Galactic *Resolved and Unresolved* gamma-ray sources at very high energy

A phenomenological study

[work with Silvia Vernetto]

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CDY seminar
March 20th 2024

Outline:

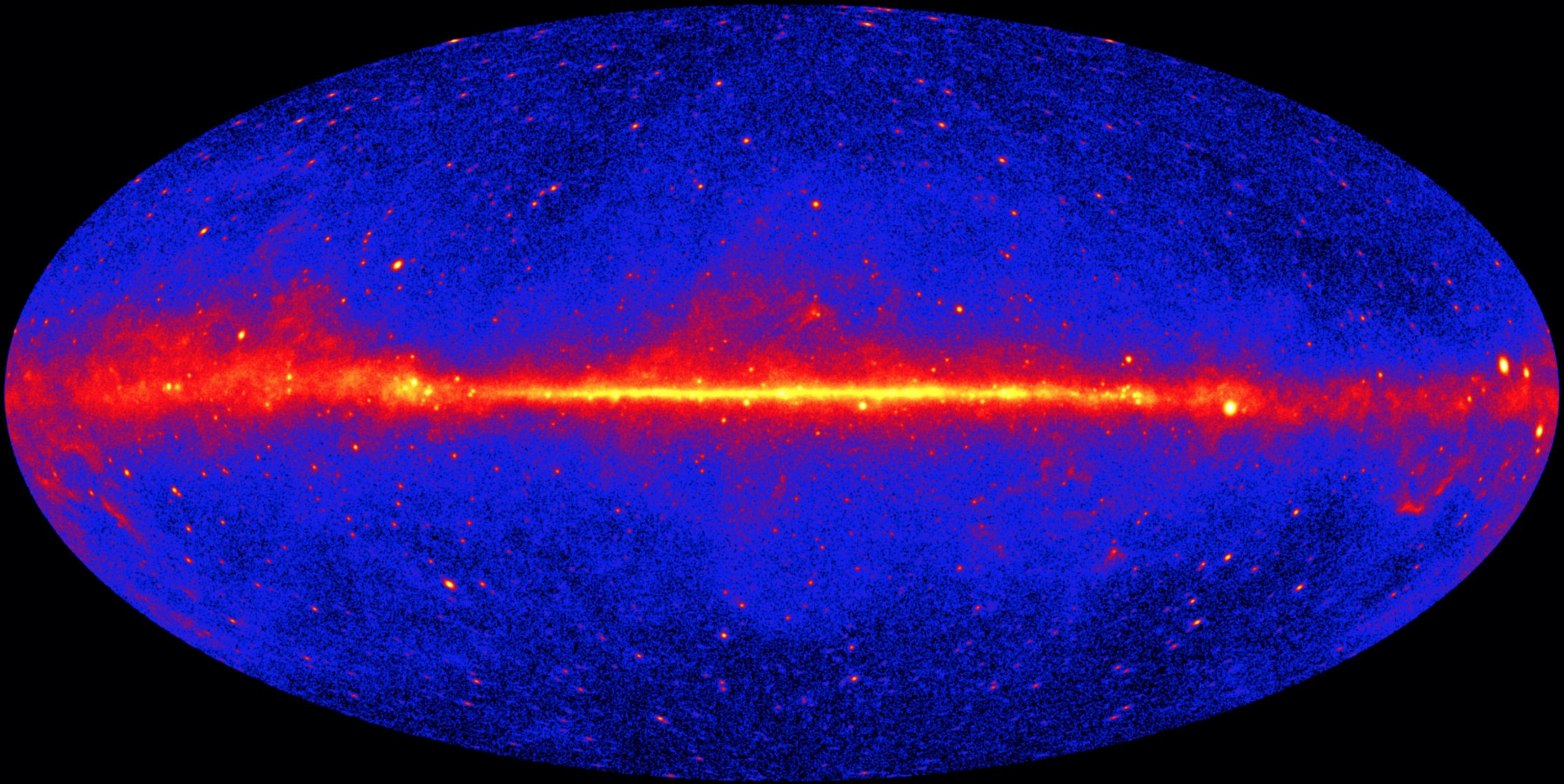
1. Introduction:
   Components of the gamma-ray sky
2. Source Catalogs
3. Spectral Shapes of the sources and
   the *“Cumulative Source Spectrum”*
4. Diffuse gamma ray flux measurements
5. *Geometrical Method*
   to estimate the Unresolved Source Flux
6. Conclusion and Outlook

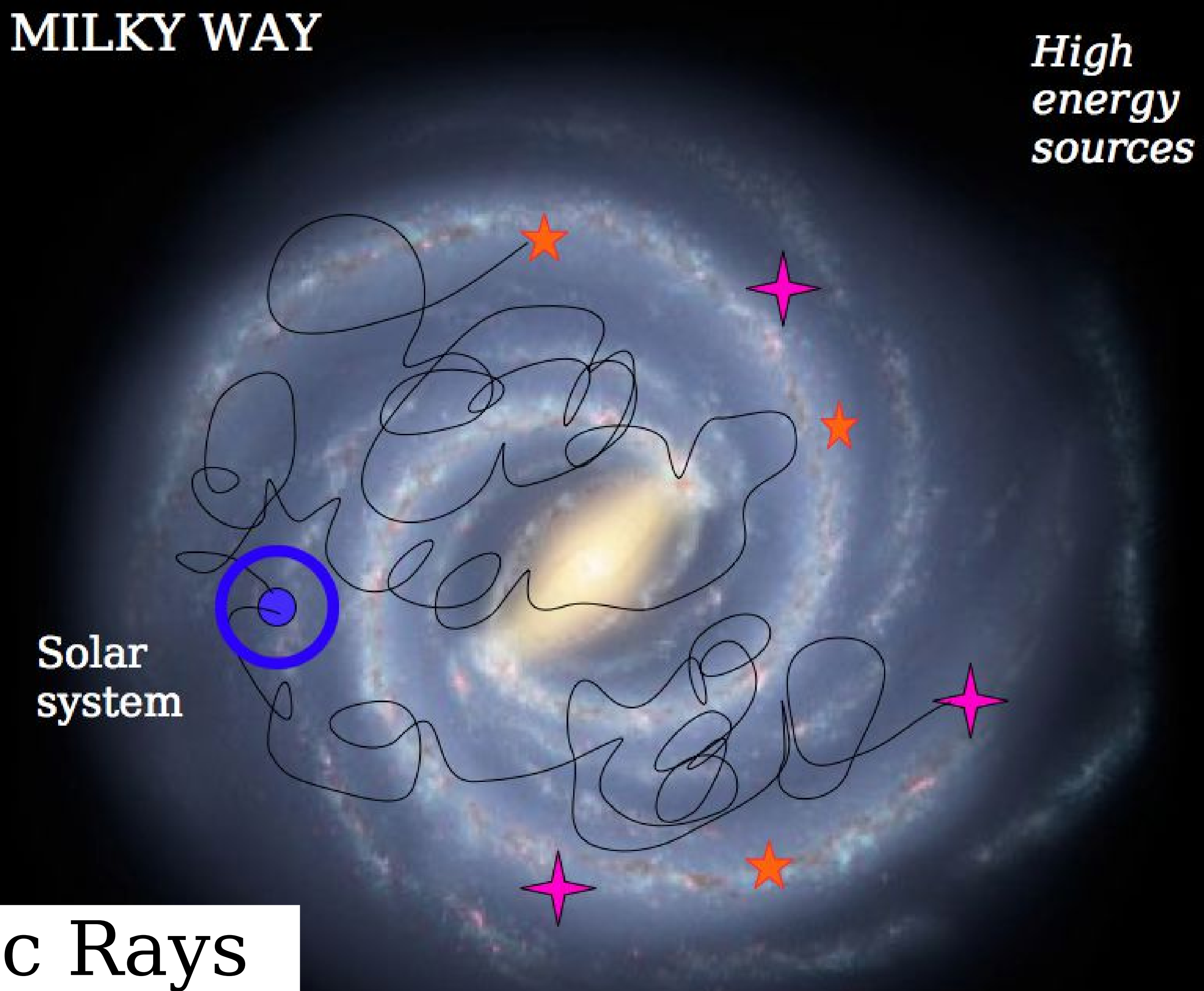
Gamma Ray Sky

Fermi-LAT (E > 100 MeV)

Ensemble of (quasi)-point-like sources [Galactic+extragalactic]

Diffuse Flux [Galactic + extragalactic (isotropic)]





Cosmic Rays

(observed at the Earth)
mostly Galactic.
Measure a space
and time average
of the source emissions,
distorted by propagation

Gamma Ray emission from the Milky Way:

$$Q(E) = Q_{\text{ism}}(E) + Q_{\text{sources}}(E)$$

- Cosmic Ray interactions during propagation in the interstellar medium.

- Sources

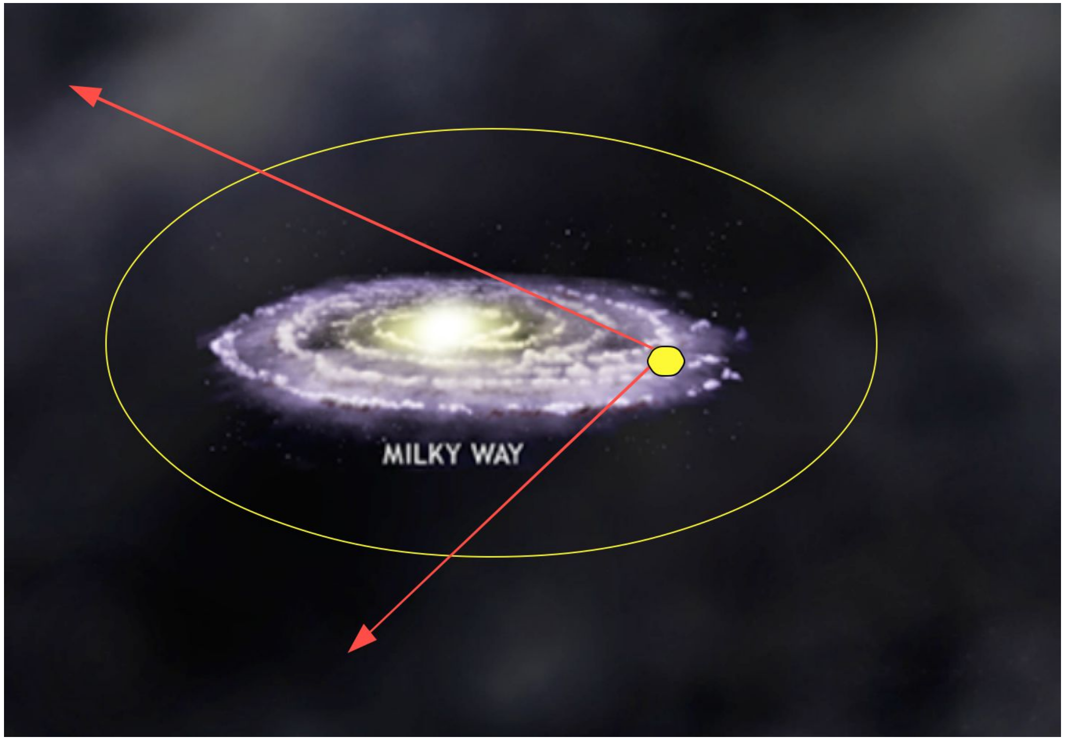
$$\phi(E, \Omega, \Delta\Omega) = \phi_{\text{ism}} + \phi_{\text{sources}}$$

$$= \phi_{\text{ism}} + \phi_{\text{sources}}^{\text{resolved}} + \phi_{\text{sources}}^{\text{unresolved}}$$

Diffuse Flux

in the direction Ω
obtained as the integral
of the emission along
the line of sight

[absorption effects
important only at high energy
$E \gtrsim 100$ TeV]



Emission generated by Cosmic Rays distributed in Galactic space

absorption

$$\phi_\gamma(E,\Omega) = \frac{1}{4\pi} \int_0^\infty d\ell \; q_\gamma[E, \vec{x}_\odot + \ell \, \hat{\Omega}] \; e^{-\tau_\gamma(E,\Omega,\ell)}$$

$$\phi_\nu(E,\Omega) = \frac{1}{4\pi} \int_0^\infty d\ell \; q_\nu[E, \vec{x}_\odot + \ell \, \hat{\Omega}]$$

Calculation of “interstellar” emission:

Leading (proton-proton) term
for hadronic mechanism:

Gas density in the
Milky Way

$$q_\gamma^{(pp)}(E_\gamma, \vec{x}) = \boxed{n_p^{\rm ism}(\vec{x})} \times$$

$$\times \int_{E_\gamma}^{\infty} dE_p \boxed{[4\,\pi\;\phi_p(E_p, \vec{x})]} \boxed{\sigma_{pp}(E_p)\frac{dN_{pp\to\gamma}}{dE_\gamma}(E_\gamma, E_p)}$$

Hadronic
Interactions

Spectra of cosmic rays in
the entire Galactic Volume

Study distribution
of Cosmic Rays
in the Galaxy

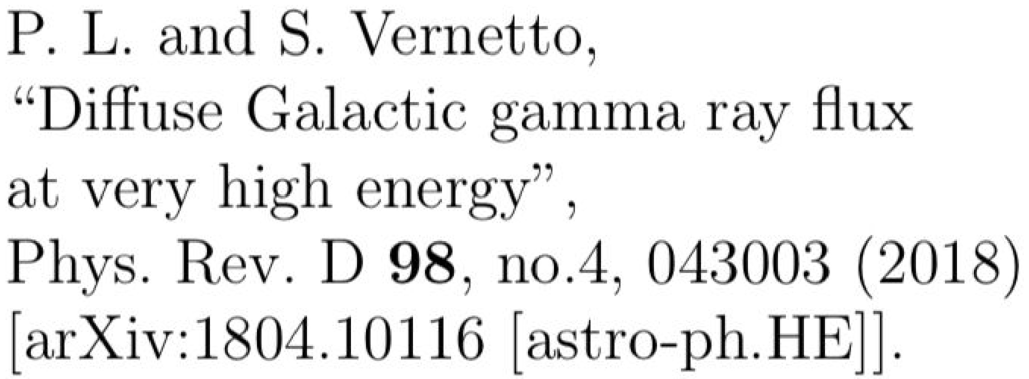
Sources of uncertainties in the calculation of the Diffuse Interstellar emission fluxes:

1. Modeling of hadronic interactions
   (good control, effects are only minor)

2. Description of matter (for hadronic mechanism)
   (+radiation and magnetic field for leptonic mechanisms)
   in the Milky Way.

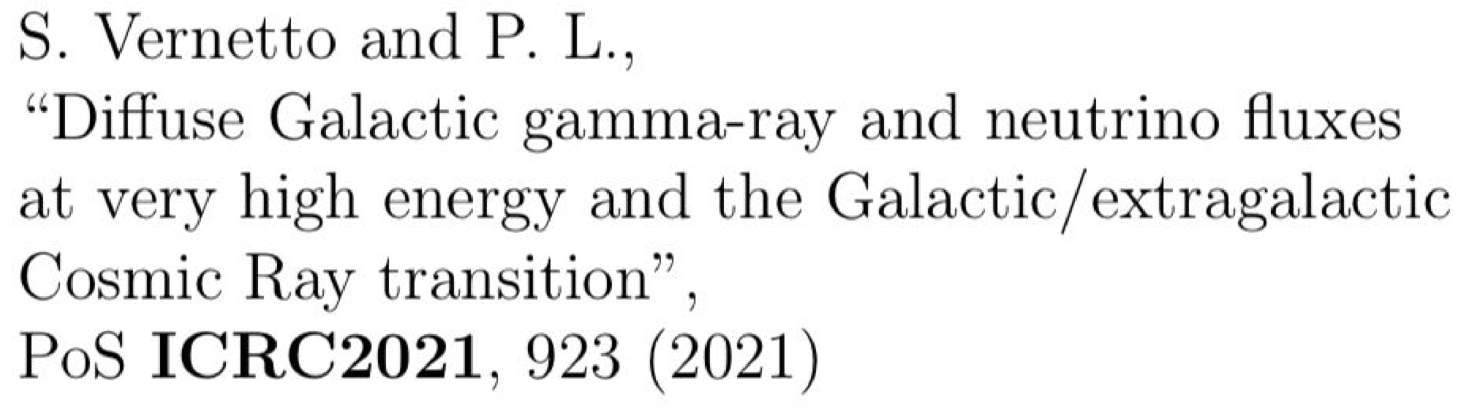
3. Description of the Cosmic Ray spectra
   - Spectra at the Earth
   - *Space dependence of the spectra*

Previous work on the diffuse (interstellar emission) gamma-ray [andnneutrino] fluxes



P. L. and S. Vernetto,
"Diffuse Galactic gamma ray flux
at very high energy",
Phys. Rev. D **98**, no.4, 043003 (2018)
[arXiv:1804.10116 [astro-ph.HE]].

LV-2018



S. Vernetto and P. L.,
"Diffuse Galactic gamma-ray and neutrino fluxes
at very high energy and the Galactic/extragalactic
Cosmic Ray transition",
PoS **ICRC2021**, 923 (2021)

Factorization (of energy and space dependences) of the CR spectra

$$\phi_p(E,\vec{x}) = \phi_p^{\rm loc}(E) \times f_{\rm space}(\vec{x})$$

Factorization of (energy and space)
for the gamma ray and neutrino source

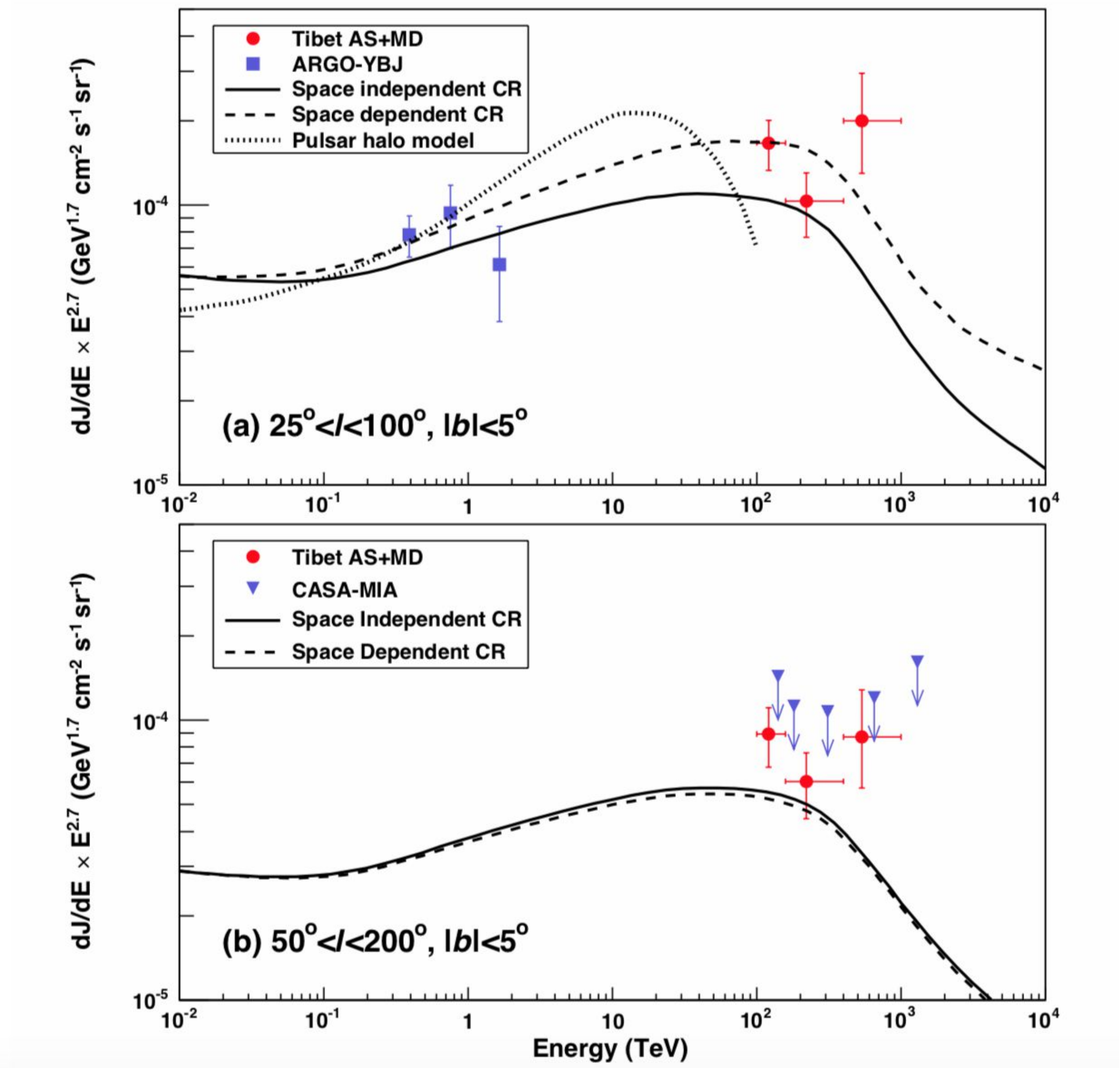
$$q_{\nu,\gamma}(E,\vec{x}) = q_{\nu,\gamma}^{\rm loc}(E) \times f_{\rm space}(\vec{x}) \times \left(\frac{n_{\rm ism}(\vec{x})}{n_{\rm ism}(\vec{x}_\odot)}\right)$$

Factorization of (energy and angle)
of the gamma ray [no-absorption]
and neutrino diffuse fluxes

$$\phi_{\nu,\gamma}(E,\Omega) = \frac{q_{\nu,\gamma}^{\rm loc}(E)}{4\,\pi}\;T(\Omega)$$

$$T(\Omega) = \frac{1}{n_{\rm ism}(\vec{x}_\odot)}\int_0^\infty dt\;f_{\rm space}(\vec{x}_\odot + t\,\hat{\Omega}) \times n_{\rm ism}(\vec{x}_\odot + t\,\hat{\Omega})$$

2021 - measurement of the Gamma Ray diffuse flux by the Tibet Asg collaboration



Models:
LV-2018

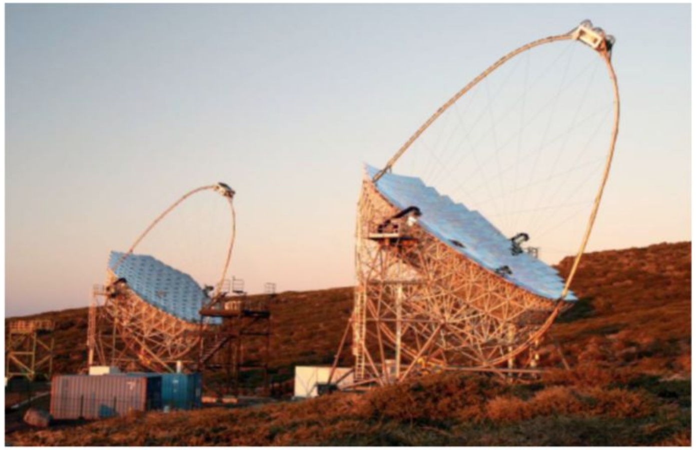
Space independent CR
Space dependent CR

M. Amenomori *et al.* [Tibet ASγ Coll.], “First Detection of sub-PeV Diffuse Gamma Rays from the Galactic Disk: Evidence for Ubiquitous Galactic Cosmic Rays beyond PeV Energies” Phys. Rev. Lett. **126**, no.14, 141101 (2021) [arXiv:2104.05181 [astro-ph.HE]].

