University of Glasgow | School of Physics & Astronomy

LIGO VIRGO KAGRA

The status of gravitational-wave astronomy

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On behalf of the
LIGO Scientific, Virgo & KAGRA Collaboration

DCC G2200657
Storming the Gravitational Wave Frontier

14 September 2015

We observed gravitational waves

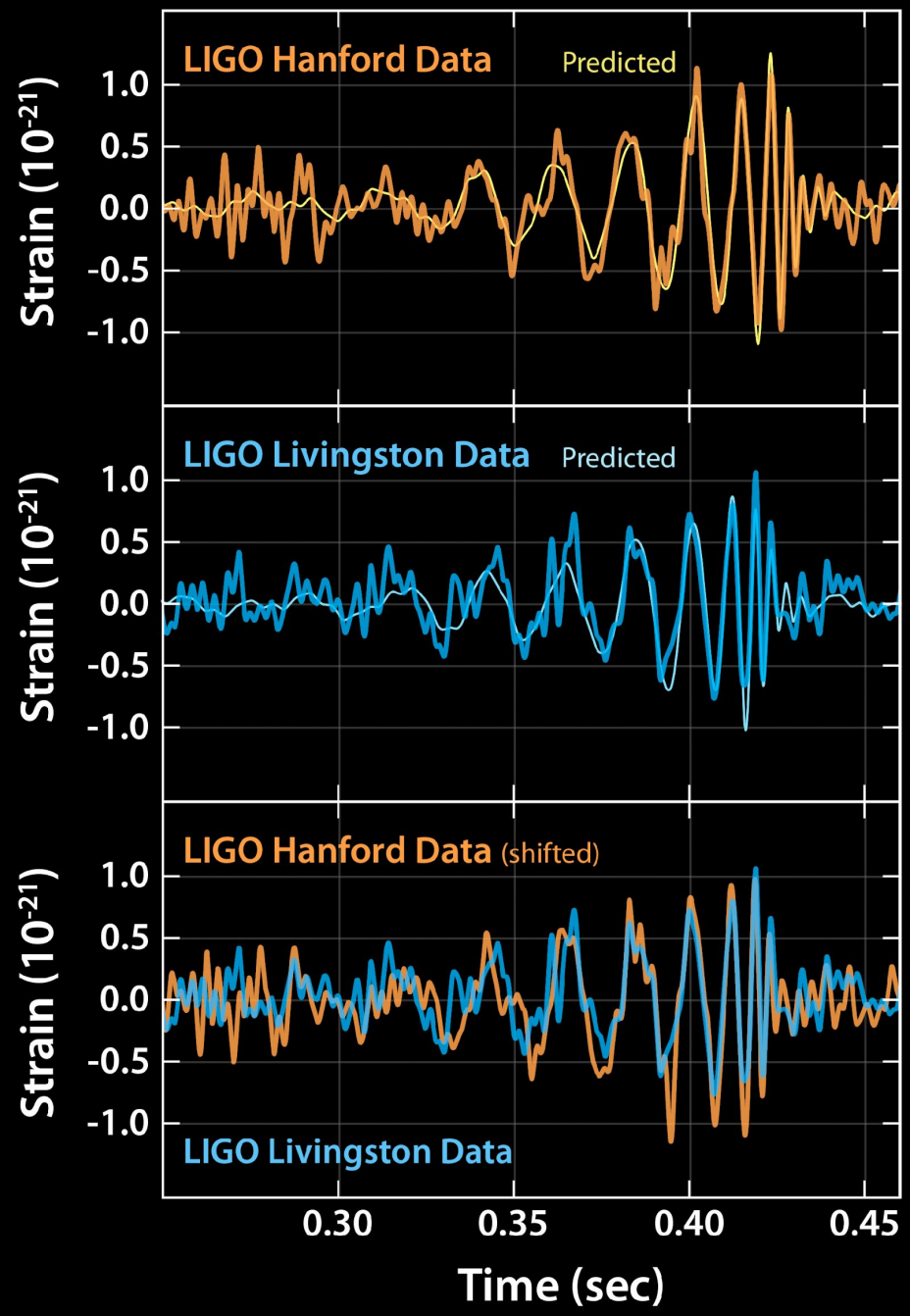
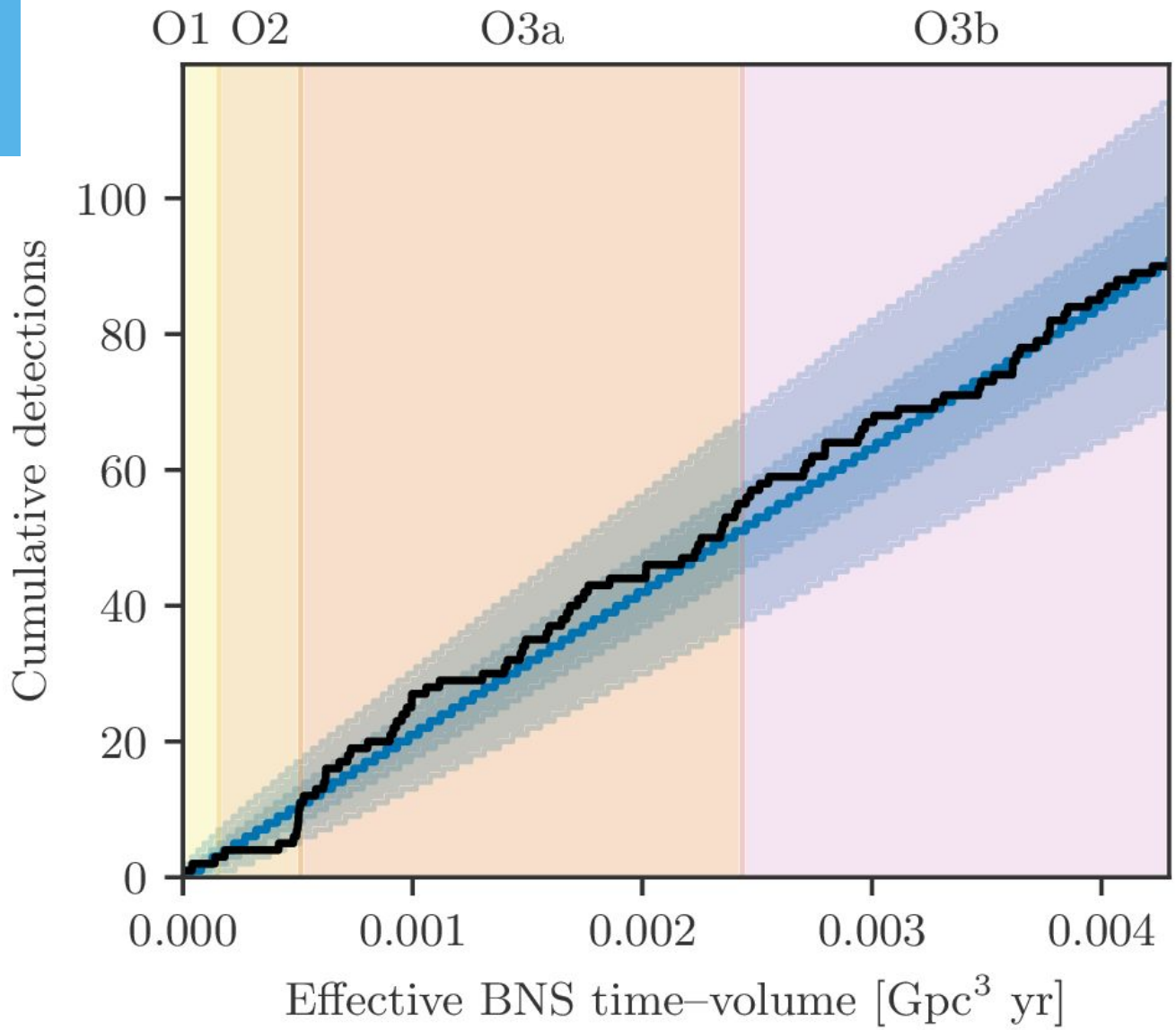


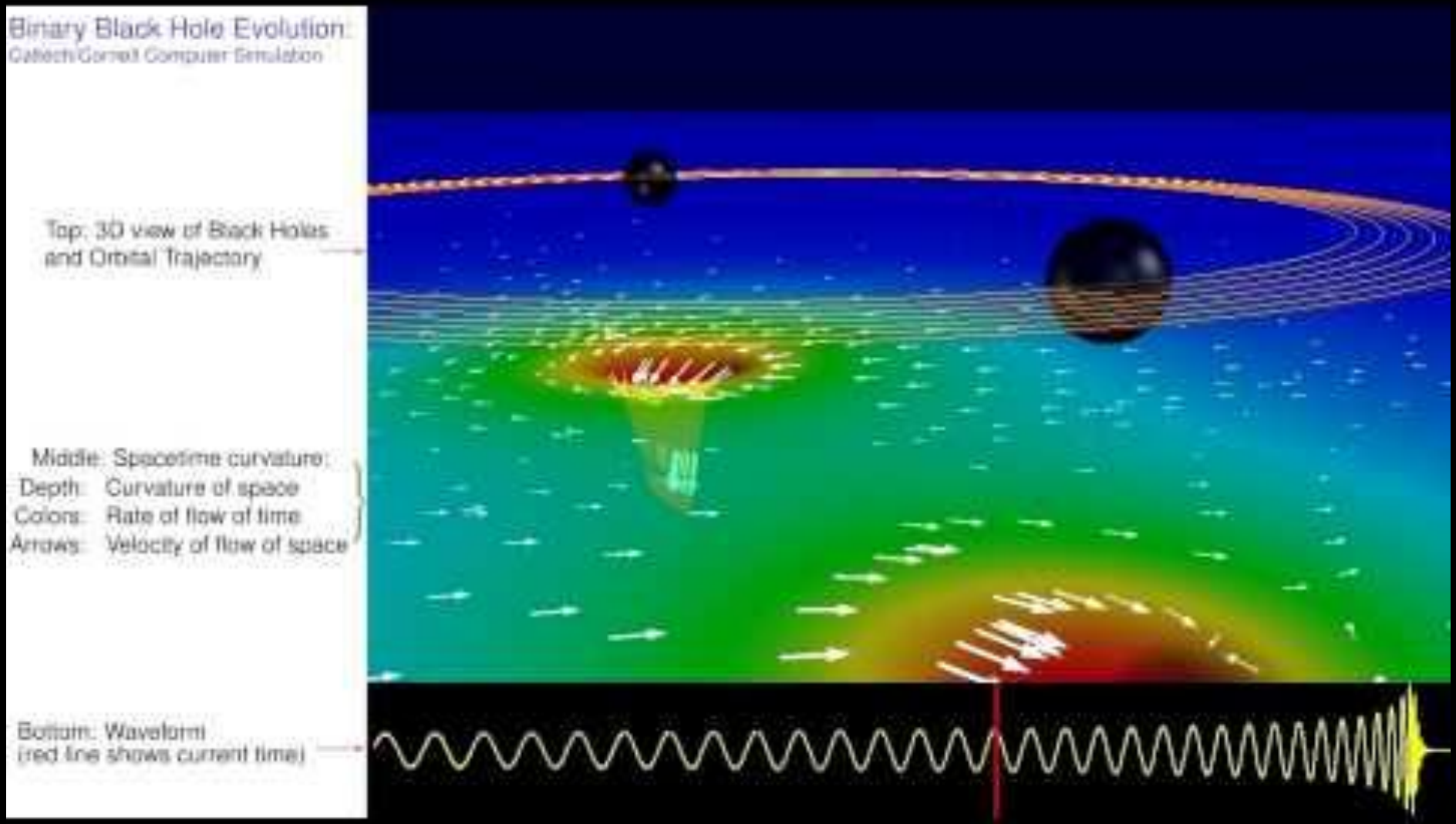
Image: LIGO

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

Today

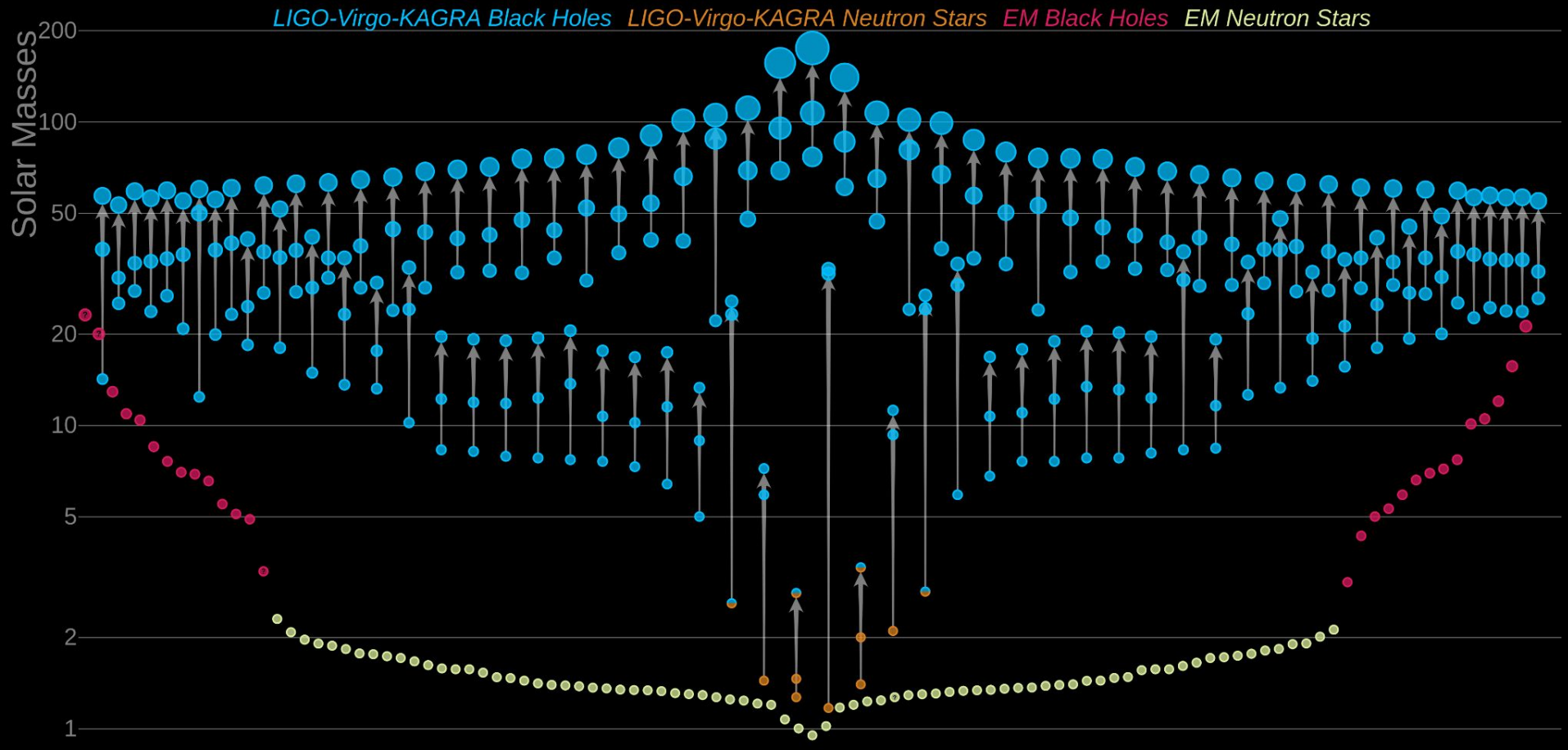


LVK arXiv:2111.03606

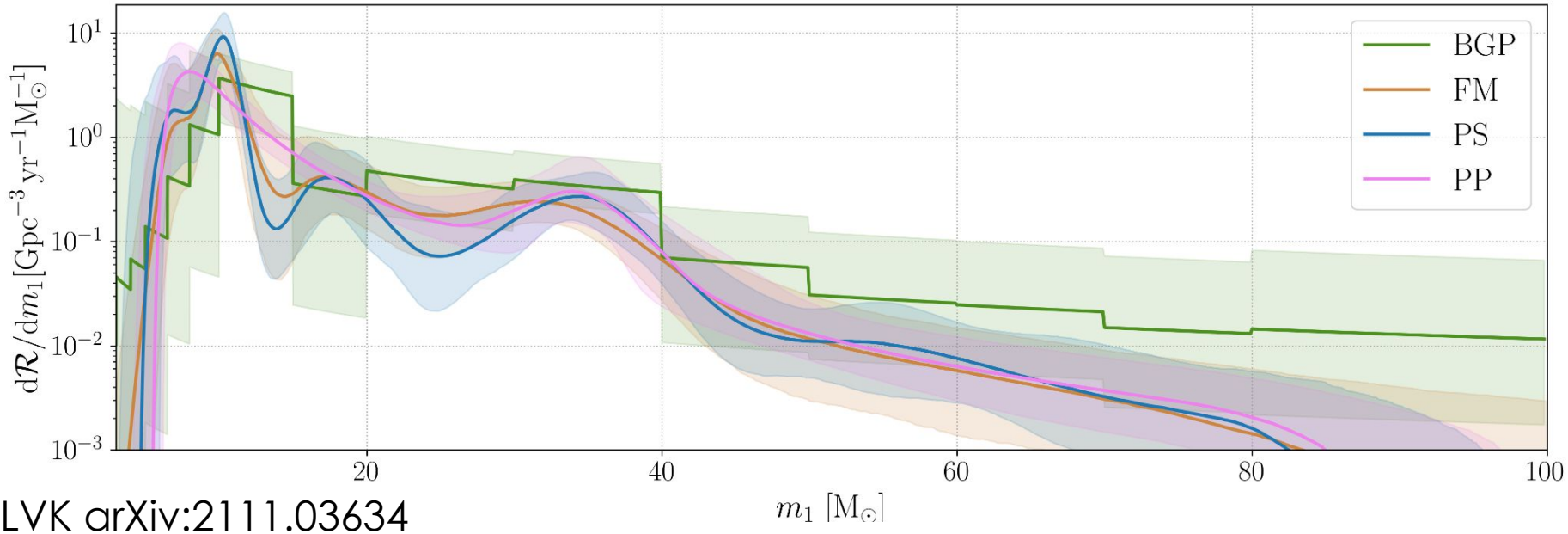

Binary Black Hole Evolution:
Caltech/Cornell Computer Simulation
Top: 3D view of Black Holes and Orbital Trajectory
Middle: Spacetime curvature:
Depth: Curvature of space
Colors: Rate of flow of time
Arrows: Velocity of flow of space
Bottom: Waveform (red line shows current time)

Video: SXS

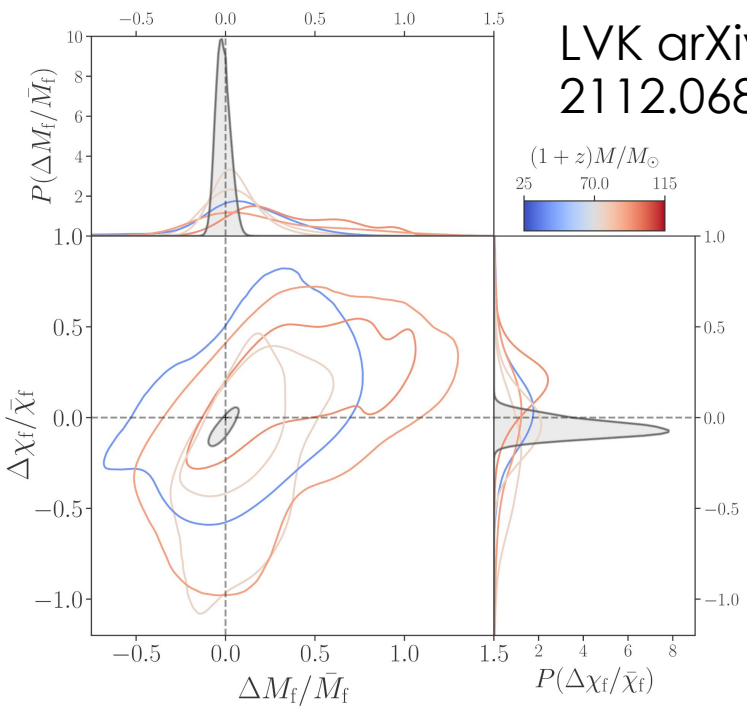
Masses in the Stellar Graveyard



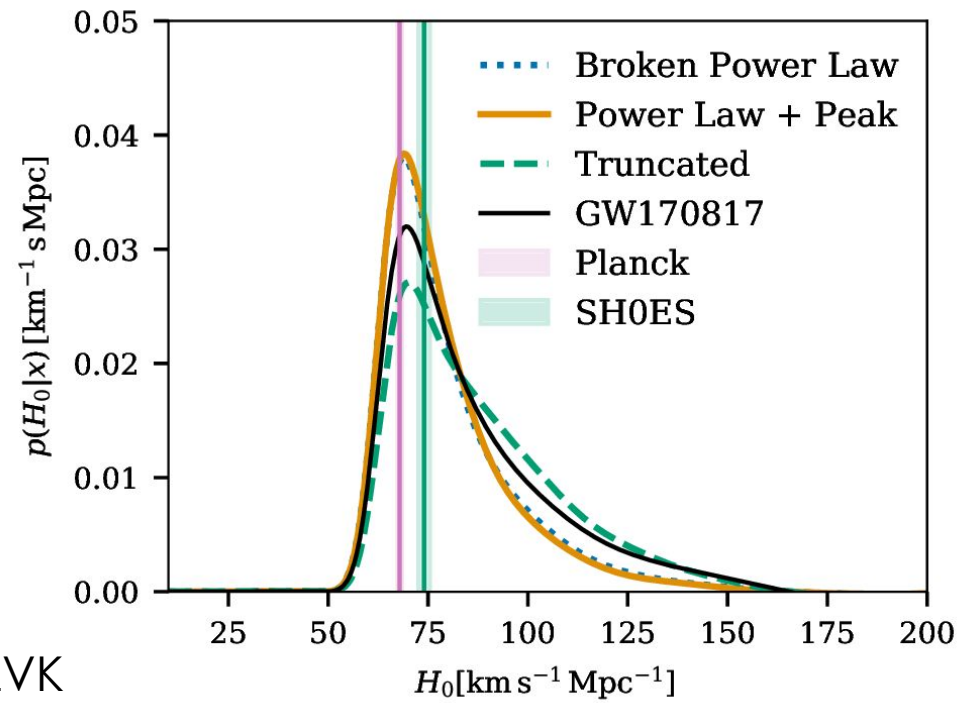
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



LVK arXiv:2111.03634



LVK arXiv: 2112.06861



LVK arXiv:2111.03604

Discoveries

Data analysis

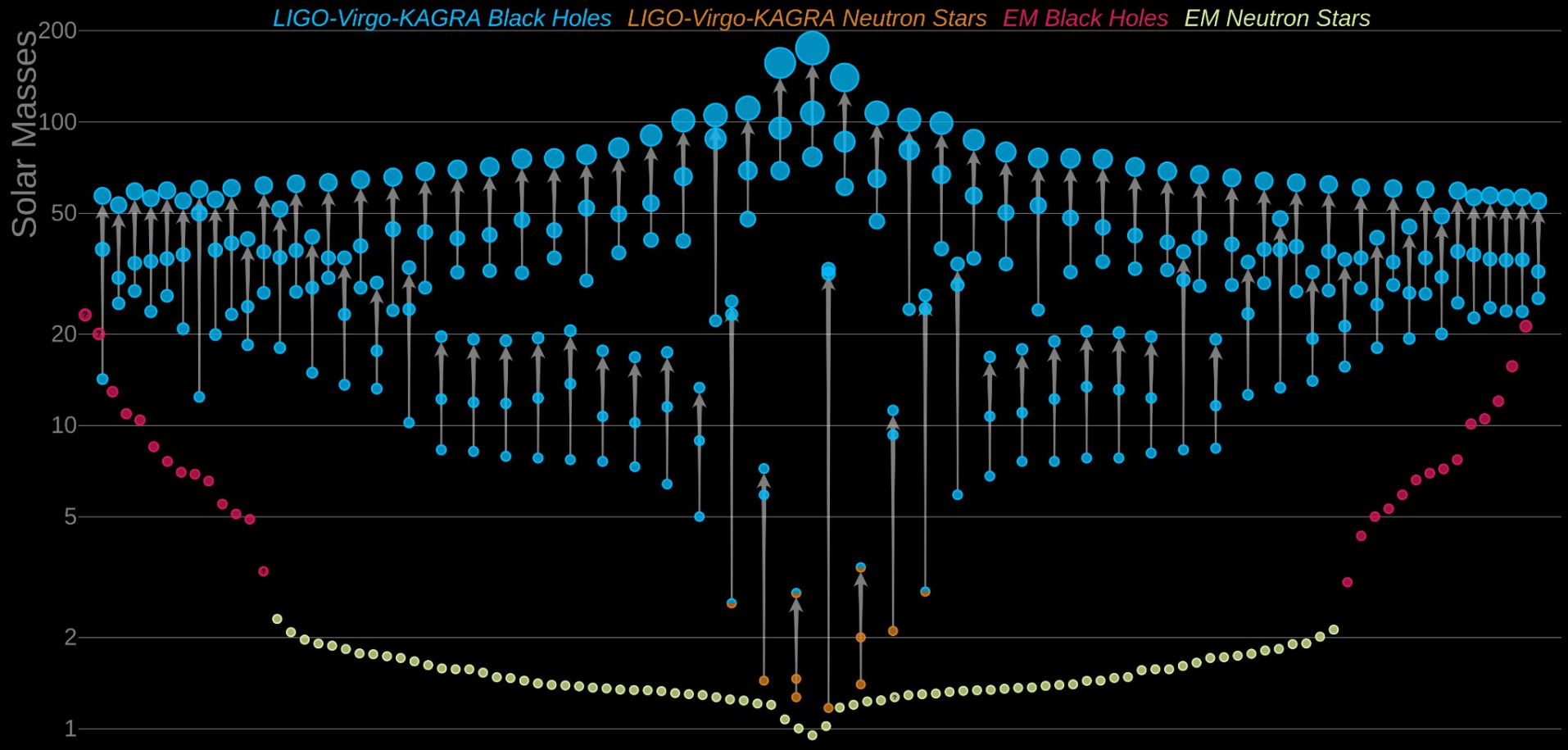
Future

Discoveries

Data analysis

Future

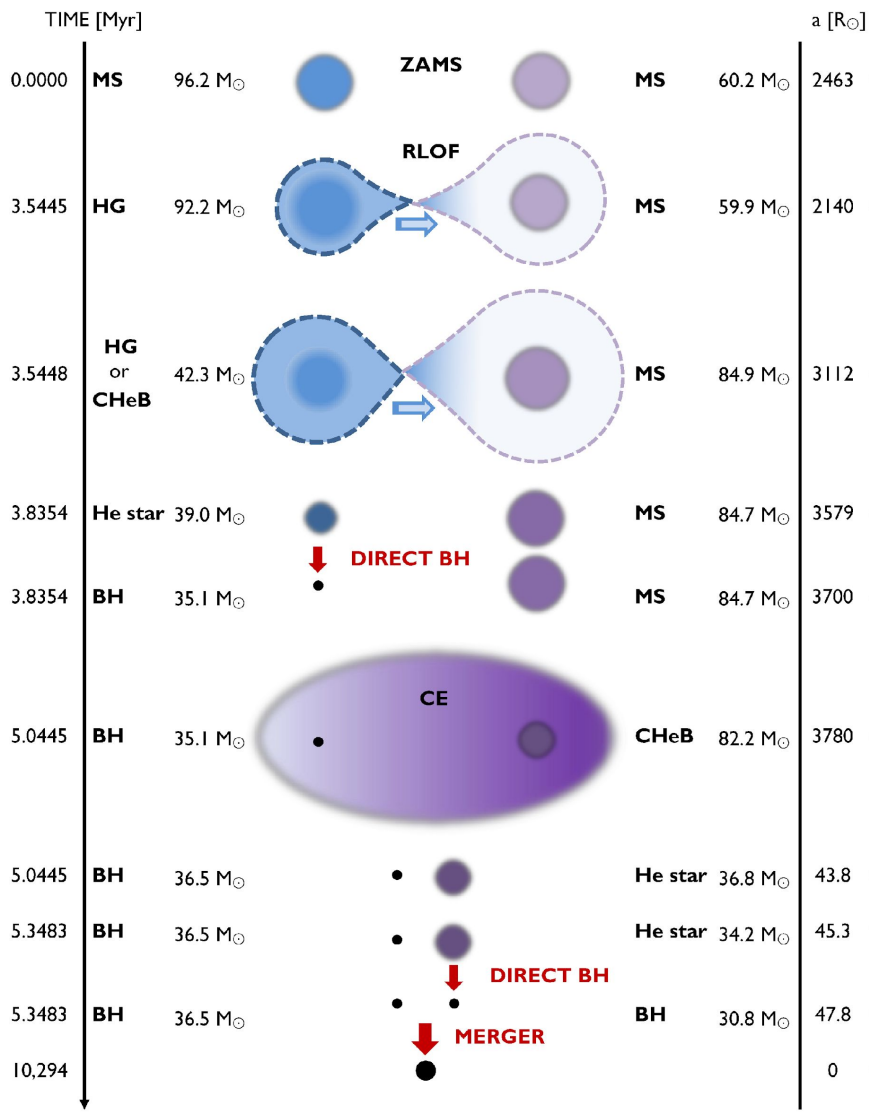
Masses in the Stellar Graveyard



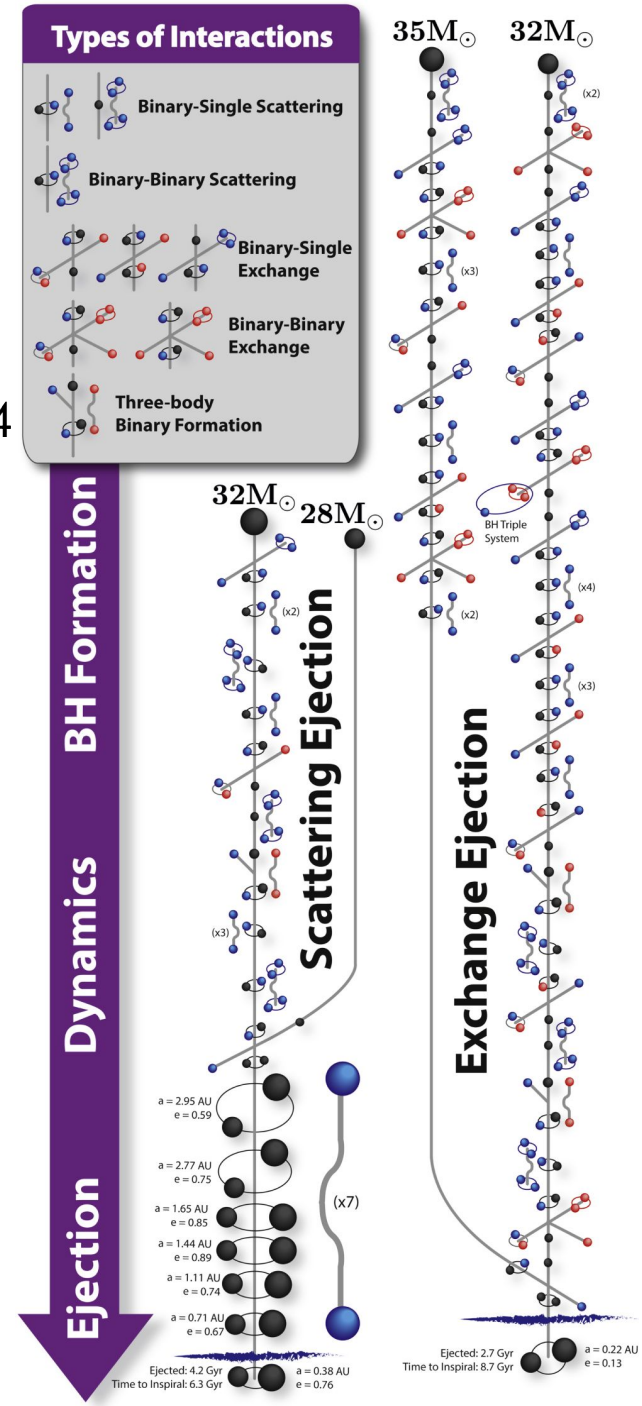
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Binary stars

Binary formation

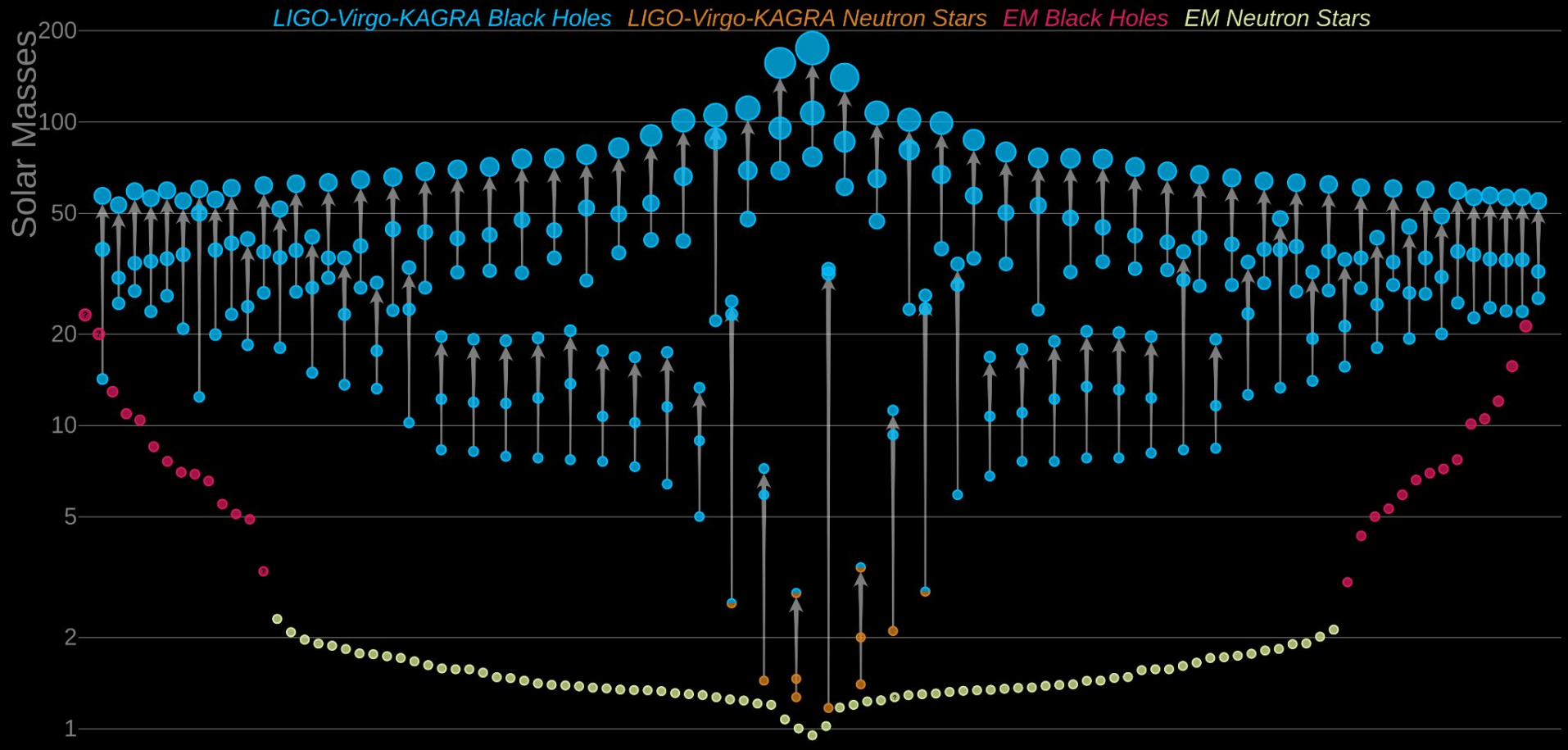


Rodriguez *et al.*
arXiv:1604.04254



Belczynski *et al.*
arXiv:1602.04531

Masses in the Stellar Graveyard



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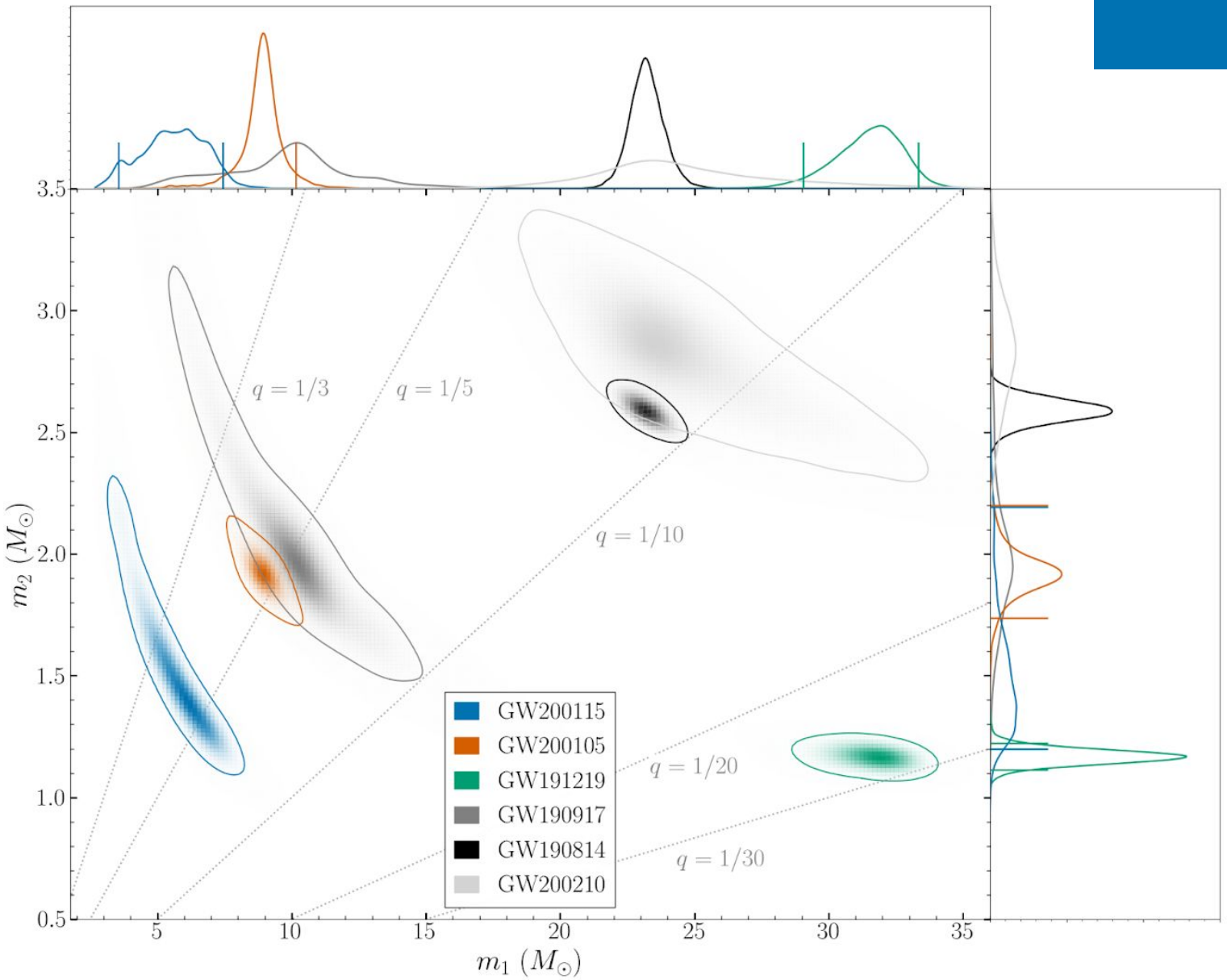
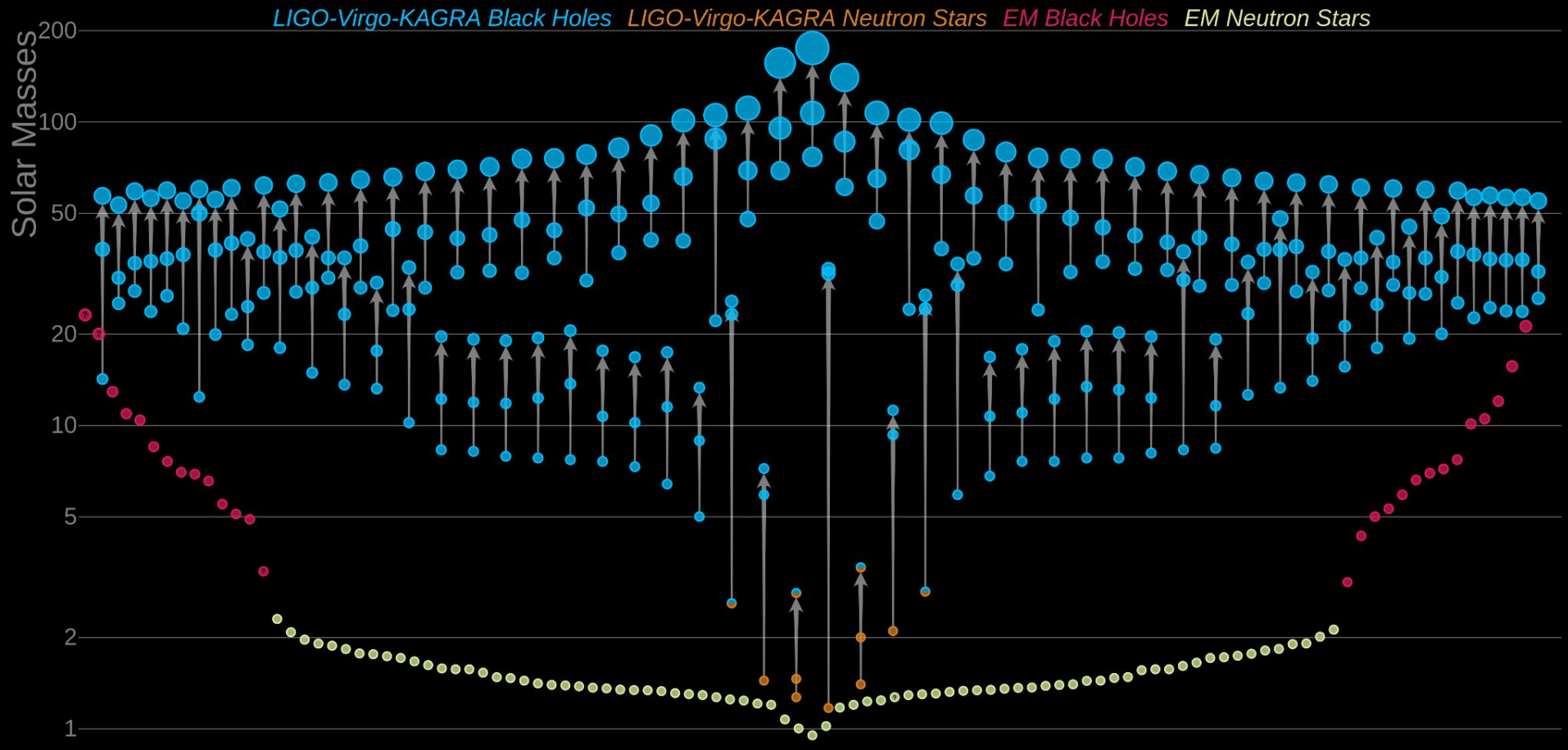
LVC arXiv:2010.14527 LVC arXiv:2108.01045
LVK arXiv:2111.03606

