Introduction

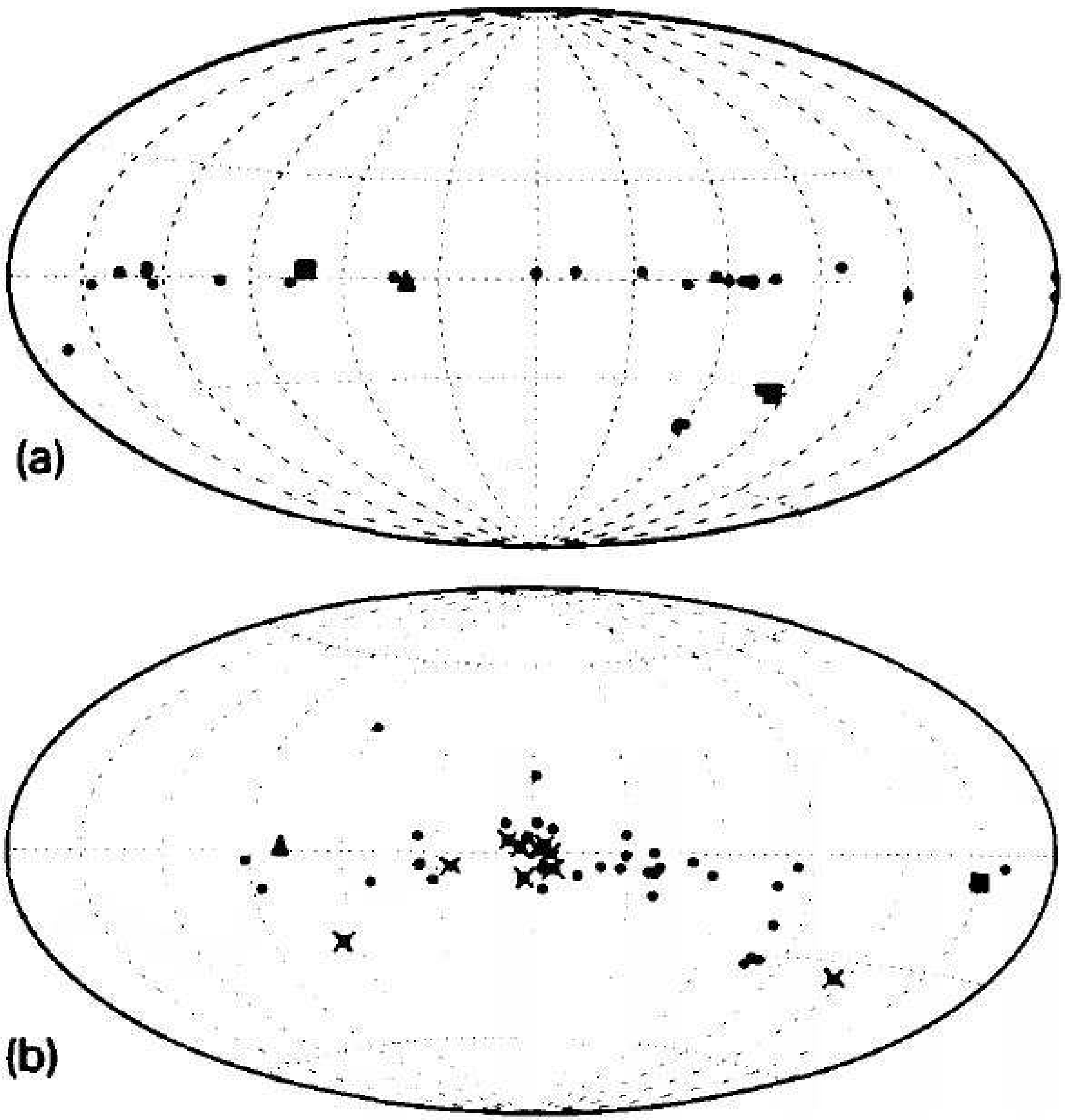
Up to now we have looked at X-ray Binaries as individual sources

Now: properties of X-ray binaries as a class of objects: statistics, general properties.

$\Longrightarrow$ Input to evolution models: *where do XRB come from?*

1. XRB Distribution in our Galaxy
2. XRB Evolution Models
3. Testing evolution withXRBs in other Galaxies

XRB in our Galaxy



Distribution of HMXB (top) and LMXB (bottom) in Galactic coordinates

$\Longrightarrow$ HMXB are disk population

(Bhattacharya & van den Heuvel, 1991, Fig. 12)

Reminder: Stellar Evolution, I

Stellar evolution governed by three timescales:

1. dynamical timescale (pulsational timescale):

$$\tau_{\text{dyn}} = 50 \left(\frac{\rho}{\rho_\odot}\right)^{-1/2} \tag{8.1}$$

where $\rho_\odot = 1.4\,\text{g}\,\text{cm}^{-3}$ and where ρ mean density of star.

2. Thermal timescale (Kelvin-Helmholtz timescale):

reaction of star to disturbances in thermal content; defined as timescale to radiate thermal energy of star (which is $\sim$ stellar binding energy)

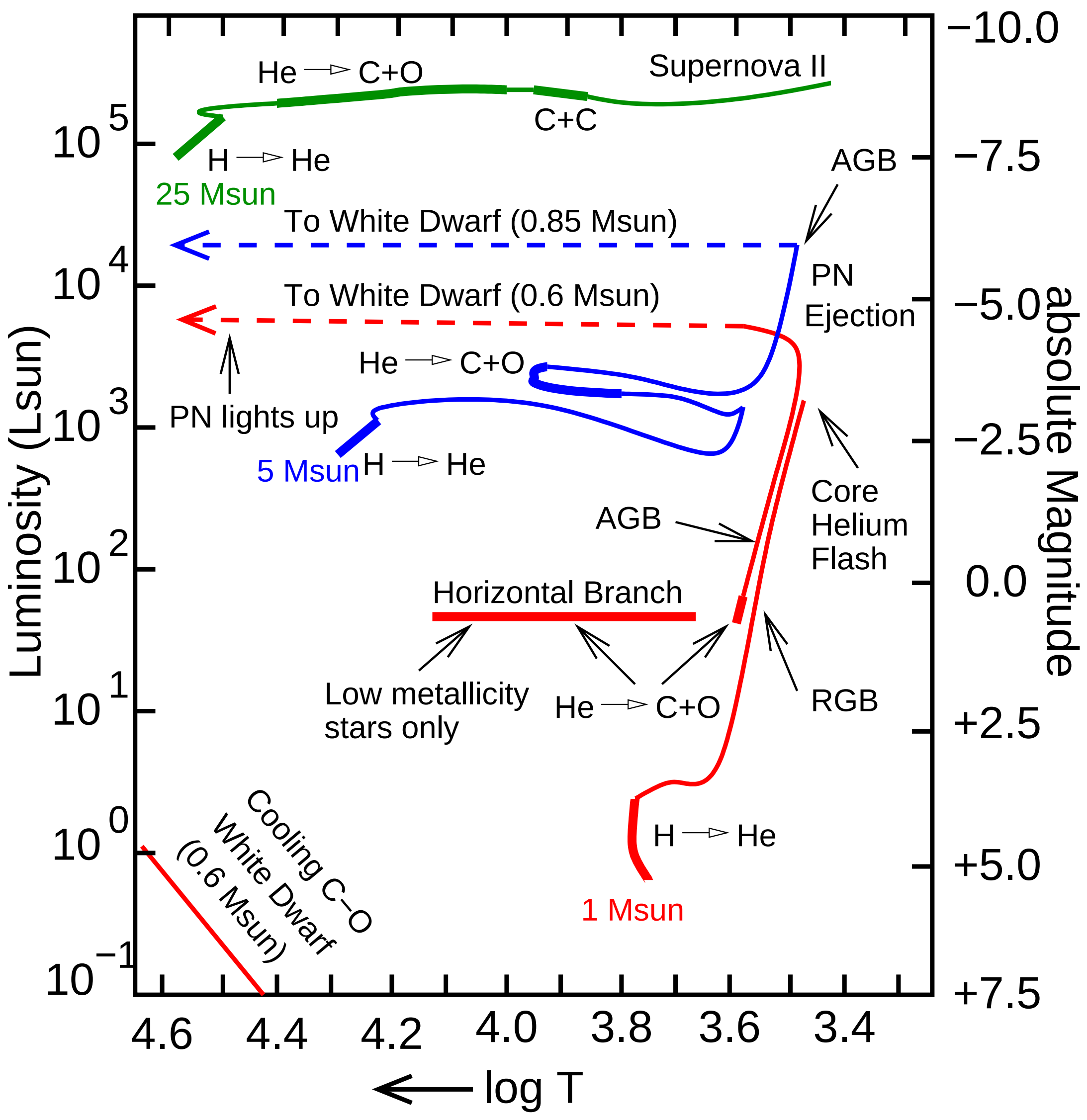
$$\tau_{\text{th}} = \frac{GM^2}{RL} = 5 \times 10^7\,\text{yr} \cdot \left(\frac{M}{M_\odot}\right)^{-2} \tag{8.2}$$

since for $M > 1\,M_\odot$: $L \propto M^{3.5}$ and $R \propto M^{1/2}$

3. Nuclear timescale: time needed to exhaust nuclear fuel at current luminosity L

$$\tau_{\text{nuc}} = 10^{10}\,\text{yr} \cdot \frac{M/L}{M_\odot/L_\odot} = 10^{10}\,\text{yr} \cdot \left(\frac{M}{M_\odot}\right)^{-2.5} \tag{8.3}$$

Reminder: Stellar Evolution, II



after Iben, 1991

Evolution of stars in the HRD from main sequence to death

Typical timescales (units of 10^6 yr; Schaller et al. 1992):

	$1\,M_\odot$	$5\,M_\odot$	$25\,M_\odot$
H→He	10000	94	6.4
He→C		12	0.6
C+C			0.01
PN	$\lesssim 0.01$	$\lesssim 0.01$	N/A
WD	∞	∞	N/A

Post-H-burning burning: need higher core temperatures (Coulomb barrier!), less energy release $\Longrightarrow$ last much shorter than hydrogen burning.

