Gravitational Waves

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Max Planck Institute for Gravitational Physics
Albert Einstein Institute
Hannover, Germany

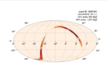
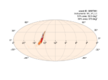
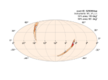
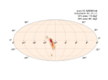
Astroparticle School September 2025

Binary Merger Observations & Numerical Relativity

MAX PLANCK INSTITUTE FOR GRAVITATIONAL PHYSICS (ALBERT EINSTEIN INSTITUTE)

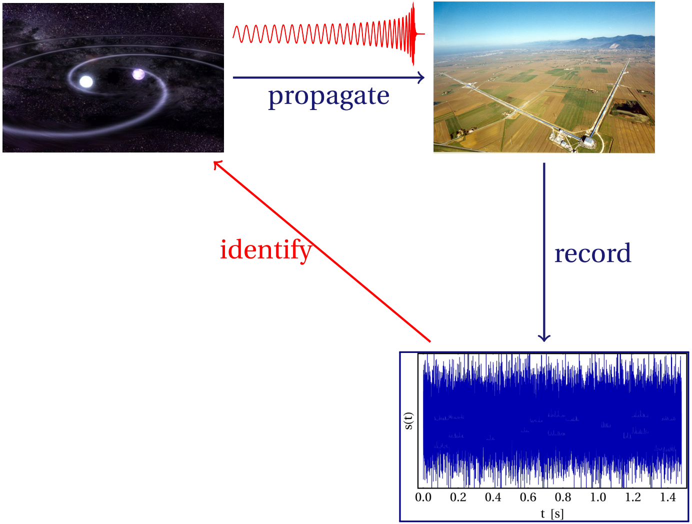
Public Alerts

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR
S250904cv	BBH (>99%)	Yes	Sept. 4, 2025 13:49:52 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years
S250904br	BBH (>99%)	Yes	Sept. 4, 2025 10:22:08 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years
S250904ae	BBH (>99%)	Yes	Sept. 4, 2025 03:33:07 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years
S250901cb	BBH (>99%)	Yes	Sept. 1, 2025 18:59:41 UTC	GCN Circular Query Notices | VOE		1 per 9.9253e+05 years

Topics

Interpreting the Signal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record
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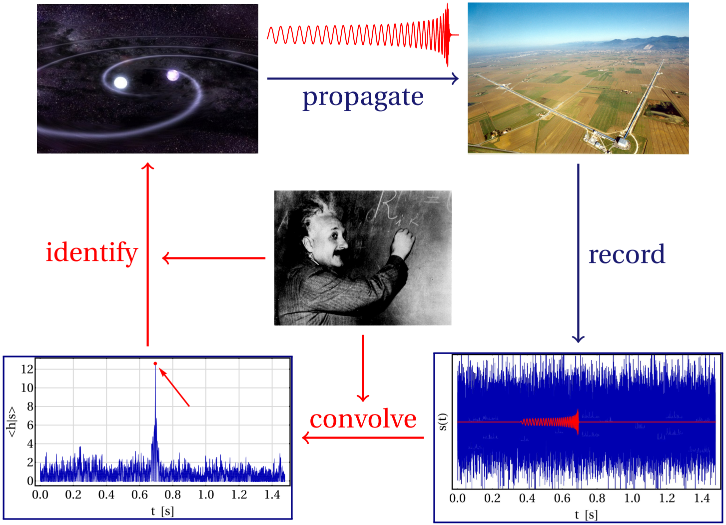
s(t)
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
t [s]


propagate
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convolve
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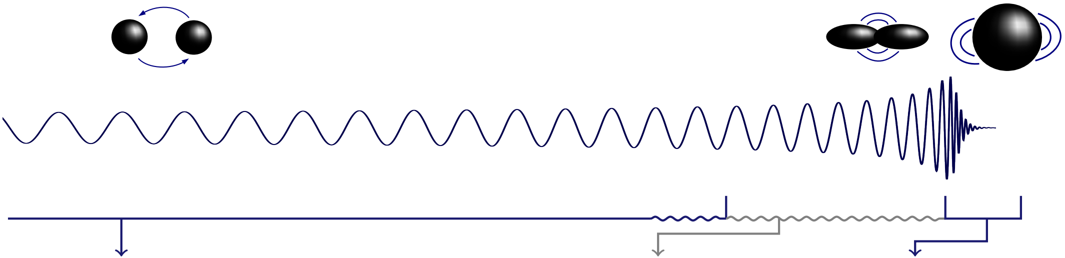
Modelling Binary Coalescences



Inspiral
post-Newtonian theory
effective one body

Merger
no analyt. model

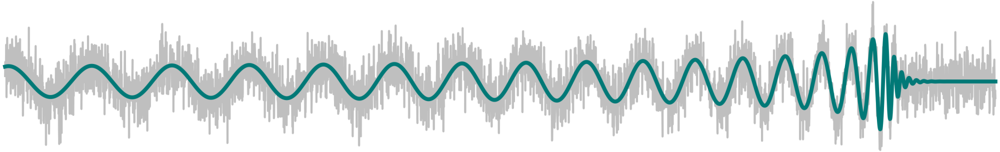
Ringdown
perturbation theory

Numerical Relativity

[*FO*, CQG 29 124002 (2012)]

