A thin diffuse component of the Galactic Ridge X-ray emission contributed by the radiation of Galactic X-ray binaries

(Molaro et al 2014, A&A, 564, A107)

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X-RAY UNIVERSE CONFERENCE

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Galactic Ridge X-ray emission (GRXE)

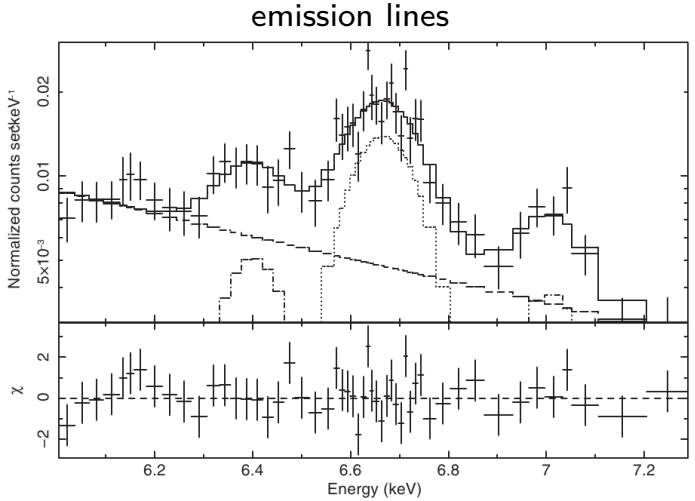
First observed by *Worral et al. 1982*

- Luminosity:

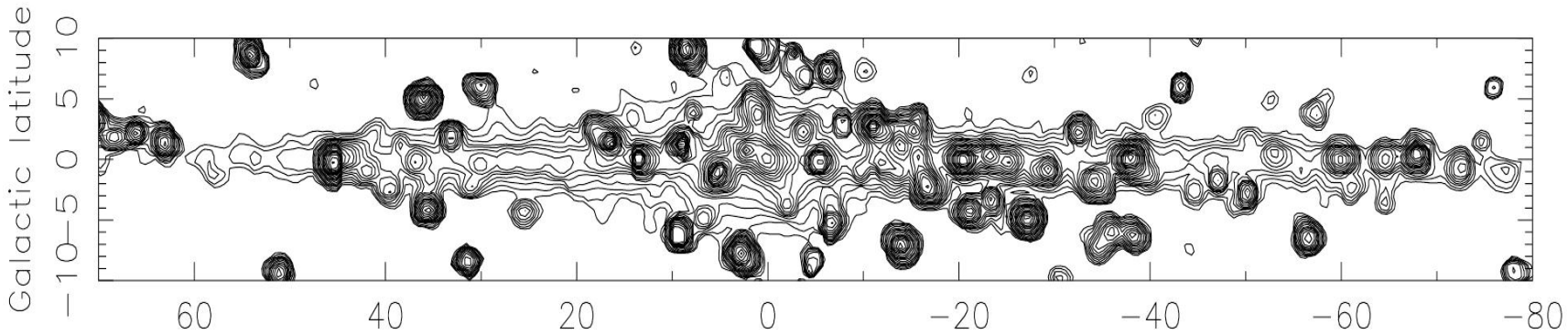
  $\sim 1.4 \times 10^{38}$ erg/s in 3-20keV
  (*Revnivtsev et al 2006*)

  $3.7 \pm 0.2 \times 10^{37}$ erg/s in 17-60keV
  (*Krivonos et al 2007*)
- Spectrum: strong emission lines in 6-7keV range (if thermal $\Rightarrow kT = 5 - 10$ keV)

Ebisawa et al 2008: neutral, He-like and HI-like Fe emission lines



Revnivtsev et al 2006: RXTE/PCA map of the Galactic plane (3-20keV)



Origin of the GRXE

Thermal emission ($\times$)

- Milky Way's potential well too shallow to contain such a hot plasma (*Koyama et al 1986, Sunyaev et al 1993, Tanaka et al 1999*)

Stellar GRXE ($\checkmark$): Low-luminosity Galactic X-ray sources

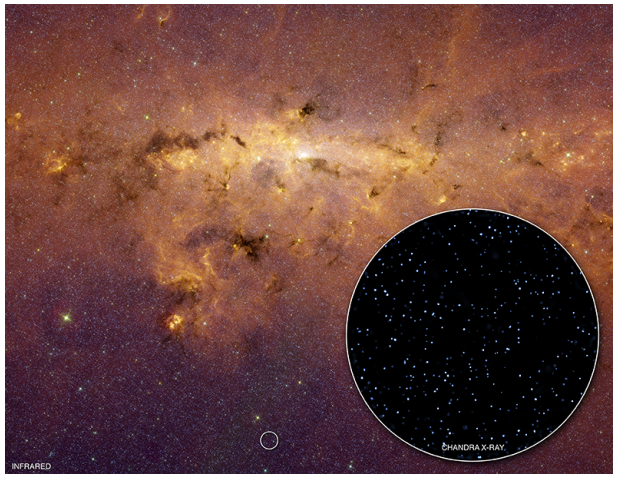
- Spectral analysis
- Direct resolution of low-luminosity sources
- Morphology of emission

Evidence of stellar origin of GRXE

Spectral analysis [*Ebisawa et al 2001,2005; Sazonov et al 2006; Revnivtsev et al 2006; Morihana et al 2013; Warwick et al 2014*]

Direct resolution of low-luminosity sources

- Chandra deep field ($l = 0.08^\circ, b = -1.42^\circ$): $80 - 90\%$ in 6-7keV *Revnivtsev et al 2009* (50% in *Morihana2012* and *Iso et al 2012*)