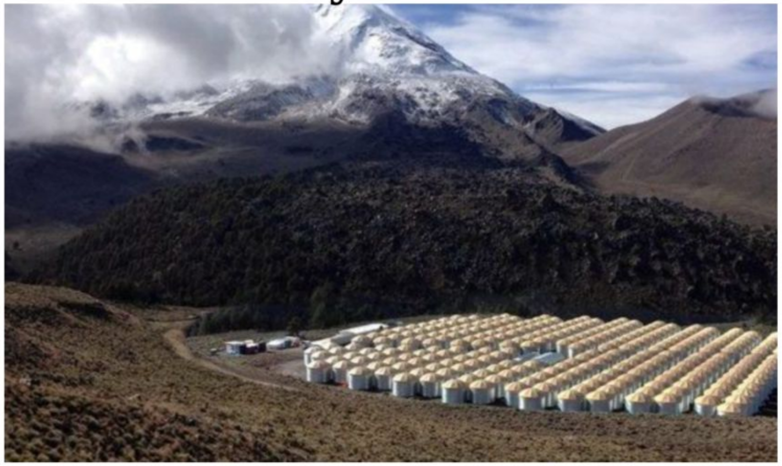
Gamma-ray source catalogs

Space $E_\gamma \simeq 0.1 \div 1000$ GeV

Cherenkov $E_\gamma \simeq 0.1 \div 100$ TeV



Ground Arrays



$E_\gamma \lesssim 30$ PeV LHAASO

Catalogs of gamma-ray sources

1. Fermi-LAT [7195 sources E > 100 MeV]

   4th General Catalog (Data Release 4) 4FGL-DR4

2. HESS Galactic Plane Survey [78 sources]

   $|b| < 3^\circ \qquad -110^\circ \leq \ell \leq +65^\circ$

3. HAWC 3rd Catalog [65 sources]

4. LHAASO 1st Catalog [90 sources (WCDA + KM2A)]

   4a LHAASO WCDA [69 sources]

   4b LHAASO KM2A [75 sources]

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EAS telescopes

LHAASO WCDA
LHAASO KM2A

- LHAASO bird view in Oct. 2019

$$Q_{\mathrm{sources}}(E) = \sum_j q_j(E)$$

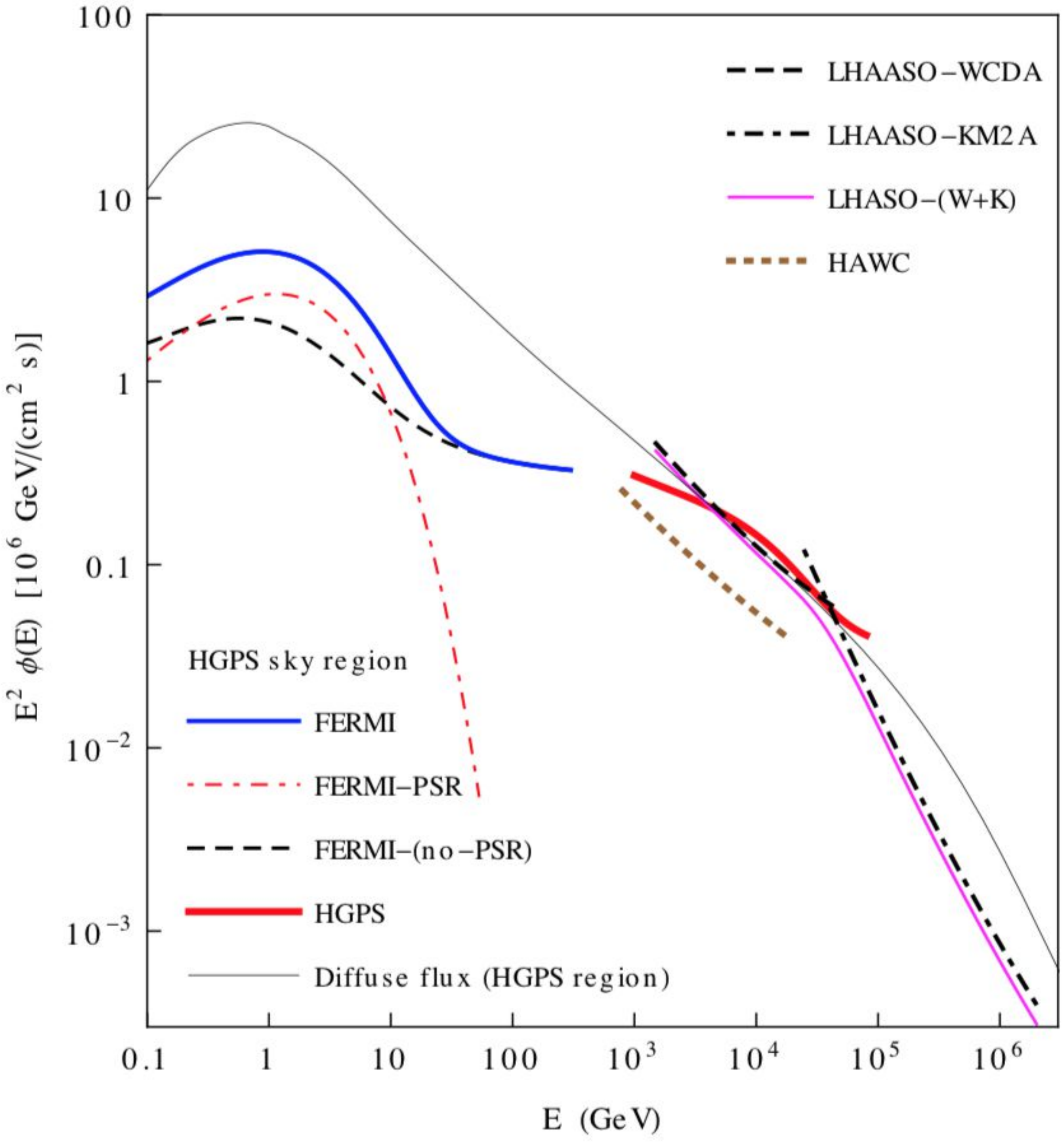
Spectral shape of
the ensemble
of all Galactic sources

Spectra of
individual sources

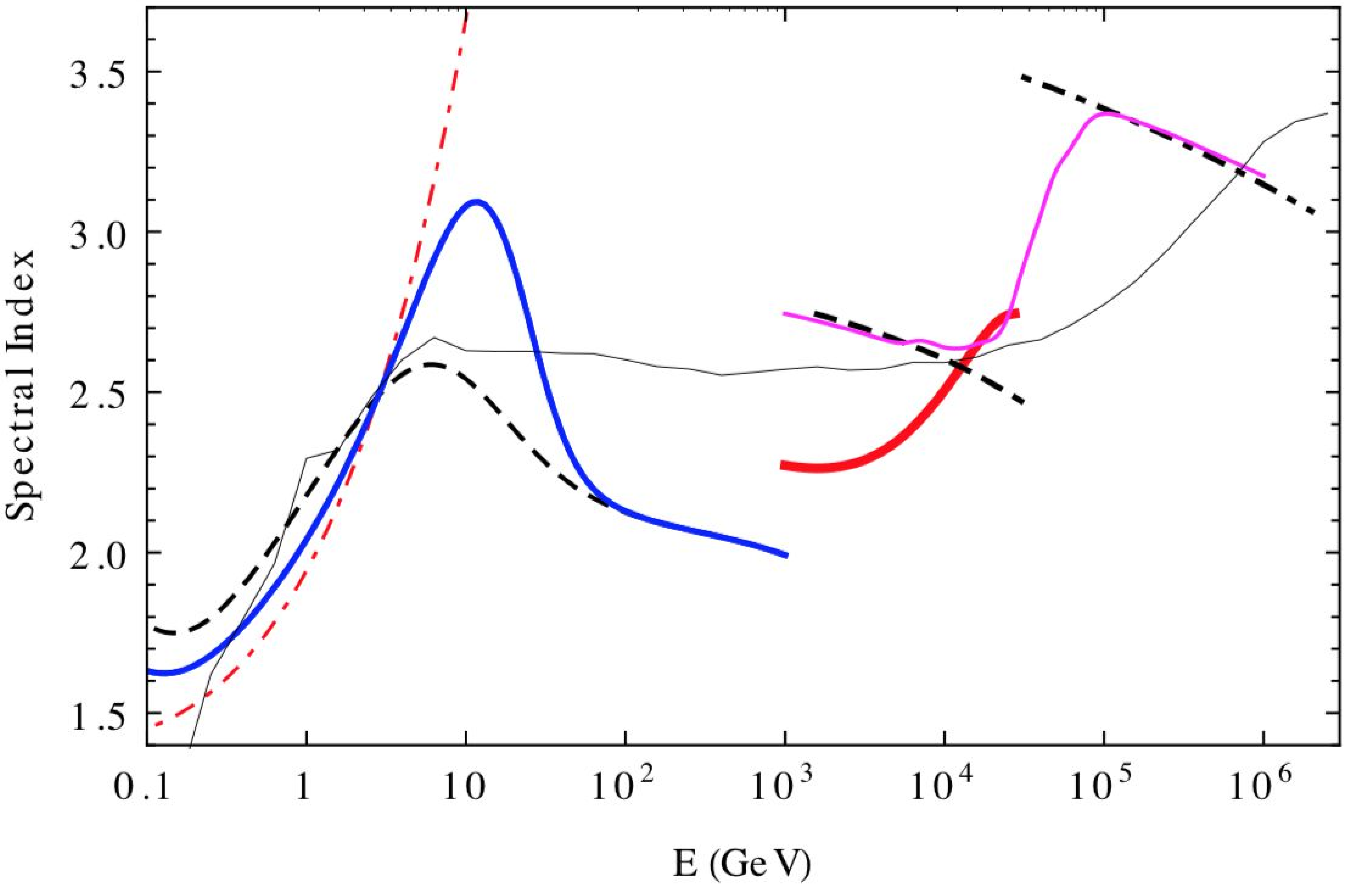
Fundamental Task:

Understanding the
properties and *nature* of
the Galactic sources

Cumulative source spectrum in the sky region



Spectral Index of the cumulative source spectrum



Spectral shapes of the fluxes:

$$\phi(E) = K \left(\frac{E}{E_0}\right)^{-\alpha}$$

Power Law

$$\phi(E) = K \left(\frac{E}{E_0}\right)^{-(\alpha_0 + \beta \, \ln E/E_0)}$$

LogParabola

$$\phi(E) = K \left(\frac{E}{E_0}\right)^{\frac{d}{b} - \alpha_0} \exp\left[-\frac{d}{b^2} \left(1 - \left(\frac{E}{E_0}\right)^{b}\right)\right]$$

Power Law
SuperExpCutoff

$$\phi(E) = K \left(\frac{E}{E_0}\right)^{-\alpha} e^{-E/E_{\mathrm{cut}}}$$

Power Law +
exponential cutoff

Spectral shapes of the fluxes:

Fermi-LAT uses these 3 forms

$$\phi(E) = K \left(\frac{E}{E_0}\right)^{-\alpha}$$

Power Law

$$\phi(E) = K \left(\frac{E}{E_0}\right)^{-(\alpha_0+\beta \ln E/E_0)}$$

LogParabola

$$\phi(E) = K \left(\frac{E}{E_0}\right)^{\frac{d}{b}-\alpha_0} \exp\left[-\frac{d}{b^2}\left(1-\left(\frac{E}{E_0}\right)^{b}\right)\right]$$

Power Law SuperExpCutoff

$$\phi(E) = K \left(\frac{E}{E_0}\right)^{-\alpha} e^{-E/E_{\mathrm{cut}}}$$

Power Law + exponential cutoff

Spectral Index
(“slope”)

$$\alpha(E) = -\frac{d\log\phi(E)}{d\log E}$$

$$\alpha(E) = \alpha_0 + 2\beta \, \ln\frac{E}{E_0}$$

Spectral index
for Logparabola shape

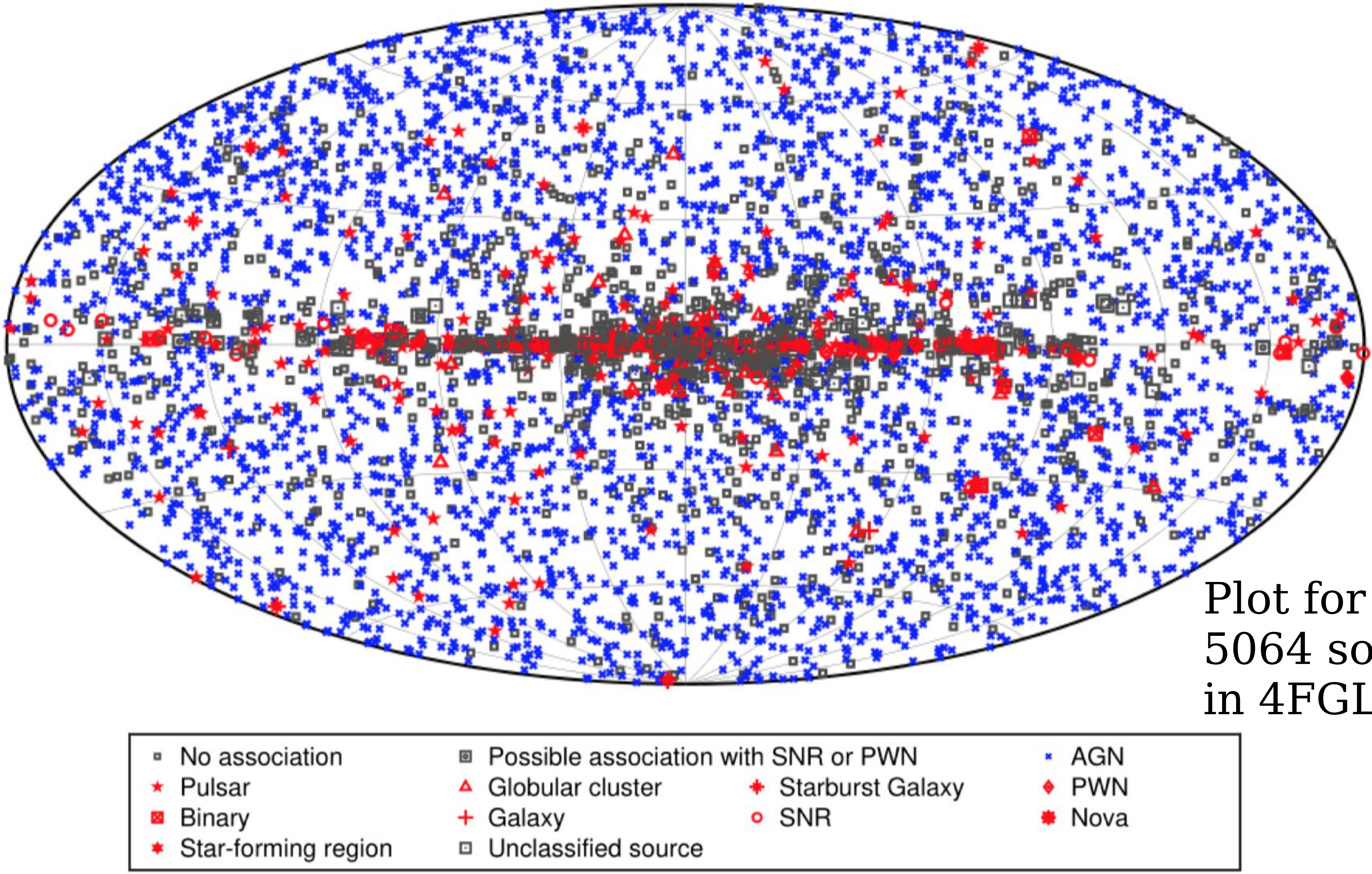
(linear in logE)

$$\phi(E) = K \, \left(\frac{E}{E_0}\right)^{-(\alpha_0+\beta \, \ln E/E_0)}$$

$$\phi(E) = K' \, \exp\left[-\frac{(\ln E - \ln E'_0)^2}{(2\beta)^{-1}}\right]$$

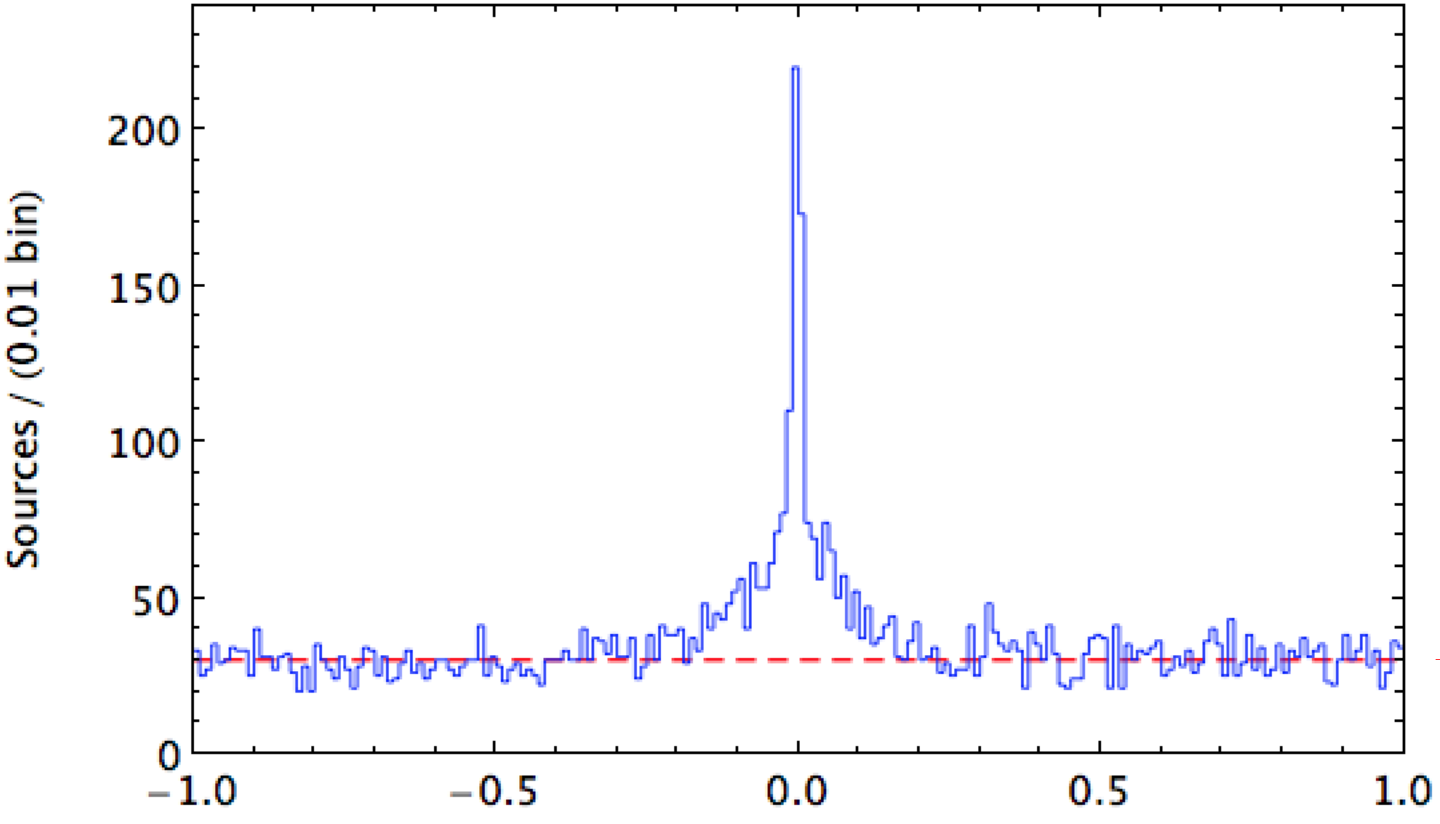
LogParabola
form

FERMI 4th General Catalog 4FGL-DR4 (7195 sources)



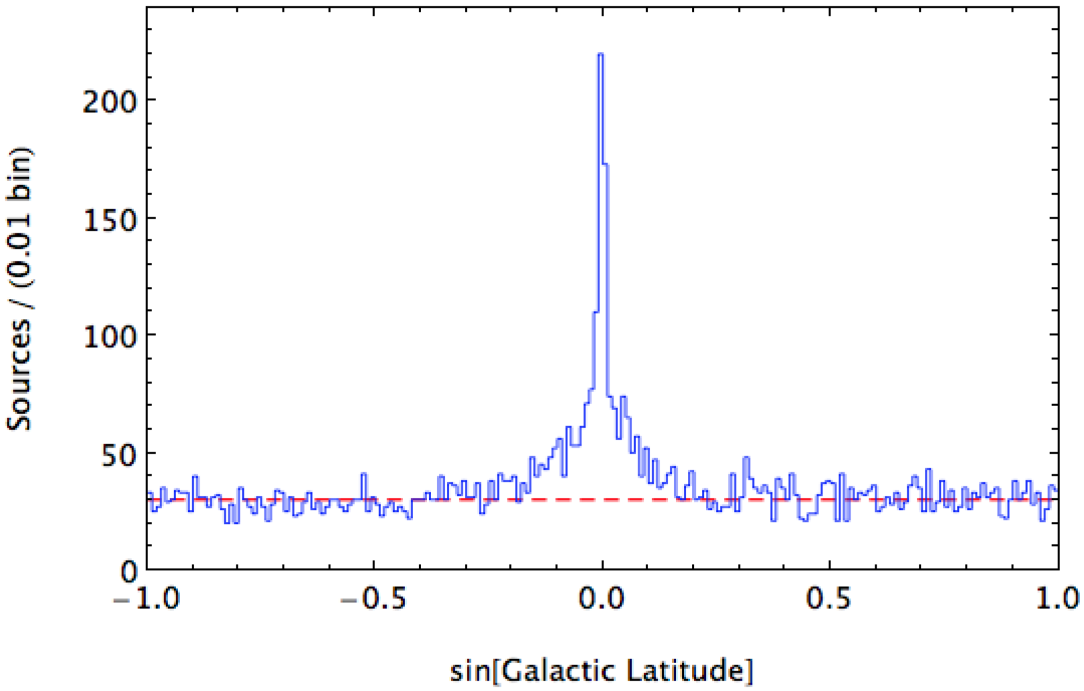
Plot for
5064 source
in 4FGL

Separation of Galactic and extra-Galactic population of sources in the Fermi-LAT data



Sin [Galactic Latitude]

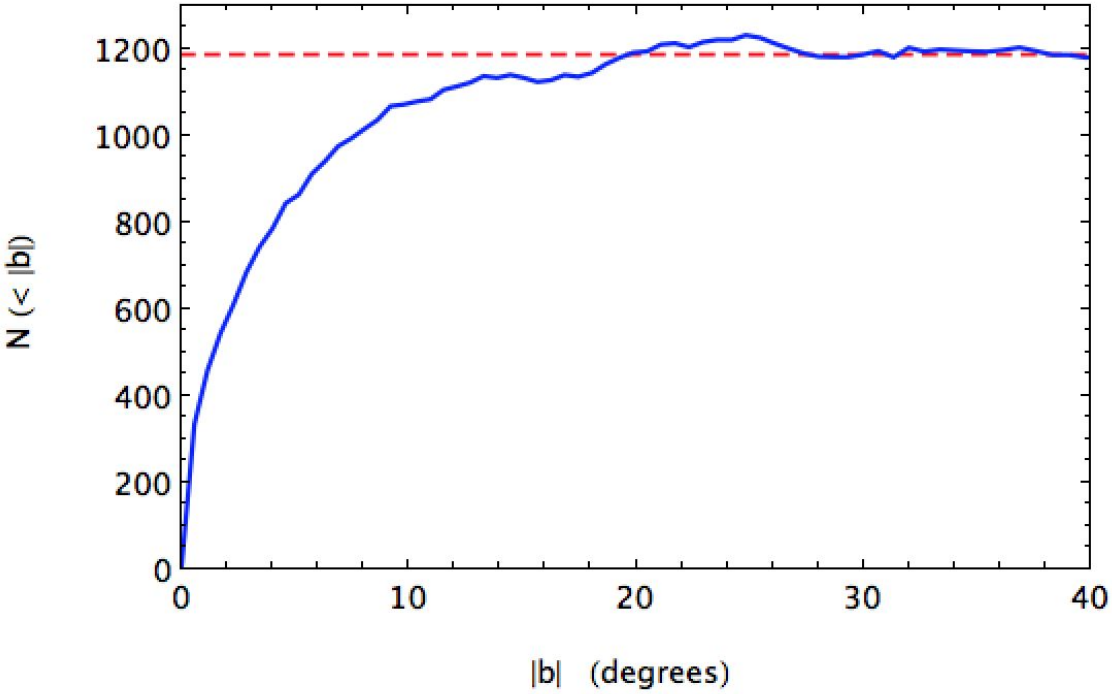
Approximately
isotropic
contribution
of extragalactic
objects



