Constraining the Black Hole population with Gravitational Waves

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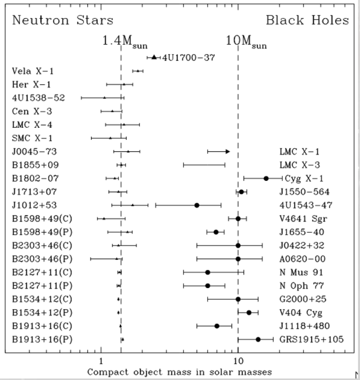
Outline

The BH population with EM observations

What did we know about stellar-mass BHs before GW observations?

- Our knowledge of stellar-mass BHs was limited to electromagnetic (EM) observations of X-ray binaries
- $\sim$ 20 stellar-origin BHs with dynamical mass measure
- Measured masses between 5 $M_\odot$ and 20 $M_\odot$
- No BBHs or BH-NSs known

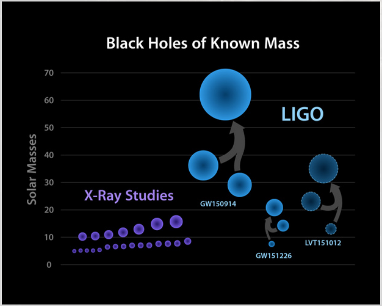


Clark, J.S. et al. 2002, A&A 392, 909

The BH population with GW observations: O1

- BBHs can form in nature and merge within a Hubble time
- First direct evidences for "heavy" stellar mass BHs ($> 25\ M_\odot$)
- From the masses we can infer information on the environment:

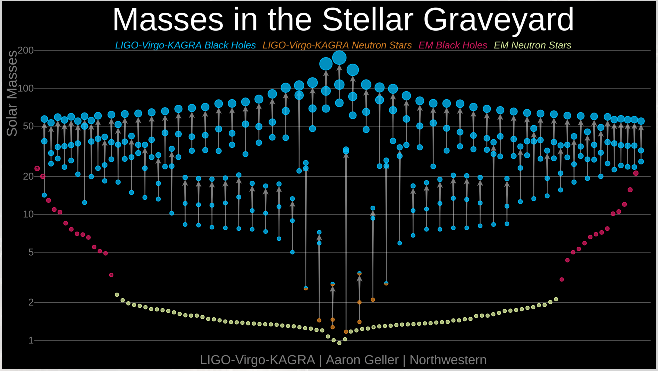
  $\rightarrow$ events like GW150914 most likely formed in low-metallicity environment ($\lesssim 0.5\ Z_\odot$)
- BBH merger rate: 9 - 240 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$



LVT151012 was later re-labeled as GW151012

LVK Collaboration 2016, ApJL, 818, 22
LVK Collaboration 2016, PRX, 6, 041015
LVK Collaboration 2017, PRL 118, 221101

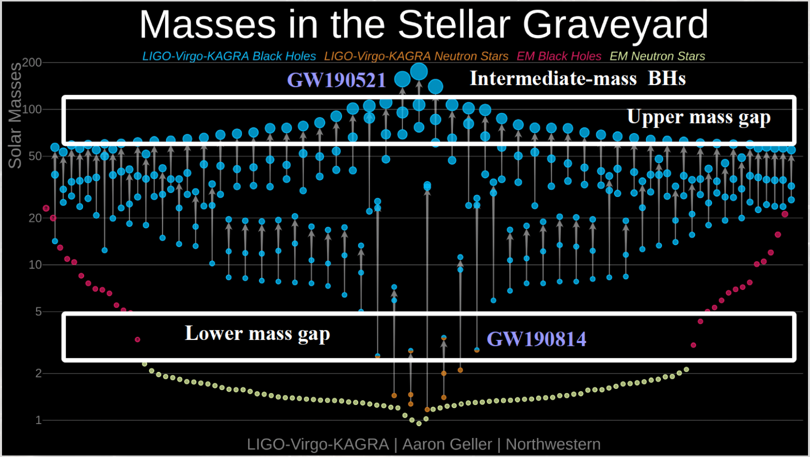
The BH population with GW observations: O1 + O2 + O3



