Title: Gravitational-wave observations of compact binary mergers

Speakers: Patricia Schmidt

Series: Colloquium

Date: April 06, 2022 - 2:00 PM

URL: https://pirsa.org/22040041

Abstract: The first direct detection of gravitational waves from merging black holes in 2015 has opened up new avenues to studying gravity in the strong-field regime, inferring the mass and spin distributions of astrophysical black holes and probing the nature of ultra-dense nuclear matter in the interior of neutron stars. Seven years on, we count approximately 100 detections of gravitational waves from compact binary mergers.

These observations are goldmines for precise measurements of the source properties and the discovery of new physics at the edge of our current understanding. Pioneering innovations in detector technology will soon let us put black holes under a microscope, allowing us to push Einstein's theory of gravity to the limit. To do so will require exquisitely accurate theoretical models for the emitted gravitational-wave signal if we are to unlock the full discovery potential.

In this talk, I will discuss some of the most spectacular discoveries from the third observing run of Advanced LIGO and Virgo and their implications. I will also highlight some of the pitfalls and challenges in interpreting gravitational-wave detections.

Zoom Link: https://pitp.zoom.us/j/96161151229?pwd=NExyMitMaWpMTVBsL0VRTjZNbFBvZz09

UNIVERSITY OF BIRMINGHAM | GRAVITATIONAL WAVE ASTRONOMY

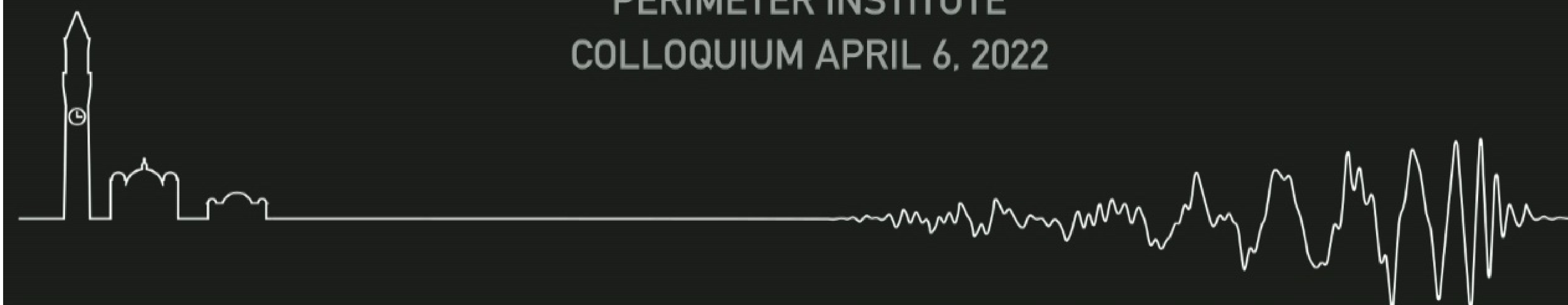
LIGO VIRGO KAGRA

GRAVITATIONAL-WAVE OBSERVATIONS OF COMPACT BINARY MERGERS

PATRICIA SCHMIDT

PERIMETER INSTITUTE

COLLOQUIUM APRIL 6, 2022

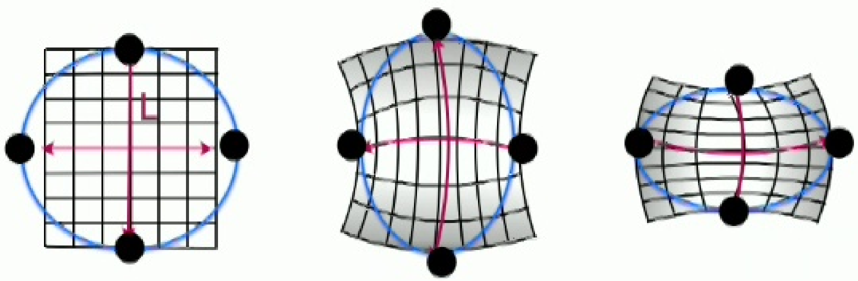


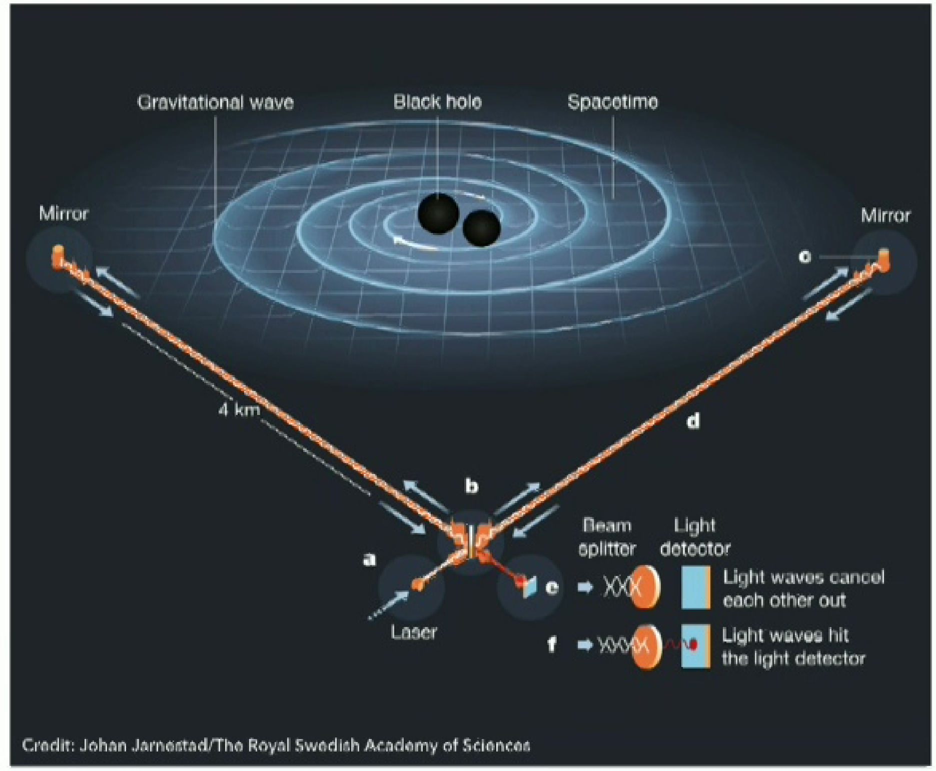
GRAVITATIONAL WAVES

- Metric perturbations caused by a time-varying quadrupole moment

$$h \sim \frac{\ddot{Q}}{D} \propto \frac{\Delta L}{L}$$

- Transverse
- Travel at the speed of light
- Two independent polarisations





$$\Delta L \sim 10^{-18}\,\mathrm{m}$$

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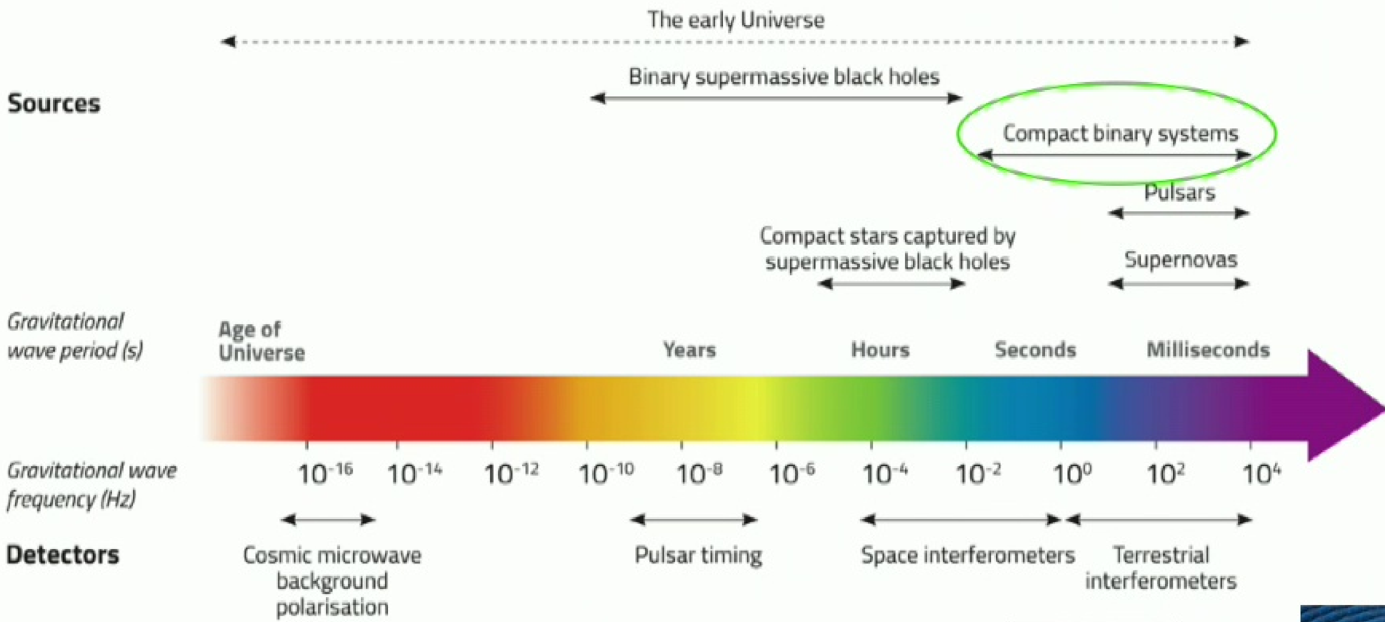
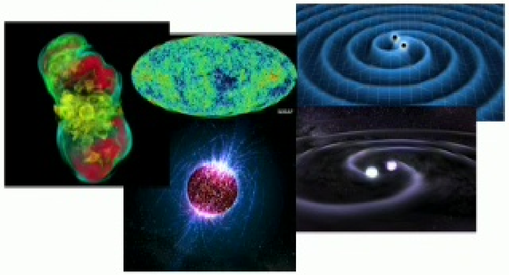
SOURCES





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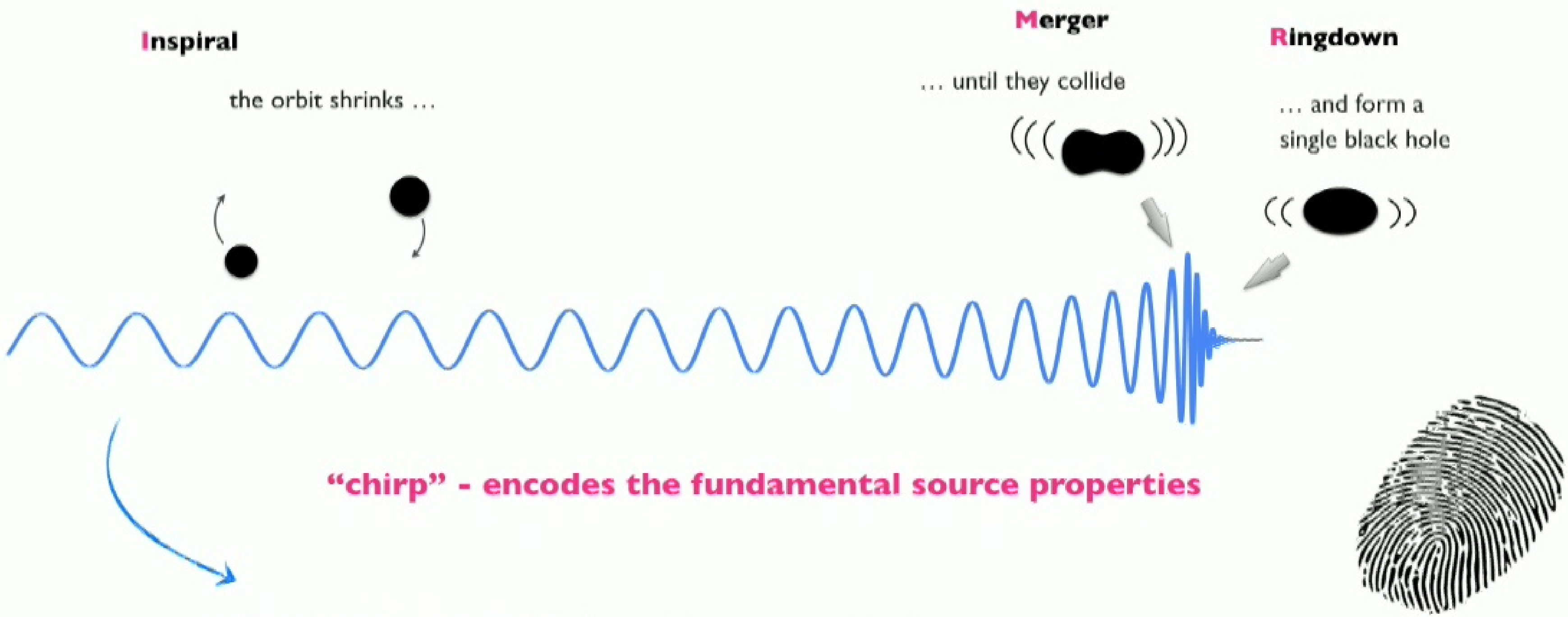
GRAVITATIONAL WAVES FROM COMPACT BINARIES