NSBHs

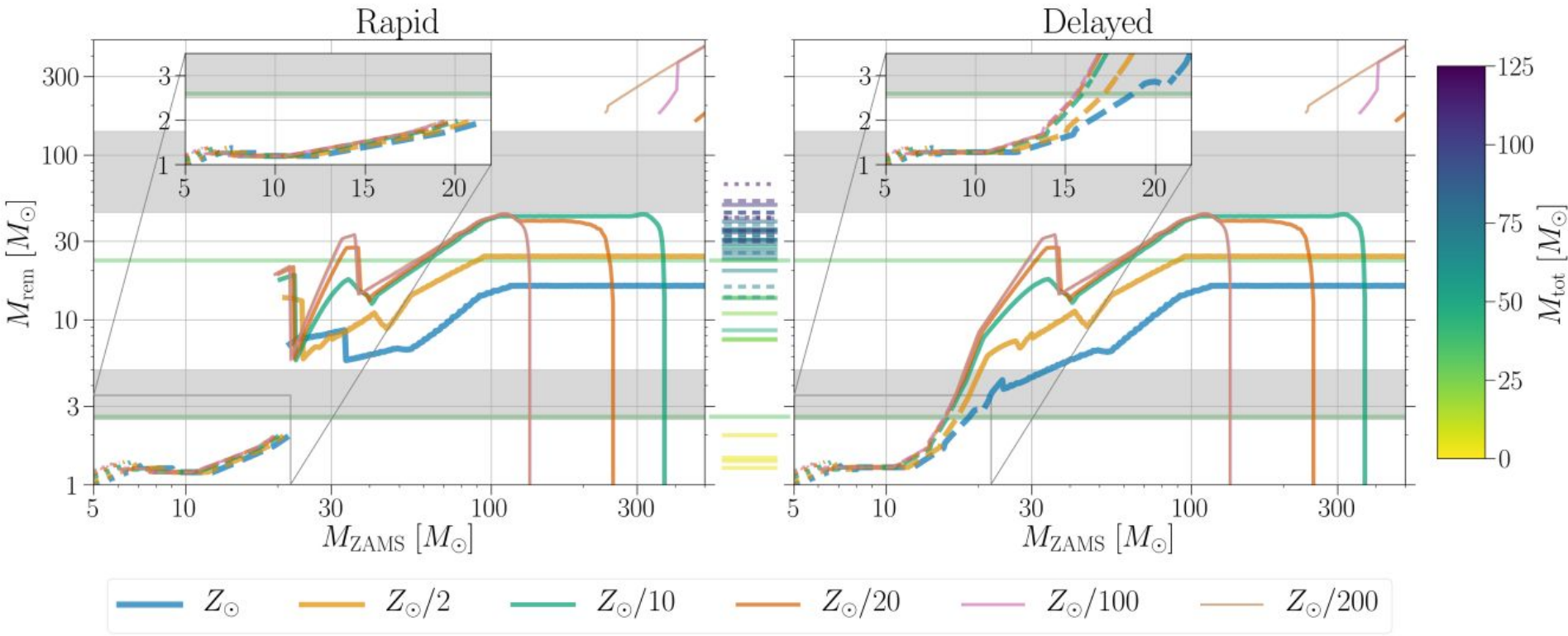


Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Compact-object masses



Zevin, Spera, **CPLB** & Kalogera arXiv:2006.14573

C S M I C

Discoveries

Data analysis

Future

Bayes' theorem

Likelihood

Prior

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

Posterior

Evidence

Likelihood

Noise-weighting

$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k \rangle\right]$$

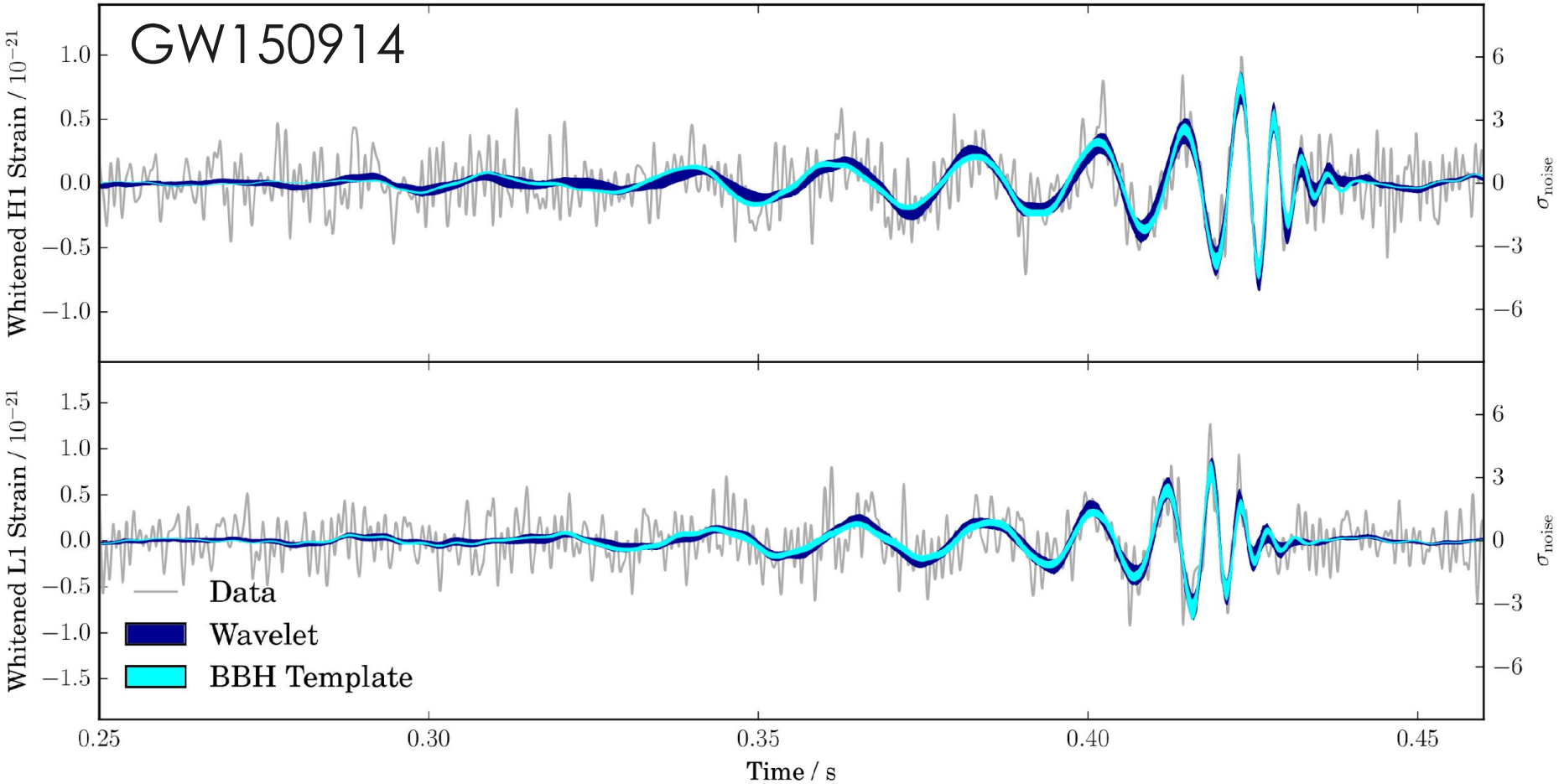
Calibration

$$h_k(\theta) \rightarrow h_k(\theta)\,[1 + \delta A_k]\exp[i\delta\phi_k]$$

Waveform

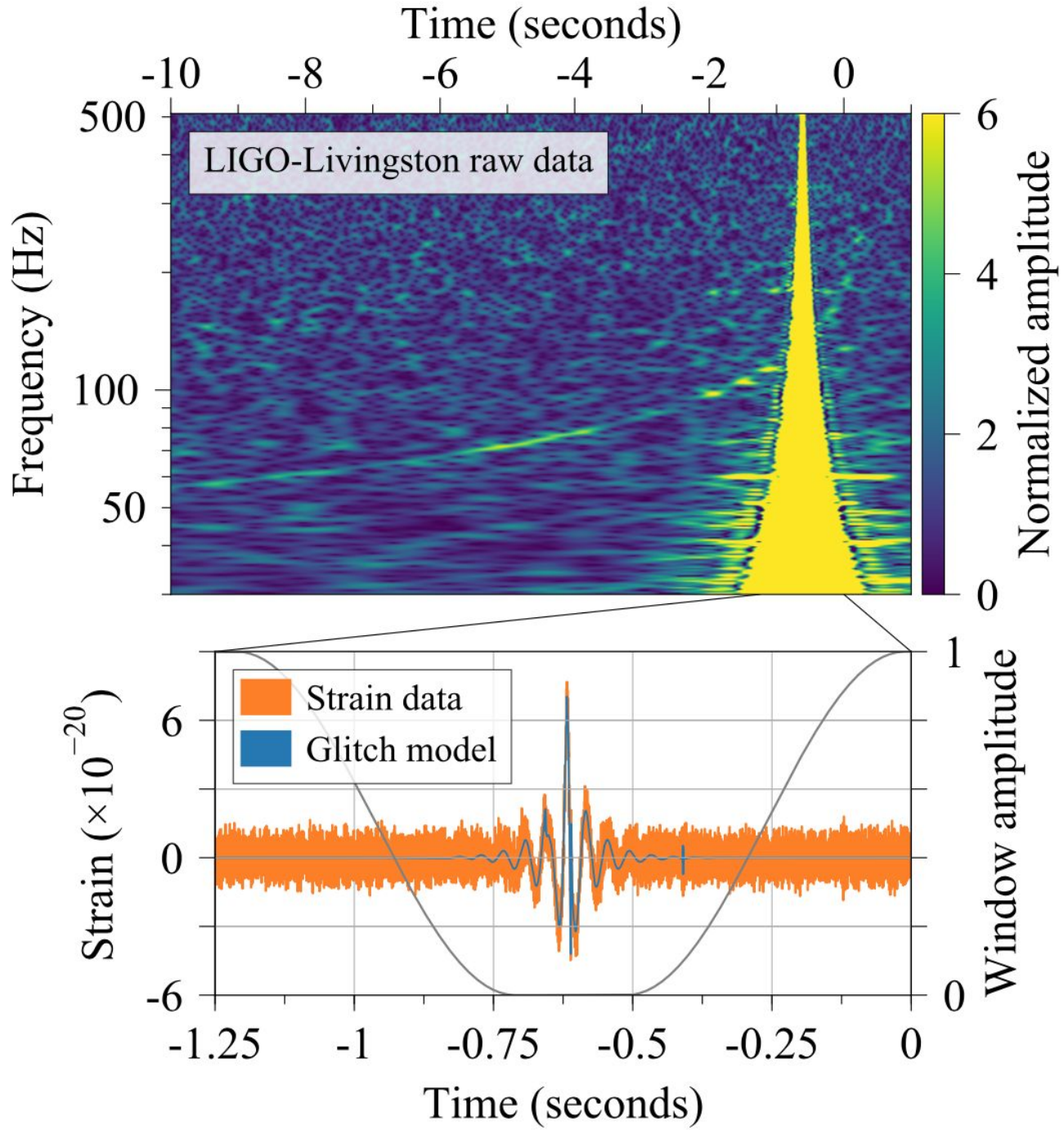
LVC arXiv:1602.03840

Waveform



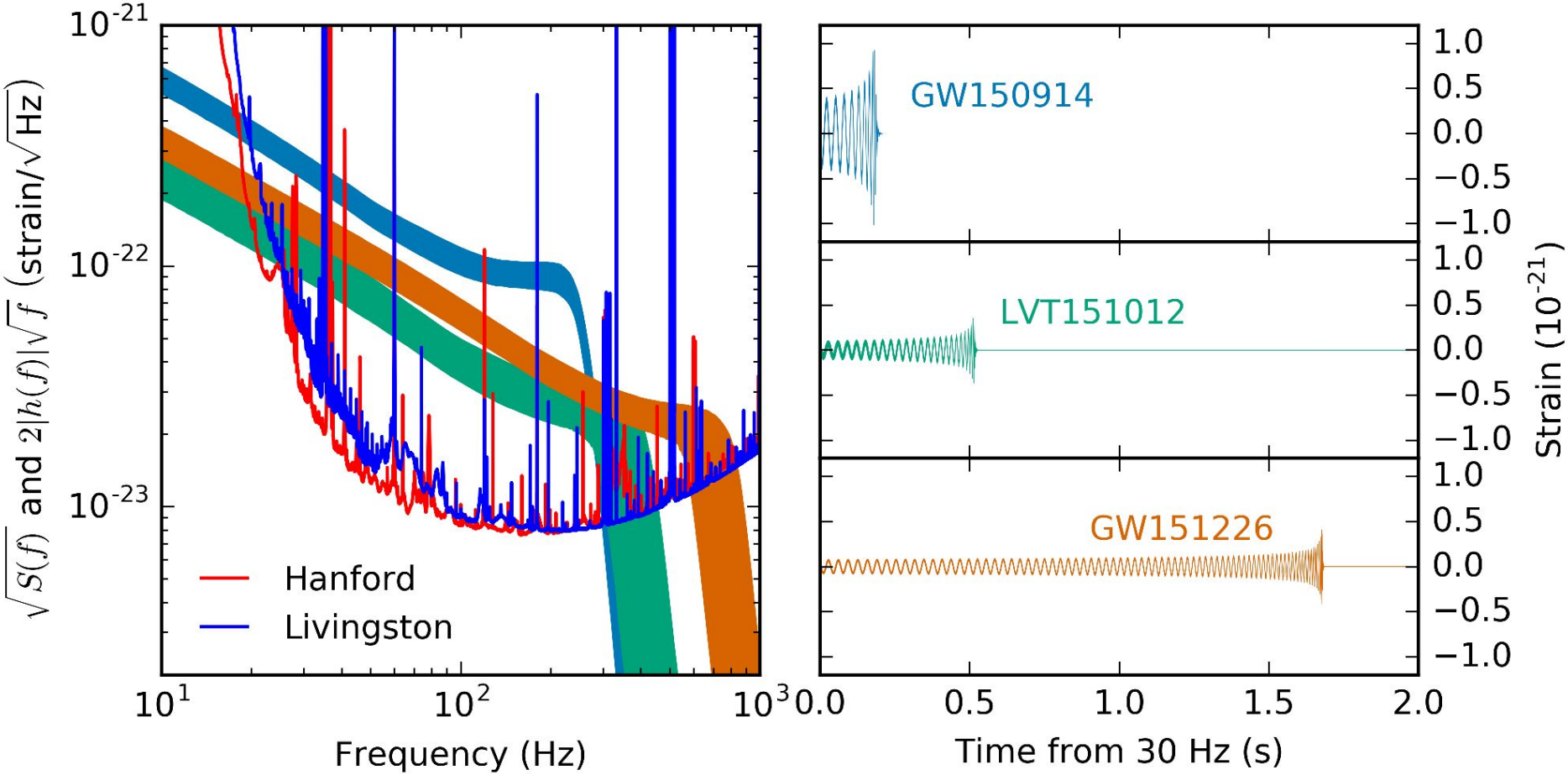
LVC arXiv:1602.03840

Glitch



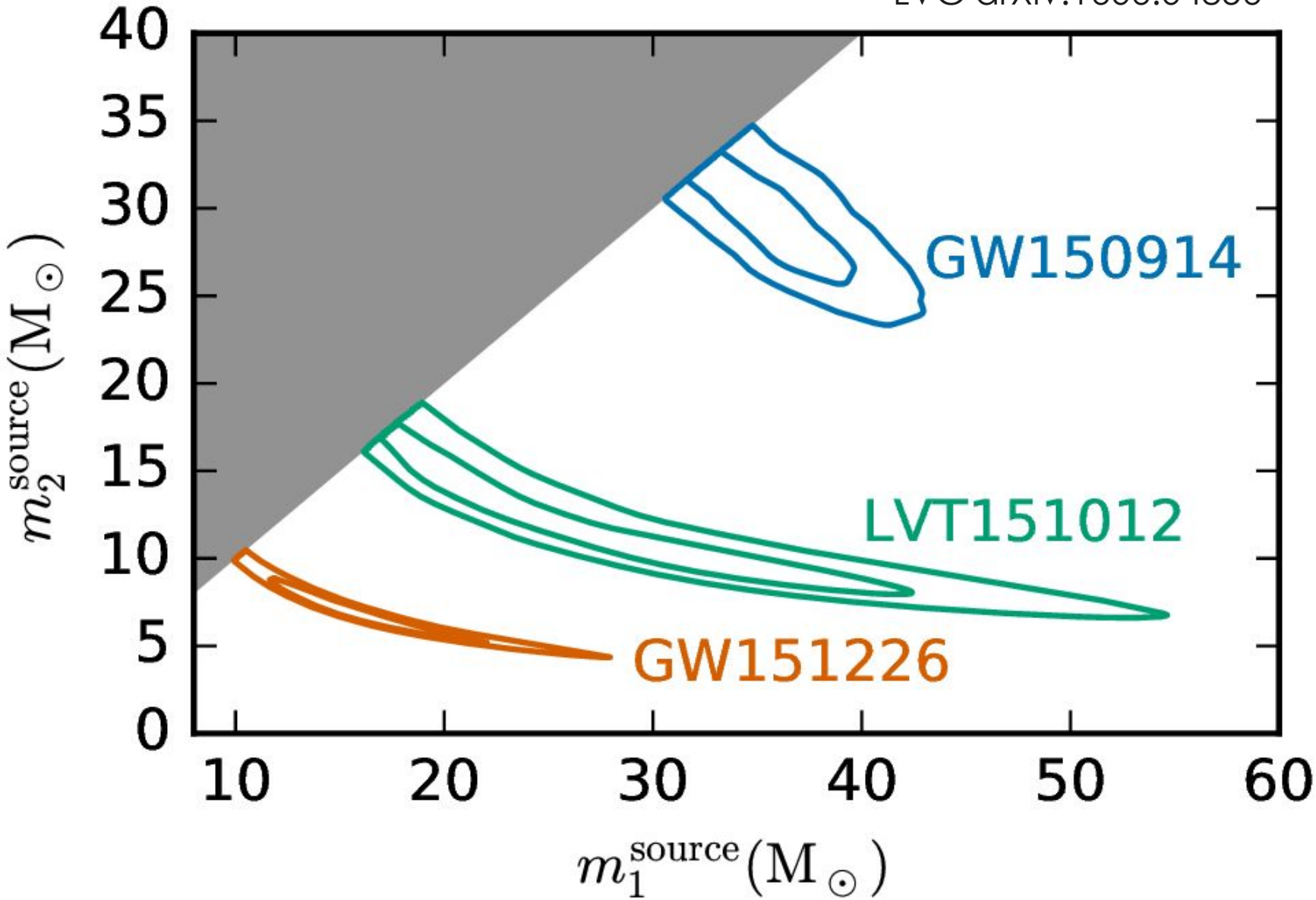
LVC arXiv:1710.05832

Gravitational-wave signals

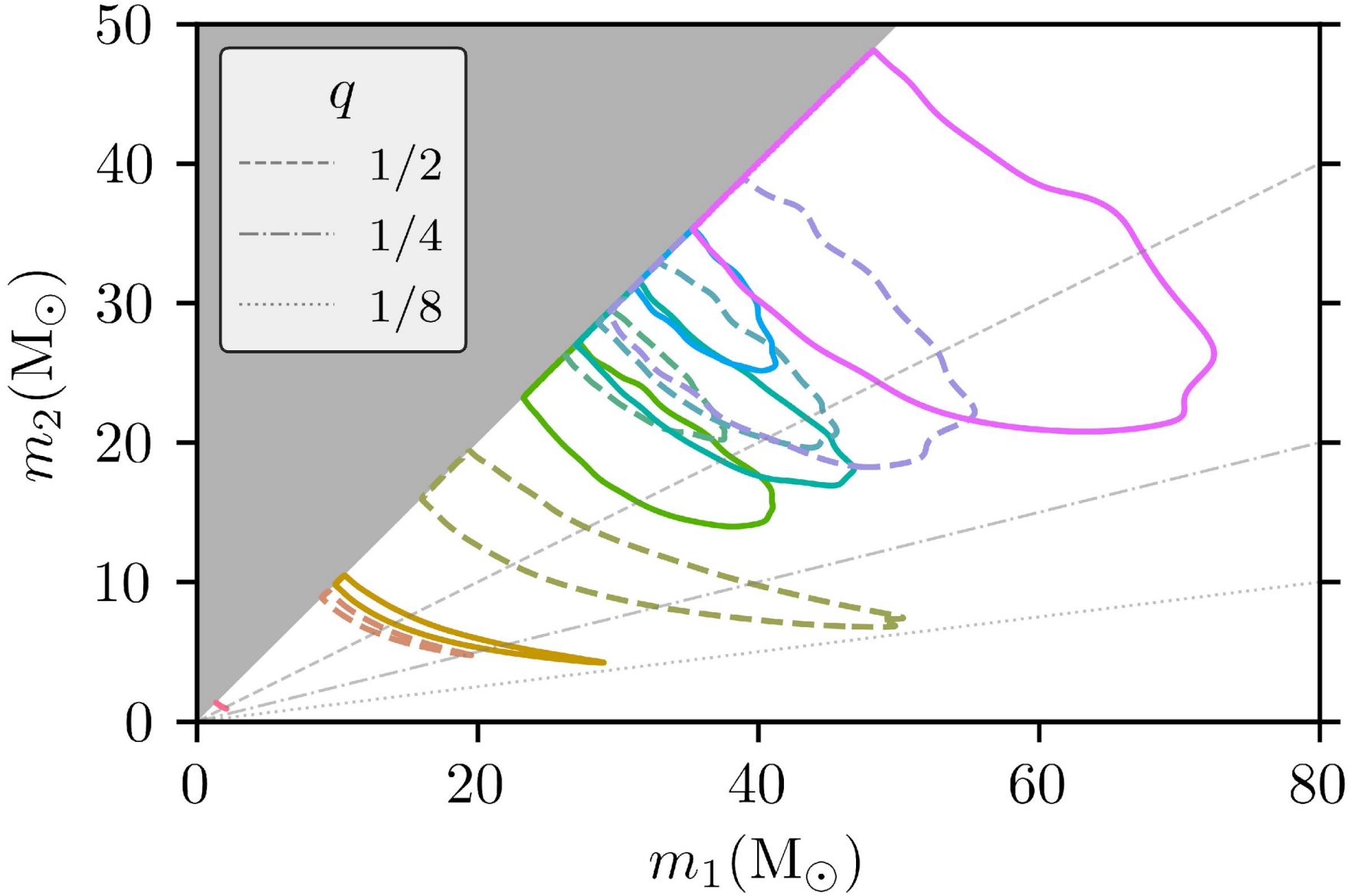


LVC arXiv:1606.04856

LVC arXiv:1606.04856

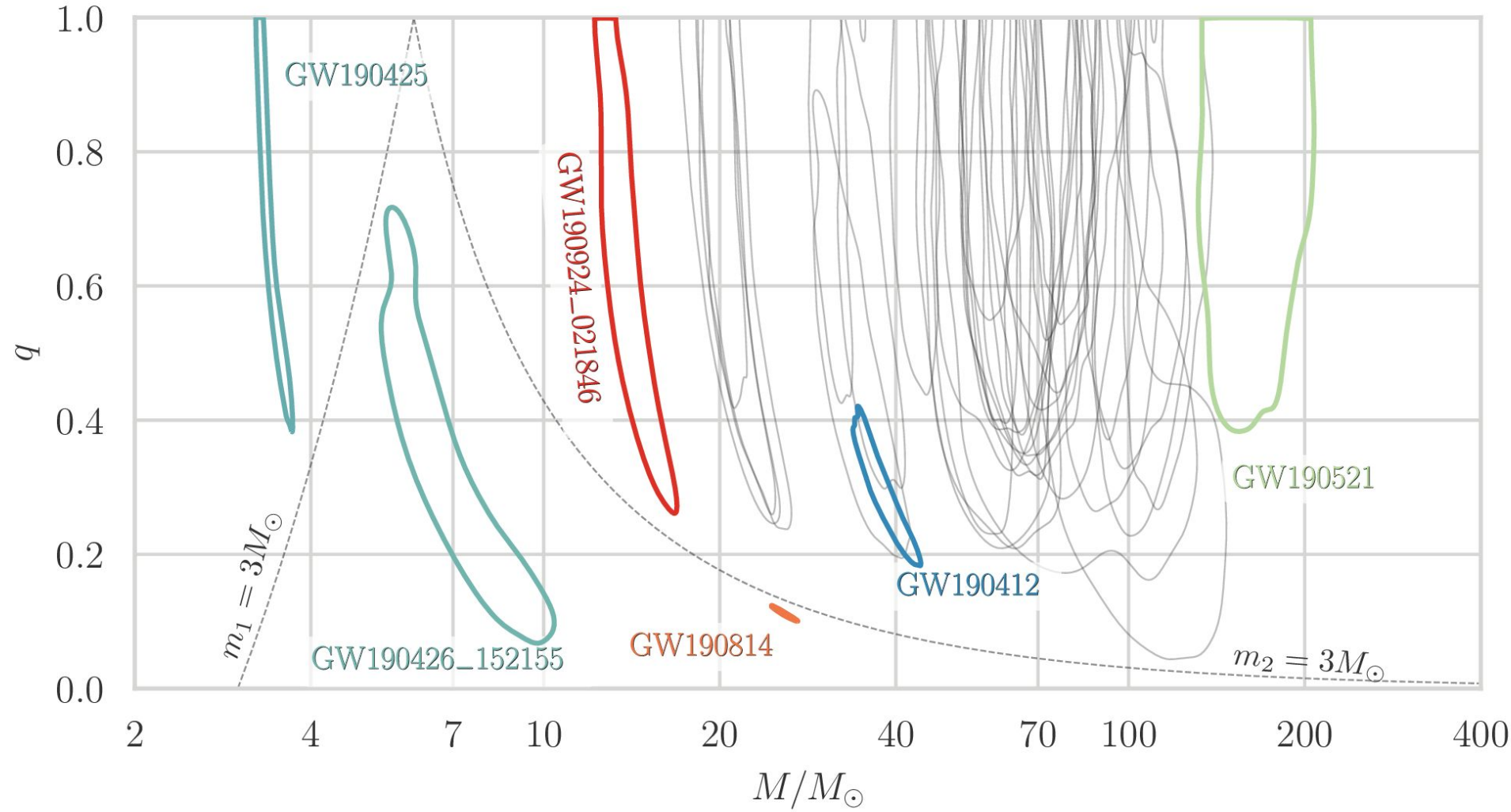


LVC arXiv:1811.12907



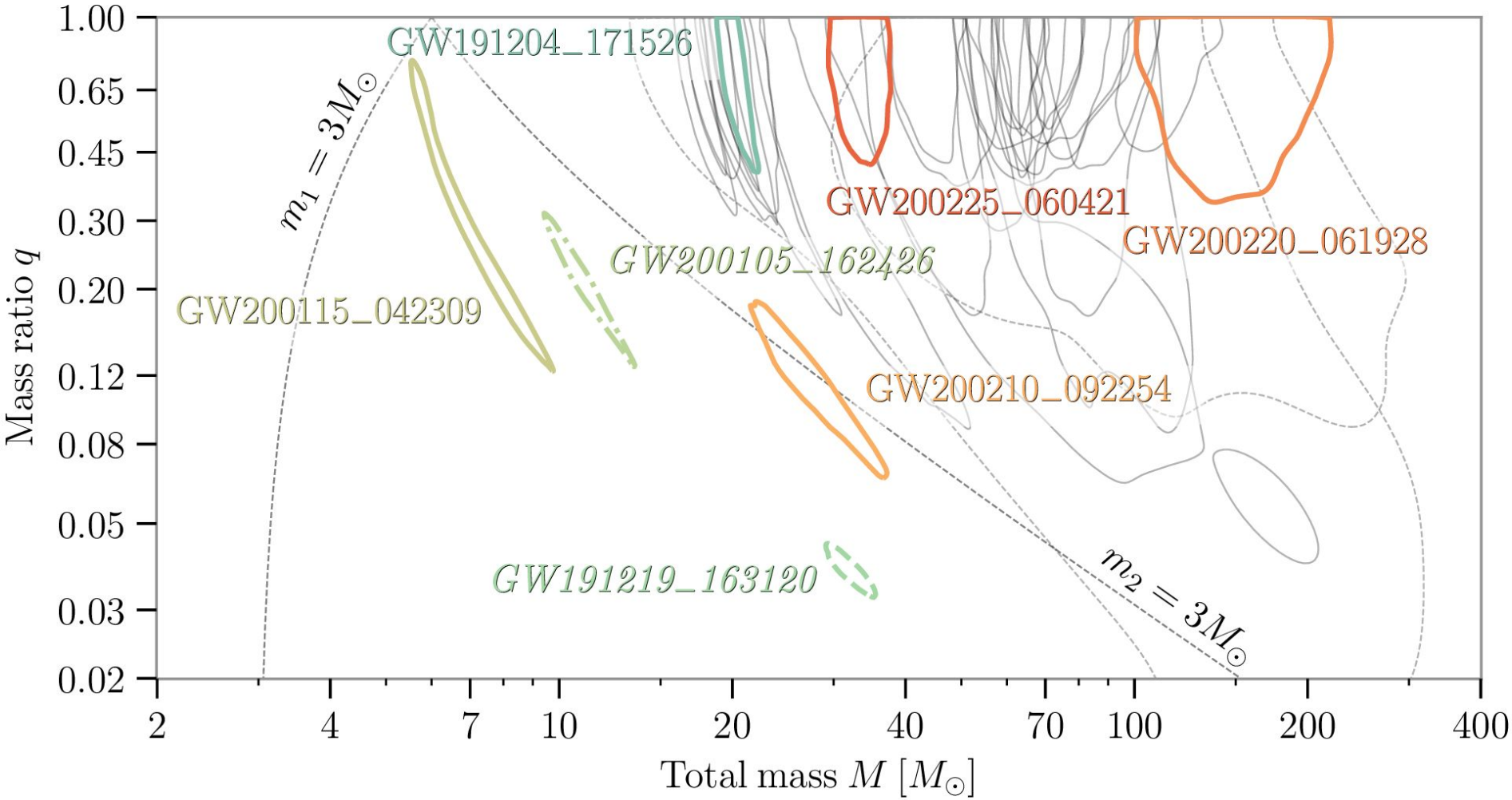
GW170817 GW151226 GW170104 GW170809 GW150914 GW170729
GW170608 GW151012 GW170814 GW170818 GW170823

