Gravitational-wave astronomy

Black holes and fundamental physics

Christopher Berry • cplberry.com • @cplberry

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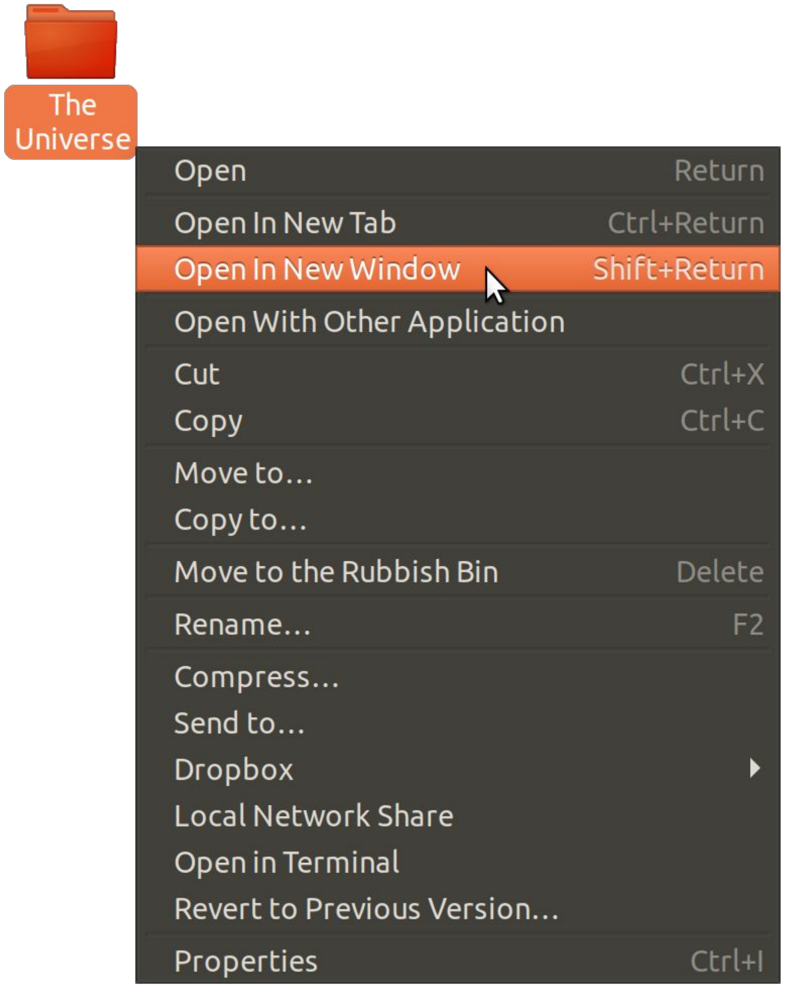
University of Glasgow | School of Physics & Astronomy

IGR

UKRI Science and Technology Facilities Council

LIGO VIRGO KAGRA

LIGO DCC G2400973



Exploring the spectrum

Gravitational waves observatories and their targets

Discoveries from the ground-based observatory network

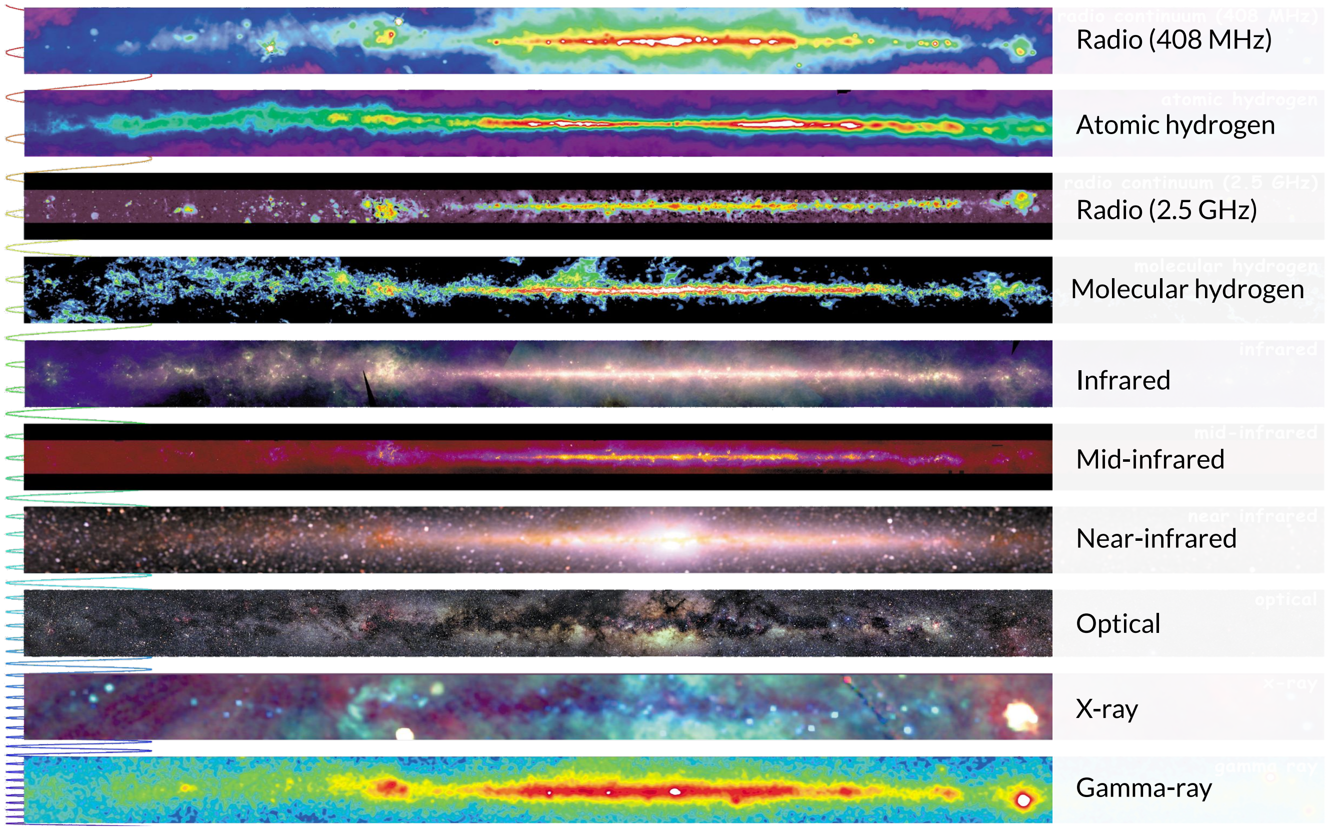
Astrophysics, cosmology and relativity

Black hole astrophysics

Challenges for binary modelling

Exploring the spectrum

Each time we observe the Universe in a new way, we discover something new



NASA

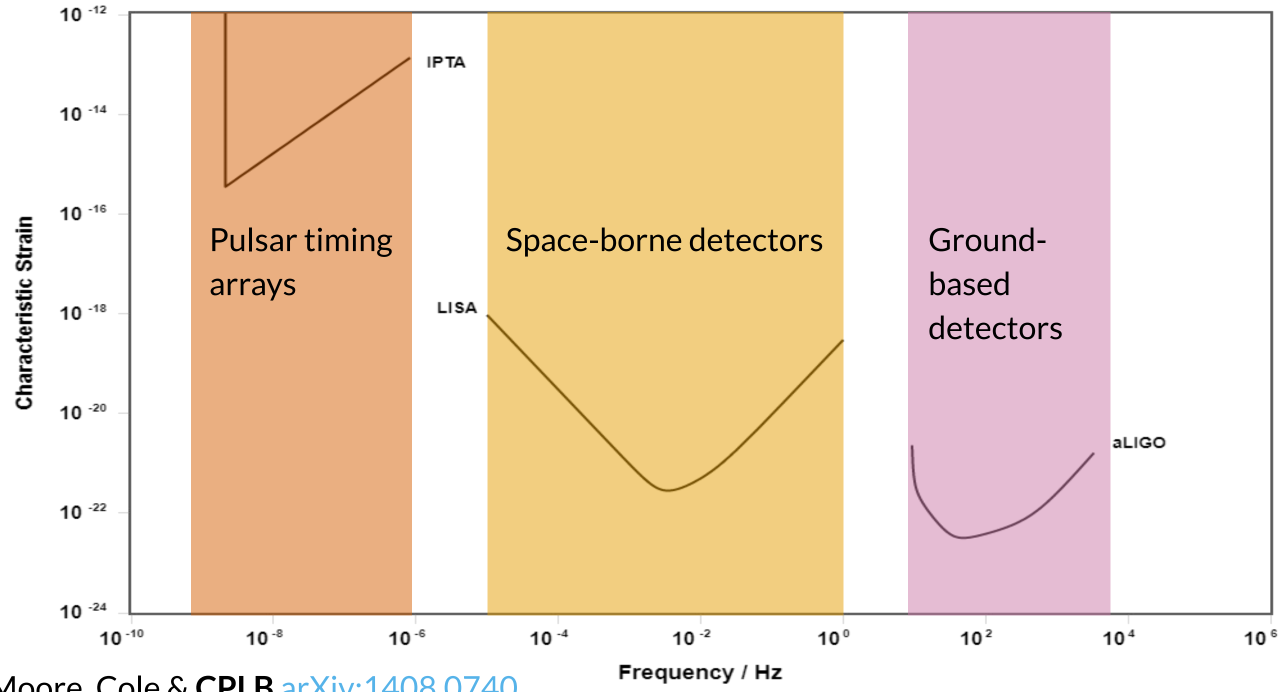
Gravitational-wave spectrum

Different technologies used for different frequency ranges

Currently, LIGO, Virgo and KAGRA observe at highest frequencies

LISA is due for launch in 2030s

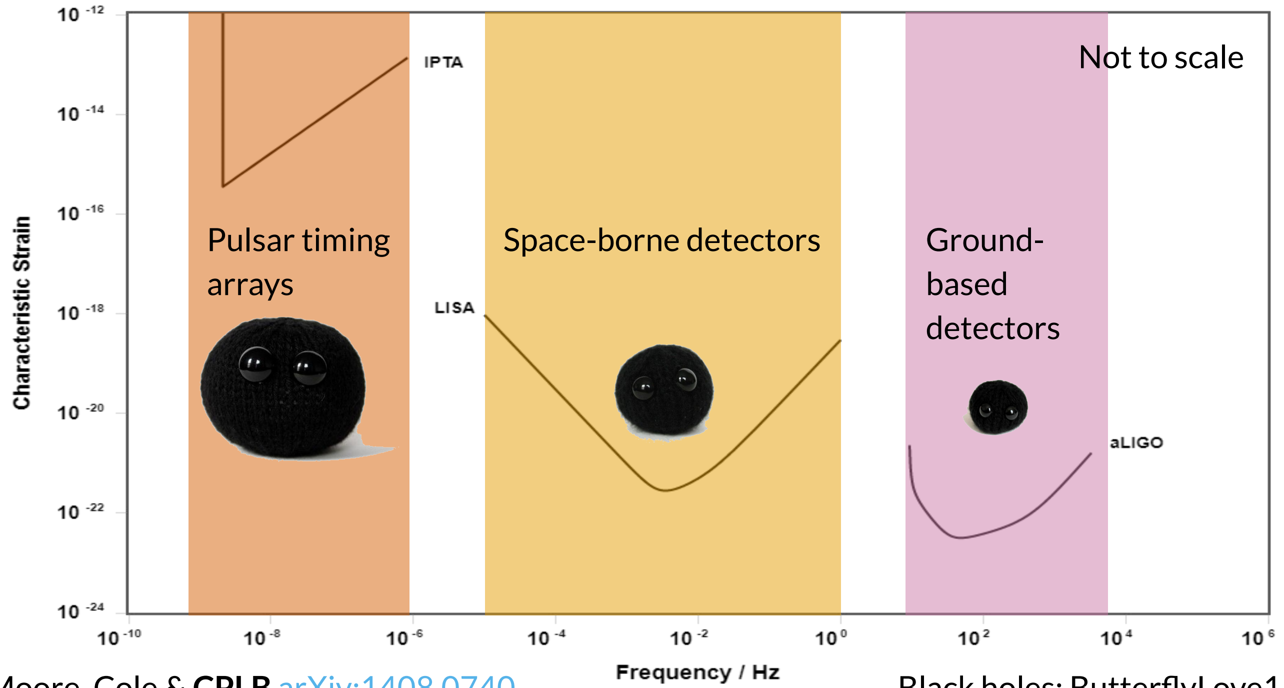
Pulsar timing arrays observe at lowest frequencies



Moore, Cole & **CPLB** arXiv:1408.0740

Gravitational-wave spectrum

Different sources wait in each part of the spectrum



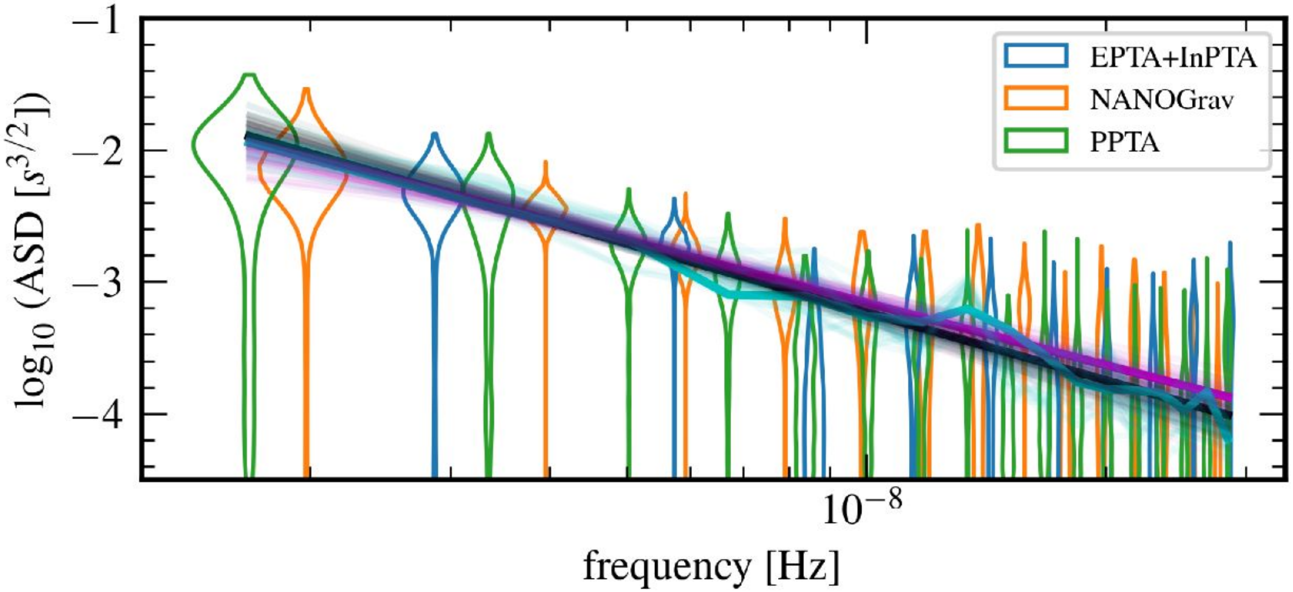
Moore, Cole & **CPLB** arXiv:1408.0740

Black holes: ButterflyLove1

Pulsar timing arrays

EPTA+InPTA
$p = 10^{-3}$
arXiv:2306.16214
NANOGrav
$p = 10^{-3}$–5×10^{-5}
arXiv:2306.16213
PPTA
$p = 0.02$
arXiv:2306.16215
CPTA
$p = 4 \times 10^{-6}$
arXiv:2306.16216

IPTA detection checklist
arXiv:2304.04767



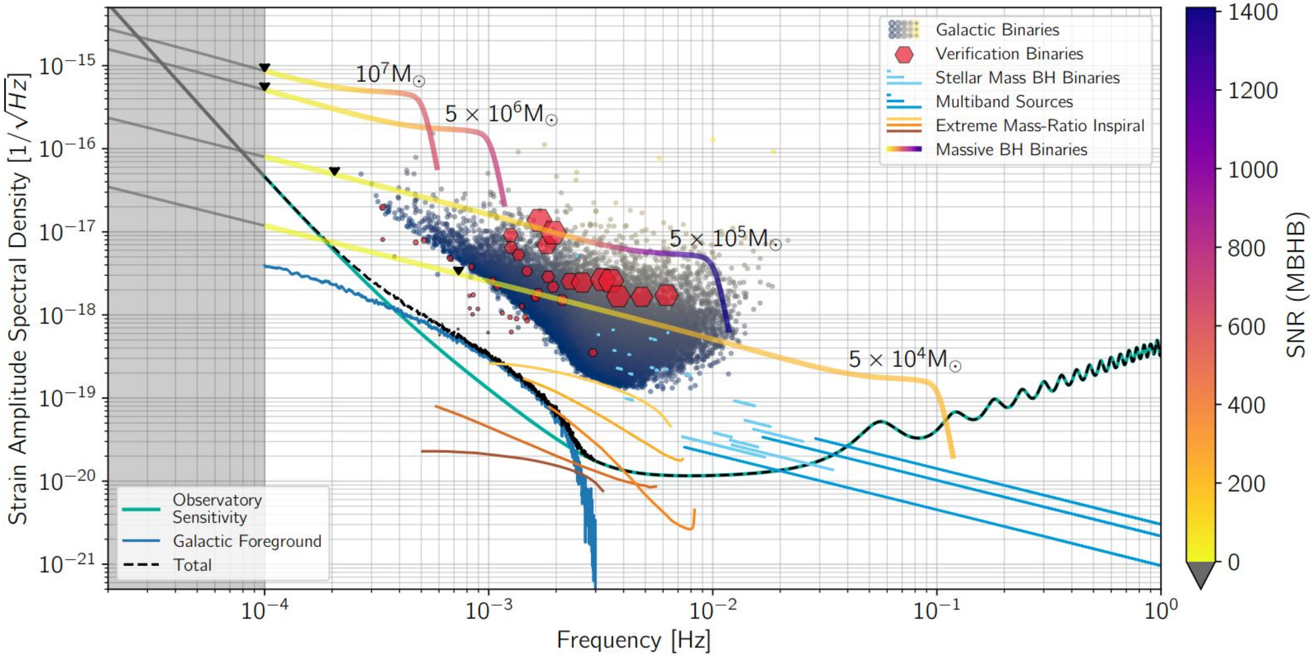
IPTA arXiv:2309.00693

LISA

LISA mission accepted by ESA in January, launch planned for 2035

LISA can contribute to a wide range of astrophysics arXiv:2203.06016

Data analysis will be extremely complicated lisa-ldc.lal.in2p3.fr

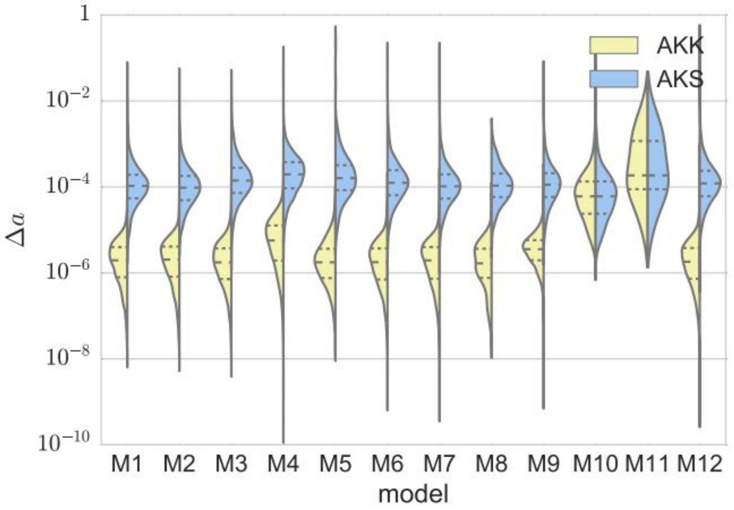


LISA arXiv:2402.07571

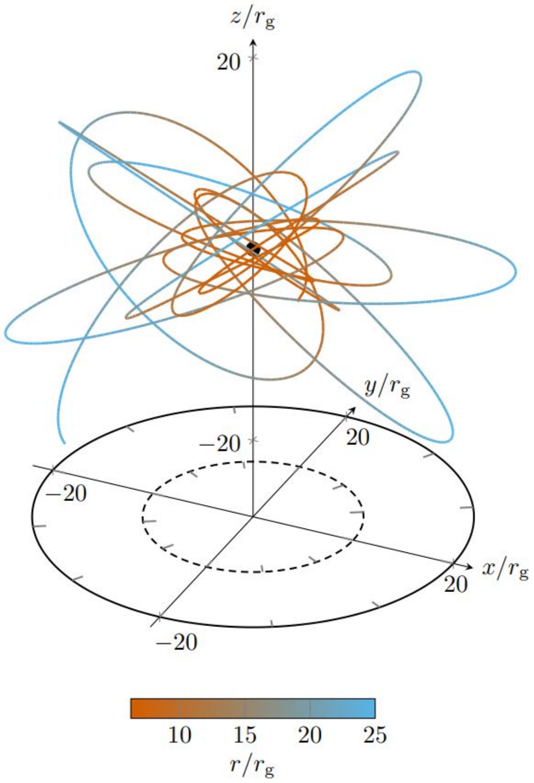
EMRIs

Extreme mass-ratio systems will enable exquisite source measurements

Waveforms have a complicated frequency structure, e.g., Speri *et al.* arXiv:2307.12585



Babak, …, **CPLB** *et al.* arXiv:1703.09722



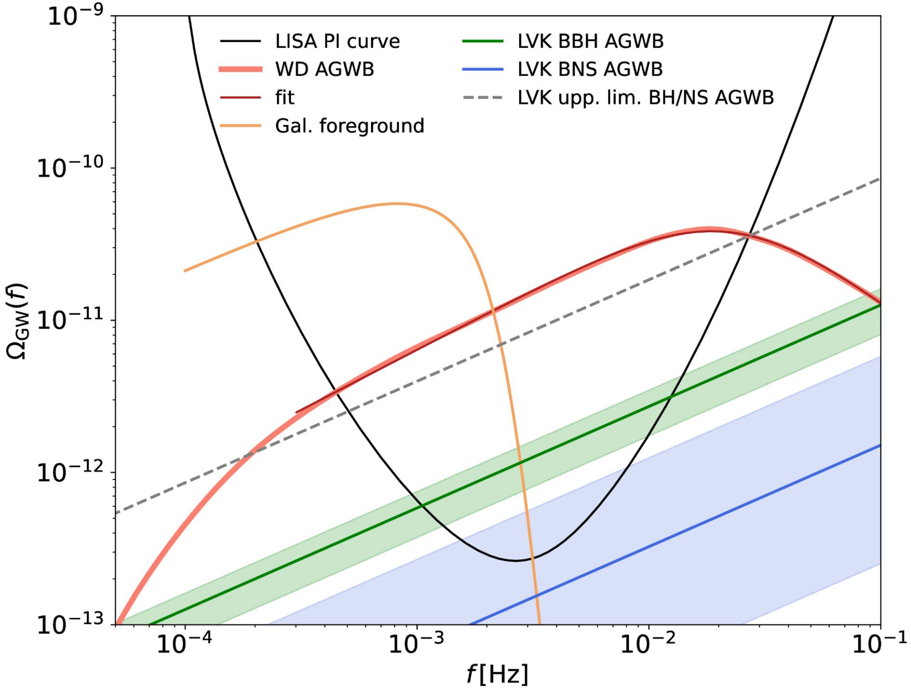
CPLB *et al.* arXiv:1903.03686

Astrophysical backgrounds

White dwarfs merge in the decihertz range

The astrophysical foreground contains useful information about sources

The foreground masks stochastic backgrounds



Staelens & Nelemans arXiv:2310.19448

GW150914

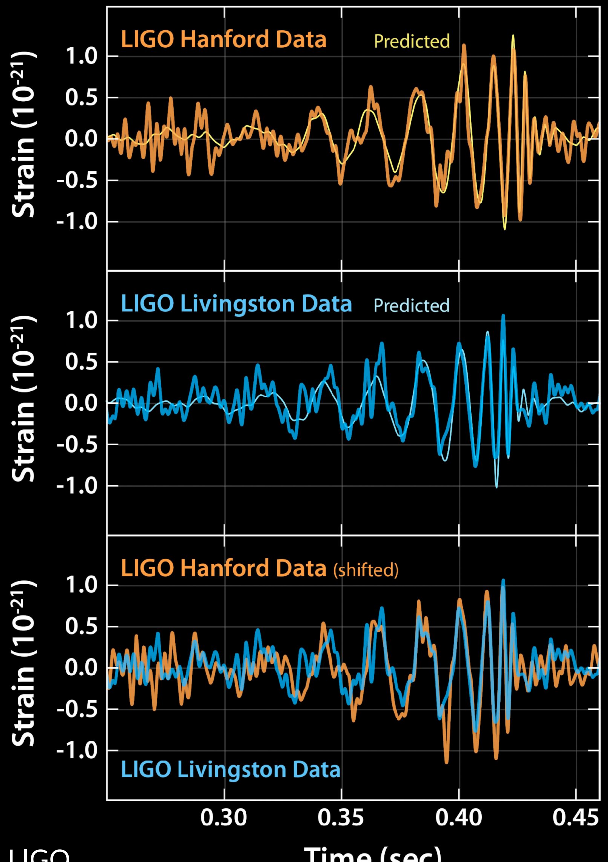
Signals encode information about their sources

