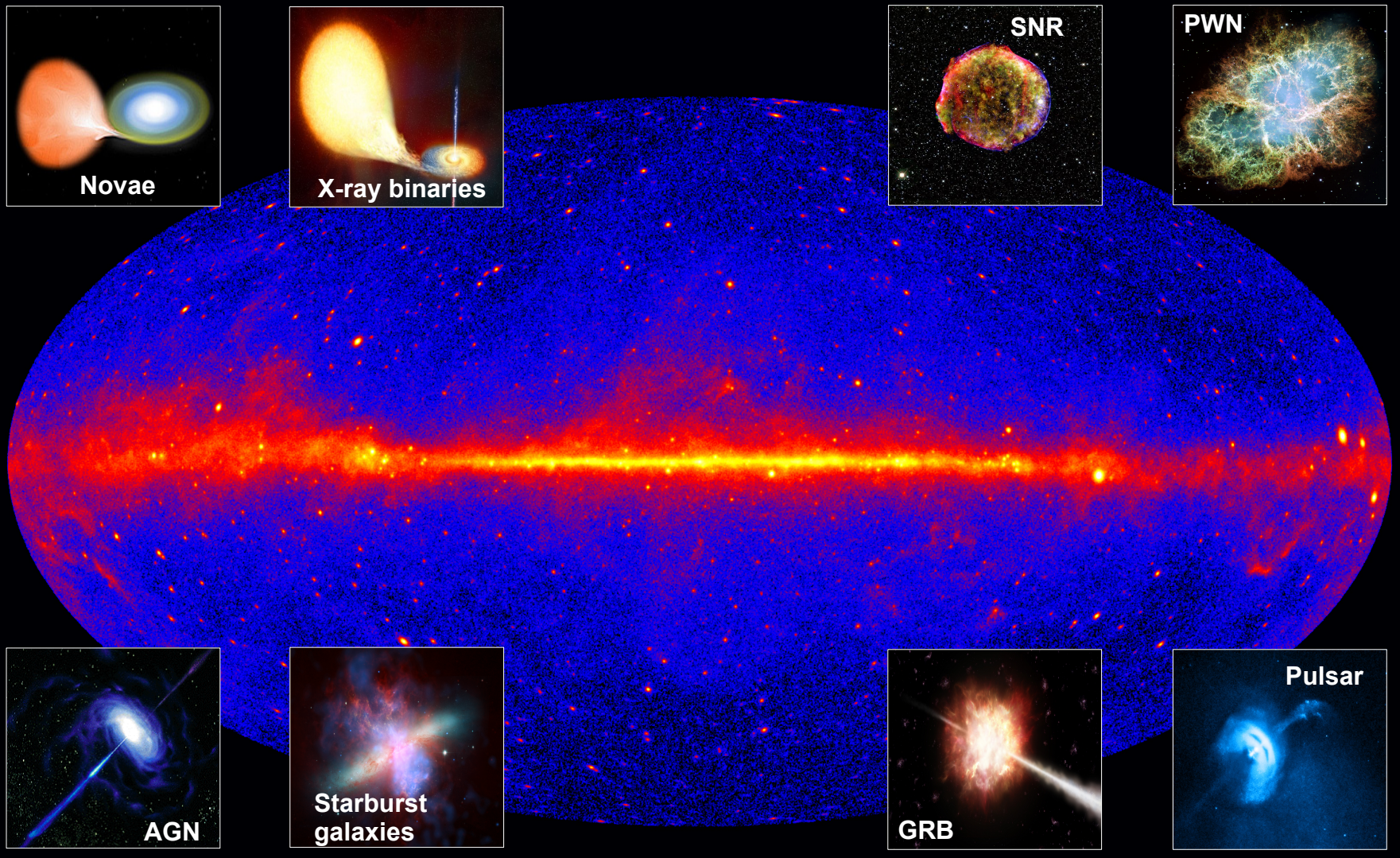

Marco Ajello

HELMHOLTZ ASSOCIATION

Alliance for Astroparticle Physics

DESY

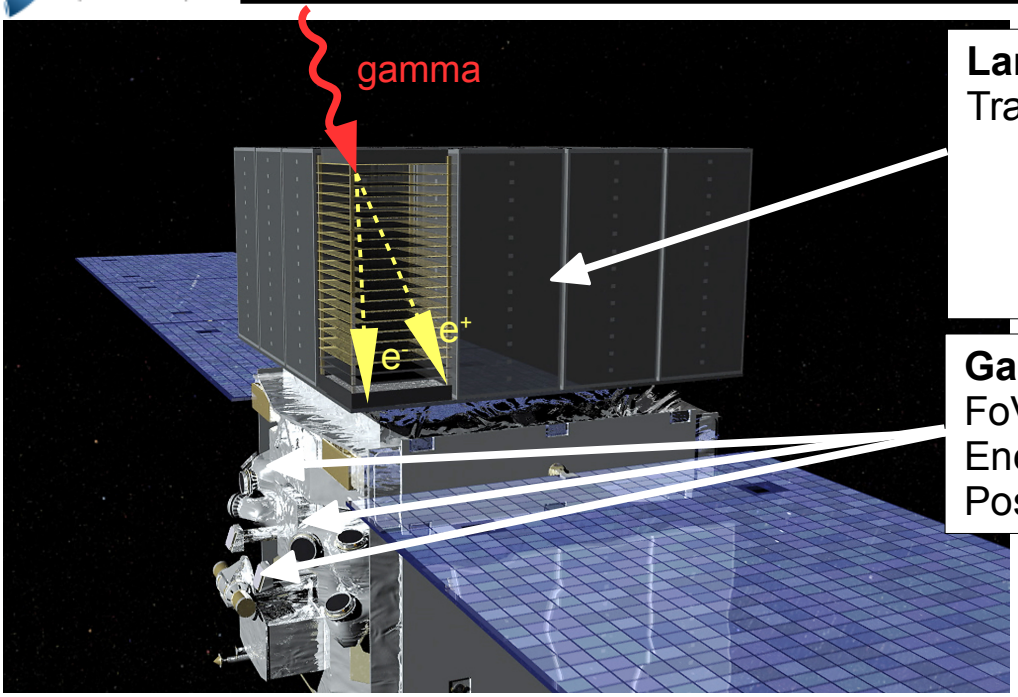
The gamma-ray sky



5years FERMI LAT > 1 GeV source: http://fermi.gsfc.nasa.gov/ssc/observations/types/allsky/

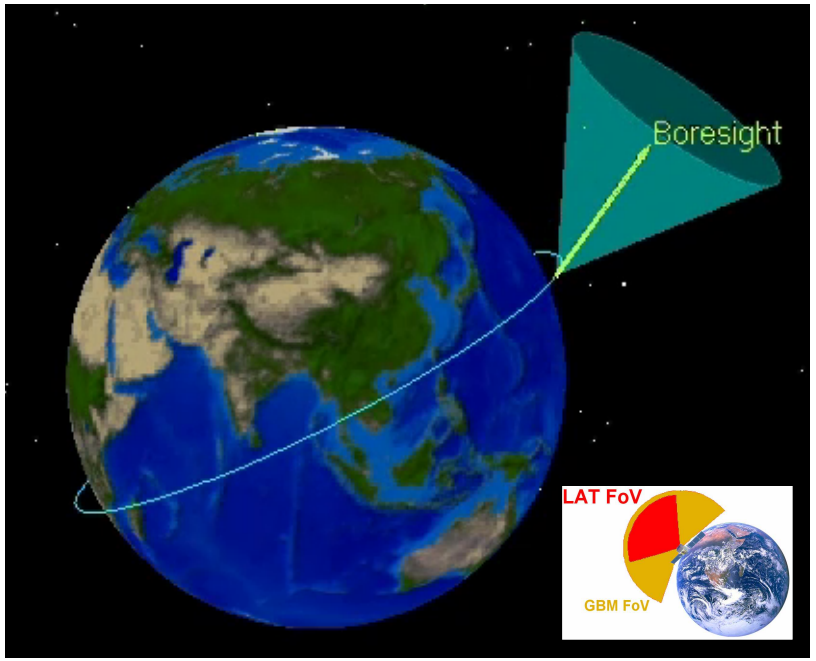
Source images from: Hubble, Spitzer, Chandra.

The *Fermi* Gamma-ray Space Telescope



Large Area Telescope (LAT):
Tracker + Calorimeter
- FoV: 2.4 sr (20% sky)
- Energies: 20 MeV to 2 TeV
- Angular resolution: 0.8° @ 1GeV
- Dead time: 15 % (SAA) + 9% (trigger)

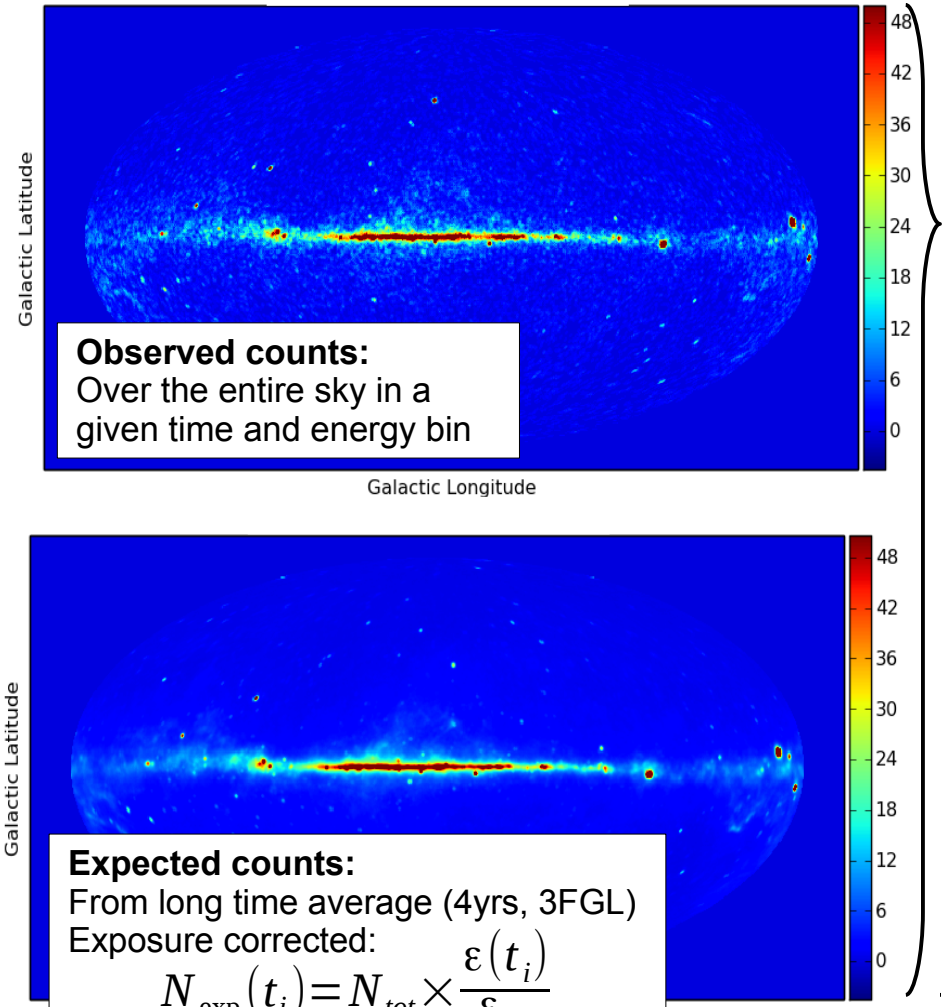
Gamma-ray Burst Monitor (GBM)
FoV: Complete unocculted sky
Energy range: 8 KeV- 40 MeV
Positional accuracy: 4°-8°

