



Fermi  
Gamma-ray Space Telescope



# The Second Fermi All-sky Variability Analysis Catalog

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collaboration**



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Dan Kocevski



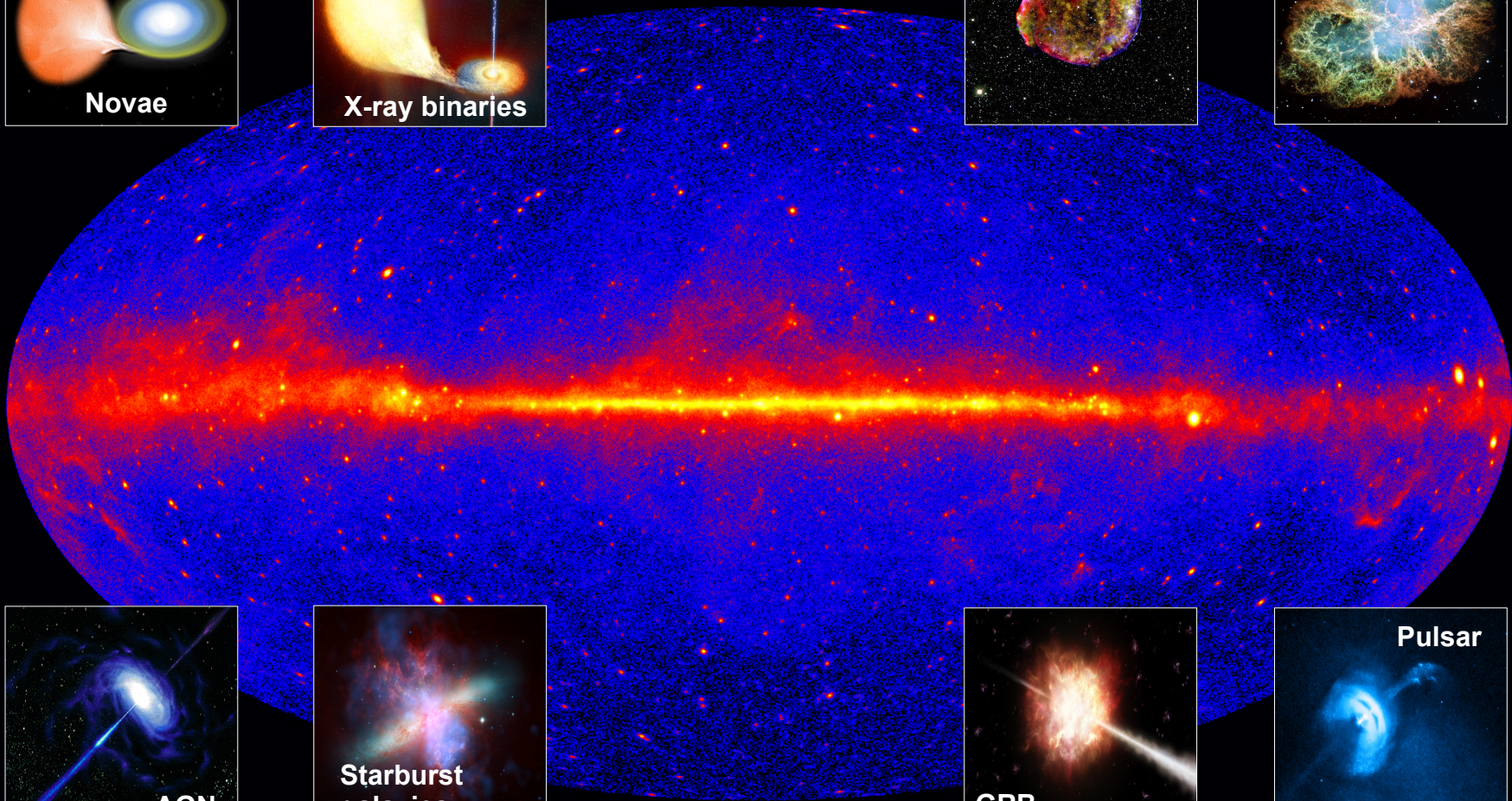
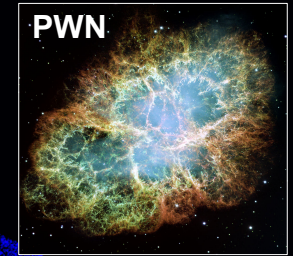
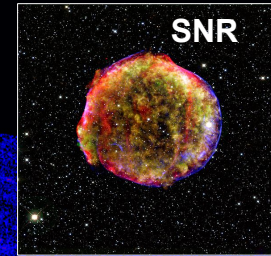
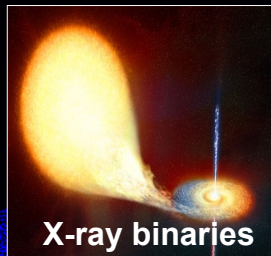
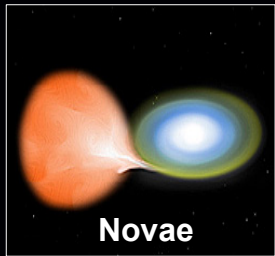
Marco Ajello



Alliance for Astroparticle Physics



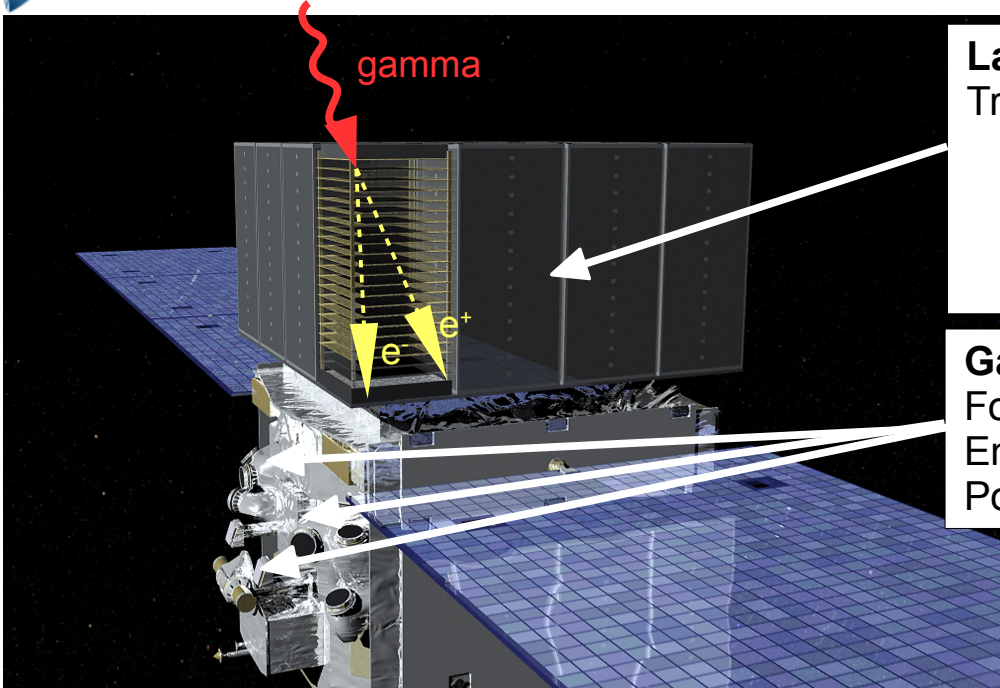
# The gamma-ray sky



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:  $0.8^\circ$  @ 1 GeV
- Dead time: 15 % (SAA) + 9% (trigger)

