LVK Data Analysis
A Crash Course

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Outline of the talk

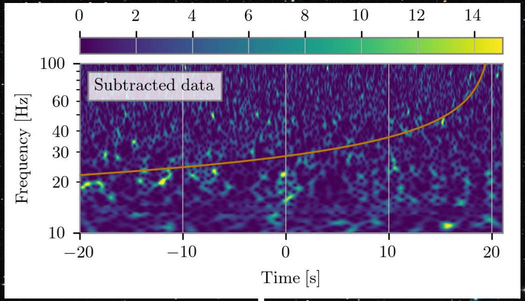
1. Search pipelines (Explained by Ester)
   1.1. General structure
   1.2. Software used

2. Parameter Estimation (the Catalog!)
   2.1. General framework
   2.2. Overview of O3
   2.3. Software used

3. Other important analysis (there are many more!)
   3.1. Populations
   3.2. Testing GR
   3.3. GW Lensing
   3.4. Subsolar Mass Search

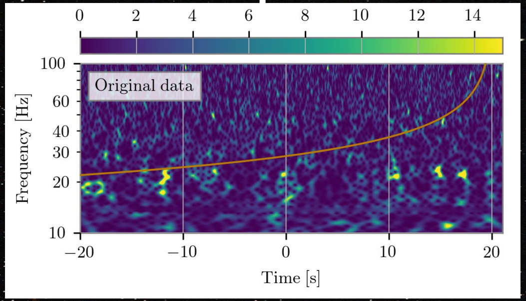
Timeline of an Event

Search pipelines (MBTA, GstLAL, PyCBC…) & IDQ

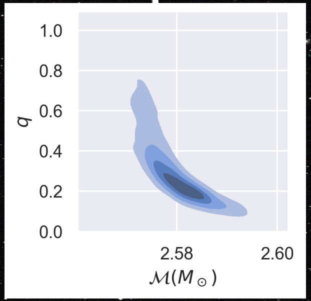


LALInference, Bilby & RIFT

(Offline) Candidate identification & validation → Noise & glitch removal → Parameter estimation → Population, Testing GR …



BayesWave



Parameter Estimation

Parameter Estimation in LVK: The Framework

- Bayes' Theorem

Likelihood

Prior probability

Posterior probability

$$p(\vec{\theta}|\mathbf{s}) = \frac{\mathcal{L}(\mathbf{s}|\vec{\theta})\pi(\vec{\theta})}{\mathcal{Z}}$$

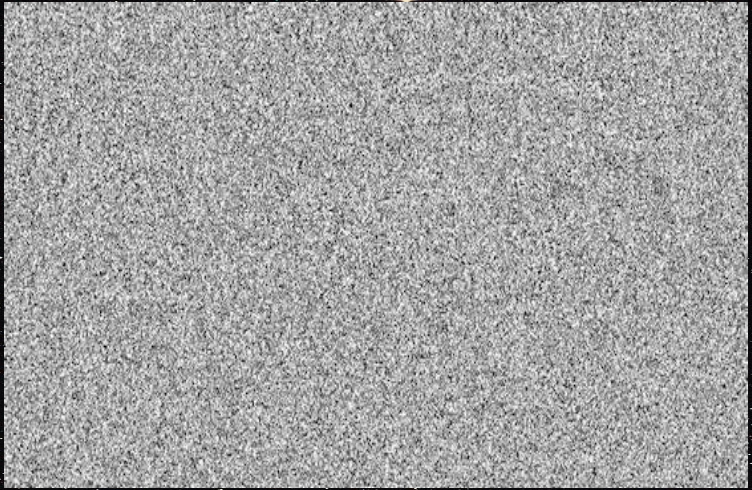
Evidence

$$\mathcal{Z} = \int \mathcal{L}(\mathbf{s}|\vec{\theta})\pi(\vec{\theta})d\vec{\theta}$$

Parameter Estimation in LVK: The Likelihood

- Gravitational waves likelihood

What is Gaussian noise?



$$\mathcal{L}(\mathbf{s}|\vec{\theta}) = \exp\left\{-\frac{1}{2}\sum_i \langle s_i - h_i(\vec{\theta}), s_i - h_i(\vec{\theta})\rangle_i\right\}$$

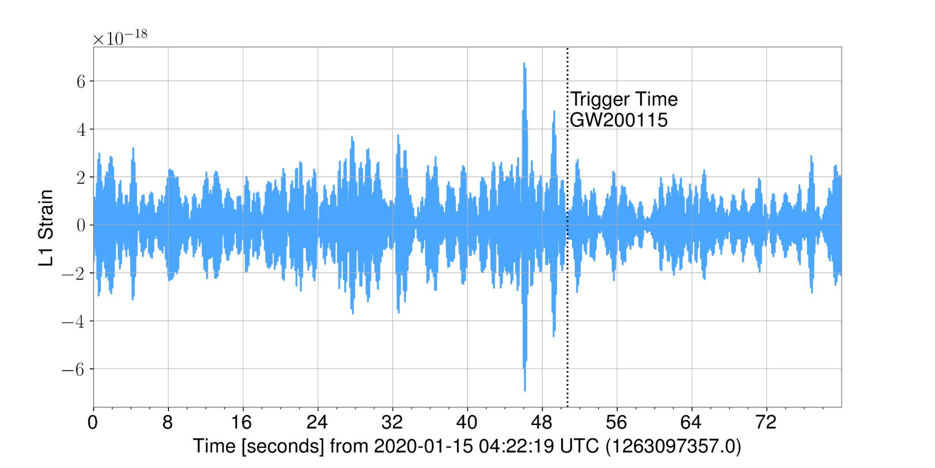
$$\langle a, b\rangle = 4\int_{f_{\min}}^{f_{\max}} \frac{\tilde{a}^*(f)\tilde{b}(f)}{S_n(f)}df$$

with $\mathbf{s}$ the strain, $h_i(\vec{\theta})$ our model evaluated at the parameters values of $\vec{\theta}$ and $S_n(f)$ the estimation of the PSD.