7195 sources

“excess” of
sources along
the Galactic disk

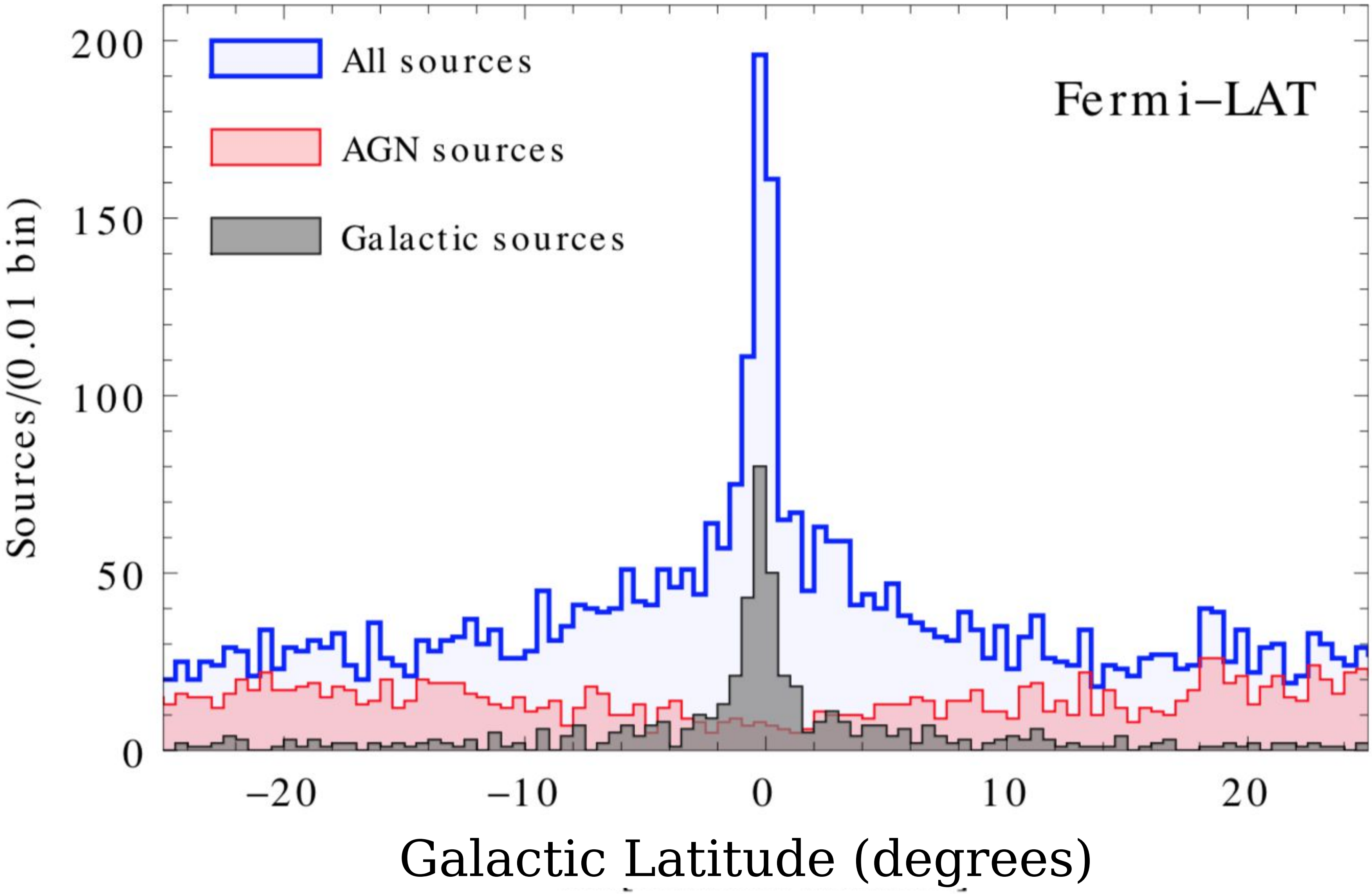
of order of
1200

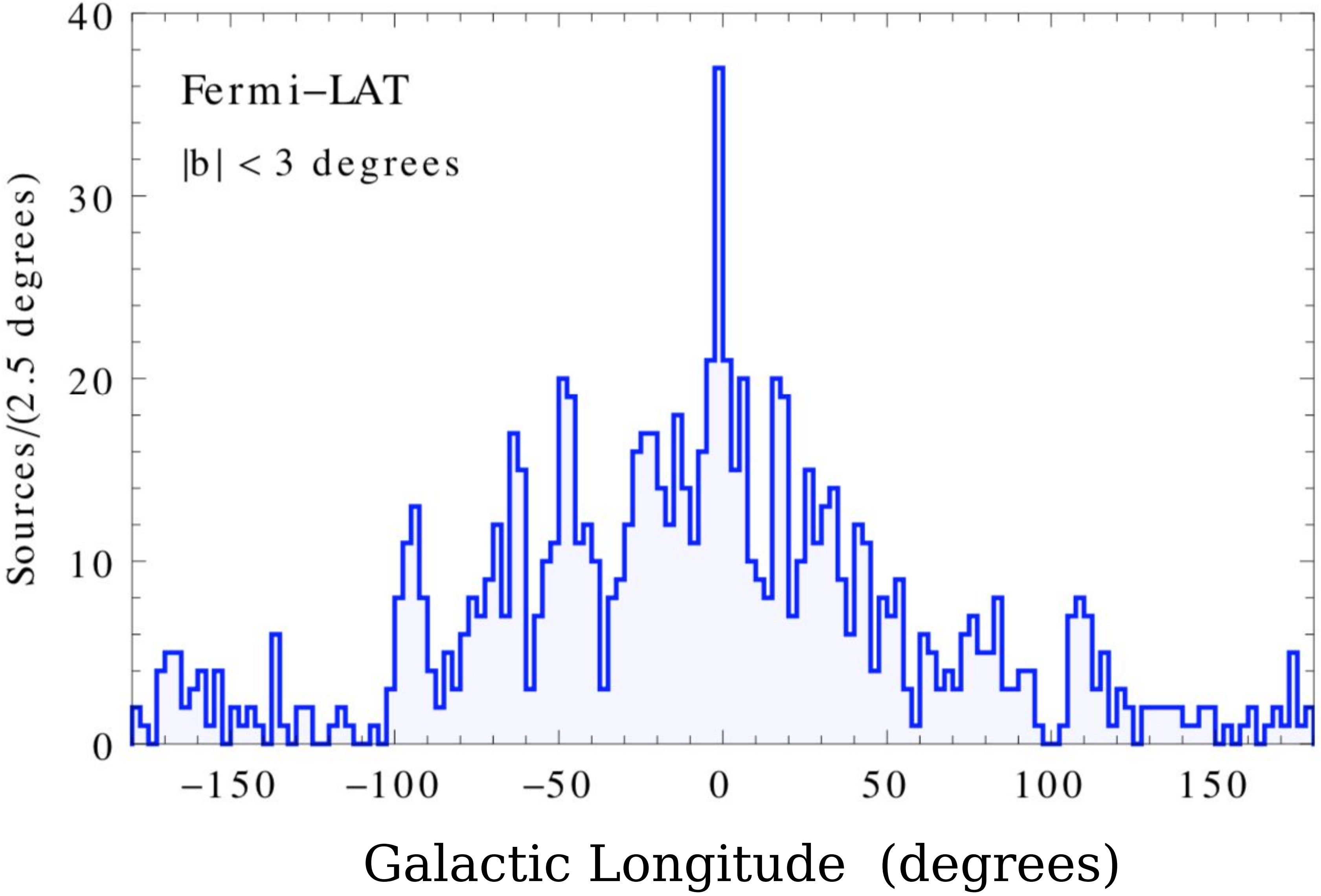


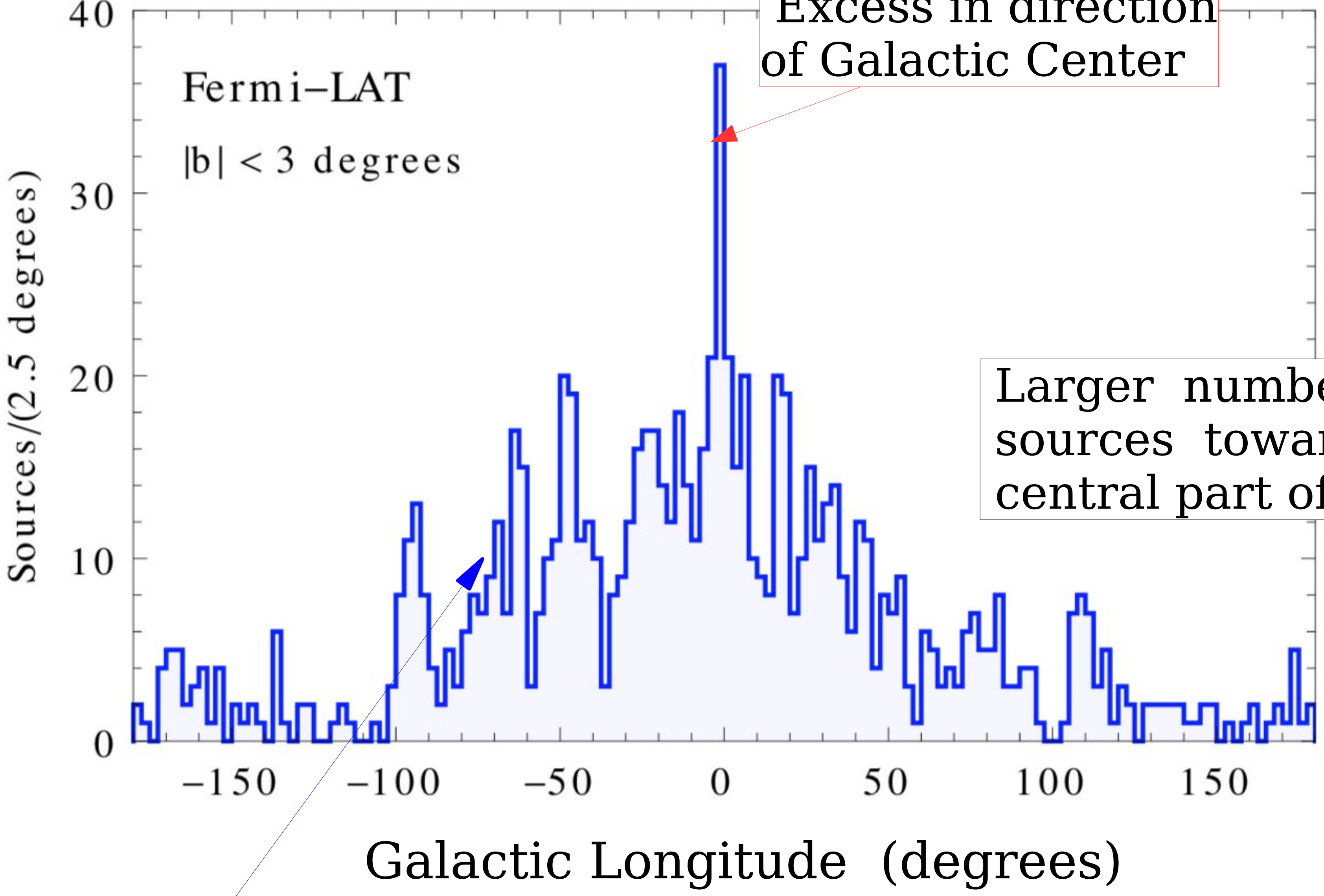
Classification of Fermi-LAT sources

48 classes in catalog.

Galactic sources:	**0.082**
Pulsars, SNR, Binary systems	590 + 8 (Novae)
Extra-Galactic sources:	**0.56**
AGN, Galaxies	4028
Do not know	**0.36**
Unassociated / Unknown	2577


All sources
AGN sources
Galactic sources
Fermi–LAT
Sources/(0.01 bin)
200
150
100
50
0
−20
−10
0
10
20
Galactic Latitude (degrees)


Fermi–LAT
|b| < 3 degrees
Sources/(2.5 degrees)
40
30
20
10
0
−150
−100
−50
0
50
100
150
Galactic Longitude (degrees)



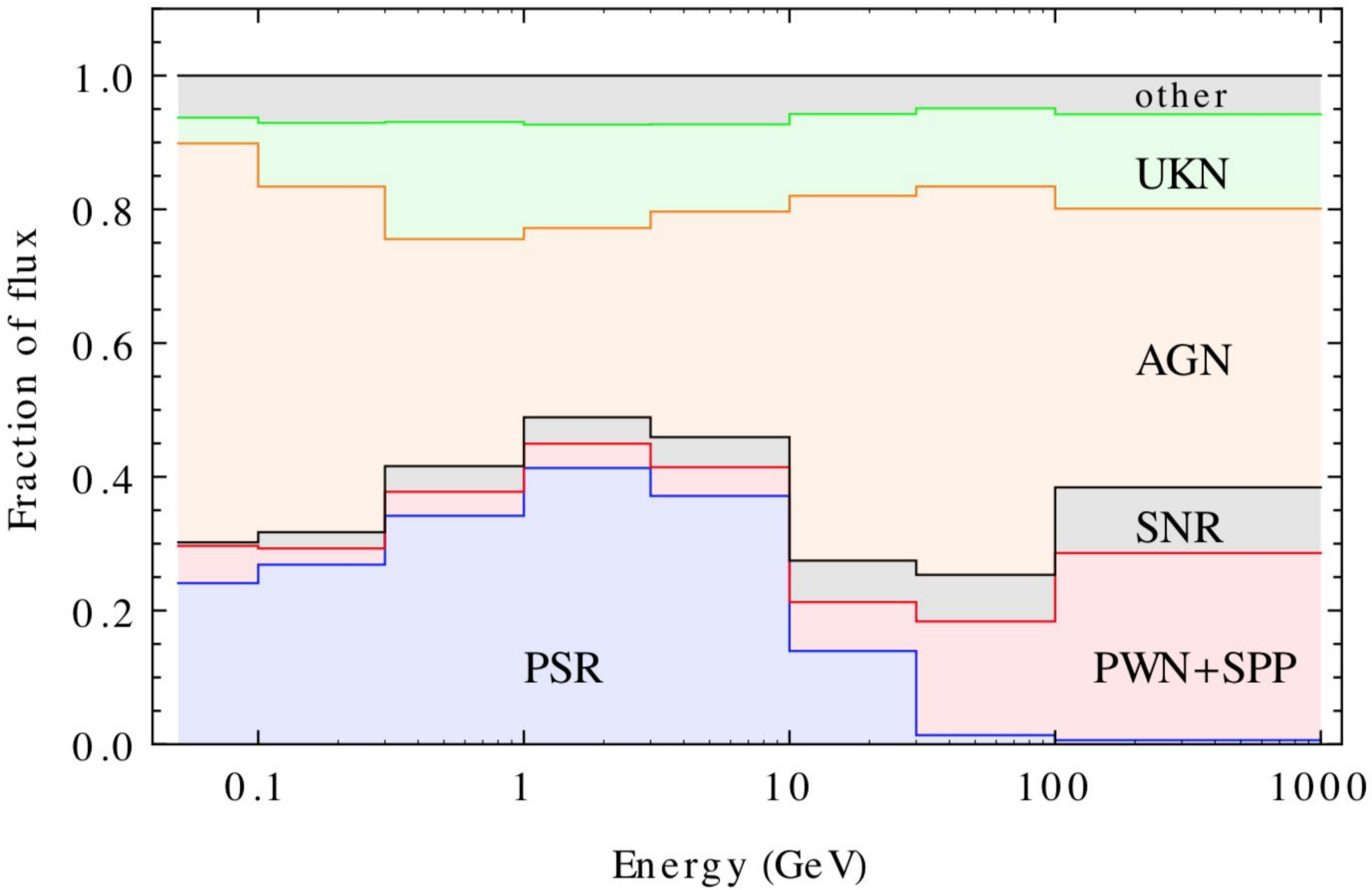
Excess in direction of Galactic Center

Larger number of sources toward central part of Galaxy

Evidence for spiral structure of the Milky Way

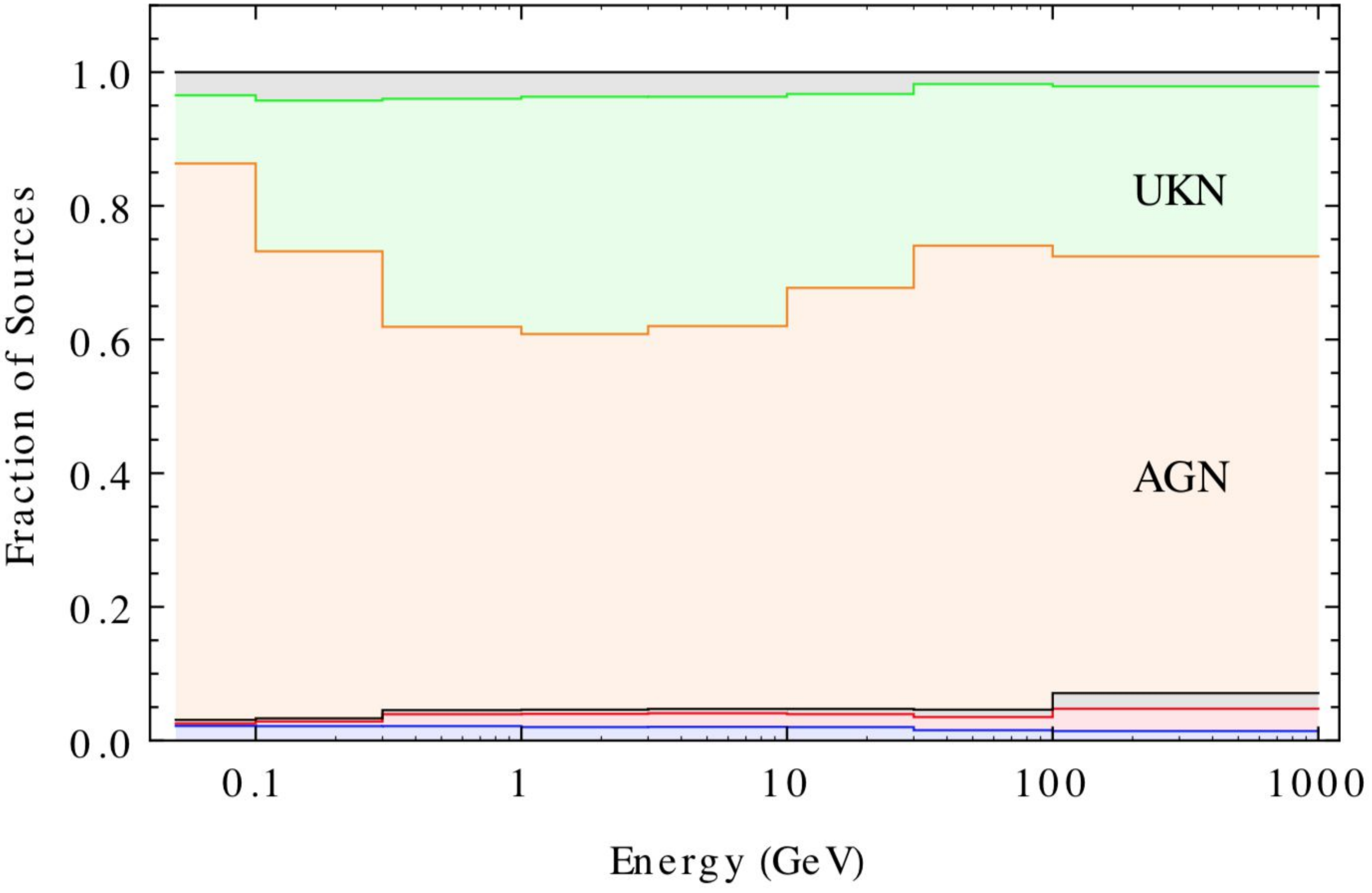
Fermi-LAT sources (4FGL-DR4)

Fraction of FLUX



Fermi-LAT sources (4FGL-DR4)

Fraction
Source Numbers



Spectral shapes of the Fermi-LAT sources
[Select sources in the disk]

$|b| < 3^\circ$ (1007 sources)

Bright Pulsars sources
108 sources
account for 58 % of the flux (> 1 GeV)

104/108 sources have the “PLSuperExpCutoff” spectral form (cutoff in the few GeV range)

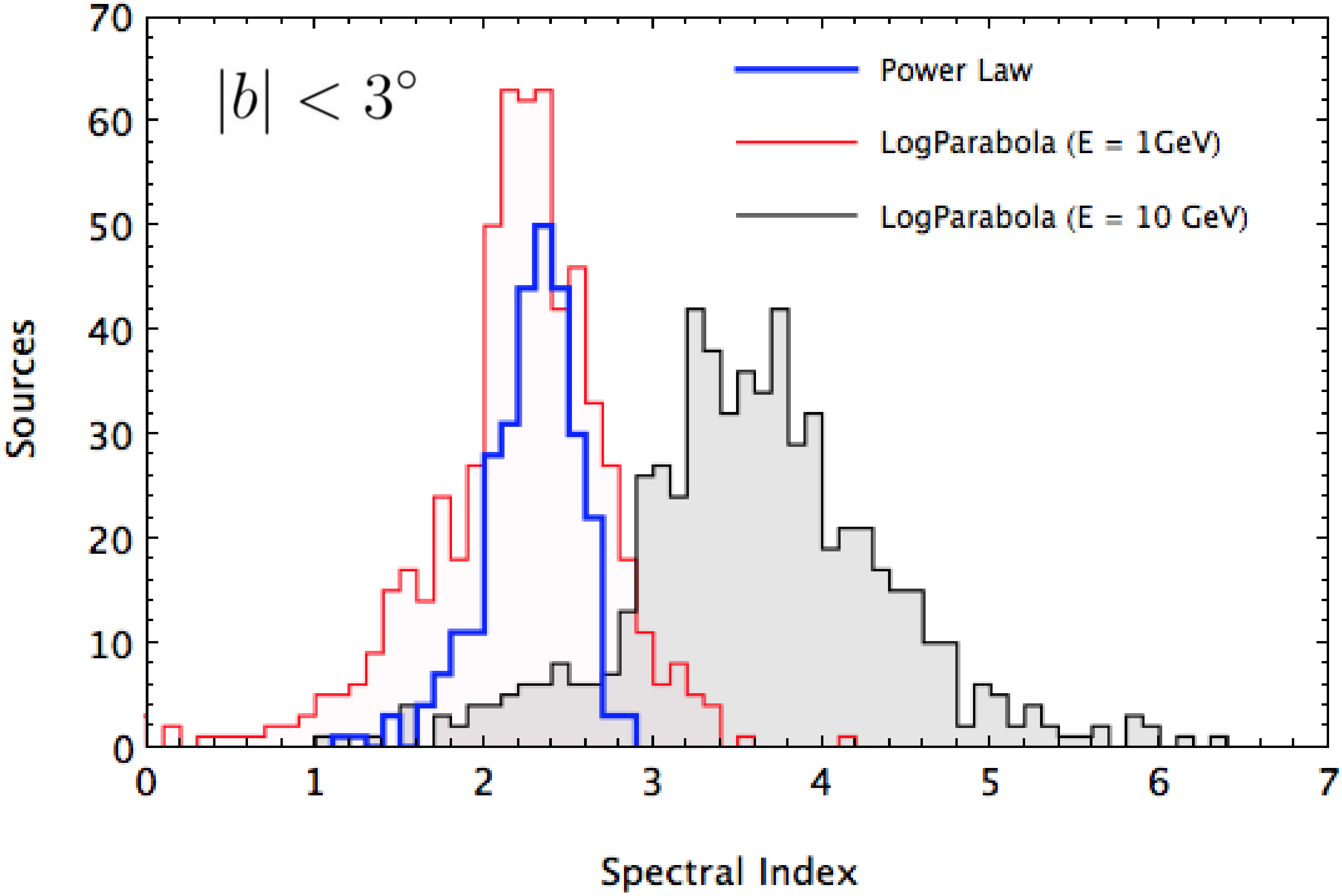
293 Power Law spectra
(15 % of Non-pulsar flux)

600 LogParabola spectra
(85 % of Non-pulsar flux)

Fermi-LAT sources
(293 PowerLaw)
(600 LogParabola)

for Log-Parabola spectra

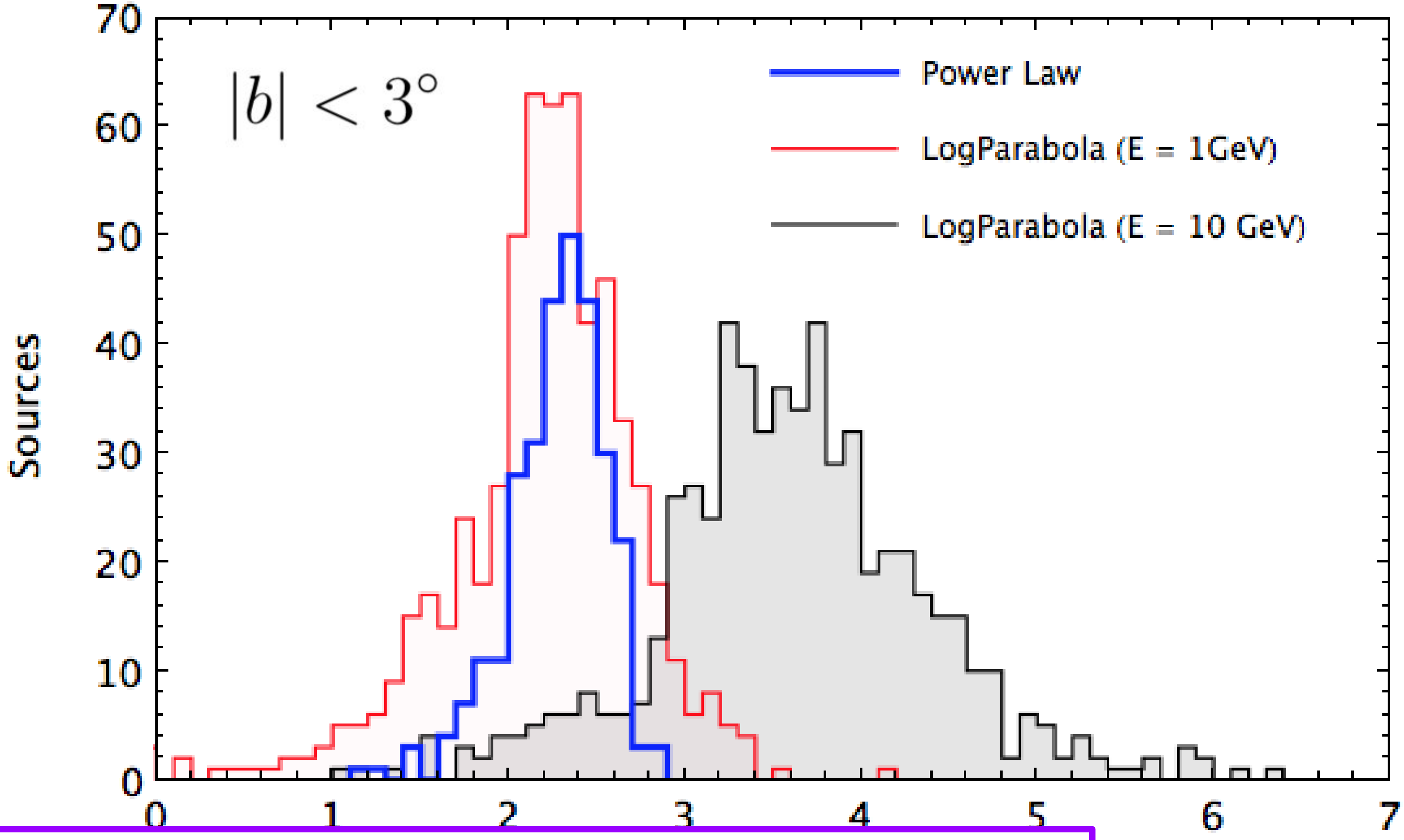
$$\langle \Delta\alpha \rangle_{\text{decade}} = 1.44$$



Fermi-LAT sources
(293 PowerLaw)
(600 LogParabola)

for Log-Parabola spectra

$$\langle \Delta\alpha \rangle_{\text{decade}} = 1.44$$

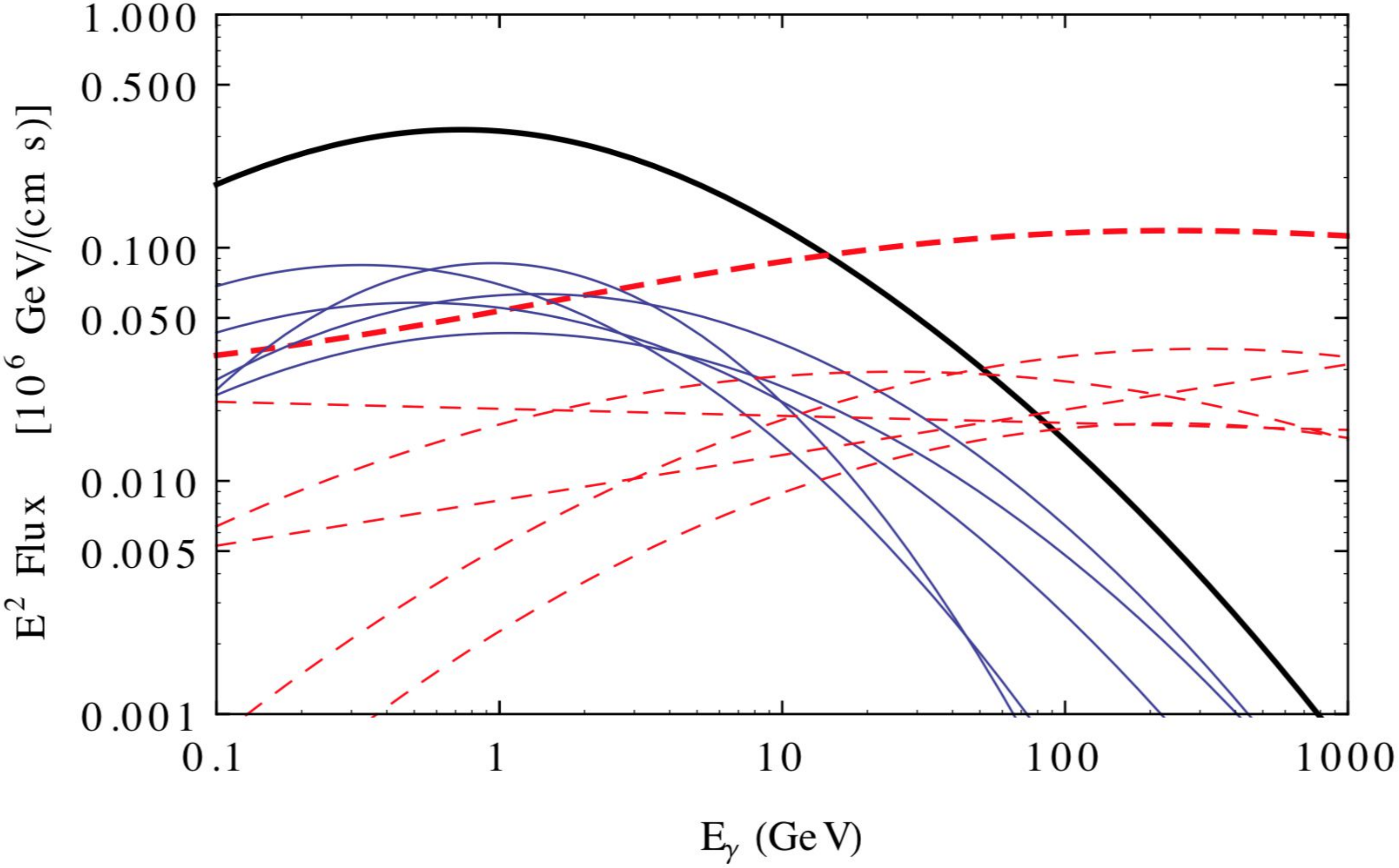


Understanding the origin
of curved spectra is a crucial problem

Fermi-LAT sources | sin b |< 0.1

5 brightest sources at   1 GeV

5 brightest sources at   10 GeV



LHAASO 1st catalog

Water Cherenkov Detector Array [WCDA]

69 sources

Power law fits

$E_0 = 3$ TeV

Kilometer Squared Array [KM2A]

