What do we know about BH spins, masses (…and kicks) from BH X-ray binaries

Tassos Fragos[1,2]
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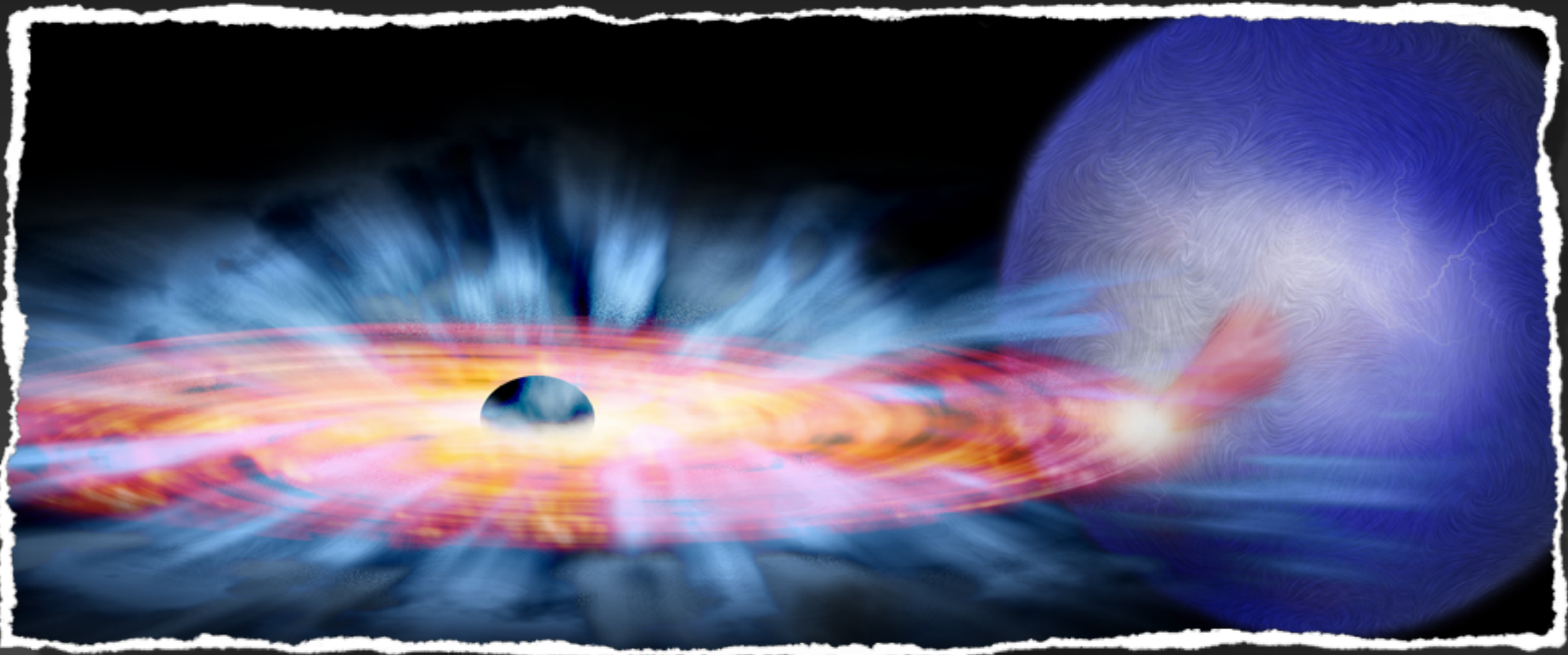
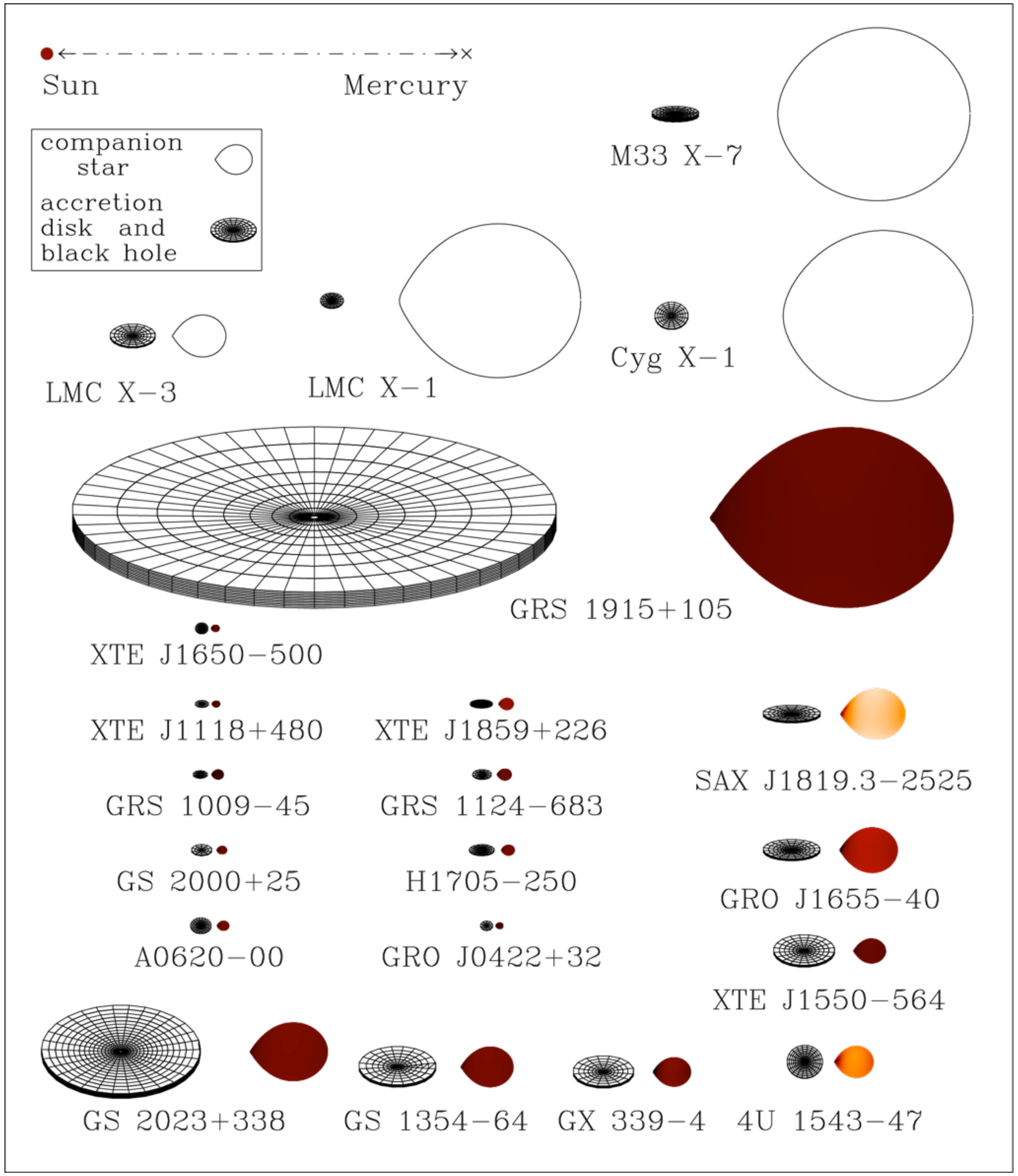
[2]*SNSF Ambizione Fellow*



KITP

March 24th 2017

Dynamically confirmed black holes



- Cyg X-1: the first BH candidate

  Bolton (1972), Webster & Mardin (1972)

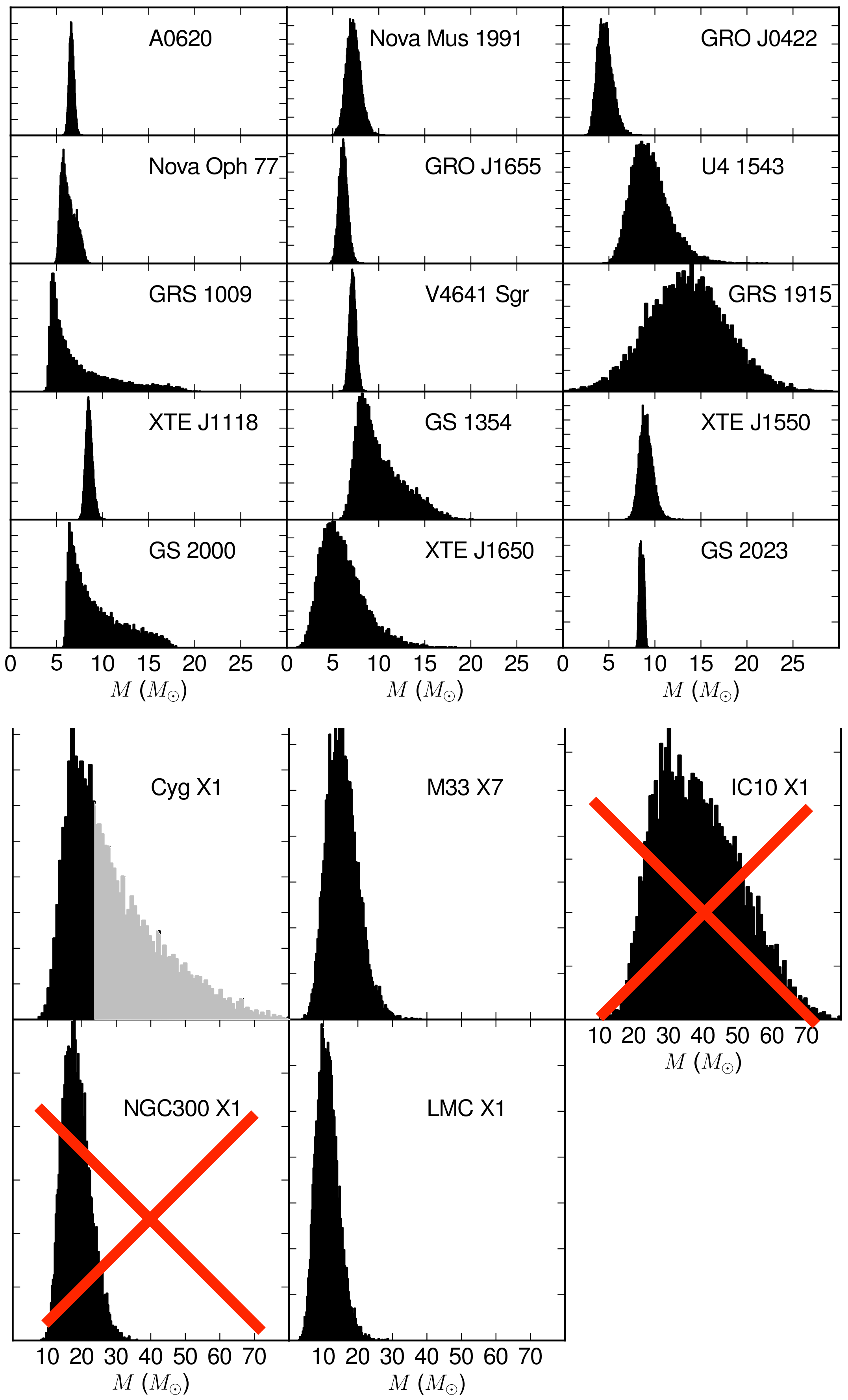
- 21 BHs with dynamical mass measurement

  McClintock &Remillard 2006, Casares & Jonker 2014

- 18 Galactic, 3 in nearby galaxies
- 33 more BH candidates

Dynamically confirmed black holes

Farr et al. (2011)



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Özel et al. (2011)

LMXBs: $M_{\mathrm{BH,current}} \sim 7.8 \pm 1.2\ M_\odot$

HMXBs: $M_{\mathrm{BH}} \sim 10\text{-}16\ M_\odot$

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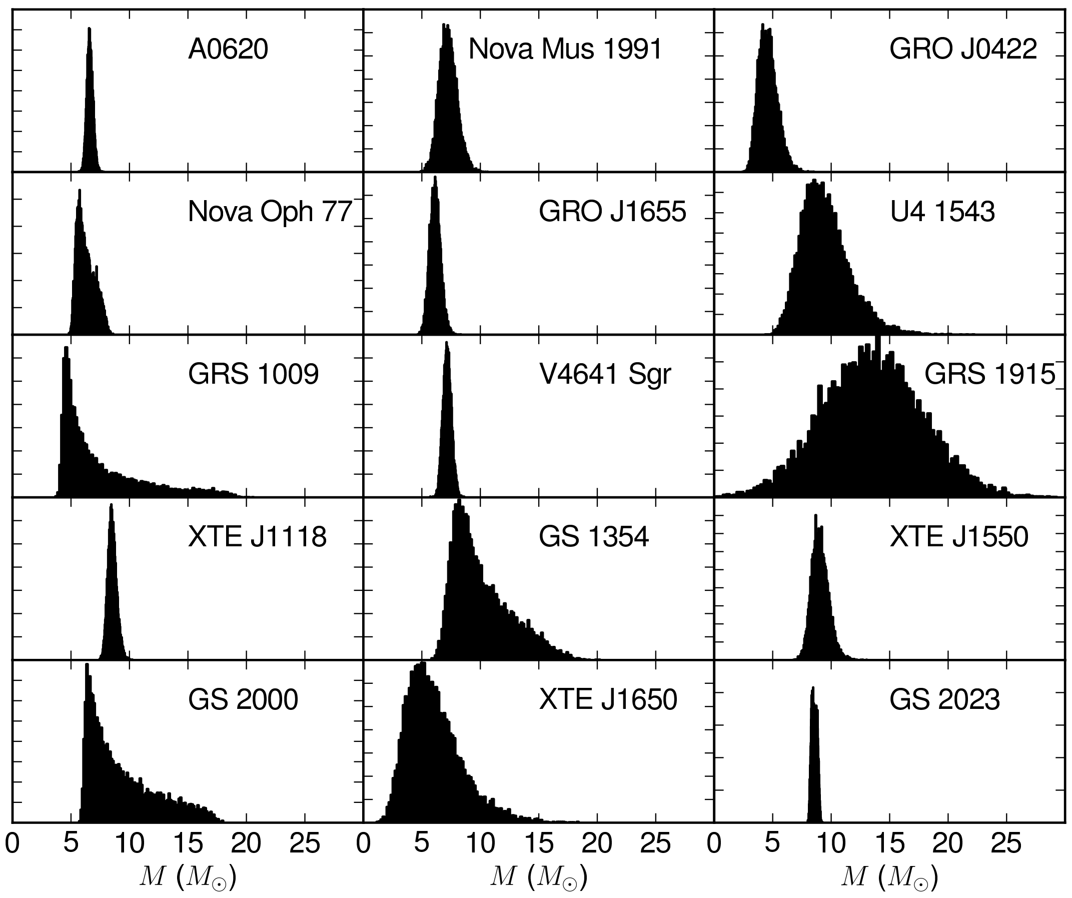

