Probing the Early Universe with Black-Hole Binaries

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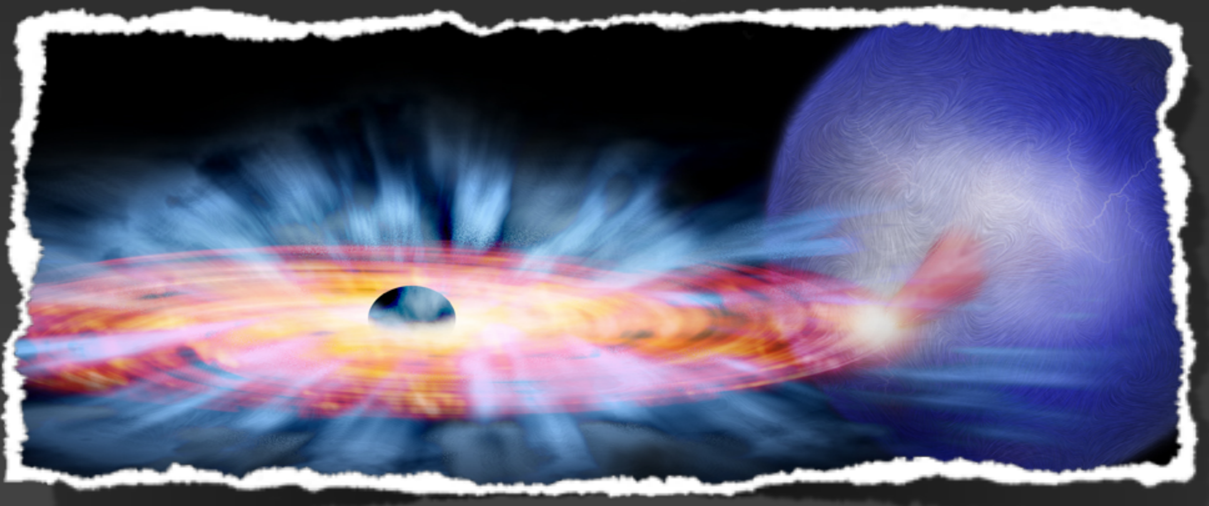

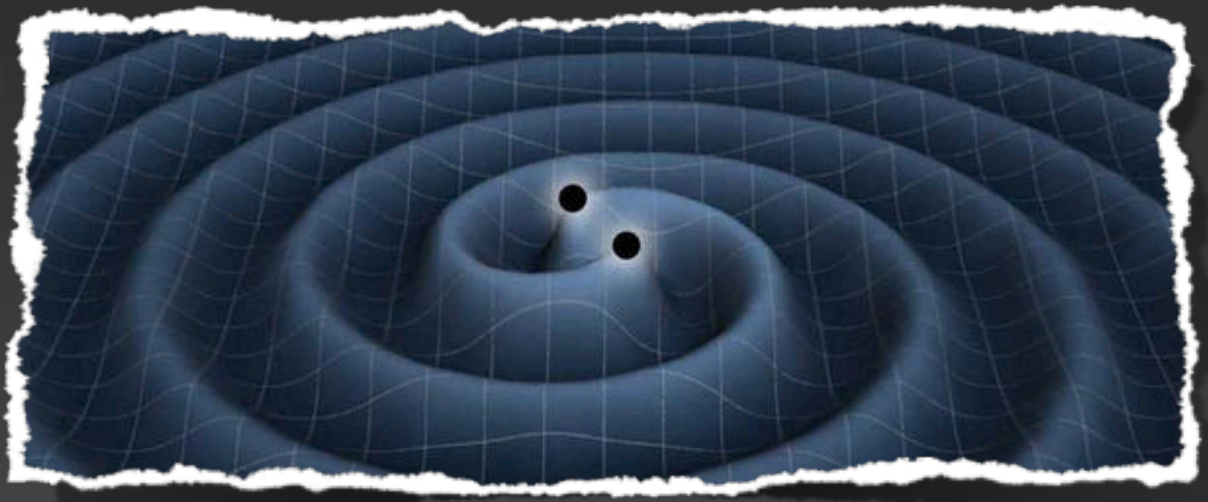

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Why care about stellar-mass black holes?

The "No-Hair" theorem

Every astrophysical black hole is fully characterized by two numbers:

M = *mass,*

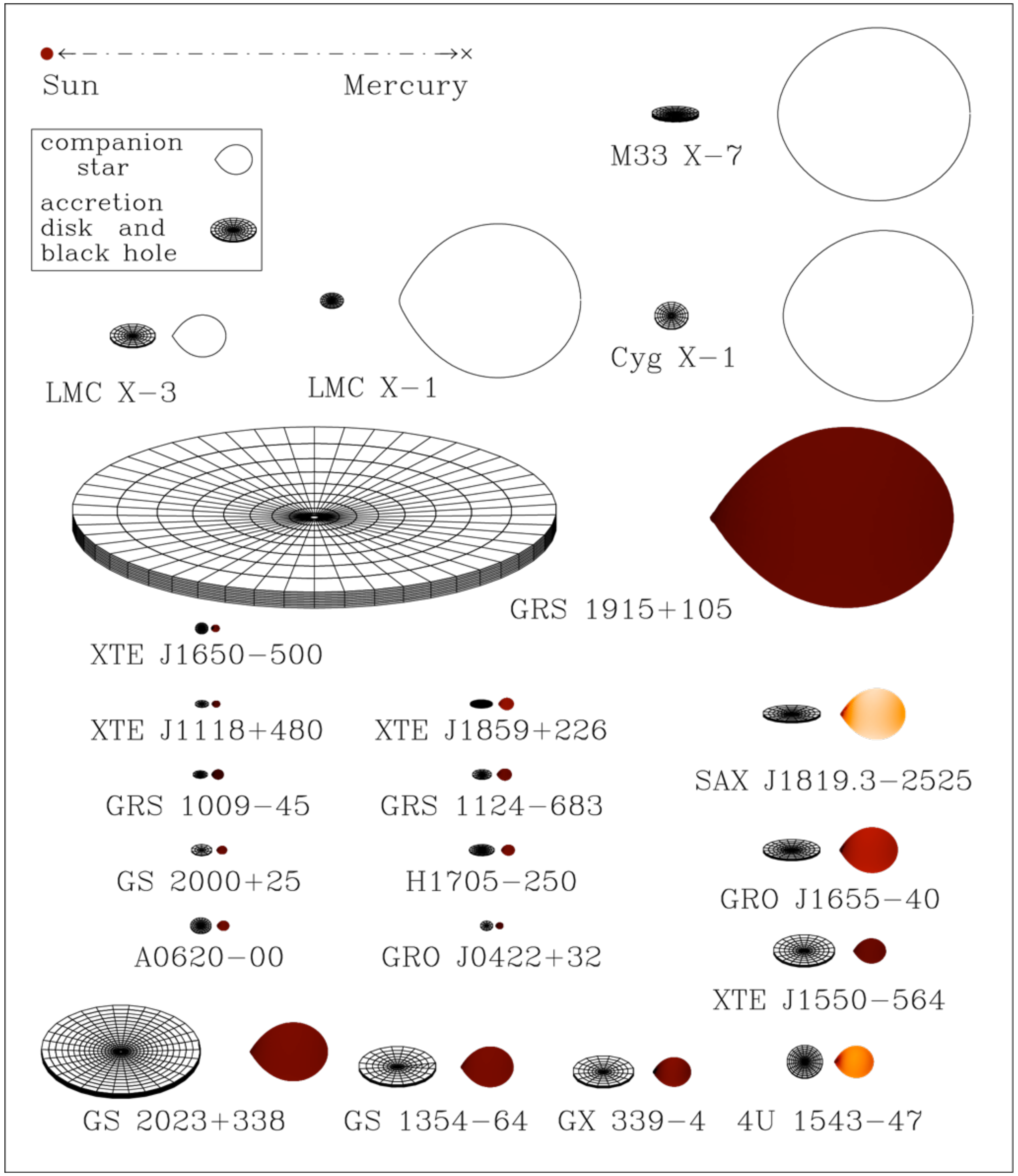
a = *spin.*

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

Energy efficiency of nuclear fusion: ~0.7%

Energy efficiency of accretion onto a black hole: ~10-40% !!!

Dynamically confirmed black holes



- Cyg X-1: the first BH candidate

Bolton (1972), Webster & Mardin (1972)

- 24 BHs with dynamical mass measurement

McClintock &Remillard 2006, Casares & Jonker 2014

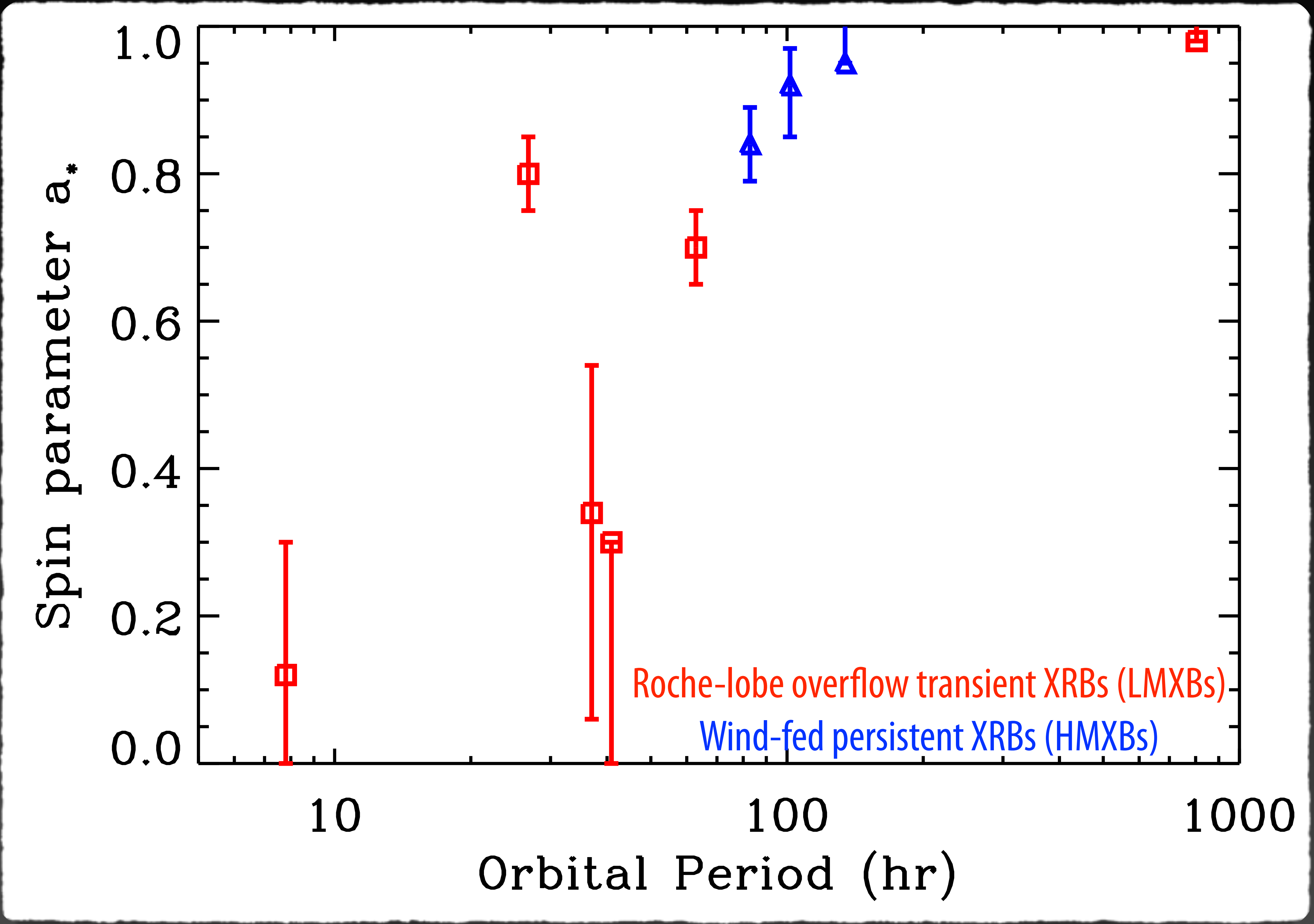
- 21 Galactic, 3 in nearby galaxies
- 33 more BH candidates

Özel et al. (2011)

