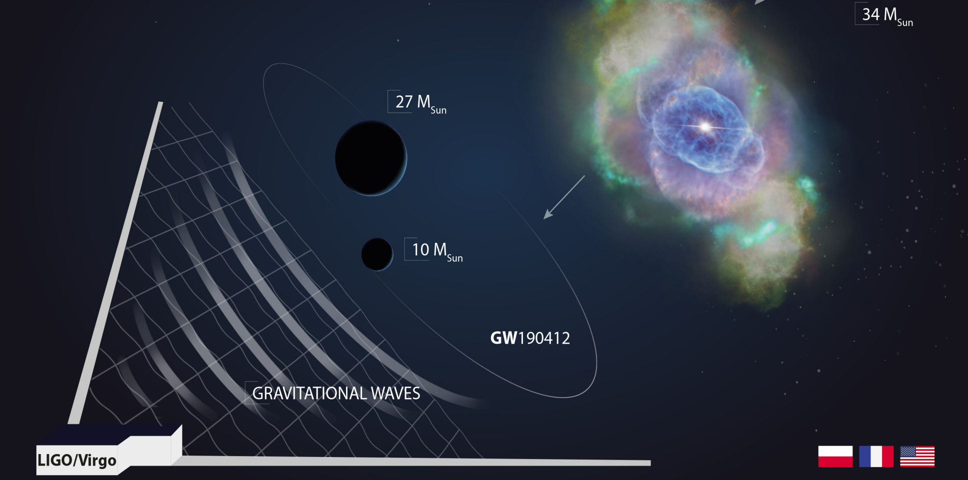
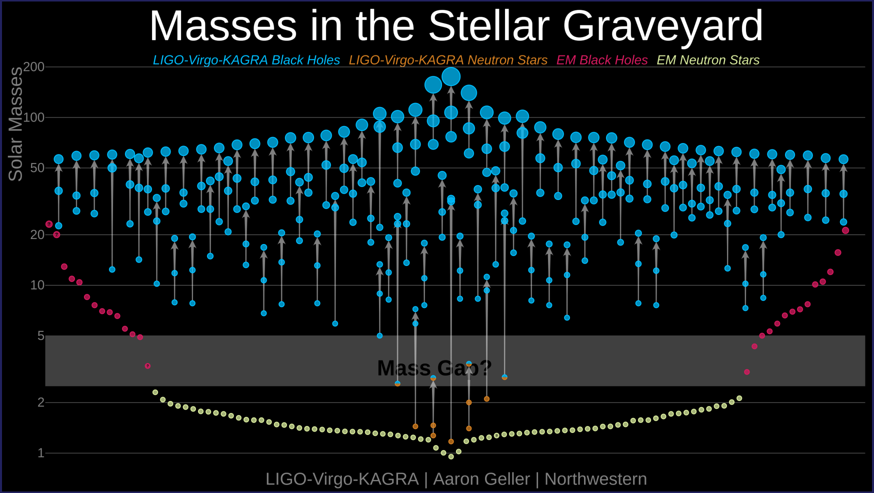
What can we learn about the stars from gravitational waves?

Aleksandra Olejak &
K. Belczynski, C. Fryer, N. Ivanova, J.P. Lasota



THE ORIGIN OF INEQUALITY: ISOLATED FORMATION OF A 30 + 10 M_{Sun} BINARY BLACK-HOLE MERGER
Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland


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

Gravitational wave detections

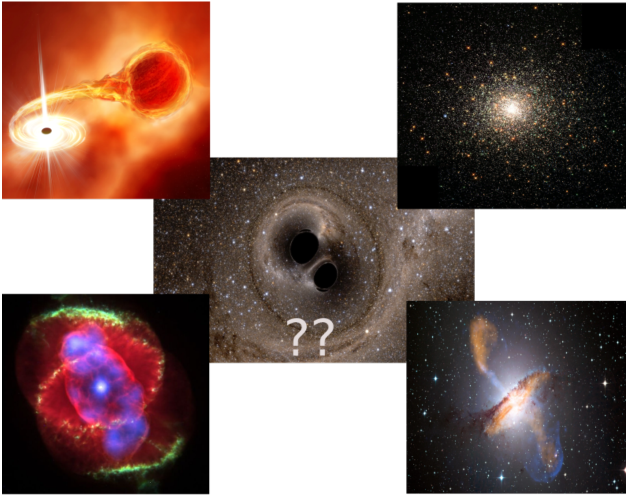
LIGO-Virgo-KAGRA reported around 90 compact binary mergers detected with gravitational waves. Classification:

- $\sim$90 BH-BH mergers
- 4 BH-NS mergers ?
- 2 NS-NS mergers ?

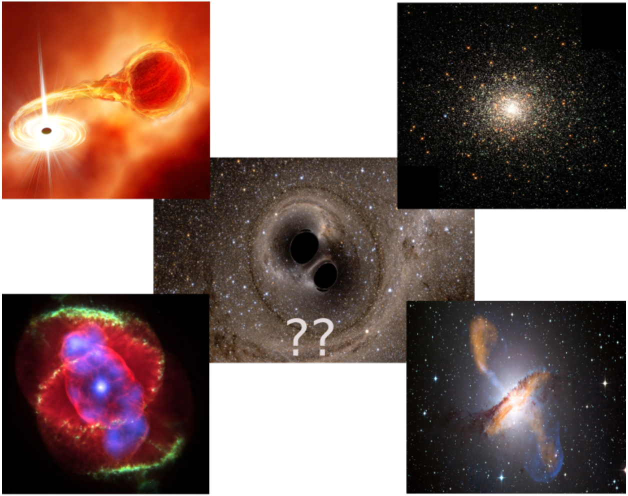
Current constrains on merger rate densities:

- 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}

The origin of double compact object mergers?

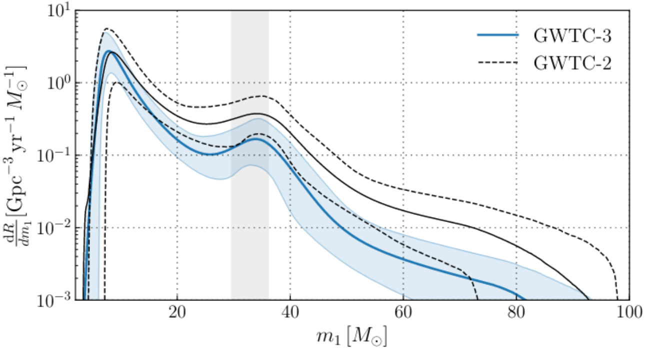


The origin of double compact object mergers?

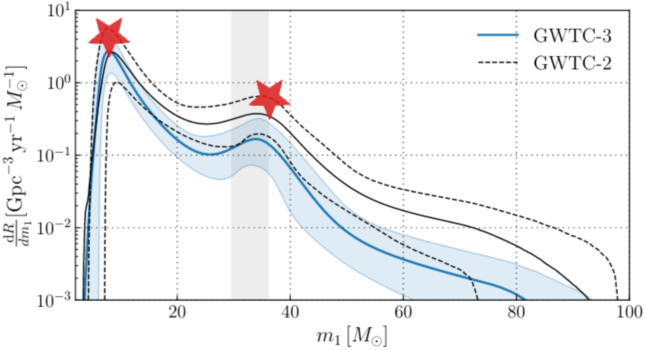


Talk of T. Bulik on Jan 9th, 10:00

Mass distribution of binary black holes

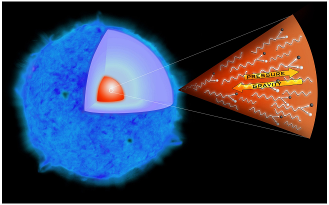


Mass distribution of binary black holes



Peaks at $10M_\odot$ (core collapse, stellar winds?) and $35M_\odot$ (stellar winds, pair-instability supernova?)