LVC arXiv:2010.14527



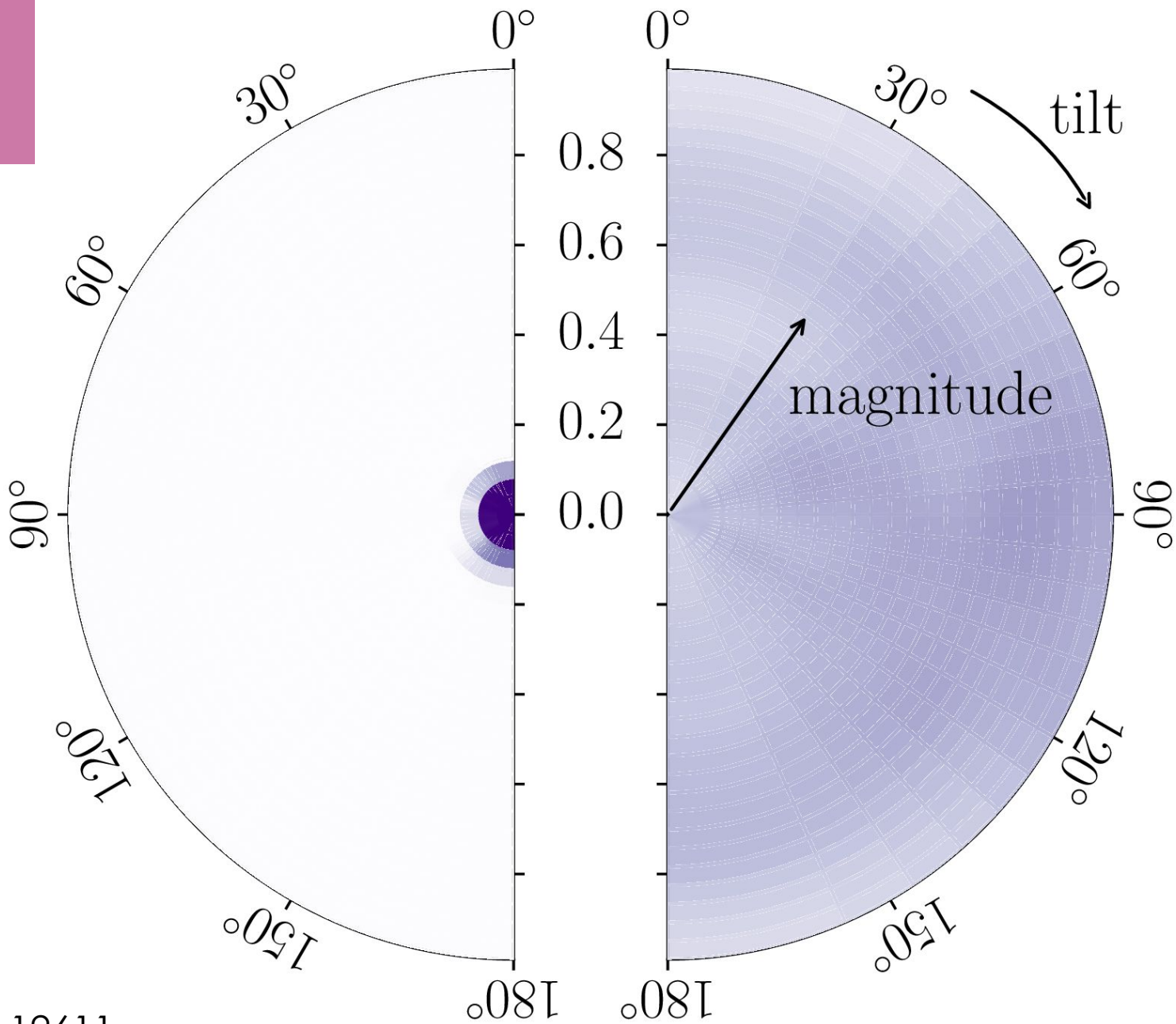
$$q = m_1/m_2 \qquad M = m_1 + m_2$$

LVK arXiv:2111.03606



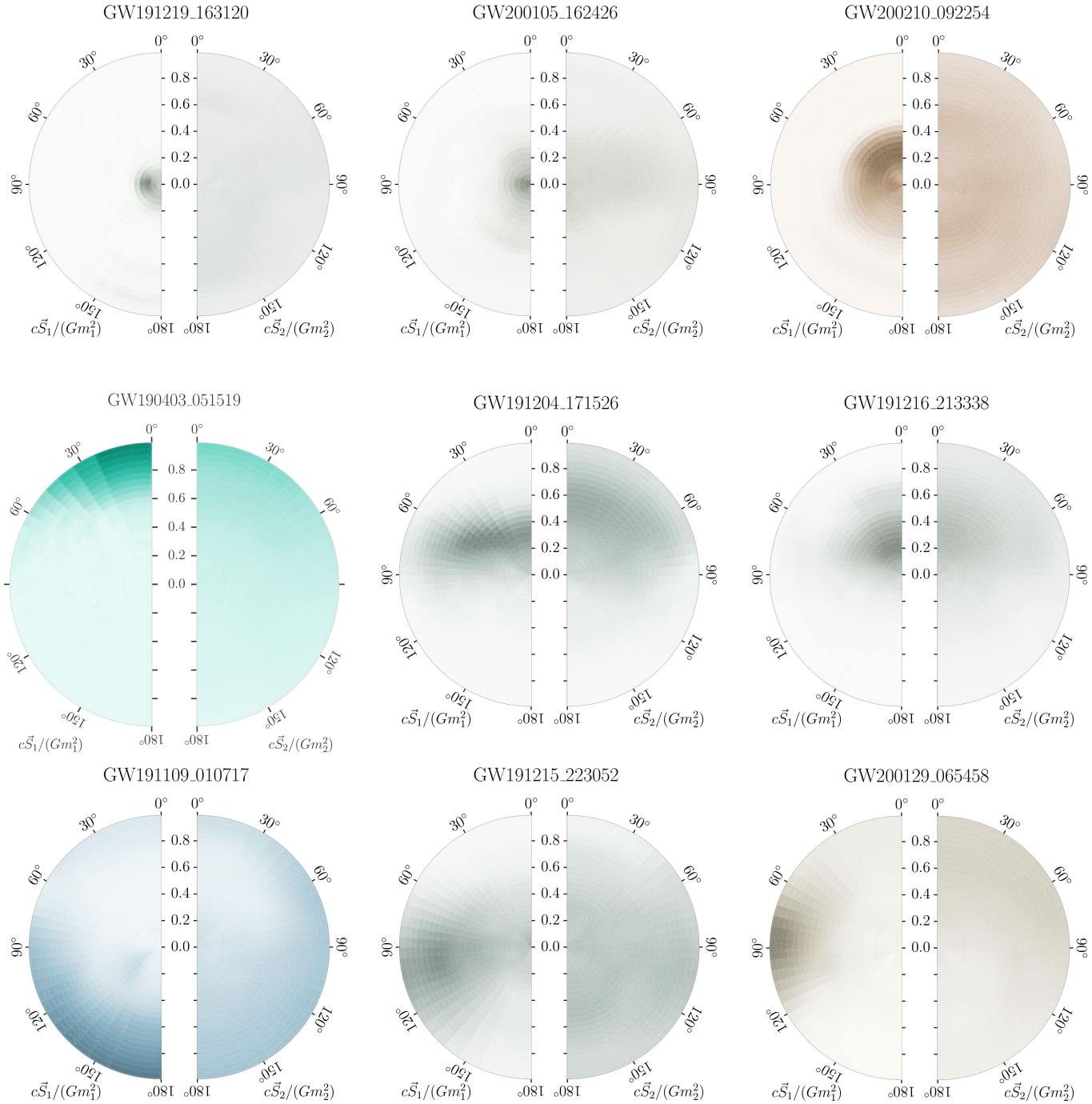
$$q = m_1/m_2 \qquad M = m_1 + m_2$$

Spin



LVC arXiv:2006.12611

Spin



LVC arXiv:2108.01045
LVK arXiv:2111.03606

Discoveries

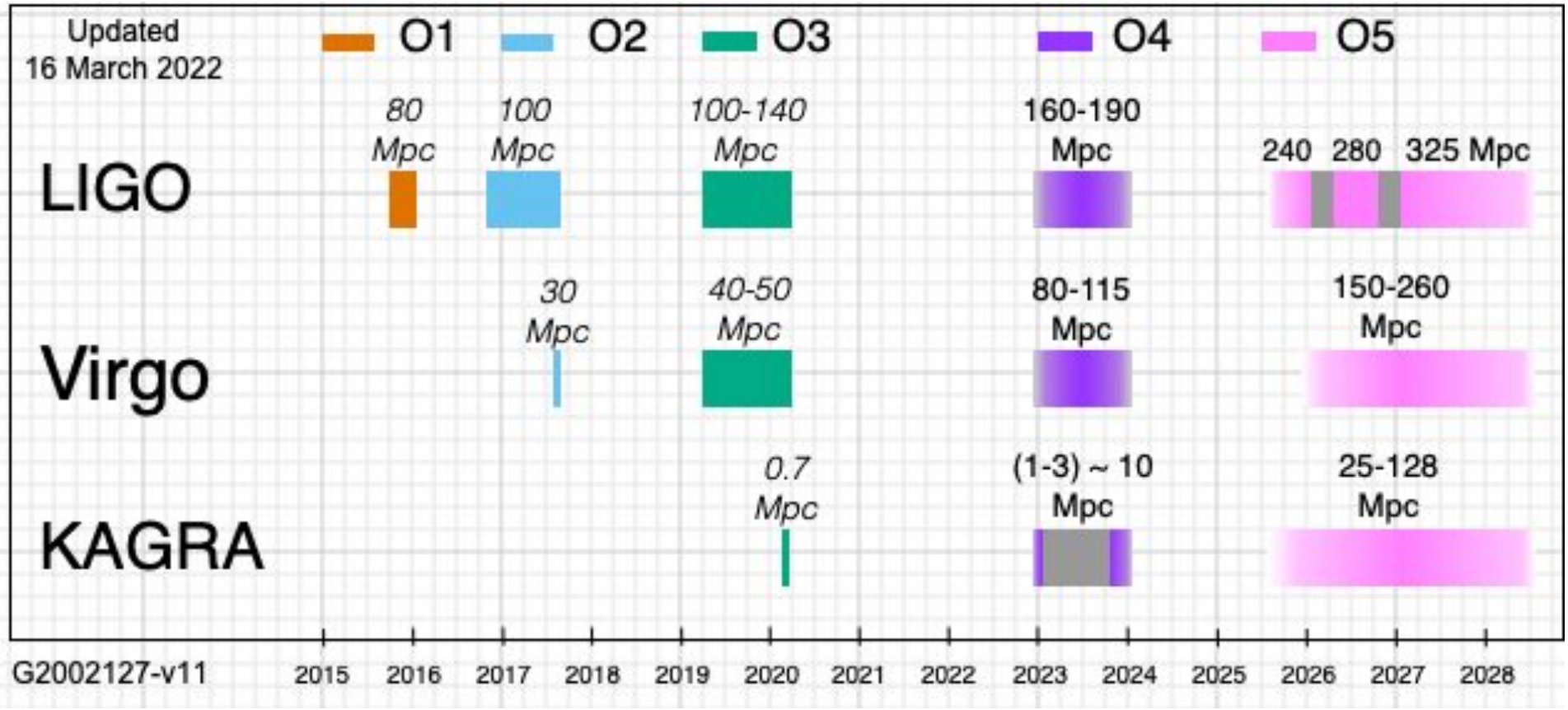
Data analysis

Future

Detector network

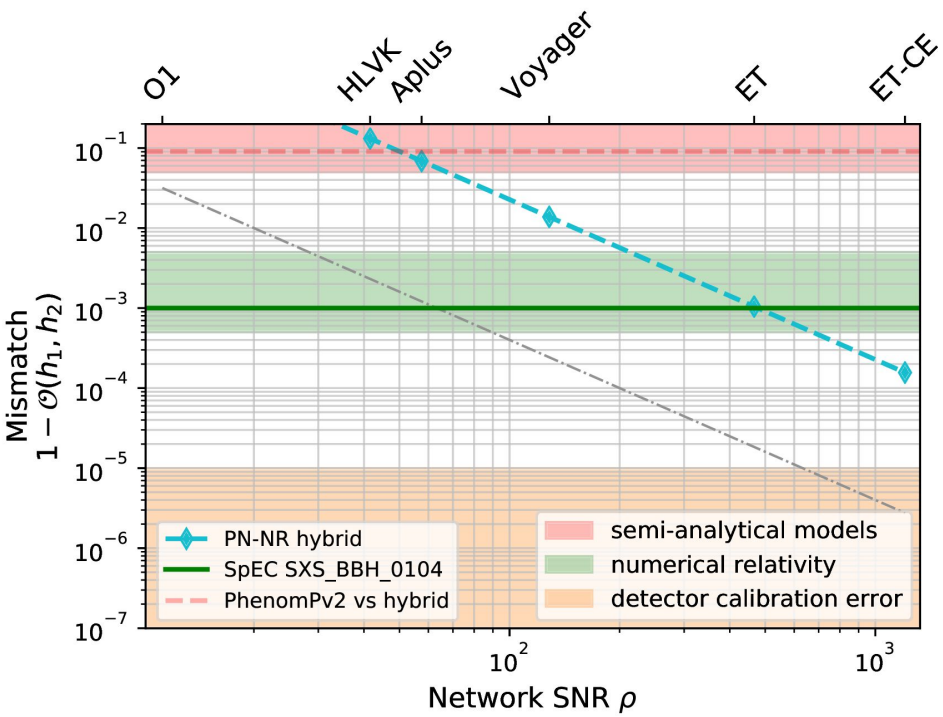
Google Maps

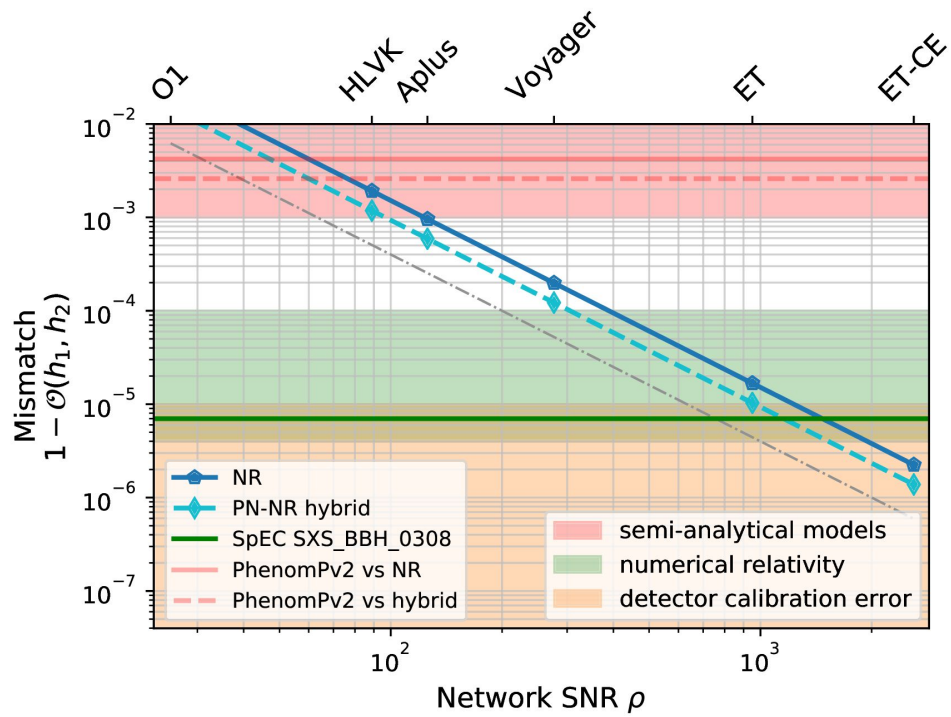
Observing plans



LVK www.ligo.org/scientists/GWEMalerts.php

Waveform accuracy





Pürrer & Haster arXiv:1912.10055

We have a diverse range of neutron star and black hole binary observations

Inferring source physics requires understanding the detectors and signals

We need fast, reliable and accurate waveforms covering parameter space

GWTC-3 has 90 compact binary candidates with probability of astrophysical origin > 50%

Sources have diverse properties: component masses range from ~1.2 solar masses to ~110 solar masses, and evidence for diverse spin magnitudes and orientations

Population provides insights into astrophysics, cosmology and fundamental physics

O4 (end of 2022) will see even more discoveries

arXiv:2111.03606 • arXiv:2111.03634 • arXiv:2111.03604 • arXiv:2112.06861
gw-openscience.org

Thank you

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LIGO Scientific Collaboration

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Bar-Ilan University
Bard College
Bellevue College
California State University Fullerton
MIT
Christopher Newport University
Colorado State University
Columbia University in the City of New York
Concordia University
Georgia Tech
Goddard
Haverford College
Hillsdale College
LSU
Maastricht University
Marquette University
Missouri S&T
Montana State University
Montclair State University
Northwestern
PennState
RIT
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ICTS Centre for Theoretical Sciences
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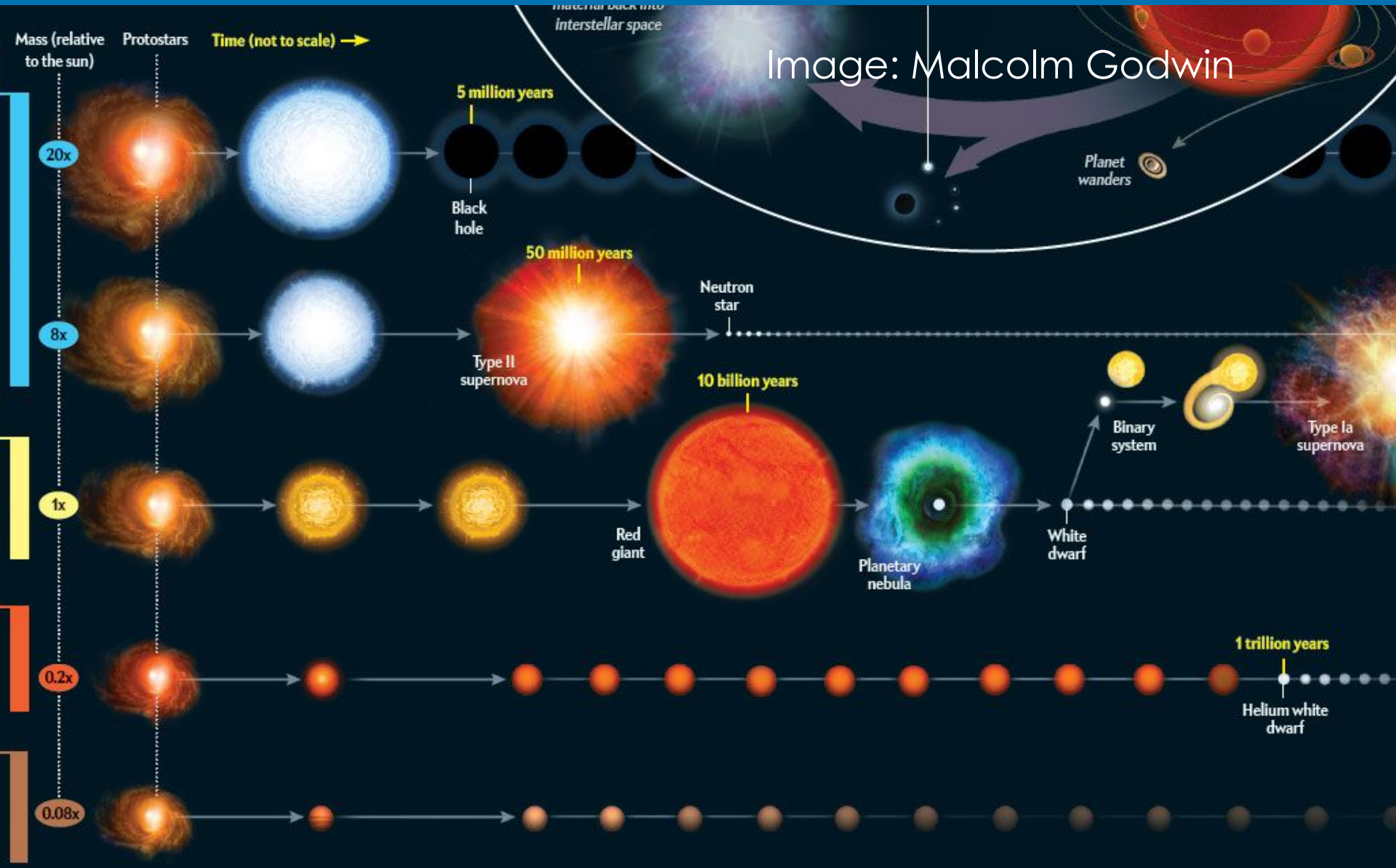
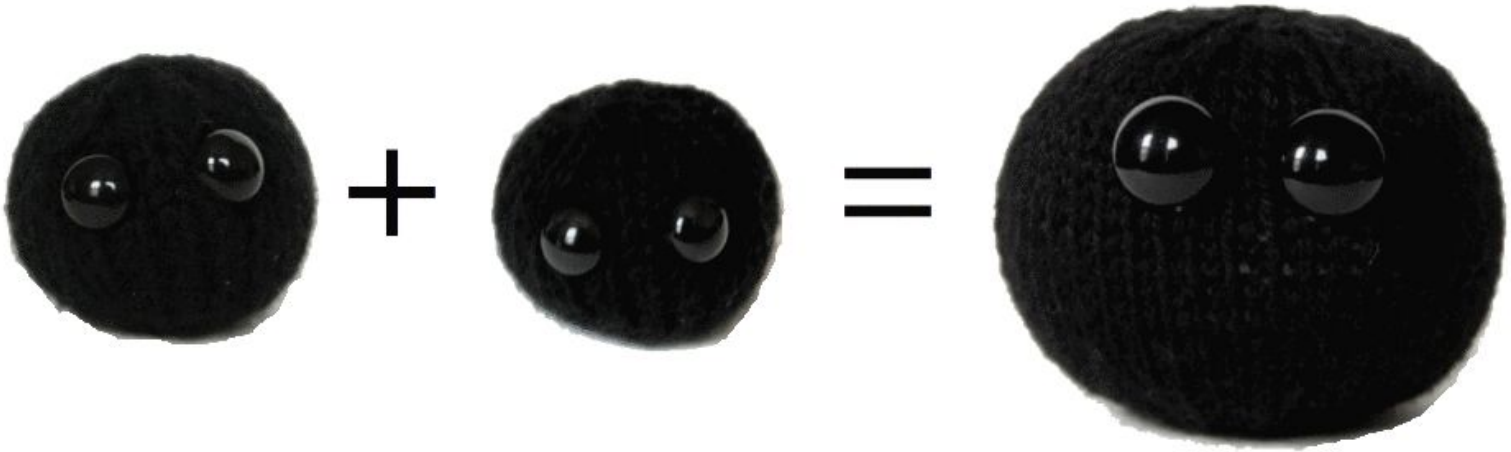
DCSEM
HRCAT
NIMS
KISTI 한국과학기술정보연구원
한양대학교 Hanyang University
UNIST
인제대학교 Inje University
LISC LIGO-India Scientific Collaboration
IUCAA
KASI Korea Astronomy and Space Science Institute
Sung Kyun Kwan University
Korean Gravitational Wave Group

Stellar remnants



Hierarchical mergers



Finding signals

Probability of astrophysical origin

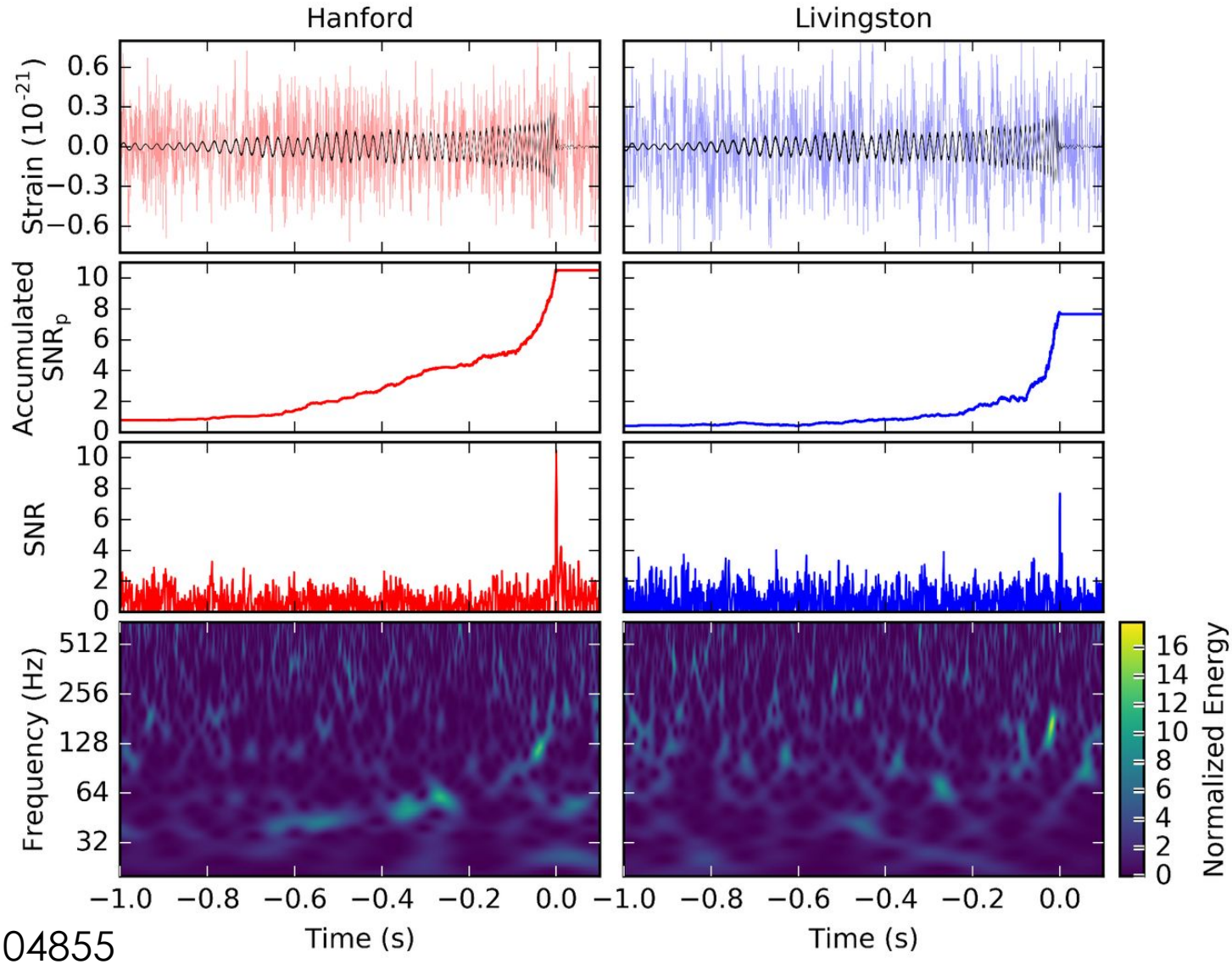
$$p_{\mathrm{astro}} = \frac{\mathrm{TAR}}{\mathrm{FAR} + \mathrm{TAR}}$$

False alarm rate

True alarm rate

For more: Farr *et al*. arXiv:1302.5341 LVC arXiv:1602.03842 Roulet *et al*. arXiv:2008.07014

Matched filtering

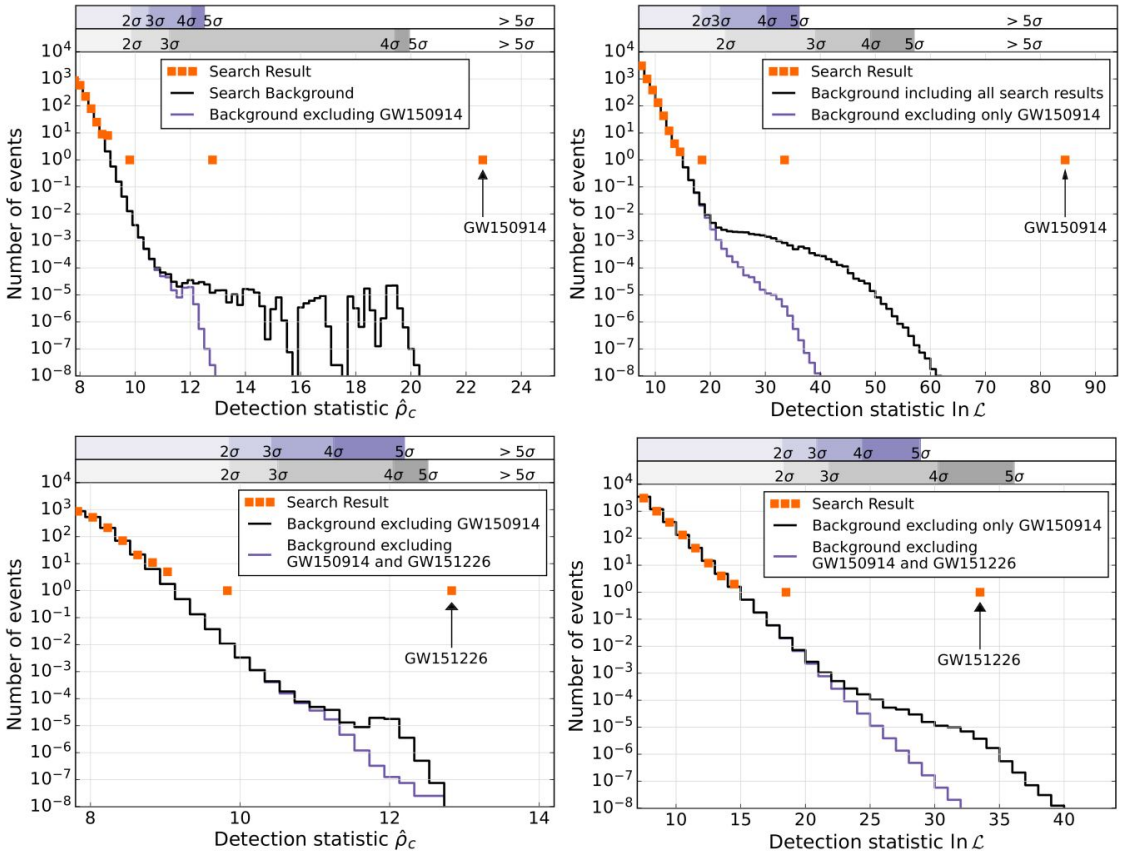


LVC
arXiv:1606.04855

Matched filtering

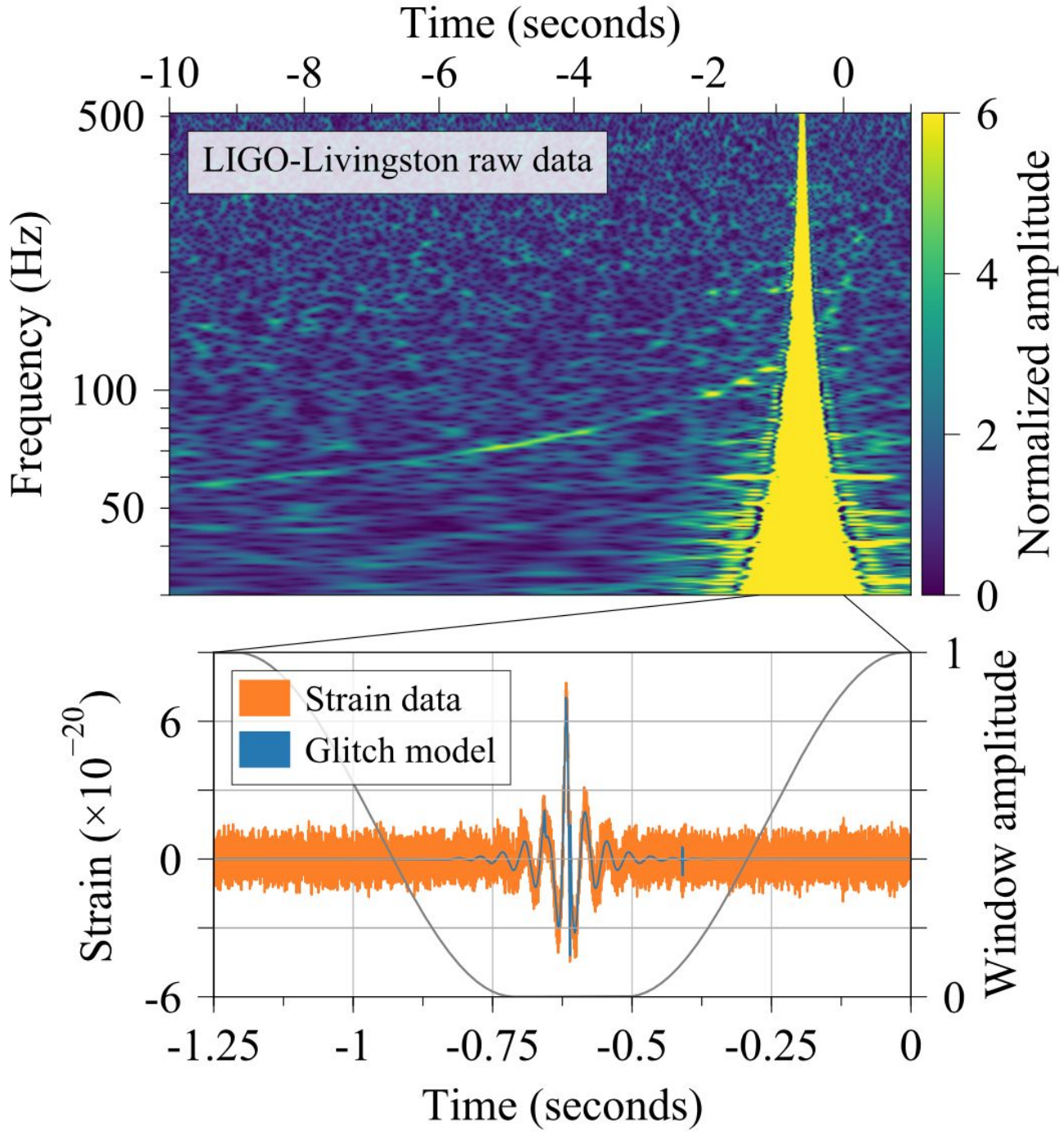
1. Template bank to filter data
2. Understanding of background noise
3. Efficient algorithms

