Leibniz-Institut für Astrophysik Potsdam

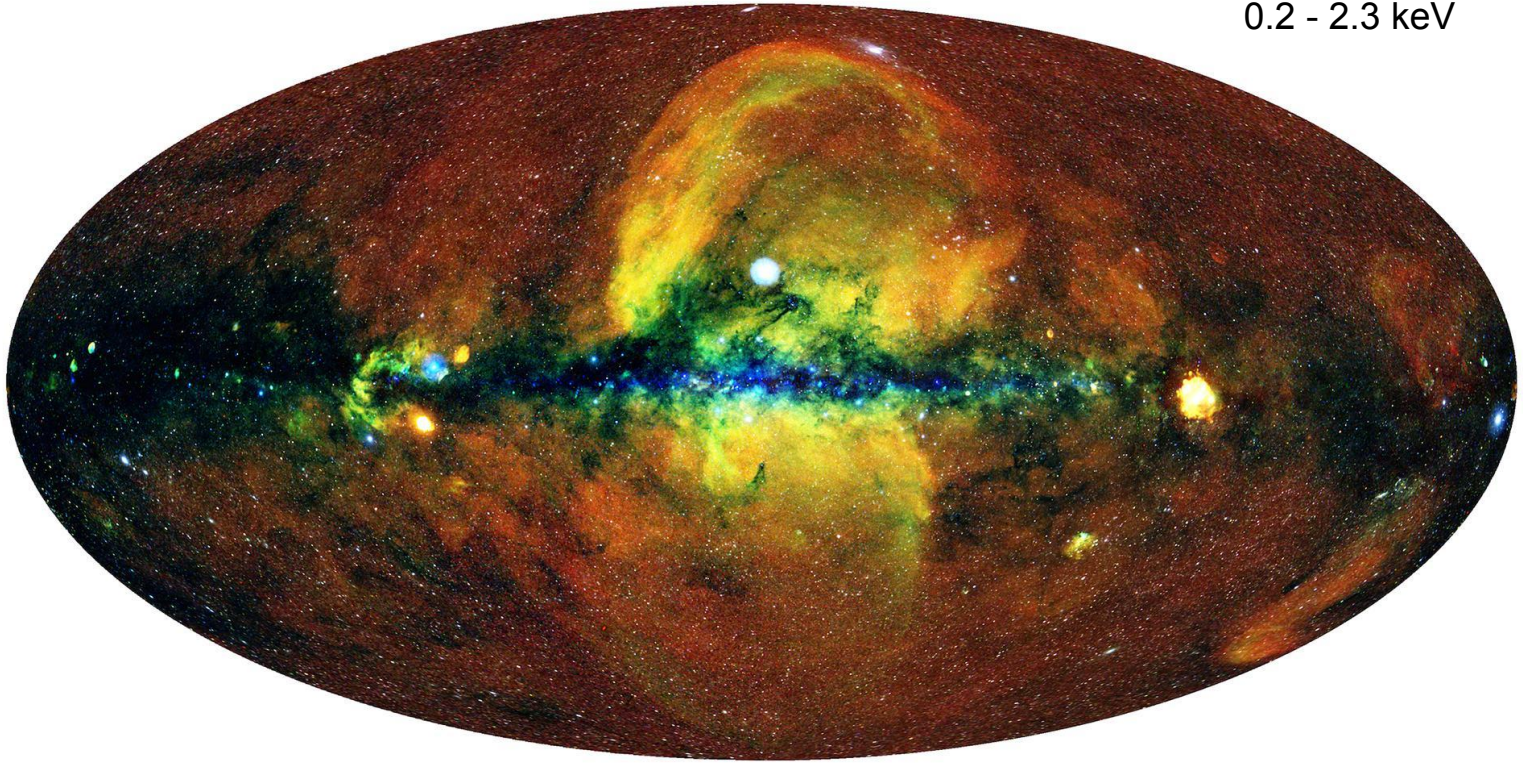
The SRG/eROSITA upper flux limits of the Galactic Western hemisphere

Dusán Tubín Arenas
dtubin@aip.de
Leibniz-Institute for Astrophysics Potsdam (AIP)

Tubín-Arenas et al. (2024), A&A, 682, A35
First Results from the SRG/eROSITA All-Sky Survey: From Stars to Cosmology.
Garching, 2024

Collaborators: Mirko Krumpe, Georg Lamer, Jonas Haase, Jeremy Sanders, Hermann Brunner, David Homan, Axel Schwope, Antonis Georgakakis, Katja Poppenhaeger, Iris Traulsen, Ole König, Andrea Merloni, Alain Gueguen, Andrew Strong, Zhu Liu.

SRG/eROSITA



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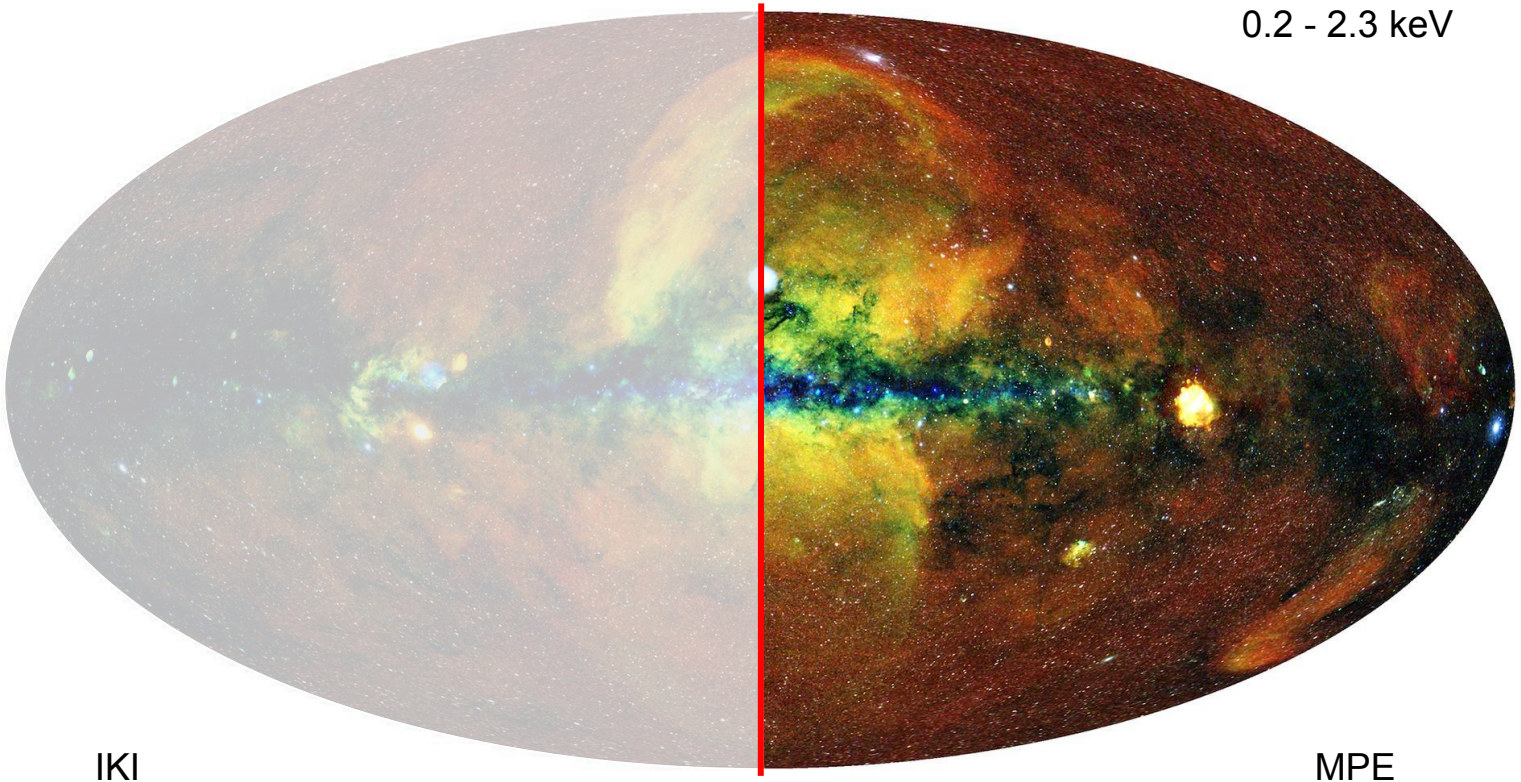

