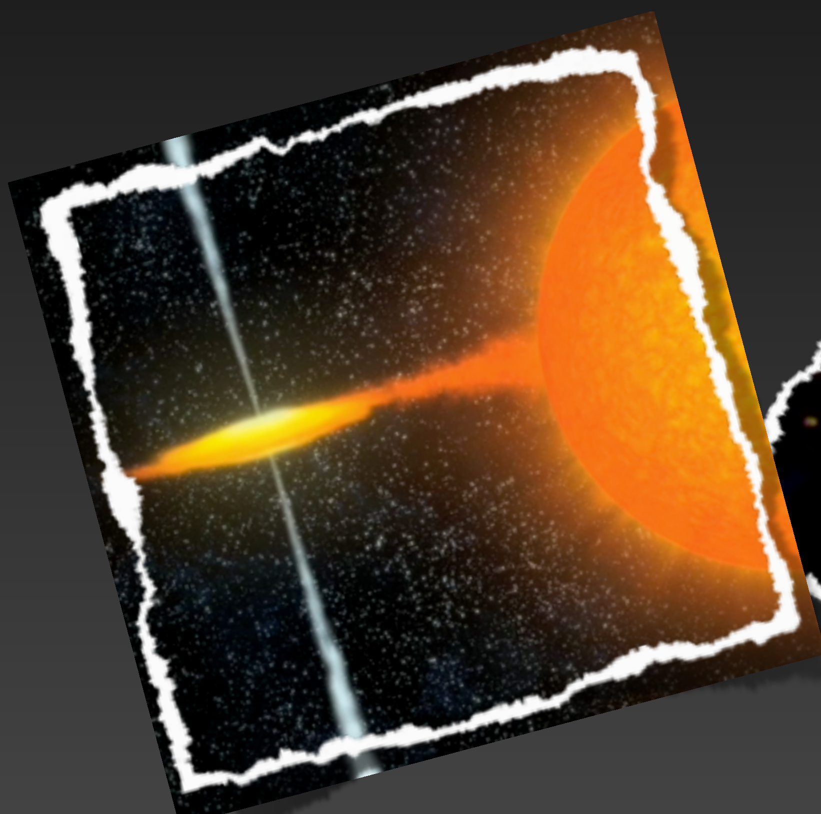
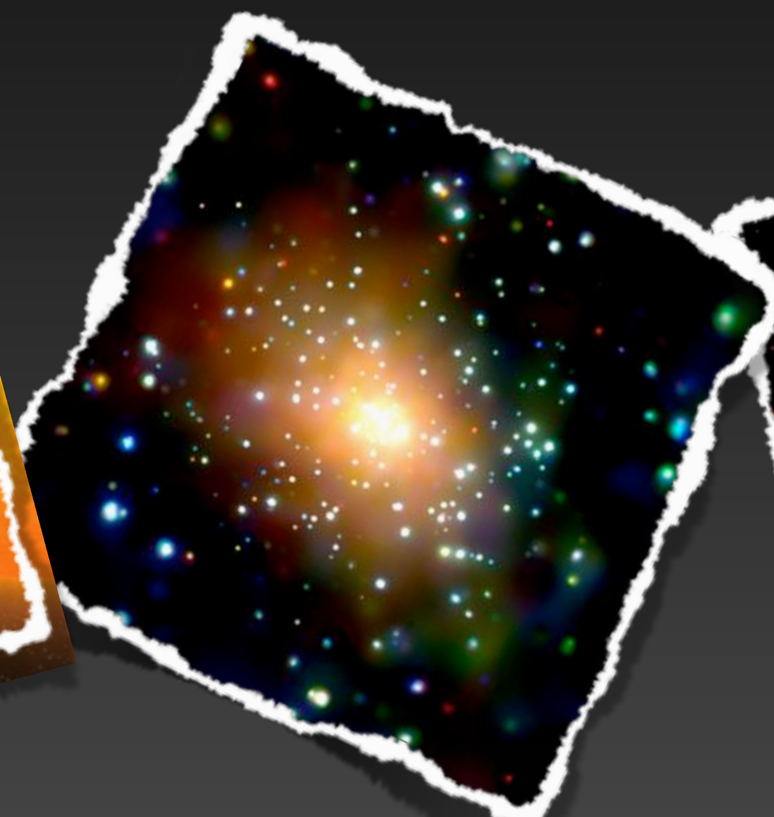
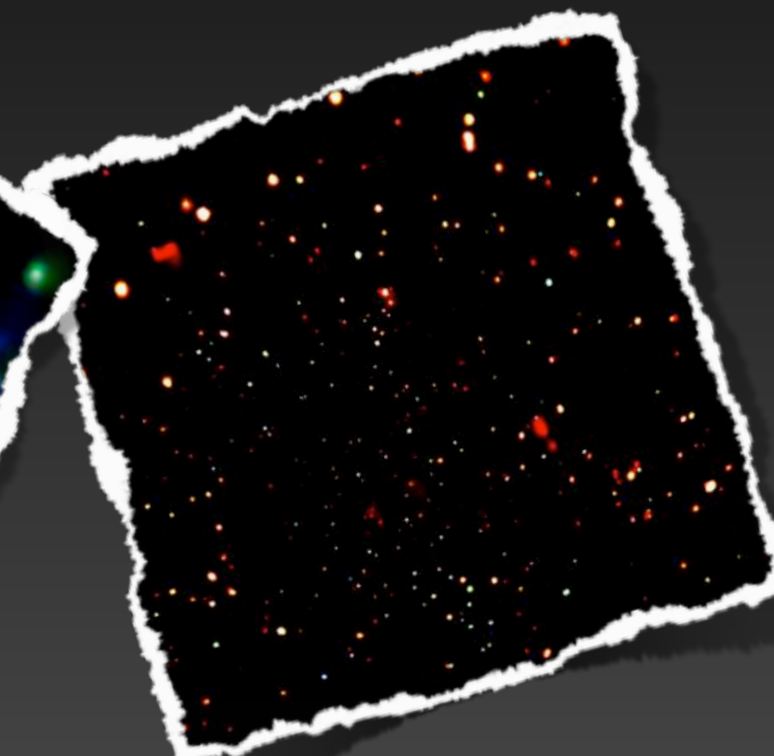
Models of X-ray Binaries:

