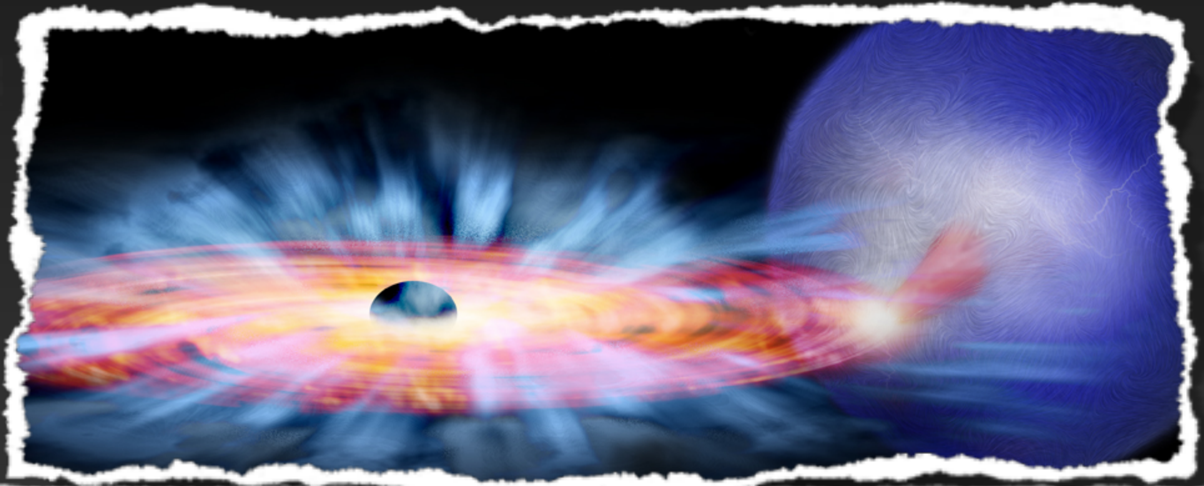
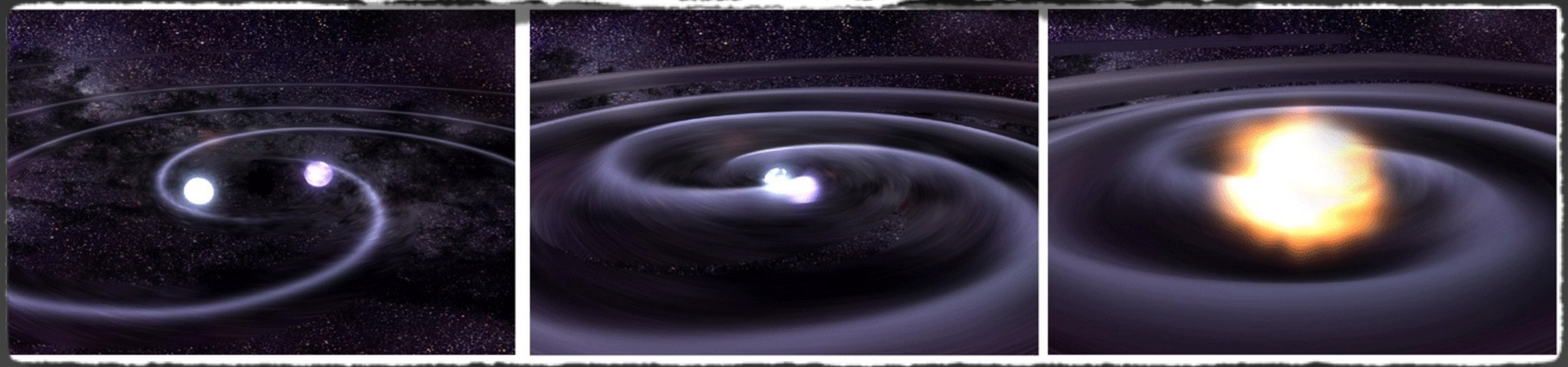
Open questions on the formation of binaries containing black holes

Tassos Fragos

Geneva Observatory - University of Geneva





UNIVERSITÉ
DE GENÈVE

OBSERVATOIRE DE GENÈVE
FONDÉ EN 1772

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

Joint SPS-APS meeting

25/08/2017

The “No-Hair” theorem

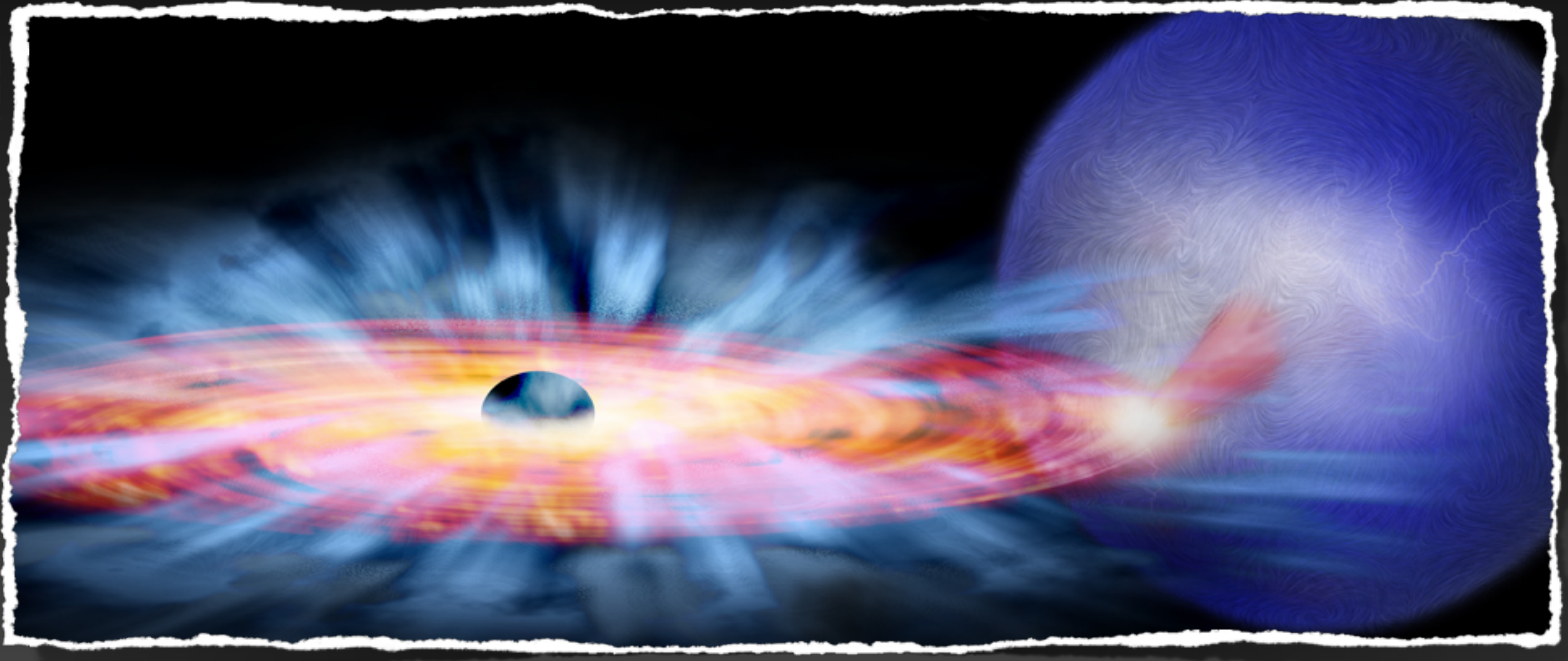
Every astrophysical black hole is fully characterized by two quantities:

$M = \mathit{mass},$

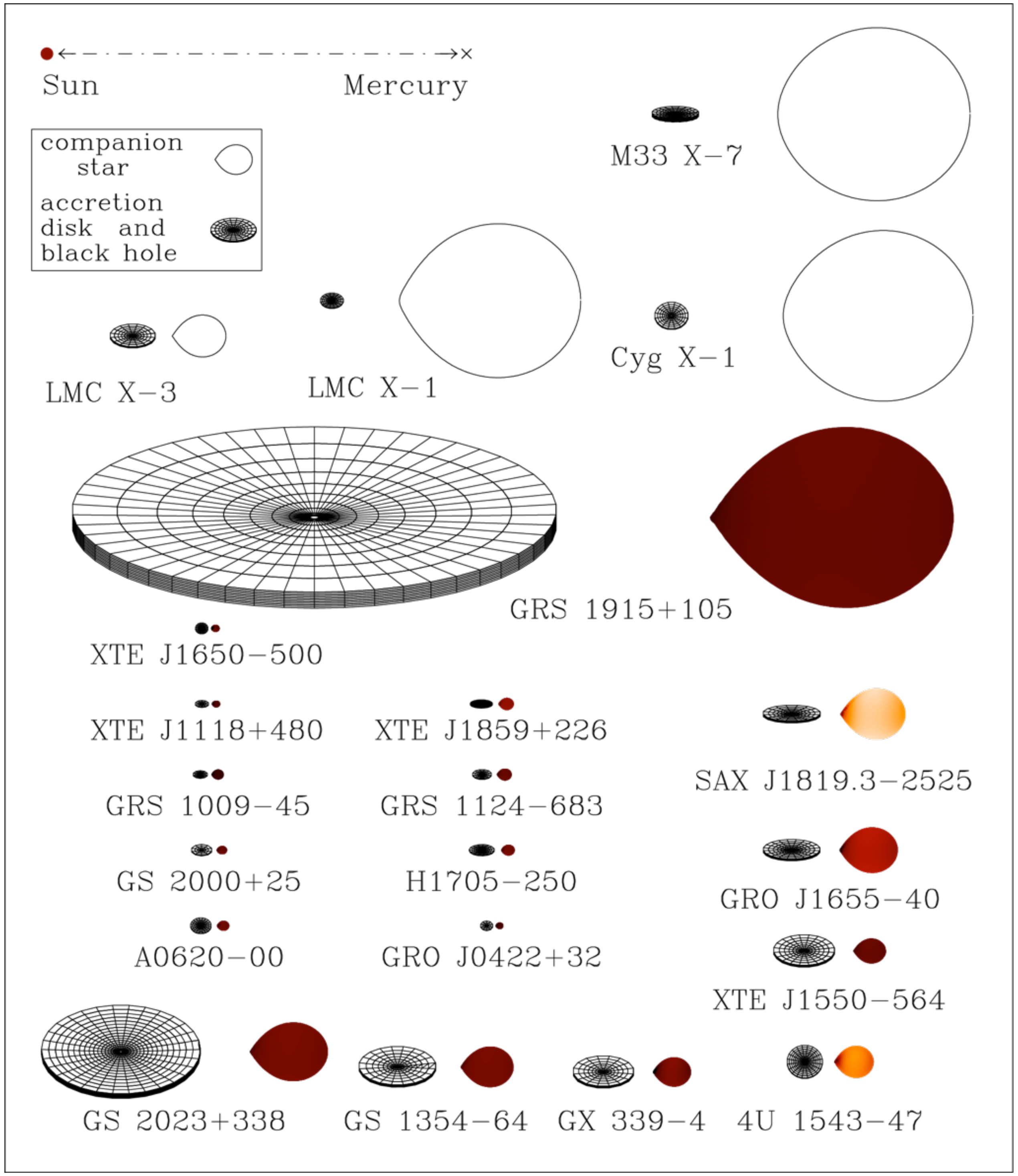
$a = \mathit{spin}.$

Black holes are as simple as elementary particles (in a sense).

Black Hole X-ray Binaries



Dynamically confirmed black holes



- Cyg X-1: the first BH candidate

Bolton (1972), Webster & Mardin (1972)

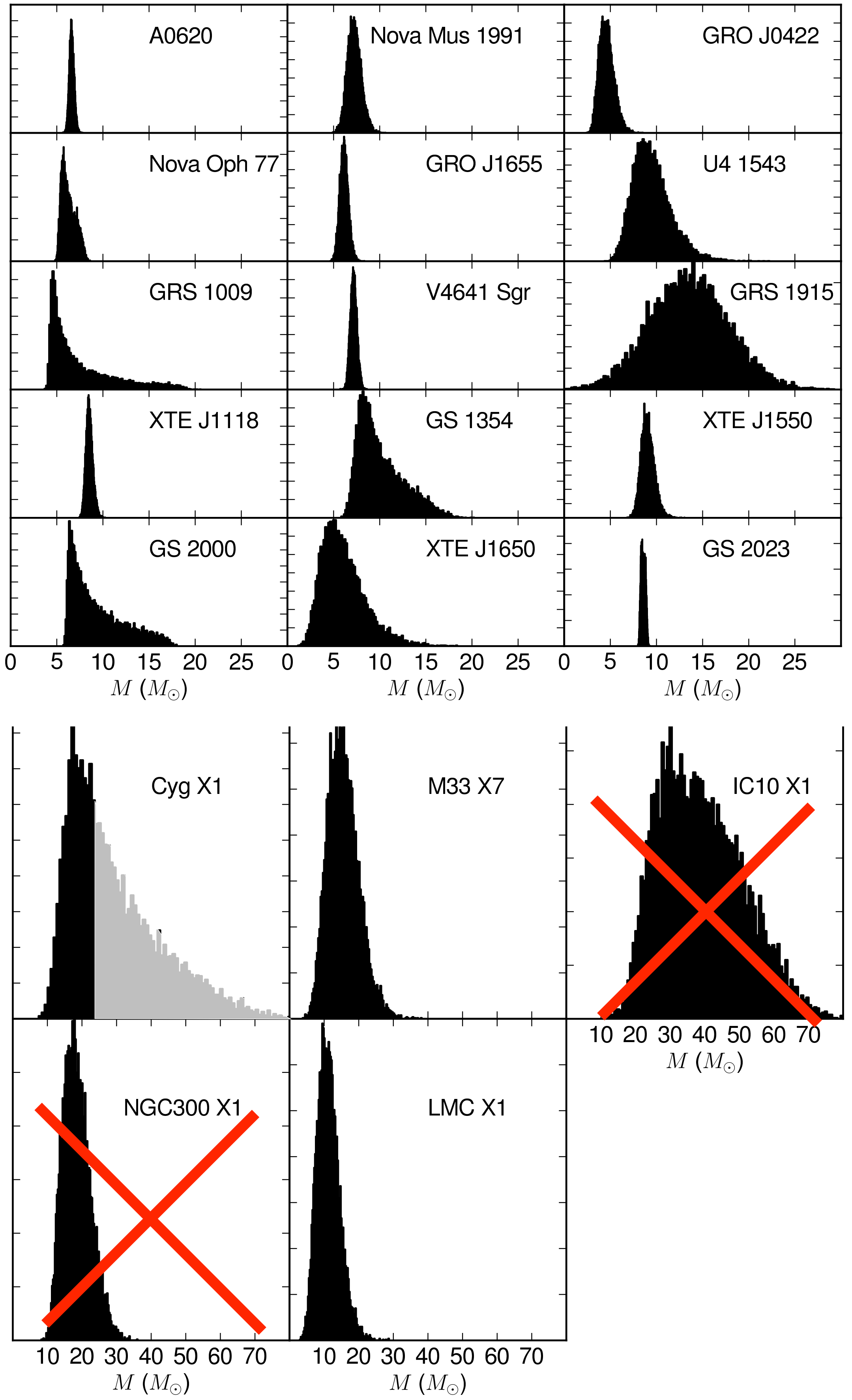
- 21 BHs with dynamical mass measurement

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

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

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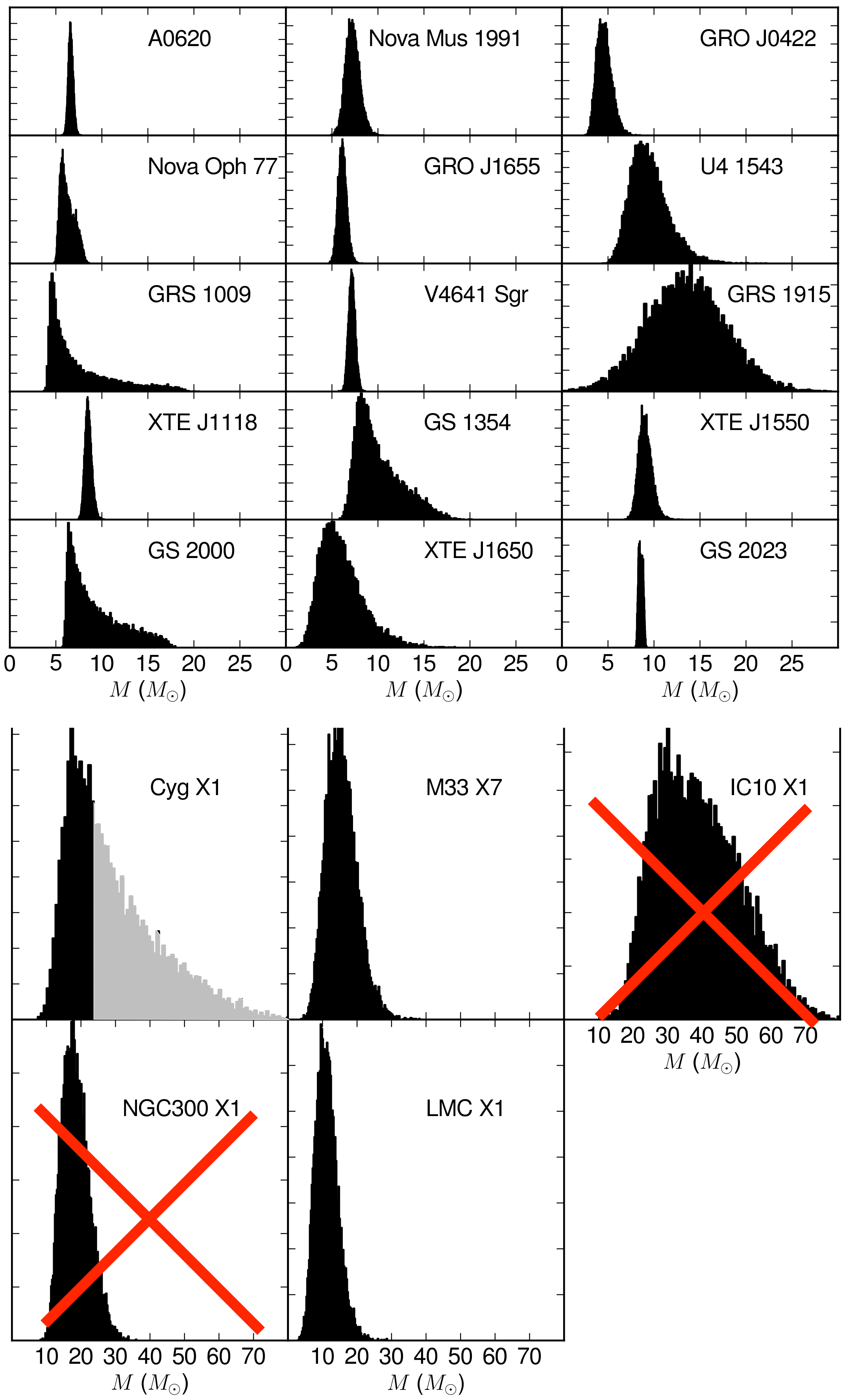