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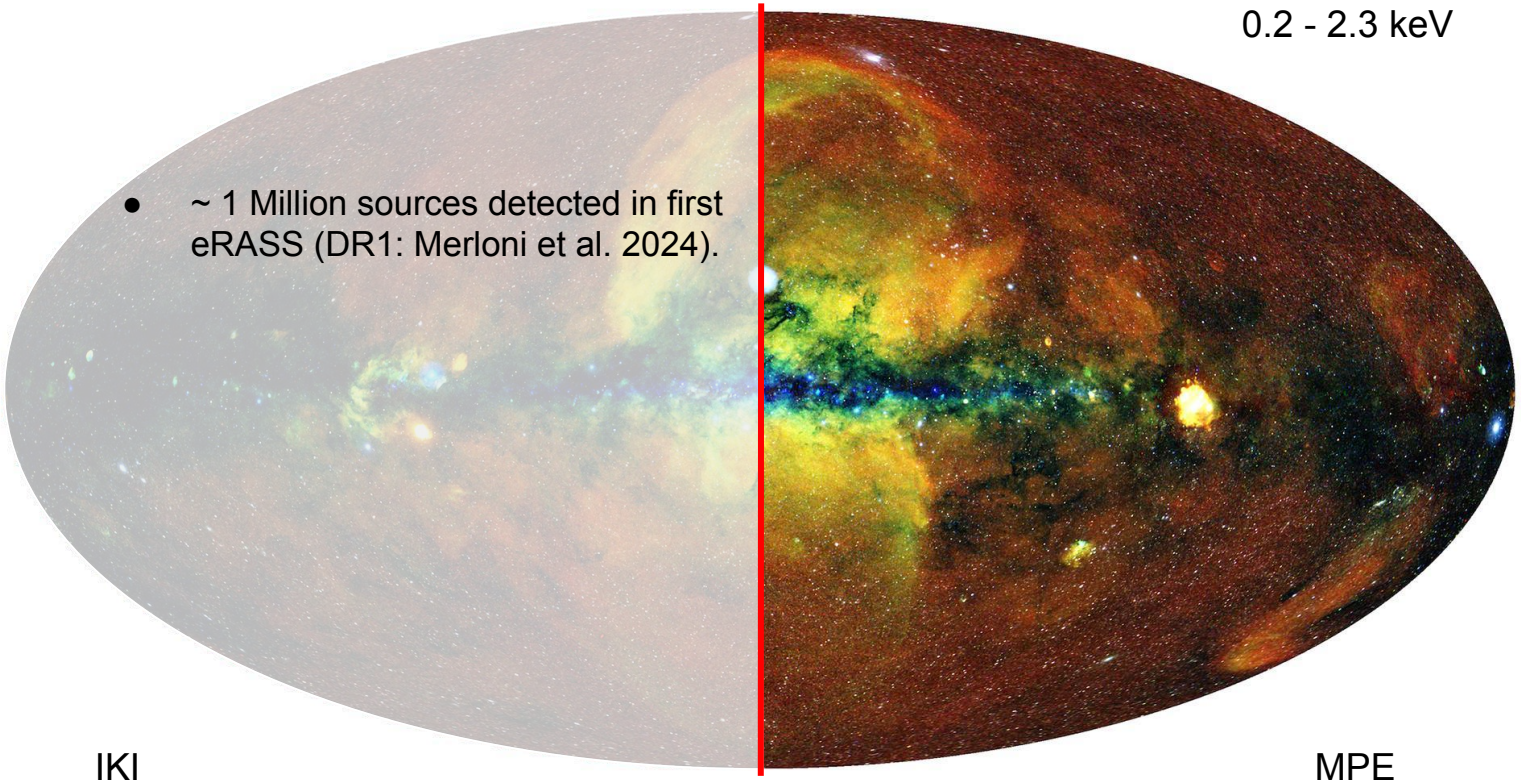
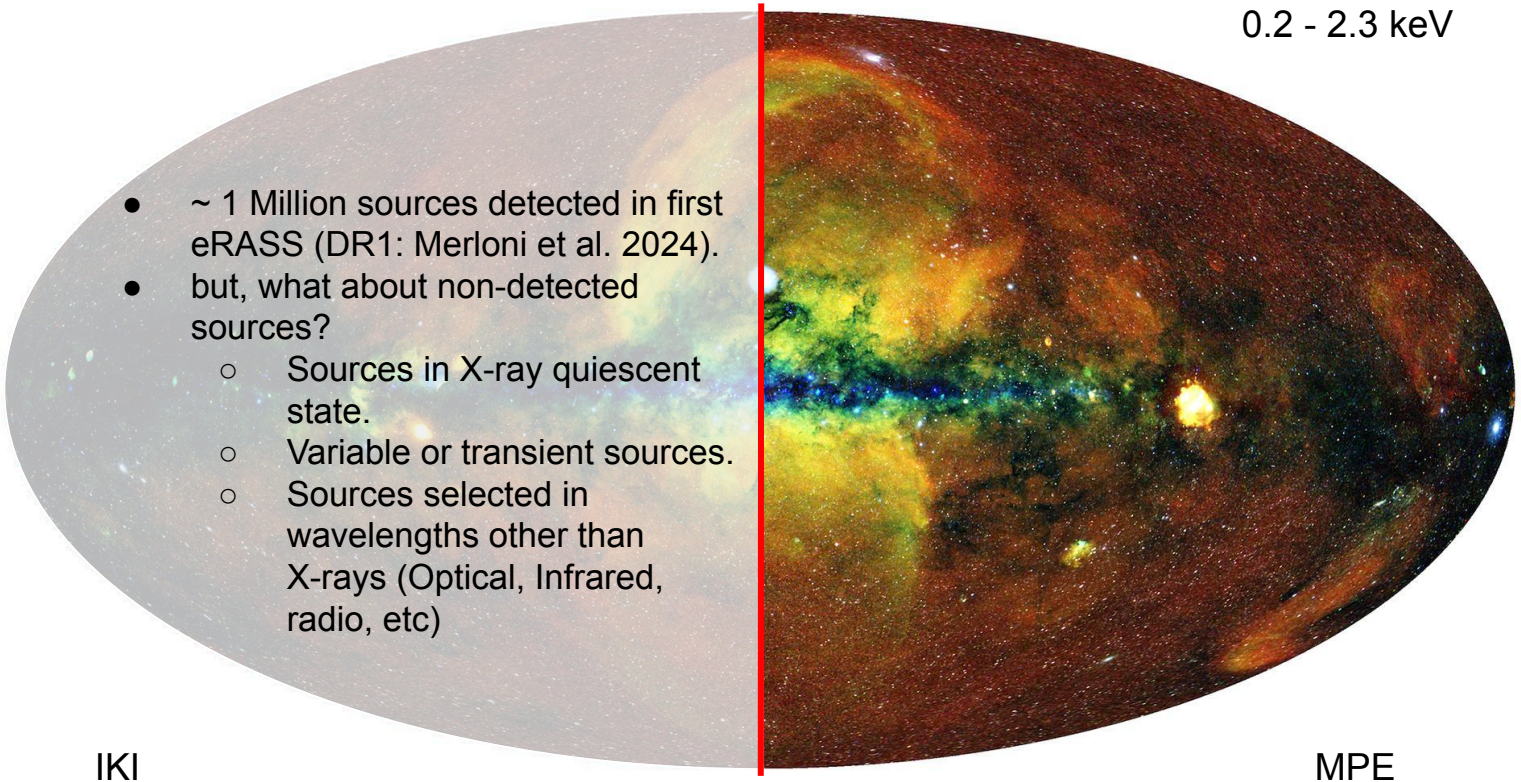


- ~ 1 Million sources detected in first eRASS (DR1: Merloni et al. 2024).

