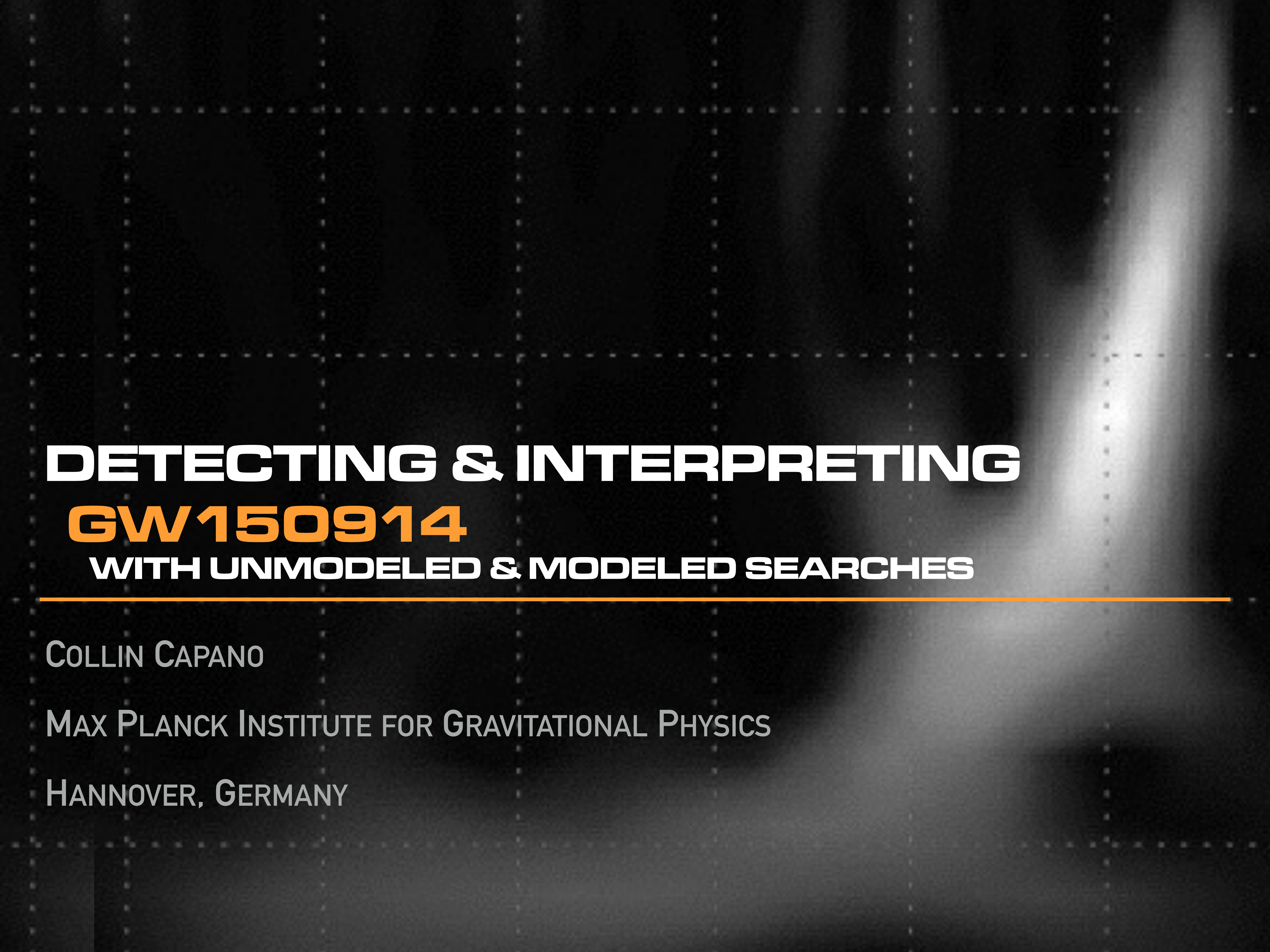


DETECTING & INTERPRETING
GW150914
WITH UNMODELED & MODELED SEARCHES

Collin Capano

Max Planck Institute for Gravitational Physics

Hannover, Germany

OVERVIEW

- How was GW150914 detected?
- How do we know it was a binary black hole (BBH)?
- Why are we confident GW150914 is a gravitational wave?

OVERVIEW

GW150914

PHYSICAL
REVIEW
LETTERS

Articles published week ending 12 FEBRUARY 2016

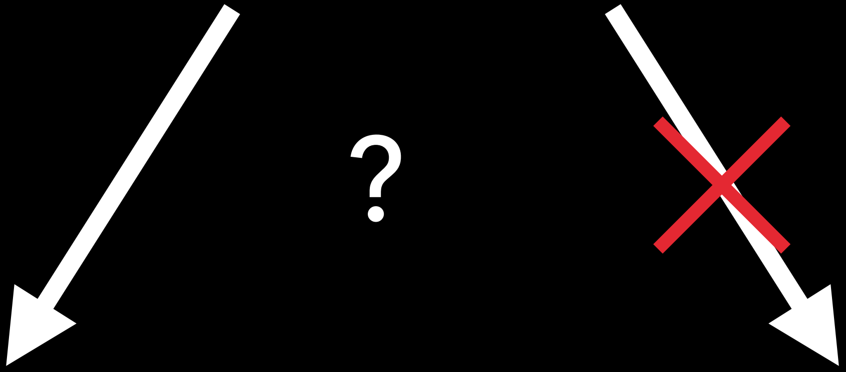
Published by
American Physical Society

APS physics

Volume 116, Number 6

OVERVIEW

GW150914



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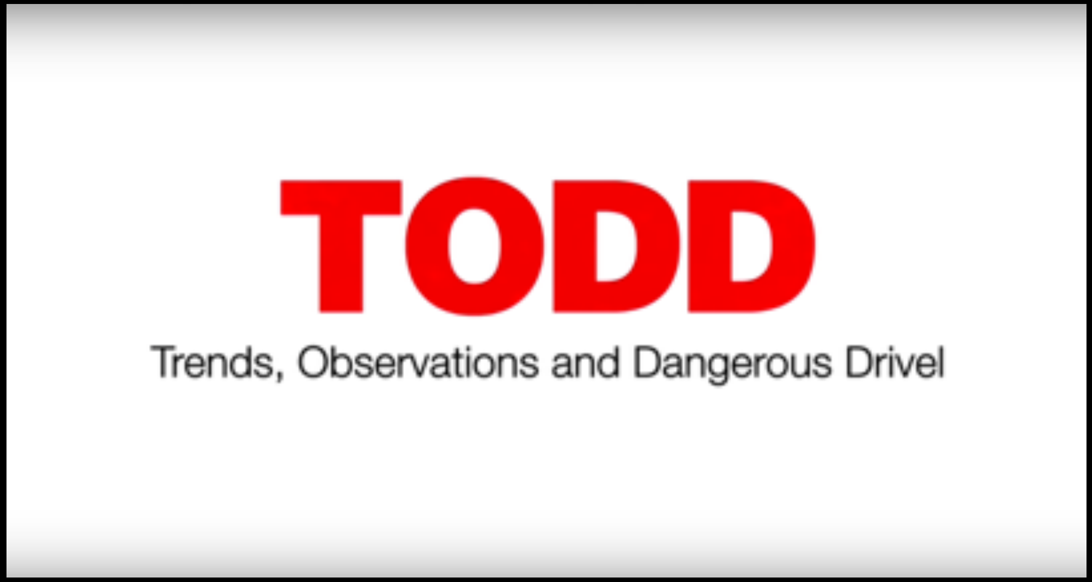


TODD

Trends, Observations and Dangerous Drivel

(TODD not TED… Google "John Oliver Scientific Studies p-hacking")

OUTLINE

1. Unmodeled Searches
2. Modeled Searches
3. Parameter estimation of GW150914
4. LVT151012

1. UNMODELED SEARCHES

arXiv:1602.03843

UNMODELED SEARCHES OVERVIEW

- Search for “bursts” of gravitational waves lasting 10^{-3}-10s
- Make minimal assumptions about waveform morphology
- Not affected by uncertainties in waveform modeling
- Can detect wide range of signals, including BBHs

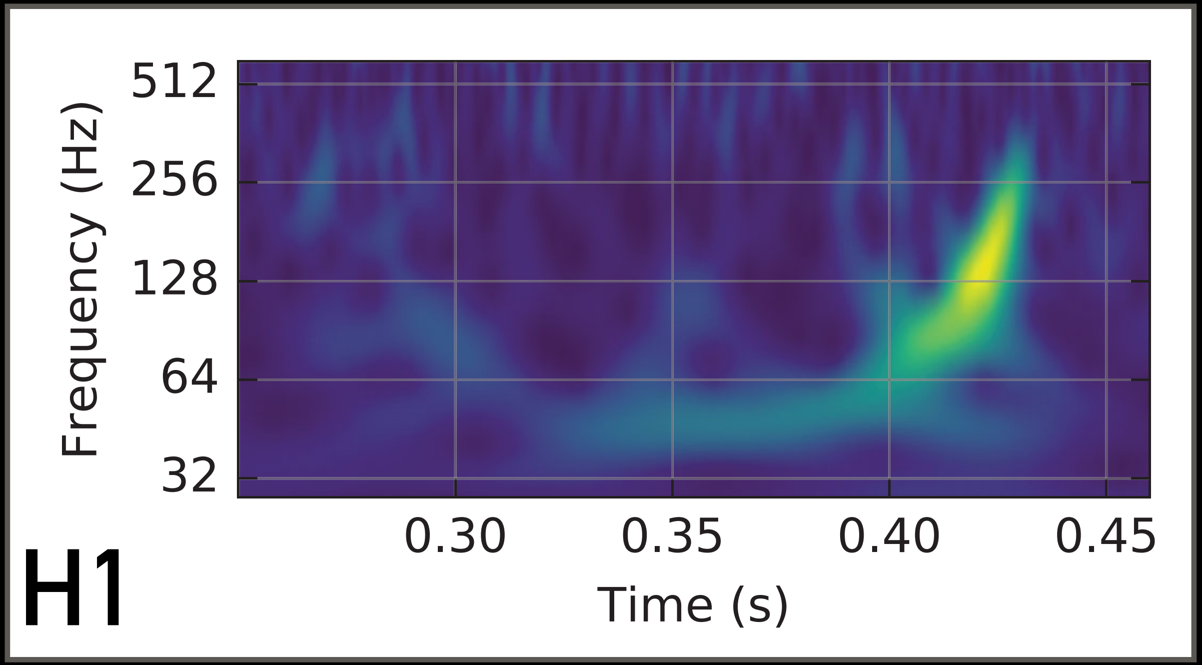
THREE SEARCHES PERFORMED ON DATA CONTAINING GW150914

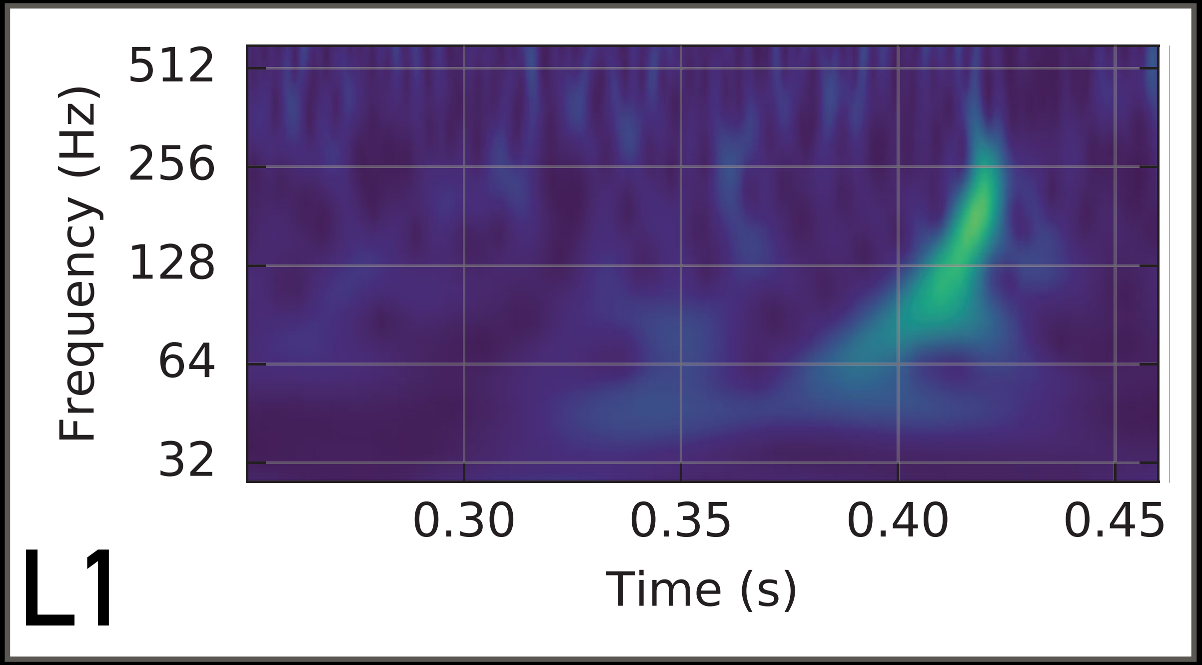
1. Coherent Wave Burst (cWB) [1]
   - Constructs coherent triggers between detectors using wavelet basis
2. Omicron-LALInference-Bursts (oLIB) [2]
   - Generates single-detector triggers using sine-Gaussians (omicron) with coherent followup (LALInference)
3. BayesWave [3]
   - Fits a superposition of sine-Gaussians to times identified by cWB
   - Number & parameters of sine-Gaussians determined by Bayesian model selection

1. S. Klimenko et al., CQG 25:114029, 2008
2. R. Lynch et al., arXiv:1511.05955
3. N. J. Cornish and T. B. Littenberg, CQG, 32(13):135012, 2015.

COHERENT WAVE BURST

- Uses a wavelet basis to search for excess energy in each detector





LSC+Virgo, PRL 116, 061102 (2016)

COHERENT WAVE BURST

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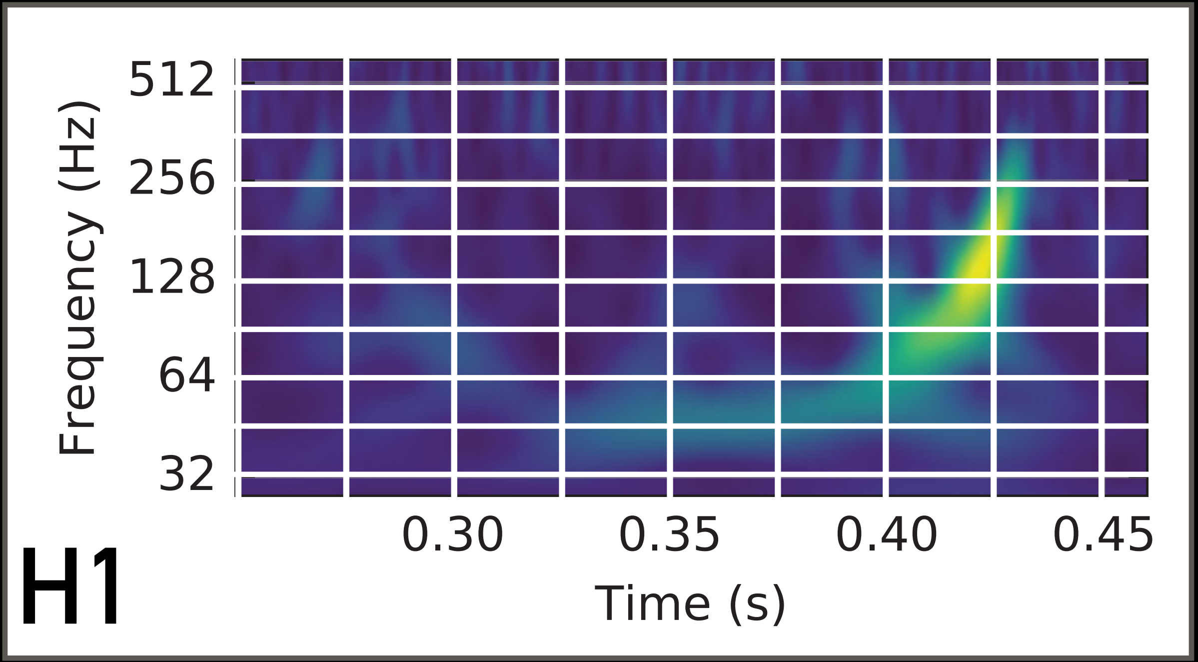
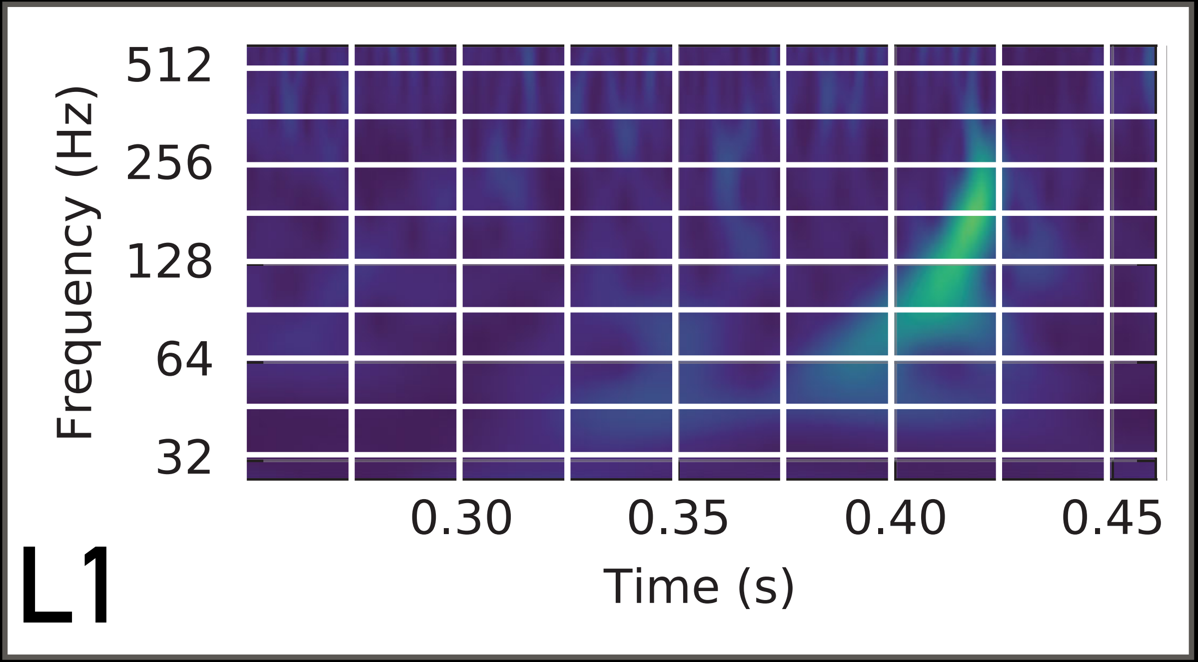
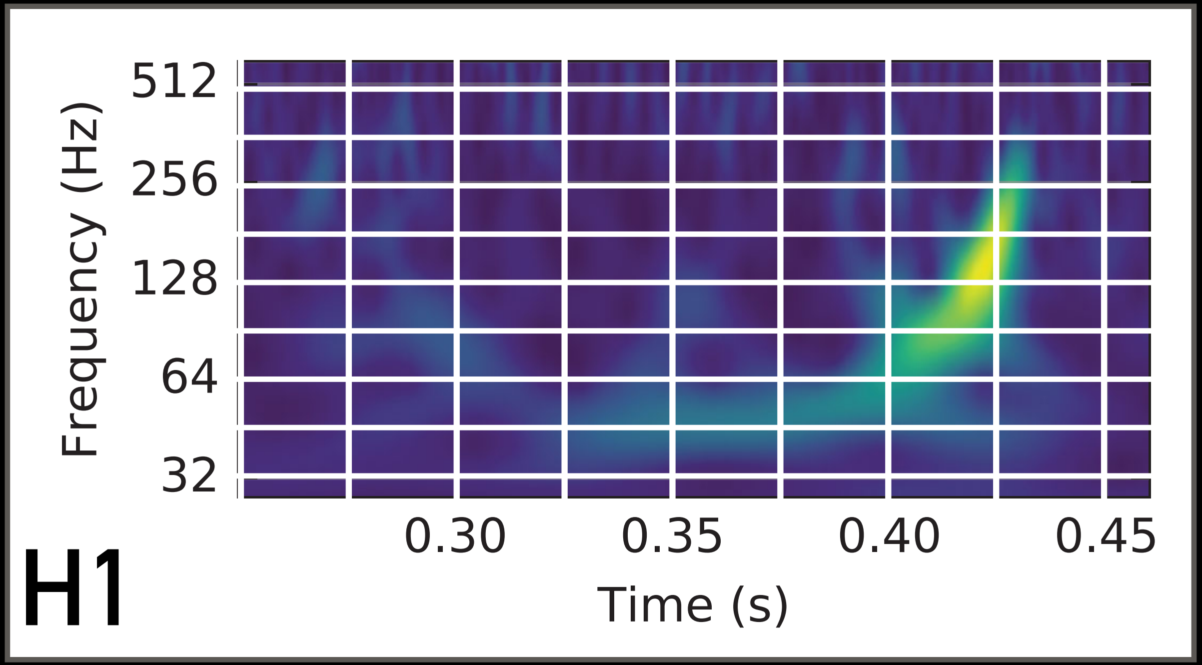




LSC+Virgo, PRL 116, 061102 (2016)

Coherent Wave Burst

- Uses a wavelet basis to search for excess energy in each detector
- Energy in each time-frequency tile is added coherently between the detectors



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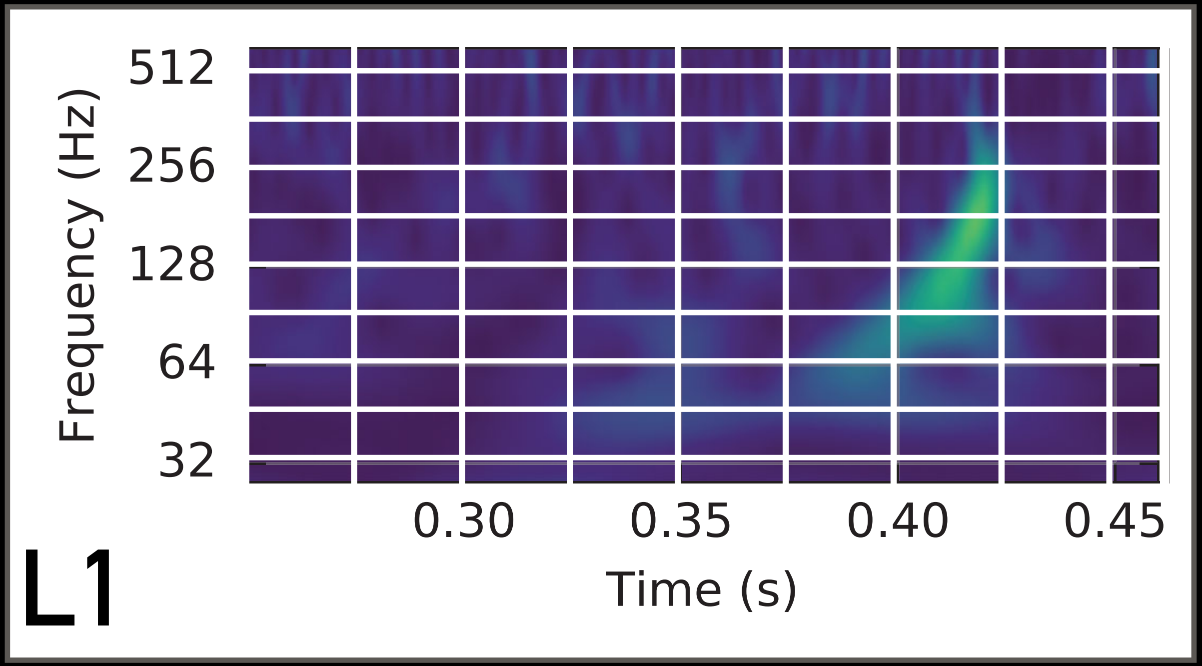
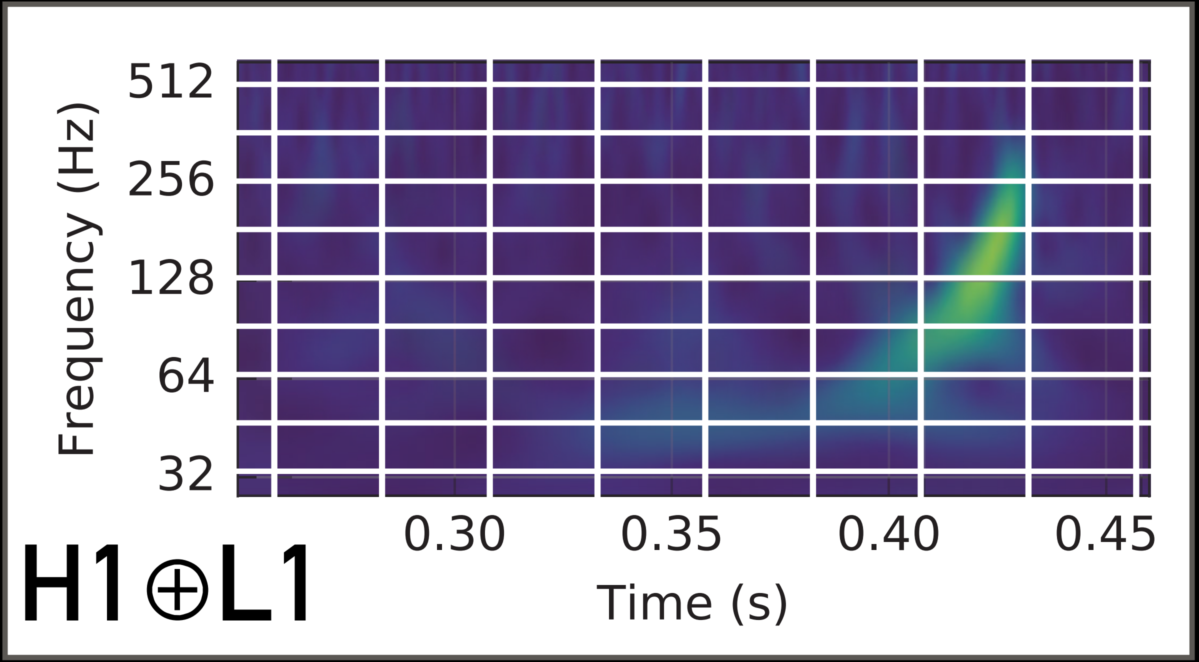


