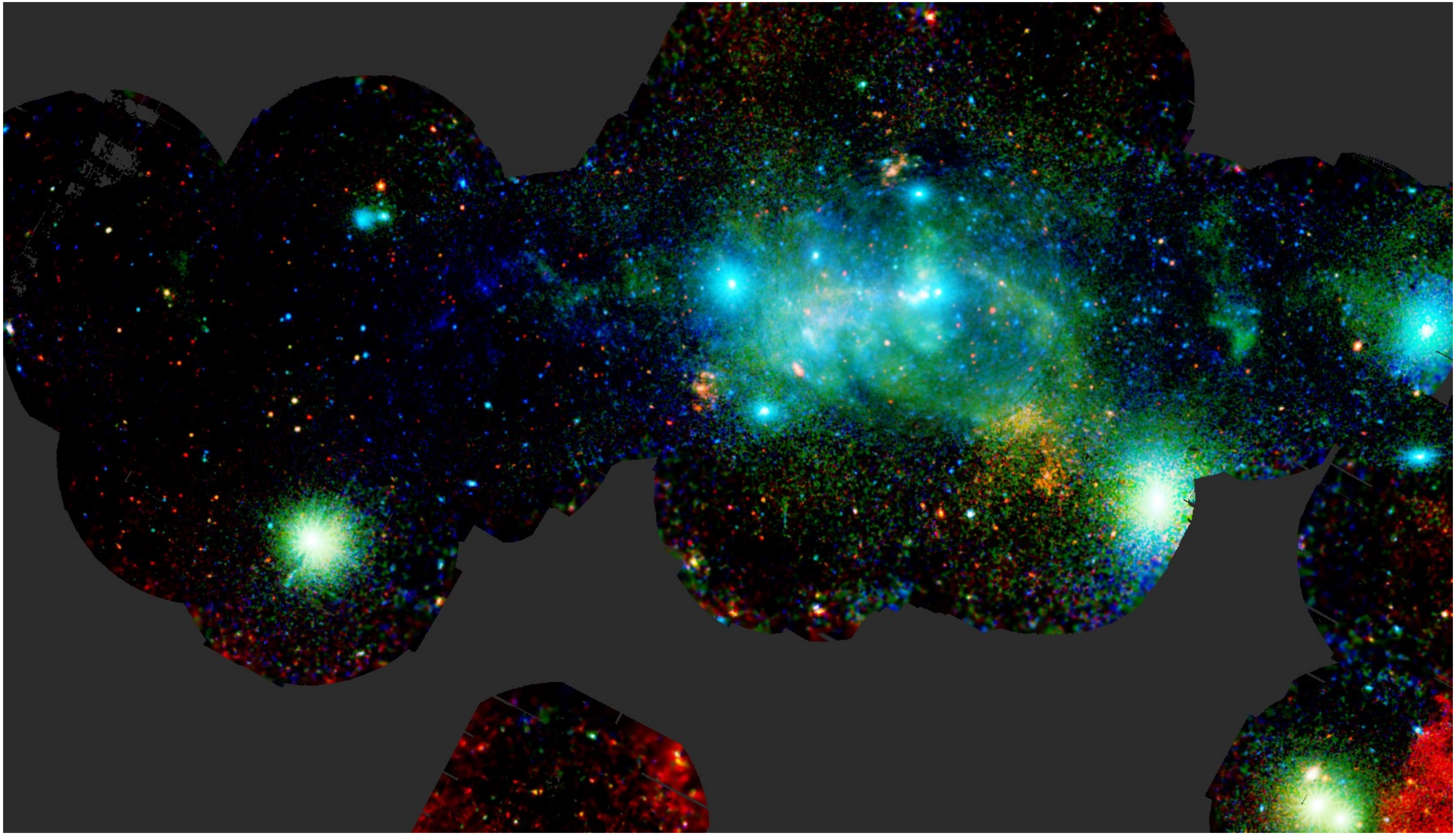
XMM scan of the Galactic center



ESA News/XMM-Newton/G. Ponti et al. 2015a

Gabriele Ponti (MPE Garching)

Morris, Terrier, Haberl, Sturm, Clavel, Soldi, Goldwurm, Predehl, Belanger, Warwick, Tatischeff

What is your background?

What is your name?

Current scientific project?

What you would like to do after this project?
Why?

When I was sitting in your position, I was expecting from the speaker…

To get a comprehensive overview of the Galactic center science

… with a theoretical framework of all the science

➜ To know the solution to tasks that I will be facing

(e.g., “Settimana enigmistica” ➜ get the correct answer)

➜ University preparation

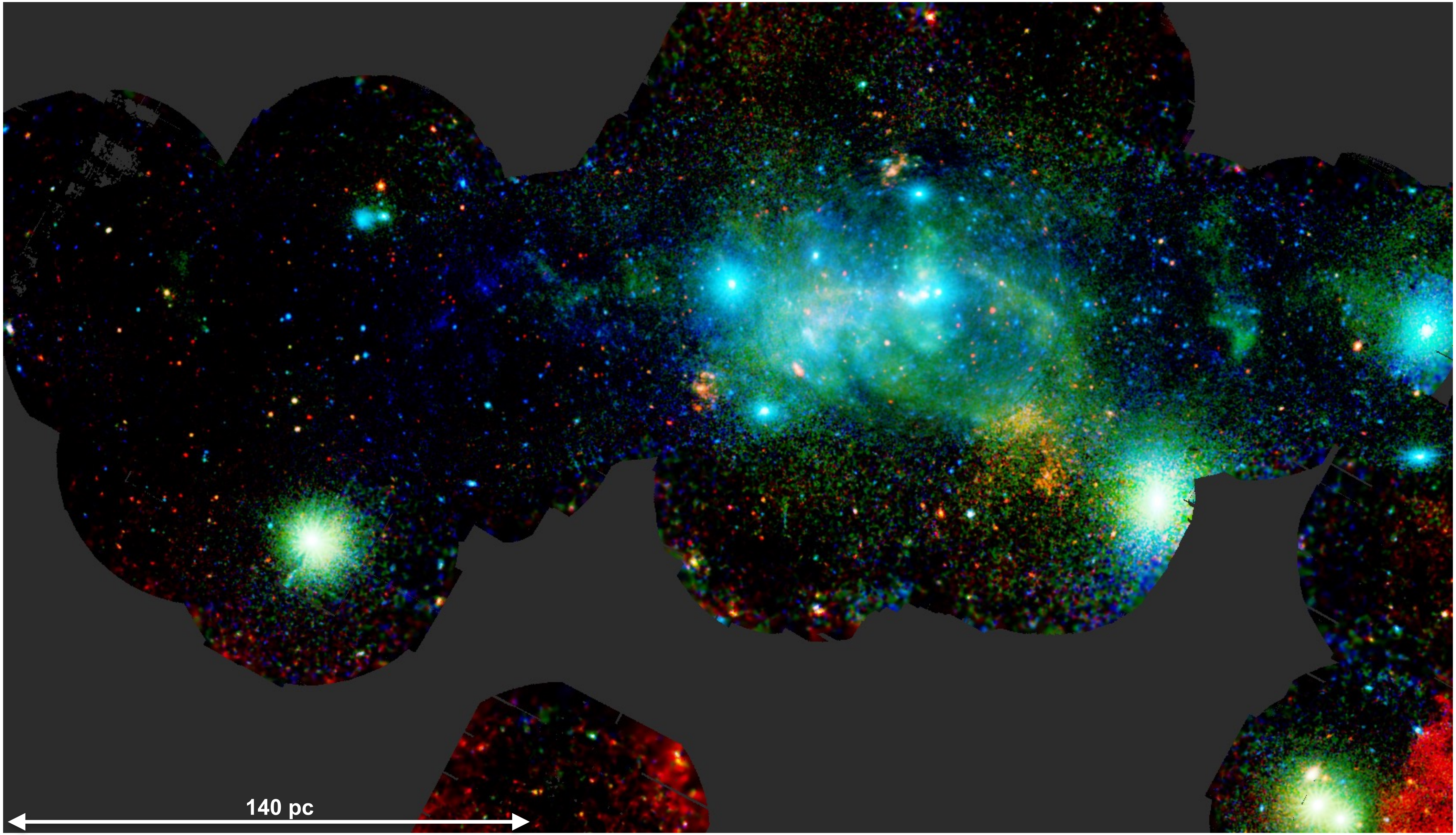
Research is adding new knowledge

➜ Nobody has the correct answer (yet)

➜ You will learn and become the expert!

➜ Present a few experiments

➜ *Explain this image!*



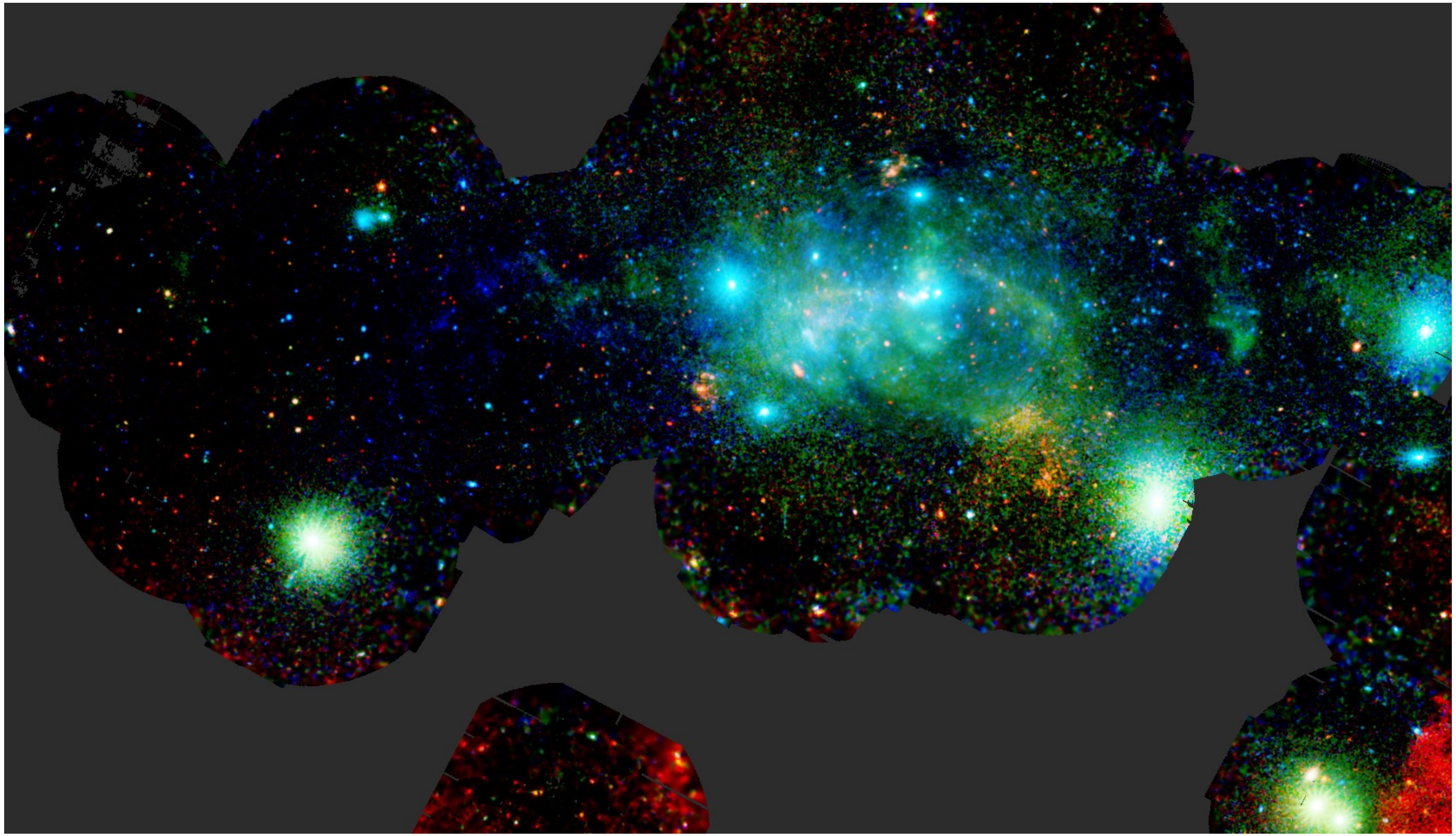
ESA News/XMM-Newton/G. Ponti et al. 2015a

Healthy questions:

Why should I do this work/project?

What are the prospects?

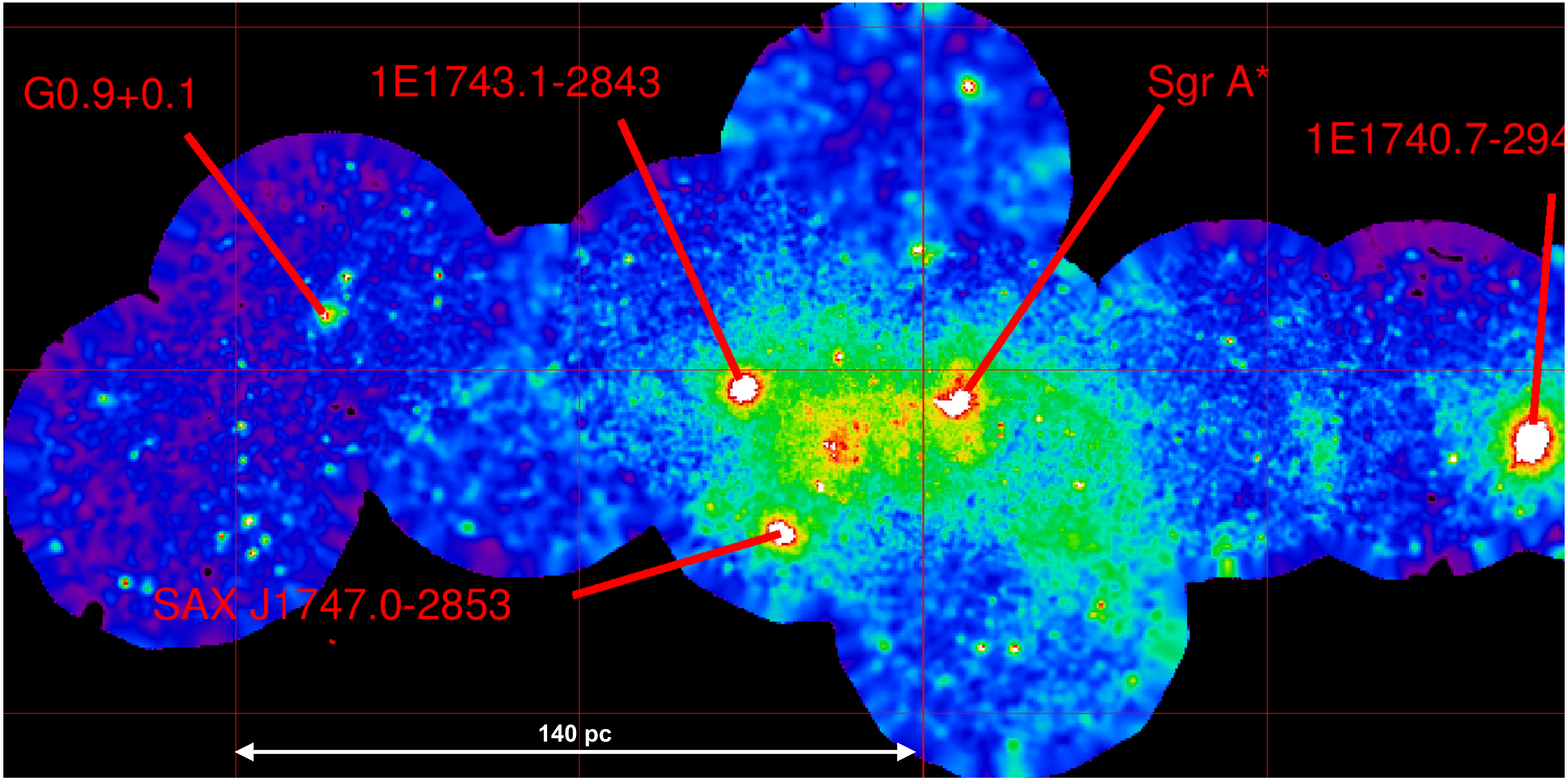
What could be my contribution?



The old XMM-Newton view of the GC

First XMM scan of CMZ (2000-2002)

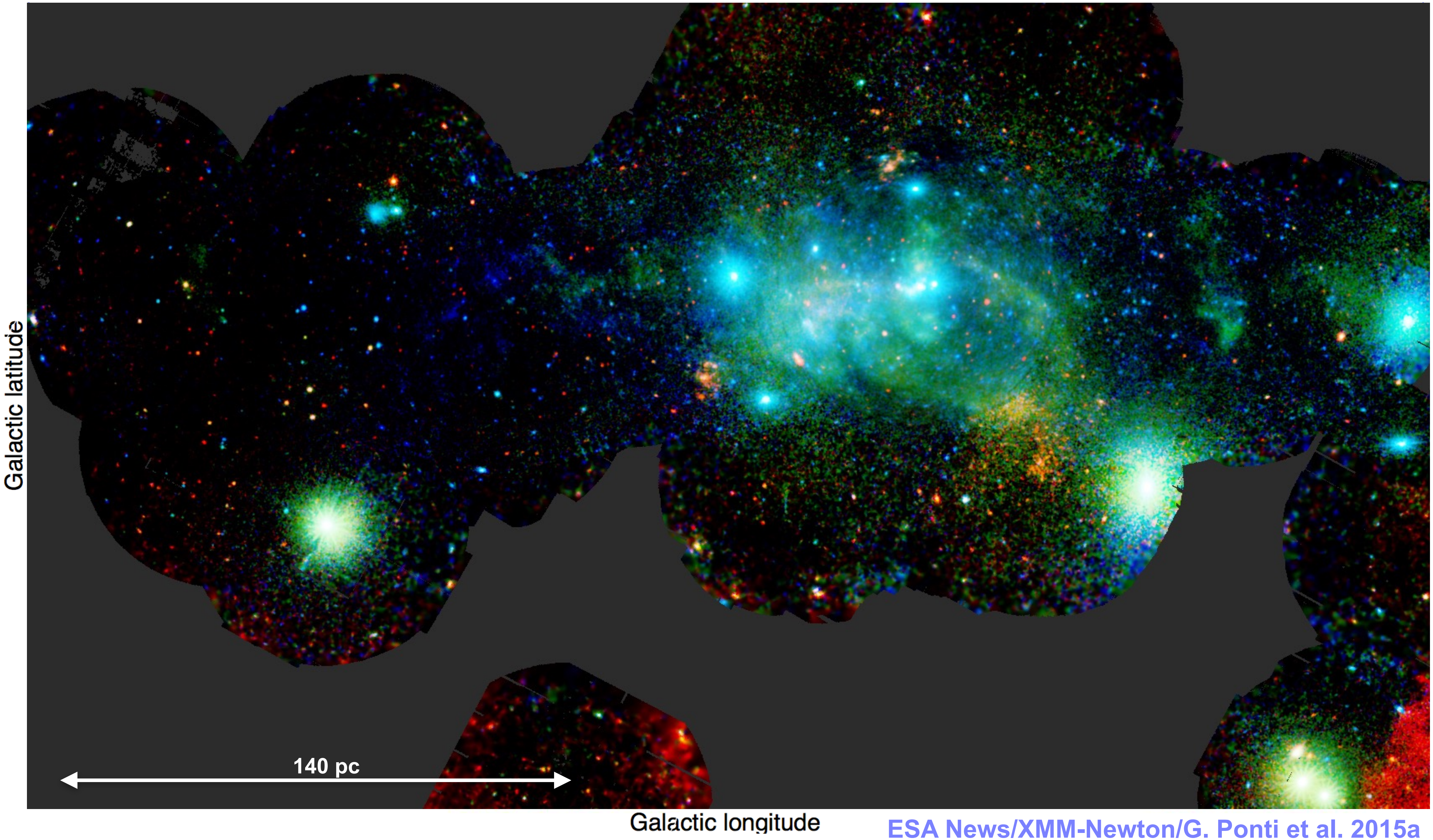
Decourchelle +02



XMM-Newton key project

The XMM-Newton view of the GC

Ponti +15

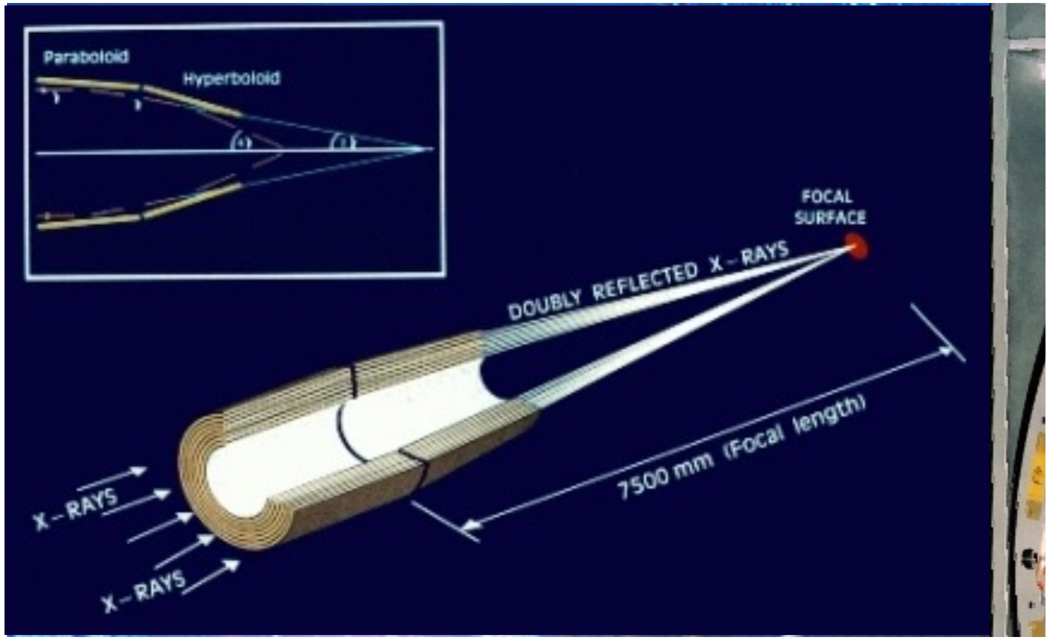


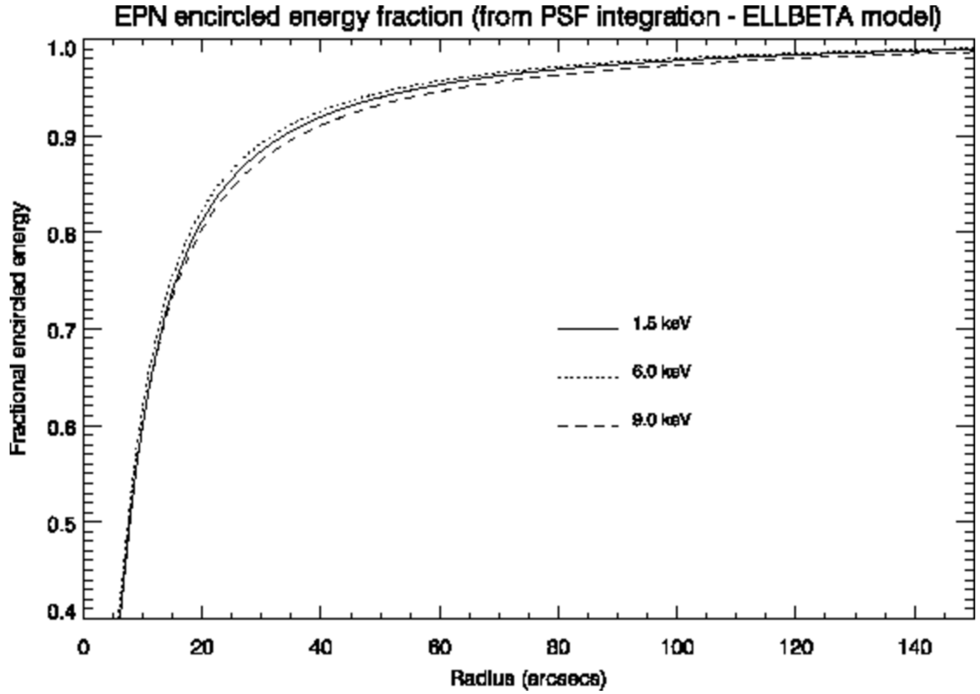
ESA News/XMM-Newton/G. Ponti et al. 2015a

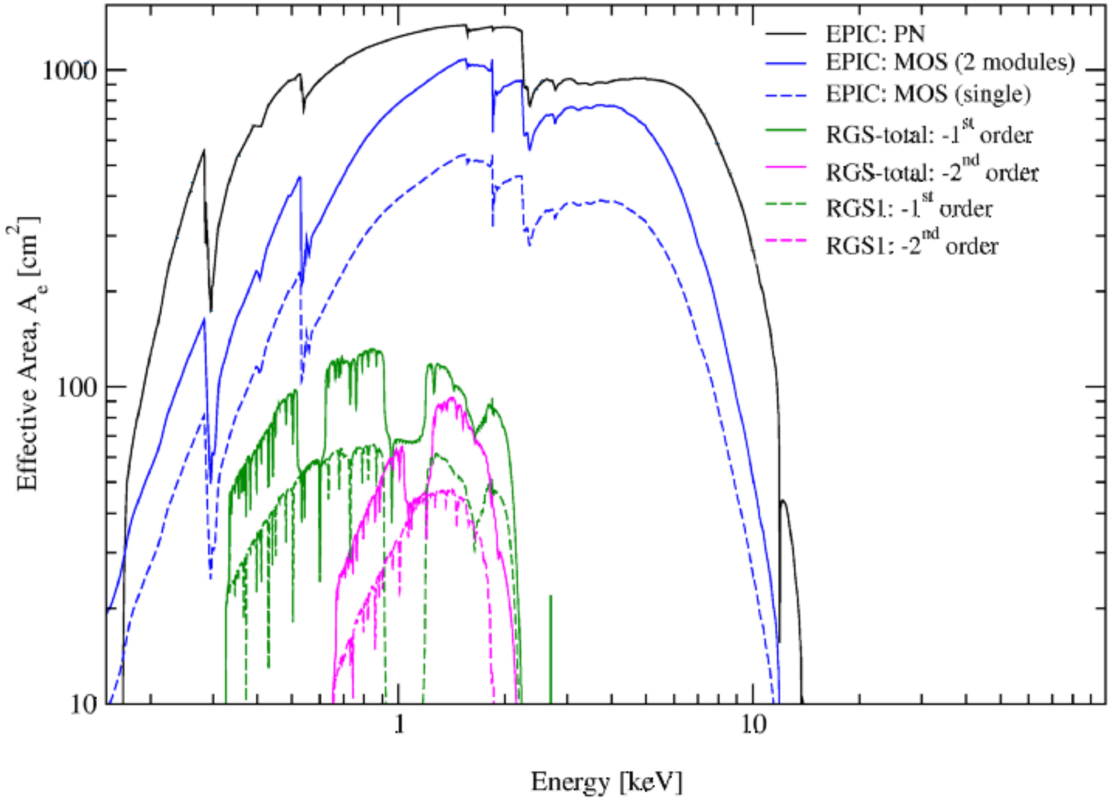
More than 100 EPIC observations

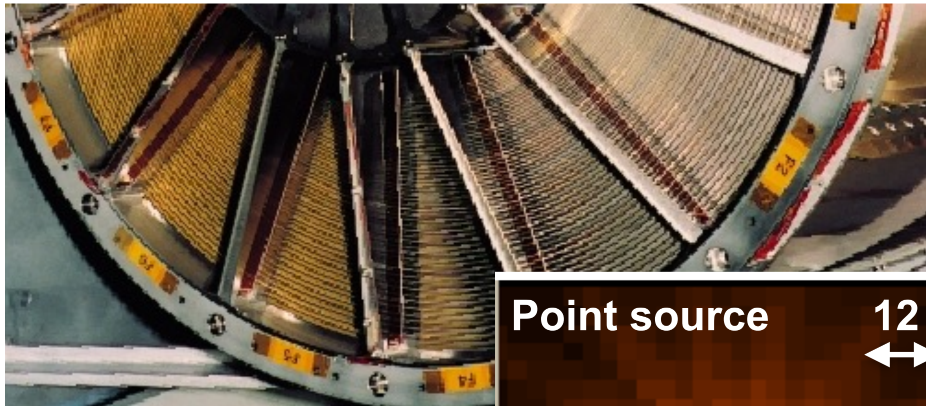
Exposure > 1.5 Ms (central 15')
> 200 ks in the plane