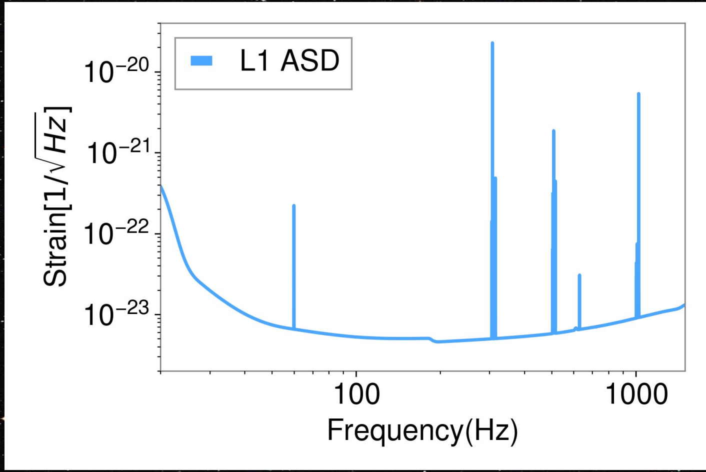
Parameter Estimation in LVK: The PSD

- Spectral estimation tool is BayesWave
- The PSD completely characterises the detector noise around the trigger time (assuming non-gaussianities/glitches have been extracted).
- It represents a critical component of template-based parameter estimation

BayesWave turns the strain …



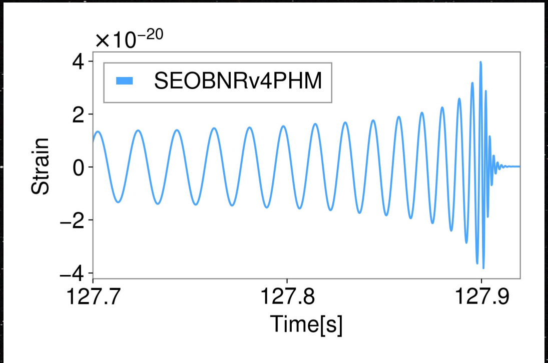
… into an ASD (PSD)

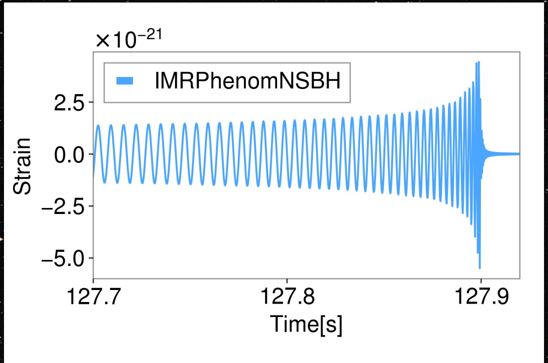


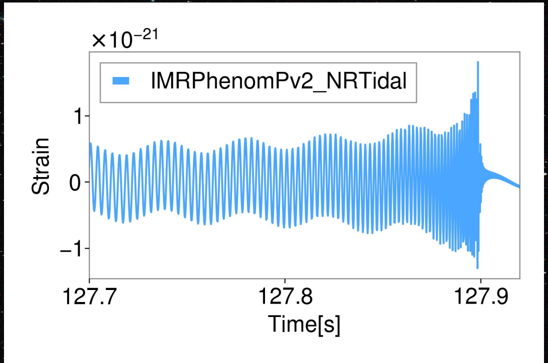
Parameter Estimation in LVK: The Priors I

- What do we think we have found? Based on trigger parameters we make an educated guess. The following waveform list is not exhaustive.