Upper mass gap and pair-instability supernova

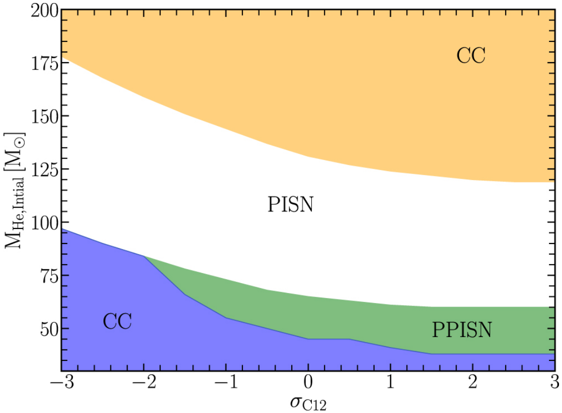


Works of Fryer C.L. (here);
Woosley S.E. and Heger A.

- very massive, hot stellar core (initial star mass $M \gtrapprox 120 M_\odot$, low metallicity) with interior temperatures above about $\sim 10^9$ K
- electron-positron pair production
- pair production -> reduction the radiation pressure -> core contraction -> temperatures increase -> avalanche of electron–positron pairs -> accelerated burning in a runaway thermonuclear reactions -> explosion (no remnant)
- PISN may prevent formation of massive stellar origin BHs ($M_{\rm BH} \gtrapprox 45 M_\odot$)
- however, big uncertainties in reaction rates?

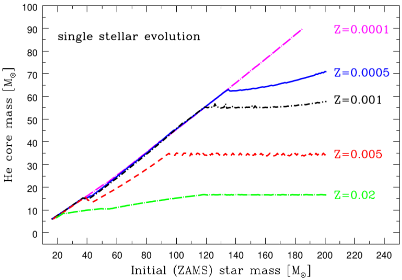
Upper mass gap and pair-instability supernova

Uncertain rates for $^{12}\mathrm{C}(\alpha, \gamma)^{16}\mathrm{O}$ reaction



R. Farmer, M. Renzo, S. E. de Mink et al. 2020.
Also e.g. Costa et al. 2021 and Woosley & Heger 2021

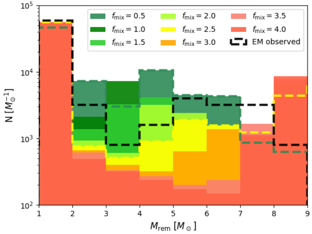
Stellar winds limits on black home mass



Belczynski, Krzysztof 2020

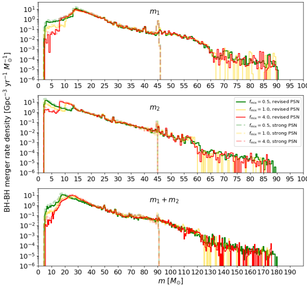
- Massive stars, especially BH progenitors in high metallicity environment are subject of significant mass loss in stellar winds.
- Star with the same initial mass of e.g. $100M_\odot$ may form $\sim 50M_\odot$ BH in $10\%Z_\odot$ and $\sim 20M_\odot$ BH in $Z_\odot$
- The luminosity of most massive stars exceed Humphreys–Davidson limit. Stars are subject of strong additional mass loss in LBV stellar winds

Lower mass gap and supernova engine



- rapid SN explosion -> low mass NSs and massive BHs (direct collapse)
- delayed SN explosion -> massive NSs and low mass BHs

'We find the BH mass distribution exhibits an interval between $2.2 M_\odot$ *and* $6.1 M_\odot$*... where merger rates are suppressed.'* The LIGO Scientific Collaboration et al. 2021



Olejak, A.; Fryer, C.; Belczynski, K. et al. 2022

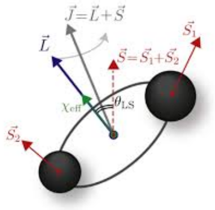
Black hole spins

- GW detections are consistent with BH-BH population dominated by low spins: $\lambda \leq 0.2$ with a small fraction of high spinning BHs.