LMXBs: $M_{BH,current}$ ~ 7.8±1.2 $M_\odot$

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

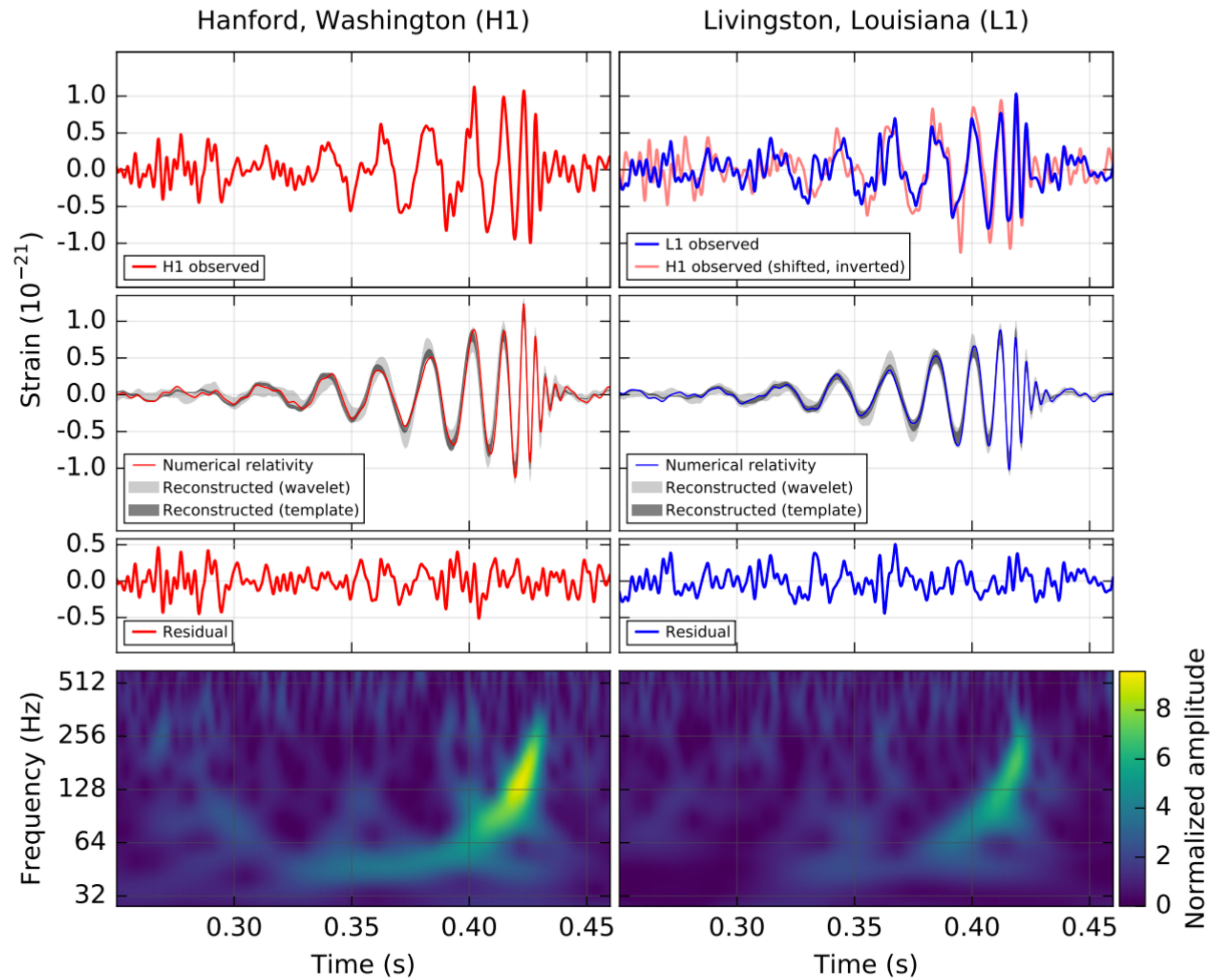
Measuring the the spin of Black Holes

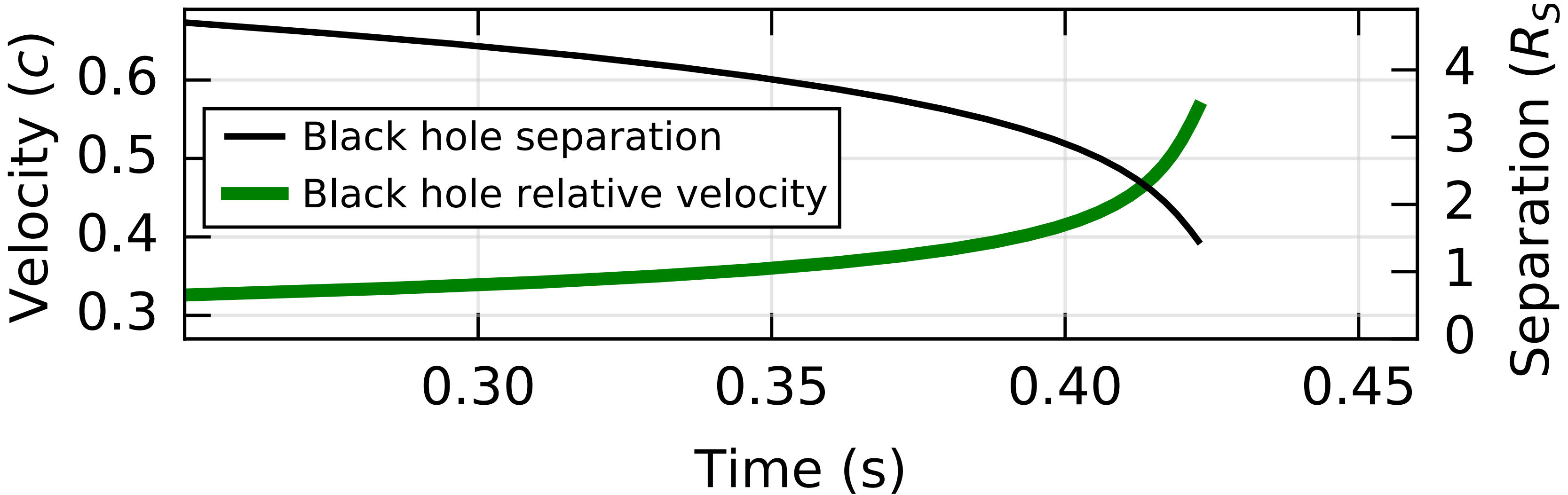


The spin of 9 stellar BHs measured with the ***continuum fitting method***

McClintock et al. (2011, 2014)

The detection





Detection with 5-sigma confidence.

This means that the rate at which a signal analogous to GW150914 is created by noise is less than 1 in every 203,000 years.

3 solar masses of energy is what was released by gravitational waves.

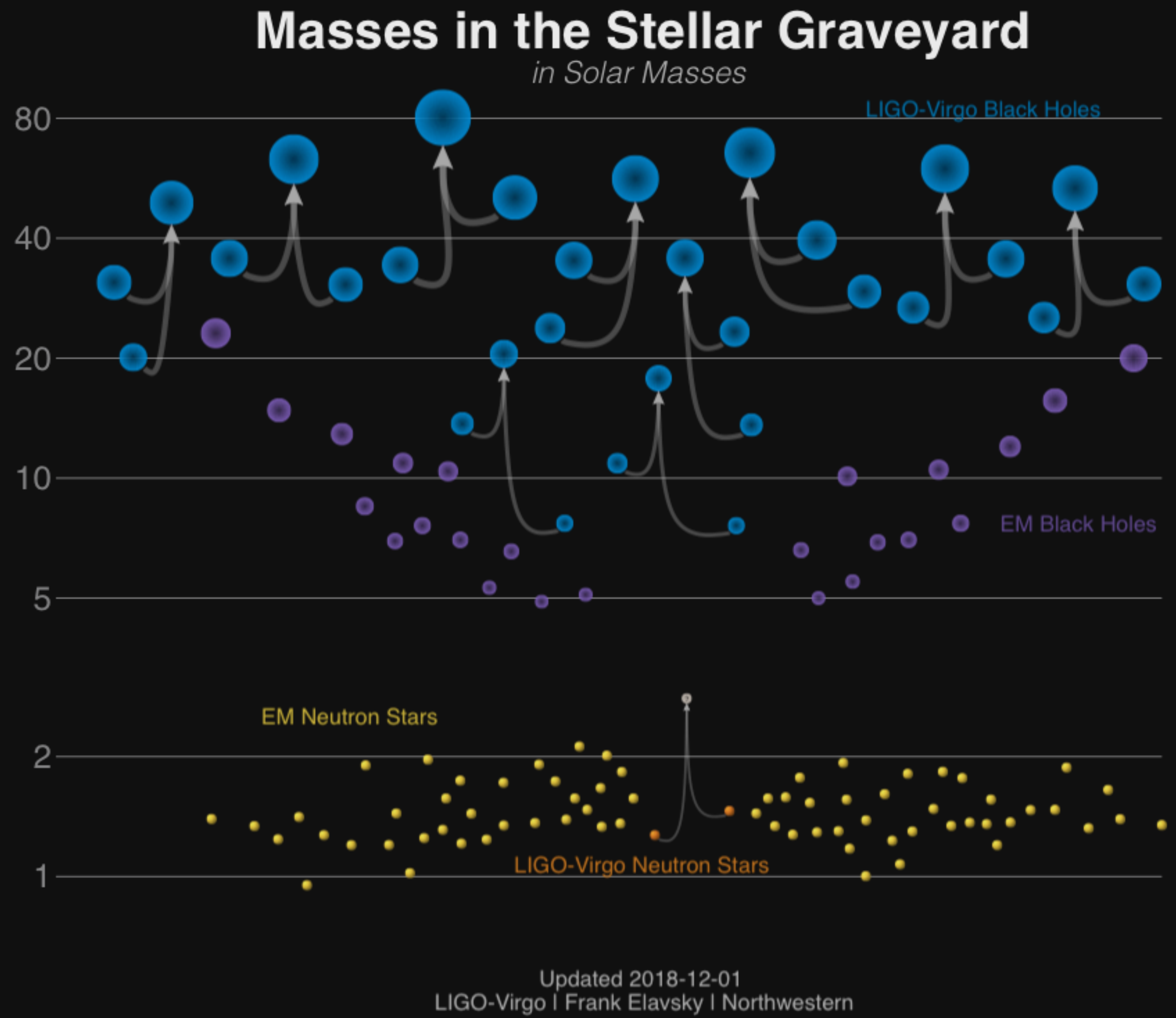
10 times more luminous that all the stars of the Universe!!!

Chirp Mass

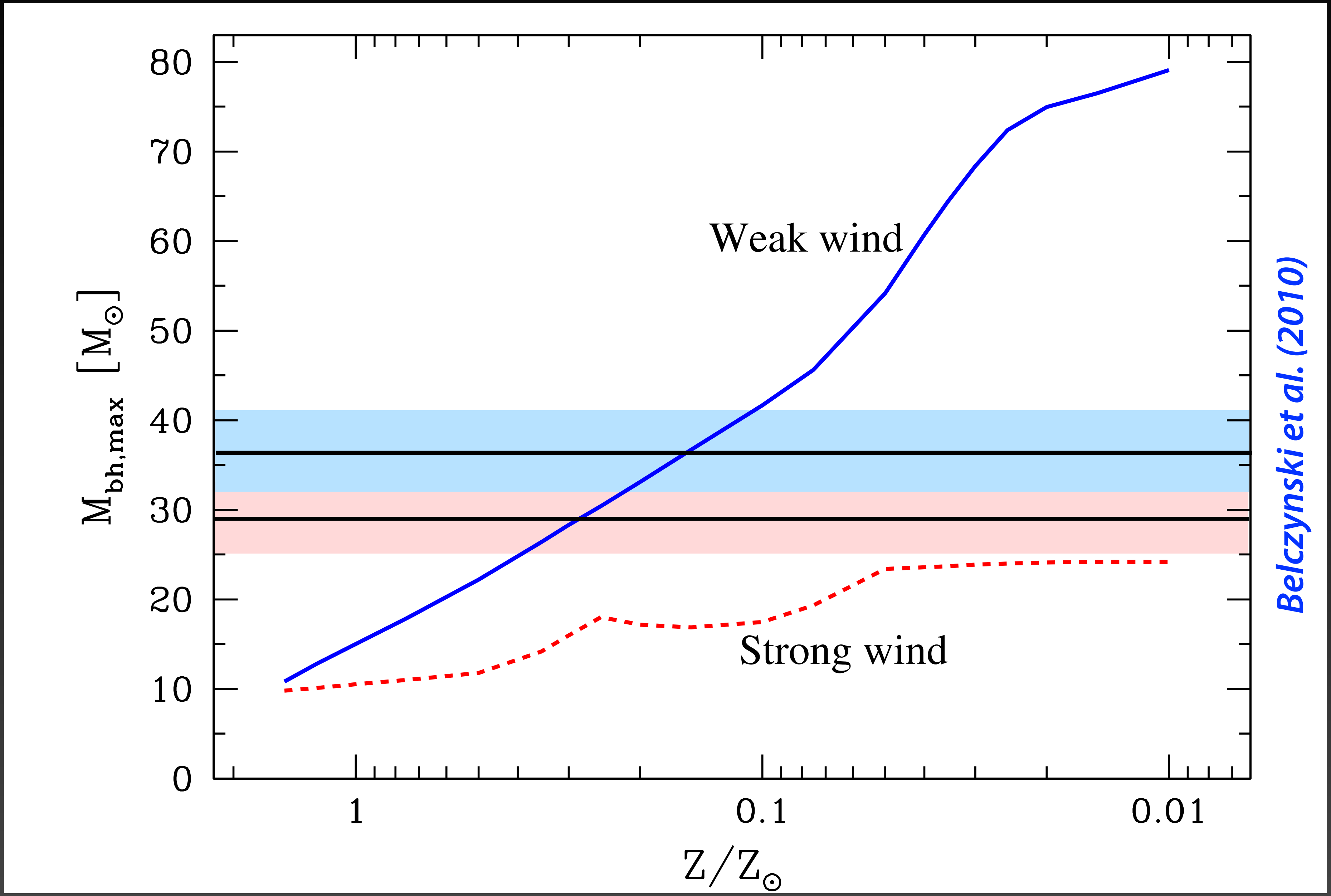
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$h = 2(4\pi)^{1/3} \frac{G^{5/3}}{c^4} f_{\mathrm{GW}}^{2/3} M_{ch}^{5/3} \frac{1}{r}$$

