Overview of data analysis and observational science

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Belgian-Dutch
Gravitational Wave meeting
23 October 2023

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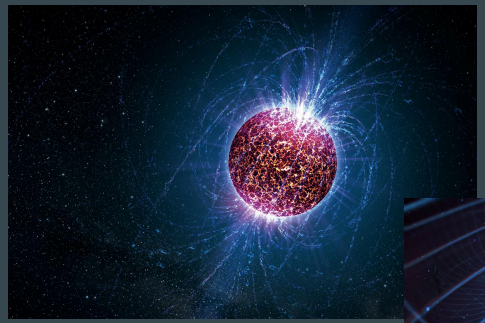
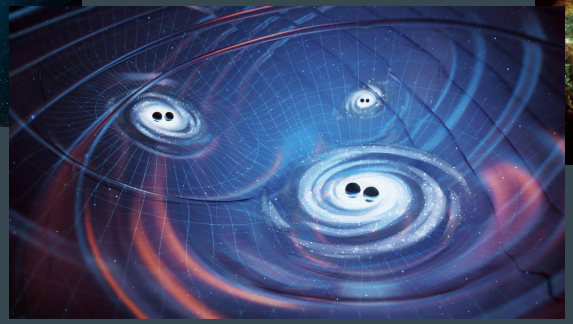
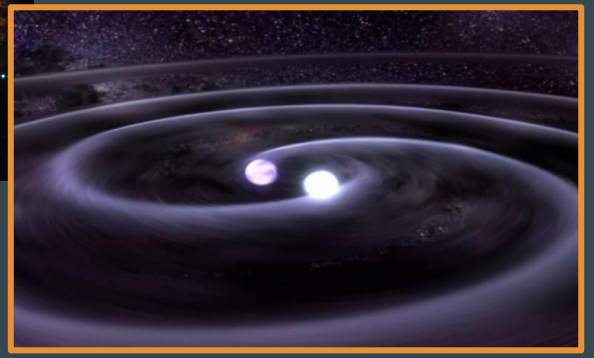
Utrecht University

Nikhef

What we have

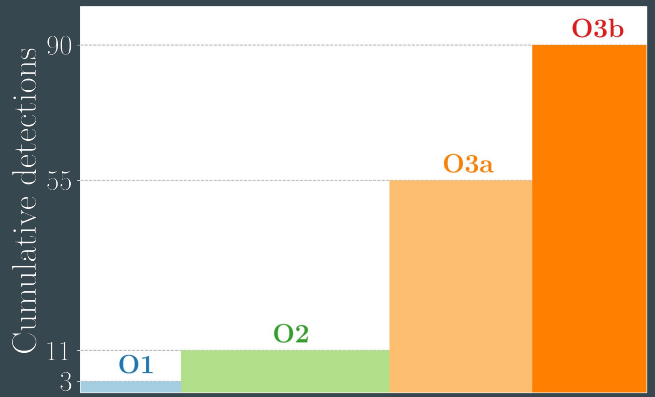






What we have

Sept '15 - Jan '16 | Nov '16 - Aug '17 | Apr '19 - Mar '20 | May '23 - ongoing



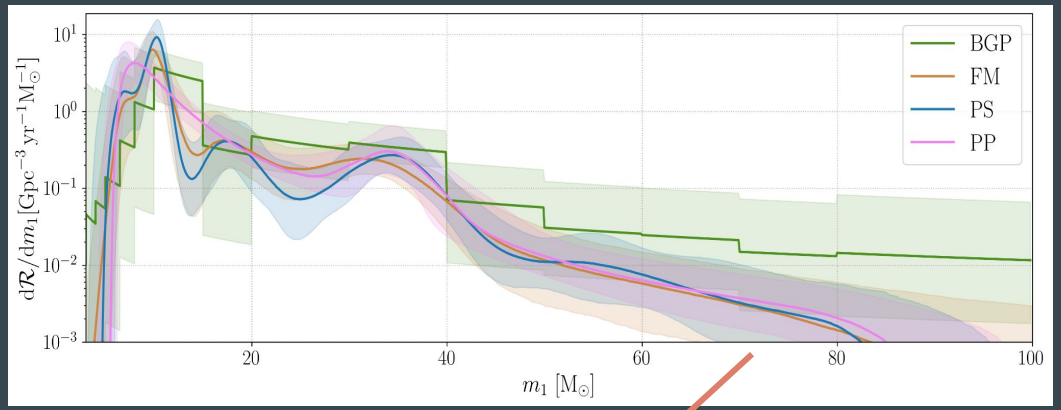
Total: 90 events

Special events

- neutron star - black hole
- unequal masses (GW190412, GW190814)
- very massive event (GW190521)
- heavy binary neutron star (GW190425)
- Object with 2.6 $M_\odot$ (GW190814)

Population properties

MASSES



LVK, *Phys.Rev.X* 13 (2023) 1, 011048

Pair instability supernovae: 50-120 $M_\odot$
(GW190521, GW200220)
Black holes of non-stellar origin?