SRG/eROSITA



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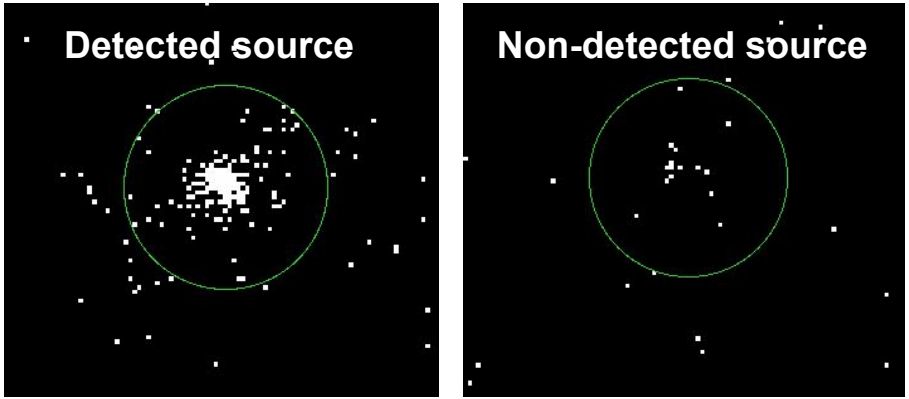
- but, what about non-detected sources?
  - Sources in X-ray quiescent state.
  - Variable or transient sources.
  - Sources selected in wavelengths other than X-rays (Optical, Infrared, radio, etc)

The need for upper limits



$\mathrm{Flux}_{0.2-2.3\ \mathrm{keV}} = 5.3 \times 10^{-12}\ \mathrm{erg\ s^{-1}\ cm^{-2}}$

$\mathrm{Flux}_{0.2-2.3\ \mathrm{keV}} = ??$

eROSITA released the first half-sky catalog in January (Merloni et al. 2024)!

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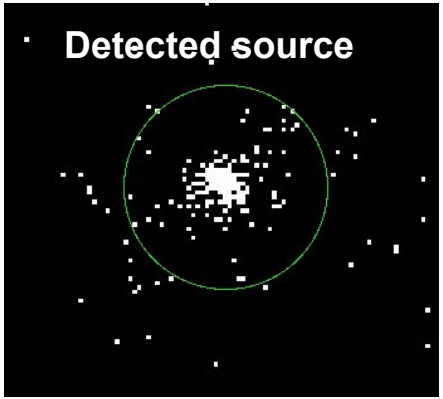

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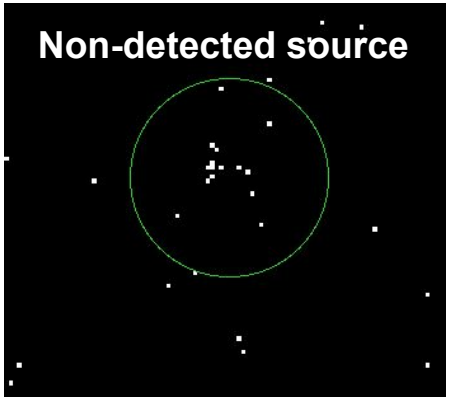

$\text{Flux}_{0.2-2.3\ \text{keV}} < 5.9 \times 10^{-13}\ \text{erg s}^{-1}\ \text{cm}^{-2}$

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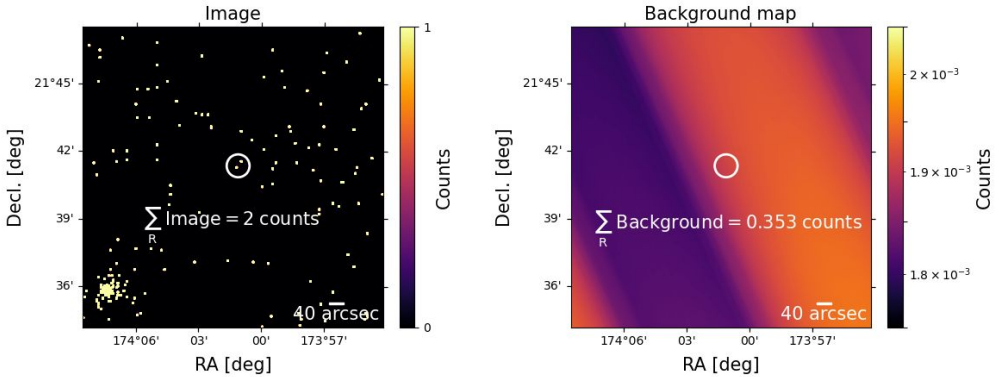
Need of a flux upper limit to understand the physical and statistical properties of a even larger sample of objects!

Method

The upper limits are calculated based on X-ray aperture photometry and Bayesian approach (Kraft et al. 1991):



$$\mathrm{UL} = \gamma^{-1}(N+1, \mathrm{CL}\cdot\Gamma(N+1,B)+\gamma(N+1,B)) - B$$

(see Ruiz et al. 2022.)

N: Observed counts.
B: Background counts.
CL: Confidence interval.

Tubín-Arenas et al. (2024), A&A, 682, A35

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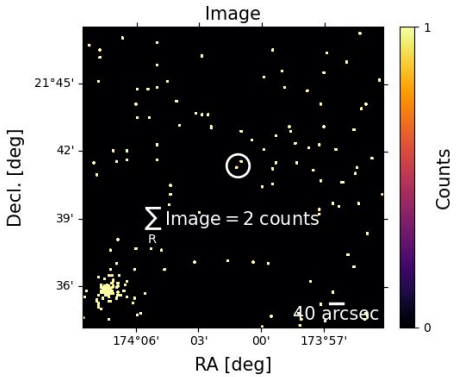

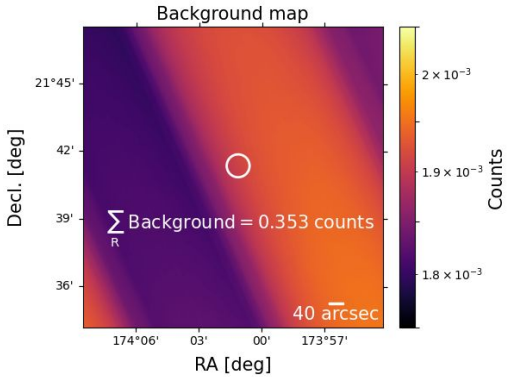

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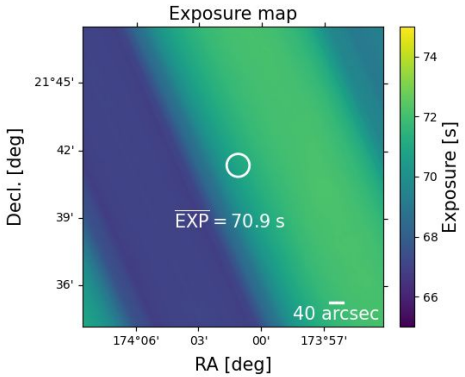

$$CR_{UL} = UL/(t \cdot EEF)$$

$$f_X = \frac{UL}{t \cdot EEF \cdot ECF}$$

t: Exposure time
EEF: Encircled energy fraction
ECF: Energy conversion factor

Tubín-Arenas et al. (2024), A&A, 682, A35

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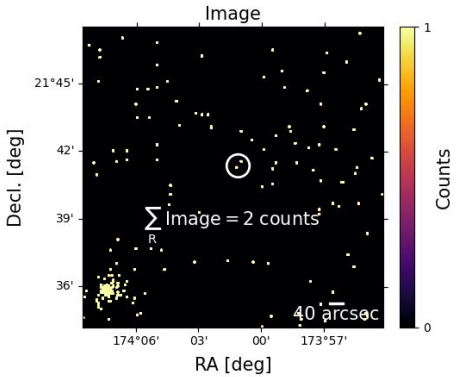

