Beyond Binaries & EM counterparts of LIGO binary black hole mergers

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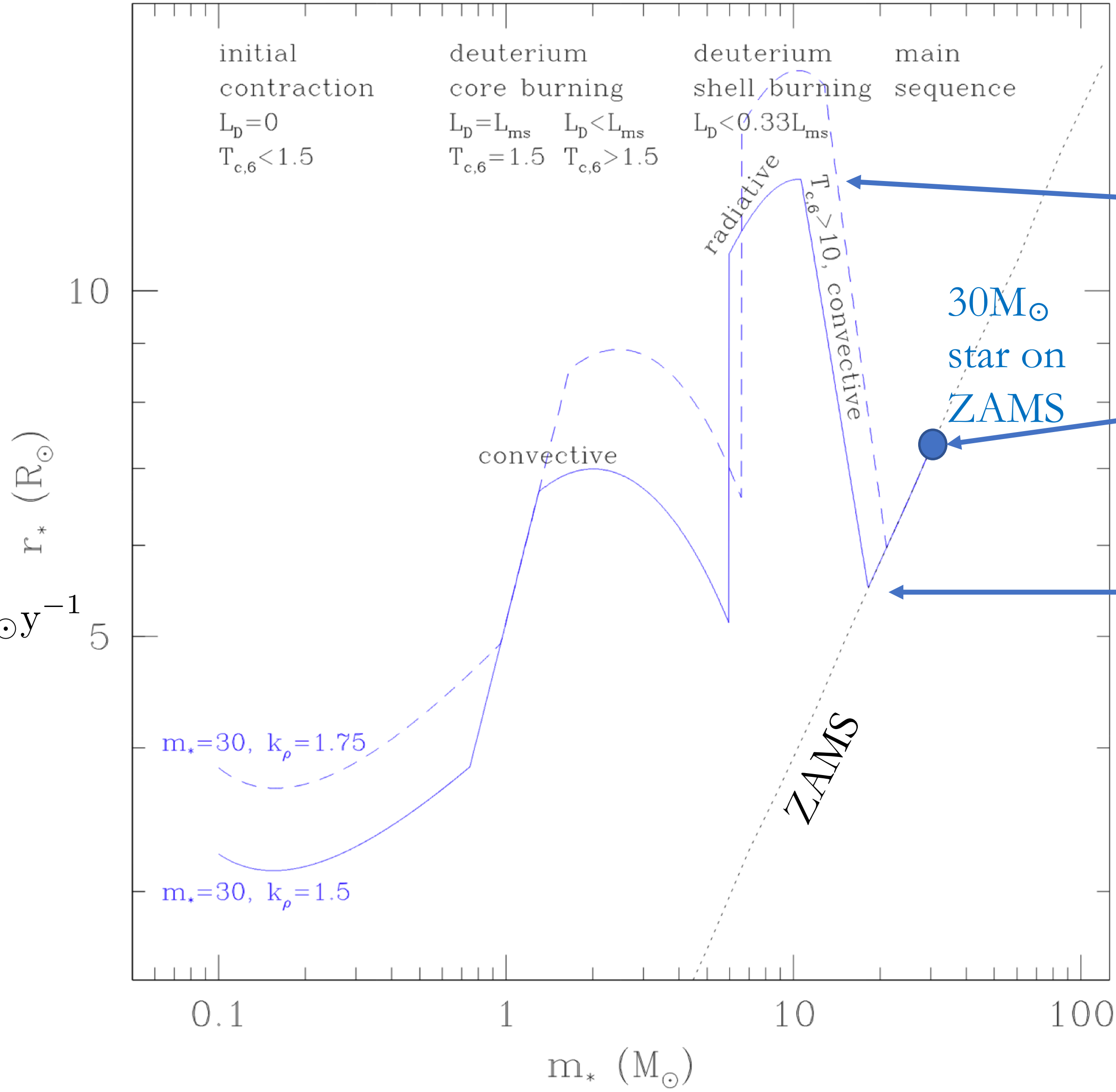
Massive star formation

- Massive stars form in dense cores of molecular cloud clumps
- $\Sigma > 1$ g cm^{-2} (for feedback not to suppress collapse)
- $t_f \sim 10^5$ y ~ free fall time of parent clump
- Accretion rate onto protostar $\dot{M} \sim 10^{-4} - 10^{-3} M_{\odot} \mathrm{y}^{-1}$
- Early in growth (1-10$M_{\odot}$) stars powered by accretion and D burning, but join main sequence when have grown to ~20$M_{\odot}$ (Kelvin-Helmholtz time < accretion time).
- Max pre-ms radii never much larger than ZAMS radius

Pre-MS evolution of 30M⊙ star rapidly accreting in a turbulent molecular core. *Not* on Hayashi track once grows beyond 2M⊙.

$$\dot M \sim 10^{-4} - 10^{-3} M_\odot y^{-1}$$

Ram pressure exceeds radiation pressure



Max pre-ms stellar radius (during D burning) is only 1.6 times ZAMS radius.

Accreting protostar joins ZAMS already at ~20M⊙.

FIG. 4.— Protostellar radius versus m_* for stars with $m_{*f} = 30\,M_\odot$ and for $\Sigma_{\rm cl} = 1\ {\rm g\ cm^{-2}}$. The *solid* and *dashed* lines show the cases with $k_\rho = 1.5$ and 1.75, respectively. The *dotted* line shows the zero age main sequence radius from Schaller et al. (1992).

McKee & Tan
2003
astro-ph/0206037.

During pre-ms accretion and growth, stars with ZAMS mass $> 70M_\odot$ never larger than their final ZAMS radius.

Stars $> 20M_\odot$ join ZAMS while still accreting. No phase of `contracting onto MS.'

McKee & Tan 2003 astro-ph/0206037.

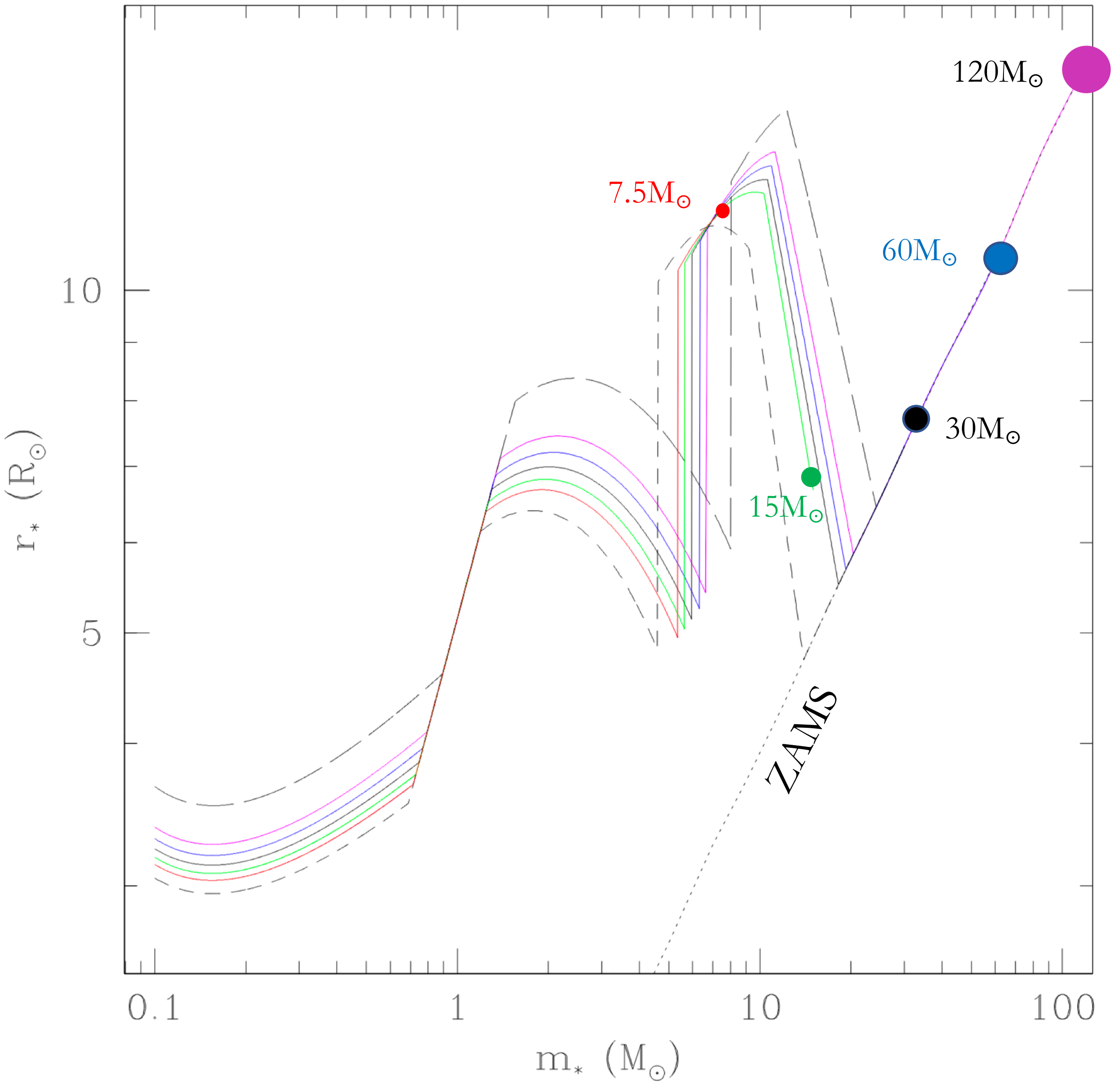


FIG. 5.— Radii of accreting protostars with $k_\rho = 1.5$. *Solid* lines show stars of final mass 7.5, 15, 30, 60 and 120 $M_\odot$ (bottom to top) accreting from cores embedded in a $\Sigma_{\rm cl} = 1\,{\rm g\,cm^{-2}}$ clump, typical of Galactic regions observed by Plume et al. (1997). The *long dashed* and short dashed lines show a 30 $M_\odot$ star forming in a clump with mean pressure 10 and 0.1 times this value, respectively. The *dotted* line shows the zero age main sequence radius from Schaller et al. (1992).

