Present and future lessons in stellar physics from gravitational waves

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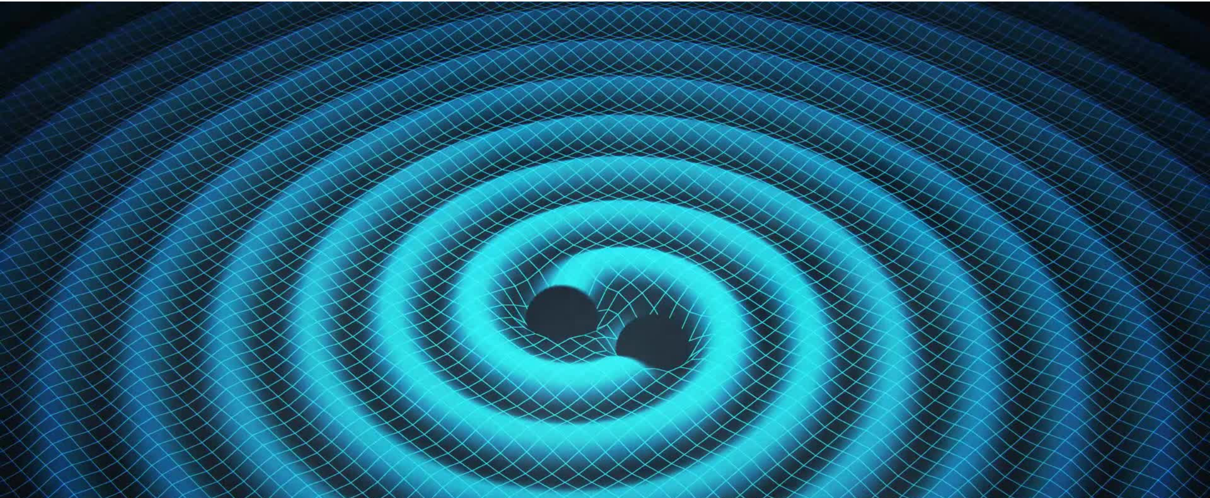
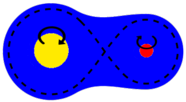
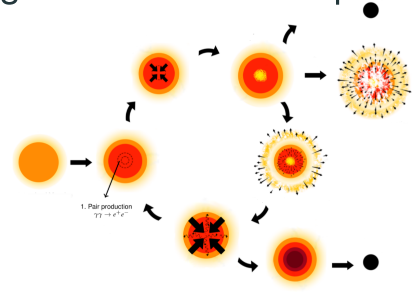


Outline

Future: LISA detection of GW from a Galactic common envelope



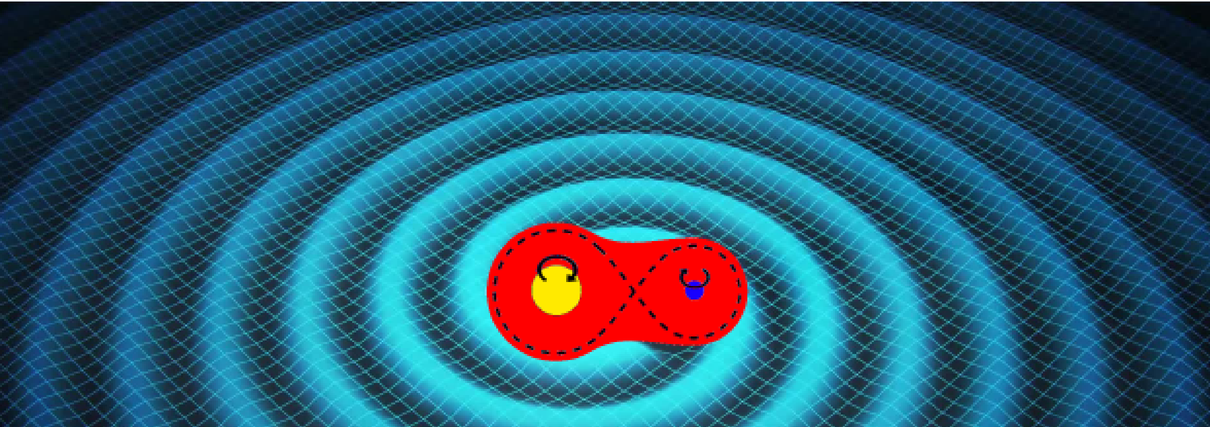
Present: LIGO/Virgo BH masses and pulsational pair instability



Prospects of gravitational-waves detections from common-envelope evolution with LISA

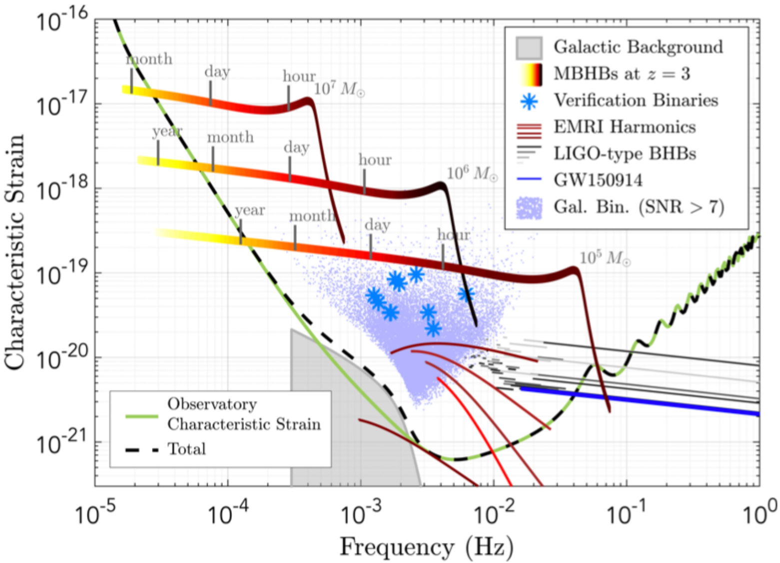
Mathieu Renzo, T. Callister, K. Chatziioannou, L. van Son, C. M. F. Mingarelli, M. Cantiello, K. E. S. Ford, B. McKernan, and G. Ashton

arXiv:2102.00078



LISA can see Galactic double white dwarfs formed via common envelope

⇐ PTA



LIGO/Virgo ⇒

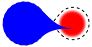
Robson *et al.* 2019

Common Envelope Evolution

Is *not* GW-driven!

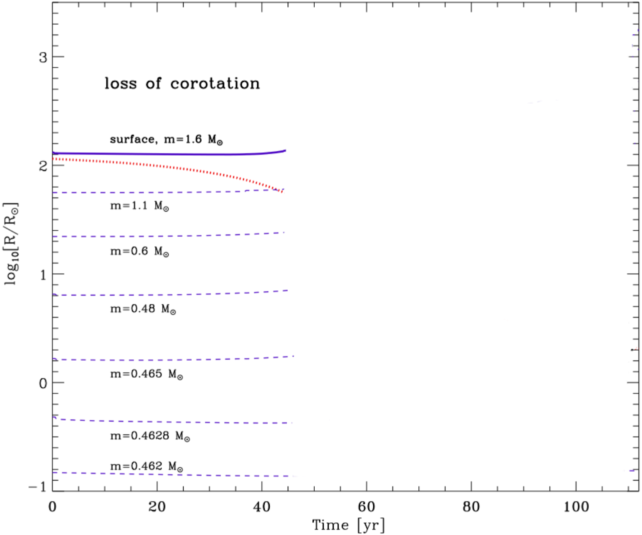
But GW passively trace the dynamics

Common envelope evolution in one slide

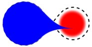


a. Mass transfer becomes dynamically unstable

Common envelope evolution in one slide



Example from Ivanova *et al.* 13b



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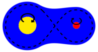
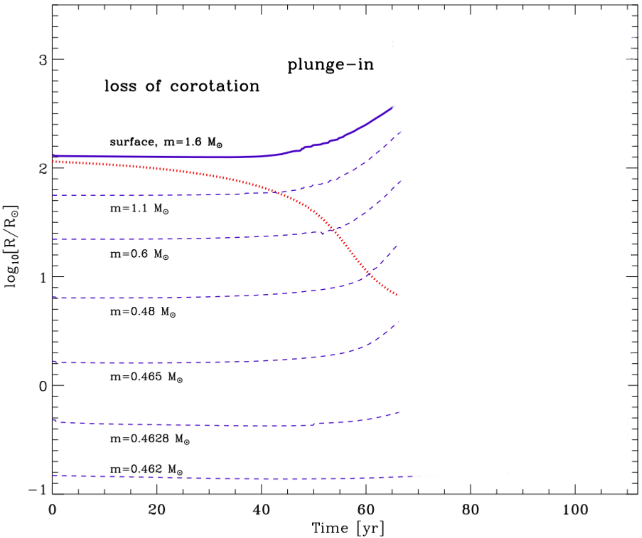
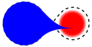


b. Loss of corotation between the cores and the envelope

Common envelope evolution in one slide

Renzo, Callister *et al.* 21





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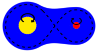

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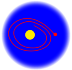
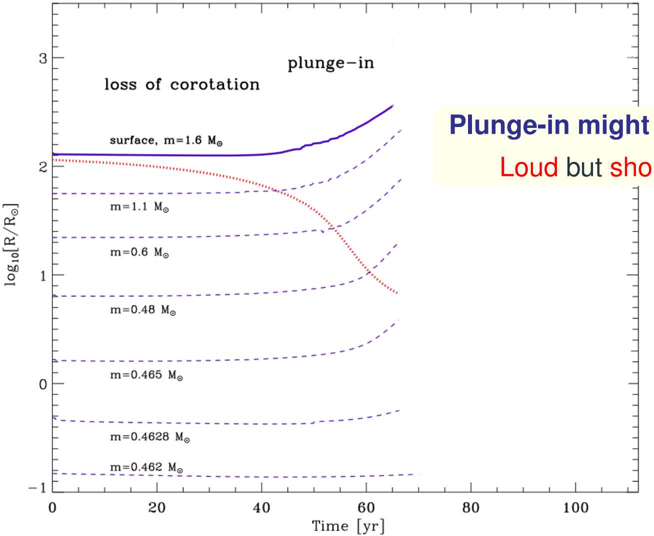


c. Dynamical plunge-in

Example from Ivanova *et al.* 13b

Common envelope evolution in one slide

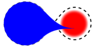
Renzo, Callister *et al.* 21



Example from Ivanova *et al.* 13b

Plunge-in might be detectable

Loud but short and rare



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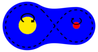

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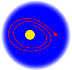

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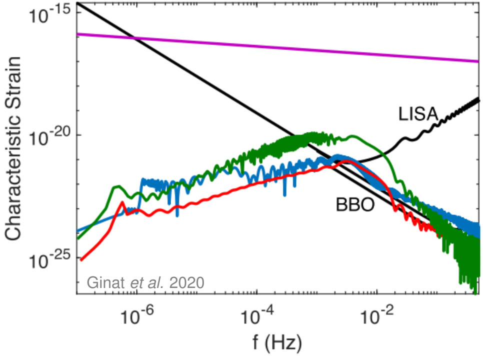
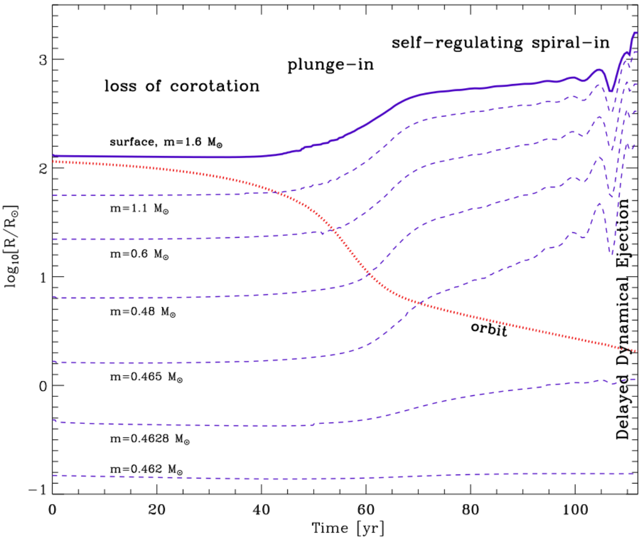
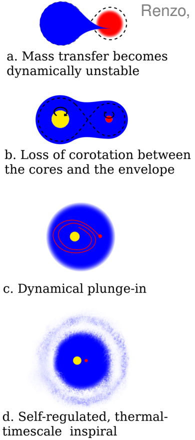