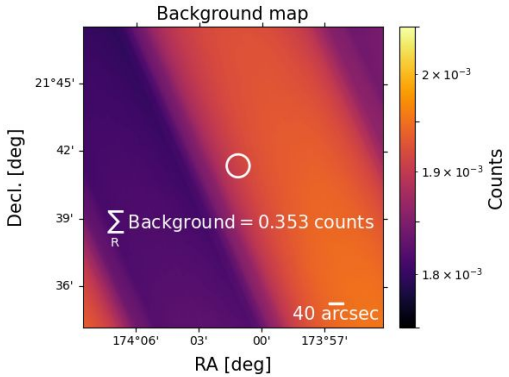

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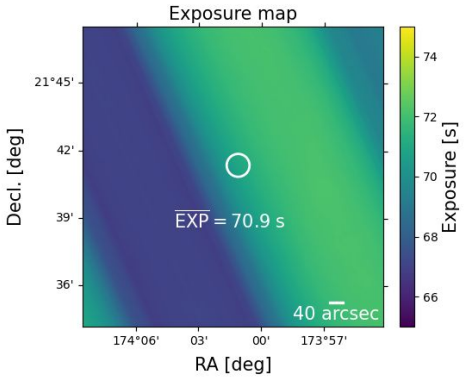

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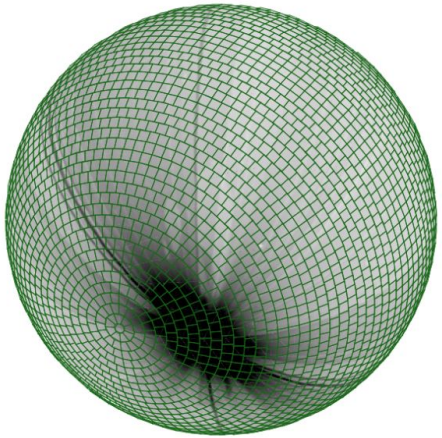
Upper limits and photometric products available for every pixel of eROSITA-DE footprint.

Tubín-Arenas et al. (2024), A&A, 682, A35

The upper limit products

Column name	Format[a]	Units	Description
HEALPix index	K	–	Projection of the coordinates into HEALPix map.
Counts	J	cts	Extracted counts within the aperture from the science image.[a]
Bkg_counts	D	cts	Extracted background counts within the aperture from the background image.[b]
Bkg_SourceMap	D	cts	Extracted counts within the aperture from the source-map image.[b]
Exposure	D	s	Average exposure time within the circular aperture.
Flag_pos	J	–	Close neighbor flag[c] .
Flux_UL_B	D	erg s^{-1} cm^{-2}	Flux upper limit at CL=0.9987 (one-sided) based on column "Bkg_counts".[d]
Flux_UL_S	D	erg s^{-1} cm^{-2}	Same as UL_B, but based on the source-map counts ("Bkg_SourceMap").[d]

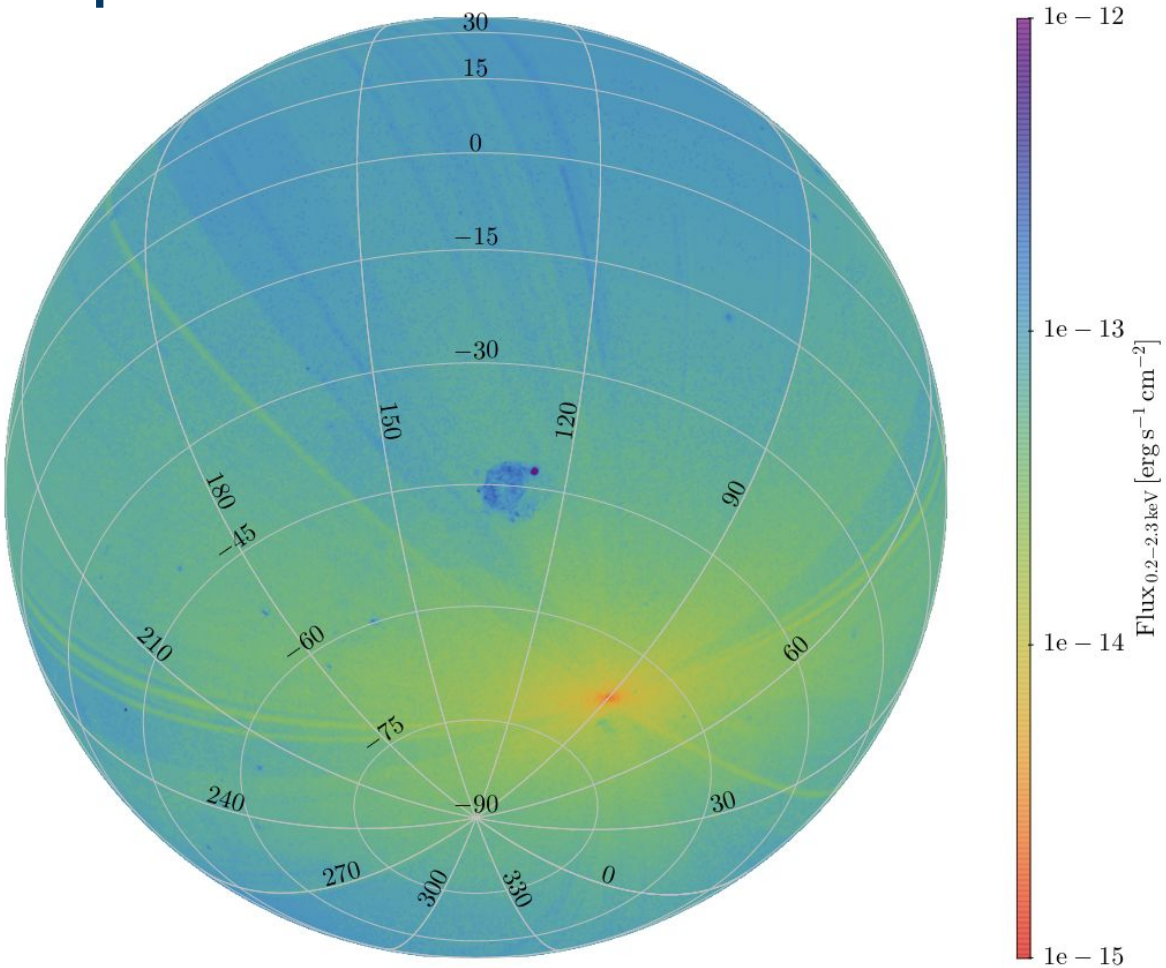


Upper limits available per sky tile and energy band at:

- 0.2 - 0.6 keV
- 0.6 - 2.3 keV
- 2.3 - 5.0 keV
- 0.2 - 5.0 keV
- 0.2 - 2.3 keV.