LSC+Virgo, PRL 116, 061102 (2016)

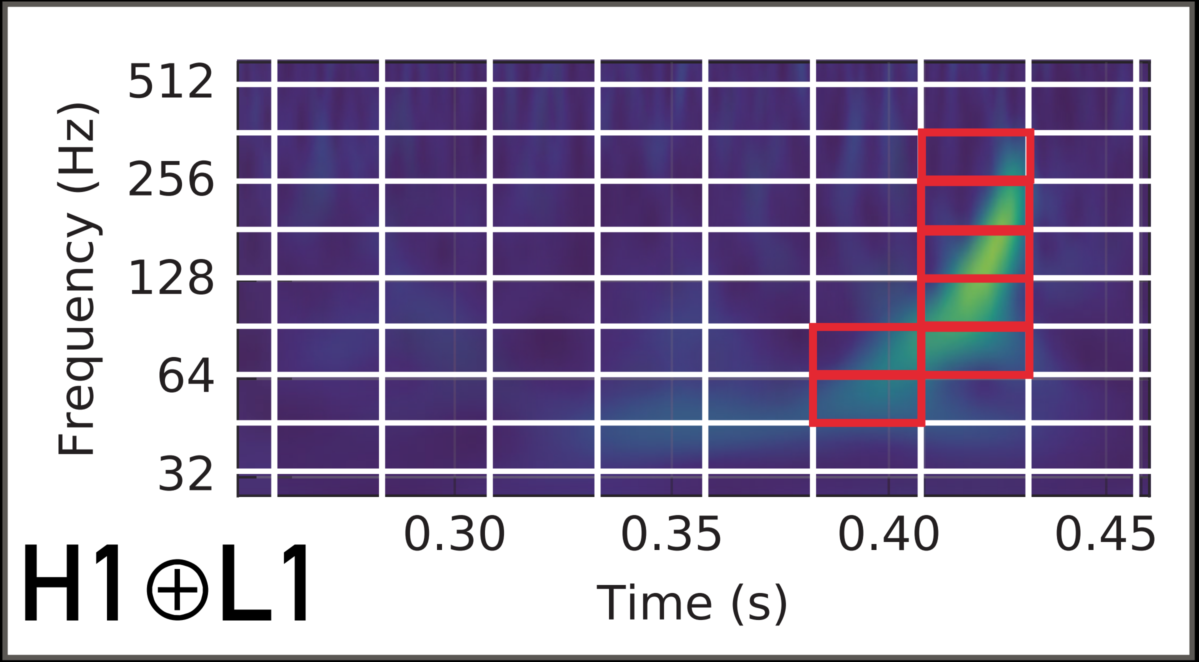
COHERENT WAVE BURST

- Uses a wavelet basis to search for excess energy in each detector
- Energy in each time-frequency tile is added coherently between the detectors
  - account for detector antenna patterns and time delays



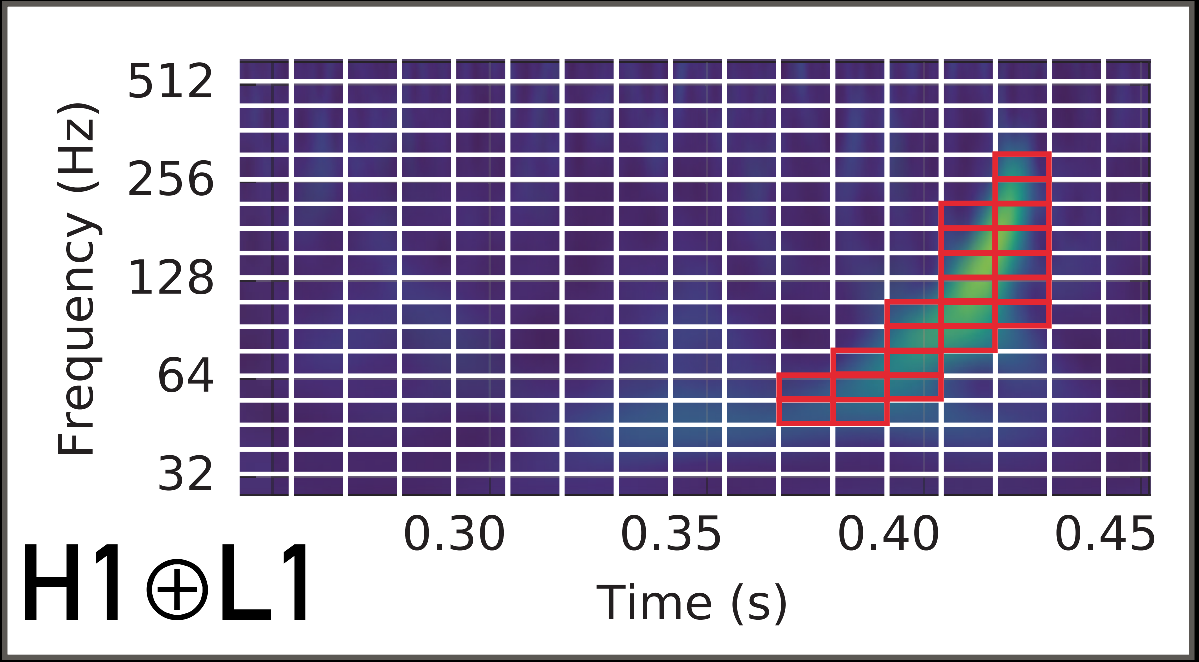
COHERENT WAVE BURST

- Uses a wavelet basis to search for excess energy in each detector
- Energy in each time-frequency tile is added coherently between the detectors
    - account for detector antenna patterns and time delays
- Clusters of tiles with coherent energy above baseline noise are identified



COHERENT WAVE BURST

- Process is repeated using different time/frequency resolutions
- Clusters at different resolutions are combined to form triggers
- Triggers are analyzed coherently to reconstruct the signal morphology



cWB RANKING STATISTIC

- A ranking statistic is constructed for each trigger:

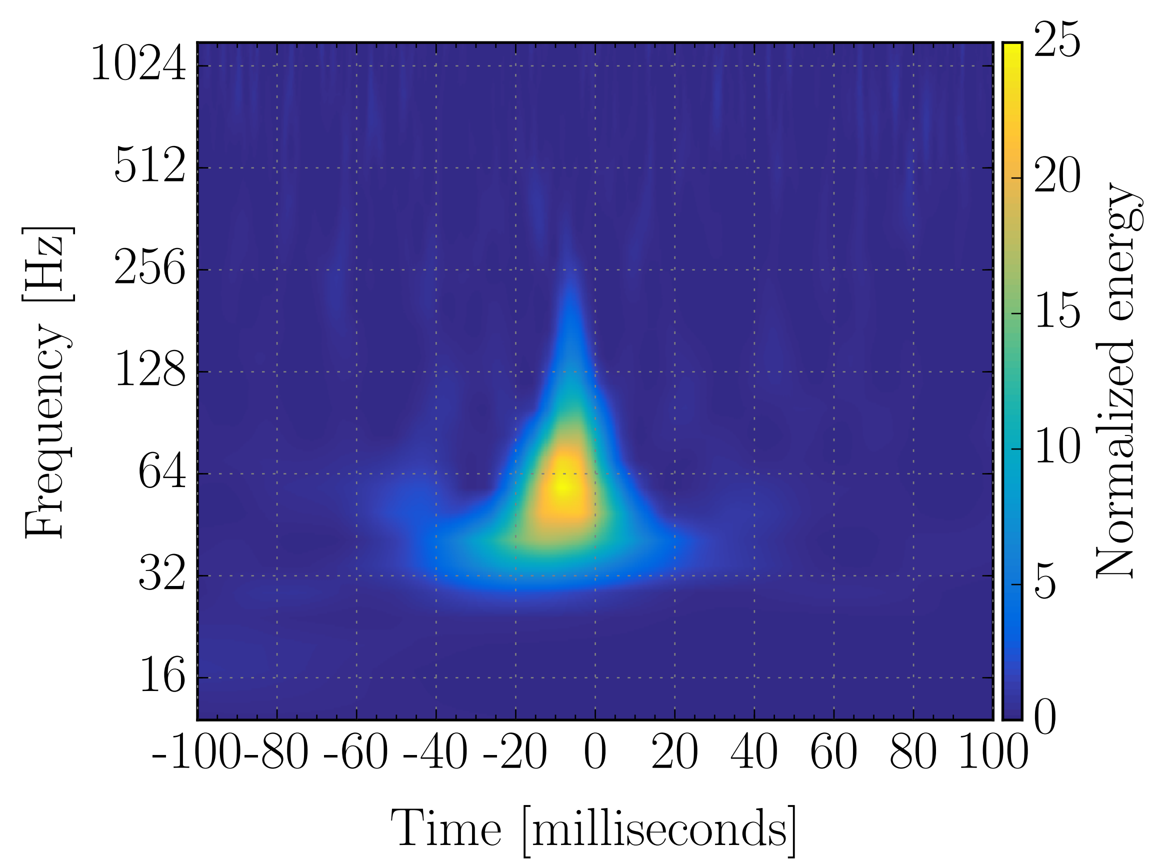
$$\boxed{\eta_c = E_c\sqrt{\frac{2}{E_c + E_n}}}$$

- E_c = the coherent energy
- E_n = residual energy after reconstructed waveform subtracted from the data

NON-GAUSSIAN TRANSIENTS

- The detectors contain non-Gaussian noise transients
- Example: the “Blip glitch”
- Not correlated between detectors
- Increases rate of false alarms

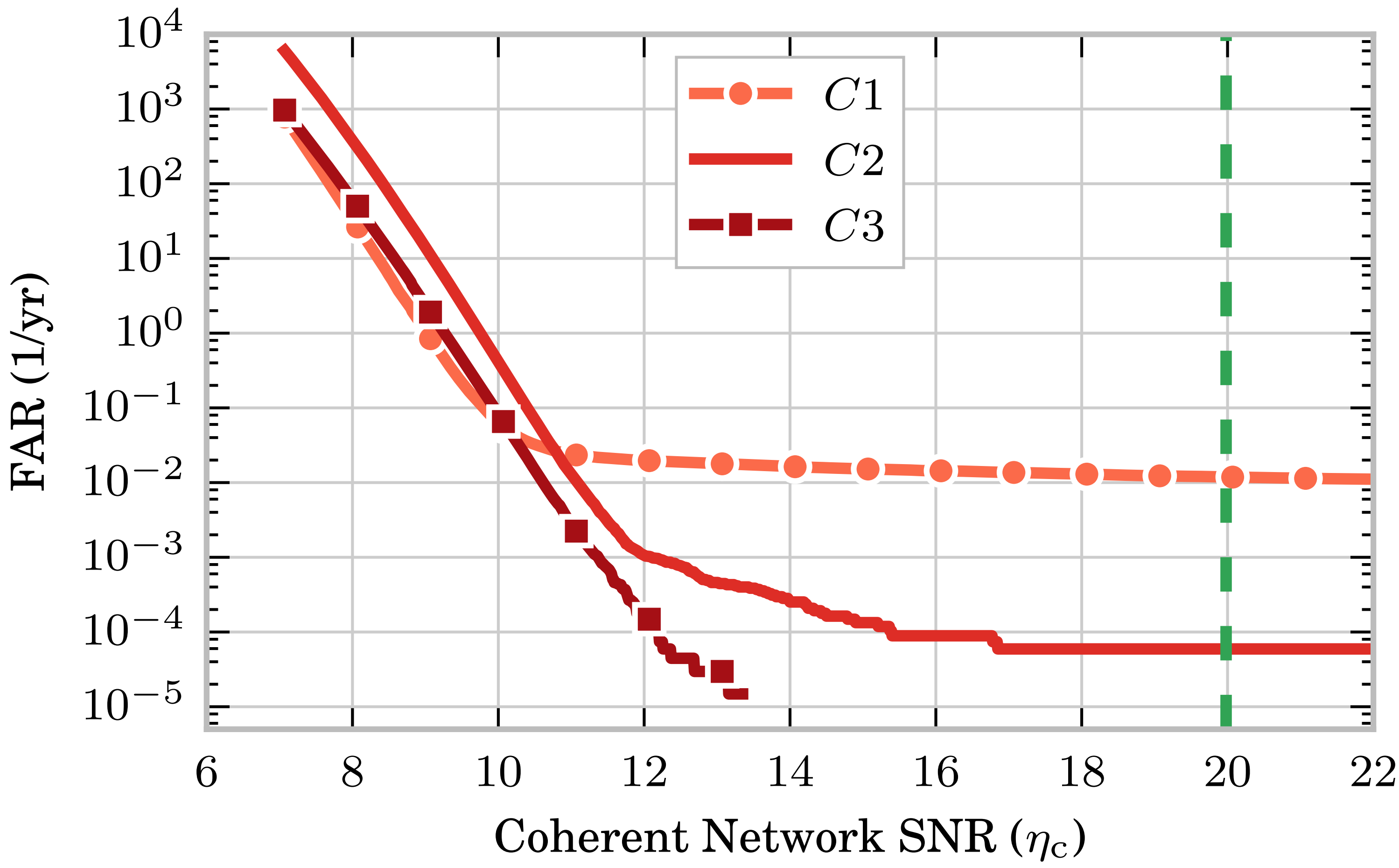
Blip Glitch



LSC+Virgo, arXiv:1602.03844

cWB SEARCH CLASSES

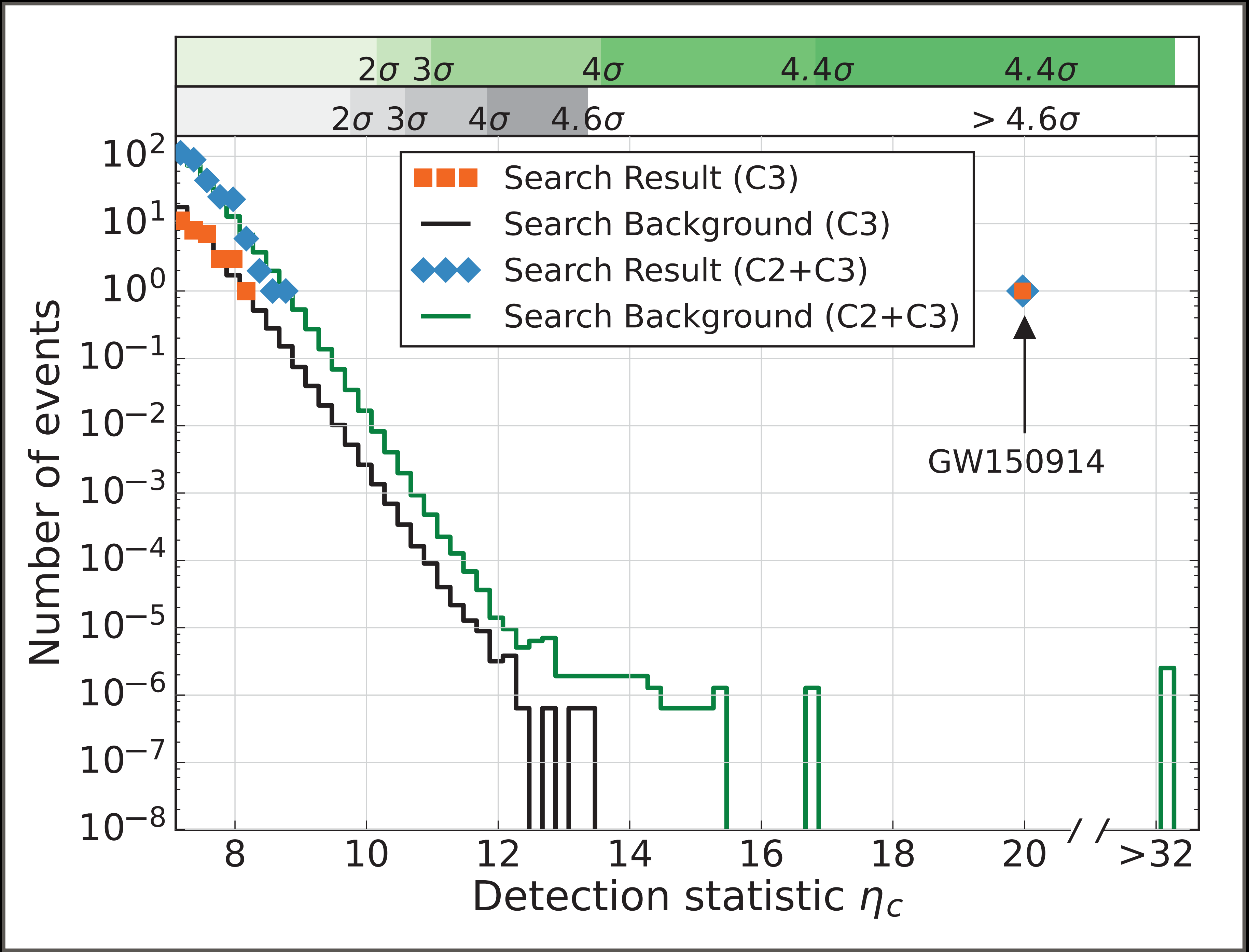
- cWB defines 3 classes of triggers:
    - *C1*: blip glitch-like
    - *C3*: chirp-like
    - *C2*: everything else
- False alarm rate (FAR) estimated in each class
- Multiply FAR of events by 3 to account for classes



LSC+Virgo, arXiv:1602.03843

Background estimated by applying 1s time shifts between detectors & reanalyzing

cWB GW150914 RESULTS



LSC+Virgo, PRL 116, 061102 (2016)

GW150914:

- C3: > 4.6σ
- C3 parameters not finalized prior to initial detection
- C2+C3: 4.4σ

DISADVANTAGES OF UNMODELED SEARCHES

- Without model, large space of possible signals leads to heightened false alarm rate
- Not sensitive to signals that accumulate power over larger range of frequencies
  - Not a problem for GW150914
  - Lower sensitivity to lower-mass signals

2. MODELED SEARCHES

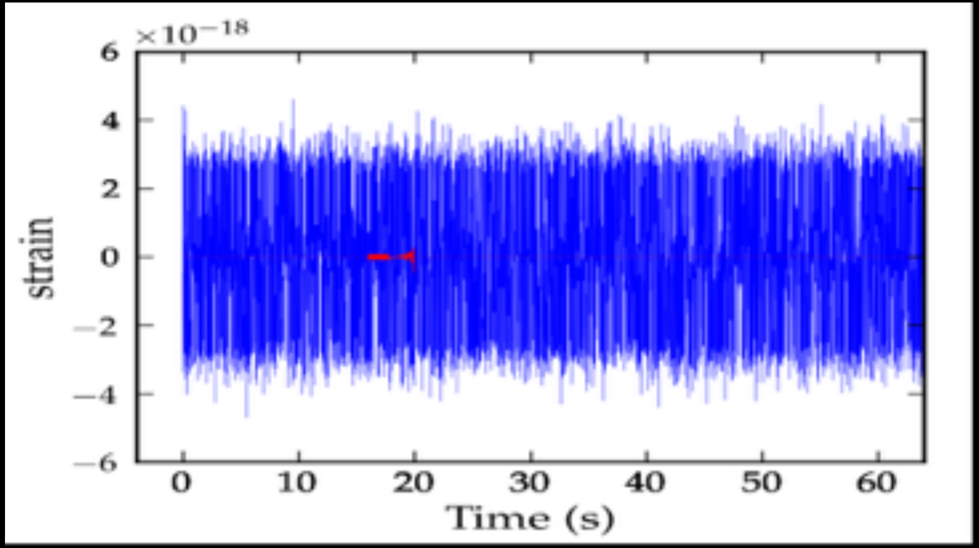
arXiv:1602.03839

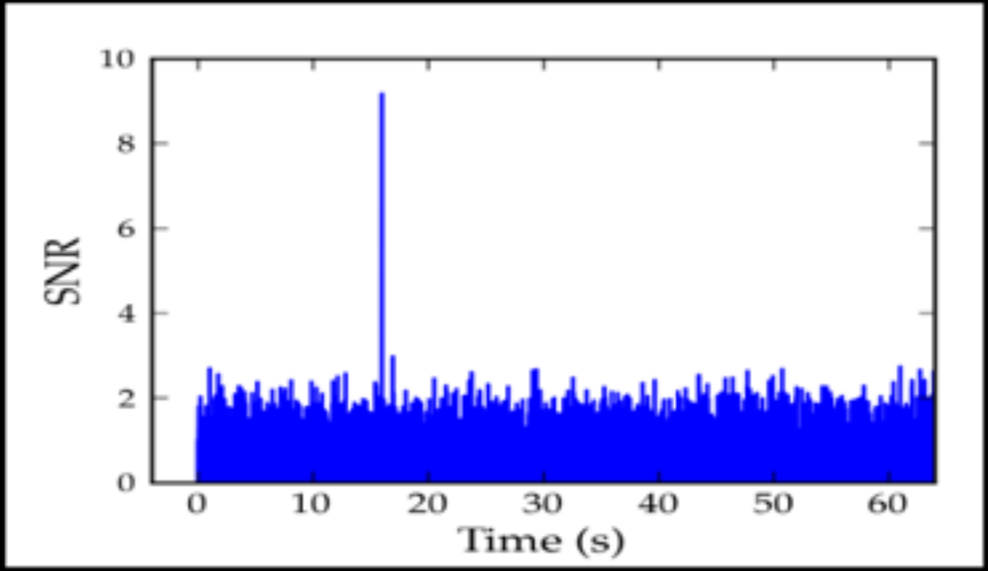
MATCHED FILTERING

- Have a signal buried in some strain s
- Use a template waveform h to calculate the signal-to-noise ratio (SNR) ρ:

$$\rho = \frac{|\langle h|s\rangle|}{\sqrt{\langle h|h\rangle}} \qquad \langle a|b\rangle \equiv 4\int_0^\infty \frac{\tilde{a}^*(f)\tilde{b}(f)}{S_n(f)}\mathrm{d}f$$

- By replacing h with $he^{-2\pi ift}$ we construct $\rho(t)$
- Triggers are points where $\rho(t)$ is maximized





Courtesy A. Nitz

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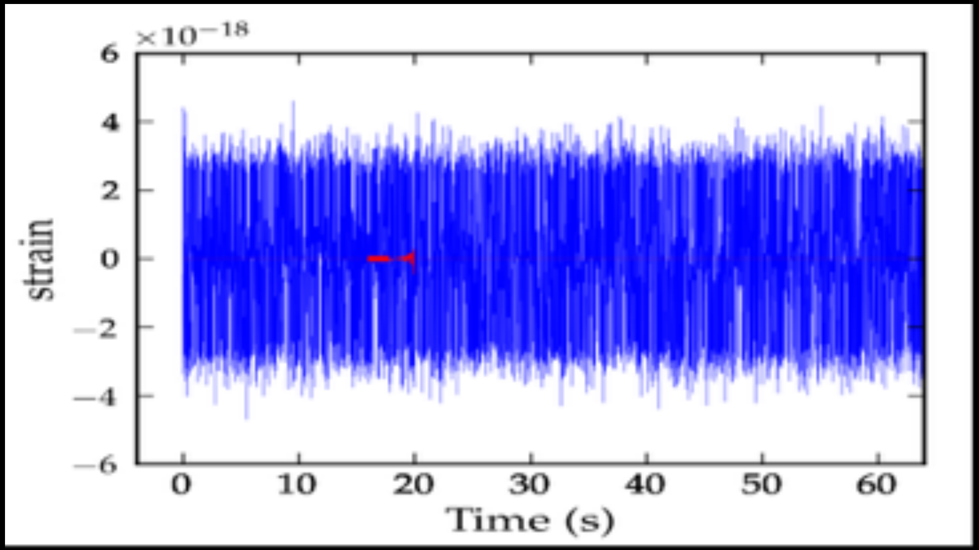
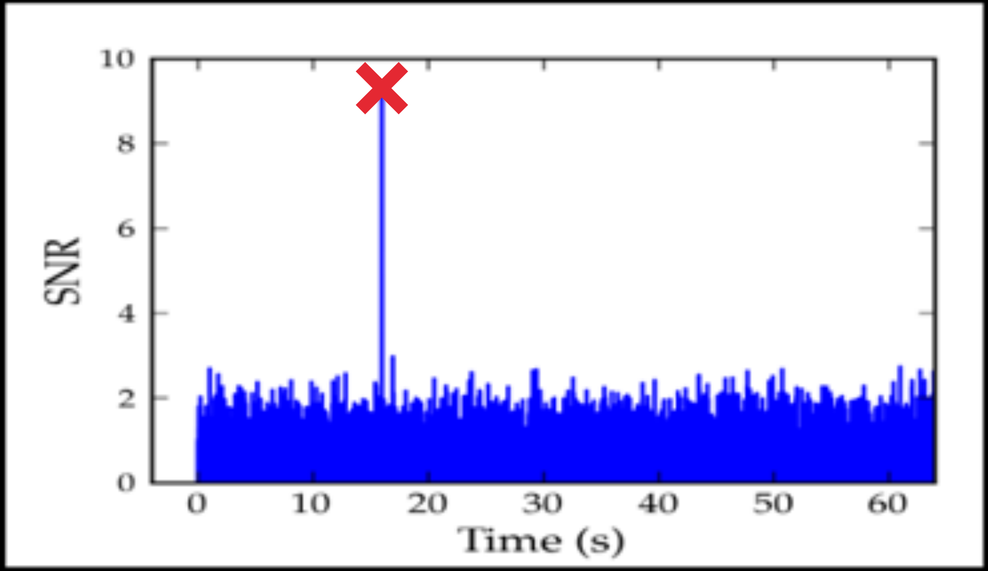