75 sources

Power law fits

$E_0 = 50$ TeV

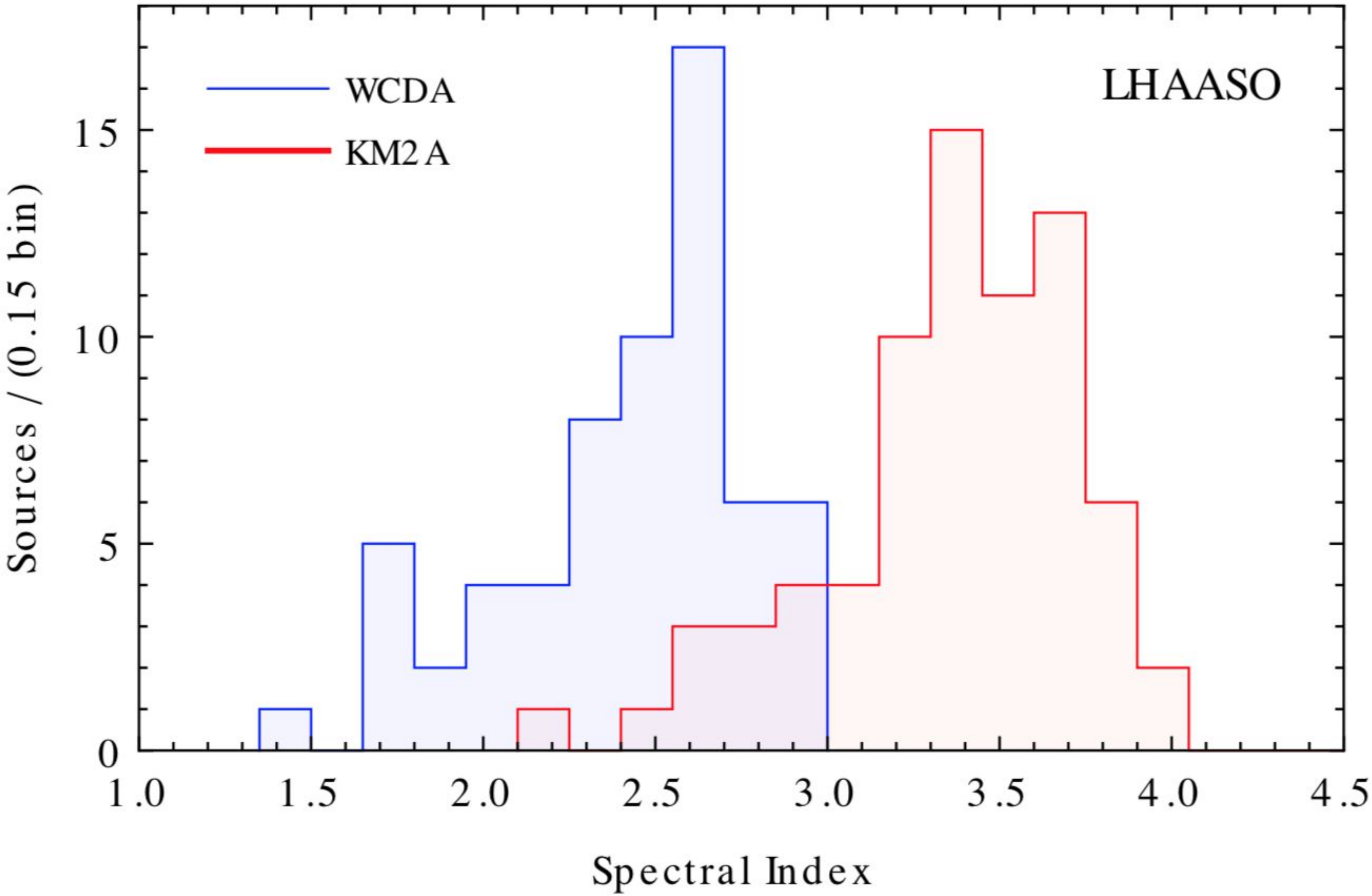
[KM2A - high]

44 KM2A sources are detected above 100 TeV

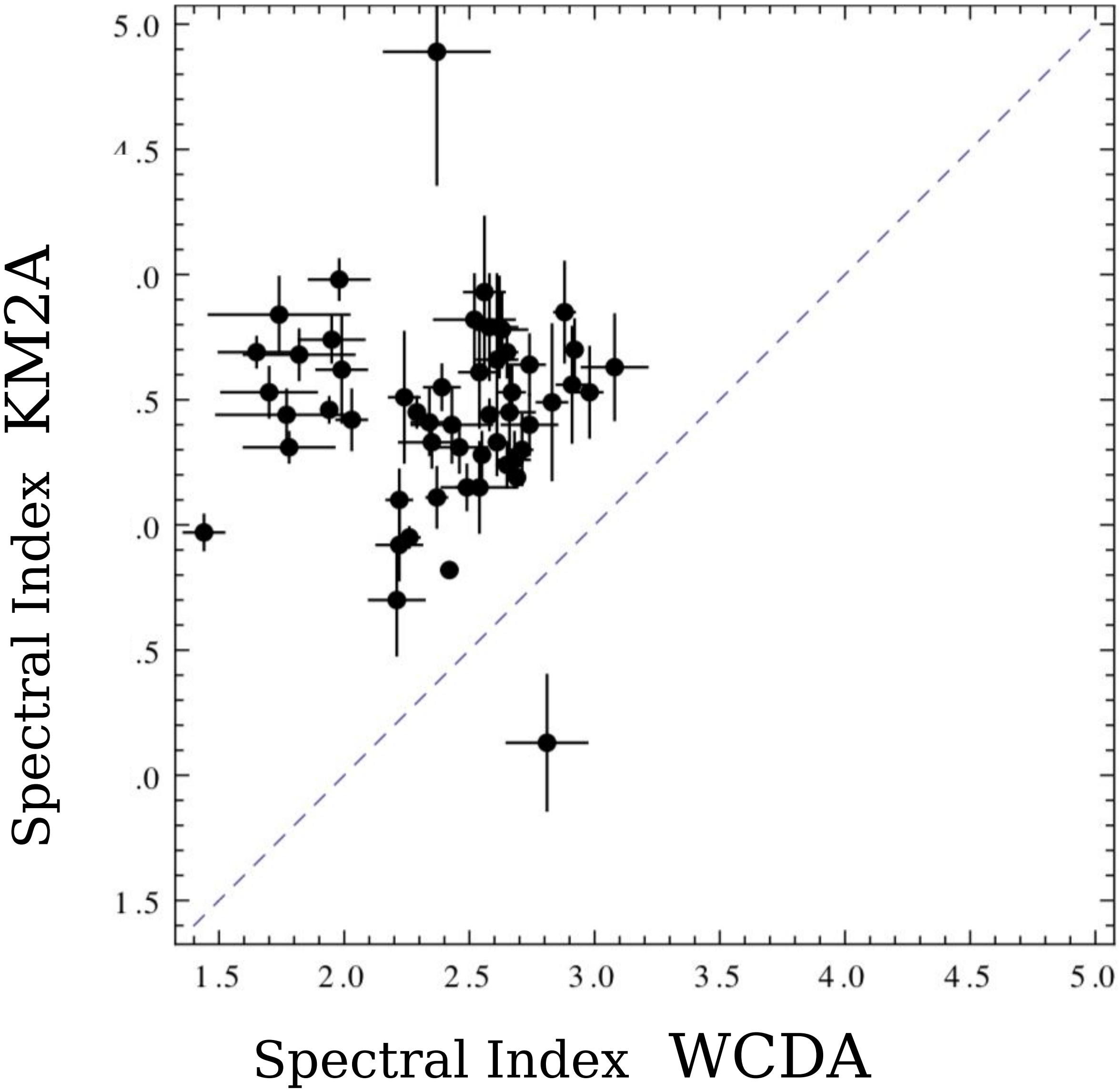
54 sources are measured by both
[WCDA + KM2A] instruments
Spectrum measured in a very broad range

Spectral indices of sources in the LHAASO catalog

Sources are significantly softer at higher energy



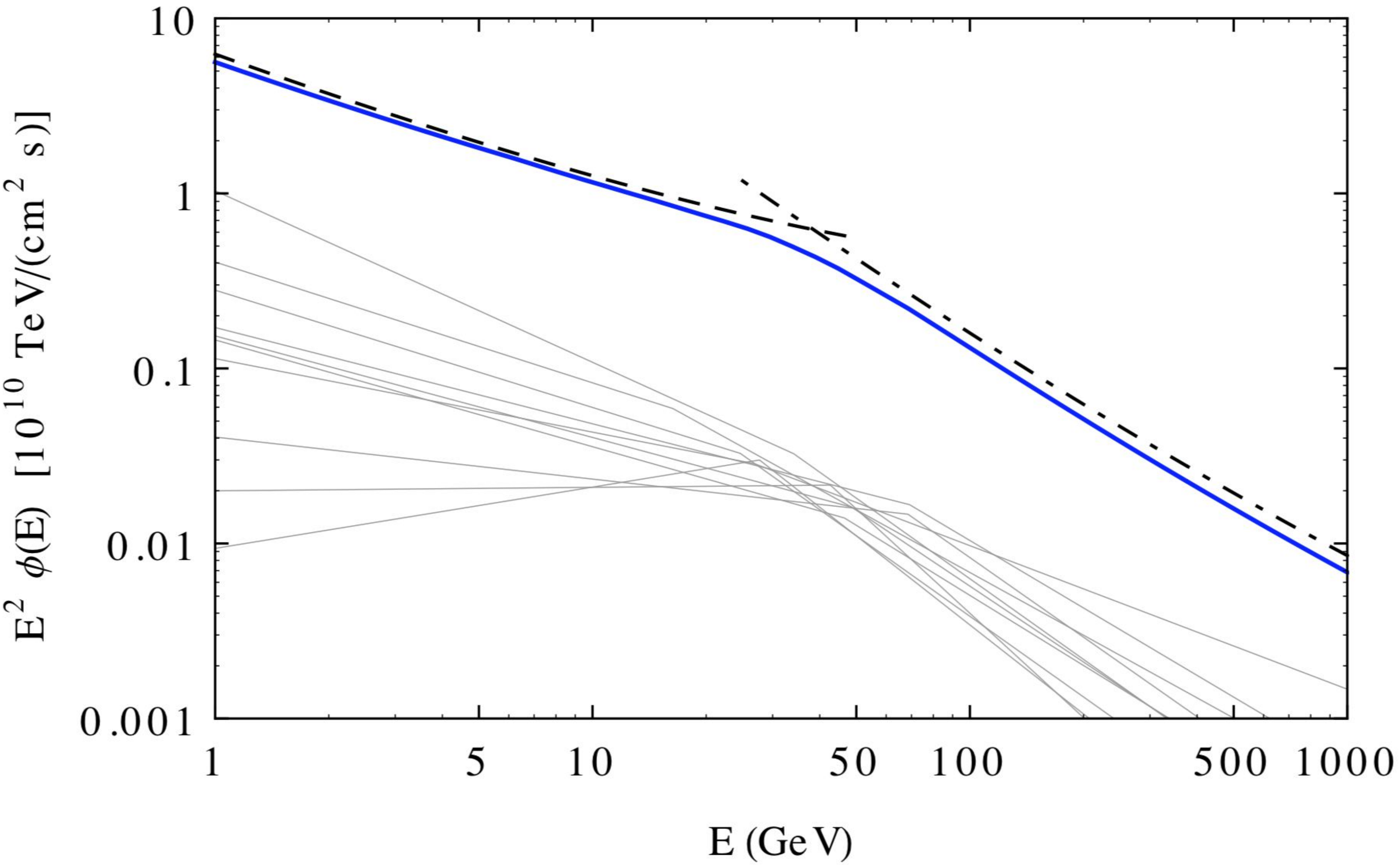
54 LHAASO sources observed by both [WCDA + KM2A]



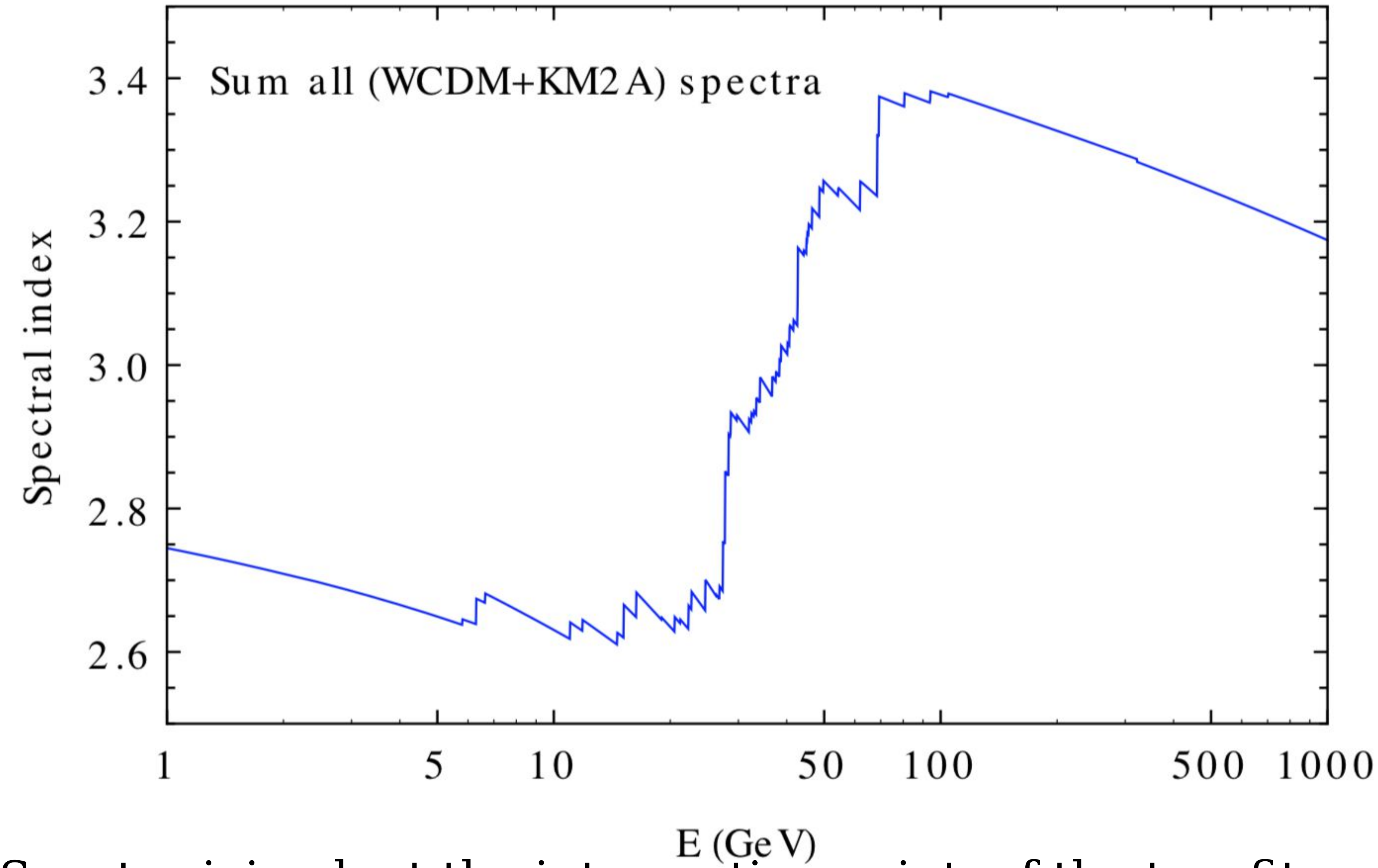
For all sources
[minus 1]

the spectrum
softens at
higher energy

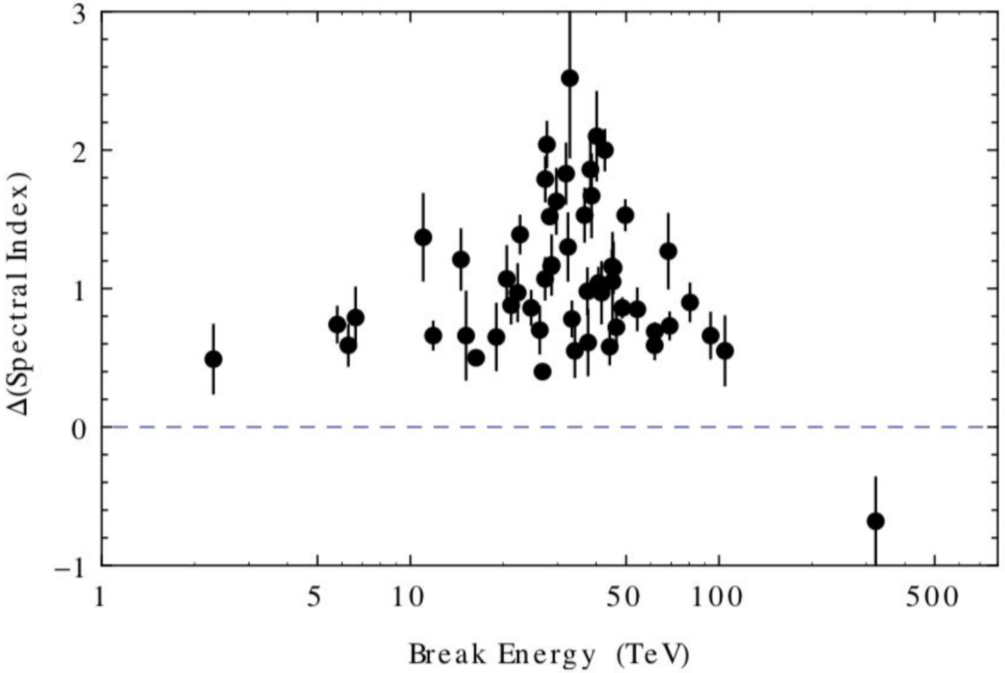
LHAASO catalog sources

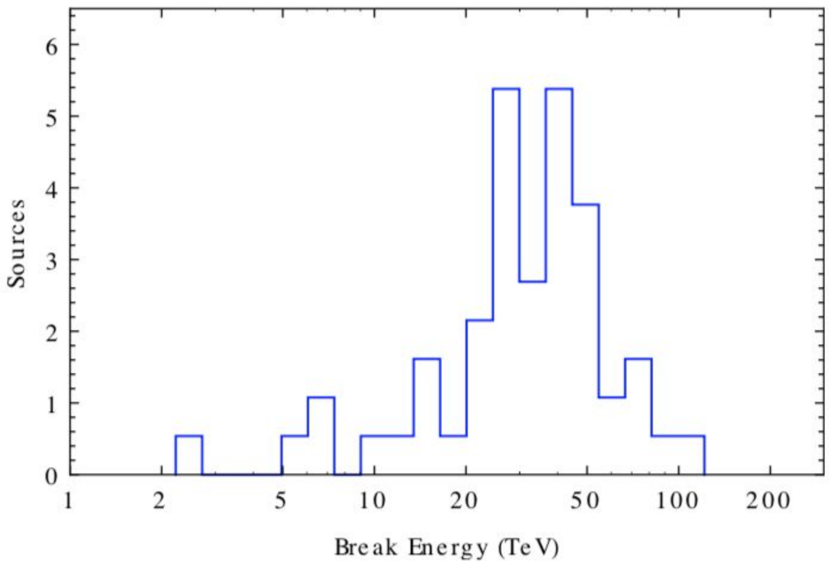


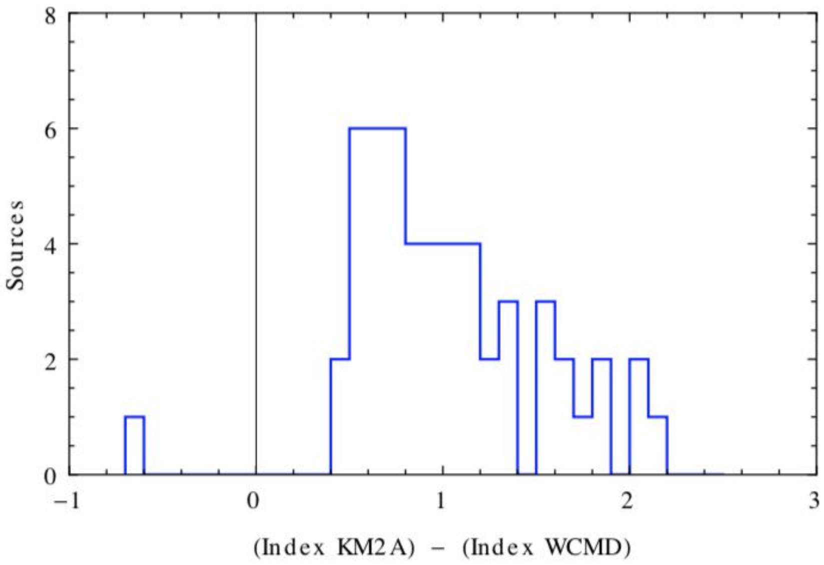
Spectral Index for the 54 LHAASO sources observed by both WCDA and KM2A



Spectra joined at the intersection point of the two fits

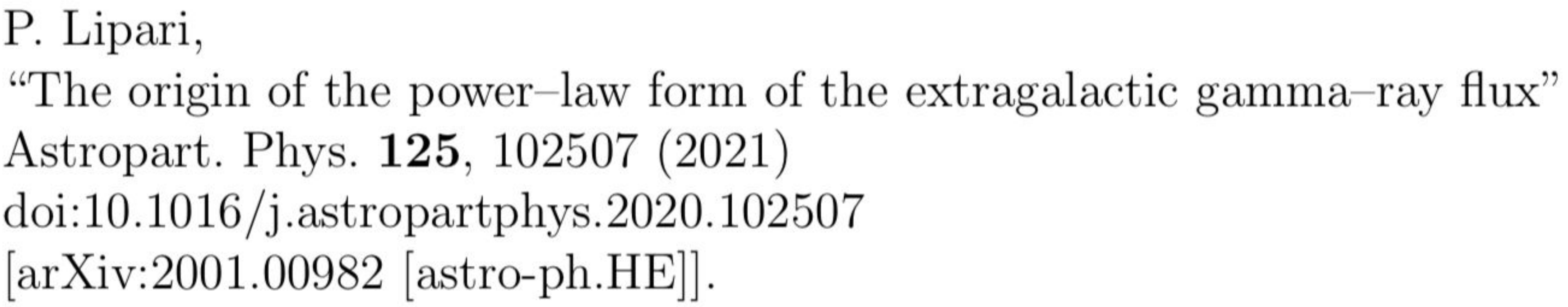

Δ(Spectral Index)
3
2
1
0
−1
1
5
10
50
100
500
Break Energy (TeV)


Sources
6
5
4
3
2
1
0
1
2
5
10
20
50
100
200
Break Energy (TeV)


Sources
8
6
4
2
0
−1
0
1
2
3
(Index KM2A) − (Index WCMD)

It is remarkable that a “cumulative spectrum”
that is in good approximation has the form of
a smooth power-law emerges from
the combination of components that have different form.

Similar result can be seen forr extragalactic sources



P. Lipari,
“The origin of the power–law form of the extragalactic gamma–ray flux”
Astropart. Phys. **125**, 102507 (2021)
doi:10.1016/j.astropartphys.2020.102507
[arXiv:2001.00982 [astro-ph.HE]].

This suggests that perhaps also the spectrum of
cosmic rays at the Earth emerges as the result of
the sum of different components, and has
potentially deep implications
for the understanding of particle acceleration

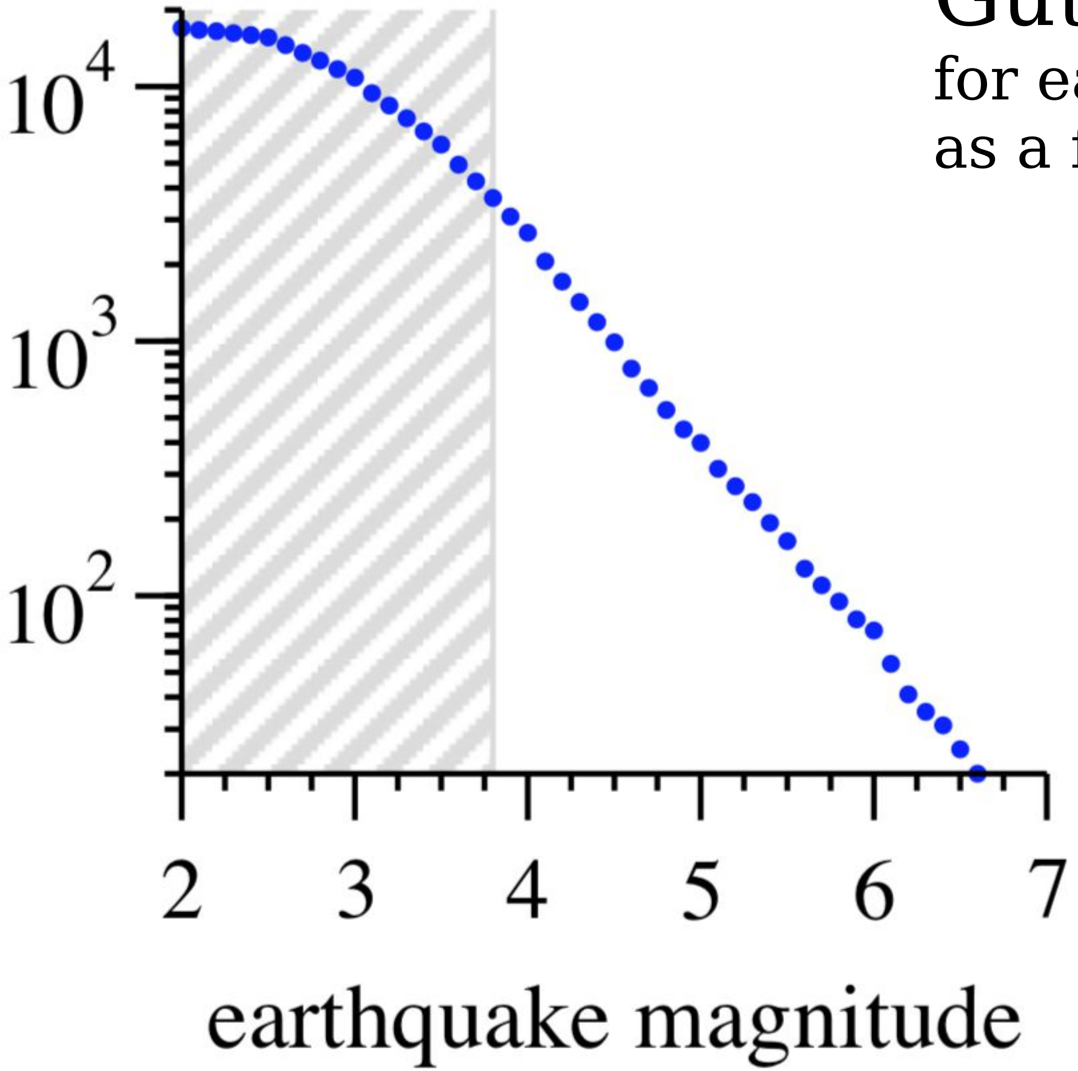
Power-law distributions

appear widely in a very broad range of fields:
physics, biology, earth and planetary science
economics and finances, social sciences,
.....

