Detection of Gamma-ray Halos around Nearby Late-type Galaxies

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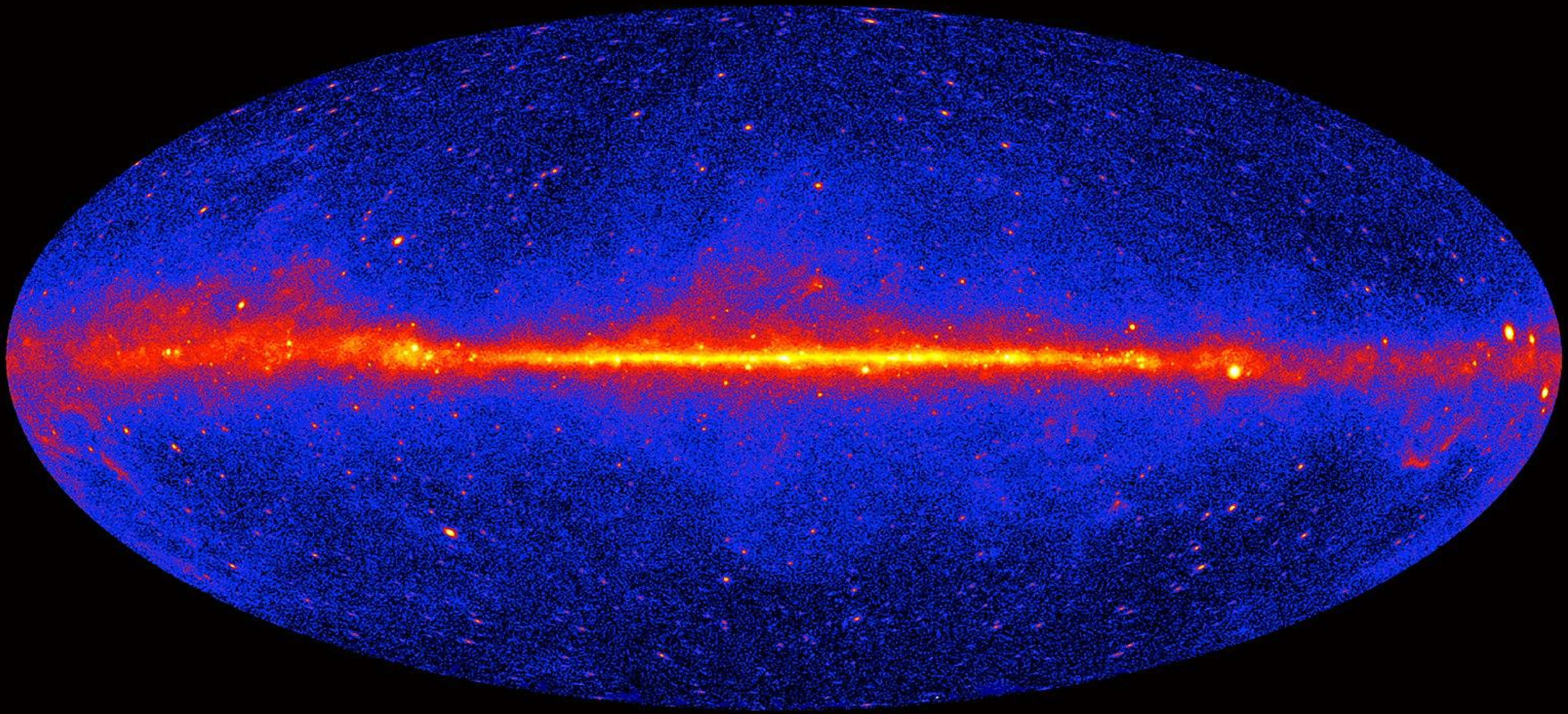
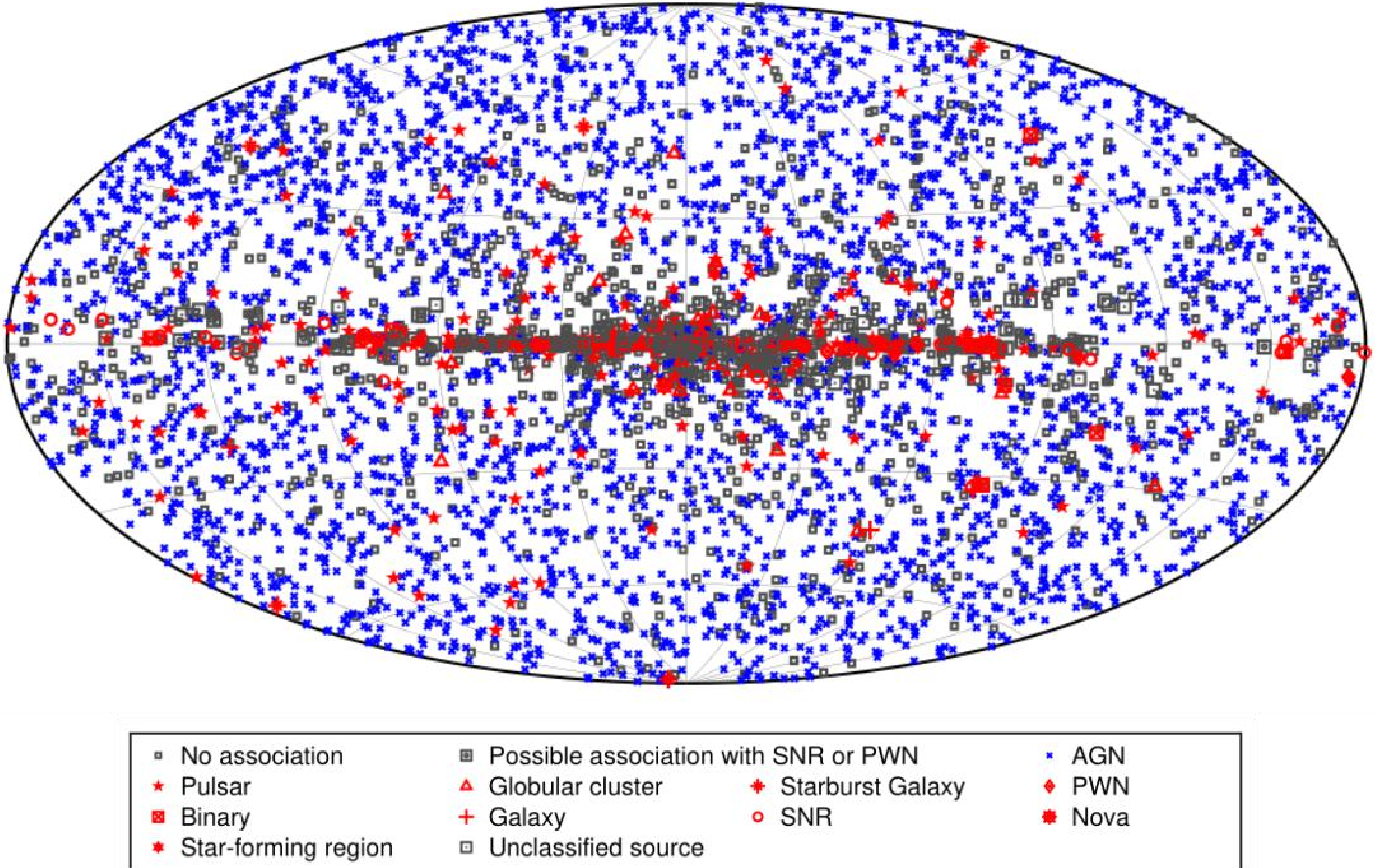
Fermi LAT: γ-ray sky



Fermi LAT: γ-ray sources



Fermi LAT: γ-ray sources

- The overwhelming majority of the extragalactic sources are blazars
- Number of AGNs of other types is considerably smaller (<100)
- Blazars are quite rare in the general population of the AGNs, *O*(%)
- Our limited sensitivity leads to an observational bias