## Gamma-ray Burst Monitor (GBM)

FoV: Complete unocculted sky

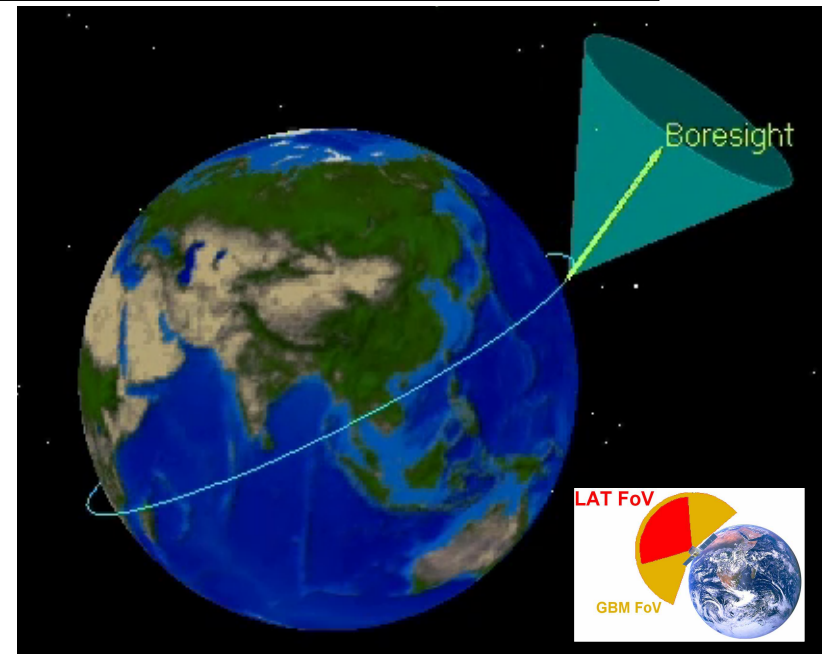
Energy range: 8 KeV- 40 MeV

Positional accuracy:  $4^\circ$ - $8^\circ$

## All Sky survey:

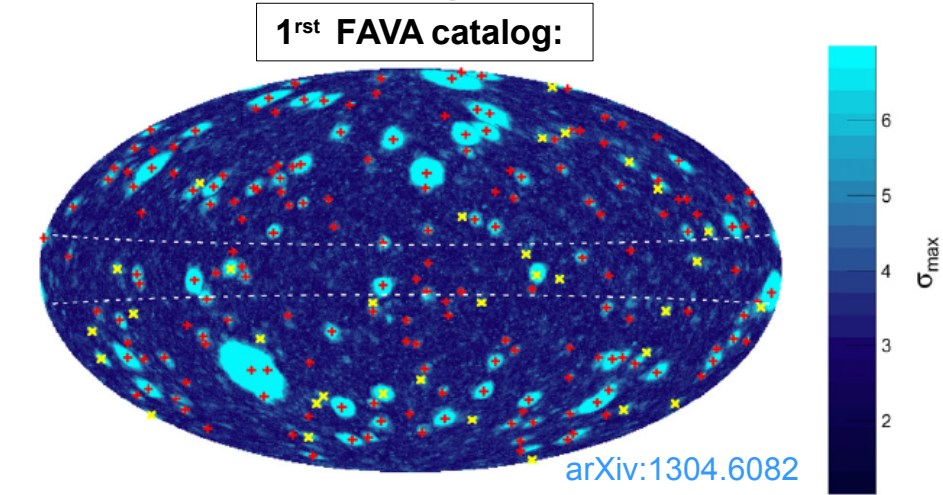
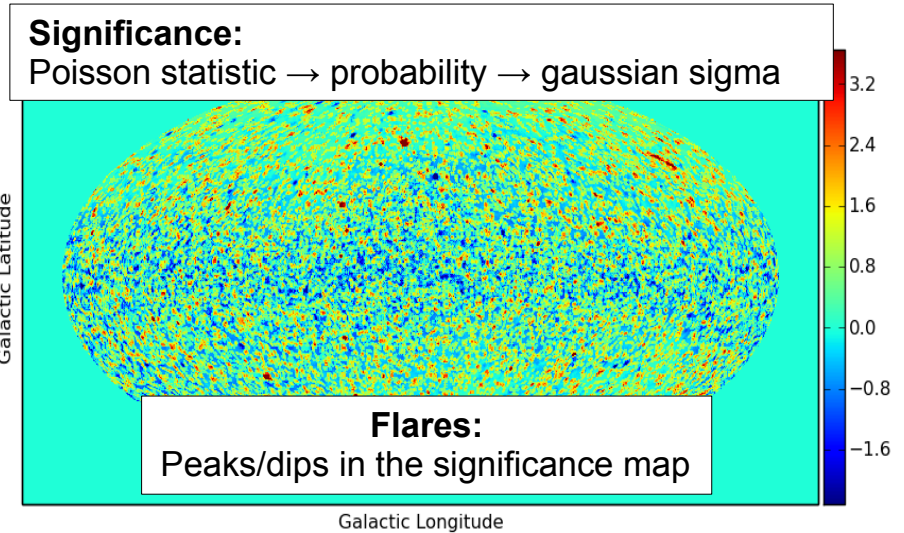
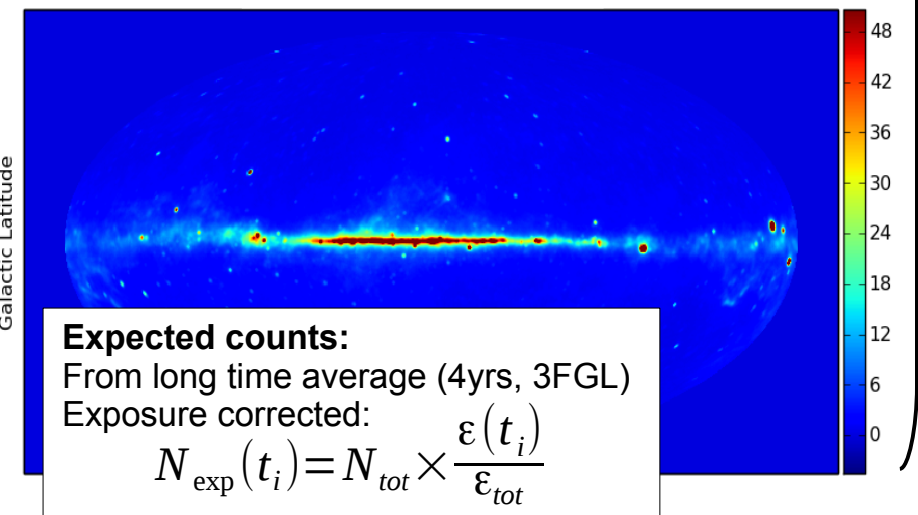
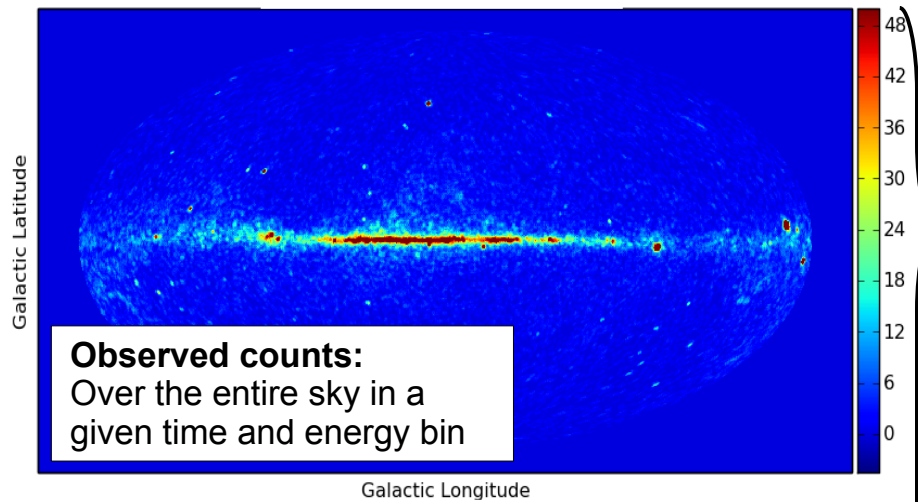
Fermi spends  $\sim 80\%$  of the time in survey mode:

- 30 minutes of livetime on each point in the sky every 3 orbits
- Complete sky every  $\sim 3$  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 ( $r_{95} \sim 1$  deg)

✗ No spectral measurement.



**Likelihood followup analysis:**

Based on test statistic (TS) maps:

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

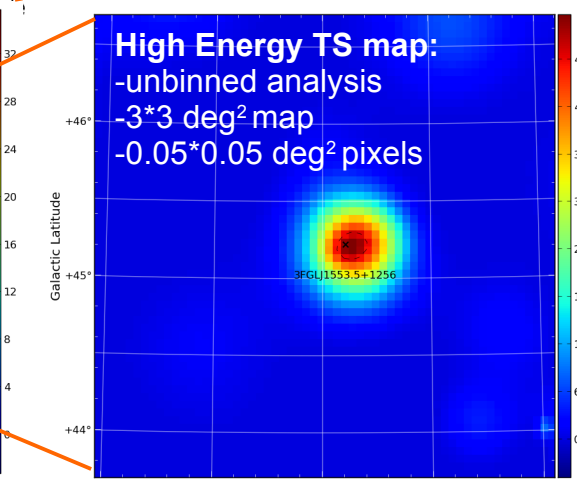
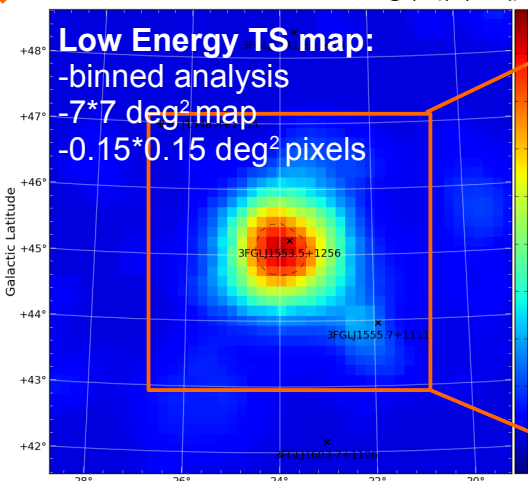
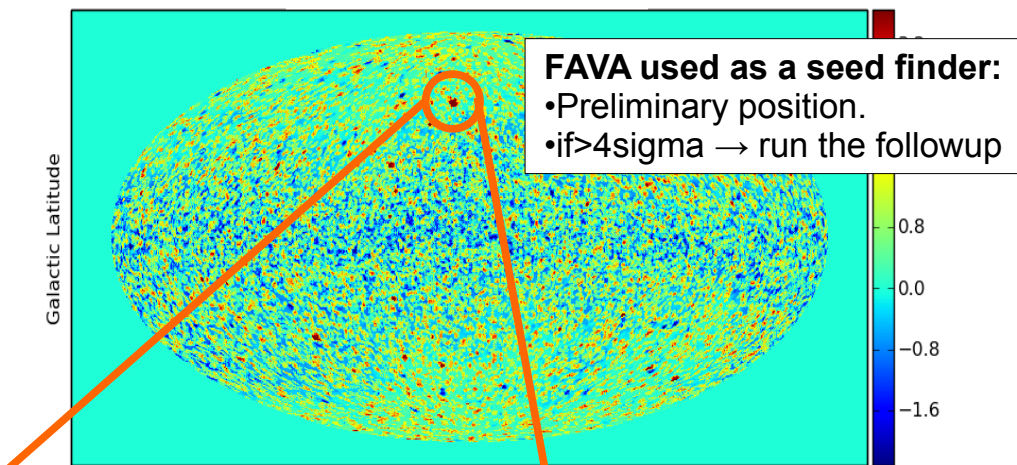
- Likelihood scan to test for putative point source
- Null hypothesis = static 3FGL sky

• From the TS maps:

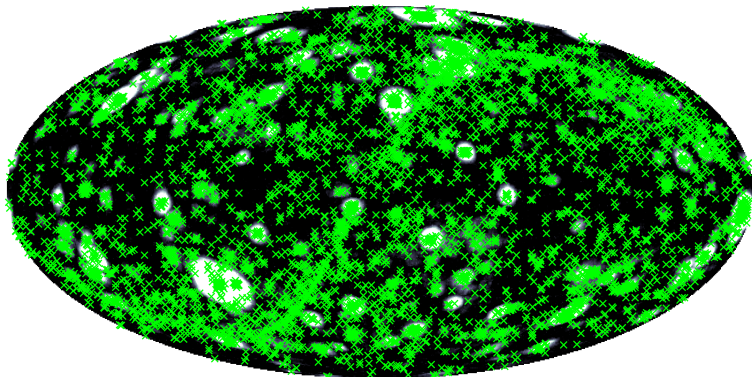
- Flare position & error:
- $r_{95} \sim 0.1$  deg (HE),  $\sim 0.3$  deg (LE)
- Flare spectrum measured with likelihood fit (`gtlike`)

