Optics for Accurate Transient Localization in the X-Ray Sky

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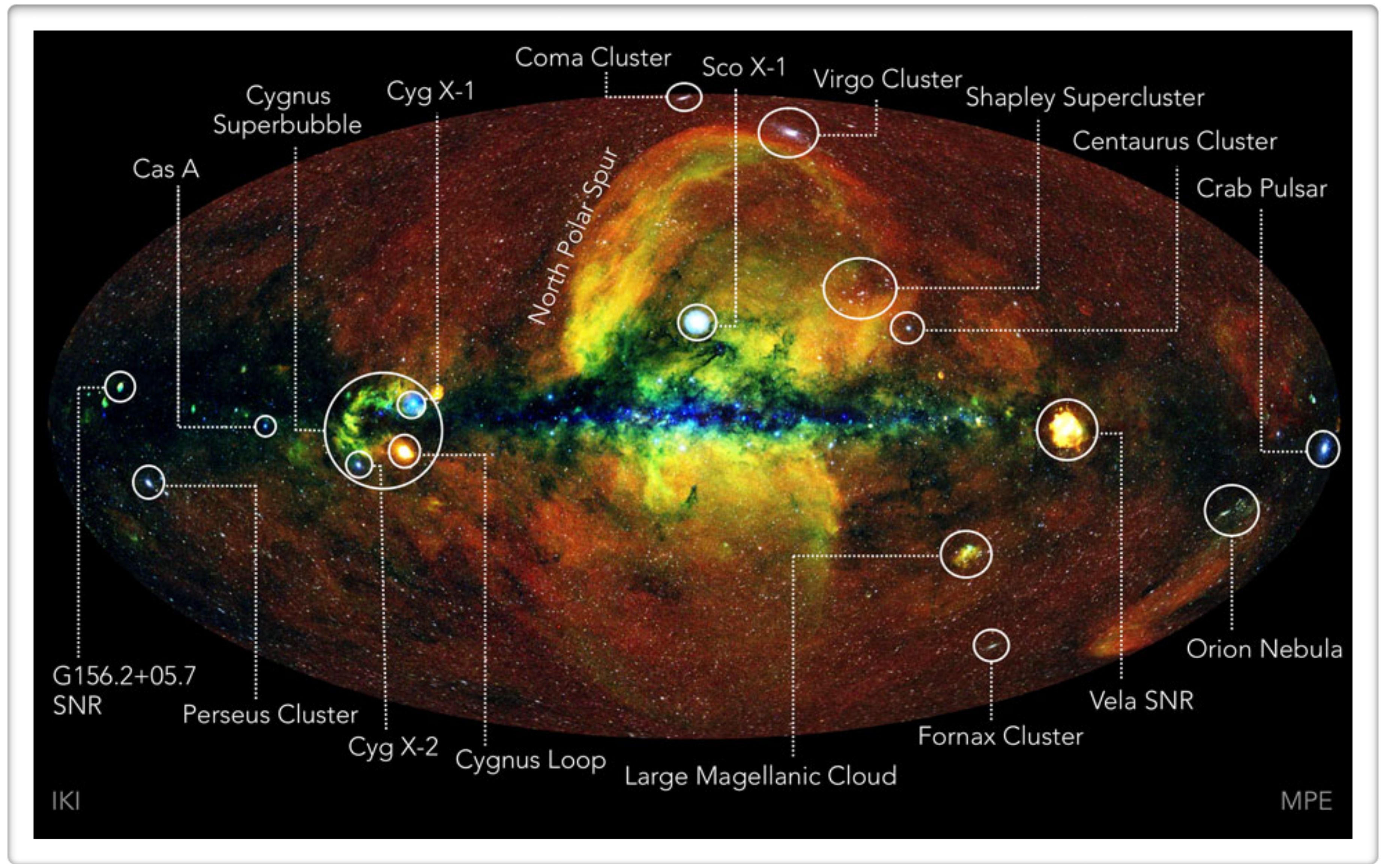
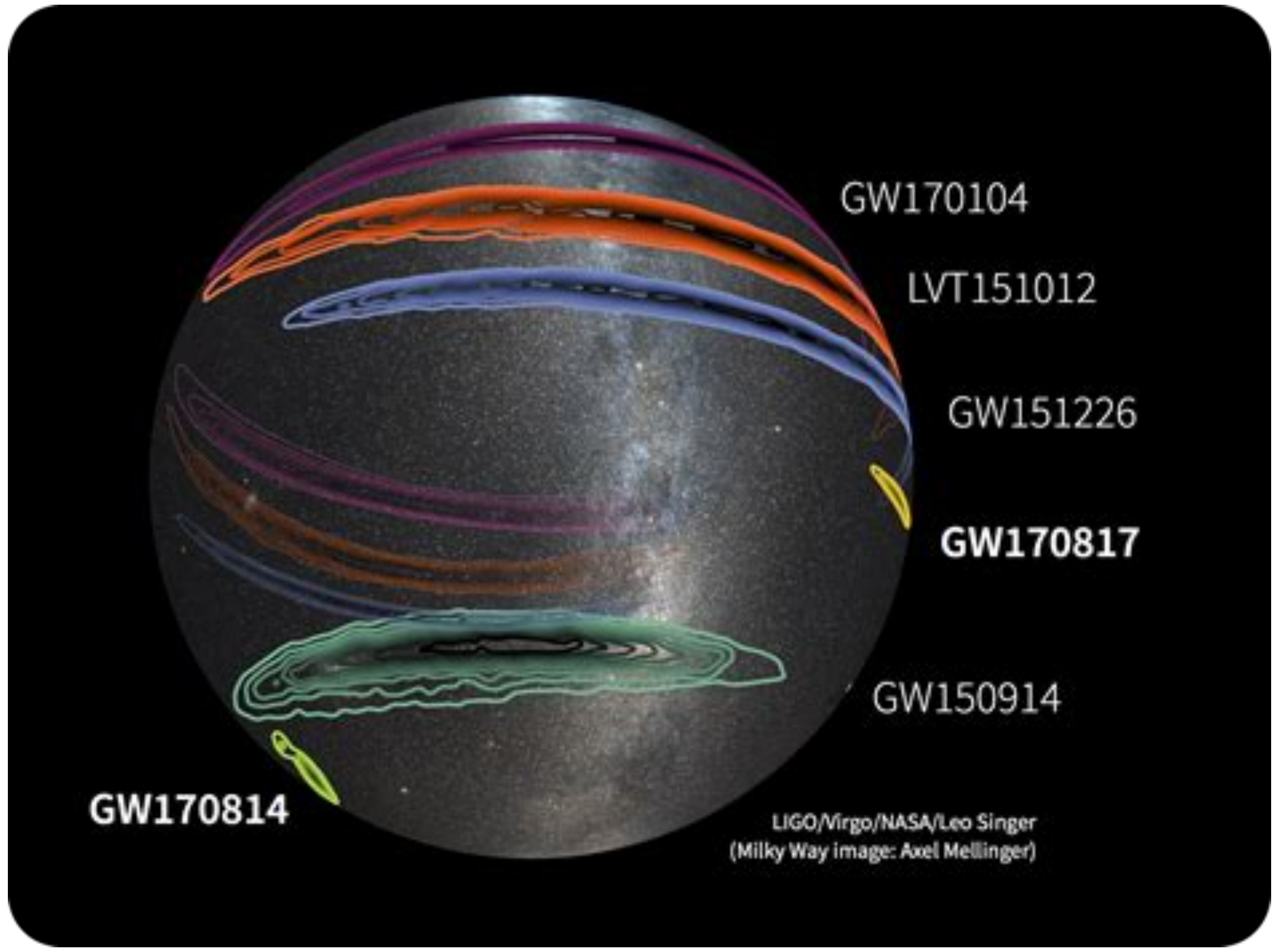
X-Ray Source Localization

- Gravitational wave observatories – such as the future Einstein Telescope – will pinpoint the localization to an area of the sky (~10-100 deg^2 also for future detectors)
    - Need capability to precisely localize the X-ray source in that area
- Same capability useful for other transients



