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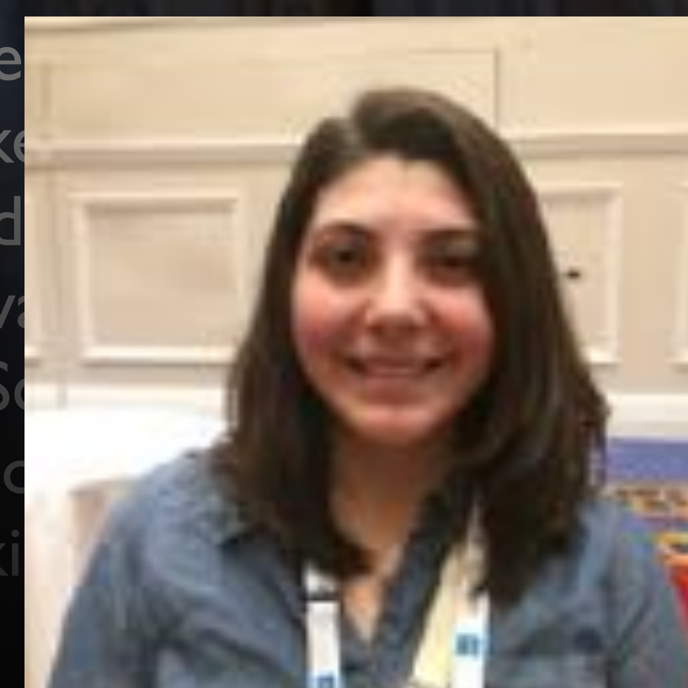
X-Ray Dust Tomography: A New Frontier in Galactic Exploration

Sebastian Heinz (UW-Madison)

Lia Corrales, UMichigan Ann Arbor

Morgan Adams, FSU Tallahassee



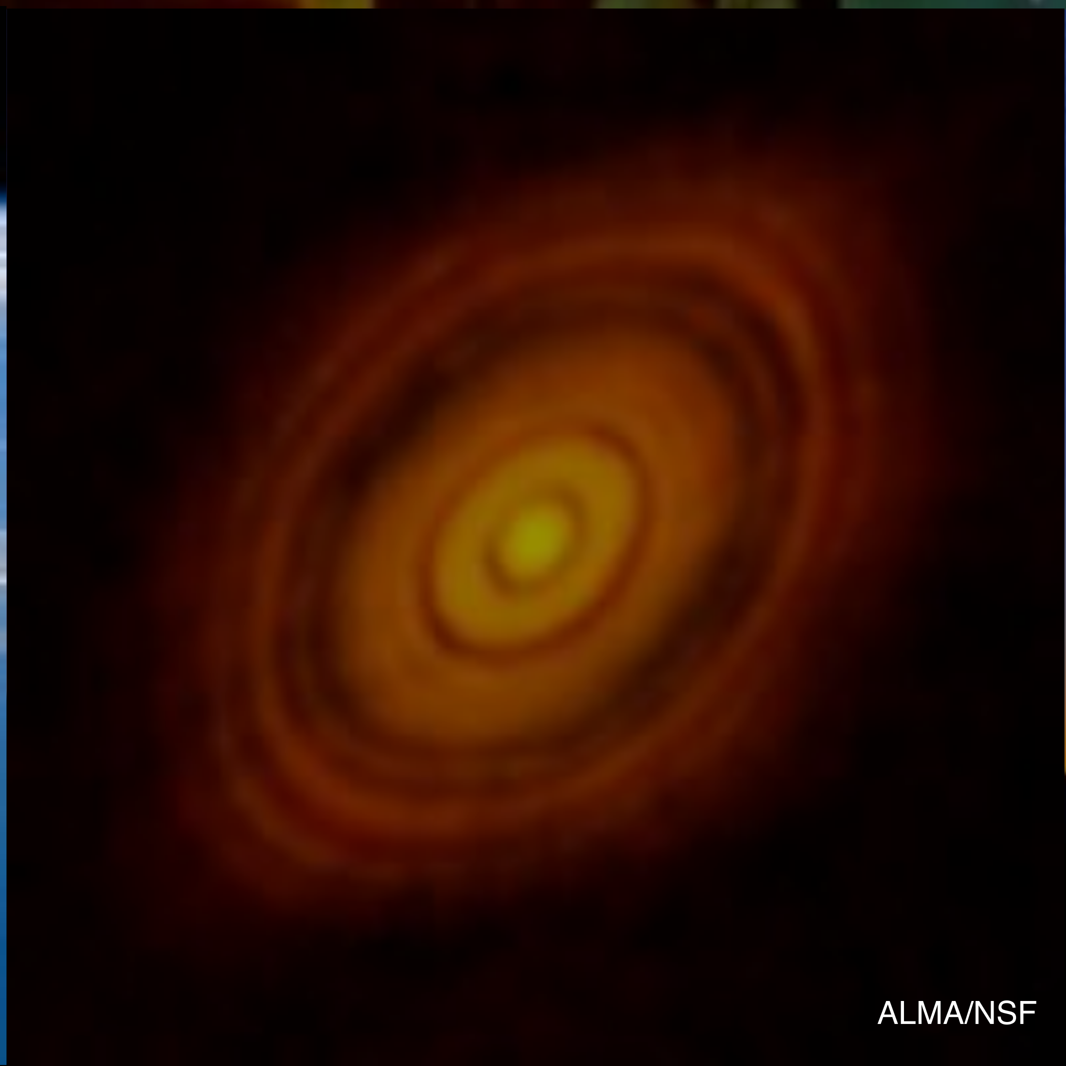
Brianna Mills, University of Virginia

Outline

- Brief introduction
- Cir X-1
- The V404 Cyg outburst
- Constraints on dust and Galaxy
- Future prospects

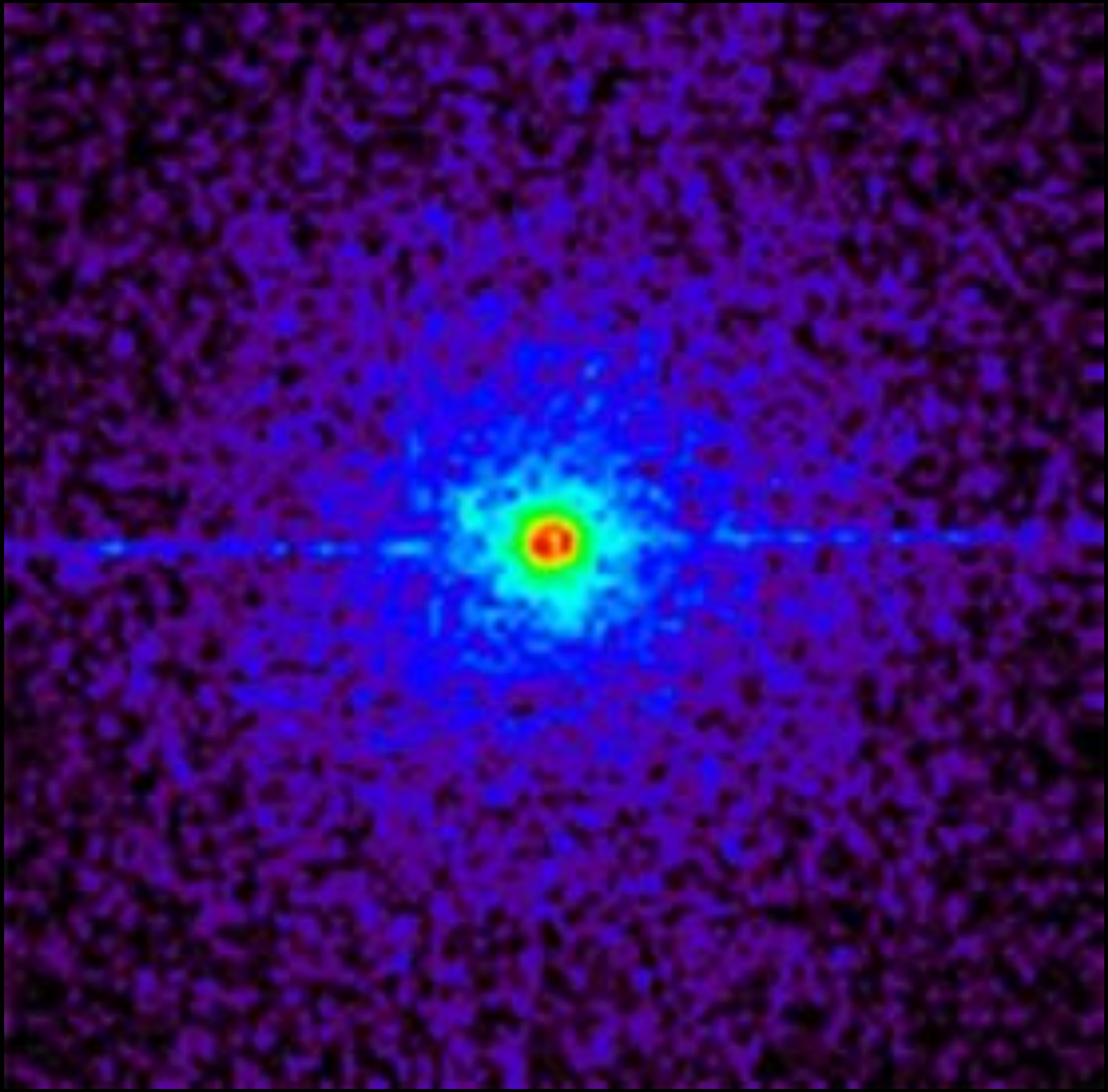
Interstellar Dust:

- The radiation shield for forming stars
- The building blocks of planets

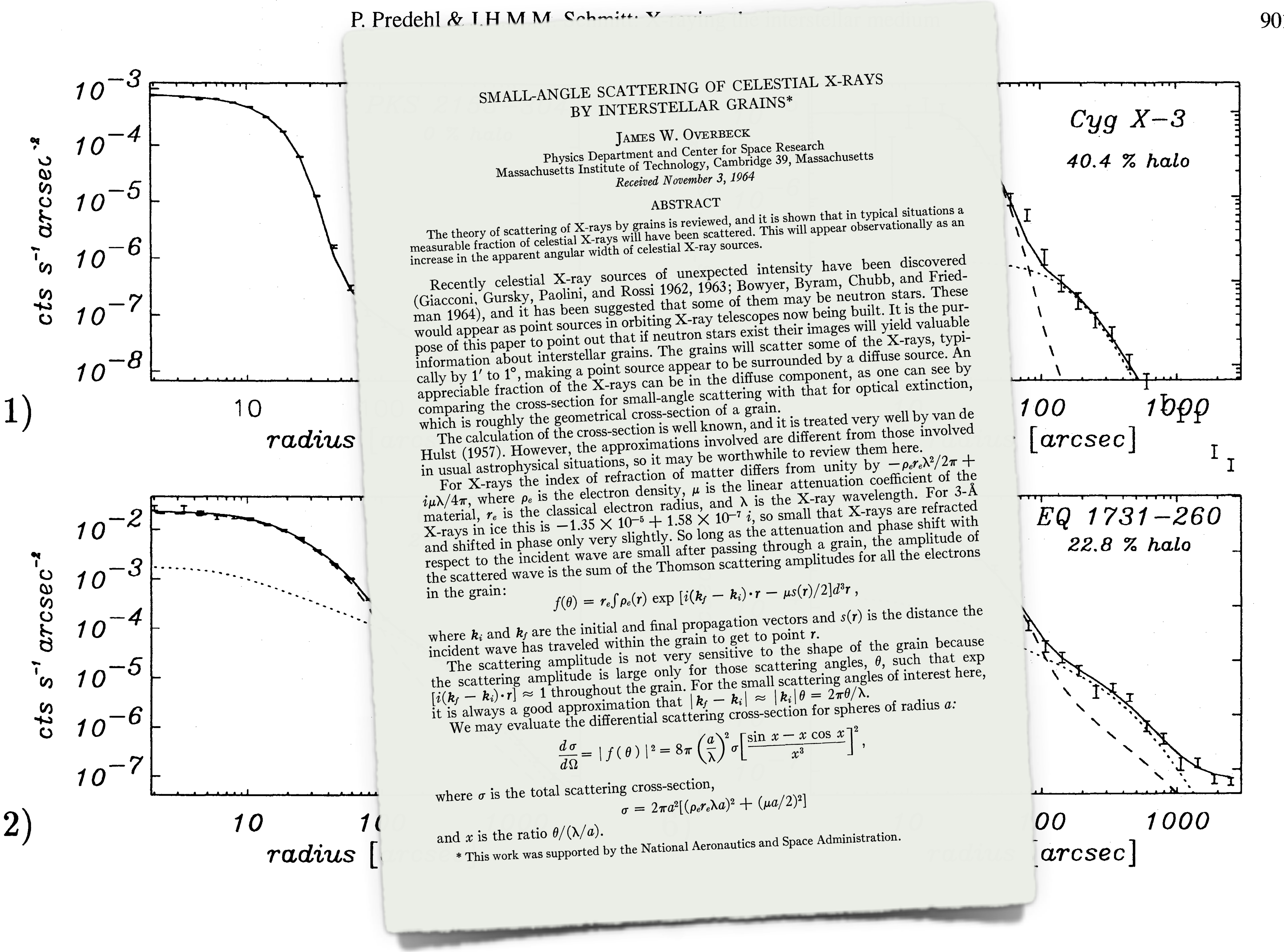


Interstellar Dust

- How do we measure its distance?
- What is its distribution in the Galaxy?
- What is it made of?
  - What is the grain size distribution?
  - What it its mineralogy?



Cygnus X-3



SMALL-ANGLE SCATTERING OF CELESTIAL X-RAYS BY INTERSTELLAR GRAINS*

JAMES W. OVERBECK
Physics Department and Center for Space Research
Massachusetts Institute of Technology, Cambridge 39, Massachusetts

Received November 3, 1964

ABSTRACT

The theory of scattering of X-rays by grains is reviewed, and it is shown that in typical situations a measurable fraction of celestial X-rays will have been scattered. This will appear observationally as an increase in the apparent angular width of celestial X-ray sources.

Recently celestial X-ray sources of unexpected intensity have been discovered (Giacconi, Gursky, Paolini, and Rossi 1962, 1963; Bowyer, Byram, Chubb, and Friedman 1964), and it has been suggested that some of them may be neutron stars. These would appear as point sources in orbiting X-ray telescopes now being built. It is the purpose of this paper to point out that if neutron stars exist their images will yield valuable information about interstellar grains. The grains will scatter some of the X-rays, typically by 1′ to 1°, making a point source appear to be surrounded by a diffuse source. An appreciable fraction of the X-rays can be in the diffuse component, as one can see by comparing the cross-section for small-angle scattering with that for optical extinction, which is roughly the geometrical cross-section of a grain.

The calculation of the cross-section is well known, and it is treated very well by van de Hulst (1957). However, the approximations involved are different from those involved in usual astrophysical situations, so it may be worthwhile to review them here.

For X-rays the index of refraction of matter differs from unity by $-\rho_e r_e \lambda^2/2\pi + i\mu\lambda/4\pi$, where ρ_e is the electron density, μ is the linear attenuation coefficient of the material, r_e is the classical electron radius, and λ is the X-ray wavelength. For 3-Å X-rays in ice this is $-1.35 \times 10^{-5} + 1.58 \times 10^{-7}\, i$, so small that X-rays are refracted and shifted in phase only very slightly. So long as the attenuation and phase shift with respect to the incident wave are small after passing through a grain, the amplitude of the scattered wave is the sum of the Thomson scattering amplitudes for all the electrons in the grain:

$$f(\theta) = r_e \int \rho_e(\boldsymbol{r}) \exp\,[i(\boldsymbol{k}_f - \boldsymbol{k}_i)\cdot \boldsymbol{r} - \mu s(\boldsymbol{r})/2]\, d^3 \boldsymbol{r}\,,$$

where $\boldsymbol{k}_i$ and $\boldsymbol{k}_f$ are the initial and final propagation vectors and $s(\boldsymbol{r})$ is the distance the incident wave has traveled within the grain to get to point $\boldsymbol{r}$.

The scattering amplitude is not very sensitive to the shape of the grain because the scattering amplitude is large only for those scattering angles, θ, such that exp $[i(\boldsymbol{k}_f - \boldsymbol{k}_i)\cdot \boldsymbol{r}] \approx 1$ throughout the grain. For the small scattering angles of interest here, it is always a good approximation that $|\boldsymbol{k}_f - \boldsymbol{k}_i| \approx |\boldsymbol{k}_i|\theta = 2\pi\theta/\lambda$.

We may evaluate the differential scattering cross-section for spheres of radius a:

$$\frac{d\sigma}{d\Omega} = |\, f(\theta)\,|^2 = 8\pi \left(\frac{a}{\lambda}\right)^2 \sigma \left[\frac{\sin x - x \cos x}{x^3}\right]^2,$$

where σ is the total scattering cross-section,

$$\sigma = 2\pi a^2 [(\rho_e r_e \lambda a)^2 + (\mu a/2)^2]$$

and x is the ratio $\theta/(\lambda/a)$.

* This work was supported by the National Aeronautics and Space Administration.

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THE SIZE DISTRIBUTION OF INTERSTELLAR GRAINS

JOHN S. MATHIS, WILLIAM RUMPL, AND KENNETH H. NORDSIECK
Washburn Observatory, University of Wisconsin–Madison
Received 1977 January 24; accepted 1977 April 11

ABSTRACT

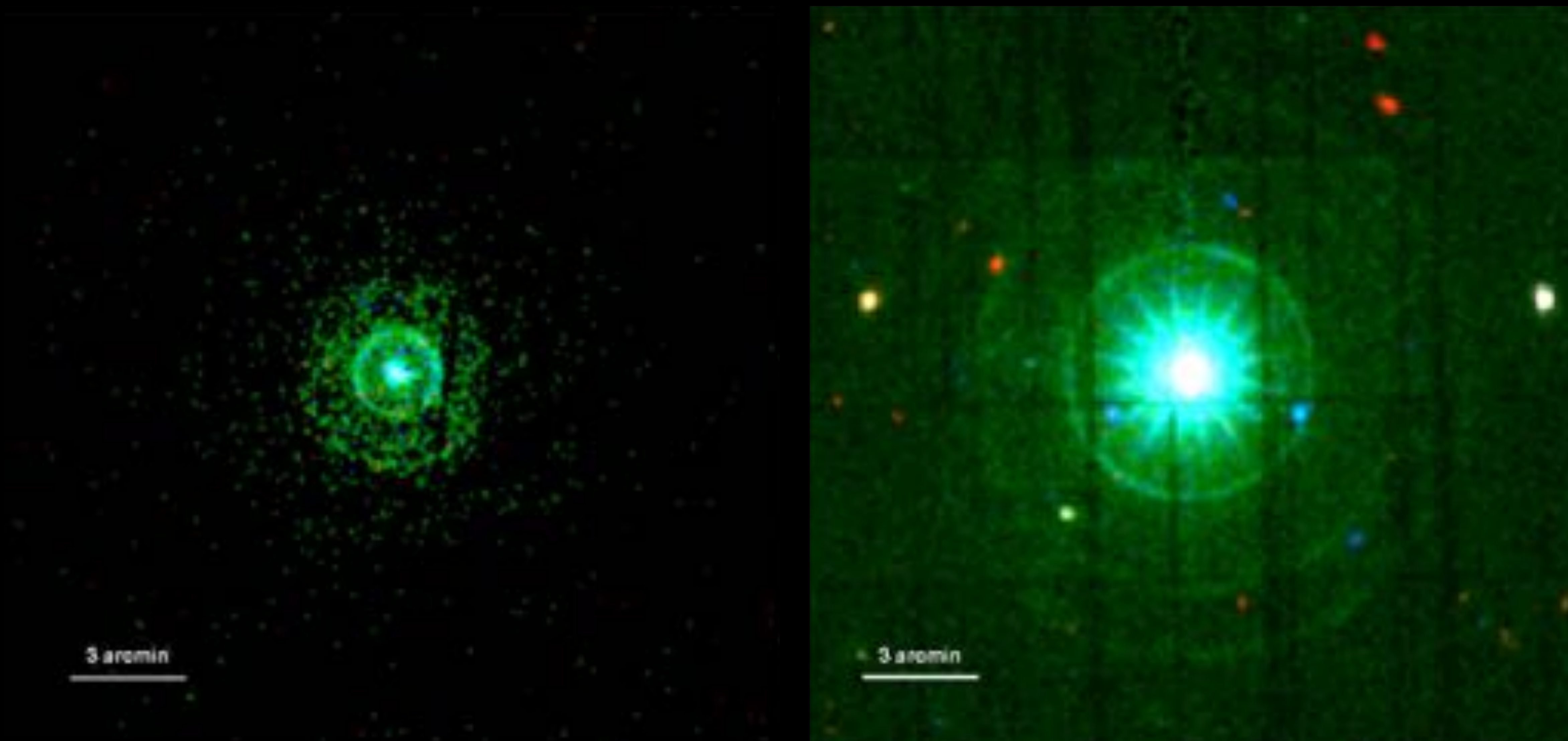
The observed interstellar extinction over the wavelength range $0.11\ \mu m < \lambda < 1\ \mu m$ was fitted with a very general particle size distribution of uncoated graphite, enstatite, olivine, silicon carbide, iron, and magnetite. Combinations of these materials, up to three at a time, were considered. The cosmic abundances of the various constituents were taken into account as constraints on the possible distributions of particle sizes.

Excellent fits to the interstellar extinction, including the narrowness of the λ2160 feature, proved possible. Graphite was a necessary component of any good mixture, but it could be used with any of the other materials. The particle size distributions are roughly power law in nature, with an exponent of about −3.3 to −3.6. The size range for graphite is about 0.005 μm to about 1 μm. The size distribution for the other materials is also approximately power law in nature, with the same exponent, but there is a narrower range of sizes: about 0.025–0.25 μm, depending on the material. The number of large particles is not well determined, because they are gray. Similarly, the number of small particles is not well determined because they are in the Rayleigh limit. This power-law distribution is drastically different from an Oort–van de Hulst distribution, which is much more slowly varying for small particles but drops much faster for particles larger than average.

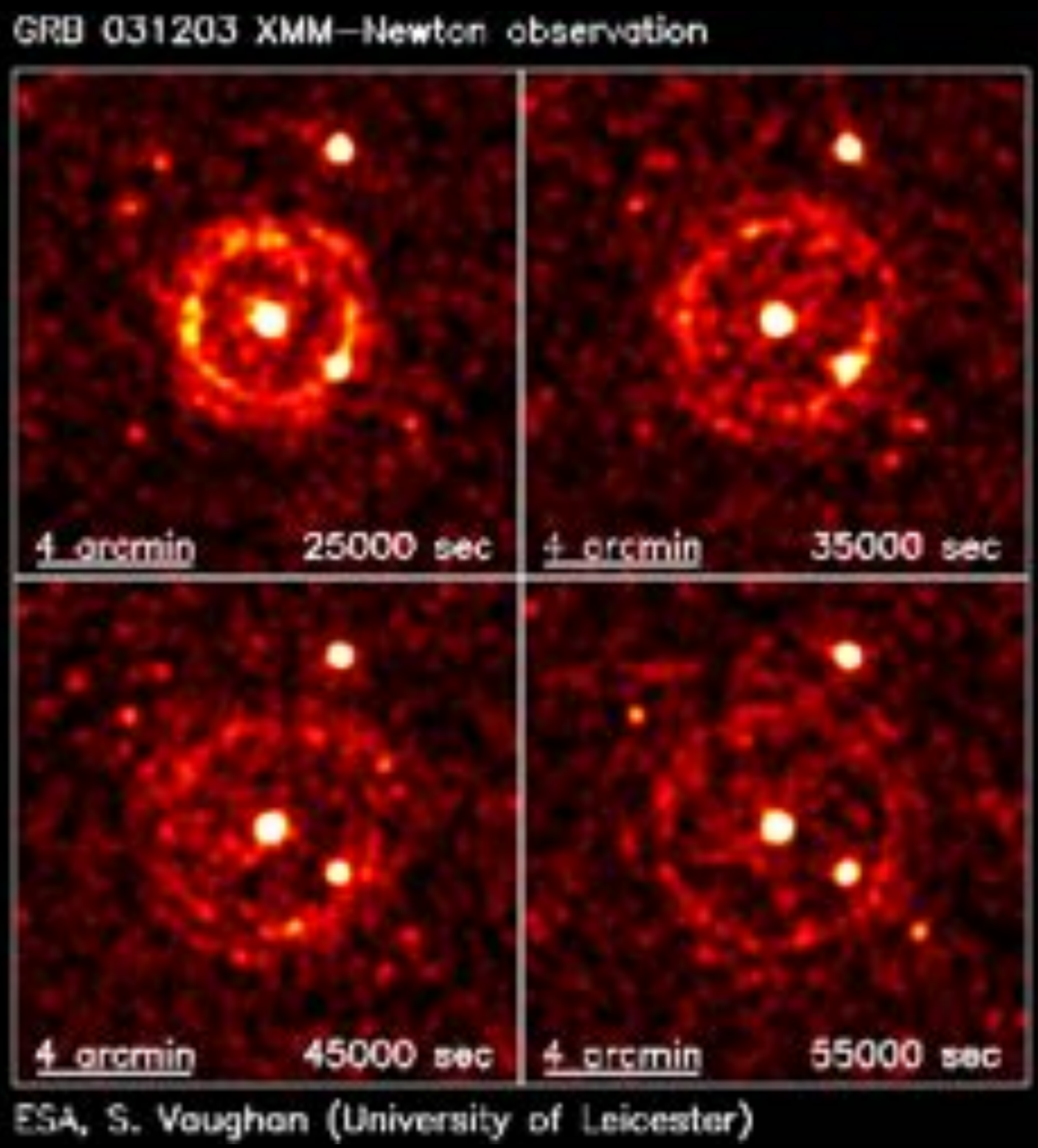
The extinction was also fitted with spherical graphite particles plus cylinders of each of the other materials. Linear and circular polarizations were then determined for the cylinders on the assumption of Davis-Greenstein alignment. The extinction was quite satisfactory, but the linear polarization reached a maximum in the ultraviolet (about 1600 Å). This is because the mixture contains many small particles. If the small particles are not elongated or aligned, the wavelength dependence of the polarization can be fitted, but the larger particles which are aligned do not provide enough polarization per magnitude of extinction. However, a fit to polarization and extinction can be achieved if the material responsible for the polarization contributes only a small part of the extinction but consists of fairly large particles and is very well aligned. Dielectric particles with coatings could also provide the polarization.