GW150914 parameter estimation
arXiv:1602.03840

GW150914 astrophysical implications
arXiv:1602.03846

14 September 2015 we observed gravitational waves

The signal came from the coalescence of a **binary black hole**



LIGO

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation

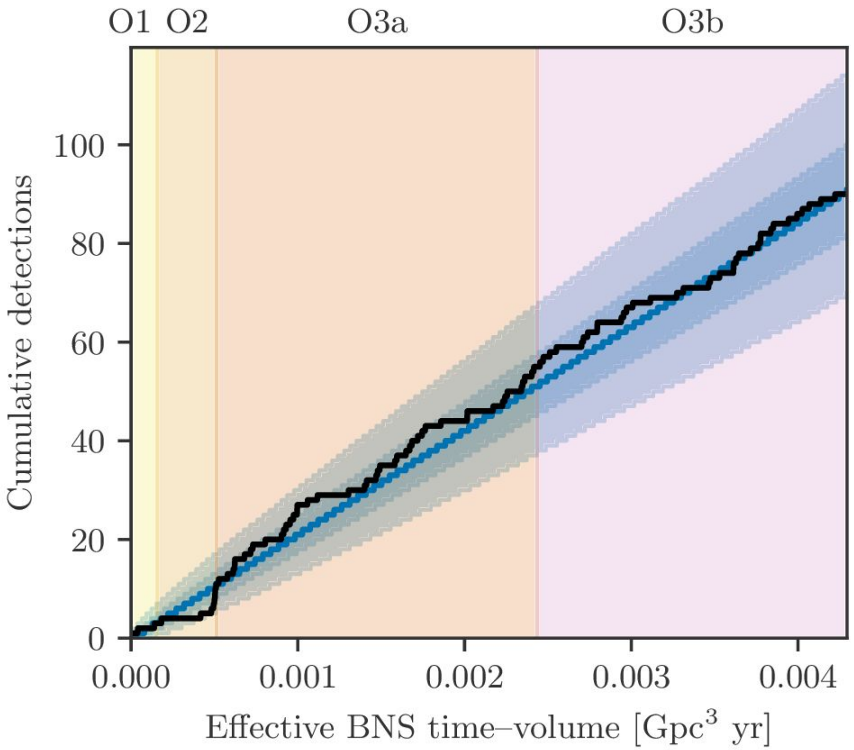
Discoveries from the ground-based observatory network

Binaries

Observing runs
O1: 2015–2016
O2: 2016–2017
O3: 2019–2020
O4: 2023–2024

A total of 90 candidates with probability of astrophysical origin > 0.5 plus many more lower probability candidates

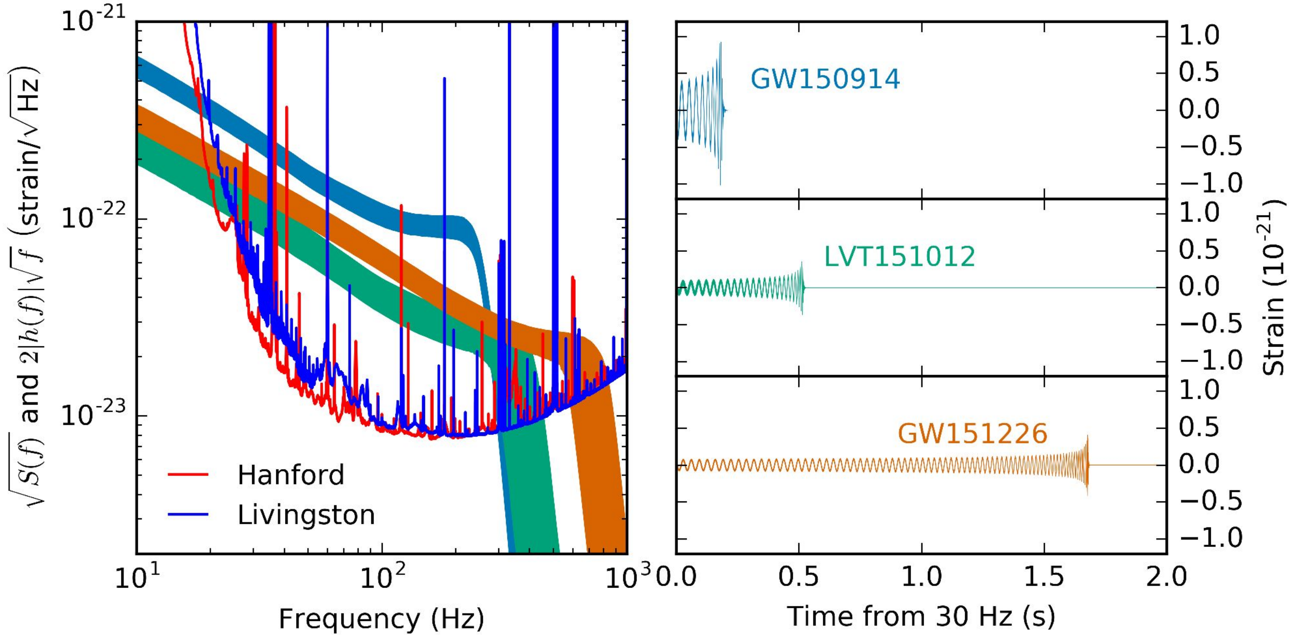
Most are binary black holes (BBHs), some are neutron star–black hole binaries (NSBHs), two are binary neutron stars (BNSs)



LVK arXiv:2111.03606

Waveforms

Detection papers
GW150914
arXiv:1602.03837
GW151012
arXiv:1602.03839
GW151226
arXiv:1606.04855



LVC arXiv:1606.04856

Chirp mass is a combination of component mass that to leading order determines the rate of inspiral:

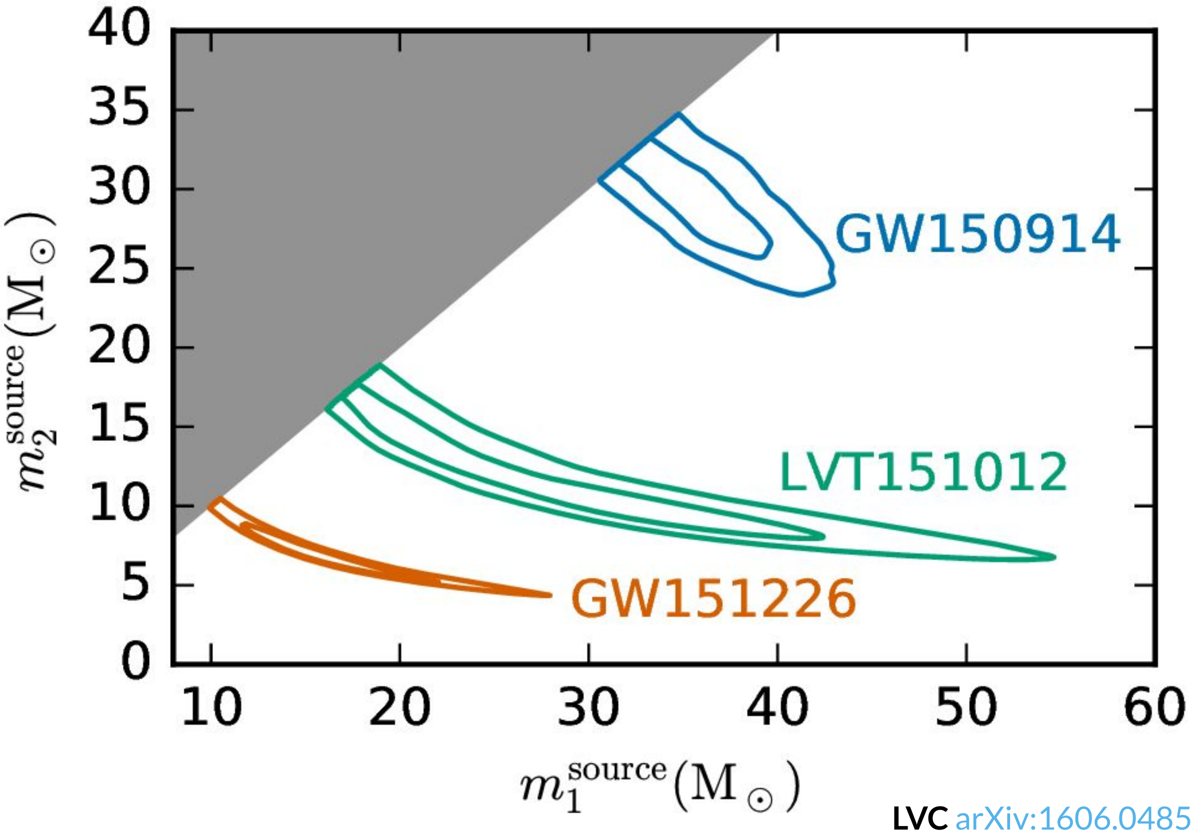
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Total mass sets properties of merger and ringdown:

$$M = m_1 + m_2$$

Mass ratio q is ratio of secondary to primary mass:

$$q = \frac{m_2}{m_1}$$



LVC arXiv:1606.04856

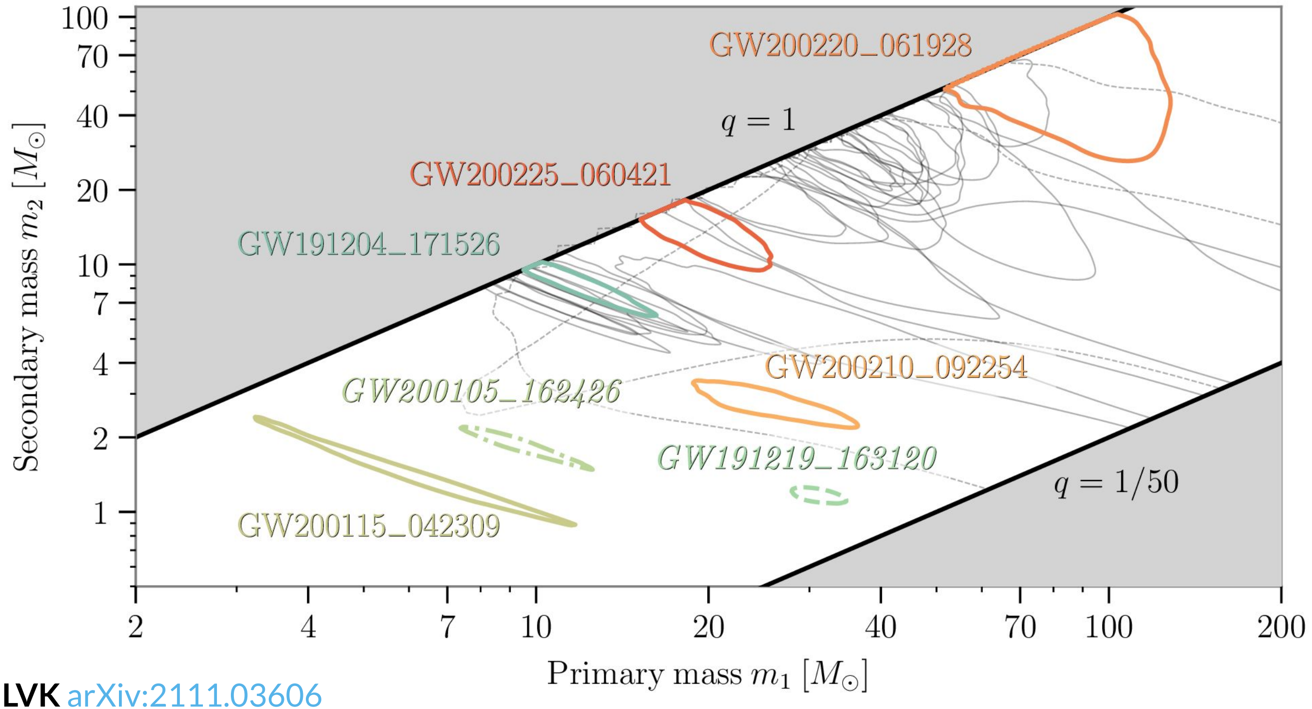
Source masses: GWTC-3

LVK
gravitational-wave catalogues:

GWTC-1 (O1+O2)
arXiv:1811.12907

GWTC-2 (O3a)
arXiv:2010.14527
youtu.be/nJD3DAaEk
GWTC-2.1 (O3a)
arXiv:2108.01045
youtu.be/tD36nX_rzic

GWTC-3 (O3b)
arXiv:2111.03606
youtu.be/MUyOVX1HqB8



LVK arXiv:2111.03606

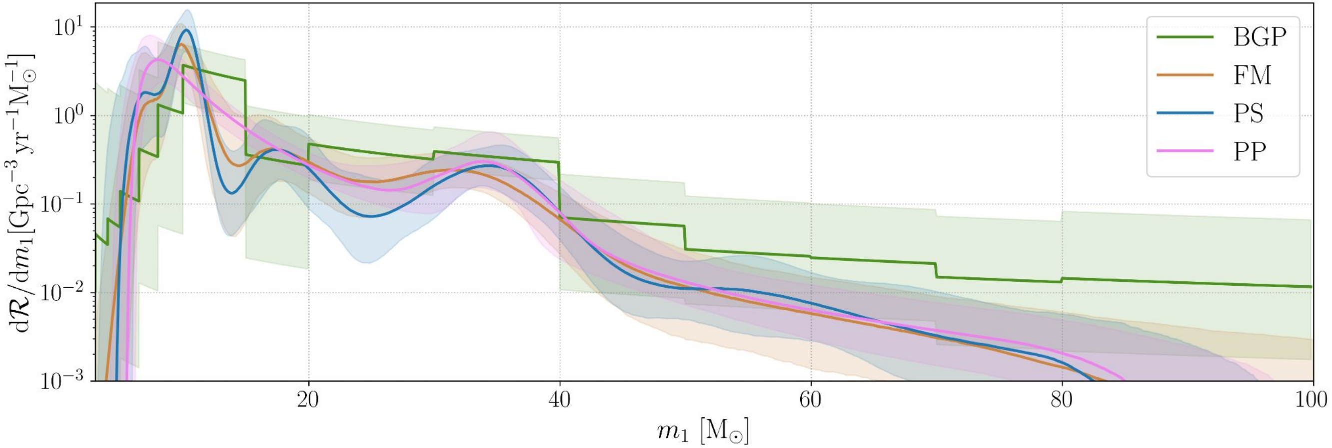
Astrophysical distribution

BGP = binned Gaussian process

FM = flexible mixtures Gaussian kernels

PS = power-law plus spline

PP = power-law plus (Gaussian) peak



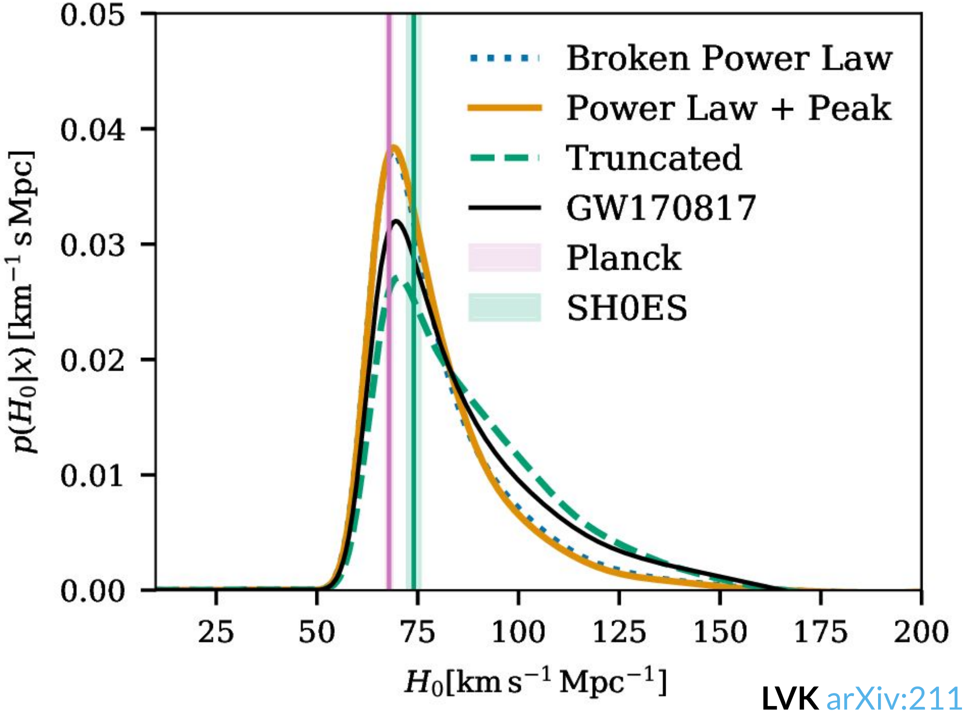
LVK arXiv:2111.03634

Cosmology

Standard siren distance measurements independent of distance ladder

Most information comes from GW170817

Different mass distributions yield different results

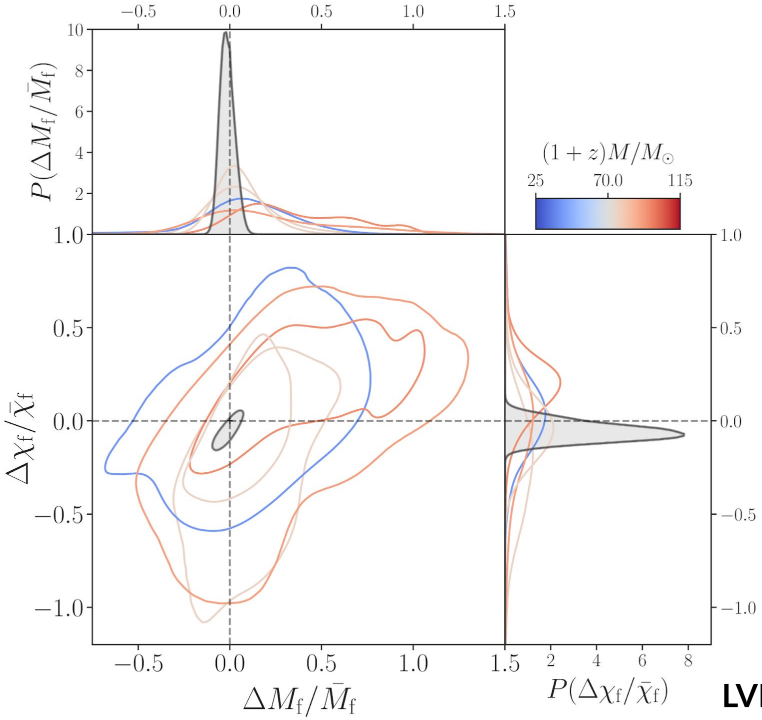


LVK arXiv:2111.03604

Tests of general relativity

Consistency tests do not assume a particular deviation from general relativity + Kerr black holes, but look self-consistency

Inspiral/merger–ringdown consistency test Ghosh *et al.* arXiv:1704.06784



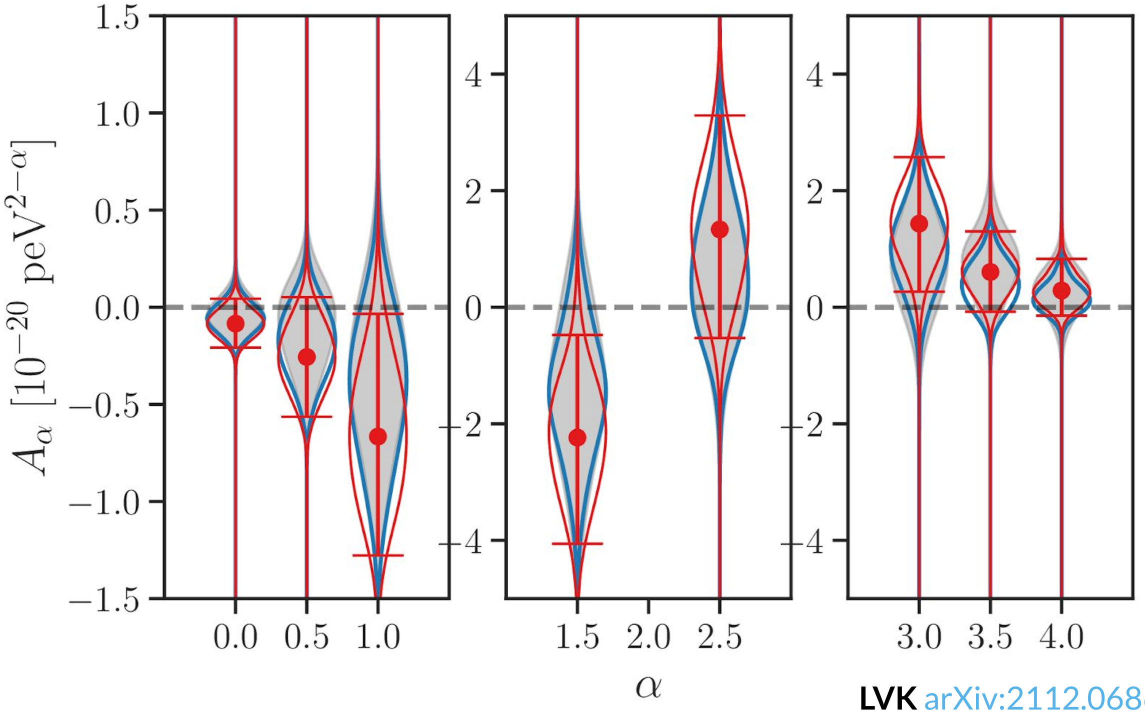
LVK arXiv:2112.06861

Tests of general relativity

Parameterized tests add additional parameters to look for deviations

For more on dispersive effects Mirshekari, Yunes & Will arXiv:1110.2720

For more on the impacts of data quality Kwok *et al.* arXiv:2109.07642



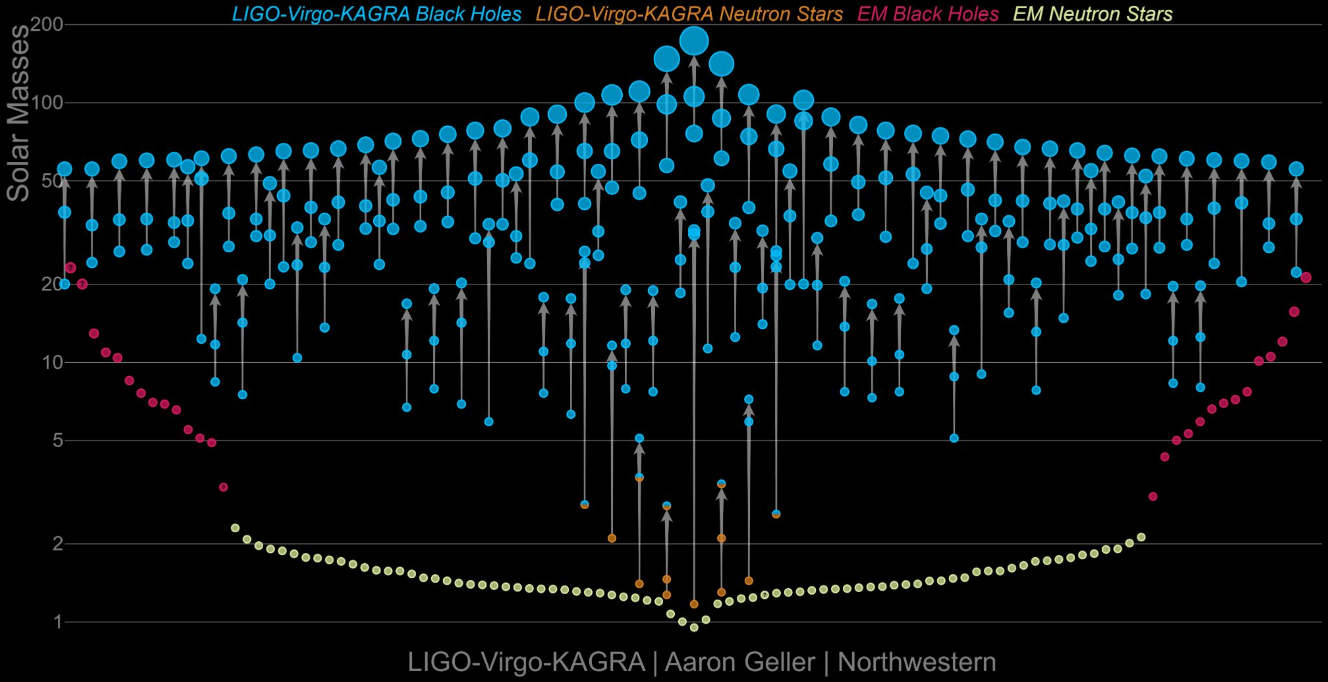
LVK arXiv:2112.06861

Black hole astrophysics

Compact object masses

We can observe black holes with multiple messengers

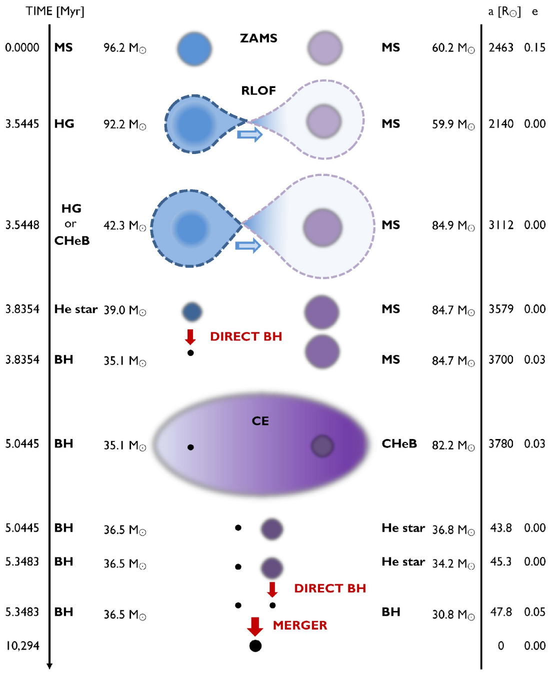
Measurements of **masses** and **spins** provide insights into black hole formation and evolution