Doubling the sample of known BH masses



Predicted Masses for Single Black Holes

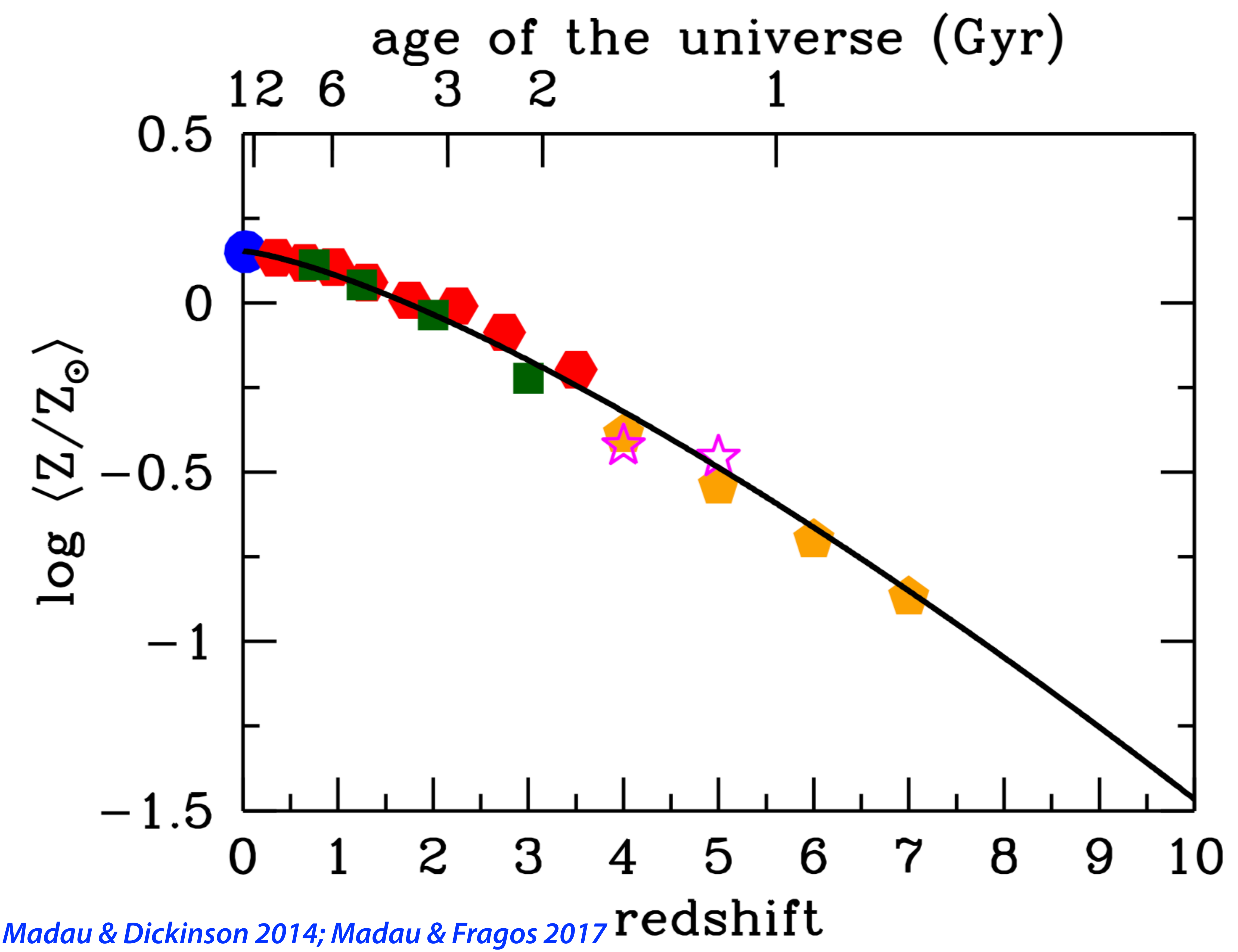


Belczynski et al. (2010)

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)

Metallicity Evolution of the Universe

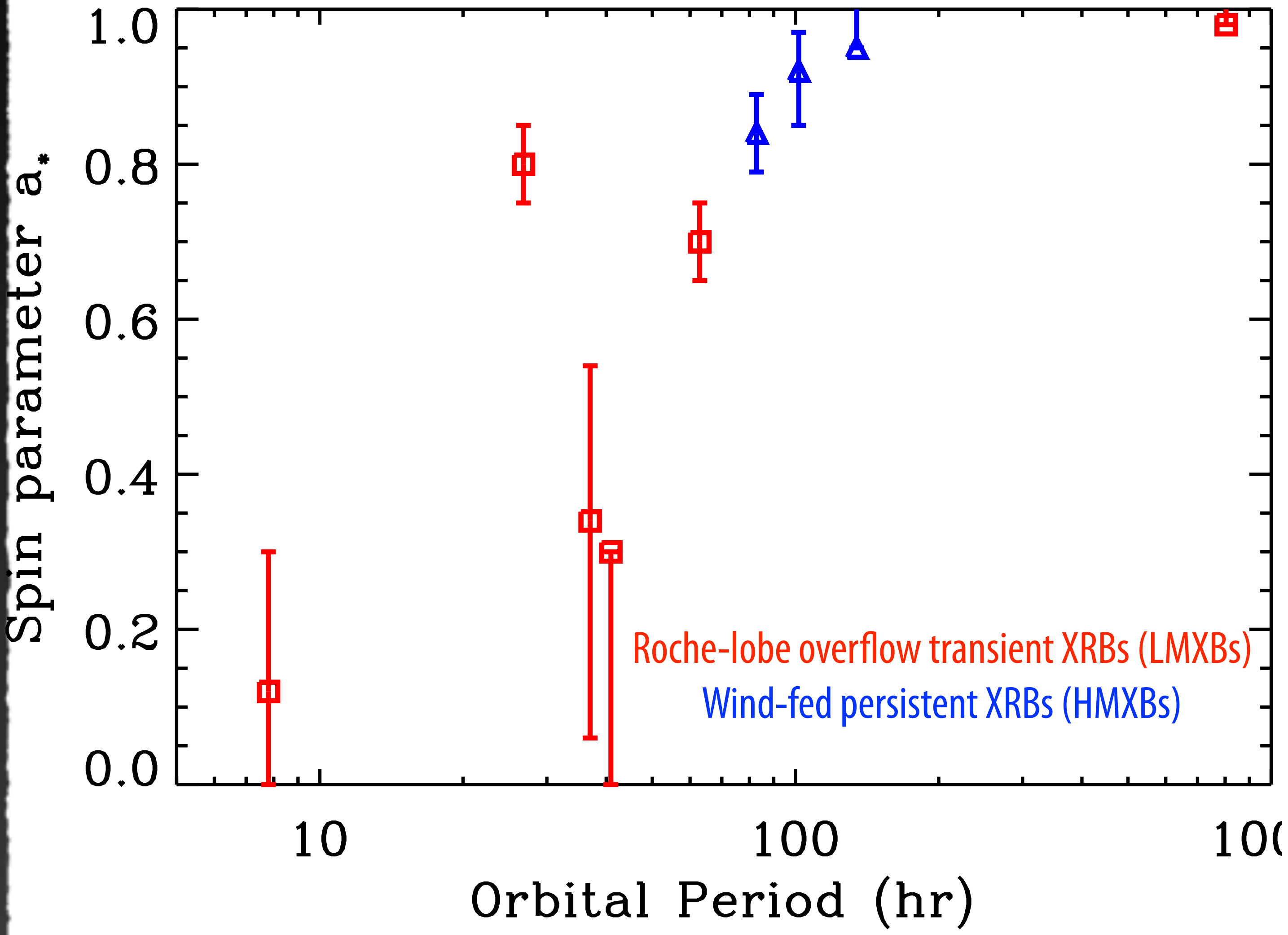


Madau & Dickinson 2014; Madau & Fragos 2017

Measurements of spin in BH XRBs and BBHs

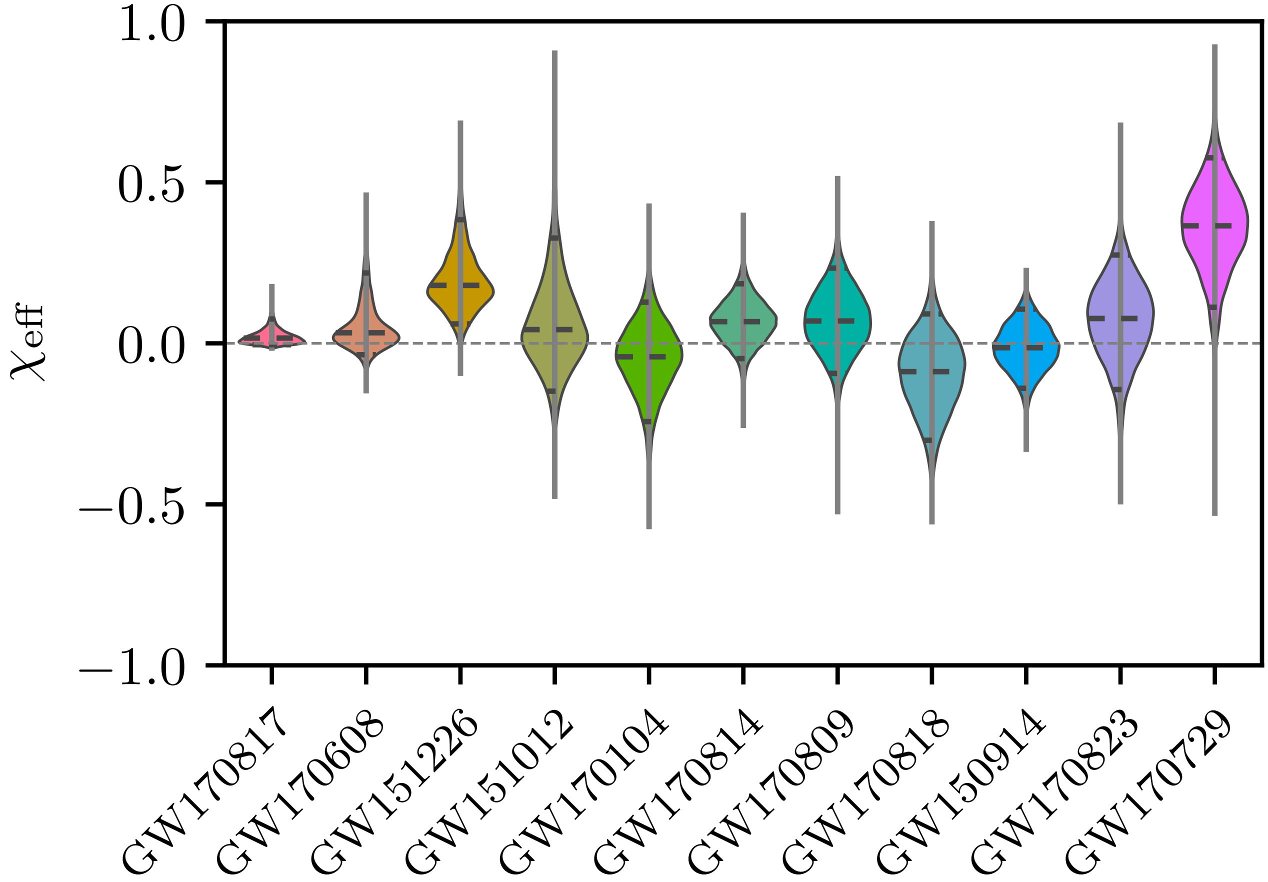
Black hole X-ray Binaries

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



McClintock et al. (2011, 2014)

Binary black hole mergers



LIGO/Virgo Collaboration

Are the two sets of measurements consistent with our current understanding of binary evolution?

Measurements of spin in BH XRBs and BBHs

Black hole X-ray Binaries

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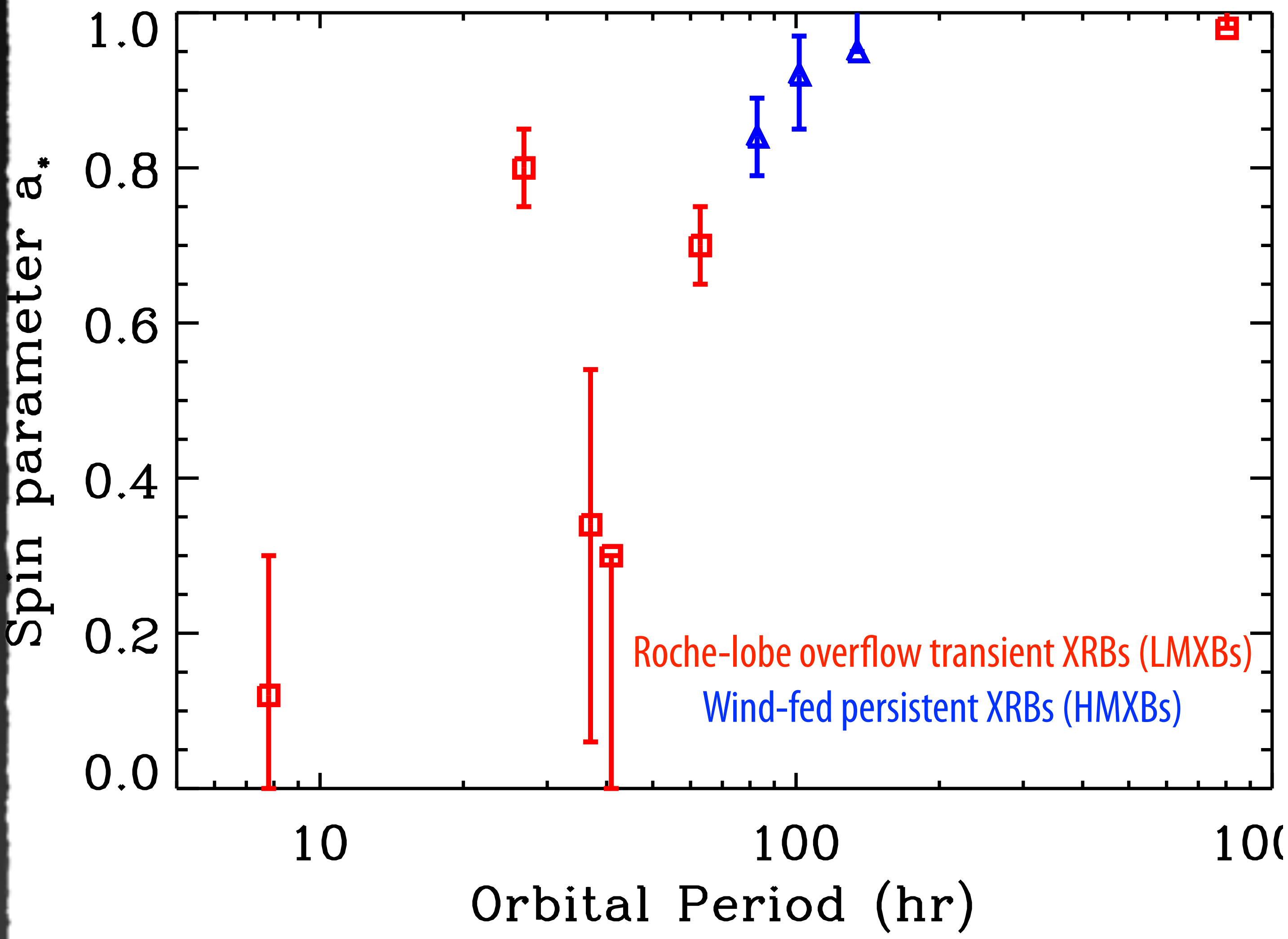

