No peaks without valleys

An investigation of the stable mass transfer channel in light of the NS-BH mass gap

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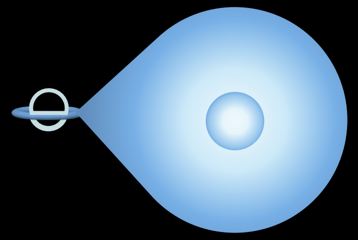
UNIVERSITY OF AMSTERDAM

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Image credit: Ligo/Virgo/Kagra

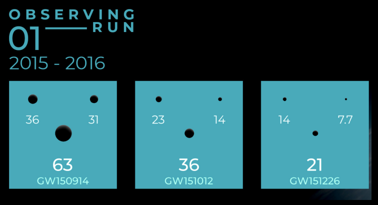


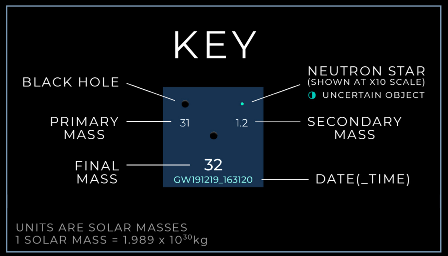
The stable mass transfer channel leads to a
minimum primary mass

this can cause a “NS-BH mass gap” in the GW inferred mass distribution

Nov 2021: GRAVITATIONAL WAVE MERGER DETECTIONS SINCE 2015 GWTC-3

OzGrav





Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

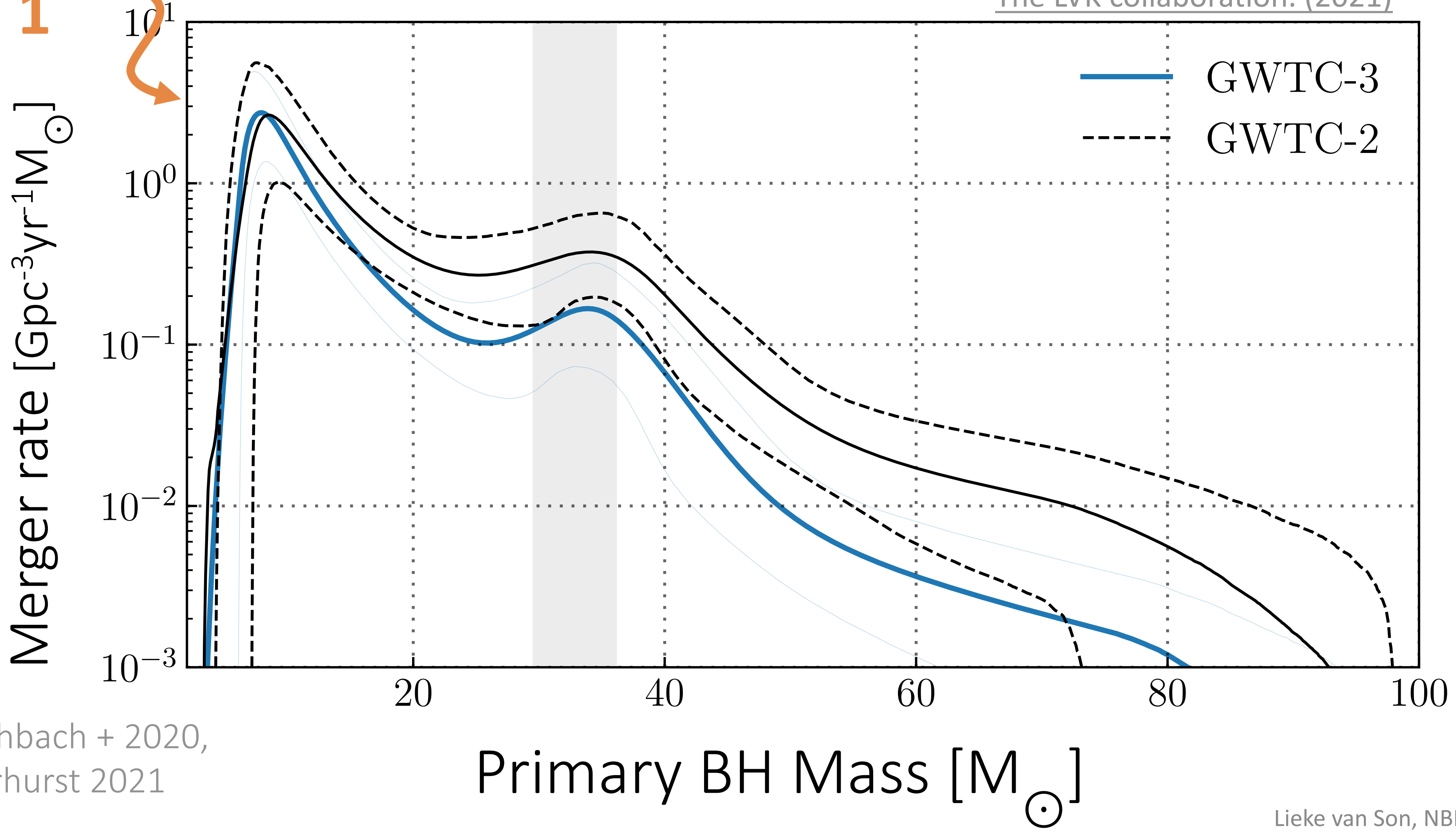
The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

LIGO VIRGO KAGRA

There are features in the mass distribution!

Feature 1

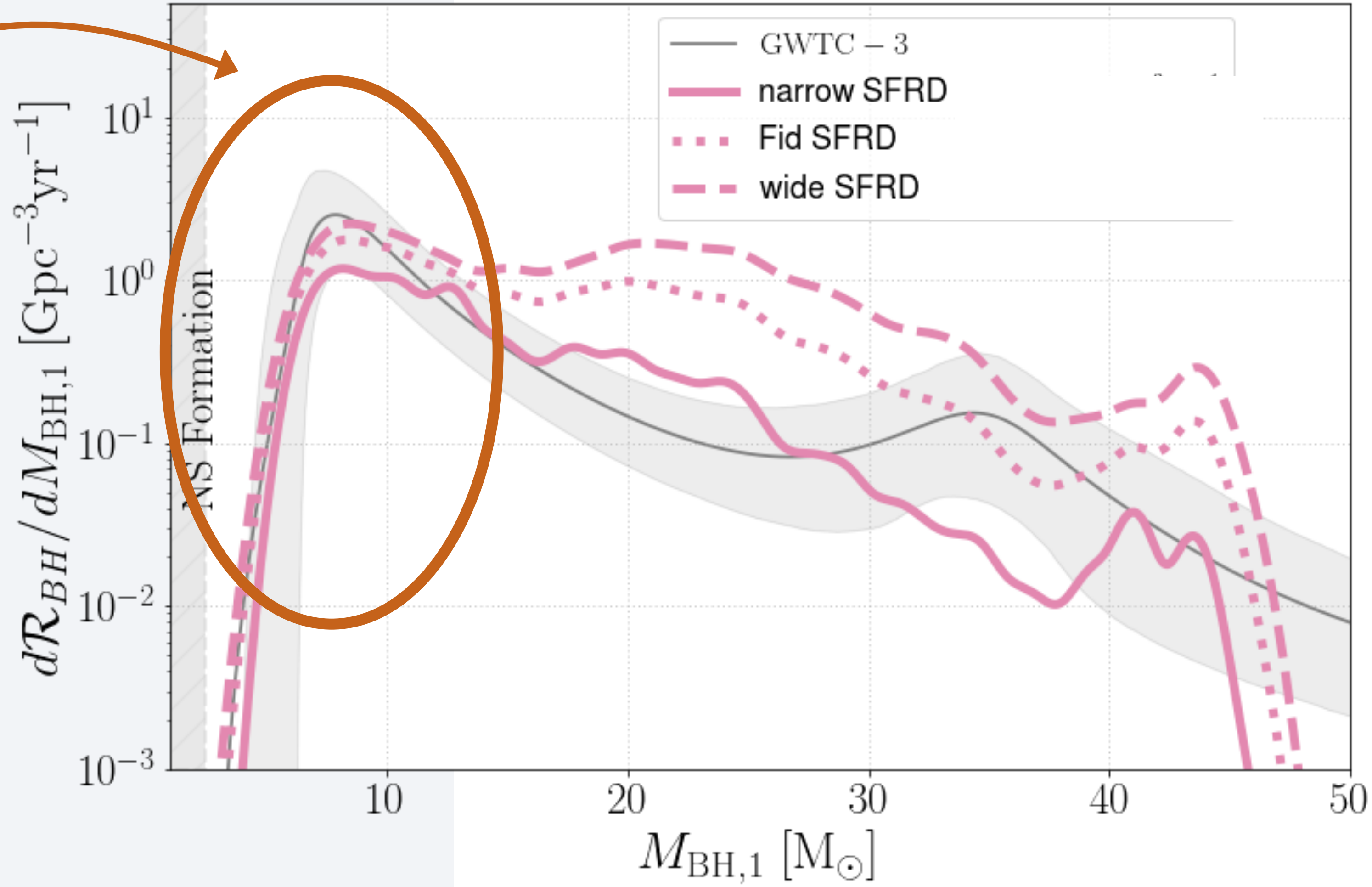
The LVK collaboration. (2021)



See also: Fishbach + 2020, Tiwari & Fairhurst 2021

The low mass end is a great place to start

less bothered by metallicity dependent star formation uncertanty

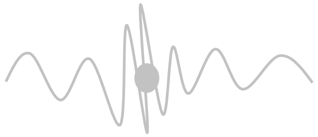


van Son et al. (in prep)

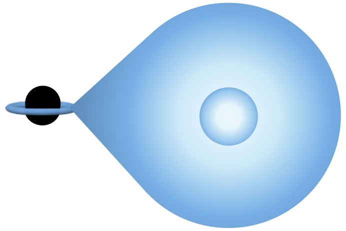
Many different channels have been proposed…

Only few are expected to have the overall peak occur at low mass!

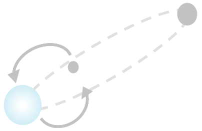
Primordial BHs?



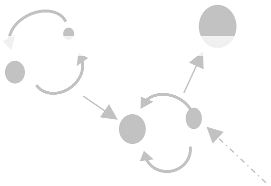
ii) Stable mass transfer



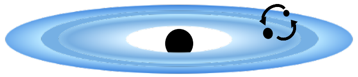
iv) Triple systems



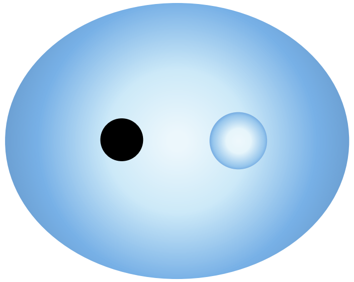
vi) Dynamical formation in massive star clusters



v) In gas disk of Active Galactic Nuclei



iii) Chemically Homogeneous

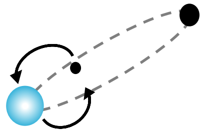


i) Classical (Common Envelope)

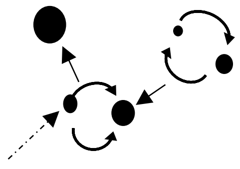
vii) Kozaii resonance with SMBH

Adapted from de Mink In prep. for Annual Review in Astronomy & Astrophysics

… most are not expected to dominate at low masses!

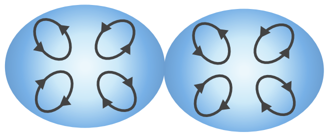


Hierarchical mergers of NS are not efficient (neither in clusters nor triples)
e.g. Samsing & Hotokezaka (2021), Lu et al. (2021), Hamers et al. (2021)

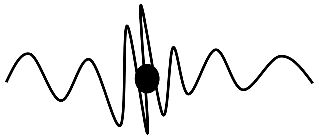


Globular clusters miss the low mass peak
e.g. Hong et al. 2018; Rodriguez et al. 2019; Antonini & Gieles 2020

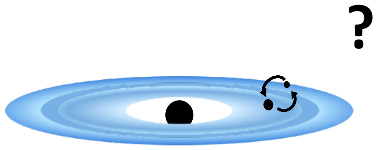
Young open clusters: light BHs are easily ejected and don’t contribute
e.g. Portegies Zwart & McMillan 2000; Ziosi et al. 2014; Bouffanais et al. 2019; Santoliquido et al. 2021; Fragione & Banerjee 2021



CHE leads to ~30 +30 $M_\odot$
e.g. de Mink et al. 2009; Song et al. 2013, 2016; Mandel & de Mink 2016; Marchant et al. 2016; Riley et al. 2021)



Population III binaries peak at ~20 $M_\odot$
e.g. Marigo et al. 2001; Belczynski et al. 2004; Kinugawa et al. 2014; Inayoshi et al. 2017)



AGN disks: rates are highly uncertain, but gas could lead to 10M BH?
e.g. Baruteau et al. 2011; Bellovary et al. 2016; Leigh et al. 2018; Yang et al. 2019; Secunda et al. 2019; McKernan et al. 2020; Cantiello et al. 2021

Isolated binary formation can be roughly split in two

Common envelope channel:

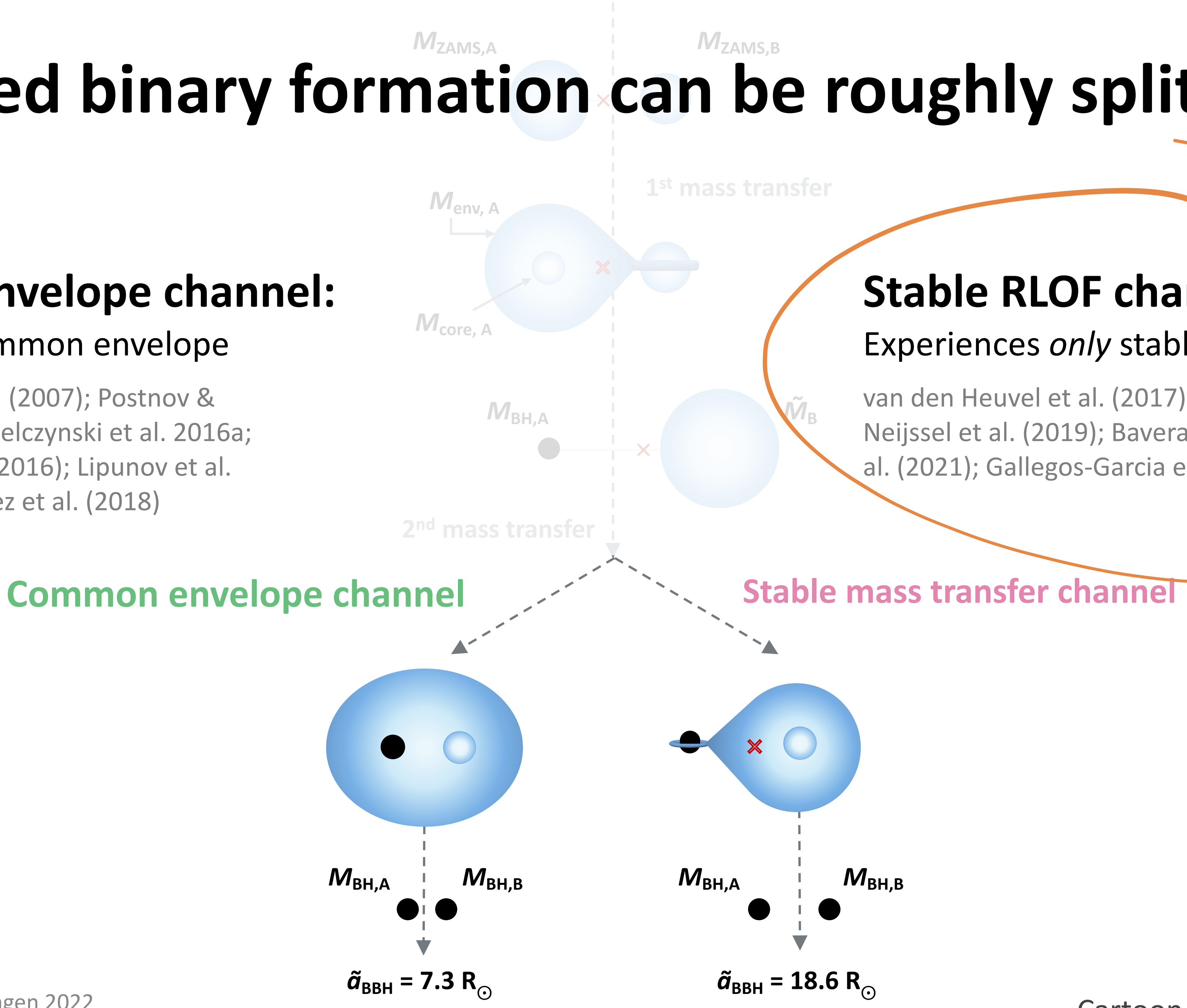
at least one common envelope

e.g. Belczynski et al. (2007); Postnov & Yungelson (2014); Belczynski et al. 2016a; Eldridge & Maund (2016); Lipunov et al. (2017); Vigna-Gomez et al. (2018)

Stable RLOF channel:

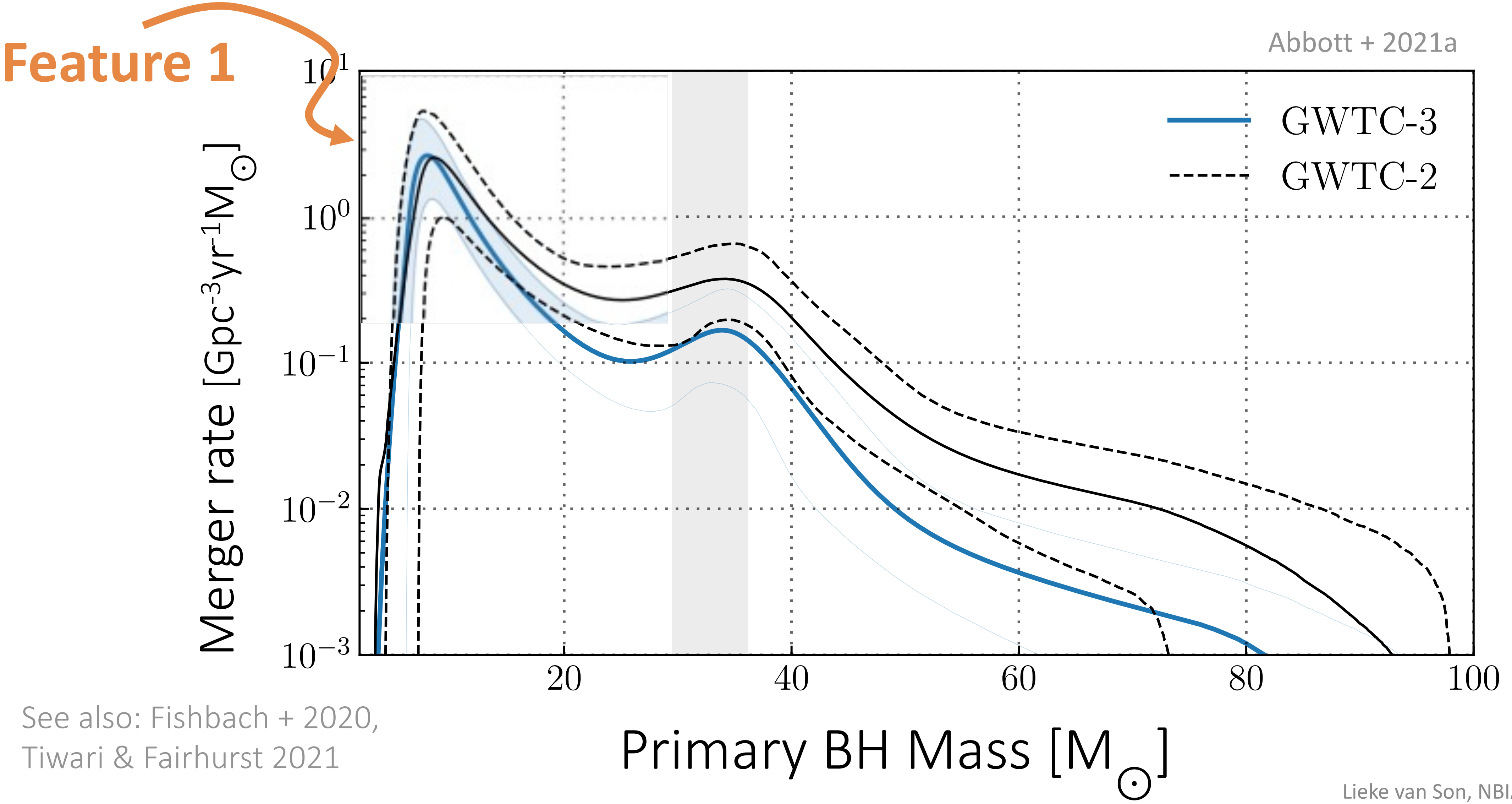
Experiences *only* stable mass transfer

van den Heuvel et al. (2017); Inayoshi et al. (2017); Neijssel et al. (2019); Bavera et al. (2021); Marchant et al. (2021); Gallegos-Garcia et al. (2021)



Cartoon from van Son et al. 2021

There are features in the mass distribution!

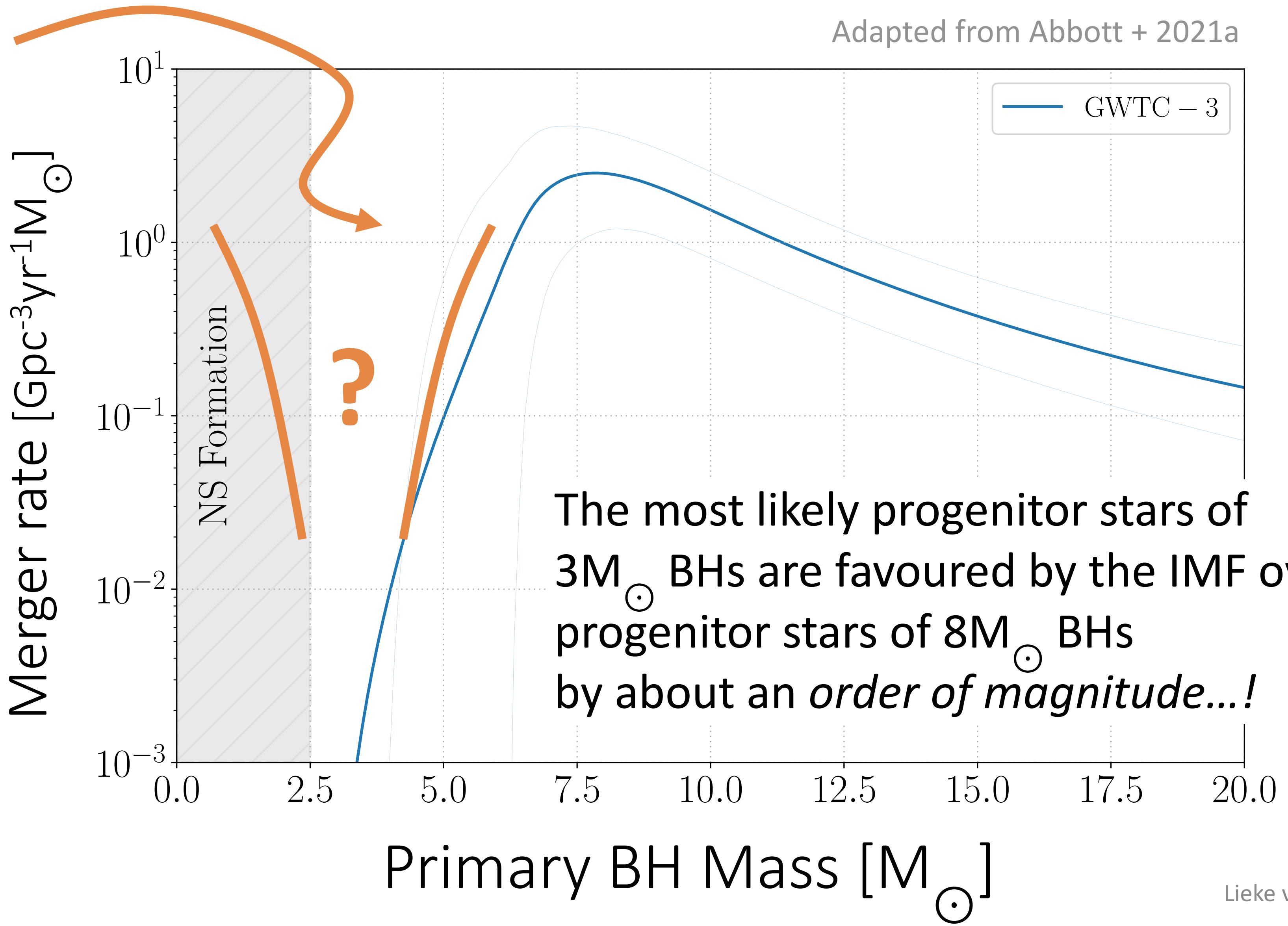


See also: Fishbach + 2020,
Tiwari & Fairhurst 2021

There are features in the mass distribution!