SPIN

Binaries formation channels:

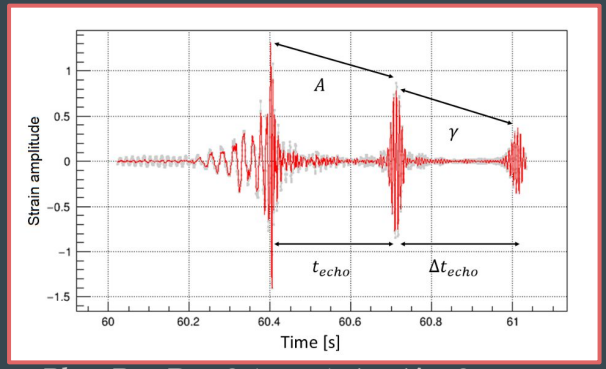
- Isolated binary evolution: aligned spins
- Dynamical interaction: precession, misaligned spins

Spin properties ⟺ Formation channels

Investigate and model different mechanisms

Testing general relativity

- ➢ Study effects of specific alternative theories
- ➢ Comparing data with general relativity predictions

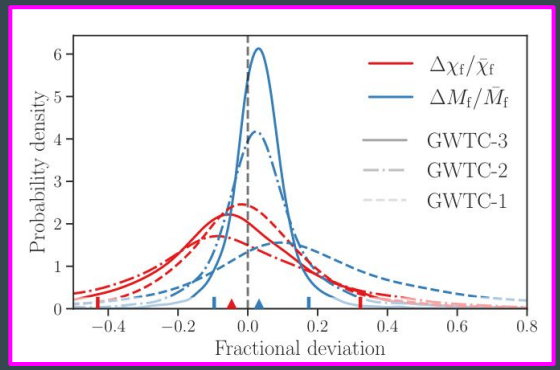


Phys.Rev.D 108 (2023) 6, 064018

- Parametrized deviations from the phase evolution
- Parametrized deviations from amplitude of higher order modes
- Test the nature of compact objects: echoes (no horizon)
- Propagation of gravitational waves
- Inspiral-merger-ringdown consistency

• • •

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5}\left[\varphi_{0\mathrm{PN}} + \varphi_{0.5\mathrm{PN}}\left(\frac{v}{c}\right) + \varphi_{1\mathrm{PN}}\left(\frac{v}{c}\right)^{2} + \ldots\right.$$



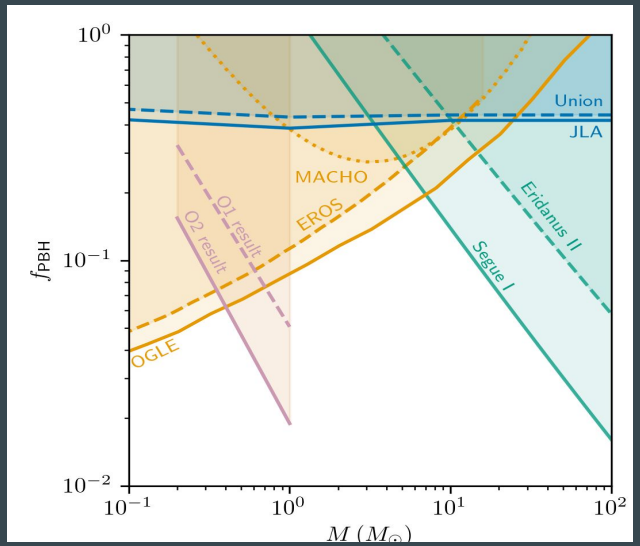
No violations of general relativity found until now!