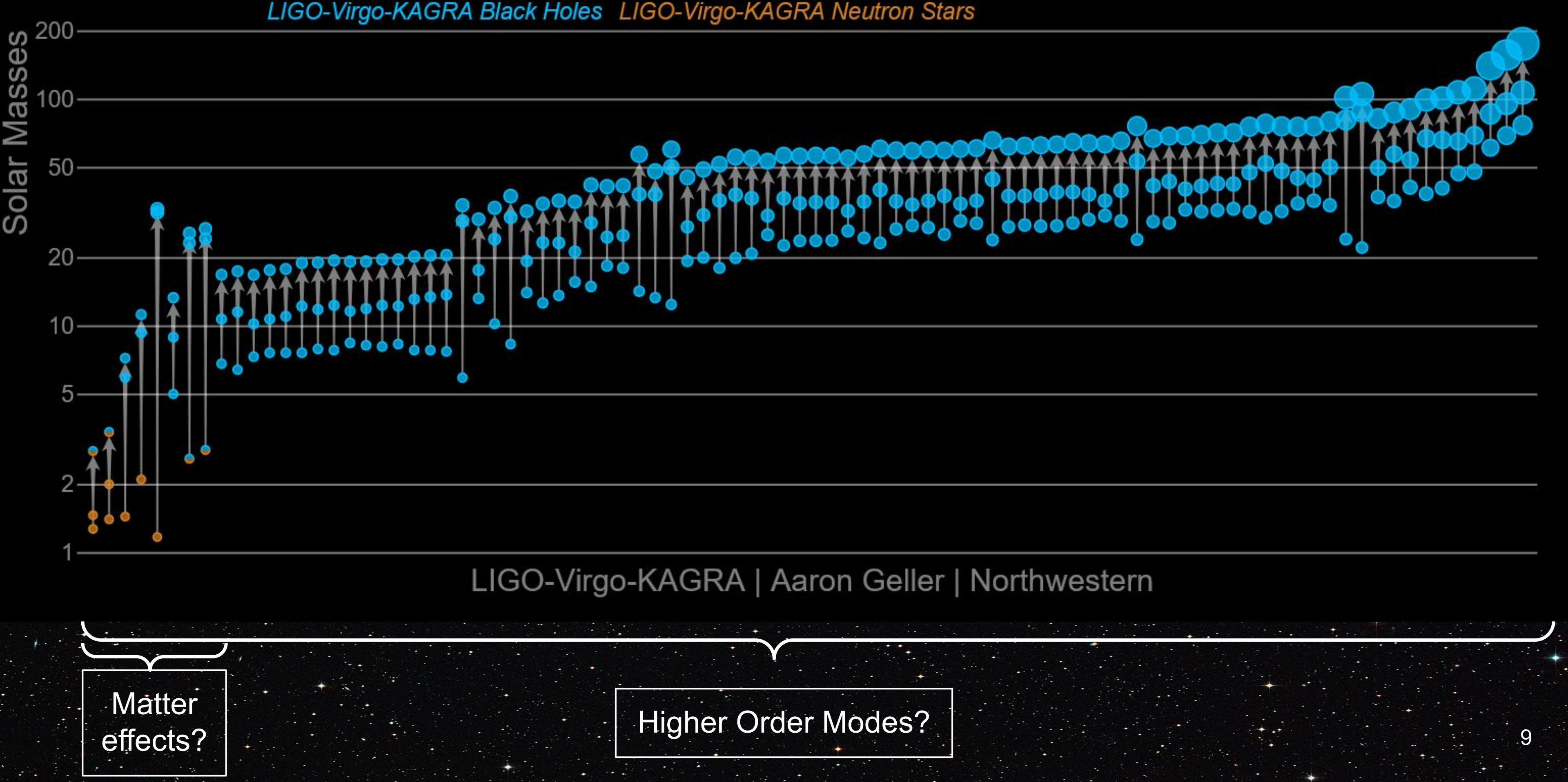
    - BBH → SEOBNRv4PHM & IMRPhenomXPHM
    - NSBH → IMRPhenomNSBH & SEOBNRv4_ROM_NRTidalv2_NSBH
    - BNS → IMRPhenomPv2_NRTidal & SEOBNRv4_T







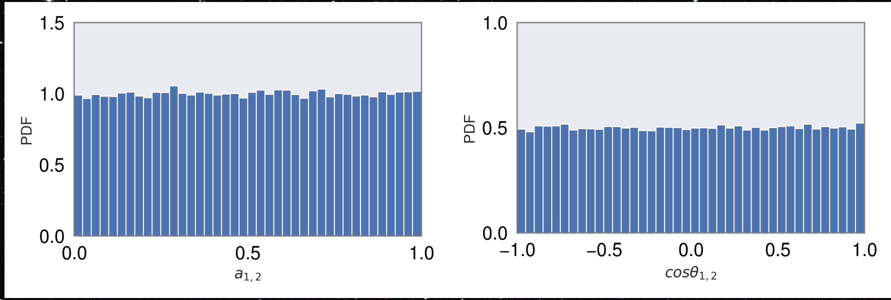
Masses in the Stellar Graveyard

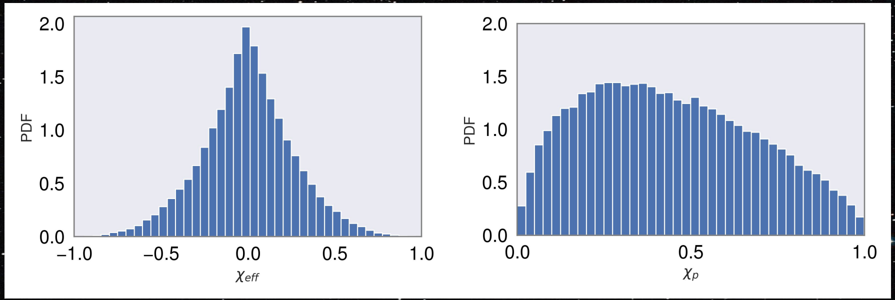


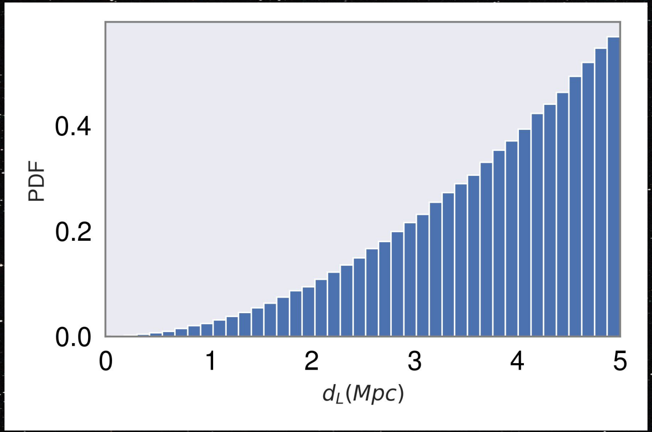
Parameter Estimation in LVK: The Priors II

Uniform in physical parameters

- What prior range and distributions?
  - How wide? $\Delta\mathcal{M} \sim 1/N_{cycles}$
- What parameters do we sample from?
  - Parameters directly used in the waveform?
  - Physical parameters?