Tubín-Arenas et al. (2024), A&A, 682, A35

The upper limit products



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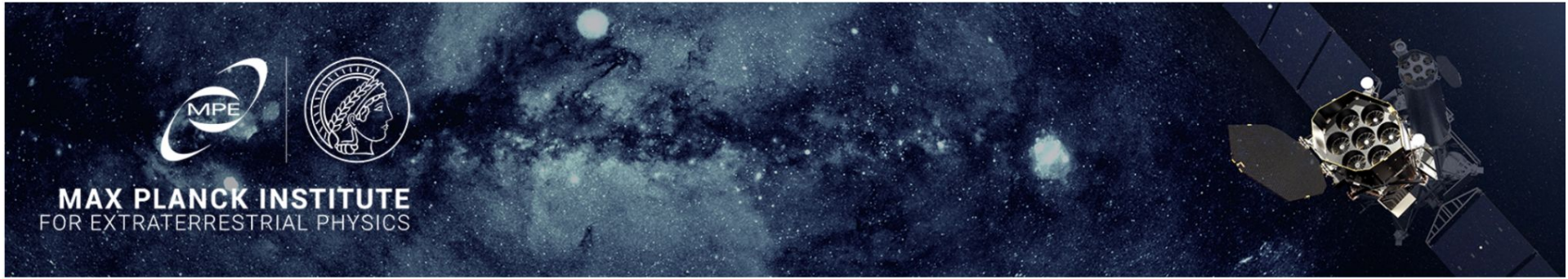

eRODat: eROSITA-DE Data Release 1 archive

Main DR1 home | eRODat home | Sky view | Skytile search | Catalogue search | Upper limits | Download area | Basket

Upper limit for a single position

Find an upper limit on the sky for a single sky position. Please either enter a position directly (in decimal degrees or sexagesimal), or give an object name and click resolve, to find the position using the Sesame name resolver.

Please see this page and Tubín-Arenas et al. (2024) for further details. Both Tubín-Arenas et al. (2024) and Merloni et al. (2024) should be referenced if these upper limits are used.

Object name: Resolve

Longitude: 180 Latitude: -45 Coordinate System: ICRS

Band: 024 (0.2-2.3 keV)

Submit query | Defaults

Imprint | Data Protection | © eROSITA-DE, MPE

DR1 upper limits: https://erosita.mpe.mpg.de/dr1/AllSkySurveyData_dr1/UpperLimitServer_dr1/

Credits: J. Sanders and J. Haase.

Tubín-Arenas et al. (2024), A&A, 682, A35

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Object name: Resolve
Longitude: 174.12238 Latitude: 21.59611 Coordinate System: ICRS
Band: 024 (0.2-2.3 keV)

Submit query Defaults

Upper limit

The flux upper limit in band 024 at the position R.A.=174.12238, Dec=21.59611 is 1.92919e-12 erg s^{-1} cm^{-2}.

Upper limit details

Entry	Description	Unit	Value
healpix	HEALPix index	-	29649239309
Count	Observed counts	Counts	77
Bkg_counts	Background counts	Counts	0.346217
Bkg_SourceMap	Source-map counts (used as background)	Counts	79.8372
Exposure	Exposure time	s	68.7760
Flag_pos	Close-neighbor flag	-	1
UL_B	Flux upper limit based on background map	erg s^{-1} cm^{-2}	1.92919e-12
UL_S	Flux upper limit based on source map	erg s^{-1} cm^{-2}	5.48027e-13
field	Sky tile	-	174069

Nearby sources from DR1_Main within 2.0 arcmin

Show 10 entries

Distance (arcmin)	iauname	detuid	ra	dec	ext	ext_like	det_like_0	ml_rate_1	ml_flux_1	Products	More
0.07	1eRASS J113629.3+213550	em01_174069_020_ML00002_002_c010	174.12231	21.59730	0.00	0.00	434.54	1.53	1.43e-12	Yes	More

DR1 upper limits: https://erosita.mpe.mpg.de/dr1/AllSkySurveyData_dr1/UpperLimitServer_dr1/

Credits: J. Sanders and J. Haase.

Tubín-Arenas et al. (2024), A&A, 682, A35

The upper limit products

Upper limits for multiple positions

Find upper limits for a list of positions given by an uploaded file. Please see this page and Tubín-Arenas et al. (2024) for further details. Both Tubín-Arenas et al. (2024) and Merloni et al. (2024) should be referenced if these upper limits are used.

- Input files should be text, consisting of two or three columns.
- The columns should be separated by whitespace, tabs, pipes ("|"), semicolons or commas (choose below).
- If there are three columns, the first should be a name for the object, and the next two the longitude and latitude of its coordinates (RA and Dec for equatorial coordinates).
- If there are two columns, these should contain longitudes and latitudes.
- The coordinates can either be given in decimal degrees, or in sexagesimal form following the format 11:22:33.3 or 11h12m3.3s / -11d12m3.3s.
- Comment lines can be prefixed by a hash symbol ("#").
- Up to 1000 entries are supported.
- Invalid values in output text or JSON are written as -9999.

Choose File No file chosen
Column Separator: Whitespace
Coordinate System: ICRS
eROSITA-DE sky only:
Output format: Web page
Band: 024 (0.2-2.3 keV)

Submit query

Show 10 entries Search:

Index	Name/index	RA (deg)	Dec (deg)	eROSITA_DE sky	UL_B	UL_S	Counts	Bkg_counts	Bkg_SourceMap	Exposure	Flag_pos	Healpix	Field
1	1	176.00142	-61.12658	true	2.47271e-13	1.03630e-13	32	1.79526	33.4130	256.937	1	39749008909	174150
2	2	56.10746	-33.45521	true	9.04828e-14	9.04779e-14	7	1.08254	1.08353	248.817	0	36225795583	55123
3	3	82.56908	-41.42582	true	1.74810e-13	9.29696e-14	21	1.22226	19.6386	266.932	1	35809743751	81132
4	4	244.38081	-50.98486	true	2.43071e-12	5.25648e-13	232	1.79001	222.658	142.838	1	44218176206	242141
5	5	286.53654	-48.84064	true	5.27155e-12	9.99261e-13	312	0.889178	300.910	86.6210	1	49631914122	288138
6	6	158.04347	-27.09883	true	1.64279e-13	1.35094e-13	3	0.521786	3.45254	92.1989	1	40742202297	158117
7	7	112.85802	-67.20453	true	1.21363e-13	4.53714e-14	57	3.38069	54.9140	820.399	1	39257980745	114156
8	8	179.47128	-3.26090	true	6.83266e-13	2.74904e-13	34	0.497467	35.2193	99.9089	1	26829767463	179093
9	9	68.07197	-30.39961	true	1.67696e-13	1.07161e-13	10	0.768891	9.89539	169.646	1	36350074730	67120
10	10	134.19501	-28.32735	true	1.28548e-13	1.06082e-13	3	0.471569	3.30356	118.303	1	42080291310	135117

Showing 1 to 10 of 556 entries Previous 1 2 3 4 5 … 56 Next

DR1 upper limits: https://erosita.mpe.mpg.de/dr1/AllSkySurveyData_dr1/UpperLimitServer_dr1/

Credits: J. Sanders and J. Haase.

Tubín-Arenas et al. (2024), A&A, 682, A35

The upper limit products

2 Upper limit API

There is an API for accessing the upper limits (see also here). See the paper Tubín-Arenas et al. (2023) for further details of how these are calculated. The URL for accessing the service follows

```
https://sciserver.mpe.mpg.de/erosita-ul/ULbyHP/{BAND}/{HEALPIXIDX}
```

Where `{BAND}` is an eROSITA band (e.g. `024`) and `{HEALPIXIDX}` is the HEALPix index (ICRS, nside=2**16) of the coordinate of interest. An example URL is here. Example code in Python for calculating the index and obtaining the upper limits is:

```
import requests
from astropy_healpix import HEALPix
from astropy.coordinates import SkyCoord

hpix = HEALPix(nside=2**16, order='nested', frame='icrs')
coord = SkyCoord(200., 3., unit='deg')
hpidx = hpix.skycoord_to_healpix(coord)

band = '024'
url = f'https://sciserver.mpe.mpg.de/erosita-ul/ULbyHP/{band}/{hpidx}'
req = requests.get(url)
assert req.status_code == 200
print(req.json())
```

Please note that more than one entry can be returned by the service for coordinates with overlapping sky tiles. The user should choose the entry which matches the canonical sky tile for the coordinate, as can be found using the FITS table provided. The results from the query are JSON format data.