- However, if the molecular core has much angular momentum, accretion

$$\dot{M}_{in} \sim \frac{c^3_{s,\mathrm{eff},\mathrm{core}}}{G}$$

does not directly make a star, but makes a rotation-supported disk

- Does the disk fragment?
  1) Depends on Toomre Q(*t,r*) and ratio μ(*t*) of disk mass to mass of growing central primary.
  2) Re-express in terms of two control parameters

$$\xi = \frac{\dot{M}_{in} G}{c_{s,\mathrm{disk}}(r)^3} \simeq \left(\frac{c_{s,\mathrm{eff},\mathrm{core}}}{c_{s,\mathrm{disk}}}\right)^3 \qquad \Gamma = \frac{\dot{M}_{\mathrm{in}}}{M_{*d}\Omega_{k,\mathrm{in}}} = \frac{\dot{M}_{\mathrm{in}}\langle j\rangle^3_{\mathrm{in}}}{G^2 M^3_{*d}}$$

$$\xi = \frac{Q}{\alpha}\frac{\dot{M}_{in}}{\dot{M}_{\mathrm{disk}}(r)}$$

Γ= Disk orbital time/acc growth time

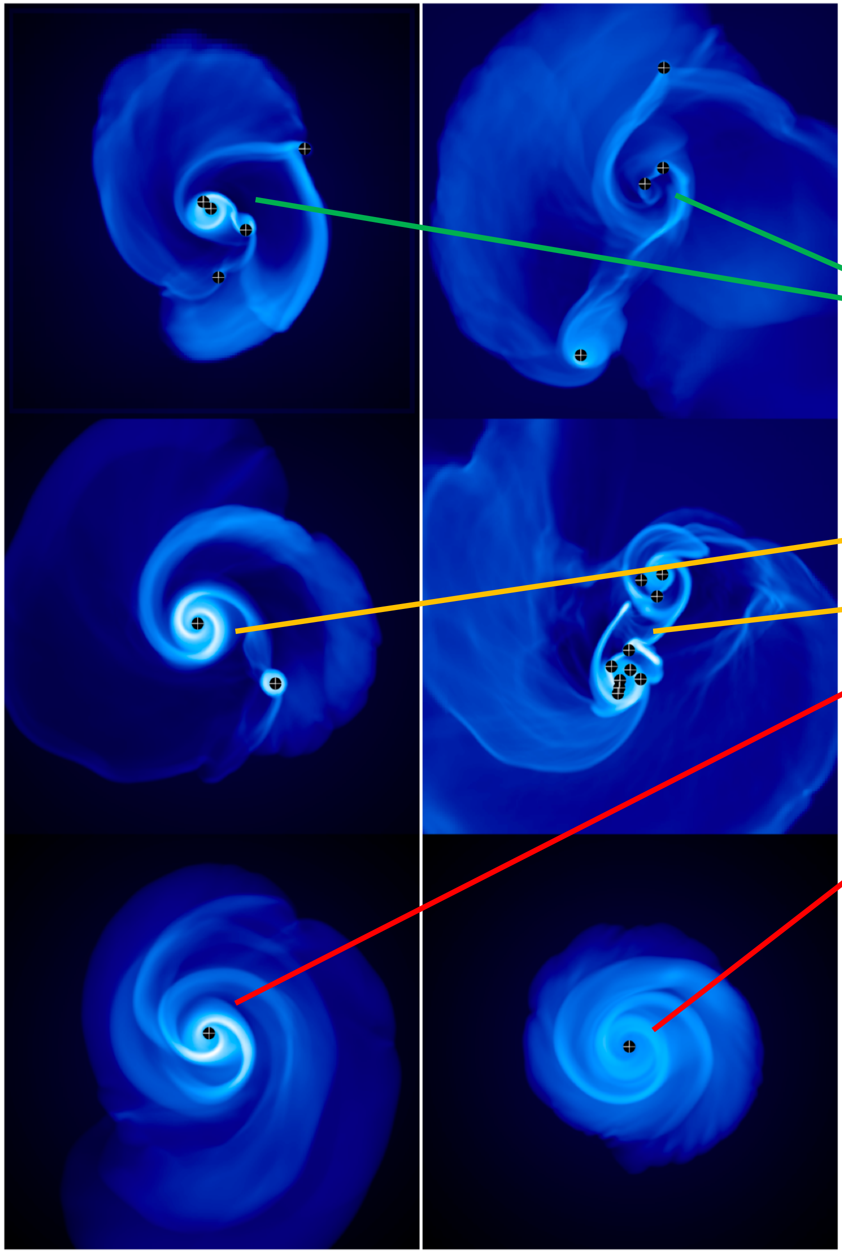
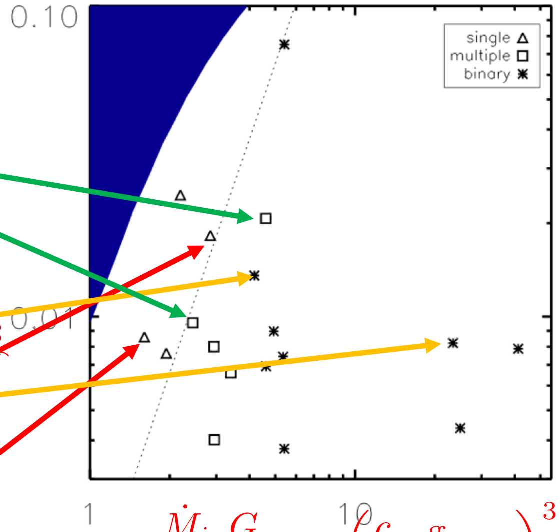


FIG. 1.— Two examples of single, binary, and multiple systems. The resolution across each panel is 328x328 grid cells. The single runs are $\xi = 2.9, \Gamma = 0.018$ (top), $\xi = 1.6, \Gamma = 0.009$ (bottom). The binaries are $\xi = 4.2, \Gamma = 0.014$ (top), $\xi = 23.4, \Gamma = 0.008$, (bottom). The multiples are $\xi = 3.0, \Gamma = 0.016$ (top), $\xi = 2.4, \Gamma = 0.01$ (bottom). Black circles with plus signs indicate the locations of sink particles. These correspond to runs 5, 1, 9, 16, 7, and 4 respectively.

$$\Gamma = \frac{\dot{M}_{\rm in}}{M_{*,d}\Omega k_{\rm in}} = \frac{t_{orb}}{2\pi t_{\rm acc}}$$



$$\xi = \frac{\dot{M}_{in} G}{c_{s,\rm disk}(r)^3} \approx \left(\frac{c_{s,\rm eff,core}}{c_{s,\rm disk}}\right)^3$$