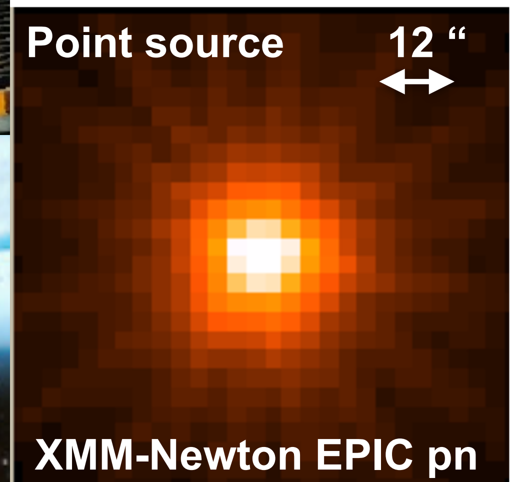
XMM-Newton the instrument





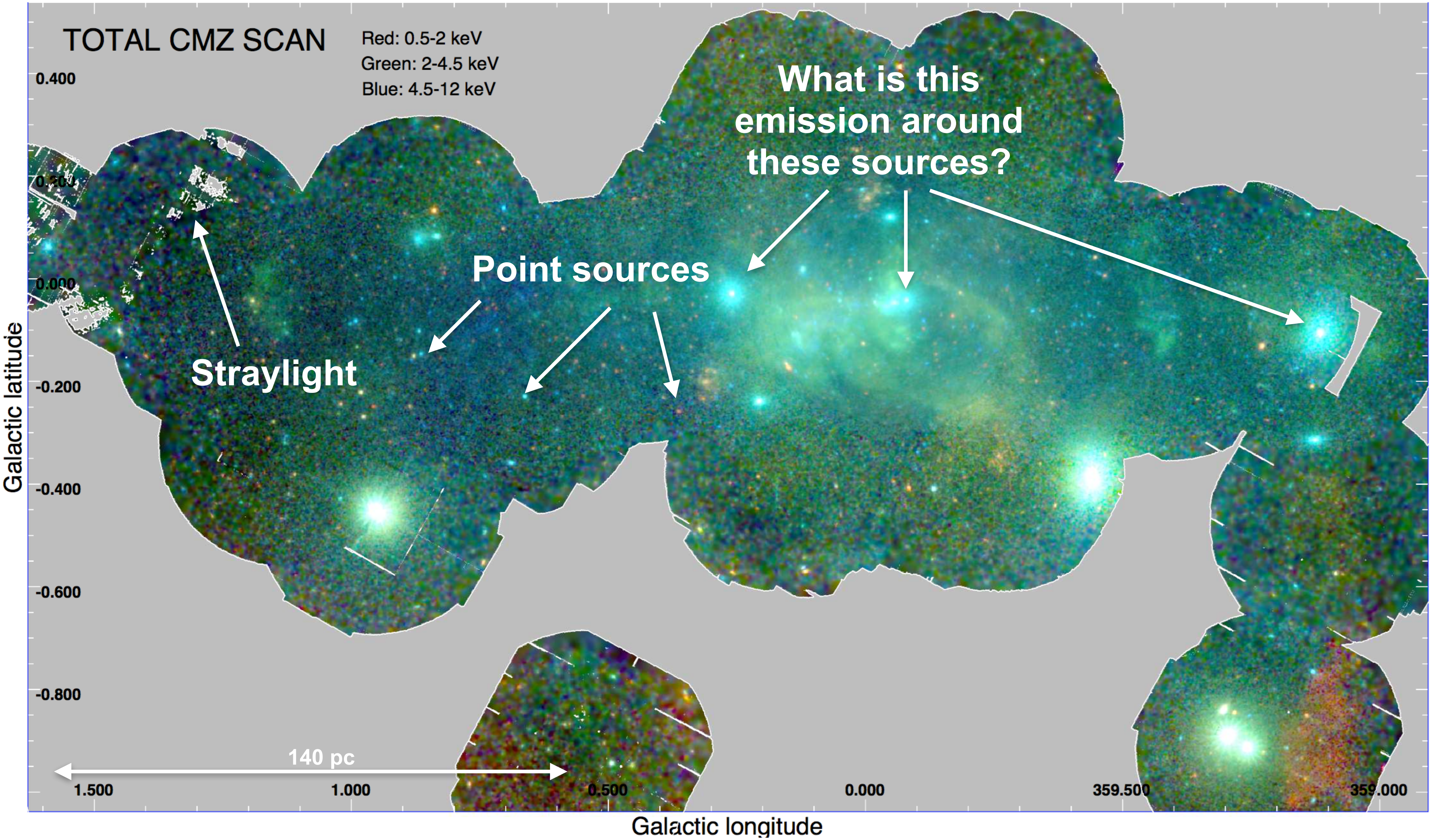






The XMM-Newton view of the GC

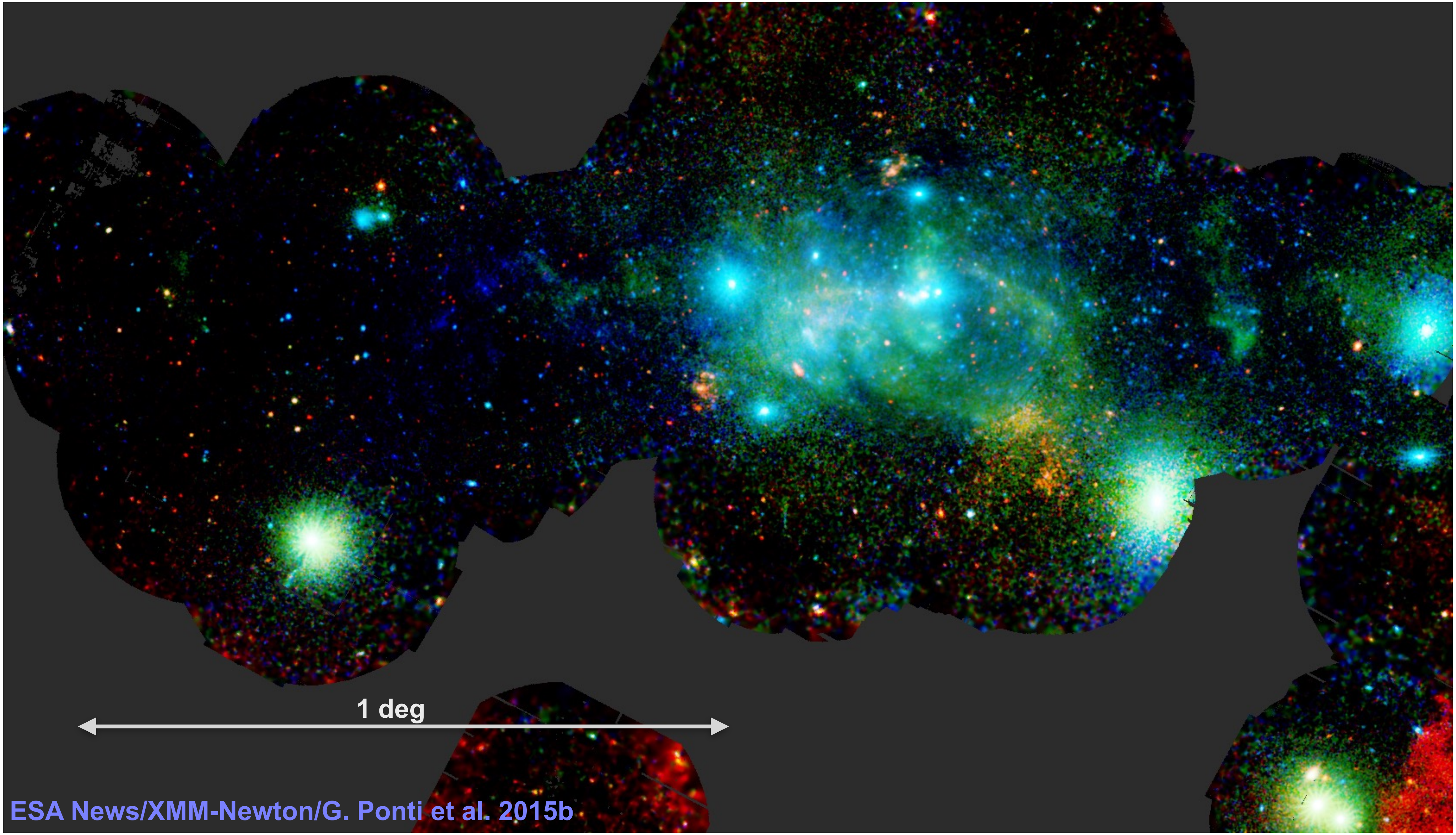
Ponti +15



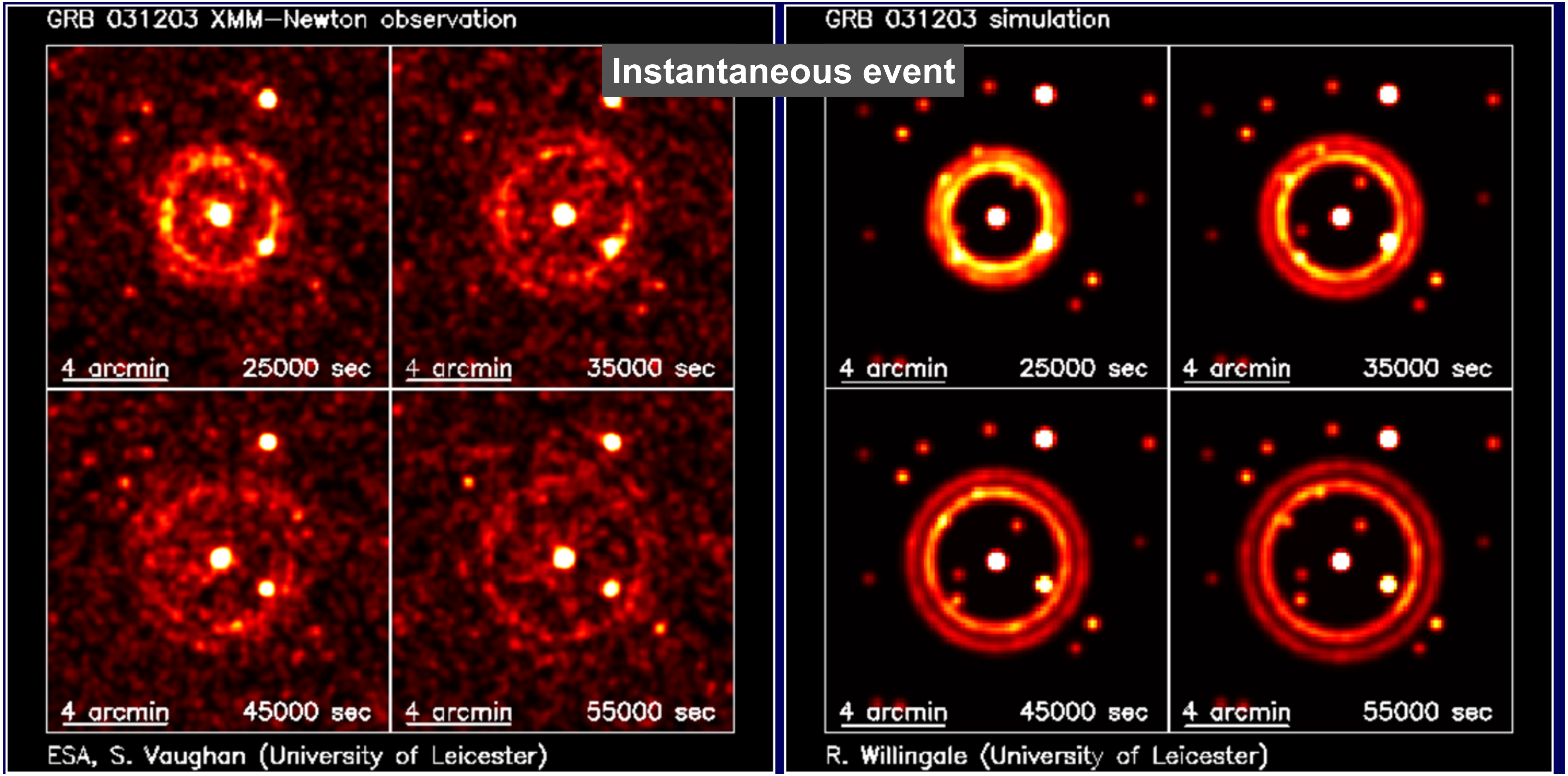
Thousands of X-ray point sources!

(Chandra detected >9000)

Scattering of X-ray radiation by dust



Dust scattering halo evolution after a GRB



Truemper +73;
Predehl +95;
Valencic +15;
Heinz +16;
Jin +17

Dust scattering produces a ring of scattered and delayed light

Number of rings ➜ number of layers

The rings increase with time

Ring size ➜ fractional distance

Scattering of X-ray radiation by dust

Source spectrum Dust size distribution

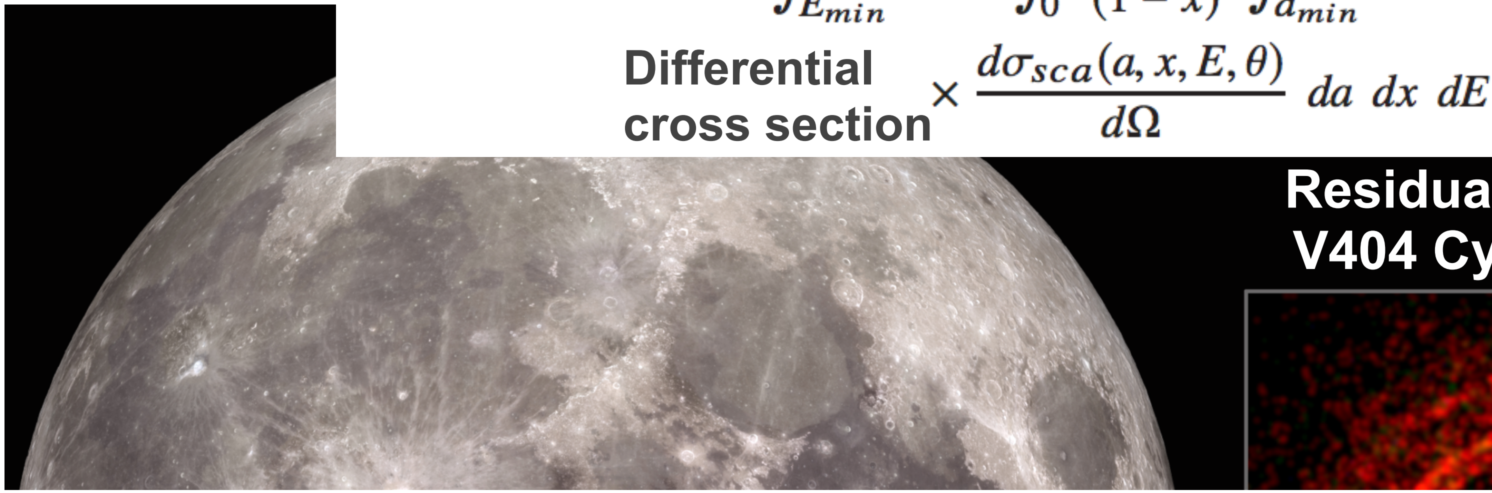
Column density Fractional distance

Intensity of scattering light

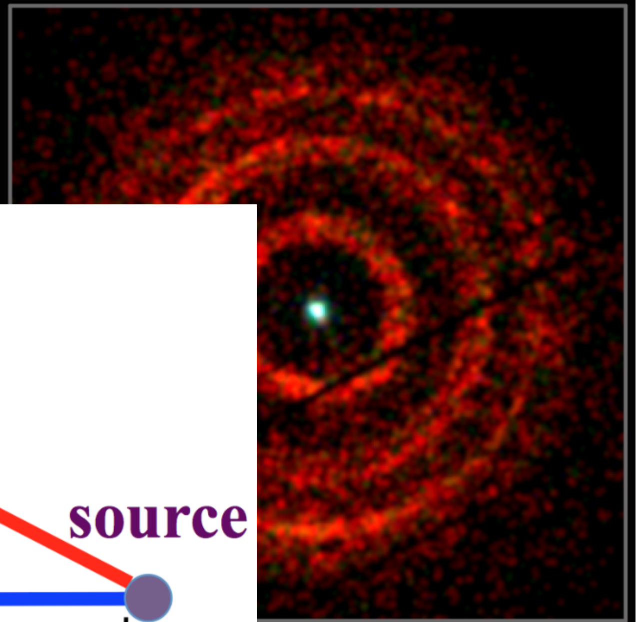
$$I^{(1)}_{sca}(\theta) = F_X N_{H,sca} \int_{E_{min}}^{E_{max}} S(E) \int_0^1 \frac{f(x)}{(1-x)^2} \int_{a_{min}}^{a_{max}} n(a) \times \frac{d\sigma_{sca}(a,x,E,\theta)}{d\Omega}\, da\, dx\, dE$$

Differential cross section

Jin, GP +17

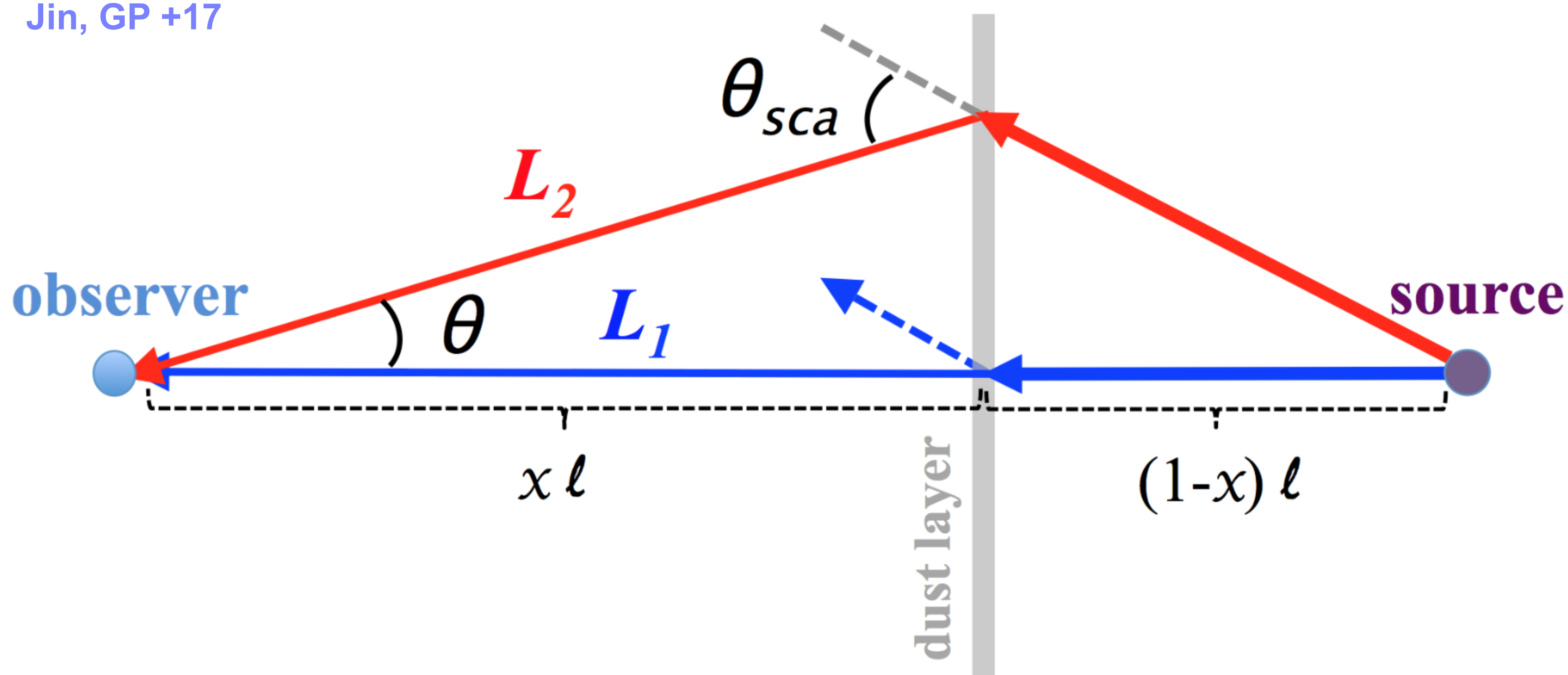


Residual X-rays after V404 Cyg's outburst



Beardmore +16

Jin, GP +17



Scattering of X-ray radiation by dust

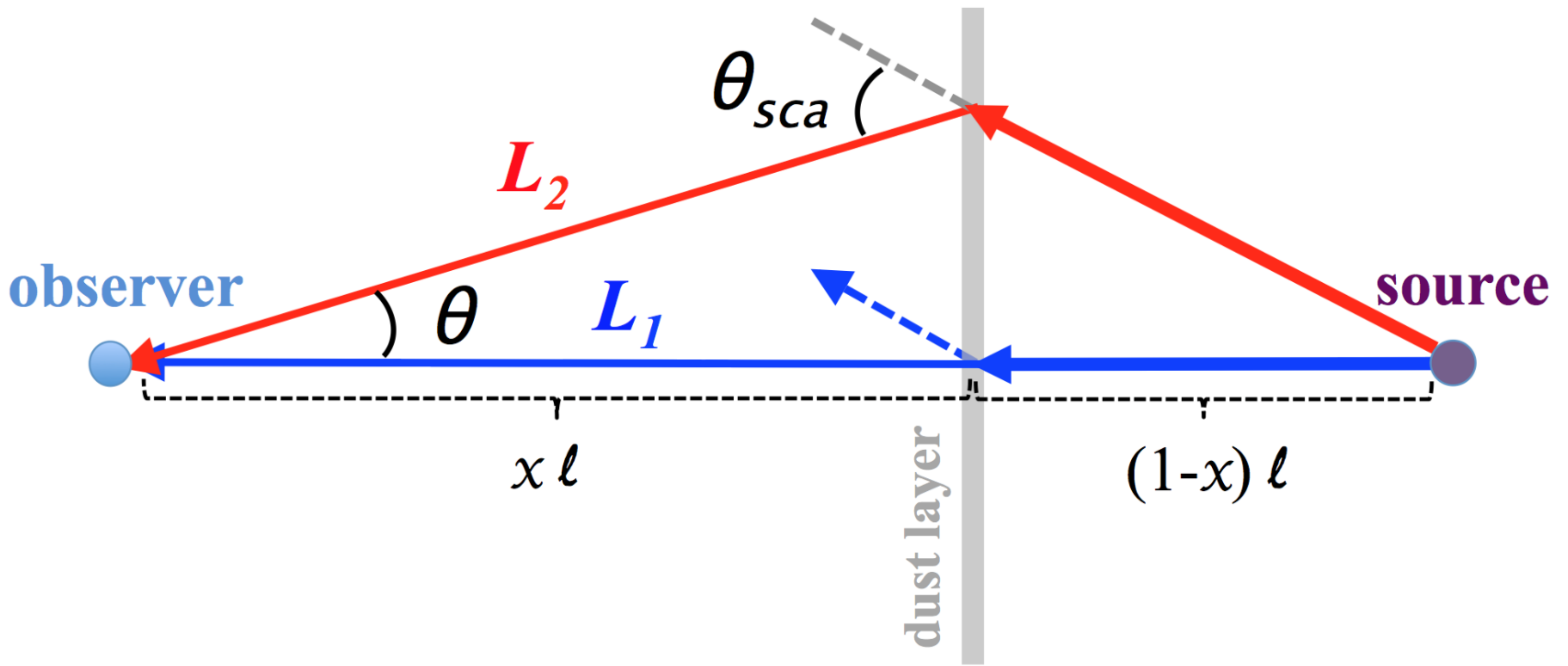
Source spectrum | Dust size distribution | Column density | Fractional distance

Intensity of scattering light

$$I^{(1)}_{sca}(\theta) = F_X N_{H,sca} \int_{E_{min}}^{E_{max}} S(E) \int_0^1 \frac{f(x)}{(1-x)^2} \int_{a_{min}}^{a_{max}} n(a) \times \frac{d\sigma_{sca}(a,x,E,\theta)}{d\Omega} \, da \; dx \; dE$$

Jin, GP +17

Differential cross section



Dust scattering halos to derive:

- ➜ Dust location along line of sight
- ➜ Dust composition
- ➜ Dust grain size
- ➜ Dust to gas ratio

Energy dependence of the halo

Source spectrum Dust size distribution

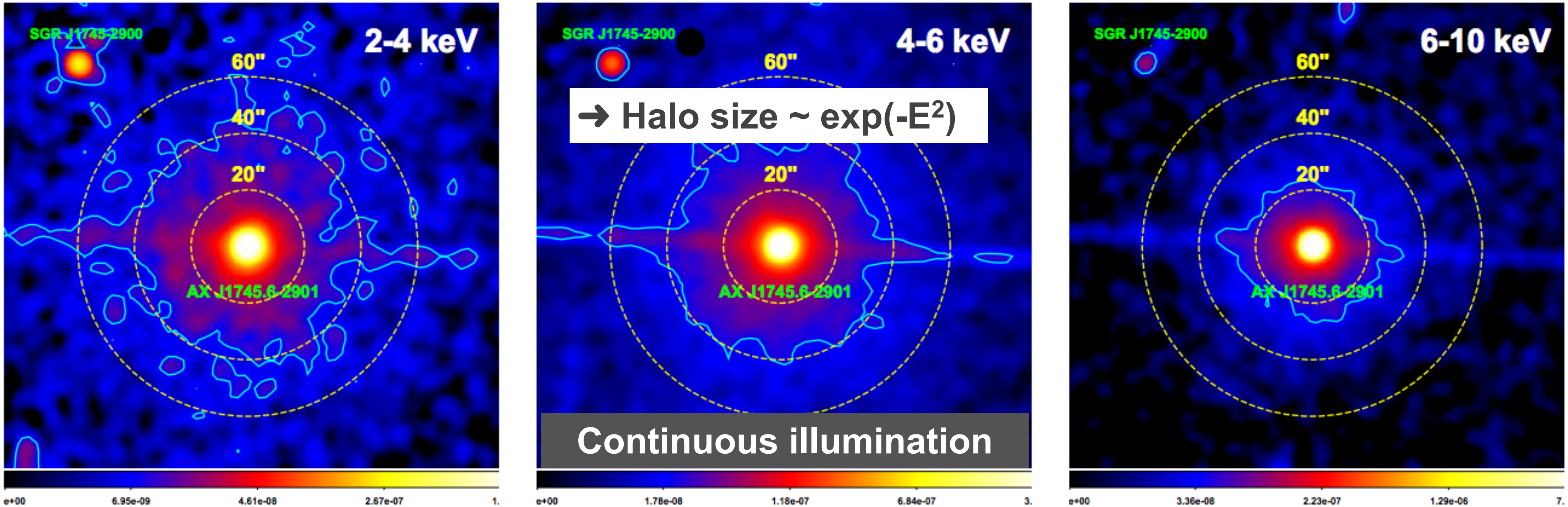
Column density Fractional distance

Intensity of scattering light

$$I^{(1)}_{sca}(\theta) = F_X N_{H,sca} \int_{E_{min}}^{E_{max}} S(E) \int_0^1 \frac{f(x)}{(1-x)^2} \int_{a_{min}}^{a_{max}} n(a)$$

Differential cross section

$$\times \frac{d\sigma_{sca}(a,x,E,\theta)}{d\Omega}\, da\; dx\; dE$$



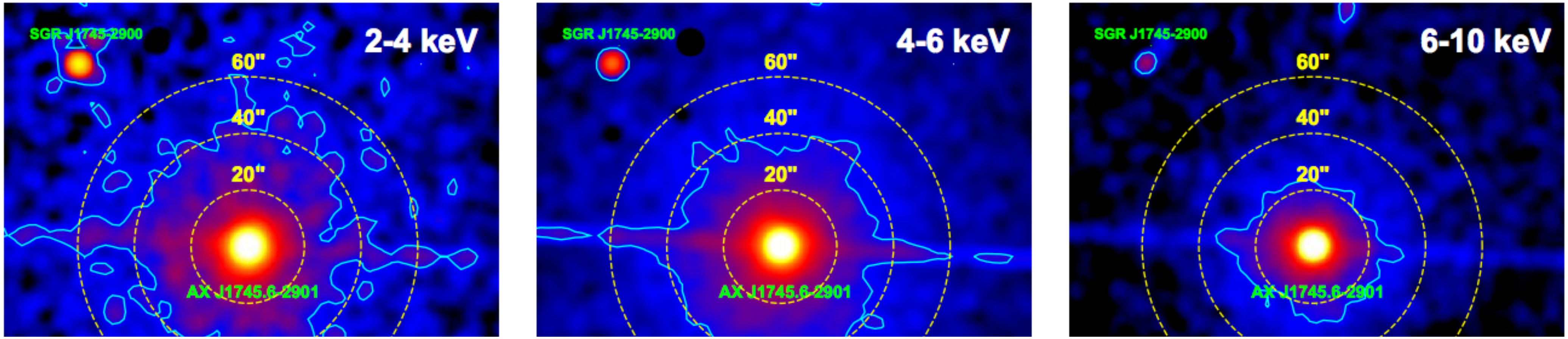
Jin, GP +17

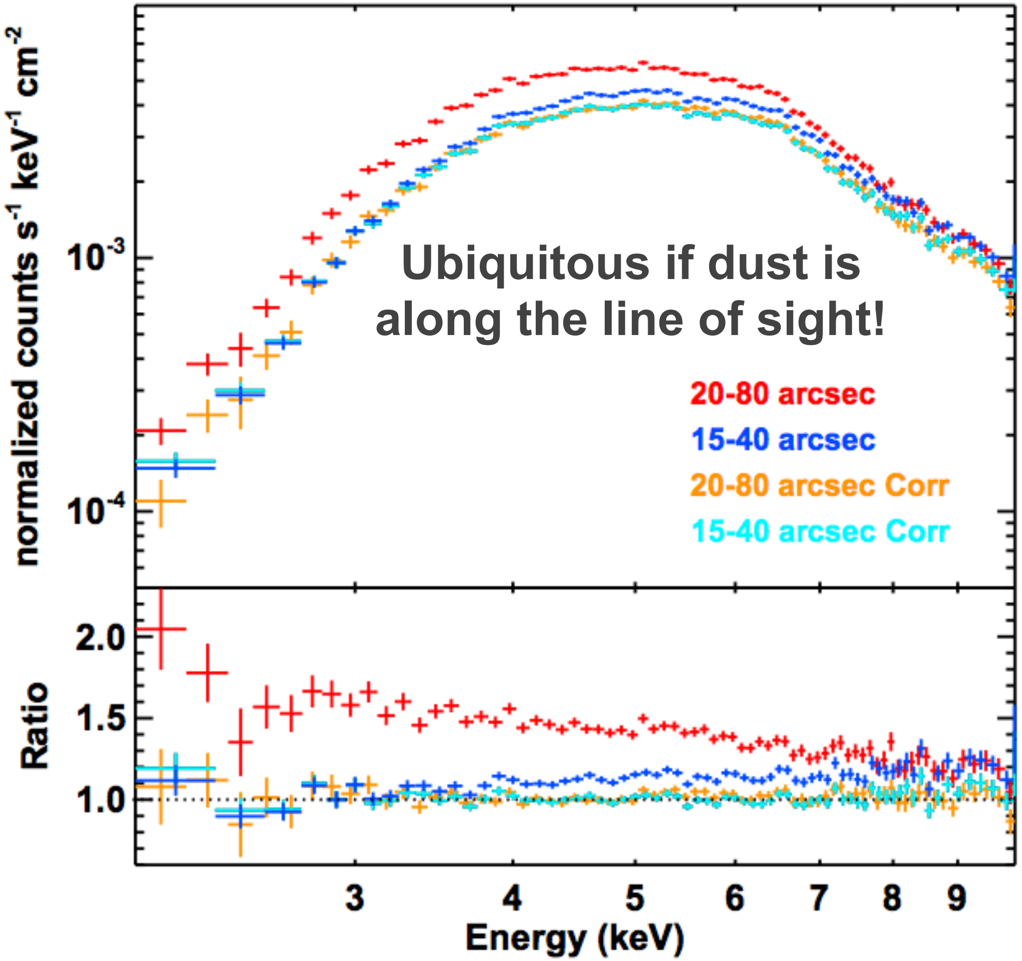
Dust scattering halo is energy dependent

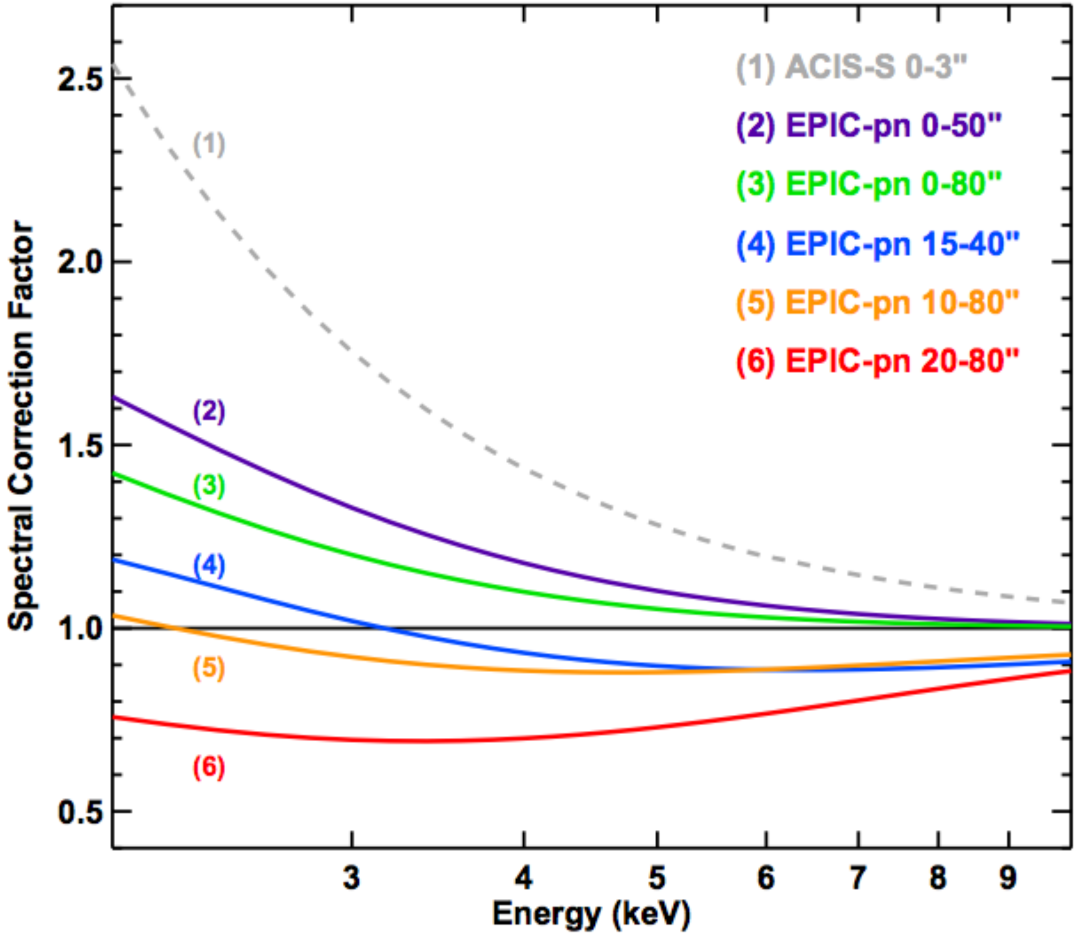
Larger cross section at lower energies ➜ Steeper spectrum