Gravitational Waves Counterpart Localization

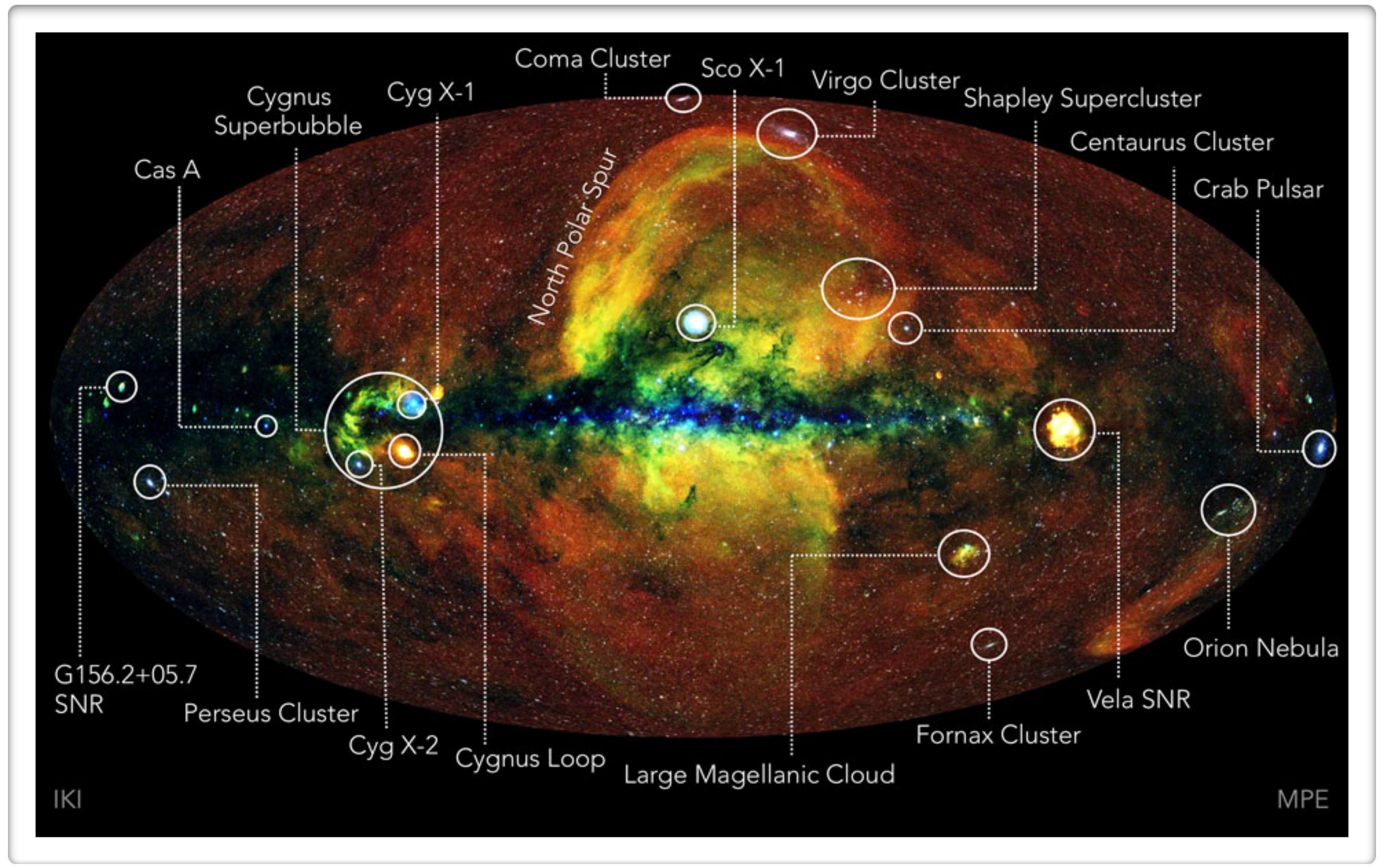
- GW signal scales as 1/D
- EM flux scales as $1/D^2$
    - Need EM telescopes to keep up, else future distant GW detections will have not EM counterpart

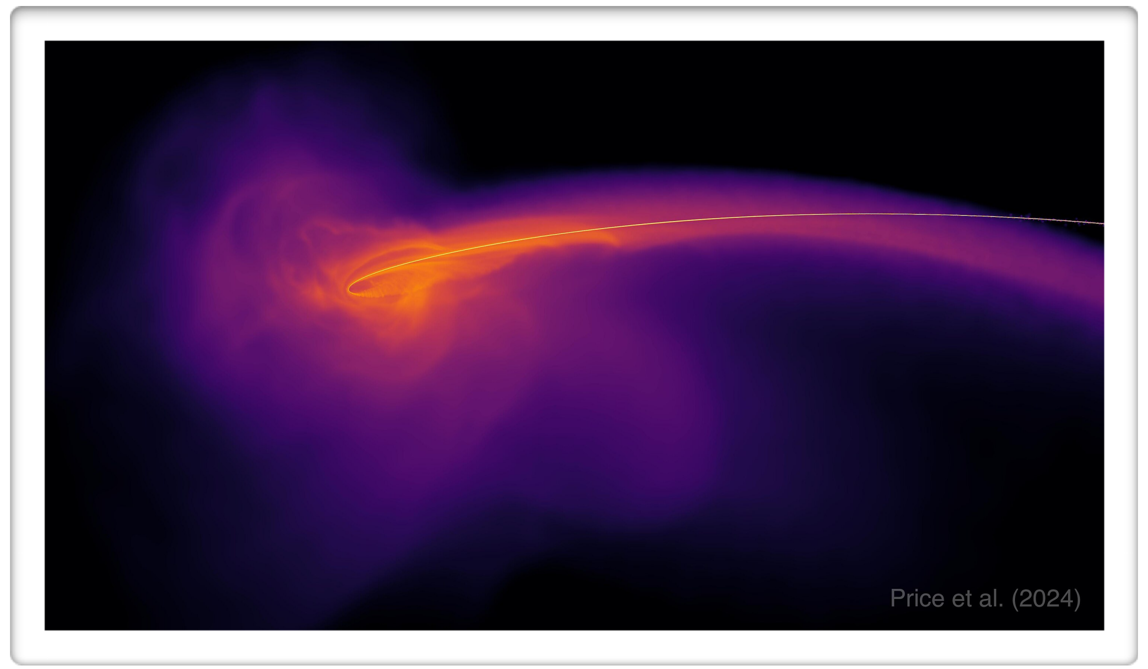


X-Ray Sky Survey

A wide field telescope with accurate localization capability can also survey the X-ray sky

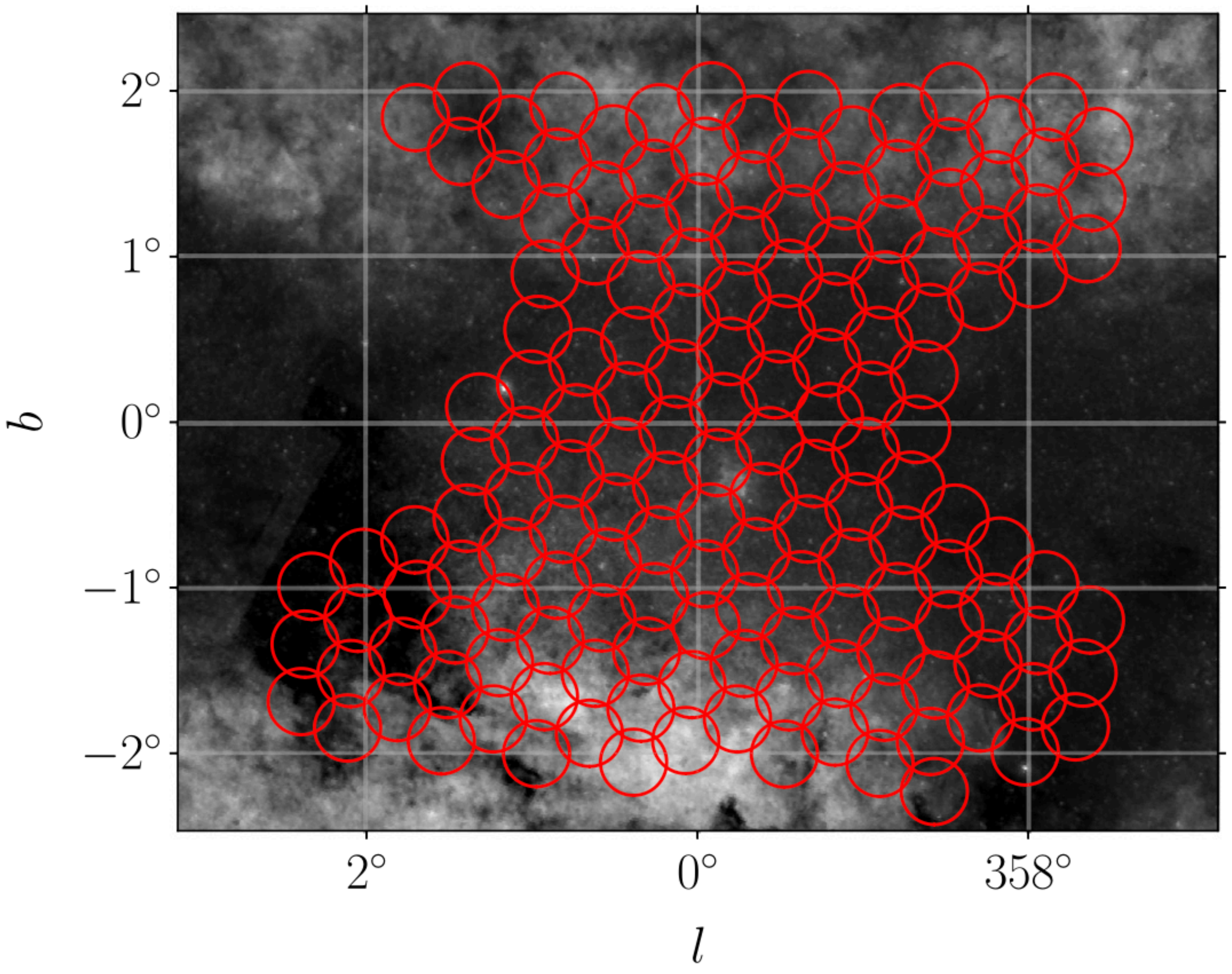
- Looking for transient sources
    - X-ray binaries
    - Supernovae and tidal disruption events shock-breakout
    - etc
- Monitoring persistent and variable sources