The Inverse Problem

The Inverse Problem



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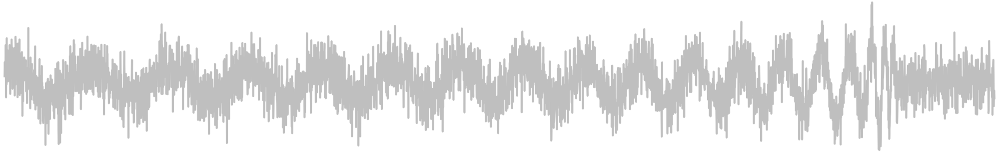

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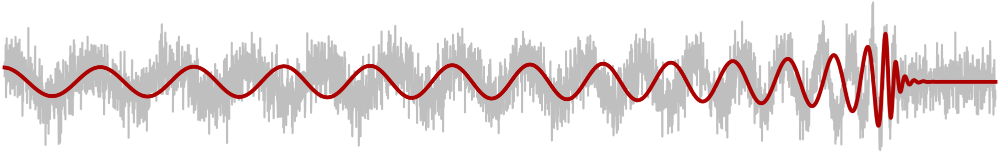

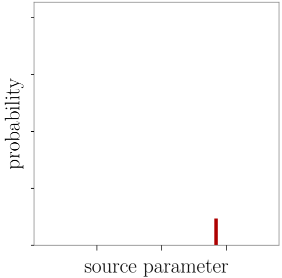

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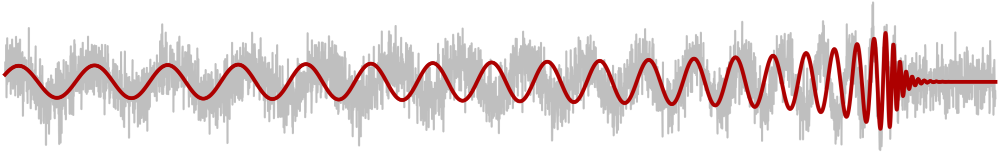

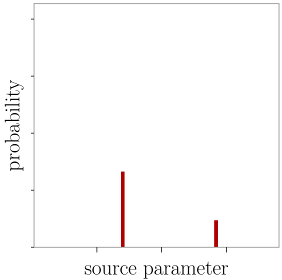

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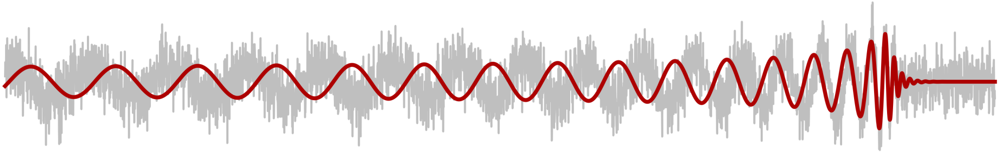

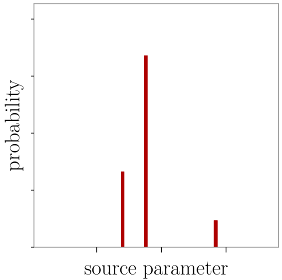

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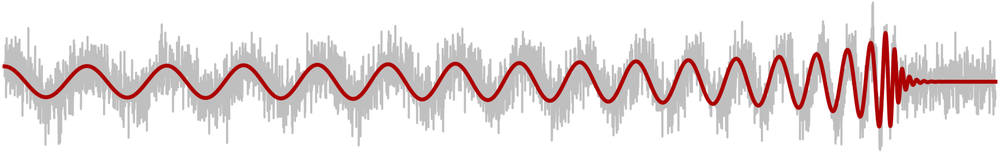

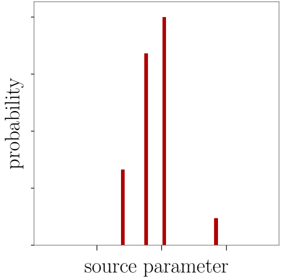

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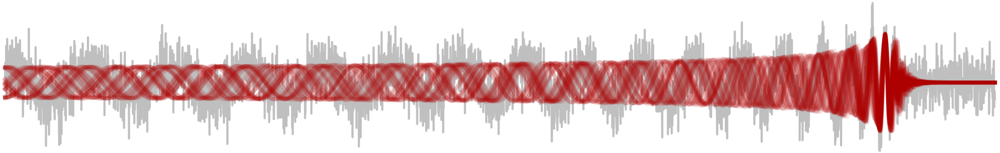

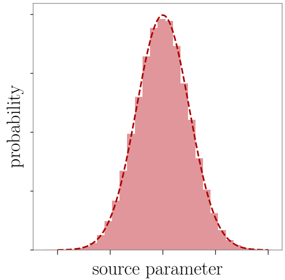

Likelihood & Posterior

Quantities d : data, h : GW model, θ : source parameters

Inner Product $\langle d, h \rangle = 4\,\mathrm{Re} \int \frac{\tilde{d}(f)\tilde{h}^*(f)}{S_n(f)} df$

