Population properties of compact objects from the second LIGO–Virgo Gravitational-Wave Transient Catalog

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on behalf of the
LIGO-Virgo-KAGRA Collaboration

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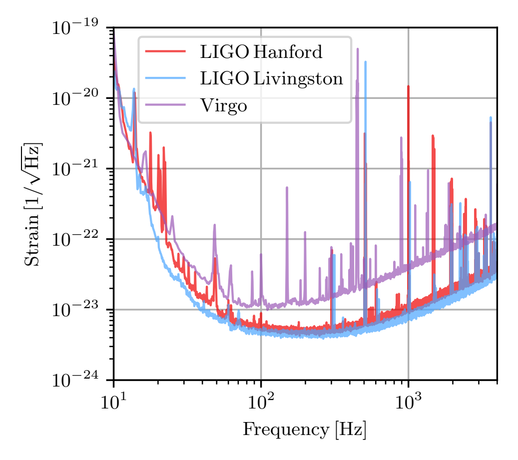
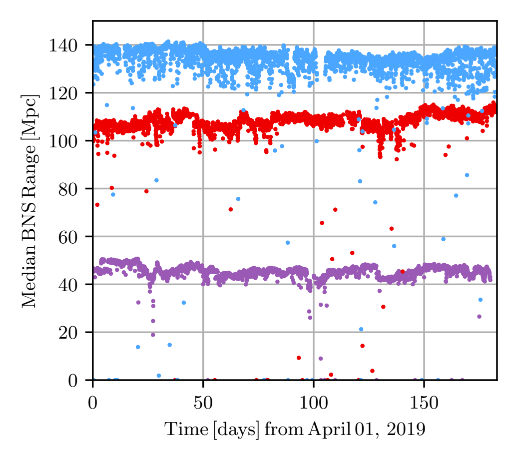
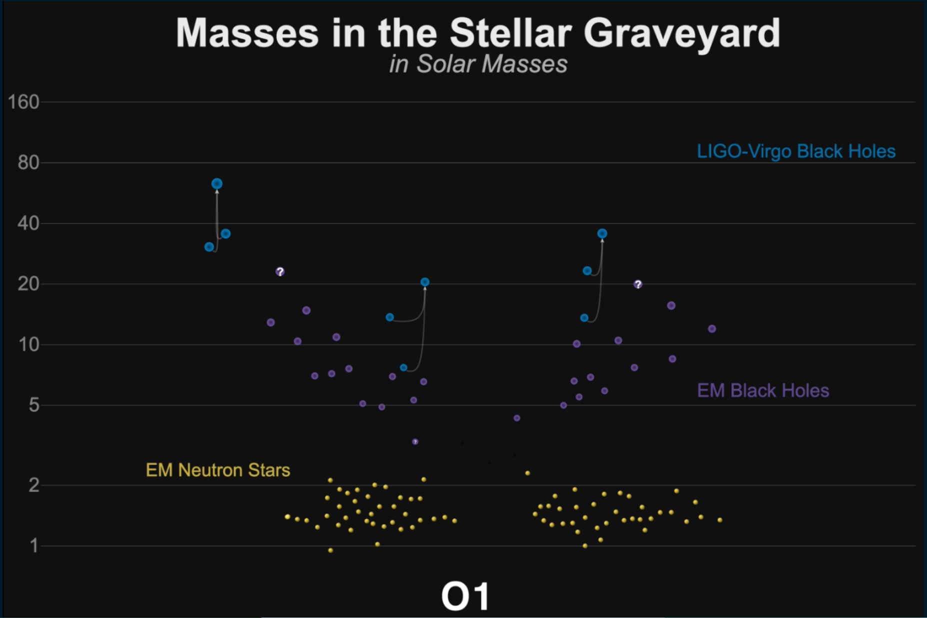
Paper: dcc.ligo.org/LIGO-P2000077/public
Slides: dcc.ligo.org/LIGO-G2002156/public

