10 Years of Gravitational Wave Detections: Updates from the fourth LVK observing run

Aaron Zimmerman

EOB@Work25: 10 years of gravitational wave detections

INFN Torino
September 3, 2025

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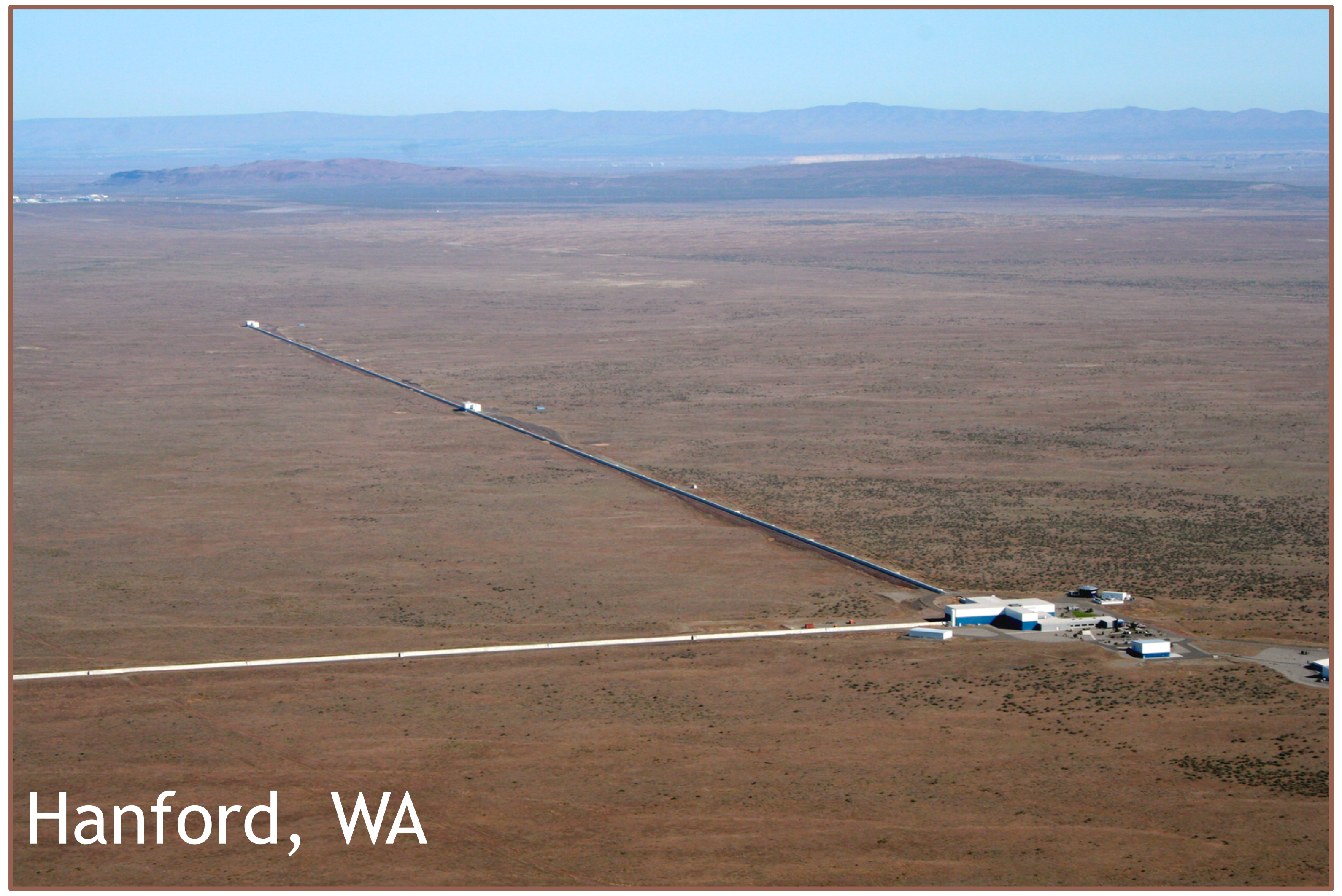
The University of Texas at Austin
Weinberg Institute
The University of Texas at Austin
Center for Gravitational Physics
LIGO
VIRGO
KAGRA

LIGO Scientific Collaboration

This talk NOT on behalf of the LIGO Scientific and Virgo collaborations!

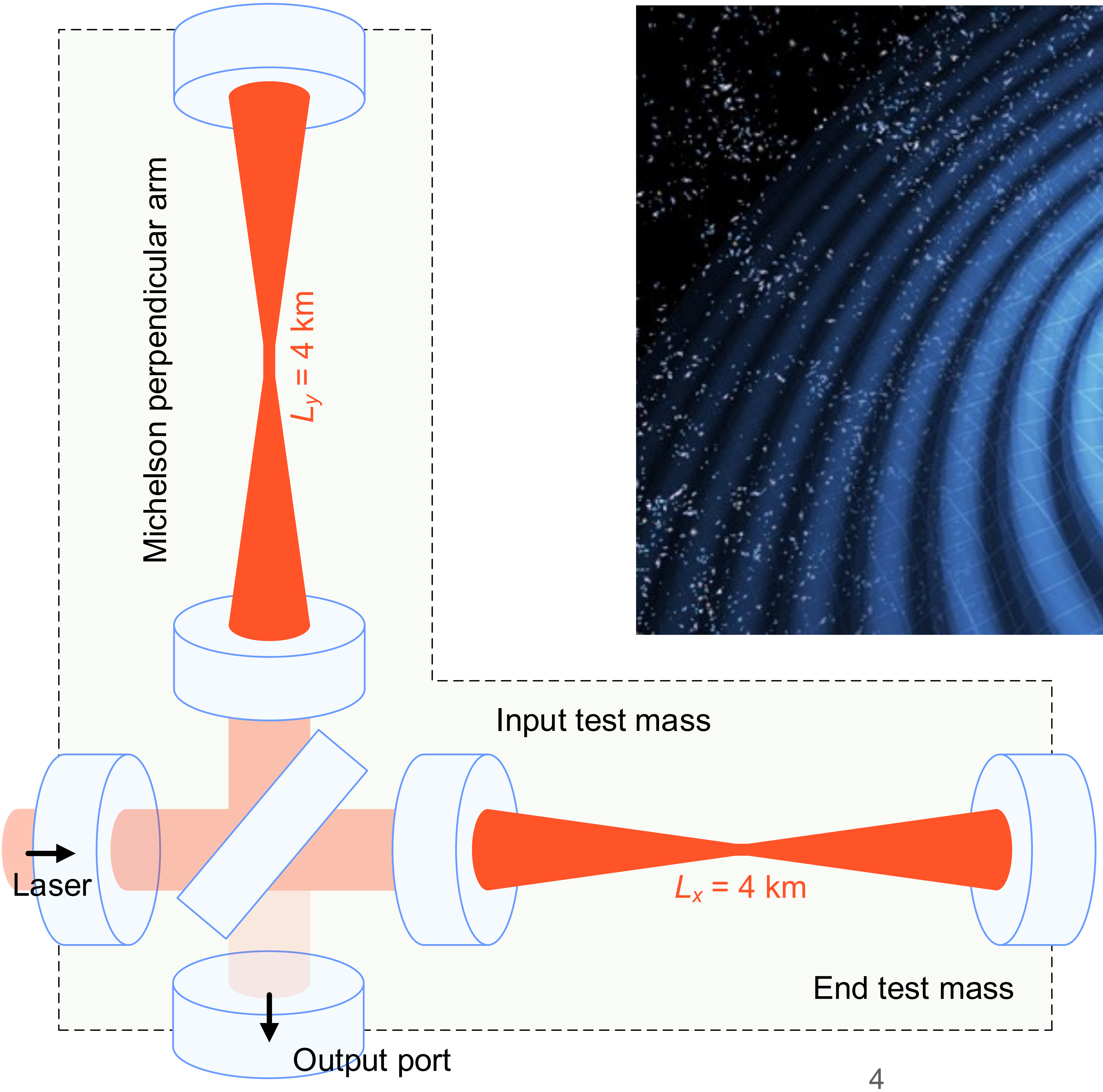
This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation

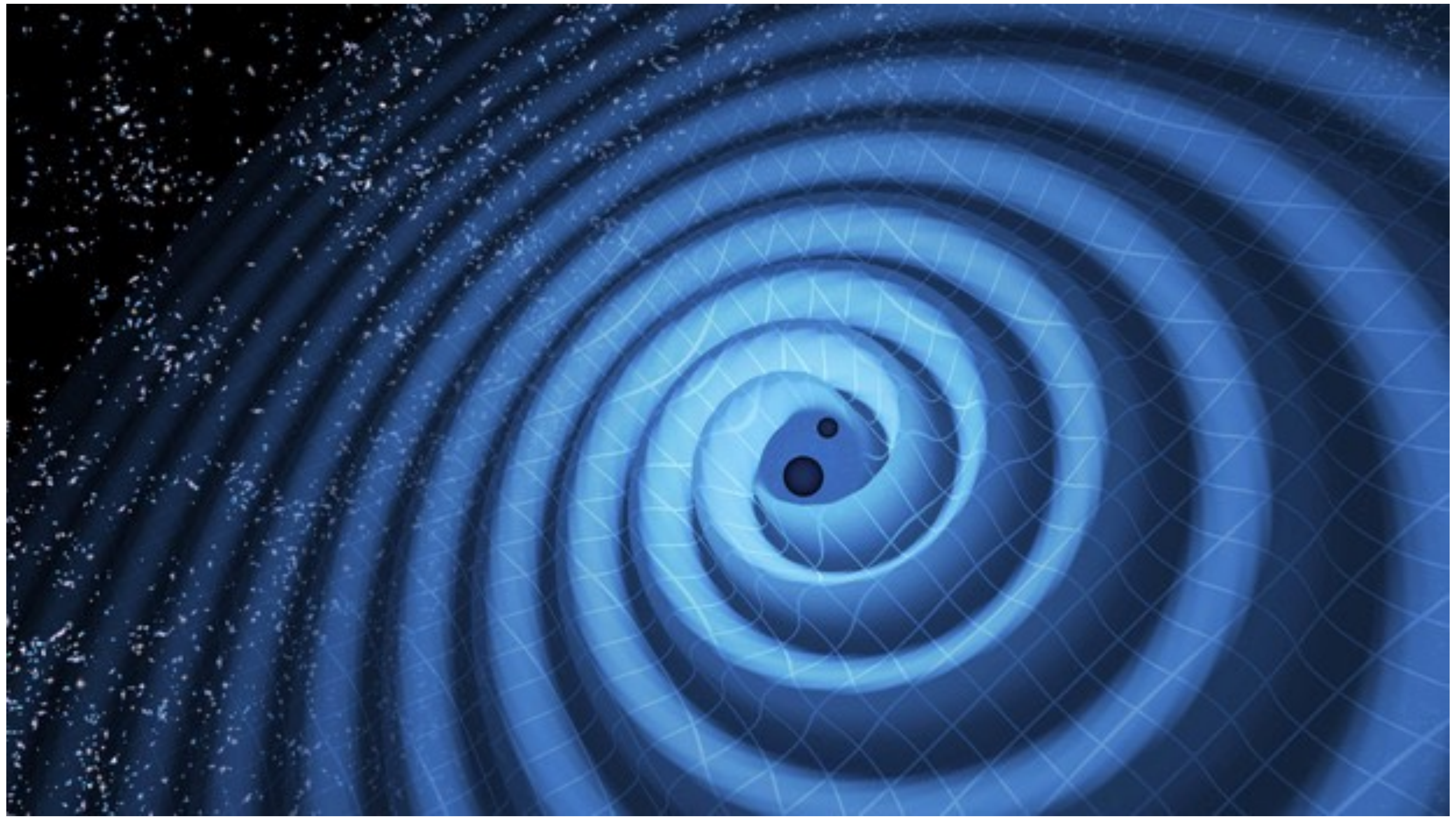
Advanced gravitational wave detectors



Images courtesy LVK

A new window

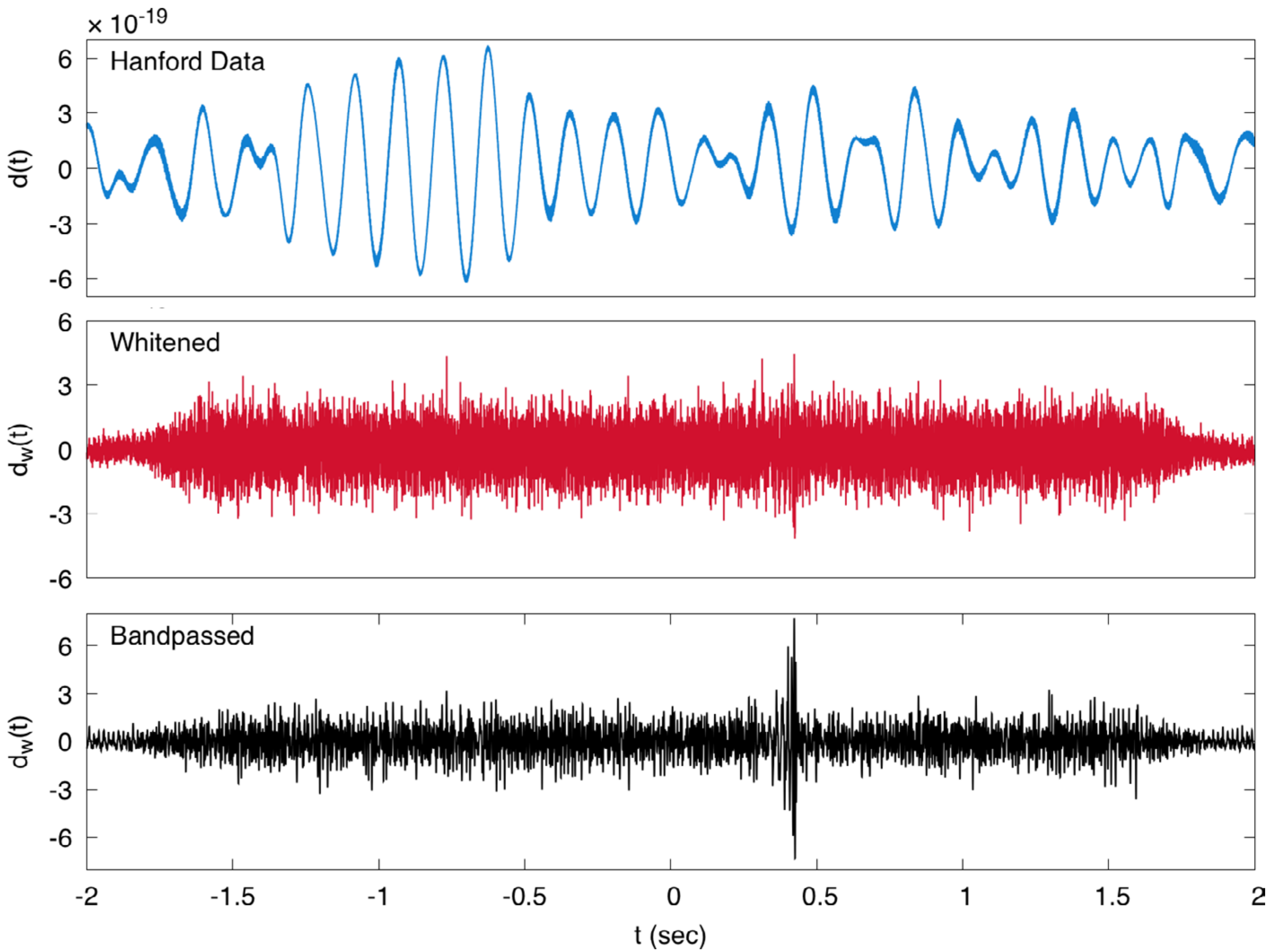




$$\Delta L \sim 10^{-19}\mathrm{m}$$

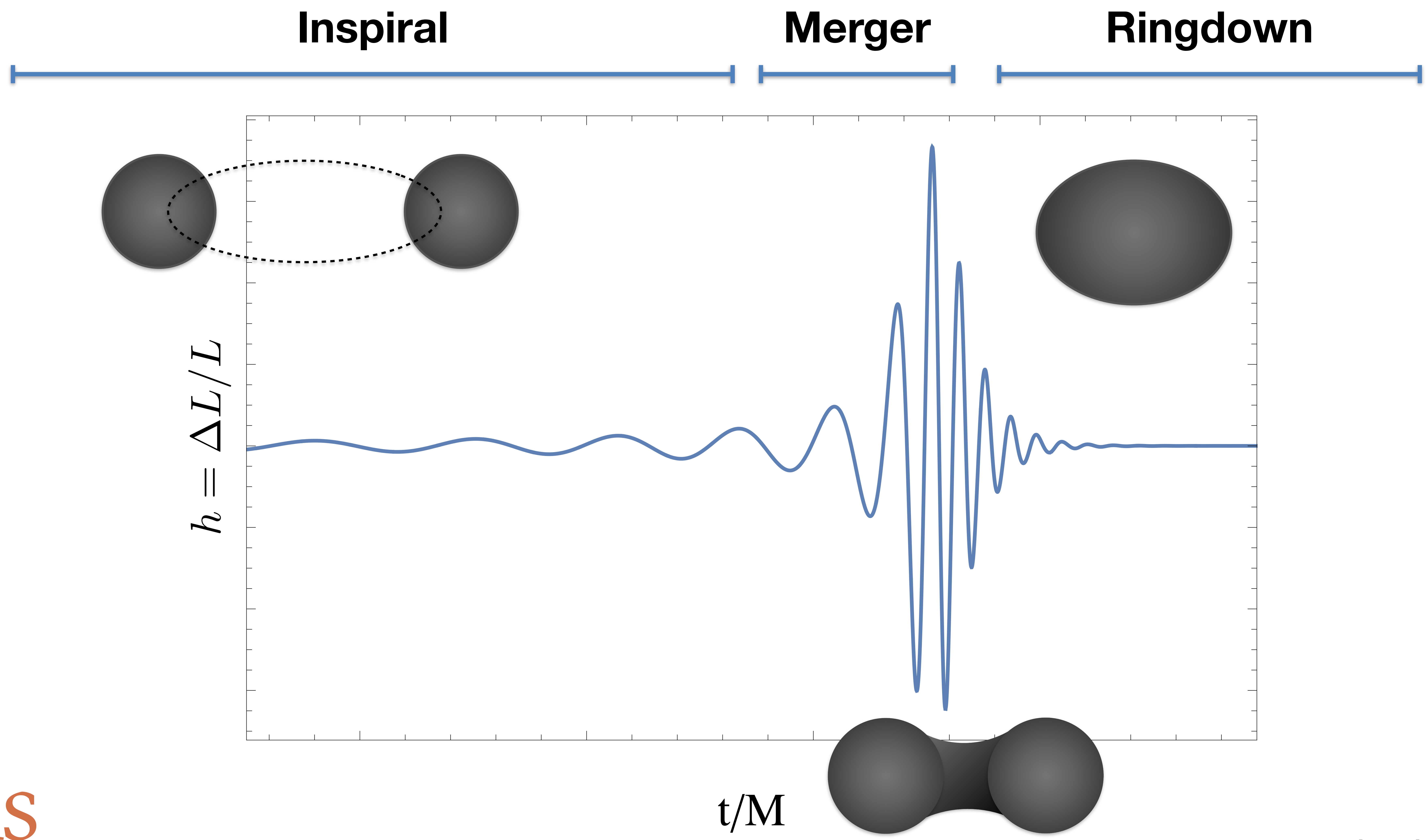
LVC PRL 116, 131103 (2016)

The search challenge



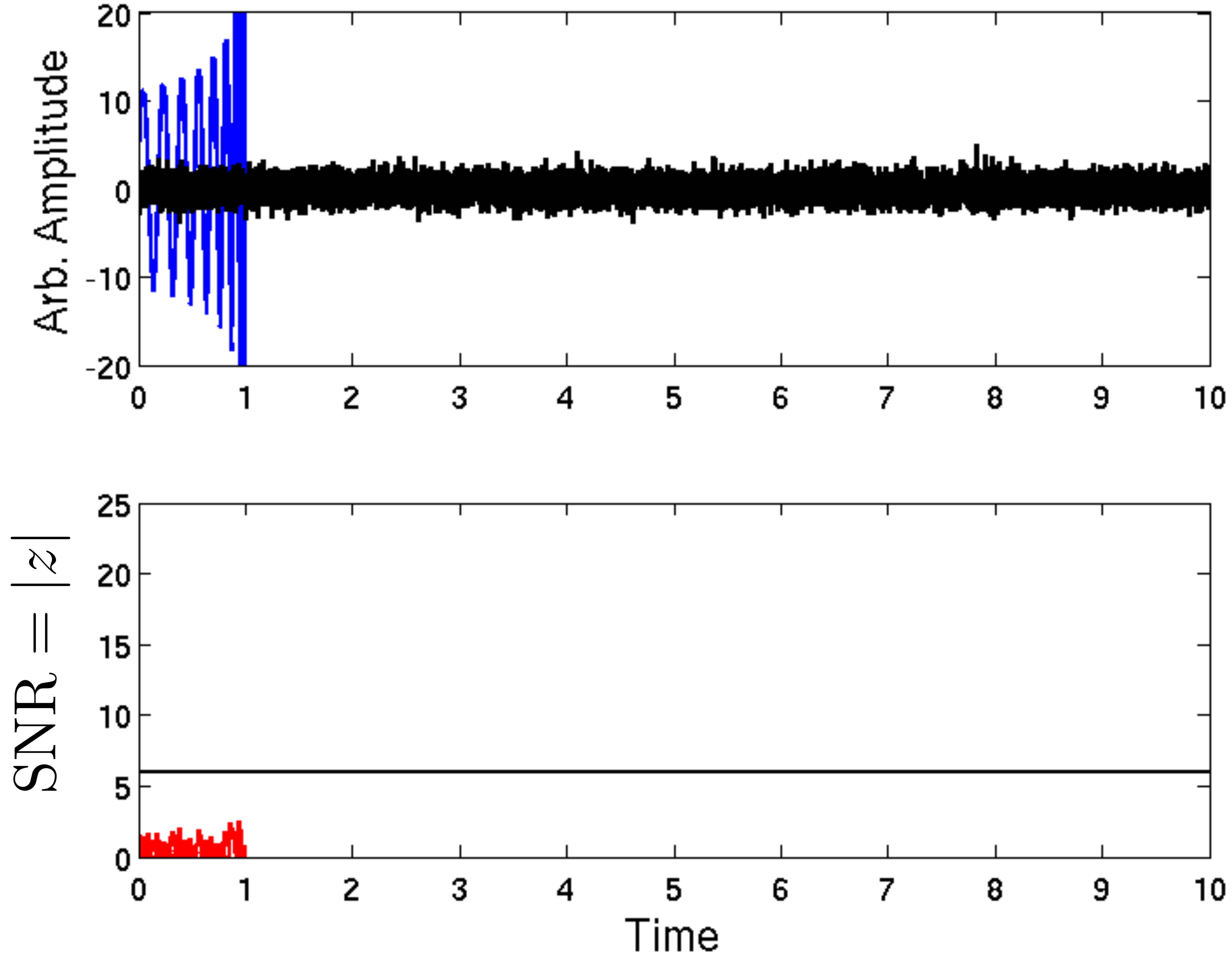
LVC CQG 37, 055002 (2020)

The signal



Scheel+ PRD 79, 024003 (2008)

Matched filtering



$$z = \langle d|\hat{h}\rangle = 4\int_{\mathrm{f_{low}}}^{\mathrm{f_{high}}} \frac{\tilde{d}(f)\hat{h}^*(f)}{S_n(f)}df$$

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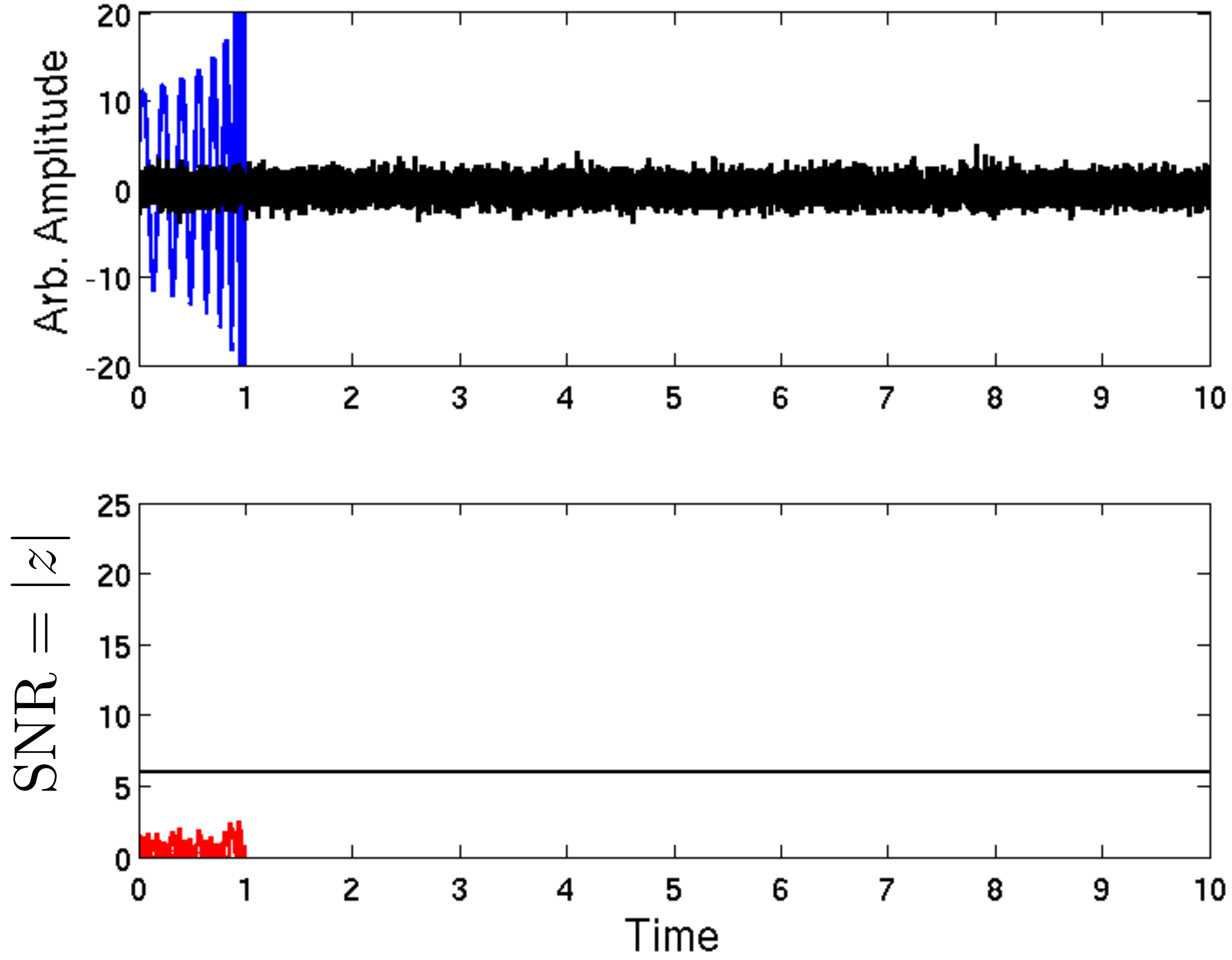
Matched filtering



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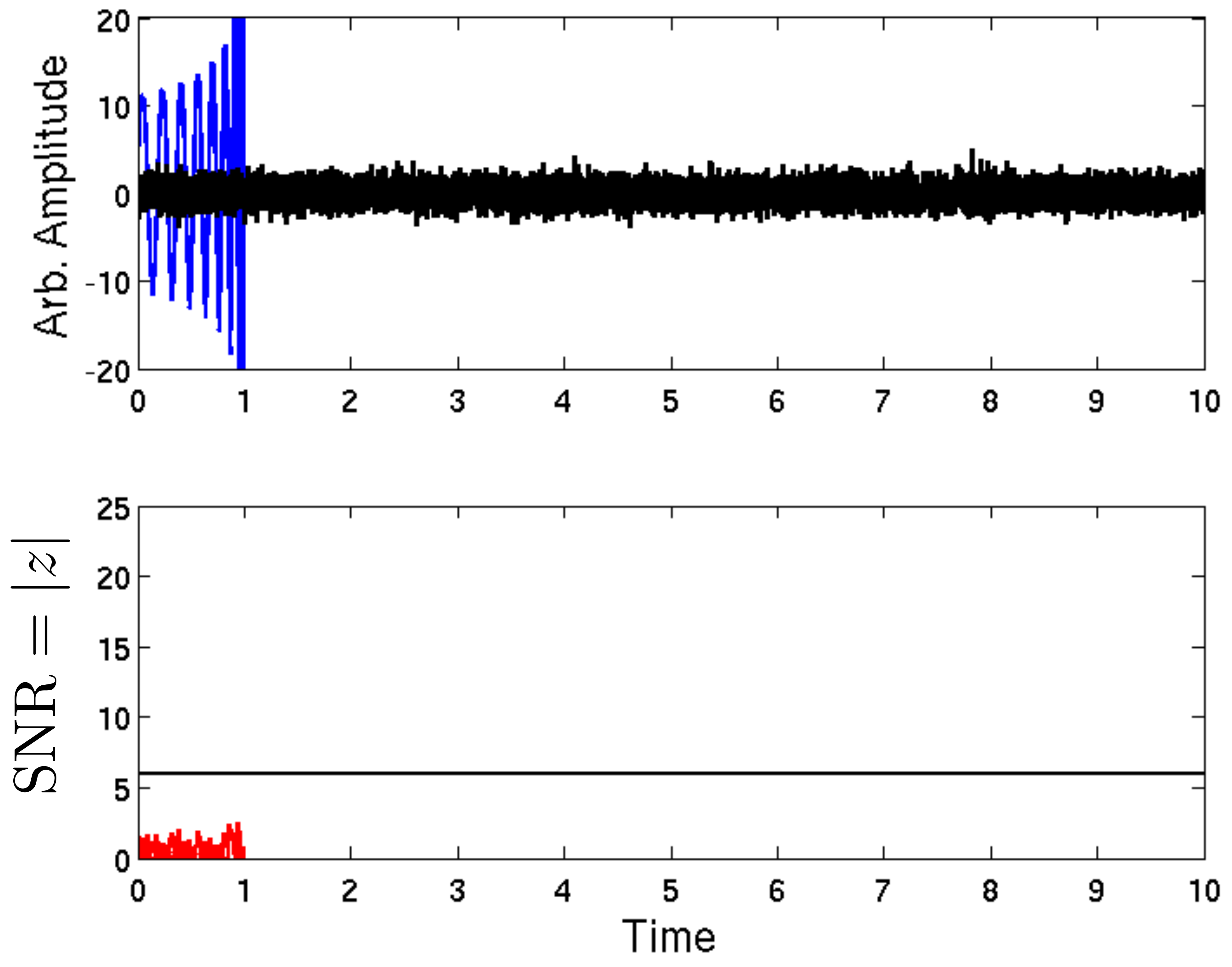
Matched filtering



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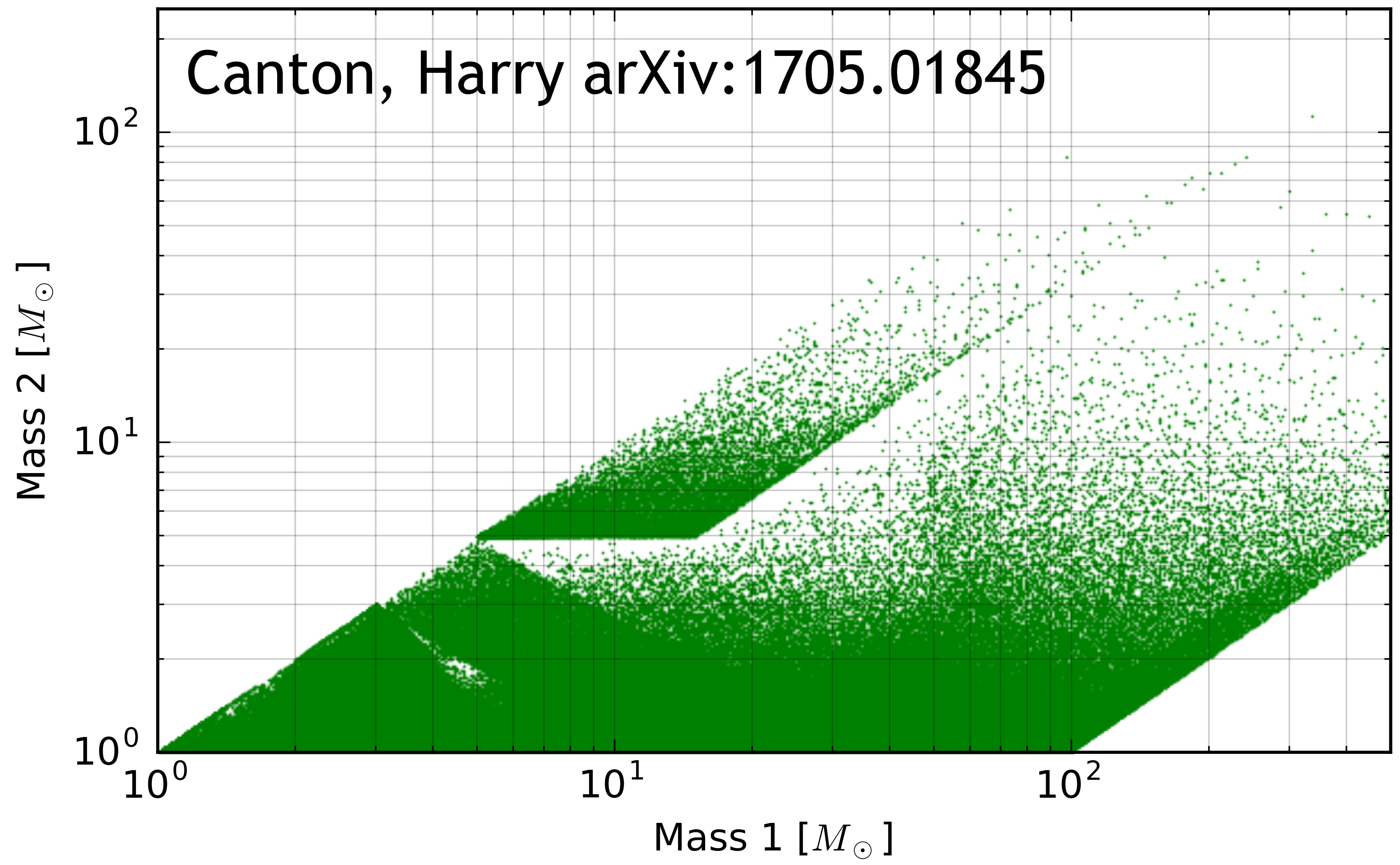
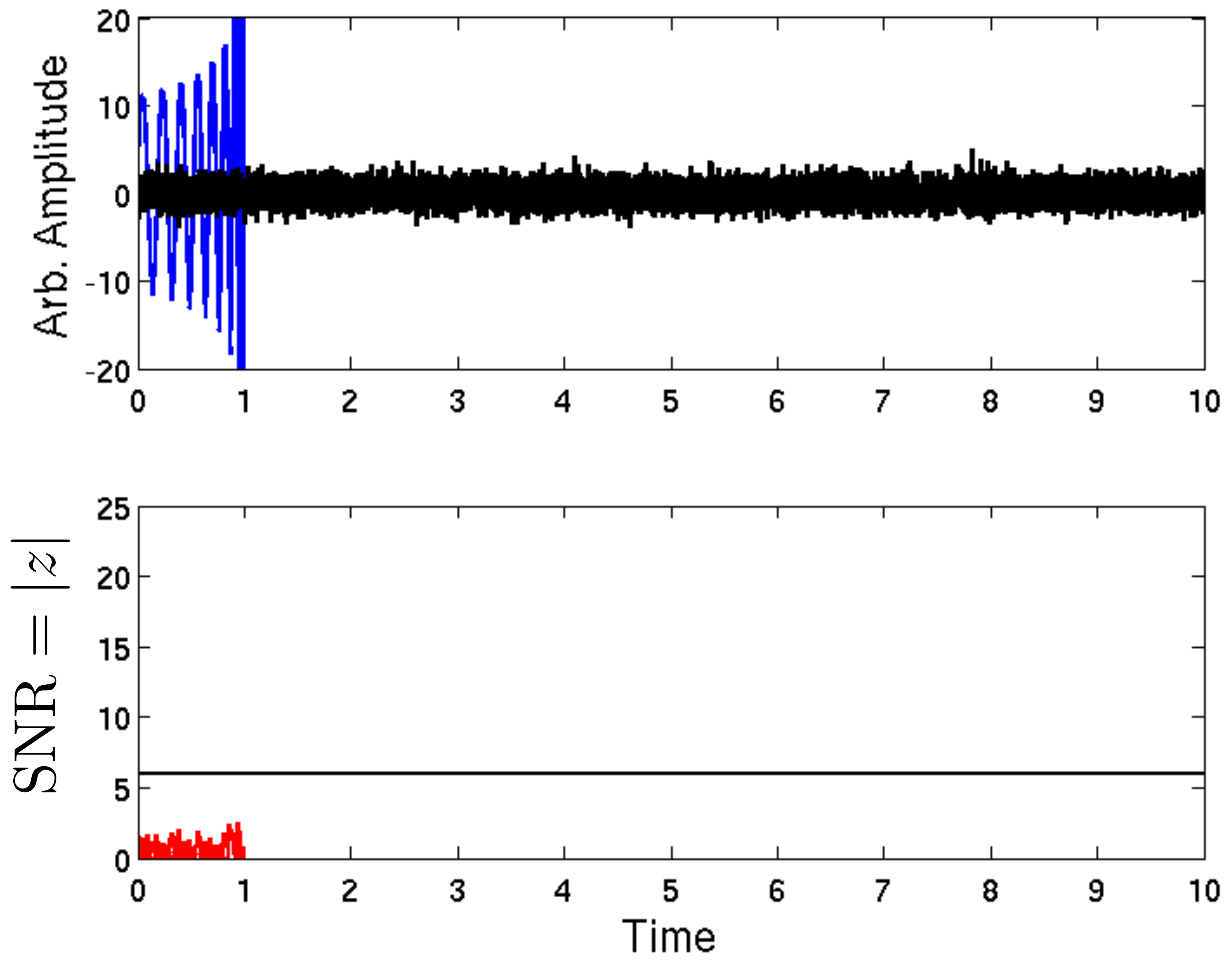