Reminder: Stellar Evolution, III

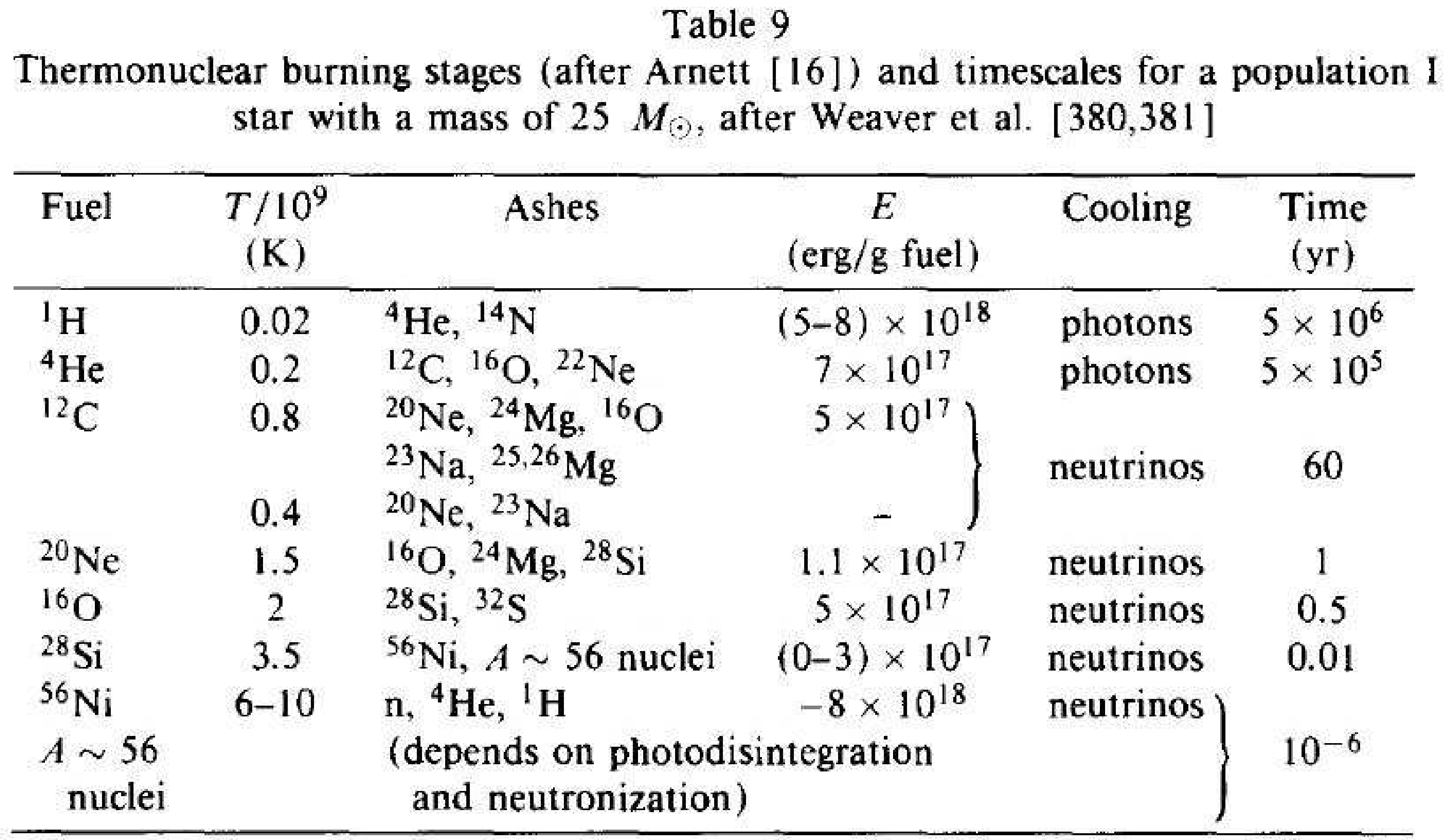


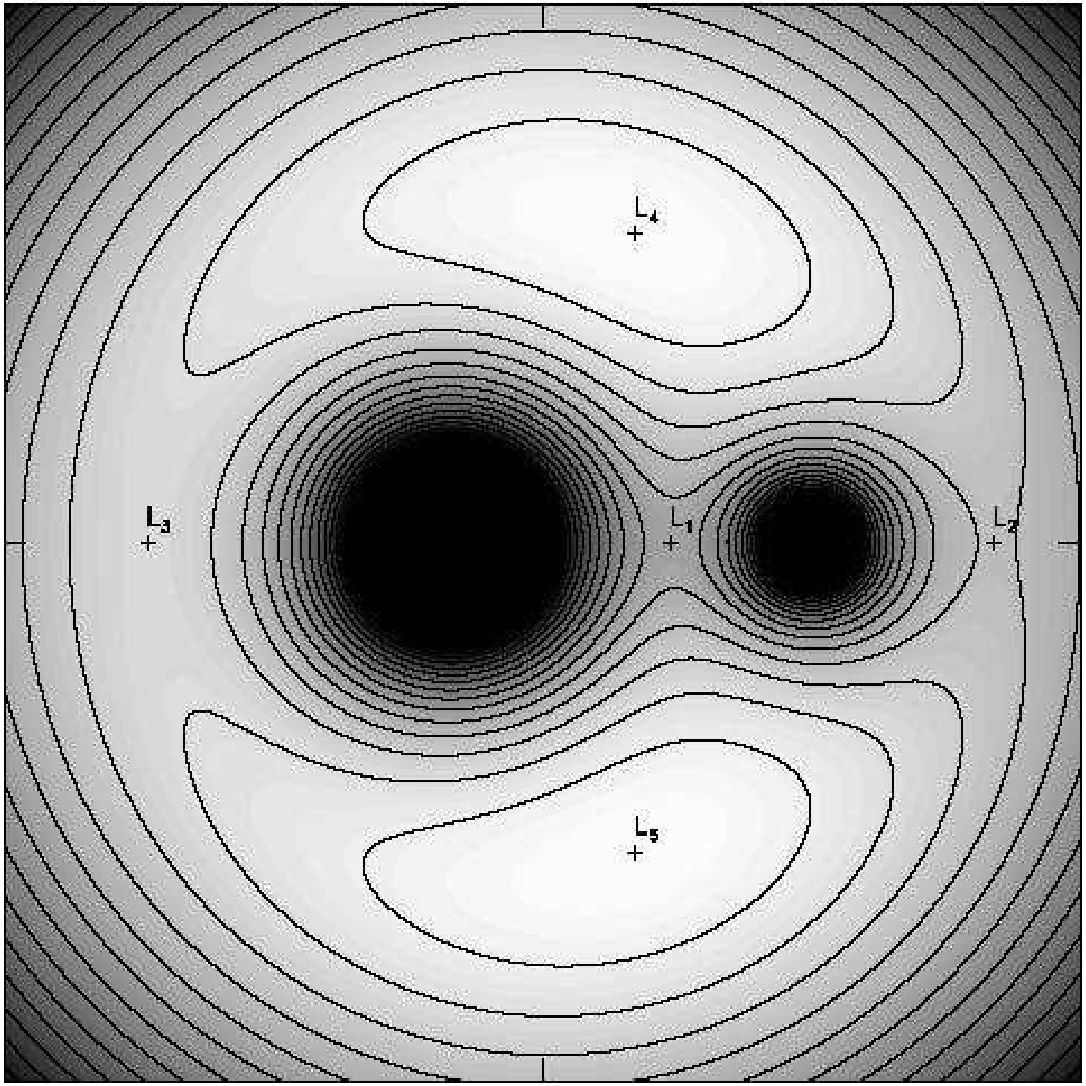
Table 9

Thermonuclear burning stages (after Arnett [16]) and timescales for a population I star with a mass of 25 $M_\odot$, after Weaver et al. [380,381]

Fuel	$T/10^9$ (K)	Ashes	E (erg/g fuel)	Cooling	Time (yr)
^{1}H	0.02	^{4}He, ^{14}N	$(5–8)\times10^{18}$	photons	5×10^{6}
^{4}He	0.2	^{12}C, ^{16}O, ^{22}Ne	7×10^{17}	photons	5×10^{5}
^{12}C	0.8	^{20}Ne, ^{24}Mg, ^{16}O ^{23}Na, ^{25,26}Mg	5×10^{17}	neutrinos	60
	0.4	^{20}Ne, ^{23}Na	–		
^{20}Ne	1.5	^{16}O, ^{24}Mg, ^{28}Si	1.1×10^{17}	neutrinos	1
^{16}O	2	^{28}Si, ^{32}S	5×10^{17}	neutrinos	0.5
^{28}Si	3.5	^{56}Ni, $A\sim56$ nuclei	$(0–3)\times10^{17}$	neutrinos	0.01
^{56}Ni	6–10	n, ^{4}He, ^{1}H	-8×10^{18}	neutrinos	10^{-6}
$A\sim56$ nuclei		(depends on photodisintegration and neutronization)			

(Bhattacharya & van den Heuvel, 1991)

Binary Evolution



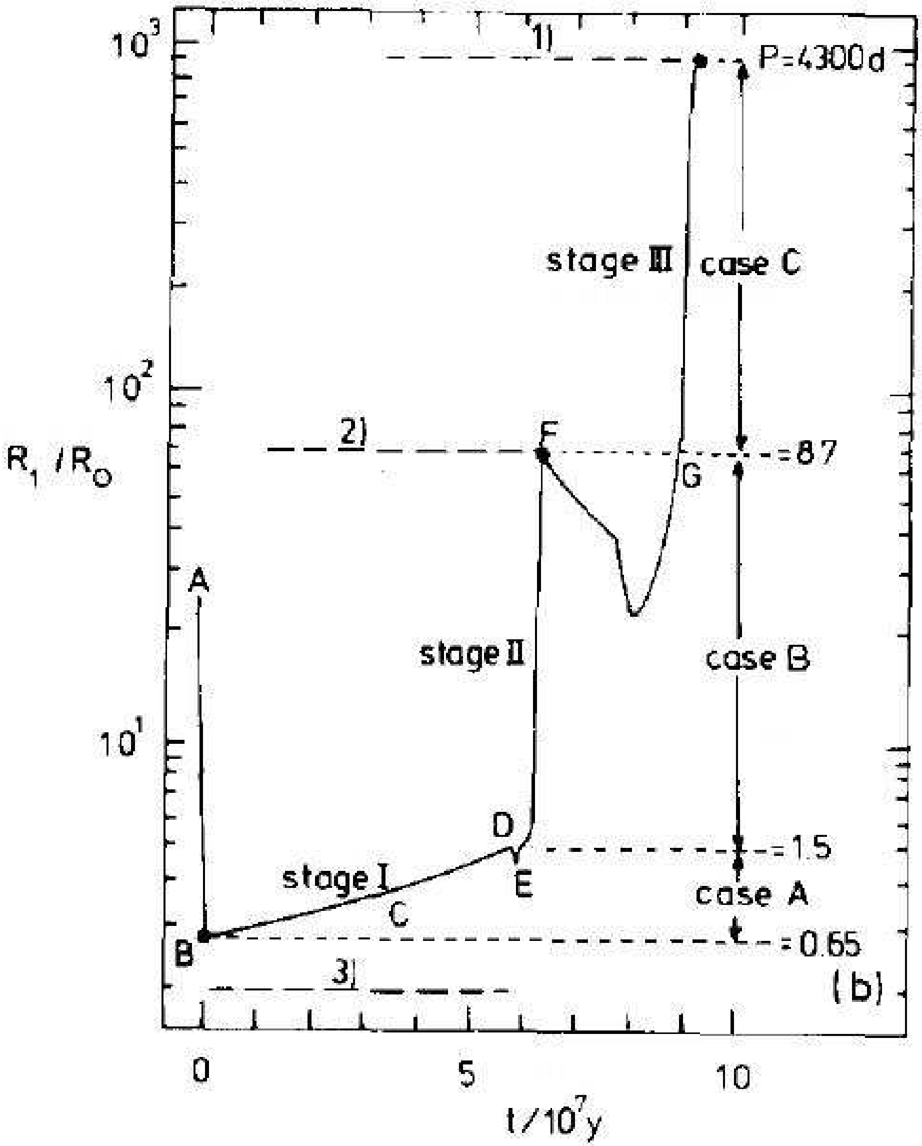
R. Hynes

Stellar evolution in binary systems:

- Evolution of individual stars on nuclear timescale
- When stars expand: mass transfer onto companion possible $\Longrightarrow$ changes mass ratio and evolutionary timescale (because M changes).

Evolutionary scenarios depend on initial mass ratio and on initial separation of stars.

Binary Evolution



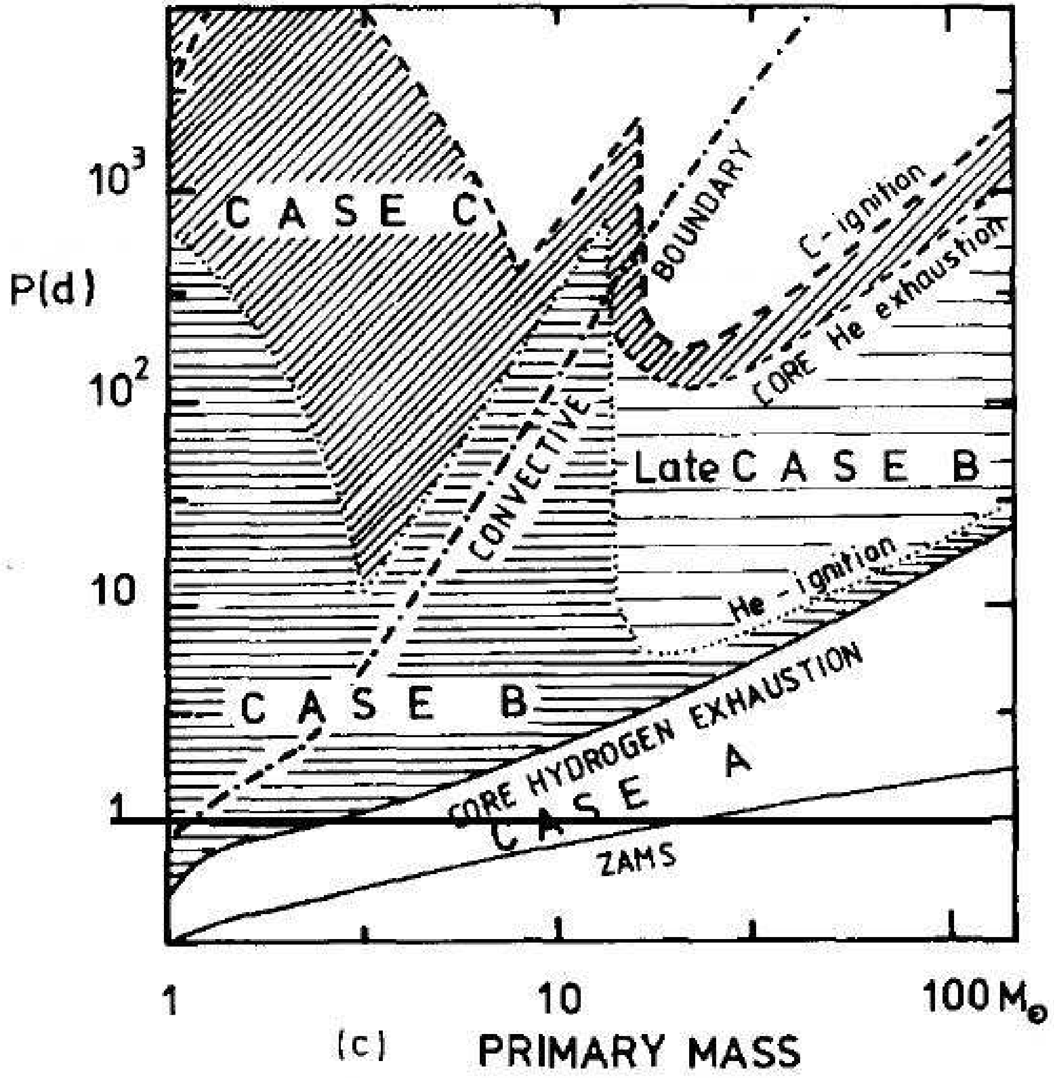
There are three types of mass transfer: case A, case B, and case C, depending on when star reaches its Roche volume during its evolution

Radius evolution of a star with and $M_1 = 5\,M_\odot$

Orbital periods required for mass transfer at a given stage are given in days for $q = M_2/M_1 = 0.5$

(Bhattacharya & van den Heuvel, 1991, Fig. 19b)

Binary Evolution



The different cases of mass transfer depend on initial separation of stars.