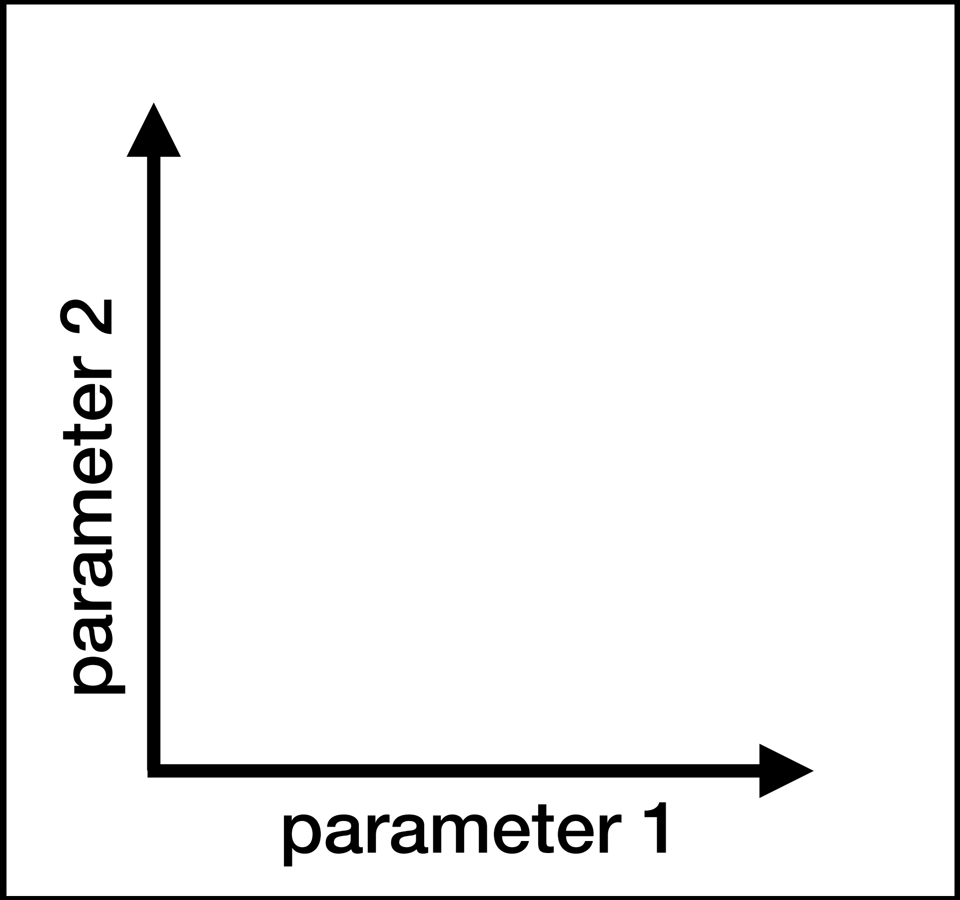


Courtesy A. Nitz

ADVANTAGES & CHALLENGES OF MODELED SEARCH

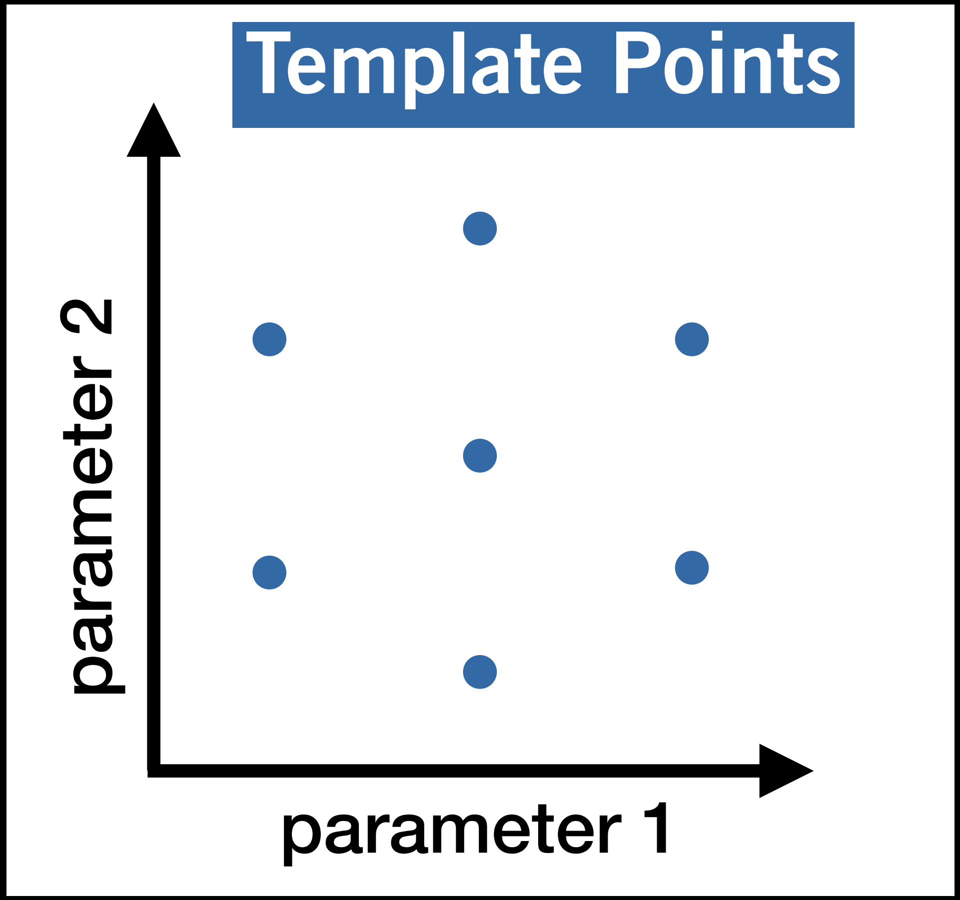
- Constraining signal space decreases false alarm rate
- Can use signal-based vetoes to separate signals from transient noise
- Better sensitivity than unmodeled search
- Lose sensitivity if templates do not match signals
    - Need accurate waveform models
    - Parameters of template must be close to signal

TEMPLATE BANK



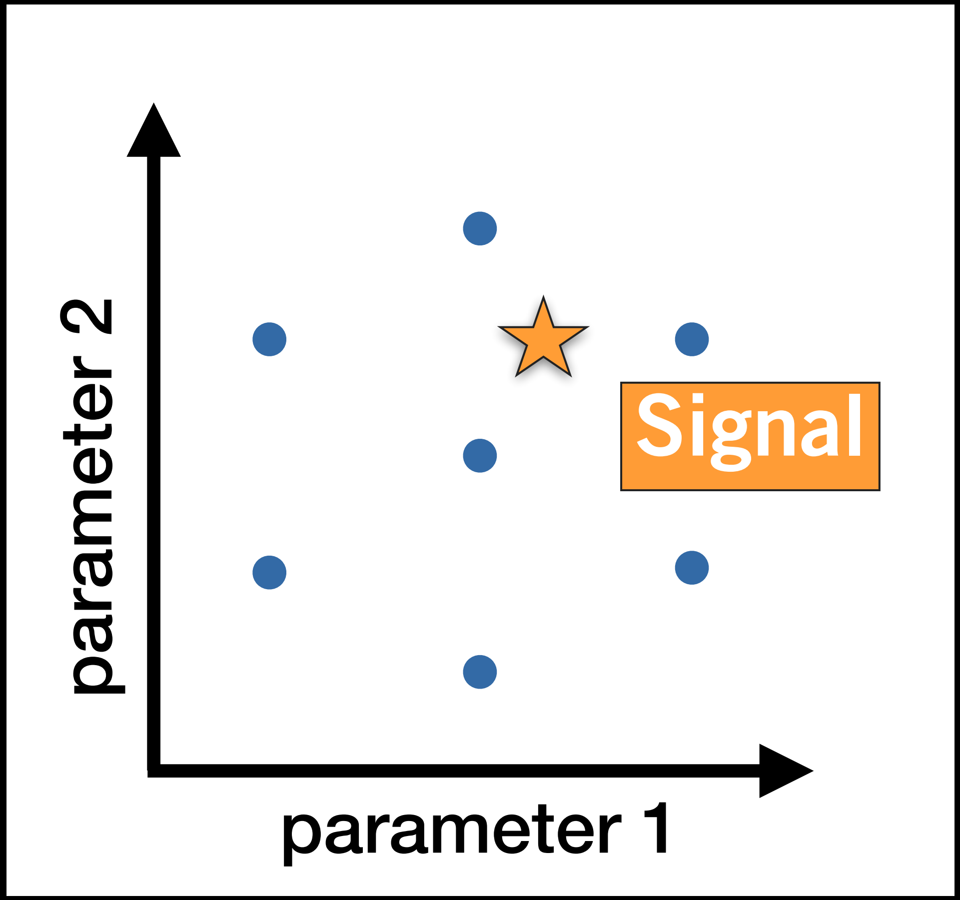
TEMPLATE BANK

- We use a “bank” of templates to search for range in possible signal parameters



TEMPLATE BANK

- We use a "bank" of templates to search for range in possible signal parameters
- Desire template placement to be such that maximum loss in SNR to target signals (the mismatch) is < 3%



CBC PARAMETERS

- Possible CBC parameters (#):

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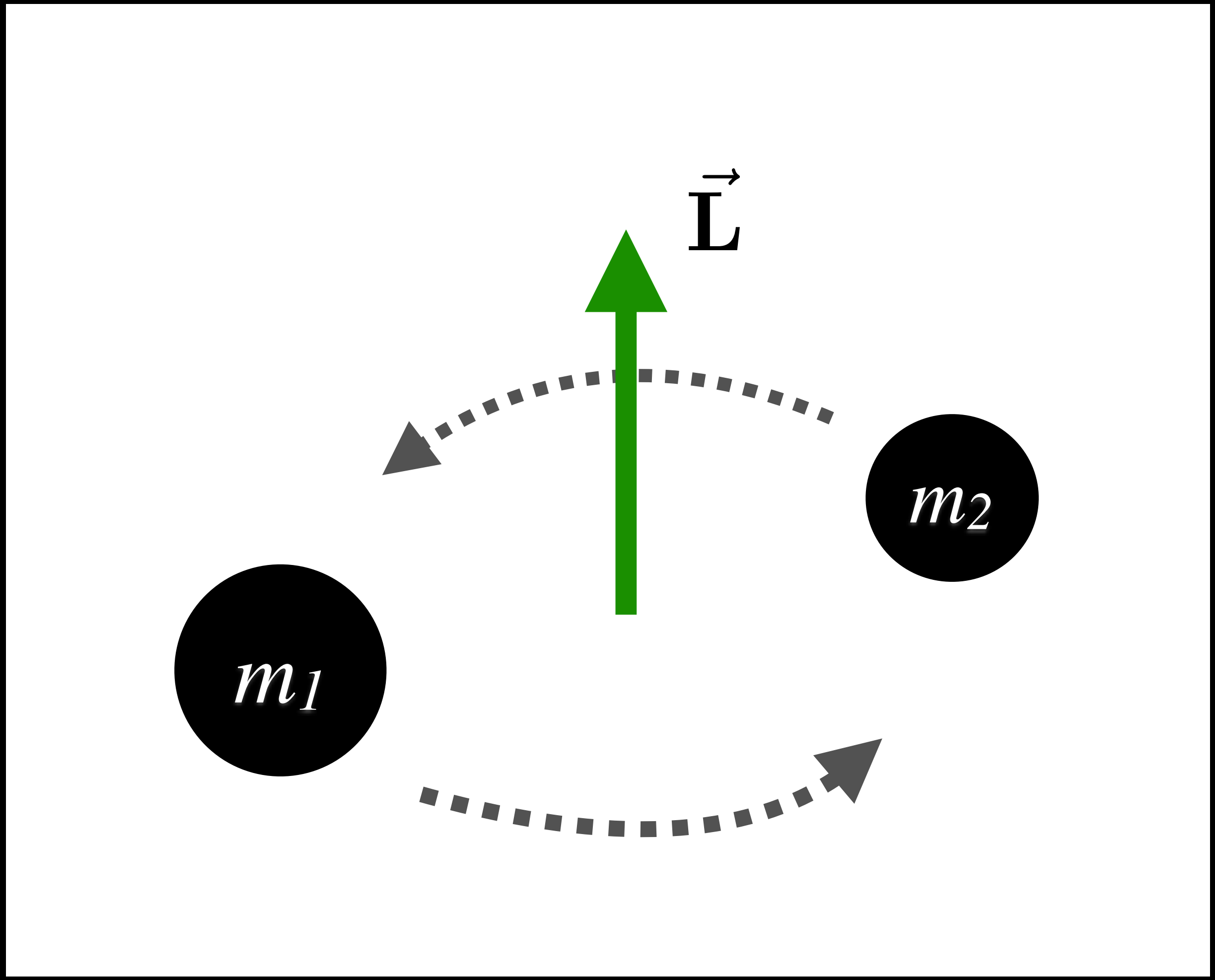
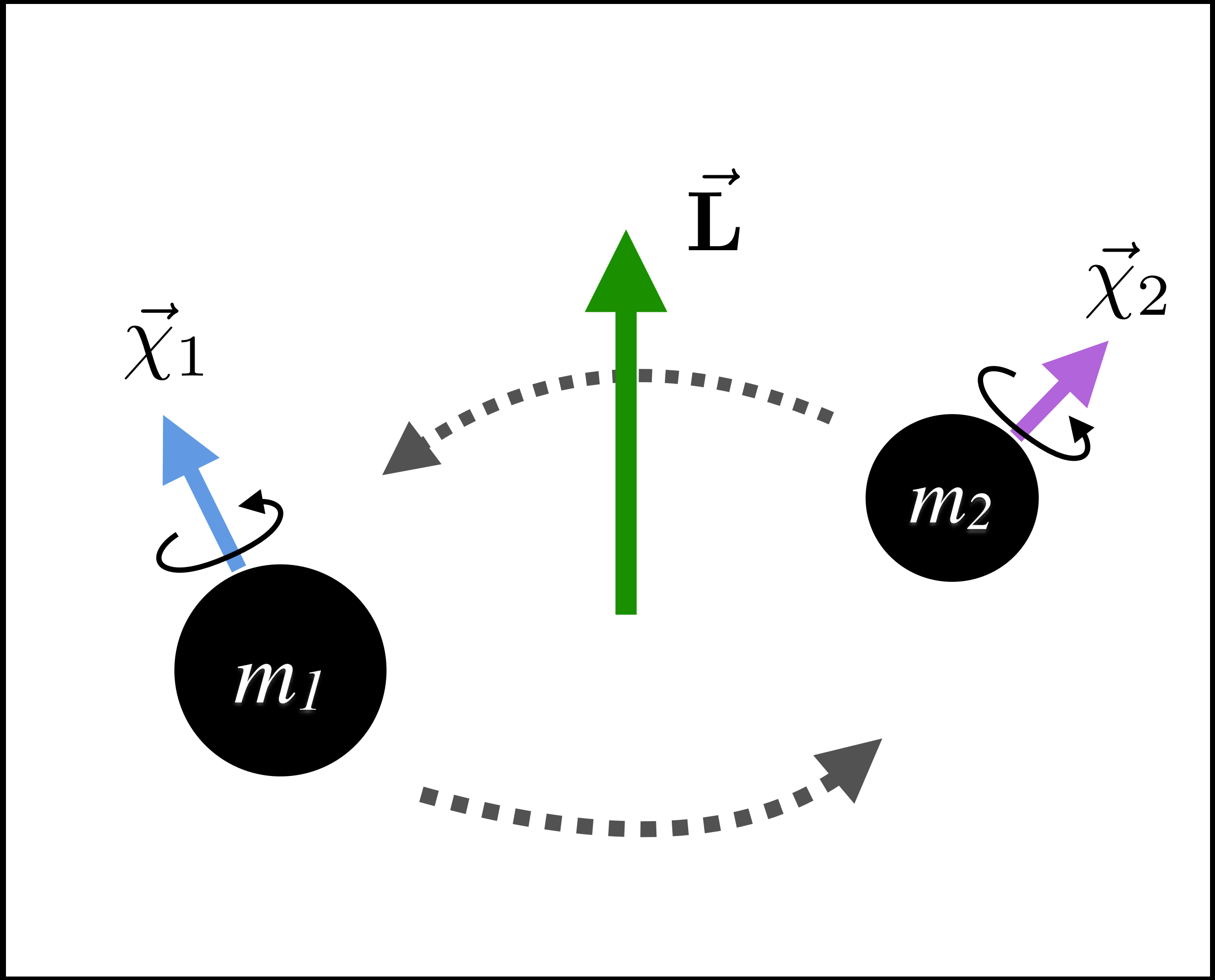
- Possible CBC parameters (#):
  - component masses m_1, m_2 (2)



CBC PARAMETERS

- Possible CBC parameters (#):
    - component masses m_1, m_2 (2)
    - dimensionless spins of components χ_1, χ_2 (6)



CBC PARAMETERS

- Possible CBC parameters (#):
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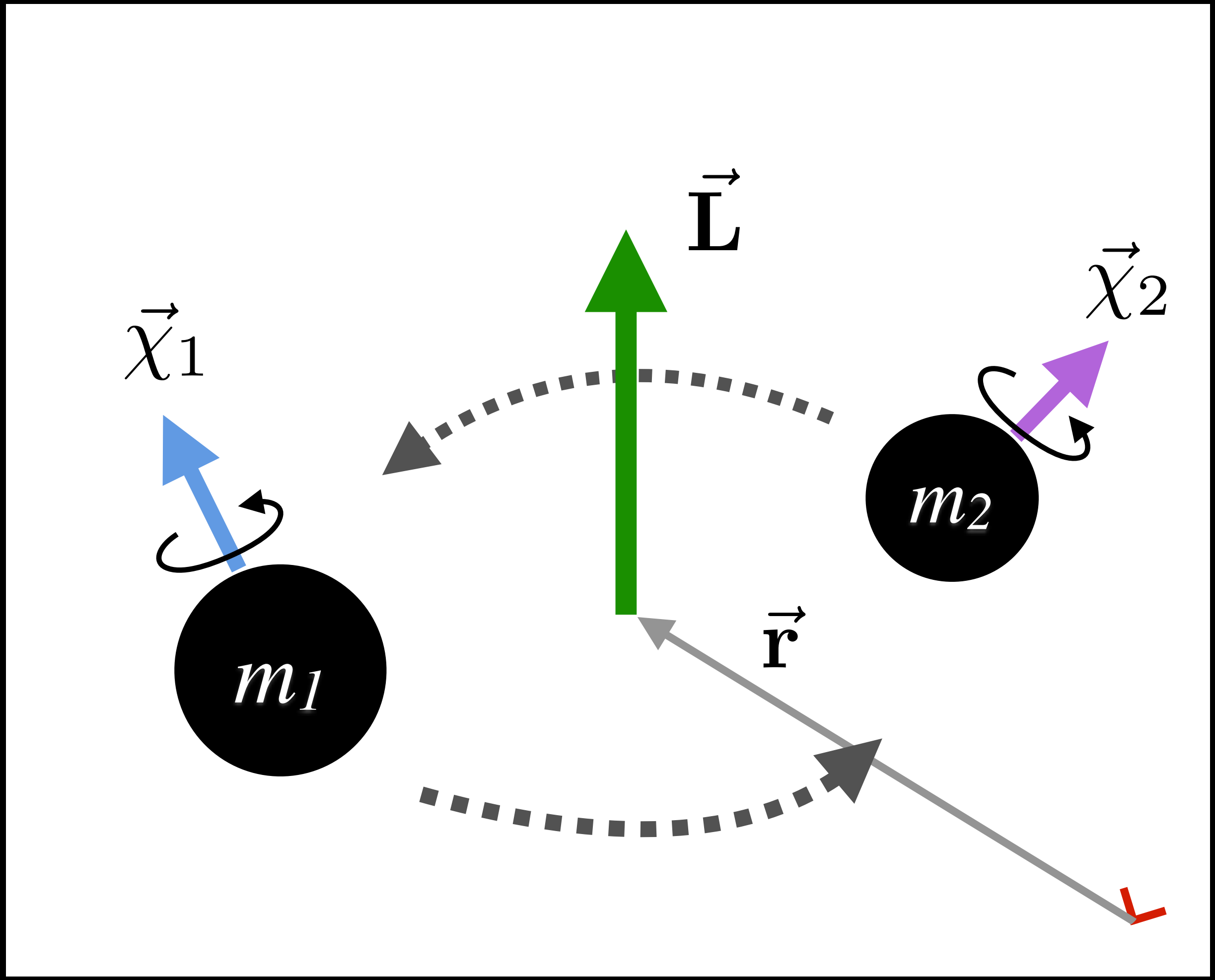
  - location & orientation (6)



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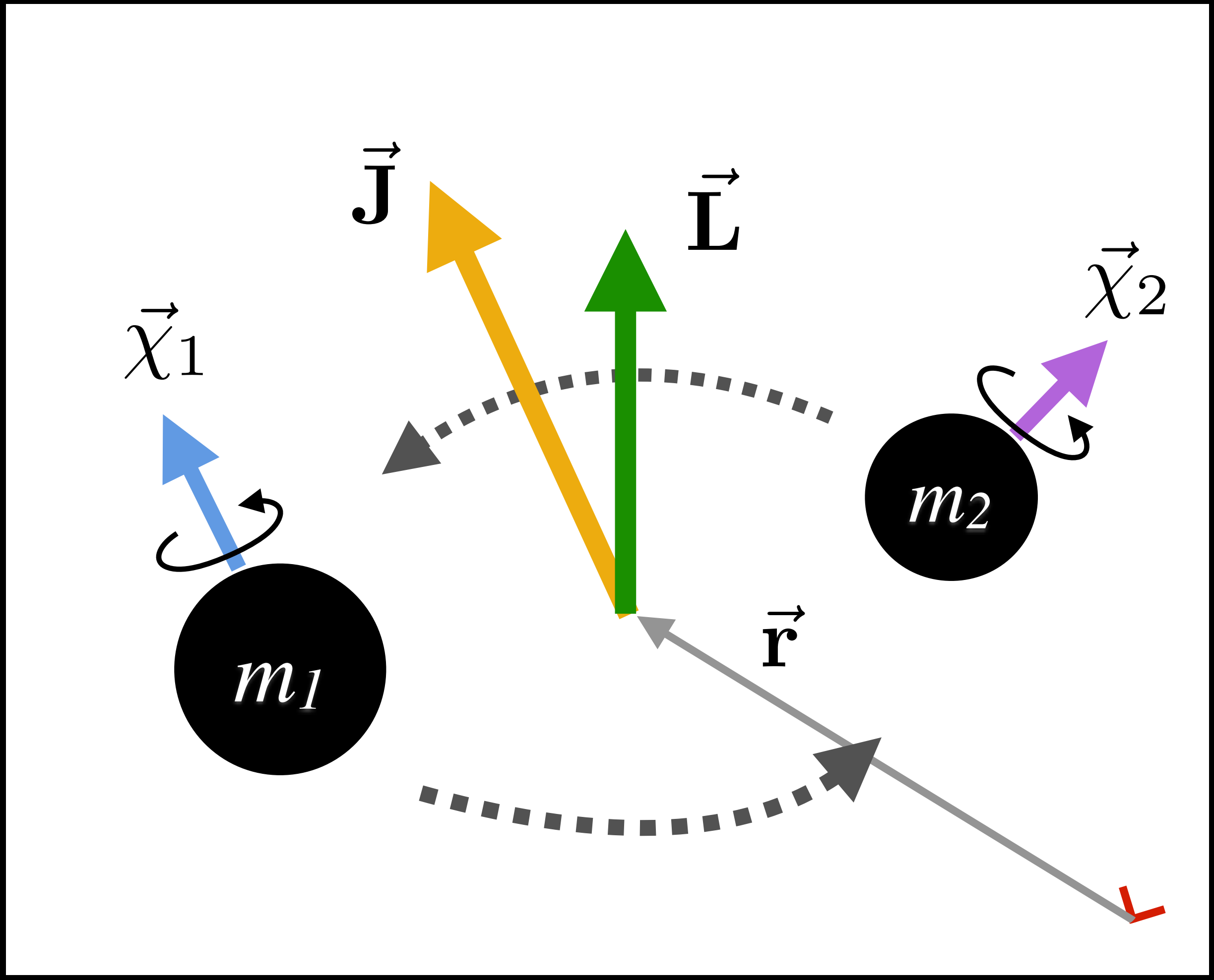
Precessing System



CBC PARAMETERS

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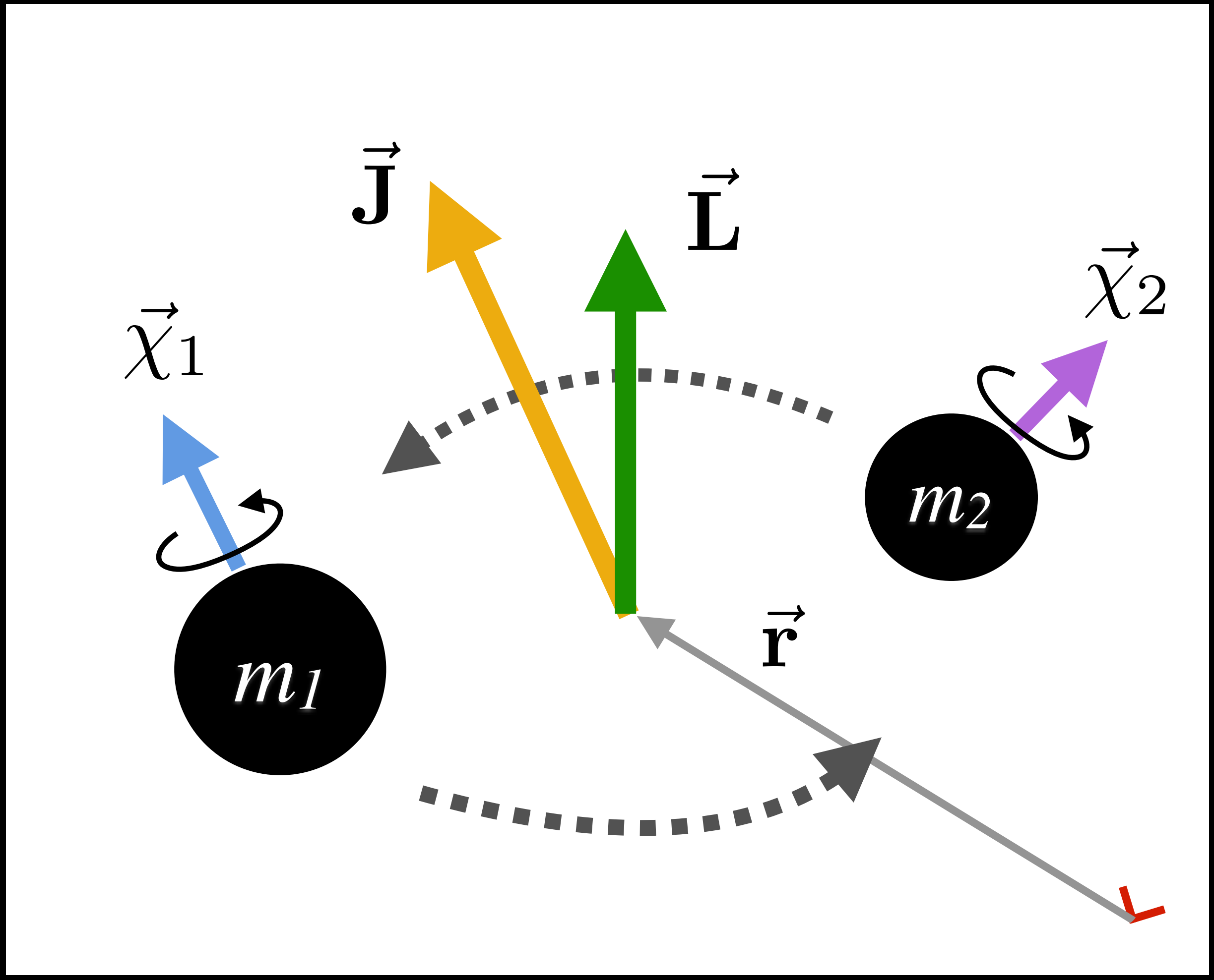
Precessing System