Most recent LVK results: arXiv:2112.06861

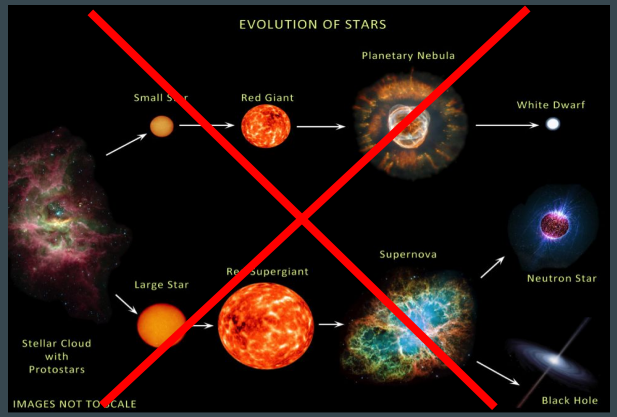
Sub-solar mass black holes

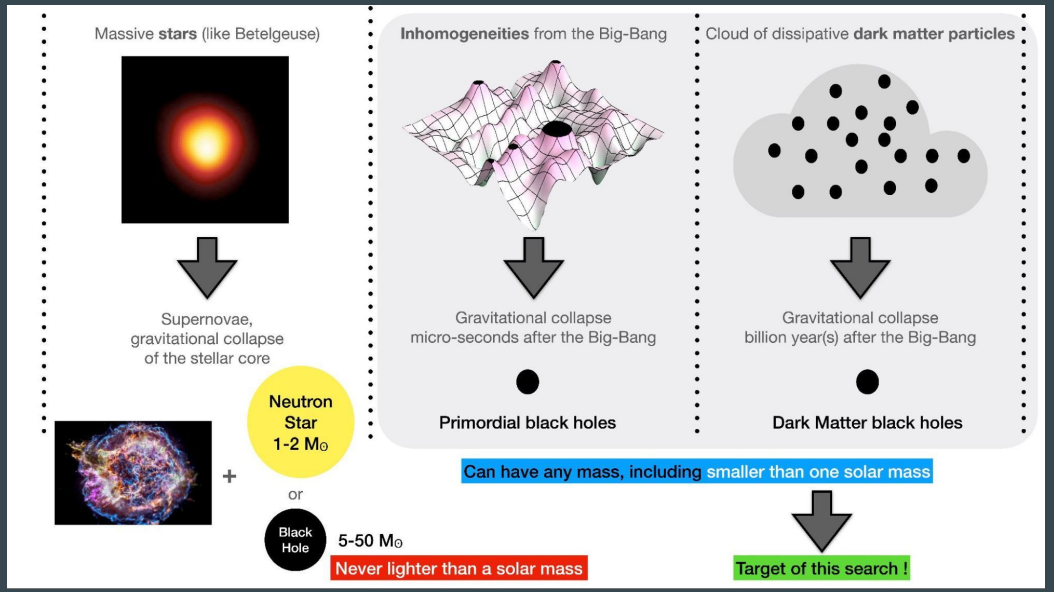
Black holes with mass $\lesssim 1\ M_\odot$?