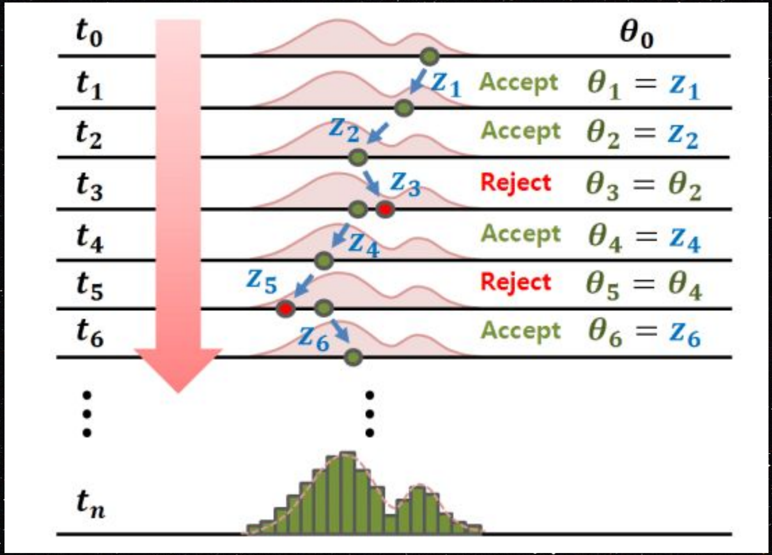




Parameter Estimation in LVK: The Algorithm

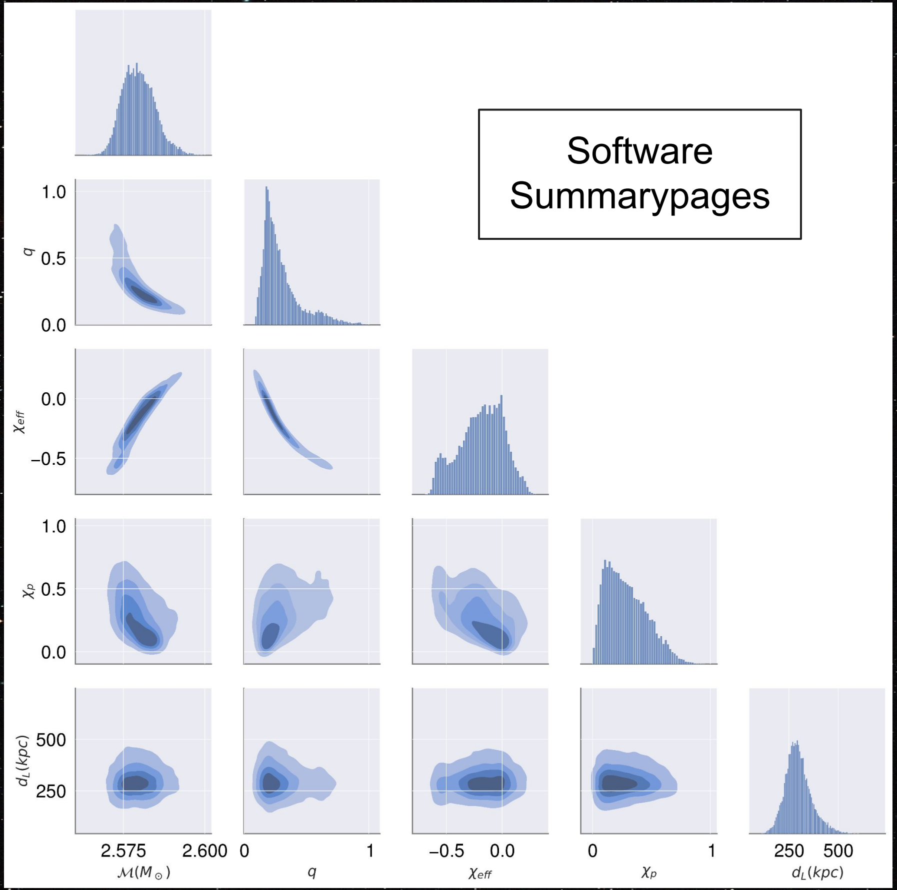
Markov Chain Monte Carlo overview

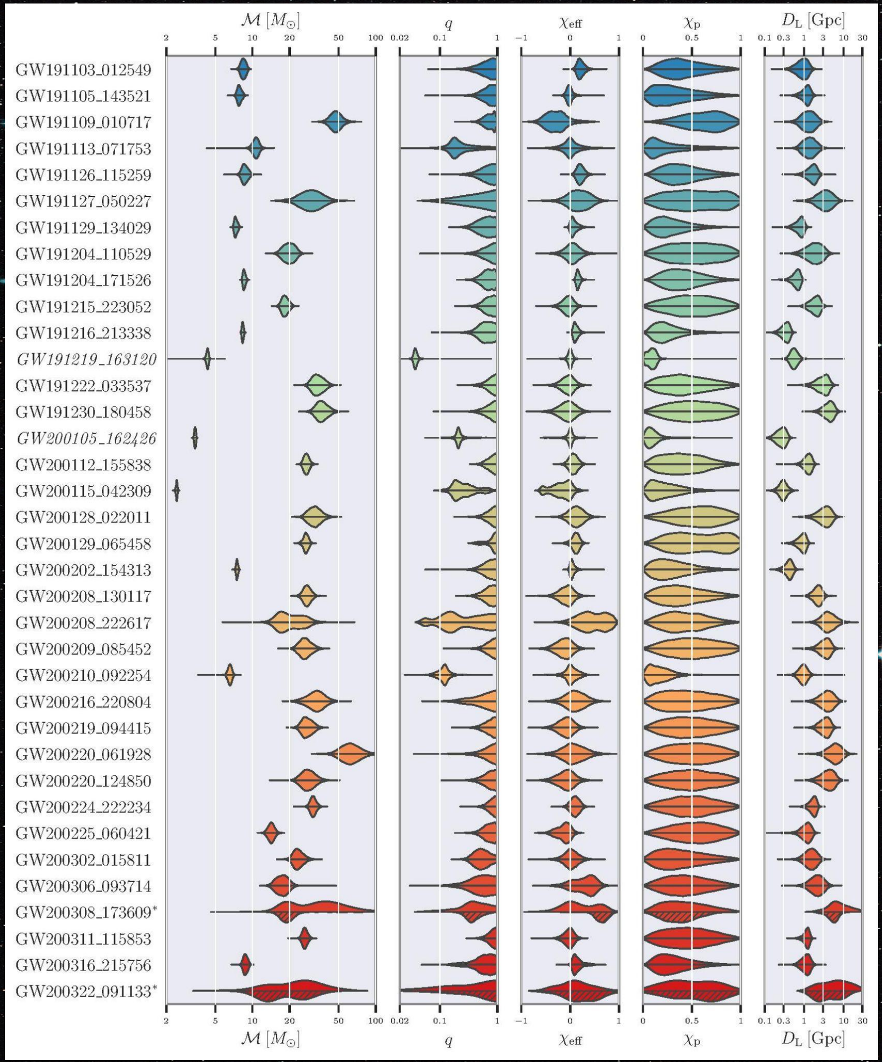
- How can we estimate the posterior PDF for our parameters?
  - Parallel Tempered MCMC with LALInference → Usually for exploratory runs/convergence checks
  - Nested Sampling with (Parallel) Bilby → Main production runs for the less computer intensive waveforms, IMRPhenomXPHM in GWTC-3
  - Gaussian-processes regression with RIFT → More costly time domain waveforms, SEOBNRv4PHM in GWTC-3



Credits: Seung-Seop Jin et al.

Visualizing the results





Some useful references for PE

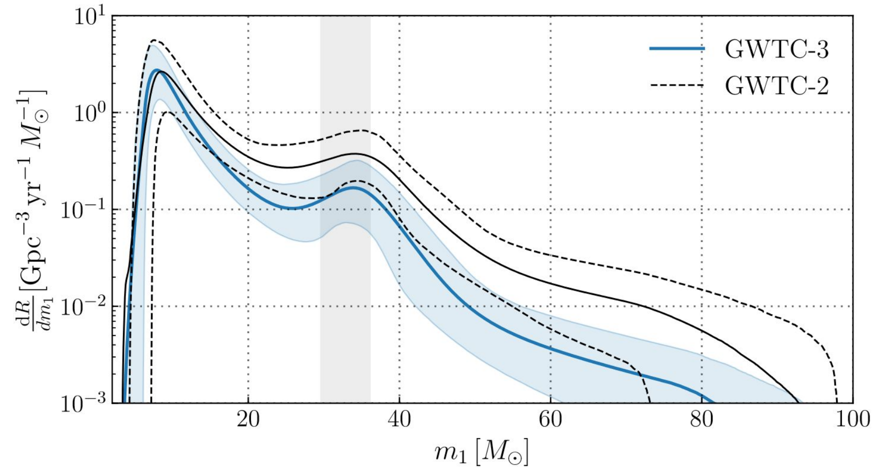
- Tutorials → Gitlab link