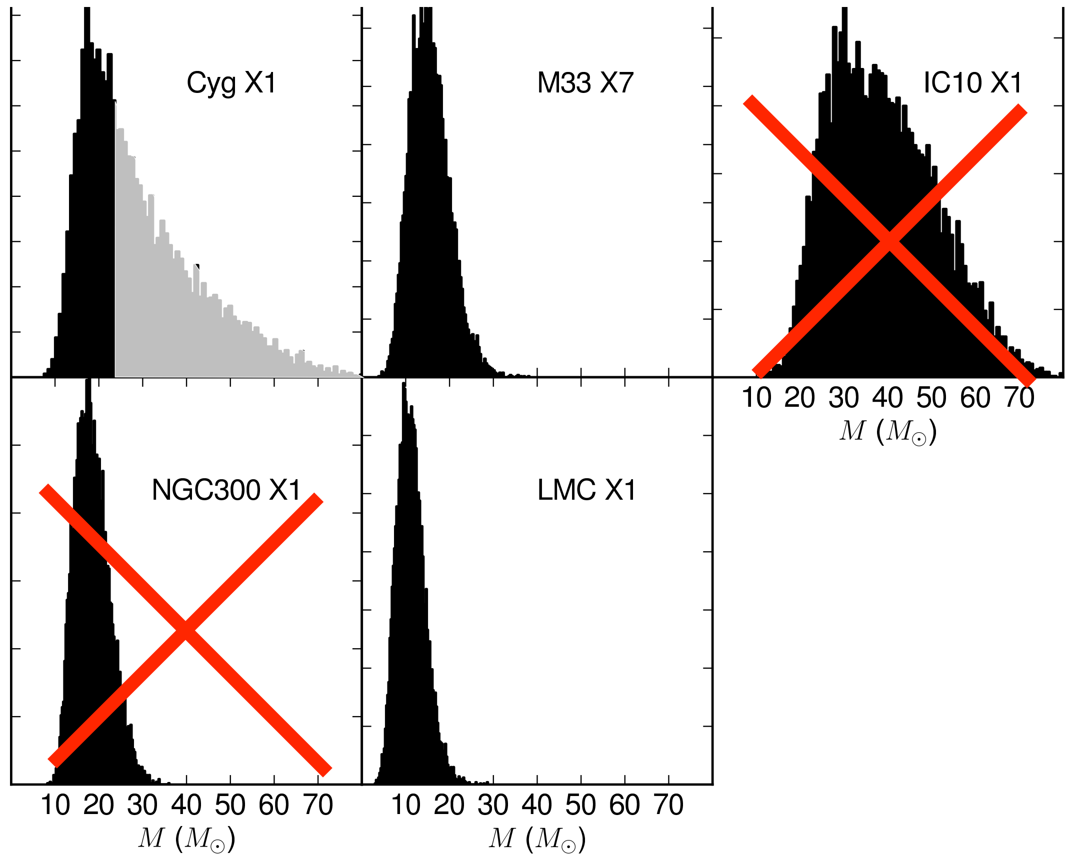

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LMXBs: $M_{BH,current} \sim 7.8 \pm 1.2\ M_\odot$

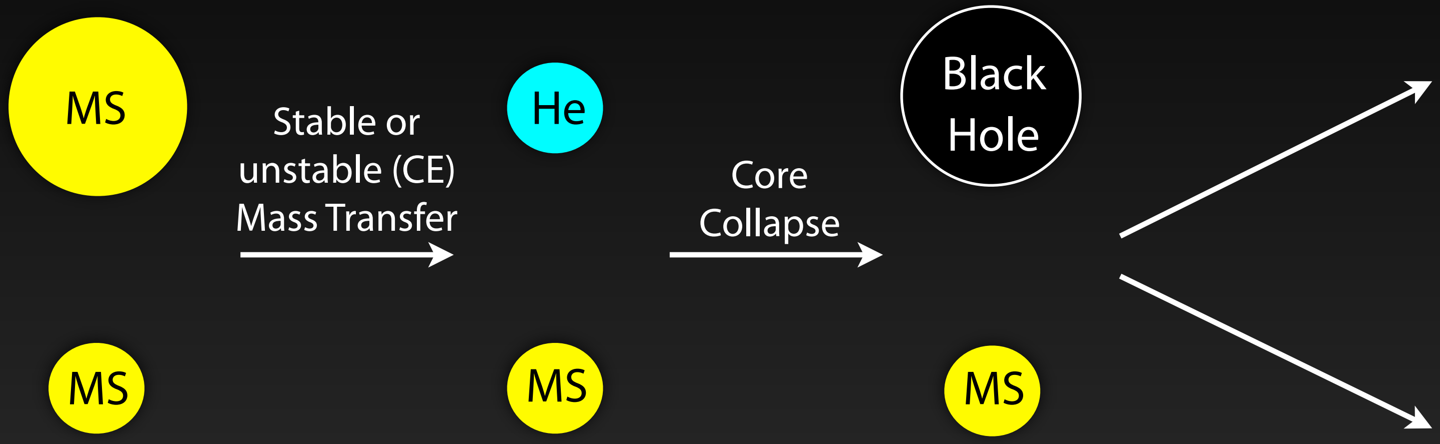
Fragos & McCLintock (2015)

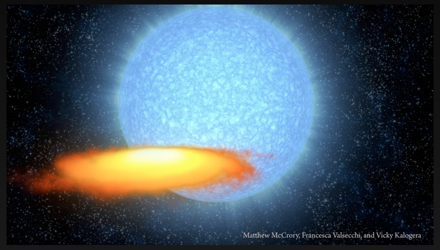
$M_{BH,natal} \sim 6.3 \pm 1.1\ M_\odot$

HMXBs: $M_{BH} \sim 10\text{-}16\ M_\odot$

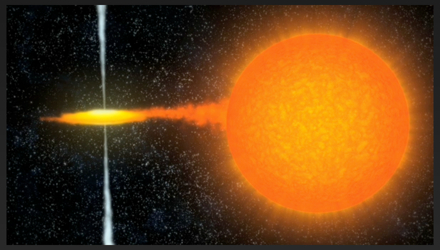
Formation of Black Hole X-ray Binaries

van den Heuvel 1992; Tauris & Van den Heuvel 1996; Podsiadlowski et al. 2003




Matthew McCrory, Francesca Valsecchi, and Vicky Kalogera

High mass X-ray Binary
(Wind-fed)



Low mass X-ray Binary
(Roche lobe overflow)

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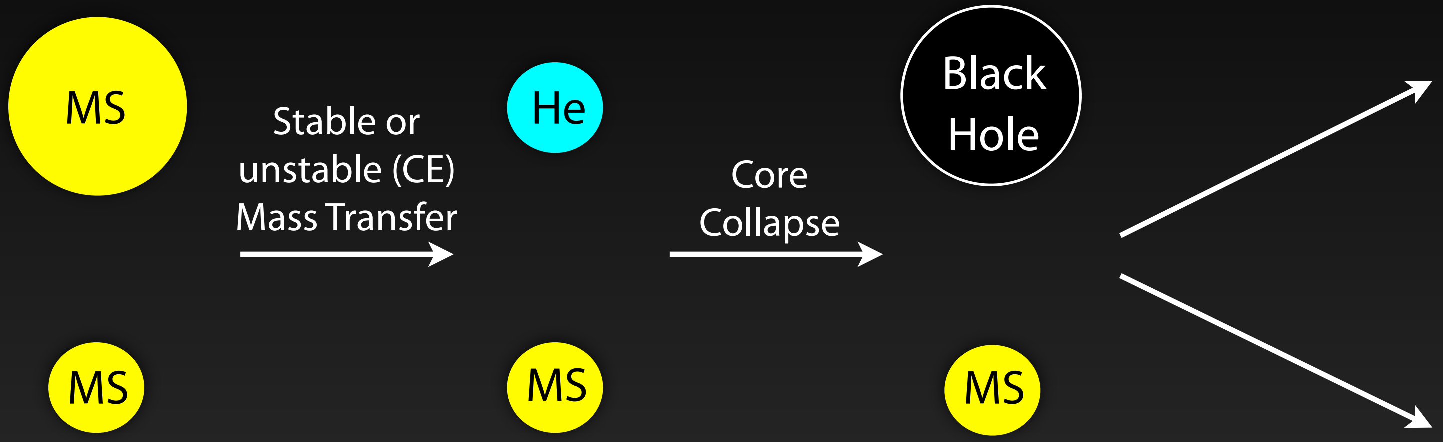

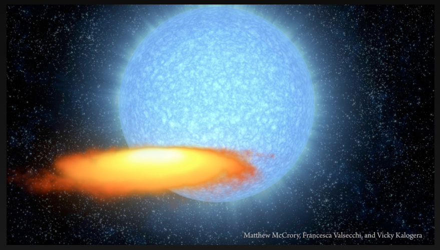
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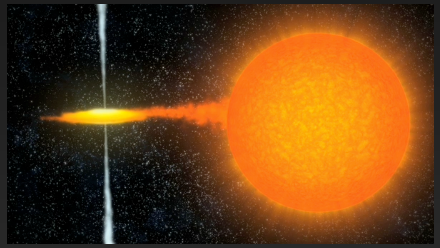


Low mass X-ray Binary
(Roche lobe overflow)

Dynamical Formation

*Voss et al. 2006; Naoz, **TF** et al 2016; Erez & Perets 2016; Jakub et al. 2016*

Explosive CE

Podsiadlowski et al. 2010

Pre-MS donors

Ivanova 2006

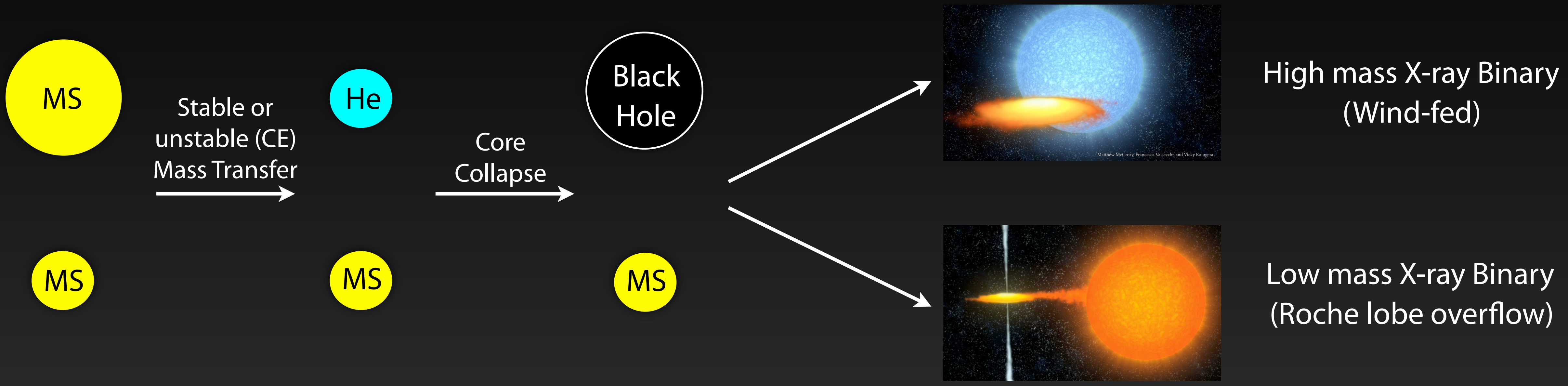
Intermediate mass donors

Justham et al. 2006;
Chen & Li 2006;
Chen & Podsiadlowski 2016

Case-M Evolution

De Mink et al. 2009

Going backwards in time



MS

MS

Stable or
unstable (CE)
Mass Transfer

He

MS

Core
Collapse

Black
Hole

MS

Matthew McCrory, Francesca Valsecchi, and Vicky Kalogera

High mass X-ray Binary
(Wind-fed)

Low mass X-ray Binary
(Roche lobe overflow)

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 (MESA; Paxton et al. 2011,2013,2015)

Step 2: Model the detached post-SN secular evolution

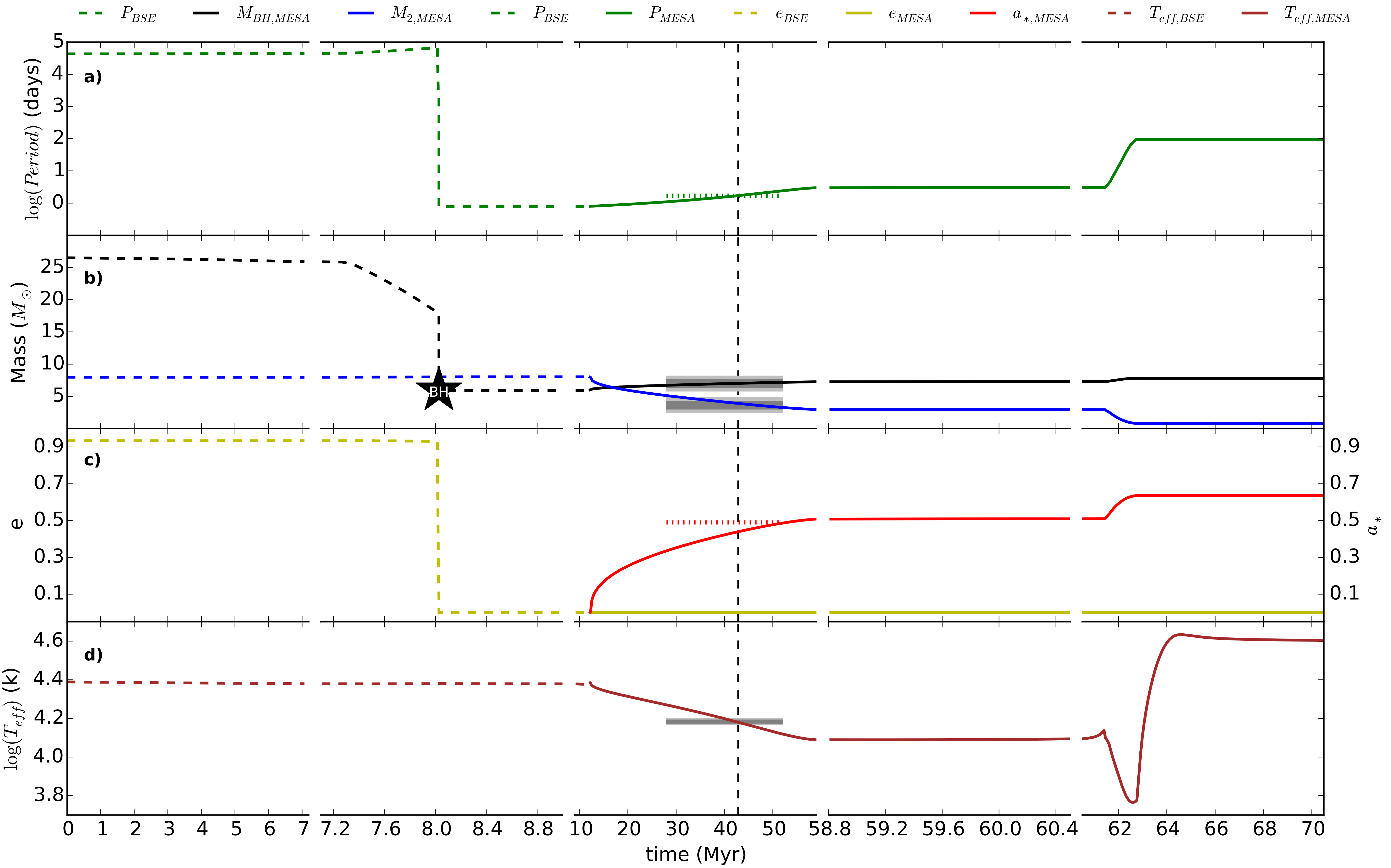
Step 3: Find the peculiar velocity post BH formation