- Primordial black holes (explain dark matter)
- Dark matter



Phys. Rev. Lett. **129**, 061104

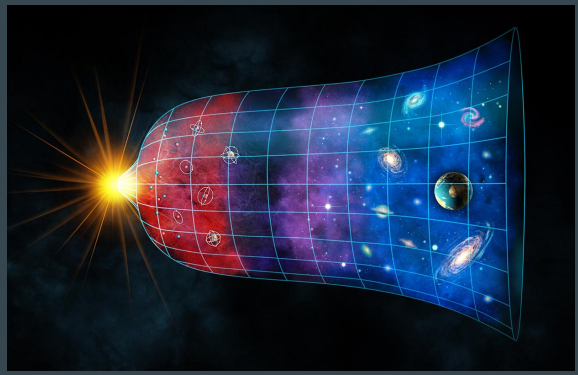




O3b results: arXiv:2212.01477

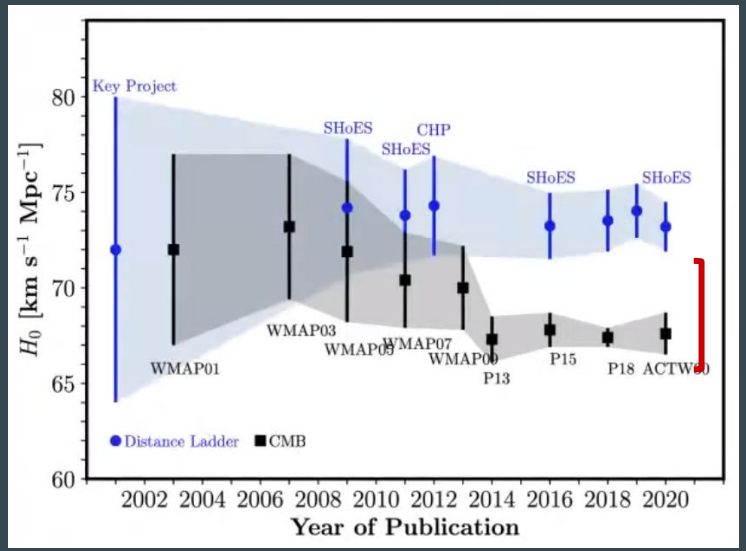
Measure Hubble constant

Expansion of the Universe ⟹ Hubble constant

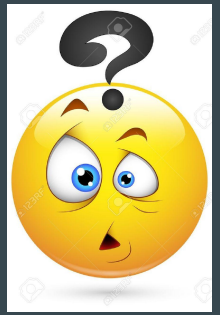


We need: distance and redshift

Different methods: **Hubble tension**



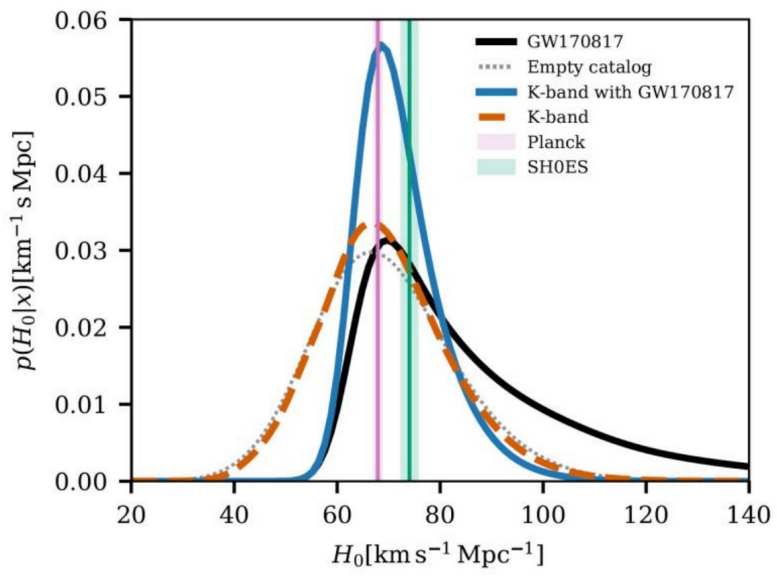
Credit: Wendy Freedman



Measure Hubble constant

Gravitational waves:

- we measure the distance of the source
- we can find the redshift → electromagnetic counterpart for neutron stars
  → comparison with catalogs

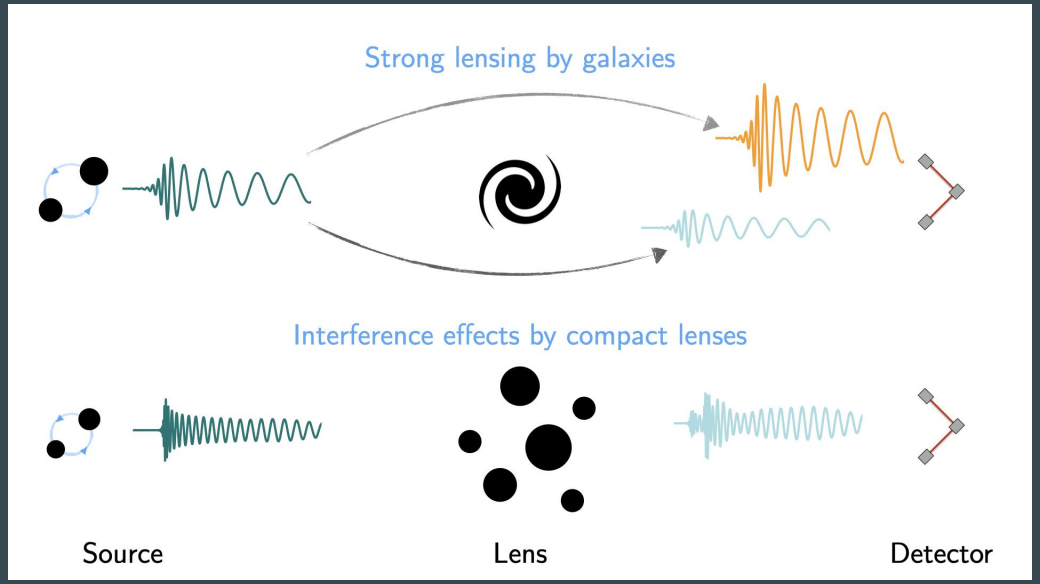


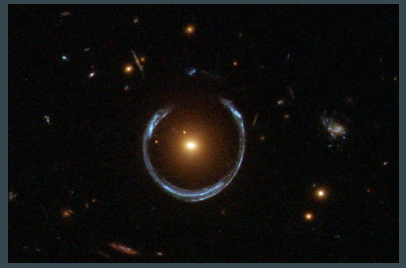
Astrophys.J. 949 (2023) 2, 76

Future:

- more detections
- more detectors (better localization)
- improved catalogs
- study of systematics