Feature 1

Adapted from Abbott + 2021a



The most likely progenitor stars of $3M_\odot$ BHs are favoured by the IMF over progenitor stars of $8M_\odot$ BHs by about an *order of magnitude…!* (Kroupa 2001)

Where are the BH's with 3-6 $M_\odot$?

(There appears to be an underabundance of 3-6$M_\odot$ BHs: Fishbach + 2020, Abbott et al. 2021b, Farah + 2021, Ye & Fishbach 2021)

We don't see them

Observational bias against detecting such systems?

(Fishbach + 2017)

A: They don't exist

You cannot form *any* BHs with masses 3-6 solar mass ("NS-BH mass gap")

e.g. Fryer & Kalogera 2001, Fryer+ 2012, Belczynski+2012, Fryer+2022, Olejak+2022

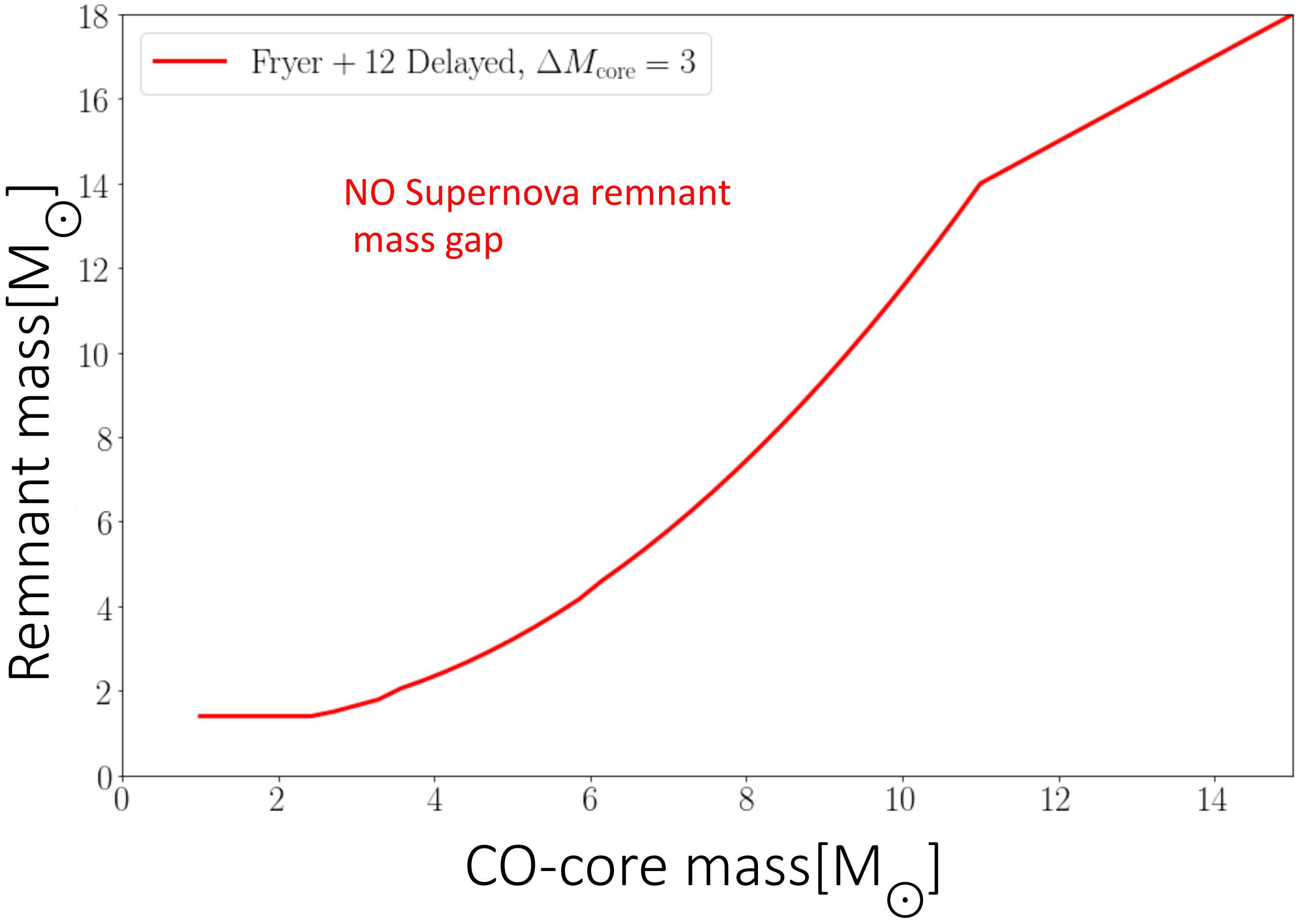
B: They don't merge

A: They don't exist?

Supernova remnant mass function can be smooth…

SN physics: Fryer & Kalogera 2001,
Fryer + 2012, Belczynski + 2012, Fryer + 2022,
Olejak + 2022

Adapted from Fryer + 2012



A: They don't exist?

…or discontinuous

SN physics: Fryer & Kalogera 2001, Fryer + 2012, Belczynski + 2012, Fryer + 2022, Olejak + 2022

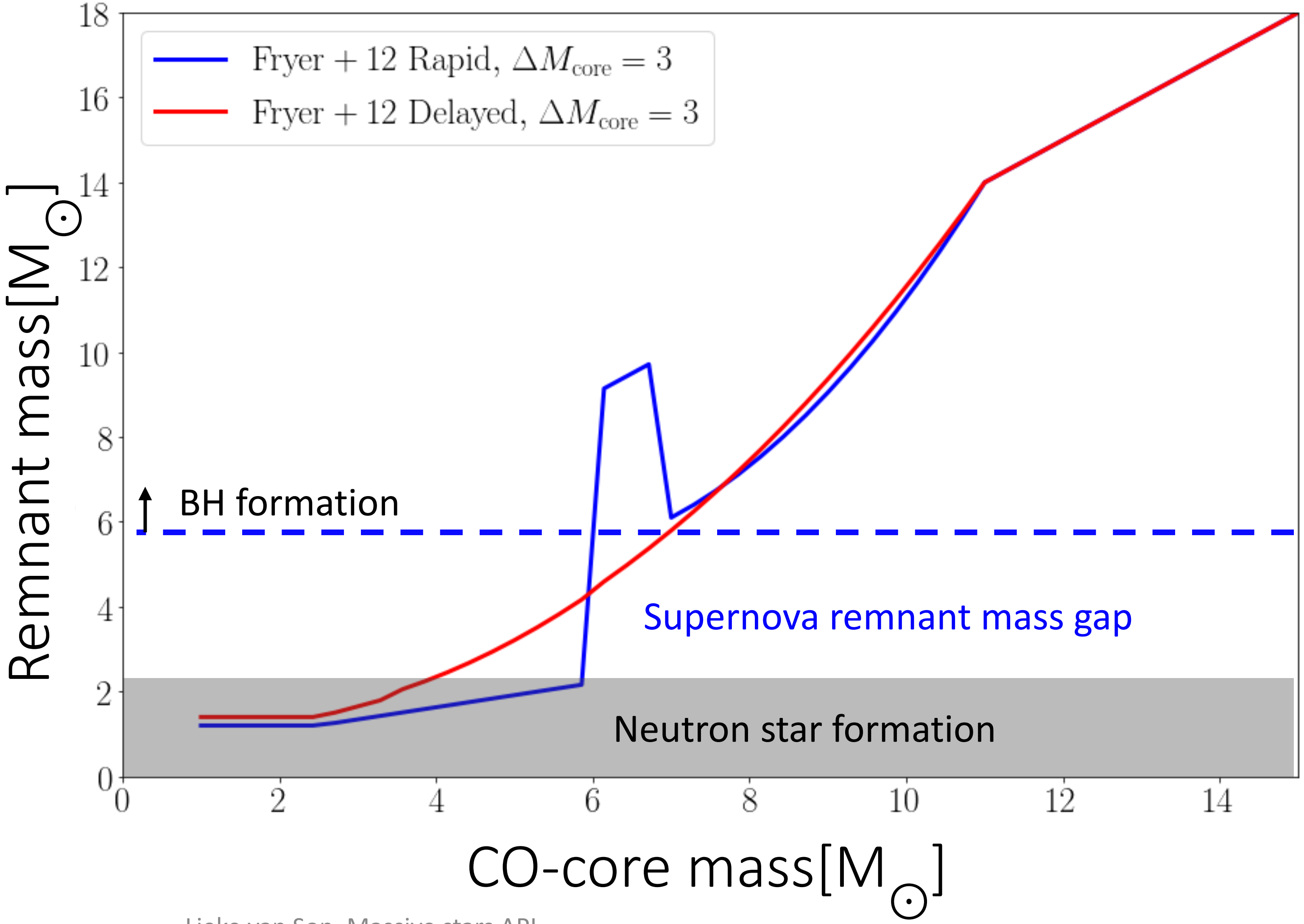
Discontinuous remnant mass distribution based on X-ray observations **(= NS-BH gap)**

Bailyn et al. 1998, Özel + 2010, Farr + 2011, Kreidberg + 2012

Claims against a gap:

Casares et al. 2017; Wyrzykowski & Mandel 2020
2MASS J0521 (RV): Thompson et al. 2019, Unicorn & Giraffe: Jayasinghe et al. 2021, 2022
GW190814 (GW): LVK 2020. **OB110462** (microlensing): Sahu+ 2022, Lam + 2022

Adapted from Fryer + 2012



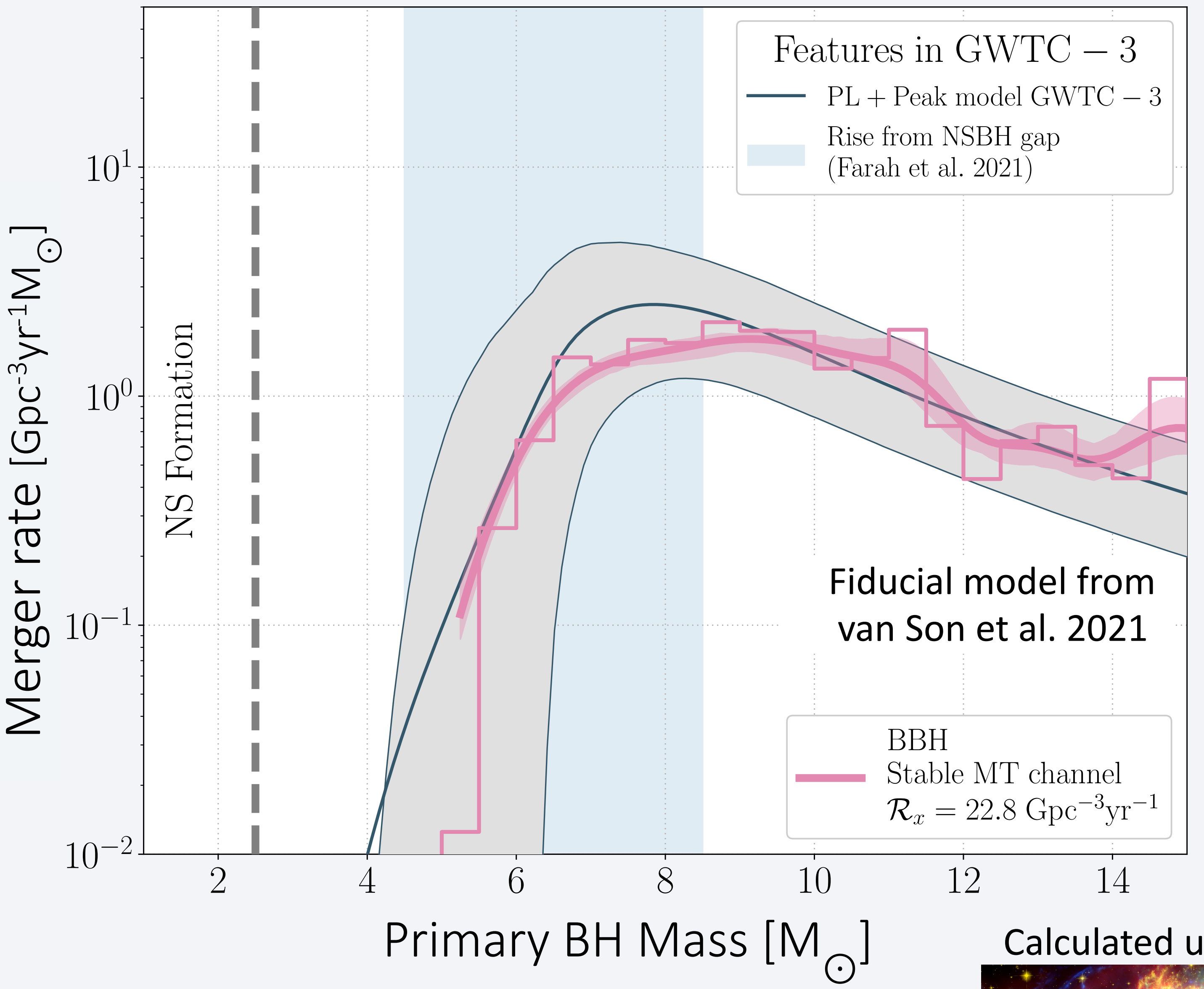
Where are the BH's with 3-6 $M_\odot$?

We don't see them	A: They don't exist	B: They don't merge
Observational bias against detecting such systems?	You cannot form *any* BHs with masses 3-6 solar mass ("NS-BH mass gap") ~	Evolutionary bias against merging double compact objects
(Fishbach + 2017)	e.g. Fryer & Kalogera 2001, Fryer+ 2012, Belczynski+2012, Fryer+2022, Olejak+2022	Van Son et al. in prep

What does the stable channel predict?

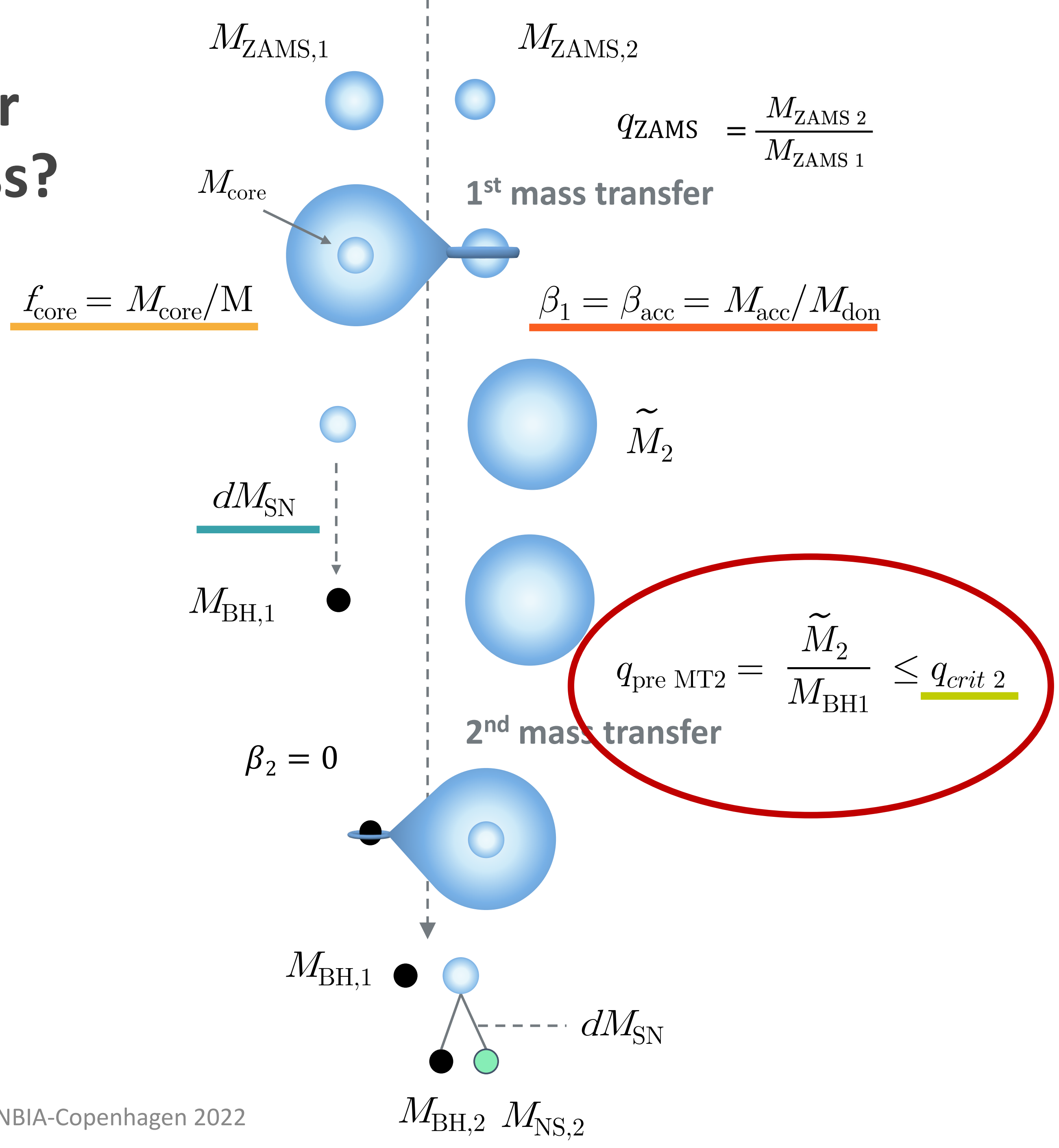
The fiducial stable channel matches the *rate* and *shape* at low mass

→ Why?



Calculated using COMPAS

Why does the stable mass transfer channel drop below a certain mass?

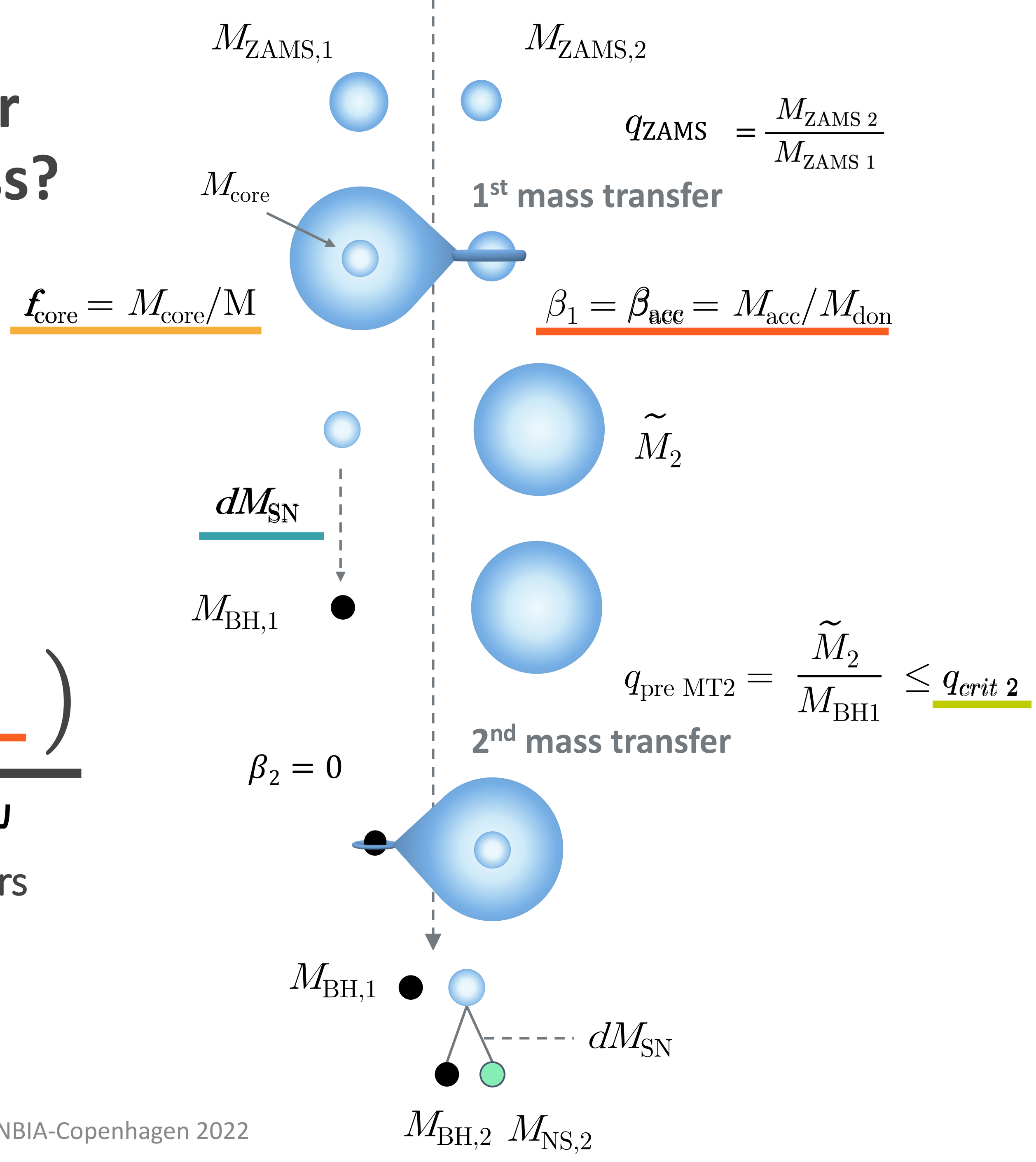


Requiring mass transfer stability imposes a minimum on the mass!

van Son et al. (in prep)

Why does the stable mass transfer channel drop below a certain mass?

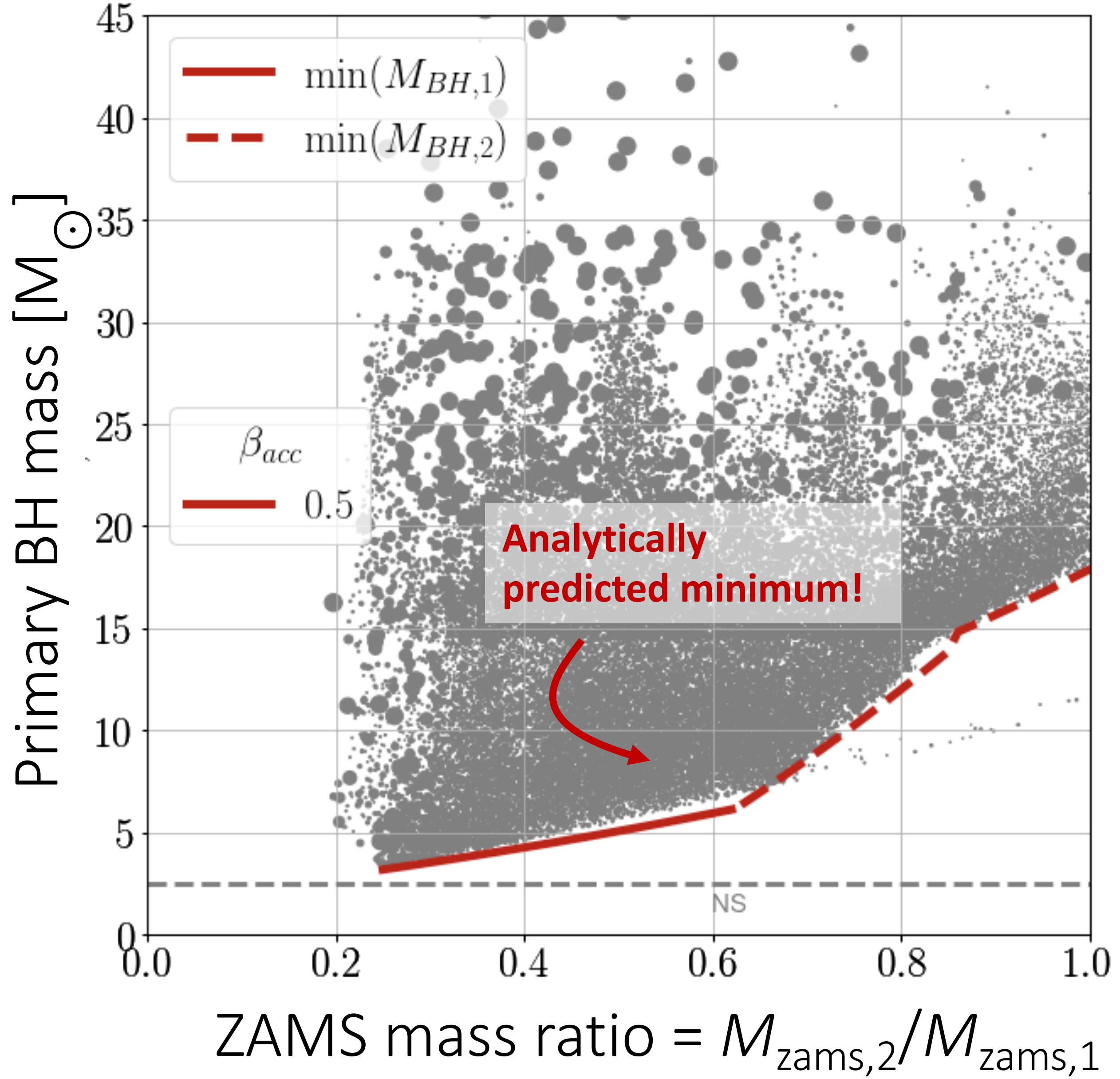
$$M_{BH} > \underbrace{f(}_{\text{Initial distribution variable}}\ \underbrace{\_\_\_\_\_\_\_\_}_{\text{Physics parameters}}\ )$$



van Son et al. (in prep)

van Son et al. (in prep)

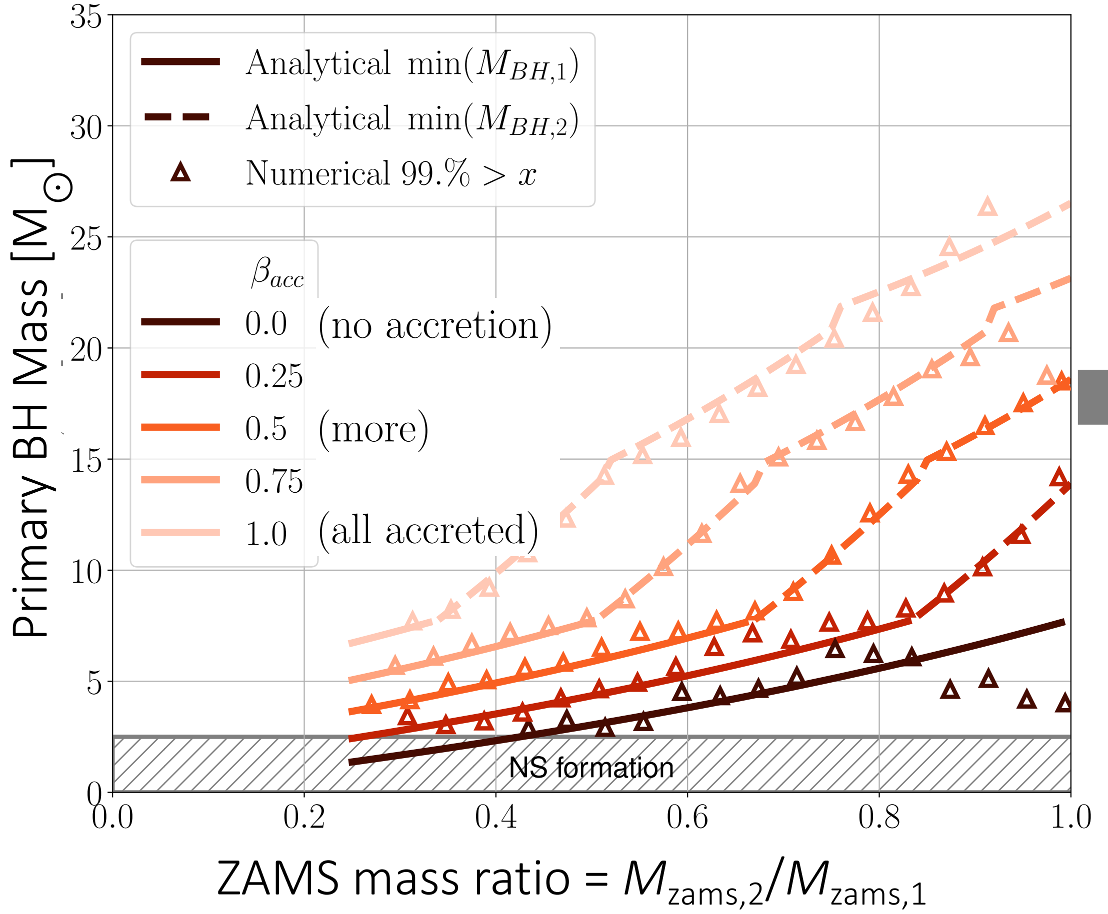
We can predict the minimum BH mass analytically ….!

