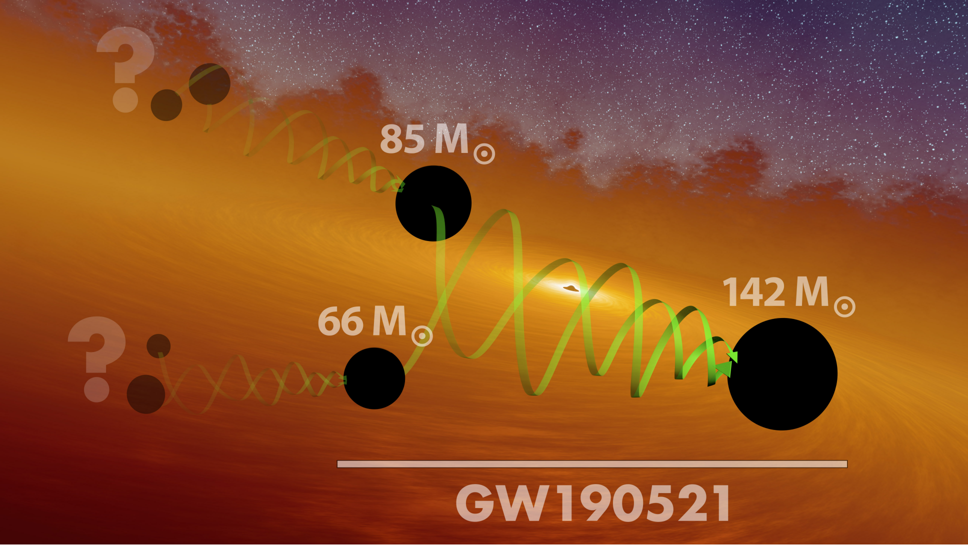


Pulsational Pair Instability

or why these black holes can't come from stars

Mathieu Renzo

Radiation pressure dominated:

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

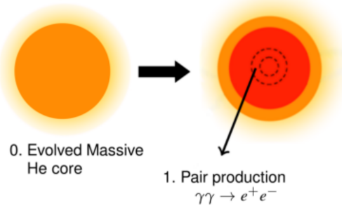
0. Evolved Massive
He core

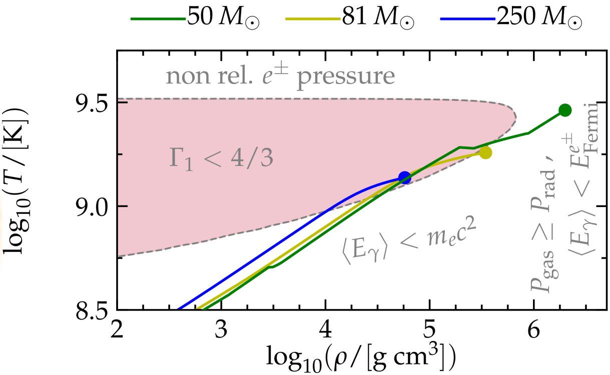
$$M_{\rm He} \gtrsim 32\,M_\odot$$

Pair-instability SNe are the best understood supernovae

see Fowler & Hoyle 1964, Rakavy & Shaviv 1967, Barkat *et al.* 1968, Fraley 1968, Glatzel *et al.* 1985, **Woosley** *et al.* 2002, 2007, Langer *et al.* 2012, Chatzopoulos *et al.* 2012, 2013, Yoshida *et al.* 2016, Woosley 2017, 2019, Leung *et al. 2019*, etc...

Renzo, Farmer *et al.* 2020b

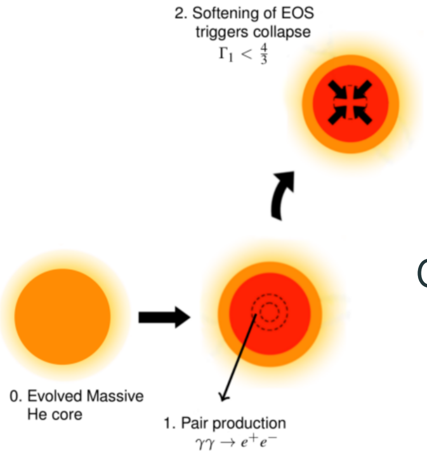




$$\Gamma_1 \stackrel{\mathrm{def}}{=} \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$$