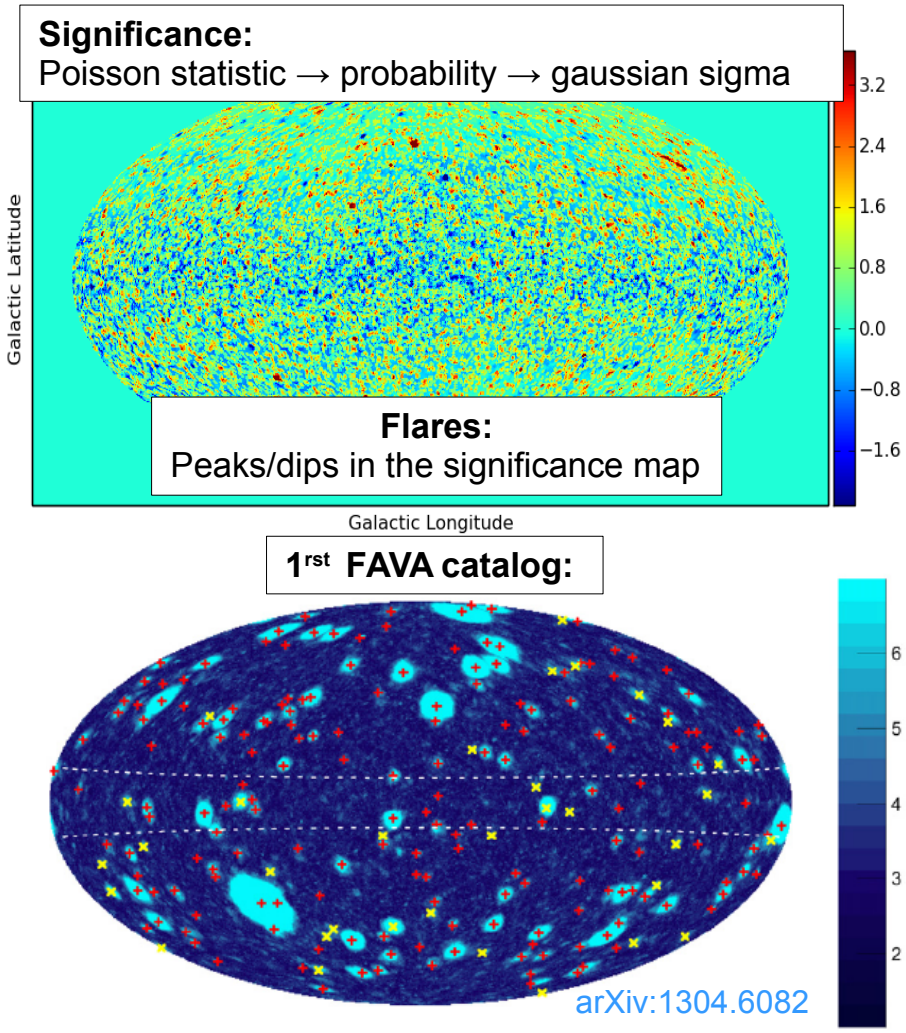


All Sky survey:
Fermi spends ~ 80% of the time in survey mode:
- 30 minutes of livetime on each point in the sky every 3 orbits
- Complete sky every ~ 3 hours

The Fermi All-sky Variability Analysis

- FAVA is a photometric technique to blindly search for transients over the entire sky.

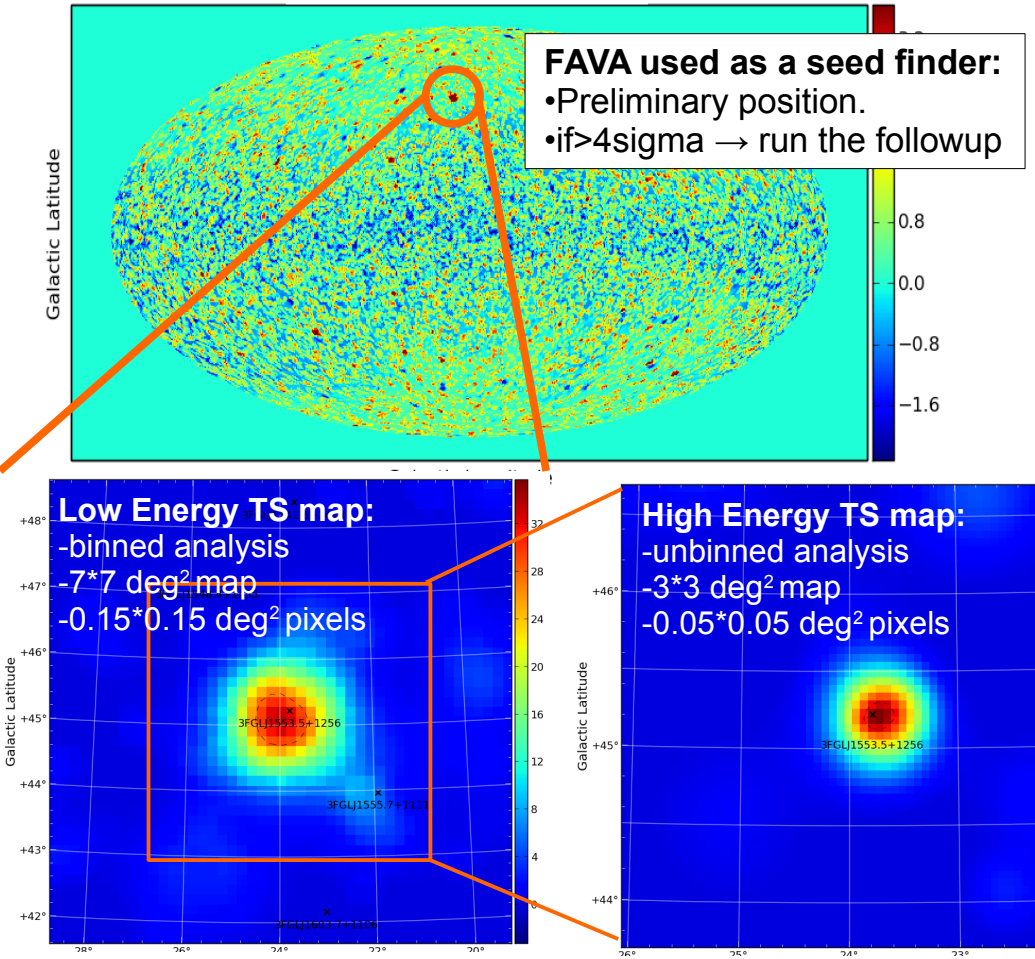




Upgraded analysis for 2FAV: likelihood followup

- ✓ Robust, model independent, sensitive to negative flares
- ✗ Poor angular resolution (r_{95}~ 1 deg)
- ✗ No spectral measurement.

→ **Likelihood followup analysis:**



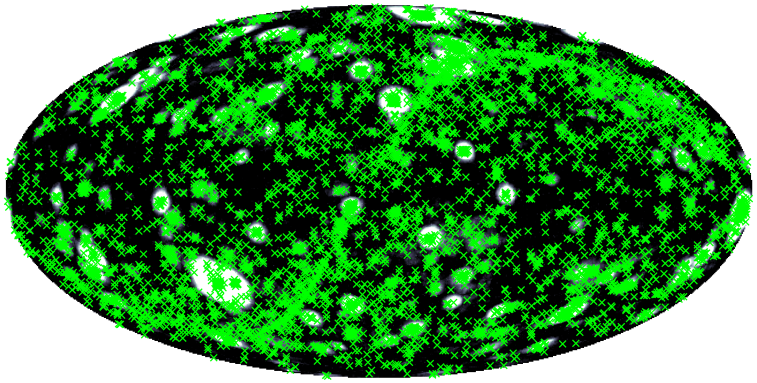
Based on test statistic (TS) maps:

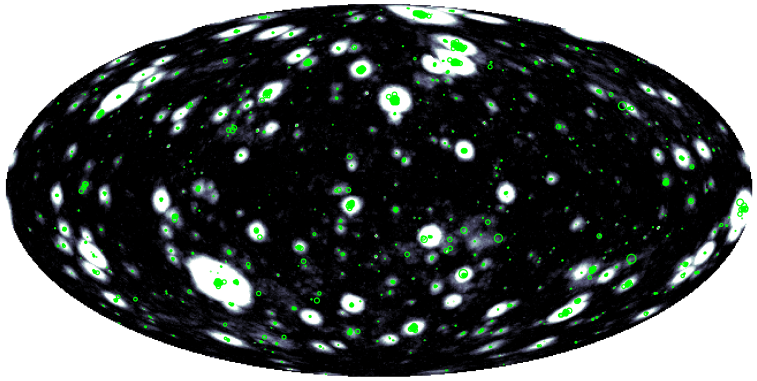
$$TS = -2\log\left(\frac{L_{max,0}}{L_{max,1}}\right)$$

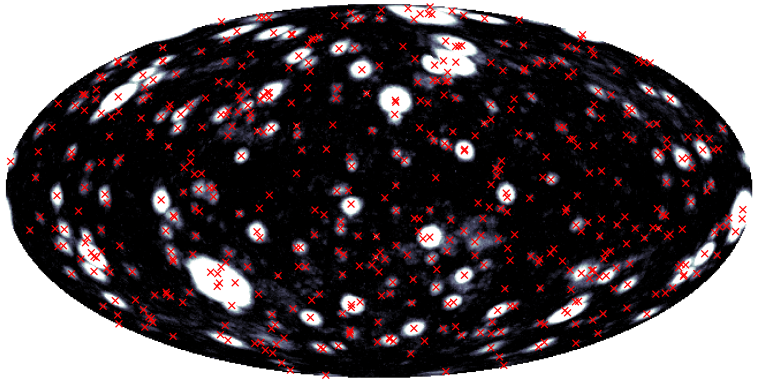
- Likelihood scan to test for putative point source
- Null hypothesis = static 3FGL sky

- From the TS maps:
  - Flare position & error:
  - r_{95}~0.1 deg (HE), ~0.3 deg (LE)
  - Flare spectrum measured with likelihood fit (`gtlike`)

Construction of the catalog



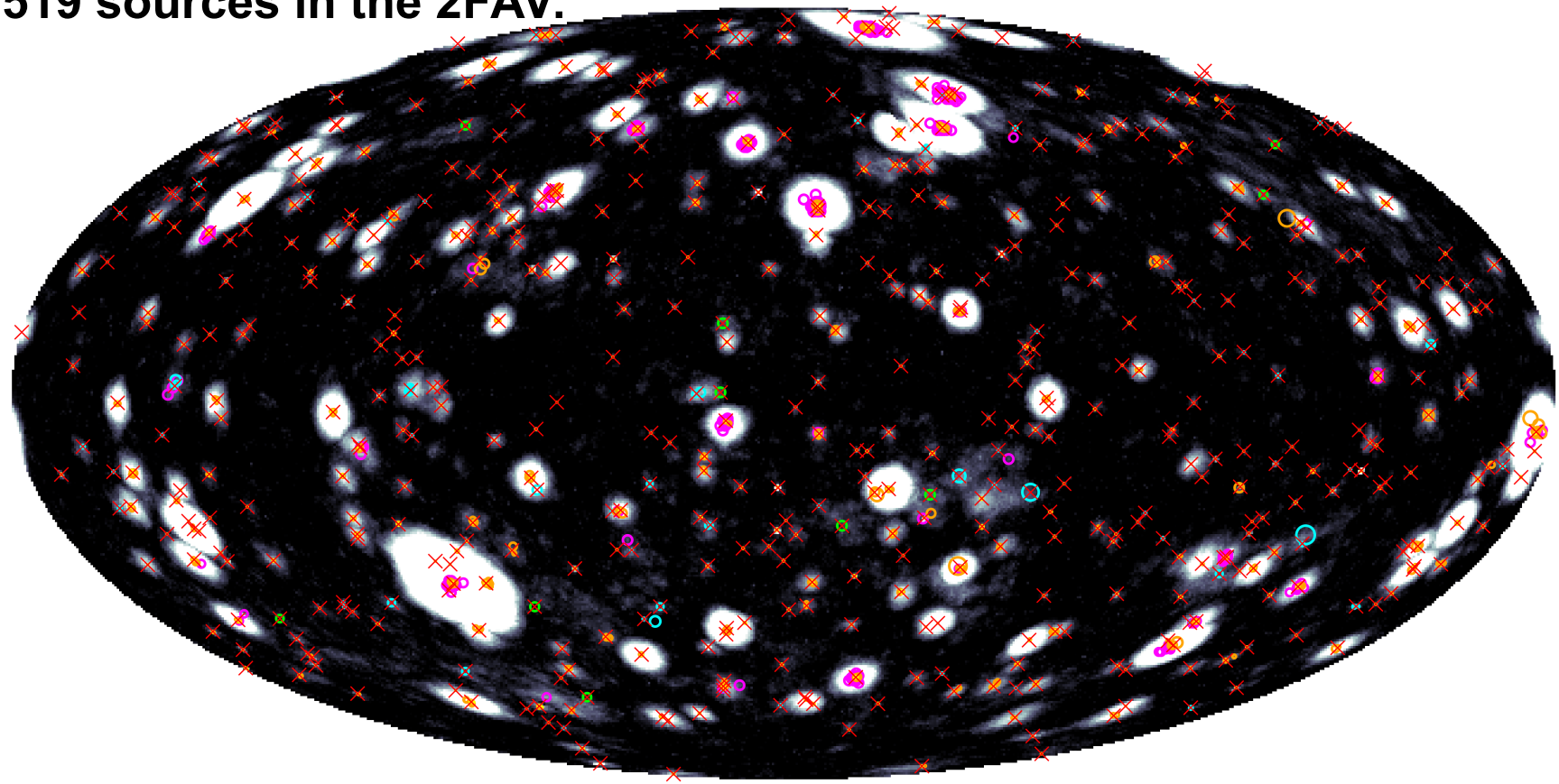




- **2FAV analysis:**
  - 387 weekly time bins:
    - » **7.4 yrs, MJD 54682 to 57391**
  - 2 energy bins:
    - » **[100, 800] MeV, [0.8, 300] GeV**
    - **> 10000 flares detected**
- **Flare cuts:**
  - > 6 sigma (TS>39) in one energy bin
  - > 4 sigma (TS>18) in both
  - > 6deg away from the sun
    - **4548 "catalog" flares**
- **2FAV source = cluster of flares**
  - Using MST, starting from better localized flares
  - Flare position averaged to locate source