The origin of power-law behavior has been a topic of debate for more than a century

Gutenberg-Richter law

for earthquake frequency
as a function of magnitude



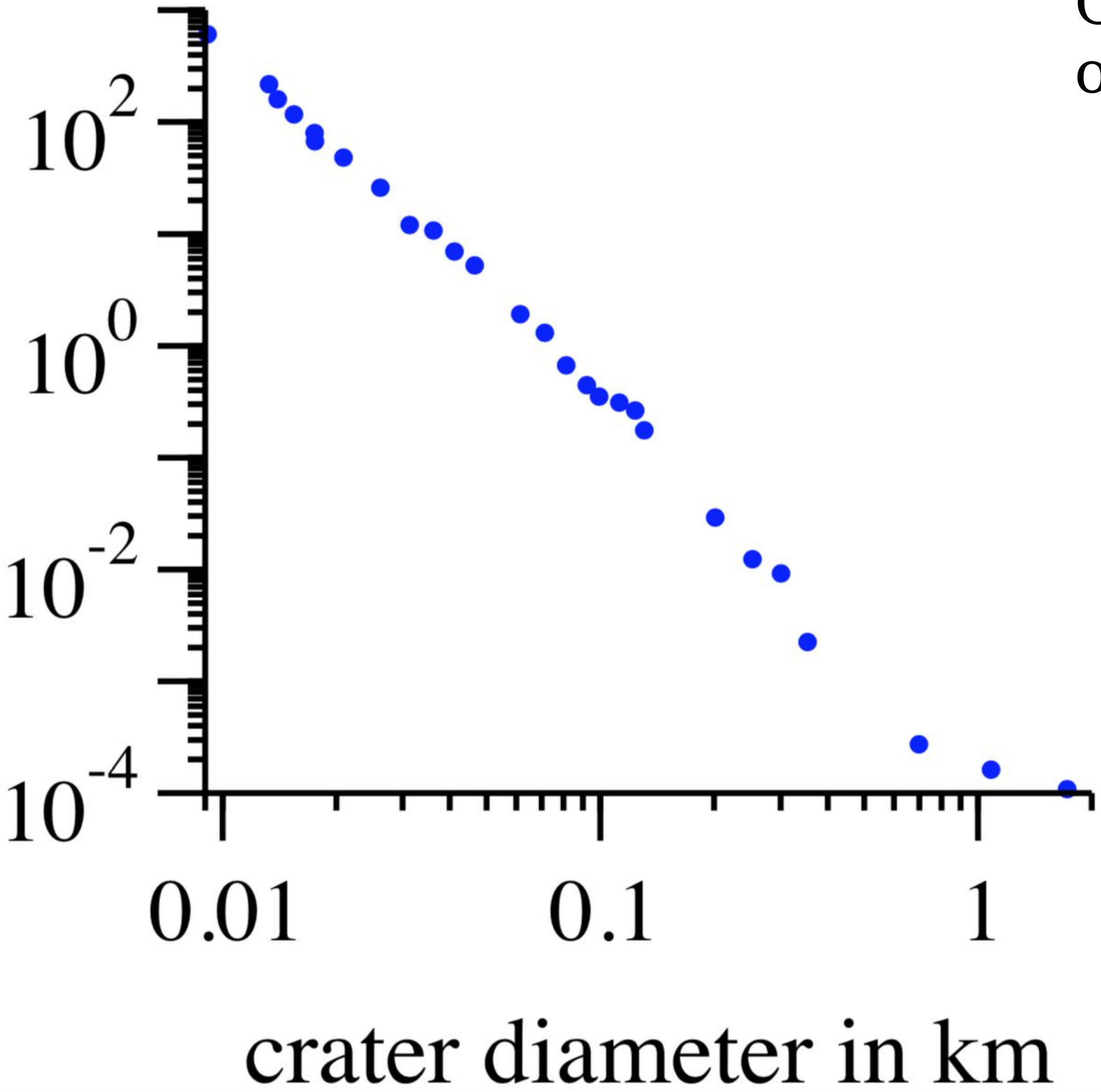
$$\log_{10} N = a - b\, m$$

$$dN/d\mathcal{E} \propto \mathcal{E}^{-(b+1)}$$

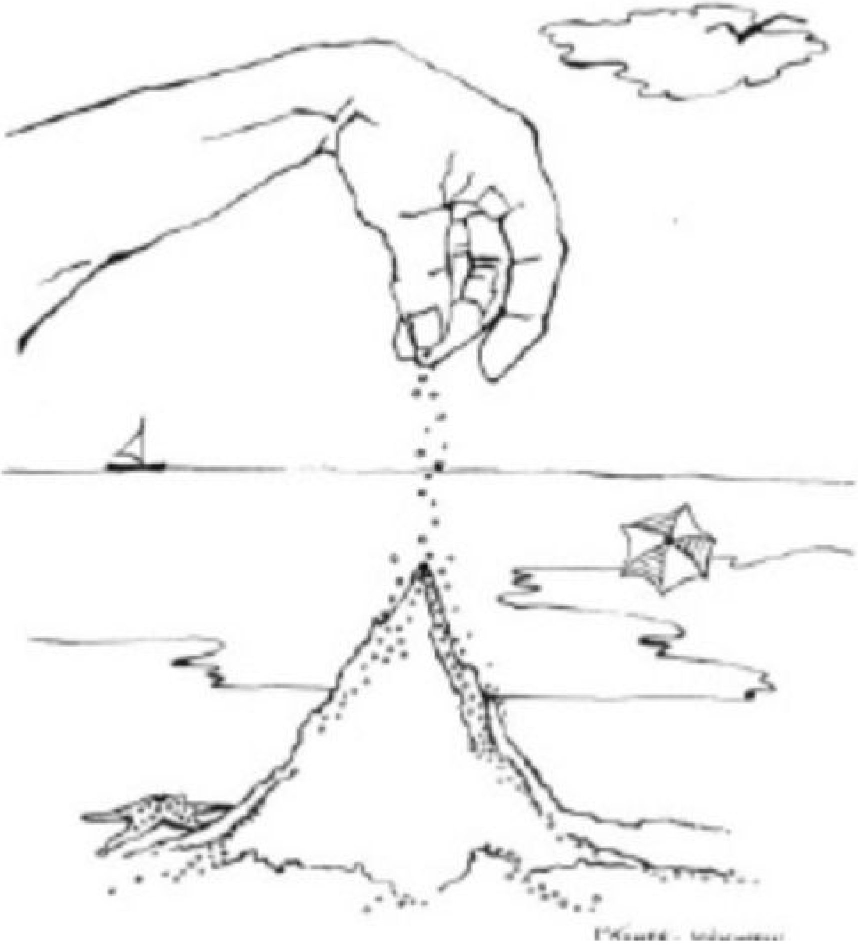
Earthquakes in California
1910-1992

M.E.J. Newman
“Power–laws, Pareto distributions and Zipf’s law”
Contemporary Physics **46**, 323 (2005)
arXiv:cond-mat/0412004 [cond-mat.stat-mech]

Cumulative distributions of Moon craters



Concept of “Self Organized Criticality”

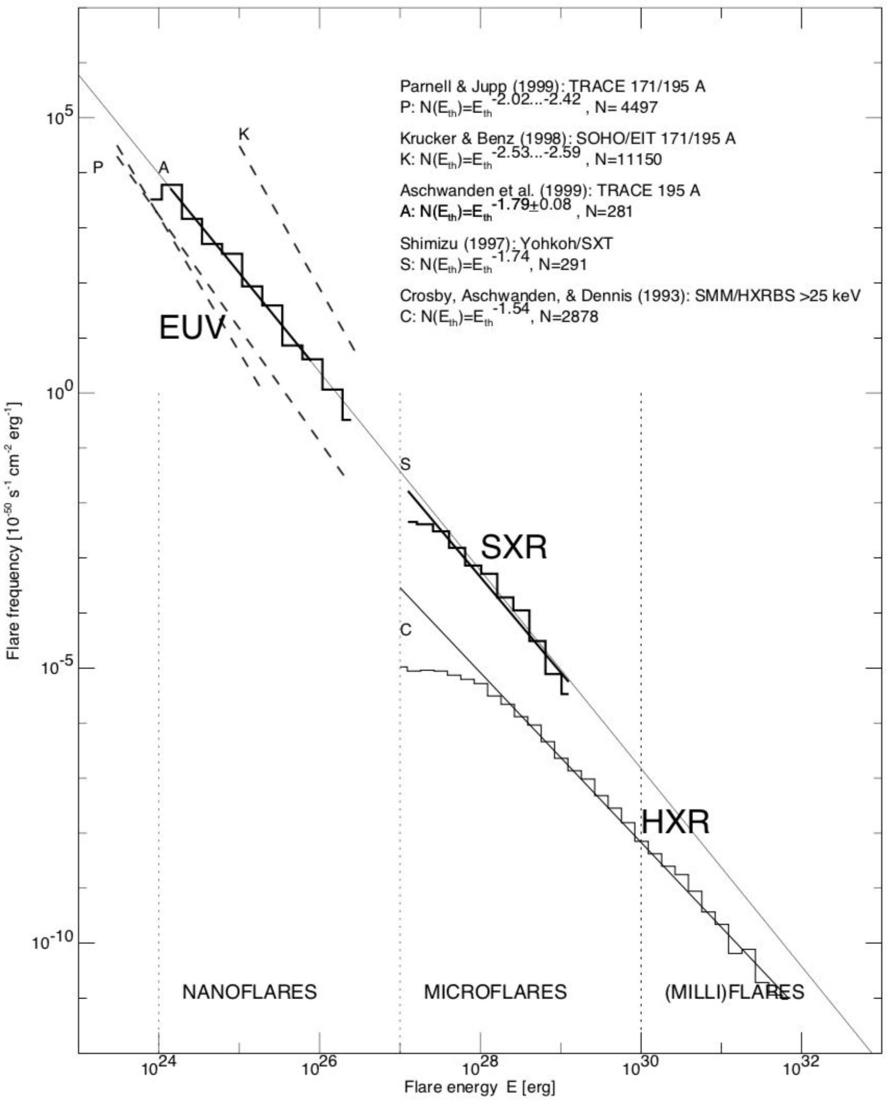


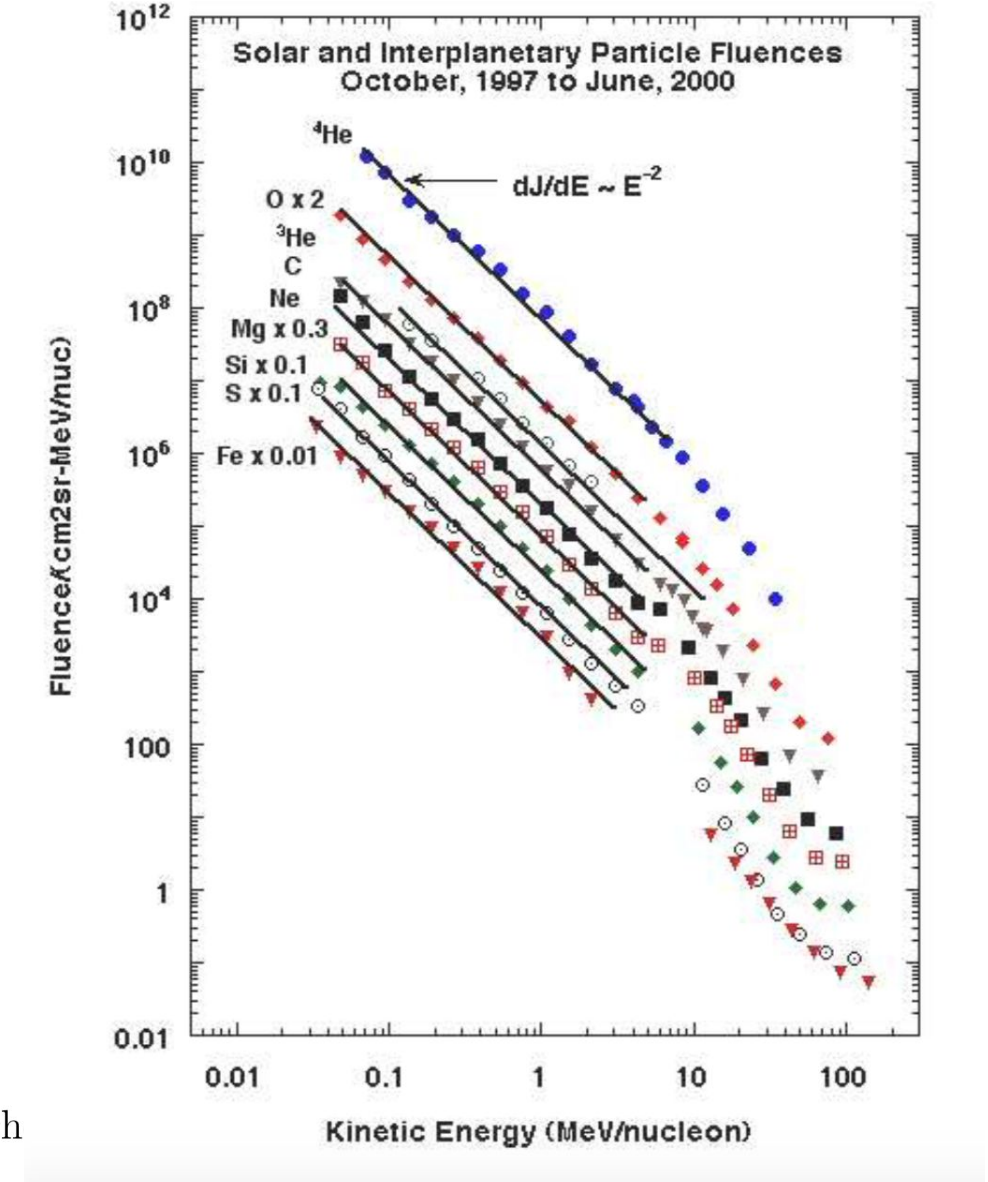
“Sand Pile”
model

P. Bak, C. Tang and K. Wiesenfeld,
“Self-organized criticality: An Explanation of 1/f noise”
Phys. Rev. Lett. **59**, 381 (1987).

P. Bak, C. Tang and K. Wiesenfeld,
“Self-organized criticality”
Phys. Rev. A **38**, 364 (1988).

Distribution of energy of solar flares





R.A. Mewaldt *et al.*
“Long-Term Fluences of Energetic Particles in the Heliosph
27th ICRC Hamburg, (2001).

Estimate of the

Unresolved Source Flux

$$\frac{dN_s}{d^3x\,dL\,dR}$$

Distribution of sources in the Milky Way

Number of sources as function of:

Position in space $\vec{x}$

Luminosity $L[E_{\min}, E_{\max}]$

Morphology (Linear size) R

Flux from one source $[E_{\min}, E_{\max}]$

$$\phi = \frac{L}{4\pi \langle E \rangle} \frac{1}{|\vec{x} - \vec{x}_\odot|^2}$$

Flux from the ensemble of all sources

$$\phi_{\text{sources}}(\Delta\Omega) = \int_{\Delta\Omega} d^3x \int dR \int dL \; L \; \frac{dN_s}{dL\, dR\, d^3x} \frac{1}{|\vec{x} - \vec{x}_\odot|^2}$$

integration in the space volume inside solid angle $\Delta\Omega$

$$\phi^{\text{unresolved}}_{\text{sources}}(\Delta\Omega) = \int_{\Delta\Omega} d^3x \int dR \int dL\ L\ \frac{dN_s}{dL\,dR\,d^3x}\ \frac{1}{|\vec{x} - \vec{x}_\odot|^2} \times$$

include cut to
select faint sources

$$\times\ \Theta[\phi < \phi^{\text{telescope}}_{\text{min}}(\Omega, L, R)]$$

Calculation of the unresolved flux
requires:

[1] Knowledge of the telescope sensitivity

[2] Good model for the Galactic sources distribuution

Factorization hypothesis:

Space, Luminosity, Morphology distributions

$$\frac{dN_s}{d^3x\,dL\,dR} = f(\vec{x})\,g(L)\;h(R)$$

Motivation for this factorization is simplicity
[but it is very likely that
this factorization is not exact, and the violations
could be significant]

Method to estimate the unresolved flux:

[0] Assume the validity of the factorization of the source distributions.

[1] Assume constant linear size R for the sources

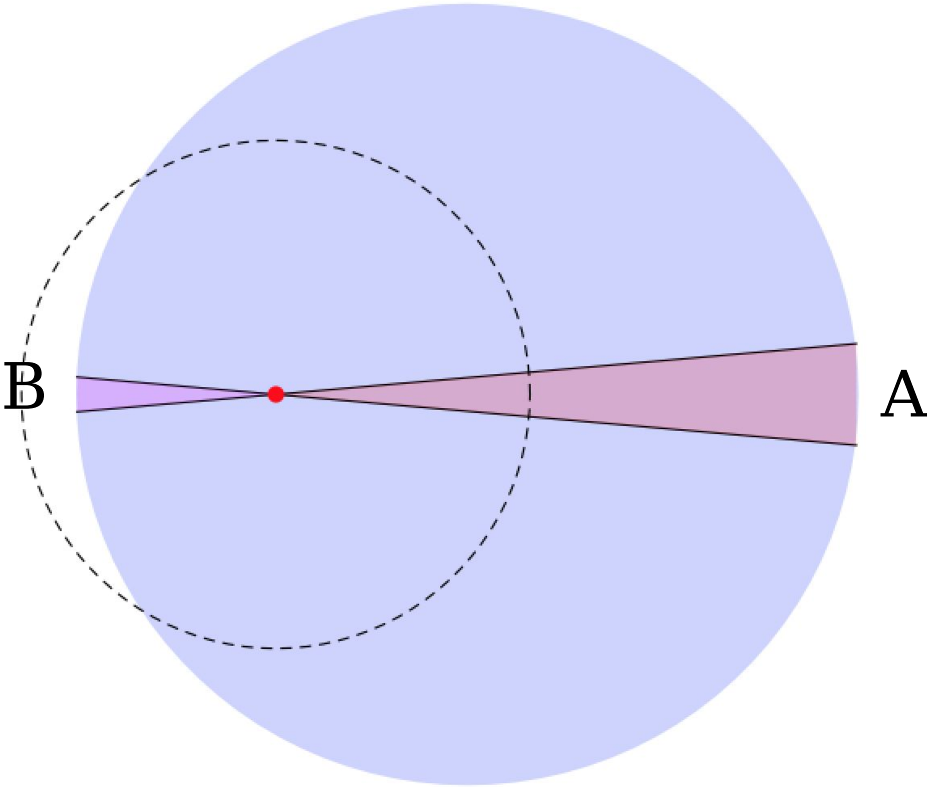
[2] Adopt a model for the space distribution of the sources
[i.e. Pulsar distribution, SNR distribution, ...]

[3] Adopt a form for the luminosity distribution that depends on few parameters.

[4.] Interpret the
Angular distribution of the Resolved Sources
to estimate the parameters of the luminosity distribution

[5] Calculate the Unresolved Source flux

Illustrate the (very simple) geometrical idea of the method:



Resolved sources in region A, B

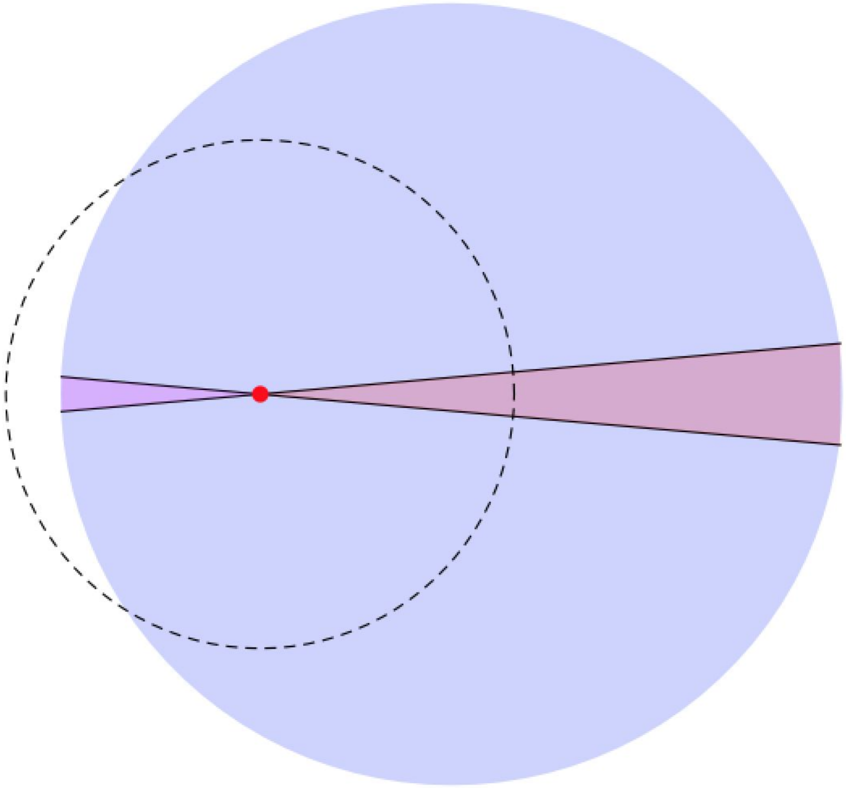
$$N_A = \rho \; \delta\Omega \; T^2$$

$$N_B = \rho \; \delta\Omega \; R_B^2$$

$$\phi_A = \frac{L}{4\pi \, \langle E \rangle} \, \rho \; \delta\Omega \; \ln R_A$$

$$\phi_A^{\rm resolved} = \frac{L}{4\pi \, \langle E \rangle} \, \rho \; \delta\Omega \; \ln T$$

Galaxy is a thin homogeneous disk
Solar system displaced with respect to the center.
Identical point like sources of luminosity L
Horizon T



$$N_A = \rho \; \delta\Omega \; T^2$$

$$N_B = \rho \; \delta\Omega \; R_B^2$$

$$\phi_A = \frac{L}{4\pi \left\langle E \right\rangle} \rho \; \delta\Omega \;\; \ln R_A$$

$$\phi_A^{\rm resolved} = \frac{L}{4\pi \left\langle E \right\rangle} \rho \; \delta\Omega \;\; \ln T$$

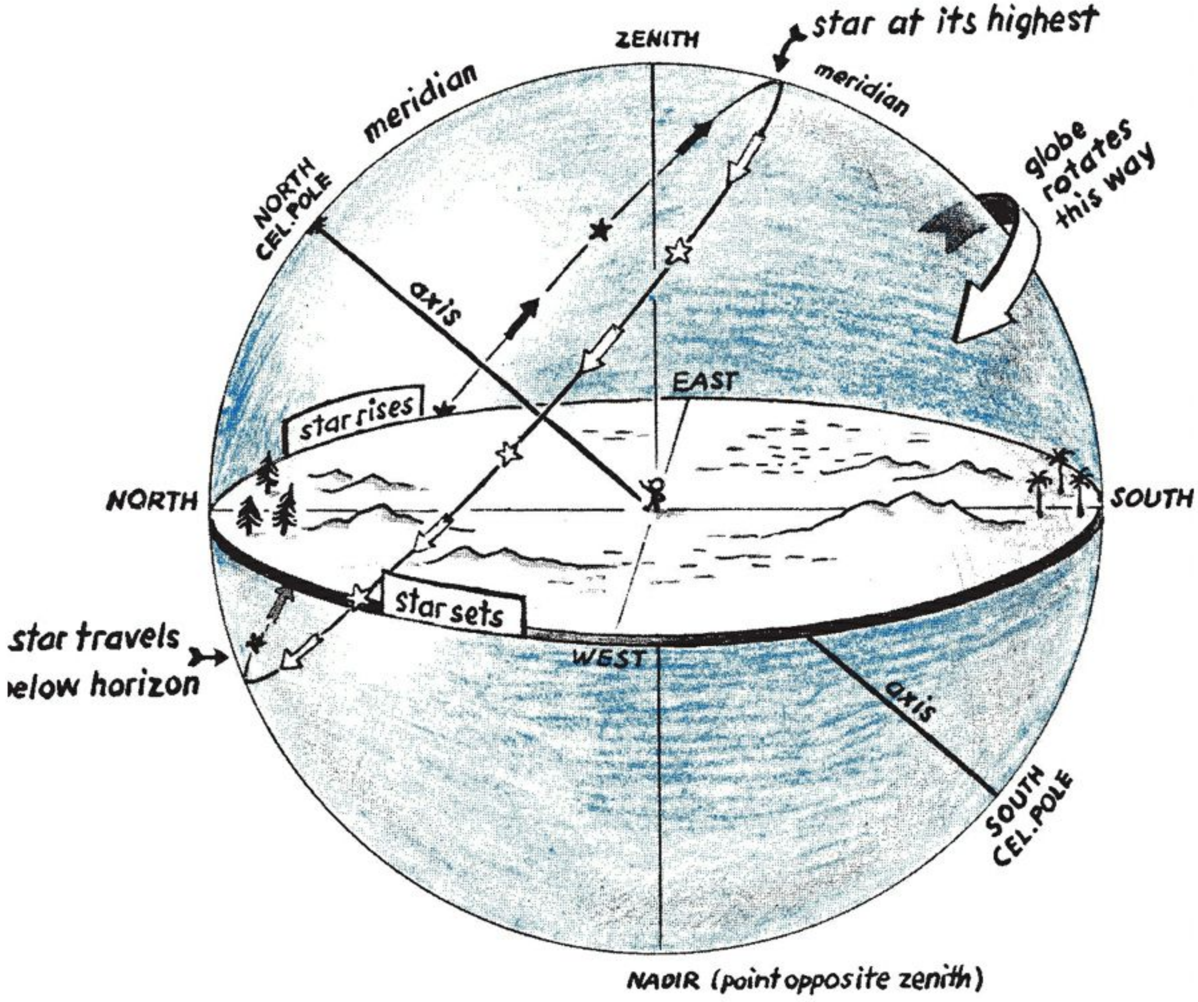
$$\frac{N_A}{N_B} \Rightarrow T \Rightarrow \frac{\phi_A^{\rm resol.}}{\phi_A}$$

$$T \Rightarrow L \Rightarrow L_{\rm tot}$$

Sensitivity of Extensive Air Shower gamma-ray Telescopes

Sensitivity determined by the celestial declination

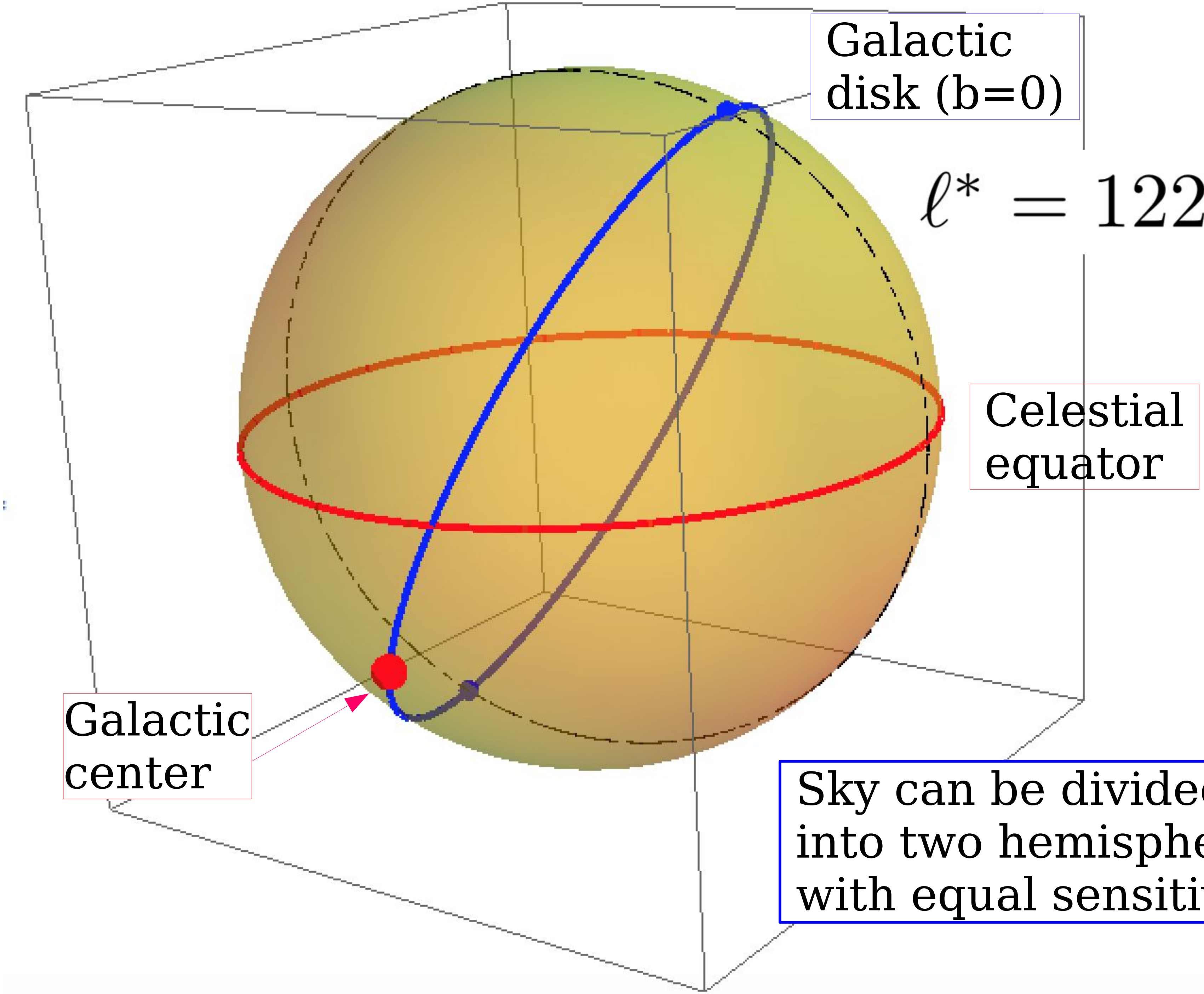
$$\delta \in [\delta_{\min}, \delta_{\max}]$$