From the Milky Way to the very first galaxies







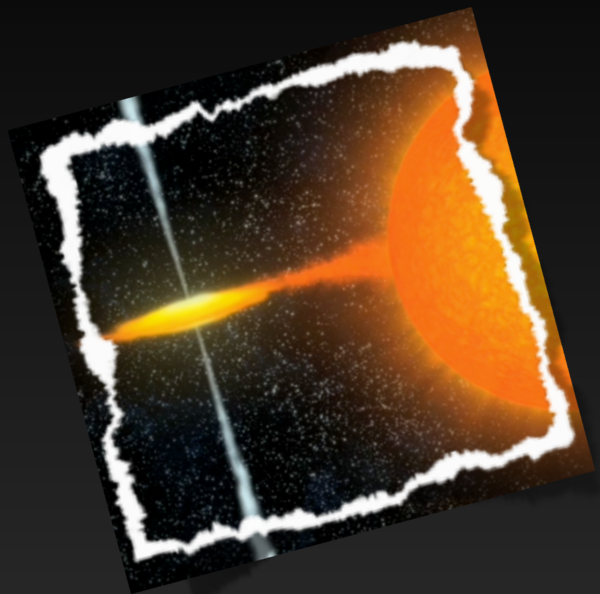
Tassos Fragos

Observatoire Astronomique de l'Université de Genève

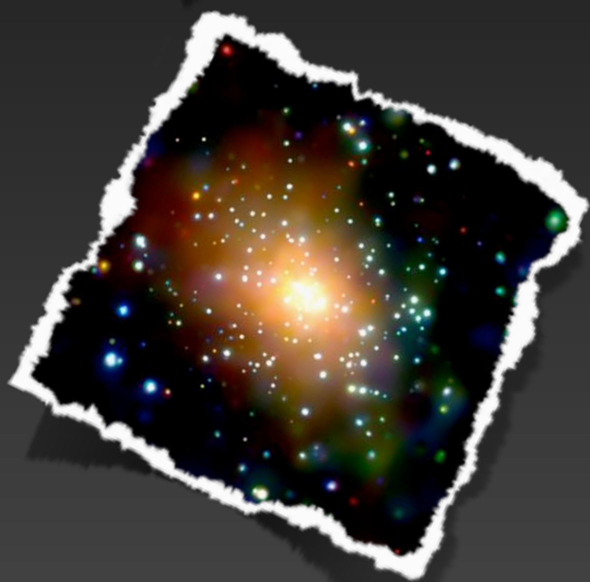
15 Years of Science with Chandra

Boston, 11/19/2014

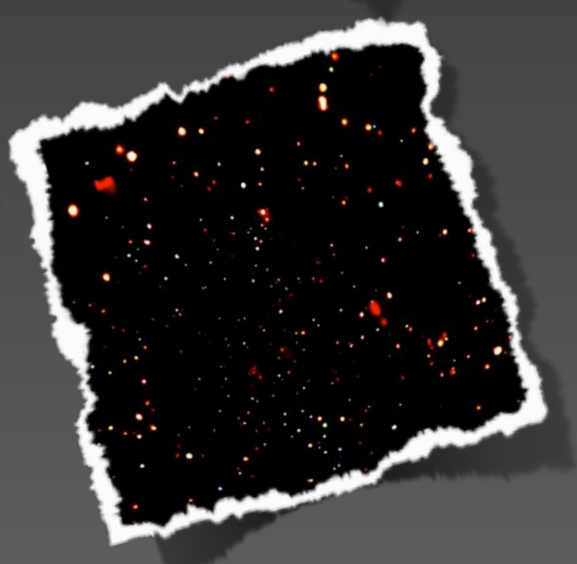
Outline



Galactic XRBs:
Detailed modeling of the evolutionary history

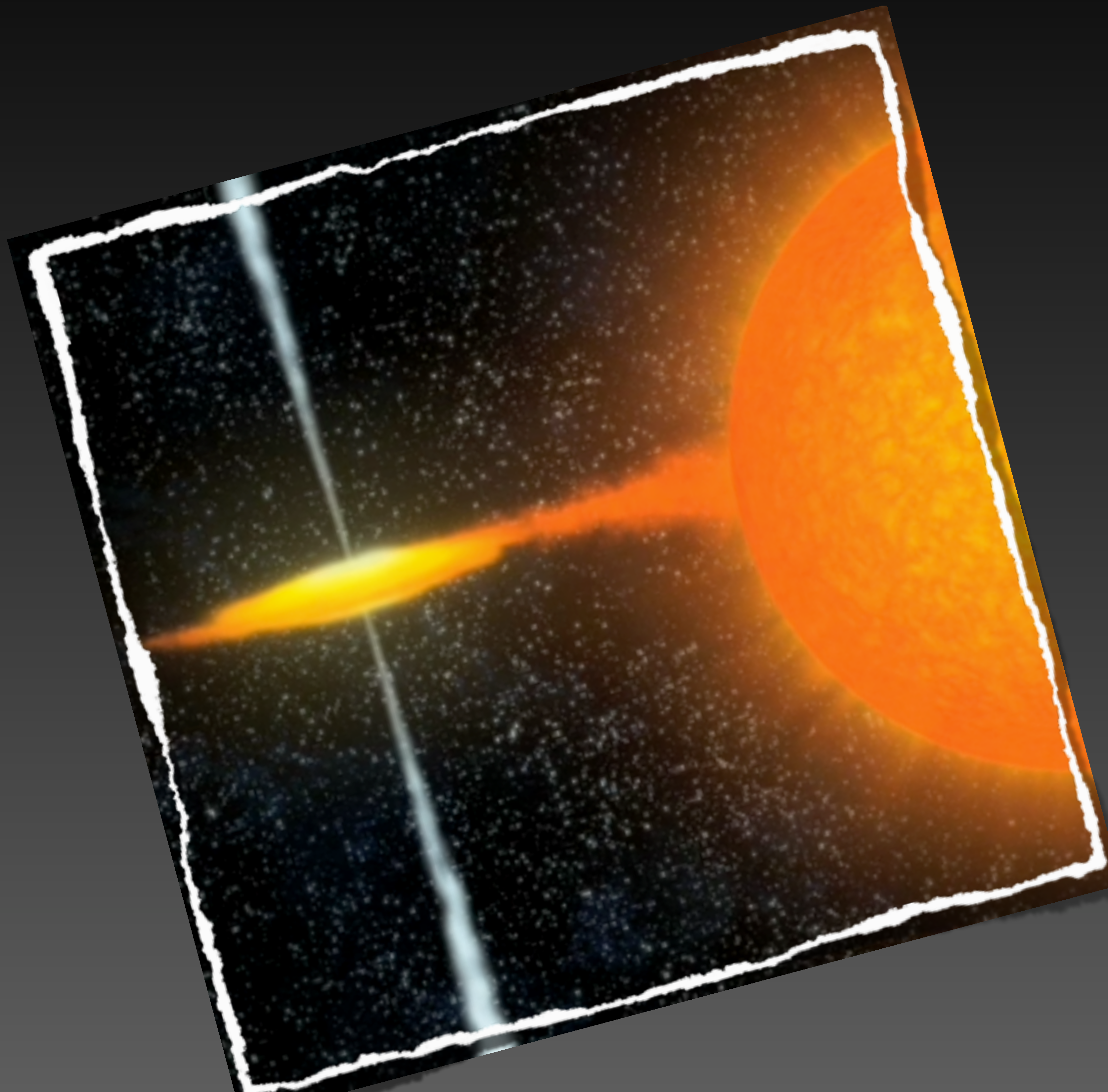


Extragalactic XRB Populations:
Population synthesis modeling

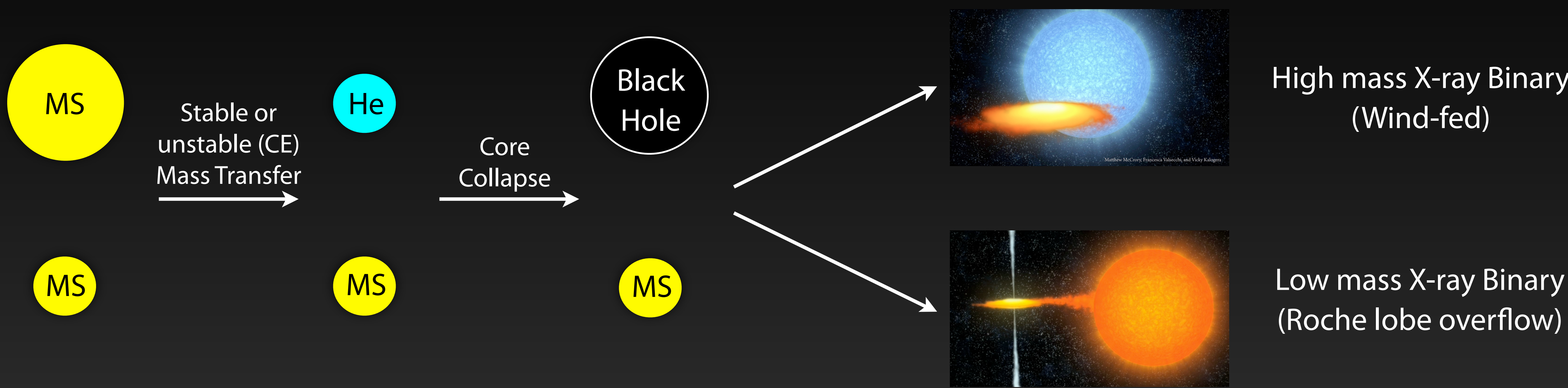


XRB Evolution across Cosmic Time:
Evolution of global XRB scaling relations

Galactic XRBs: Unraveling the Evolutionary History



Going backwards in time



Currently observed properties: Donor's position on the H-R (T_{eff} vs. L) diagram, BH and donor masses,orbital period, position in the galaxy and 3-D systemic velocity

Step 1: Model the mass-transfer phase

Step 2: Model the detached post-SN secular evolution

Step 3: Find the peculiar velocity post BH formation

Step 4: Compute the dynamics involved in core collapse

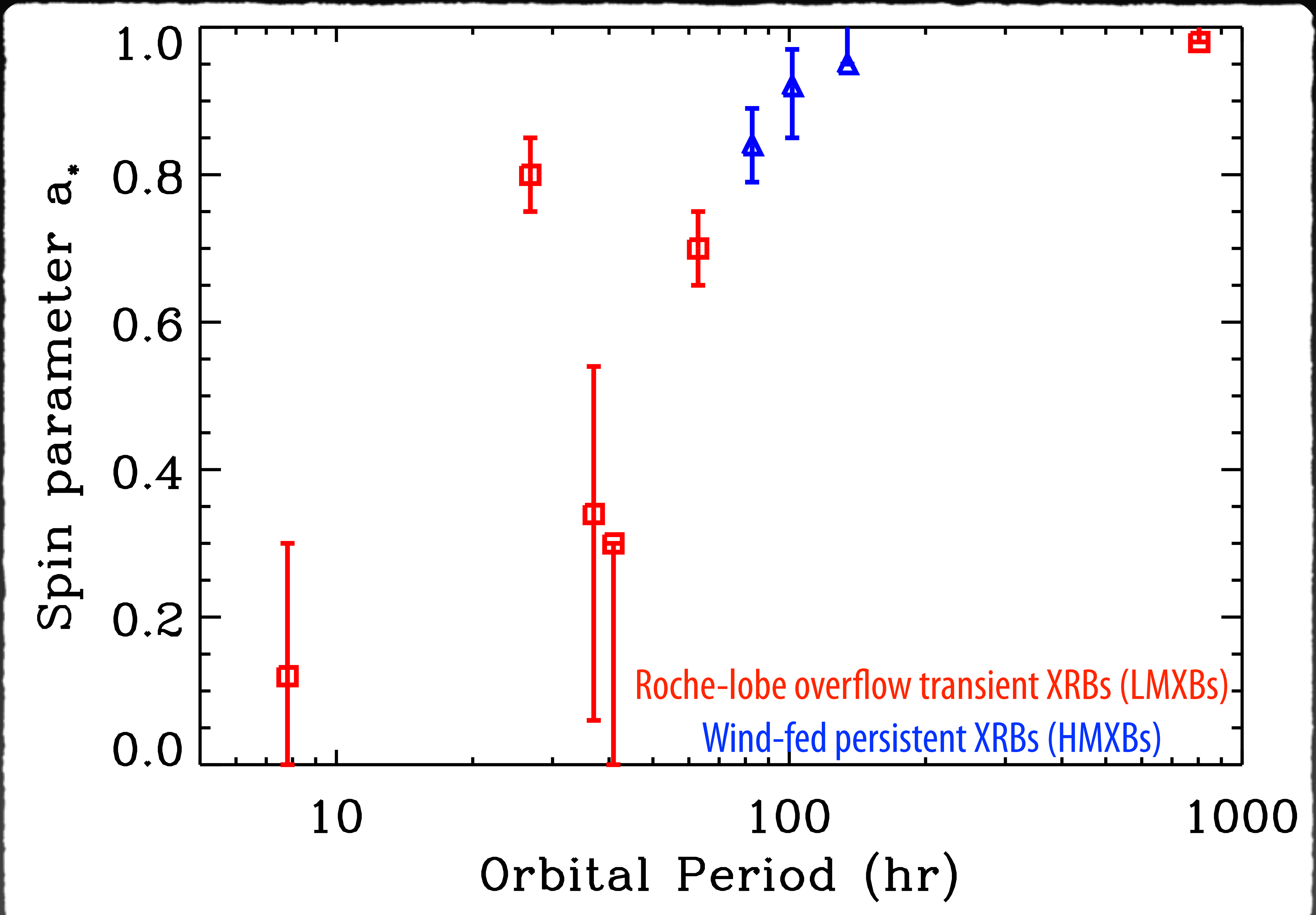
Derive limits on immediate progenitor mass and natal kicks magnitude

Results so far...