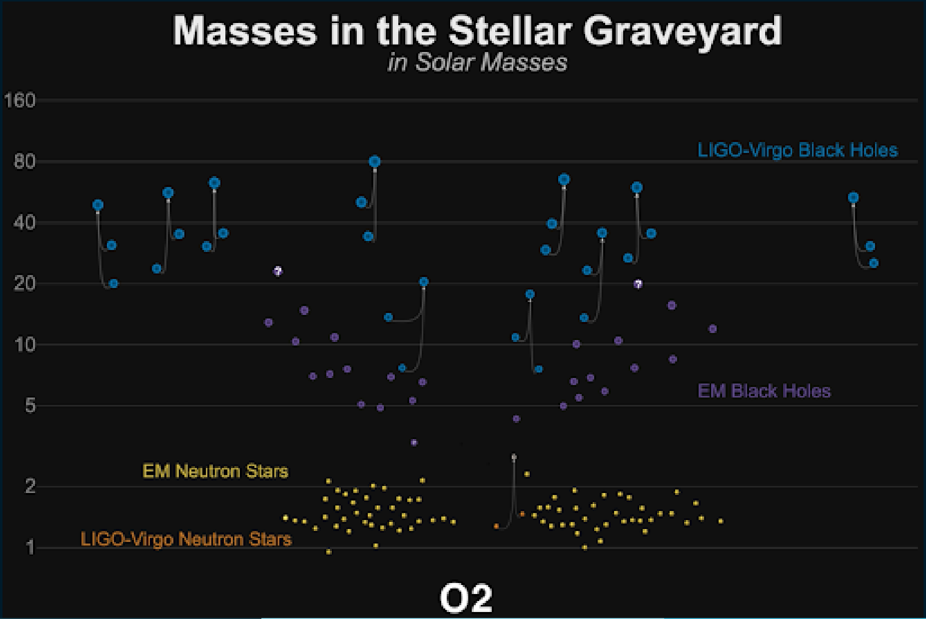
LIGO/Virgo O3a observing run





Source: GWTC-2 (arXiv:2010.14527)


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
O1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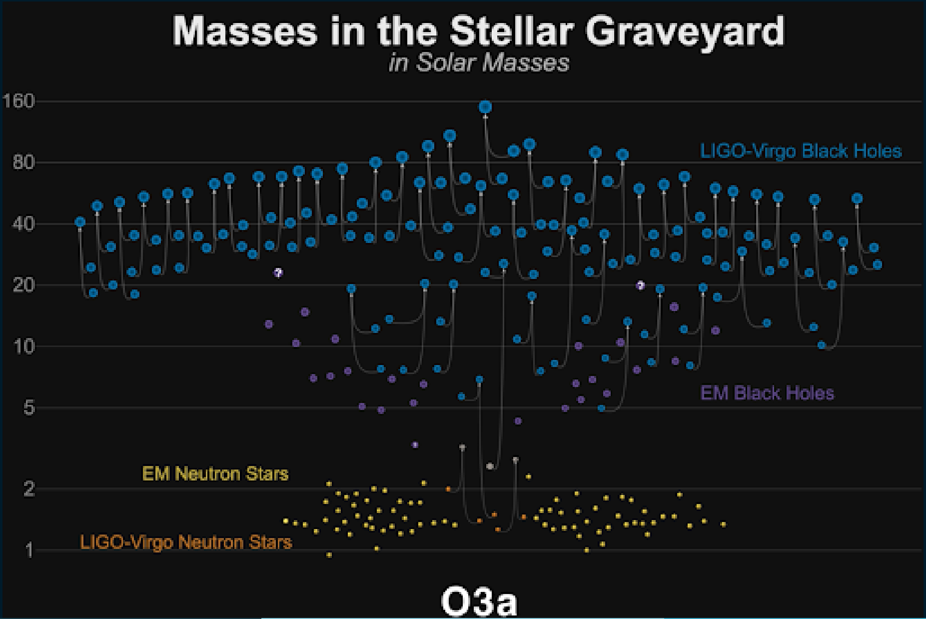
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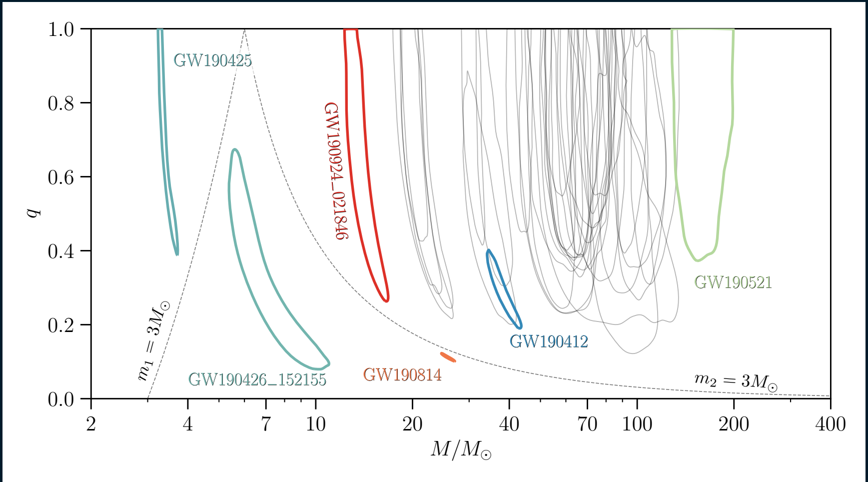
O3a