Shown here for a system with $q = M_2/M_1 = 0.5$ and $M_1 = 5\,M_\odot$.

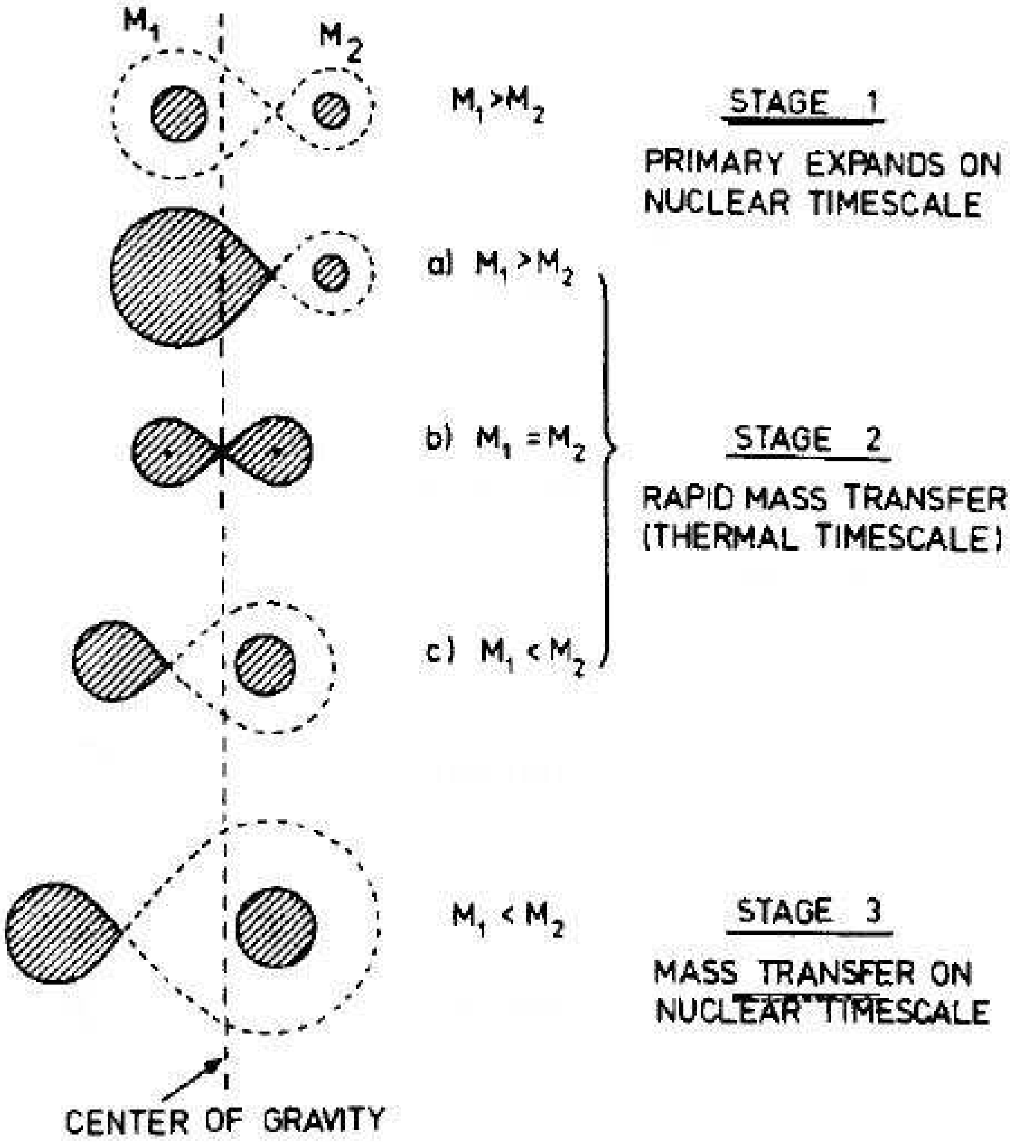
If above "convective boundary": both stars have convective hulls

$\Longrightarrow$ common envelope phase, very fast mass transfer

$\Longrightarrow$ spiral in

(Bhattacharya & van den Heuvel, 1991, Fig. 19b)

Binary Evolution

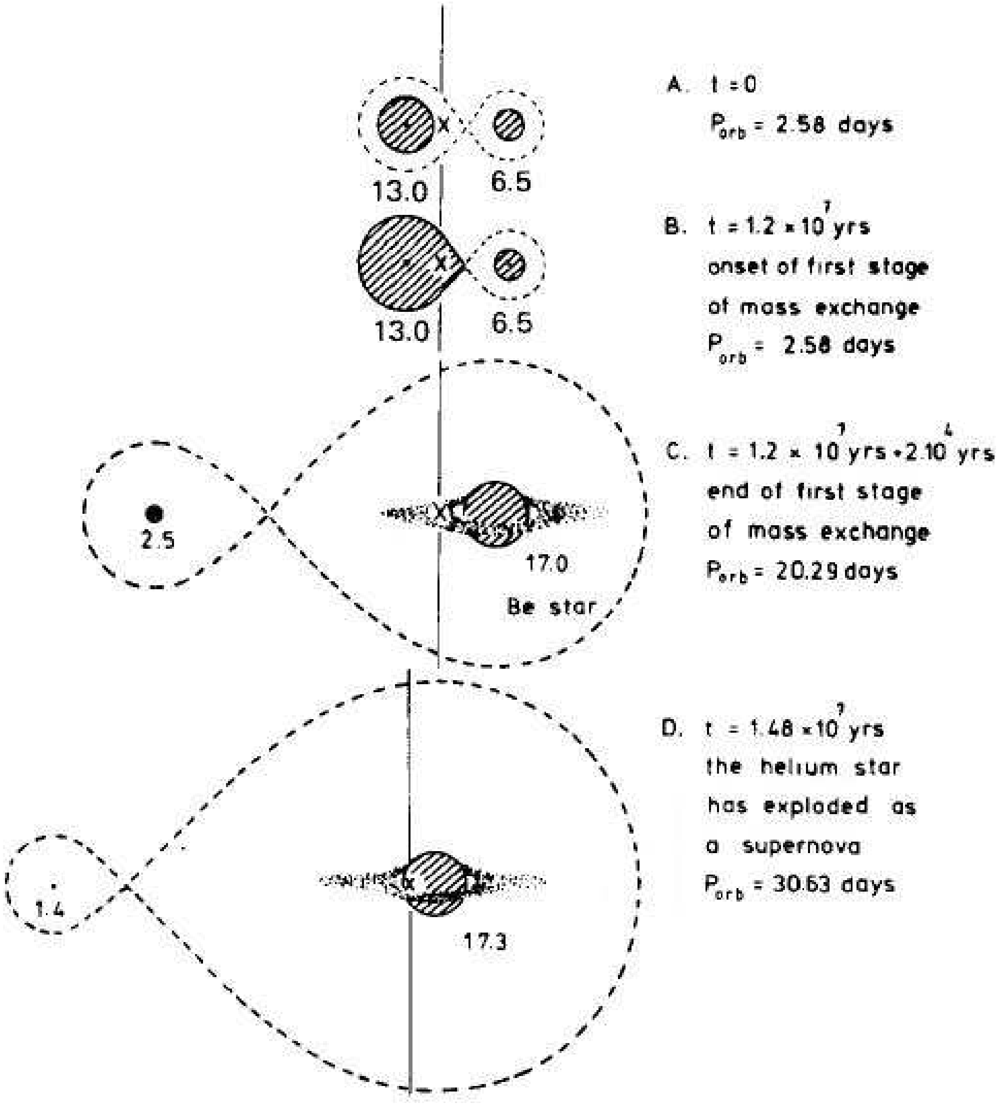


If star has radiative envelope: can react to mass loss on thermal timescale until equilibrium is reached.

Then further evolution on nuclear timescale.

(Bhattacharya & van den Heuvel, 1991, Fig. 24)

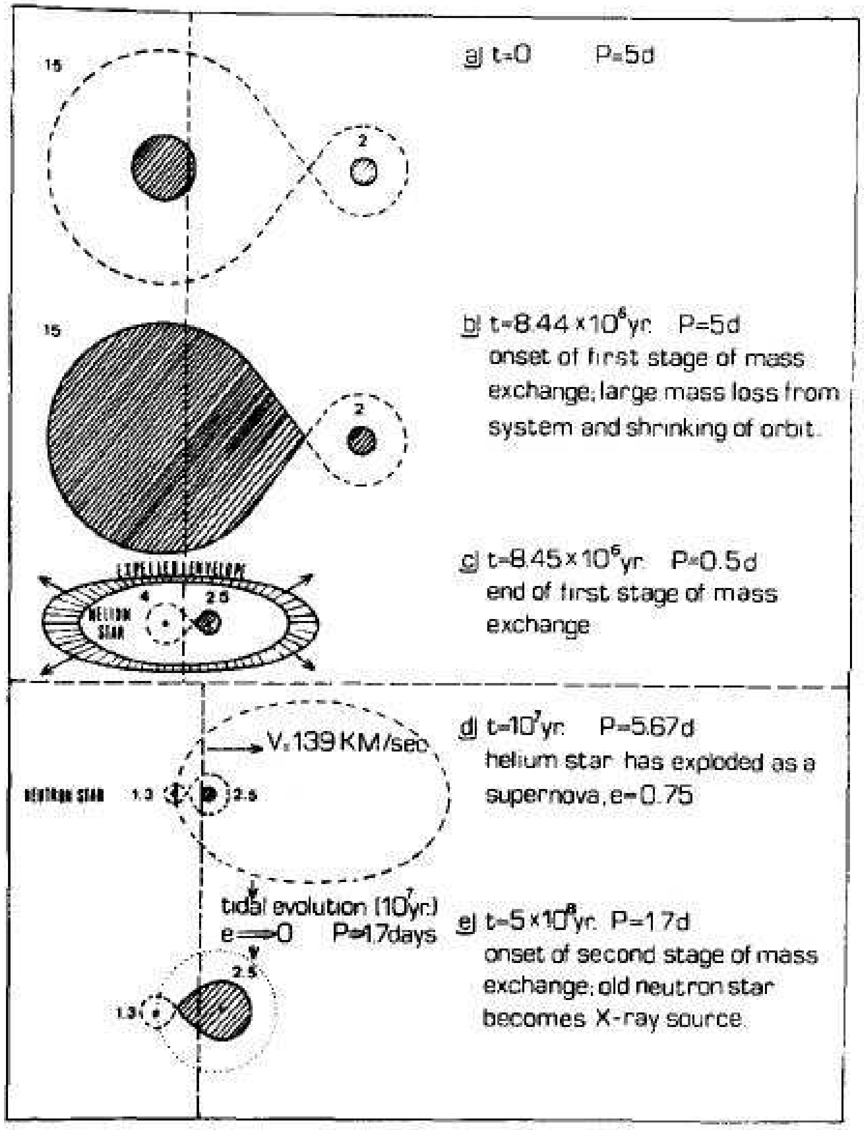
Binary Evolution



After initial mass transfer: further evolution until more massive star evolves into a compact object.

(evolution of a Be system
Bhattacharya & van den Heuvel, 1991,
Fig. 25)

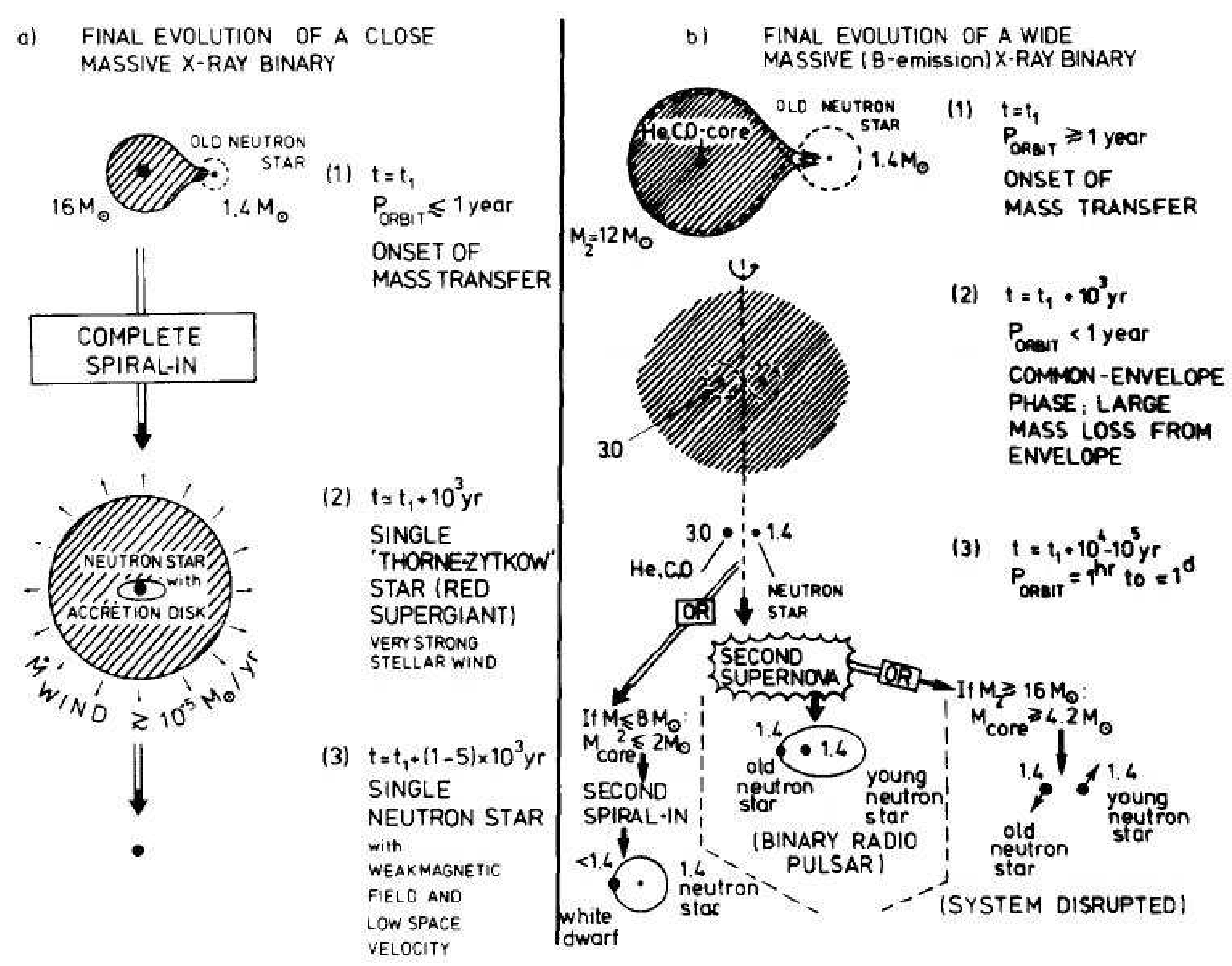
Binary Evolution



Formation of a system like Her X-1 from a very massive binary.