System	Observed Current BH mass ($M_\odot$)	Post-SN BH mass ($M_\odot$)	Immediate Progenitor mass ($M_\odot$)	Natal Kick (km/s)
XTE J1118+480 (late-type, P<1d)	8.0 ± 2.0 (McClintock et al. 2001, Wagner et al. 2001, Gelino et al. 2006)	6.0 – 10.0 (Fragos et al. 2009)	6.5 – 20.0 (Fragos et al. 2009)	80 – 310 (Fragos et al. 2009)
GRO J1655-40 (early-type, P>1d)	6.3 ± 0.5 (Greene et al. 2001) 5.4 ± 0.3 (Beer & Podsiadlowski 2002)	5.5 – 6.3 (Willems et al. 2005) 3.5 – 5.4 (Willems et al. 2005)	5.5 – 11.0 (Willems et al. 2005) 3.5 – 9.0 (Willems et al. 2005)	30 – 160 (Willems et al. 2005) ≤ 210 (Willems et al. 2005)
LMC X-3 (early-type, P>1d)	6.98 ± 0.56 (Orosz et al. 2014)	6.0 – 9.0 (Sorensen et al. 2015)	COMING SOON	COMING SOON
Cygnus X-1 (wind-fed, high mass)	14.81 ± 0.98 (Orosz et al. 2011)	13.8 – 15.8 (Wong et al. 2012)	15.0 – 20.0 (Wong et al. 2012)	≤ 77 (Wong et al. 2012)
IC10 X-1 (wind-fed, high mass)	23.0 - 34.0 (Orosz et al. 2011)	23.0 - 34.0 (Wong et al. 2014)	>31.0 (Wong et al. 2014)	≤ 130 (Wong et al. 2014)
M33 X-7 (wind-fed, high mass)	13.5 – 20.0 (Orosz et al. 2007, Valsecchi et al.2010)	13.5 – 14.5 (Valsecchi et al.2010)	15.0 – 16.1 (Valsecchi et al.2010)	≤ 850 (Valsecchi et al.2010)

Willems et al. 2005, ApJ, 625, 324
Fragos et al. 2009, ApJ, 697, 1057
Valsecchi et al. 2010, Nature, 468, 77
Wong et al. 2012, ApJ, 747, 111
Wong et al. 2014, ApJ, 790, 417
Sorensen et al. 2015, (In preparation)

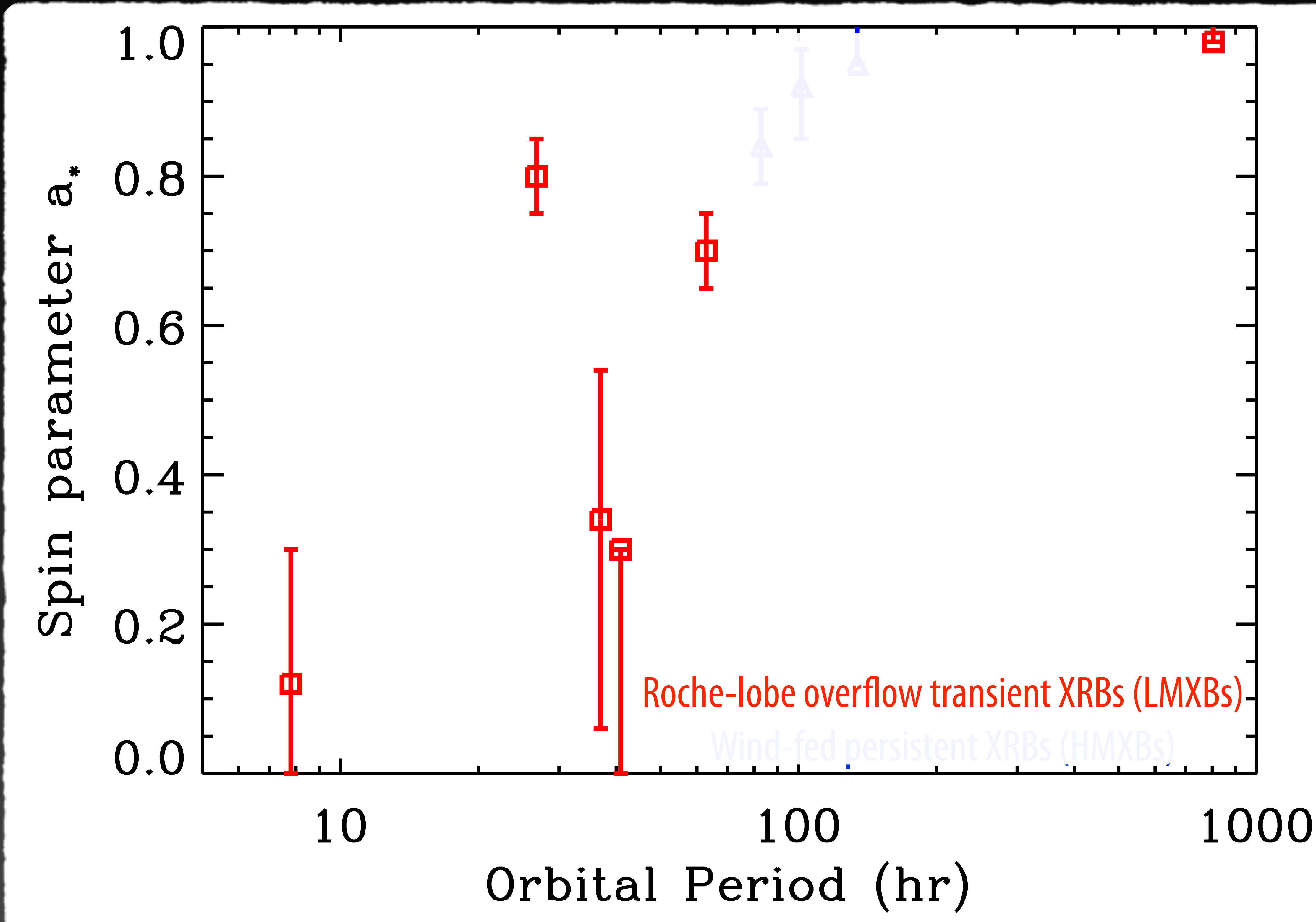
The origin of black-hole spin



The spin of 9 stellar BHs measured with the ***continuum fitting method***

McClintock et al. (2011, 2013)

The origin of black-hole spin



The spin of 9 stellar BHs measured with the ***continuum fitting method***

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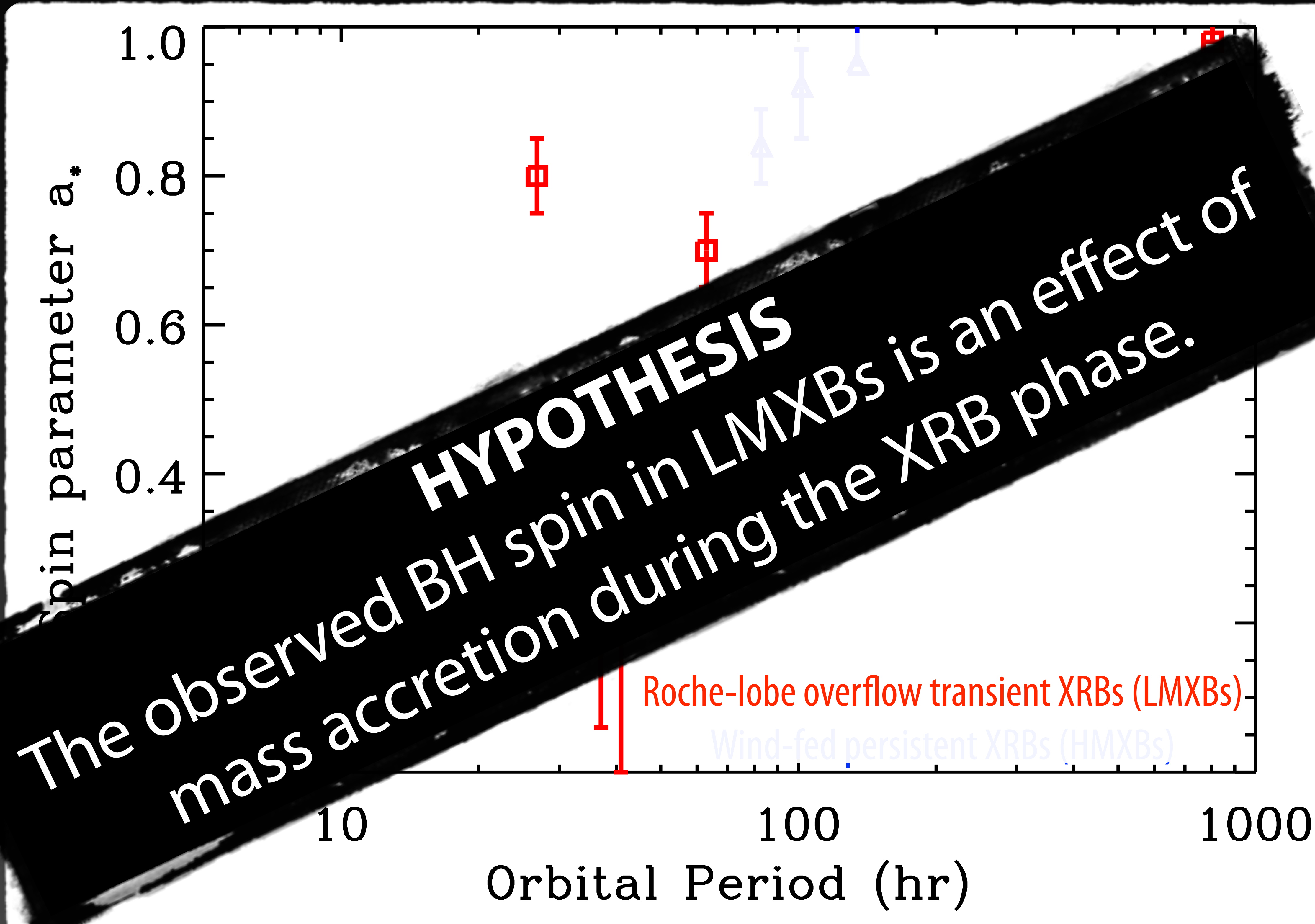
The origin of black-hole spin



HYPOTHESIS
The observed BH spin in LMXBs is an effect of mass accretion during the XRB phase.