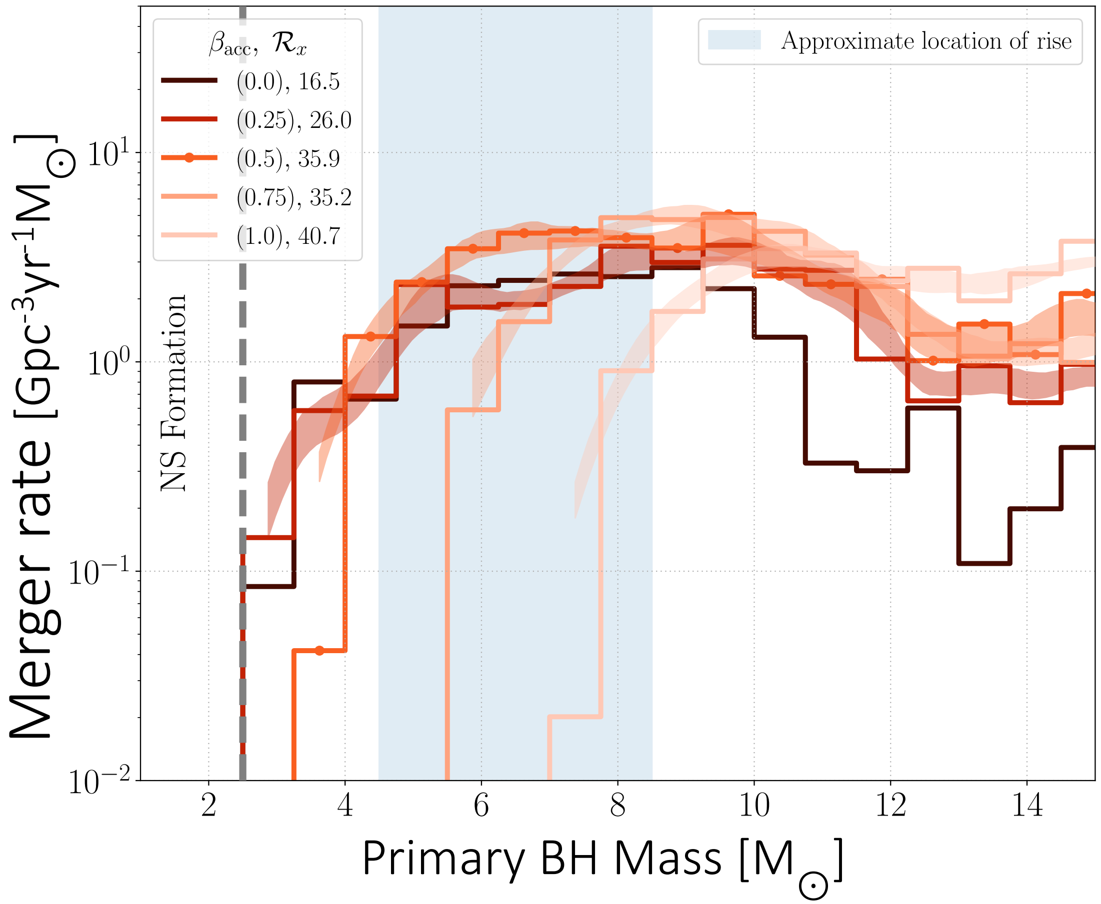


This creates a dearth of low mass BHs without the need for a gap in the remnant mass distribution..!

Variations in mass accreted

van Son et al. (in prep)

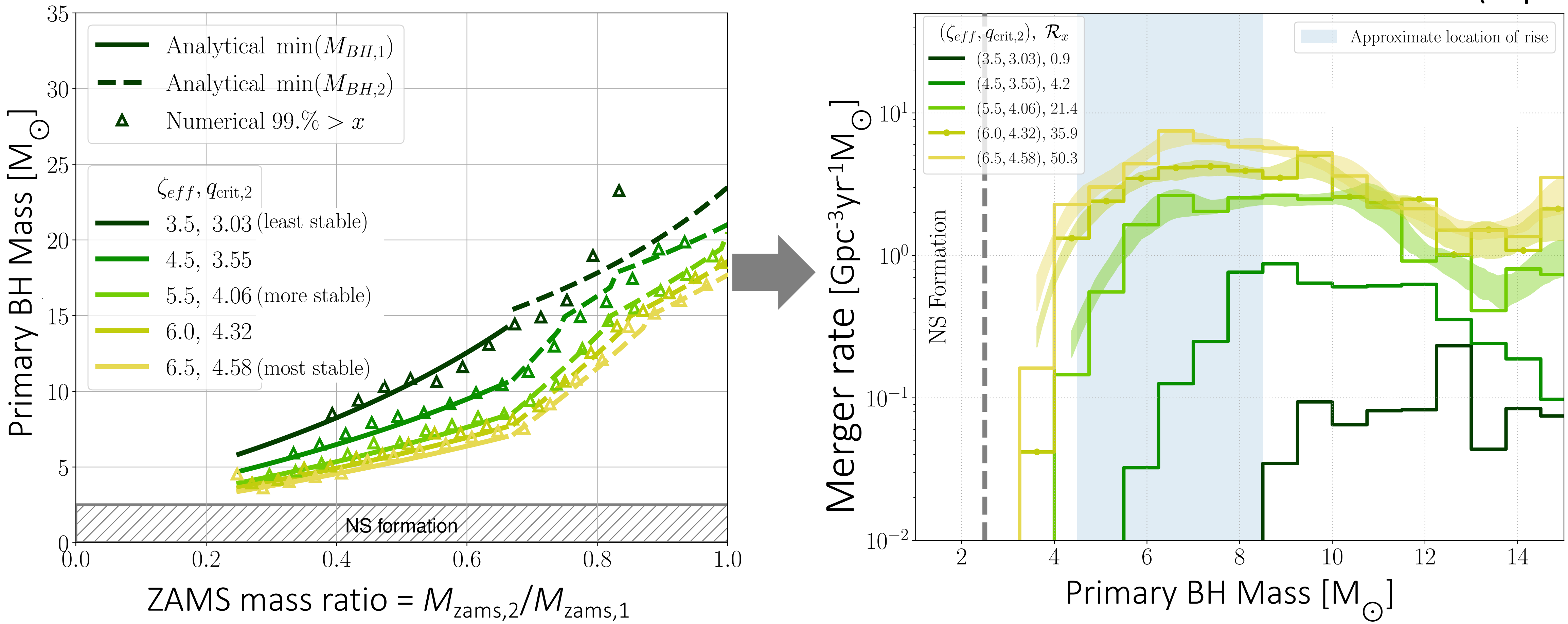




This creates a dearth of low mass BHs without the need for a gap in the remnant mass distribution..!

Variations in mass transfer stability

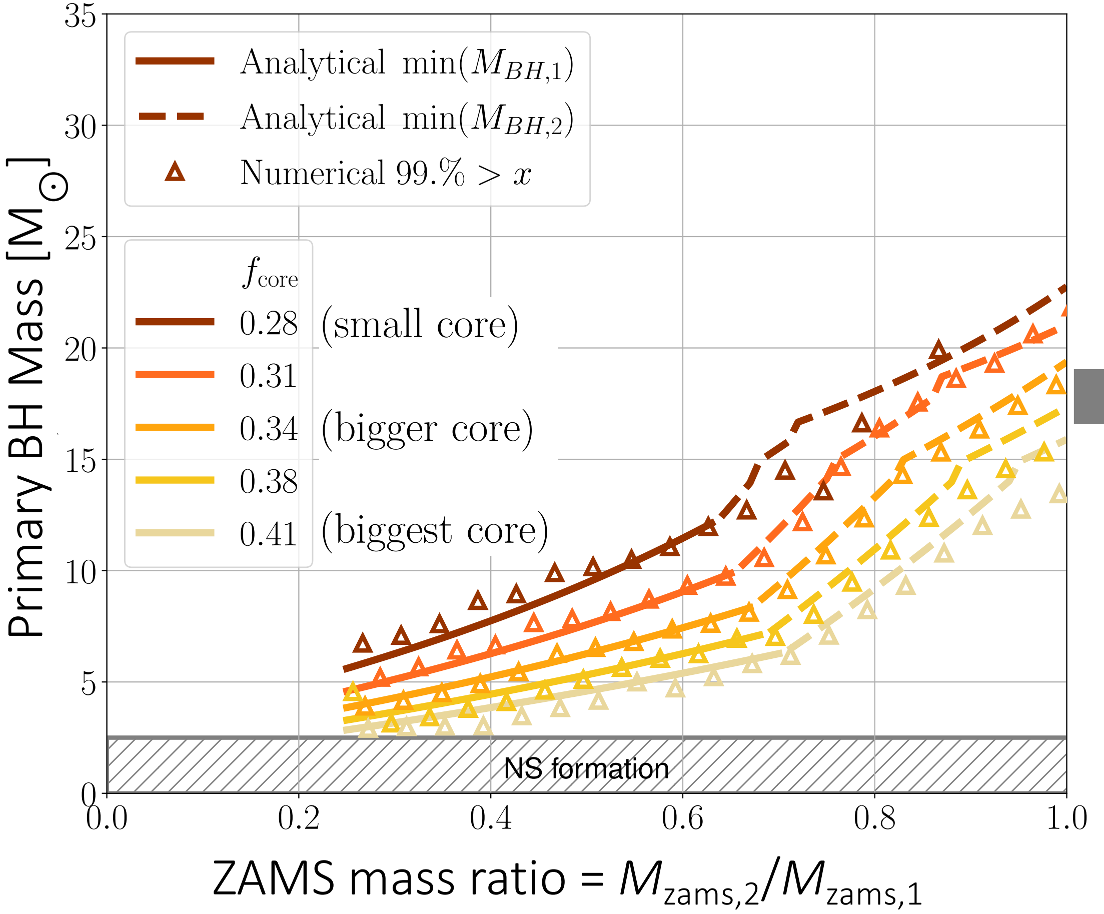
van Son et al. (in prep)

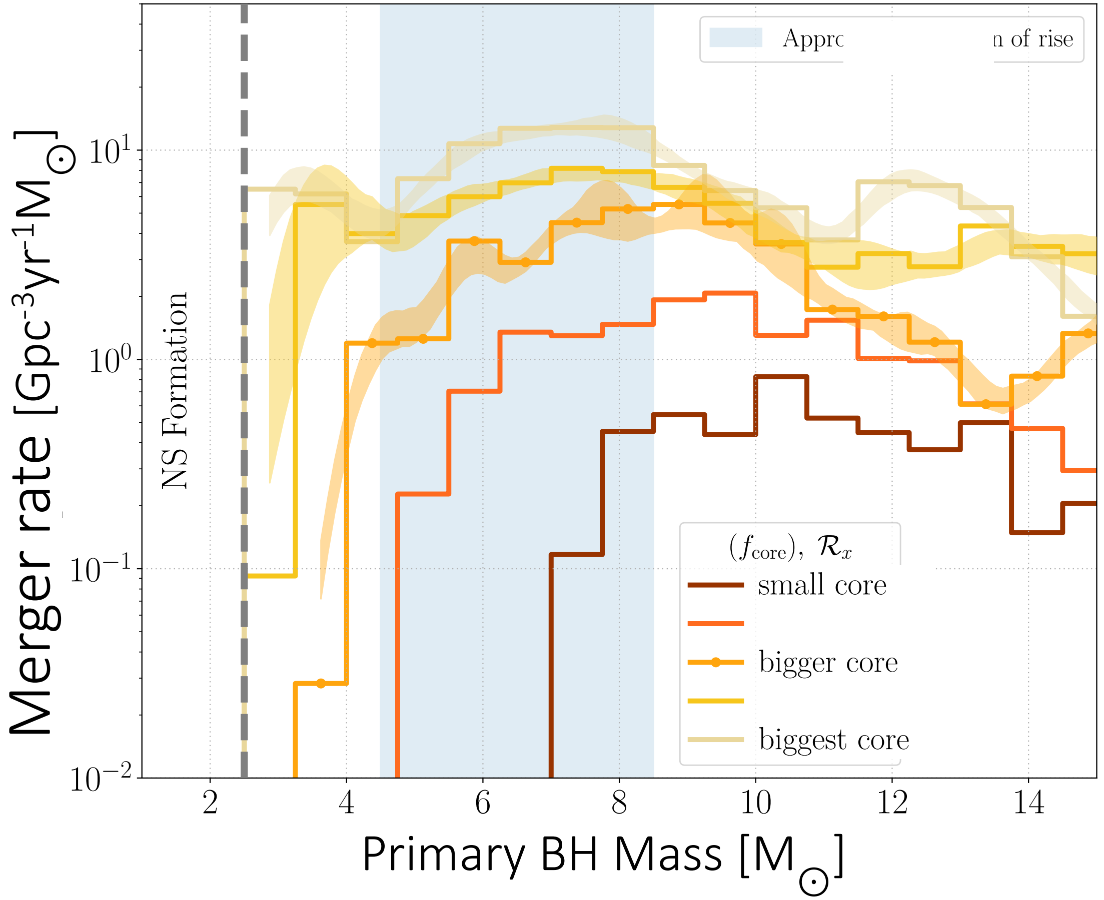


This creates a dearth of low mass BHs without the need for a gap in the remnant mass distribution..!

Variations in core mass fraction

van Son et al. (in prep)





Implications

A GW-observed dearth of BHs below ~6 $M_\odot$
could be caused by:

A) The supernova engine (BHs with 3-6 $M_\odot$ don't *exist*)

Detections of BHs with masses between 3-8$M_\odot$ through e.g. Gaia
(e.g. Janssens et al. 2022)

B) Binary evolution physics (BHs with 3-6 $M_\odot$ don't merge)

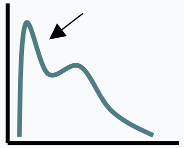
The stable mass transfer channel naturally produces such a death
(van Son et al. in prep)

Discussion:

The stable mass transfer channel is bad at making the lowest mass BHs

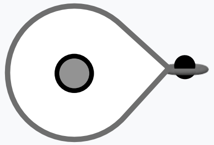
Is the channel you work on bad at something?

Main takeaways



The **low mass end of the BH hole mass distribution** is a great place to start constraining physics/formation channels

No peaks without valleys:
The dearth of BHs between 3-5 $M_\odot$ and the peak at ~9 $M_\odot$ should be jointly investigated



The **stable mass transfer channel** to BBHs imposes a **minimum mass** that could **dismiss the need for a gap** in the remnant mass distribution

Extra slides

recent work that manages to get a peak at 9 $M_\odot$ in the mass distribution adopt a gap.

(e.g. Belczynski et al. 2016a; Giacobbo & Mapelli 2018; Giacobbo et al. 2018; Wiktorowicz et al. 2019; Belczynski et al. 2020.)

More and more claims against a gap:

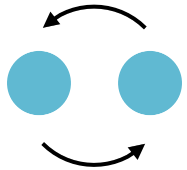
Casares et al. 2017; Wyrzykowski & Mandel 2020
2MASS J0521 (RV): Thompson et al. 2019,
Unicorn & Giraffe: Jayasinghe et al. 2021, 2022
GW190814 (GW): LVK 2020. **OB110462** (microlensing): Sahu+ 2022, Lam + 2022

No peaks without valleys:

The dearth of BHs between 3-5 $M_\odot$ and the peak at ~9 $M_\odot$ should be jointly investigated

The things we hope to do..

Understanding these features can teach us about:



→ Constrain formati

ssive stars

irect distance measurement (‘dark sirens’)

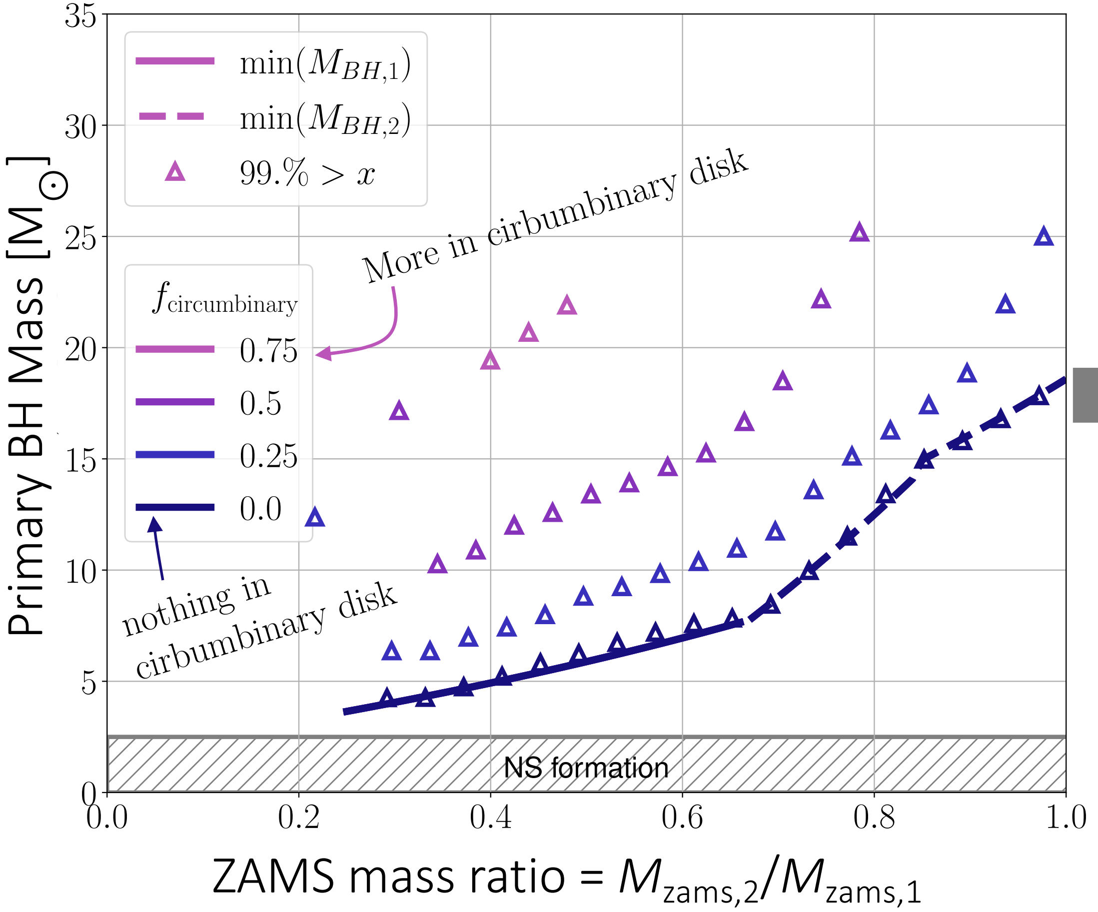
We need unique and falsifiable predictions!!

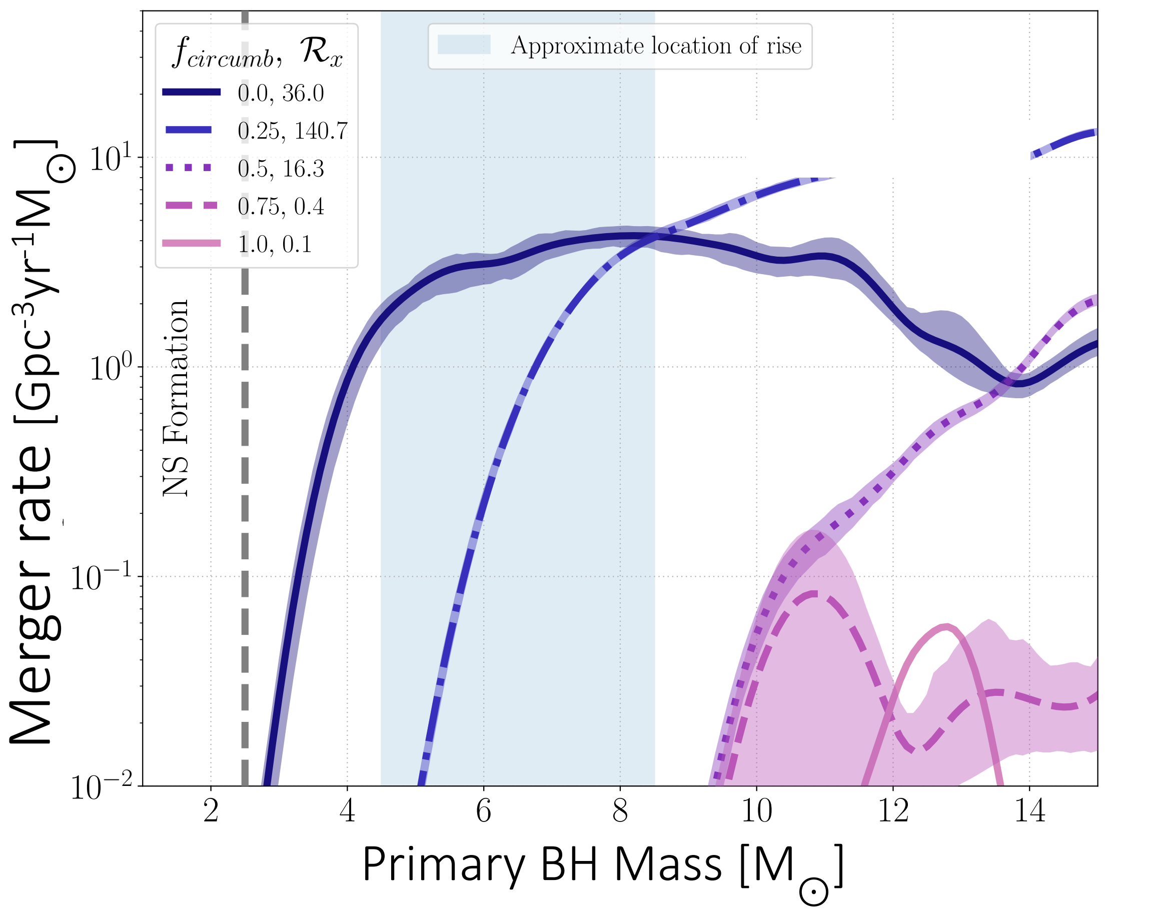
Formation channels: e.g. ; Wong et al. ‘21, Zevin et al. ‘21, Mapelli et al. ‘22
Progenitor physics: e.g. Farmer et al. ‘19;’20, **van Son et al. 2020,** Bavera et al. ‘21,
Cosmology: e.g. Holz & Hughes ‘05, Chen et al. ‘18, Ye & fishbach’21, Abbott et al. 21, María Ezquiaga & Holz '22, Mukherjee et al. ‘22
SF: e.g., Vitale et al. '19, Ken et al. '21, **van Son et al. 2021.**

This creates a low mass dearth without the need for a gap in the remnant mass distribution..!