- Tutorials needed for O4 PE Rota → Gitlab link
- Bilby reference → Gitlab link
- RIFT reference → Gitlab link
- LALSuite reference → Gitlab link
- BayesWave reference → Gitlab link

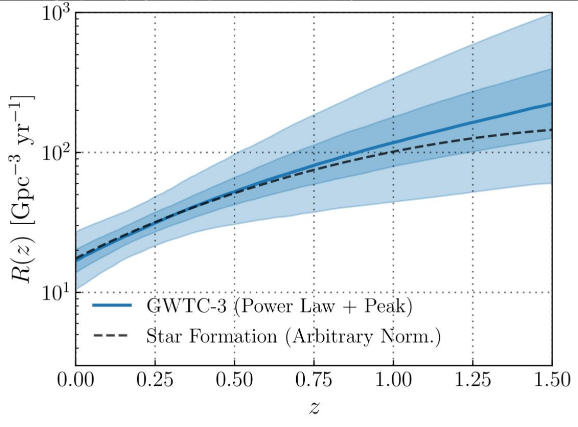
Also there exist Mattermost channels for the various software and papers

Other important analysis

Populations - arXiv:2111.03634

- Astrophysical distribution of sources taking selection effects into account
- Uses hierarchical Bayesian analysis
- Mass, spins and distance models for astrophysical population
- Try to answer questions such as
    - Is there a lower mass gap?
    - What is the NS mass distribution?
    - Can we find substructure in the BH mass distribution?
    - Does the BBH rate evolve with redshift?