λ Telescope geographical latitude

$\delta = \lambda$ source trajectory at zenith

$$\delta_{\min} = \mathrm{Max}[\lambda - \theta_{\max}, -90^\circ]$$
$$\delta_{\max} = \mathrm{Min}[\lambda + \theta_{\max}, +90^\circ]$$



Galactic disk (b=0)

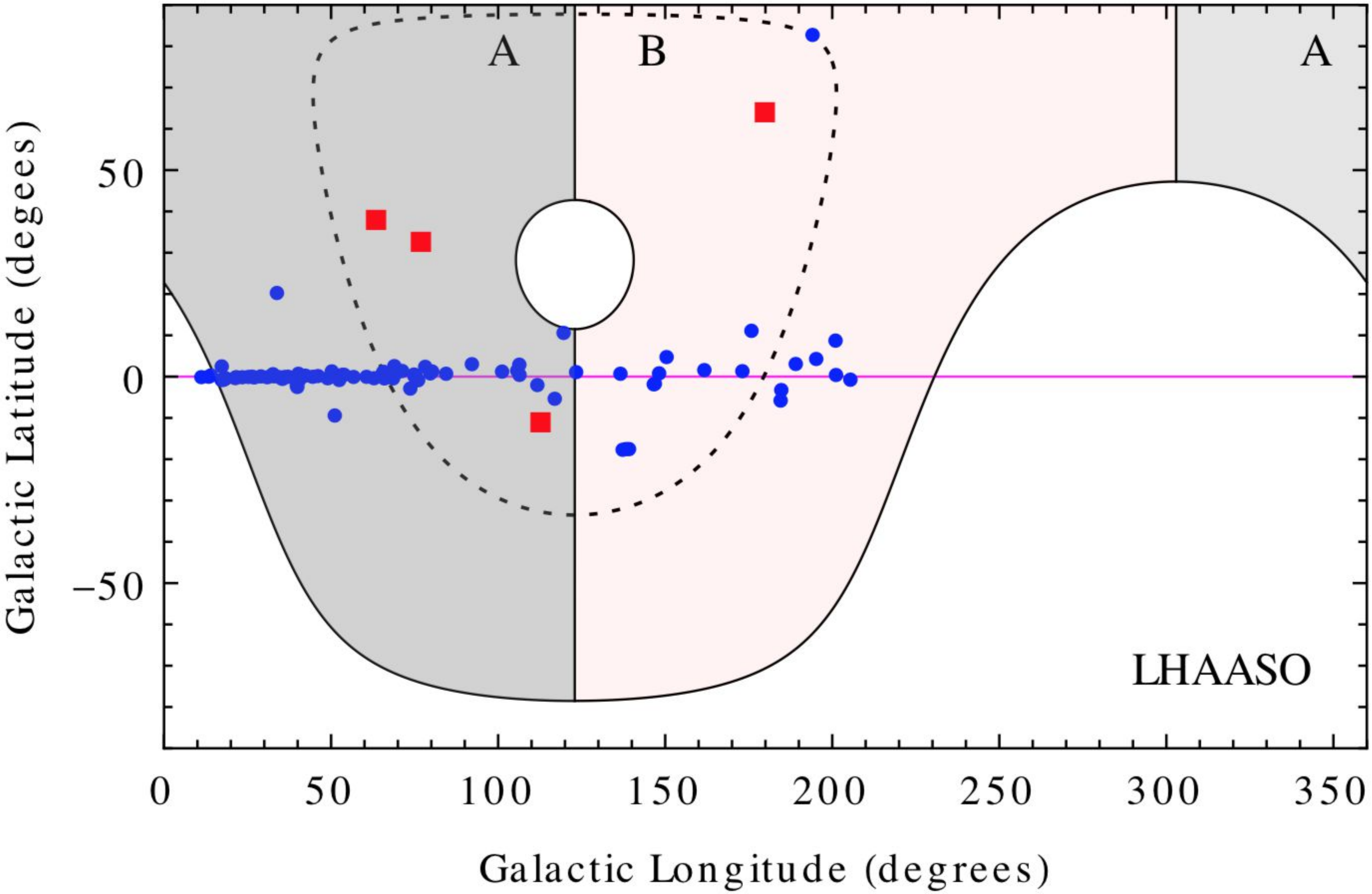
$$\ell^* = 122.9^\circ$$

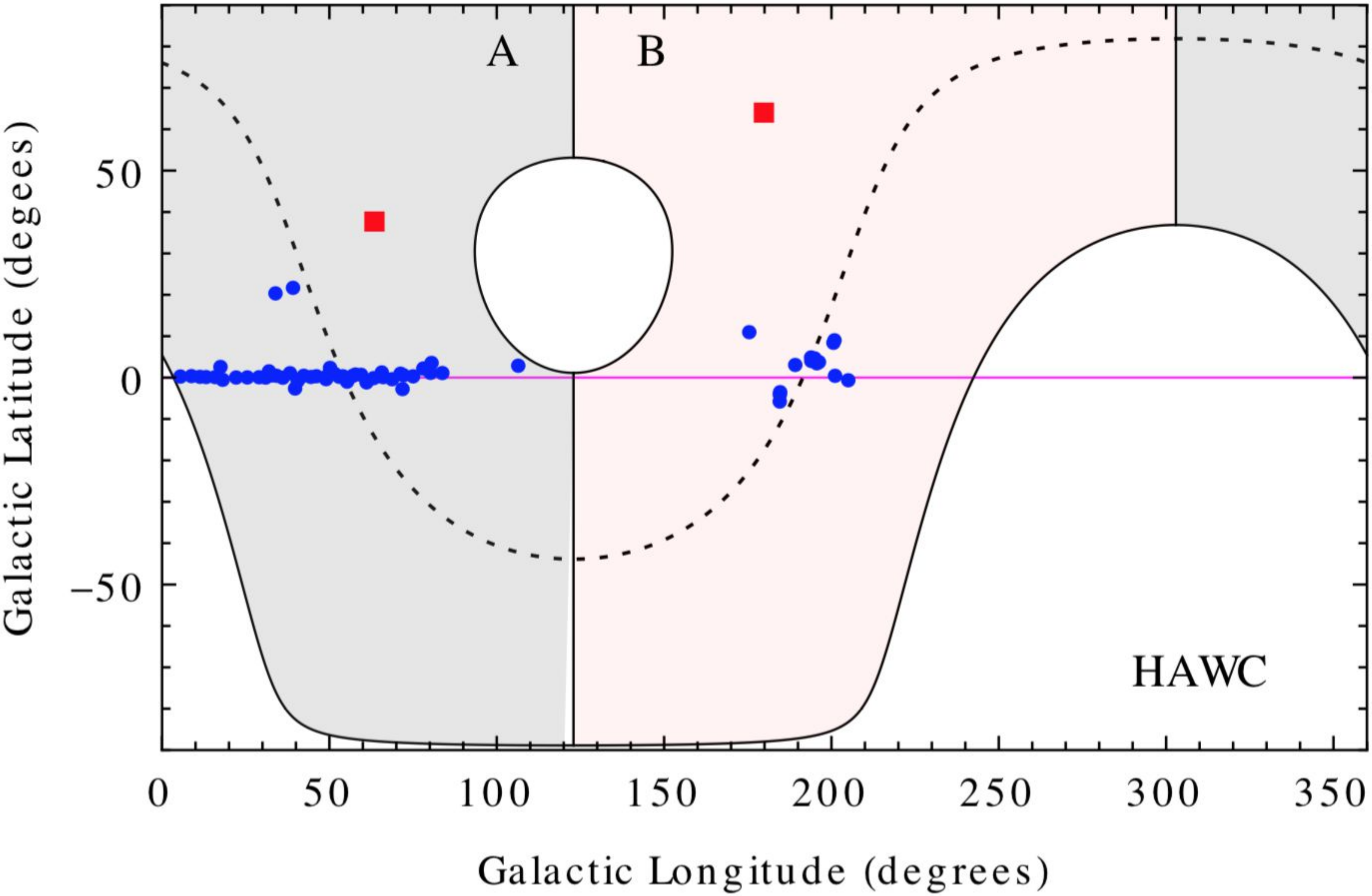
Celestial equator

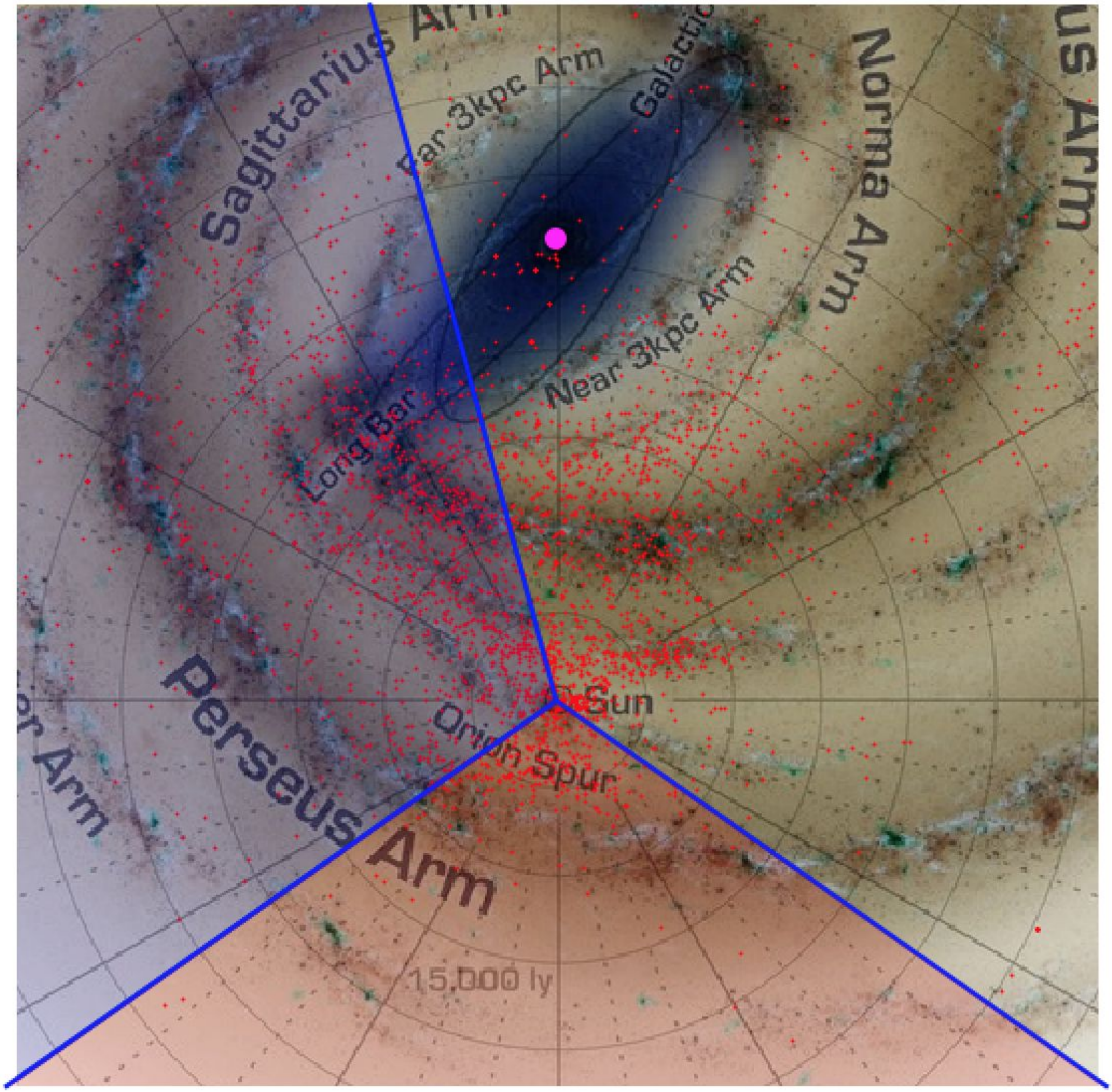
Galactic center

Sky can be divided into two hemisphere with equal sensitivity

LHAASO 1st catalog

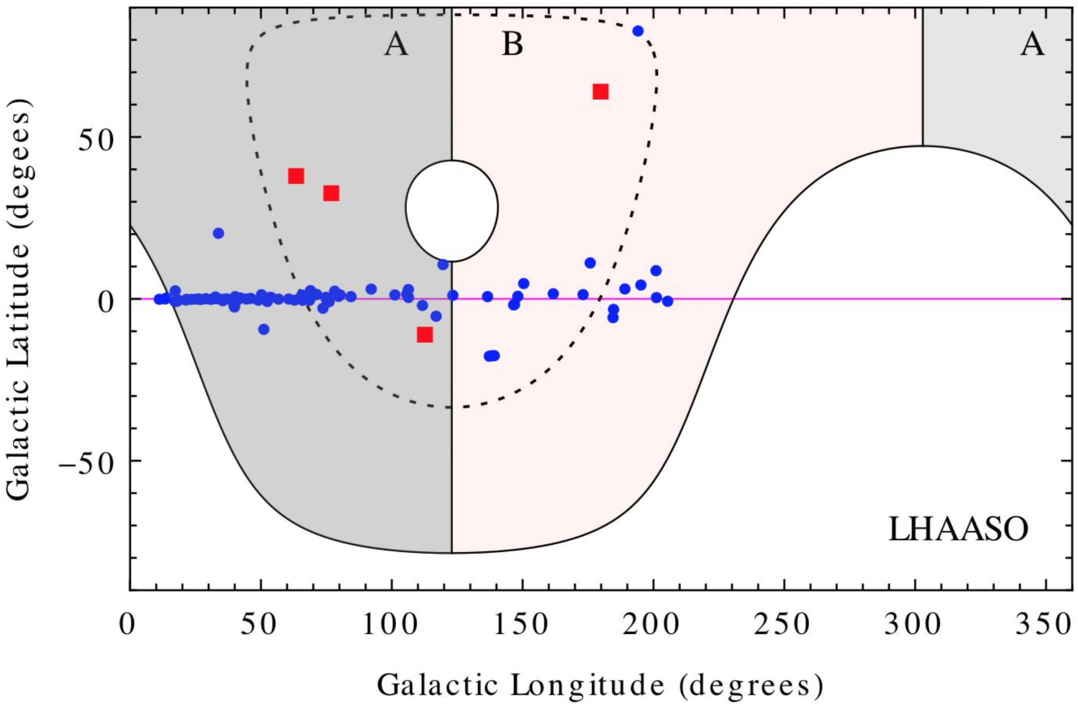



A
B
HAWC
Galactic Latitude (degees)
50
0
−50
Galactic Longitude (degrees)
0
50
100
150
200
250
300
350

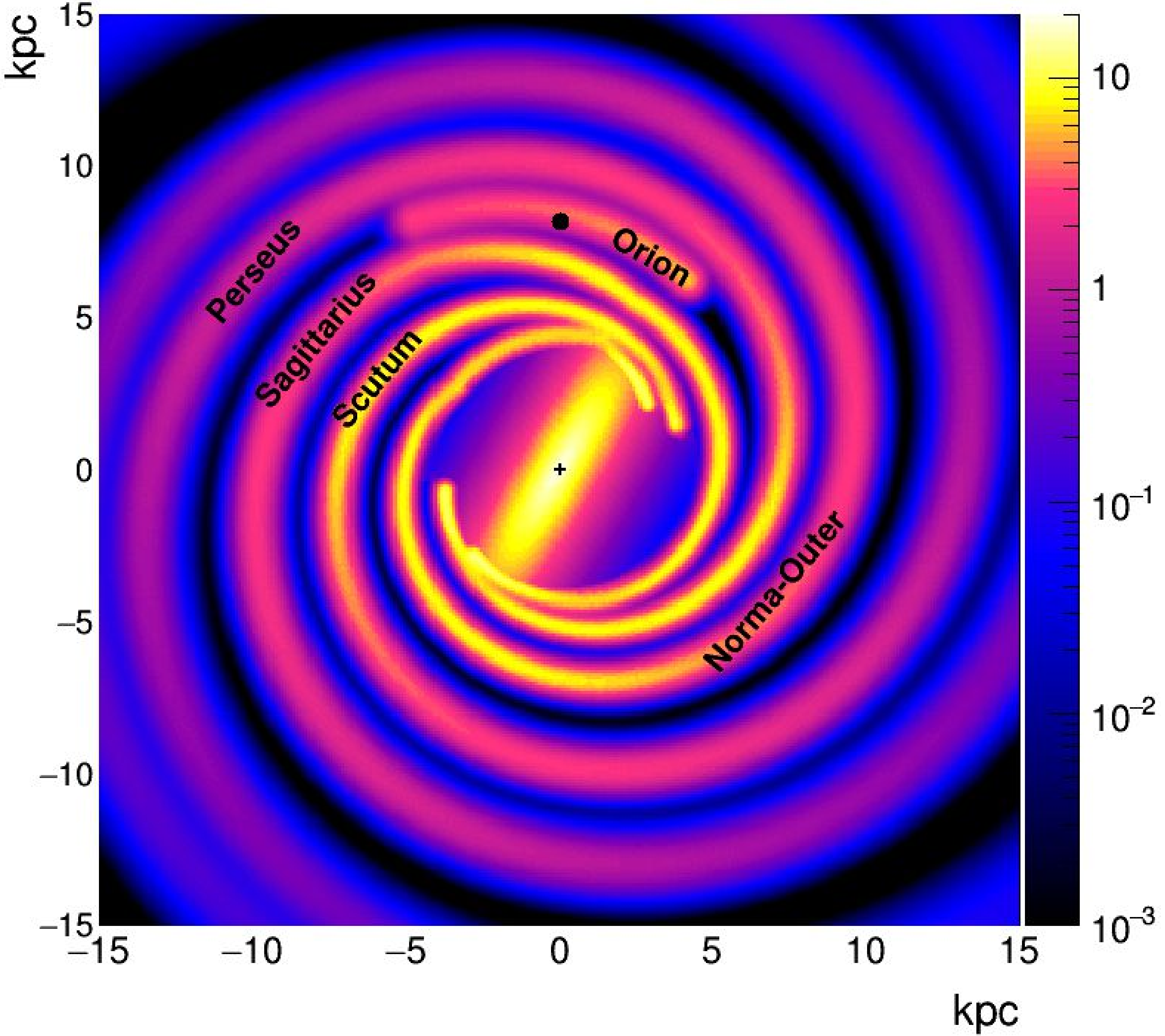

Sagittarius Arm
Far 3kpc Arm
Galactic
Norma Arm
us Arm
Near 3kpc Arm
Long Bar
Sun
Perseus Arm
Orion Spur
or Arm
15,000 ly

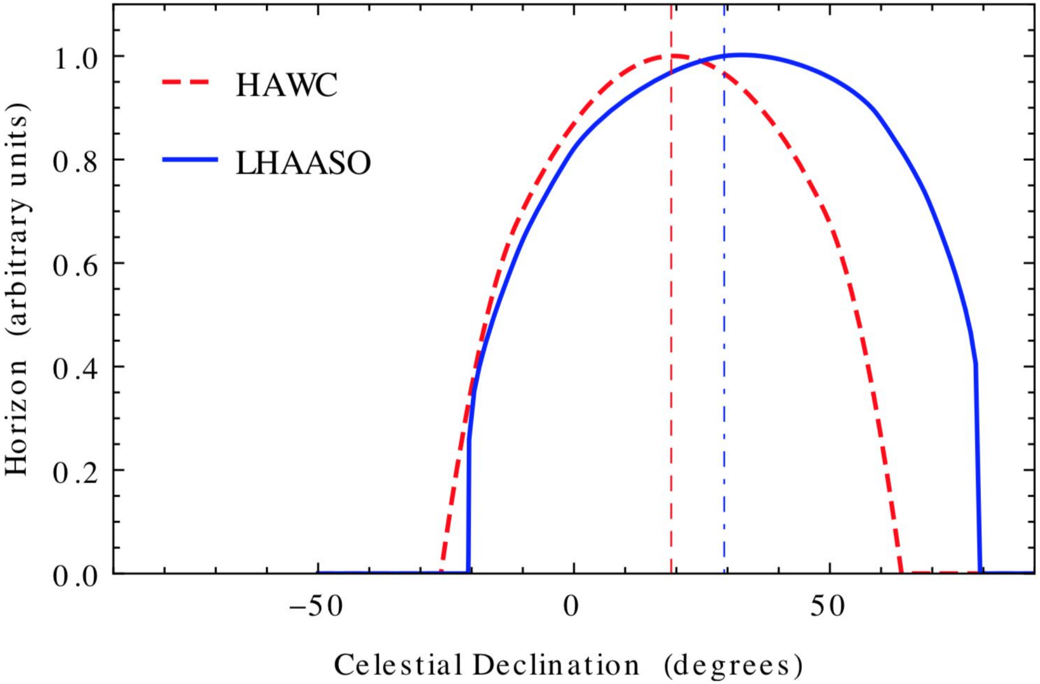
	All longitudes			
Telescope	N	N_A	N_B	N_A/N_B
HAWC	63	49	14	3.5 ± 1.1
LHAASO	86	66	20	3.3 ± 0.84
LHAASO–WCDA	65	51	14	3.6 ± 1.1
LHAASO–KM2A	75	58	17	3.4 ± 0.94
LHAASO–High	44	36	8	4.5 ± 1.8

	All longitudes				$\lvert b\rvert \leq 3^\circ$				$\lvert b\rvert > 3^\circ$			
Telescope	N	N_A	N_B	N_A/N_B	N	N_A	N_B	N_A/N_B	N	N_A	N_B	N_A/N_B
HAWC	63	49	14	3.5 ± 1.1	48	46	2	$23. \pm 17.$	15	3	12	0.25 ± 0.16
LHAASO	86	66	20	3.3 ± 0.84	70	61	9	6.8 ± 2.4	16	5	11	0.45 ± 0.25
LHAASO–WCDA	65	51	14	3.6 ± 1.1	55	49	6	8.2 ± 3.5	10	2	8	0.25 ± 0.2
LHAASO–KM2A	75	58	17	3.4 ± 0.94	62	54	8	6.8 ± 2.6	13	4	9	0.44 ± 0.27
LHAASO–High	44	36	8	4.5 ± 1.8	34	32	2	$16. \pm 12.$	10	4	6	0.67 ± 0.43



Model of the Spiral structure of the Galaxy



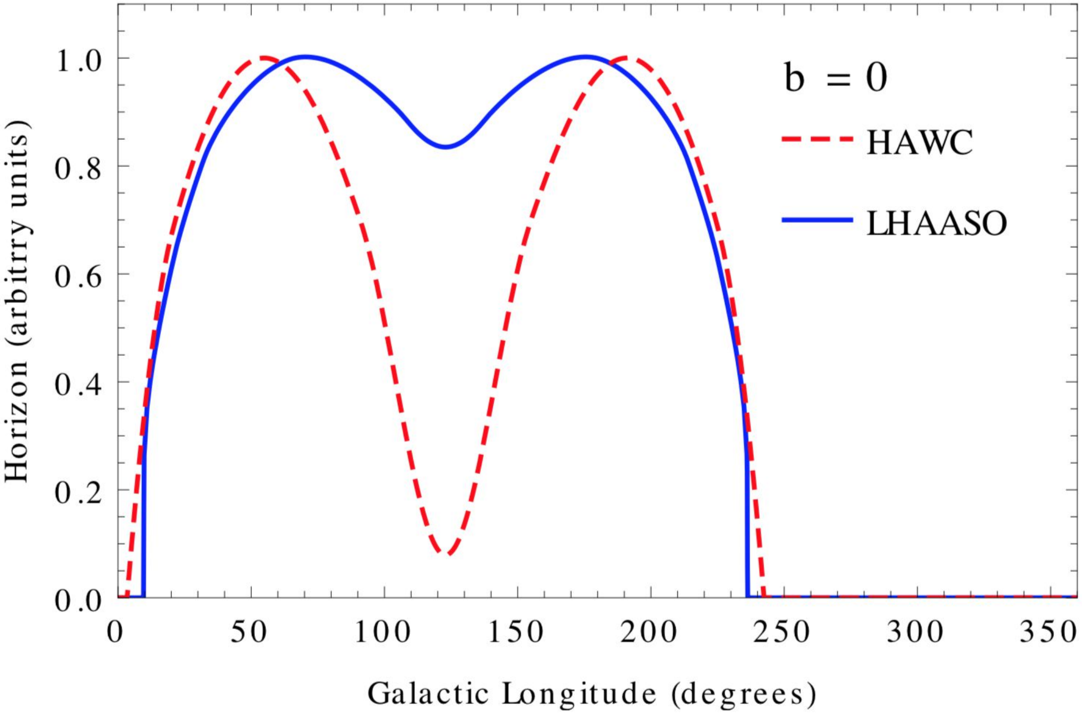


Horizon for

LHAASO and HAWC

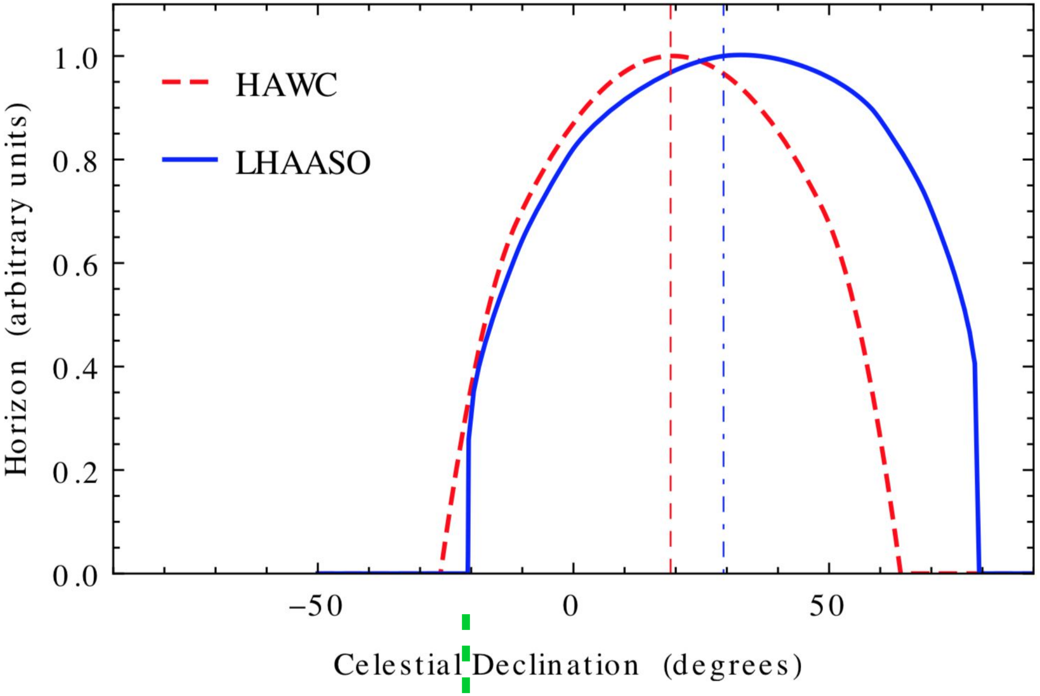
$\theta_{\max} = 50^\circ$ $\theta_{\max} = 45^\circ$