Variations in mass angular momentum loss

van Son et al. (in prep)

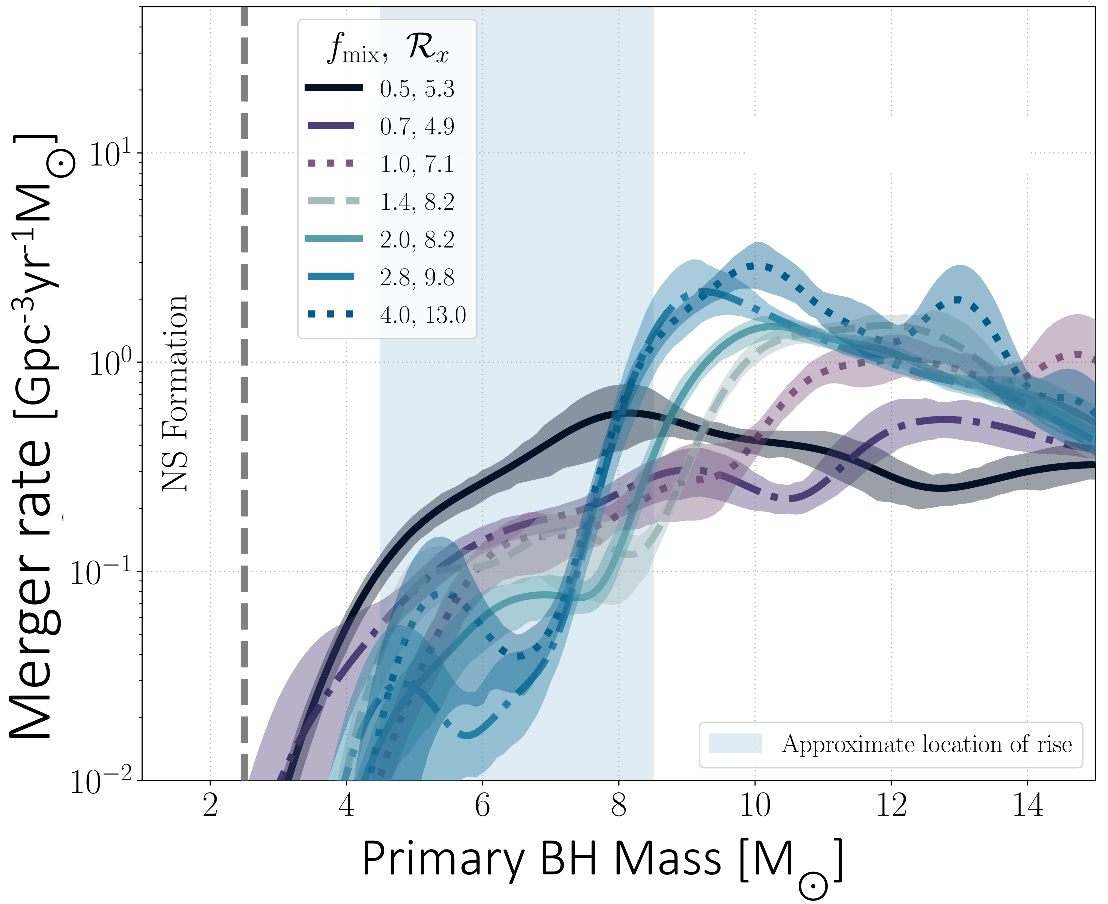




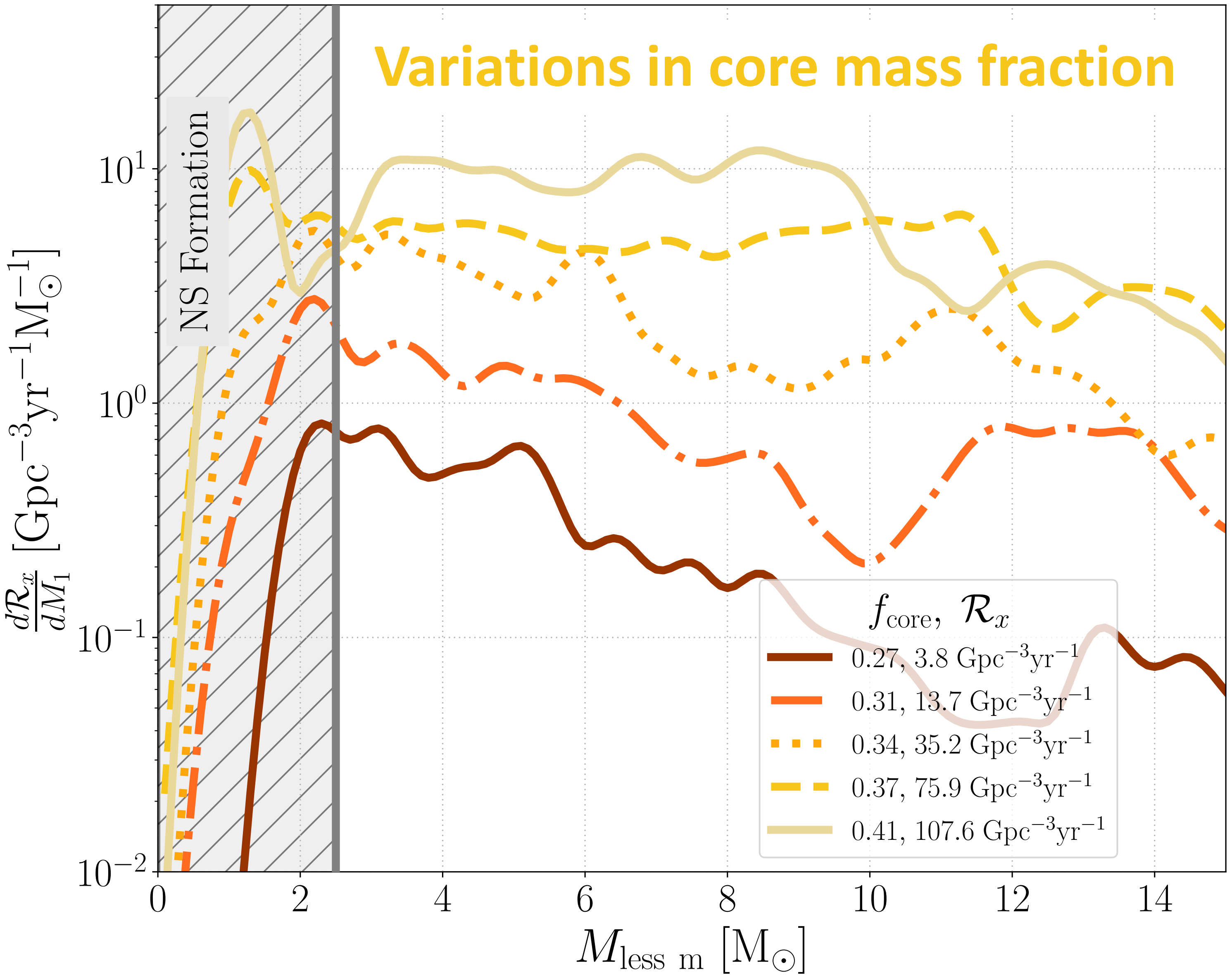
This creates a low mass dearth without the need for a gap in the remnant mass distribution..!

Variations in the supernova remnant mass function

van Son et al. (in prep)

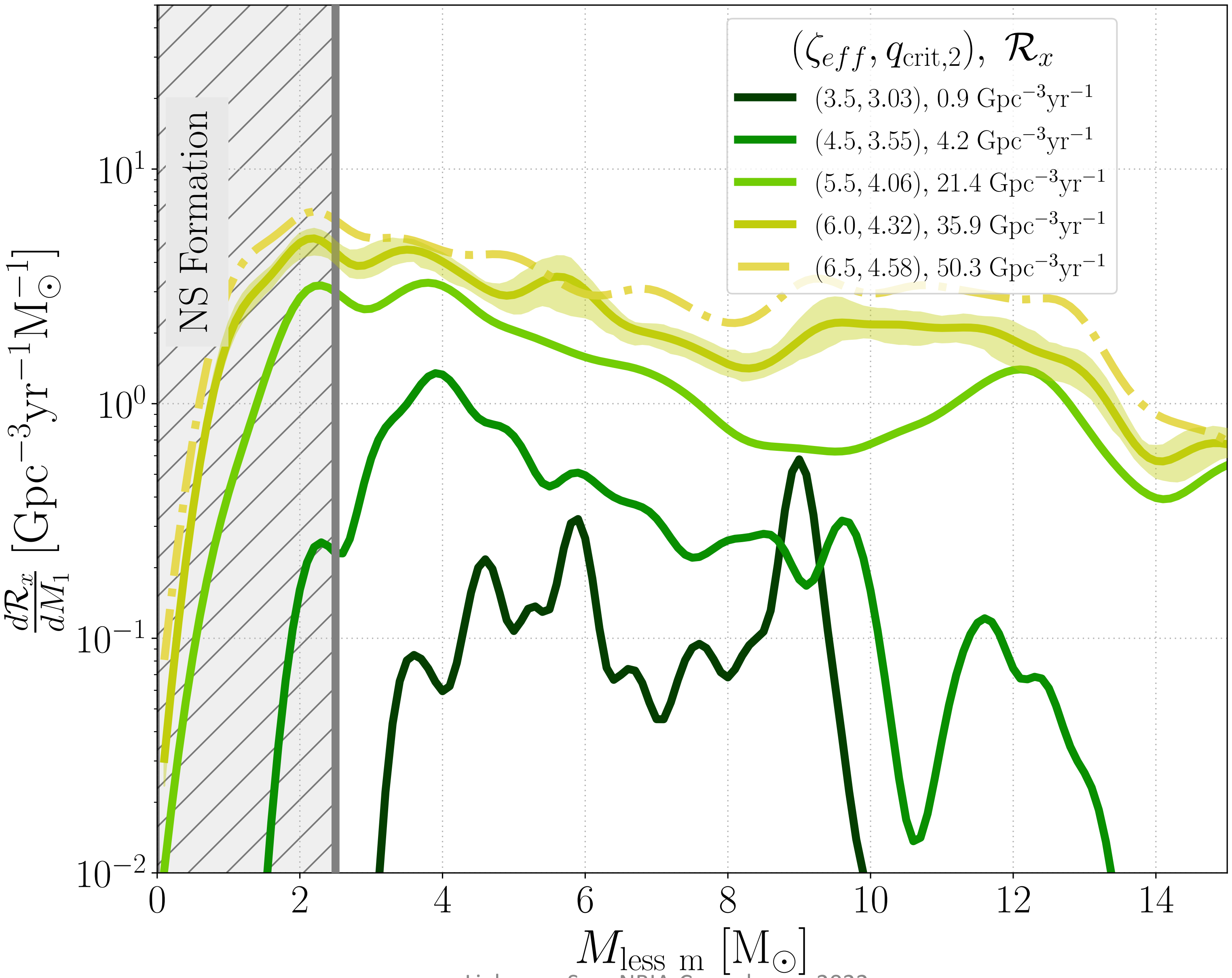


Less massive component dist



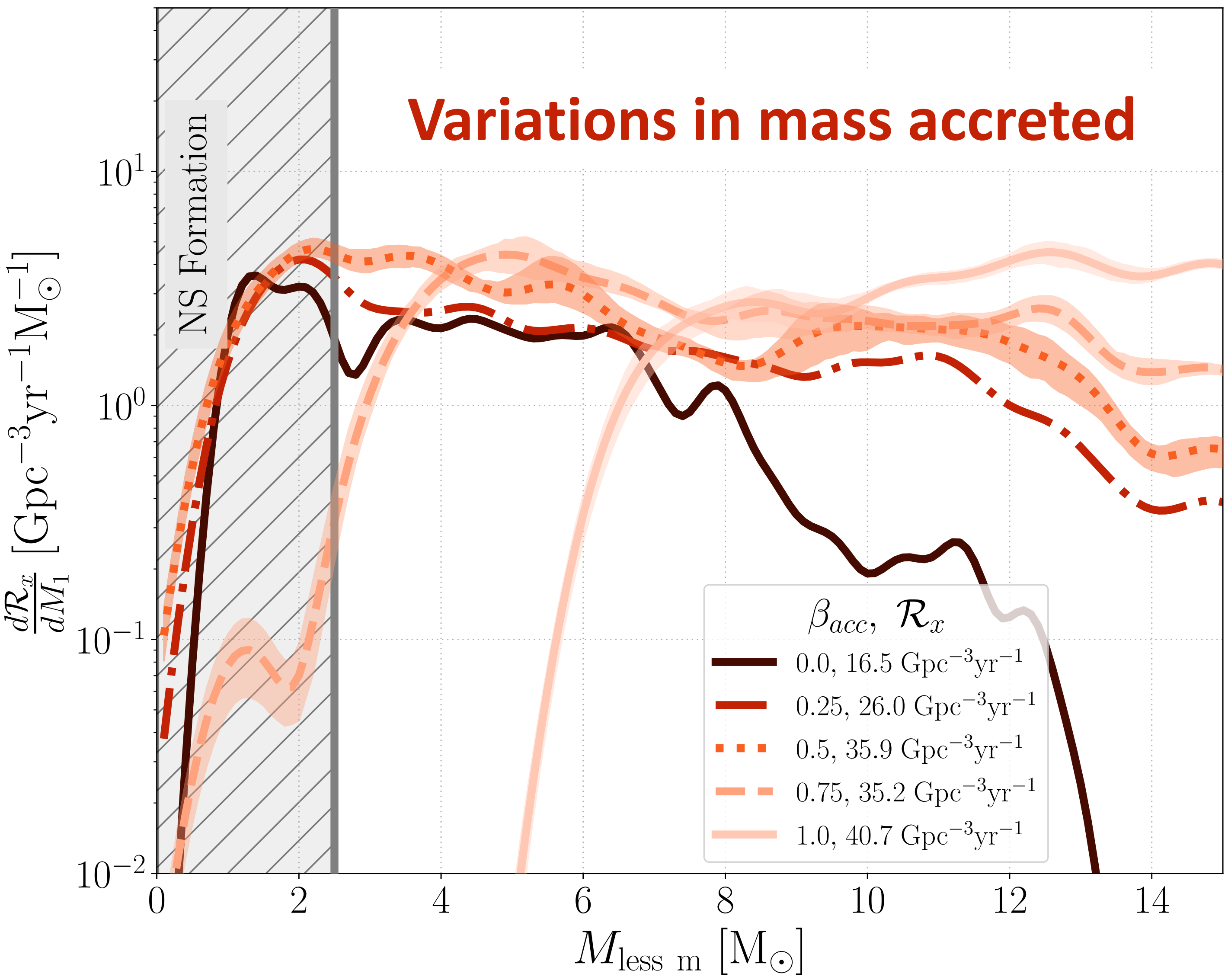
Less massive component dist

Variations in mass transfer stability

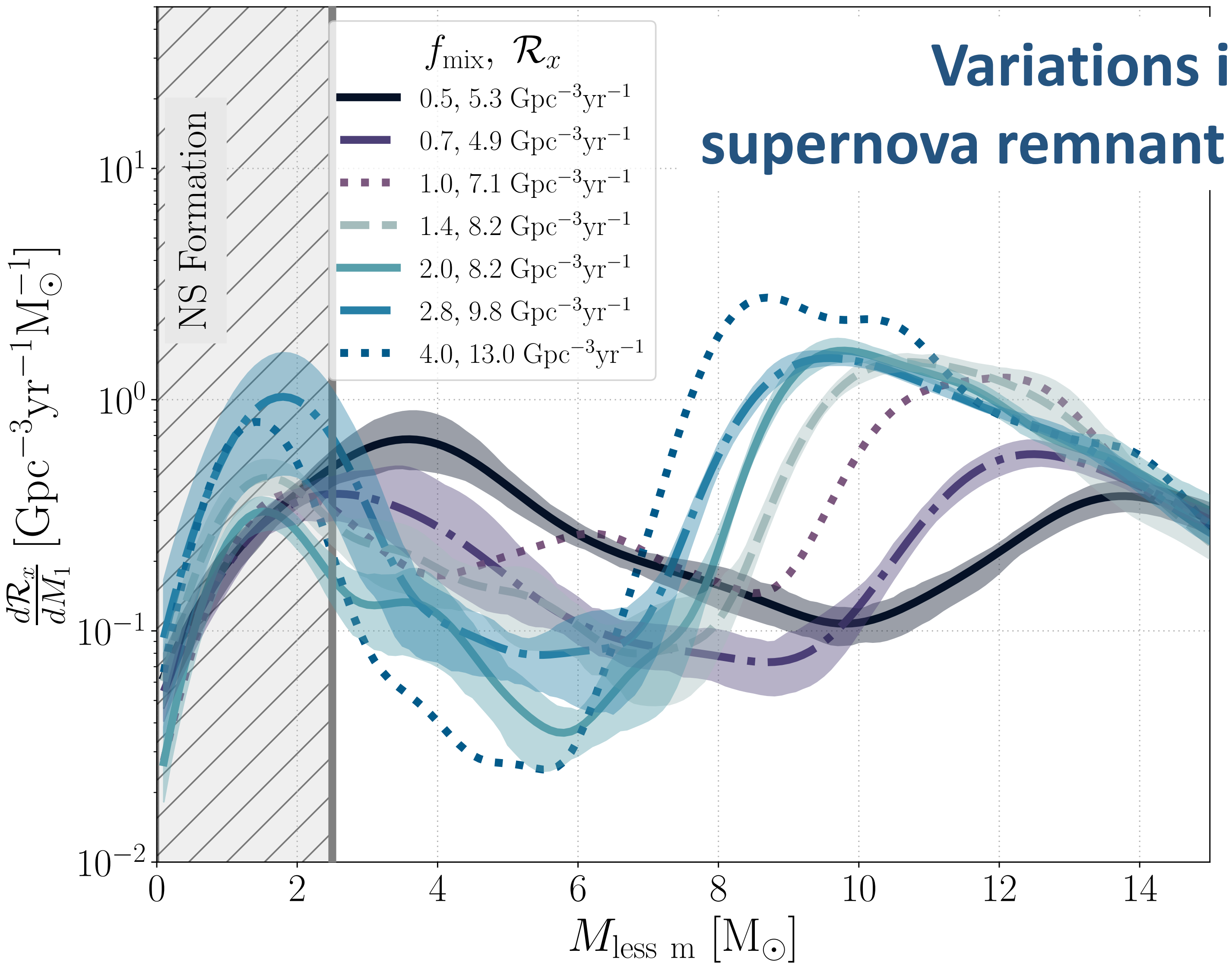


Lieke van Son, NBIA-Copenhagen 2022

Less massive component dist



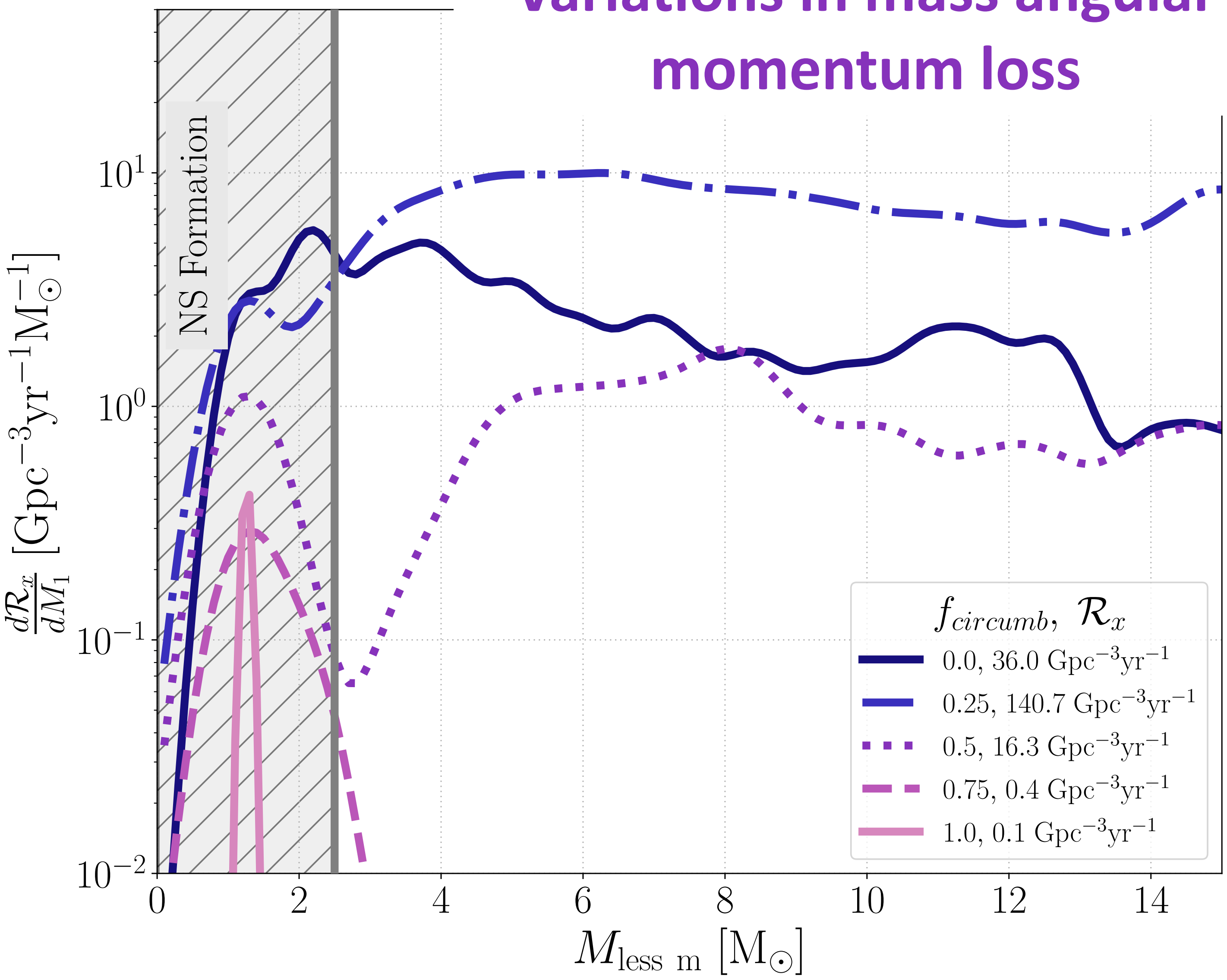
Less massive component dist



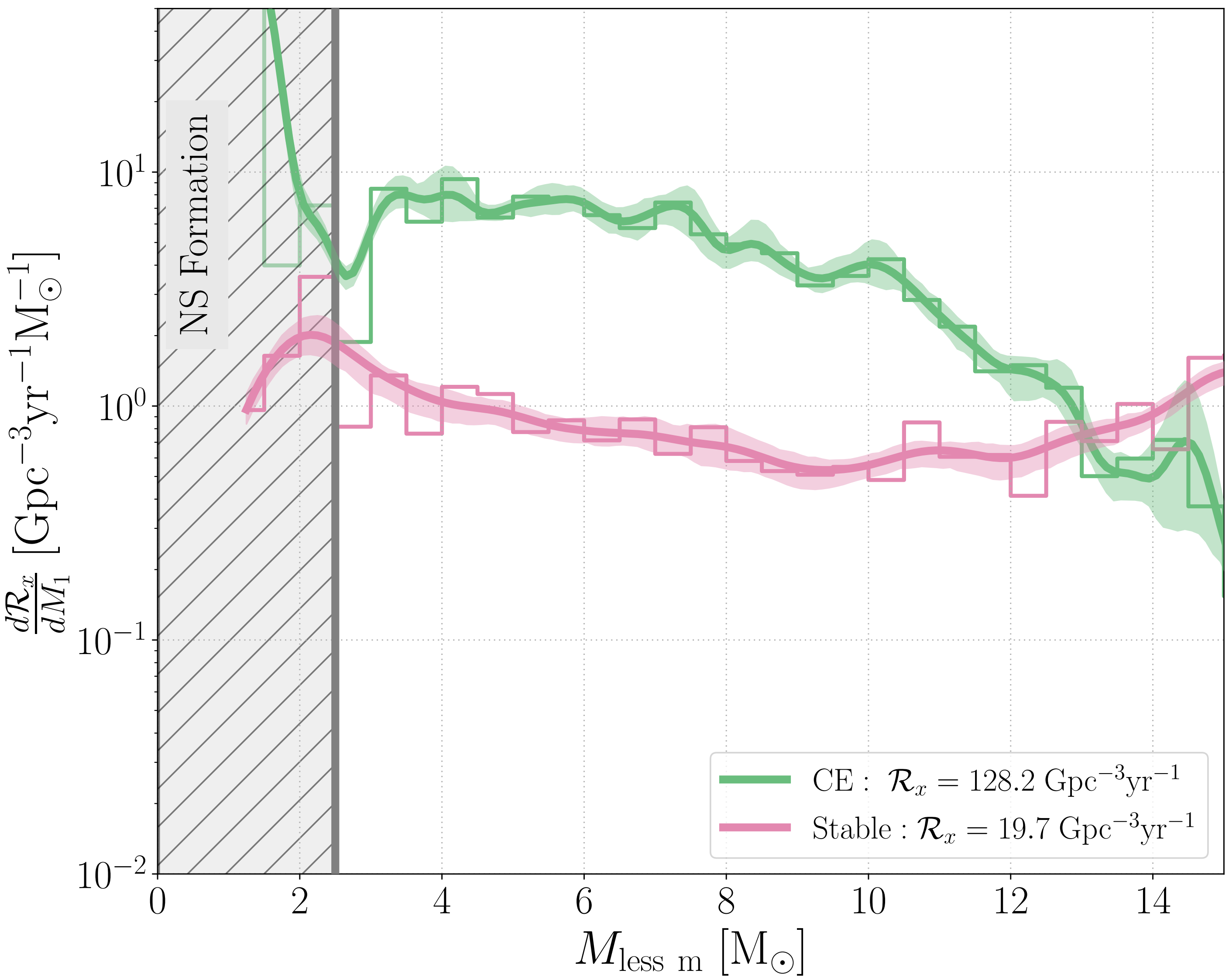
Variations in the supernova remnant mass function

Less massive component dist

Variations in mass angular momentum loss



Less massive component dist



Evidence against a gap appears to be accumulating:

Surveys

(OGLE-III): Wyrzykowski & Mandel 2020,
(NGC 3201): Giesers et al. 2019;

BH with gap masses

- 2MASS J0521 (RV): Thompson et al. 2019,
- Unicorn & Giraffe: Jayasinghe et al. 2021, 2022
- HD96670 Gomez & Grindlay 2021;
- (HR 6819): Rivinius et al. 2020
- GW190814 (GW): LVK 2020.
- GW190917 (GW): LVK 2020.
- OB110462 (microlensing): Sahu+ 2022, Lam + 2022

… yet recent work that manages to get a peak in the mass distribution all adopt a gap.