Common envelope evolution in one slide





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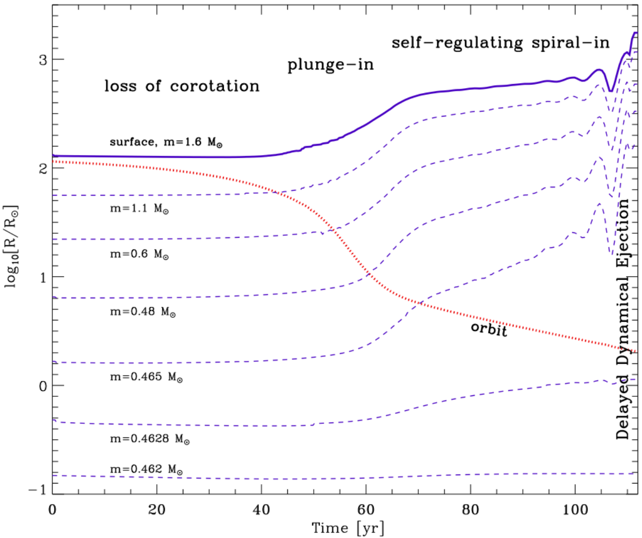

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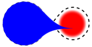

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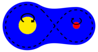

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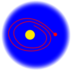

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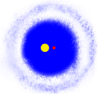
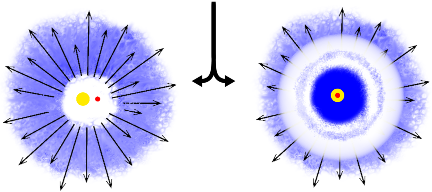


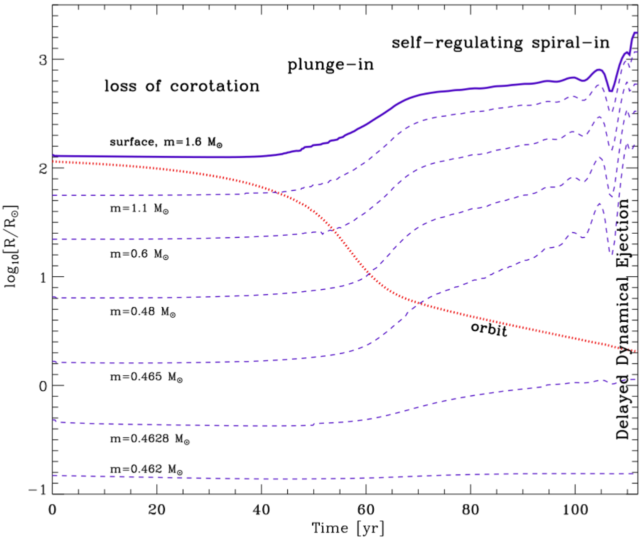
d. Self-regulated, thermal-timescale inspiral



Common envelope ejection and formation of a short period binary

Stellar merger

Common envelope evolution in one slide



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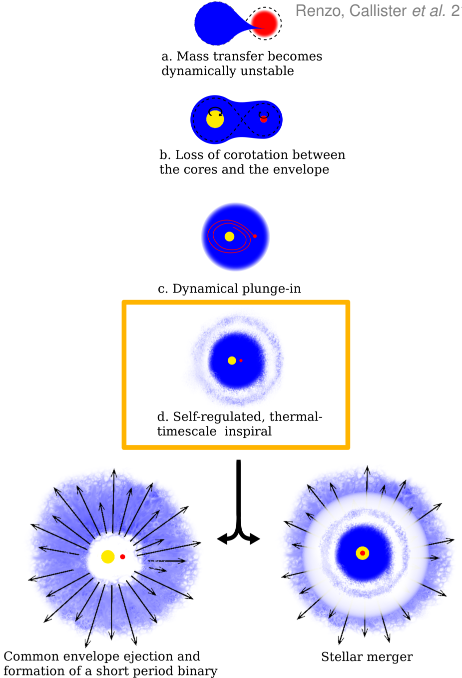

How many sources do we expect?

$$N_{\mathrm{CE}} = R_{\mathrm{CE,init}} \times \Delta t_{\mathrm{CE}}$$

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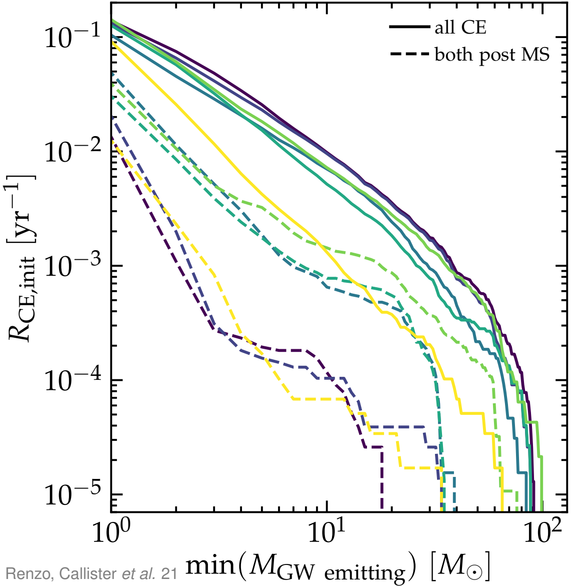

Renzo, Callister *et al.* 21

$$R_{\rm CE,init} = 0.18^{+0.02}_{-0.09} \quad (0.06^{+0.03}_{-0.02})$$

c.f. LRN rate $\sim 0.3\ {\rm yr}^{-1}$

Kochaneck *et al.* 14, see also Howitt *et al.* 20

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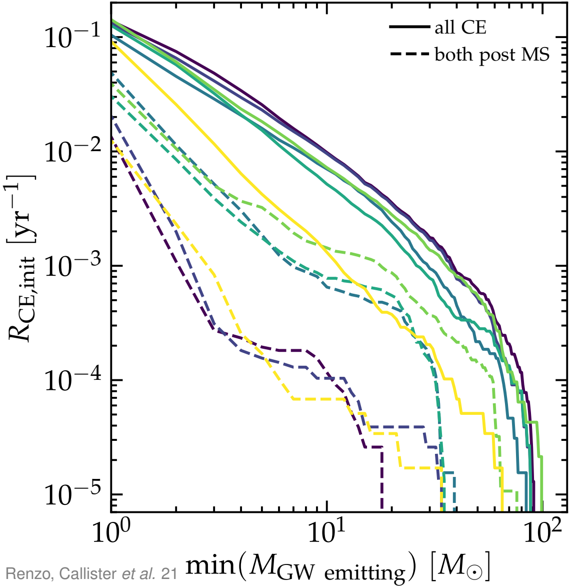

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Duration (in band) is very uncertain

$\Delta t_{\rm CE} \simeq 10^{-2} - 10^5$ years

(e.g., Meyer & Meyer-Hofmeister 79, Fragos *et al.* 19, Igoshev *et al.* 20, Chamandy *et al.* 20, Law-Smith *et al.* 20)

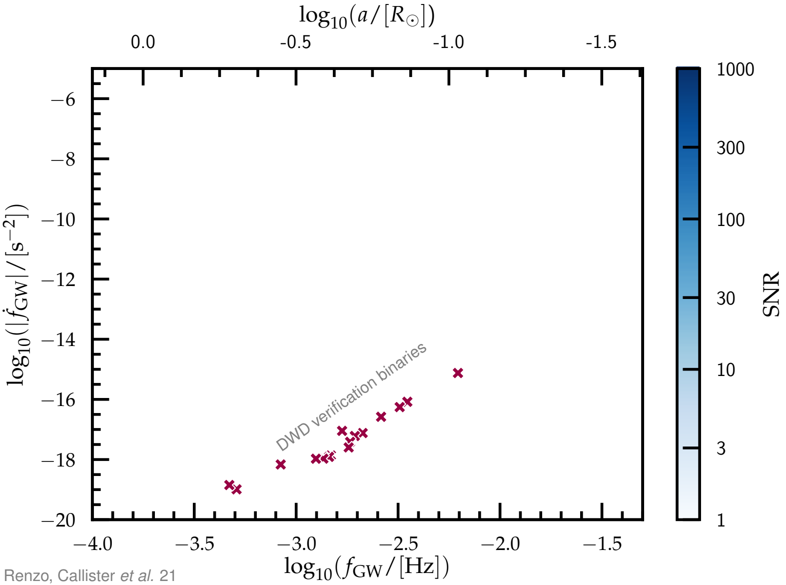
$$\Downarrow$$

$$0 \lesssim N_{\rm CE} \lesssim 1000$$

COSMIC
Breivik *et al.* 20

Could we detect something?

Could we see it? An answer not relying on a specific model



$M_{core} = 0.5\,M_\odot$, $M_2 = 0.3\,M_\odot$,
$D = 3\,\mathrm{kpc}$, $T = 5$ years,
averaged over
orientation and sky location

Renzo, Callister *et al.* 21

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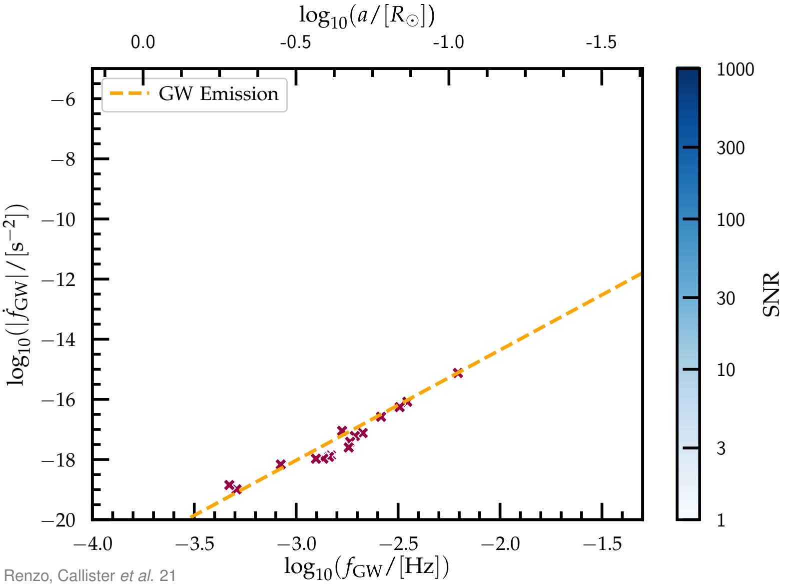