Subject headings: interstellar: matter — polarization — ultraviolet: spectra

SGR 1E 1547.0-5408



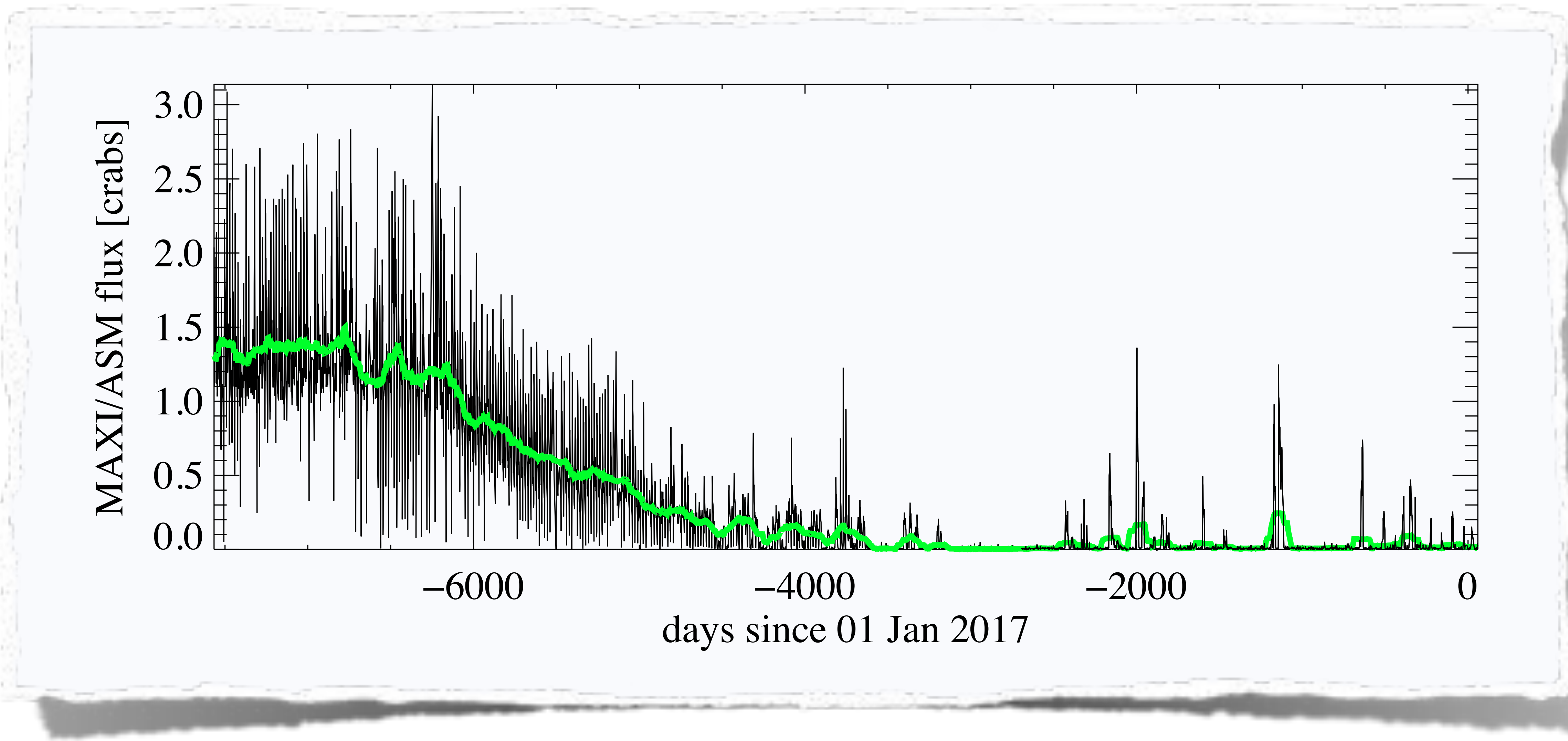
Tiengo+'10

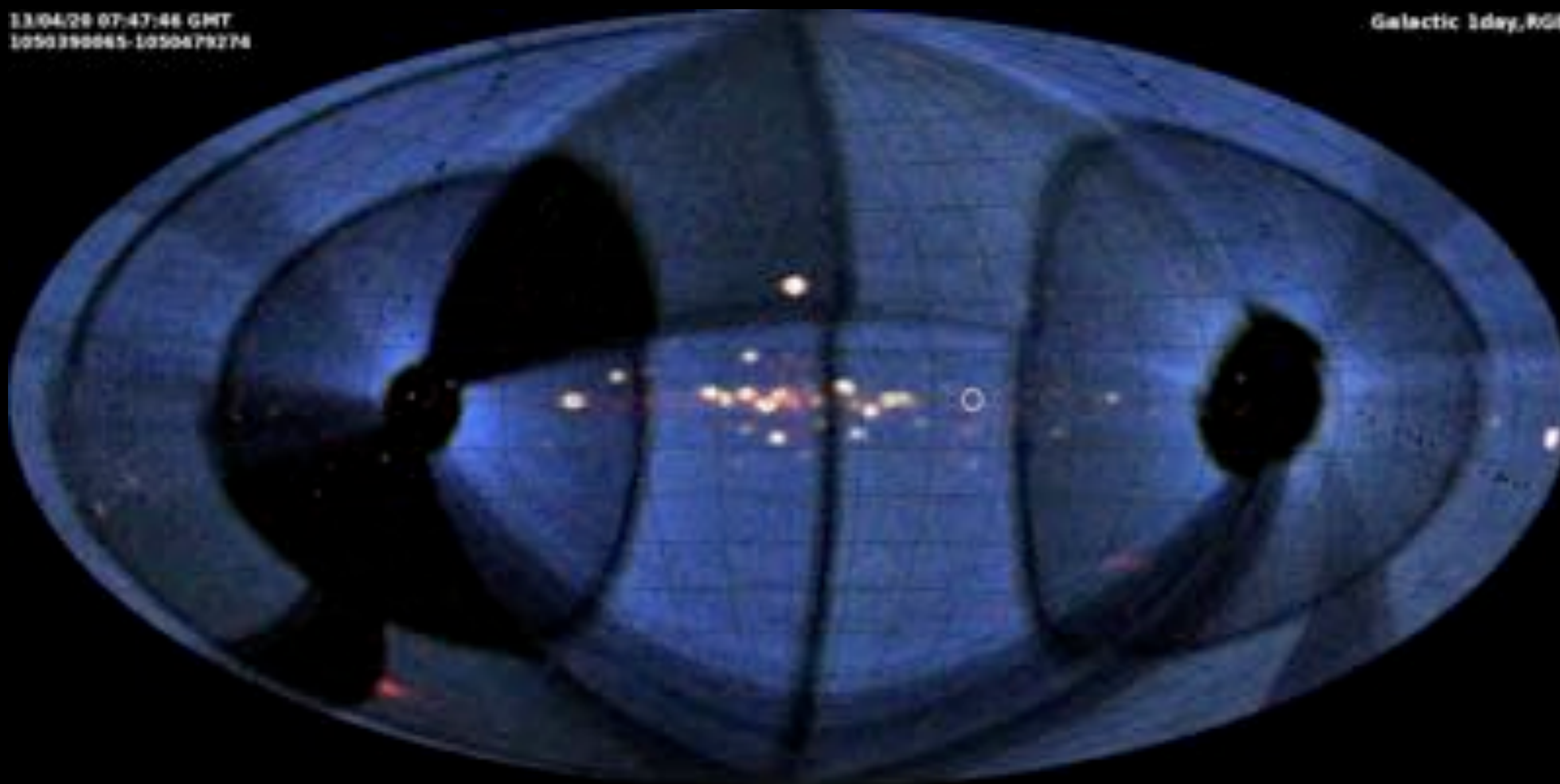

GRB 031203 XMM–Newton observation
4 arcmin
25000 sec
4 arcmin
35000 sec
4 arcmin
45000 sec
4 arcmin
55000 sec
ESA, S. Vaughan (University of Leicester)

Vaughan+'03

Circinus X-1

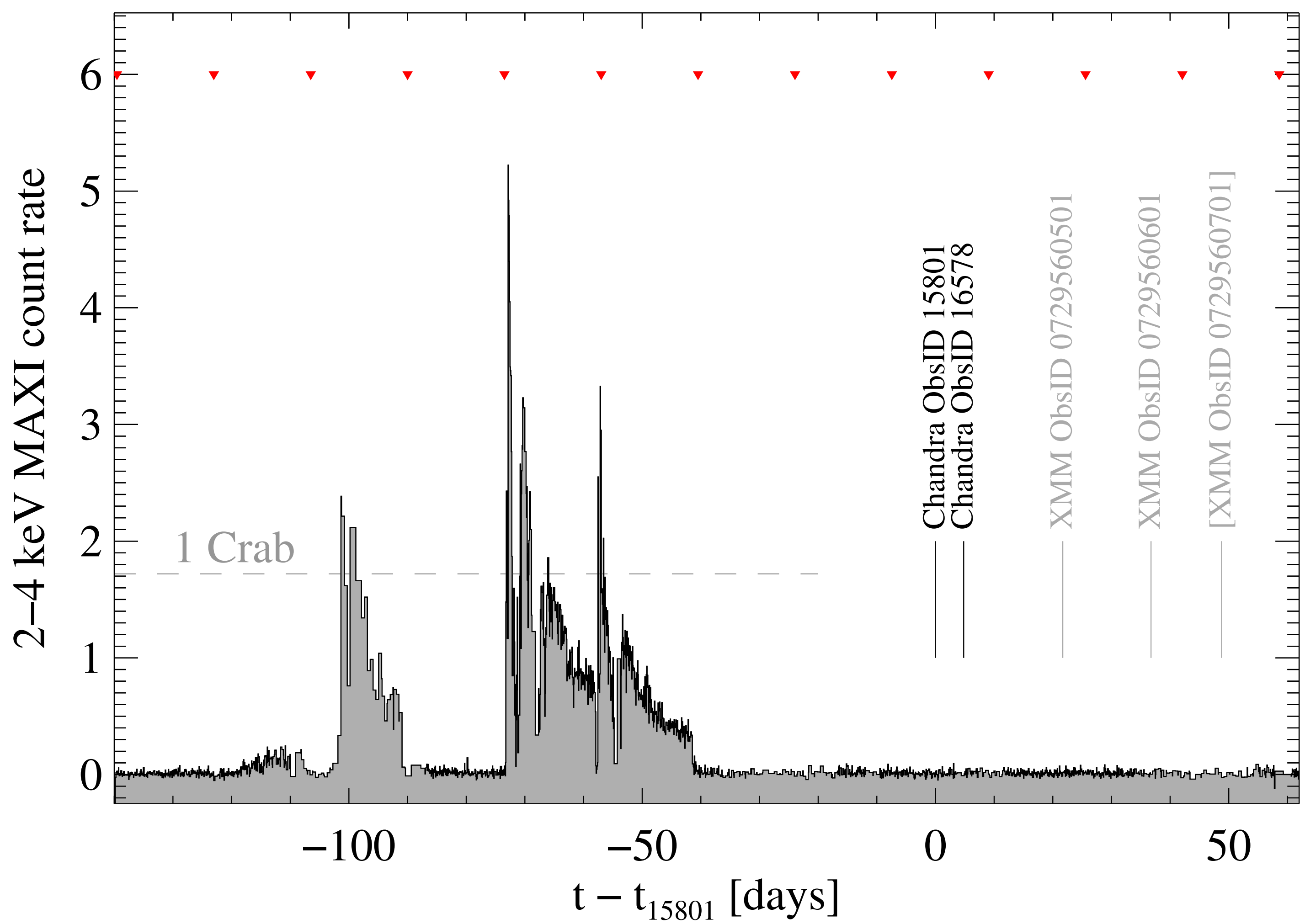
- An extraordinary X-ray source
- Distance unknown (5 to 15 kpc)