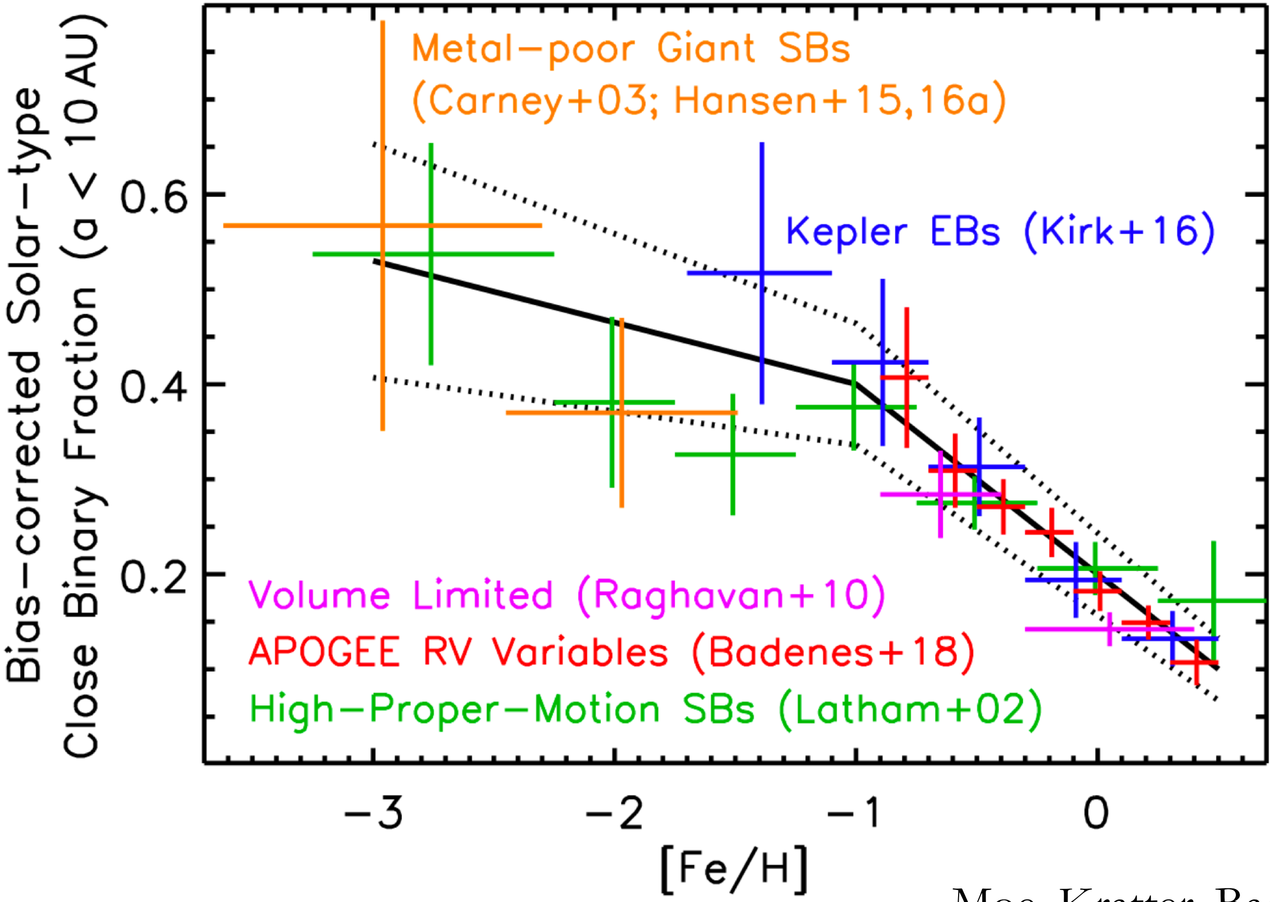
FIG. 2.— Distribution of runs in $\xi - \Gamma$ parameter space. The single stars are confined to the low ξ region of parameters space, although increasing Γ has a small stabilizing effect near the transition around $\xi = 2$ due to the increasing ability of the disk to store mass at higher values of Γ. The dotted line shows the division between single and fragmenting disks: $\Gamma = \xi^{2.5}/850$. As ξ increases disks fragment to form multiple systems. At even higher values of ξ disks fragment to make binaries. We discuss the distinction between different types of multiples in §5.3. The shaded region of parameter space shows where isothermal cores no longer collapse due to the extra support from rotation.

Kratter, Matzner, Krumholz & Klein 2010

Subsequent evolution of the fragmented disk

- Depends on accretion by fragments and disk torques
  1) cf MacFadyen++, Munoz++
  2) Thin disk: secondary accretes more, drives to equal mass, q=1.
  3) Thick disk: if secondary >isolation mass, can preserve high mass ratio.
  4) Disk torques –controversy (Munoz++: expand orbit, drive high *e;* MacFadyen++ -only sometimes; sink particles, resolution of minidisks and isothermal vs energy-conserving are issues).

For solar-mass stars, close binary fraction and triple/quad fraction rises for low metallicity.



Moe, Kratter, Badenes 2019

FIG. 18.— The intrinsic close binary fraction ($P < 10^4$ days; $a < 10$ AU) of $M_1 \approx 1\,\mathrm{M}_\odot$ primaries as a function of metallicity *after* correcting for incompleteness and other selection biases. We compare the measurements from: (1) SBs in samples of metal-poor giants (orange), (2) *Kepler* EBs with solar-type dwarf primaries (blue), (3) a volume-limited sample of solar-type primaries (magenta), (4) RV variables in the APOGEE survey of GK IV/V stars (red), and (5) SBs in the Carney-Latham survey of high-proper-motion stars (green). All five samples / methods show a consistent metallicity trend that can be fitted by two line segments (black) in which the close binary fraction decreases from $F_{\rm close} = 53\% \pm 12\%$ at [Fe/H] $= -3.0$ to $F_{\rm close} = 40\% \pm 6\%$ at [Fe/H] $= -1.0$ and then to $F_{\rm close} = 10\% \pm 3\%$ at [Fe/H] $= +0.5$. Even after accounting for systematic uncertainties, the close binary fraction of solar-type stars is anti-correlated with metallicity at the $\approx 9\sigma$ significance level.

For solar-mass stars, close binary fraction and triple/quad fraction rises for low metallicity.

Wide binary fraction, and close binary fraction for massive stars does not change w/ metallicity.

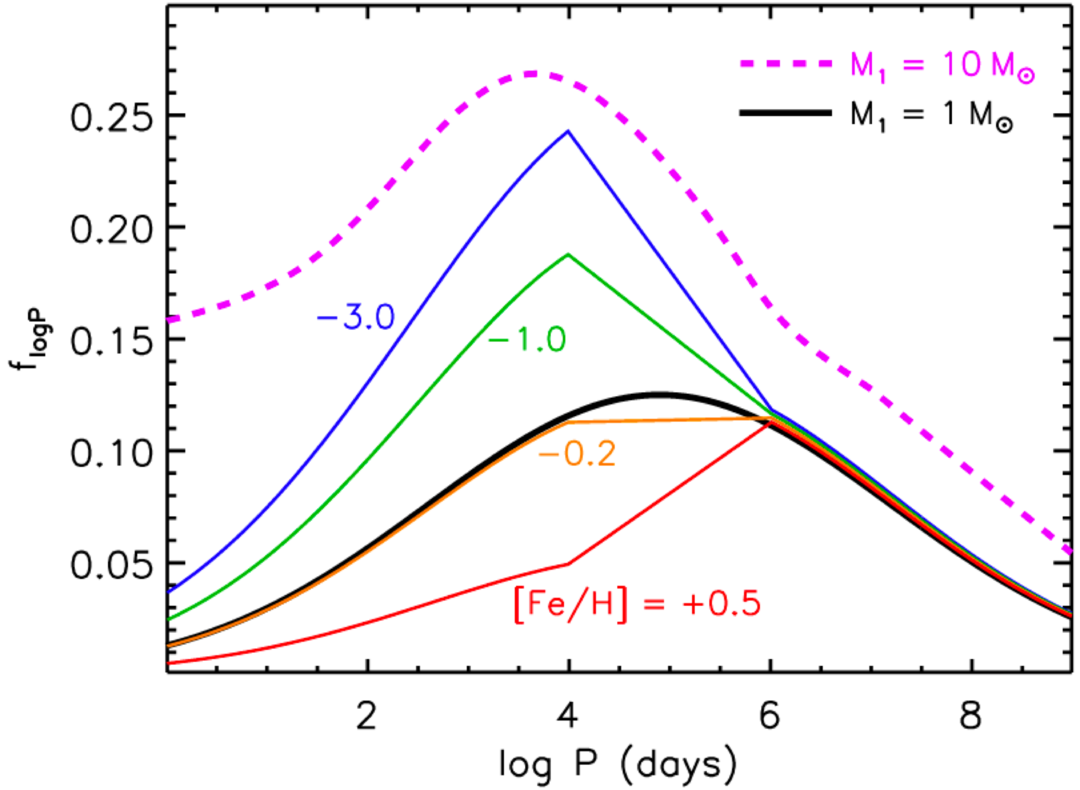


FIG. 19.— The frequency $f_{\log P}$ of stellar companions per decade of orbital period. We compare the canonical log-normal period distribution of solar-type multiples in the solar neighborhood (thick black) to the companion distribution of early-B stars (thick dashed magenta). We also show the metallicity-dependent period distributions for solar-type primaries with [Fe/H] = −3.0 (blue), −1.0 (green), −0.2 (orange), and +0.5 (red). The close binary fraction ($\log P < 4$; $a < 10$ AU) of solar-type stars is significantly anti-correlated with metallicity while the frequency of wide companions ($\log P > 6$; $a > 200$ AU) is metallicity invariant. As solar-type stars decrease in metallicity, both their binary fraction and binary period distribution approaches that of early-B stars.