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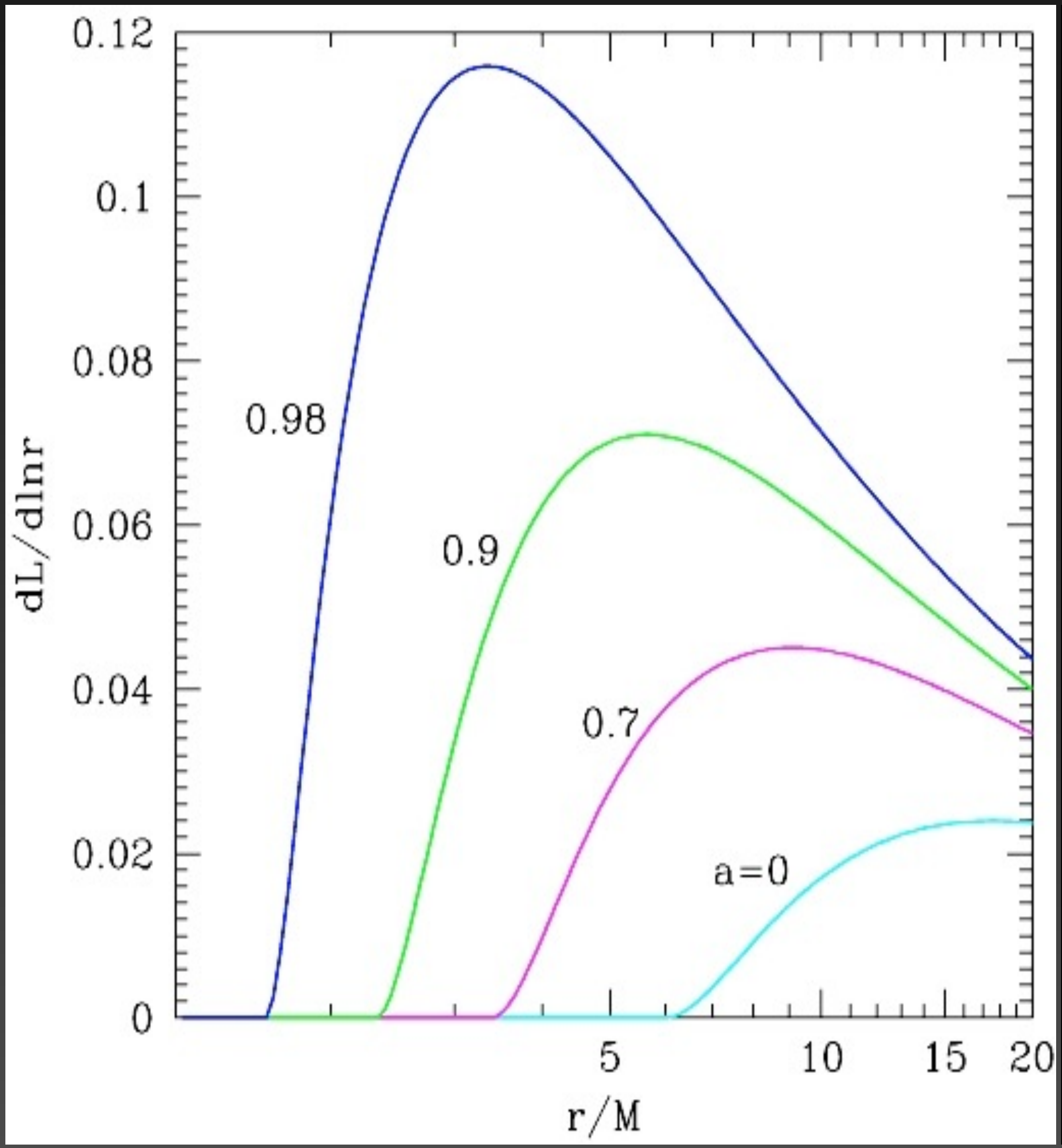
Fragos & McCLintock (2015)

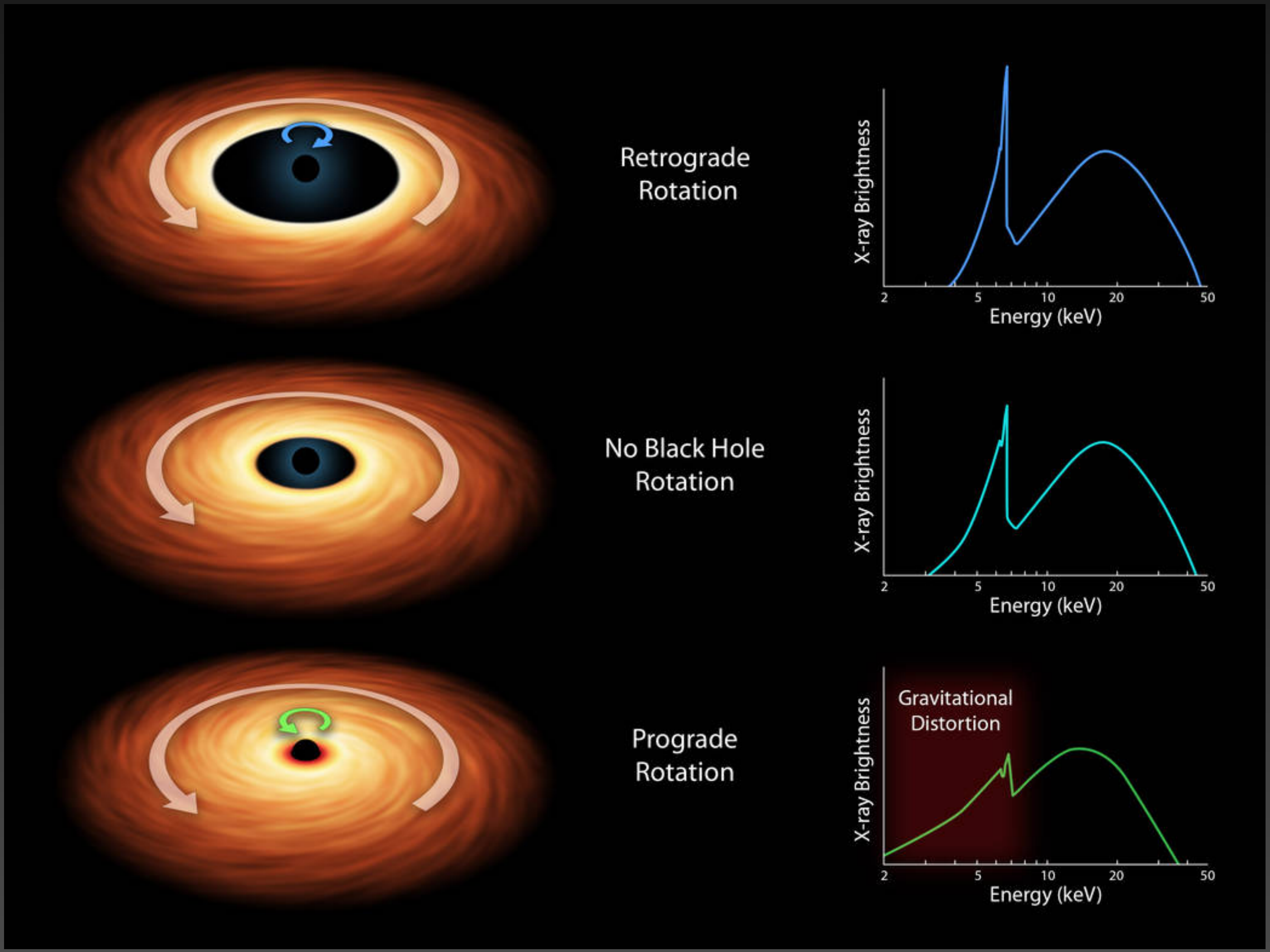
$M_{BH,natal} \sim 6.3 \pm 1.1\ M_\odot$

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

Measuring the the spin of Black Holes

Continuum-fitting and Reflection methods





McClintock et al. (2011, 2014)

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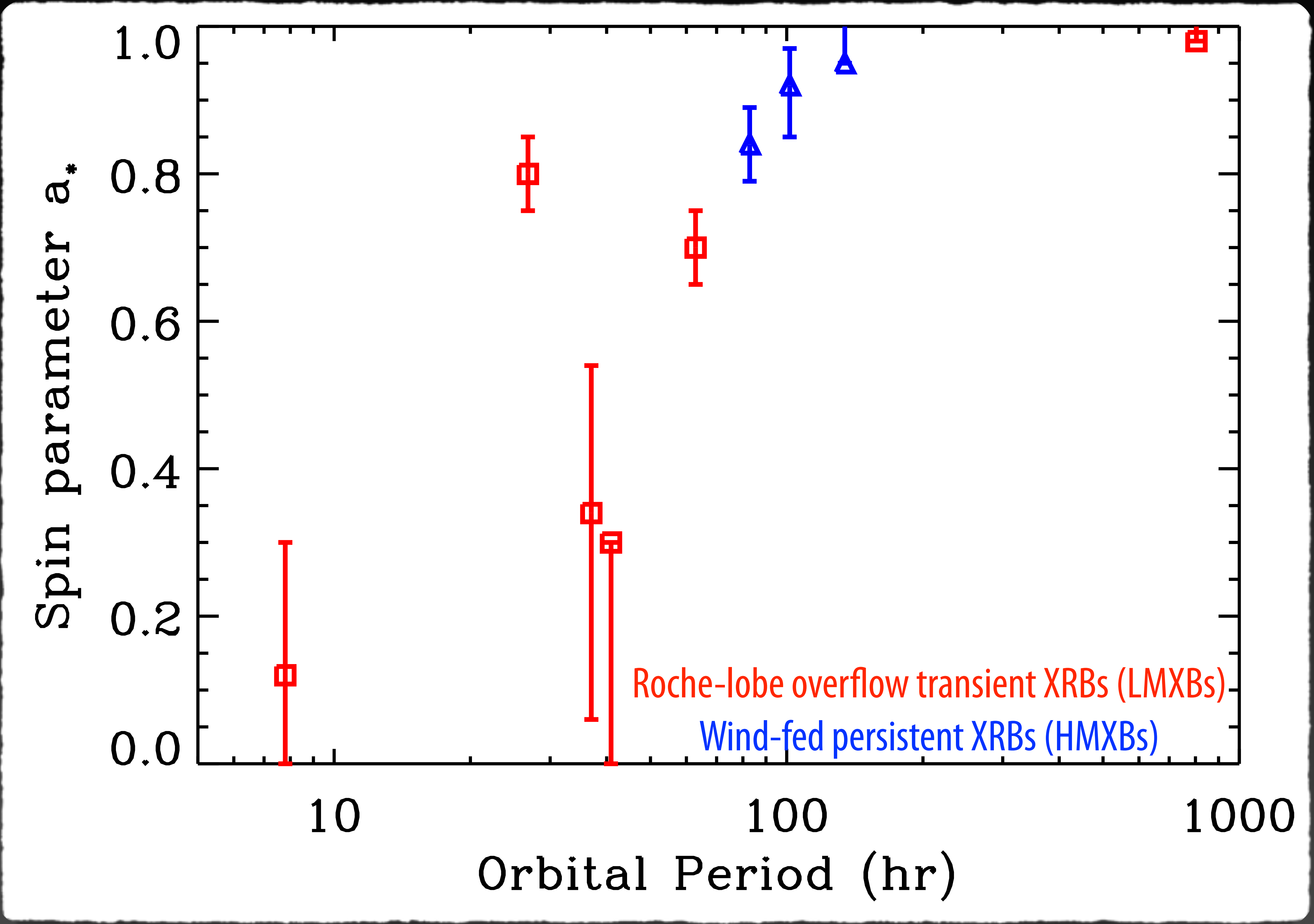
The origin of black-hole spin



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

McClintock et al. (2011, 2014)

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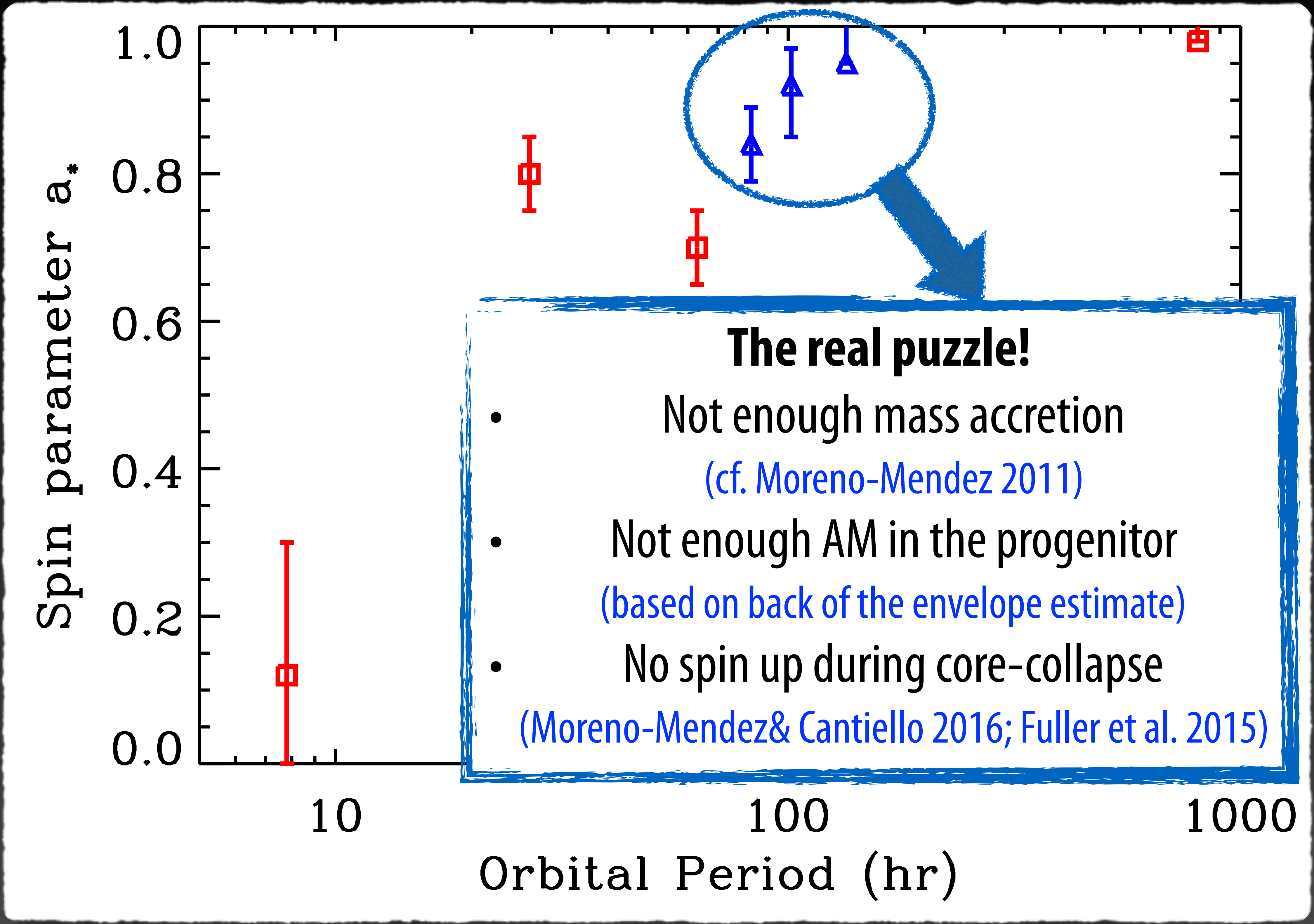

The real puzzle!

- 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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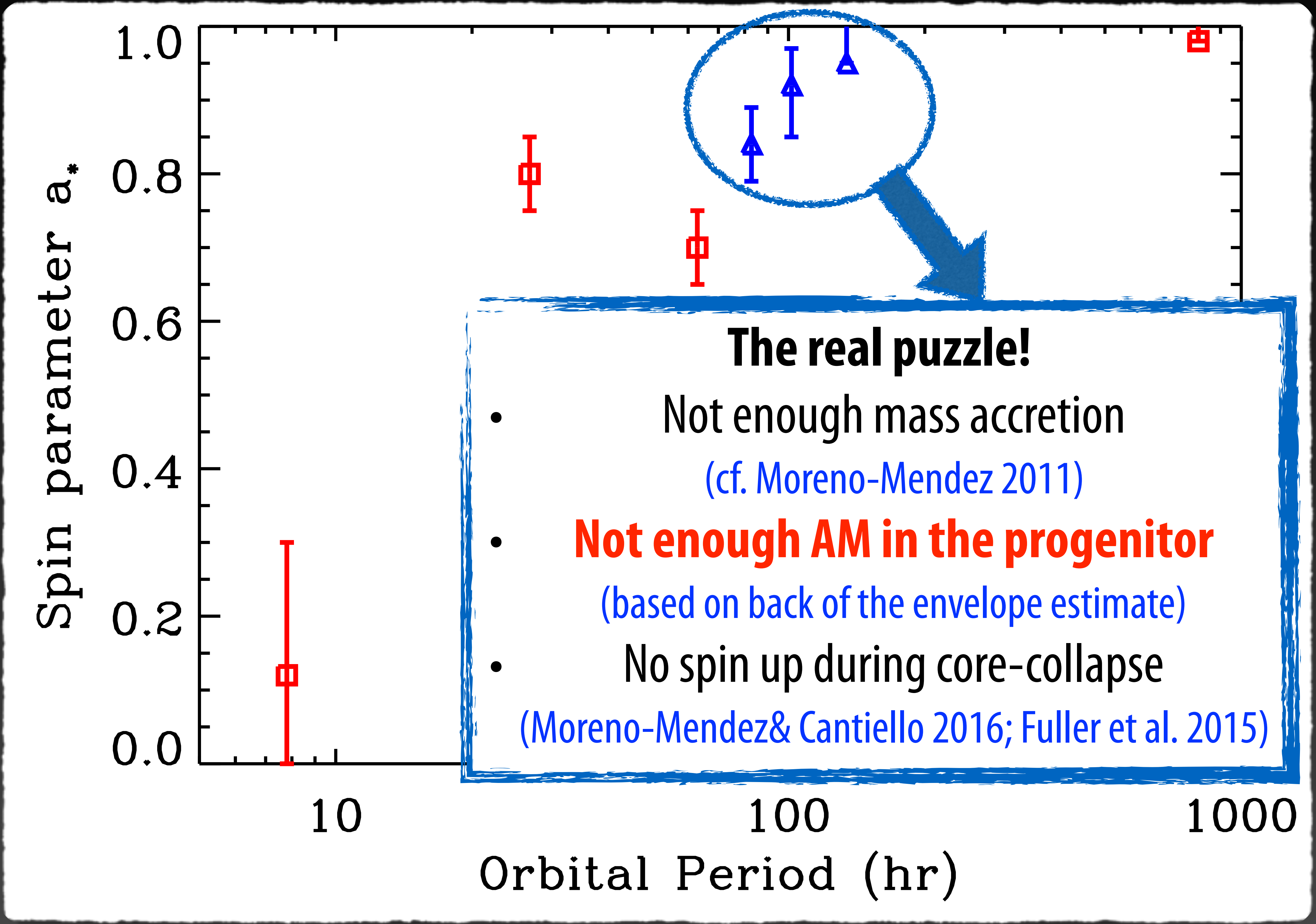

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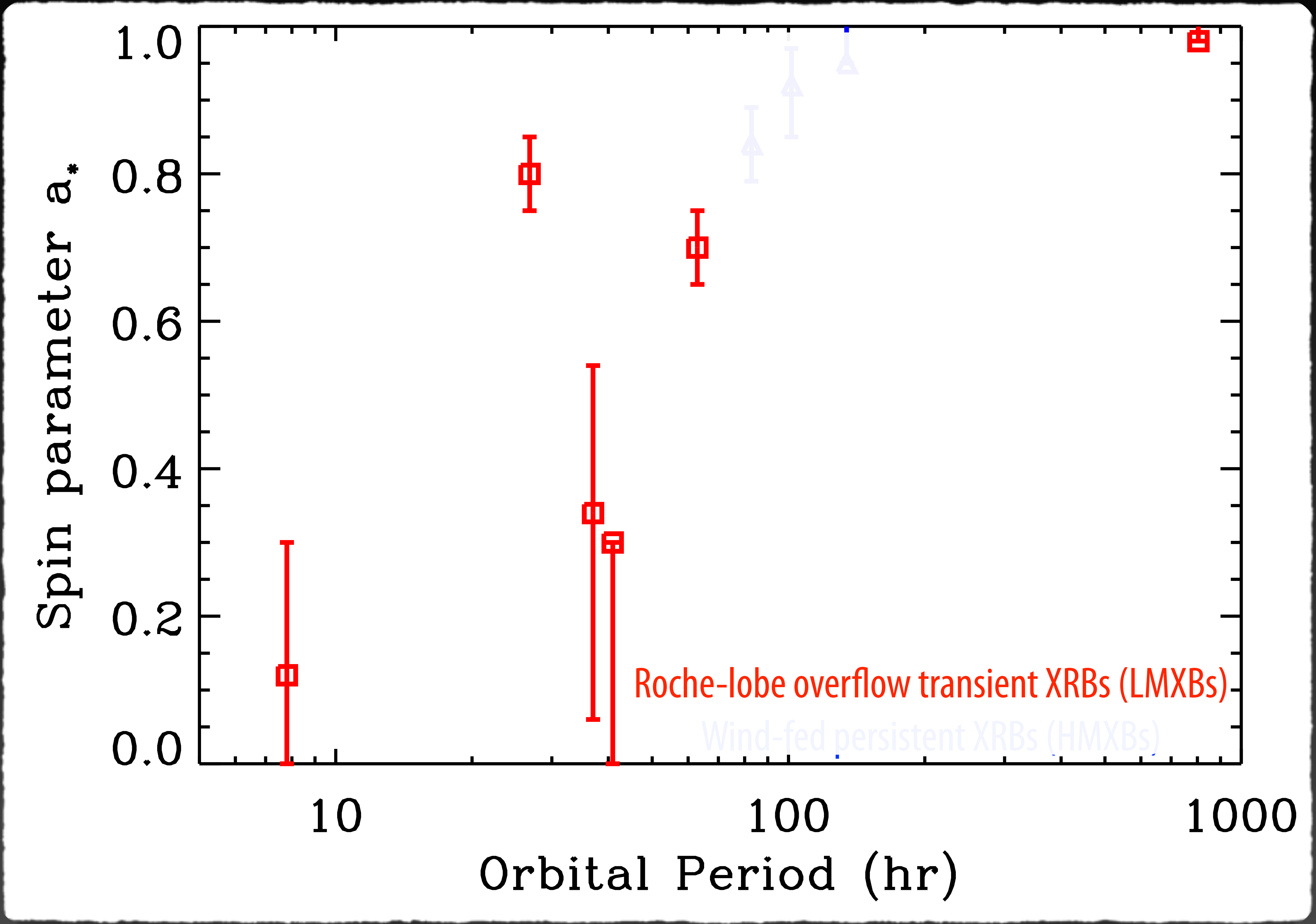