theoretical knowledge to ID the binary necessary

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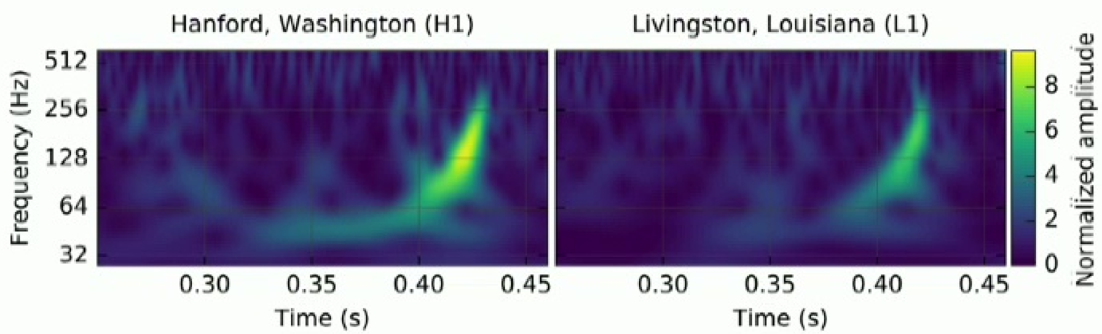
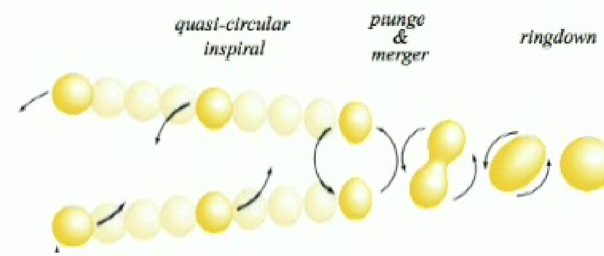
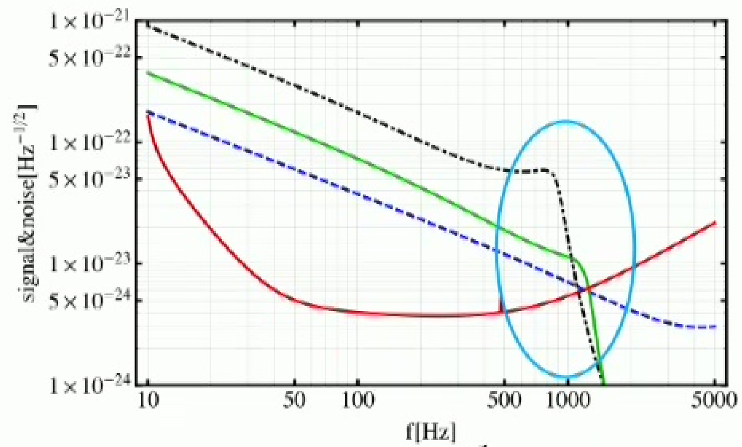
GRAVITATIONAL WAVES FROM COMPACT BINARIES

- Signal „sweeps" through the detector's sensitivity band
- Depending on the total mass of the binary, the merger regime is visible
  - Inspiral-merger-ringdown (IMR) waveforms are key
  - Need accurate theoretical model to infer the science







$$f_{\rm ISCO} = \frac{1}{6^{3/2}\pi M}$$

DETECTOR NETWORK

- Kilometre-scale interferometres
- Sensitive to GWs between a few Hz to a few kHz
- Simultaneous detection increases detection confidence
- Improved sky localisation & polarisation
- Increased duty cycle

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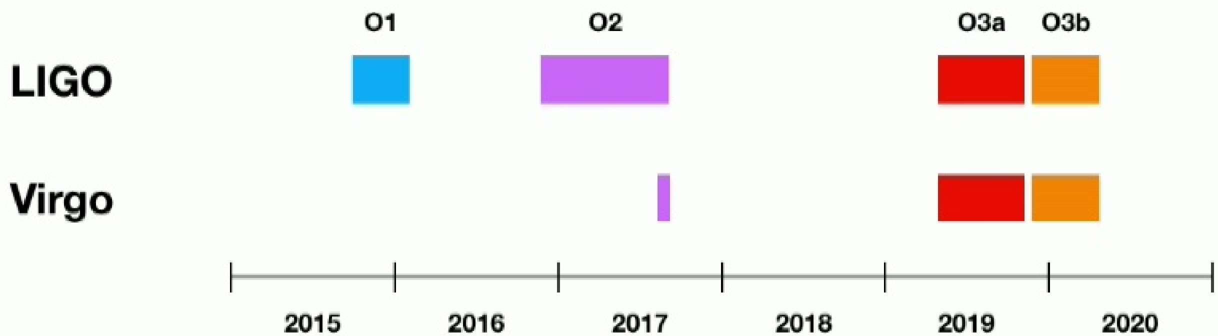
OBSERVATION TIMELINE



- O1: Sept 12,2015 - Jan 30, 2016
  - HL coincident time: 48.6 days
- O2: Nov 30, 2016 - Aug 25, 2017
  - HL-coincident time: 118 days
  - HLV-coincident time: 15 days
- O3a: April 1, 2019 - Nov 1, 2019
  - HLV coincident time: 81.4 days
- O3b: Nov 1, 2019 - March 27, 2020
  - HLV coincident time: 75 days

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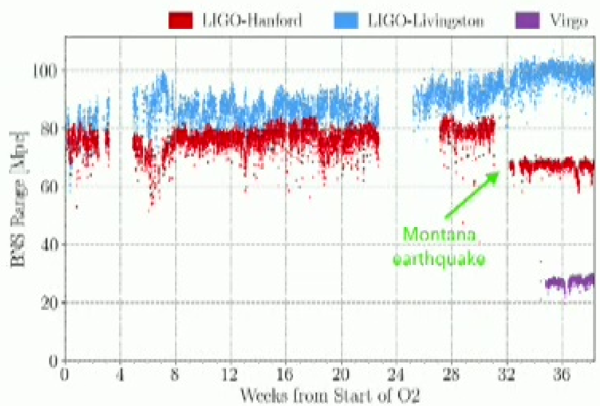
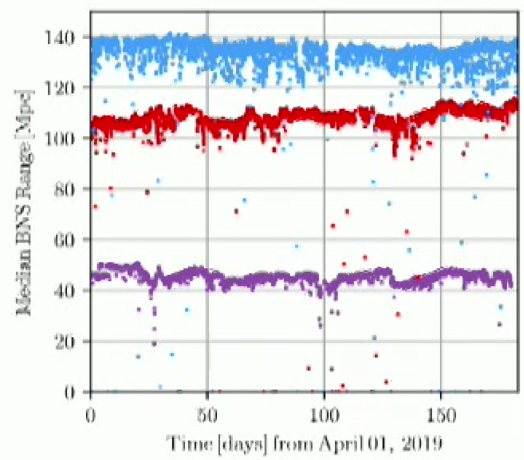
SENSITIVITY IMPROVEMENTS

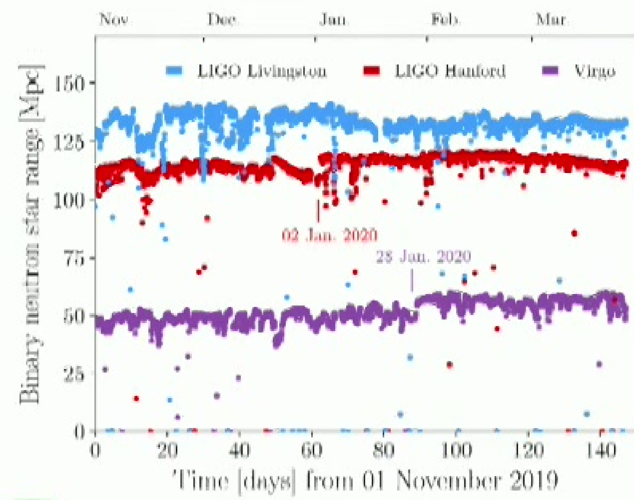
O2

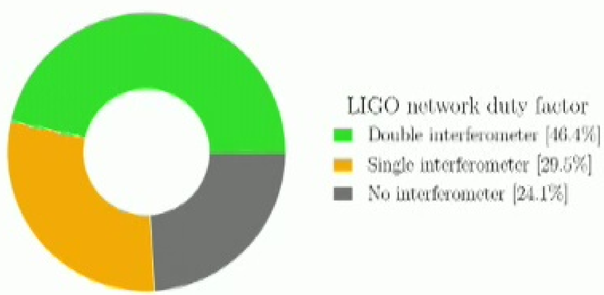


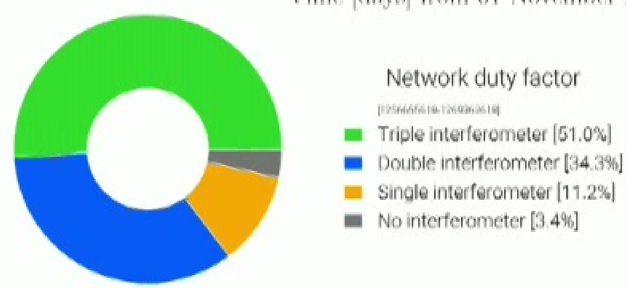
O3a



O3b







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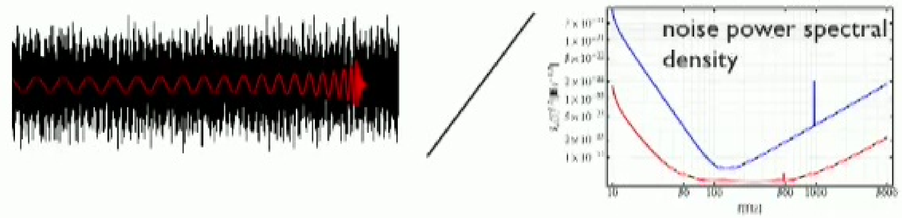
GWTC-1:LVC, PRX 9, 031040 (2019), GWTC-2: LVC, PRX 11, 021053 (2021), GWTC-3: LVC, arXiv:2111.03606

EVENT IDENTIFICATION

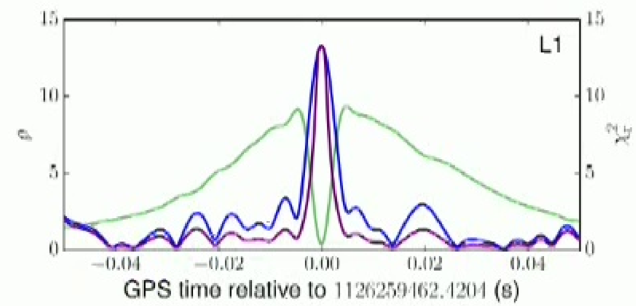
- **Matched filtering**
  - Comparison of theoretical templates against the data
  - Results from three matched filter searches: PyCBC, GstLAL, MBTA
  - Detector-frame masses: $2 - 758 M_\odot$

Optimal matched filter:

$$\langle d|h\rangle = \int \frac{\tilde{d}(f)\tilde{h}^*(f)}{S_n(f)} df$$



- **Coherent excess power statistics**
  - Time-frequency representation of the strain
  - Minimal assumptions
  - Limited to merger signals



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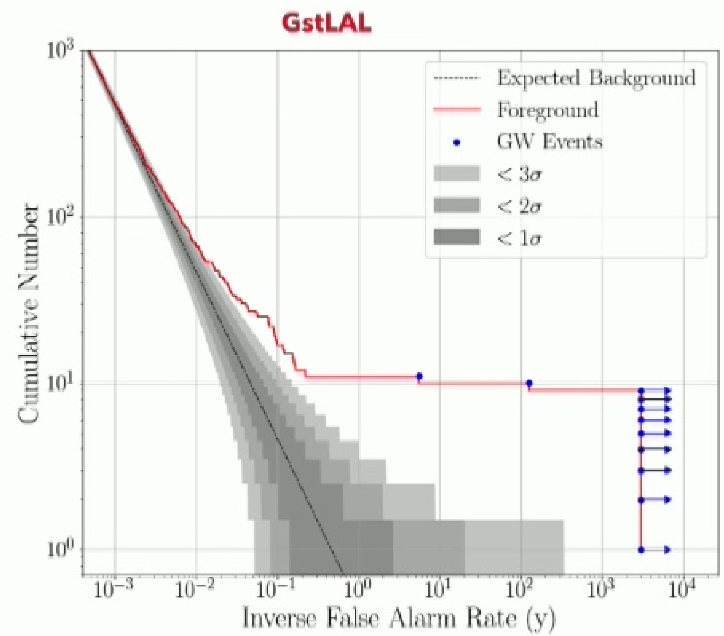
EVENT SELECTION