Likelihood $\Lambda(d|h(\theta)) \sim \exp(-\|d - h(\theta)\|^2/2)$

Posterior $p(\theta|d) = \frac{\Lambda(d|\theta)\pi(\theta)}{p(d)}$

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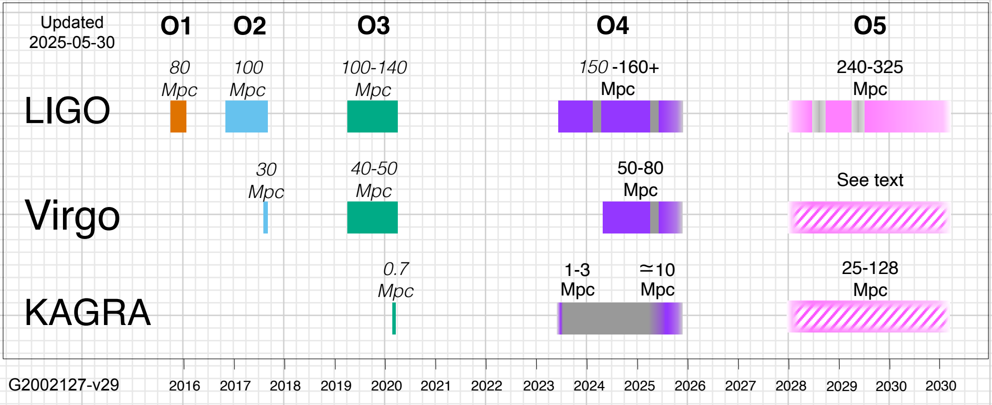
- Integrals become simple operations on set Θ, e.g.,

$$E[\theta_1] = \int \theta_1 \, p(\theta|s, I) d\vec{\theta} \approx \text{median}(\theta_1 \in \Theta)$$

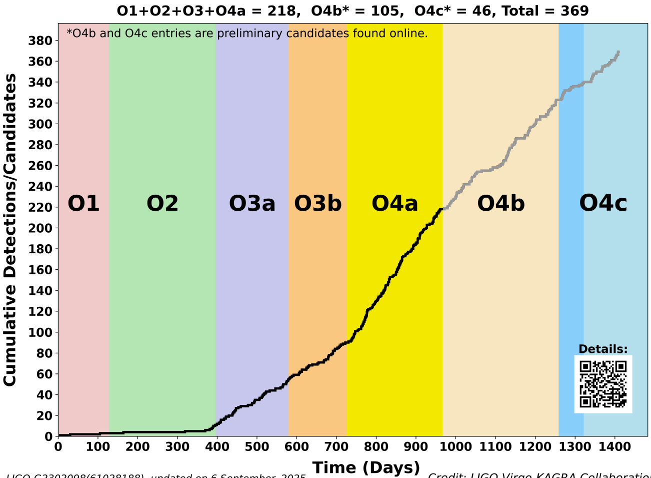
Gravitational-Wave Observations

Timeline



[https://observing.docs.ligo.org/plan/]

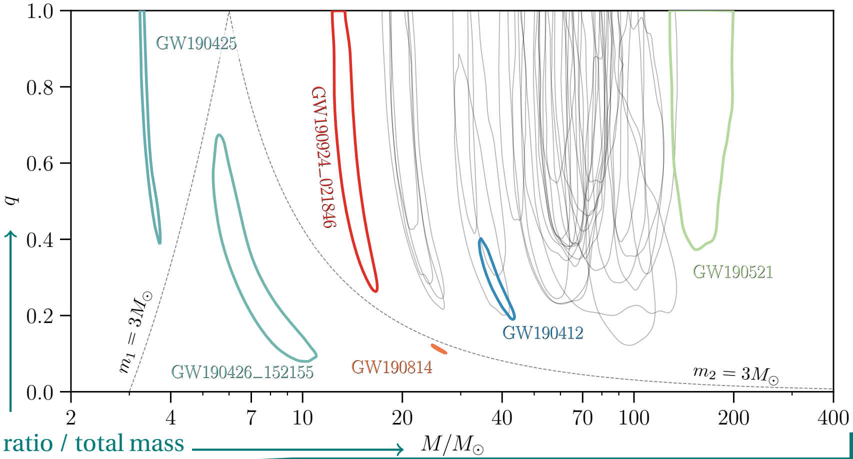
Observations



LIGO-G2302098(61028188), updated on 6 September, 2025

Credit: LIGO-Virgo-KAGRA Collaboration

Mass Posteriors



[GWTC-2 2010.14527]