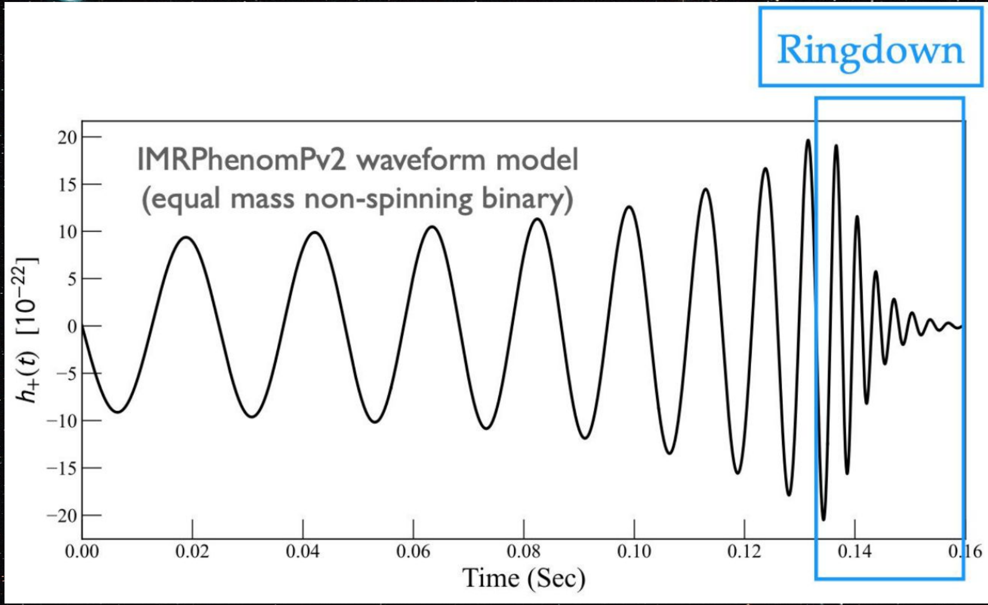




Testing GR - arXiv:2112.06861

- Find deviations from General Relativity imprinted on the strain
  List of tests:

- Consistency Tests
- Tests of GW generation
- Tests of GW propagation
- Tests of GW polarizations
- Remnant Properties and Ringdown tests



Testing GR - Ringdown analysis with pyRing

Higher modes

Spin-weighted spheroidal harmonics

$$h_+(t) - i h_\times(t) = \sum_{\ell=2}^{+\infty}\sum_{m=-\ell}^{\ell}\sum_{n=0}^{+\infty} A_{\ell mn} \exp\left[-\frac{t-t_0}{(1+z)\tau_{\ell mn}}\right]\exp\left[-\frac{2\pi i f_{\ell mn}(t-t_0)}{1+z}\right] {}_{-2}S_{\ell mn}(\theta,\phi,\chi_\mathrm{f})$$