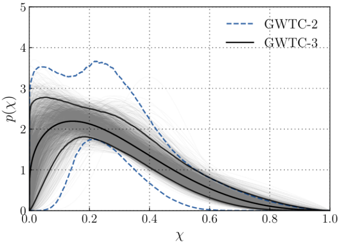
Effective spin parameter:

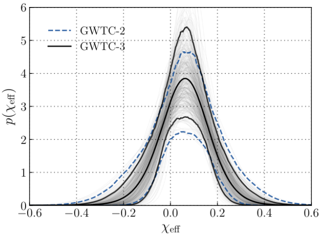
$$\chi_{\rm eff} = \frac{m_1 \lambda_1 \cos\theta_1 + m_2 \lambda_2 \cos\theta_2}{m_1 + m_2} \approx 0,$$

$$\lambda = cJ_i / Gm_i^2$$



Source: https://bhdynamics.com/





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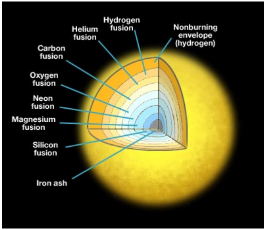

Pre-SN massive star structure. Credit: Penn State Astronomy Astrophysics

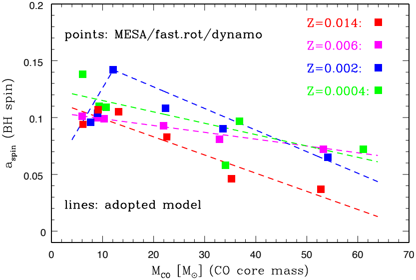

Fig. Magnitude of natal BH spin as a function of the CO core mass of the collapsing star for the MESA stellar models with the Tayler-Spruit magnetic dynamo.

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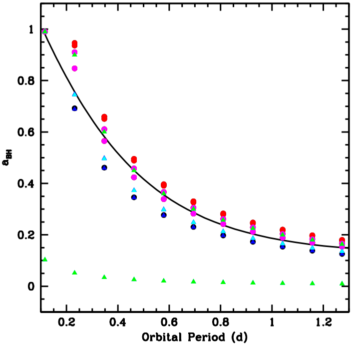
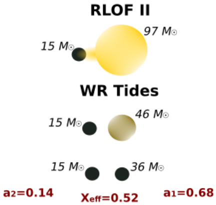
- possibility of Wolf-Rayet (WR) tidal spin-up



WR tidal spin up: BH spin magnitude as a function of the orbital period $P_{orbit} < 1.3$ days (Belczynski et al. 2020).



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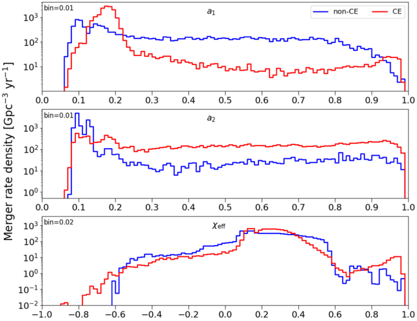

Effective spin distribution for BH-BH binary system formation with and without CE (Olejak & Belczynski 2021).

Conclusions

- The origin of double compact object mergers as well as contribution fractions of each formation channel is still unknown.
- PISN and stellar winds may be responsible for the peak in mass distribution $\sim 35 M_{\odot}$.
- Core-collapse SN and stellar winds may be responsible for the peak in mass distribution $\sim 10 M_{\odot}$.
- Low black hole spins points towards efficient angular momentum in massive stars.