- Maximize over time and phase shift
- Maximize over template bank

Matched filtering



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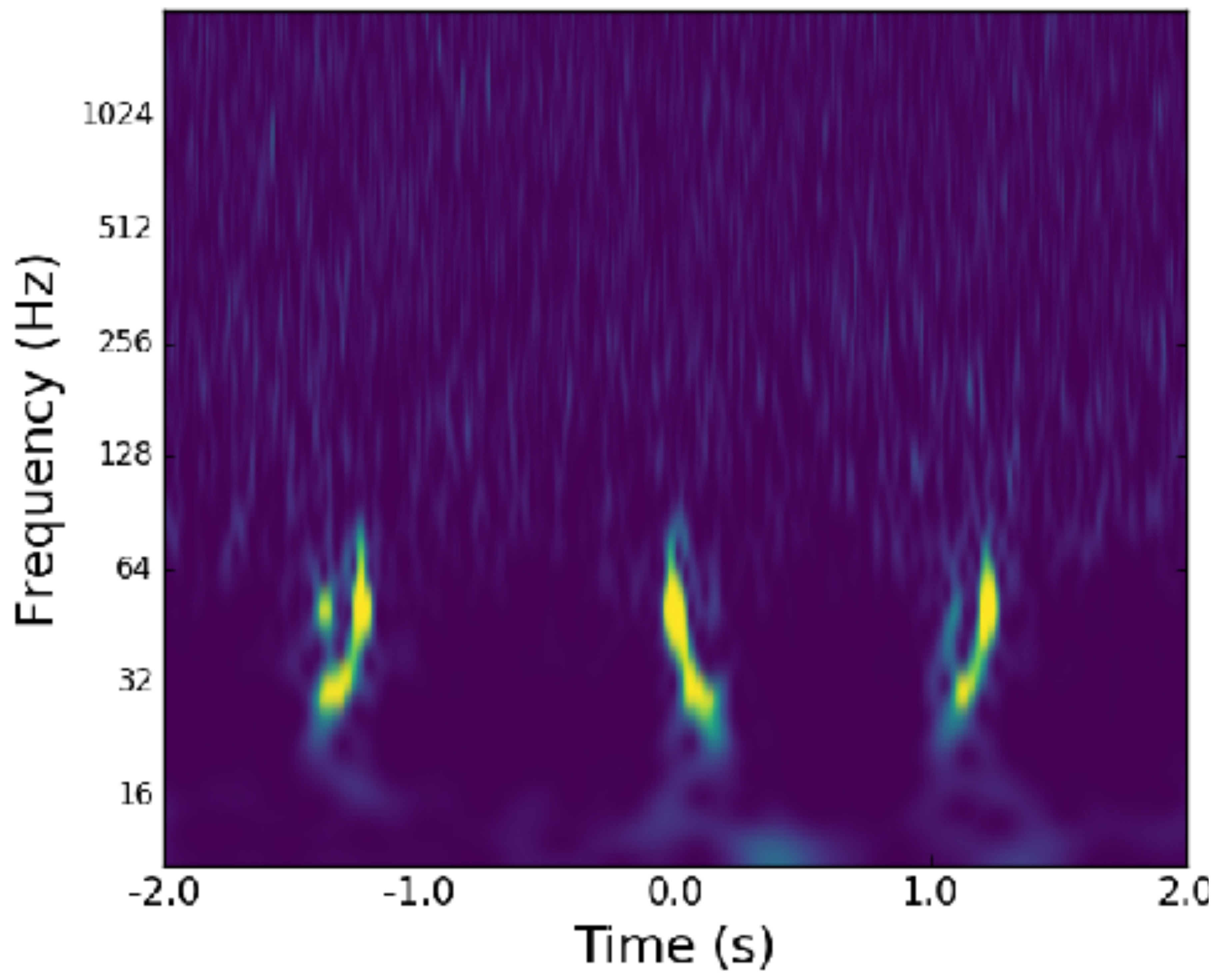

- Maximize over time and phase shift
- Maximize over template bank
- Apply signal consistency tests

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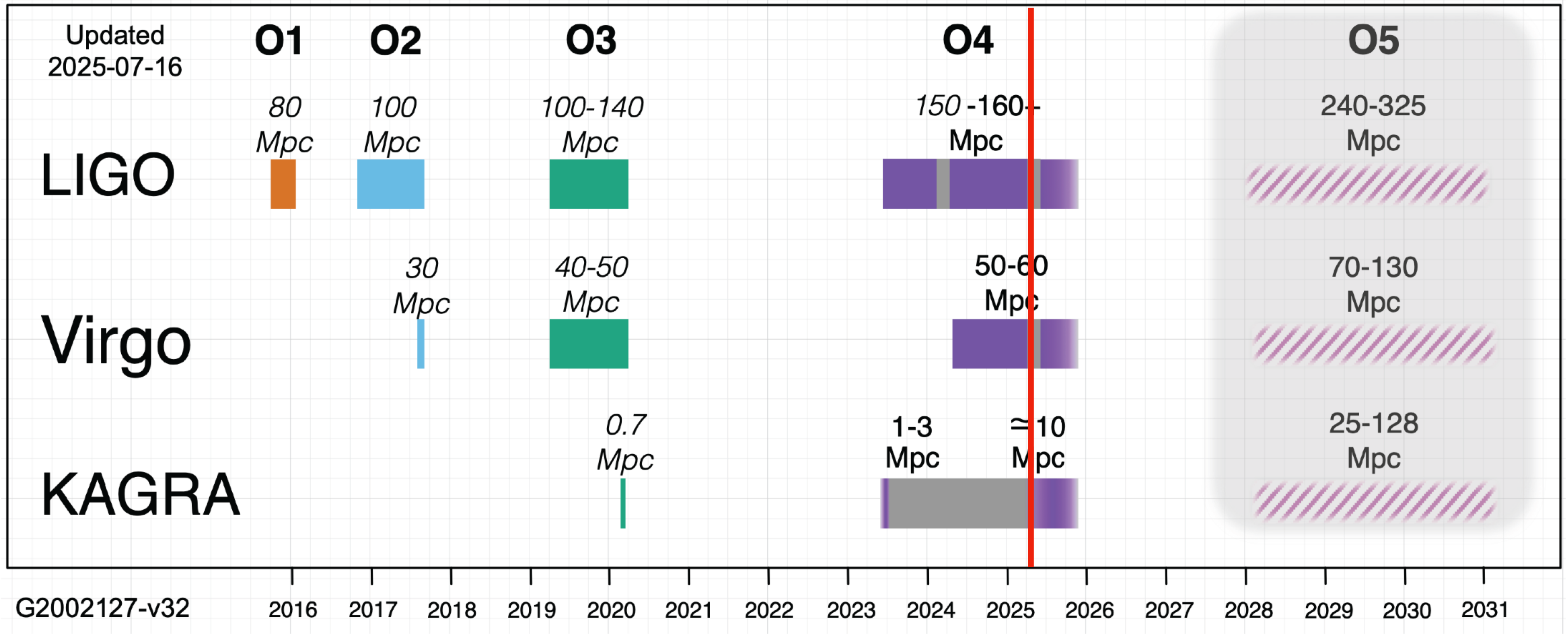
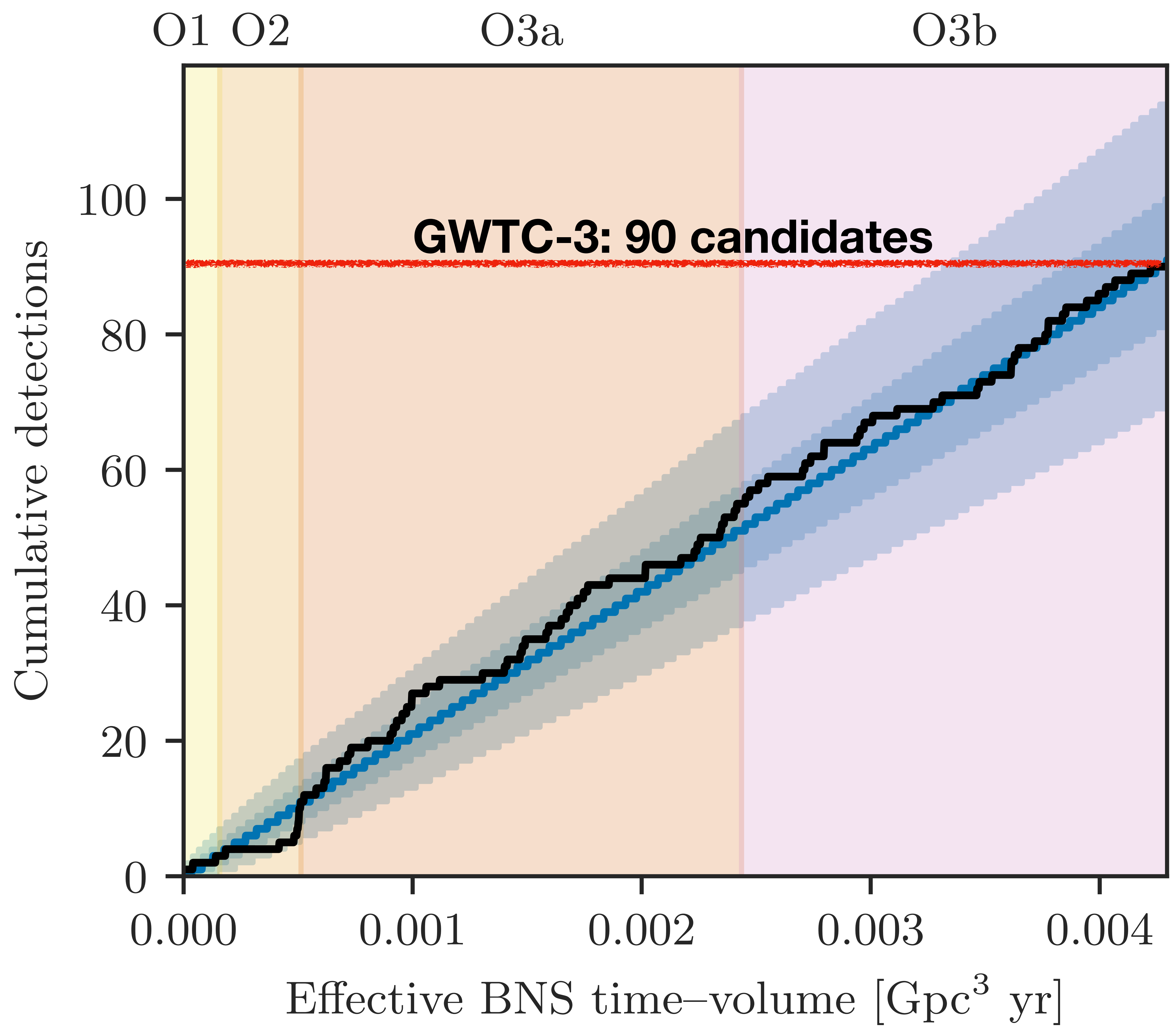
Zevin et al CQG 34, 064003 (2017)

Observing runs to date



+ 224 low-latency candidates in O4



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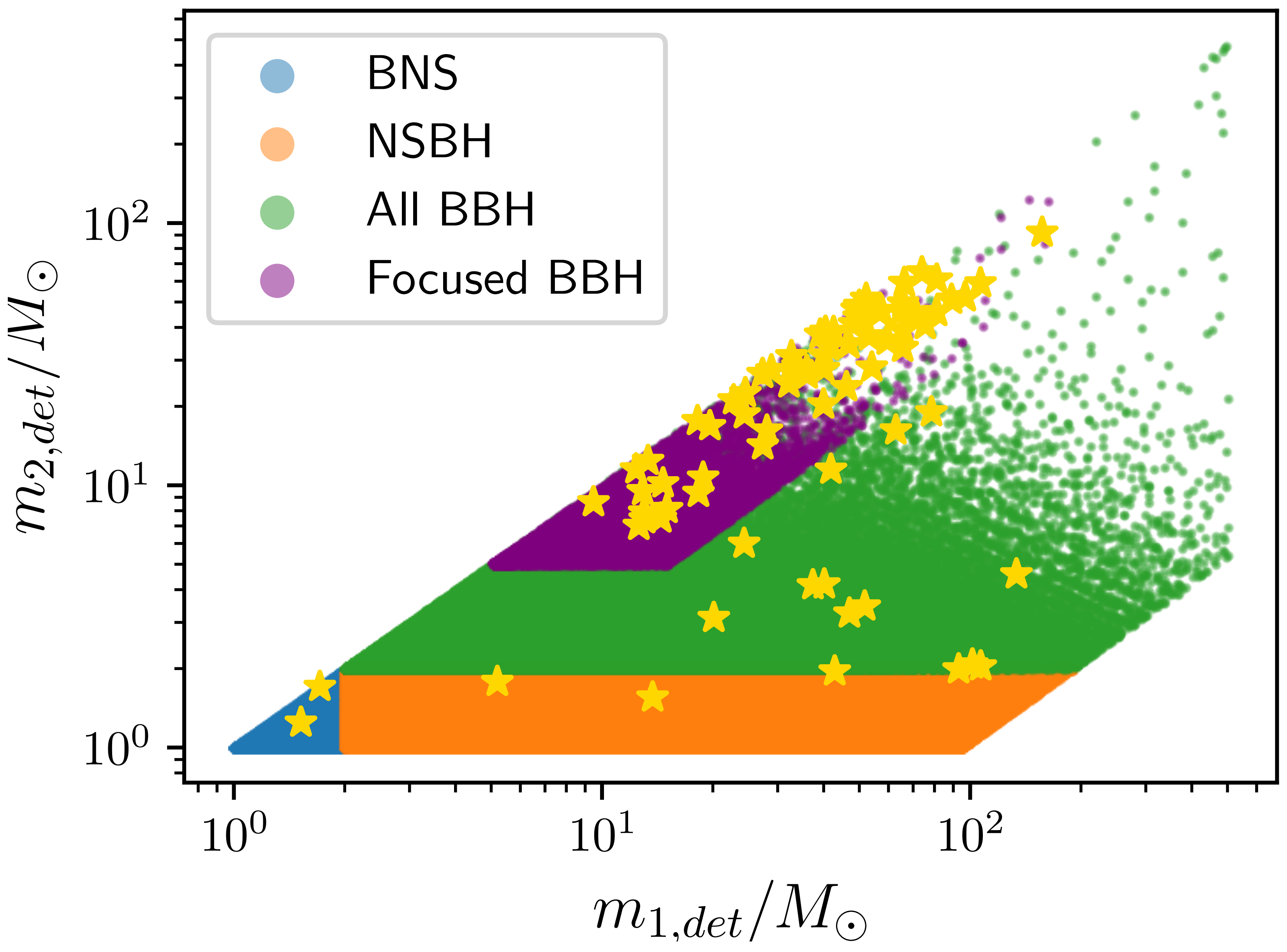
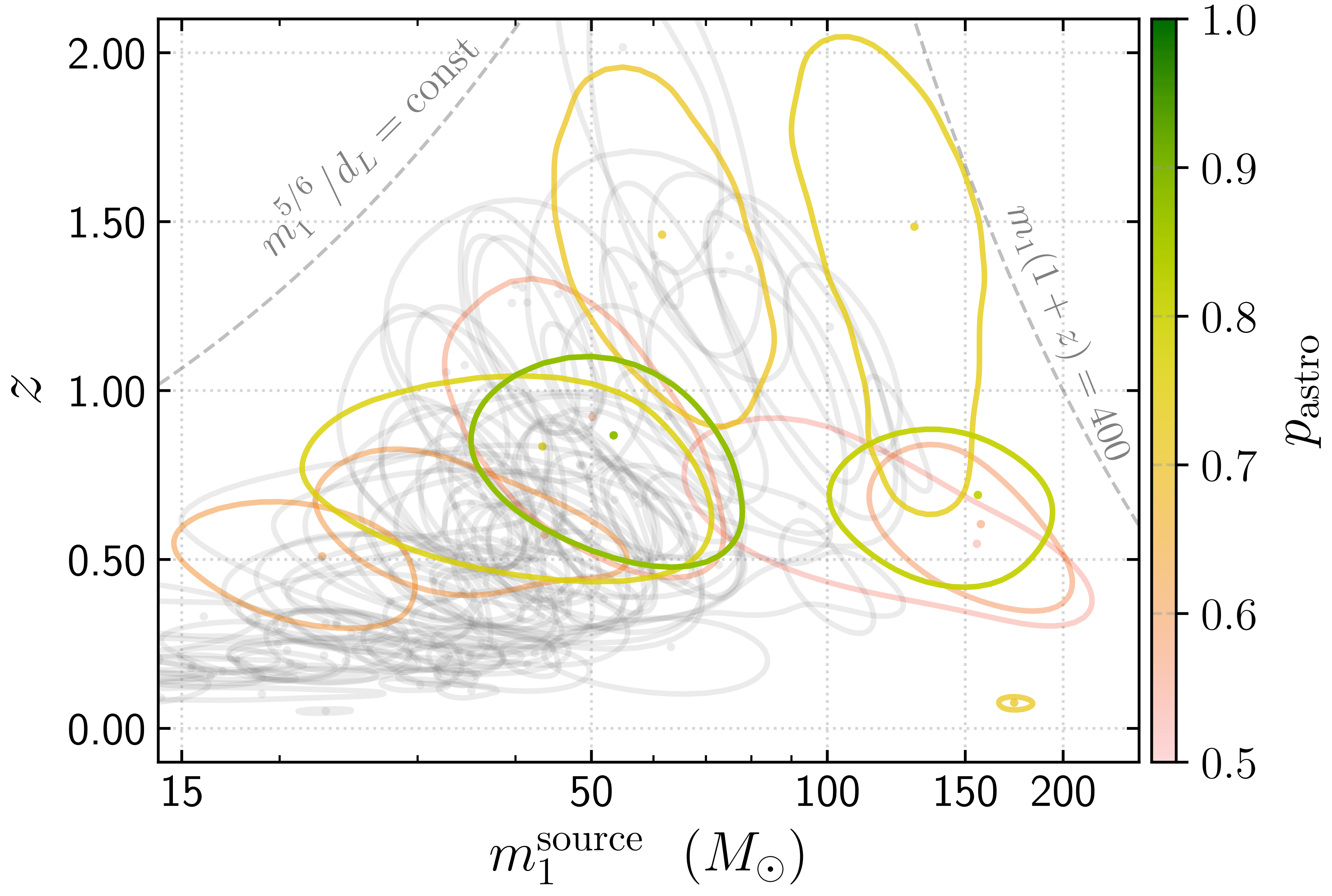
LVK, Living Rev. Rel. 23, 3 (2020)
https://observing.docs.ligo.org/plan/

LVK, arXiv:2111.03606
https://www.ligo.org/scientists/GWEMalerts.php

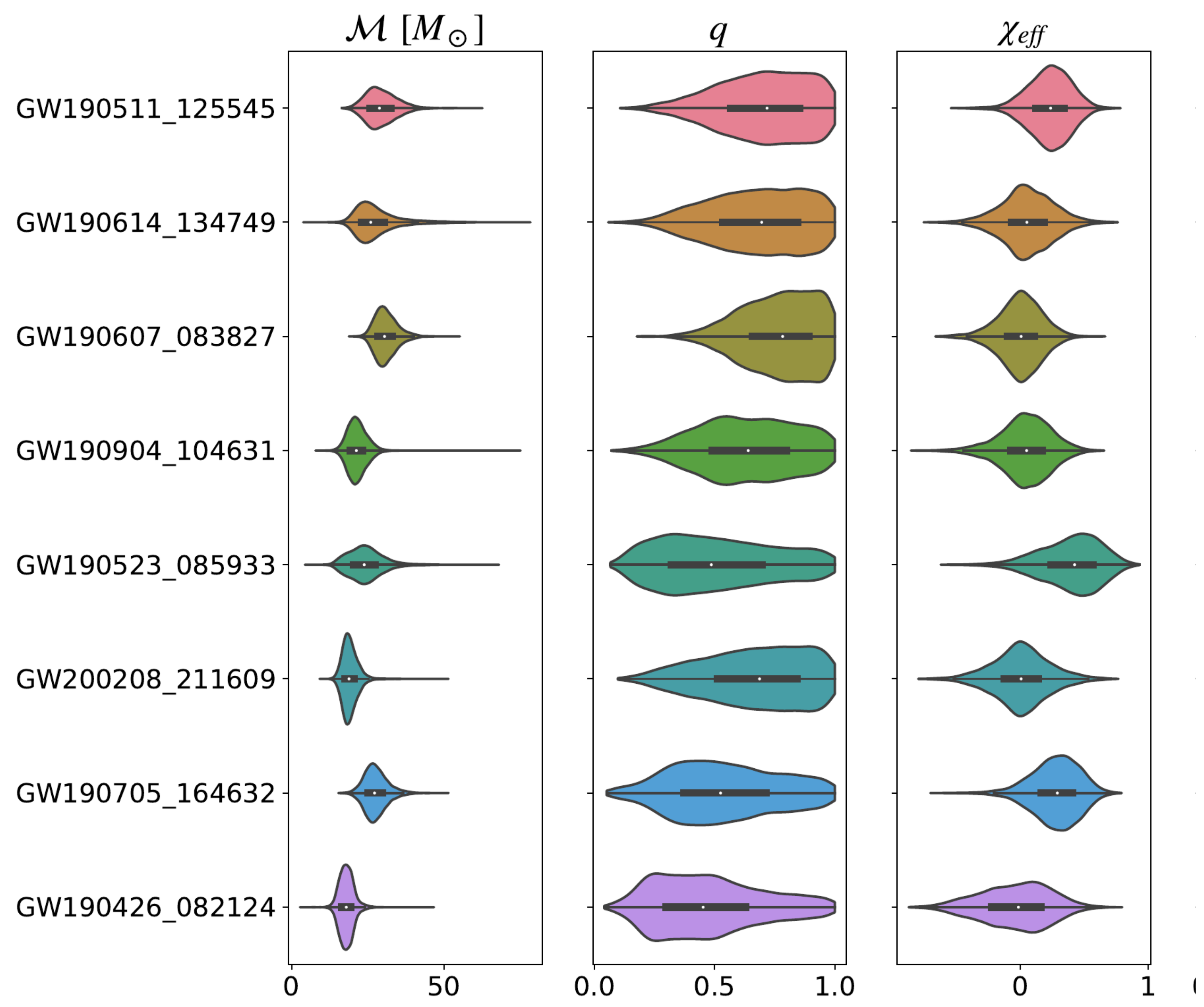
Open data analysis



Nitz et al., arXiv: 2112.06878

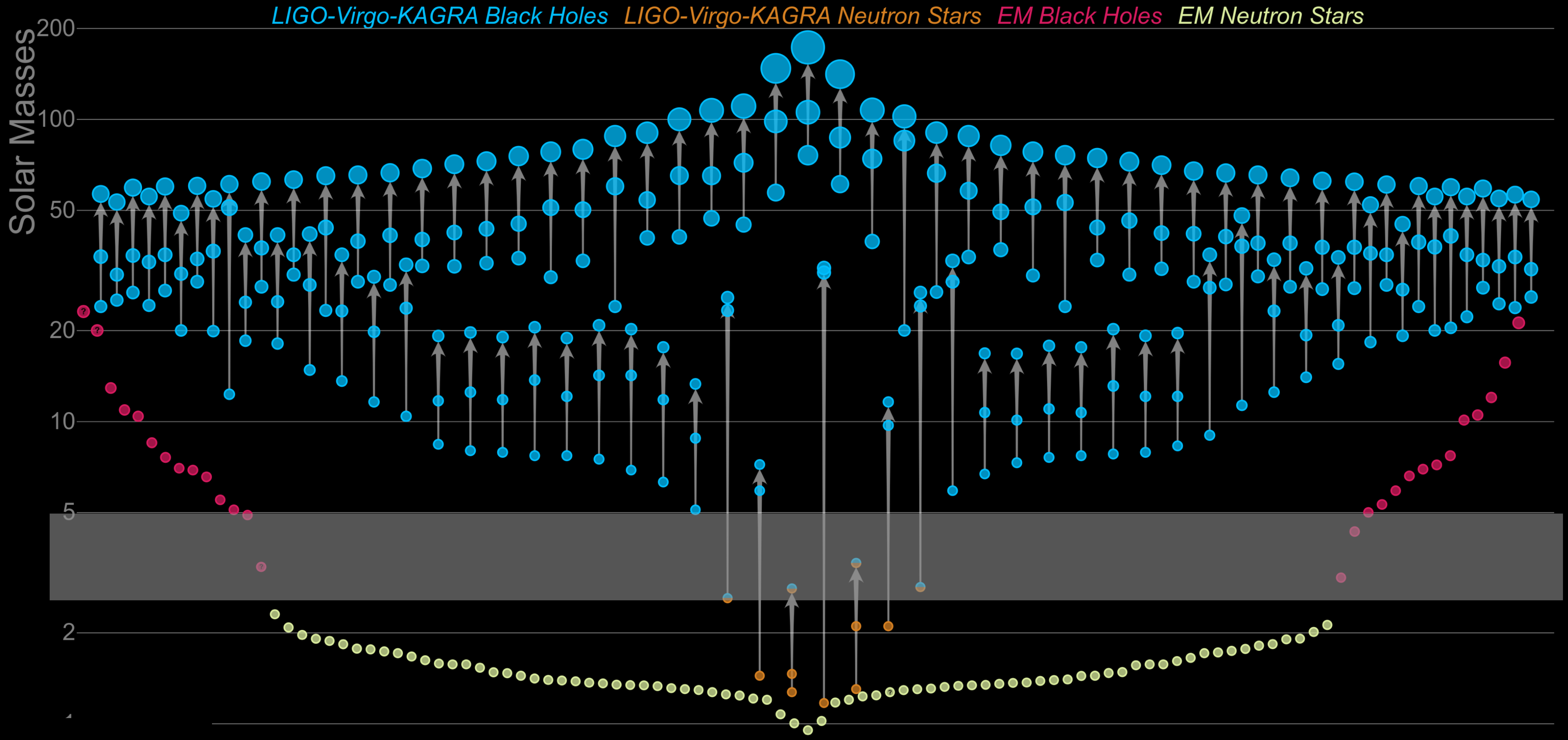


Wadekar et al, arXiv: 2201.02252



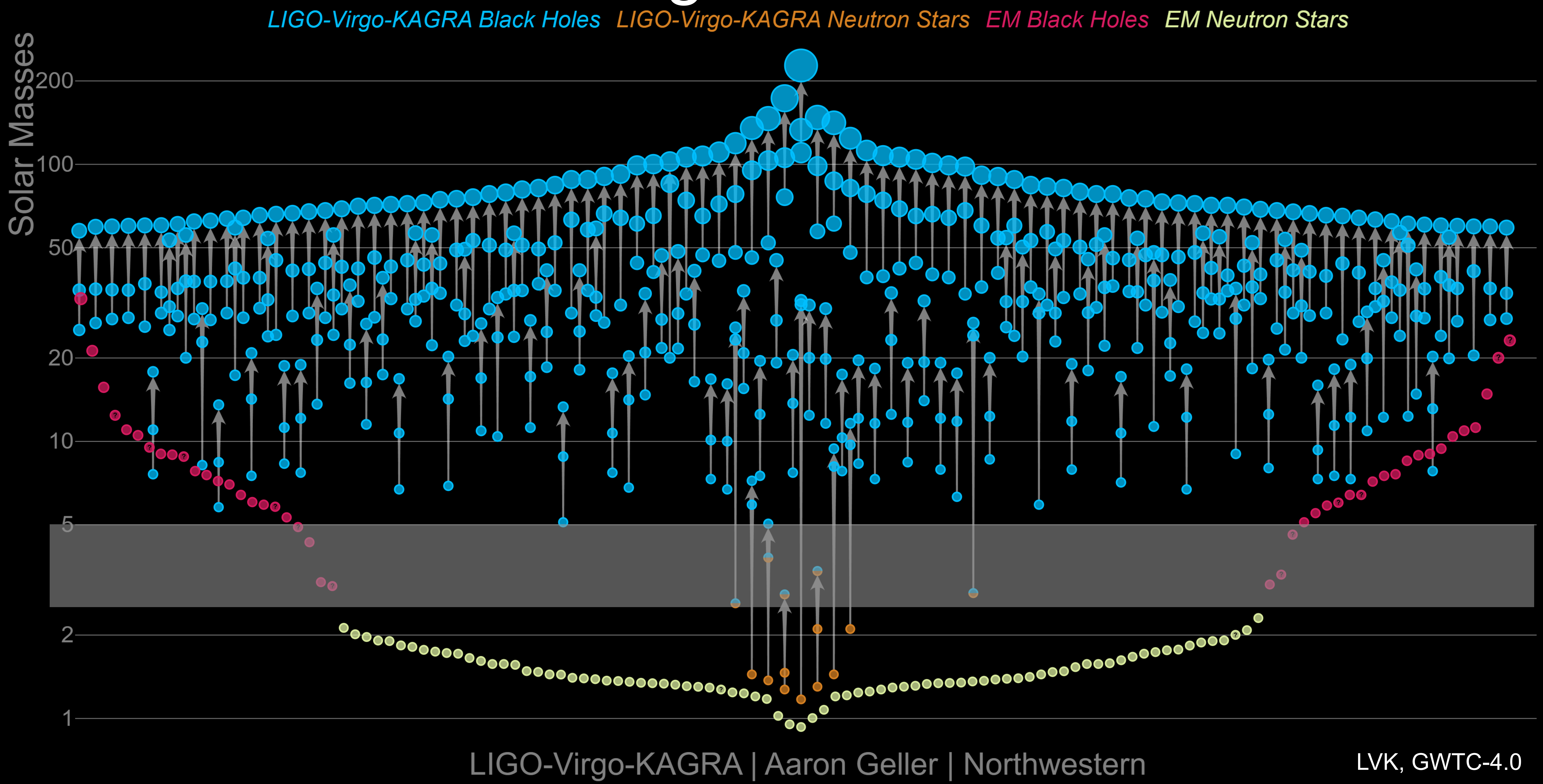
Koloniari et al., arXiv:2407.07820

GWTC-3: All events through O3



LVK, Phys. Rev. X. 13, 041039 (2023)

GWTC-4: Adding observations from O4a

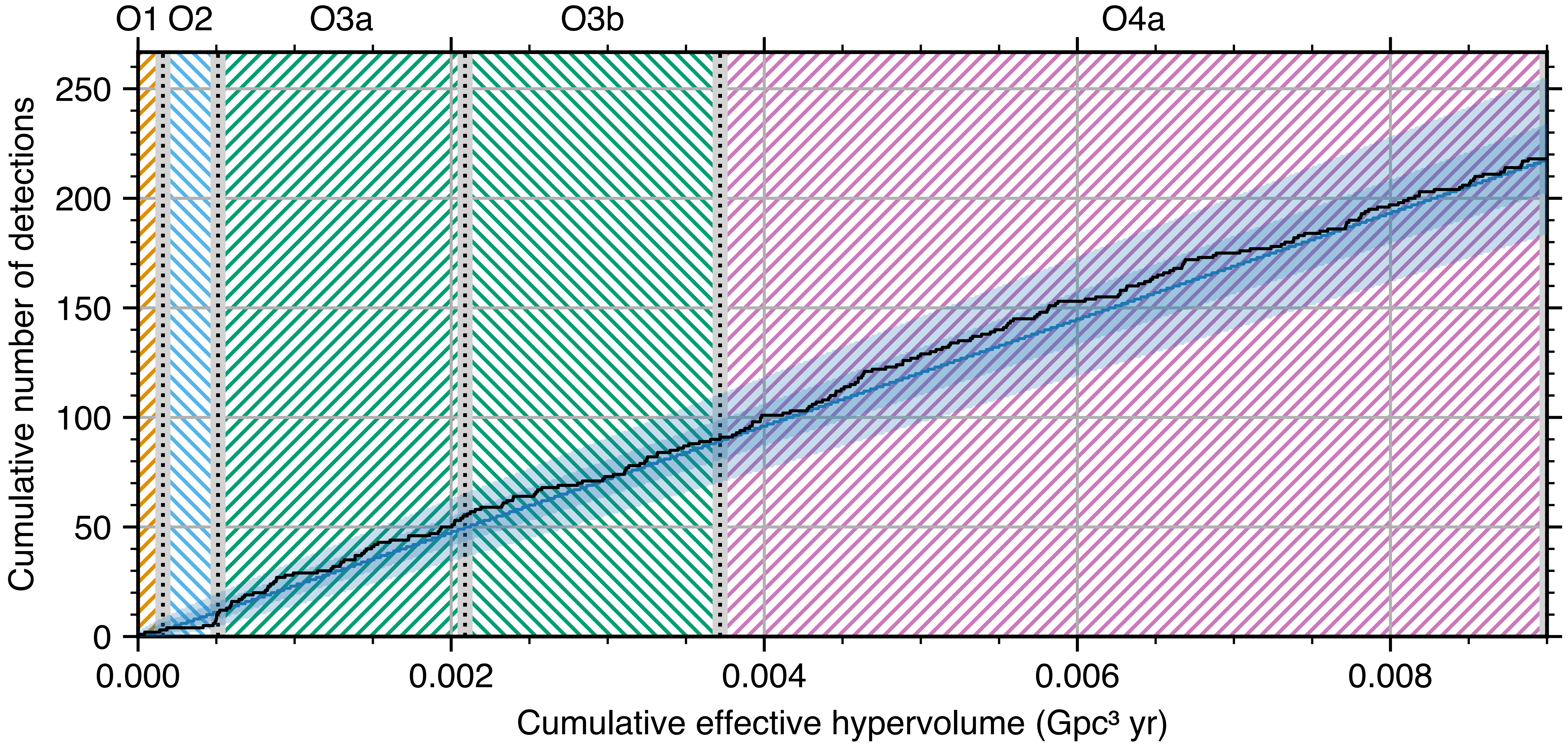


LVK, GWTC-4.0

GWTC-4.0

Overview of GWTC-4.0

- Cumulative catalog from O1 to O4a
- Results presented in GWTC-4.0 Focus Issue
  - Introduction, methods, observational results, open data guide
  - Population and cosmological inferences
  - Tests of GR
  - Searches for lensed events
  - Special event papers: GW231123



218 GW Candidates

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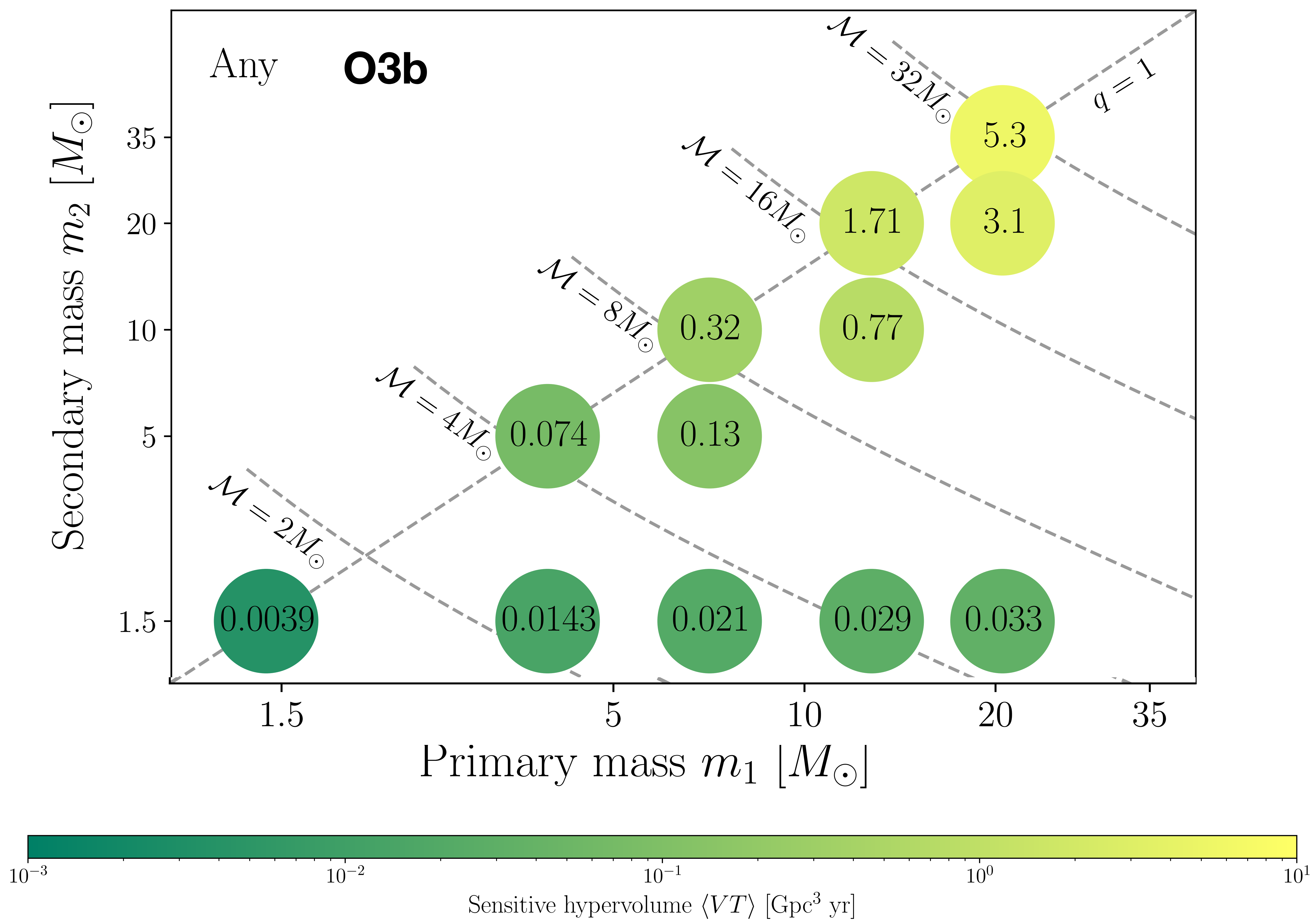
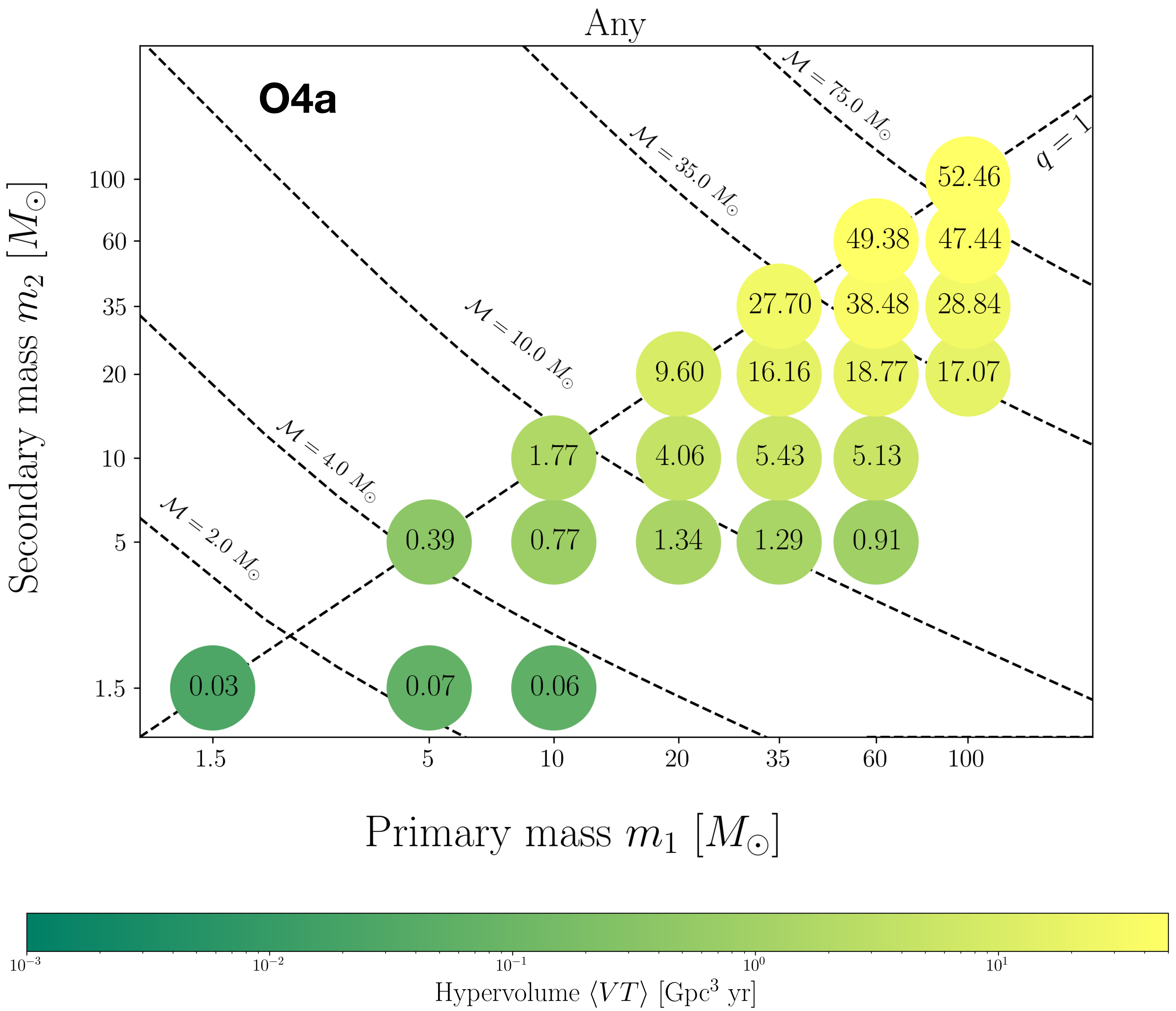
LVK, arXiv:2508.18080