Overtones

Damping time

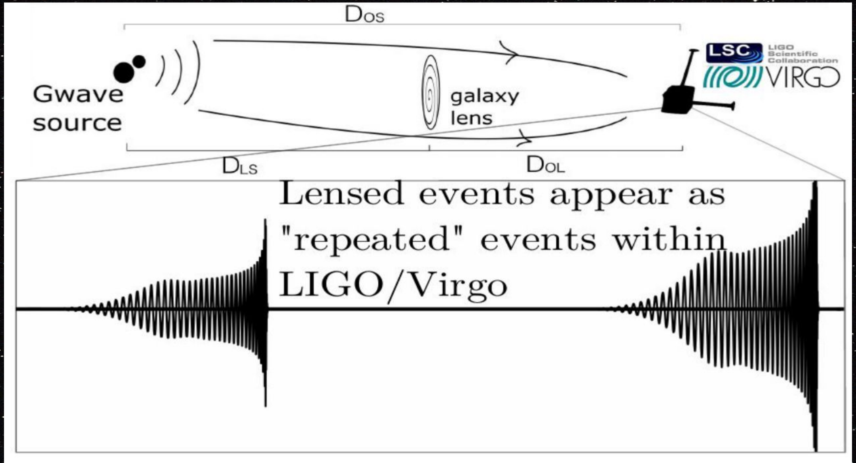
Oscillation frequency

Event	Redshifted final mass $(1+z)M_\mathrm{f}$ $[M_\odot]$				Final spin χ_f				Higher modes	Overtones	
	IMR	Kerr_{220}	Kerr_{221}	$\mathrm{Kerr}_{\mathrm{HM}}$	IMR	Kerr_{220}	Kerr_{221}	$\mathrm{Kerr}_{\mathrm{HM}}$	$\log_{10}\mathcal{B}^{\mathrm{HM}}_{220}$	$\log_{10}\mathcal{B}^{221}_{220}$	$\log_{10}\mathcal{O}^{\mathrm{modGR}}_{\mathrm{GR}}$
GW191109_010717	$132.7^{+21.9}_{-13.8}$	$181.7^{+28.5}_{-30.6}$	$179.0^{+23.7}_{-21.7}$	$174.5^{+38.1}_{-30.1}$	$0.60^{+0.22}_{-0.19}$	$0.81^{+0.10}_{-0.24}$	$0.81^{+0.08}_{-0.14}$	$0.77^{+0.11}_{-0.21}$	−0.11	1.03	−0.27
GW191222_033537	$114.2^{+14.3}_{-11.7}$	$111.4^{+69.3}_{-29.7}$	$110.3^{+36.2}_{-23.8}$	$118.3^{+97.0}_{-46.2}$	$0.67^{+0.08}_{-0.10}$	$0.46^{+0.41}_{-0.41}$	$0.52^{+0.31}_{-0.43}$	$0.60^{+0.28}_{-0.66}$	0.08	−0.83	−0.20
GW200129_065458	$71.8^{+4.4}_{-3.9}$	$60.0^{+16.7}_{-8.9}$	$77.0^{+14.4}_{-14.2}$	$219.1^{+110.4}_{-140.0}$	$0.75^{+0.06}_{-0.06}$	$0.31^{+0.43}_{-0.28}$	$0.74^{+0.17}_{-0.59}$	$0.54^{+0.35}_{-0.59}$	−0.00	−0.47	−0.09
GW200224_222234	$90.3^{+6.4}_{-6.3}$	$84.4^{+23.2}_{-20.3}$	$88.6^{+15.5}_{-15.2}$	$119.4^{+142.6}_{-34.3}$	$0.73^{+0.06}_{-0.07}$	$0.61^{+0.27}_{-0.49}$	$0.60^{+0.23}_{-0.42}$	$0.64^{+0.27}_{-0.59}$	0.20	0.95	−0.11
GW200311_115853	$72.1^{+5.4}_{-4.7}$	$68.5^{+23.6}_{-13.5}$	$72.2^{+28.6}_{-16.3}$	$213.2^{+167.8}_{-141.5}$	$0.68^{+0.07}_{-0.08}$	$0.30^{+0.44}_{-0.28}$	$0.58^{+0.30}_{-0.47}$	$0.56^{+0.32}_{-0.54}$	0.02	−1.16	−0.15

- Remnant properties from ringdown templates are consistent with IMR counterparts
- No evidence for higher modes
- Weak evidence for overtones in some

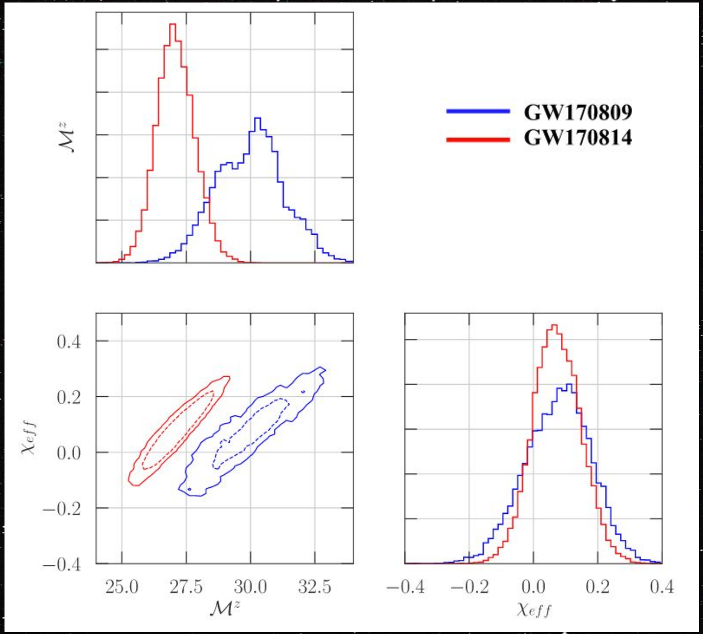
Gravitational lensing of GW - arXiv:2105.06384

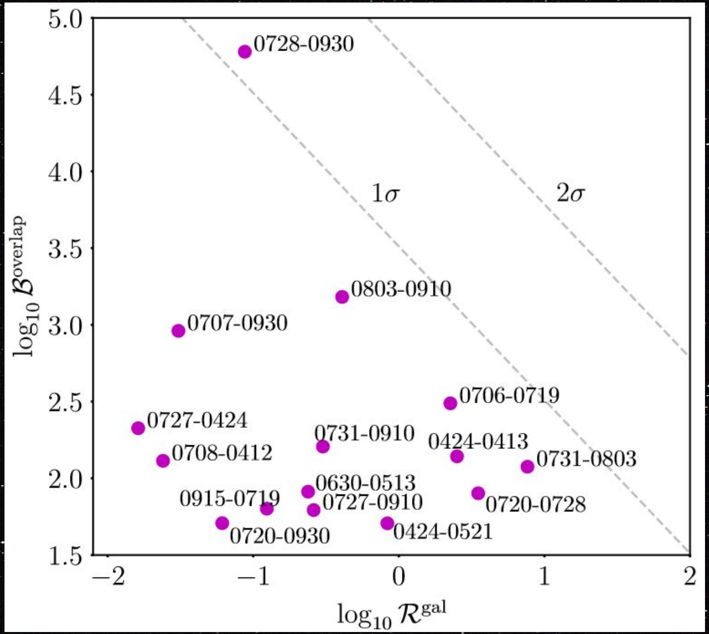
- Similar to light, gravitational waves can be gravitationally lensed.
- However, detection methodologies and the science cases are very different compared to lensing of light.
- GWs experience lensing magnification, multiple images, frequency-dependent deformations
- May bias population estimates!