Dust scattering halo distorts the source spectrum if not taken into account

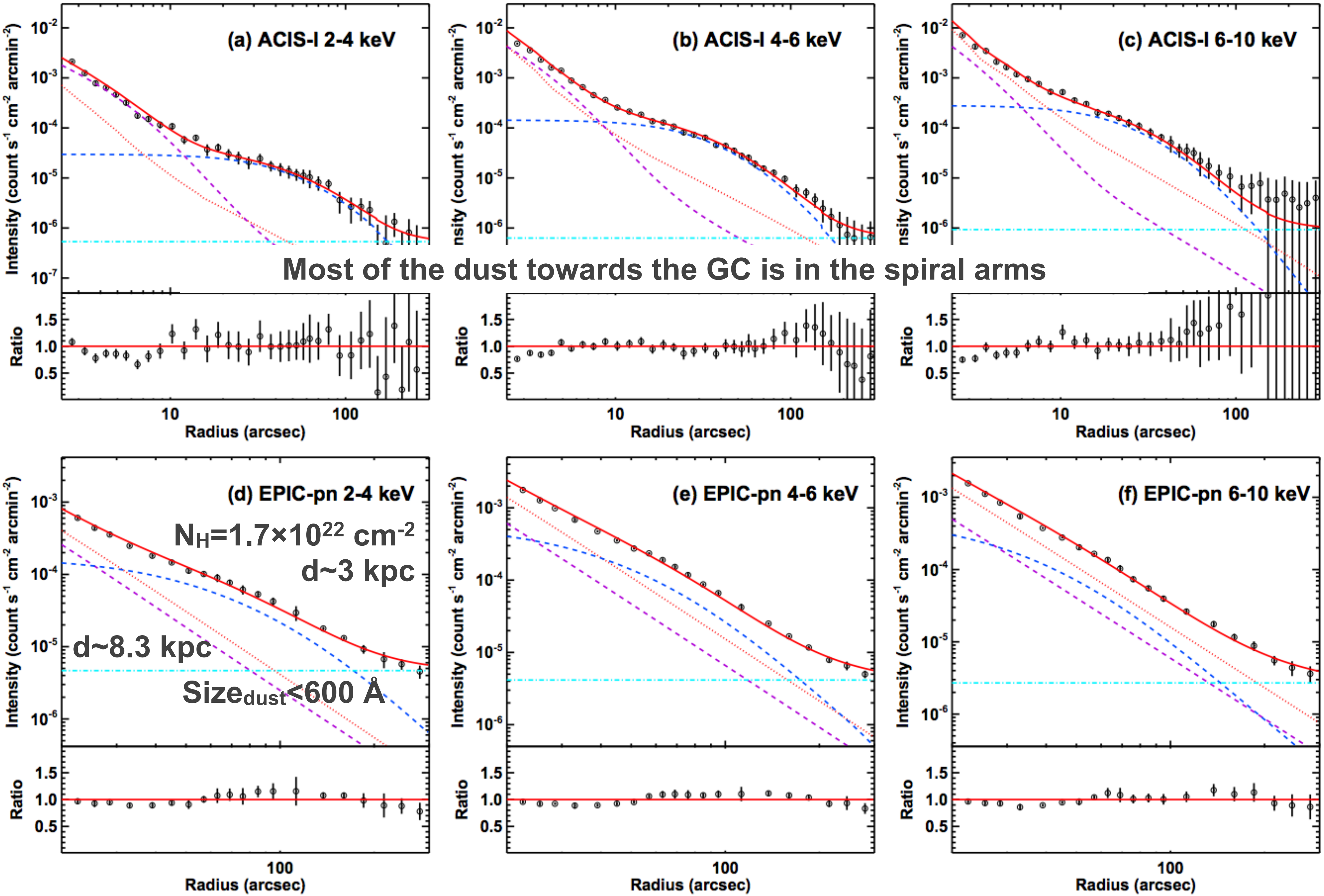
Spectral corrections





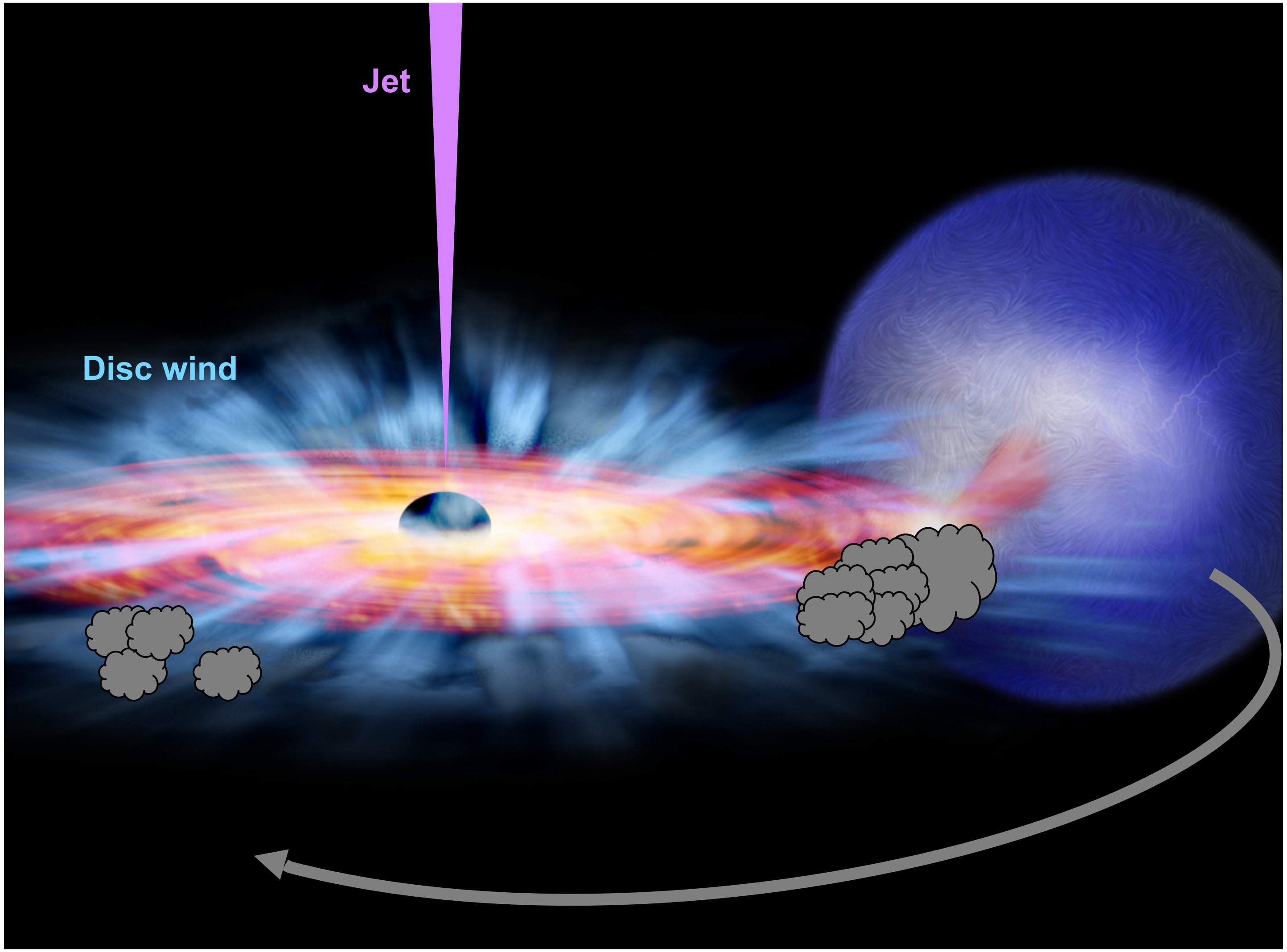


Scattering of X-ray radiation by dust



Most of the dust towards the GC is in the spiral arms

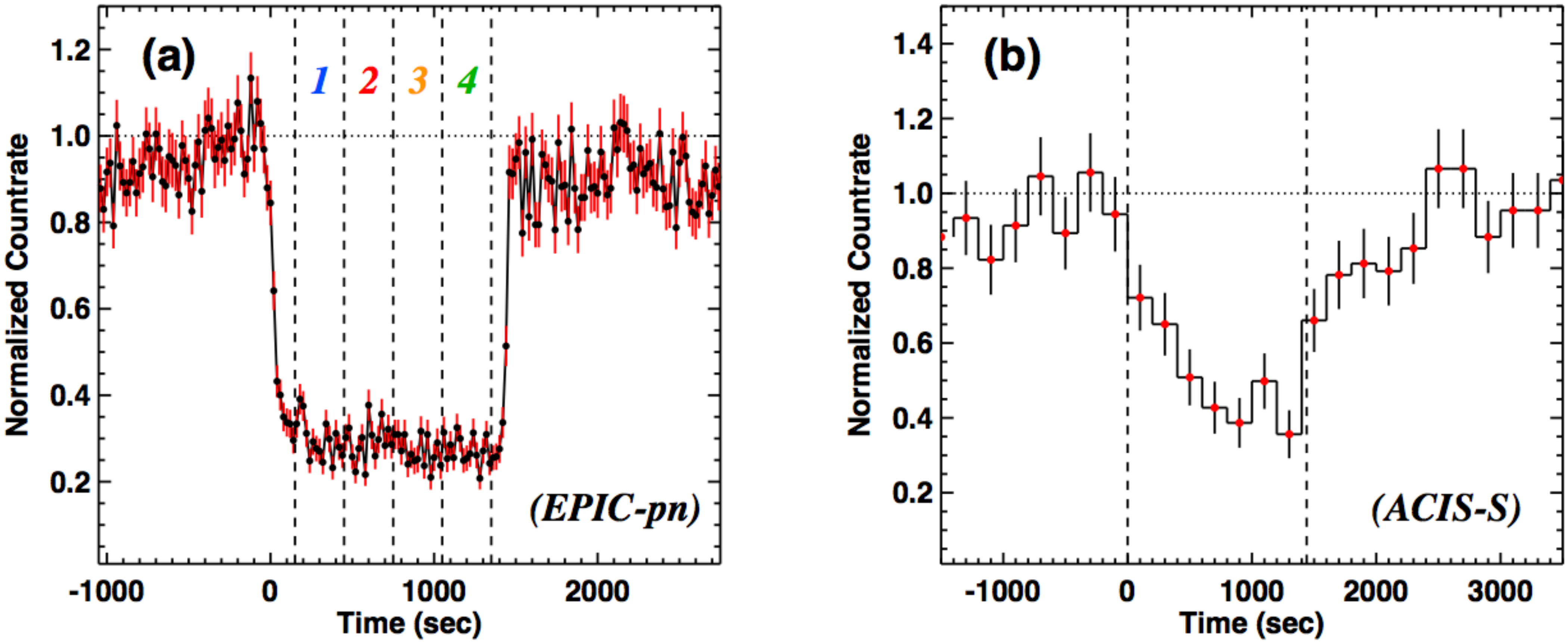
The eclipsing binary: AX J1745.6-2901

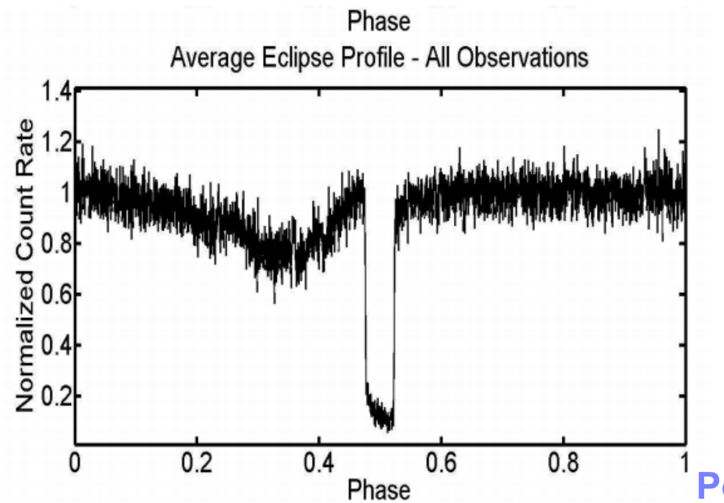


Ponti +16

During eclipses these systems are completely obscured

The eclipsing binary: AX J1745.6-2901





Ponti +16

During eclipses ➜ residual flux
Why?

XMM and Chandra measure a different flux for the same eclipses
Why?

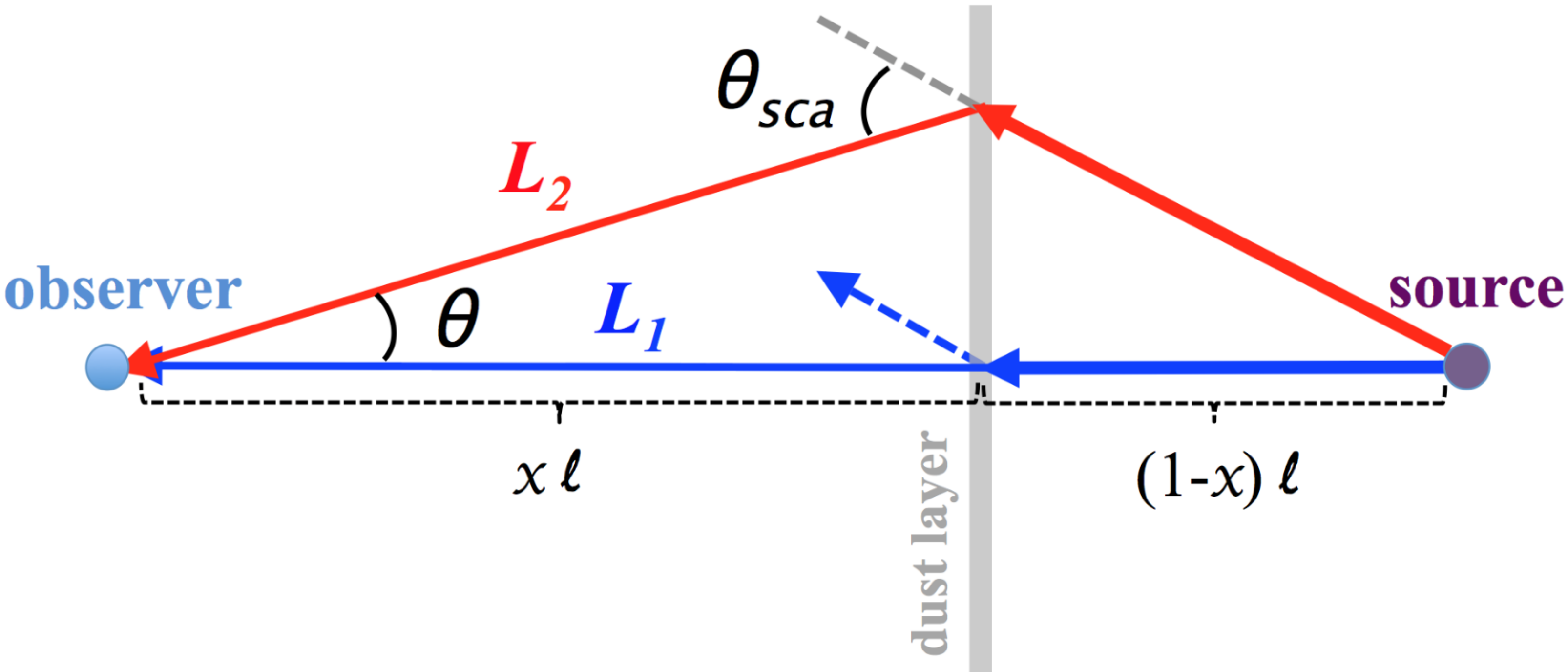
Variability of dust halo

Time lag of scattered photon

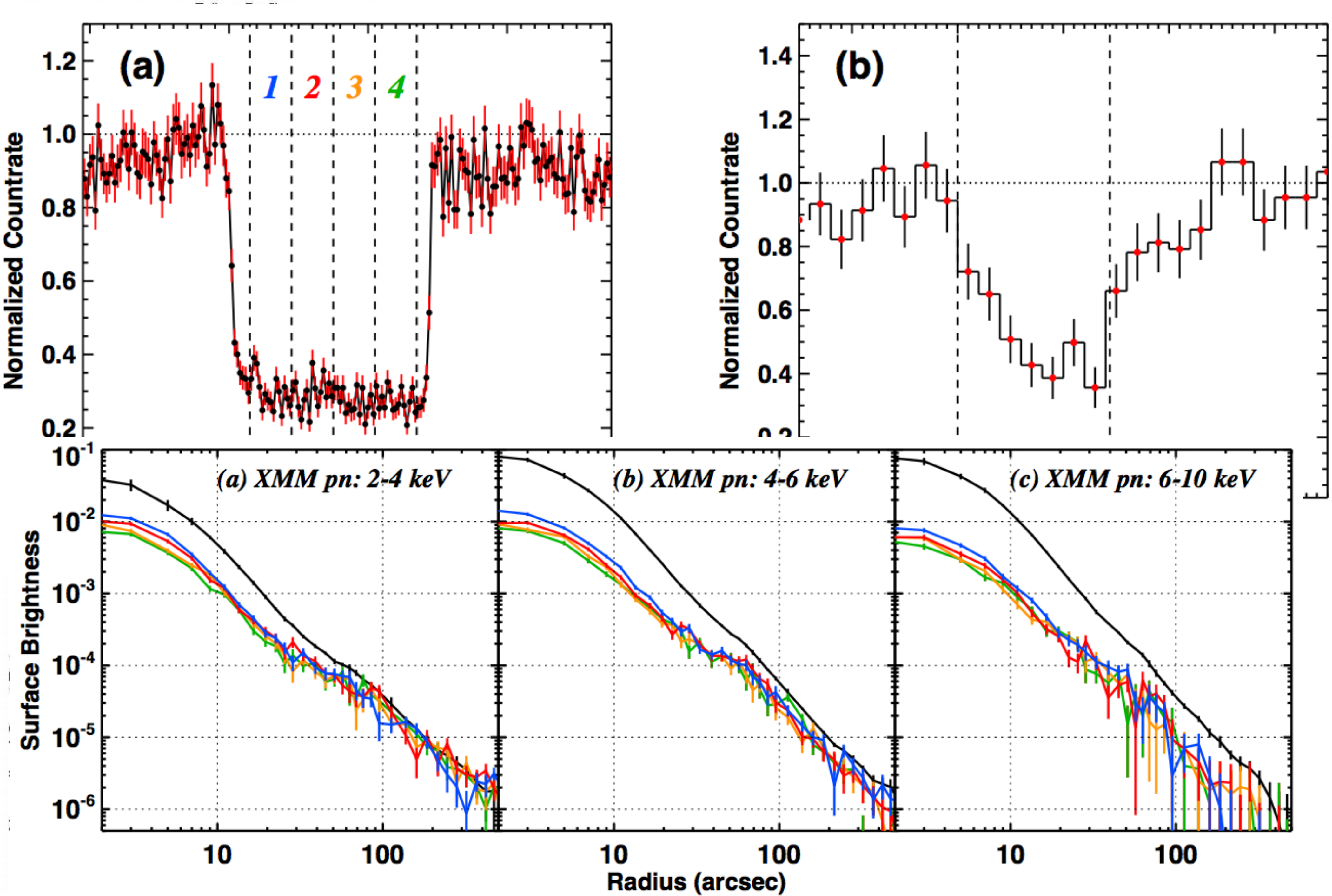
$$\Delta t(x,\theta,\ell) = \frac{\ell}{c}\left(\sqrt{\left(\frac{x}{\cos\theta}\right)^2 - 2x + 1} + \frac{x}{\cos\theta} - 1\right)$$

$$\Delta\ell(x,\theta) \equiv L_2 - L_1 = \sqrt{\left(\frac{x}{\cos\theta}\right)^2 - 2x + 1} + \frac{x}{\cos\theta} - 1$$

$$\Delta t(x,\theta,\ell) \equiv \frac{\Delta\ell}{c} \approx 1.21(\mathrm{s})\ \frac{x}{1-x}\ \theta(\mathrm{arcsec})^2\ \ell(\mathrm{kpc})$$

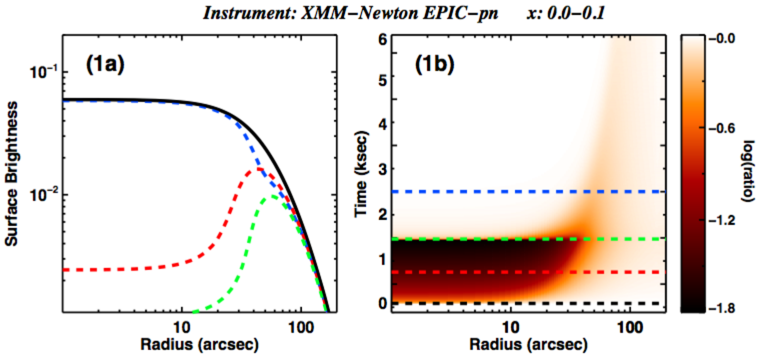


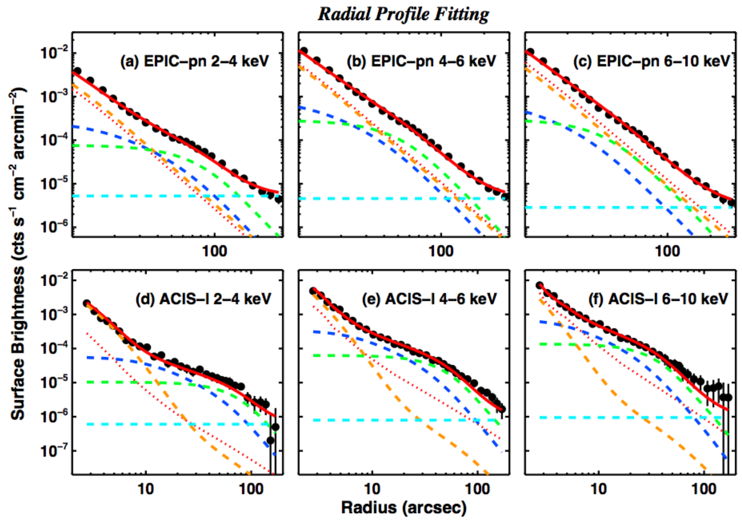
Residual emission → delayed halo

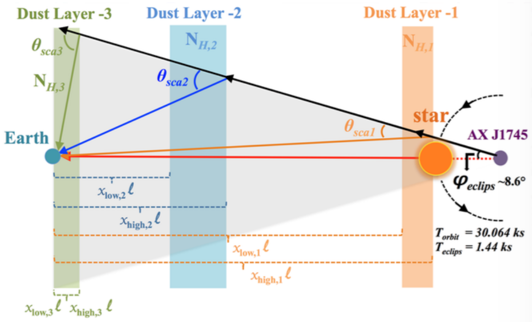


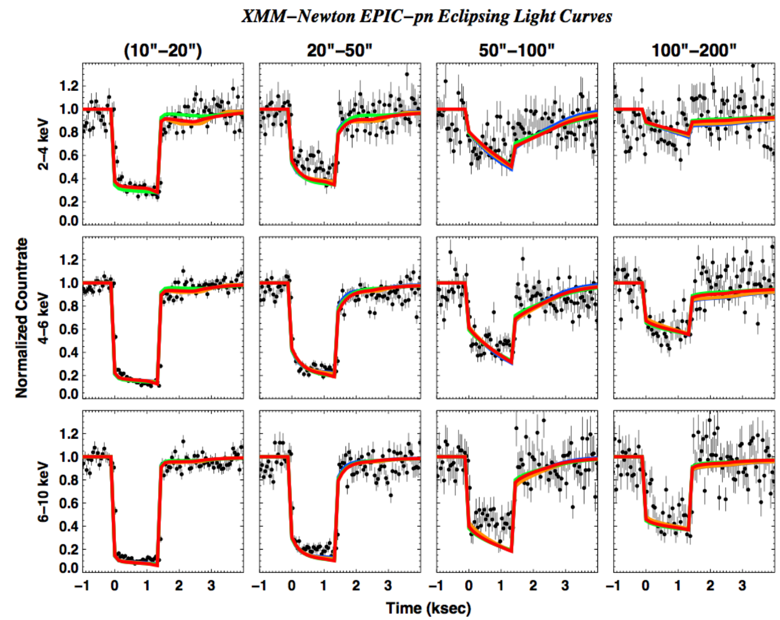
Predicted variations

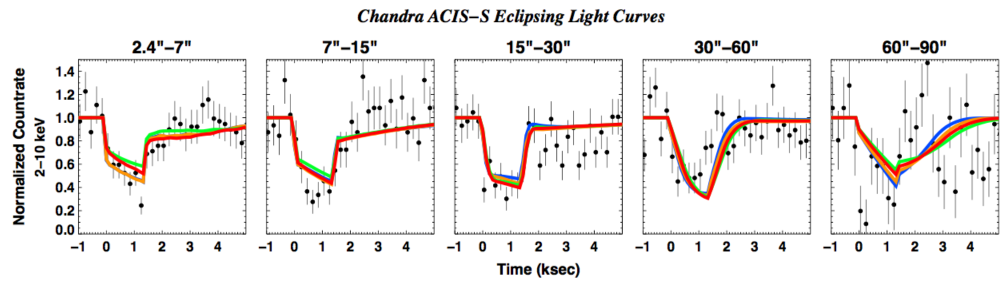
Jin, GP +17b





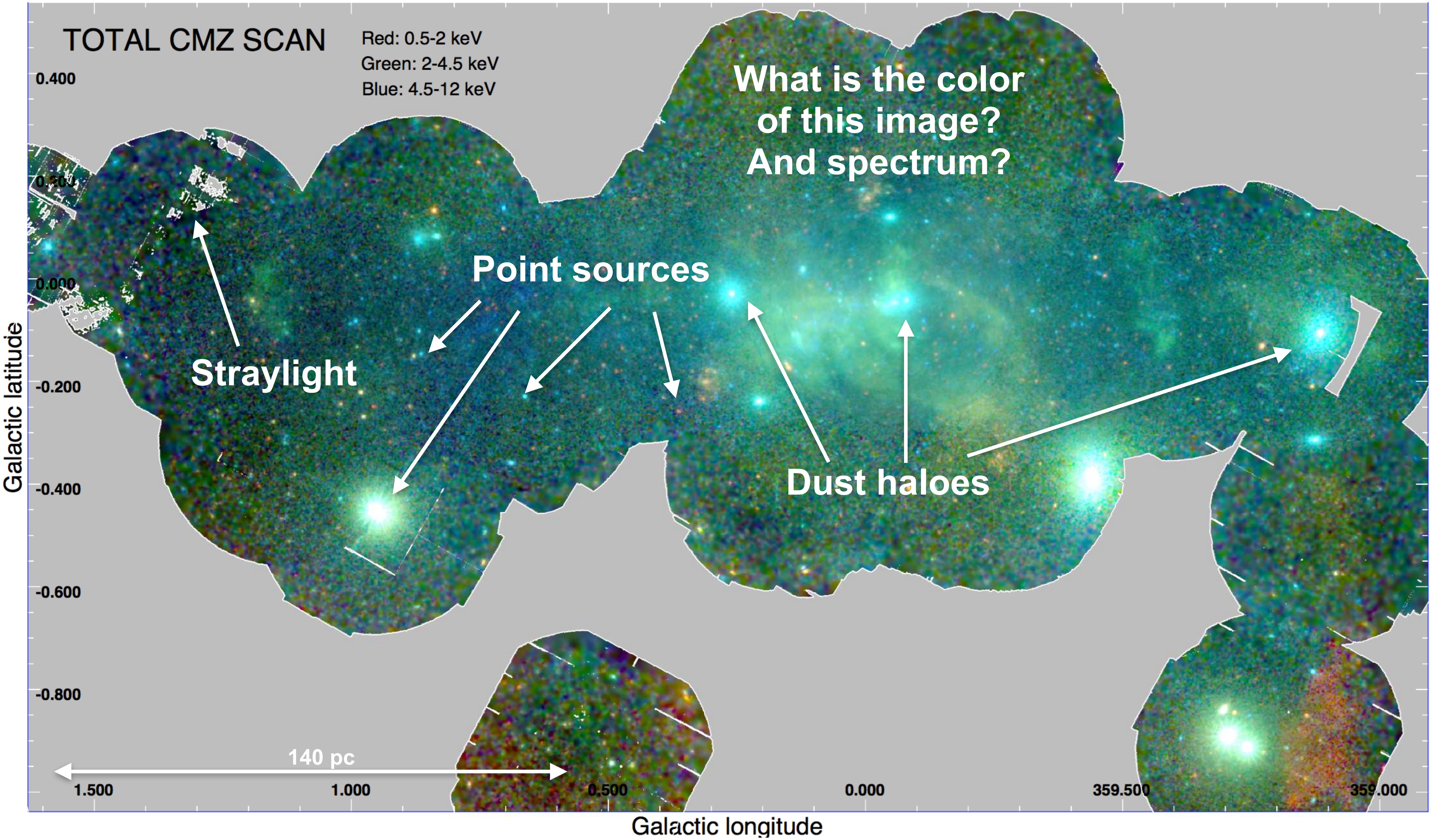






The XMM-Newton view of the GC

Ponti +15

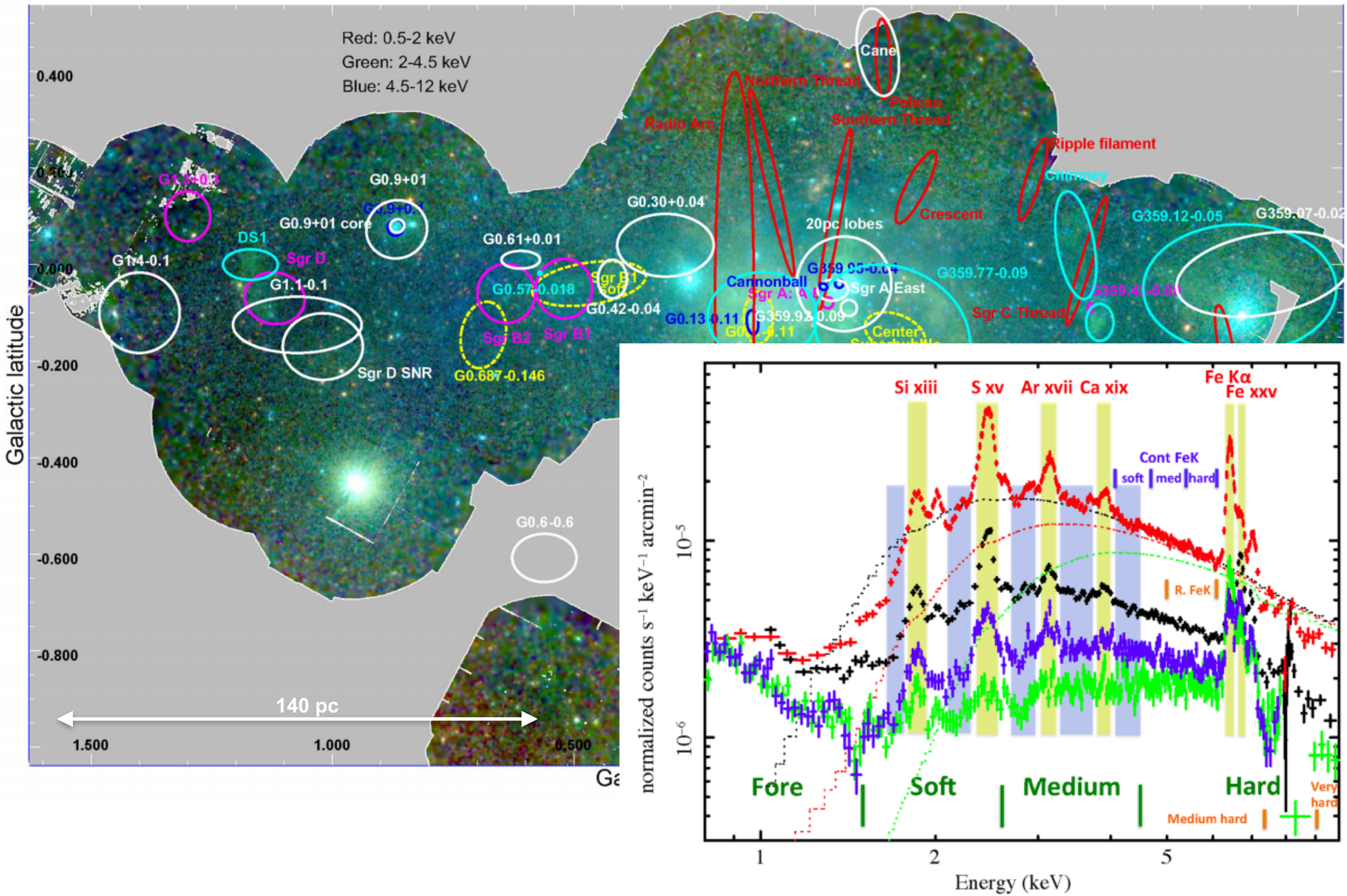


Thousands of X-ray point sources!