Renzo, Farmer *et al.* 2020b

He cores computed with MESA

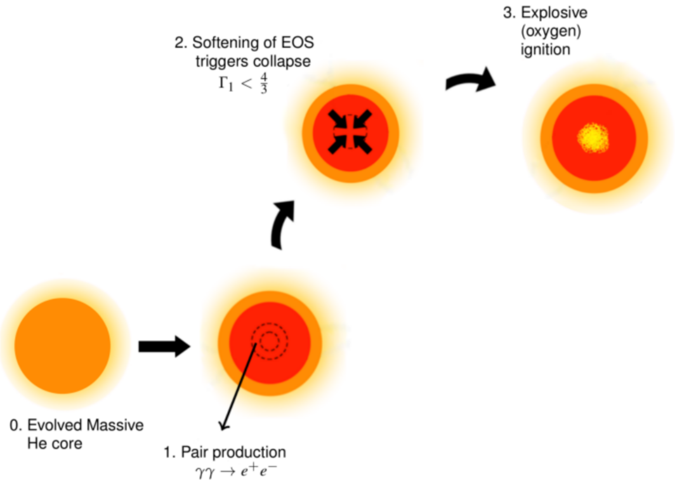


Collapse on thermal timescale

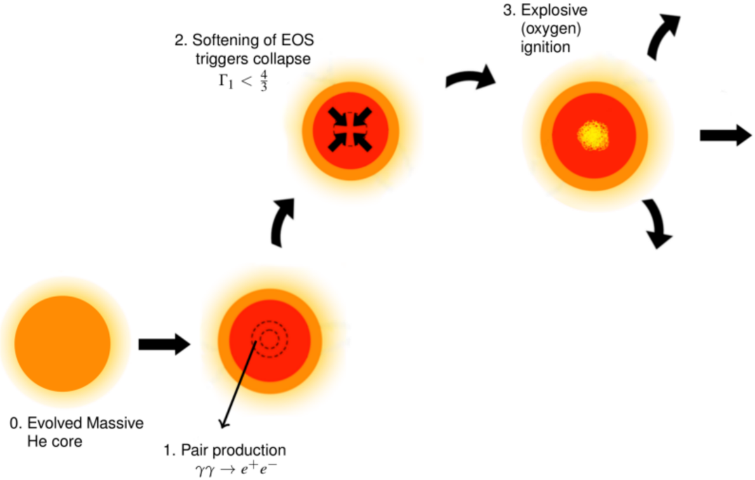
$$\tau \propto \frac{GM_{\mathrm{He}}^2}{RL_\nu} \quad , \quad L_\nu \gg L$$

(Fraley 68)