mass ratio / total mass

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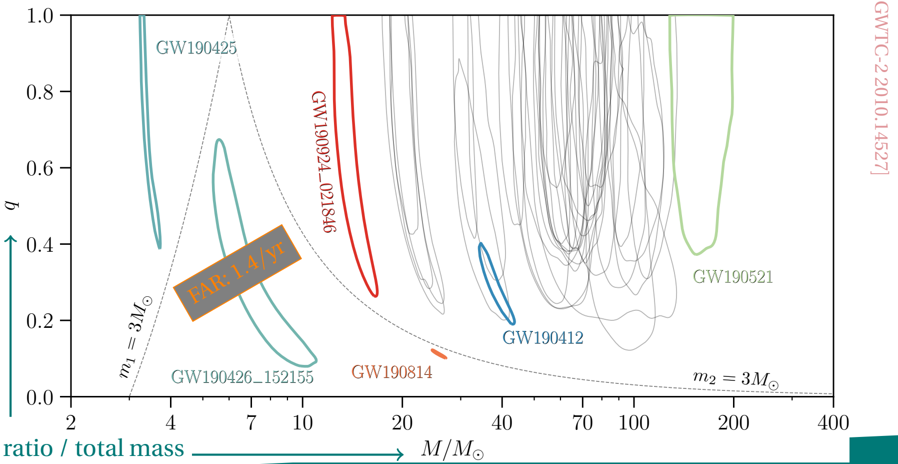
Mass Posteriors



mass ratio / total mass

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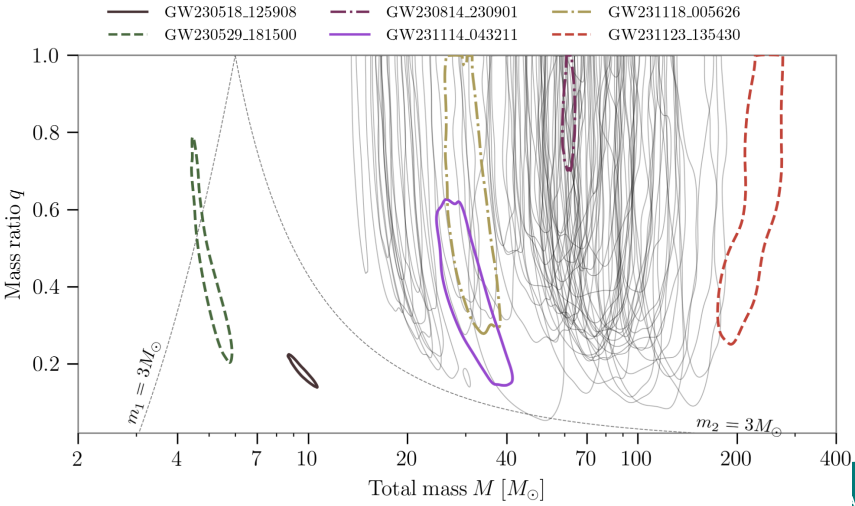

[GWTC-4 2508.18082]

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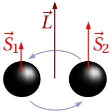
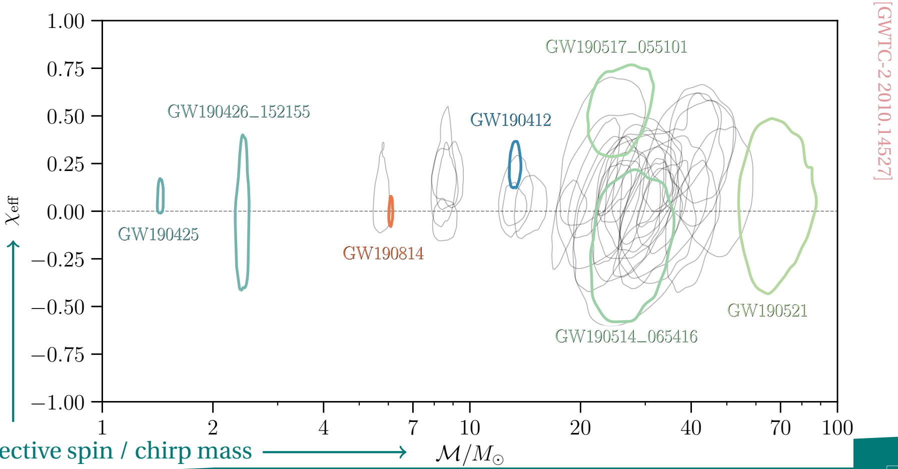
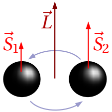
Spins