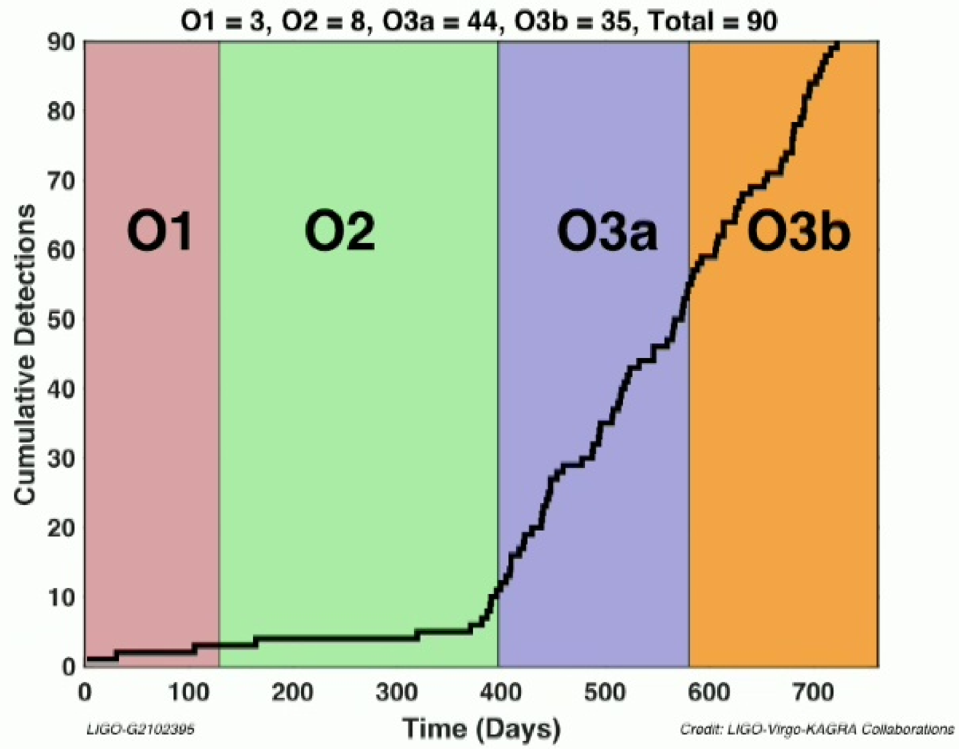
- False-alarm-rate (FAR)
  - Quantifies how often we expect noise to produce an event with the same ranking statistic
  - FAR < 2 per day in GWTC-3
- Astrophysical probability $p_{\rm astro}$
  - Taking into account the astrophysical merger rate, assesses how foreground and background ranking statistic distributions compare
- Select candidates with $p_{\rm astro} > 0.5$ in any search pipeline
  - Catalogue contamination fraction ~10-15%



[GWTC-2]

CONFIDENT GW DETECTIONS

- GWTC-1: 11 GW events from O2 & O2 including GW150914 and GW170817
- GWTC-2 & GWTC-2.1: 44 new GW events (O3a)
- GWTC-3: 35 new GW events



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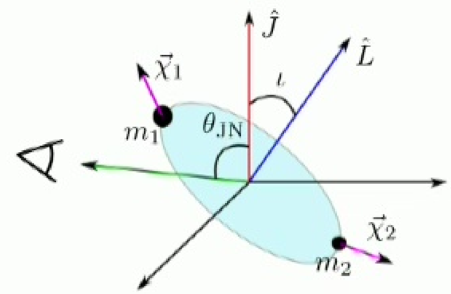
MEASURING PARAMETERS: BAYESIAN INFERENCE

- Circular binary black hole:

$$\vec{\lambda}_{\rm BBH} = \{\underbrace{m_1, m_2, \vec{\chi}_1, \vec{\chi}_2}_{\text{intrinsic}}, \underbrace{D_L, \theta_{\rm JN}, \iota, \alpha, \delta, \phi_c, t_c, \psi}_{\text{extrinsic}}\}$$



- Bayes' theorem:

$$p(h(\vec{\lambda})|d) \propto p(\vec{\lambda}) \times \mathcal{L}(d|h(\vec{\lambda}))$$

posterior prior likelihood

$$\log \mathcal{L} = \frac{1}{2}\langle d - h(\vec{\lambda})|d - h(\vec{\lambda})\rangle$$

Whittle likelihood: assumes stationary, Gaussian noise

- On average, stochastic sampling requires $\mathcal{O}(10^7)$ waveform evaluations
  - Requires efficient sampling methods & computationally fast waveform models

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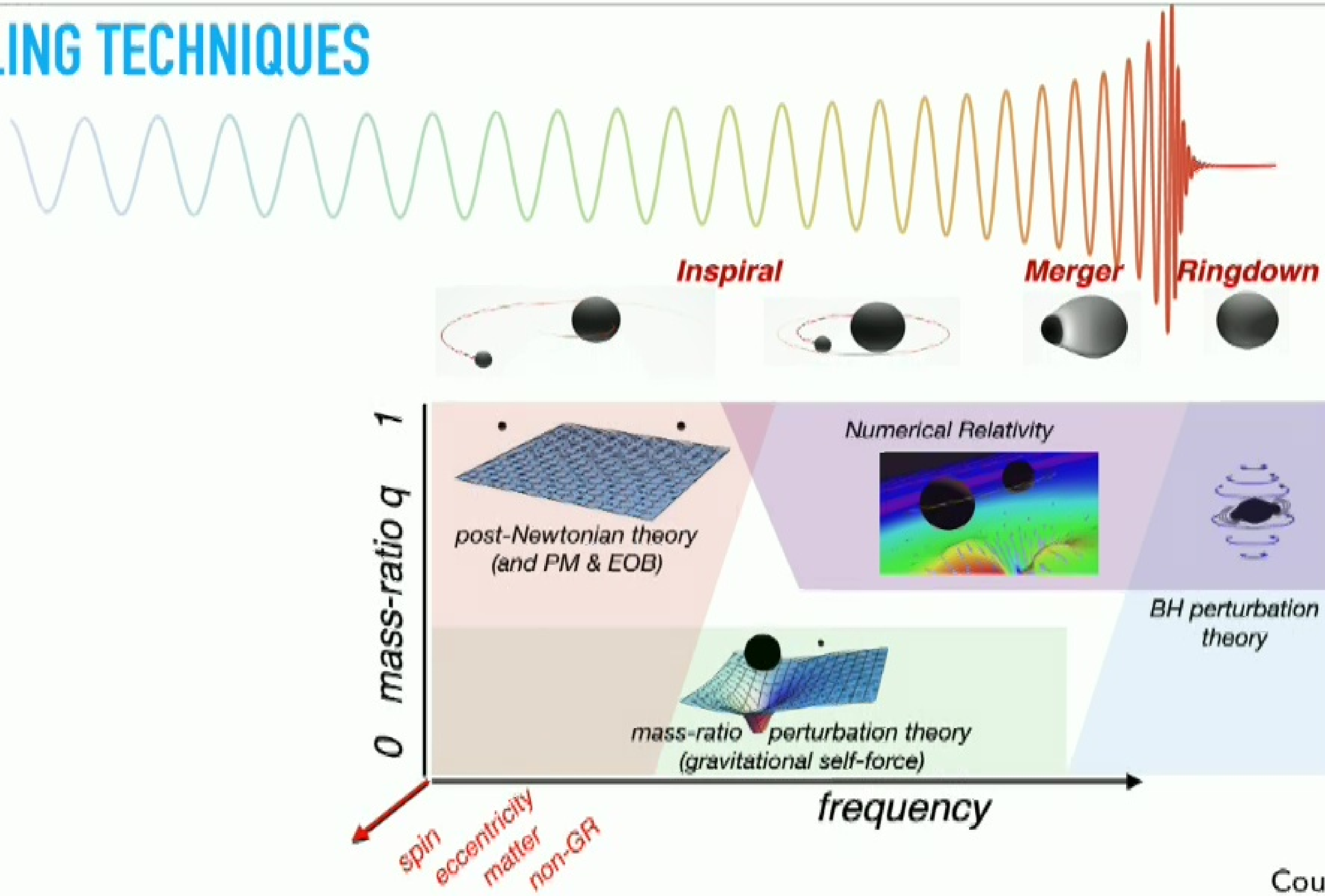
MODELLING TECHNIQUES



Courtesy: H. Pfeiffer

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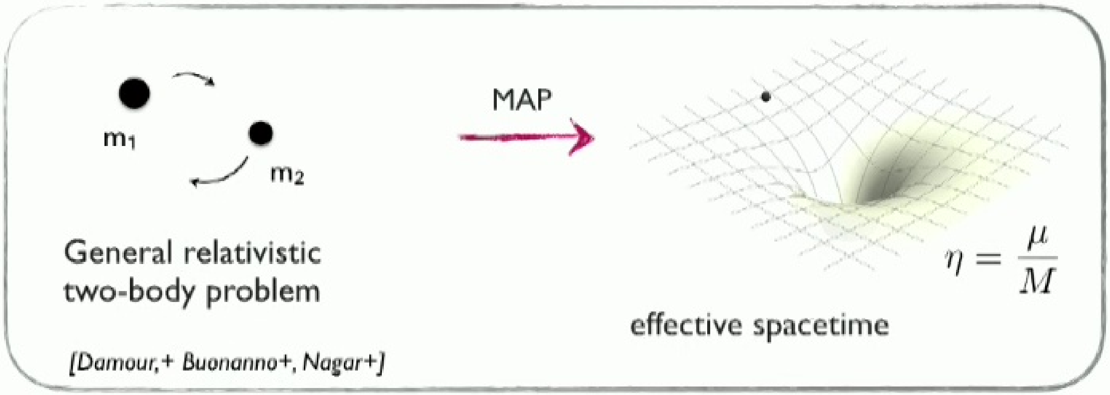
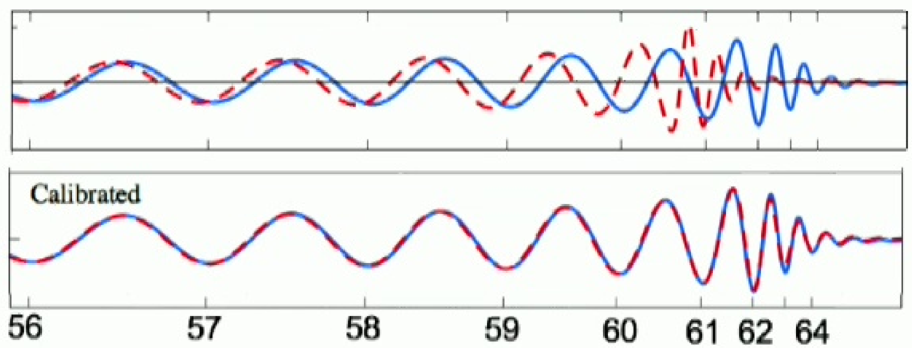
STATE-OF-THE-ART IMR WAVEFORM MODELS

- **Effective-one-body (EOB) models**





[Credit: A. Taracchini]

Key ingredients:

Conservative EOB Hamiltonian of the relative motion

GW dissipation (radiation reaction force)

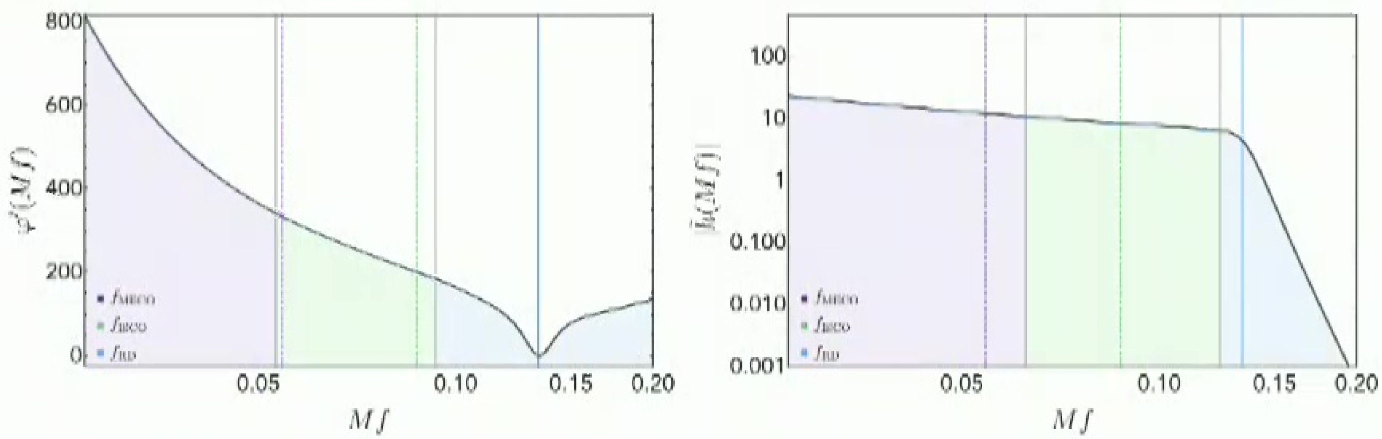
Factorised waveforms

NR simulations for calibration

STATE-OF-THE-ART IMR WAVEFORM MODELS

- **Phenomenological waveform models (IMRPhenom)**
  - Closed-form expressions
  - Analytical information from PN/EOB + pseudo terms
  - NR calibration in the strong-field regime

$$\tilde{h}_{\ell m}(f) = \tilde{A}_{\ell m}(f)e^{-i\tilde{\phi}_{\ell m}(f)}$$

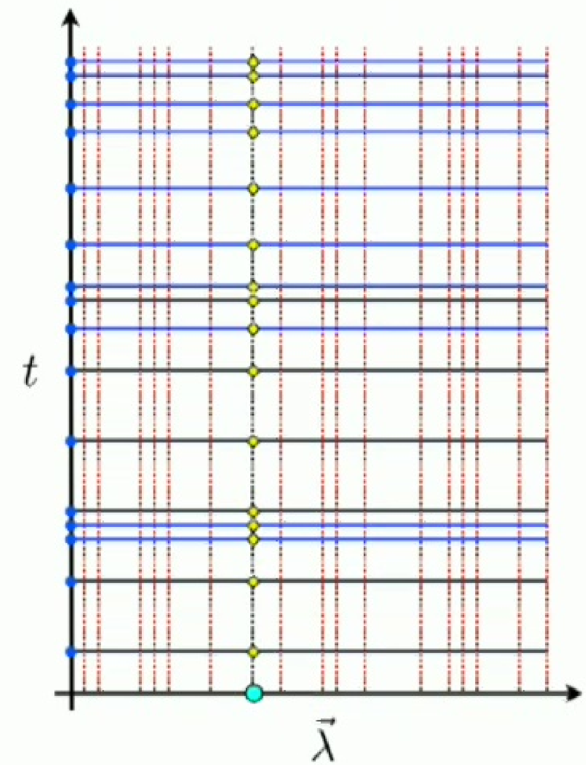


[Ajith+, Santamaria+, Husa+, Khan+, Hannam+, Schmidt+, Pratten+, Garcia-Quiros+, Hamilton+]