If you would like the upper limits for a large number of coordinates, there exists a second interface where a list of HEALPix indices can be POSTed to the upper limit service:

```
import requests

HPidxList = [4438400831, 49976614773]
url = "https://sciserver.mpe.mpg.de/erosita-ul/ULbyHPlist/024/"
req = requests.post(url, json=HPidxList)
assert req.status_code == 200
print(req.json())
```

Again, the user must choose the result for the canonical sky tile, in the case of positions where there are results for multiple sky tiles.

There exists an alternative API which does not require a HEALPix index and only returns the result for the main sky tile for the position. The URL scheme for this API (example here) follows

```
https://erosita.mpe.mpg.de/dr1/erodat/upperlimit/service?ra={RA}&dec={DEC}&band={BAND}
```

DR1 upper limits: https://erosita.mpe.mpg.de/dr1/AllSkySurveyData_dr1/UpperLimitServer_dr1/

Credits: J. Sanders and J. Haase.

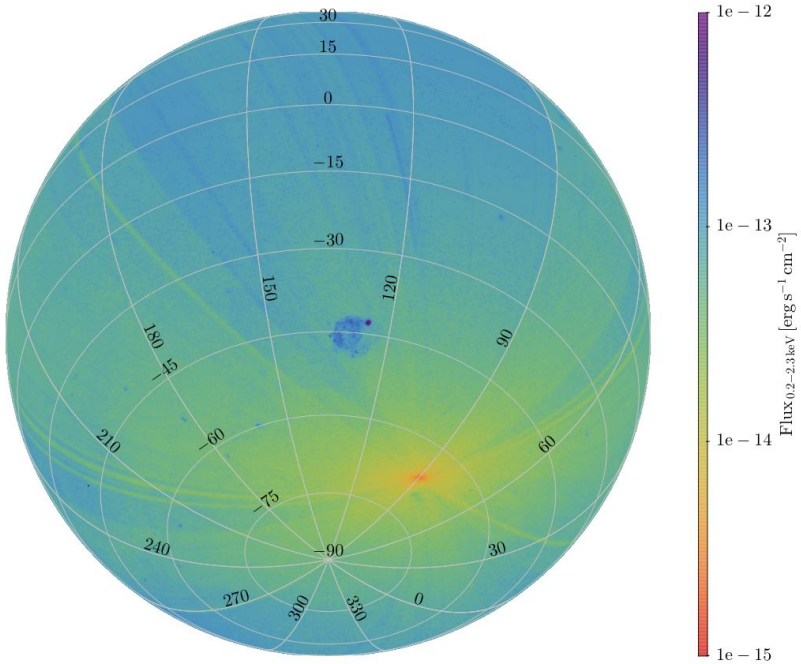
Tubín-Arenas et al. (2024), A&A, 682, A35

The eROSITA Upper Limits

eRASS1 upper limits are publicly available for all X-ray community together with DR1!

- Upper limits available in 0.2 - 0.6 keV, 0.6 - 2.3 keV, 2.3 - 5.0 keV, 0.2 - 5.0 keV, and 0.2 - 2.3 keV.
- Access through the web: https://erosita.mpe.mpg.de/dr1/AllSkySurveyData_dr1/UpperLimitServer_dr1/
- Choose the ECF wisely!

Upper limits of subsequent eROSITA surveys will be published together with the future data releases.



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The SRG/eROSITA upper flux limits of the Galactic Western hemisphere

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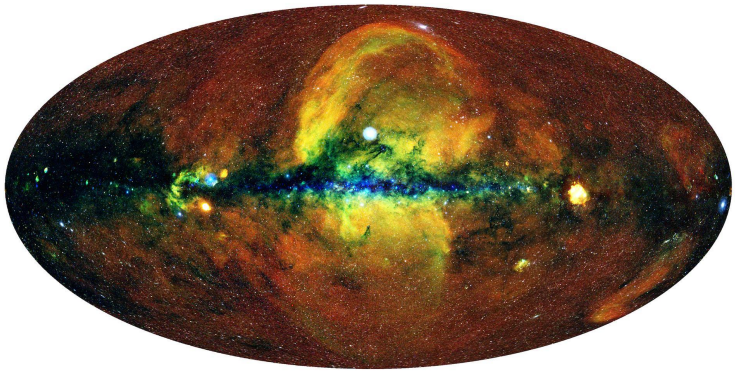
The eROSITA Upper Limits

The eROSITA Upper Limit Server (Tubín et al. in prep.)

Need of an ***flux upper limit*** to understand the physical and statistical properties of non-detected sources such as variables, quiescents, transients, or sources selected in wavelengths other than X-rays.



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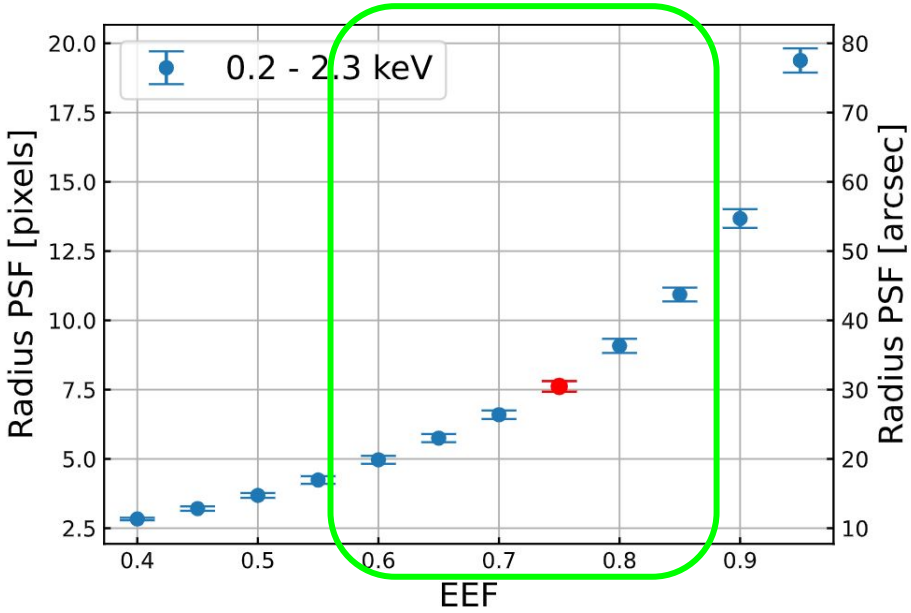

EEF: Encircled energy fraction

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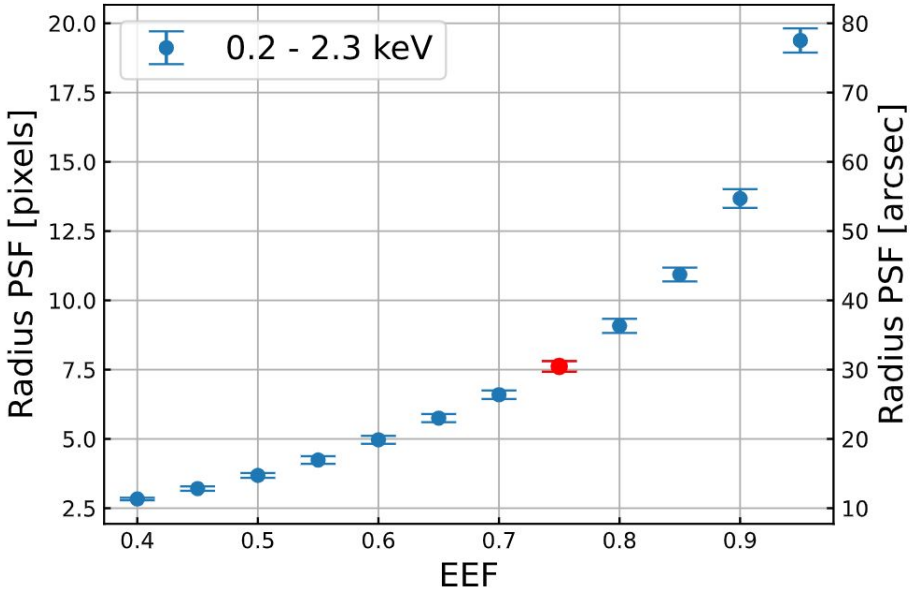