Note: Supernova gives system a “kick”: also required from observations (Her X-1 is 3 kpc away from plane).

(Bhattacharya & van den Heuvel, 1991, Fig. 29, initial masses 15 $M_\odot$ and 2 $M_\odot$)



(Bhattacharya & van den Heuvel, 1991, Fig. 32)

Tests of XRB Evolution

To test theory of XRB evolution: need access to X-ray binary samples

Problem: XRB in our Galaxy are difficult to study statistically, due to because of strong absorption in the Galactic plane

$\Longrightarrow$ Observe other galaxies, where much less biasing

but see (Grimm, Gilfanov & Sunyaev, 2002)!

The LMC, an irregular galaxy, from the *ROSAT* All Sky Survey, colors are hardness ratio $(H-S)/(H+S)$; very red: Super Soft Sources.

Super Soft Sources

Super Soft Sources (SSS) are X-ray binaries characterized by

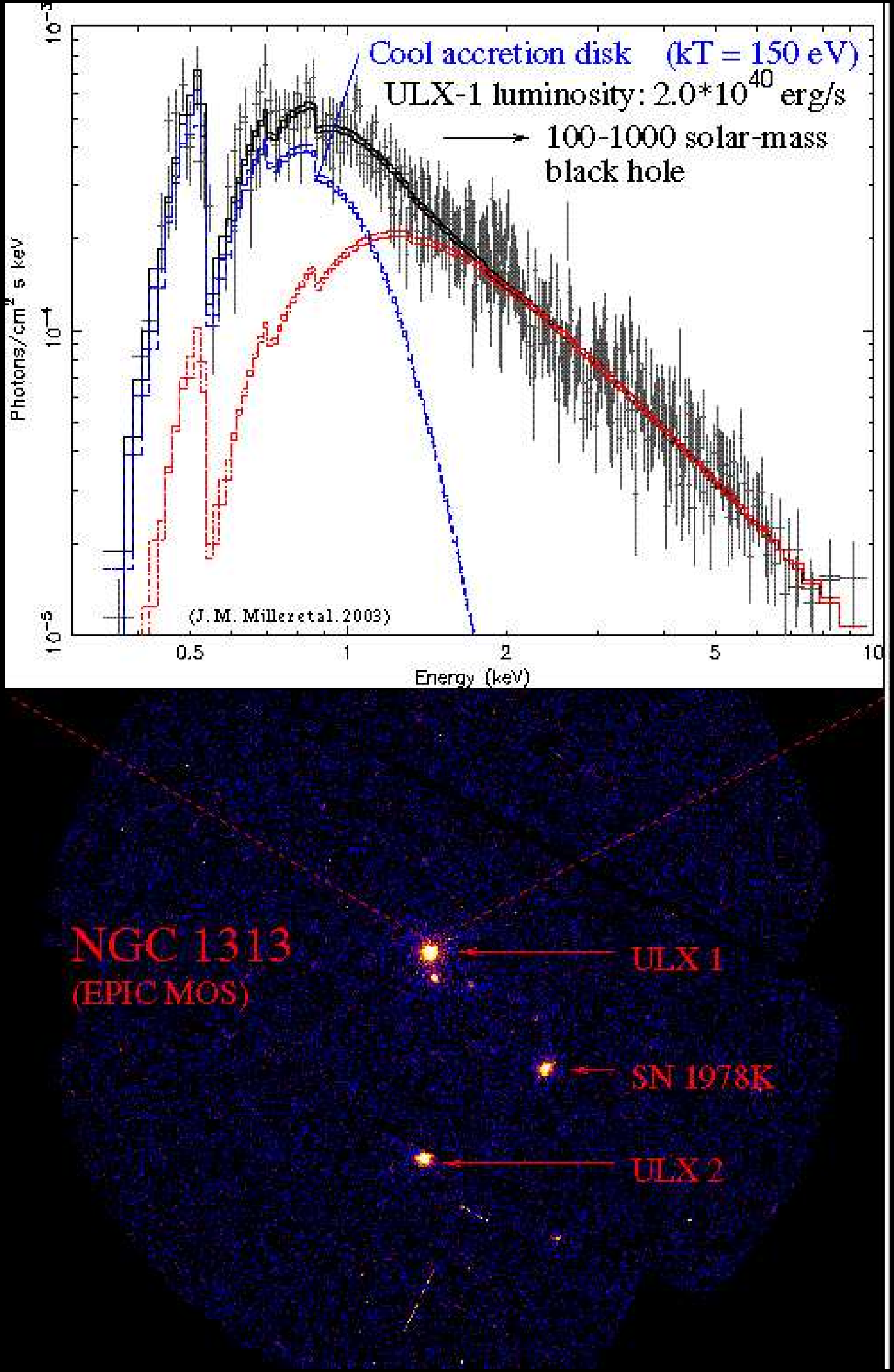
- extremely steep thermal spectra, $T_{\mathrm{BB}} \sim 3 \times 10^5\,\mathrm{K}$
- high luminosity (close to L_{Edd} for $M = 1\,M_\odot$)

Five sources in the LMC (Cal 83, Cal 87, and others), two in the SMC, 15 in M31, many more in other galaxies

Theories for their nature (Kahabka, Pietsch & Hasinger, 1994):

- accretion disks around white dwarfs
- steady hydrogen burning on accreting WDs

Other models appear to be ruled out due to the high luminosity.

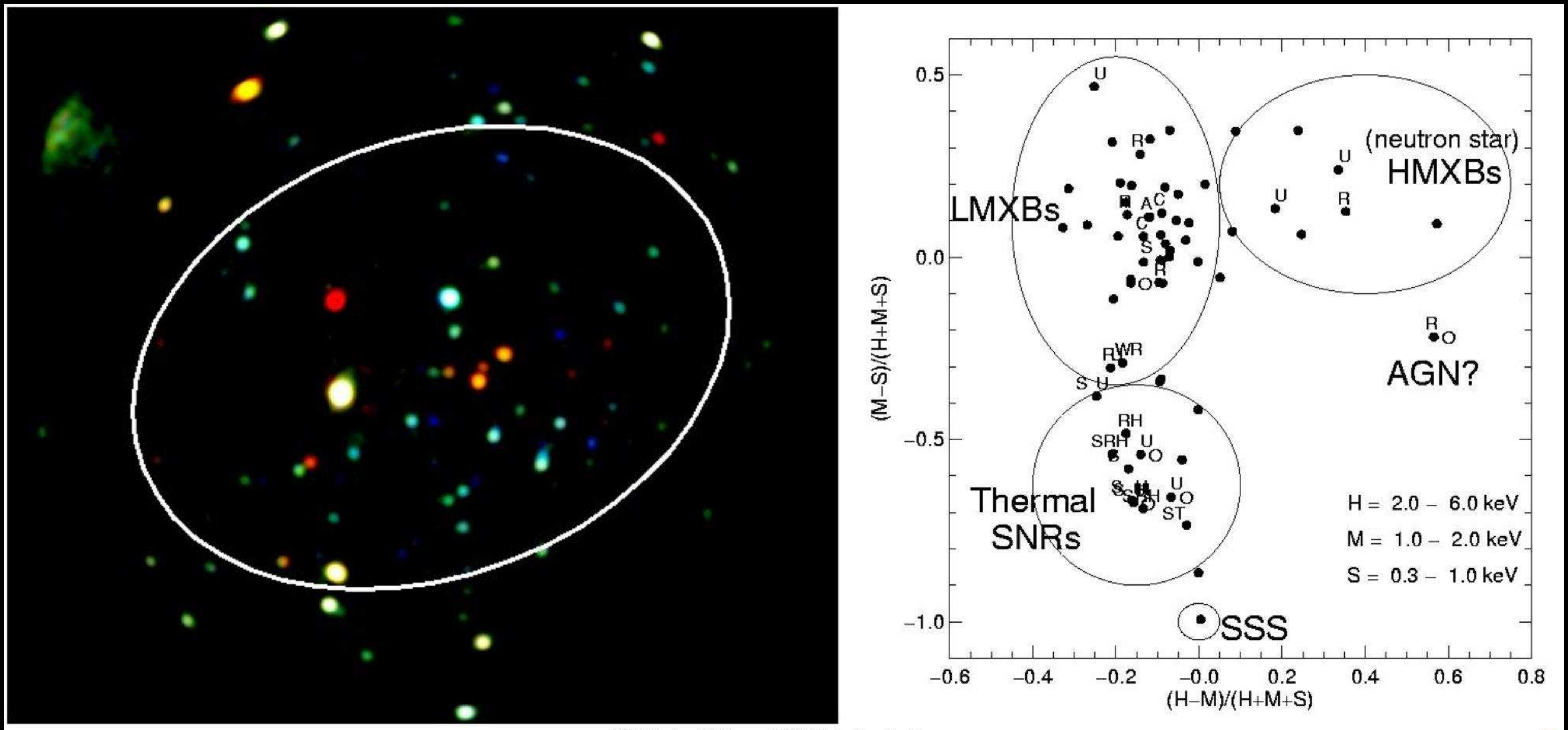


Ultraluminous X-ray Sources (ULX):

Soft sources with luminosities comparable to Eddington for a 1000 $M_\odot$ black hole

$\Longrightarrow$ intermediate mass black holes?

Origin and interpretation still unclear



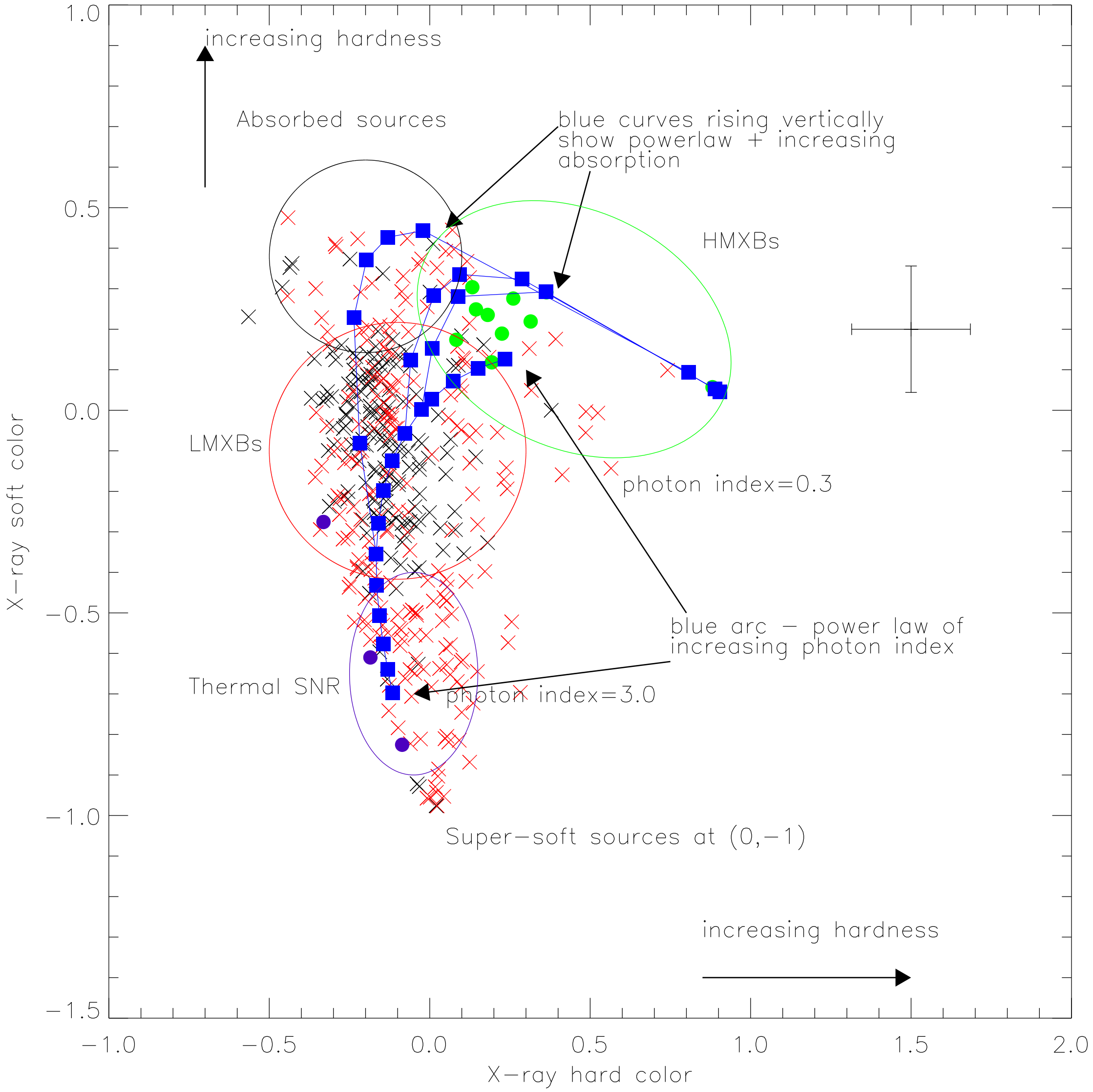
XMM-Newton RGB image of NGC 300 & color-color diagram