Measured properties



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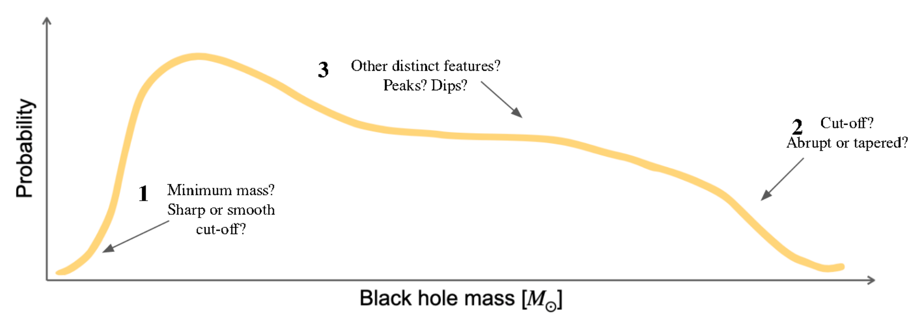
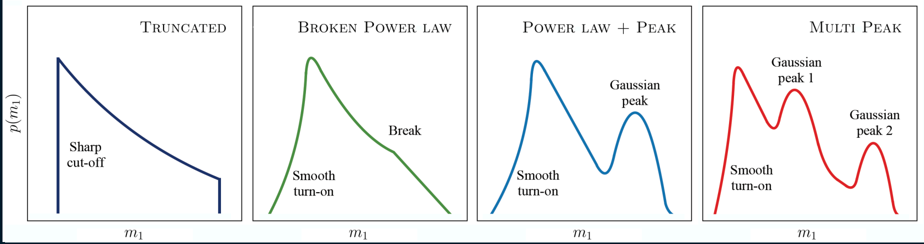
Mass distribution