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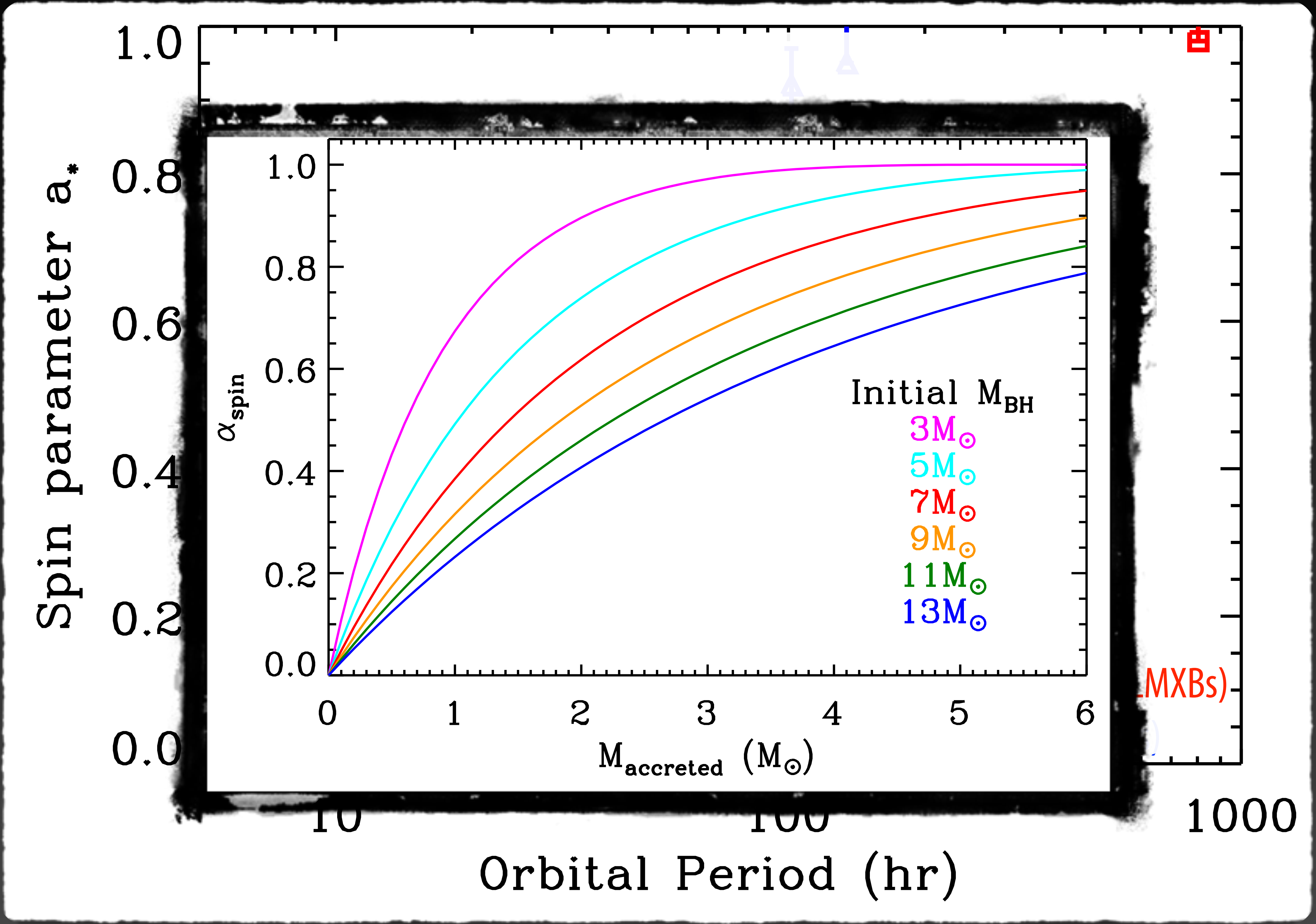

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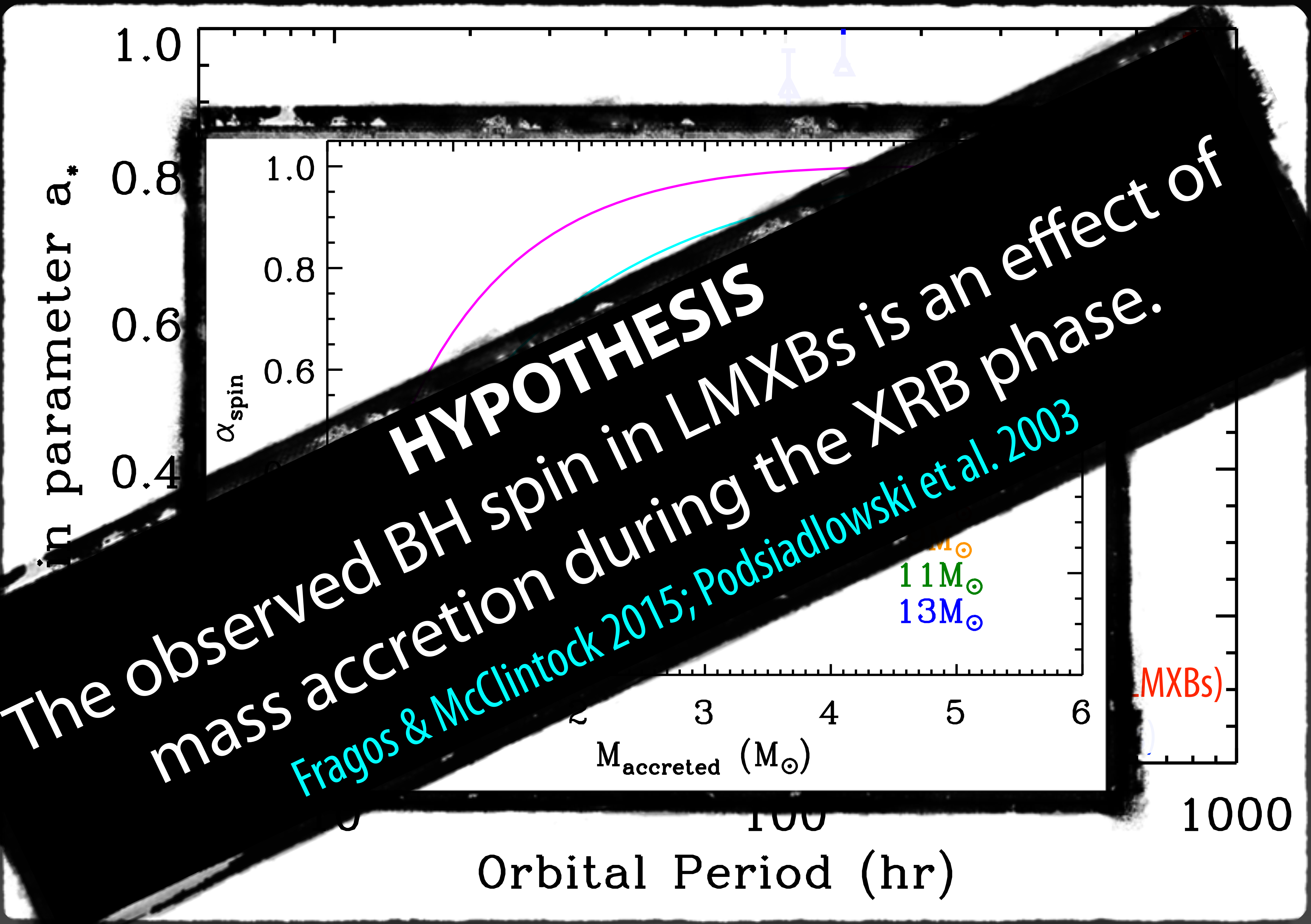

HYPOTHESIS

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

Fragos & McClintock 2015; Podsiadlowski et al. 2003

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

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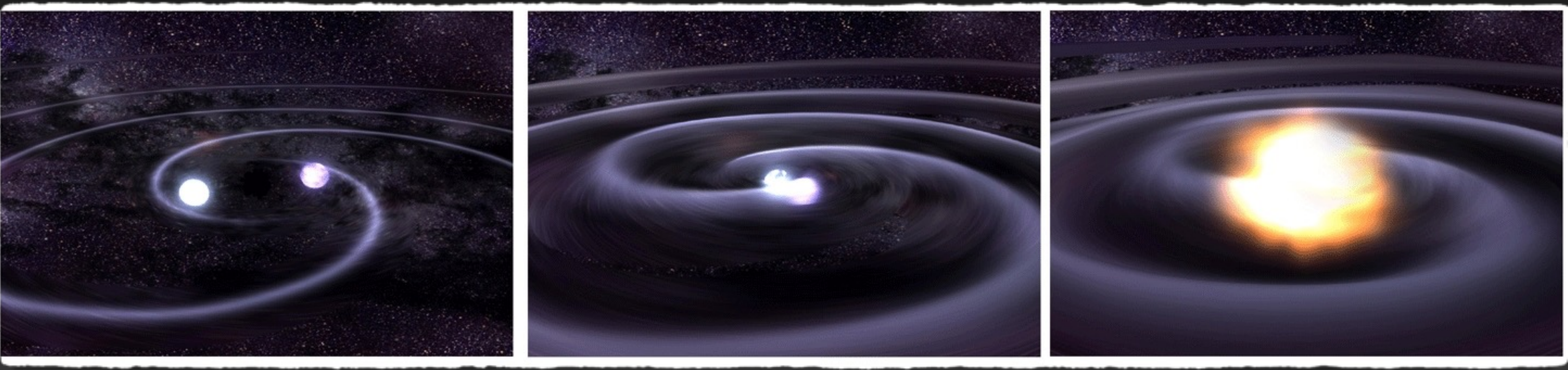
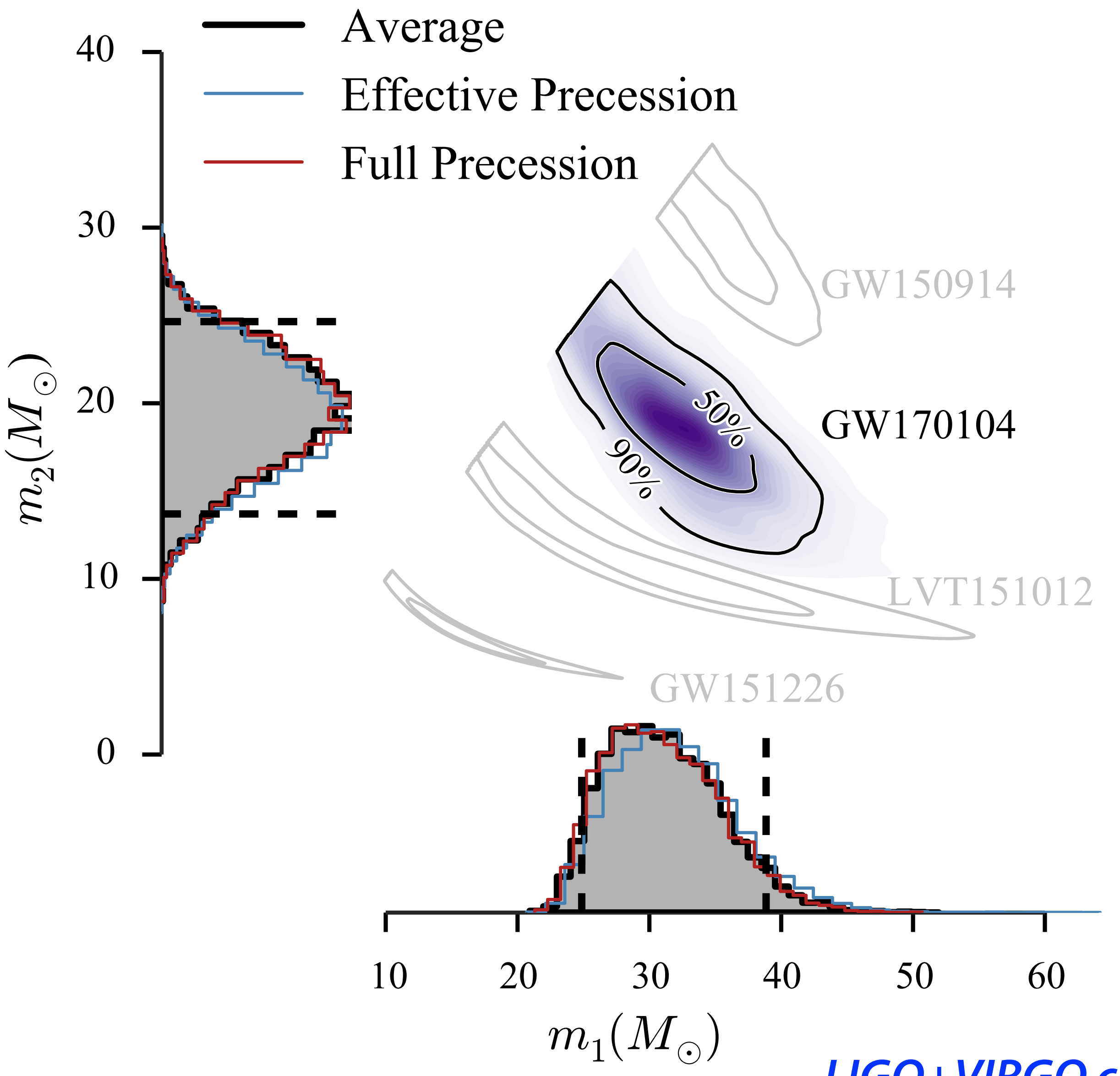
Coalescing Binary Black Holes

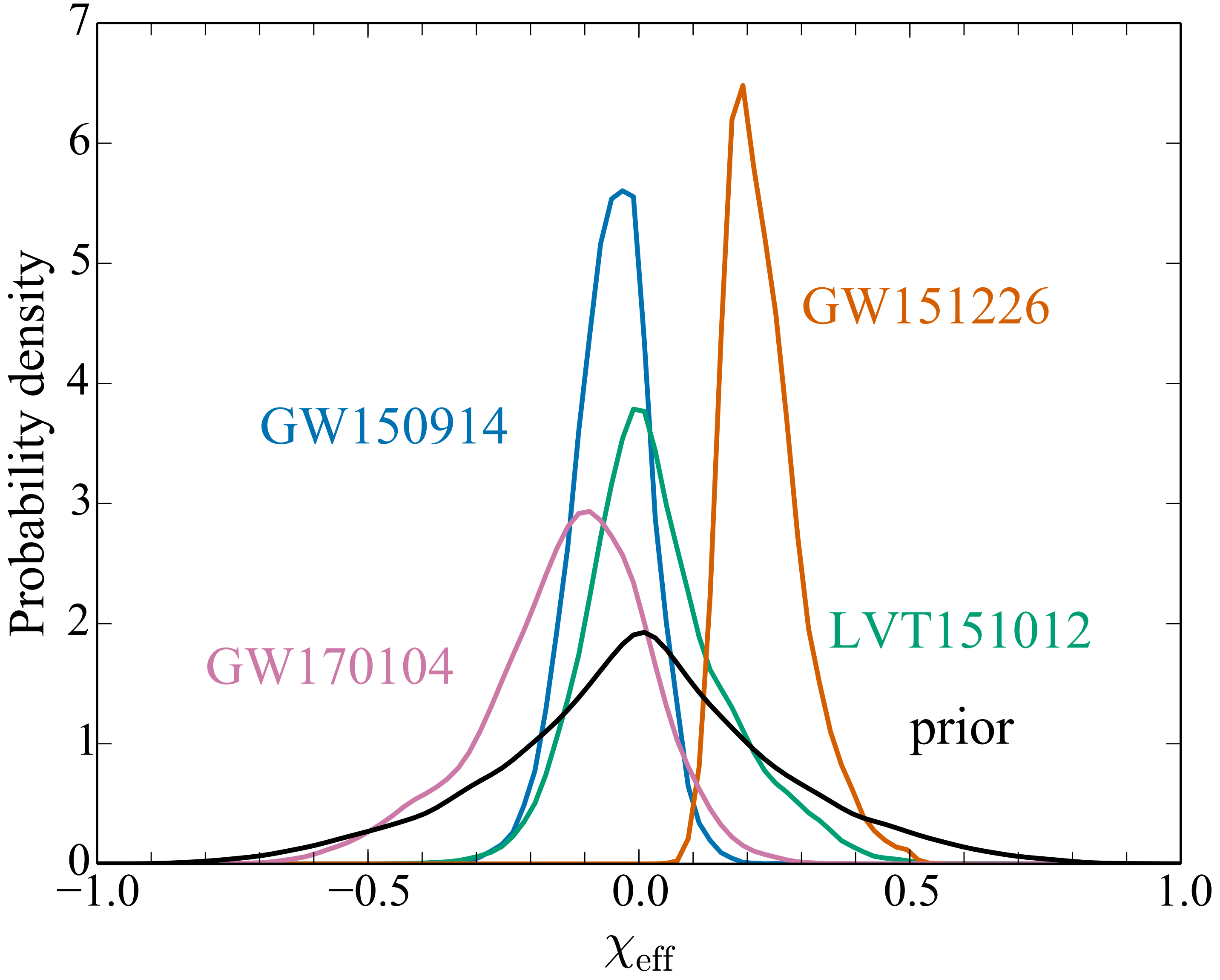


Binary BH mergers detected with LIGO

$$M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$\chi_{\rm eff} = \frac{M_1 \vec{a_1} + M_2 \vec{a_2}}{M_1 + M_2} \hat{\vec{L}}$$