The spin of 9 stellar BHs measured with the ***continuum fitting method***

McClintock et al. (2011, 2013)

The origin of black-hole spin

Retrieved binary properties at the onset of RLO

	$M_{BH,init}$ ($M_\odot$)	$M_{2,init}$ ($M_\odot$)	$P_{orb,init}$ (days)
GRS 1915+105	3-10	1.0-10.0	0.6-30.0
4U 1543-47	3-10	2.2-6.4	0.6- 1.1
GRO J1655-40	4- 6	2.6-5.0	0.7- 1.7
XTE J1550-564	7- 9	0.9-1.5	0.3- 0.9
A0620-00	5- 6	1.1-1.8	0.6- 0.8
GRS 1124-683	4- 8	1.0-1.8	0.3- 0.9
GX 339-4	3- 9	0.6-8.8	0.2- 1.7
XTE J1859+226	5- 9	0.6-1.8	0.2- 0.9
GS 2000+251	5- 9	0.9-1.8	0.3- 0.9
GRO J0422+32	5- 9	0.8-1.5	0.3- 0.7
GRS 1009-45	6-10	1.0-1.6	0.6- 0.8
GS 1354-64	3- 9	1.6-6.8	0.6- 2.4
GS 2023+338	7- 9	1.0-2.0	0.6- 2.0
H1705-250	4- 6	1.0-1.5	0.4- 0.9
V4641 Sgr	3- 4	7.0-7.8	1.2- 1.7
XTE J1118+480	6- 7	1.0-1.8	0.6- 0.8

Fragos & McClintock (2014) - arXiv:1408.2661

The origin of black-hole spin

Retrieved binary properties at the onset of RLO

	$M_{BH,init}$ ($M_\odot$)	$M_{2,init}$ ($M_\odot$)	$P_{orb,init}$ (days)	M_{acc} ($M_\odot$)
GRS 1915+105	3-10	1.0-10.0	0.6-30.0	0.0-9.0
4U 1543-47	3-10	2.2-6.4	0.6- 1.1	0.0-4.0
GRO J1655-40	4- 6	2.6-5.0	0.7- 1.7	0.5-3.2
XTE J1550-564	7- 9	0.9-1.5	0.3- 0.9	0.6-1.2
A0620-00	5- 6	1.1-1.8	0.6- 0.8	0.7-1.3
GRS 1124-683	4- 8	1.0-1.8	0.3- 0.9	0.3-1.1
GX 339-4	3- 9	0.6-8.8	0.2- 1.7	0.0-5.8
XTE J1859+226	5- 9	0.6-1.8	0.2- 0.9	0.1-1.5
GS 2000+251	5- 9	0.9-1.8	0.3- 0.9	0.1-1.3
GRO J0422+32	5- 9	0.8-1.5	0.3- 0.7	0.2-1.0
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GS 2023+338	7- 9	1.0-2.0	0.6- 2.0	0.4-1.4
H1705-250	4- 6	1.0-1.5	0.4- 0.9	0.9-1.4
V4641 Sgr	3- 4	7.0-7.8	1.2- 1.7	2.3-2.6
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Fragos & McClintock (2014) - arXiv:1408.2661

The origin of black-hole spin

Retrieved binary properties at the onset of RLO

	$M_{BH,init}$ $(M_\odot)$	$M_{2,init}$ $(M_\odot)$	$P_{orb,init}$ (days)	M_{acc} $(M_\odot)$	a_*
GRS 1915+105	3-10	1.0-10.0	0.6-30.0	0.0-9.0	0.01-1.00
4U 1543-47	3-10	2.2-6.4	0.6- 1.1	0.0-4.0	0.01-1.00
GRO J1655-40	4- 6	2.6-5.0	0.7- 1.7	0.5-3.2	0.26-0.94
XTE J1550-564	7- 9	0.9-1.5	0.3- 0.9	0.6-1.2	0.21-0.44
A0620-00	5- 6	1.1-1.8	0.6- 0.8	0.7-1.3	0.34-0.59
GRS 1124-683	4- 8	1.0-1.8	0.3- 0.9	0.3-1.1	0.12-0.62
GX 339-4	3- 9	0.6-8.8	0.2- 1.7	0.0-5.8	0.01-1.00
XTE J1859+226	5- 9	0.6-1.8	0.2- 0.9	0.1-1.5	0.02-0.63
GS 2000+251	5- 9	0.9-1.8	0.3- 0.9	0.1-1.3	0.05-0.57
GRO J0422+32	5- 9	0.8-1.5	0.3- 0.7	0.2-1.0	0.09-0.49
GRS 1009-45	6-10	1.0-1.6	0.6- 0.8	0.5-1.3	0.15-0.50
GS 1354-64	3- 9	1.6-6.8	0.6- 2.4	0.0-5.1	0.01-1.00
GS 2023+338	7- 9	1.0-2.0	0.6- 2.0	0.4-1.4	0.13-0.49
H1705-250	4- 6	1.0-1.5	0.4- 0.9	0.9-1.4	0.40-0.63
V4641 Sgr	3- 4	7.0-7.8	1.2- 1.7	2.3-2.6	0.85-0.94
XTE J1118+480	6- 7	1.0-1.8	0.6- 0.8	0.7-1.6	0.29-0.59

Fragos & McClintock (2014) - arXiv:1408.2661

The origin of black-hole spin

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A0620-00	5- 6	1.1-1.8	0.6- 0.8	0.7-1.3	0.34-0.59
GRS 1124-683	4- 8	1.0-1.8	0.3- 0.9	0.3-1.1	0.12-0.62
GX 339-4	3- 9	0.6-8.8	0.2- 1.7	0.0-5.8	0.01-1.00
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GRO J0422+32	5- 9	0.8-1.5	0.3- 0.7	0.2-1.0	0.09-0.49
GRS 1009-45	6-10	1.0-1.6	0.6- 0.8	0.5-1.3	0.15-0.50
GS 1354-64	3- 9	1.6-6.8	0.6- 2.4	0.0-5.1	0.01-1.00
GS 2023+338	7- 9	1.0-2.0	0.6- 2.0	0.4-1.4	0.13-0.49
H1705-250	4- 6	1.0-1.5	0.4- 0.9	0.9-1.4	0.40-0.63
V4641 Sgr	3- 4	7.0-7.8	1.2- 1.7	2.3-2.6	0.85-0.94
XTE J1118+480	6- 7	1.0-1.8	0.6- 0.8	0.7-1.6	0.29-0.59