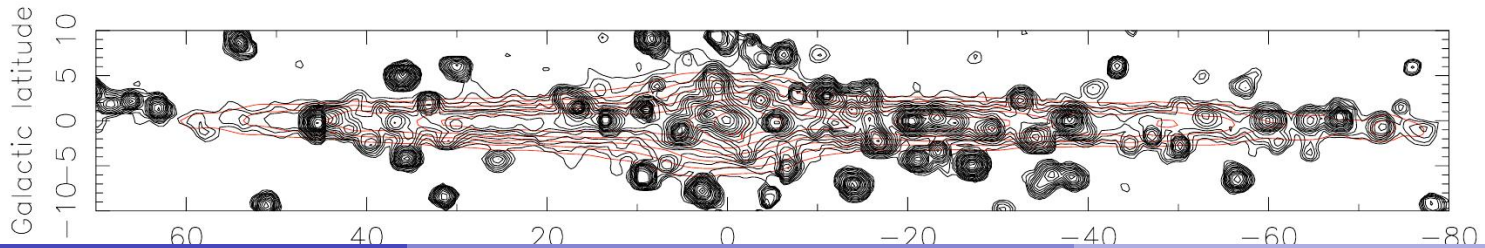


Chandra X-ray observatory: Revnivtsev et al 2009

GRXE morphology and Galactic stellar population

- Stellar bulge/bar & disk models ($z_d \sim 130$pc) (*Revnivtsev et al 2006*)
- Linear relation with Galactic near-infrared emission (*Revnivtsev et al 2006* in 3-20keV, *Krivonos et al 2007* in 17-60keV)

Revnivtsev et al 2006: RXTE/PCA map of the Galactic plane & near-infrared inferred GRXE (3-20keV)



Origin of the GRXE

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Scattered GRXE (?): Scattering of luminous Galactic X-ray binaries by the interstellar medium

Predicted by *Sunyaev et al 1993*

Scattered GRXE

Emissivity/sr due to scattered XBs

$$\epsilon_{\mathrm{XBs}}(l, b, s, \nu) = \sum_Z \sum_i \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(s, \nu) \right)_Z n_Z(s) \frac{L_i(\nu)}{4\pi R_i^2(s)}$$

Scattered GRXE

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- interstellar gas (ISM) distribution

Scattered GRXE

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- interstellar gas (ISM) distribution
- X-ray binary sources (XBs)

Scattered GRXE

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- interstellar gas (ISM) distribution
- X-ray binary sources (XBs)
- bound-electron scattering

Catalog of Galactic XB sources

3-20keV (61 HMXBs,81 LMXBs)

Flux (2-10keV):

- RXTE/ASM (*Grimm et al 2002*)
- 20 NS obj($L_{2-10\text{keV}} \sim 0.5 L_{17-60\text{keV}}$, *Filippova et al 2005*)

Spectrum: $E^{-\alpha}\exp(-E/\beta)$

- LMXBs: $\alpha = 1, \beta = 4.6$ keV (GX 340+0 *Gilfanov et al 2003*)
- HMXBs: $\alpha = 1, \beta = 20$ keV (*Lutovinov et al 2005*)

17-60keV (70 HMXBs,86 LMXBs)

Flux (17-60keV):

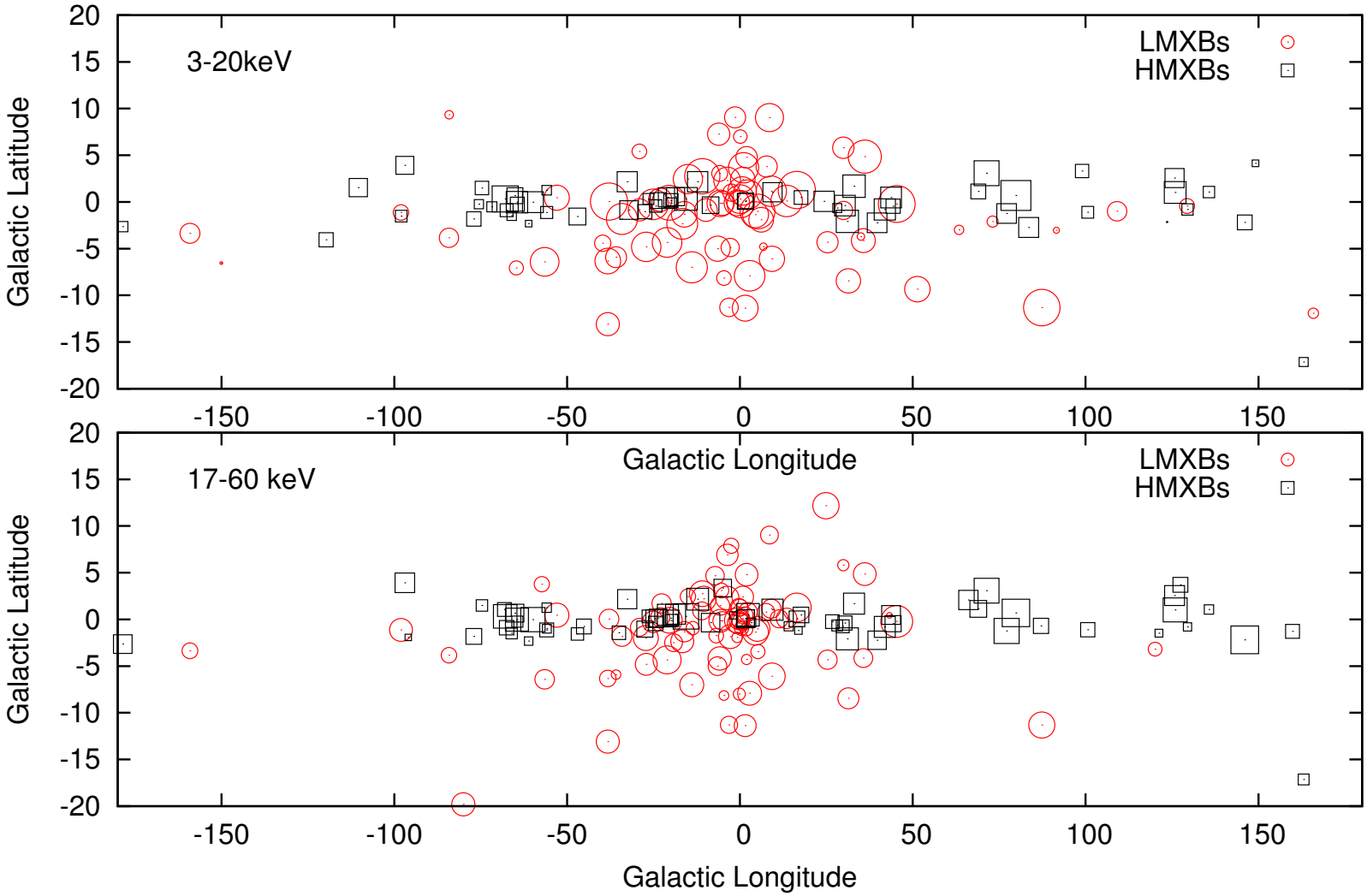
- INTEGRAL/SWIFT (*Krivonos et al 2007, Krivonos et al 2012, Lutovinov 2013*)