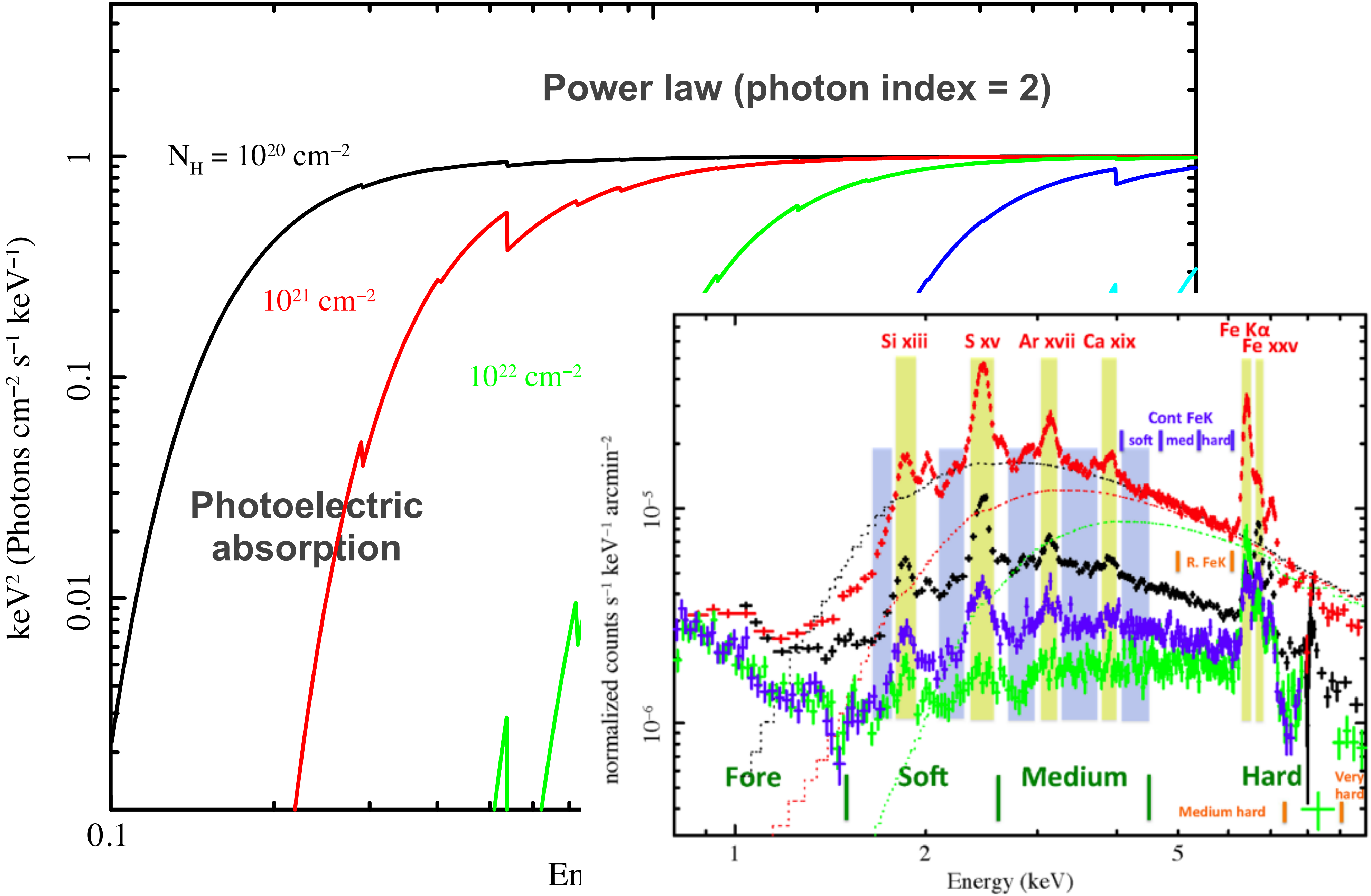
(Chandra detected >9000)

Spectra ➜ powerful infomation

Ponti +15

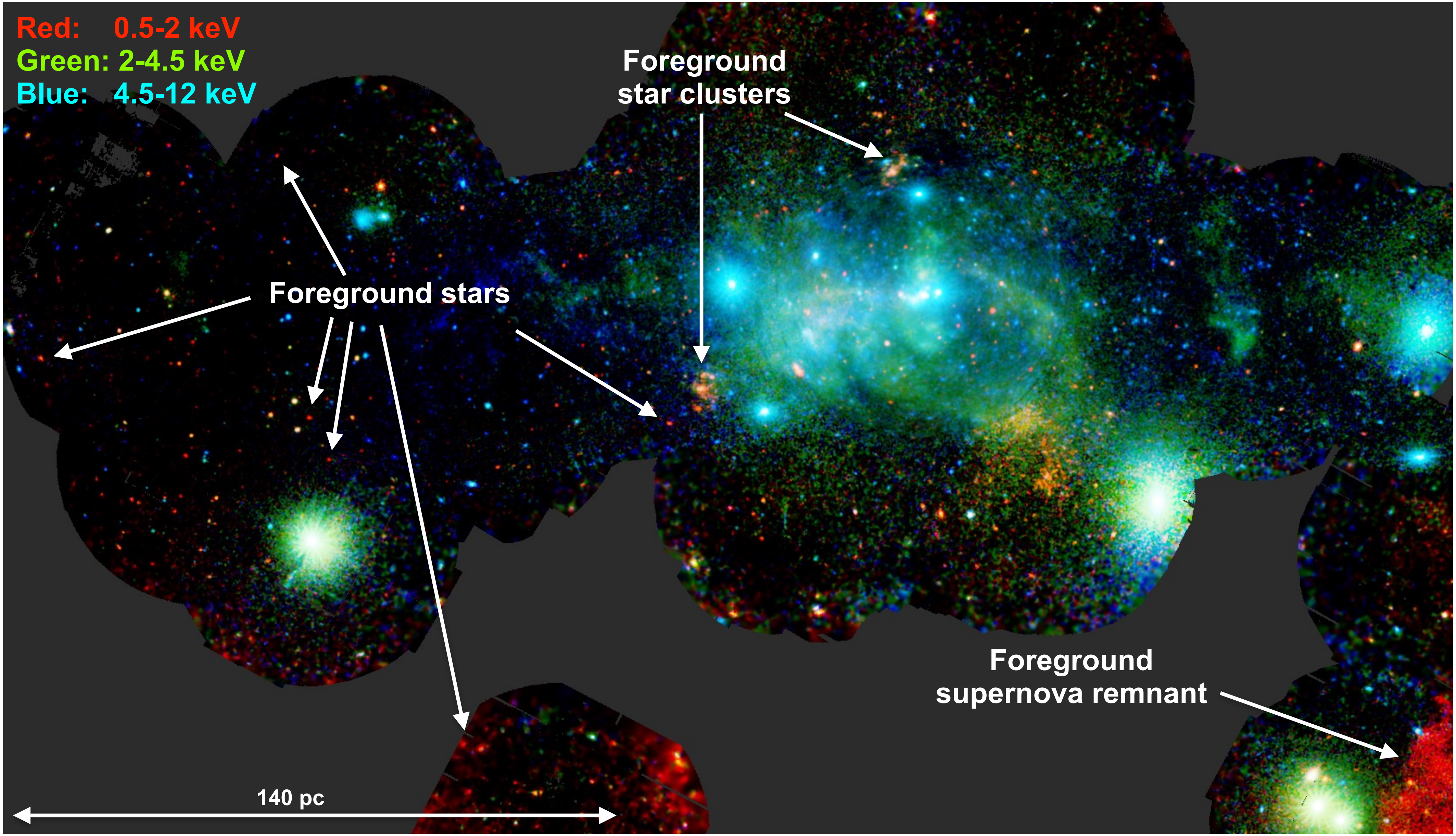


X-ray absorption from neutral material

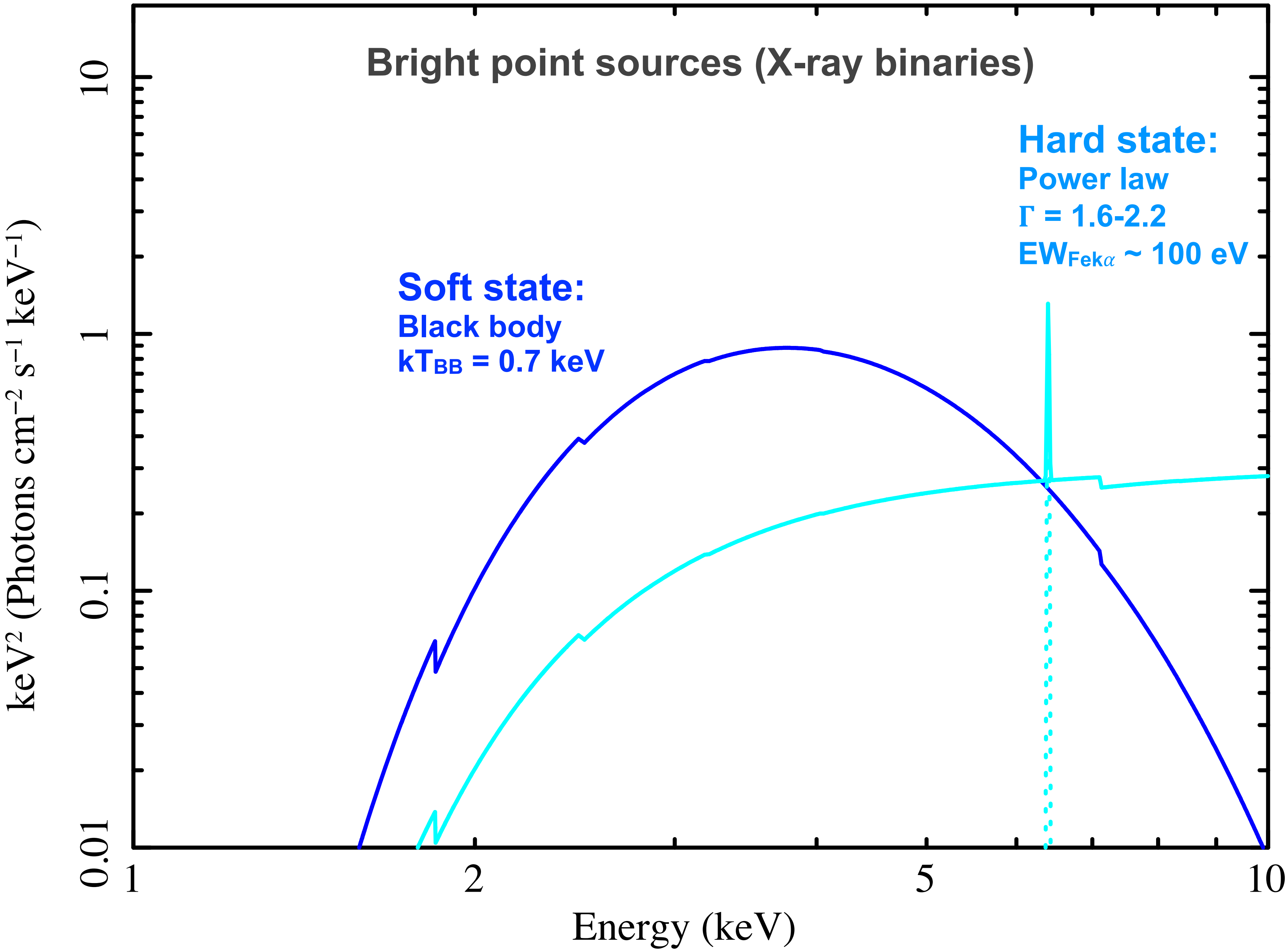


Typical GC $N_H \sim 6\times10^{22}$ cm^{-2}

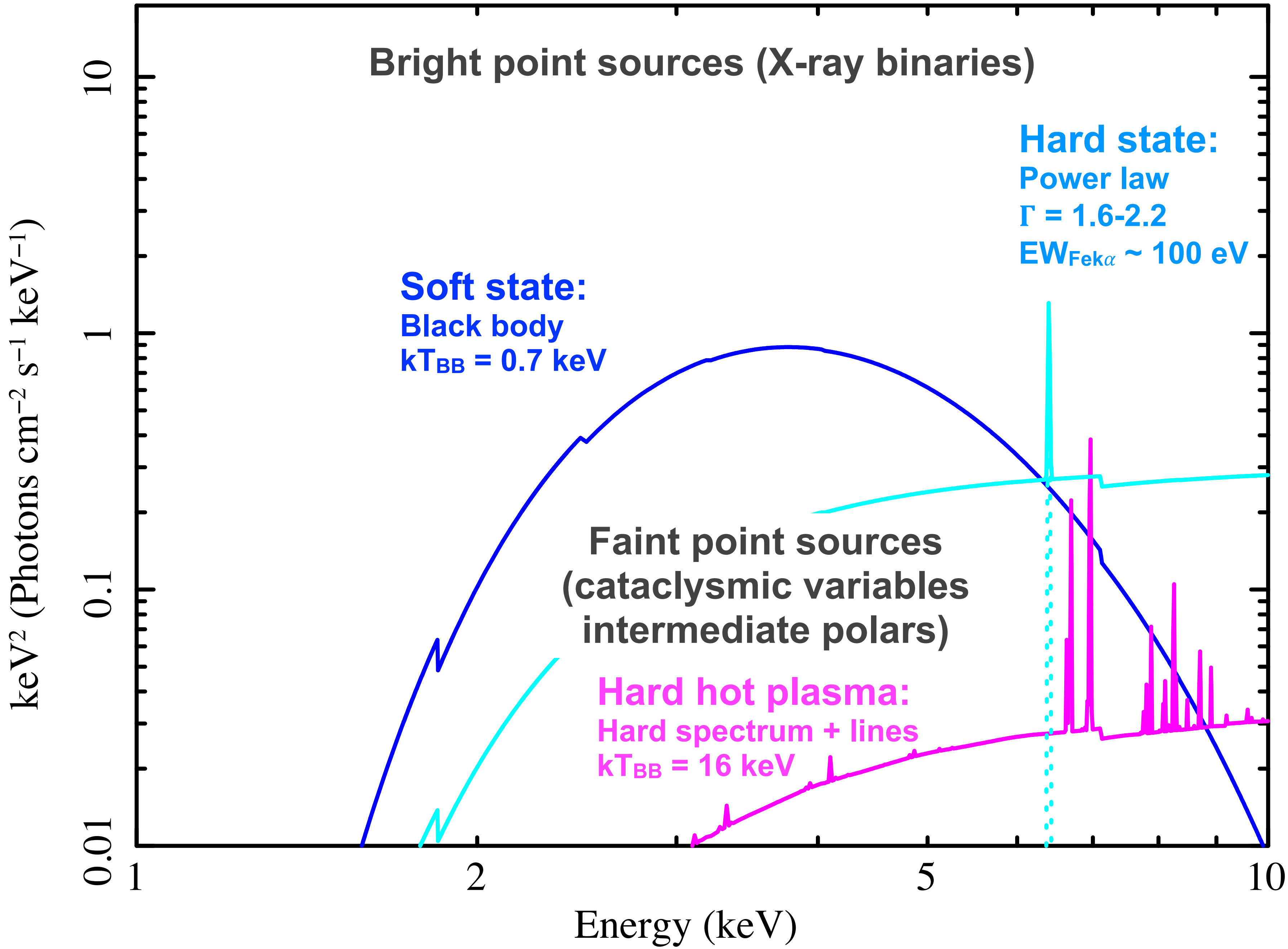
Foreground emission



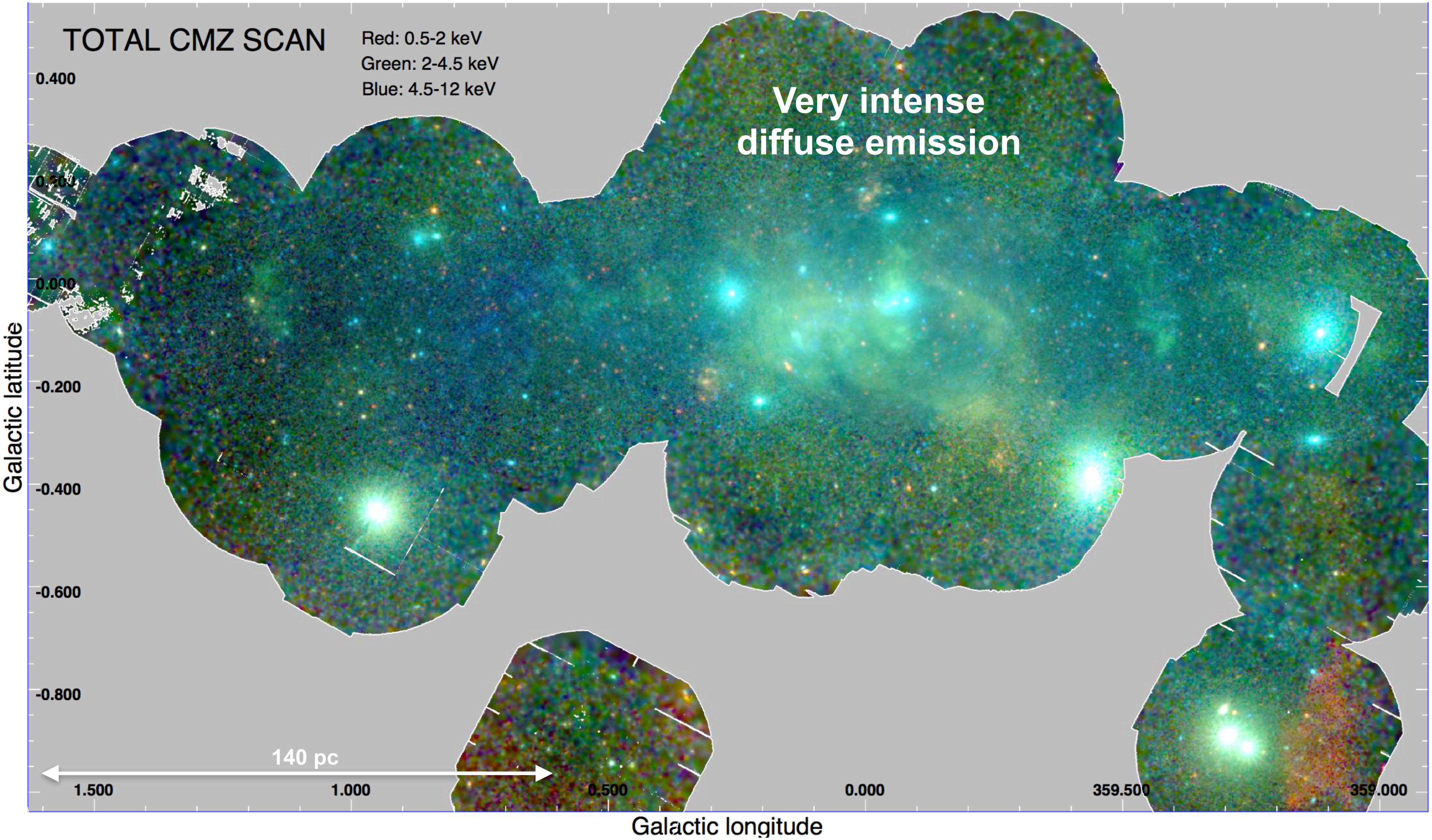
X-ray emission from bright GC point sources



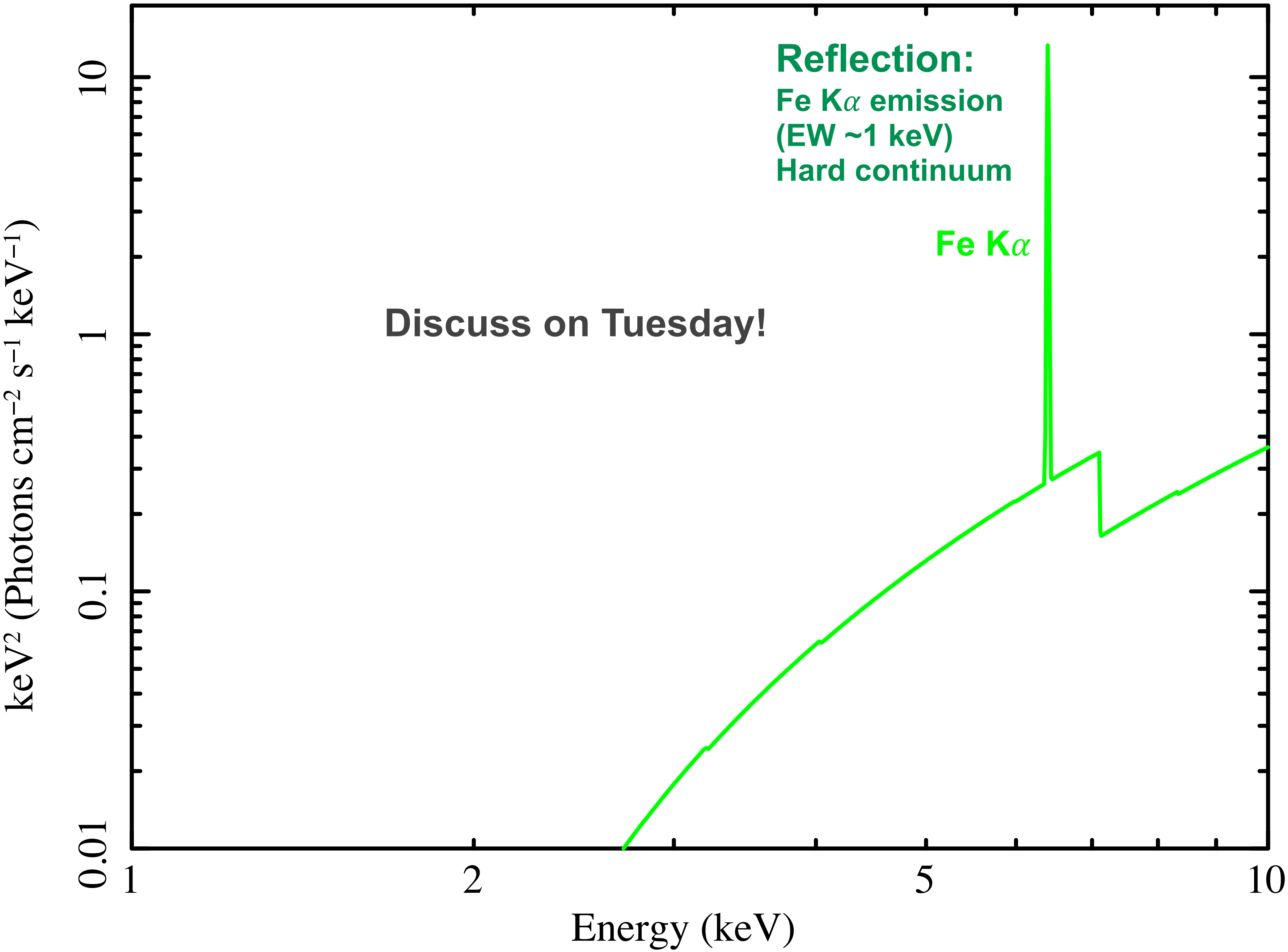
X-ray emission from GC point sources



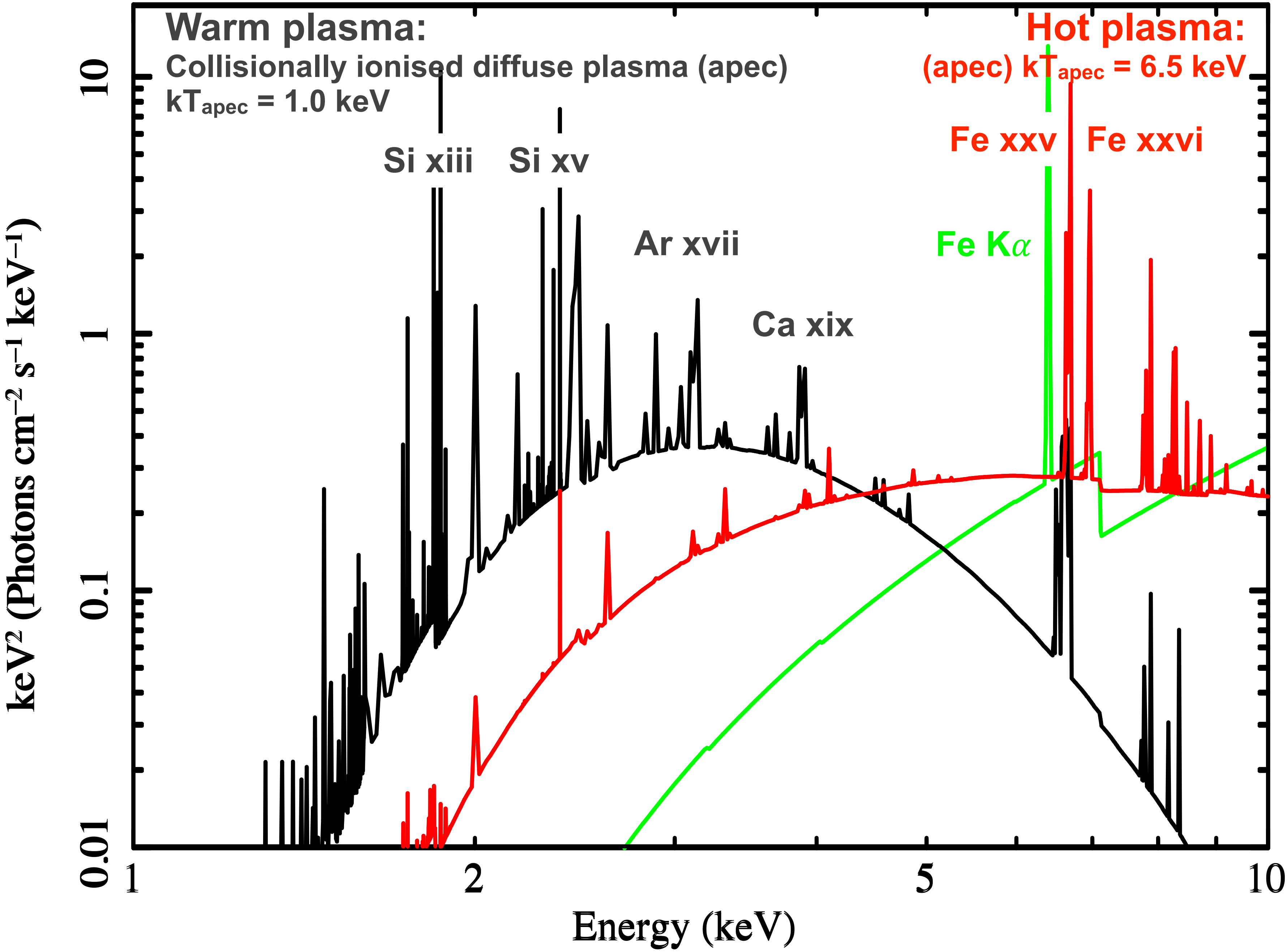
X-ray emission from bright GC point sources



X-ray emission from bright GC point sources

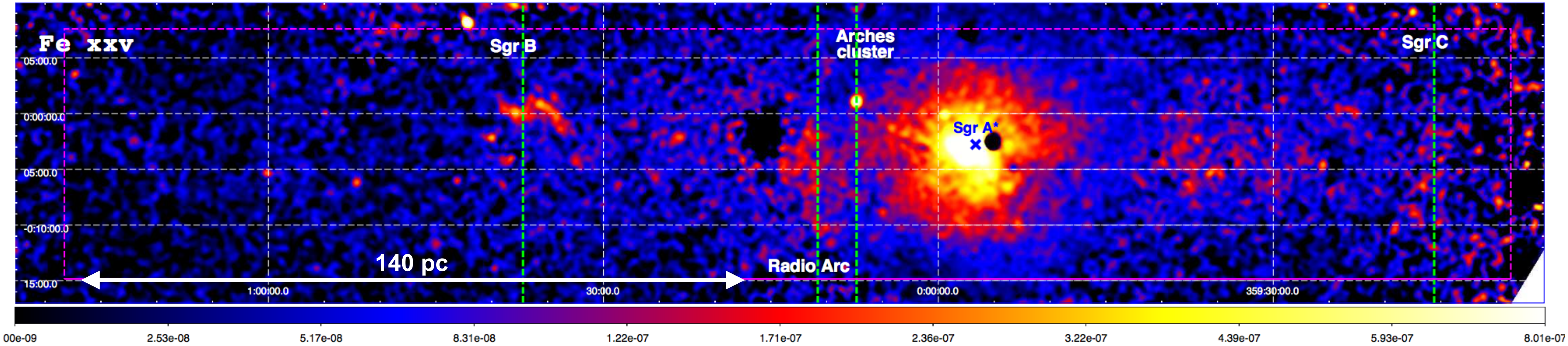


X-ray emission from bright GC point sources



Distribution of hot plasma

Ponti +13; +14



Homogeneous distribution peaking at GC

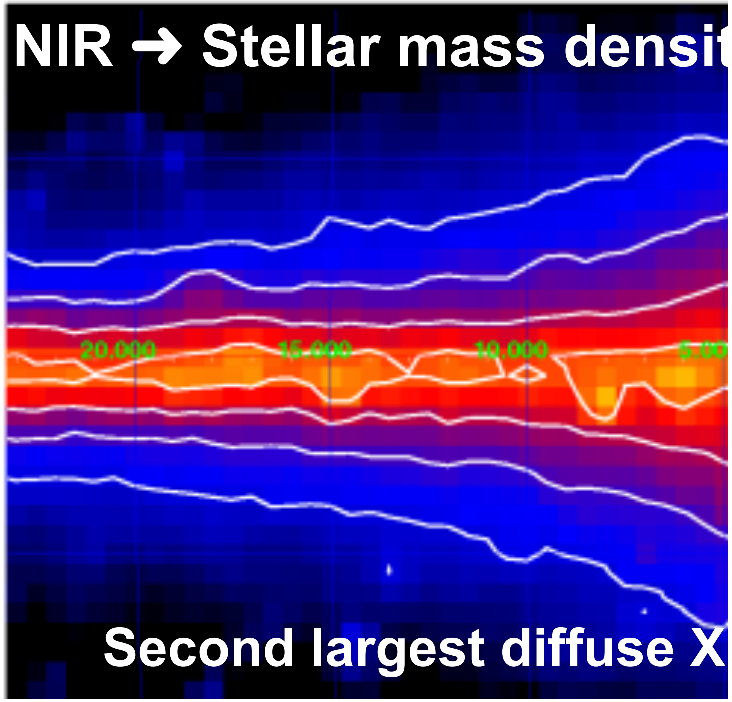
Hot plasma pervading the GC ➜ Galactic ridge emission

Cooke +70; Bleach +72; Worral +82

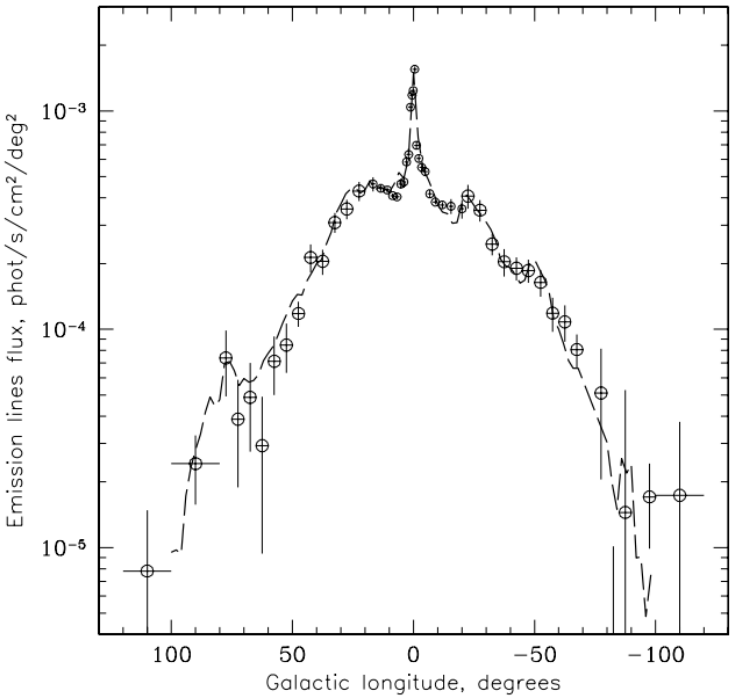
Second largest diffuse X-ray structure (>100°) $L_{2\text{-}10keV}=2\times10^{38}$ erg s^{-1}