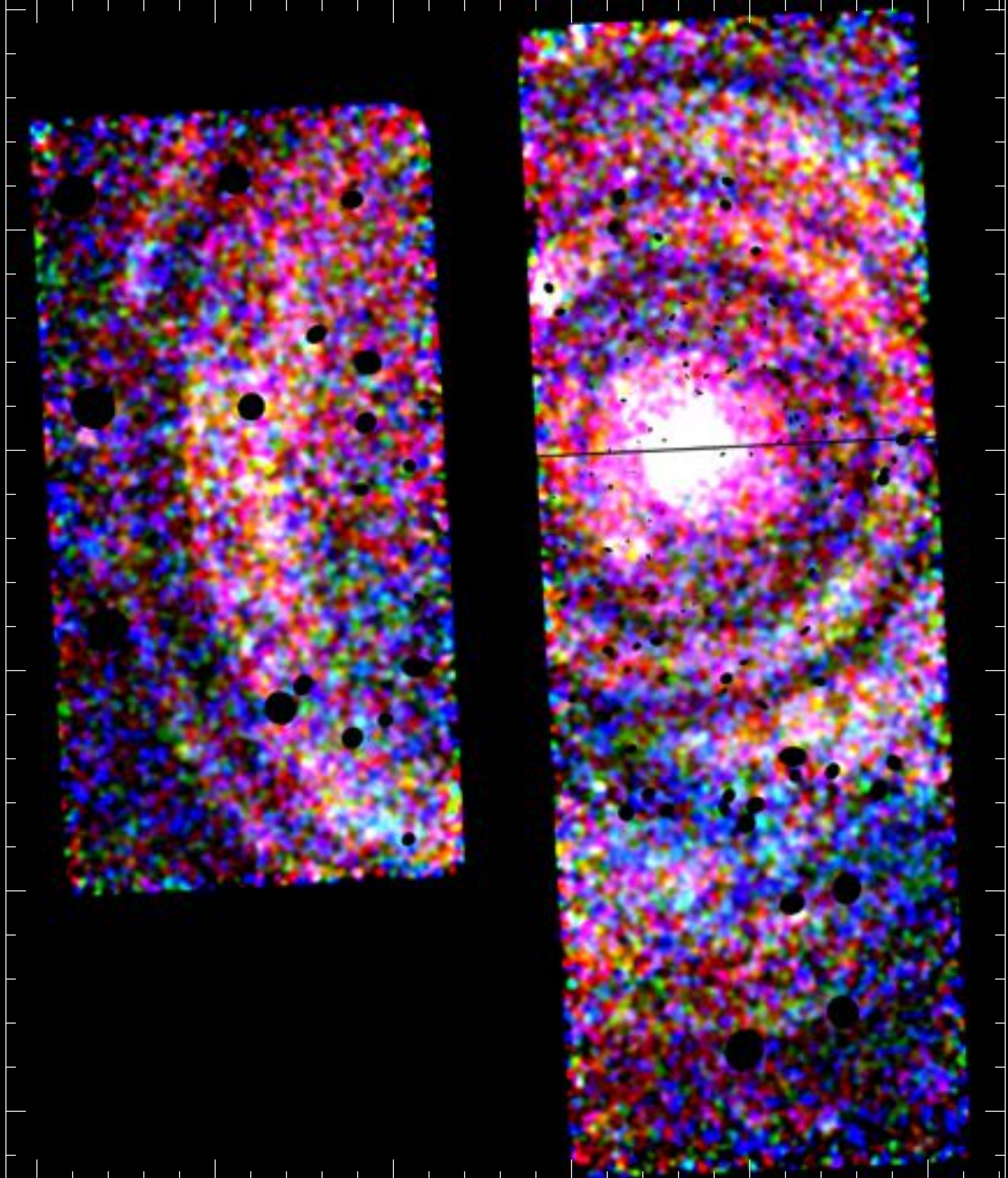


The MAXI all sky X-ray movie

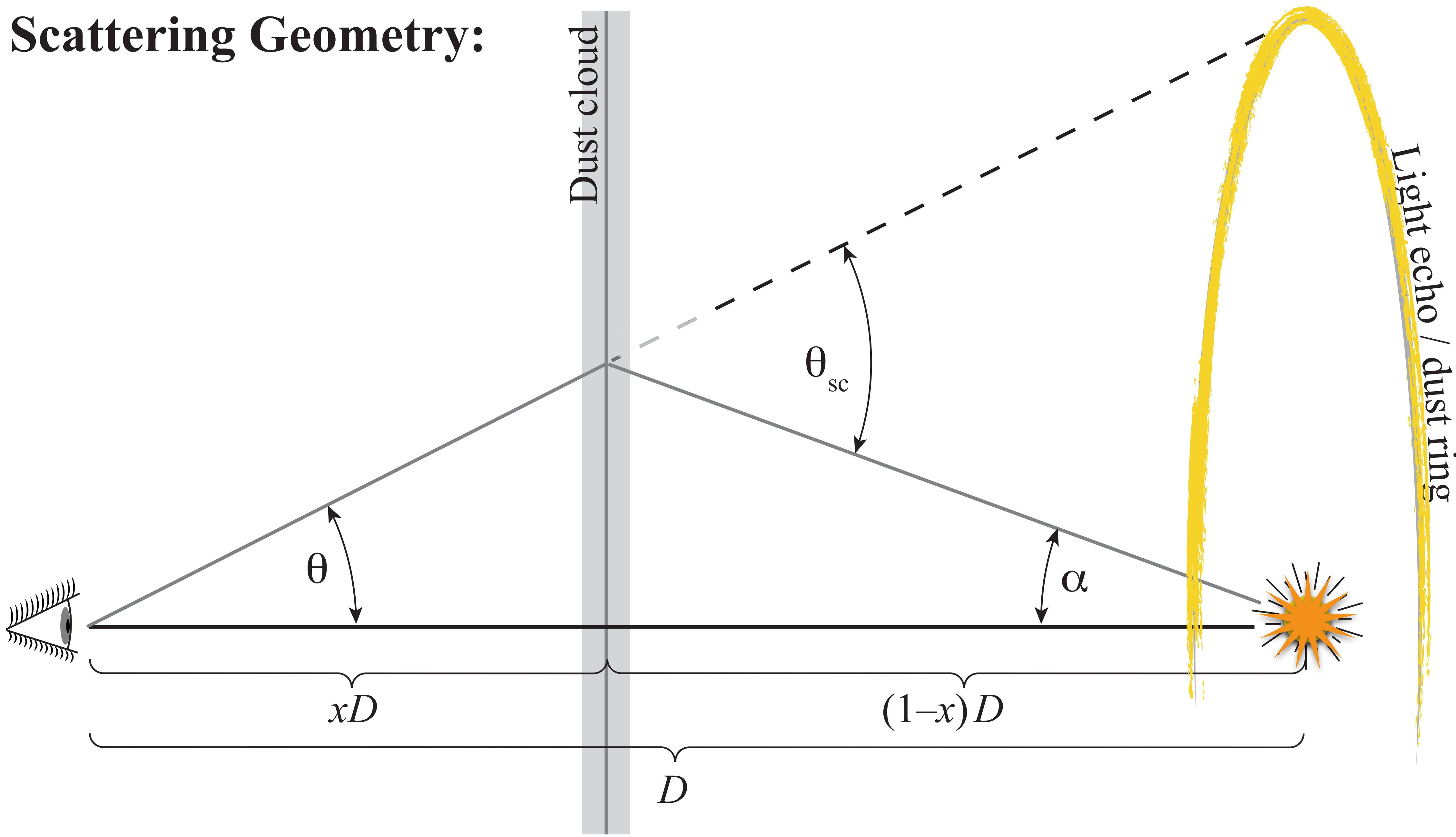
Cir X-1 wakes up…

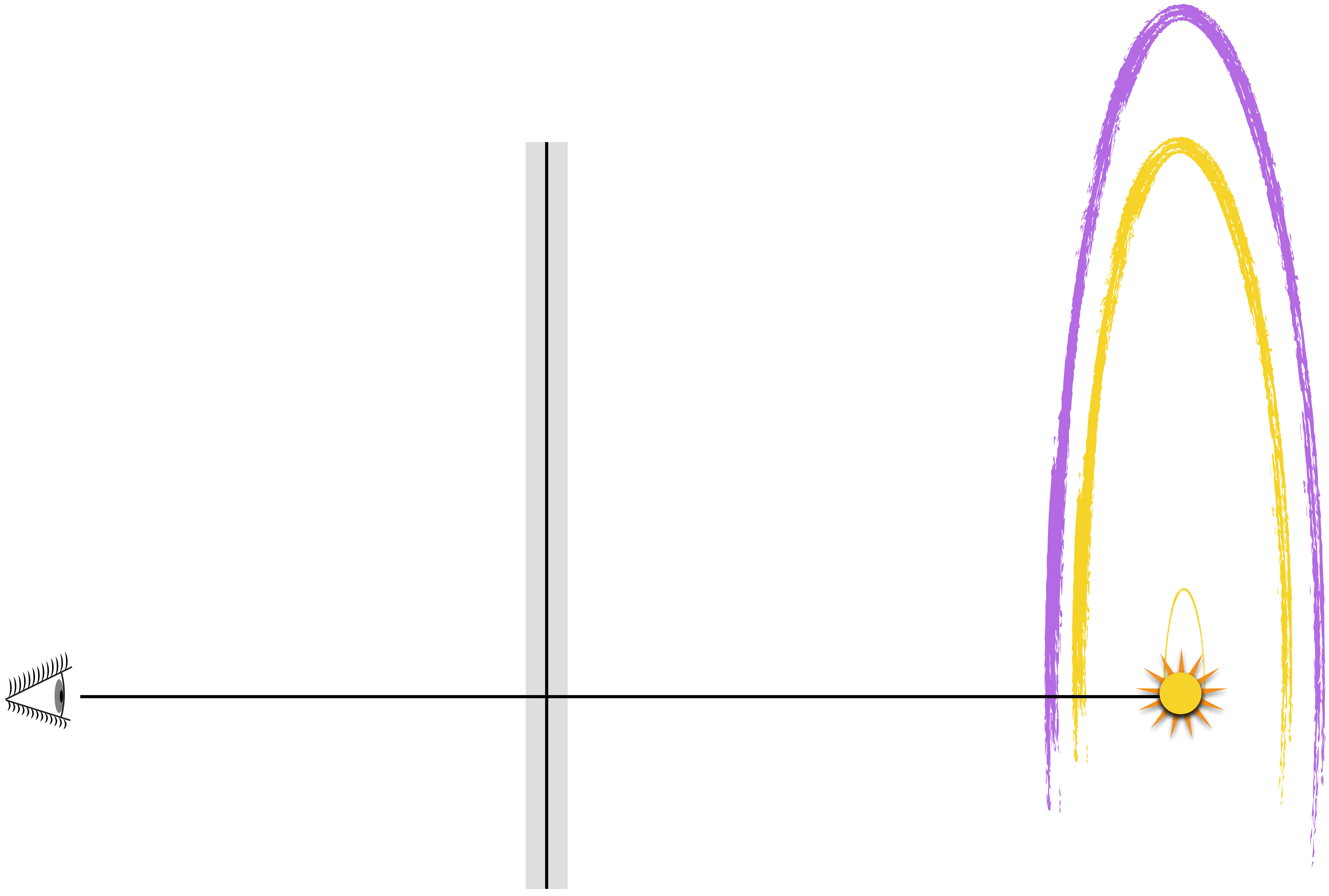


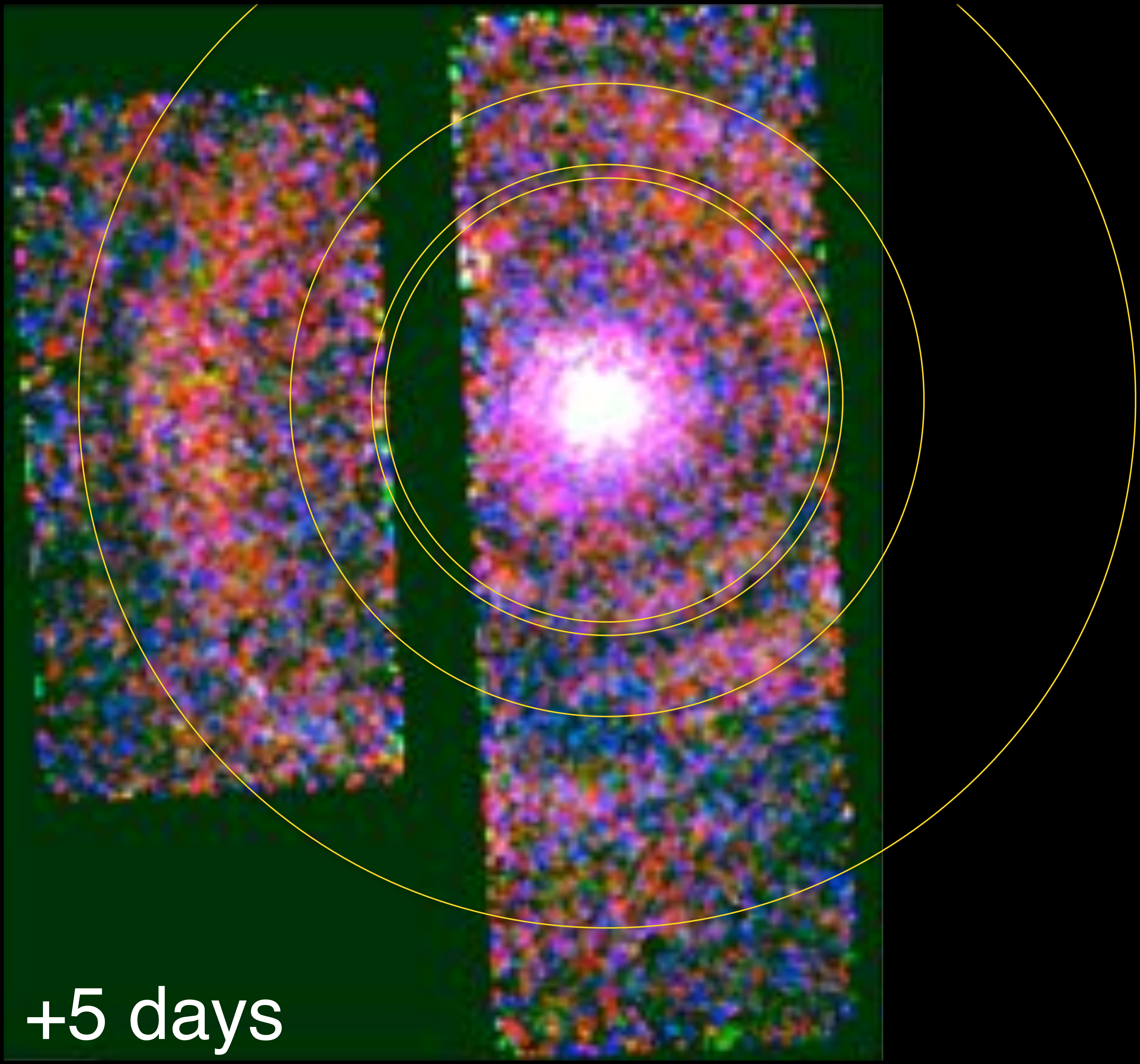
…and goes back to sleep



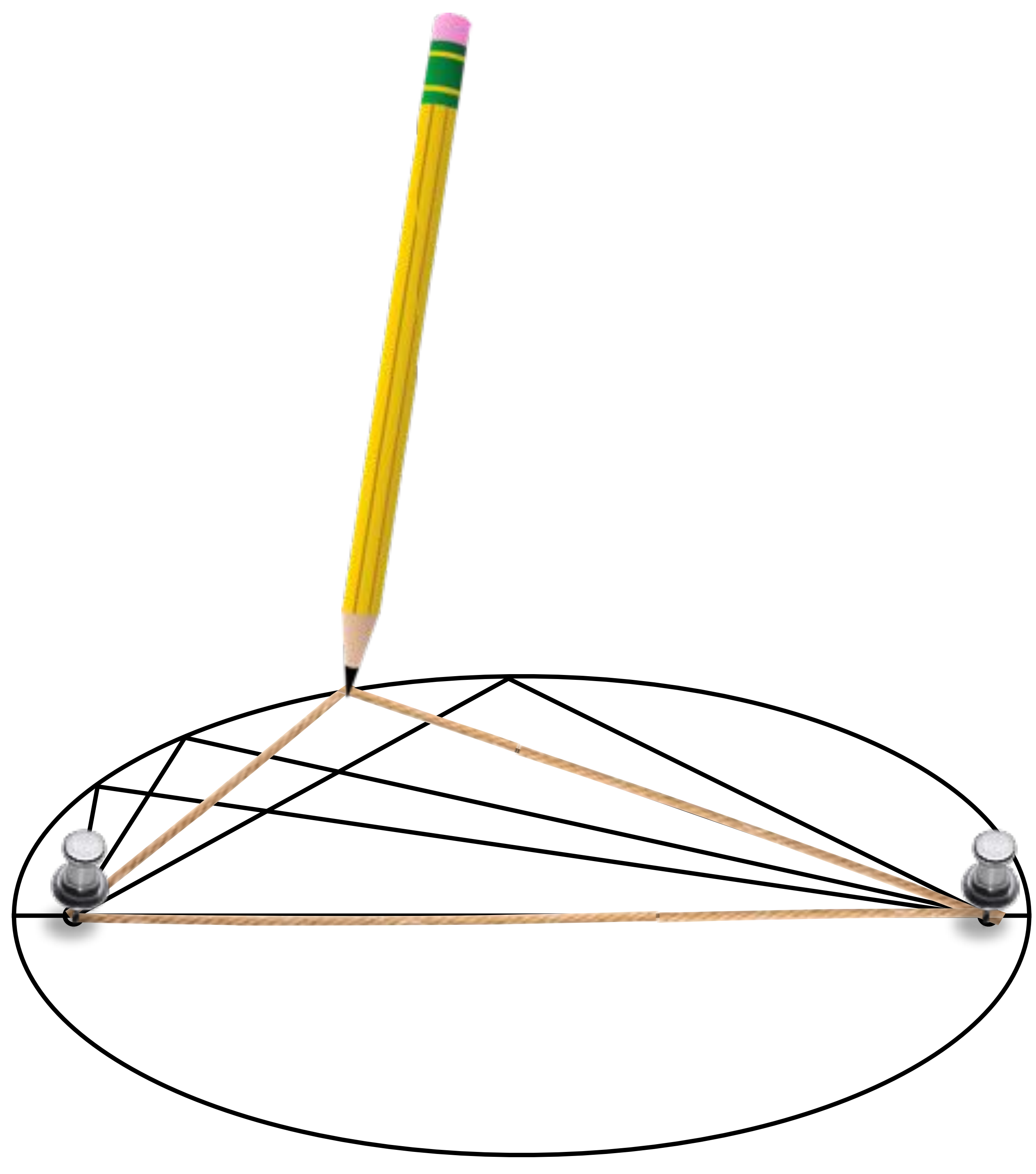
Dust Scattering Geometry:

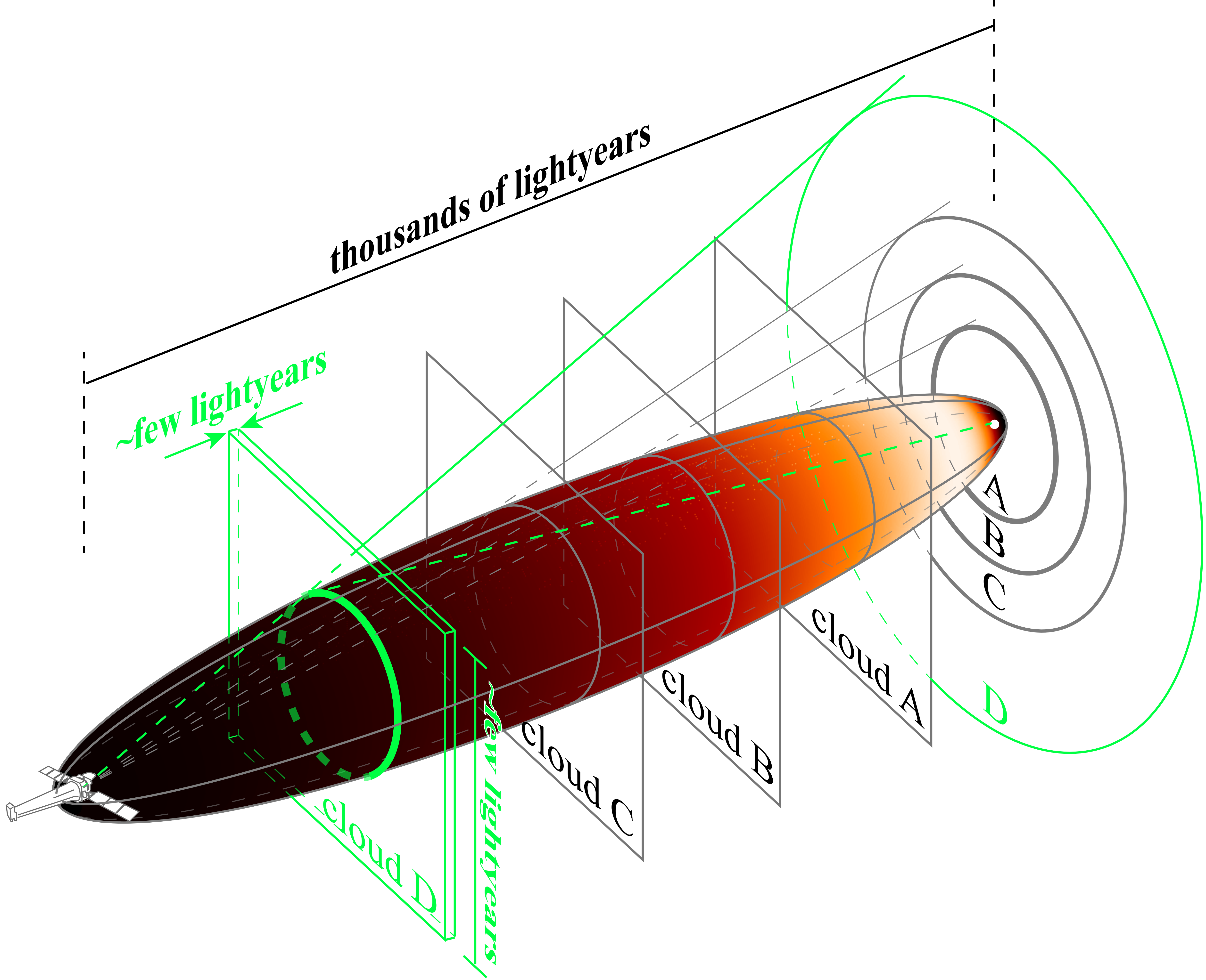





+5 days

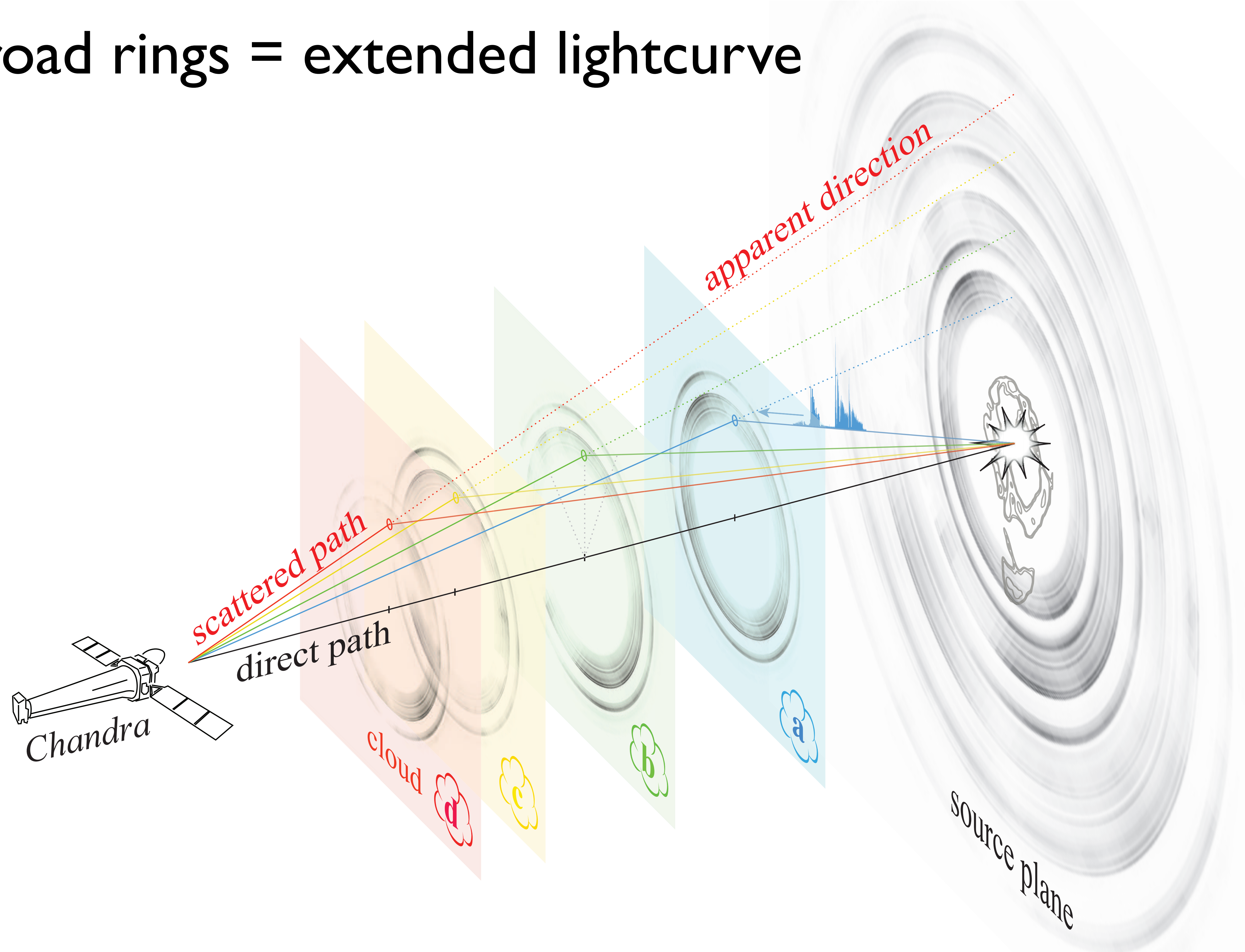
Dust echoes



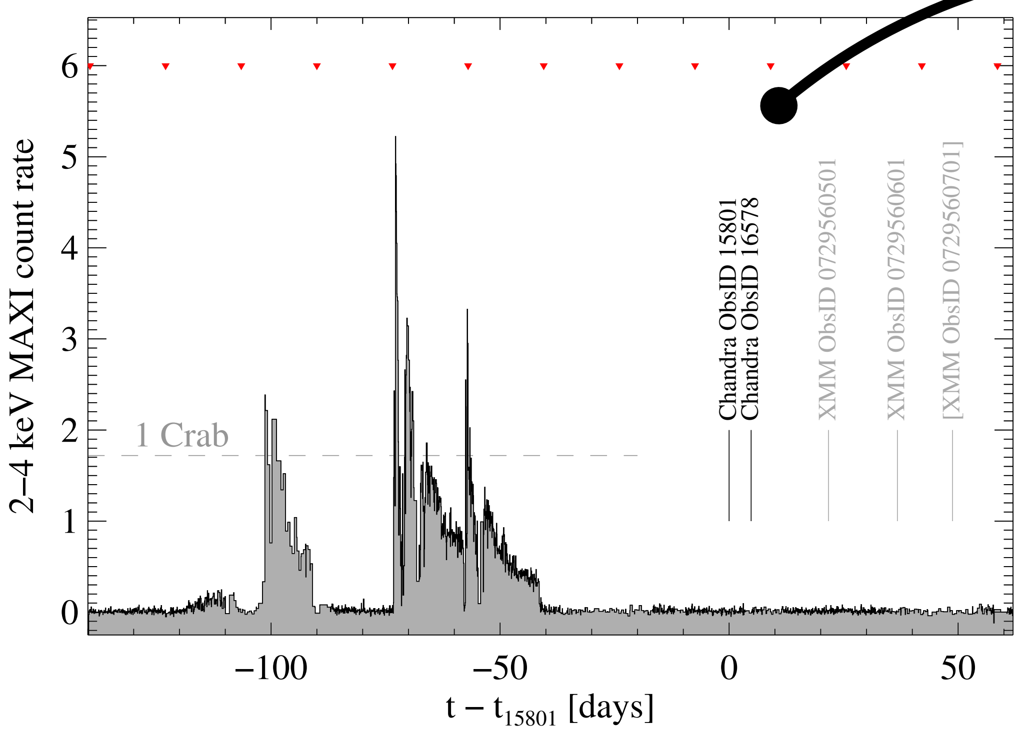


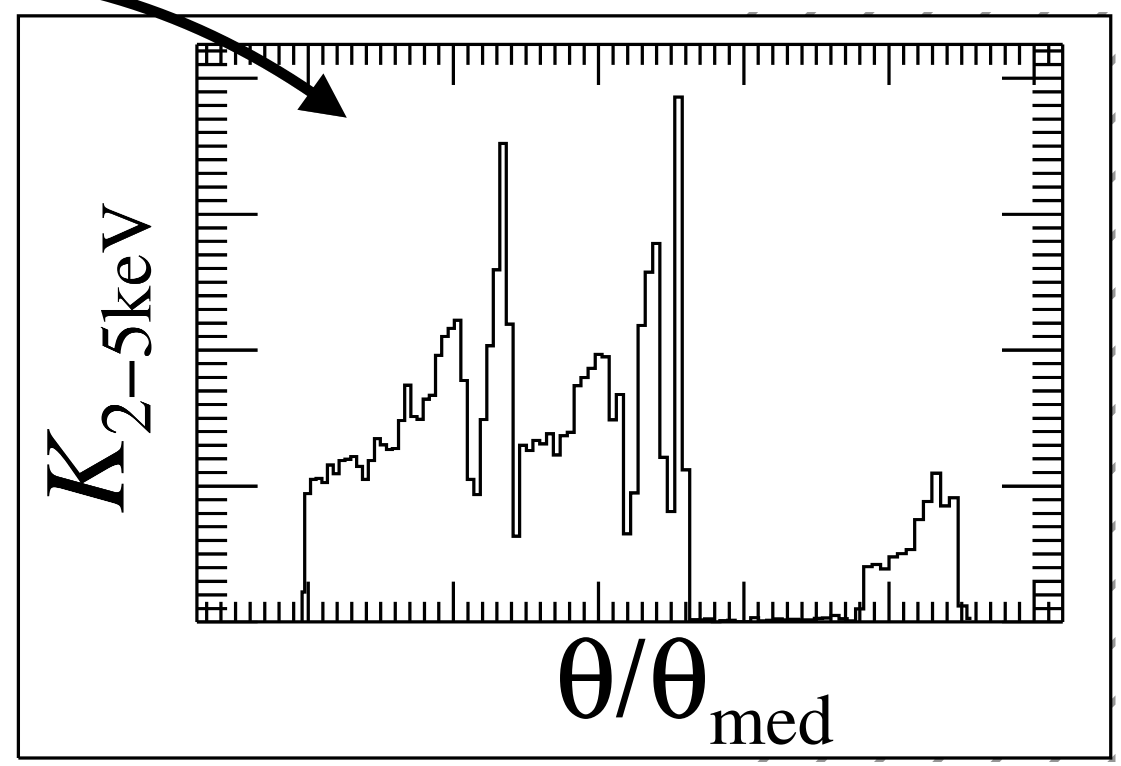
thousands of lightyears
~few lightyears
~few lightyears
cloud A
cloud B
cloud C
cloud D
A
B
C
D

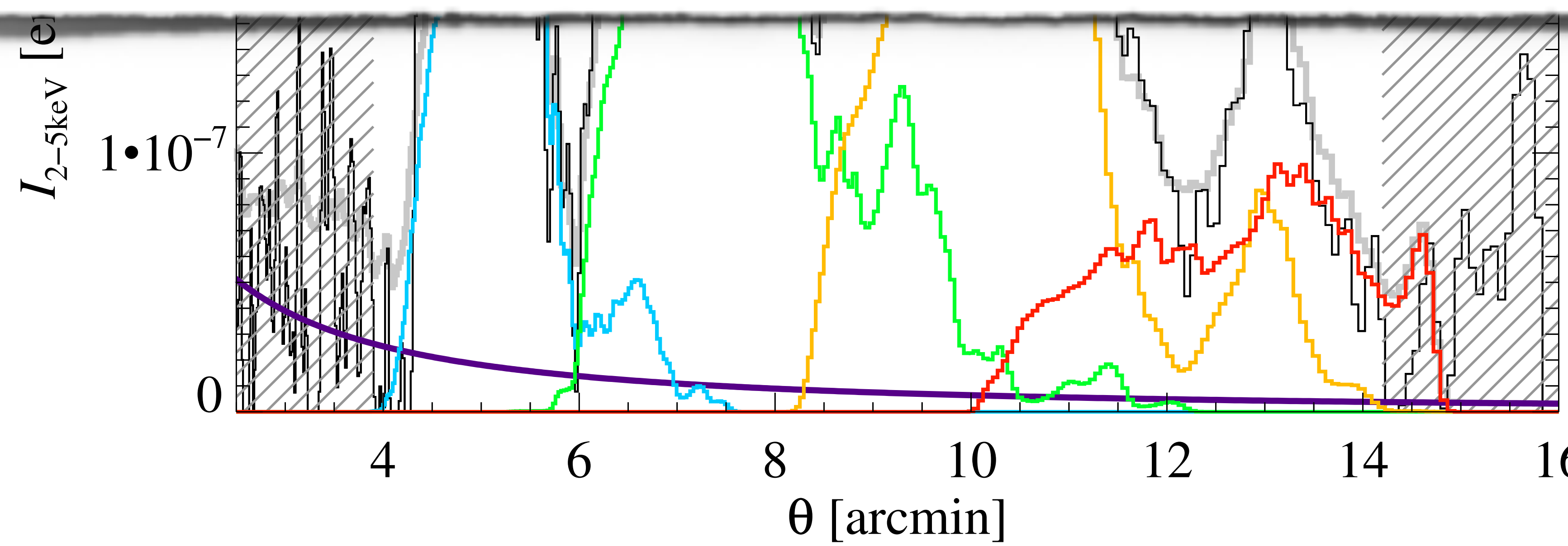
- Multiple rings = multiple clouds
- Broad rings = extended lightcurve



Scattering profile from a single sheet of dust:



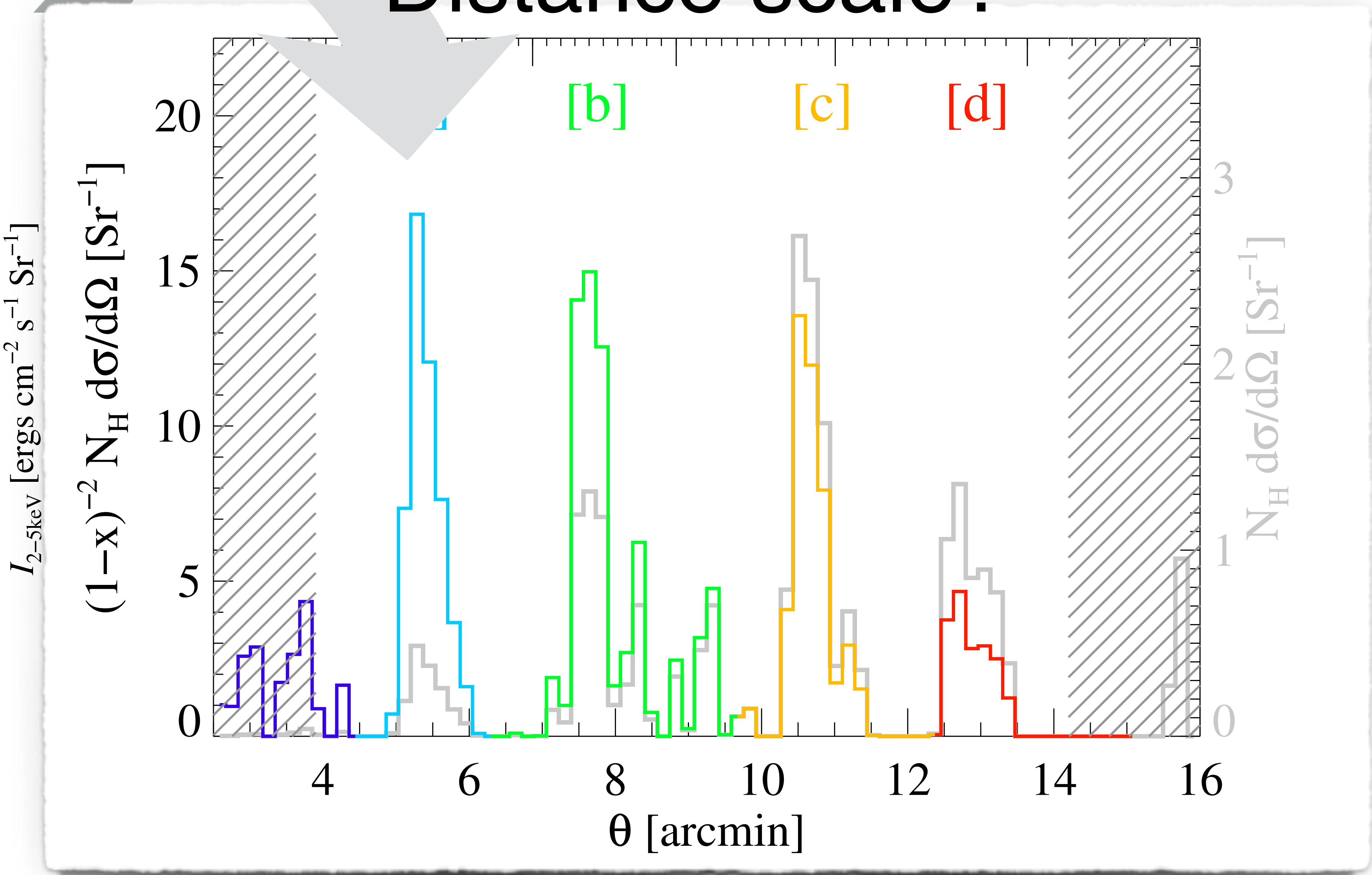




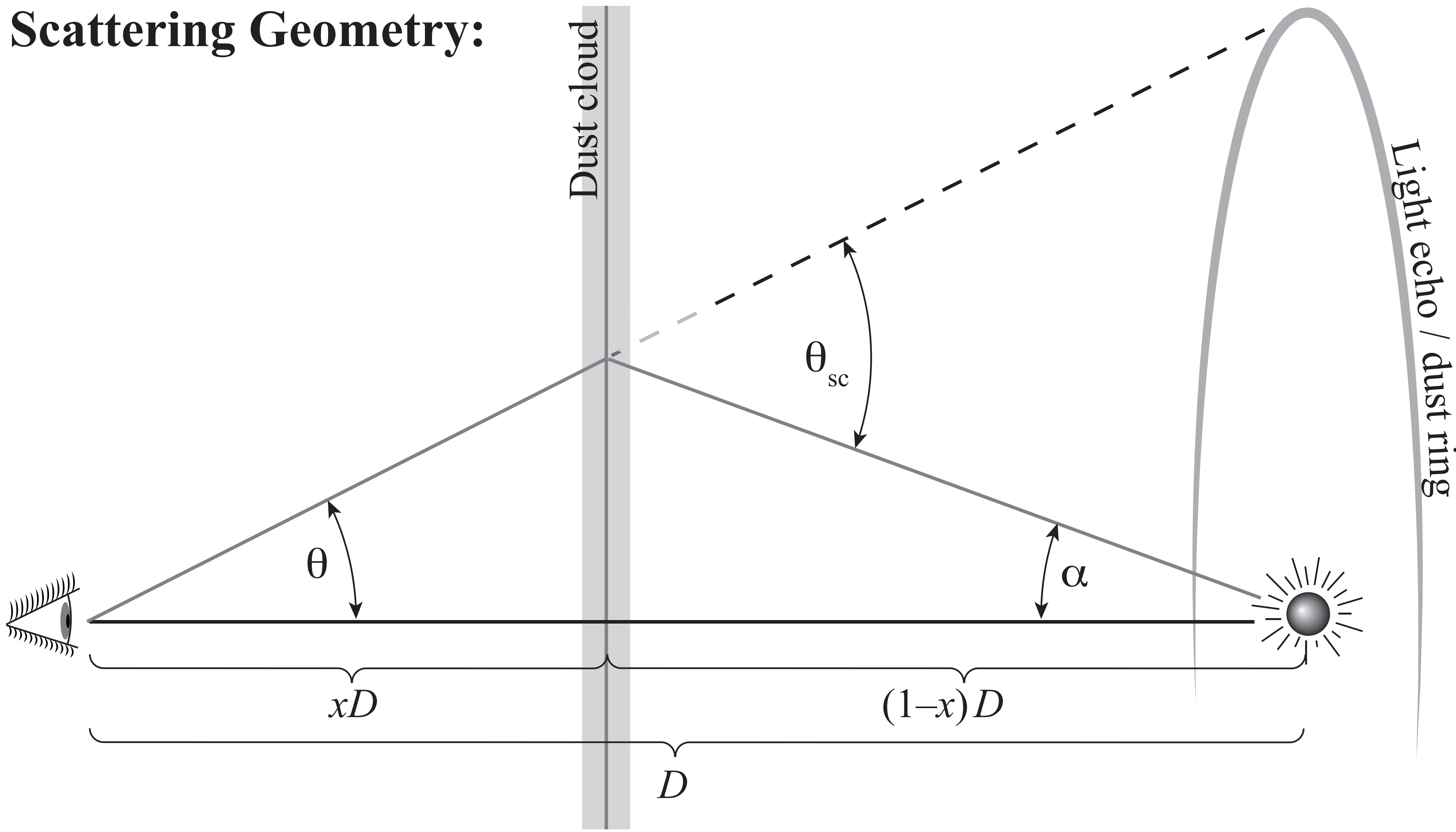
Heinz+'15

Where is the Dust?

Distance scale?



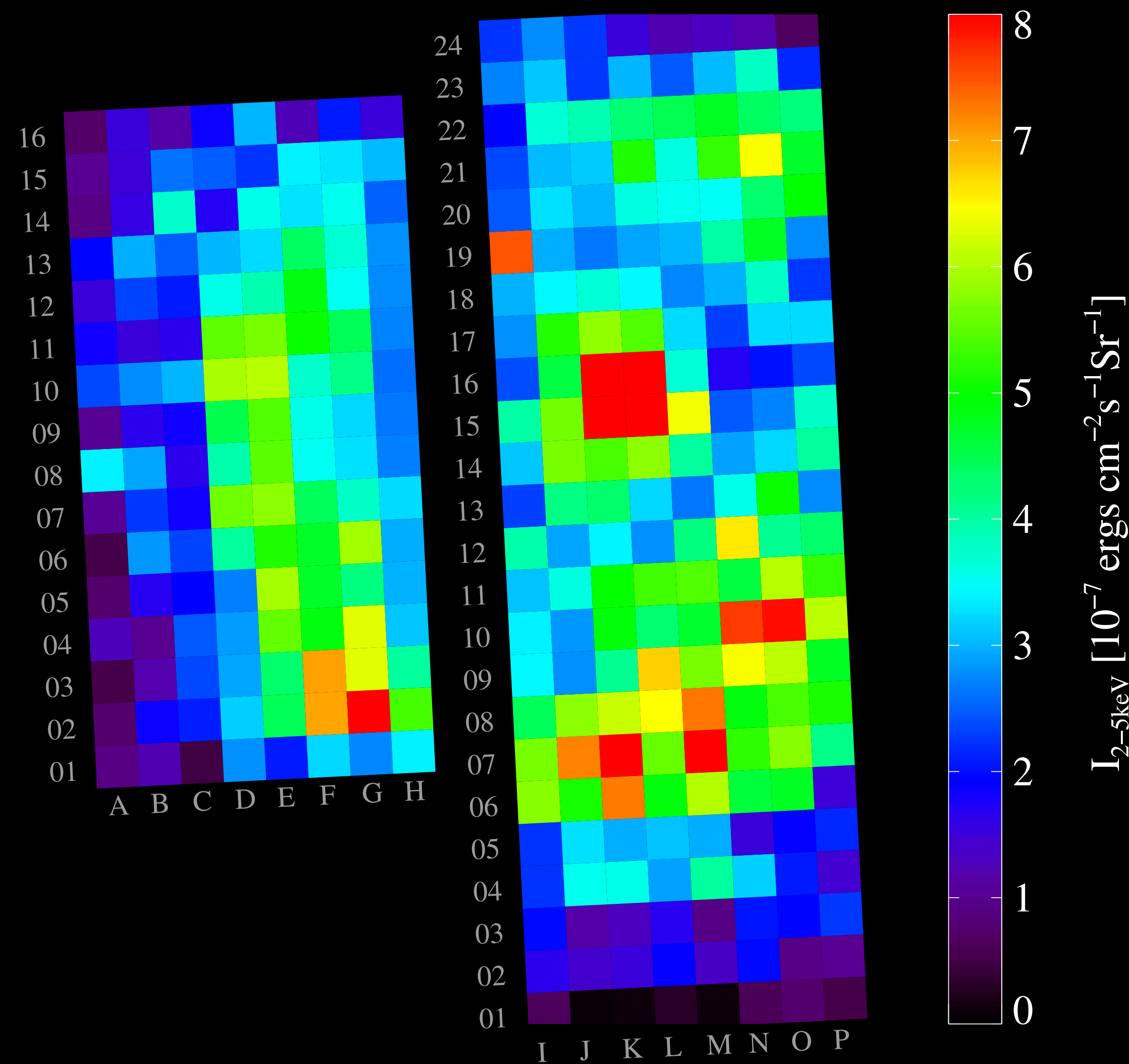
Dust Scattering Geometry:



$$\theta = \sqrt{\frac{2c\Delta t\,(1-x)}{xD}}$$

Heinz+'15

Chandra spectra:



Scattering Intensity

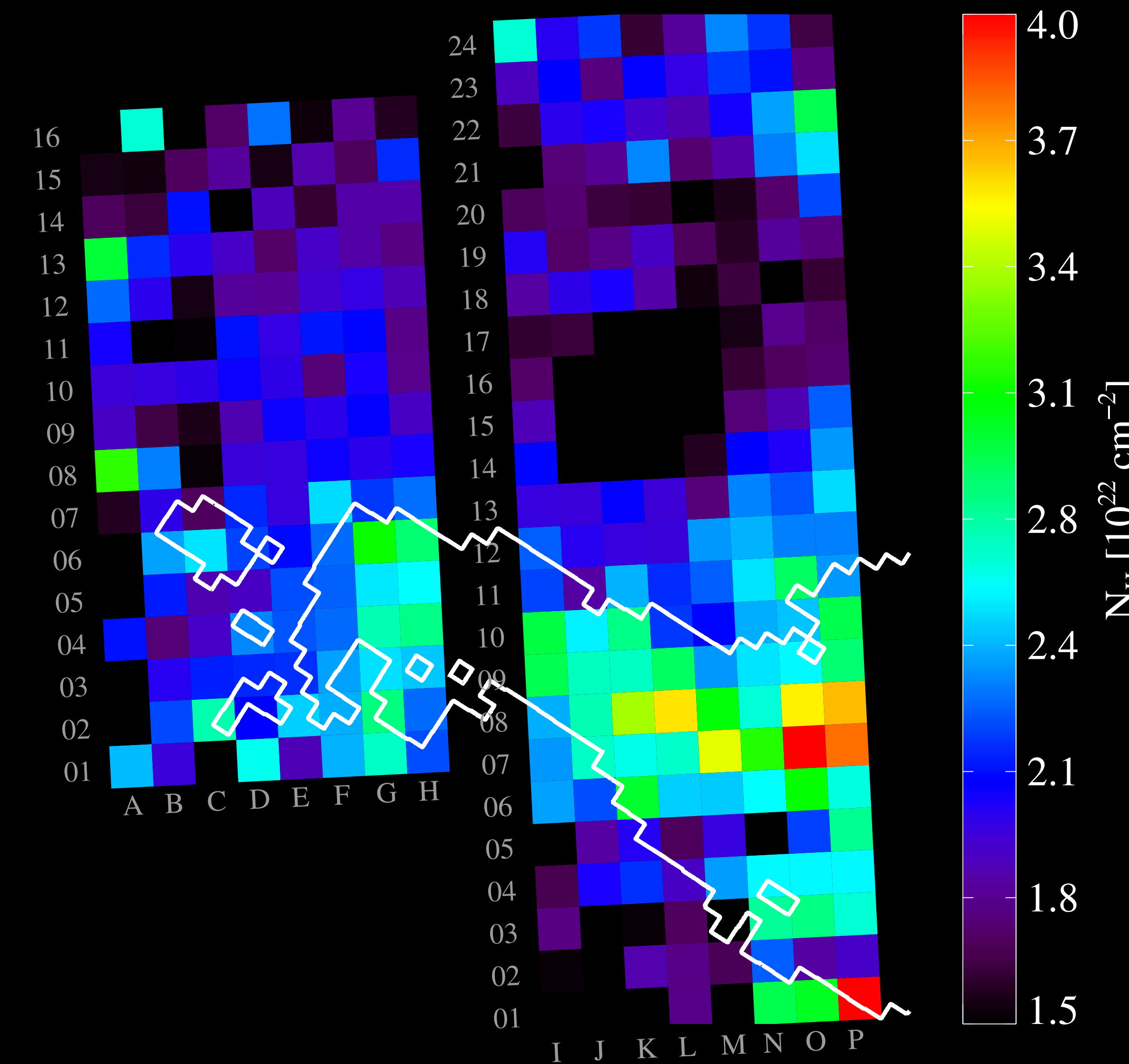
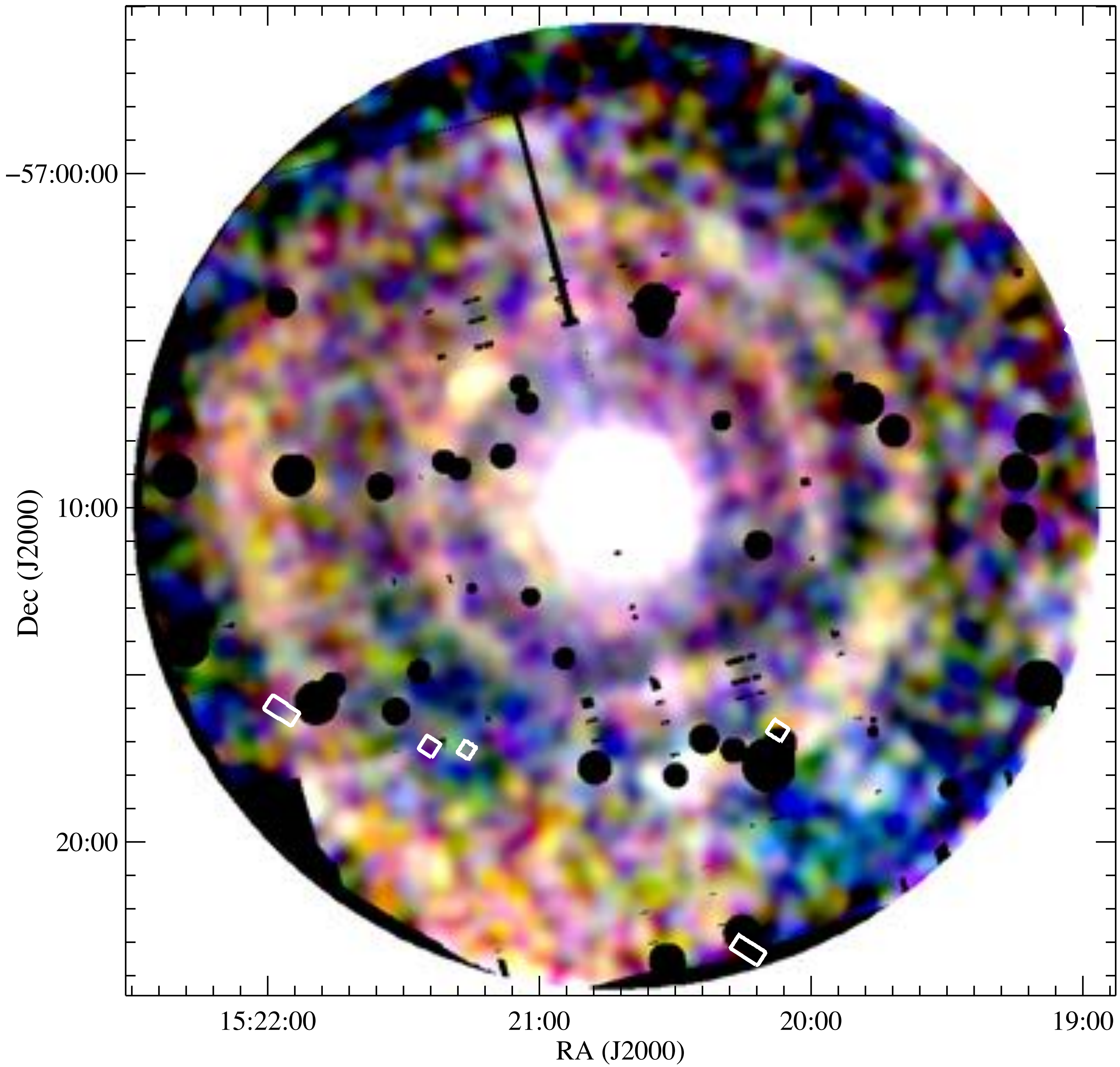
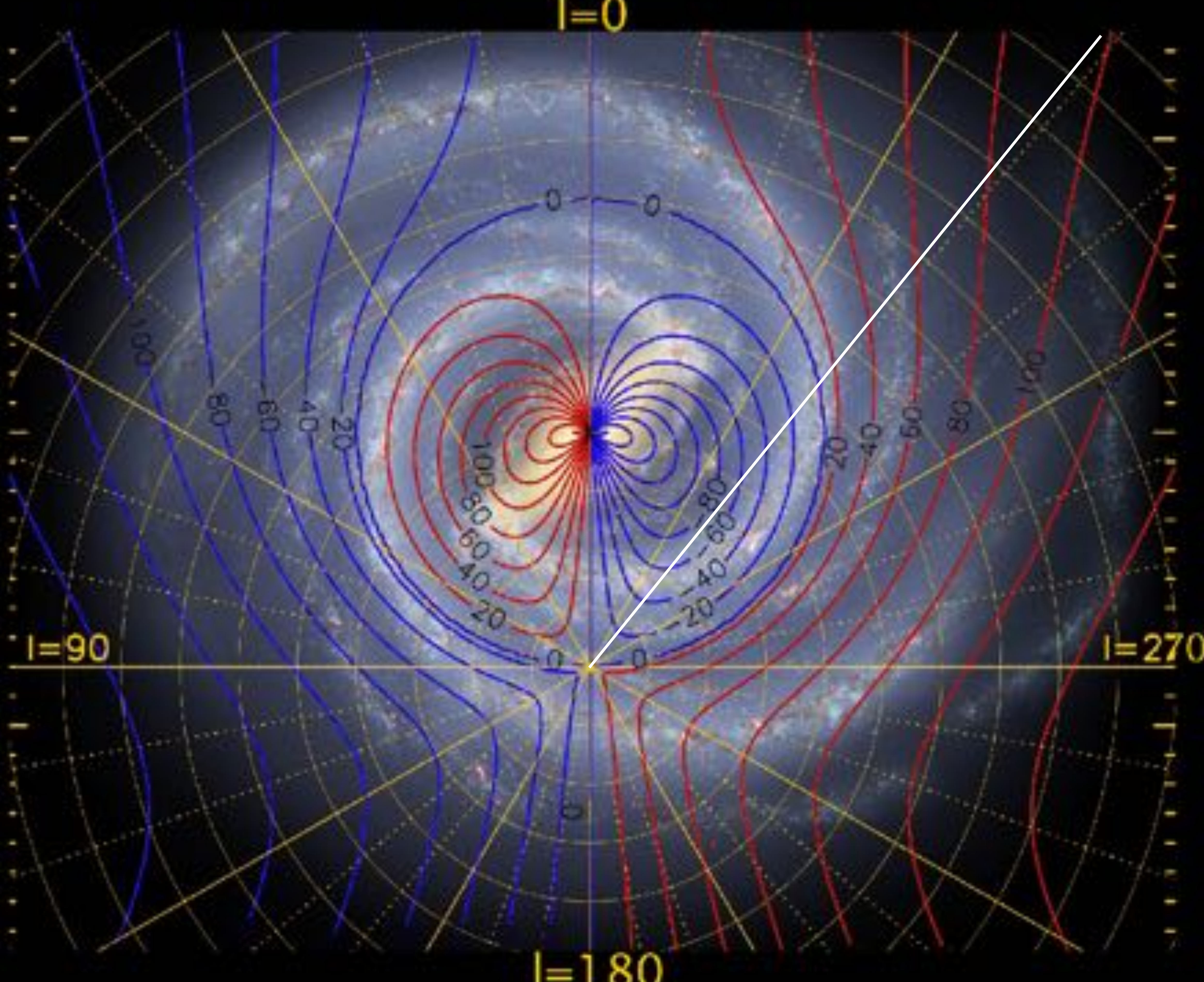


