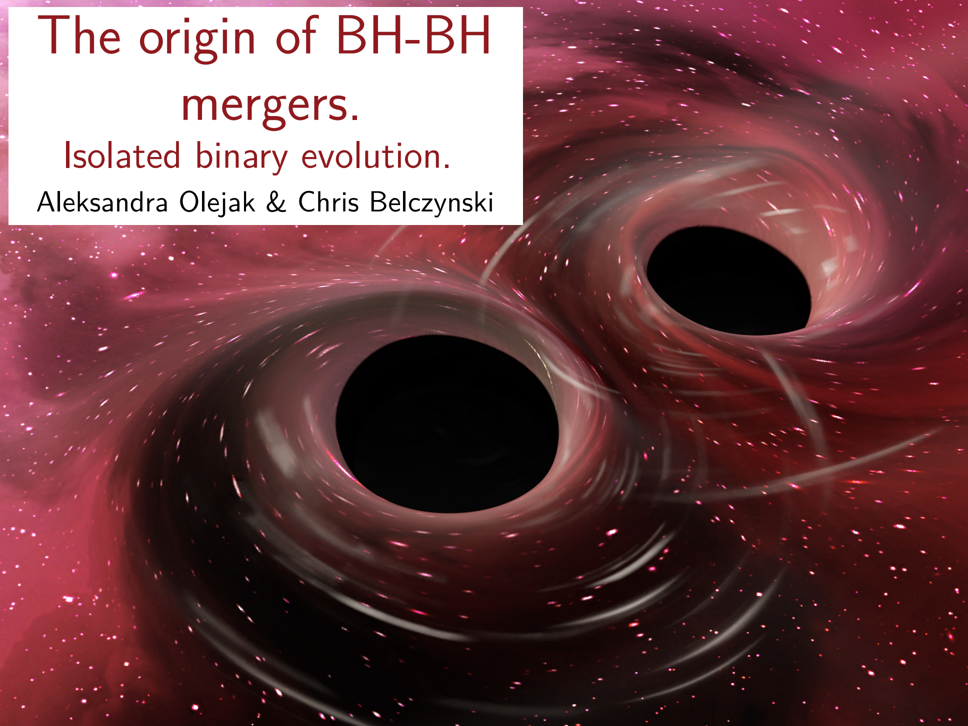
The origin of BH-BH mergers.

Isolated binary evolution.

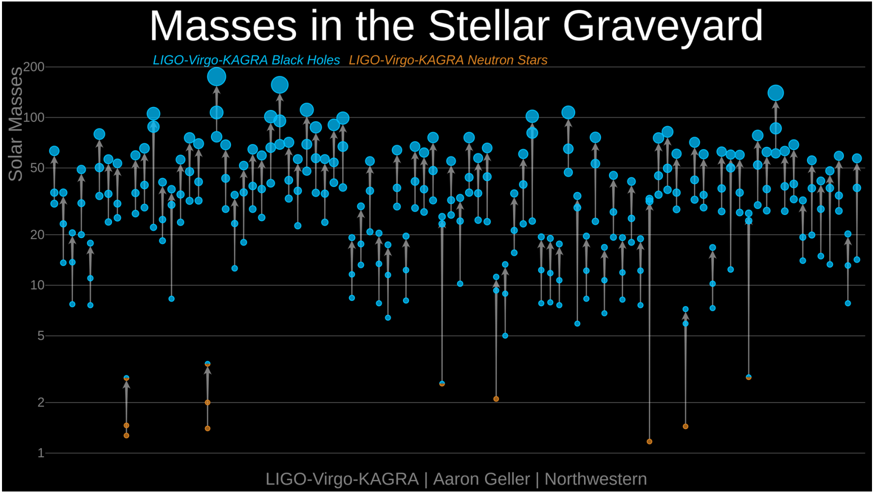
Aleksandra Olejak & Chris Belczynski



Presentation plan

- Summary of (so far) LIGO/Virgo detections
- Possible origin of detected GW sources
- Population synthesis method and the Startrack code
- Isolated binary evolution scenario with CE and non CE channel. The impact of RLOF physcis on the masses and spins of BH-BH mergers.