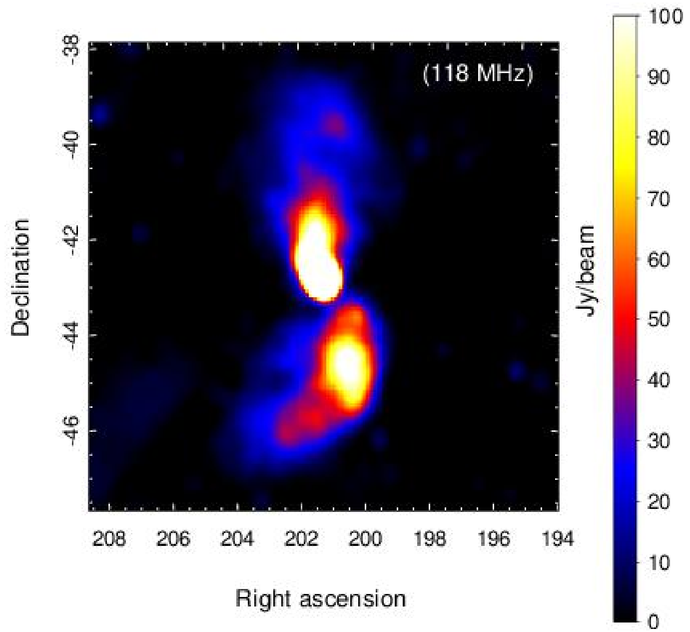
Table 1. LAT FL16Y Source Classes

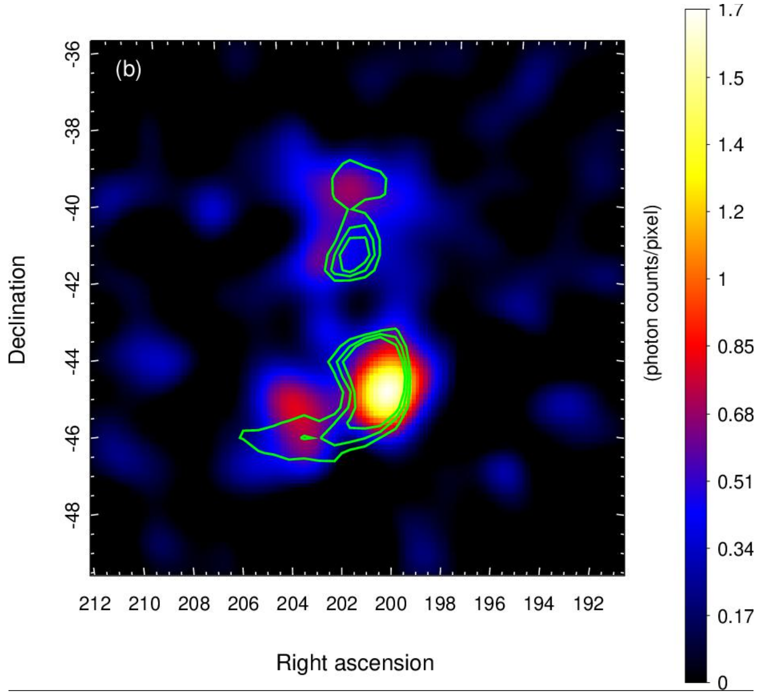
Description	Identified		Associated	
	Designator	Number	Designator	Number
Young pulsars, identified by pulsations	PSR	140	...	...
Young pulsars, no pulsations seen in LAT yet	...	...	psr	5
Millisecond pulsars, identified by pulsations	MSP	167	...	...
Millisecond pulsars, no pulsations seen in LAT yet	...	...	msp	31
Pulsar wind nebula	PWN	12	pwn	8
Supernova remnant	SNR	26	snr	17
Supernova remnant / Pulsar wind nebula	SPP	6	spp	128
Globular cluster	GLC	0	glc	36
Star-forming region	SFR	3	sfr	25
High-mass binary	HMB	7	hmb	3
Low-mass binary	LMB	2	lmb	7
Binary	BIN	1	bin	22
Nova	NOV	7	nov	0
BL Lac type of blazar	BLL	22	bll	1803
FSRQ type of blazar	FSRQ	44	fsrq	791
Radio galaxy	RDG	6	rdg	75
Non-blazar active galaxy	AGN	1	agn	5
Steep spectrum radio quasar	SSRQ	0	ssrq	2
Compact Steep Spectrum radio source	CSS	0	css	4
Blazar candidate of uncertain type	BCU	1	bcu	1512
Narrow-line Seyfert 1	NLSY1	4	nlsy1	2
Seyfert galaxy	SEY	0	sey	4
Starburst galaxy	SBG	0	sbg	8
Normal galaxy (or part)	GAL	2	gal	2
Unknown	UNK	3	unk	161
Total	...	455	...	4651
Unassociated	...	0	...	2114

NOTE—The designation 'spp' indicates potential association with SNR or PWN. Designations shown in capital letters are firm identifications; lower case letters indicate associations.

Extended γ-ray sources

- Almost all the extragalactic sources are point-like
- Exceptions -- there are several detections of extended emission around AGNs nearby
- Cen A, Fornax A

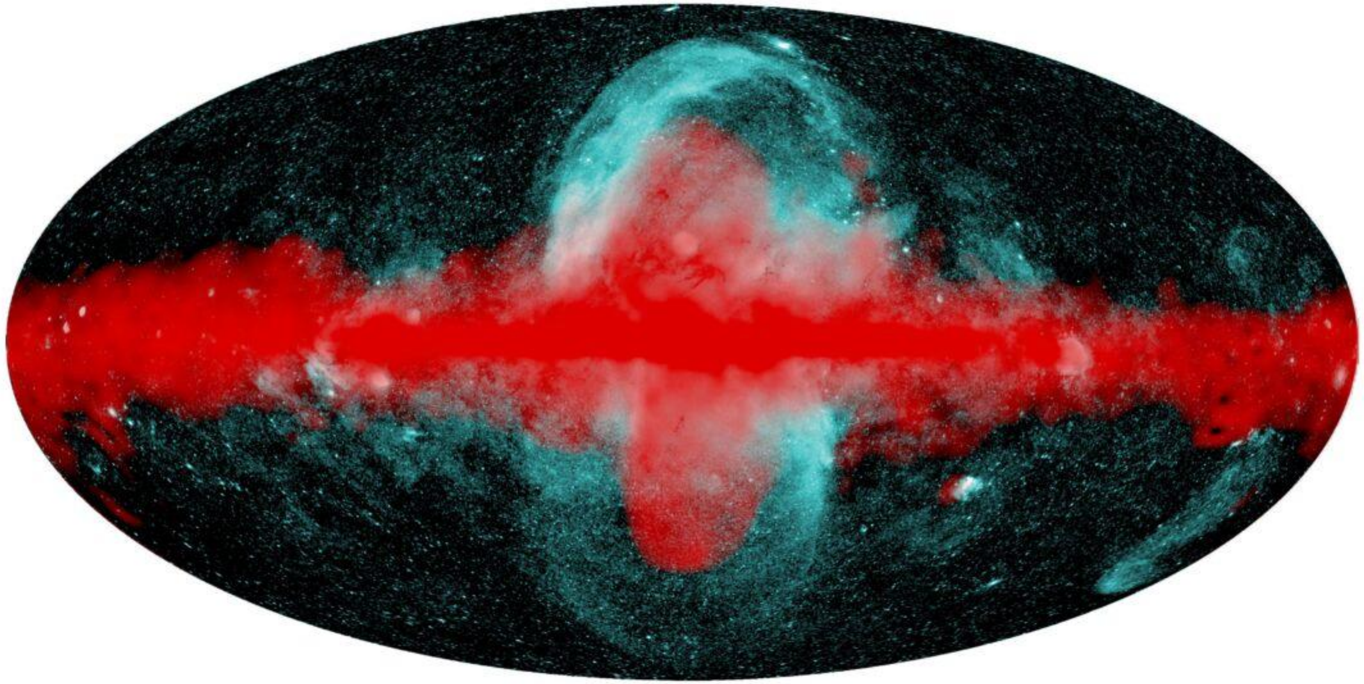




- Cen A (left--radio, right-- γ from *X.Sun et al, 2016*)

Extended γ-ray sources

- Galactic "mega-source"
- «Fermi bubbles» in the center of the Galaxy, h~10 kpc
- γ-ray luminosity~4×10^{37} erg/s
- Remnants of recent AGN activity/burst of star-formation?
- Were detected in radio and X-ray as well (WMAP/Planck, eROSITA)



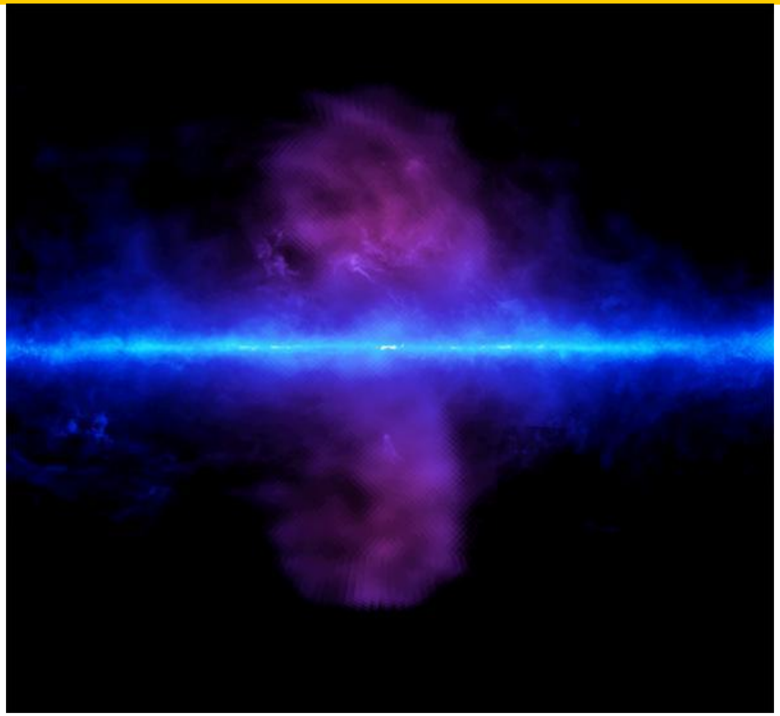
Predehl et al,2020

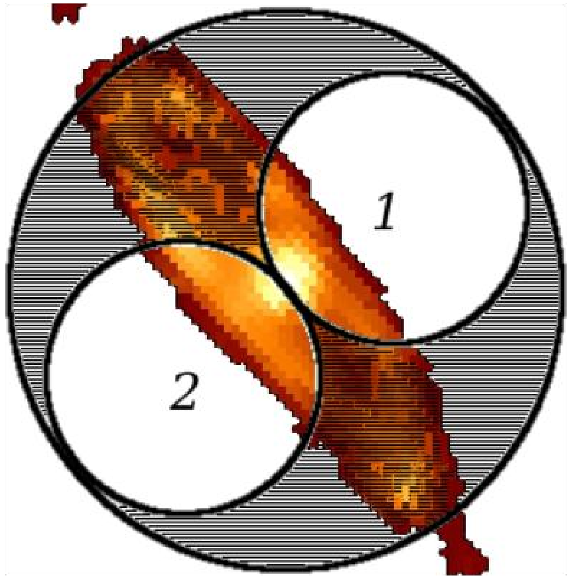
Extended γ-ray sources

- Fermi Bubbles -- are they unique?