**FAVA used as a seed finder:**

- Preliminary position.
- if  $> 4\sigma$  → run the followup



# 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**

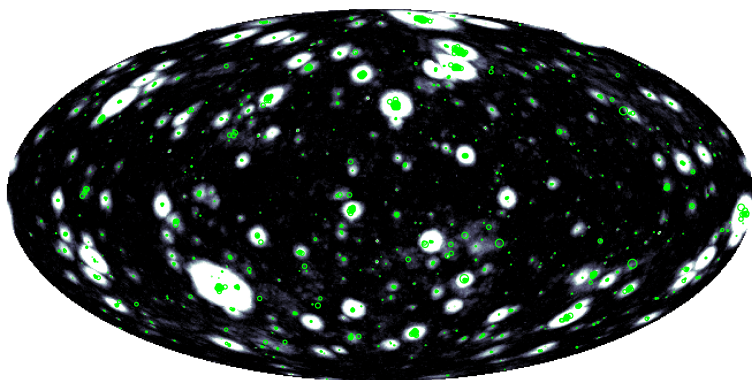
- **Flare cuts:**

- > 6 sigma (TS>39) in one energy bin

- > 4 sigma (TS>18) in both

- > 6deg away from the sun

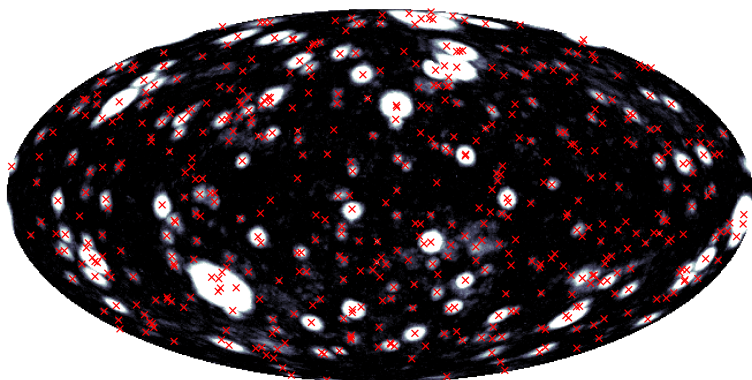
- **4548 “catalog” flares**



- **2FAV source = cluster of flares**

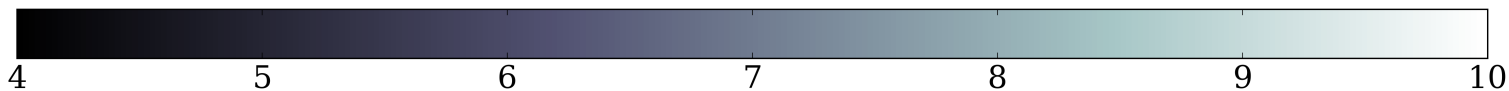
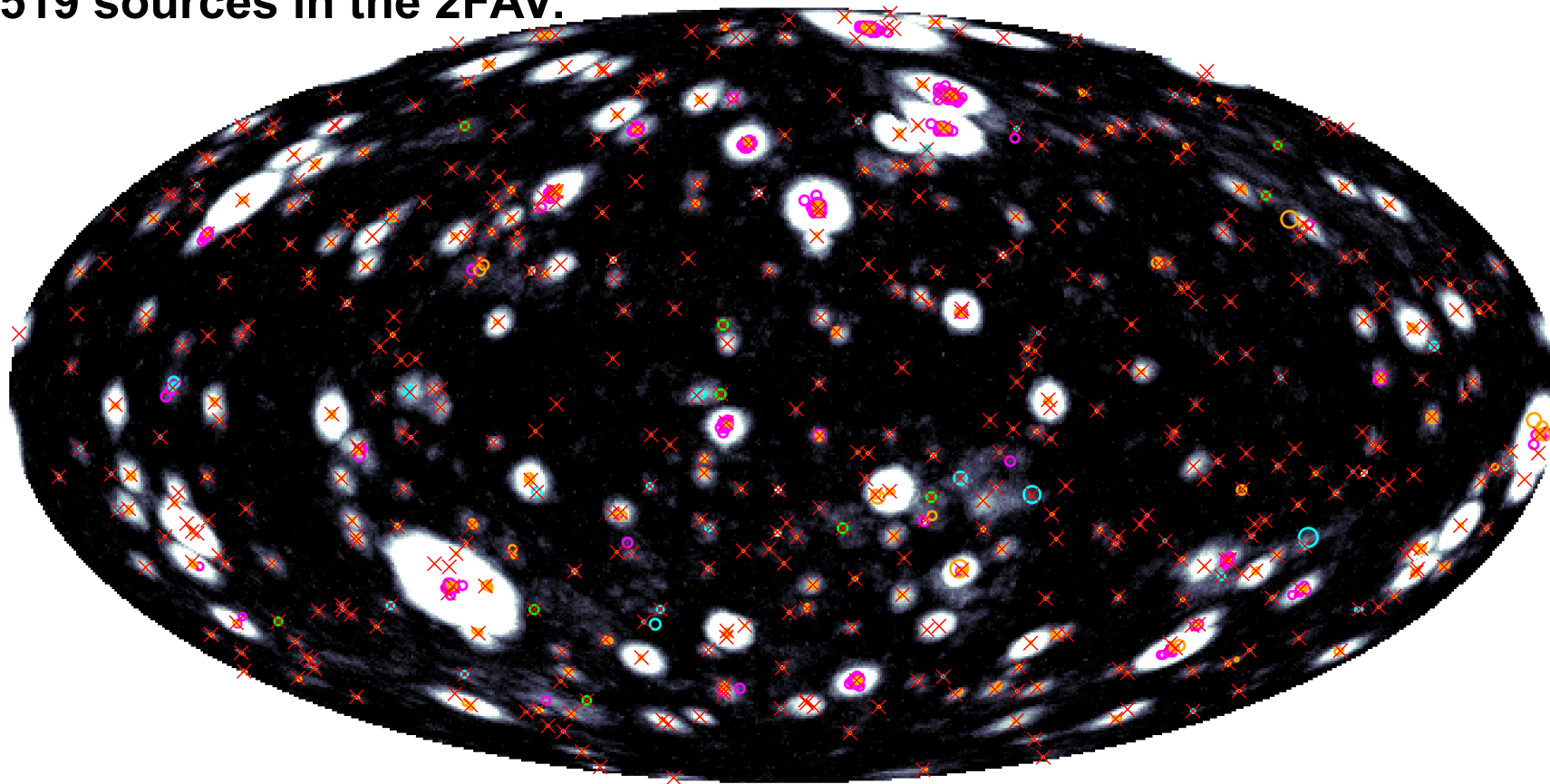
- Using MST, starting from better localized flares