For more: LVC
arXiv:1602.03839
arXiv:1908.11170



LVC arXiv:1606.04856

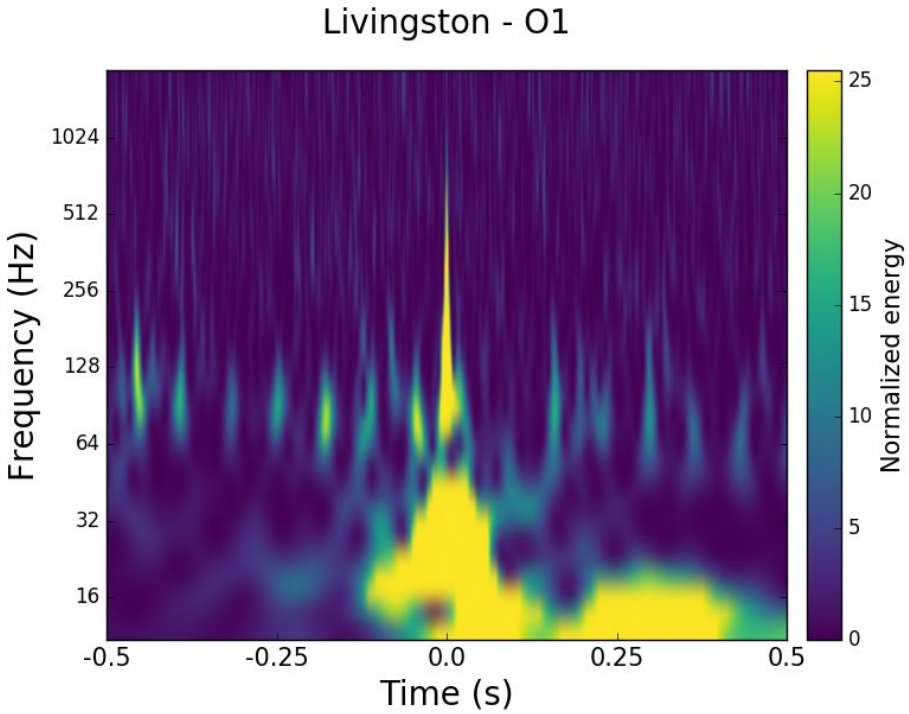
Glitch

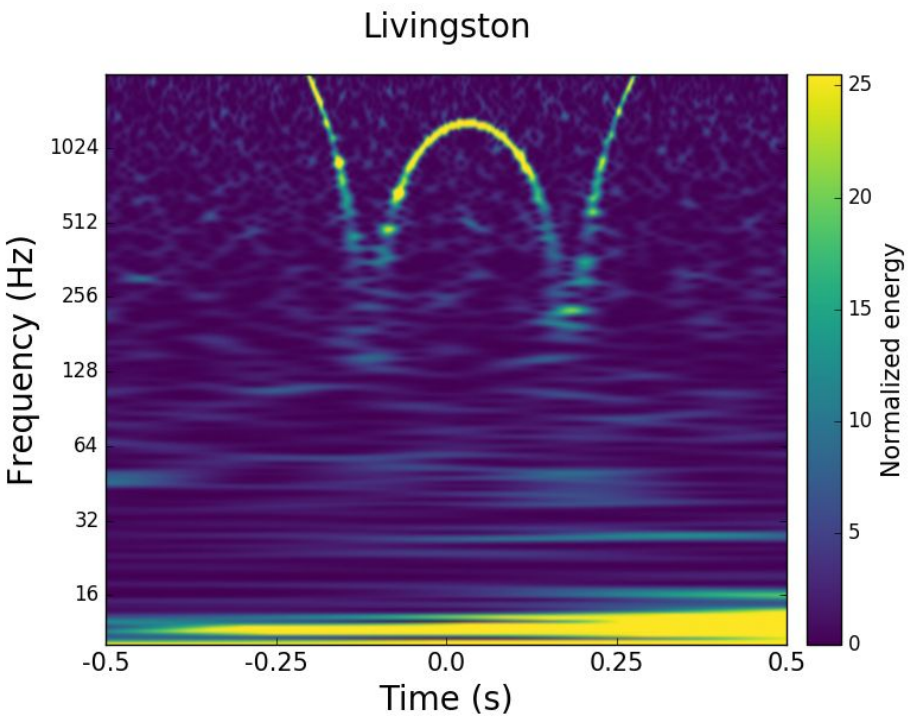


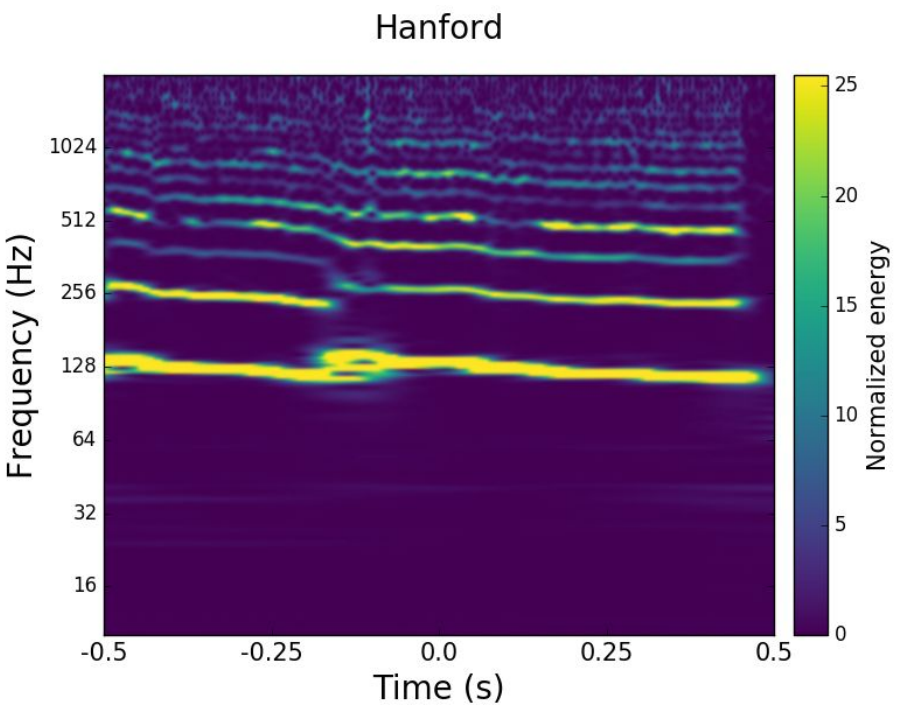
LVC arXiv:1710.05832

Glitch zoo

gravityspy.org
Zevin *et al*. arXiv:1611.04596
LVC arXiv:1602.03844

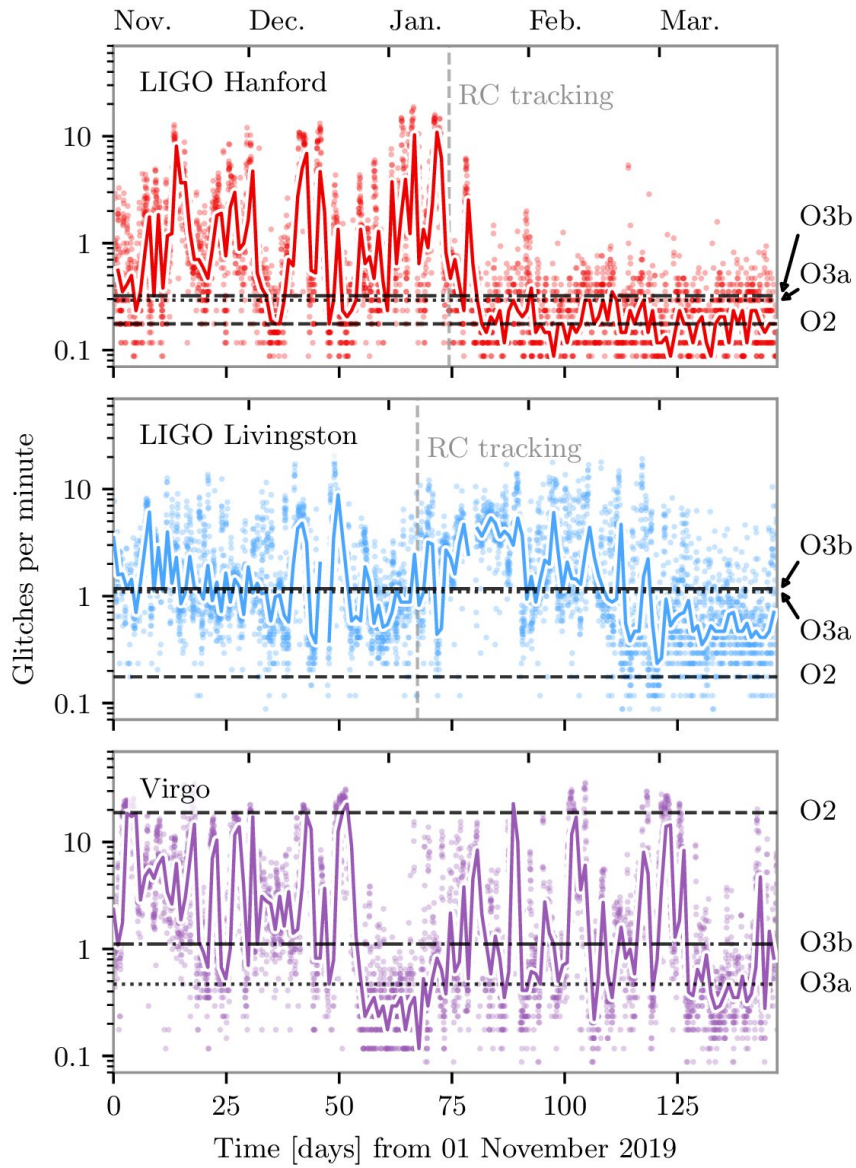






LVC Chirp

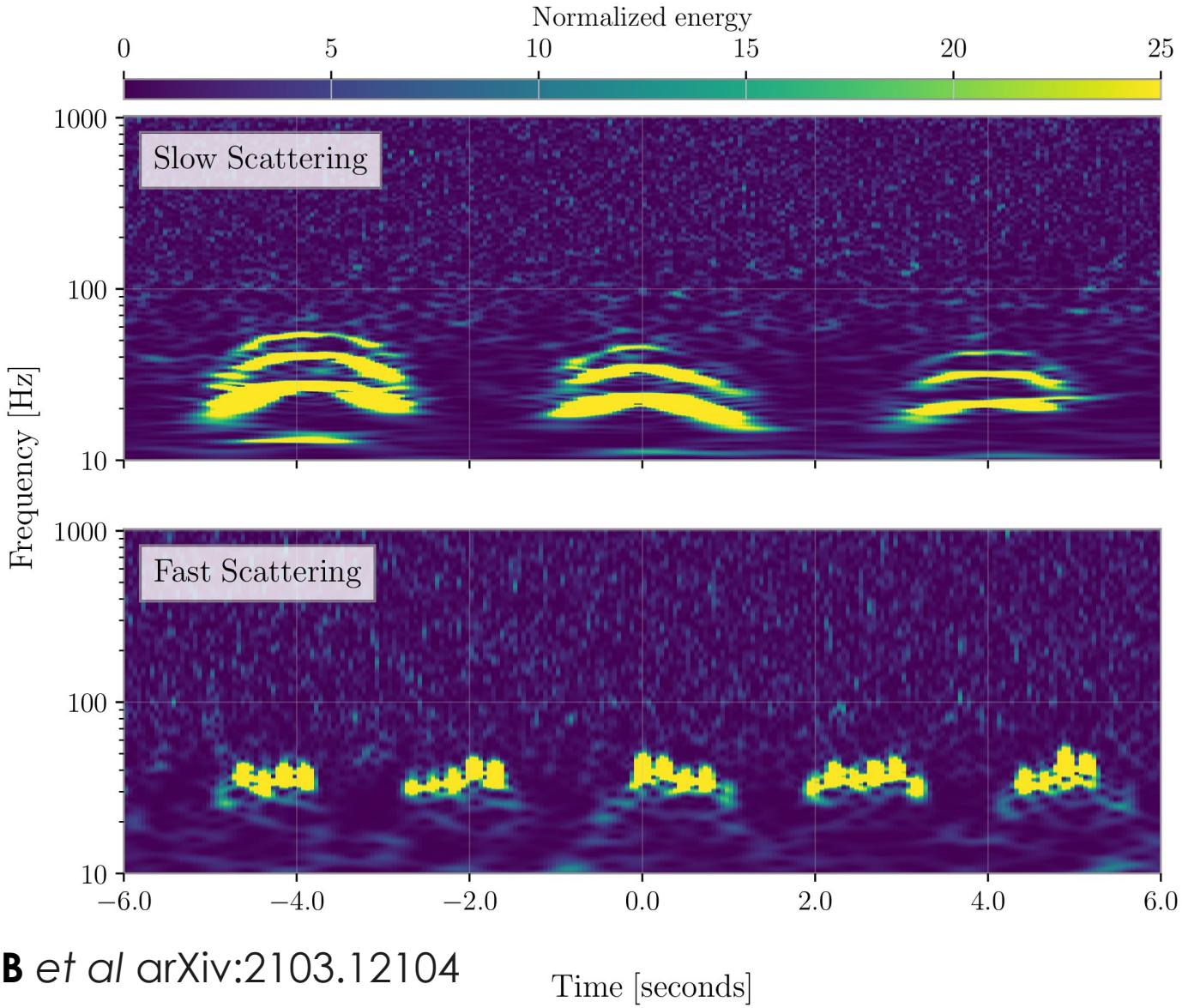
Transient noise in O3



LVK arXiv:2111.03606

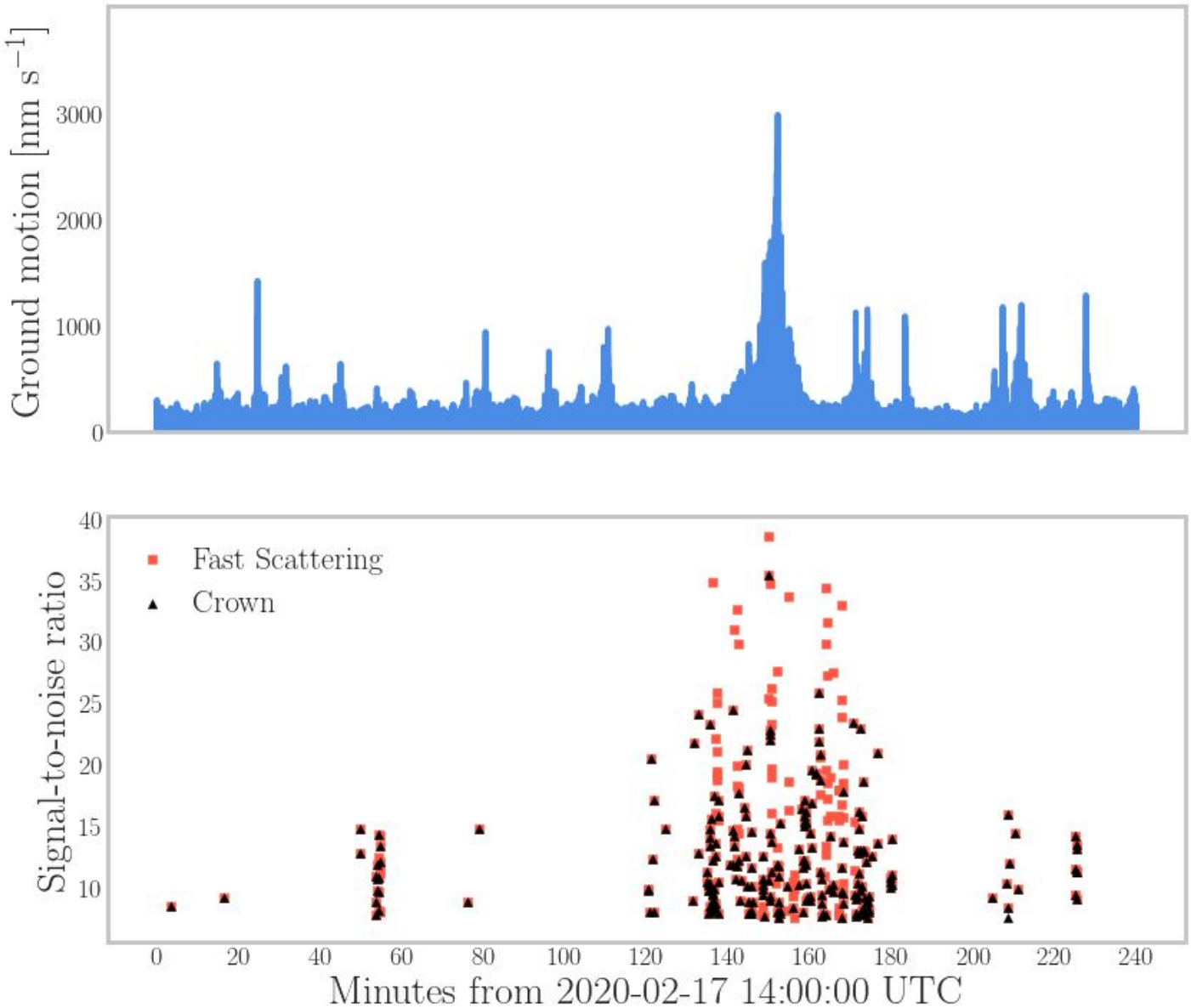
For more:
LVC arXiv:1602.03844
Davis *et al.*
arXiv:2101.11673

Scattering



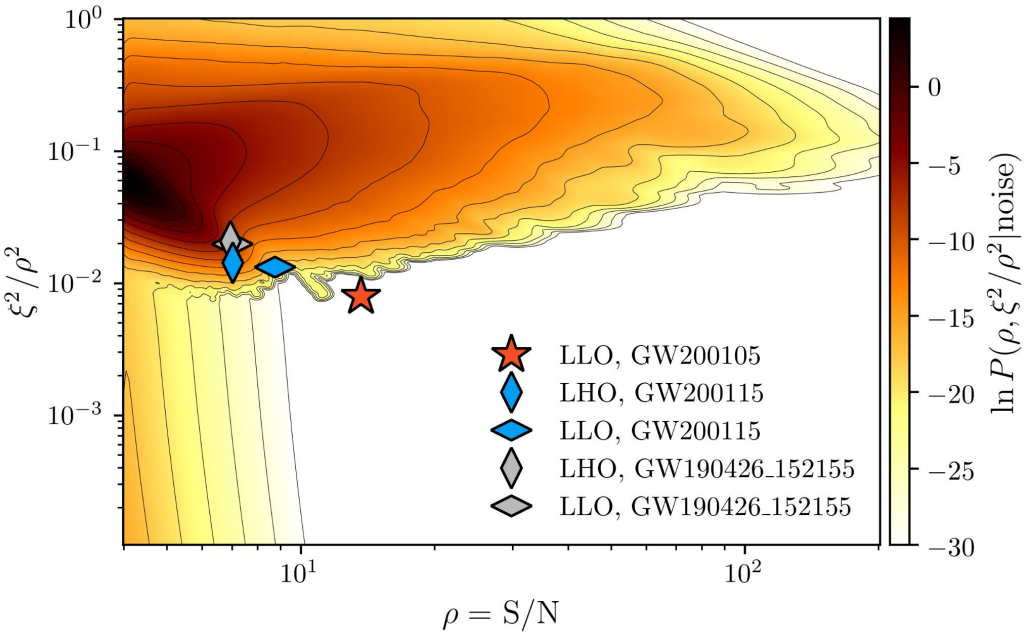
Soni, **CPLB** *et al* arXiv:2103.12104

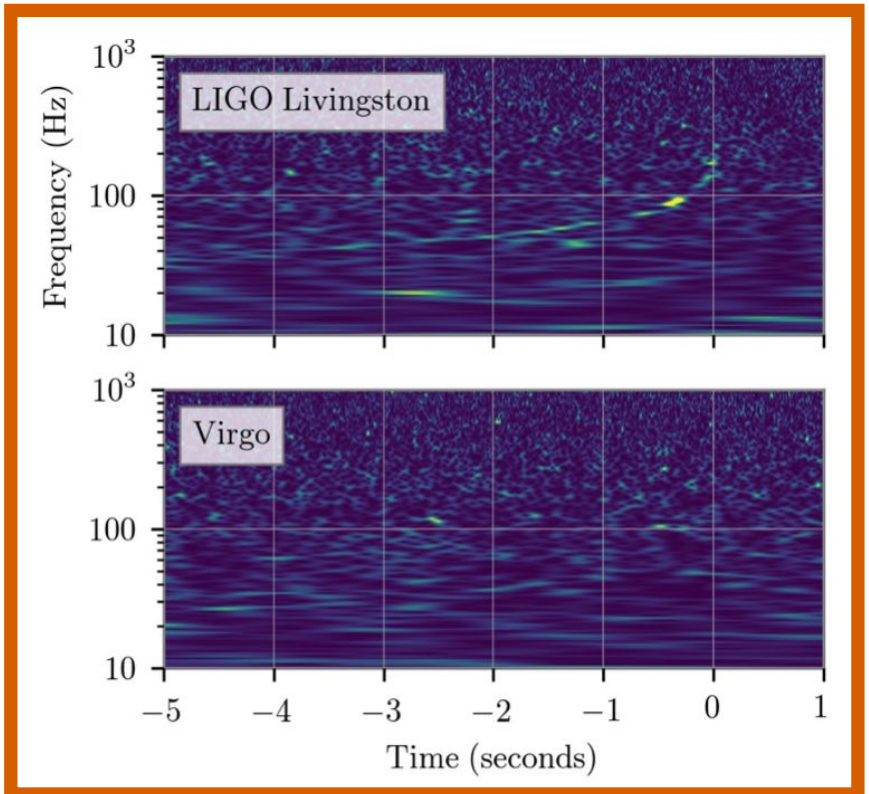
Origin



Soni, **CPLB** *et al*. arXiv:2103.12104

GW200105_162426





LVK arXiv:2106.15163

Bayes' theorem

Likelihood

Prior

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

Posterior

Evidence

Likelihood

Noise-weighting

$$p(d|\theta) \propto \exp\left[-\frac{1}{2}\sum_k \langle h_k(\theta) - d_k | h_k(\theta) - d_k \rangle\right]$$

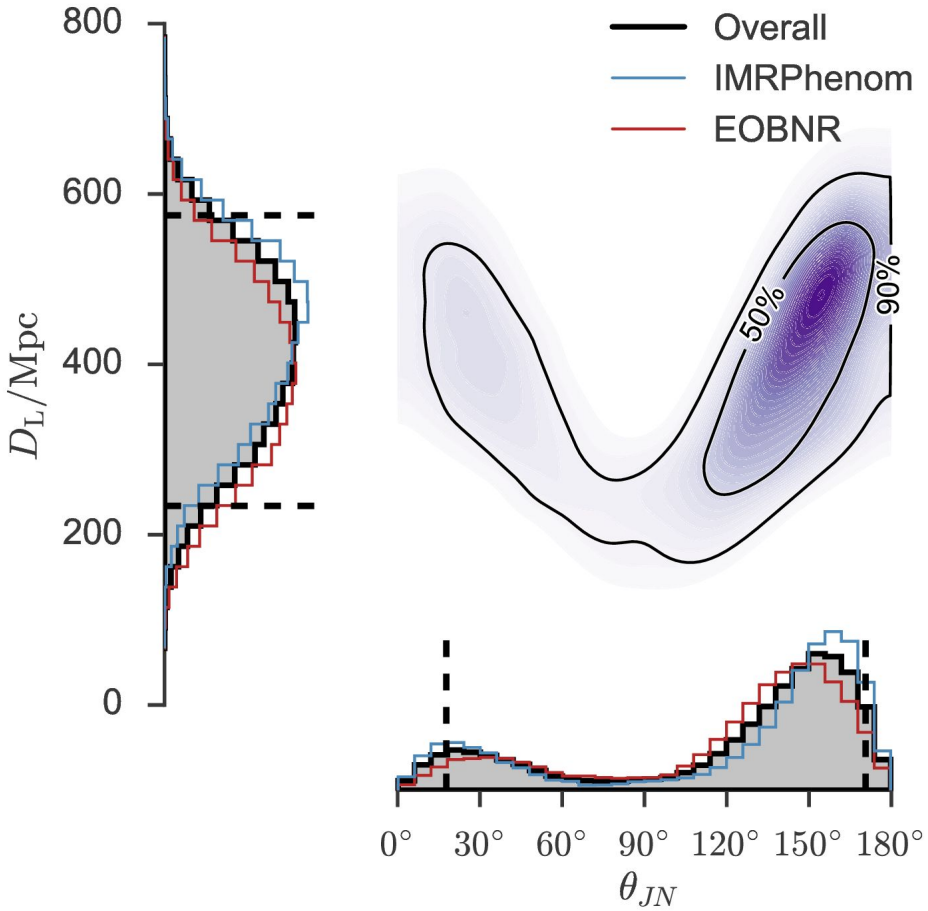
Calibration

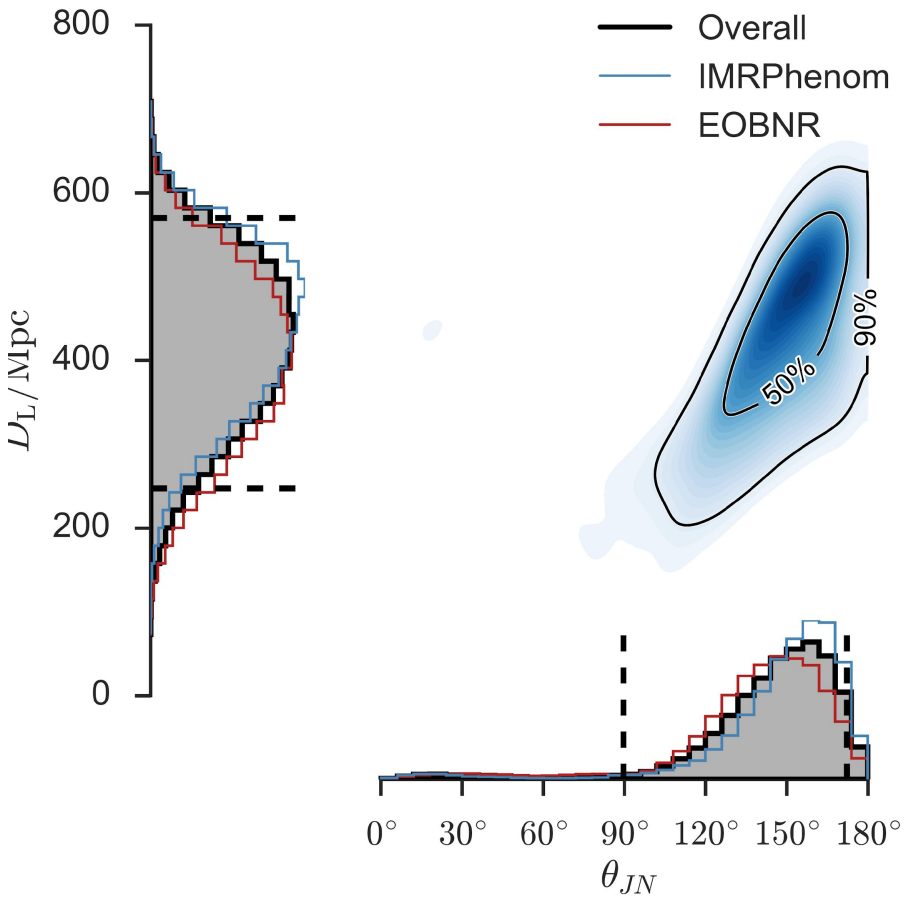
$$h_k(\theta) \rightarrow h_k(\theta)\,[1 + \delta A_k]\exp[i\delta\phi_k]$$

Waveform

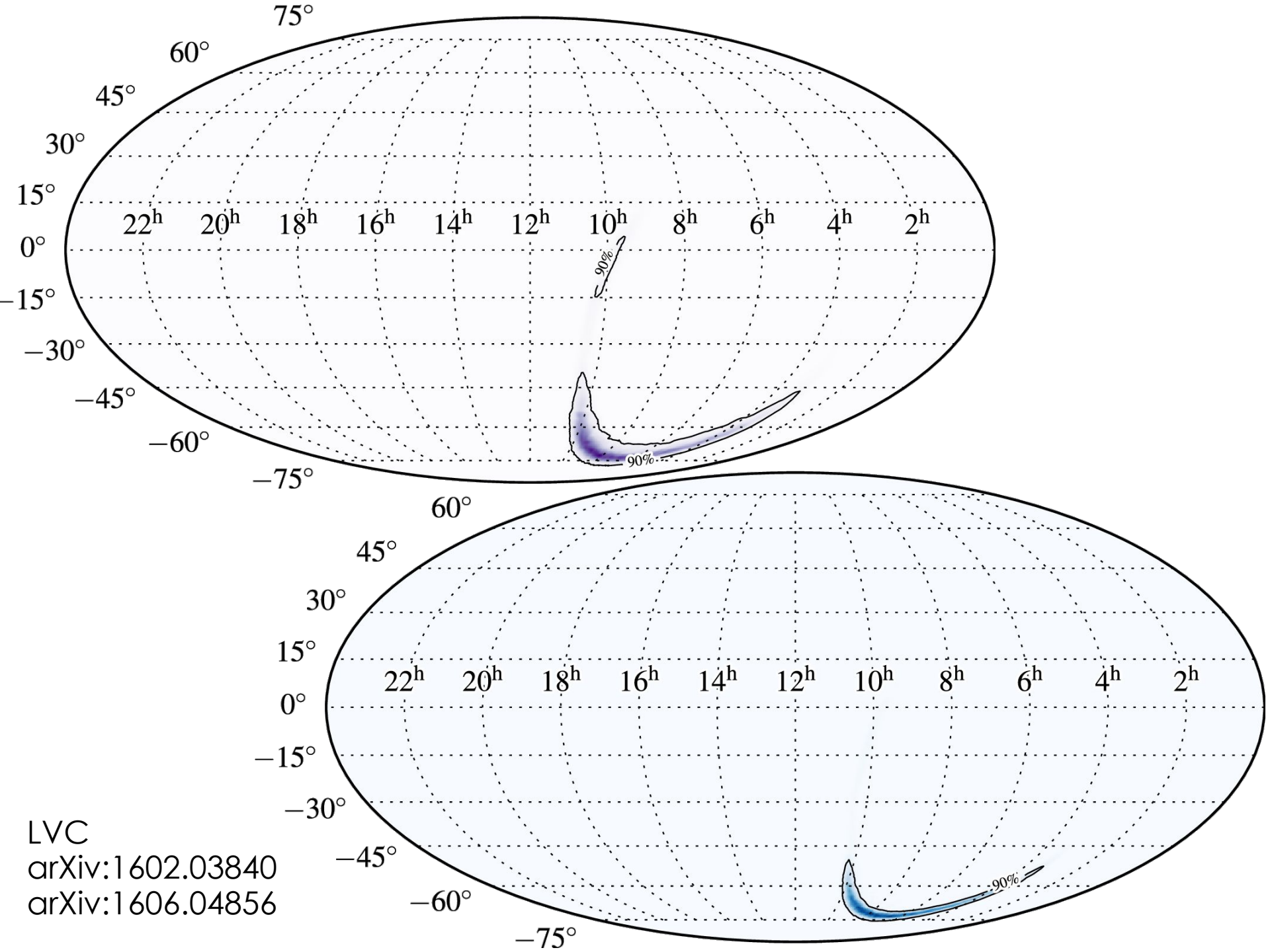
LVC arXiv:1602.03840

Inclination





LVC
arXiv:1602.03840
arXiv:1606.04856



LVC
arXiv:1602.03840
arXiv:1606.04856

Bayes' theorem

Likelihood

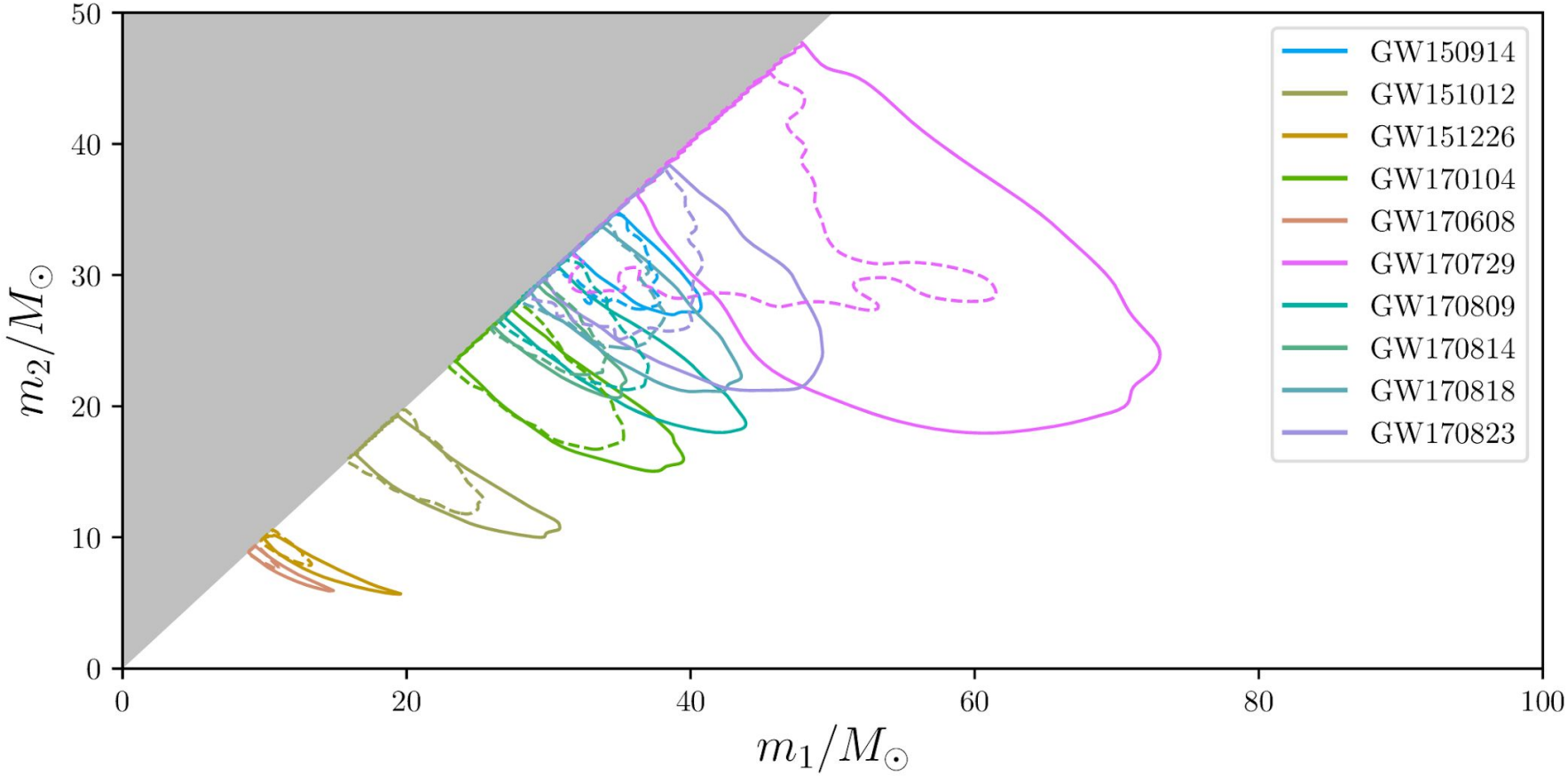
Prior

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

Posterior

Evidence

Population reweighting



Kimball, Talbot, **CPLB** *et al.* arXiv:2005.00023

Bayes' theorem

Evidence

Model prior

$$\boxed{p(\lambda|\{d\})} = \frac{\boxed{p(\{d\}|\lambda)}\,\boxed{p(\lambda)}}{p(\{d\})}$$

Model posterior

Chirp mass

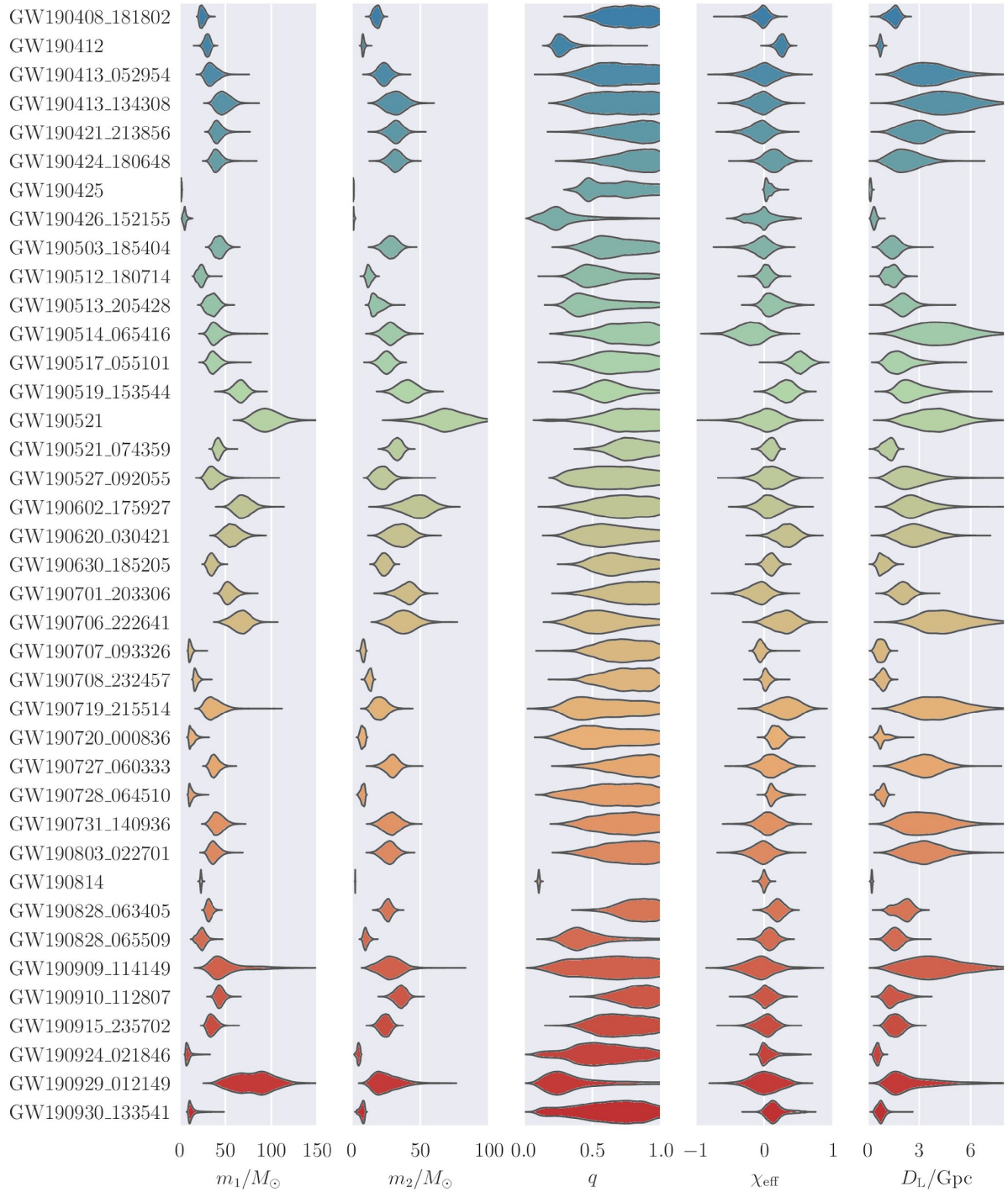
$$\mathcal{M}_{\mathrm{c}} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Chirp mass gives leading-order amplitude and phase evolution (Blanchet *et al*. arXiv:gr-qc/9501027 Poisson & Will arXiv:gr-qc/9502040)

Effective inspiral spin

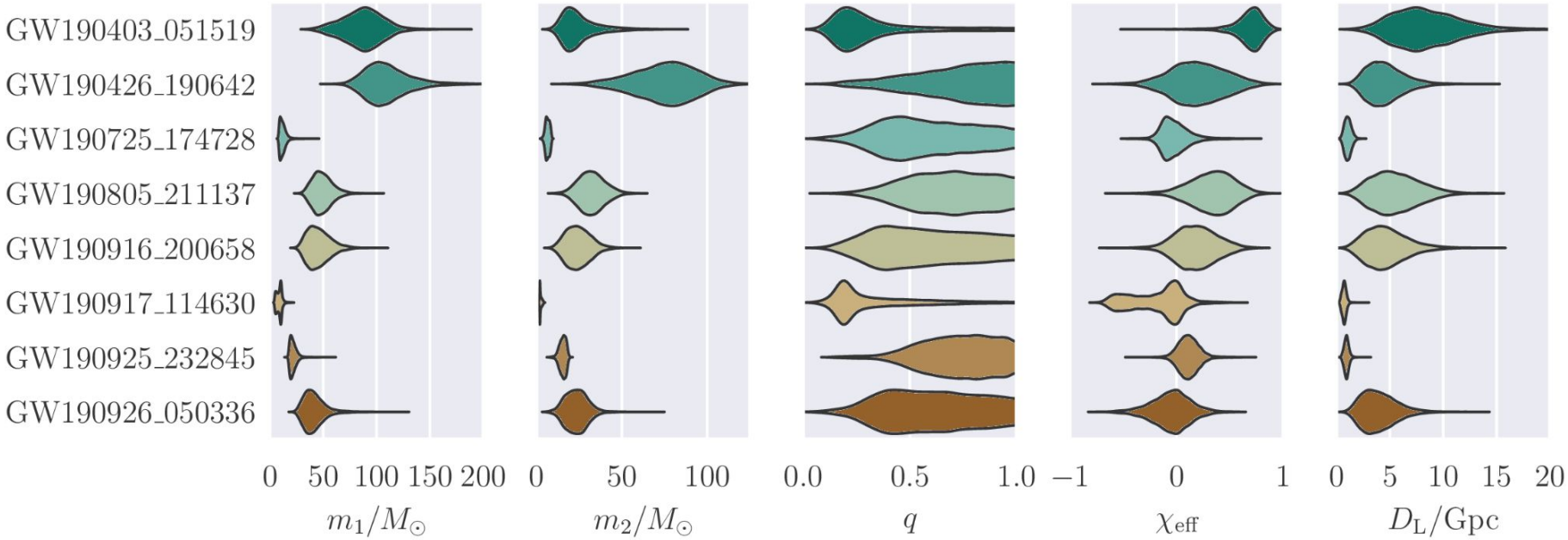
$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \hat{\boldsymbol{L}}$$

Most important combination of spins for evolution of inspiral (Ajith *et al*. arXiv:0909.2867, Santamaría *et* al. arXiv:1005.3306)



LVC arXiv:2010.14527

LVC arXiv:2108.01045



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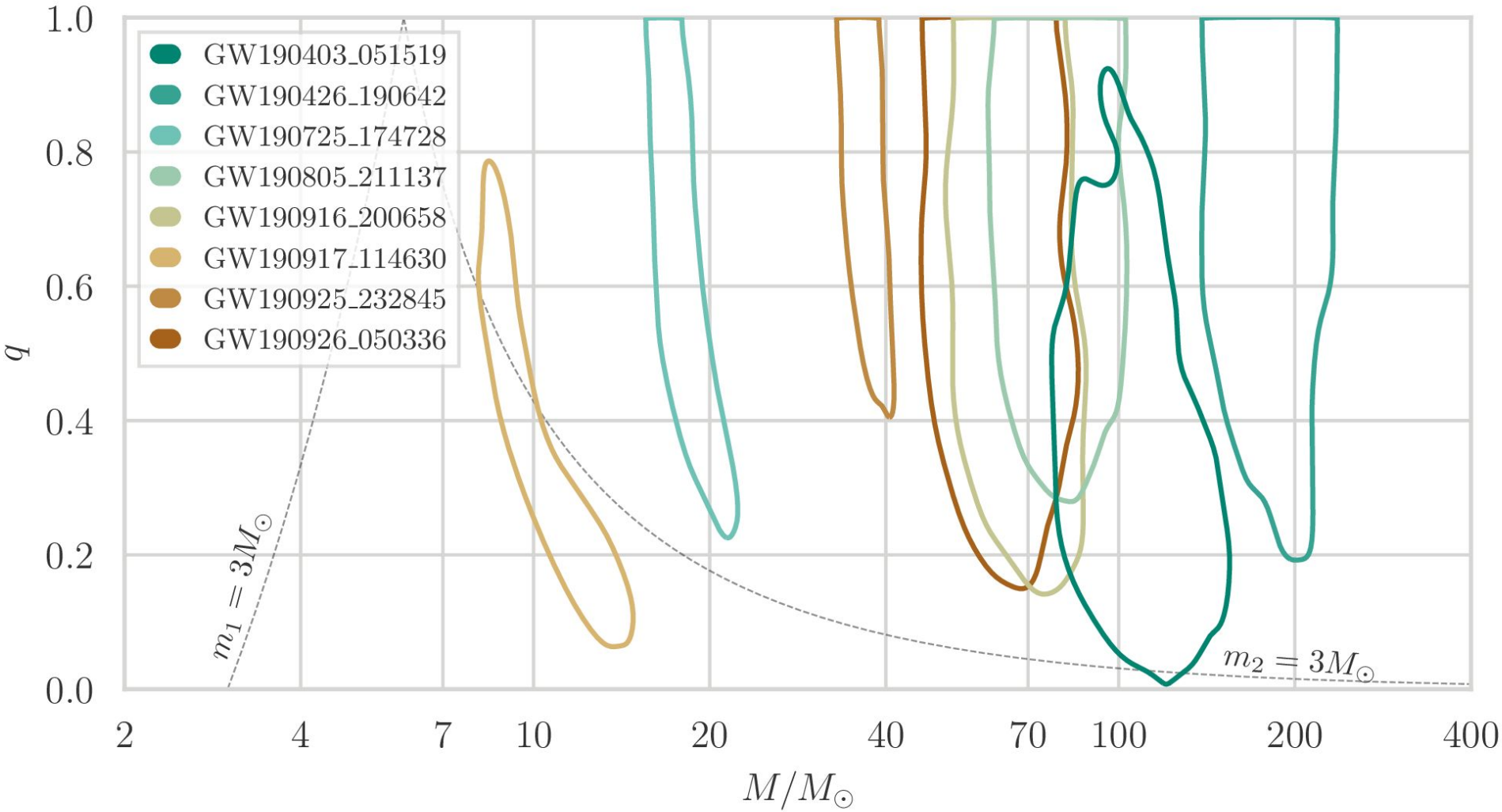
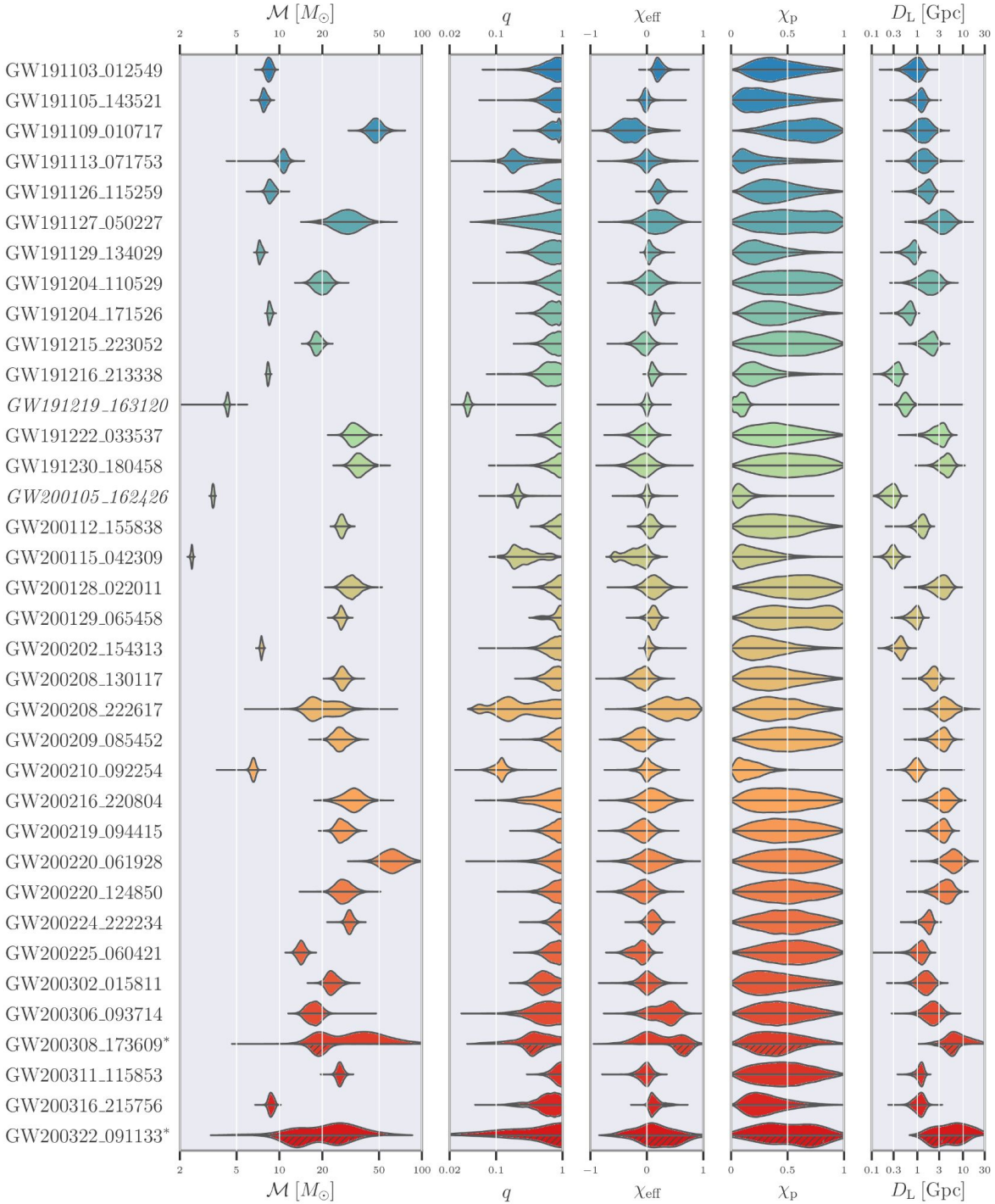
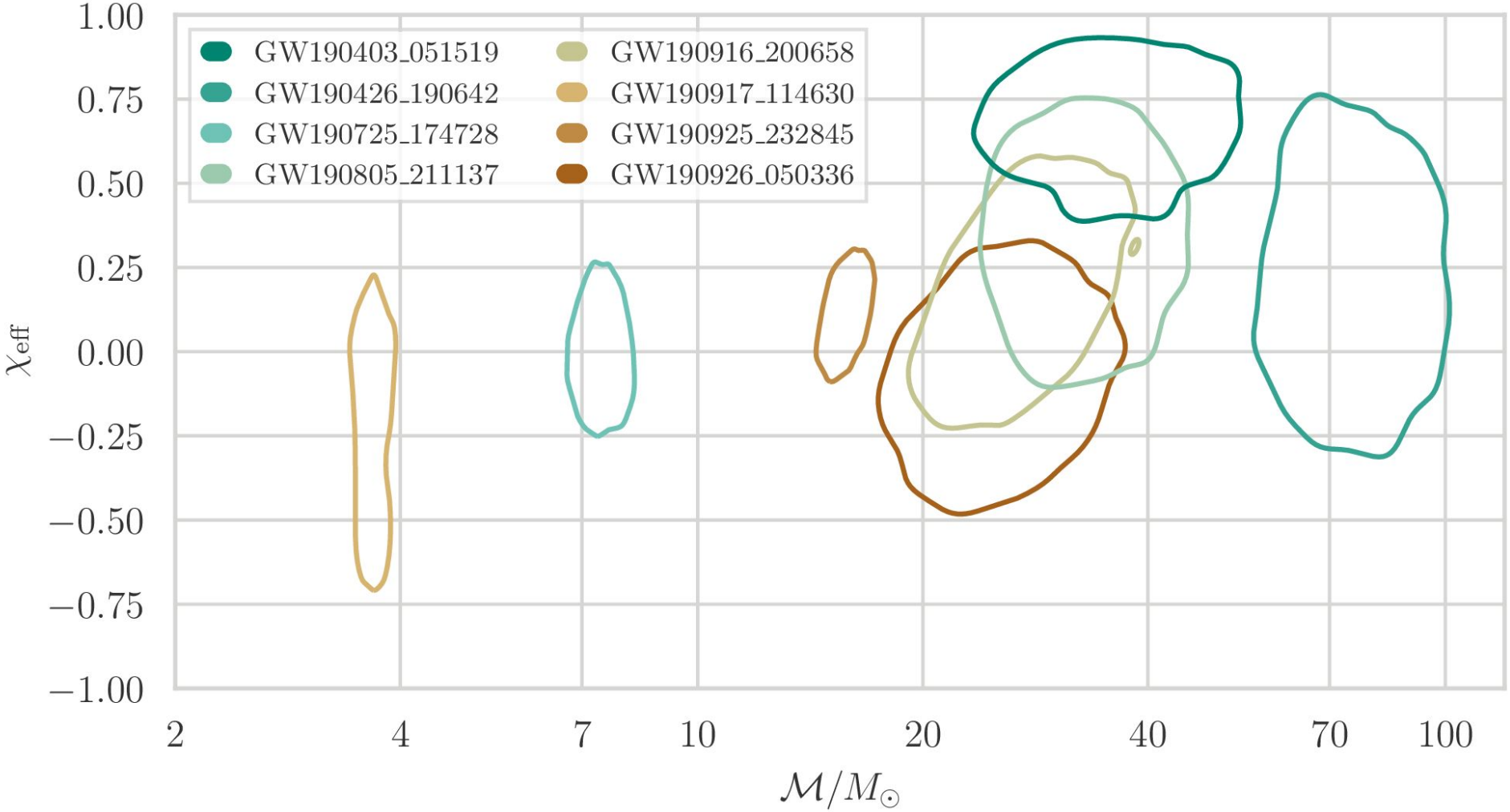