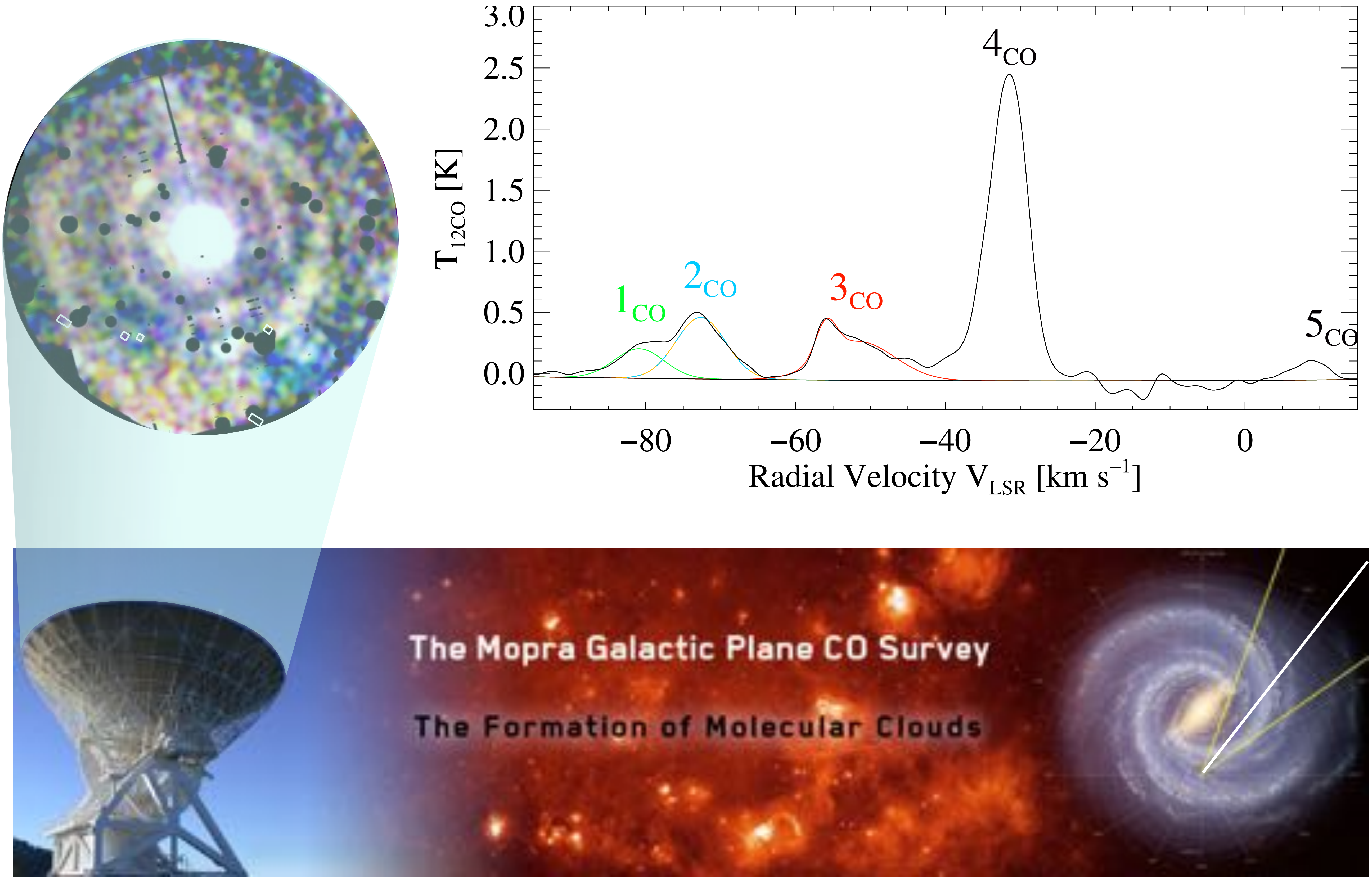
Photo-electric column

The XMM View



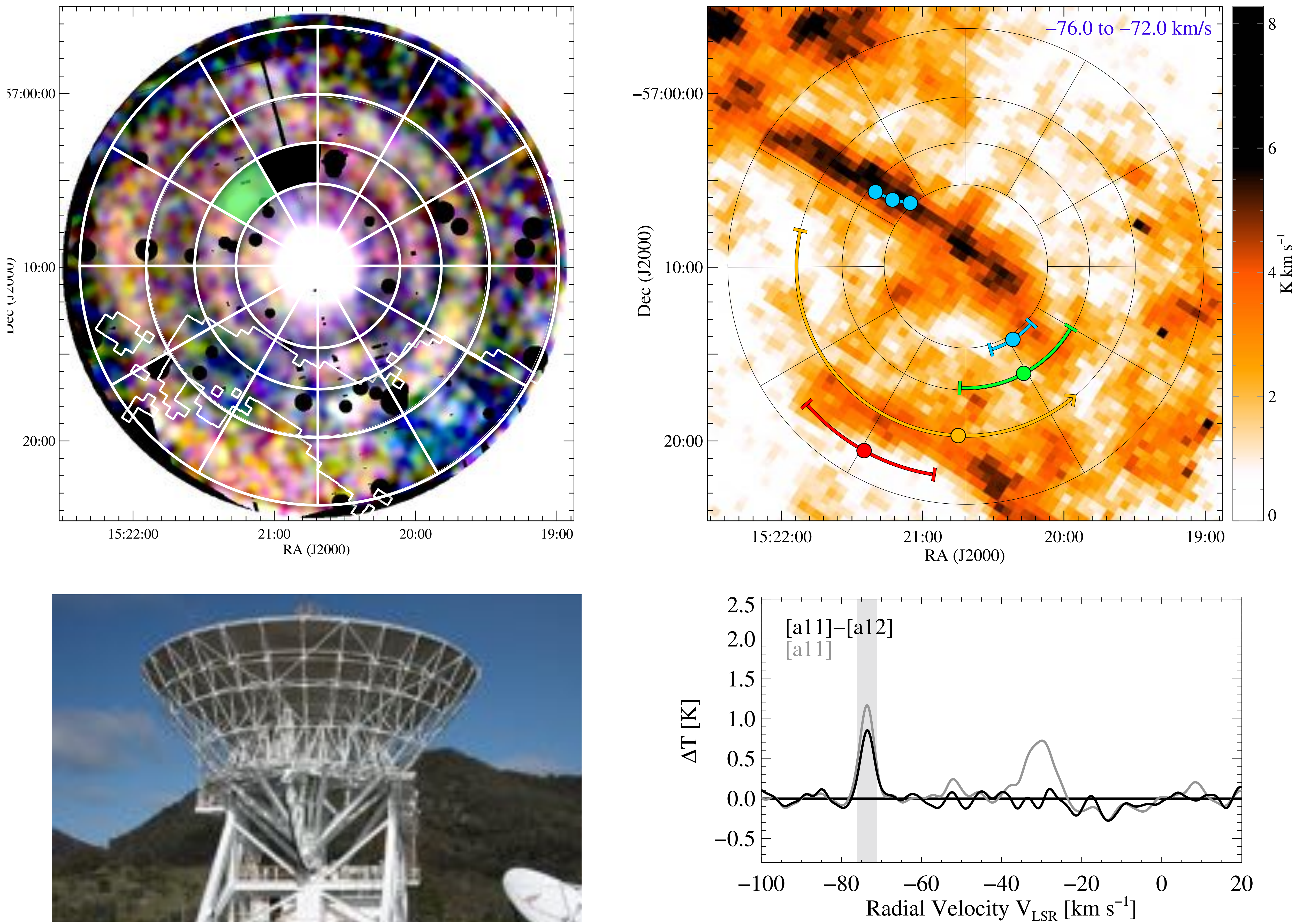
Heinz+'15


l=0
l=90
l=270
l=180
0
0
0
0
20
40
60
80
100
-20
-40
-60
-80
100
80
60
40
20
20
40
60
80
100
0

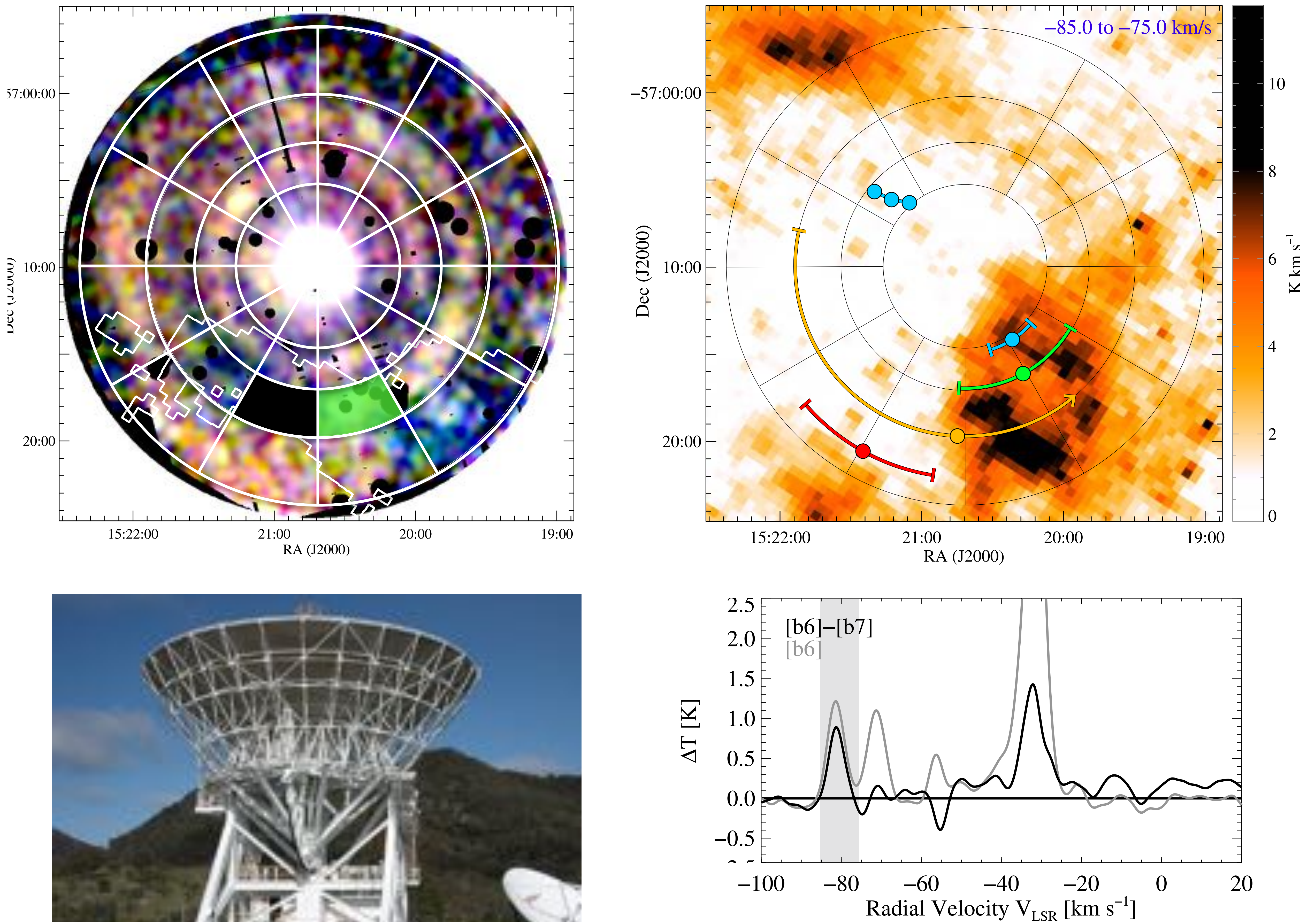


3.0
2.5
2.0
1.5
1.0
0.5
0.0
T_{12CO} [K]
4_{CO}
1_{CO}
2_{CO}
3_{CO}
5_{CO}
−80
−60
−40
−20
0
Radial Velocity V_{LSR} [km s^{-1}]
The Mopra Galactic Plane CO Survey
The Formation of Molecular Clouds

Heinz+'15

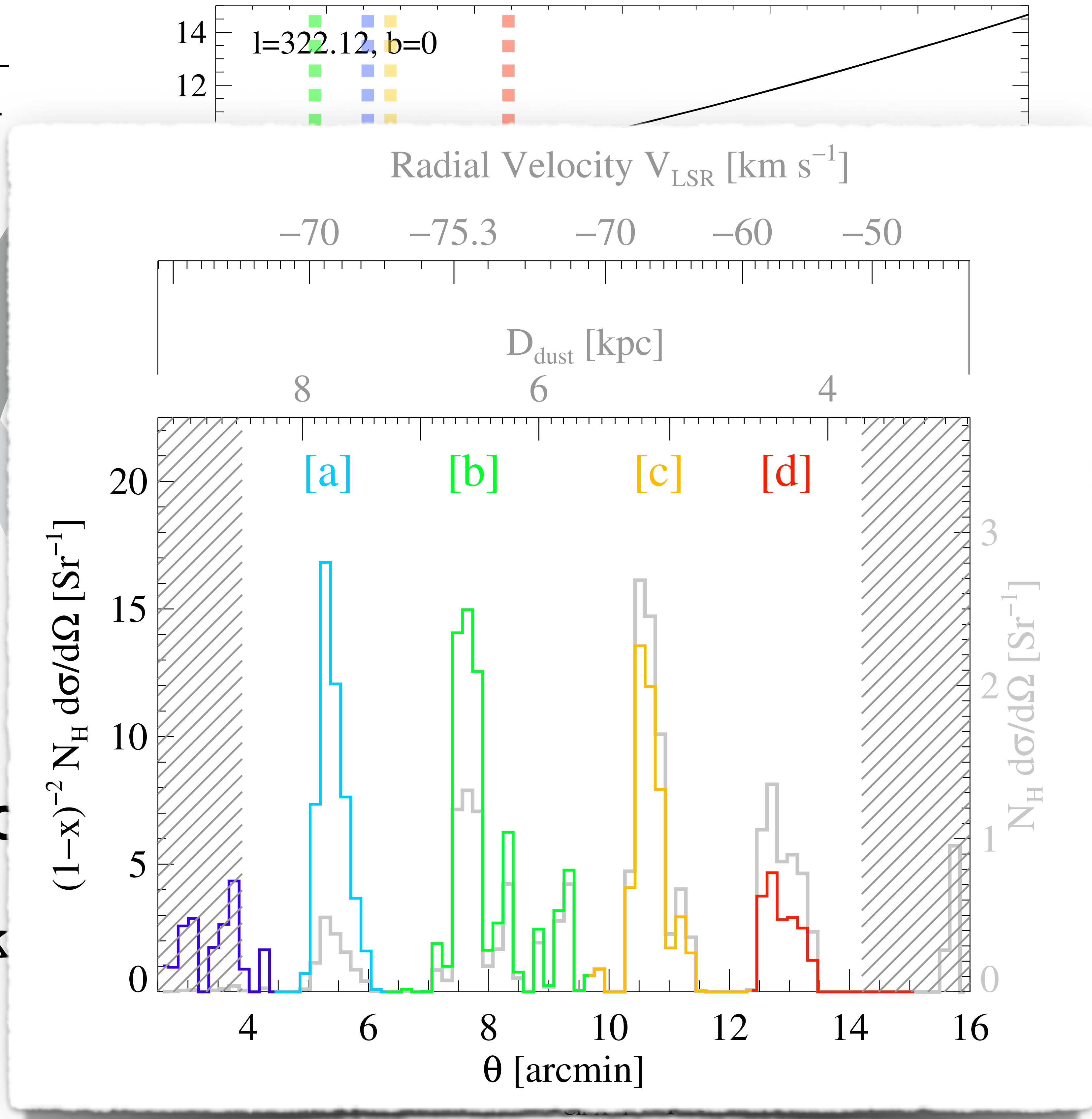


57:00:00
10:00
20:00
Dec (J2000)
15:22:00
21:00
20:00
19:00
RA (J2000)
−76.0 to −72.0 km/s
−57:00:00
10:00
20:00
Dec (J2000)
15:22:00
21:00
20:00
19:00
RA (J2000)
8
6
4
2
0
K km s^{-1}
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
ΔT [K]
[a11]−[a12]
[a11]
−100
−80
−60
−40
−20
0
20
Radial Velocity V_{LSR} [km s^{-1}]


57:00:00
10:00
20:00
Dec (J2000)
15:22:00
21:00
20:00
19:00
RA (J2000)
−85.0 to −75.0 km/s
−57:00:00
10:00
20:00
Dec (J2000)
15:22:00
21:00
20:00
19:00
RA (J2000)
K km s^{-1}
0
2
4
6
8
10
[b6]−[b7]
[b6]
ΔT [K]
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−100
−80
−60
−40
−20
0
20
Radial Velocity V_{LSR} [km s^{-1}]

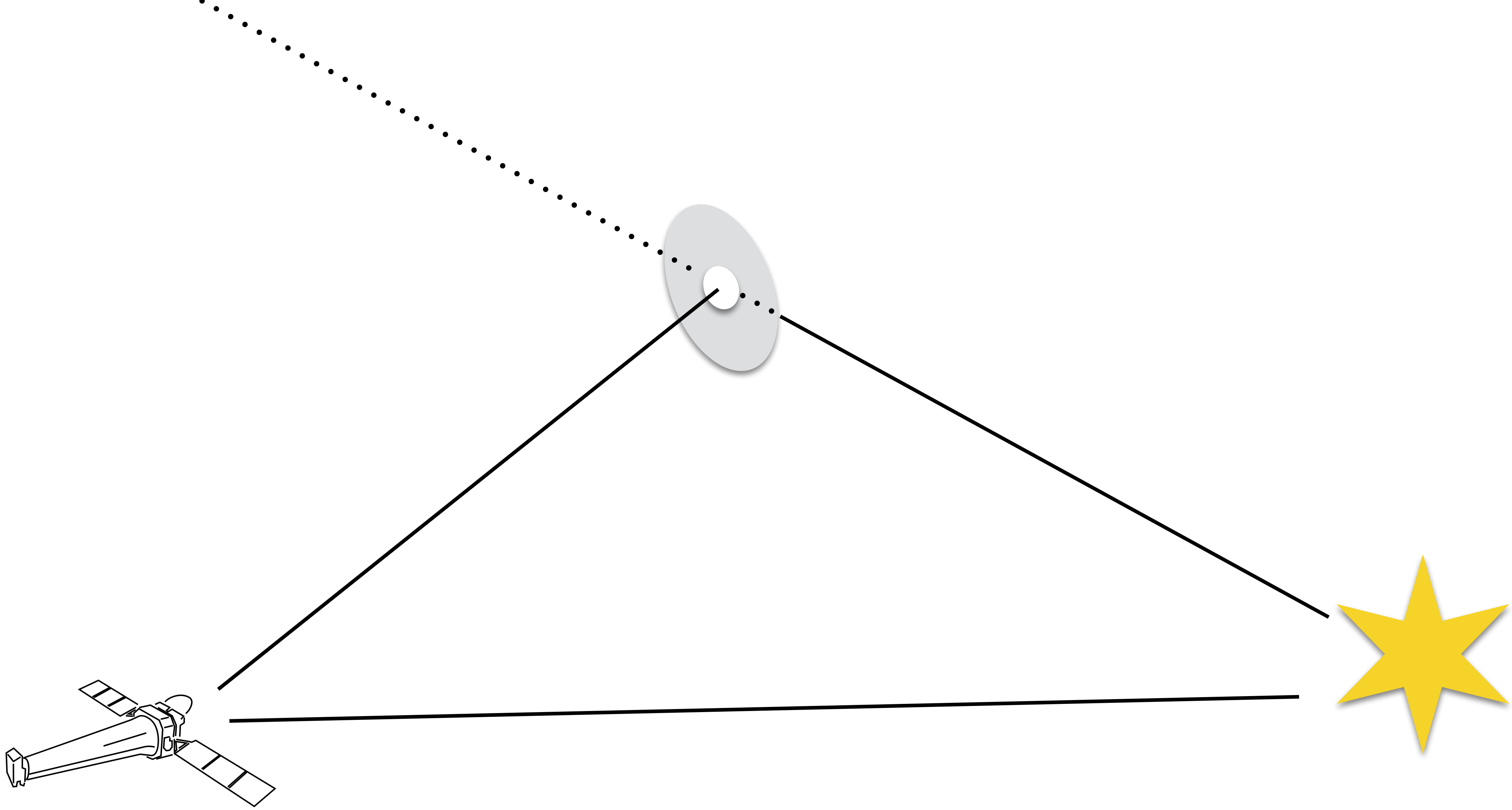
$$D_{\rm dust} = \frac{D_{\rm Cir}}{1 + \frac{2c\Delta t}{\theta^2 D_{\rm Cir}}}$$

$$v_{\rm LSR}(D_{\rm Dust}, \phi_{\rm Gal})$$



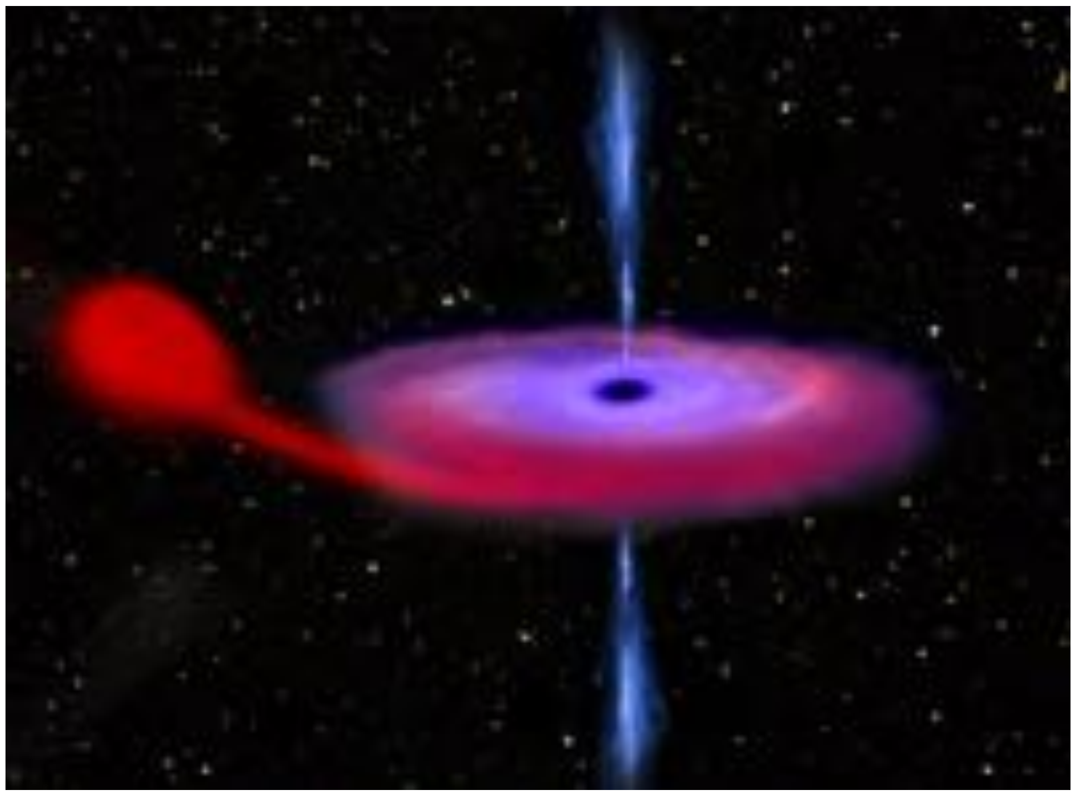
- Best fit distanc

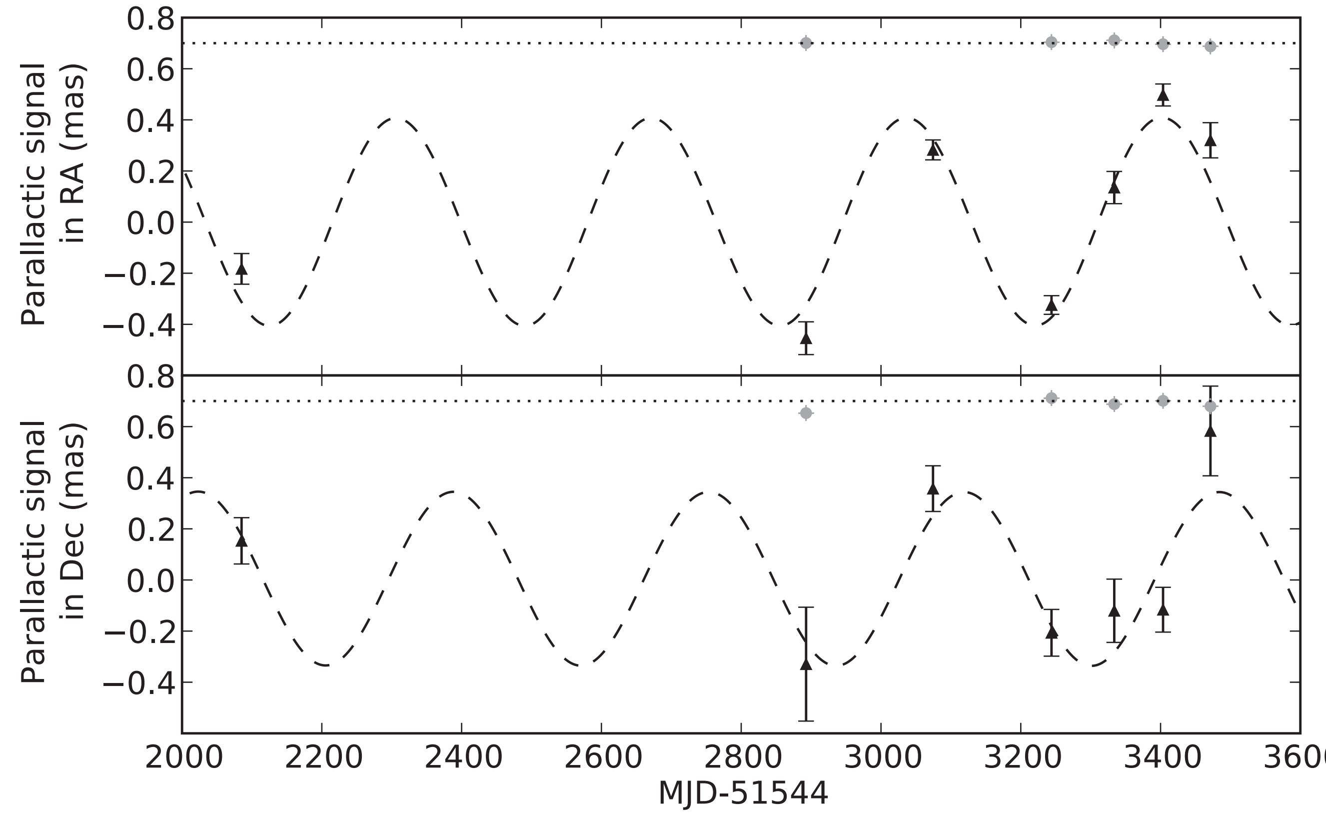
$$D_{\rm Cir} = 9.4^{+0.8}_{-1.0}\ {\rm k}$$



$$I_\nu(\theta, t_{\mathrm{obs}}) = N_{\mathrm{H}} \frac{F_\nu(t_{\mathrm{obs}} - \Delta t_\theta)}{(1-x)^2} \frac{d\sigma_\nu}{d\Omega}$$