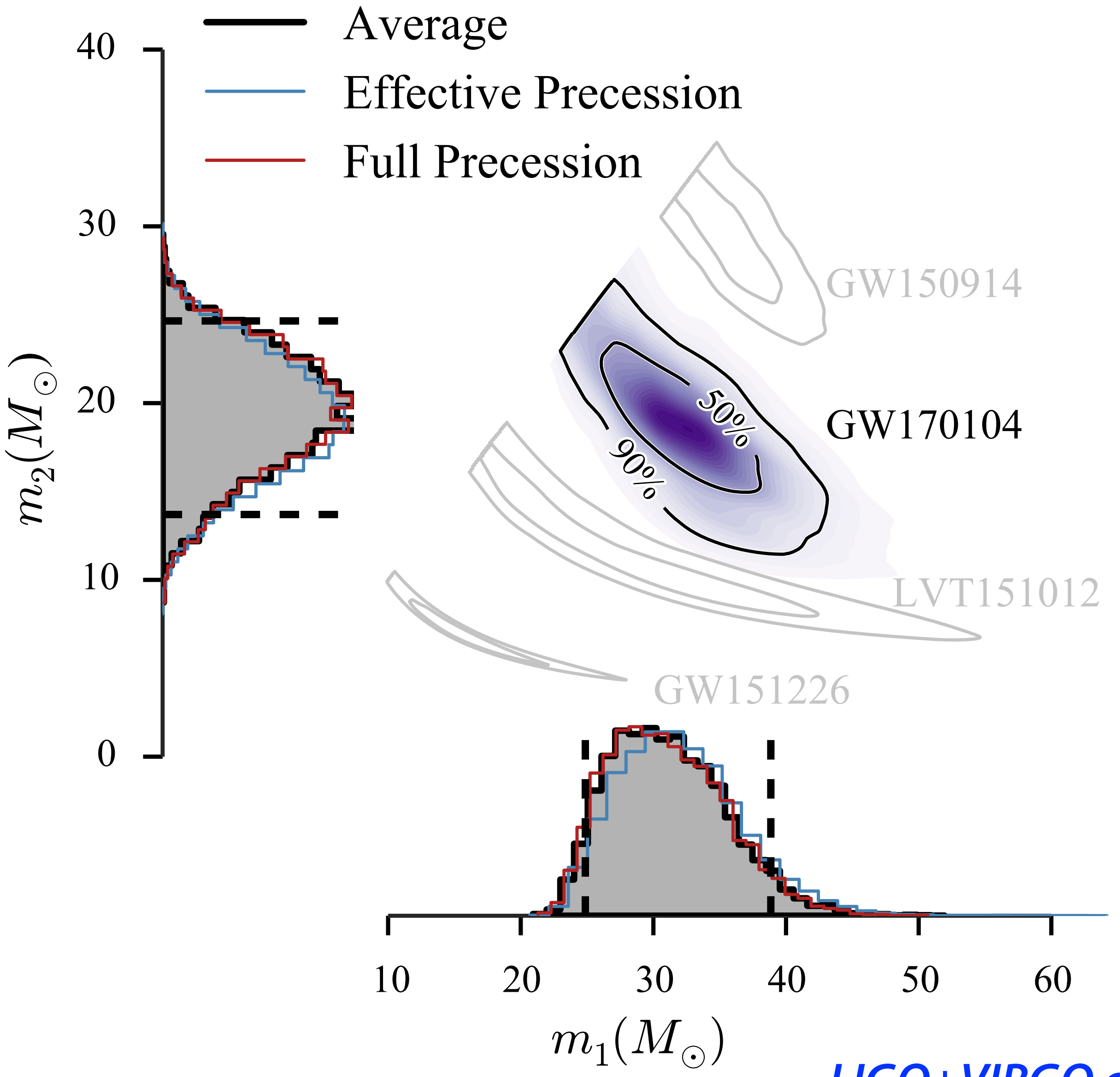


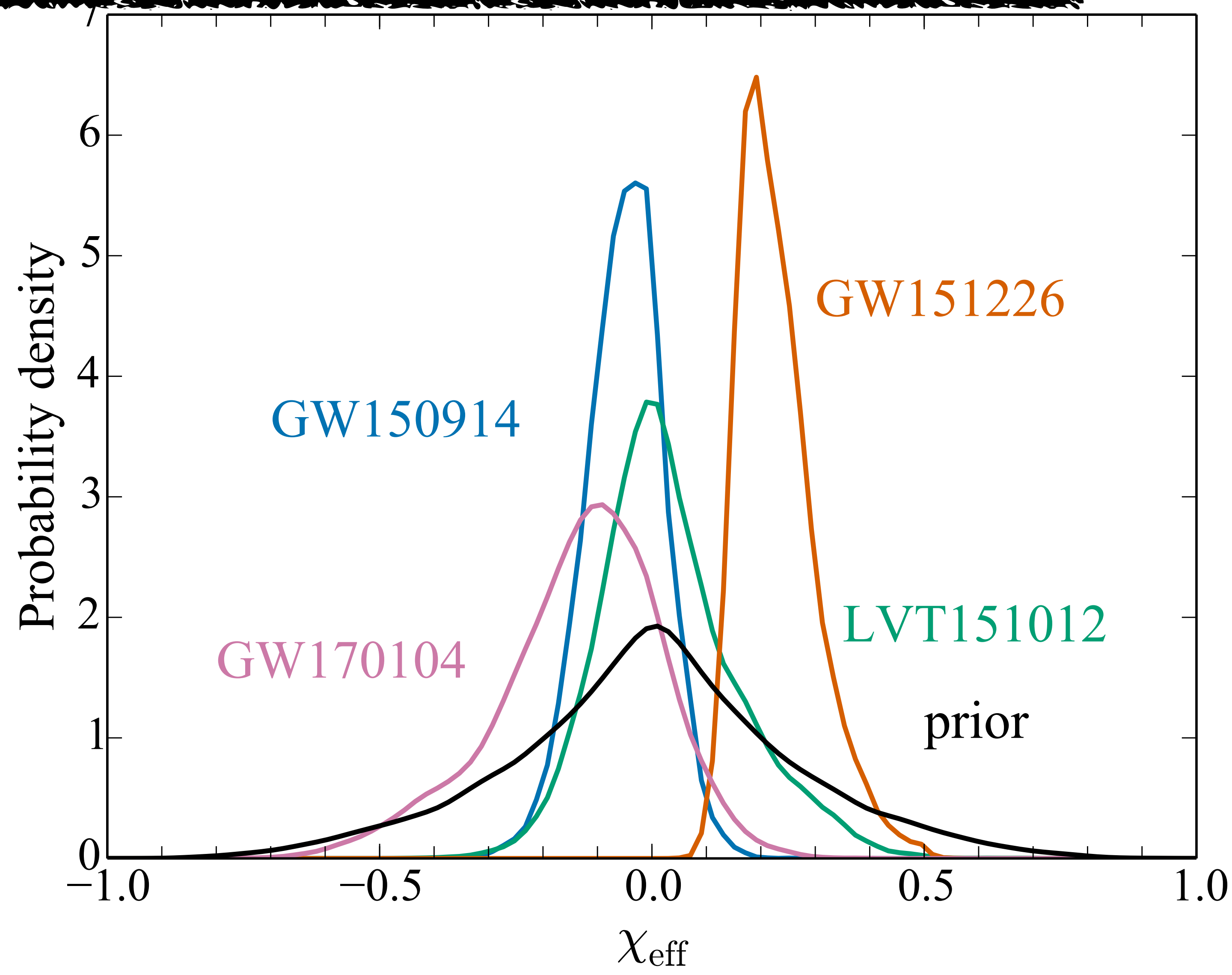
LIGO+VIRGO collaboration (2016a,d, 2017a,b)

Binary BH mergers detected with LIGO

The detection confirms that:

1) “heavy” black holes exist
2) binary black holes form in nature
3) binary black holes merge within a Hubble time(at a detectable rate)





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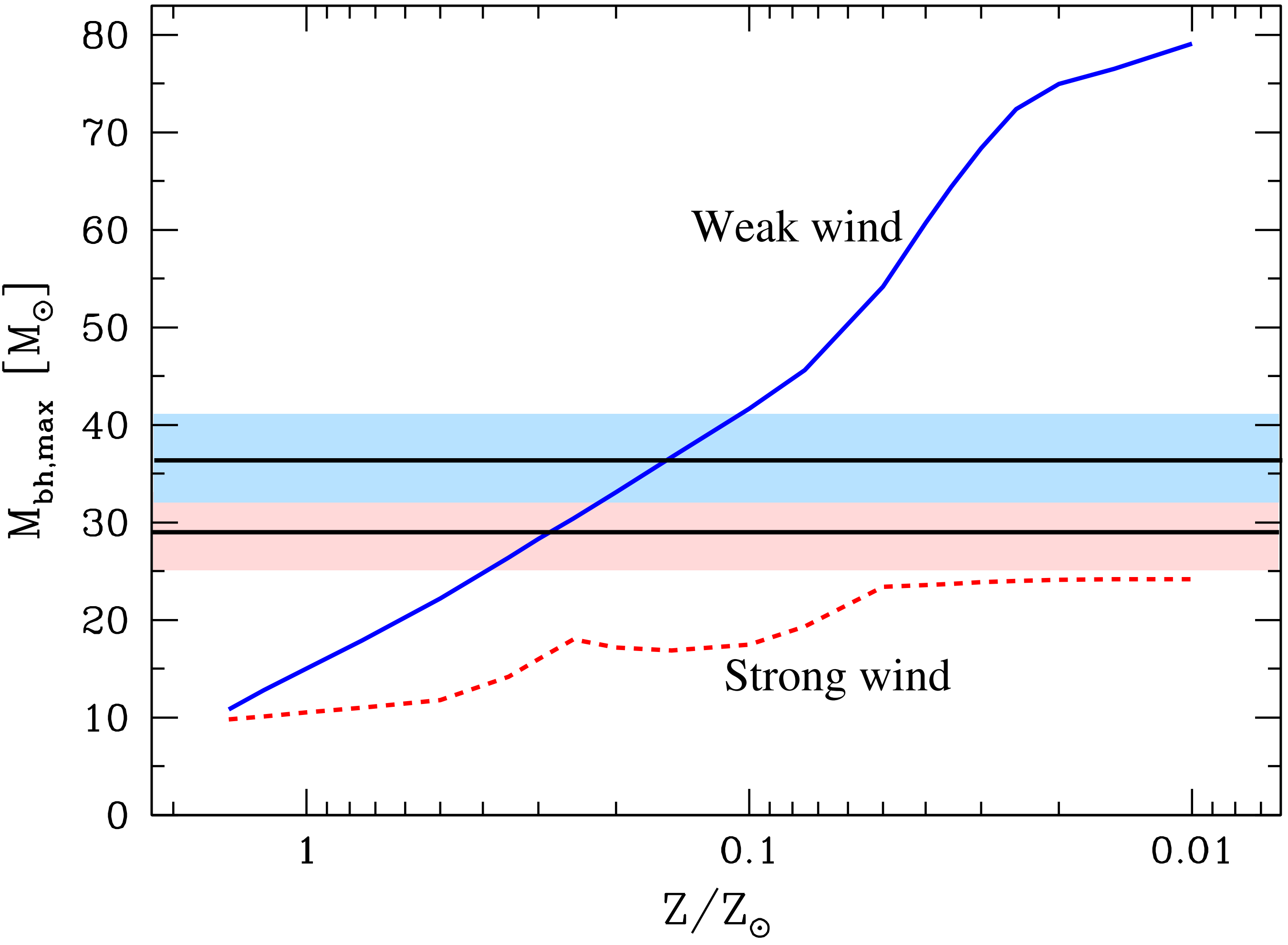
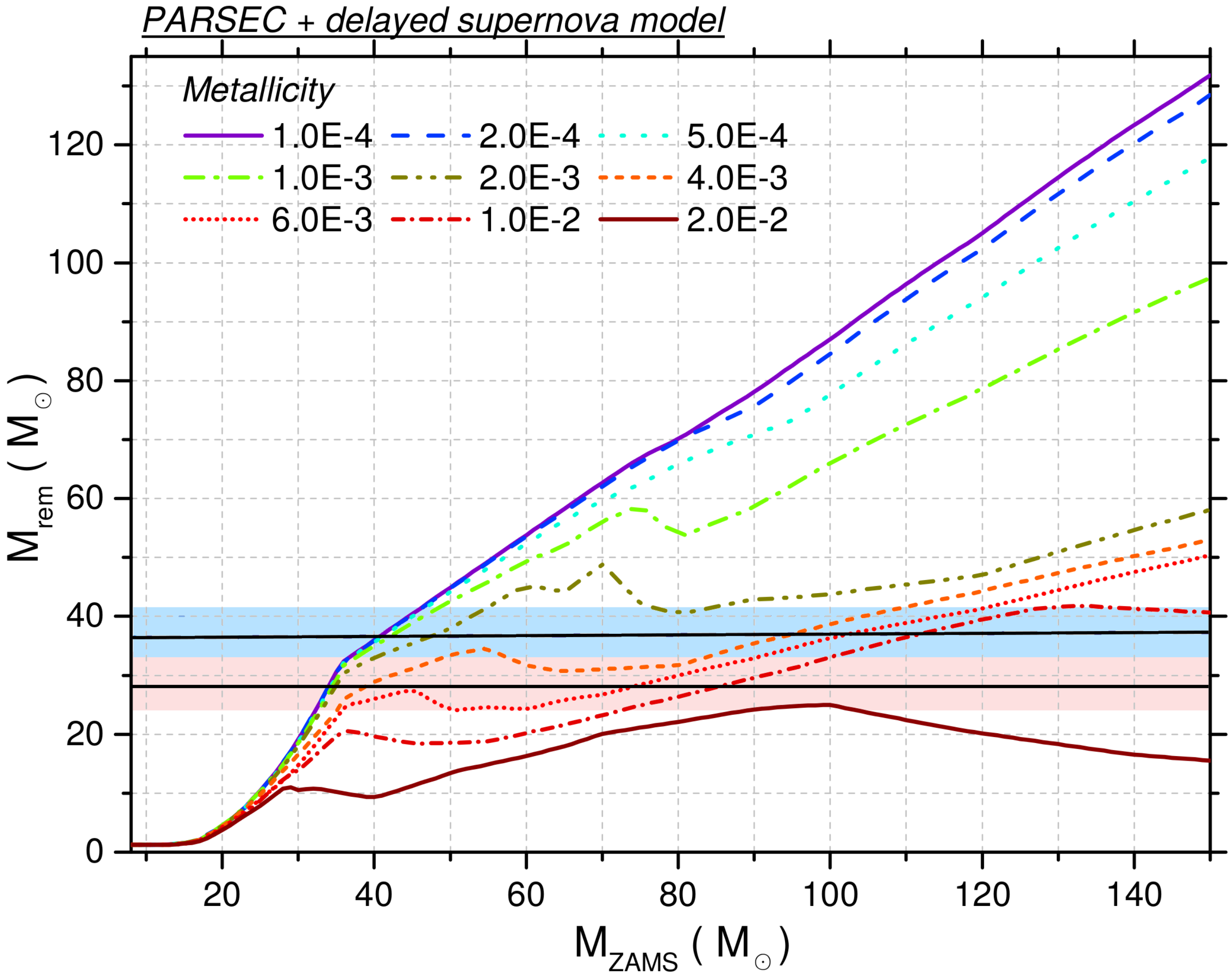
Predicted Masses for Single Black Holes

Belczynski et al. (2010)



Spera et al. (2015)



Minimum metallicity: $Z < 0.003$

Indirect formations channels for "heavy" black holes have been suggested, but are unlikely:
e.g. BH+star mergers (Mapelli & Zampieri 2014; Ziosi 2014)
or star+star mergers (Portegies Zwart et al. 1999; c.f. Glebbeek et al. 2009)

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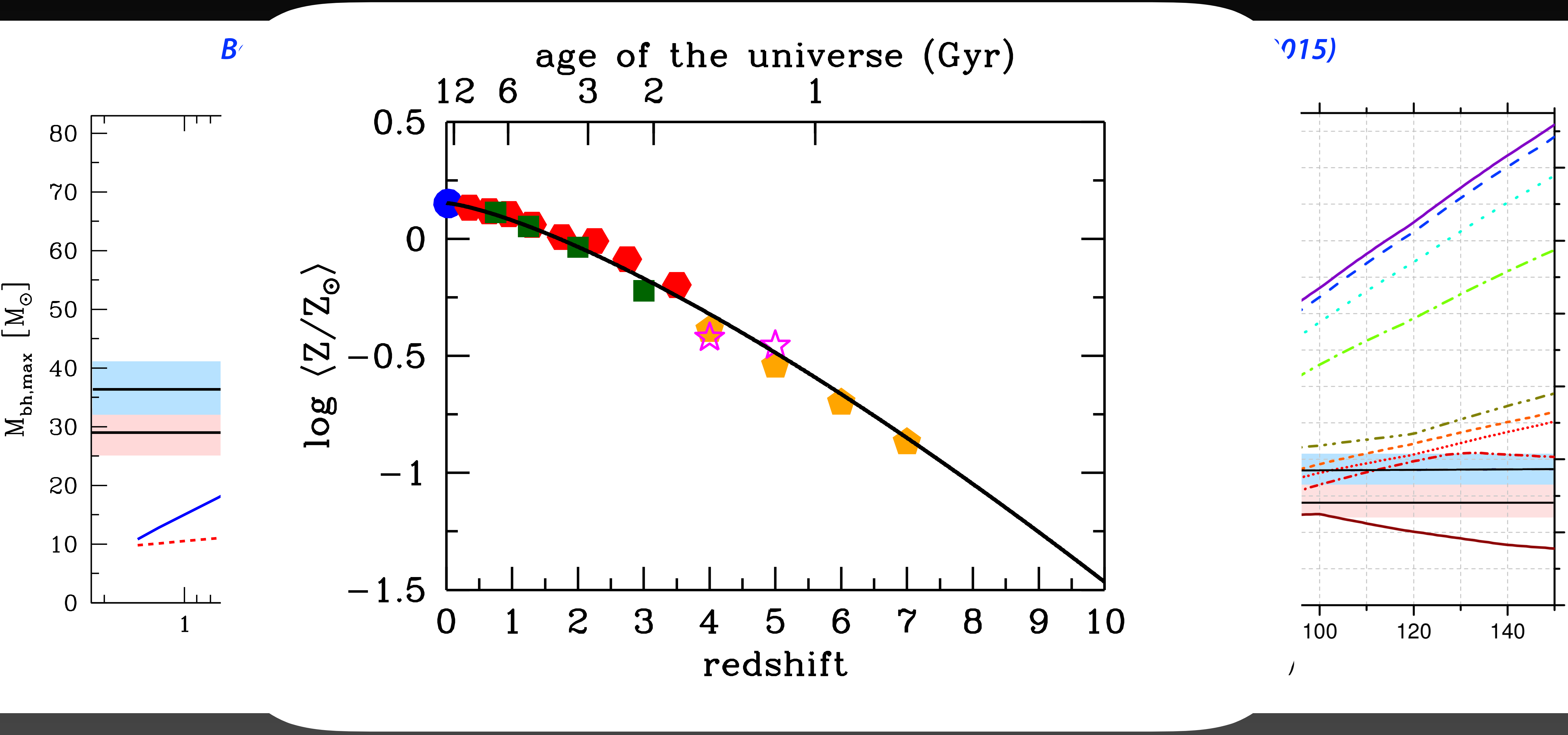