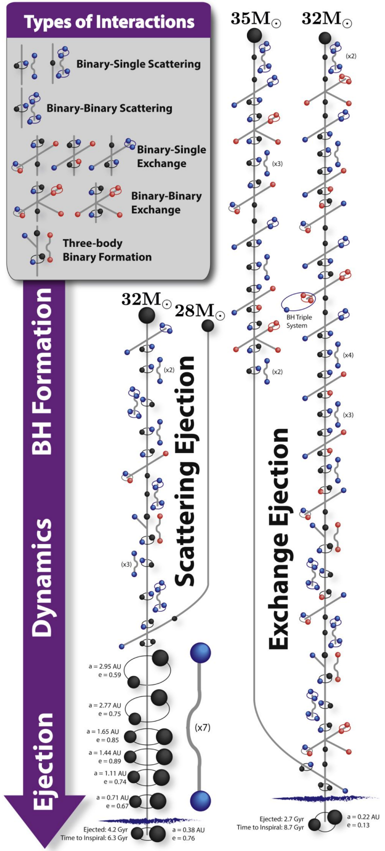
Binary evolution

Black holes must be close enough to merge due to gravitational wave emission

For a review of black hole formation: Mapelli arXiv:2106.00699



Belczynski *et al.* arXiv:1602.04531



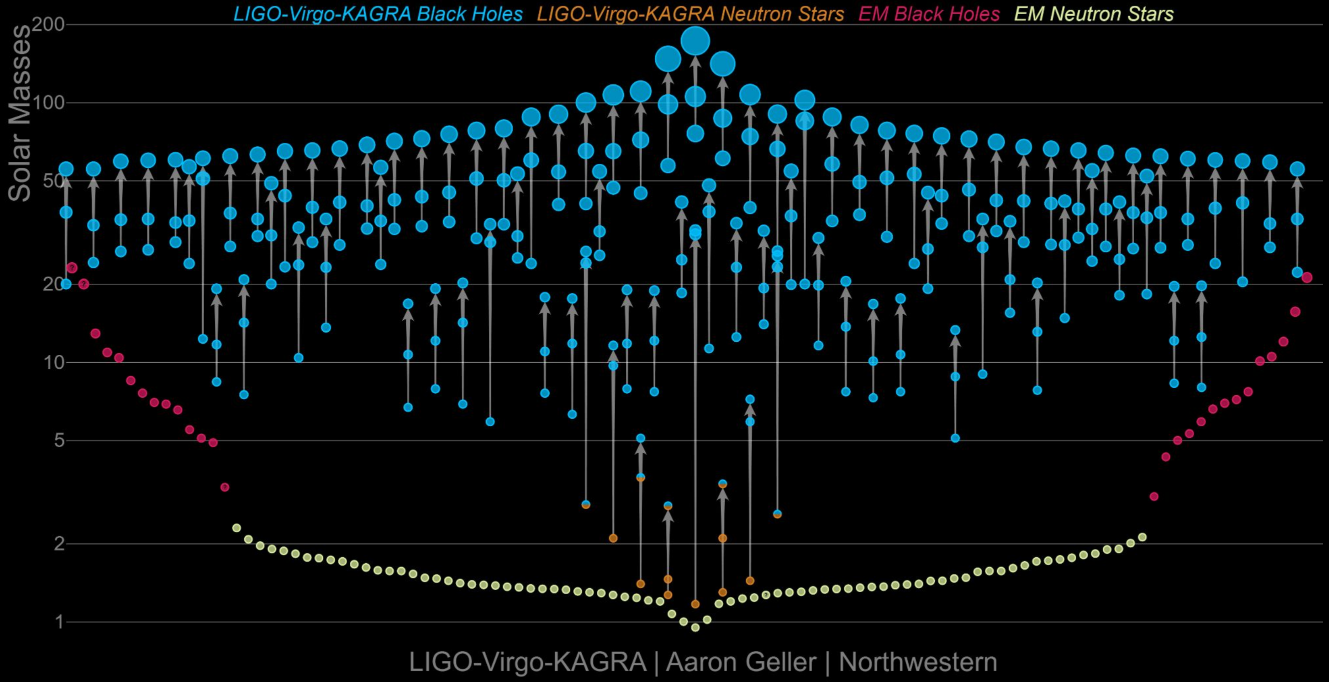
Rodriguez *et al.* arXiv:1604.04254

Compact object masses

We can observe black holes with multiple messengers

Black hole **mass distribution** exceeds **electromagnetic observations**

Different types of observations probe **different populations** and have different **selection effects**



Astrophysical distribution

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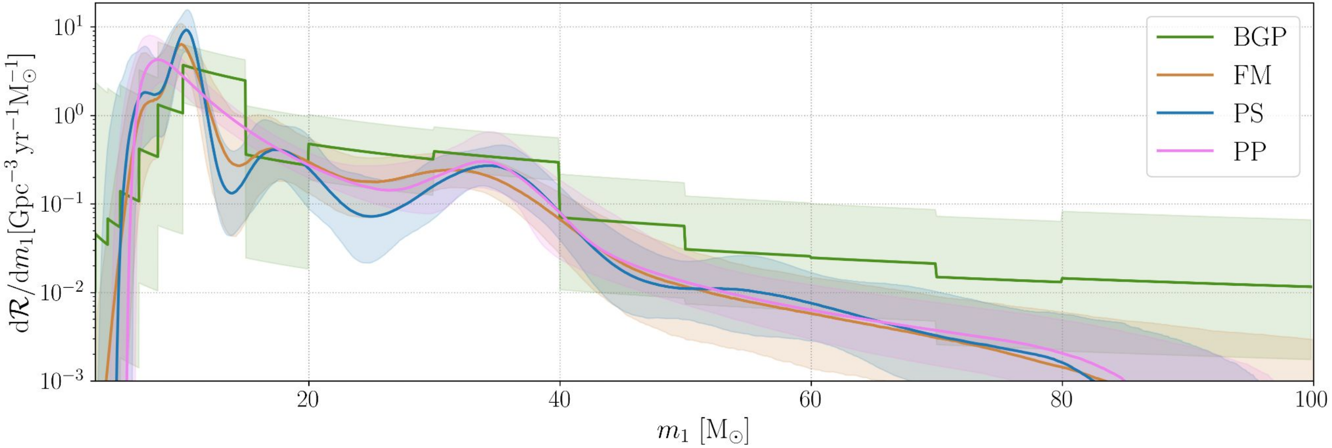
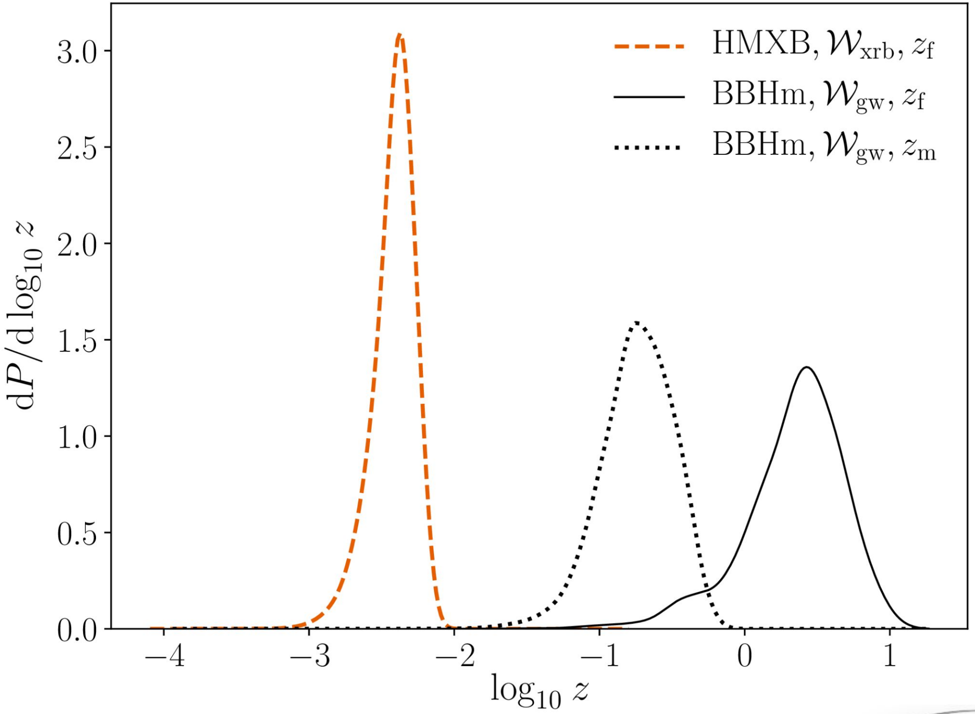


LVK arXiv:2111.03634

Observable high-mass X-ray binaries (HMXB) form at lower redshift than observable **merging binary black holes** (BBHm)

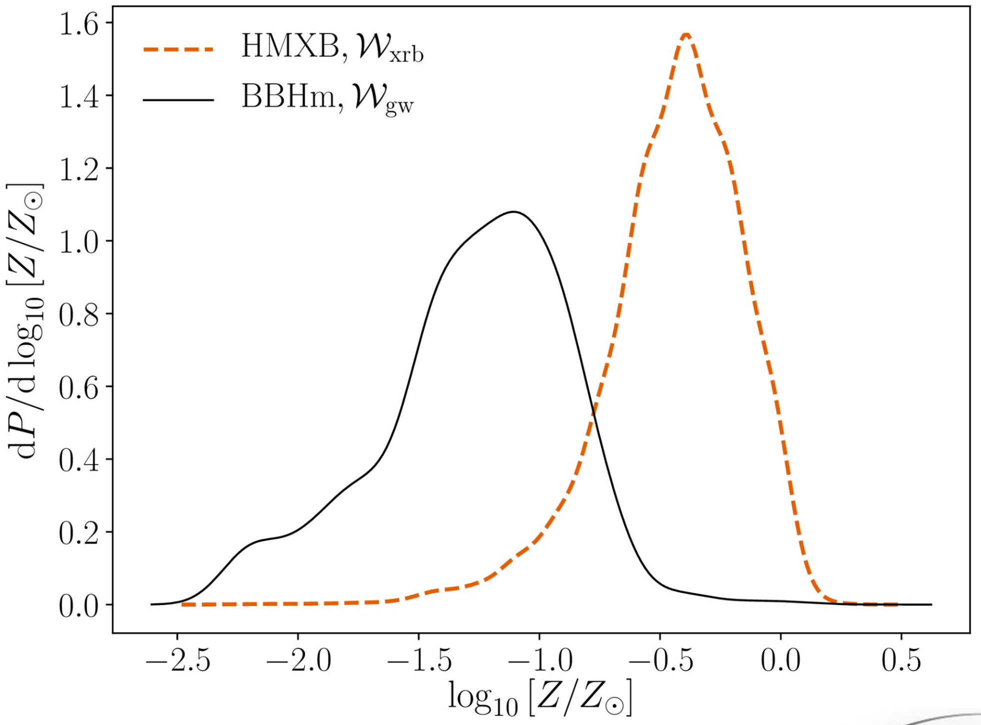
Consider binaries simulated from isolated binary evolution



Camille Liotinel

Liotine, Zevin, **CPLB**, Doctor & Kalogera
arXiv:2210.01825

Observable high-mass X-ray binaries (HMXB) form at higher metallicity than observable **merging binary black holes** (BBHm)

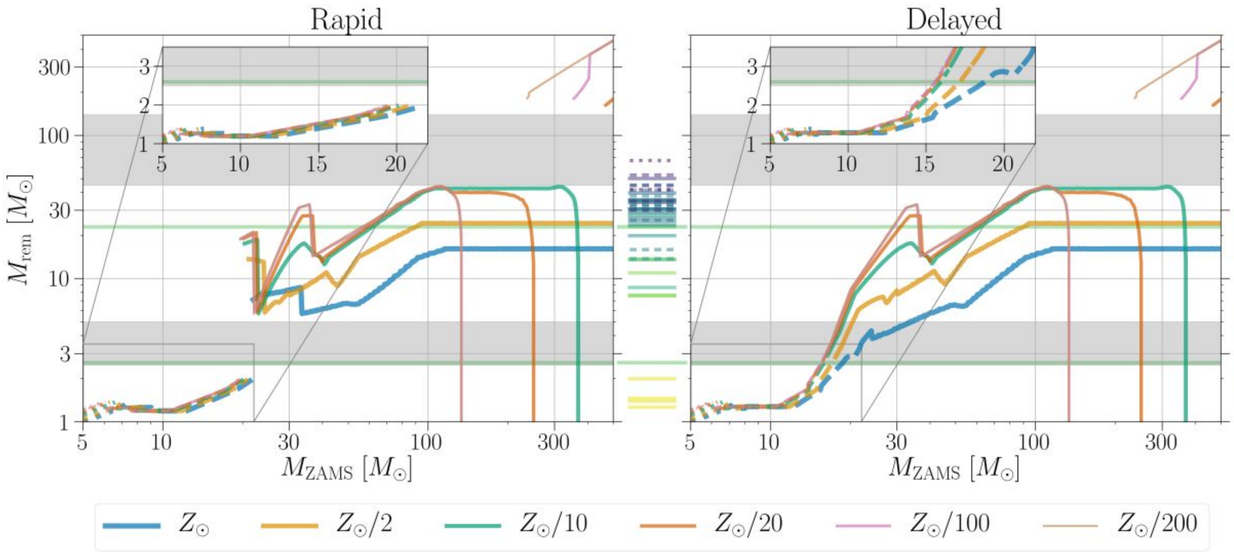


Camille Liotinel

Liotine, Zevin, **CPLB**, Doctor & Kalogera
arXiv:2210.01825

Single star remnant masses

Wind mass loss increases with metallicity

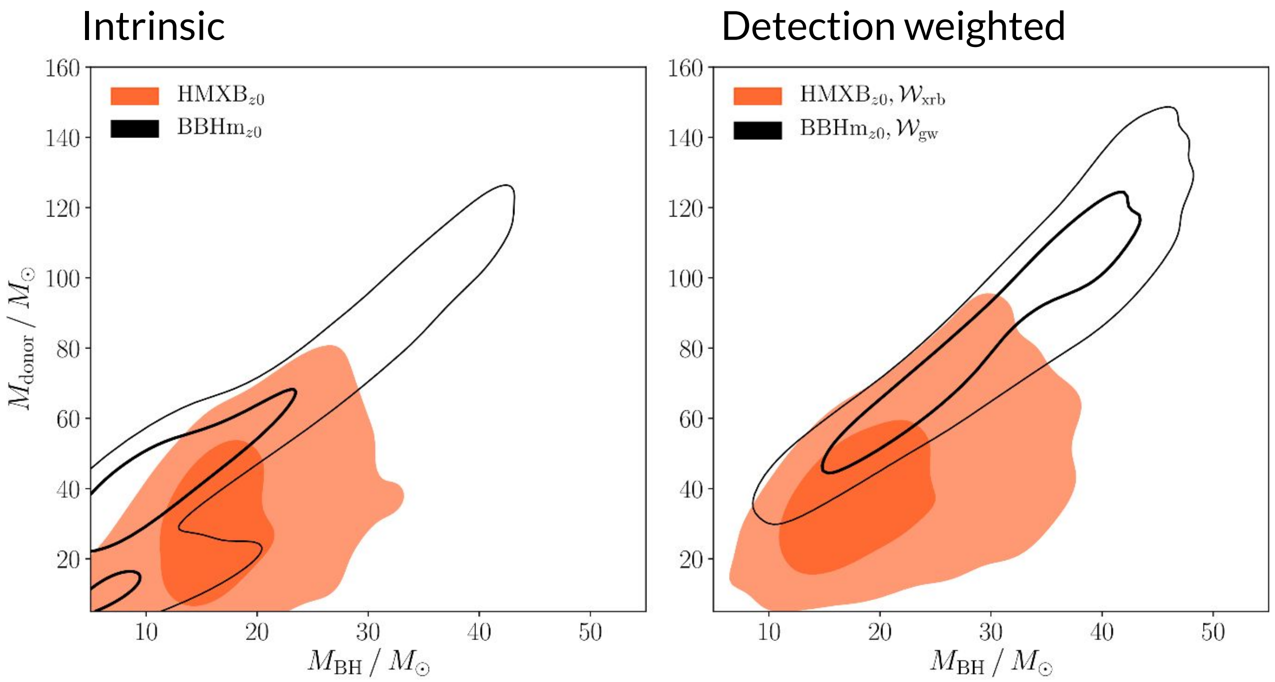


Zevin, Spera, **CPLB** & Kalogera
arXiv:2006.14573

Merging binary black holes are a subpopulation of high-mass X-ray binaries

Observational and evolutionary selection effects differentiate the populations

X-ray and gravitational waves give complementary information

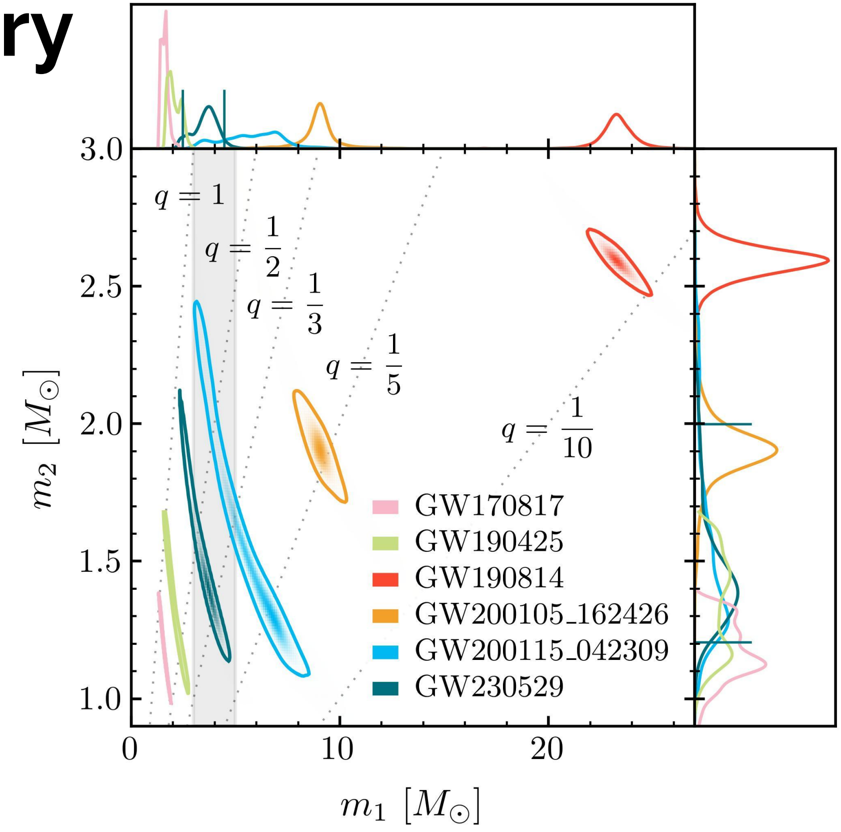


Liotine, Zevin, **CPLB**, Doctor & Kalogera
arXiv:2210.01825

O4a discovery

GW230529 is the first discovery announced from O4a

The source is probably a neutron star–black hole binary



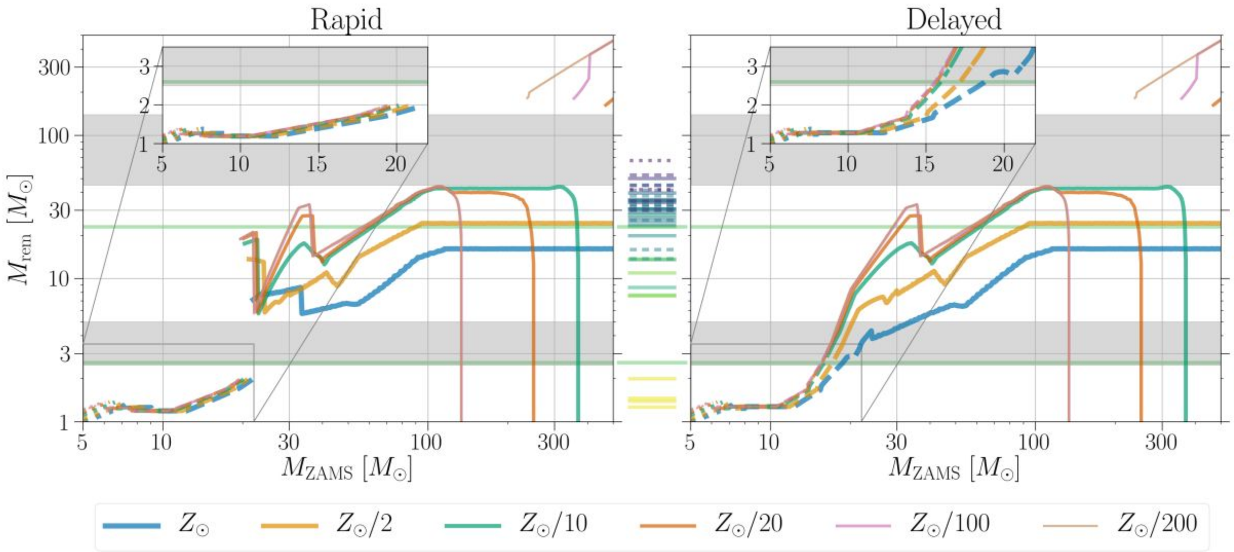
LVK arXiv:2404.04248

Single star remnant masses

Lower mass gap due to core-collapse supernovae

Upper mass gap due to (pulational) pair-instability supernovae

For more on massive stellar evolution Woosley, Heger, & Weaver (2002)



Zevin, Spera, **CPLB** & Kalogera
arXiv:2006.14573

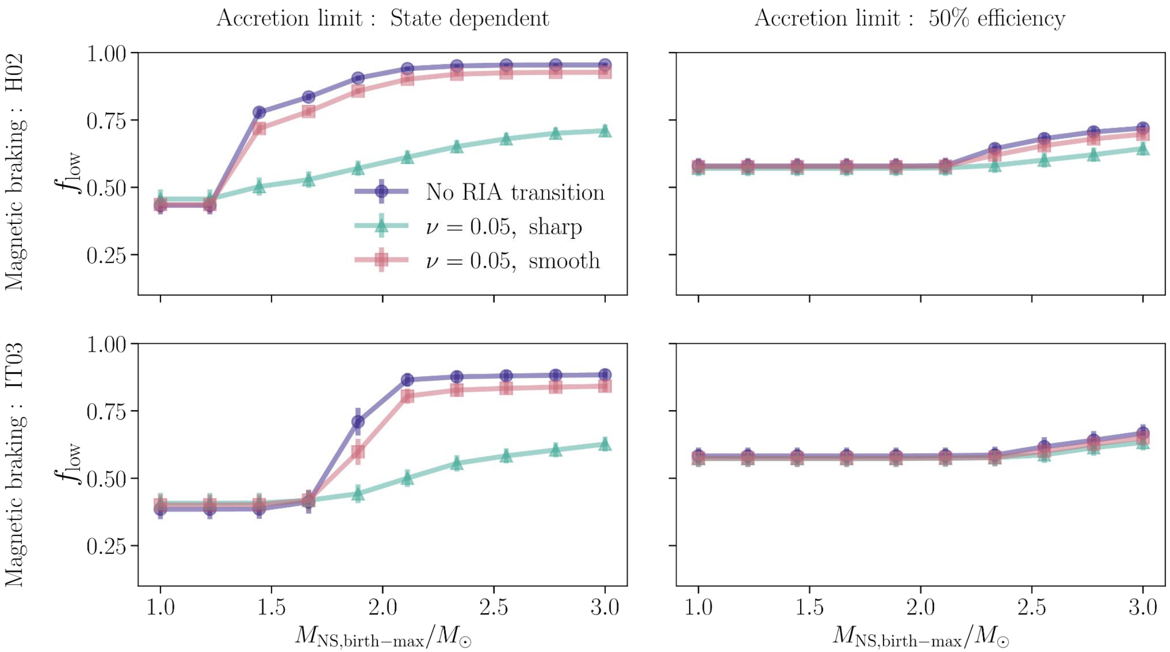
COSMIC

Lower mass gap

Selection effects suppress mass gap observations in low-mass X-ray binaries

Some mass gap objects still predicted to be found in low-mass X-ray binaries

Jared Siegel



Siegel, ..., **CPLB** *et al.* arXiv:2209.06844

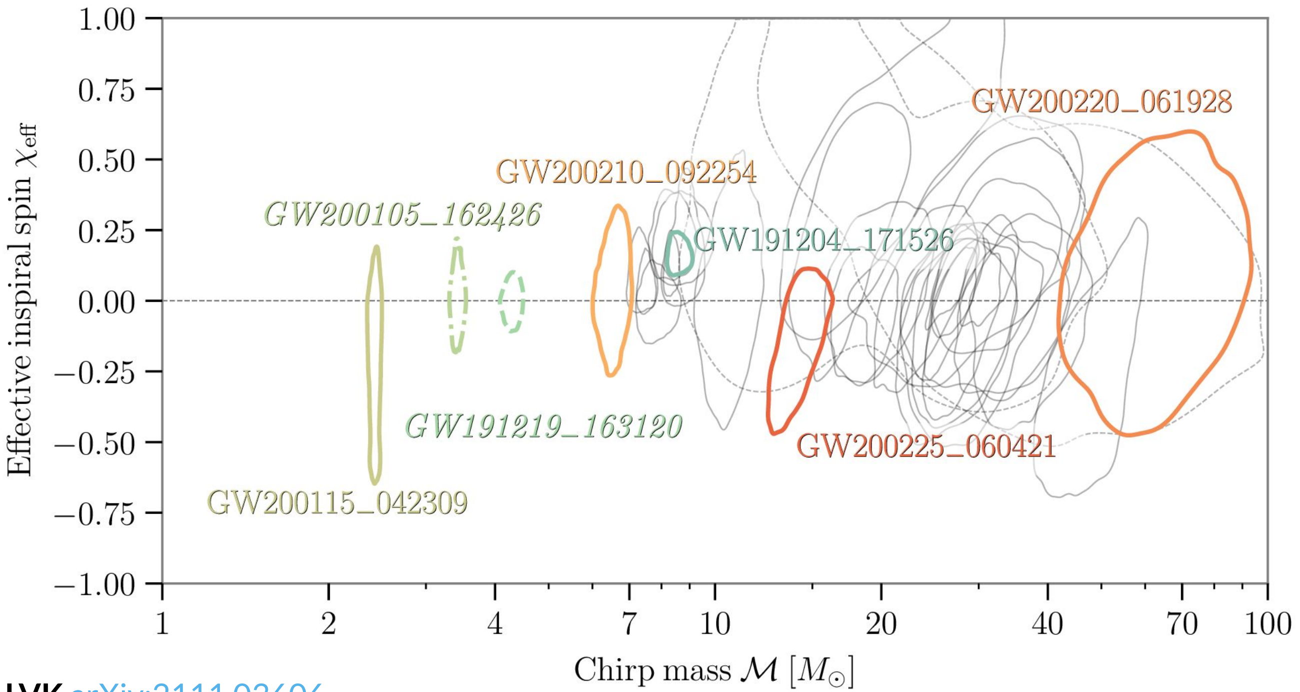
Effective inspiral spin

Mass-weighted combination of spins parallel to orbital angular momentum

Multiple events with non-zero values

More candidates with positive values than negative

GW191109 and **GW200225** have significant support for negative values

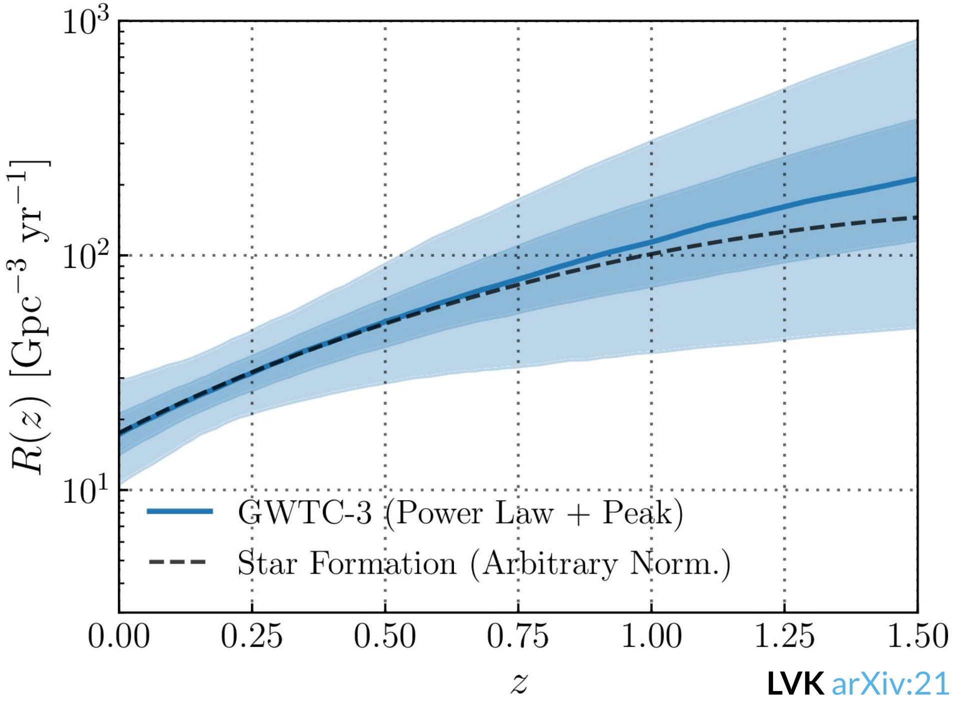


LVK arXiv:2111.03606

Redshift distribution

Information from (lack of) observations of lensing and the stochastic background can constrain higher redshifts