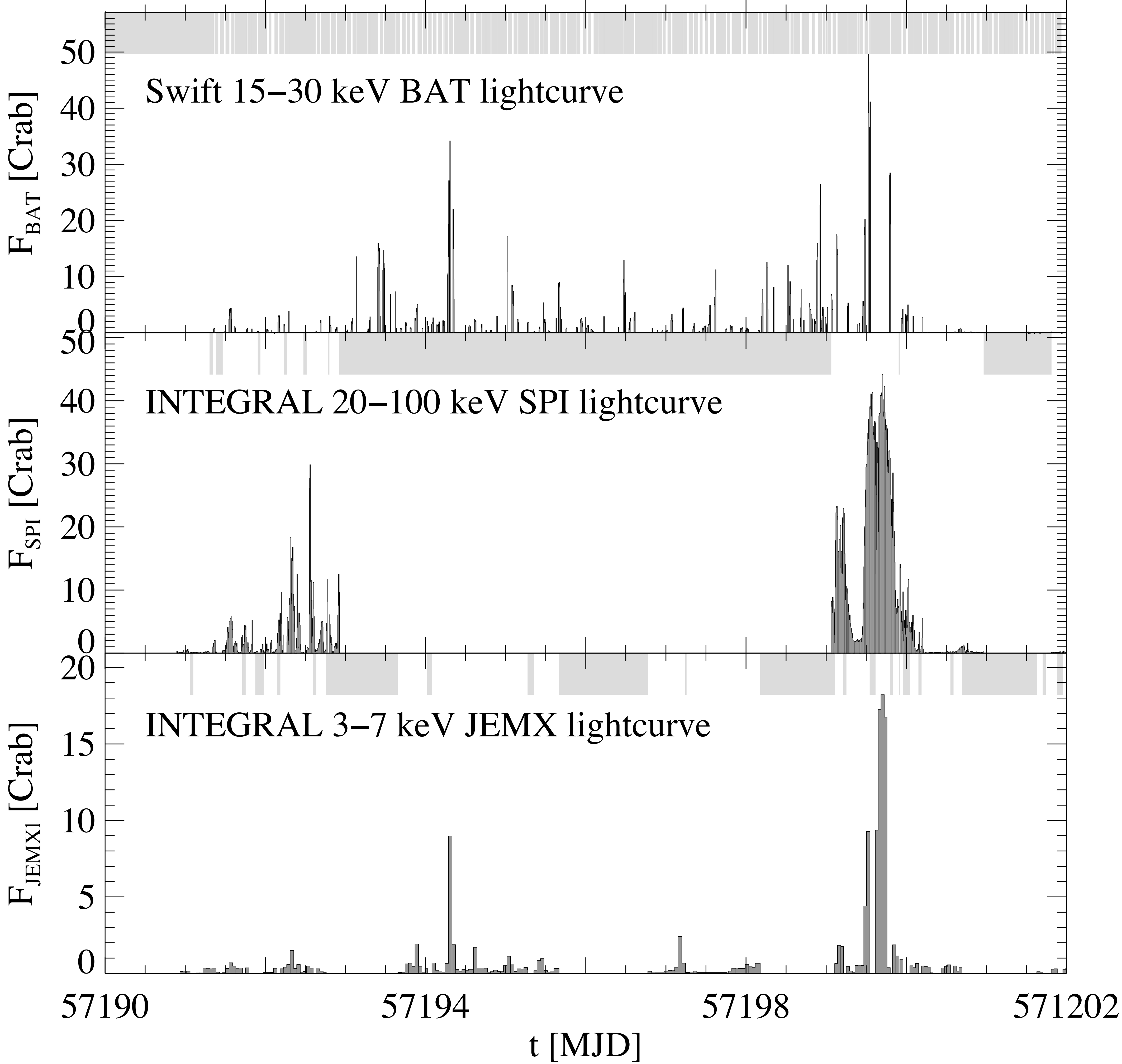
V404 Cygni



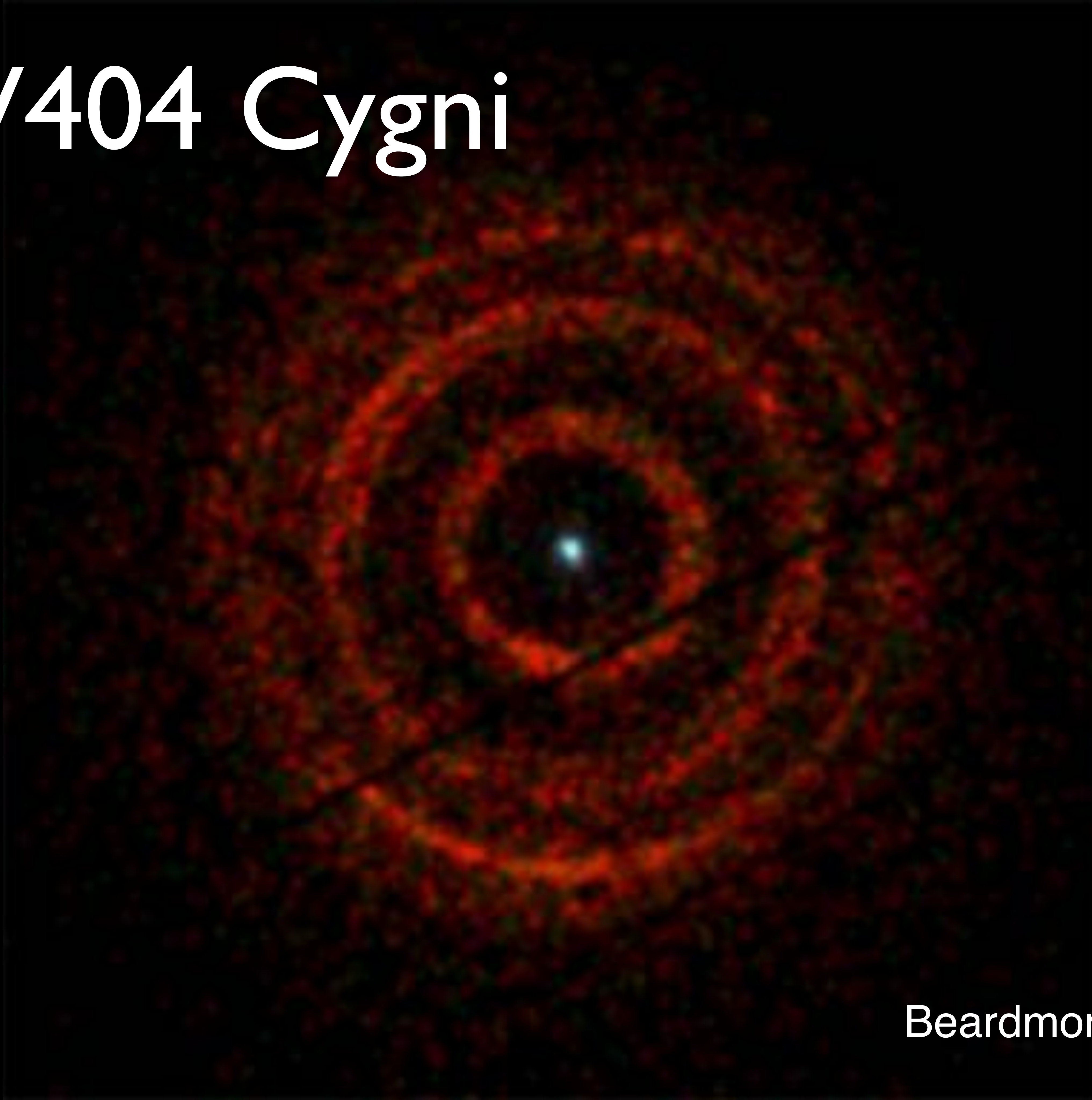


$$D = 2.39 \pm 0.14\,\mathrm{kpc}$$

$$M = 12 \pm 3 M_\odot$$

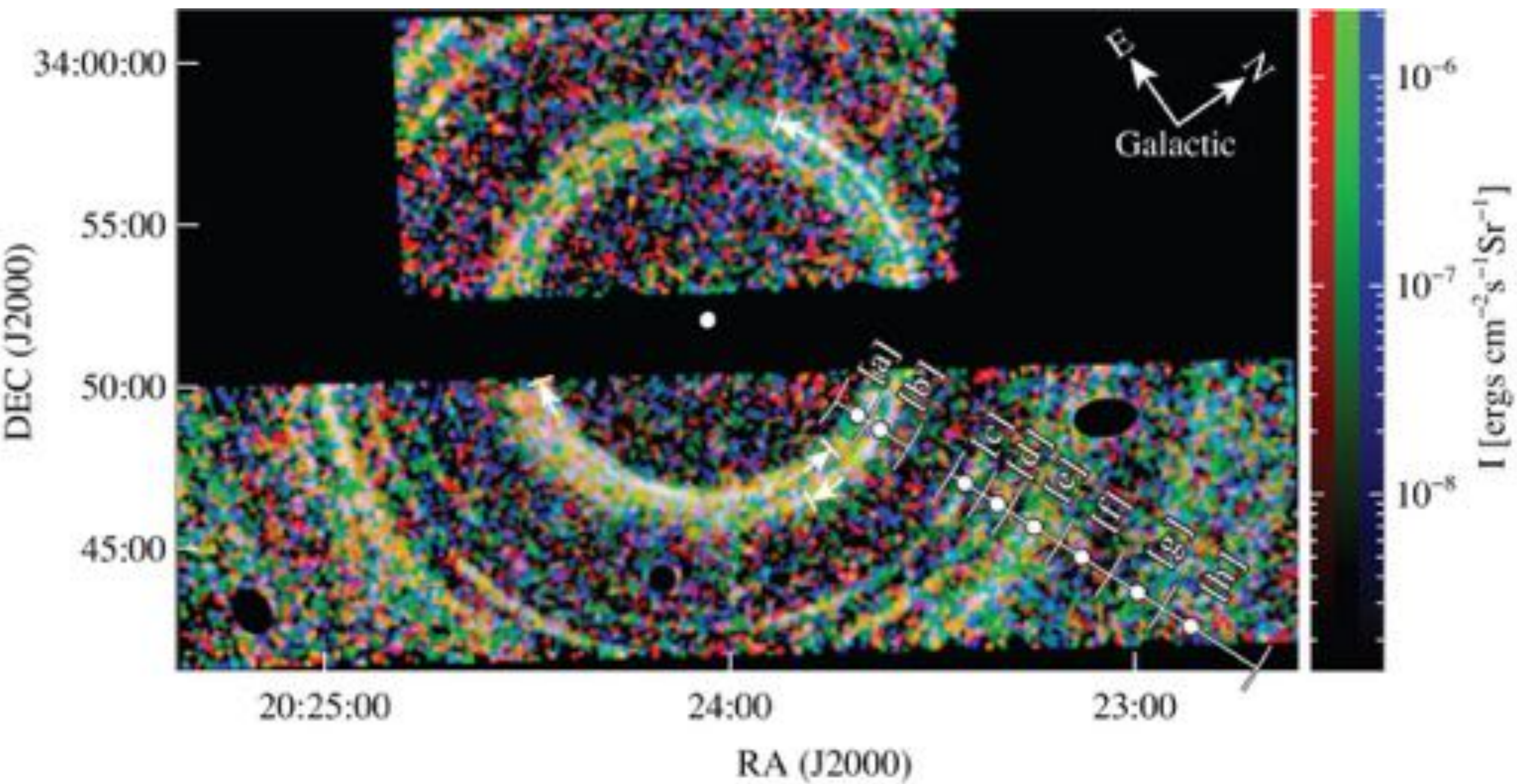

Swift 15−30 keV BAT lightcurve
INTEGRAL 20−100 keV SPI lightcurve
INTEGRAL 3−7 keV JEMX lightcurve
F_{BAT} [Crab]
F_{SPI} [Crab]
F_{JEMX1} [Crab]
t [MJD]
57190
57194
57198
571202

V404 Cygni



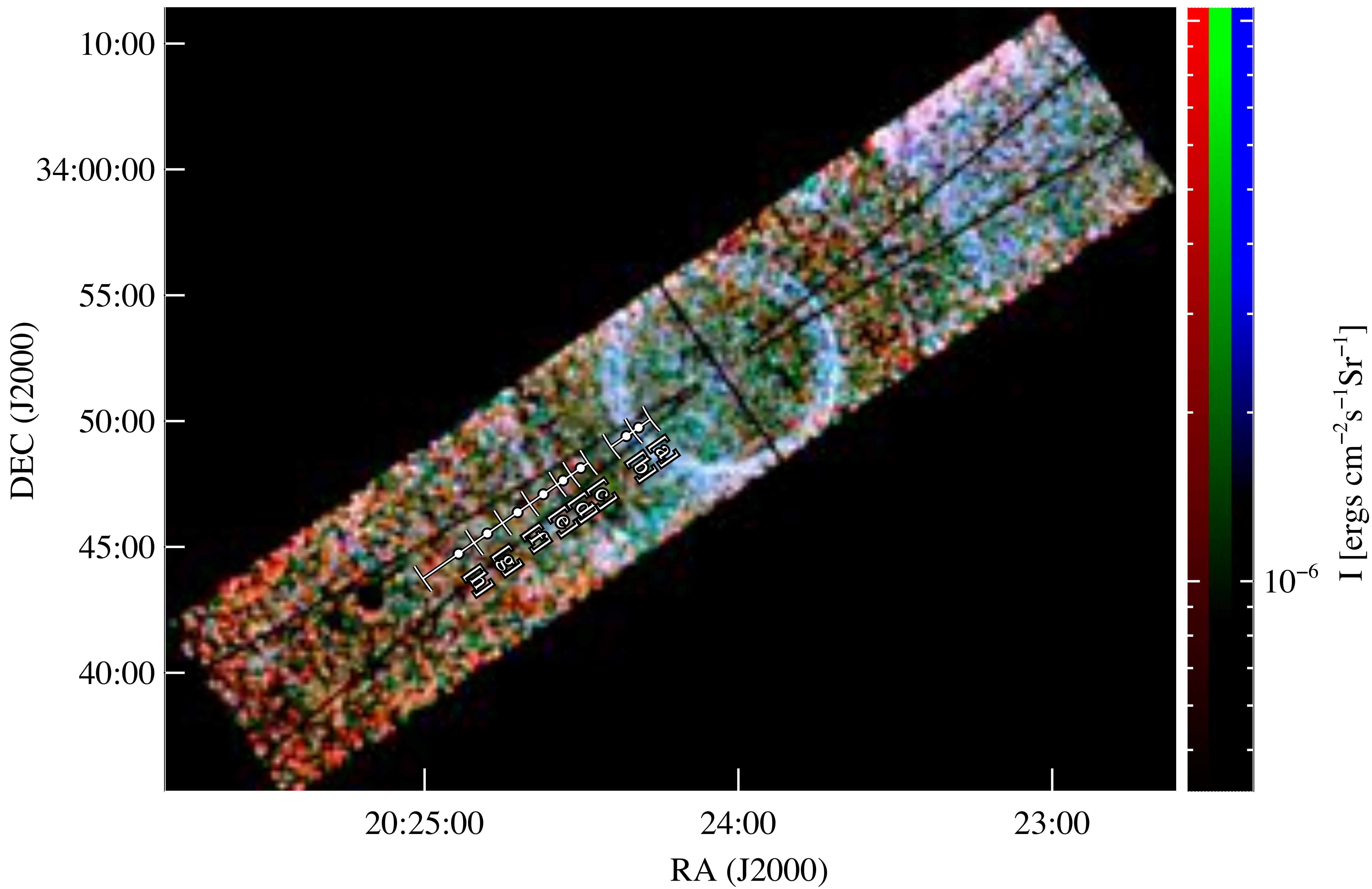
Beardmore+'15

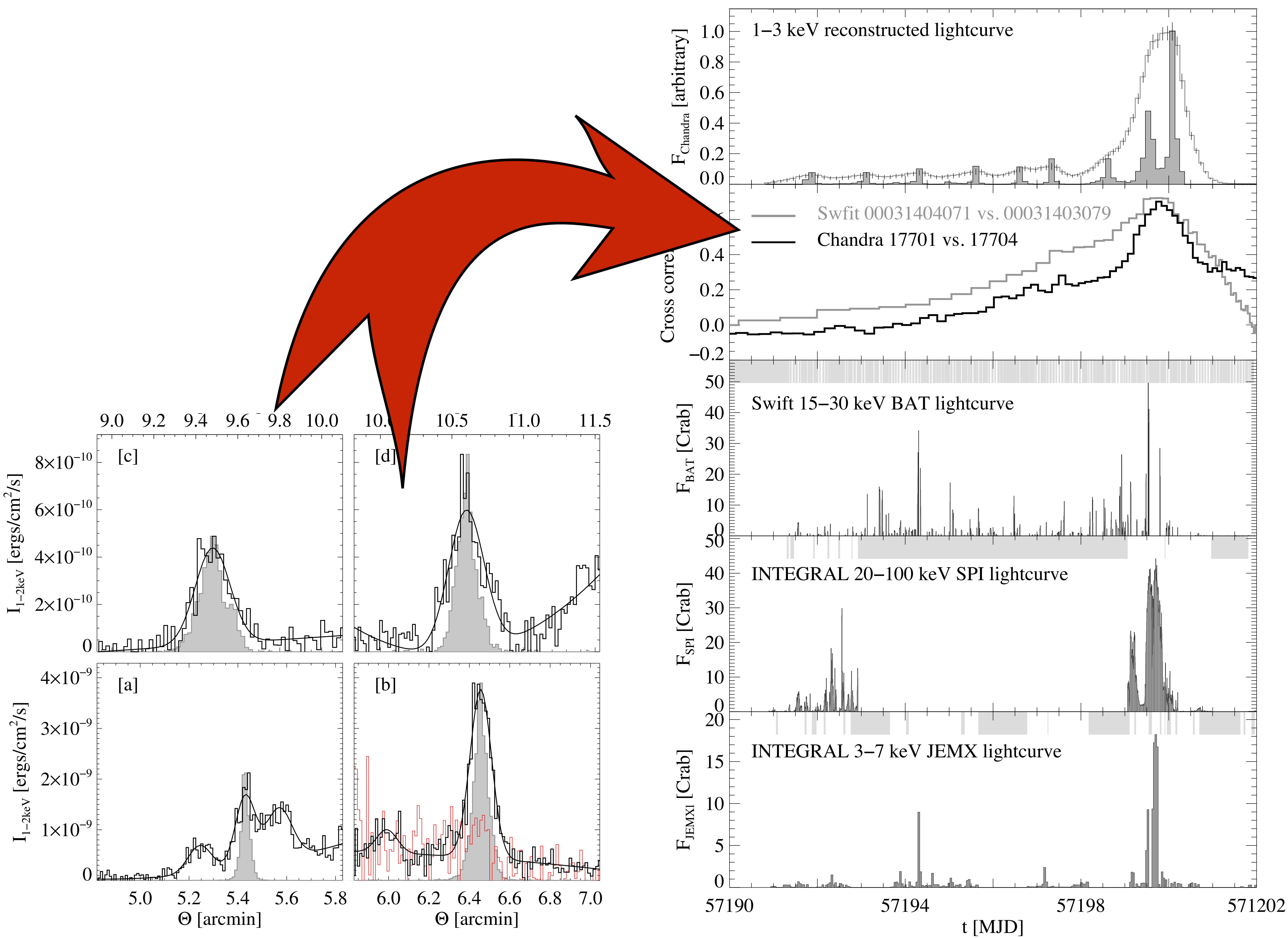
Chandra (DDT)



34:00:00
55:00
50:00
45:00
DEC (J2000)
20:25:00
24:00
23:00
RA (J2000)
E
N
Galactic
[a]
[b]
[c]
[d]
[e]
[f]
[g]
[h]
10^{-6}
10^{-7}
10^{-8}
I [ergs cm^{-2}s^{-1}Sr^{-1}]

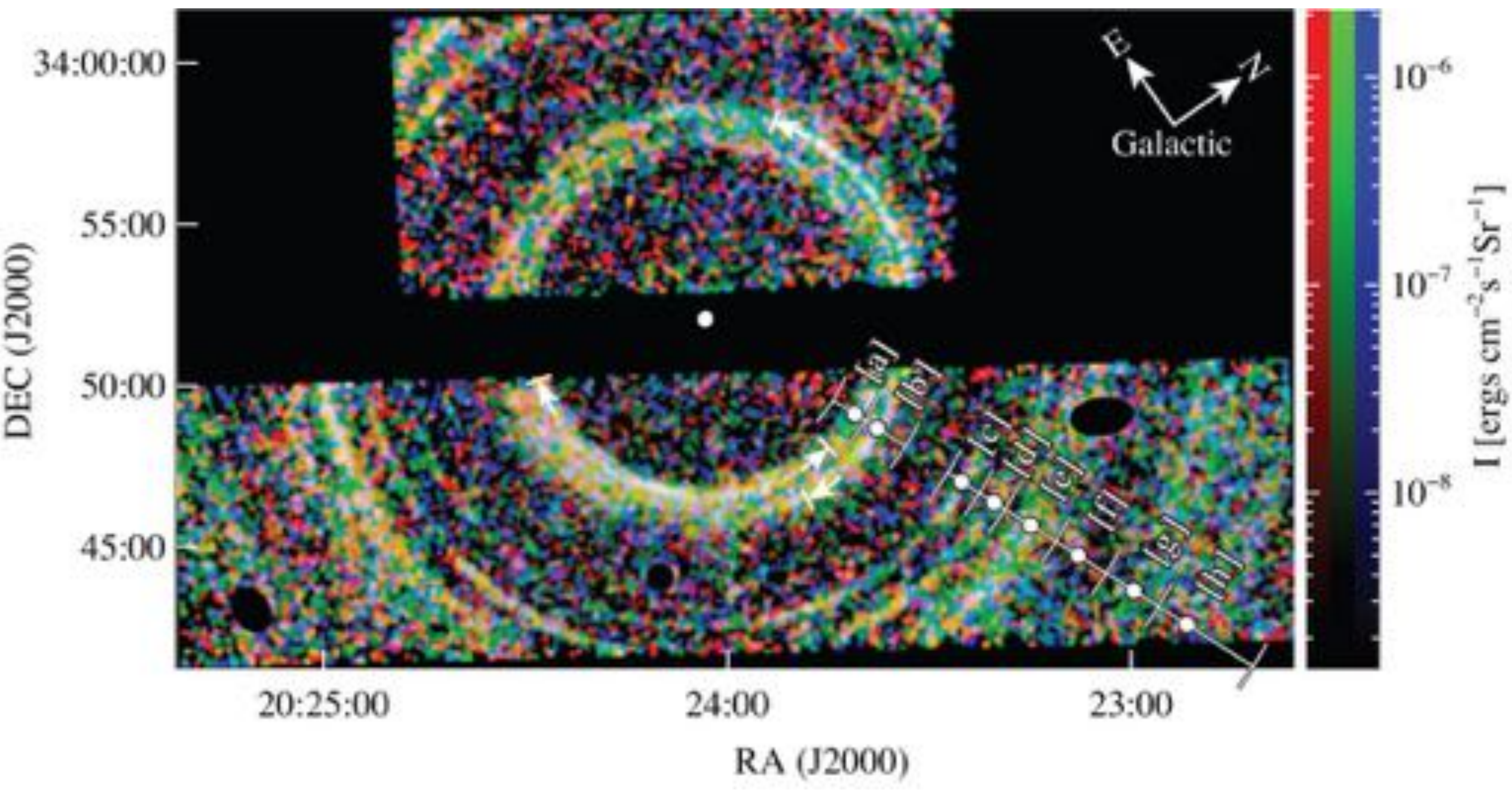
Chandra (DDT-2)