Courtesy: G. Pratten

NUMERICAL RELATIVITY SURROGATES

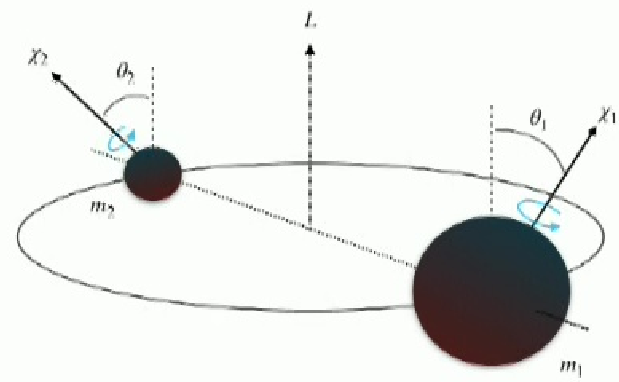
- NR simulations are computationally expensive
  - Limited coverage of the full binary parameter space
- Are pure NR-based waveform models achievable, i.e. no analytic approximations?
  - NR surrogate models *[Canizares+, Field+, Blackman+, Varma+]*
  - Continuous interpolation between discrete waveforms *[Field+, Galley+]*
  - 5D precessing NR surrogate around GW150914:
    - ~270 NR simulations spanning ~20 orbits [Blackman+ inc. PS]
  - 7D precessing NR surrogate between mass ratios 1-4 and spins ≤ 0.8
    - ~1528 NR simulations



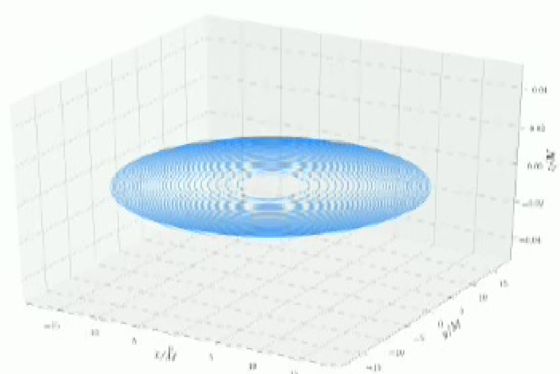
[Blackman+, 2016]

PRECESSION

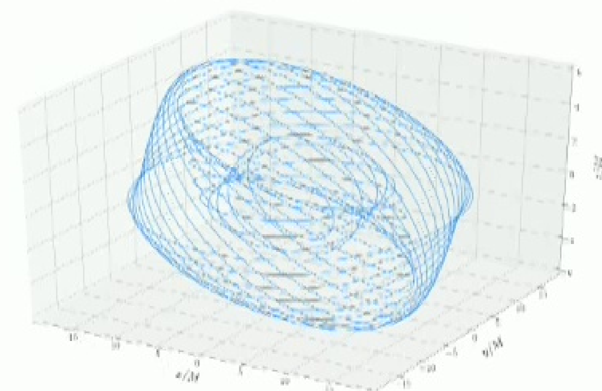
- Spins misaligned with the orbital angular momentum source precession:
  - Time-dependent spatial orientation of spins and orbital plane (quasi-spherical orbits)
  - Lense-Thirring precession ("frame-dragging")
  - Occurs at 1.5PN (spin-orbit coupling)
  - Spin-spin couplings (2PN) induce nutation
  - 7D



No spins/aligned spins



Precessing spins



Courtesy: G. Pratten

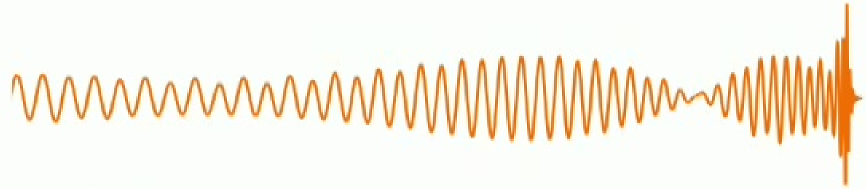
PRECESSION

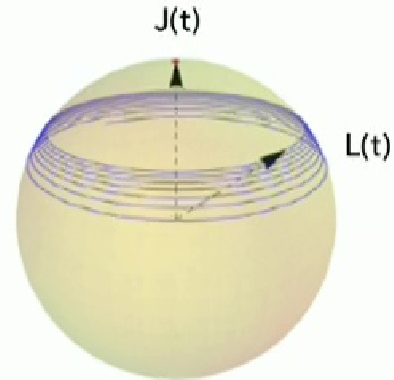
- Impact of precession on the gravitational-wave signal:
  - Amplitude & phase modulations
    - Note: Strength depends on orientation relative to an observer
  - Excitation of higher-order multipoles
- Modelled approximately in all IMR waveform models:

$$h^{\mathrm{P}}_{\ell m} = \sum_{m'=-\ell}^{\ell} \mathbf{R}_{\ell m m'} h^{\mathrm{co-prec}}_{\ell m'} \times h^{\mathrm{RD}}_{\ell m} \approx \sum_{m'=-\ell}^{\ell} \mathbf{R}_{\ell m m'} h^{\mathrm{AS}}_{\ell m'} \times h^{\mathrm{RD}}_{\ell m}$$

[Schmidt+, 2010&2012]

  - (Almost) No calibration to NR in the precessing sector



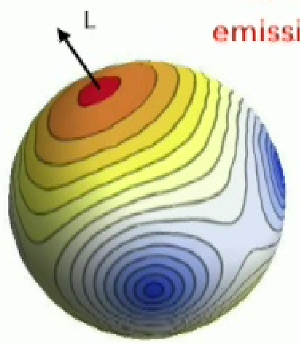


HIGHER-ORDER MODES

- Asymmetries in the binary excited higher-order multipoles

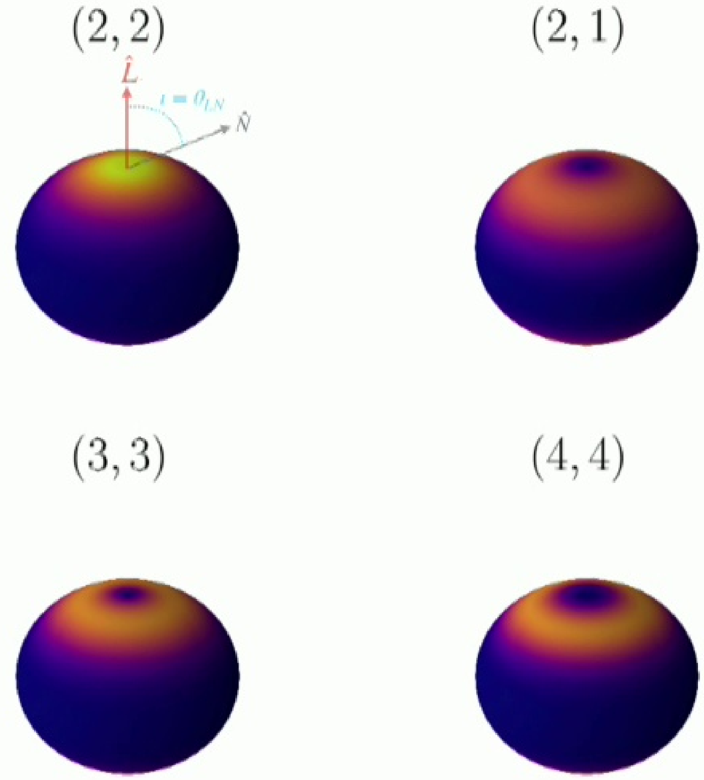
$$h(t) = \sum_{m=-\ell}^{m} {}^{-2}Y_{\ell m}(\theta, \phi) h_{\ell m}(t)$$

  - Unequal masses
  - Unequal spins
  - (Eccentricity)
  - Precession



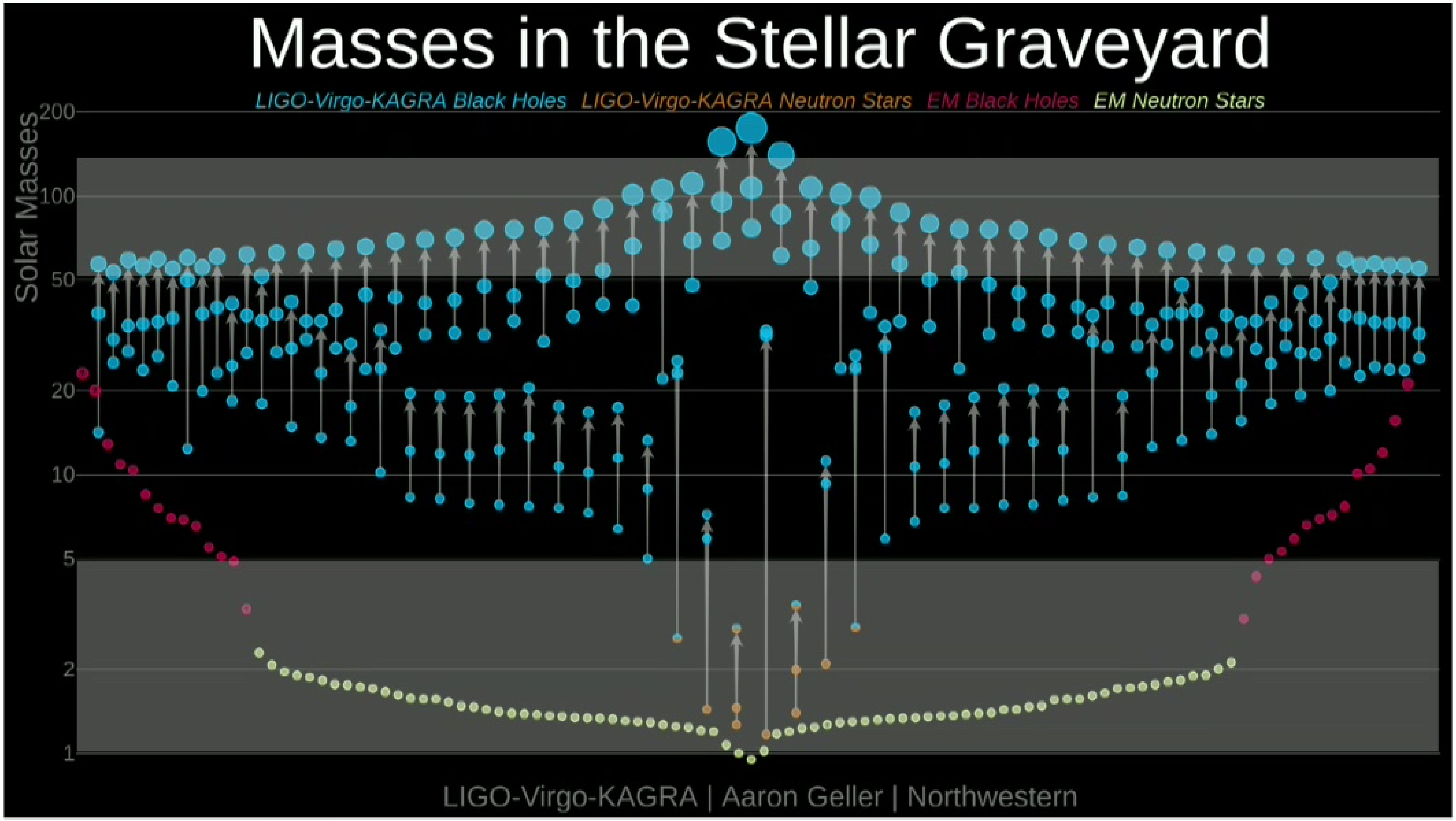
maximum GW emission along L

spherical harmonics



CURRENT GENERATION OF BBH WAVEFORMS

- IMRPhenomXPHM [Pratten+]
  - NR calibration for the aligned-spin sector
  - Precession: PN approximation, no calibration to NR
  - Higher-order modes: $(2, \pm 2), (2, \pm 1), (3, \pm 3), (3, \pm 2), (4, \pm 4)$
- SEOBNRv4PHM [Ossokine+]
  - NR calibration for the aligned-spin sector
  - Precession: from EOB dynamics, no calibration to NR
  - Higher-order modes: $(2, \pm 2), (2, \pm 1), (3, \pm 3), (4, \pm 4), (5, \pm 5)$
- NRSur7dq4 [Varma+]:
  - Higher-order modes: all $\ell \leq 4$
  - NR precession