Step 4: Compute the orbital dynamics involved in core collapse

Derive limits on immediate progenitor mass and natal kicks magnitude

Step 5: Compute priors based on population synthesis models and derive PDFs
(BSE; Hurley et al. 2002)

The case of LMC X-3



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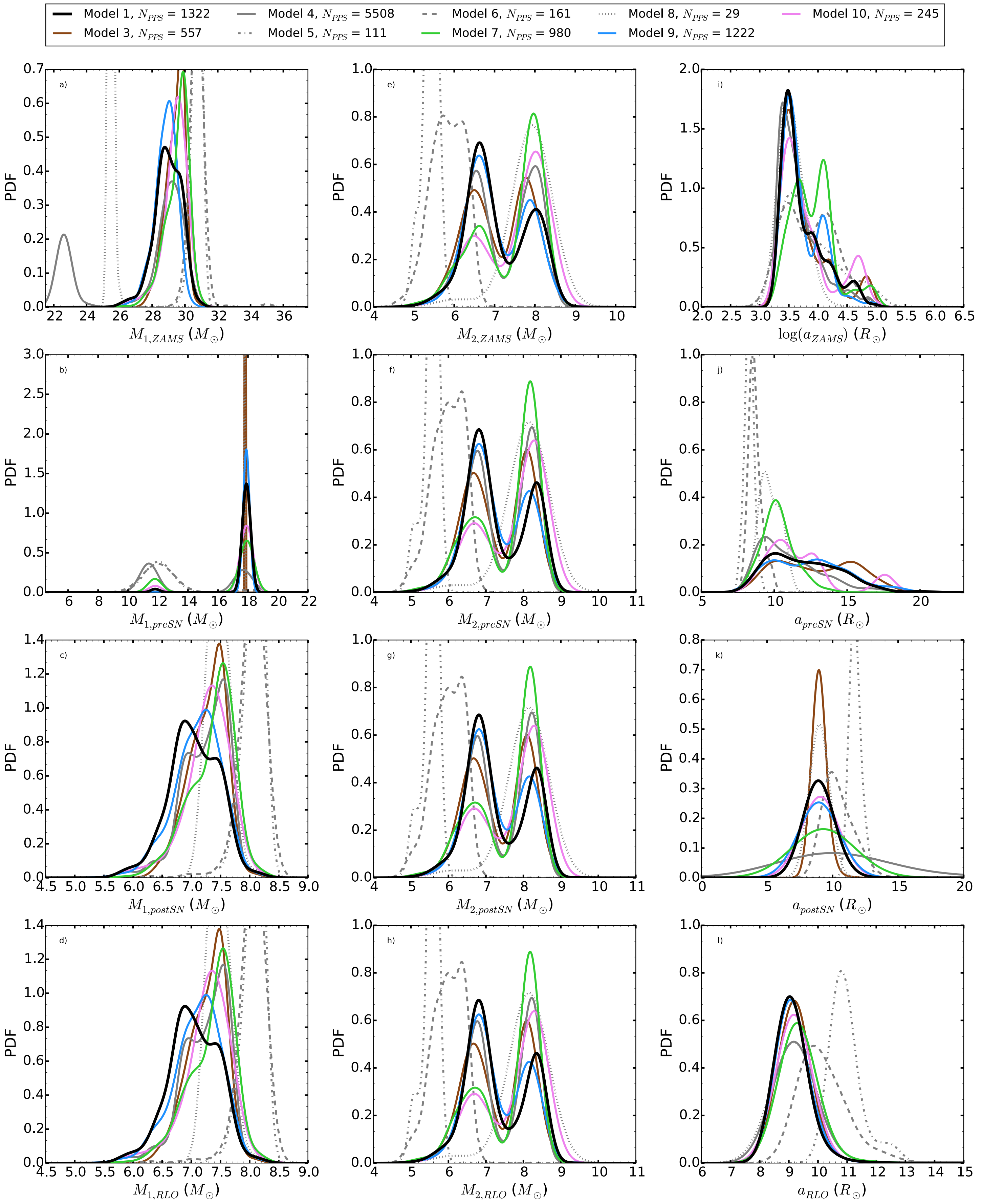

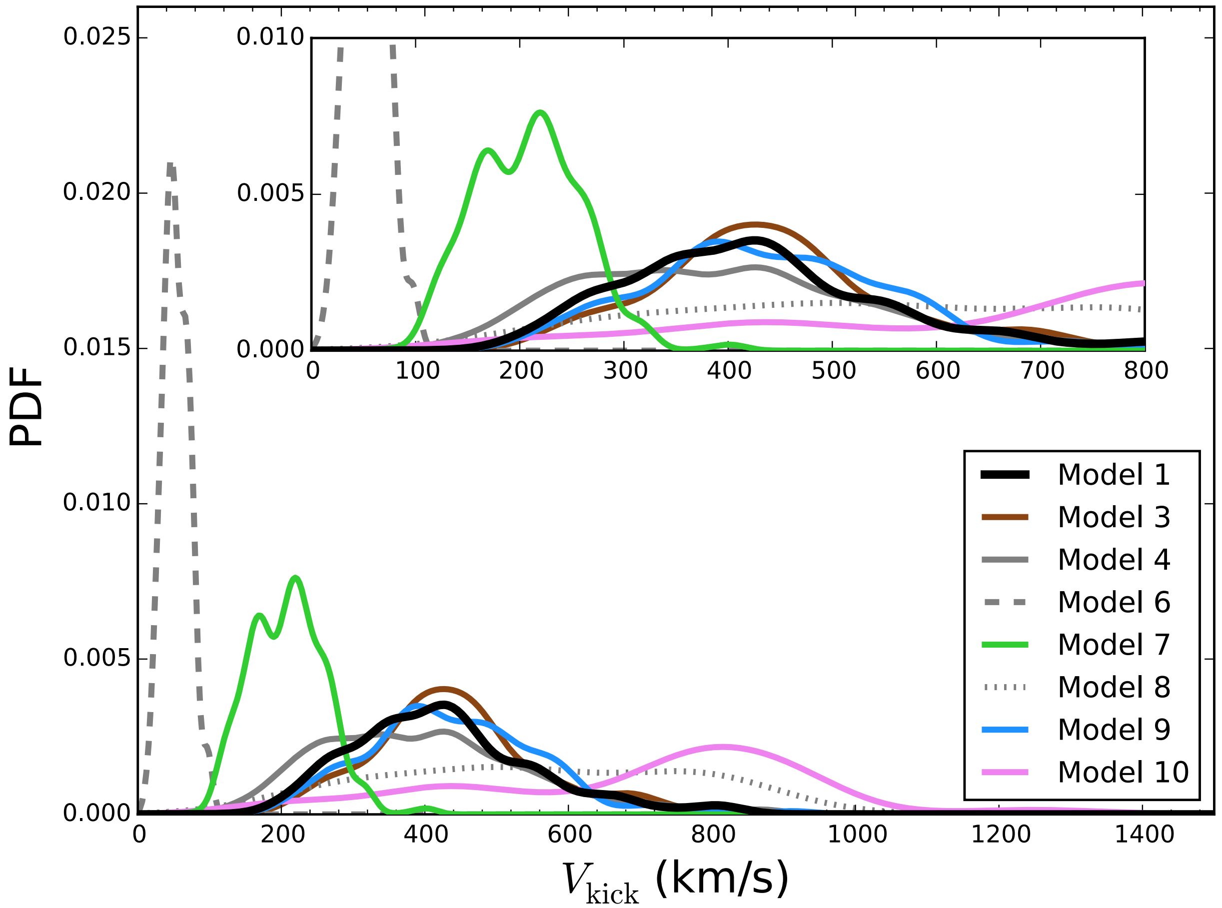

Results so far...

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)	**6.4 – 8.2** (Sorensen, **TF** et al. 2017)	**11.1 – 18.0** (Sorensen, **TF** et al. 2017)	**≤ 600** (Sorensen, **TF** et al. 2017)
GRS 1915+105 (late-type, P>1d)	**12.4 ± 2.0** (Reid et al. 2014)	**5.0-16.0** (Kimball, **TF** et al. 2017, in prep.)	COMING SOON	**consistent with ~0** (Kimball, **TF** et al. 2017, in prep.)
V404 Cyg (late-type, P>1d)	**9.0 ± 0.6** (Khargharia et al. 2010)	**7.5-9.5** (Kimball, **TF** et al. 2017, in prep.)	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)	**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); Fragos et al (2009); Valseccchi et al. (2010); Wong et al. (2012); Wong et al. (2014)
Sorensen, **TF** et al. (2017); Kimball, **TF** et al. (2017, in prep.)

Results so far...

System	Observed Current BH mass (M⊙)	Post-SN min. BH mass (M⊙)	min. Immediate Progenitor mass (M⊙)	Natal Kick (km/s)
XTE J1118+480 (late-typ P<1d)	8.0 ± 2.0 (McClintock et al. 2001, Wagner	6.0 – 10.0 (Fragos et al. 2009)	6.5 – 20.0 (Fragos et al. 2009)	80 – 310 (Fragos et al. 2009)
GRO J1 (early-typ				160 al. 2005) 10 al. 2005)
LMC (early-typ				00 et al. 2017)
GRS 19 (late-typ				with ~0 2017, in prep.)
V404 (late-typ				SOON
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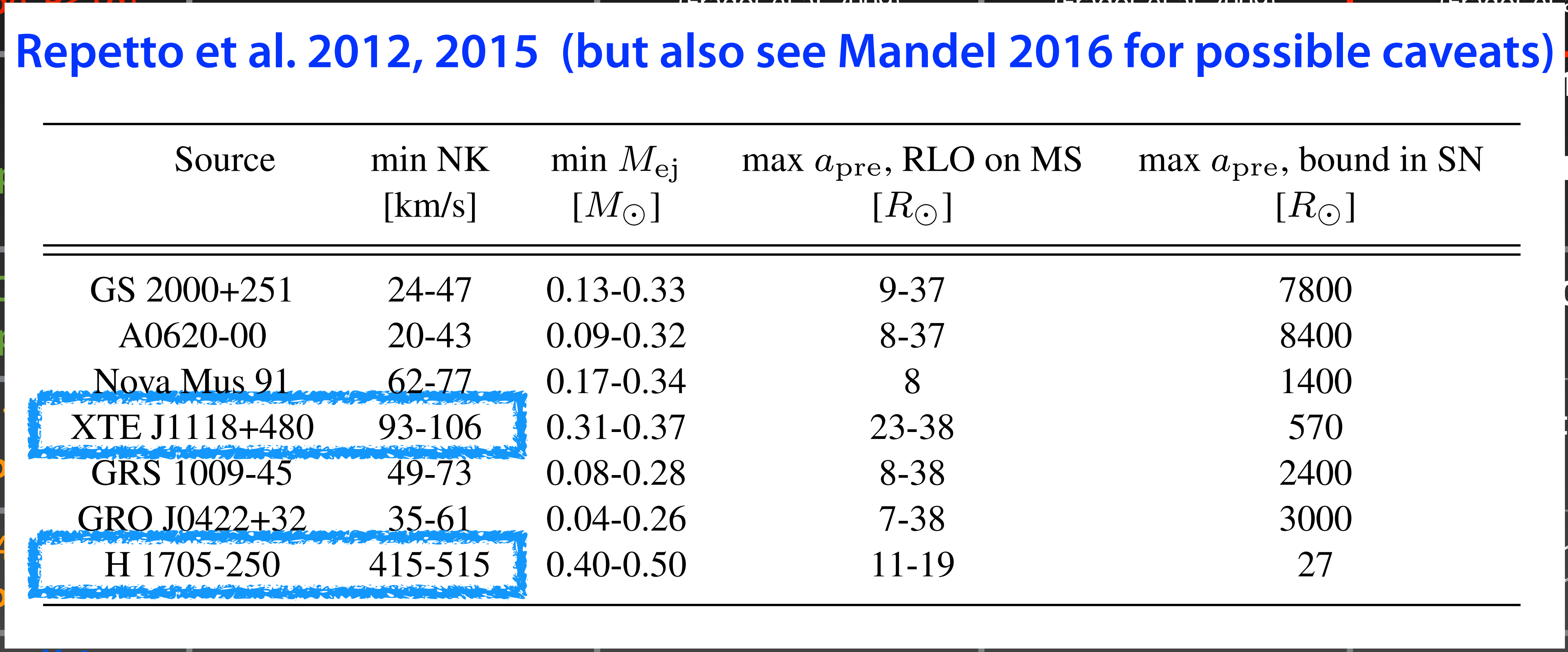

Repetto et al. 2012, 2015 (but also see Mandel 2016 for possible caveats)

Source	min NK [km/s]	min $M_{\rm ej}$ [$M_\odot$]	max $a_{\rm pre}$, RLO on MS [$R_\odot$]	max $a_{\rm pre}$, bound in SN [$R_\odot$]
GS 2000+251	24-47	0.13-0.33	9-37	7800
A0620-00	20-43	0.09-0.32	8-37	8400
Nova Mus 91	62-77	0.17-0.34	8	1400
XTE J1118+480	93-106	0.31-0.37	23-38	570
GRS 1009-45	49-73	0.08-0.28	8-38	2400
GRO J0422+32	35-61	0.04-0.26	7-38	3000
H 1705-250	415-515	0.40-0.50	11-19	27