For more on lensing, **LVK** arXiv:2304.08393



LVK arXiv:2111.03634

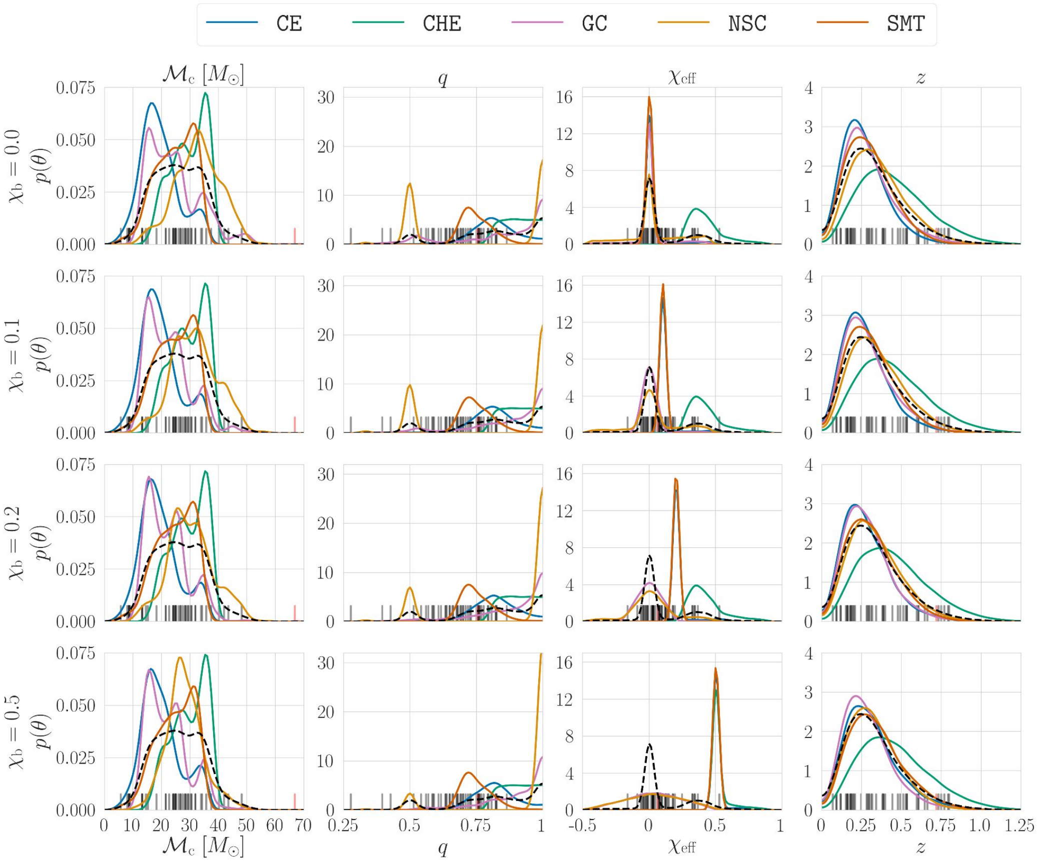
Formation channels

CE = common envelope
CHE = chemically homogeneous evolution
GC = globular cluster
NSC = nuclear star cluster
SMT = stable mass transfer

Model data release
DOI:10.5281/zenodo.4277619

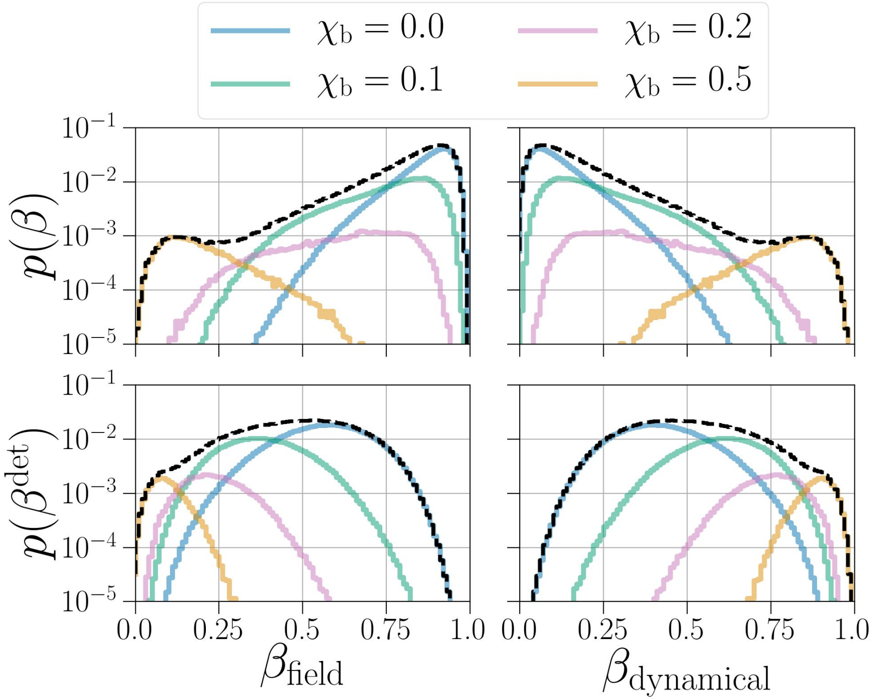
Michael Zevin

Zevin, Bavera, **CPLB** *et al.*
arXiv:2011.10057



Branching ratios

Varying the birth spin of black holes

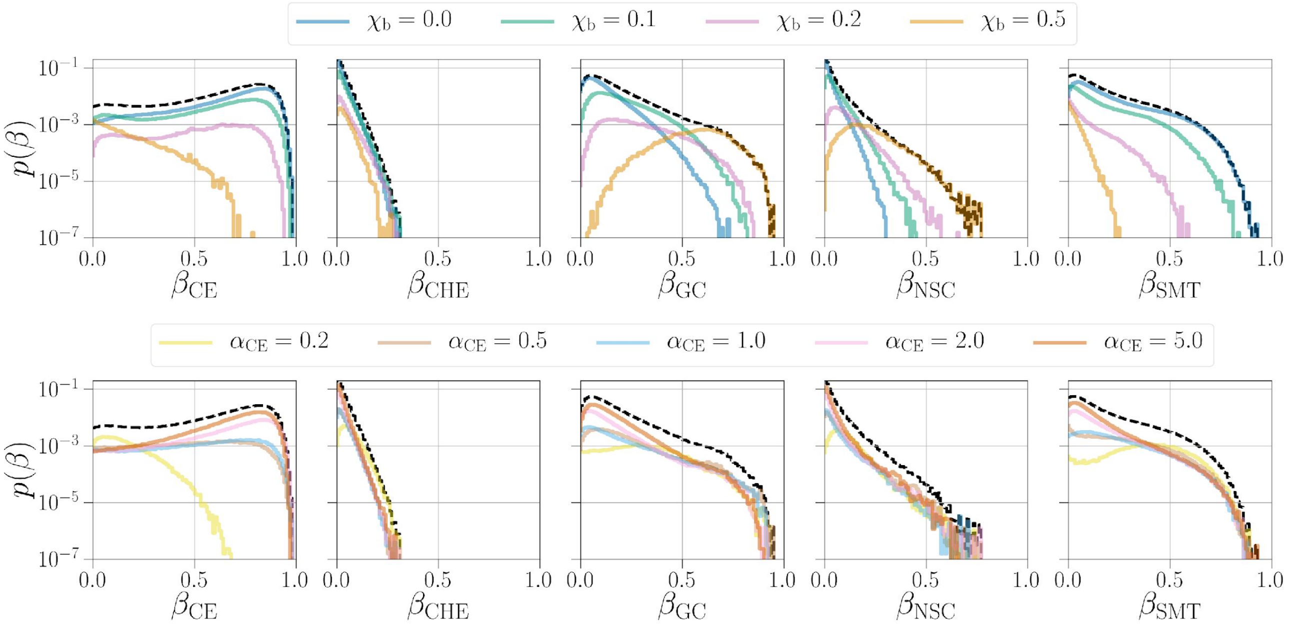


Zevin, Bavera, **CPLB** *et al.*
arXiv:2011.10057

The astrophysical mix

Common envelope efficiency only influences the CE channel, but there are correlations between channels

Probably a **mix of different channels**

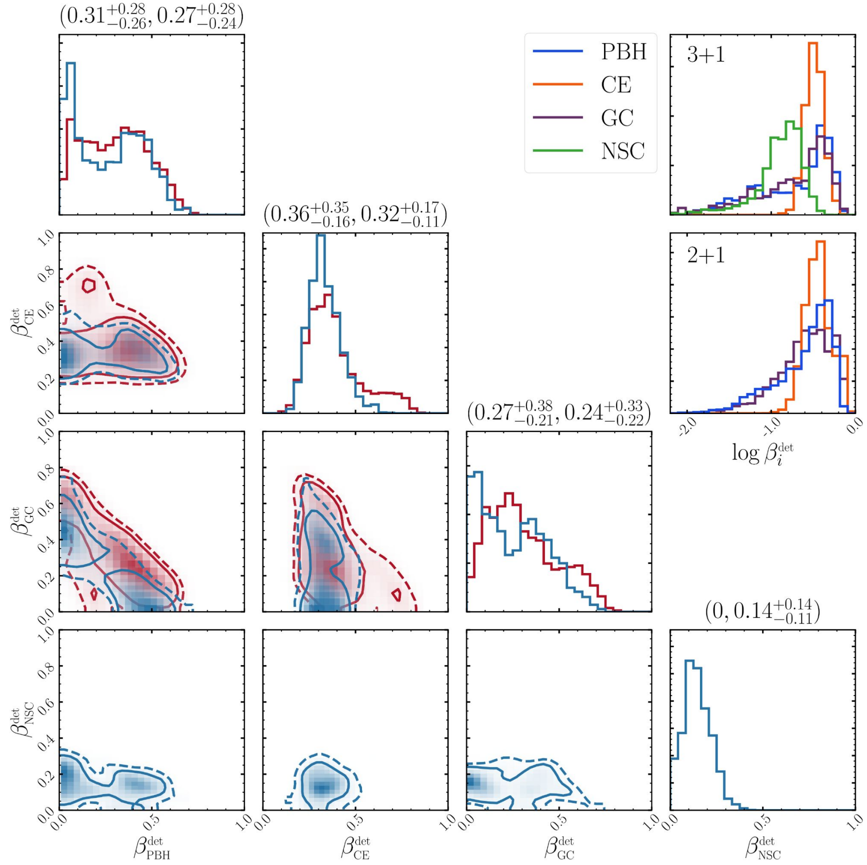


Zevin, Bavera, **CPLB** *et al.* arXiv:2011.10057

Primordial

Including others channels

PBH = primordial black holes



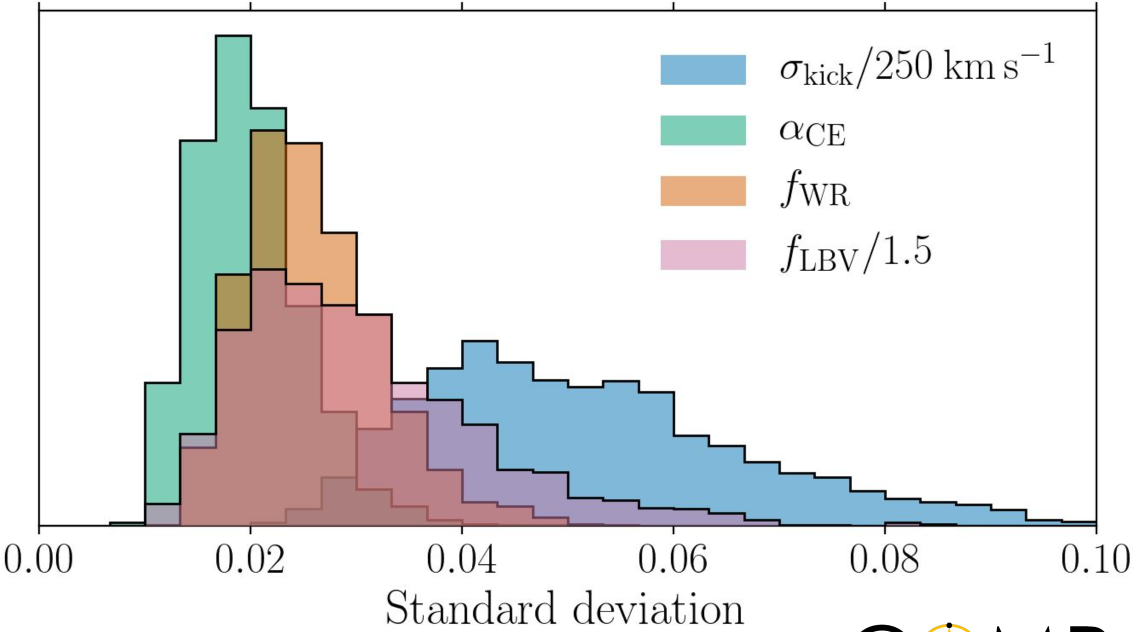
Franciolini *et al.*
arXiv:2105.03349

Precision astrophysics

Using 1000 detections of binaries from isolated evolution channels

Systematic modelling uncertainty dominates over statistical uncertainty

Simon Stevenson Jim Barrett



Barrett, …, **CPLB** *et al.* arXiv:1711.06287

COMPAS

ButterflyLove1

1. **Gravitational waves** enable discovery of a **diverse** range of sources
2. **LVK** observations cover black holes from ~4 to ~110 solar masses likely from **multiple formation channels**
3. Large number of detections will provide **precision constraints** on **black hole physics**

Thank you

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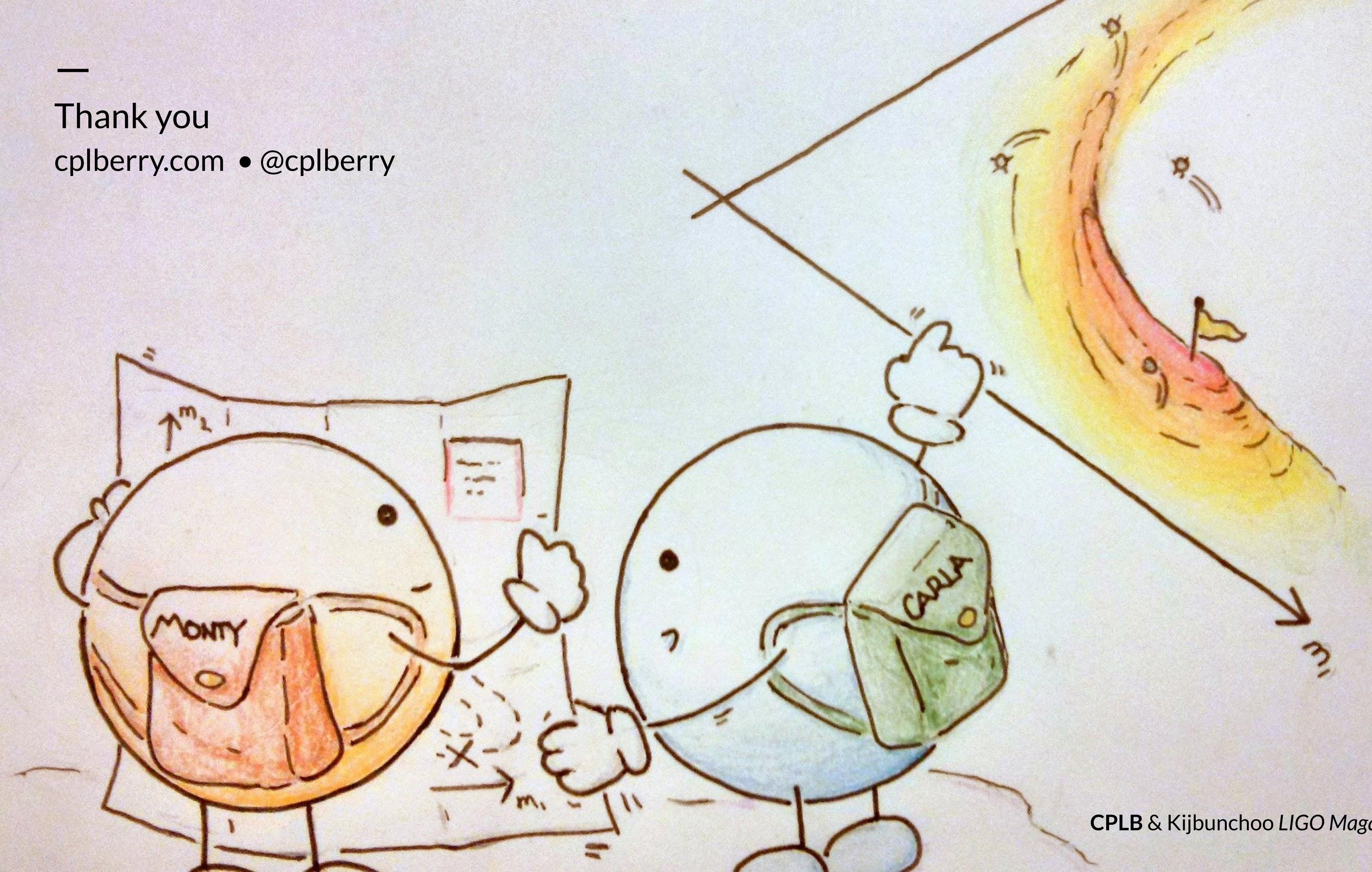
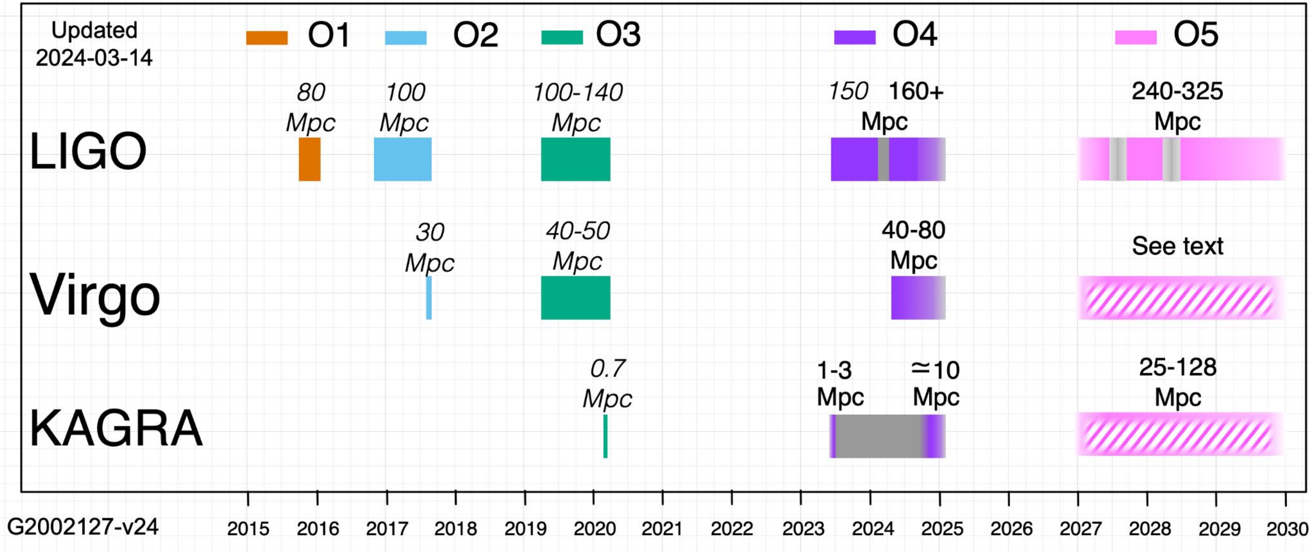


Observing plans

O4 is planned for 18 months of observing. **O4b** started 10 April

January 2024 earthquake has impacted KAGRA work

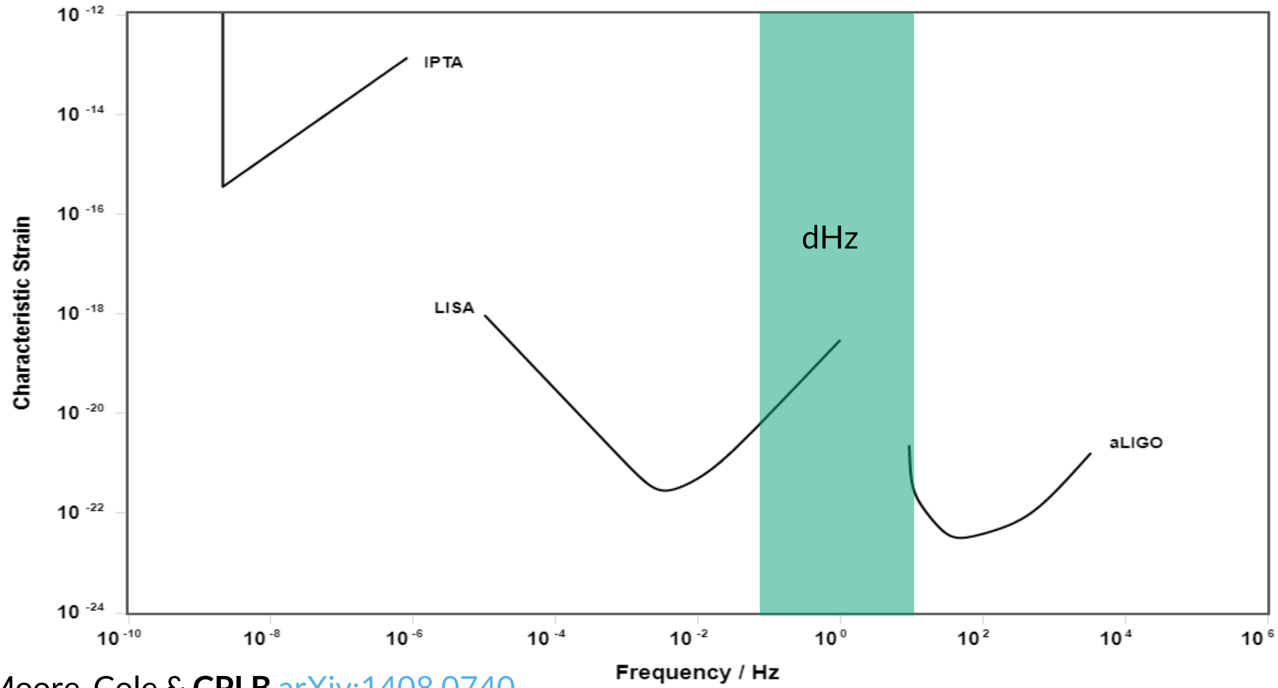
O5 start dates, duration and sensitivities will be adjusted closer to the time



LVK observing.docs.ligo.org/plan/

ALIA Bender, Begelman & Gair 2013
TianQin Luo *et al.* arXiv:1512.02076
Taiji Ruan *et al.* arXiv:1807.09495
DECIGO Kawamura *et al.* arXiv:2006.13545
TianGO Kuns *et al.* arXiv:1908.06004
GADFLI McWillians arXiv:1111.3708
gLISA Tinto *et al.* arXiv:1410.1813
SAGE Lacour *et al.* arXiv:1811.04743
MAGIS Graham *et al.* arXiv:1711.02225
AEDGE Abou El-Neaj *et al.* arXiv:1908.00802
Big Bang Observer Crowder & Cornish arXiv:gr-qc/0506015
DO-Conservative & DO-Optimal Arca Sedda, **CPLB** *et al.* arXiv:1908.11375