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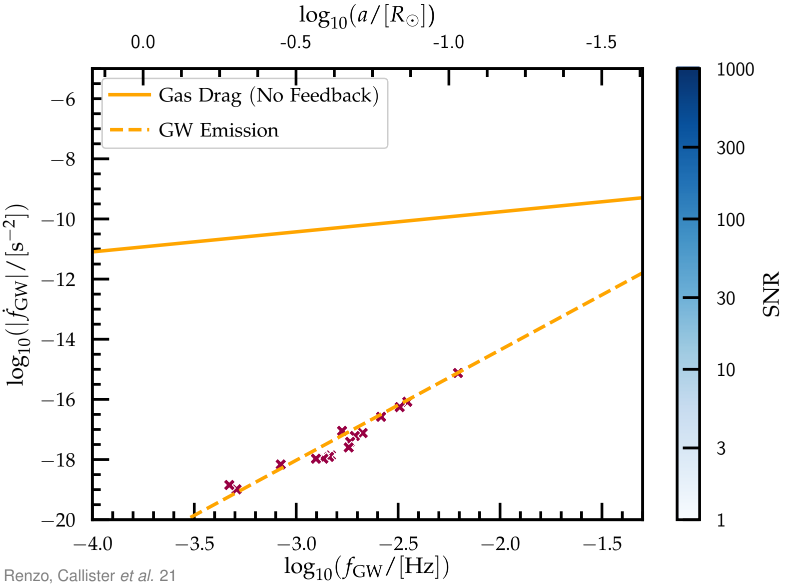

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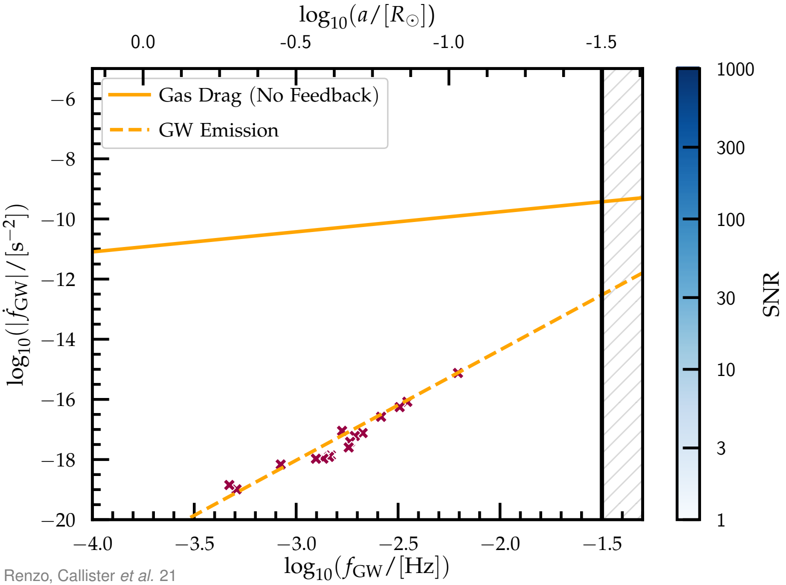

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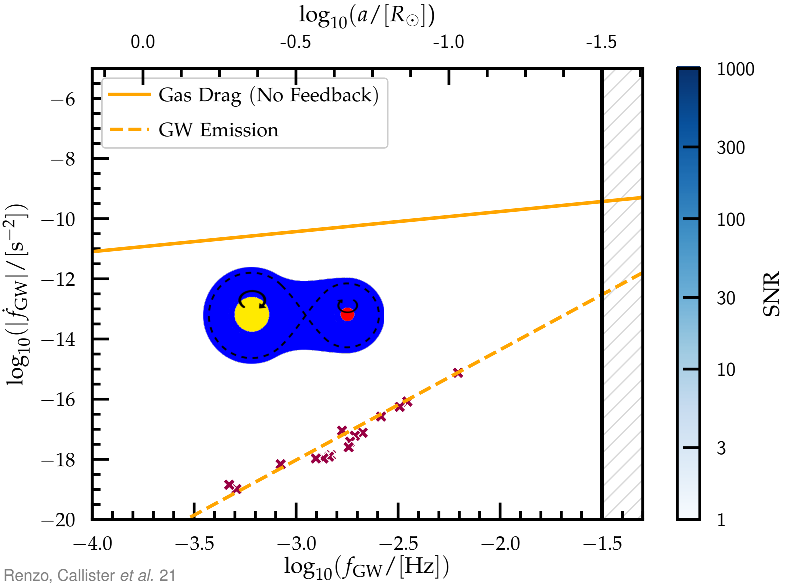

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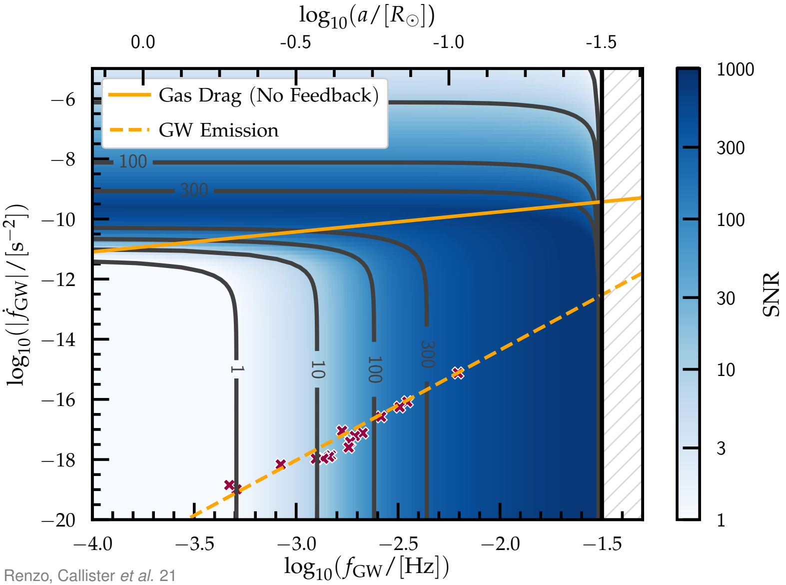

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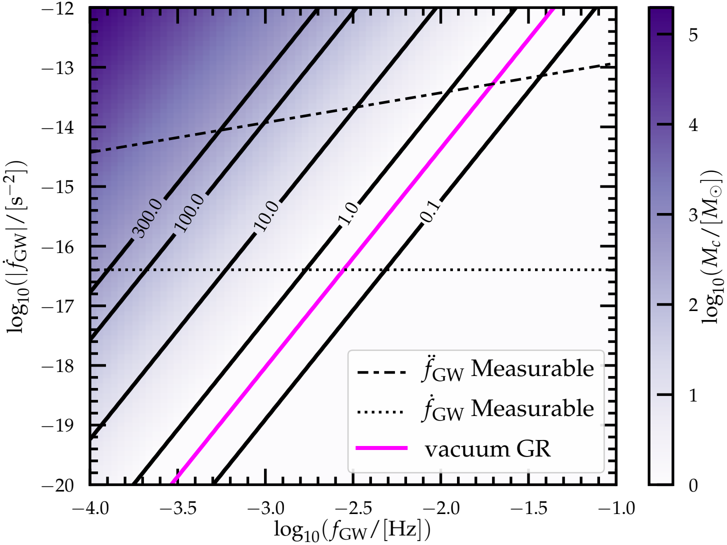
Renzo, Callister *et al.* 21

Would we recognize GWs from common envelope?

“Stealth bias” assuming GR in vacuum: chirp mass

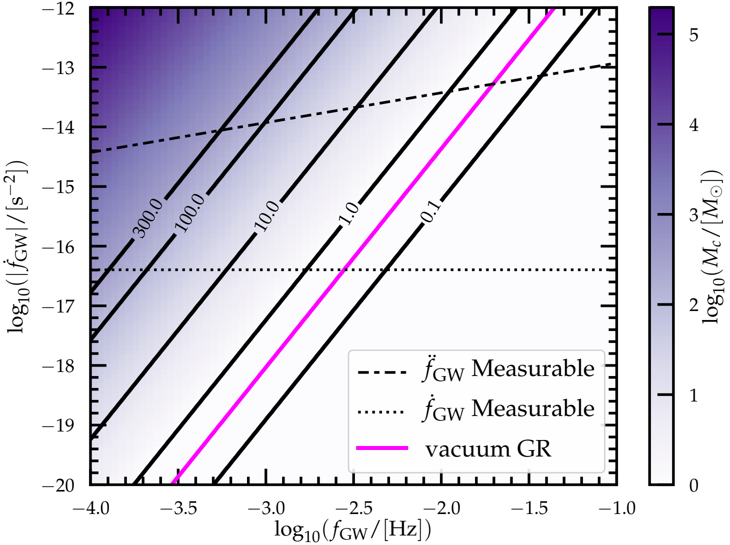


Renzo, Callister *et al.* 21

"Stealth bias" assuming GR in vacuum: chirp mass

"Braking index"

$$n = f\ddot{f}/\dot{f}^2$$
$$\Downarrow$$
$$n_{GR} = \frac{11}{3}$$



Renzo, Callister *et al.* 21

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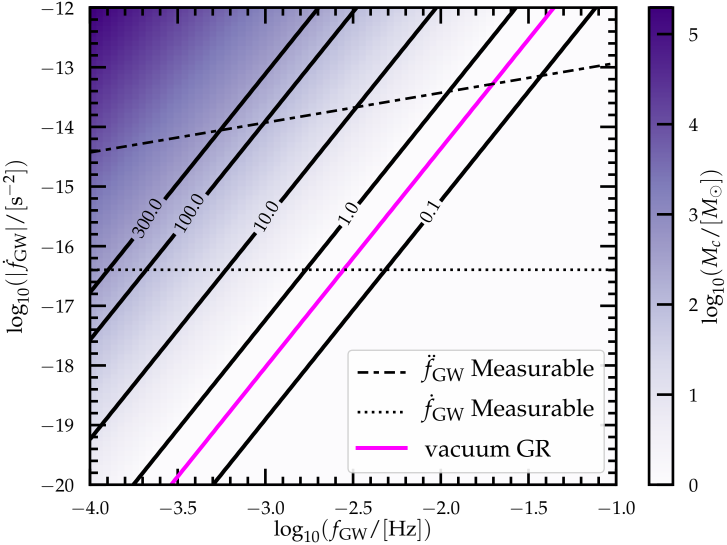
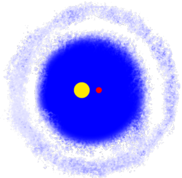




EM counterparts:

- Optical/IR transients

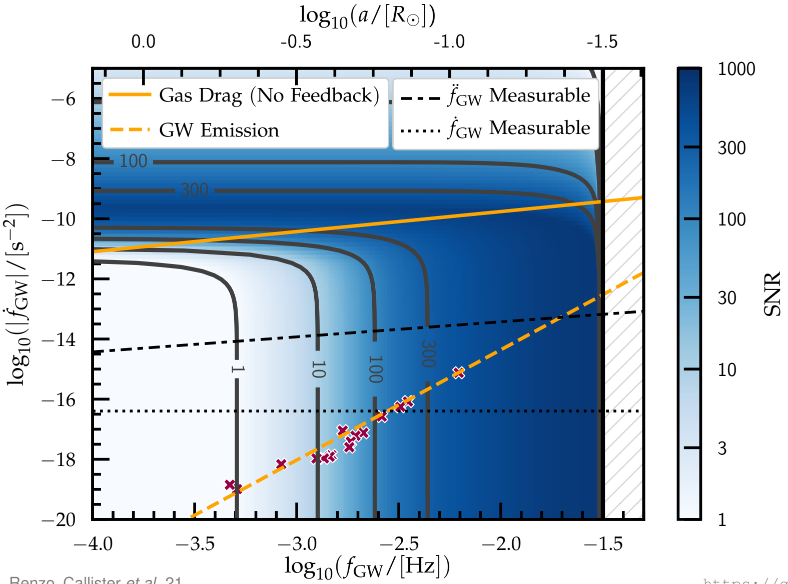
  (Blagorodnova *et al.* 20)

- "weird" red giant star

  (Clayton *et al.* 17)

Renzo, Callister *et al.* 21

Can LISA see common-envelope events? Maybe!