Lensing



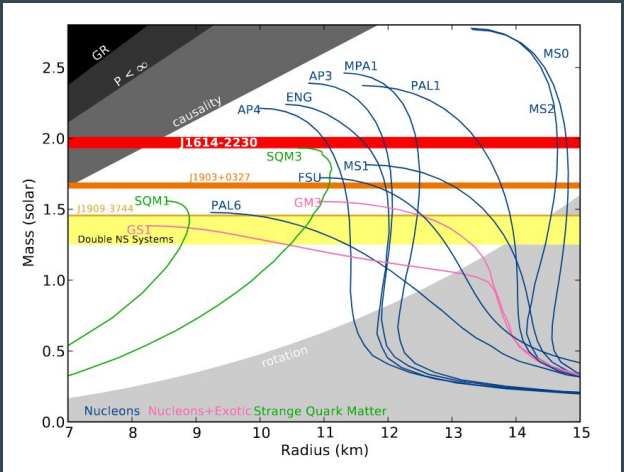


Lensing applications:
- fundamental physics
- cosmology
- ...

Complete O3 analysis:
arXiv:2304.08393

No evidence for lensing found, but expected in the next years

Neutron stars



Nature **467**, 1081–1083 (2010)

- measure the parameters
- combine with nuclear information [Nature 606, 276 (2022)]
- study the postmerger
- multimessenger astrophysics

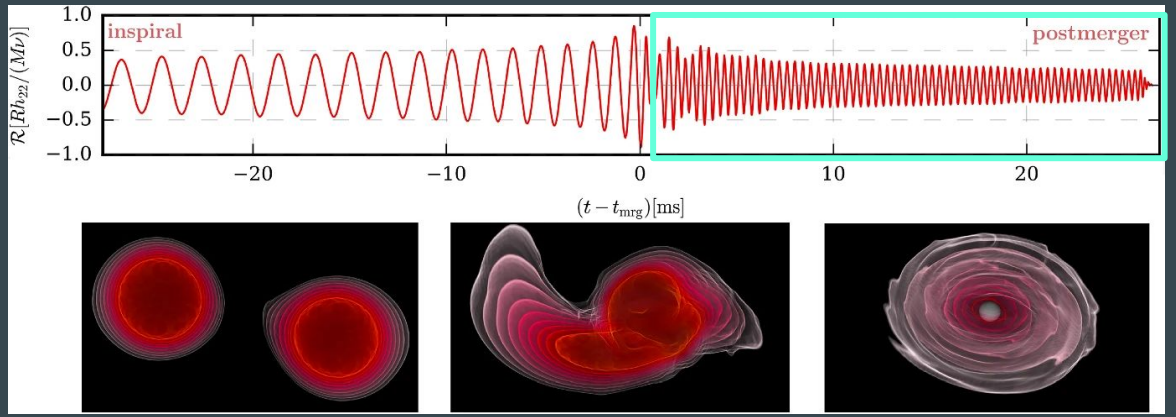
Neutron stars: supranuclear-dense matter

Equation of state:

relation between pressure and density

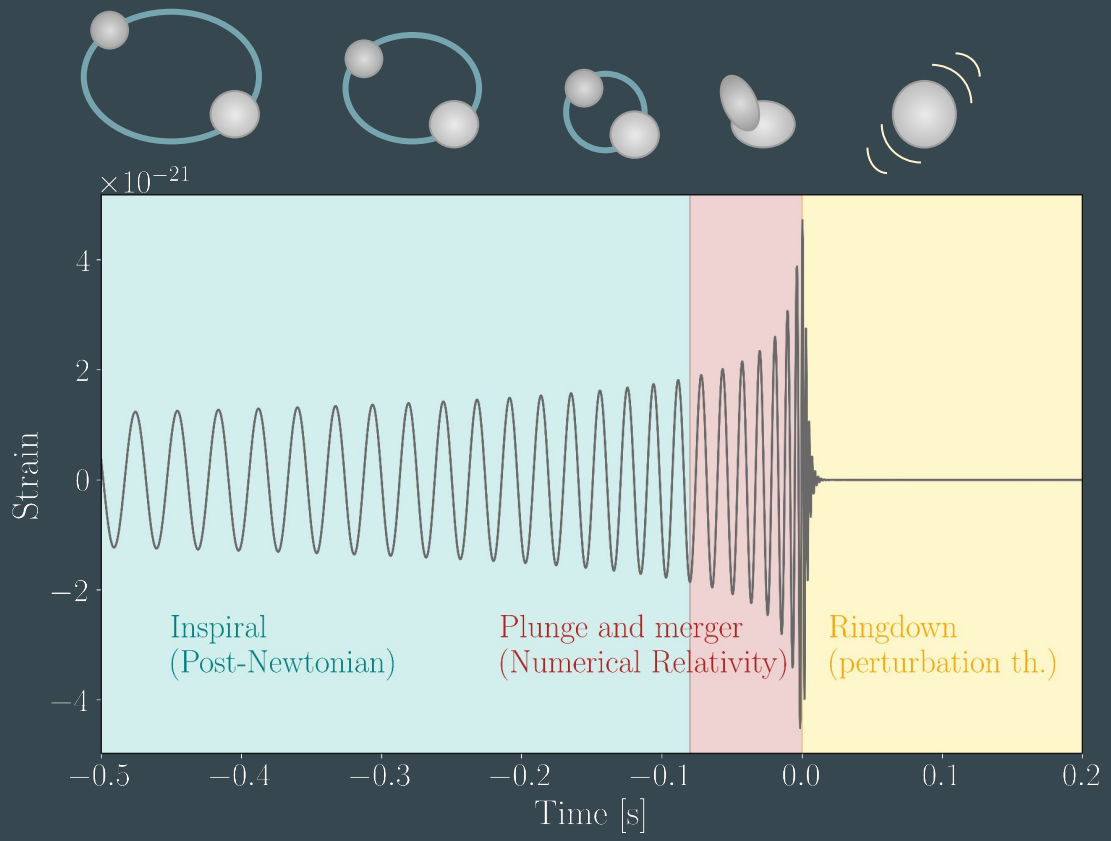
⇕

parameters of the neutron stars



Gen. Rel.Grav. 53, 27 (2021)

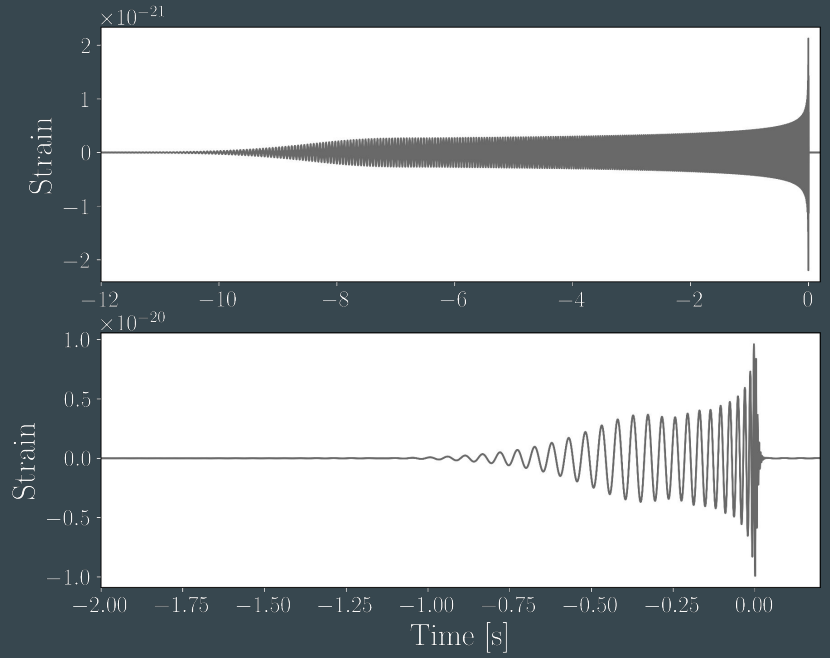
Develop tools - waveform models



Develop tools - waveform models

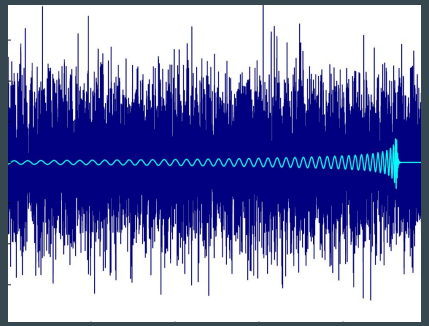
$m_1 = 10\,M_\odot$
$m_2 = 8\,M_\odot$

$m_1 = 45\,M_\odot$
$m_2 = 36\,M_\odot$



Essential for:

- parameter estimation
- matched filtering (template banks)