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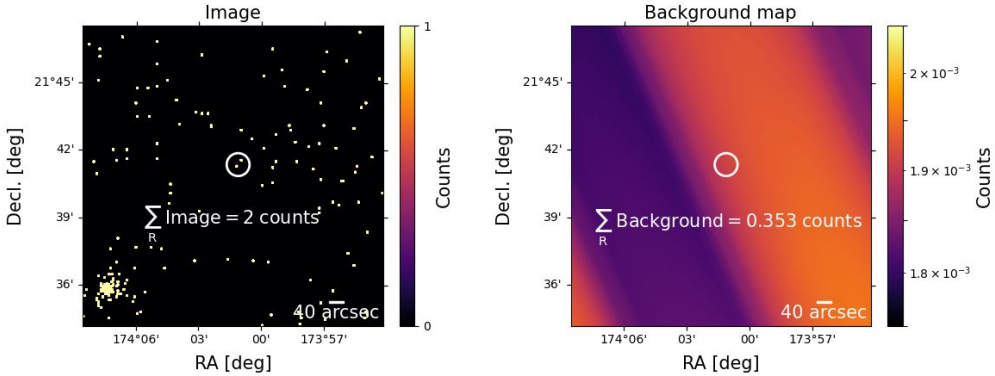
The eROSITA Upper Limit Server (Tubín et al. in prep.)

Upper limit calculations based on X-ray aperture photometry and bayesian approach from Kraft et al. 1991.



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(see Ruiz et al. 2022.)

Theoretical background

The upper limits are calculated based on Bayesian approach (Kraft et al. 1991):

see also Ruiz et al. 2022.

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- Low count regime → Poisson statistics!

$$P(N \mid S + B) = \frac{(S + B)^N \cdot e^{-(S+B)}}{N!}$$

see also Ruiz et al. 2022.

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- Using Bayes Theorem:

$$P(S \mid N, B) = C \cdot \frac{(S + B)^N \cdot e^{-(S+B)}}{N!}$$

$$\begin{aligned} C^{-1} &= \int_0^\infty \frac{(S + B)^N \cdot e^{-(S+B)}}{N!} dS \\ &= \int_B^\infty \frac{T^N \cdot e^{-T}}{N!} dT = \Gamma(N + 1, B) \end{aligned}$$

$$\Gamma(s, x) = \int_x^\infty t^{s-1} \exp(-t) dt$$

see also Ruiz et al. 2022.

Theoretical background

The upper limits are calculated based on Bayesian approach (Kraft et al. 1991):

- Low count regime → Poisson statistics!

$$P(N \mid S + B) = \frac{(S + B)^N \cdot e^{-(S+B)}}{N!}$$

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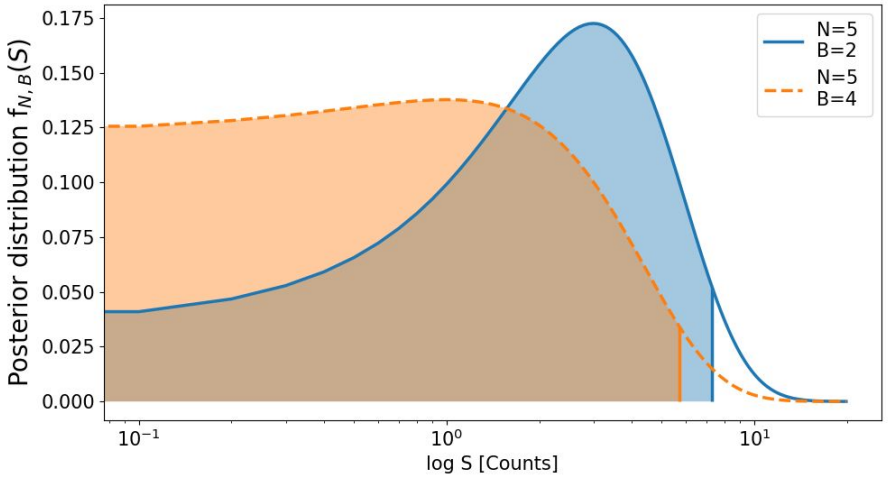

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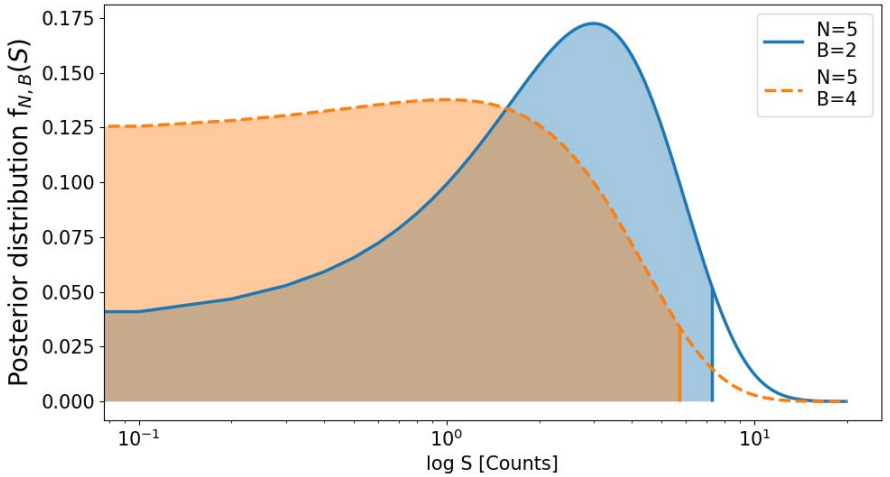
$$C \cdot \int_0^{UL} \frac{(S+B)^N \cdot e^{-(S+B)}}{N!} dS = CL$$



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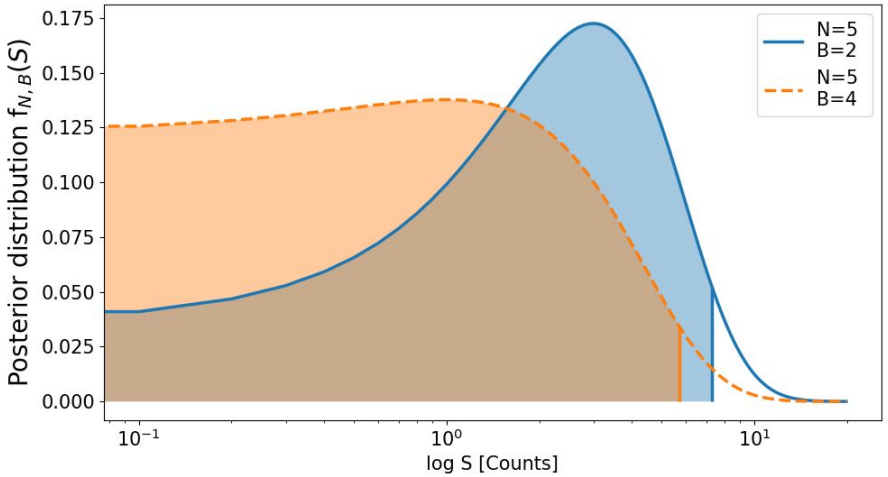

The upper limit, UL, at an arbitrary confidence interval CL is then defined as the value of S for which the cumulative probability equals CL.

see also Ruiz et al. 2022.