- Obvious idea -- look at the MW 'analogues', first of all the M31 galaxy

- FB-like structures with a larger luminosity were detected $L_\gamma = 3 \times 10^{38}$ эрг/с (*MP, Vasiliev, Postnov, 2016*)



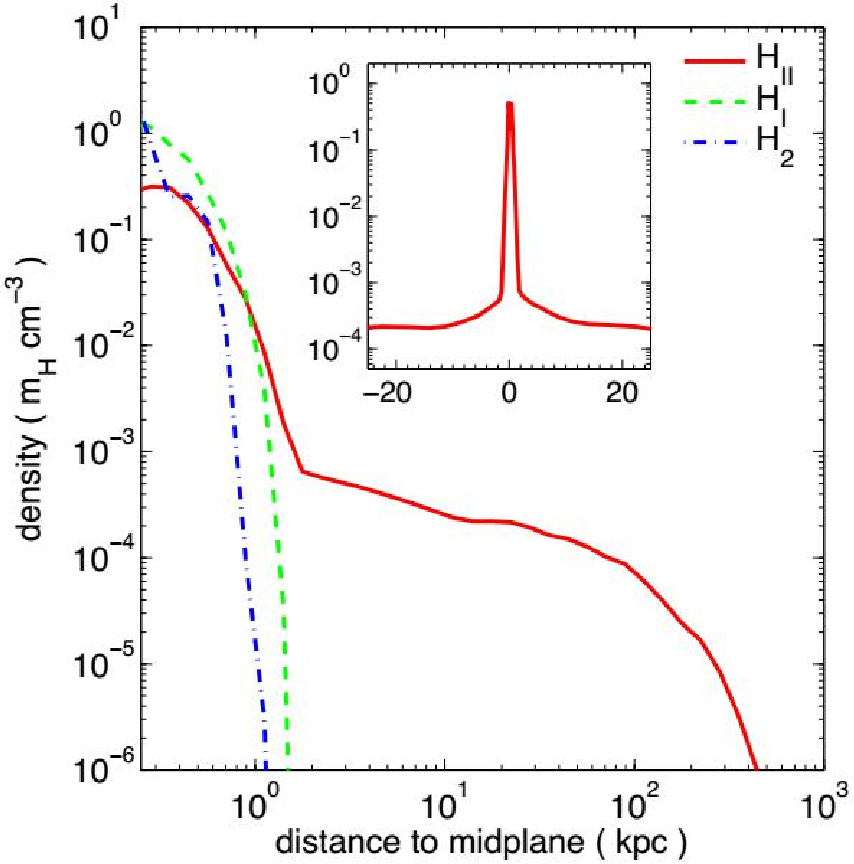


Extended γ-ray sources

- The existence of excess around M31 was confirmed in other works as well, i.e. *Karwin et al, 2019* *("Fermi-LAT observations of γ-ray emission towards the outer halo of M31")*
- + Detection of extended γ-ray halo with a radius up to 100 kpc.

Extended γ-ray sources: theory

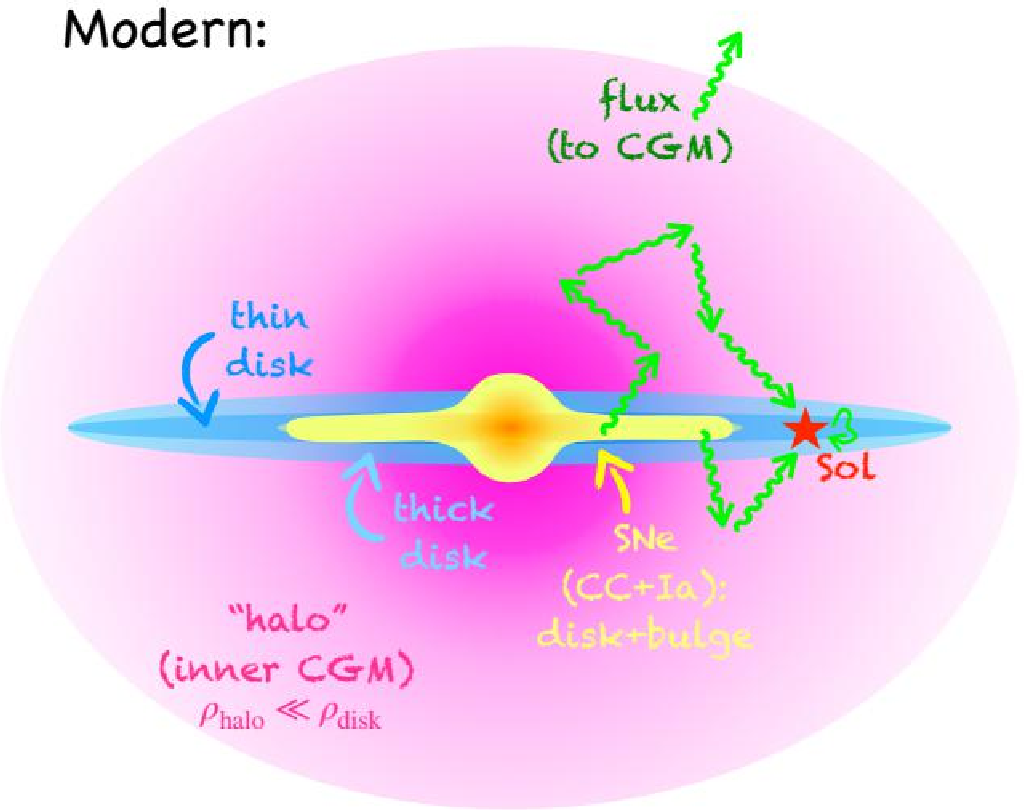
- Early attempt to explain FB -- radiation from galactic cosmic rays that had accumulated for billions of years *Crocker&Aharonian, " Fermi Bubbles: Giant, Multibillion-Year-Old Reservoirs of Galactic Center Cosmic Ray" 2011;*
- It is disfavored in the FB case, but the mechanism of interactions with a diluted CGM gas could operate *Feldmann, Hooper, Gnedin, " Circum-galactic Gas and the Isotropic Gamma-Ray Background , 2013*)