The second FAVA catalog (2FAV)

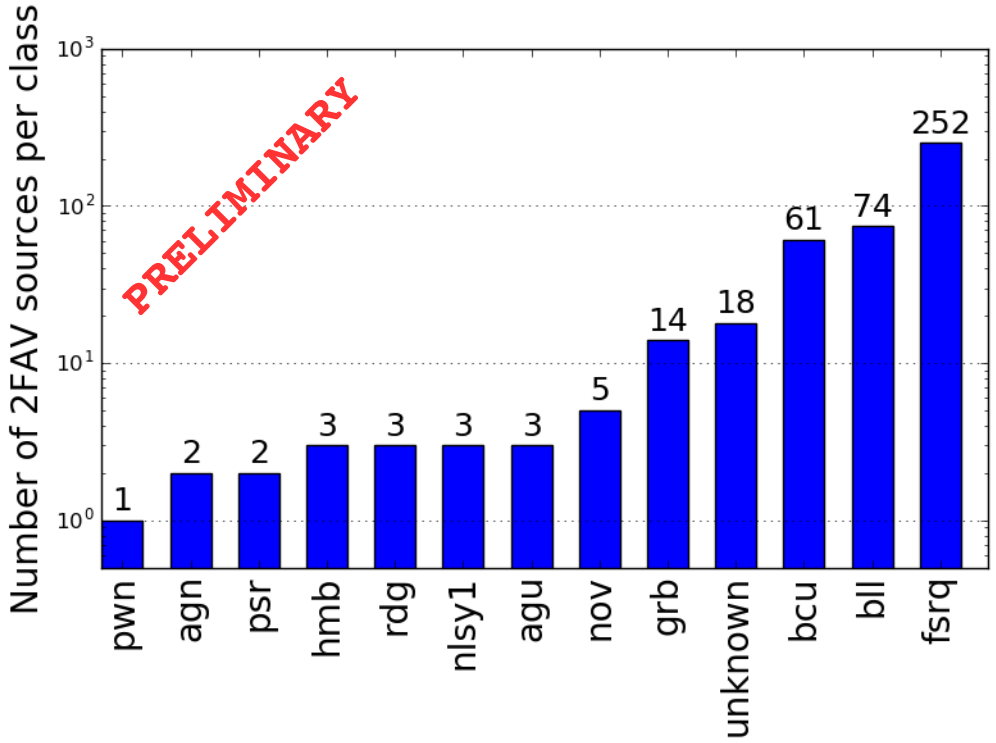
- **519 sources in the 2FAV:**



Background image: maximum (all time) significance detected in each pixel at either high or low energy

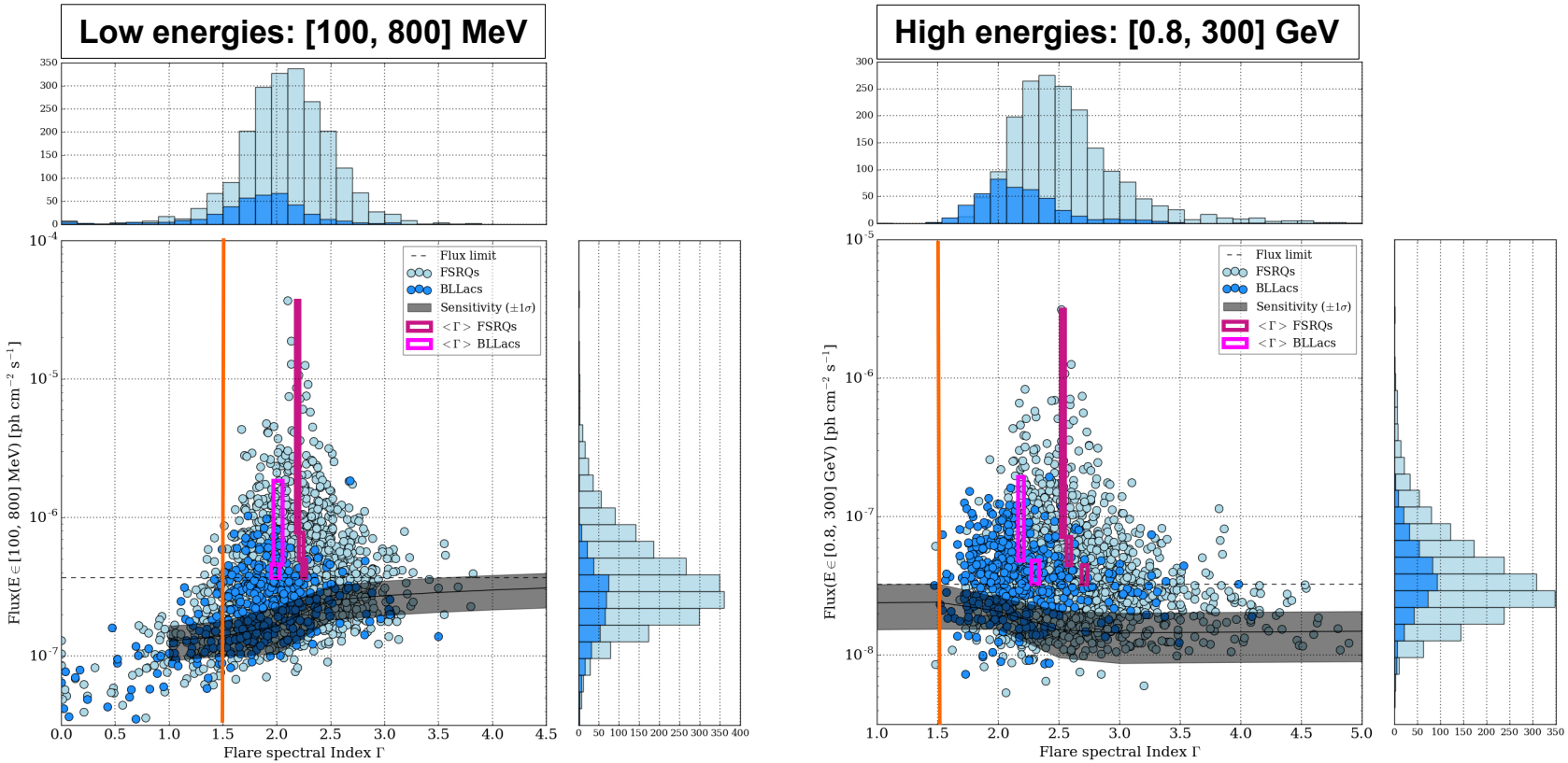
Likely counterparts

- Search for counterparts of 2FAV sources:
  - based only on positional coincidence. **(handle with care)**
  - In 3FGL, 2FGL, 1FGL, 3EG, 1AGL, LAT ATels, LAT GRBs, BZCAT
  - Variable counterpart has priority over closest counterpart



- 441 2FAV sources with counterpart:
  - 89% AGN (mostly FSRQs)
  - But also GRBs, Novae, Crab, Binaries, ecc..
- 78 2FAV sources with no counterpart.
  - “new” gamma-ray sources

Flare spectra of blazars



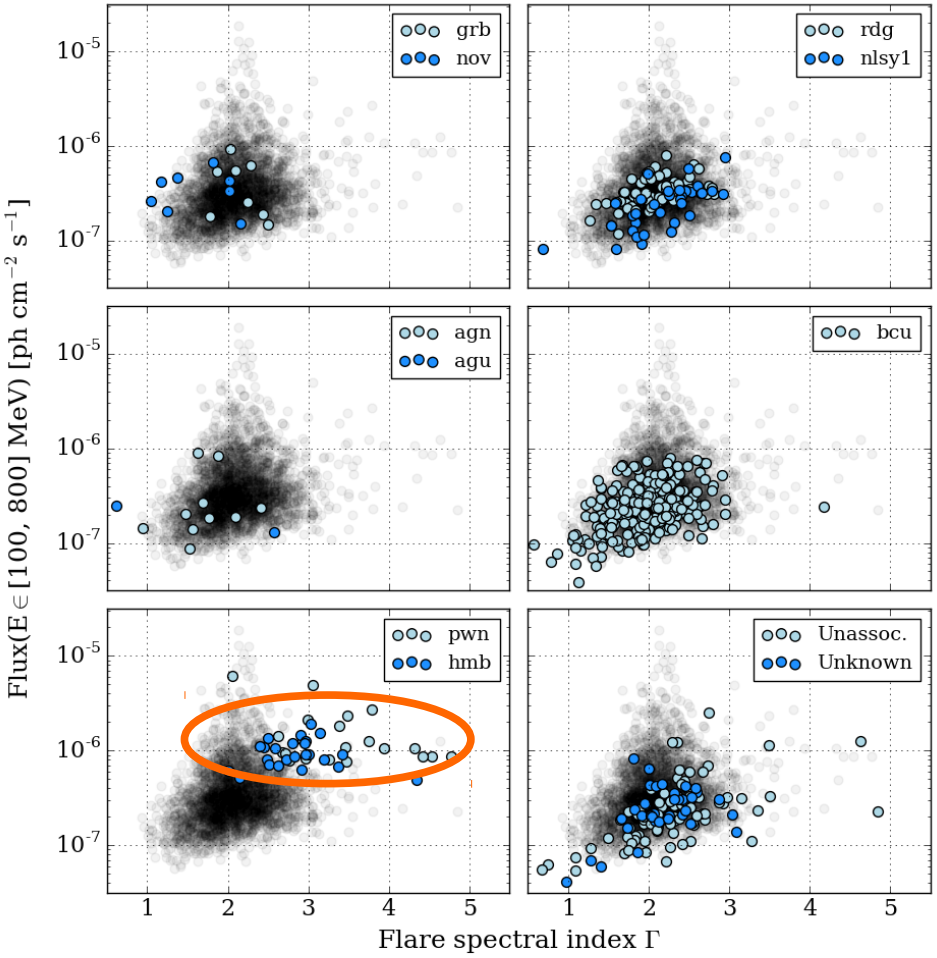
- BL Lacs flares are on average harder than the ones from FSRQs, as noted in the 3LAC
- No flare significantly harder than 1.5 detected above the sensitivity threshold.