- Flare position averaged to locate source



# The second FAVA catalog (2FAV)

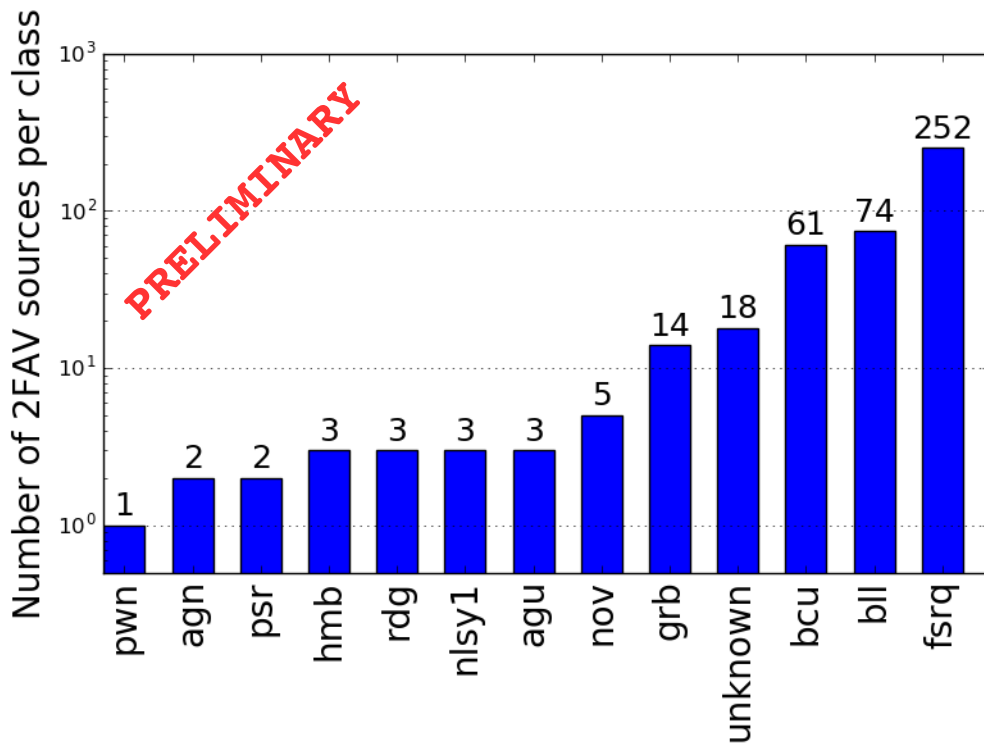
- **519 sources in the 2FAV:**



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

# Likely counterparts

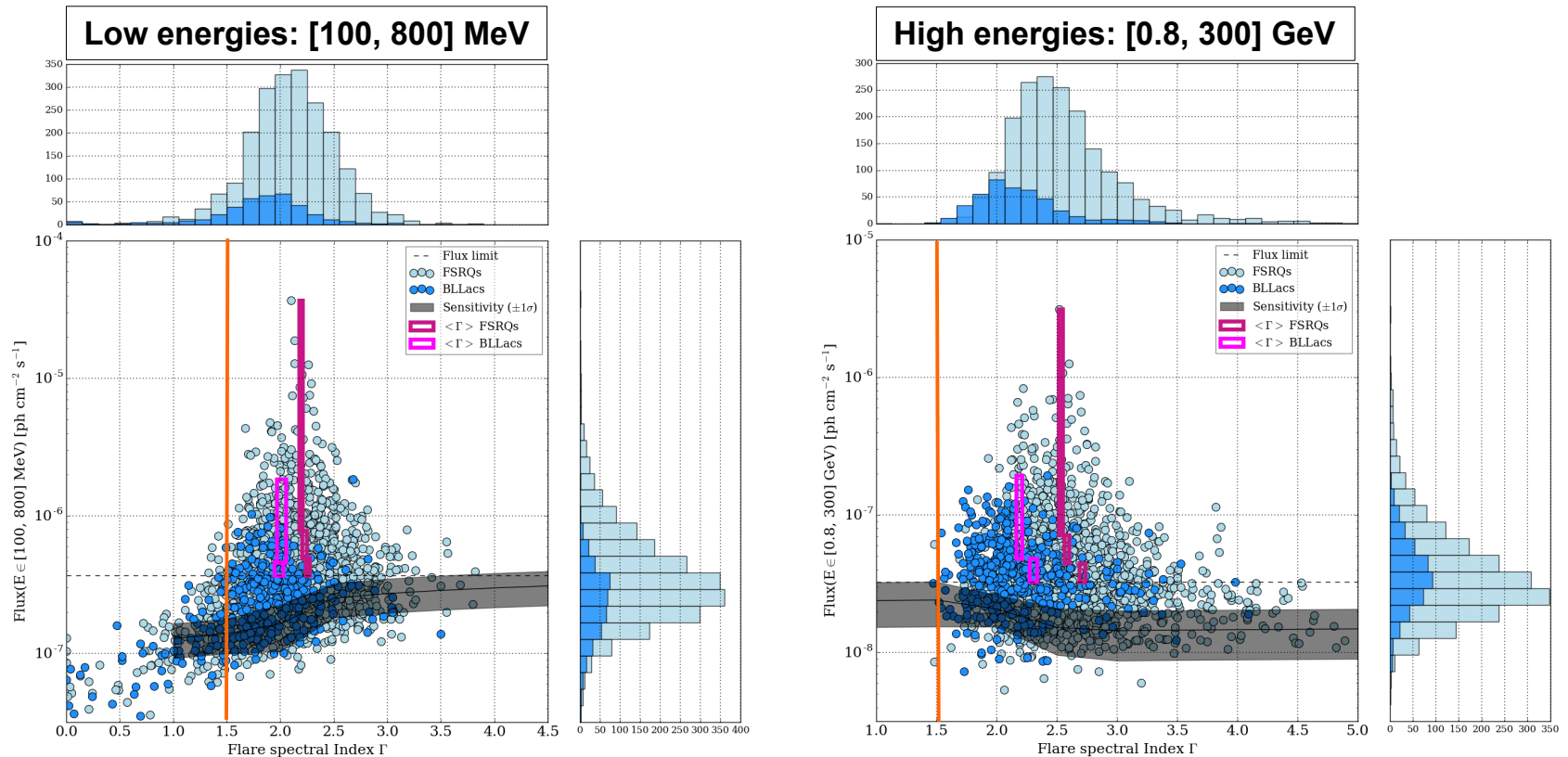
- Search for counterparts of 2FAV sources:
  - based only on positional coincidence. **(handle with care)**
  - In 3FGL, 2FGL, 1FGL, 3EG, 1AGL, LAT ATels, LAT GRBs, BZCAT
  - Variable counterpart has priority over closest counterpart



- 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



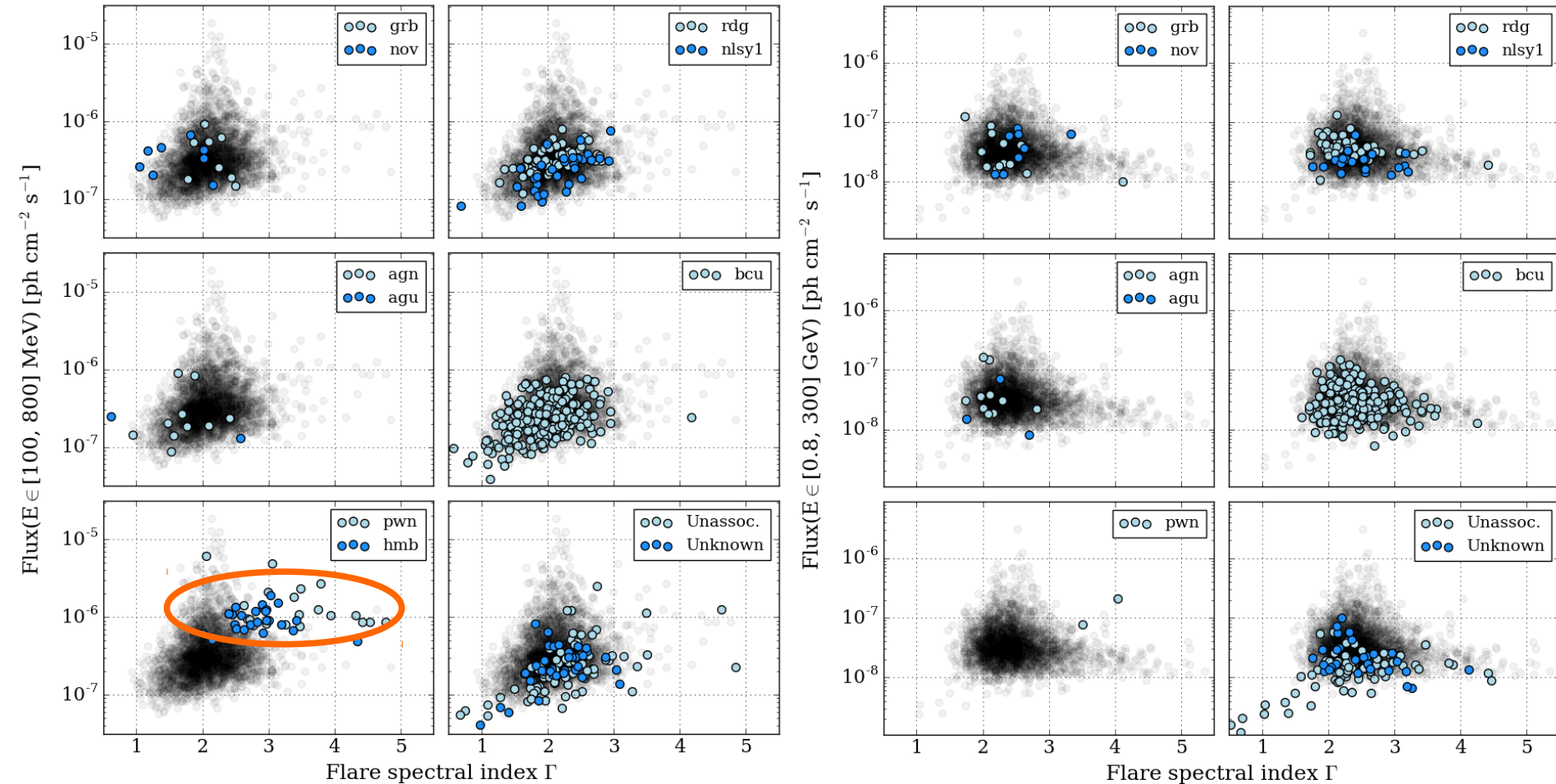
# Flare spectra of blazars



- 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  $\Gamma \geq 1.5 \rightarrow$  Injected electron spectra never harder than  $\sim 2$
- Compatible with particle acceleration at shocks and magnetic reconnection (with low magnetization)

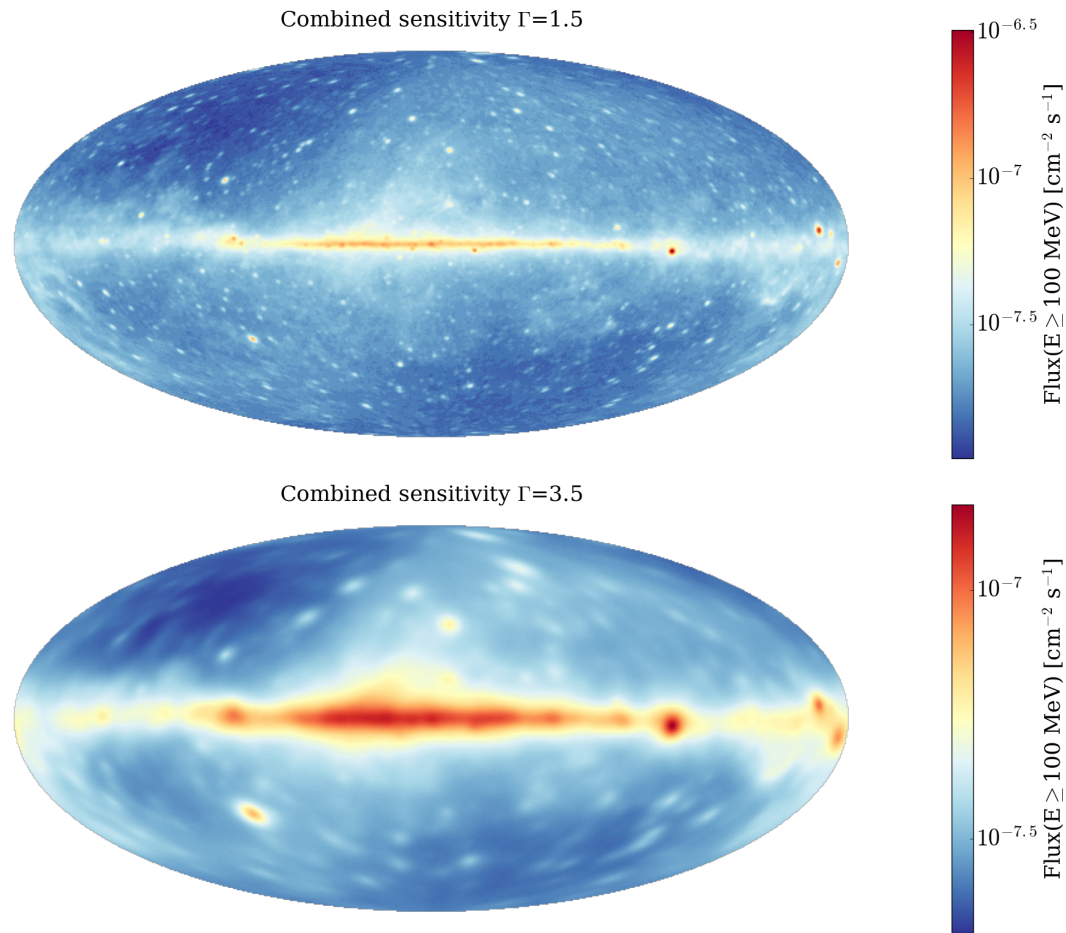
<http://arxiv.org/abs/1006.5210>  
<http://adsabs.harvard.edu/abs/1987PhR...154....1B>  
<http://arxiv.org/abs/1506.02034>