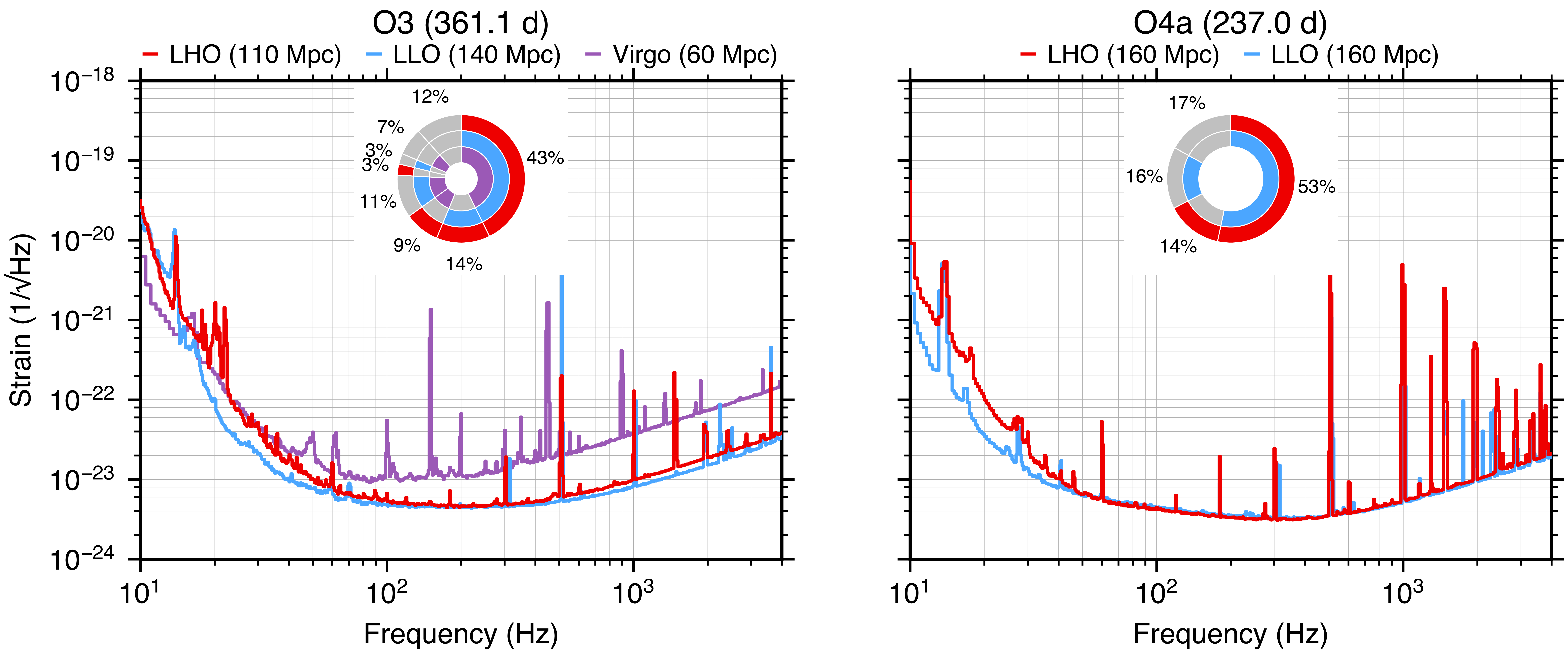
Sensitive Volume





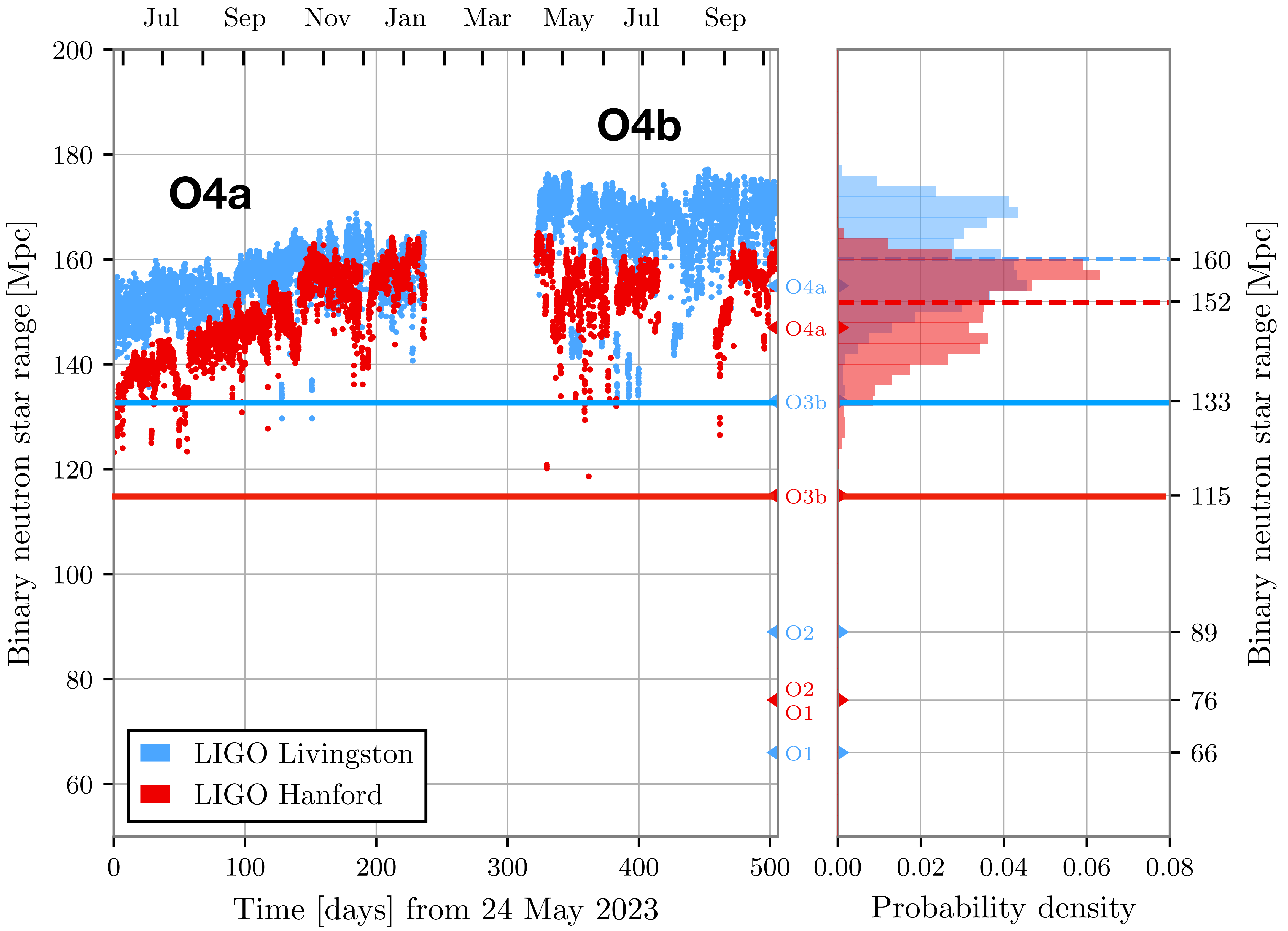
LVK, arXiv:2508.18082

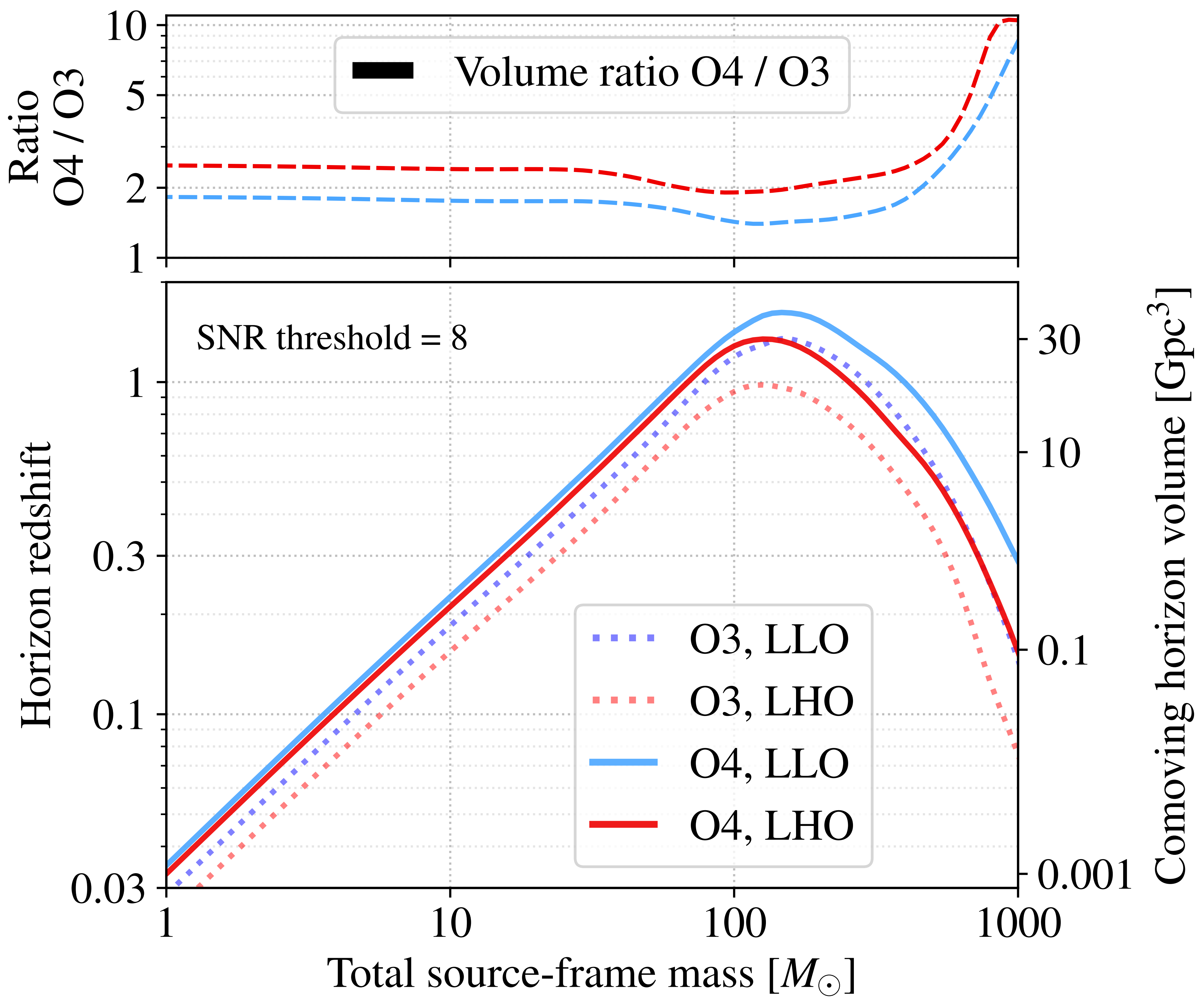
O4a: Detectors and observing



LVK, arXiv:2508.18080

Detectors in O4a+b





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Capote, Jia, Aritomi, Nakano, Xu et al.
PRD 111, 062002 (2025)

Significance of events

- False alarm rate (FAR) one measure of significance
  - How often does pure noise create a signal with same “score”?
- Probability of astrophysical origin

$$p_{\text{astro}}(x, \theta | \Lambda_0, \Lambda_i) = \frac{\sum_i \Lambda_i f_i(x, \theta)}{\Lambda_0 b(x, \theta) + \sum_i \Lambda_i f_i(x, \theta)} \qquad \Lambda_i = R_i \langle V_i T \rangle$$

- p_{astro} used in previous catalog as measure of significance

Farr, Gair, Mandel, Cutler PRD91, 023005 (2013)
LVC ApJL 833:L1 (2016)
LVK, arXiv:2111.03606

Significance of events

- False alarm rate (FAR) one measure of significance
  - How often does pure noise create a signal with same “score”?
- Probability of astrophysical origin

Knowledge of “foreground” rates makes searches more sensitive

$$p_{\rm astro}(x,\theta|\Lambda_0,\Lambda_i) = \frac{\sum_i \Lambda_i f_i(x,\theta)}{\Lambda_0 b(x,\theta) + \sum_i \Lambda_i f_i(x,\theta)} \qquad \Lambda_i = R_i \langle V_i T \rangle$$

- $p_{\rm astro}$ used in previous catalog as measure of significance

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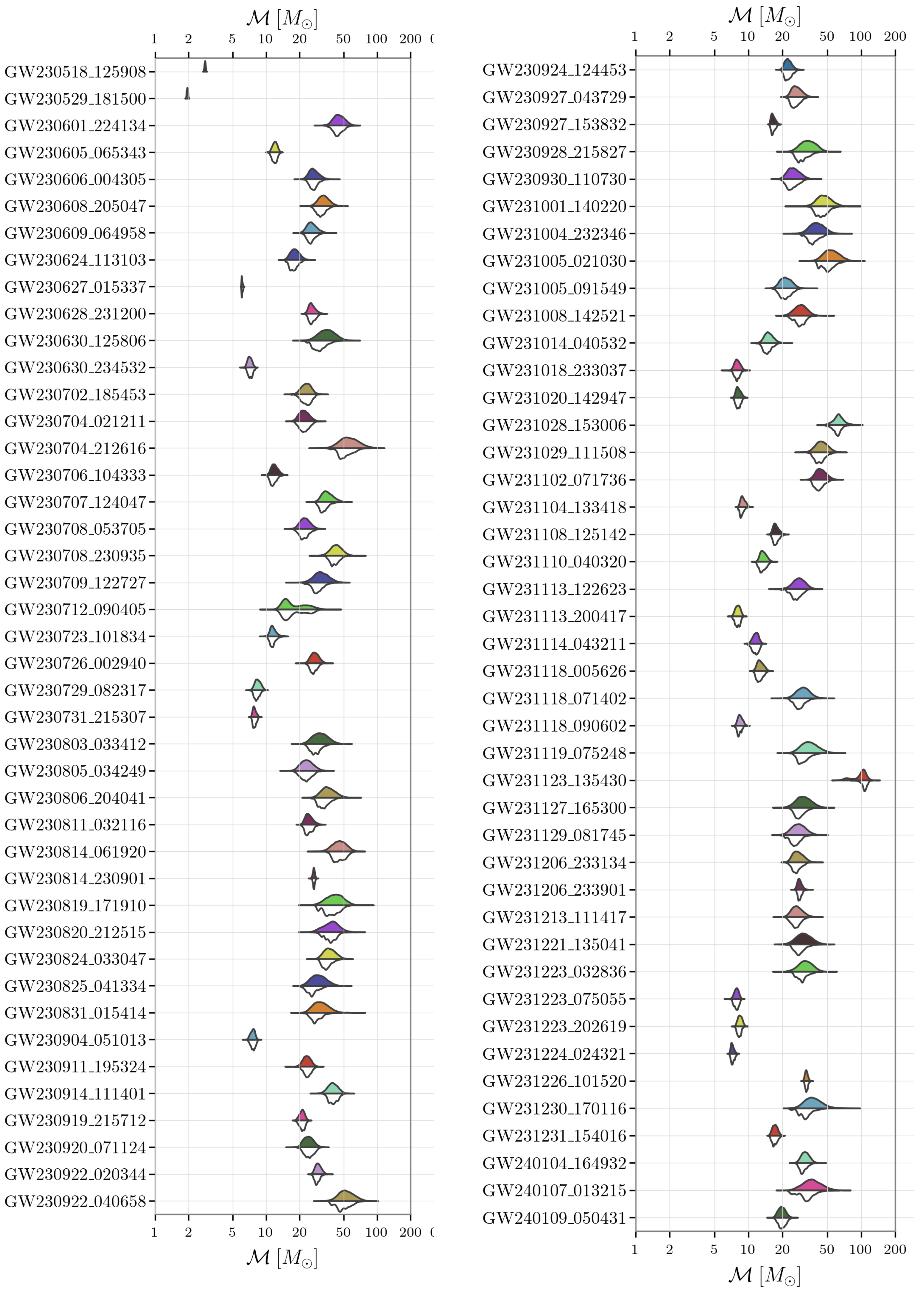
Farr, Gair, Mandel, Cutler PRD91, 023005 (2013)
LVC ApJL 833:L1 (2016)
LVK, arXiv:2111.03606

GWTC-4.0

- Low-latency candidates: 81 in O4a w/ FAR $< 2/\mathrm{yr}$ (after trials factor)
- 128 new candidates w/ $p_{\mathrm{astro}} \geq 0.5$
  - 90 for GWTC-3
- 86 w/ FAR $< 1/\mathrm{yr}$ to
  - Detailed source measurements
  - Used by some downstream analysis
  - 75 in GWTC-3



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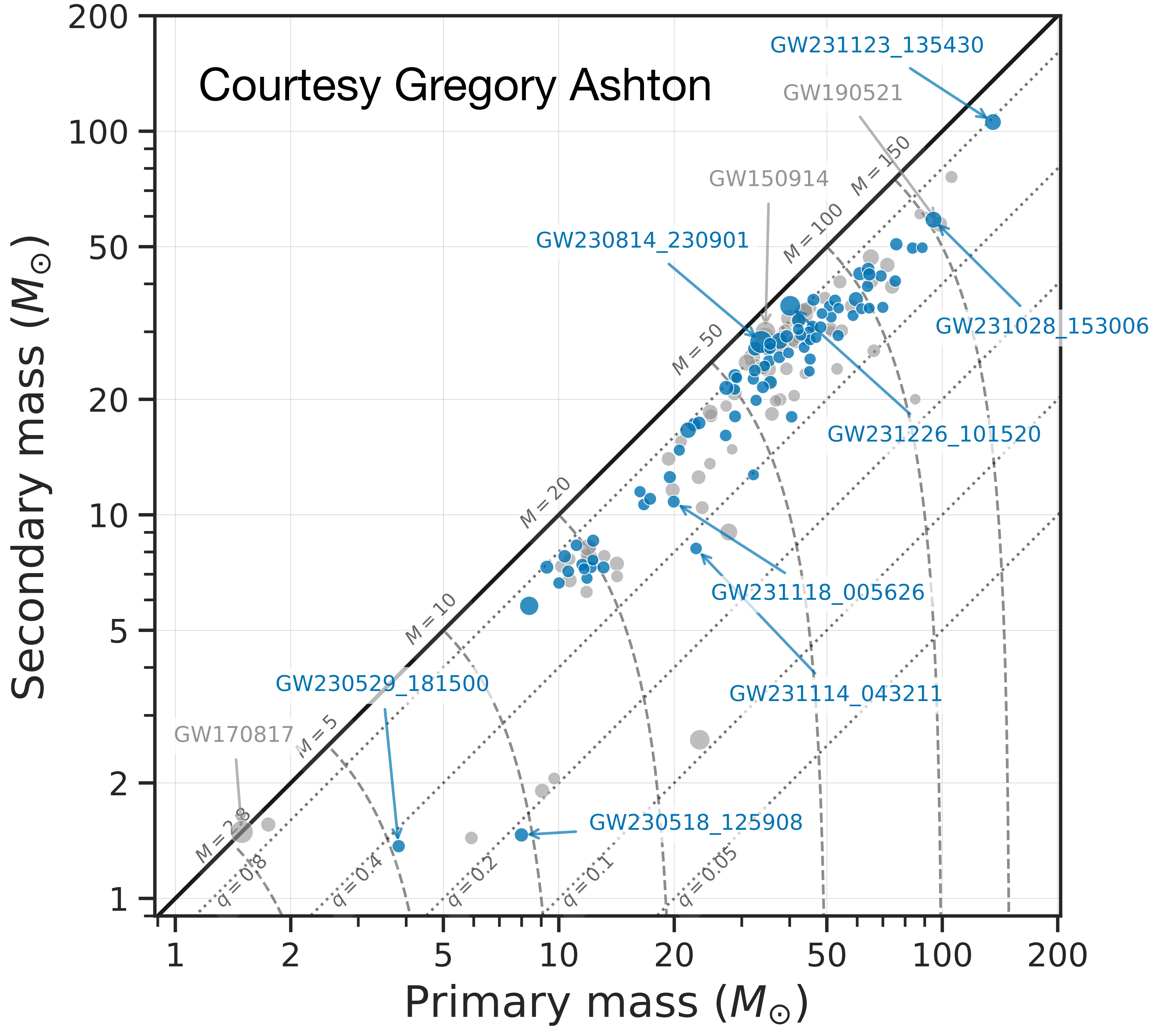
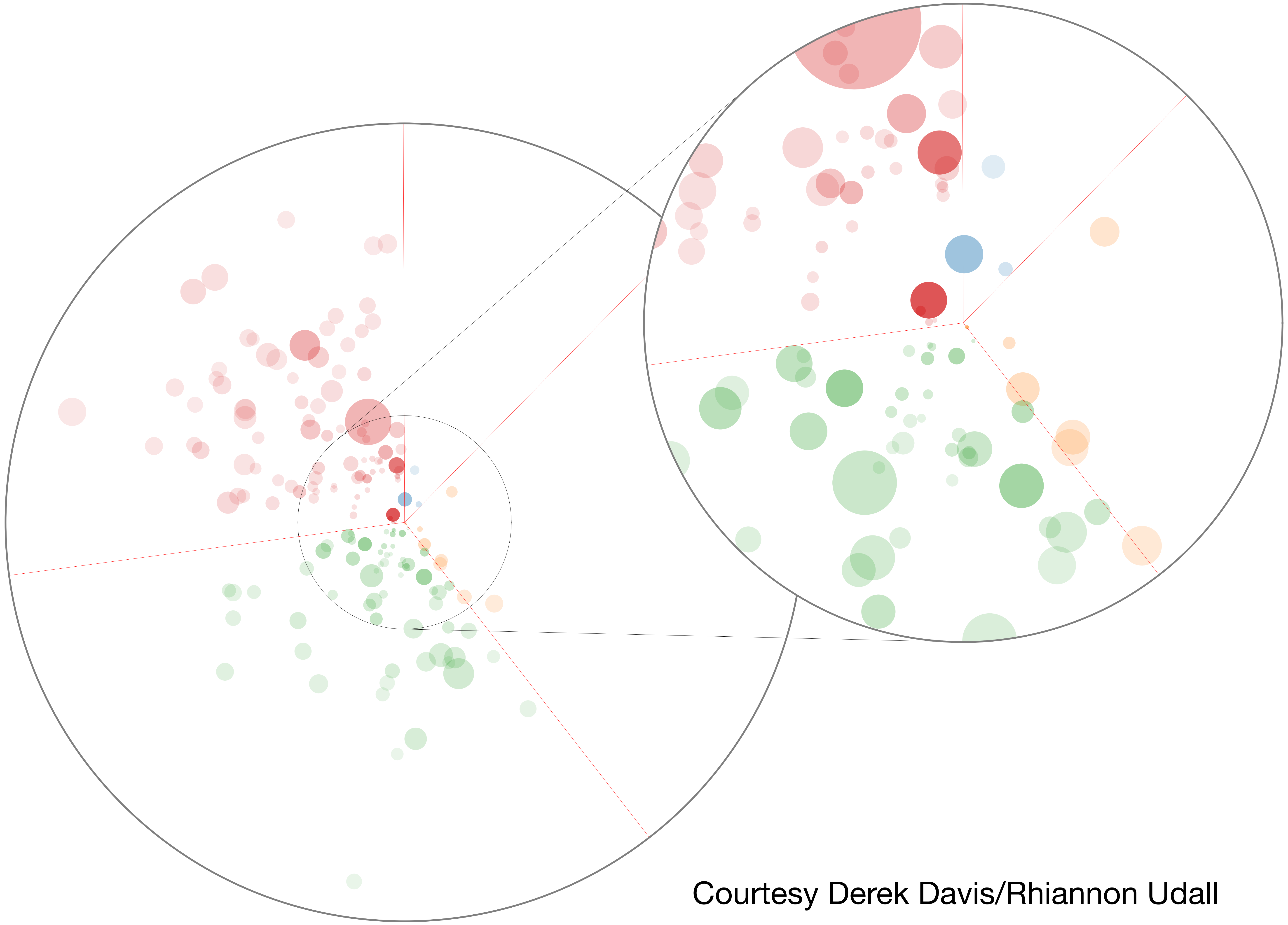
LVK, arXiv:2508.18082

New events in GWTC-4.0

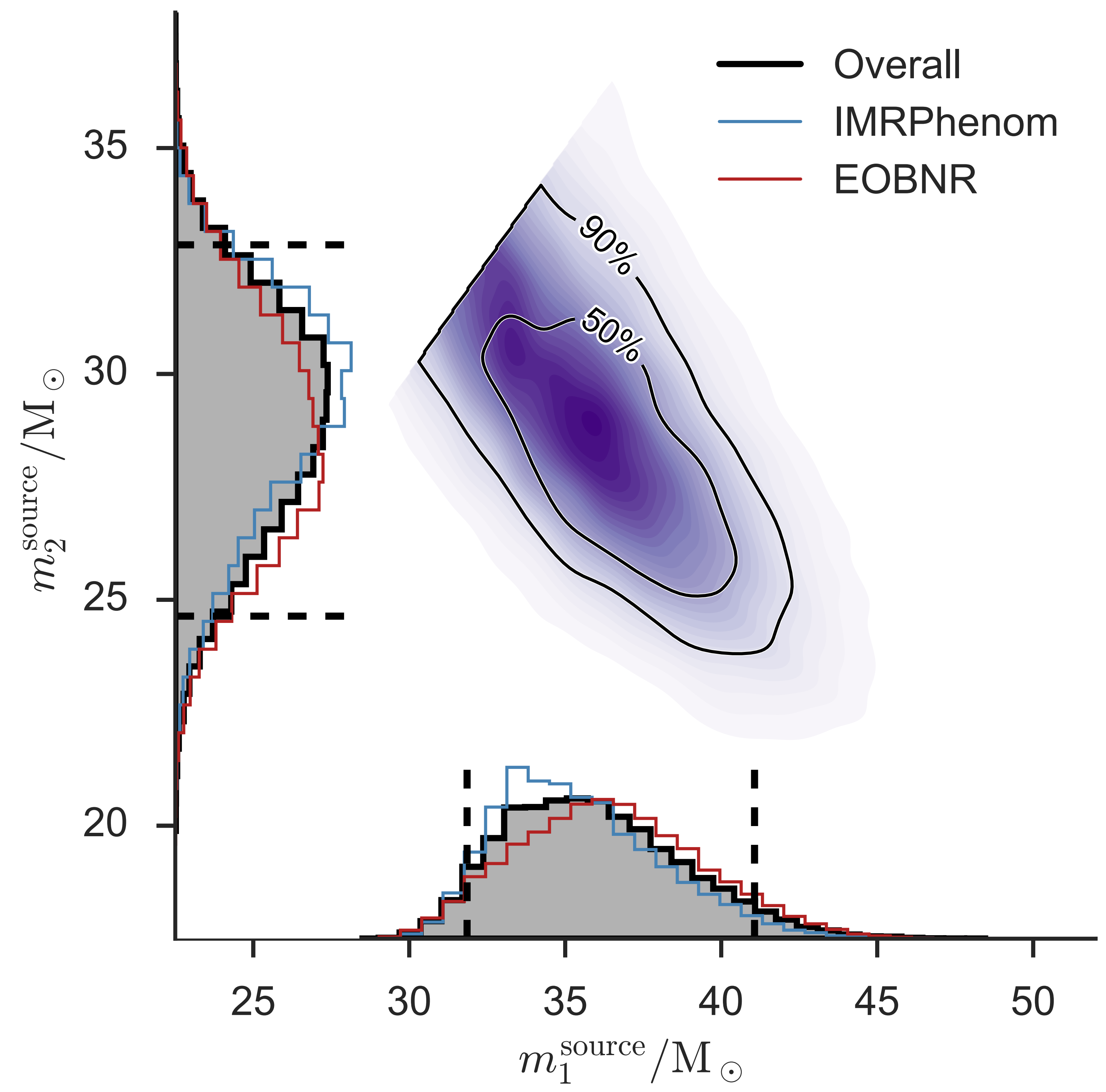




Courtesy Derek Davis/Rhiannon Udall

Bayesian parameter estimation

$$p(\vec{\theta}|d, M) = \frac{p(d|\vec{\theta}, M)p(\vec{\theta}|M)}{p(d|M)}$$



- Likelihood: $p(d|\vec{\theta}, M)$
- Priors: $p(\vec{\theta}|M)$
- Evidence: $p(d|M) = \int p(d|\vec{\theta}, M)p(\vec{\theta}|M)d\vec{\theta}$

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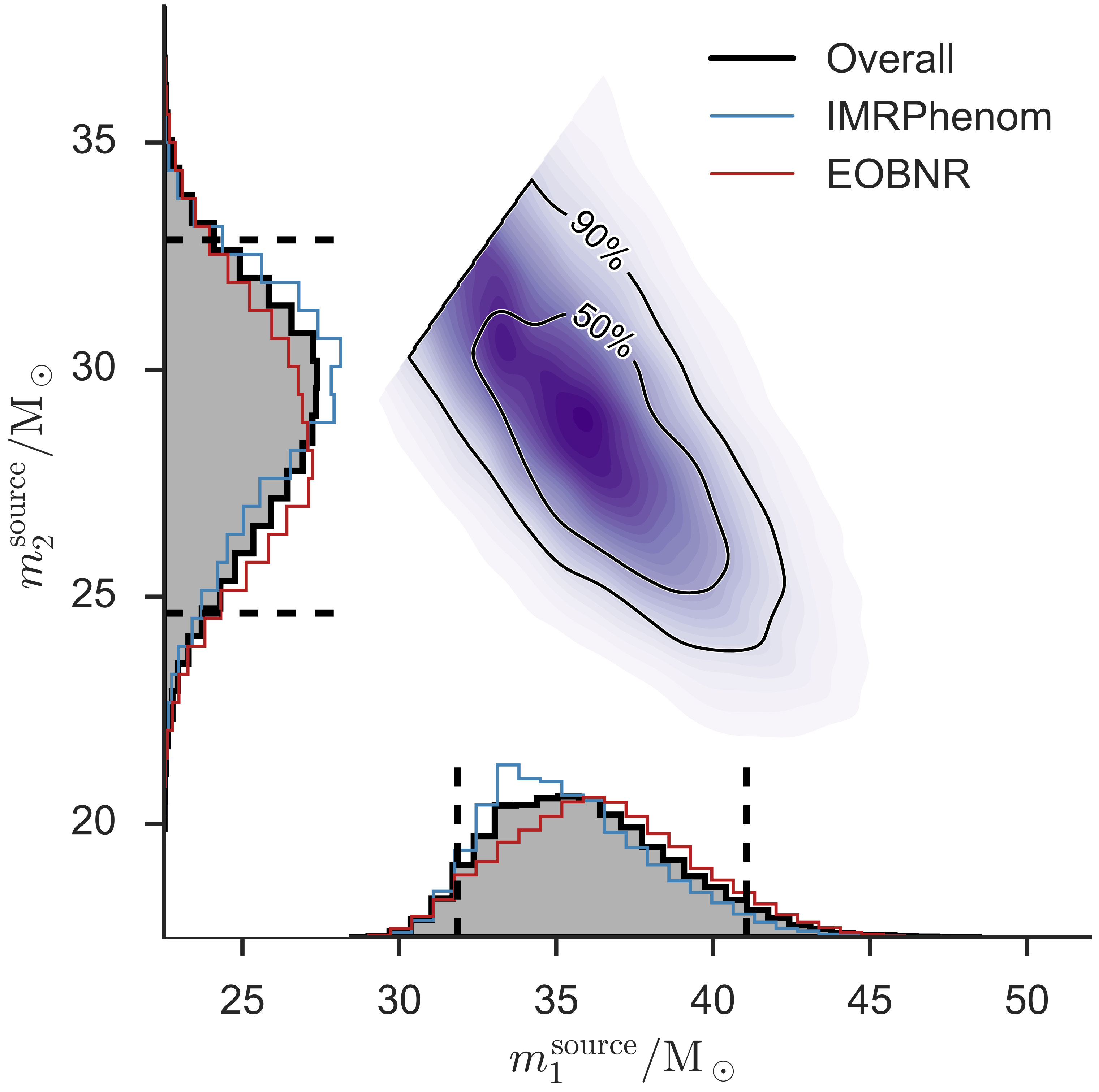
LVC PRL 116, 061102 (2016)

Bayesian parameter estimation

$$p(\vec{\theta}|d, M) = \frac{p(d|\vec{\theta}, M)p(\vec{\theta}|M)}{p(d|M)}$$

- Colored Gaussian noise assumption gives likelihood

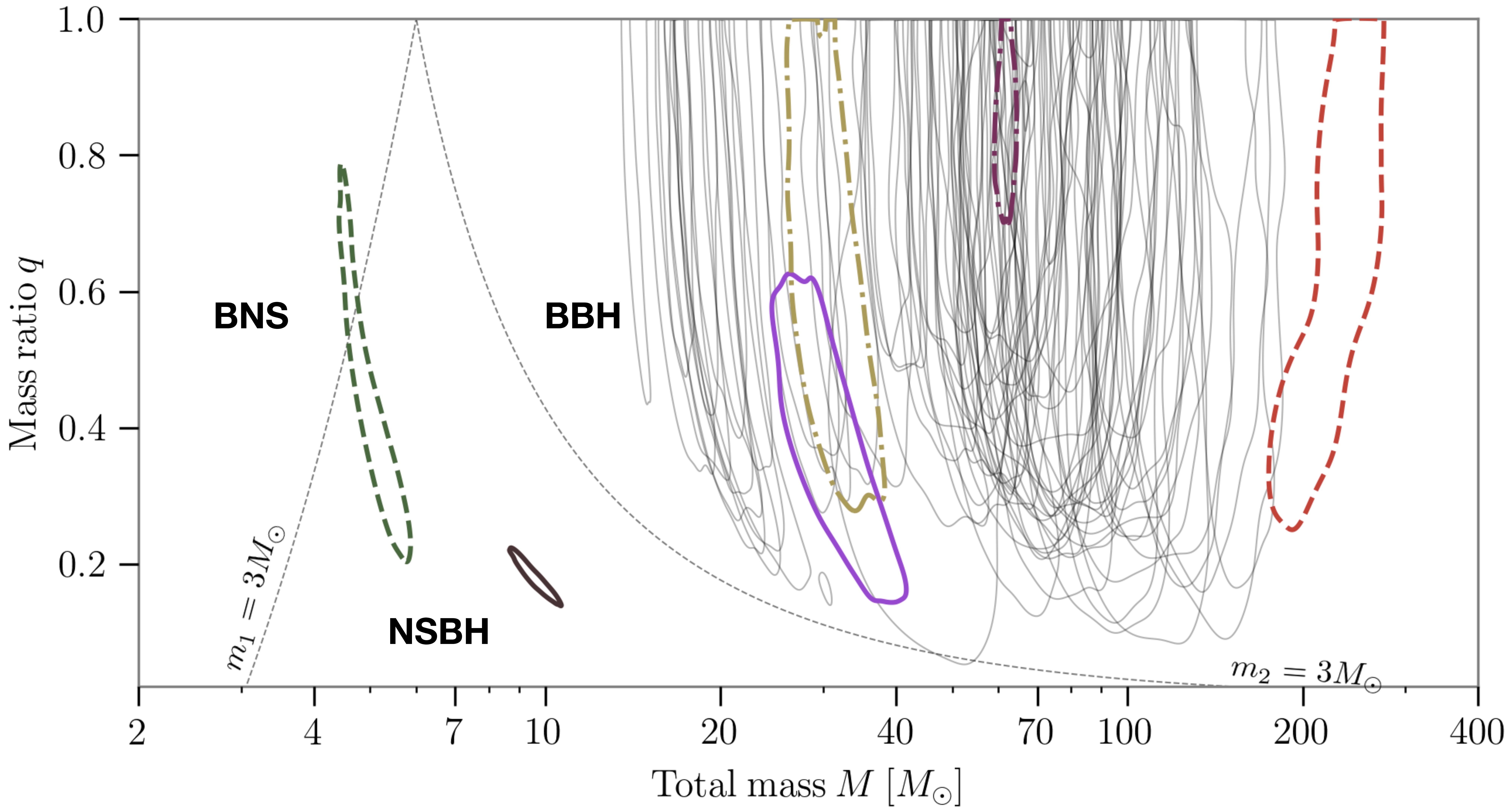
$$d(t) = h(t) + n(t)$$



$$p(d|\vec{\theta}) \propto \exp\left[-\frac{1}{2}\langle d - h(\vec{\theta})|d - h(\vec{\theta})\rangle\right] = p(n) \qquad n = d - h(\vec{\theta})$$