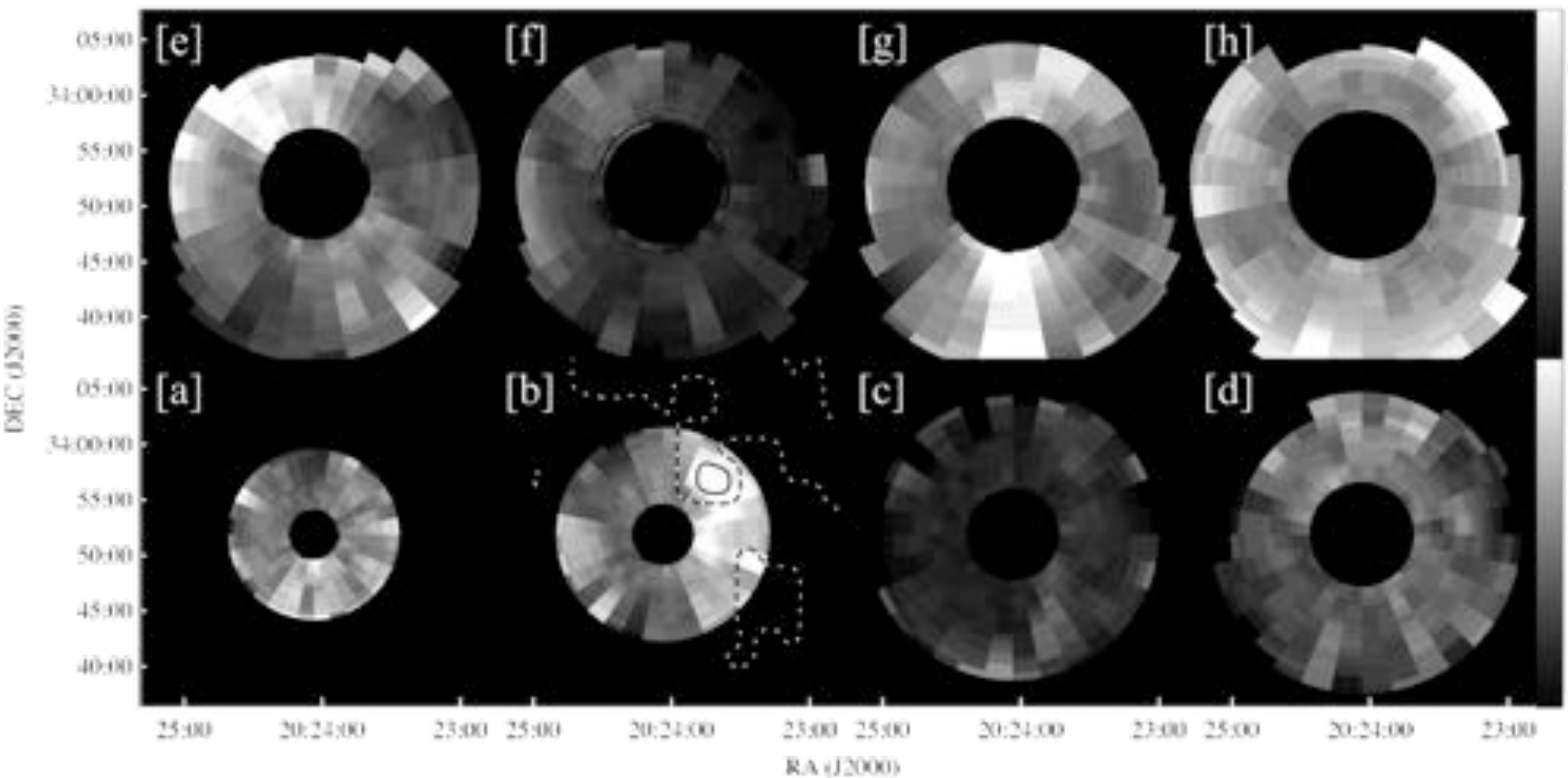
1–3 keV reconstructed lightcurve
F_Chandra [arbitrary]
Swfit 00031404071 vs. 00031403079
Chandra 17701 vs. 17704
Cross corre
Swift 15–30 keV BAT lightcurve
F_BAT [Crab]
INTEGRAL 20–100 keV SPI lightcurve
F_SPI [Crab]
INTEGRAL 3–7 keV JEMX lightcurve
F_JEMX1 [Crab]
t [MJD]
[c]
[d]
[a]
[b]
I_1−2keV [ergs/cm^2/s]
Θ [arcmin]

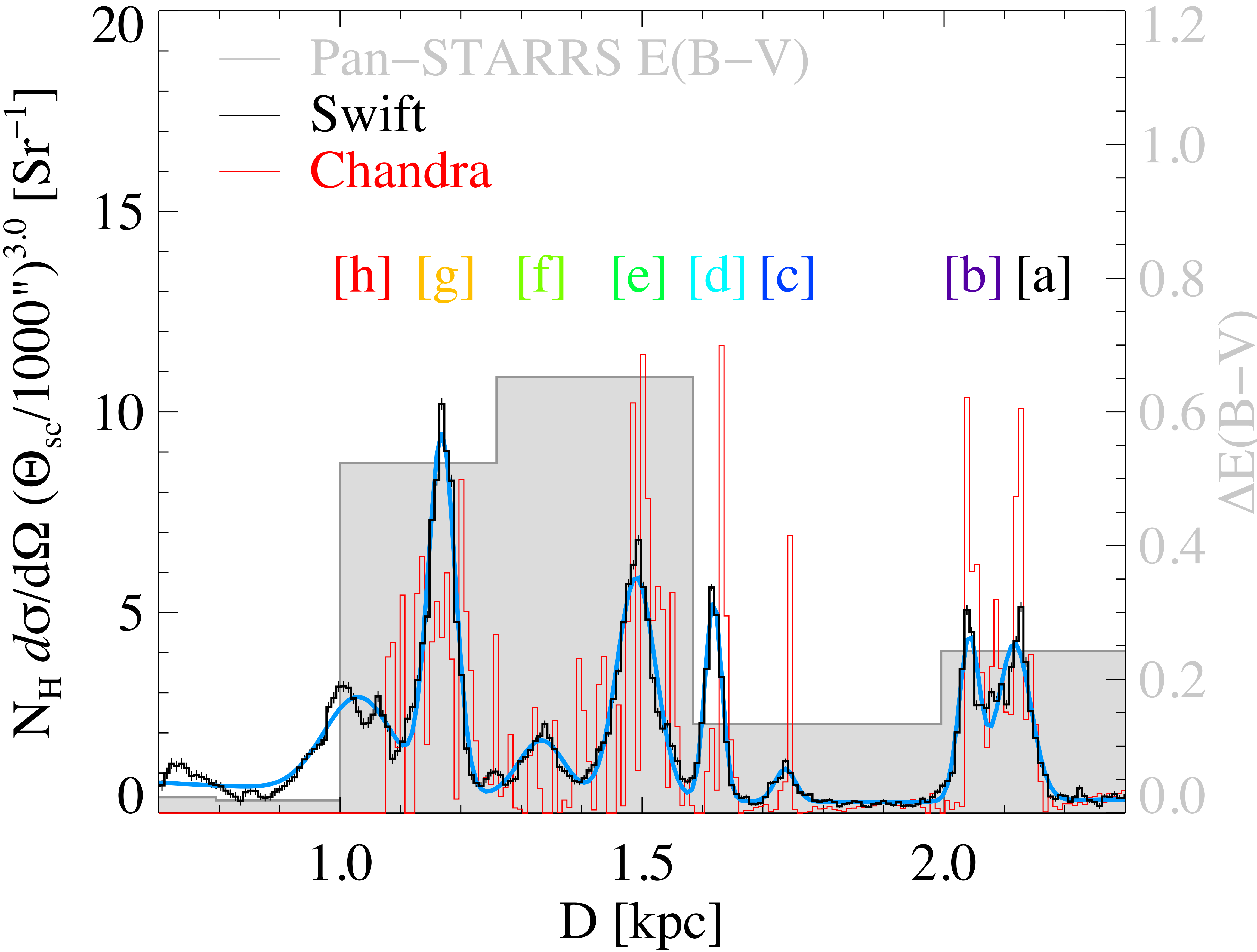
8 Clouds



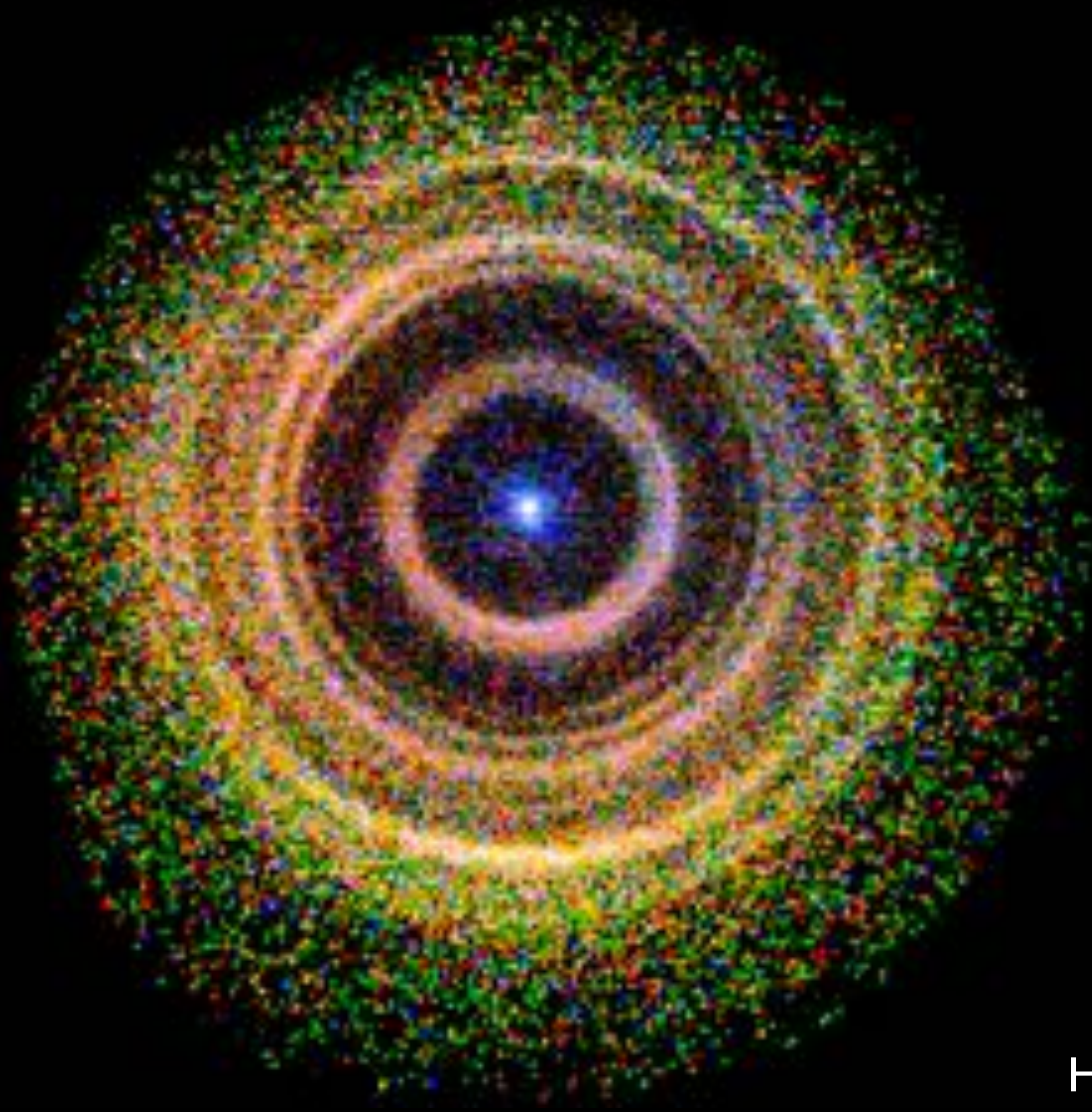
34:00:00
55:00
50:00
45:00
DEC (J2000)
20:25:00
24:00
23:00
RA (J2000)
E
N
Galactic
[a]
[b]
[c]
[d]
[e]
[f]
[g]
[h]
10^{-6}
10^{-7}
10^{-8}
I [ergs cm^{-2}s^{-1}Sr^{-1}]

8 Clouds





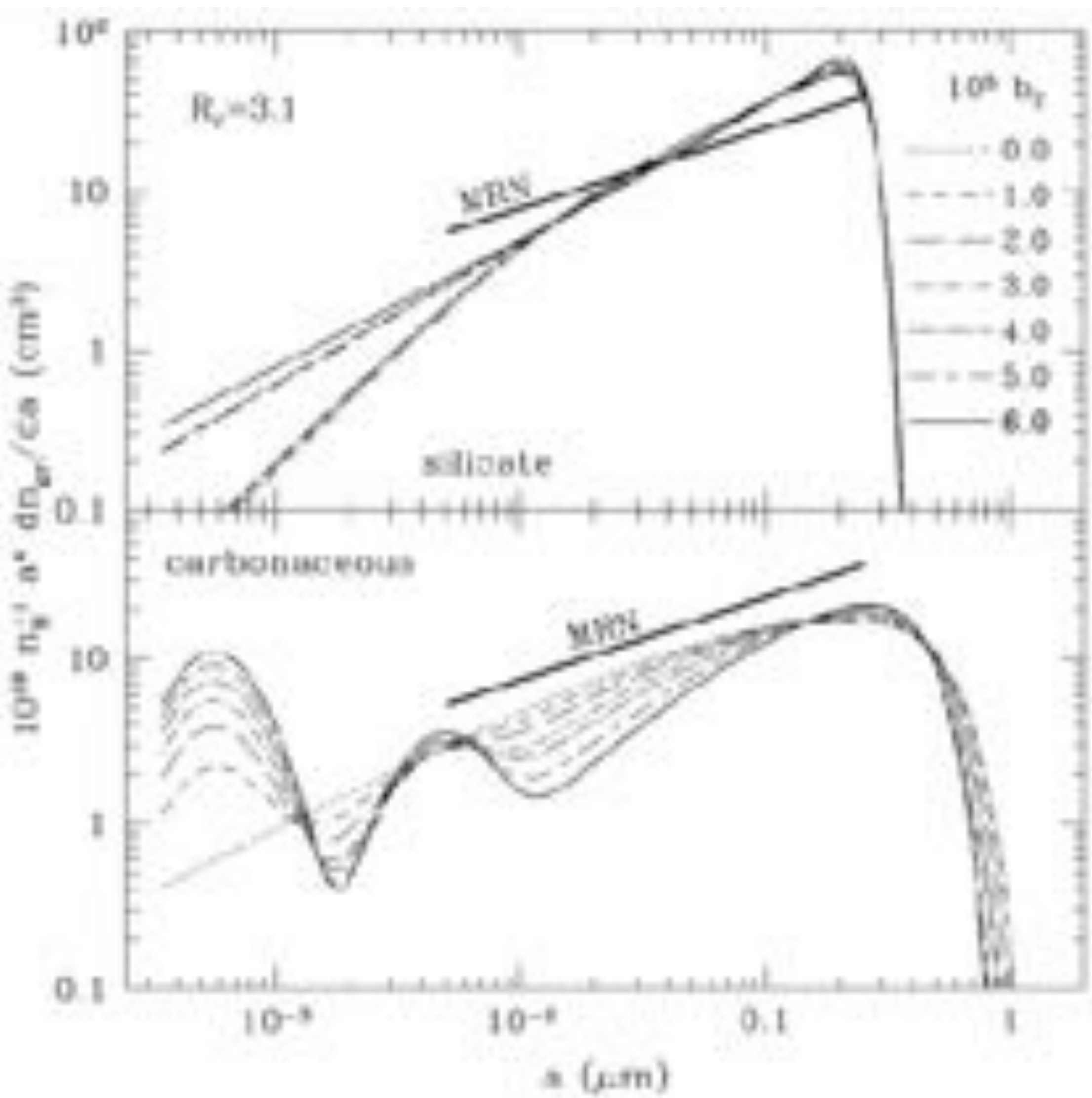
Pan−STARRS E(B−V)
Swift
Chandra
[h] [g] [f] [e] [d] [c] [b] [a]
$N_H\ d\sigma/d\Omega\ (\Theta_{sc}/1000'')^{3.0}$ [Sr^{-1}]
0
5
10
15
20
ΔE(B−V)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.0
1.5
2.0
D [kpc]



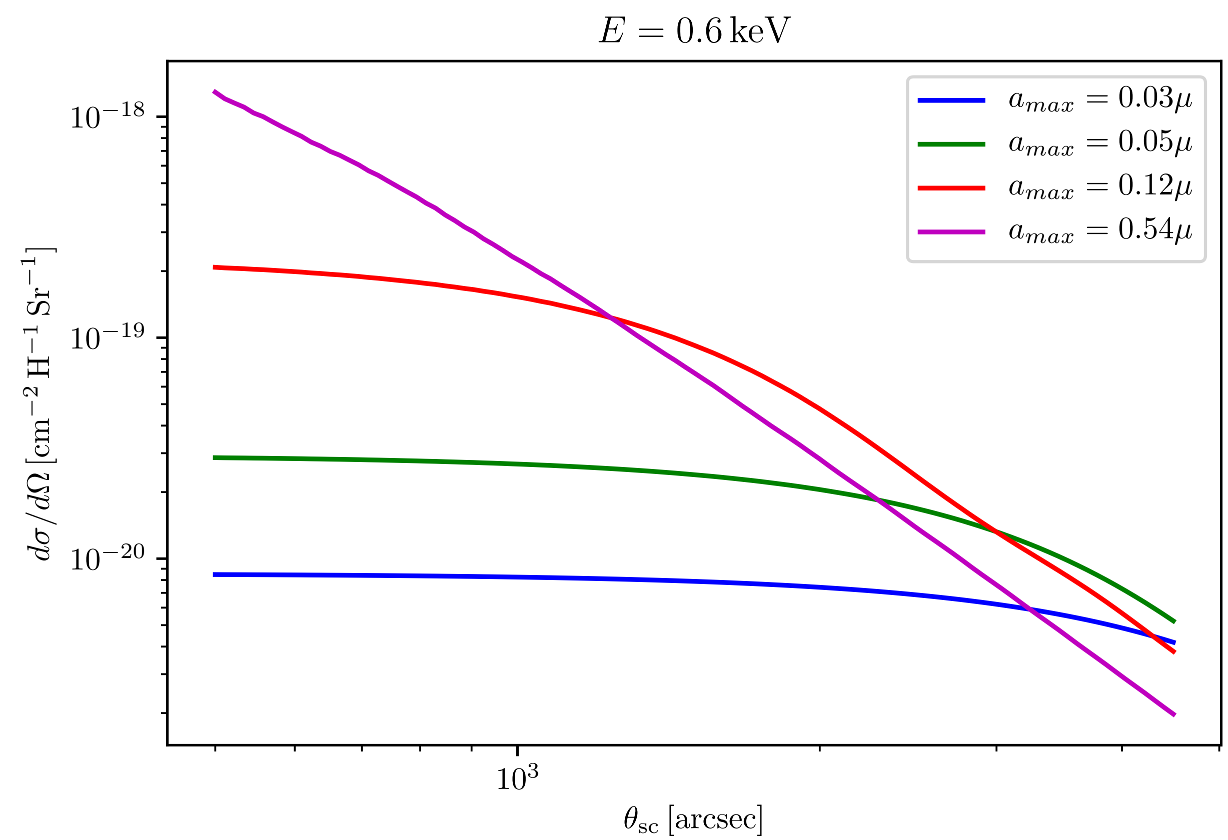
Heinz+'16

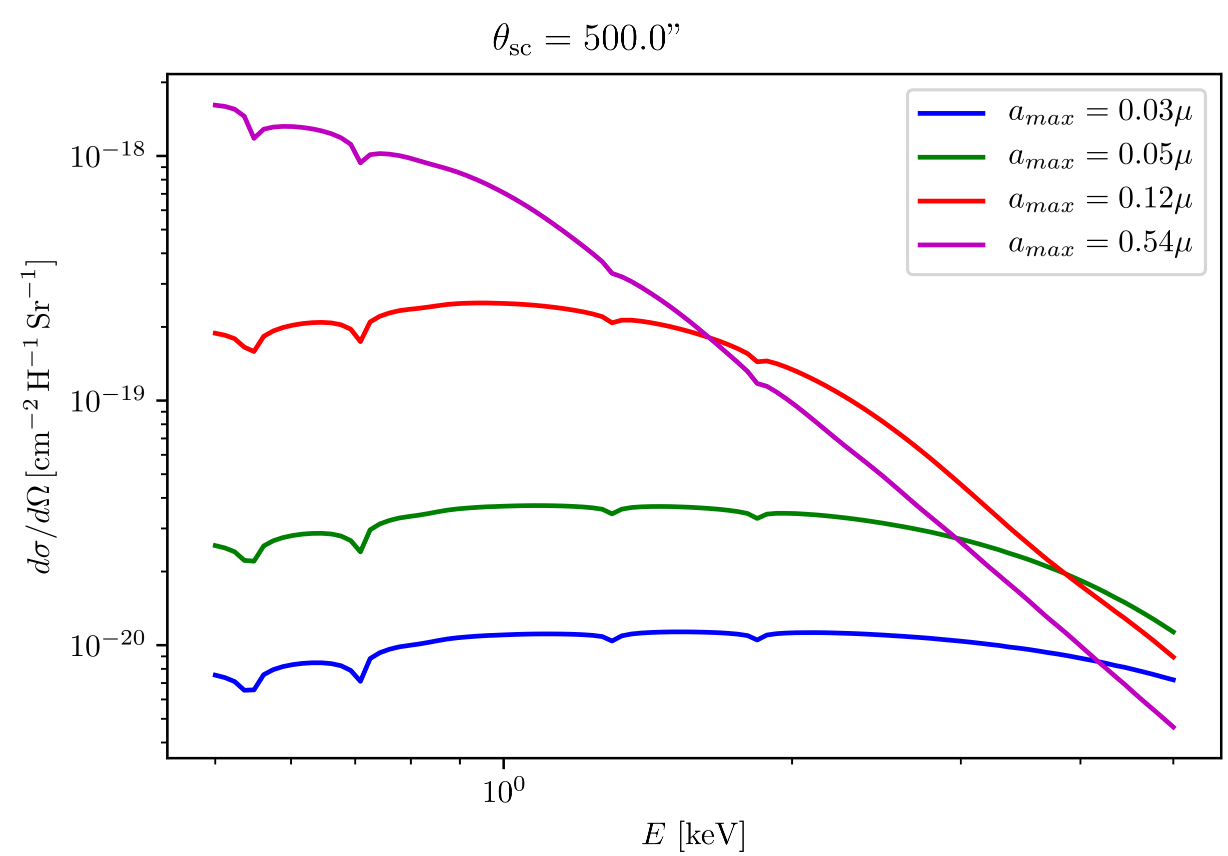

wiseGEEK

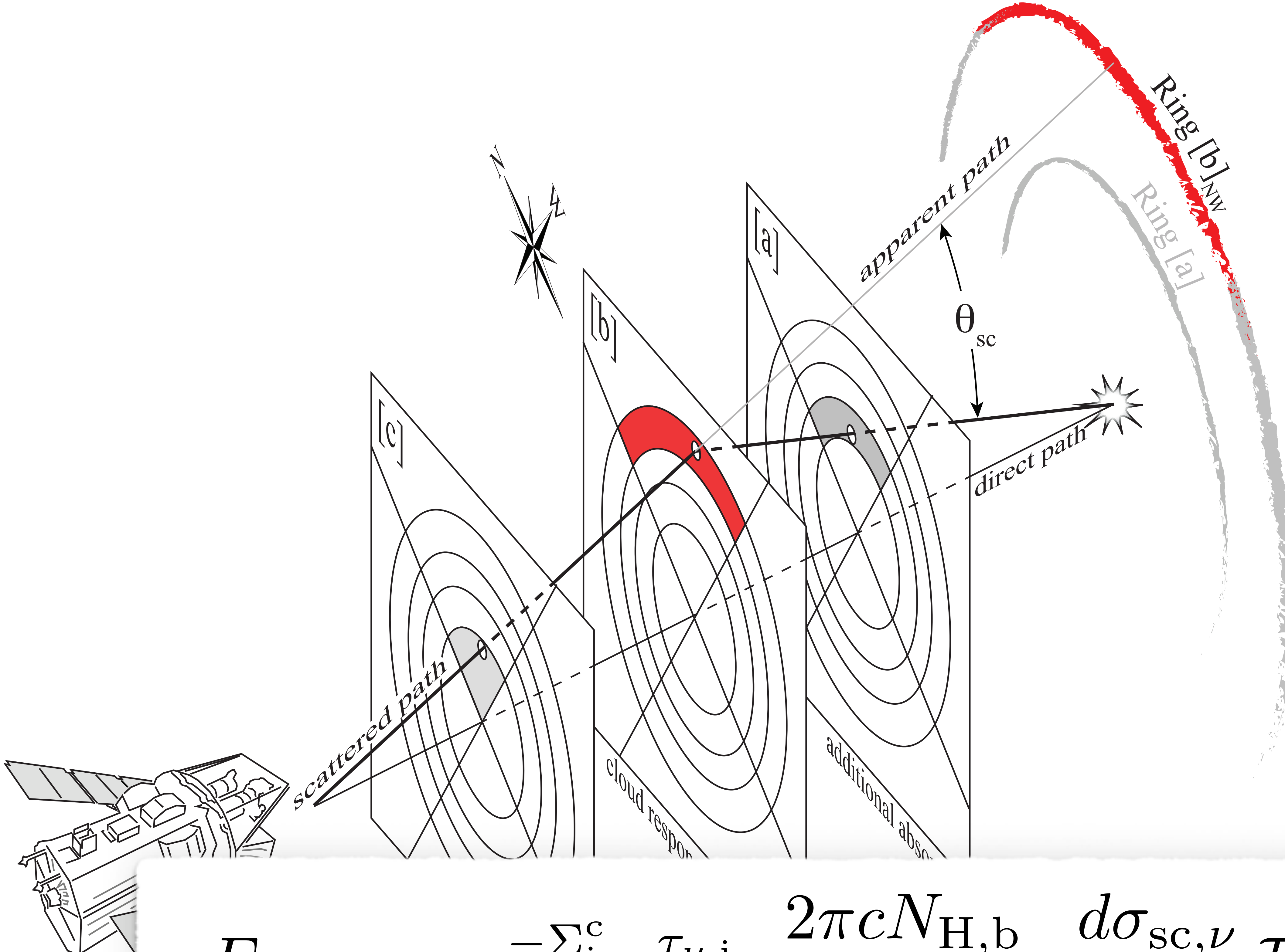
Grain Size Distributions



Mathis, Rumpl, & Nordsieck '77
Weingartner & Draine '01
Zubko, Dwek, & Arendt '04