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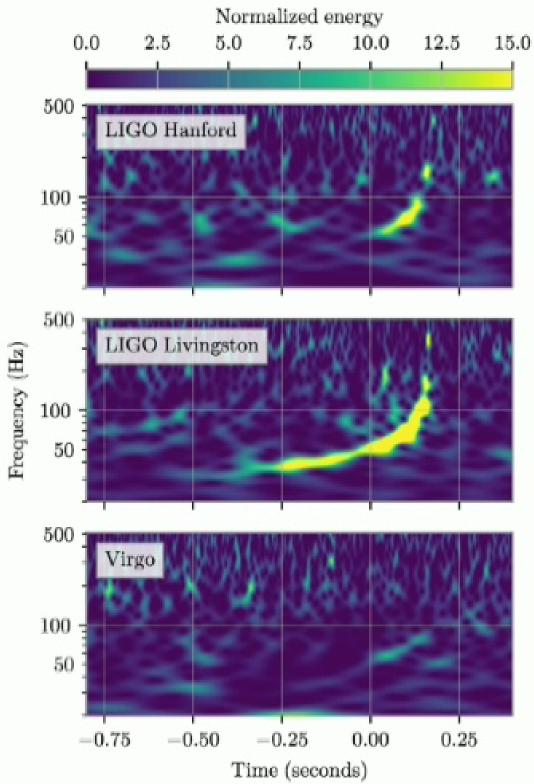
HIGHLIGHTS FROM O3

GW190412

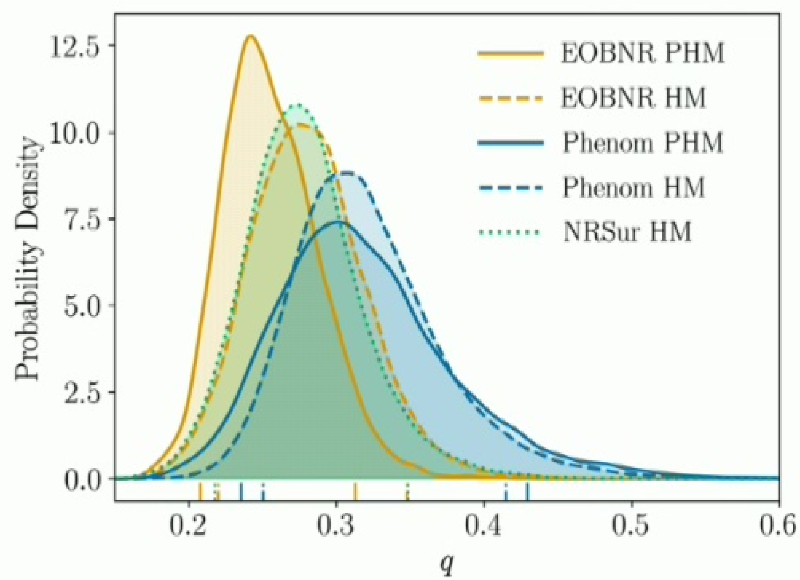
[LVC, PRD 102, 043015 (2020)]

- The first clear asymmetric (=unequal mass) binary black hole



$$m_1 \sim 30 M_\odot,\ m_2 \sim 8 M_\odot$$

$$q = 0.28^{+0.12}_{-0.07}$$



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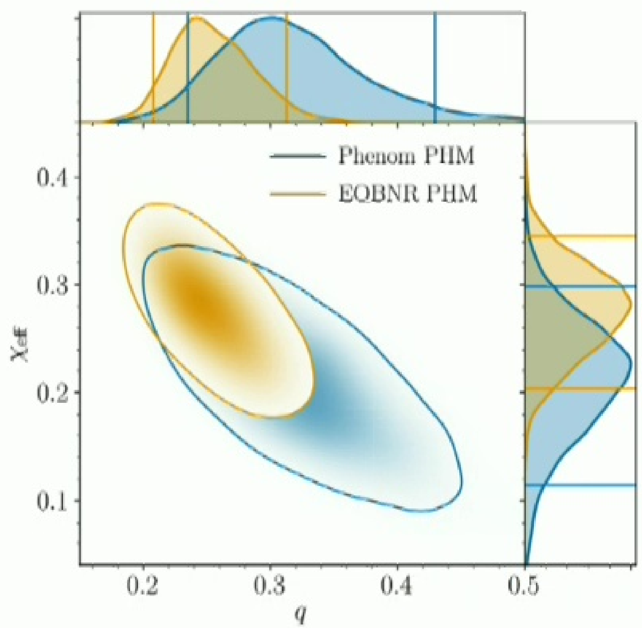
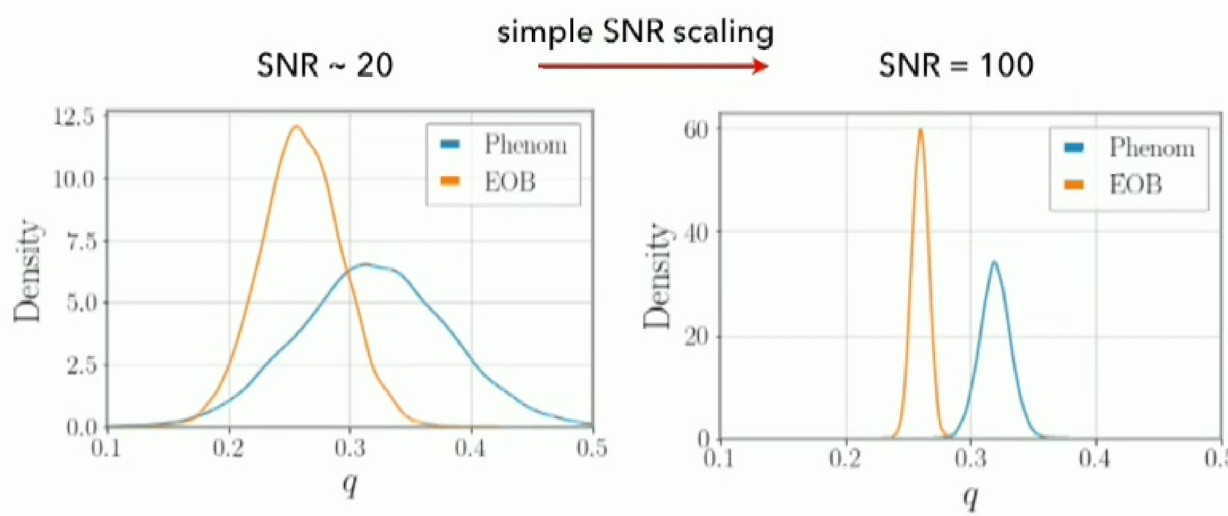
GW190412

- First signs of waveform systematics?





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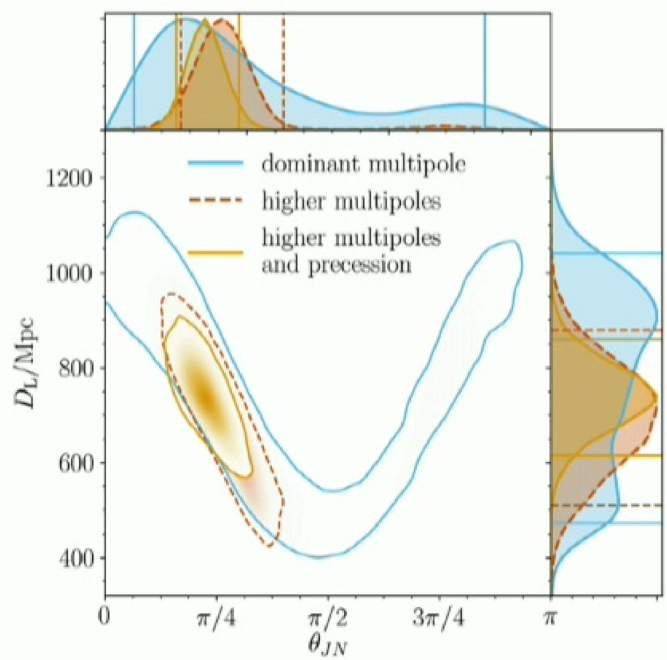
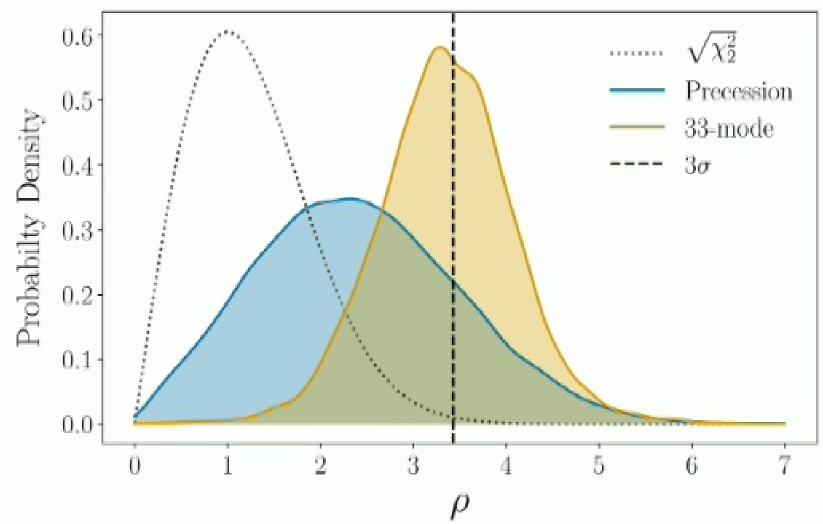
GW190412

- Higher-Order modes break parameter degeneracies





(3,3)-mode is found to be the strongest higher-order mode

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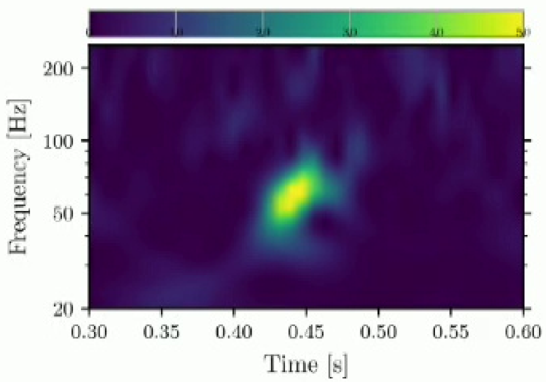
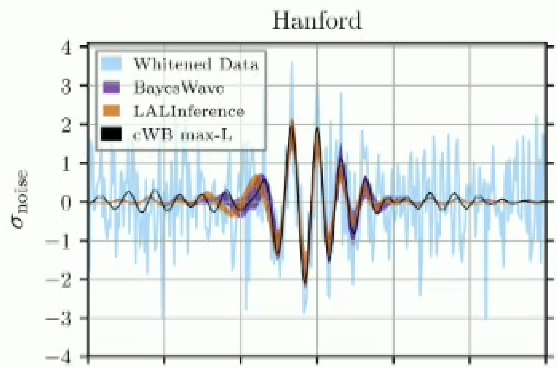
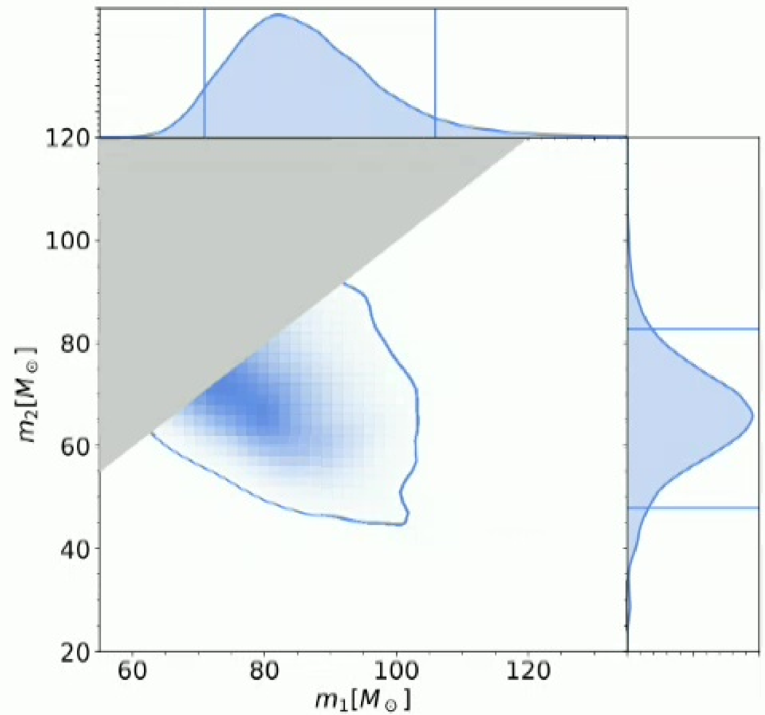
GW190521