(e.g. Belczynski et al. 2016a; Giacobbo & Mapelli 2018; Giacobbo et al. 2018; Wiktorowicz et al. 2019; Belczynski et al. 2020.)

Please let me know if you know of an exception!

Evolutionary models: Pols 1998 Hurley+2000	Metallicity flat in log distributed $0.0001 < Z < 0.03$	accretion rate <10 tKH accretor (Hurley 2000)
Kroupa IMF (Kroupa 2002)	SN prescription Fryer delayed (Fryer+2012)	Isotropic reemission of lost mass (Soberman et al. 1997)
flat distribution of mass ratios (Kouwenhoven+2005)	Remnant masses (Fryer+20120 and Farmer+ 2019)	CE $\alpha\,\lambda$ prescription (Webbink 1984, de Kool 1990; Xu & Li 2010a,b)
Öpik distribution of initial separations (i.e. flat in log, Opik 1924)	Stellar winds: Vink et al (2001), Nieuwenhuijzen & de Jager (1990) Kudritzki & Reimers (1978), Vassiliadis & Woods Hamann & Koesterke (1998) + Vink & de Koter 2005,	Adaptive importance sampling (Broekgaarden et al. 2019) LBV 'erruptions': Hurley et al. (2000)

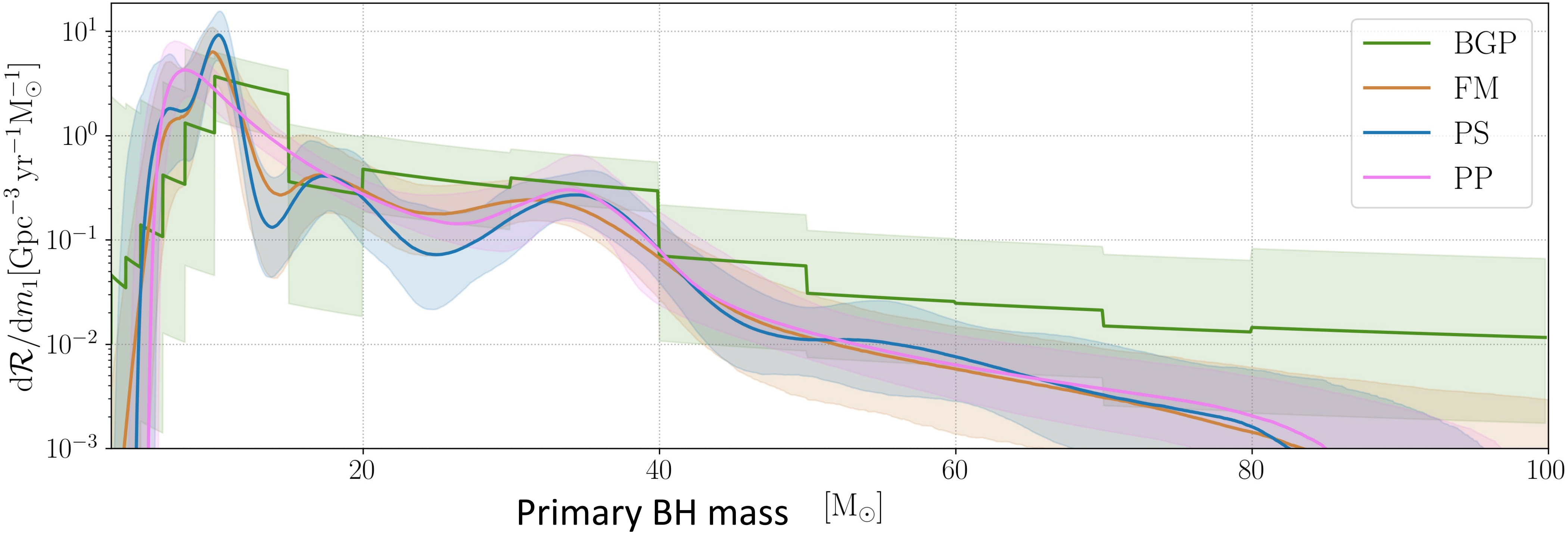
Team COMPAS, Riley et al. (2021); Stevenson et al. 2017; Vigna-Gomez et al. 2018; Neijssel et al. (2019); Broekgaarden et al. (2019)

https://compas.science/

Implications/discussion points

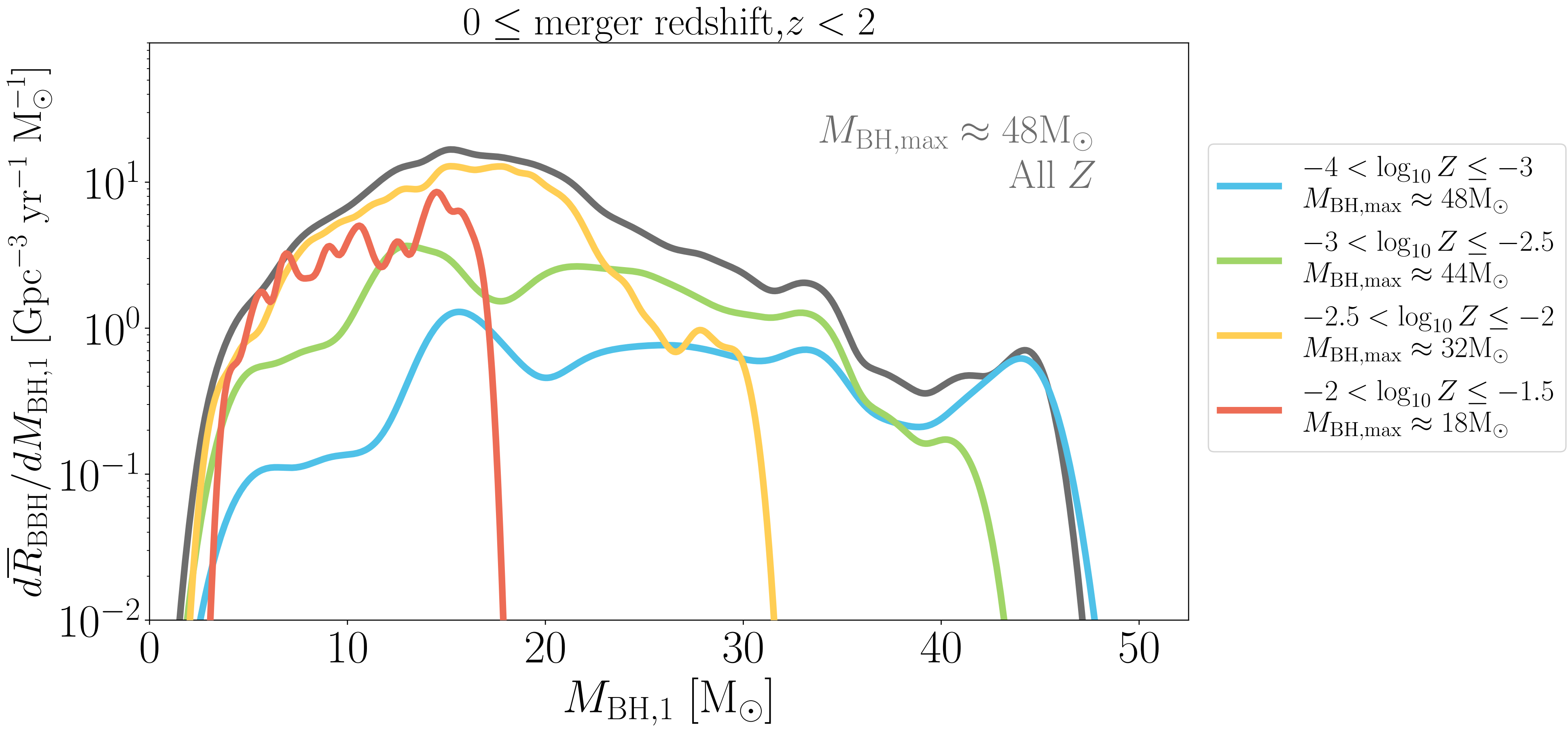
- The stable channel is bad at:
  - making low mass BHs ⟷ Could look like a NS-BH gap!
  - making NSNS and WDWD
- What about X-Ray Binaries?
  Different XRB represent different evolutionary states!
  - In principle this mechanism should apply to post MT XRB (SS433)
  - 'missing WR X-ray binaries' (van Beveren et al. 1982; Lommen et al. 2005; van den Heuvel et al. 2017)

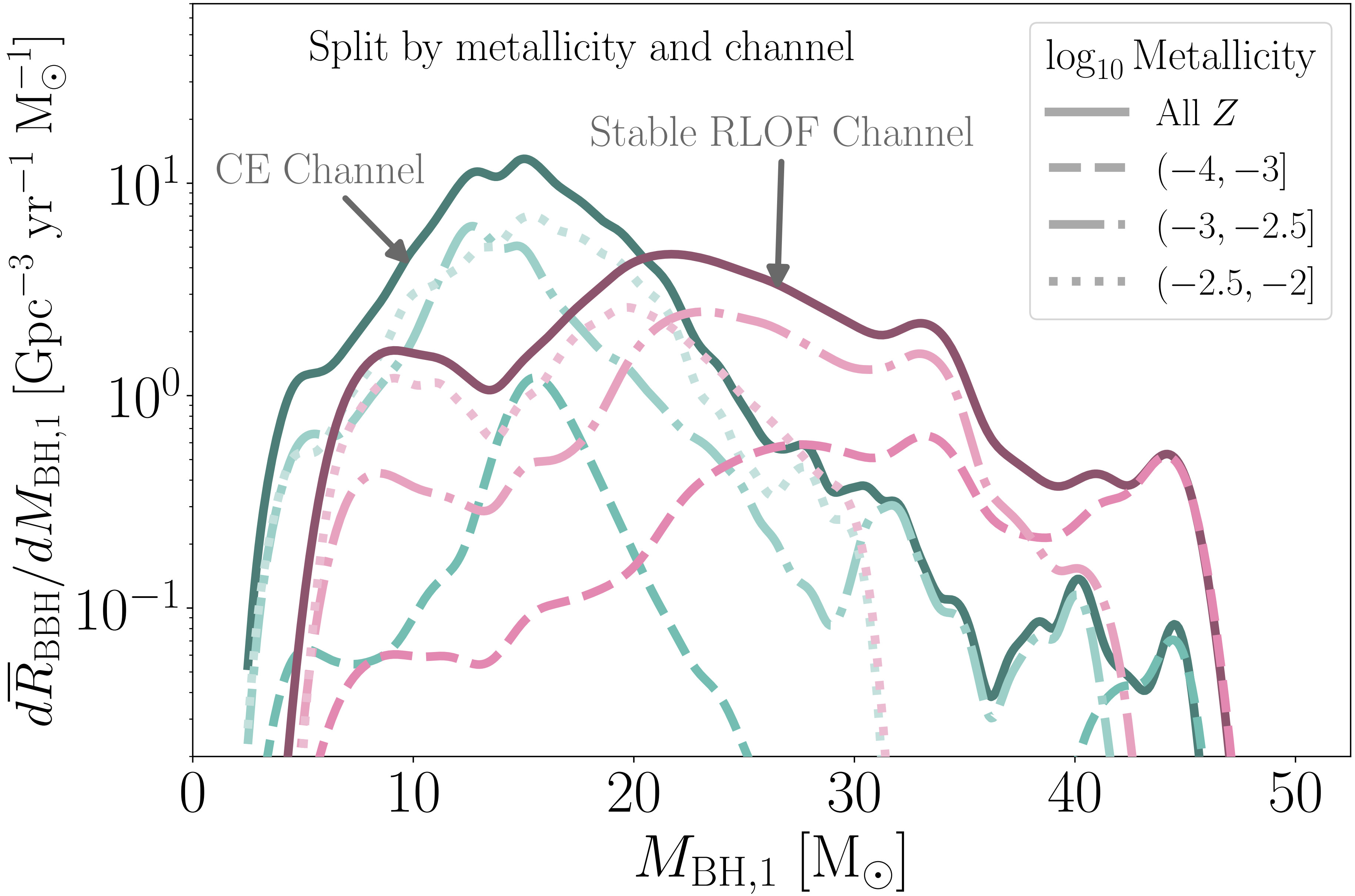
BBH mass distribution



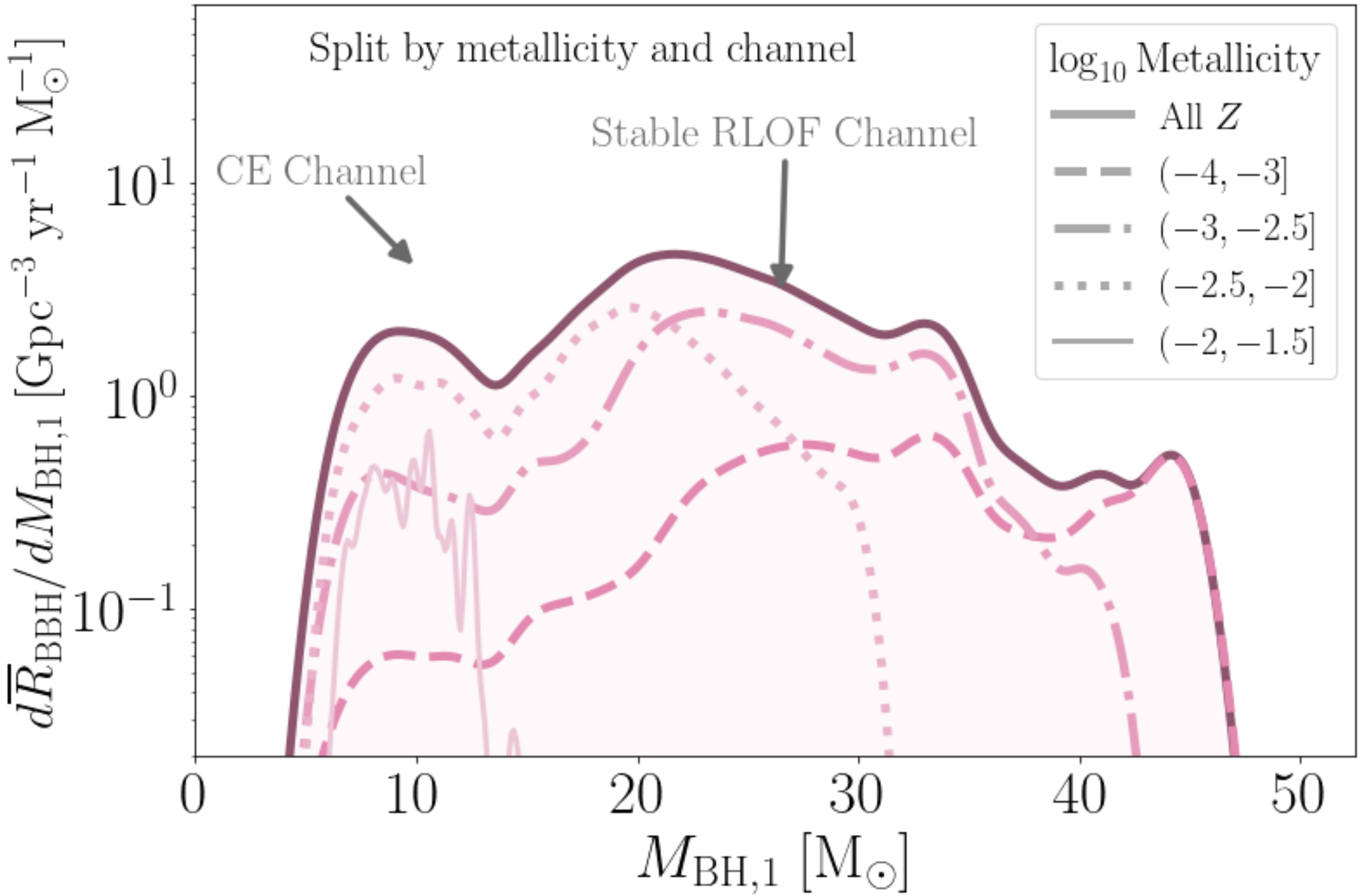
The LVK collaboration, Abott et al. (2021)

Metallicity contribution

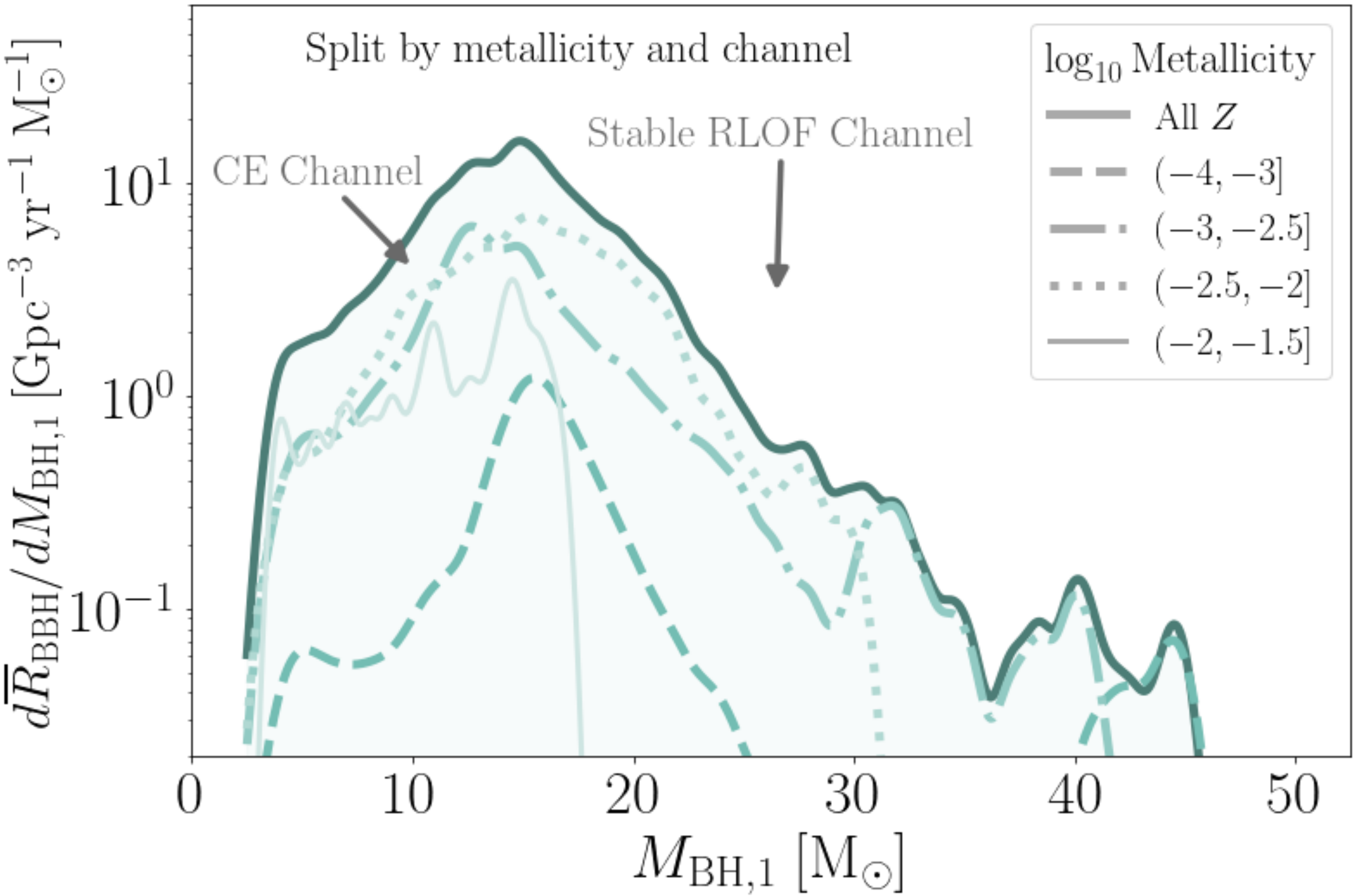




Lieke van Son, NBIA-Copenhagen 2022



Split by metallicity and channel
CE Channel
Stable RLOF Channel
$\log_{10}$ Metallicity
All Z
$(-4, -3]$
$(-3, -2.5]$
$(-2.5, -2]$
$(-2, -1.5]$
10^1
10^0
10^{-1}
$d\overline{R}_{\mathrm{BBH}}/dM_{\mathrm{BH,1}}$ [$\mathrm{Gpc^{-3}\ yr^{-1}\ M_\odot^{-1}}$]
0
10
20
30
40
50
$M_{\mathrm{BH,1}}$ [$\mathrm{M_\odot}$]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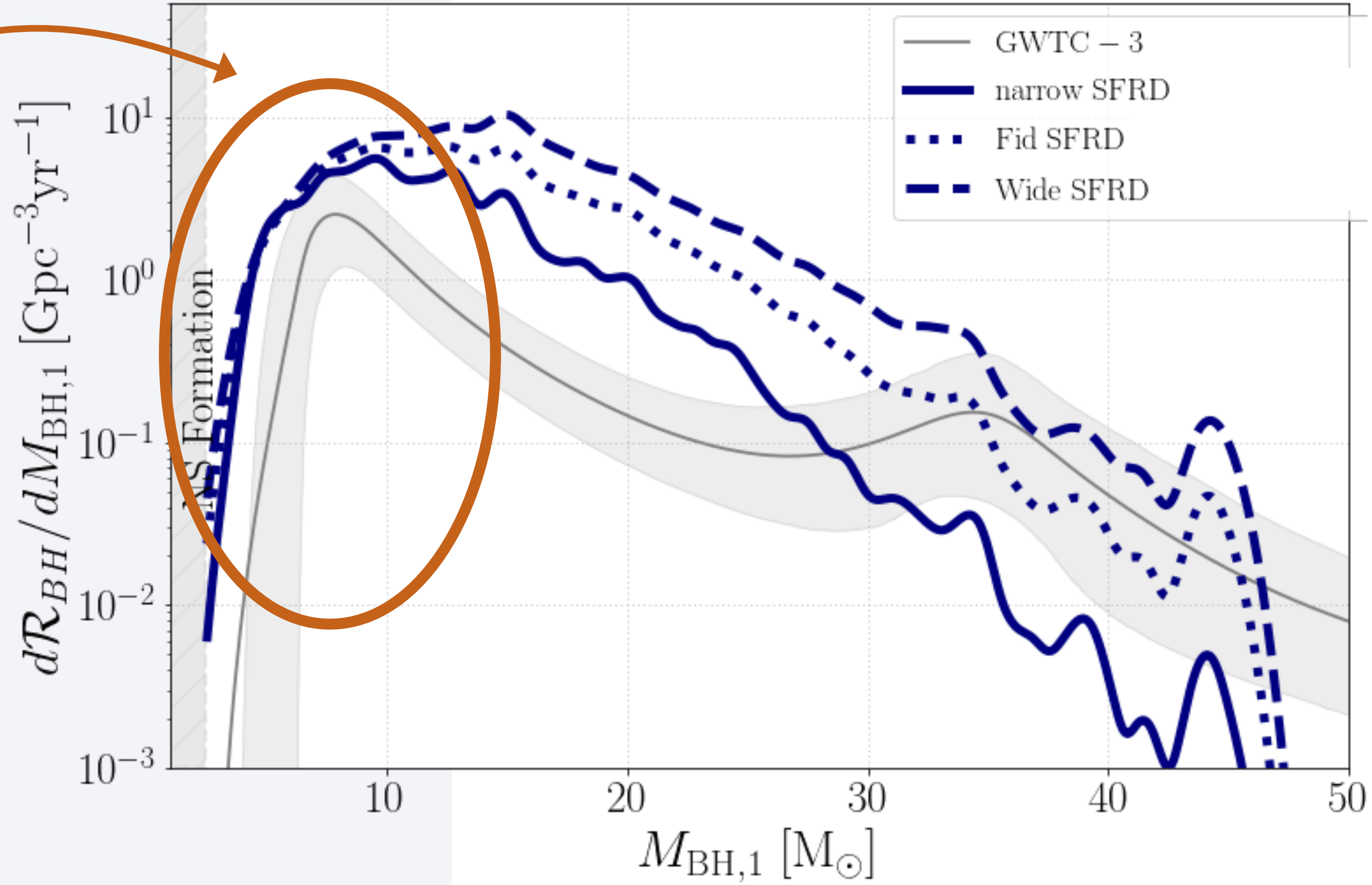
10^1
10^0
10^{-1}
0
10
20
30
40
50
$M_{\rm BH,1}$ [M$_\odot$]

The low mass end is a great place to start

less bothered by metallicity dependent star formation uncertanty

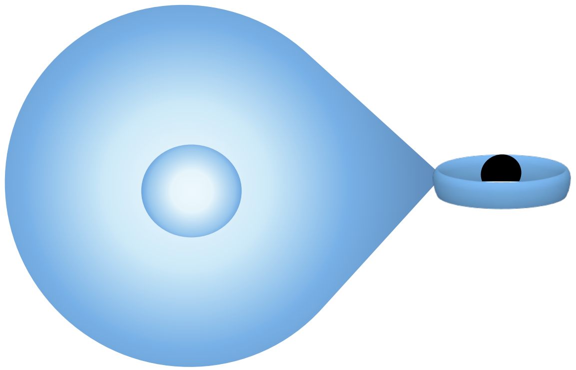


van Son et al. (in prep)

What about accretion onto the black hole?