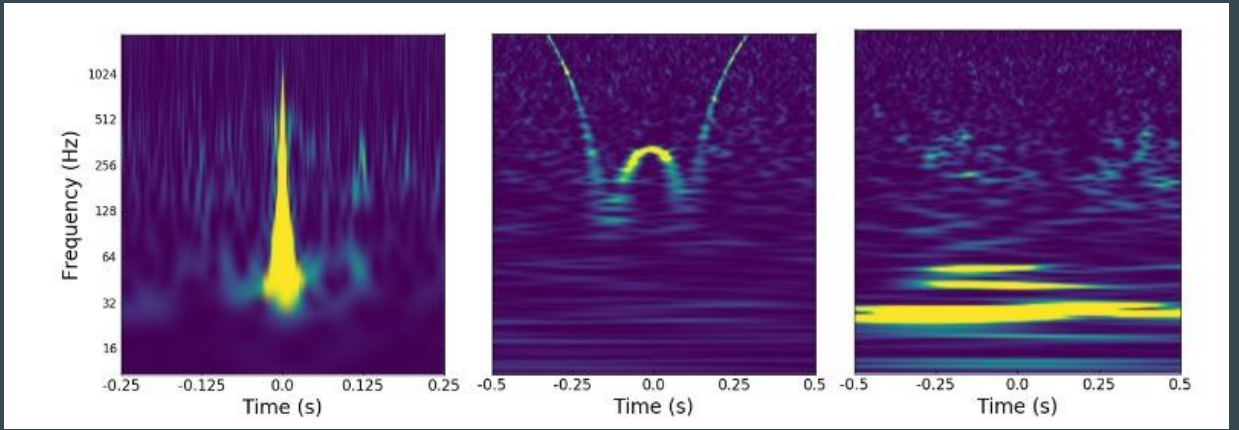


Accurate models needed: include precession, higher-order modes, eccentricity...

Develop tools - new methods

- *SIMULATION-BASED INFERENCE:*
  alternative to traditional sampling methods *[talks: Weniger, Wermersson, Bhardwaj]*

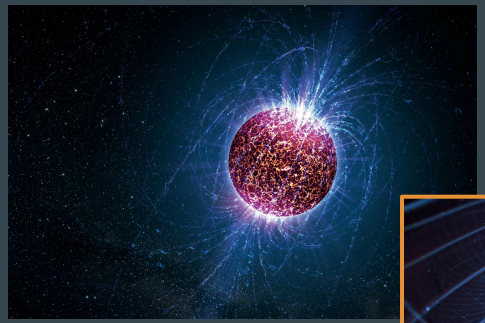
- *MACHINE LEARNING:*
  parameter estimation, tests of general relativity, models,
  glitches classifications...