[LVC, Phys. Rev. Lett. 125, 101102 (2020)]

- Very massive binary black hole: $m_1 = 85^{+21}_{-14} M_\odot \quad m_2 = 66^{+17}_{-16} M_\odot$







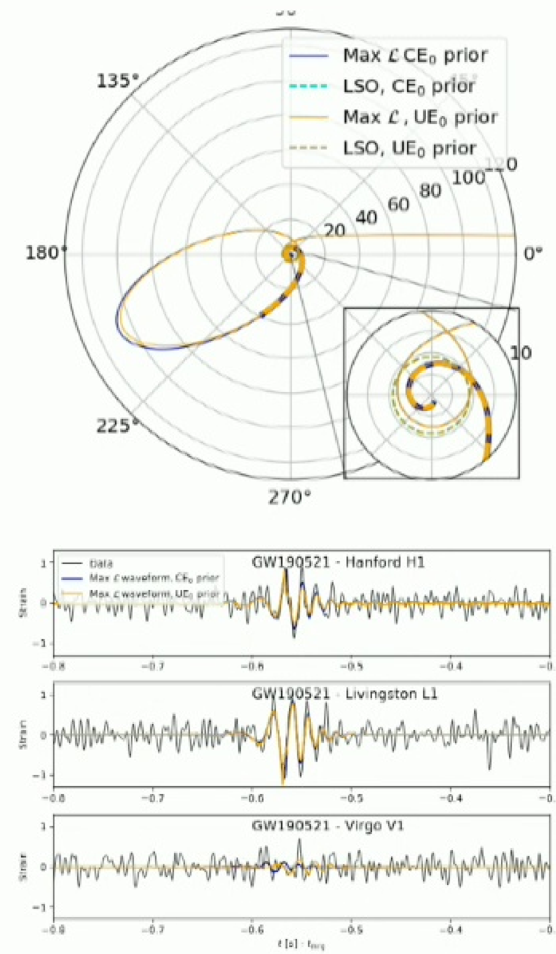
- Remnant mass: $142^{+28}_{-16} M_\odot$

Intermediate mass black hole!

GW190521

- Primary mass challenges formation scenarios
  - Pair instability supernova upper mass gap
  - Hierarchical mergers?

- High mass = short duration
  - Fits a chirp but … there is room for alternative interpretations
- Eccentric merger [Gayathri+], hyperbolic encounter [Gamba+]
- Head-on collision of Proca stars [Calderon-Bustillo+]

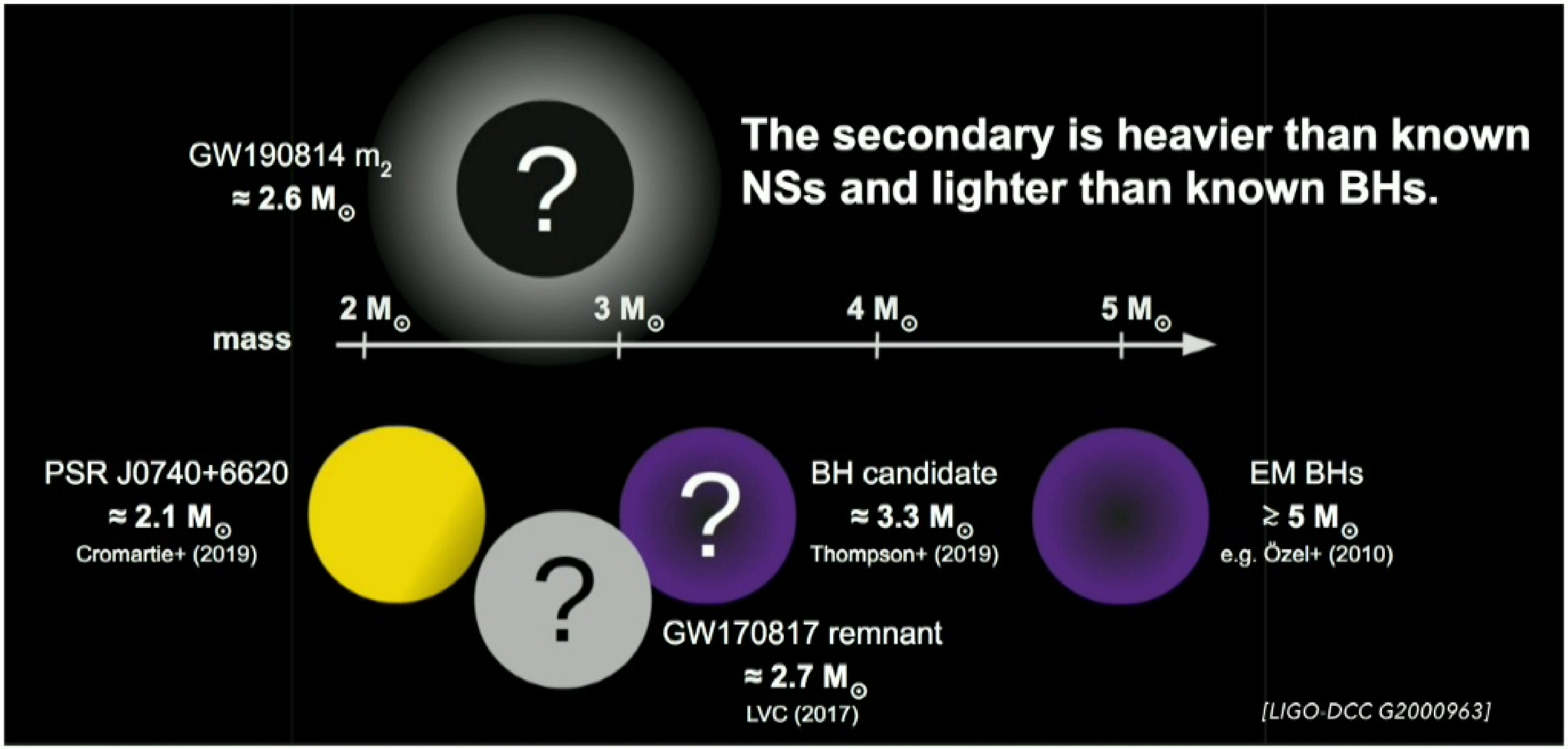


[Gamba+]

GW190814

[LVC, ApJL 896:L44 (2020)]

- A binary black hole or a neutron star – black hole binary?



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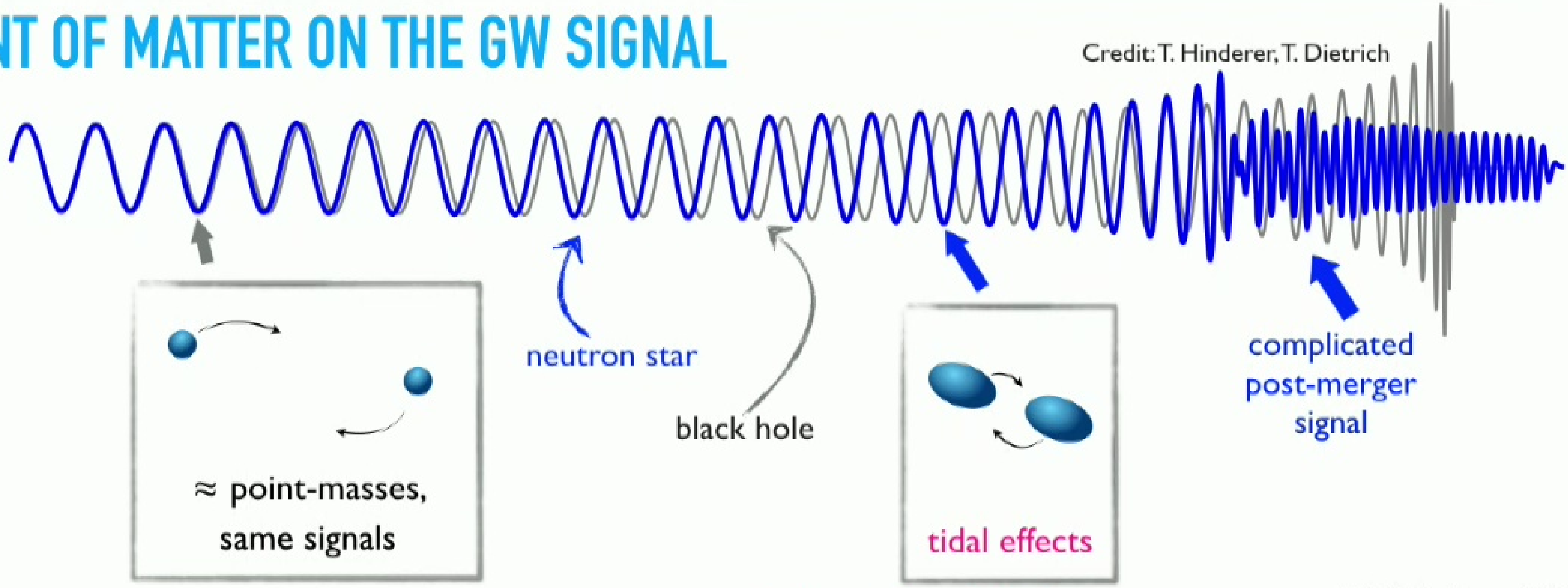
IMPRINT OF MATTER ON THE GW SIGNAL



+ tidal excitation of internal oscillation modes

Some energy used to deform the NS

Moving tidal bulges produce GWs

$$\dot{E}_{\rm GW} \sim \left[\frac{d^3}{dt^3}\left(Q_{\rm orbit} + Q_{\rm NS}\right)\right]^2$$

Tidally induced quadrupole moment

$$Q_{ij}^{(\ell)} = -\lambda_\ell \mathcal{E}_{ij}^{(\ell)}$$

tidal deformability

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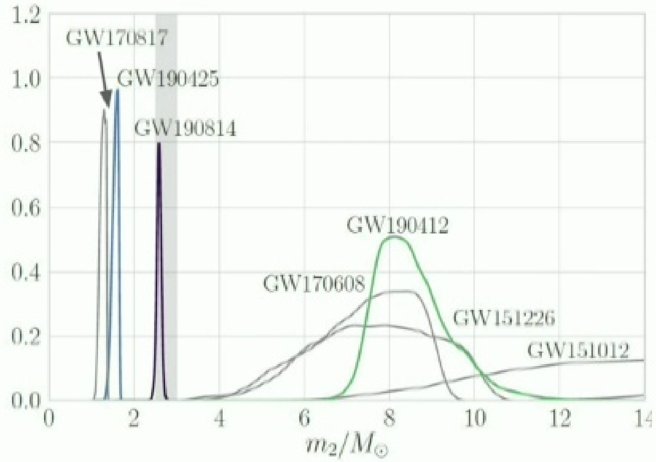
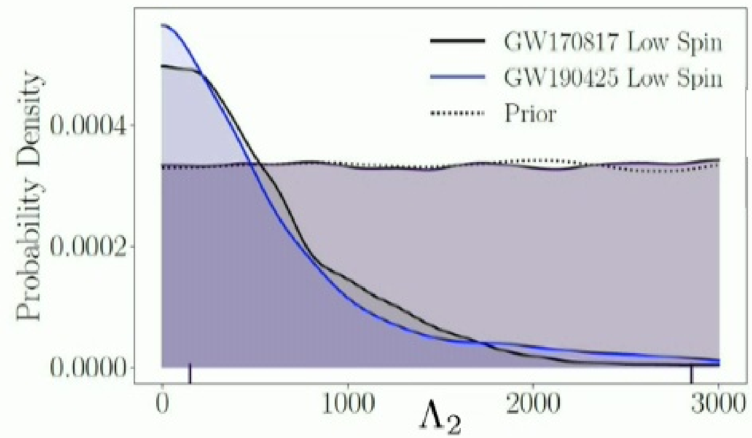
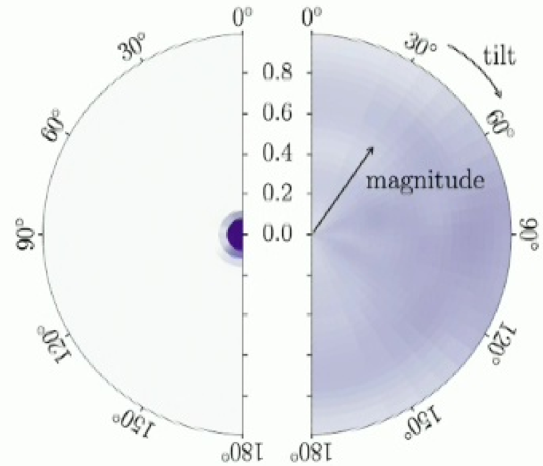
GW190814 – WHAT IS THE NATURE OF THE SECONDARY?