Moe, Kratter, Badenes 2019

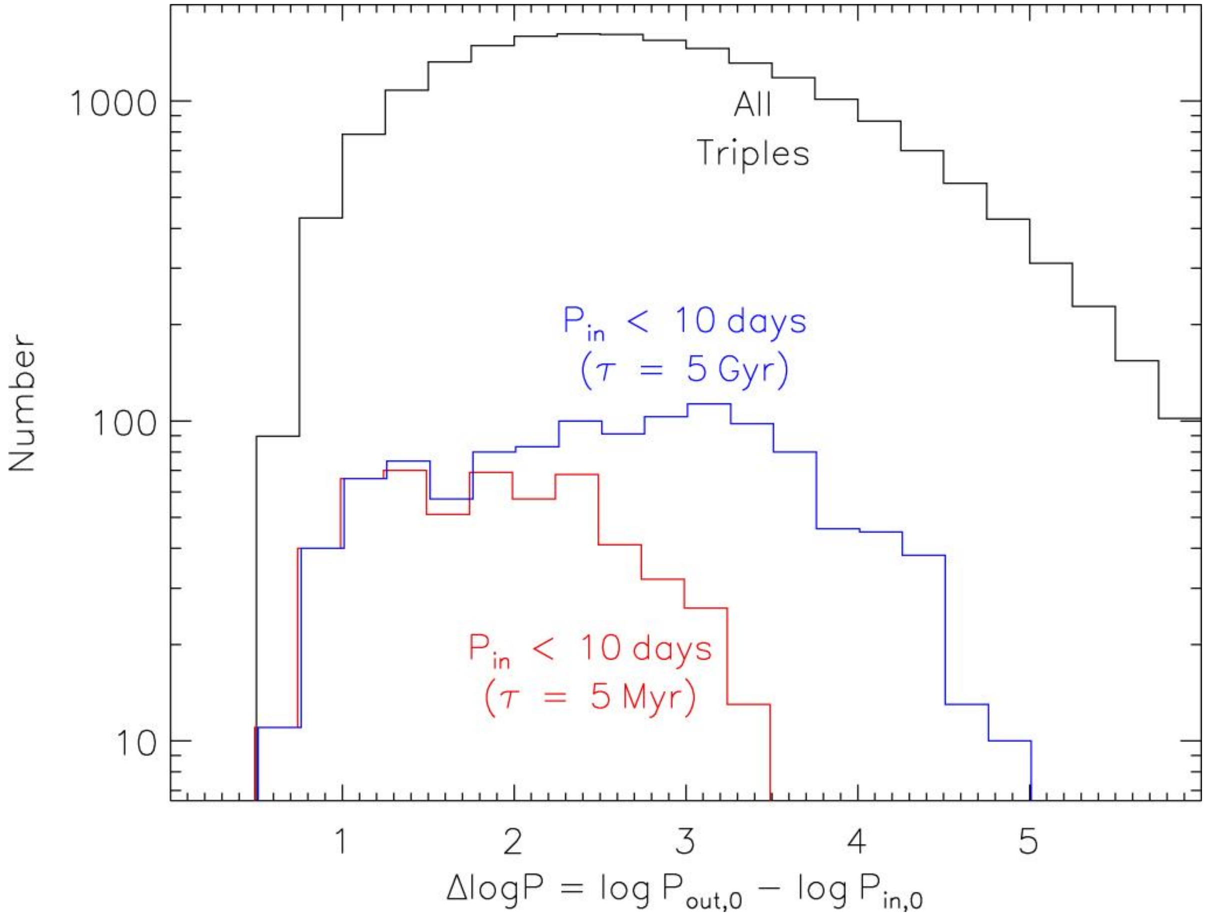
Origin of close binaries?

1) Disk fragmentation and migration.

2) Bifurcation of rapidly rotating protostar

3) Hierarchical triples: Kozai + tides

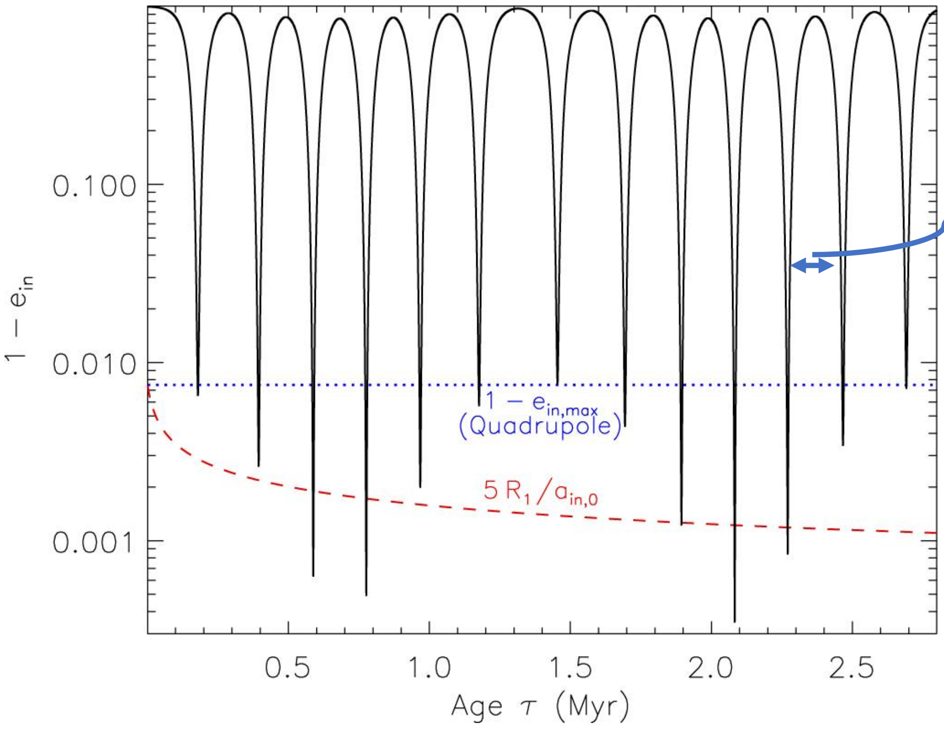
(For solar mass triples)



Moe & Kratter 2018

(formation of close *solar mass* binaries in triples via Lidov-Kozai & tides;

cf. Eggleton & Kisseleva-Eggleton 2006, Fabrycky & Tremaine 2007, Naoz & Fabrycky 2014)



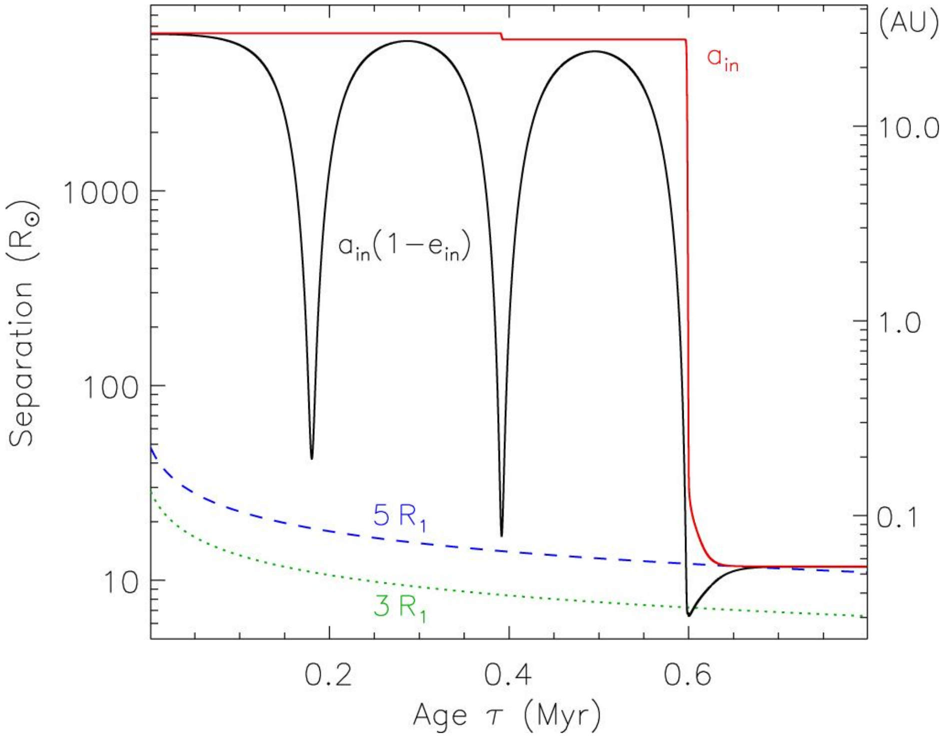
$$T_K = \frac{M_i}{M_o}\frac{P_o^2}{P_i}(1-e_o^2)^{3/2}$$

$$= 3\times 10^4\text{y for } M_i = 50, M_o = 2, \\ P_i = 2\text{d}, P_o = 1200\text{d}, e_o = 0.5\ .$$

$$= 6\times 10^5\text{y for } M_i = 50, M_o = 2, \\ P_i = 100\text{d}, P_o = 100\text{y}, e_o = 0.5\ .$$

Eccentric Kozai-Lidov in hierarchical triples, (incl octupole).