Willems et al. (2005); Fragos et al (2009); Valseccchi et al. (2010); Wong et al. (2012); Wong et al. (2014)
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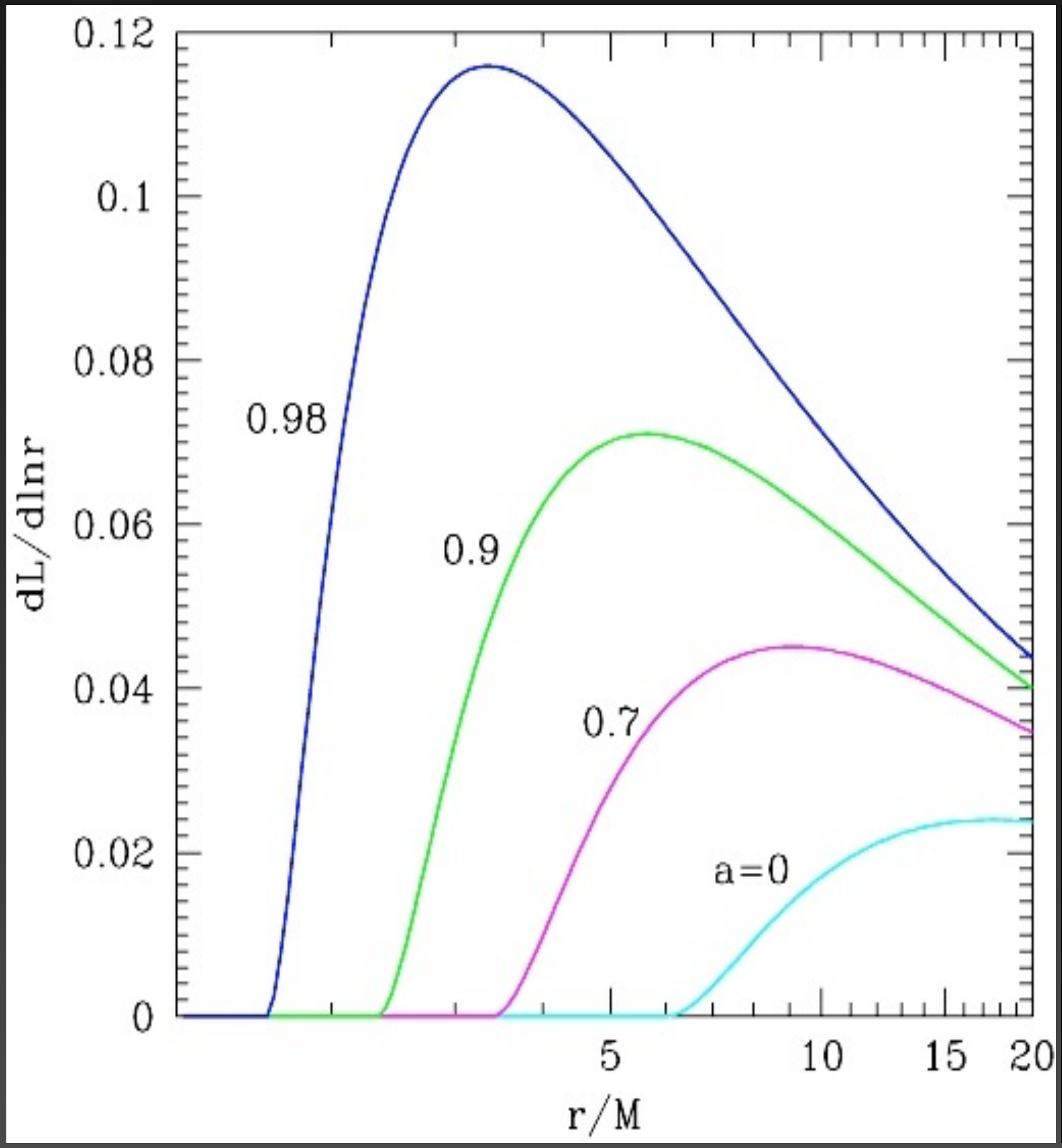
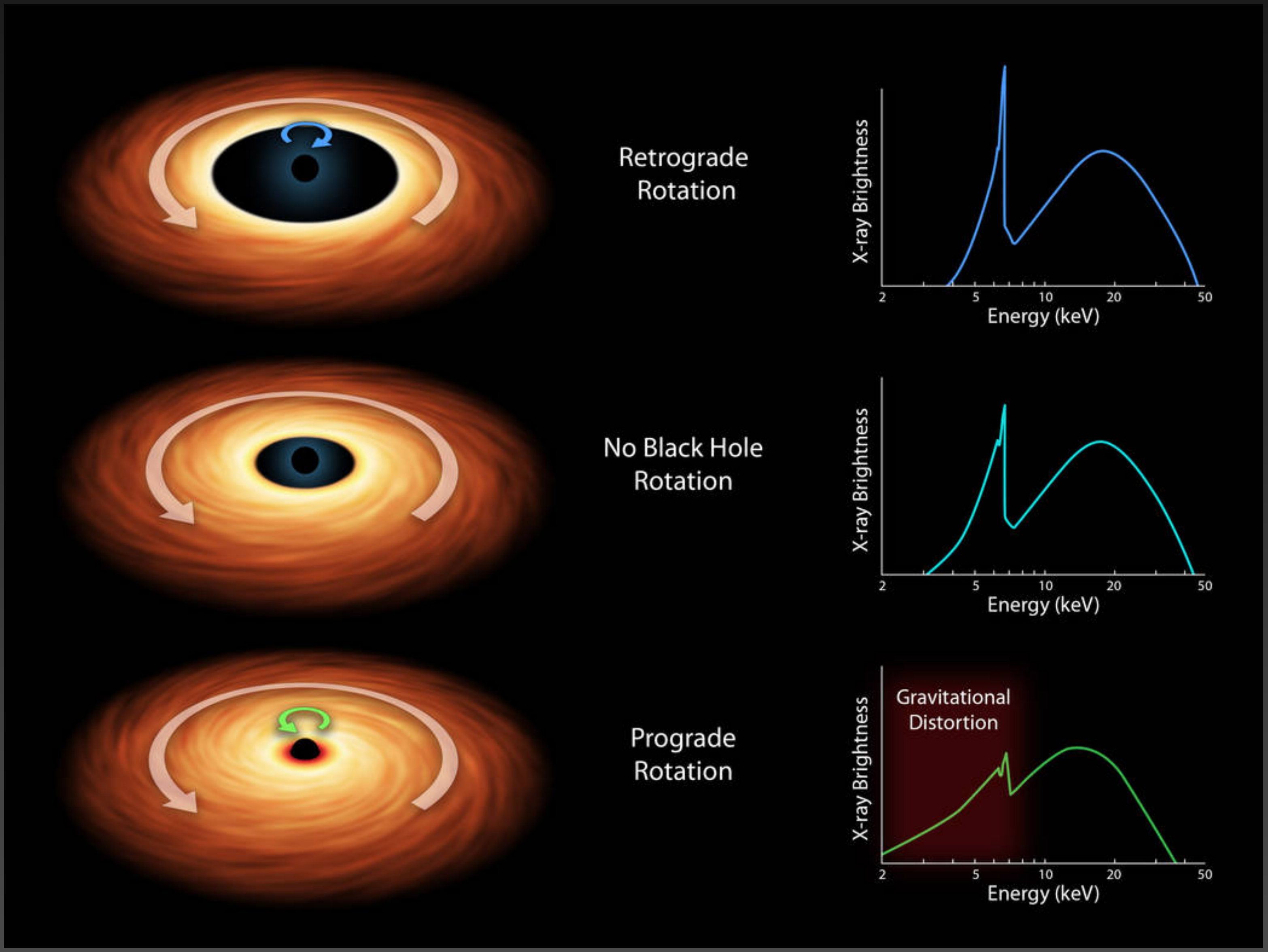
Measuring the the spin of Black Holes

Continuum-fitting and Reflection methods



McClintock et al. (2011, 2014)



McClintock et al. (2011, 2014)

Measuring the the spin of Black Holes

Continuum-fitting and Reflection methods

- ✓ Simple physical model
- ✓ Availability of high-quality data
- ✓ Thorough analysis of systematic errors

- x Need accurate measurements of M,i,D
- x Assumption of spin-orbit alignment
- x Only applicable to stellar mass BHs
- x All available data have been analyzed

McClintock et al. (2011, 2014)

- ✓ Independent of M,D
- ✓ inclination can be a fit parameter
- ✓ applicable also to SMBH
- ✓ data available for more BH XRBs

- x Need careful removal of X-ray continuum
- x Need assumption on irradiation profile
- x Poor understanding of systematic errors
- x A lot of studies with poor application of the method

McClintock et al. (2011, 2014)

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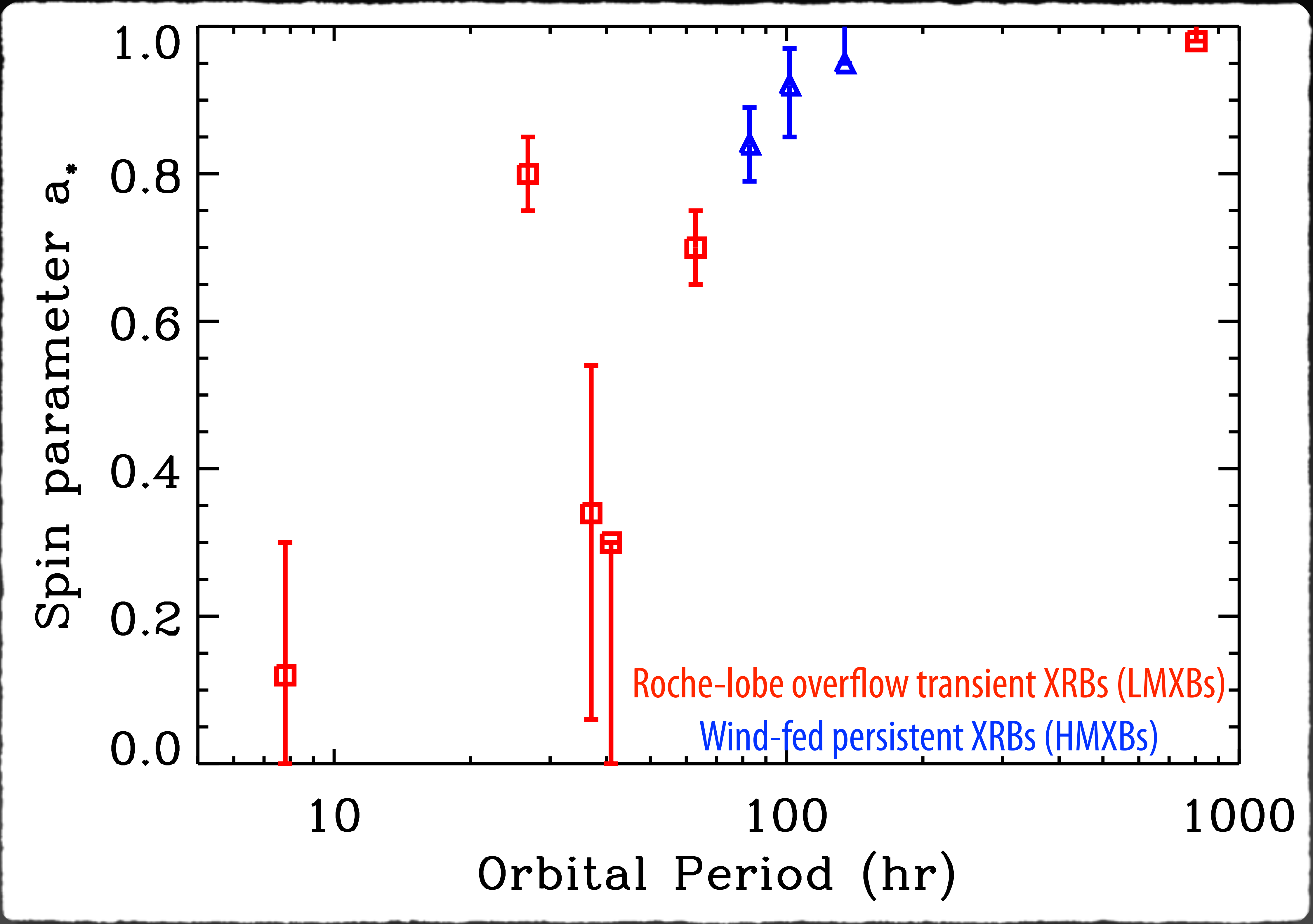
McClintock et al. (2011, 2014)

The two methods currently give consistent results for 5 out 7 BH XRBs where both have been applied!

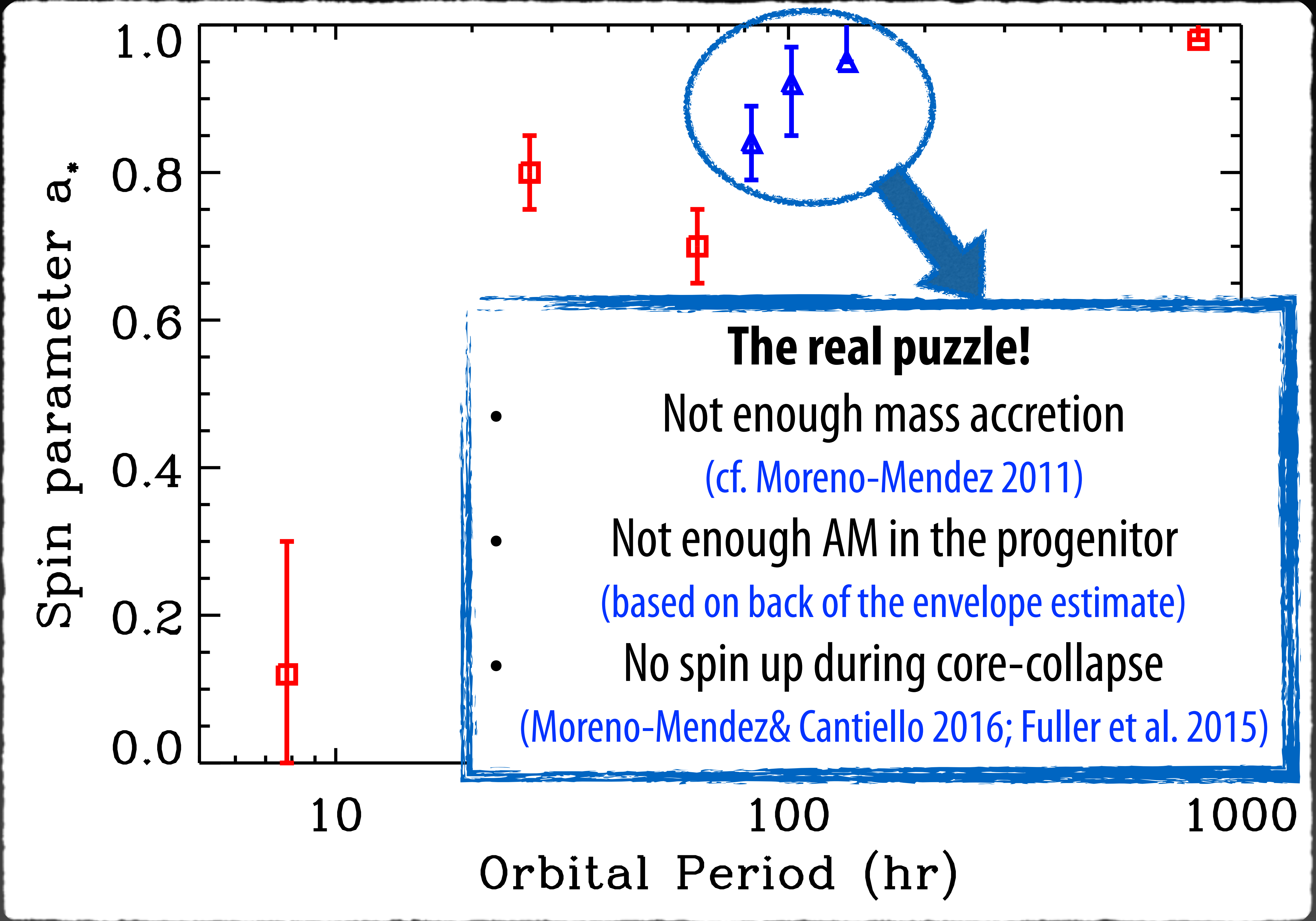
The origin of black-hole spin



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

McClintock et al. (2011, 2014)

The origin of black-hole spin



The real puzzle!

