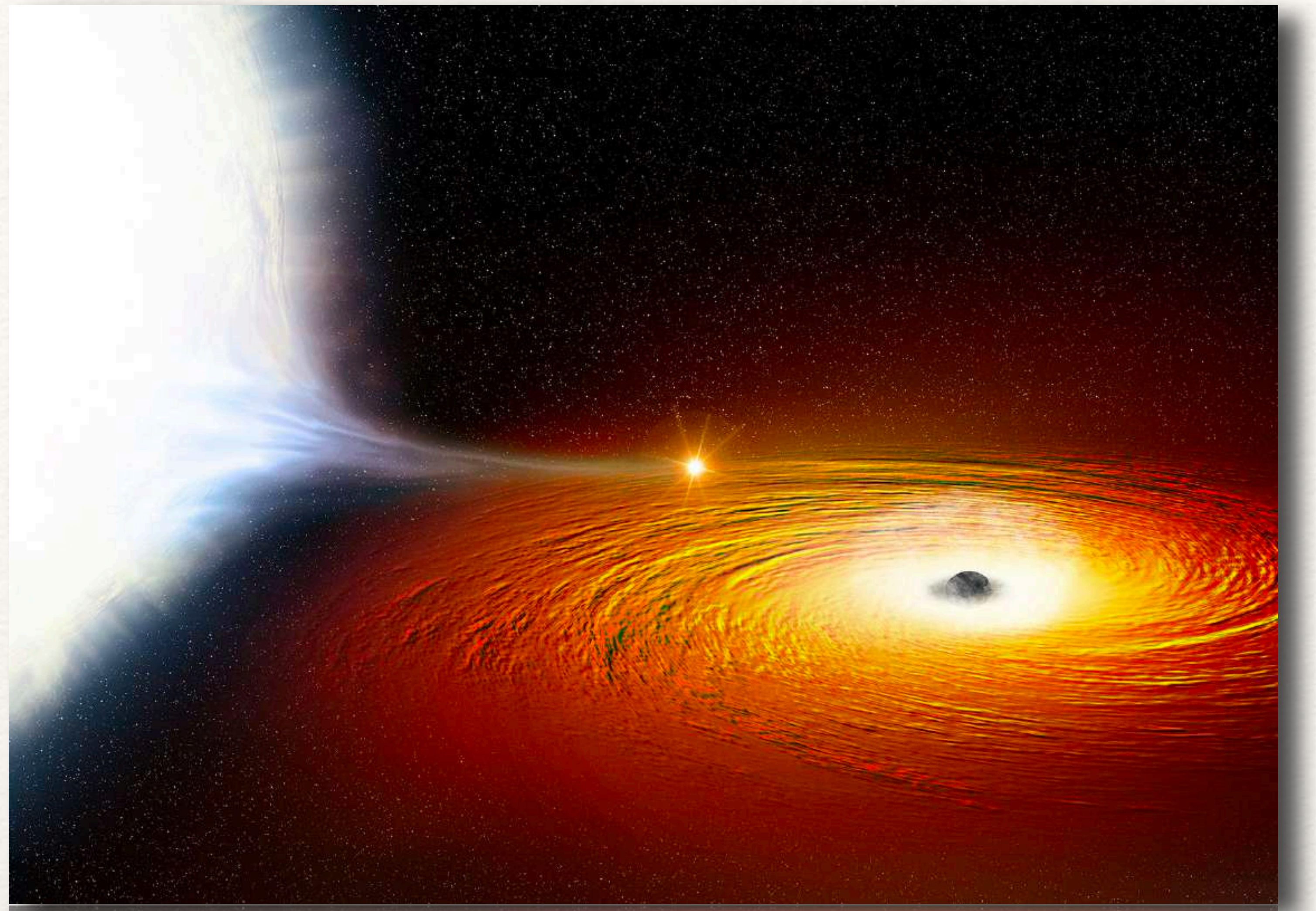

Stellar and super-stellar black holes

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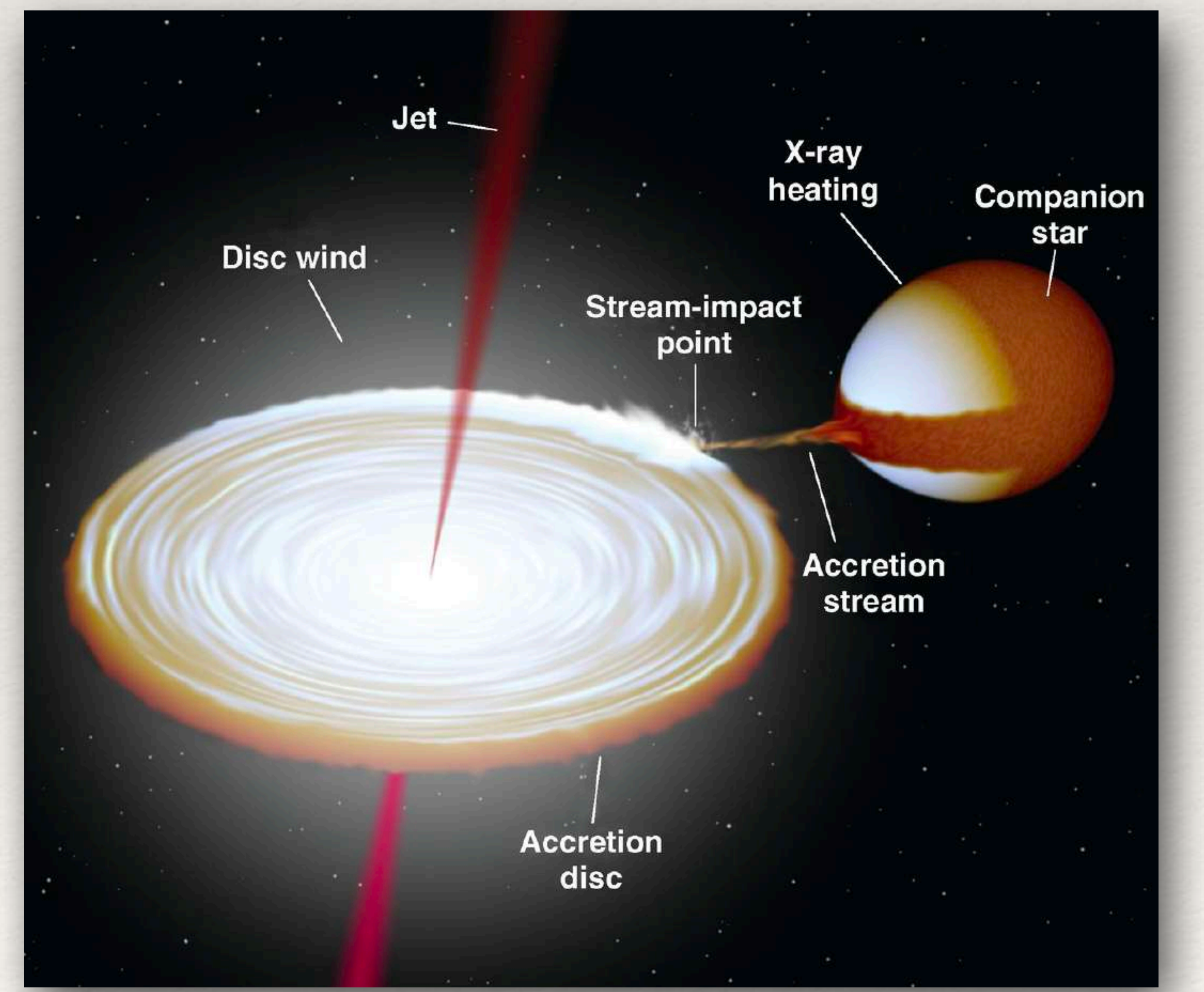
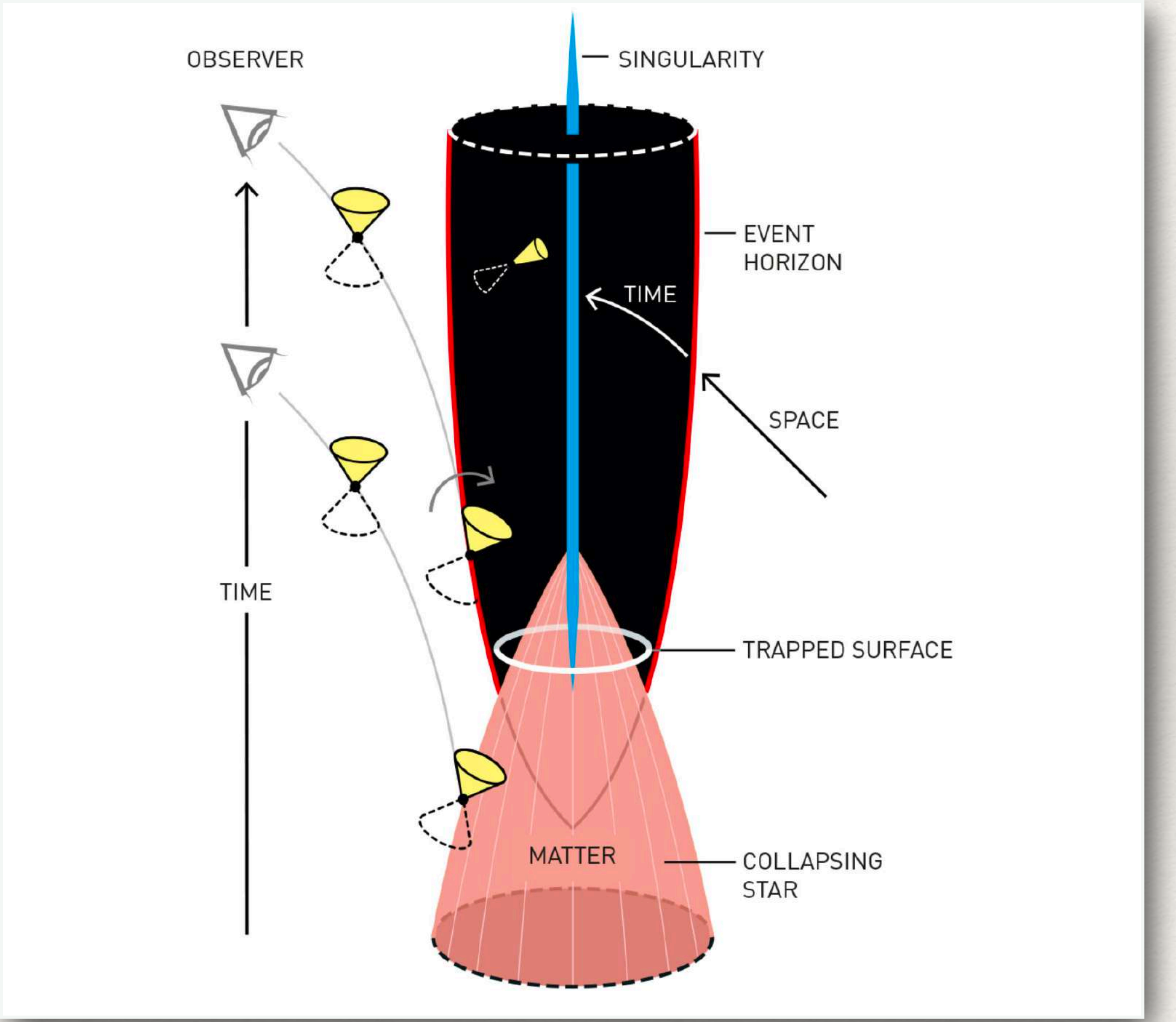
Argentina

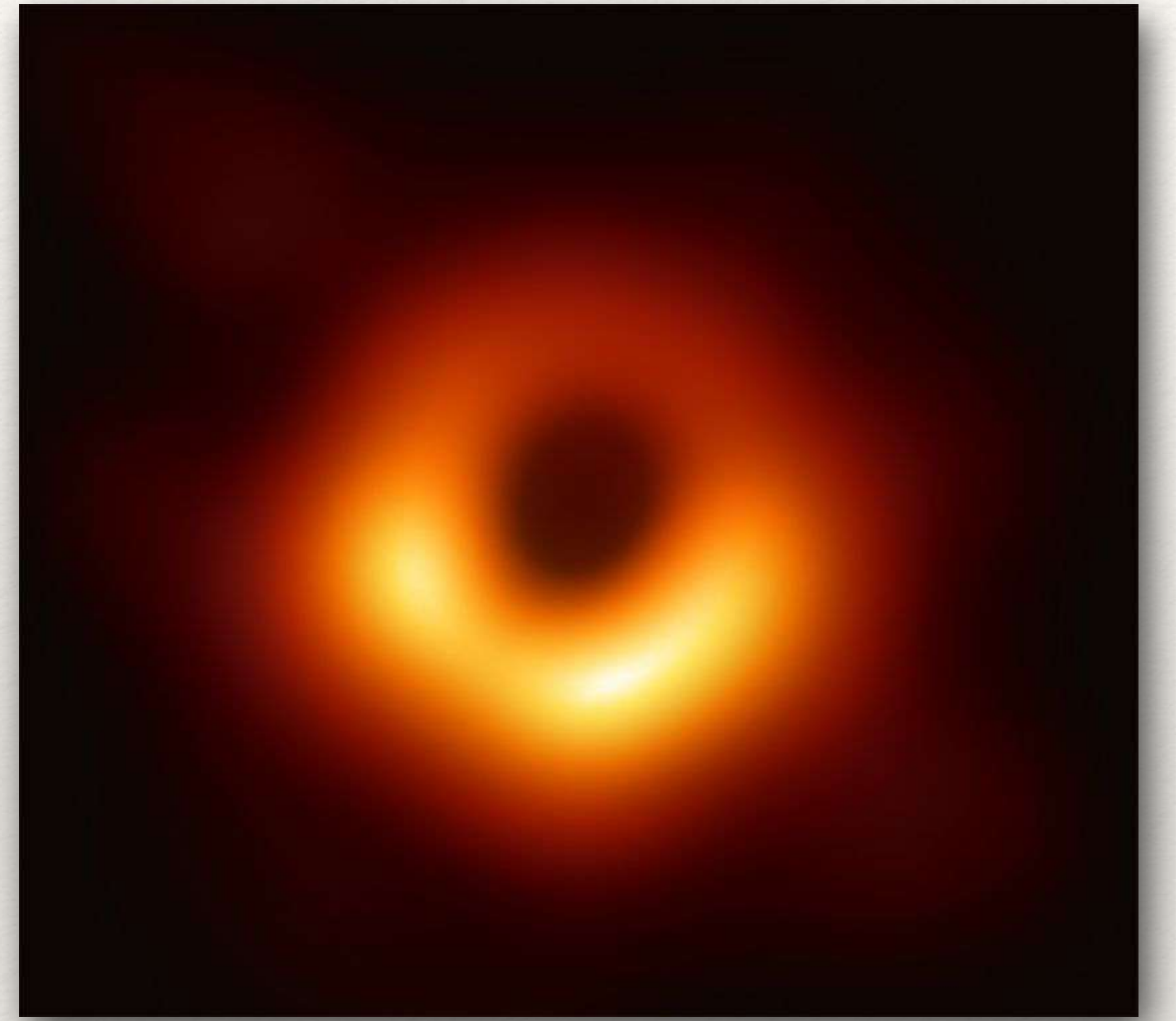
Astrophysical black holes are fully gravitationally collapsed objects

- First predicted by Oppenheimer & Snyder (1939).
- Seriously considered only after the discovery of QSOs in 1963
- Supermassive black holes: Salpeter (1964).
- X-ray binaries: Zeldovich (1964).