# 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

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

**All flares light curve generator**

Light Curve Generator

RA:

Dec:

Submit

FAVA Analysis Overview

- Weeks Analyzed: 395
- FAVA Detections (> 6σ): 3666
- Associated Detections: 3289
- Unassociated Detections: 377

FAVA Resources

- FAVA Weekly Flare List
- FAVA Light Curve Generator
- 1st FAVA Catalog
- 2nd FAVA Catalog
- About FAVA

Weekly FAVA Runs

Week Number	Start MET
395	477849618
394	477243818
393	476639018
392	476034218
391	475429418
390	474824618
389	474219818
388	473615018

**Details of each week**

Weekly FAVA Flares

Flare Number	Best RA	Best Dec	Best galactic $l$	Best galactic $b$	Position Source (L <sub>1</sub> )	Expected Events (E <sub>1</sub> )	Observed Events (O <sub>1</sub> )	Expected Significance (S <sub>1</sub> )	Observed Significance (O <sub>1</sub> )	Sun Distance (AU)	SFGL Association	Object Association	Likelihood (L <sub>1</sub> )	Flux (L <sub>1</sub> )	Index (L <sub>1</sub> )				
1.0	40.26	60.09	0.025	1.61	0.73	LiA L6	6.41	805.56	1060.0	44.0	41.03	0.56	84.92	3FGL J0005.046113	LS 141 303	41.84	45.32	-1.9	12
5.0	337.32	10.88	0.042	2.34	5.95	LiA L6	9.08	87.74	185.0	5.0	5.71	3.73	19.11	None	None	520.78	-42.0	-42.0	11
9.0	0.32	21.55	0.262	-0.71	LiA HE	9.84	82.39	186.0	2.0	0.95	1.46	37.74	3FGL J00016.421210	TXS 0359-209	128.91	-42.0	-42.0	20	
16.0	216.69	10.95	0.112	2.71	-6.83	LiA HE	1.79	64.74	112.0	11.0	1.16	5.76	121.10	3FGL J1436.6-1191	CG 253	9.12	3.514	-1.0	46
19.0	209.0	0.155	0.155	3.09	-0.20	LiA HE	2.78	97.89	126.0	12.0	1.40	5.79	118.81	3FGL J1443.9-2502	PKS 1441-05	47.67	13.67	-1.78	3
20.0	184.09	71.08	0.062	1.79	0.60	LiA HE	15.42	106.5	301.0	36.0	1.41	13.01	115.63	3FGL S5 1217-71	452.29	43.3	-1.56	215	
21.0	159.44	28.43	0.059	3.09	0.40	LiA HE	4.0	118.07	164.0	35.0	1.75	12.15	142.76	3FGL J1037.5-2821	PKS 1035-281	73.29	16.48	-1.43	18
22.0	130.29	70.83	0.247	2.42	0.72	LiA HE	7.53	161.13	265.0	11.0	1.81	4.89	115.03	3FGL S5 0836-71	85 0836-71	73.81	-42.0	-42.0	20
23.0	205.12	42.16	0.155	4.76	-0.38	LiA HE	4.91	116.75	173.0	12.0	1.96	5.10	61.87	3FGL J1041.2-6210	PKS 1035-620	21.21	20.76	-2.07	31
25.0	261.57	-77.2	0.114	5.68	-0.61	LiA HE	2.56	165.98	190.0	12.0	2.50	4.55	78.61	3FGL J1723.7-7713	PKS 1716-771	27.54	11.75	-1.3	36
29.0	341.03	49.97	0.059	2.88	-0.01	LiA HE	8.68	175.64	302.0	40.0	3.24	11.46	50.03	3FGL J2044.1-0357	PKS 2241-035	138.42	33.9	-1.75	161
31.0	338.19	11.78	0.051	2.65	-0.81	LiA HE	33.73	147.38	719.0	158.0	3.76	29.83	20.87	None	None	1427.7	267.6	2.16	103
36.0	5.19	73.42	0.102	2.42	0.34	LiA HE	7.84	410.87	579.0	32.0	7.67	6.69	84.08	None	None	143.88	48.08	2.0	152

**Details of each flare**

Flare Details

- RA: 17.761
- Dec: -29.008
- Date: 2016 Feb 23
- Time: 00:00
- Altitude: 10000
- Distance: 10000
- Height: 10000
- Maximum Velocity: 80000
- Minimum Velocity: 10000
- Standard Deviation: 10000

High Energy Light Curve (800 MeV - 300 GeV)

Low Energy TS Map (100 - 800 MeV)

High Energy TS Map (300 GeV)

Flare Map

# 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  $\sim 0.1$  deg.
- The 2<sup>nd</sup> 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  $\rightarrow$  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.



**BACKUPS  
&  
MISCELLANEOUS**

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

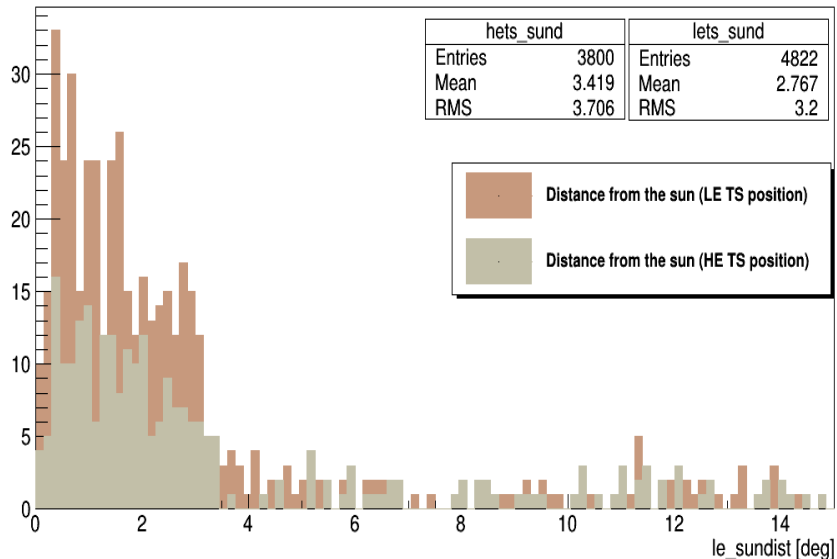
# Flares cut

- Number of trials:  $N_{trials} \approx \frac{41253}{\pi R_{PSF68}^2}$

$$R_{PSF68}(E > 100 \text{ MeV}) \approx 3^\circ$$

$$R_{PSF68}(E > 800 \text{ MeV}) \approx 0.6^\circ$$

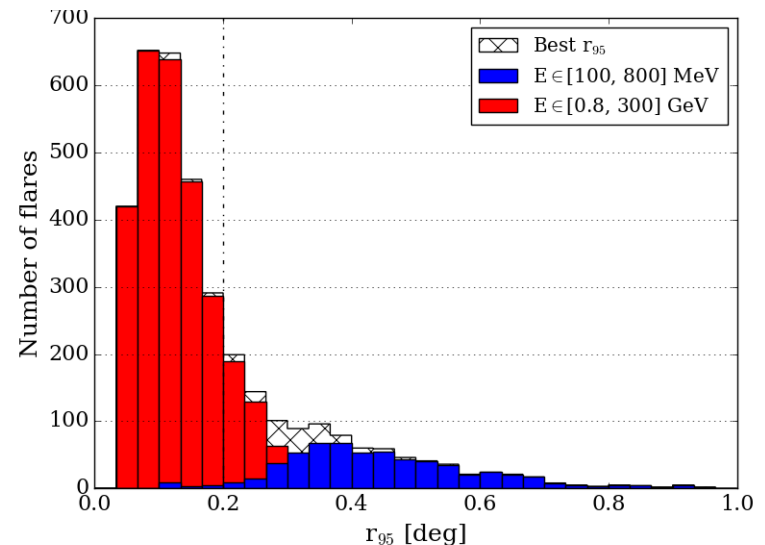
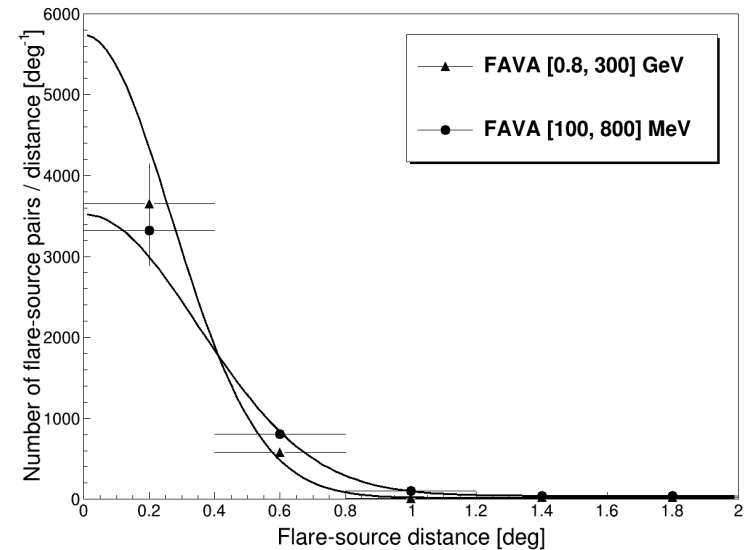
- Expected number of false positives above 6 sigma:
  - ~0.001 at low-energies,
  - ~0.03 at high energies.