CAMK
PAN


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GW detections

LIGO-Virgo-KAGRA reported population properties of 76 compact binary mergers detected with gravitational waves below a false alarm rate of 1 per year. Classification:

- $\sim$70 BH-BH mergers
- 4 BH-NS mergers ?
- 2 NS-NS mergers ?

Current constrains on merger rate densities:

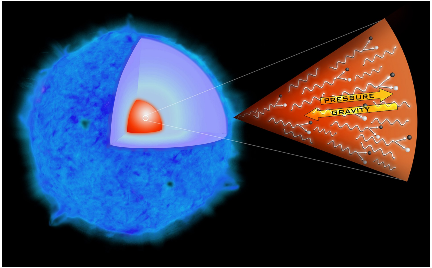
- BH-BH: $16 - 130$ Gpc^{-3}yr^{-1}
- BH-NS mergers: $7.4 - 320$ Gpc^{-3}yr^{-1}
- NS-NS mergers: $13 - 1900$ Gpc^{-3}yr^{-1}

Accounting for the BH-BH merger rate to evolve with redshift: $17.3 - 45$ Gpc^{-3} yr^{-1}$(z = 0.2)$.

Masses

- **Lower (first) mass gap:** Observations of X-ray binaries indicate a dearth of compact objects in the mass range from $\sim 2.5 - 5\ M_{\odot}$.
- **Upper (second) mass gap:** pulsational pair-instability supernova and pair-instability supernova from $M_{\mathrm{BH}} \gtrapprox 45\ M_{\odot}$?.

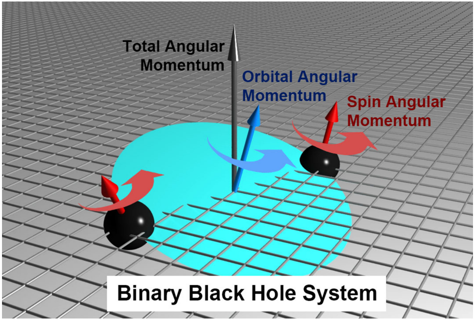
GWTC-3: *BH mass distribution exhibits an interval between* $2.1 - 5.8 M_{\odot}$ *where merger rates are suppressed, which could be consistent with past X-ray observations suggesting a mass gap. [...] so far, no evidence for or against an upper mass gap.*



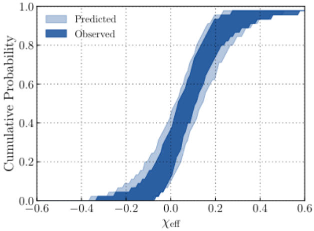
Effective spin parameter:

$$\chi_{\rm eff} = \frac{m_1 a_1 \cos\theta_1 + m_2 a_2 \cos\theta_2}{m_1 + m_2} \approx 0,$$

m_i - BH masses, $a_{\rm i} = cJ_i/Gm_i^2$ - dimensionless BH spin magnitudes (J_i - BH angular momentum, c - the speed of light, G - the gravitational constant), θ_i - angles between the individual BH spins and the system orbital AM.