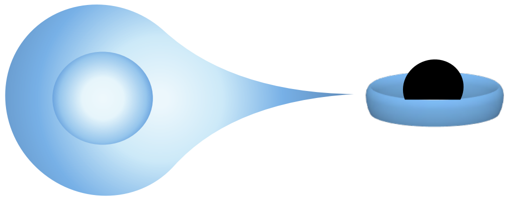
(fully conservative)

$M_{donor} > M_{accretor}$



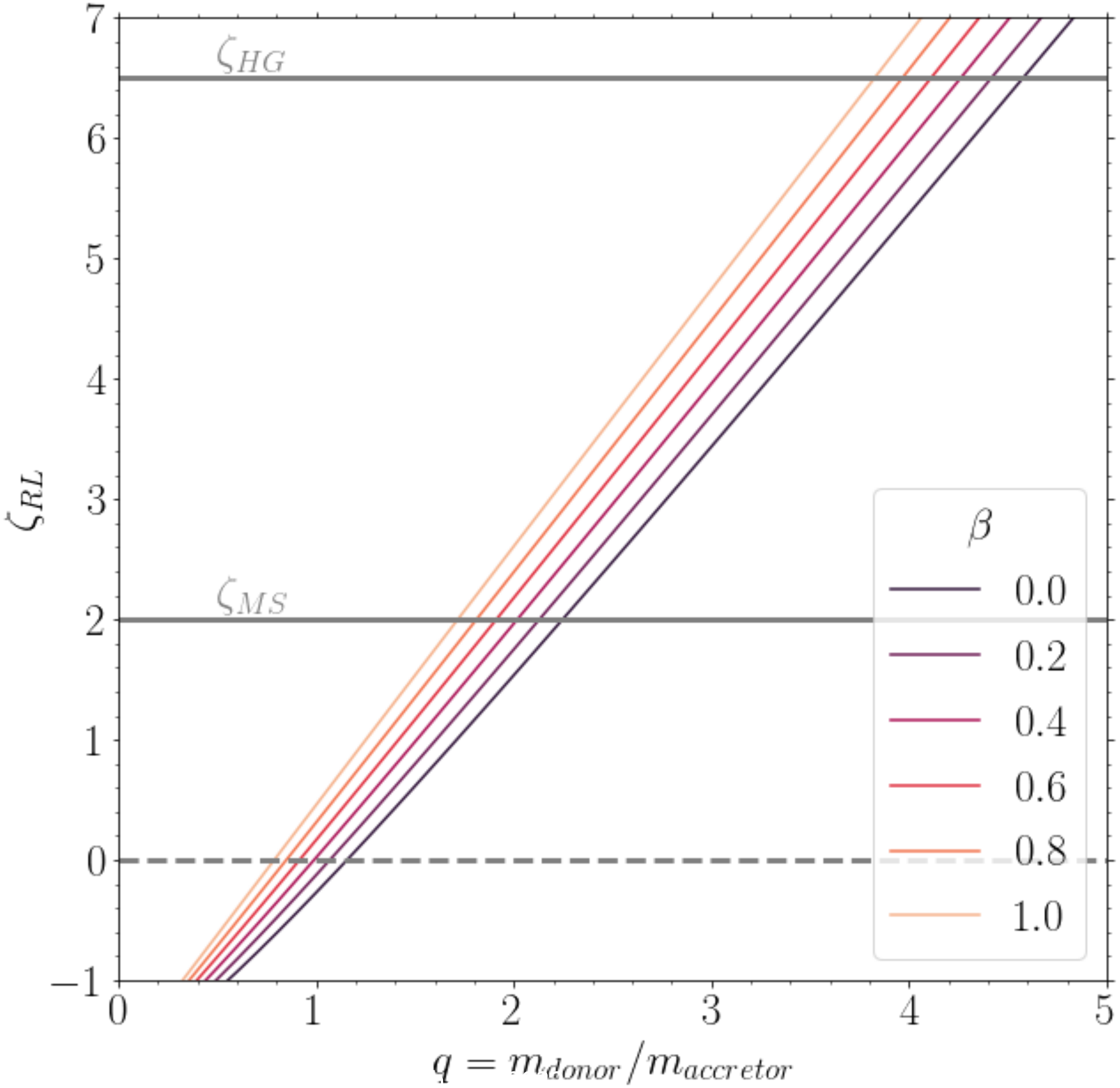
Orbit shrinks

$M_{donor} < M_{accrretor}$



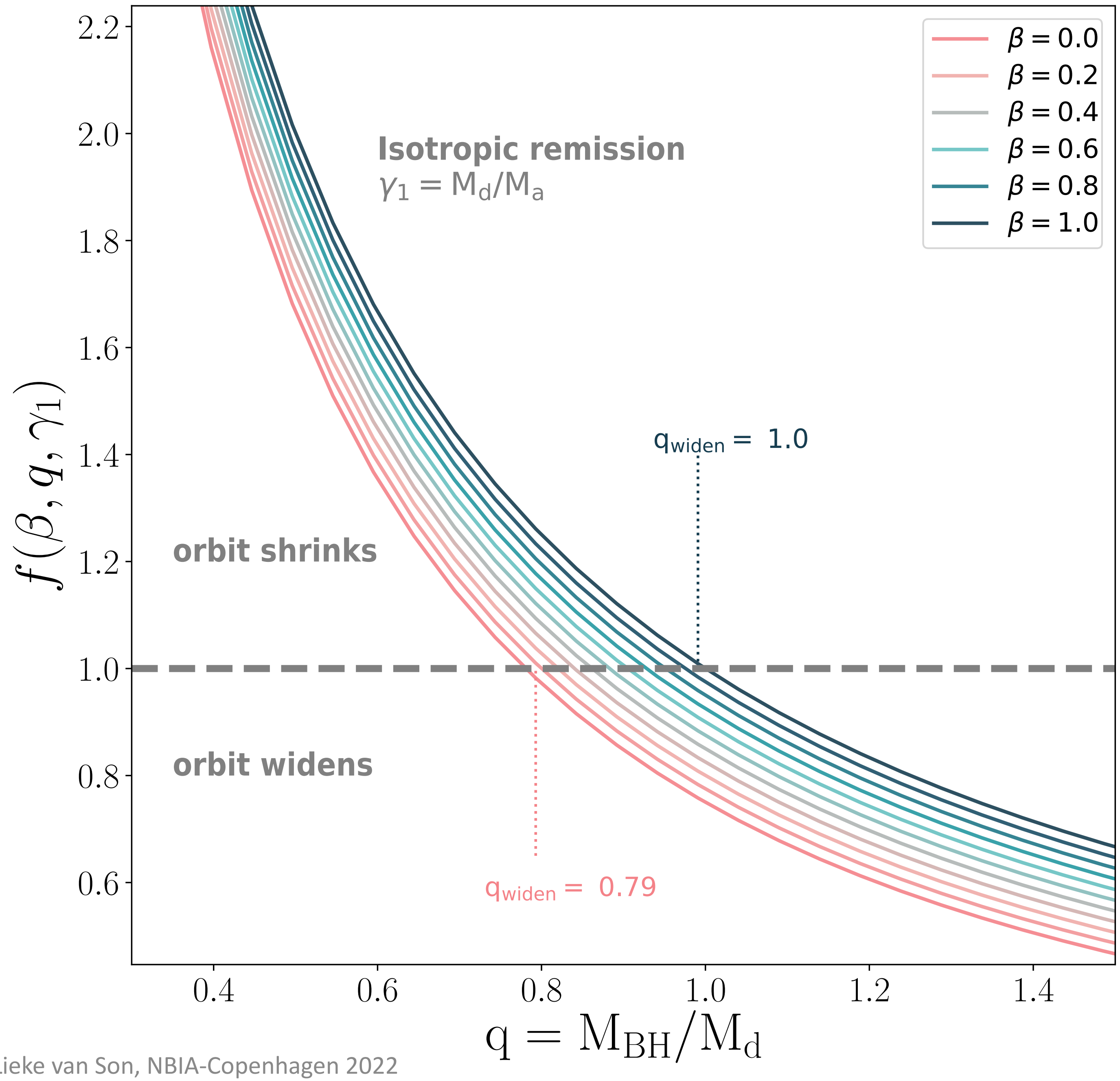
Orbit widens

Mass transfer stabillity



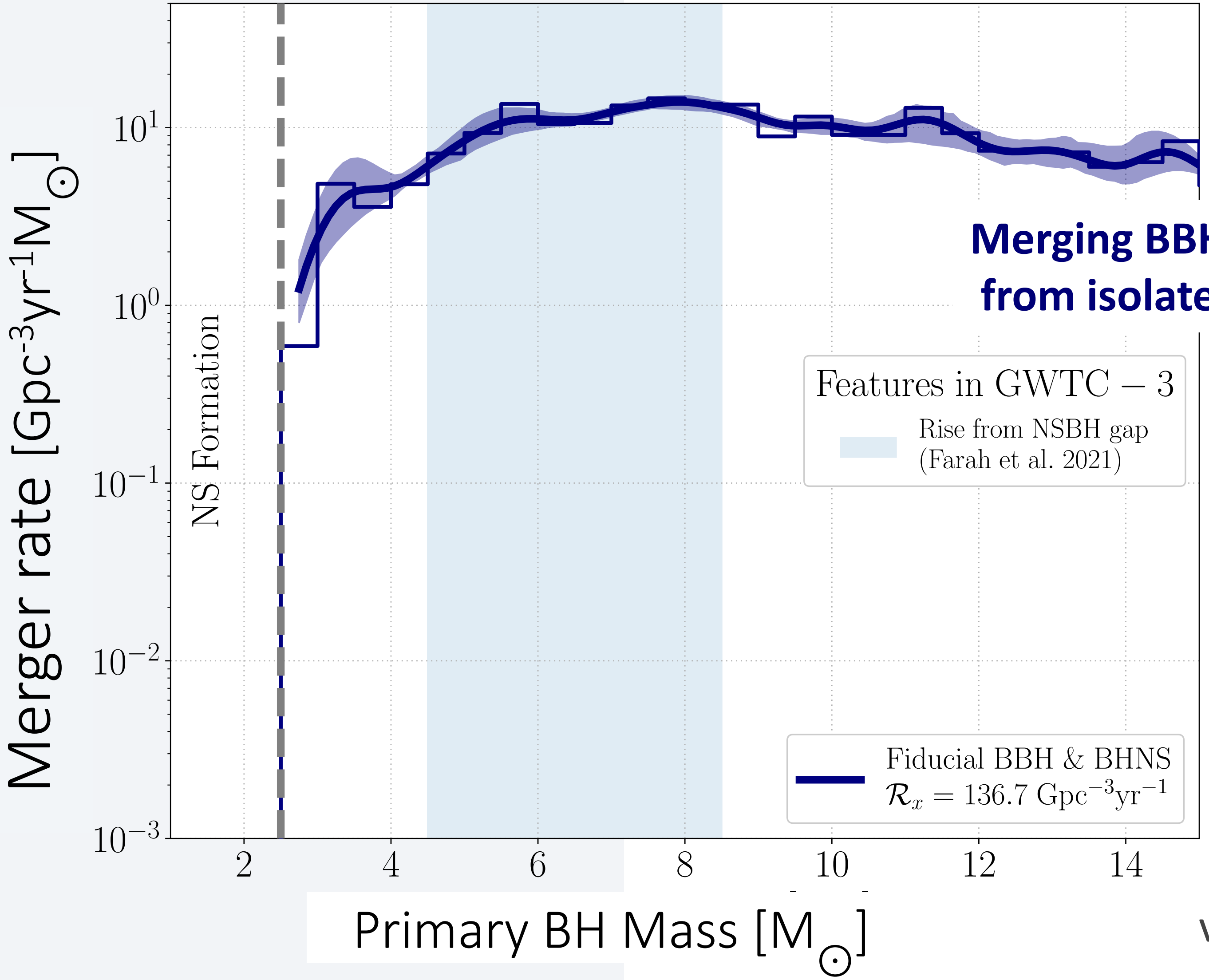
$$\frac{\dot{a}}{a} = -2\frac{\dot{M}_{\rm d}}{M_{\rm d}}\left[1 - \beta\frac{M_{\rm d}}{M_{\rm a}} - (1-\beta)(\gamma + \tfrac{1}{2})\frac{M_{\rm d}}{M_{\rm d} + M_{\rm a}}\right]$$

Considering total angular momentum



B)

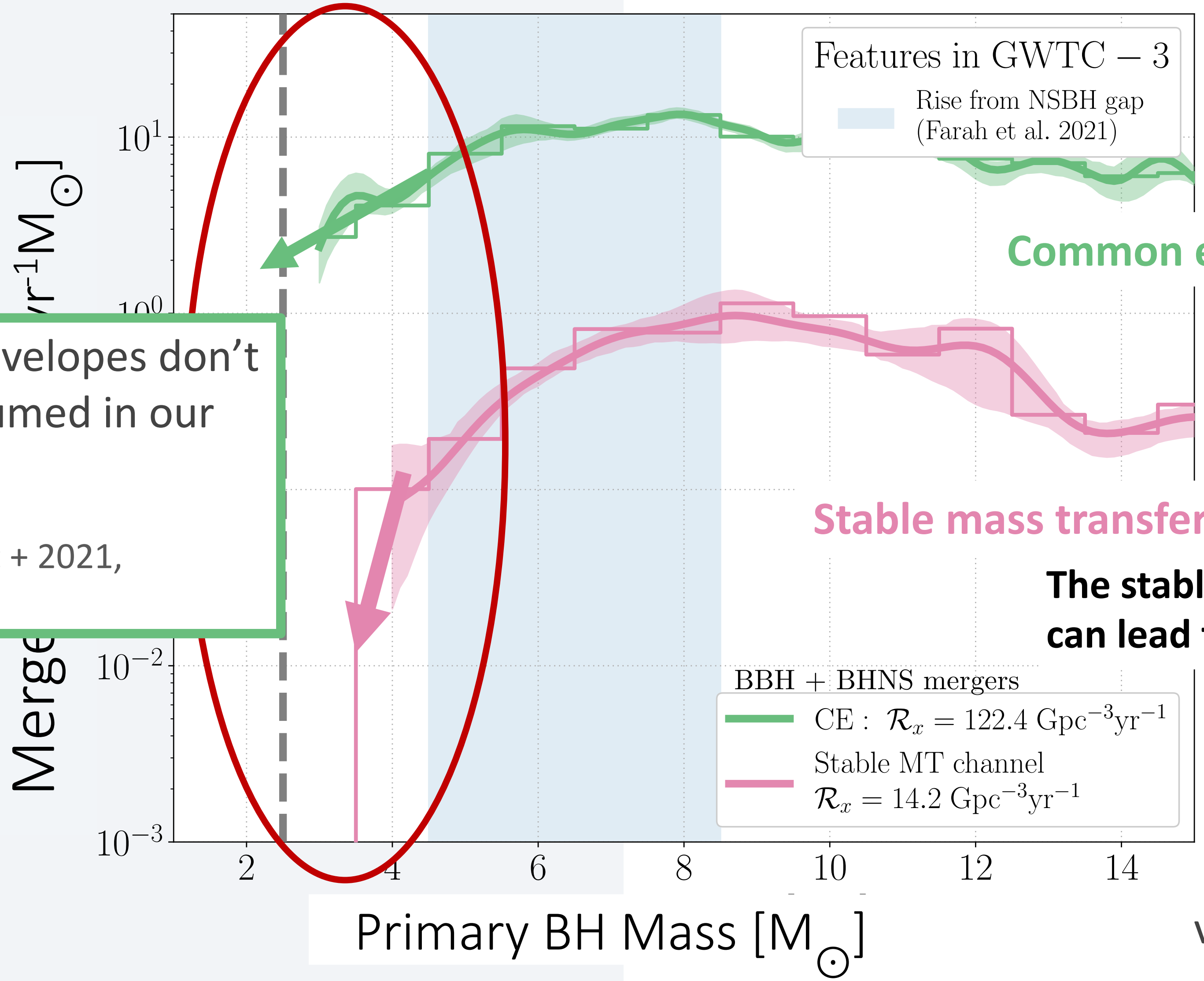
What do we expect from isolated binaries?



Calculated using

van Son et al. (in prep)

B) Let's split isolated binaries into sub-channels



What if common envelopes don't work as well as assumed in our simulations?

Klencki+ 2020, Marchant + 2021, Gallegos-Garcia+ 2021,

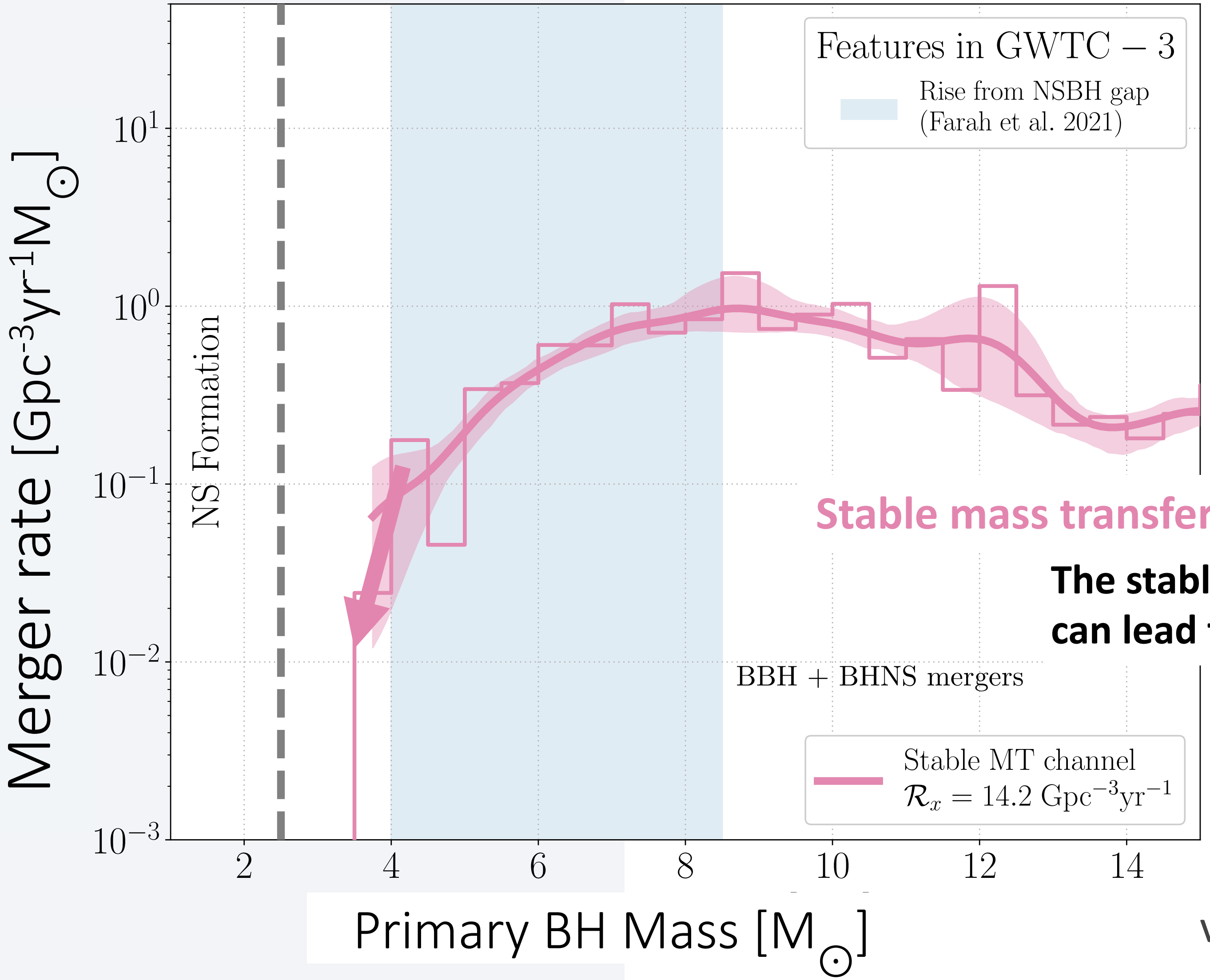
The stable mass transfer channel can lead to a low mass "gap"!

Calculated using COMPAS

van Son et al. (in prep)

B)

What does the stable channel predict? BBH + BHNS



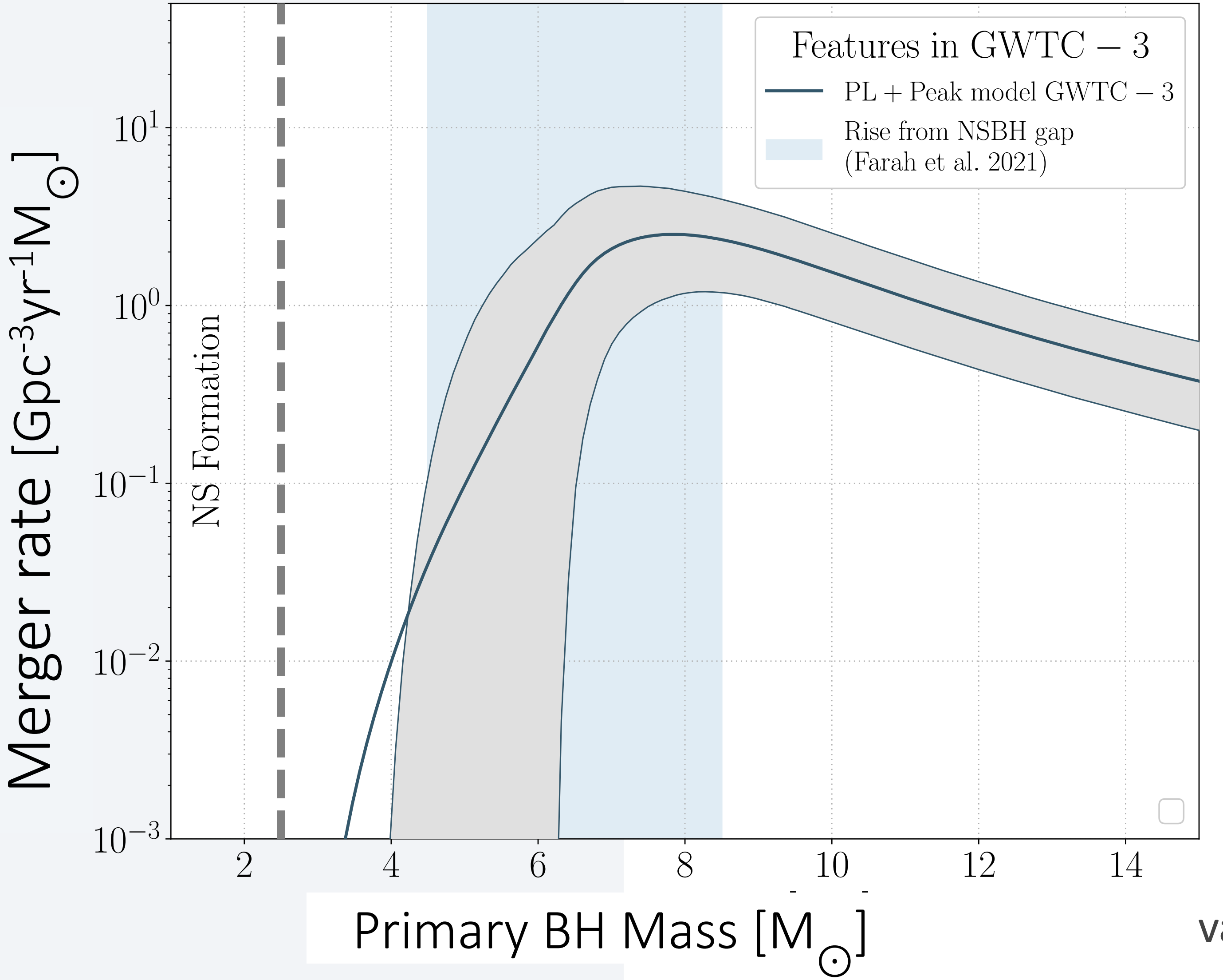
Stable mass transfer channel

The stable mass transfer channel can lead to a low mass "gap"!