Spectrum: $E^{-\alpha}$

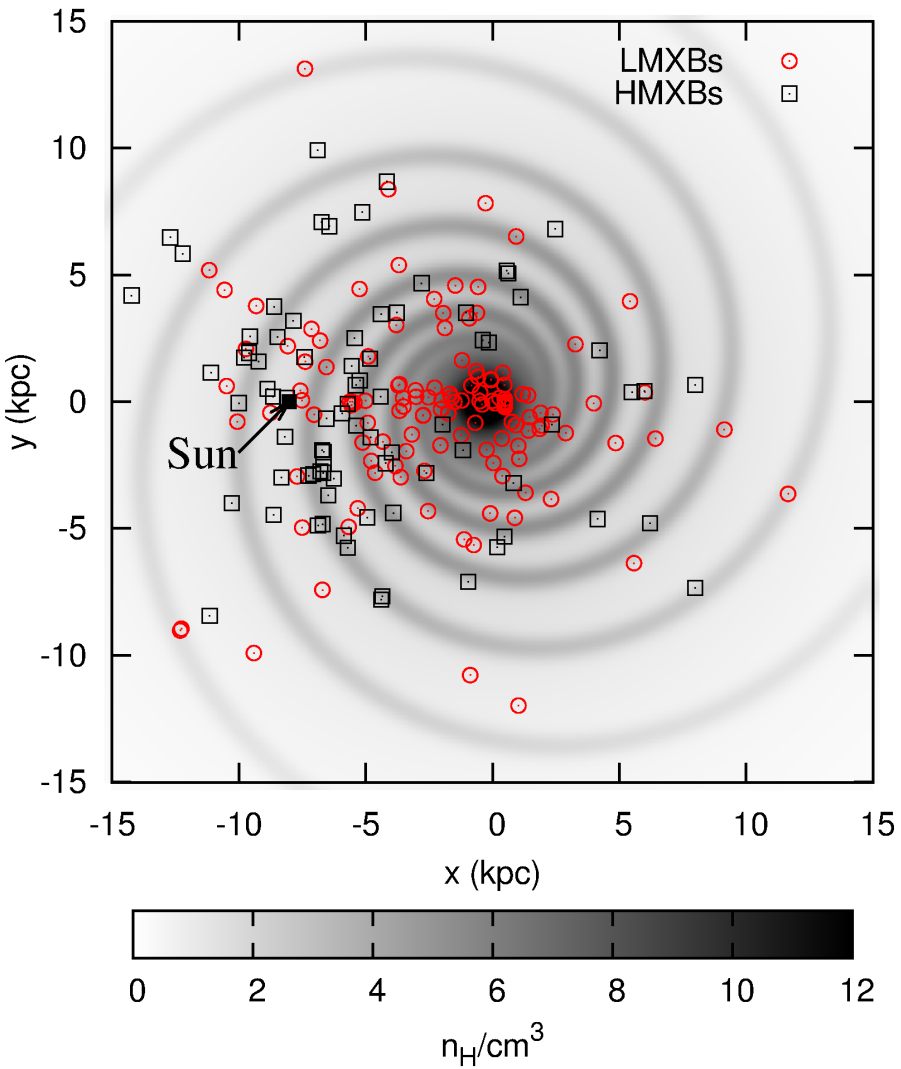
- Indices from *Krivonos et al 2007*

Spatial distribution (distances + (l, b) coords): SIMBAD database

Catalog of Galactic XB sources



ISM distribution



Smooth disk model:

$$\rho_{\rm HI} \propto \frac{1}{2z_d}\exp\left(-\frac{R_m}{R}-\frac{R}{R_d}-\frac{|z|}{z_d}\right)$$

$R_m = 4$kpc, $R_d = 6.4$kpc,
$z_d = 80$pc [*Binney&Tremaine2008*]

$\rho_{\rm H2} \propto \exp(-R/R_{\rm H2} - |z|/z_d)$
$R_{\rm H2} = 2.57$ kpc, $z_d = 80$pc
[Misiriotis et al 2006]

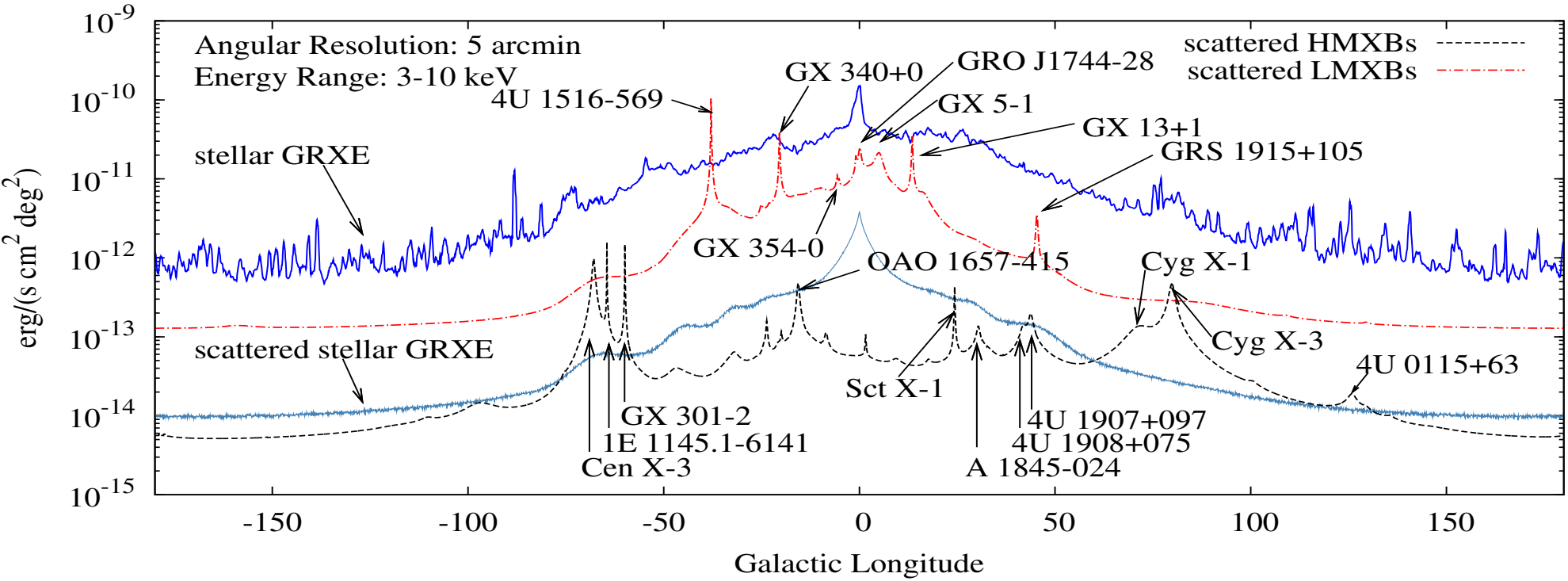
Spiral structure:

4 spiral arms, $p = 12^\circ$ (inward)
[*Vallee 1995, 2008*]
width$= 500$pc & $\times 3$ overdensity

$M_{MW} = 9.5 \times 10^9\ M_\odot$[*Kalberla & Kerp 2009*]
Solar abundances [*Asplund et al 2009*]

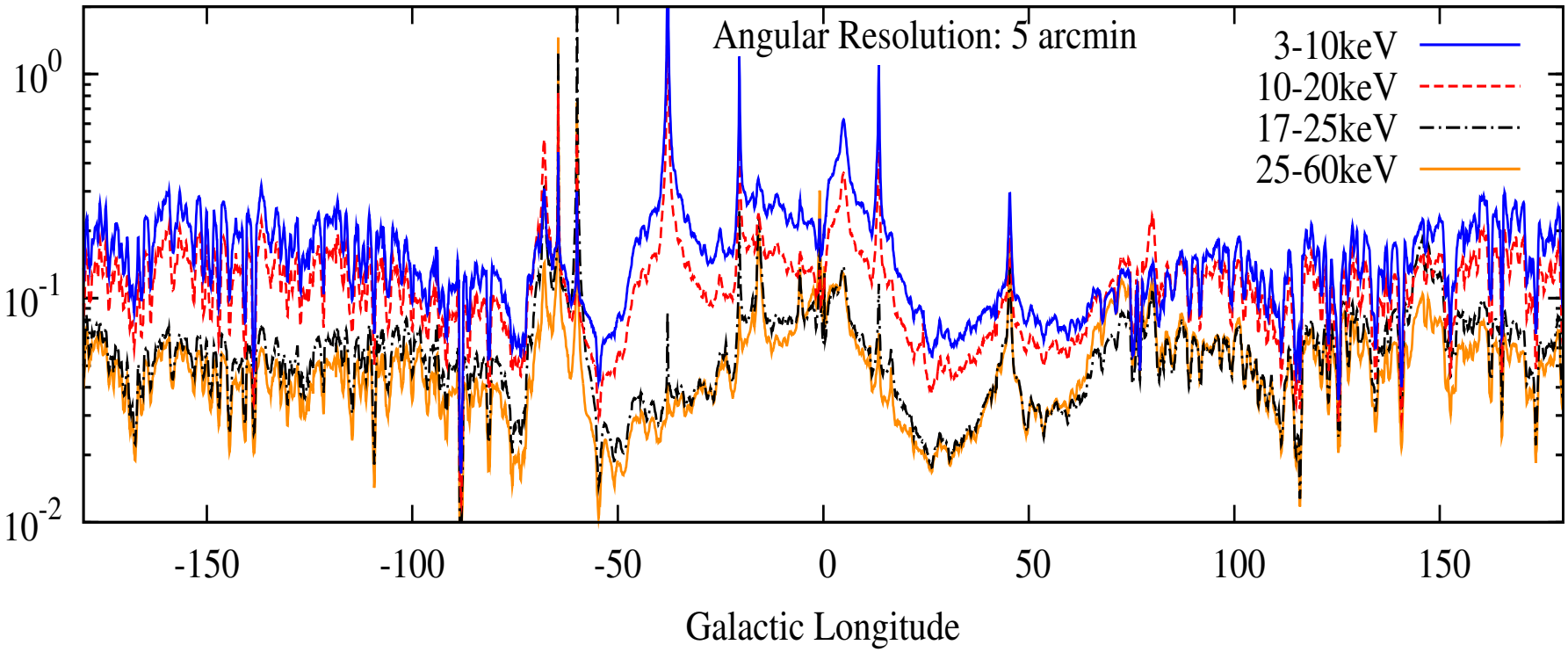
GRXE components on Galactic plane ($b = 0^\circ$)

3-10 keV range:



Note: stellar GRXE is near-infrared inferred (COBE/DIRBE data + linear relations in *Revnivtsev et al 2006, Krivonos et al 2007*)

Ratio of scattered GRXE to stellar GRXE on Galactic plane ($b = 0°$)



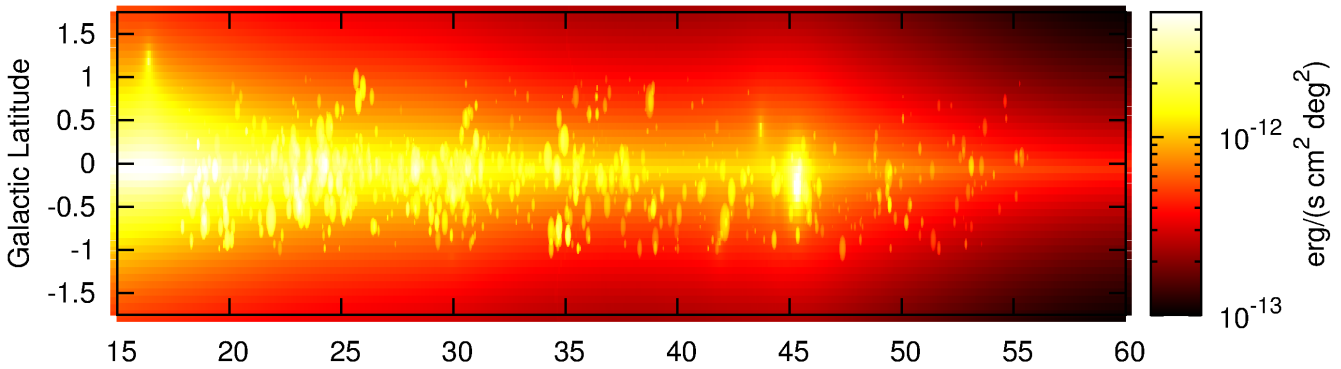
3-20keV: Average scattered GRXE contribution on plane 10-30%