Example: Galactic Center Monitoring

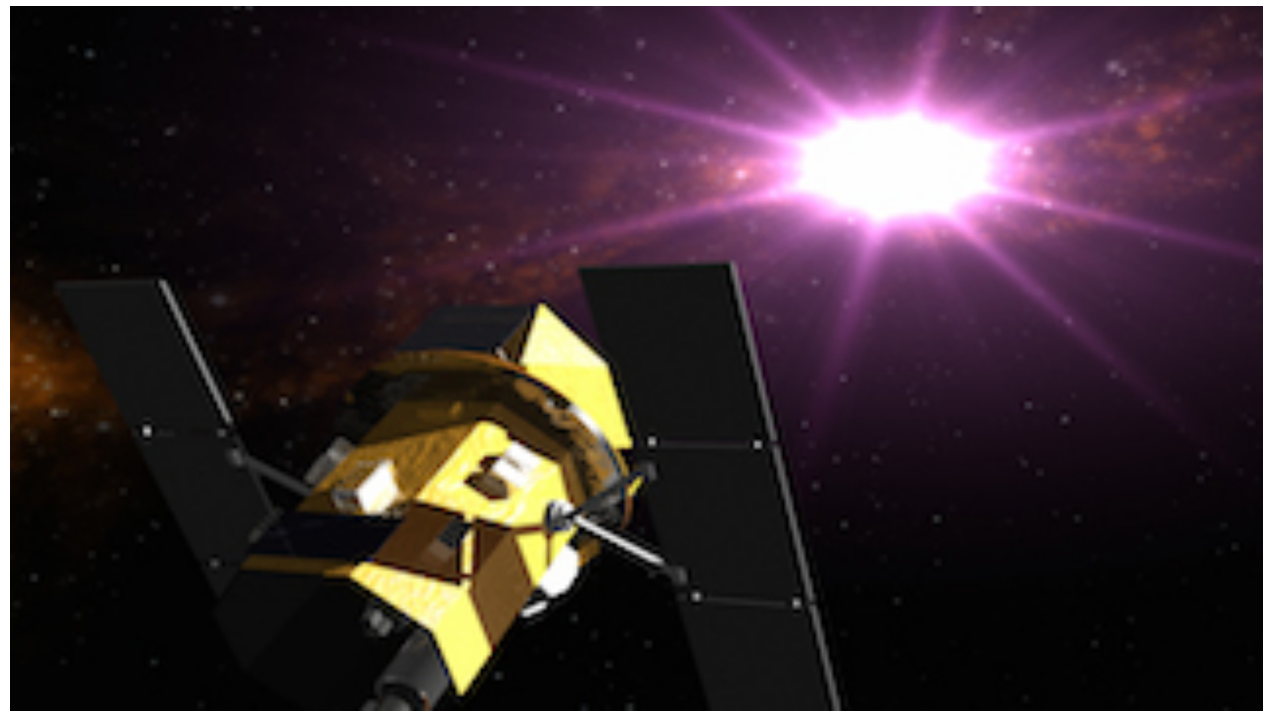
- Already 2357 X-ray sources in 17 arcmin square field around Sgr A* (Muno+ 2003)
    - Some transients have long or unknown recurrence time
    - Swift's field of view is 23 arcmin, a larger one allows monitoring the galactic center

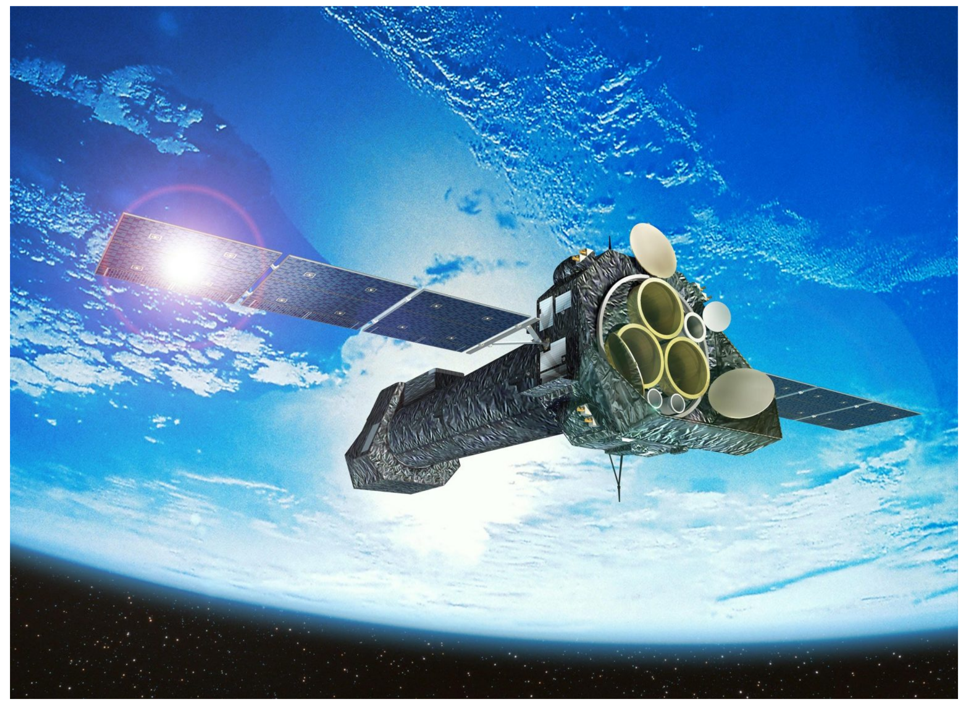


Swift Bulge Survey of the galactic center (Bahramian+ 2021)

Current X-Ray Telescopes

- Fermi, INTEGRAL, Swift/BAT: codified mask – high energy
- MAXI: codified mask – 2-20 keV
- Swift/XRT and Swift/UVOT: 23 arcmin diameter field
- Chandra and XMM-Newton: not suitable for fast surveys