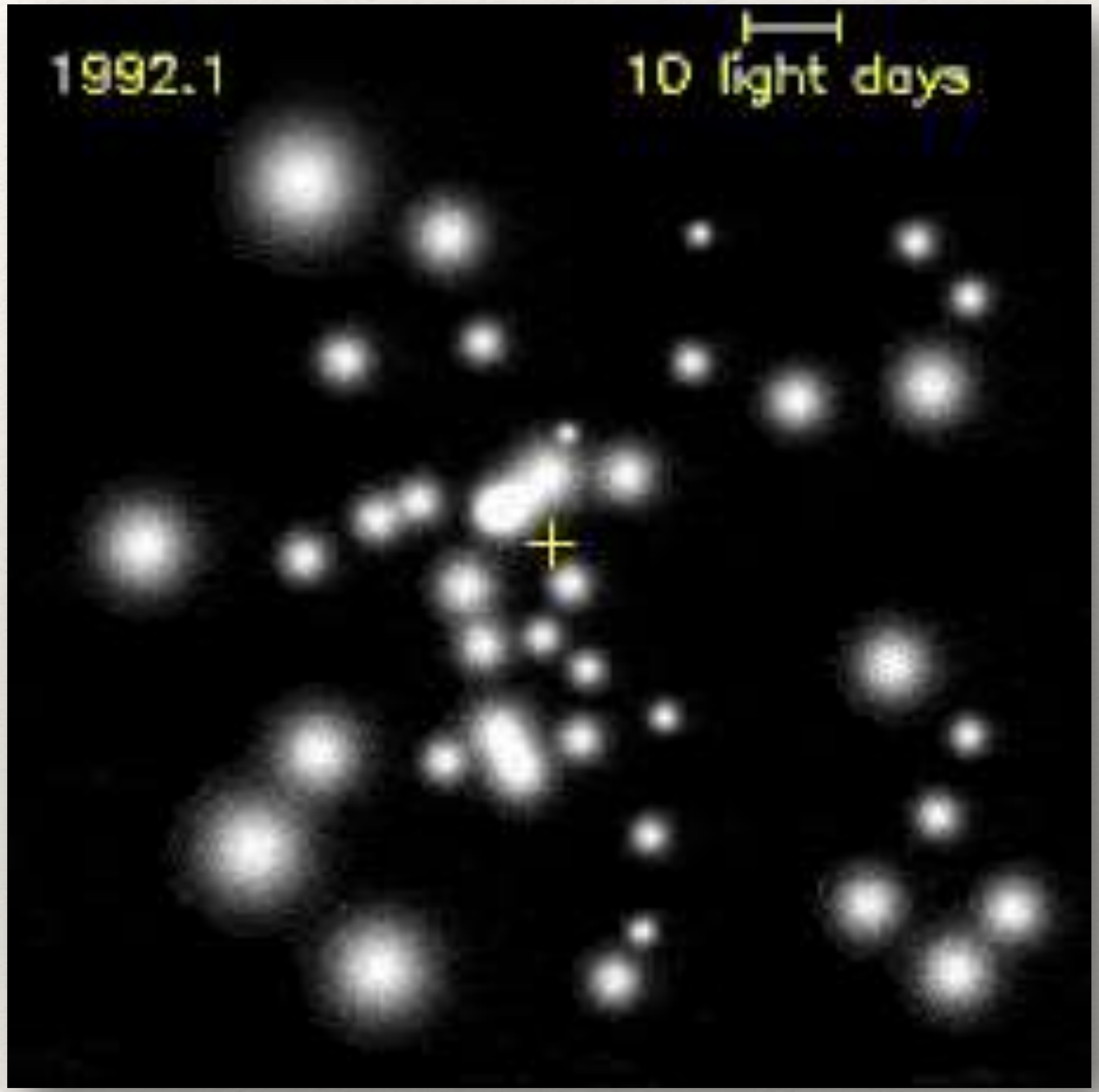




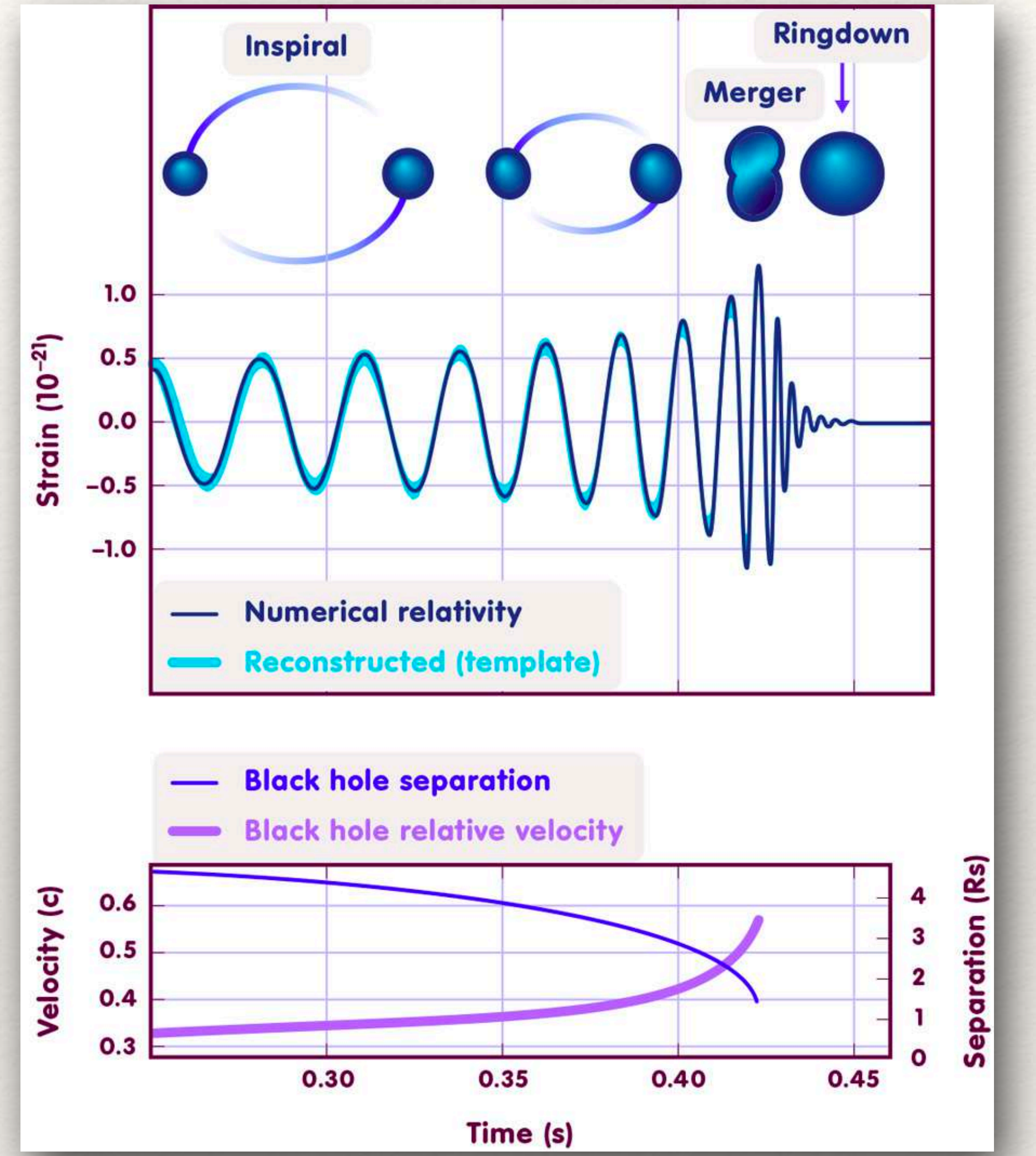
Astronomically, black holes (BHs) manifest through the emission of radiation by the accreting matter, the gravitational effect on nearby luminous bodies, or by generation of gravitational waves (GWs).



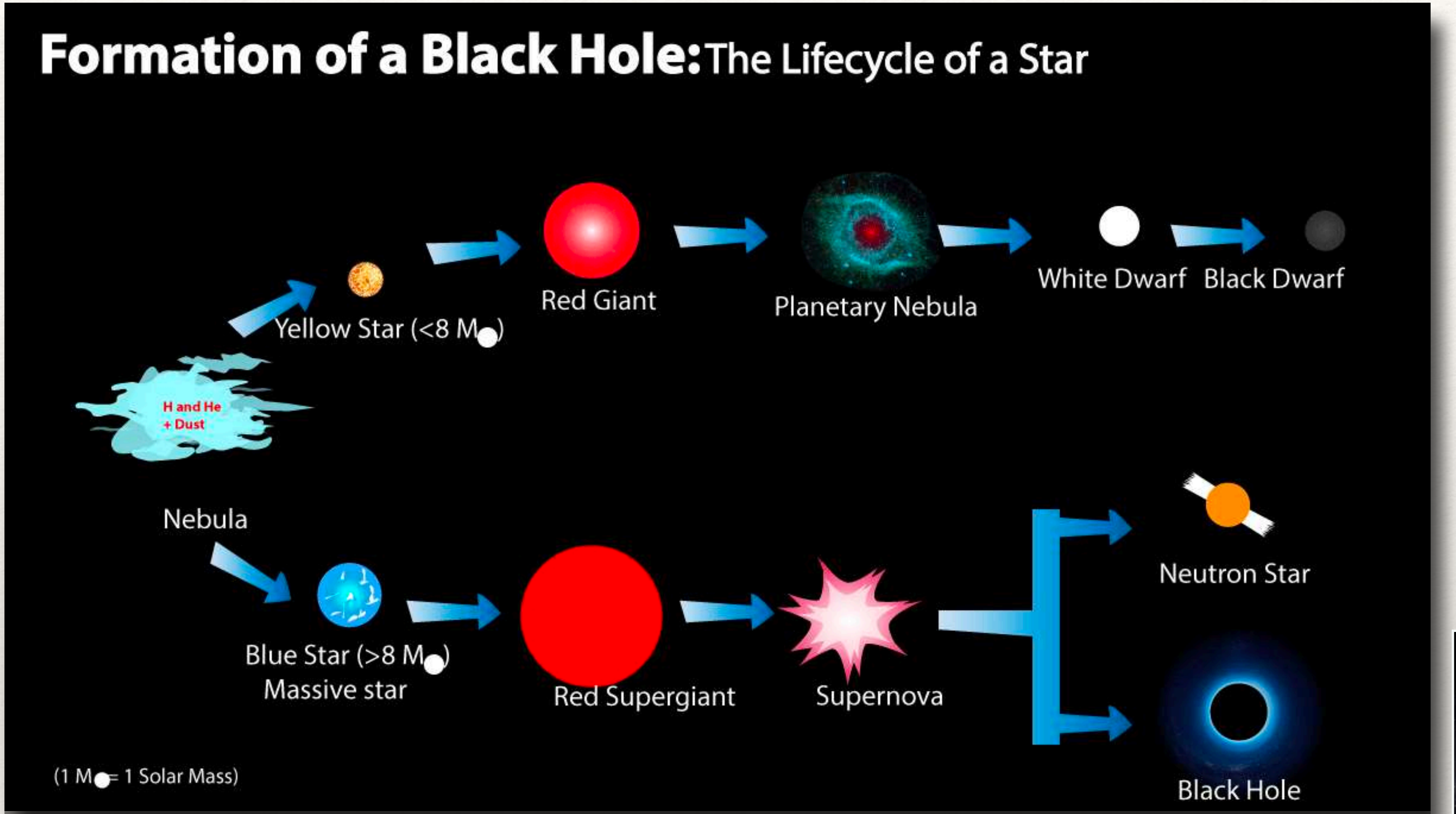
Sub-mm emission from the vicinity of the supermassive BH in M87 (EHT image)



Stars at the Galactic Center (Gravity collaboration)



BH binary merger in GWs (LIGO)



The mass function of BHs is highly uncertain, because it may be affected by a number of barely understood processes such as matter removal by supernova (SN) explosions and stellar winds.

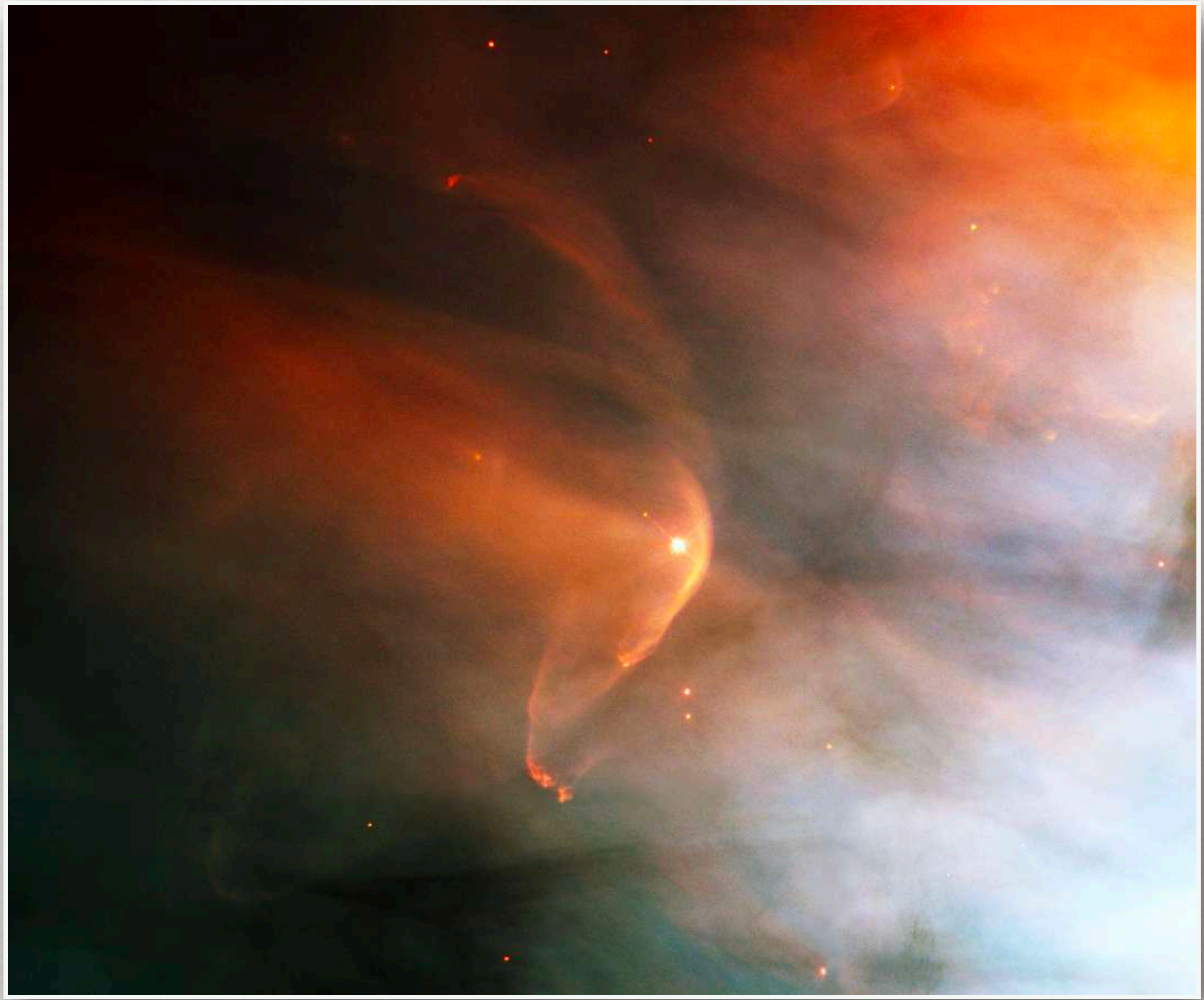
Supernova (SN) explosions

- As the thermonuclear burning proceeds and mass of the central degenerate core reaches the Chandrasekhar mass, the degeneracy pressure of relativistic electrons becomes insufficient to support it against collapse.
- Electrons are increasingly removed, because protons capture them producing neutrons and neutrinos. This takes the core into a new state, where matter is essentially composed of neutrons, which support the core against collapse by their degeneracy pressure.
- The core collapses from a radius of few thousand km down to a radius of few ten km in less than a second. The gravitational energy is huge ($\sim 10^{53}$ erg).
- This gravitational energy can be –at least partially– transferred to the stellar envelope triggering the SN explosion.
- The collapsing core drives a bounce shock. For the SN explosion to occur, this shock must reverse the supersonic infall of matter from the outer layers of the star. The details are barely known.
- Most of the energy in the shock consists in a flux of neutrinos. Most simulations use simply a "thermal bomb".