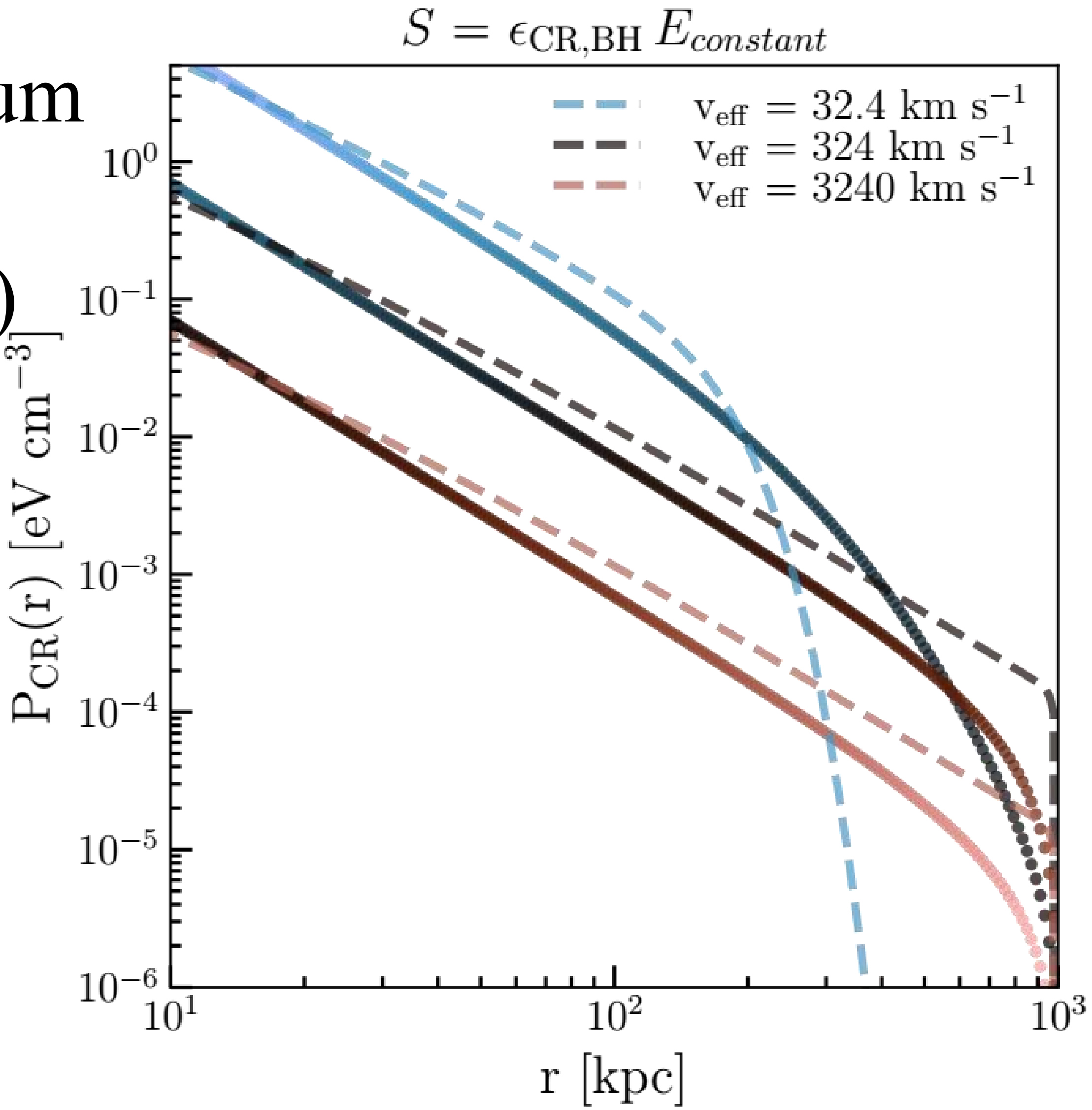


- γ-rays from MW halo could contribute up to 10% into diffuse gamma-ray background

Extended γ-ray sources: theory

- Up-to-date modelling: broad spectrum of predictions (depend on diffusion coefficient, gal. wind, etc.)

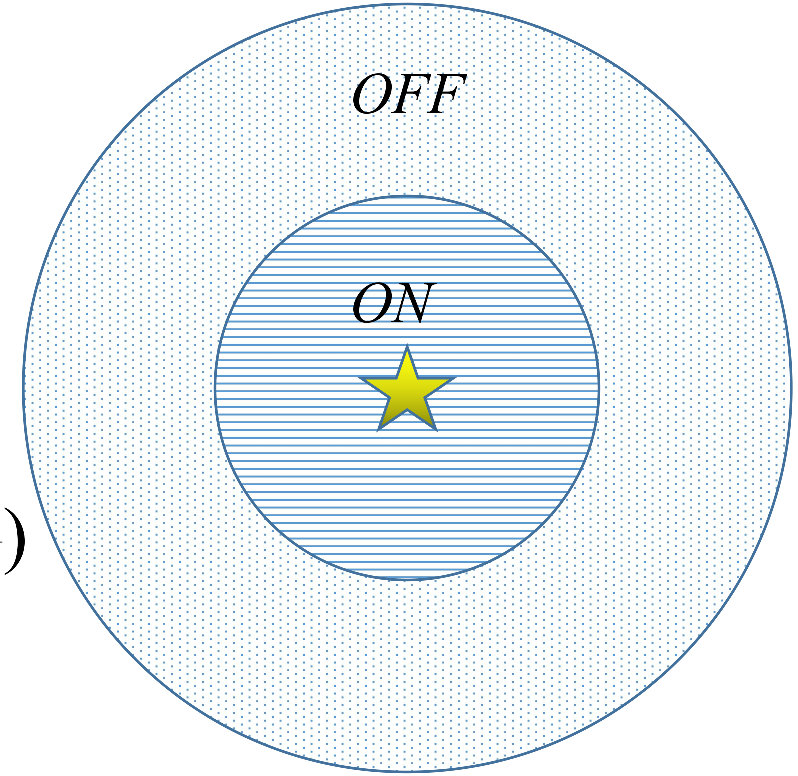




Hopkins, Ponnada 2025

Extended γ-ray sources

- M31: gamma-ray luminosity 10^{38}-10^{39} erg/s
- **Idea**-- search for a signal from a whole sample of nearby galaxies, with masses close to the MW mass
- **Method** -- aperture photometry:
    - signal (observed) from a circle R_{ON}
    - compare with our expectations from a background estimation region: a ring with R_{OFF} and R_{ON} radii
    - $R_{\mathrm{OFF}}=2R_{\mathrm{ON}}$.
    - Expectations ($N_{\mathrm{OFF}}/3$) vs observations (N_{ON})



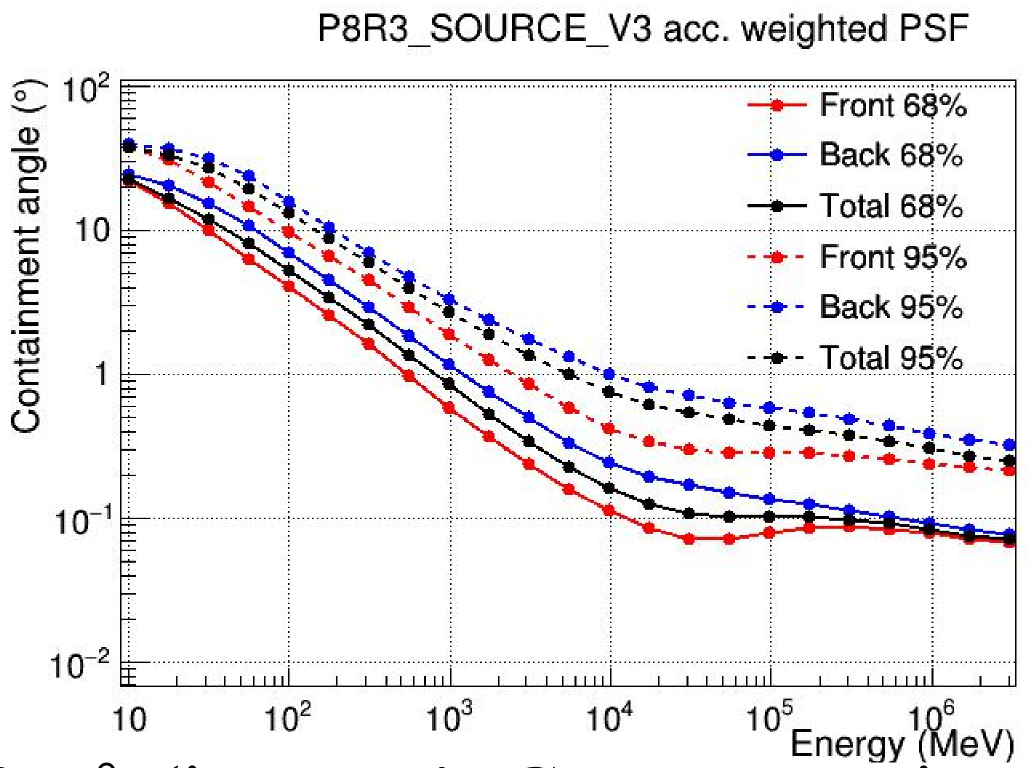
Data and analysis

- Data: 16 years of Fermi LAT observations (2008-2024), *E*>1 GeV
- Galaxy catalogue *Ohlson et al 2024*, 15424 closer than 50 Mpc
- Our initial cuts:
    - 5 Mpc<*D*<15 Mpc (our signal should be neither too extended, nor too weak)
    - $M_{*,\mathrm{min}}=10^{10}\ M_{\odot}$

- 87 sources passed
- Background suppression (otherwise aperture photomety would not work): a) $|b|>20^{\circ}$; б) no 4FGL-DR4 sources closer than $3\mathrm{PSF}_{68}$

Data and analysis

- Strong dependence PSF(*E*)
- If *E* is too high-- more targets pass the 4FGL cut, but the analysis is weaker due to a smaller number of photons at these energies
- *E* is too low, e.g. 1 GeV -- no targets left



- Compromise -- 2 GeV, R_{ON}=PSF=0.5° (i.e. no 4FGL sources in 1.5 degrees)
- 22 galaxies left, 16 of them are late type ('spirals'), 6 --early ('ellipticals')

Data and analysis

- 22 galaxies were analyzed, E>2 GeV
- Properties of the late-type sample (16 galaxies):

#	Name	$l,°$	$b,°$	D, Mpc	$\log M/M_\odot$
1	NGC0628	138.617	-45.705	10.19	10.128 ± 0.136
2	NGC0660	141.607	-47.347	11.57	10.098 ± 0.331
3	NGC1291	247.524	-57.042	9.08	10.707 ± 0.136
4	NGC1433	255.691	-51.195	9.04	10.070 ± 0.201
5	NGC1512	248.668	-48.166	11.63	10.172 ± 0.160
6	NGC1532	233.168	-46.584	14.26	10.528 ± 0.600
7	NGC2903	208.710	44.540	8.87	10.404 ± 0.136
8	NGC3368	234.435	57.010	10.42	10.523 ± 0.136
9	NGC3877	150.719	65.956	14.63	10.096 ± 0.476
10	NGC4192	265.434	74.960	12.68	10.371 ± 0.136
11	NGC4666	299.538	62.368	14.70	10.298 ± 0.136
12	NGC4818	305.212	54.323	11.04	10.008 ± 0.530
13	NGC5248	335.929	68.751	13.75	10.264 ± 0.606
14	NGC7331	93.722	-20.724	12.62	10.724 ± 0.327
15	NGC7814	106.410	-45.175	14.40	10.520 ± 0.136
16	PGC032861	245.103	55.513	14.45	12.827 ± 0.502