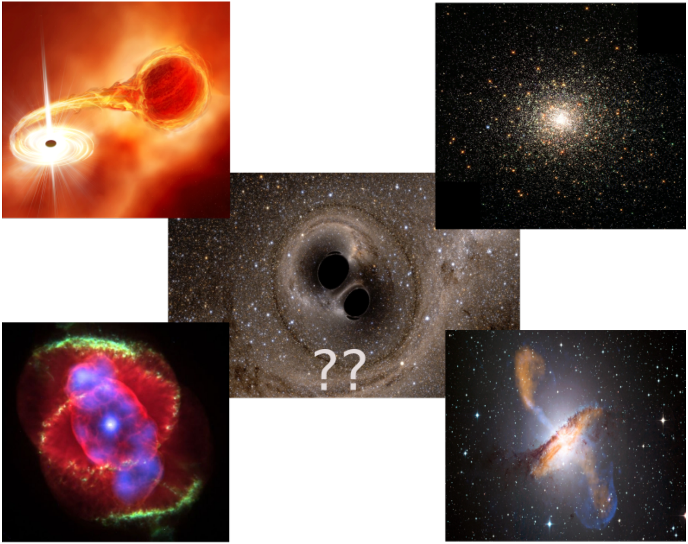
Majority of BH-BH mergers with low $\chi_{\text{eff}} < 0.2$; GWTC-3: *Observed black hole spins are small, with half of spin magnitudes below 0.26.*



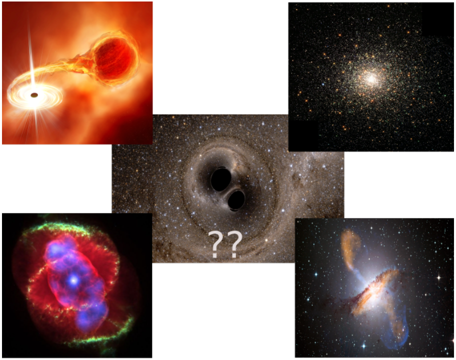
But 7 of BH-BH mergers have high effective spins $\chi_{\text{eff}} > 0.3$.

No.	Name[a]	χ_{eff}	m_1	m_2	a_1
1	GW190517	$0.52^{+0.19}_{-0.19}$	$37.4^{+11.7}_{-7.6}$	$25.3^{+7.0}_{-7.3}$	–
2	GW170729	$0.37^{+0.21}_{-0.25}$	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	–
3	GW190620	$0.33^{+0.22}_{-0.25}$	$57.1^{+16.0}_{-12.7}$	$35.5^{+12.2}_{-12.3}$	–
4	GW190519	$0.31^{+0.20}_{-0.22}$	$66.0^{+10.7}_{-12.0}$	$40.5^{+11.0}_{-11.1}$	–
5	GW190706	$0.28^{+0.26}_{-0.29}$	$67.0^{+14.6}_{-13.3}$	$38.2^{+14.6}_{-13.3}$	–
6	GW190403	$0.70^{+0.15}_{-0.27}$	$88.0^{+28.2}_{-32.9}$	$22.1^{+23.8}_{-9.0}$	$0.92^{+0.07}_{-0.22}$
7	GW190805	$0.35^{+0.30}_{-0.36}$	$48.2^{+17.5}_{-12.5}$	$32.0^{+13.4}_{-11.4}$	$0.74^{+0.22}_{-0.60}$

The origin of BH-BH mergers



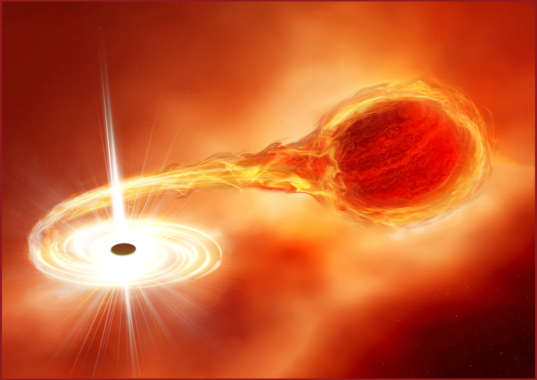
The origin of BH-BH mergers



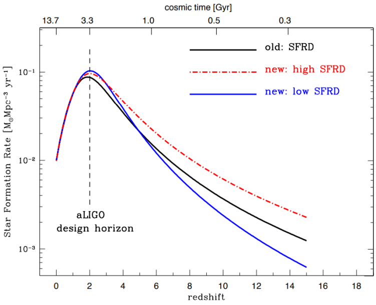
- Local density merger rates;
- Distribution of masses;
- Distribution of spins (values and orientation);
- Eccentricity of orbit;
- Time delays and evolution with redshifts;

Degeneracy between several formation channels.