14 Parameters*

*not including coalescence time t_c, assuming circular orbit & 0 or negligible tidal deformation

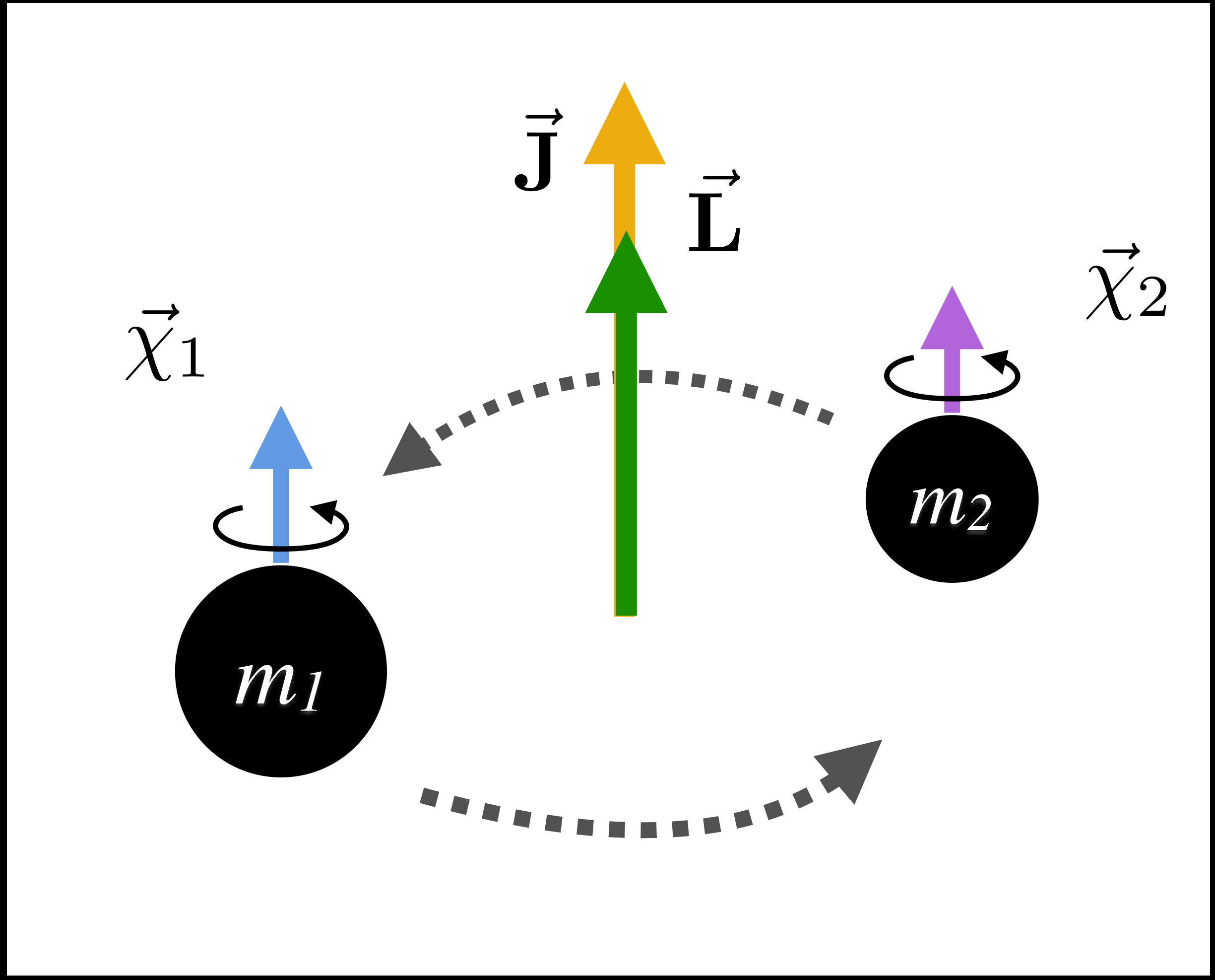
CBC PARAMETERS

- Possible CBC parameters (#):
  - component masses m_1, m_2 (2)
  - dimensionless spins of components χ_1, χ_2 (~~6~~) (2)
  - ~~location & orientation (6)~~

  analytically maximized over for non-precession

- We consider non-precessing systems in our searches

Non-Precessing System

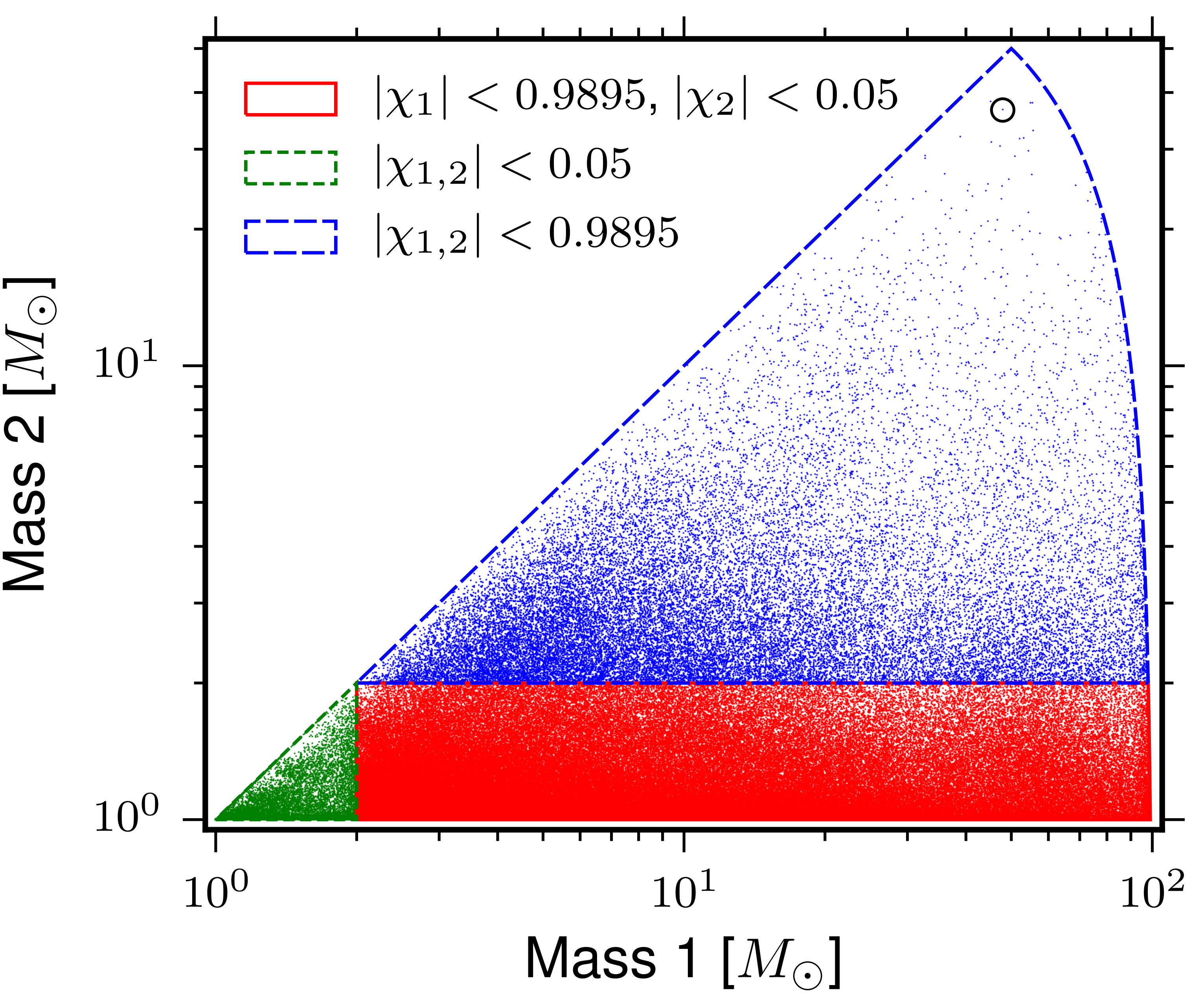


4 Parameters*

*not including coalescence time t_c, assuming circular orbit & 0 or negligible tidal deformation

THE BANK USED IN O1

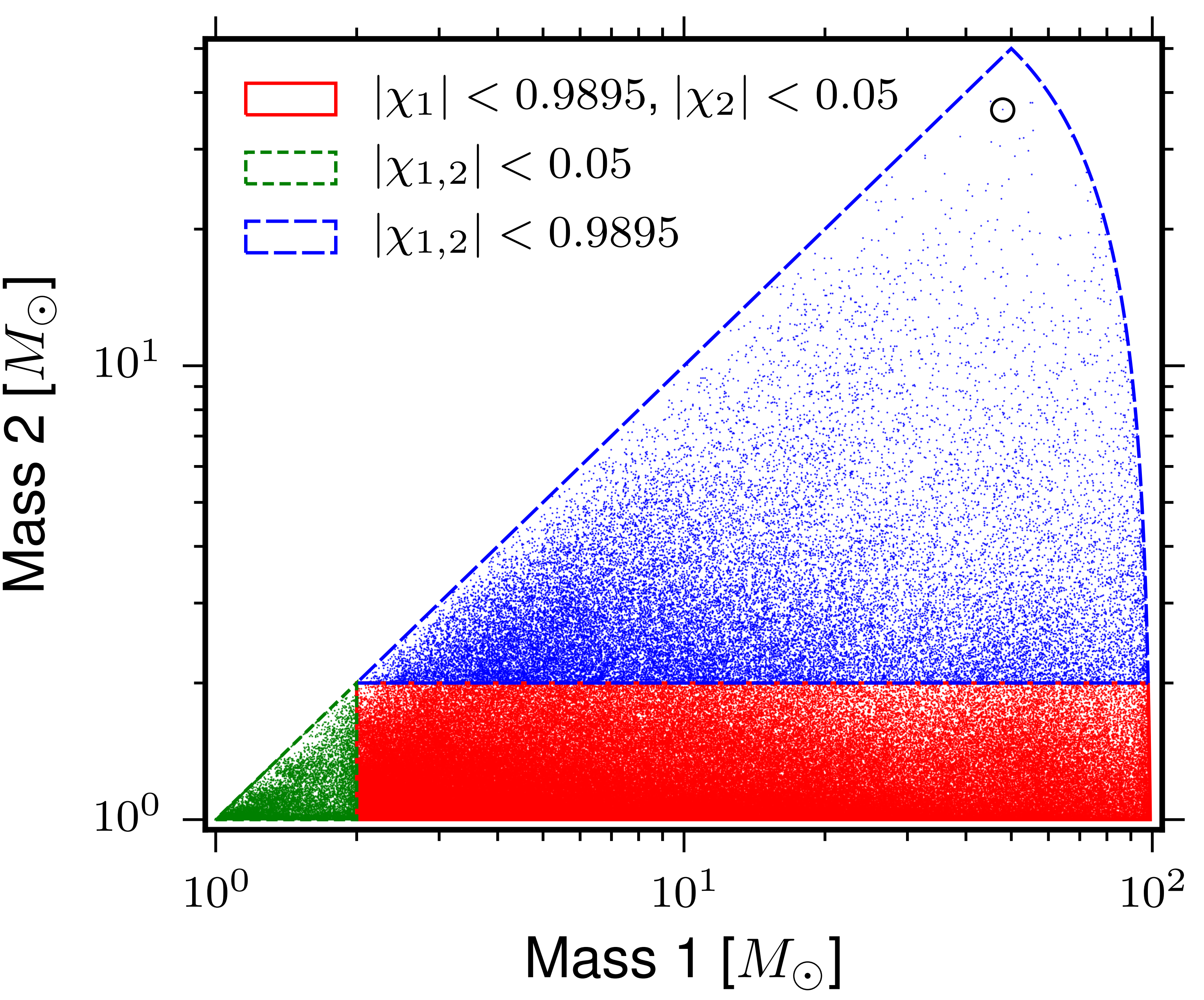
- Targets:
  - Binary neutron stars (BNS)
  - Stellar-mass binary black holes (BBH)
  - Binaries containing a neutron star & a black hole (NSBH)



LSC+Virgo, arXiv:1602.03839

THE BANK USED IN O1

- We limit NS spin to $|\chi_{NS}| < 0.05$
- Is sensitive to NS with $|\chi_{NS}| < 0.4$
- Assume BHs can have $m \geq 2\ M_\odot$
- $|\chi_{BH}| < 0.9895$



LSC+Virgo, arXiv:1602.03839

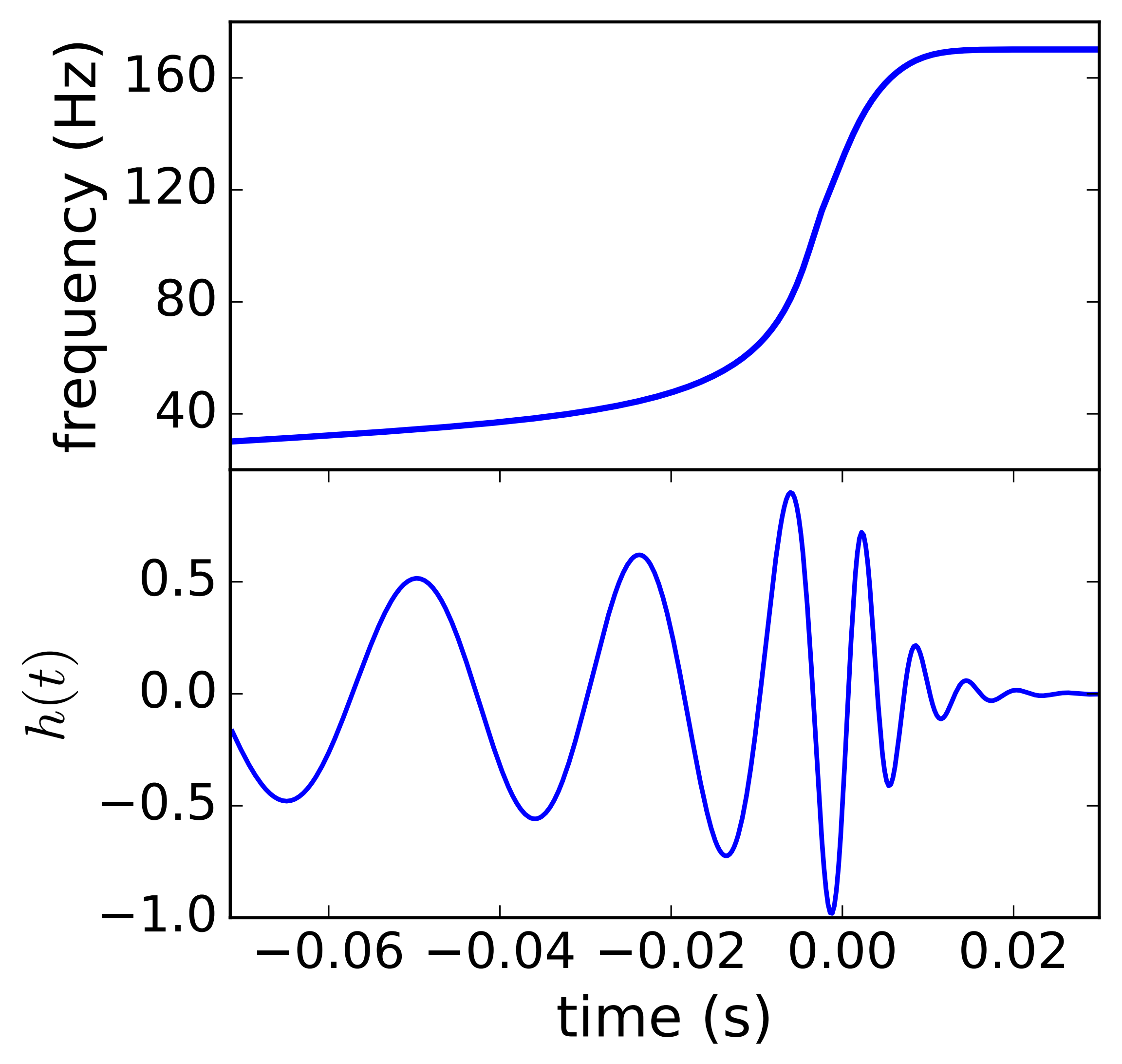
TWO "OFFLINE" SEARCHES PERFORMED

- PyCBC [4]
  - Python based, frequency-domain matched filter workflow
  - Evolution of CBC pipeline used in Initial LIGO
- GstLAL [5]
  - gStreamer based, time-domain matched filter workflow
  - implements a different ranking statistic from PyCBC

4. S. A. Usman et al., arXiv:1508.02357
5. C. Messick et al., arXiv:1604.04324

PYCBC CHI-SQUARED TEST

- Divide template h into p frequency bins of equal power



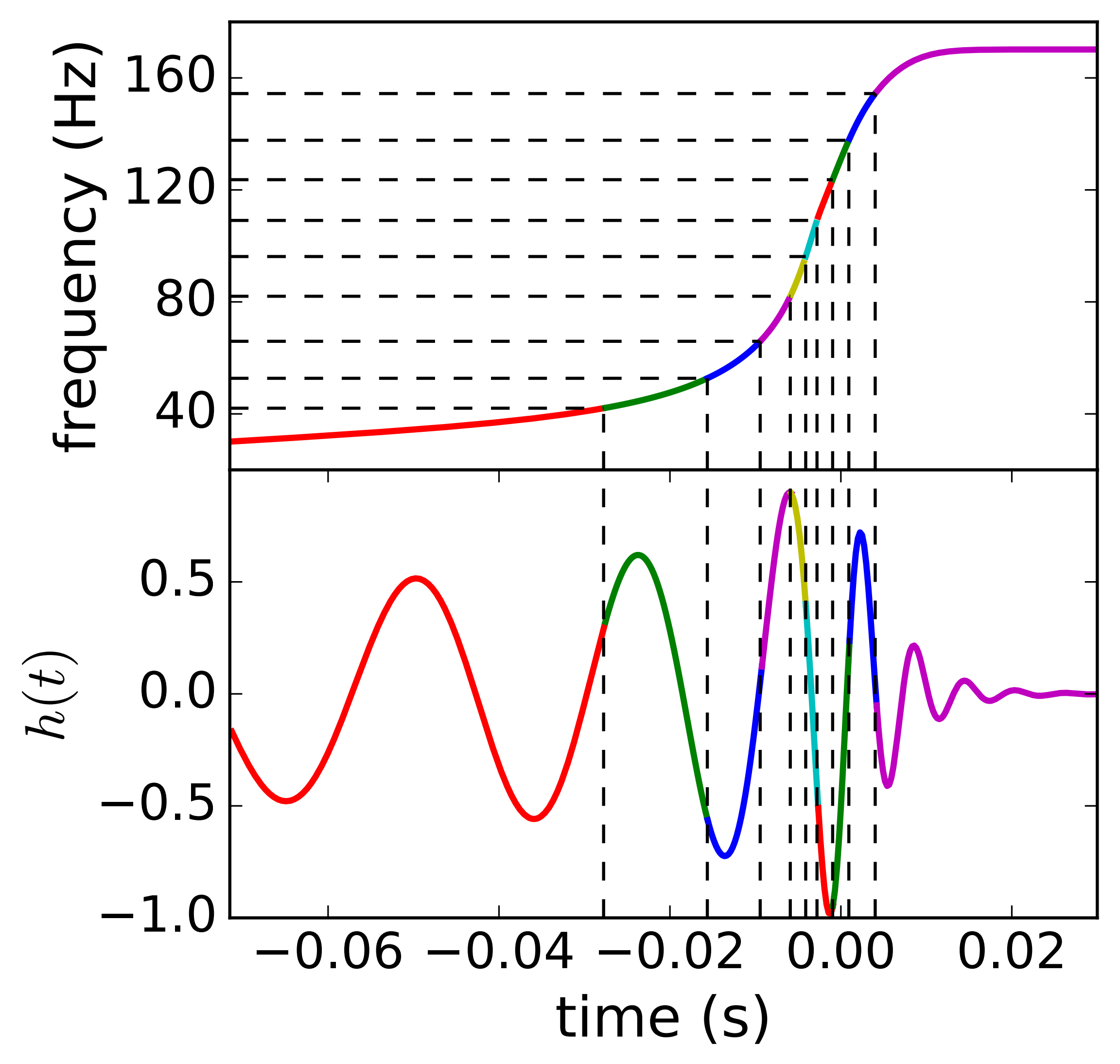
PyCBC Chi-Squared Test

- Divide template h into p frequency bins of equal power
- Filter each h_i with the data s
- If template matches signal, expect:

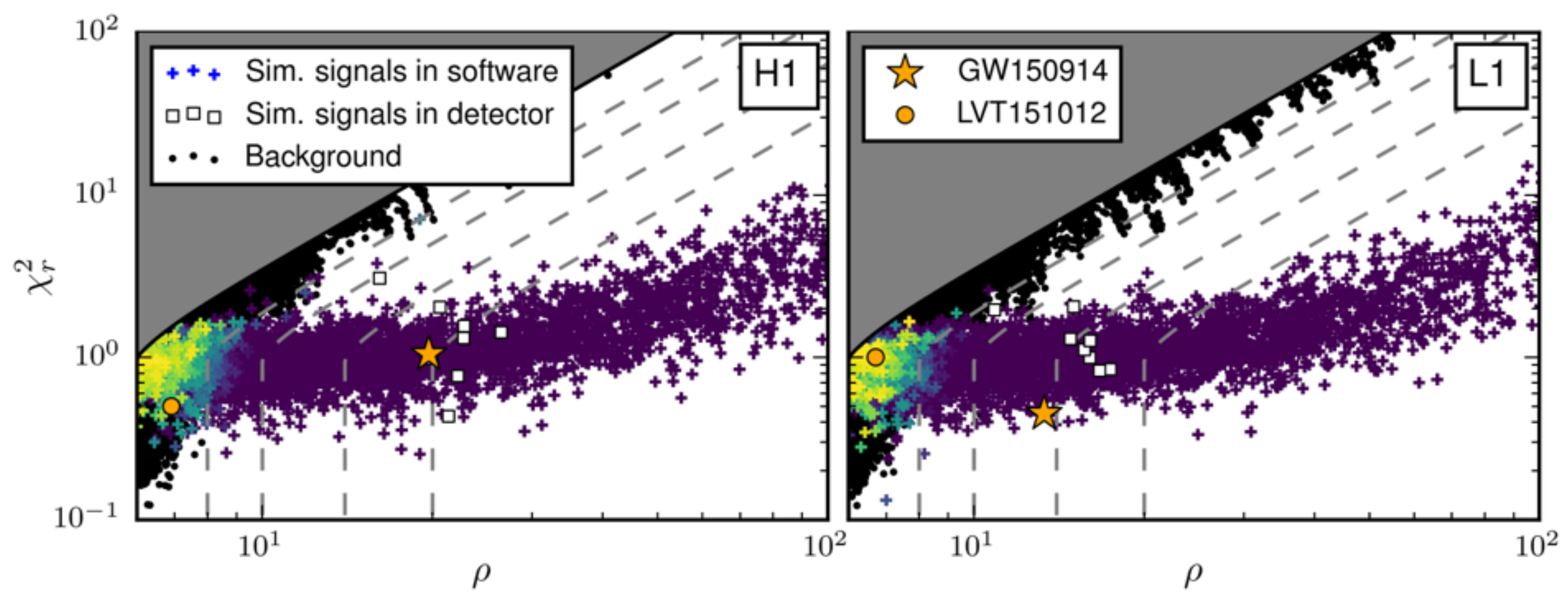
$$\langle h_i | s \rangle = \langle h | s \rangle / p$$

- Calculate:

$$\boxed{\chi_r^2 = \frac{p}{2p-2} \frac{1}{\langle h | h \rangle} \sum_{i=1}^{p} \left| \langle h_i | s \rangle - \frac{\langle h | s \rangle}{p} \right|^2}$$