Theoretical background

Solving for UL:

$$\mathrm{UL} = \gamma^{-1}(N+1, \mathrm{CL}\cdot\Gamma(N+1,B) + \gamma(N+1,B)) - B.$$

$$\gamma(s,x) = \int_0^x t^{s-1}\exp(-t)dt$$

$$\Gamma(s,x) = \int_x^\infty t^{s-1}\exp(-t)dt$$

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UL only depends on N, B, and CL:

- N: Observed counts from image.fits
- B: Background counts from bkg.fits
- CL: Confidence interval.

see also Ruiz et al. 2022.

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To convert from upper limit to count rate and flux:

$$\mathrm{CR_{UL}} = \mathrm{UL}/(t\cdot\mathrm{EEF}) \qquad f_X = \frac{UL}{t\cdot EEF\cdot ECF}$$

- *t*: Exposure time
- EEF: Encircled energy fraction
- ECF: Energy conversion factor

see also Ruiz et al. 2022.

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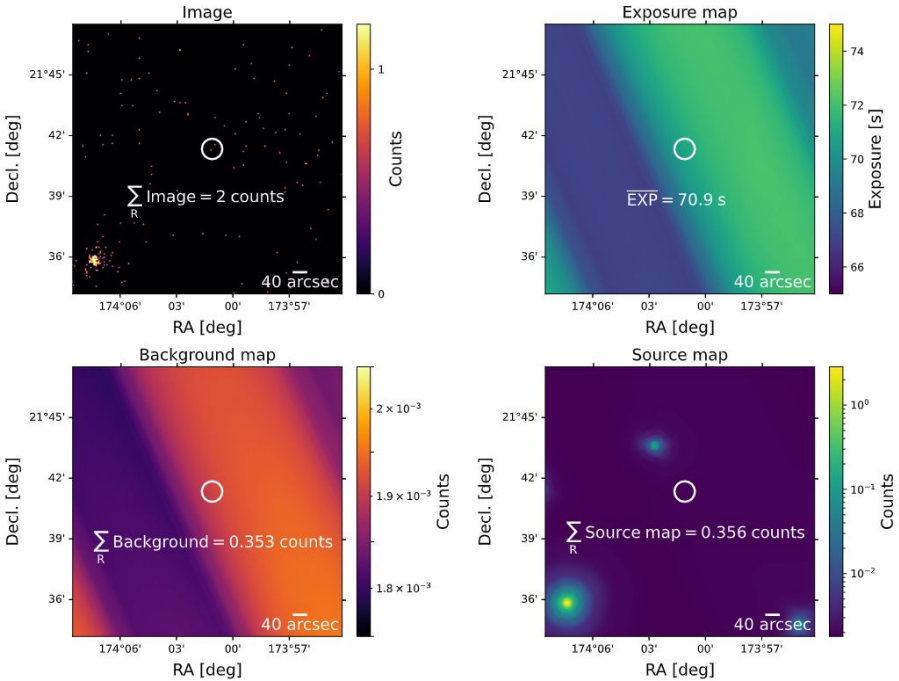


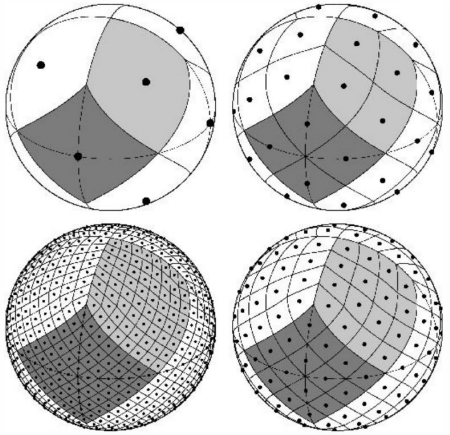
see also Ruiz et al. 2022.

The upper limit products

Column name	Format[a]	Units	Description
HEALPix index	K	–	Projection of the coordinates into HEALPix map.
Counts	J	cts	Extracted counts within the aperture from the science image.[a]
Bkg_counts	D	cts	Extracted background counts within the aperture from the background image.[b]
Bkg_SourceMap	D	cts	Extracted counts within the aperture from the source-map image.[b]
Exposure	D	s	Average exposure time within the circular aperture.
Flag_pos	J	–	Close neighbor flag[c] .
Flux_UL_B	D	erg s^{-1} cm^{-2}	Flux upper limit at CL=0.9987 (one-sided) based on column "Bkg_counts".[d]
Flux_UL_S	D	erg s^{-1} cm^{-2}	Same as UL_B, but based on the source-map counts ("Bkg_SourceMap").[d]

HEALPix: Hierarchical Equal Area isoLatitude Pixelation

The sphere is hierarchically tessellated into curvilinear quadrilaterals



```
from astropy_healpix import HEALPix
from astropy.coordinates import ICRS
hp = HEALPix(nside=2**16, order='nested', frame=ICRS())
print(hp.npix,'pixels -',hp.pixel_resolution.to(u.arcsec))
```

```
51539607552 pixels - 3.220768511078818 arcsec
```

```
healpix_index = hp.skycoord_to_healpix(coord)
coords = hp.healpix_to_skycoord(healpix_index)
```

Tubín-Arenas et al. (2024), A&A, 682, 35

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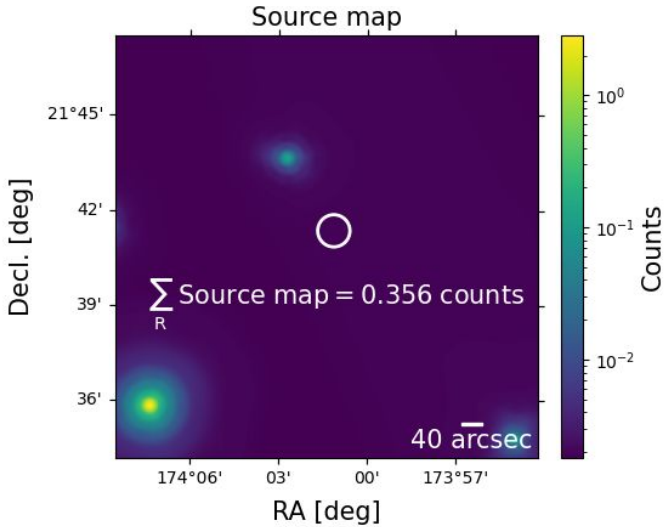

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$$f_X = \frac{UL}{t \cdot EEF \cdot ECF}$$

- Absorbed power-law spectral model:

$$\Gamma = 2.0$$
$$N_{\rm H} = 3 \times 10^{20} {\rm cm}^{-2}$$

Tubín-Arenas et al. (2024), A&A, 682, 35

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Model	Parameters	ECF[a] (cm^2 erg^{-1})	Multiplication Factor[b]
tbabs*pow	**$N_H = 3\times10^{20}$ cm^{-2}, $\Gamma = 2.0$**	**1.074×10^{12}**	**1**
	$N_H = 3\times10^{20}$ cm^{-2}, $\Gamma = 1.7$	1.060×10^{12}	1.013
tbabs*bbody	$N_H = 3\times10^{20}$ cm^{-2}, $kT = 0.05$ keV	7.566×10^{11}	1.419
	$N_H = 3\times10^{20}$ cm^{-2}, $kT = 0.15$ keV	1.229×10^{12}	0.874
apec	$kT = 0.3$ keV	1.202×10^{12}	0.892
	$kT = 1.0$ keV	1.212×10^{12}	0.885

Tubín-Arenas et al. (2024), A&A, 682, 35