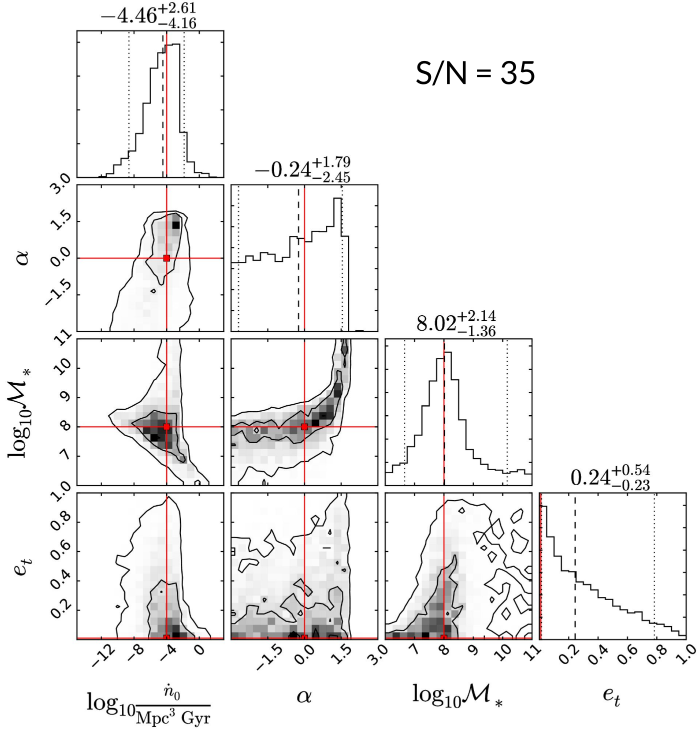
Gravitational-wave spectrum



Moore, Cole & **CPLB** arXiv:1408.0740

Pulsar timing arrays

Future constraints on the supermassive black hole binary population



Chen *et al.* arXiv:1612.02826

EMRI population inference

For sources with redshift < 6 and an optimistic event rate

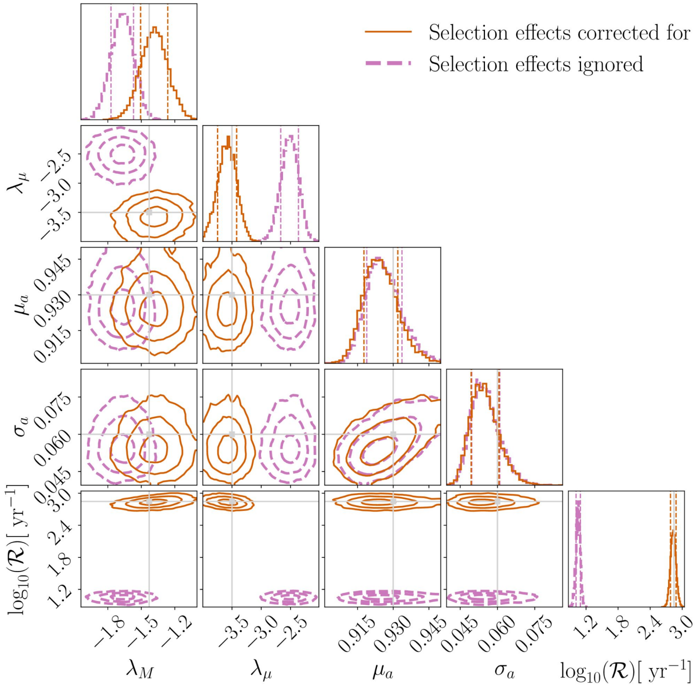
MBH mass function slope: 9%

CO mass function slope 5%

Width of the MBH spin magnitude distribution 10%

Event rate 12%

Christian Chapman-Bird

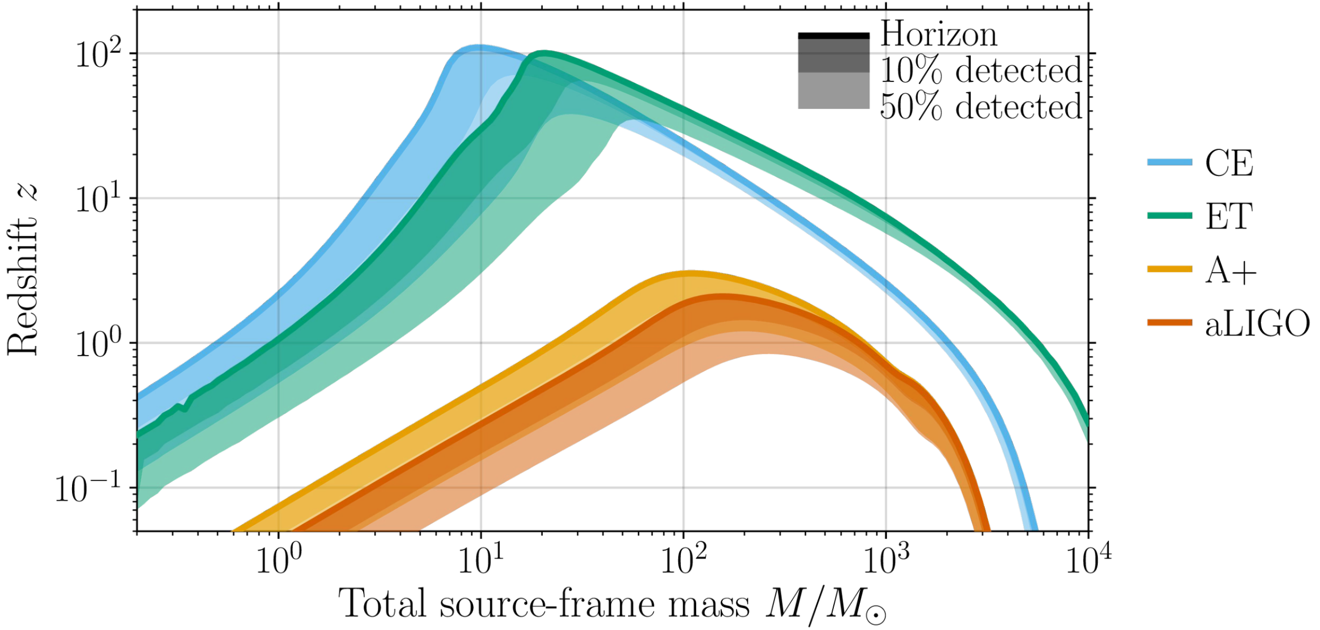


Chapman-Bird, **CPLB** & Woan arXiv:2212.06166

Next-generation detectors

Next-generation detectors will see further and have a wider mass range

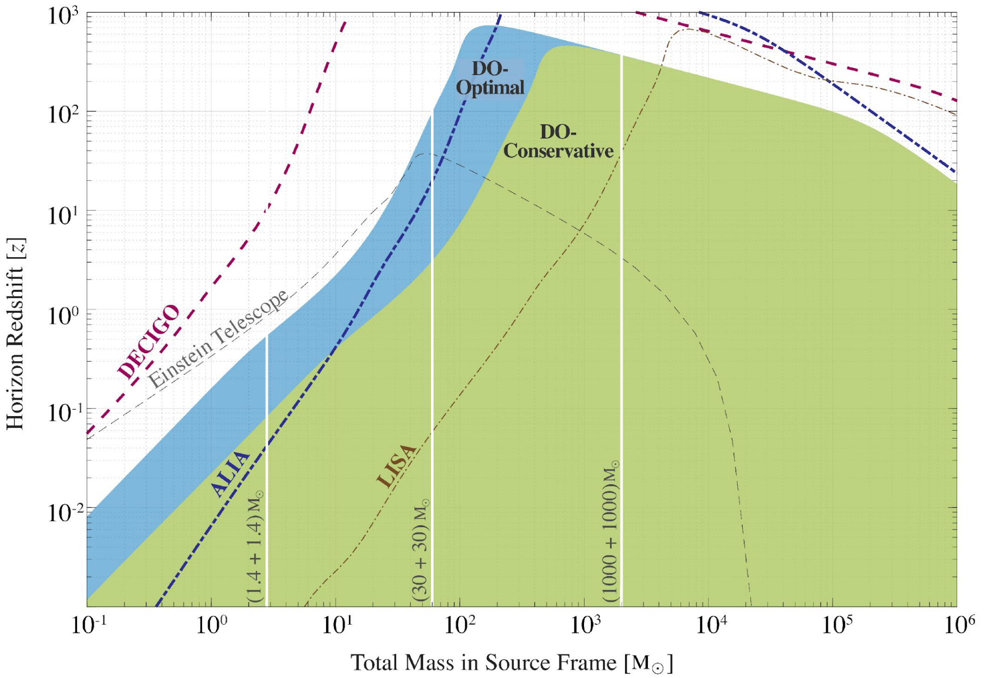
The 3G Science Book
Kalogera, …, **CPLB** *et al.*
arXiv:2111.06990



Adapted from Hall & Evans arXiv:1902.09485

Intermediate-mass black holes

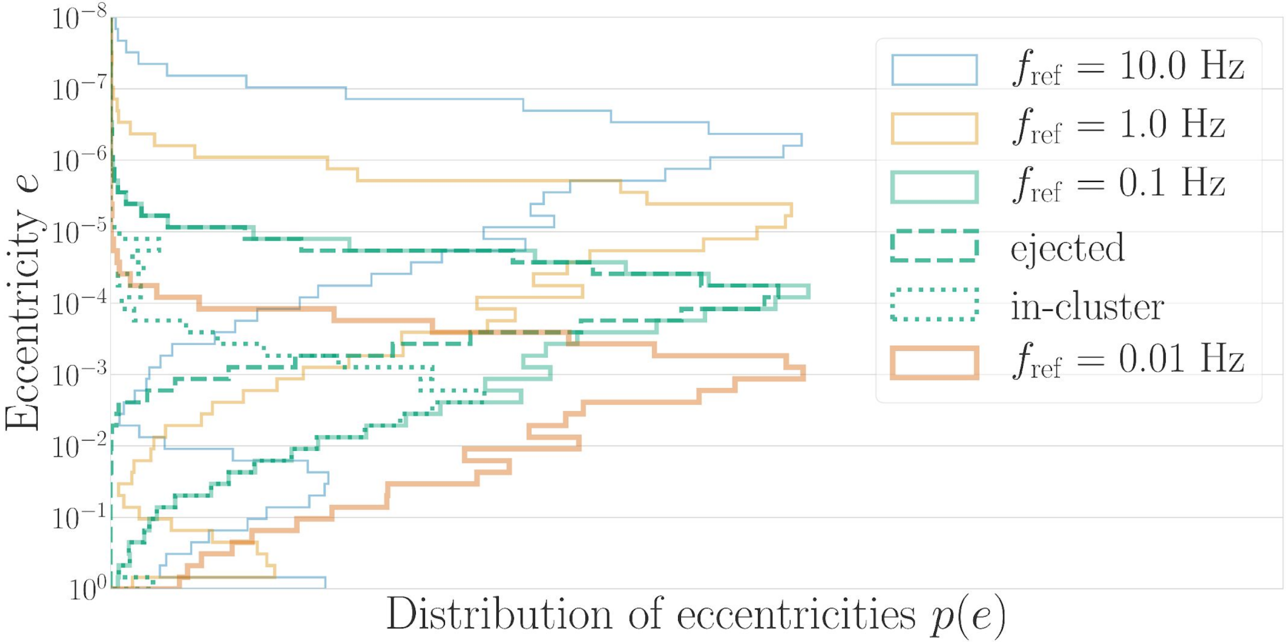
Is there a missing link between stellar-mass and massive black holes?



Arca Sedda, **CPLB** *et al.* arXiv:1908.11375

Eccentricity

Eccentricity is a key tracer of formation mechanism



Arca Sedda, **CPLB** *et al.* arXiv:1908.11375

Transient sources

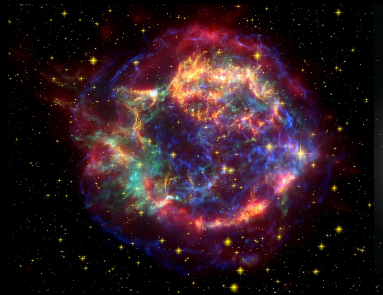
Some signals lack comprehensive models: cannot use templates for searching

Short-duration burst search
arXiv:2107.03701

Long-duration burst search
arXiv:2107.13796

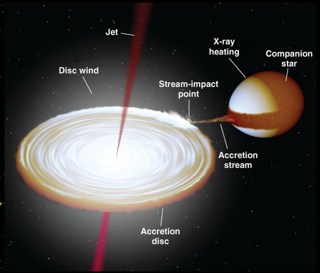
Cosmic string search
arXiv:2101.12248

Supernovae



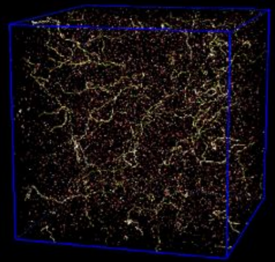
NASA/JPL-Caltech

Disc instabilities



R Hynes

Cosmic strings



B Allen/E P Shellard

Neutron star glitches

NASA/CXC/ASU

The unknown

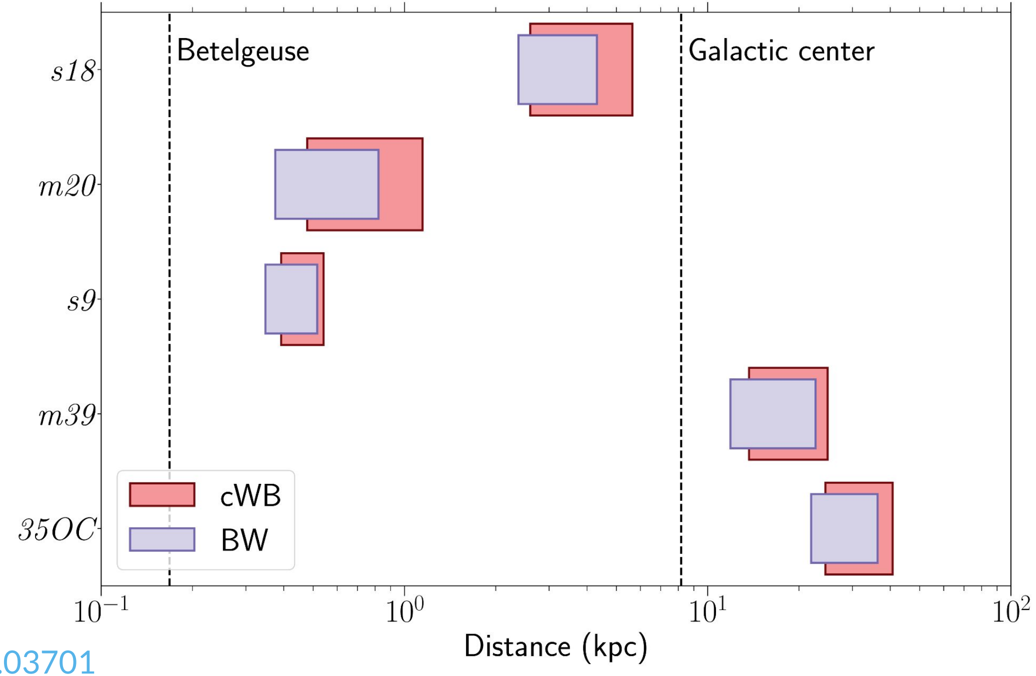
Upper limits

Non-detections let us place upper limits on rates

Distance to which a source can be detected depends upon the energy emitted and the signal's structure

cWB: coherent WaveBurst
BW: BayesWave

Core collapse supernovae



LVK arXiv:2107.03701

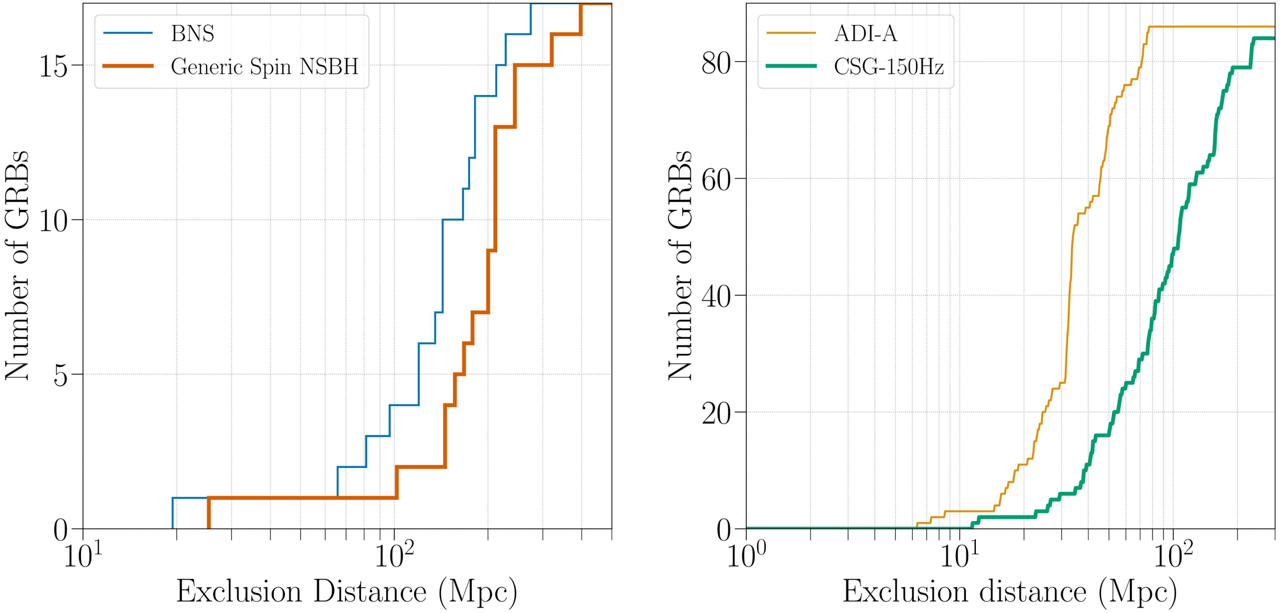
Counterpart searches

Targeted searches offer improved sensitivity

Gamma-ray bursts
arXiv:2111.03608

Fast radio bursts
arXiv:2203.12038

Magnetar bursts
arXiv:210.10931

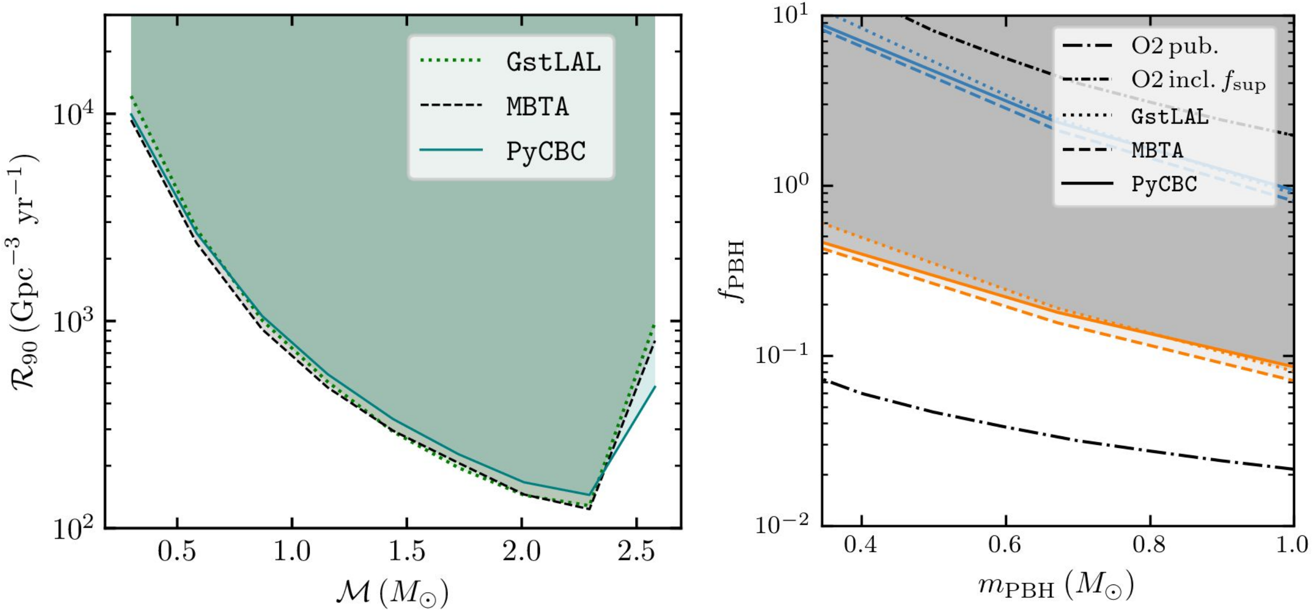


LVK/Fermi/Swift arXiv:2111.03608

Subsolar mass searches

Constraints are model dependent

Lower mass signals are longer and hence more computationally expensive to search for



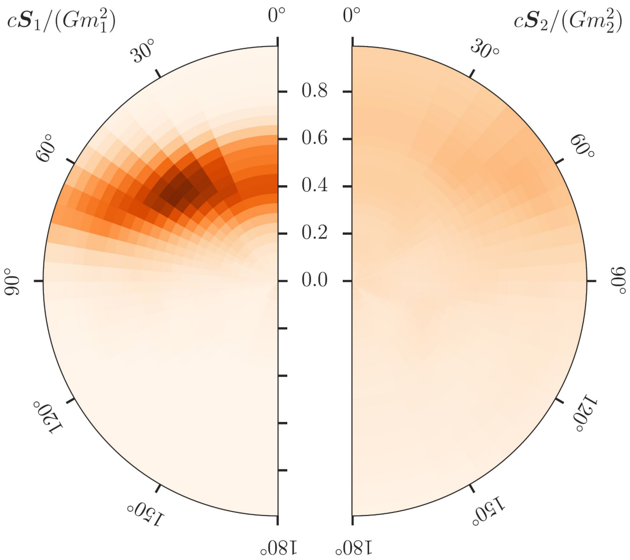
LVK arXiv:2212.01477

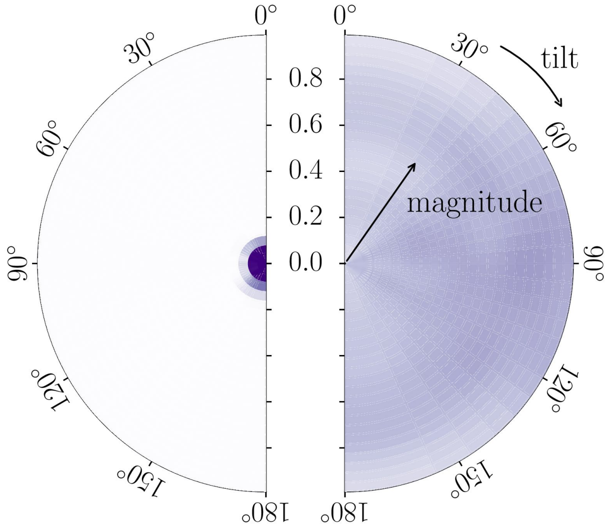
Spins

Gravitational-wave measurements of spins can be a tracer of formation mechanism, e.g., Stevenson, **CPLB** & Mandel arXiv:1703.06873

GW151226 had first evidence for non-zero spin and positive effective inspiral spin

GW190814 has tightest constraints on primary spin and precession



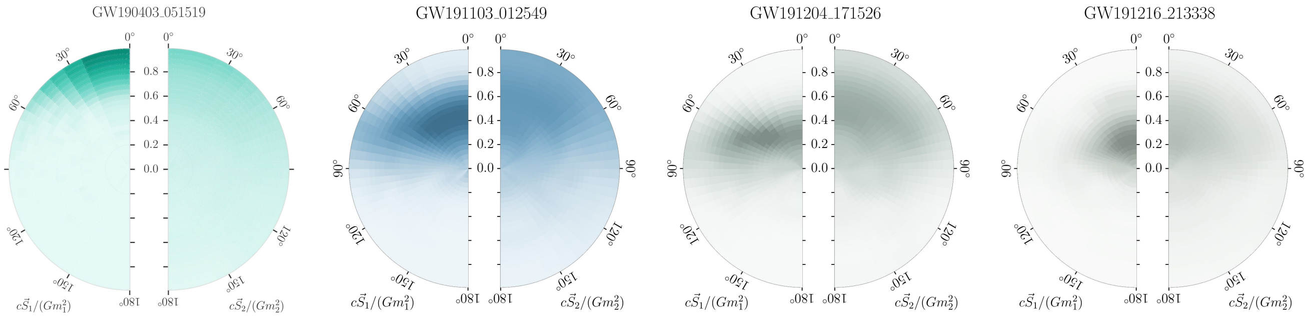


LVC arXiv:1606.04855 **LVC** arXiv:2006.12611

Spins: non-zero spins

GW190403 has support for near maximal spins

Spins in X-ray binaries extend close to the Kerr limit of 1

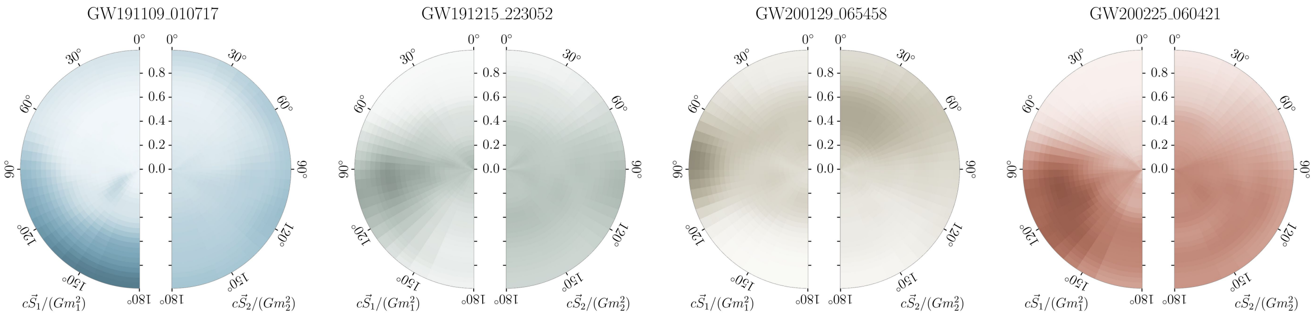


LVC arXiv:2108.01045 **LVK** arXiv:2111.03606

Spins: misaligned spins

GW200129 shows best evidence for precession, but differences between waveform models