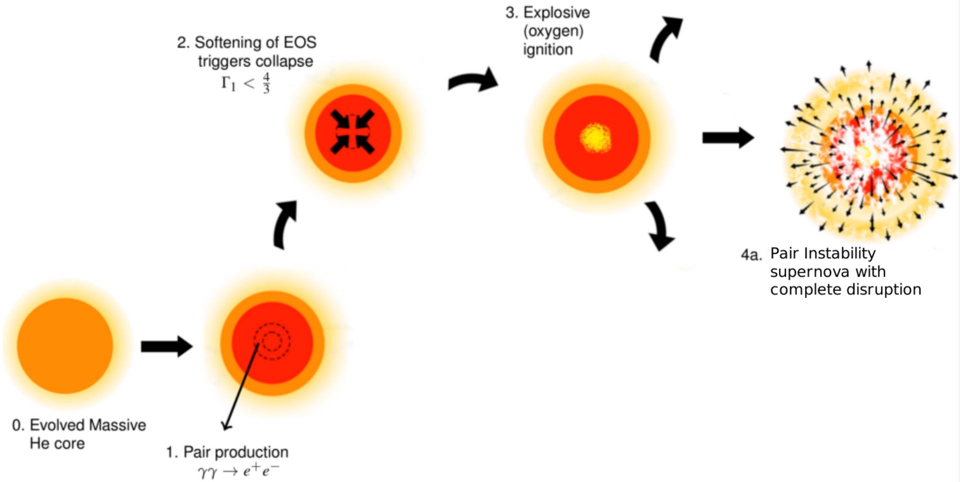
Renzo, Farmer *et al.* 2020b



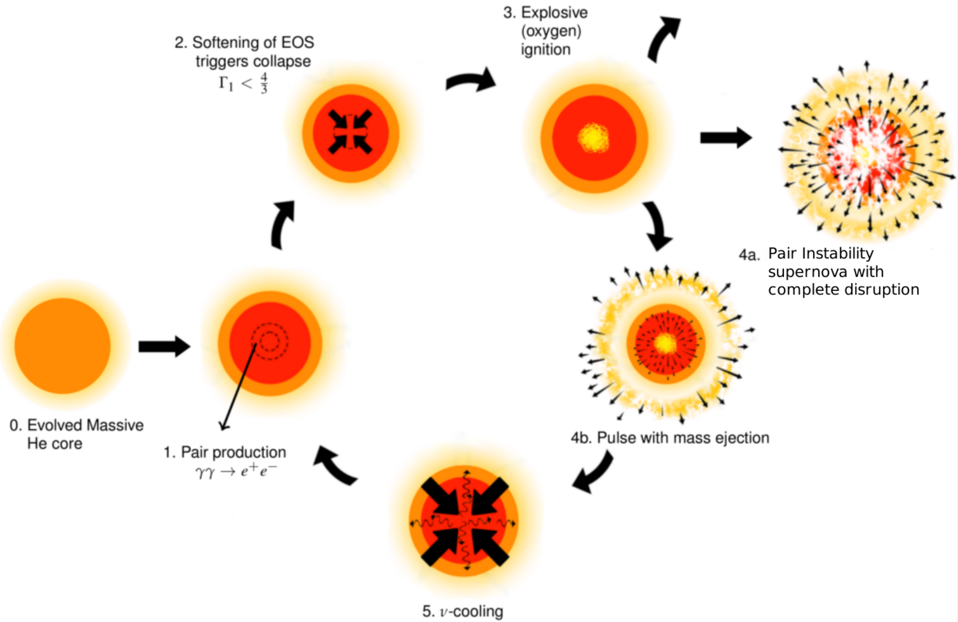
Renzo, Farmer *et al.* 2020b



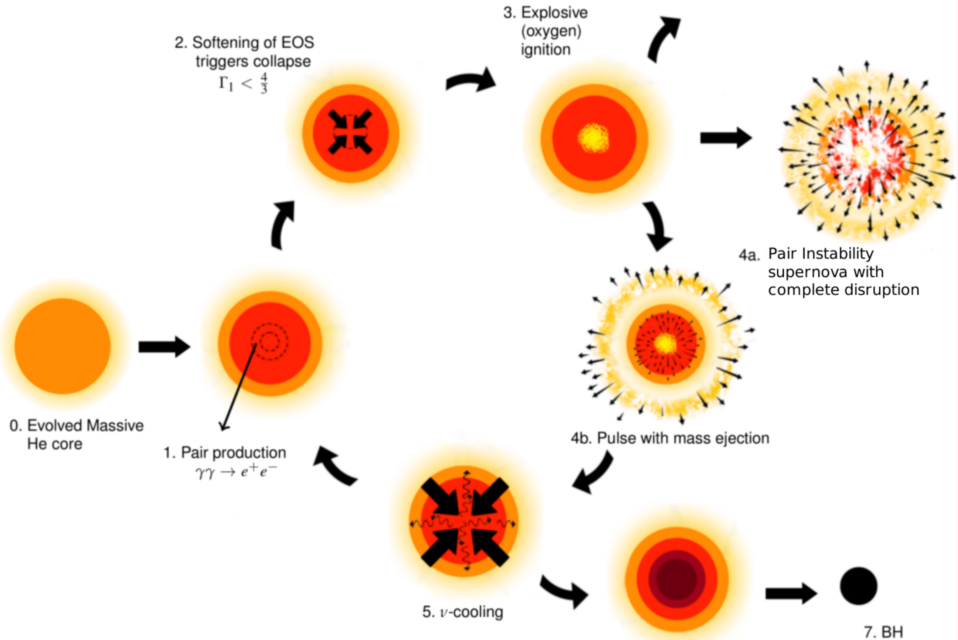
Renzo, Farmer *et al.* 2020b



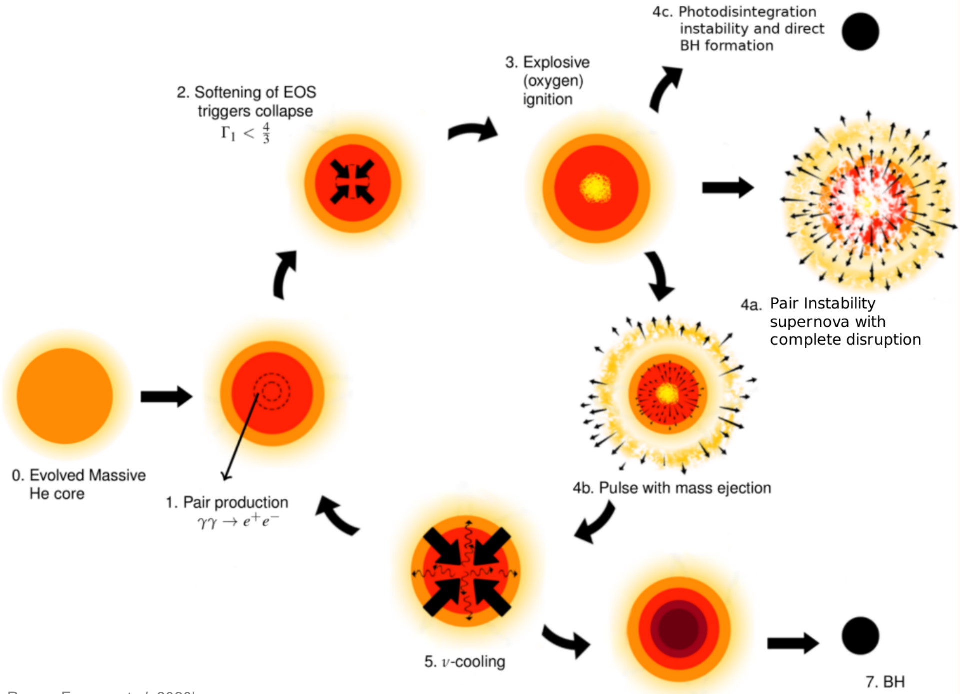
Renzo, Farmer *et al.* 2020b



Renzo, Farmer *et al.* 2020b



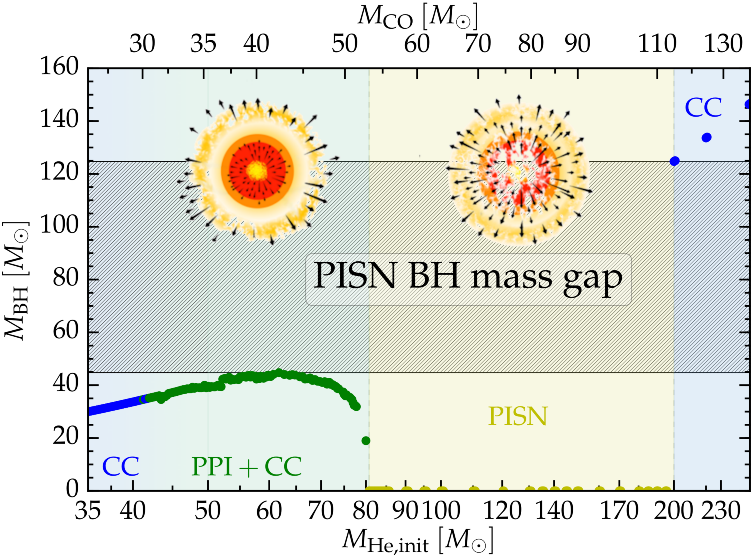
Renzo, Farmer *et al.* 2020b