- $\sim$ One CE-begin per 10 yr
- $0 \lesssim N_{CE} \lesssim 1000$
- if stalls at short separation they might detectable

$\Downarrow$

Direct window on the inside

If non-detection

- stalls at large separation

and/or

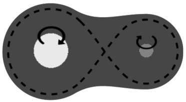
- stalling phase is short

Renzo, Callister *et al.* 21

https://github.com/tcallister/LISA-and-CE-Evolution

Outline

Future: LISA detection of GW from a Galactic common envelope



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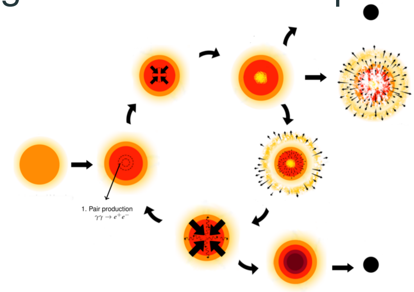
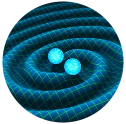
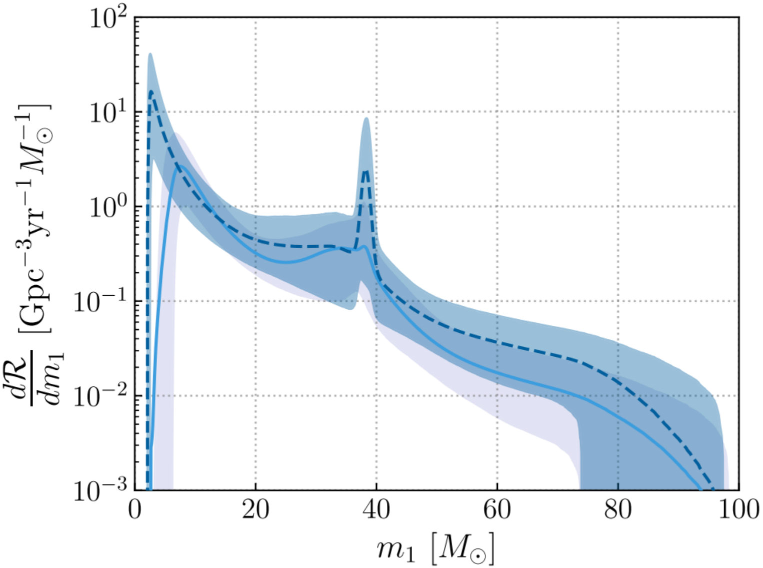


Gravitational wave mergers offer an unprecedented view on massive BHs



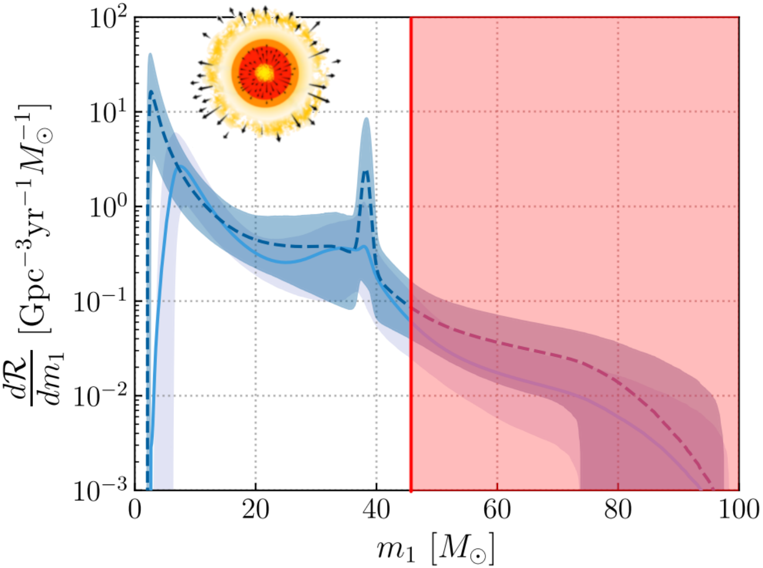
"Merger rate"



Abbott *et al.* 2020b

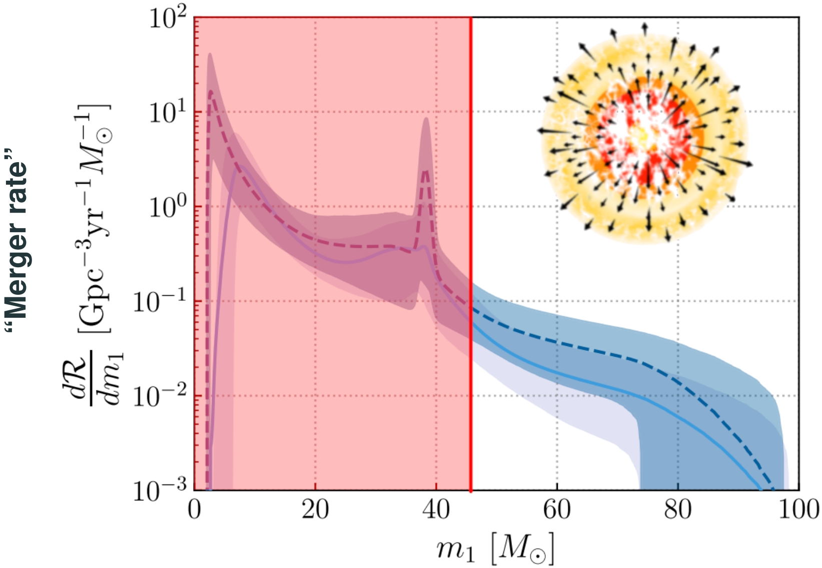
Part 1: Life and death of the most massive black-hole progenitors

“Merger rate”



Abbott *et al.* 2020b

Part 2: Making forbidden black holes ?

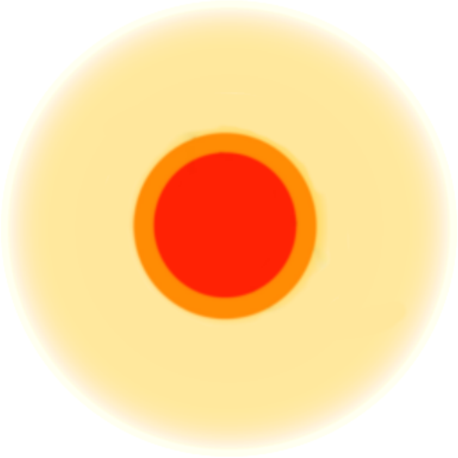


Abbott *et al.* 2020b

Part 1: Life and death of the progenitors of BHs $\lesssim 45\,M_\odot$

(Pulsational) pair instability evolution

Pair-production happens in the interior† after carbon depletion



† can be off-center

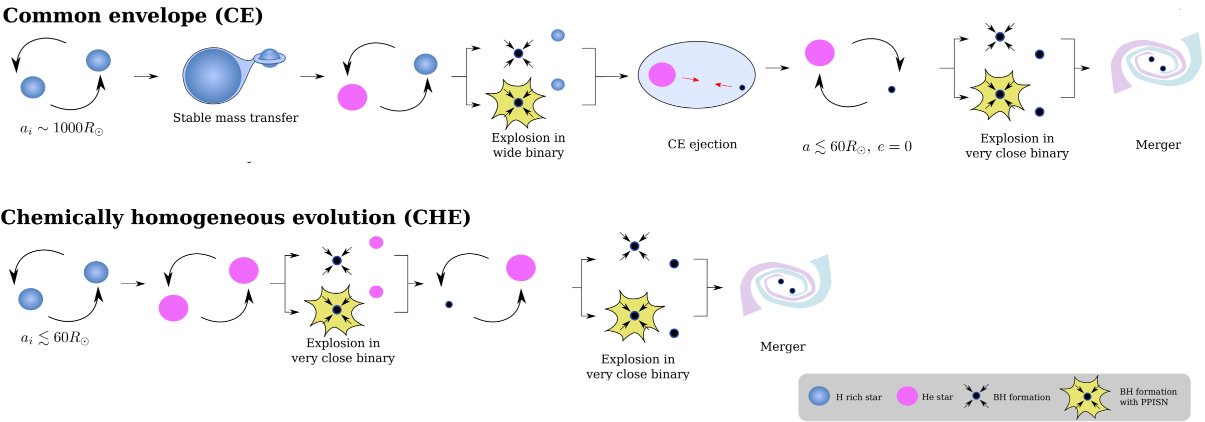
Simulating the He core captures the important dynamics

H-rich envelope can be lost to:

- winds
- binary interactions
- first pulse

He cores computed with MESA

Isolated binary evolution removes the H-envelope anyways



Marchant, Renzo *et al.* 2019

Pair-instability SNe are the best understood supernovae

0. Evolved Massive He core

Radiation pressure dominated:

$$P_{\rm tot} \simeq P_{\rm rad}$$

$$M_{\rm He} \gtrsim 32\, M_\odot$$

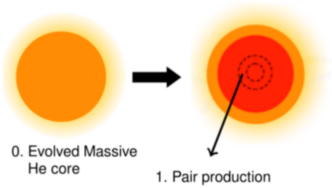
see Fowler & Hoyle 1964, Rakavy & Shaviv 1967, Barkat *et al.* 1967, 1968, Fraley 1968,

Glatzel *et al.* 1985, **Woosley** *et al.* 2002, 2007, Langer *et al.* 2007, Chatzopoulos *et al.* 2012, 2013, Yoshida *et al.* 2016,

Woosley 2017, 2019, Marchant, Renzo *et al.* 2019, Farmer, Renzo *et al.* 2019, 2020, Leung *et al.* 2019, 2020,

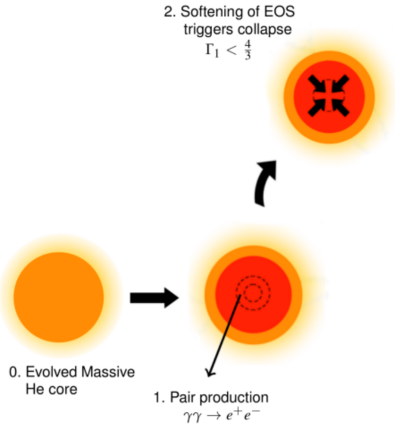
Renzo *et al.* 2020a,b, Croon *et al.* 2020a,b, Sakstein *et al.* 2020, Costa *et al.* 2021, Woosley & Heger 2021, etc...