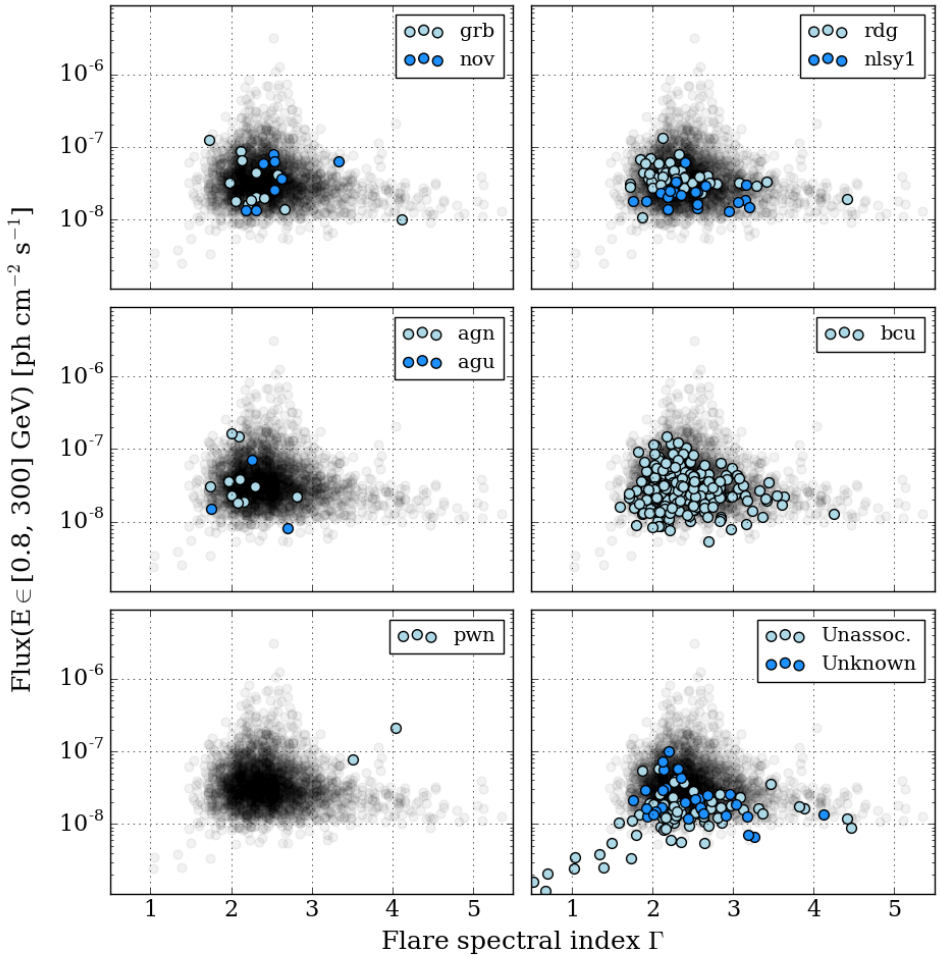
  In leptonic models Γ≥1.5 → Injected electron spectra never harder than ~2

  Compatible with particle acceleration at shocks and magnetic reconnection (with low magnetization)

http://arxiv.org/abs/1006.5210
http://adsabs.harvard.edu/abs/1987PhR...154....1B
http://arxiv.org/abs/1506.02034

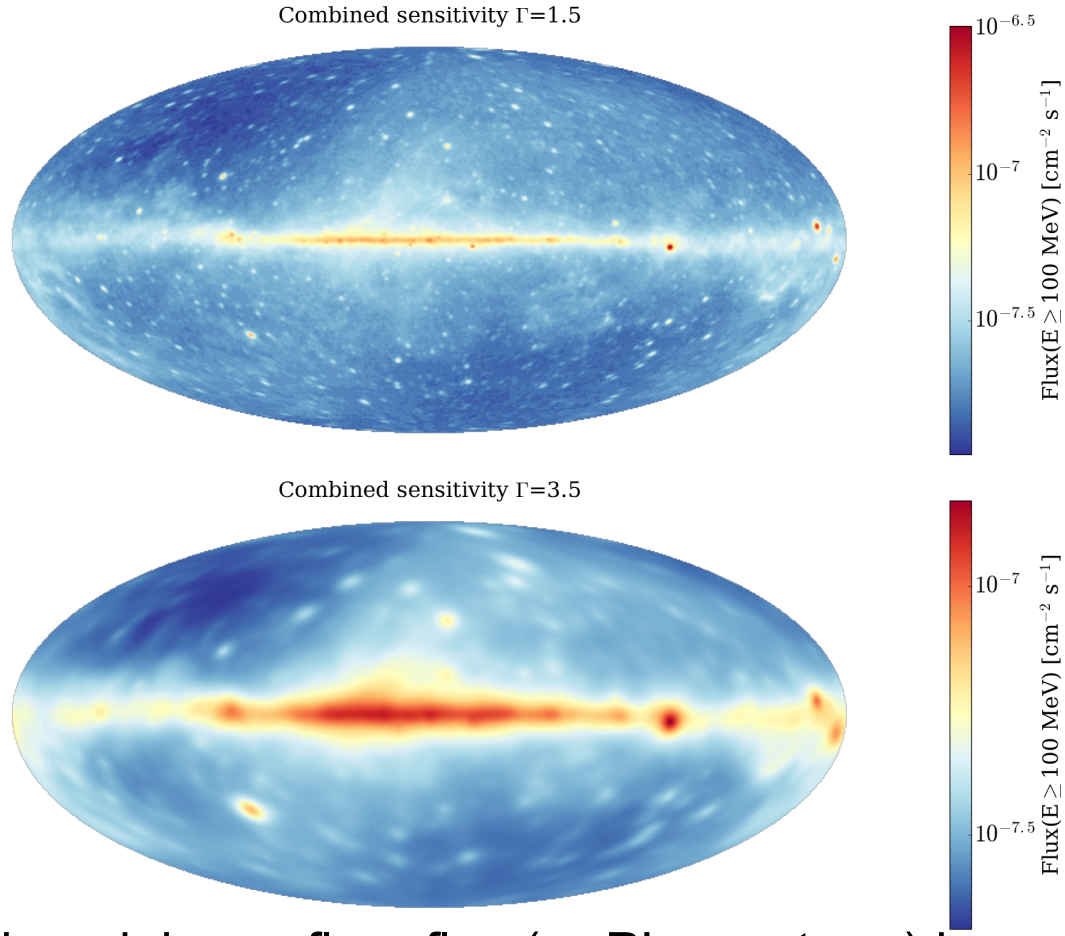
Flare spectra (other sources)





- Flares from the Crab PWN and High-Mass binaries (Cyg X-3, LS I+61 303, and PSR B1259-63/LS 2883) populates different region of the spectra parameter space. Different emission mechanism? (MR?)

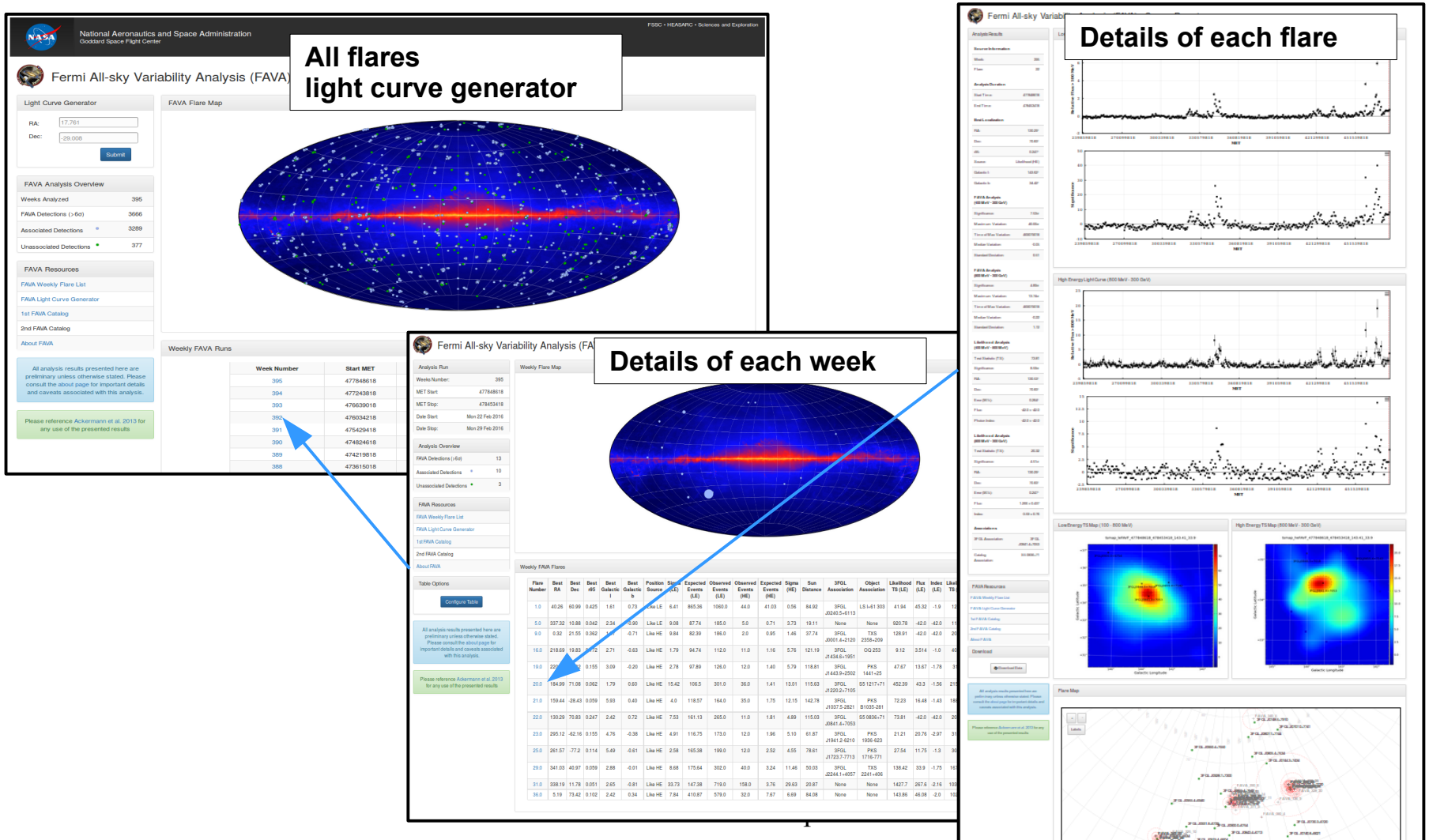
2FAV sensitivity maps



- Maps show the minimum flare flux (w. PL spectrum) in a one week time bin to be included in the catalog.
- Maps can provide all sky upper limits to the existence of new flaring sources for a given period