GW200129 is the second highest signal-to-noise ratio ever observed, but is also impacted by data-quality issues



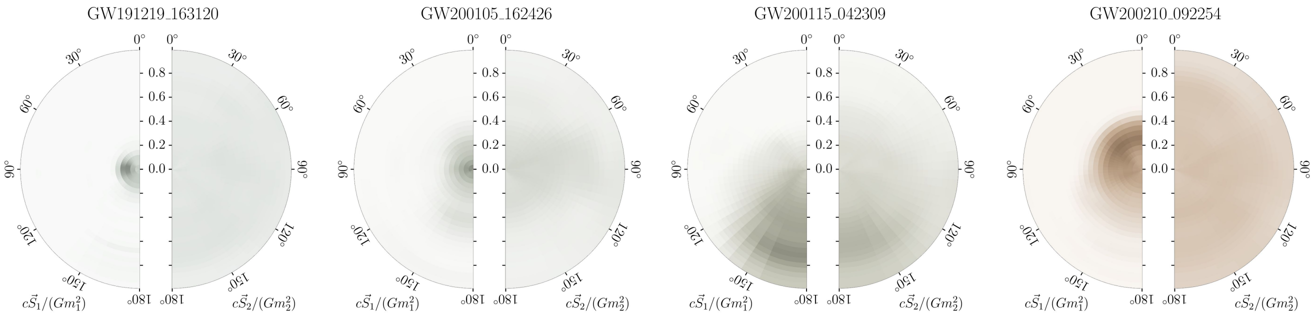
LVK arXiv:2111.03606

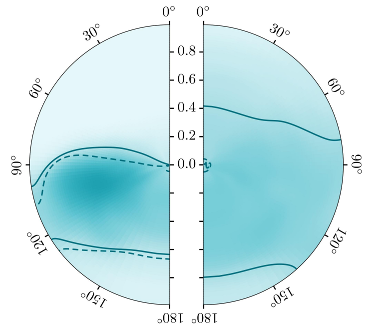
Spins: neutron star–black holes

Primary spin better measured as more important for dynamics

Spin components in the orbital plane better measured for more extreme mass ratios

GW230529 has significant support for a misaligned primary



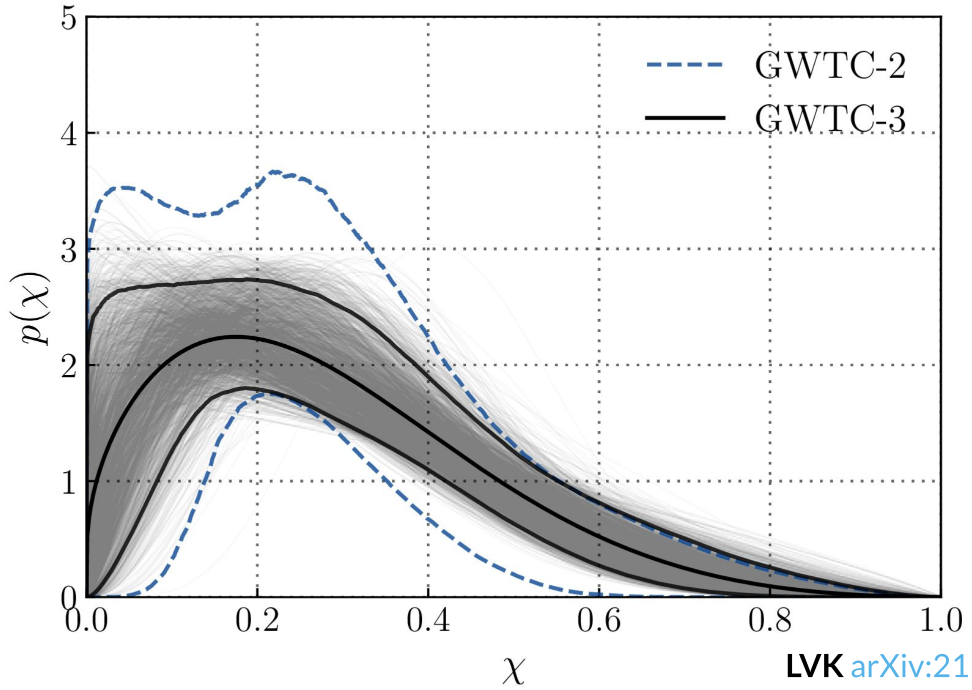


LVK arXiv:2111.03606 arXiv:2404.04248

Spin distribution

Most spin magnitudes are small

The same spin distribution is assumed for primary and secondary spins

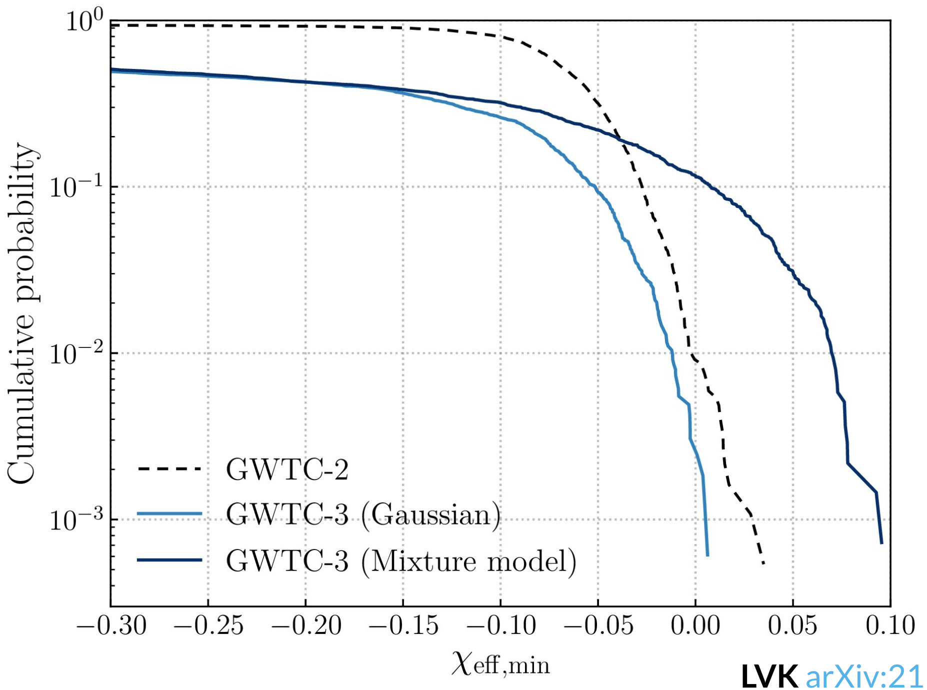


LVK arXiv:2111.03634

Spin distribution

Evidence for negative effective inspiral spin implies at least some misalignment of spins

Effective precession spin distribution also favours some spin misalignment



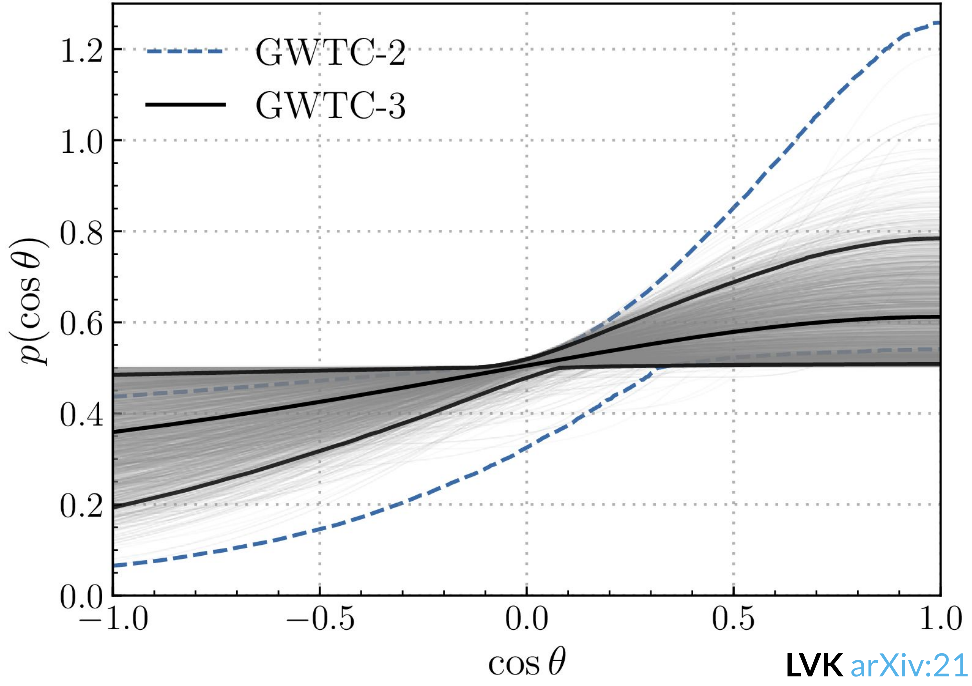
LVK arXiv:2111.03634

Spin distribution

More support for aligned spins

Still consistent with an isotropic distribution of spins

Measurements of spins can be a tracer of formation mechanism Stevenson, **CPLB** & Mandel arXiv:1703.06873

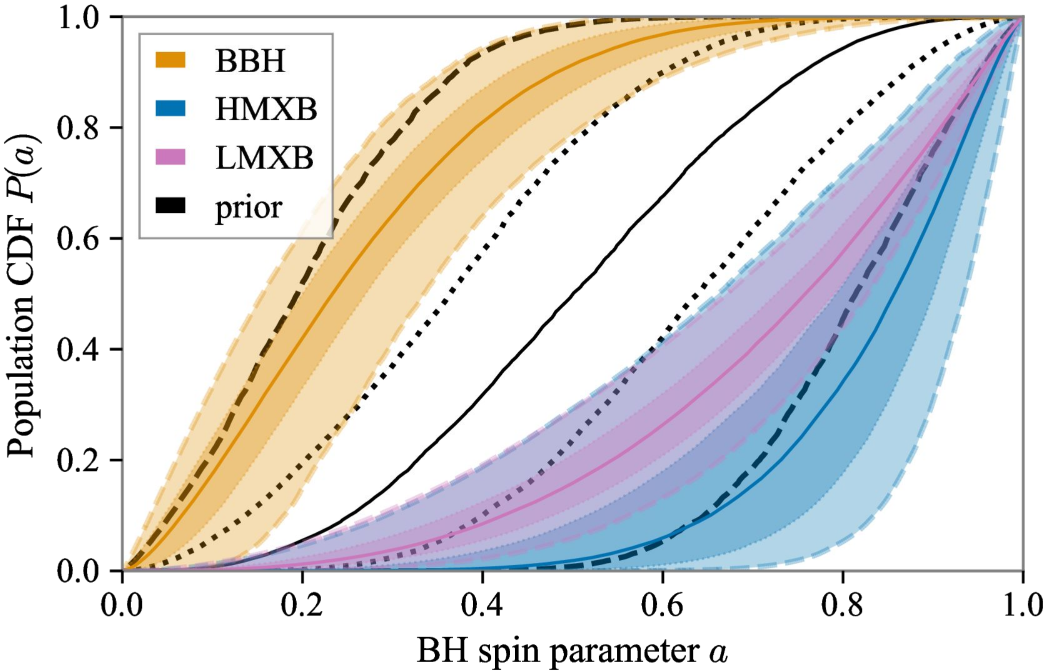


LVK arXiv:2111.03634

Spin

High-mass X-ray binaries have larger spin magnitudes than binary black holes

For a review: Reynolds arXiv:2011.08948

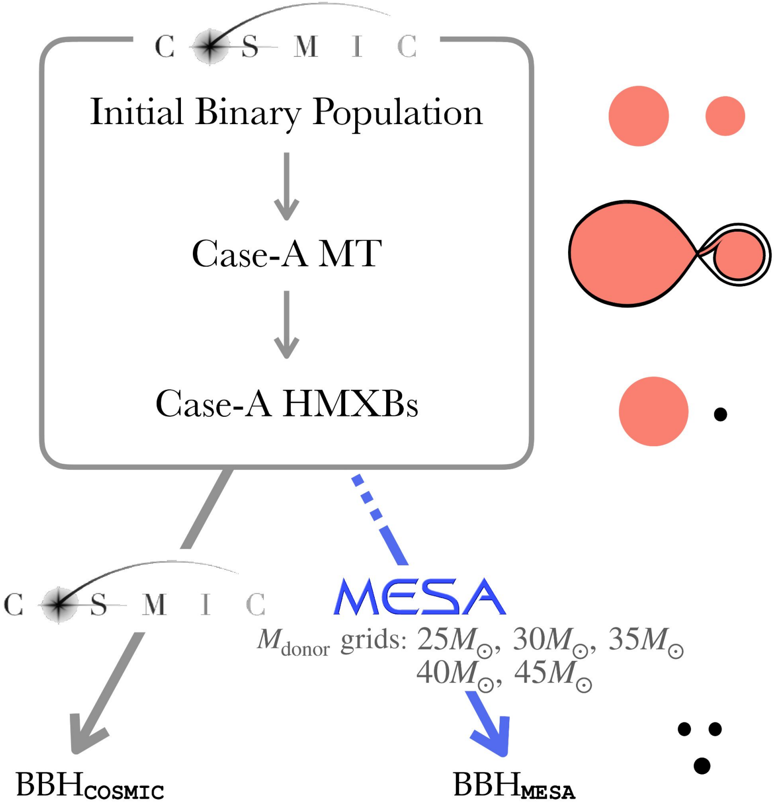


Fishbach & Kalogera arXiv:2210.01825

Spin origins?

Binaries going through Case-A mass transfer could have significant spin
Qin *et al.* arXiv:1810.13016

Monica Gallegos-Garcia



Gallegos-Garcia, ..., **CPLB** *et al.* arXiv:2207.14290

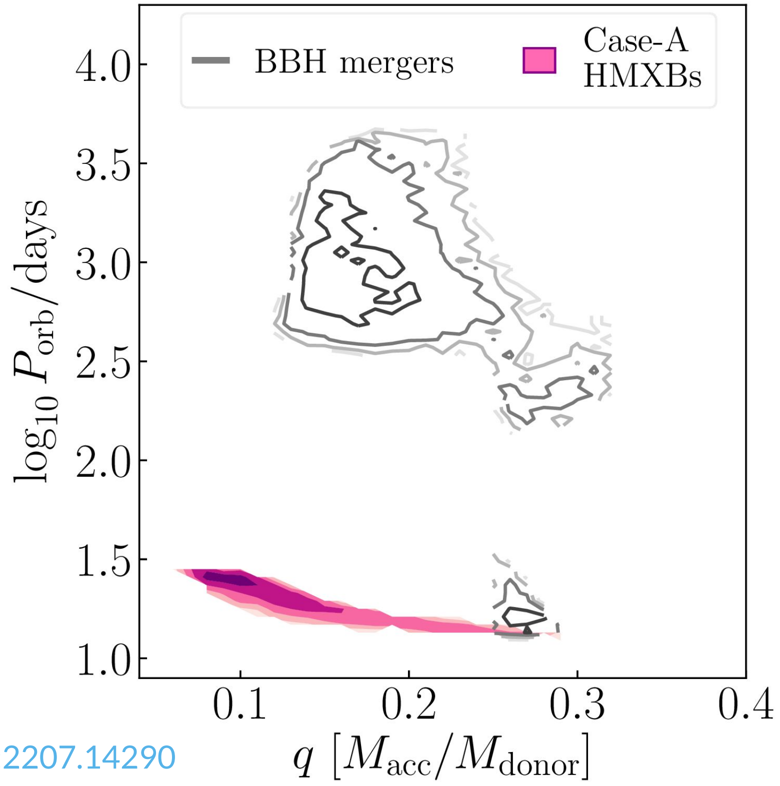
Overlap

Few Case-A mass transfer binaries could form merging **binary black holes**

Few **binaries black holes** form from Case-A mass transfer binaries

Different evolutionary channels could be linked to different spins

40 solar mass donors



Gallegos-Garcia, ..., **CPLB** *et al.* arXiv:2207.14290

Source masses: GWTC-1

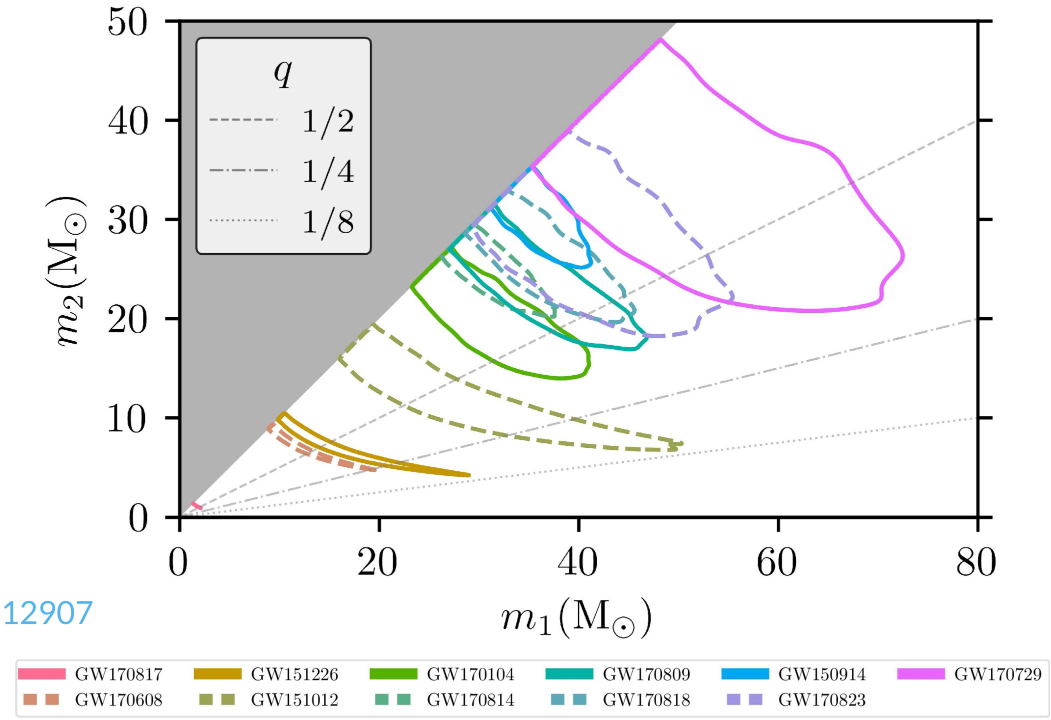
LVK gravitational-wave catalogues:

GWTC-1 (O1+O2)
arXiv:1811.12907

GWTC-2 (O3a)
arXiv:2010.14527
youtu.be/nJD3DAaEk

GWTC-2.1 (O3a)
arXiv:2108.01045
youtu.be/tD36nX_rzic

GWTC-3 (O3b)
arXiv:2111.03606
youtu.be/MUyOVX1HqB8



LVC
arXiv:1811.12907

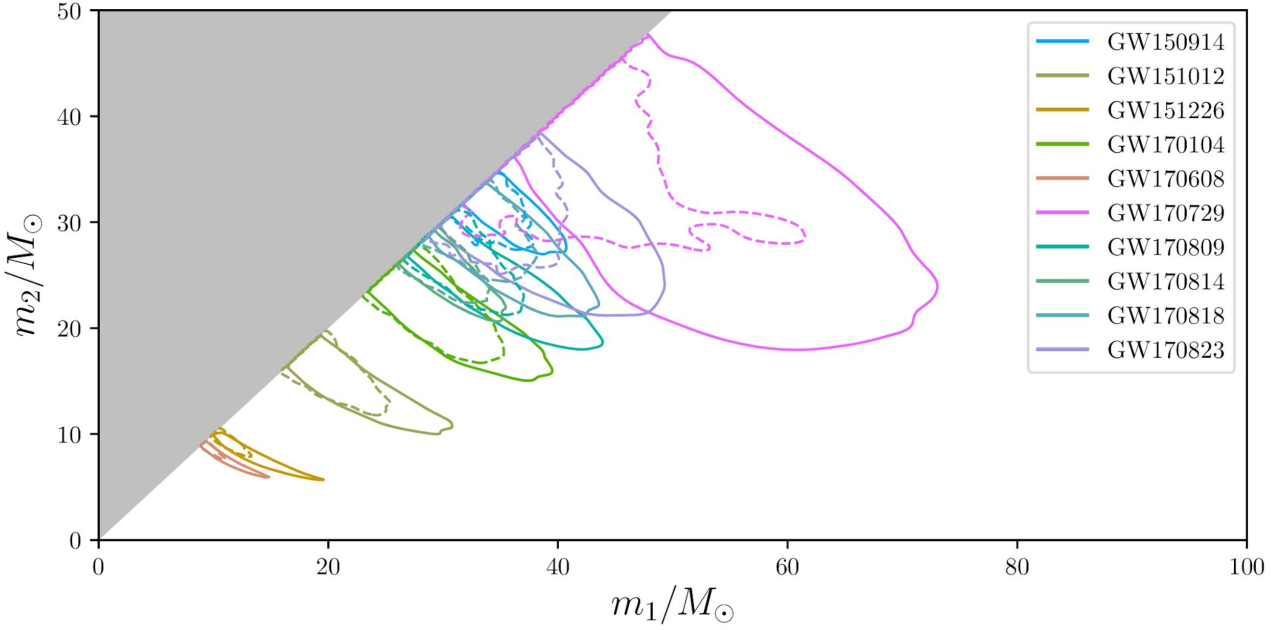
Population prior

Solid lines default prior from GWTC-1

Dashed lines with population prior including hierarchical mergers

Population prior pulls in higher masses and give tighter constraint on mass ratio

GW170729 has most support for a hierarchical merger

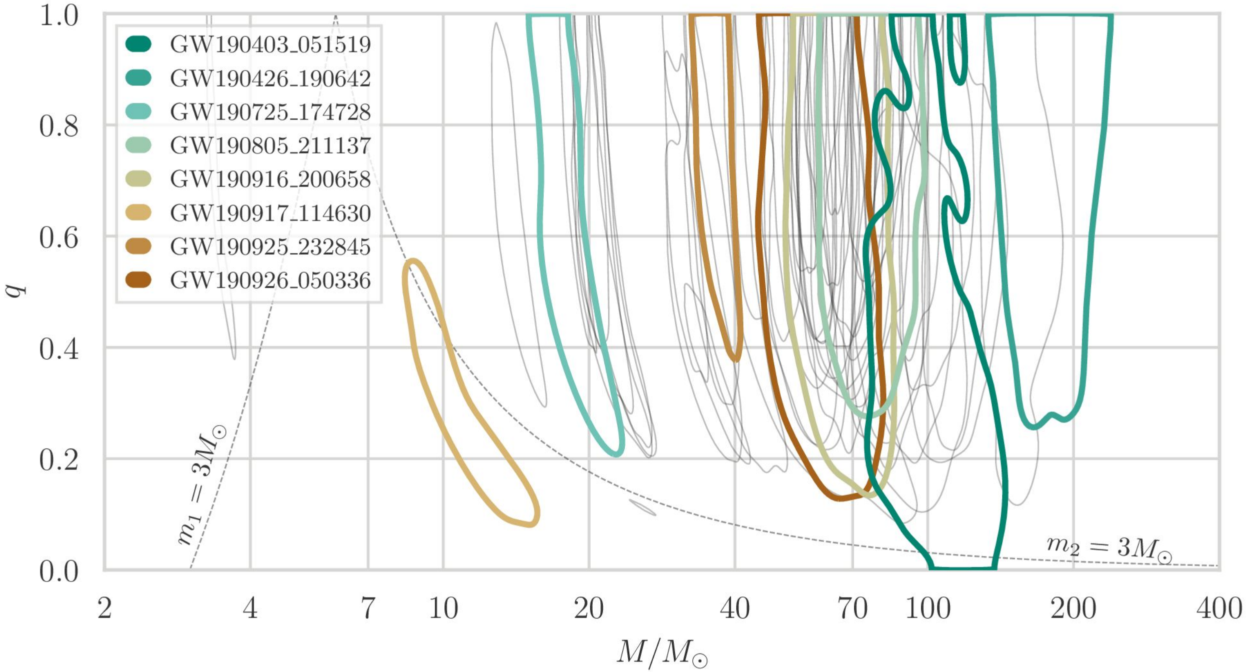


Kimball, Talbot, **CPLB** *et al.* arXiv:2005.00023

Source masses: GWTC-2.1

GW190425 is a second binary neutron star after GW170817

GW190814 has a well-measured secondary mass that could correspond either to a neutron star or a black hole