$$q = m_1/m_2 \qquad M = m_1 + m_2$$



LVK arXiv:2111.03606

LVC arXiv:2108.01045



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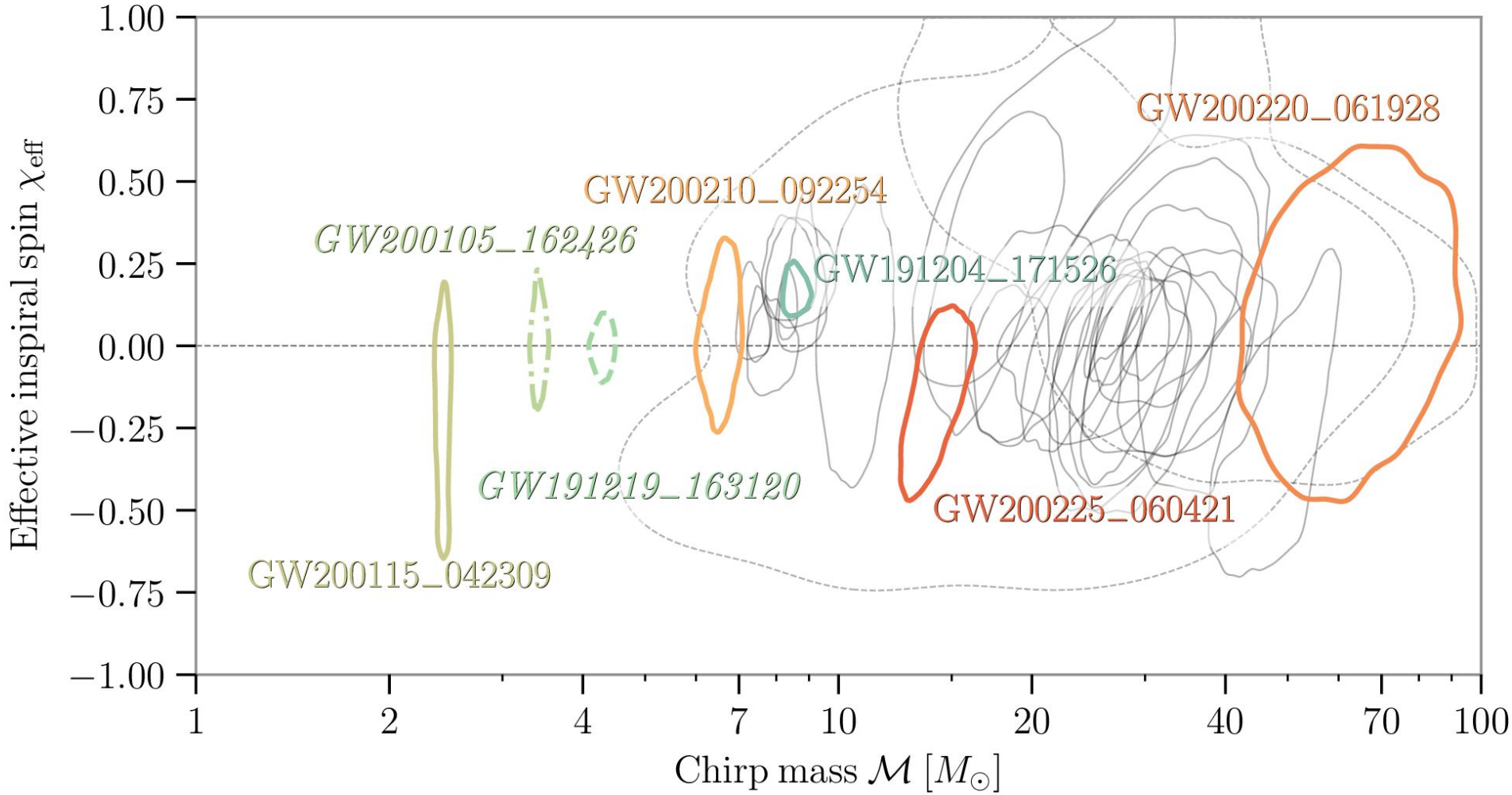
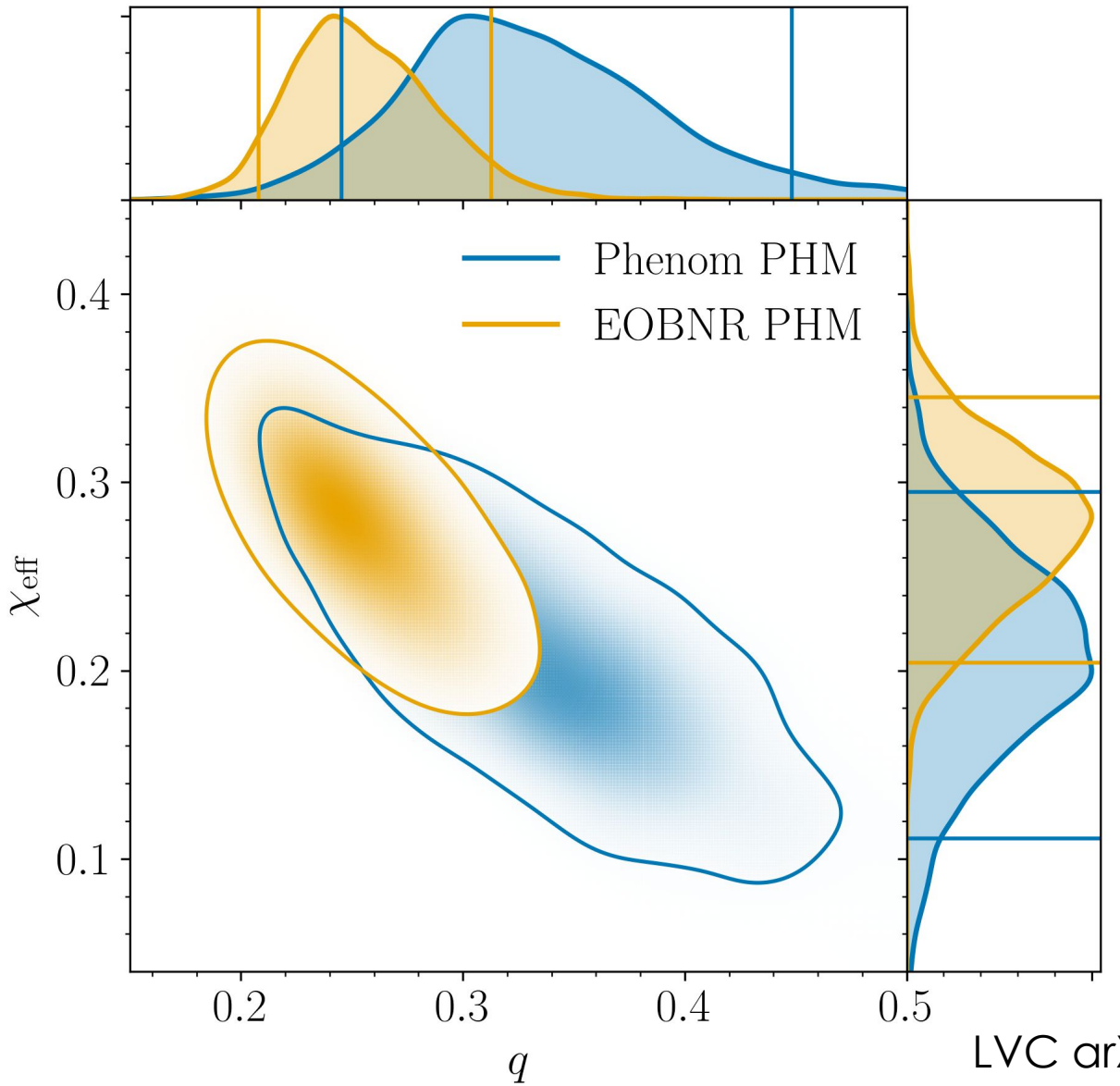
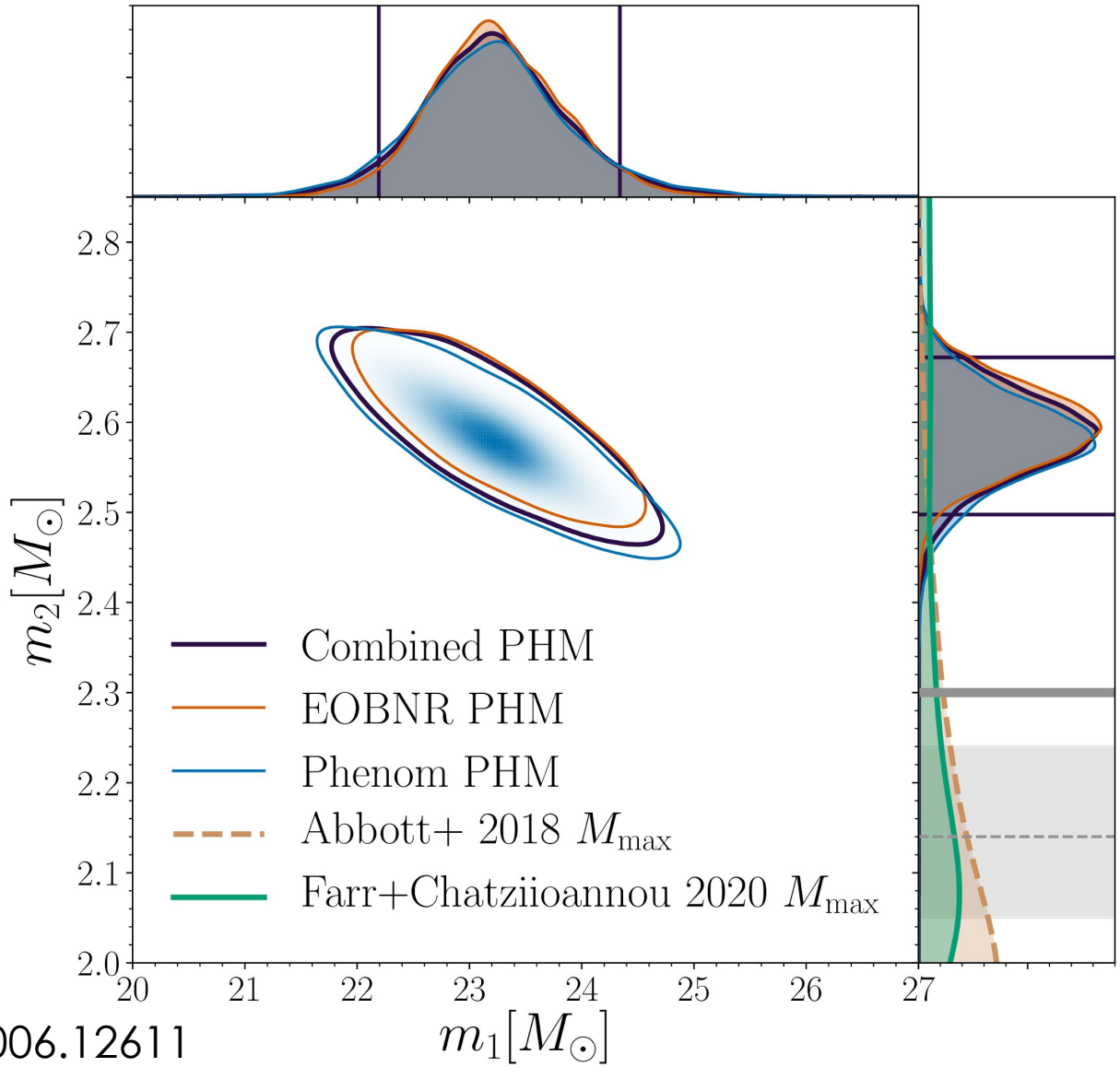


GW190412



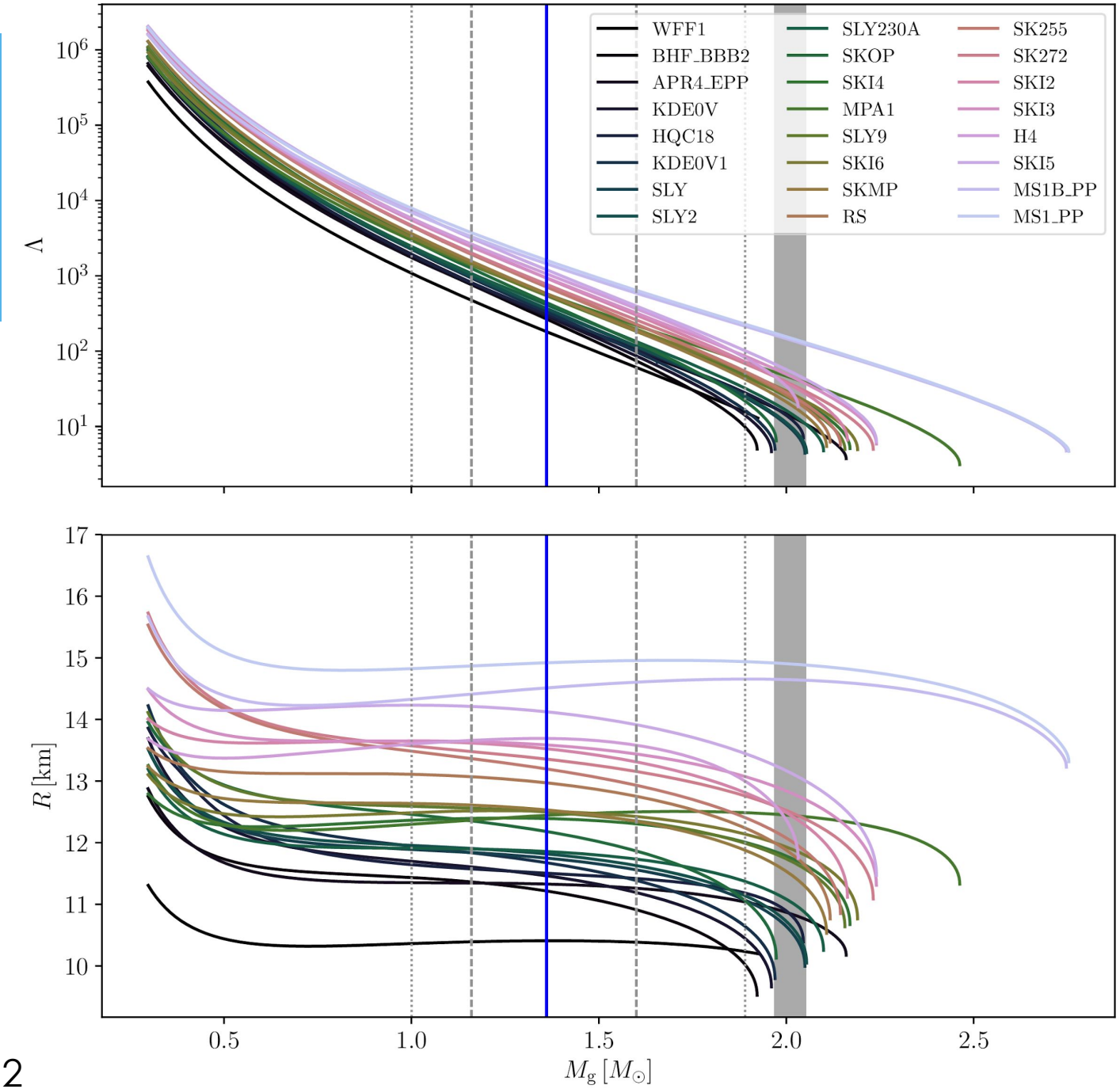
LVC arXiv:2004.08342

GW190814

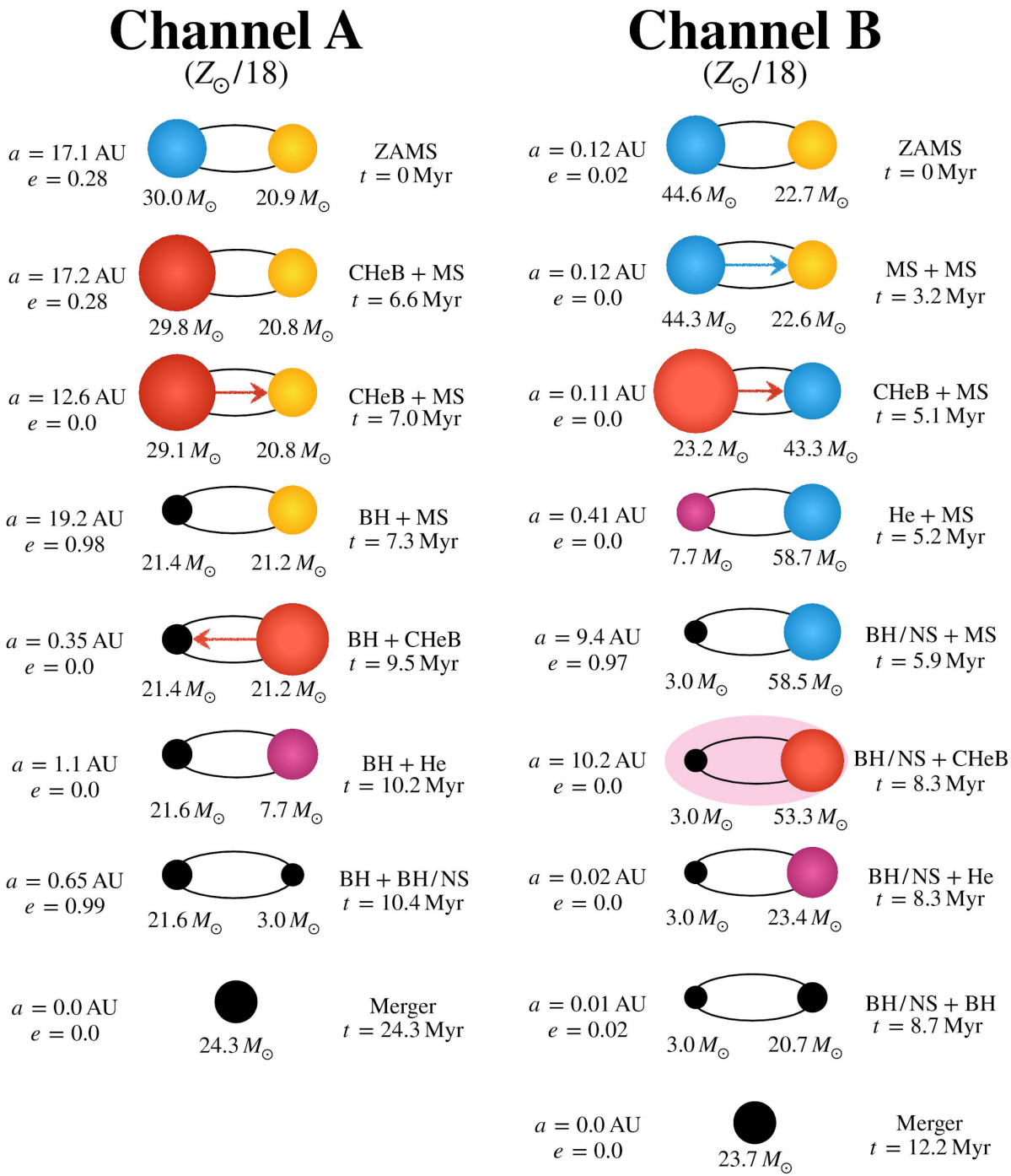


LVC arXiv:2006.12611

Neutron star stuff



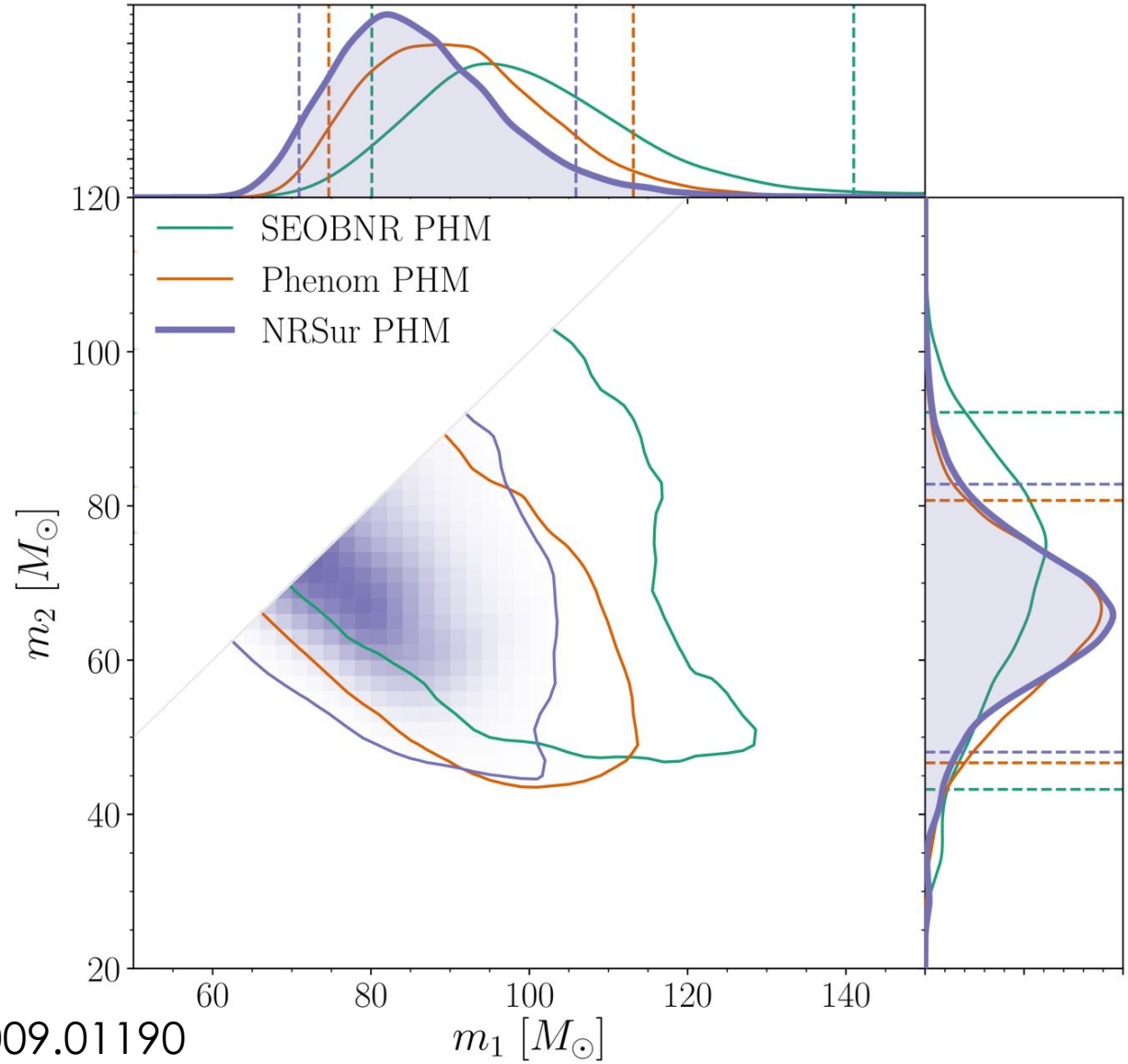
LVC arXiv:1908.01012



GW190814

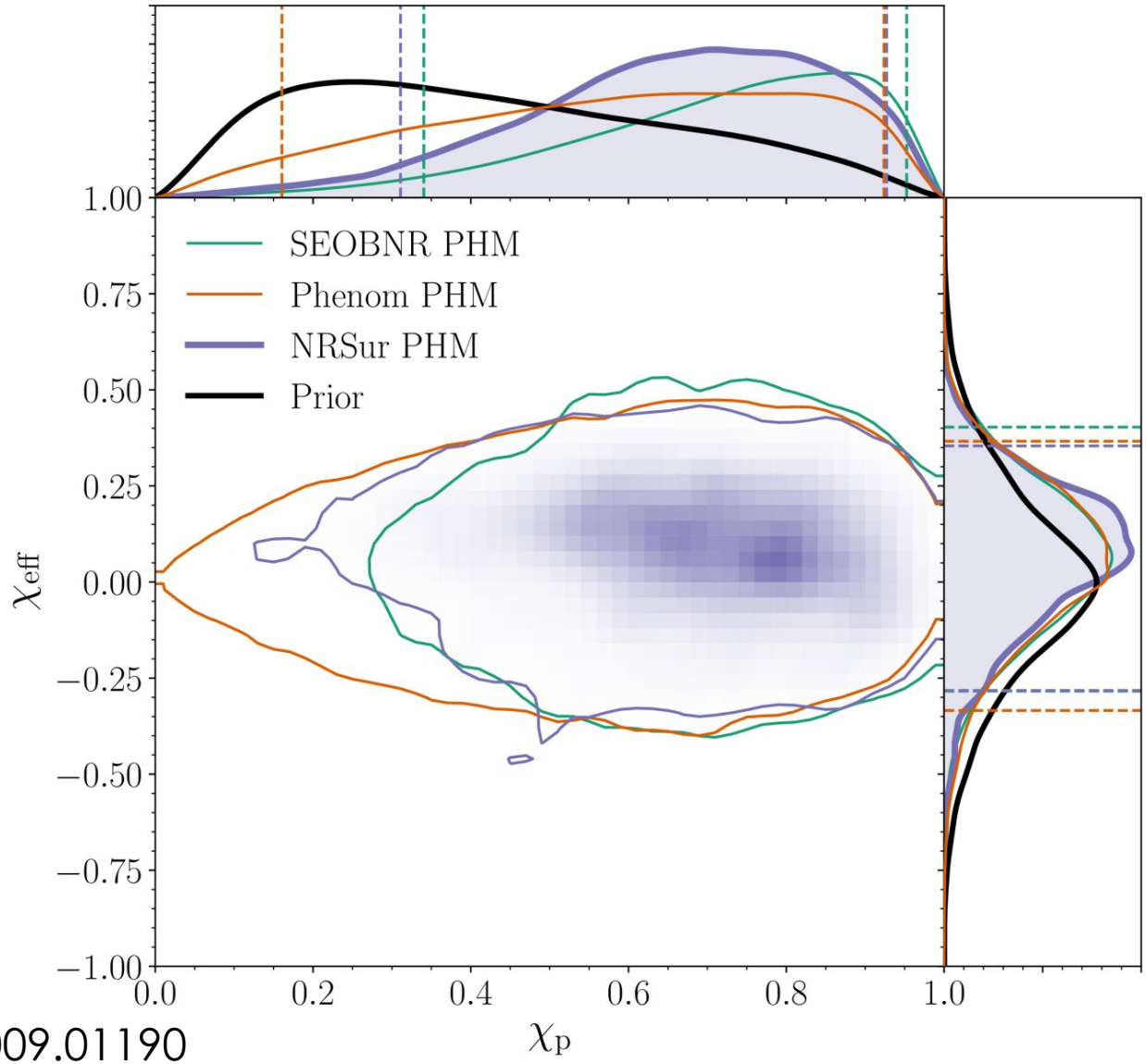
Zevin, Spera,
CPLB & Kalogera
arXiv:2006.14573