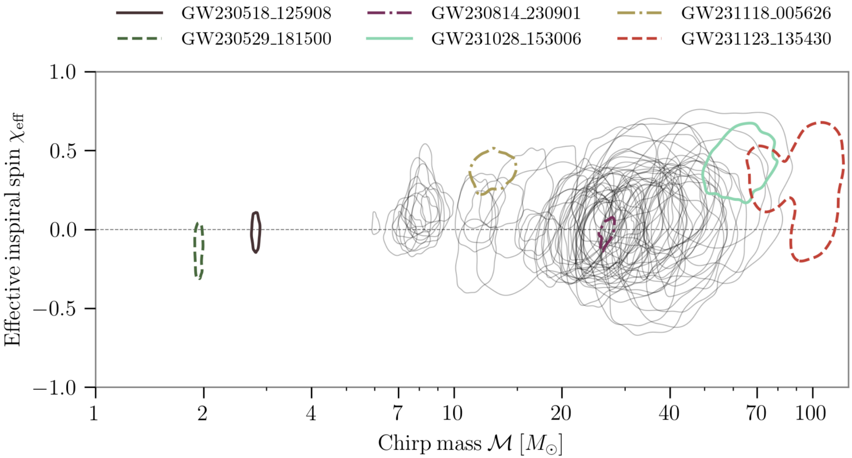




effective spin / chirp mass →

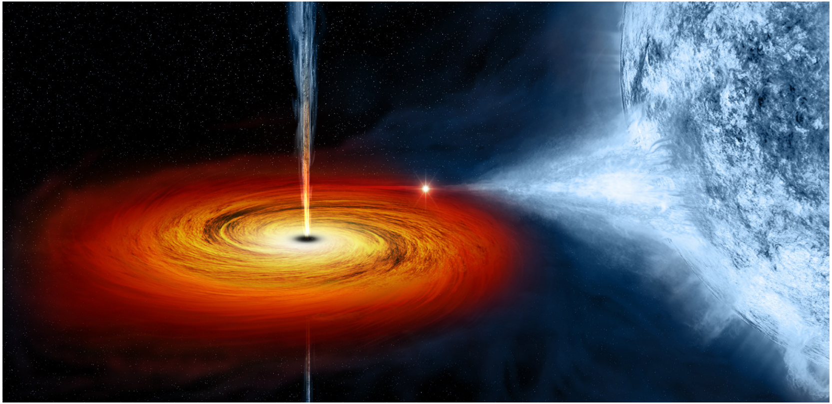
Spins





[GWTC-4 2508.18082]

Binary Evolution



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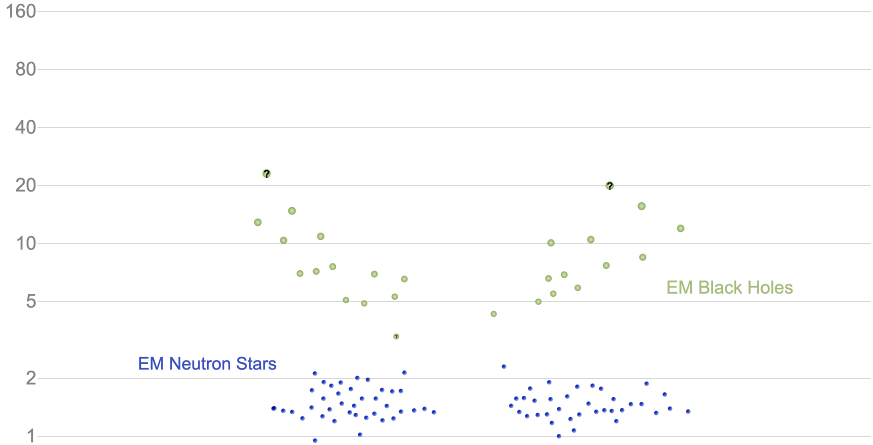
Material to Download

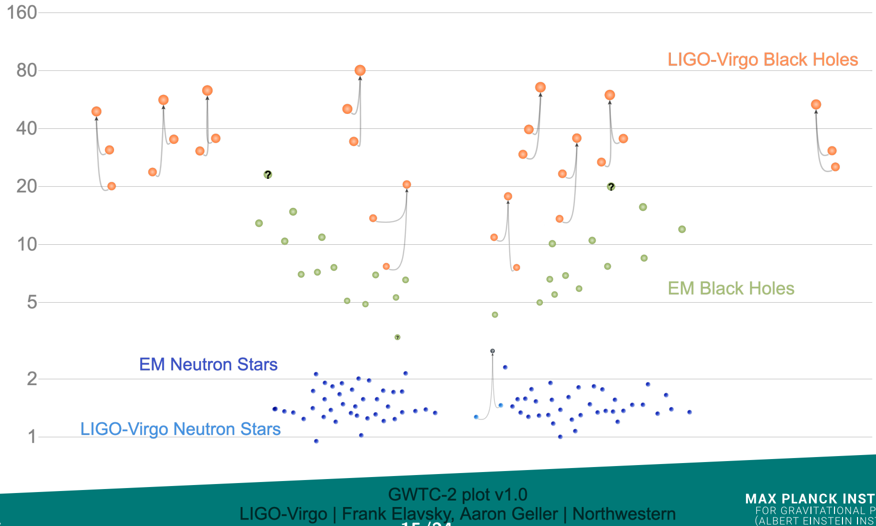
https://s.gwdg.de/th635p

Masses in the Stellar Graveyard



GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Masses in the Stellar Graveyard



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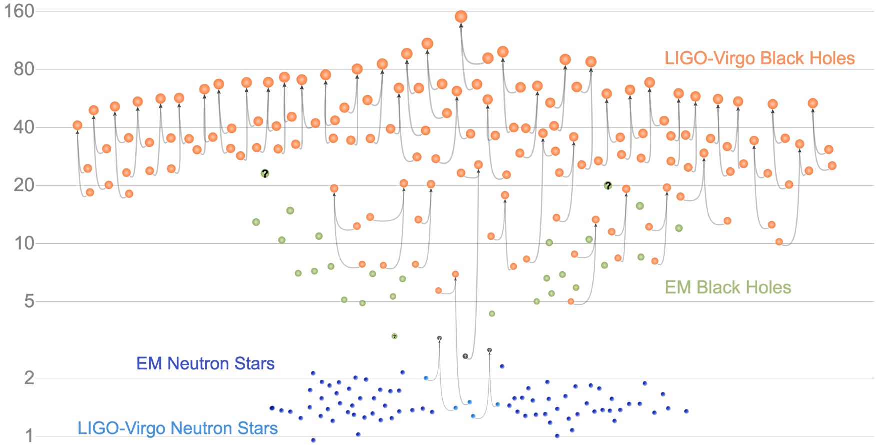