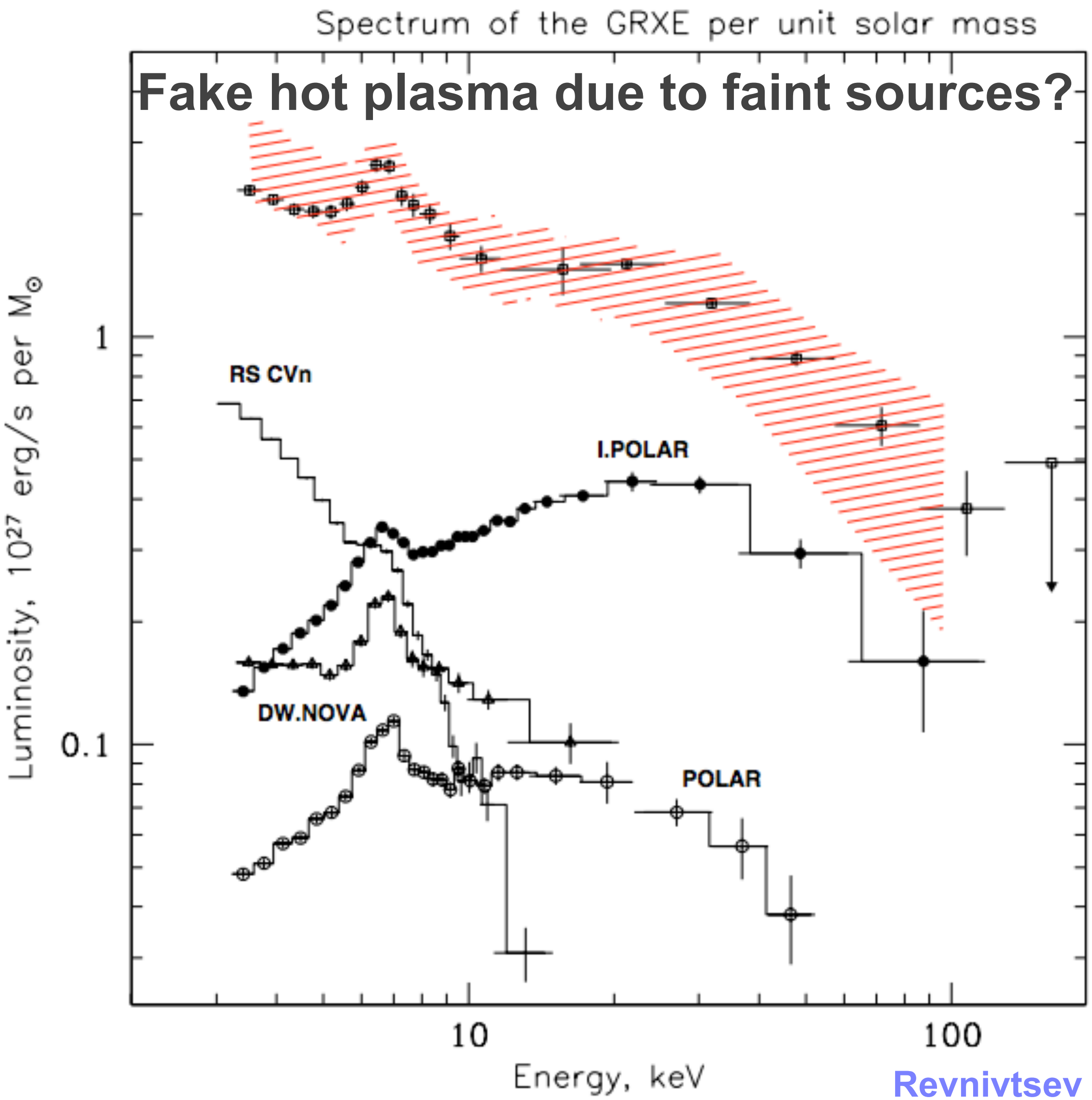
Galactic ridge emission

Revnivtsev 2006a,b

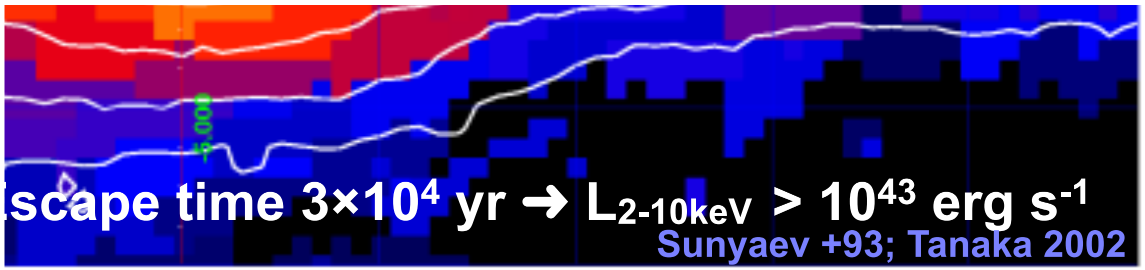


Revnivtsev 2006a



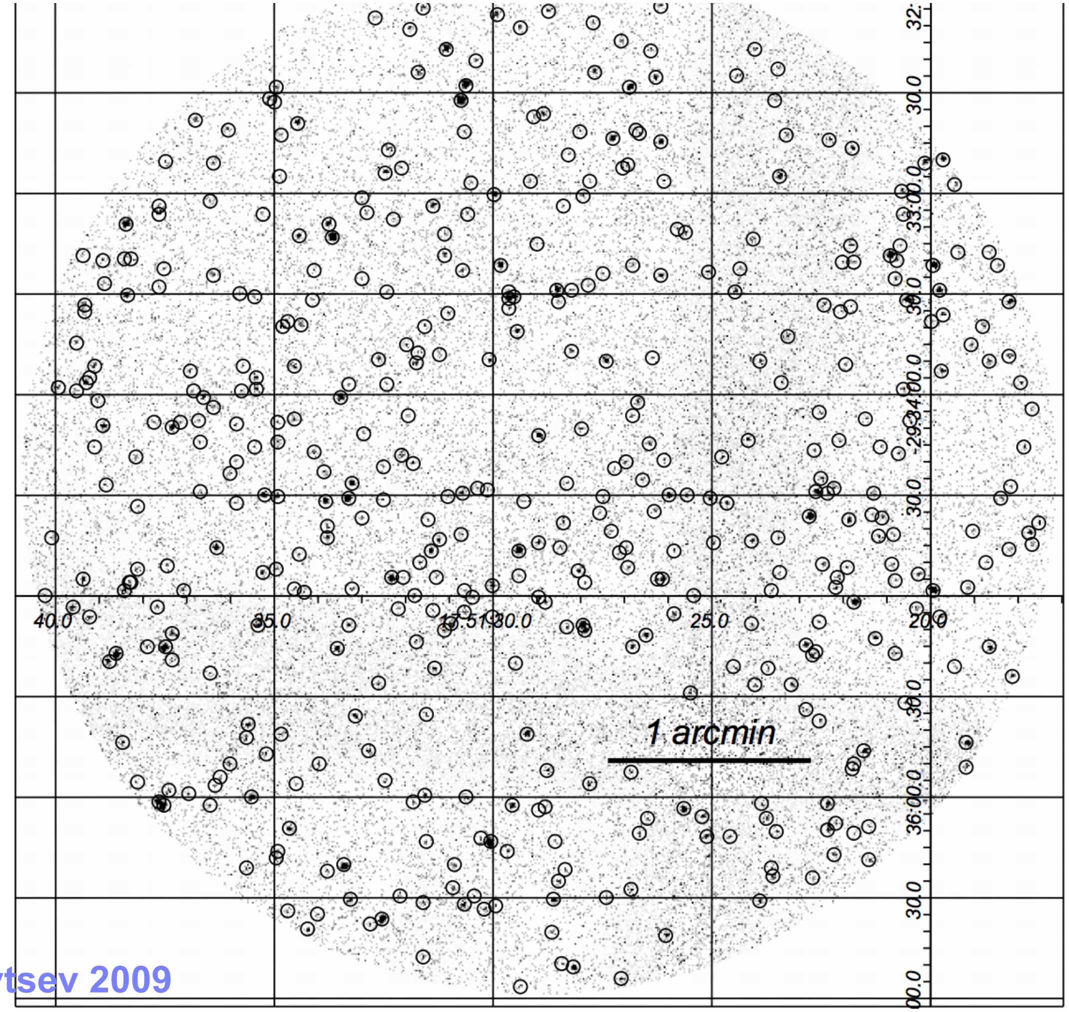


Revnivtsev 2006

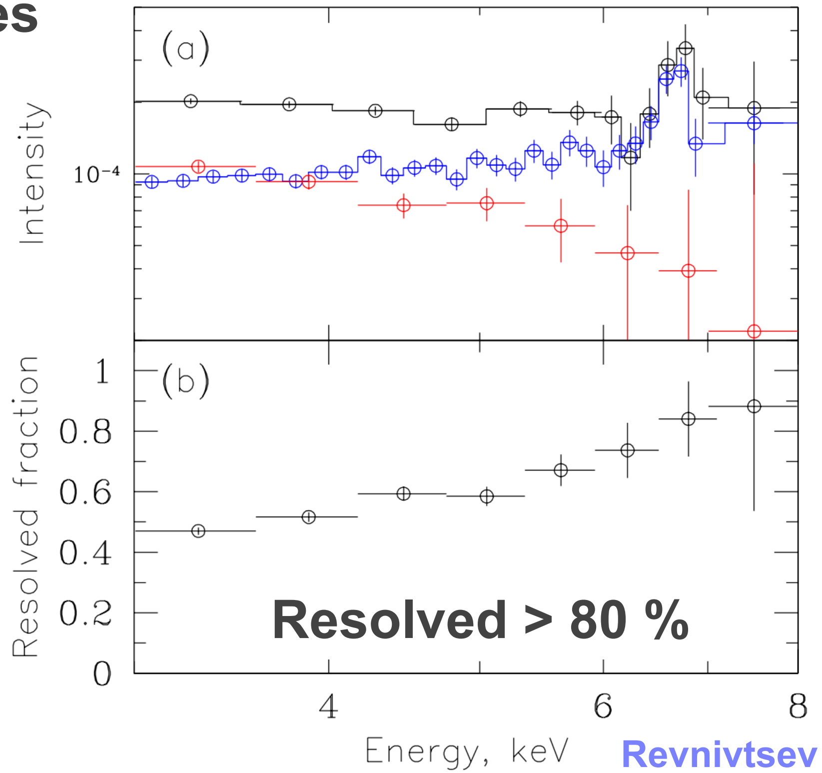


Point sources ➜ Galactic ridge emission

Hot plasma ➜ resolved in faint point sources

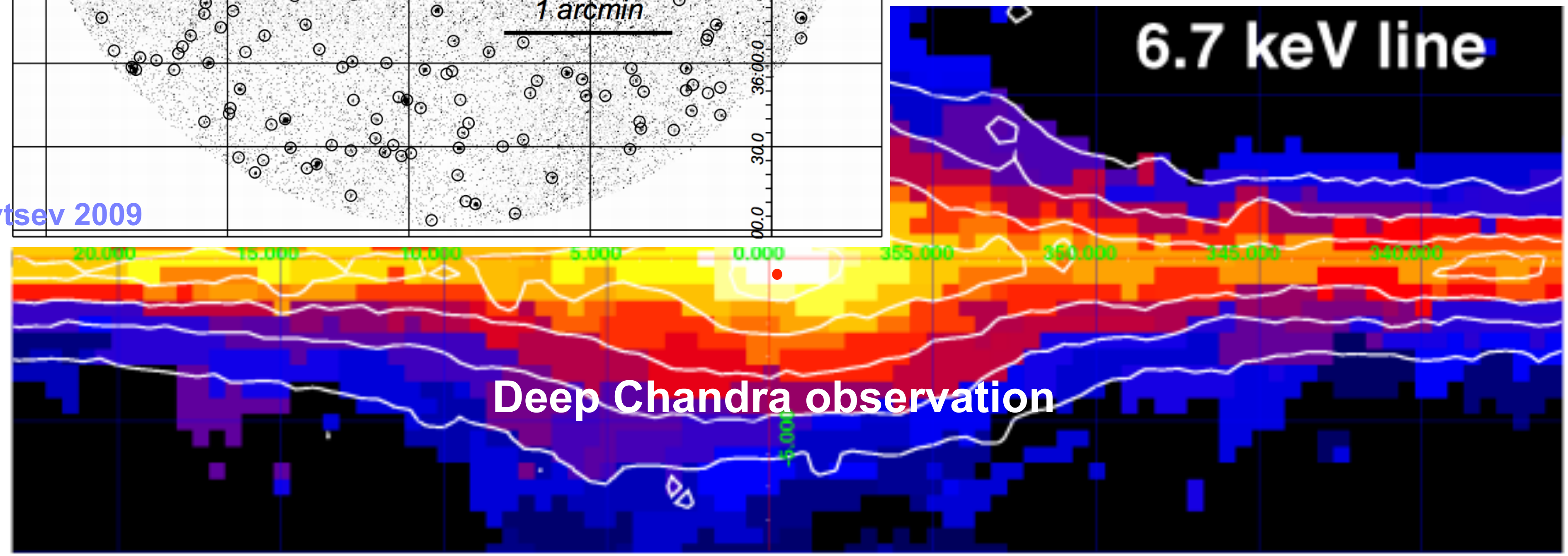


Revnivtsev 2006a,b



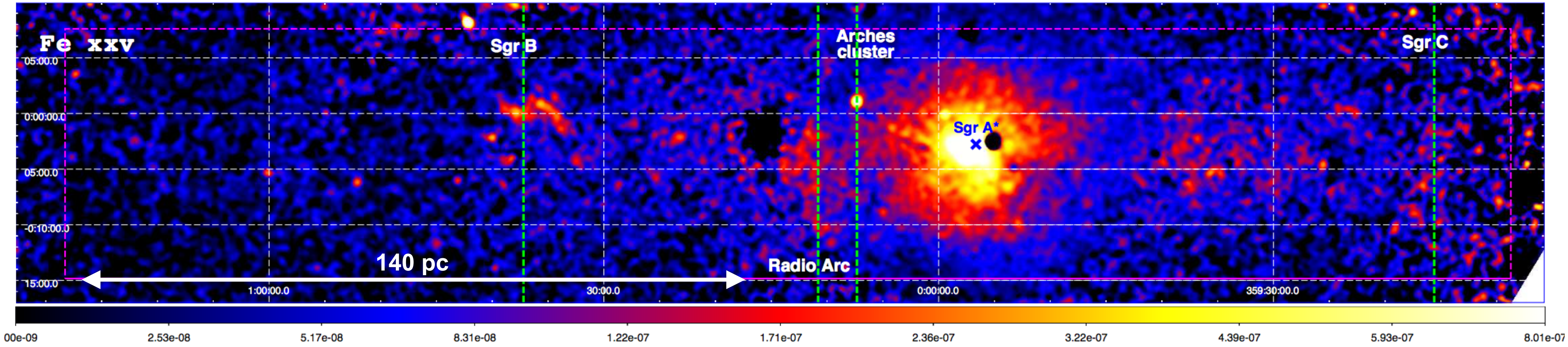
Revnivtsev 2009

Revnivtsev 2009



Galactic ridge due to point sources

Ponti +13; +14



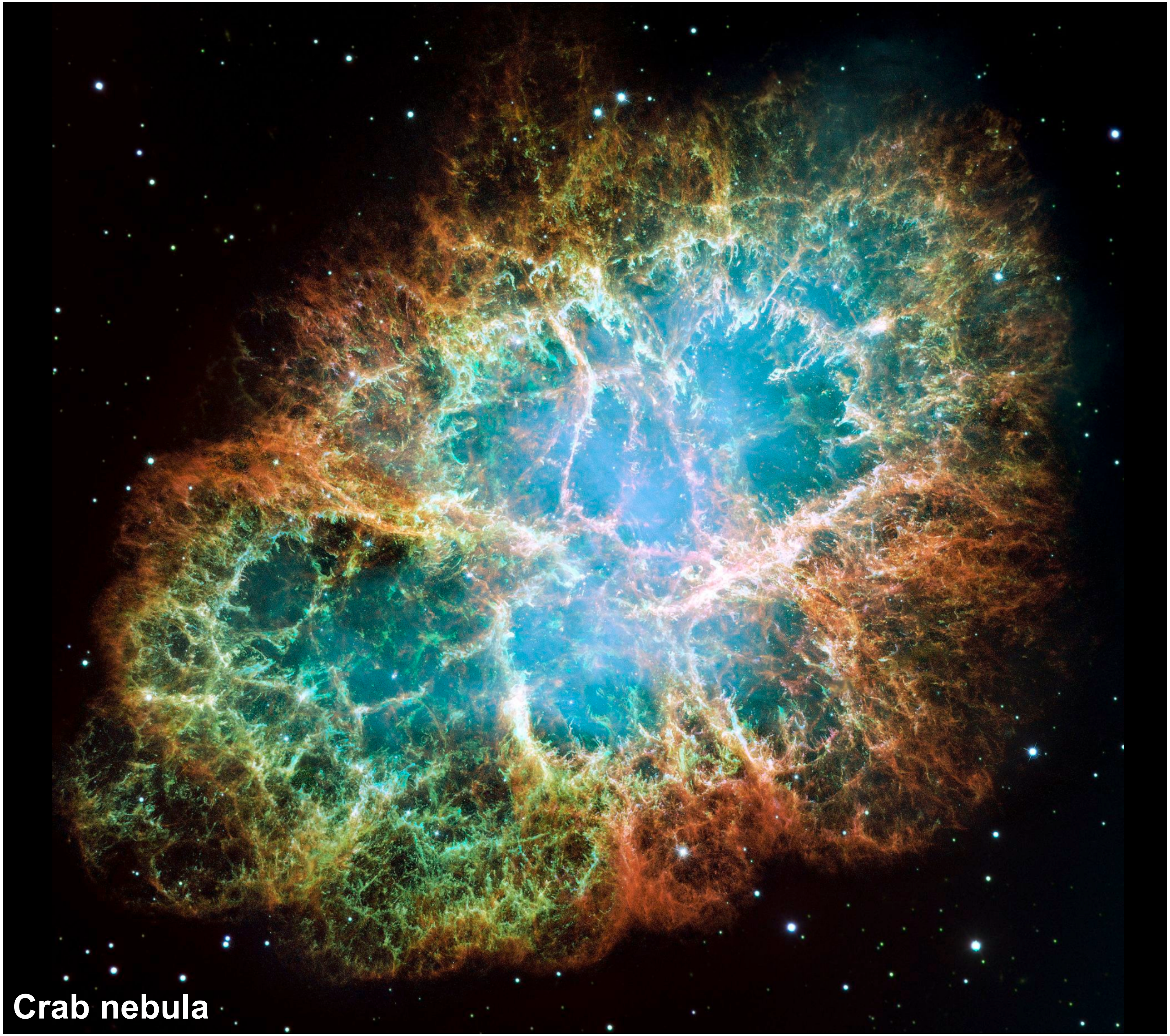
Hot plasma produced by faint X-ray sources in the Galactic Ridge

Revnivtsev +09

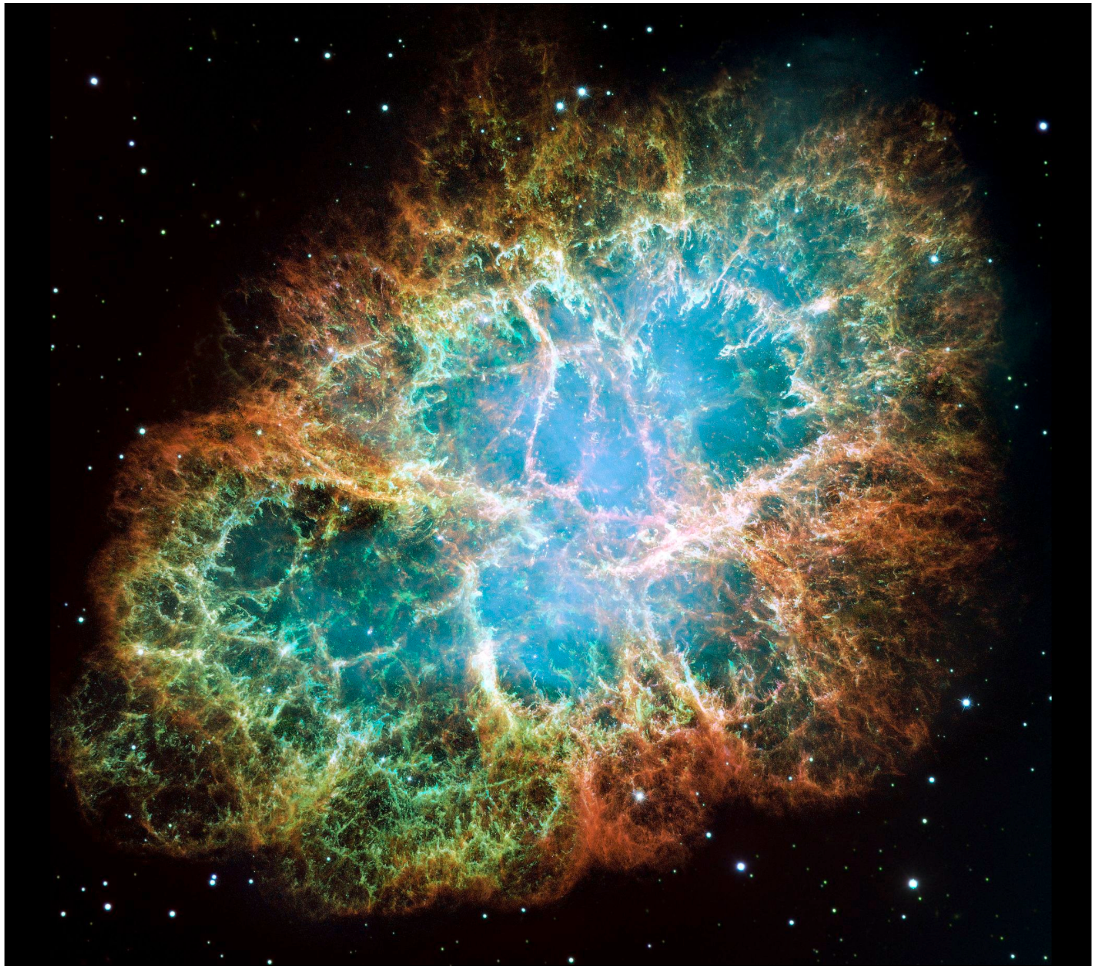
Excess emission (maybe) in the central region?

Koyama +11; Uchiyama +11

Supernova remnants



Supernova remnants



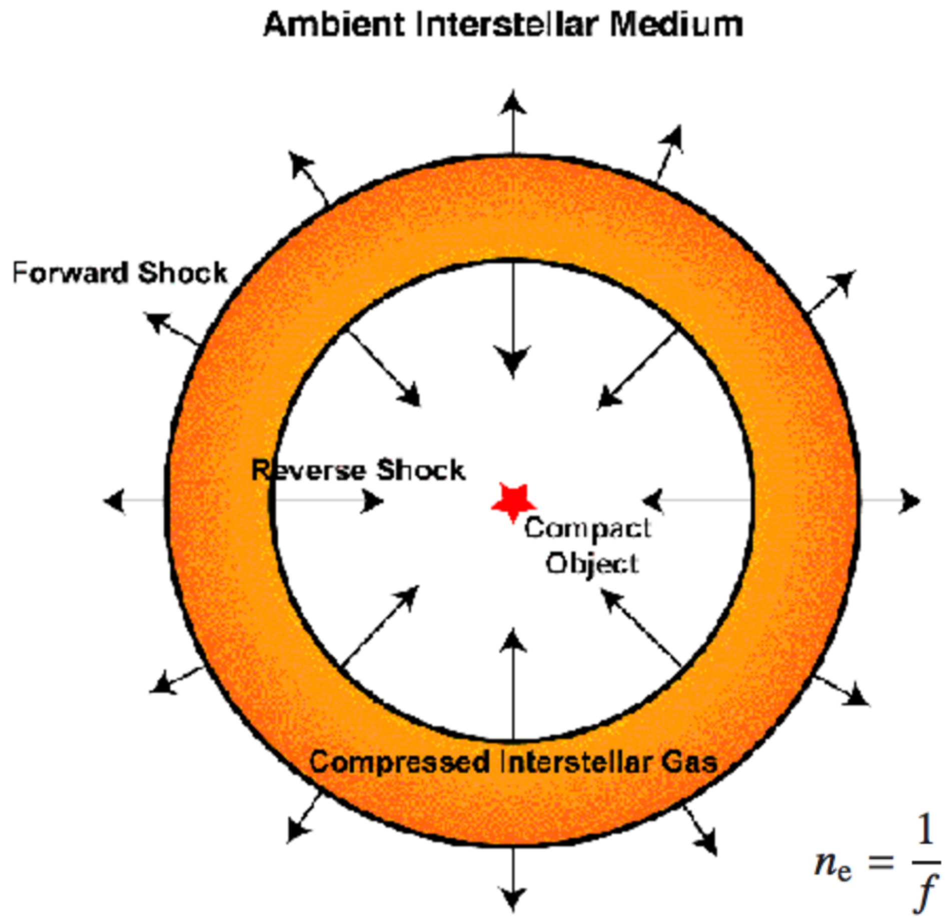
Stars with M > 8 M_{Sun} end their lives with an explosive ejection

Total kinetic energy E_{kin} ~ 10^{51} erg

The interstellar medium (ISM) has typically low density (1 cm^{-3})
➜ Strong shock!

➜ Expands; Heats ISM; creates a hot bubble; pushes away cold material

Different phases of supernova remnants



Free expansion phase

t ~ 2-3×10^2 yr
No deceleration (R ∝ t)
velocity ejecta (v) ~ 10^4 km s^{-1}
Mass swept-up (M) < M_{Sun}

Adiabatic or Taylor-Sedov

t ~ 2×10^4 yr
M ~ M_{ejecta}
Kinetic energy to heat ISM (E conserved)
➜ No ionisation equilibrium

$$n_e = \frac{1}{f}\sqrt{r_e \frac{EM}{V}} \quad (cm^{-3})$$

$$n_H = n_e/r_e \quad (cm^{-3})$$

$$t_{dyn} = 1.3 \times 10^{-16} \frac{R}{\sqrt{kT_s}} \quad (yr)$$

$$t_i = 3.17 \times 10^{-8} \frac{\tau}{n_e} \quad (yr)$$

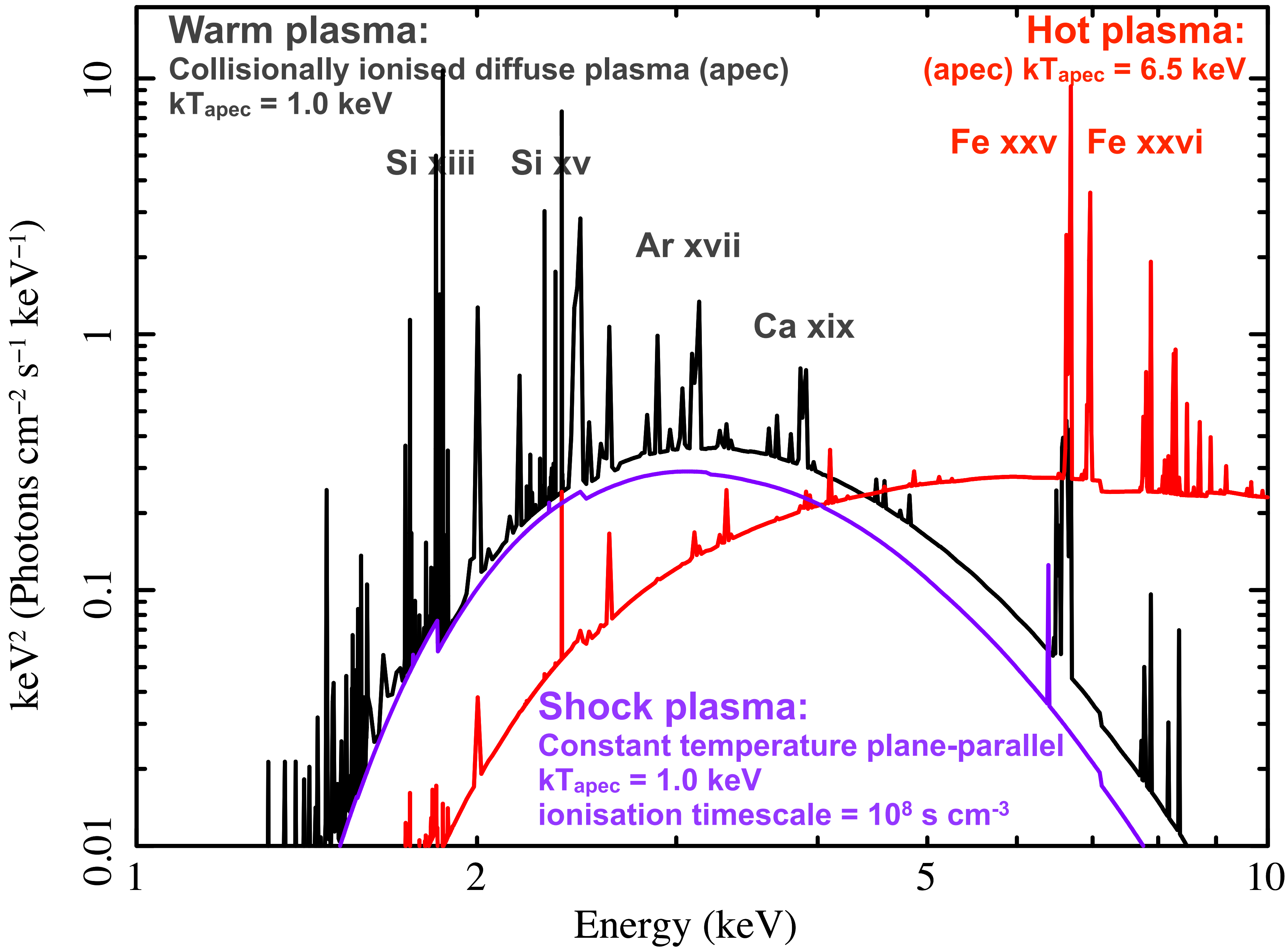
$$M = 5 \times 10^{-34} m_p\, r_m\, n_e\, f^2\, V \quad (M_\odot)$$

$$E_0 = 2.64 \times 10^{-8} kT_s\, R^3\, n_H \quad (erg),$$

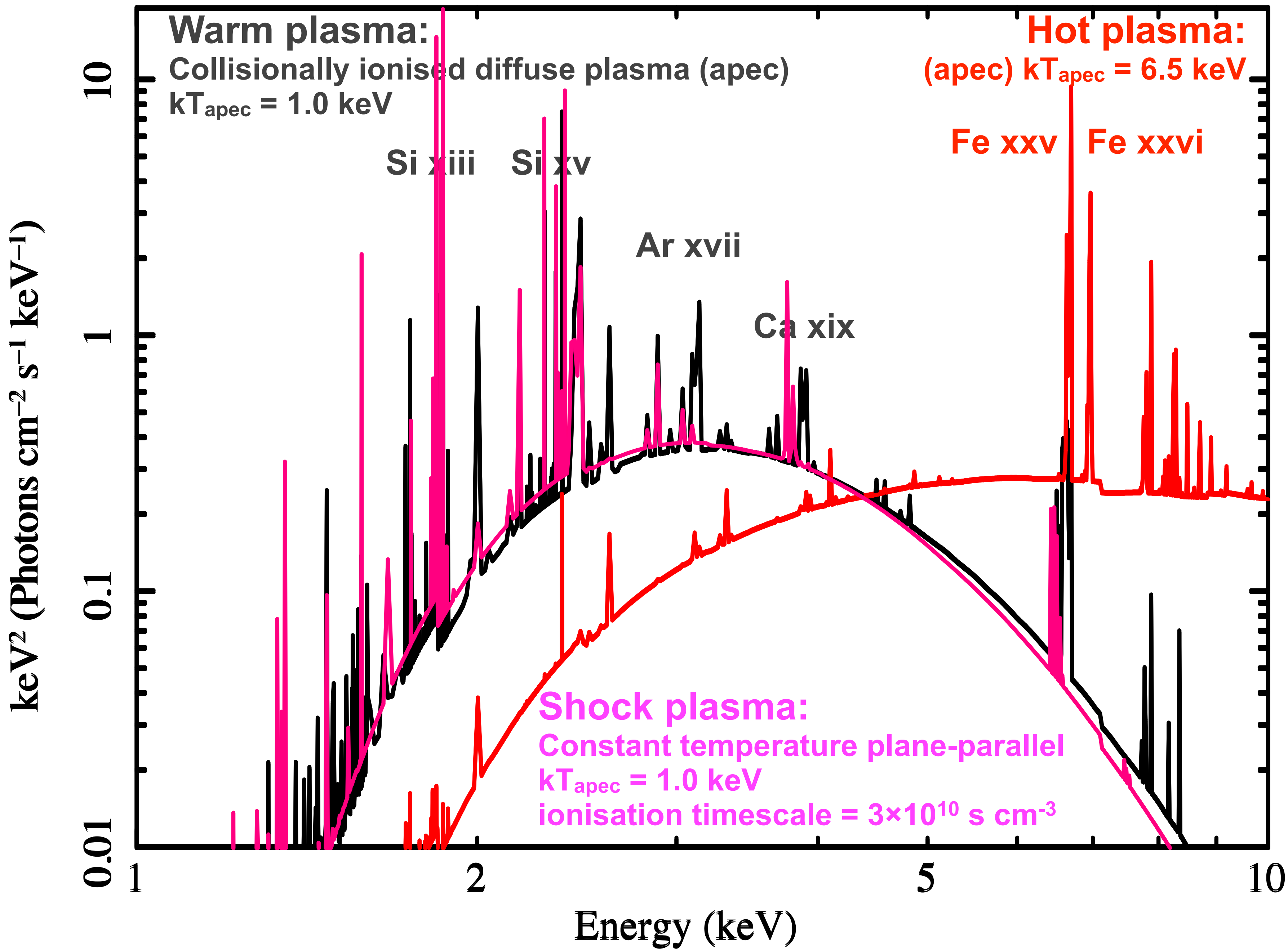
n_e: electron density
n_H: hydrogen density
E_0: initial energy
t_{dyn}: dynamical age
t_i: ionisation age
EM = $n_e n_H V$
R: remnant radius (cm)
V: volume (cm^3)
kT_s: shock temperature (keV)
tau: ionisation timescale (s cm^{-3})
m_p: proton mass (g)
r_m: baryon per hydrogen