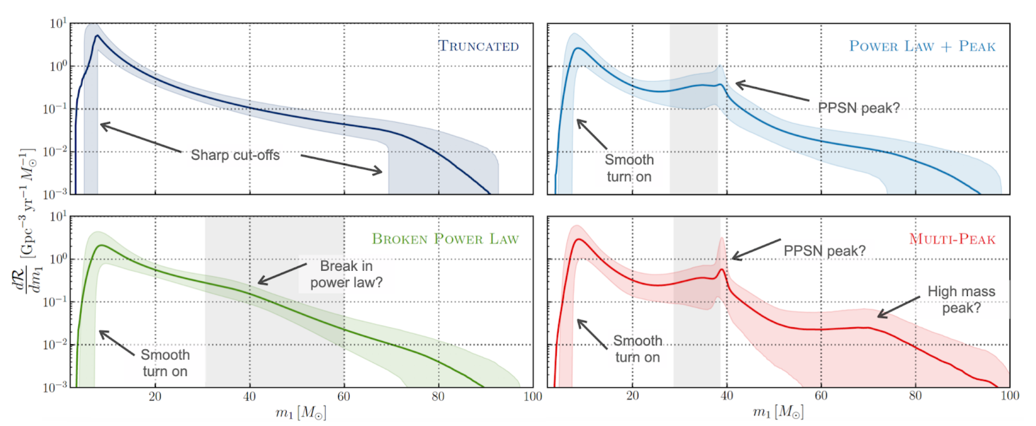
Choosing a model



Models used in this study

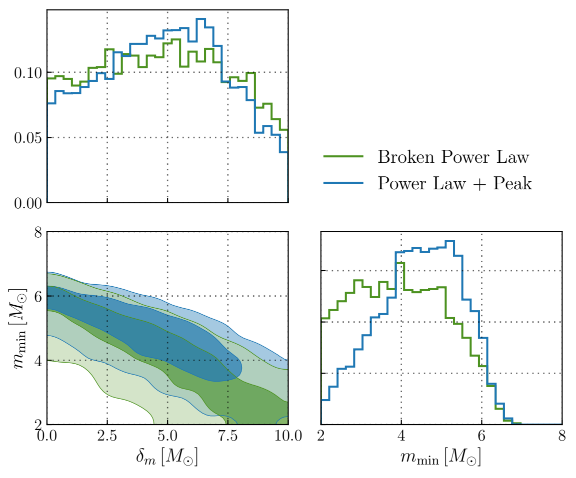


Inferred mass distribution



Features at low masses

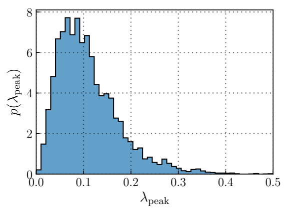
- Rule out a low minimum BH mass ($\sim 2\,M_\odot$) with a sharp cutoff
  - Indicates an underabundance at low mass
- Additional study including GW190814 in contention
  - Minimum BH mass constrained to $\sim 2\,M_\odot$ due to presence of $\sim 2.6\,M_\odot$ object
  - This event is an outlier: population inferred the other 44 BBH has a 0.02% chance of producing GW190814



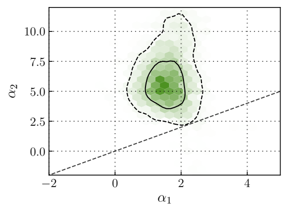
Structure beyond a power law

- Support for a Gaussian subpopulation (most favored model, Power law + Peak)
- Power-laws have different slopes (slightly disfavored model (factor of 8), Broken power law)

Power law + Peak

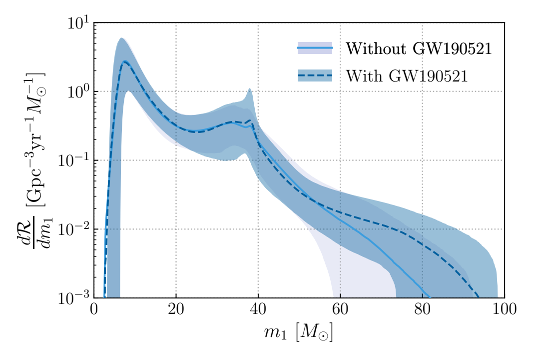


Broken power law



- Simple power law with sharp cutoffs (Truncated) is strongly disfavored (factor of 100)

Masses larger than $45 M_\odot$



- No cutoff feature at $\sim 45\, M_\odot$
- True with/without GW190521 – does not appear to be an outlier

Spin distribution

Different model choices

Default model

- Models the dimensionless spin magnitude and spin tilt distributions.
- Magnitude follows beta distribution with free parameters.
- Cosine tilt follows a mixture of a truncated Gaussian (peaked at perfect alignment) and perfect isotropy.