Calculated using

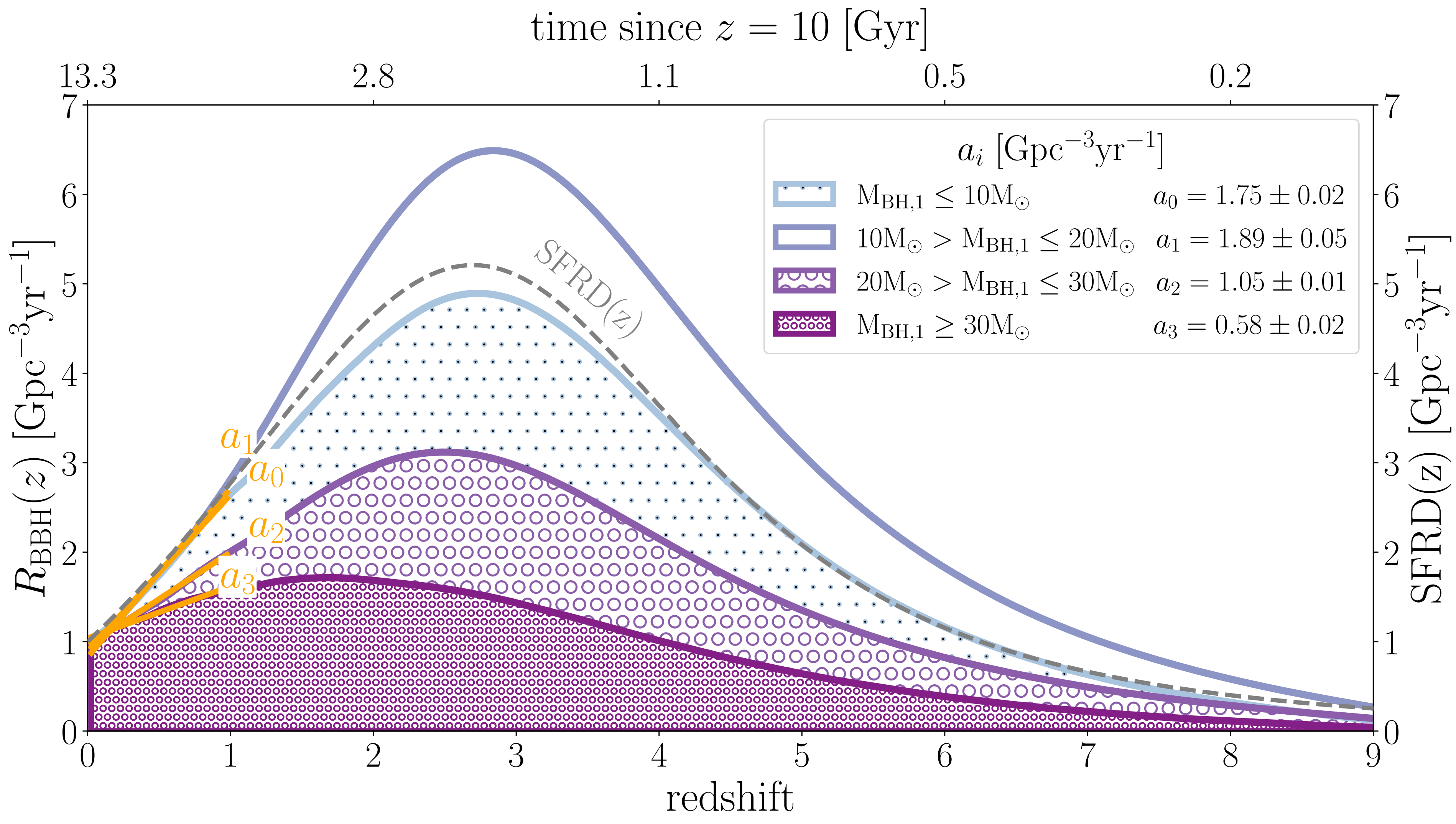
van Son et al. (in prep)

B) The peak at 8 $M_\odot$ and a dearth between 3-5 $M_\odot$ are two sides of the same coin

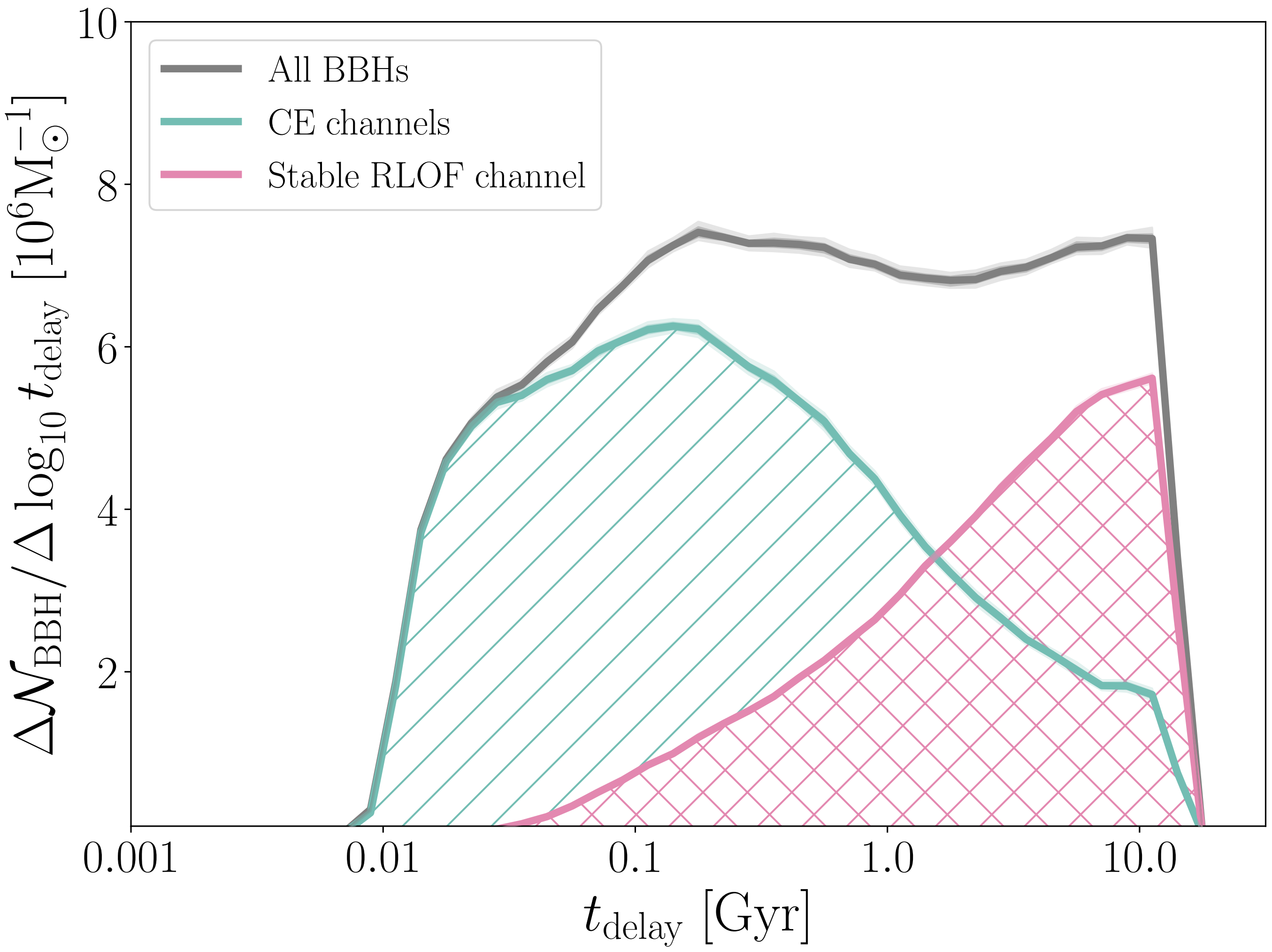


van Son et al. (in prep)

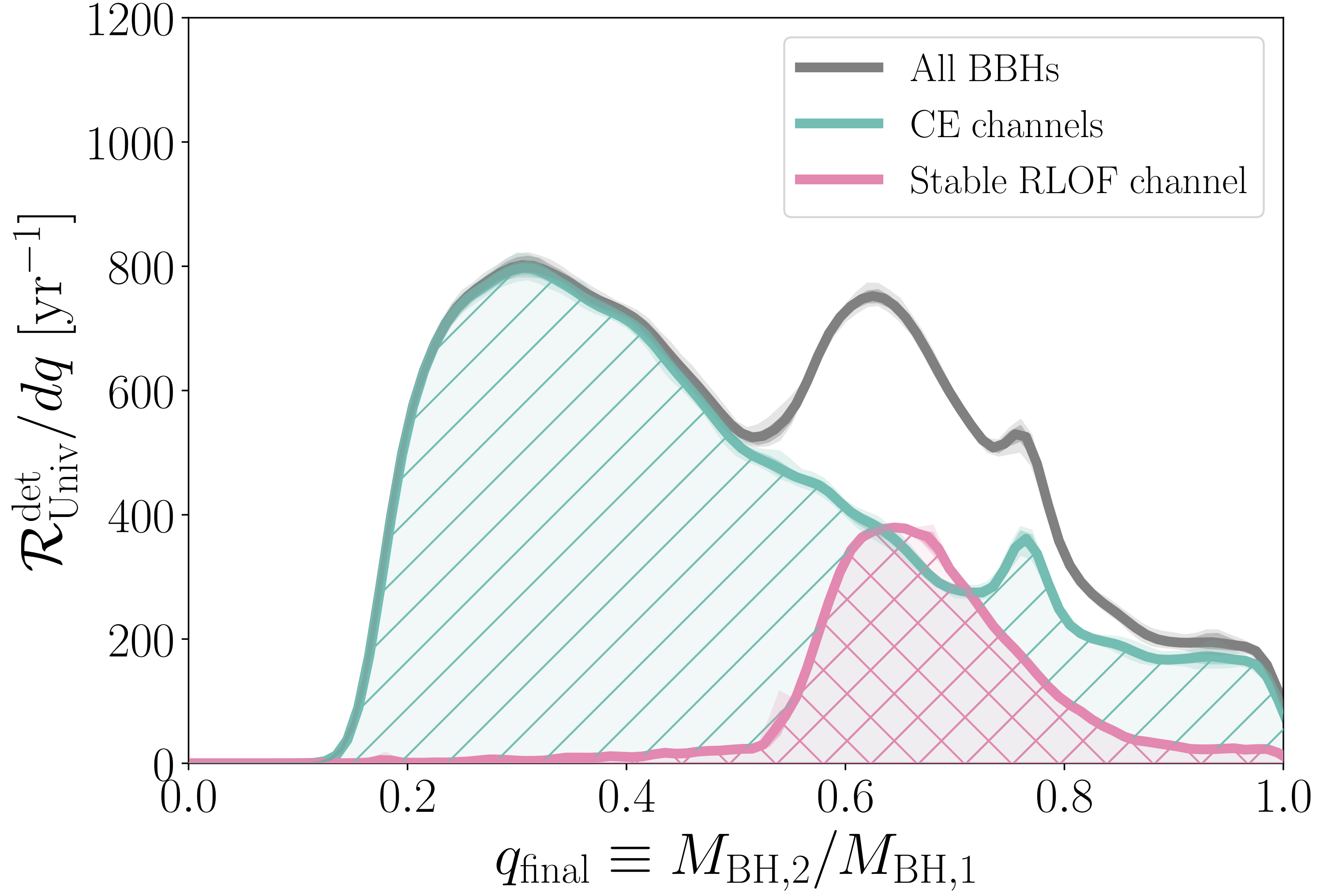
Rate – redshift evolution



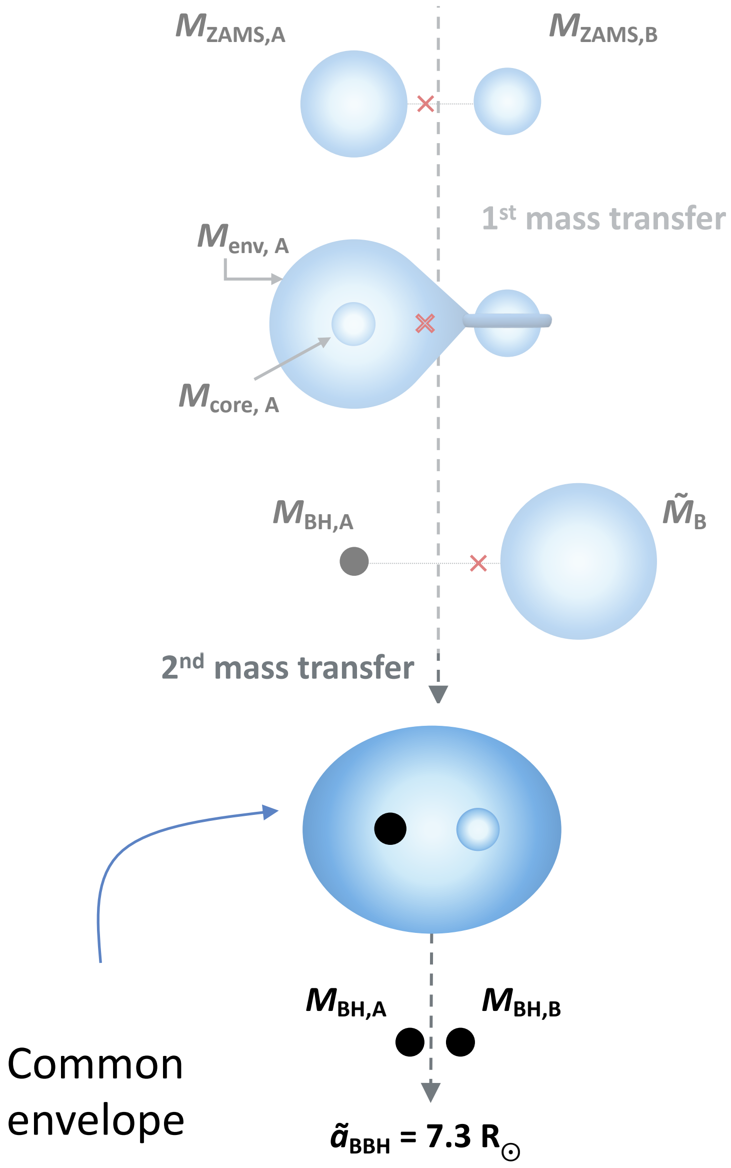
Delay time distributions



Final mass ratio



Common envelope channel



Common envelope channel → lower mass BHs

You need high mass stars (> 60$M_\odot$) for high mass BHs (> 30$M_\odot$)

These stars:

I. Don't have much of an envelope
- due to wind stripping

II. Don't like to engage in a common envelope (unstable mass transfer)
- radiative envelopes contract when losing mass

III. Are unlikely to survive a common envelope event
- too hot!

IV. Reverse CE is unlikely
- due to accretion from first mass transfer

I) LBV e.g. Smith 2014; Sanyal et al. 2017; Kalari et al. 2018; Davies et al.2018; Higgins & Vink 2020; Sabhahit et al. 2021; Gilkiset al. 2021,
→ no RLOF: Mennekens & Vanbeveren + 2014; Belczynski + 2016, deMink et al. 2008;

II) Hjellming & Webbink 1987, : Pavlovskii & Ivanova2015; Pavlovskii et al. 2017; Marchant + 2021; Klencki et al. 2020

III) Convective envelope needed: Klencki + 2020, 2021; Marchant + 2021; Monica Gallegos-Garcia + 2021