European Space Agency

(Carpano et al., 2005)

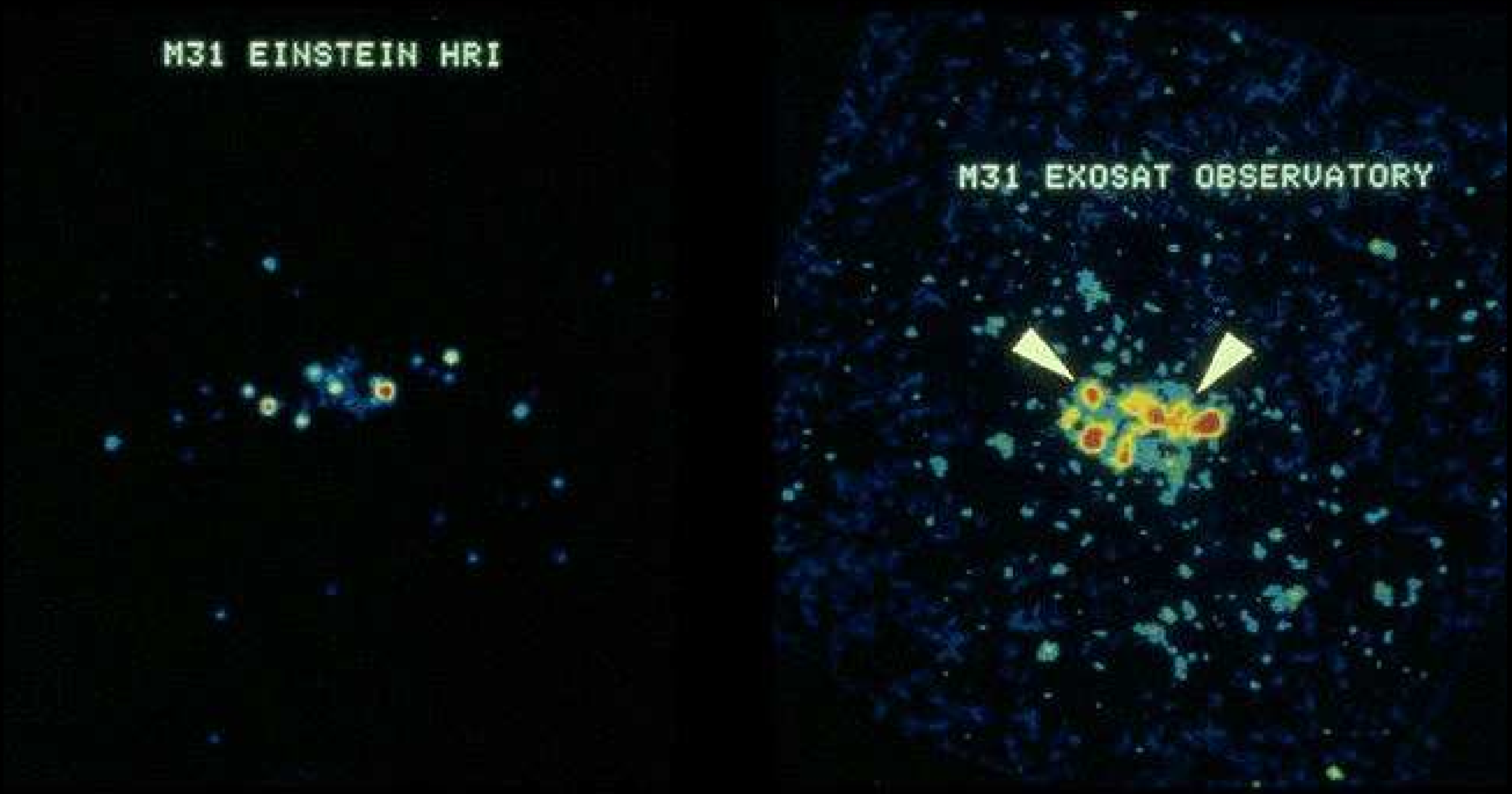
NGC 300: nearby galaxy, point sources classified with Color-Color diagram

Color Color Diagrams, II



The location of sources in an X-ray color-color diagram depends on the source type and the intrinsic absorption.

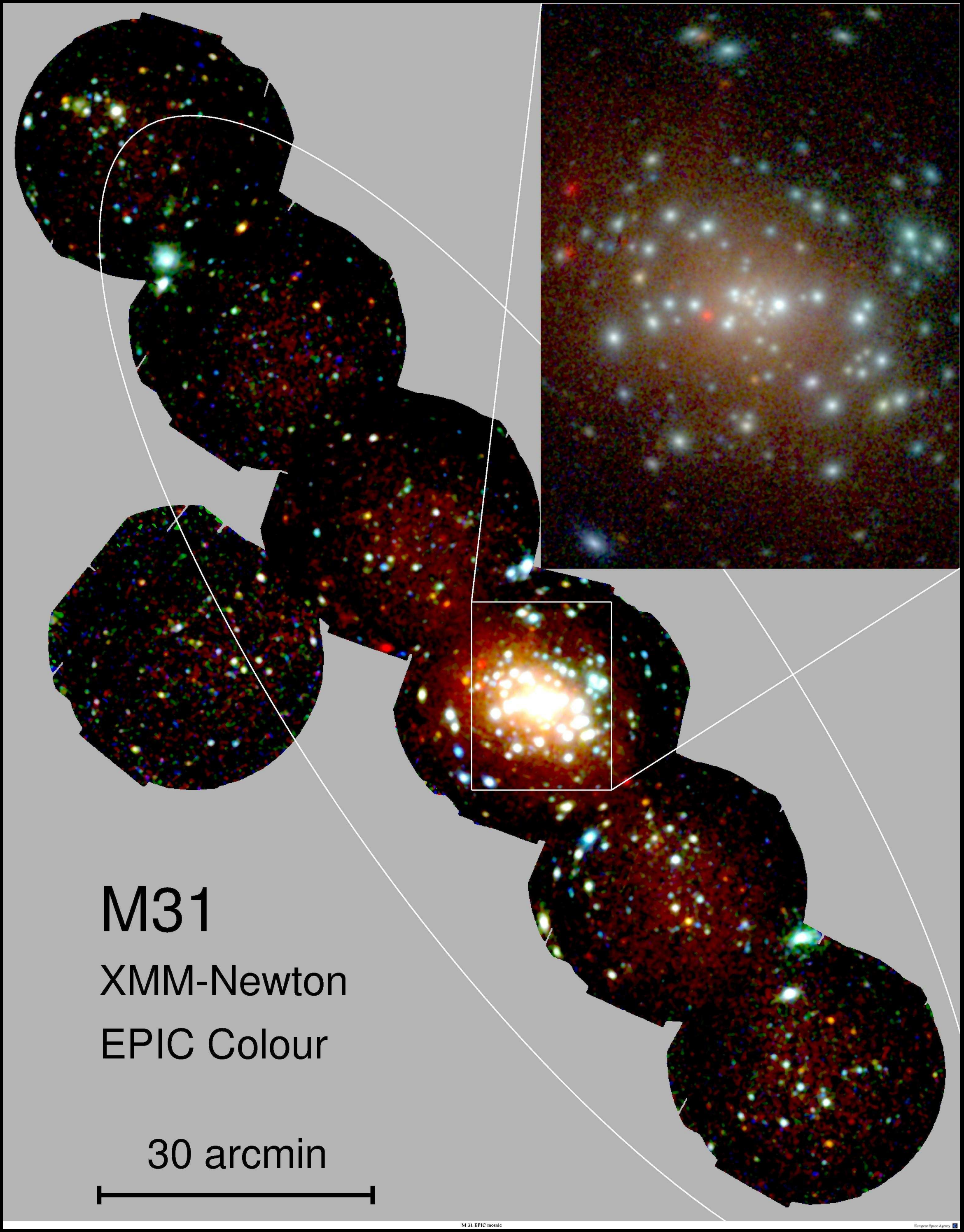
(Prestwich et al., 2003, Fig. 4)



M31 as seen from *Einstein* and *EXOSAT*.

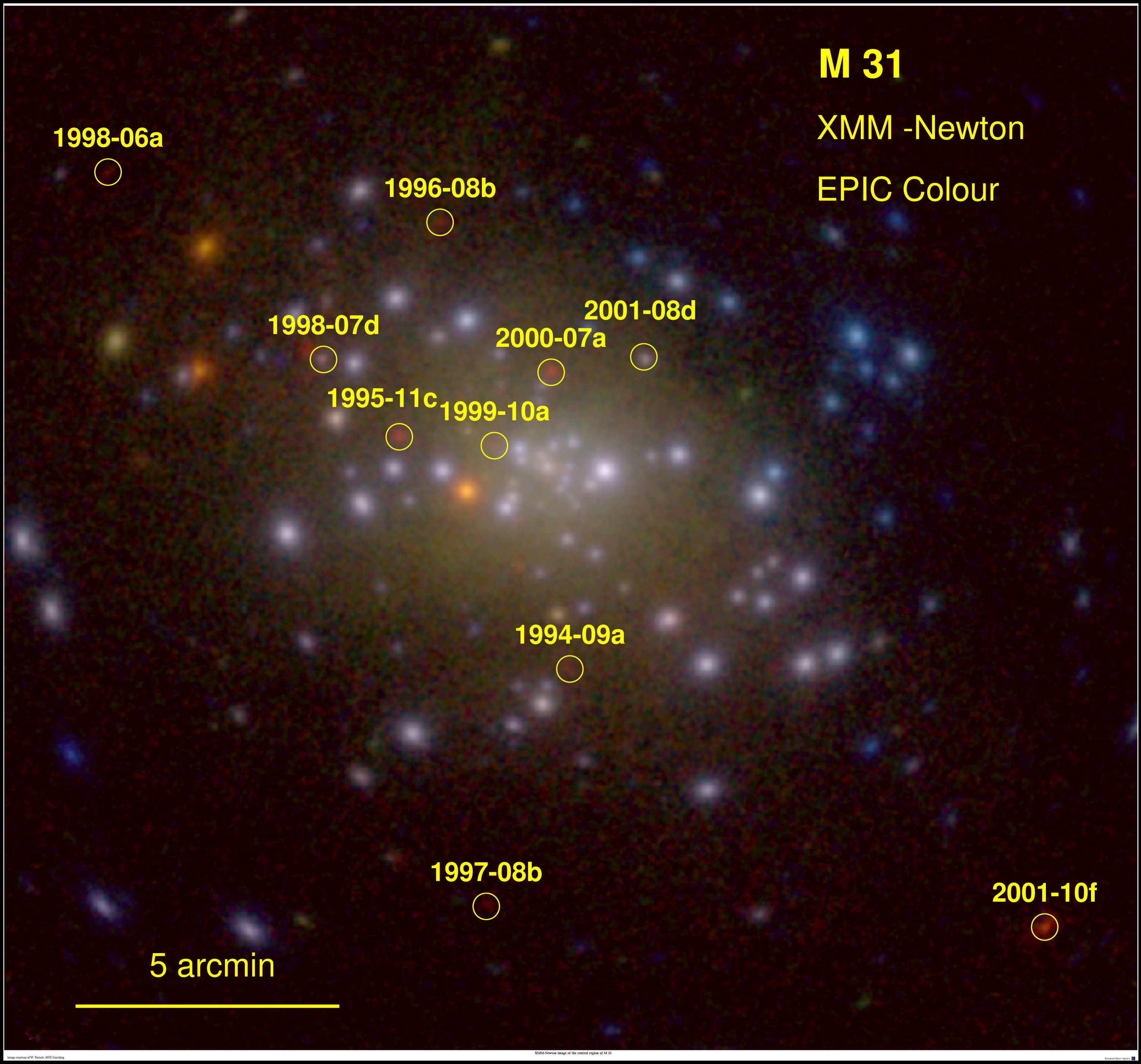
Andromeda nebula (M31): closest spiral galaxy to milky way ($d = 690\,\mathrm{kpc}$).
First studies of Andromeda nebula with early imaging instruments.
Einstein: 108 individual point sources, L_X between $5 \times 10^{36}\,\mathrm{erg/s}$ and $> 10^{38}\,\mathrm{erg\,s^{-1}}$ (Trinchieri et al., 1991), a few coincidences with SNRs.
Total X-ray luminosity: $3 \times 10^{39}\,\mathrm{erg\,s^{-1}}$

M31, different deep *ROSAT* pointings (note characteristic PSPC fingerprints; Supper et al. 1997). About 400 sources detected, 50 of which are foreground (more than in *UHURU* catalogue!). Spectra or hardness ratios are compatible with accreting objects ($\Gamma \sim 2$, $N_{\rm H} \sim 10^{21}$ cm^{-2}); 15 SSS found; residual diffuse emission from hot gas.