Pair Instability Supernovae

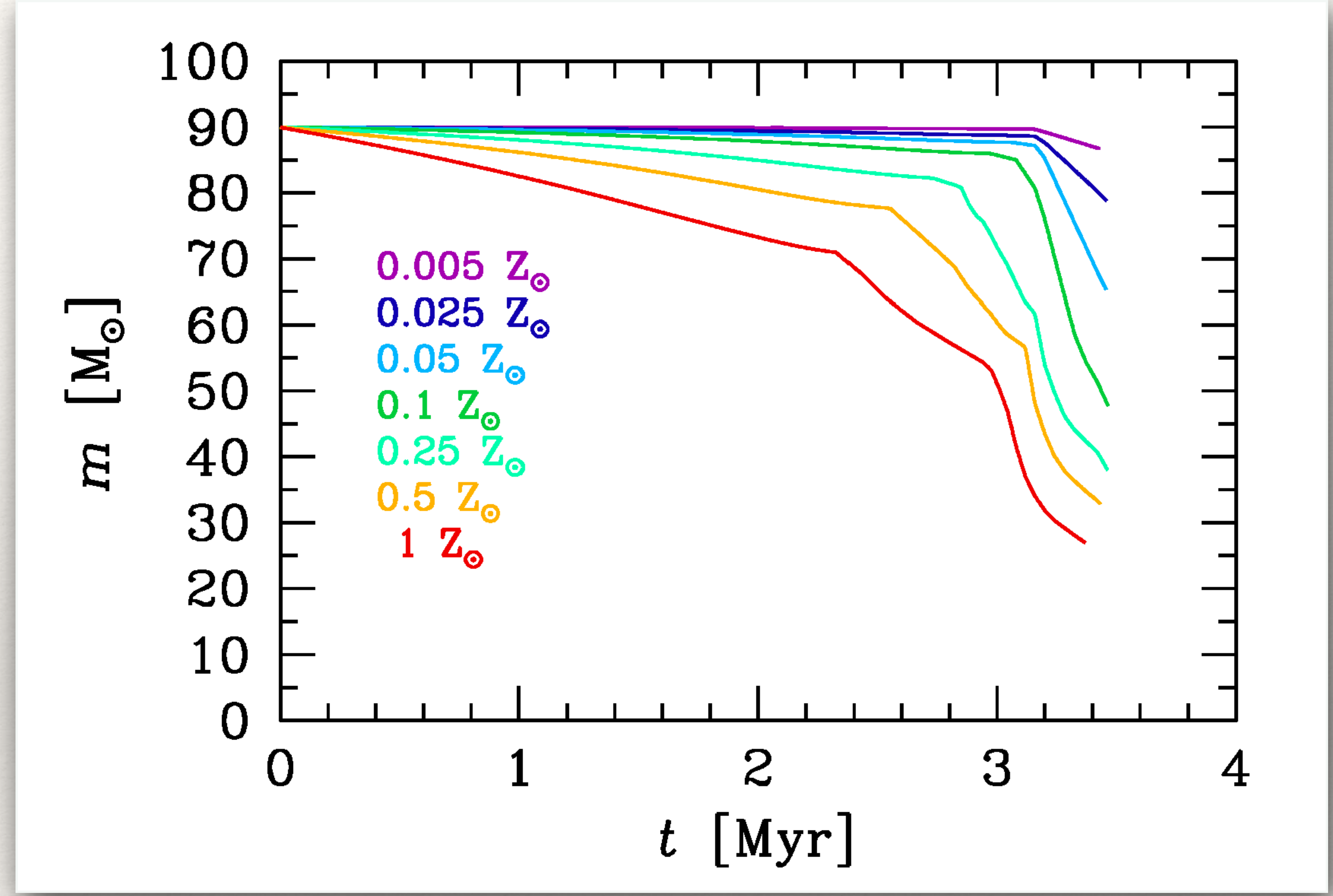
- If the helium core of a star grows above 30 M_{sol} and the core temperature is >7 10^{8} K at the end of carbon burning, the process of electron-positron pair production becomes effective.
- Energy from the collapse does not raise the temperature, but creates pairs.
- This process removes photon pressure from the core producing a sudden contraction of the carbon-oxygen core, before the formation of an iron core.
- For $m_{He} > 135\ M_{sol}$ the contraction cannot be reversed and the star collapses directly into a BH.
- For $64 < m_{He} < 135\ M_{sol}$, the collapse triggers an explosive burning of heavier elements, especially oxygen and silicon. This leads to a pair instability SN (PISN): the star is completely disrupted, leaving no compact remnant.
- For $32 < m_{He} < 64\ M_{sol}$, pair production induces a series of pulsations of the core (pulsational pair instability), which trigger an enhanced mass loss.
- The main effect of (pulsational) pair instability is to **open a gap in the mass spectrum of BHs between approximately 50 and 120 M_{sol}.**

Stellar winds

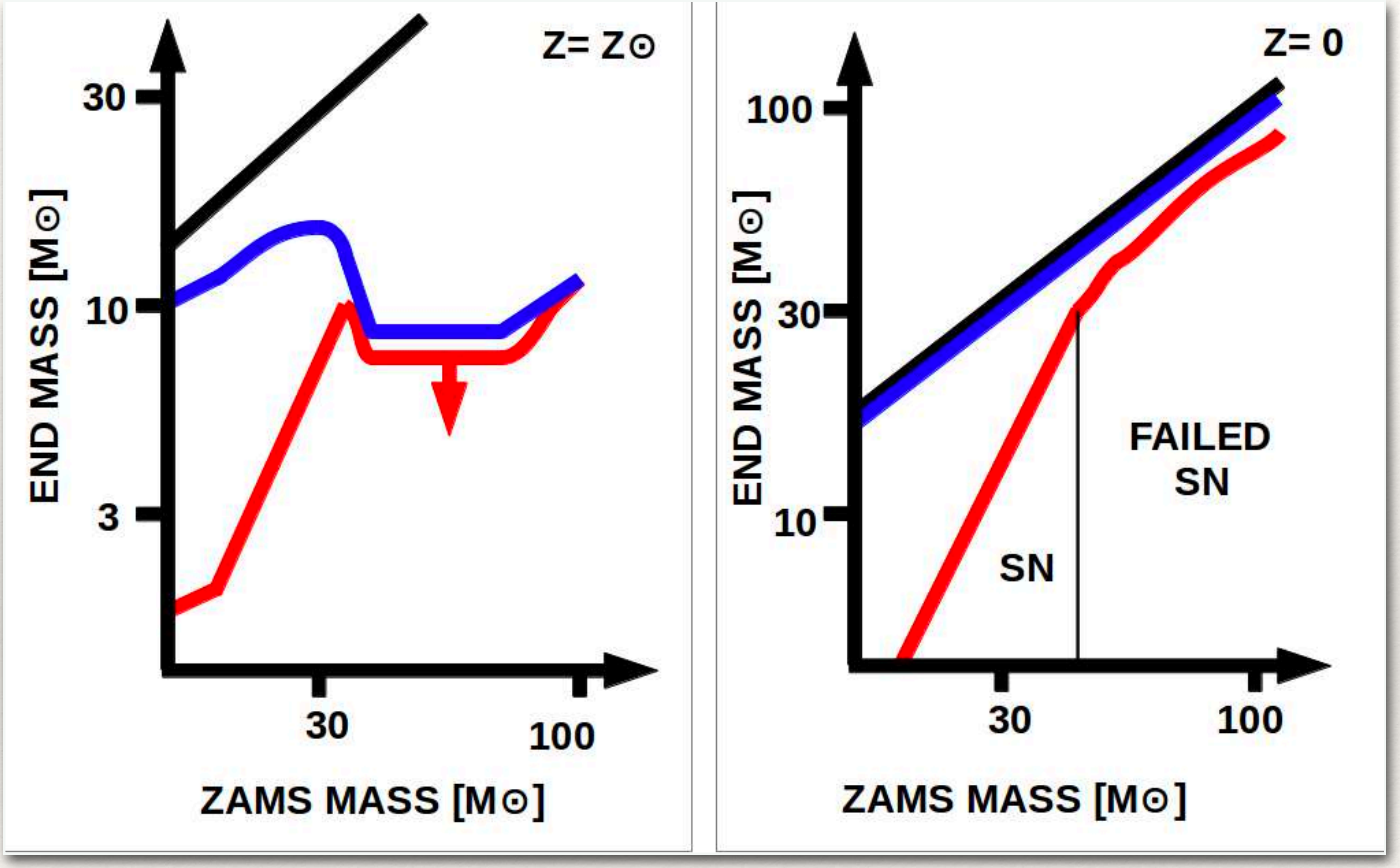


- Stellar winds are outflows of gas from the atmosphere of a star.
- In cold stars (e.g. red giants and asymptotic giant branch stars) they are mainly induced by radiation pressure on dust, which forms in the cold outer layers.
- In massive hot stars (O and B main sequence stars, luminous blue variables and Wolf-Rayet stars), stellar winds are powered by the coupling between the momentum of photons and that of metal ions present in the stellar photosphere.
- $\dot{m} \propto Z^{0.85}\, v_\infty^p$ with $p \sim -1.5$

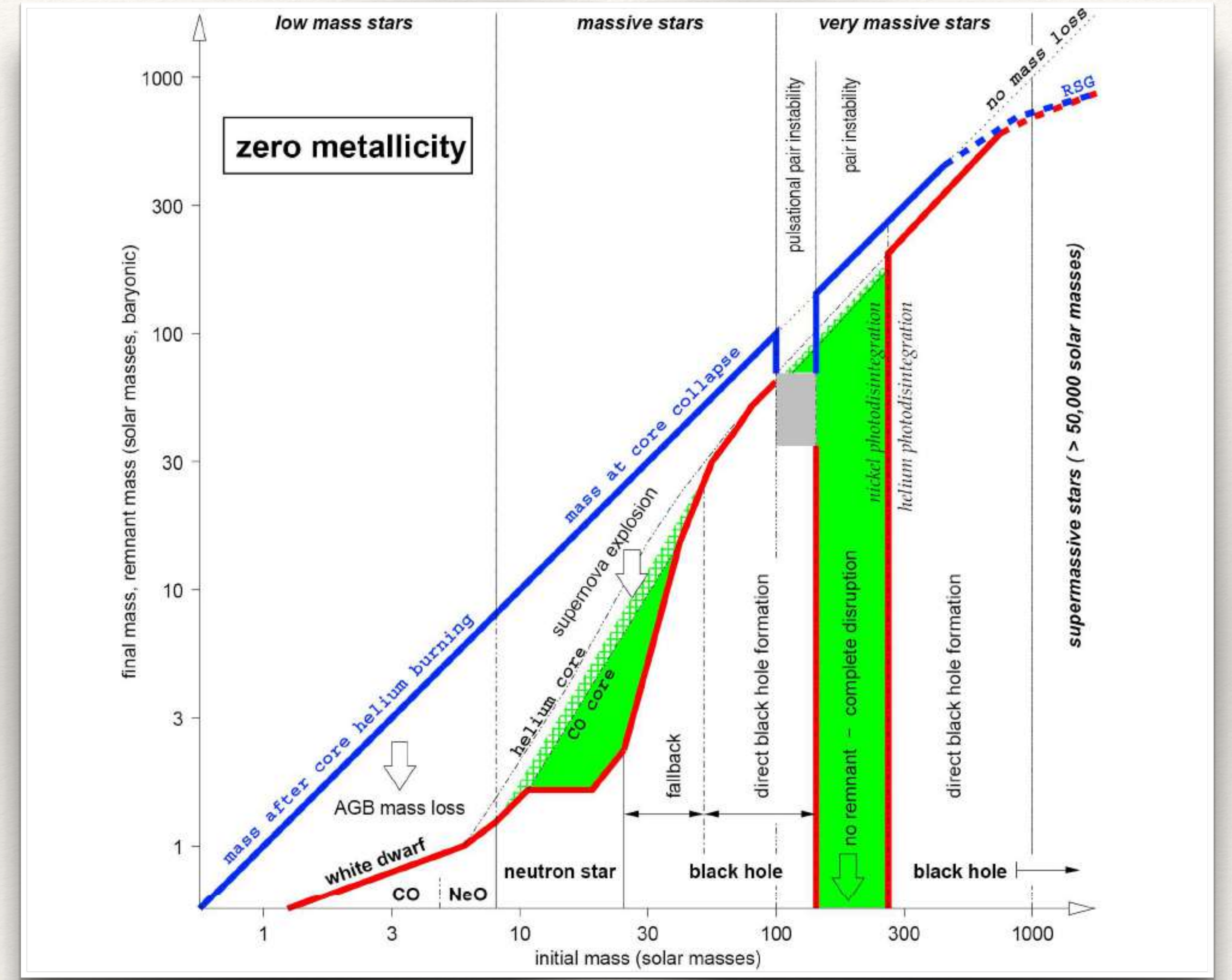
Massive stars can lose a significant fraction of their initial mass in their lifetime through winds. This will constrain the mass of the remnant.



Evolution of stellar mass as a function of time for a star with ZAMS mass m_{ZAMS} =90 M_{sol} and seven different metallicities, ranging from 0.005 Z_{sol} up to $Z_{sol.}$ **ZAMS: zero-age main sequence.**

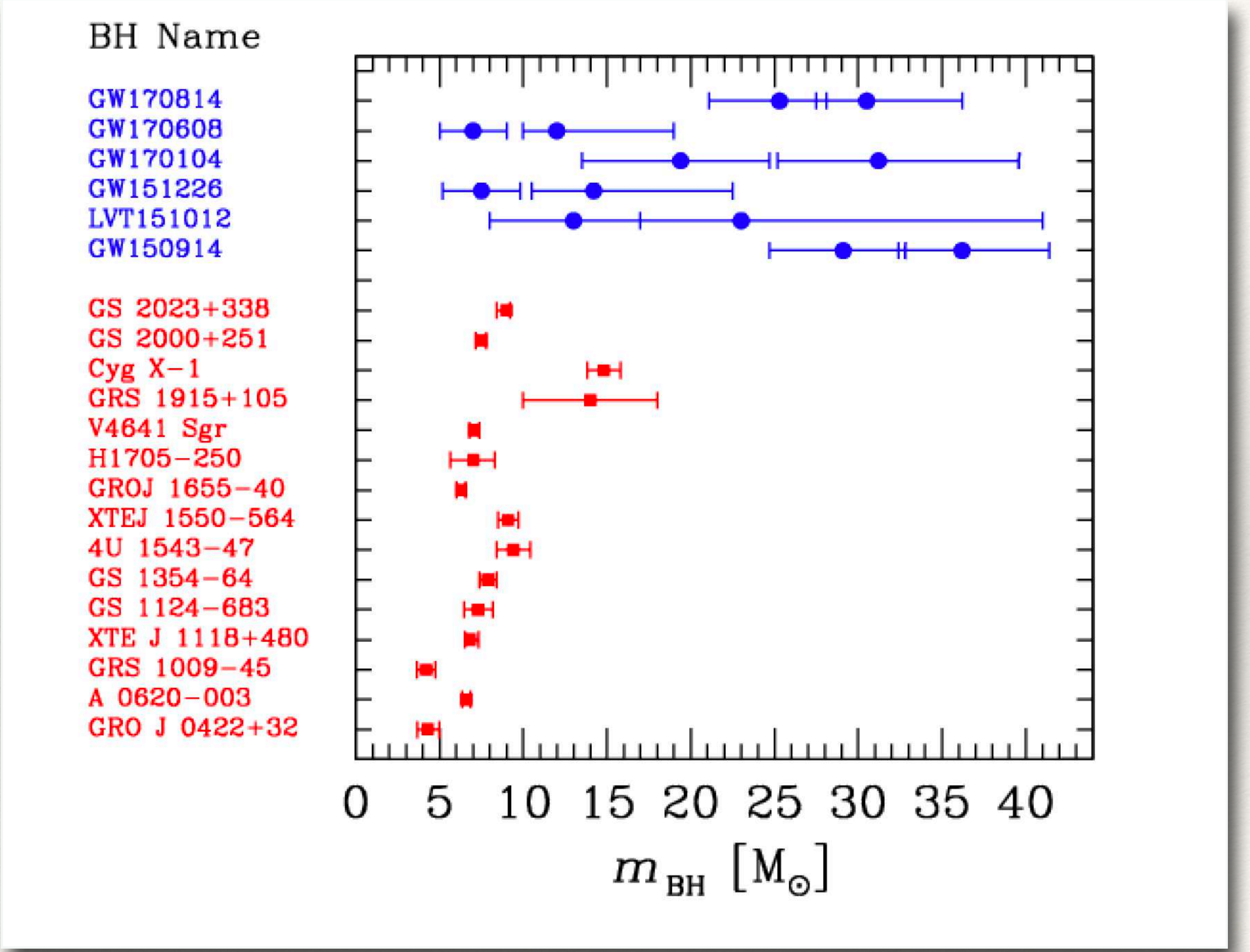


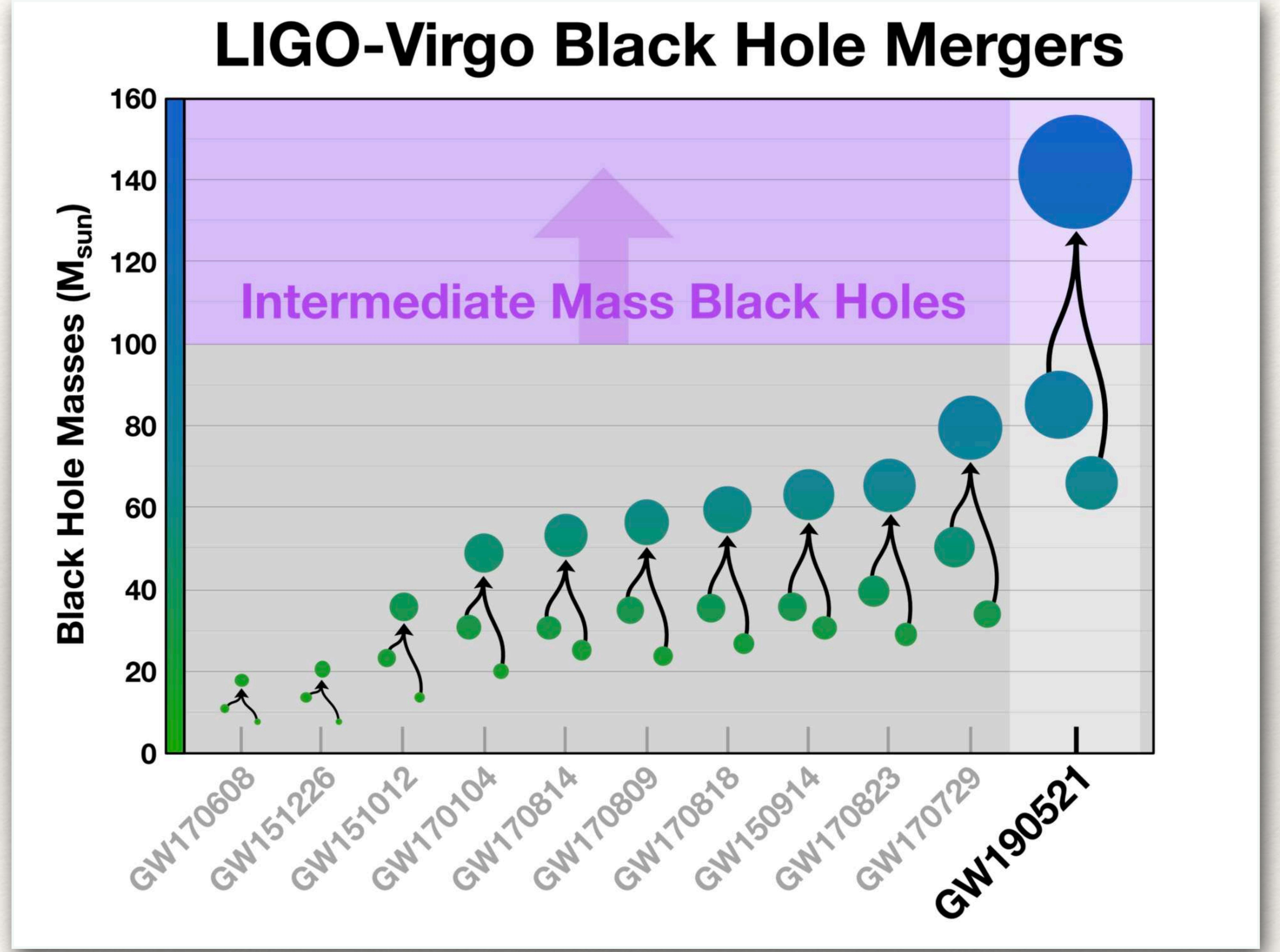
Final mass of a star (m_{fin}, blue lines) and mass of the compact remnant (m_{rem}, red lines) as a function of the ZAMS mass of the star.