Moe & Kratter 2018
(formation of close *solar mass* binaries in triples)



EM counterparts to stellar mass black hole binary mergers

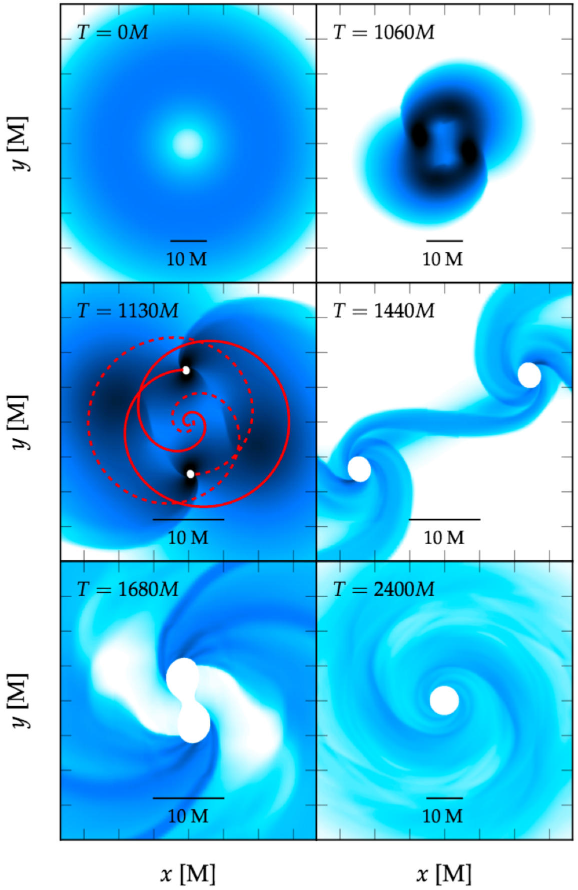
- Charged binary black holes’ magnetospheric interactions (pulsar-like)
  1) Zhang 2016, 2019
     - $Q/M \sim 10^{-4}$ could produce GRB fluence
     - $Q/M \sim 10^{-8}$ could produce faint FRB luminosity

$$L_{\mathrm{e,dip,max}} = (5.0 \times 10^{42}\ \mathrm{erg\ s^{-1}})\ \hat{q}^2_{-7},$$
$$E_{\mathrm{e,dip}} = (1.0 \times 10^{40}\ \mathrm{erg})\ \hat{q}^2_{-7},$$

     - BUT: spontaneous vacuum breakdown limits $Q/M < 10^{-5}$
     - Astrophysical pair creation (cascades initiated by backgrounds and cosmic rays) limits $Q/M < 10^{-33}$

EM counterparts to stellar mass black hole binary mergers

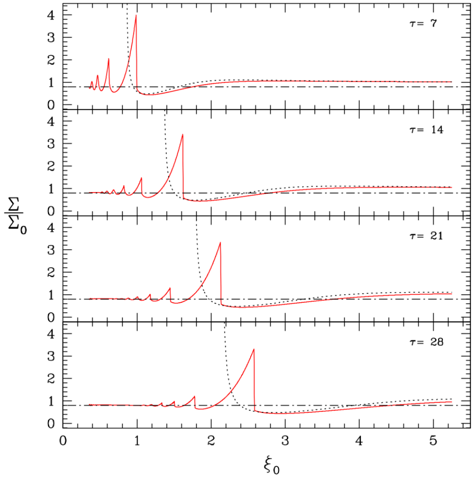
- Collapse of a massive star with rapidly rotating core
    1) Core forms rotating bar, bifurcates into two massive stars which collapse to black holes and merge, producing two or one hypernova/GRBs
        - ➢ Invented to explain possible (2.5σ) γ-rays 0.5s before GW150914 (Verrecchia+2017, Connaughton+ 2016, 2018).
        - ➢ No subsequent GW-γ-ray associations other than GW170817 (NSNS): [arXiv:1907.01443](https://arxiv.org/abs/1907.01443) (LSC paper)
        - ➢ Reisswig, Ott+ 2013, Loeb 2016, D'Orazio & Loeb 2018
- Could get similar situation in common-envelope leading to merger?
    1) Synchronization of collapse of core to merger with inspiralling black hole rare.



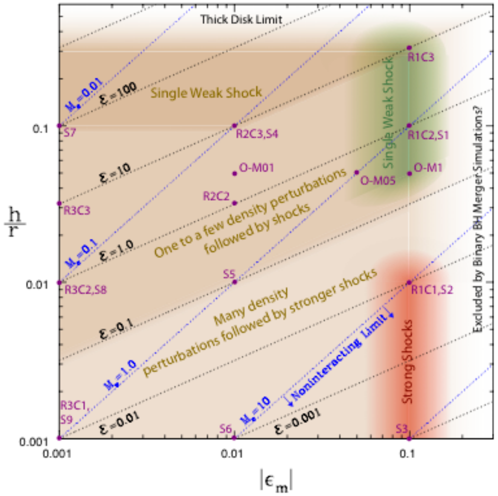
Reisswig, Ott + 2013

EM counterparts to stellar mass black hole binary mergers

- Zombie disks
    1) My-Gy old dead circumbinary disks (too cold and neutral for MRI, so negligible viscosity) shocked, ionized by mass loss of central black hole merger. Ionization triggers accretion after merger.
        - ➢ Bode & ESP 2007, Bode 2011, de Mink & King 2017, Martin, Nixon+ 2018
        - ➢ Time for escape of photons an issue (decade vs hours).
    2) Or zombie minidisk around one black hole revitalized by tidal perturbation of inspiraling second black hole just before merger
        - ➢ Perna, Lazzati+ 2016



Bode 2011



EM counterparts to stellar mass black hole binary mergers

- Binary black holes in AGN accretion disks
  1) Stars of nuclear clusters damped by disk and captured in disk, grow by accretion of dense circumbinary disk from `Hill sphere', move to migration traps where Σ peaks and torques cancel.
     - Baruteau, Cuadra & Lin 2011, McKernan, Ford, Lyra & Perets 2012, McKernan, Ford+ 2014, Bellovary, Mac Low+ 2016, Bartos, Kocsis+ 2017, McKernan, Ford++ 2018, Yi, Cheng & Taam 2018; Stone, Metzger & Haiman 2017, Seconda+ 2019, Derzinski+ 2019, Yang+ 2019
     - NB –can potentially grow to IMBH, no respect for PISN gap.
     - Rate estimates vary over many orders of magnitude.

Other EM-GW possibilities

- Supernova mass loss/kick at formation of second BH (in binary or higher mult). Sometimes leads to near-radial orbit of BH binary and merger within months-decades of SN.
  - Michaely & Perets 2017
  - 0.01-1% of sources

- Gravitational self-lensing
  - If at least one BH is accreting before merger, and high inclination, lensing by other BH can modulate signal
    - D'Orazio & Di Stefano 2019

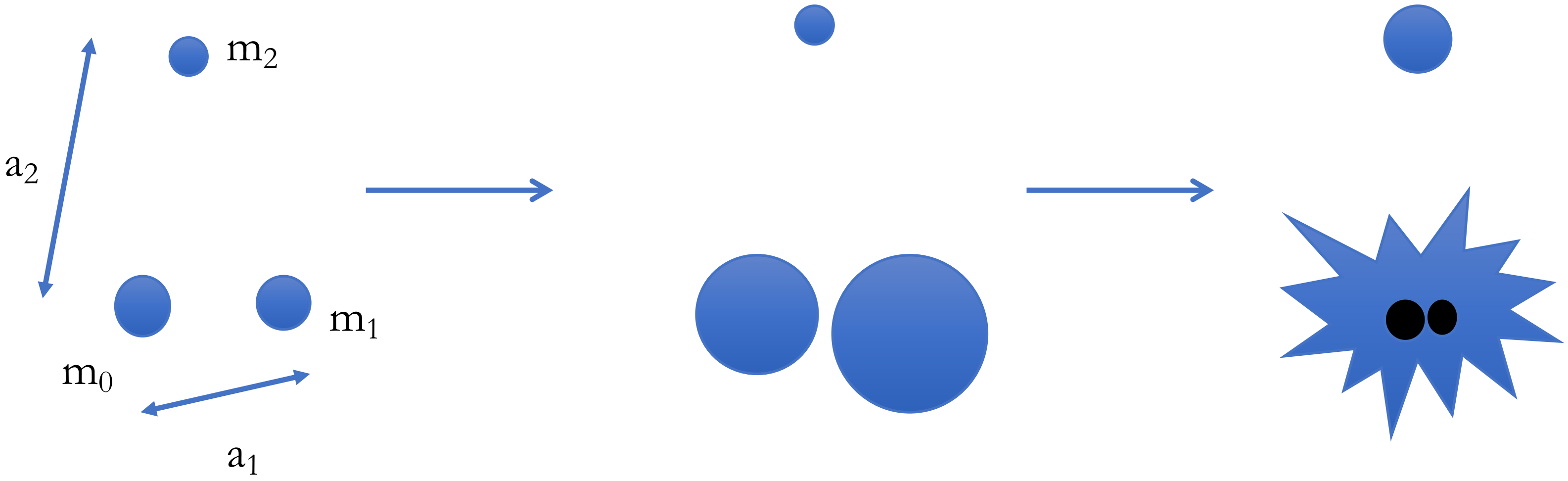
EM counterparts to stellar mass black hole binary mergers

- Hierarchical triples, quads or more

  Accretion from outer star brought to fill Roche lobe by evolutionary expansion, Lidov-Kozai in quad, or passing stars in a cluster.