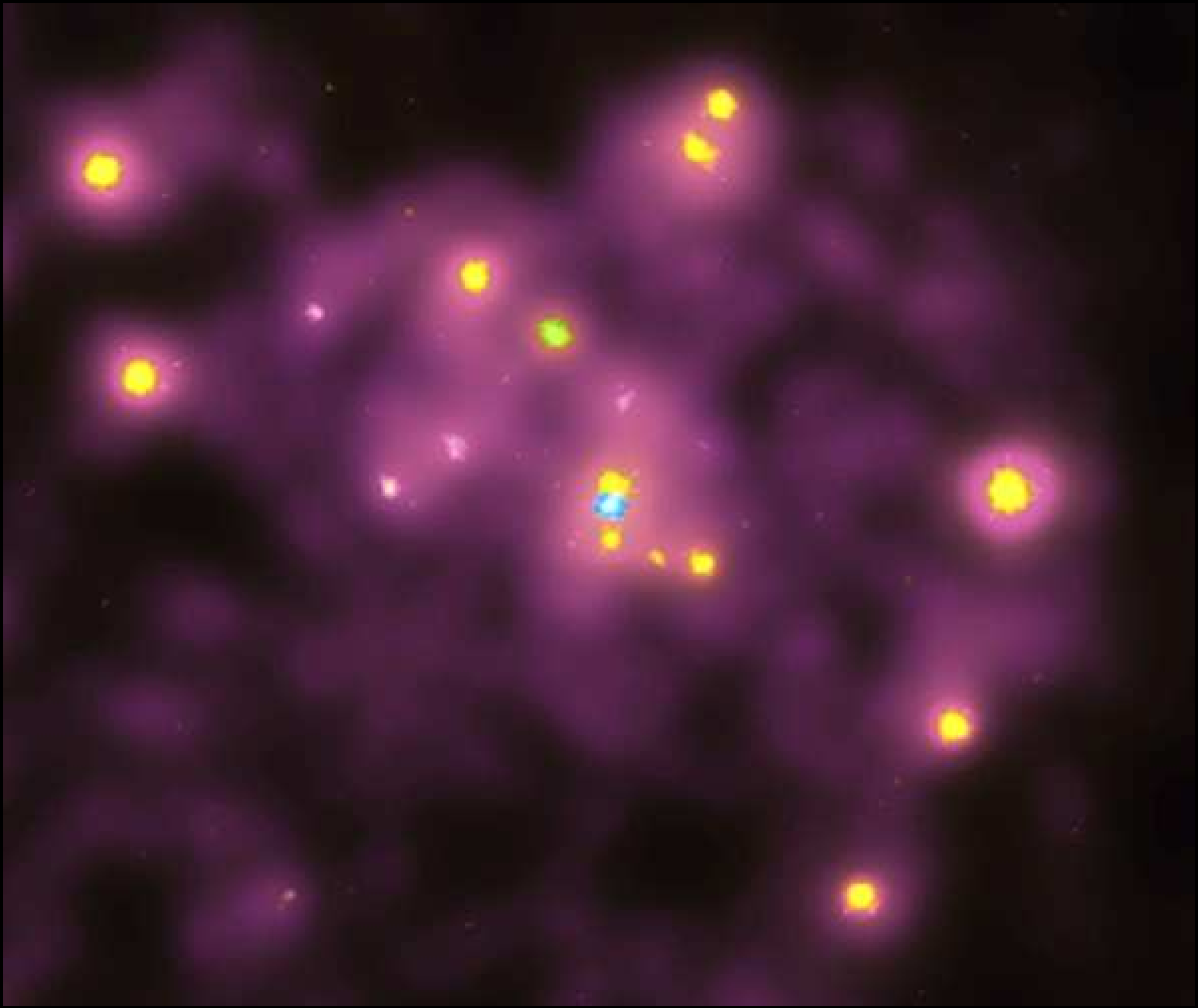


M31 with *XMM-Newton* (courtesy W. Pietsch and ESA)

X-ray: NASA/CXC/MPE/W.Pietsch et al; Optical: NOAO/AURA/NSF/T.Rector & B.A.Wolpa

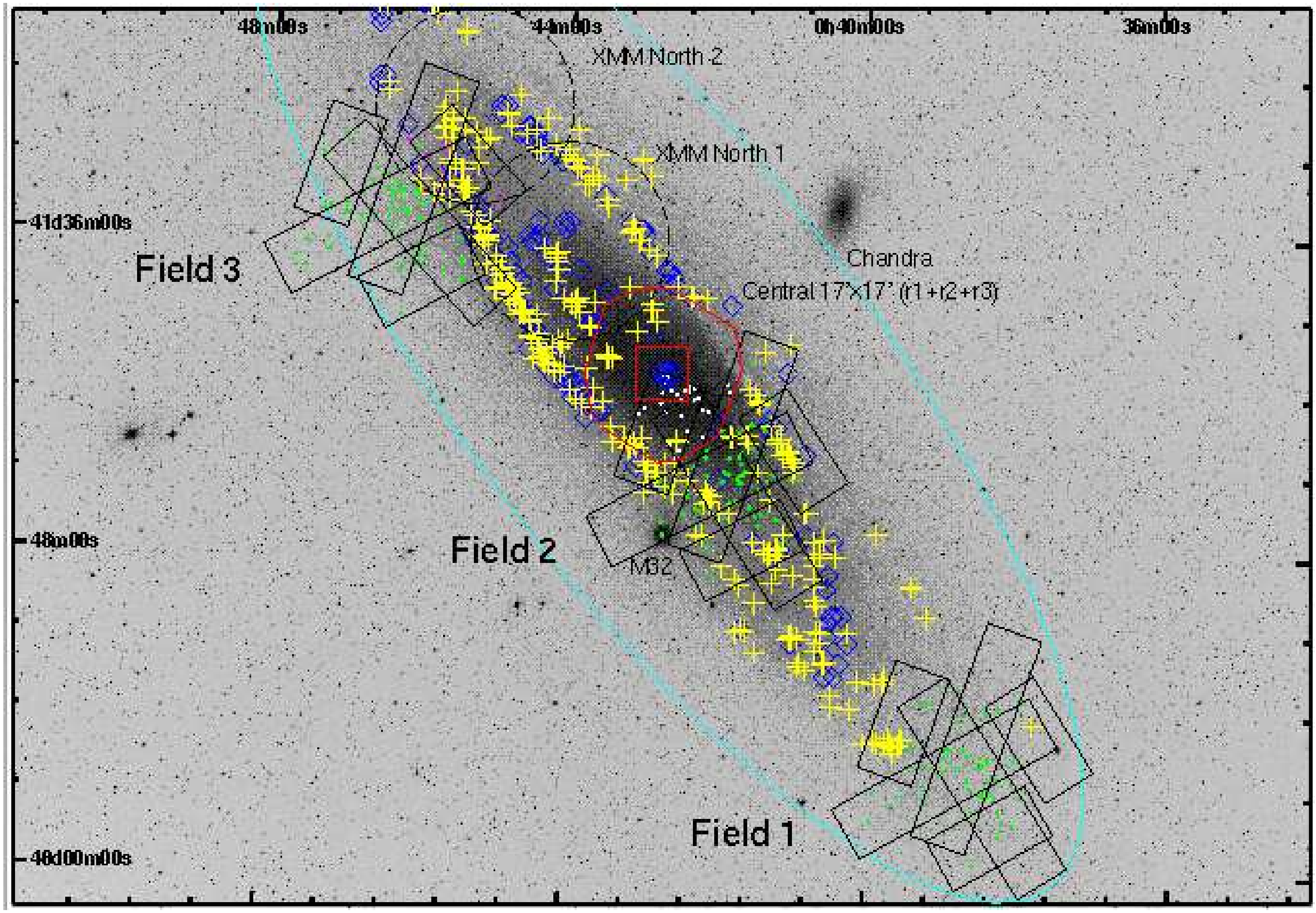


M31 with *XMM-Newton* (2000–2004; courtesy W. Pietsch and ESA)



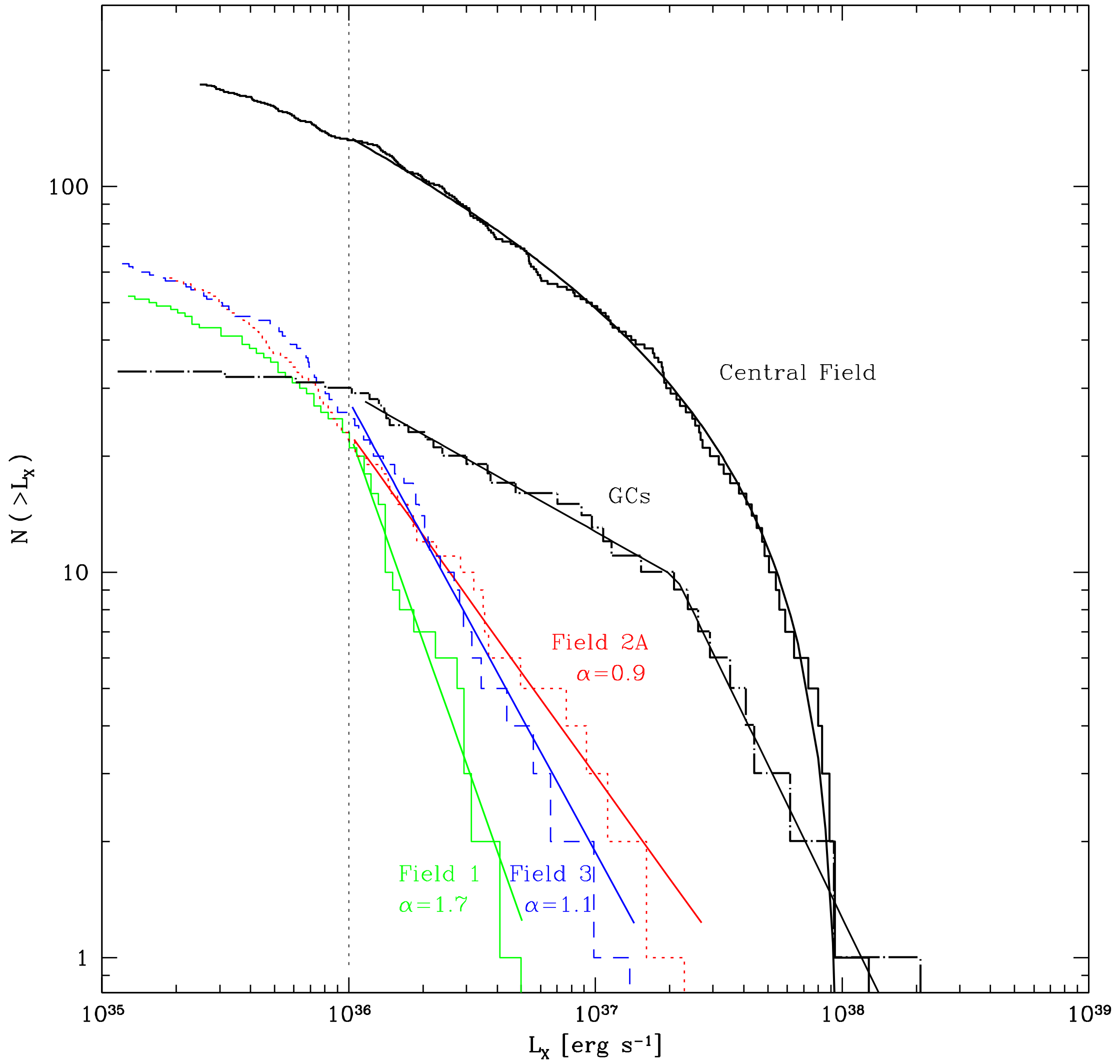
Center of Andromeda with Chandra: blue: very soft source close to supermassive black hole in center ($M \sim 10^7\,M_\odot$); other sources: XRBs