Renzo, Farmer *et al.* 2020b

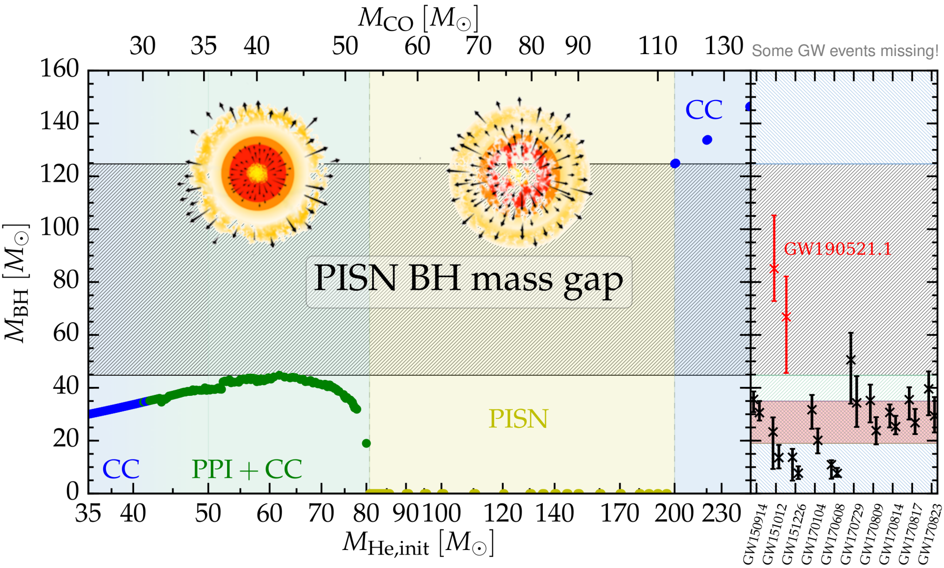
The pair-instability BH mass gap

The distribution of stellar BH masses



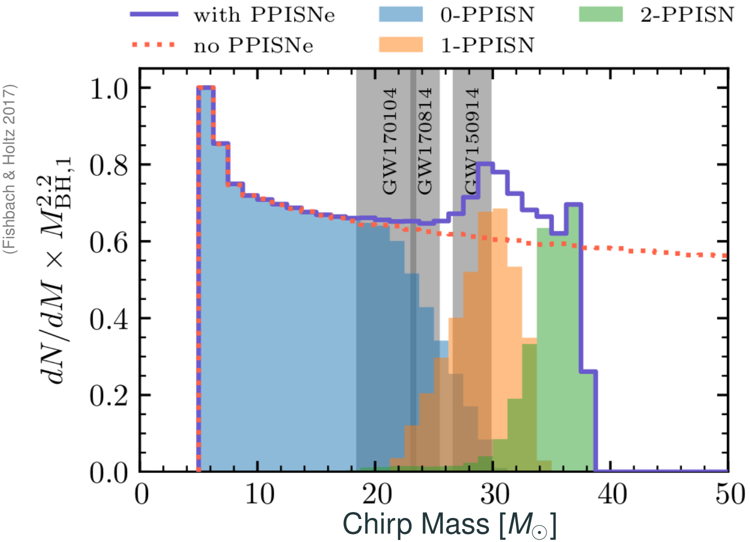
Renzo, Farmer, *et al.* 2020b

The distribution of stellar BH masses



Renzo, Farmer, *et al.* 2020b

Chirp mass distribution – weighted by LIGO's sensitivity



$$\frac{dN}{dM_{\rm BH}} \propto M_{\rm BH}^{-2.35}$$

$$q \geq 0.5$$