Stable RLOF channel → long delay times

Stable RLOF leads to **wider separations**

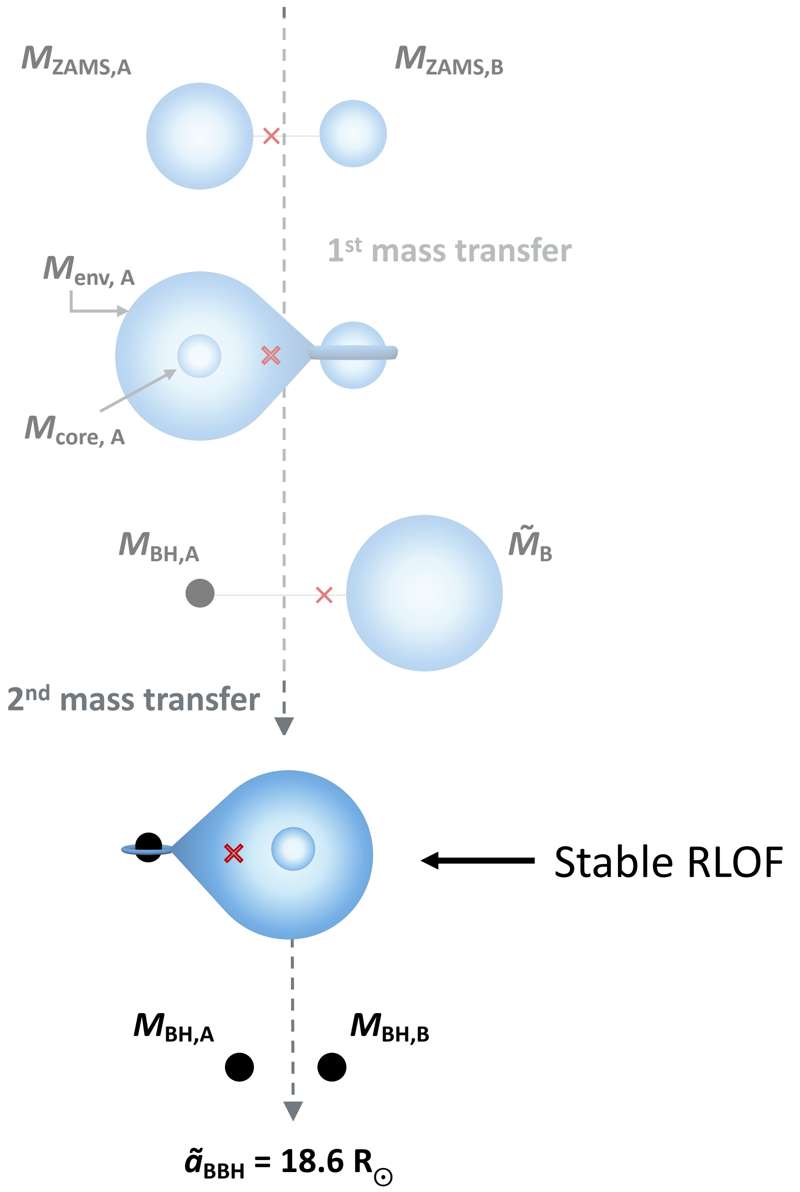
→ Longer delay time

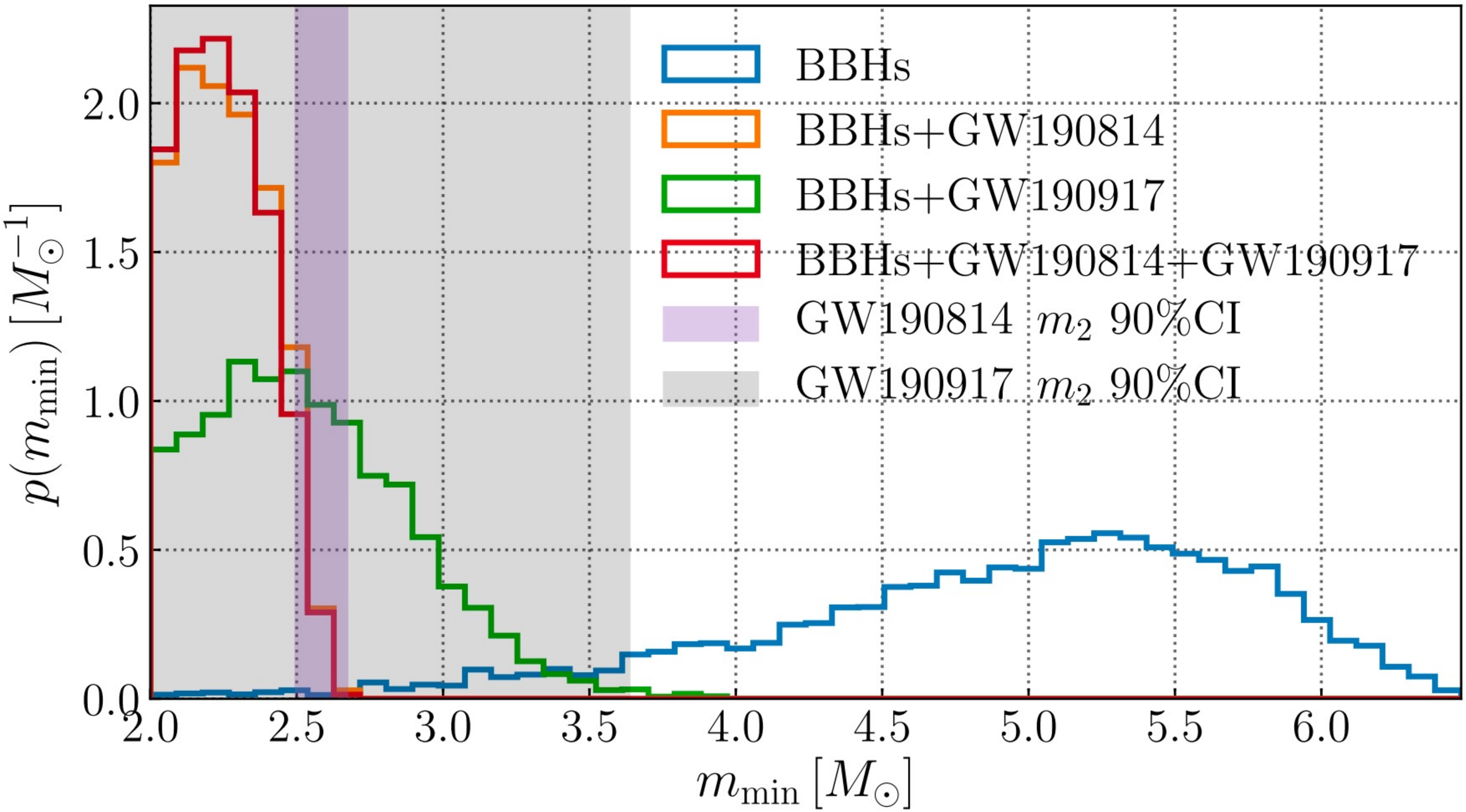
$$T_c(a_0) = a_0^4/(4\beta)$$

$$\beta = \frac{64}{5}\frac{G^3 m_1 m_2 (m_1 + m_2)}{c^5}$$

Peters (1964) Orbital evolution: Soberman et al. 1997

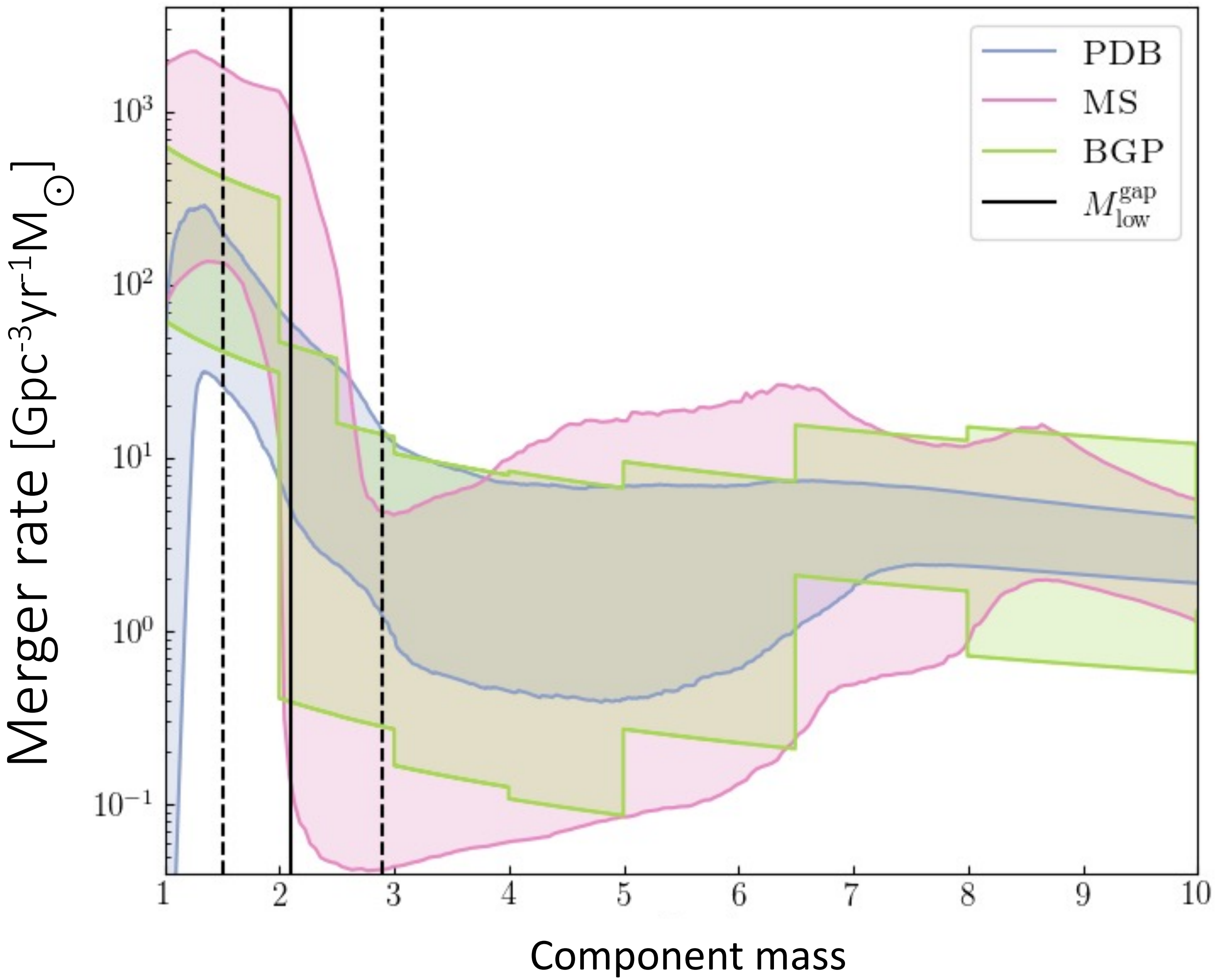
Stable RLOF channel





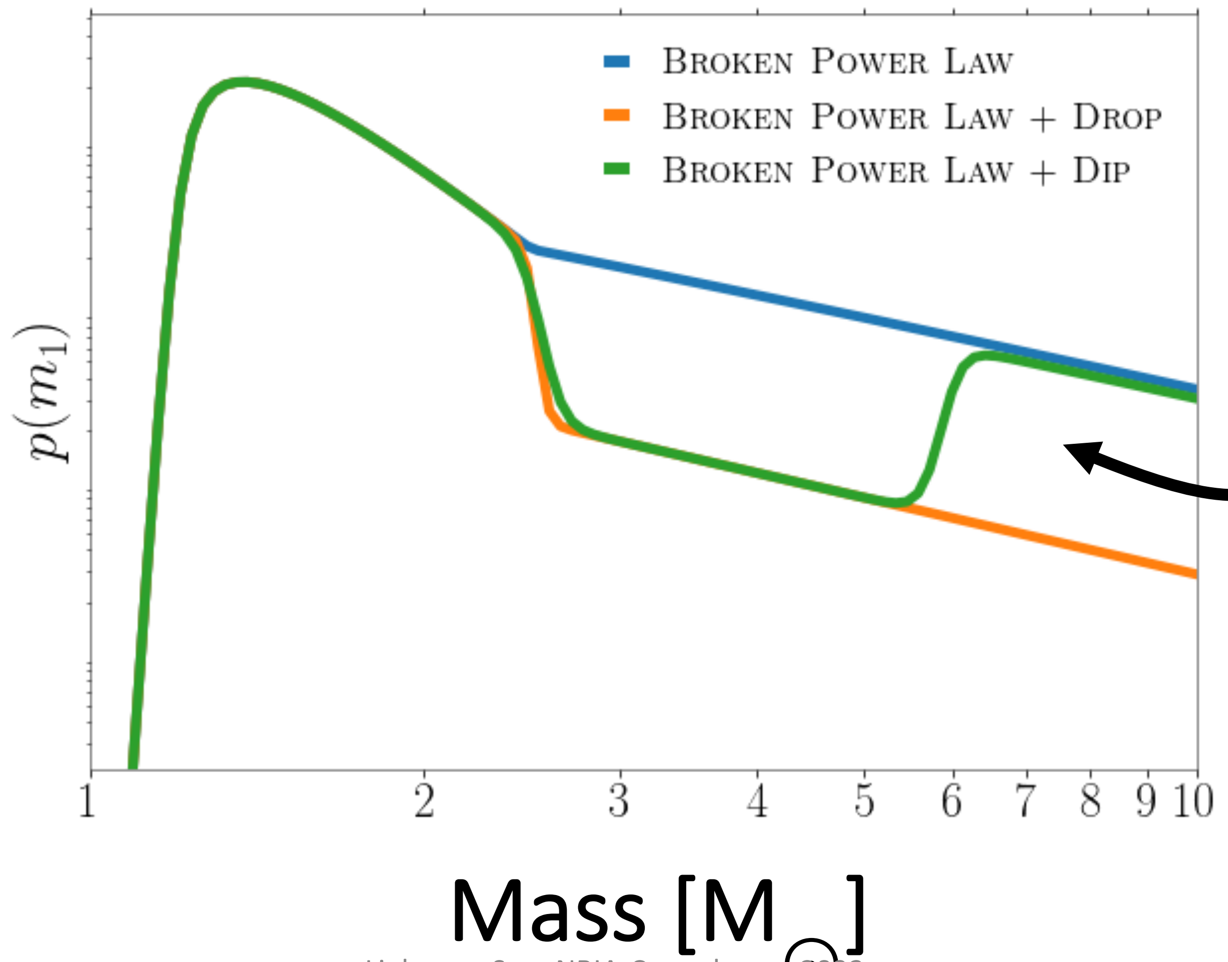
BBHs
BBHs+GW190814
BBHs+GW190917
BBHs+GW190814+GW190917
GW190814 m_2 90%CI
GW190917 m_2 90%CI
$p(m_{\min})\,[M_\odot^{-1}]$
$m_{\min}\,[M_\odot]$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0

Mass distribution from LIGO



Does the data prefer a drop below 7$M_\odot$ or not?

Farah et al. 2021



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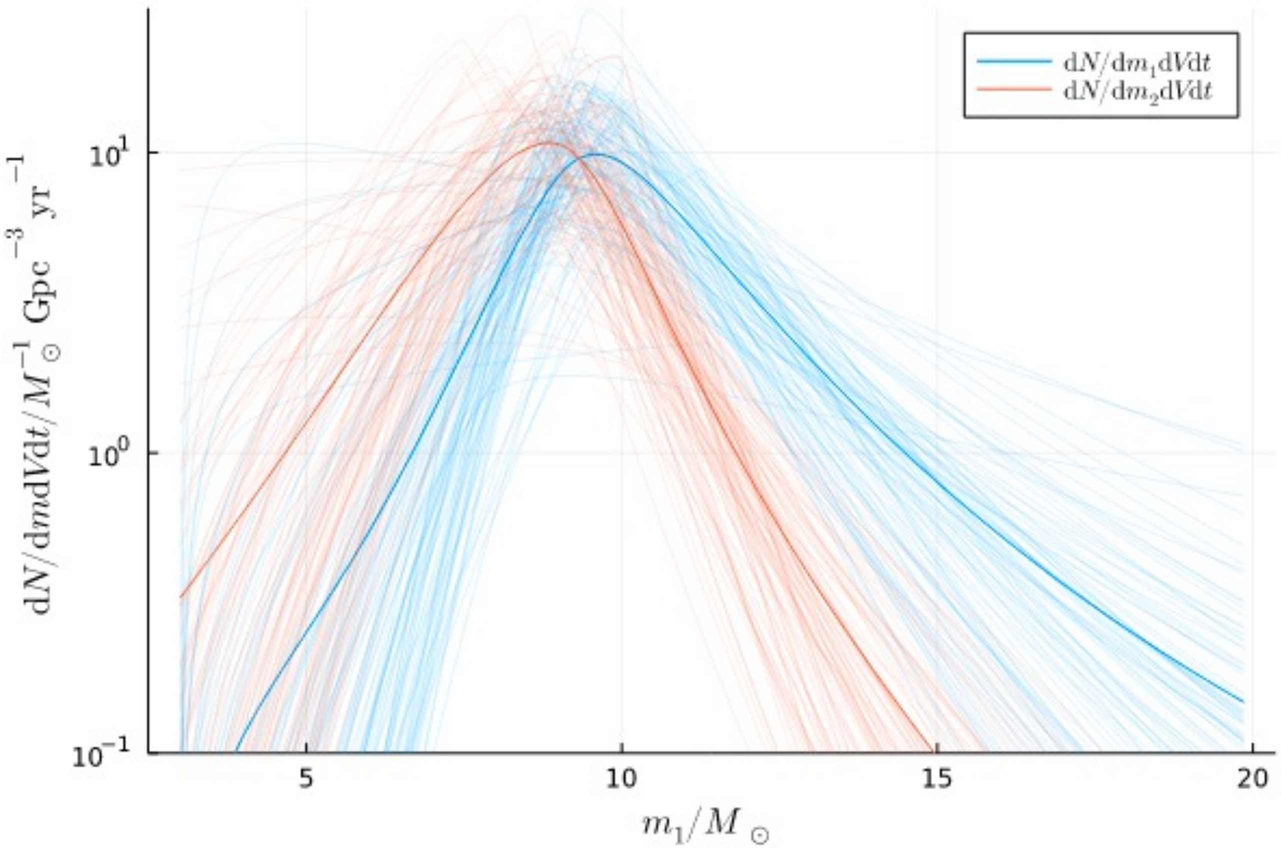


Derivation of minimum BH mass (part I)

$$q_{\mathrm{preMT},2} = \frac{\tilde{M}_2}{M_{\mathrm{BH},1}} \leq q_{\mathrm{crit},2}. \qquad (1)$$

$$\tilde{M}_2 \approx M_{\mathrm{ZAMS},2} + M_{\mathrm{ZAMS},1} \cdot \beta_{\mathrm{acc}}(1 - f_{\mathrm{core},1}), \qquad (2)$$

and $M_{\mathrm{BH},1}$ as,

$$M_{\mathrm{BH},1} = f_{\mathrm{core},1} \cdot M_{\mathrm{ZAMS},1} - dM_{\mathrm{SN},1}, \qquad (3)$$

$$\frac{q_{\mathrm{ZAMS}} + \beta_{\mathrm{acc}}(1 - f_{\mathrm{core},1})}{f_{\mathrm{core},1} - \frac{dM_{\mathrm{SN},1}}{M_{\mathrm{ZAMS},1}}} \leq q_{\mathrm{crit},2} \qquad (4)$$

Derivation of minimum BH mass (part I)

$$\frac{q_{\mathrm{crit},2} f_{\mathrm{core},1} - \beta_{\mathrm{acc}}(1 - f_{\mathrm{core},1}) - q_{\mathrm{ZAMS}}}{q_{\mathrm{crit},2}} \geq \frac{dM_{\mathrm{SN},1}}{M_{\mathrm{ZAMS},1}}$$

$$dM_{\mathrm{SN}}(M_{\mathrm{core}}) = \begin{cases} a_{sn} M_{\mathrm{core}} + b_{sn} & M_{\mathrm{core}} \leq M_{\mathrm{thresh}} \\ 0 & M_{\mathrm{core}} > M_{\mathrm{thresh}} \end{cases} \tag{5}$$

$$\boxed{M_{\mathrm{ZAMS},1} \geq \frac{b_{sn} \cdot q_{\mathrm{crit},2}}{q_{\mathrm{crit},2} f_{\mathrm{core},1}(1 - a_{sn}) - \beta_{\mathrm{acc}}(1 - f_{\mathrm{core},1}) - q_{\mathrm{ZAMS}}}}$$

Derivation of minimum BH mass (part II)

$$\min(M_{\mathrm{BH},1}) \approx f_{\mathrm{core},1} \cdot min(M_{\mathrm{ZAMS},1}) - dM_{\mathrm{SN},1} \quad (11)$$

$$\min(M_{\mathrm{BH},2}) \approx f_{\mathrm{core},2} \cdot \min(\tilde{M}_2) - dM_{\mathrm{SN},2} \quad (12)$$

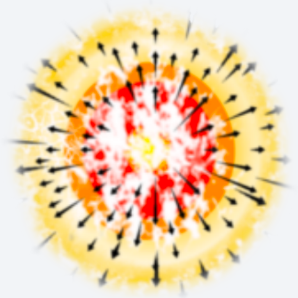
$$\min(\tilde{M}_2) = \; q_{\mathrm{crit},2} \min(M_{\mathrm{BH},1}).$$

$$\boxed{\min(M_{\mathrm{m.mass\ \ BH}}) = \max\left\{\min(M_{\mathrm{BH},1}), \min(M_{\mathrm{BH},2})\right\}}$$

Isolated binaries don't make BHs with ~45-140 $M_\odot$

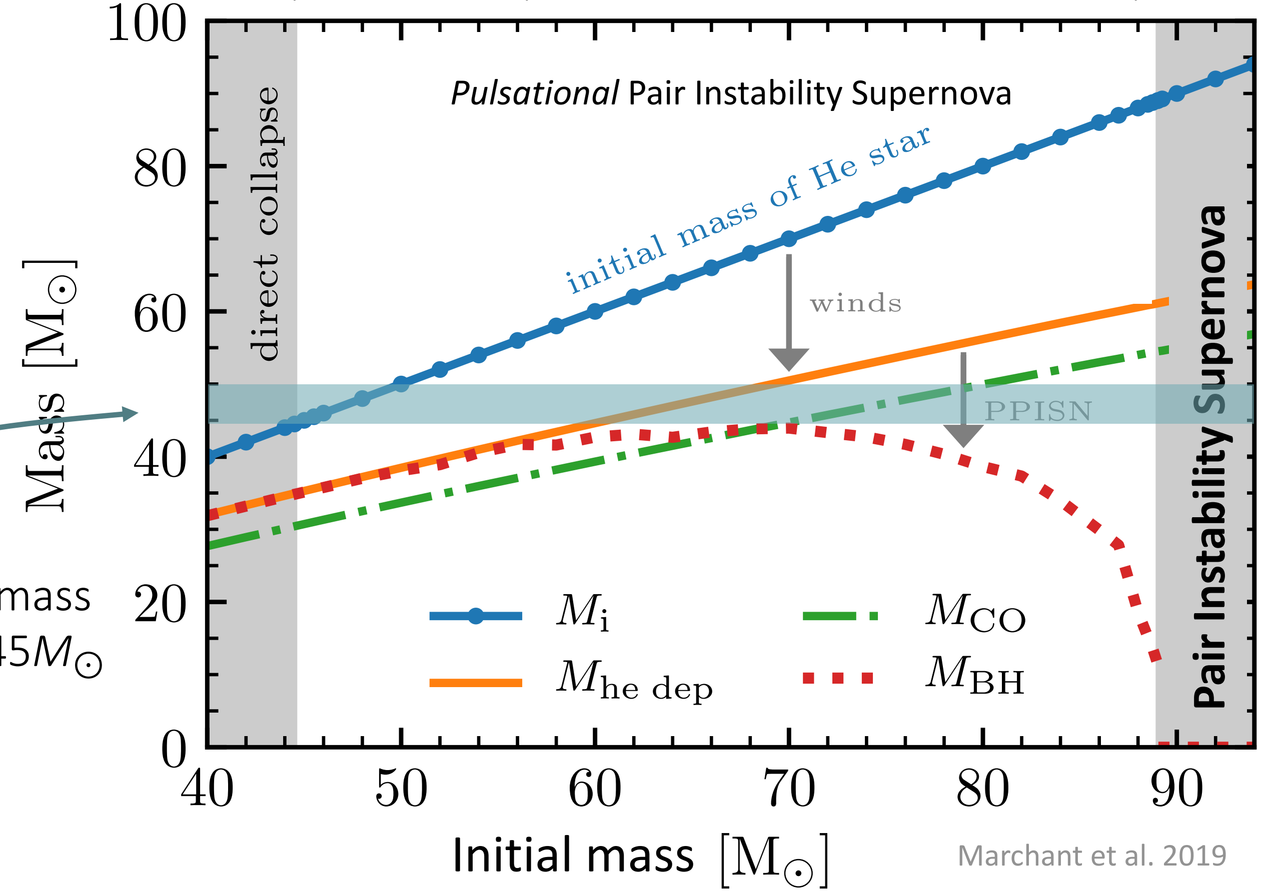
PISN: Fowler & Hoyle 1964; Rakavy & Shaviv 1967; Barkat et al. 1967; Fraley 1968

Pair-instability Supernovae



(Renzo et al. 2020)

Max BH mass around $45M_\odot$

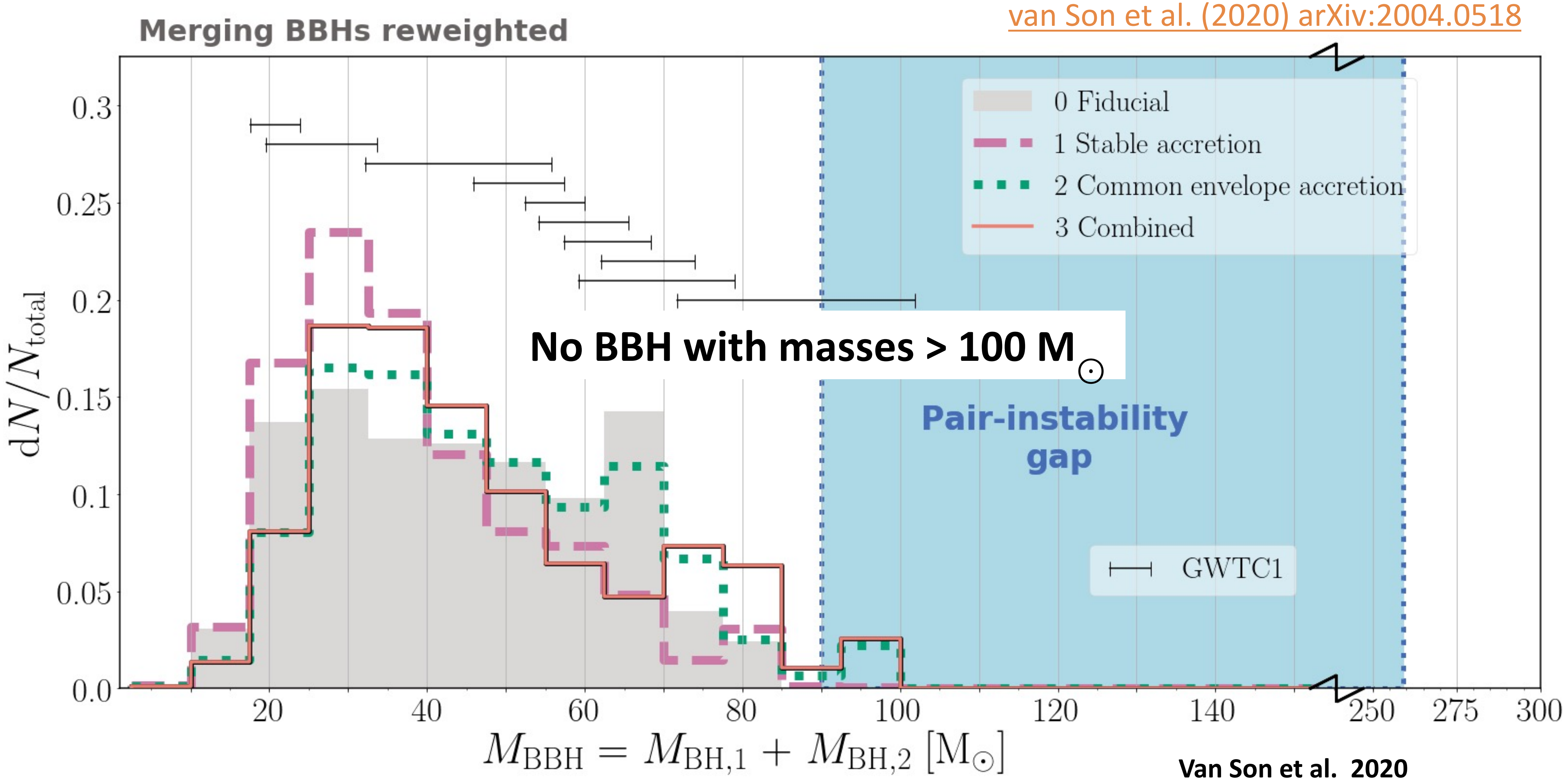


Marchant et al. 2019

Effects of PISN: Stevenson et al. 2019, Farmer et al. 2019, Marchant et al. 2019, Renzo et al. 2020, Farmer et al. 2020, Marchant & Moriya 2020, Woosley & Heger 2021

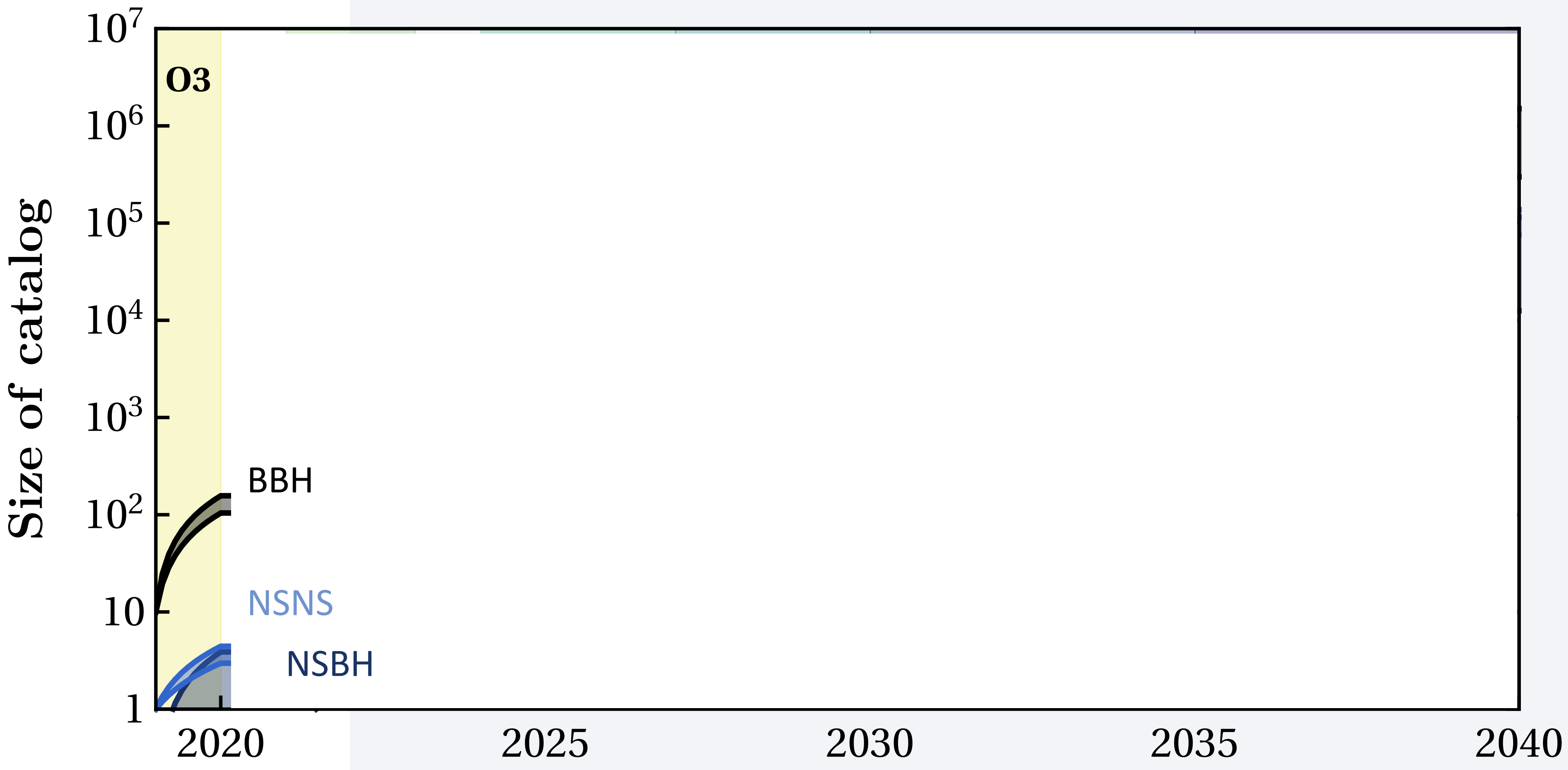
This is true even under extreme assumptions

van Son et al. (2020) arXiv:2004.0518



Van Son et al. 2020

A lot more data is imminent



Baibhav et al. 2019