Andromeda Galaxy, VII



Kong et al. (2003): XRB populations in different places in M31

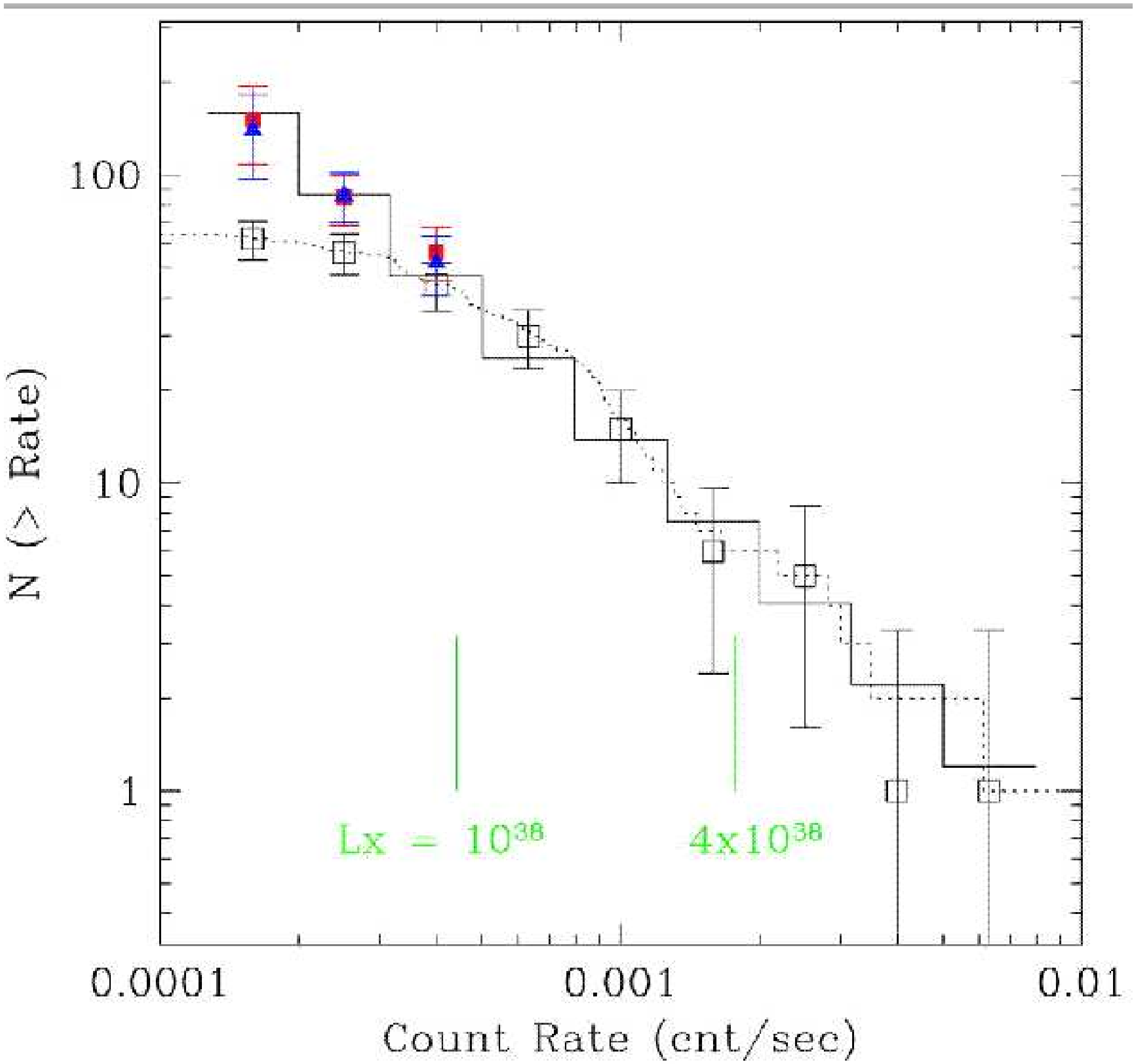
Andromeda Galaxy, VIII



Study of different fields of M31 with *Chandra* using the X-ray luminosity function (XLF): XRB population depends on location.

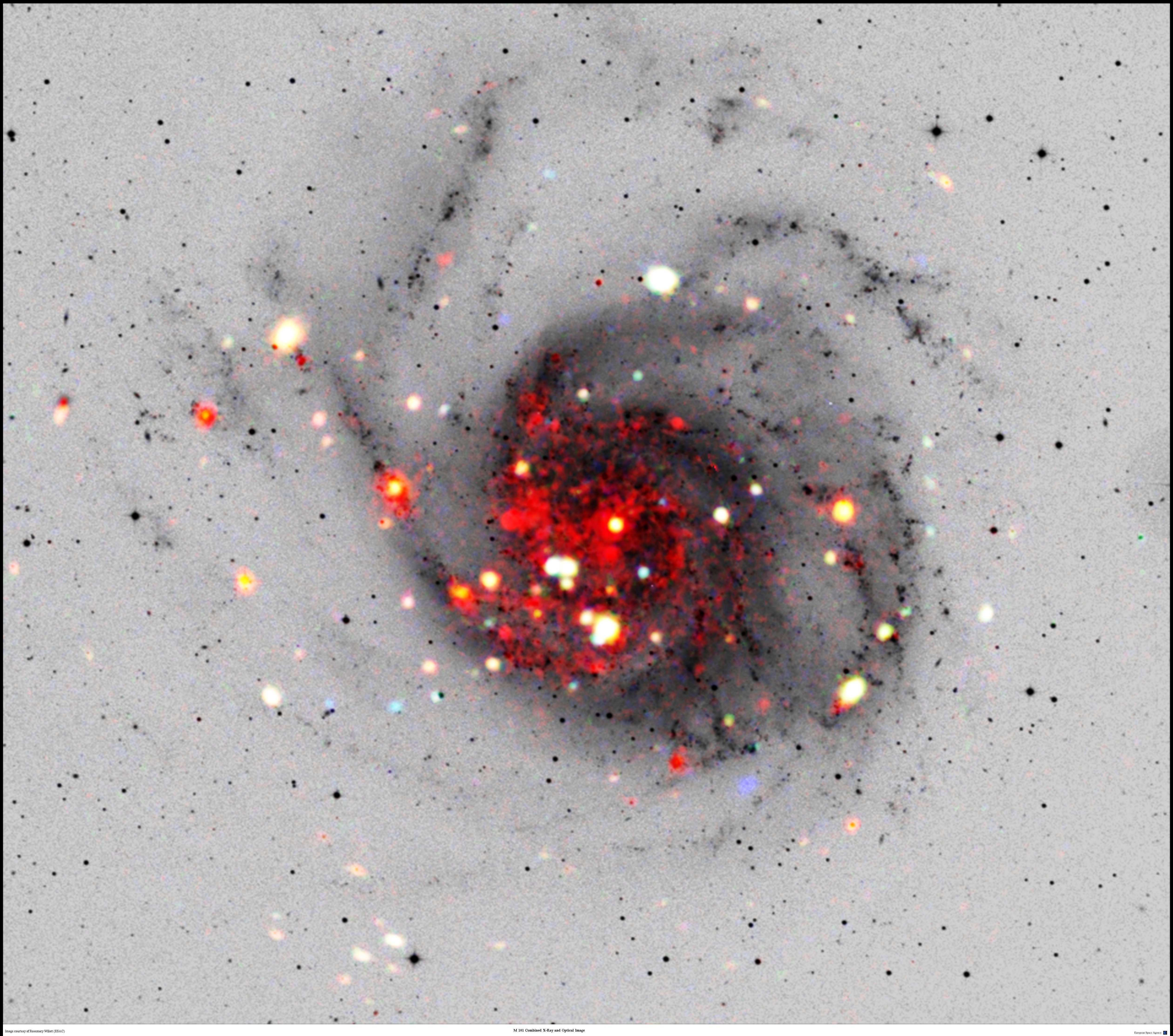
(Kong et al., 2003)

Andromeda Galaxy, IX



XLF for NGC 1316: similar to M31

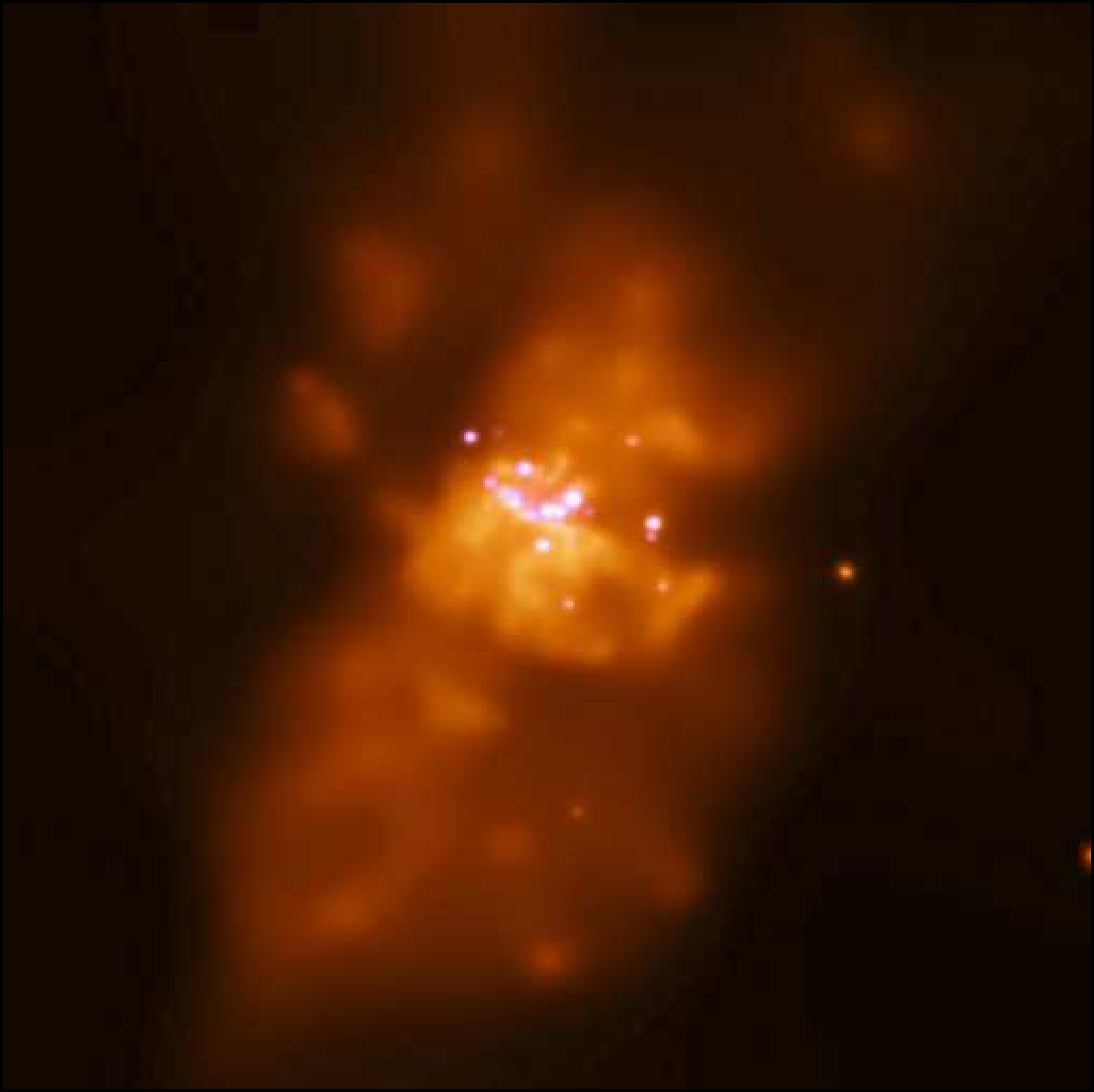
(Kim & Fabbiano, 2004)



M101 with *XMM-Newton* (Rosemary Willat and ESA): HMXB located in star forming regions (arms!)

M82 (R. Gendler)

M82 (R. Gendler)

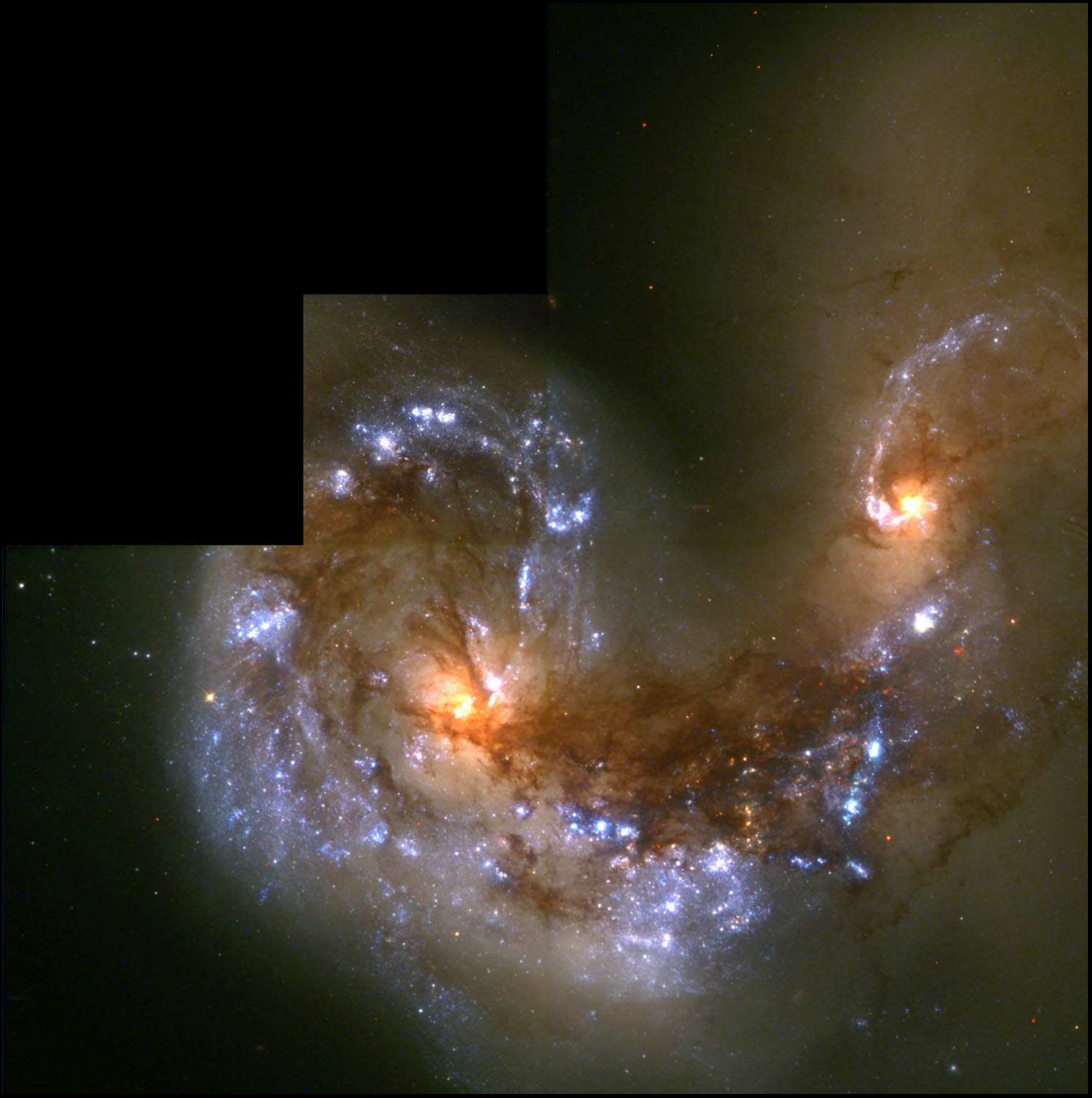


M82: Large population of XRBs in starburst region, hot gas flowing outwards.