GW190521



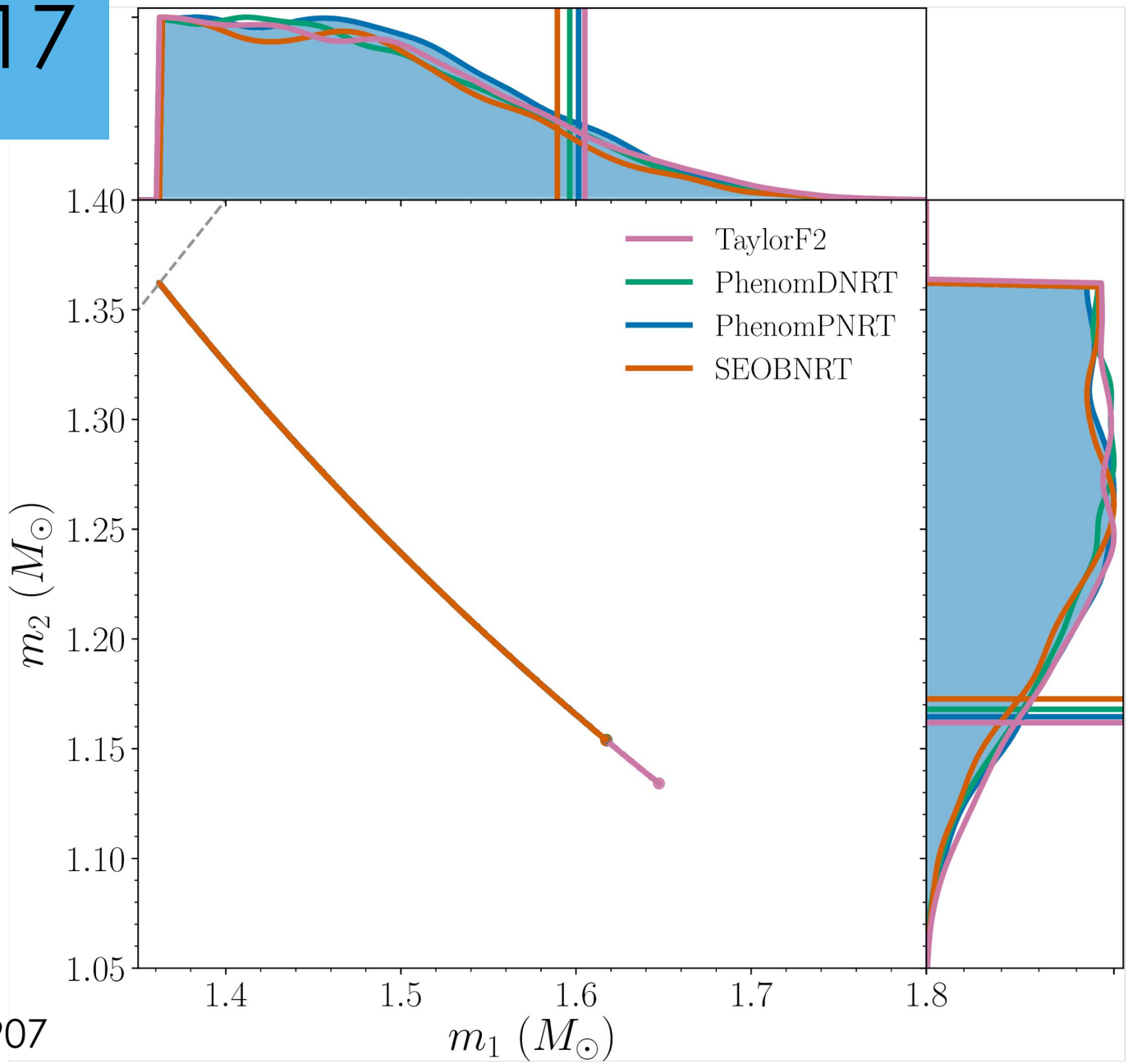
LVC arXiv:2009.01190

GW190521

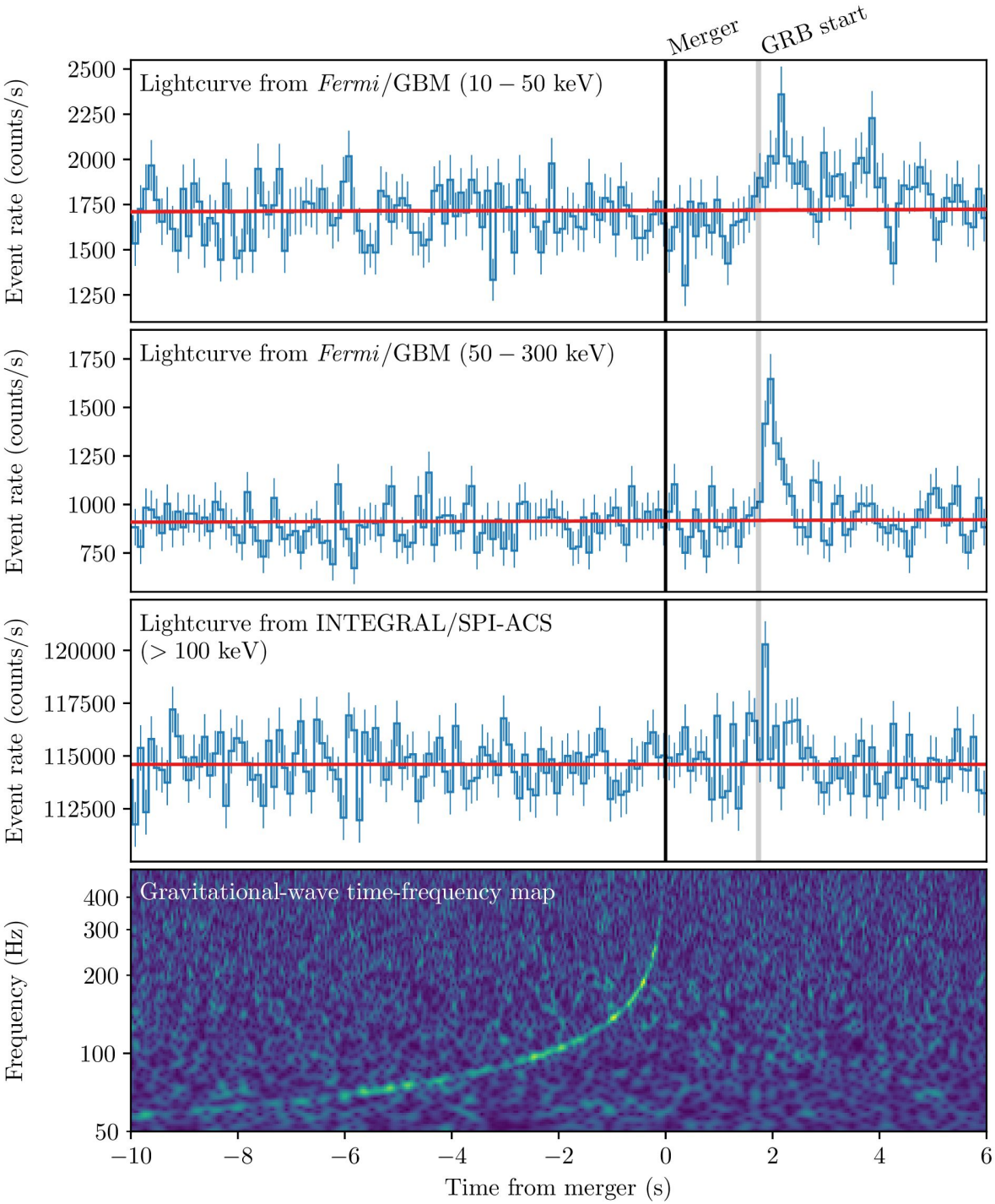


LVC arXiv:2009.01190

GW170817

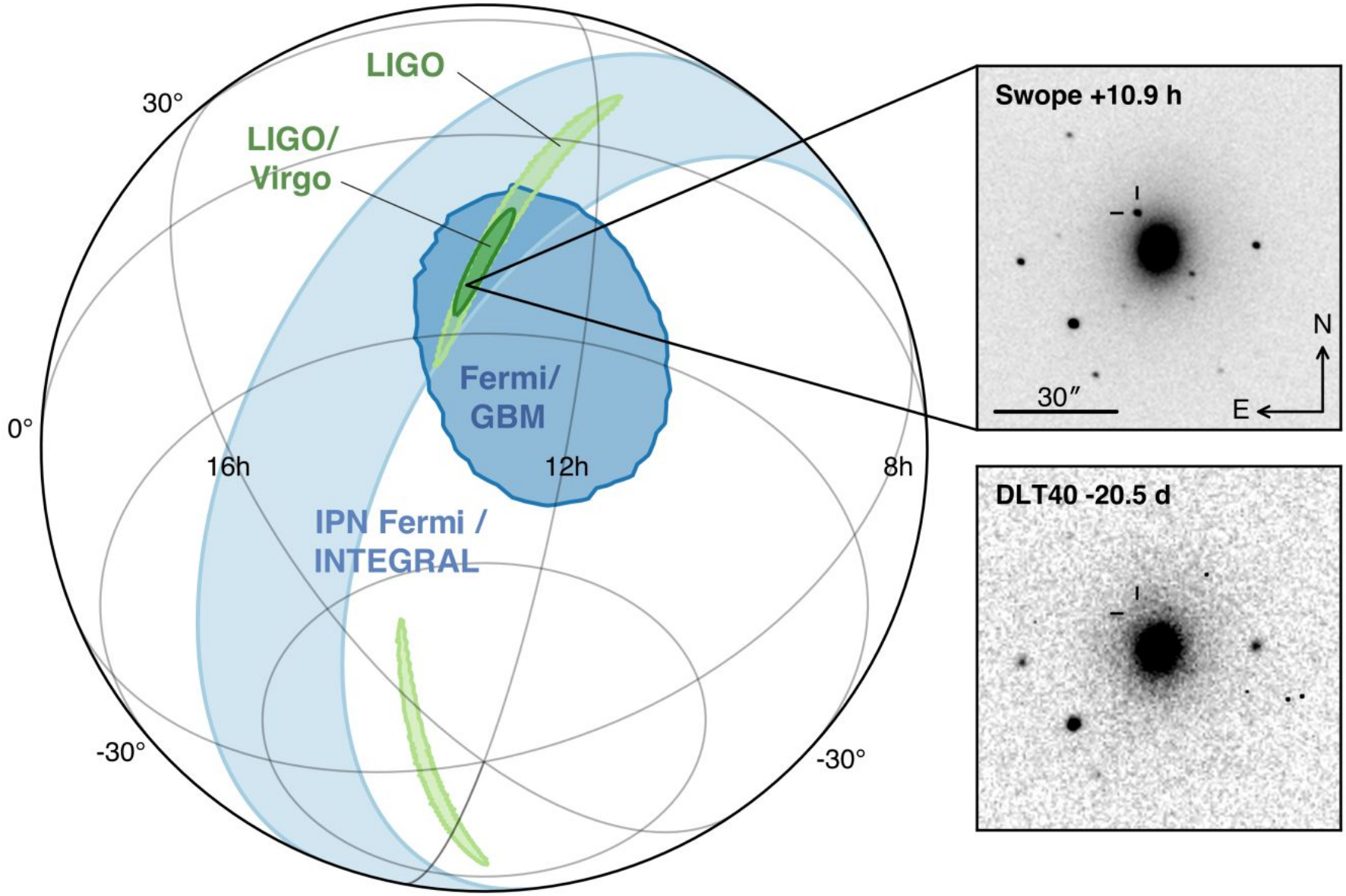


LVC arXiv:1811.12907



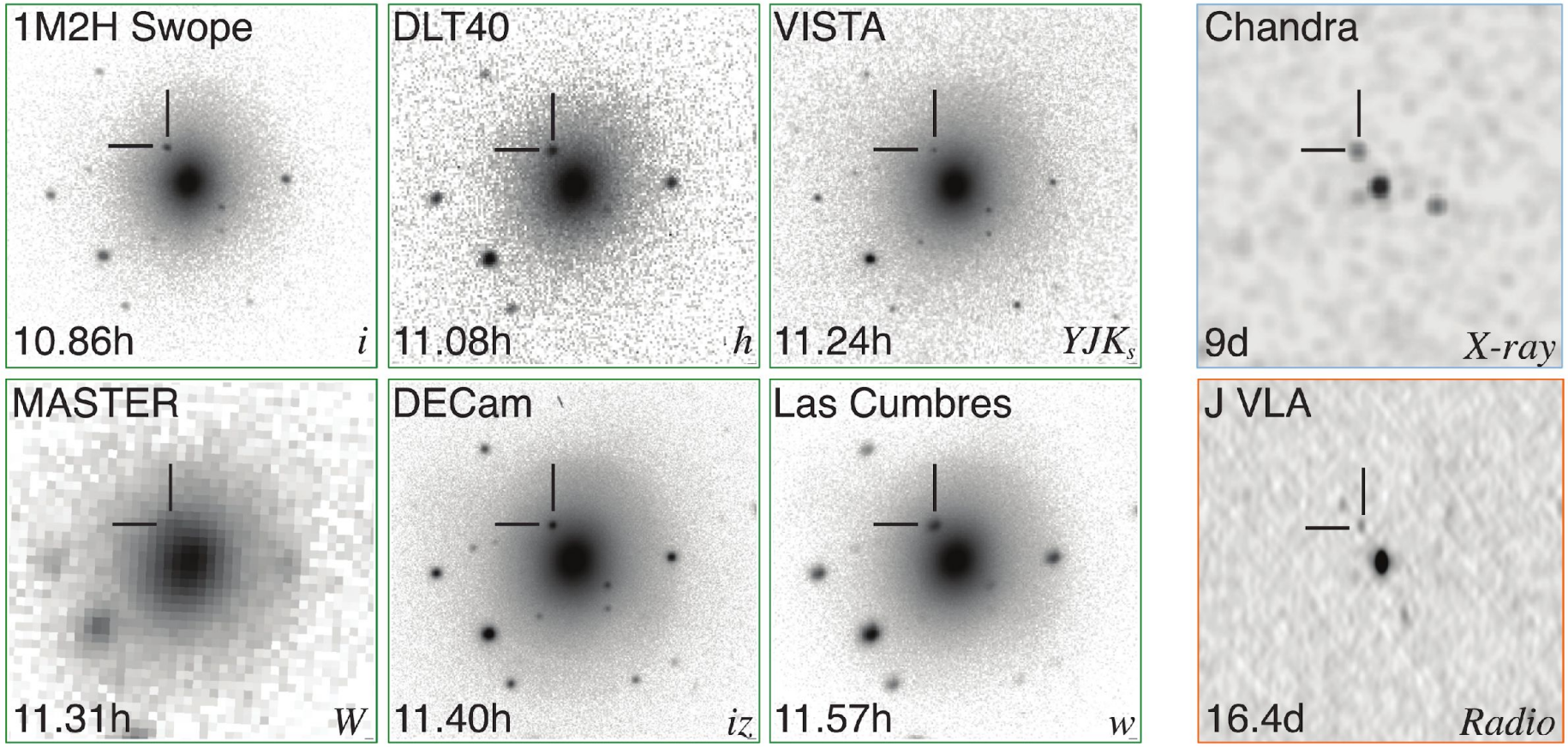
Gamma-rays

LVC, Fermi, INTEGRAL
arXiv:1710.05834



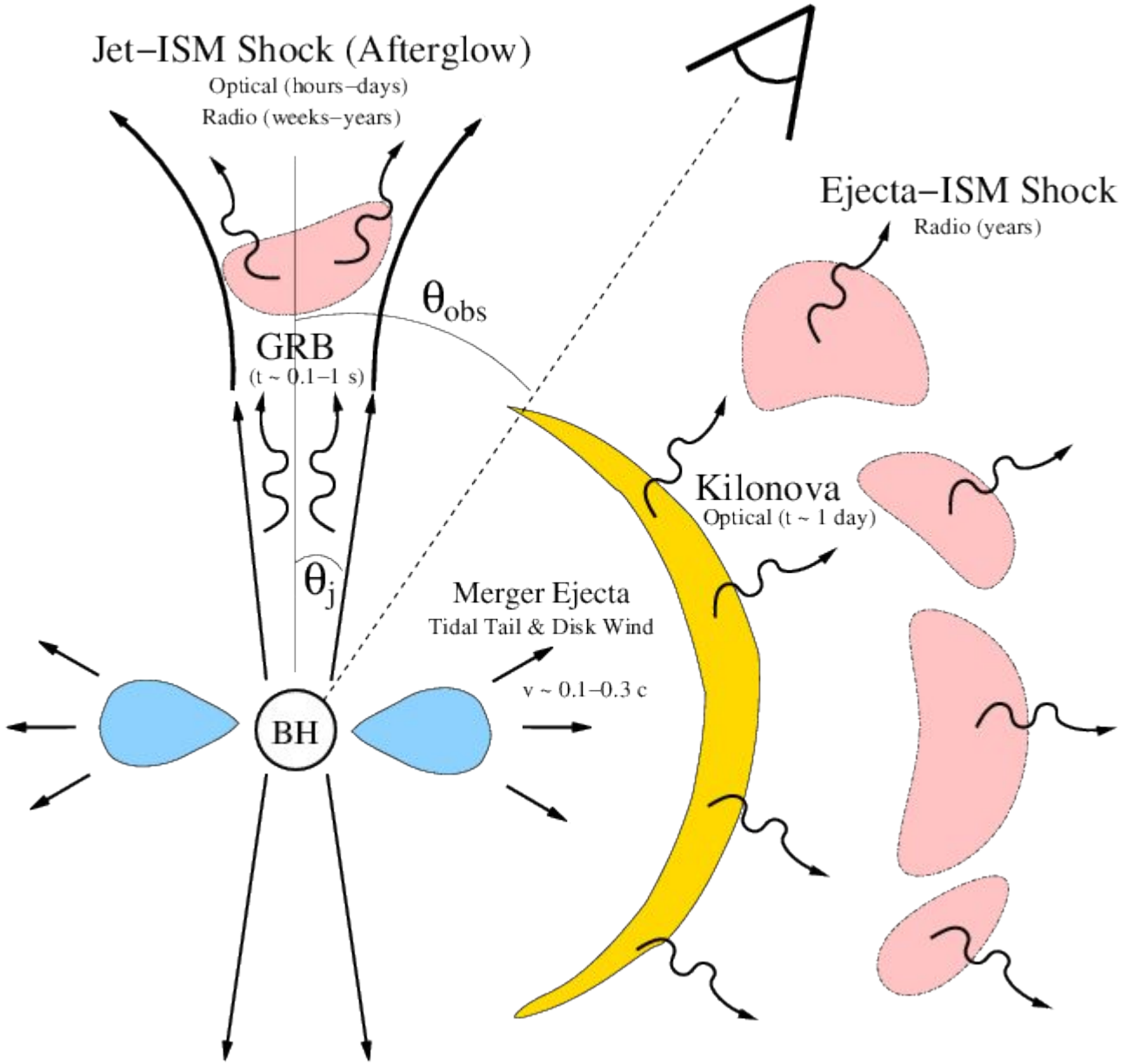
LVC+ arXiv:1710.05833

Spectrum of observations



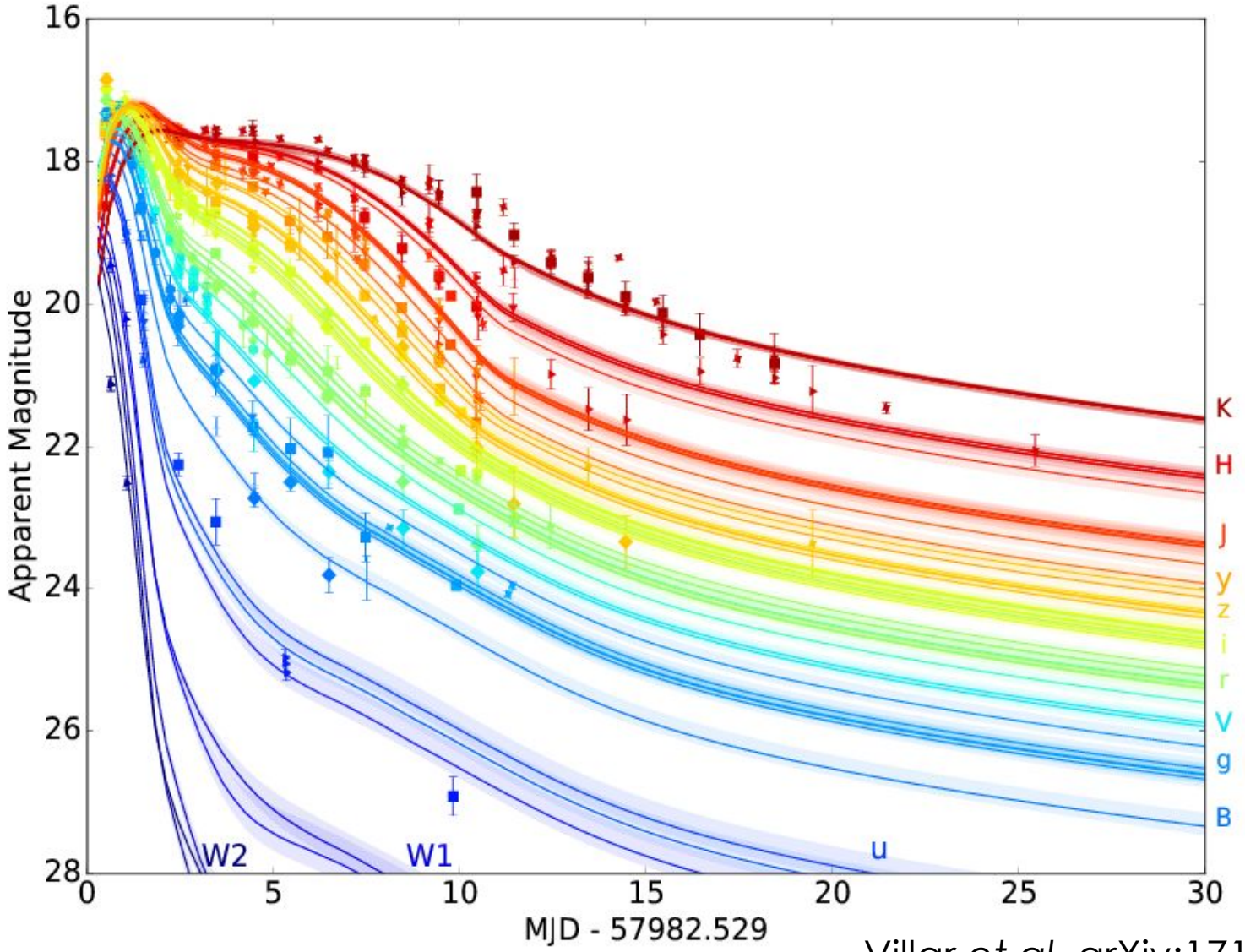
LVC+ arXiv:1710.05833

Light



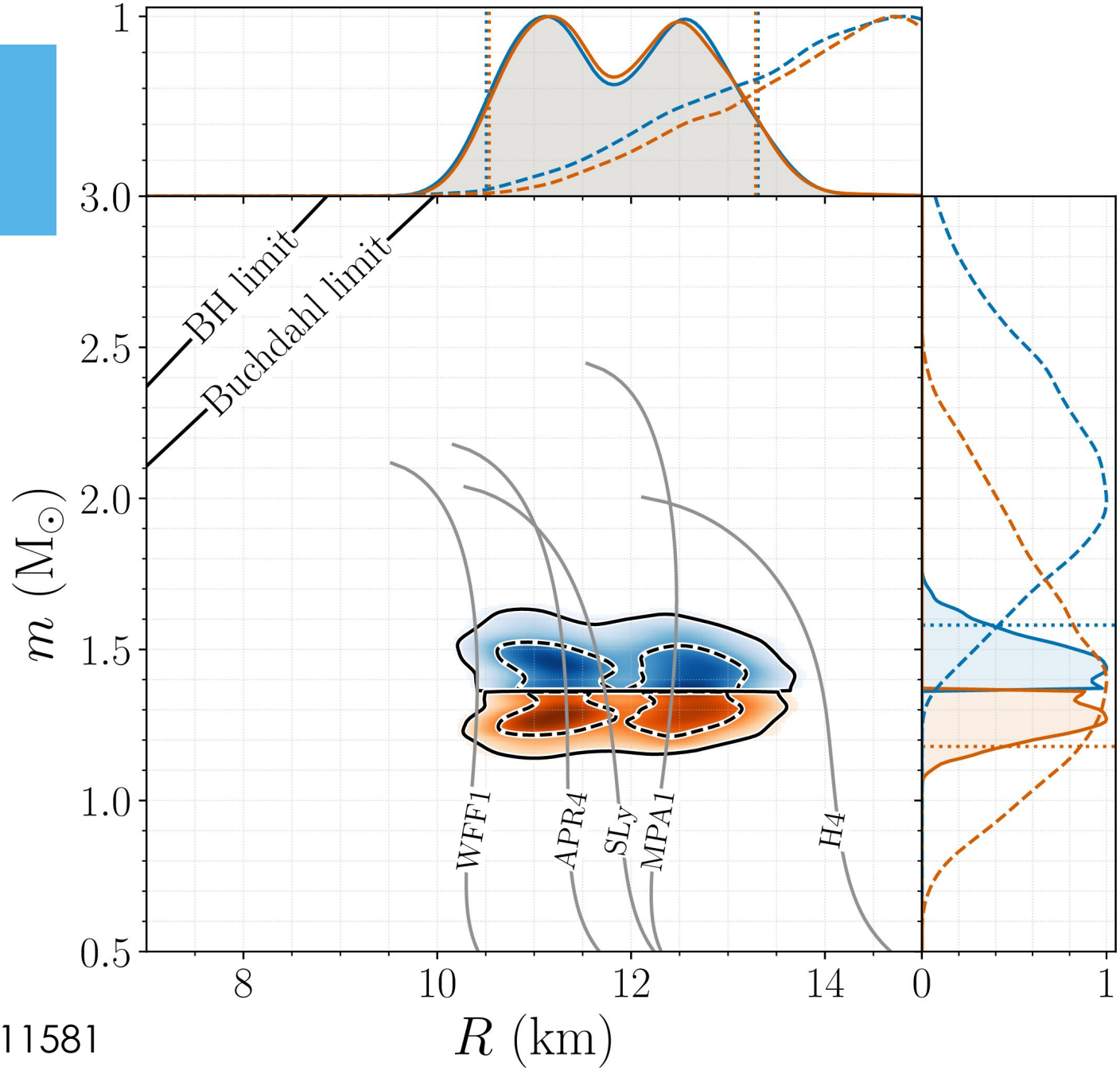
Metzger & Berger
arXiv:1108.6056

Spectrum of observations



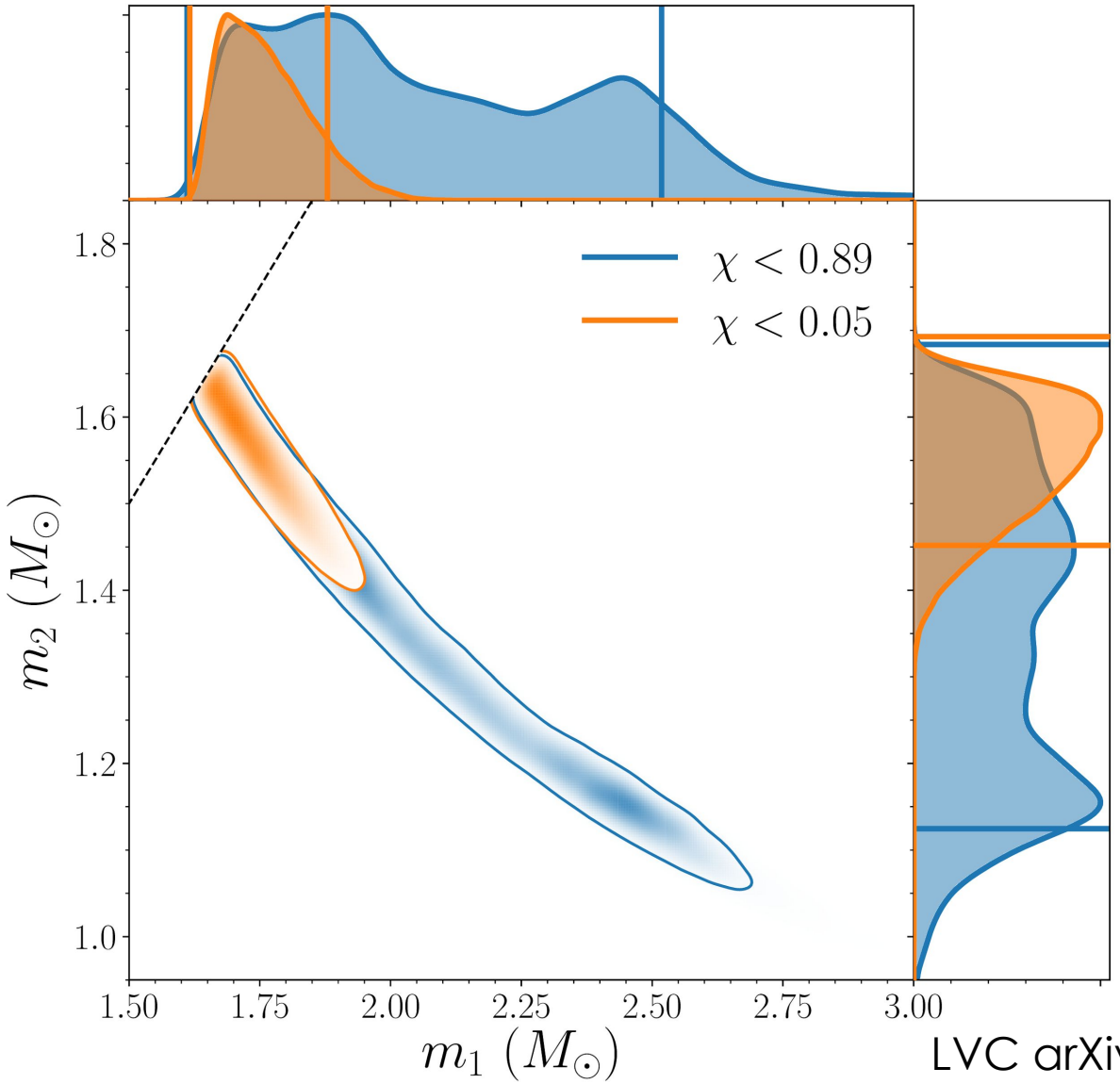
Villar *et al*. arXiv:1710.11576

Radius



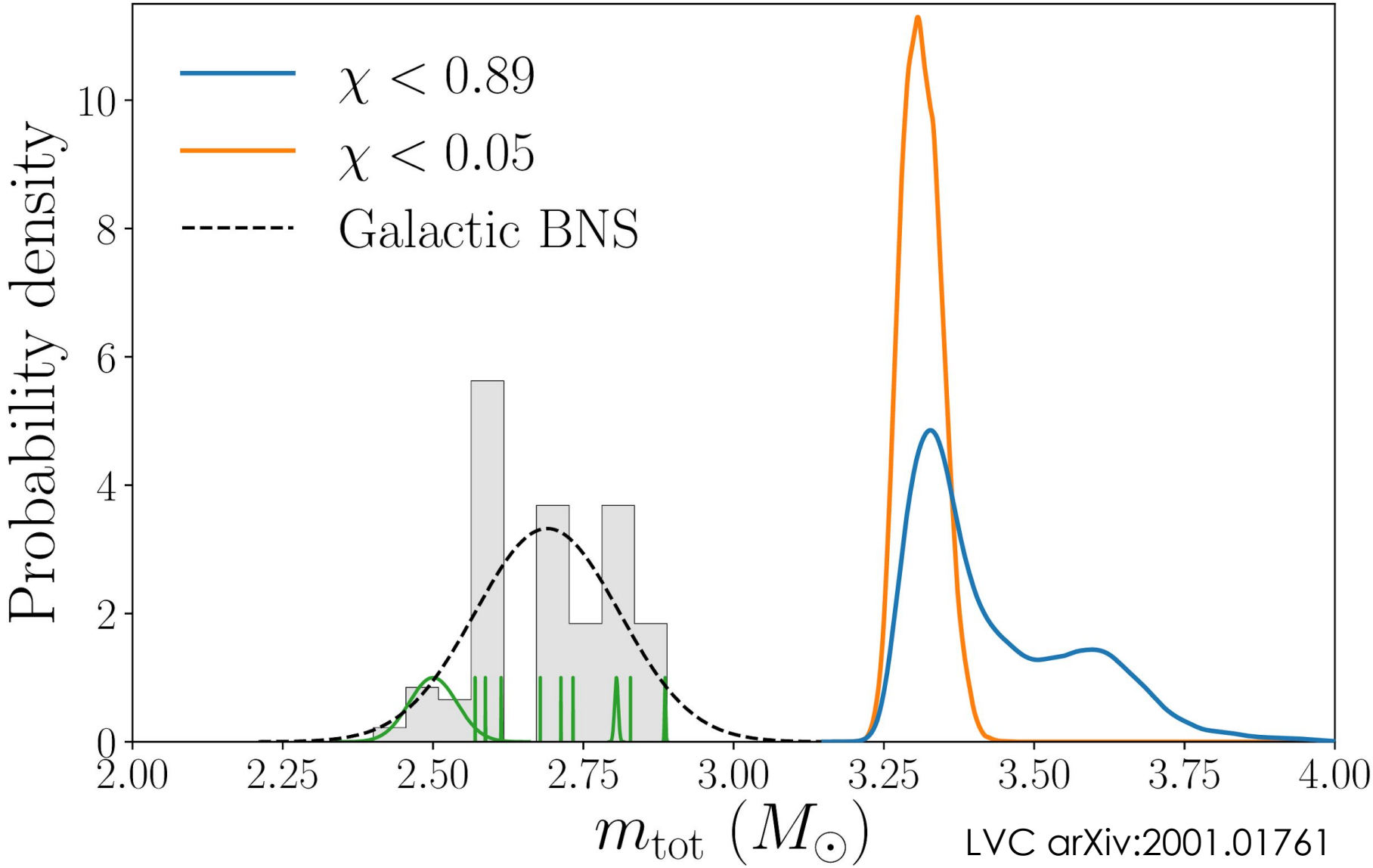
LVC arXiv:1805.11581

GW190425



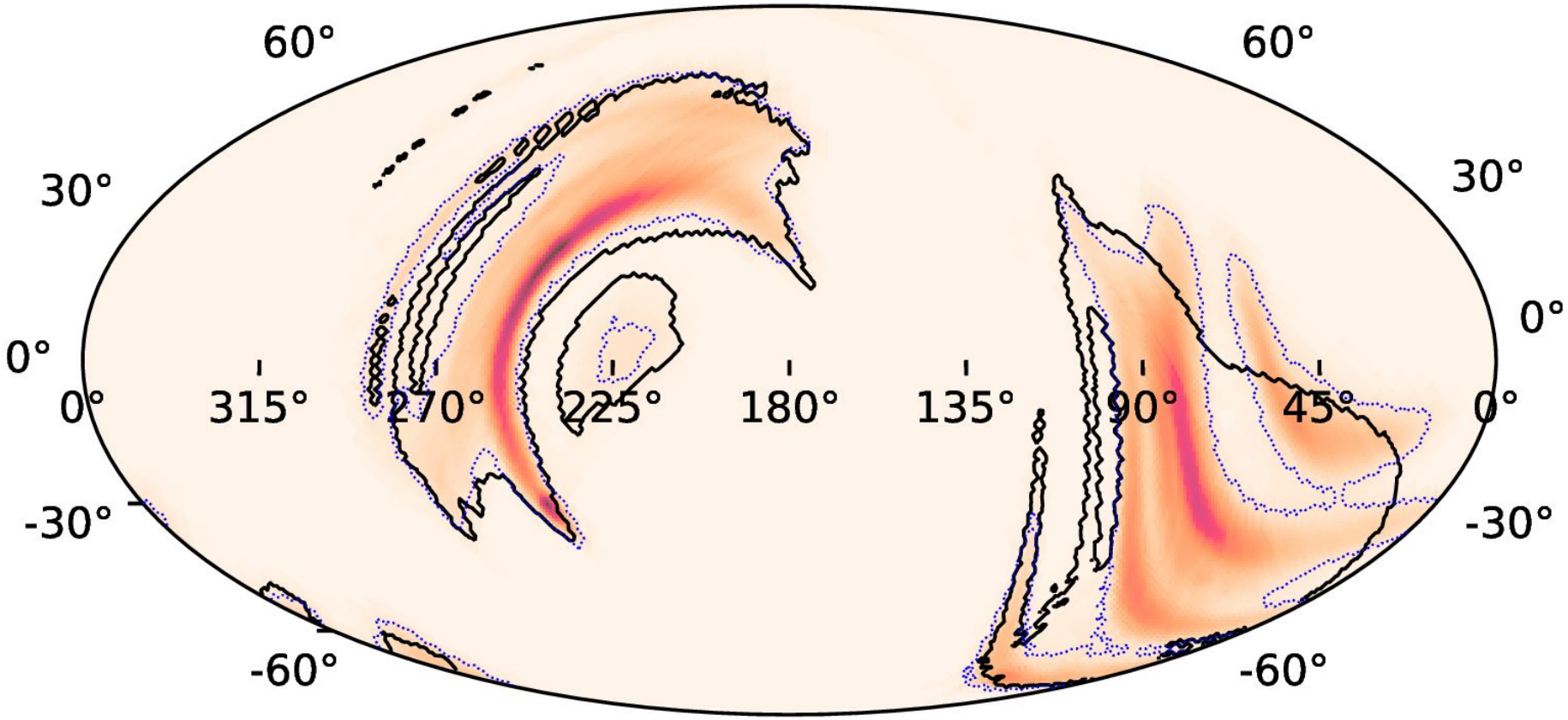
LVC arXiv:2001.01761

GW190425



LVC arXiv:2001.01761

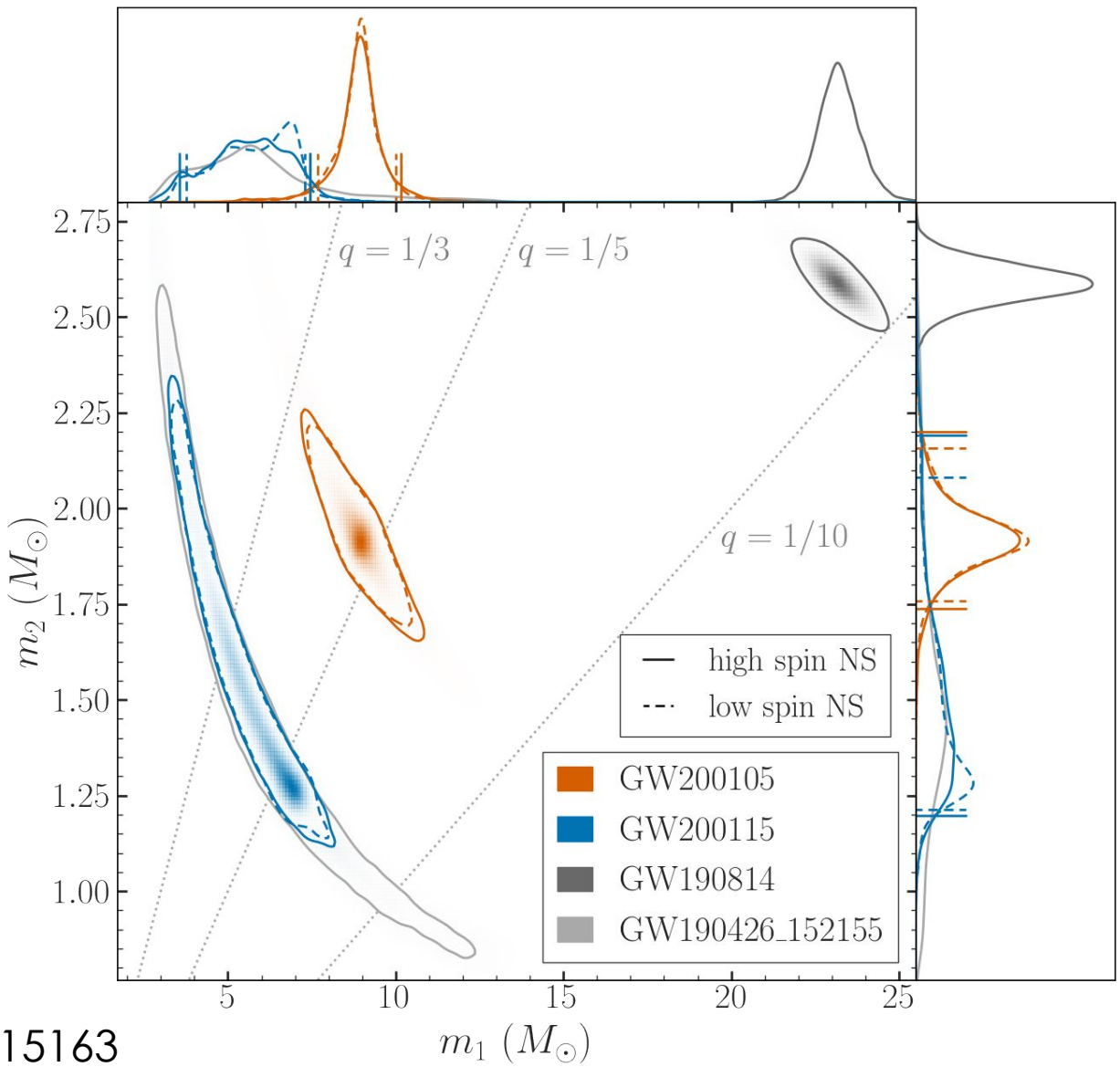
GW190425



LVC arXiv:2001.01761

GW200105 & GW200115

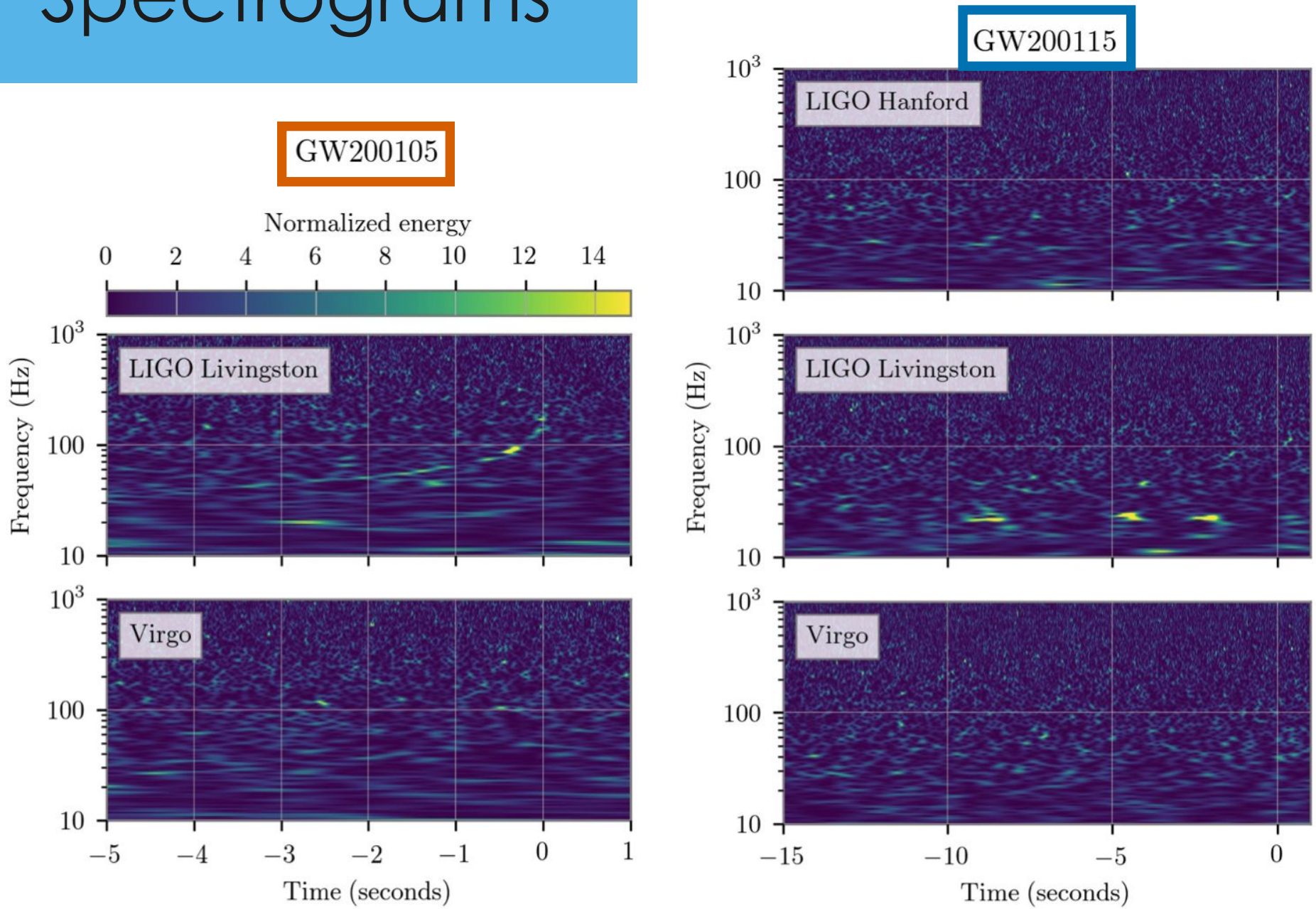
No tidal information



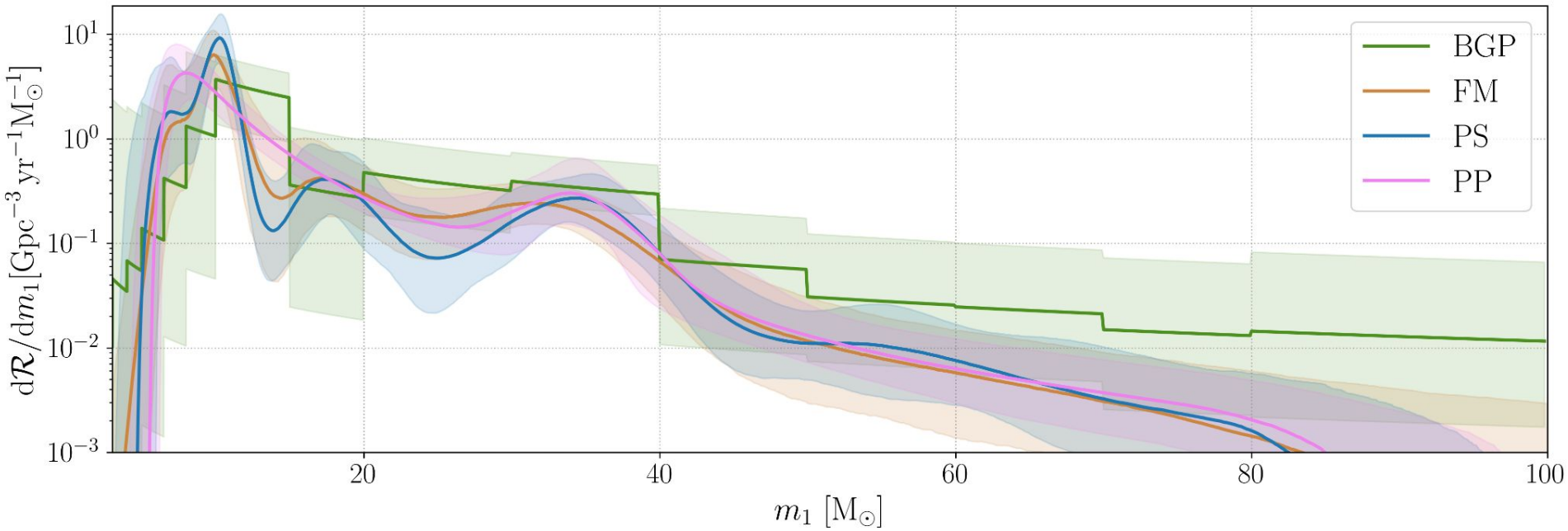
LVK arXiv:2106.15163