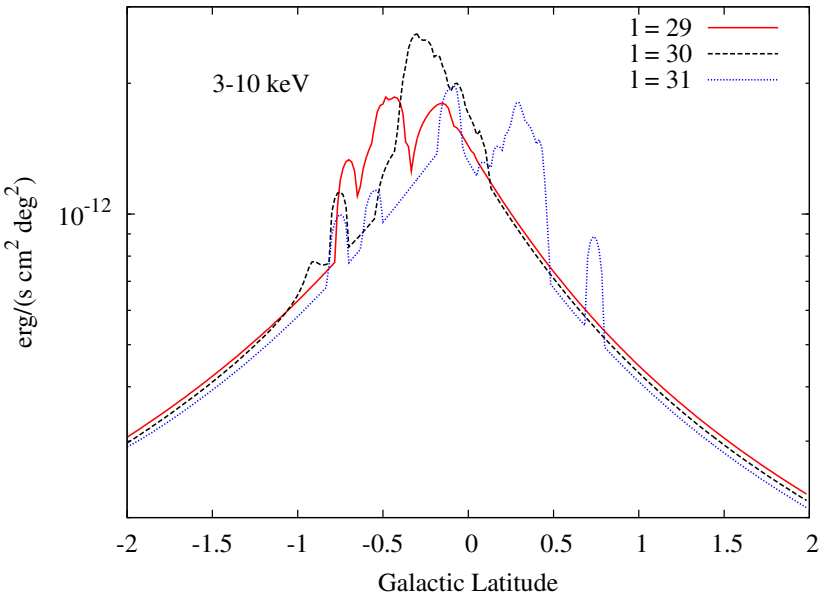
Incompleteness of catalog $\Rightarrow$ lower bound on contribution

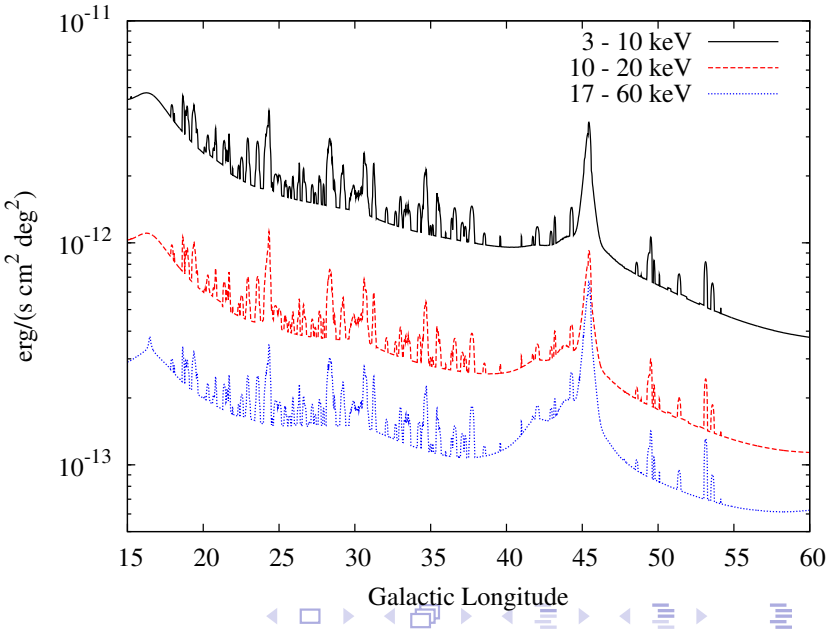
Molecular clouds: prominent narrow spikes in the GRXE

Boston University - Five College Radio Astronomy Observatory Galactic Ring Survey (GRS)

3-10keV







What can we learn about the Galactic XBs population from the scattered GRXE?

Galactic XBs population compared to other galaxies

Relation between XBs luminosity and galactic properties:

$$L_{XBs}^{2-10\mathrm{keV}} \sim \underbrace{\alpha \times M_\star}_{\text{low-mass XBs}} + \underbrace{\beta \times SFR}_{\text{high-mass XBs}}$$

Milky Way[(1)]:

$\alpha \sim 4 \times 10^{28}$ erg s^{-1} $M_\odot{}^{-1}$

$\beta \sim 2.5 \times 10^{38}$ erg s^{-1} $M_\odot{}^{-1}$ yr

Other galaxies[(2)]:

$\alpha \sim 8 \times 10^{28}$ erg s^{-1} $M_\odot{}^{-1}$

$\beta \sim 2.2 - 2.6 \times 10^{39}$ erg s^{-1} $M_\odot{}^{-1}$ yr

(1) *luminosities from Grimm et al 2002* (2) *Grimm+2003, Ranalli+2003, Gilfanov 2004, Colbert+2004, Persic & Rephaeli 2007, Lehmer+2010, Mineo+2012, Mineo+2014*

Is the Milky Way underluminous in 2-10keV range?

Reasons for discrepancy:

- *SFR*: $10^6 - 10^7$ yrs delay *[Gilfanov+2004, Shtykovskiy & Gilfanov 2007]*
- Temporal fluctuations (brighter X-ray past?) *[Gilfanov+2004, Mineo+2014]*