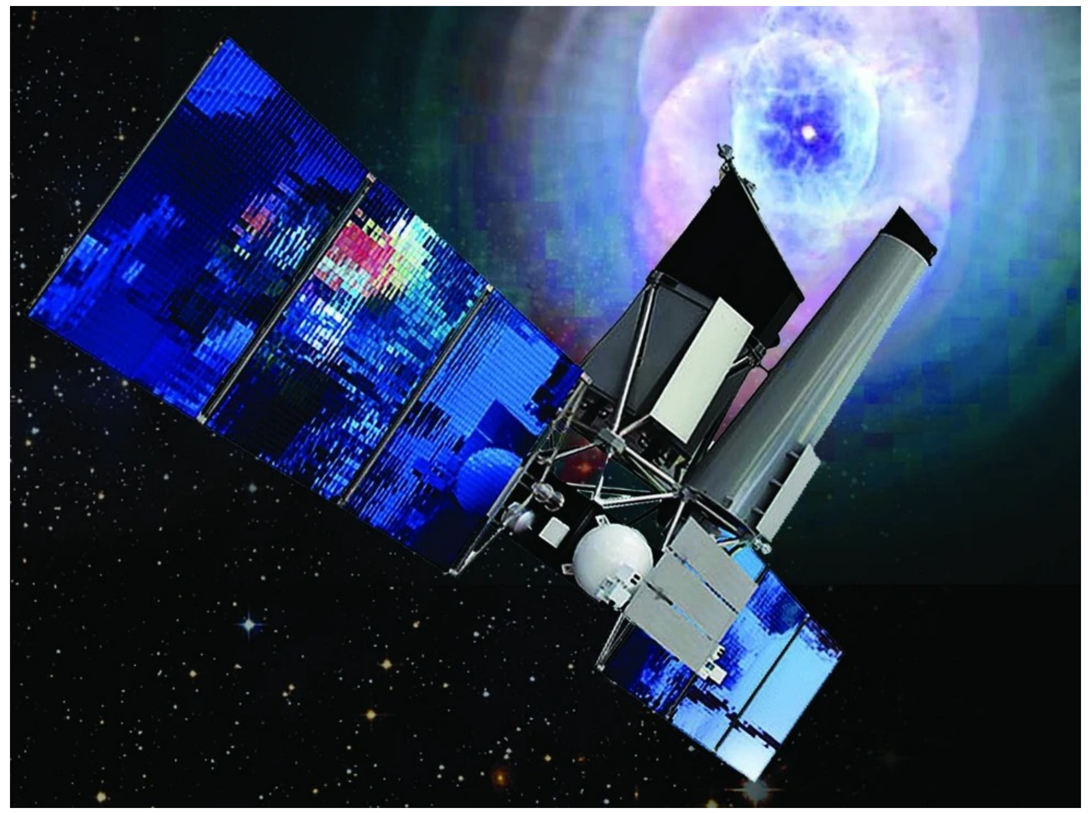


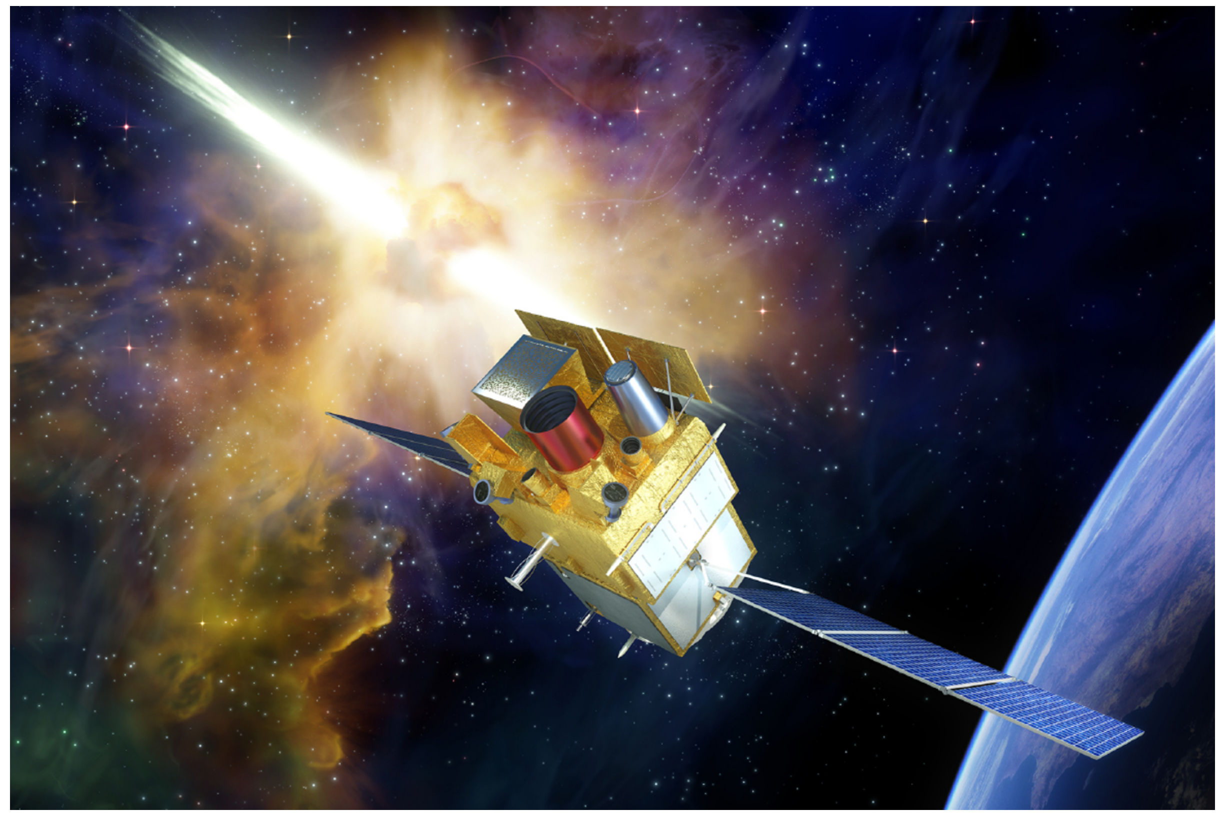


Images credits: NASA, ESA

Current X-Ray Surveys

- eROSITA (1 deg^2): currently not used
- MAXI: large field of view, very low sensitivity
- Einstein probe monitor: large field of view, low sensitivity
- SVOM: large field of view, low sensitivity

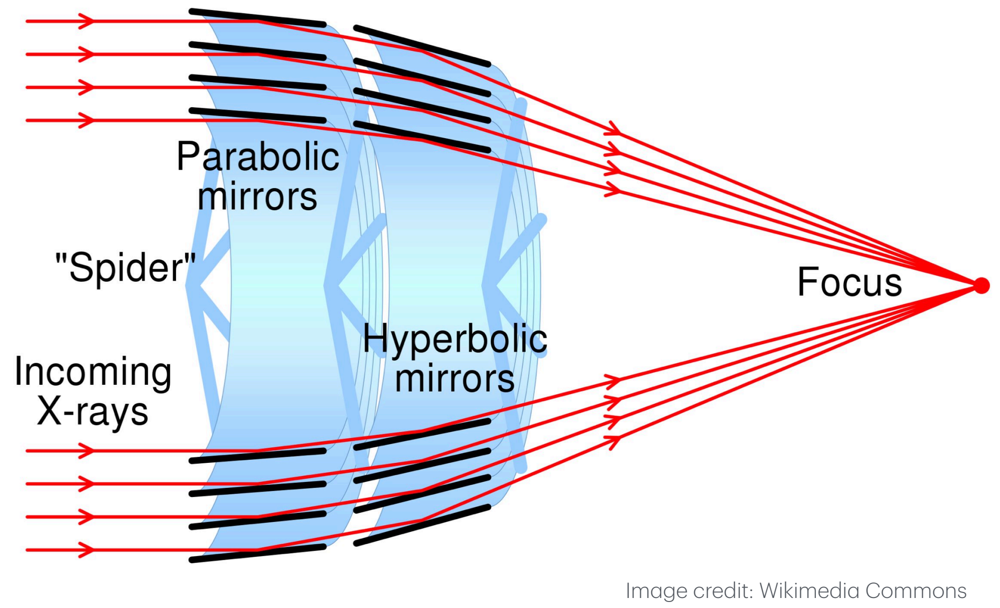




Images credits: eROSITA, Einstein Probe, SVOM

X-Ray Telescopes Today

- Most missions use the Wolter-I design
    - Same technology used for decades
- A few telescopes are suited as all sky monitors



No wide field telescope with accurate localization capabilities

Lobster Eye Design

Two designs:

- Angel design: square tubes
    - Has been used – with short focal lengths – to build all-sky monitors
- Schmidt design: two arrays of flat orthogonal mirrors