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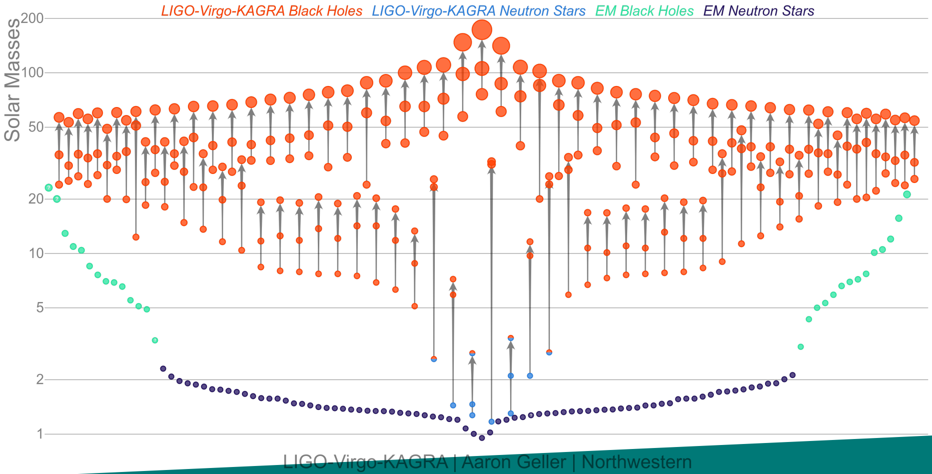

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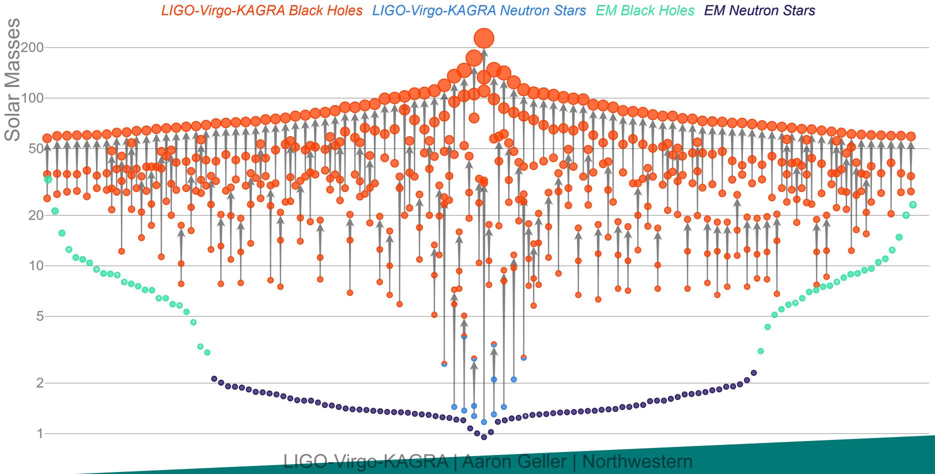
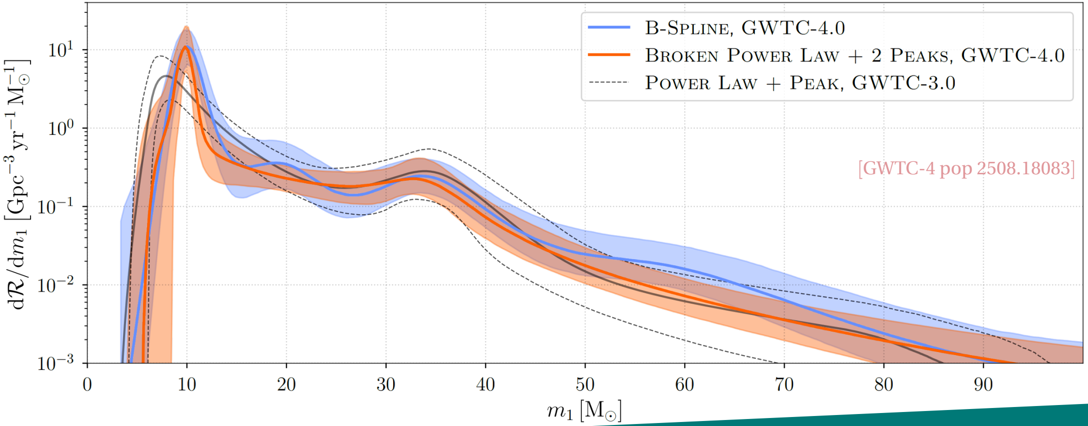


Population Properties



My Personal Highlights

GW150914	The first GW signal. Loud, but now considered typical.
GW170817	The first (and only) GW-multi-messenger event. Merger of two neutron stars. Largest coordinated global observation campaign across the EM spectrum.
GW190412	Black holes of unequal masses. First higher harmonics.
GW190521	Black holes with masses that shouldn't have formed in a supernova. Where did they come from?
GW190814	Very unequal masses. The less massive object is a ...?
GW200129	Precessing black holes and potentially a remnant with a kick.
GW200115_042309	A black holes swallowing (or disrupting) a neutron star.
GW25xxxx	[redacted]