- Total number of candidates: 90
- Most are binary black holes (BBHs)
- Some are neutron star - black hole (NSBH) binaries
- Two are binary neutron stars (BNSs)

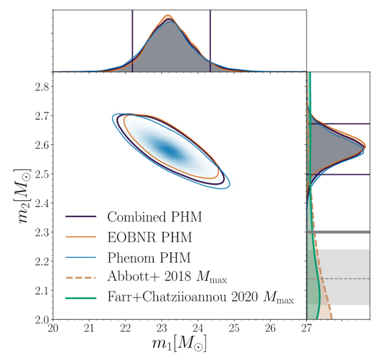
LVK Collaboration 2021, arXiv:2111.03606

The BH population with GW observations: O1 + O2 + O3



LVK Collaboration 2021, arXiv:2111.03606

Lower mass gap: GW190814



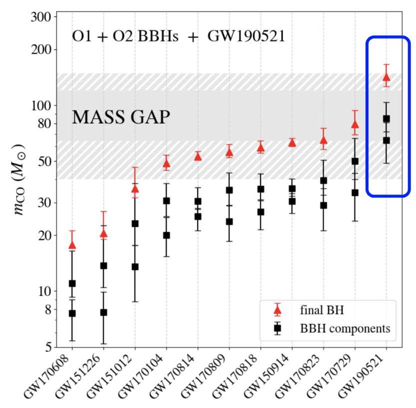
- GW event observed by the two LIGO detectors and Virgo
- m_1: $23.2^{+1.1}_{-1.0}$ $M_\odot$

  m_2: $2.59^{+0.08}_{-0.09}$ $M_\odot$

  BBH or NS-BH merger?
- Challenging for current formation scenarios
- 90 % C.R.: 18.5 deg^2; D_L=241^{+41}_{-45} Mpc
- No EM counterpart

LVK Collaboration 2020, ApJL, 896, 44

Upper mass gap: GW190521



- GW event observed by the two LIGO detectors and Virgo
- m_1: 85^{+21}_{-14} $M_{\odot}$, m_2: 66^{+17}_{-18} $M_{\odot}$
- The primary falls in the mass gap by (pulsational) pair-instability SN

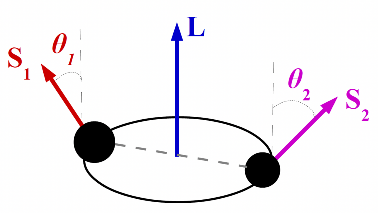
Challenge for stellar evolution

- Isolated binary evolution is disfavoured
- **Dynamical scenario?**

LVK Collaboration 2020, PRL, 125, 101102

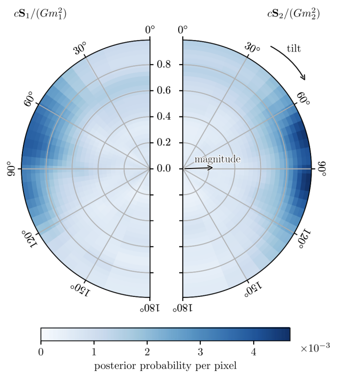
LVK Collaboration 2020, ApJL, 900, 13

GW190521: the spin



$$\chi_i = \frac{c\mathbf{S_i}}{Gm_i^2} \quad \text{Dimensionless spin}$$

$$\theta_i : \quad \text{Tilt angle}$$



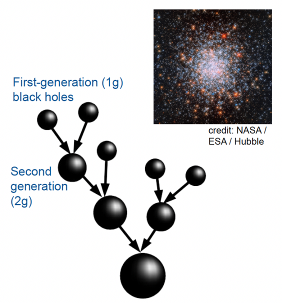
Mild evidence for large spins nearly in the orbital plane
... **dynamical origin of the system?**