Gravitational lensing of GW - Posterior Overlap Analysis

$$\mathcal{B}^{\rm overlap} = \int d\Theta \frac{p(\Theta|d_1)p(\Theta|d_2)}{p(\Theta)} \quad with \quad \Theta = \{\chi_{eff}, q, \mathcal{M}, \delta, \alpha\}$$

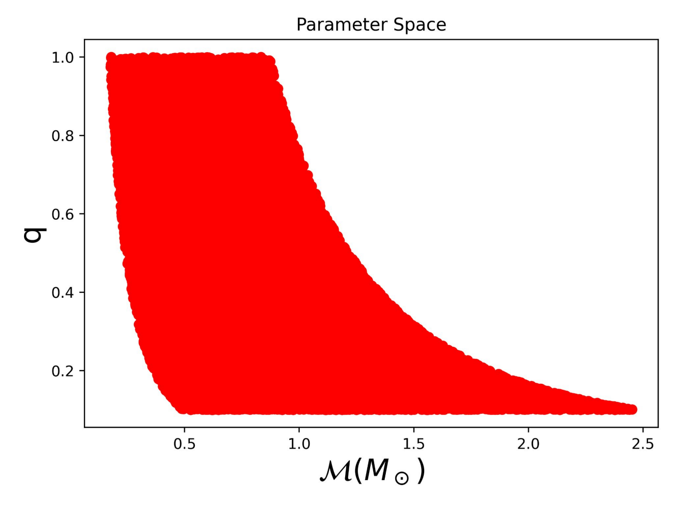




[Hannuksela et al. 2021](#)

Subsolar Mass Search

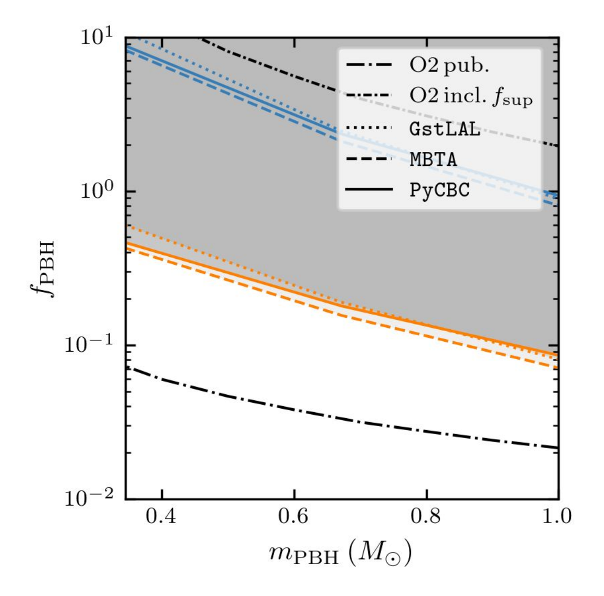
- Search for Subsolar mass objects.
  Different parameter space than Catalog:



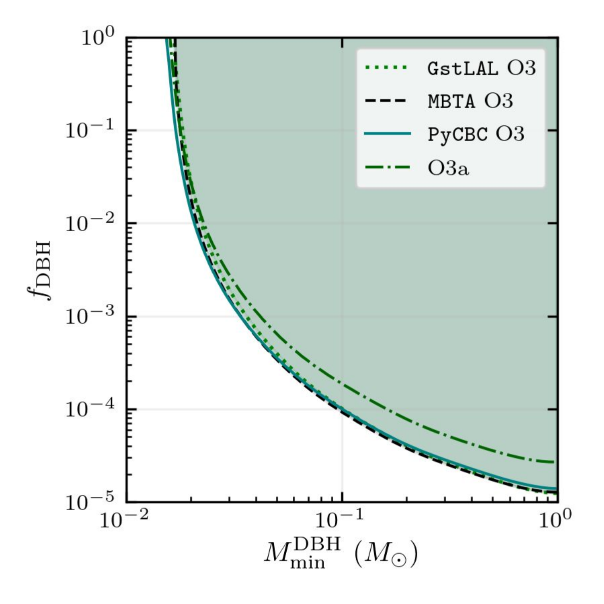
- $m_1 \in [0.2, 10] M_\odot$
- $m_2 \in [0.2, 1] M_\odot$
- $0.1 < q < 1.0$ with $q \doteq m_2/m_1$
- $\chi_{1,2} = |\mathbf{S}_{1,2}|/m_{1,2}^2$ $\begin{cases} \text{Uniform(0,0.9) if } m > 0.5 M_\odot \\ \text{Uniform(0,0.1) if } m < 0.5 M_\odot \end{cases}$

Subsolar Mass Search

Constraints on DM fraction of PBHs for a monochromatic mass function



Constraints on abundance of DBHs as a function of the lower limit of the DBH mass distribution M_{min}^{DBH}



Conclusions

- There are many things to do in LVK!
- This was a non-exhaustive list of analysis conducted on the data
- Process of entering any of these analysis pipelines is just asking
- You can also propose ideas!

Questions?

Acknowledgments

I have created this slides with the inspiration of the various public webinar’s slides for the different papers:

- Population slides
- Testing GR slides
- GW lensing slides