Spectrograms

LVK arXiv:2106.15163

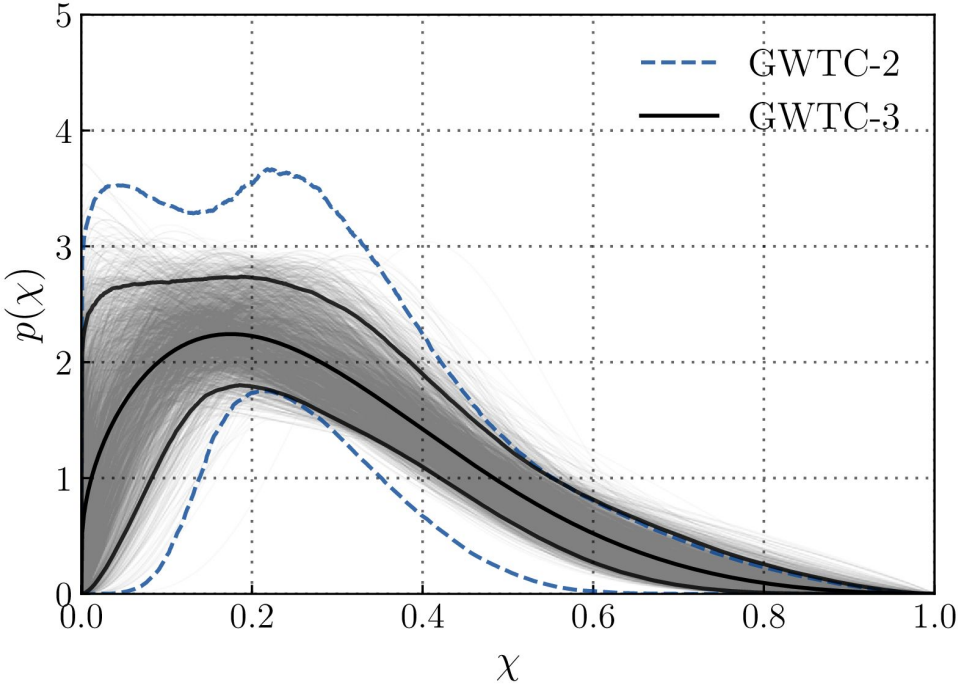


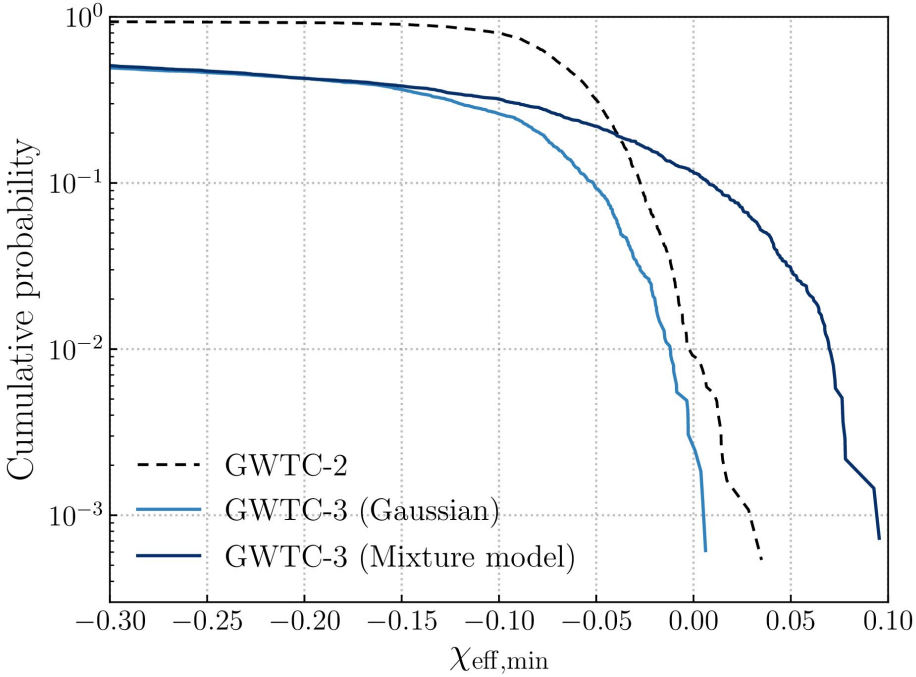
Mass spectrum



LVK arXiv:2111.03634

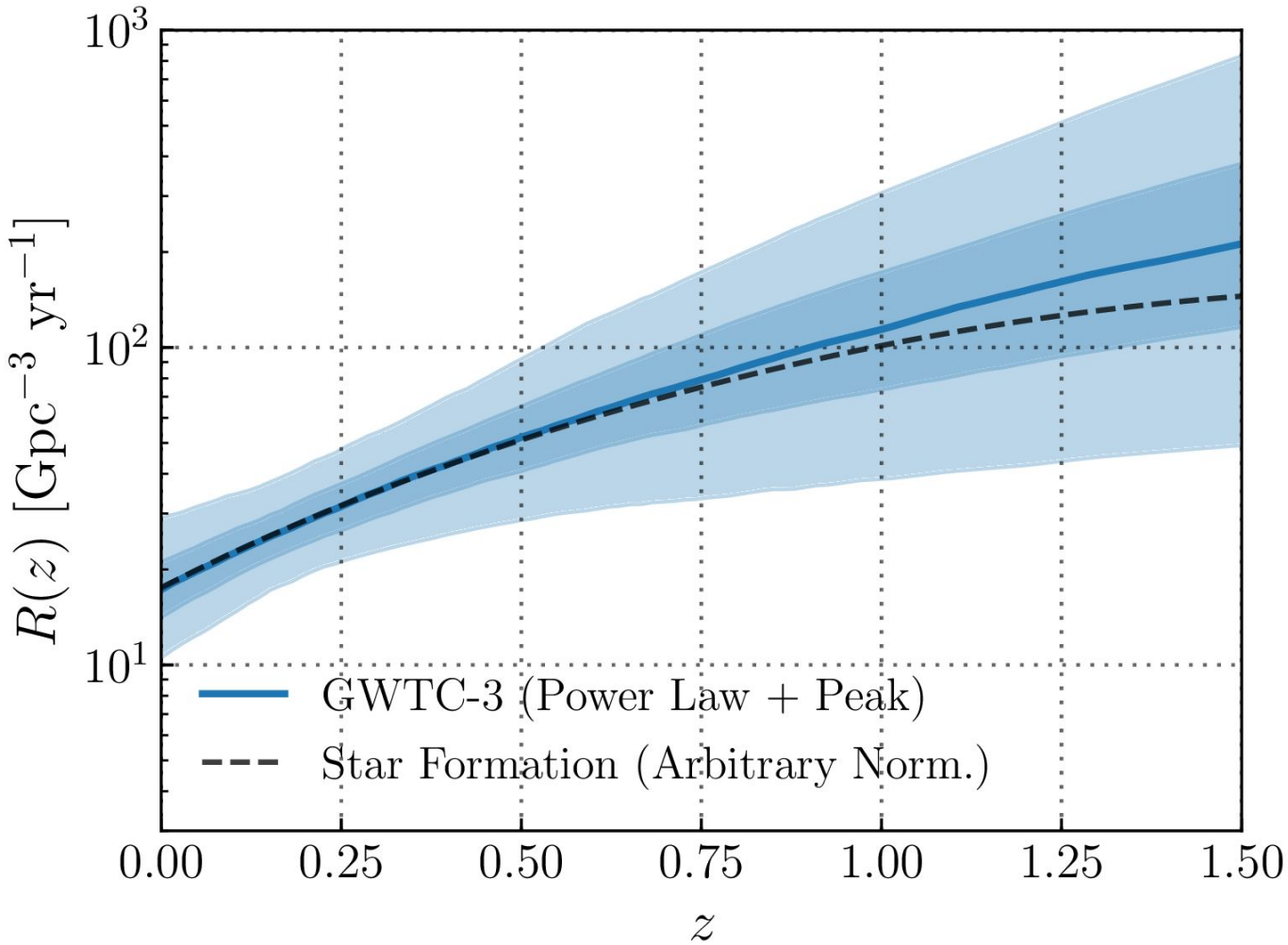
Spin distribution





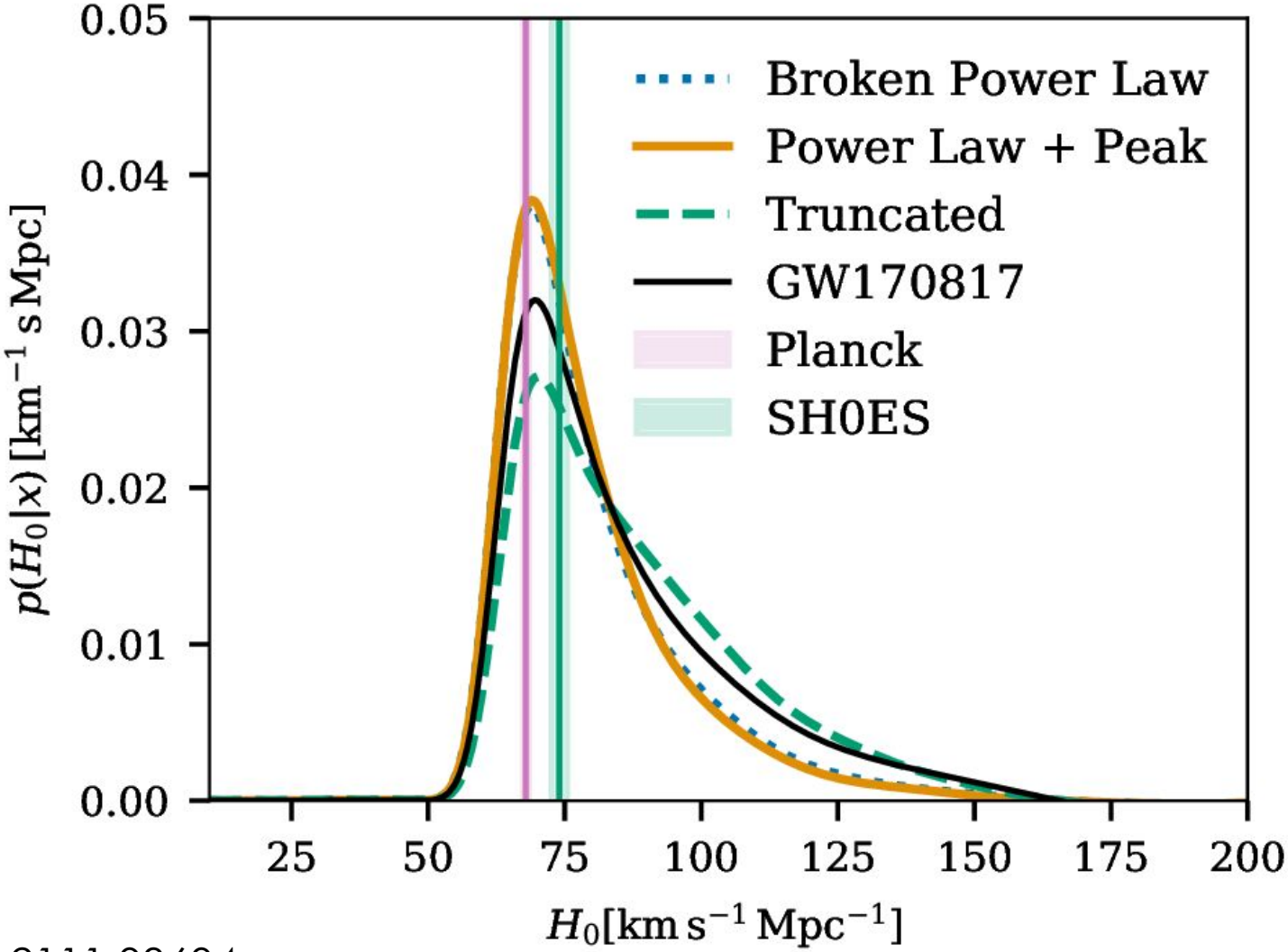
LVK arXiv:2111.03634

Redshift evolution



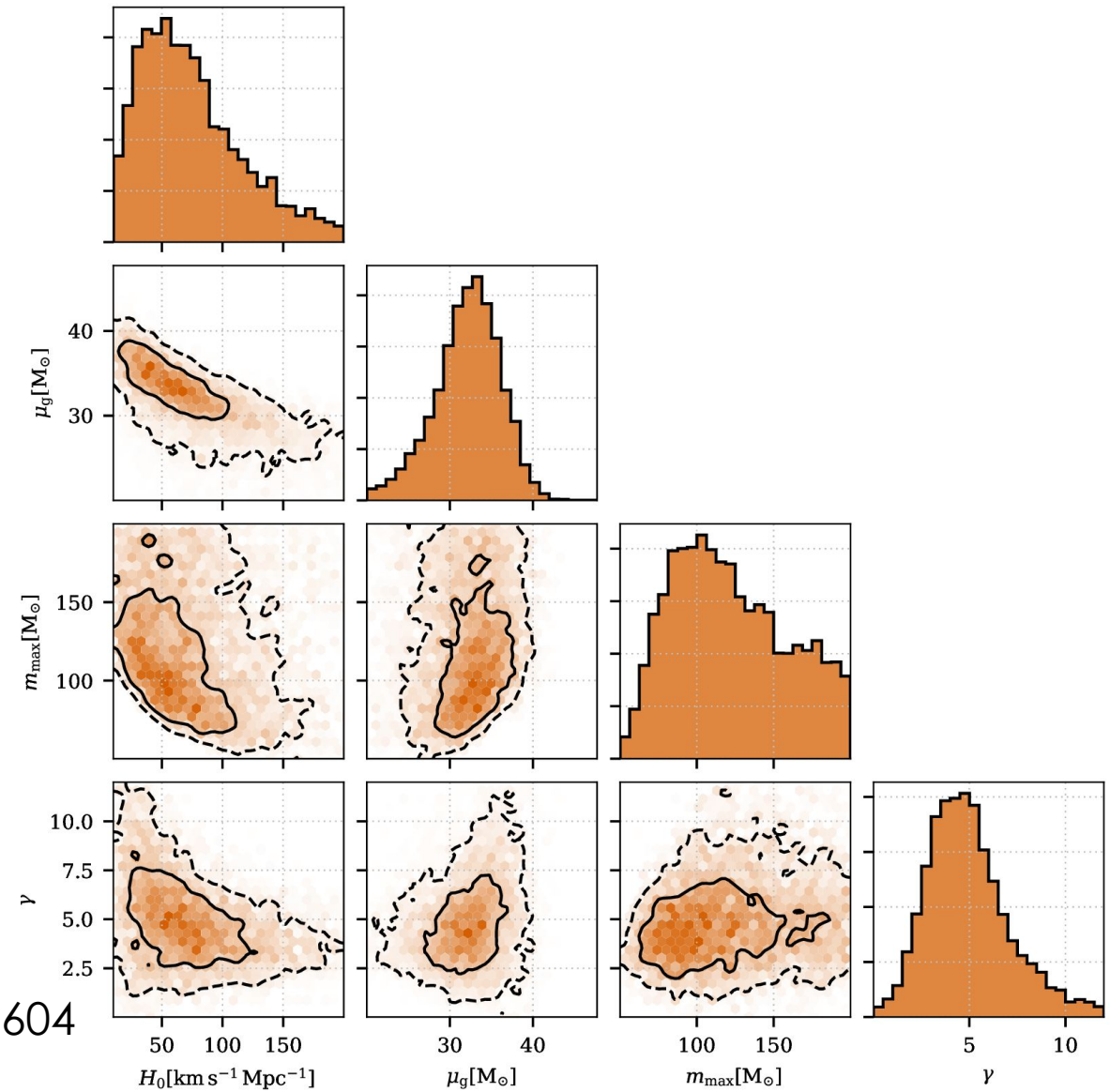
LVK arXiv:2111.03634

Hubble constant



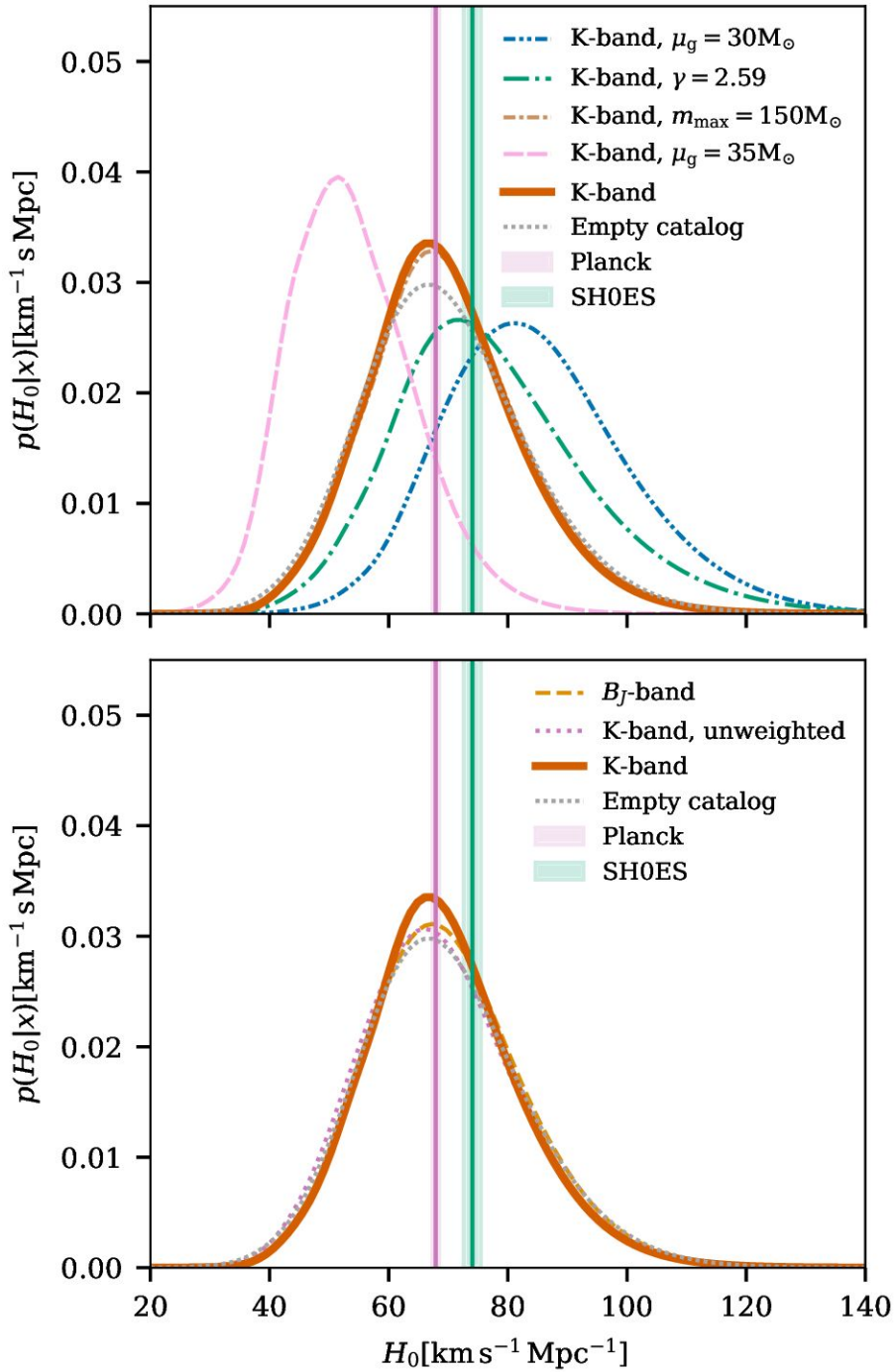
LVK arXiv:2111.03604

Hubble constant



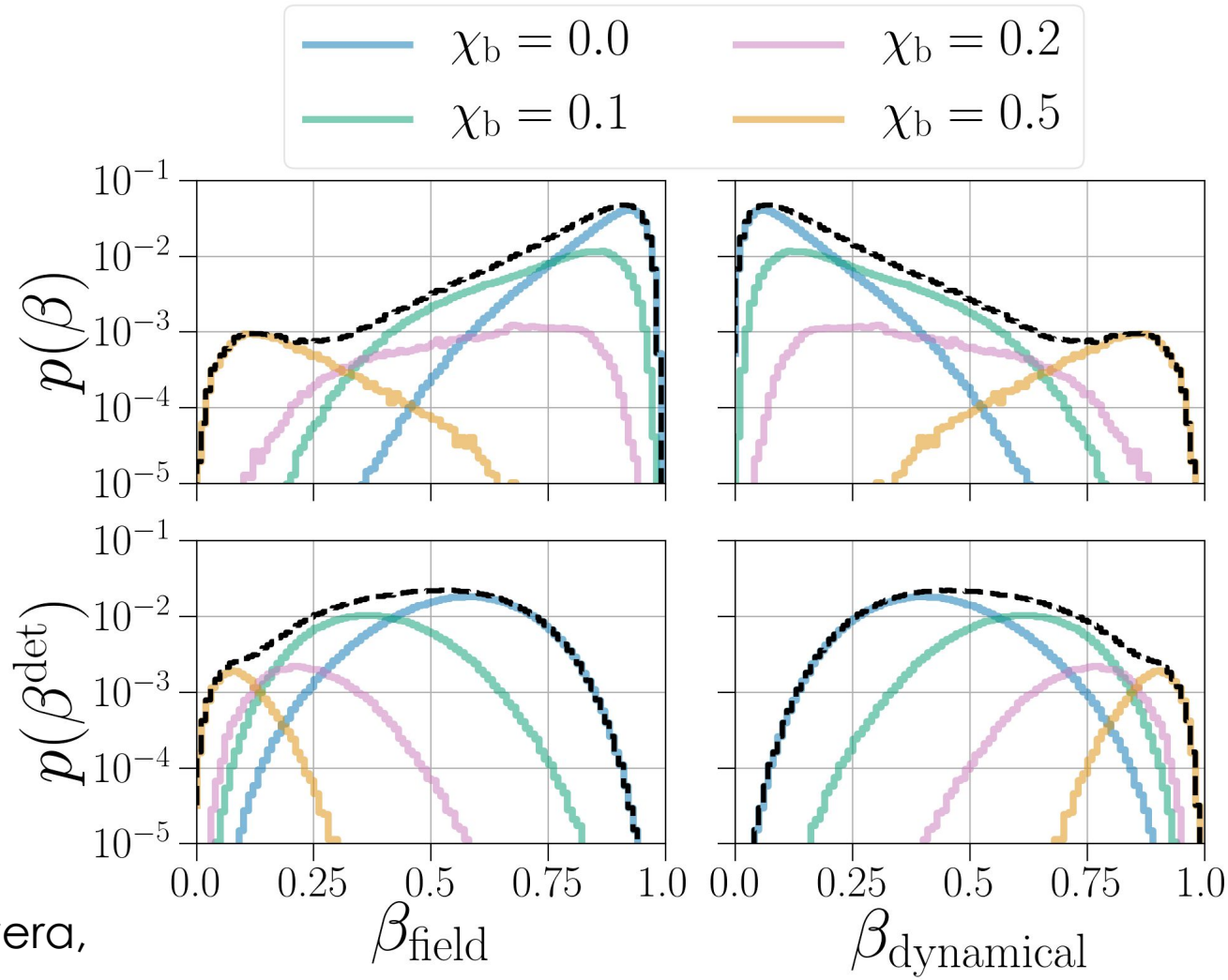
LVK arXiv:2111.03604

Systematics



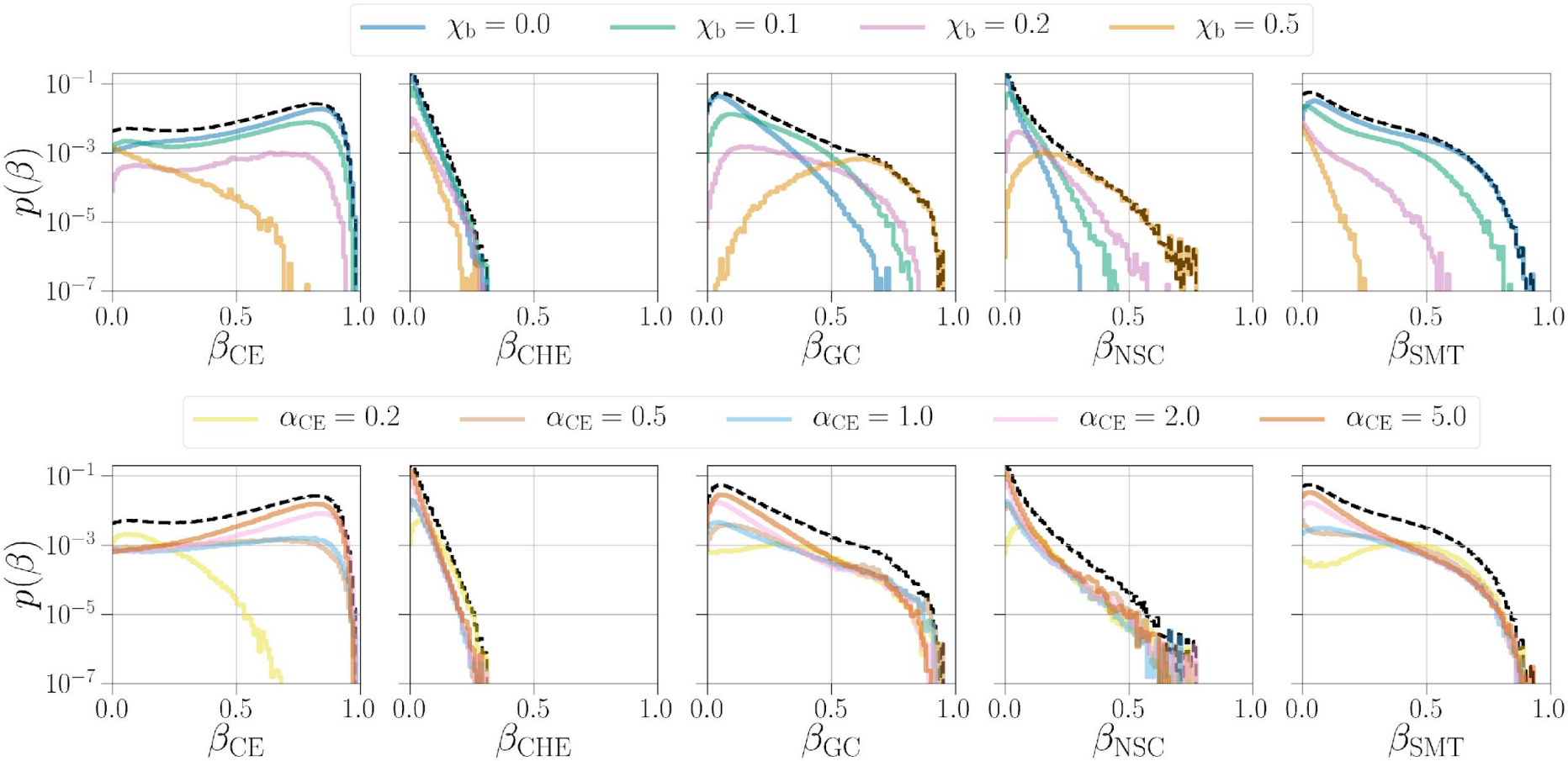
LVK arXiv:2111.03604

Comparing to predictions



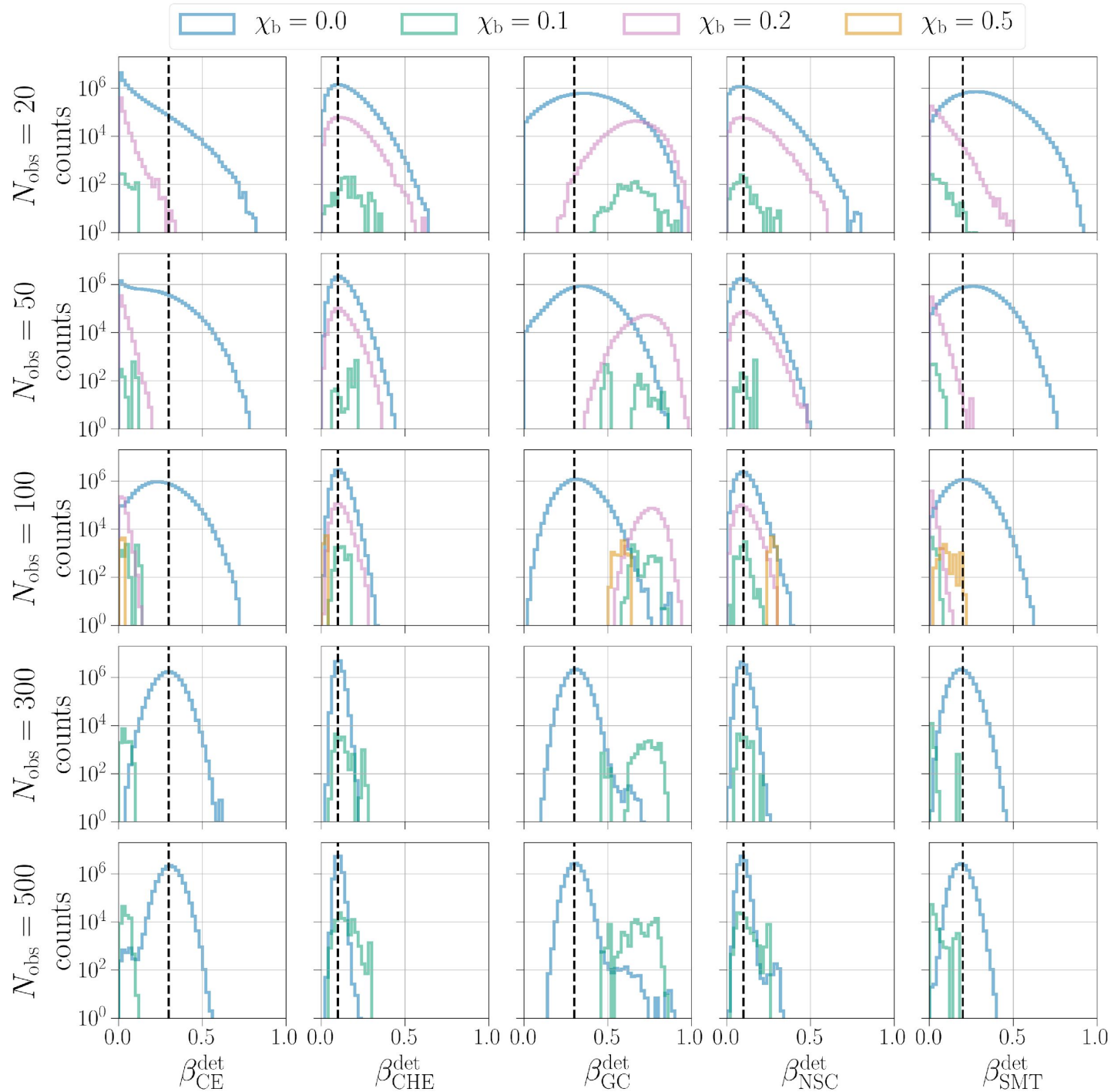
Zevin, Bavera,
CPLB *et al.*
arXiv:2011.10057

Branching ratios



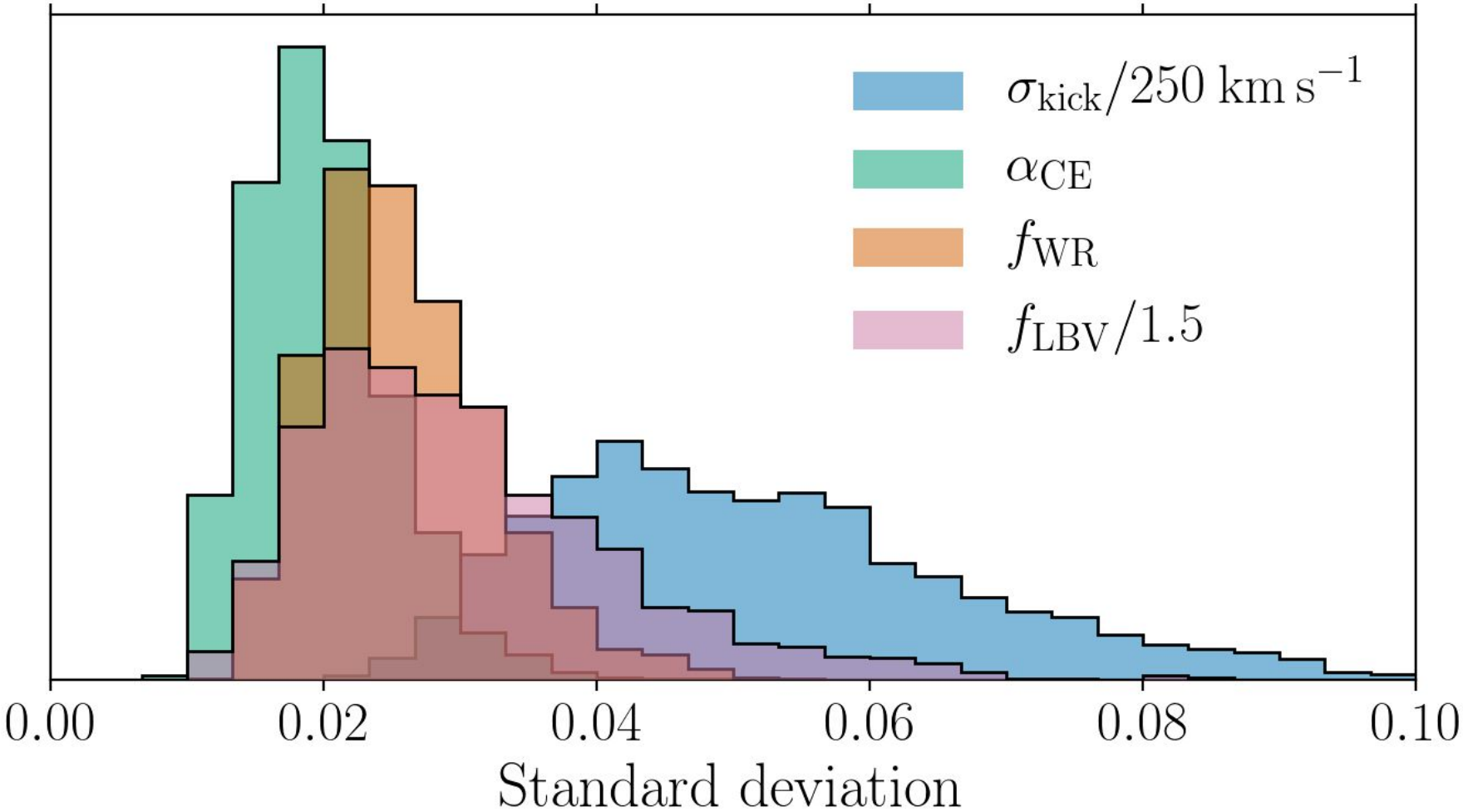
Zevin, Bavera,
CPLB *et al.*
arXiv:2011.10057

Future



Zevin, Bavera, **CPLB** *et al.* arXiv:2011.10057

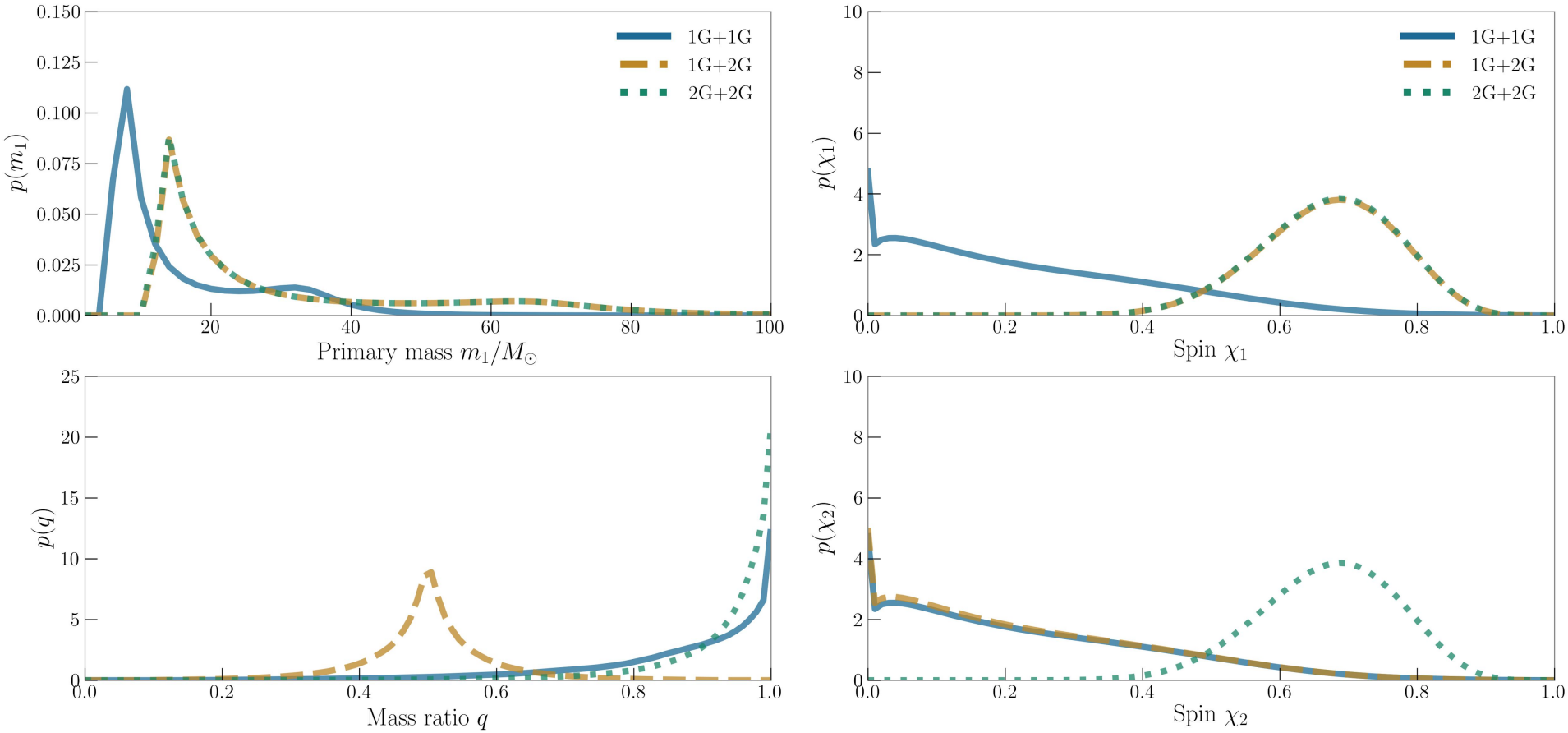
Population synthesis parameters



COMPAS

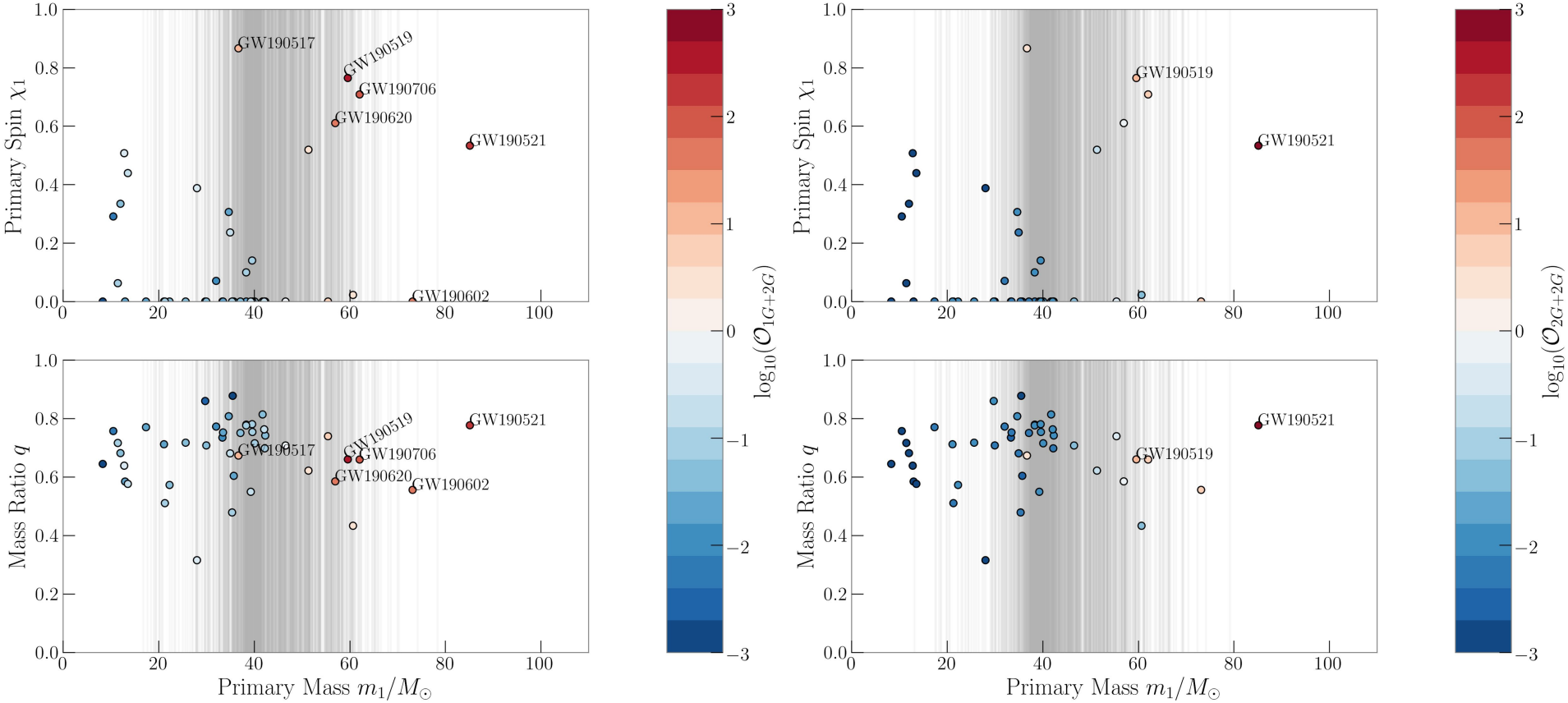
Barrett, …, **CPLB** *et al.* arXiv:1711.06287