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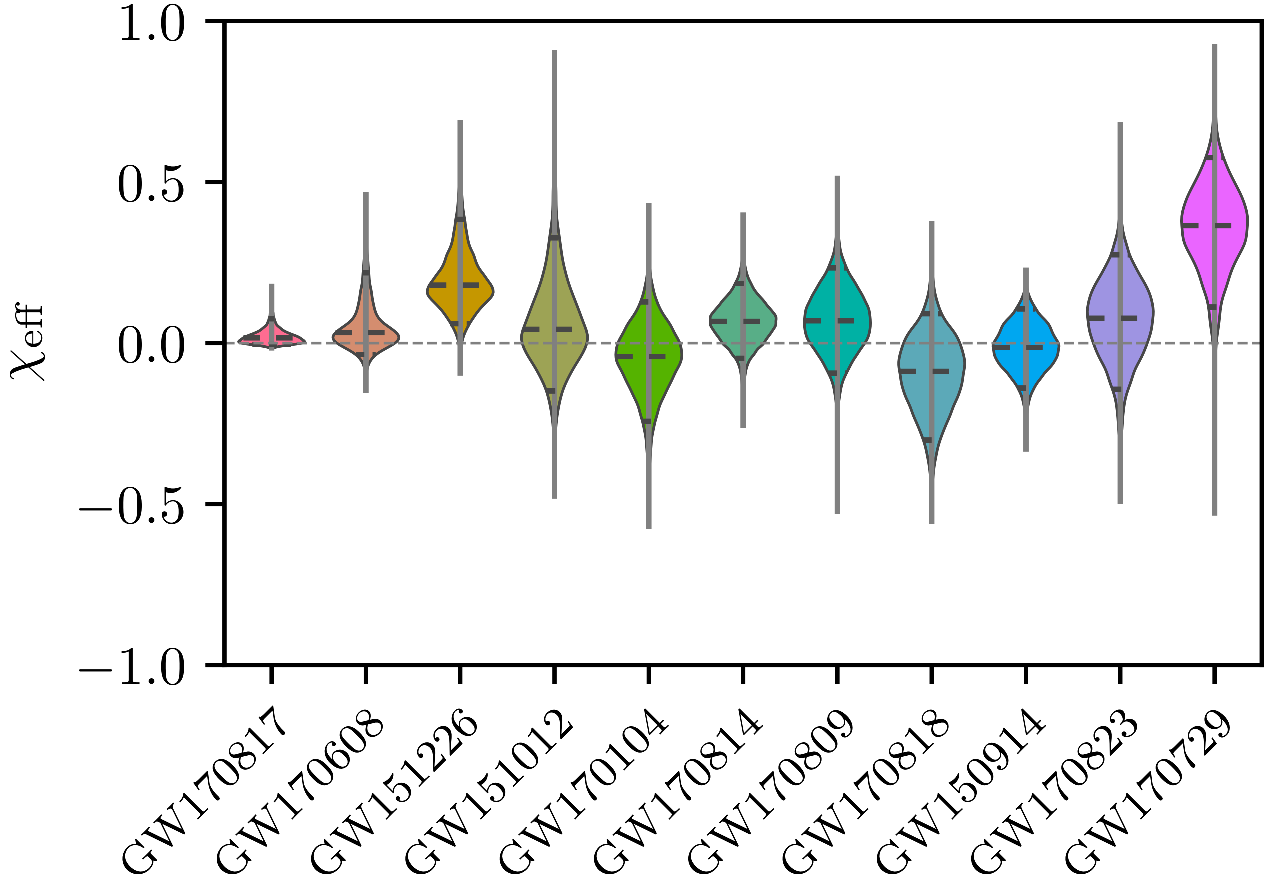


LIGO/Virgo Collaboration

The observed BH spin *does not have a memory of the initial rotation of stars but* ***is a result of binary interaction phases****.*

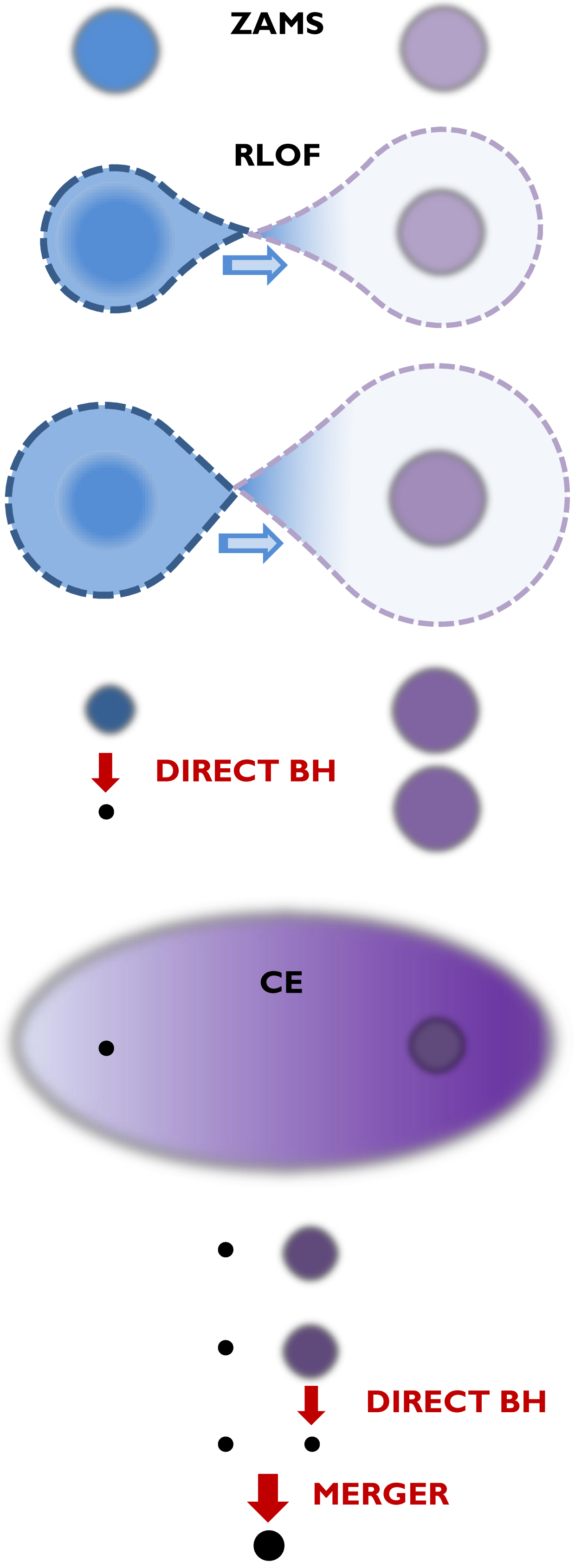
Fragos & McClintock (2015); Qin, Fragos et al. (2018); Qin, Marchant, Fragos et al. (2019); Bavera, Fragos et al. (2019)

Formation Channels of Binary BHs

- “Chemically Homogeneous” Field Binary Evolution
- Dynamical Black Hole Binary Formation
- ***“Classical” or “common envelope” Binary Evolution***

"Classical" Field Binary Evolution

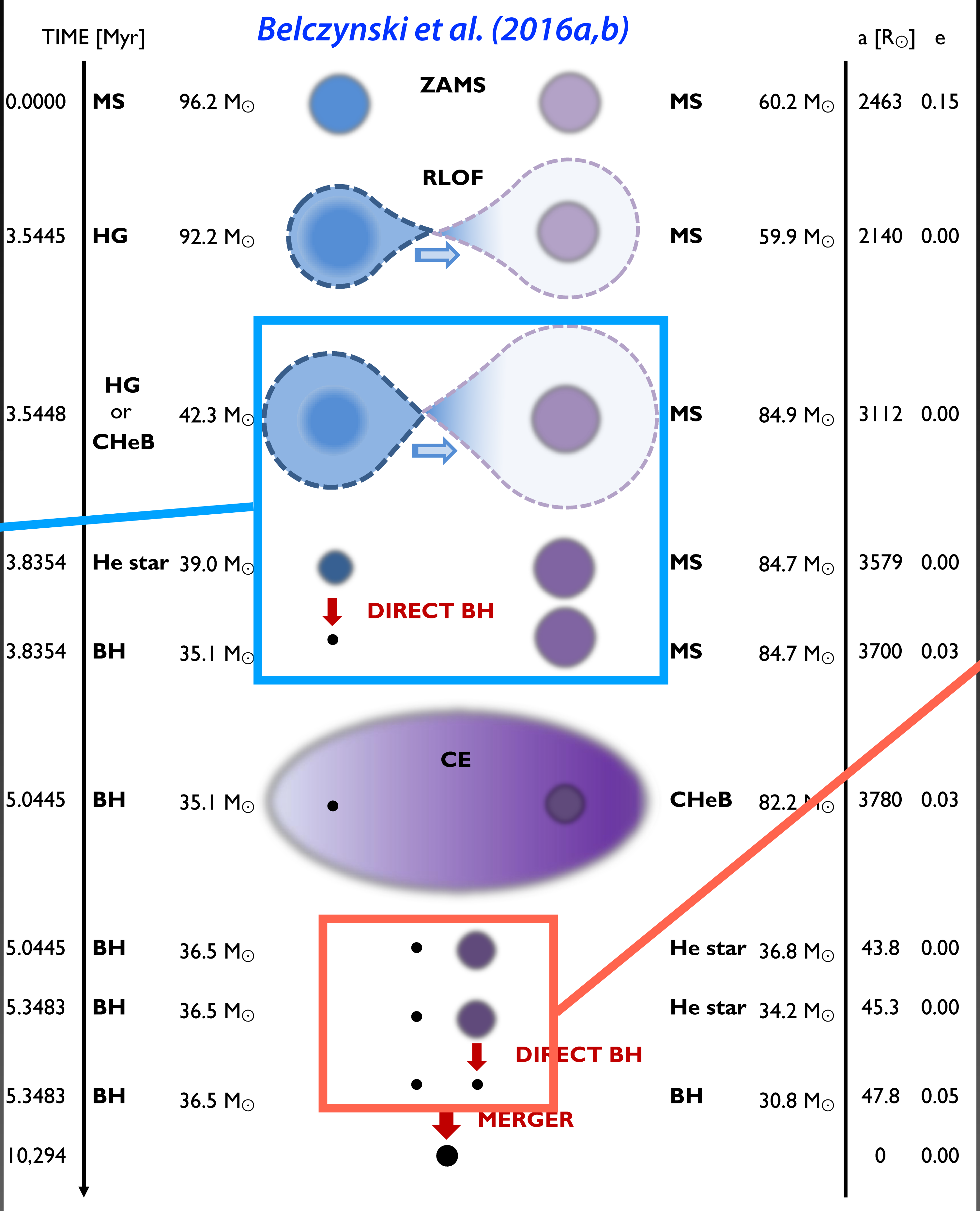
Belczynski et al. (2016a,b)



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

“Classical” Field Binary Evolution

Stripping of the giant’s envelope:
the first-born black hole has ~0 spin



Belczynski et al. (2016a,b)