- Not enough mass accretion
  (cf. Moreno-Mendez 2011)
- Not enough AM in the progenitor
  (based on back of the envelope estimate)
- No spin up during core-collapse
  (Moreno-Mendez& Cantiello 2016; Fuller et al. 2015)

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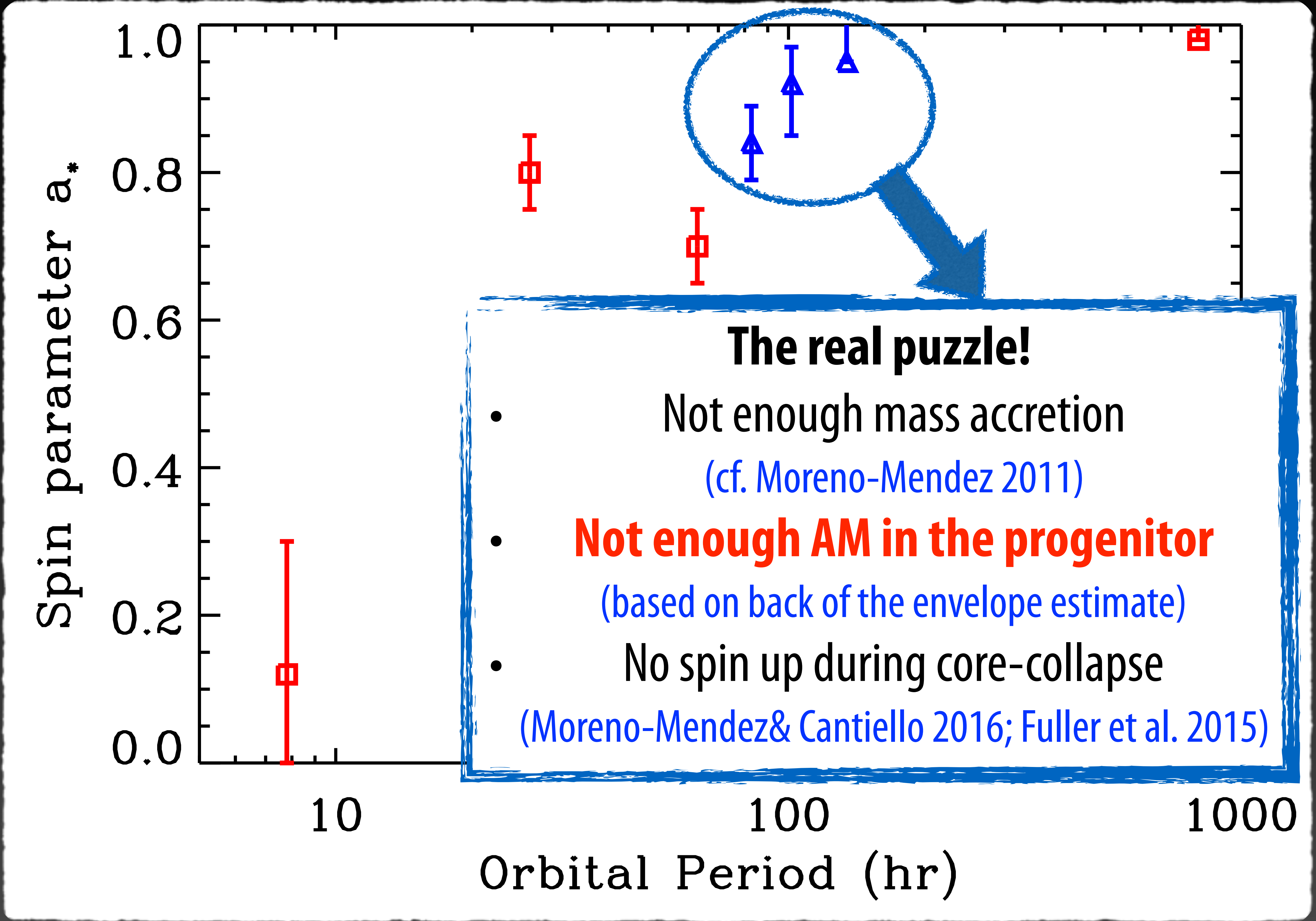

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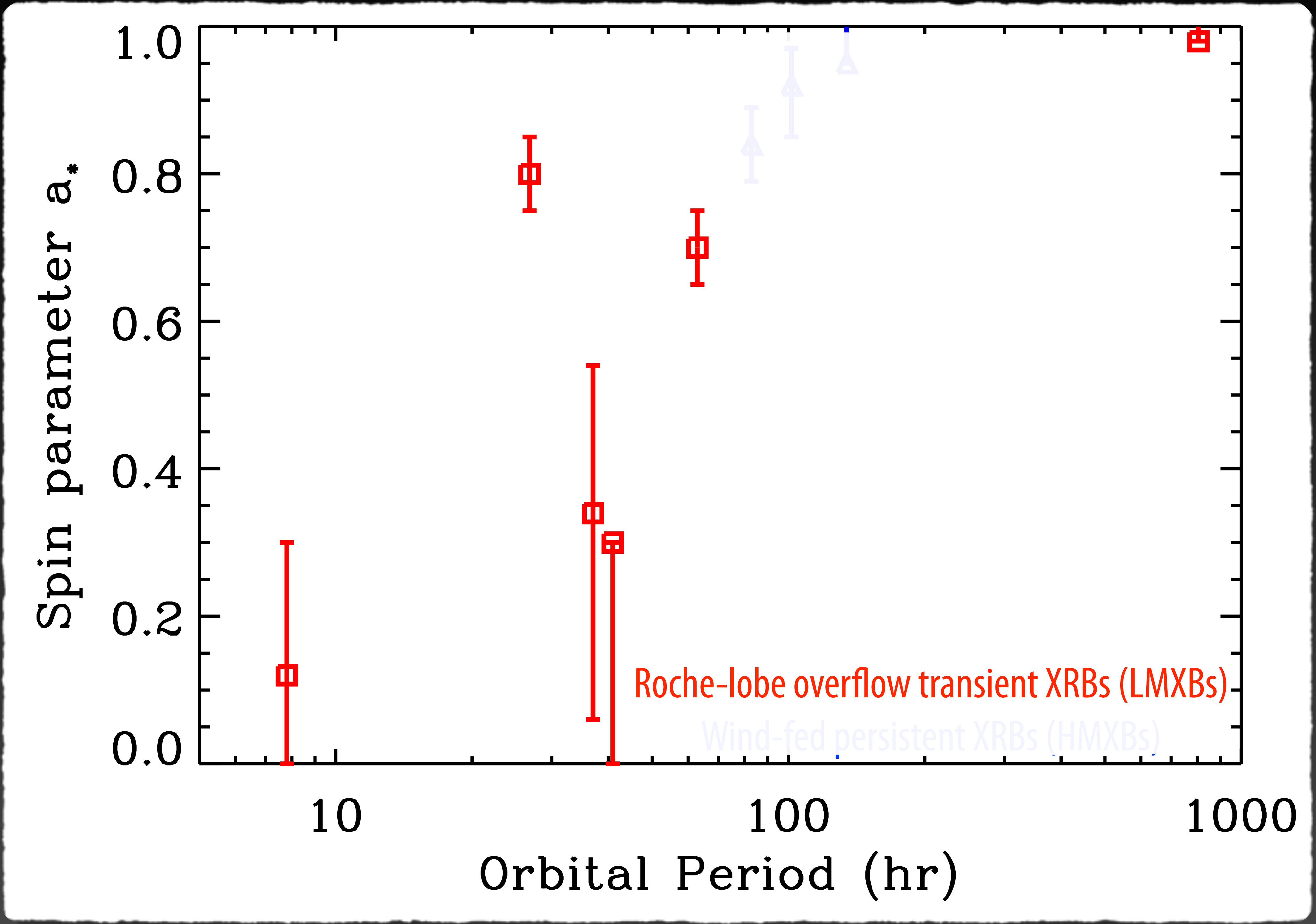

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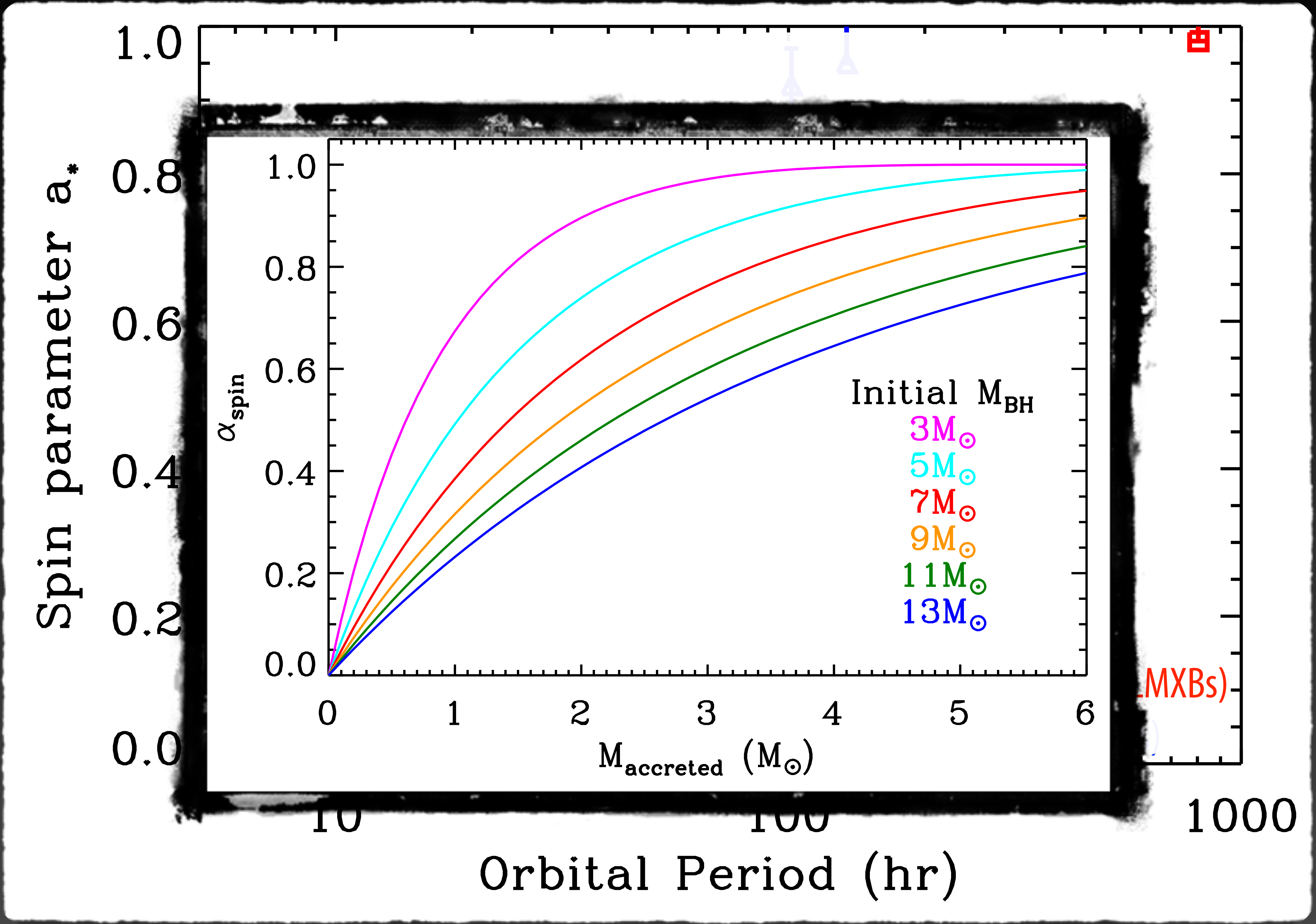

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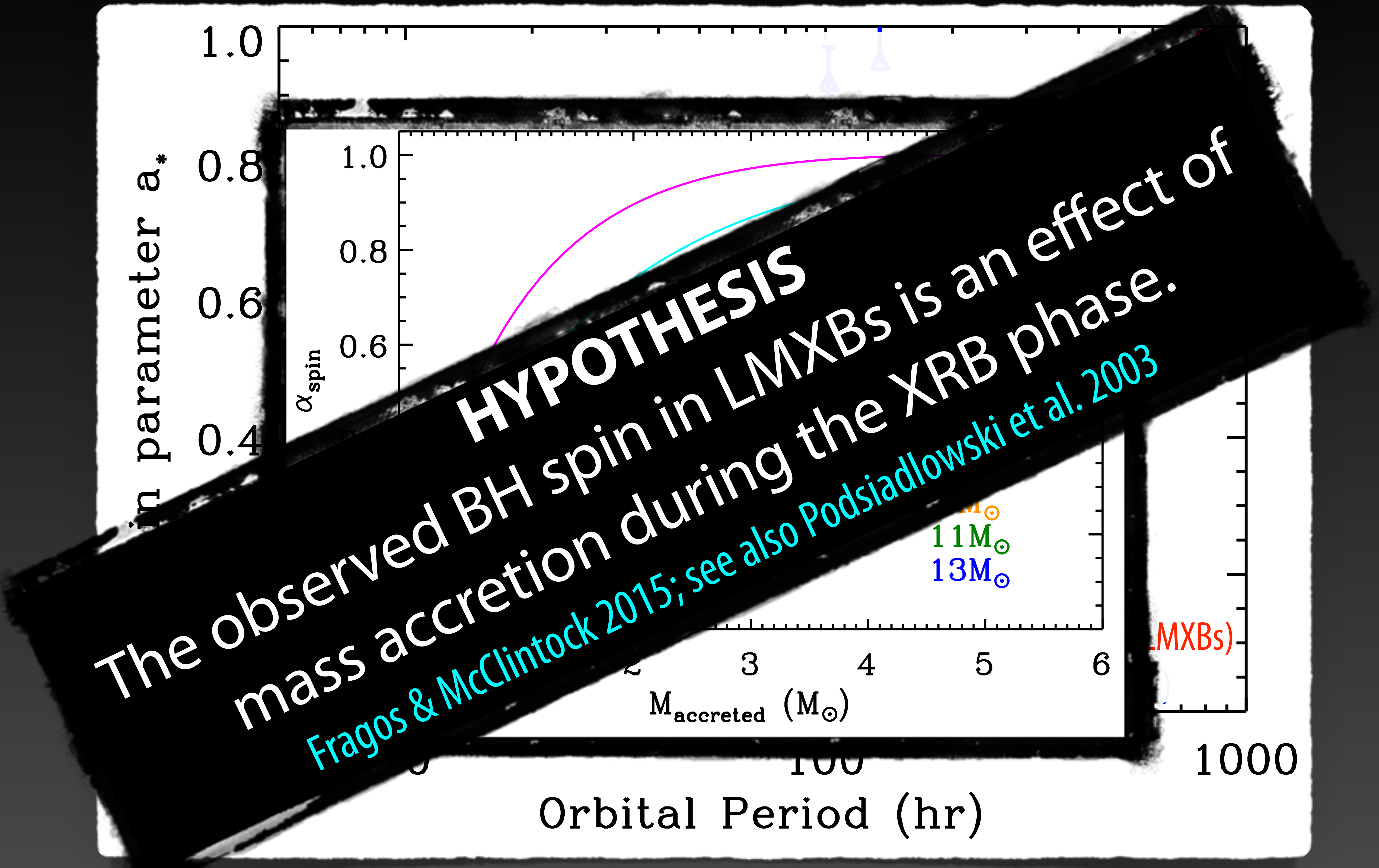