Simulate XBs catalog to test brighter X-ray past case

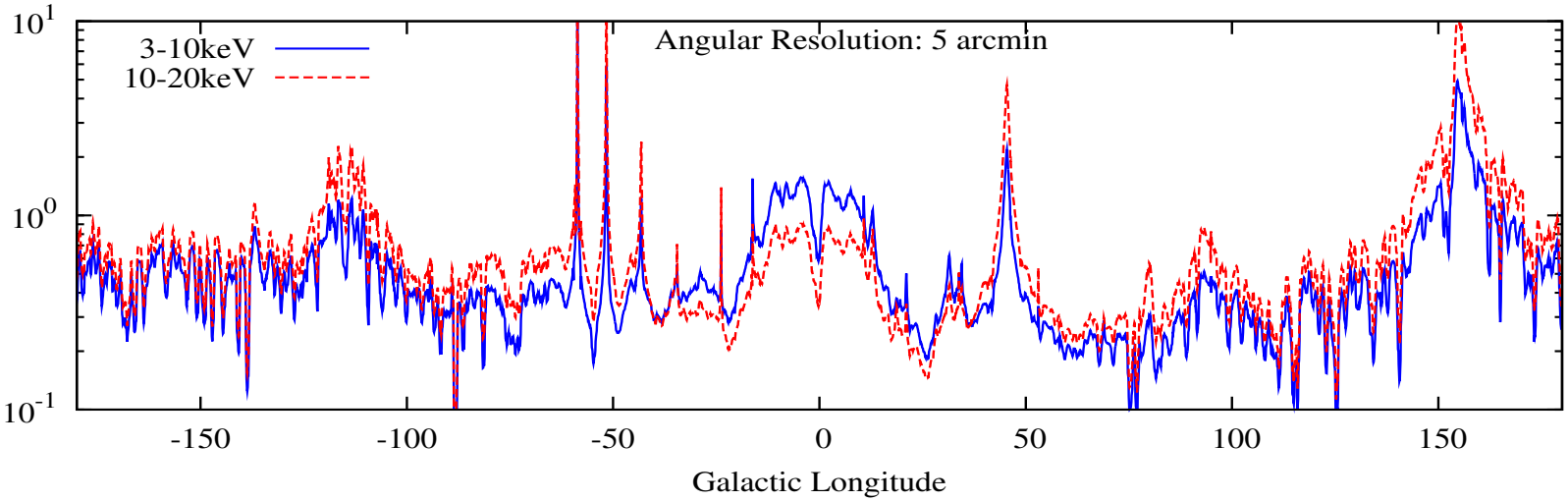
Assume:

- $M_\star = 6 \times 10^{10} M_\odot$ [*McMillan 2011*]
- $SFR \sim 1 M_\odot/yr$ [*Robitaille & Whitney 2010*]

Monte Carlo sampling:

- density pdfs (LMXBs $\propto M_\star$, HMXBs $\propto ISM$)
- luminosity functions (LMXBs: *Gilfanov 2004*, HMXBs: *Grimm et al 2003*)

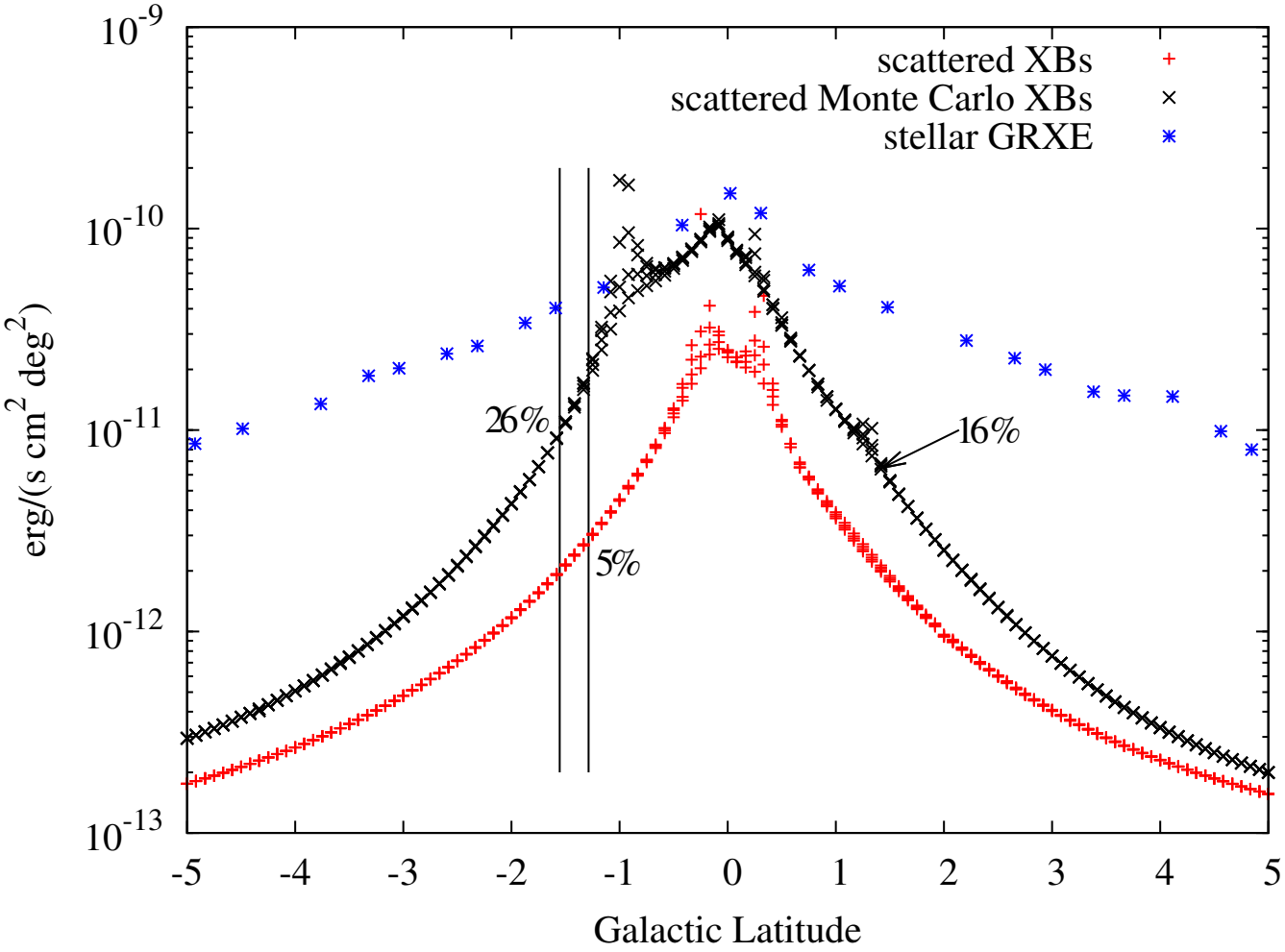
Ratio of scattered GRXE to stellar GRXE on Galactic plane ($b = 0°$):



3-20keV: over 50%, can even dominate stellar emission

Inconsistency with resolution of sources?