Hierarchical mergers



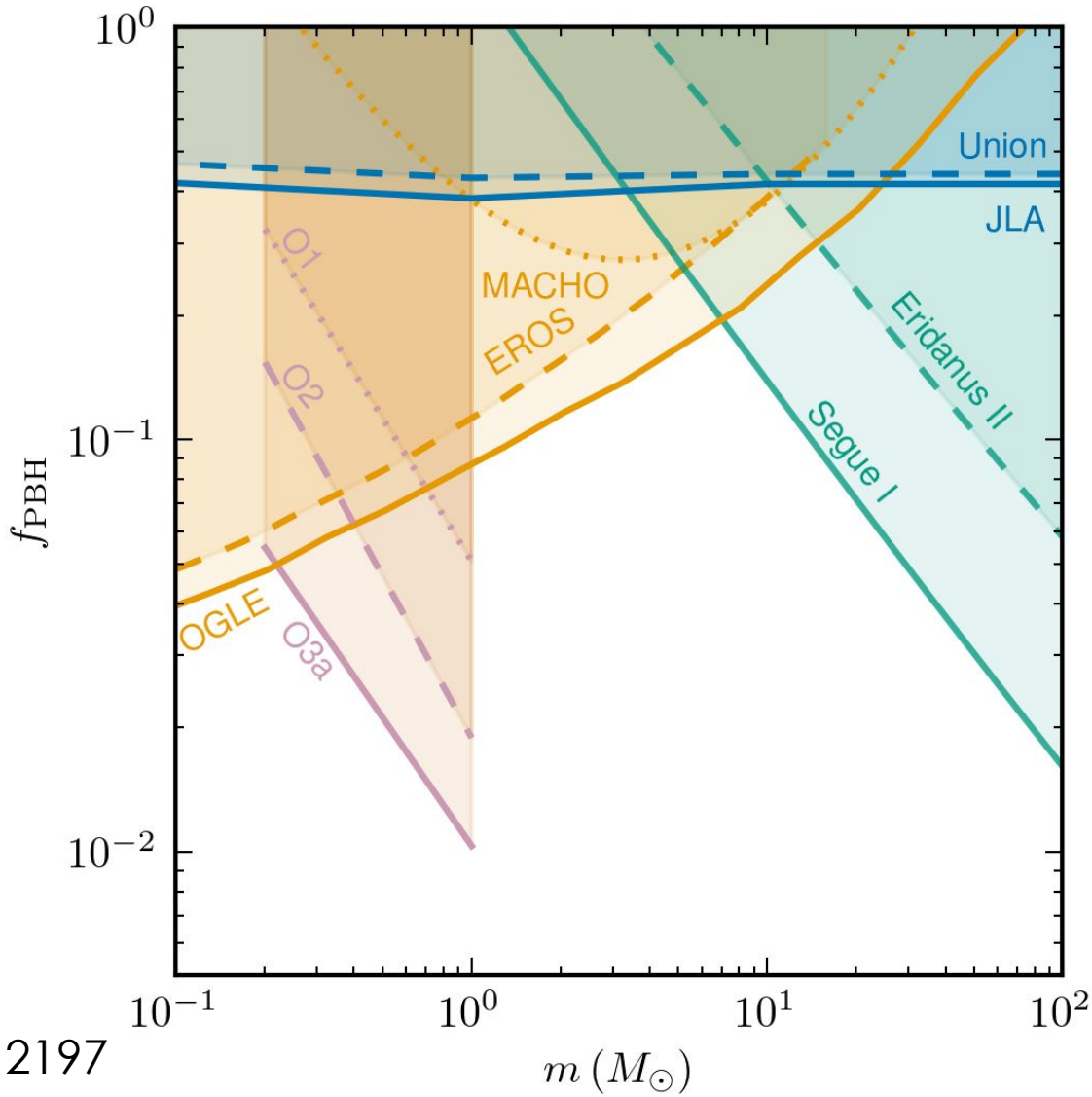
Kimball, Talbot, **CPLB** *et al*. arXiv:2011.05332

Example cluster



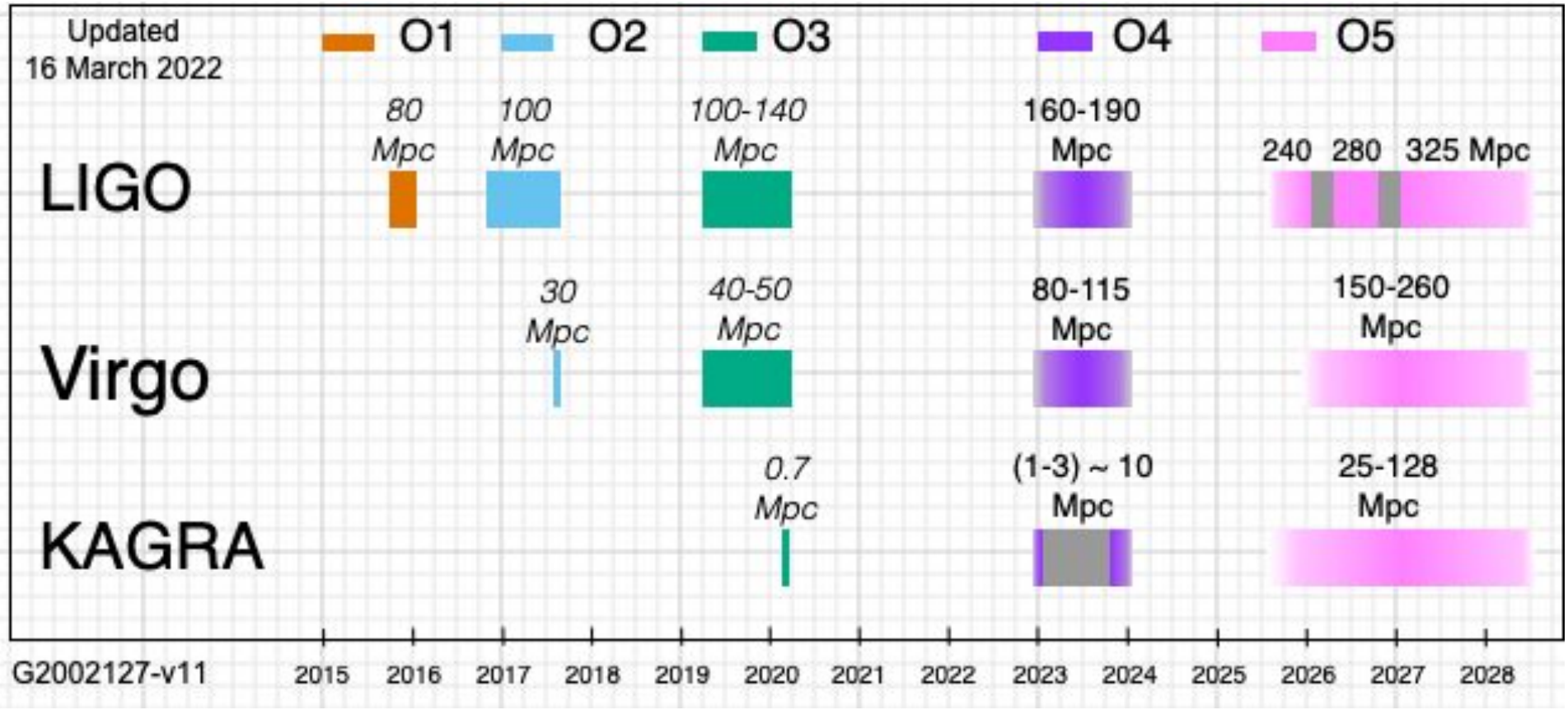
Kimball, Talbot, **CPLB** *et al*. arXiv:2011.05332

Subsolar mass search



LVC arXiv:2109.12197

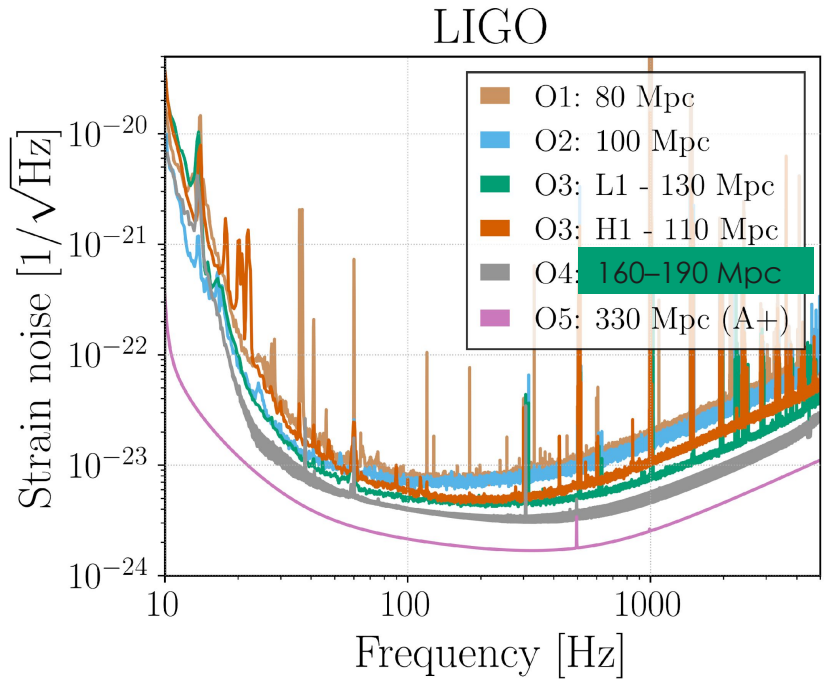
Observing plans

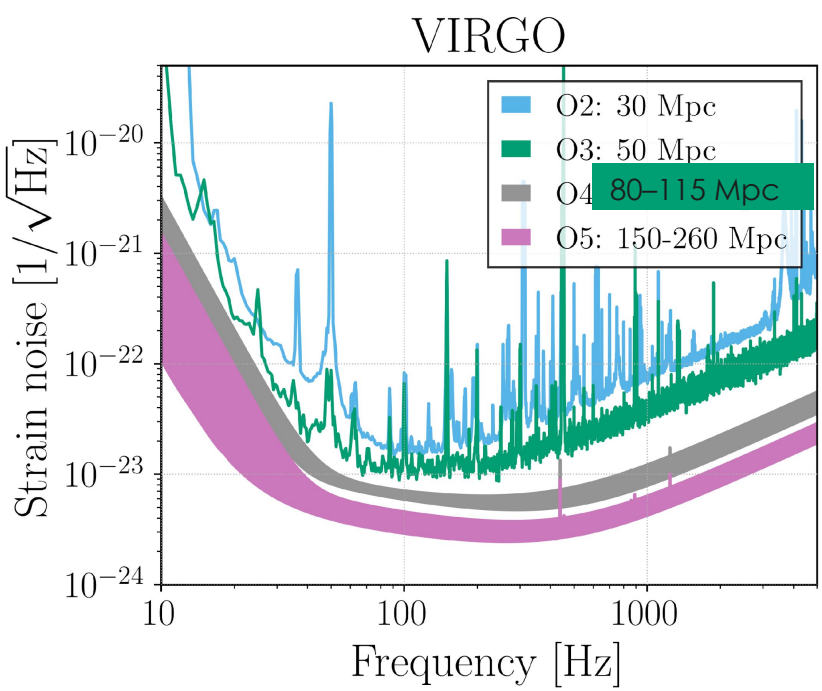


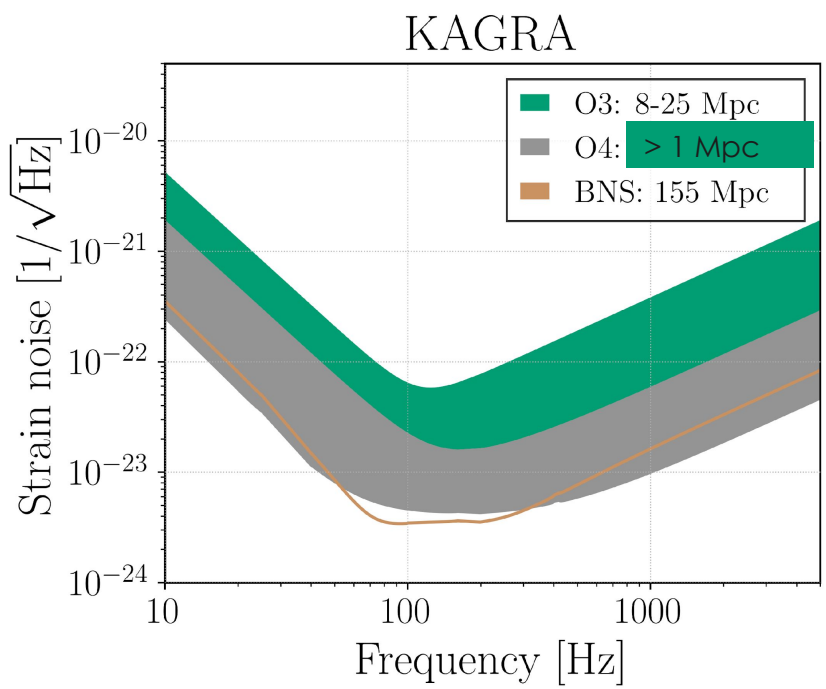
LVK www.ligo.org/scientists/GWEMalerts.php

Plausible detector sensitivities

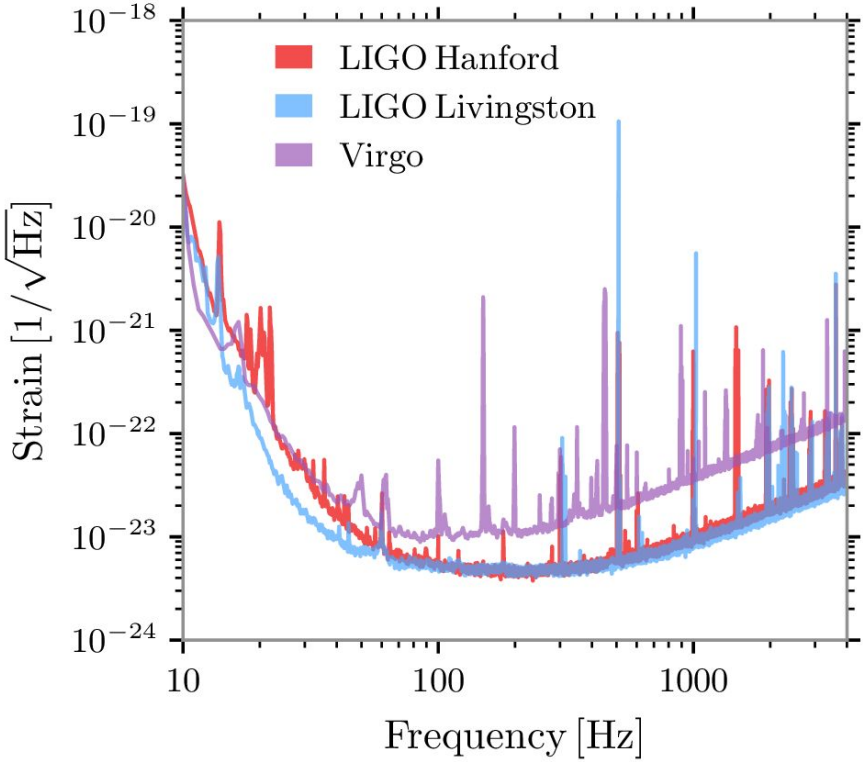
LVK arXiv:1304.0670

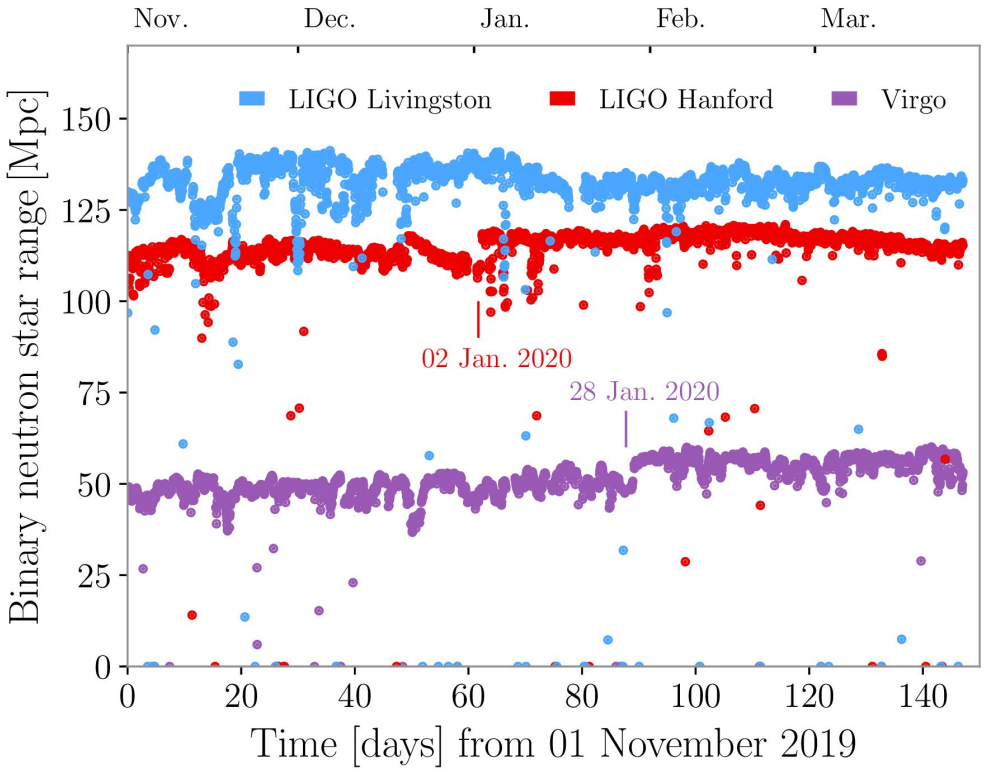






O3b sensitivity

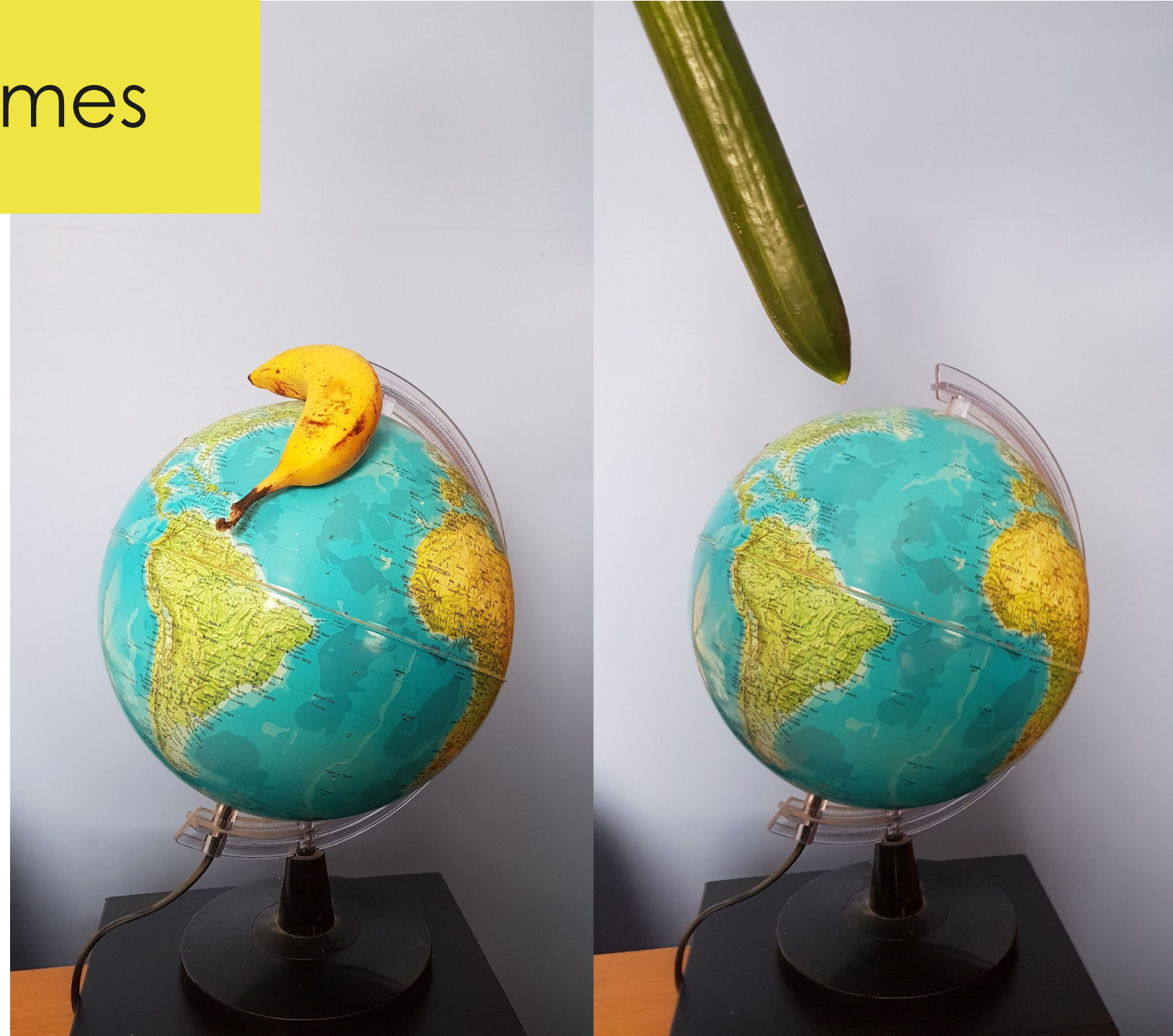




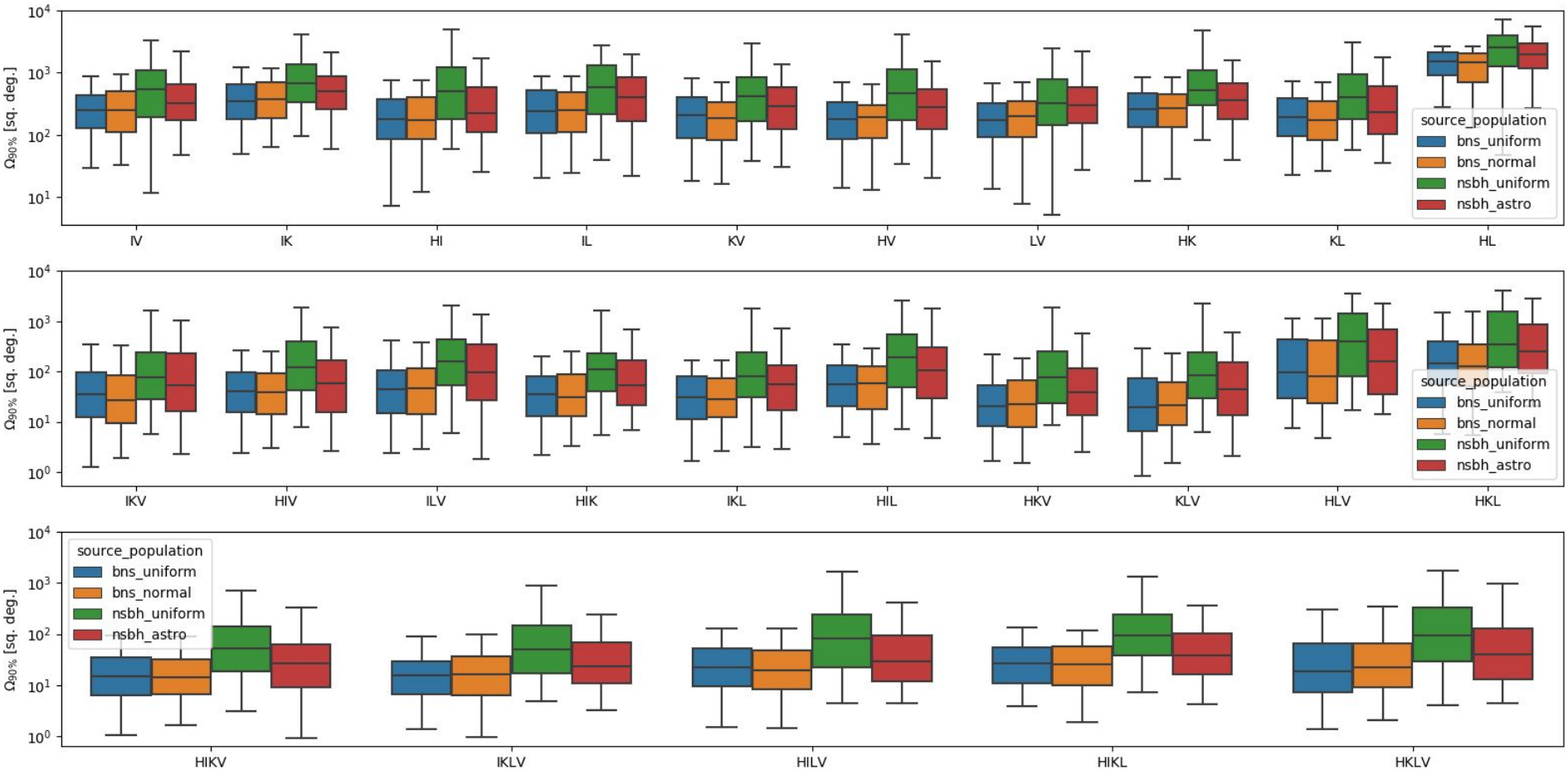
LVK arXiv:2111.03606

Volumes

Not to scale

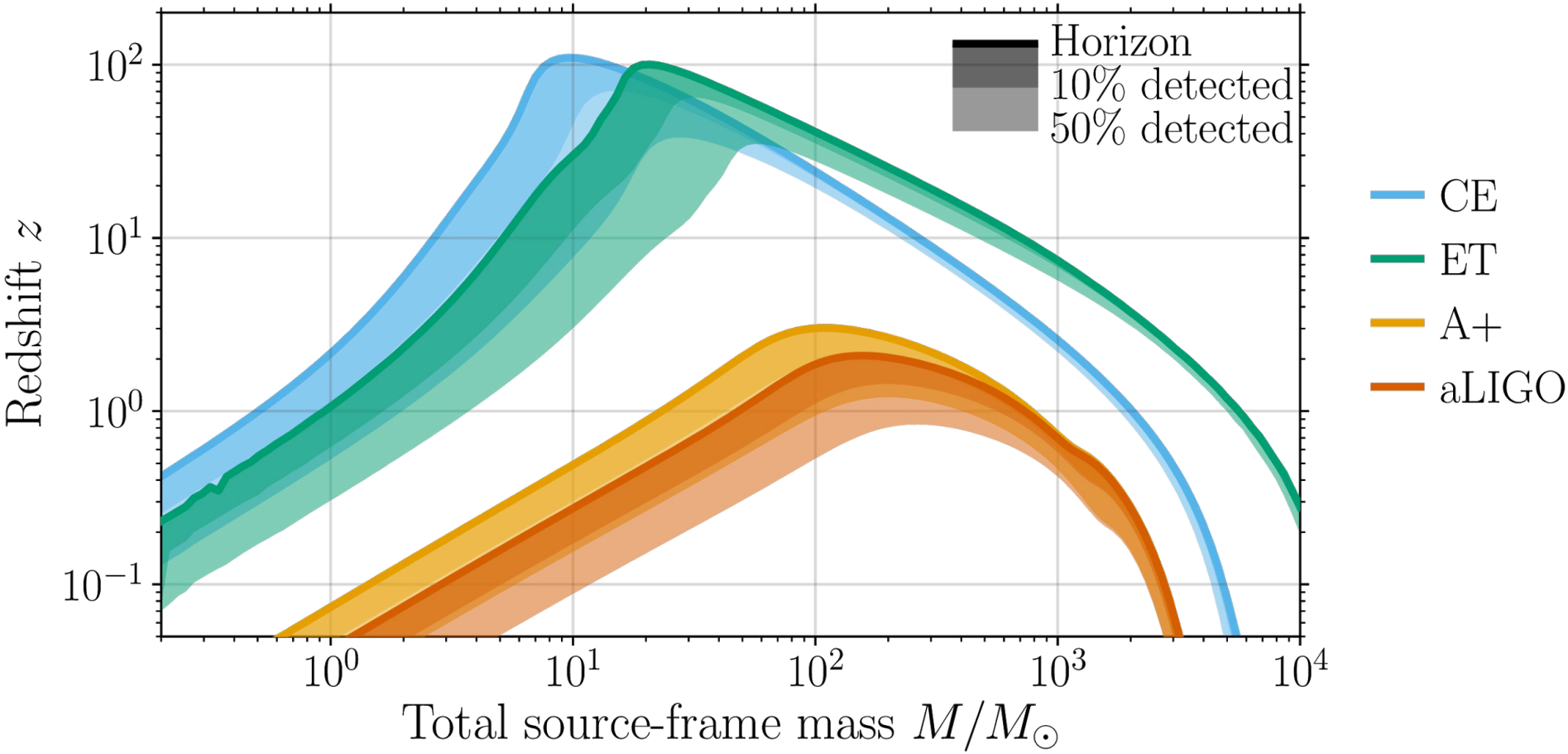


Design sensitivity



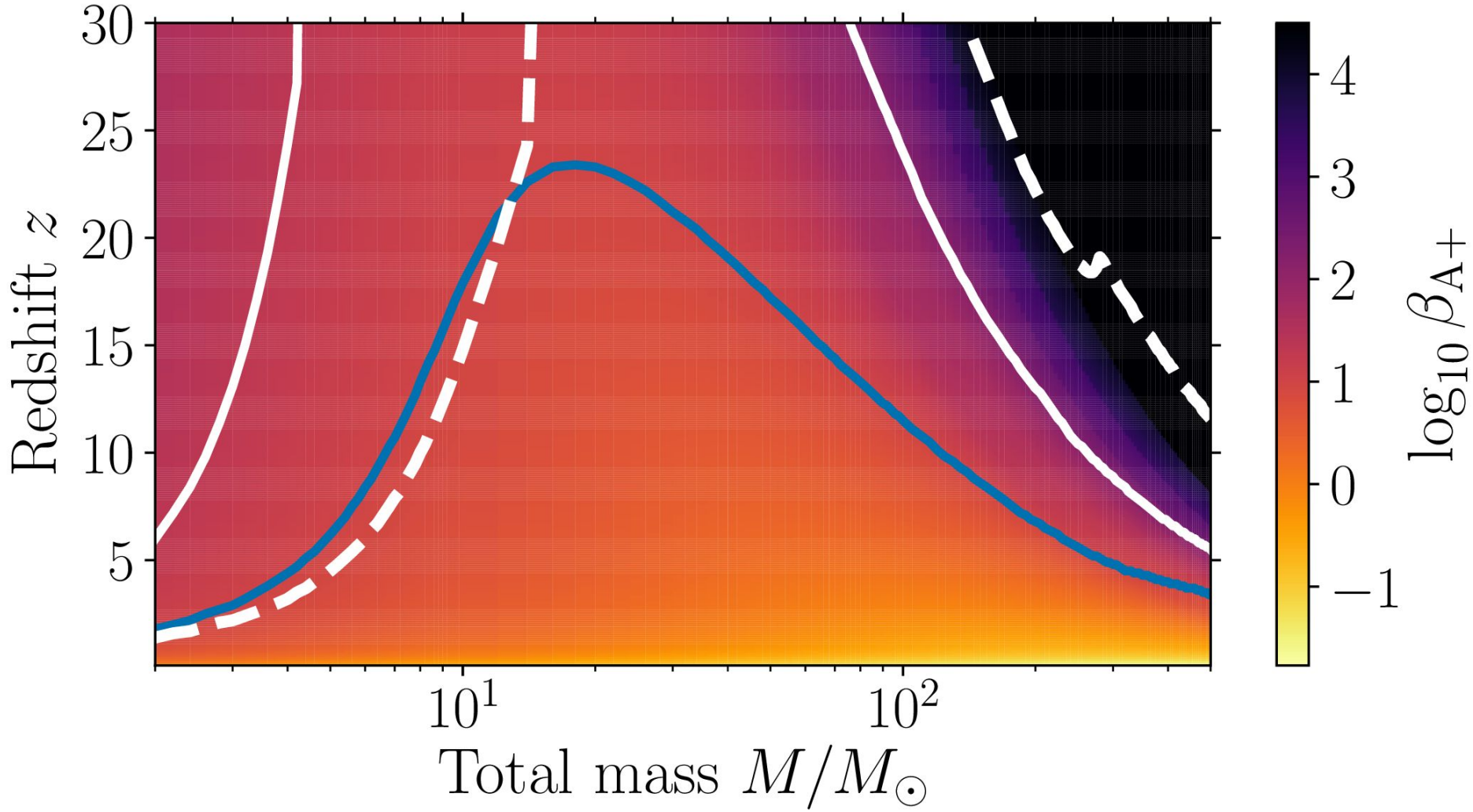
Pankow, …, **CPLB** *et al.*
arXiv:1909.12961

Cosmological reach



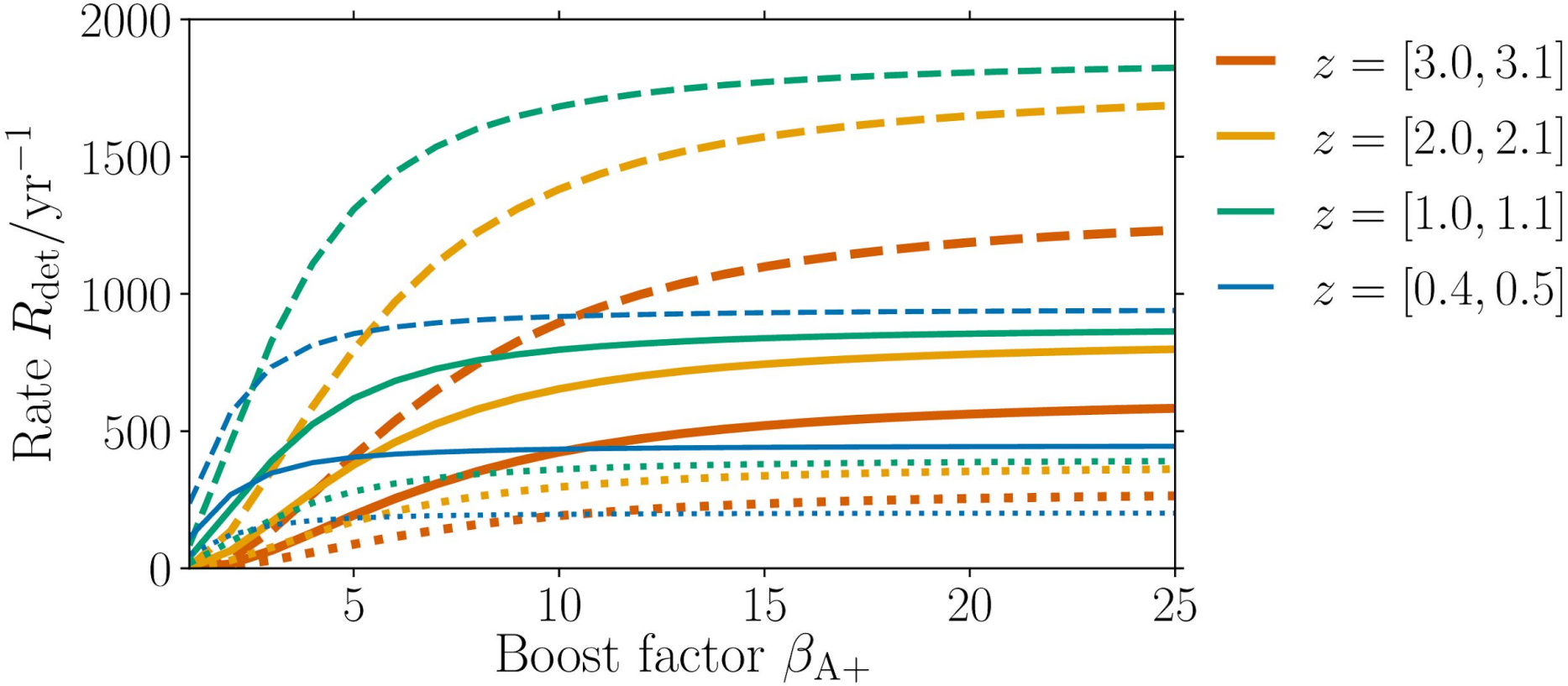
Adapted from Hall & Evans arXiv:1902.09485

Detector boost



Kalogera, **CPLB** *et al*. arXiv:1903.09220

Large sample size



Kalogera, **CPLB** *et al*. arXiv:1903.09220

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