Renzo, Farmer *et al.* 2020b

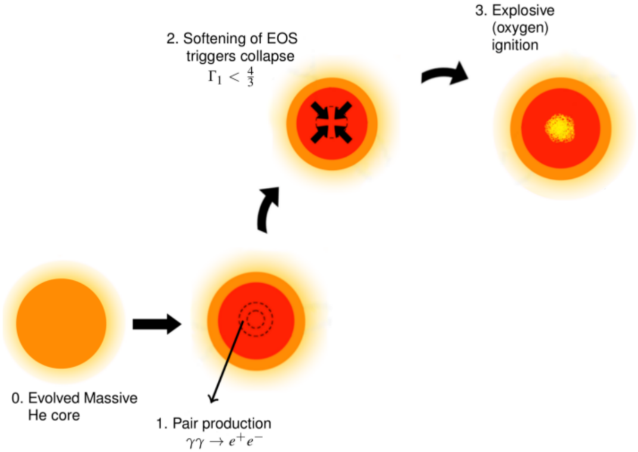


$$\gamma\,\gamma \rightarrow e^{+}\,e^{-}$$

Renzo, Farmer *et al.* 2020b



Renzo, Farmer *et al.* 2020b



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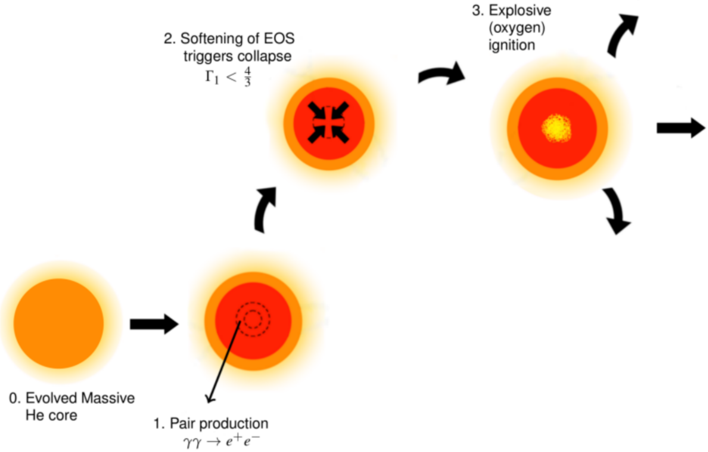

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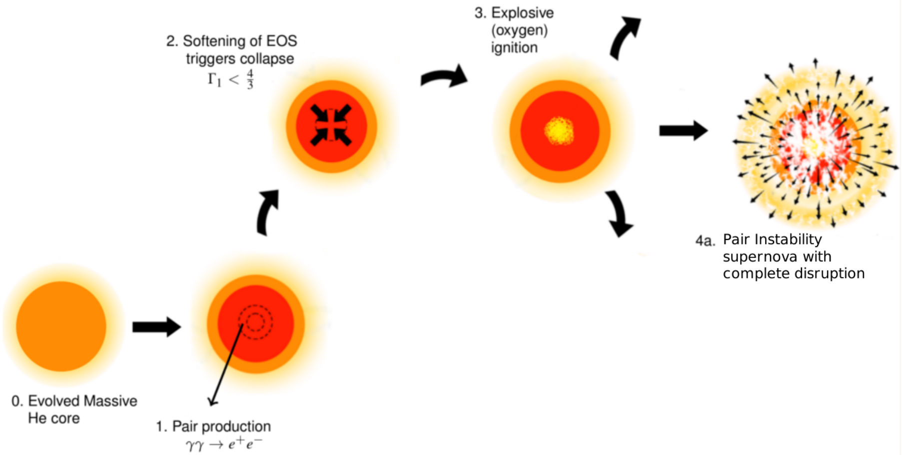

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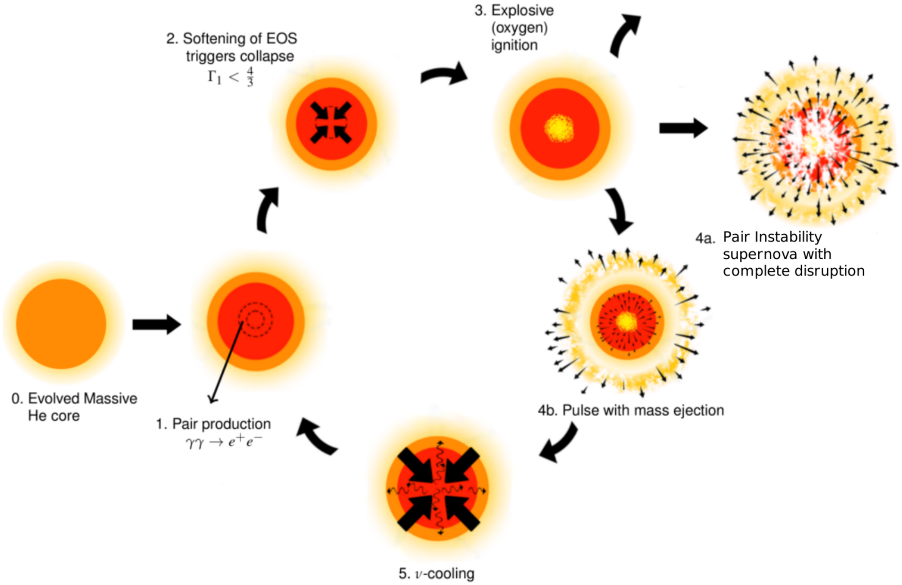
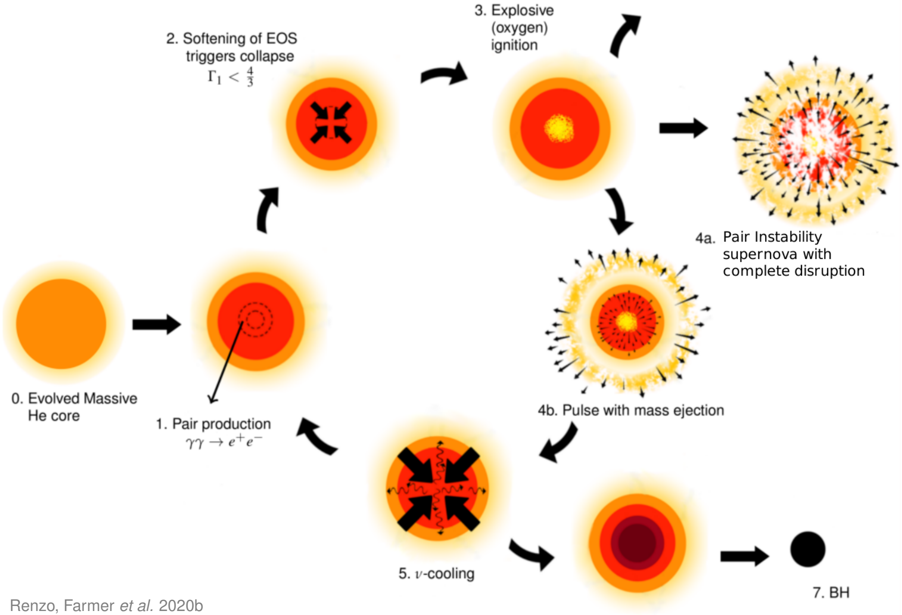
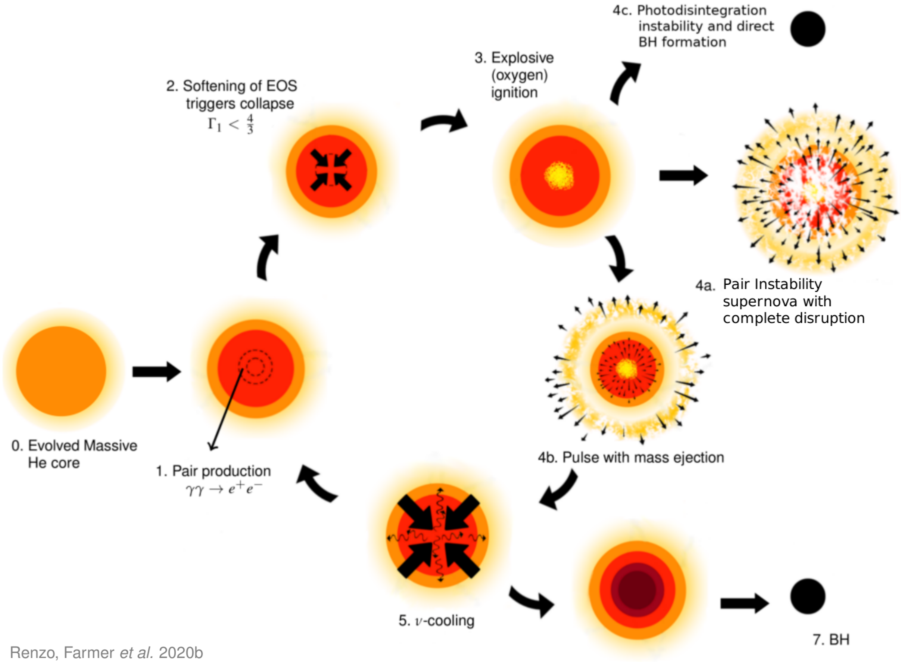


Renzo, Farmer *et al.* 2020b



Renzo, Farmer *et al.* 2020b



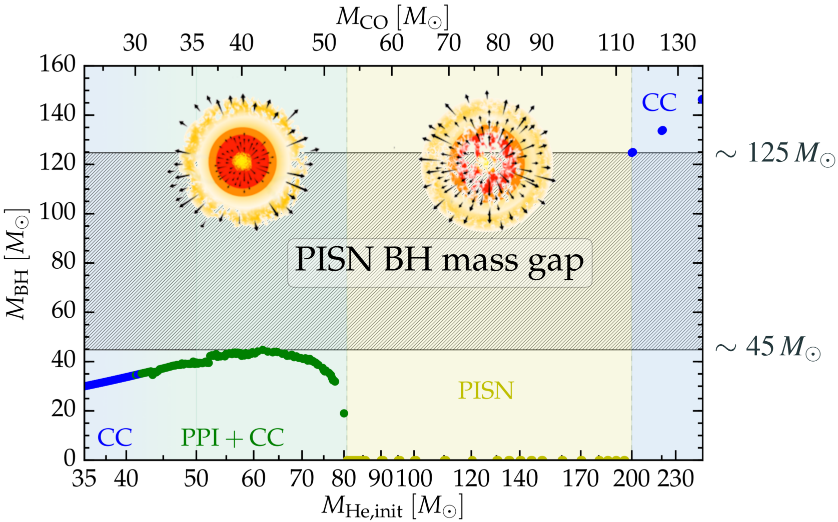
BH

no BH

BH

Renzo, Farmer *et al.* 2020b

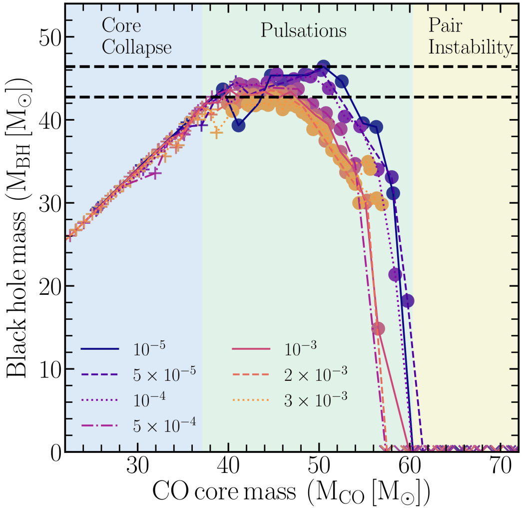
Resulting stellar BH masses



Renzo, *et al.* 2020b, see also Woosley *et al.* 2002, 2007, Woosley 2017, 2019, Marchant *et al.* 2019, Leung *et al.* 2019, Farmer *et al.* 2019, 2020, Stevenson *et al.* 2019, Spera & Mapelli 2019, van Son *et al.* 2020, Costa *et al.* 2021, Woosley & Heger 2021

Weak dependence on primordial metallicity

Focus on lower edge of the gap



$\Delta \max\{M_{BH}\} \sim 7\%$

over 2.5 orders of magnitude

Comparable or smaller effects:

resolution, winds, overshooting, neutrino cooling, α_{MLT}, etc..