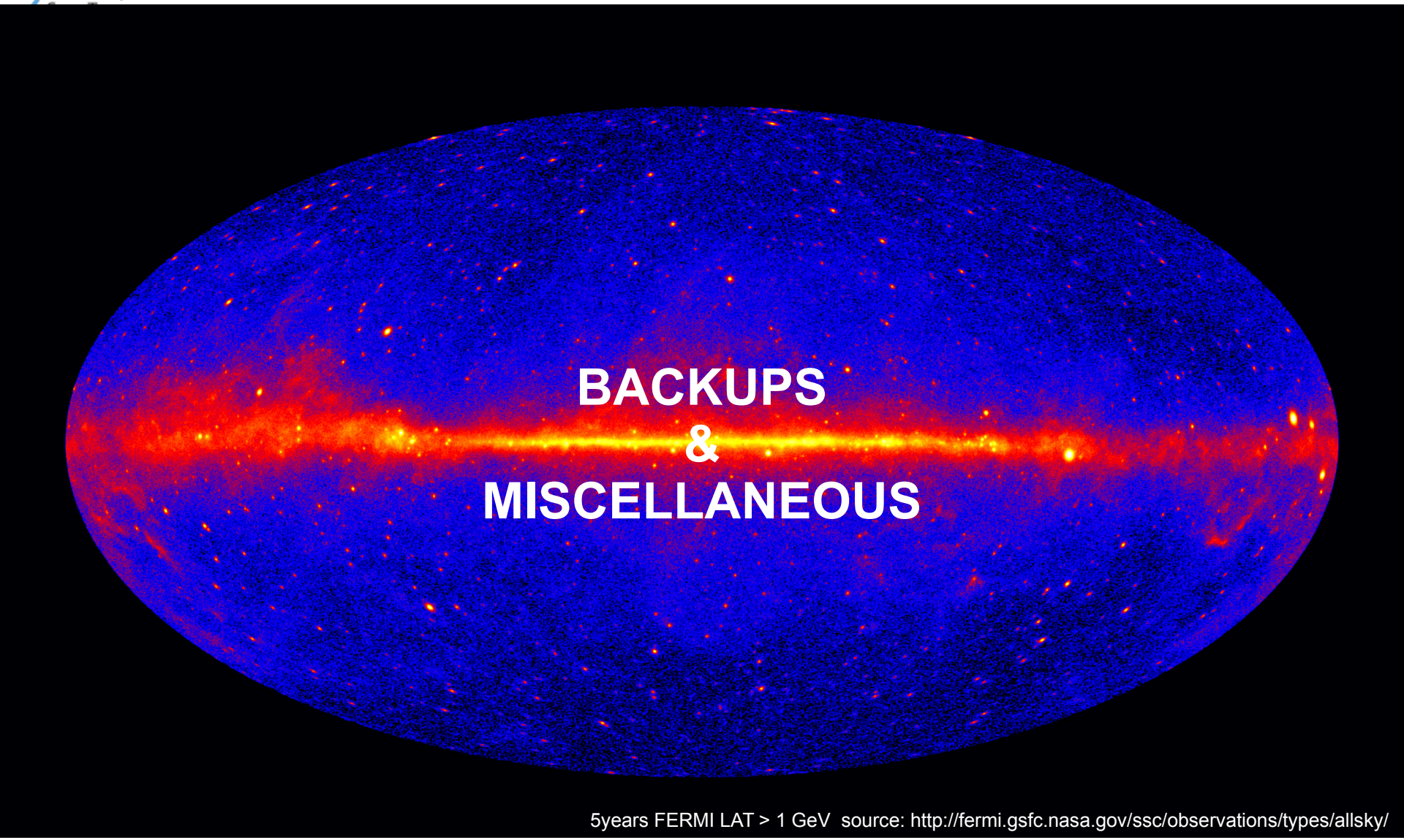
FAVA Online

- Webpage by Dan Kocevski: http://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/index.php
- Updated weekly as new data is processed.



Outlook and conclusions

- FAVA searches for weekly variability over the entire gamma ray sky.
- The analysis has been upgraded, and the positional accuracy for the single flares is ~0.1 deg.
- The 2nd FAVA catalog is based on >7 years of data.
  - 519 sources, mostly AGN, all the variable gamma-ray emitters are represented
  - 78 sources that have no counterpart in the catalogs used to look for associations.
- Measured spectra for > 4500 flares:
  - “Harder when brighter” behavior collectively observed for FSRQs flares
  - No flare harder than 1.5 → spectra of the freshly injected electron softer than 2 (assuming leptonic models and isotropy)
- FAVA is running in real time, and all the results are publicly available upon completion.



5years FERMI LAT > 1 GeV source: http://fermi.gsfc.nasa.gov/ssc/observations/types/allsky/

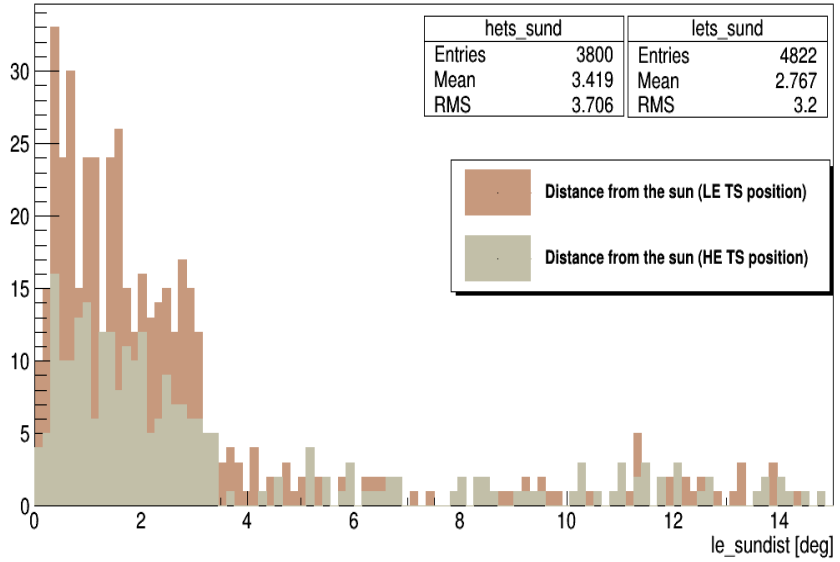
Flares cut

- Number of trials: $N_{trials} \approx \frac{41253}{\pi R^2_{PSF\,68}}$

$$R_{PSF\,68}(E>100\,MeV) \approx 3^o$$

$$R_{PSF\,68}(E>800\,MeV) \approx 0.6^o$$

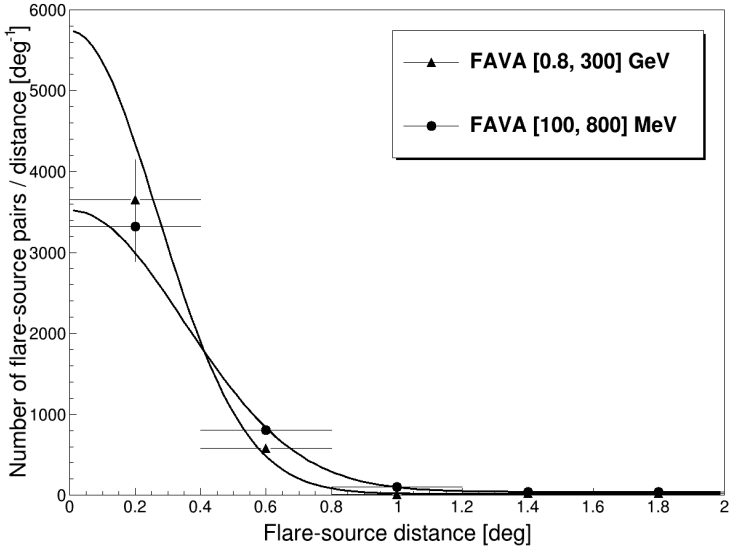
- Expected number of false positives above 6 sigma:
  - ~0.001 at low-energies,
  - ~0.03 at high energies.

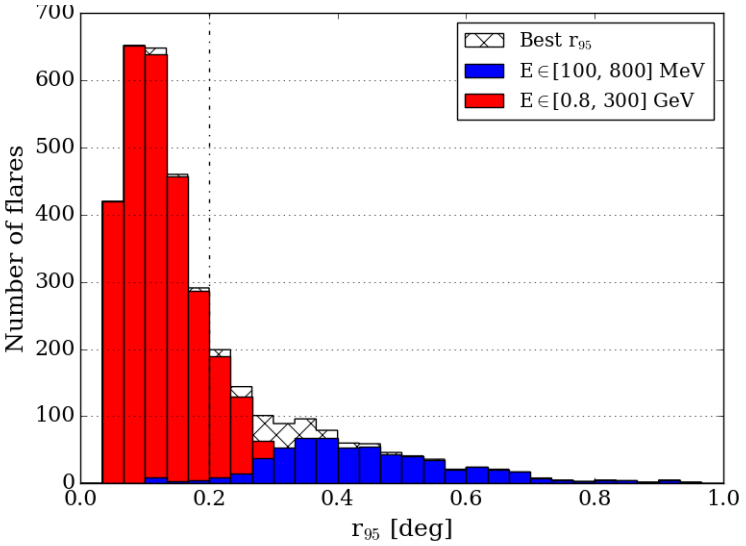


Energy Bin	Std FAVA analysis	Likelihood followup
[100-800] MeV	$\|\sigma_{LE}\|>6$ & sundist>6°	$TS_{LE}>39$ & $sundist_{LE}>6^o$ & good contour
[0.8-300] GeV	$\|\sigma_{HE}\|>6$ & sundist>6°	$TS_{HE}>39$ & $sundist_{HE}>6^o$ & good contour
Both	($\|\sigma_{LE}\|>4$ & $\|\sigma_{HE}\|>4$) & sundist>6° & dist(HE, LE)<3°	$TS_{LE}>18$ & $TS_{HE}>18$ & $sundist_{LE}>6^o$ & $sundist_{HE}>6^o$ & dist(HE, LE)<1.5° & good contours