as function of
celestial declination



Horizon along the
Galactic disk
(Latitude b=0)

as a function of
Galactic longitude

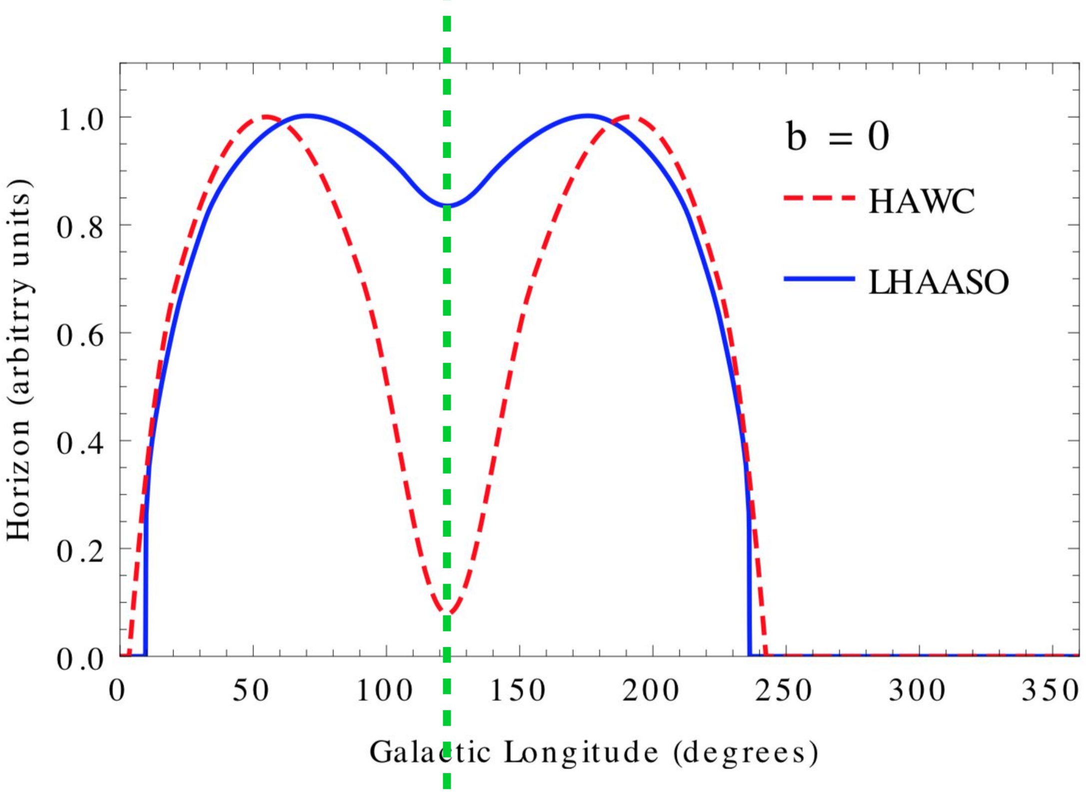


Horizon for

LHAASO and HAWC

$\theta_{\max} = 50°$ $\theta_{\max} = 45°$

as function of
celestial declination



Horizon along the
Galactic disk
(Latitude b=0)

as a function of
Galactic longitude

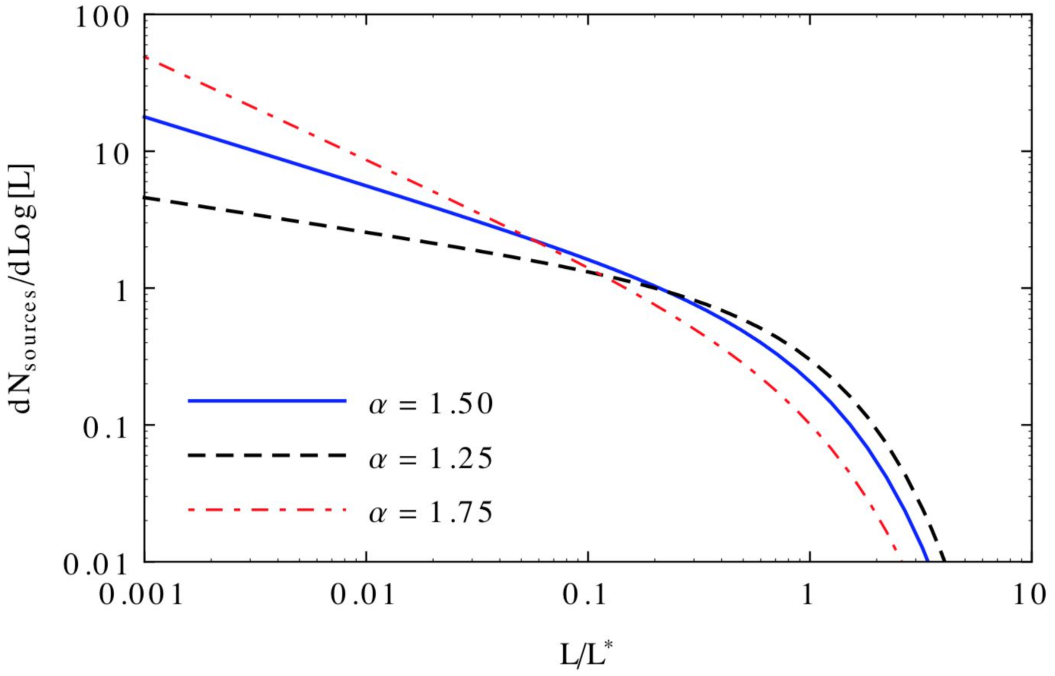
This argument can be generalized
for a more realistic luminosity distribution

Form used by several authors
Power law distribution with a
maximum luminosity cutoff
[One motivation : "fading sources"]

$$\frac{dN_s}{dL} = \frac{L_{\rm tot}}{\Gamma(2-\alpha)\,(L^*)^2} \left(\frac{L}{L^*}\right)^{-\alpha} \exp\left[-\left(\frac{L}{L^*}\right)\right]$$

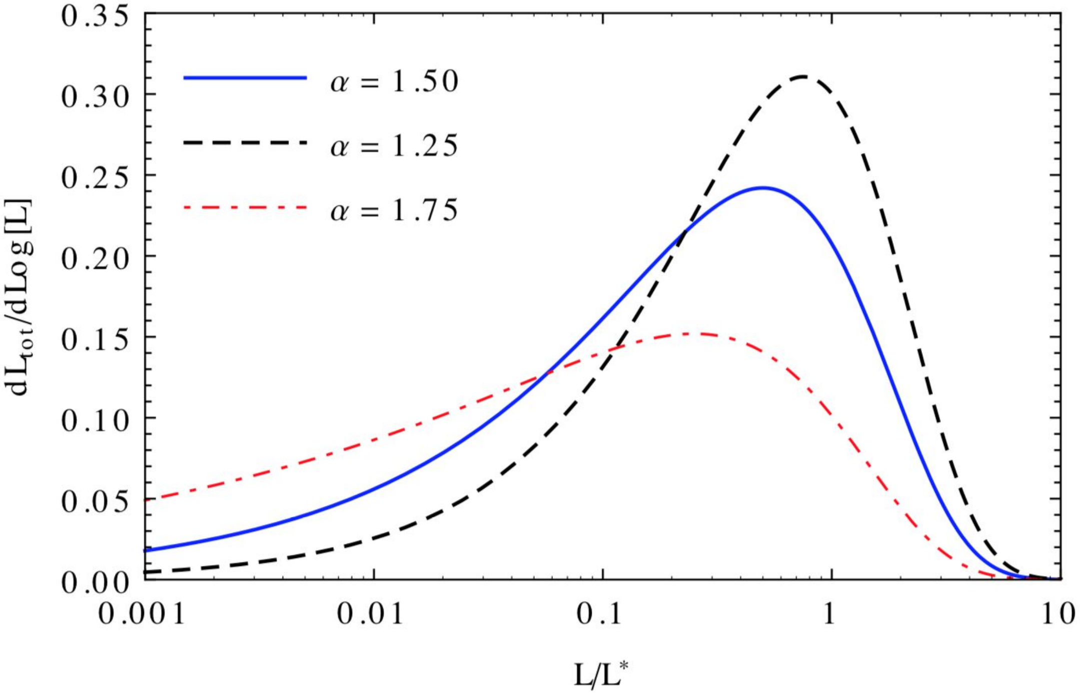
$\{L_{\rm tot},\ L^*,\ \alpha\}$ 3 parameter model

1. Milky Way luminosity $L_{\rm tot}$
2. Characteristic luminosity L^*
3. Exponent α



Number of faint sources diverges for

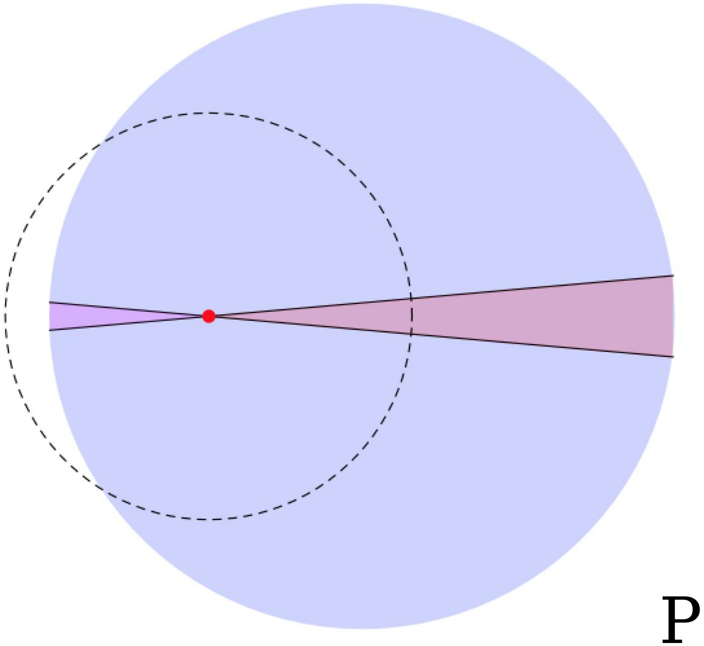
$$L \to 0$$



Total luminosity (total flux) remain finite for

$$\alpha < 2$$

Important result for a power law luminosity distribution;



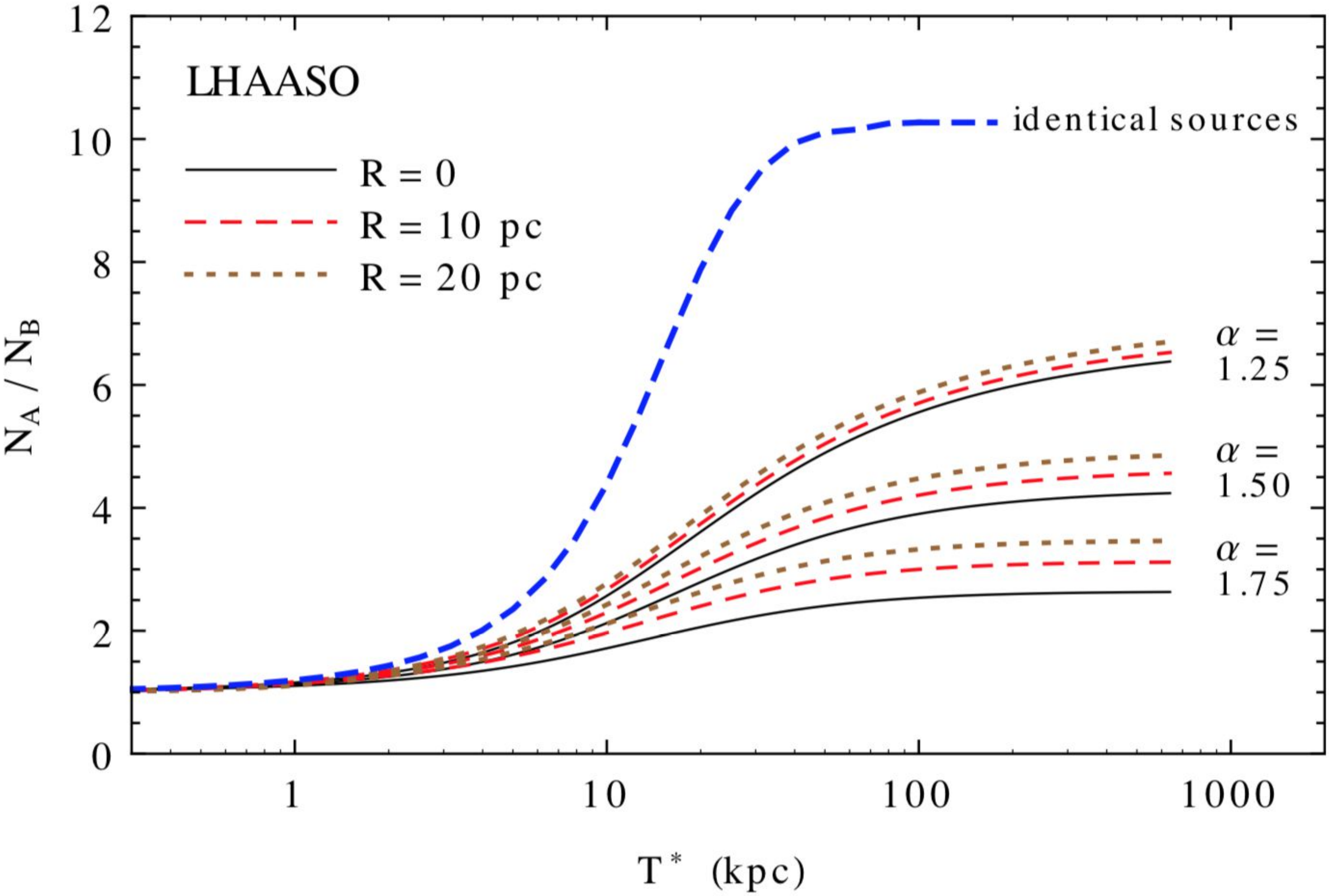
Identical sources

$$1 \le \frac{N_A}{N_B} \le \frac{R_A^2}{R_B^2} = \frac{N_A^{\rm tot}}{N_B^{\rm tot}}$$

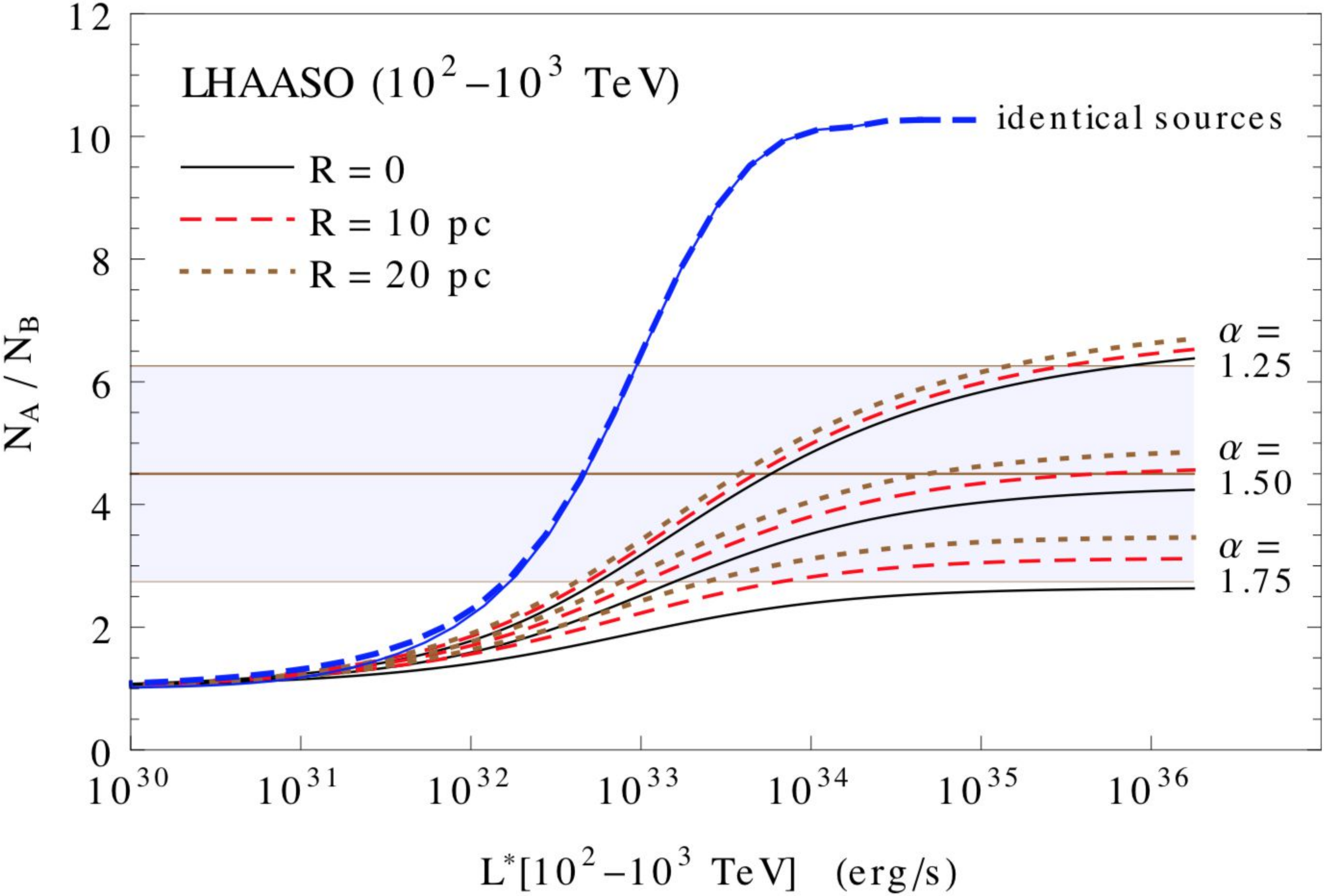
Power Law luminosity distribution
(low luminosity cutoff negligible)

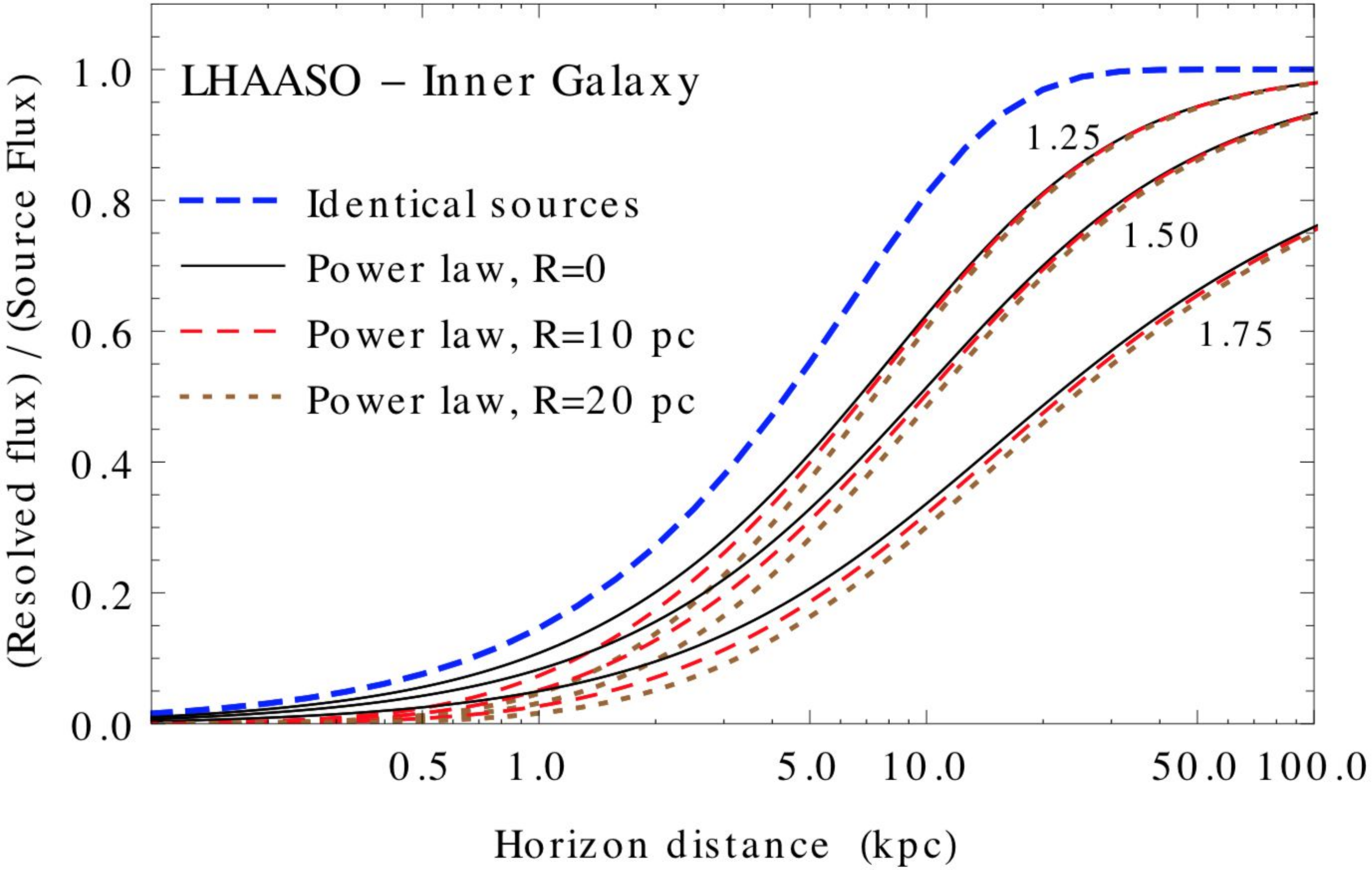
Effect of increase
in number of near
intrinsically faint sources

$$1 \le \frac{N_A}{N_B} \le \left(\frac{N_A^{\rm tot}}{N_B^{\rm tot}} \right)^{2-\alpha}$$

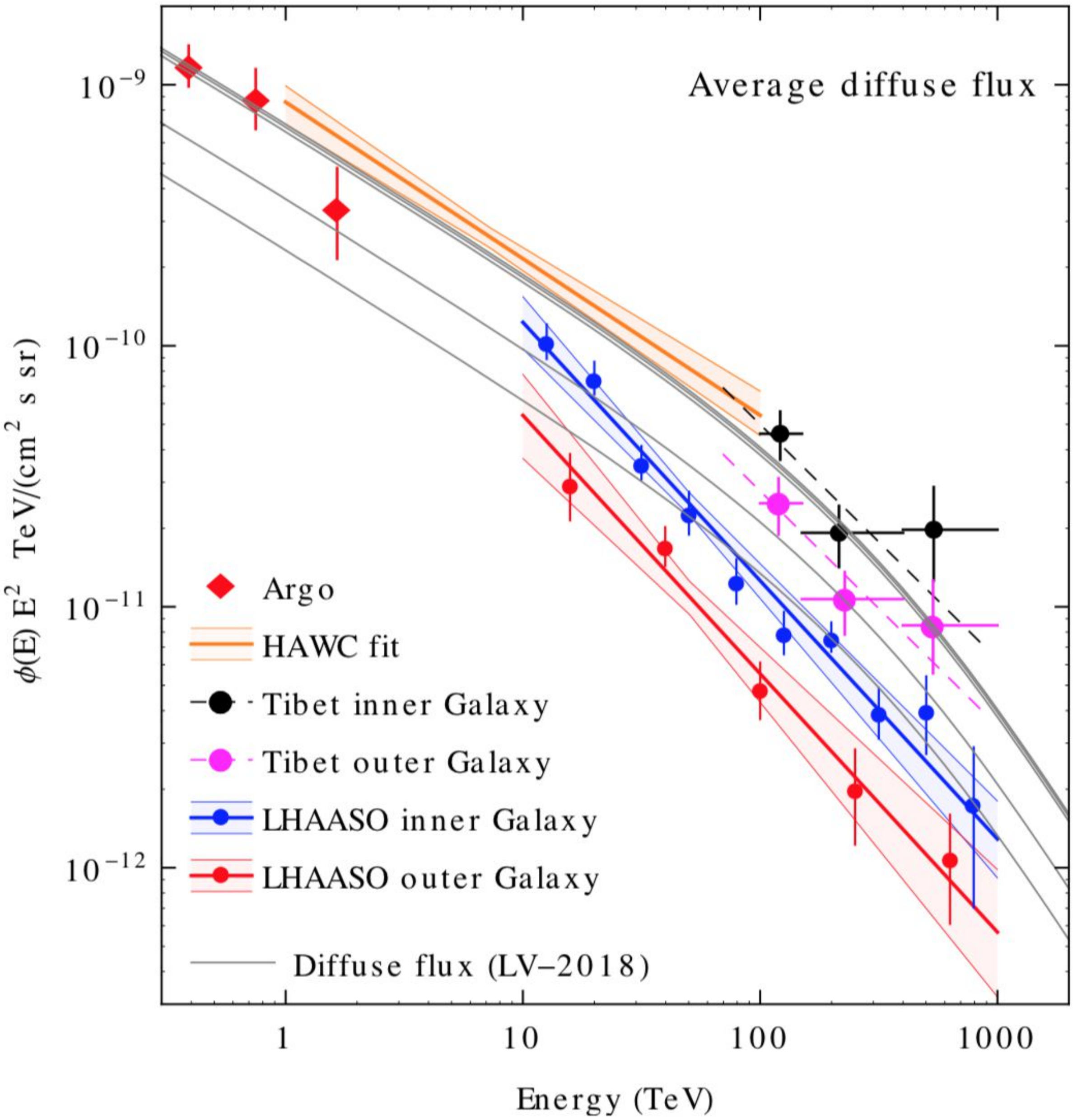


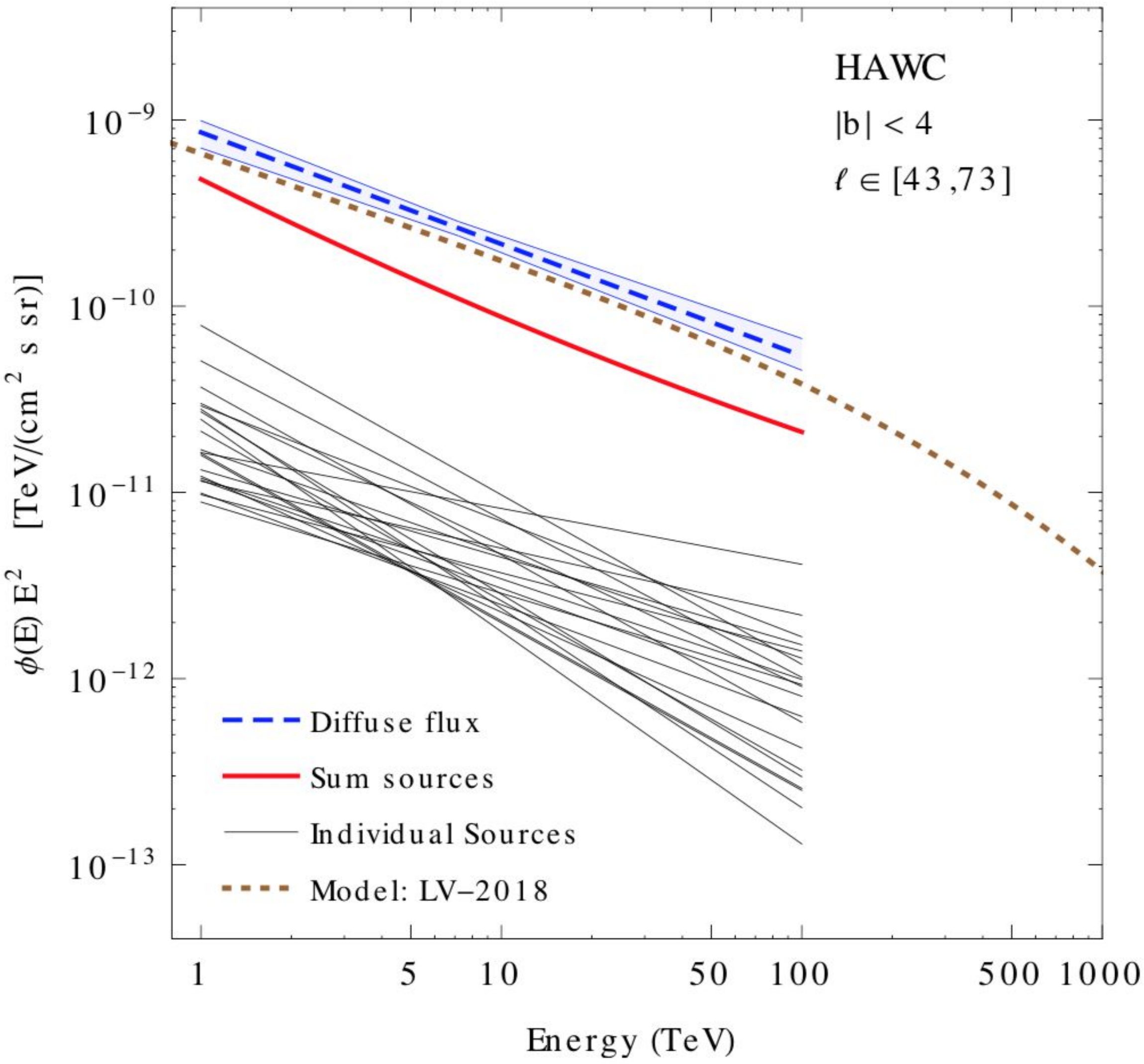
Horizon
for the direction $\delta = \lambda_{\text{telescope}}$ $L = L^*$