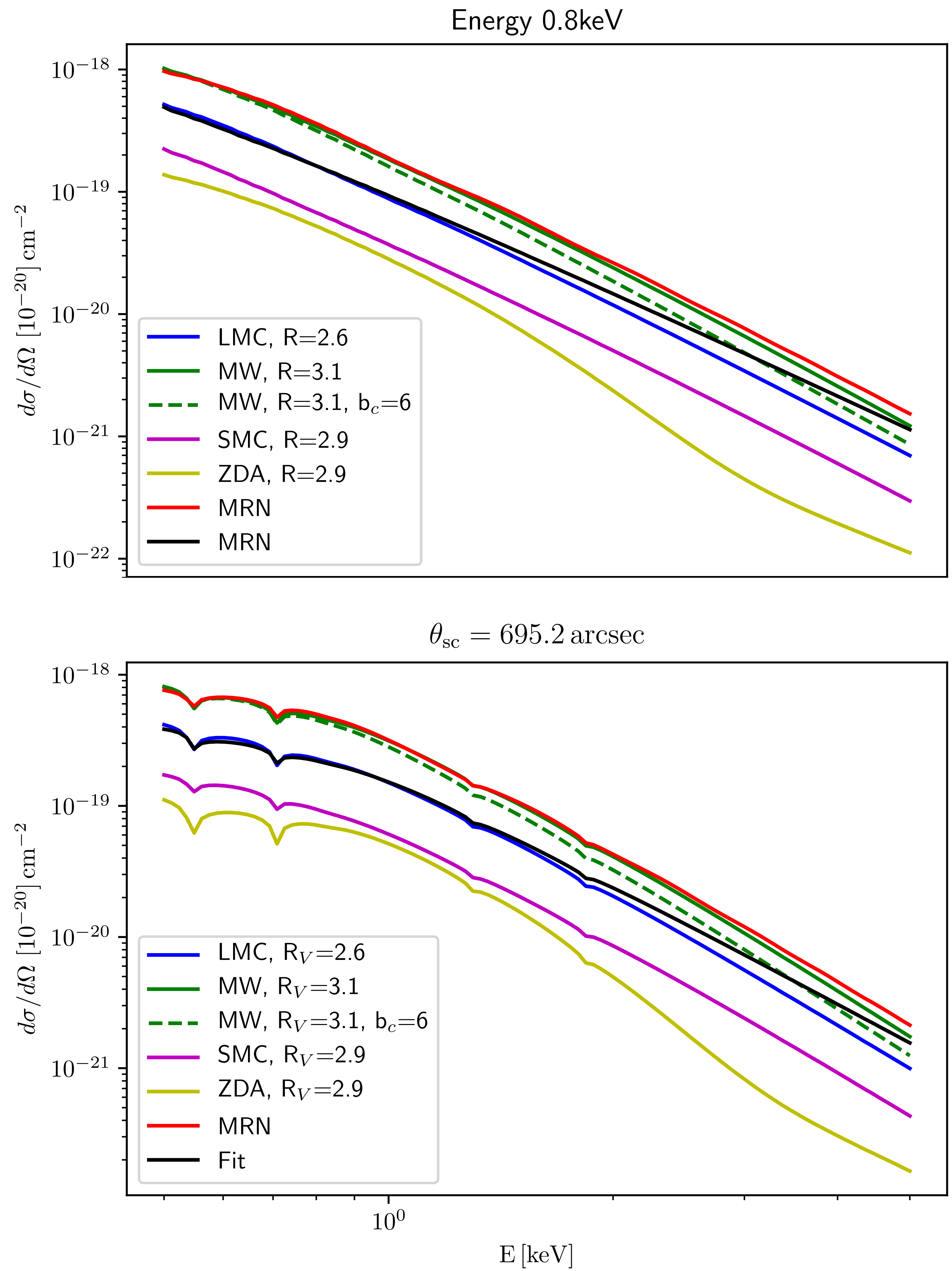




$$F_{\mathrm{ring},\nu} = e^{-\Sigma_{\mathrm{i=a}}^{\mathrm{c}} \tau_{\nu,\mathrm{i}}} \frac{2\pi c N_{\mathrm{H,b}}}{x\,(1-x)\,D} \frac{d\sigma_{\mathrm{sc},\nu}}{d\Omega} \mathcal{F}_\nu$$

Fit:

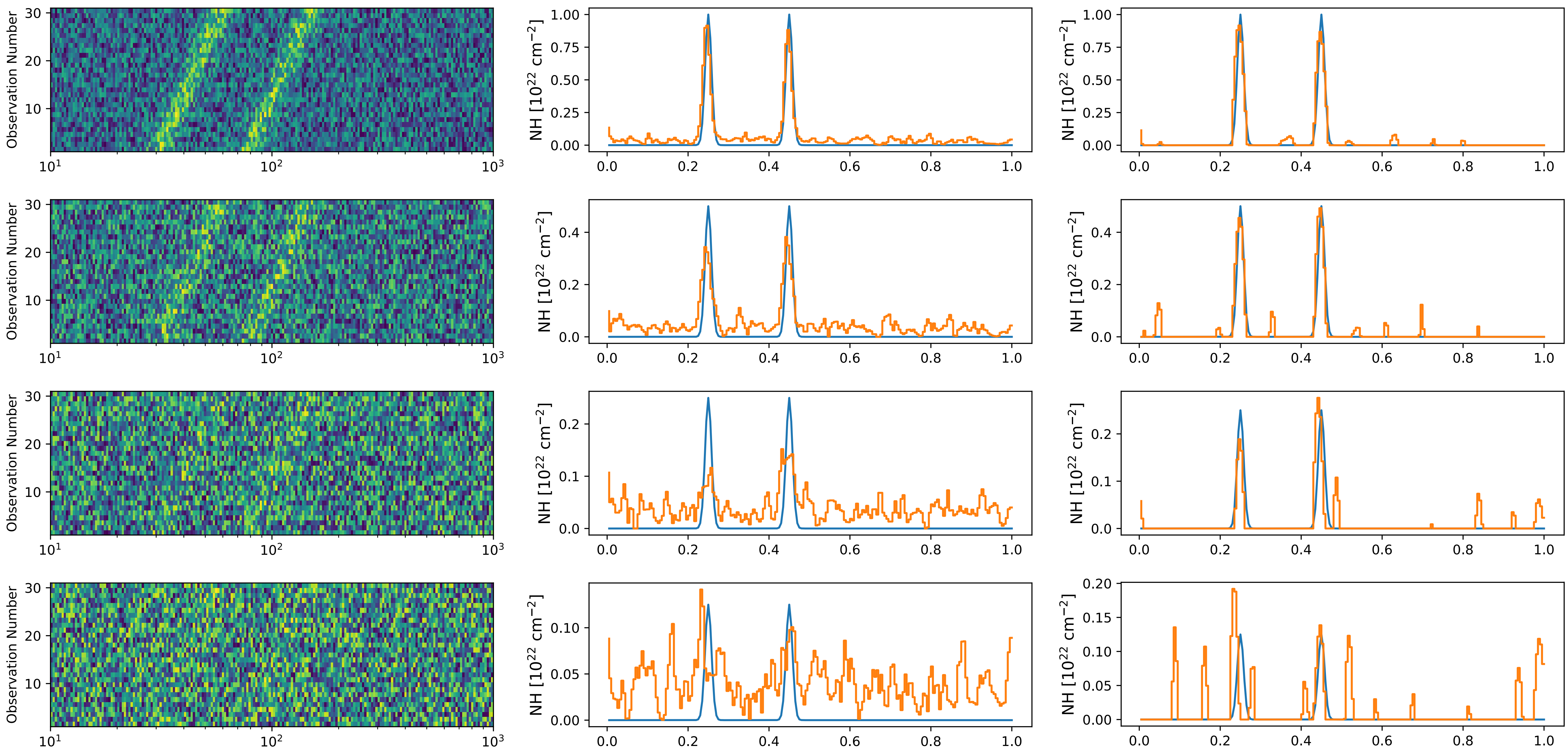
- Dust slope:
  - ★ Best fit: a ~ 4.0
  - ★ A bit steeper than classic MRN
- Dust size:
  - ★ amax > 0.15m
- Composition:
  - ★ <u>Standard graphite/ silicate mix, no ice</u>



A Constrained 2D Lucy-Richardson Deconvolution

30 x 1D

C2D

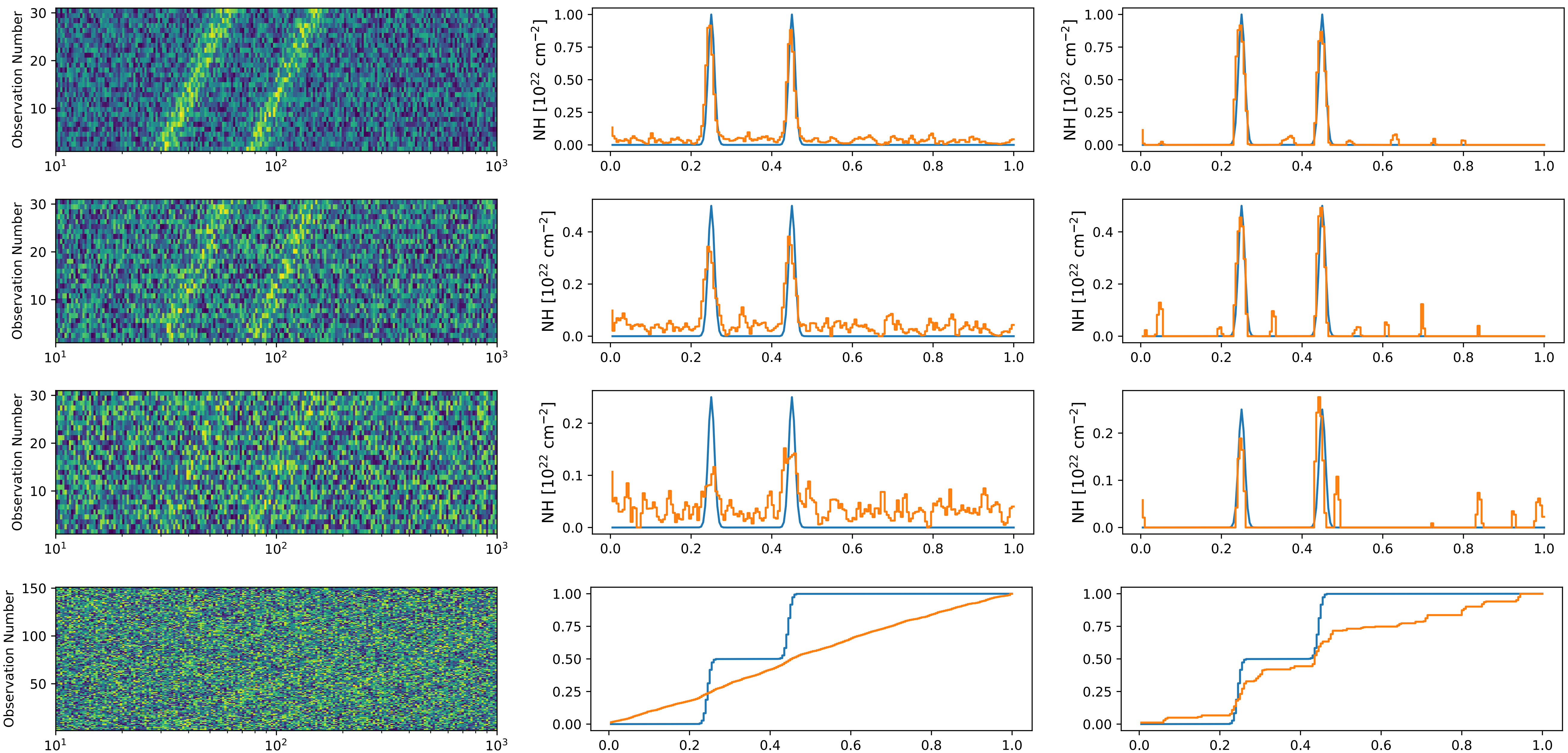


Adams+'21, in prep

A Constrained 2D Lucy-Richardson Deconvolution

30 x 1D

C2D

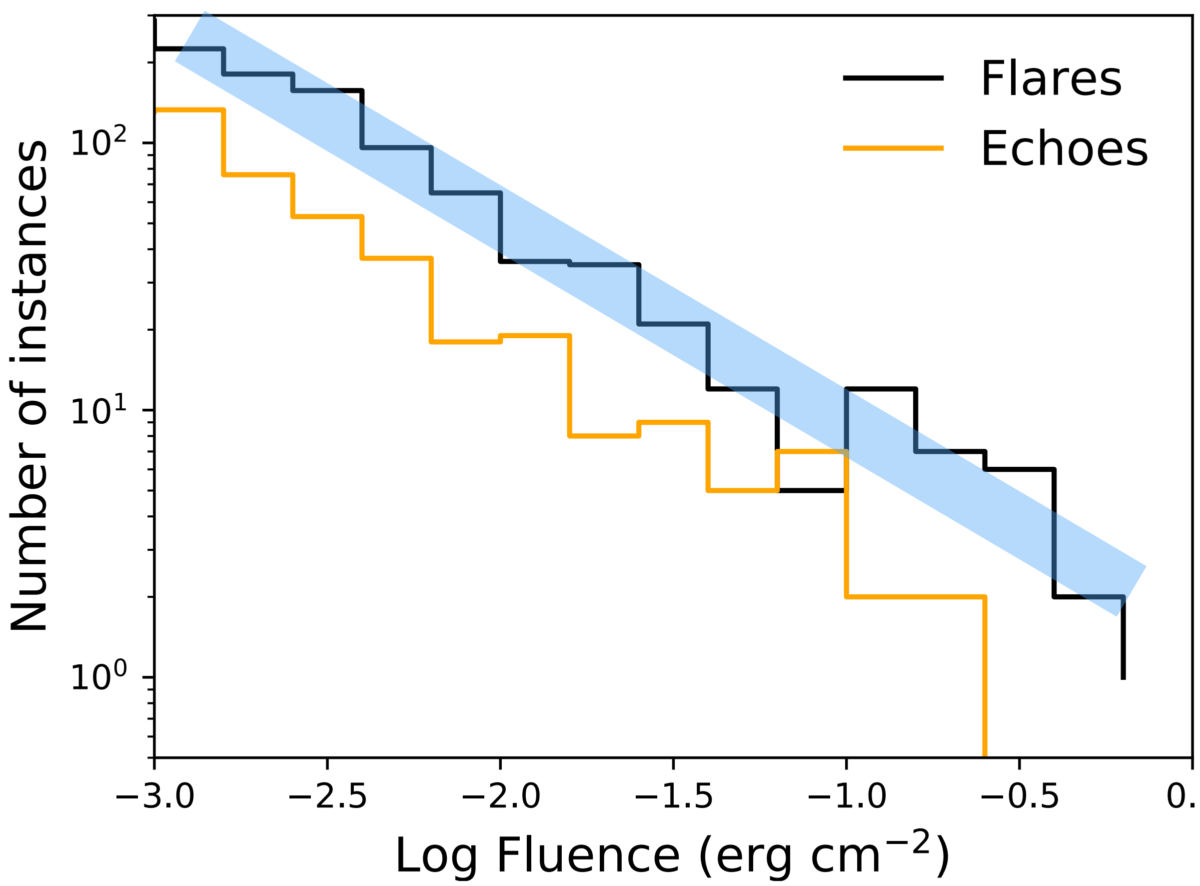


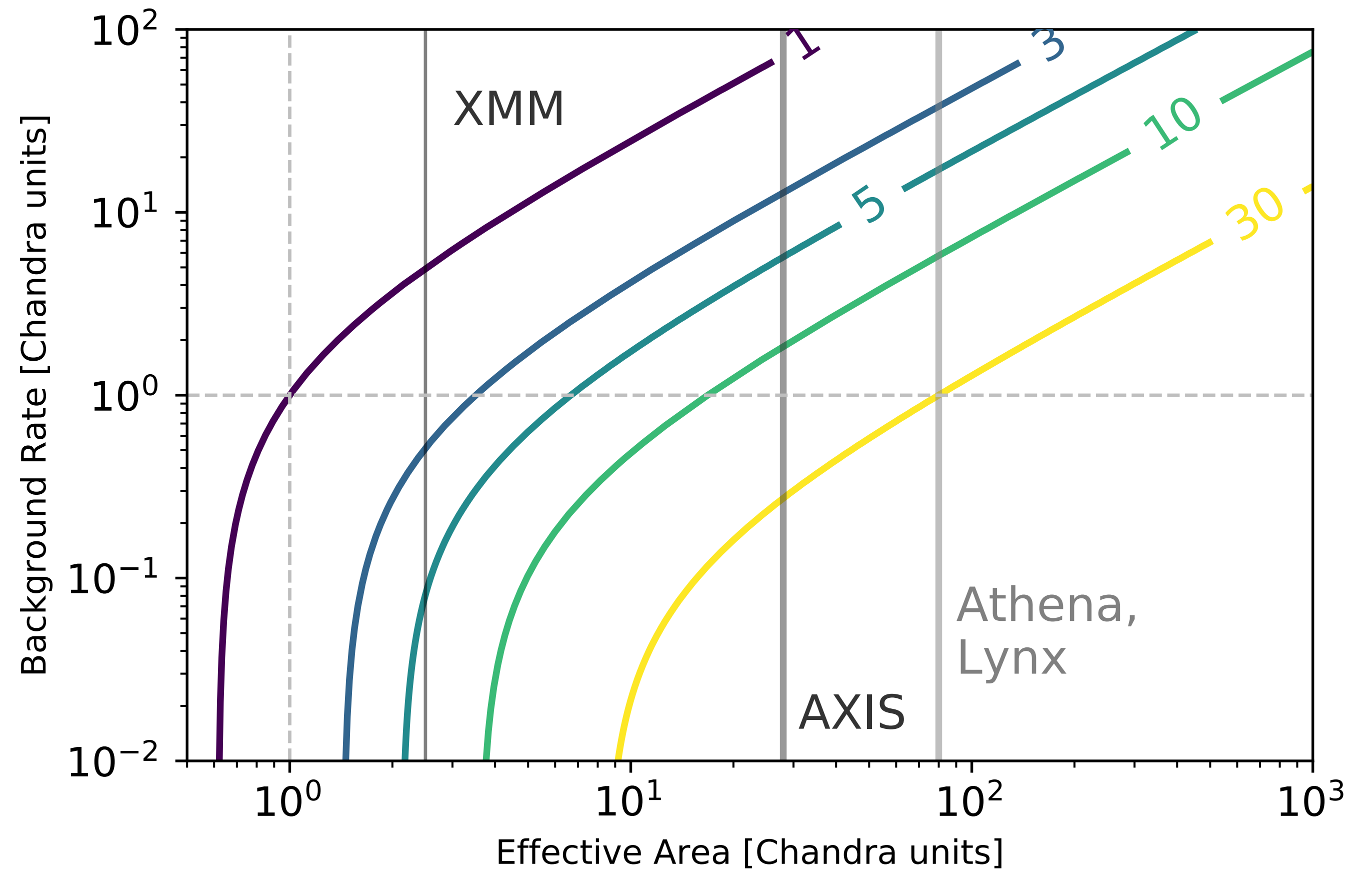
Adams+'21, in prep

The Future

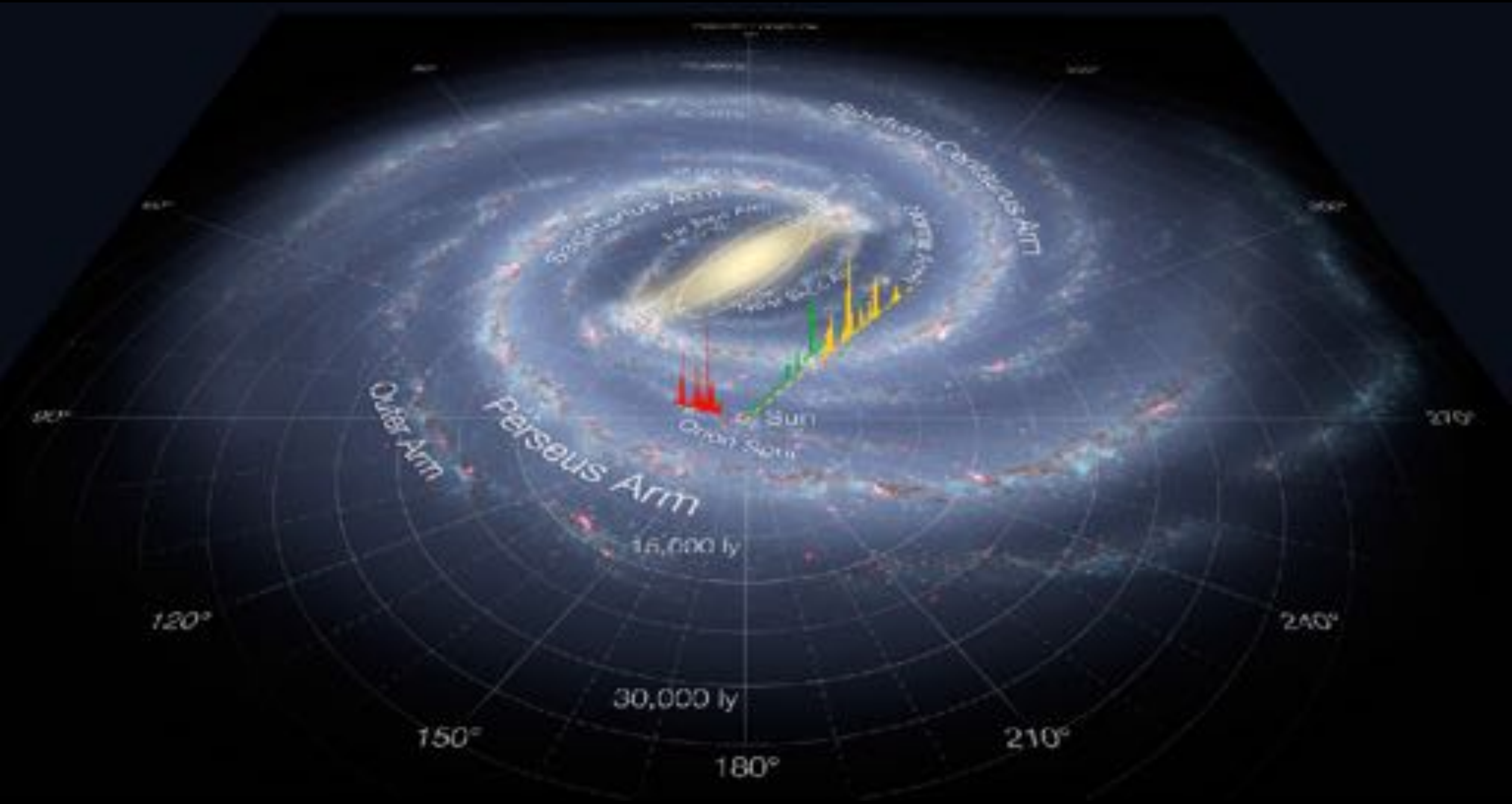
Science requirements:	Athena:
⋆ Angular resolution (~5”)	✔
⋆ Big field of view	✔
⋆ Large collecting area	✔
⋆ Low, stable background	(✔)
⋆ ToO capabilities	(✔)
⋆ Availability of all-sky monitor	(✘)
⋆ Ability to observe bright point sources	(✘)

What does the future hold?





Corrales et al. 2019



Perseus Arm
Outer Arm
Sagittarius Arm
Sun
Orion Spur
16,000 ly
30,000 ly
120°
150°
180°
210°
240°
270°
90°