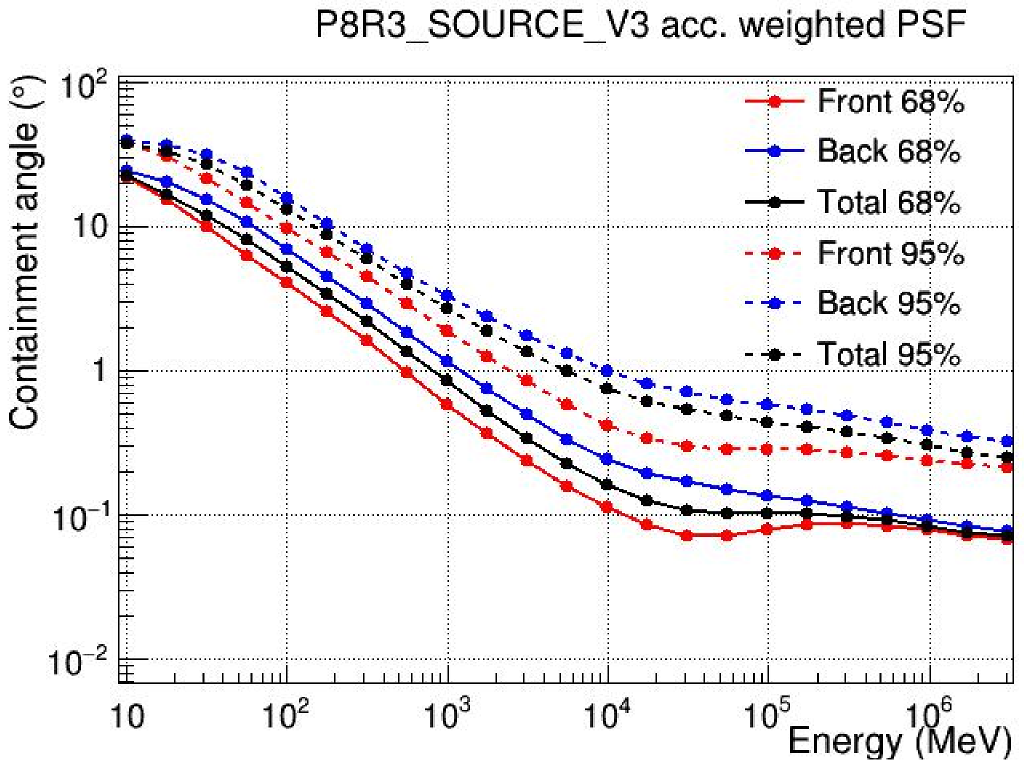
Data and analysis

- Statistics from 22 galaxies, E>2 GeV

	EXP	**OBS**	**p-val**
All galaxies	1728	1872	1.3×10^{-4}
Early type (6 gals)	513	480	--
Late type (16 gals)	1215	1392	3.7×10^{-7}

Data and analysis

- A fluctuation?
- What about spatial extension? At the moment we can say that r<150 kpc (0.5° at 15 Mpc), i.e. almost everything goes
- We can repeat tests at higher energies, although they would not be independent.



Data and analysis

Expectations:

1. If we had a fluctuation at 2 GeV (or, coincidentally, the source size is ~0.5°), then at any energy (and corresponding angular resolution) the maximal significance would be reached at R_{ON}=0.5°
2. Point-like source would have maximal signigicance at $R_{ON}(E)$=PSF(E)

Data and analysis

- Also we can use photons with better reconstructed directions of arrival (front-conversion, ~50% of all photons) to obtain better angular resolution

Energies	PSF_{68}, °
2 GeV	0.50
2 GeV front	0.34
3 GeV	0.36
3 GeV front	0.25
5 GeV	0.25
5 GeV front	0.17
10 GeV	0.17
30 GeV	0.11

Results

- Different energies and conversion types (front/total)
- $R_{ON}(E)$=PSF(E) case is given with the boldface
- OBS/EXP, p-val

	0.25°	0.35°	0.5°
2 GeV	-	713/607 1.50×10^{-5}	**1392/1215, $\mathbf{3.66 \times 10^{-7}}$**
2 GeV front	-	**391/312, $\mathbf{9.17 \times 10^{-6}}$**	758/617, 2.30×10^{-8}
3 GeV	-	**392/326, $\mathbf{2.12 \times 10^{-4}}$**	772/670, 6.29×10^{-5}
3 GeV front	**116/106, 0.177**	226/165, 3.89×10^{-6}	435/340, 4.32×10^{-7}
5 GeV	**95/93, 0.431**	195/153, 6.16×10^{-4}	373/324, 4.14×10^{-3}
5 GeV front	57/54, 0.359	118/79, 2.52×10^{-5}	220/168, 7.09×10^{-5}
10 GeV	43/36, 0.140	84/55, 1.66×10^{-4}	150/124, 0.01
10 GeV front	27/20, 0.077	51/28, 6.02×10^{-5}	88/68, 0.01
30 GeV	4/7.3, —	15/12, 0.228	26/24, 0.368

Results: morphology

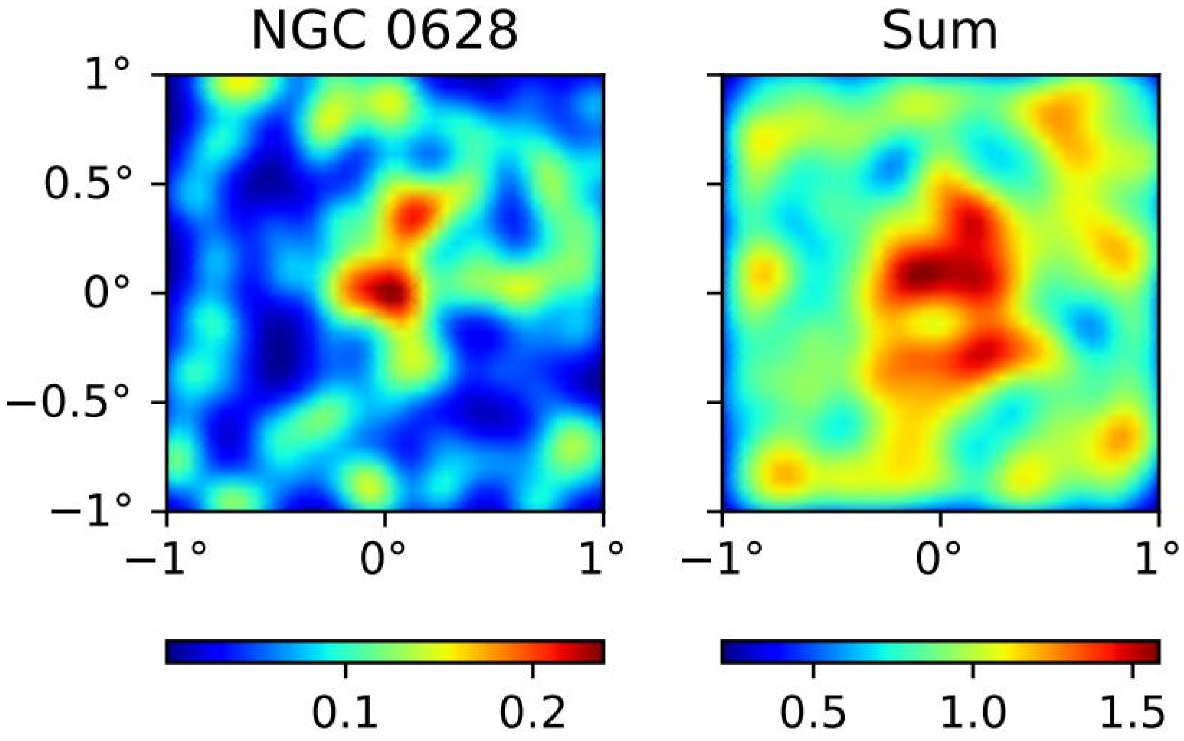
- Does not look like a fluctuation.

- Does not look like a point-like source either! R_{ON}, corresponding to the maximal significance decreases with an increase of energy E and then saturates at R_{ON}=0.3° (even if PSF ≤0.3°, E>3 GeV).