(Starburst caused by close encounter with M81?)

M82 (Chandra/CXC)

The Antennae (NGC 4038/4039) ⓒ David M. Jurasevich



STScI/NASA

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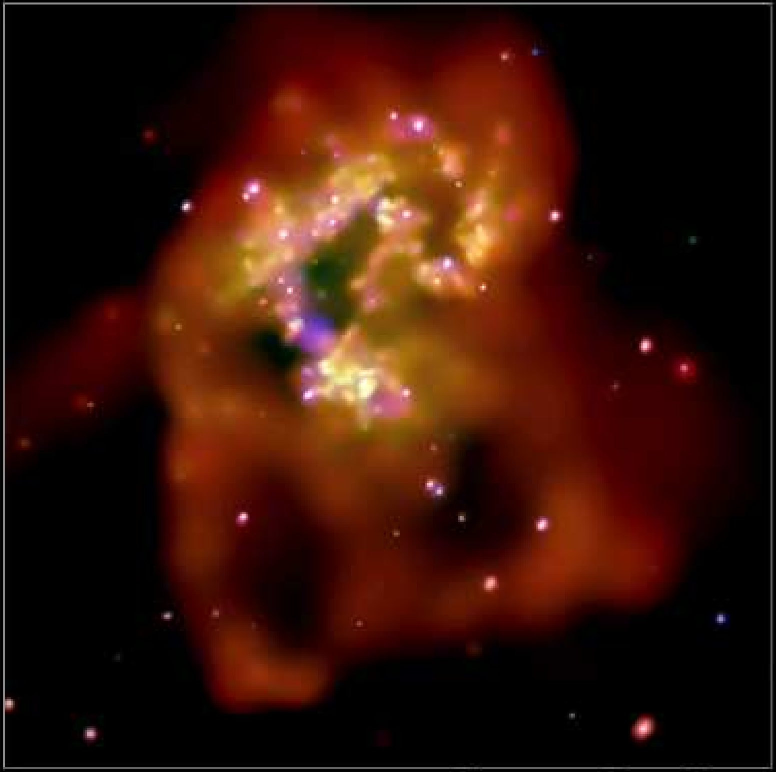
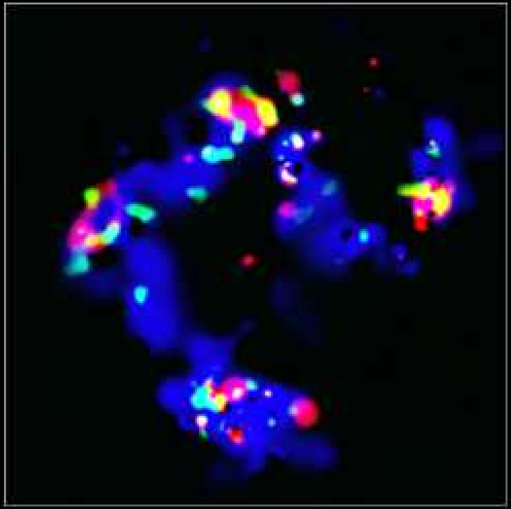


3-Color, Full Field

Diffuse Emission

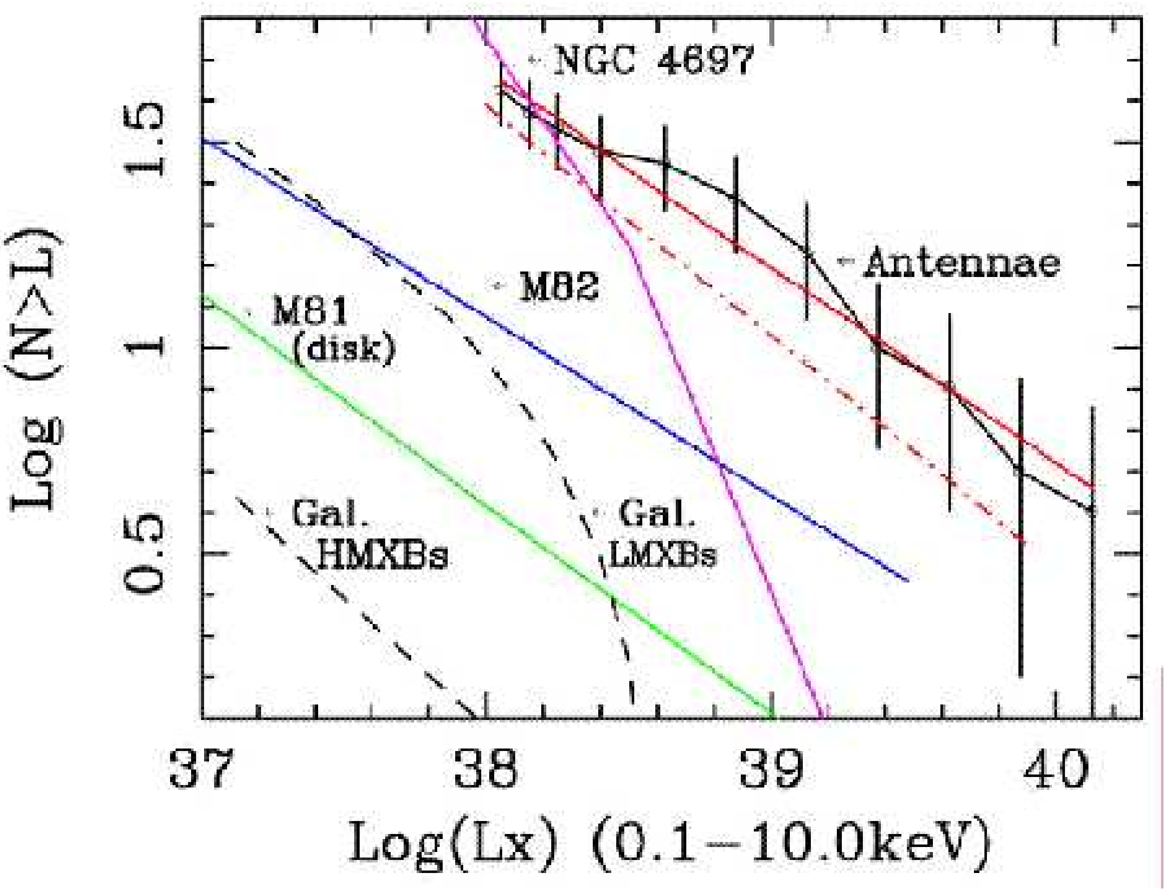


Element Map

The Antennae: an extreme example for galaxy interaction

CXC/NASA (note, image flipped compared to previous ones)

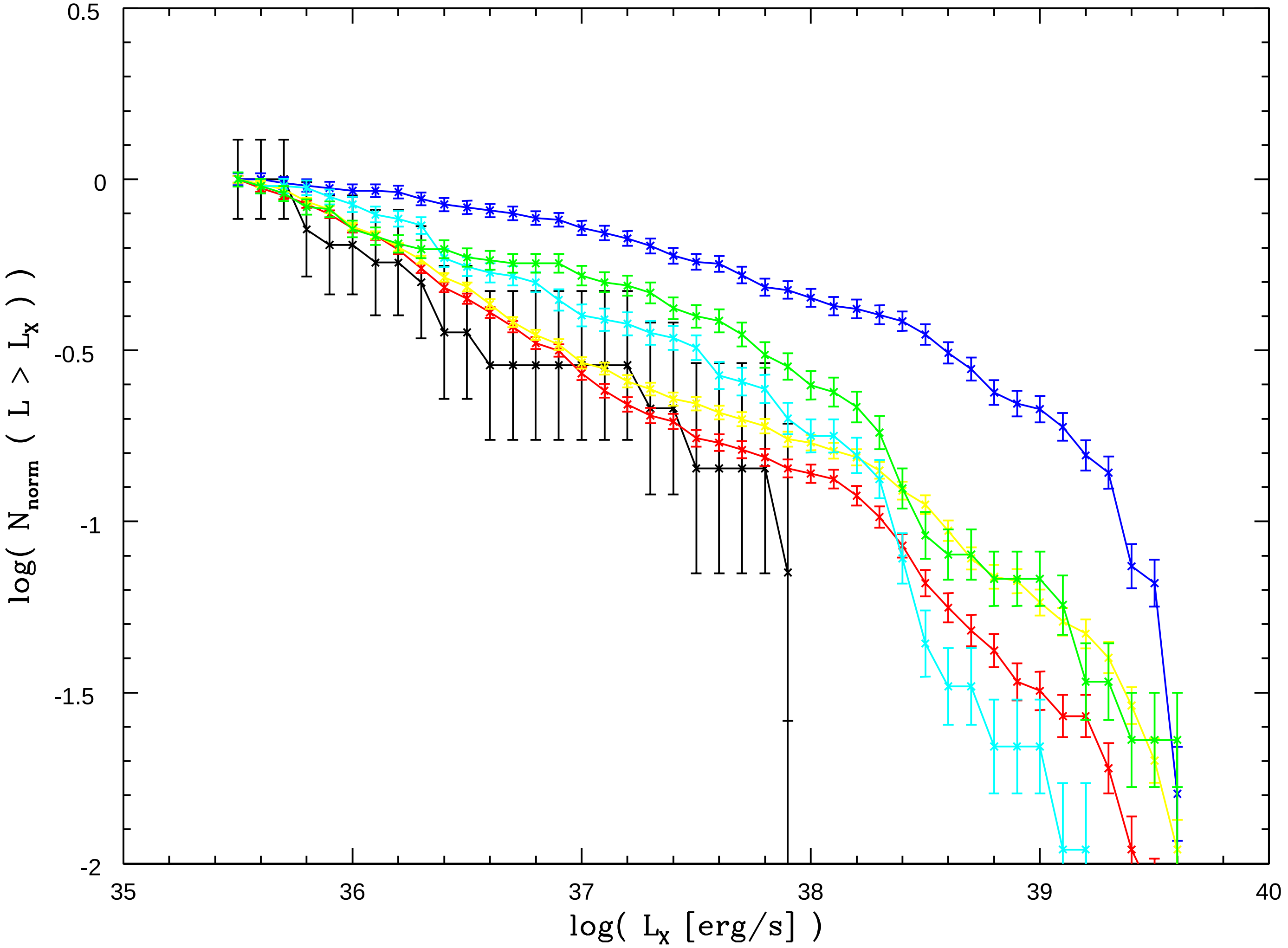
Antennae



Antennae (Fabbiano & White, 2006)

Interacting galaxies show strongly increased number of XRB due to triggered star formation.

Antennae



(Fabbiano & White, 2006)

For starbursts, predicted evolution of XLF (colors) and data agree well.

Figure shows XLF evolution for NGC 1569, starburst is 105–110 Myr old.

Bhattacharya, D., & van den Heuvel, E. P. J., 1991, Phys. Rep., 203, 1

Carpano, S., Wilms, J., Schirmer, M., & Kendziorra, E., 2005, A&A, 443, 103

Fabbiano, G., & White, N. E., 2006, in Compact stellar X-ray sources, ed. W. Lewin, M. van der Klis, (Cambridge: Cambridge Univ. Press), 475–506

Grimm, H.-J., Gilfanov, M., & Sunyaev, R., 2002, A&A, 391, 923

Kahabka, P., Pietsch, W., & Hasinger, G., 1994, A&A, 288, 538

Kim, D.-W., & Fabbiano, G., 2004, ApJ, 611, 846

Kong, A. K. H., DiStefano, R., Garcia, M. R., & Greiner, J., 2003, ApJ, 585, 298

Prestwich, A. H., Irwin, J. A., Kilgard, R. E., Krauss, M. I., Zezas, A., Primini, F., Kaaret, P., & Boroson, B., 2003, ApJ, 595, 719

Supper, R., Hasinger, G., Pietsch, W., Trümper, J., Jain, A., Magnier, E. A., Lewin, W. H. G., & van Paradijs, J., 1997, A&A, 317, 328