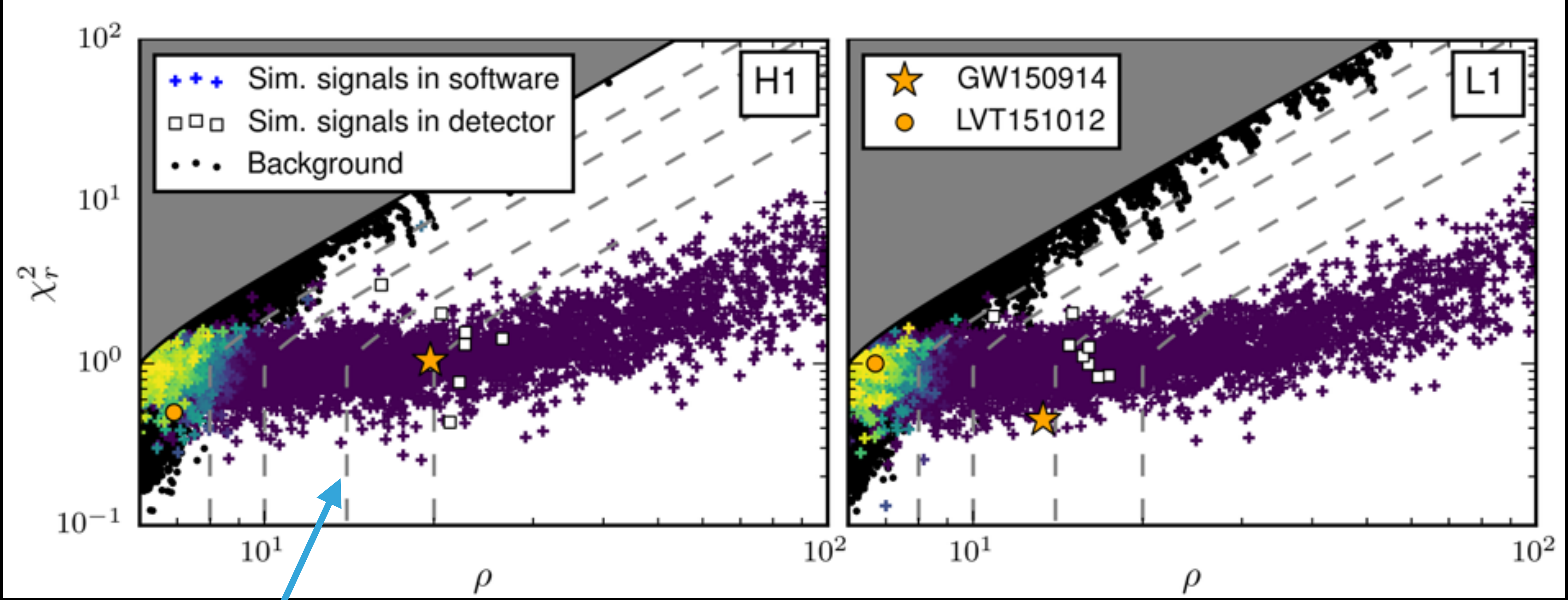


PYCBC CHI-SQUARED TEST



LSC+Virgo, arXiv:1602.03839

REWEIGHTED SNR



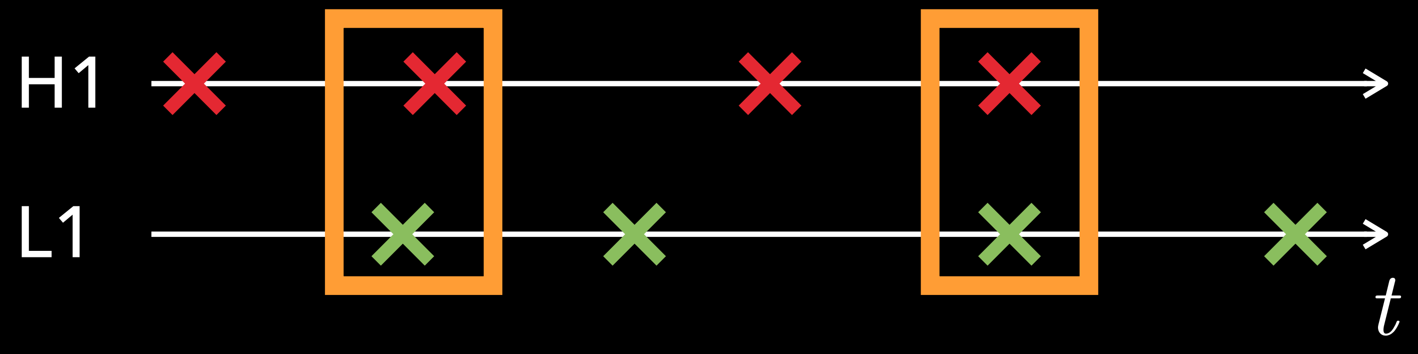
LSC+Virgo, arXiv:1602.03839

Reweighted SNR

$$\hat{\rho} = \begin{cases} \rho\left[(1+(\chi_r^2)^3)/2\right]^{-\frac{1}{6}}, & \text{if } \chi_r^2 > 1, \\ \rho, & \text{if } \chi_r^2 \leq 1. \end{cases}$$

COINCIDENCE TEST

- Apply a coincidence test to single-detector triggers
- Must be in same template & within ±15ms

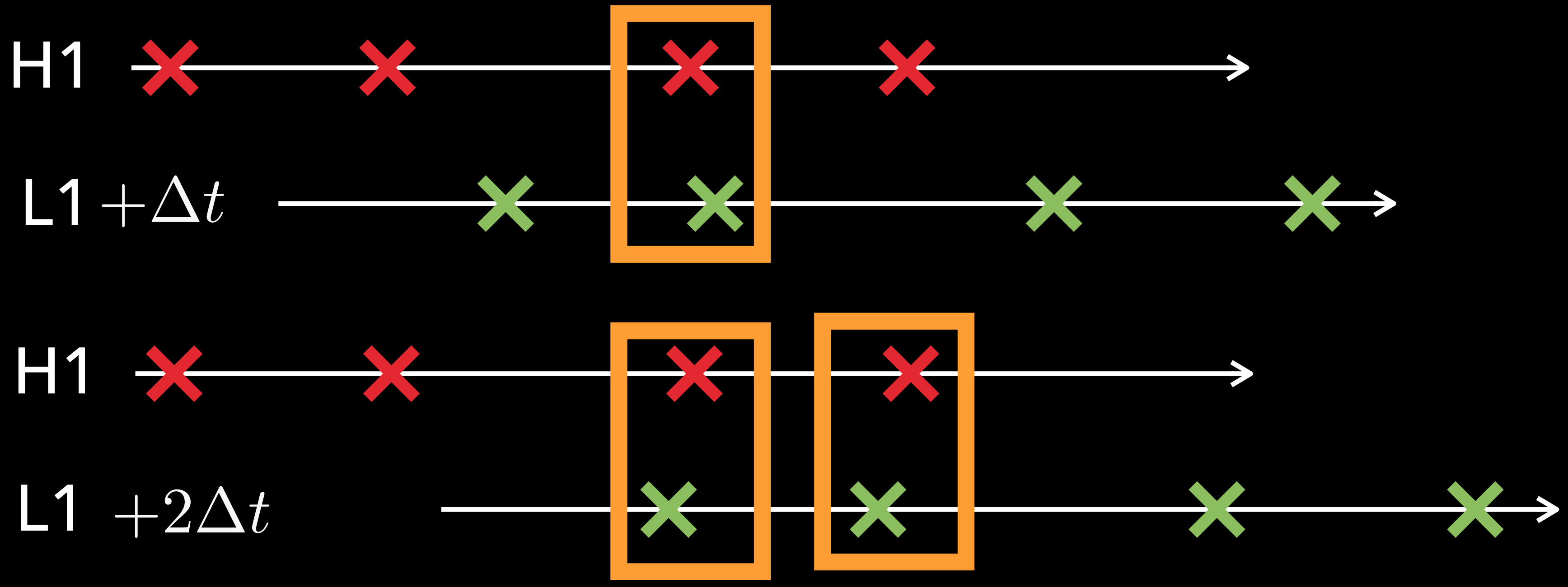


- Construct ranking statistic from reweighted SNR of coincident triggers:

$$\boxed{\hat{\rho}_c = \sqrt{\hat{\rho}_H^2 + \hat{\rho}_L^2}}$$

BACKGROUND ESTIMATE

- Do time slides to estimate background rate of false alarms



- Perform all possible Δt = 0.1s slides; Ns ~ 10^7 slides

$$\boxed{\mathcal{F}(\hat{\rho}_c) \approx \frac{n_b(\hat{\rho}_c)}{N_S}; \quad \mathrm{FAR}(\hat{\rho}_c) \approx \frac{n_b(\hat{\rho}_c)}{N_S T}}$$

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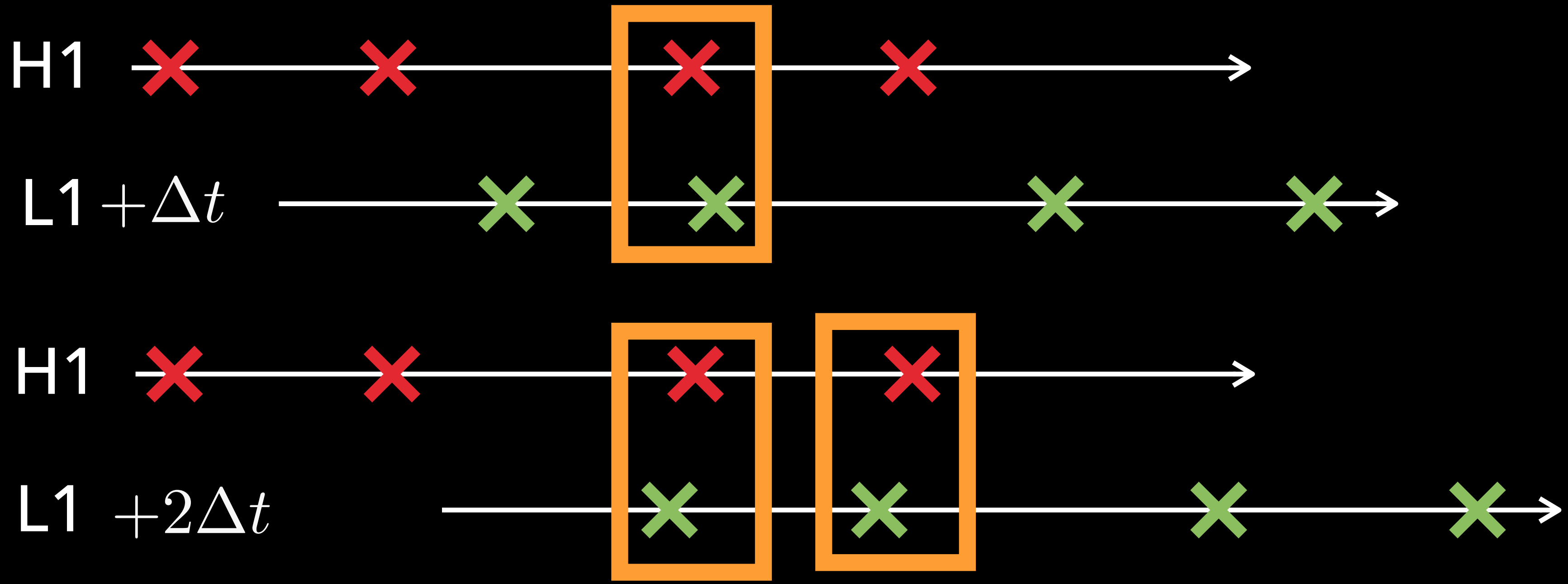

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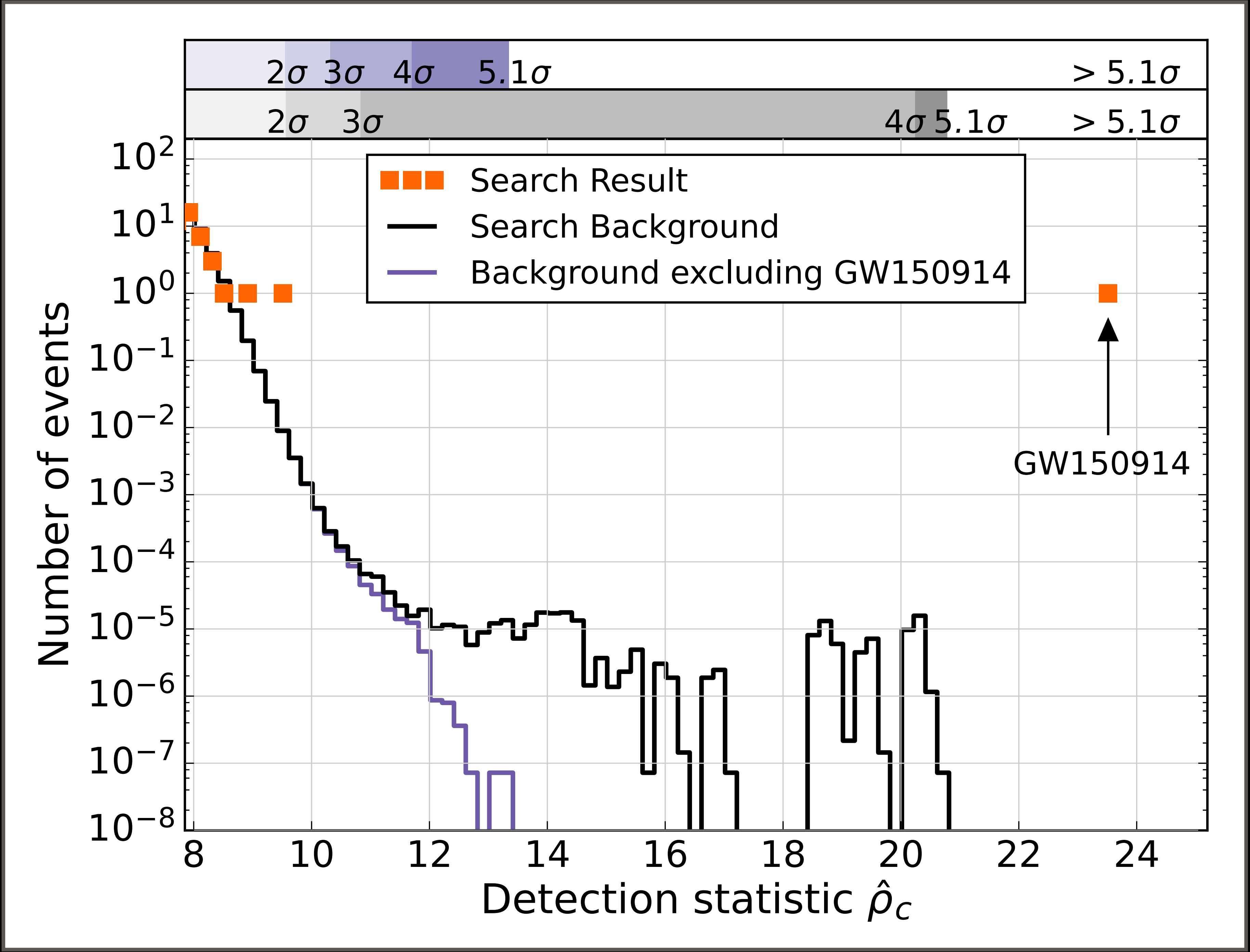
$T = 16$ days

$N_S \approx 10^7$ slides

PYCBC GW150914 RESULTS



GW150914:

- FAR < 5×10^{-6}/yr
- $\mathcal{F}$ < 2×10^{-7}
- Significance > 5.1σ

LSC+Virgo, PRL 116, 061102 (2016); LSC+Virgo, arXiv:1602.03839

UNCORRELATED VS CORRELATED SOURCES

- FAR estimate gives rate of chance coincidences from uncorrelated noise sources
- Use environmental sensors to investigate any correlated noise sources
- No other environmental influences could be found [6]

6. LSC+Virgo, arXiv:1602.03844

UNCORRELATED VS CORRELATED SOURCES

- FAR estimate gives rate of chance coincidences from uncorrelated noise sources
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- No other environmental influences could be found [6]

GW150914 IS A GRAVITATIONAL WAVE.

6. LSC+Virgo, arXiv:1602.03844

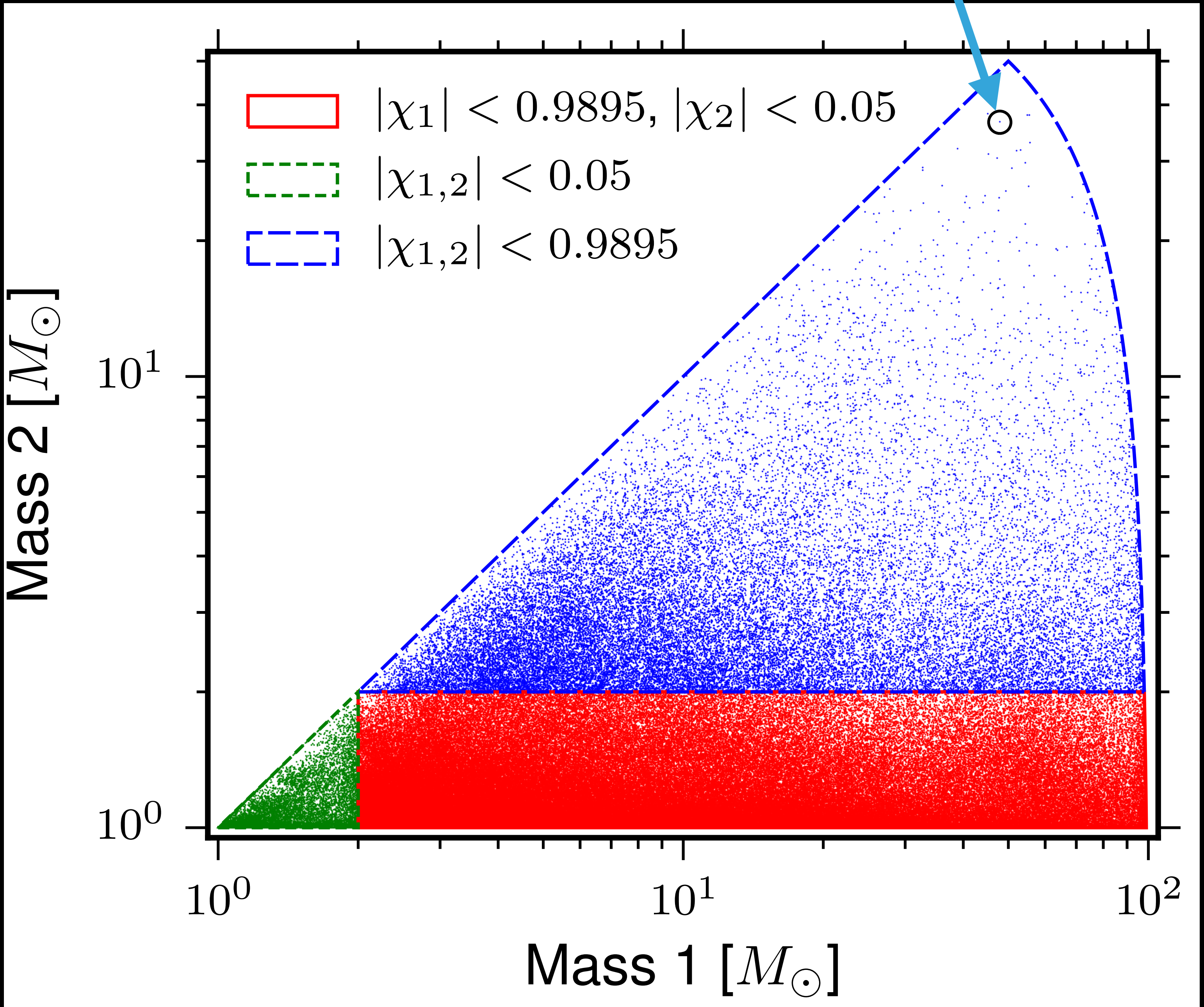
3. PARAMETER ESTIMATION

arXiv:1602.03840

NEED FOR PE CODE

- Modeled searches are designed to identify times when a signal exists, estimate significance given non-Gaussian transients
- Discreetness of template bank ⇨ parameters of waveform not estimated accurately
- Need followup code

GW150914



LSC+Virgo, arXiv:1602.03839

BAYES THEOREM

- Probability that a waveform h with parameters $\vartheta = \{m_1, m_2, \ldots\}$ exists in data s is given by:

$$P(h[\vec{\vartheta}]|s) = \mathcal{L}(s|h[\vec{\vartheta}])P(h[\vec{\vartheta}]);$$

$$\mathcal{L}(s|h[\vec{\vartheta}]) = \text{“likelihood ratio”} \equiv \frac{P(s|h[\vartheta])}{P(s|0)}$$

- In N_d detectors with stationary Gaussian noise:

$$\mathcal{L}(s_k|h_k[\vec{\vartheta}]) \propto \exp\left[-\frac{1}{2}\sum_{k=1}^{N_d}\left\langle h_k[\vec{\vartheta}] - s_k \,\middle|\, h_k[\vec{\vartheta}] - s_k\right\rangle\right]$$

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Matched-filter SNR = $\log\mathcal{L}$ maximized over phase & amplitude in single detector assuming non-precessing, dominant mode waveforms

MCMC & NESTED SAMPLING

- Use 2 independent stochastic sampling engines to evaluate $\mathcal{L}$ over multi-dimensional parameter space
  - Markov-chain Monte Carlo (MCMC) [7,8]
  - Nested sampling [9,10]
- Time and mass estimate from searches used to inform prior
  - t_c: +/-0.1s uniform prior centered on searches' t_c
  - $m_{1,2}$: uniform prior $\in$ [10,80] $M_\odot$

7. C. Rover et al., CQG 23, 4895 (2006)
8. M. van der Sluys et al., CQG 25, 184011(2008)
9. J. Skilling, Bayesian Analysis 1, 833 (2006)
10. J. Veitch & A. Vecchio, PRD 81, 062003 (2010)

WAVEFORM MODELS

- Two waveform models used
- “EOBNR”: non-precessing spin model using effective-one-body (EOB) formalism tuned to numerical relativity (NR) (11 parameters) [11,12]
- “IMRPhenom”: precessing waveform model derived from phenomenological fits of hybridized EOB & NR waveforms (13 parameters) [13,14]

11. A. Taracchini et al., PRD 89, 061502 (2014)
12. M. Pürrer, CQG 31, 195010 (2014)
13. M. Hannam et al., PRL 113, 151101 (2014)
14. P. Schmidt Ph.D. Thesis (2014)

QUOTED VALUES

- Waveform models give consistent results for GW150914
  - nearly equal Bayes factors
- We average parameter estimates from both models ("Overall") & use them to estimate systematic errors
- Quoted parameter values are the median of the marginalized posterior distribution with symmetric 90% credible interval

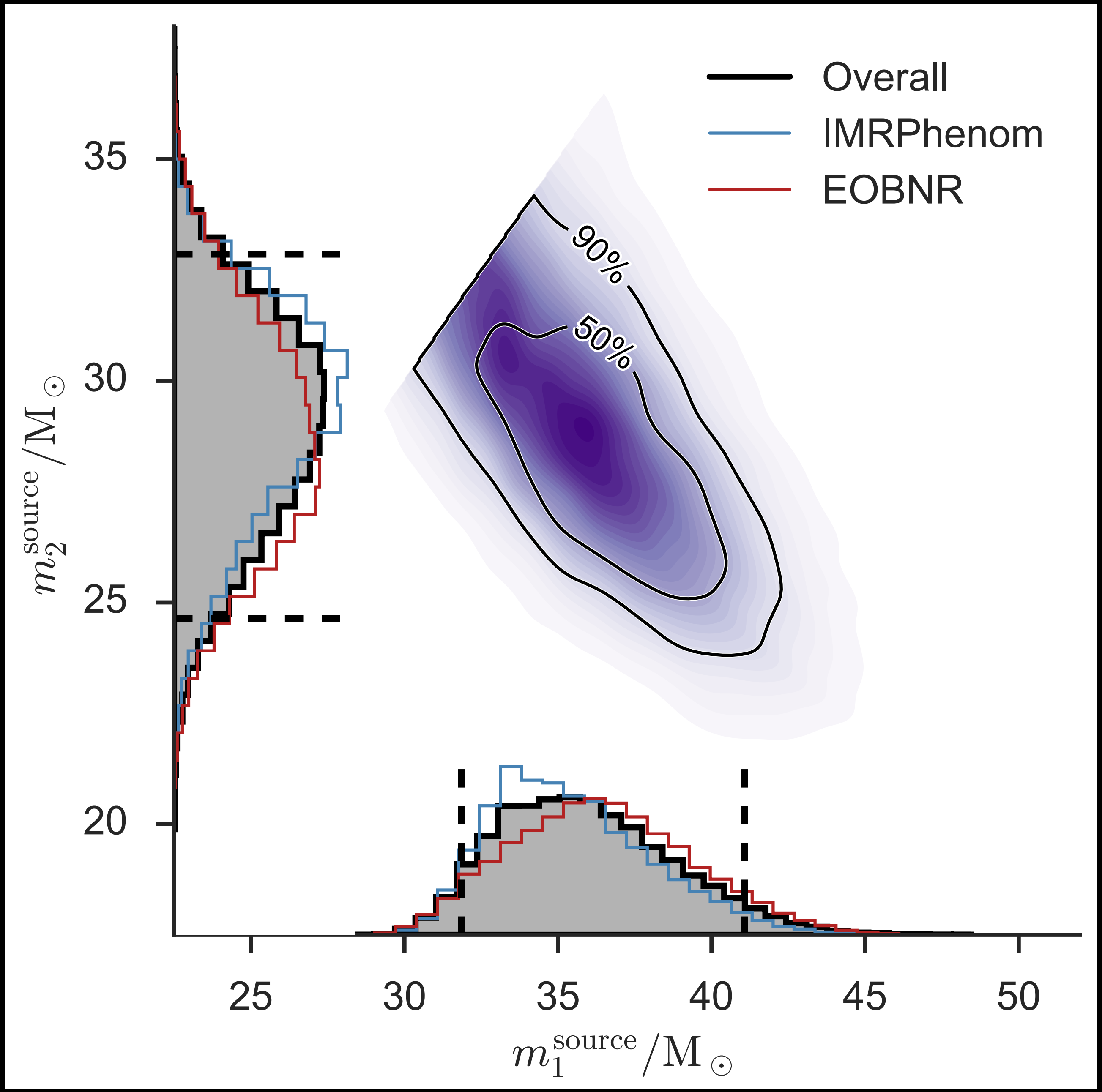
GW150914 RESULTS: MASSES

- Both components are BHs:

$$\boxed{\begin{aligned} m_1^{\mathrm{source}} &= 36^{+5}_{-4}\mathrm{M}_\odot \\ m_2^{\mathrm{source}} &= 29^{+4}_{-4}\mathrm{M}_\odot \end{aligned}}$$