Isolated binary evolution



Population syntheis and StarTrack code

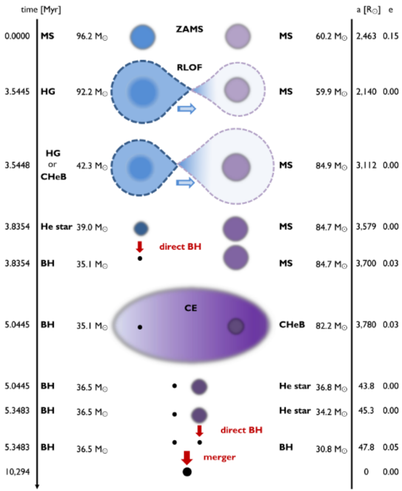


SFR(z) based on Madau & Dickinson (2014).

- Evolution of isolated binary stellar systems (mass transfer, SN engine, natal kicks...).
- Generating synthetic population of many systems (SFR, metallicity distribution, IMF, many other initial parameters...).
- Constraining parameters/models comparing them with observed/detected systems.

CE vs stable MT channel for BH-BH formation

Fig. Belczynski et al. 2016

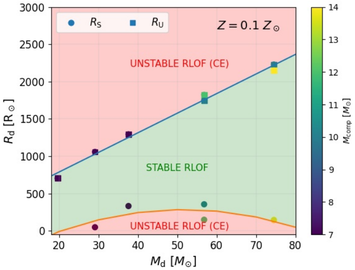


Overestimation of CE events: stability of MT & (un)successful envelopes ejections:

Pavlovskii et al. 2017; van den Heuvel et al. 2017; Andrews et al. 2020; Zevin et al. 2020; Vigna-Gómez et al. 2020; Klencki et al. 2021; Bavera et al. 2020; Marchant et al. 2021; Olejak et al. 2021; Yong et al. 2021 and others...

Our (StarTrack) revised mass transfer stability criteria based on **Pavlovskii et al. 2017** take into account:

- Donor type.
- System mass ratio.
- Donor mass and radius relation (stability diagrams).
- Metallicity.



Systems with $q = M_{acc}/M_{don} < 0.125$ always unstable.

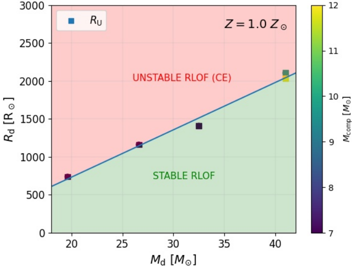
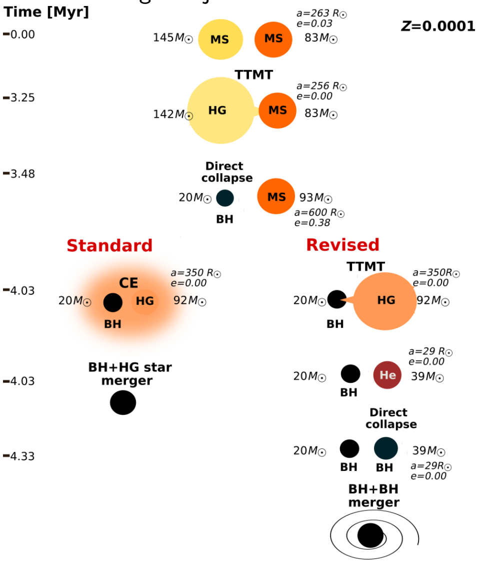
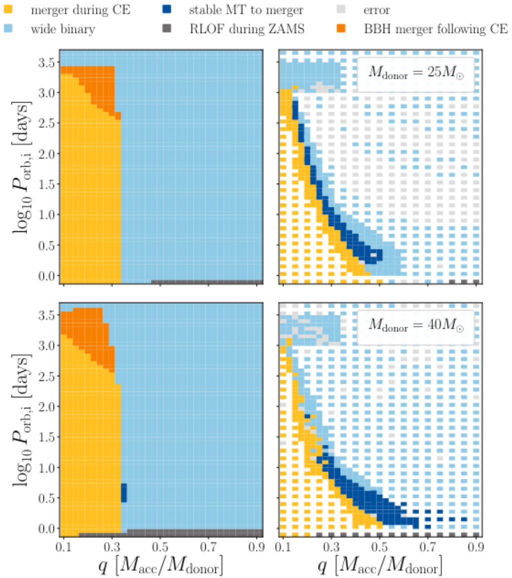