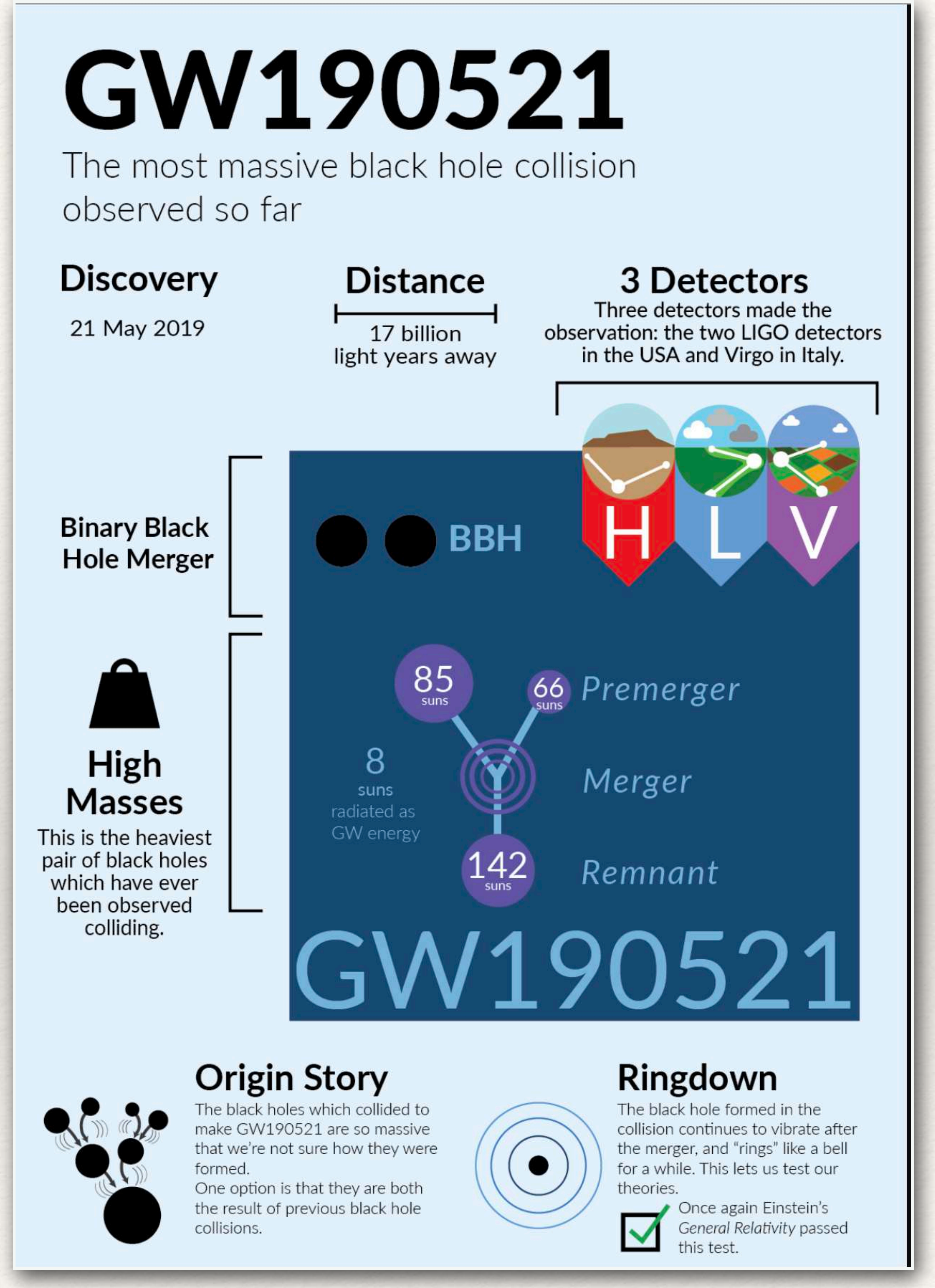


low mass stars
massive stars
very massive stars
zero metallicity
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
1000
300
100
30
10
3
1
1
3
10
30
100
300
1000
mass after core helium burning
mass at core collapse
no mass loss
RSG
pulsational pair instability
pair instability
nickel photodisintegration
helium photodisintegration
supermassive stars (> 50,000 solar masses)
supernova explosion
helium core
CO core
AGB mass loss
white dwarf
CO
NeO
neutron star
fallback
direct black hole formation
no remnant - complete disruption
direct black hole formation
black hole
black hole

Inferred black holes masses



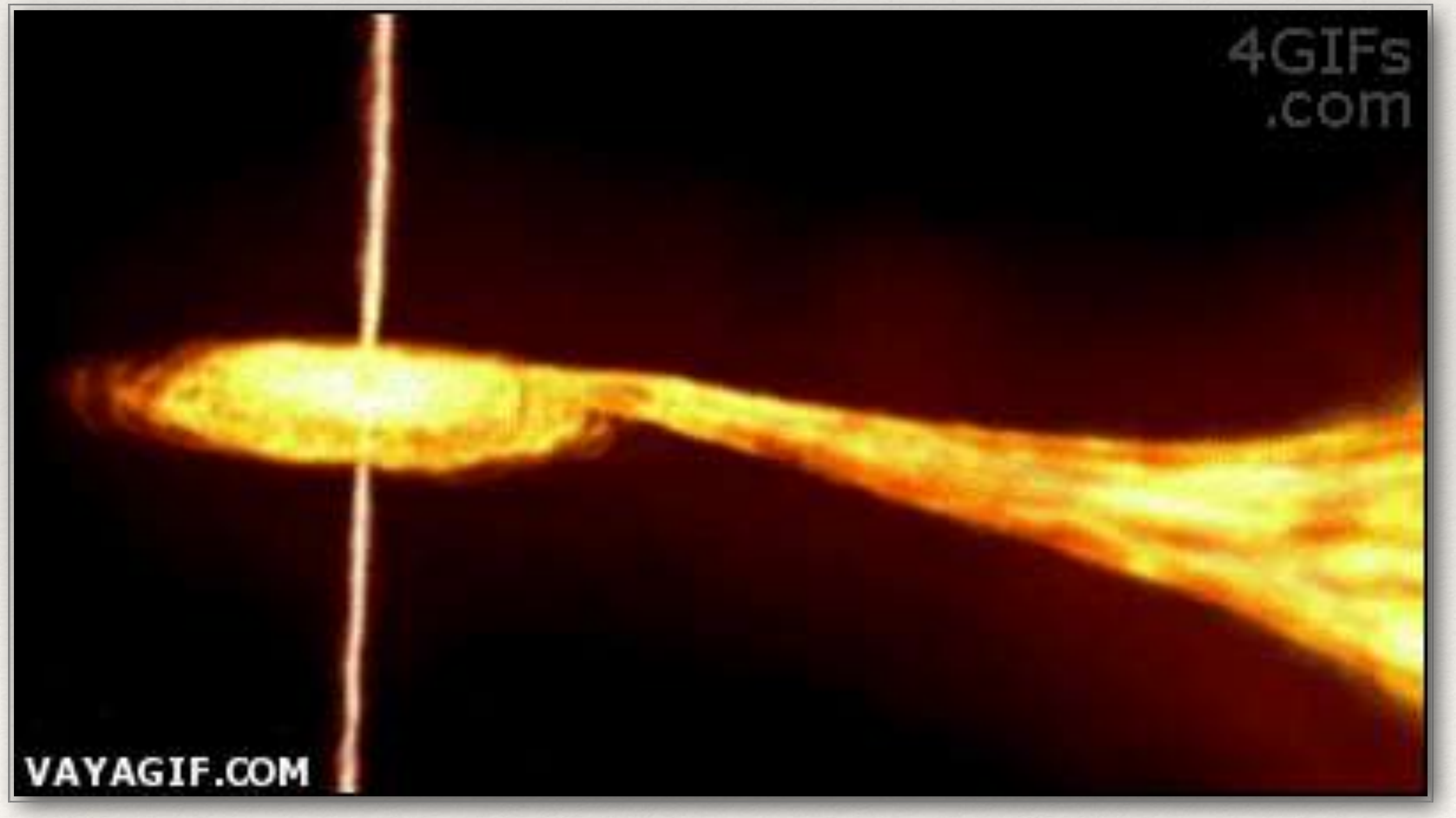

LIGO-Virgo Black Hole Mergers
Black Hole Masses (M_{sun})
160
140
120
100
80
60
40
20
0
Intermediate Mass Black Holes
GW170608
GW151226
GW151012
GW170104
GW170814
GW170809
GW170818
GW150914
GW170823
GW170729
GW190521


GW190521
The most massive black hole collision observed so far
Discovery
21 May 2019
Distance
17 billion light years away
3 Detectors
Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.
Binary Black Hole Merger
BBH
H
L
V
High Masses
This is the heaviest pair of black holes which have ever been observed colliding.
85 suns
66 suns
Premerger
8 suns radiated as GW energy
Merger
142 suns
Remnant
GW190521
Origin Story
The black holes which collided to make GW190521 are so massive that we're not sure how they were formed.
One option is that they are both the result of previous black hole collisions.
Ringdown
The black hole formed in the collision continues to vibrate after the merger, and "rings" like a bell for a while. This lets us test our theories.
Once again Einstein's General Relativity passed this test.

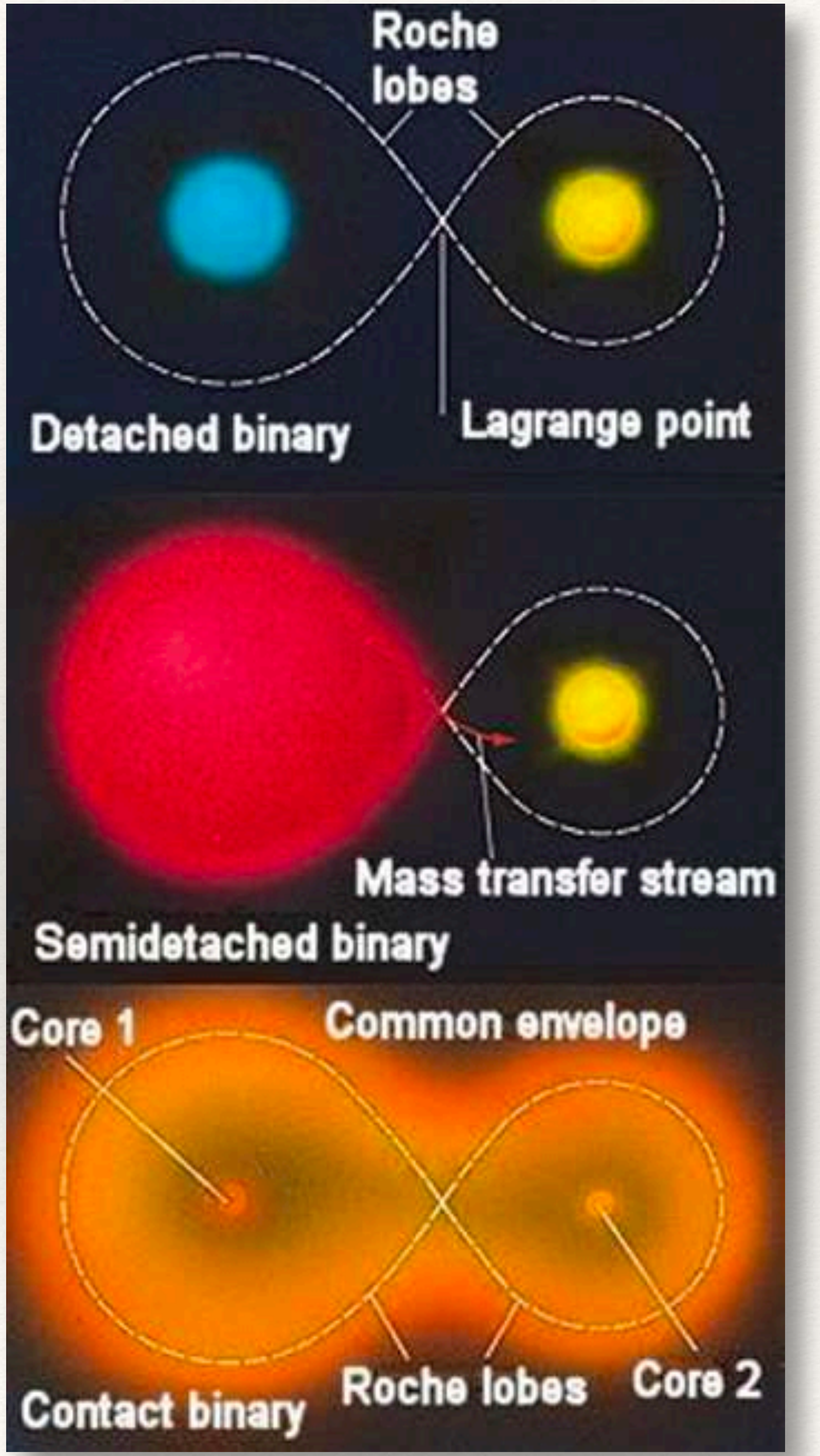
What is the origin of these very massive BHs?

There must be other effects: rotation, magnetic fields, binary systems with mass transfer…

Can we feed a BH till ~100 M_{sol} on the lifetime of a massive star?