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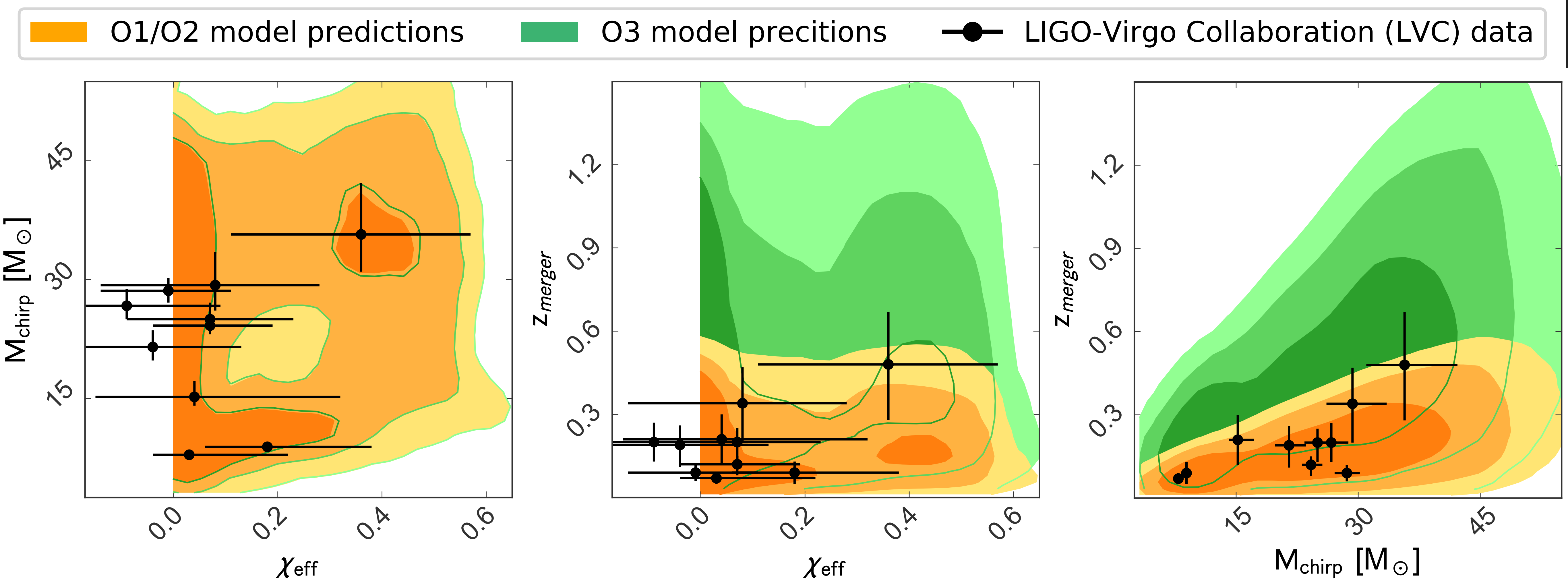
5.3483	**BH**	36.5 $M_\odot$	**DIRECT BH**	**BH**	30.8 $M_\odot$	47.8	0.05
10,294			**MERGER**			0	0.00

If the orbit is sufficiently close
the helium-star companion is tidally span up

Understanding the observed BBH population

$$R_{det,O1/O2} \simeq 13\,yr^{-1}$$

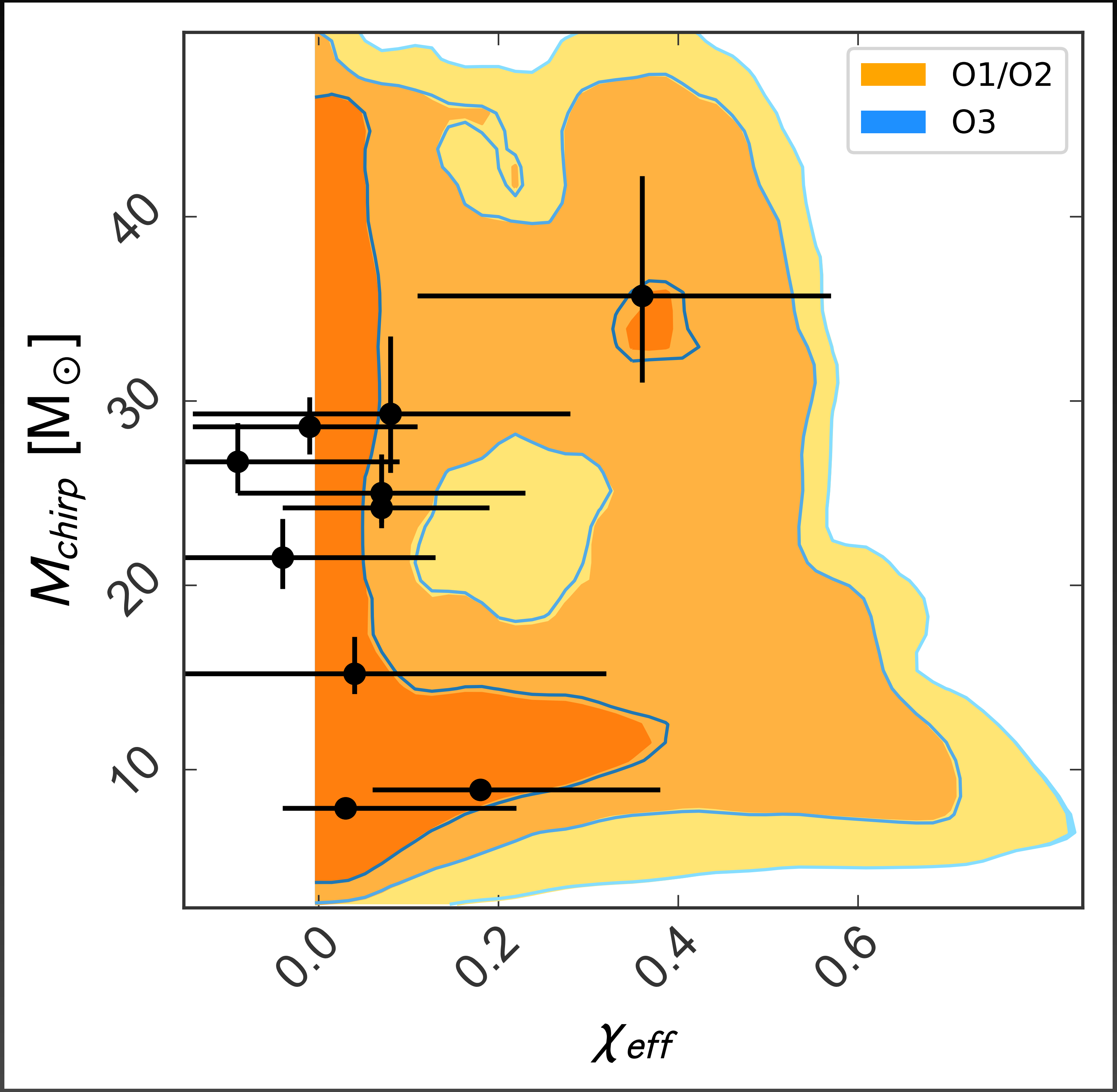


Bavera, Fragos et al. (2019)

$$\chi_{eff} = \frac{M_1 \mathbf{a}_1 + M_2 \mathbf{a}_2}{M_1 + M_2} \mathbf{L}_{orb}$$

The origin of spin in coalescing binary black holes

Bavera, Fragos et al. (2019)



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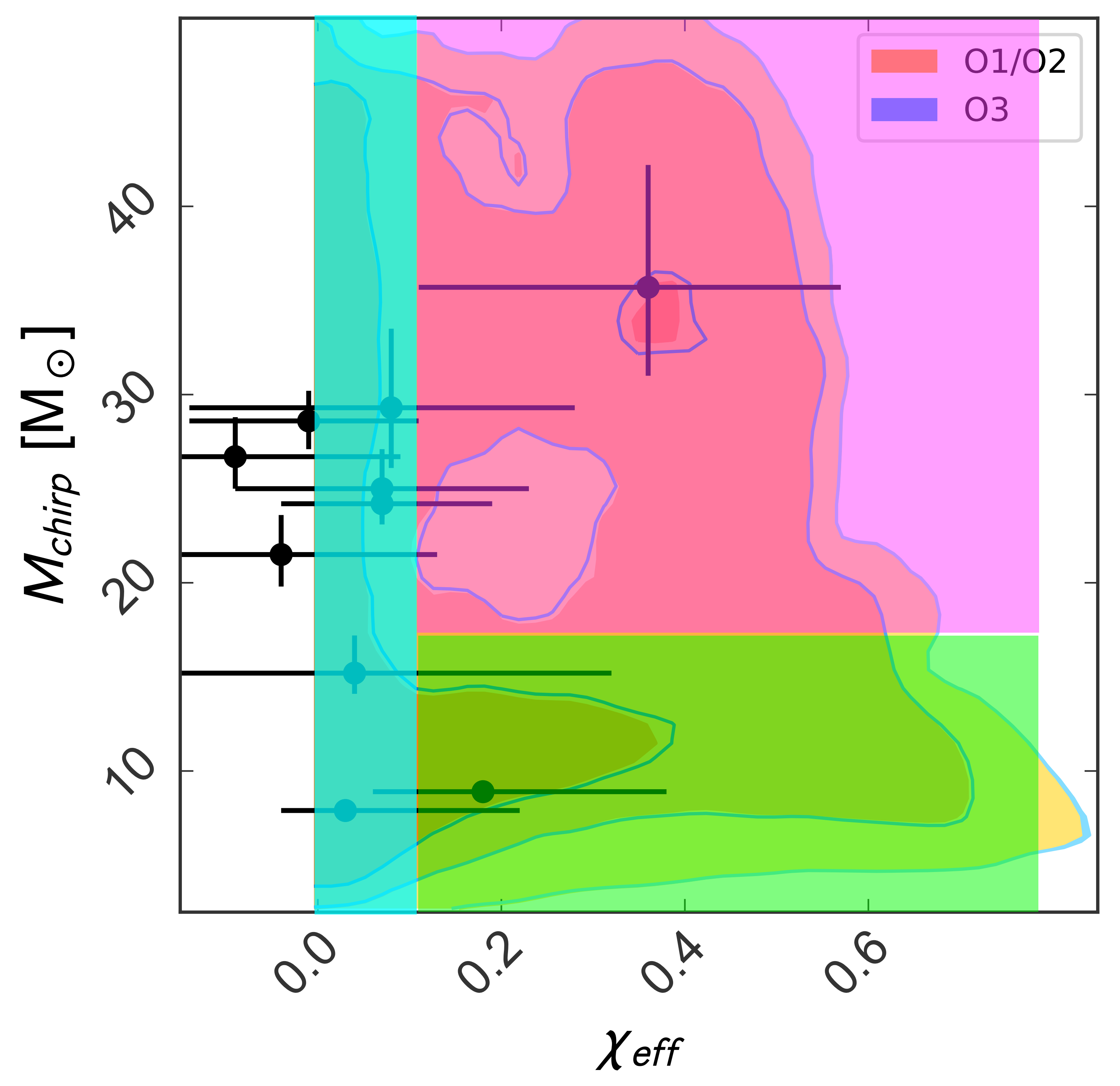


60%

- long τ_{merger}
- $z_{formation}$ up to 3
- wide range of metallicities

30%

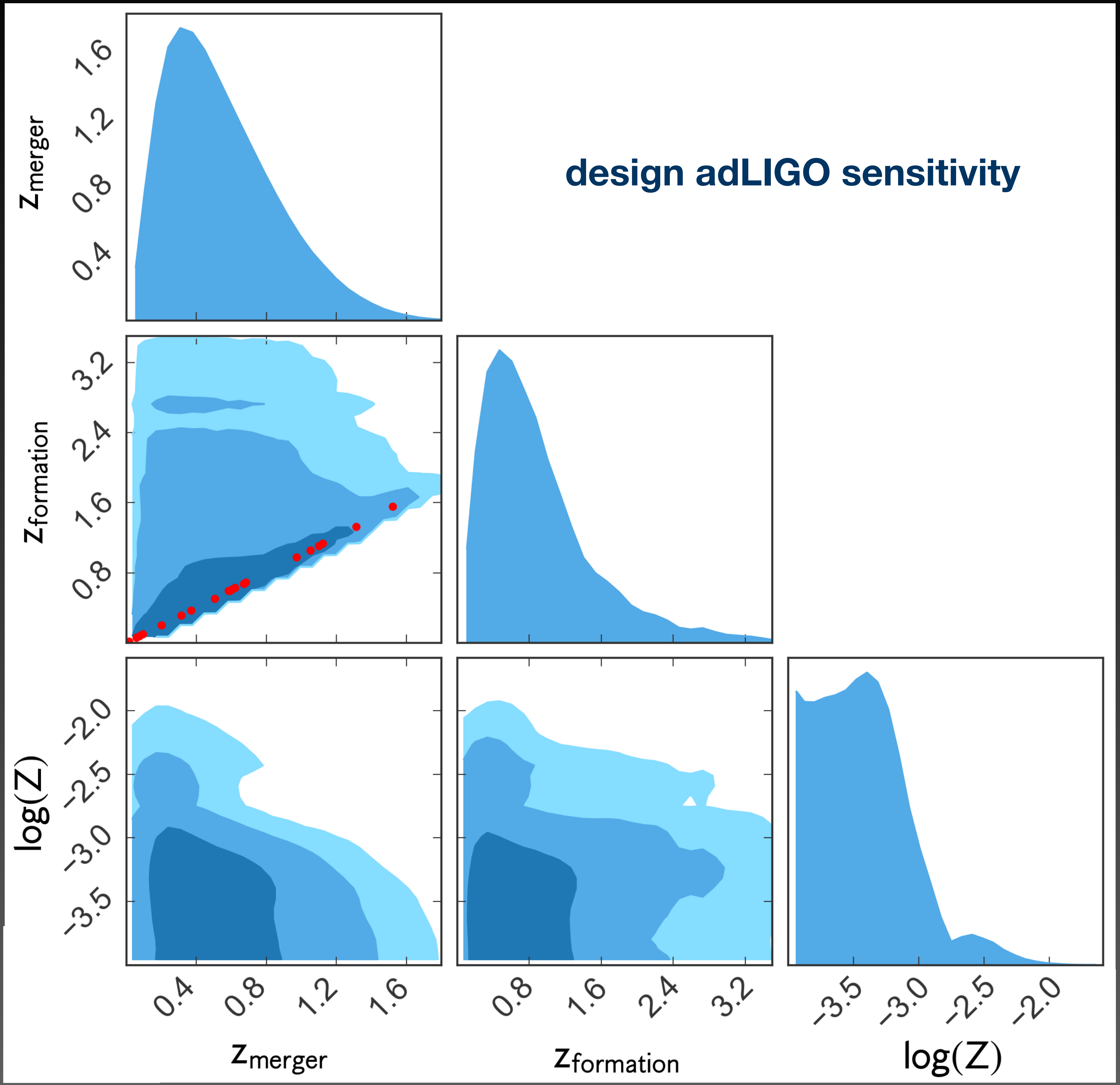
- short τ_{merger}
- low-metallicity
- LIGO selection effect