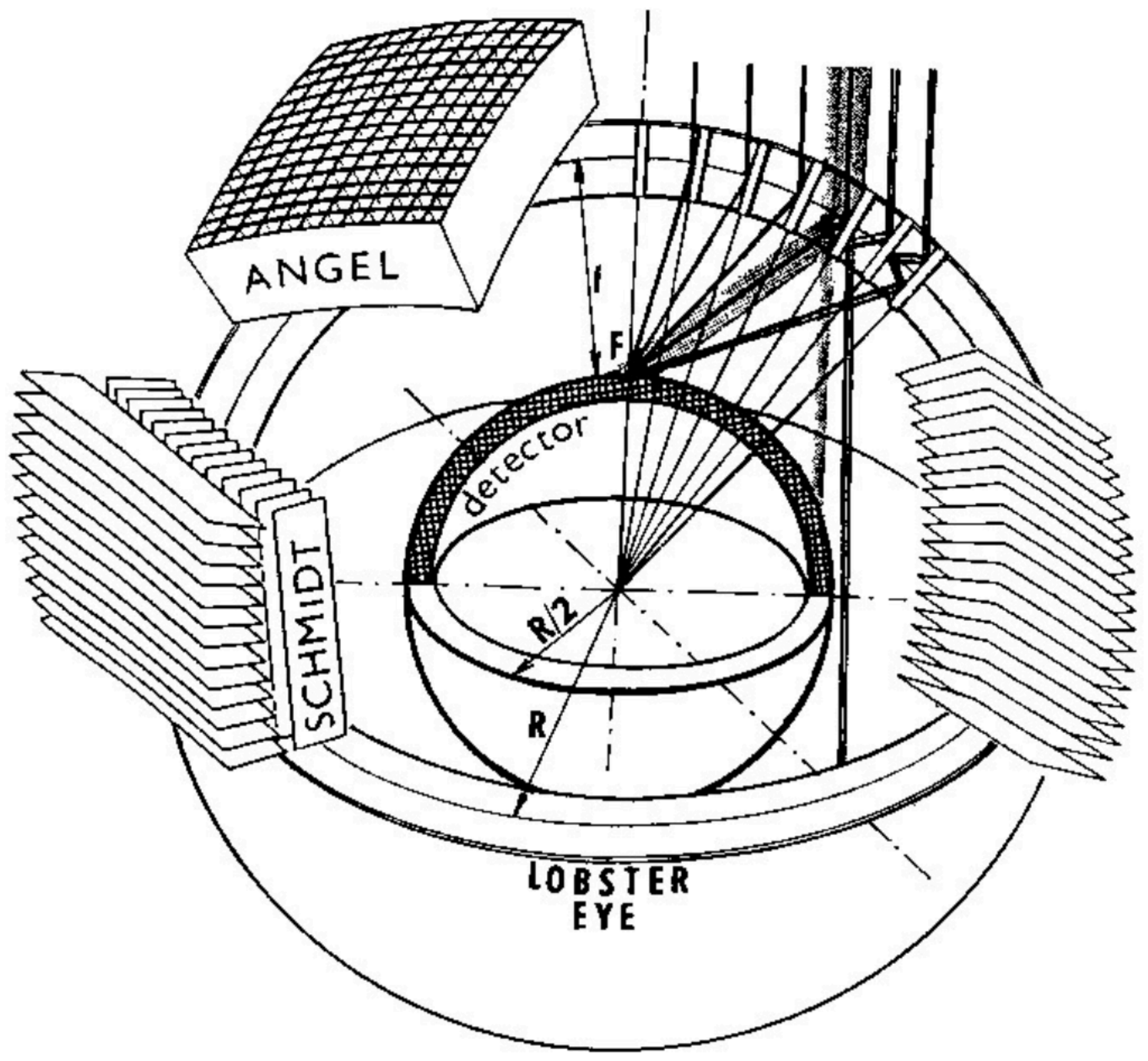
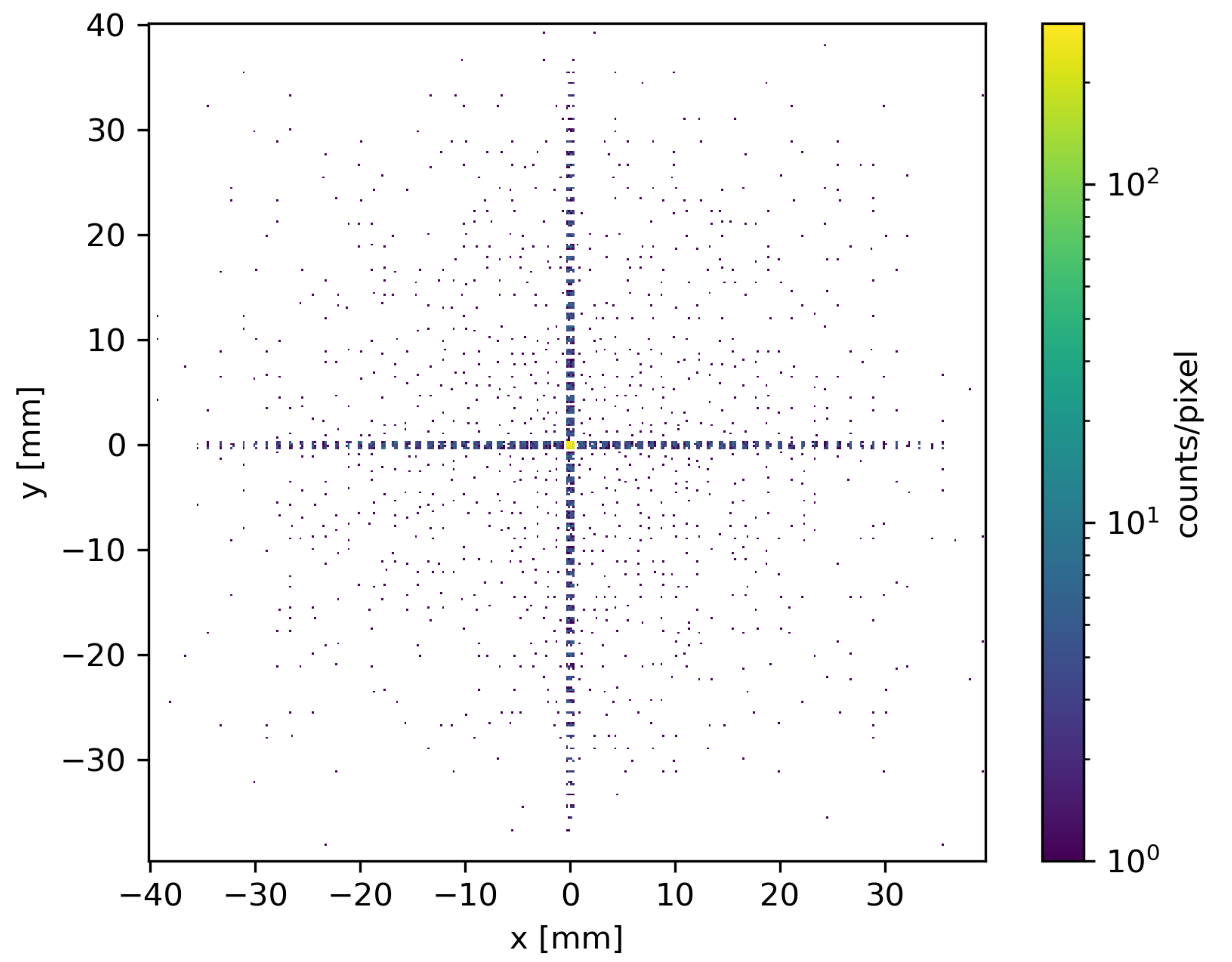
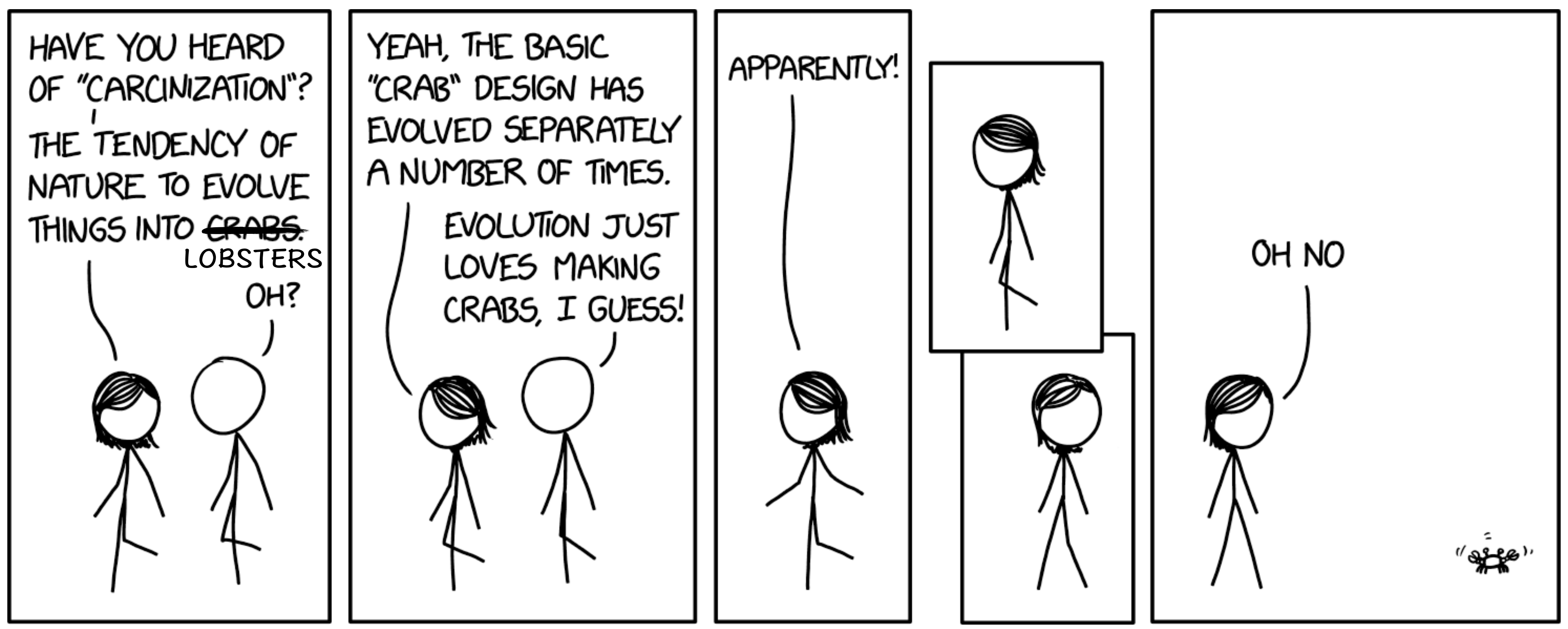


Image credit: Inneman 2001





Kirkpatrick-Baez

First historical idea to focus X-rays (Kirkpatrick and Baez 1948)

- Two arrays of parabolic (on one axis) reflecting surfaces:
    - The first array reflects the X-rays on a line, which are then focused to a point by the second — orthogonal — array