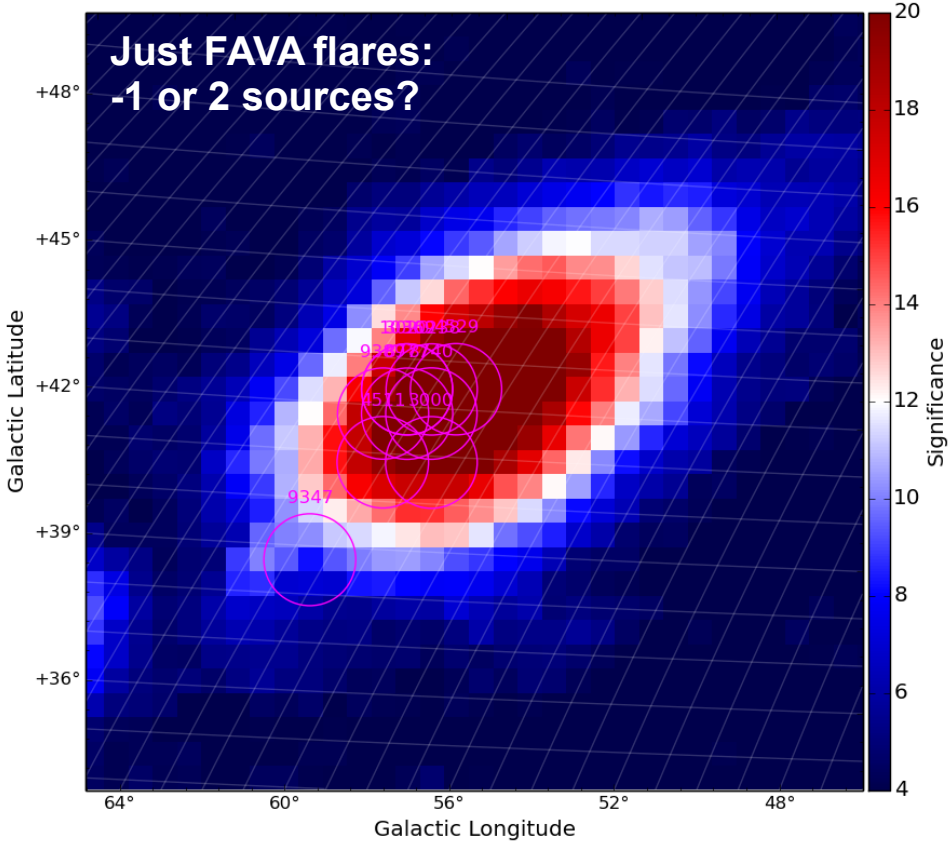
Angular resolution

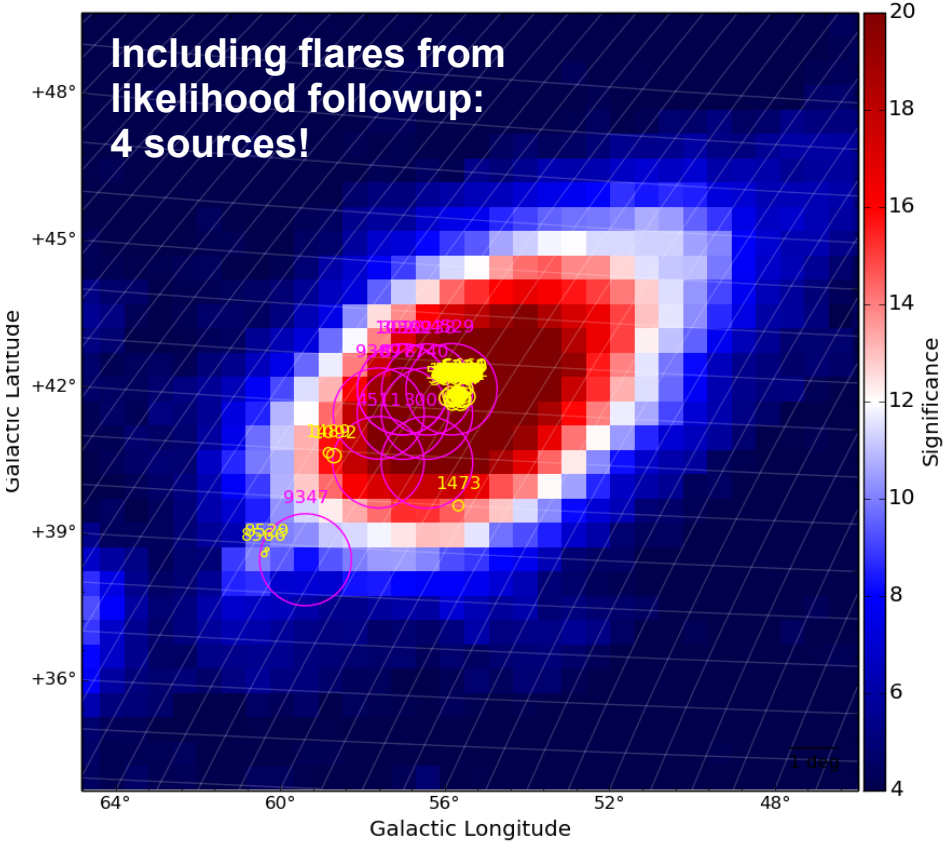
- FAVA positional accuracy is estimated comparing flare positions to known flaring sources:
  - FAVA low energy $r_{95} \sim 1^{o}$
  - FAVA high energy $r_{95} \sim 0.8^{o}$
- The error on the flare position from the TS maps is measured using the 95% CL contour:
  - $\langle r_{95} \rangle$ low energy TS ~ 0.3^{o}
  - $\langle r_{95} \rangle$ high energy TS ~ 0.1^{o}
- Up to a factor 8 improvement.
- Flare position from TS map are more reliable, as accompanied by the error





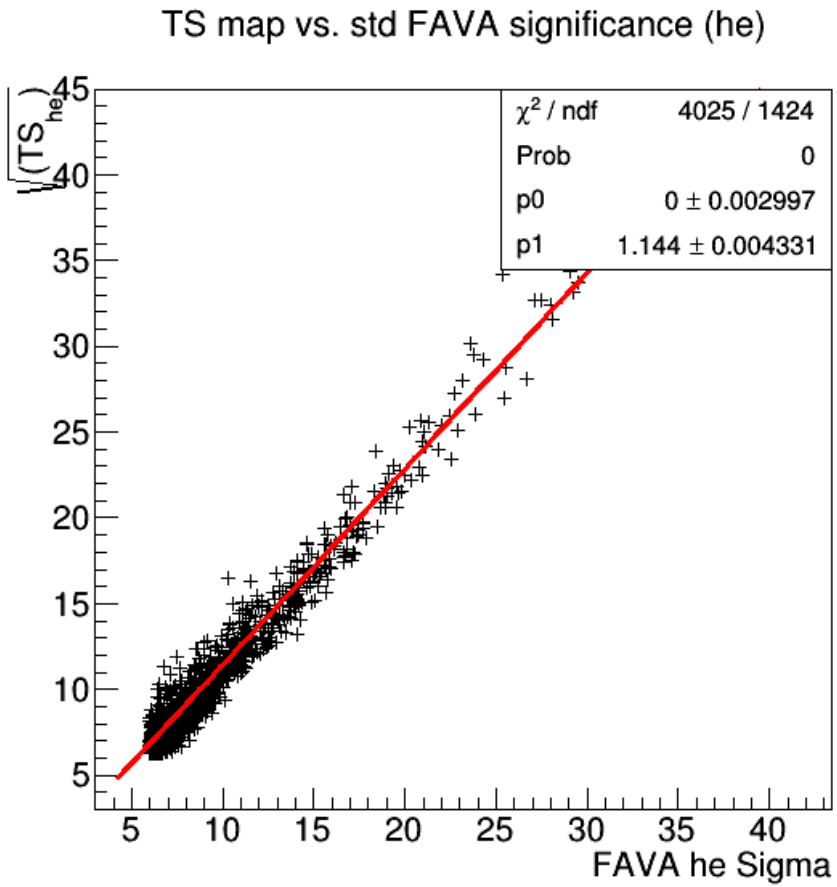
Better flare localization: practical advantage.

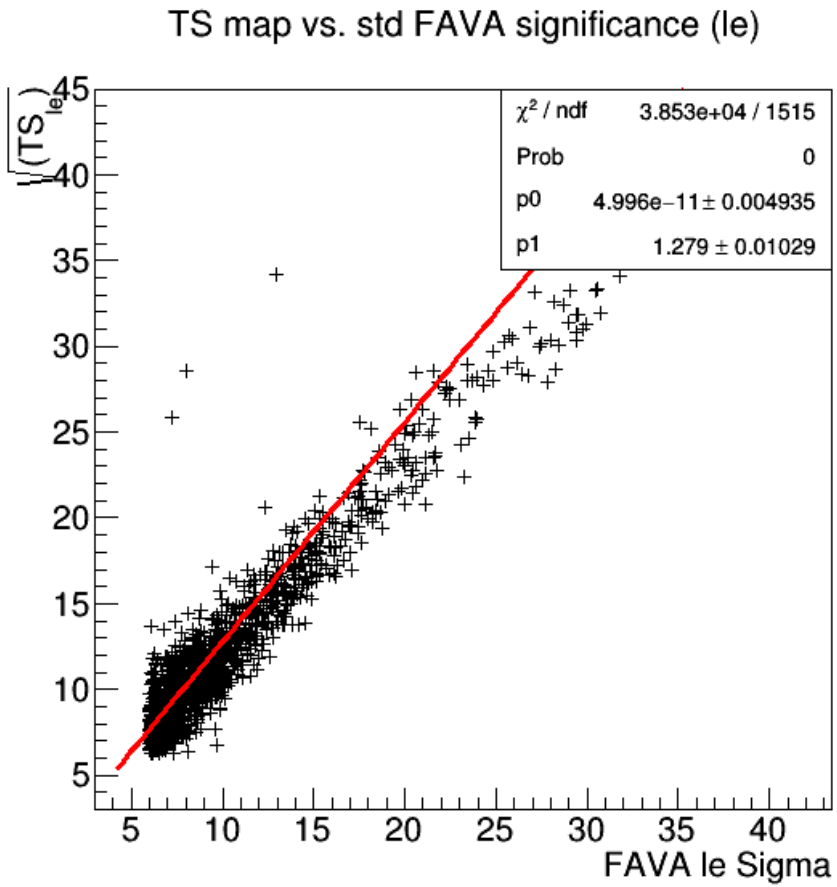




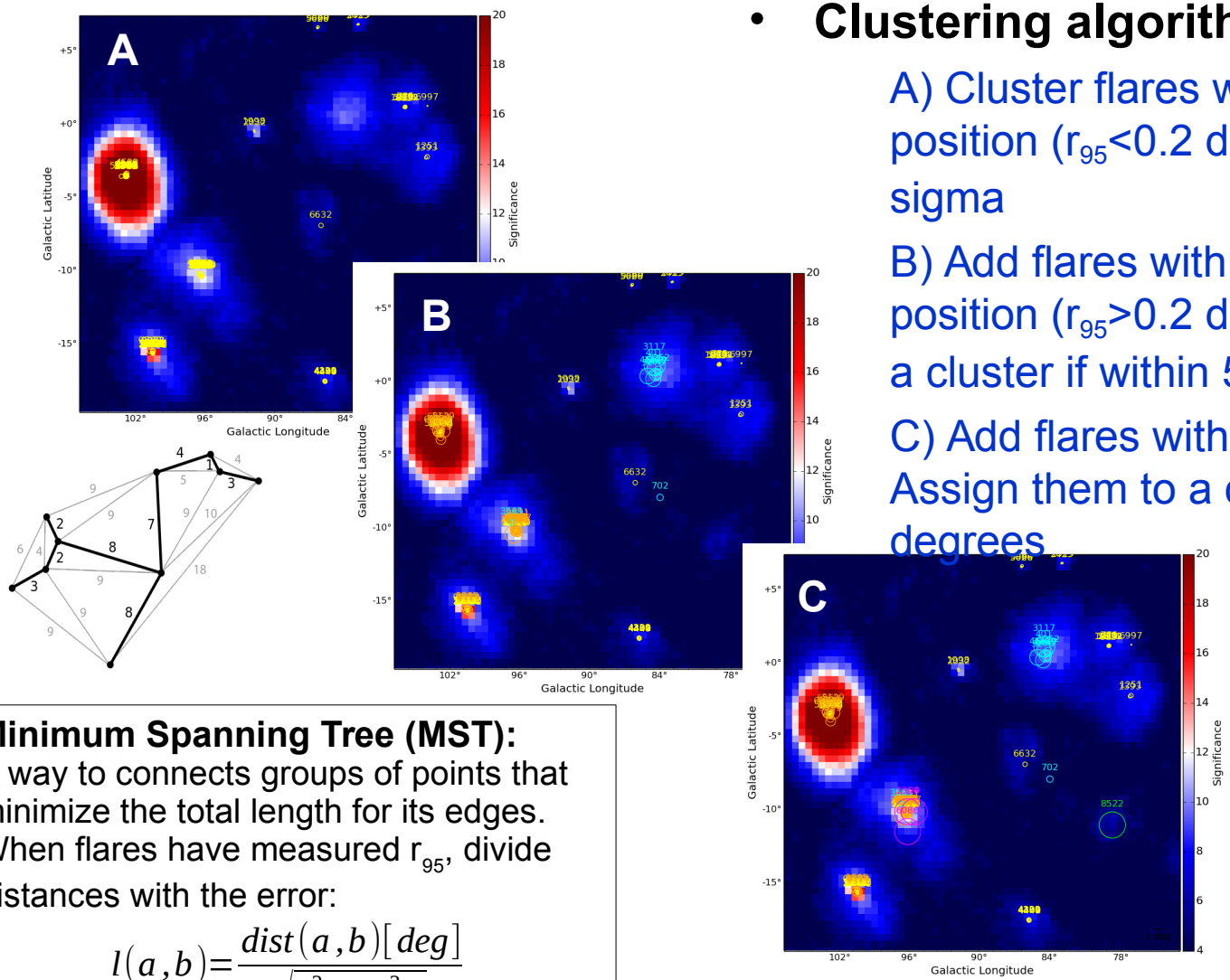
FAVA significance vs likelihood TS:

- Likelihood analysis has a slightly improved sensitivity:





Clustering



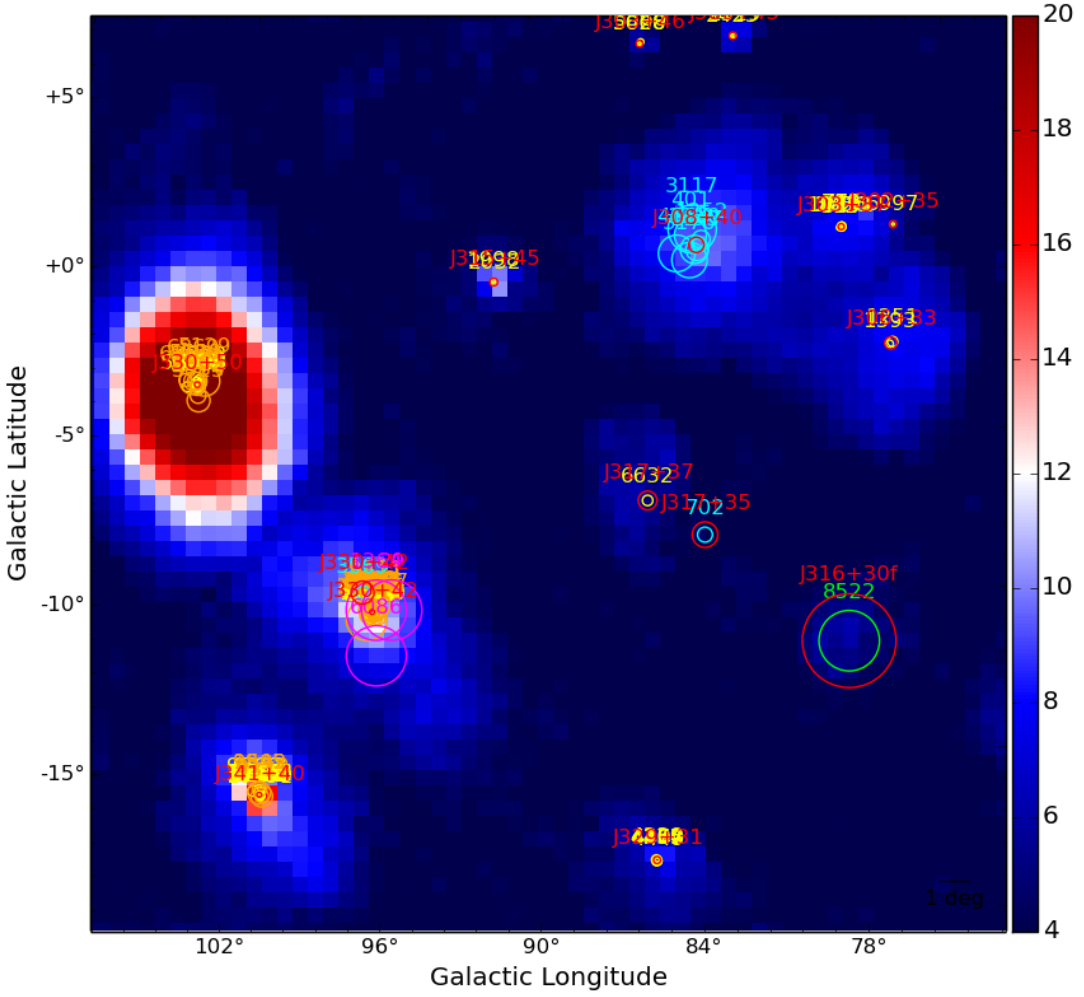
- **Clustering algorithm**:
  - A) Cluster flares with better TS map position (r_{95}<0.2 deg). Edge cut at 5 sigma
  - B) Add flares with worst TS map position (r_{95}>0.2 deg). Assign them to a cluster if within 5 sigma
  - C) Add flares with just FAVA position. Assign them to a cluster if within 3.5 degrees

Minimum Spanning Tree (MST):
A way to connects groups of points that minimize the total length for its edges. When flares have measured r_{95}, divide distances with the error:

$$l(a,b)=\frac{dist(a,b)[deg]}{\sqrt{r_{95a}^2+r_{95b}^2}}$$

Otherwise use flare-flare distance

Construction of the 2 FAV sources

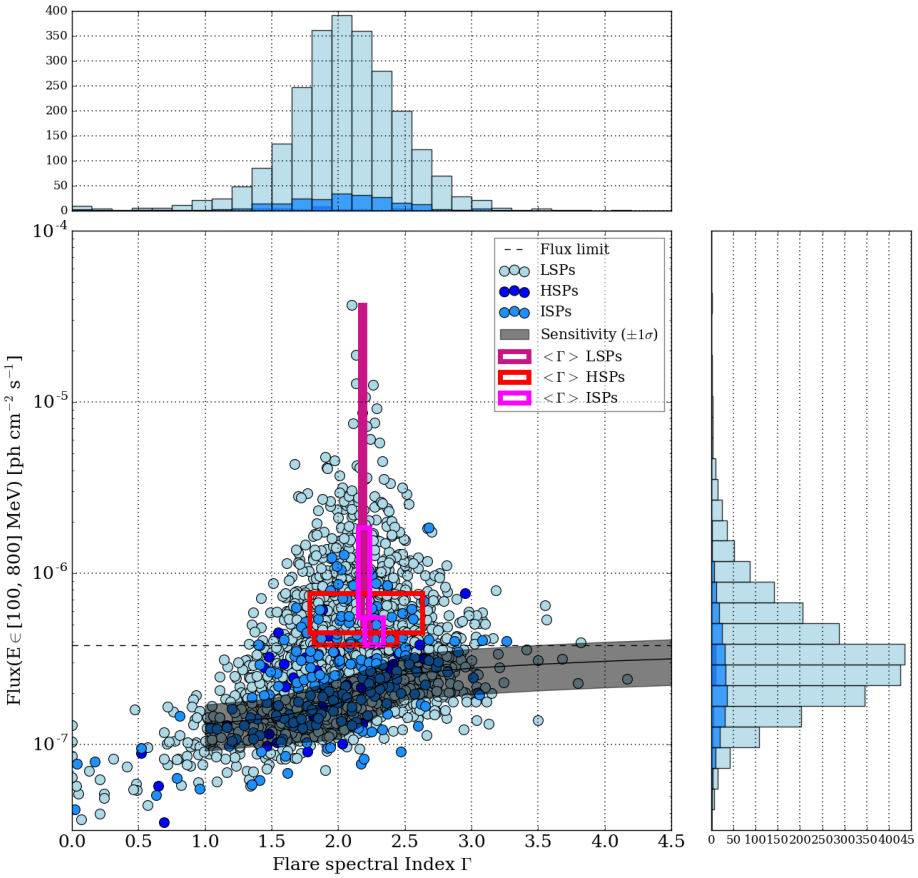


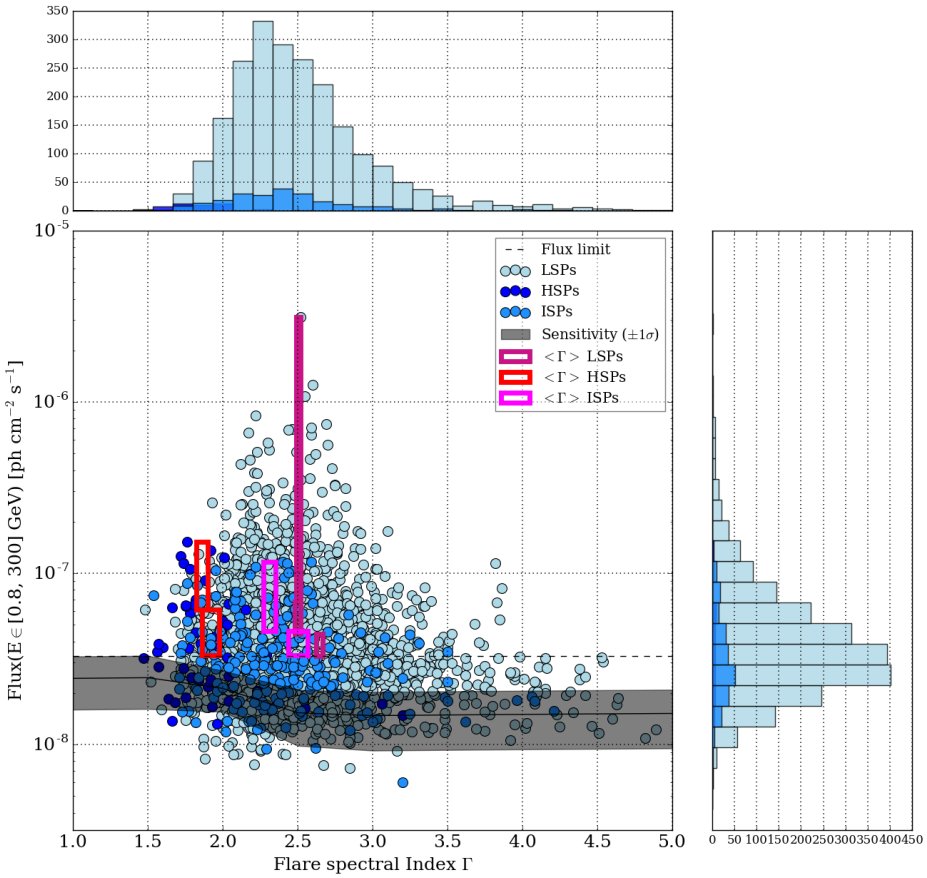
- Position of the 2FAV source as weighted average of the flares position:
  - Weights = $1/r_{95}^2$
  - Only better localized flares are considered
- Systematic error obtained comparing 2FAV sources position to known bright flaring sources:
  - R_{sys}= 0.1 deg
- **Search radius:** $R_s=r_{99}+R_{sys}$ used to look for counterparts

Non-AGN 2FAV sources:

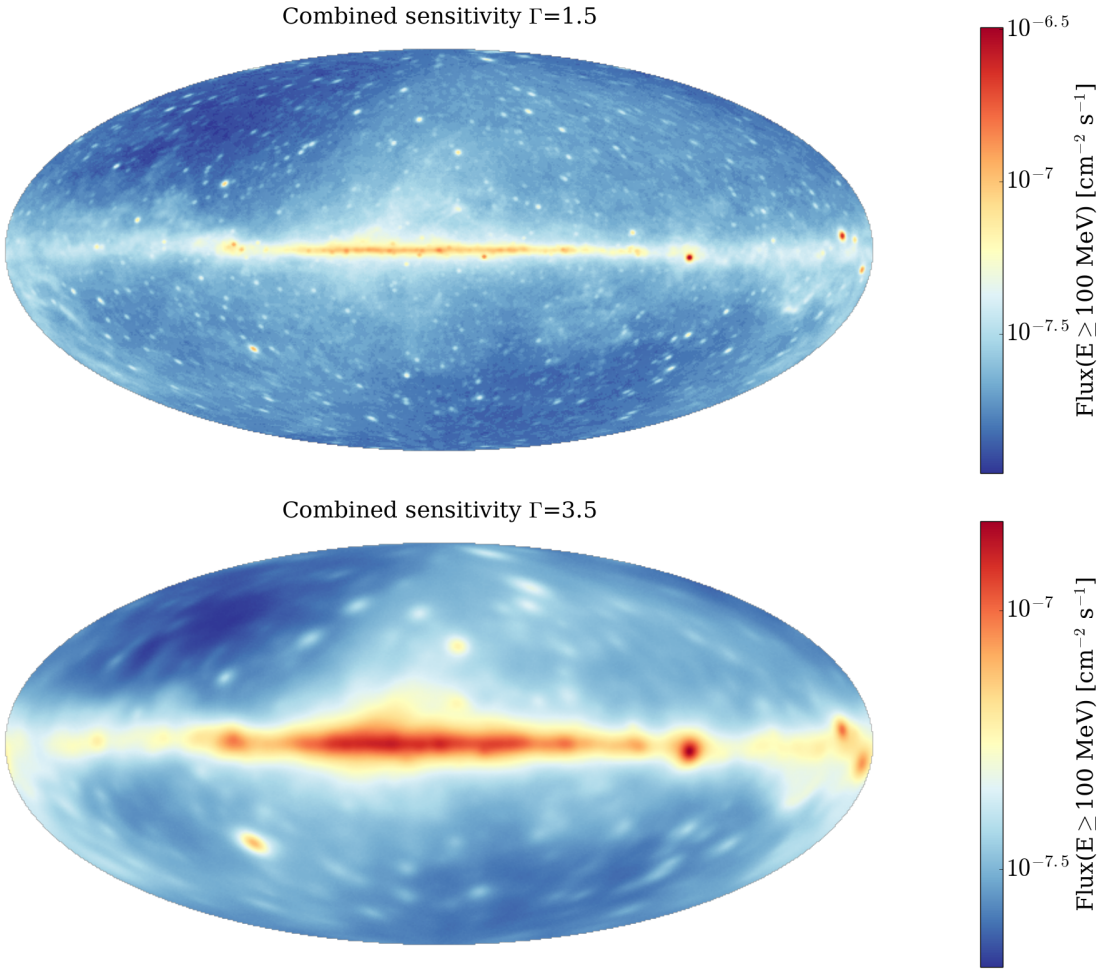
- 5 Novae:
  - V407 Cyg, Nova Mon 2012, Nova Sco 2012, Nova Delphini, and Nova Centauri. http://asd.gsfc.nasa.gov/Koji.Mukai/novae/novae.html
- GRBs:
  - GRB150627A, GRB150523A, GRB141207A, GRB140206B, GRB131231A, GRB131108A, GRB130427A, GRB120711A, GRB090926A, GRB090902B, GRB090510A, GRB090328A, GRB090323A, GRB080916C
- pulsar/Be-star binary: PSR B1259-63/LS 2883
- High mass binary systems: Cyg X-3 and LS I+61 303
- NL Seyfert & radio galaxies:
  - Narrow-line Seyfert 1 galaxies: PMN J0948+0022 (D'Ammando et al. 2015), SBS 0846+513 (D'Ammando et al. 2012), and 1H 0323+342 (Paliya et al. 2014)
  - Radio galaxies: 3C 111 (Grandi et al. 2012), NGC 1275 (Abdo et al 2009), and 3C 120
- Crab PWN
- Pulsars:
  - millisecond pulsar binary PSR J1023+0038. arXiv:1312.0605
  - PSR J1826-1256. Very populated region. FAVA alone can not confirm the association. Need MW!