LVK Collaboration 2020, PRL, 125, 101102

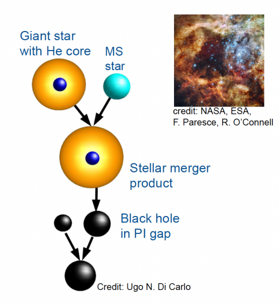
LVK Collaboration 2020, ApJL, 900, 13

Dynamical scenarios for GW190521

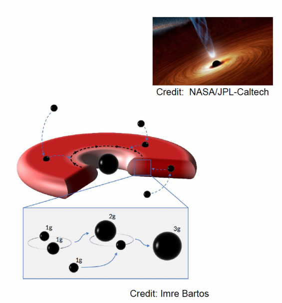
Hierarchical mergers



Stellar mergers in young star clusters

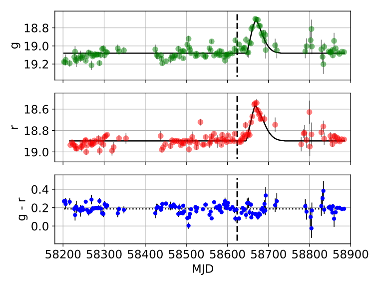


Active Galactic Nucleus (AGN) disks



GW190521: an EM counterpart?

The Zwicky Transient Facility (ZTF) detected a candidate optical counterpart in AGN J124942.3+344929



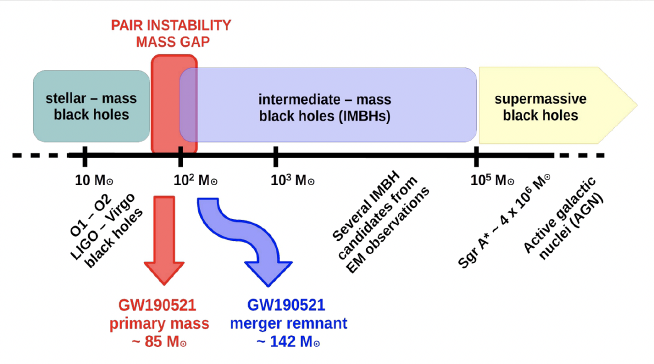
- GW sky localization: 765 deg^2 (90% C.R.)
- ZTF observed 48% of the 90% C.R. of the GW skymap
- An EM flare observed $\sim$ 34 days after the GW event
- It is consistent with expectations for a **BBH merger in the accretion disk of an AGN** (see McKernan et al. 2019, ApJL, 884, 50)

Graham et al. 2020, PRL, 124, 251102

However, this association is not yet clear and is under investigation (Ashton et al. 2021, CQG, 38, 235004, Palmese et al. 2021, ApJL 914, 34)

GW190521: the birth on a intermediate massive BH

The remnant BH mass is $\sim 142\ M_\odot \Rightarrow$ **First strong observational evidence for an intermediate-mass BH**: the missing link between stellar and supermassive BHs



A population of BHs

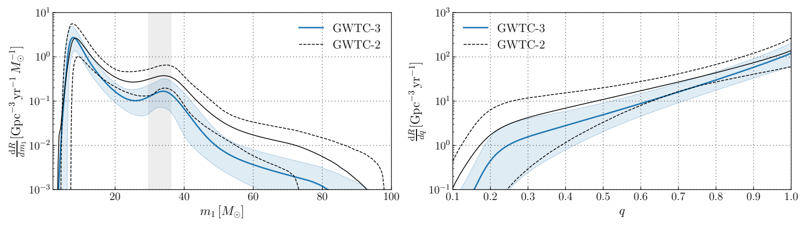
From single events to a population

- Individual GW events can reveal the properties of unique single sources, but ...
- ... a population of events is needed to shed light on how these systems form and evolve throughout the Universe

  $\rightarrow$ the statistical distribution of BH source properties such as their **mass**, **spin** and **redshift** can be used to probe the astrophysics of BBH formation and evolution