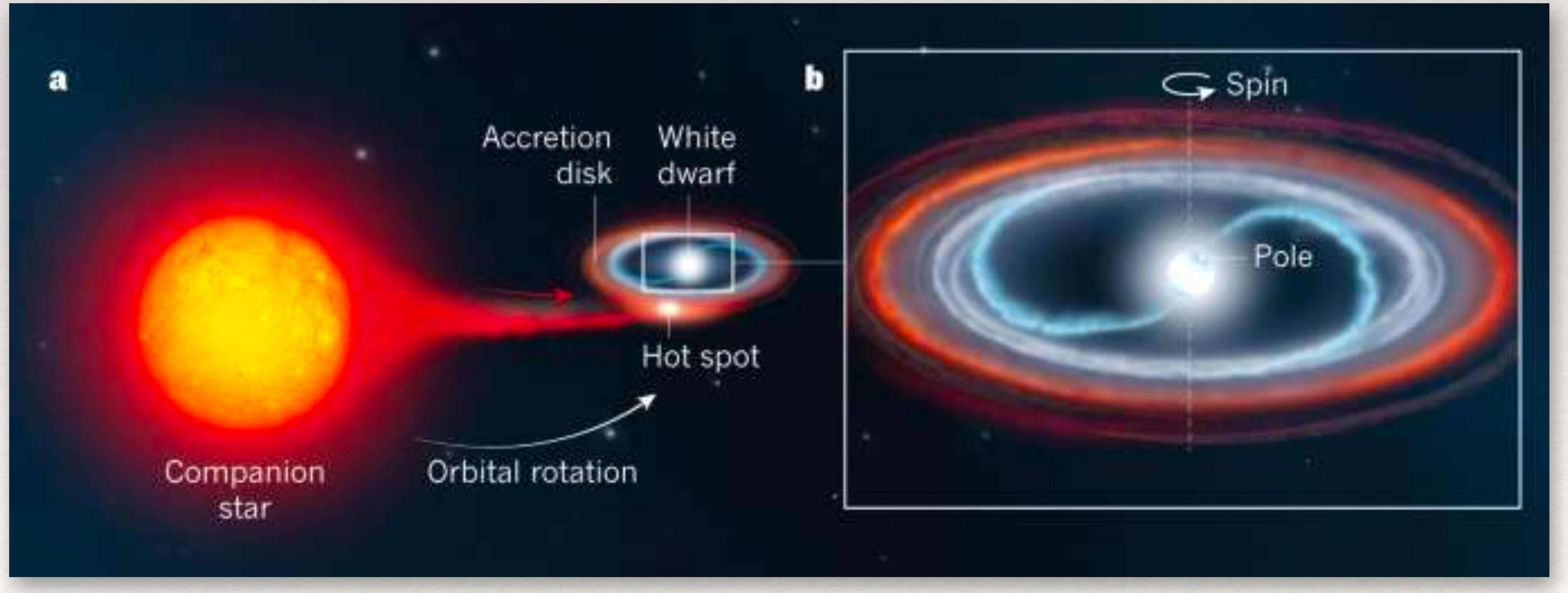
Binary evolution



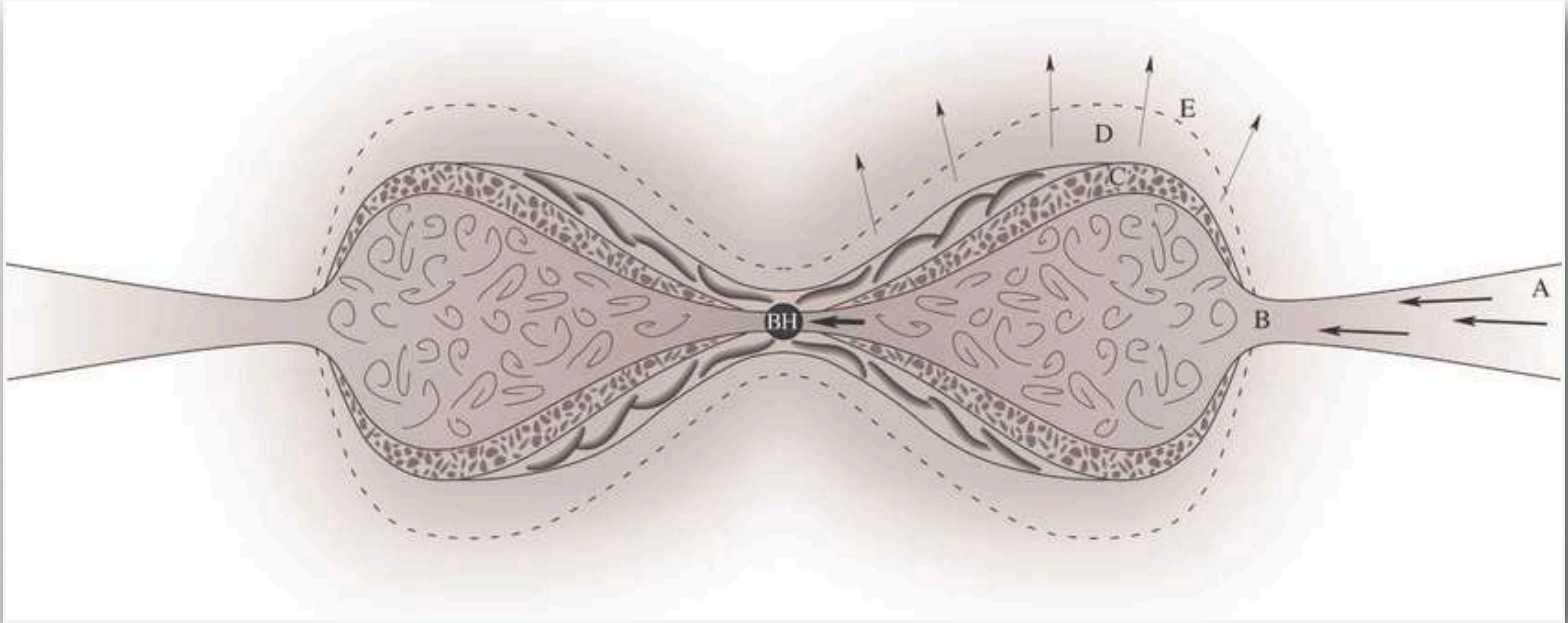
$$\dot{m}_2 = \frac{1}{\sqrt{1-e^2}} \left(\frac{G m_2}{v_{\rm w}^2}\right)^2 \frac{\alpha_{\rm w}}{2a^2} \frac{1}{[1+(v_{\rm orb}/v_{\rm w})^2]^{3/2}} |\dot{m}_1|,$$

$$R_{\rm L,1} = a \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln\left(1+q^{1/3}\right)},$$

$$q = m_1/m_2$$



What happens if we feed the disk at super-Eddington rates?



$$\dot{M}_{\rm crit} \equiv \frac{L_{\rm E}}{c^2} = 1.39 \times 10^{17} \frac{M}{M_\odot} \, {\rm g\,s^{-1}}, \qquad \dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\rm crit}},$$

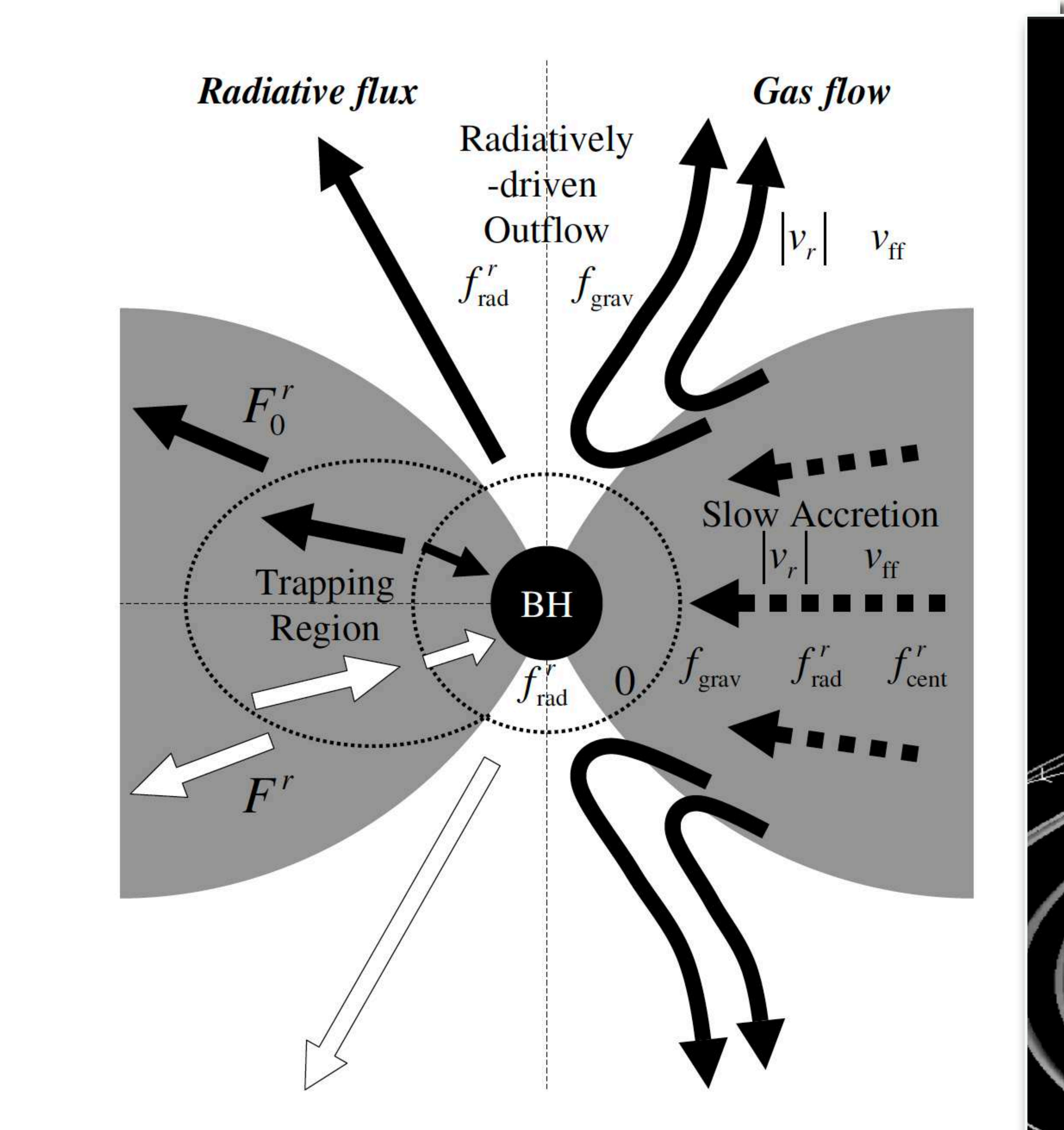
The critical radius $r_{\rm cr}$ is such that outside it the radiation-pressure dominated standard disk is valid, and inside of which the radiative force overcomes the gravity and the traditional standard picture is violated.

Accreting matter is removed by a strong wind

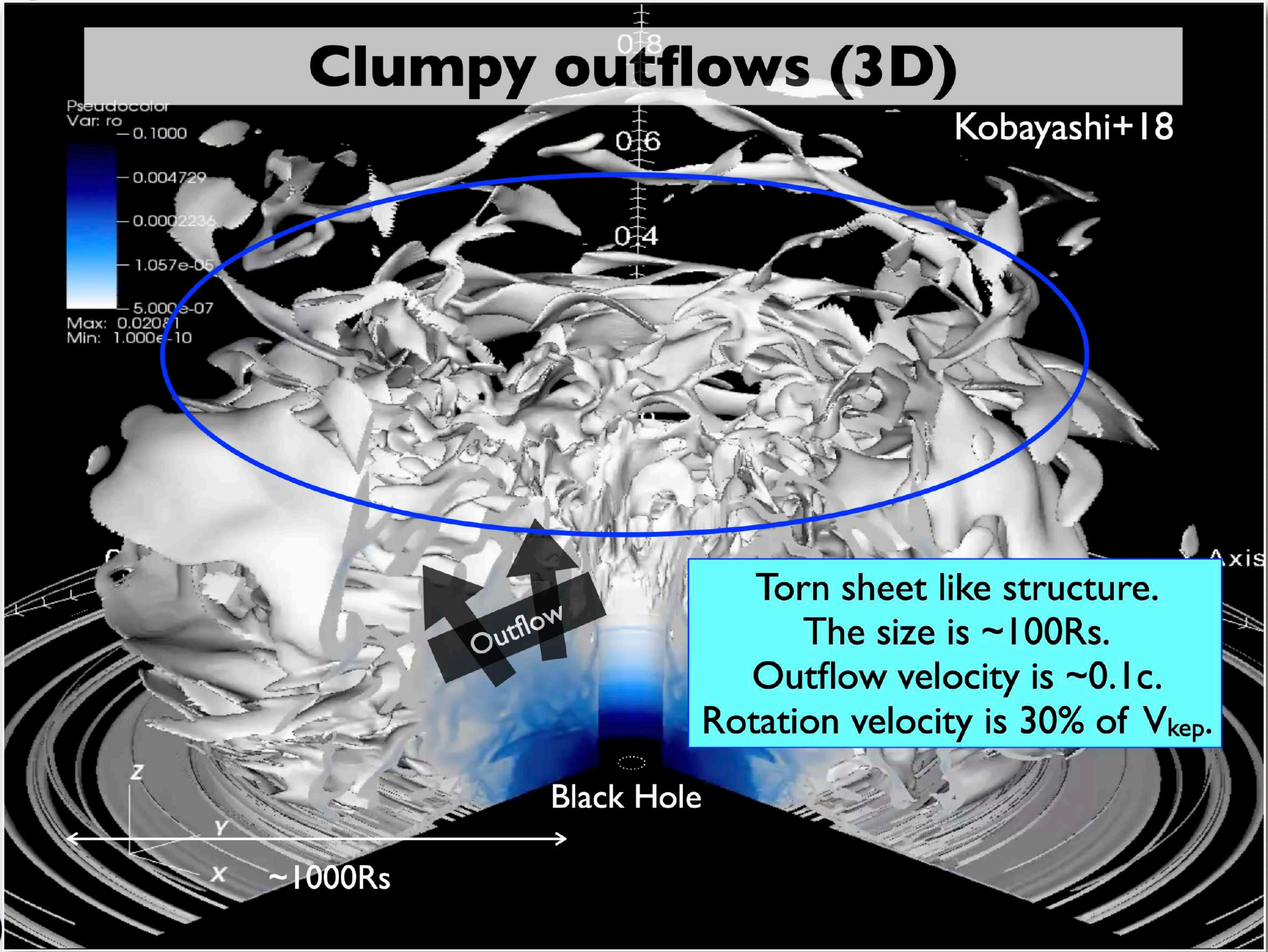
$$r_{\rm cr} = \frac{9\sqrt{3}\sigma_{\rm T}}{16\pi m_{\rm p} c} \dot{M} = 5.71 \times 10^5 \frac{M}{M_\odot} \frac{\dot{M}}{\dot{M}_{\rm crit}} \, {\rm cm}, \quad \sim 2\dot{m} r_{\rm g}.$$