Fig. Olejak et al. 2021:



Channel noted by: van den Heuvel et al. 2017

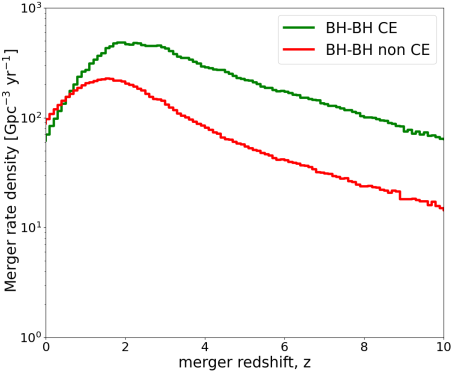
COSMIC vs MESA, results by Gallegos-Garcia et al. 2021



Revised criteria influence BH-BH:
-merger rate densities
-mass and mass ratio distribution
-time delay distribution
-final BH spins (WR tides)

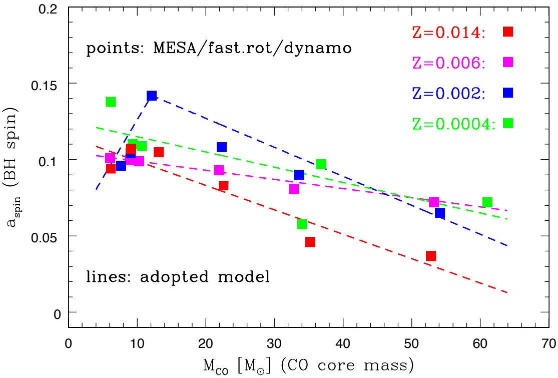
Tab. Local ($z\sim 0$) BH-BH merger rate density.

	Revised	**Standard**
No CE	94%	0.5%
CE	6%	99.5%



Natal BH spin - Tayler-Spruit dynamo.

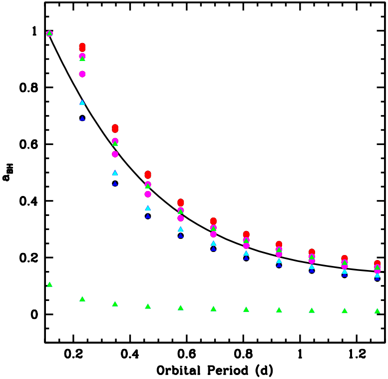
Fig. Magnitude of natal BH spin as a function of the CO core mass of the collapsing star for the MESA stellar models with the Tayler-Spruit magnetic dynamo.



Natal BH spins $a_{\rm spin}$ takes values around 0.1 (Belczynski et al. 2020). Gives low effective spin parameters $\chi_{\rm eff} \approx 0$

Tidal spin-up of Wolf-Rayet stars.

BH spin magnitudes as a function of the orbital period, MESA models (Belczynski et al. 2020). For very close ($P_{orbit} < 1.3$ days) BH-WR, WR-BH or WR-WR binaries.