  Wen & Phinney 2019

The Story …

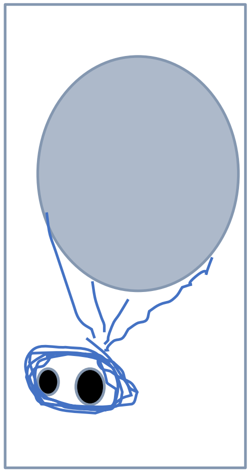


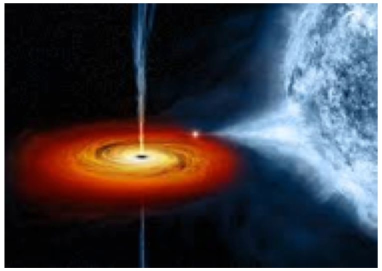
A stable hierarchical triple system of massive stars (commonly formed by ZAMS in Galactic disk; also dynamical exchange in globular clusters). Simplest case: low mutual inclination, no Kozai

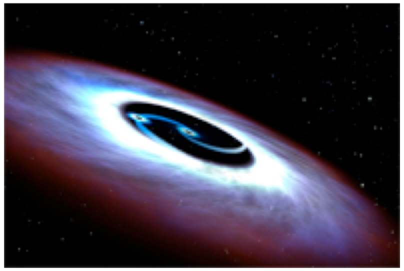
Inner binary evolves the same way as lone binary progenitors for compact binary BHs, but allowing wider binary orbits. Common envelope unfavorable: would limit 3rd body to v. wide orbit. (irrelevant for exchange), but Kozai in quad or cluster encounter could also allow

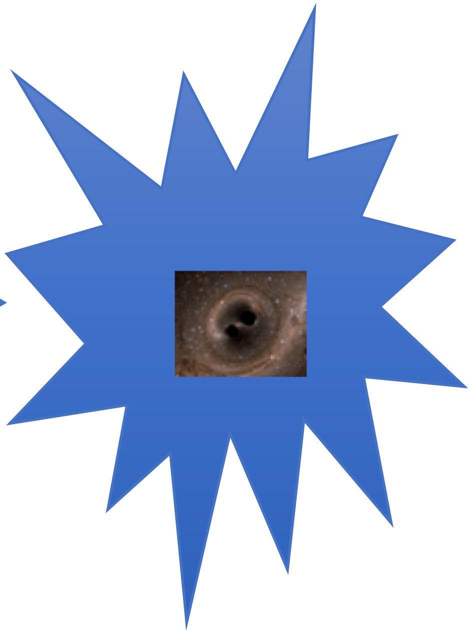
Inner binary forms binary BHs the same way as in lone binaries. If kicks are not too large and not huge mass loss, 3rd star survives the process that forms BBH.

The Story (cont.)







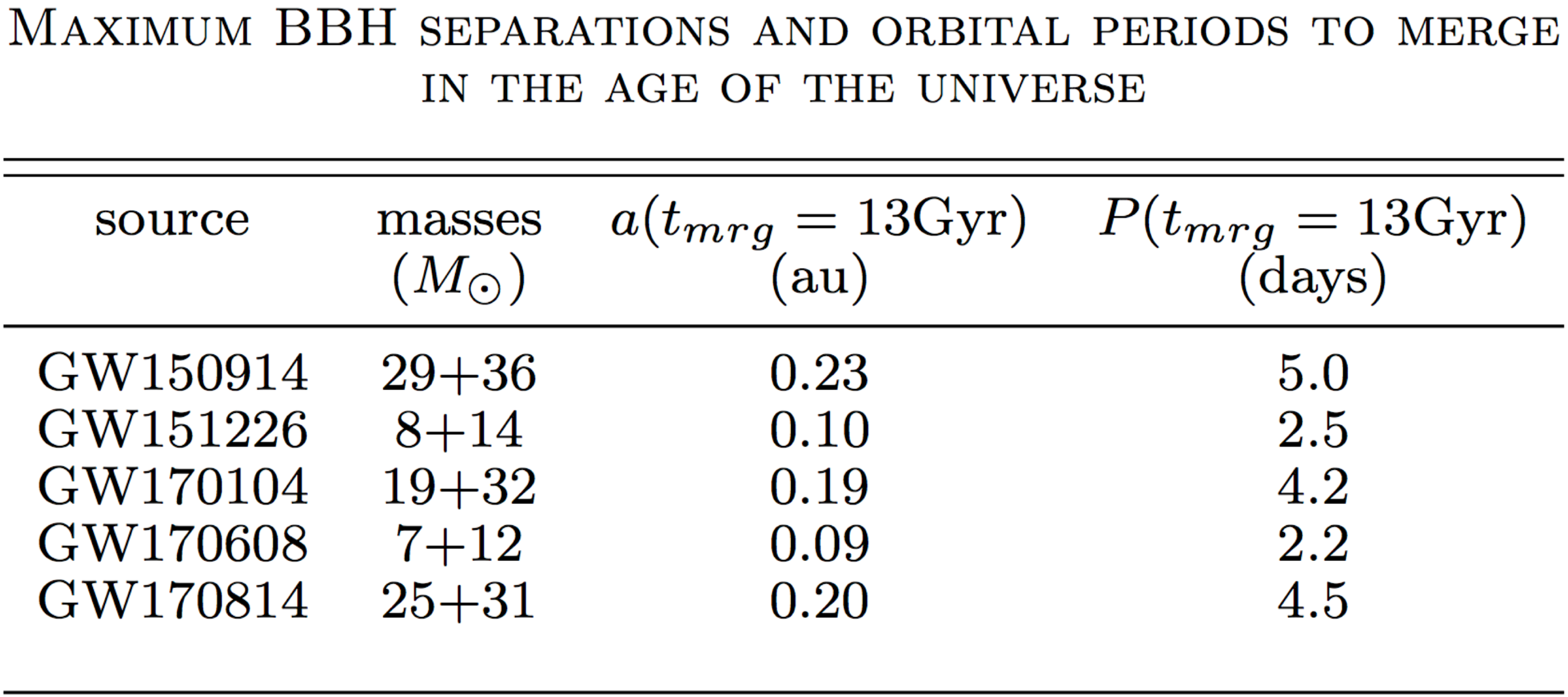


After forming binary BHs, the 3rd star starts to fill its Roche Lobe, accreting onto Binary BHs, looking like bright X-ray binary sources.

Accretion can (slightly) help drive BBH to merge for wider periods and faster

Formation of circum-binary disk, mini-disks, super-Eddington accretion at binary merger, shock heated disks at merger

Possible EM counterparts in X-rays, optical and radio for BHB merger in LIGO band.



Maximum BBH separations and orbital periods to merge in the age of the universe

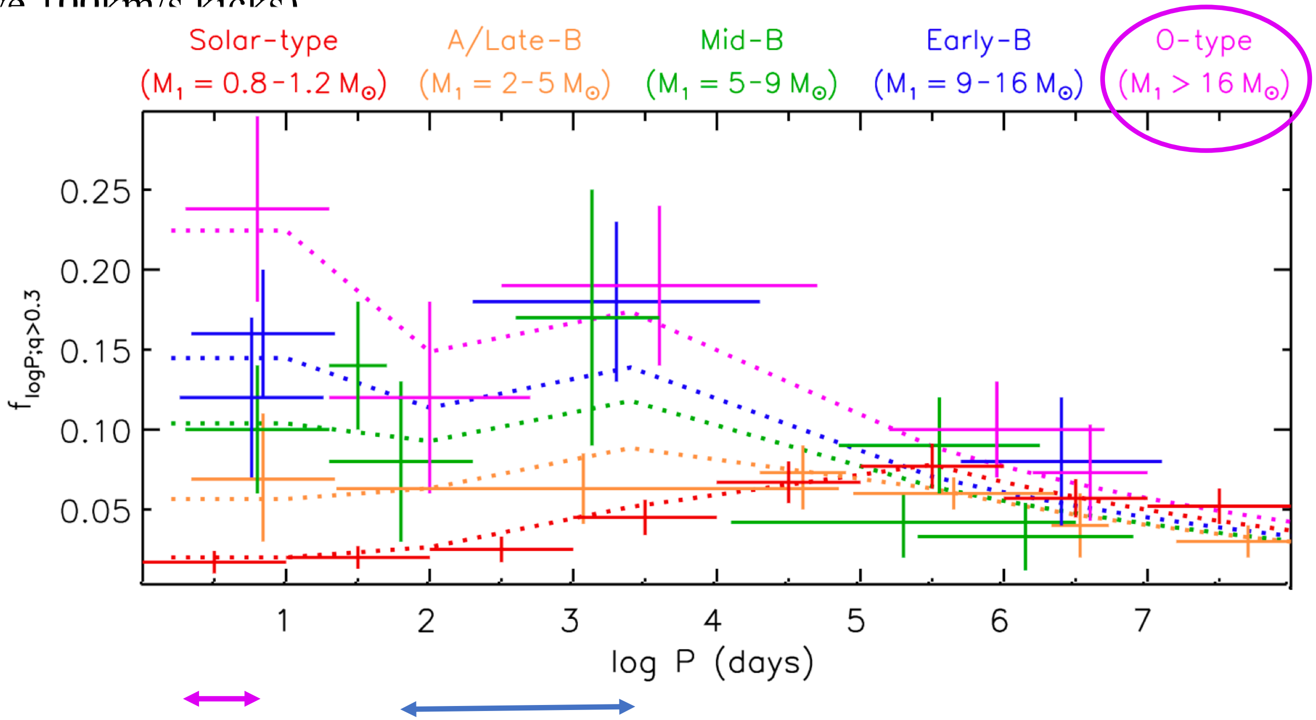
source	masses ($M_\odot$)	$a(t_{mrg} = 13\text{Gyr})$ (au)	$P(t_{mrg} = 13\text{Gyr})$ (days)
GW150914	29+36	0.23	5.0
GW151226	8+14	0.10	2.5
GW170104	19+32	0.19	4.2
GW170608	7+12	0.09	2.2
GW170814	25+31	0.20	4.5

(circular orbits)

Massive stars in triples (selection corrected)

- Moe & DiStefano 2016: arXiv: 1606.05347: reproduce Eggleton 2009
  1) Of O triple/quadruples with a close inner binary, ~30% have $3a_{12} < a_3 < 100a_{12}$ (easily survive 100km/s kicks)

Orbital period distribution



good for primary BHBH to merge

good for tertiary to survive kick and have later mass transfer

Compared to Lone BBH Systems

- Assuming the same mechanism that forms compact/close BBHs

- Progenitors of coalescing BBHs in inner binary of stable triples/ lone binaries > ~ 50%
  - Eggleton: O star systems have 40% triple/binary ratio, 165% multiple/binary ratio!
  - Adopt 2/3 chance for O star to be in inner binary with wide third companion.