- Nearly equal mass:

$$\boxed{0.65 \leq m_2/m_1 \leq 1}$$



LSC+Virgo, arXiv:1602.03840

GW150914 RESULTS: MASSES

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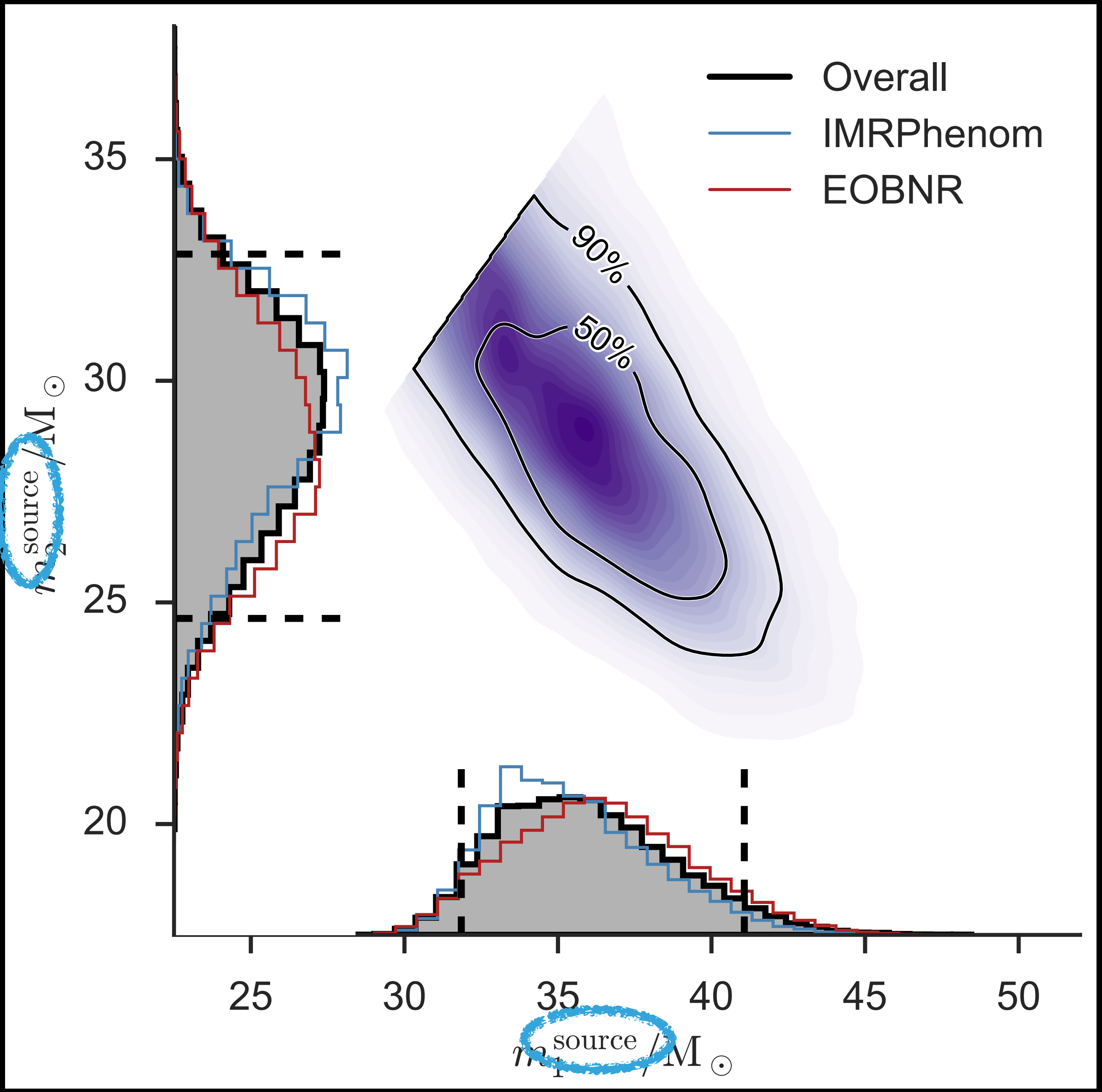

LSC+Virgo, arXiv:1602.03840

GW150914 RESULTS: MASSES

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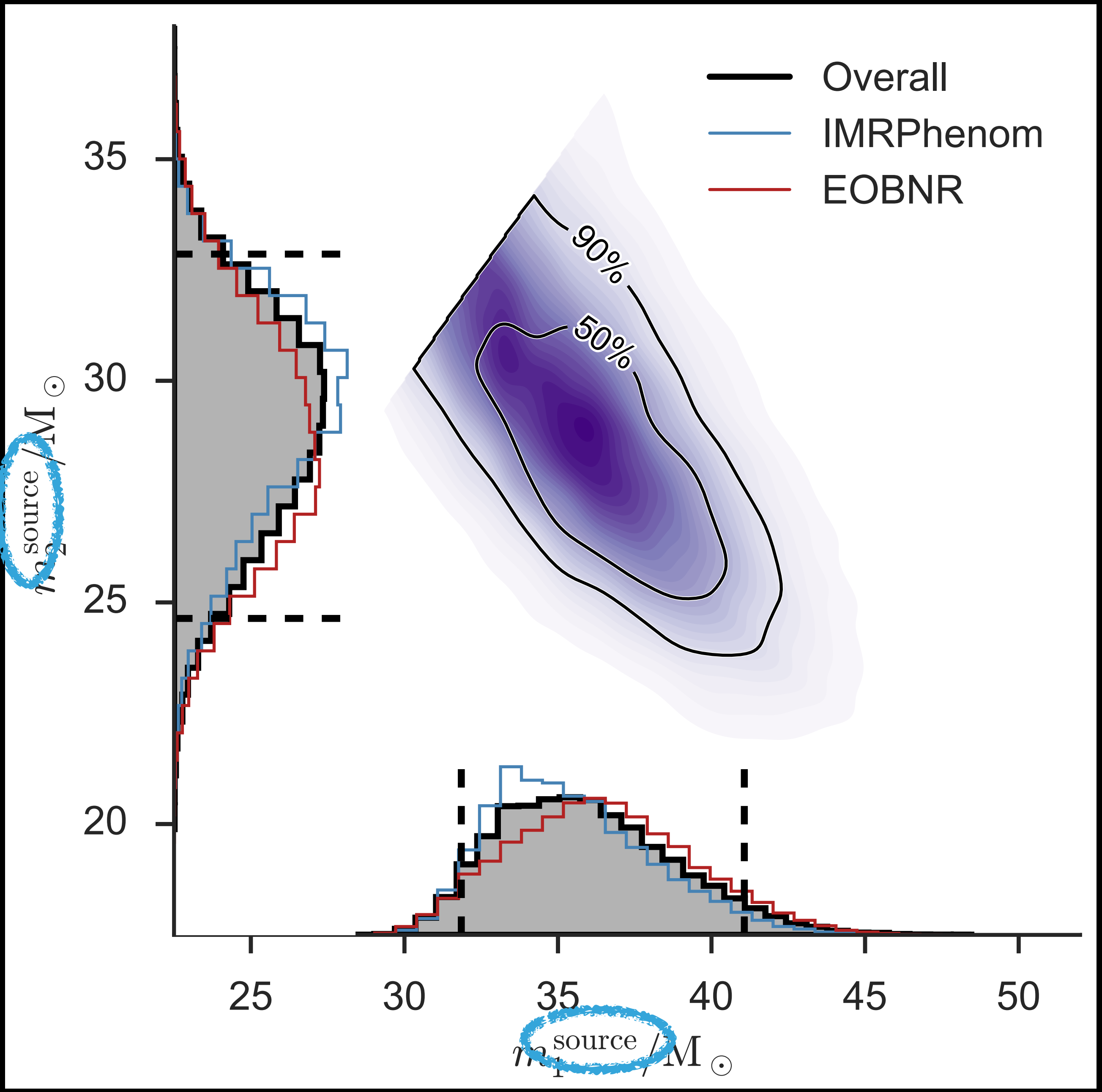
$$m_1^{\text{source}} = 36^{+5}_{-4}\mathrm{M}_\odot$$
$$m_2^{\text{source}} = 29^{+4}_{-4}\mathrm{M}_\odot$$

- Observed masses:

$$m_1^{\text{obs}} = 39^{+6}_{-4}\mathrm{M}_\odot, \quad m_2^{\text{obs}} = 32^{+4}_{-5}\mathrm{M}_\odot$$

- Source mass estimated using redshift:

$$m^{\text{source}} = m^{\text{obs}}/(1+z)$$



LSC+Virgo, arXiv:1602.03840

GW150914 RESULTS: DISTANCE

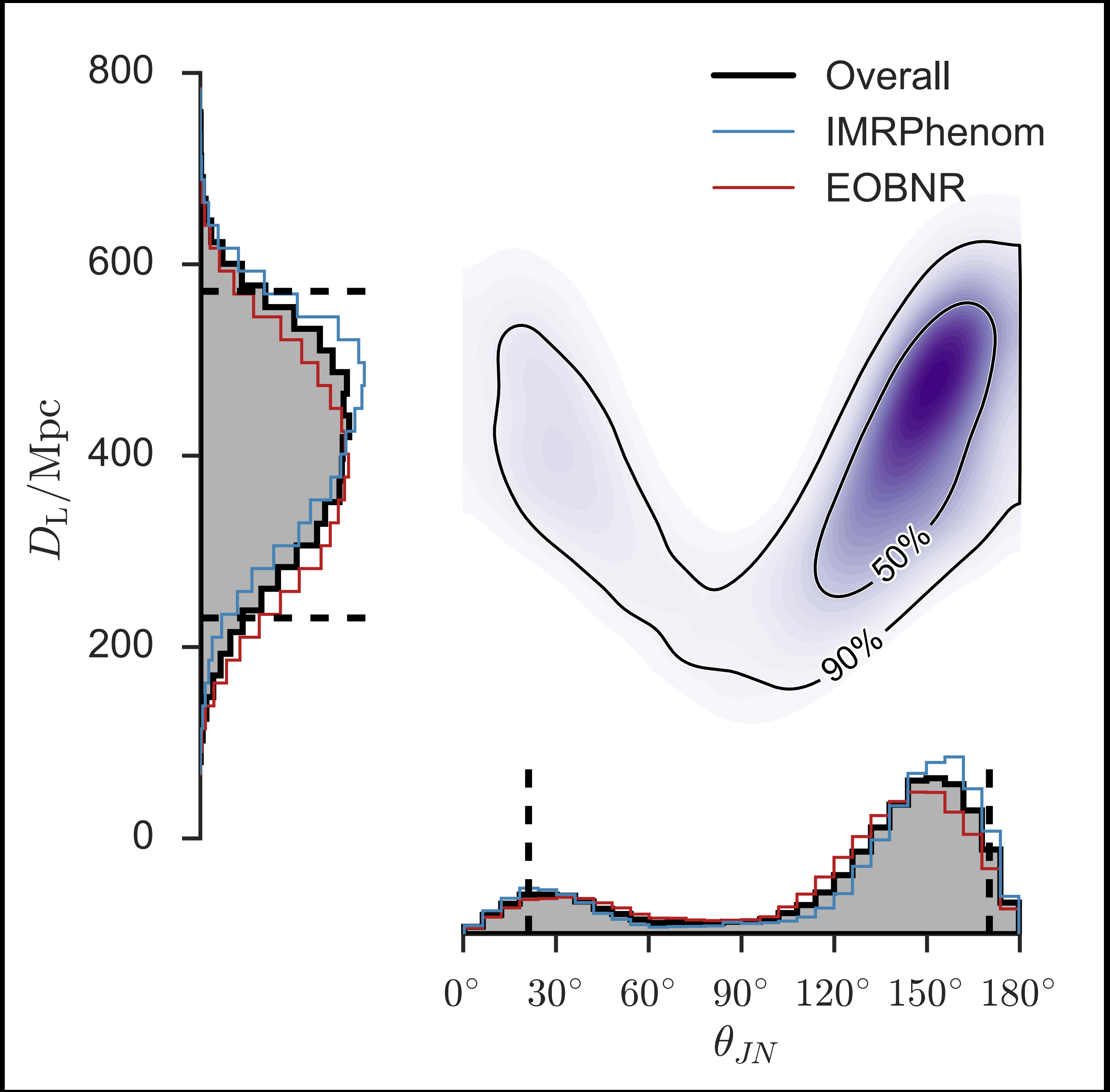
- Luminosity distance:

$$\boxed{D_{\rm L} = 410^{+160}_{-180}\,\mathrm{Mpc}}$$

- Assuming flat ΛCDM cosmology*:

$$\boxed{z = 0.09^{+0.03}_{-0.04}}$$

- Inclination θ_{JN} = angle between total angular momentum J & line of sight
- Edge-on disfavored: only 35% chance 45° < θ_{JN} < 135°

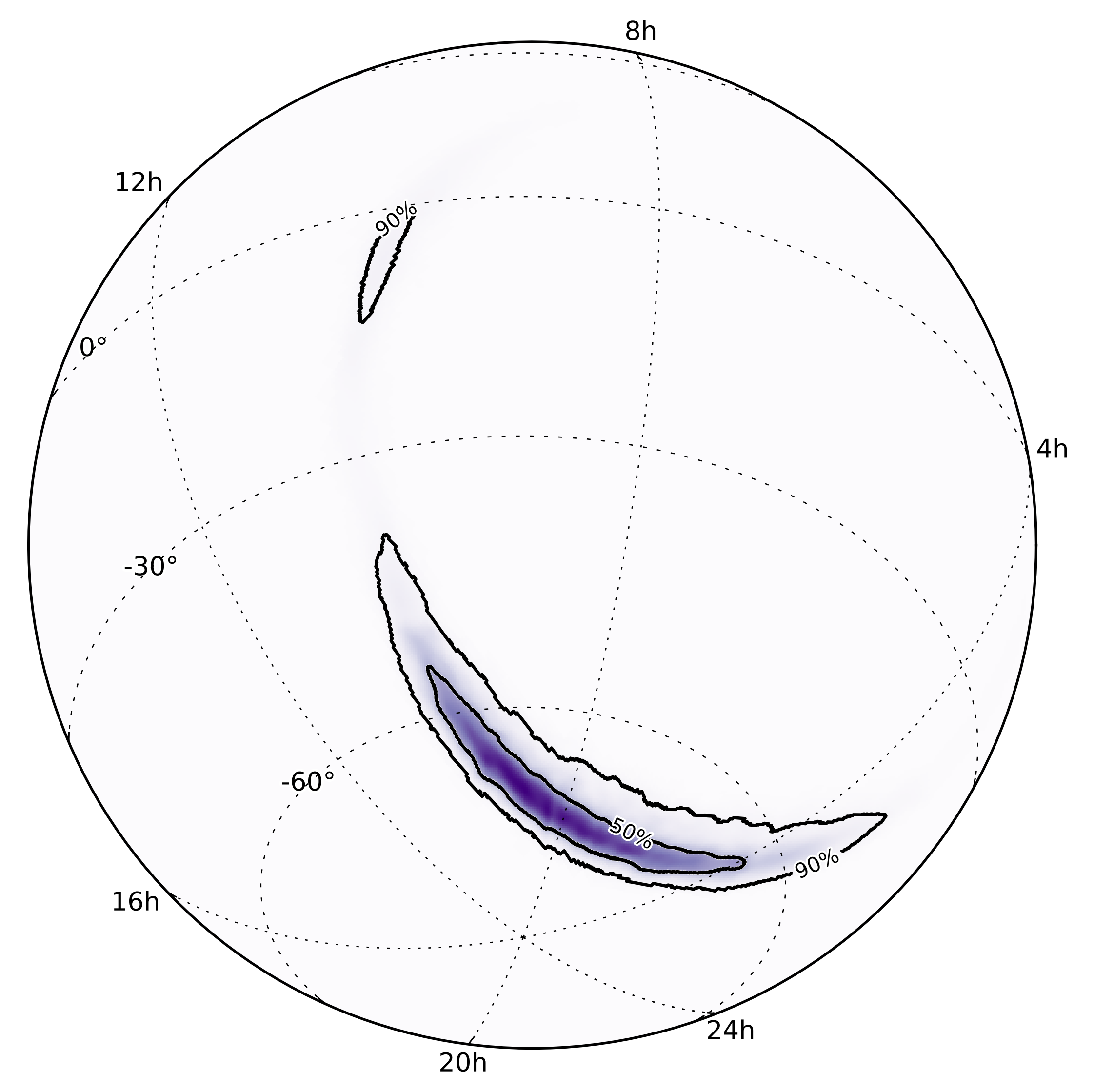


LSC+Virgo, arXiv:1602.03840

$^{*}H_0 = 67.9\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$
$\Omega_{\rm m} = 0.306$

GW150914 RESULTS: SKY MAP

- With 2 detectors can only limit location to annulus on the sky
- 50% probability region: 140 deg^2
- 90% probability region: 590 deg^2
  - Co-moving volume: ~0.01Gpc^3
- Co-moving MWEG density is $10^7/\text{Gpc}^3$



LSC+Virgo, arXiv:1602.03840

GW150914 RESULTS: SPIN

- Individual component spins not well constrained:

$$\boxed{|\vec{\chi}_1| < 0.7, \quad |\vec{\chi}_2| < 0.9}$$

- Dominant spin effect:

$$\chi_{\mathrm{eff}} = \left[\frac{m_1\vec{\chi}_1 + m_2\vec{\chi}_2}{m_1 + m_2}\right] \cdot \hat{\mathbf{L}}$$

- Effective precession parameter:

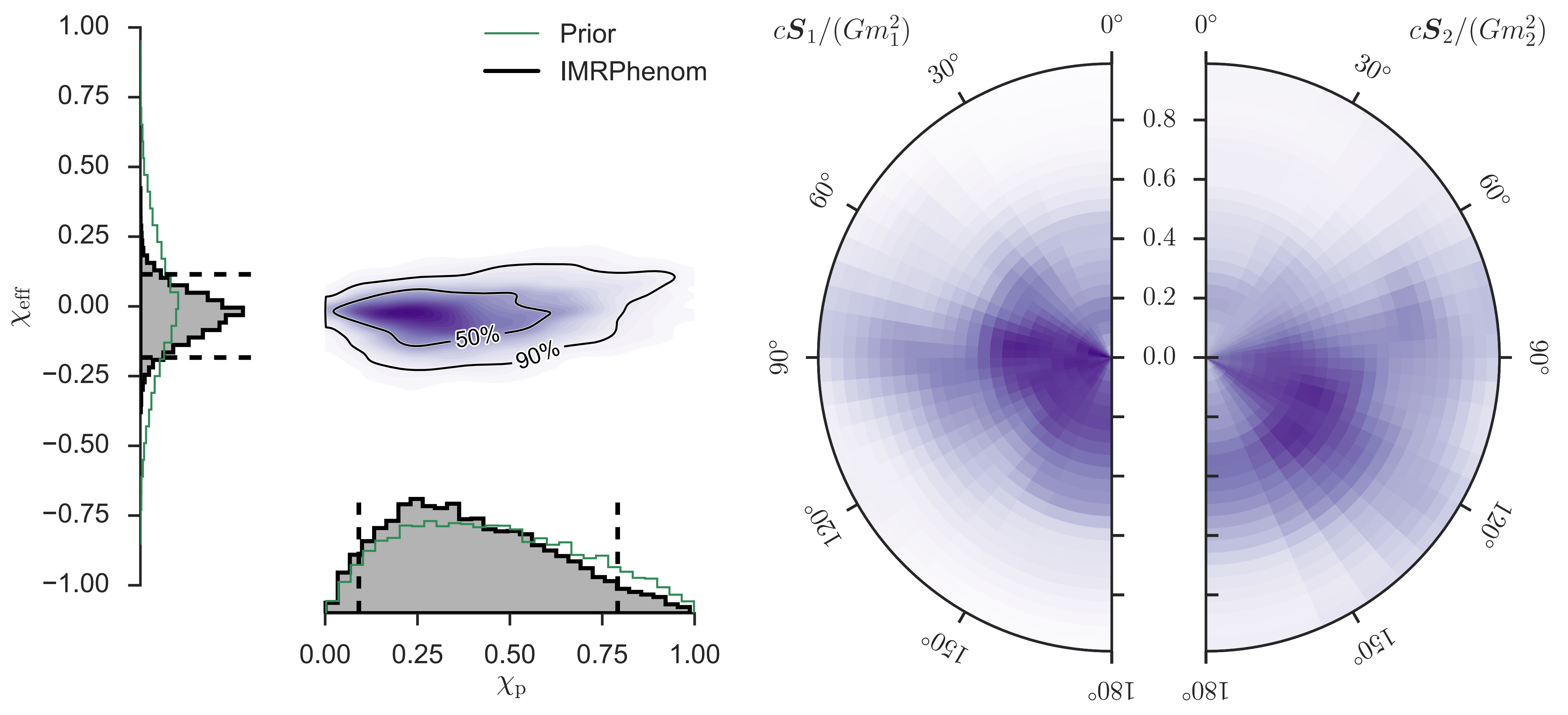
$$\chi_{\mathrm{p}} = \max\left[\chi_{1\perp}, \quad \frac{4q+3}{3q+4} q\chi_{2\perp}\right]; \quad q = m_2/m_1$$

- χ_{p} = 0 for EOBNR model (no precession)

LSC+Virgo, arXiv:1602.03840

GW150914 RESULTS: SPIN

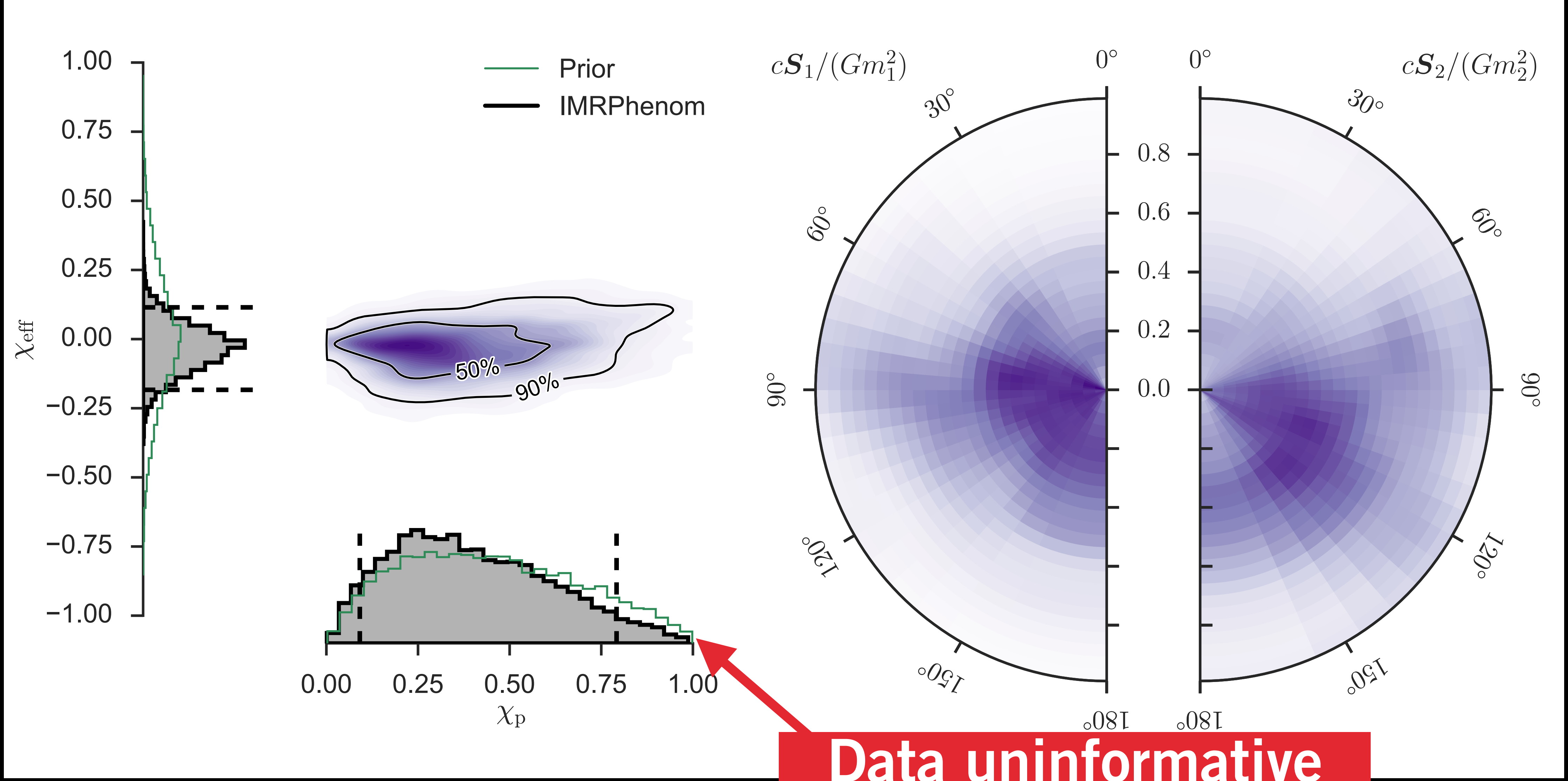
$$\chi_{\text{eff}} = -0.06^{+0.17}_{-0.18}$$