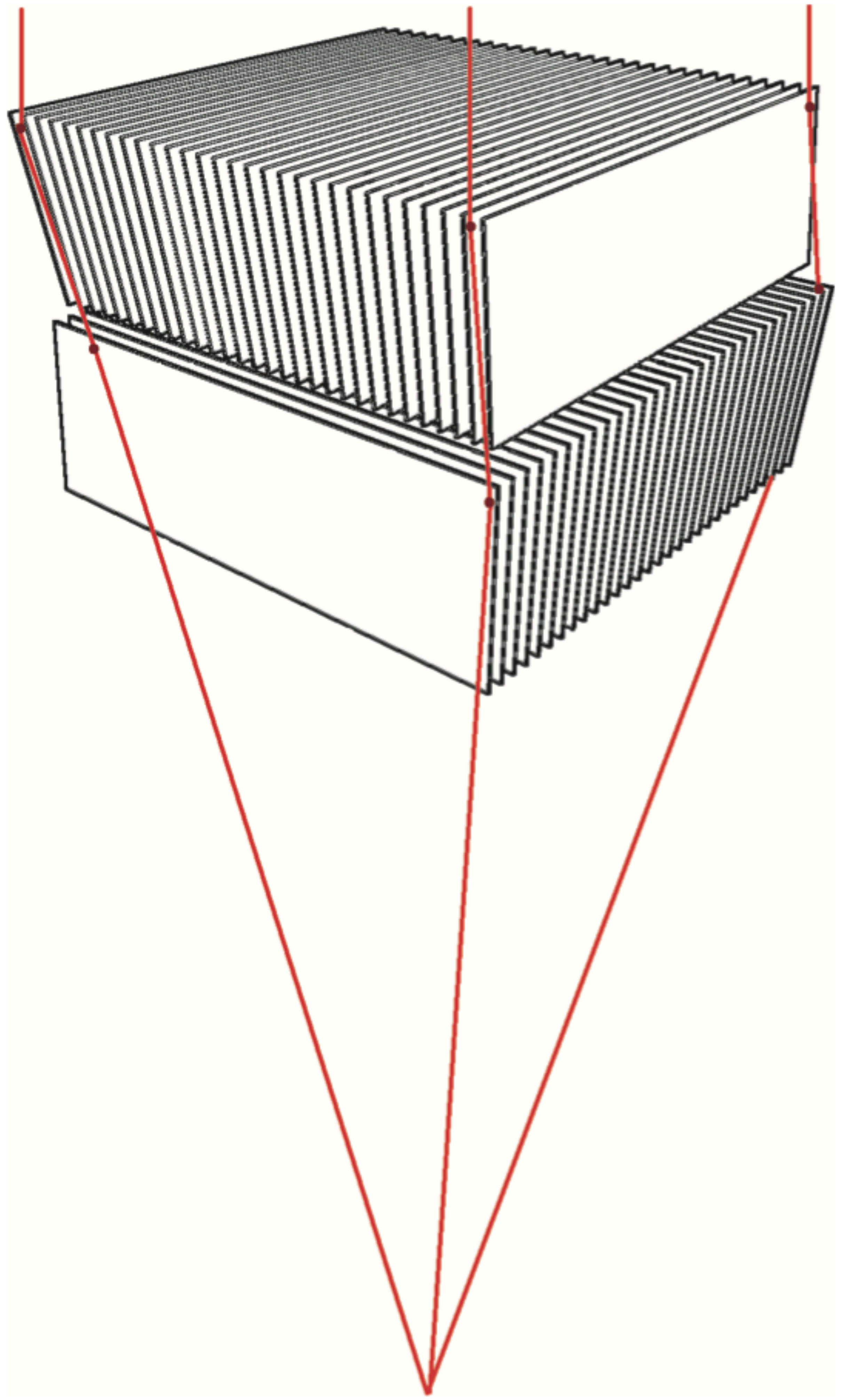
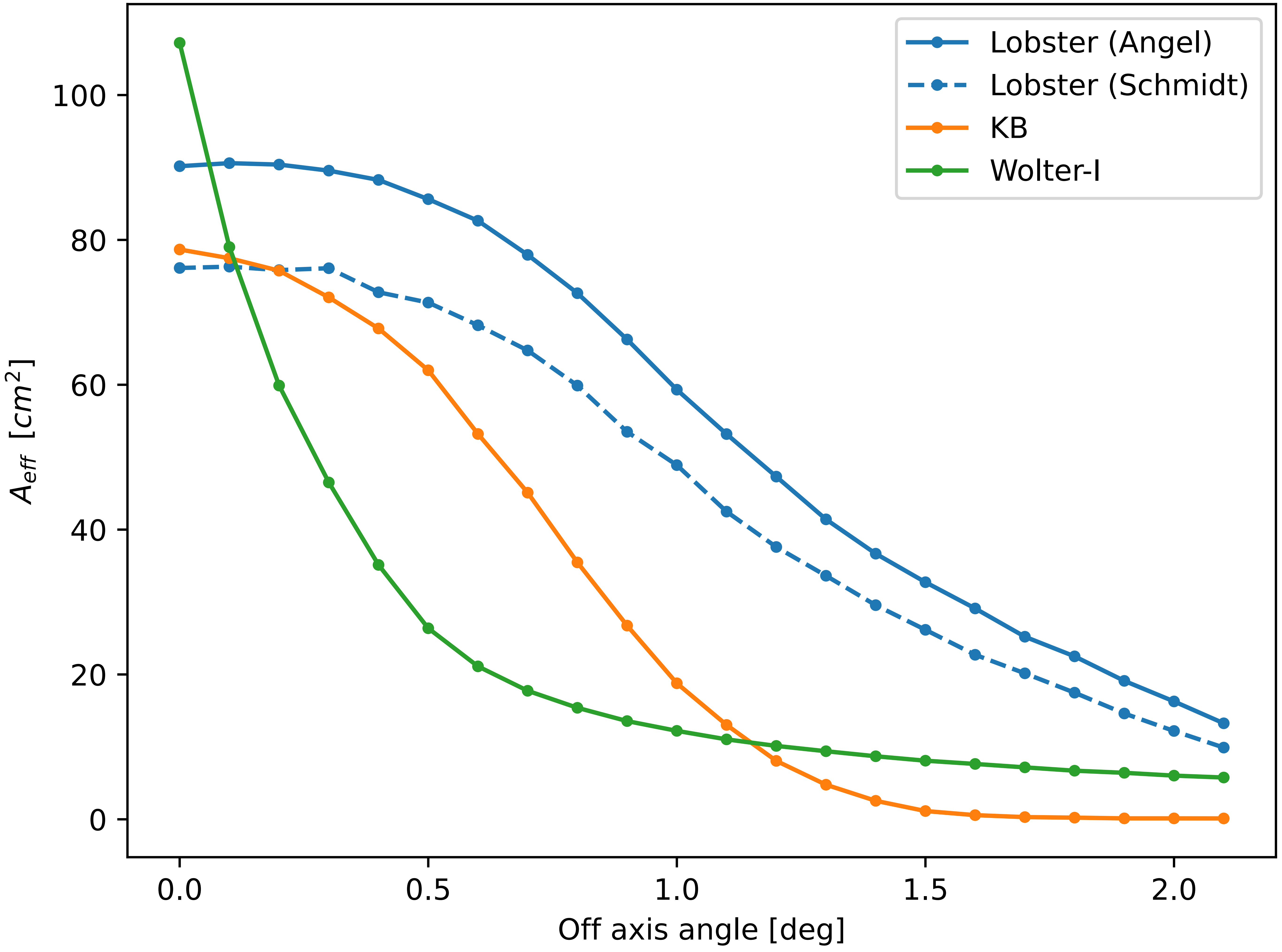