LVC PRL 116, 061102 (2016)

GWTC-4: mass inferences



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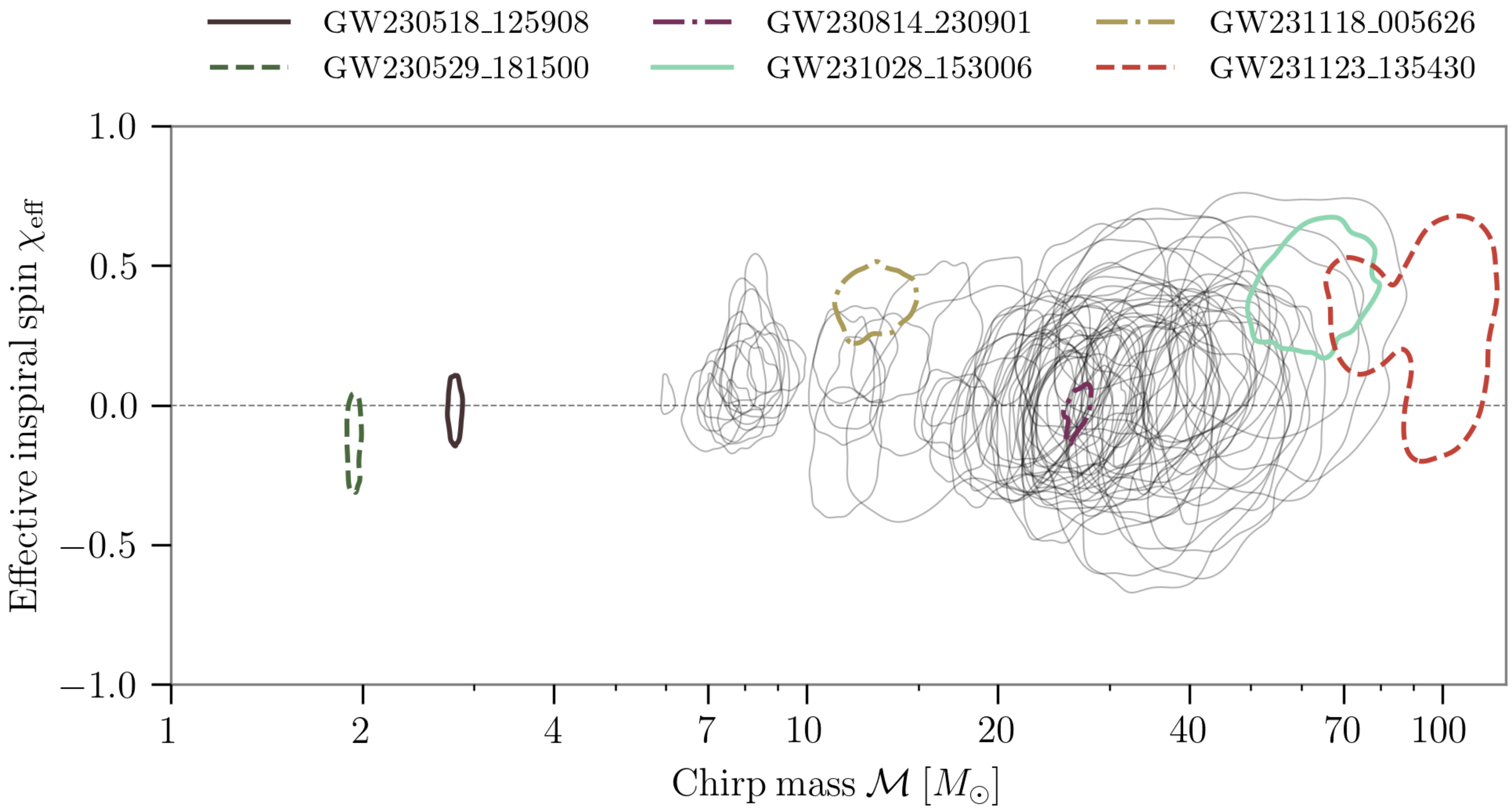
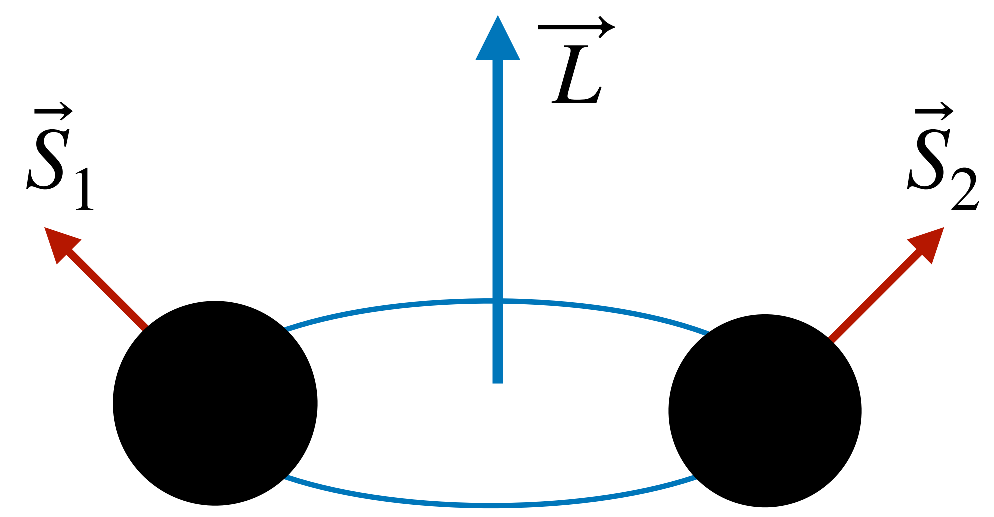
LVK, arXiv:2508.18082

GWTC-4: Effective spin



$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$\chi_{\rm eff} = \left(\frac{\vec{S}_1}{m_1} + \frac{\vec{S}_2}{m_2}\right) \cdot \frac{\hat{L}}{m_1 + m_2}$$



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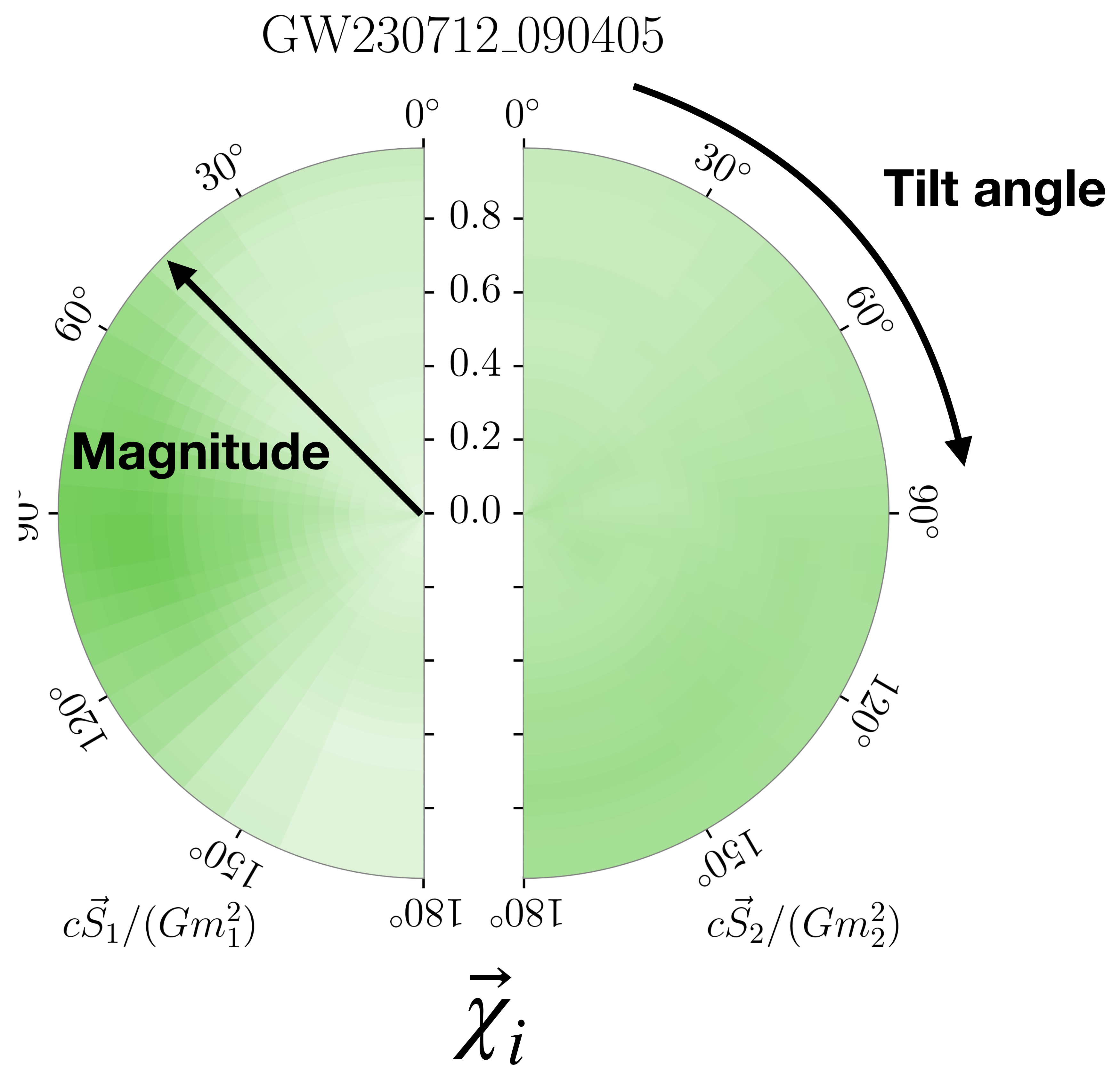
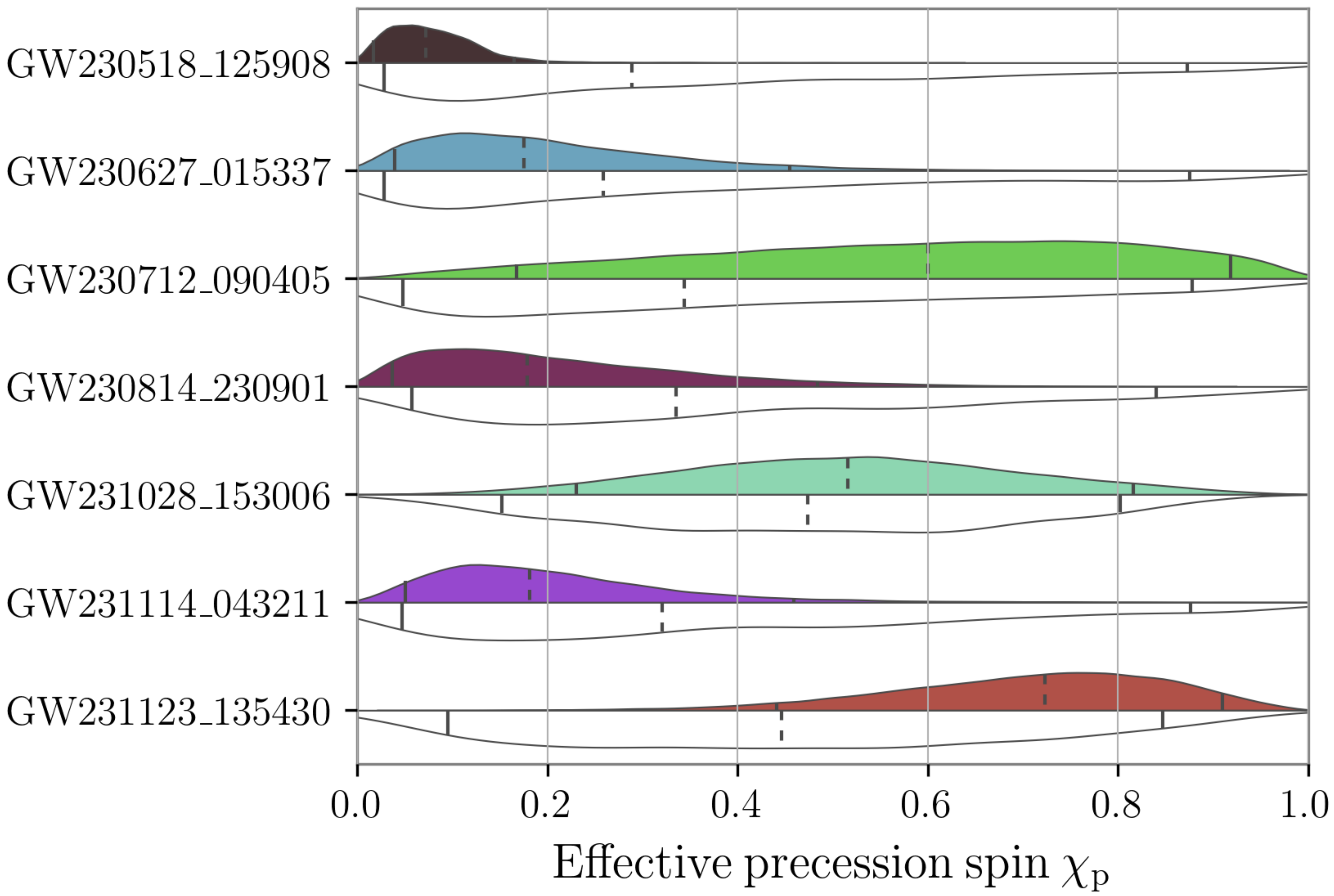
LVK, arXiv:2508.18082

Measuring imprints of precession

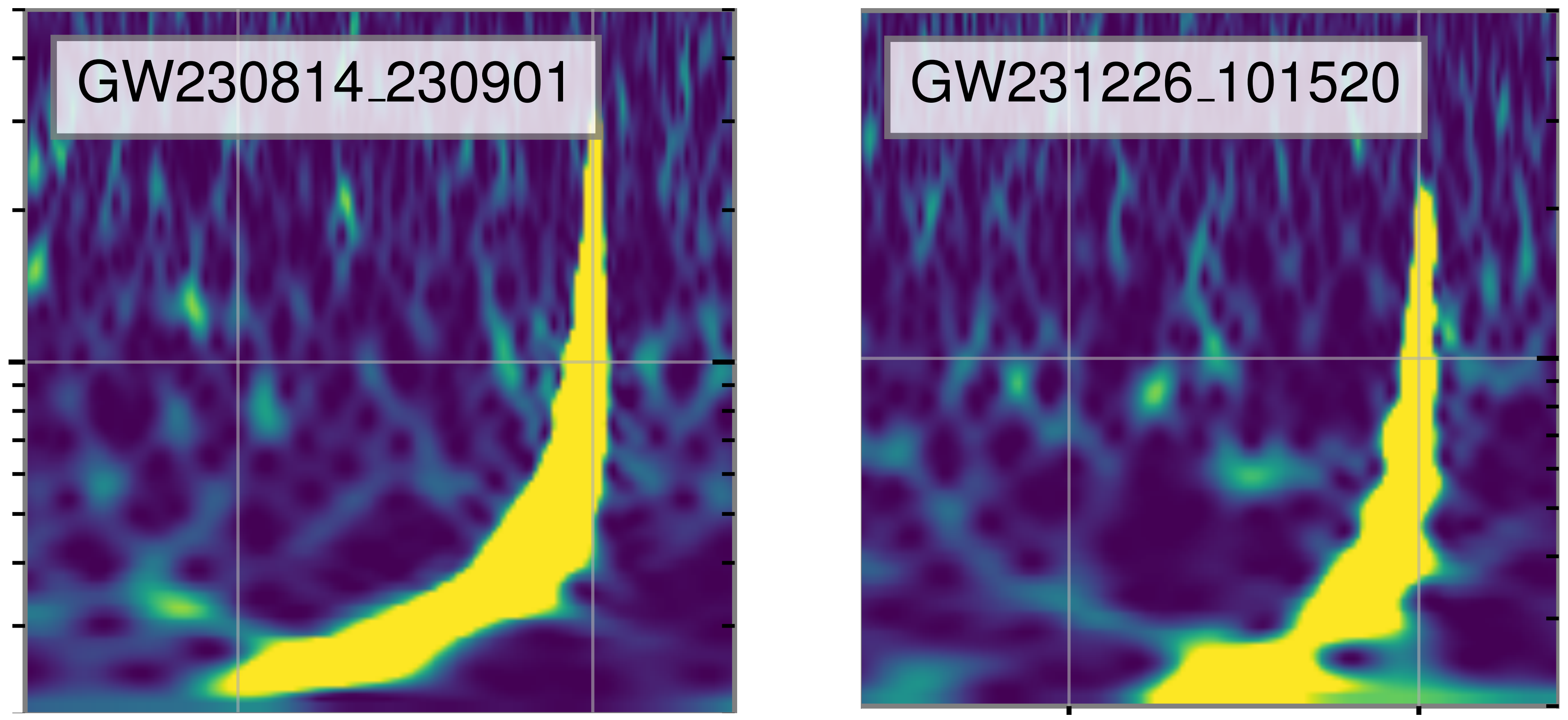




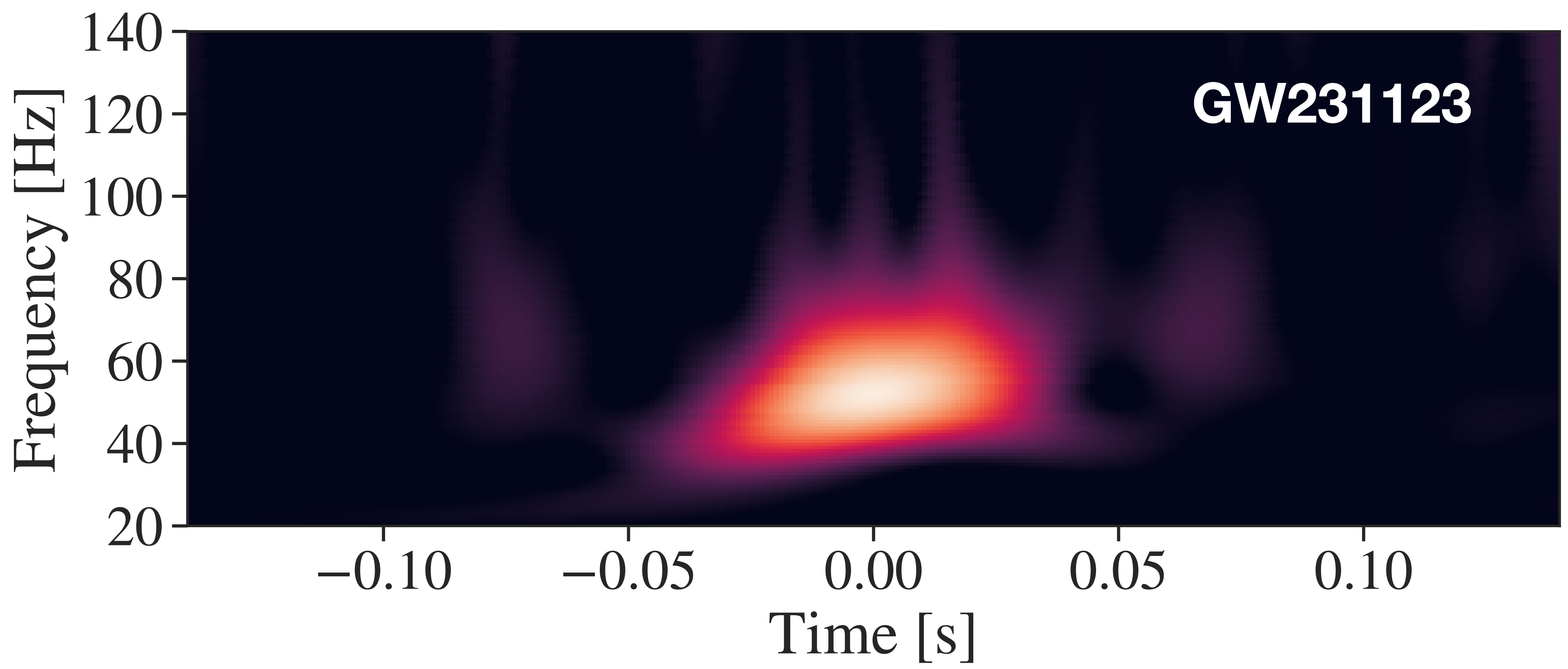
LVK, arXiv:2508.18082

Exceptional events

- New NSBHs
  - GW230518: “Typical” NSBH
  - GW230529: Mass-gap BH
- GW230814: Highest SNR event up to O4a
- GW231123: Heaviest BBH in O4a
- Many additionally interesting events
  - GW231028: Massive with high spins
  - GW231118_00: Unequal mass with tightly measured primary spin



Courtesy Derek Davis



LVK 2507.08219

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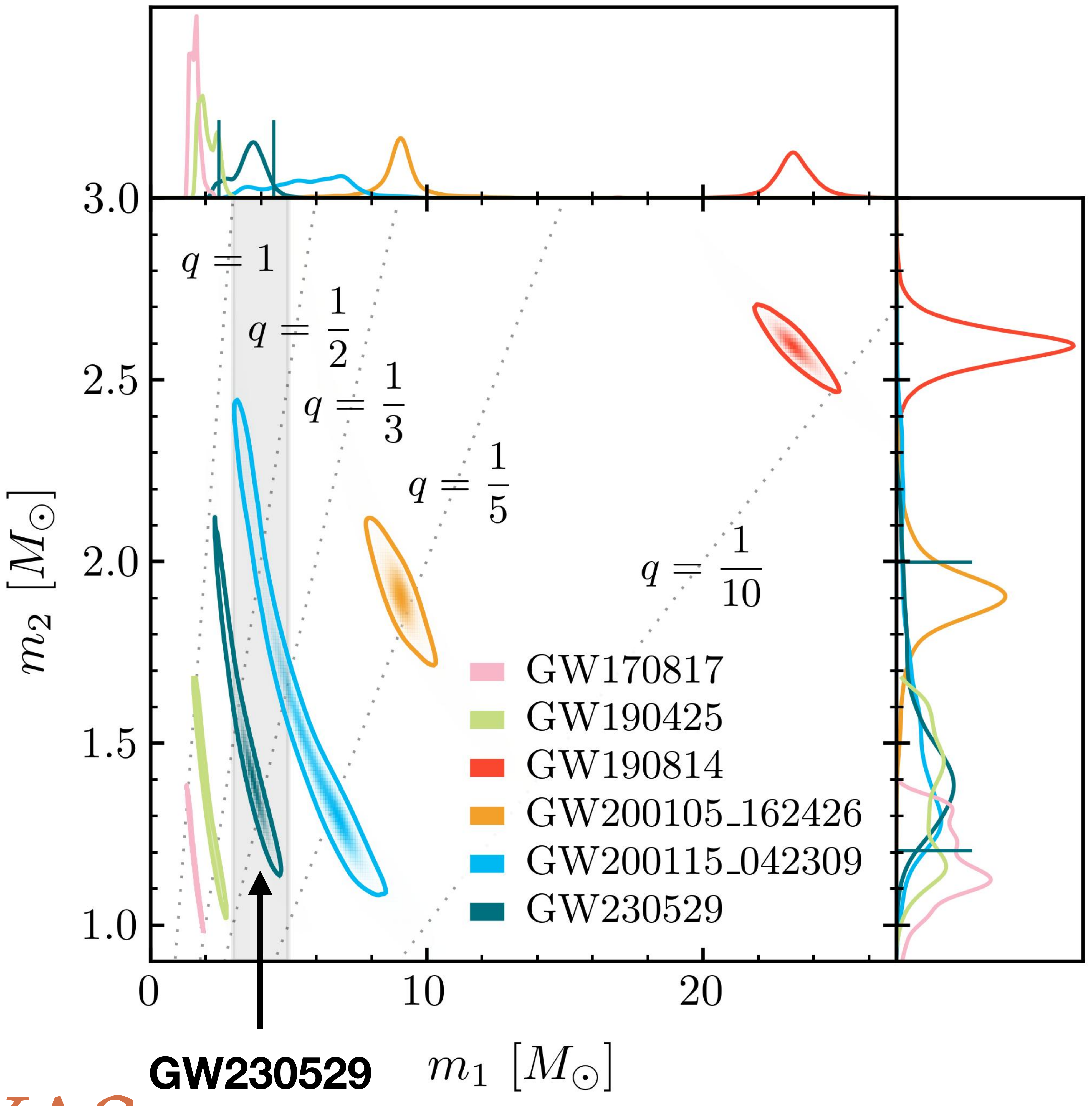
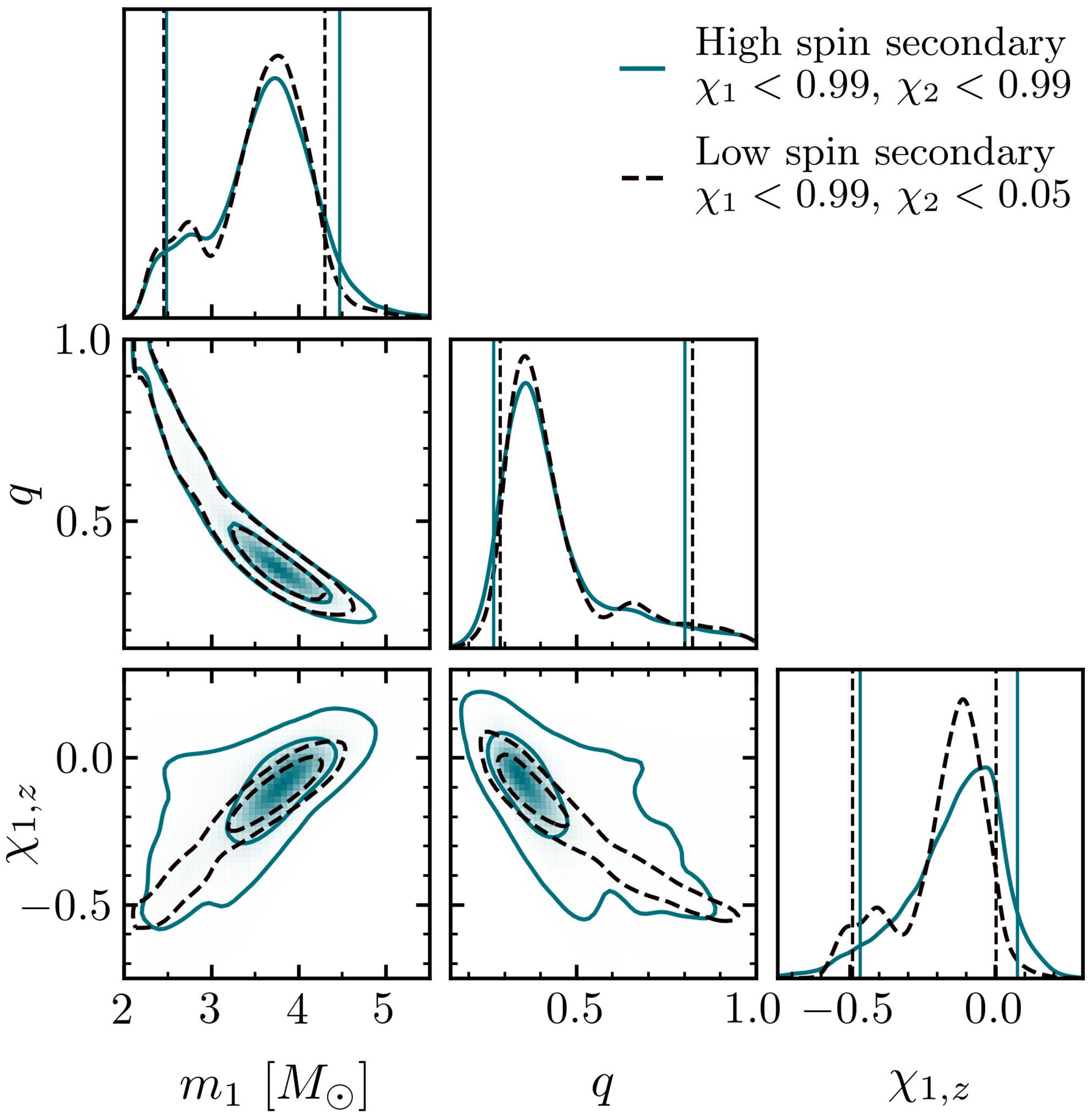
Mass-gap NSBH:GW230529





LVK ApJL 970, L34 (2024)

LVK, arXiv:2508.18082

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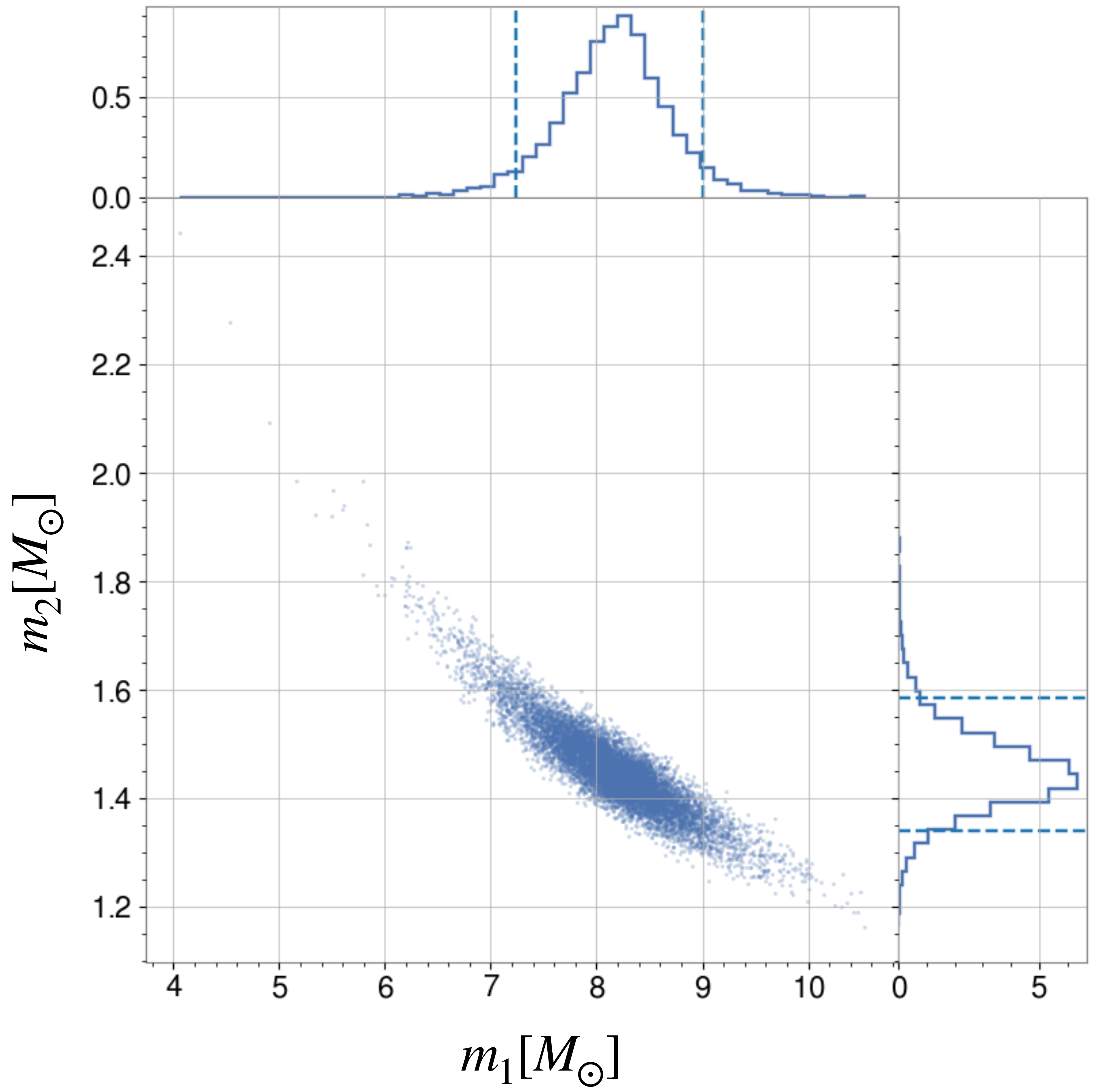
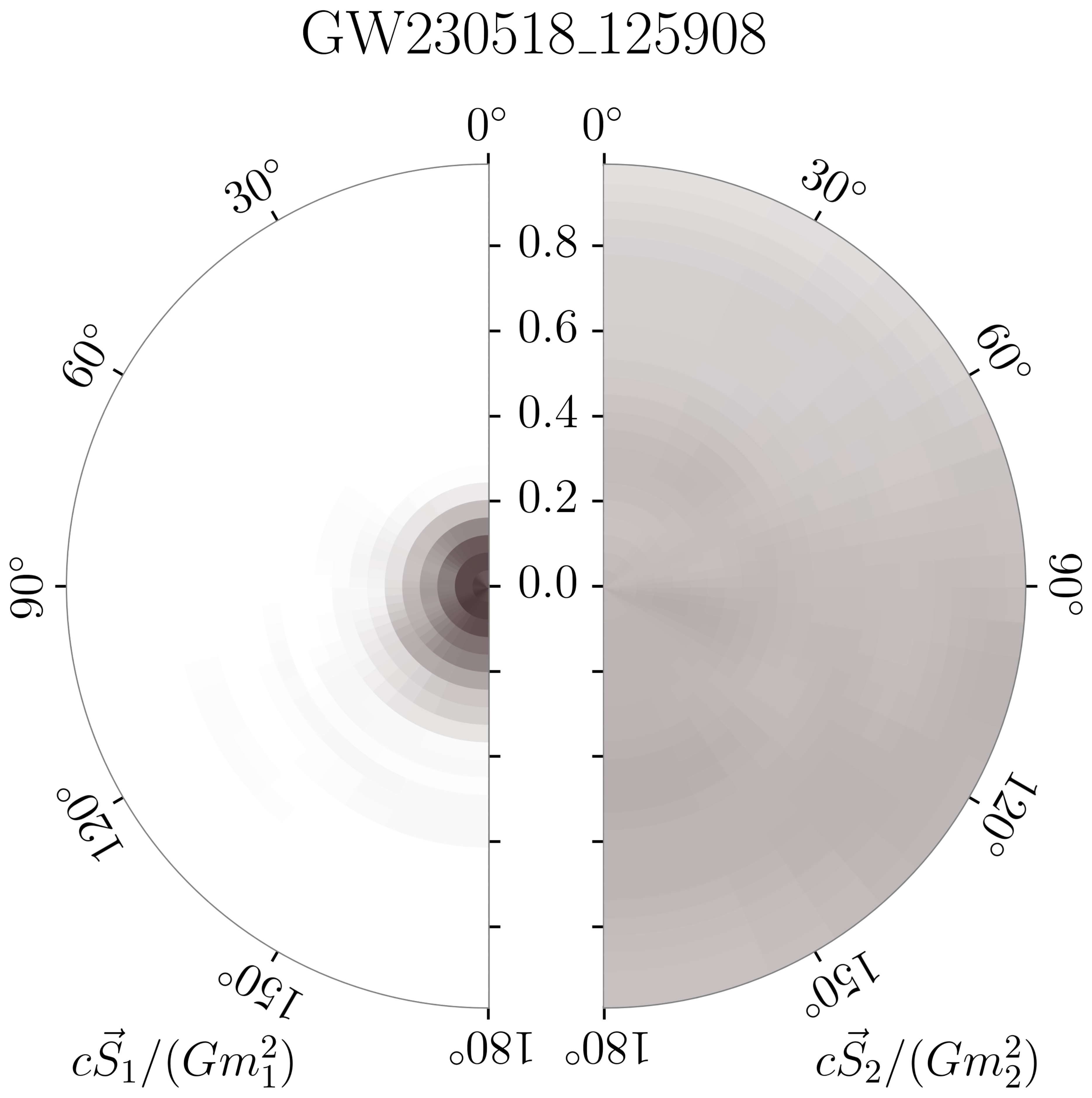
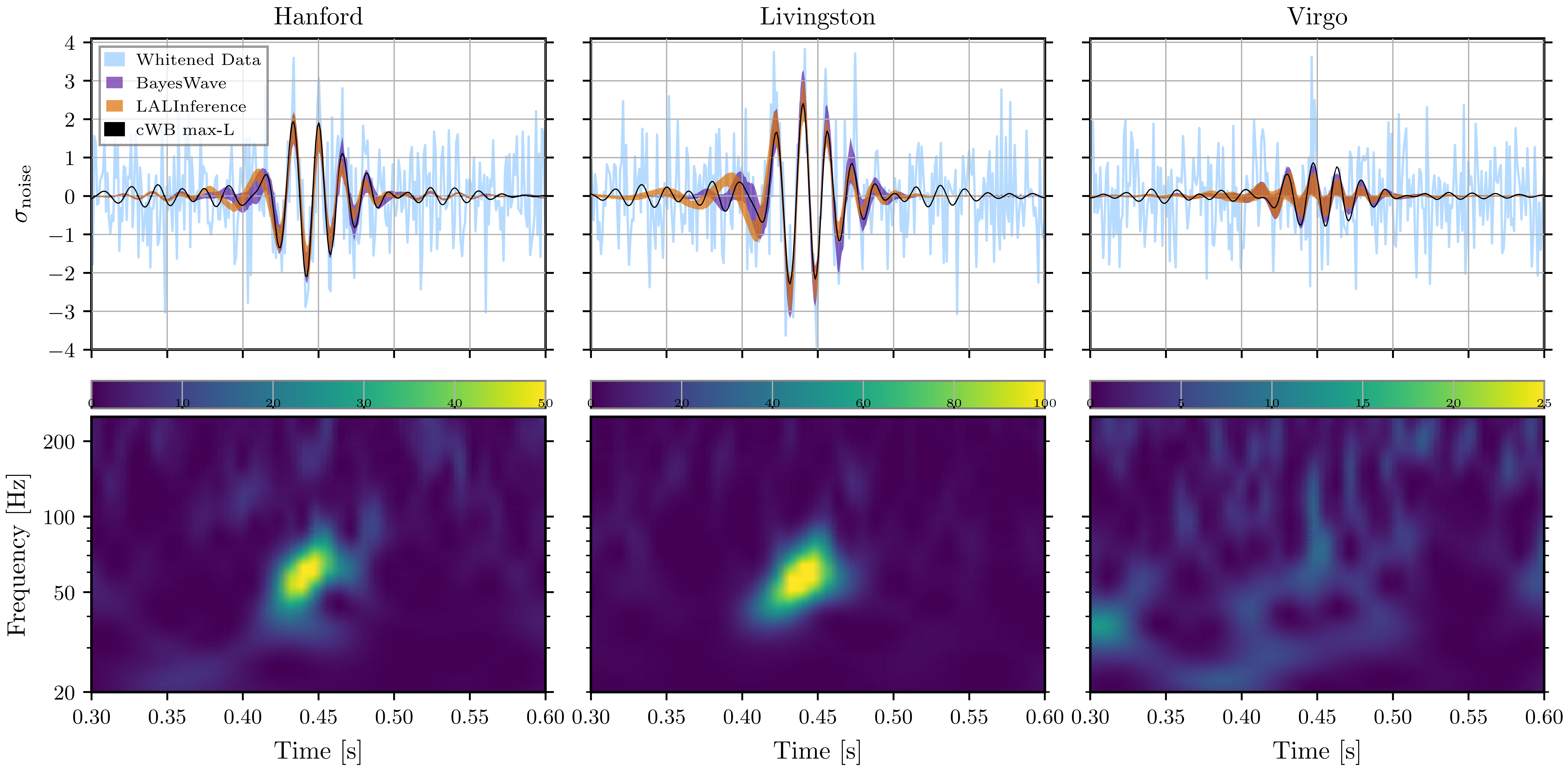
NSBH: GW230518