10%

- short τ_{merger}
- high-metallicity

Probing BBH formation at hight redshift

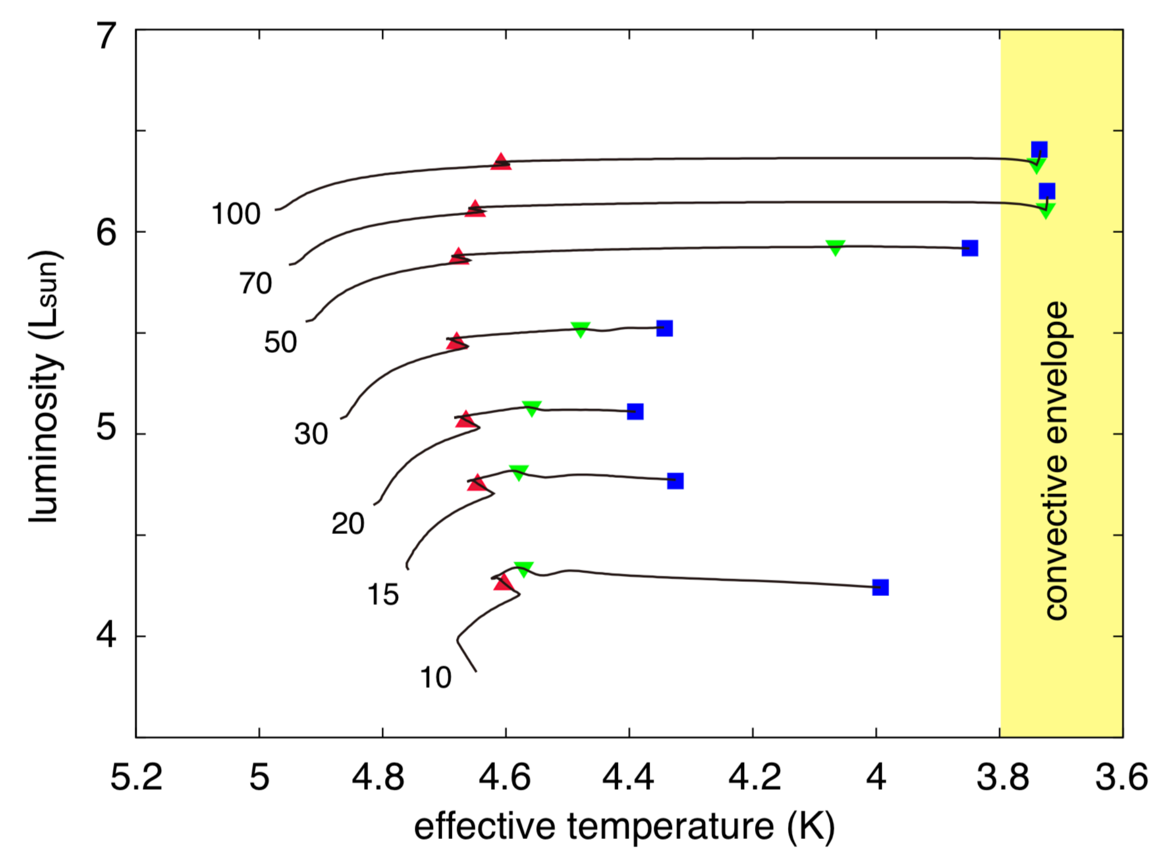
Bavera, Fragos et al. (2019)

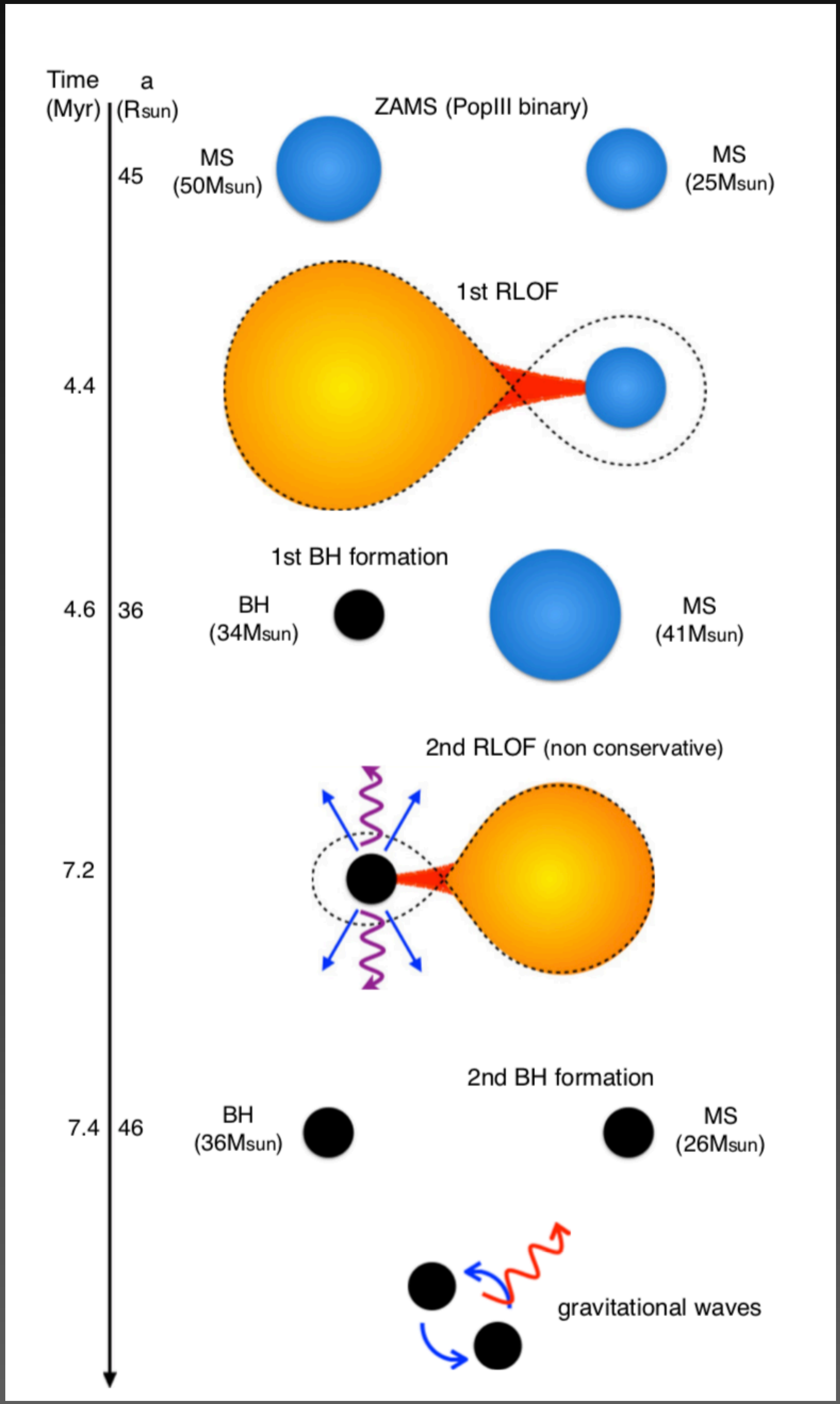


BBH formation from pop-III binaries

The different radial evolution and envelope structure of pop-III stars help the stability of binary mass-transfer events

Inayoshi et al. (2017)





Inayoshi et al. (2017)

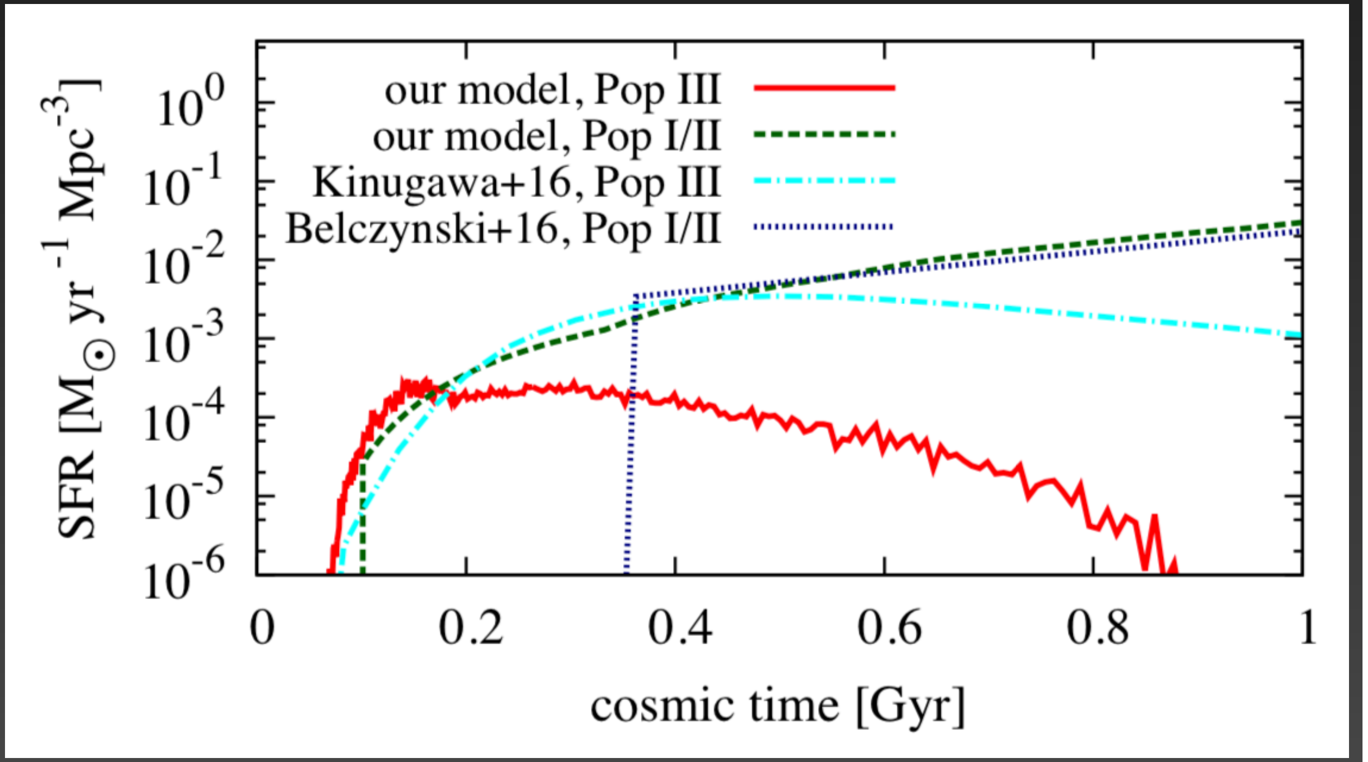
BBH formation efficiency ~1%

~1-2 orders of magnitude higher that pop-I/II

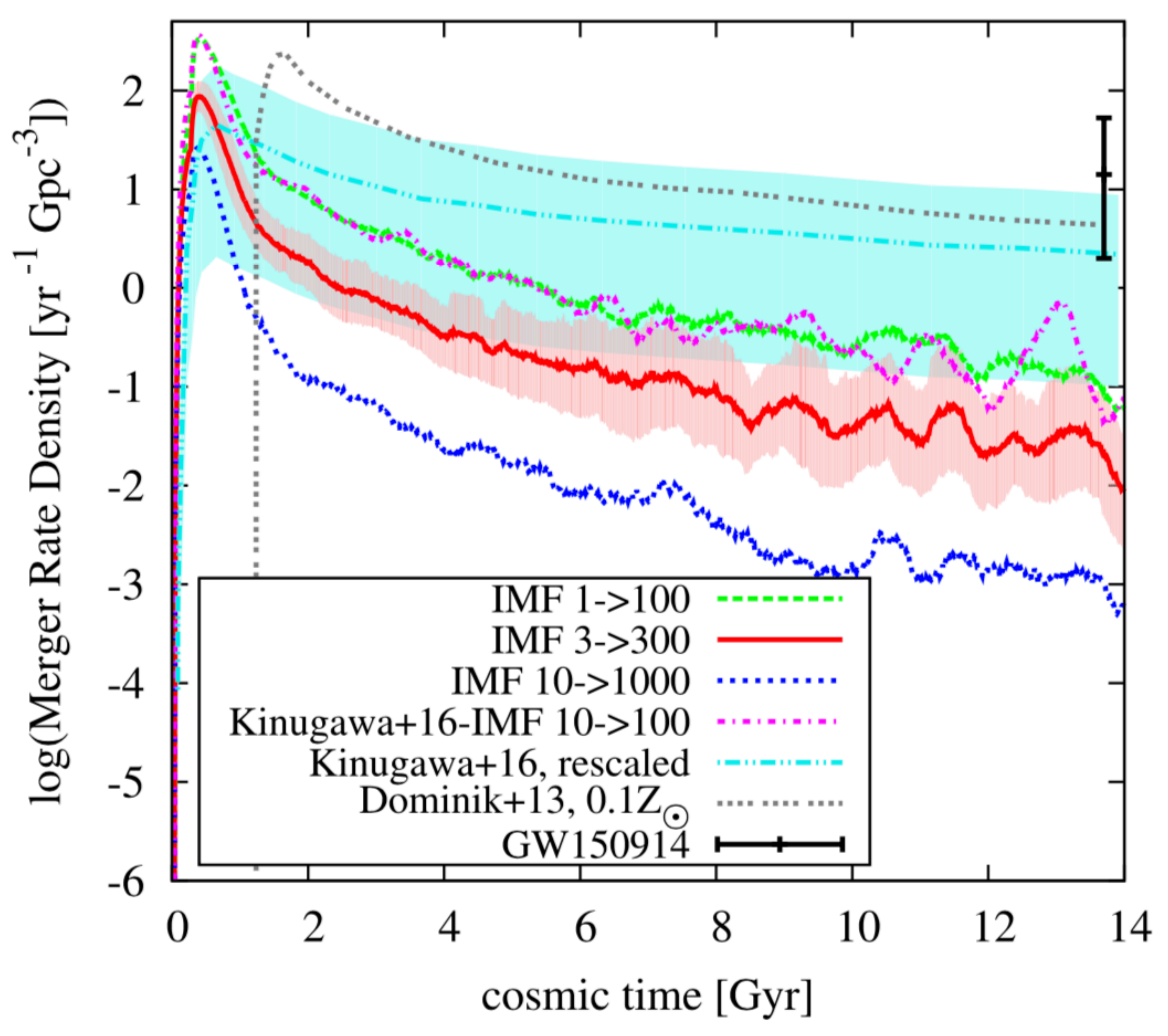
BBH formation from pop-III binaries

Can we observe pop-III binary black-hole mergers?