Fragos & McClintock (2014) - arXiv:1408.2661

The origin of black-hole spin

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GRS 1124-683	4- 8	1.0-1.8	0.3- 0.9	0.3-1.1	0.12-0.62
GX 339-4	3- 9	0.6-8.8	0.2- 1.7	0.0-5.8	0.01-1.00
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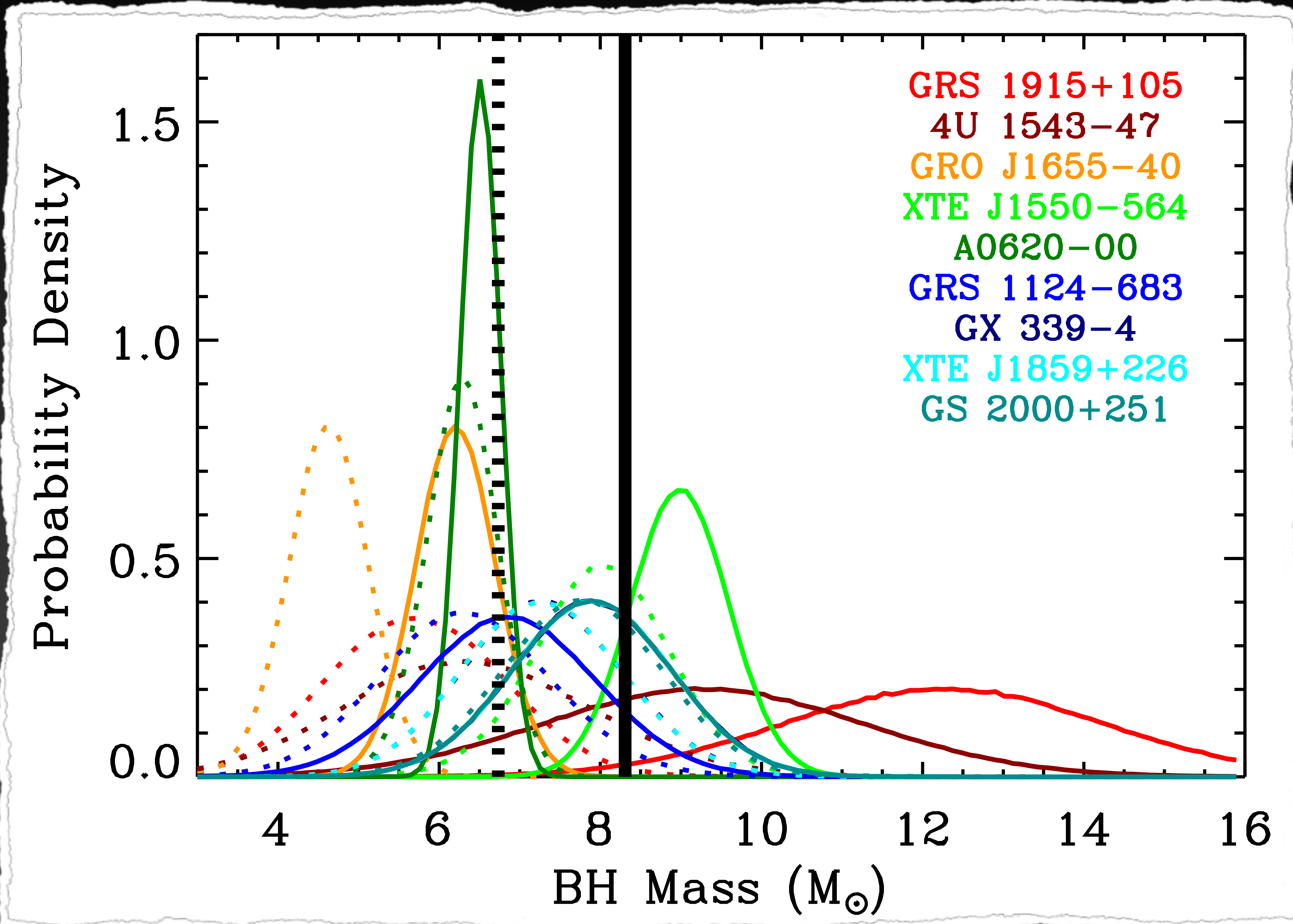
V4641 Sgr	3- 4	7.0-7.8	1.2- 1.7	2.3-2.6	0.85-0.94
XTE J1118+480	6- 7	1.0-1.8	0.6- 0.8	0.7-1.6	0.29-0.59

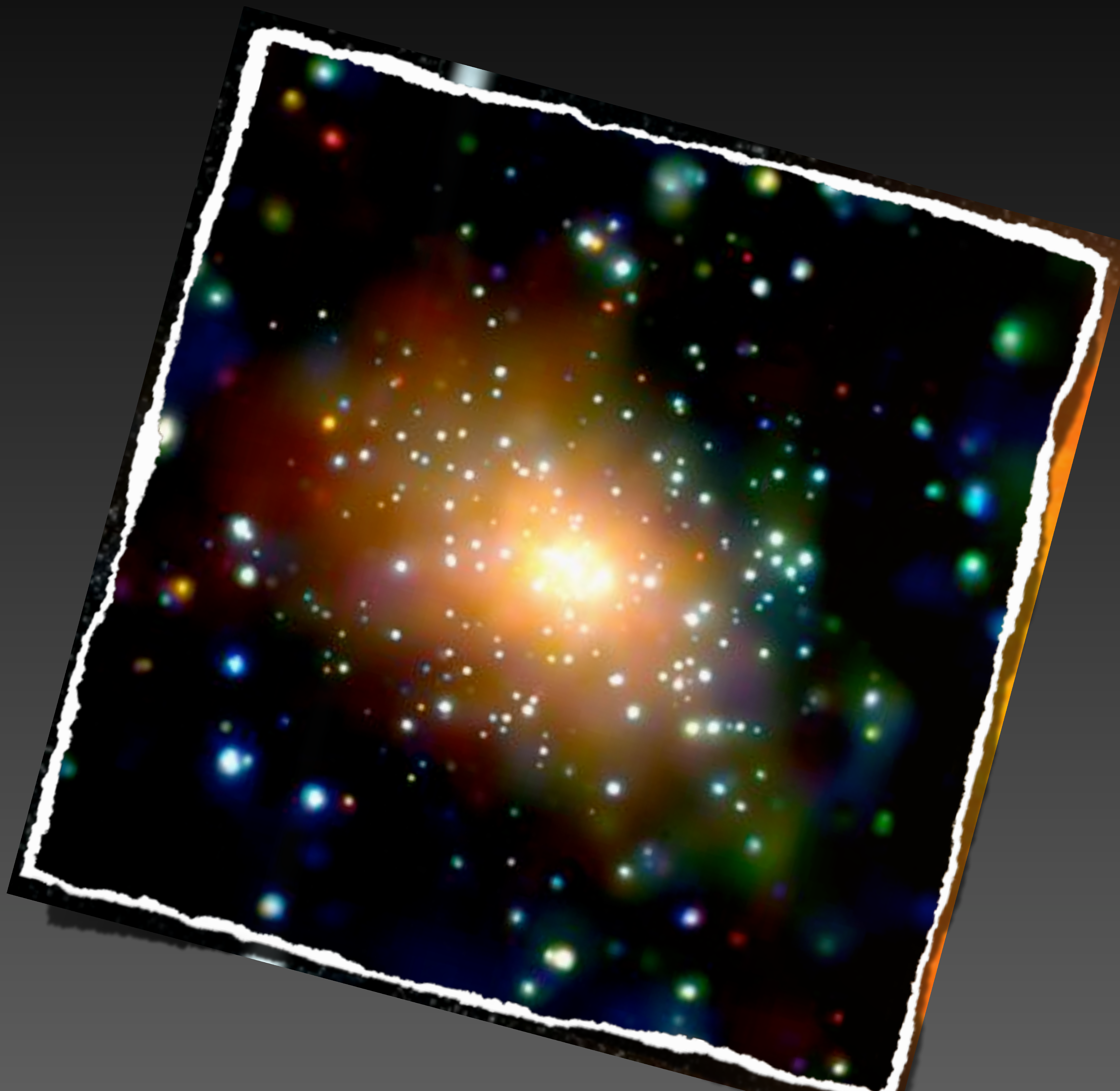
Fragos & McClintock (2014) - arXiv:1408.2661

Implications on birth black-hole mass



Fragos & McClintock (2014) - arXiv:1408.2661

Extragalactic XRBs: Population Synthesis Models



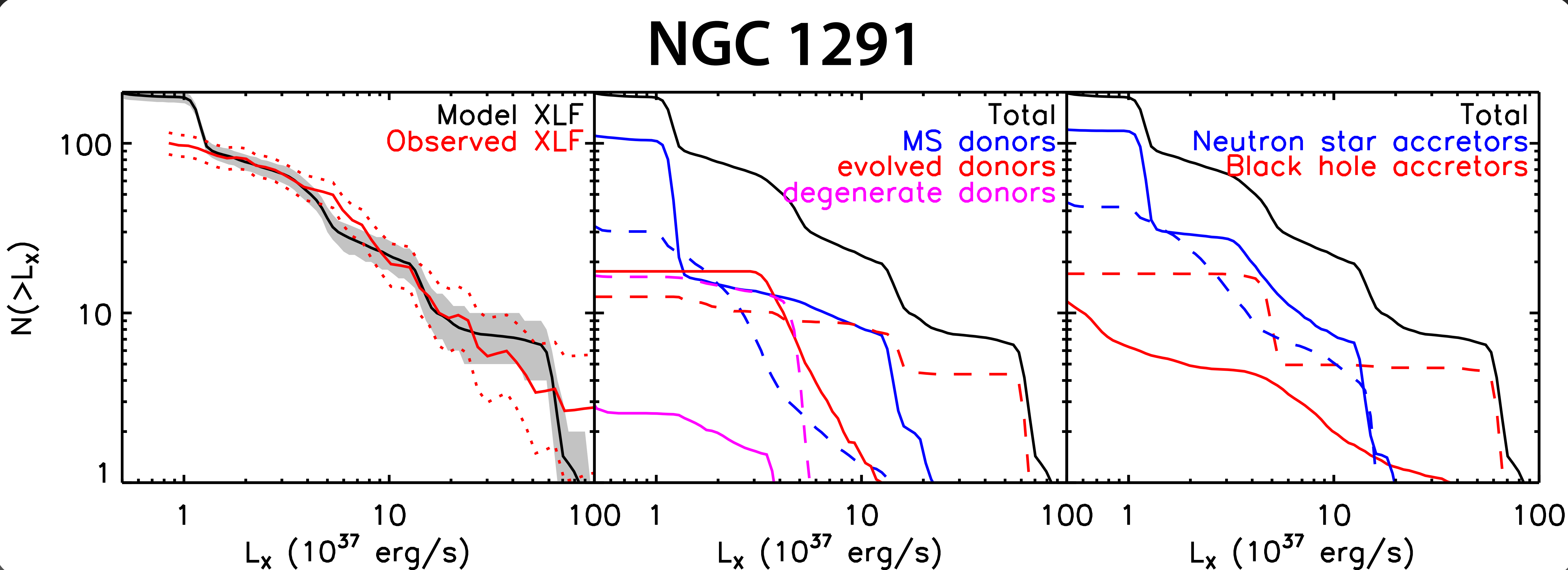
Elliptical Galaxies: NGC3379, NGC4278, NGC1291