Farmer, Renzo *et al.* 2019, see also Woosley & Heger 2021

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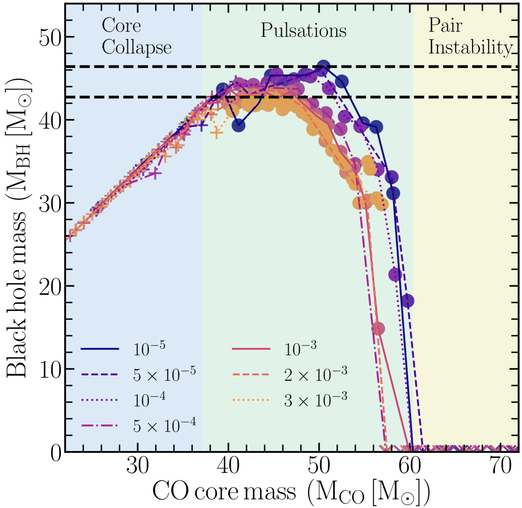


$\Delta\,\max\{M_{\rm BH}\}$ ~7%

over 2.5 orders of magnitude

Comparable or smaller effects:

resolution, winds, overshooting, neutrino cooling, $\alpha_{\rm MLT}$, etc..

$\max(M_{\rm BH})$ below the gap robust

&

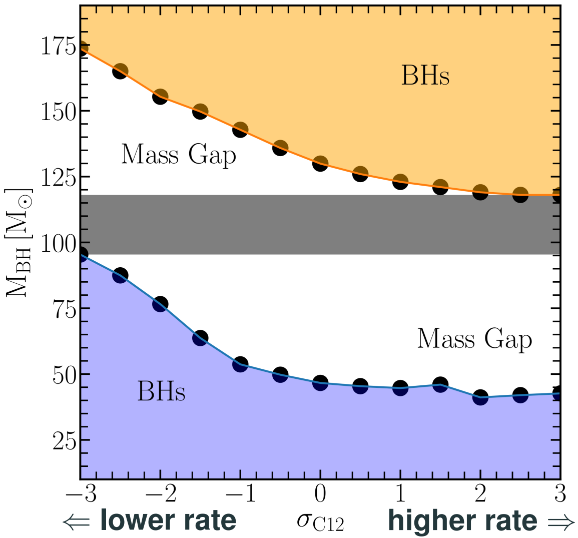
$\sim$ constant throughout the Universe

$\Downarrow$

Standardizable siren?

Farmer, Renzo *et al.* 2019, see also Woosley & Heger 2021

The dominant uncertainty is the $^{12}C(\alpha,\gamma)^{16}O$ rate



Change in $^{12}C/^{16}O$ ratio

$\Downarrow$

different C-shell behavior and CO core mass

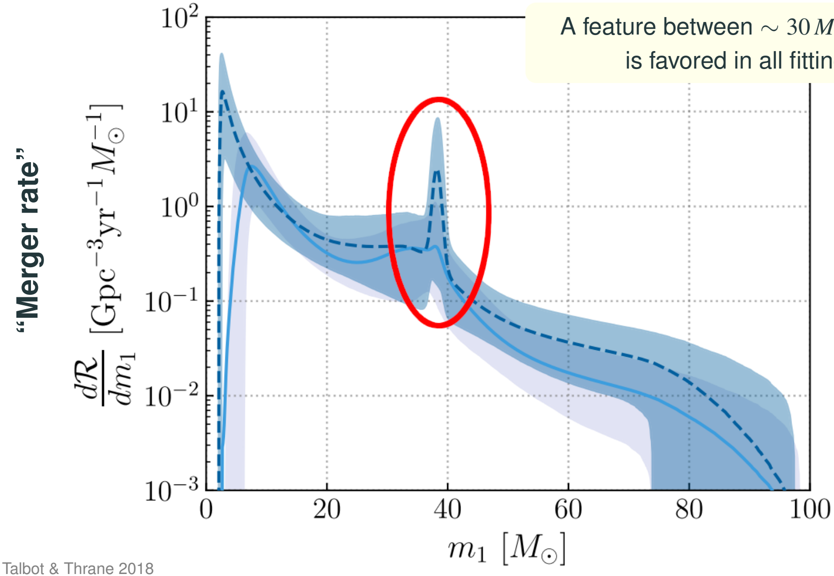
The lower edge of the gap can give GW constrain on nuclear rates...

...if $2^{nd}+$ generations don't pollute it too much

Farmer, Renzo *et al.* 2020, see also Takahashi 2018, Farmer, Renzo *et al.* 2019, Costa *et al.* 2021, Woosley & Heger 2021

The feature at $\sim 40\,M_\odot$ suggests PPI happens in nature

A feature between $\sim 30\,M_\odot$ and $\sim 60\,M_\odot$ is favored in all fitting models



Abbott *et al.* 2020b, Talbot & Thrane 2018

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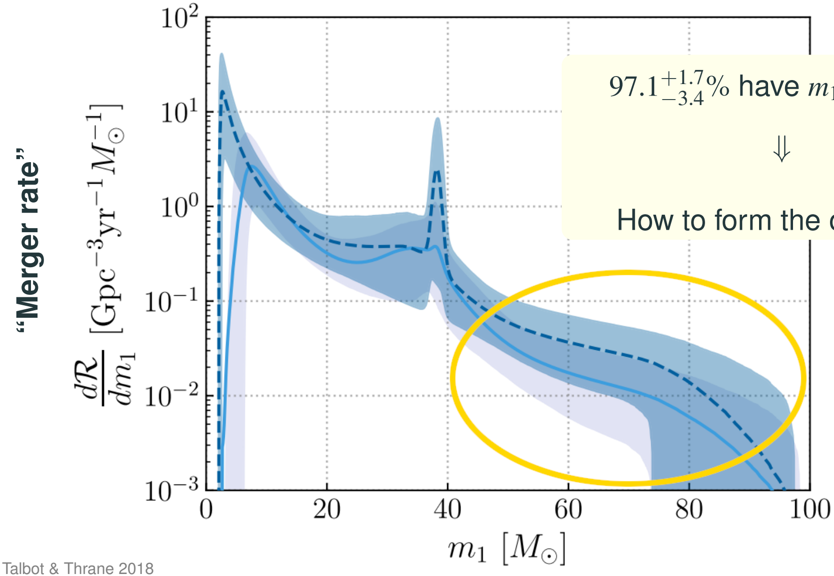


$97.1^{+1.7}_{-3.4}\%$ have $m_1 < 45\,M_\odot$

$\Downarrow$

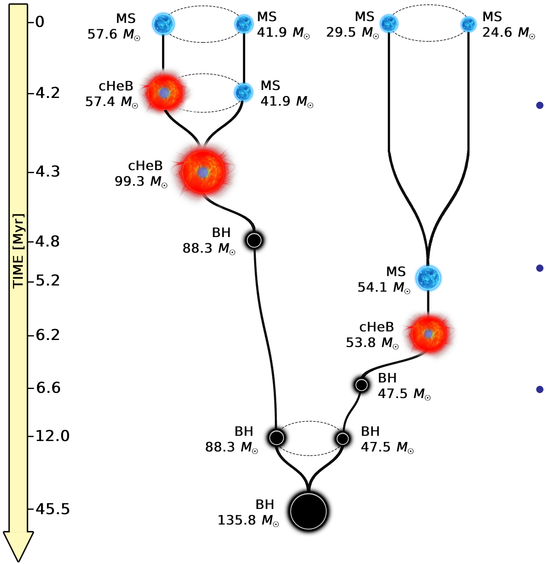
How to form the others ?

Abbott *et al.* 2020b, Talbot & Thrane 2018

Part 2: Making forbidden BHs ?

The “stellar merger” scenario

The “stellar merger scenario”

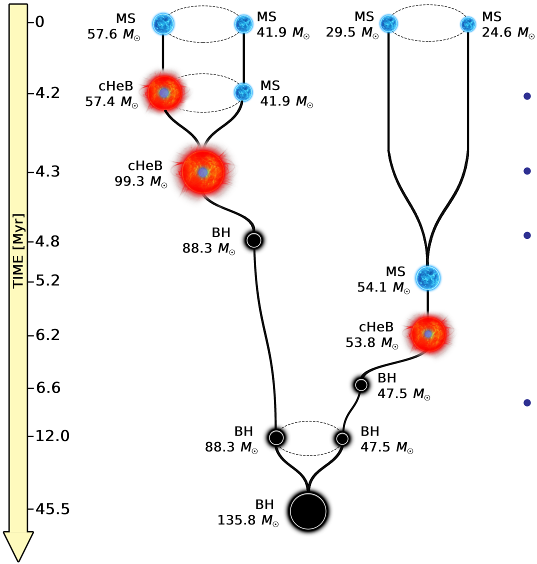


- Make a star with a small core and oversized envelope to avoid PPISN
- Collapse it to a BH in the gap
- Pair it in a GW source with dynamics

di Carlo *et al.* 20a

See also Spera *et al.* 19, di Carlo *et al.* 19, 20b, see also Kremer *et al.* 20, Mapelli *et al.* 20, Renzo *et al.* 20c

Four challenges of the "stellar merger scenario"



- Mass loss (and rejuvenation) **?** Assumed zero
- Wind and eruptions **?** Assumed zero
- Loss of envelope at core-collapse **?**

  Because of ν losses – Assumed zero

  see Nadhezin 1980, Lovegrove & Woosley 2013

- Need dynamics to pair with 2^{nd} BH

  $\Downarrow$

  Requires nuclear cluster and/or AGN disk?

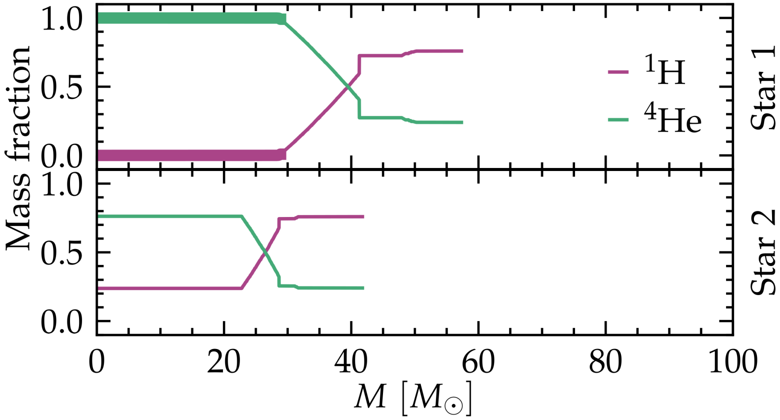
di Carlo *et al.* 20a

See also Spera *et al.* 19, di Carlo *et al.* 19, 20b, see also Kremer *et al.* 20, Mapelli *et al.* 20, Renzo *et al.* 20c

Part 2: Making forbidden BHs ?