Compare with *Revnivtsev et al 2009* FoV ($l = 0.08°, b = -1.42°$) in 3-10keV (80-90% emission resolved in 6-7keV band)



Brighter X-ray past allowed by observations!

Conclusions

Scattered GRXE:

- Truly diffuse component of GRXE (lower bound on contribution: 10-30% of total GRXE in 3-20keV on Galactic plane)
- Thin (scale height $z_d \sim 80$ pc vs $z_d \sim 130$ pc of stellar GRXE)

  i) Morphology follows ISM distribution

  ii) Molecular clouds show up as prominent features in profiles and maps

Comparison between scattered GRXE and stellar GRXE:

- Can help constrain the average X-ray luminosity of the Galaxy over the past 10,000-30,000 years.
- Current GRXE observations consistent with a brighter X-ray past in Milky Way

Galactic 2-10keV luminosity due to XBs

		LMXBs	**HMXBs**
MW	Expected[(1)]	2-3 $\times 10^{39}$ erg/s	2-3 $\times 10^{38}$ erg/s
	Sources catalog	2.56 $\times 10^{39}$ erg/s	5.5×10^{37} erg/s
Simulated MW	Expected[(2)]	5 $\times 10^{39}$ erg/s	2-3 $\times 10^{39}$ erg/s
	Simulated sources	4.7 $\times 10^{39}$ erg/s	1.7×10^{39} erg/s

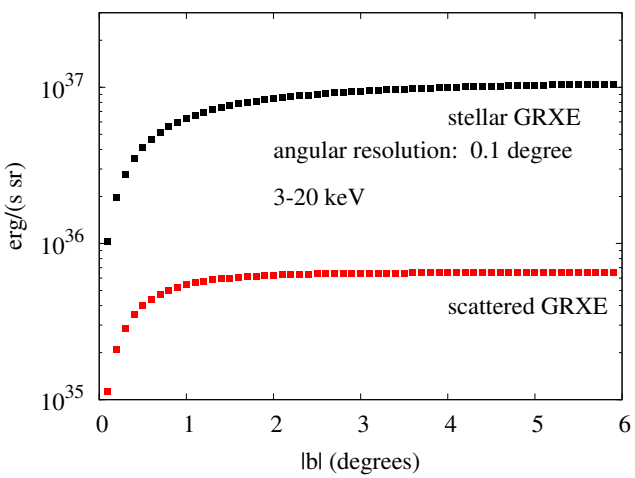
(1) *Grimm et al 2002*

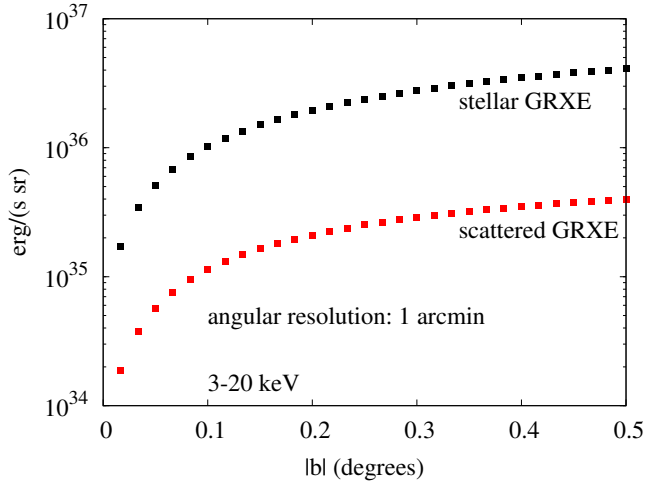
(2) $M_\star = 6 \times 10^{10}\ M_\odot$[*McMillan 2011*]

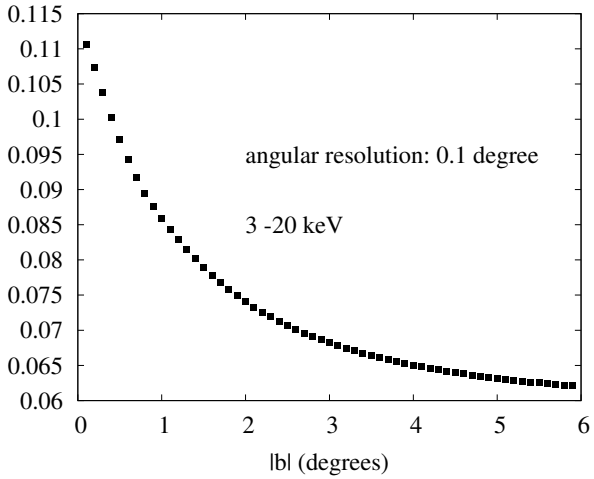
SFR $= \sim 1\ M_\odot$/yr [*Robitaille & Whitney 2010*]

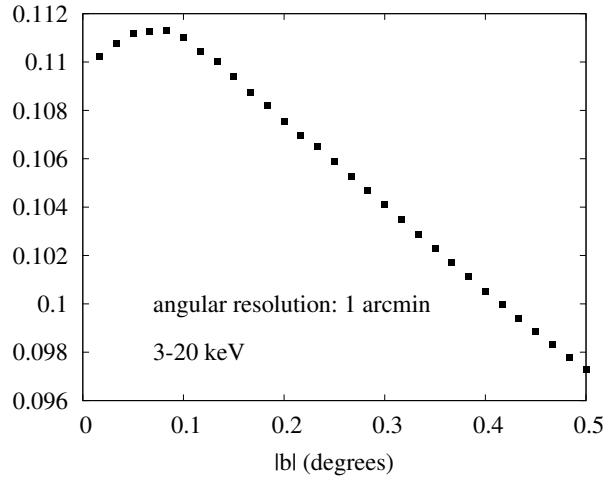
Luminosity/sr profiles

$$L_{\rm GRXE,stellar} = \frac{1}{4\pi}\iiint f(\nu)\rho_{\rm GRXE}(x,y,z)s^2 {\rm d}\nu {\rm d}s{\rm d}\Omega$$
$$L_{\rm GRXE,scatt} = \iint [\epsilon_{\rm XBs}(s,\nu) + \epsilon_{\rm stellar}(s,\nu)]s^2 {\rm d}\nu {\rm d}s{\rm d}\Omega$$