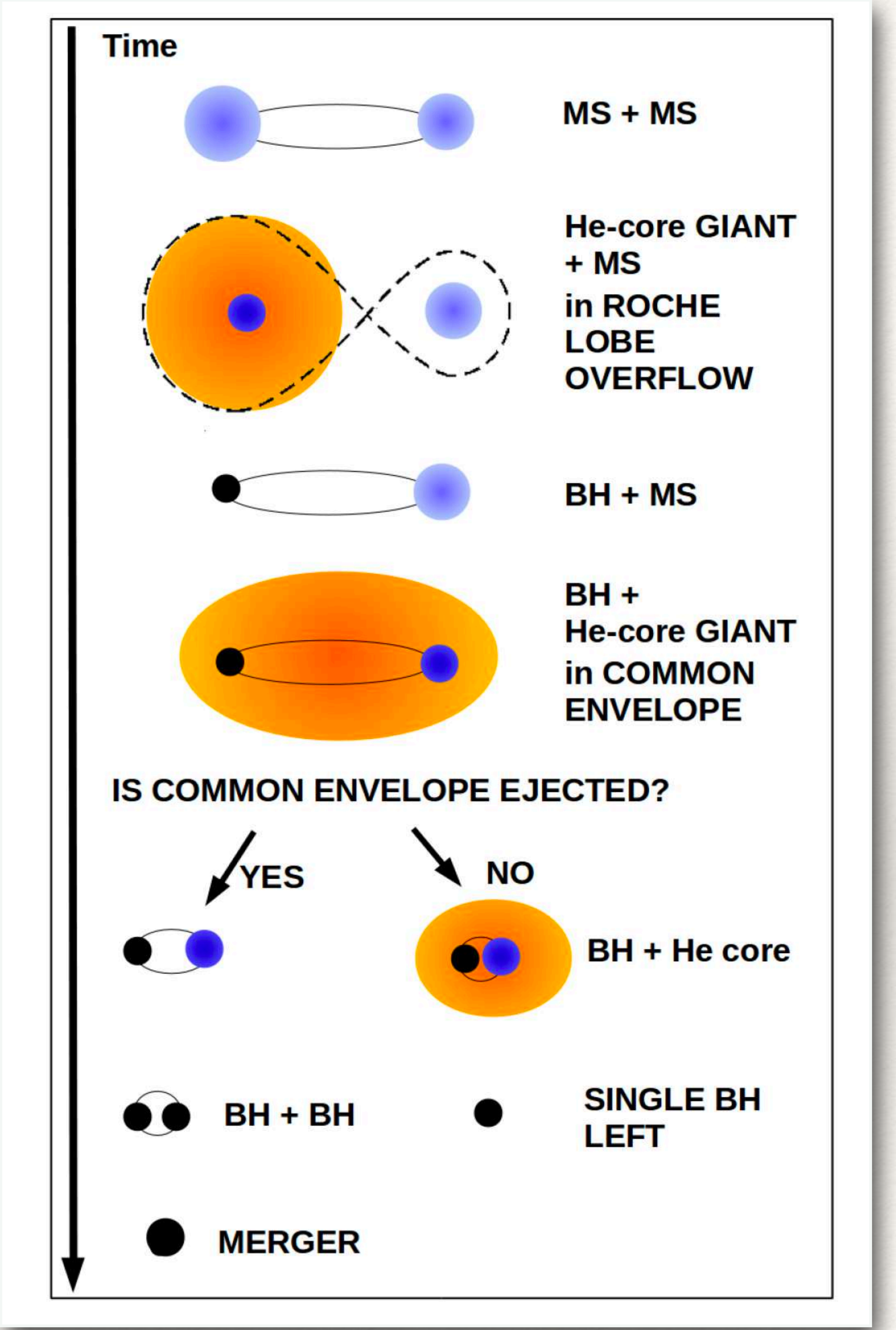
Inside $r_{\rm cr}$

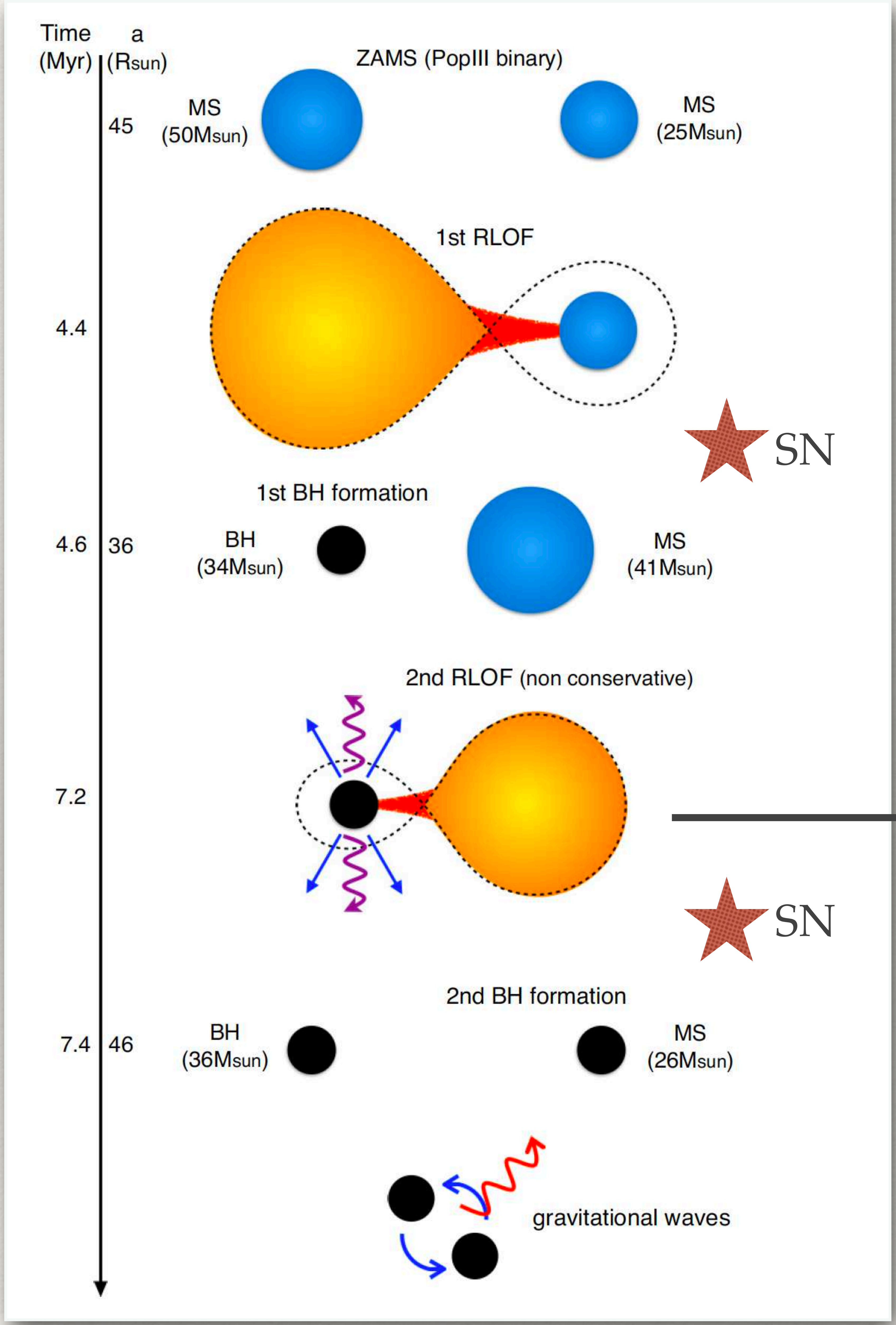
$$\dot{M}(r) = \frac{16\pi c m_{\rm p}}{9\sqrt{3}\sigma_{\rm T}} r \;\longrightarrow\; \dot{M}_{\rm wind} = \dot{M}_{\rm input} - \dot{M}(r),$$



Schematic diagram. (Ohsuga & Mineshige 2007)



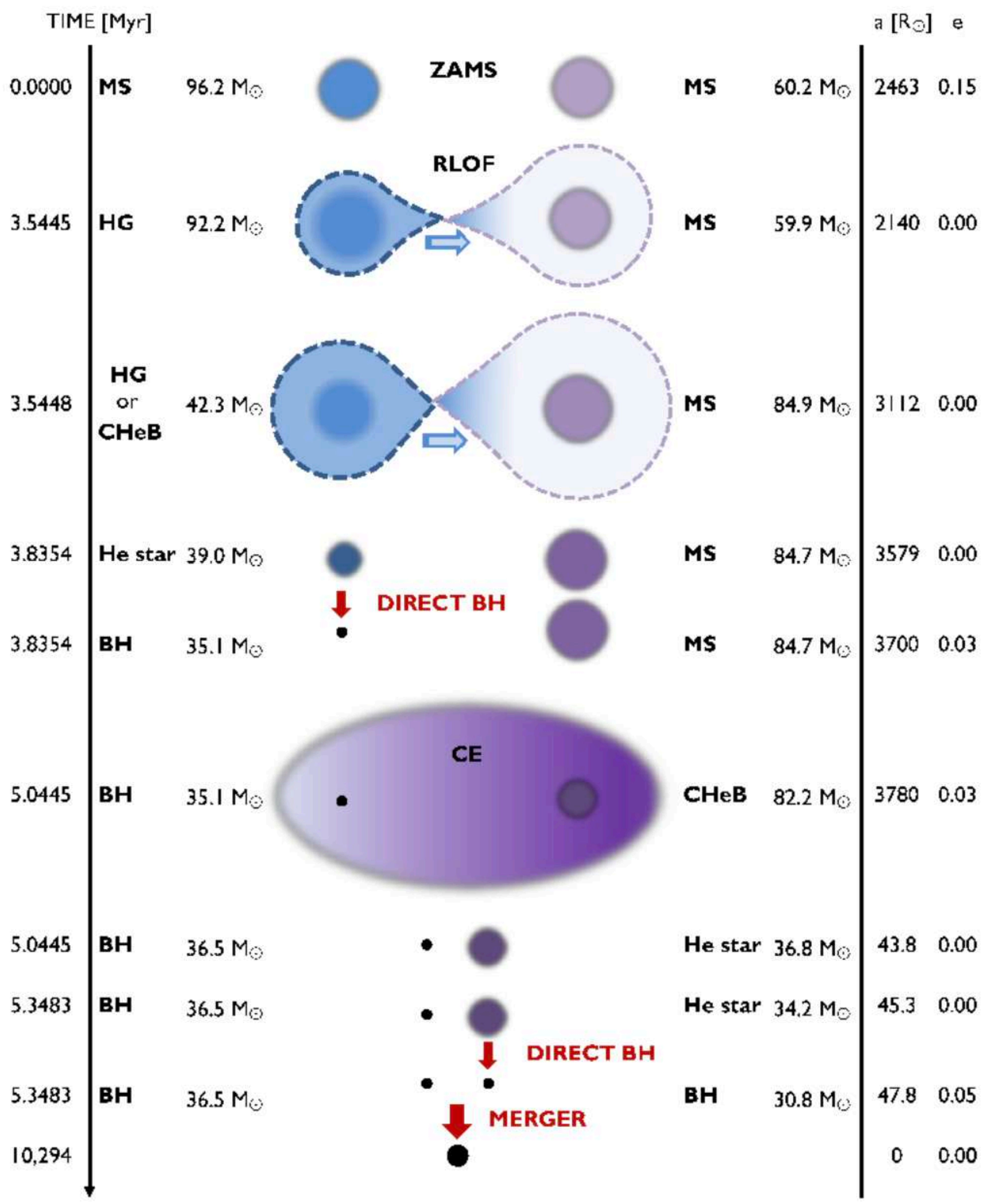




Inayoshi et al. (2017)

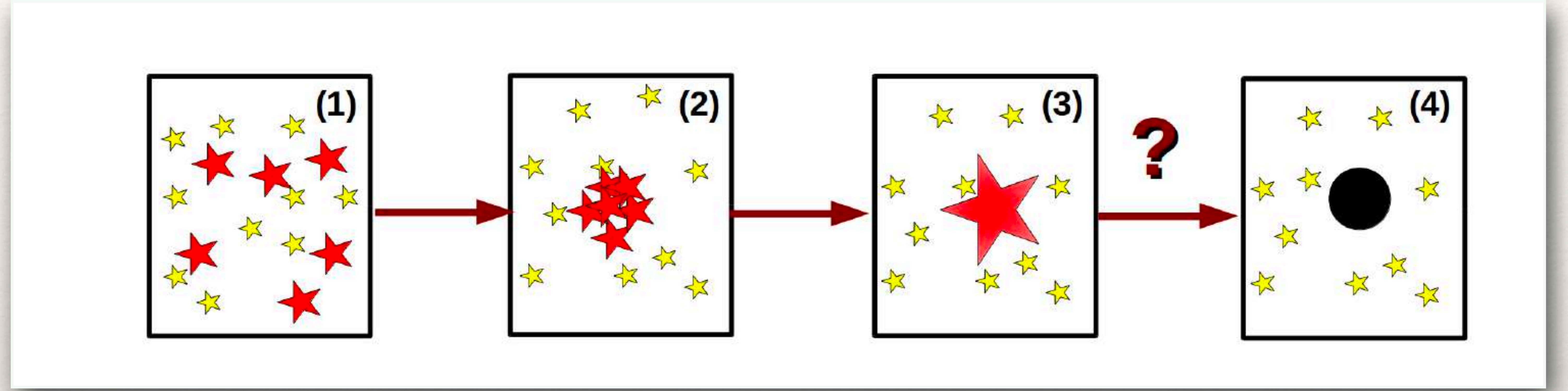
POP III MQ
Sotomayor Checa & Romero (2019)

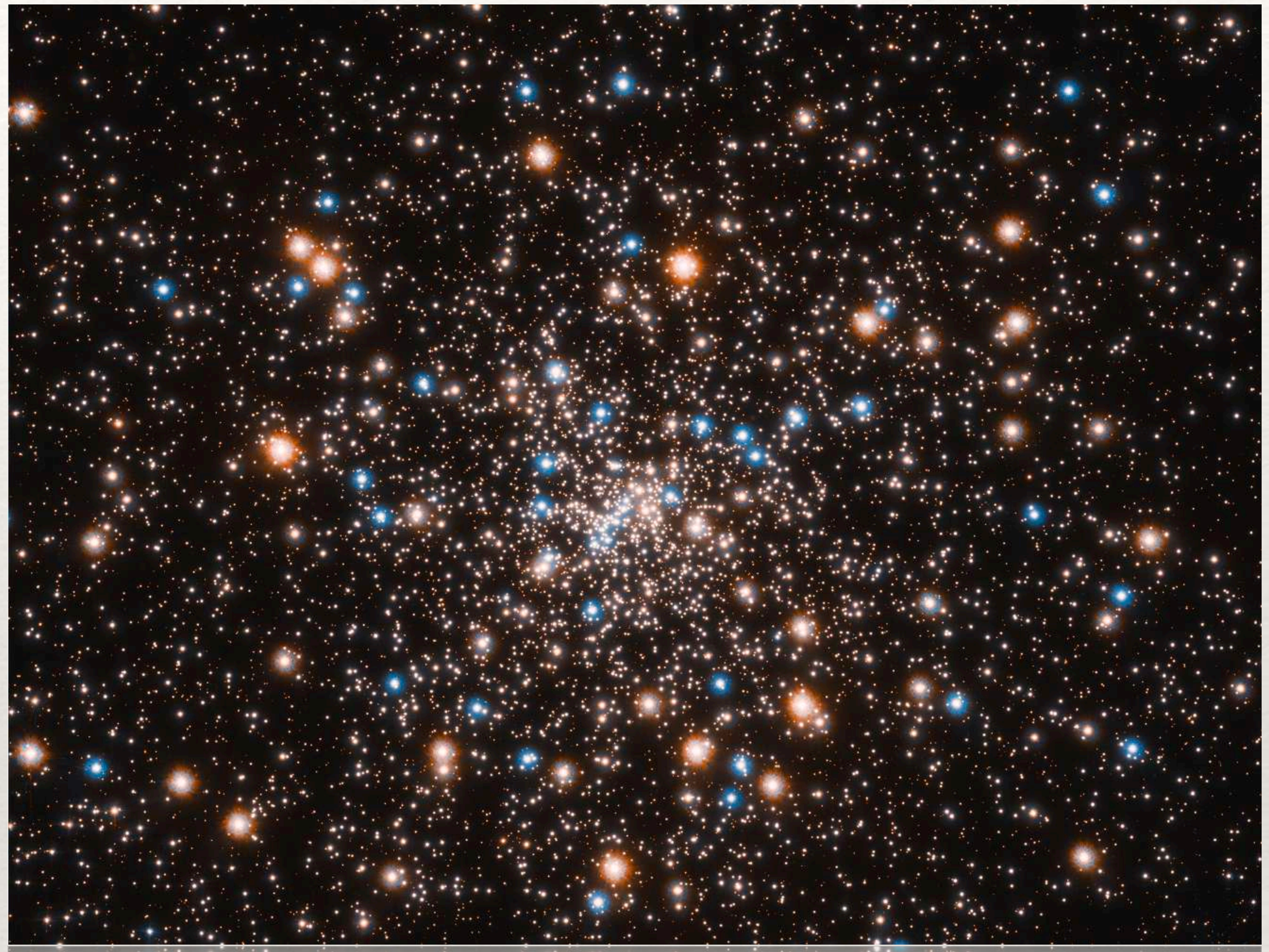
Schematic evolution of isolated binary stars which give birth to BBH mergers (Mapelli 2021).



Belczynski (2016)