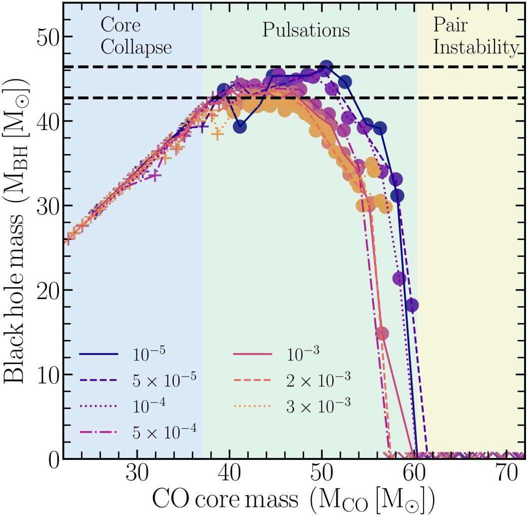
(motivated by LVC 2016)

Marchant, Renzo, *et al.* 2019

How robust is this prediction?

Metallicity? Small effect

Focus on lower edge of the gap



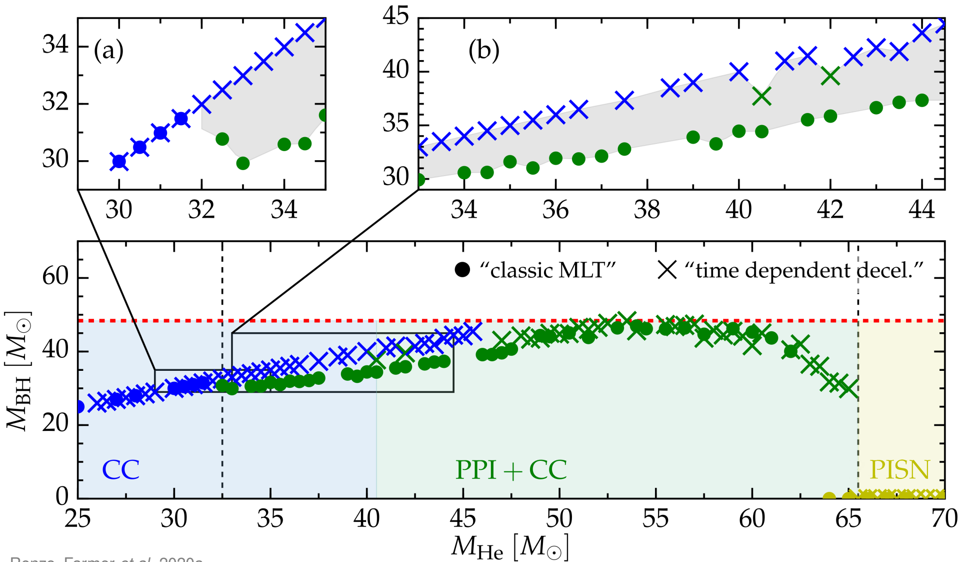
$\sim$7% shift over

2.5 orders of magnitude in Z

Farmer, Renzo *et al.* 2019

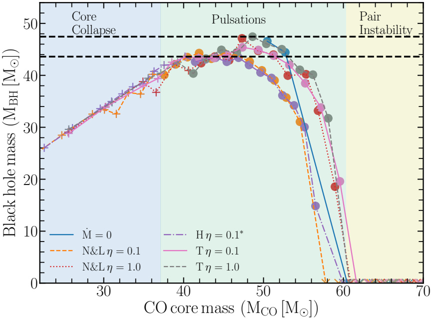
Treatment of time-dependent convection? Not the edge