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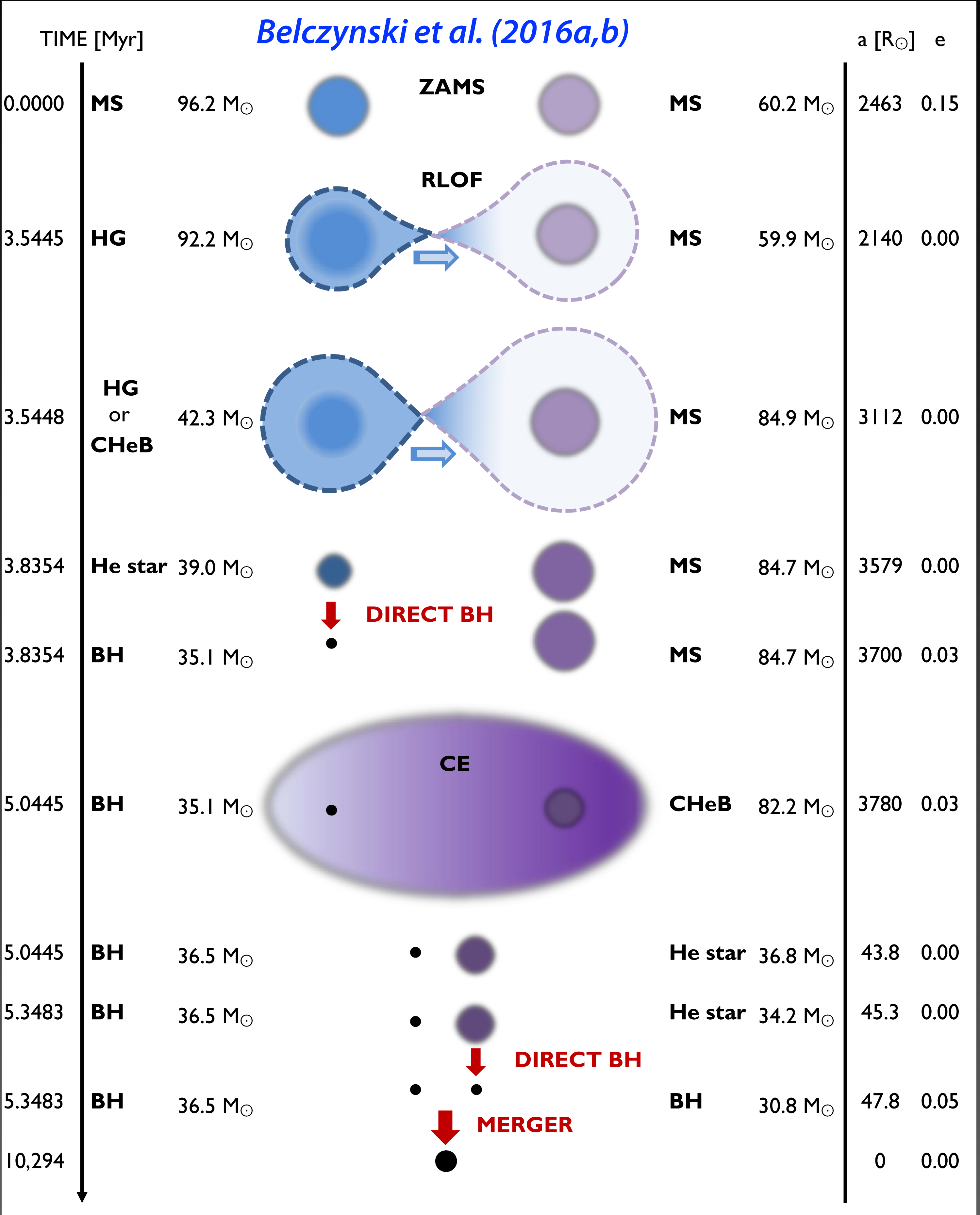
Formation Channels of Binary BHs

- “Classical” Field Binary Evolution
- “Chemically Homogeneous” Field Binary Evolution
- Dynamical Black Hole Binary Formation

“Classical” Field Binary Evolution



Belczynski et al. (2016a,b)

TIME [Myr]						a [R⊙]	e
0.0000	**MS**	96.2 M⊙	**ZAMS**	**MS**	60.2 M⊙	2463	0.15
3.5445	**HG**	92.2 M⊙	**RLOF**	**MS**	59.9 M⊙	2140	0.00
3.5448	**HG** or **CHeB**	42.3 M⊙		**MS**	84.9 M⊙	3112	0.00
3.8354	**He star**	39.0 M⊙	**DIRECT BH**	**MS**	84.7 M⊙	3579	0.00
3.8354	**BH**	35.1 M⊙		**MS**	84.7 M⊙	3700	0.03
5.0445	**BH**	35.1 M⊙	**CE**	**CHeB**	82.2 M⊙	3780	0.03
5.0445	**BH**	36.5 M⊙		**He star**	36.8 M⊙	43.8	0.00
5.3483	**BH**	36.5 M⊙	**DIRECT BH**	**He star**	34.2 M⊙	45.3	0.00
5.3483	**BH**	36.5 M⊙	**MERGER**	**BH**	30.8 M⊙	47.8	0.05
10,294						0	0.00

Sources of uncertainty:

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Kicks in Neutron Stars

Hobbs et al. (2005)

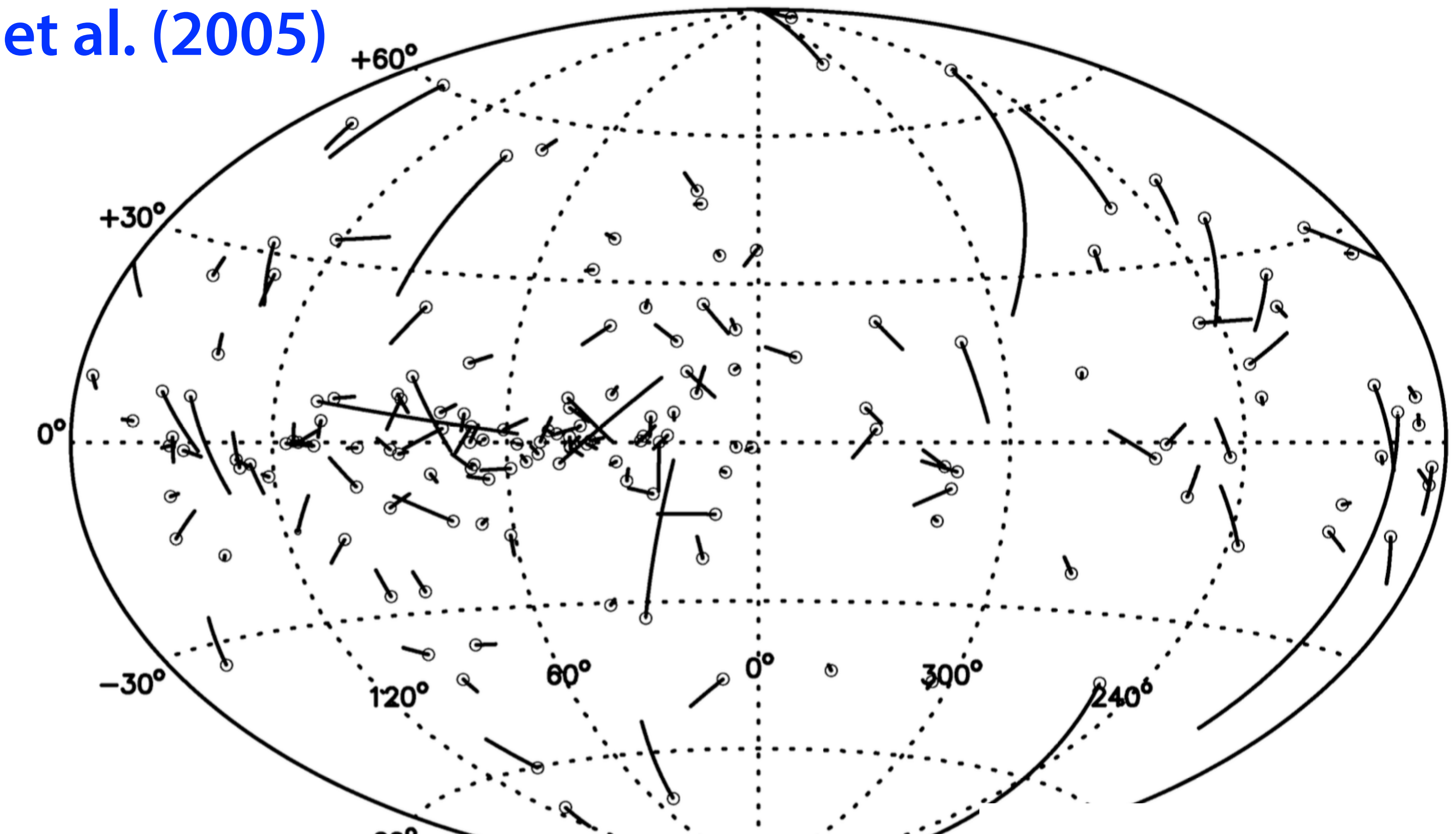
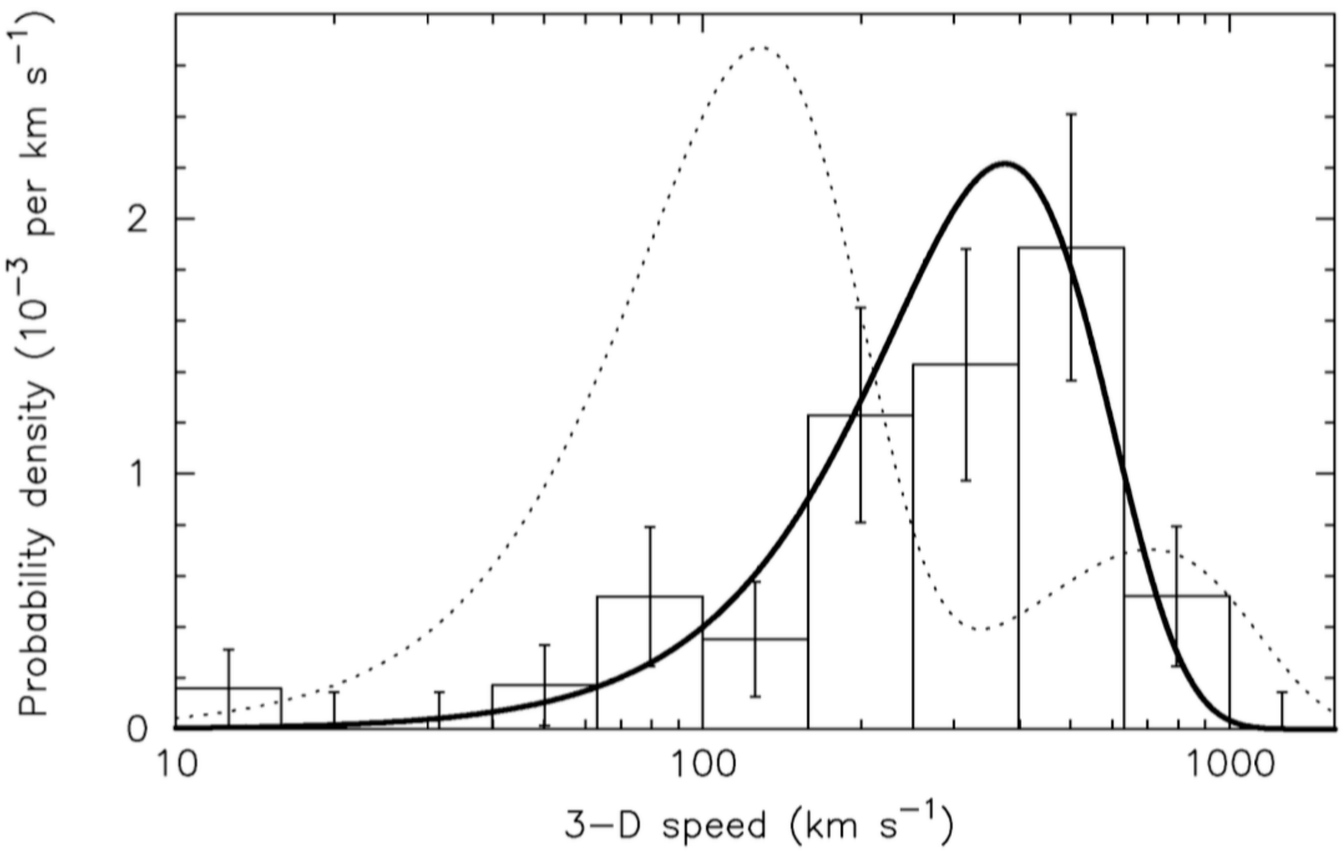


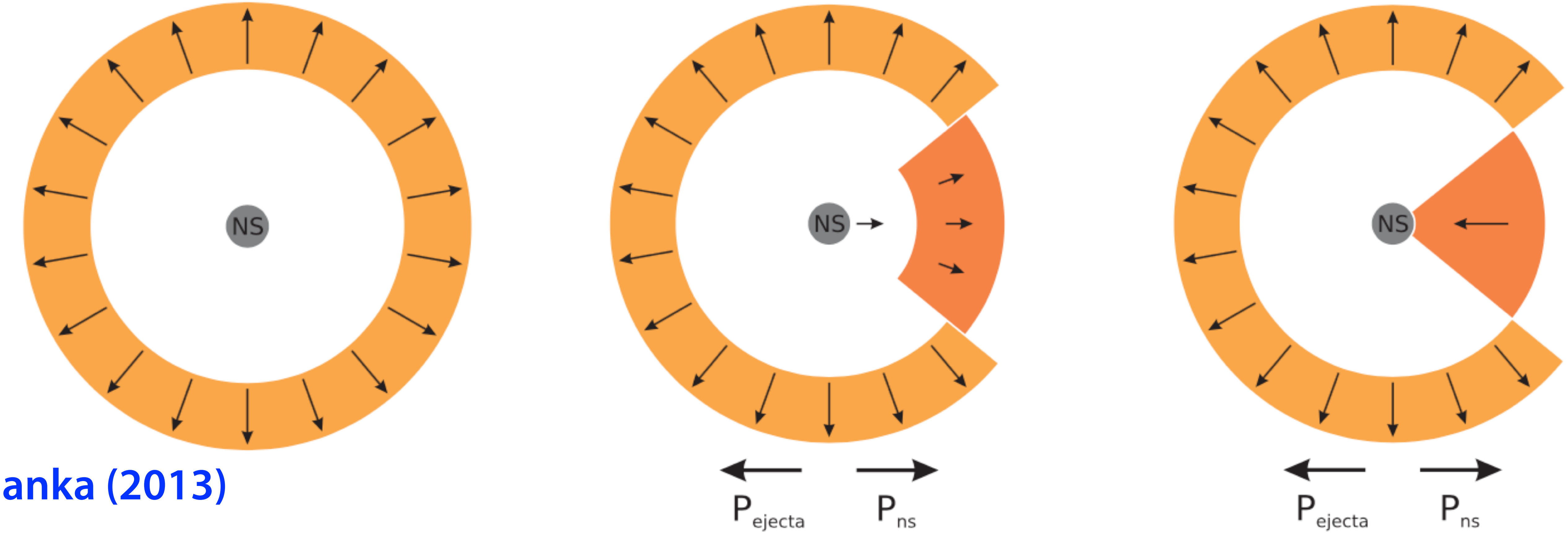
Figure 1. The Galactic motions of the pulsars in our sample. A pulsar is currently at the positior
the last 1 Myr assuming no radial velocity.



What about black holes????

Supernova kick mechanisms

1) Asymmetries in the supenova ejecta (large possible kicks ~100km/s, explosion required)



Janka (2013)

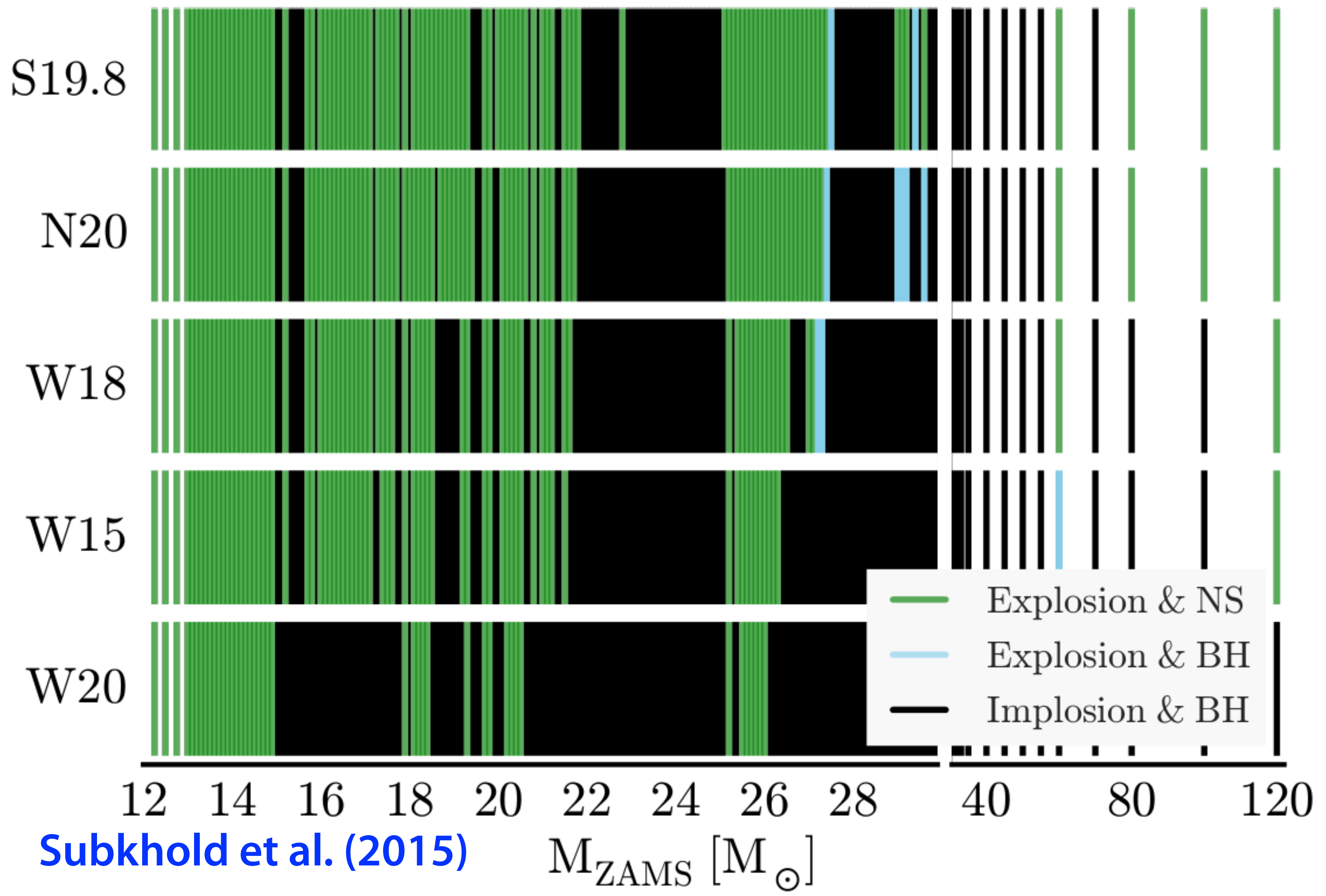
Figure 1. Schematic visualization of SN mass ejection and compact remnant kicks. In the left-hand image the ejecta are spherically symmetric and no recoil is imparted to the central object. Asymmetric mass ejection must lead to compact remnant motion with the opposite linear momentum (middle panel). The momentum can be transferred by gravitational forces and by direct hydrodynamical forces in the case of accretion. The latter are crucial when the protoneutron star is accreting fallback matter to collapse to a BH (right-hand panel). (Image taken from Scheck et al. (2006); reproduced with permission ©ESO.)

2) or Asymmetries in the neutrino emission (small possible kicks ~10km/s, no explosion required)

Why do we care?