Image credit: Stefano Basso

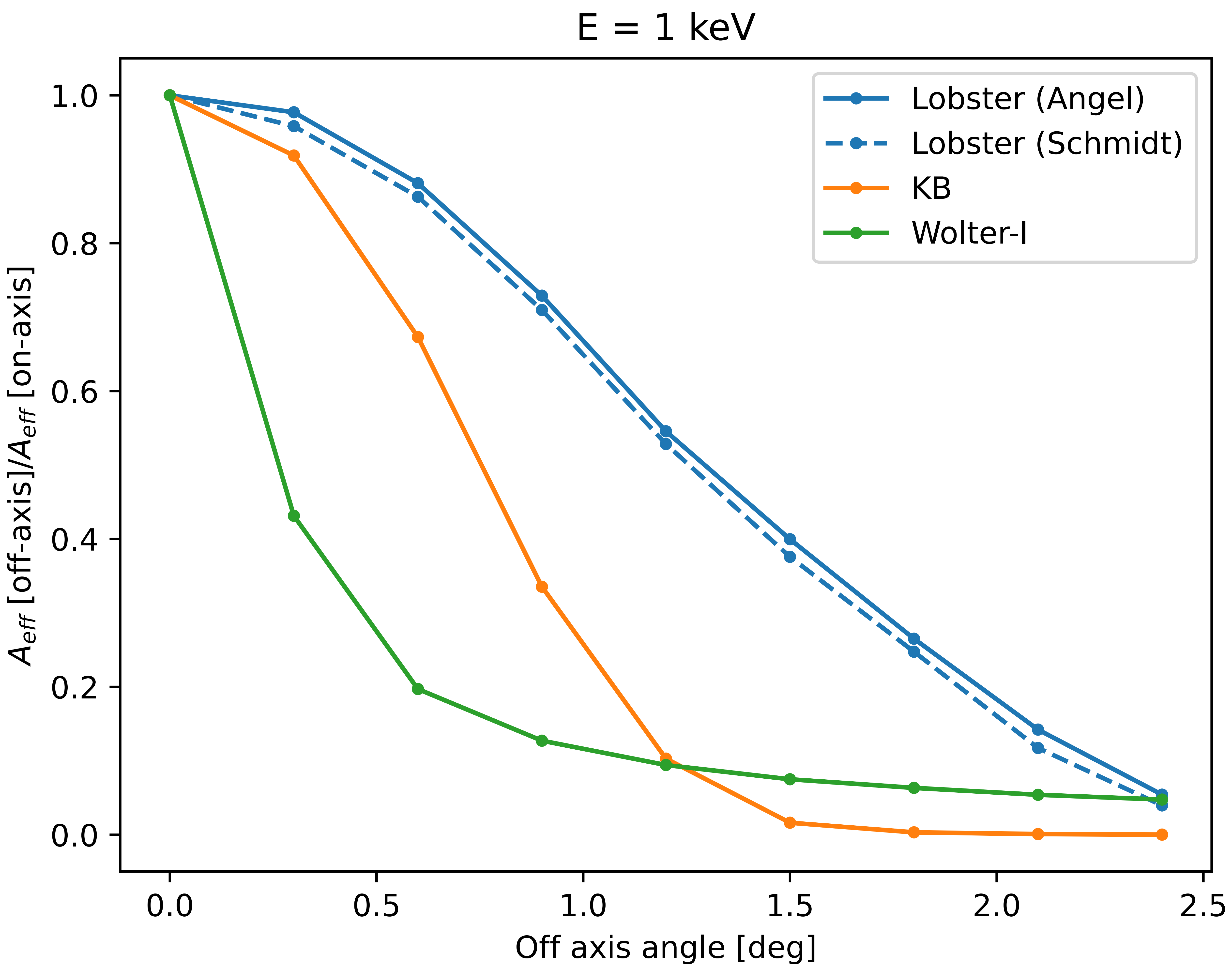
Effective Area Comparison

Focal distance	2.5 m
Energy	1 keV
Mirror length	75 mm
N mirrors per side	200
Mirror separation	0.75 mm
Mirror thickness	0.35 mm
Reflecting material	Au
Size	22×22 cm²



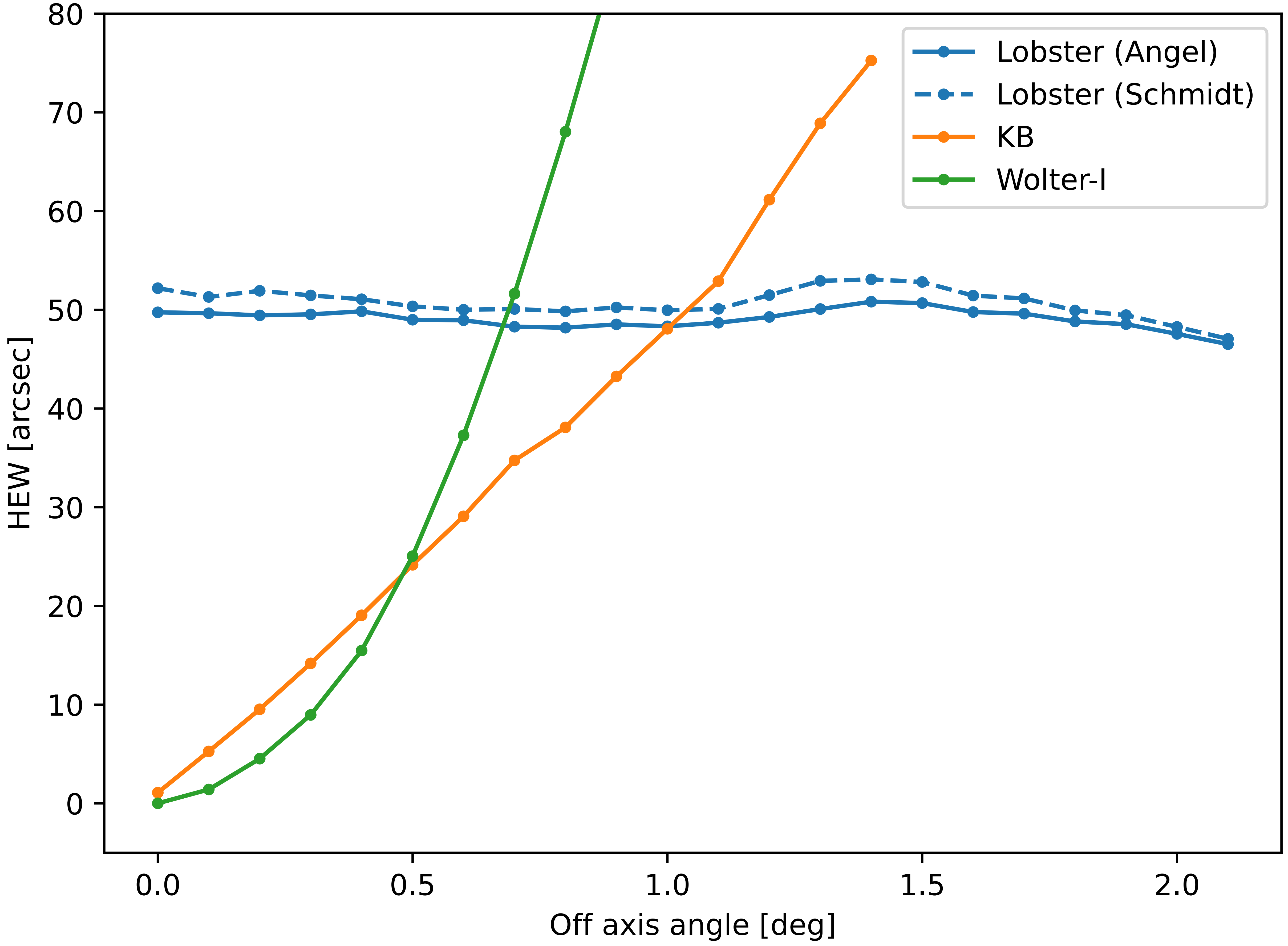
The focal distance considered is much longer than for all-sky monitors

Vignetting


E = 1 keV
Lobster (Angel)
Lobster (Schmidt)
KB
Wolter-I
A_{eff} [off-axis]/A_{eff} [on-axis]
Off axis angle [deg]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
2.5

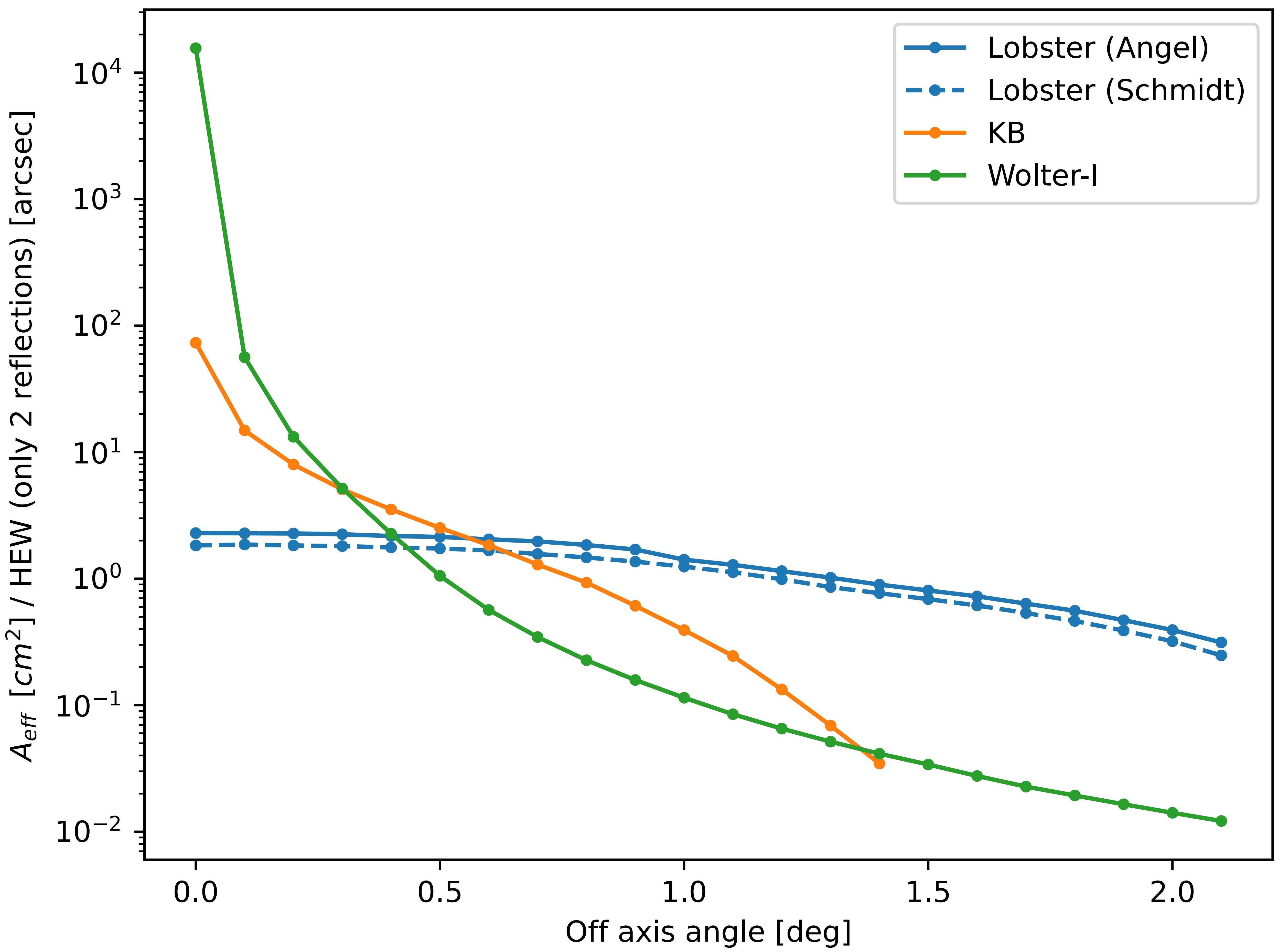
Half Energy Width Comparison

On-axis Kirkpatrick-Baez (and Wolter-I) give better half energy width, but off-axis decreases faster than Lobsters