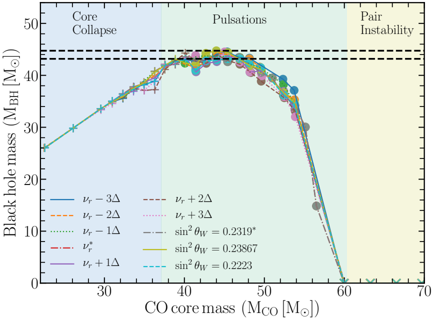
Matters for least massive PPI, not for the most massive BH

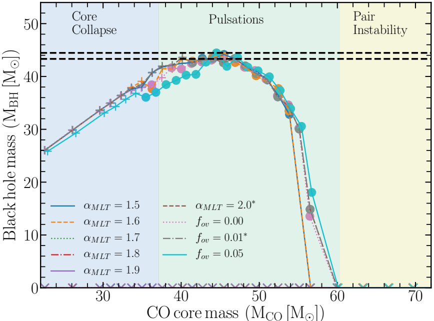


Renzo, Farmer *et al.* 2020a

Winds, mixing, ν physics? Also small effects



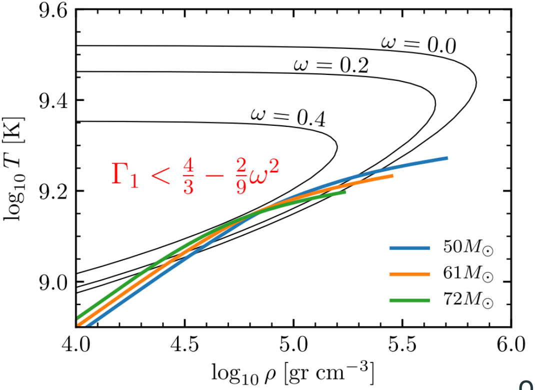




Farmer, Renzo *et al.* 2019

Can rotation move the gap? Barely...

Rotation can stabilize the core,
but sufficient rotation only for *very* extreme assumptions...



- No core-envelope coupling
- large initial rotation
- low Z ($\simeq$ no winds)

$\Downarrow$

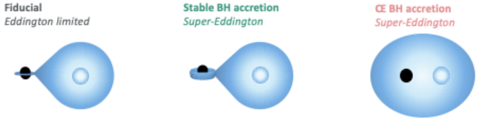
only $\sim$20% shift of gap, $\lesssim$4% for "realistic" core-envelope coupling

Marchant & Moryia 2020

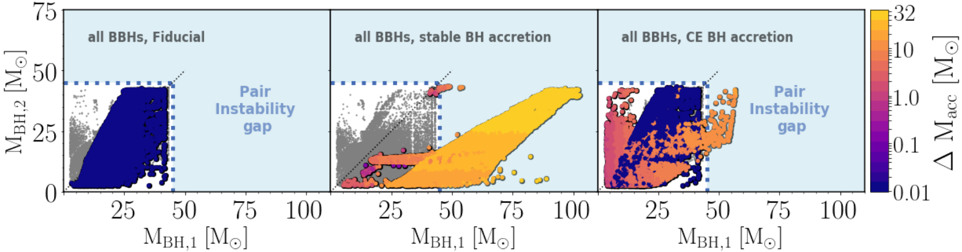
How robust is this prediction?

Does binarity move the gap?

Can isolated binary evolution "pollute" the gap?

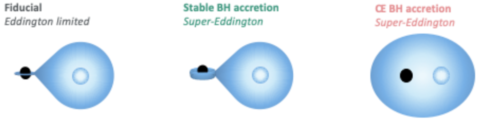


With unlimited accretion, some binary BHs can enter the gap...

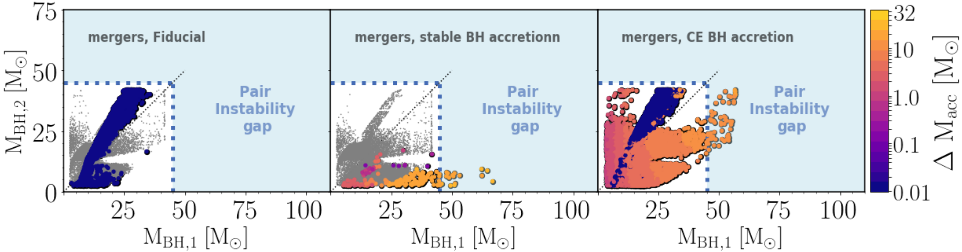


van Son *et al.*, incl. MR, 2020

Can isolated binary evolution "pollute" the gap?