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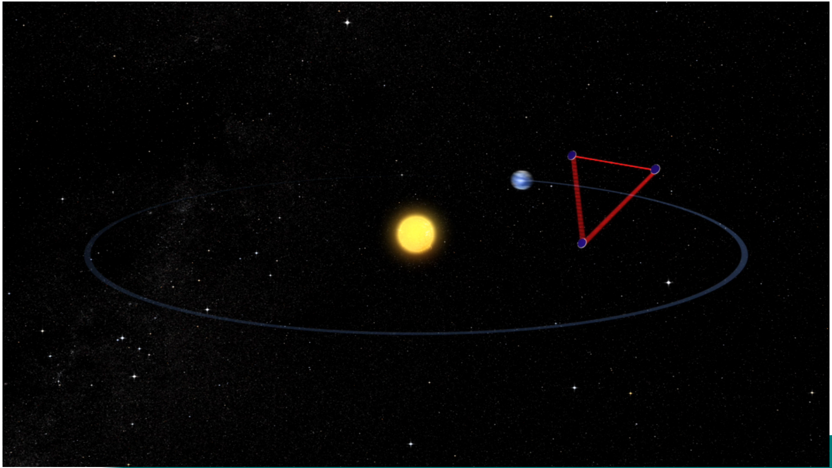
The Future

LISA



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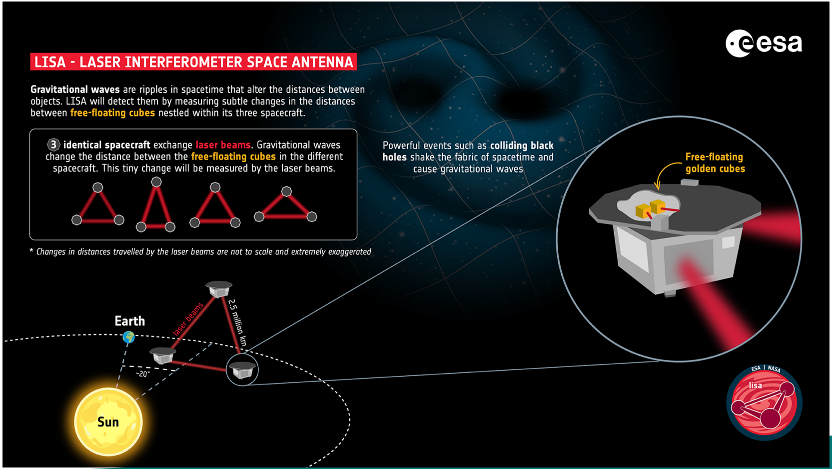
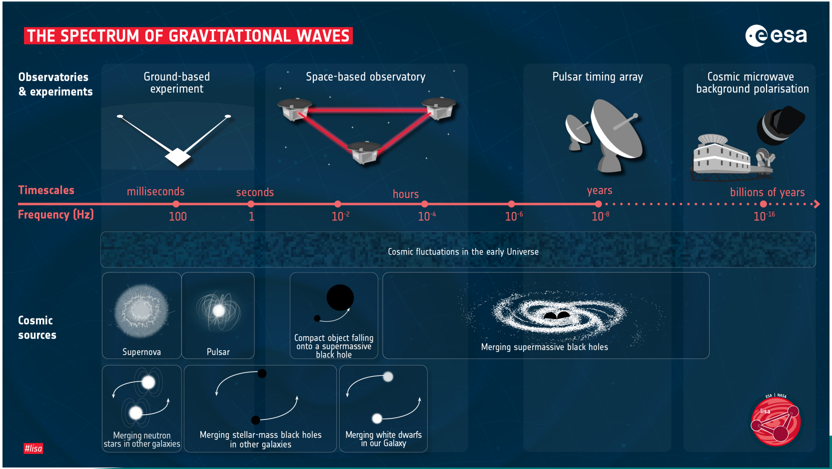
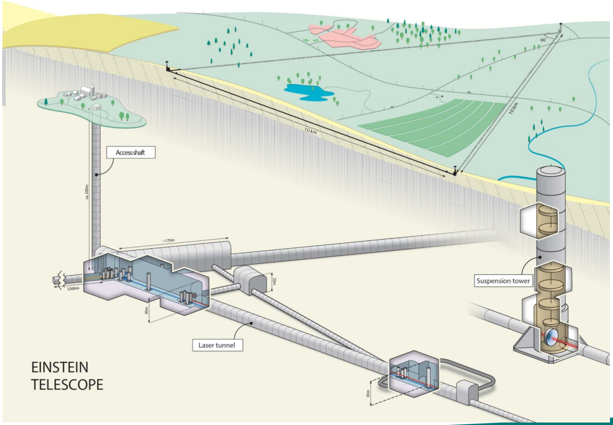


esa
LISA - LASER INTERFEROMETER SPACE ANTENNA
Gravitational waves are ripples in spacetime that alter the distances between objects. LISA will detect them by measuring subtle changes in the distances between free-floating cubes nestled within its three spacecraft.
3 identical spacecraft exchange laser beams. Gravitational waves change the distance between the free-floating cubes in the different spacecraft. This tiny change will be measured by the laser beams.
* Changes in distances travelled by the laser beams are not to scale and extremely exaggerated
Powerful events such as colliding black holes shake the fabric of spacetime and cause gravitational waves
Free-floating golden cubes
Earth
laser beams
2.5 million km
~20°
Sun
ESA | NASA
lisa