Hartwig et al. (2016)



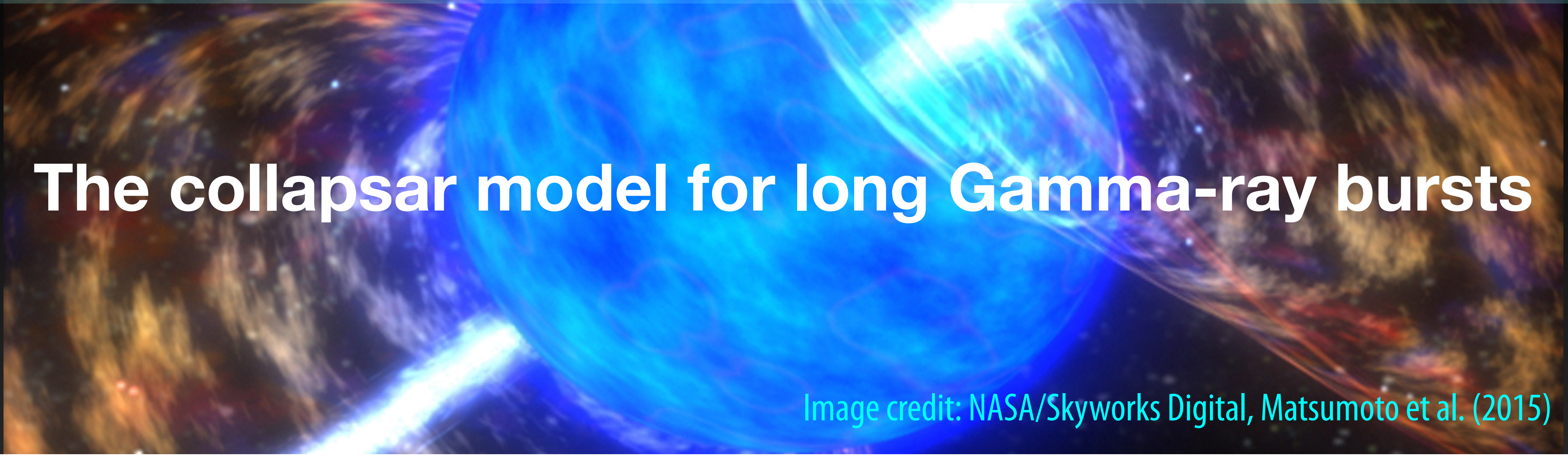
Hartwig et al. (2016)



We probably have to wait for Einstein Telescope and Cosmic Explorer

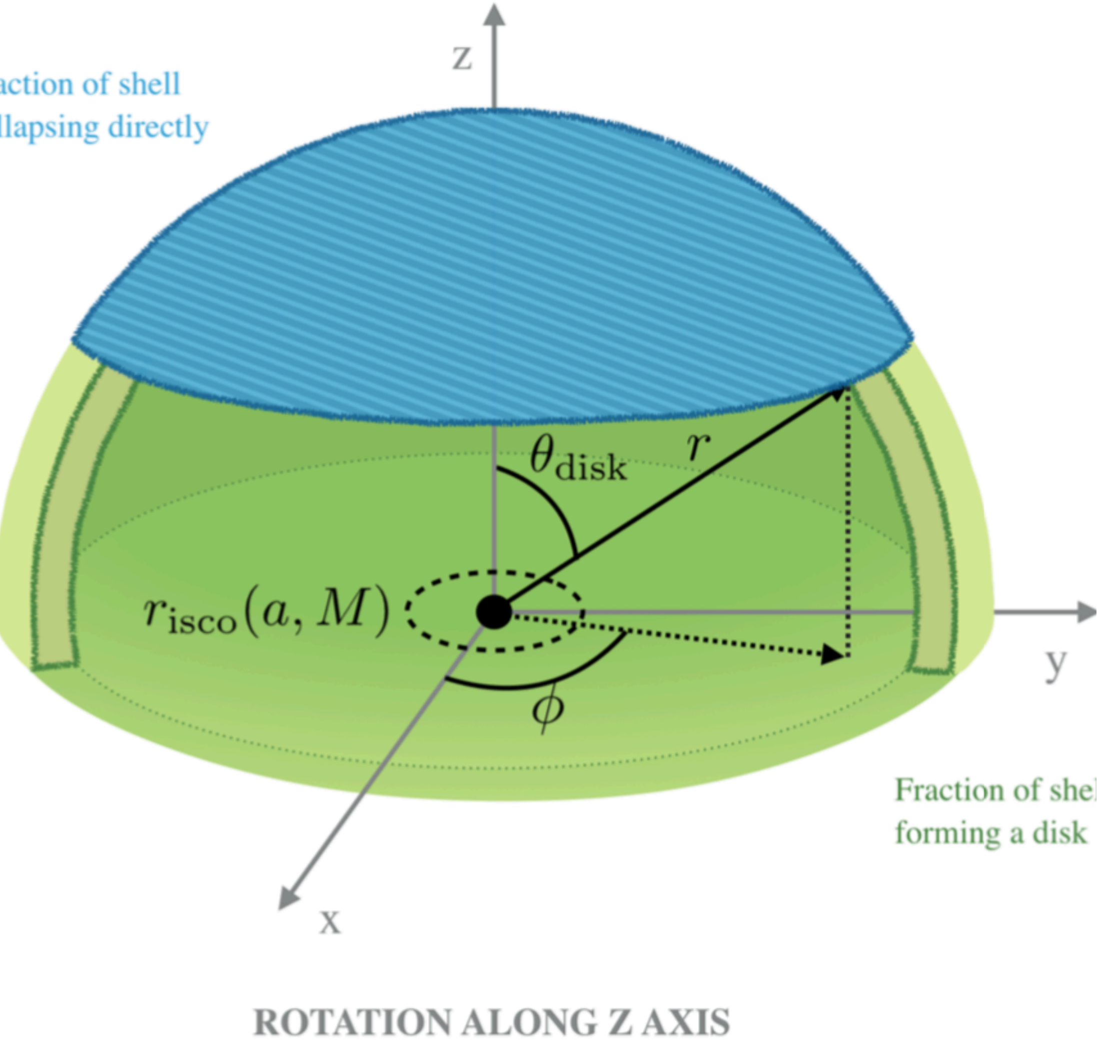
see also Belczynski et al. (2017)

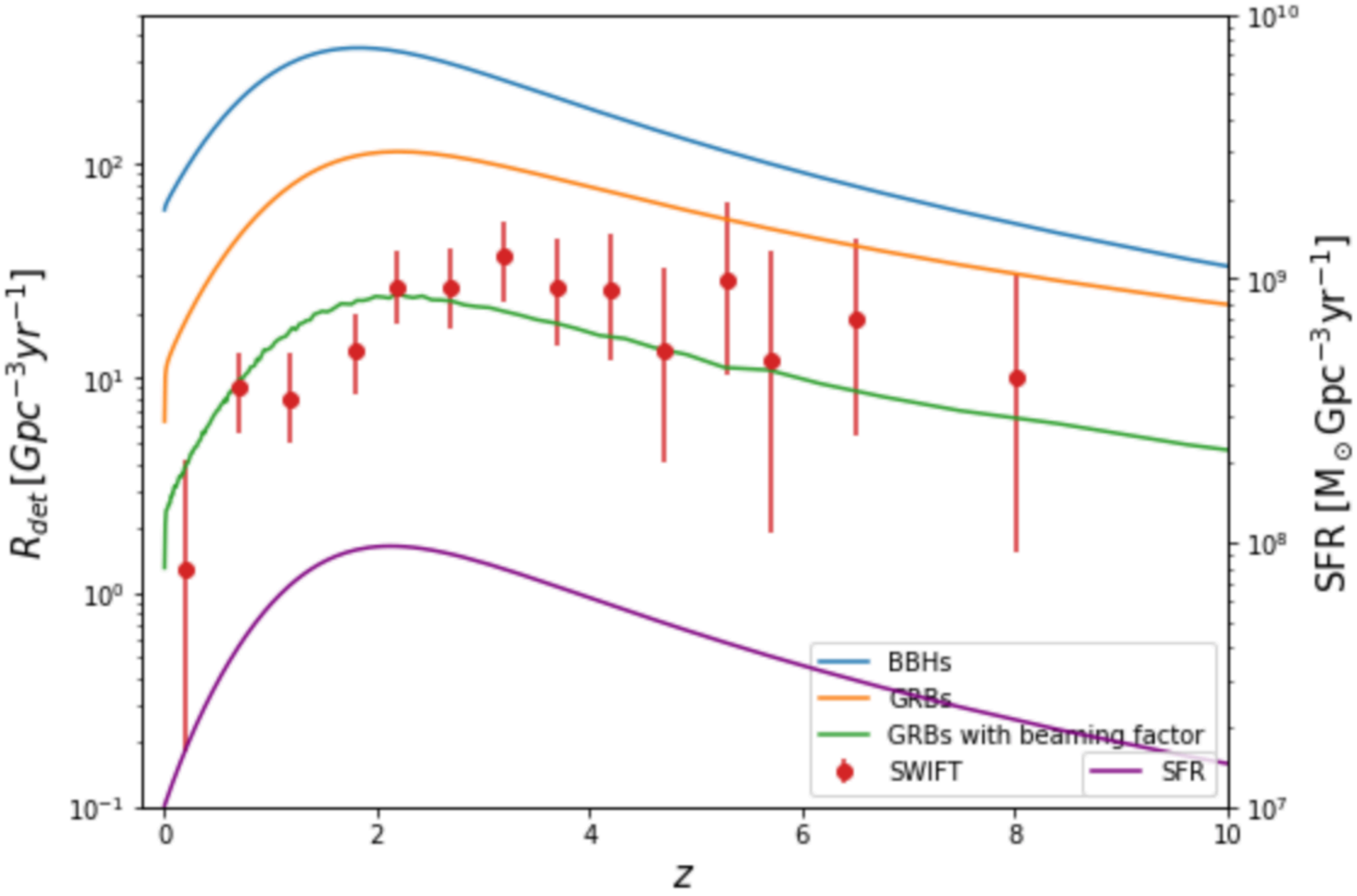
Probing the formation of the first black holes



The collapsar model for long Gamma-ray bursts

Image credit: NASA/Skyworks Digital, Matsumoto et al. (2015)