... but those entering the gap don't merge within 13.7 Gyr



van Son *et al.*, incl. MR, 2020

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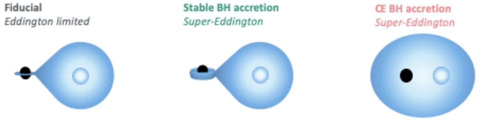

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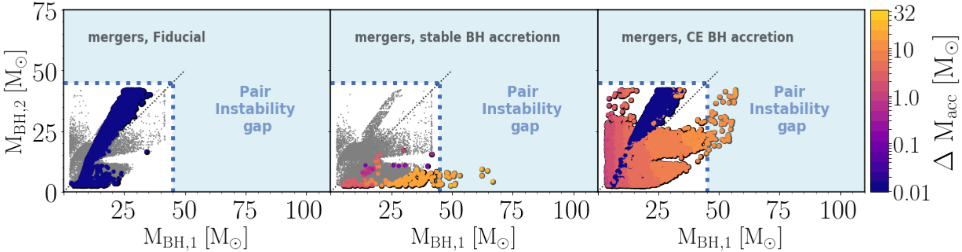


Mass accretion leads to orbital widening

With most optimistic assumptions:

- $\lesssim$ 1% systems with $M_{tot} \gtrsim 90\, M_\odot$
- No systems with $M_{tot} > 100\, M_\odot$

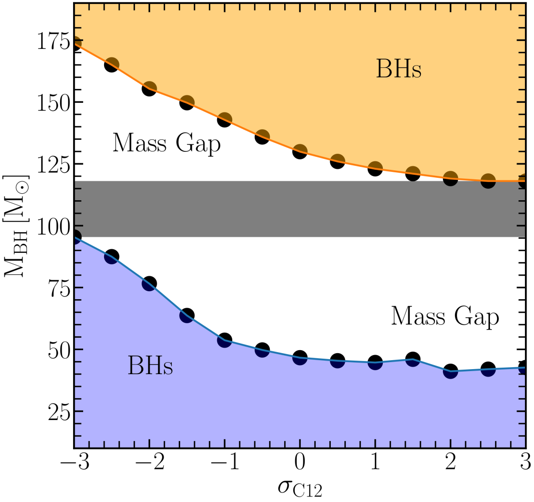
van Son *et al.*, incl. MR, 2020

The only known large uncertainty

Nuclear reaction rates

The most important reaction $^{12}C(\alpha, \gamma)^{16}O$ reaction rate

Change in C/O ratio ⇒ different C-shell behavior



GW can constrain nuclear rates with the gap...

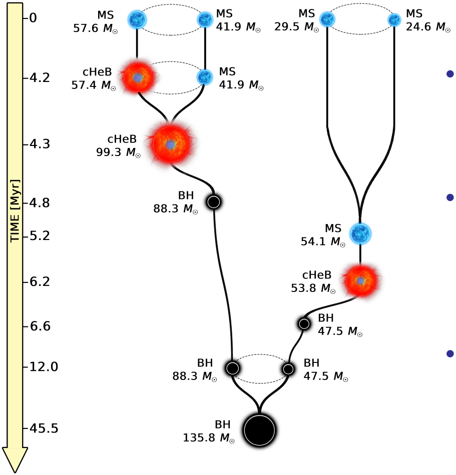
...if other channels don't pollute it too much

Farmer, Renzo *et al.* 2020, see also Takahashi 2018, Farmer, Renzo *et al.* 2019

Possible ways to bridge the gap

The *speculative* stellar merger scenario

Population synthesis assumptions *not quite* backed up by detailed models



- Mass loss during merger?
- Loss of envelope at core-collapse?

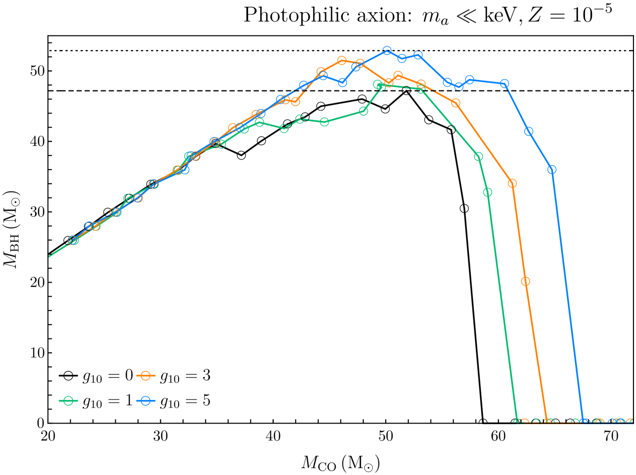
  see Nadhezin 1980, Lovegrove & Woosley 2013
- Need dynamics to pair with 2^{nd} BH