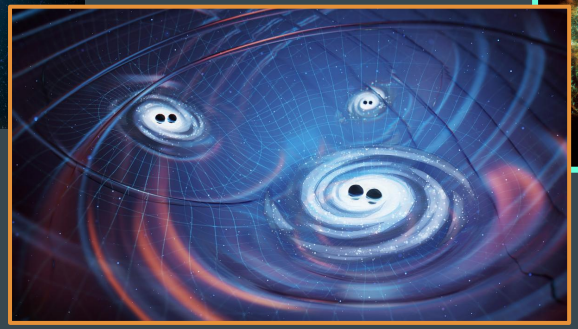


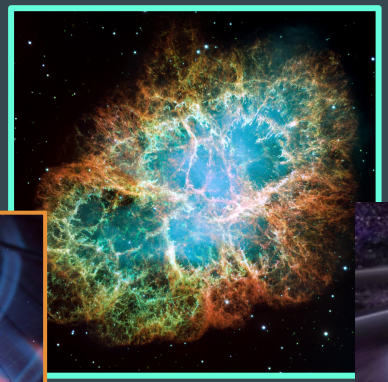
Class.Quant.Grav. 35 (2018) 15, 155017

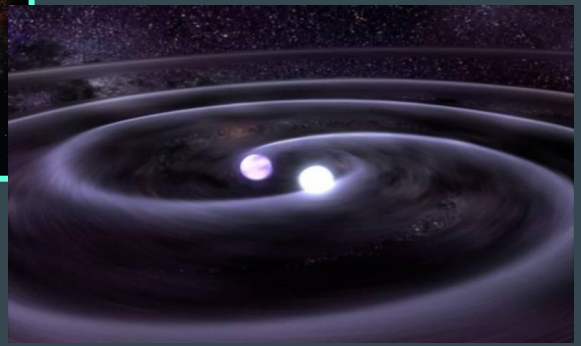
Other sources

Supernovae:
- modelling
- detection



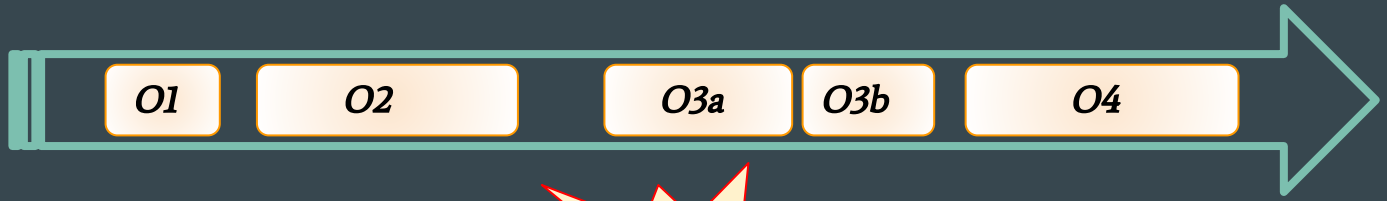






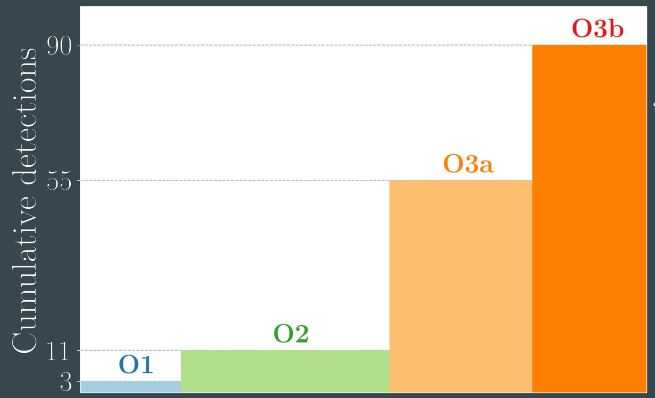
- Early evolution of the Universe
- Superposition of many independent sources ⟹ Pulsar Timing Array

Looking at the future



Einstein Telescope
and
Cosmic Explorer

LISA



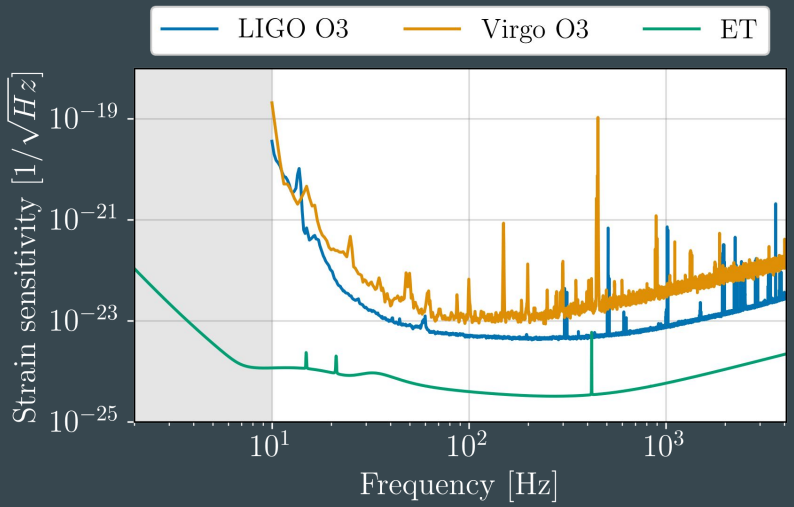
	# of detections	SNR_{net}	# with $SNR_{net} > 250$	# with $SNR_{net} > 100$
BBH				
Low rate	53756	$81.1^{+94.2}_{-57.3}$	3069 (5%)	20605 (35%)
Median rate	85725	$81.3^{+93.9}_{-57.5}$	4972 (5%)	33148 (39%)
High rate	137225	$81.5^{+94.2}_{-57.4}$	7860 (6%)	53419 (39%)
BNS				
Low rate	98898	$19.2^{+22.1}_{-4.9}$	17 (0.017%)	298 (0.30%)
Median rate	396793	$19.1^{+22.0}_{-4.8}$	73 (0.018%)	1257 (0.32%)
High rate	1004525	$19.1^{+22.1}_{-4.8}$	196 (0.020%)	3255 (0.32%)

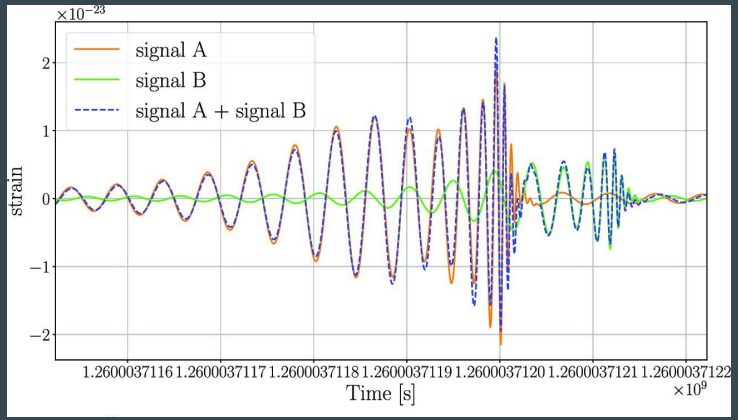
Phys.Rev.D 104 (2021) 4, 044003

Looking at the future

More events, louder, more time in band

- Overlapping signals
- Systematics (ex: waveform models)
- Computational issues:
  automation,
  develop methods to reduce the cost





Mon.Not.Roy.Astron.Soc. 523 (2023) 2, 1699-1710

Thank you!