X-ray observations provide:
EM, kTs, R, tau

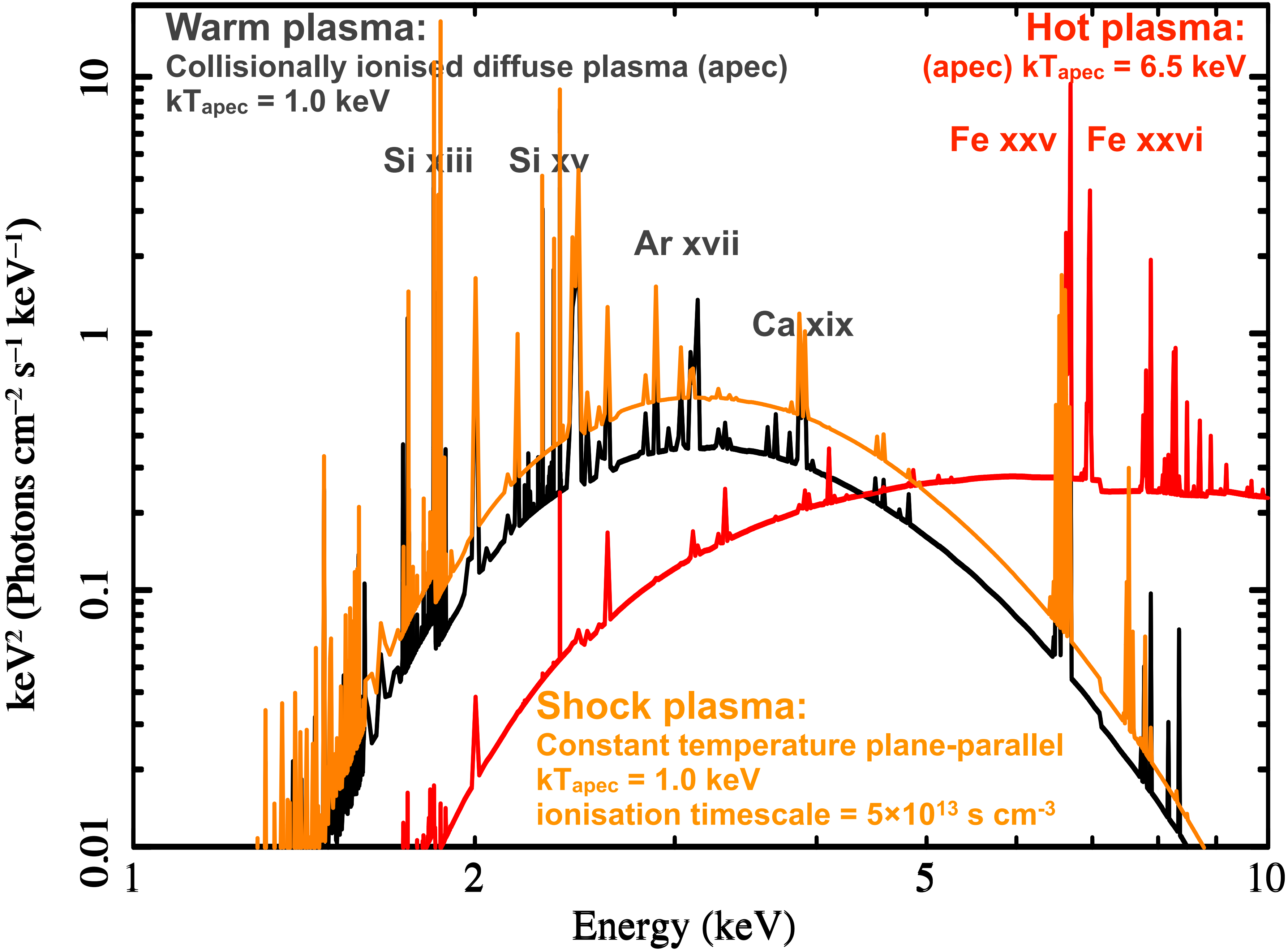
X-ray emission from bright GC point sources



X-ray emission from bright GC point sources

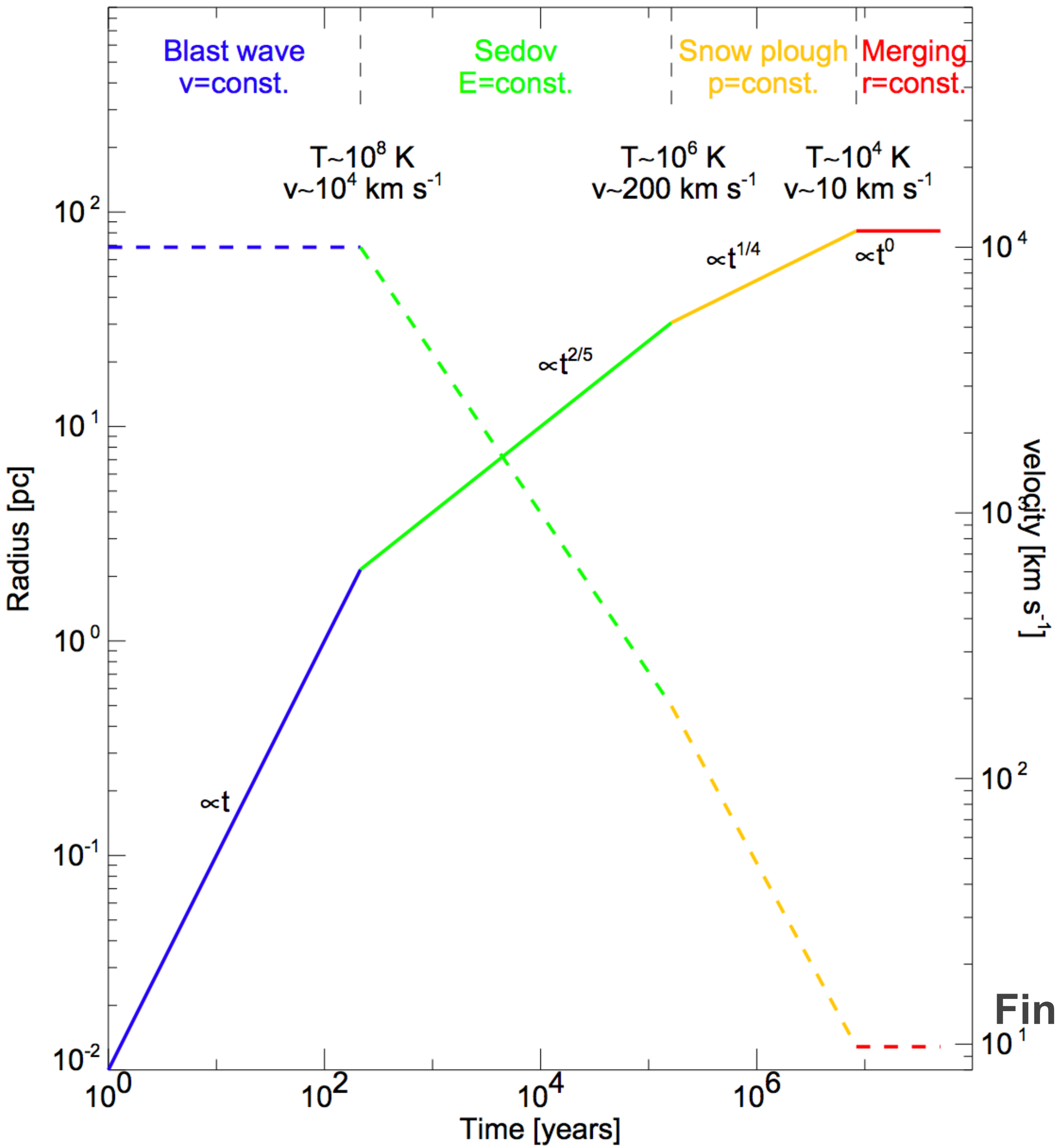


X-ray emission from bright GC point sources



X-ray provide: EM, kTs, R, tau ➜ Determine explosion energetics & ISM parameters

Different phases of supernova remnants



Free expansion phase

$t \sim 2\text{-}3\times10^2$ yr
No deceleration ($R \propto t$)
velocity ejecta (v) ~ 10^4 km s^{-1}
Mass swept-up (M) < M_{Sun}

Adiabatic or Sedov phase

$t \sim 2\times10^4$ yr
M ~ M_{ejecta}
(E conserved)
➜ No ionisation equilibrium

Snow plough phase

$t \sim 5\times10^5$ yr
kT_s drops below kT_{recomb}
Rapid recombination
Finally the remnants merges with ISM

Stellar winds & superbubbles

All main sequence stars earlier than B2 and late type B stars

➜ high speed winds with high $\dot{M}_{out}$

Typically:

$v_{out} = 2\times10^{3}$ km s^{-1}

➜ after t ~ 10^{6} yr

➜ $E_{kin} > 10^{50}$ erg s^{-1}

➜ large impact on ISM

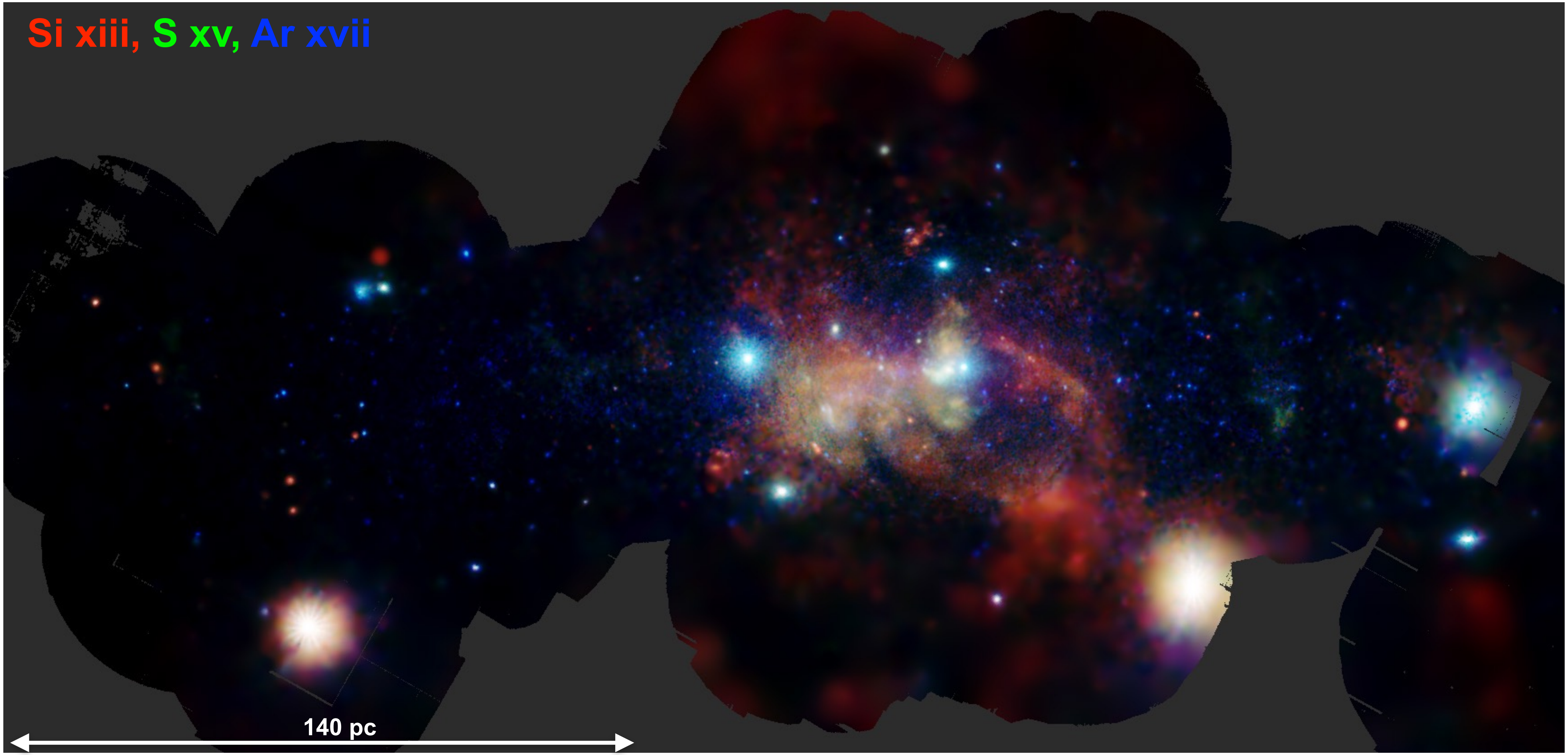
Castor +75; Weaver +77; Mac Low +88

Evolution similar to SNR
Reach R ~ 30-60 pc
Hot bubble surrounded by cold material

➜ Escape Galactic potential
➜ enrich Galactic halo

Distribution of warm plasma

Ponti +15



Patchy distribution with small and large structures

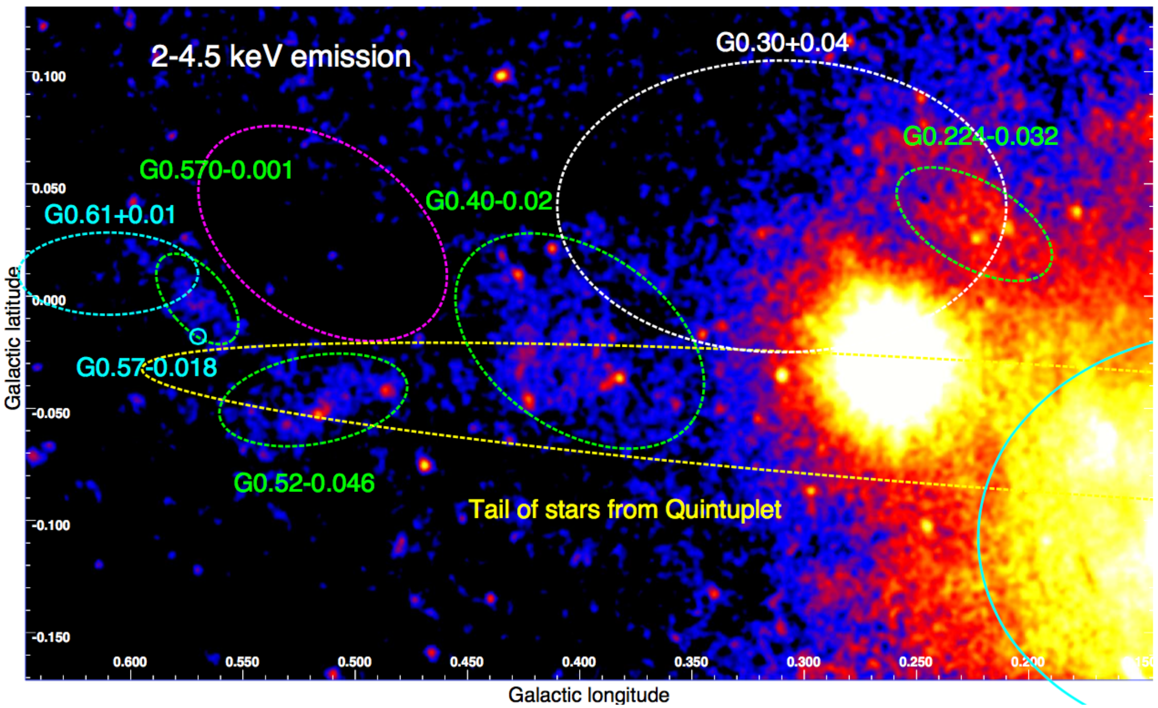
Total luminosity of soft plasma: $L_X \sim 3.4\times10^{36}$ erg s^{-1}

Bound to the Galaxy

Origin?

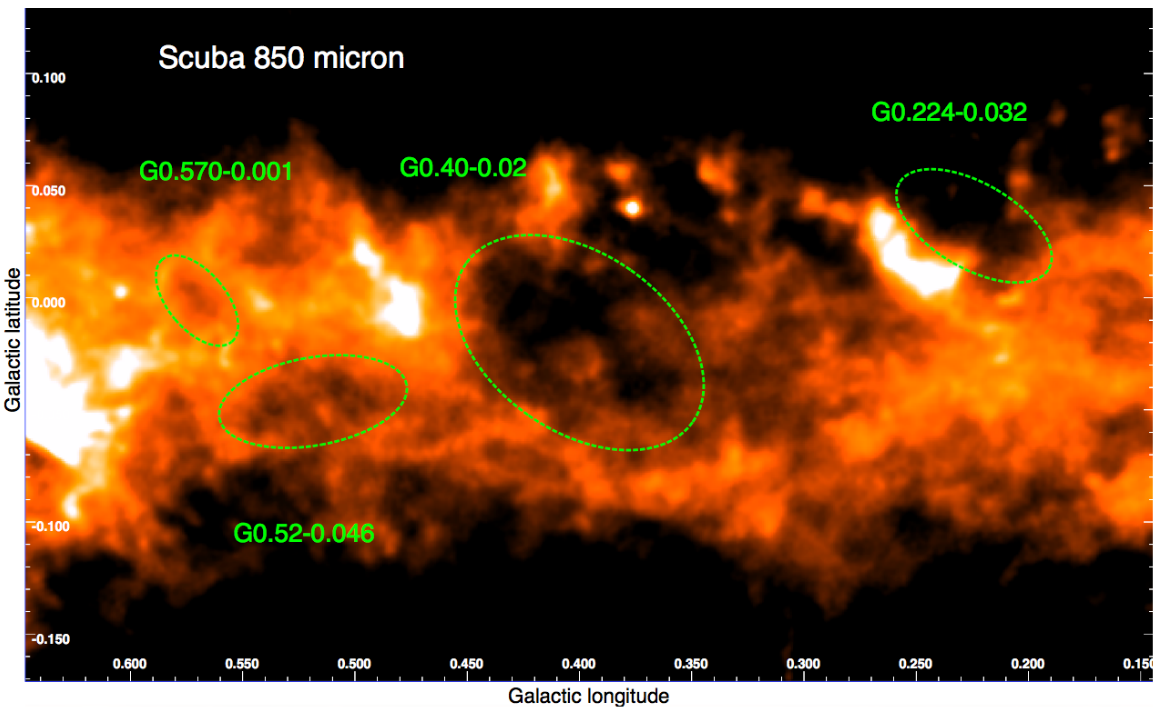
New SNR, excavating bubbles in MCZ?

Ponti +15



New soft X-ray features

$E_{th} \sim 10^{49-50}$ erg
Probably SNR



Holes in MC distribution

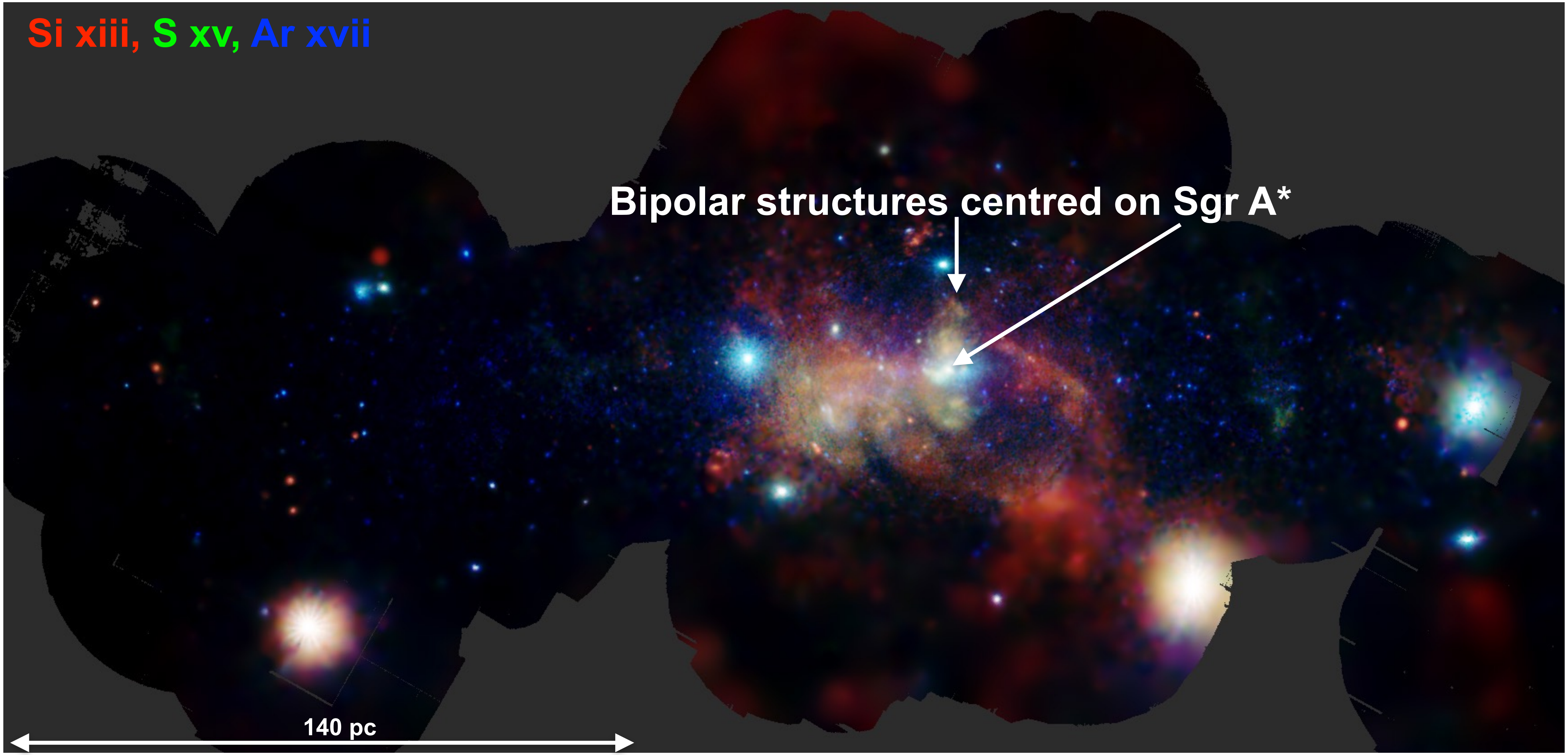
Expanding molecular shell?

G0.570-0.001 confirmed!!

Tanaka +09

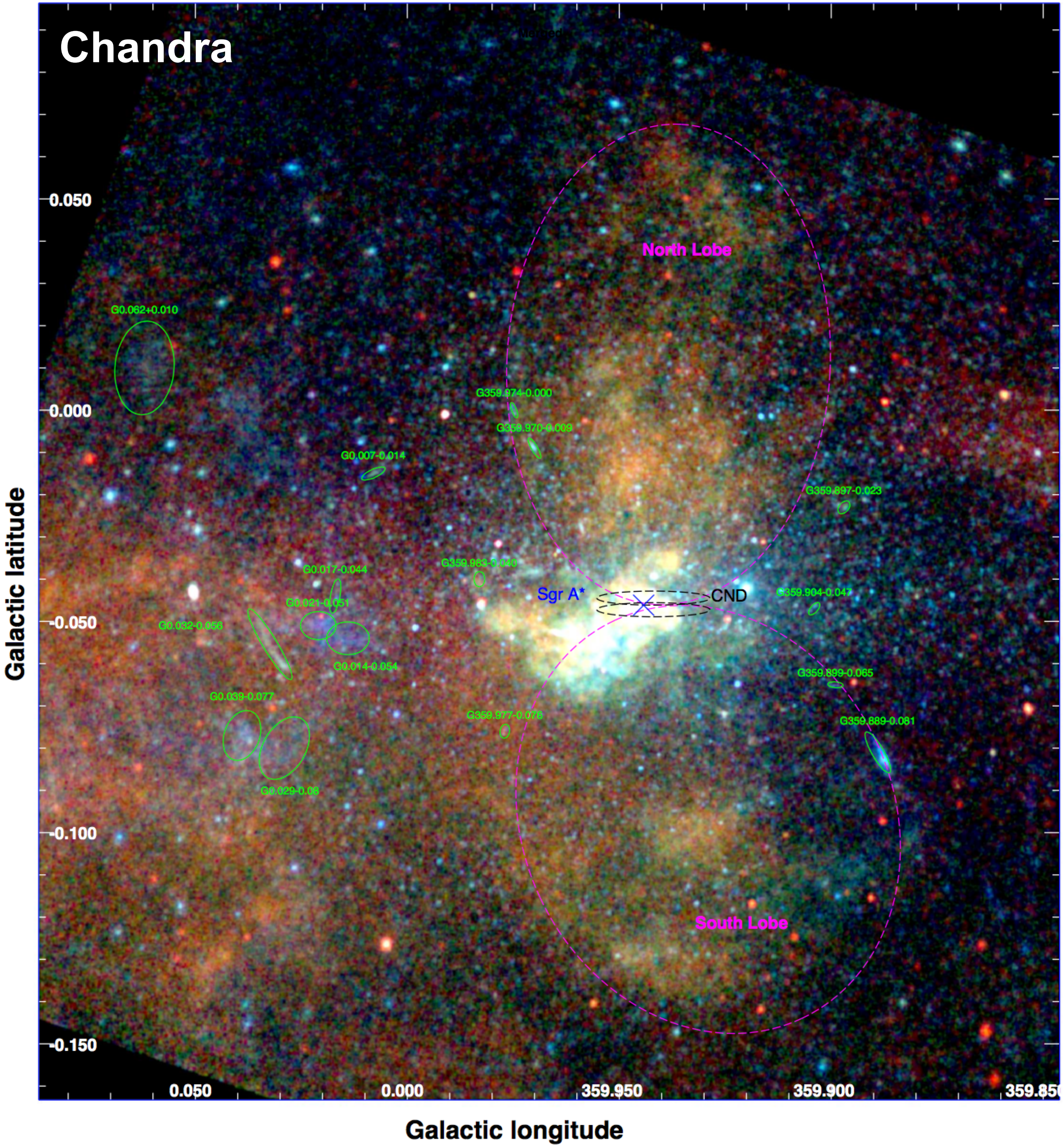
The lobes of the Sgr A complex

Ponti +15



Sgr A's lobes

Ponti +15



Bipolar thermal (kT~1keV) features (5×10pc)

➜ Signatures of outflow (collimated by the circum-nuclear disc) from Sgr A*'s region

Morris +03; Baganoff +03; Markoff +10; Heard +12; Ponti +12

E_{th} ~ 9×10^{49} erg

➜ Winds from central star cluster

➜ Winds from Sgr A*'s accretion flow Wang +13

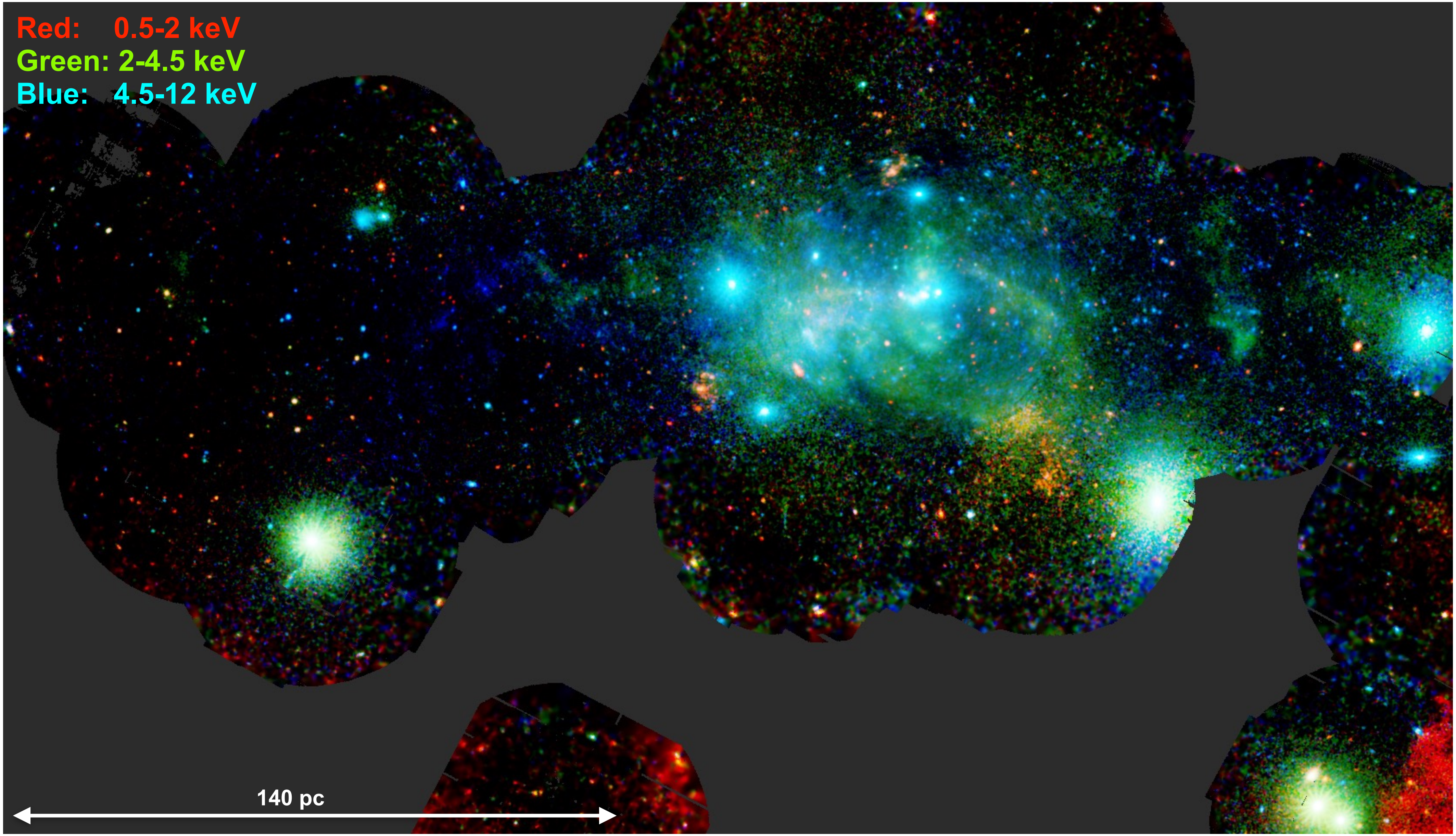
Sharp edges

➜ Explosive event

SGR J1745-2900?

SNR of PWN G359.945-0.044?

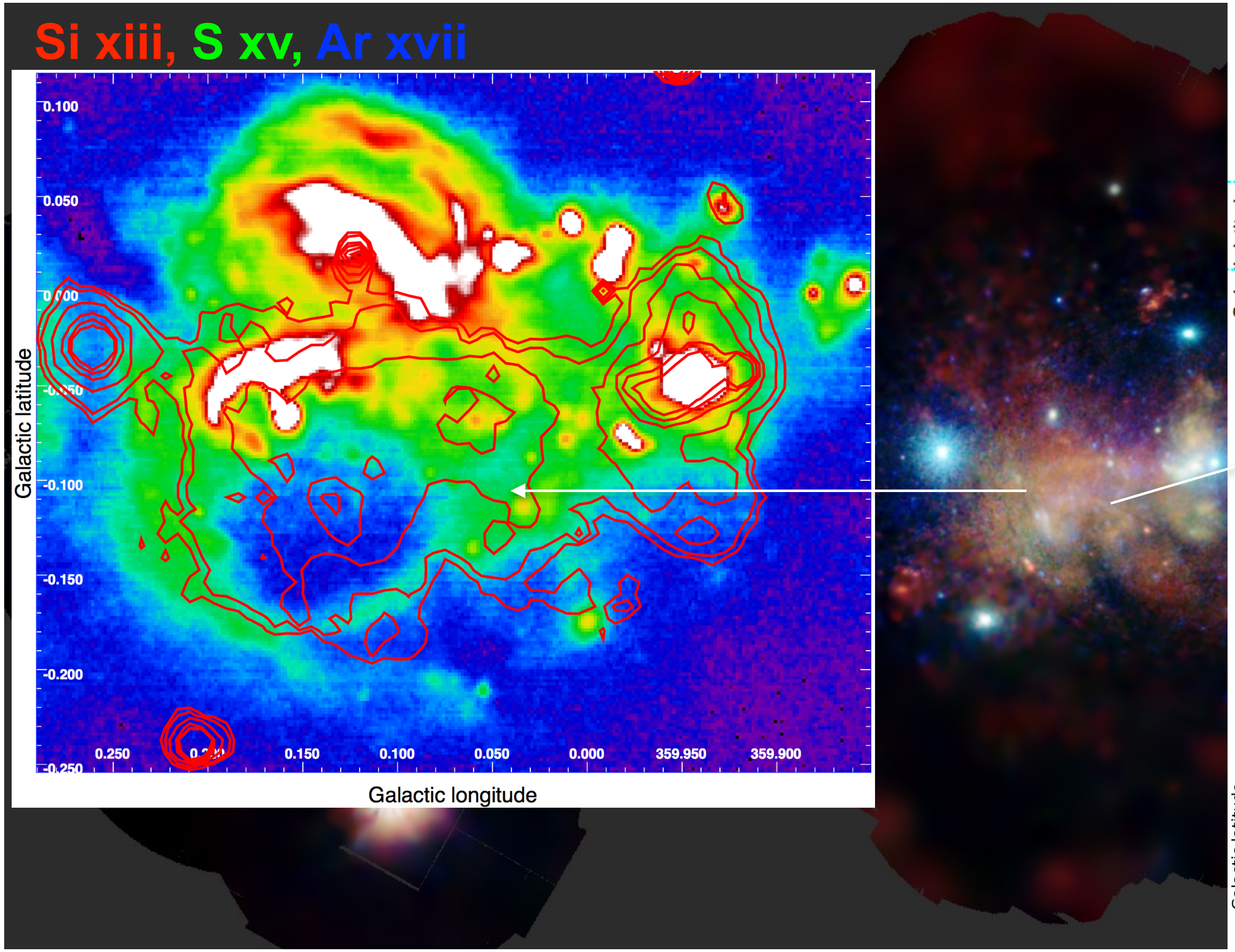
Summary

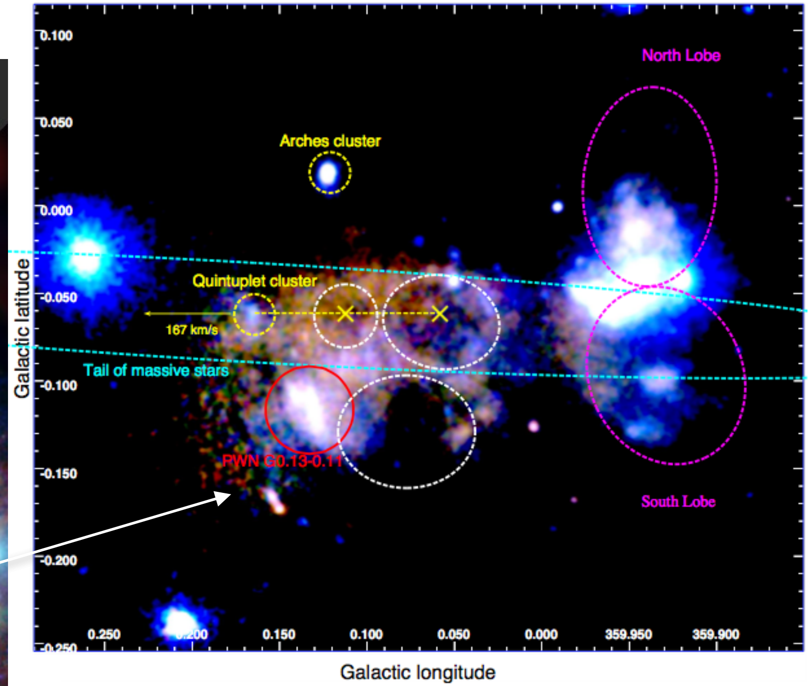


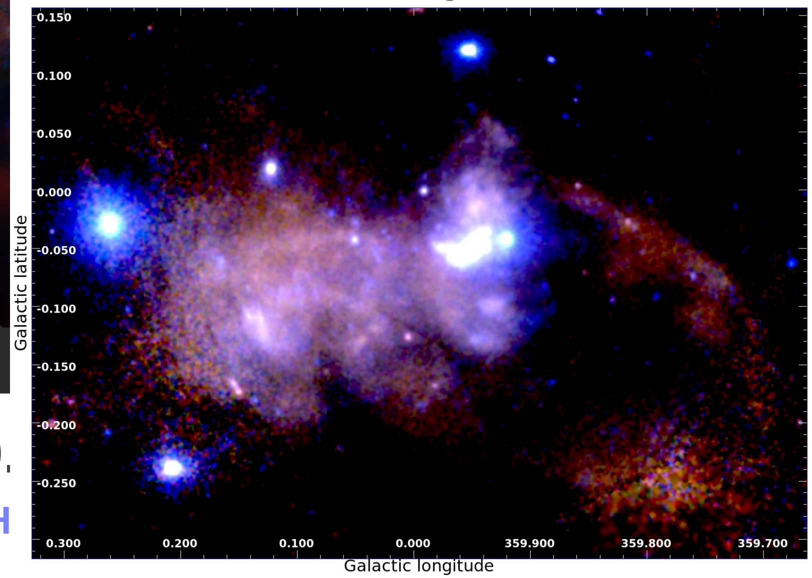
Dust scattering halos
Highly absorbed ($N_H \sim 10^{23}$ cm^{-2})
Soft X-ray foreground star
Hot plasma ➜ point sources

SNR interacting with clouds
Sgr A lobes ➜ outflow from central parsec

Super-bubbles and outflows!