LVK, arXiv:2508.18082

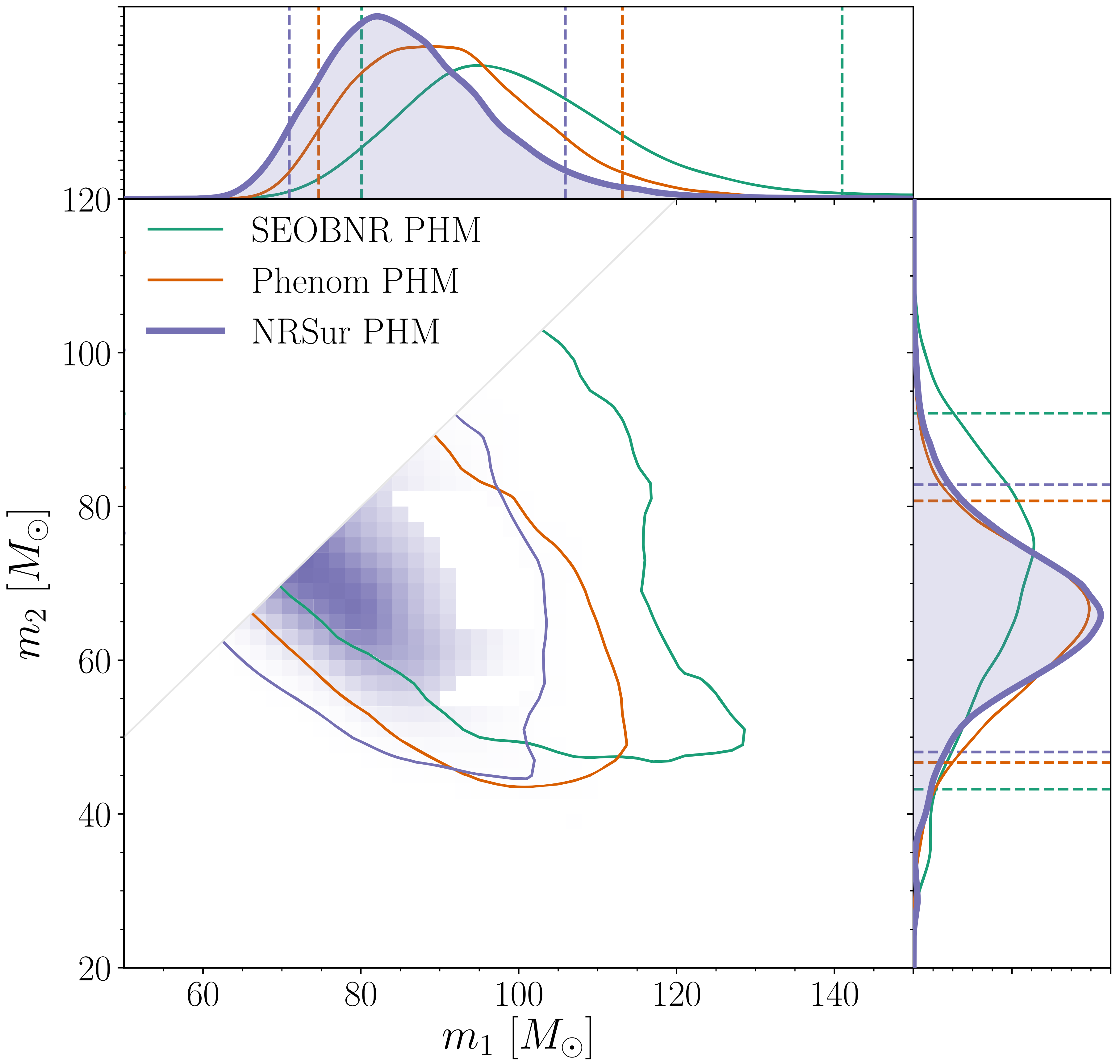
GW190521: A stand out in O3

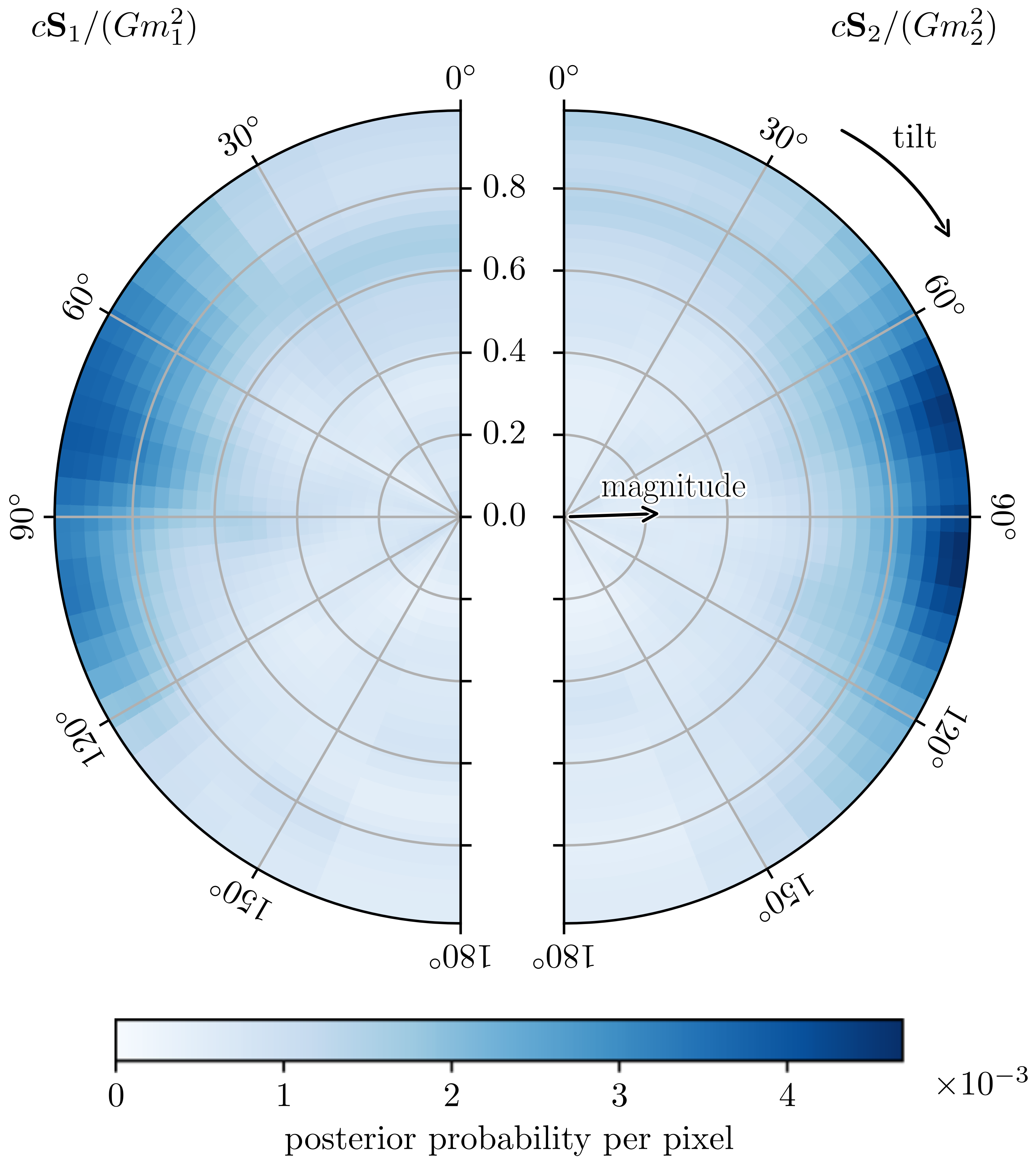


LVC PRL 125, 101102 (2020)
LVC, ApJL 900, L13 (2020)

GW190521: A stand out in O3

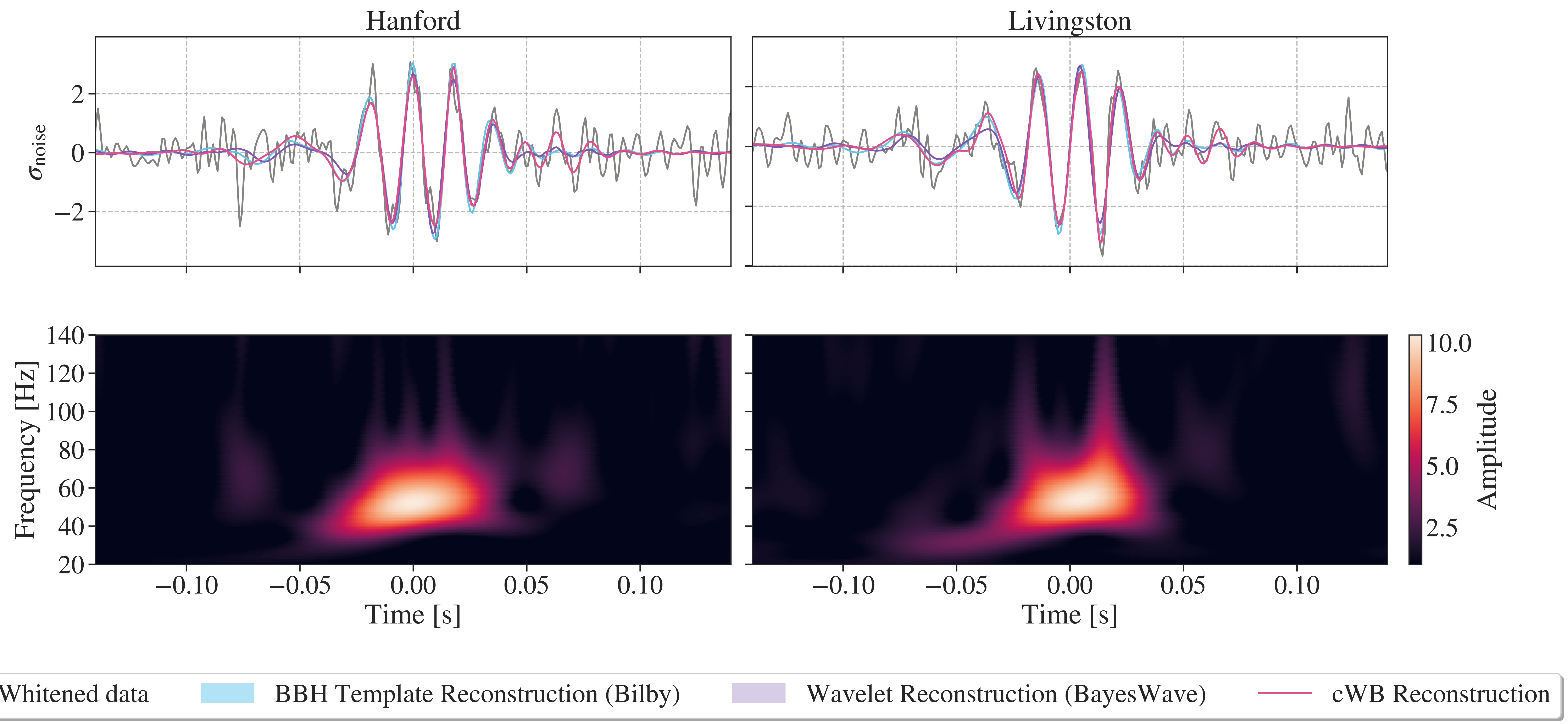
GW190521: Intermediate mass BH





LVC PRL 125, 101102 (2020)
LVC, ApJL 900, L13 (2020)

GW231123: Most massive BBH



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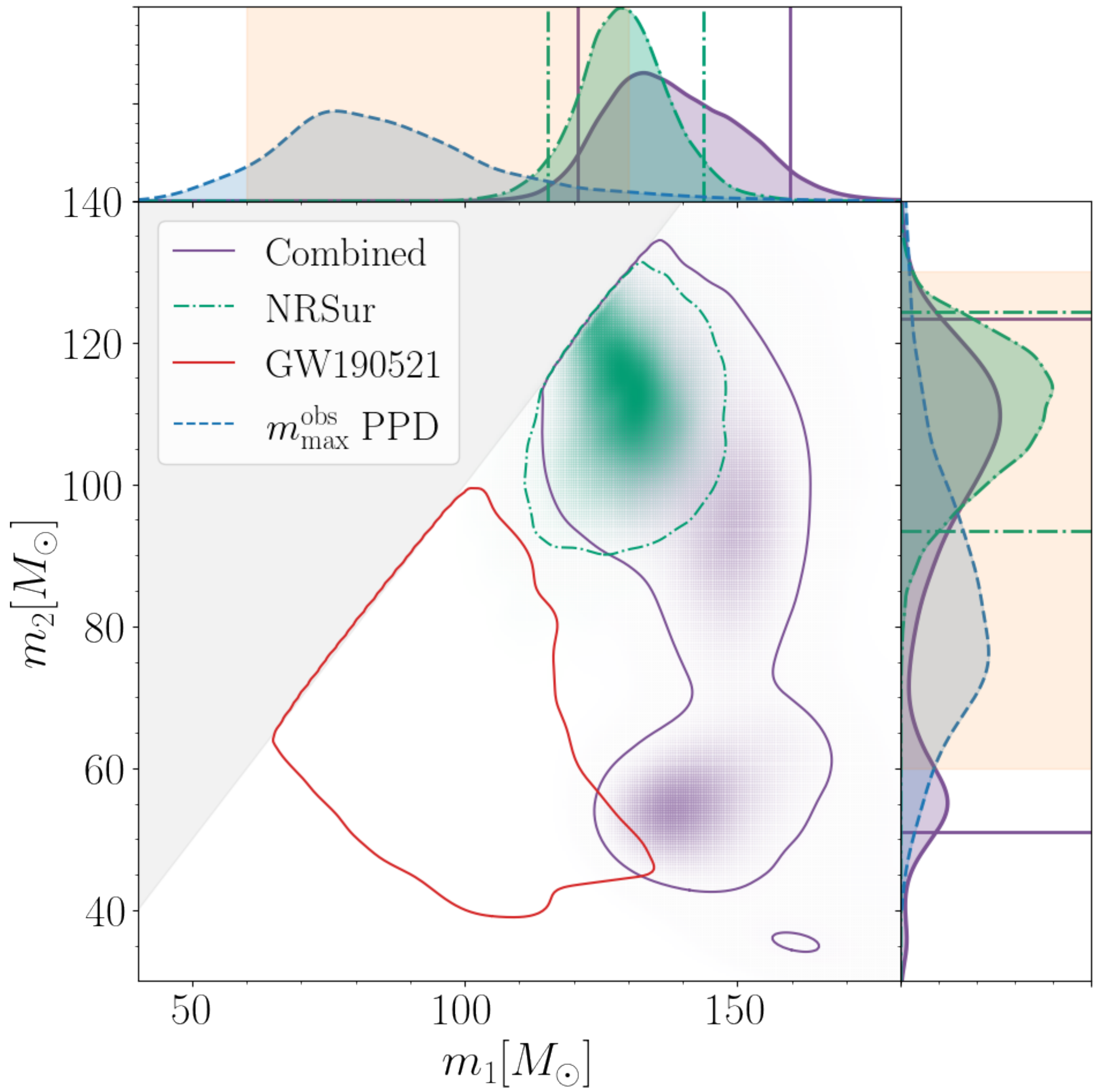
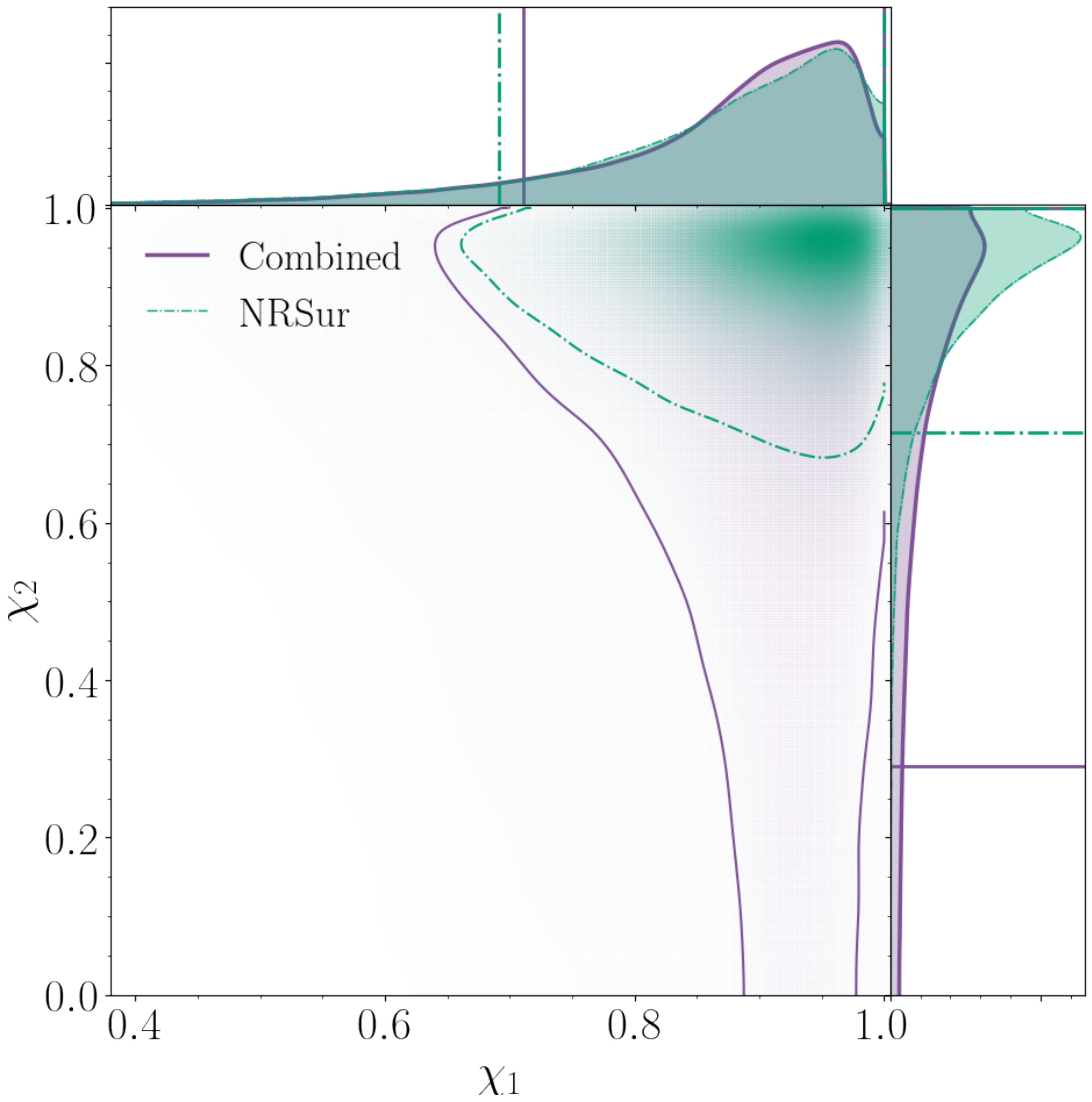
GW231123: Most massive BBH





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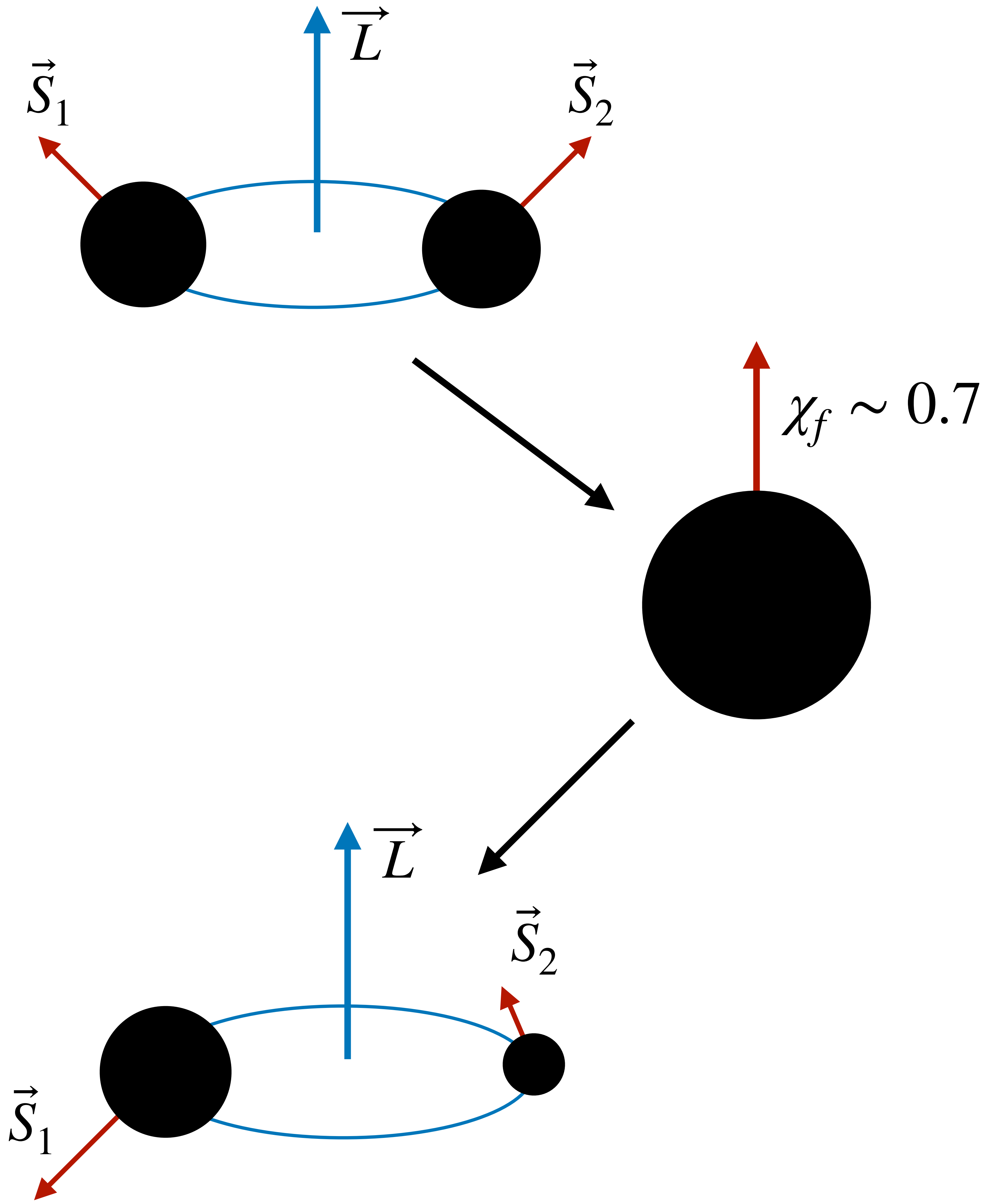
GW231123: Filling the mass gap

- Both components very massive, $m_1 \sim 137 M_\odot, m_2 \sim 103 M_\odot$
- Upper mass gap $\sim 40 - 130 M_\odot$:
  - Empty due to pair instability
- Hierarchical mergers from dynamically formed binaries one pathway
- Multiple mergers may be required for GW231123



LVK, 2507.08219

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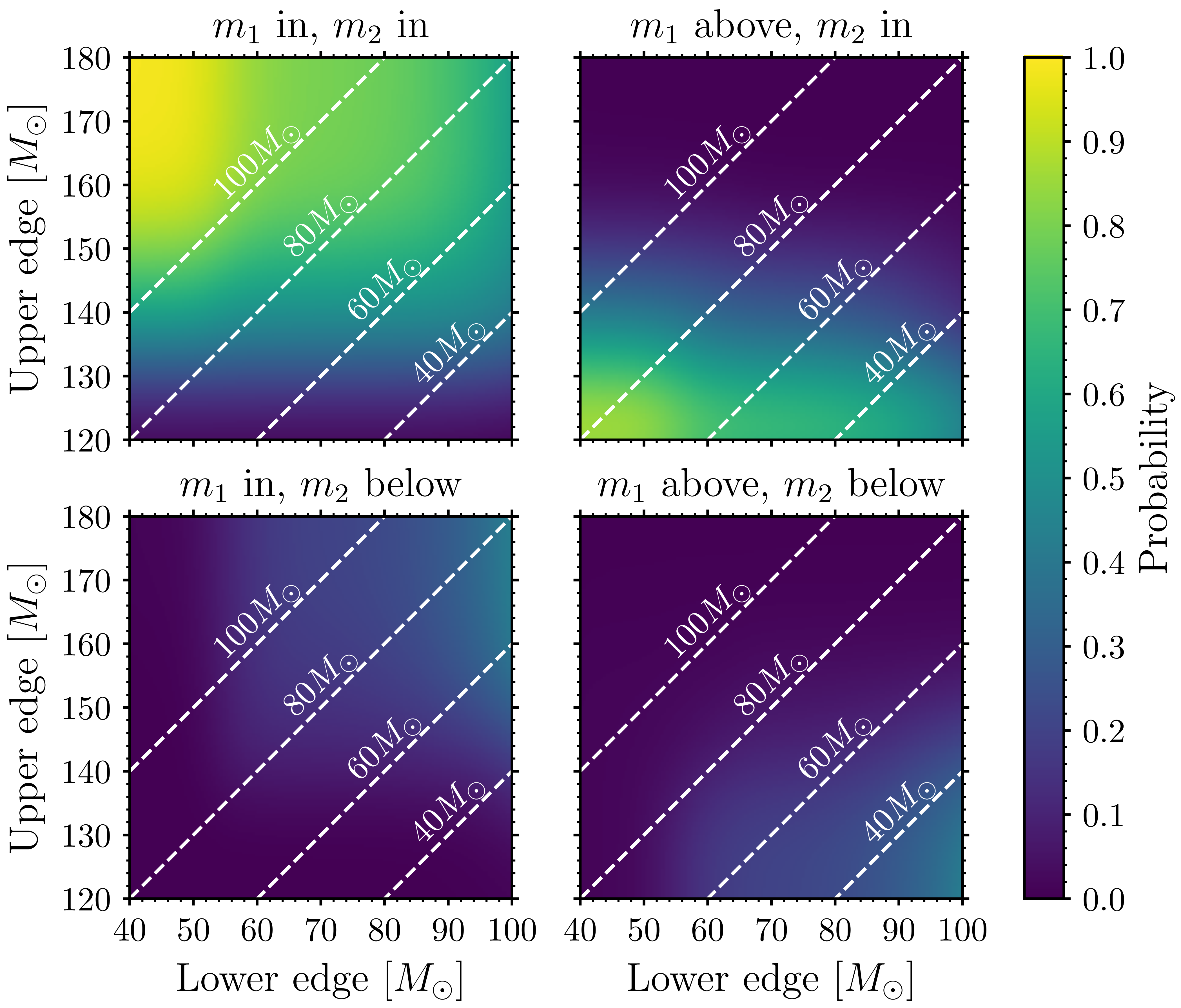

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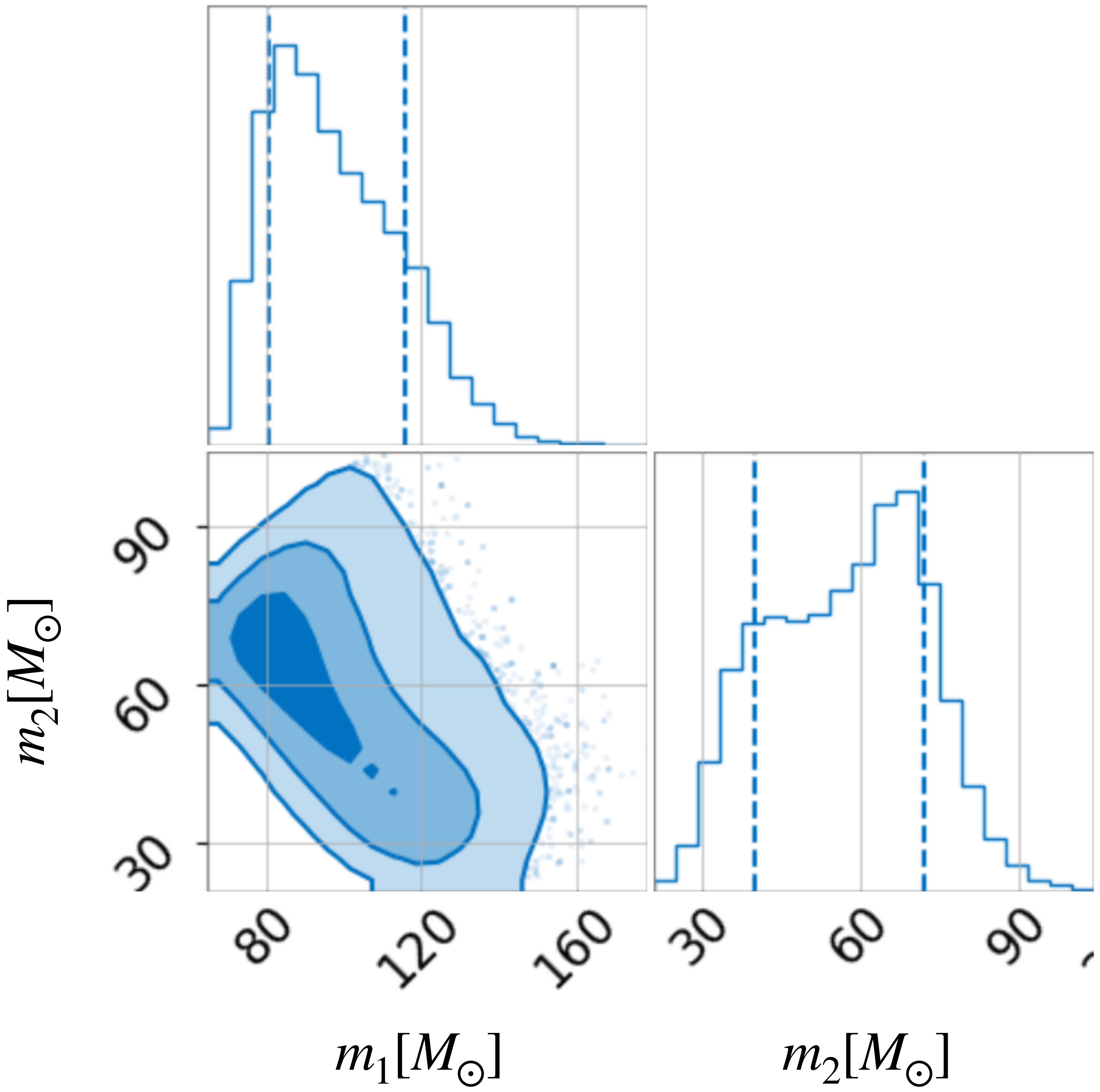
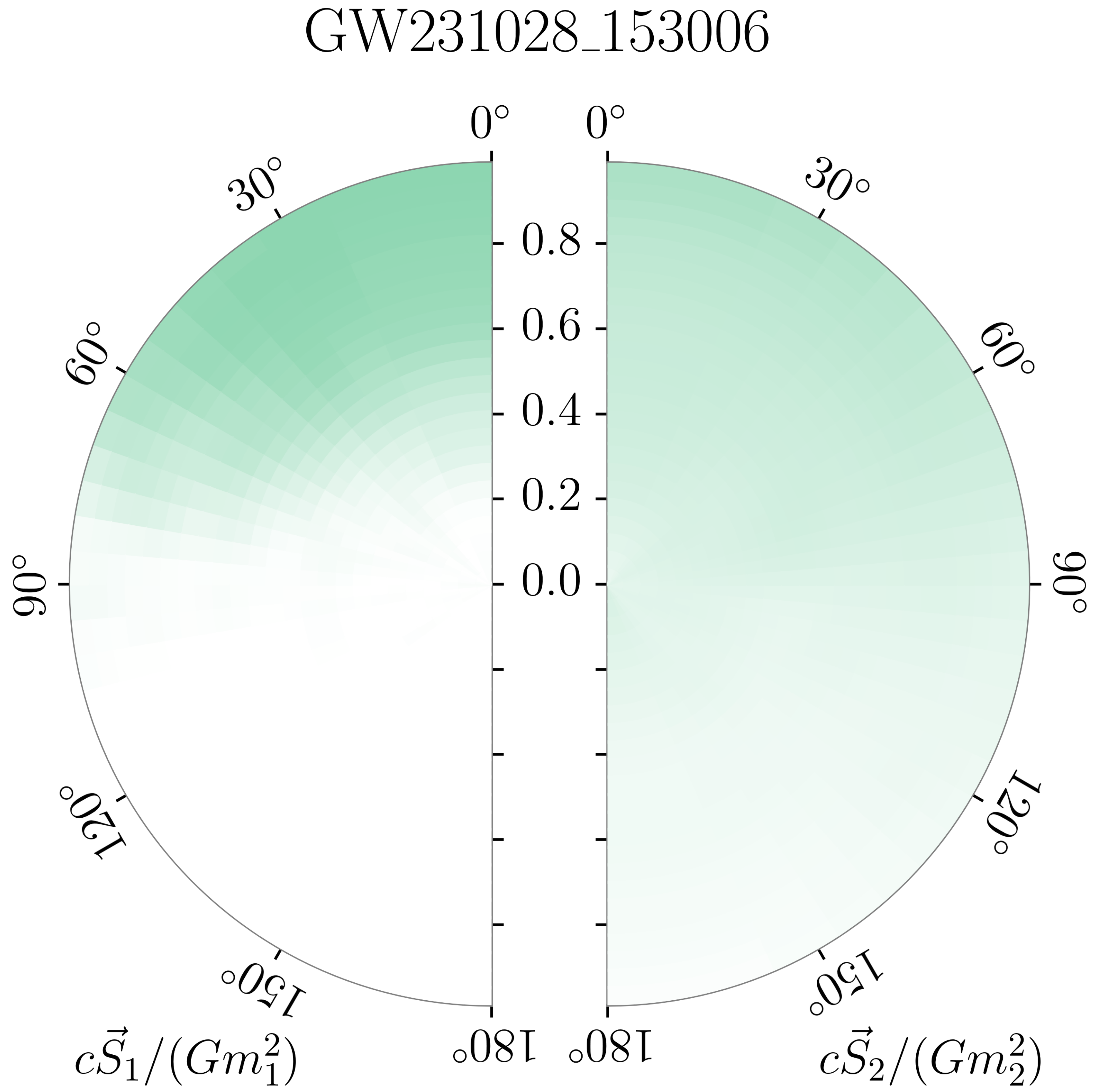
LVK, 2507.08219