Formation of intermediate-mass black holes by runaway collisions

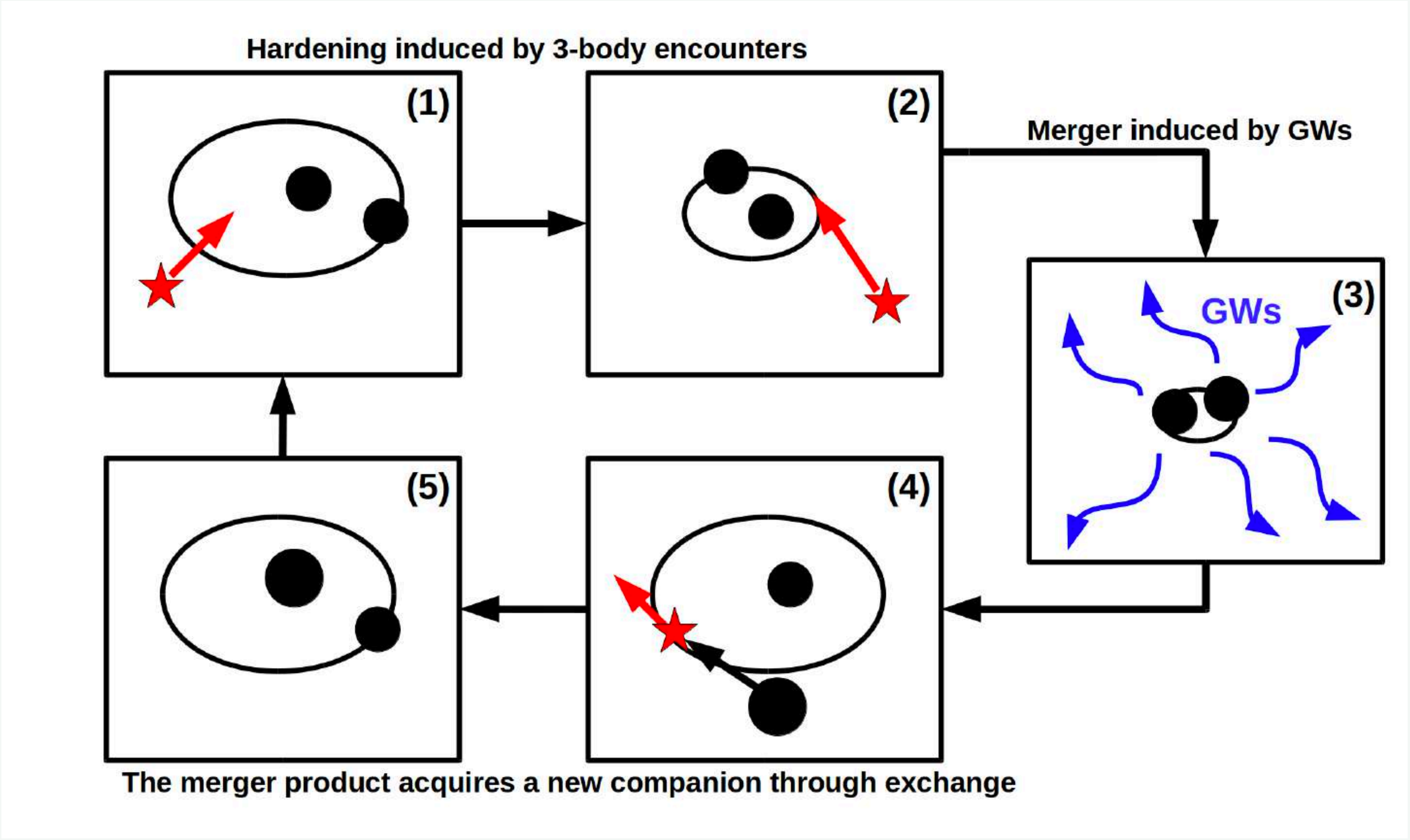


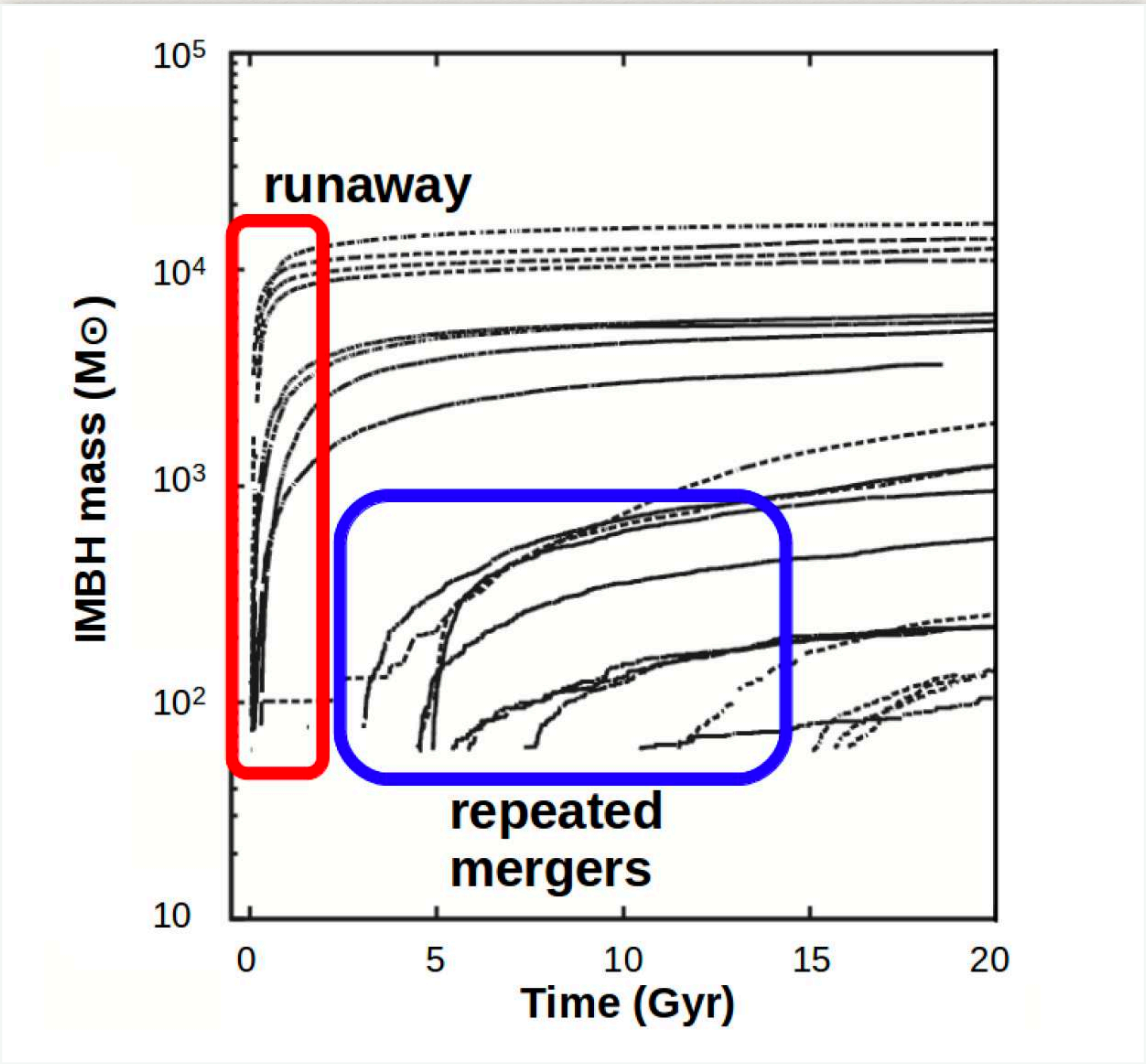


(1) The massive stars (red big stars) and the low-mass stars (yellow small stars) in a dense cluster follow the same initial spatial distribution; (2) dynamical friction leads the massive stars to sink to the core of the cluster, where they start colliding between each other; (3) a very massive star (>100 M_{sol}) forms as a consequence of the runaway collisions; (4) this massive star might be able to directly collapse into a BH.

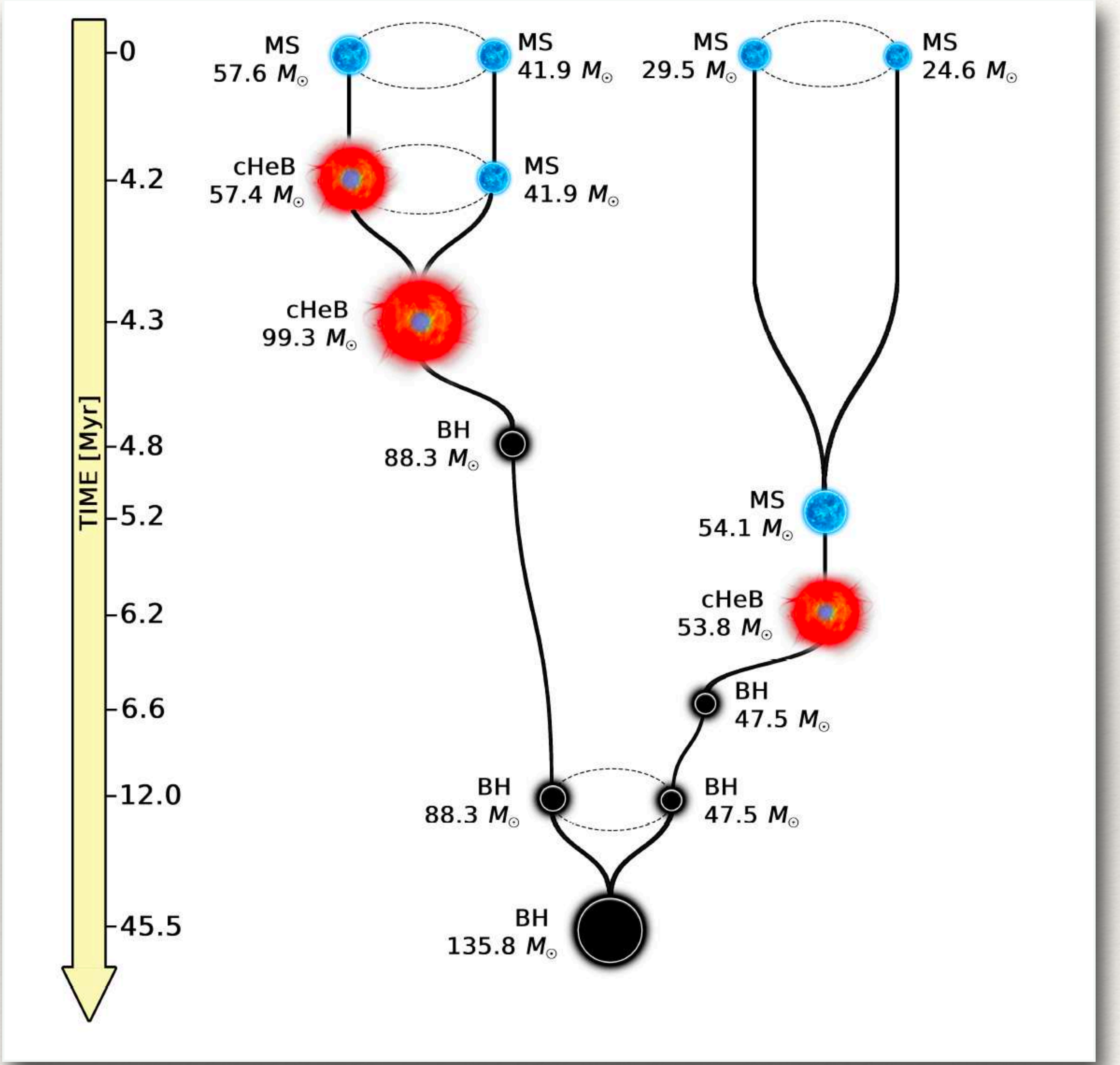
Hierarchical binary BH formation

(1) A BBH undergoes three-body encounters in a star cluster;
(2) three-body encounters harden the BBH, shrinking its semi-major axis; (3) the BBH hardens by three-body encounters till it enters the regime where GW emission is efficient: the BBH semimajor axis decays by GW emission and the binary merges;
(4) a single bigger BH forms as result of the merger and may acquire a new companion by dynamical exchange (if it is not ejected by GW recoil); (5) the new BBH containing the bigger BH starts shrinking again by three-body encounters
(1). This loop may be repeated several times till the main BH becomes an IMBH.





Giersz et al. (2015)

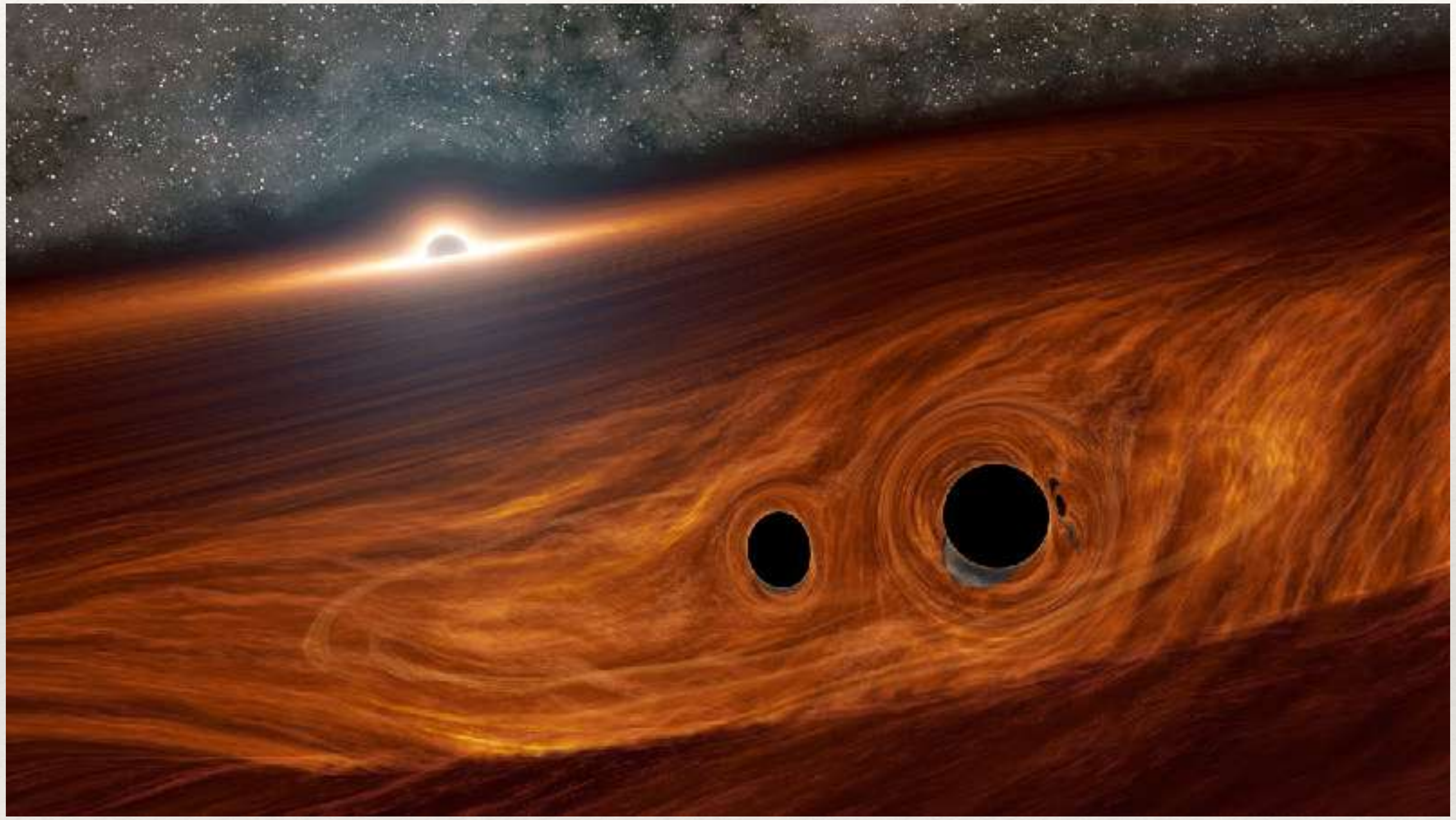


The primary BH has a mass in the pair-instability mass gap. Its formation is possible because its stellar progenitor is the result of the merger between a giant star with a well-developed He core and a main sequence companion (MS). The result of this stellar merger is a massive-core helium-burning (cHeB) star with an over-sized hydrogen envelope with respect to the He core. Given the short timescale for He, C, O, Ne and Si burning with respect to H burning, the star collapses to a BH before the He core grows above the threshold for pair instability: the result is a BH of 88 solar masses.

Di Carlo et al. (2020).

Cartoon of the dynamical assembly of a GW190521-like BBH from the simulations (Mapelli 2021).

IMBH formation in the accretion disks of AGNs



Nuclear star cluster members trapped in the accretion disk of a SMBH are subject to orbital damping due to gas drag. Gas damping is expected to quench the relative velocity between nuclear cluster members thus enhancing the collision rate. This favours the growth of IMBHs via both gas accretion and multiple stellar collisions.

Conslusions

- Stellar black holes in the range of 3-30 solar masses are the result of gravitational collapse of massive stars of different metallicities.
- More massive BHs can form only from massive relatively metal-poor stars. At low-metallicity, stellar winds are quenched and stars end their life with a larger mass than their metal-rich analogues. If its final core mass is sufficiently large, a star can directly collapse to a BH with mass $> 30\ M_{sol}$.
- More massive black holes can be the result of a variety of astrophysical processes in a dynamically active environment, including:
  - ✓ Coalescence of BH binaries through dynamical hardening.
  - ✓ Massive BH binaries formed via dynamical exchanges.
  - ✓ Hierarchical dynamical assembly.
  - ✓ Runaway collisions in dense clusters.
  - ✓ Repeated mergers.
  - ✓ Stimulated accretion and mergers in accretion disks.

No need for exotic origin

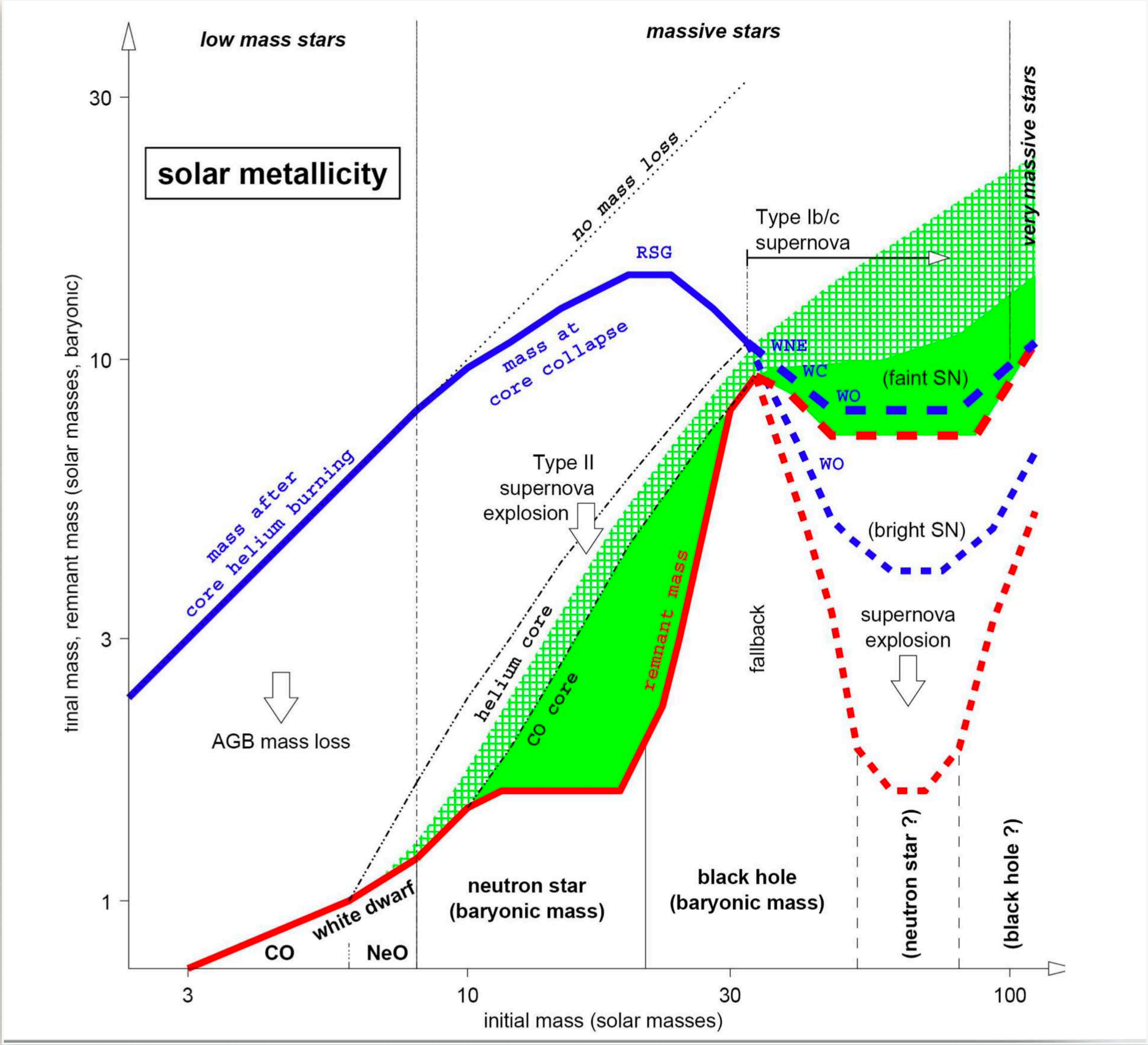
Open problems

- Most research focus only on old clusters. Very few studies of black hole formation in open young clusters exist.
- Effects of gas in clusters should be included.
- What room there is for primordial black holes?
- Do black holes survive a cosmological bounce? (See Pérez, Perez Bergiaffa & Romero 2021).