LSC+Virgo, arXiv:1602.03840

GW150914 RESULTS: SPIN

$$\boxed{\chi_{\mathrm{eff}} = -0.06^{+0.17}_{-0.18}}$$



Data uninformative about prcession

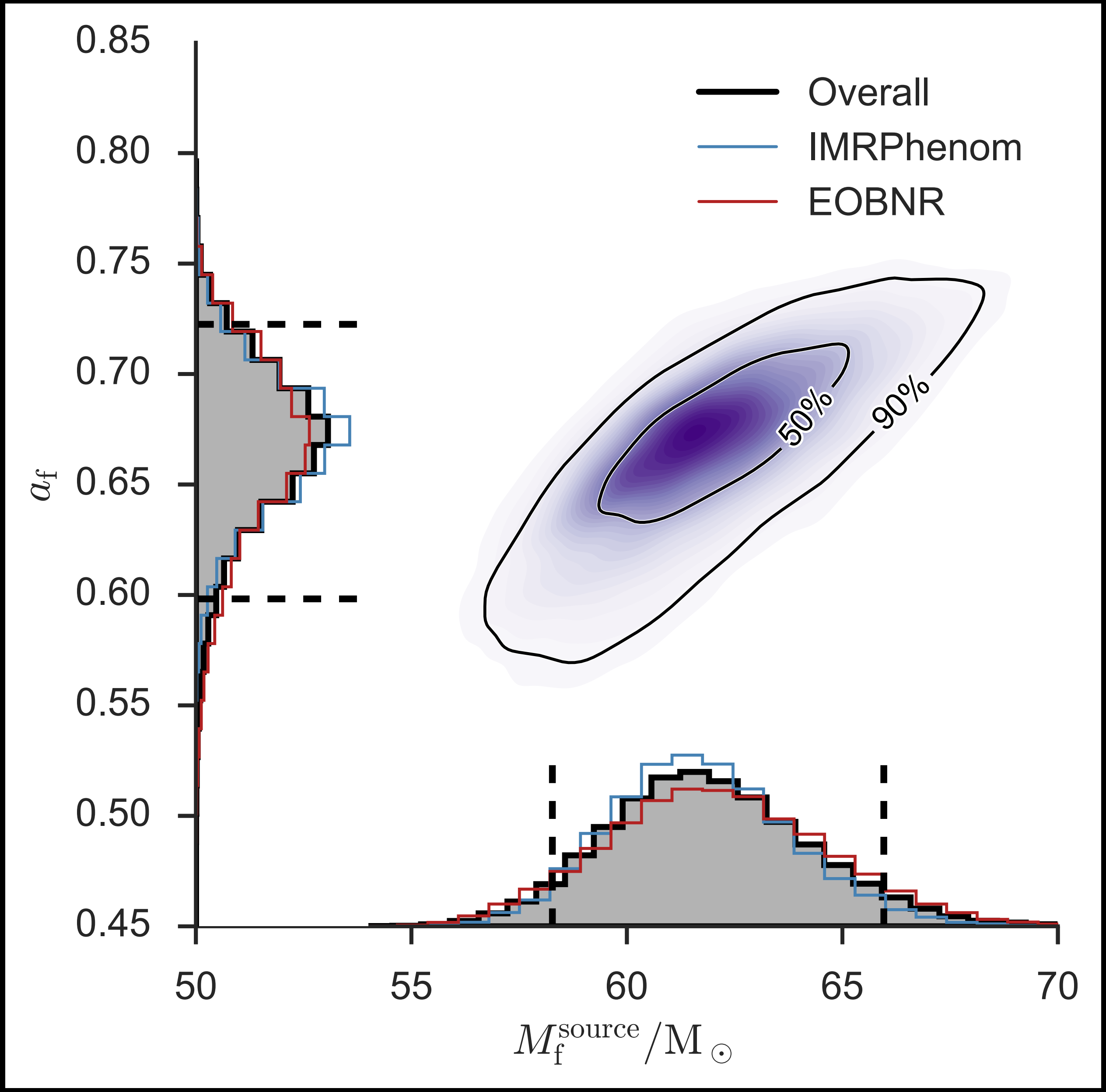
602.03840

GW150914 RESULTS: FINAL MASS & SPIN

- Use mass & spin estimates to infer final mass & spin of BH [15]:

$$\boxed{\begin{aligned} M_\mathrm{f}^\mathrm{source} &= 62^{+4}_{-4}\mathrm{M}_\odot \\ a_\mathrm{f} &= 0.67^{+0.05}_{-0.07} \end{aligned}}$$

- 3.0±0.5 $\mathrm{M}_\odot c^2$ radiated in gravitational waves

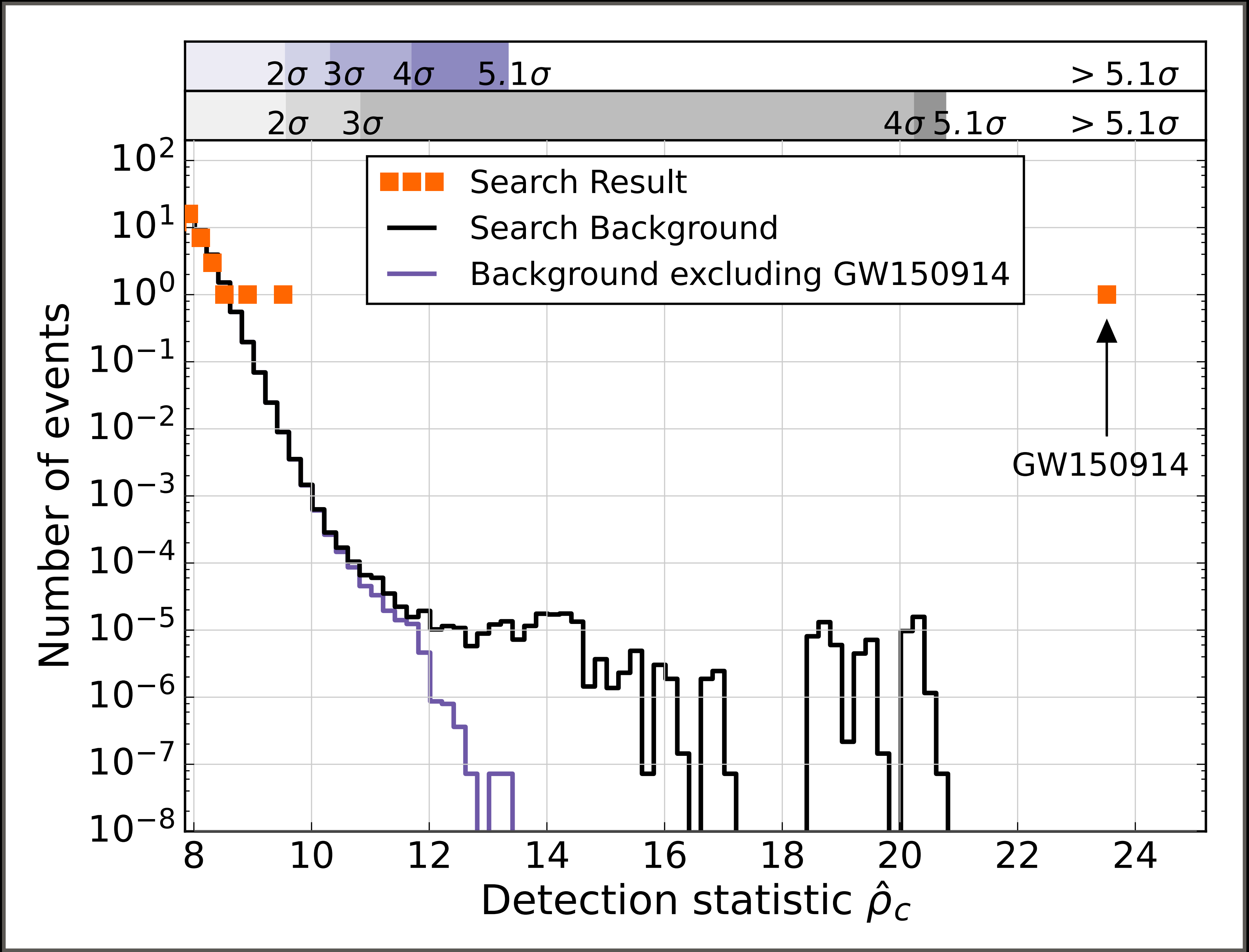


LSC+Virgo, arXiv:1602.03840

15. J. Healy, C. O. Lousto, & Y. Zlochower, PRD 90, 104004 (2014)

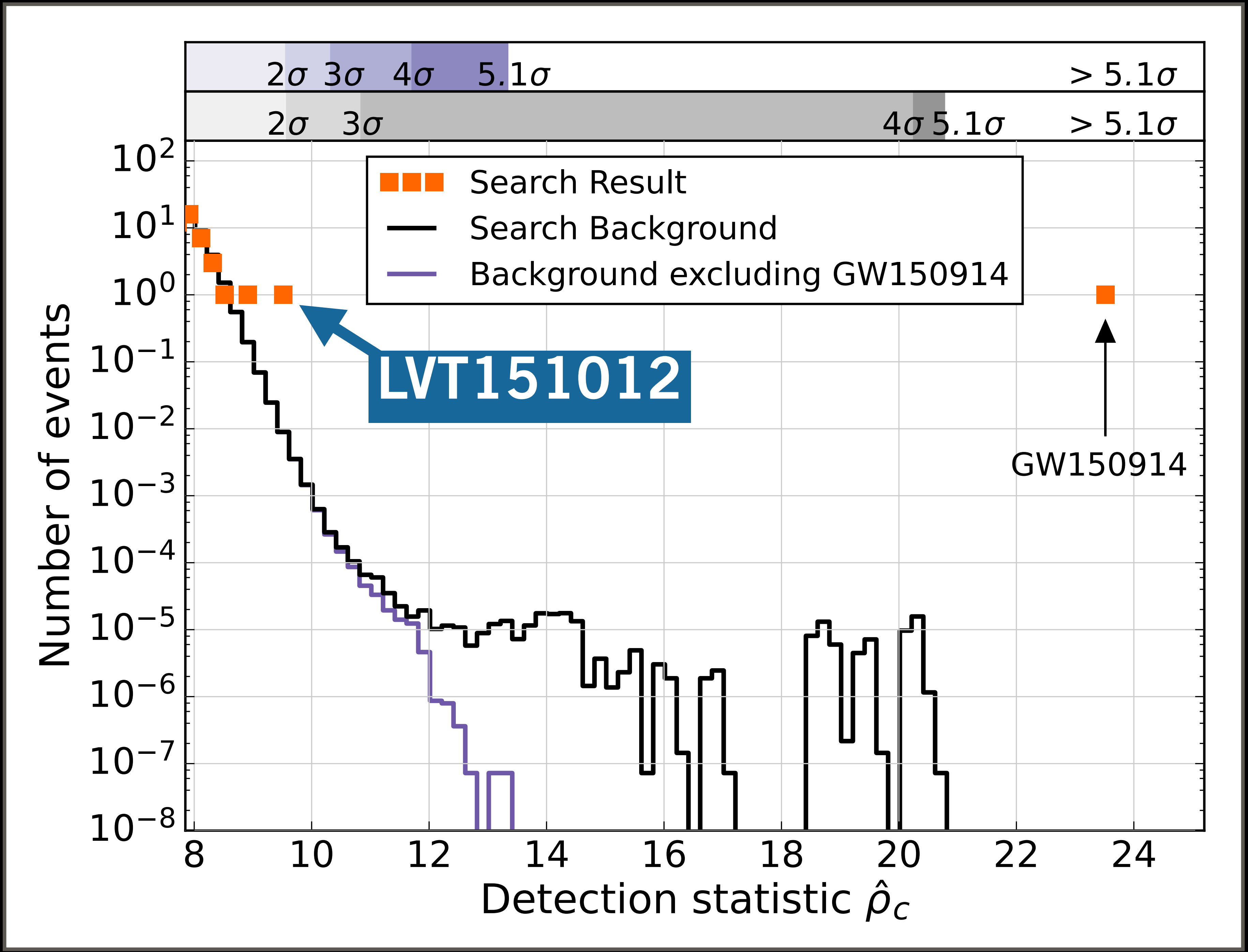
4. LVT151012

PyCBC Results



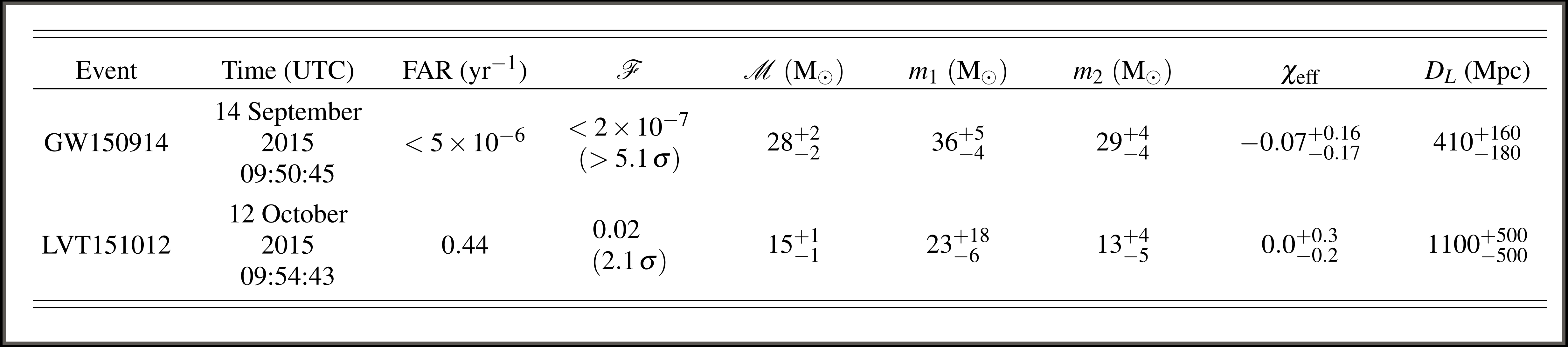
LSC+Virgo, PRL 116, 061102 (2016); LSC+Virgo, arXiv:1602.03839

PYCBC RESULTS



LSC+Virgo, PRL 116, 061102 (2016); LSC+Virgo, arXiv:1602.03839

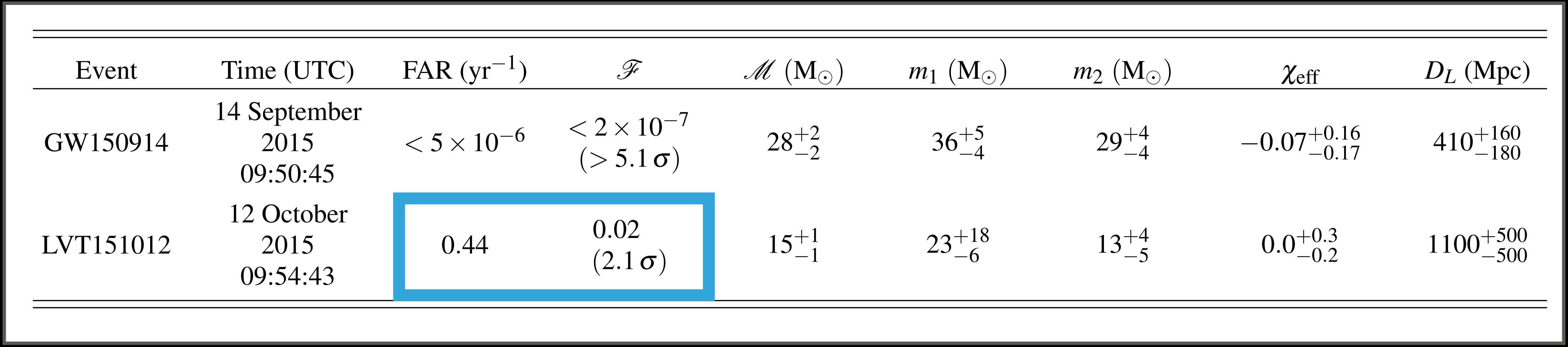
LVT151012 PARAMETERS



Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($\mathrm{M}_\odot$)	m_1 ($\mathrm{M}_\odot$)	m_2 ($\mathrm{M}_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ $(> 5.1\,\sigma)$	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.07^{+0.16}_{-0.17}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 $(2.1\,\sigma)$	15^{+1}_{-1}	23^{+18}_{-6}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}

LSC+Virgo, arXiv:1602.03839

LVT151012 PARAMETERS



Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($\mathrm{M}_\odot$)	m_1 ($\mathrm{M}_\odot$)	m_2 ($\mathrm{M}_\odot$)	χ_{eff}	D_L (Mpc)
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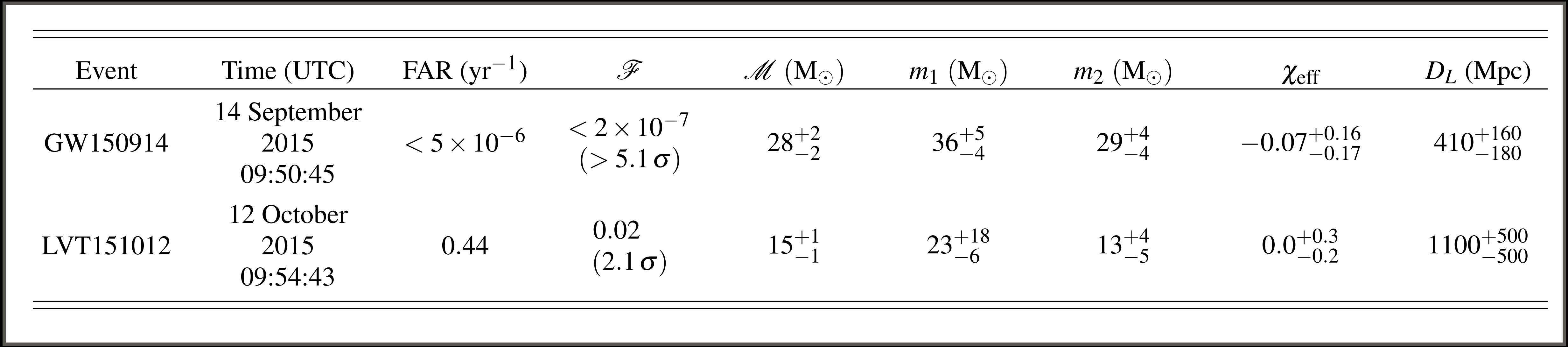
LSC+Virgo, arXiv:1602.03839

- Not significant enough to claim as definitive event

LVT151012 PARAMETERS



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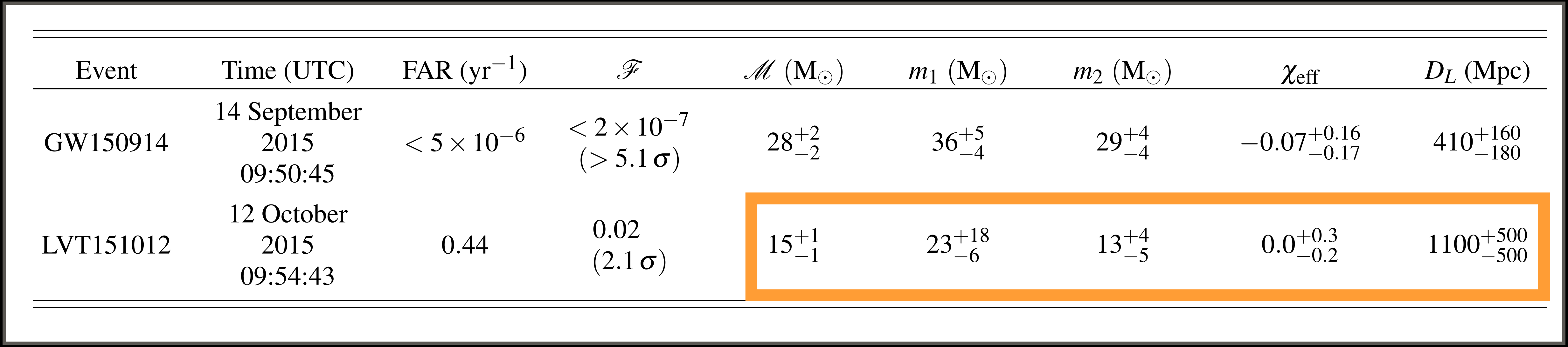
However…

LVT151012 PARAMETERS



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LSC+Virgo, arXiv:1602.03839

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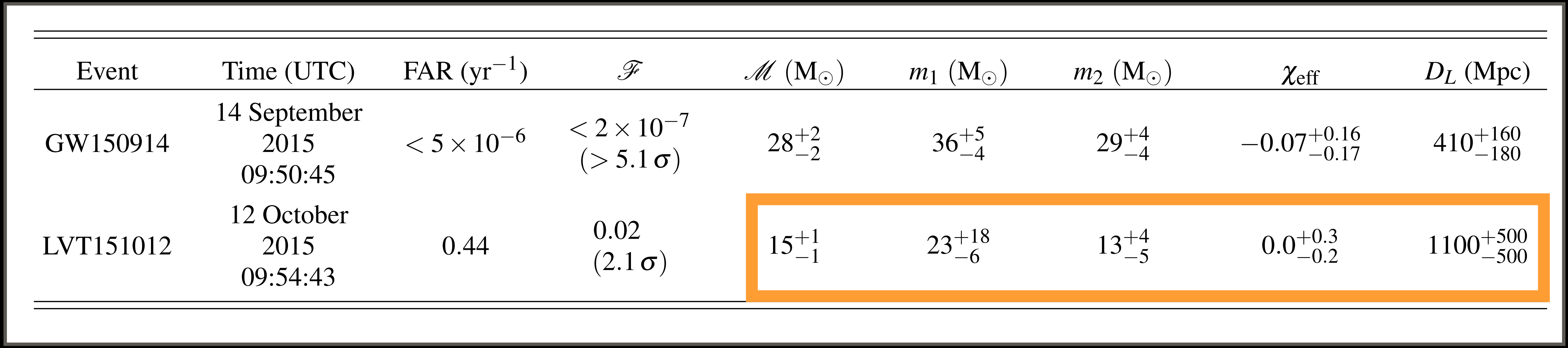
However…

- Parameter estimates consistent with population of BBH

LVT151012 PARAMETERS



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LSC+Virgo, arXiv:1602.03839

- Not significant enough to claim as definitive event

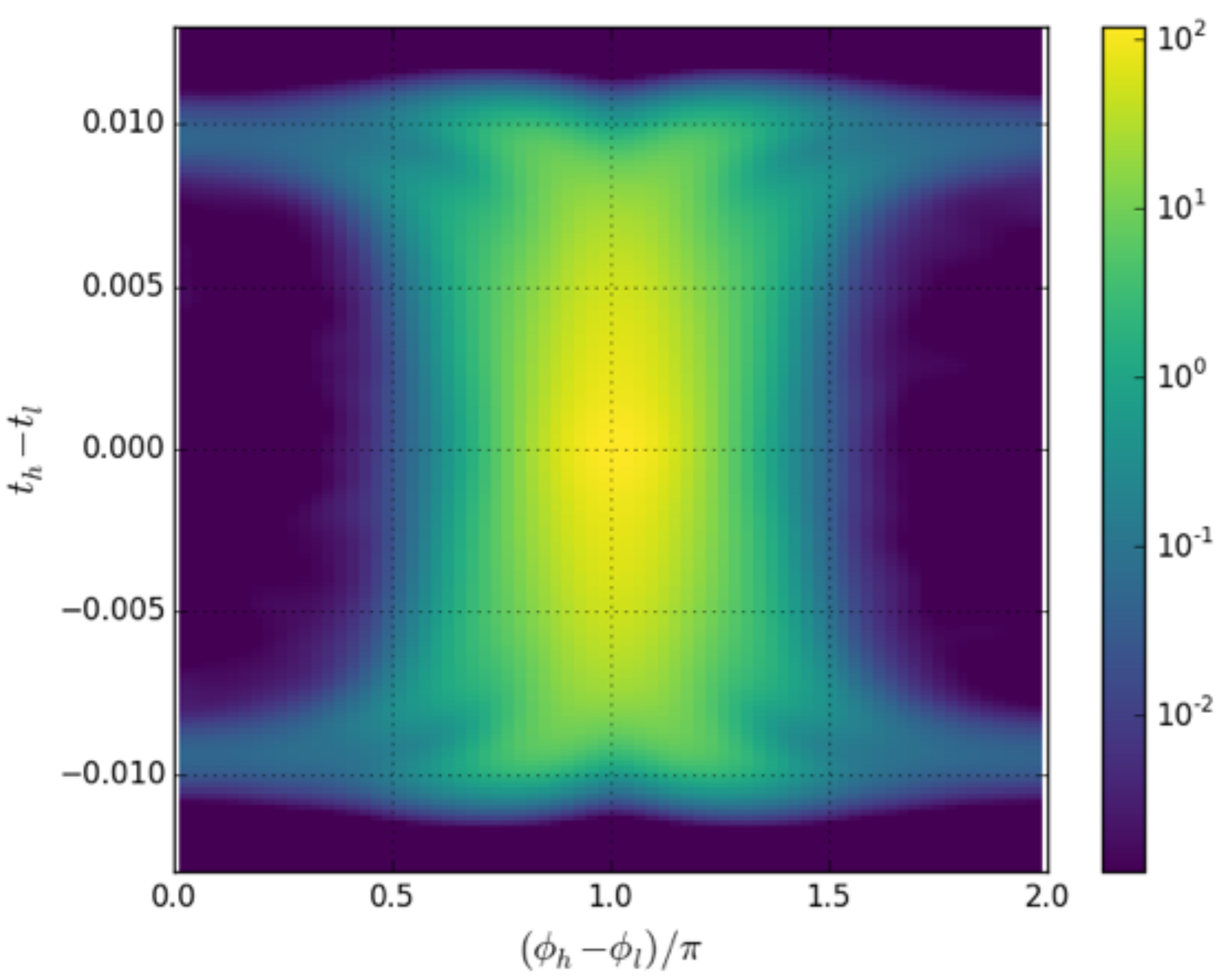
$$\rho_{H1} = 6.9$$
$$\rho_{L1} = 6.7$$
$$\hat{\rho}_c = 9.6$$

However…

- Parameter estimates consistent with population of BBH
- Second most significant event in both PyCBC & GstLAL searches

PHASE/TIME CONSISTENCY

- Any phase difference & time delay < 10ms is possible between 2 detectors
- Due to antenna pattern of detectors, signals are more likely to have certain phase and time differences
- Noise has uniform distribution
- This is currently not included in modeled searches' detection statistic