GW231028: Massive and highly spinning





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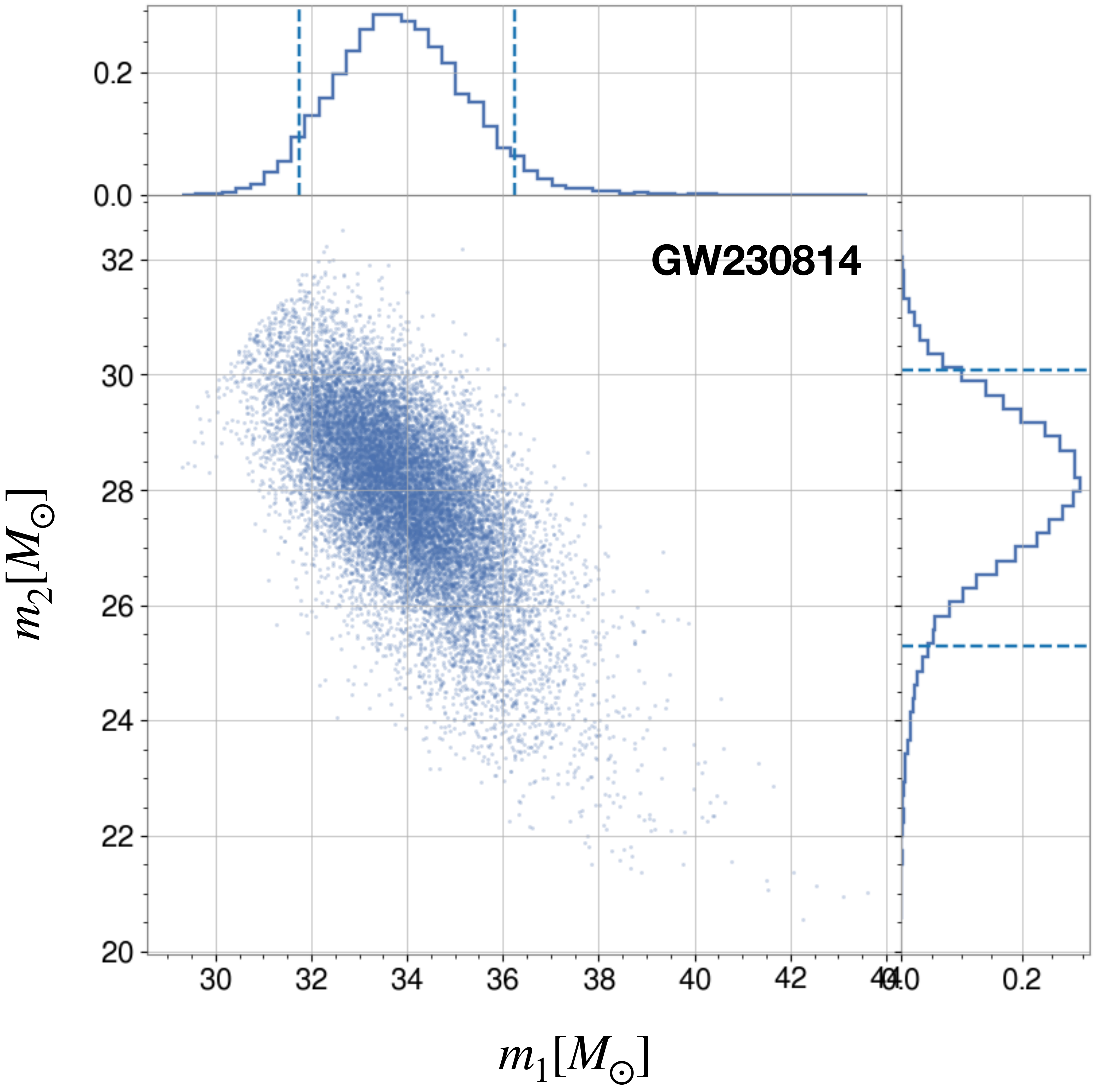
LVK, arXiv:2508.18082

High SNR BBHs

- Two BBHs with SNRs above 30
- GW230814_23: SNR ~ 42
  - Very “vanilla”, $M \sim 62\,M_{\odot}$ similar to GW150914
  - Spins constrained to be small
- GW231226: SNR ~ 34
  - Slightly more massive $M \sim 75\,M_{\odot}$
  - Prefers negative $\chi_{\rm eff}$



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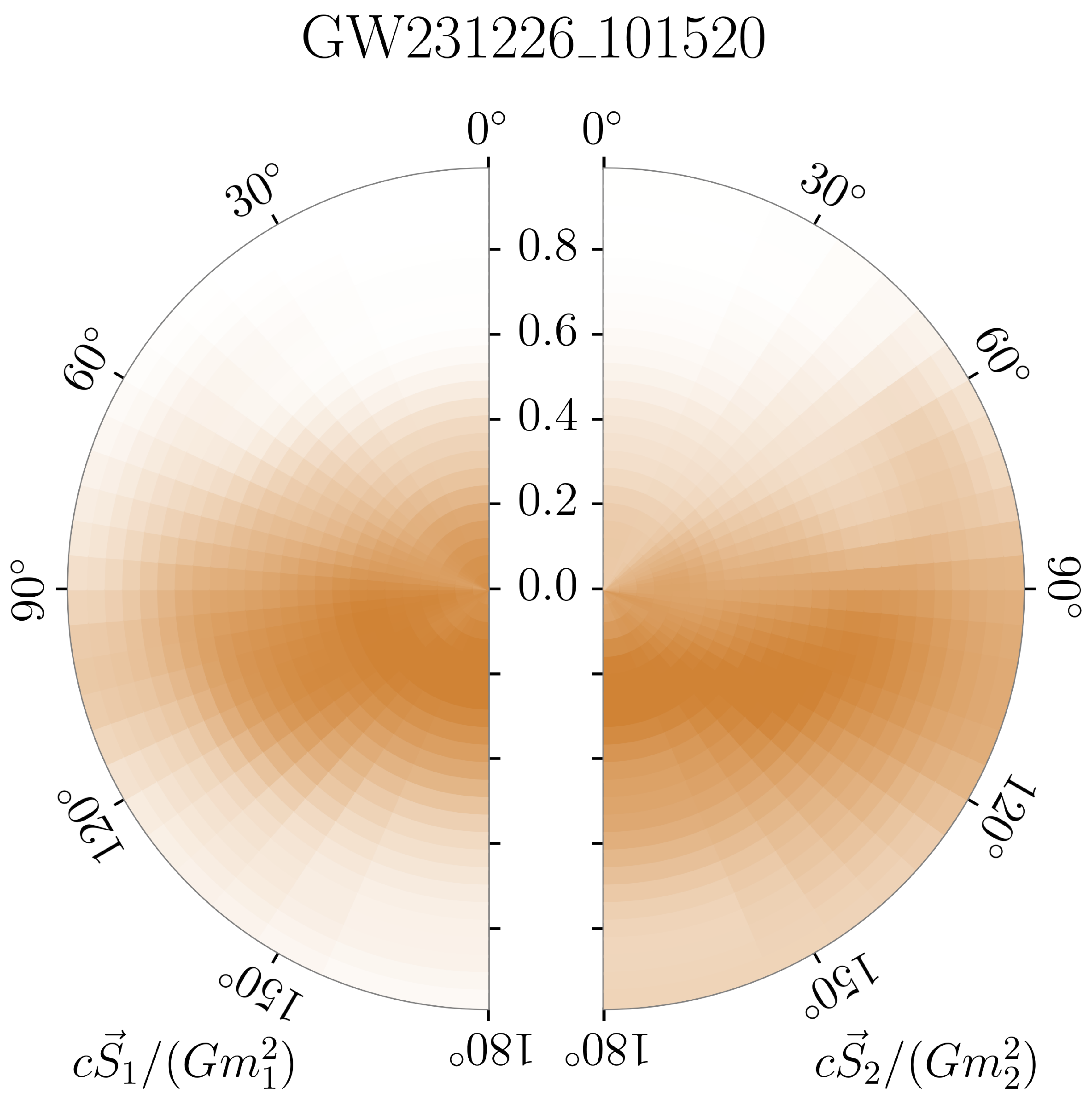
  - Spins constrained to be small
- GW231226: SNR ~ 34
  - Slightly more massive $M \sim 75\, M_{\odot}$
  - Prefers negative $\chi_{\rm eff}$



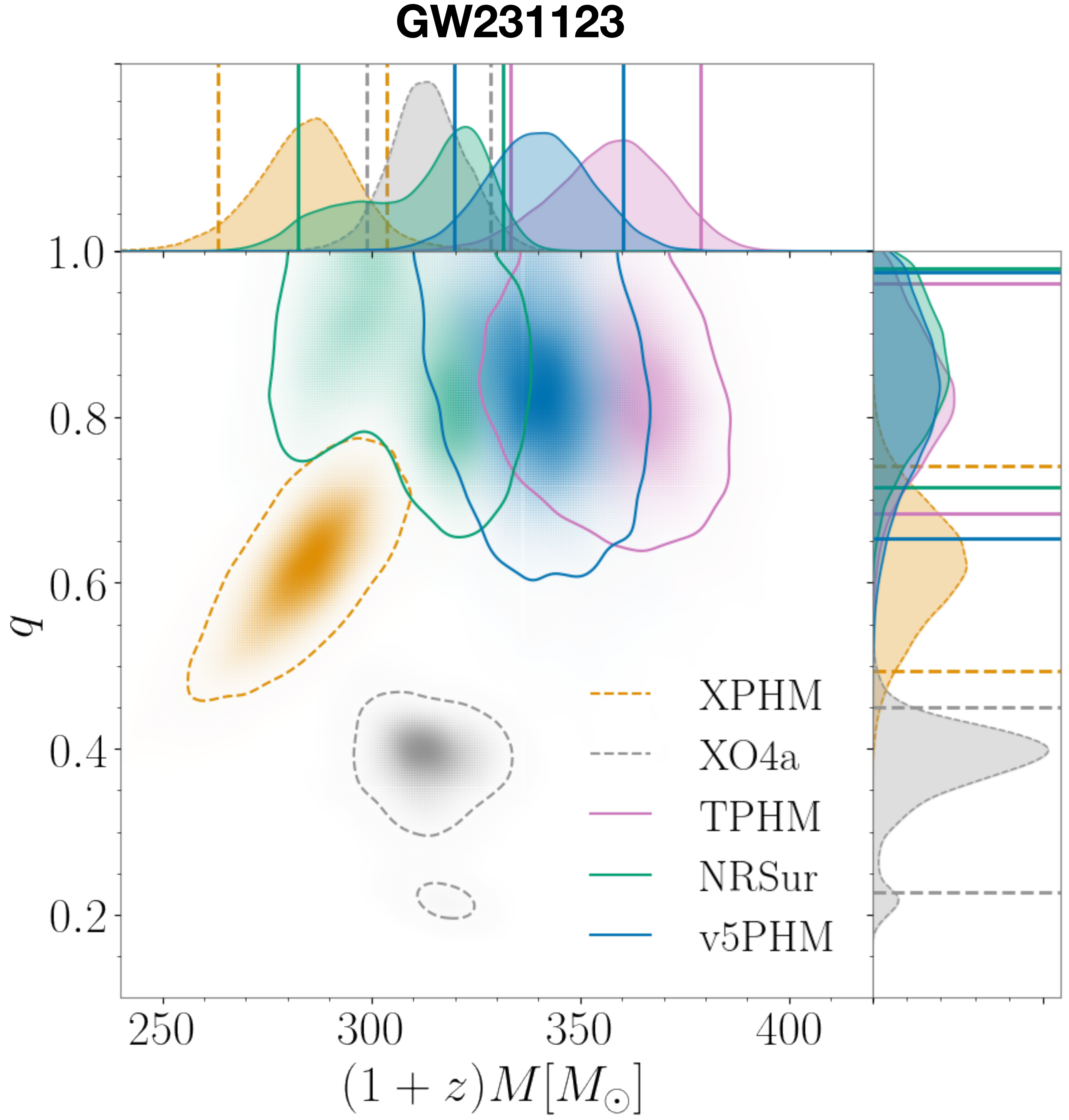
LVK, arXiv:2508.18082

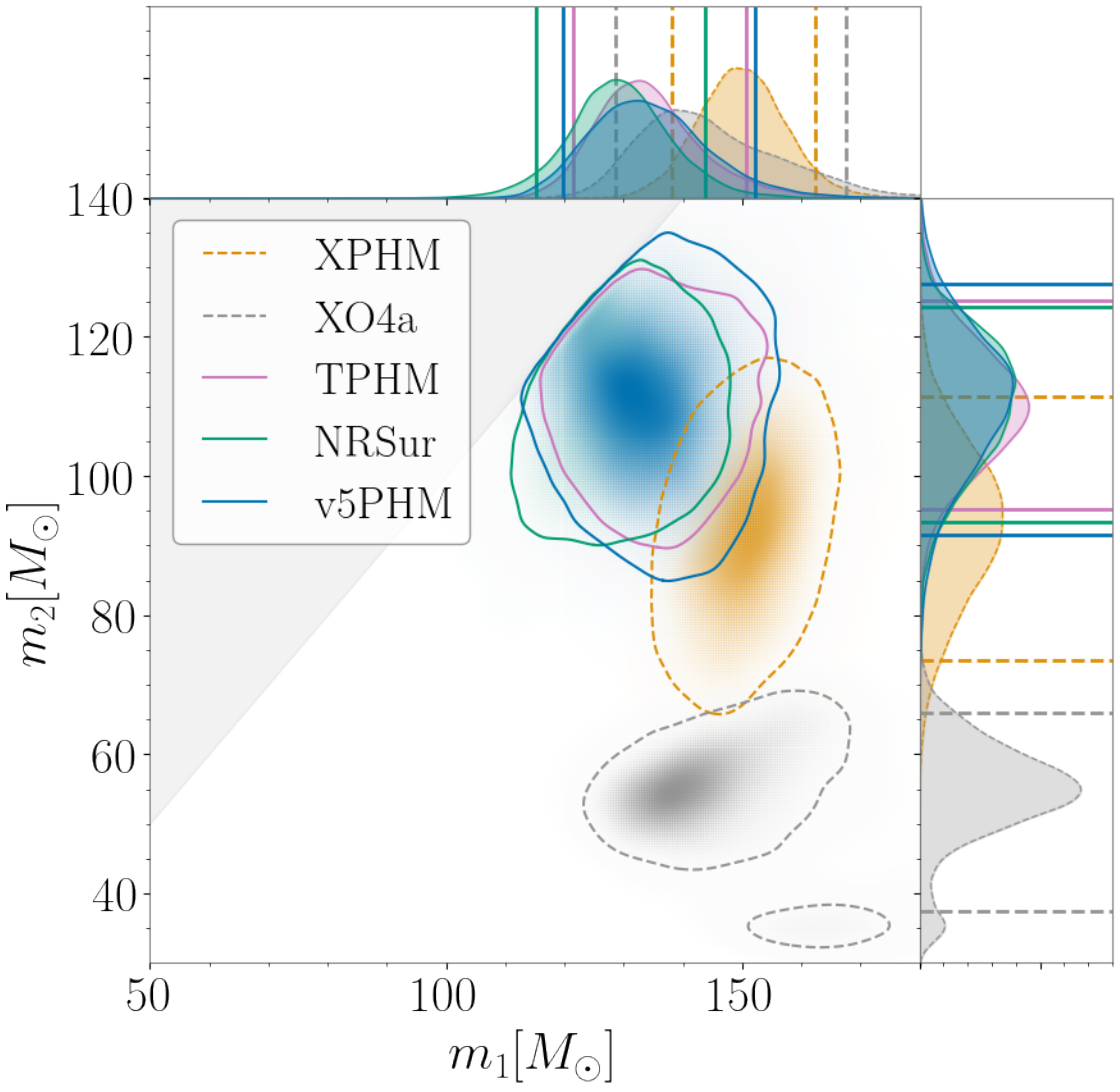
More events, new challenges

- GWTC-4.0 contains more high SNR events, events that expand observed parameter space
  - High spins, high masses, possibly strong precession
  - Some events push the limits of our models: strong systematic uncertainties
- Uncovered analysis issues with percent-level impact
  - Issues with calibration marginalization
  - Issues with treatment of windowing corrections for GW data

LVK, arXiv:2508.18081

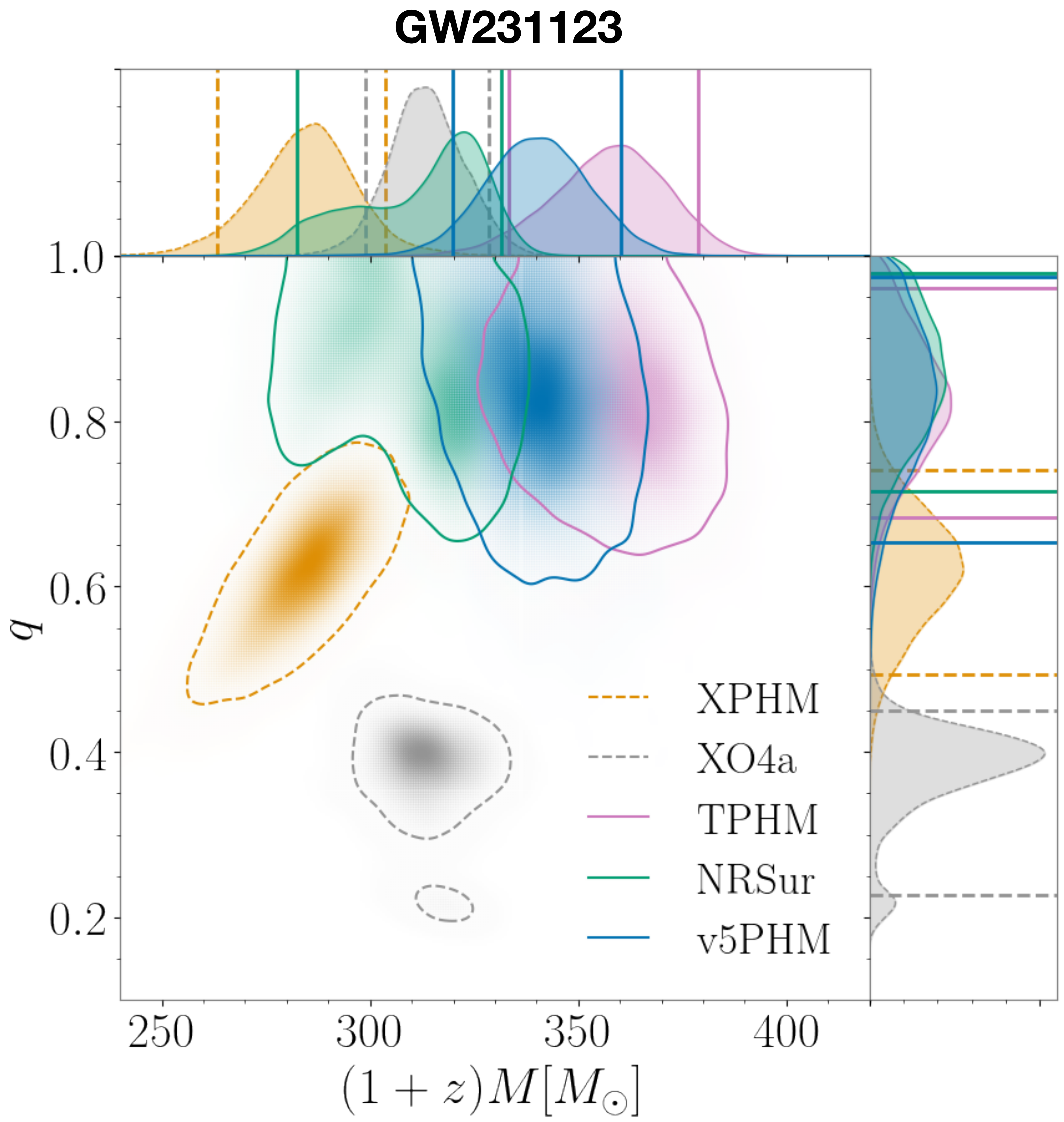
Systematic uncertainties: GW231123

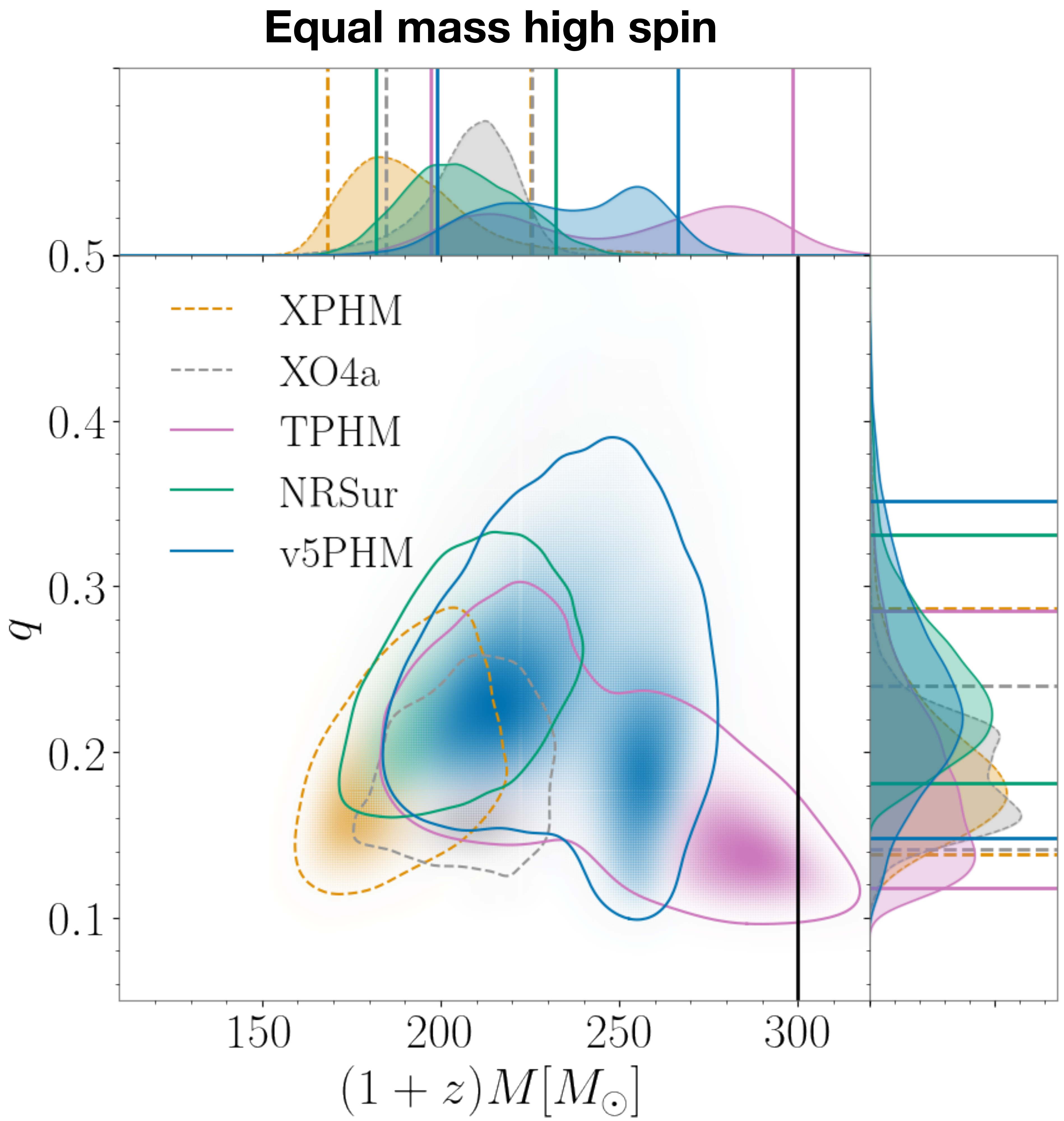




LVK 2507.08219

Systematic uncertainties: GW231123

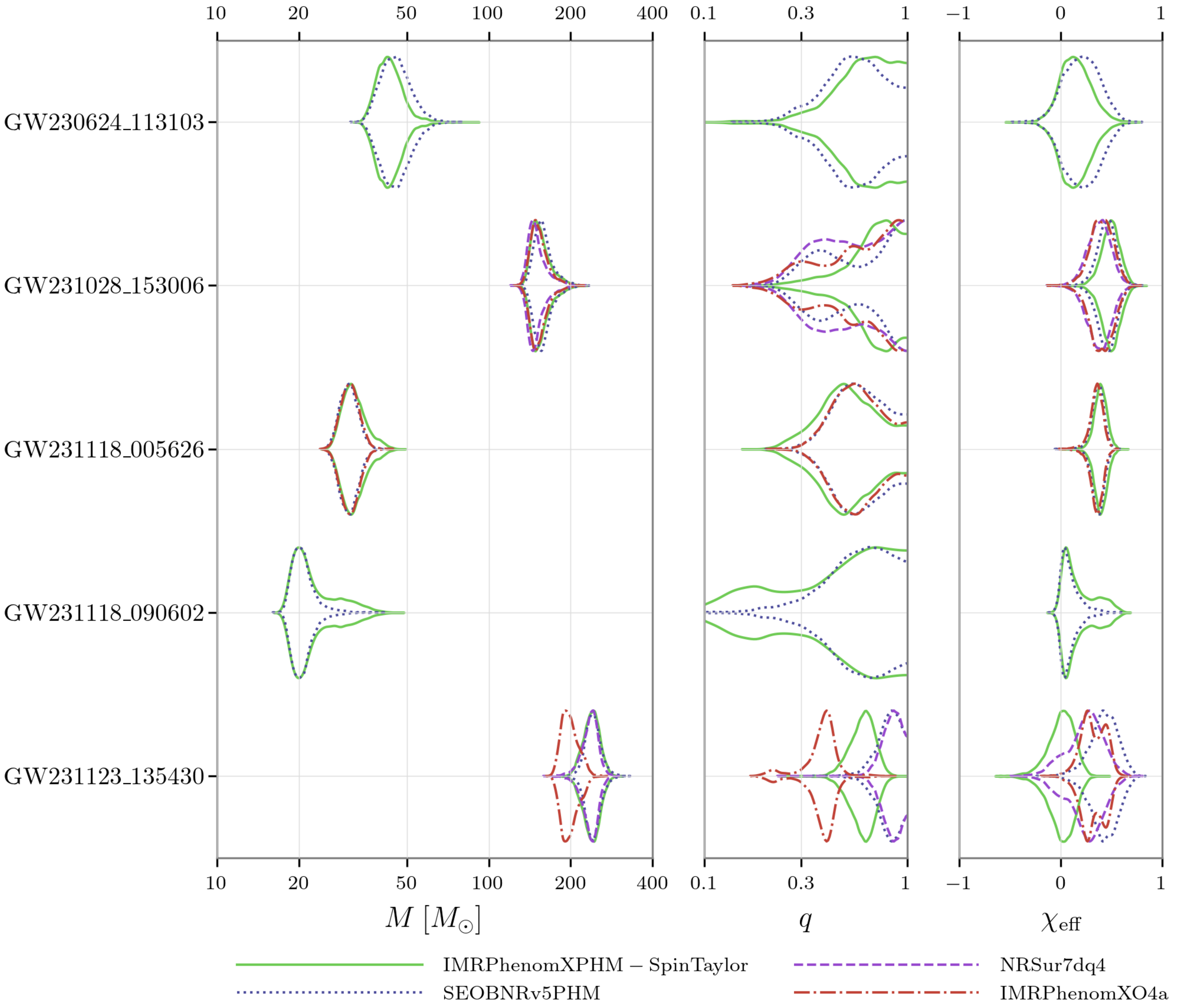




LVK 2507.08219

SXS:BBH:4030
Scheel + (2025)

Systematic uncertainties: GWTC-4.0



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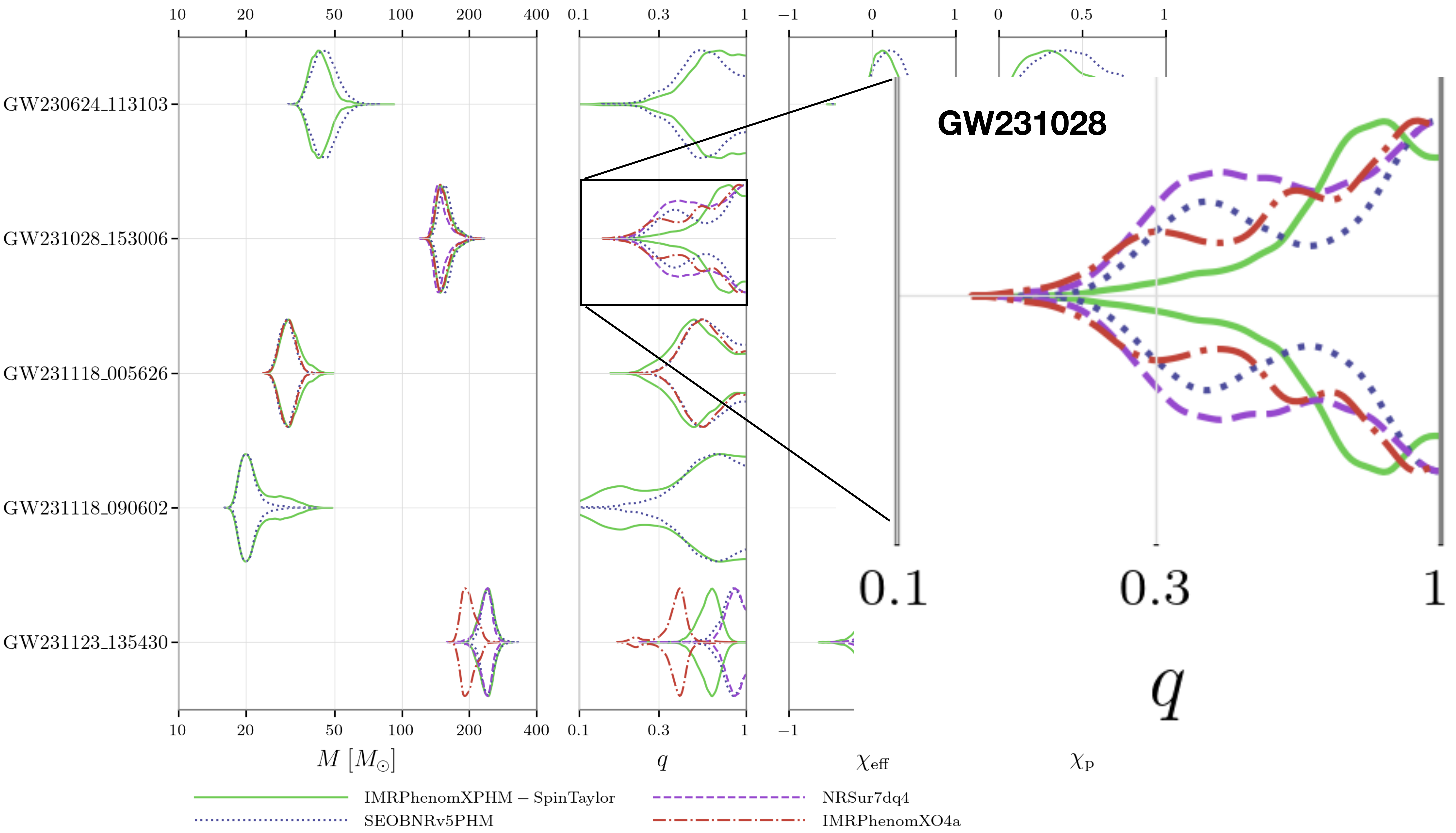
LVK, arXiv:2508.18082

Systematic uncertainties: GWTC-4.0



LVK, arXiv:2508.18082

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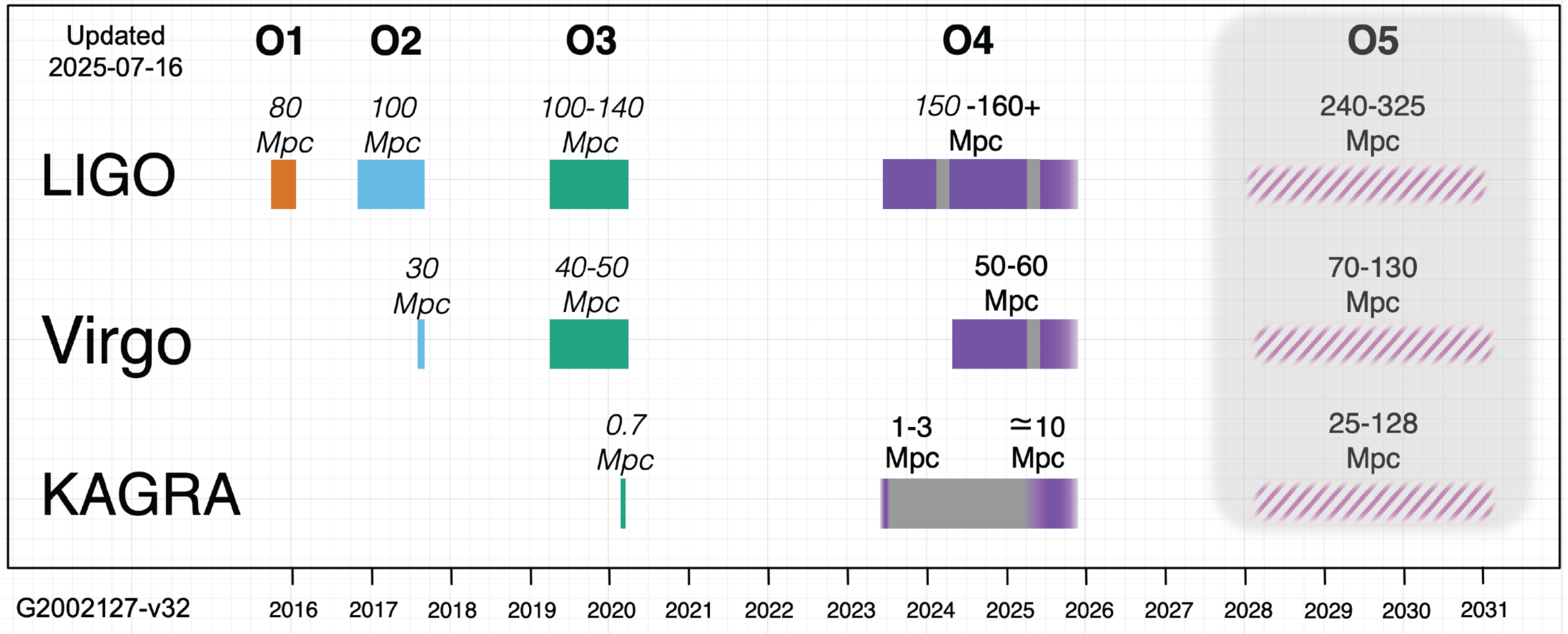
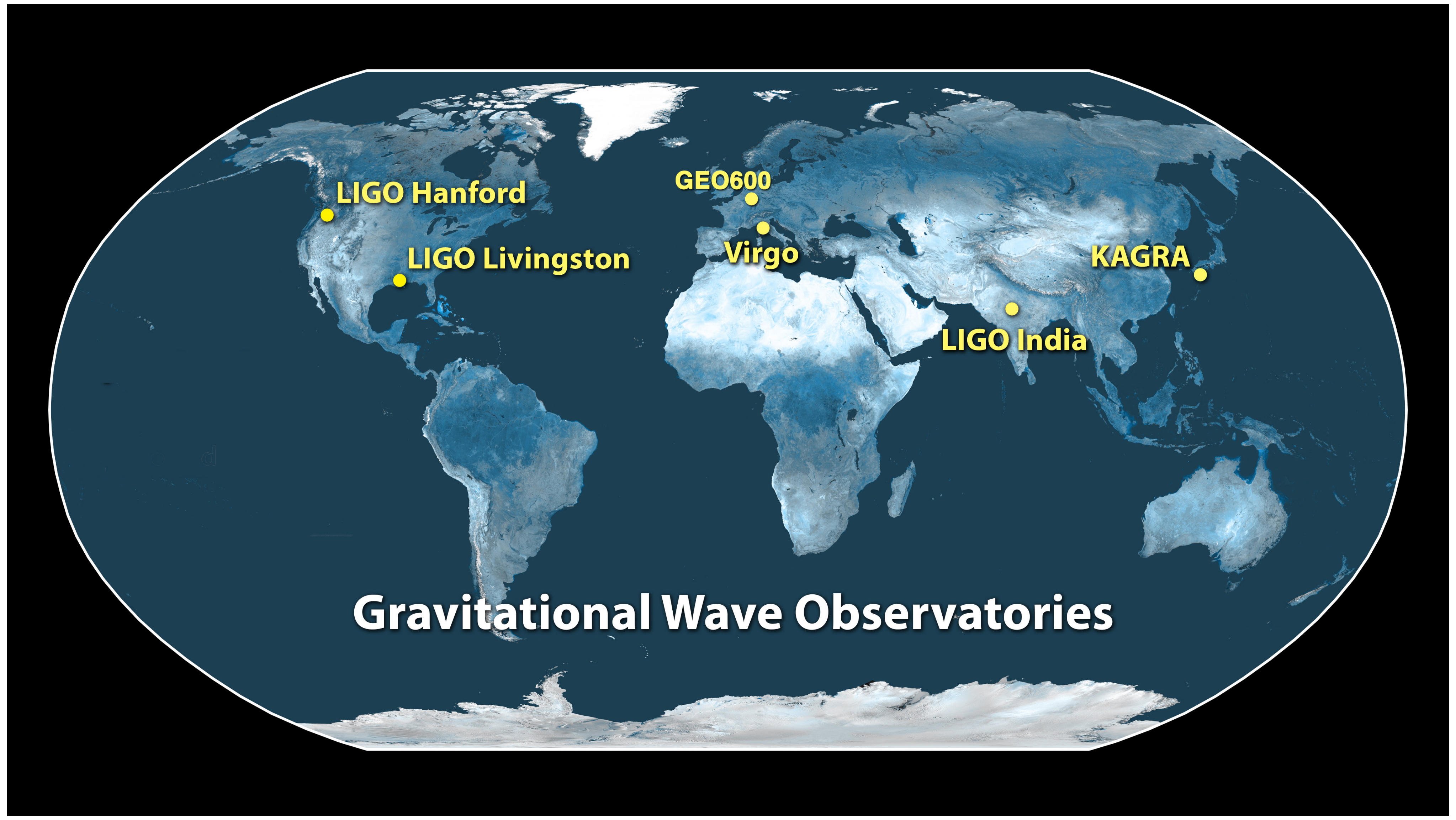
Looking ahead