The mass distribution of BHs in binaries

Primary BH mass distribution **Mass ratio ($q=m_2/m_1$)**



The mass distribution is non-uniform, with peaks at $\sim 10\ M_\odot$ and $\sim 35\ M_\odot$; tail up to $\sim 80\ M_\odot$

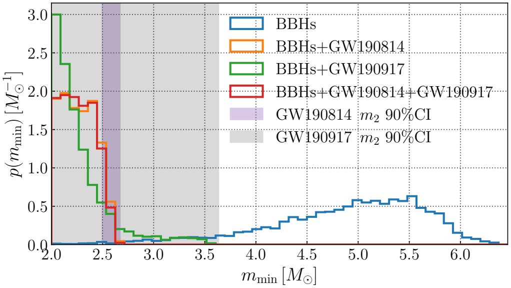
The distribution of mass ratios is broad, with a mild preference for equal-mass pairings

LVK Collaboration 2022, arXiv:2111.03634
LVK Collaboration 2021, ApJL, 913, L7

Outliers in the BBH population

In the previous analysis GW190814 and GW190917 were excluded...what happens if we include them?

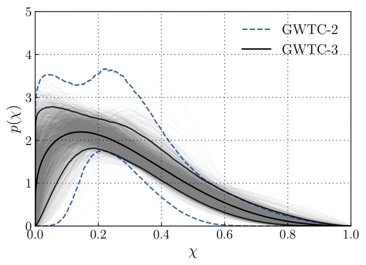
- The secondary masses of these two events are in tension with the remainder of the population
- This could suggest the existence of a separate sub-population of binaries



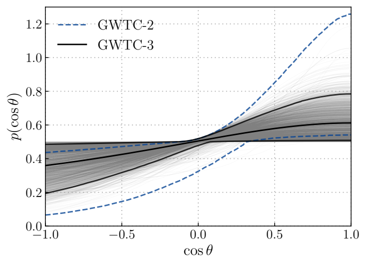
LVK Collaboration 2022, arXiv:2111.03634

The spin distribution of BHs in binaries

Spin magnitudes generally small (peak at χ ~0.2), with a possible tail up to high spins

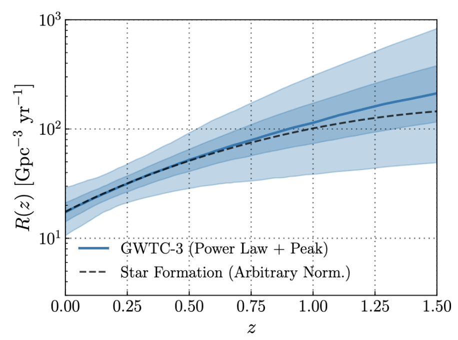


Evidence for a broad distribution of **spin-orbit tilts**, with mild preference for aligned systems



LVK Collaboration 2022, arXiv:2111.03634
LVK Collaboration 2021, ApJL, 913, L7

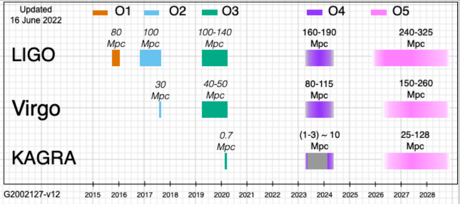
The evolution of the merger rate with redshift



- BBH merger rate (z=0.2): $\sim$ 18 - 44 Gpc^{-3} yr^{-1}
- BBH merger rate is observed to increase with redshift
- trend is similar to cosmic SFR

LVK Collaboration 2022, arXiv:2111.03634

Prospects with 2$^{\mathrm{nd}}$ generation GW detectors



https://dcc.ligo.org/LIGO-G2002127/public

Network	Expected BBH Det.	90% C.R. (deg^2)
HLVK (O4)	79^{+89}_{-44}	41^{+7}_{-6}

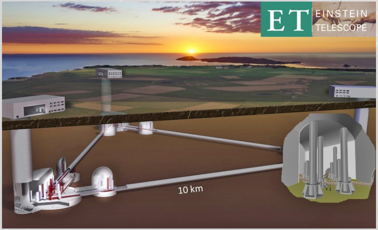
Network	Expected NS-BH Det.	90% C.R. (deg^2)
HLVK (O4)	1^{+91}_{-1}	50^{+8}_{-8}