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

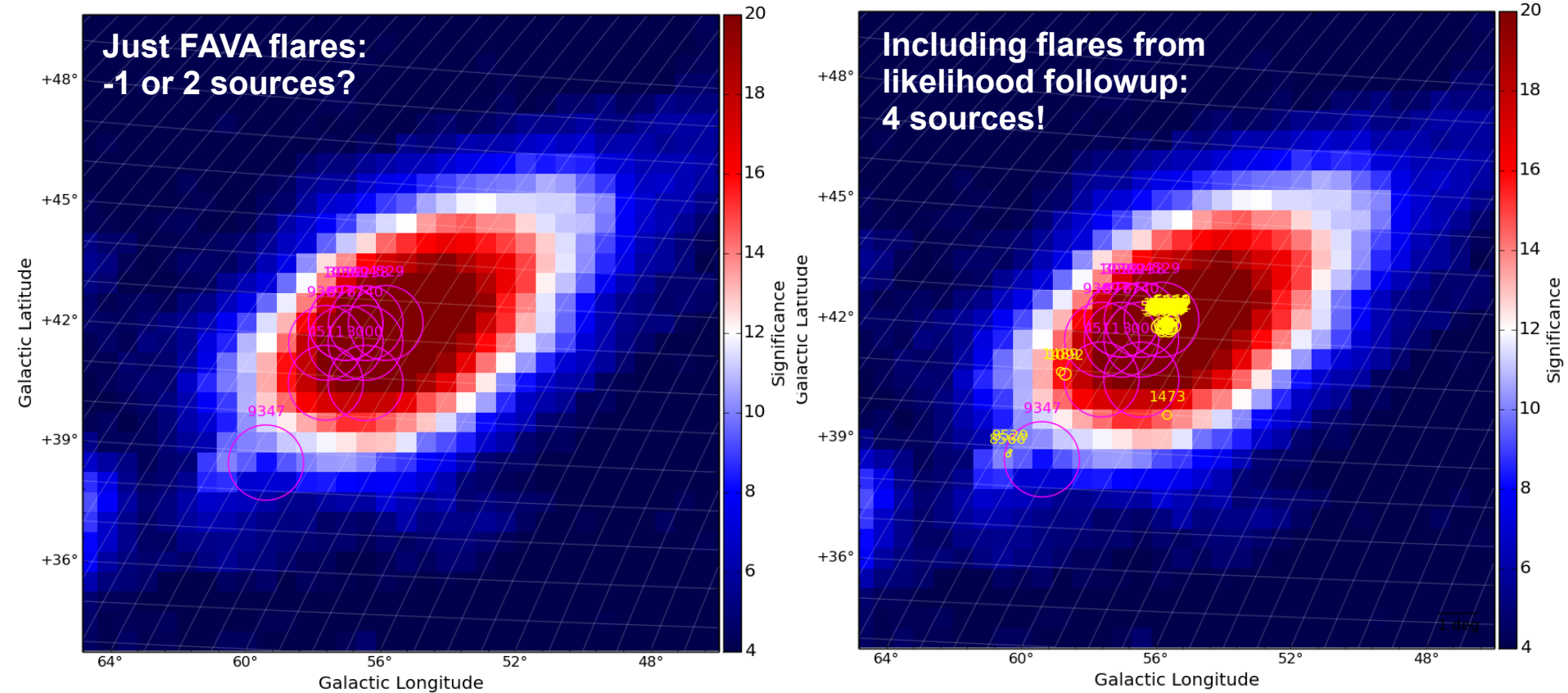
# Angular resolution

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





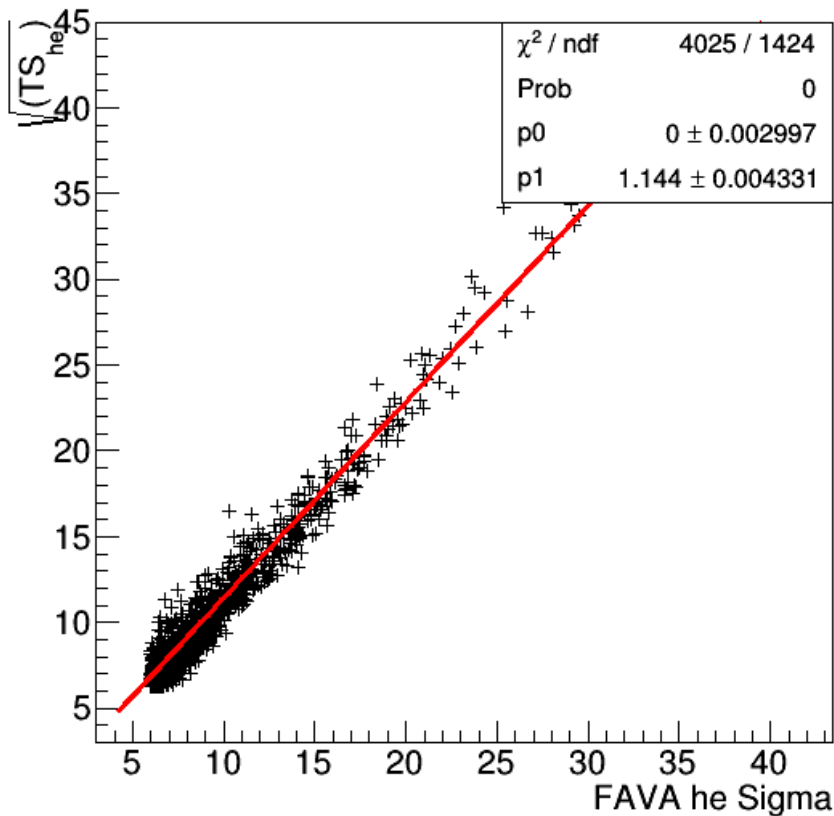
# Better flare localization: practical advantage.



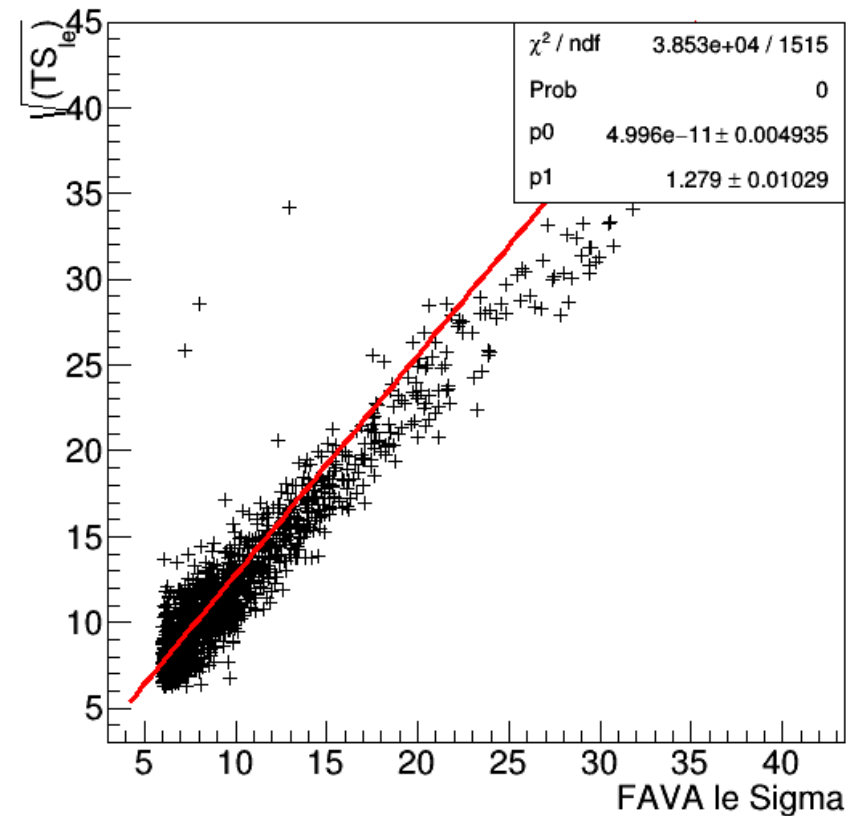
# FAVA significance vs likelihood TS:

- Likelihood analysis has a slightly improved sensitivity:

TS map vs. std FAVA significance (he)



TS map vs. std FAVA significance (le)



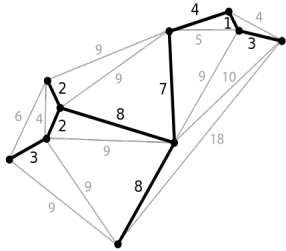
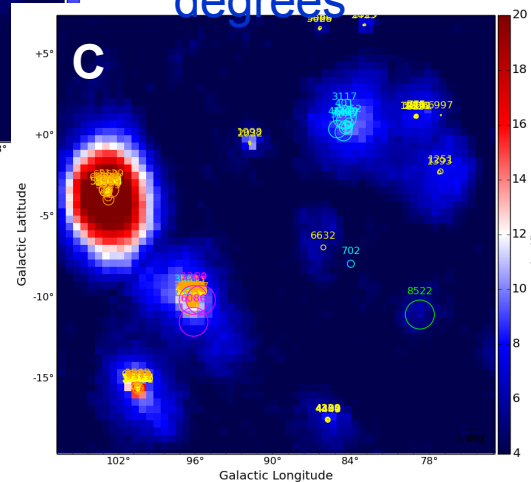
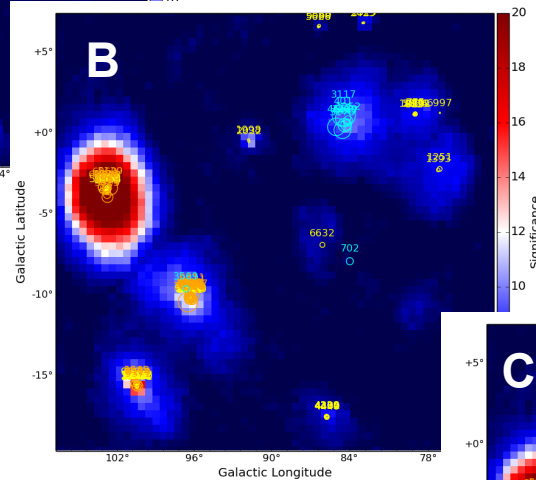
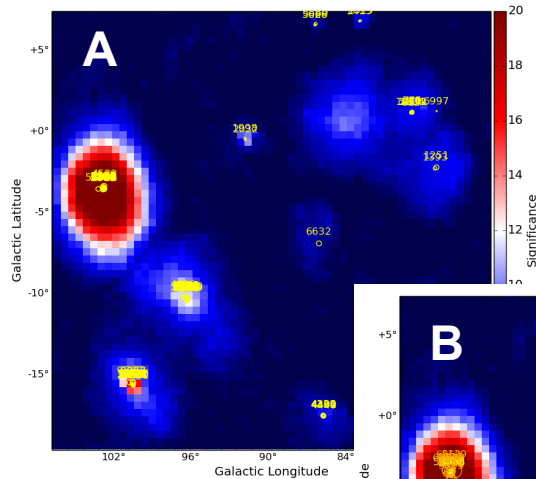
# Clustering