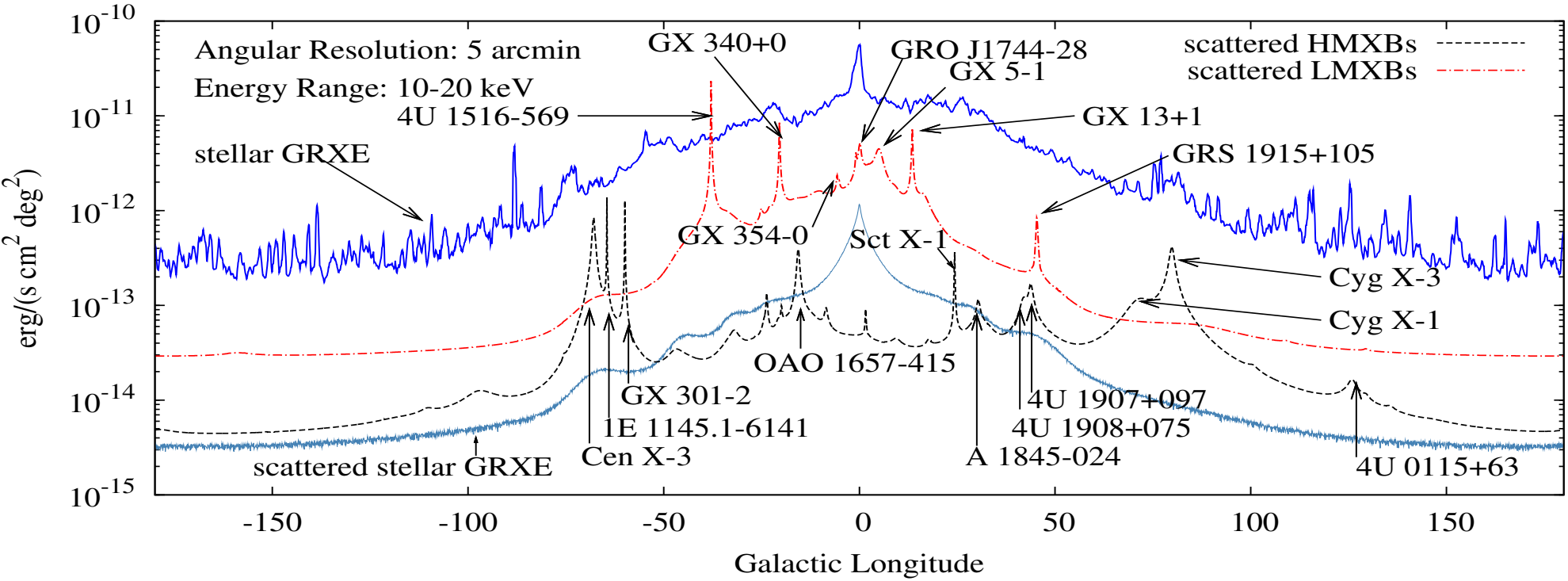






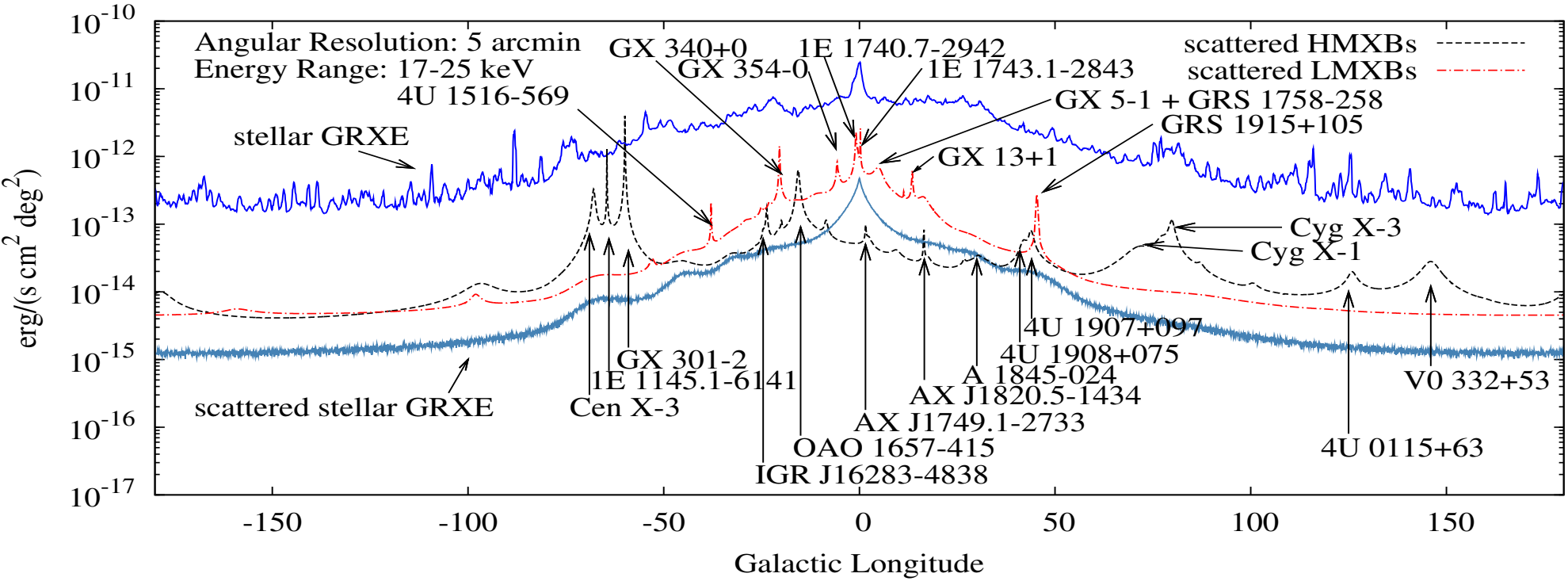
Scattered GRXE: sources catalog (10-20keV)

Longitude profiles on Galactic plane



Scattered GRXE: sources catalog (17-25keV)

Longitude profiles on Galactic plane



Scattered GRXE: sources catalog (25-60keV)

Longitude profiles on Galactic plane