Summary and Outlook

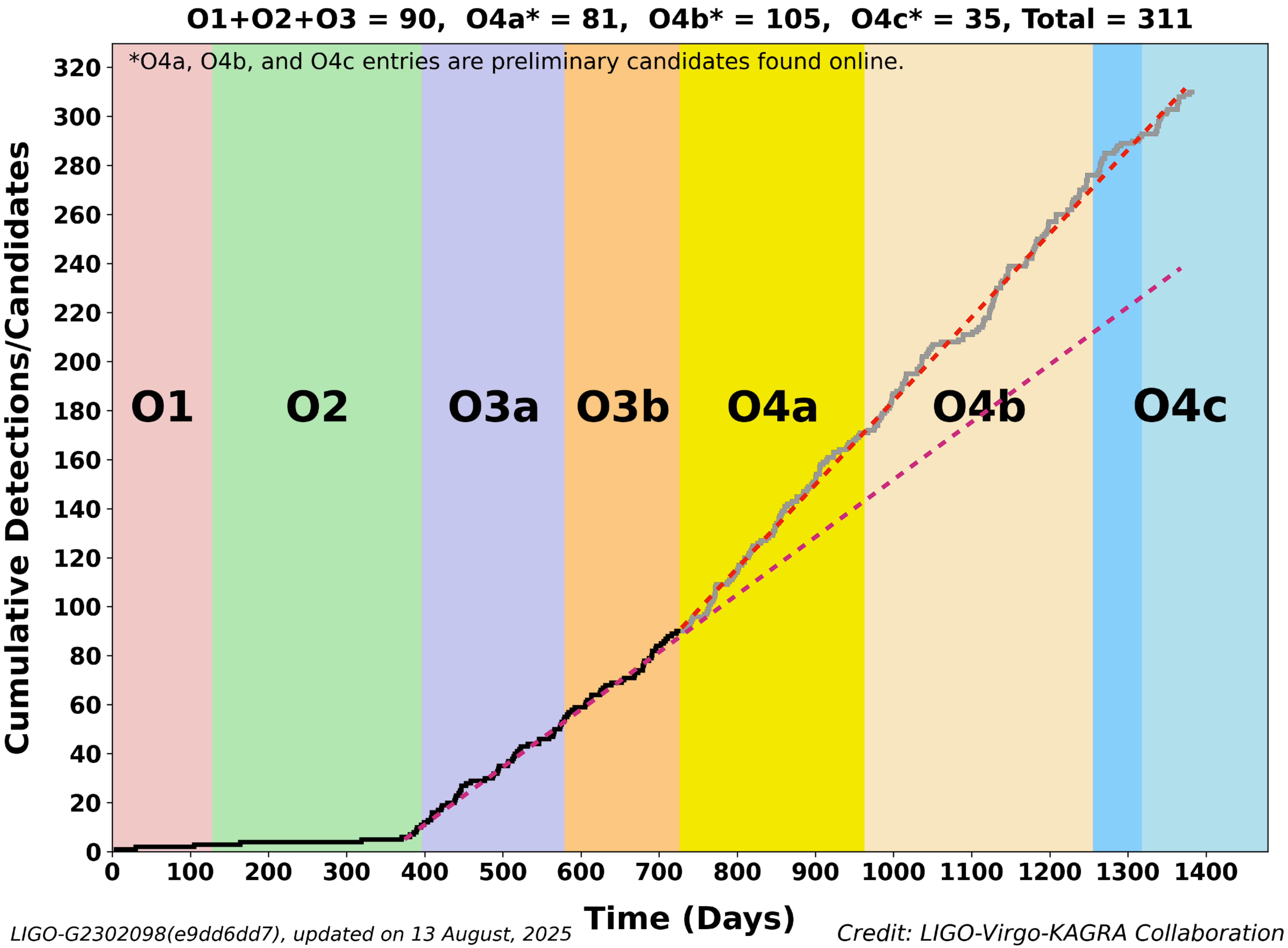
- GWTC-4.0: 128 new candidate signals
  - Detailed source parameters of 86
- O4b completed, O4c ongoing
  - 224 low latency candidates announced
- Coming years: detectors expected to exceed design sensitivity, growing network
  - Detect many more events, louder signals

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





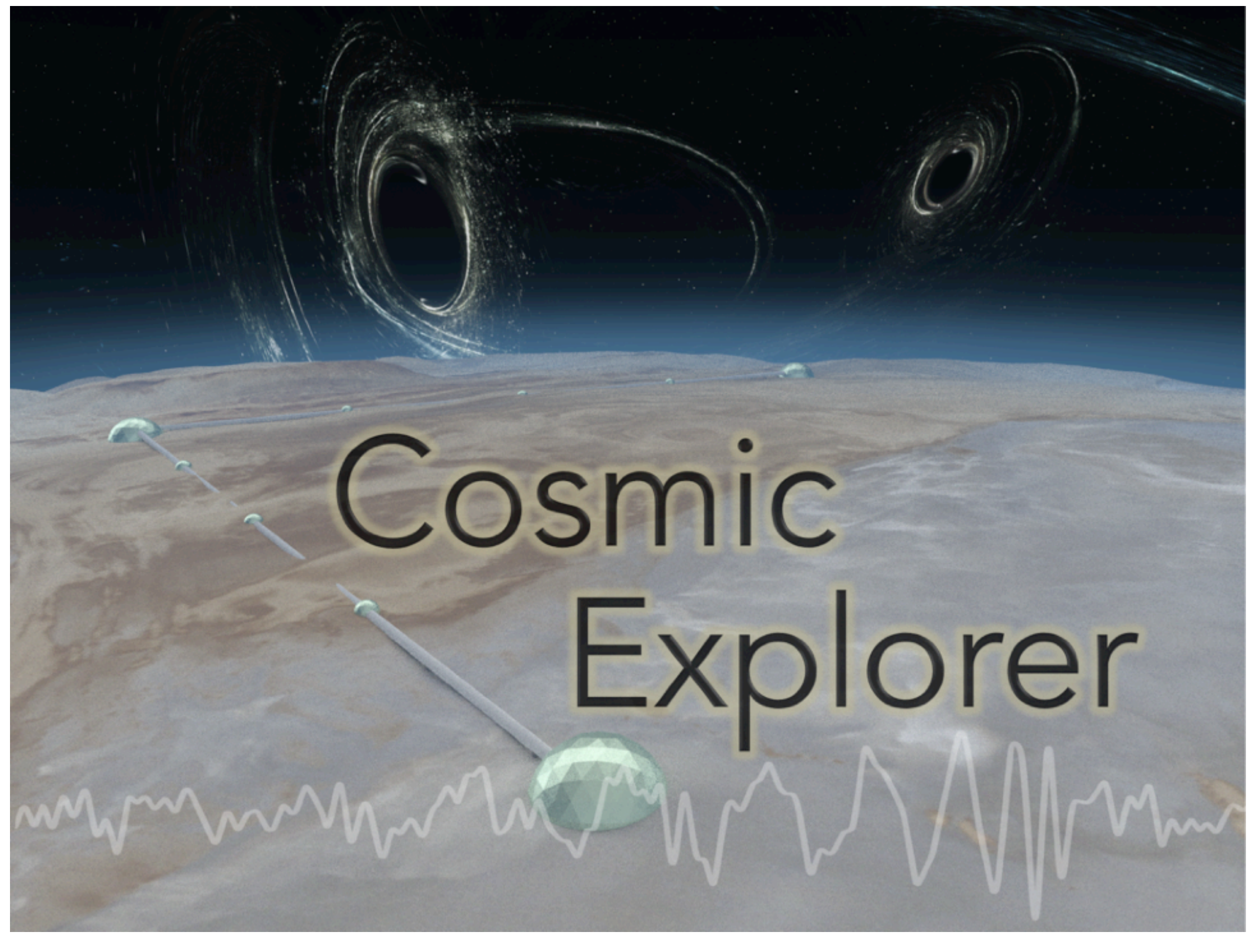
Detections to date

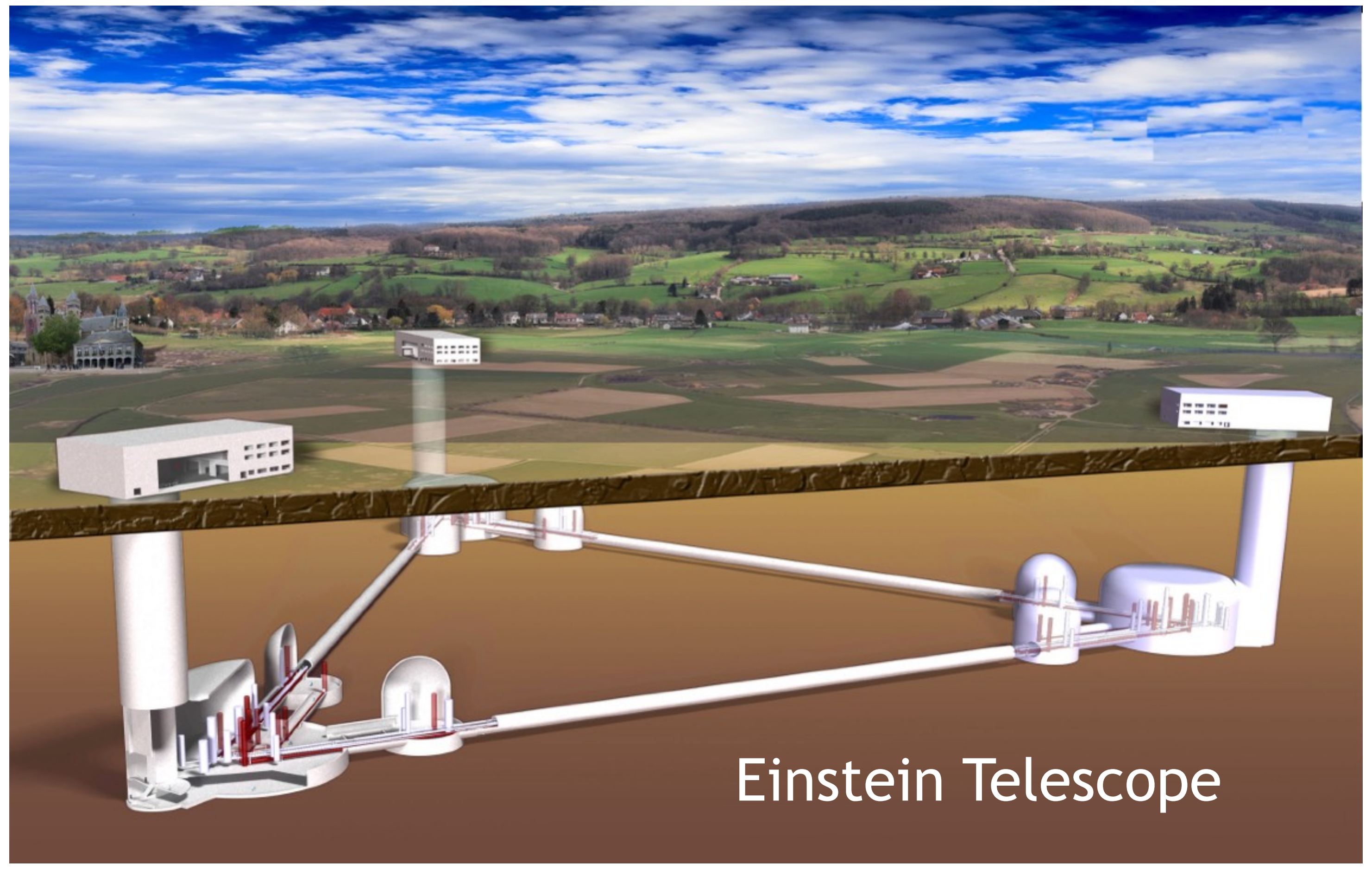


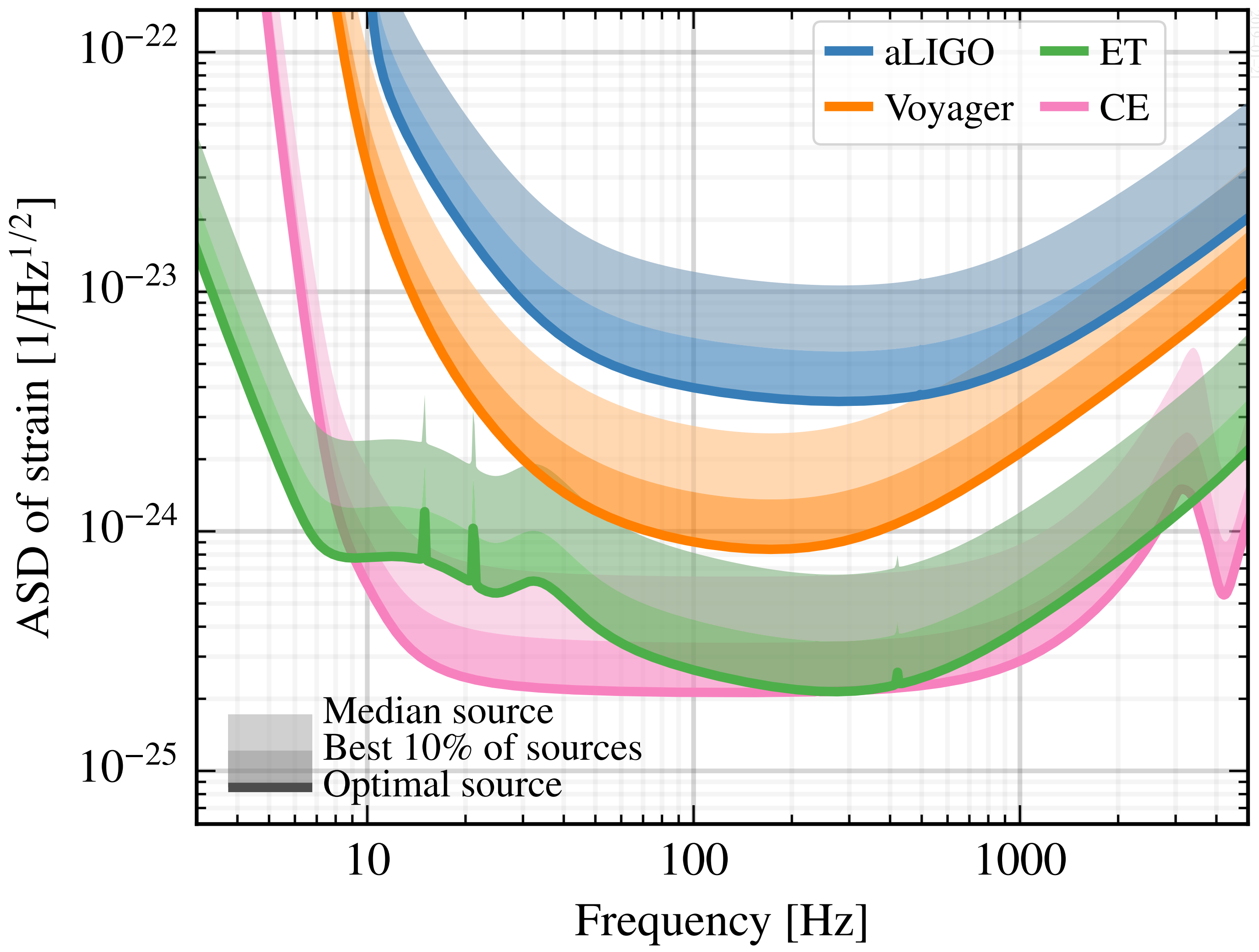
LIGO-G2302098(e9dd6dd7), updated on 13 August, 2025

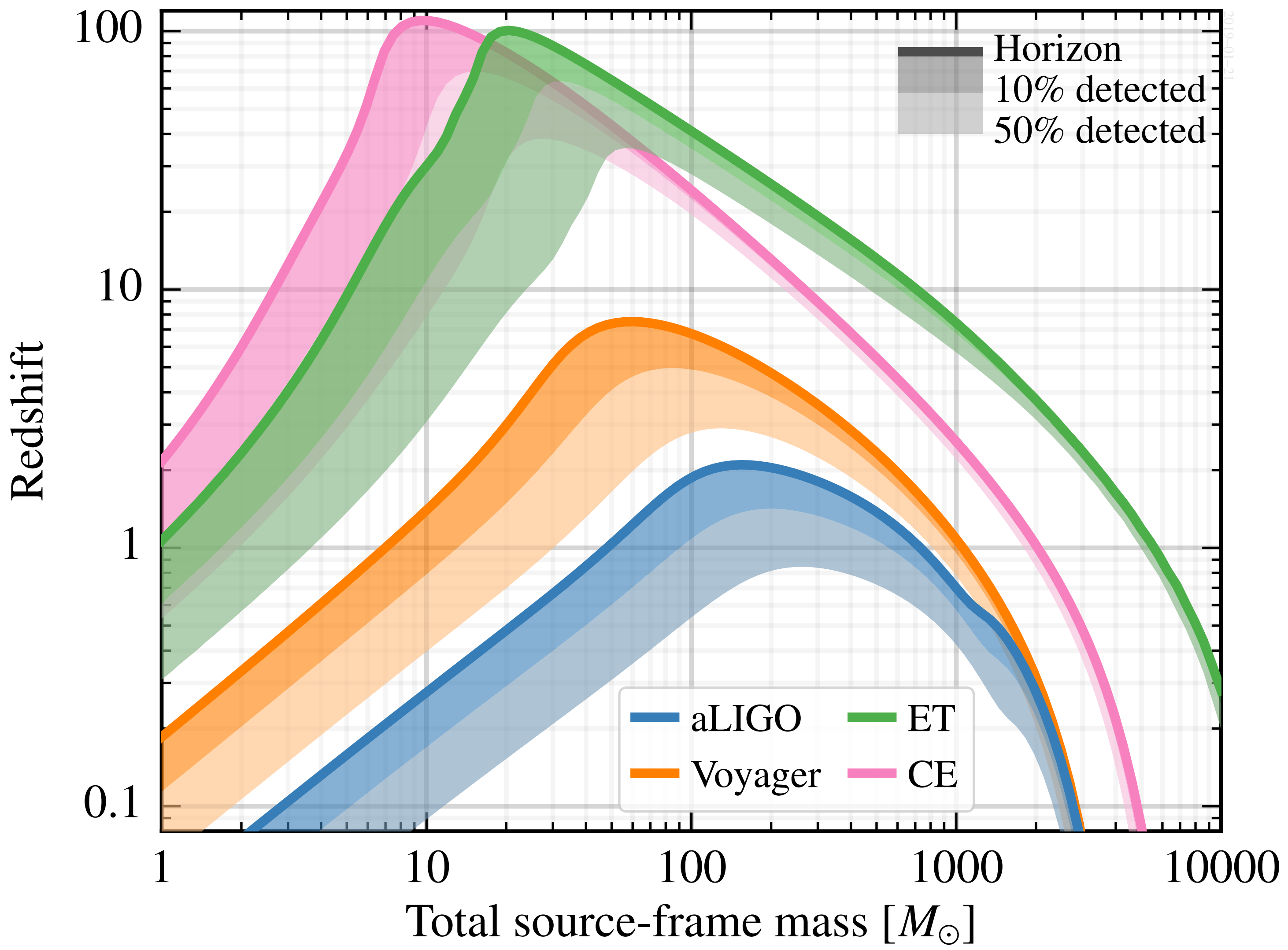
Credit: LIGO-Virgo-KAGRA Collaboration

3rd Generation Detectors









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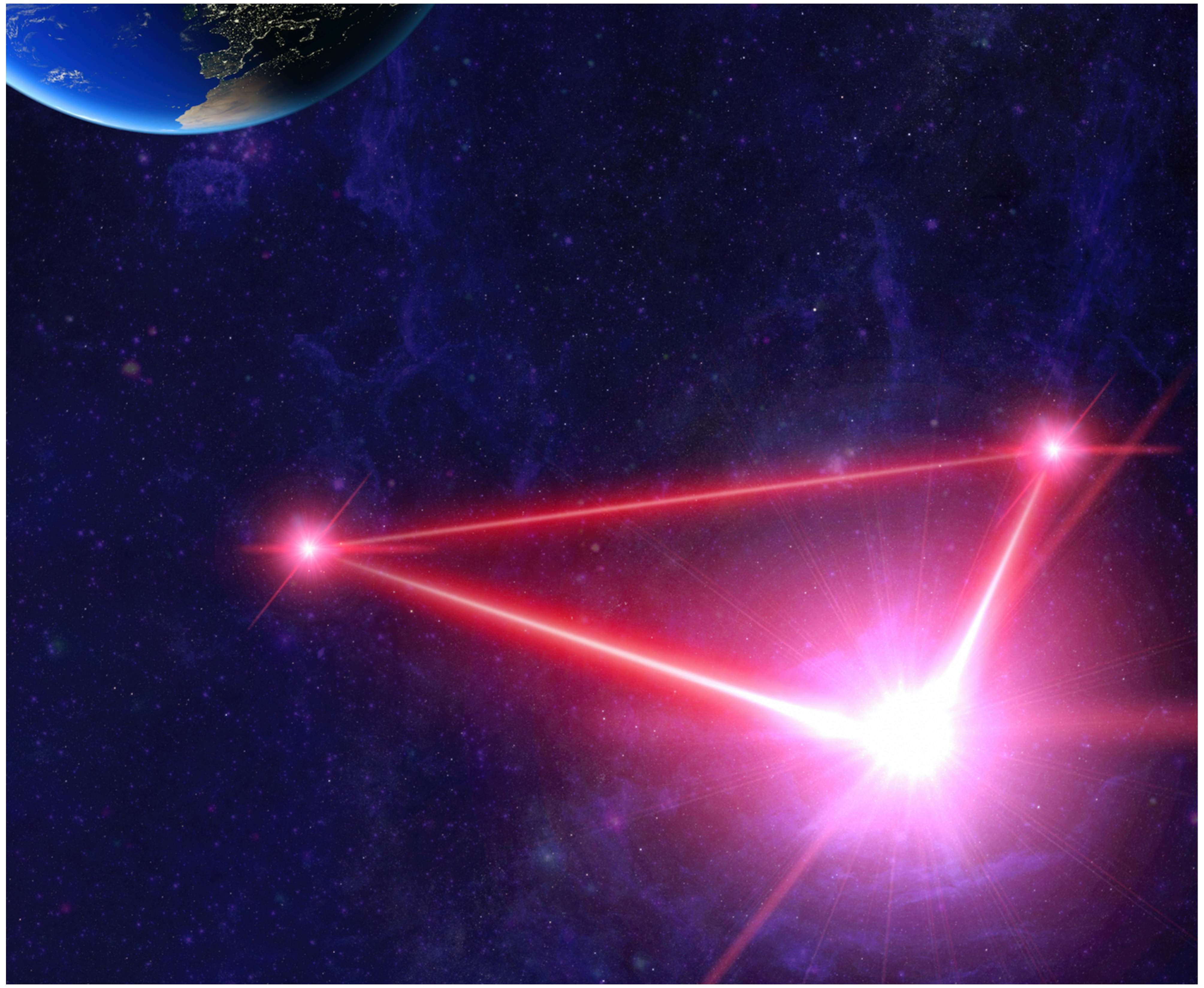
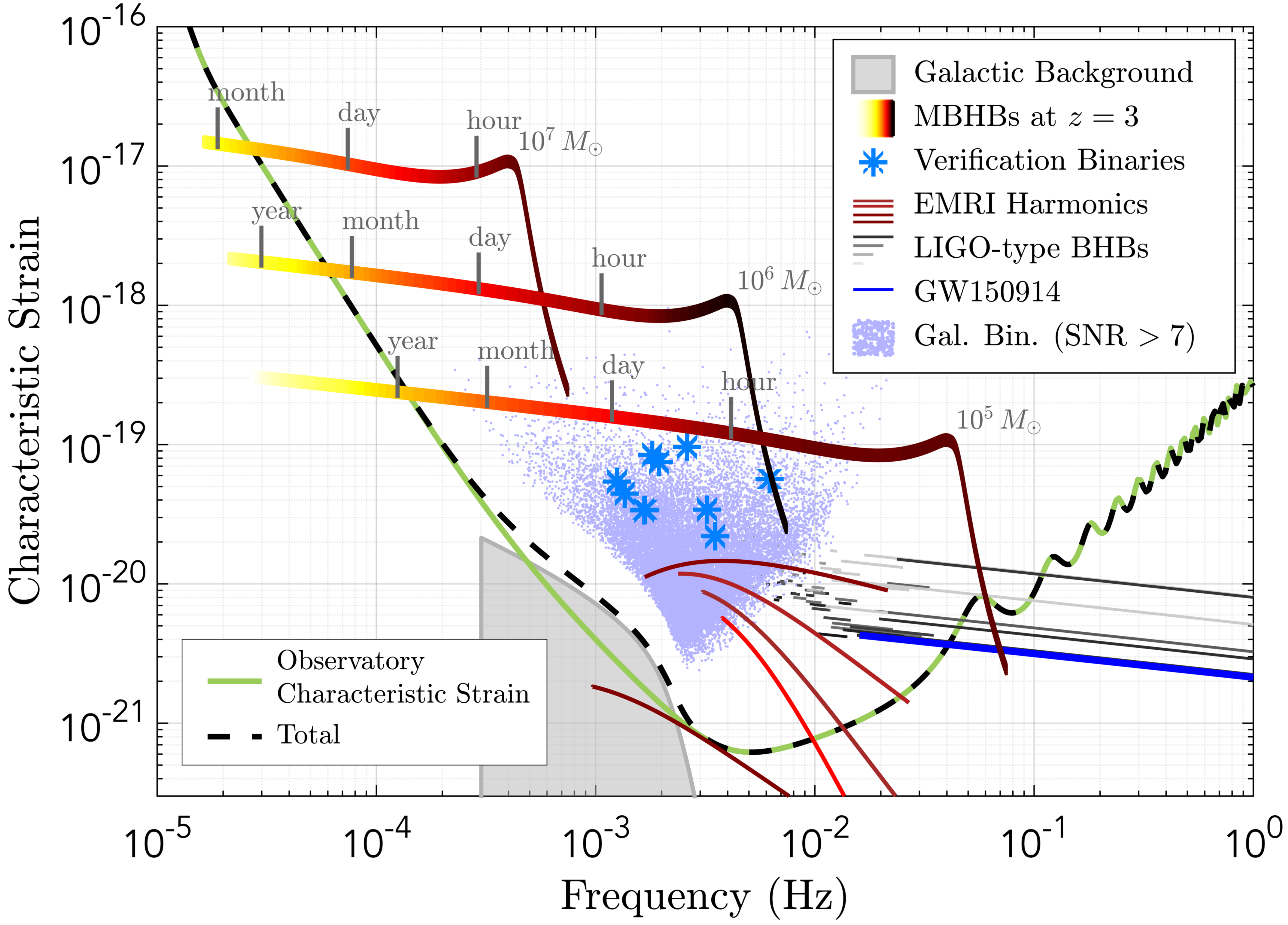
Hall, Evans, CQG 36 225002 (2019)

LISA





Characteristic Strain
Frequency (Hz)
Galactic Background
MBHBs at $z = 3$
Verification Binaries
EMRI Harmonics
LIGO-type BHBs
GW150914
Gal. Bin. (SNR > 7)
Observatory Characteristic Strain
Total
$10^7 M_\odot$
$10^6 M_\odot$
$10^5 M_\odot$
month
day
hour
year

Thank you

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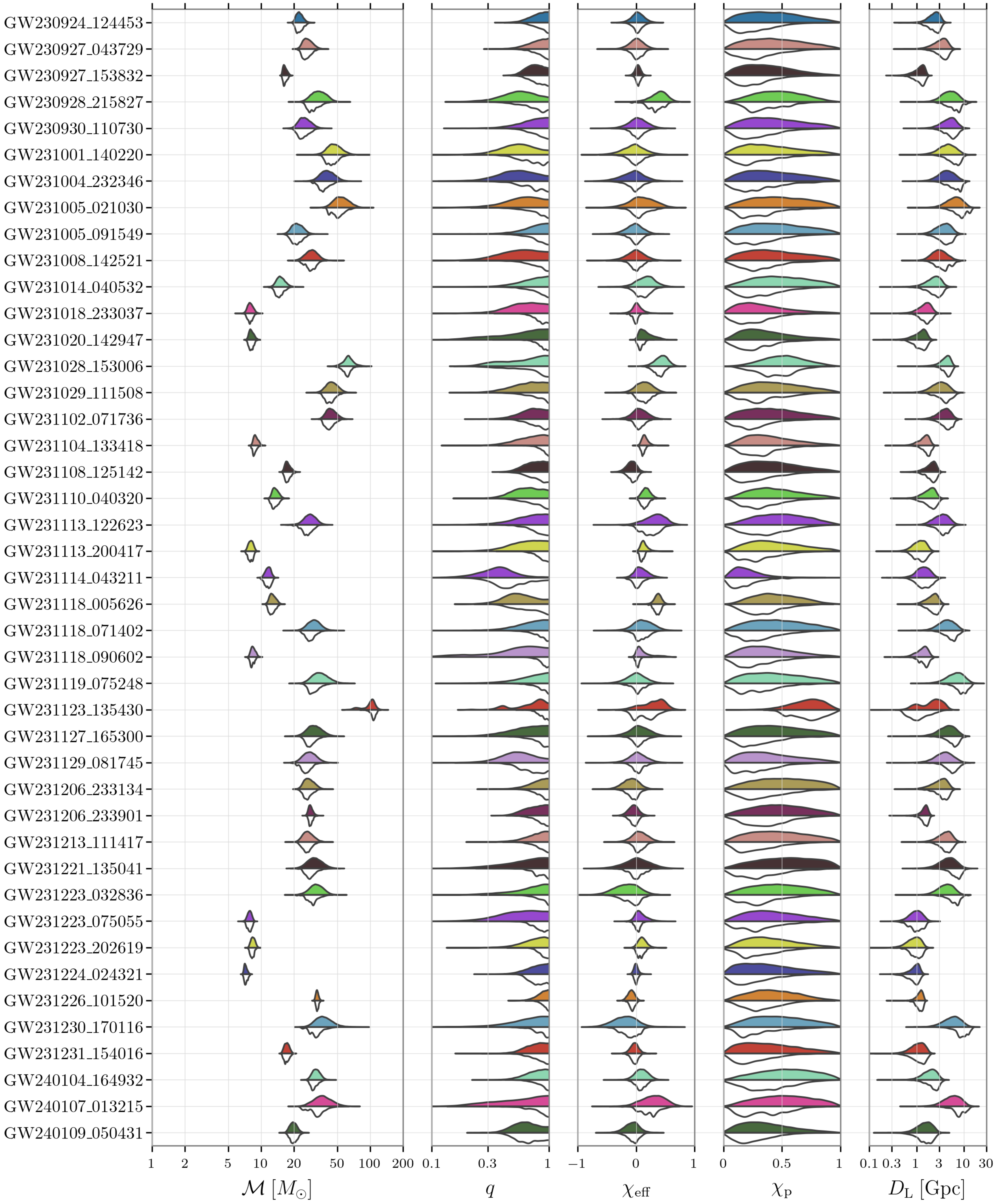
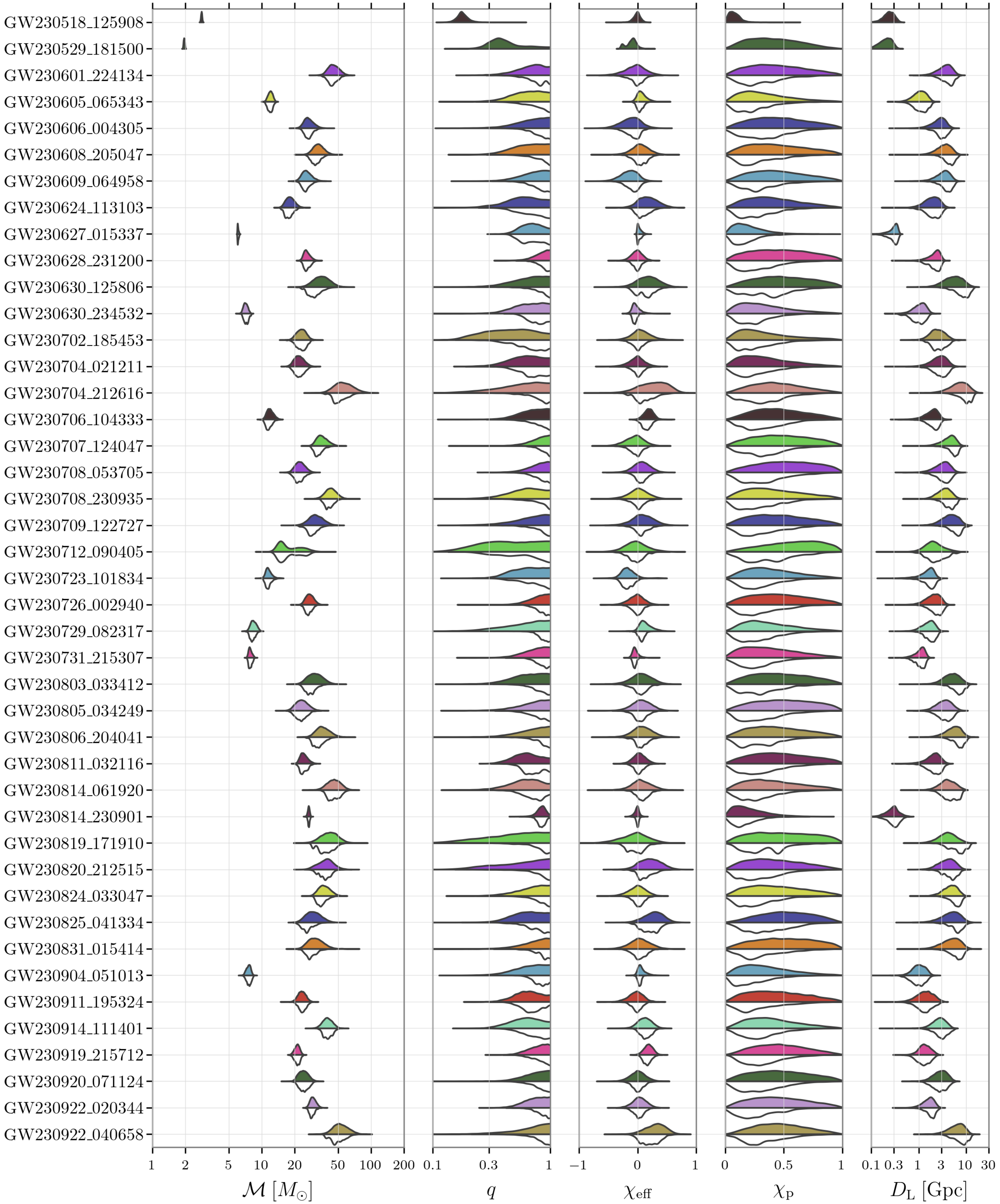
Extras

GWTC-4

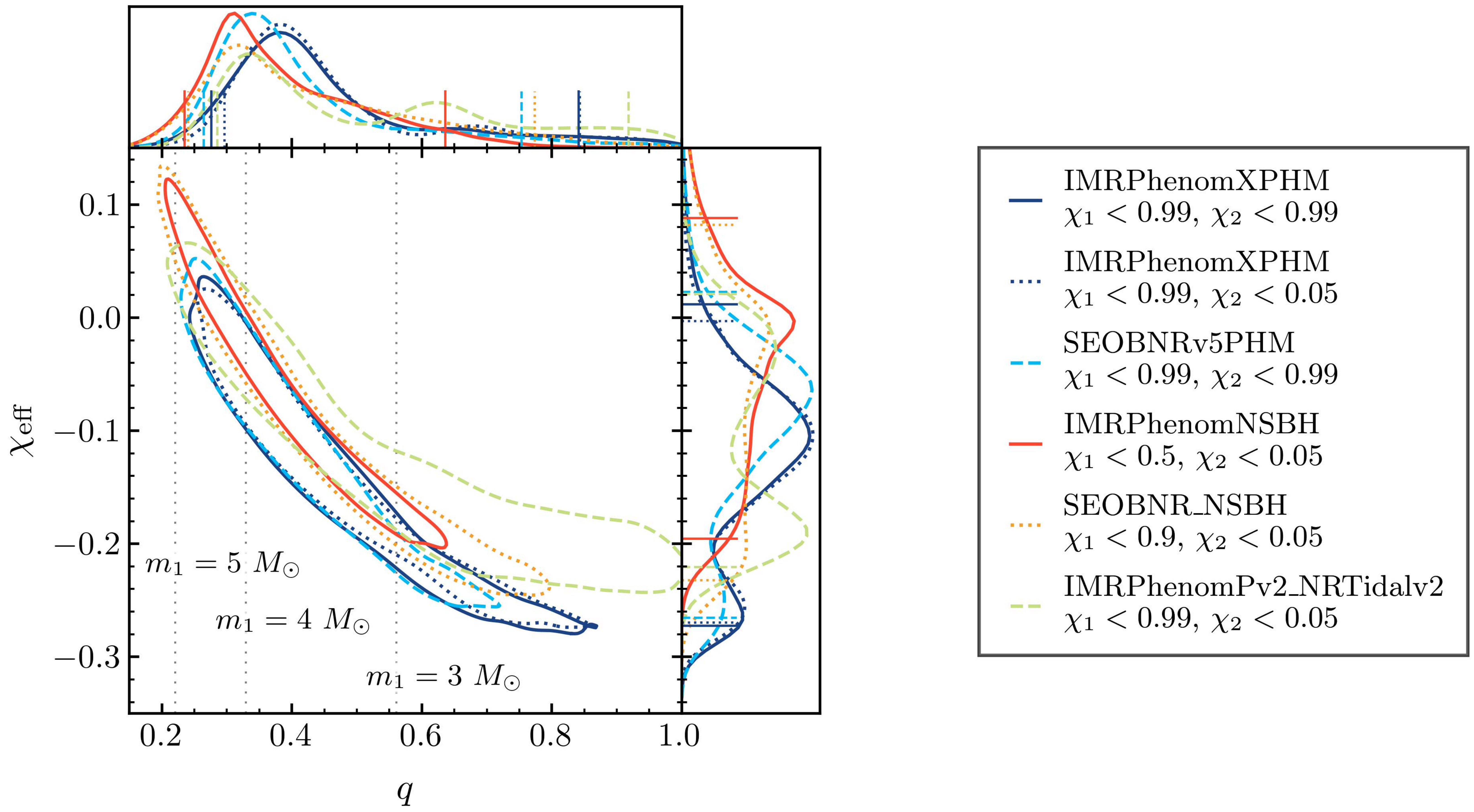


GW230924_124453
GW230927_043729
GW230927_153832
GW230928_215827
GW230930_110730
GW231001_140220
GW231004_232346
GW231005_021030
GW231005_091549
GW231008_142521
GW231014_040532
GW231018_233037
GW231020_142947
GW231028_153006
GW231029_111508
GW231102_071736
GW231104_133418
GW231108_125142
GW231110_040320
GW231113_122623
GW231113_200417
GW231114_043211
GW231118_005626
GW231118_071402
GW231118_090602
GW231119_075248
GW231123_135430
GW231127_165300
GW231129_081745
GW231206_233134
GW231206_233901
GW231213_111417
GW231221_135041
GW231223_032836
GW231223_075055
GW231223_202619
GW231224_024321
GW231226_101520
GW231230_170116
GW231231_154016
GW240104_164932
GW240107_013215
GW240109_050431
1 2 5 10 20 50 100 200
$\mathcal{M}$ [$M_\odot$]
0.1 0.3 1
q
−1 0 1
$\chi_{\rm eff}$
0 0.5 1
$\chi_{\rm p}$
0.1 0.3 1 3 10 30
$D_{\rm L}$ [Gpc]