SNR associated to PWN G0.

E_{th} ~ 3×10^{49} erg H

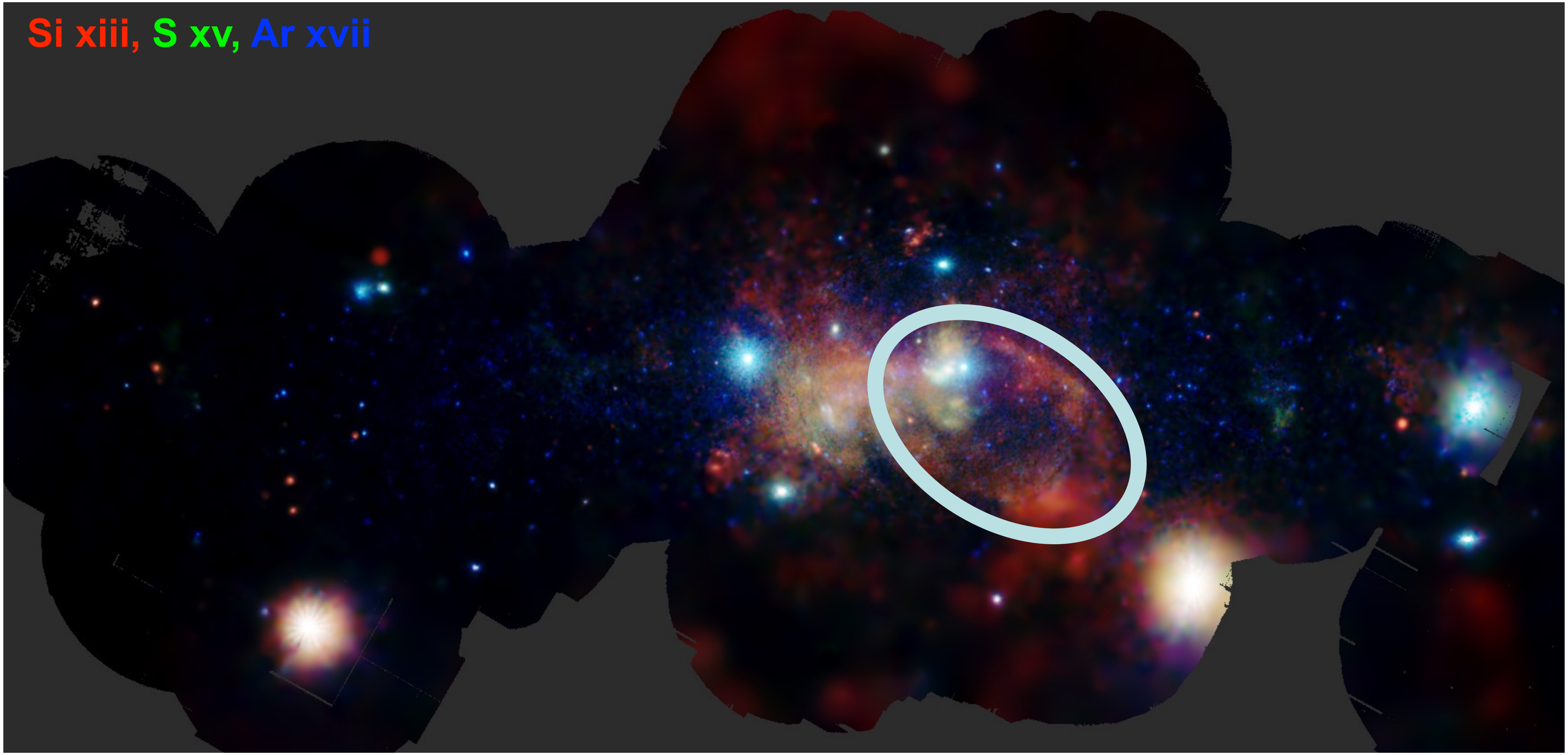
Thermal X-rays fill the MIR arc bubble

E_{th} ~ 1.5×10^{51} erg

A super-bubble powered by the Quintuplet cluster?

Super-bubbles and outflows!

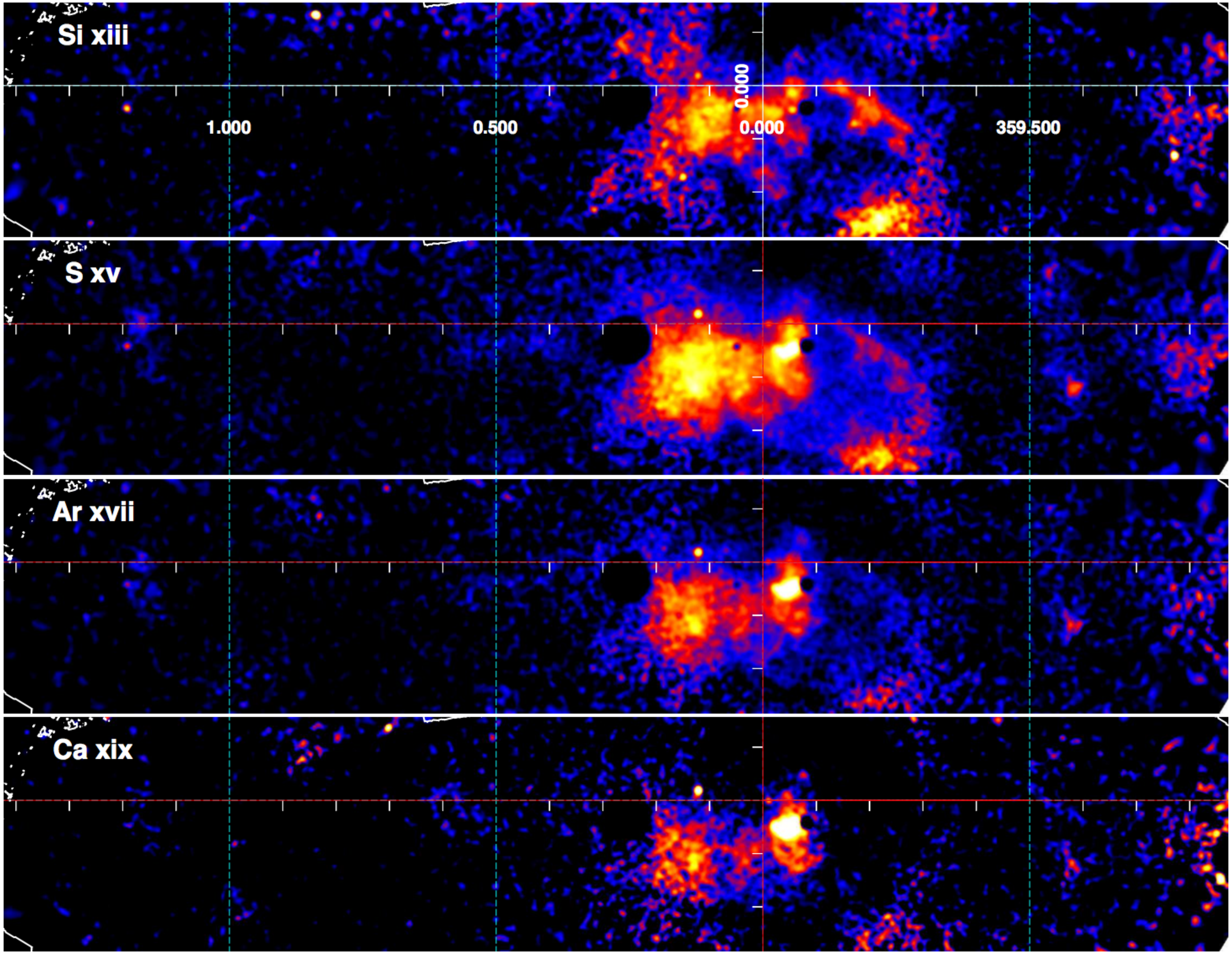
Ponti +15



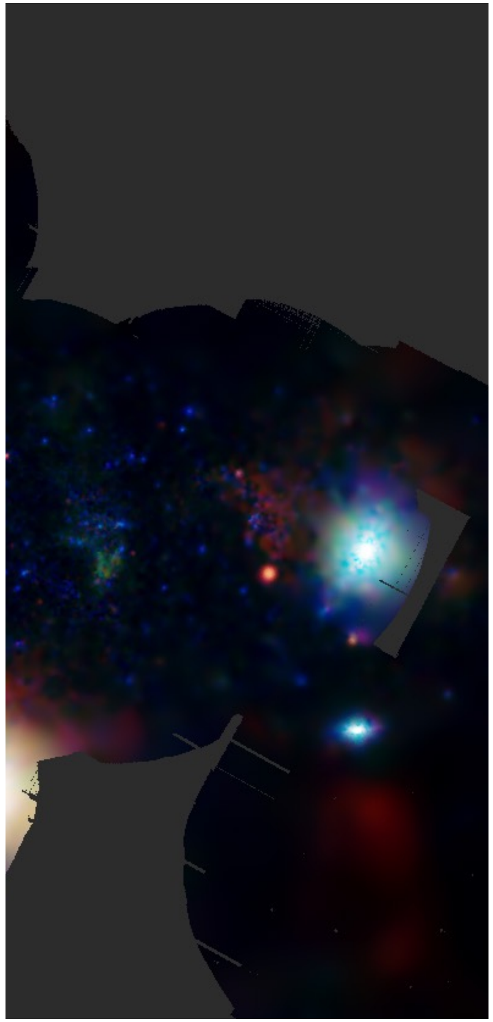
Series of SNR producing an apparently coherent structure

Mori +09; Heard +13

Super-bubbles and outflows!



Ponti +15

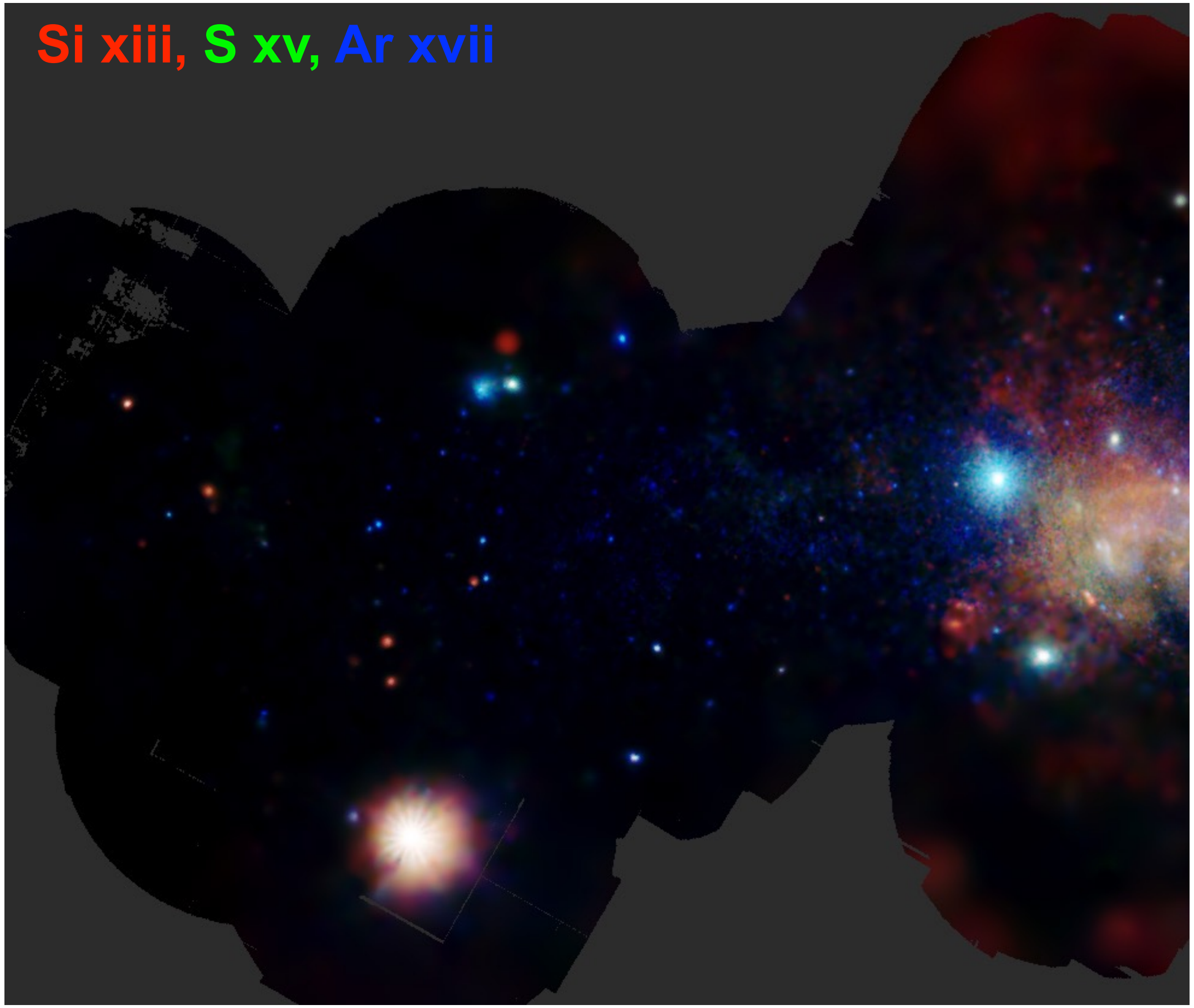


Filled (S xv) elliptical structure 3d shell morphology

E_{th} ~ 1.5×10^{51} erg (another super-bubble?) Mori +09; Heard +13

Remnant of a tidal disruption event? (1 every 10^4 yr) Guillochon +15

Super-bubbles and outflows!



ATLAS OF DIFFUSE X-RAY EMITTING FEATURES

Name	Other name	Coordinates (l, b)	Size arcsec	References
STAR CLUSTERS:				
Central star cluster		359.9442, -0.046	0.33	45,116,117,118
Quintuplet		0.1604, -0.0591	0.5	1,63,11
Arches	G0.12+0.02	0.1217, 0.0188	0.7	1,2,3,4,5,6,7,8,9,39,40,11
Sh2-10	DB00-6	0.3072,-0.2000	1.92	10,11,12,63,11
Sh2-17	DB00-58	0.0013, 0.1588	1.65	13,63,11
DB00-05	G0.33-0.18	0.31 -0.19	0.4	22,63,11
SNR - BUBBLES - SUPER-BUBBLES:				
G359.0-0.9	G358.5-0.9 - G359.1-0.9	359.03,-0.96	26 × 20	X-R 48,51,75,76,81,119,120
G359.07-0.02	G359.0-0.0	359.07,-0.02	22 × 10	R 14,48,51,66
	G359.12-0.05	359.12,-0.05	24 × 16	X 66
G359.10-0.5		359.10,-0.51	22 × 22	X-R 37,48,51,56,74,75,81,120,121
G359.41-0.12		359.41,-0.12	3.5 × 5.0	X 14
Chimney		359.46,+0.04	6.8 × 2.3	X 14
G359.73-0.35‡		359.73,-0.35	4	X 58
G359.77-0.09	Superbubble	359.84,-0.14	20 × 16	X 15,16,17,58
	G359.79-026♮	359.79,-0.26	8 × 5.2	X 15,16,17,58
	G0.0-0.16††	0.00,-0.16		X This work
G359.87+0.44	Cane	359.87,+0.44	11 × 5	R 48
	G359.85+0.39			
20pc Sgr A⋆’s lobes		359.94, -0.04	5.88	R 32,33,34,17
G359.92-0.09‡	Parachute - G359.93-0.07	359.93,-0.09	1	R 35,38,43,47,58,60,61
Sgr A East	G0.0+0.0	359.963, -0.053	3.2 × 2.5	X-R 5,18,19,20,48,75,81
G0.1-0.1	Arc Bubble	0.109,-0.108	13.6 × 11	X This work
	G0.13,-0.12♭	0.13,-0.12	3 × 3	X 17
G0.224-0.032		0.224,-0.032	2.3 × 4.6	X This work
G0.30+0.04	G0.3+0.0	0.34,+0.045	14 × 8.8	R 21,48,51,81,82
	G0.34+0.05			
	G0.33+0.04			
G0.40-0.02	Suzaku J1746.4-2835.4	0.40,-0.02	4.7 × 7.4	X 22
	G0.42-0.04			
G0.52-0.046		0.519,-0.046⋄	2.4 × 5.1	This work
G0.57-0.001		0.57,-0.001	1.5 × 2.9	This work
G0.57-0.018†	CXO J174702.6-282733	0.570,-0.018	0.2	X 23,24,58,59,68,80
G0.61+0.01†	Suzaku J1747.0-2824.5	0.61,+0.01	2.2 × 4.8	X 22,65,79
G0.9+01♡	SNR 0.9+0.1	0.867,+0.073	7.6 × 7.2	R 25,26,27,28,29,48,75,81,82
DS1	G1.2-0.0	1.17,+0.00	3.4 × 6.9	X 31
Sgr D SNR	G1.02-0.18	1.02,-0.17	10 × 8.0	R 30,31,48,51,75,77,81,82
	G1.05-0.15			
	G1.05-0.1			
	G1.0-0.1			
G1.4-0.1		1.4,-0.10	10 × 10	R 73,81,82

Atlas of all (~15) SNR and SB candidate in the region

Assume SN emission is visible during h_{CMZ}/c_s ~ 10-40 kyr

3.5×10^{-4} yr^{-1} < SN rate < 15×10^{-4} yr^{-1}

Assuming Kroupa IMF: SFR ~ 0.035-0.15 M_{sun} yr^{-1}

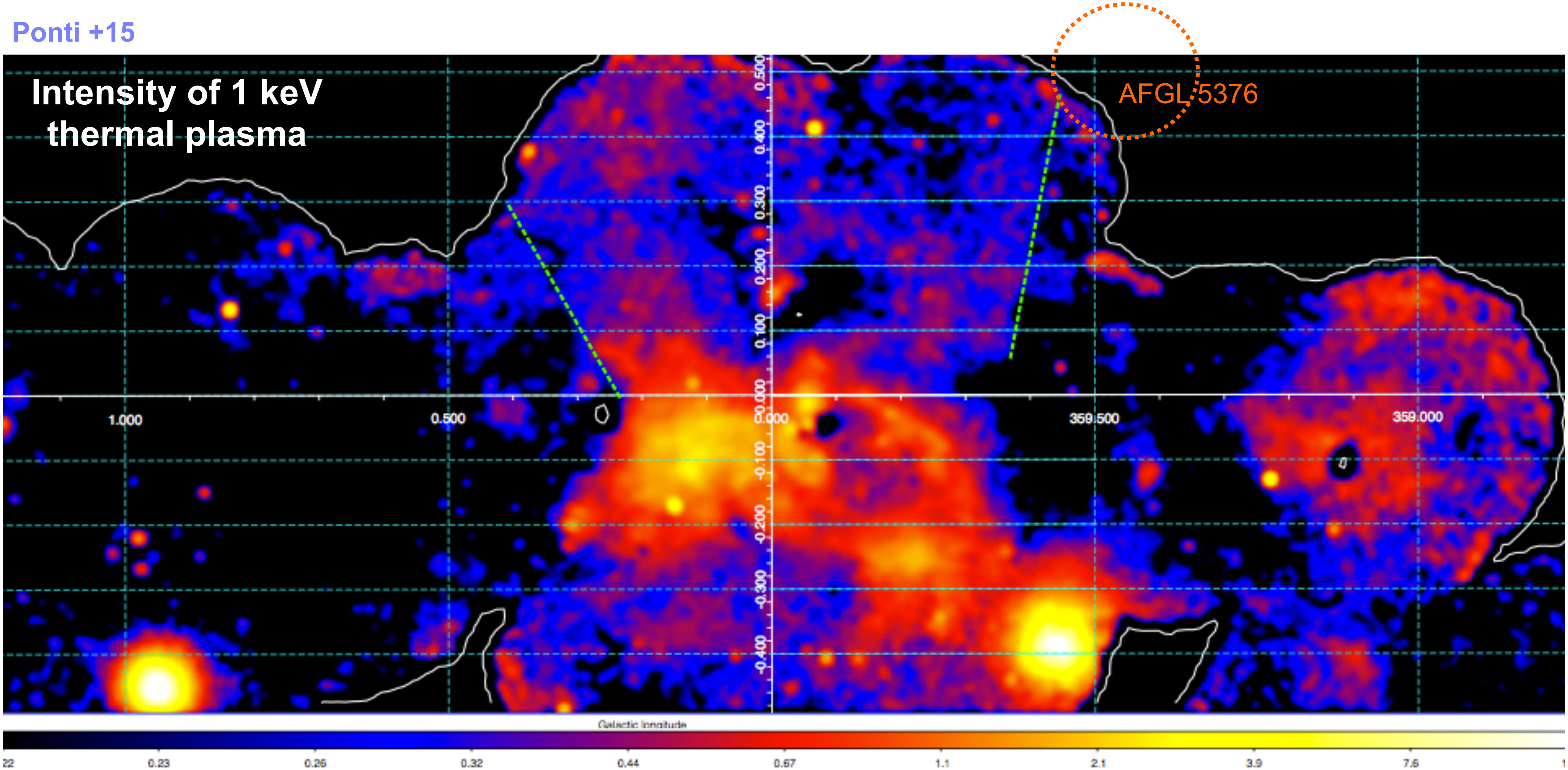
Massive kinetic energy input > 1.1×10^{40} erg s^{-1}

➜ Powering outflows to GCL?

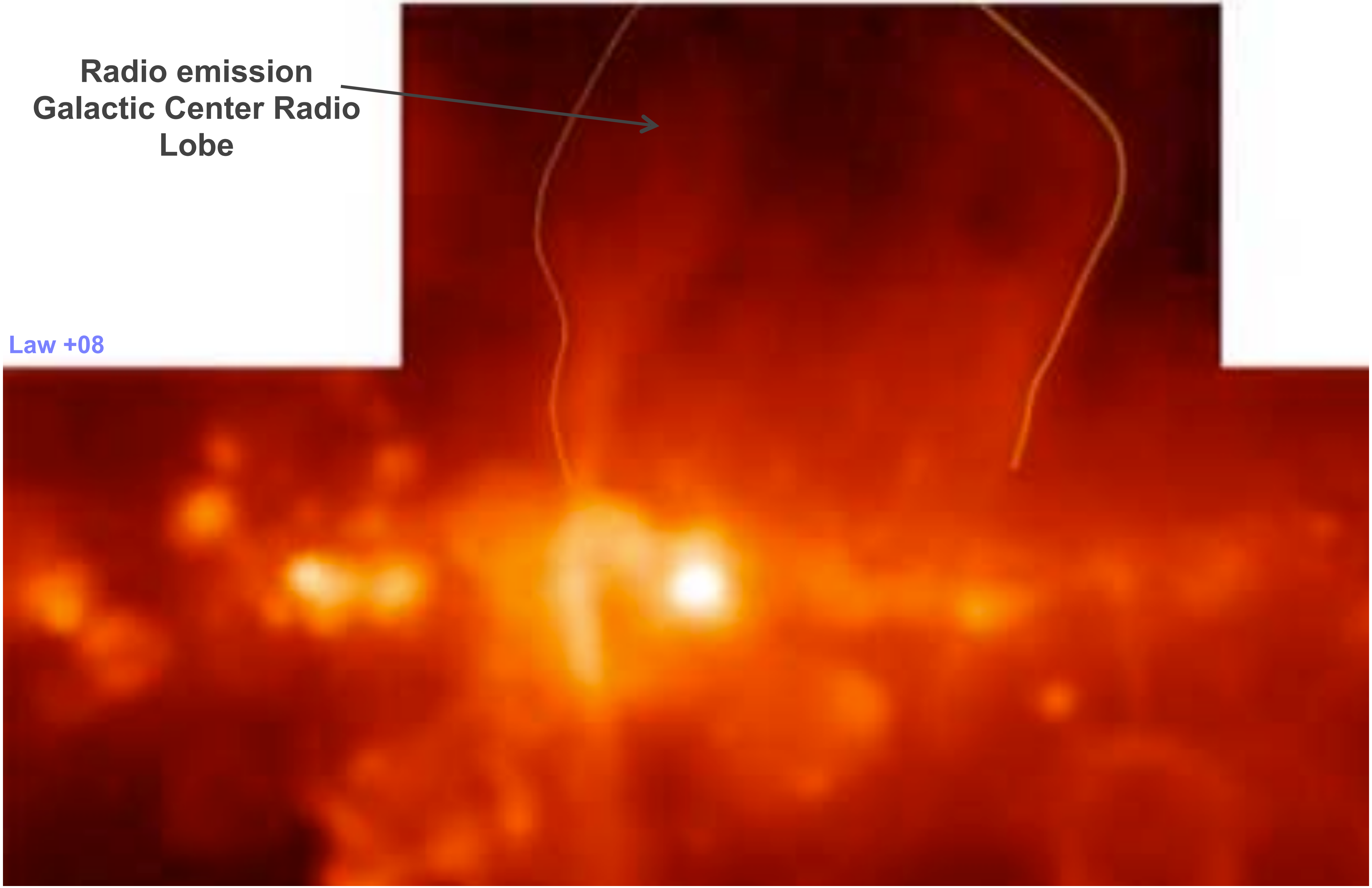
Law +11; Crocker +11; 12; Yoast-Hull +14; Jouvin +15