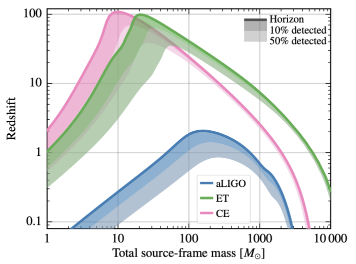
LVK Collaboration 2020, arXiv: 1304.0670

Detection rate and sky localization estimates have been obtained under these assumptions:
$\mathcal{R}_{\mathrm{BBH}}$=25-109 Gpc^{-3} yr^{-1}; $\mathcal{R}_{\mathrm{NS\text{-}BH}}$=0.6-1000 Gpc^{-3} yr^{-1};
BNS range: 190 Mpc (L,H), 120 Mpc (V) and 80 Mpc (K)

Prospects with 3rd generation GW detectors

In the next decade, 3rd generation GW detectors such as the Einstein Telescope (ET) or Cosmic Explorer (CE) will become operative





With ET:

- 10^6 BBHs/year
- Broad BH mass range
- BBHs with total mass in the range 20 - 100 $M_\odot$: up to z $\sim$ 20

Maggiore et al. 2020, JCAP, 03, 050

Conclusions

Thanks to GW observations we are collecting more and more information on the BH population:

- BBHs can form in nature and merge within a Hubble time
- First clear evidences for "heavy" stellar mass BHs ($> 25\ M_\odot$); first observations of BHs in the pair-instability mass gap and of IMBHs
- Constraints on the mass and spin distribution of BHs in binaries
- Constraints on the BBH merger rate and its evolution with redshift

In the next years a larger population of BBH mergers is expected to be detected ... we will learn much more on the formation and evolution of these systems, stay tuned!

Backup

Backup Slides

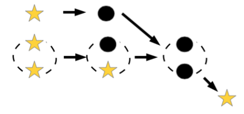
The spin

The spin orientations can help us to discriminate

between different formation channels

Isolated binary in galactic fields

Dynamical interactions in clusters

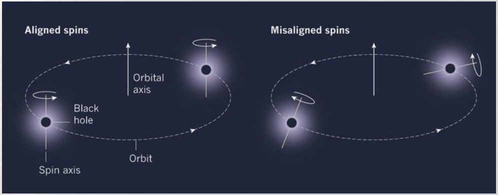


Isolated binary:

Spins preferentially aligned with the binary orbital angular momentum

Cluster binary:

Isotropic spin orientations



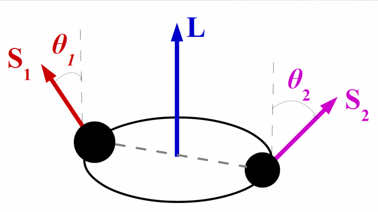
The effective spins

With GWs we can estimate two "effective spins": the **effective inspiral spin ($\chi_{\rm eff}$)** and the **effective precession spin ($\chi_{\rm p}$)**

$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\mathbf{S_1}}{m_1} + \frac{\mathbf{S_2}}{m_2}\right)\hat{\mathbf{L}}$$