Difficult to reconcile with neutron star maximum mass constraints

No tidal information obtained

Asymmetric mass ratio suppresses tidal effects

Low black hole spin makes tidal disruption unlikely

$$\delta\varphi_{\rm tidal} \propto -\frac{117}{16}\frac{q^4}{(1+q)^5}\frac{\Lambda_2}{X_1X_2}x^{5/2} \times ({\rm PN\ Corrections})\,;\ q \leq 1$$

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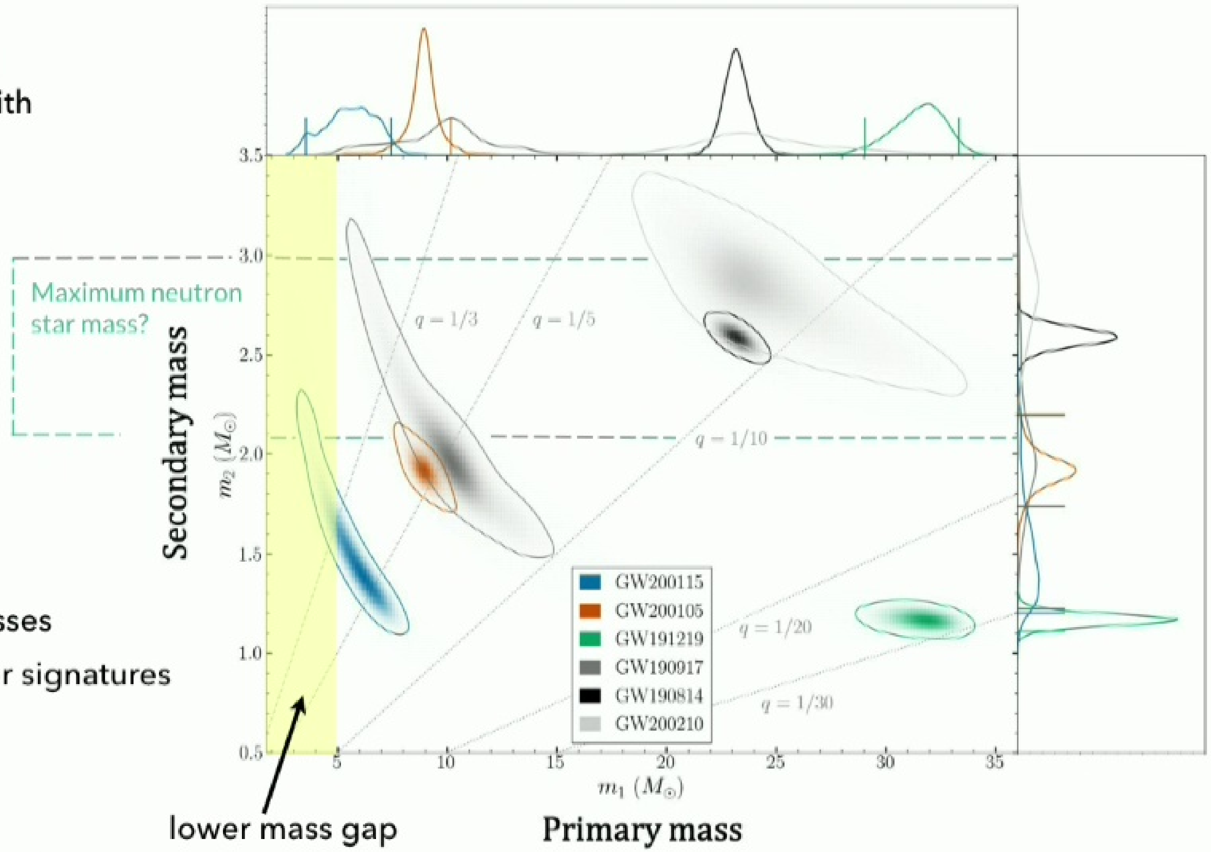
NEUTRON STAR – BLACK HOLE BINARIES

First detections of binaries consistent with NSBH



Consistency based on masses

No measurement of matter signatures

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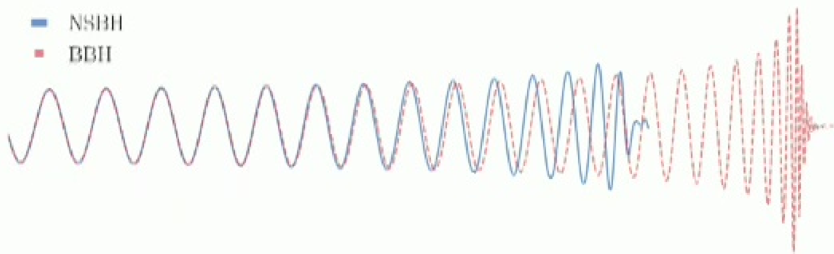
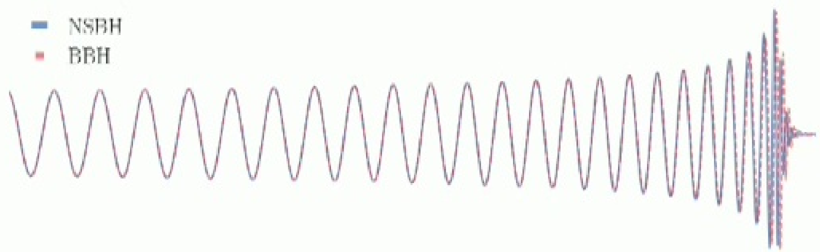
Credit: LVK, LIGO-G2102416

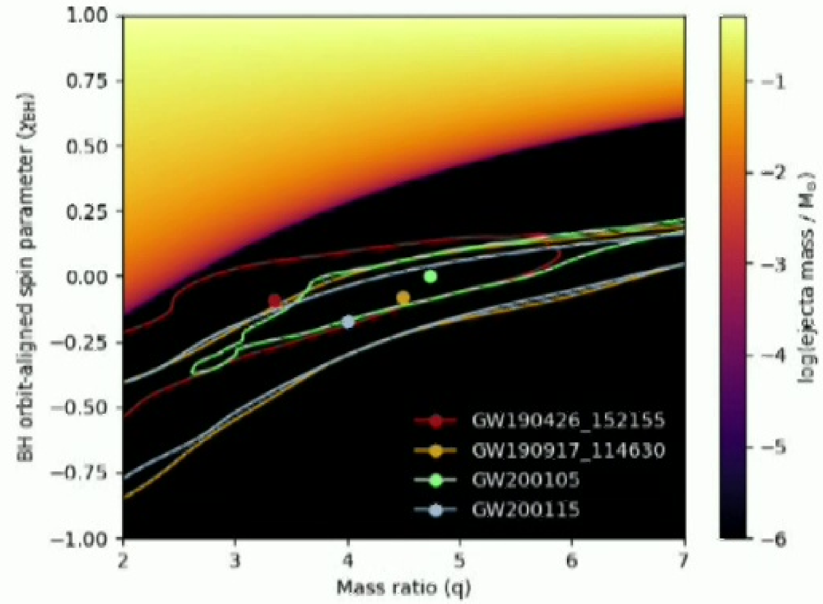
WHAT ABOUT MATTER SIGNATURES?

- Comparable masses & aligned BH spin: tidal disruption



- Unequal masses & anti-aligned BH spin: indistinguishable from BBH





[Gompertz+, inc. PS]

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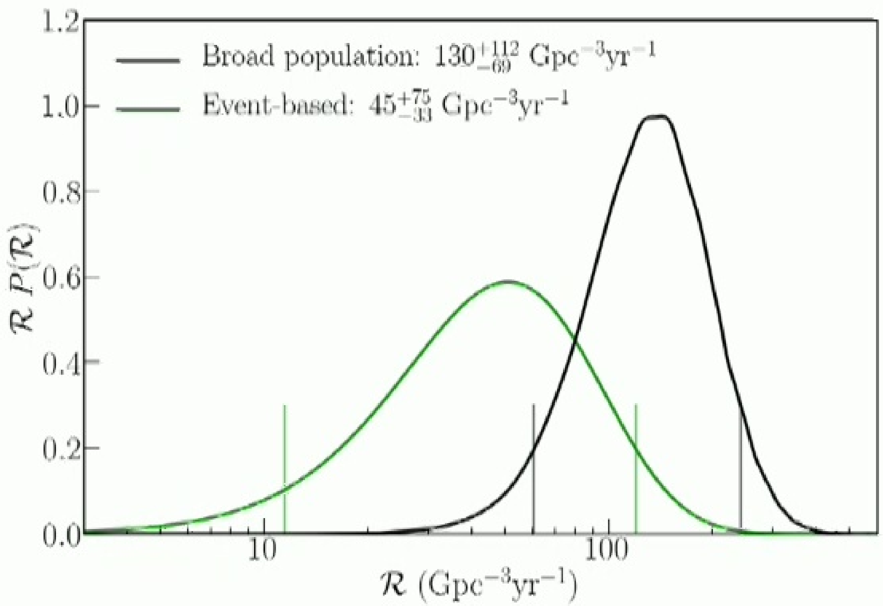
NEUTRON STAR – BLACK HOLE BINARIES

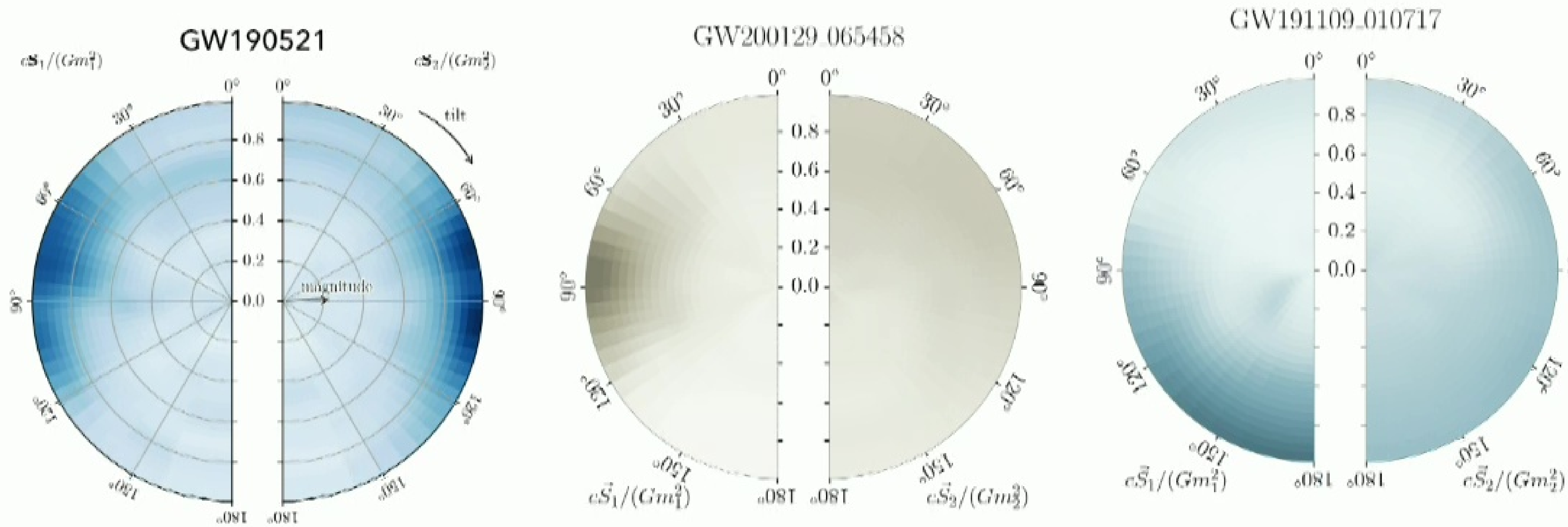
- No detections in O1 & O2: upper limit on NSBH merger rate of $610\,\mathrm{Gpc^{-3}\,yr^{-1}}$
- O3 detections allow the first direct measurement of the NSBH merger rate of $130^{112}_{-69}\,\mathrm{Gpc^{-3}\,yr^{-1}}$



[LVK, ApJL 915:L5]

BLACK HOLE SPINS

- Most BHs are consistent with having small and positive spins
- But there are some tantalising exceptions:



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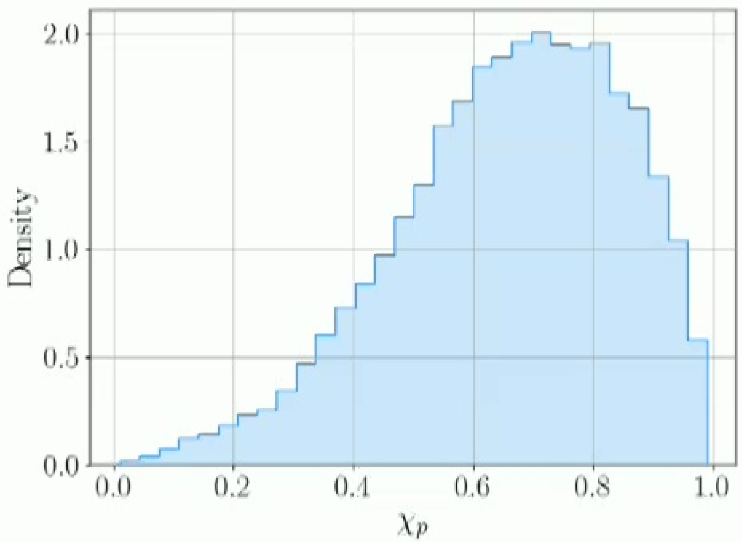
[LVK, ApJL 900:L13 (2020), LVK arXiv:2011.03606]

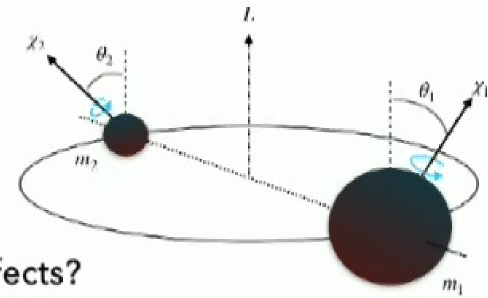
GW190521



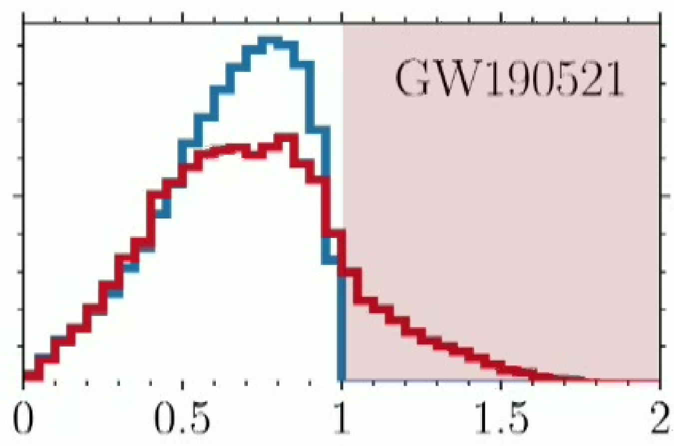
$$\chi_p := \max\left\{\frac{||\vec{S}_{1\perp}||}{m_1^2}, \kappa\frac{||\vec{S}_{2\perp}||}{m_2^2}\right\}$$

$$\kappa = q(4q+3)/(4+3q)$$

[Schmidt+]



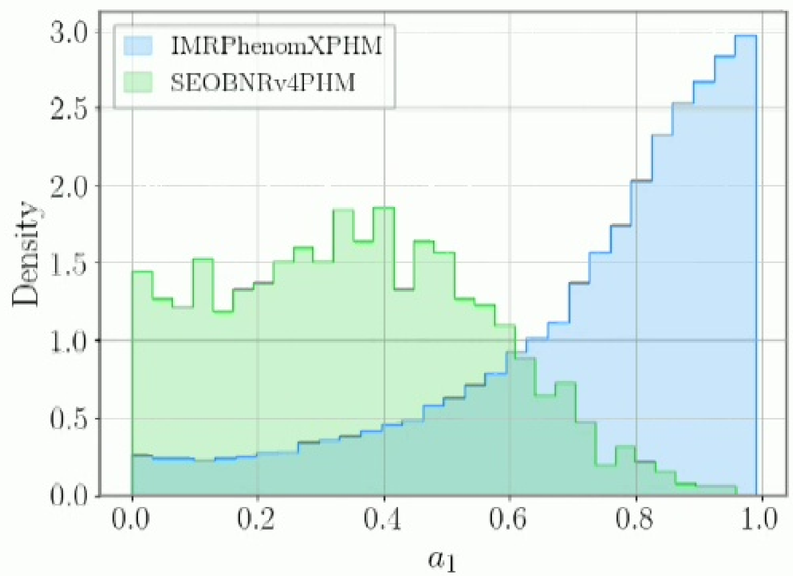
Two-spin effects?

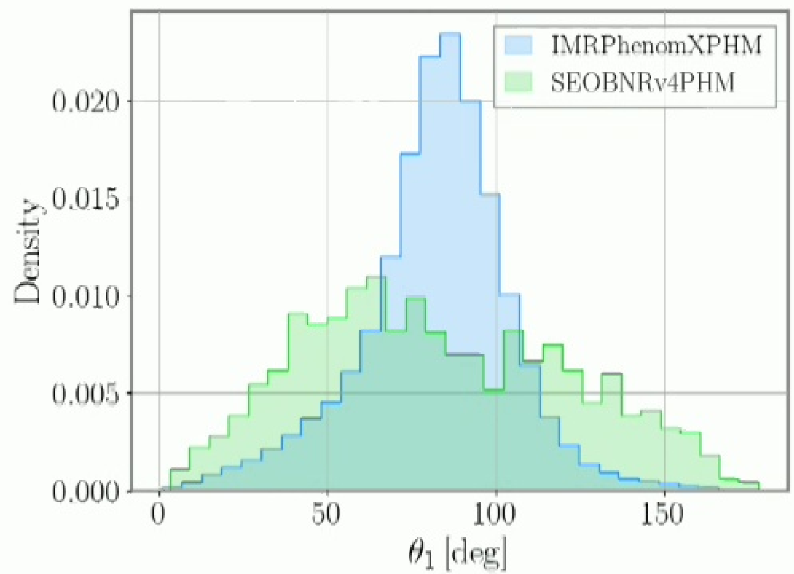


[Gerosa+, inc PS]

GW200129

- "Vanilla" BBH: $m_1 = 34.5^{+9.9}_{-3.2} M_\odot$ $m_2 = 28.9^{+3.4}_{-9.3} M_\odot$
- Loudest BBH to date: SNR ~ 27
- Astrophysical origin probability > 99%





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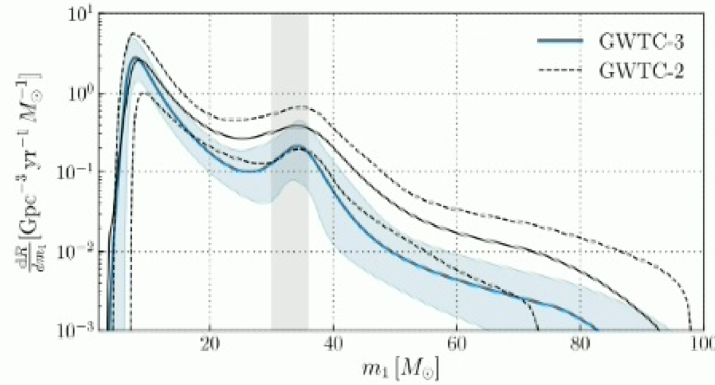
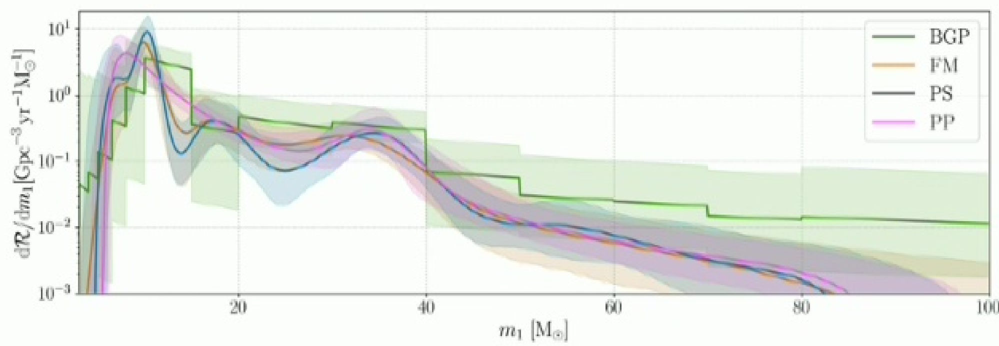
POPULATIONS OF BLACK HOLES

[LVC, arXiv 2111.03634 (2021)]

- Primary mass distribution consistent with a power law distribution with a Gaussian feature
  - Feature appears at $\sim 34 M_\odot$
  - BH mass spectrum likely turns over at $\sim 7.8 M_\odot$
  - Minimum BH mass in BBH is $2.5^{+0.67}_{-0.44} M_\odot$
  - Evidence for substructure





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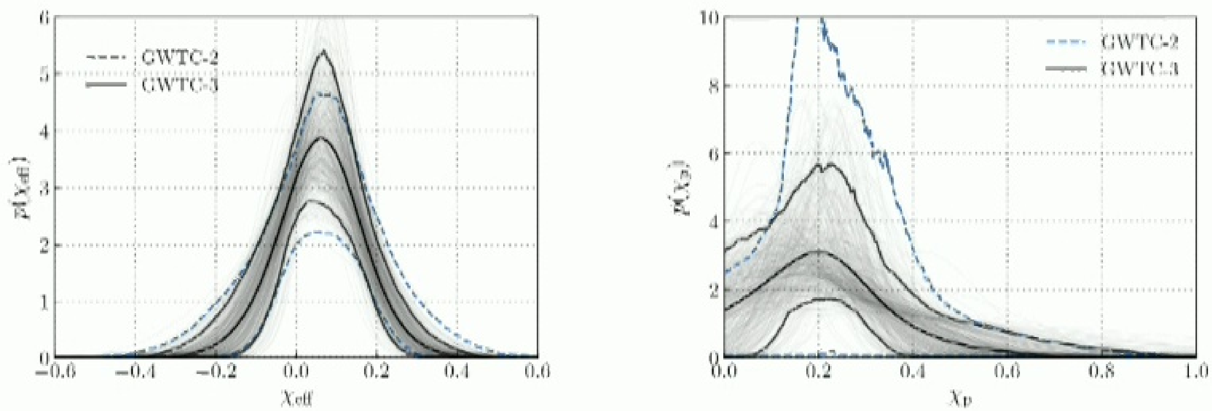
WHAT ABOUT SPINS?

[LVC, arXiv 2111.03634 (2021)]

- Spin distributions tightly coupled to formation channel



- $\chi_{\rm eff}$ mean at 0.06 $\quad \chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot \hat{L}_N}{M}$ *[Damour;Racine; Ajith+]*
    - But fraction of BBH with $\chi_{\rm eff} < 0$
- Weak evidence of orbital precession among the population of BBHs in GWTC-3

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TESTING GENERAL RELATIVITY

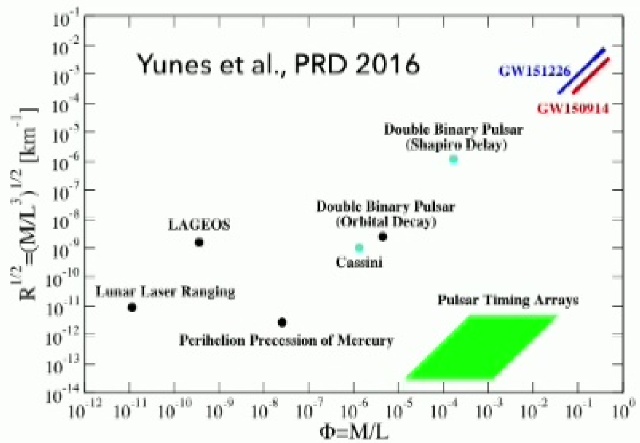
- Residual power
- Propagation of gravitational waves (dispersion)

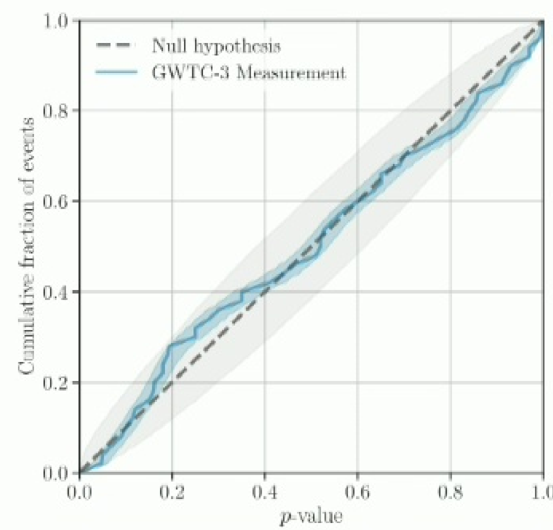
$$m_g \leq 1.27 \times 10^{-23}\,\mathrm{eV/c^2}$$

- Generation of gravitational waves (parameterised tests)
- Polarisation tests
- Tests of the nature of the remnant
- Consistency between progenitor and remnant

We find no evidence for new physics beyond general relativity, for black hole mimickers, or for any unaccounted systematics.

[LVK, arXiv:2111.06861]





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