- Survival of the 3rd accreting star is the concern

To Survive …

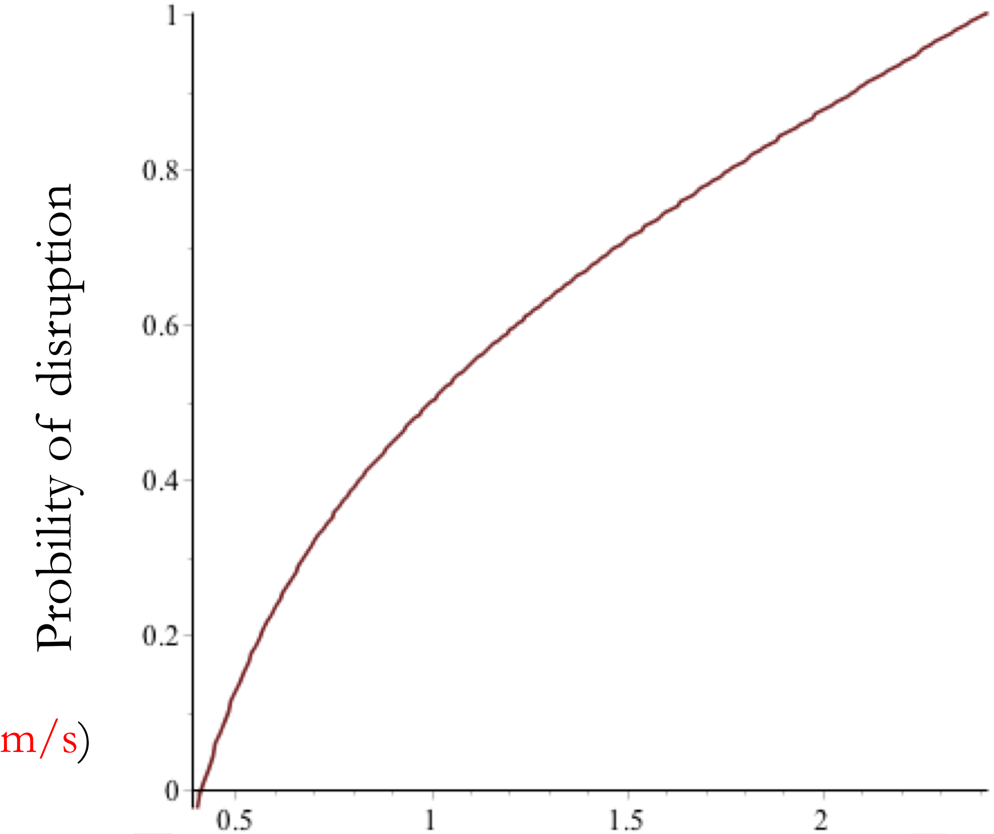
- Simplest survival scenarios for triple to survive
  - No mass loss or kick from inner binary BH formation
    - Direct core collapse into BHs with no SN
    - e.g. Fryer, C. 1999
  - No strong post-MS expansion of BH progenitor star
    - e.g., rotational mixing during H burning: de Mink+ 2010, de Mink & Mandel 2016, Marchant+ 2016.
- More complex situations if progenitor stars evolves and expands, or if black hole formation not via direct collapse.

Disruption by kicks with negligible mass loss

$$v_{rel} \equiv \left(\frac{G(M_1 + M_2)}{a^3} \right)^{1/2} a$$

Inner binary:
=710km/s (35+35 Chem homog)
=465km/s (8+16 2nd collapse)
= 550km/s (CE 2nd collapse)
=82km/s (CE 1st collapse)

Outer binary
(sees CM kick ~1/2 v_{kick} for equal mass BBH: ~50km/s for v_{kick}=100km/s)
>50% survival for
a<5000 $R_\odot$ (30+30) or
a<1500 $R_\odot$ (10+10):
stable hierarchical, mass transfer likely at or before red giant phase).



$\sqrt{2} - 1$ $\quad v_{kick}/v_{rel} \quad$ $\sqrt{2} + 1$

Wen & ESP 2017

To Survive…

- If SN/CE, 3rd star should be massive enough to survive kicks from supernova
    - but not too massive to live longer than progenitors of inner binary T ~ $M^{-2.5}$
    - 3rd star not engulfed by the expanding progenitor
- 3rd star should accrete after BBH formation
    - Fraction of Roche-Lobe overflow accreting binaries f ~ 30-40 %
- Therefore high mass companion star helps with survival and substantial accretion
    - MS B star: 1%
    - Consider high-mass companion only (M(progenitor) >M >~ M(BHs))

Later Accretion

$$t(>P) \simeq 10^8 \mathrm{y} (P/120\mathrm{d})^{-1}$$

<- lifetime of Roche-lobe filling tertiary giant's accretion phase (stable transfer)

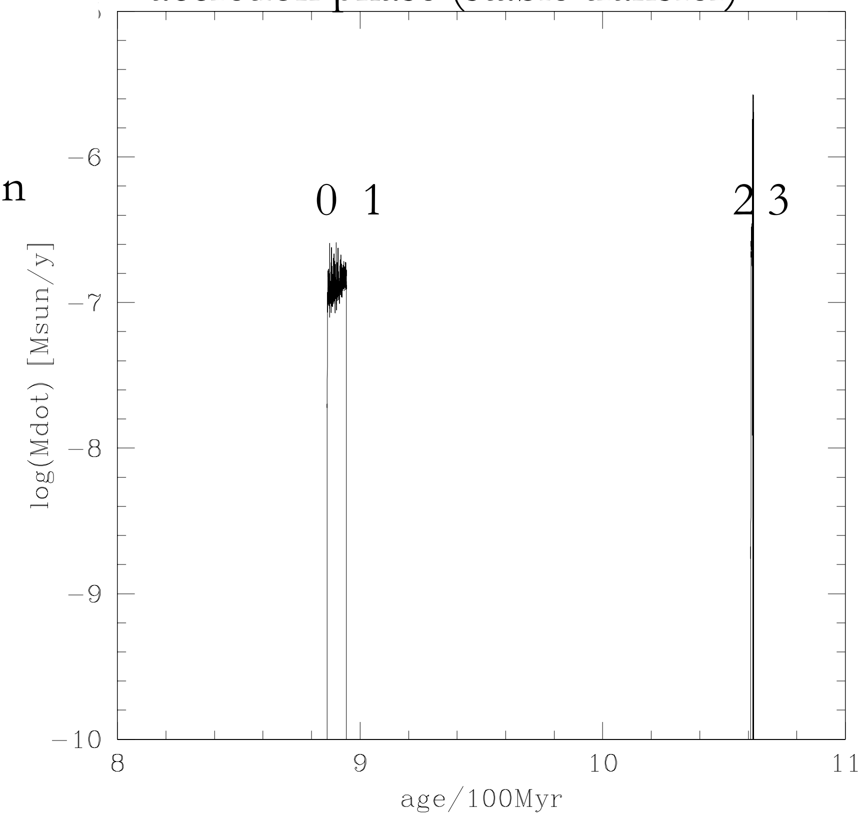
MESA binary, conservative J,
isotropic reemission of superEddington

$M_3(0)=2.1M_\odot$, $P_3(0)=50d$

$M_3(1)=1.0M_\odot$, $P_3(1)=300d$

$M_3(3)=0.7M_\odot$, $P_3(3)=1300d$

duration of first accretion phase 1.4×10^7 y.



EM Emission from Binary Black Hole Merger

- If nearby, looks like bright X-ray binaries before and after
  - unless merger kick (>100km/s) for high-spin black holes unbinds the tertiary, in which case accretion will cease after.