HEW was computed from the thickness of the cross

Ratio of effective area/half energy width



Convolution of effective area and field of view

$$\text{Etendue} = \int \frac{A_{eff}}{hew^k} \cdot \mathrm{d}FOV$$

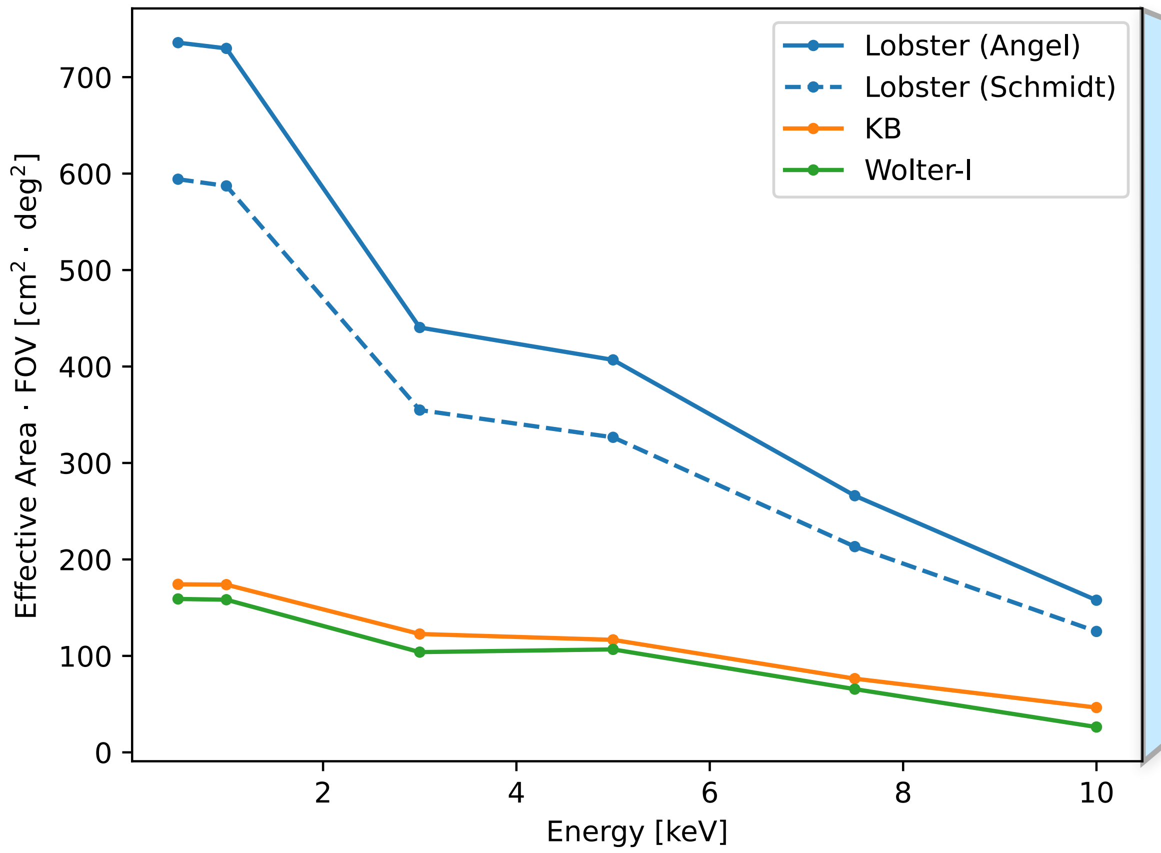
k	Angel	Schmidt	Kirkpatrick-Baez	Wolter-I
0	730.06	587.59	173.64	158.19
1	15.08	11.71	7.12	4.65
2	0.31	0.23	0.47	0.47

E = 1keV

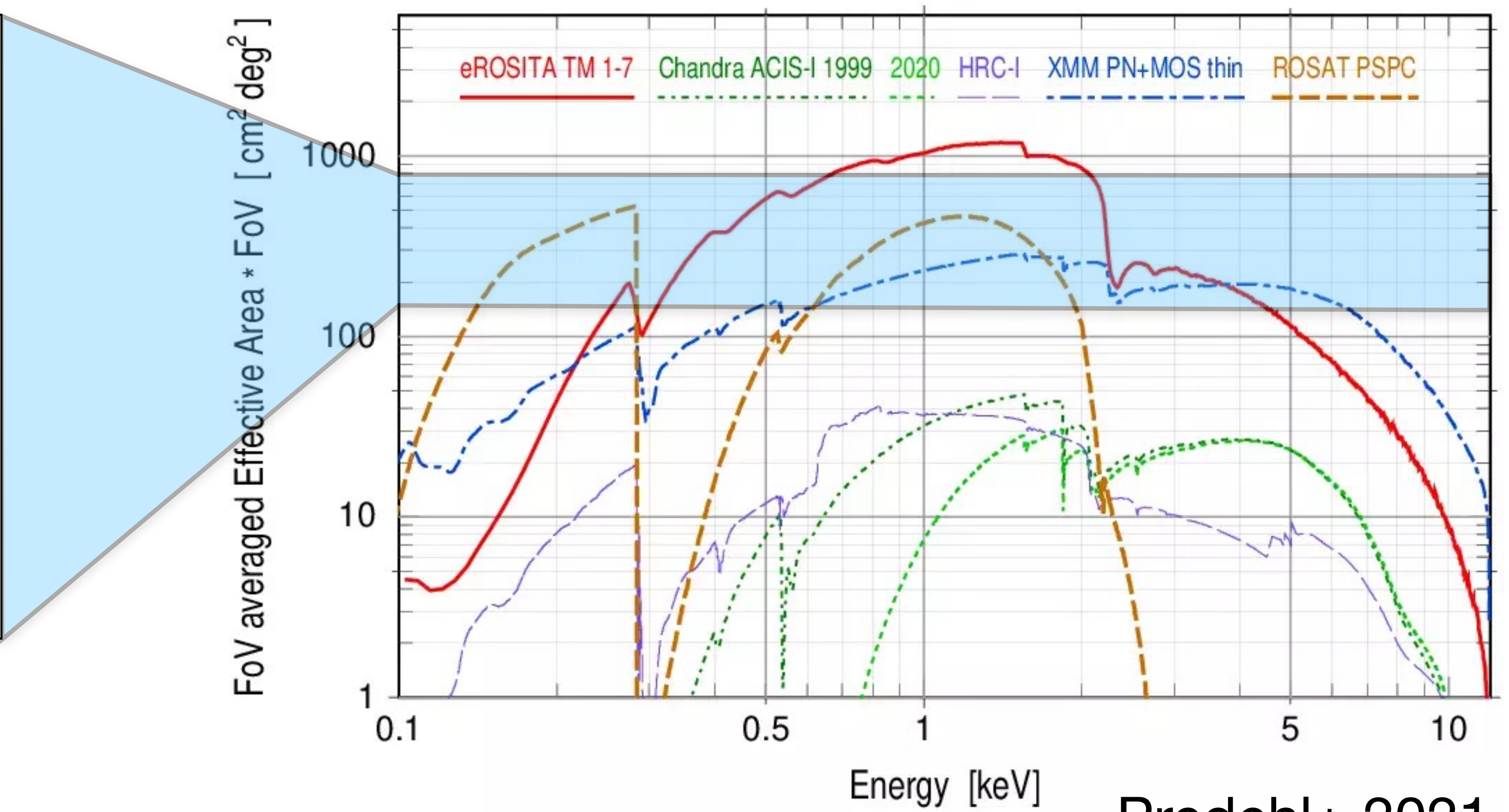
(Also considered a 10 arcsec fabrication error)

Comparison with other Missions

Grasp with our designs



Grasp with other telescopes



Predehl+ 2021

- Greater grasp than Chandra, comparable to eROSITA – made however of 7 modules
  - Design simulated here could also be expanded in area or number of modules
- Smaller field of view but greater effective area than wide-field/all-sky monitors

	Our design	Einstein probe	SVOM/MXT
Focal distance	2-4 m	0.375 m	1.15 m
Effective Area	100 cm^2	2-3 cm^2	35 cm^2
Field of view	10 deg^2	3600 deg^2	1 deg^2
Angular resolution	0.5-1 arcmin	5 arcmin	<2 arcmin

Conclusion

Need for accurate transient localizator for follow-up of gravitational wave telescopes – such as the forthcoming Einstein telescope, and as transient monitor

- Lobster eyes with long focal lengths, or Kirkpatrick-Baez, could be suitable
    - A ~10deg^2 field of view, with effective area of ~100cm^2 and localization capability of tens arcsec is possible