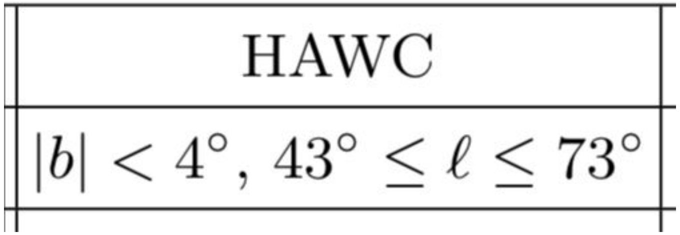

LHAASO ($10^2 - 10^3$ TeV)
identical sources
R = 0
R = 10 pc
R = 20 pc
α = 1.25
α = 1.50
α = 1.75
N_A / N_B
0
2
4
6
8
10
12
10^{30}
10^{31}
10^{32}
10^{33}
10^{34}
10^{35}
10^{36}
$L^*[10^2 - 10^3$ TeV] (erg/s)


LHAASO – Inner Galaxy
Identical sources
Power law, R=0
Power law, R=10 pc
Power law, R=20 pc
1.25
1.50
1.75
(Resolved flux) / (Source Flux)
0.0
0.2
0.4
0.6
0.8
1.0
0.5
1.0
5.0
10.0
50.0
100.0
Horizon distance (kpc)

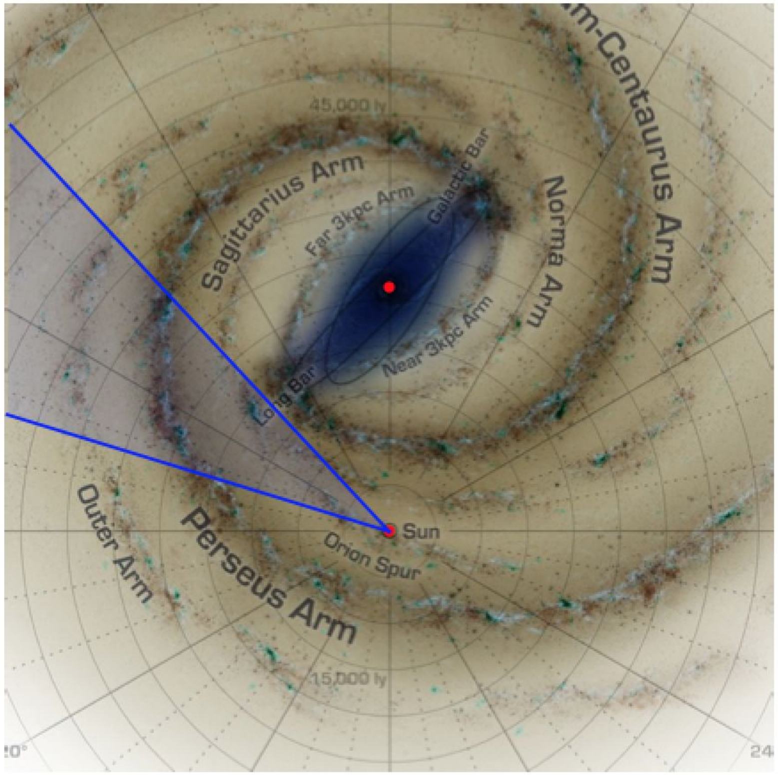
Diffuse gamma-ray flux measurements at high energy

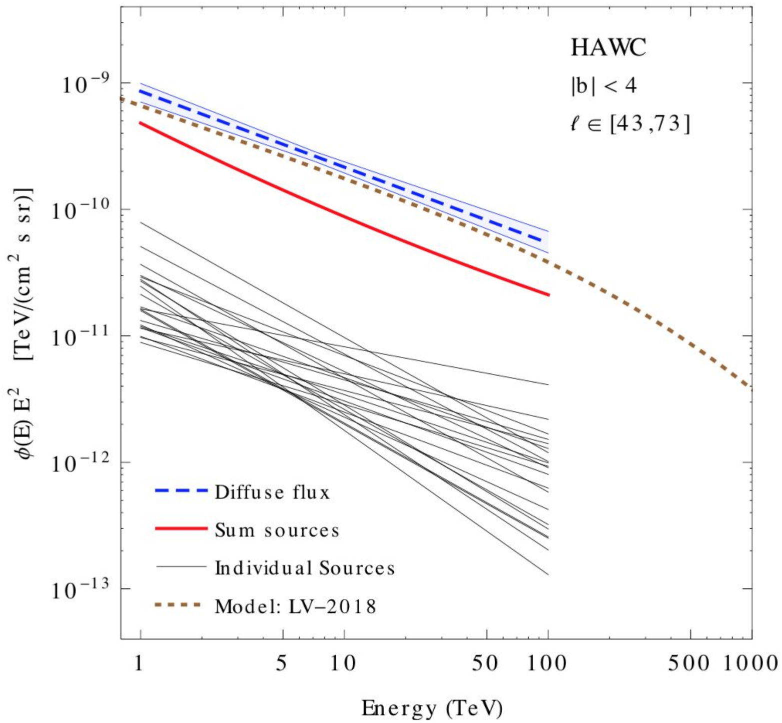






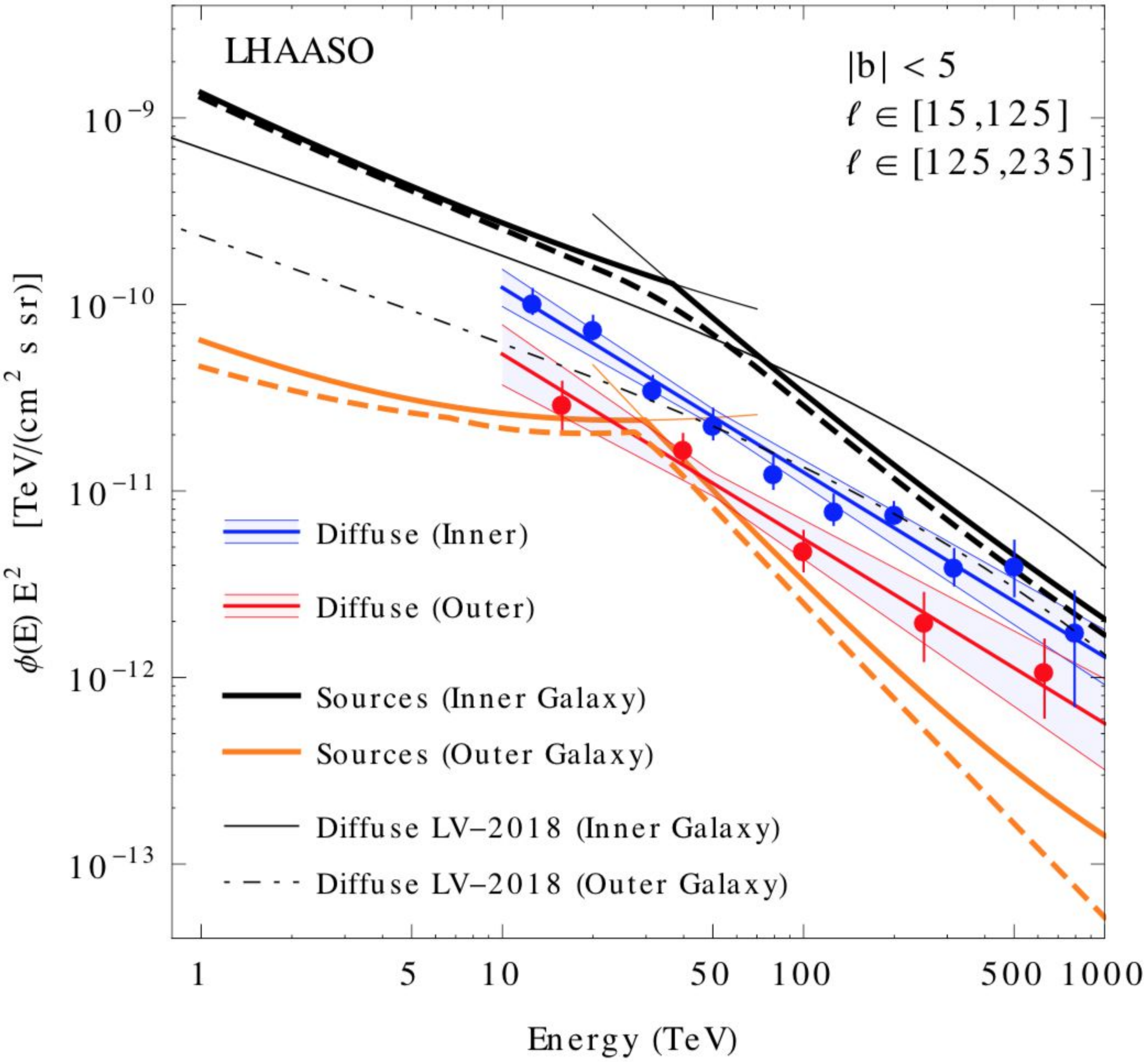
HAWC
$\lvert b\rvert < 4^\circ,\ 43^\circ \leq \ell \leq 73^\circ$



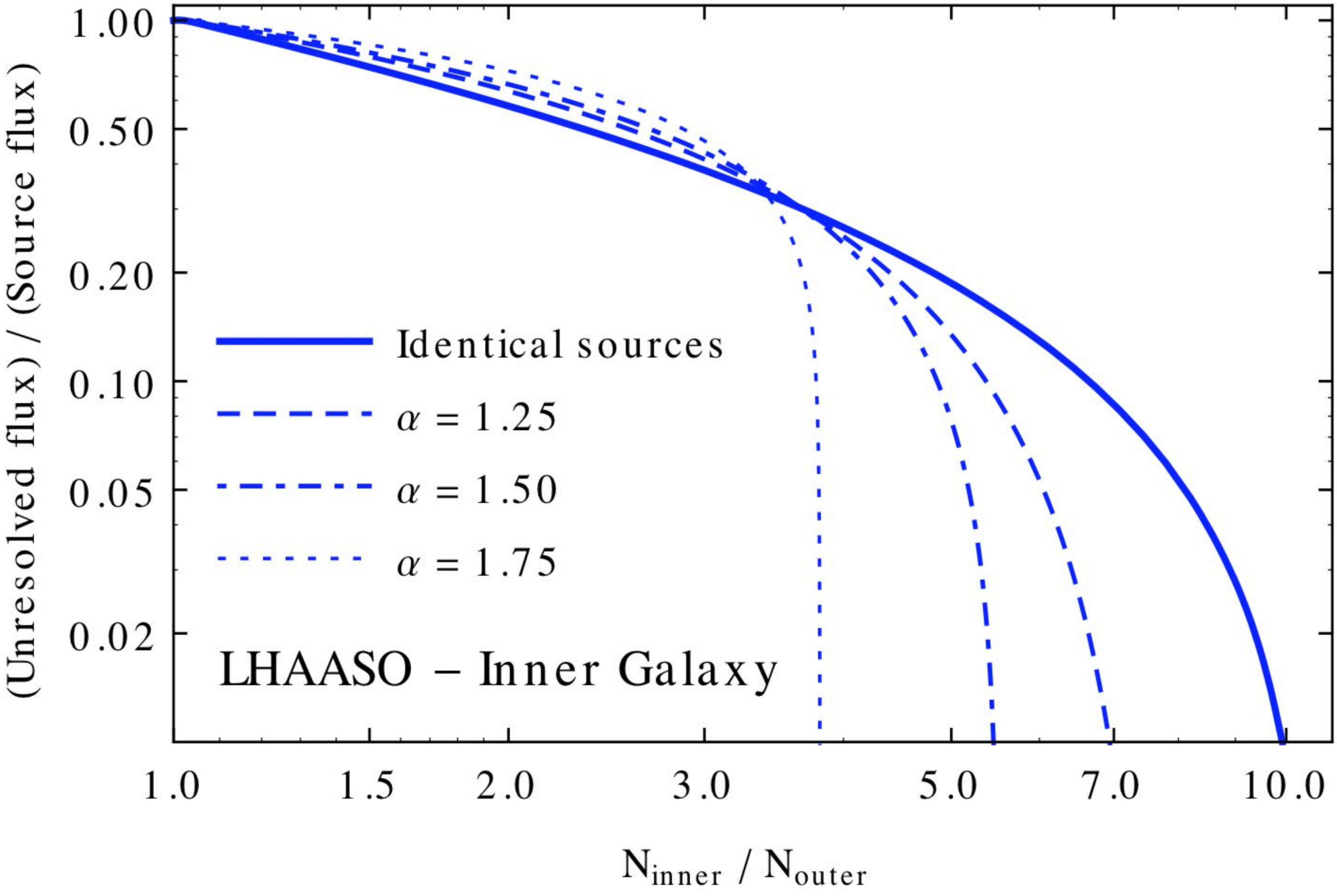


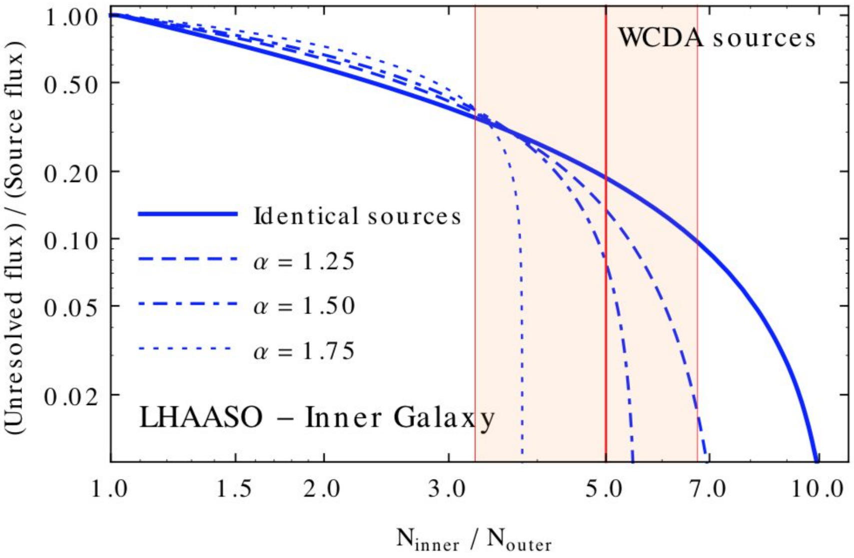
$E \in [1, 10]$ TeV	
$\langle\phi\rangle_{\rm diff}$ $({\rm cm}^2\ {\rm s\ sr})^{-1}$	$(5.23^{+0.7}_{-0.8}) \times 10^{-10}$
$\langle\phi\rangle^{\rm resolved}_{\rm sources}$ $({\rm cm}^2\ {\rm s\ sr})^{-1}$	2.67×10^{-10}
$\langle\phi\rangle^{\rm resolved}_{\rm sources}$ / $\langle\phi\rangle_{\rm diff}$	$0.51^{+0.092}_{-0.06}$
$L^{\rm sources}_{\rm min}$ [erg/s]	3.33×10^{36}
$L^{\rm sources}_{\rm max}$ [erg/s]	1.02×10^{37}

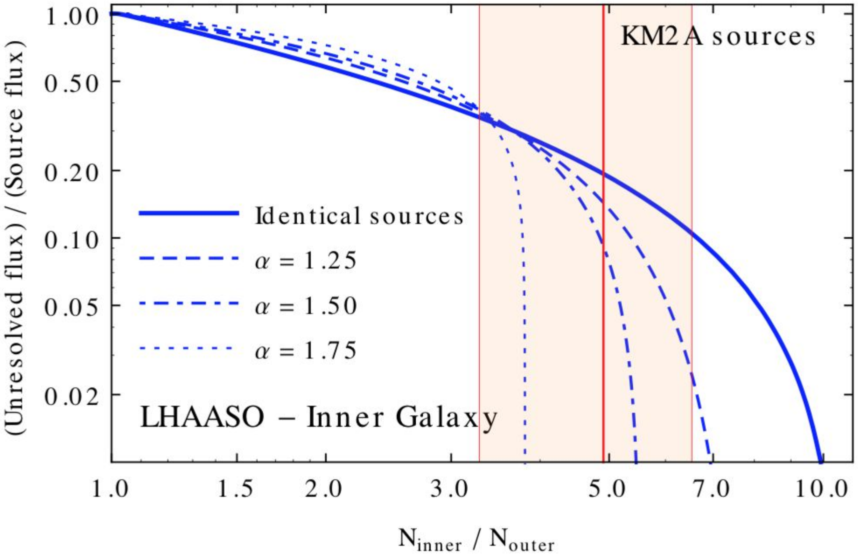
$E \in [10, 10^2]$ TeV	
$\langle\phi\rangle_{\rm diff}$ $({\rm cm}^2\ {\rm s\ sr})^{-1}$	$(1.31^{+0.18}_{-0.15}) \times 10^{-11}$
$\langle\phi\rangle^{\rm resolved}_{\rm sources}$ $({\rm cm}^2\ {\rm s\ sr})^{-1}$	5.18×10^{-12}
$\langle\phi\rangle^{\rm resolved}_{\rm sources}$ / $\langle\phi\rangle_{\rm diff}$	$0.394^{+0.052}_{-0.047}$
$L^{\rm sources}_{\rm min}$ [erg/s]	6.73×10^{35}
$L^{\rm sources}_{\rm max}$ [erg/s]	2.4×10^{36}

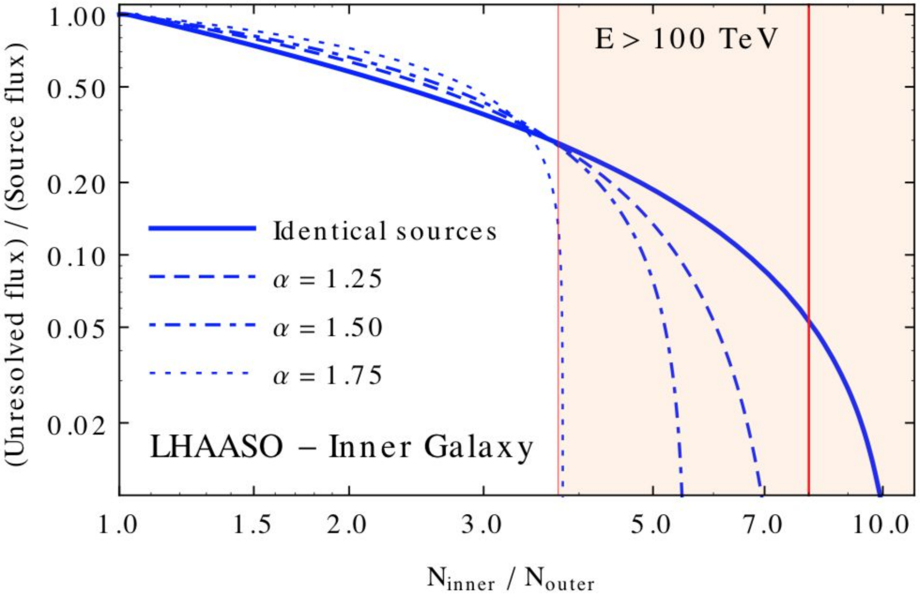

LHAASO
|b| < 5
ℓ ∈ [15,125]
ℓ ∈ [125,235]
φ(E) E² [TeV/(cm² s sr)]
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
Diffuse (Inner)
Diffuse (Outer)
Sources (Inner Galaxy)
Sources (Outer Galaxy)
Diffuse LV–2018 (Inner Galaxy)
Diffuse LV–2018 (Outer Galaxy)
1
5
10
50
100
500
1000
Energy (TeV)

	HAWC	LHAASO Inner Galaxy	LHAASO (Outer Galaxy)
	$\lvert b\rvert < 4^\circ,\ 43^\circ \leq \ell \leq 73^\circ$	$\lvert b\rvert < 5^\circ,\ 15^\circ \leq \ell \leq 125^\circ$	$\lvert b\rvert < 5^\circ,\ 125^\circ \leq \ell \leq 235^\circ$
$\mathcal{N}$	0.0871	0.330	0.0309
$[\langle d_{\mathrm{s}}^{-2}\rangle]^{-\frac{1}{2}}$ (kpc)	6.31	6.34	3.13
$E \in [1, 10]$ TeV			
$\langle\phi\rangle_{\mathrm{diff}}$ $(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}$	$(5.23^{+0.7}_{-0.8}) \times 10^{-10}$	—	—
$\langle\phi\rangle^{\mathrm{resolved}}_{\mathrm{sources}}$ $(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}$	2.67×10^{-10}	—	—
$\langle\phi\rangle^{\mathrm{resolved}}_{\mathrm{sources}}$ / $\langle\phi\rangle_{\mathrm{diff}}$	$0.51^{+0.092}_{-0.06}$	—	—
$L^{\mathrm{sources}}_{\mathrm{min}}$ [erg/s]	3.33×10^{36}	—	—
$L^{\mathrm{sources}}_{\mathrm{max}}$ [erg/s]	1.02×10^{37}	—	—
$E \in [10, 10^2]$ TeV			
$\langle\phi\rangle_{\mathrm{diff}}$ $(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}$	$(1.31^{+0.18}_{-0.15}) \times 10^{-11}$	$(6.12^{+1.3}_{-1.1}) \times 10^{-12}$	$(2.69^{+0.94}_{-0.73}) \times 10^{-12}$
$\langle\phi\rangle^{\mathrm{resolved}}_{\mathrm{sources}}$ $(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}$	5.18×10^{-12}	1.63×10^{-11}	1.93×10^{-12}
$\langle\phi\rangle^{\mathrm{resolved}}_{\mathrm{sources}}$ / $\langle\phi\rangle_{\mathrm{diff}}$	$0.394^{+0.052}_{-0.047}$	$2.67^{+0.58}_{-0.46}$	$0.718^{+0.27}_{-0.19}$
$L^{\mathrm{sources}}_{\mathrm{min}}$ [erg/s]	6.73×10^{35}	2.49×10^{36}	$8. \times 10^{35}$
$L^{\mathrm{sources}}_{\mathrm{max}}$ [erg/s]	2.4×10^{36}	3.37×10^{36}	1.8×10^{36}
$E \in [10^2, 10^3]$ TeV			
$\langle\phi\rangle_{\mathrm{diff}}$ $(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}$	—	$(6.26^{+1.3}_{-1.1}) \times 10^{-14}$	$(2.75^{+0.97}_{-0.75}) \times 10^{-14}$
$\langle\phi\rangle^{\mathrm{resolved}}_{\mathrm{sources}}$ $(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}$	—	1.46×10^{-13}	1.3×10^{-14}
$\langle\phi\rangle^{\mathrm{resolved}}_{\mathrm{sources}}$ / $\langle\phi\rangle_{\mathrm{diff}}$	—	$2.34^{+0.51}_{-0.4}$	$0.471^{+0.18}_{-0.12}$
$L_{\mathrm{min}^{\mathrm{sources}}}$ [erg/s]	—	1.96×10^{35}	4.33×10^{34}
$L^{\mathrm{sources}}_{\mathrm{max}}$ [erg/s]	—	2.86×10^{35}	1.46×10^{35}


(Unresolved flux) / (Source flux)
1.00
0.50
0.20
0.10
0.05
0.02
Identical sources
α = 1.25
α = 1.50
α = 1.75
LHAASO – Inner Galaxy
1.0
1.5
2.0
3.0
5.0
7.0
10.0
N_{inner} / N_{outer}


WCDA sources
Identical sources
$\alpha = 1.25$
$\alpha = 1.50$
$\alpha = 1.75$
LHAASO – Inner Galaxy
(Unresolved flux) / (Source flux)
1.00
0.50
0.20
0.10
0.05
0.02
1.0
1.5
2.0
3.0
5.0
7.0
10.0
N_{inner} / N_{outer}


KM2A sources
Identical sources
$\alpha = 1.25$
$\alpha = 1.50$
$\alpha = 1.75$
LHAASO – Inner Galaxy
(Unresolved flux) / (Source flux)
1.00
0.50
0.20
0.10
0.05
0.02
1.0
1.5
2.0
3.0
5.0
7.0
10.0
N_{inner} / N_{outer}


E > 100 TeV
Identical sources
$\alpha = 1.25$
$\alpha = 1.50$
$\alpha = 1.75$
LHAASO – Inner Galaxy
(Unresolved flux) / (Source flux)
1.00
0.50
0.20
0.10
0.05
0.02
1.0
1.5
2.0
3.0
5.0
7.0
10.0
N_{inner} / N_{outer}

Conclusions [part 1]

1. The cumulative spectrum of all Galactic sources undergoes a significant softening above 10~TeV.

$E \simeq 20 \div 80$ TeV

spectral index :

$\Gamma \sim 2.6 \to 3.4$

The spectral shape is quite similar to the shape of the diffuse – interstellar flux [intriguing ?] and makes a separation difficult.

2. Most (or all) spectra in the energy range 1-100 TeV show significant curvature.

3. The spectra of individual sources have a broad range of shapes with a cumulative spectrum that is much smoother.

Conclusions [part 2]

4. The unresolved sources gamma-ray flux can be estimated extrapolating from the observed objects.

   The "geometrical" method of studying the number of sources in different angular regions is very promising.

5. Understanding the space distribution of the sources (and the spiral structure of the Milky Way) is however important.

6. The separation of the "unresolved flux" and the "diffuse interstellar flux" remains a difficult problem, because they are of (approximately) the same order.

   [More detailed discussion in preparation]