Courtesy A. Nitz

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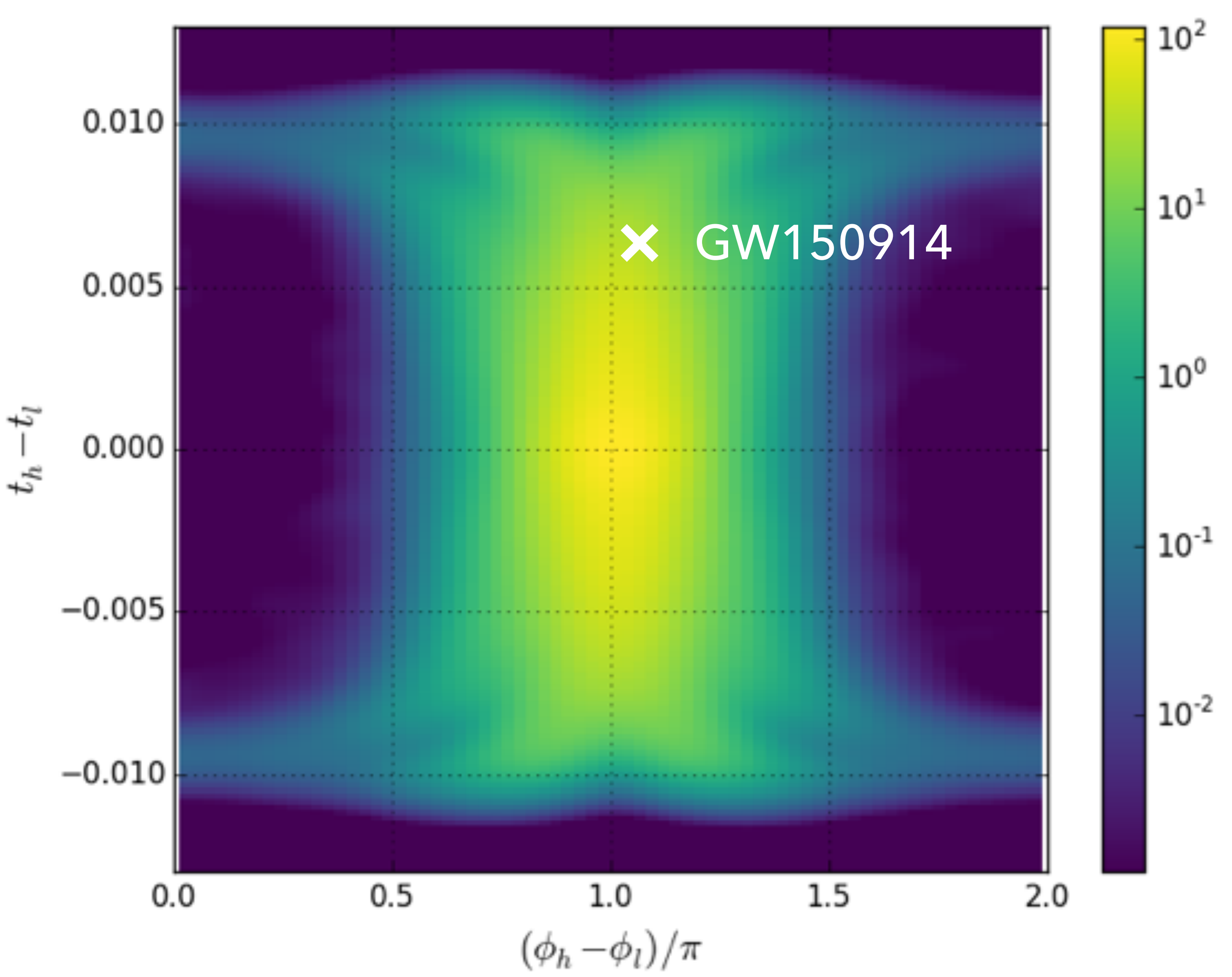

Courtesy A. Nitz

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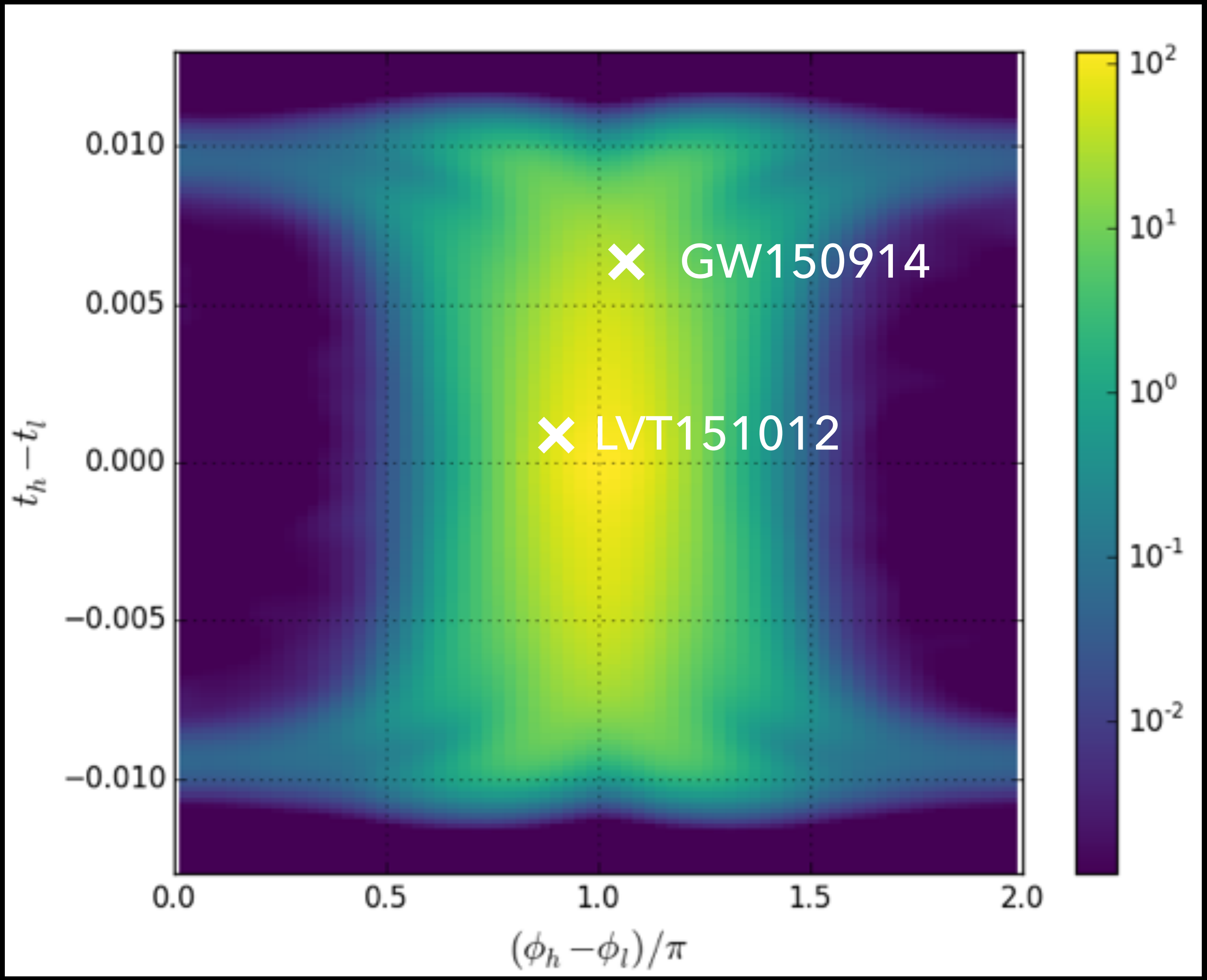


Courtesy A. Nitz

CONCLUSIONS

GW150914

- Multiple pipelines & methods found GW150914 with high significance
- No other environmental sources could be found
- Parameter estimates indicate a BBH with little to no spin

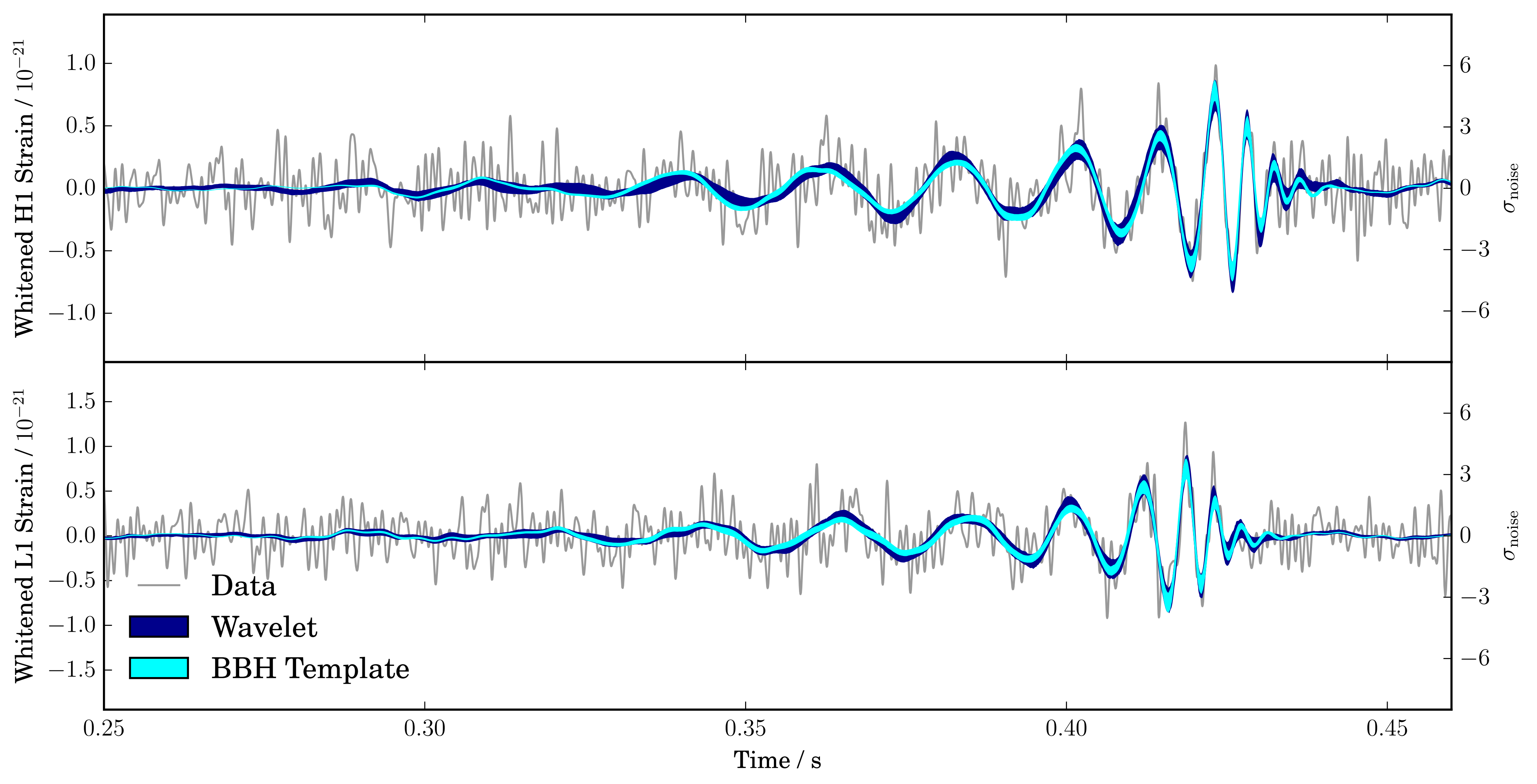
LVT150914

- Detected by modeled searches with significance = 2.1σ
- Consistent with BBH signal

EXTRAS

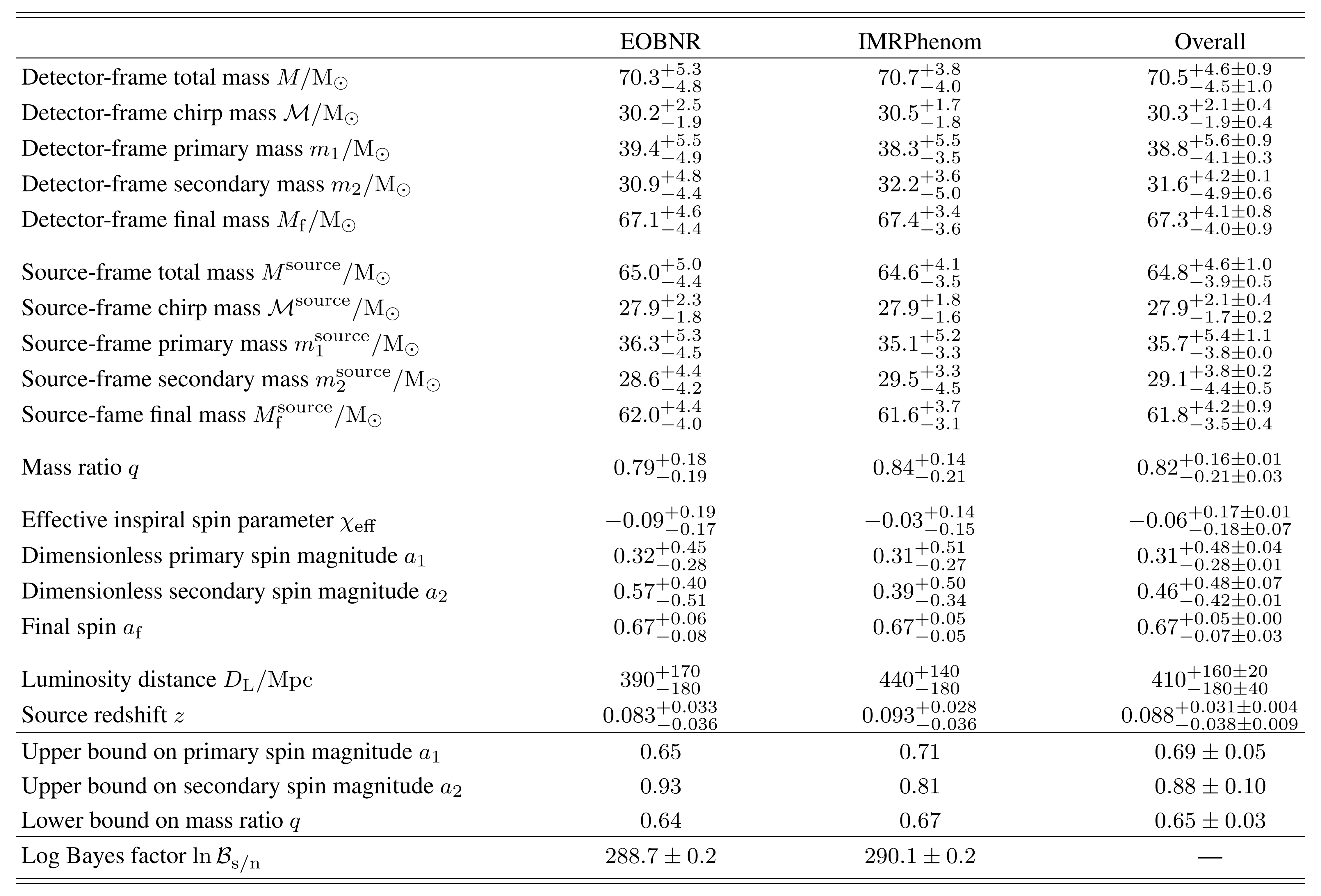
GW150914 WAVEFORM CONSISTENCY

- Use parameter estimates to produce waveform estimate
- Excellent agreement with waveform reconstructed using minimal assumptions (BayesWave)



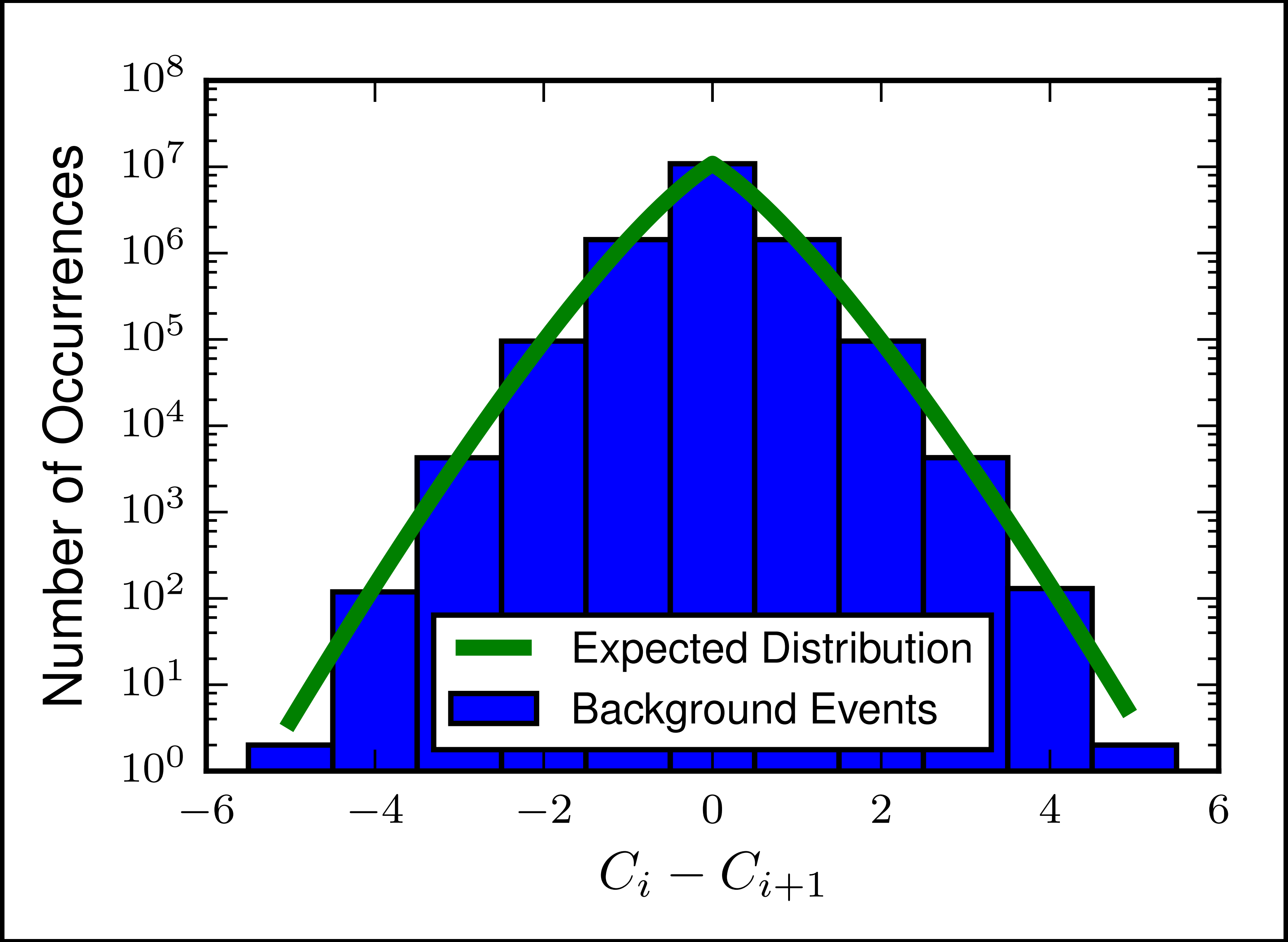
LSC+Virgo, arXiv:1602.03840

GW150914 PARAMETER ESTIMATES



	EOBNR	IMRPhenom	Overall
Detector-frame total mass $M/\mathrm{M}_\odot$	$70.3^{+5.3}_{-4.8}$	$70.7^{+3.8}_{-4.0}$	$70.5^{+4.6\pm0.9}_{-4.5\pm1.0}$
Detector-frame chirp mass $\mathcal{M}/\mathrm{M}_\odot$	$30.2^{+2.5}_{-1.9}$	$30.5^{+1.7}_{-1.8}$	$30.3^{+2.1\pm0.4}_{-1.9\pm0.4}$
Detector-frame primary mass $m_1/\mathrm{M}_\odot$	$39.4^{+5.5}_{-4.9}$	$38.3^{+5.5}_{-3.5}$	$38.8^{+5.6\pm0.9}_{-4.1\pm0.3}$
Detector-frame secondary mass $m_2/\mathrm{M}_\odot$	$30.9^{+4.8}_{-4.4}$	$32.2^{+3.6}_{-5.0}$	$31.6^{+4.2\pm0.1}_{-4.9\pm0.6}$
Detector-frame final mass $M_\mathrm{f}/\mathrm{M}_\odot$	$67.1^{+4.6}_{-4.4}$	$67.4^{+3.4}_{-3.6}$	$67.3^{+4.1\pm0.8}_{-4.0\pm0.9}$
Source-frame total mass $M^\mathrm{source}/\mathrm{M}_\odot$	$65.0^{+5.0}_{-4.4}$	$64.6^{+4.1}_{-3.5}$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^\mathrm{source}/\mathrm{M}_\odot$	$27.9^{+2.3}_{-1.8}$	$27.9^{+1.8}_{-1.6}$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$	$36.3^{+5.3}_{-4.5}$	$35.1^{+5.2}_{-3.3}$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$	$28.6^{+4.4}_{-4.2}$	$29.5^{+3.3}_{-4.5}$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$
Source-fame final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$	$62.0^{+4.4}_{-4.0}$	$61.6^{+3.7}_{-3.1}$	$61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$	$0.84^{+0.14}_{-0.21}$	$0.82^{+0.16\pm0.01}_{-0.21\pm0.03}$
Effective inspiral spin parameter χ_eff	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm0.01}_{-0.18\pm0.07}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$	$0.31^{+0.51}_{-0.27}$	$0.31^{+0.48\pm0.04}_{-0.28\pm0.01}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$	$0.39^{+0.50}_{-0.34}$	$0.46^{+0.48\pm0.07}_{-0.42\pm0.01}$
Final spin a_f	$0.67^{+0.06}_{-0.08}$	$0.67^{+0.05}_{-0.05}$	$0.67^{+0.05\pm0.00}_{-0.07\pm0.03}$
Luminosity distance $D_\mathrm{L}/\mathrm{Mpc}$	390^{+170}_{-180}	440^{+140}_{-180}	$410^{+160\pm20}_{-180\pm40}$
Source redshift z	$0.083^{+0.033}_{-0.036}$	$0.093^{+0.028}_{-0.036}$	$0.088^{+0.031\pm0.004}_{-0.038\pm0.009}$
Upper bound on primary spin magnitude a_1	0.65	0.71	0.69 ± 0.05
Upper bound on secondary spin magnitude a_2	0.93	0.81	0.88 ± 0.10
Lower bound on mass ratio q	0.64	0.67	0.65 ± 0.03
Log Bayes factor $\ln \mathcal{B}_\mathrm{s/n}$	288.7 ± 0.2	290.1 ± 0.2	—

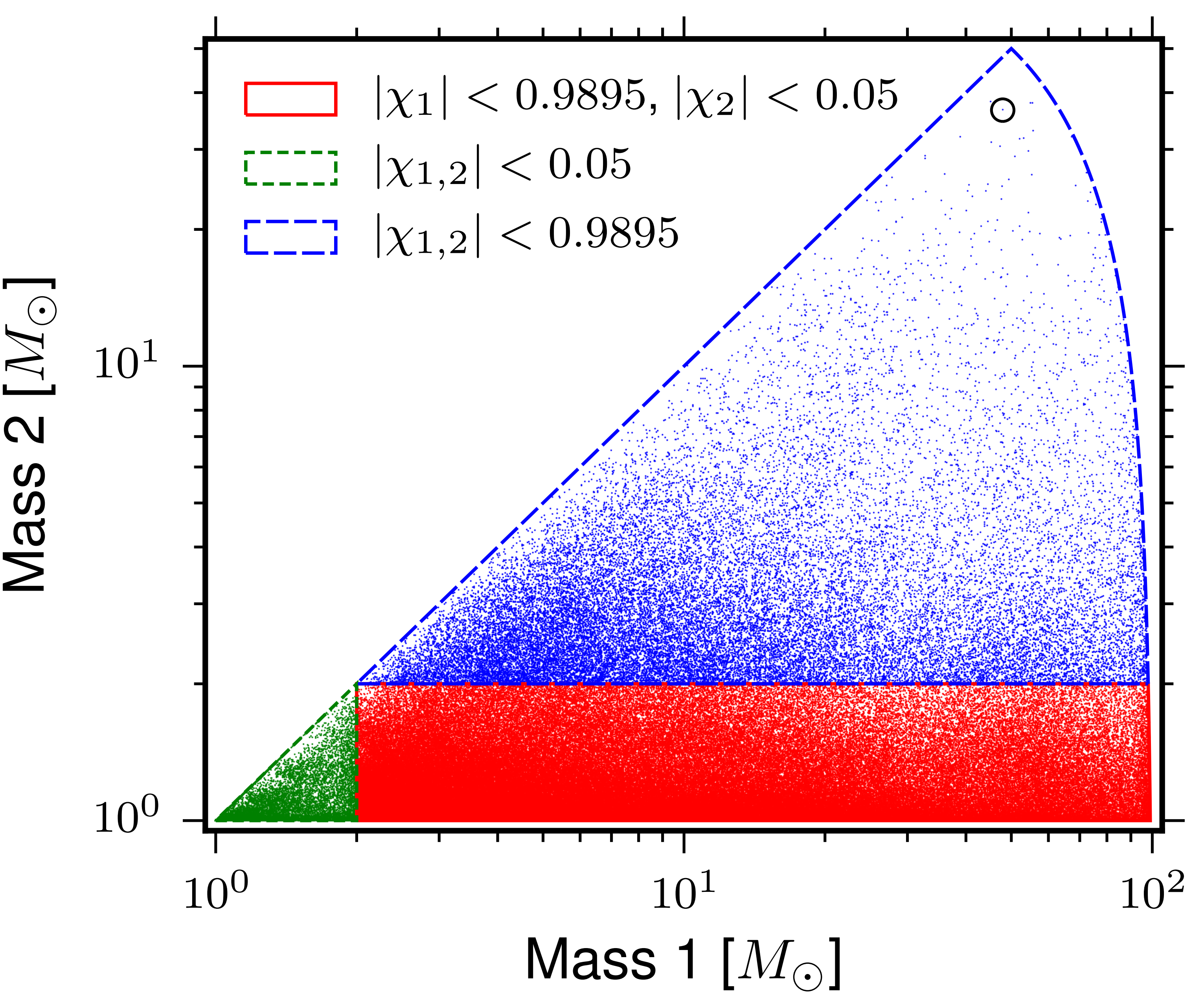
INDEPENDENCE OF TIME SLIDES



LSC+Virgo, arXiv:1602.03839

THE BANK USED IN O1

- Component masses ≥1$M_\odot$
- Total mass ≤ 100$M_\odot$
  - Based on data quality concerns
  - stellar-mass BH ≳30$M_\odot$ uncertain prior to O1
- Work on-going to search for higher mass, IMBH signals



LSC+Virgo, arXiv:1602.03839