Flare spectra of blazars (SED classification)





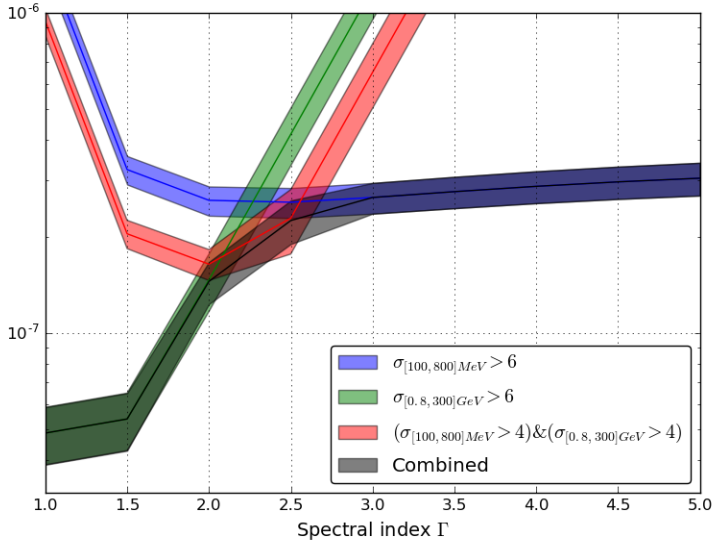
2FAV sensitivity maps



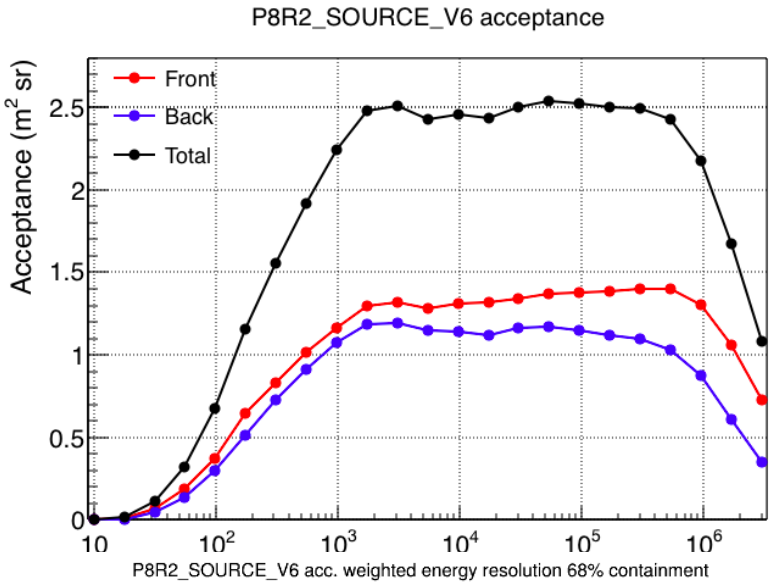
Not accounting likelihood followup.

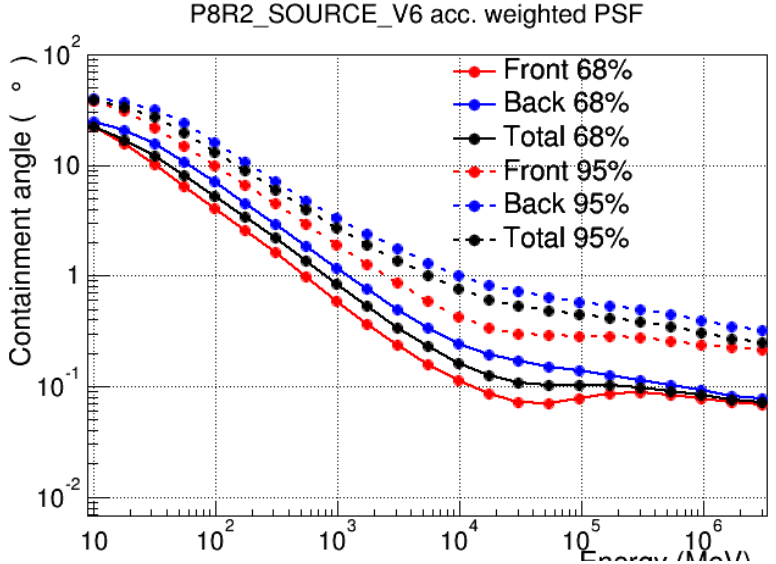
Ref values for blazars:

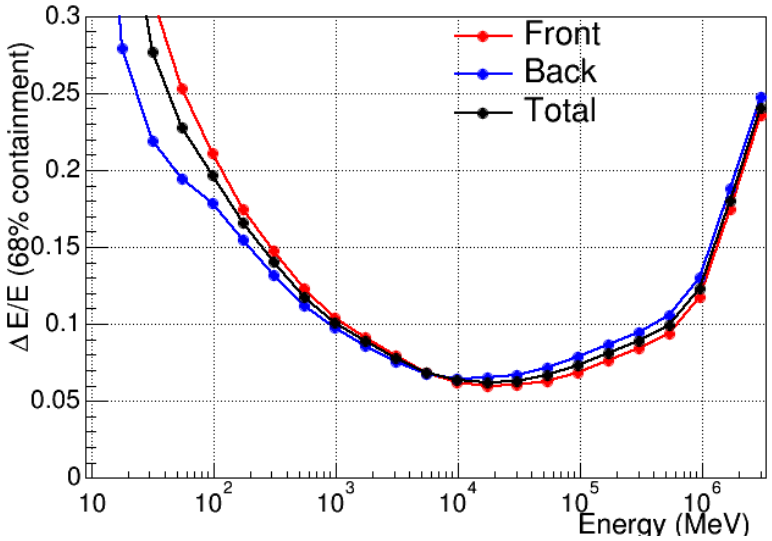
- Sens(LE)~3.7 10^{-7}cm^{-2} s^{-1}
- Sens(HE)~3.3 10^{-8}cm^{-2}s^{-1}

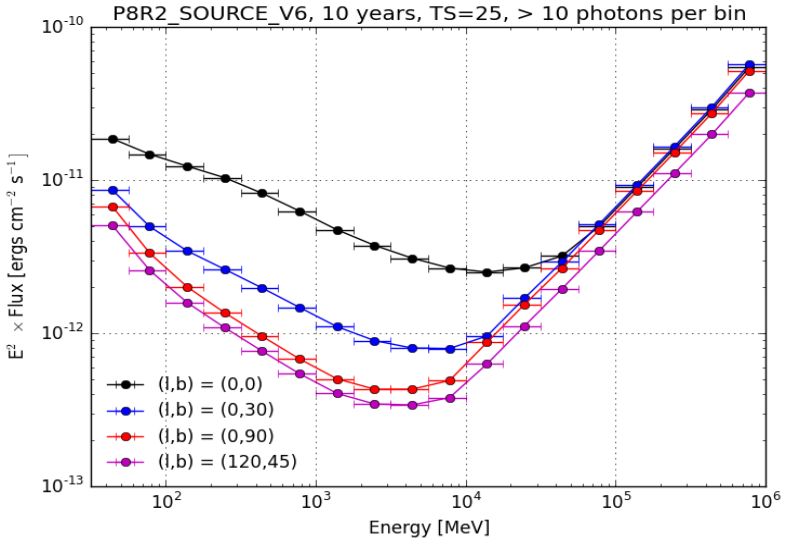


LAT Instrument response functions



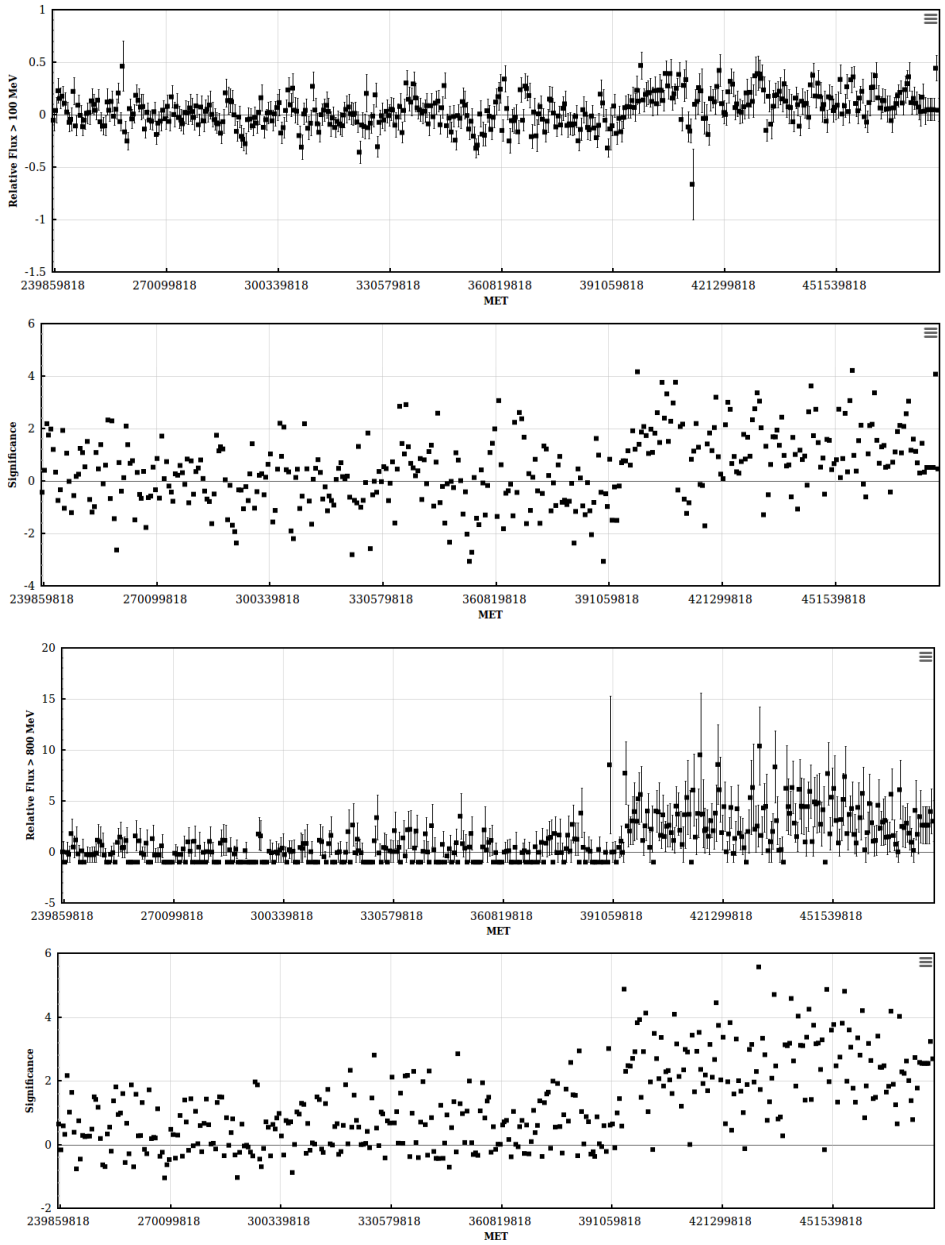






- http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_PSF.html
- https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Example source: PSR J1023+0038



- Link between Low mass x-ray binary and millisecond pulsar
- In 2000/2001 had accretion disk
- The disk has disappeared and radio pulsation found in 2007
- Accretion disk probably re-formed in june/july 2013:
  - Radio pulsation are gone
  - Strong doble peaked H-alpha lines
  - Gamma-ray and X-ray brighter

arXiv:1312.0605

Example source: PSR B1259-63/LS 2883