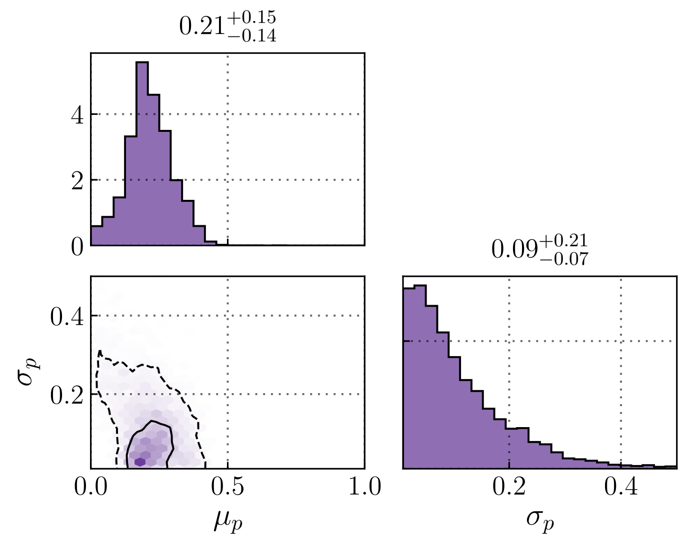
Gaussian model

- Measures the distribution of "effective" spin parameters χ_{eff} and χ_{p}.
- Both follow truncated Gaussians with mean and variance fit to data.

MultiSpin model

- Multiple instances of the Default model
- Applies separate spin distribution to power law continuum and high-mass peak
- Tests whether spin varies with mass

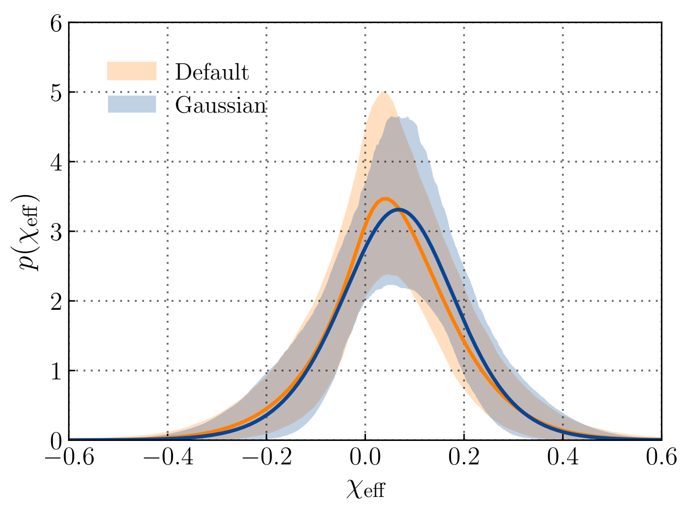
Some BBH are precessing



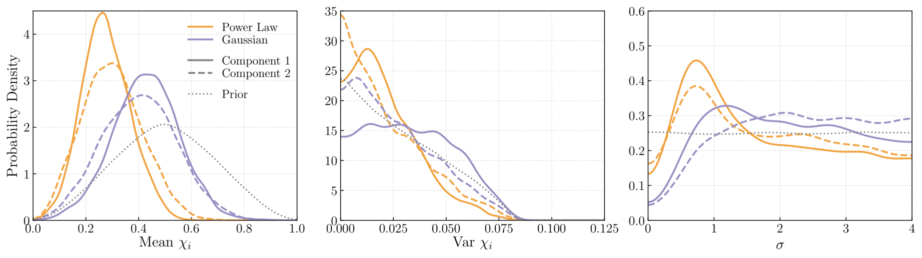
Excludes a δ-function at $\chi_\mathrm{p} = 0$

Some events have negative effective spin

- Negative χ_{eff} implies at least one **spin tilted by more than** 90° relative to orbital angular momentum.
- Between 12 and 44% of BBHs have negative χ_{eff}.
- If we assume all systems with negative χ_{eff} are formed dynamically, then **between 25% and 93% of BBH mergers are formed dynamically**.