- Could be explained by extended sources with a radial size ~70-80 kpc

Results: morphology

- Sum of all counts *E*>3 GeV, front-converted



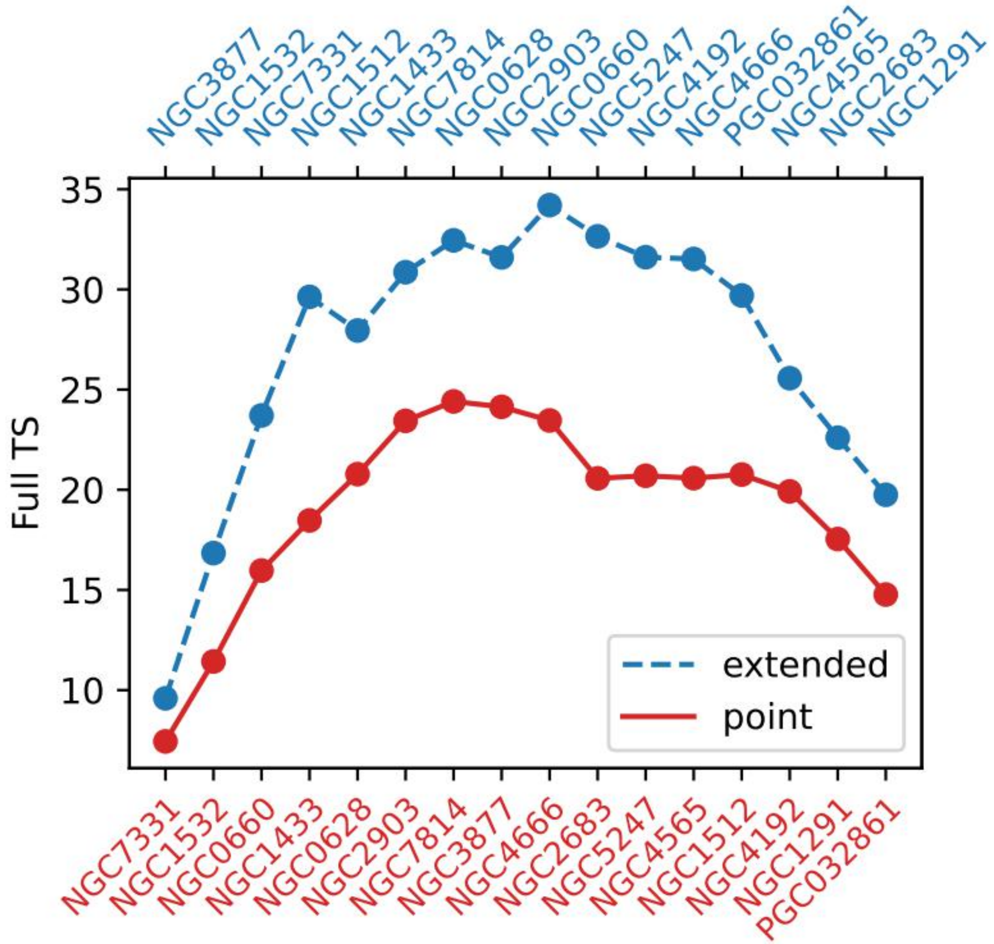
- NGC0628 -- the largest individual signal, p-val~10^{-3}
- Figures are given for all counts, without any background subtraction!
- The excess looks asymmetric?

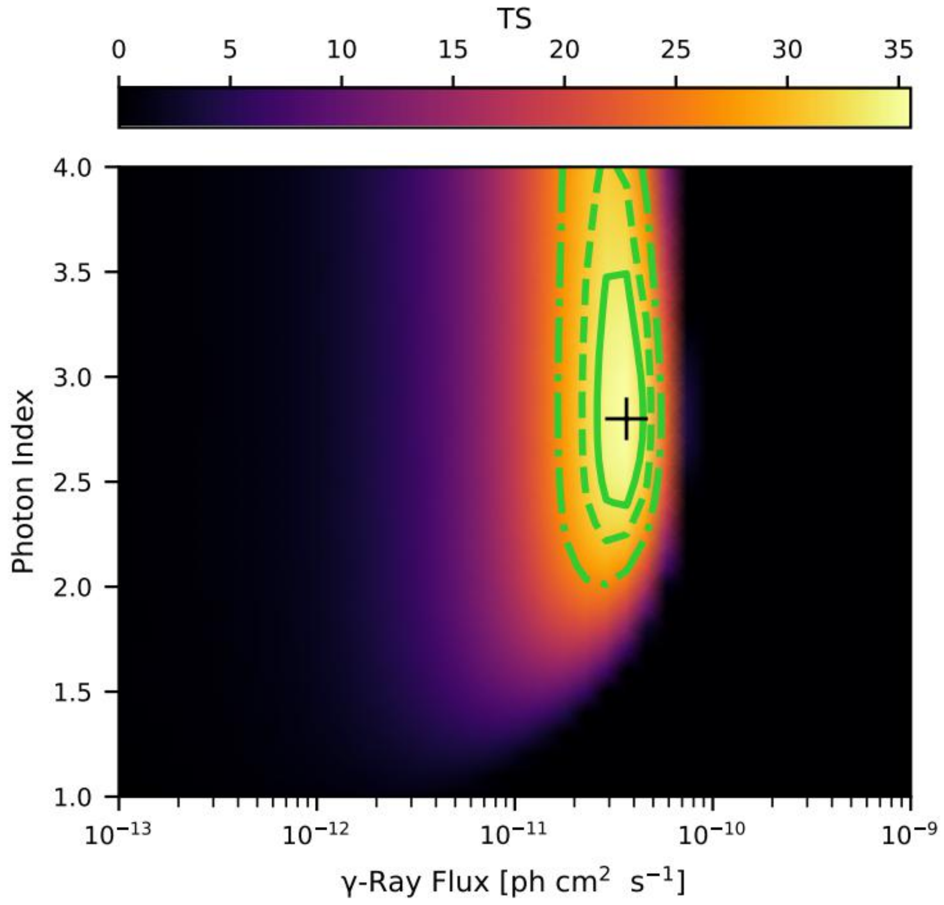
Standard Fermi analysis

- Maximum likelihood
- *FERMI_STACKING*: https://fermi-stacking-analysis.readthedocs.io/
- en/latest
- Using the same sample of the late-type galaxies:
    - assume that all sources have identical fluxes F and spectral indexes α.
    - add into the ML model sources (point-like or disk with a radius equal to 0.3°) at the positions, coinciding with our galaxies
    - search on the F- α grid for the parameters that maximize statistical significance (TS)
    - Analysis at E>2 GeV

Standard Fermi analysis

- Even at such low energies the extended template works better.
- Some galaxies give non-physical negative contribution, this is a bug of the method