Oversimplified MESA mergers

Merger model: the pre-merger stars



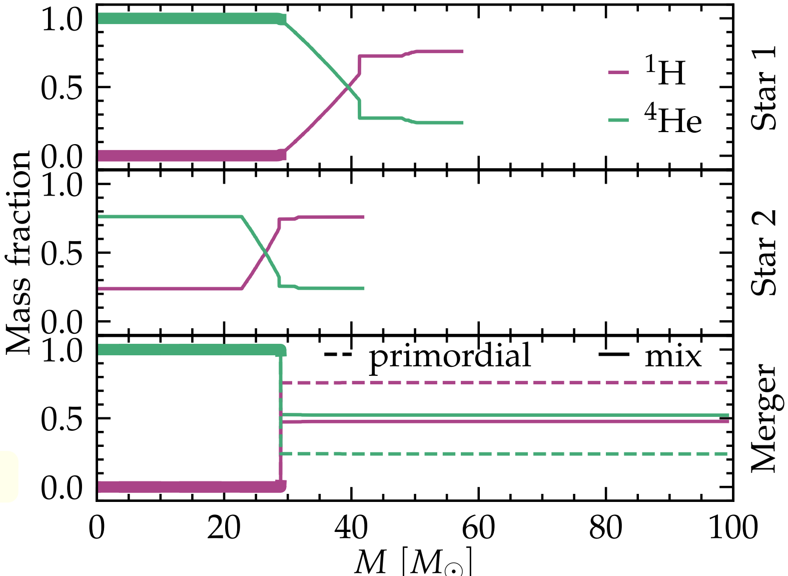
$58\,M_\odot$

$42\,M_\odot$

$Z = 2 \times 10^{-4}$

Renzo, Cantiello *et al.* 20

Merger model: composition of the merger



$58\,M_\odot$

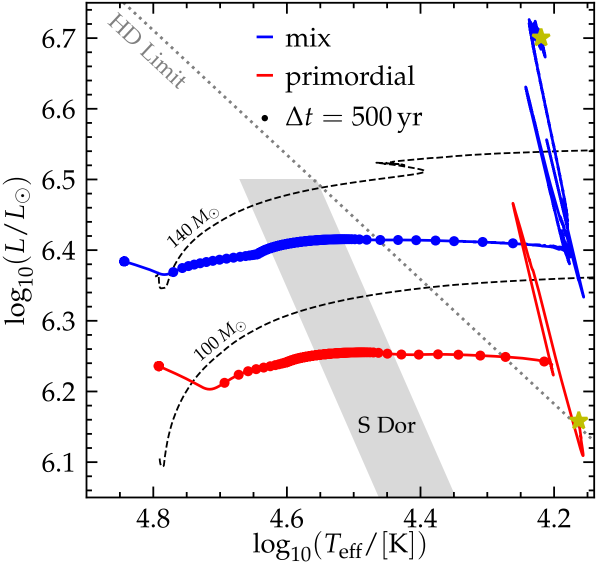
$42\,M_\odot$

$99\,M_\odot$

$Z = 2 \times 10^{-4}$

Renzo, Cantiello *et al.* 20

Merger products are He-rich and blue ⇒ envelope instabilities?



Renzo, Cantiello *et al.* 20

Very massive stars are hardly stable

- $\sim 10^5$ years in S Dor instability strip
- reach core-collapse as BSG

⇓

- LBV eruptions, helped by He opacity?

Jiang *et al.* 18

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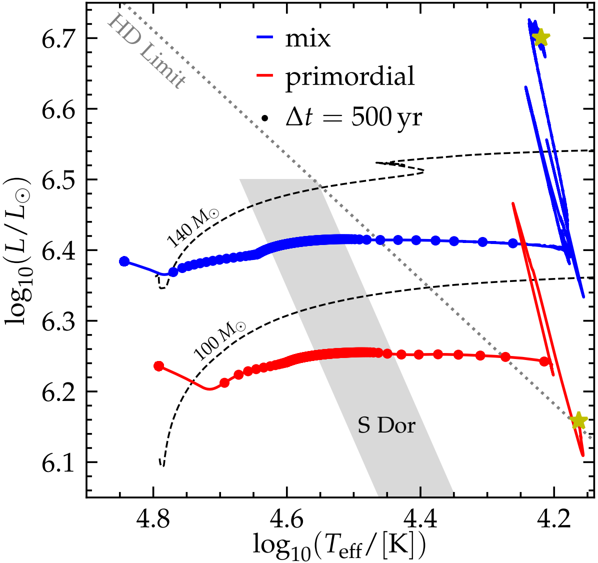

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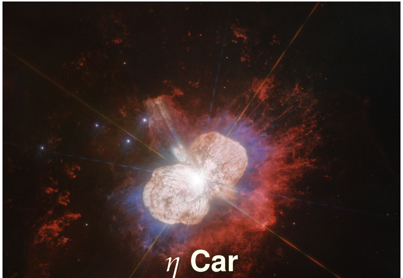


Hirai *et al.* 2021

Part 2: Making forbidden BHs ?

Envelope fate at BH formation

Do BHs form via a failed, weak, or full blown SN explosion?

$$\Delta E_\nu \simeq 10^{53}\ \mathrm{erg}$$

Possible causes for mass ejection at BH formation:

- ν-driven shocks

  Nadhezin 1980, Lovegrove & Woosley 2014, Fernandez *et al.* 2018, Ivanov & Fernandez 2021

- Jets and disk wind

  (even without net rotation)

  Gilkis & Soker 2014, Perna *et al.* 2018, Quataert *et al.* 2019

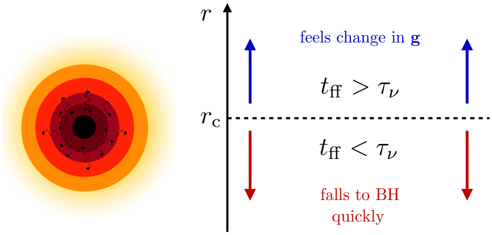
- (weak) fallback powered explosion

  Ott *et al.* 2018, Kuroda *et al.* 2018, Chan *et al.* 2020, Powell *et al.* 2021

see also Adams *et al.* 2017 for possible EM counterpart to BH formation

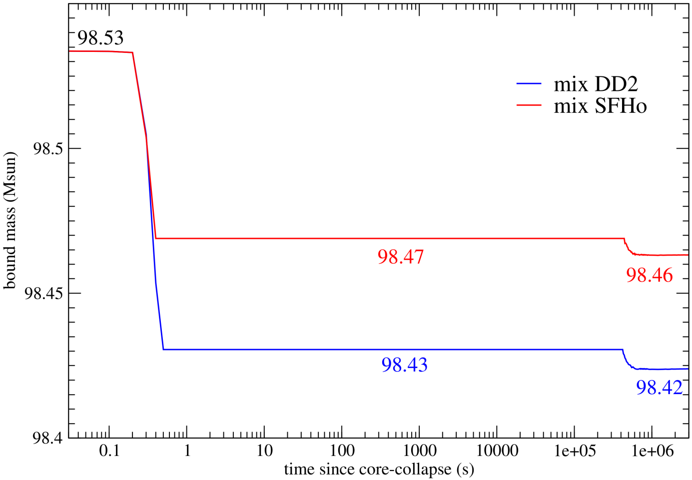
Accretion disks and ν-driven shocks remove little mass for BSG

$$M_{\mathrm{BH},0} \simeq M_{\mathrm{core}} - E_\nu / c^2$$



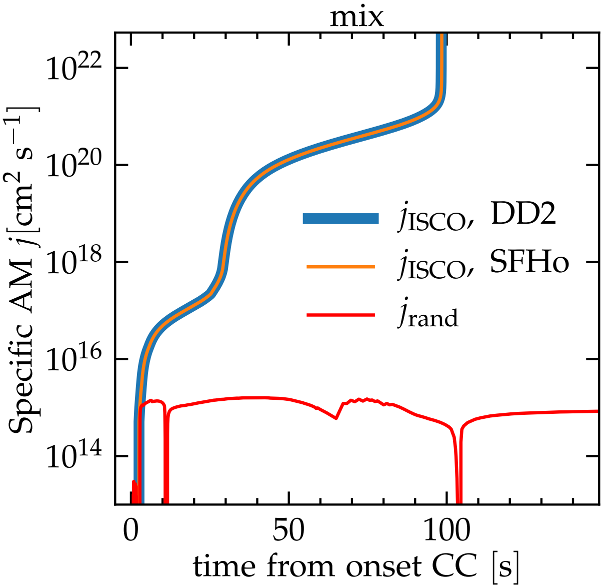
Fernàndez *et al.* 2018

MESA → GR1D+FLASH credits: R. Fernàndez



Nadhezin 1980, Lovegrove & Woosley 2013, Piro *et al.* 2013, Coughlin *et al.* 2018, Fernàndez *et al.* 2018, Ivanov & Fernàndez 2021

Can convective random motion cause disk formation and collapsar?



$$j_{\rm rand} = \frac{H_p v_{\rm conv}}{\sqrt{4\pi}}$$

c.f. Gilkis & Soker *et al.* 14, Quataert *et al.* 19

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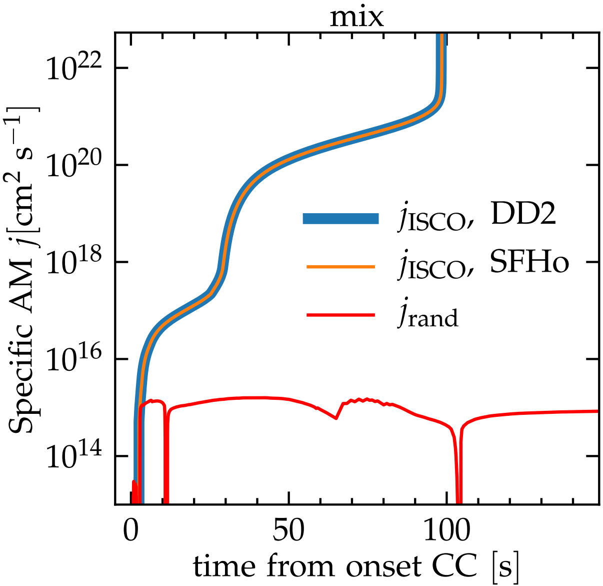


$$j_{\rm rand} = \frac{H_p v_{\rm conv}}{\sqrt{4\pi}}$$

Not enough in non-rotating models

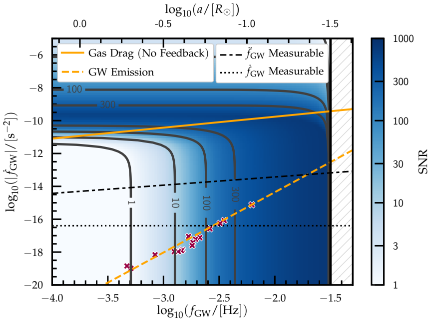
But the merger process might inject AM

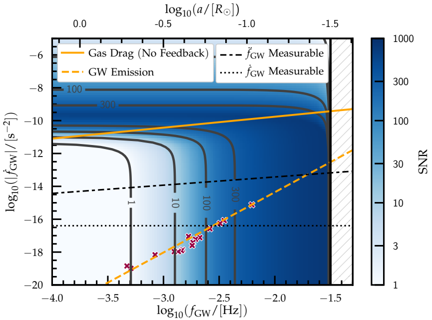
c.f. Gilkis & Soker *et al.* 14, Quataert *et al.* 19

Conclusions

Future: LISA might detect Galactic CE

(or rule out existing models with non-detections)





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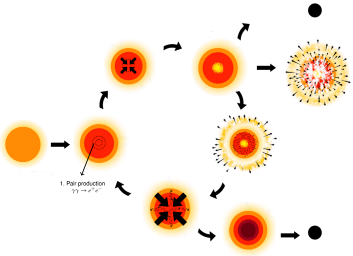
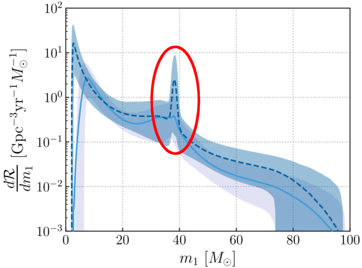
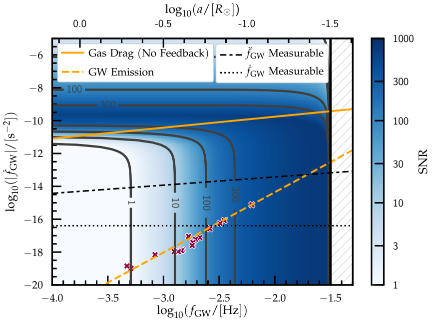


Present:

GW detections of BBHs...