HYPOTHESIS

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

Fragos & McClintock 2015; see also Podsiadlowski et al. 2003

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

McClintock et al. (2011, 2013)

Sample of Galactic BH LMXBs

	M_{BH} ($M_\odot$)	M_2 ($M_\odot$)	P_{orb} (days)	T_{eff} (K)	a_*
GRS 1915+105	12.4±2.0	0.52±0.41	33.85	4100-5433	0.95±0.05
4U 1543-47	9.4±2.0	2.7±1.0	1.116	9000±500	0.8±0.1
GRO J1655-40	6.3±0.5	2.4±0.4	2.622	5706-6466	0.7±0.1
XTE J1550-564	9.1±0.61	0.3±0.07	1.542	4700±250	0.34±0.2
A0620-00	6.61±0.25	0.4±0.045	0.323	3800-4910	0.12±0.19
GRS 1124-683	6.95±1.1	0.9±0.3	0.433	4065-5214	0.25±0.15
GX 339-4	8.0±1.0*	--	1.754	--	0.25±0.15
XTE J1859+226	8.0±1.0*	--	0.383	--	0.25±0.15
GS 2000+251	8.0±1.0*	0.35±0.05	0.344	3915-5214	0.05±0.05
GRO J0422+32	8.0±1.0*	0.95±0.25	0.212	2905-4378	--
GRS 1009-45	8.5±1.0	0.54±0.1	0.285	3540-4640	--
GS 1354-64	8.0±1.0	--	2.545	4985-6097	--
GS 2023+338	9.0±0.6	0.54±0.05	6.471	4100-5433	--
H1705-250	6.4±0.75	0.245±0.0875	0.521	3540-5214	--
V4641 Sgr	6.4±0.6	2.9±0.4	2.817	10500±200	--
XTE J1118+480	7.55±0.325	0.17±0.07	0.17	3405-4640	--

Fragos & McClintock (2015) - ApJ, 800, 17

* No reliable BH mass measurement is available. Using fiducial value from Ozel et al. (2010)

† Spin estimates from Steiner et al. (2013) using the BH spin - jet power correlation (Narayan & McClintock, 2012)

The origin of black-hole spin

Retrieved binary properties at the onset of RLO

Fragos & McClintock (2015) - ApJ, 800, 17

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

Using MESA; Paxton et al. 2011,2013,2015

The origin of black-hole spin

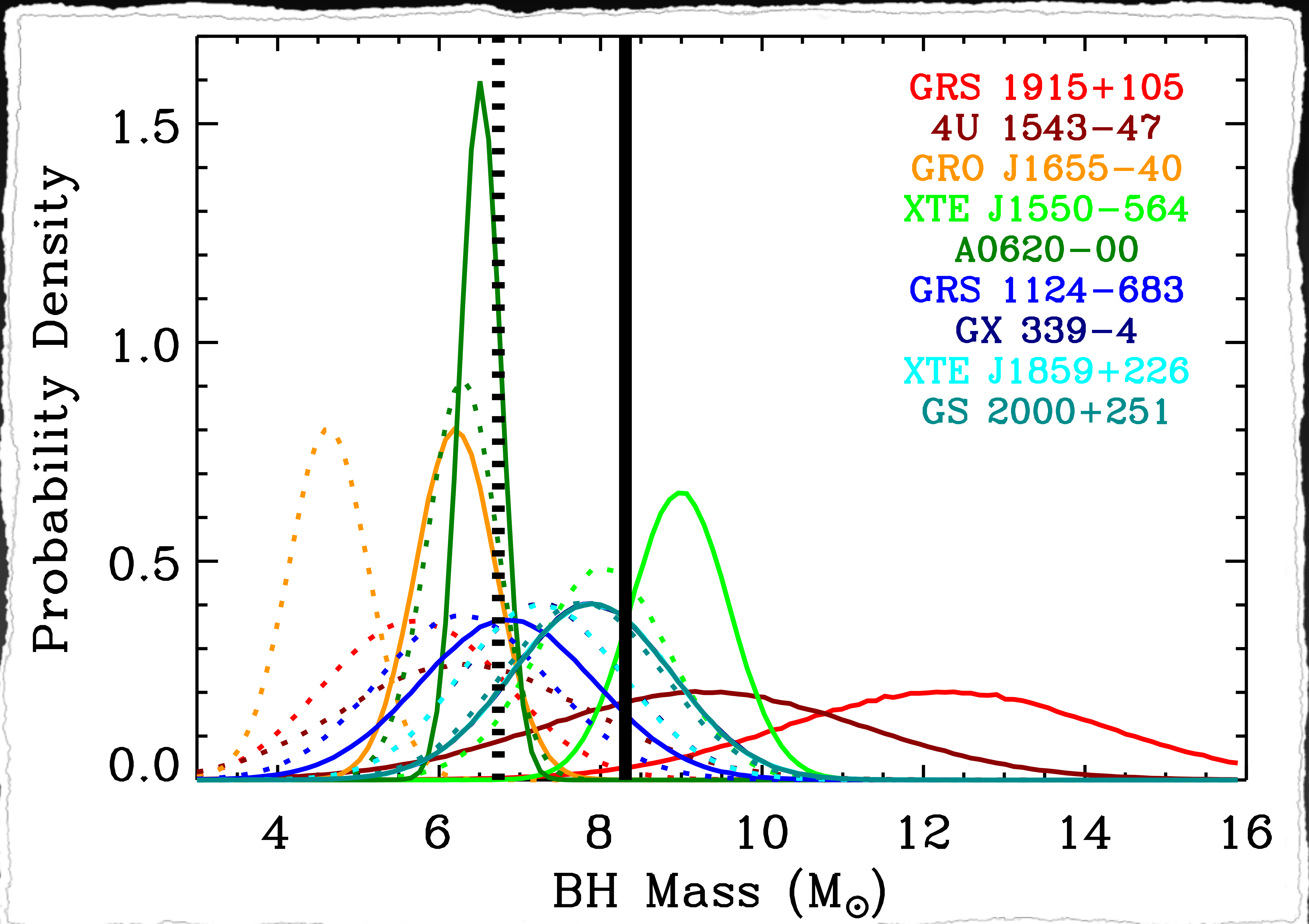
Retrieved binary properties at the onset of RLO

Fragos & McClintock (2015) - ApJ, 800, 17

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

Using MESA; Paxton et al. 2011,2013,2015

Implications on birth black-hole mass

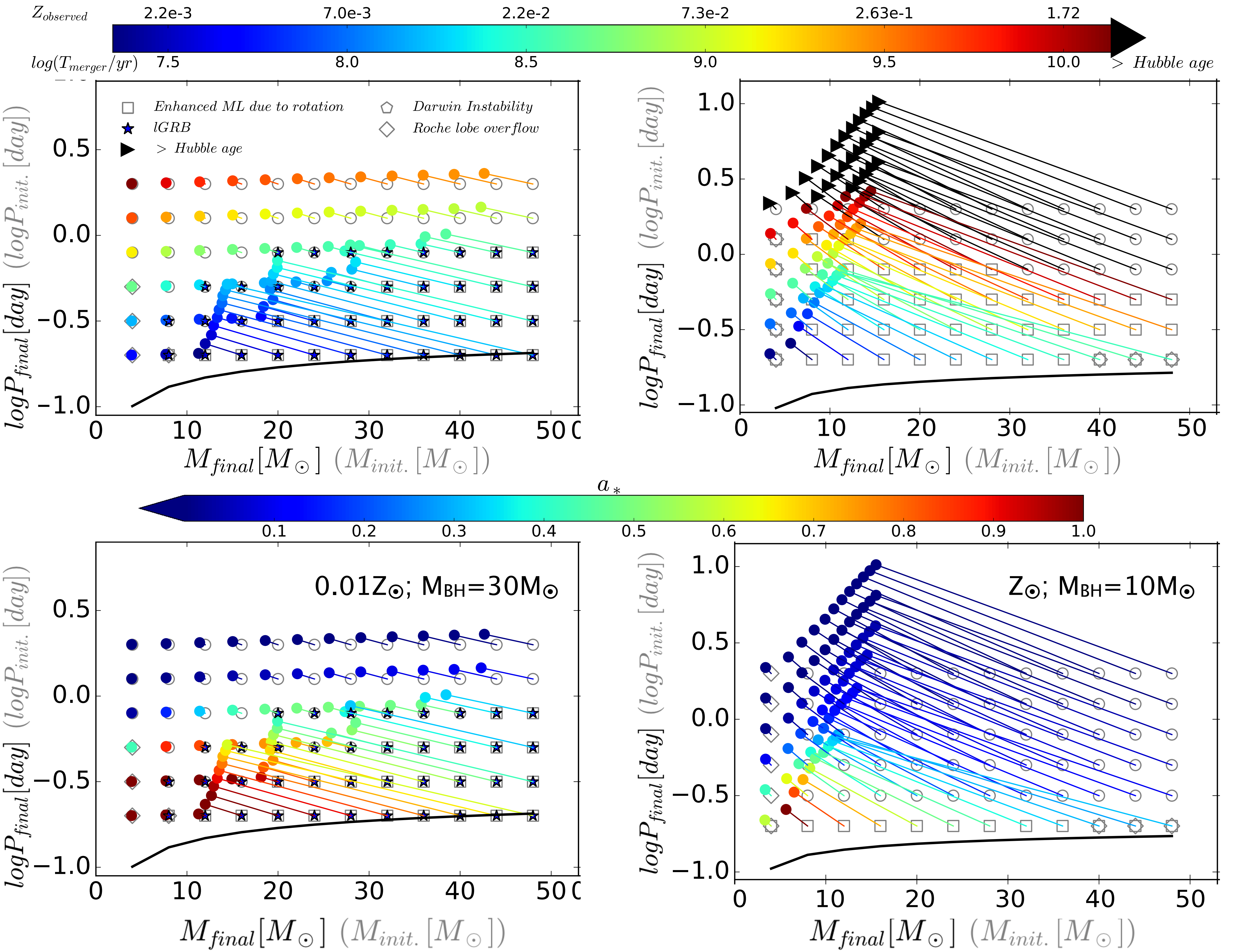


Fragos & McClintock (2015) - ApJ, 800, 17

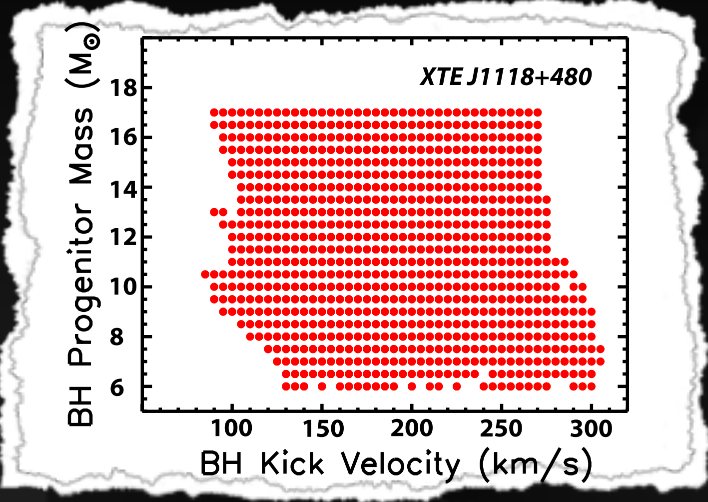
Spinning up a BH progenitor via tides

Qin, **TF** et al. (2017; in preparation)

see also Detmers et al. 2007; Kushnir et al. 2016a,b; Hotokezaka & Piran 2017



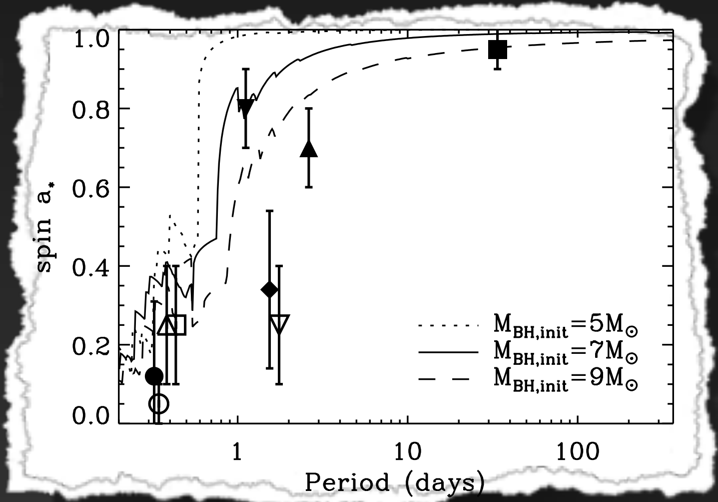
Summary



Based on the currently observed properties of BH XRBs, one can recover their evolutionary history and put constraints on natal kicks.

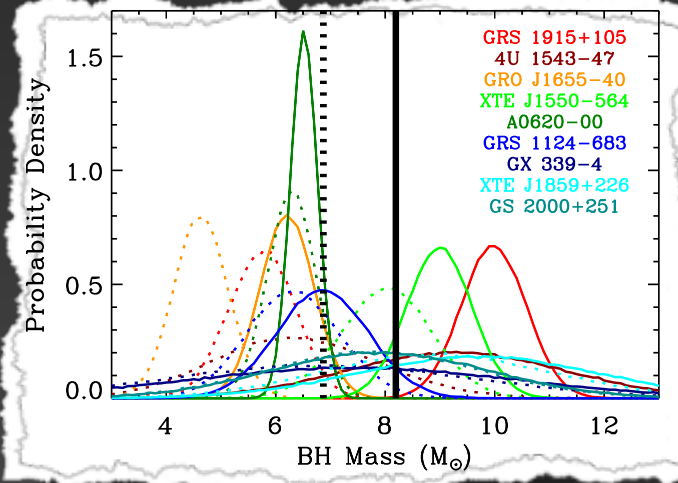
Strong evidence for large kick (>100 km/s) only for XTE J1118+480.

We should wait for GAIA proper motions in mid-2018

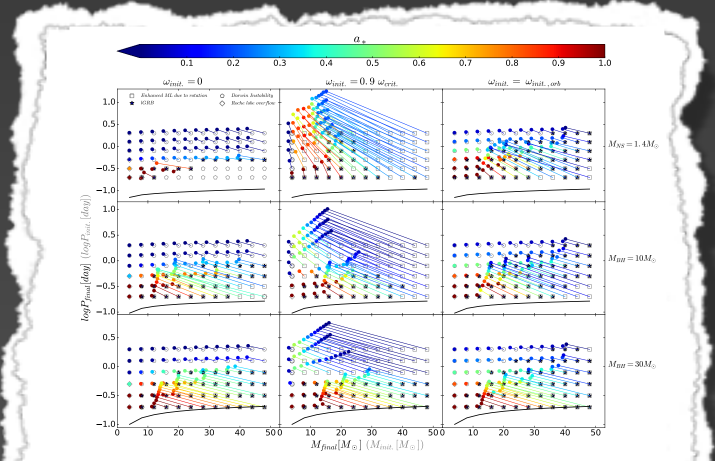


The observed BH spin in LMXBs ***can*** be due to mass accretion during the XRB phase.