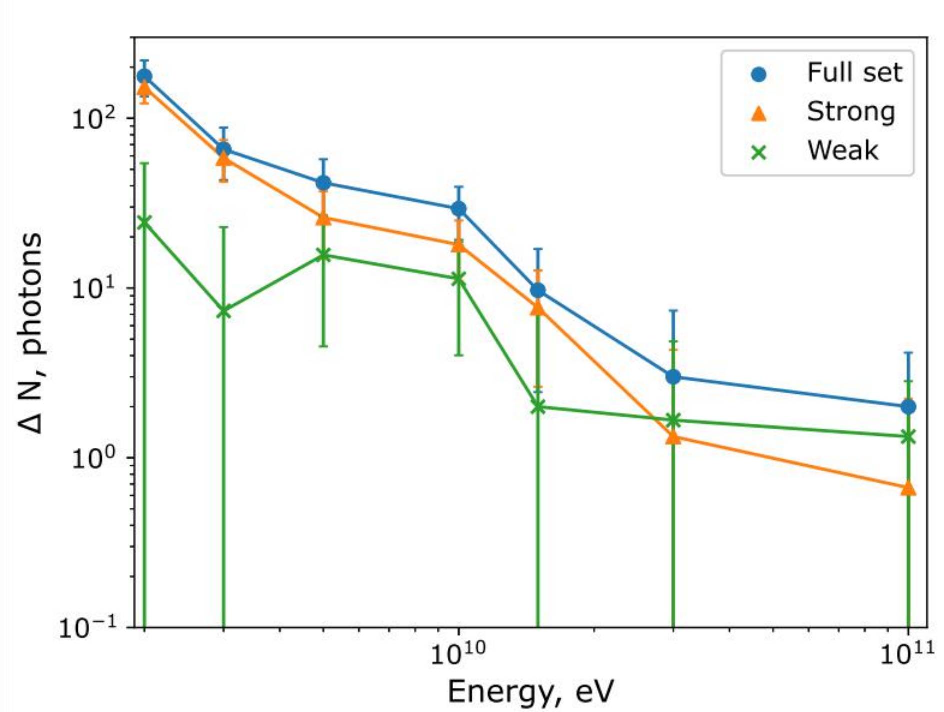


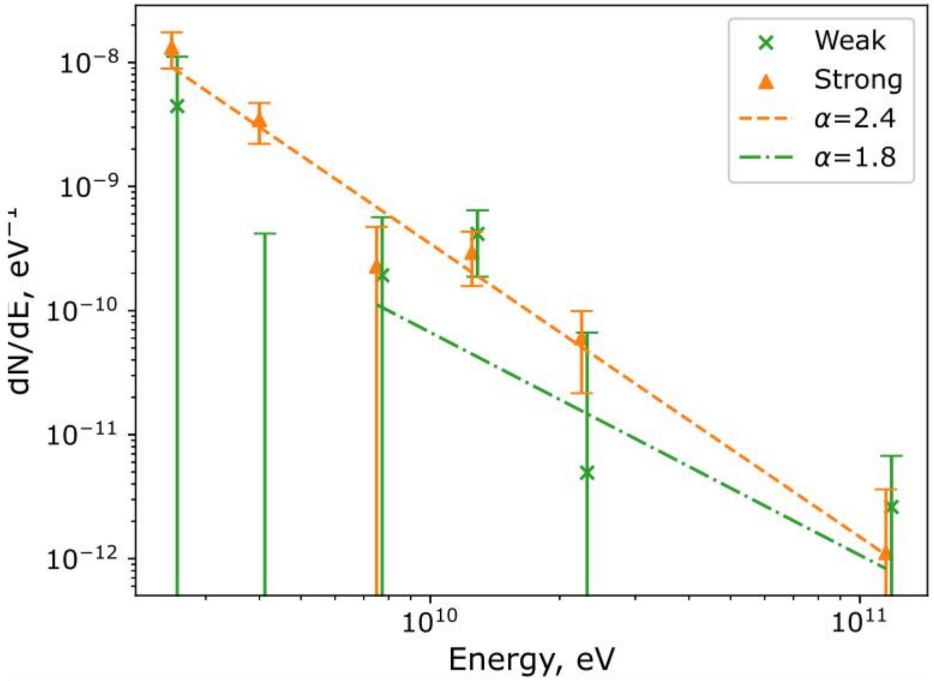
Energetics and spectrum

- At E>2 GeV only 7 galaxies significantly contribute to the joint significance (NGC0628, NGC0660, NGC1512,NGC1532, NGC3877, NGC7331, NGC7814)
- We split the set into "strong" and "weak" subsets and repeat the aperture analysis separately. Could the second set be just a noise?
- At 2 GeV the first subset demonstrates much stronger 'signal' : 710/558, p–val = 3.7×10^{-10} , the second one fares much worse: 682/658, p–val = 0.18
- At 10 GeV it is a bit more complicated, R=0.35°: 41/23, p–val = 4.5×10^{-4} and 43/32, p–val = 3.6×10^{-2}
- The sources are not identical, they have different luminoisty and different spectrum, 'weak' sources' spectra are much harder.

Energetics and spectrum

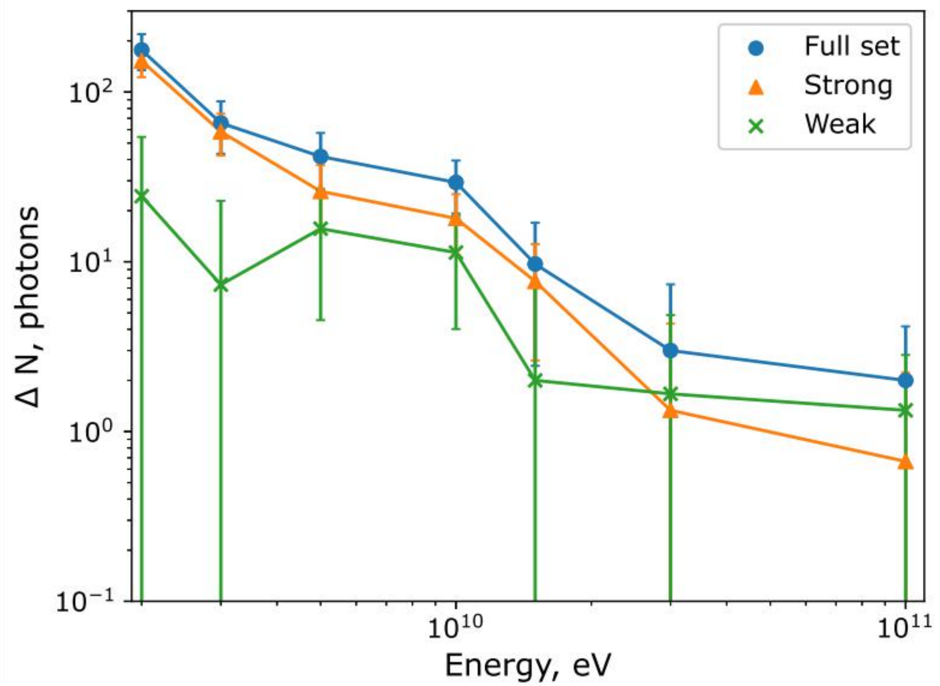
- Very crude estimate -- for a 0.3° radius circle we take a number of excess photons (over the background) at different energies and try to get a spectrum

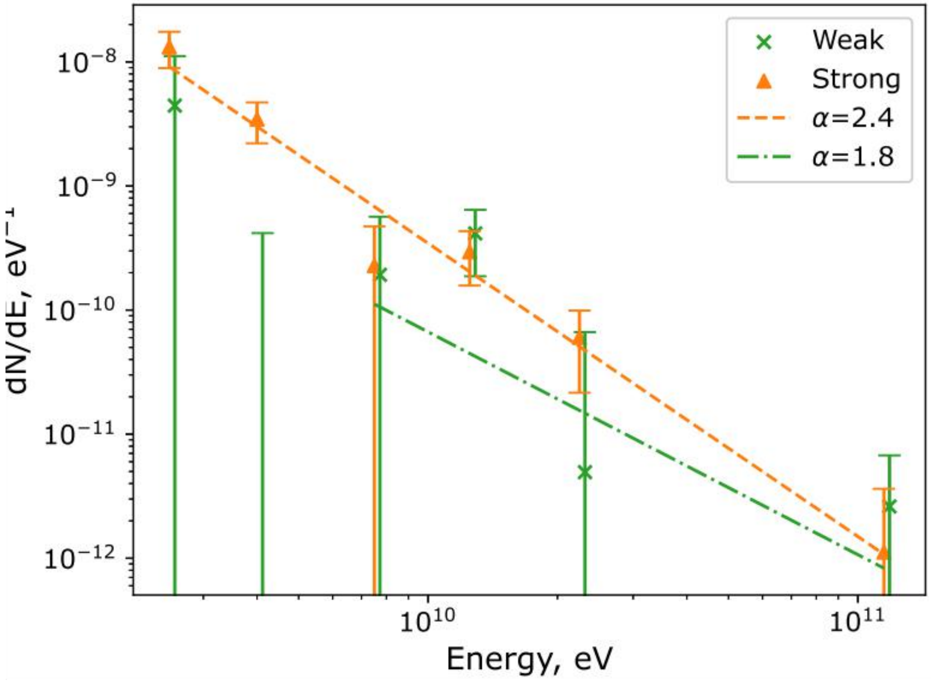




- α=2.4 (1.8) for «strong» («weak») sources
- Close to the *FERMI_STACKING* results: $2.8^{+0.6}_{-0.4}$ and $1.7^{+1.1}_{-0.5}$

Energetics and spectrum





- Average luminosity could be estimated as follows:

L_{strong}~5.3x10^{39} erg/s and L_{weak}~1.8x10^{39} erg/s

Origin

- Does not look like DM-related:
  - hints at complicated morphology
  - absence of signal from the early-type galaxies
  - absence of signal from less massive galaxies 10^9-10^{10} $M_\odot$

- Could be related to the previous phases of galactic activity-- AGN or starburst.

- The age of the gamma-ray halo, could it be cosmological? The morphology is not in favor of it, but the statistics is too limited.

Other wavelengths/energies

- Radio
  - Look at 7 «strong» sources (NGC0628, NGC0660, NGC1512,NGC1532, NGC3877, NGC7331, NGC7814) in GLEAM, VLSSR, NVSS surveys data
  - no statistically significant excess.
  - expected, as a in the "WMAP/Planck haze"

- X-ray
  - ART-XC --nothing
  - Need to look in the eROSITA data

Conclusions

- We detected weak signal from a set of massive late-type galaxies nearby (D<15 Mpc) in the high-energy range. The maximal statistical significance reached p-val=2.3×10^{-8}