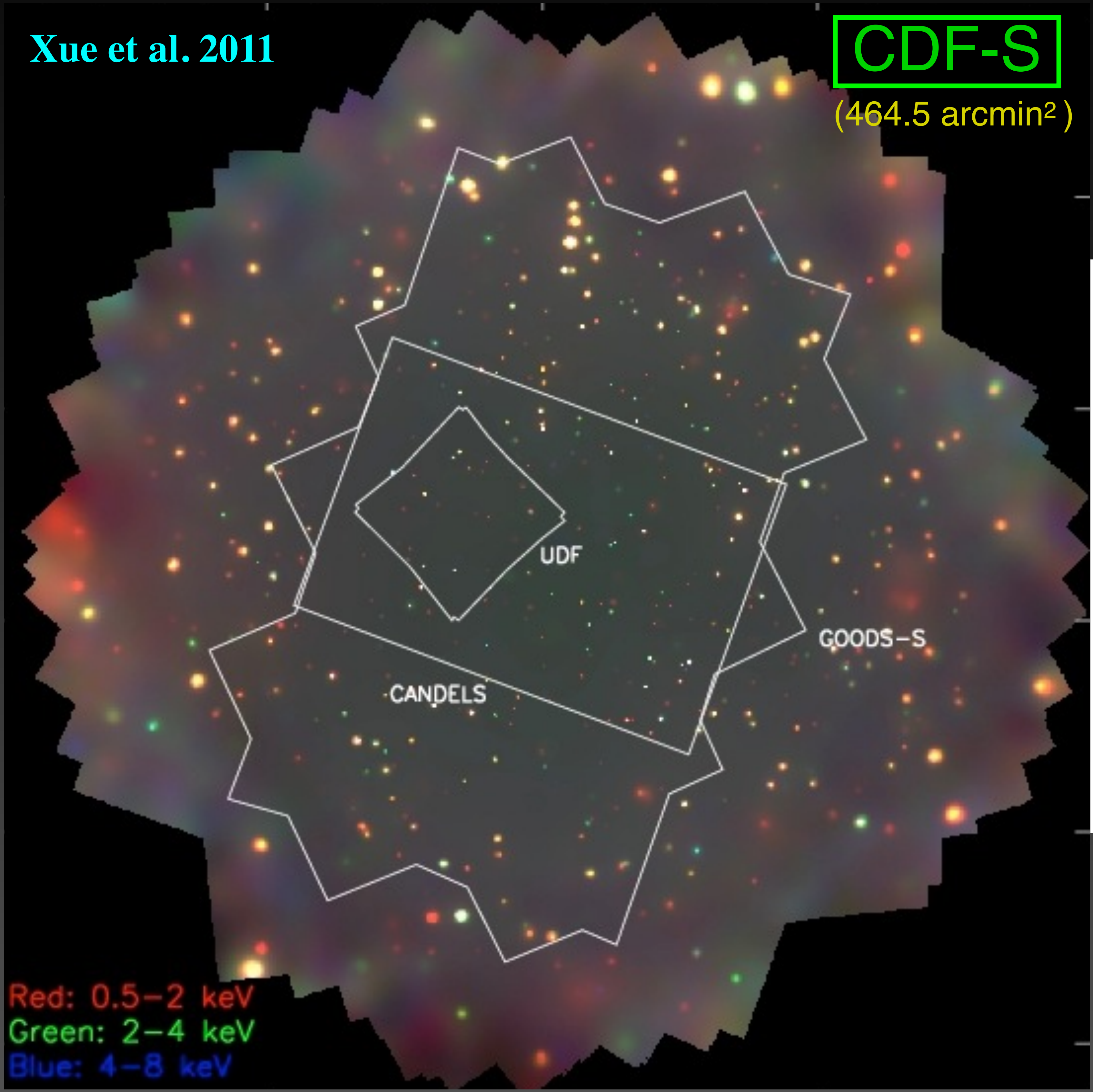


Batta & Ramirez (2019)

Bavera, Zapartas, Fragos et al. (2019; in preparation)

Accreting Black Holes in the Early Universe

The Deepest X-ray Survey:The 4Ms CDF-S

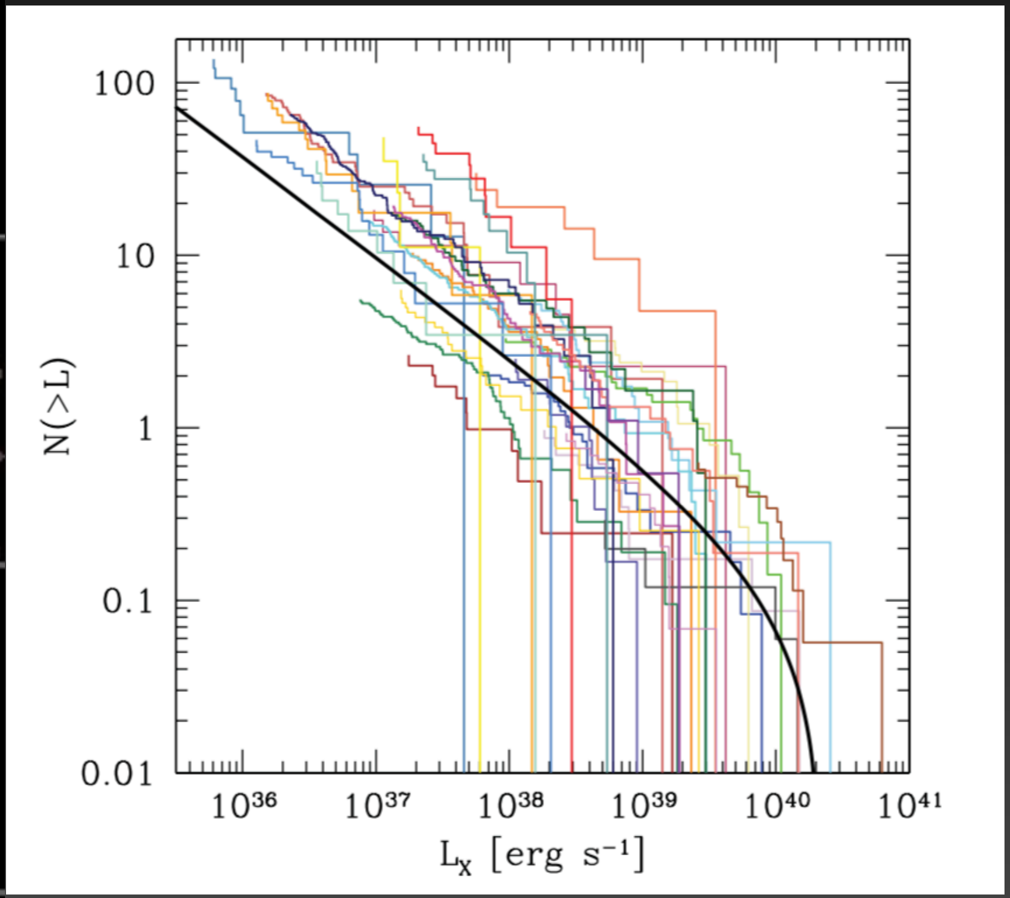


Xue et al. 2011

CDF-S

(464.5 arcmin^2)

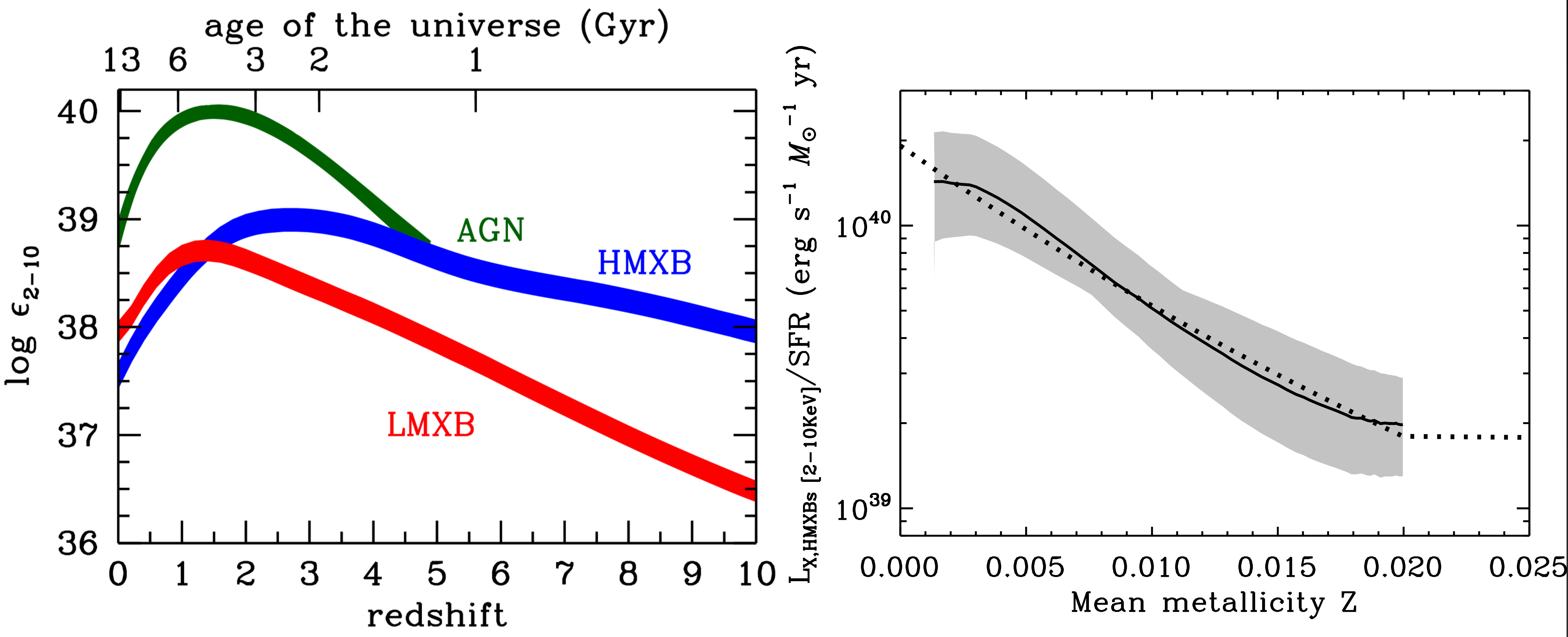
X-ray luminosity function of star-forming galaxies



Mineo et al. (2012)

Evolution of X-ray Binaries across Cosmic Time

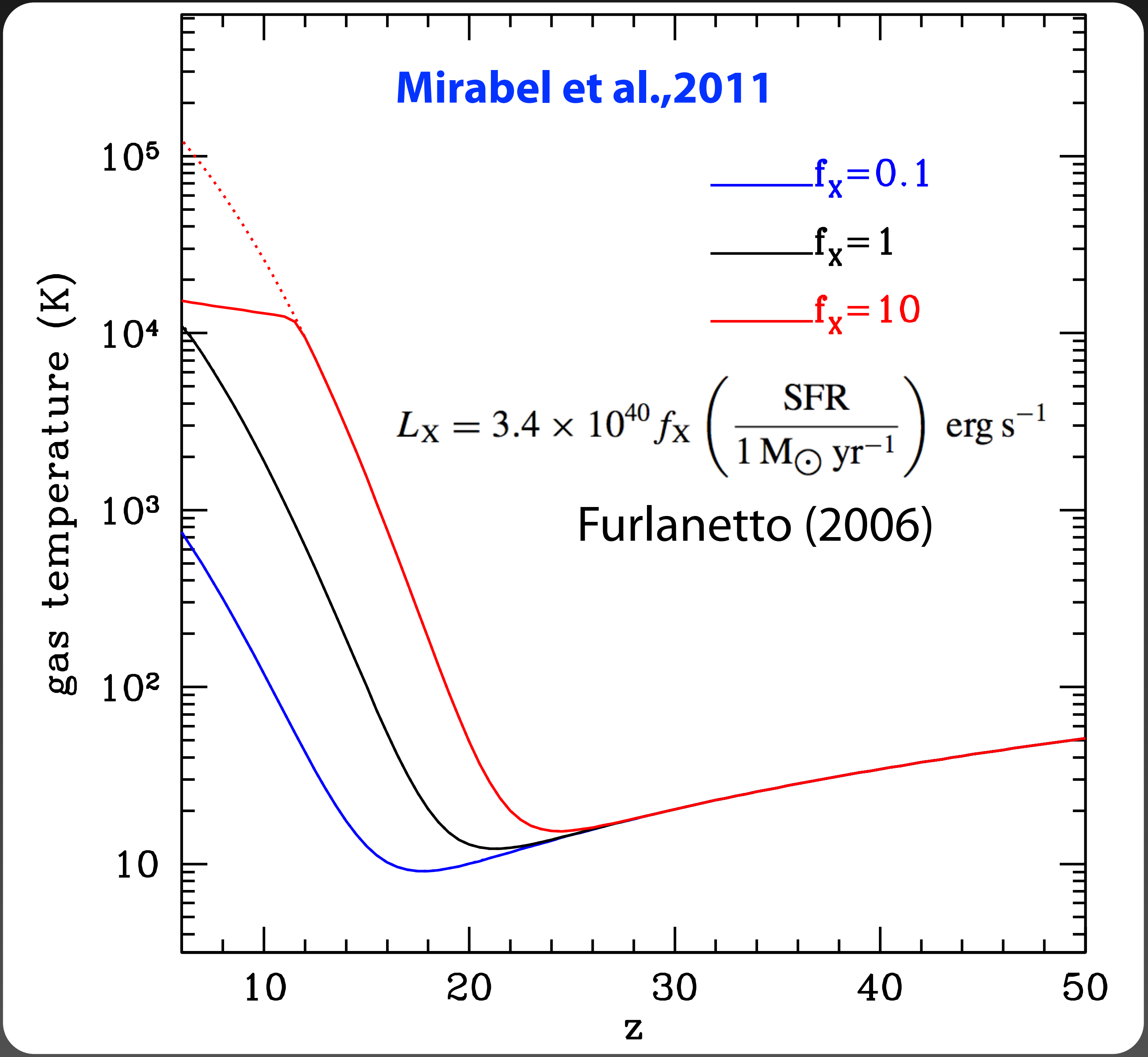
Fragos et al. (2013a,b); Madau & Fragos (2017)



Radiative feedback from XRBs

X-ray photons have long mean free path

The radiation field by XRBs may be important in the thermal evolution of the early universe



Mirabel et al.,2011

$$L_X = 3.4 \times 10^{40} f_X \left(\frac{\text{SFR}}{1\,\text{M}_\odot\,\text{yr}^{-1}} \right) \text{erg s}^{-1}$$

Furlanetto (2006)

Results are sensitive to:

- **Star-formation history @ z>8**
- **emission spectrum of X-ray binaries**
- **X-ray binary formation efficiency from pop-III stars**

See also:

Fialkov & Barkana (2014)
Mesinger et al. (2013)
Madau & Fragos (2017)
Arpan et al. (2017)

Take-Home Messages

- *Gravitational waves from coalescing binary black holes opened a new window to massive binary evolution (at low metallicity). Black hole spin carries important information about the formation history of black hole binaries.*

- *Pop-III binaries can produce coalescing binary black holes very efficiently, but their star-formation history renders them invisible to current GW observatories*

- *Accreting black holes at $z>8$ dominate the X-ray background, making them a non-negligible feedback source and perhaps leaving a distinct signature in 21cm*

- *Long Gamma-ray burst may be closely linked to binary black hole formation, providing a view of black hole formation at redshifts not accessible to GW and X-rays*