1) **Significantly affect binary populations synthesis studies. E.g., prediction for BH mergers rates varies by two orders of magnitude! (Dominique at al., 2012)**

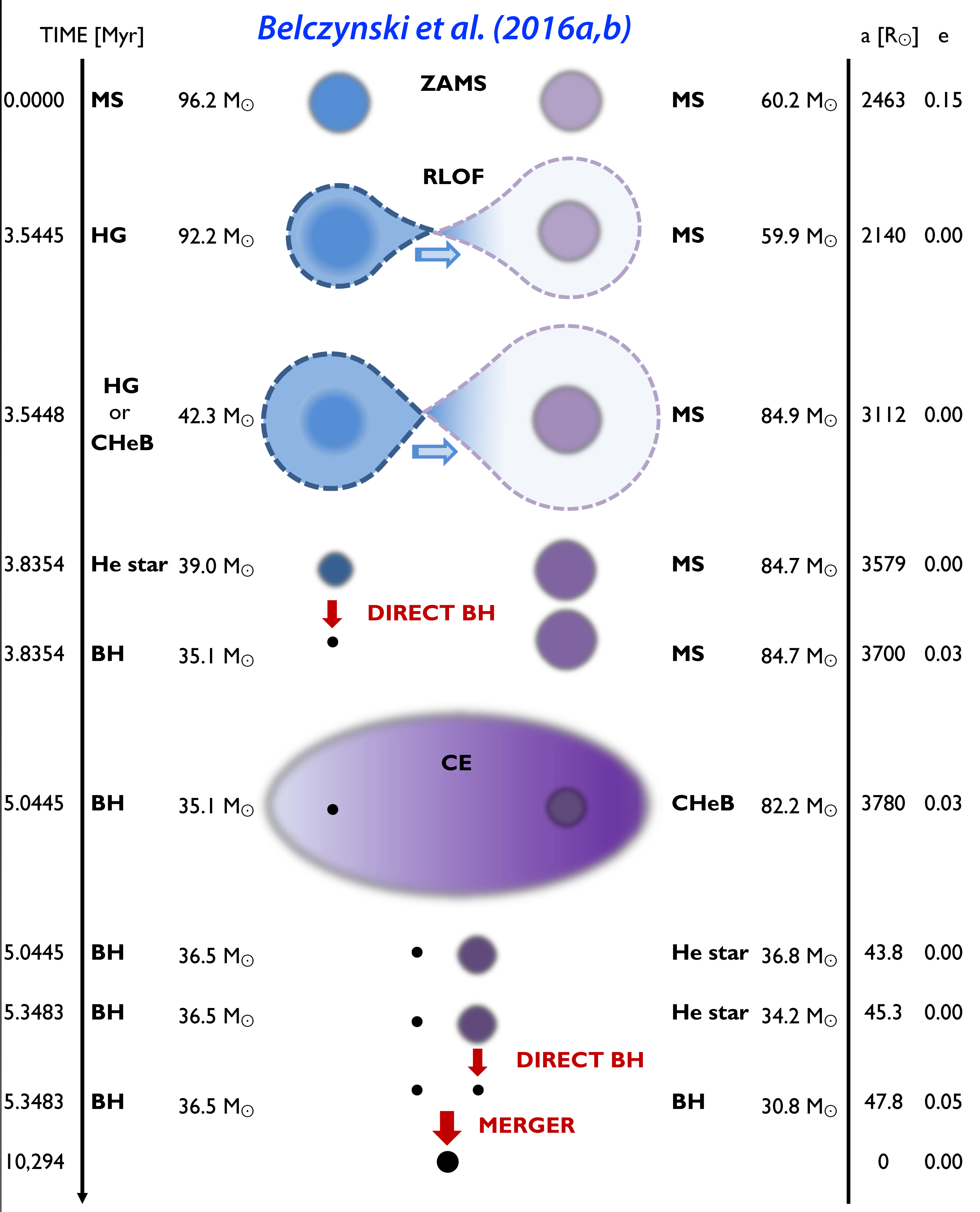
2) **Constraints core collapse physics.**



Subkhold et al. (2015)

“Classical” Field Binary Evolution

Belczynski et al. (2016a,b)



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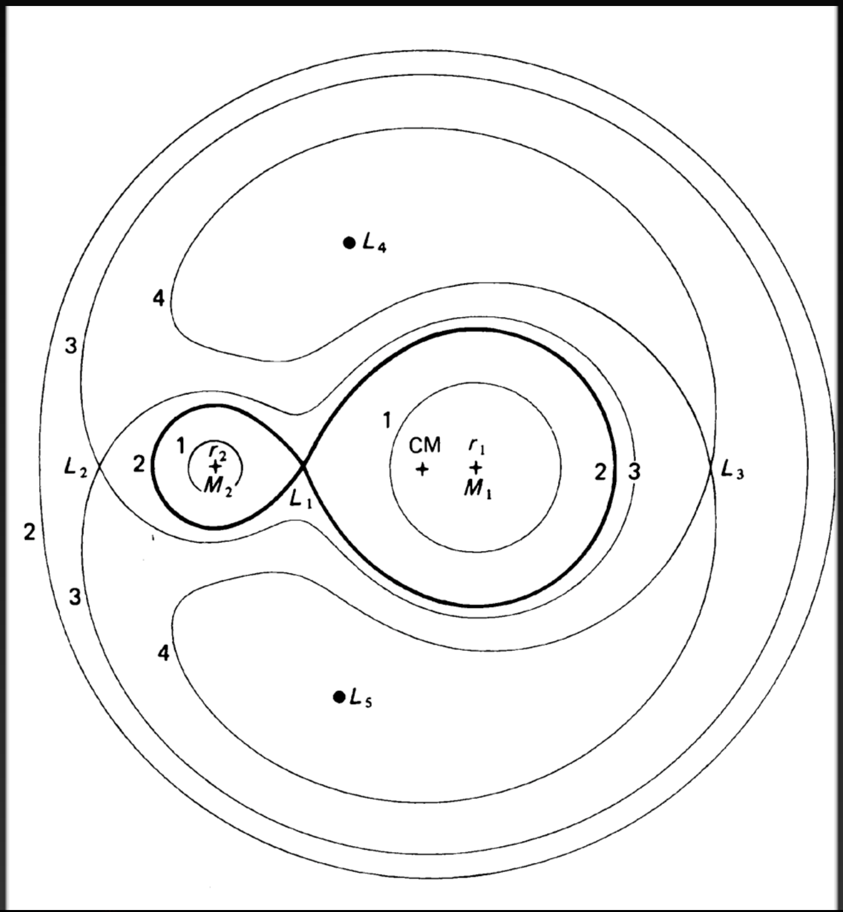
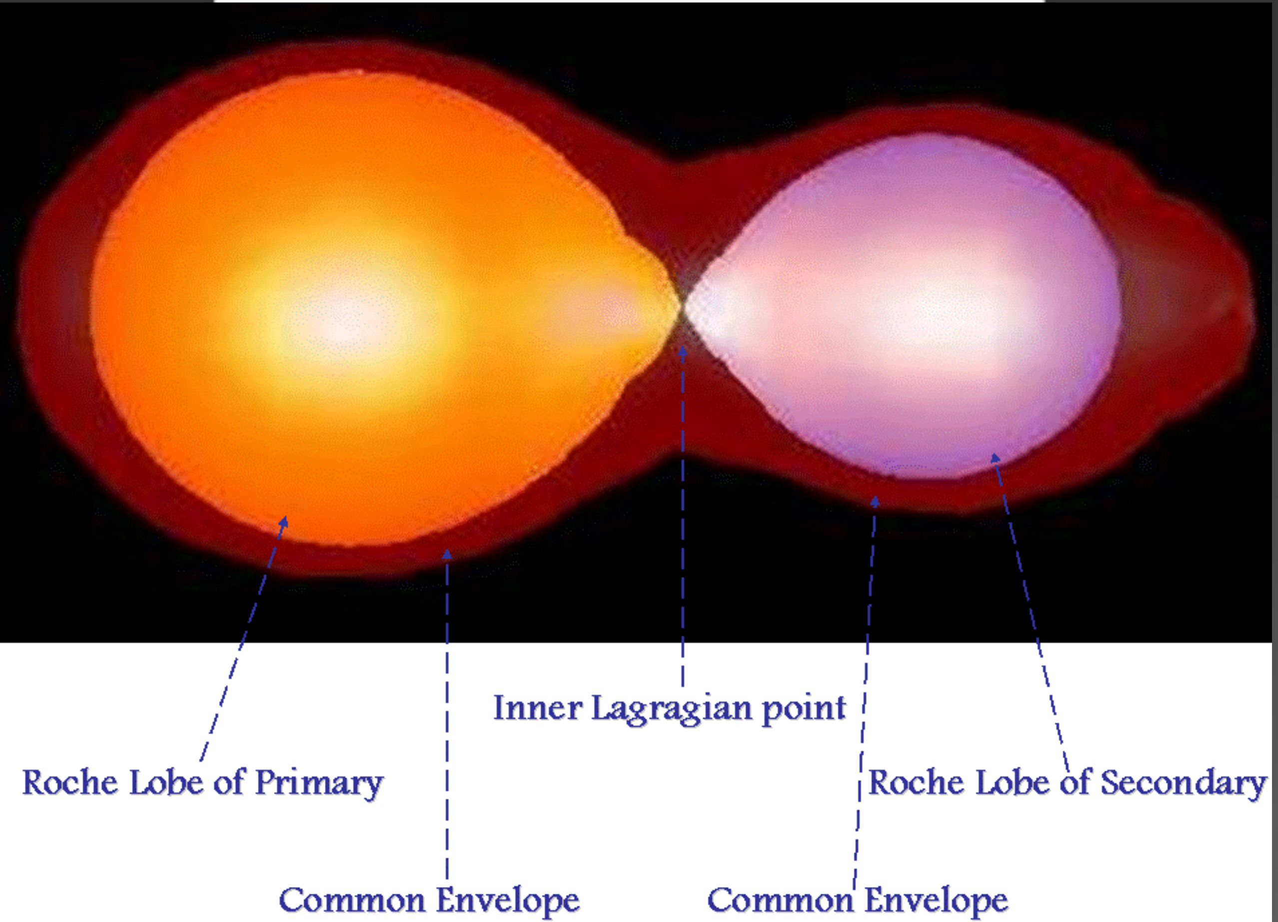
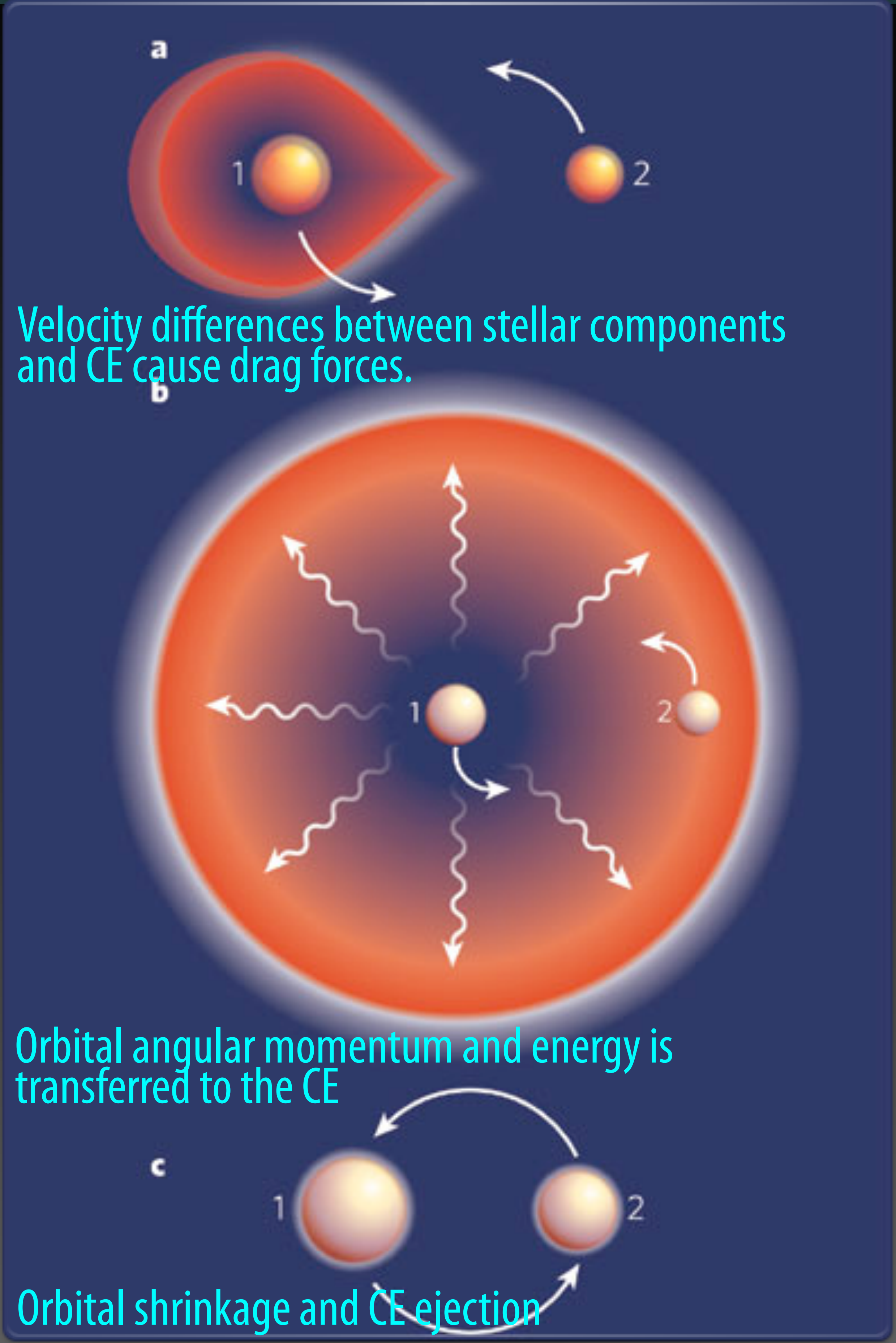
What is the Common Envelope?







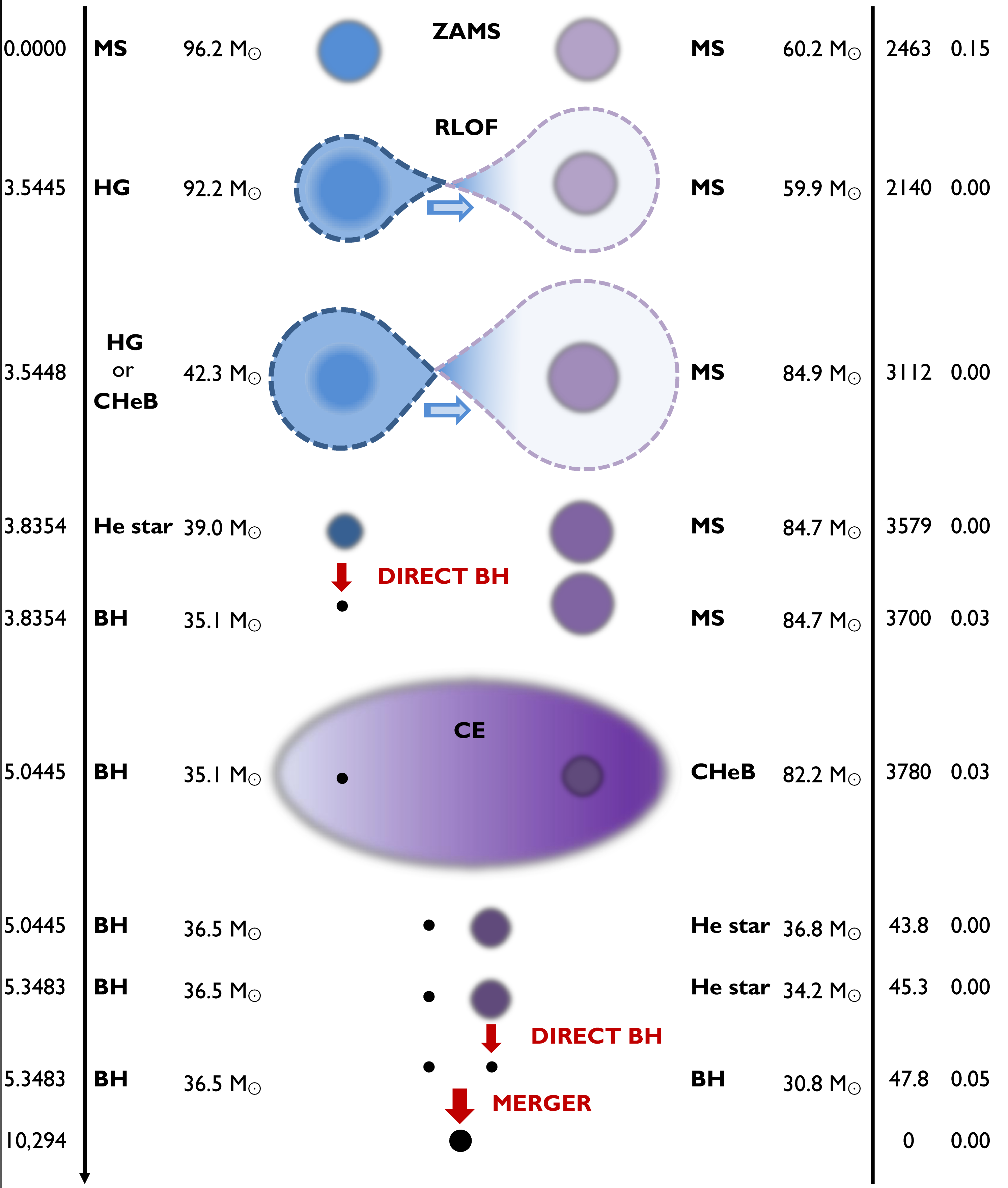
Velocity differences between stellar components and CE cause drag forces.

Orbital angular momentum and energy is transferred to the CE

Orbital shrinkage and CE ejection

“Classical” Field Binary Evolution

Belczynski et al. (2016a,b)



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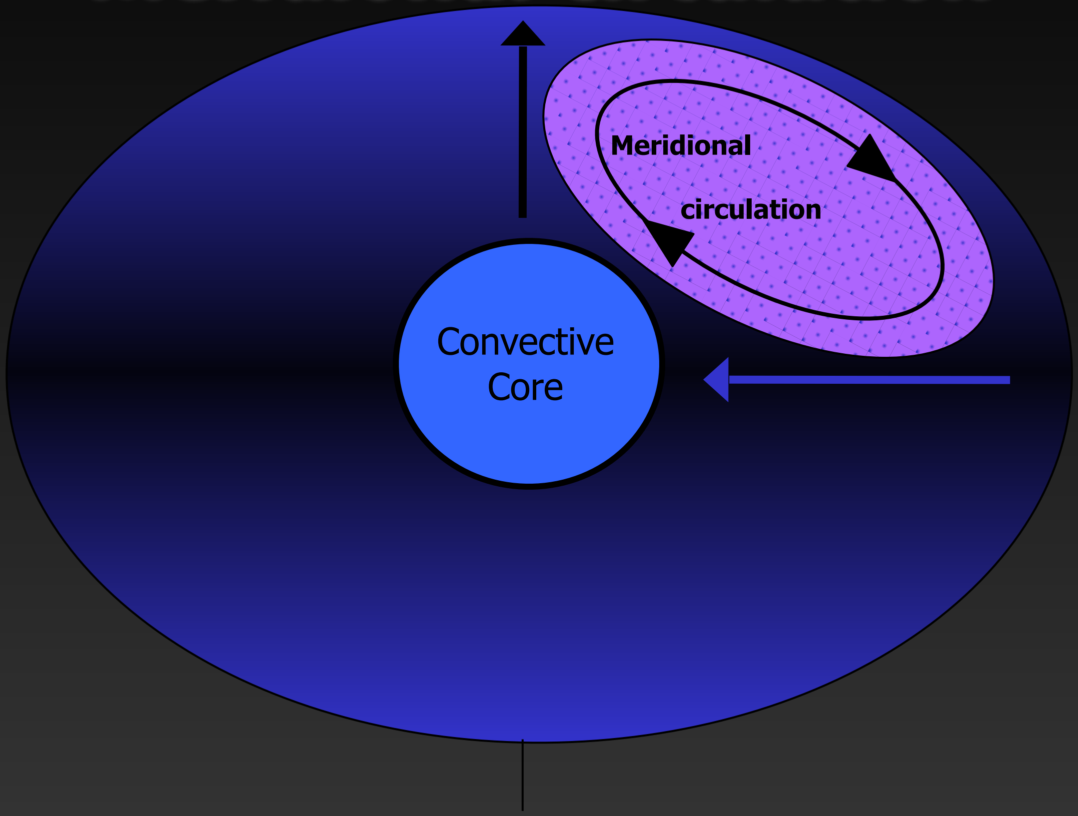
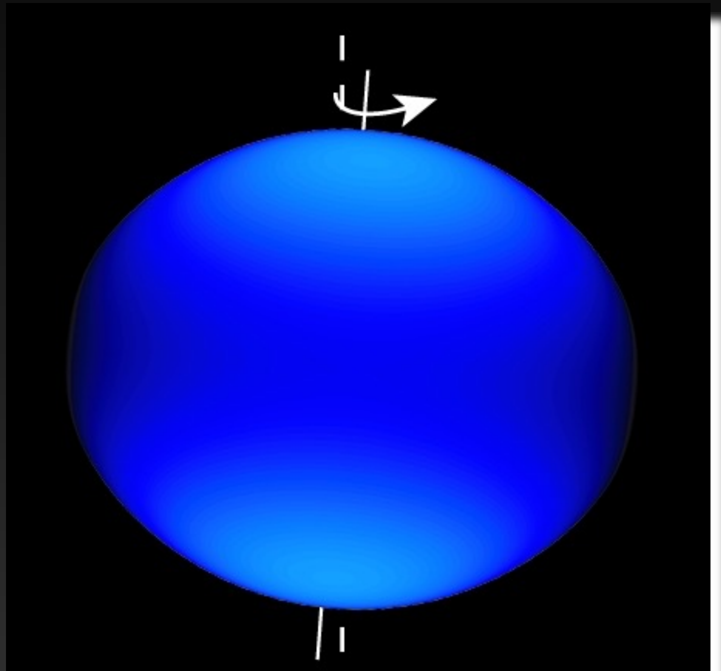
"Chemically Homogeneous" Evolution