Andreas Zezas

XSINGS: X-ray Luminosity Functions of Star-forming Galaxies

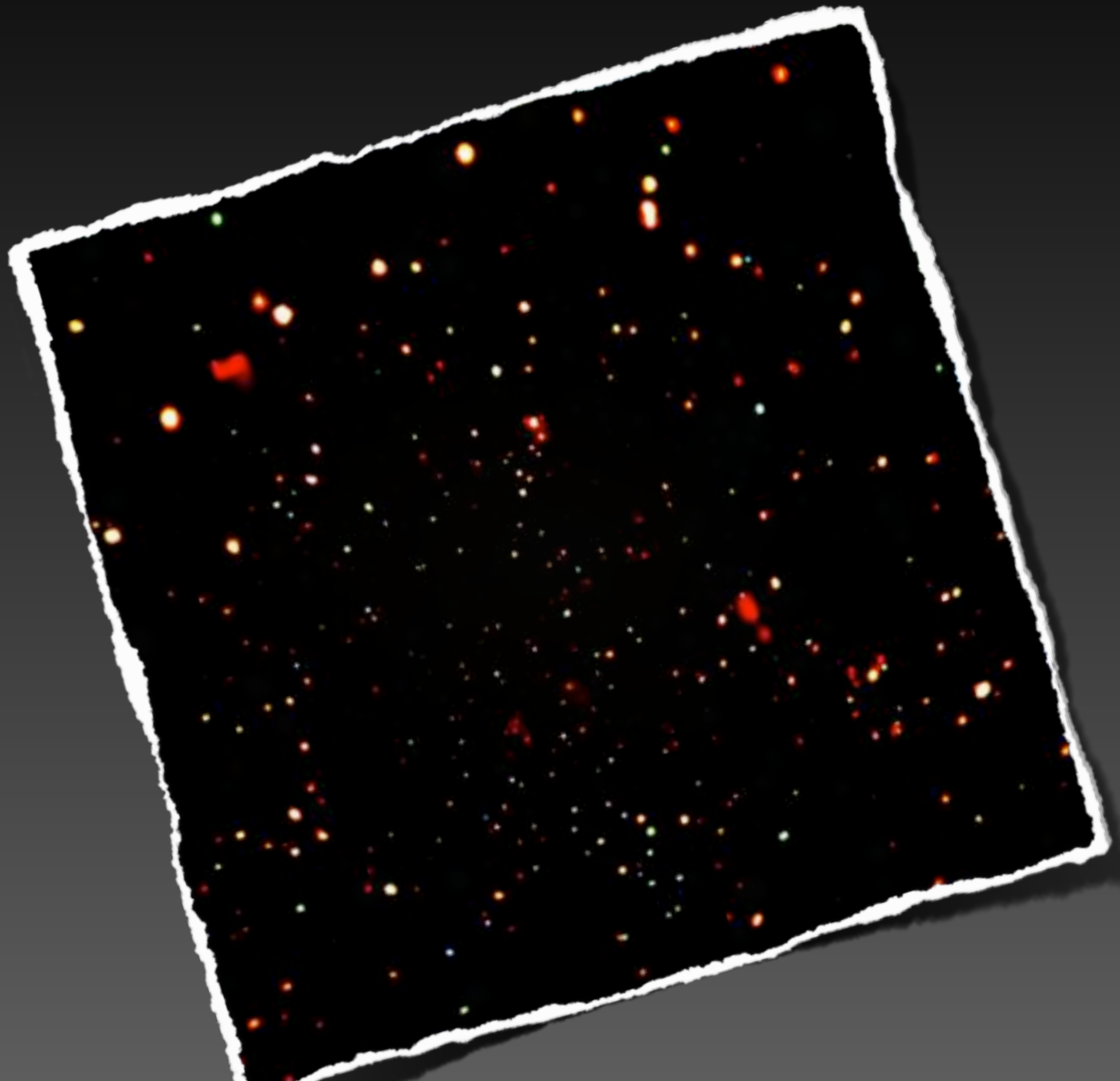
Tim Linden

Modeling of High-Mass X-ray Binaries

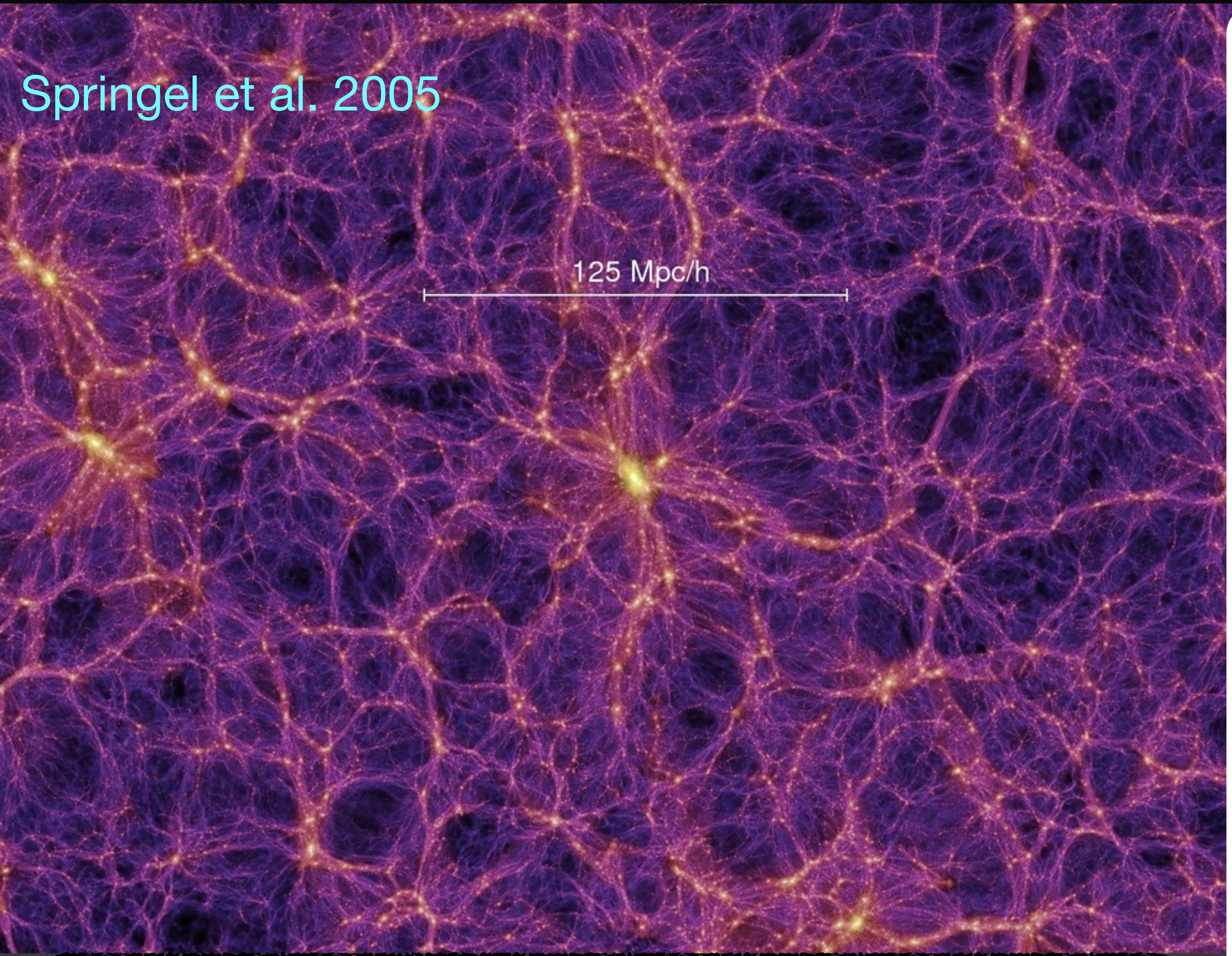


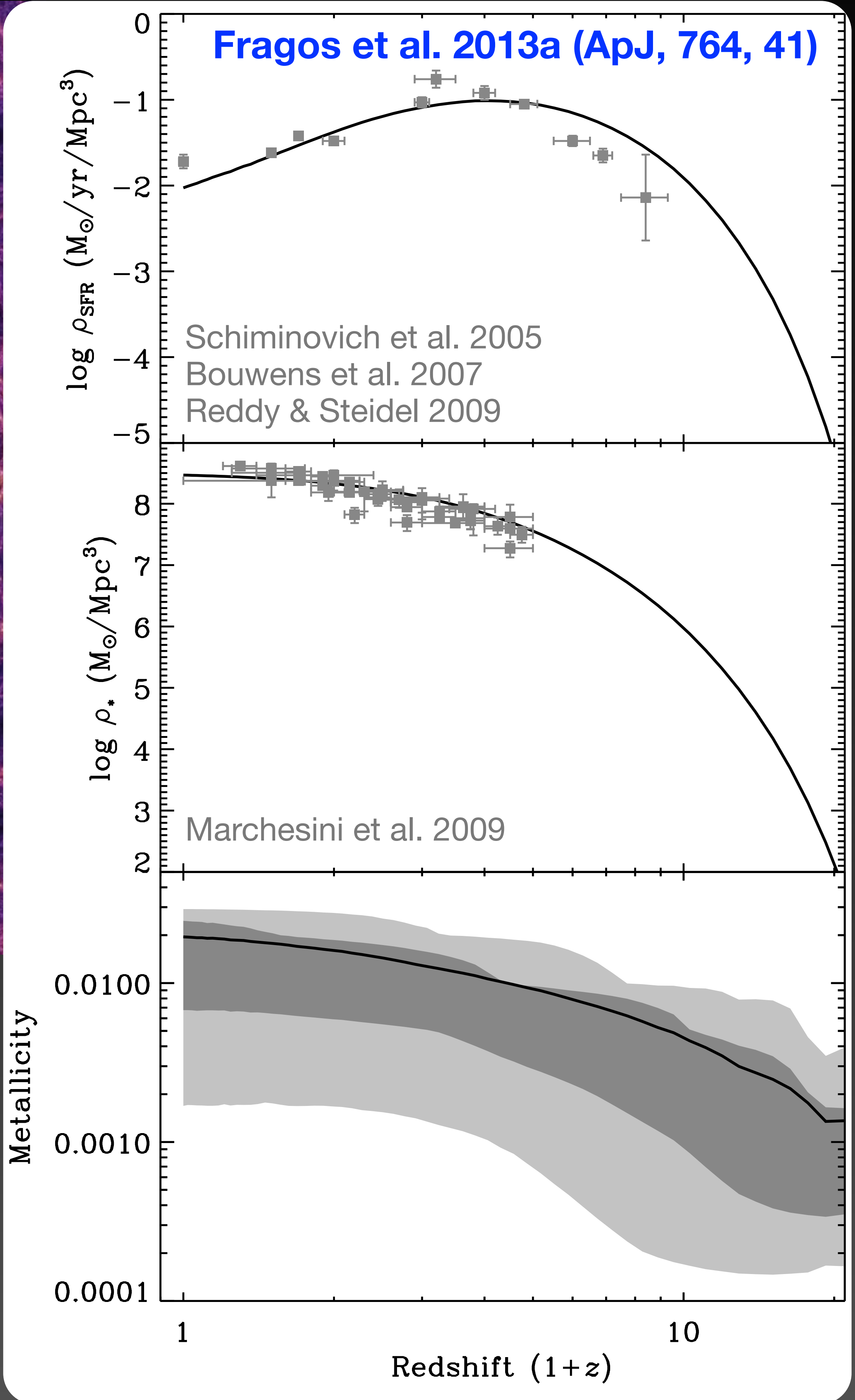
Fragos et al. 2008, ApJ, 683, 346
Fragos et al. 2009, ApJL, 702, 143
Luo et al. 2011, ApJ, 749, 130