Evolution of spin distribution with mass not measured



- Hint of mass-dependence to spin, as preferred distributions different for continuum (Power Law) and high-mass (Gaussian)
- Large overlap between the posteriors, so inconclusive with current dataset.

Merger rates

Assuming no cosmic evolution

Binary neutron stars

With two confident BNS mergers as of GWTC-2, we infer a local merger rate of

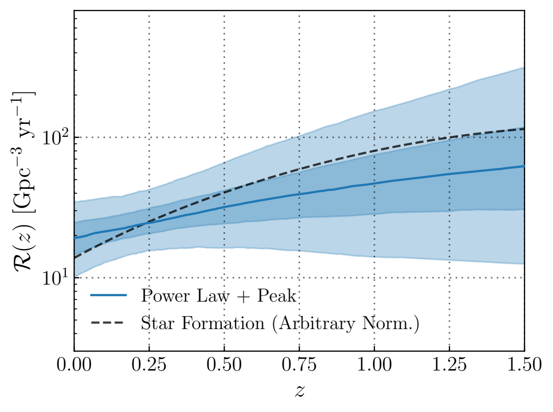
$$\mathcal{R}_{\text{BNS}} = 320^{+490}_{-240}\,\text{Gpc}^{-3}\,\text{yr}^{-1}$$

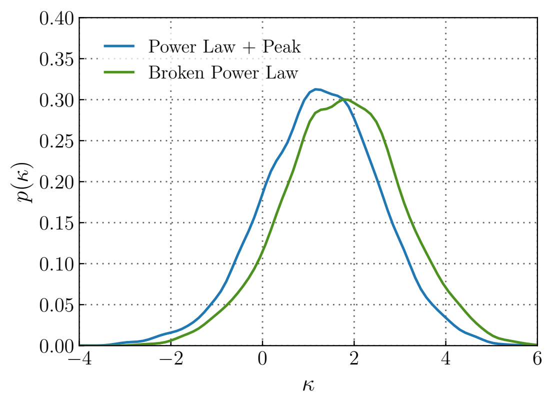
Binary black holes

Simultaneously fitting for the mass, spin, and merger rate, we infer a local merger rate of

$$\mathcal{R}_{\text{BBH}} = 23.9^{+14.9}_{-8.6}\,\text{Gpc}^{-3}\,\text{yr}^{-1}$$

Assuming $R(z) \propto (1+z)^\kappa$





Conclusions

Lessons from GWTC-2: Masses

- **The black hole mass spectrum does *not* terminate abruptly at** $45\,M_\odot$, but *does* show a feature at $\sim 40\,M_\odot$, which can be represented by a break in the power law *or* a Gaussian peak.
- **There is a dearth of low-mass black holes** between ~ 2.6 to $6\,M_\odot$.
- **The distribution of mass ratios is broad** in the range ~ 0.3–1, with a mild preference for equal-mass pairings
  - GW190814 is an outlier

Lessons from GWTC-2: Spins

- Some binary black holes have measurable in-plane spin components, leading to **precession of the orbital plane**
- Some binary black holes have spins **misaligned by** $> 90^\circ$ but the distribution of spin tilts is not perfectly isotropic
- There are hints, but **no clear evidence that the spin distribution varies with mass**.

Lessons from GWTC-2: Rates

- In the local Universe, the average **binary black hole merger rate is between** 15–40 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$.
- The binary black hole merger rate **probably evolves with redshift, but slower than the star-formation rate**, increasing by a factor of ~ 2.5 between $z = 0$ and $z = 1$.

Open questions

- What is the physical origin for the feature at $\sim 40\,M_\odot$?
- What is the origin of black holes with masses $\gtrsim 45\,M_\odot$?
- Is there a mass gap between neutron stars and black holes?
- What is the nature of the $\sim 2.6\,M_\odot$ object in GW190814?
- Are the systems with misaligned spins the result of dynamical assembly?
- Are we observing binary black holes from multiple formation channels?

Questions?