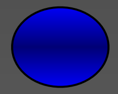
Meridional Circulation

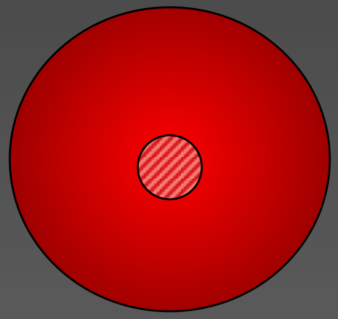


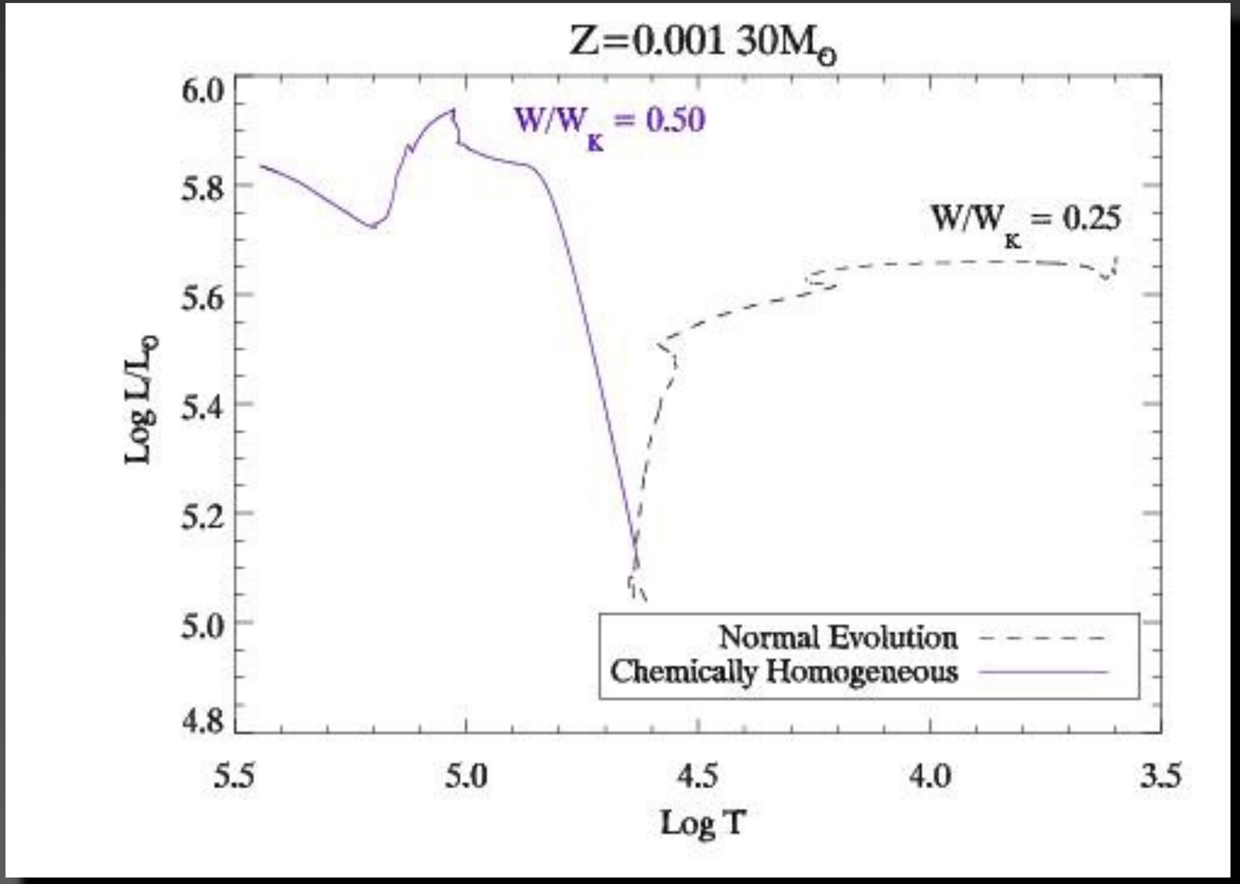

(Vega, a Fast rotating star - J.Aufdenberg)

If rotationally induced chemical mixing during the main sequence occurs faster than the built-up of chemical gradients due to nuclear fusion the star evolves chemically homogeneous (Maeder, 1987)

$$\frac{\tau_{ES}}{\tau_{MS}} < 1$$

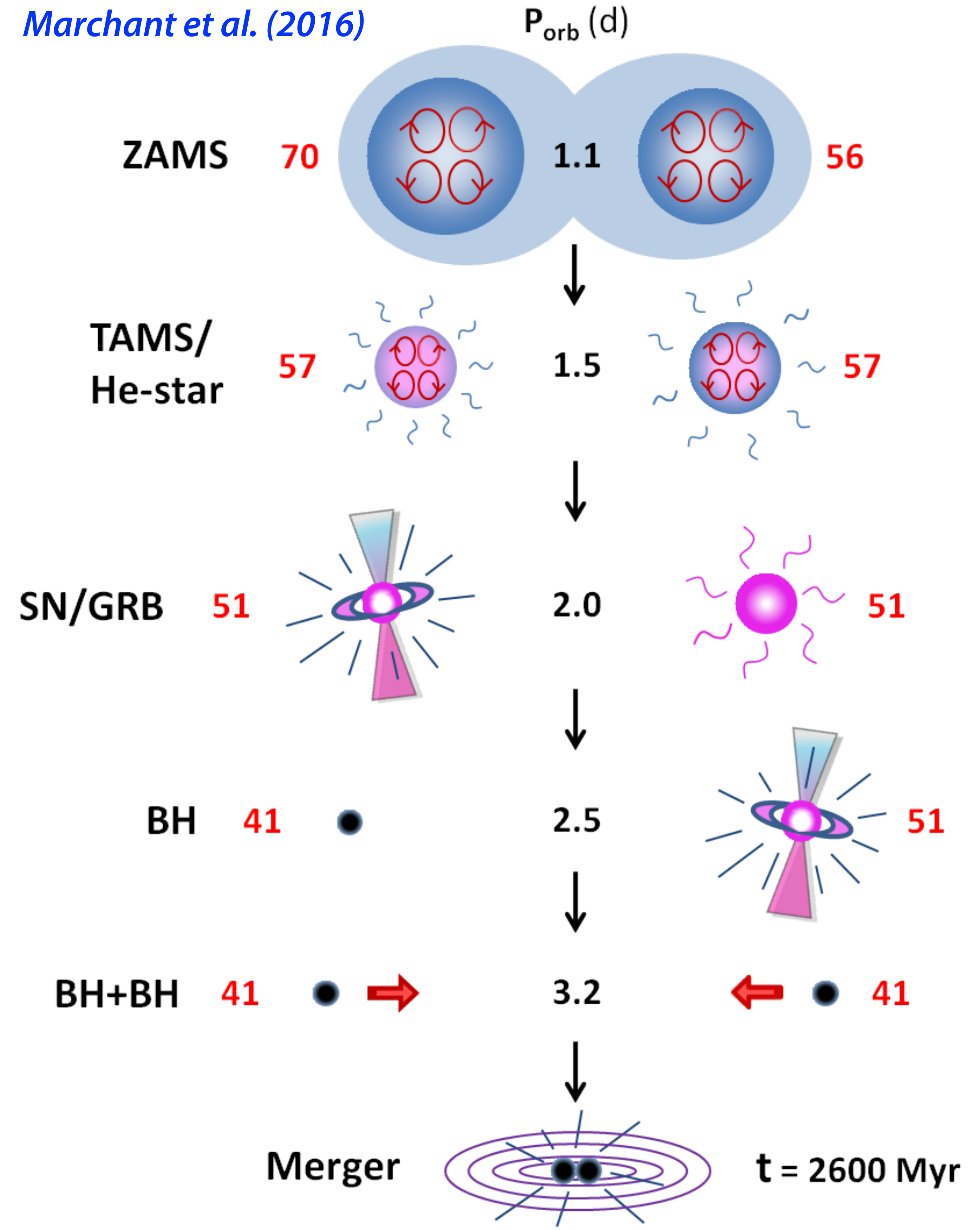

R~1 Rsun


R~1000 Rsun



“Chemically Homogeneous” Evolution

Marchant et al. (2016)



de Mink et al 2009; Song et al. (2015); Mandel & de Mink (2016)

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Dynamical formation of binary BHs

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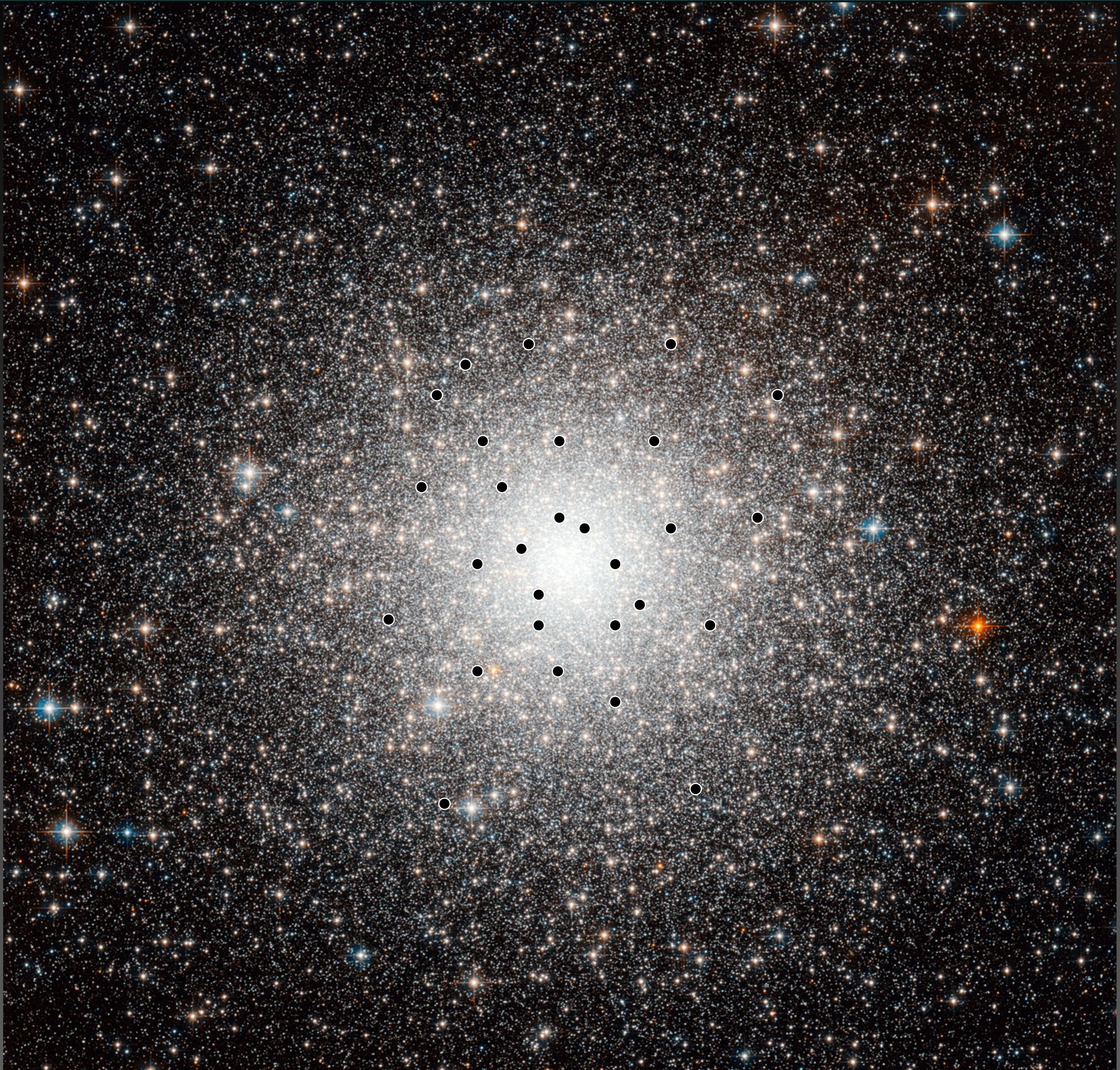

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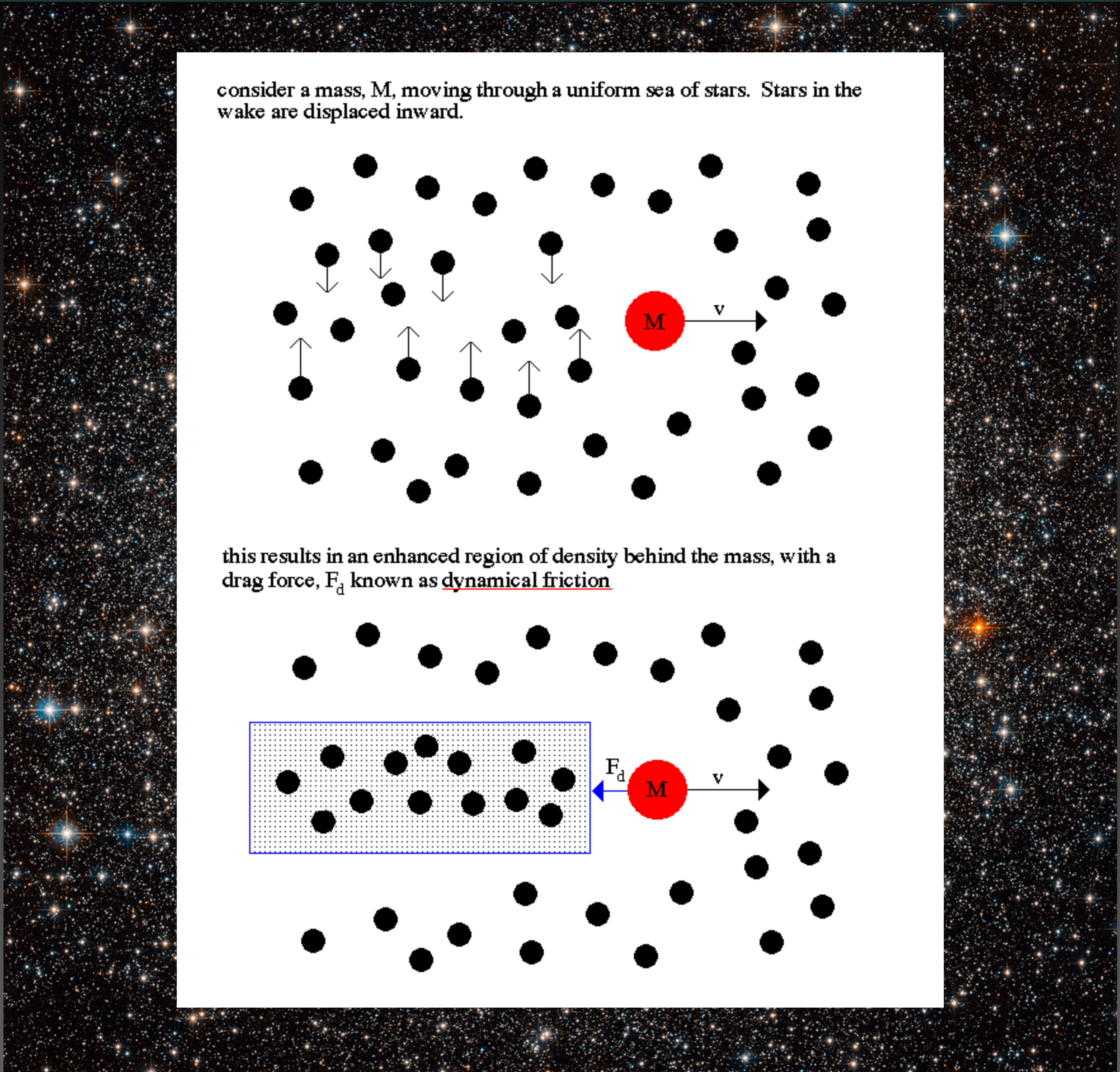
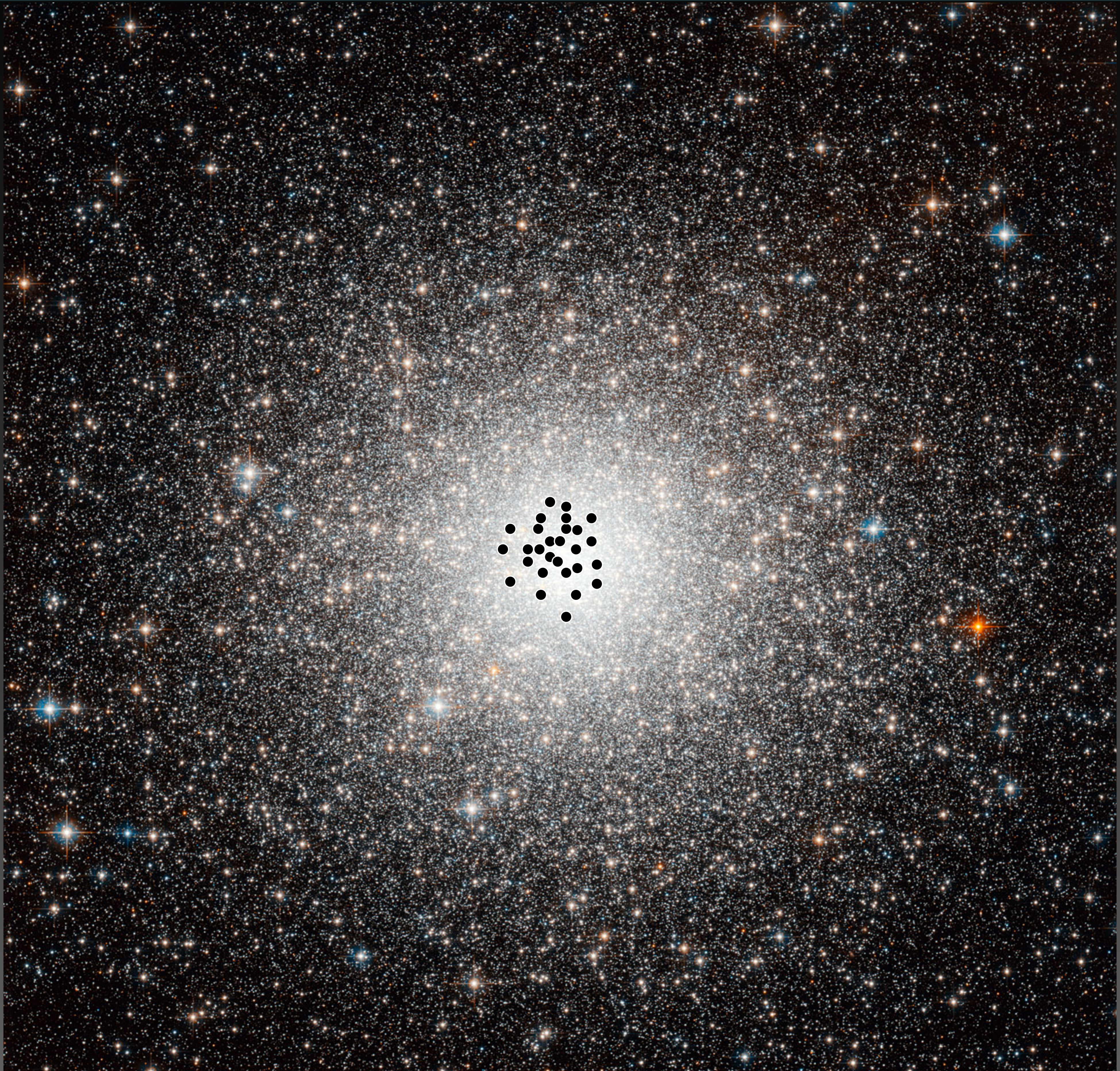