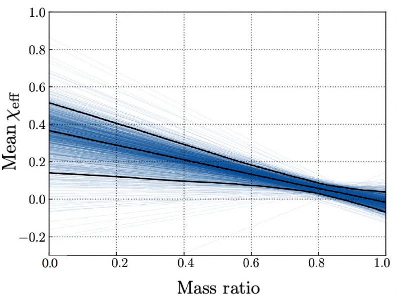
$$\chi_{\rm p} = \frac{c}{B_1 G m_1^2} \max\left(B_1 S_{1\perp}, B_2 S_{2\perp}\right);$$

$$B_1 = 2 + 3q/2, \qquad B_2 = 2 + 3/(2q)$$



- $\chi_{\rm eff}$ quantifies the total spin parallel to the binary's orbital angular momentum
  ($\chi_{\rm eff}$ <0 implies at least one component spin tilted by $\theta > 90^\circ$ with respect to **L**)
- $\chi_{\rm p}$ depends on the component of the spins perpendicular to the binary's orbital angular momentum
  ($\chi_{\rm p} \neq 0$ implies spin-induced general relativistic precession of the orbital plane)

Correlation between spin and mass ratio



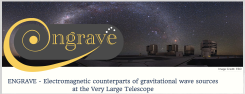
$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\mathbf{S_1}}{m_1} + \frac{\mathbf{S_2}}{m_2}\right)\hat{\mathbf{L}}$$

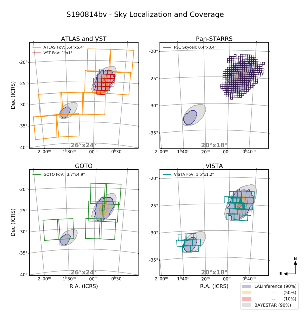
- On average, BBHs with more unequal masses have larger effective spins...
- ... This could be an indication for preferentially larger or more aligned spins with unequal mass ratios

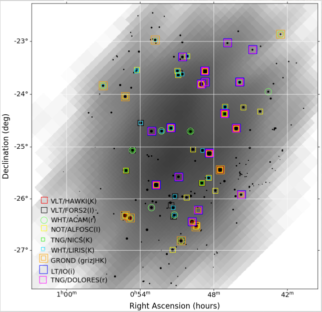
LVK Collaboration 2022, arXiv:2111.03634

GW190814: the EM follow-up

Example: optical counterpart searches by ENGRAVE







No EM counterpart has been observed

Ackley et al. 2020, A&A, 643, 113

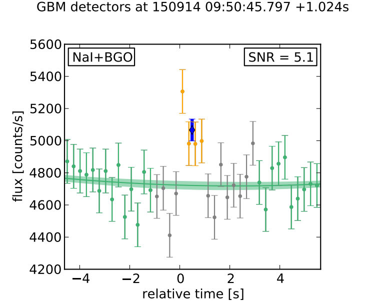
EM counterparts to BBH mergers

Do BBH mergers have EM counterparts?

BBH mergers are not expected to produce bright EM signal due to the absence of baryonic matter left outside the merger remnant...

An EM counterpart for GW150914?

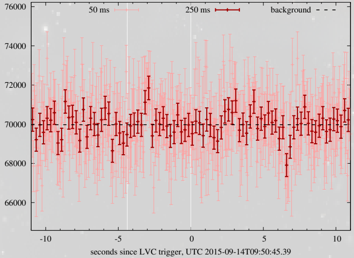
Fermi-GBM: sub-threshold **weak signal above 50 keV 0.4 s after GW150914** (at 2.9 σ), consistent with the direction of GW 150914



Its duration and spectrum are consistent with a weak short GRB (Connaughton et al. 2016).

but...

- no signal detected by INTEGRAL (Savchenko et al. 2016), AGILE (Tavani et al. 2016) and *Fermi*-LAT (Ackermann et al. 2016)



INTEGRAL data, Savchenko et al. 2016

- Greiner et al. 2016: GBM transient consistent with a background fluctuation (see also Xiong 2016)

Do BBH mergers have EM counterparts?

After GW150914-GBM some rare scenarios which predict an unusual presence of matter around the BBH have been proposed, e.g.:

- the matter comes from the remnants of the stellar progenitors (Loeb 2016, Perna et al. 2016, Janiuk et al. 2017)
- the matter comes from the tidal disruption of a star in triple system with two BHs (Seto & Muto 2011, Murase et al. 2016)
- the BBH merger takes place in the gas rich environment in the disks of AGNs (Bartos et al. 2017)