- **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:

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

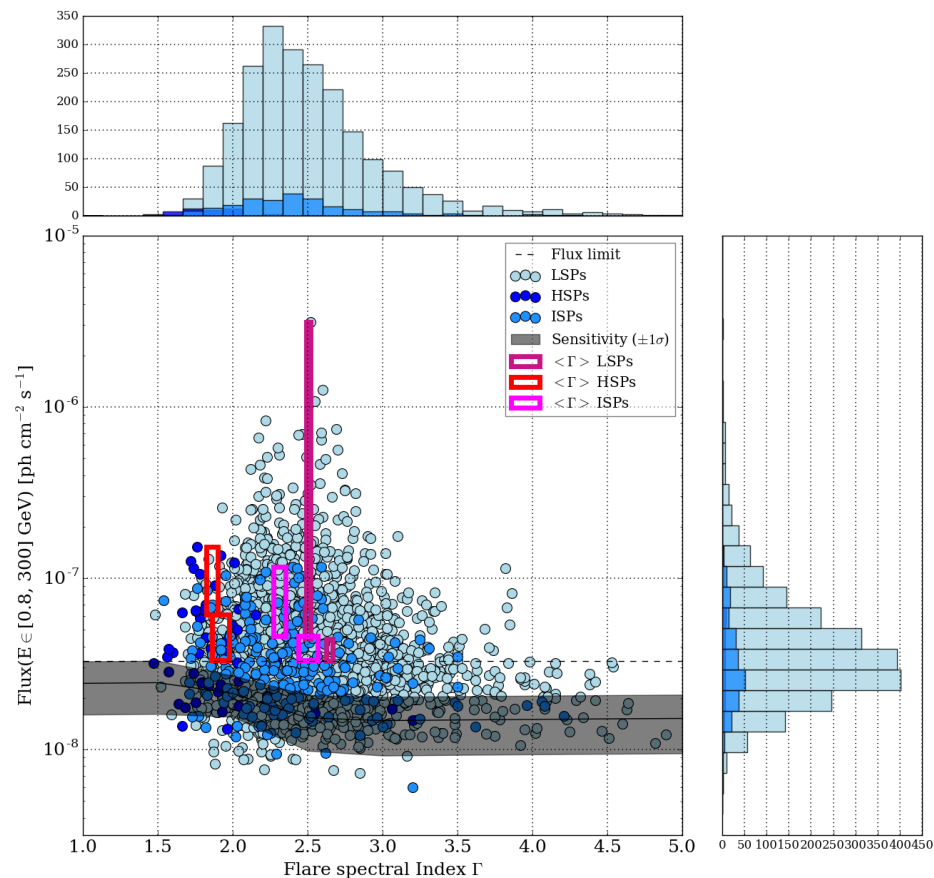
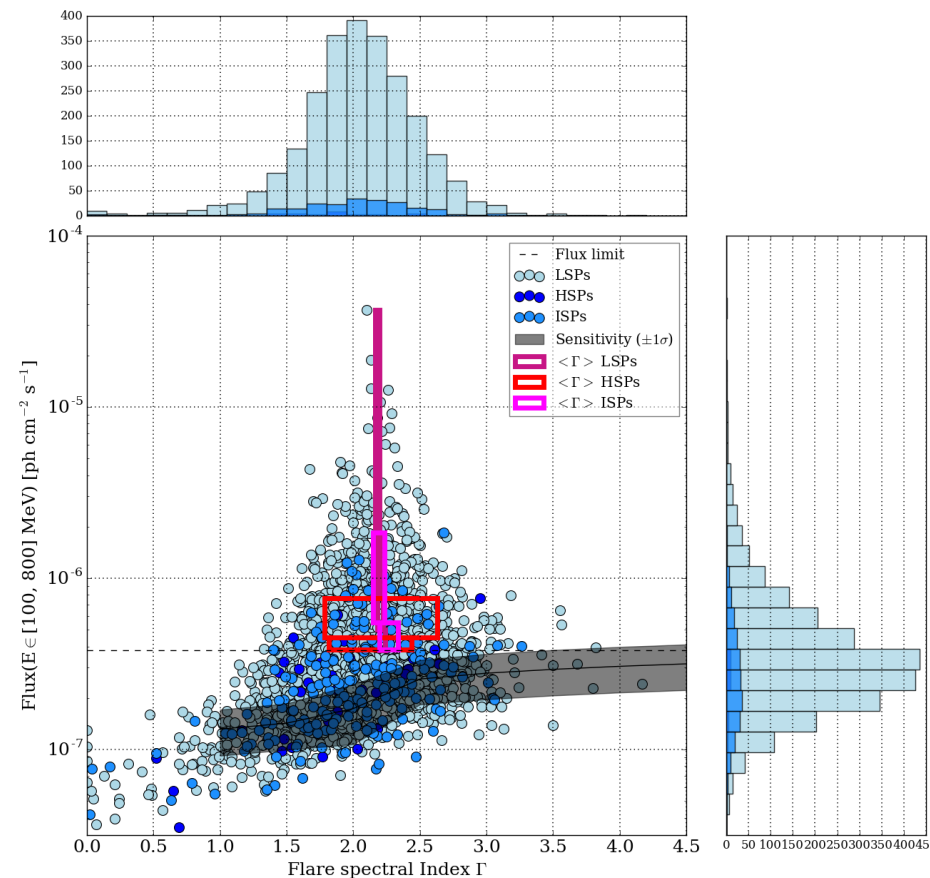
Otherwise use flare-flare distance



## Non-AGN 2FAV sources:

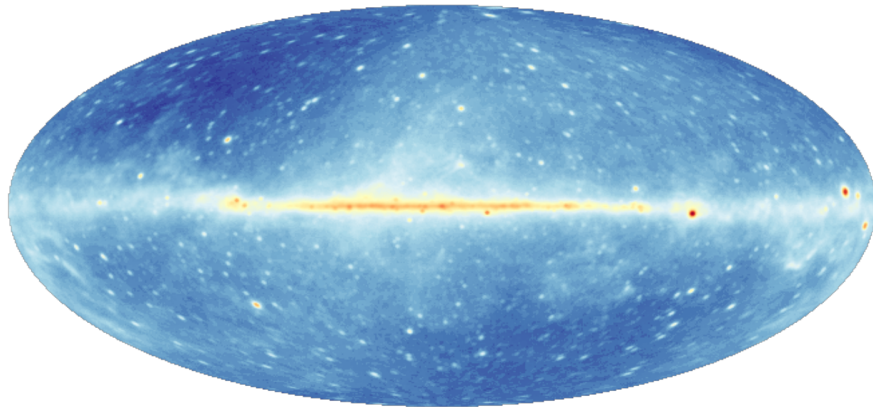
- 5 Novae:
  - V407 Cyg, Nova Mon 2012, Nova Sco 2012, Nova Delphini, and Nova Centauri. <http://asd.gsfc.nasa.gov/Koji.Mukai/novae/novae.html>
- GRBs:
  - GRB150627A, GRB150523A, GRB141207A, GRB140206B, GRB131231A, GRB131108A, GRB130427A, GRB120711A, GRB090926A, GRB090902B, GRB090510A, GRB090328A, GRB090323A, 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](https://arxiv.org/abs/1312.0605)
  - PSR J1826-1256. Very populated region. FAVA alone can not confirm the association. Need MW!

# Flare spectra of blazars (SED classification)

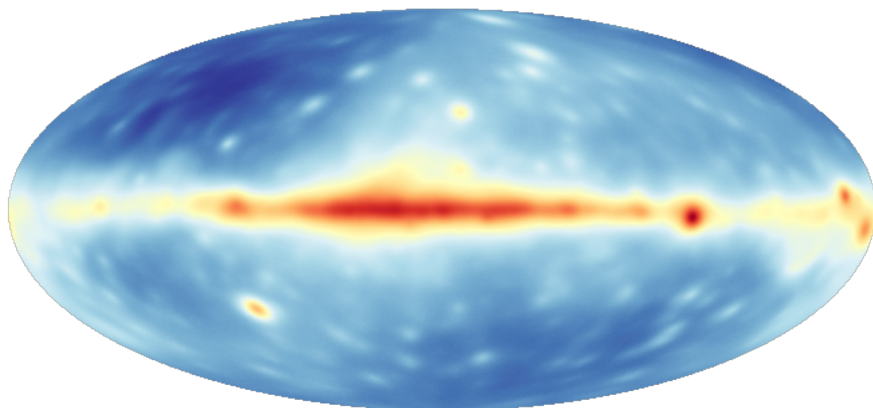


# 2FAV sensitivity maps

Combined sensitivity  $\Gamma=1.5$



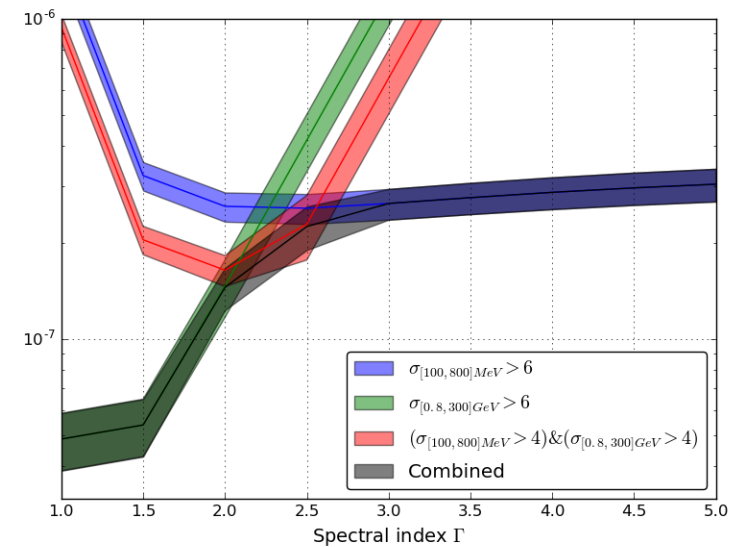
Combined sensitivity  $\Gamma=3.5$



Not accounting likelihood followup.