Global XRB scaling relations: Evolution across cosmic time



Input: The Millennium II Simulation





Millennium-II Simulation

100Mpc^3/h volume - 125x better mass resolution - 5x better spatial resolution (Boylan-Kolchin et al. 2009)

Updated semi-analytic galaxy catalogs by Guo et al. 2011

Energy feedback from XRBs

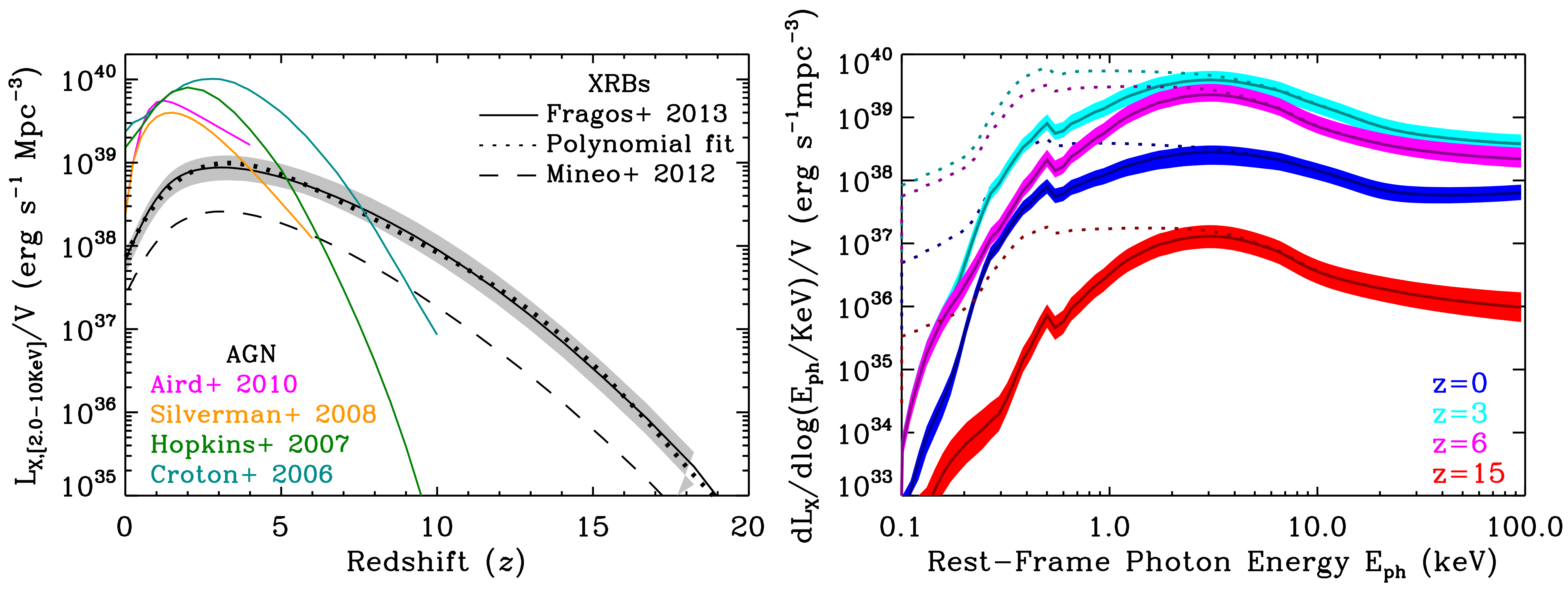
Good agreement with high-z normal galaxy observations:

✓X-ray stacking of Lyman-break galaxies in the 4Ms CDF-S
(Basu-Zych et al., 2013, ApJ, 742, 45)

✓X-ray stacking of star-forming galaxies in the 4Ms CDF-S
(Mineo et al., 2014, MNRAS, 437,1698)

✓Shape and evolution of galaxy XLF with redshift
(Tremmel et al. 2013, ApJ, 766, 19)

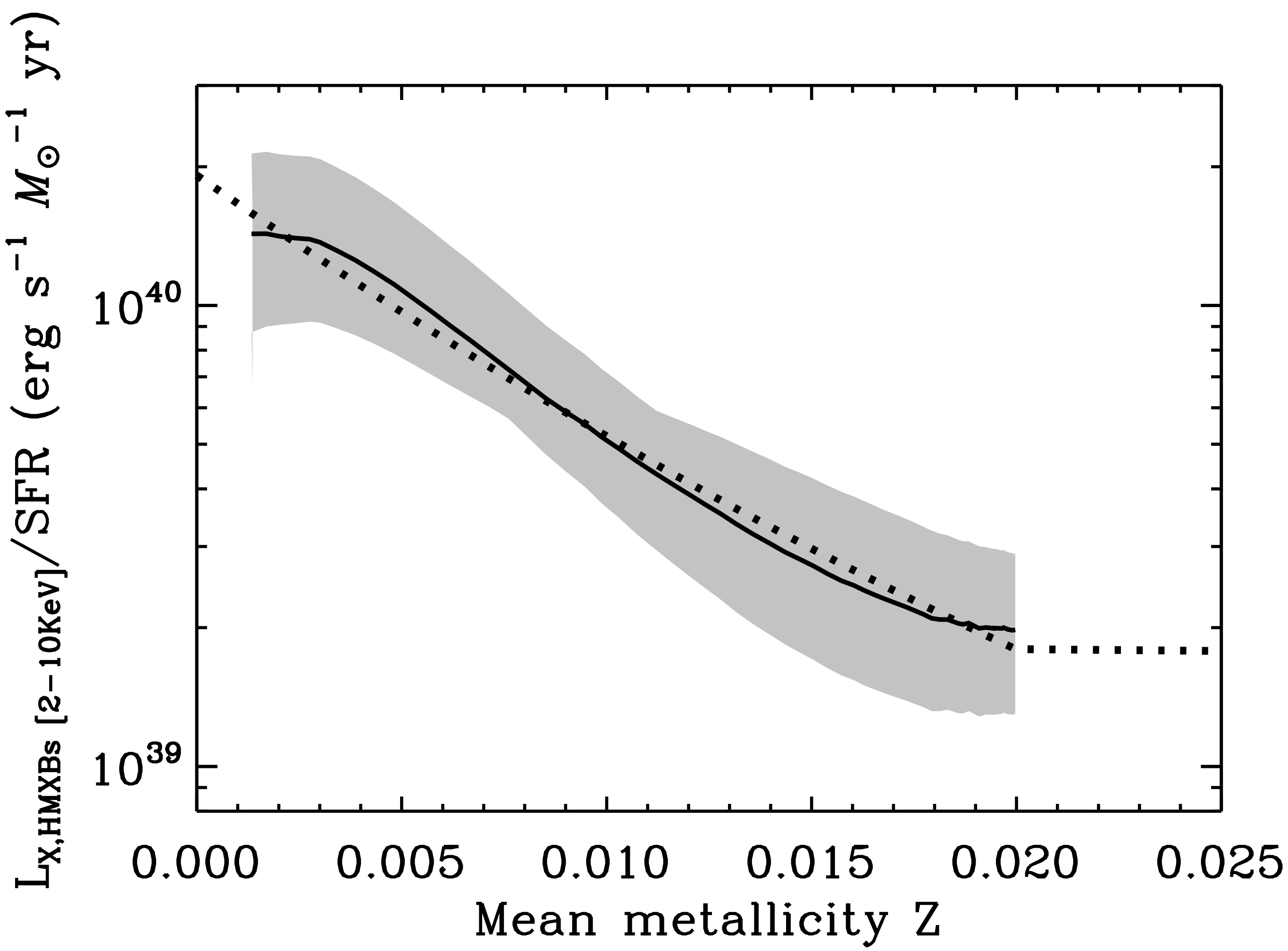
Fragos et al. 2013b (ApJL, 776, 13)