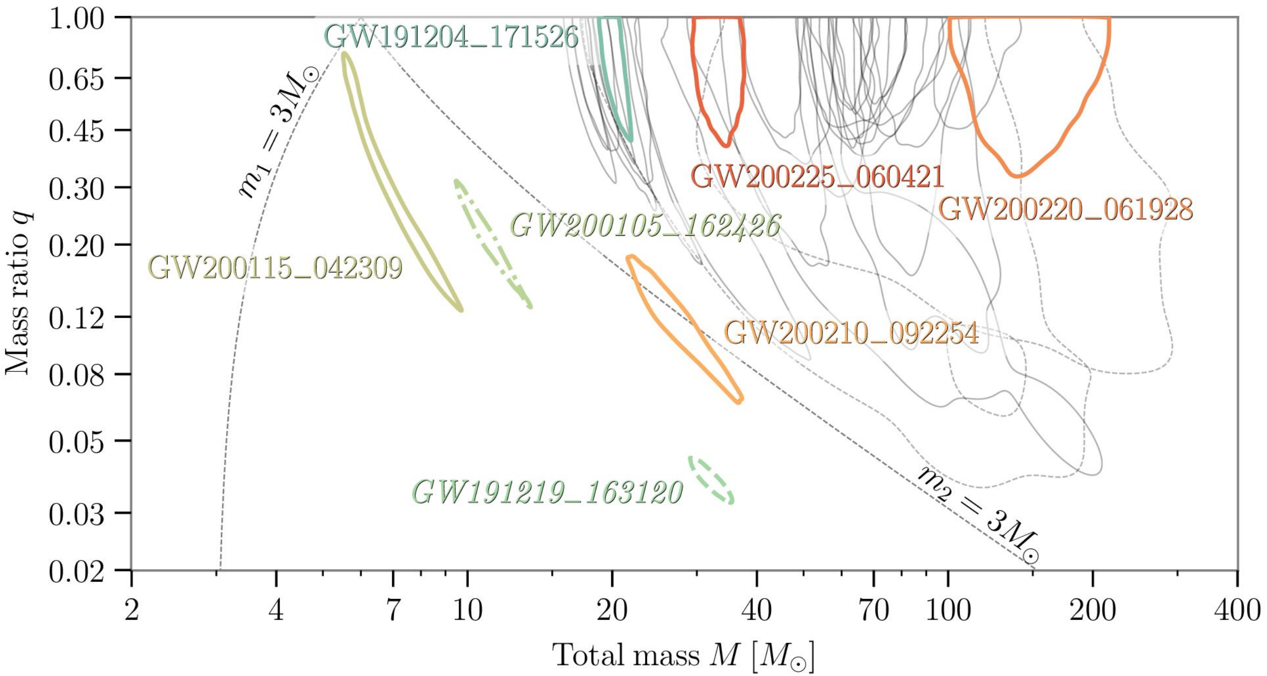
LVK arXiv:2108.01045

Source masses: O3b

No tidal information so must identify neutron stars by component masses

GWTC-2.1 release
DOI:10.5281/zenodo.5117702

GWTC-3 release
DOI:10.5281/zenodo.5546662

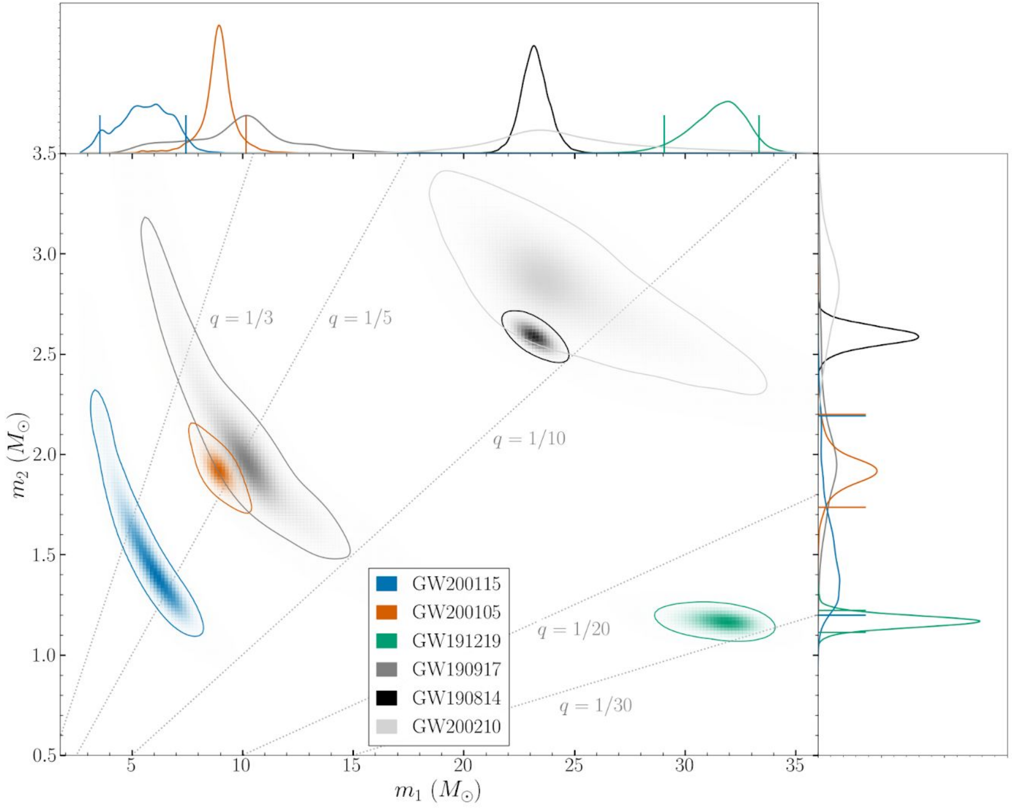


LVK arXiv:2111.03606

The maximum neutron star mass is uncertain, so there are several potential neutron star–black hole binaries

Coloured contours in this plot are confident neutron star–black hole pairs

Grey contours in this plot are ambiguous, with secondary that may be a black hole or a neutron star



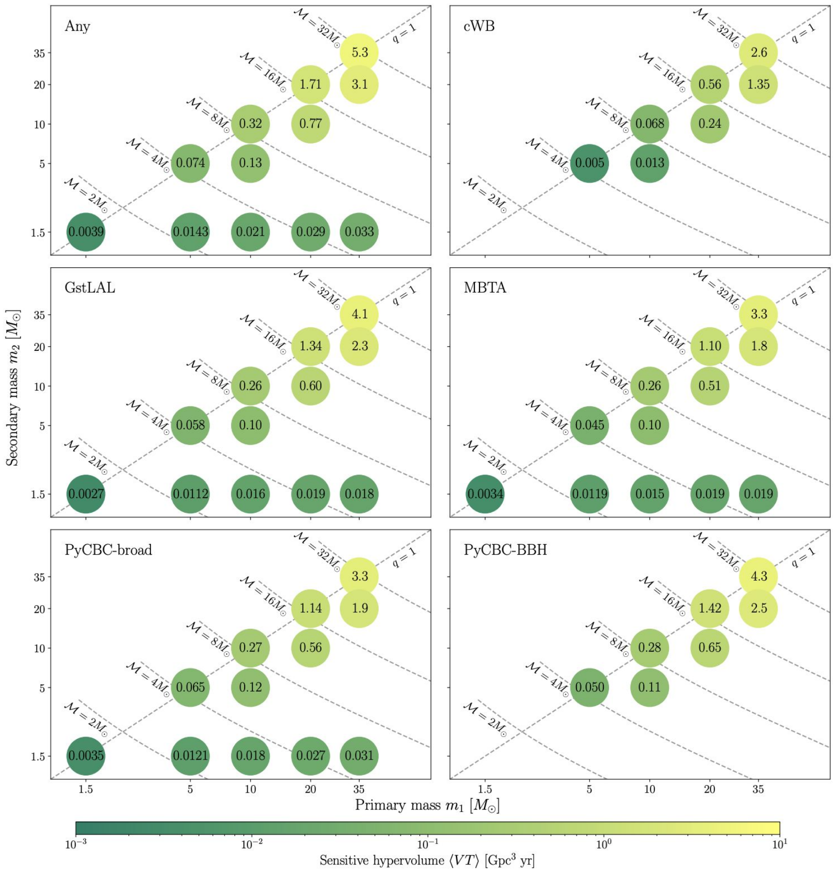
LVC arXiv:2010.14527 **LVC** arXiv:2108.01045 **LVK** arXiv:2111.03606

To map between observations and underlying astrophysical distribution, we need to account for selection effects

Search sensitivity quantified by search volume–time (**VT**)

More massive binaries can be detected to greater distance

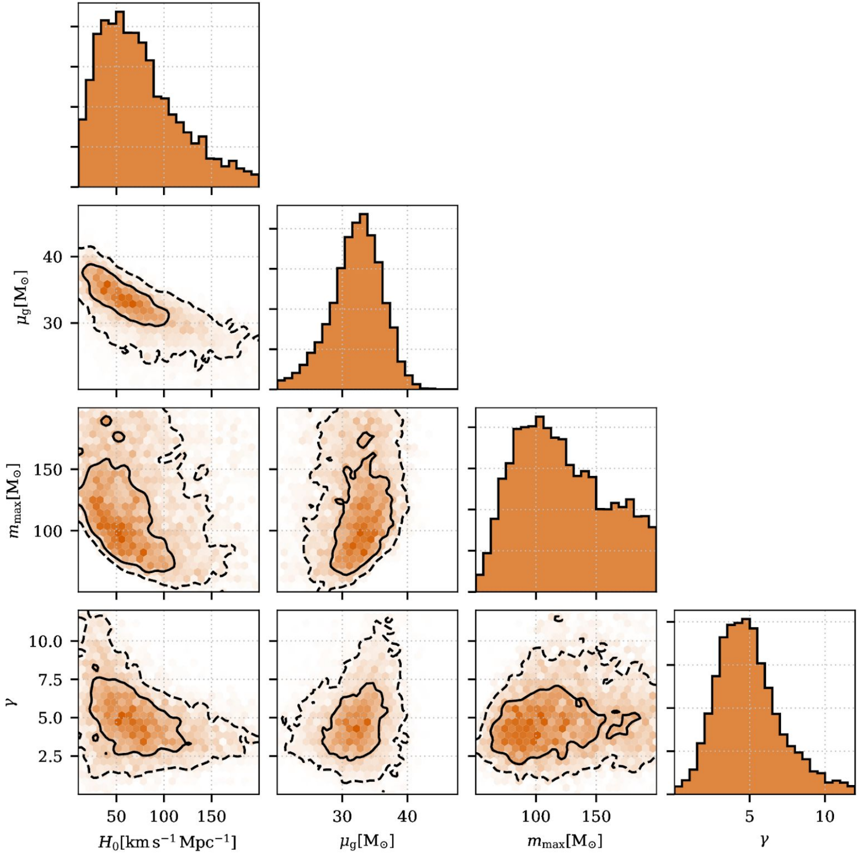
LVK arXiv:2111.03606



Correlation

Power law plus peak model

For more on population uncertainties Pierra *et al.* arXiv:2312.11627



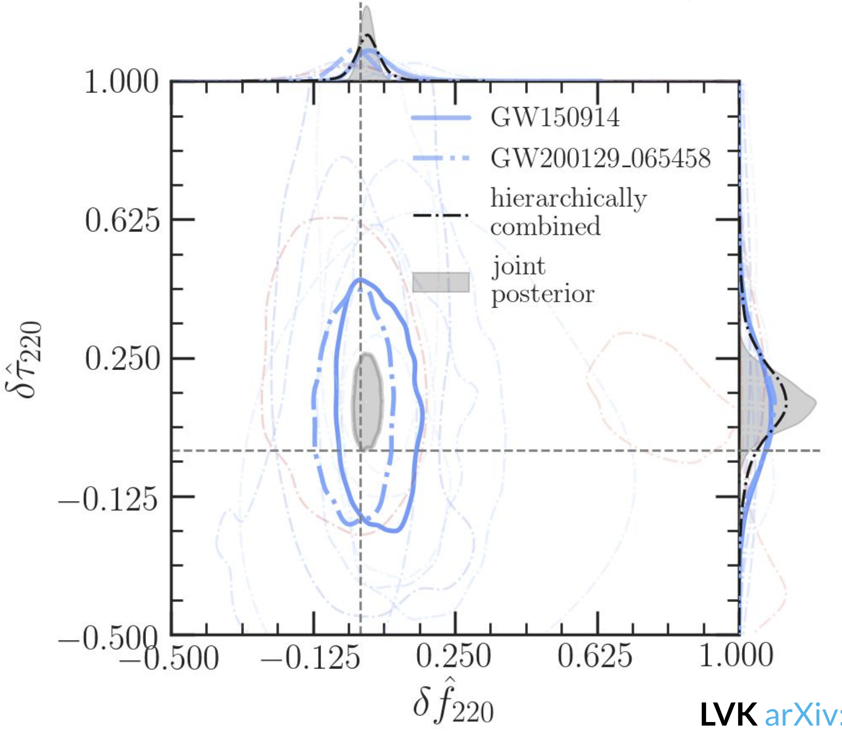
LVK arXiv:2111.03604

Tests of general relativity

Tests cover both the nature of gravity (if described by general relativity) and the nature of black holes (if described by the Kerr metric)

Black hole spectroscopy looks at the ringdown of the remnant black hole

For results marginalising over sky position and time Correia *et al.* arXiv:2312.14118

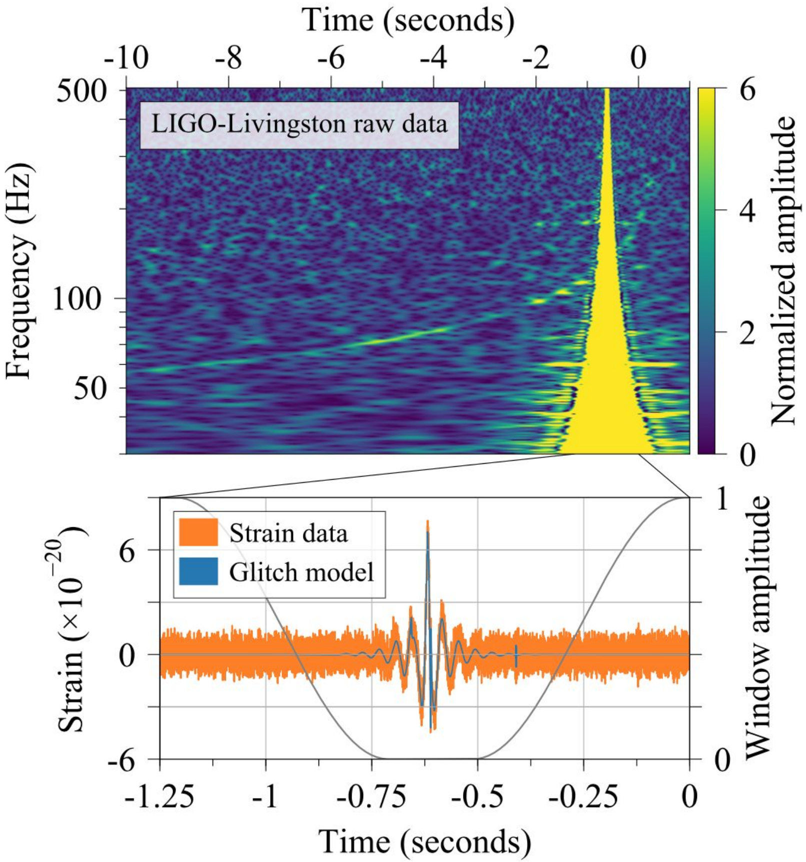


LVK arXiv:2112.06861

Glitches

[Glitches](#) are transient bursts of non-Gaussian noise. They can have high signal-to-noise ratios

For more on detector characterisation and data quality:
LVC arXiv:1602.03844
Davis et al. arXiv:2101.11673



LVC arXiv:1710.05832

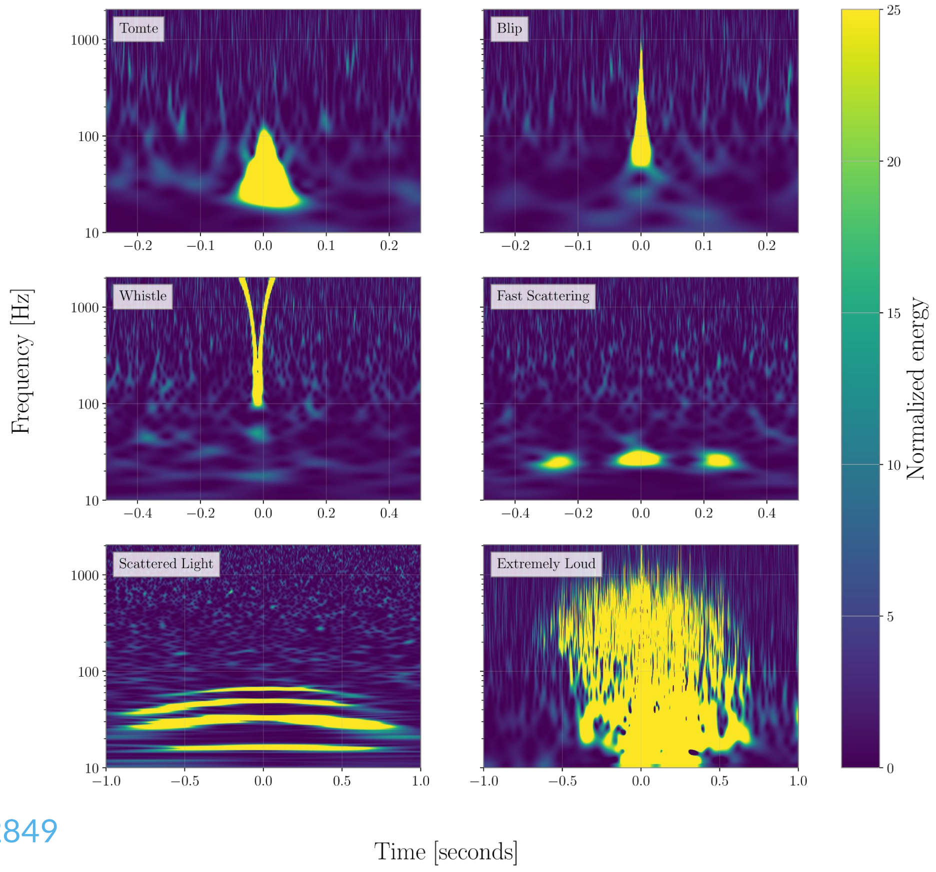
Glitch zoo

Glitches come in a variety of types

Some glitches have identified environmental or instrumental causes. Others do not

Key to studying glitches is having a large sample of different glitch classes

Spectrograms show time–frequency morphology



Glanzer *et al.* arXiv:2208.12849

Glitch rate

New glitch types can arise from instrument changes or sensitivity increases

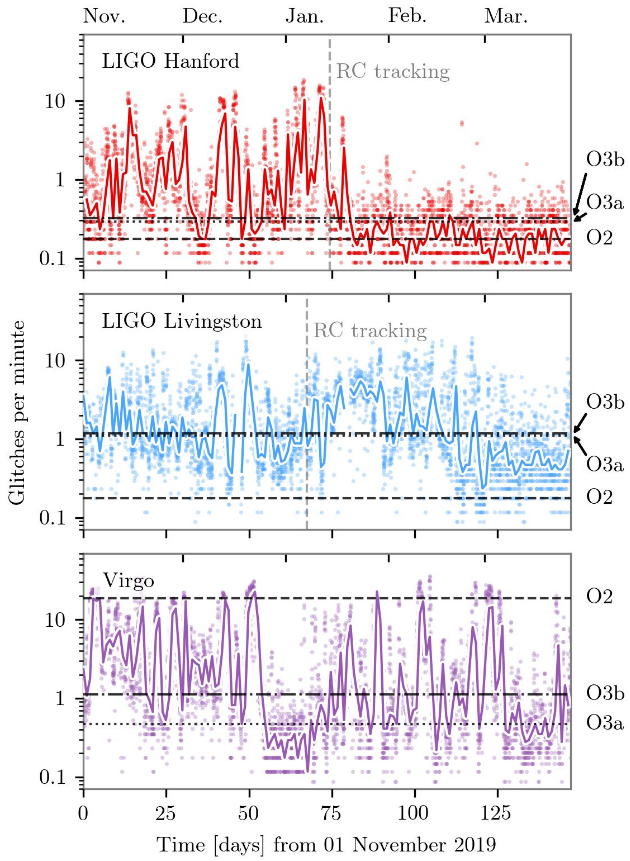
A high glitch rate can drive up noise background estimates for gravitational-wave searches

For more on scattered light and reaction-chain tracking: Soni *et al.* arXiv:2007.14876

Hanford sees a significant drop in glitch rate after reaction-chain tracking was implemented.

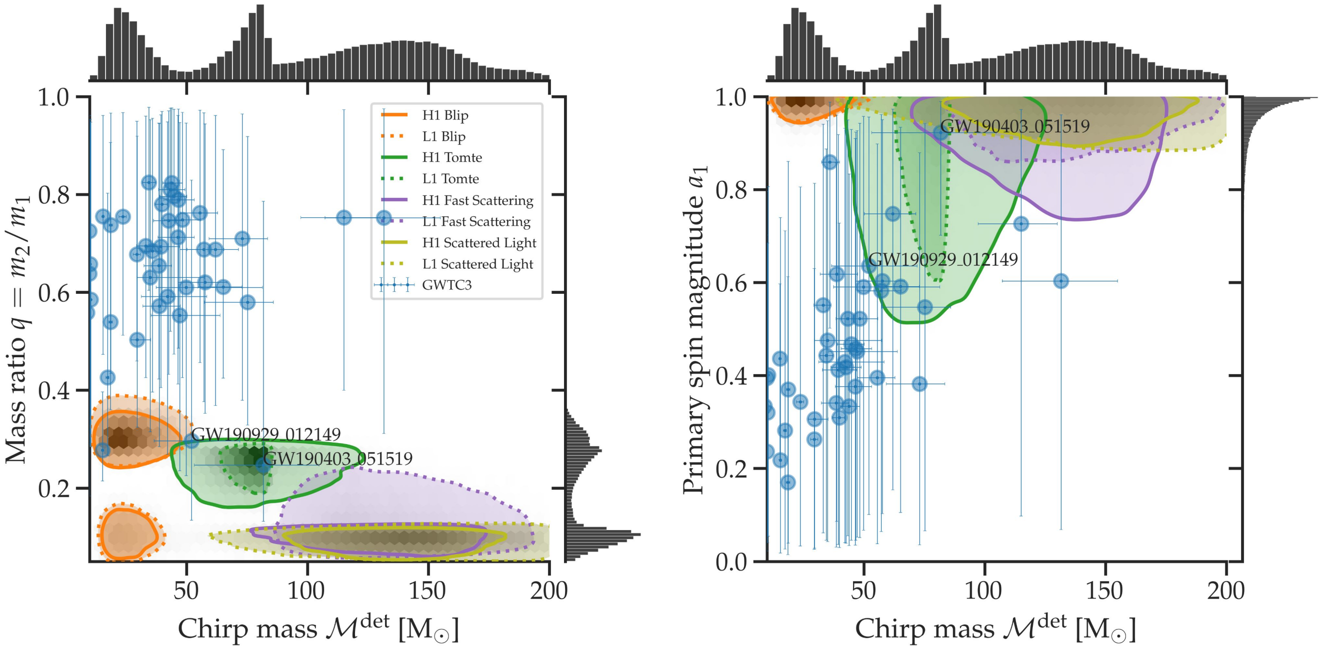
Virgo glitch rate contains peaks largely correlated to unstable weather conditions.