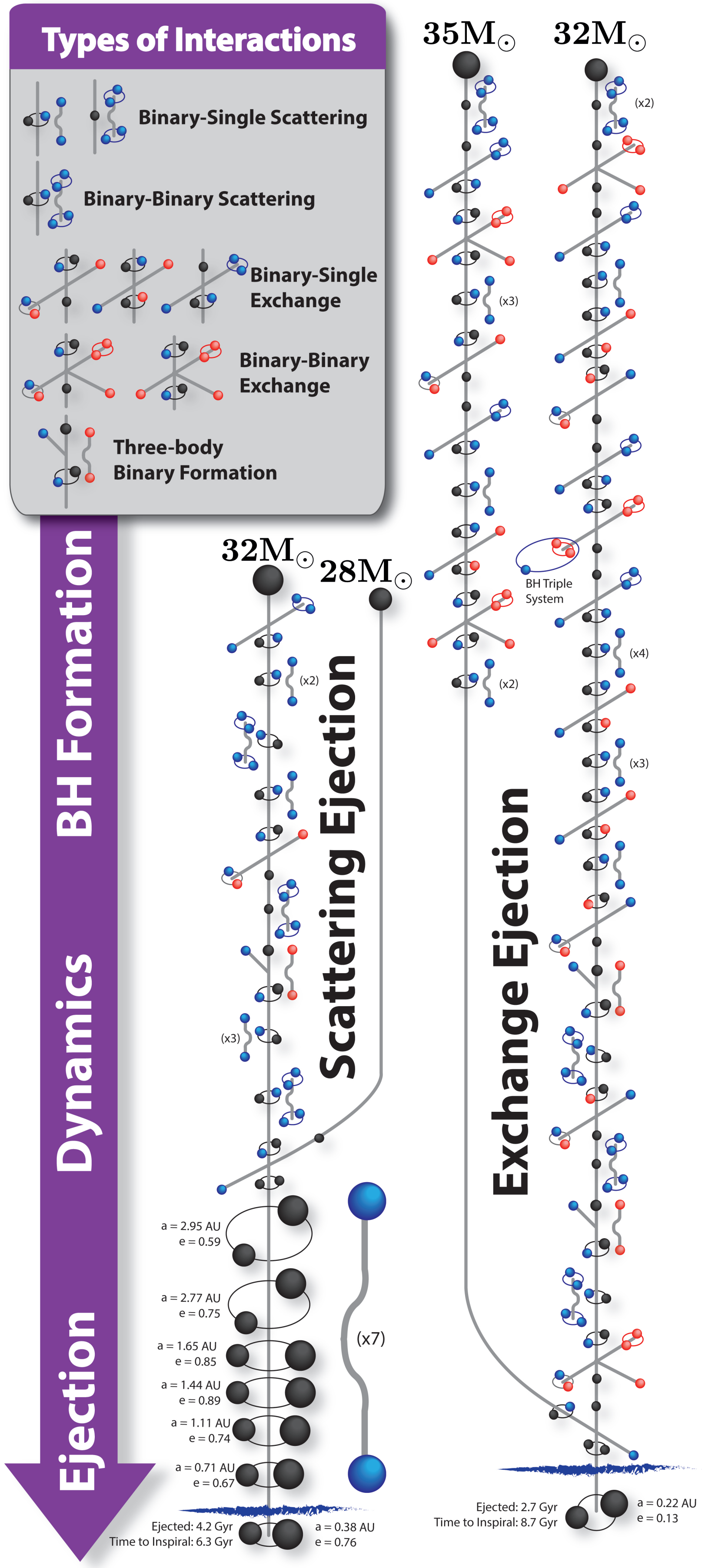
consider a mass, M, moving through a uniform sea of stars. Stars in the wake are displaced inward.

this results in an enhanced region of density behind the mass, with a drag force, F_d known as dynamical friction

Dynamical formation of binary BHs



Dynamical formation of binary BHs



Rodriguez et al. (2015, 2016)

Sources of uncertainty:

(i) **Initial GC properties**

(ii) initial binary properties (masses, mass ratios, and orbital periods)

(iii) stellar evolution models including metallicity-dependent wind mass loss

(iv) **BH natal kicks**

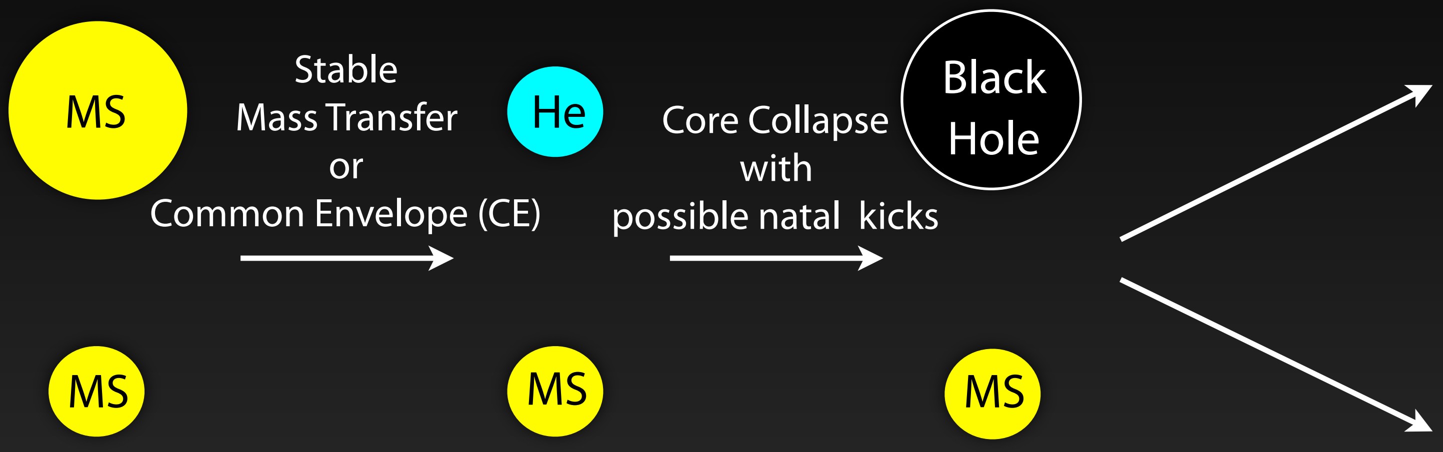
(v) **Computational cost -small number statistics**

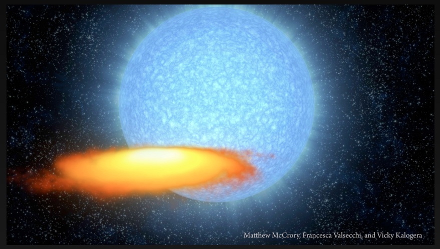
Comparison of different channels

	Classical field binaries	Chemically homogeneous evolution	Dynamical Formation
Merger rate	~200 Gpc^{-3}yr^{-1}	~10 Gpc^{-3}yr^{-1}	~2-20 Gpc^{-3}yr^{-1}
O1 detection rate	2-470 yr^{-1}	~400 yr^{-1}	20-700 yr^{-1}
total BH mass	20-80	57-103	32-64
mass ratio	broad range	~1	close to ~1
PISN BH mass gap	yes	yes	maybe no…
BH Spins	Alligned	Alligned, high	Misalligned
Observable Progenitors	Ultralumonous X-ray sources	Maybe… WR+BH HMXBs	NO

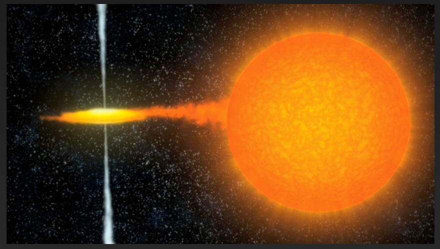
Empirically inferred merger rate: 2-400 Gpc^{-3}yr^{-1}

Going back in time to constrain SN kicks




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)

Results so far...

System	Observed Current BH mass (M☉)	Post-SN BH mass (M☉)	Immediate Progenitor mass (M☉)	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)	**6.5-13.5** (Kimball et al. 2017, in prep.)	**13.0 – 18.0** (Kimball et al. 2017, in prep)	**≤ 150** (Kimball 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)

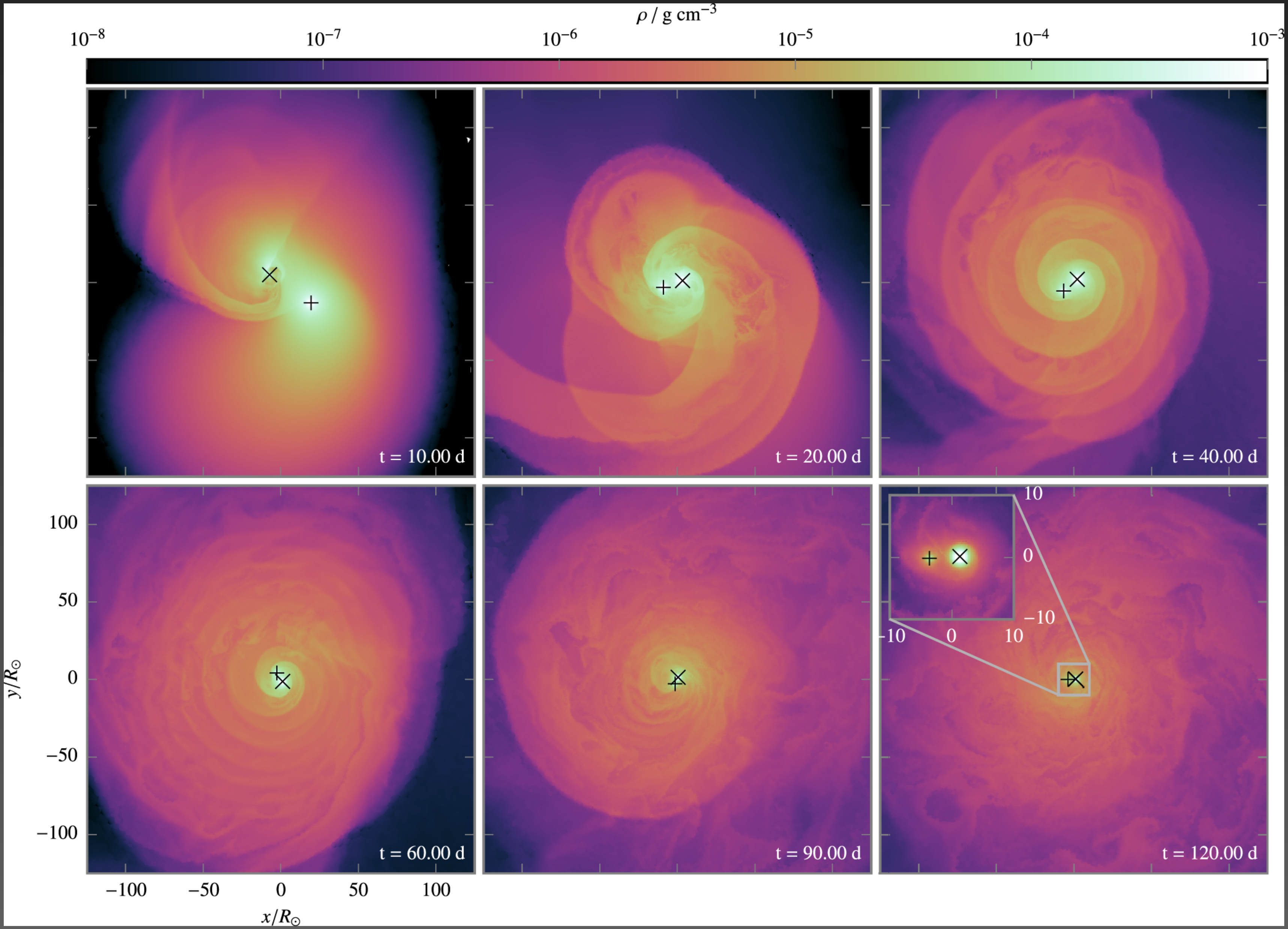
Willems et al. (2005); Fragos et al (2009); Valseccchi et al. (2010); Wong et al. (2012); Wong et al. (2014)
Sørensen, **TF** et al. (2017); Kimball, Sørensen,**TF** et al. (2017, in prep.)

The common envelope phase

The energy budget prescription

$$\alpha_{\rm CE}\left(\frac{GM_{\rm don,fin}M_{\rm acc}}{2A_{\rm fin}}-\frac{GM_{\rm don,int}M_{\rm acc}}{2A_{\rm int}}\right)=\frac{GM_{\rm don,int}M_{\rm don,env}}{\lambda R_{\rm don,\,lob}}$$

The “muscle” approach

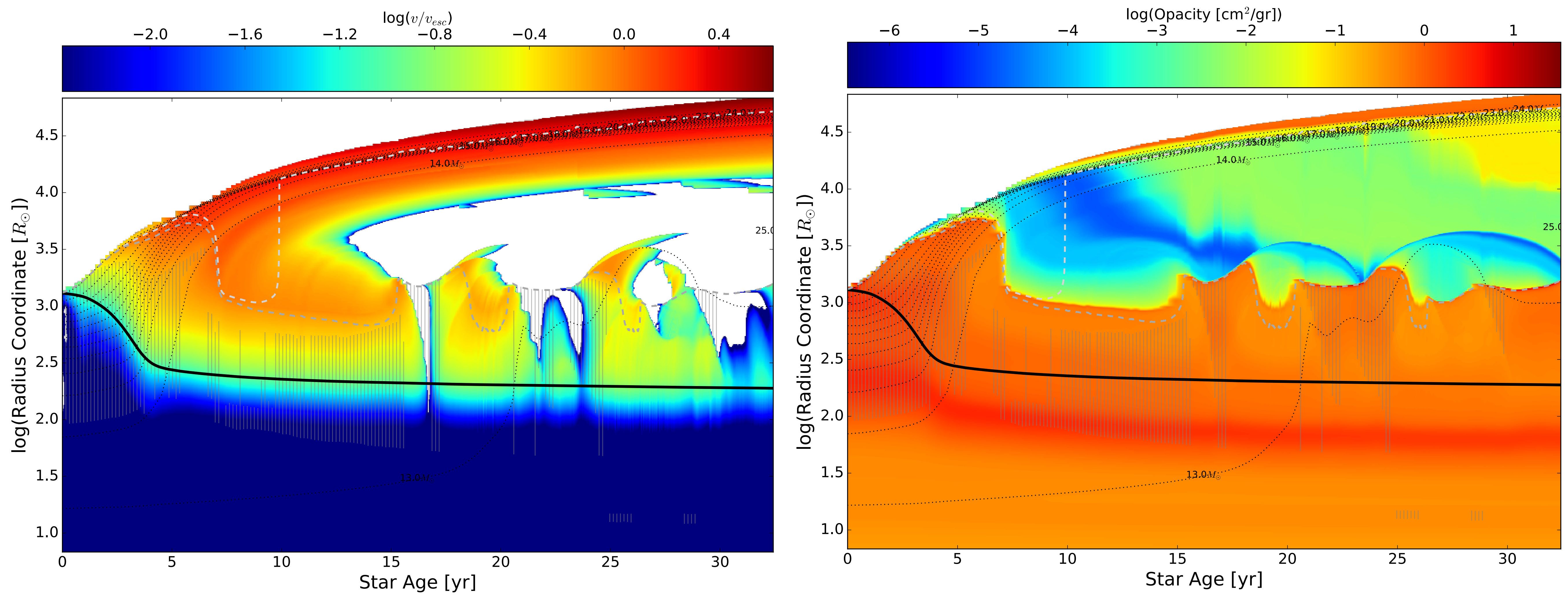


Ohlman et al. 2015; Ivanova et al. 2013

The common envelope phase

The 1D approach:

- Rich physics: Energy, radiation and angular momentum transport
- Computational efficient
- Applicable to progenitor of coalescing double compact objects



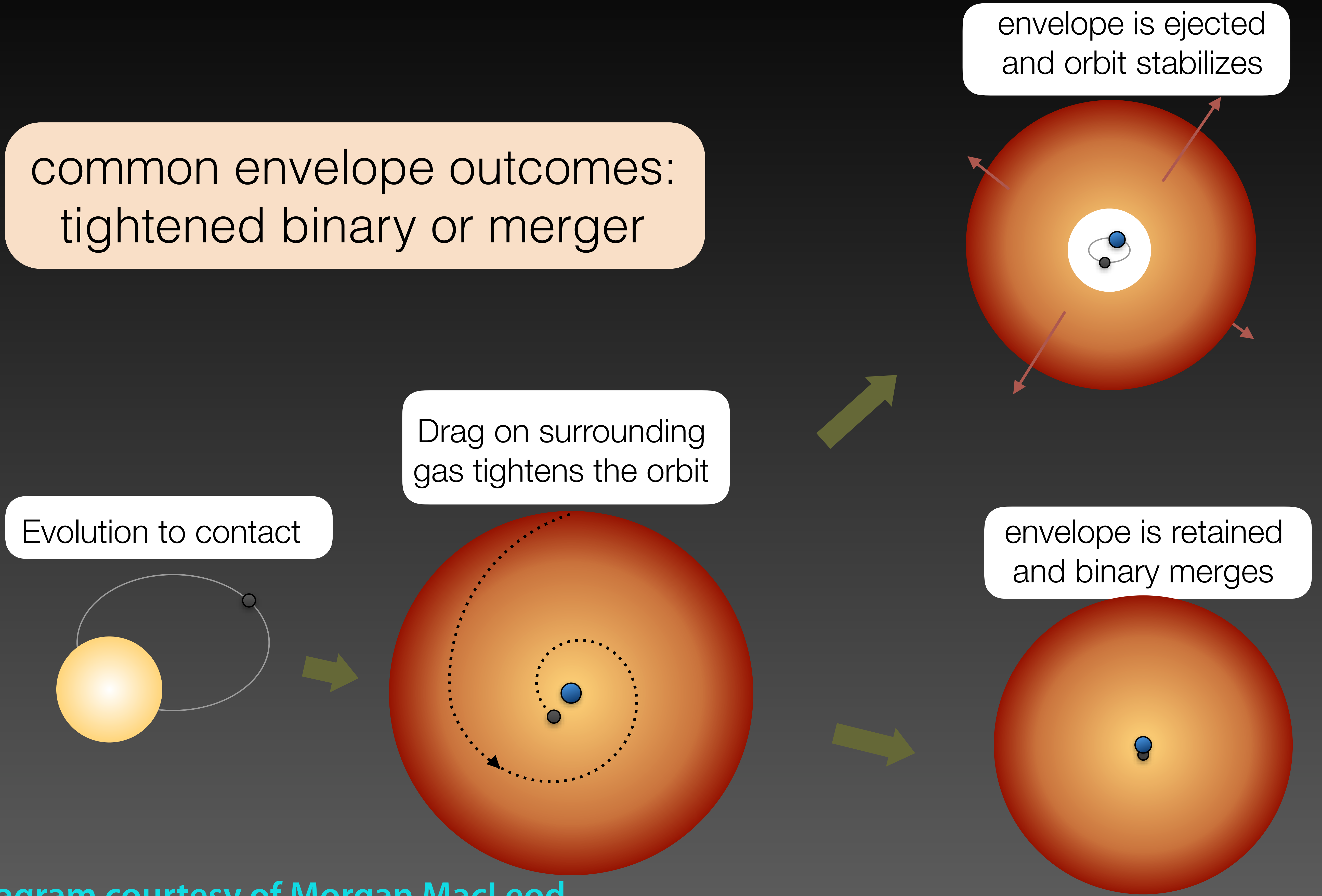
Fragos & Andrews 2017 (in prep)

Summary

- LIGO detections provide the first direct evidence for the existence of “heavy” BH and binary BHs
- All three main formation channels predict merger rates and properties (marginally) consistent with LIGO detections so far. A population of 100s of binary BHs will be able to do this.
- BH spin and binary mass ratios will likely be the differentiating factors
- Large BH kicks “kill” all three channels
- Coalescing binary neutron star are believed to be formed via the “classical” channel. Advances in our understanding of the common envelope phase are badly needed!

The common envelope phase

common envelope outcomes:
tightened binary or merger



Evolution to contact

Drag on surrounding gas tightens the orbit

envelope is ejected and orbit stabilizes

envelope is retained and binary merges

Diagram courtesy of Morgan MacLeod