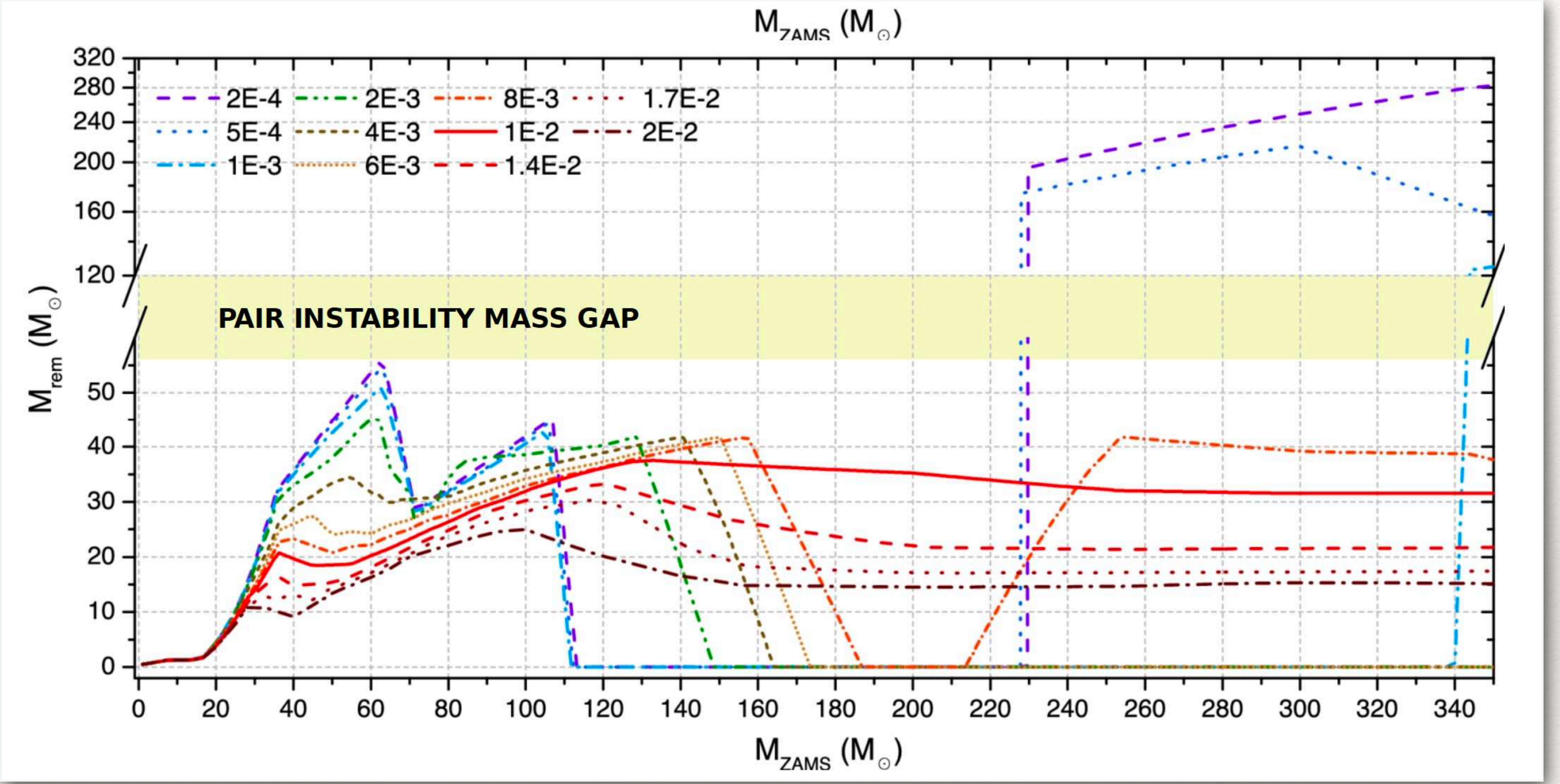
Further readings

- Mapelli, M. et al. 2020, Hierarchical mergers in young, globular and nuclear star clusters: black hole masses and merger rates, arXiv:2007.15022
- Mapelli, M. 2021, Formation channels of single and binary stellar-mass black holes, arXiv:2106.00699v1
- B. McKernan, K. E. S. Ford, W. Lyra, and H. B. Perets 2012, Intermediate mass black holes in AGN discs - I. Production and growth. *MNRAS*, 425(1):460–469.
- Vink, J.S. 2017, Mass loss and stellar superwinds, *Philosophical Transactions of the Royal Society A*, Volume 375, Issue 2105, id.20160269

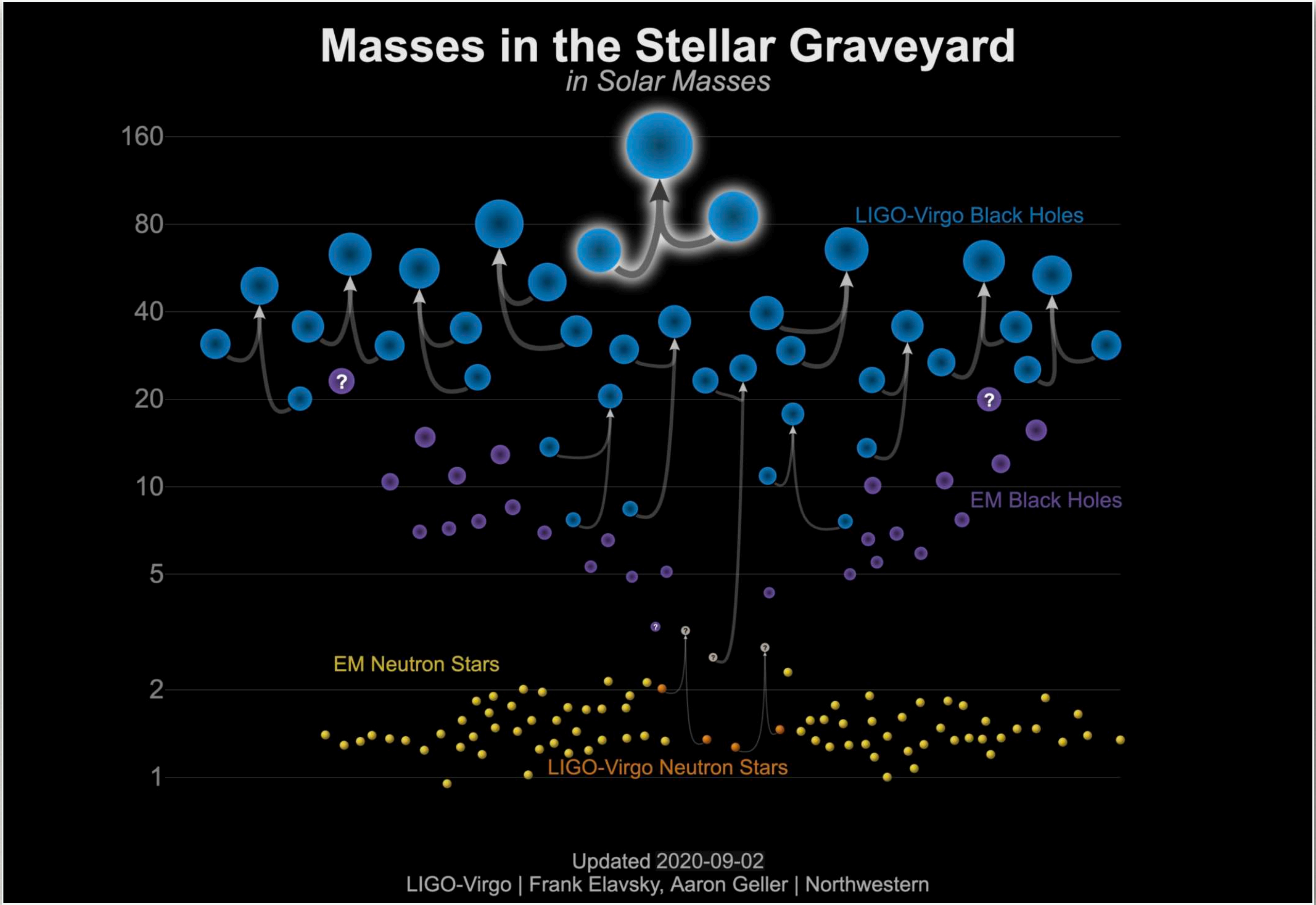
Thanks!

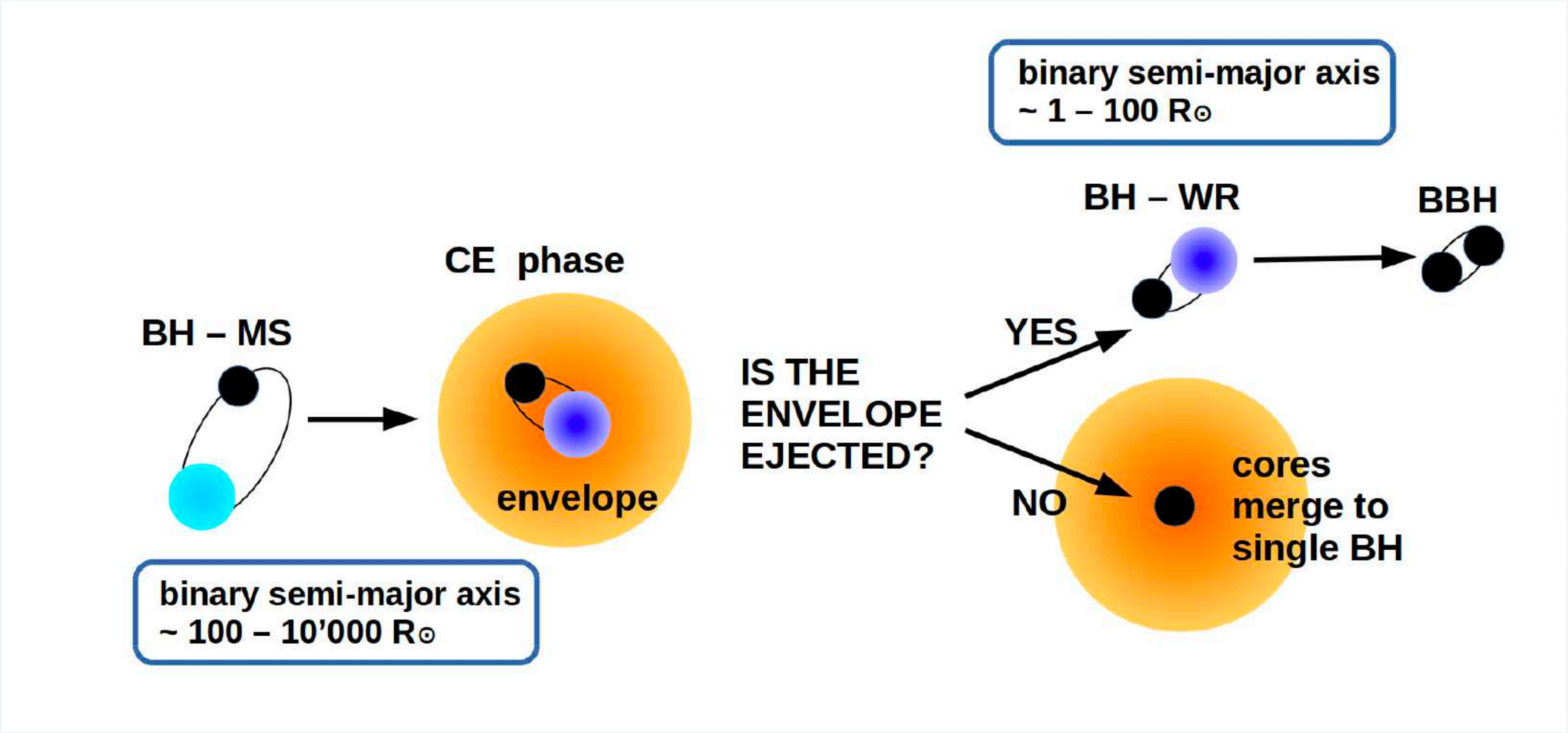


low mass stars
massive stars
very massive stars
solar metallicity
no mass loss
RSG
mass after core helium burning
mass at core collapse
Type Ib/c supernova
WNE
WC
WO
(faint SN)
WO
(bright SN)
Type II supernova explosion
helium core
CO core
remnant mass
fallback
supernova explosion
AGB mass loss
white dwarf
CO
NeO
neutron star (baryonic mass)
black hole (baryonic mass)
(neutron star ?)
(black hole ?)
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
30
10
3
1
3
10
30
100

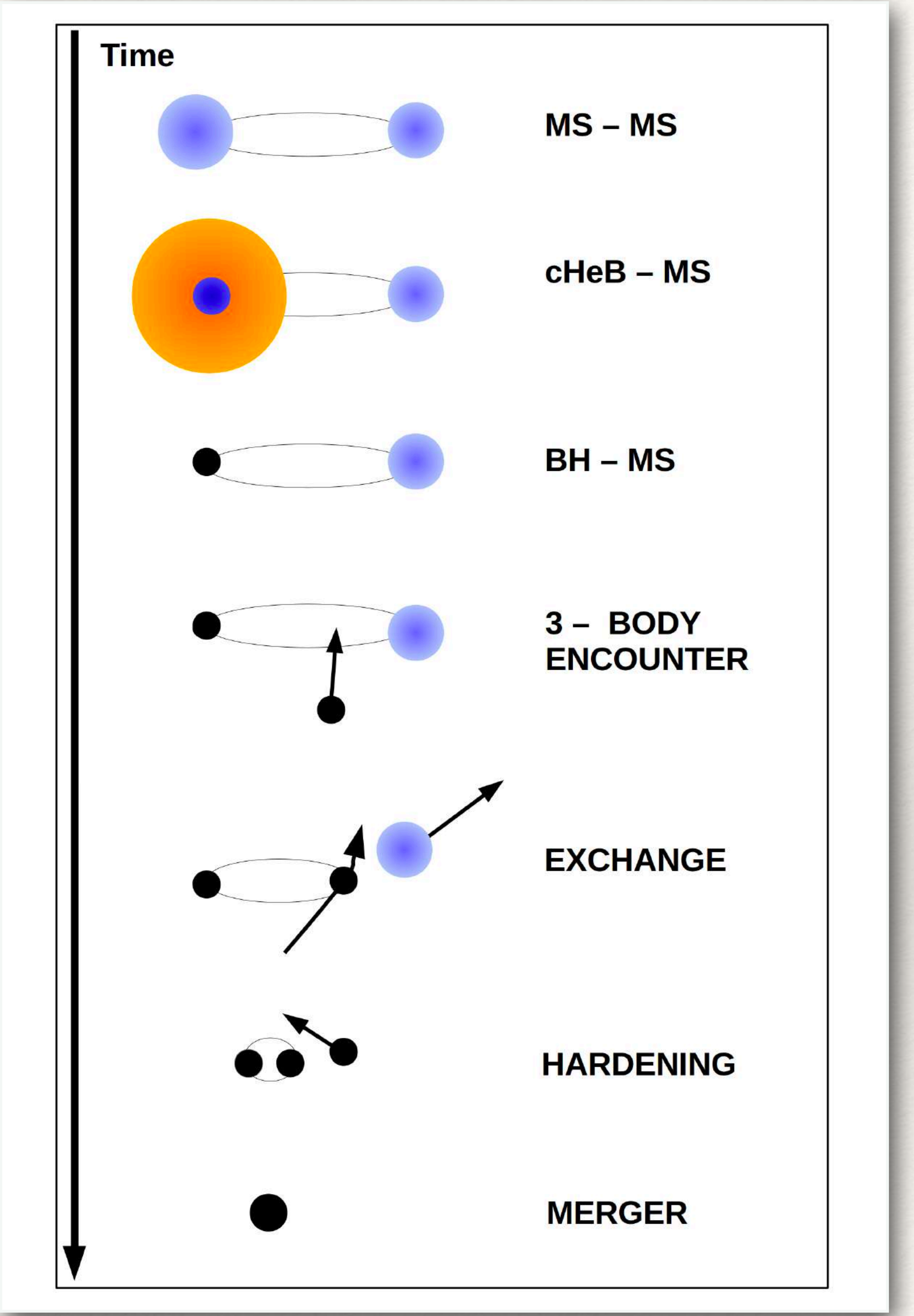


Mass of the compact remnant (m_{rem}) as a function of the ZAMS mass of the star (m_{ZAMS}) Spera & Mapelli (2017).


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



Schematic representation of the evolution of a BBH through CE. The companion of the BH is initially in the main sequence (MS), Mapelli (2021).



Dynamical exchange