The BH spin in HMXBs is likely a result of the angular momentum of the BH progenitor, *but some fine-tuning is needed.*



If the observed BH spin in LMXBs is due to accretion, the observed M_{BH} spectrum can differ significantly from the birth one.

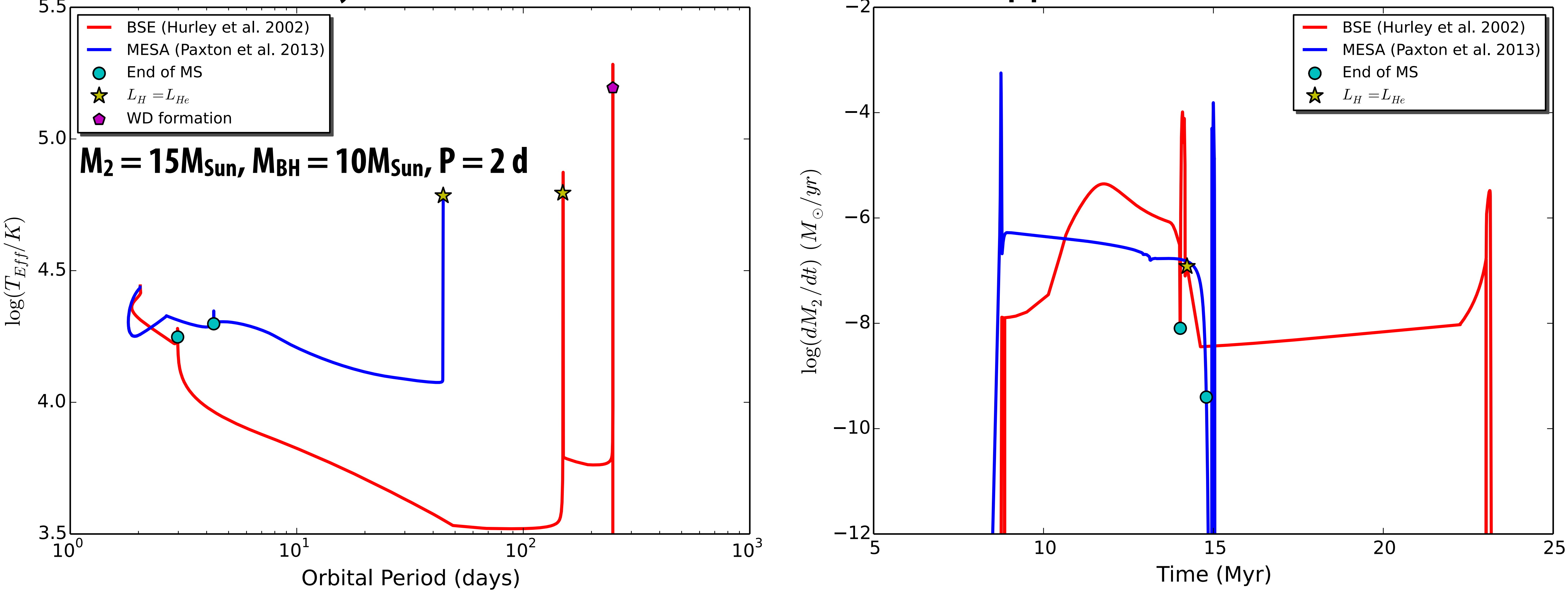


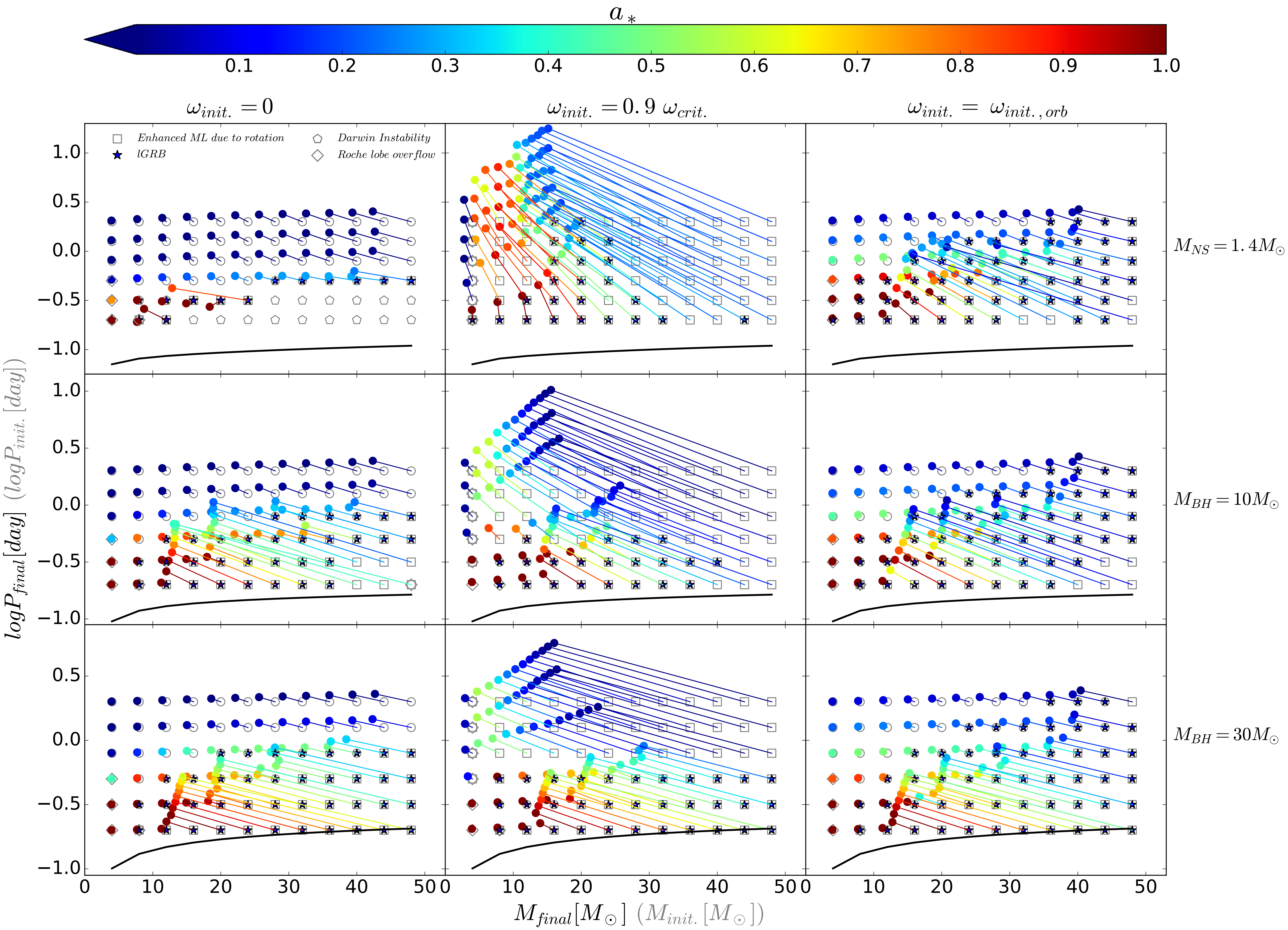
LIGO constraints on the second-born BH are consistent with the "Classical" binary formation channel. Observed spins are expected to be small as high spins correlate with short merger times

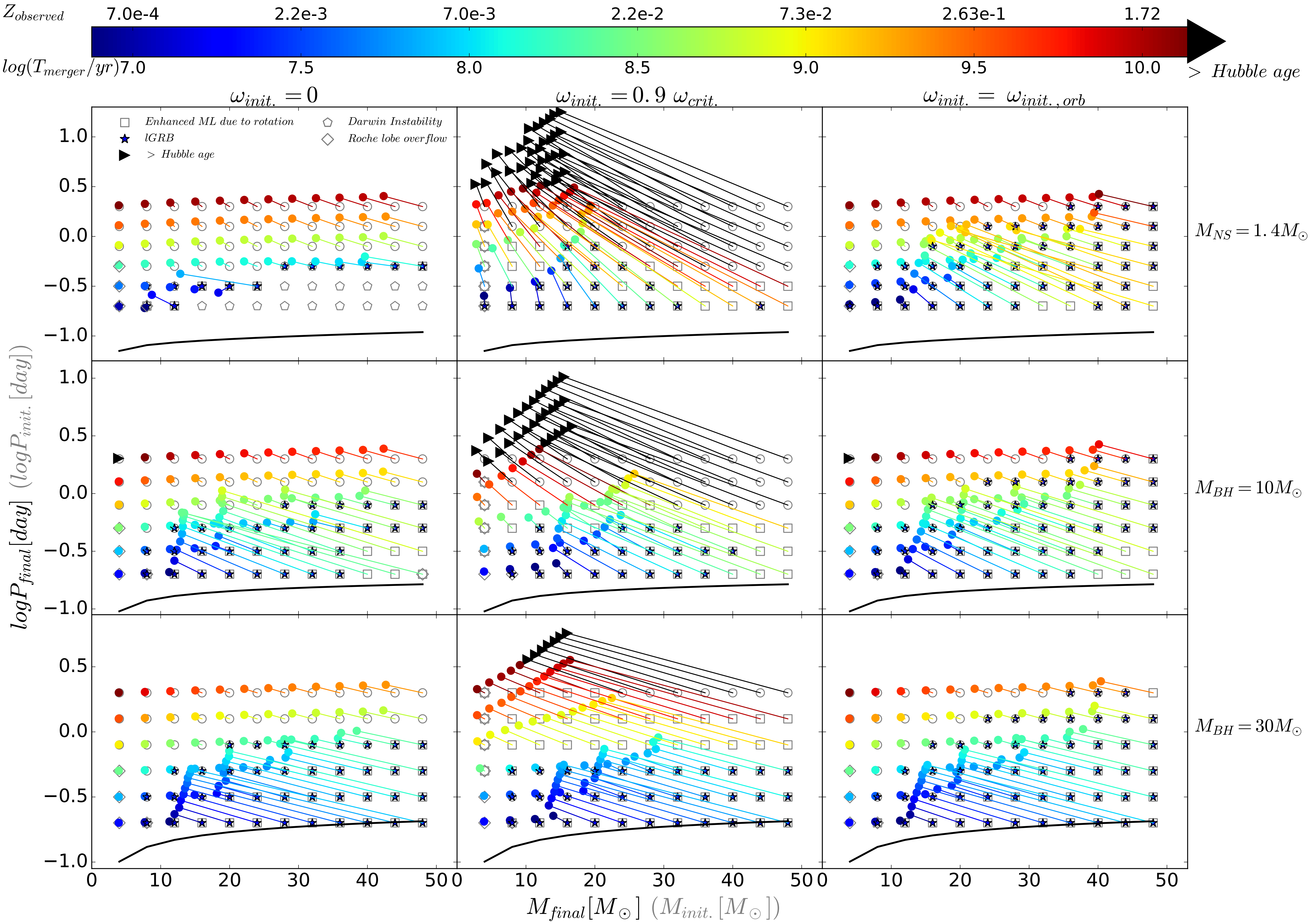
Stability of mass-transfer

- Assuming hydrostatic equilibrium and adiabatic mass-loss, $q=M_2/M_{NS} > 2.2 - 3$ leads to dynamical instability (e.g. Hjellming & Webbink 1987; Ivanova & Taam 2004) BUT see more recent: Passy et al. (2012) and Pavlovskii & Ivanova (2015)
- Accuracy of thermally unstable mass-transfer in parametric binary population synthesis codes

Thermally unstable mass-transfer: Detailed vs Approximate treatment




a_*
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$\omega_{init.} = 0$
$\omega_{init.} = 0.9\ \omega_{crit.}$
$\omega_{init.} = \omega_{init.,orb}$
Enhanced ML due to rotation
lGRB
Darwin Instability
Roche lobe overflow
$M_{NS} = 1.4 M_\odot$
$M_{BH} = 10 M_\odot$
$M_{BH} = 30 M_\odot$
$logP_{final}[day]$ $(logP_{init.}[day])$
$M_{final}[M_\odot]$ $(M_{init.}[M_\odot])$
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50