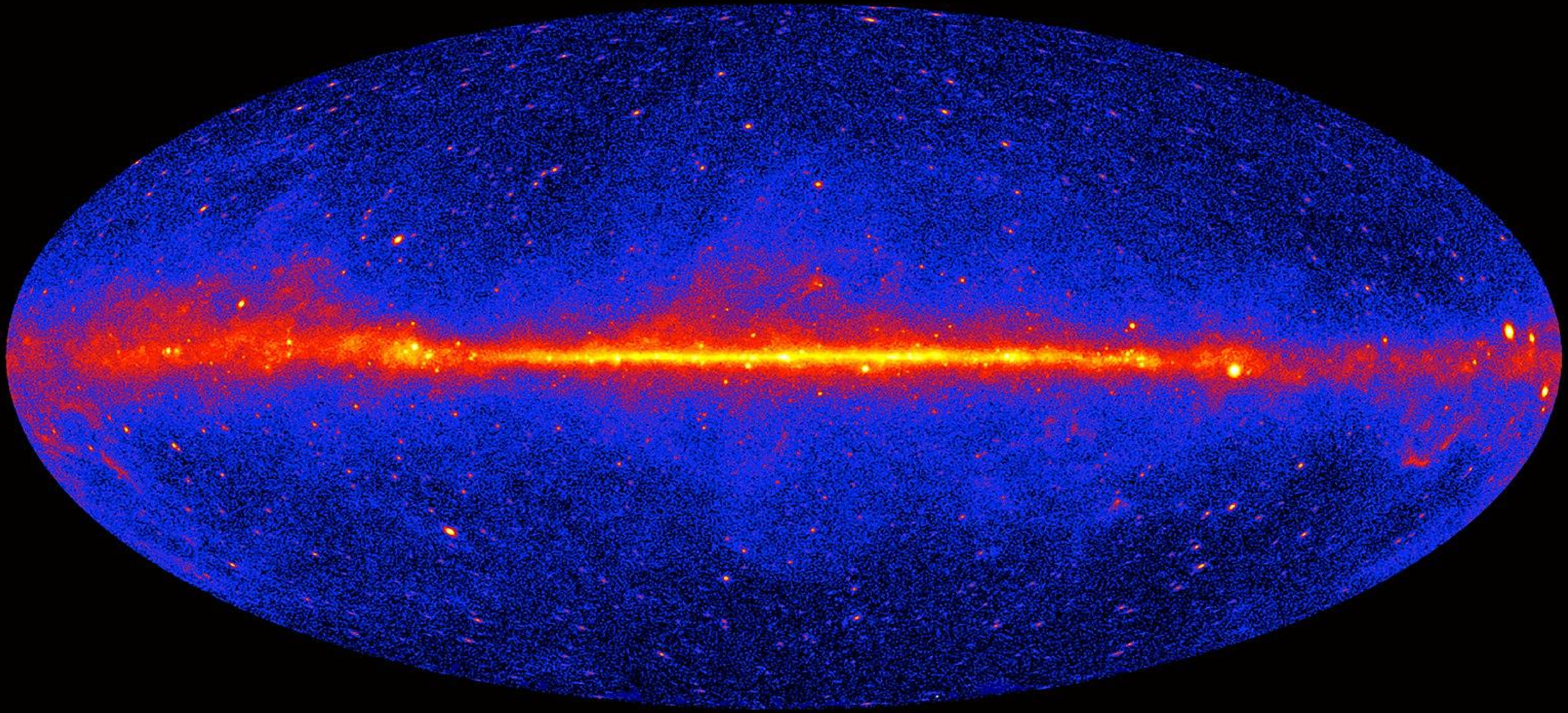
- Could be explained as a signal from extended sources with a characteristic angular radius 0.3° (~80 kpc at this distance)

- The galaxy set is heterogenous: brighter galaxies has softer spectrum, α=2.4, while less luminous have much harder one: α=1.8.

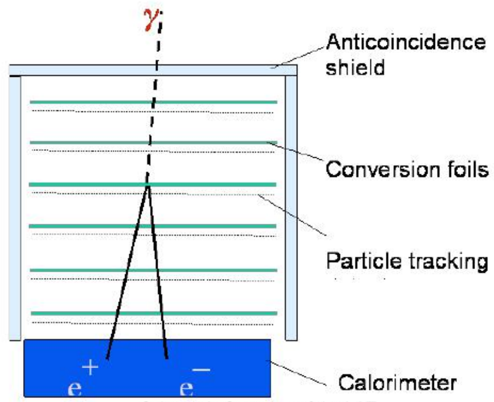
- arXiv:2410.02066, Phys. Rev. Lett. **136**, 081201 (2026)

Thank you for your attention

Fermi LAT: γ-ray sky



Fermi LAT



Schematic Structure of the LAT

12 front layers 3% rad. length (W)

4 back layers18% rad. length

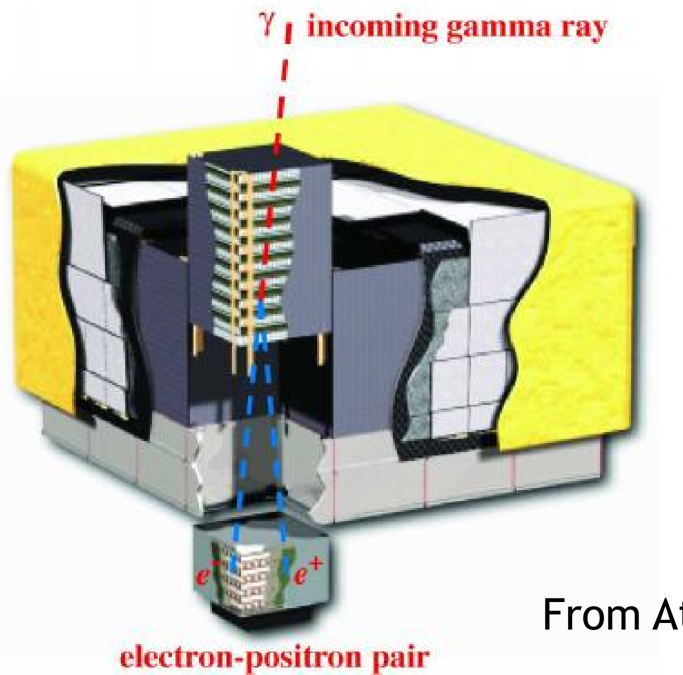
FoV 2.4 sr

~0.9 m^2 effective area

Orbit : H~550 km, T~95 min

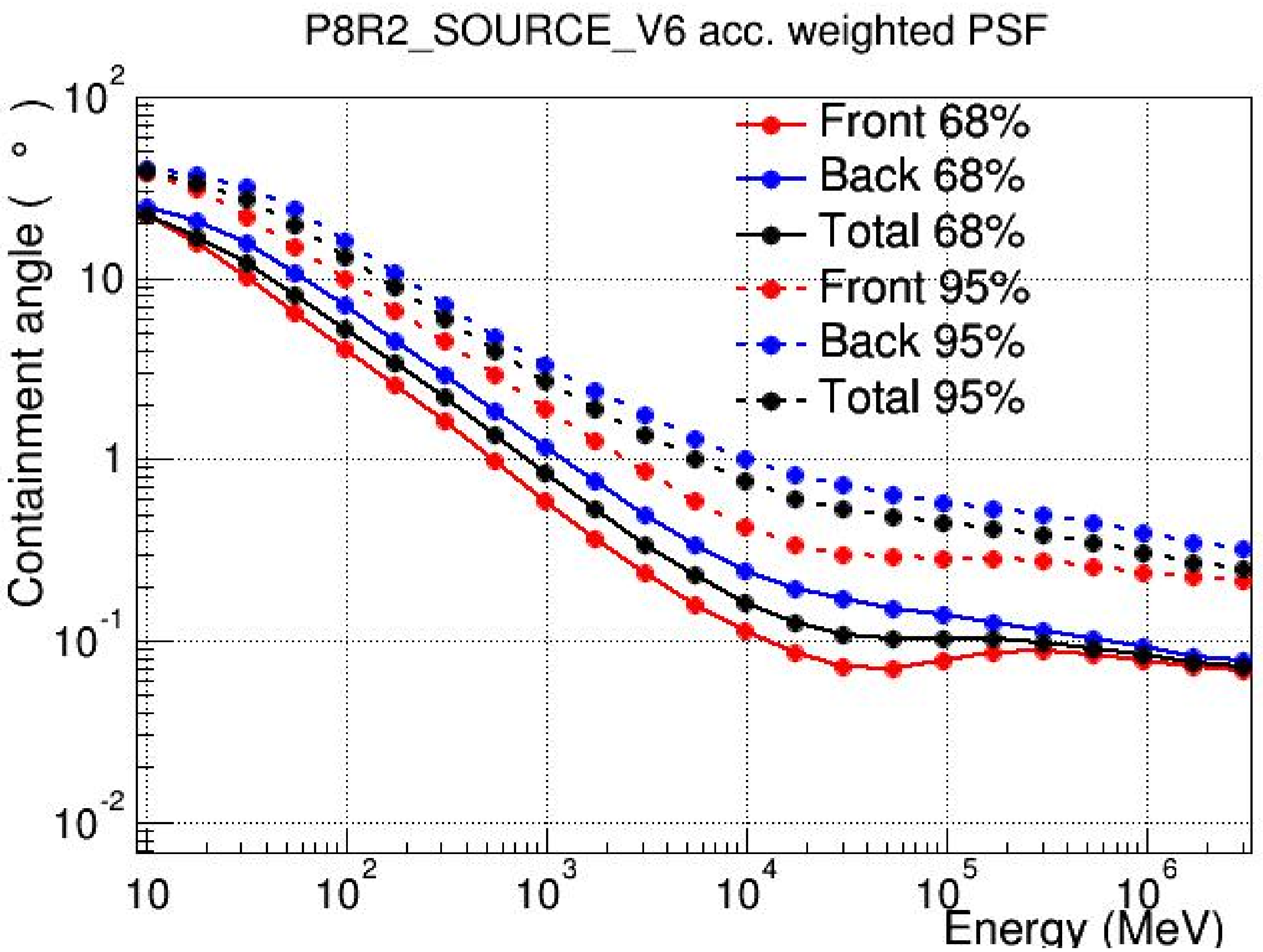
Data since 04.08.2008
http://fermi.gsfc.nasa.gov/ssc/data/

>6x10^8 events (SOURCE class) in 10 years of observations



From Atwood et al, 2009

Fermi LAT: point spread function (PSF)



Fermi LAT: effective area