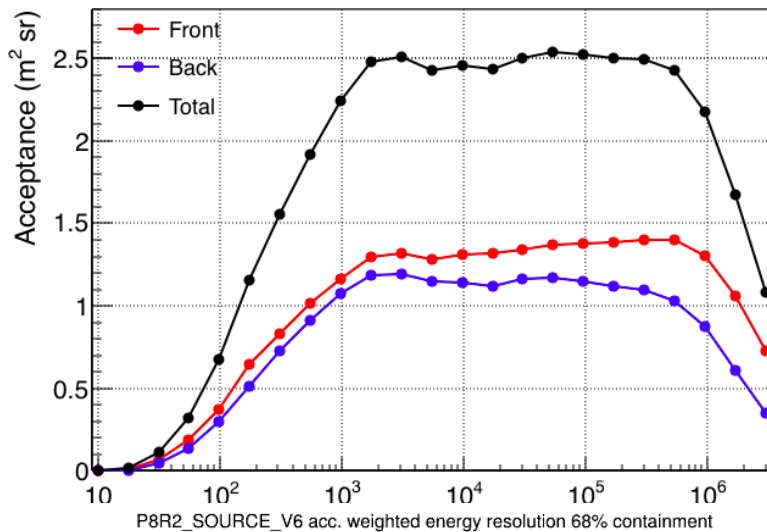
Ref values for blazars:

- Sens(LE)  $\sim 3.7 \cdot 10^{-7} \text{cm}^{-2} \text{s}^{-1}$
- Sens(HE)  $\sim 3.3 \cdot 10^{-8} \text{cm}^{-2} \text{s}^{-1}$

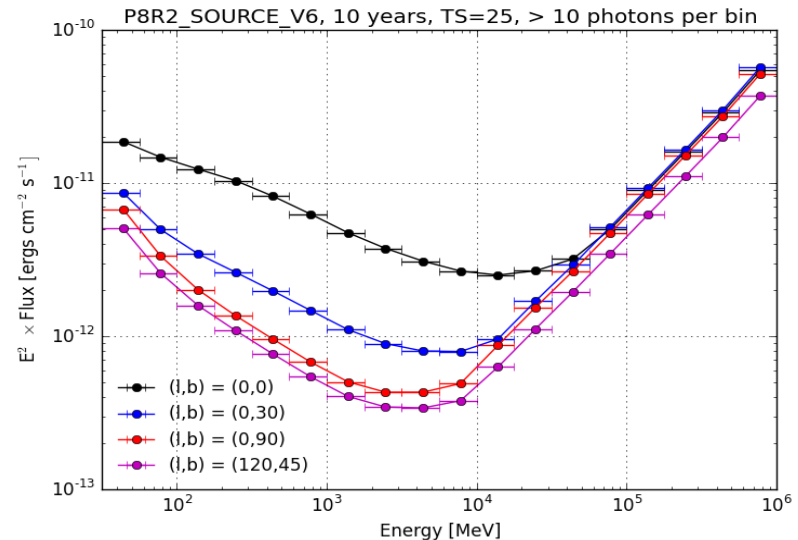
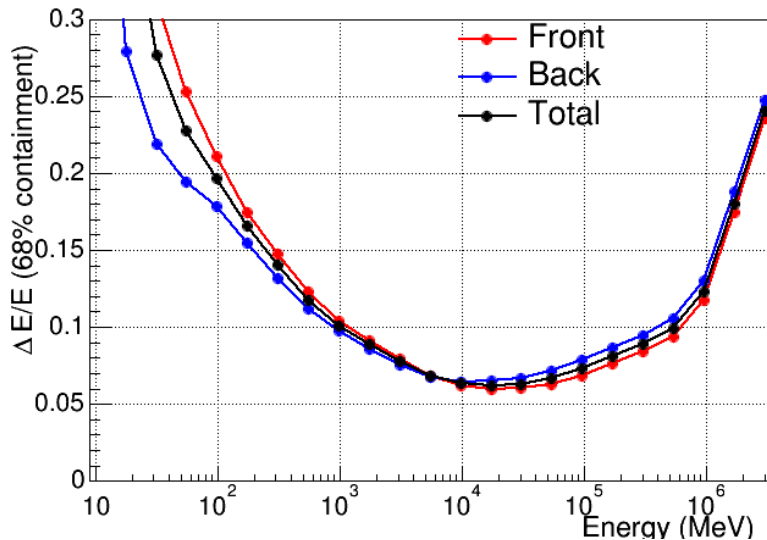
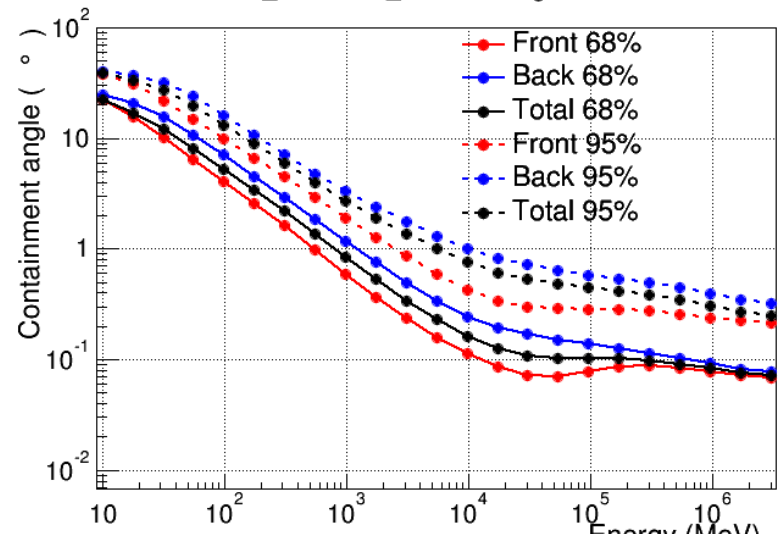


# LAT Instrument response functions

P8R2\_SOURCE\_V6 acceptance

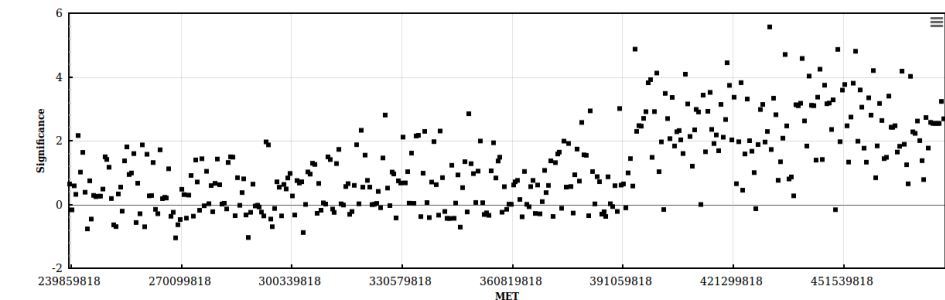
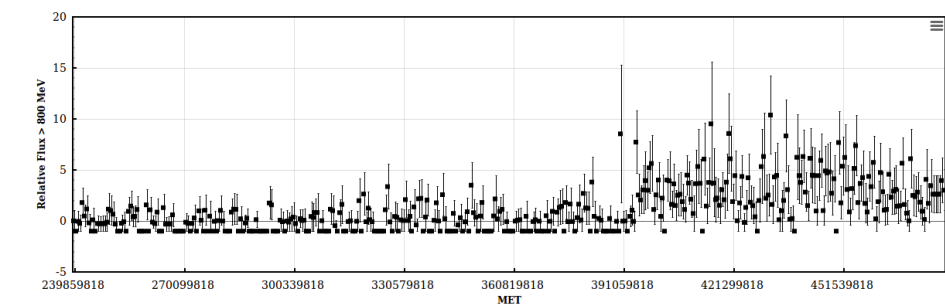
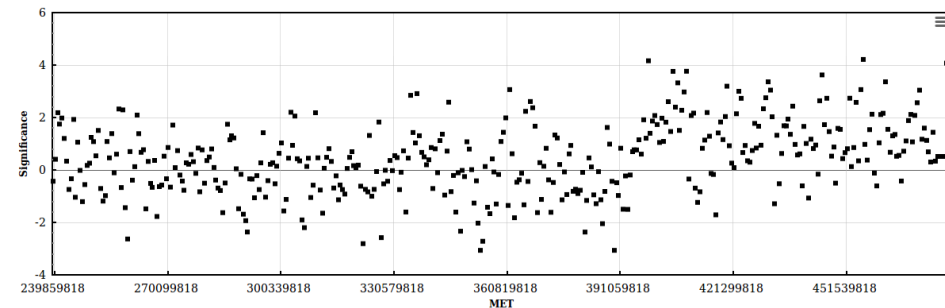
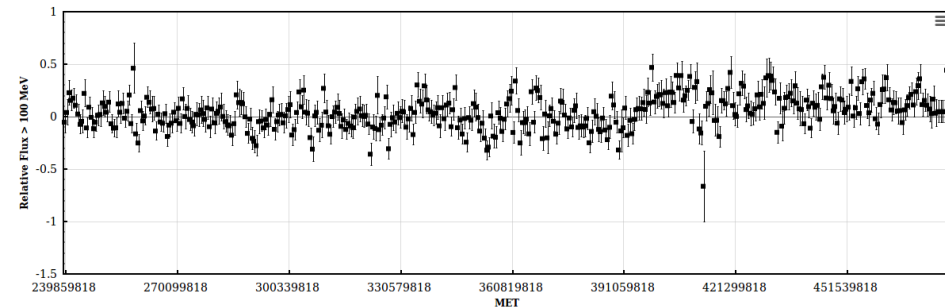


P8R2\_SOURCE\_V6 acc. weighted PSF





# 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 double peaked H-alpha lines
  - Gamma-ray and X-ray brighter

arXiv:1312.0605

# Example source: PSR B1259-63/LS 2883