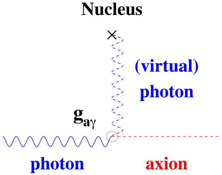
  ⇓

  Requires nuclear cluster and/or AGN disk?

di Carlo *et al.* 20, see also Mapelli *et al.* 20

Beyond standard model physics





Choplin *et al.* 17

Other possibilities:

- dark photons
- other axions
- change *G*
- ν magnetic moment
- extra dimensions

Effectively change the cooling during He core burning

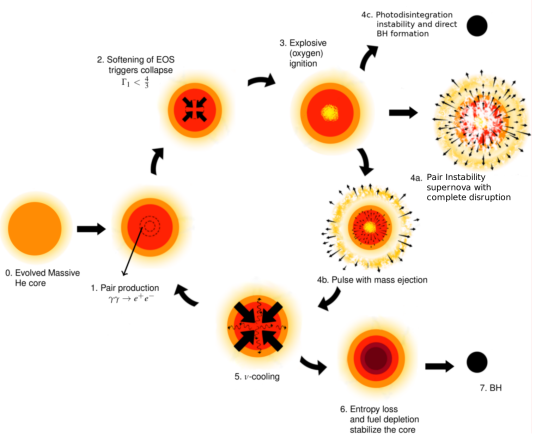
Changes C/O ratio, ρ-structure, decrease $P_{\rm rad}\,/\,P_{\rm tot}$

Croon *et al.* 20a, see also Croon *et al.* 20b, Sakstein *et al.* 20

Conclusions

PISN are the theoretically best understood SNe

although observationally elusive

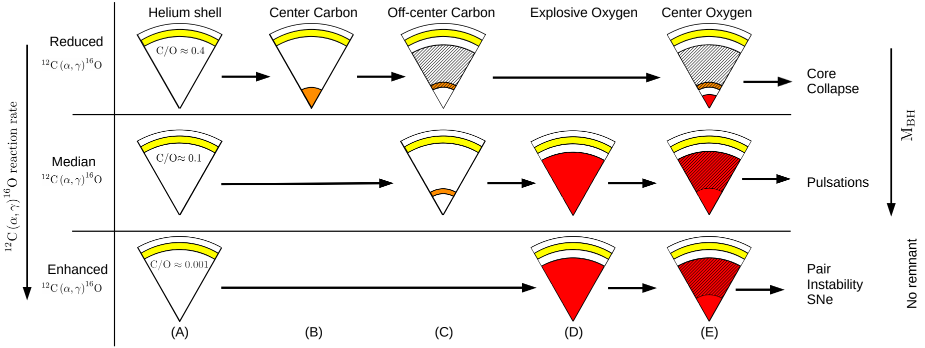


- PISN BH mass gap very robust prediction
- BH formation after PPI poorly understood
- Binary effect seem small
- Populating the gap requires non-stellar (2nd gen. +) BHs
  or
  new physics

Backup slides

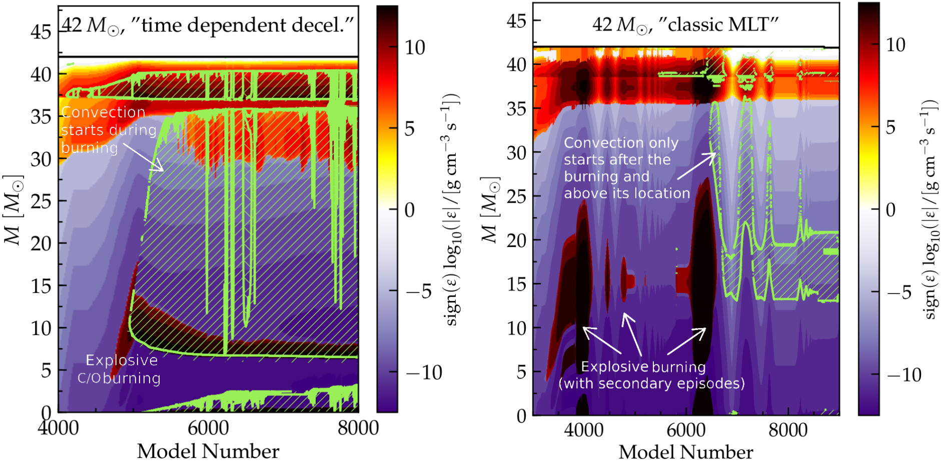
The $^{12}C(\alpha,\gamma)^{16}O$ ends He core burning

More $^{12}C \Rightarrow$ C shell burning delays ^{16}O ignition to higher ρ



Farmer, Renzo *et al.* 2020

Convection during the pulses quenches the PPI mass loss



Renzo, Farmer *et al.* 2020a