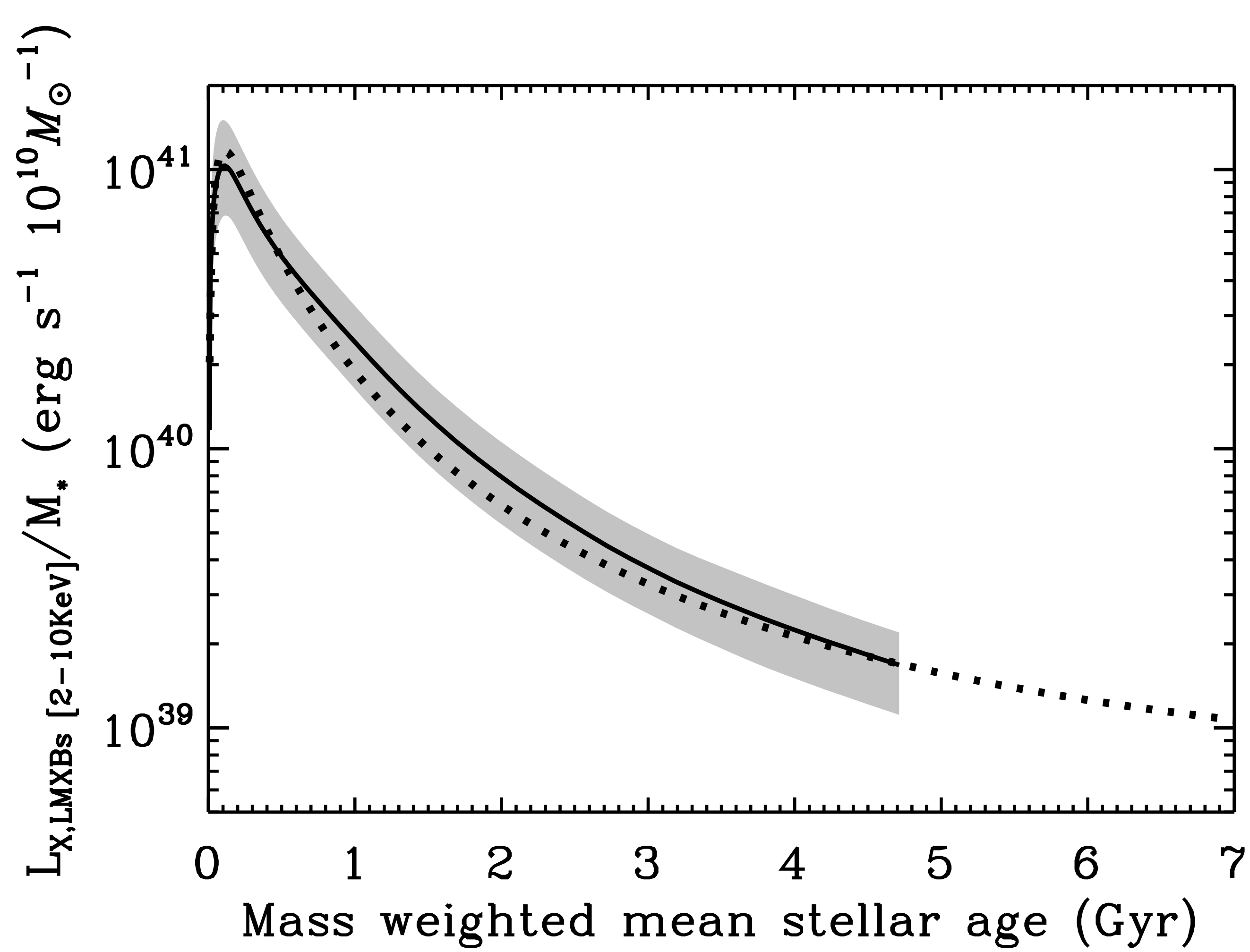


Energy feedback from XRBs

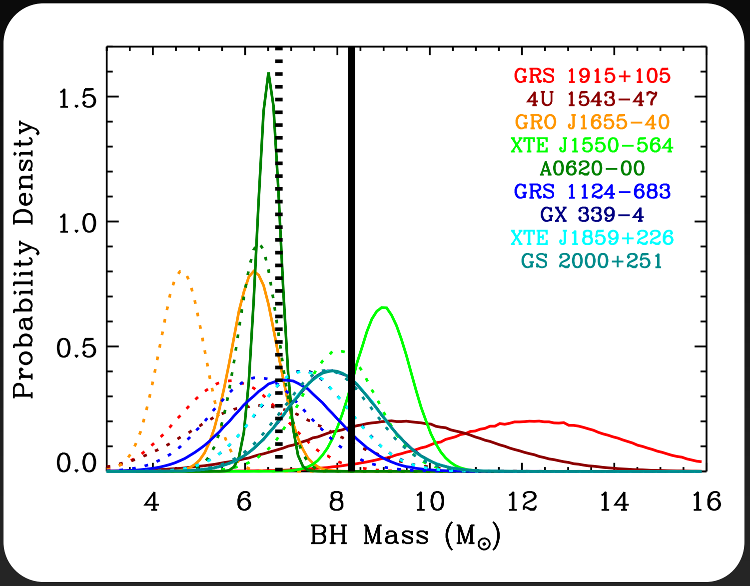
- $L_{X,HMXBs}$/SFR varies by factor of ~10 with metallicity
- $L_{X,LMXBs}/M_*$ peaks at ~300 Myr and then gradually decreases
- $L_{X,LMXBs}/M_*$ varies little for stellar ages larger than 3 Gyr

Fragos et al. 2013b (ApJL, 776, 13)





Summary

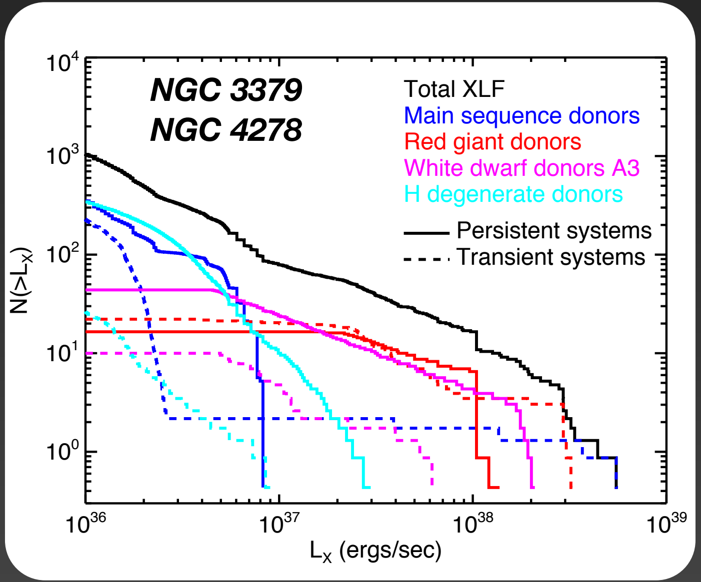


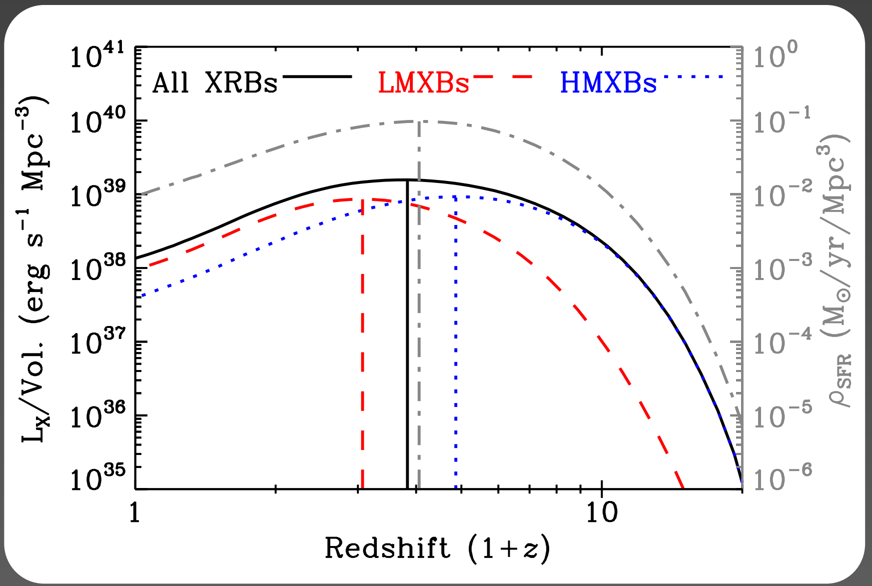
We studied the origin of BH spin in Galactic LMXBs, and the **detailed evolutionary history** of six Galactic BH X-ray binaries, taking into account **all available observational constraints** was examined.

Fragos et al. (2014; arxiv:1408.2661), Willems et al. (2005; ApJ,625,324), Fragos et al. (2009; ApJ, 697,1057) Valsecchi et al. (2012; Nature,468,77), Wong et al. (2011; ApJ, 747,111), Wong et al. (2014; ApJ, 790,417)

We developed **models for the XRB populations** of elliptical and star-forming galaxies and **compared them with the observed XLFs**.

Fragos et al. (2008; ApJ, 683, 346), Fragos et al. (2009; ApJL, 702, 143), Luo et al. (2011; ApJ, 749, 130), Tzanavaris, Fragos et al. (2013; ApJ, 774,136), Ivanova, Fragos et al (2013; ApJL, 760,24)





We studied the evolution of **XRB populations across cosmic time**, studying the **evolution of global scaling relations**.

Fragos et al. (2013; ApJ,764,41), Fragos et al. (2013; ApJL,726,31), Basu-Zych et al. (2013; ApJ,742,45) Tremmel, Fragos et al. (2013; ApJ,766,19), Basu-Zych et al. (2013; ApJ, 152,12)