High latitude soft plasma

Ponti +15

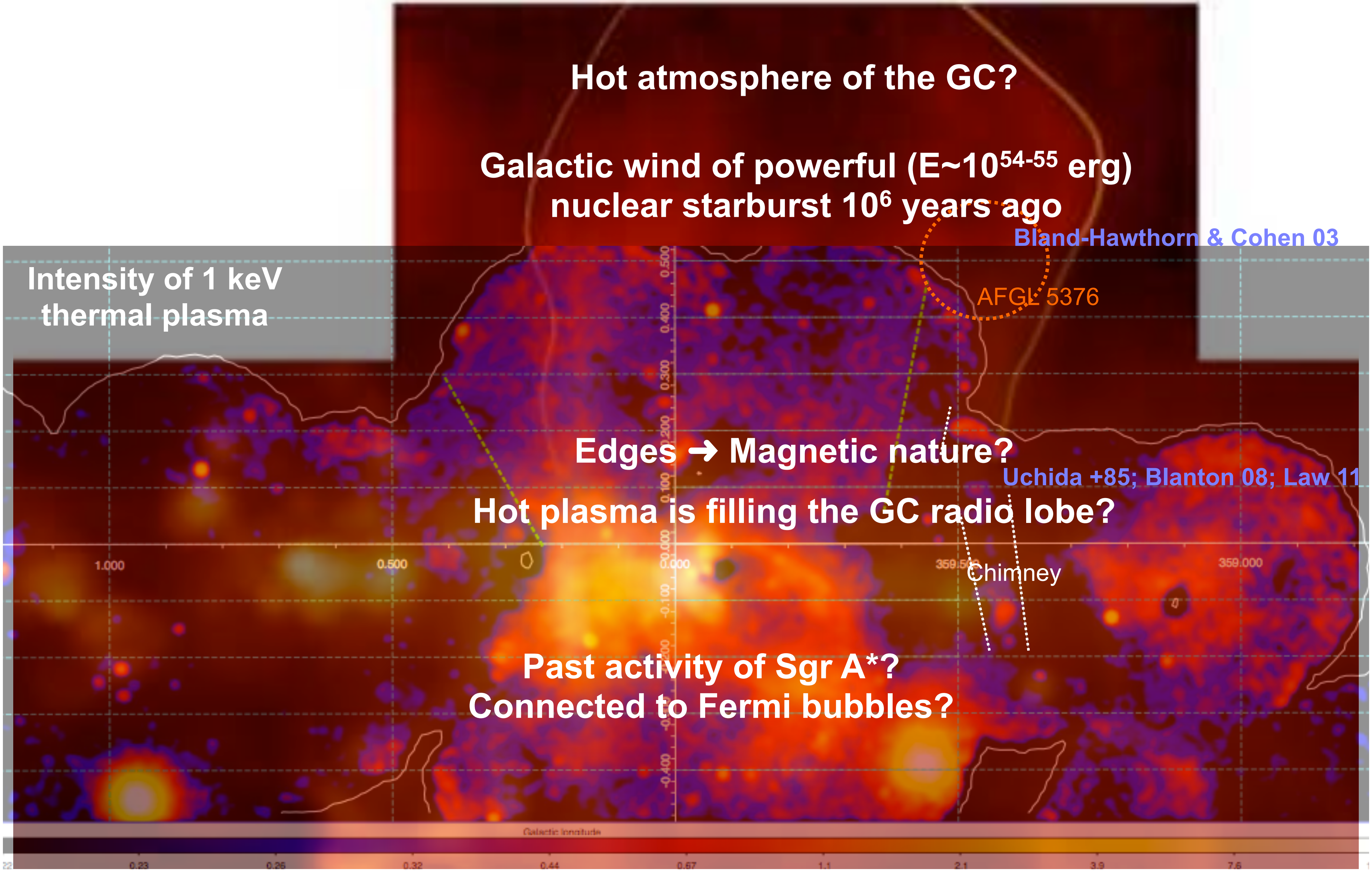


High latitude soft plasma

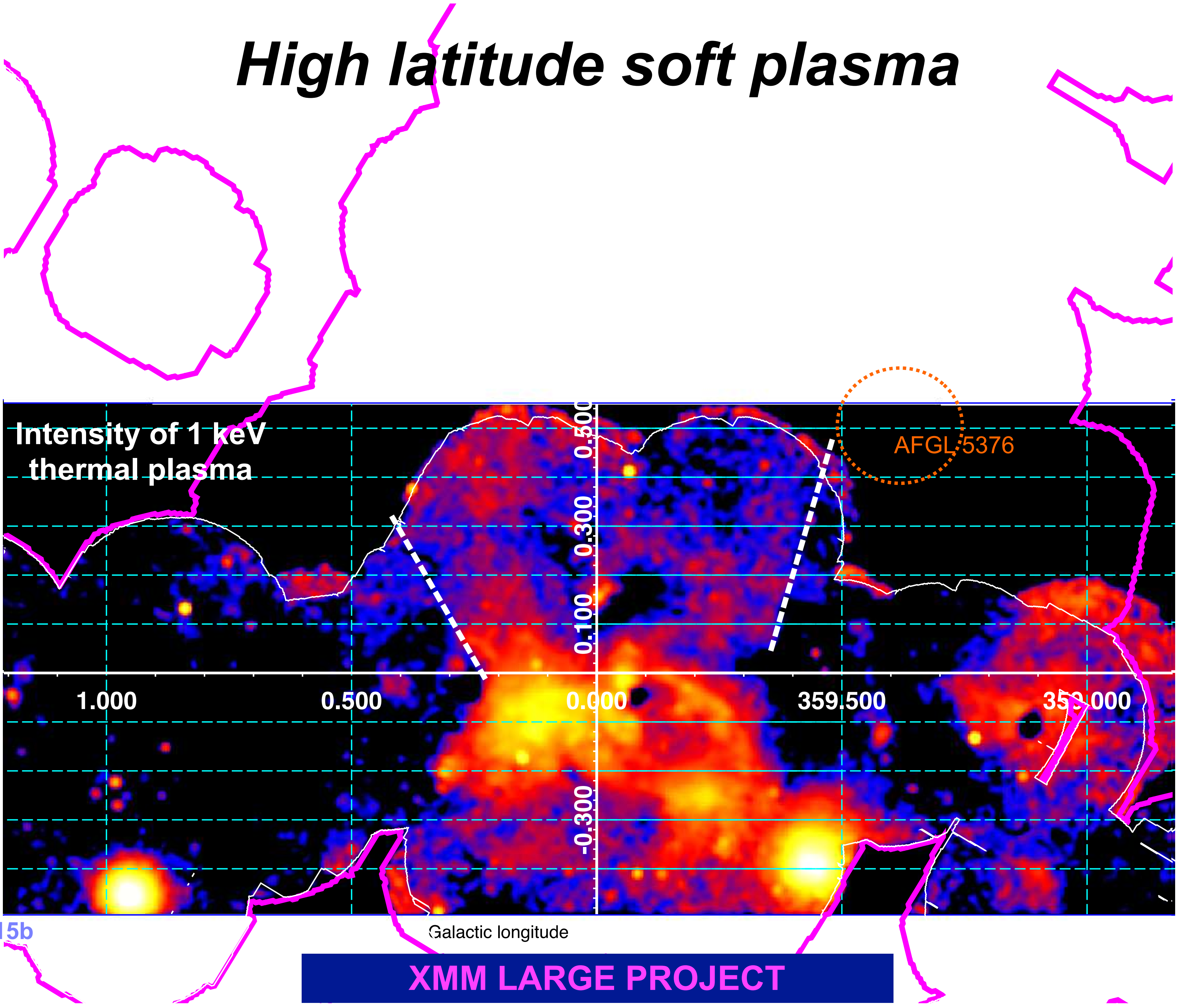


High latitude soft plasma

GC mini-starburst environment ➜ Outflows Crocker +12



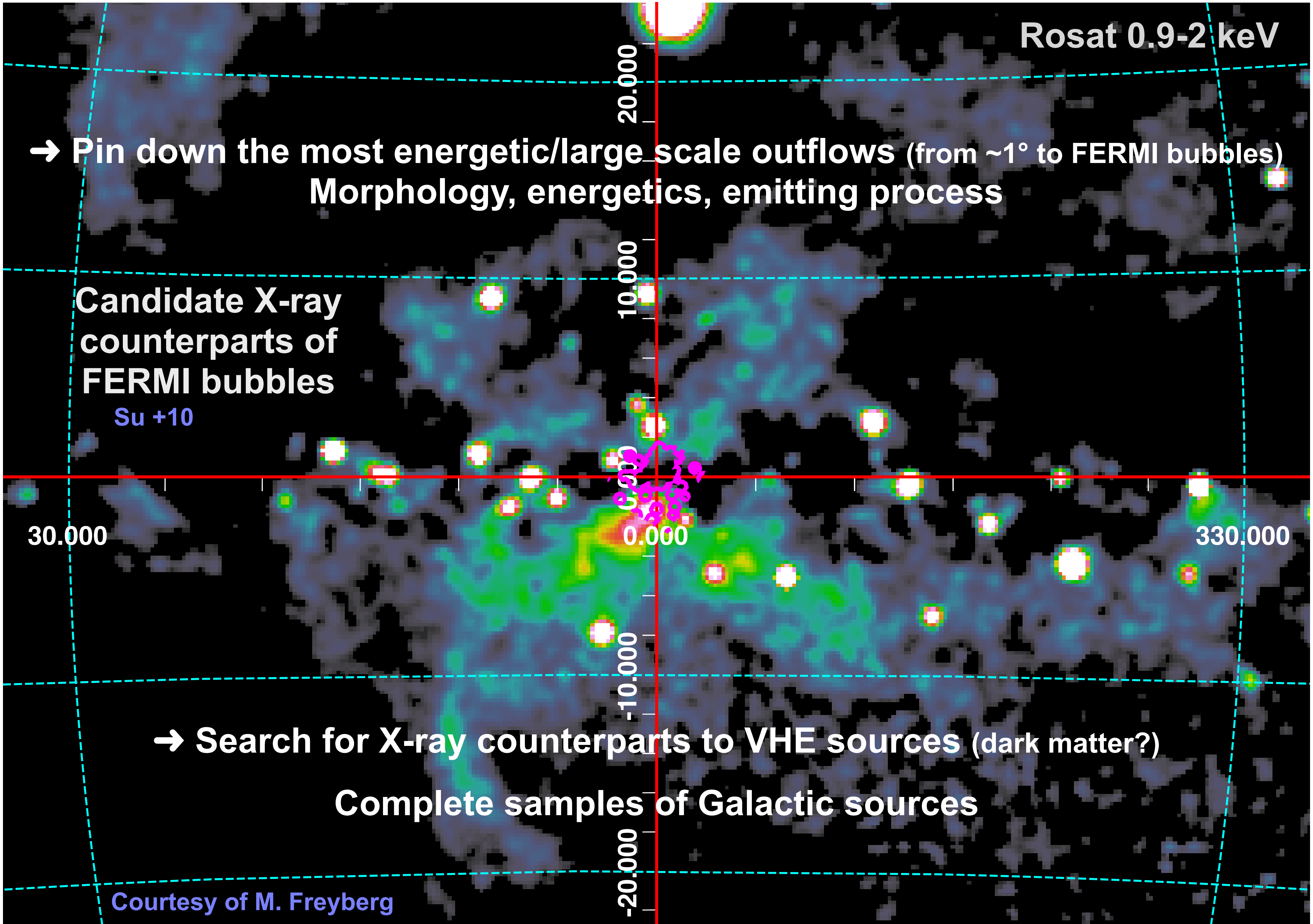
High latitude soft plasma



Ponti +15b

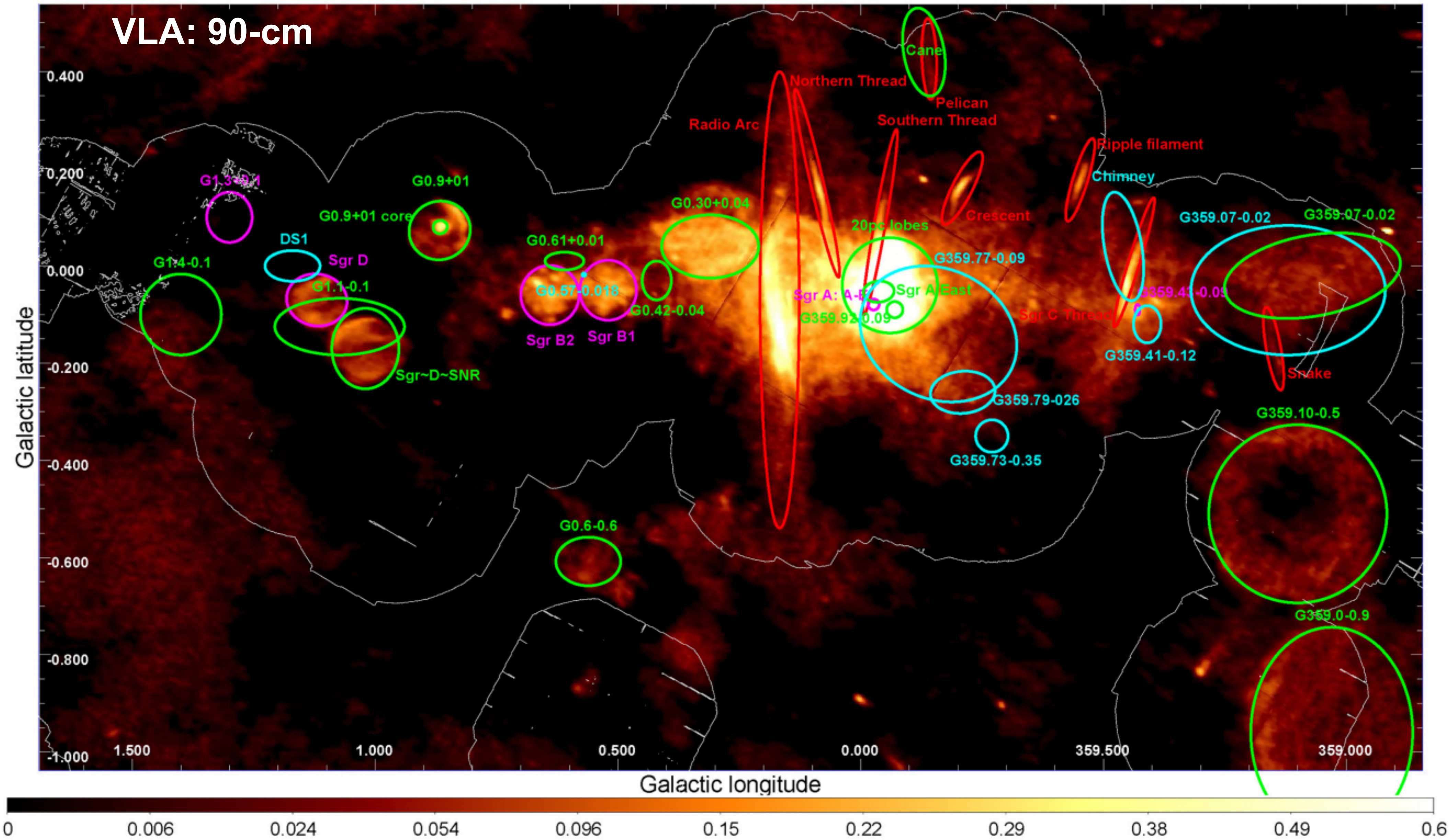
XMM LARGE PROJECT

The future: eROSITA!



Radio arcs and filaments

La Rosa +00



GC region is filled with radio filaments and radio arcs! Morris +90; Ferriere +11

Tracers of accelerated particles, trapped by the intense (1 mG?) GC magnetic field

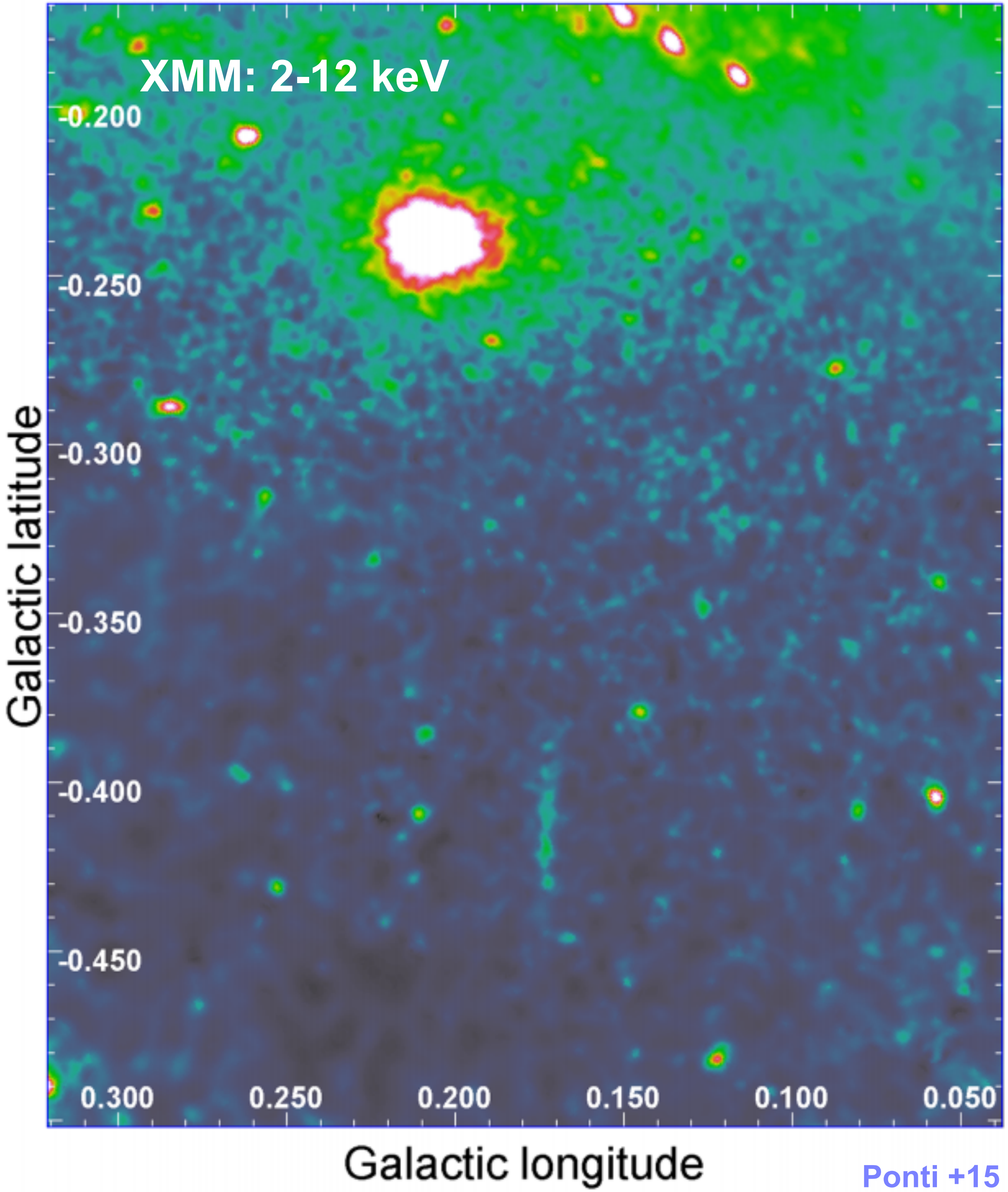
Magnetic field energy 10^{55} erg ➜ more than cloud rotation ➜ staggering!

Poloidal field but toroidal in clouds

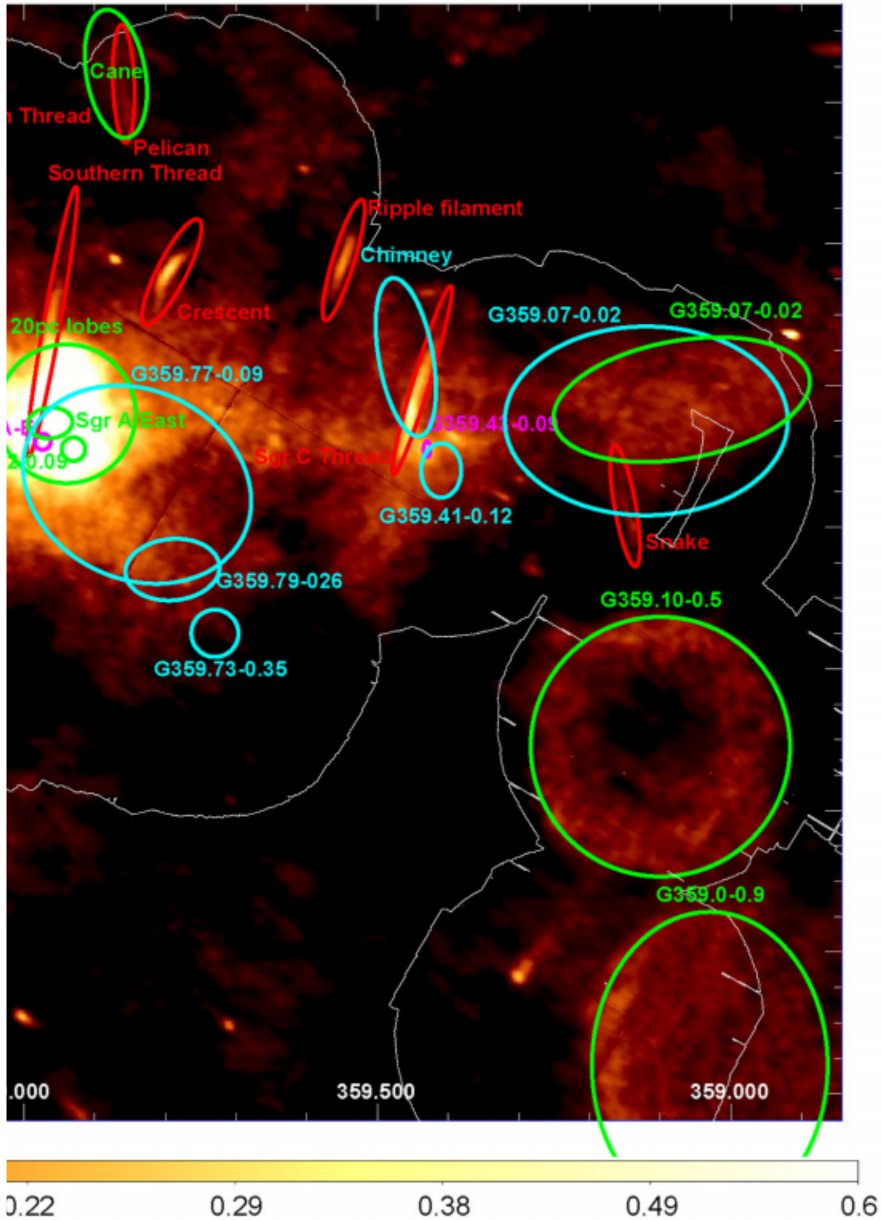
Novak +03; Nishiyama +09

Radio arcs and filaments

La Rosa +00

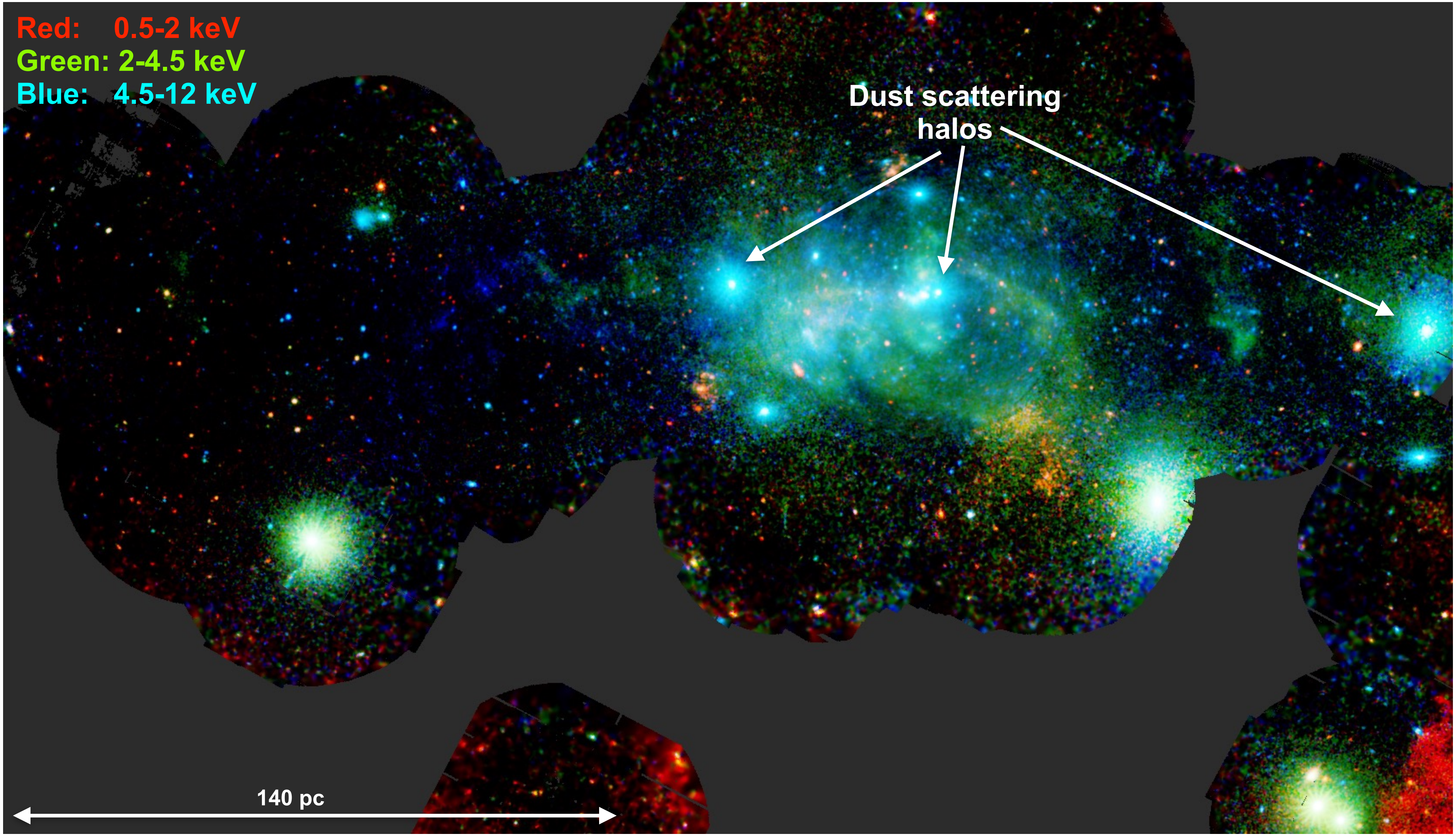


Ponti +15



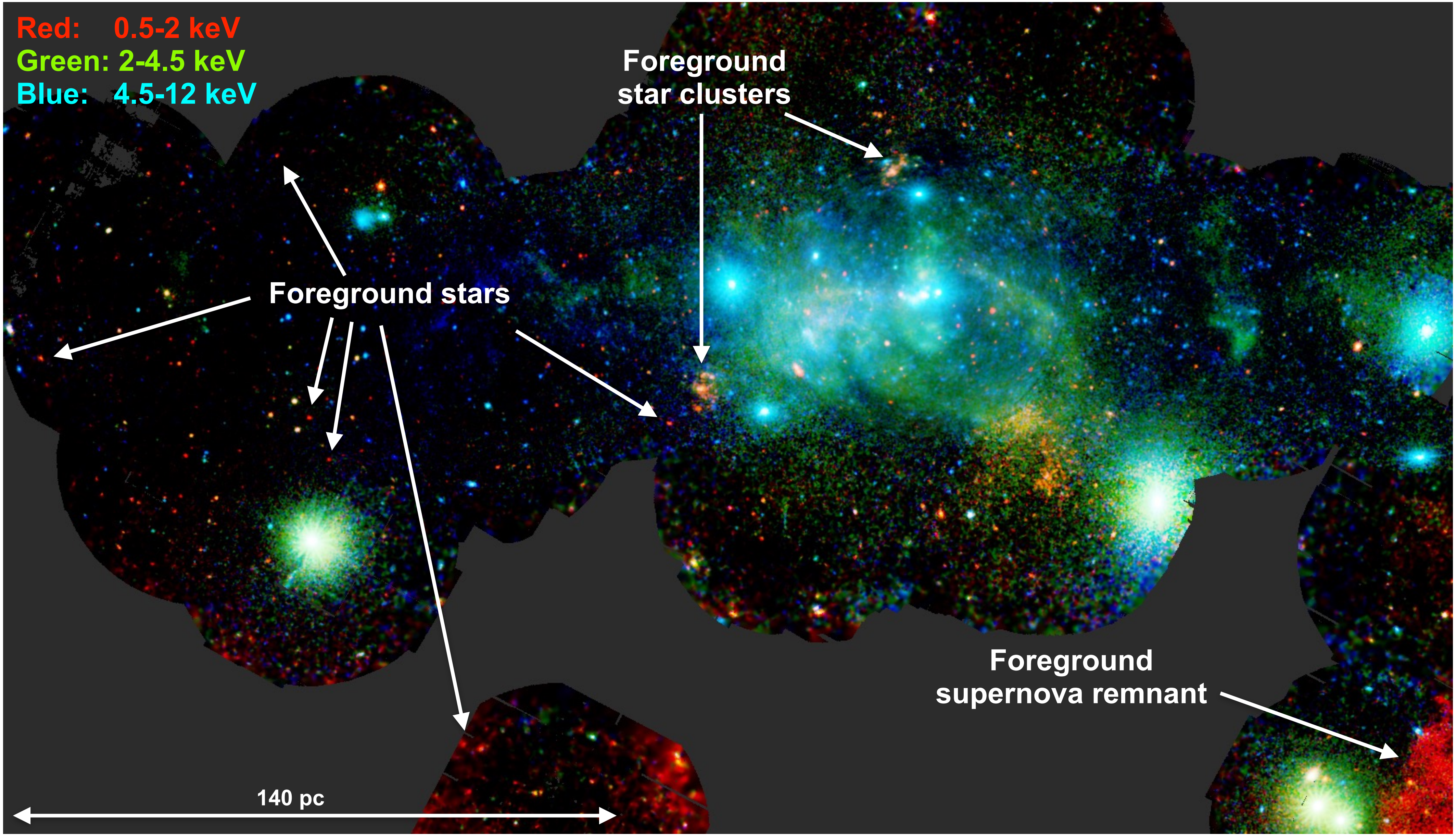
Discovery of X-ray counterpart of a radio filament
Magnetic reconnection?
First time on a linear filament!

Conclusions



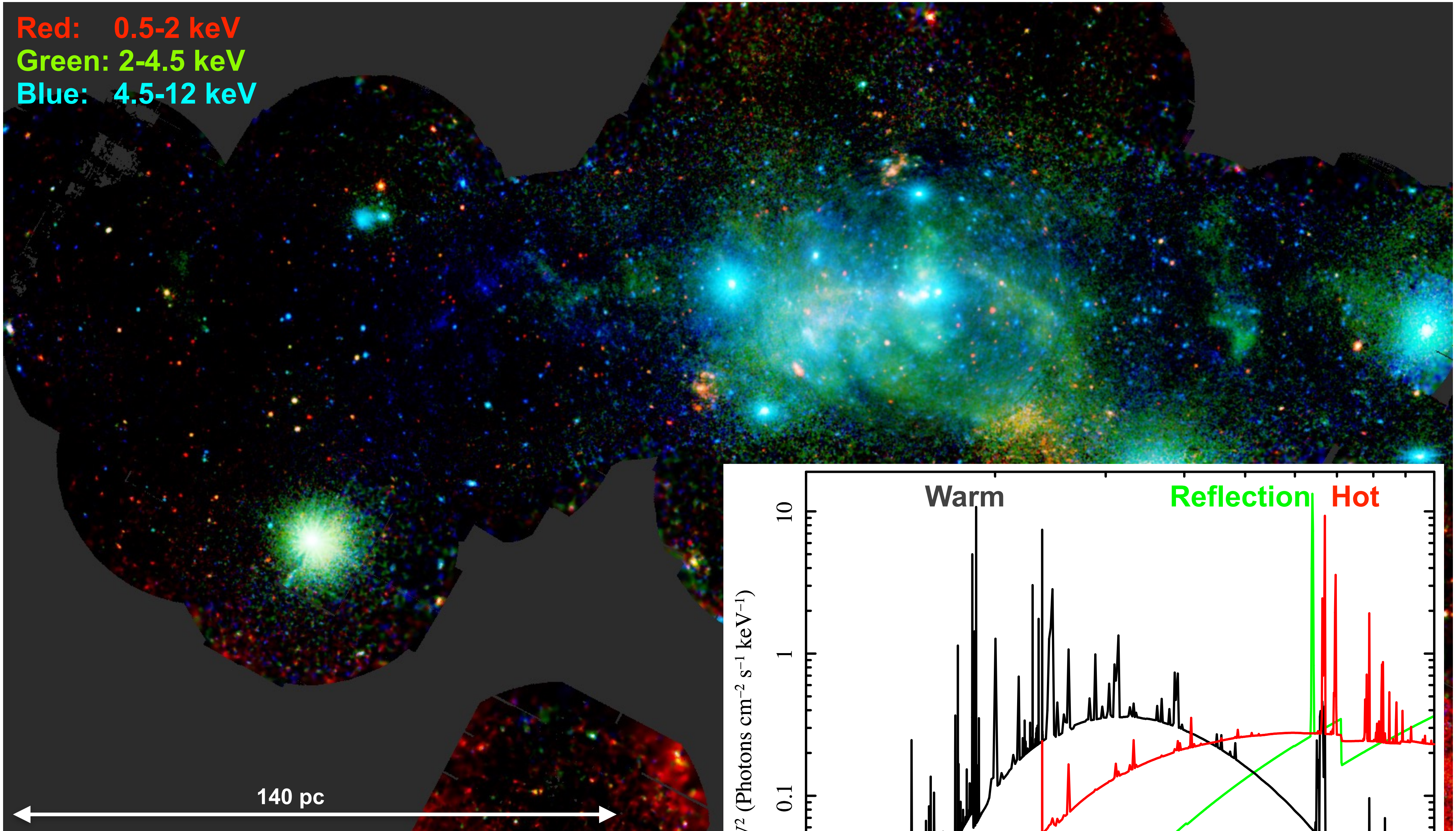
Dust scattering halos

Conclusions



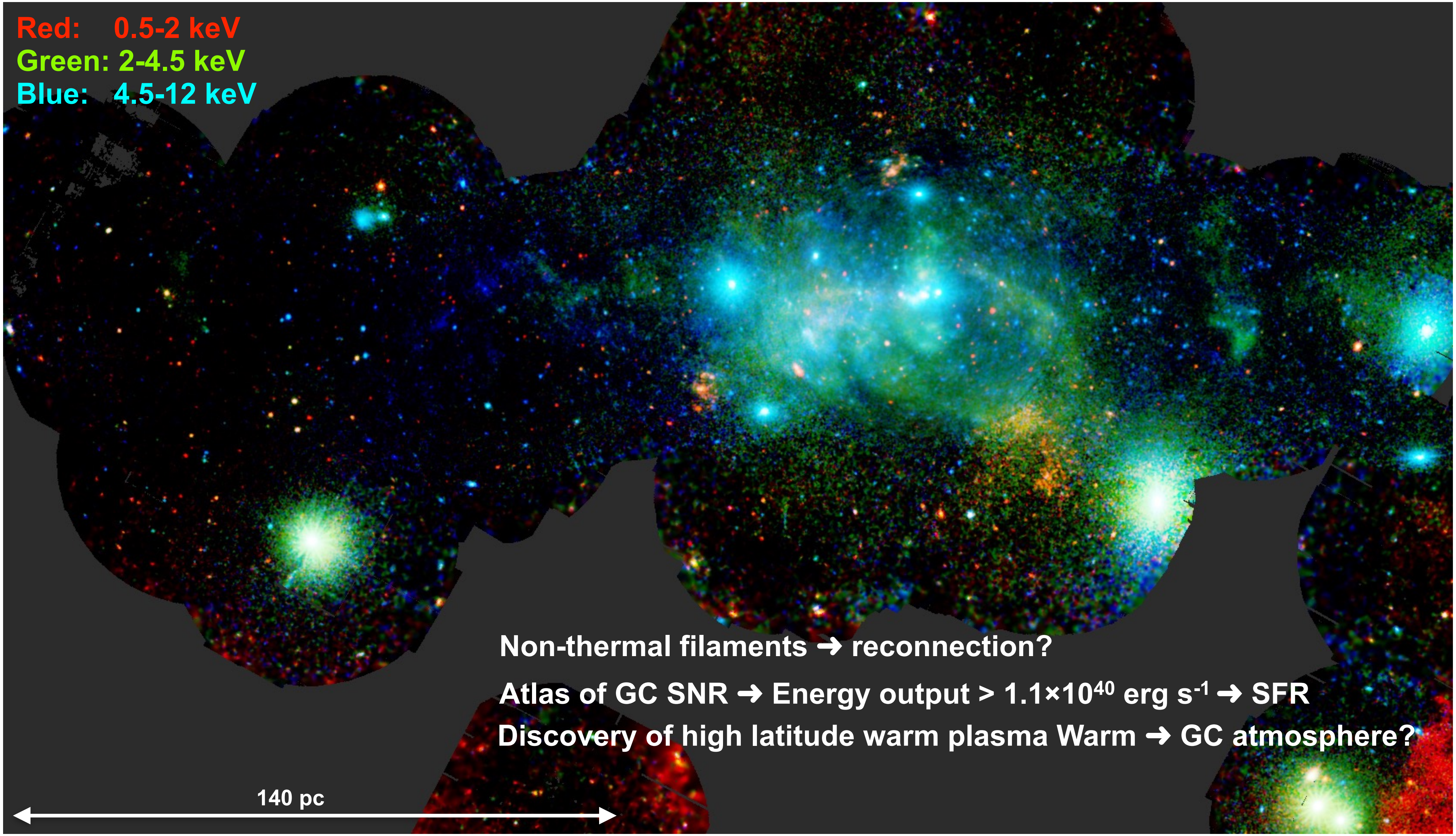
Dust scattering halos
Highly absorbed (N_H~10^{23} cm^{-2})
Soft X-ray foreground star

Conclusions



Dust scattering halos
Highly absorbed ($N_H \sim 10^{23}$ cm^{-2})
Soft X-ray foreground star
Hot component ➔ point sources

Conclusions



Dust scattering halos
Highly absorbed (N_H~10^{23} cm^{-2})
Soft X-ray foreground star
Hot plasma ➜ point sources

SNR interacting with clouds
Sgr A lobes ➜ outflow from central parsec
Superbubble filling the arc bubble ➜ Quintuplet cluster?
Superbubble close to Sgr A* ➜ TDE?