The Gravitational-Wave Spectrum



Einstein Telescope



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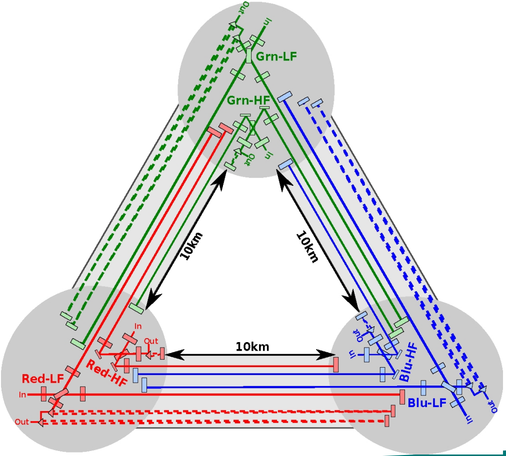
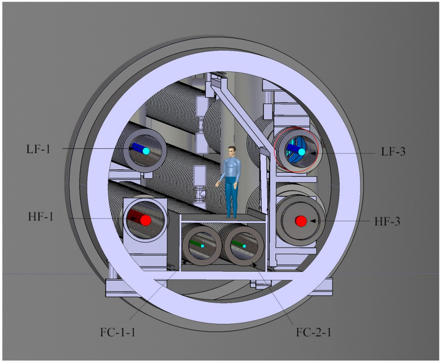
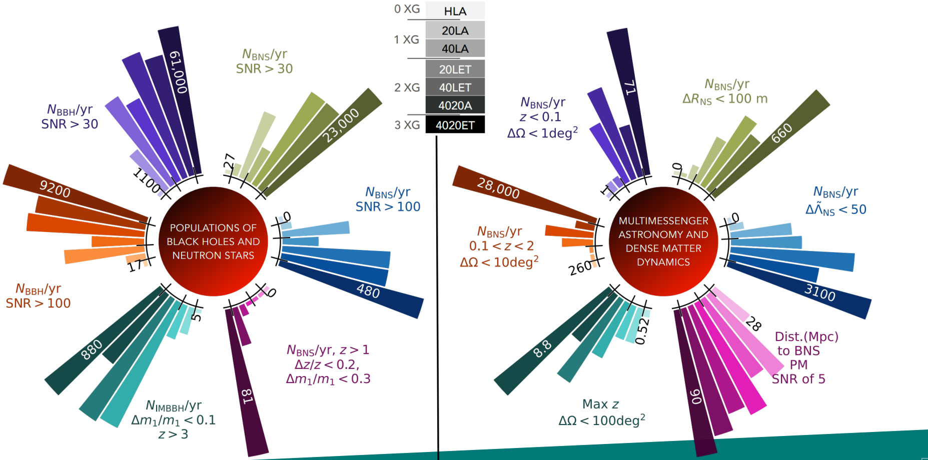




Science Prospects



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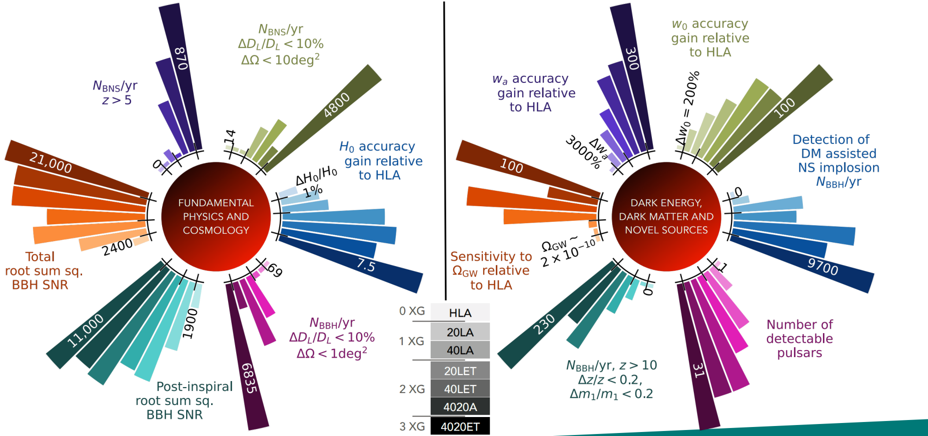

Conclusions

- Gravitational-wave astronomy is reality
- The Universe is full of black holes with (surprisingly) diverse properties
  $\rightarrow$ diverse formation channels?
- More observations to come and needed to unravel big questions (formation, environment, evolution, expansion, early Universe, ...)
- So far, no signs of Einstein's theory failing
- Continued work needed on possible systematics in the models and analyses
- Exciting future: LIGO Indida, LISA, Einstein Telescope
- Multimessenger astronomy will become the norm, not the exception

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