LVK arXiv:2111.03606



Glitch properties

Different glitches would correspond to different sources if assumed to be signals

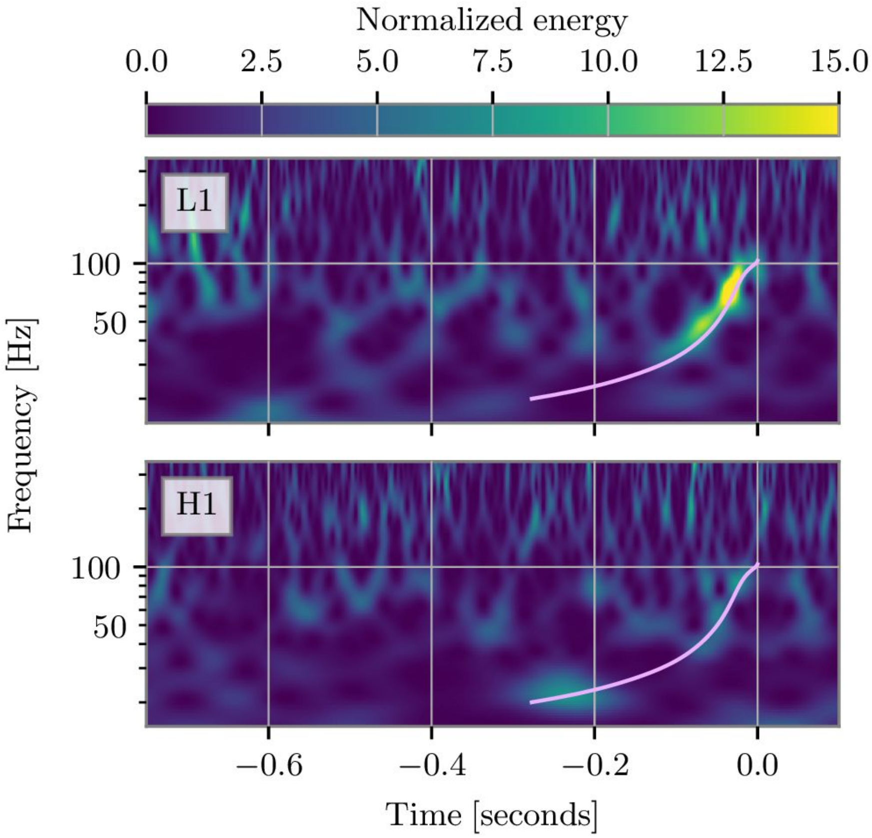


Ashton *et al.* arXiv:2110.02689

GW190403

GW190403 does **not** look like a Tomte

For more on how Gravity Spy classifies **signals** Glanzer *et al.* arXiv:2208.12849



Ashton *et al.* arXiv:2110.02689

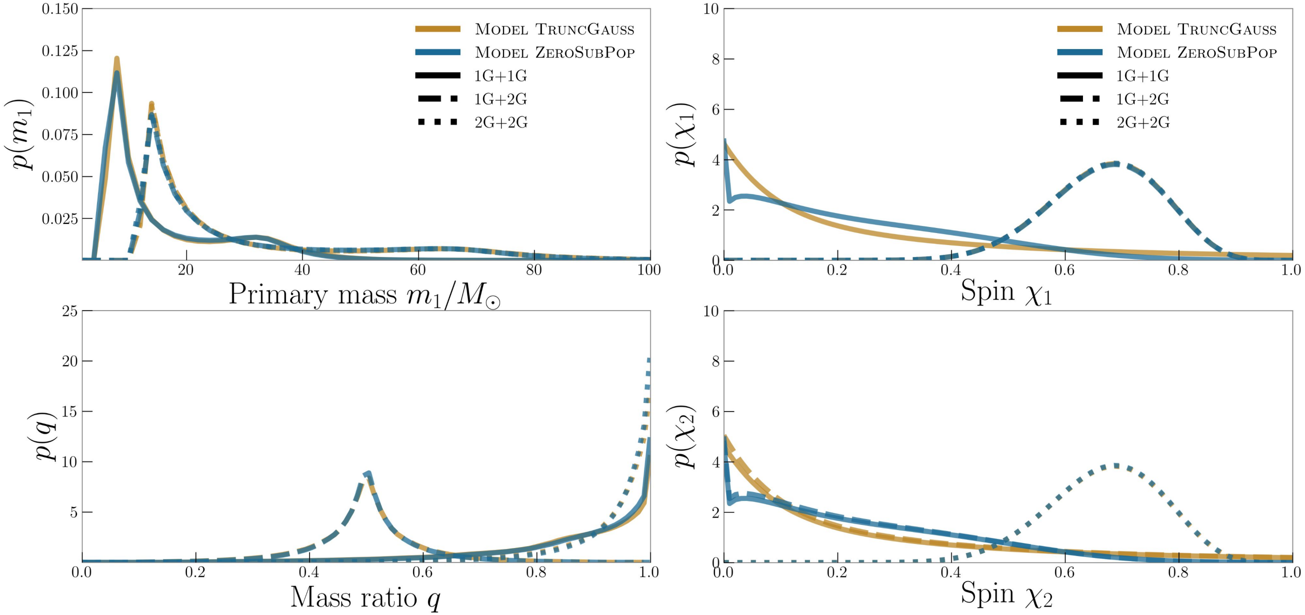
Hierarchical mergers

Merger products (**2G**) have higher masses and characteristic spins

Hierarchical merger rates depend upon recoil kicks and hence spins

Inference methods
Kimball, Talbot, **CPLB** *et al.* arXiv:2005.00023

Chase Kimball



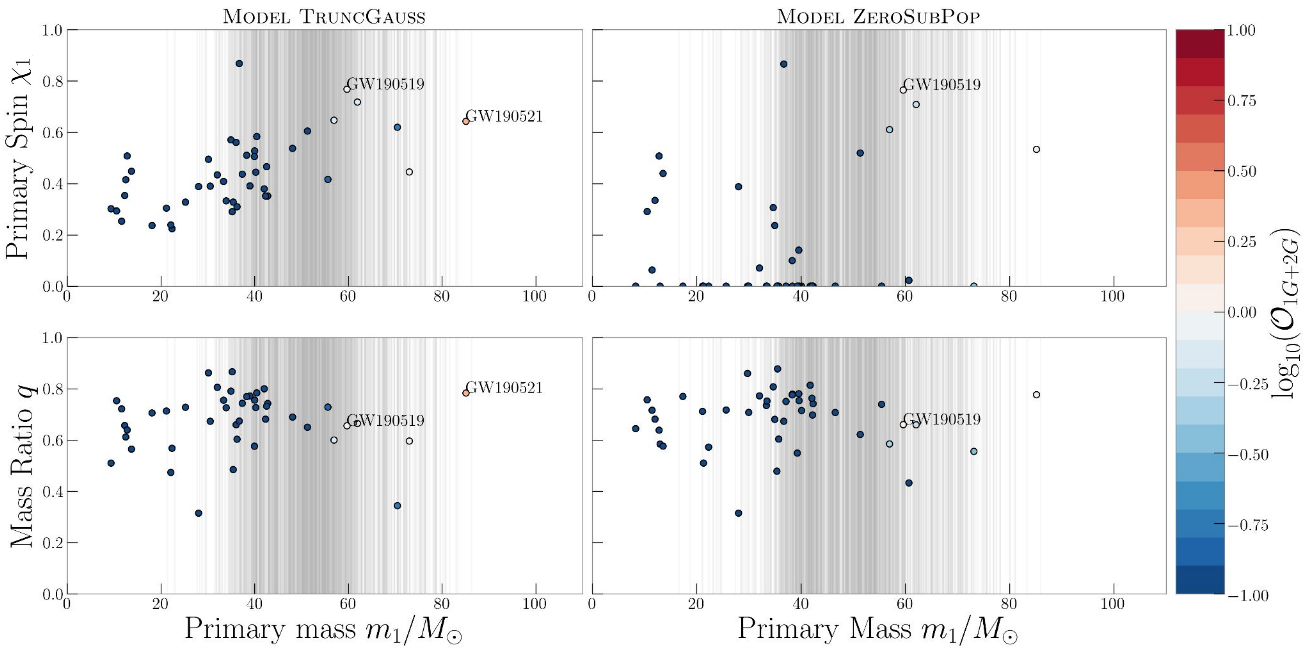
Kimball, Talbot, **CPLB** *et al.* arXiv:2011.05332

Example cluster

For a cluster with an escape velocity of ~300 km s^{-1}

Assumes that all coalescences come from dynamical mergers in a single type of cluster

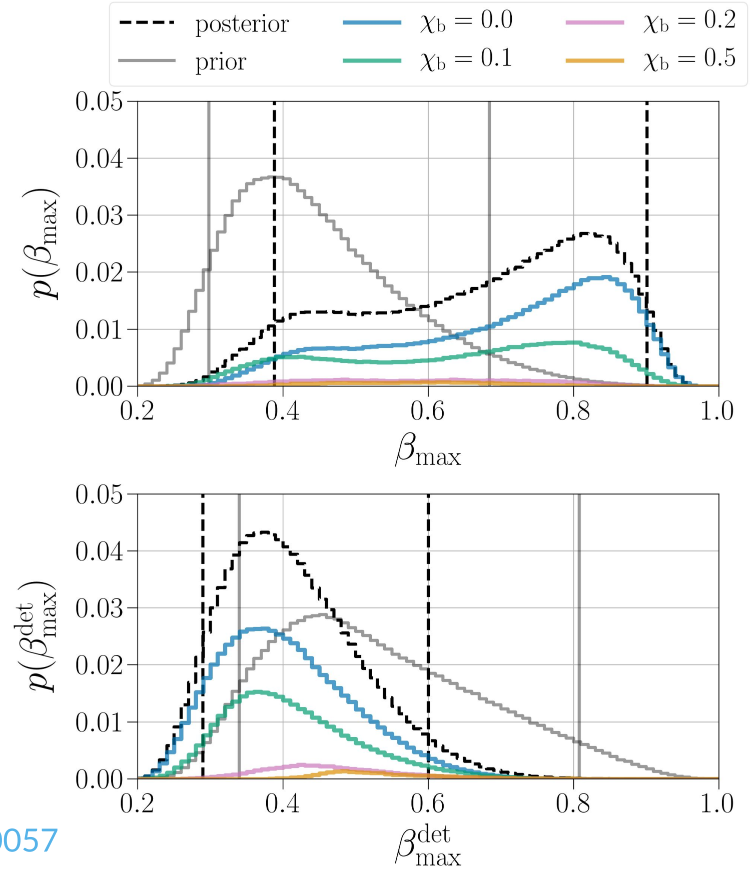
From GWTC-2, GW190521 and GW190519 have the best odds of being hierarchical



Kimball, Talbot, **CPLB** *et al.* arXiv:2011.05332

Mixing

Probably a **mix** of different channels



Zevin, Bavera, **CPLB** *et al.* arXiv:2011.10057

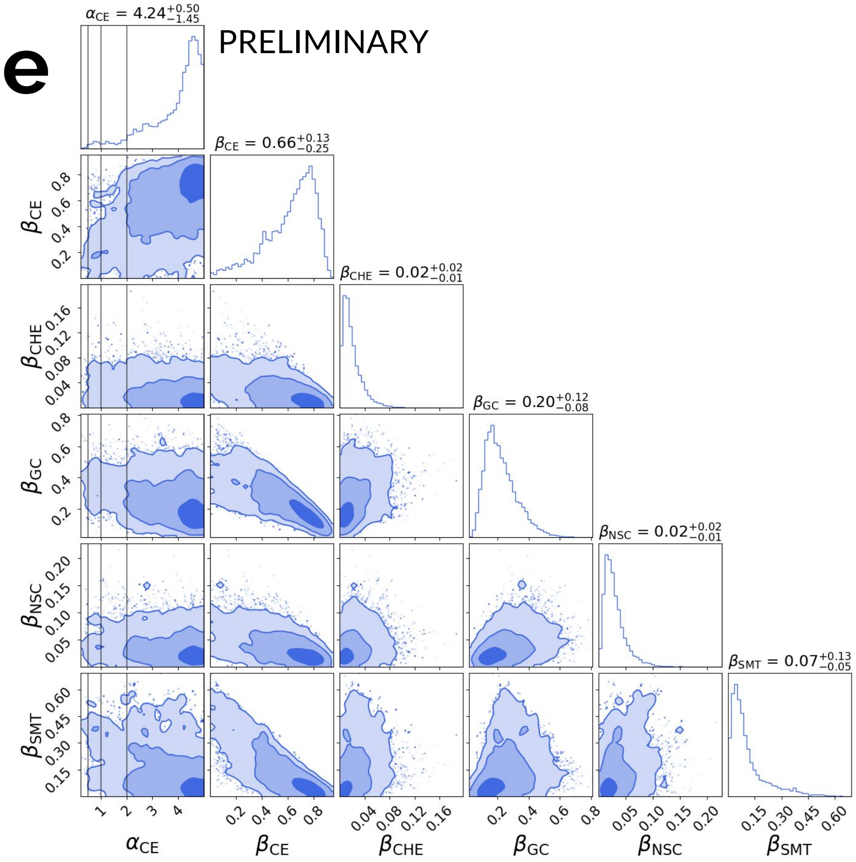
Cutting edge

Continuous inference across population parameters requires interpolation

Use **normalising flows** to emulate populations

Strom Colloms

Colloms, **CPLB** *et al.* (in prep)



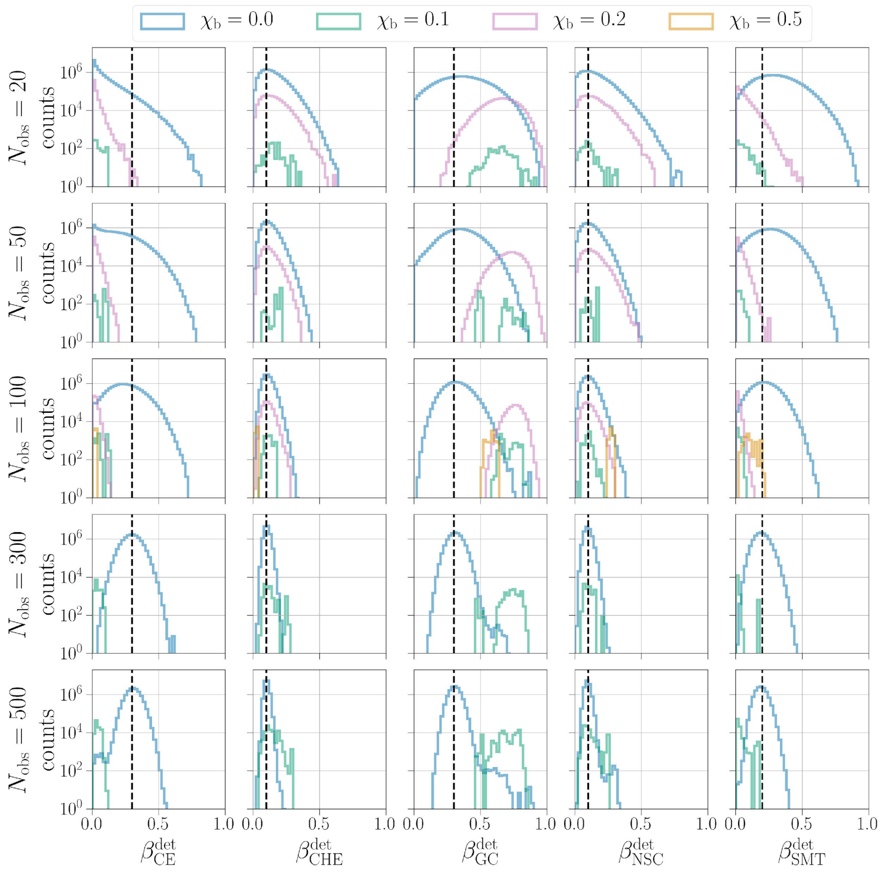
Future

Including incorrect physics in models or excluding channels will lead to biased results

O4 should yield hundreds of candidates

For a review of merger rates: Mandel & Broekgaarden arXiv:2107.14239

Zevin, Bavera, **CPLB** *et al.* arXiv:2011.10057



Rates

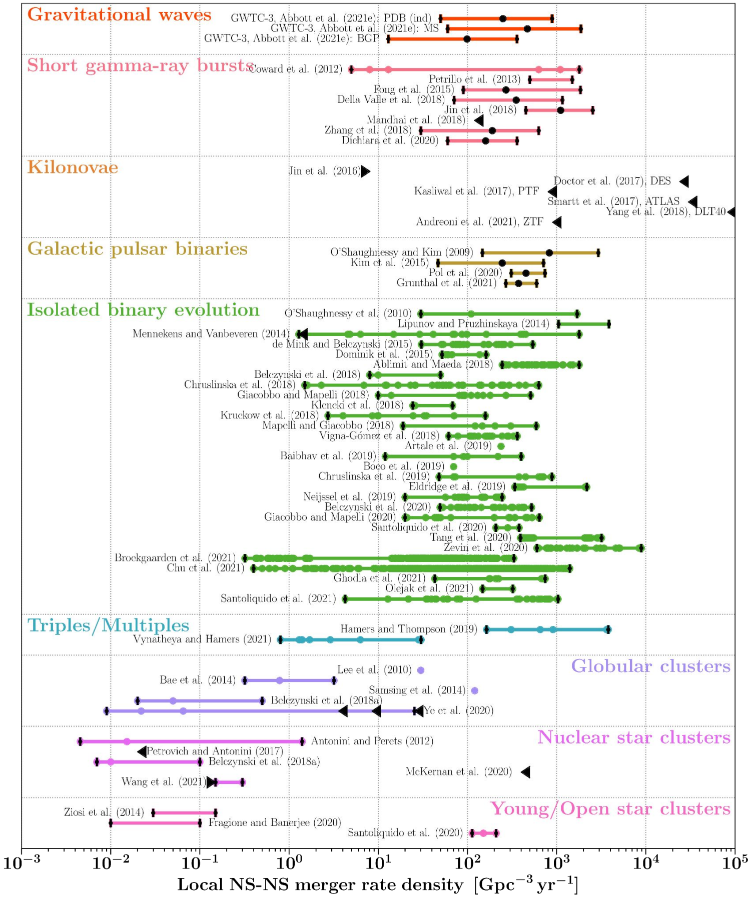
Rates encode information about formation

Rate density evolves with redshift

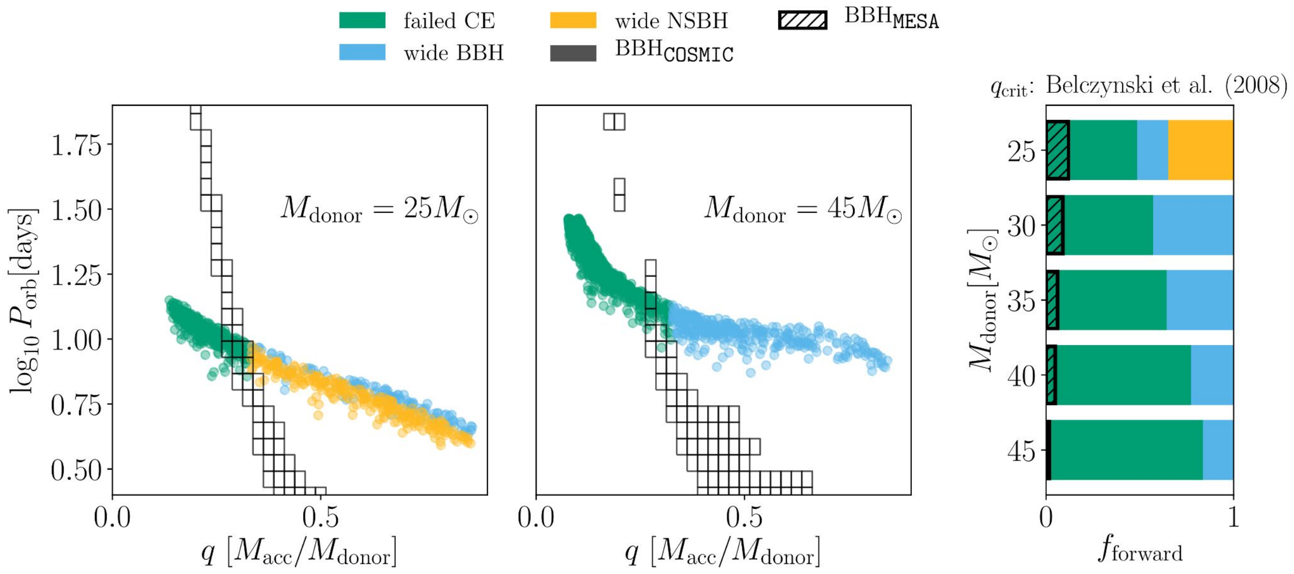
Multiple channels likely contribute: can only rule out models that over predict

For predictions of rates prior to the first detection LVC arXiv:1003.2480

Mandel & Broekgaarden arXiv:2107.14239



A minority of Case-A binaries become merging binary black holes, and a minority of merging binary black holes underwent Case-A mass transfer



Monica Gallegos-Garcia

COSMIC MESA

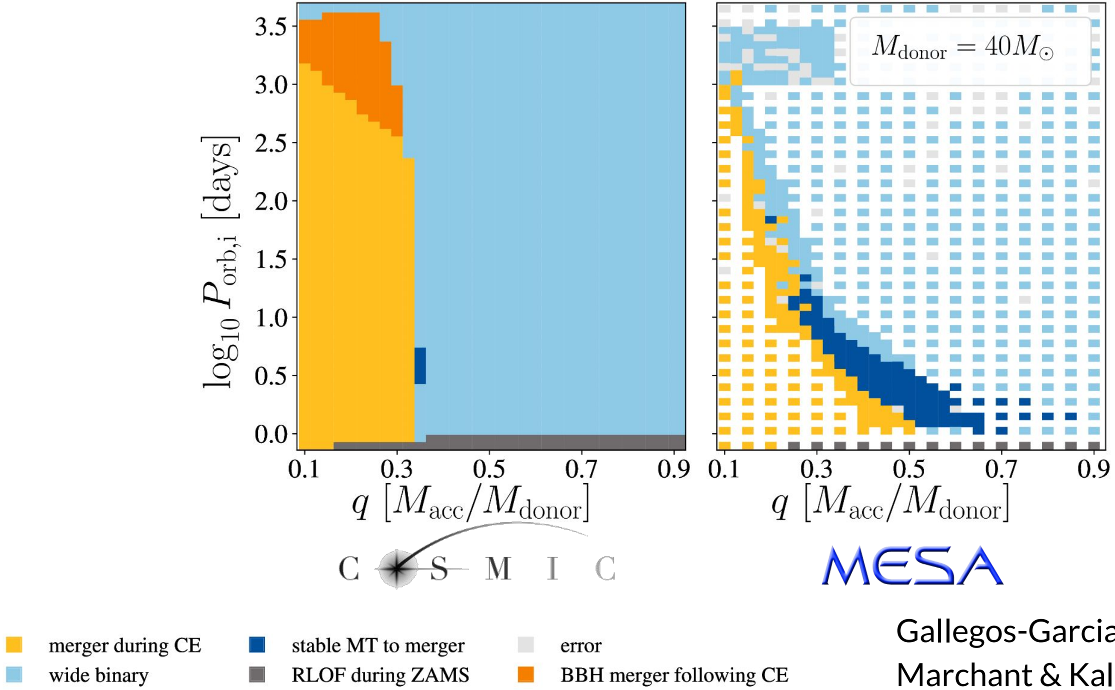
Gallegos-Garcia, …, **CPLB** *et al.* arXiv:2207.14290

Improving simulations

Tracking stellar structure is important for understanding mass transfer

Binary neutron stars form mostly through common envelope
Gallegos-Garcia, **CPLB** & Kalogera
arXiv:2211.15693

Monica Gallegos-Garcia



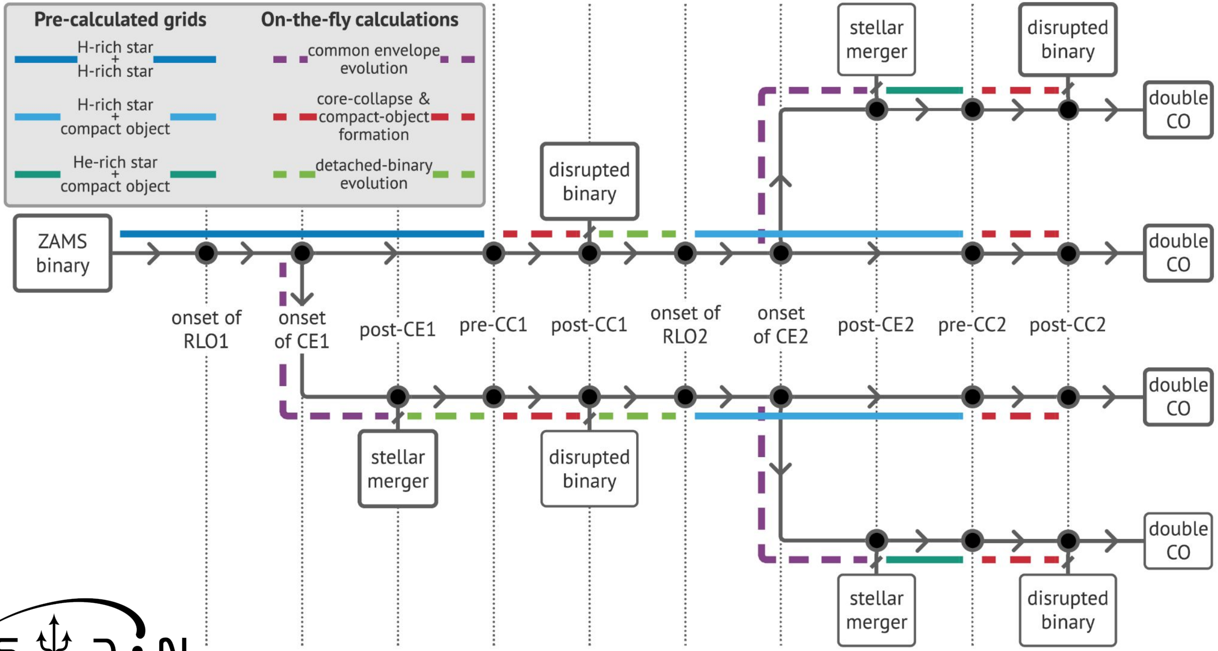
Gallegos-Garcia, **CPLB**, Marchant & Kalogera
arXiv:2107.05702

Using detailed evolution

Posydon is a binary population synthesis code that models full stellar structure using MESA simulations

posydon.org Fragos, …, **CPLB** *et al.* arXiv:2202.05892
Rocha, Andrews, **CPLB** *et al.* arXiv:2203.16683


Simone Bavera Kyle Rocha

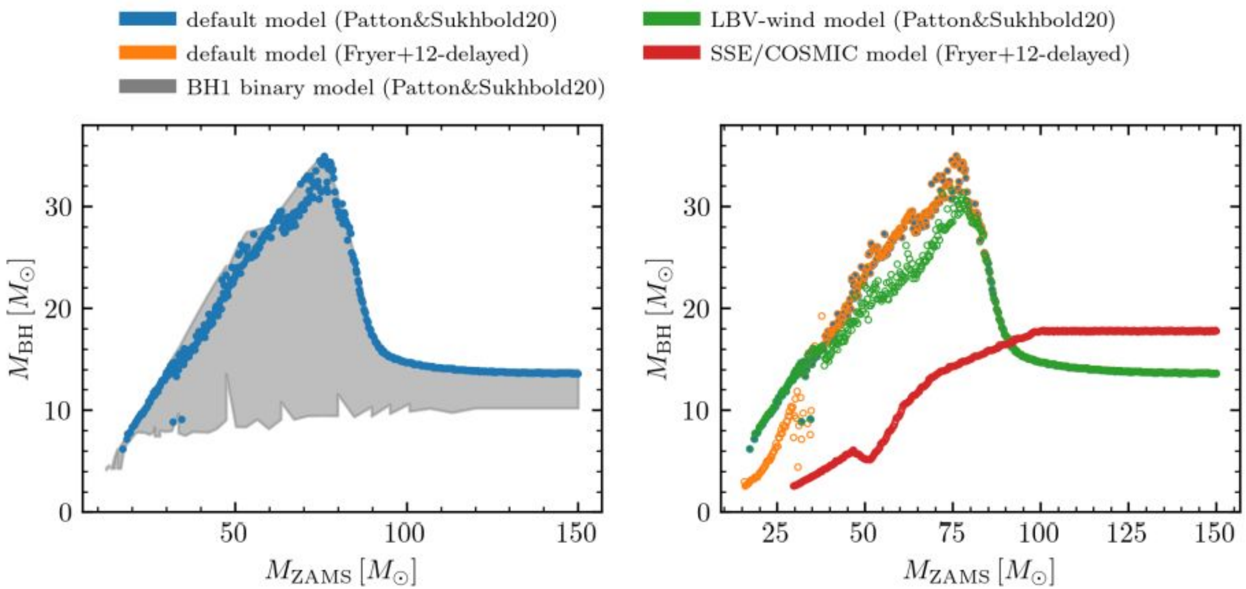


Improving simulations

Tracking stellar structure and mass transfer self-consistently, stars expand less

Avoiding significant dust driven and luminous blue variable winds reduces mass loss

Possible to form 30 solar mass black holes at solar metallicity



Bavera, ..., **CPLB** *et al.* arXiv:2212.10924

1. **Gravitational waves** enable discovery of a **diverse** range of sources

2. **LVK** observations cover black holes from ~4 to ~110 solar masses likely from **multiple formation channels**

3. Large number of detections will provide **precision constraints** on **black hole physics**

ButterflyLove1