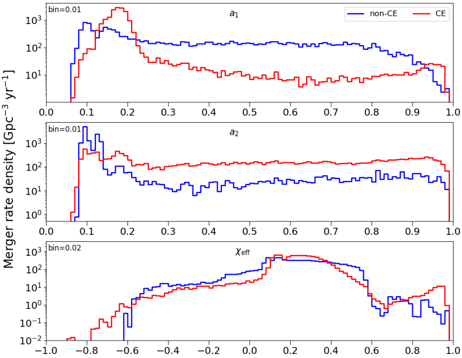


Also: Kushnir et al. (2016); Zaldarriaga et al. (2017); Kushnir et al. (2017); Hotokezaka Piran (2017); Qin et al. (2018); Bavera et al. (2021)

Tab. Fractions of BH-BH mergers produced in our two population synthesis models satisfying a given condition.

No.	condition[a]	CE model	non-CE model
1	$\chi_{\rm eff} > 0.0$	97%	93%
2	$\chi_{\rm eff} > 0.1$	95%	85%
3	$\chi_{\rm eff} > 0.2$	70%	60%
4	$\chi_{\rm eff} > 0.3$	36%	39%
5	$\chi_{\rm eff} > 0.4$	10%	21%
6	$\chi_{\rm eff} > 0.5$	2%	7%
7	$a_1 > 0.5$	3%	34%
8	$a_1 > 0.7$	2%	15%
9	$a_1 > 0.9$	1%	1%
10	$a_2 > 0.5$	52%	11%
11	$a_2 > 0.7$	33%	7%
12	$a_2 > 0.9$	12%	2%

Fig. Distribution of spin parameters a_1 (top), a_2 (middle) and $\chi_{\rm eff}$ (bottom) in CE (red line) and non-CE channel (blue line).



High spins - formation channels

Fig. Non-CE formation scenario.

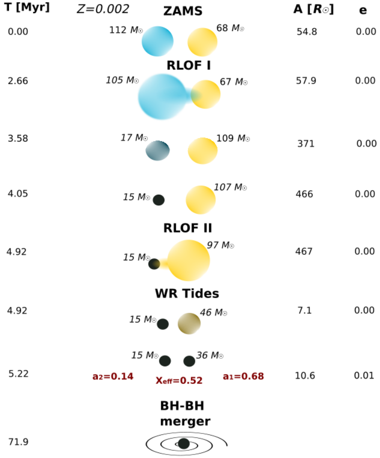
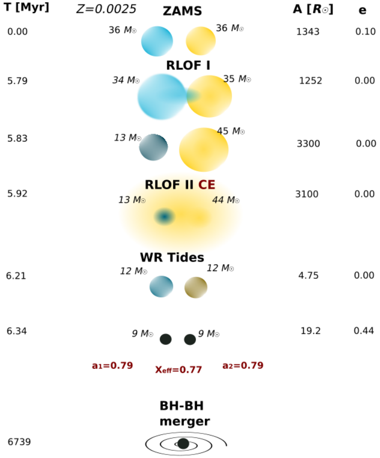
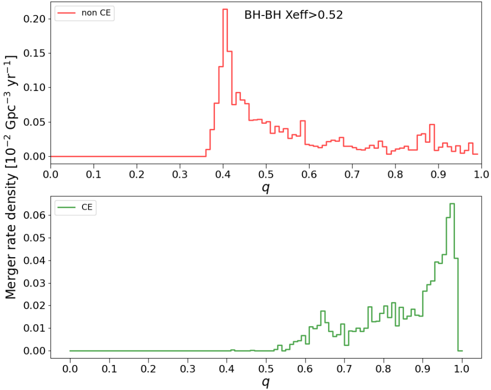


Fig. CE formation scenario.



High spins - difference in CE and non CE channels

Fig. Mass ratio of high spinning BH-BH mergers.



Conclusions

Highly uncertain assumptions on RLOF physics may significantly affect:

- dominant evolutionary formation, with and without CE
- time delays and local merger rate density
- shape of the mass and mass ratio distributions
- shape of the spin distribution

One is not able to draw fully reliable statements about the population of BH-BH systems based on population synthesis studies.