$Z_{observed}$
7.0e-4
2.2e-3
7.0e-3
2.2e-2
7.3e-2
2.63e-1
1.72
$log(T_{merger}/yr)$
7.0
7.5
8.0
8.5
9.0
9.5
10.0
> Hubble age
$\omega_{init.} = 0$
$\omega_{init.} = 0.9\ \omega_{crit.}$
$\omega_{init.} = \omega_{init.,orb}$
Enhanced ML due to rotation
lGRB
> Hubble age
Darwin Instability
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$M_{NS} = 1.4 M_{\odot}$
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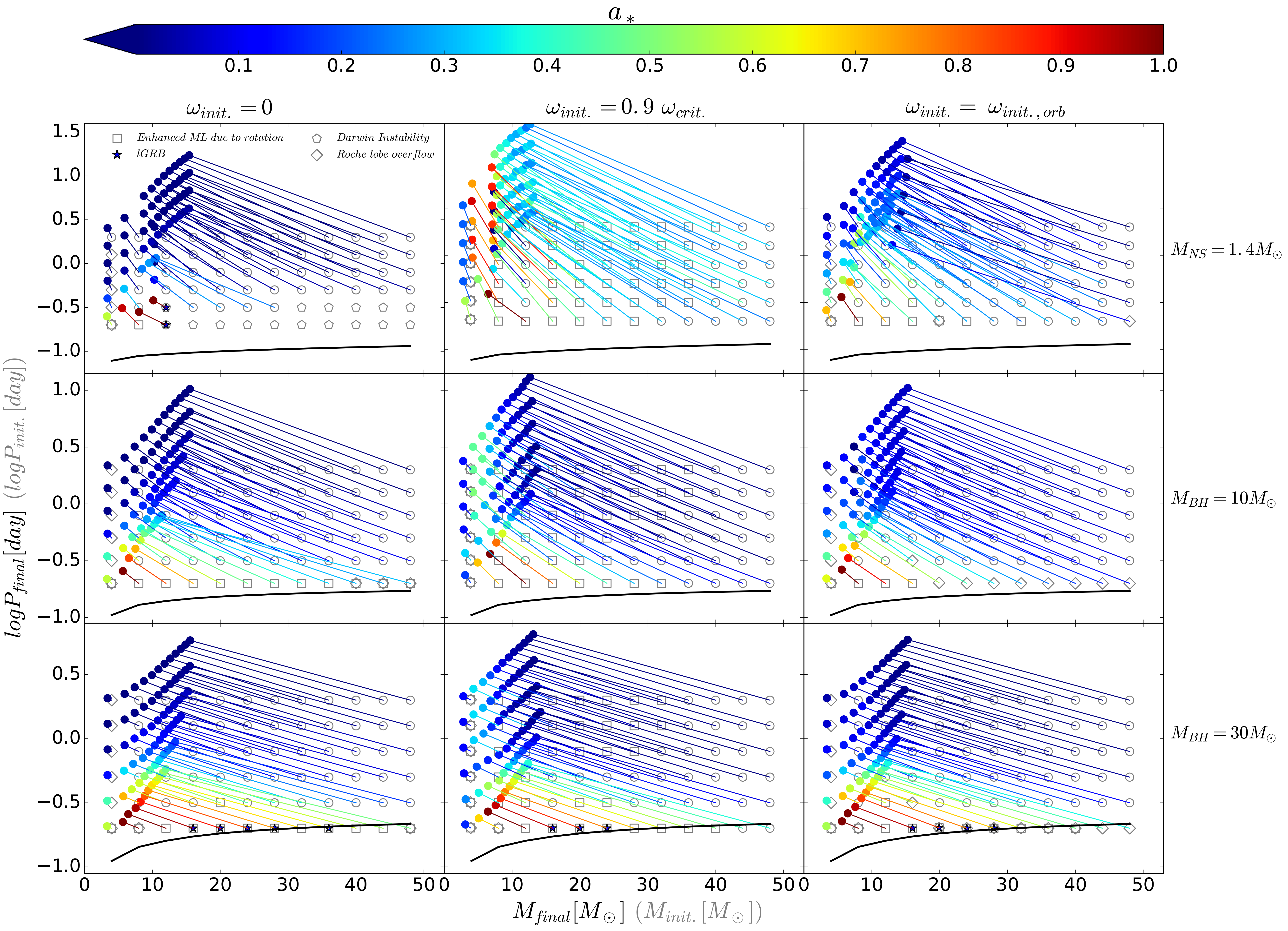
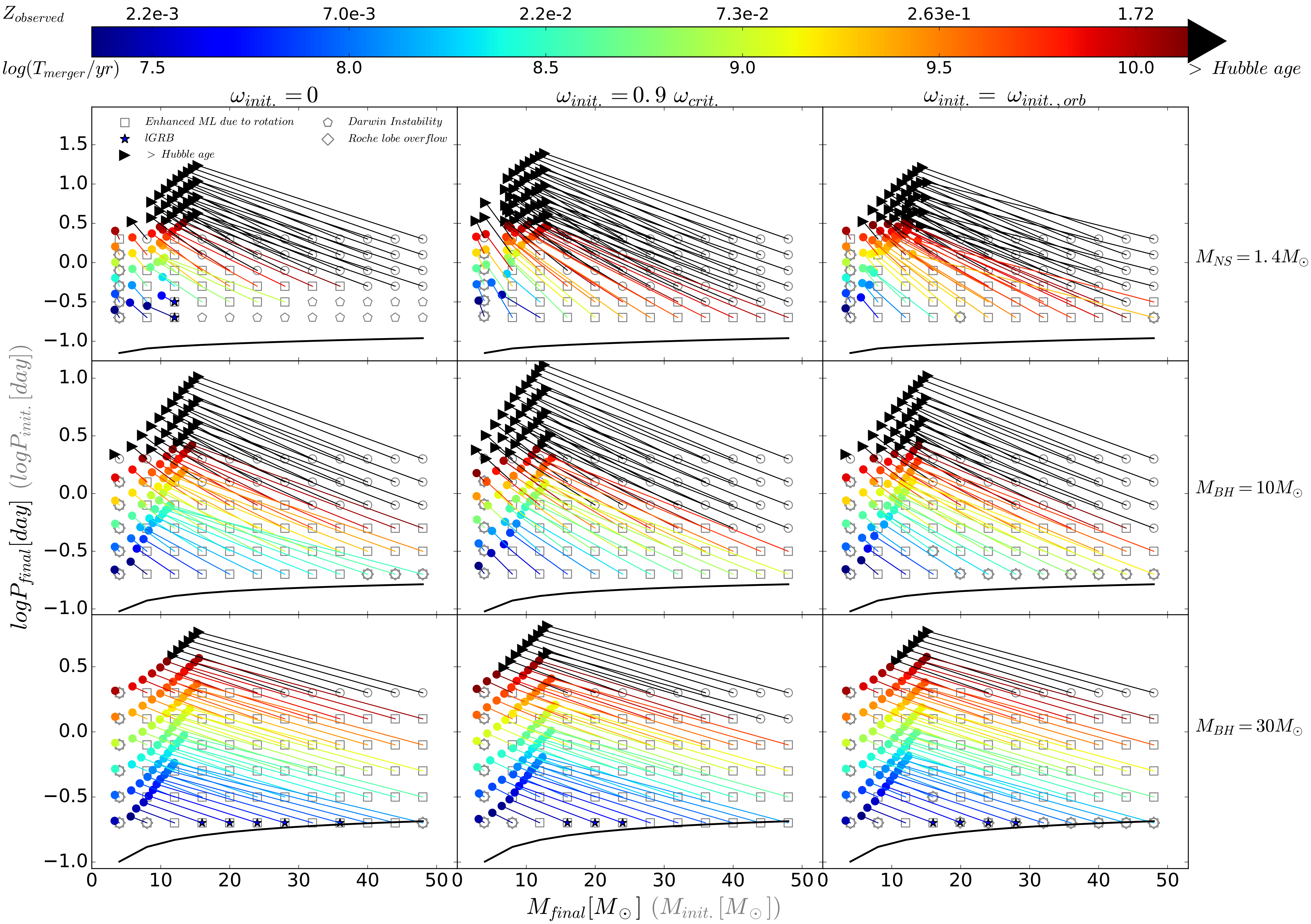
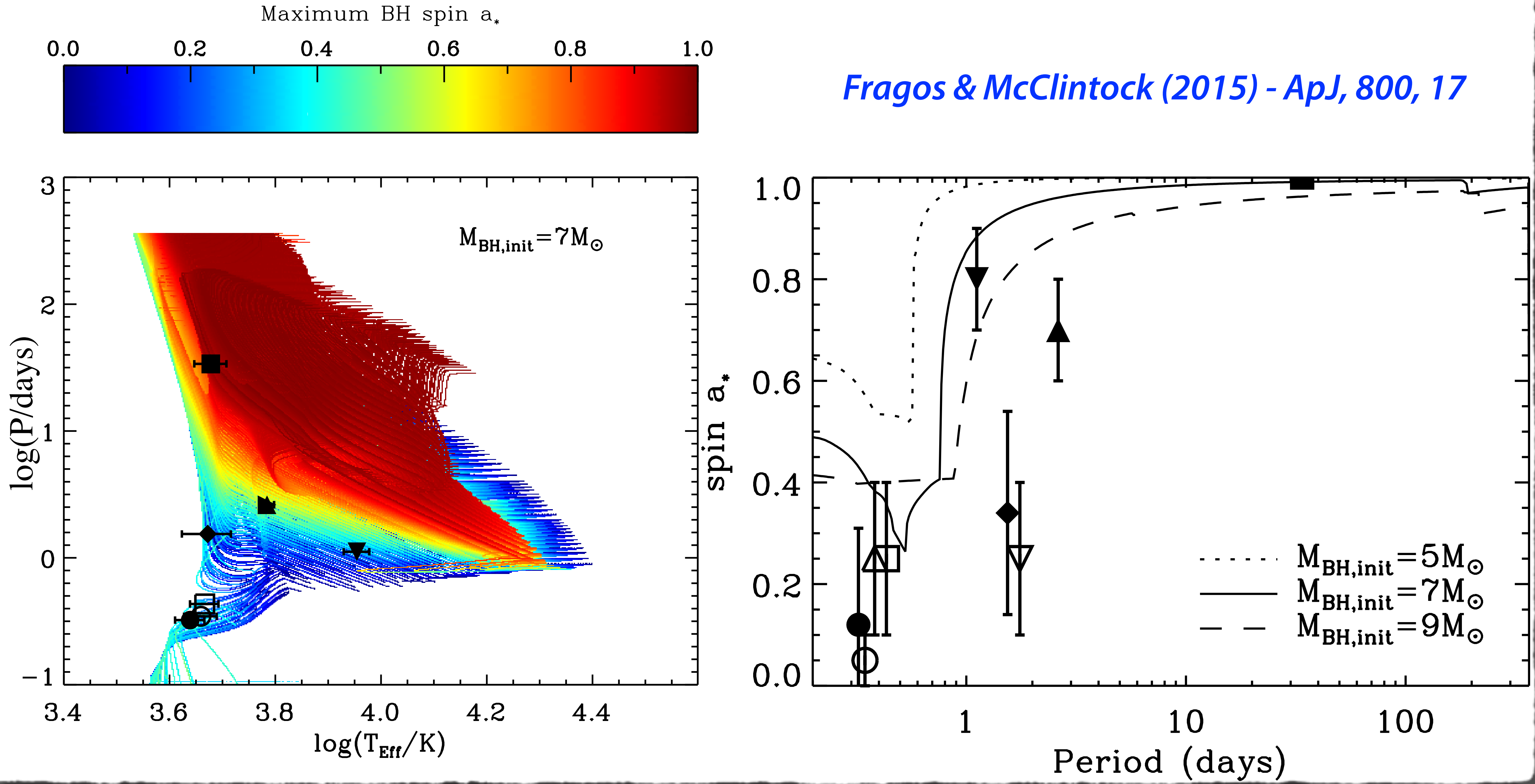
$logP_{final}[day]$ $(logP_{init.}[day])$
$M_{final}[M_{\odot}]$ $(M_{init.}[M_{\odot}])$
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50


a_*
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
$\omega_{init.} = 0$
$\omega_{init.} = 0.9\ \omega_{crit.}$
$\omega_{init.} = \omega_{init.,orb}$
Enhanced ML due to rotation
lGRB
Darwin Instability
Roche lobe overflow
$M_{NS} = 1.4 M_\odot$
$M_{BH} = 10 M_\odot$
$M_{BH} = 30 M_\odot$
$logP_{final}[day]$ $(logP_{init.}[day])$
$M_{final}[M_\odot]$ $(M_{init.}[M_\odot])$
1.5
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50


$Z_{observed}$
2.2e-3
7.0e-3
2.2e-2
7.3e-2
2.63e-1
1.72
$log(T_{merger}/yr)$
7.5
8.0
8.5
9.0
9.5
10.0
$> Hubble\ age$
$\omega_{init.} = 0$
$\omega_{init.} = 0.9\ \omega_{crit.}$
$\omega_{init.}\ =\ \omega_{init.,orb}$
Enhanced ML due to rotation
lGRB
> Hubble age
Darwin Instability
Roche lobe overflow
$M_{NS} = 1.4M_{\odot}$
$M_{BH} = 10M_{\odot}$
$M_{BH} = 30M_{\odot}$
$logP_{final}[day]$ $(logP_{init.}\ [day])$
$M_{final}[M_{\odot}]$ $(M_{init.}[M_{\odot}])$
1.5
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50

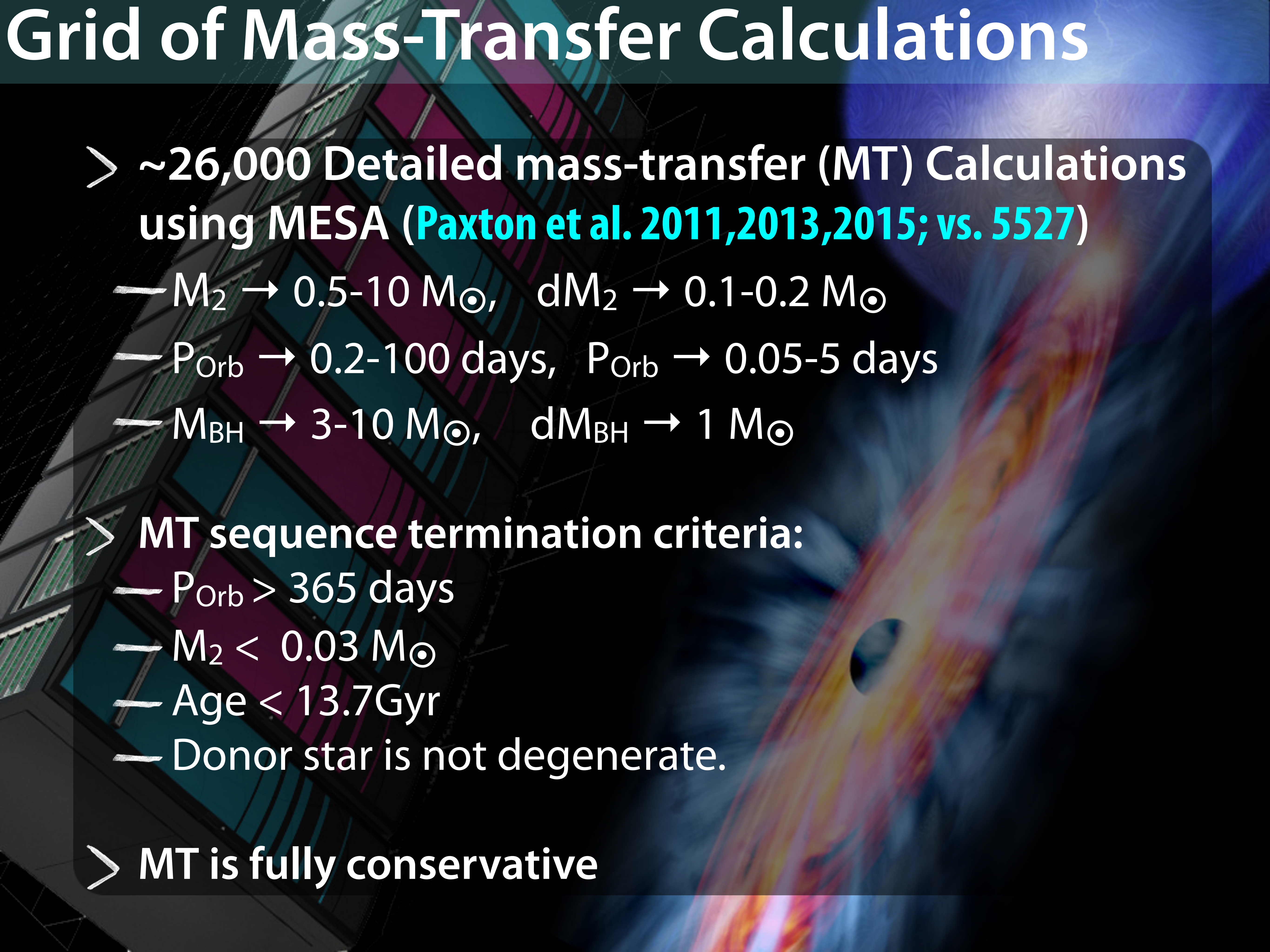
Maximum Black Hole Spin

▲ **GRO J1655-40**
■ **GRS 1915+105**
△ **XTE J1859+226**
▼ **4U 11543-47**
◆ **XTE J1550-564**
□ **GRS 1124-683**
● **A0620-00**
○ **GS 2000+251**
▽ **GX339-4**



Fragos & McClintock (2015) - ApJ, 800, 17

Grid of Mass-Transfer Calculations



- **~26,000 Detailed mass-transfer (MT) Calculations using MESA (Paxton et al. 2011,2013,2015; vs. 5527)**
  - M_2 → 0.5-10 $M_\odot$, dM_2 → 0.1-0.2 $M_\odot$
  - P_{Orb} → 0.2-100 days, P_{Orb} → 0.05-5 days
  - M_{BH} → 3-10 $M_\odot$, dM_{BH} → 1 $M_\odot$
- **MT sequence termination criteria:**
  - $P_{Orb} > 365$ days
  - $M_2 < 0.03\ M_\odot$
  - Age < 13.7Gyr
  - Donor star is not degenerate.
- **MT is fully conservative**