...provide first uncontroversial evidence for PPI



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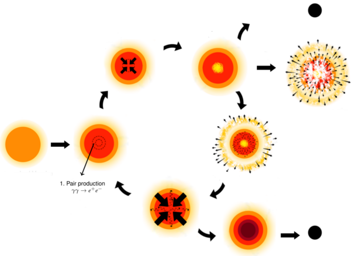

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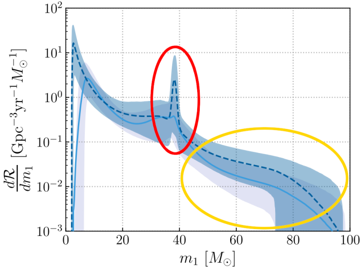
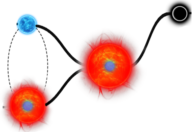


...provide first uncontroversial evidence for PPI

$\Rightarrow$ require **dynamics** and, if merging stars,

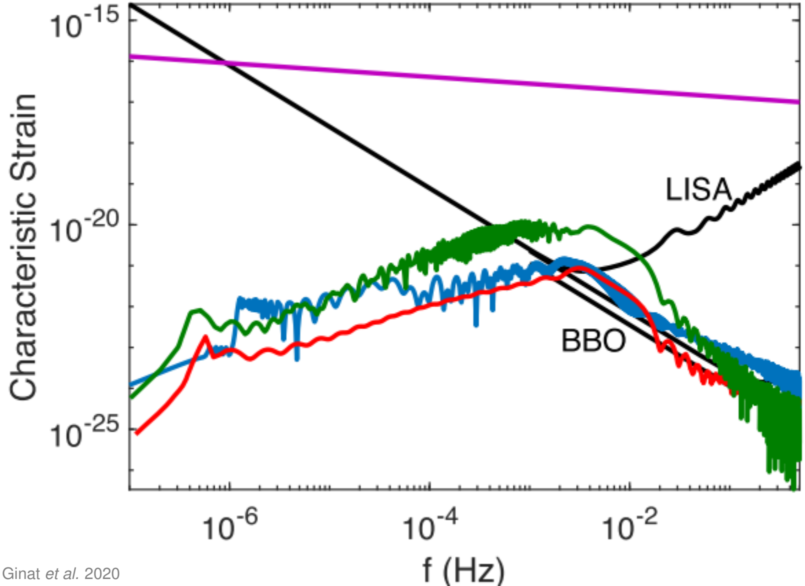
unperturbed core & full envelope fallback

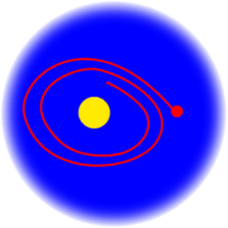
but better stellar merger models needed



Backup slides

Dynamical phases are loud but short and thus rare

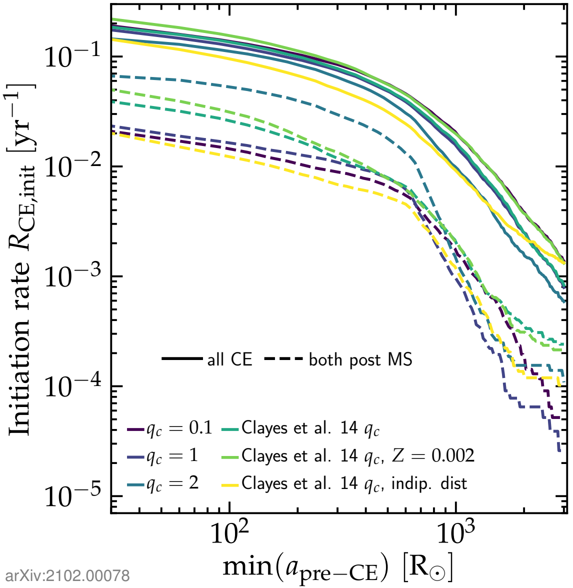


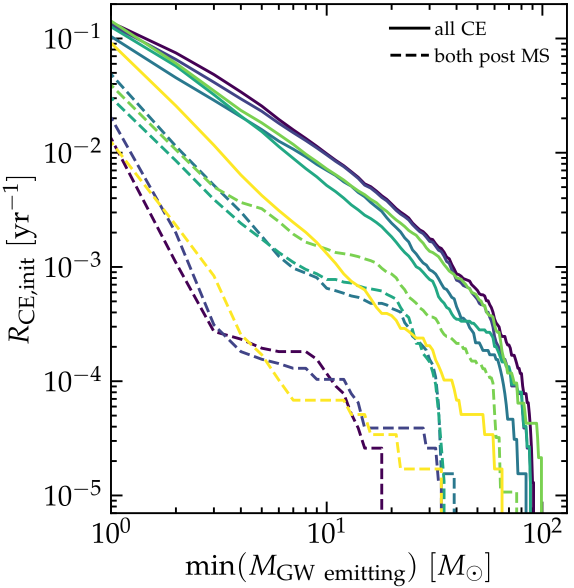


Requires massive donor star

Ginat *et al.* 2020

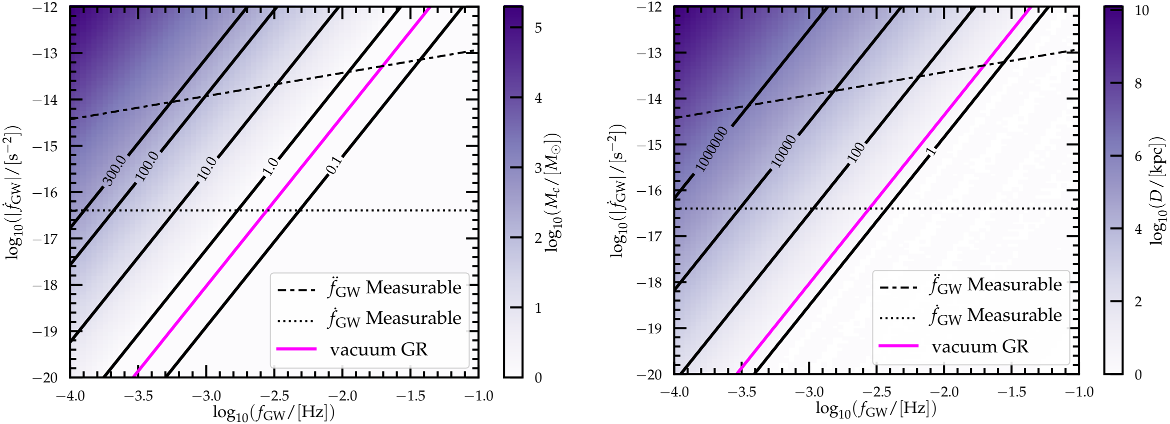
Rate of common-envelope initiation with pre-CE separation





arXiv:2102.00078

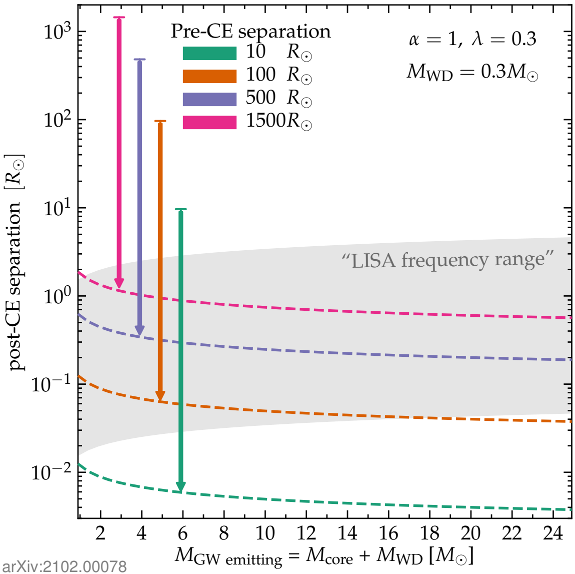
“Stealth bias” assuming GR in vacuum: chirp mass & distance

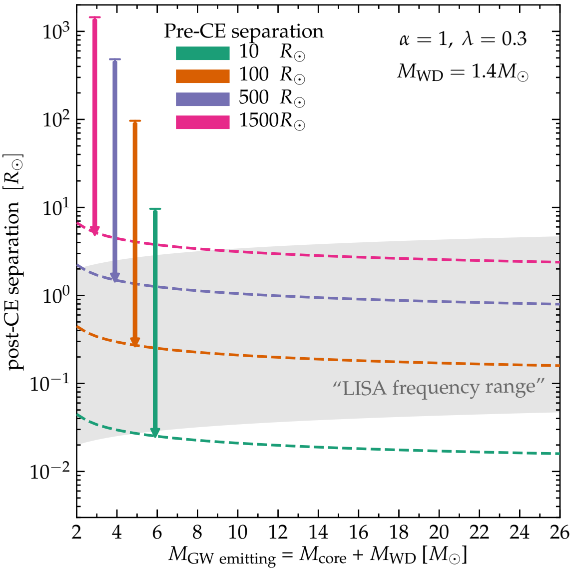


“Braking index” $n = f\ddot{f}/\dot{f}^2 \Rightarrow n_{GR} = \frac{11}{3}$

arXiv:2102.00078

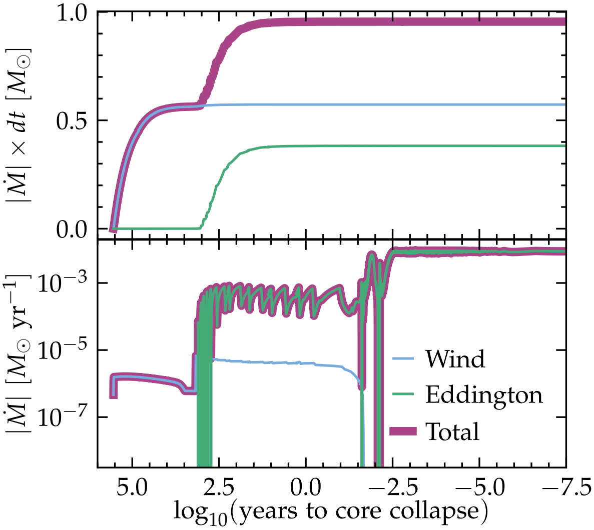
Most common envelope events cross the LISA band





arXiv:2102.00078

The estimated radiation-driven mass loss is not significant



$$\dot{M} = \frac{L - L_{\mathrm{Edd}}}{v_{\mathrm{esc}}^2}$$

$L > L_{\mathrm{Edd}}$ only for few 100 years

(higher $Z \Rightarrow$ higher $\kappa \Rightarrow$ higher $\dot{M}$)

Renzo, Cantiello *et al.* 20

Filling the PISN BH mass gap

pre-BH formation

post-BH formation

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pre-BH formation

post-BH formation

Move the gap

- decrease by $\sim 2.5\sigma$ the $^{12}C(\alpha, \gamma)^{16}O$

Farmer et al. 20, Belczynski 20

- beyond standard model physics

Choplin *et al.* 17, Croon*et al.* 20a,b, Sakstein *et al.* 20,

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Avoid pair-instability

- stellar merger scenario

Spera & Mapelli 2019, di Carlo *et al.* 19, 20a, 20b, Renzo *et al.* 20c

- decrease overshooting (in pop. III)

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- PBHs before re-ionization — de Luca *et al.* 2020
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Multiple generations of BBH mergers

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McKernan *et al.* 12, Bartos *et al.* 17, Stone *et al.* 19

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"Impostor" GW events: High eccentricity merger? Lensing?