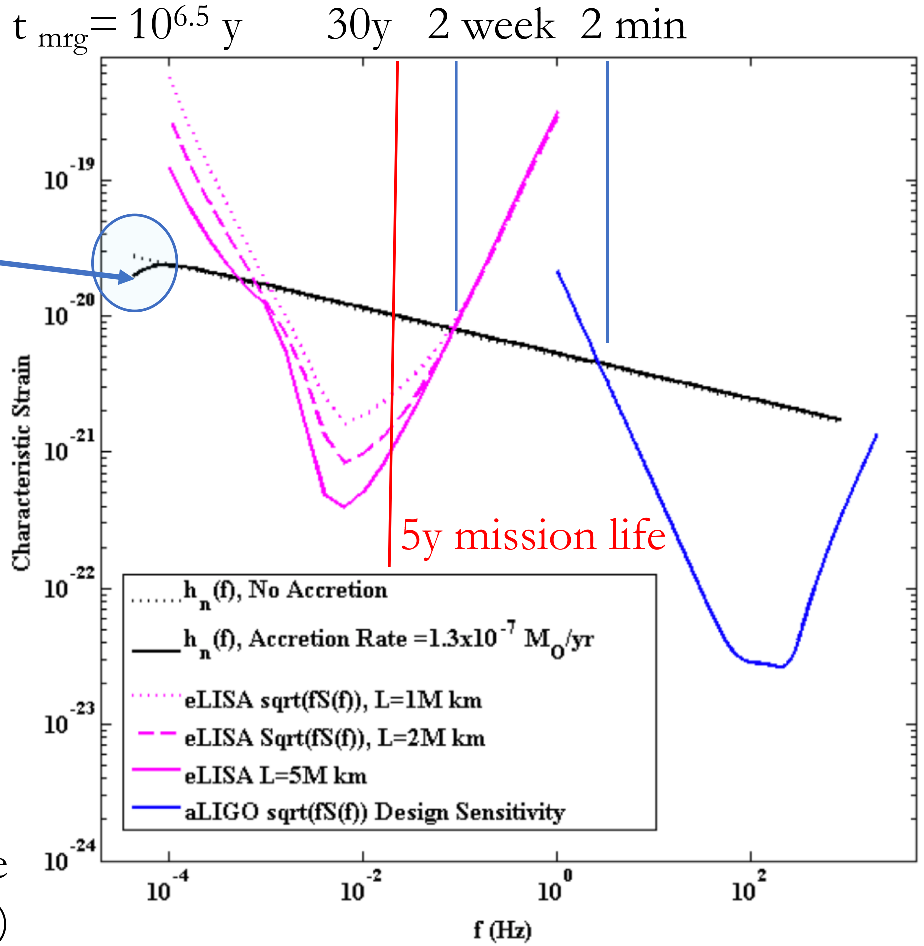
- If minidisks are present shortly before merger: in final GW-driven stages, accretion rate may be greatly enhanced: faint (m~22, hour-day @ 400 Mpc) Xray-optical transient, or radio from outflow jet (mJy, yrs)
  - (e.g. Murase et al 2016 arXiv: 1602.06938)

Identifying triples with eLISA

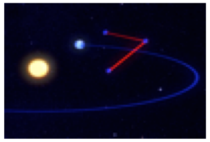
(30+30)$M_\odot$ @200Mpc
Mdot=10^{-7} $M_\odot y^{-1}$
(negative torque per Tang+2017: speeds inspiral)

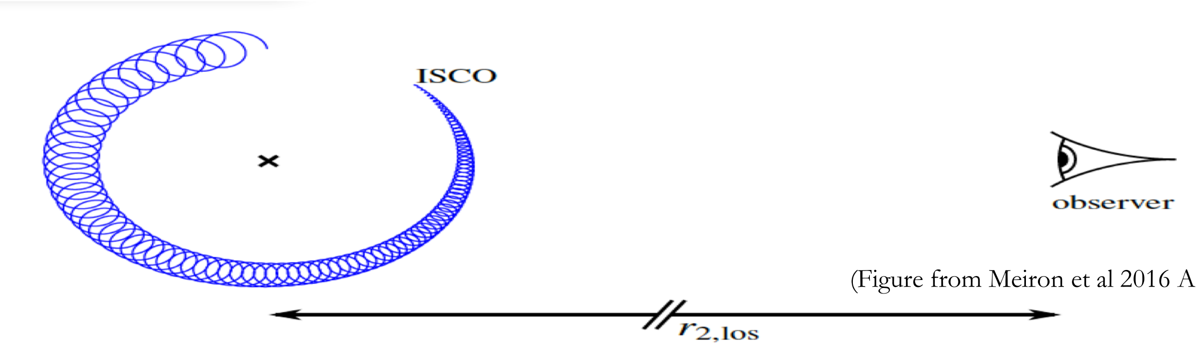
Positive torque per Munoz (Tues) would turn up [slows inspiral]

Mdot phaseshift undetectable (degenerate with mass in LISA band)



Doppler Effect on inner binary GW





(Figure from Meiron et al 2016 Arxiv: 1604.0214)

- Inner binary spends long time in eLISA band
  - A few x 100 yrs for 5+5 $M_\odot$, a few years for 30+30$M_\odot$
- Outer binary has ~100 orbits in 2 yrs

$$N = T_{\rm obs} f = 400 \left(\frac{T_{\rm obs}}{2{\rm yr}}\right) \left(\frac{M}{10M_\odot}\right)^{1/2} \left(\frac{a}{0.1{\rm AU}}\right)^{-3/2} \;\; {\rm cycles}.$$

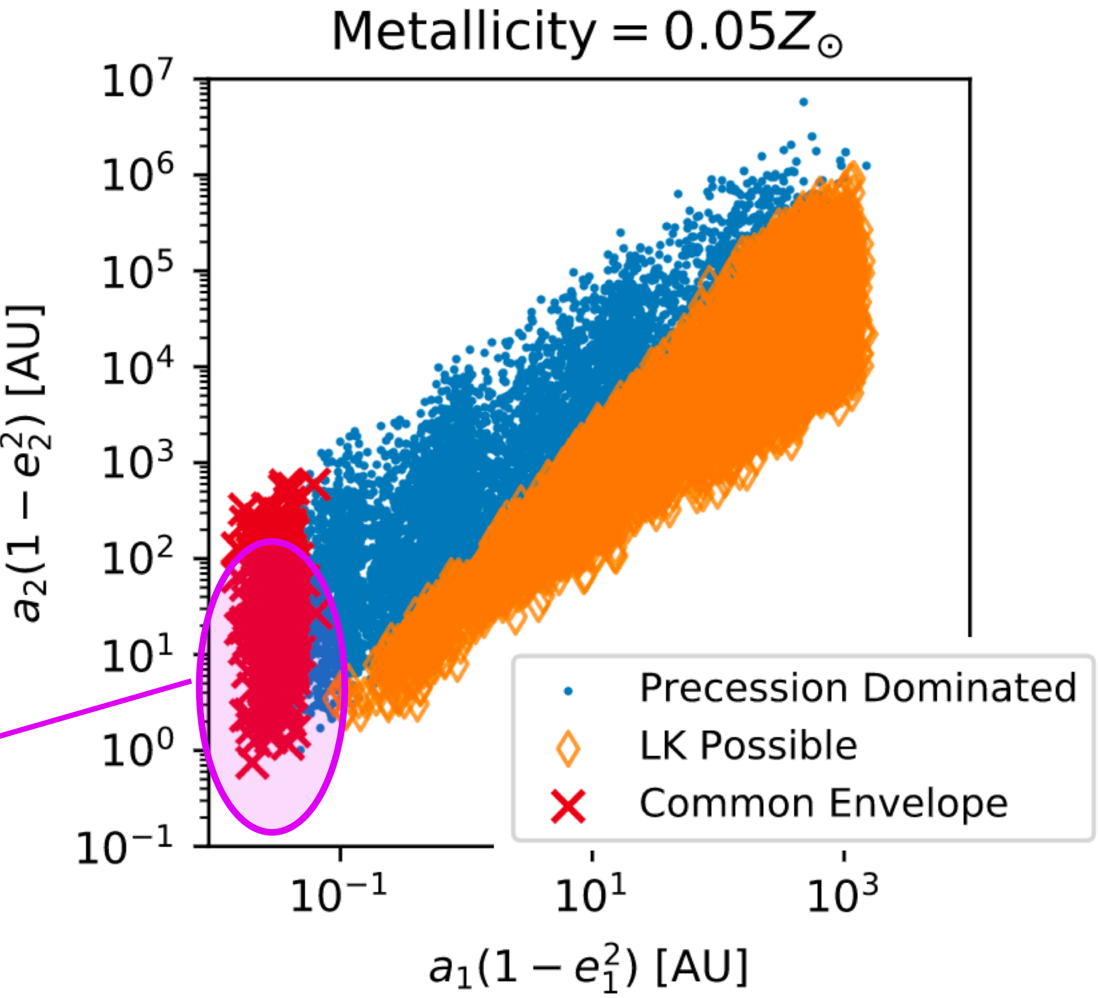
- Doppler effect on GW signals potentially observable

$$\delta t = 25 \left(\frac{M_1/M_2}{0.5}\right) \left(\frac{a_2}{0.1AU}\right) \sin i_2 \cos\phi_2 \;\; {\rm seconds},$$

- Sinusoid oscillation in arrival timing residuals – PTA style signal processing?

Formation via common-envelope instead of homogeneous evolution?

Possible for
Z<<Z⊙ &
M<15M⊙



BBH binaries that will merge with tertiary companions that can transfer mass

Rodriguez & Antonini 2018