GW230518_125908
GW230529_181500
GW230601_224134
GW230605_065343
GW230606_004305
GW230608_205047
GW230609_064958
GW230624_113103
GW230627_015337
GW230628_231200
GW230630_125806
GW230630_234532
GW230702_185453
GW230704_021211
GW230704_212616
GW230706_104333
GW230707_124047
GW230708_053705
GW230708_230935
GW230709_122727
GW230712_090405
GW230723_101834
GW230726_002940
GW230729_082317
GW230731_215307
GW230803_033412
GW230805_034249
GW230806_204041
GW230811_032116
GW230814_061920
GW230814_230901
GW230819_171910
GW230820_212515
GW230824_033047
GW230825_041334
GW230831_015414
GW230904_051013
GW230911_195324
GW230914_111401
GW230919_215712
GW230920_071124
GW230922_020344
GW230922_040658
1 2 5 10 20 50 100 200
$\mathcal{M}$ [$M_\odot$]
0.1 0.3 1
q
−1 0 1
$\chi_{\rm eff}$
0 0.5 1
$\chi_{\rm p}$
0.1 0.3 1 3 10 30
$D_{\rm L}$ [Gpc]

GW230529: mass-spin degeneracy



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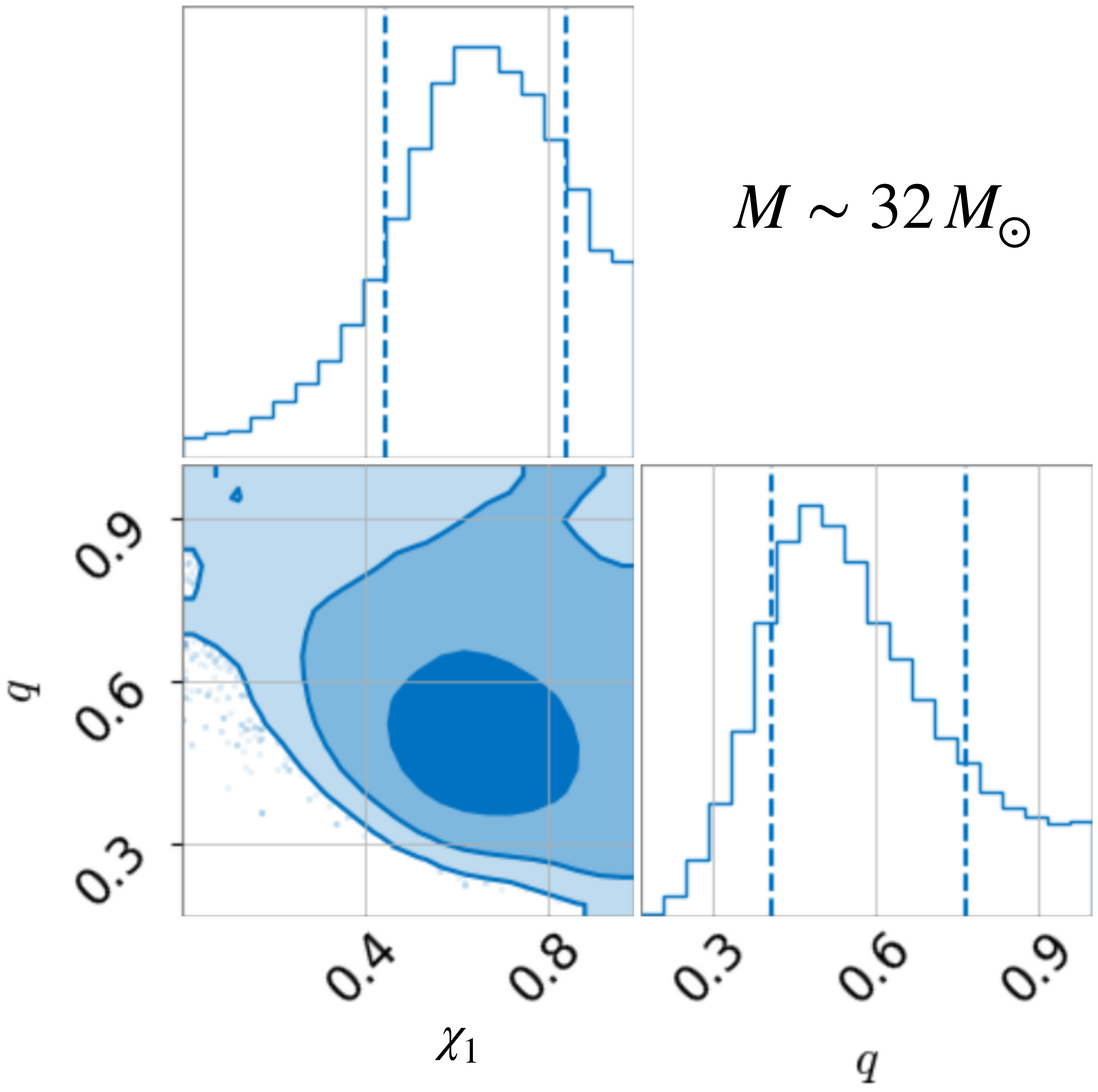
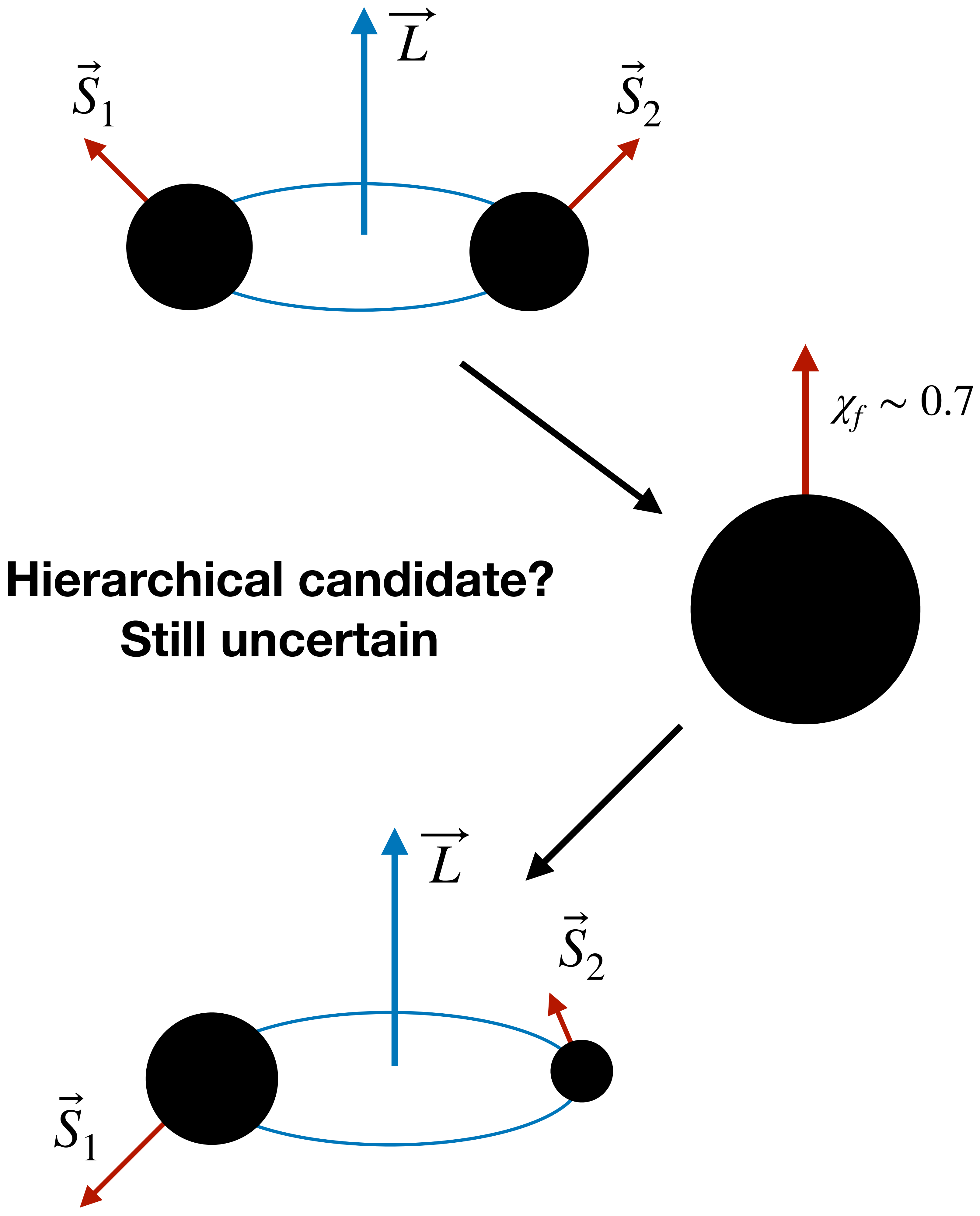
LVK ApJL 970, L34 (2024)

GW231118_00: Unequal masses and spinning primary





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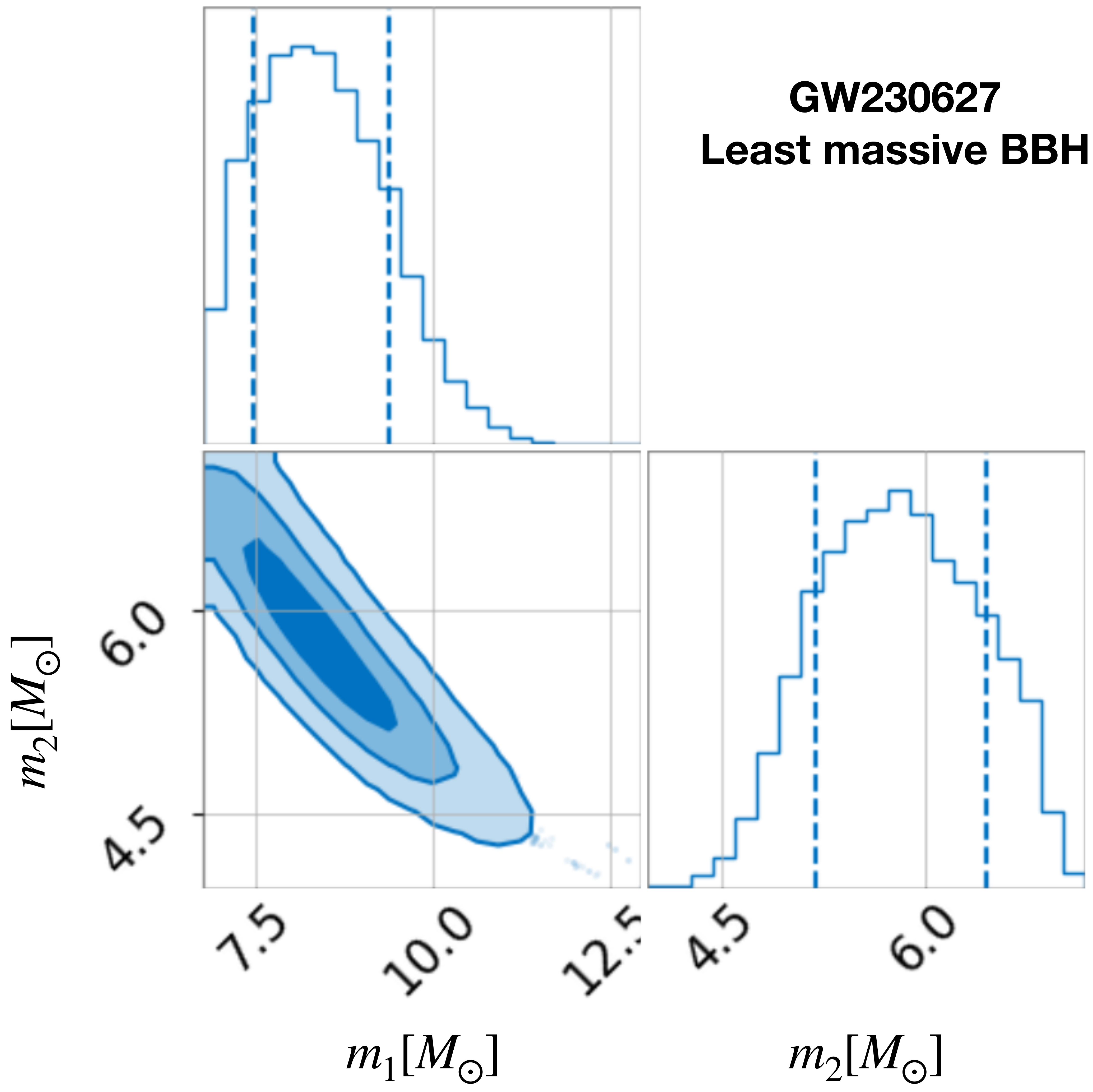
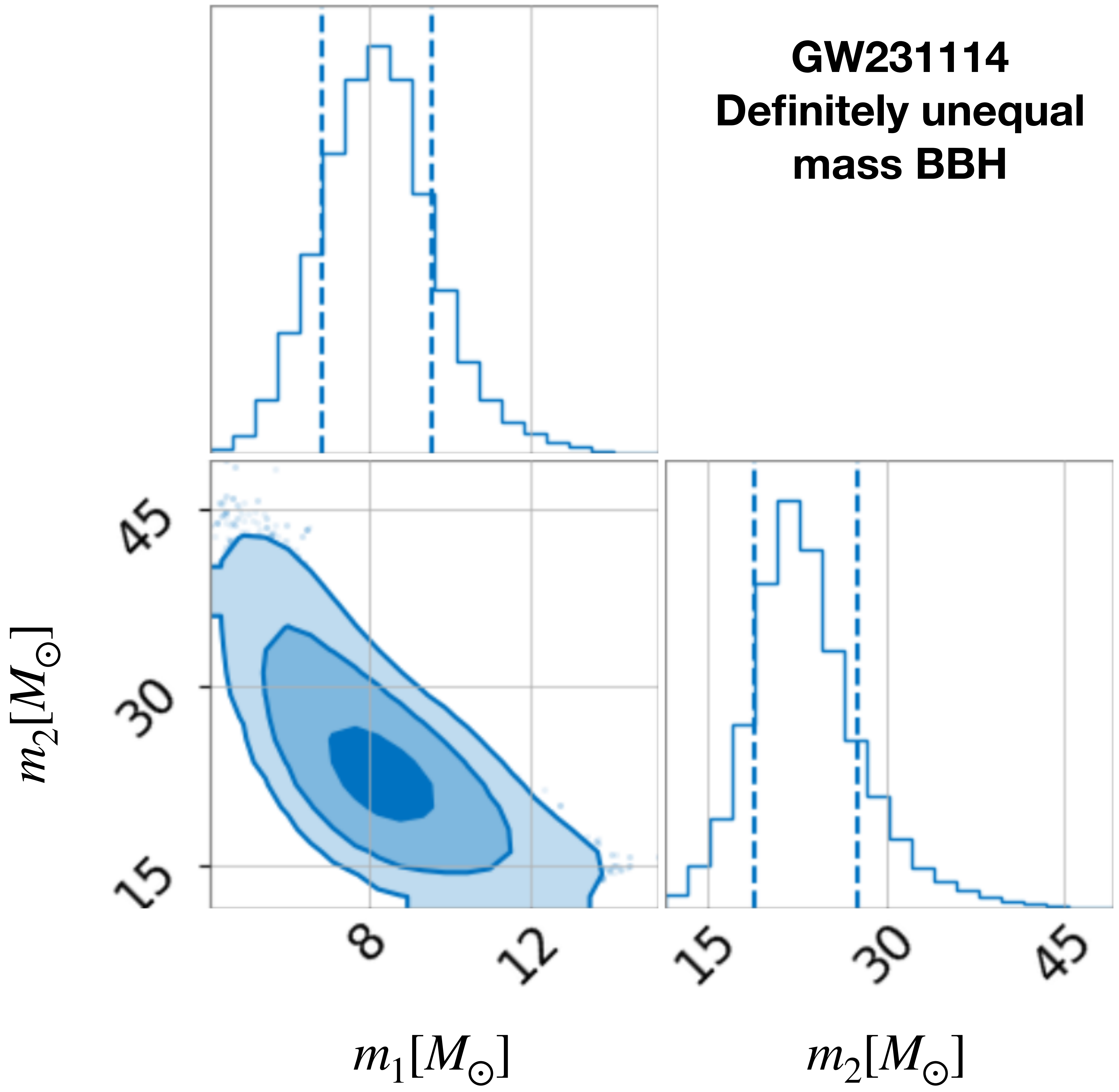
LVK, arXiv:2508.18082

Other stand outs





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LVK, arXiv:2508.18082

GWTC-4.0: glitch mitigation

Candidate	GPS time [s]	Detector	Time window [s]	Frequency range [Hz]	f_{low} [Hz]
GW230911_195324	–	H	–	–	28.38
GW230920_071124	–	H	–	–	40
GW231001_140220	–	L	–	–	40
GW231014_040532	–	H	–	–	50
GW231018_233037	–	H	–	–	30
GW231020_142947	–	H	–	–	45
GW231102_071736	–	H	–	–	20.13
GW231102_071736	–	L	–	–	20.13
GW231113_122623	1383913601.88	L	$[0.01, 0.22]$	[70.0, 120.0]	–
GW231114_043211	1383971549.25	H	$[-0.95, -0.6]$	[10.0, 30.0]	–
GW231118_005626	–	H	–	–	30
GW231118_071402	–	H	–	–	50
GW231118_090602	1384333580.01	H	$[-4.81, -4.51]$	[15.0, 50.0]	–
GW231123_135430	1384782888.63	H	$[-1.7, -1.1]$	[15.0, 30.0]	–
GW231127_165300	–	H	–	–	50
GW231129_081745	1385281083.64	L	$[1.4, 1.8]$	[10.0, 170.0]	–
GW231129_081745	–	H	–	–	60
GW231206_233134	–	H	–	–	40
GW231206_233134	–	L	–	–	30
GW231221_135041	1387201859.32	H	$[0.3, 0.4]$	[200.0, 450.0]	–
GW231223_032836	1387337334.05	H	$[-0.55, -0.25]$	[10.0, 25.0]	–
GW231223_075055	–	H	–	–	40
GW231223_075055	–	L	–	–	30
GW231223_202619	–	H	–	–	40
GW231224_024321	–	H	–	–	40
GW240107_013215	–	H	–	–	40

NOTE— For each candidate, we show the GPS time, and the interferometer(s) where glitch subtraction was applied (H and L indicate LIGO Hanford and LIGO Livingston respectively). For candidates where glitch subtraction was performed using BAYESWAVE, we provide the time and frequency windows used for subtraction. For candidates where the low-frequency cut-off, f_{low}, was changed (from the standard 20 Hz) to excise contaminate data, we quote the cut-off used.

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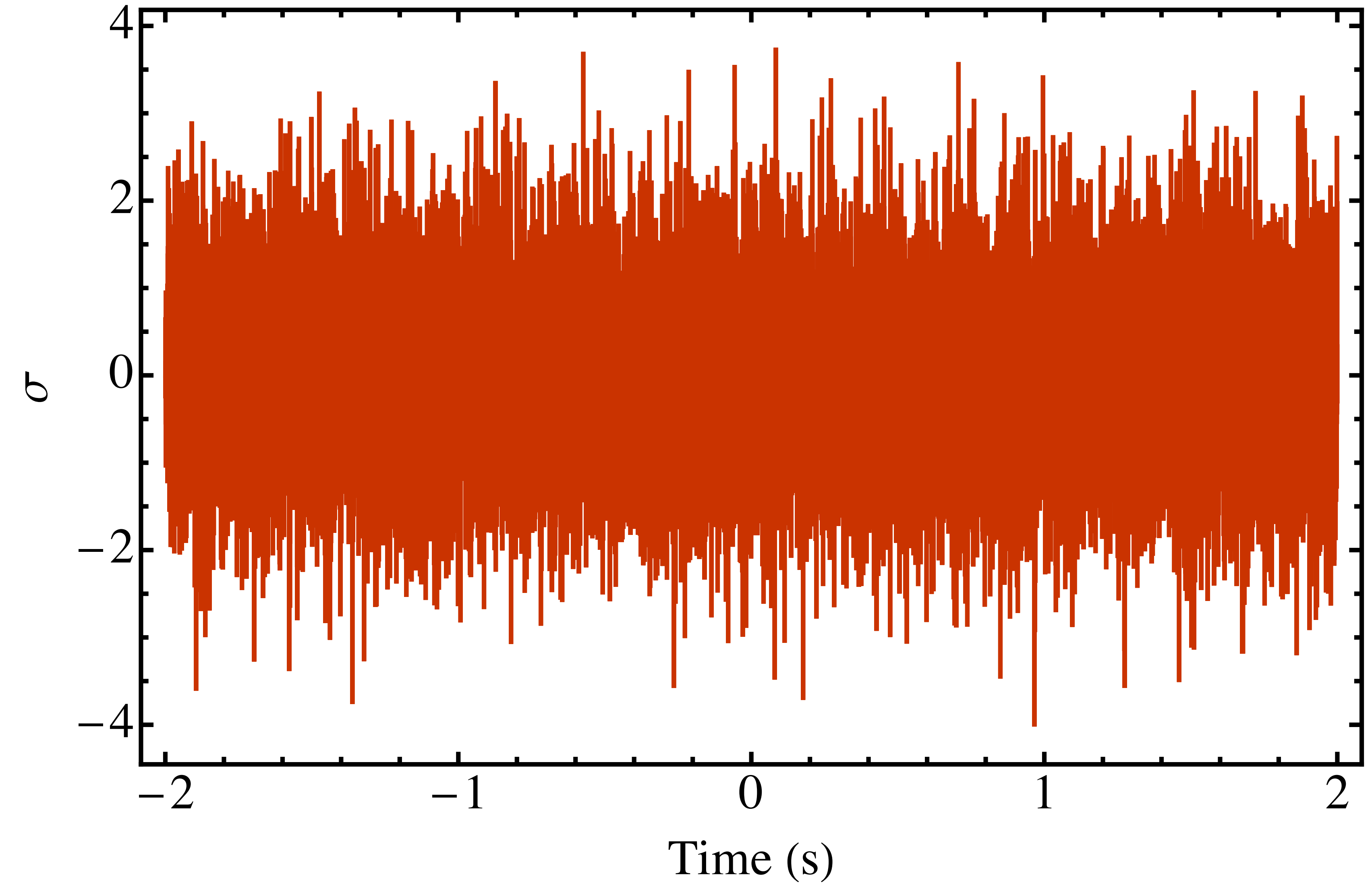
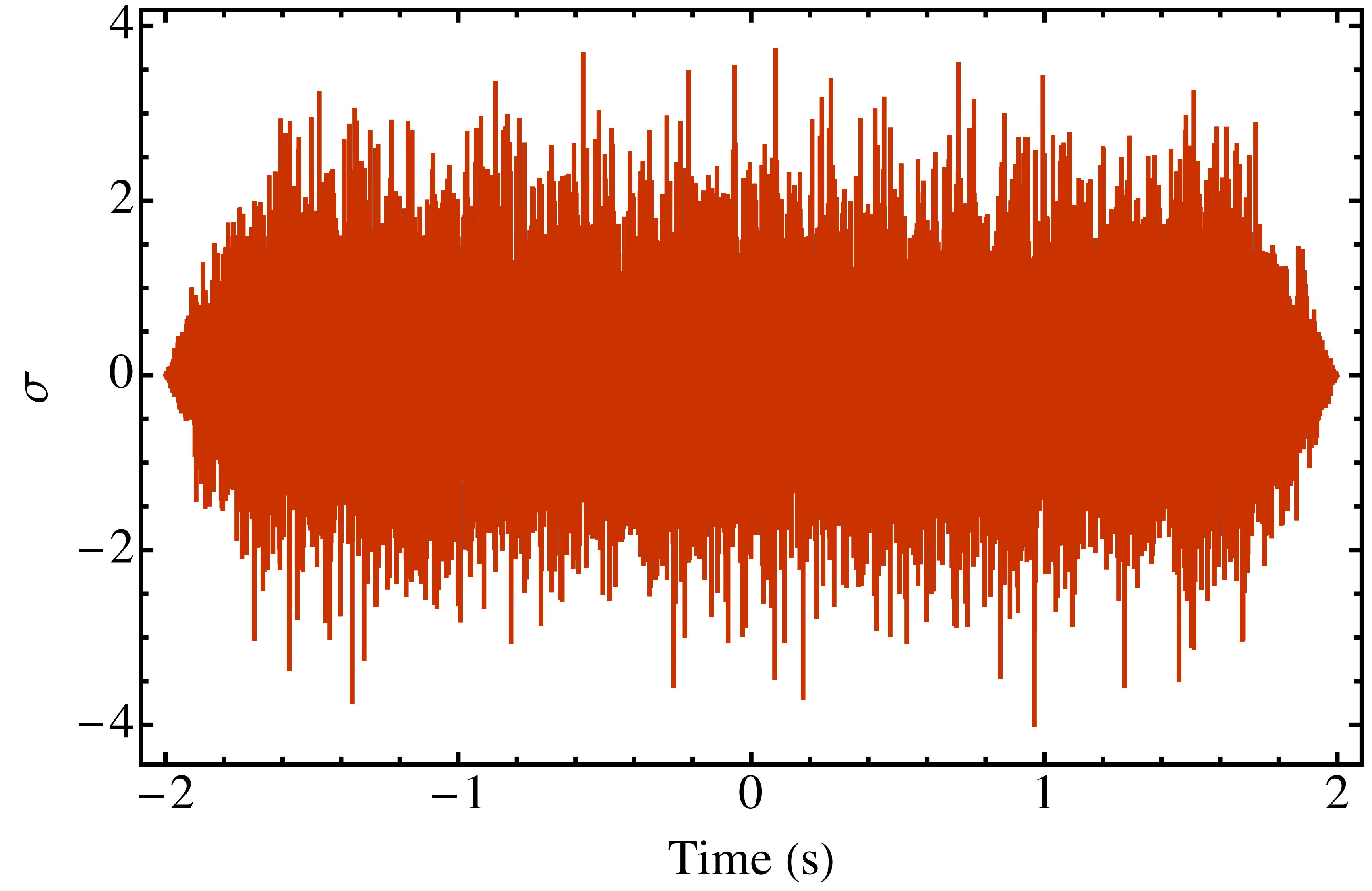
Windows and parameter estimation

- Noise covariance diagonal in freq domain
- Need to apply window to data before FT
- For noise covariance, correct for power lost due to window
- In GW inference correction has been (incorrectly) applied to in the likelihood
  - Biases SNR and effectively tightens the posteriors





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Talbot + 2508.11091

Windows and parameter estimation

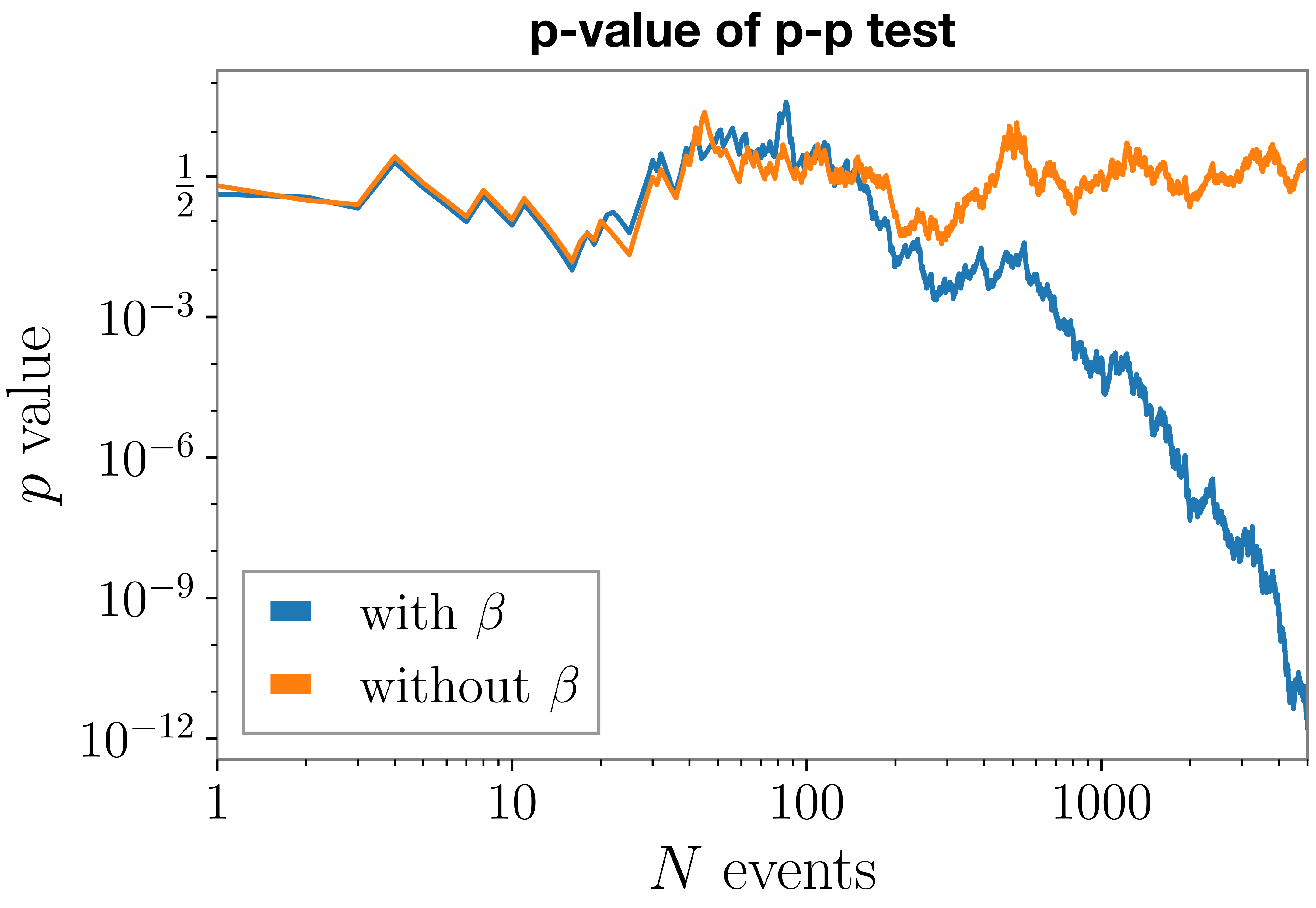
- Incorrect application of correction:

$$\ln p(d_w|\vec{\theta}) = -2\sum \frac{|\tilde{d}_w - \tilde{h}_k(\vec{\theta})|^2}{\beta T S(f_k)} + \text{const}$$

- Show theoretically and numerically can ignore effect of windowing:

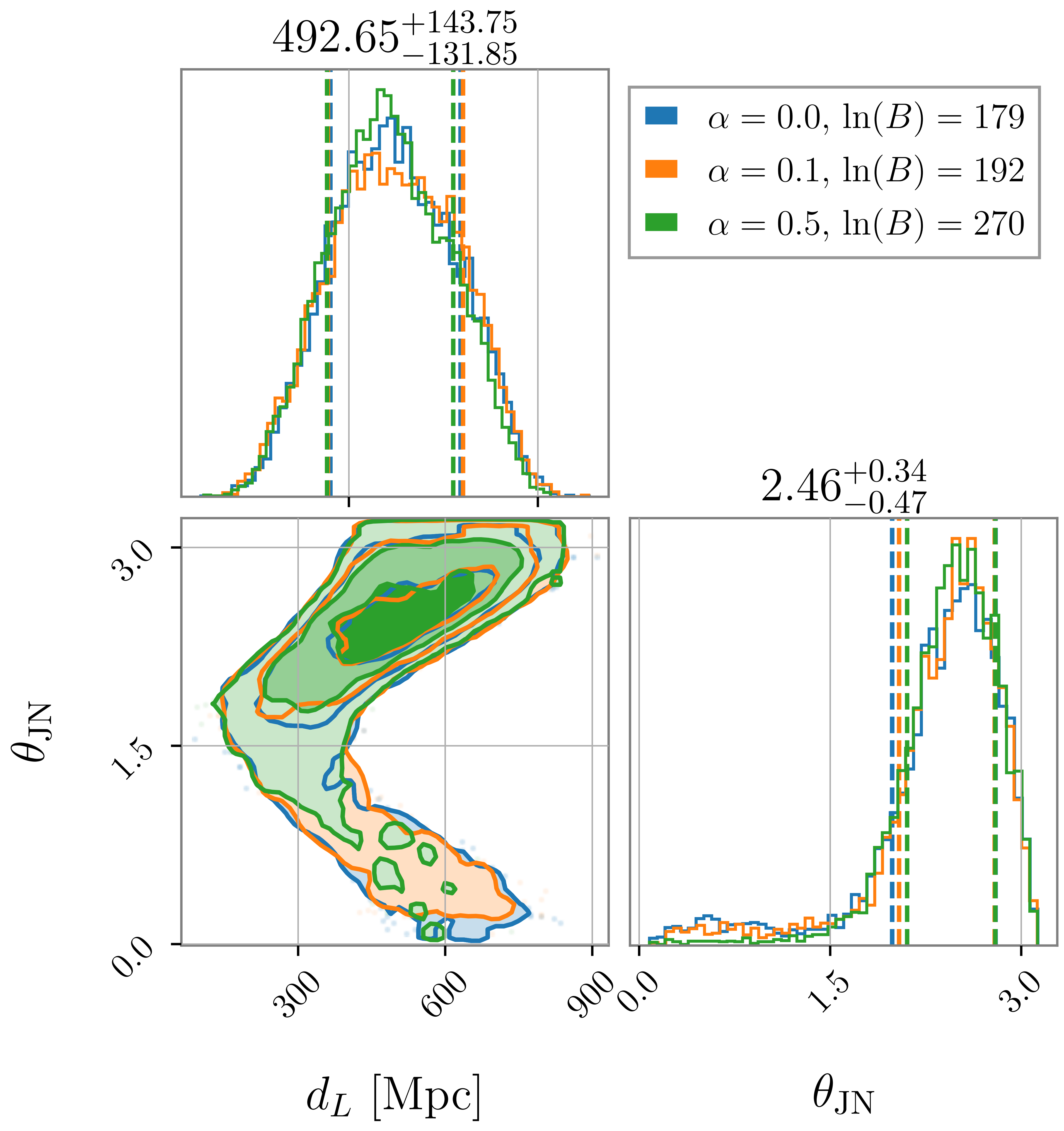
$$\ln p(d_w|\vec{\theta}) = \ln p_w(d_w|\vec{\theta}) + \sum h_i(\vec{\theta}) C^{-1}_{ij}(d_j - d_{w,j}) + \text{const}$$

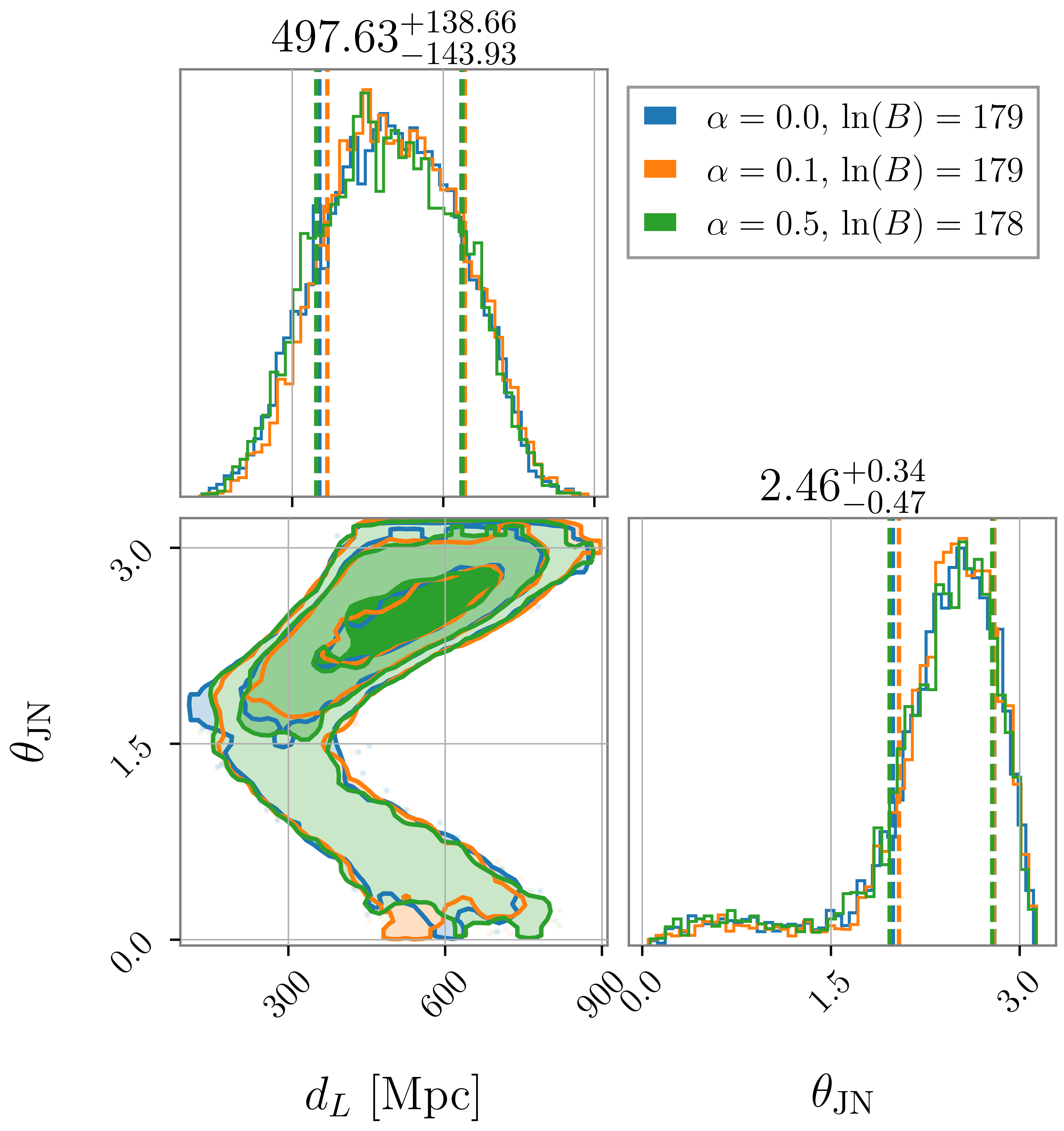
- Effect is small; not noticeable in p-p plots without many trials



Talbot + 2508.11091

Windowing and GW150914





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