

Current status and future prospects for gravitational wave astrophysics

Katerina Chatziioannou

Flatiron Institute

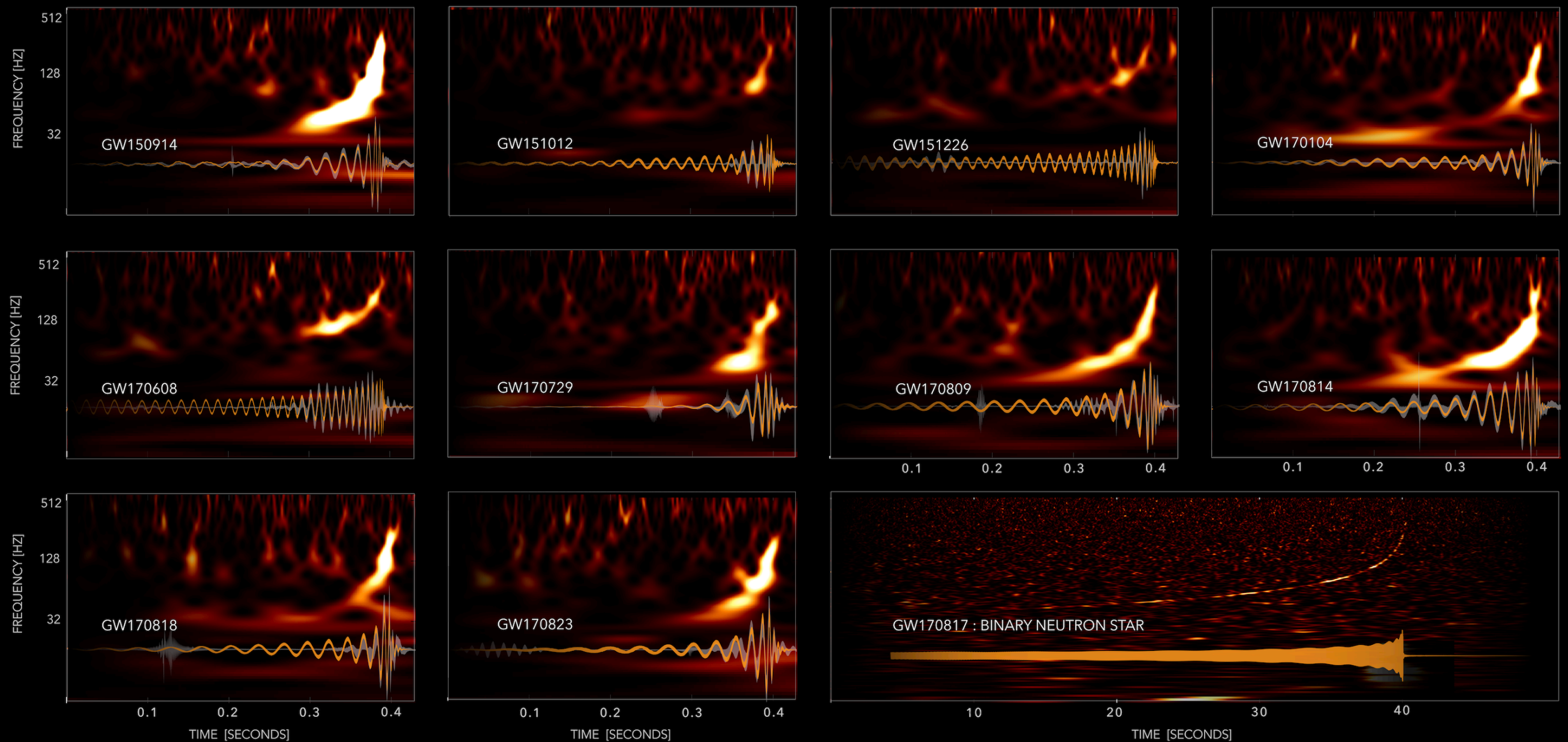


**Brookhaven Forum 2019:
Particle Physics and Cosmology in the 2020's**



Gravitational Wave Astrophysics

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



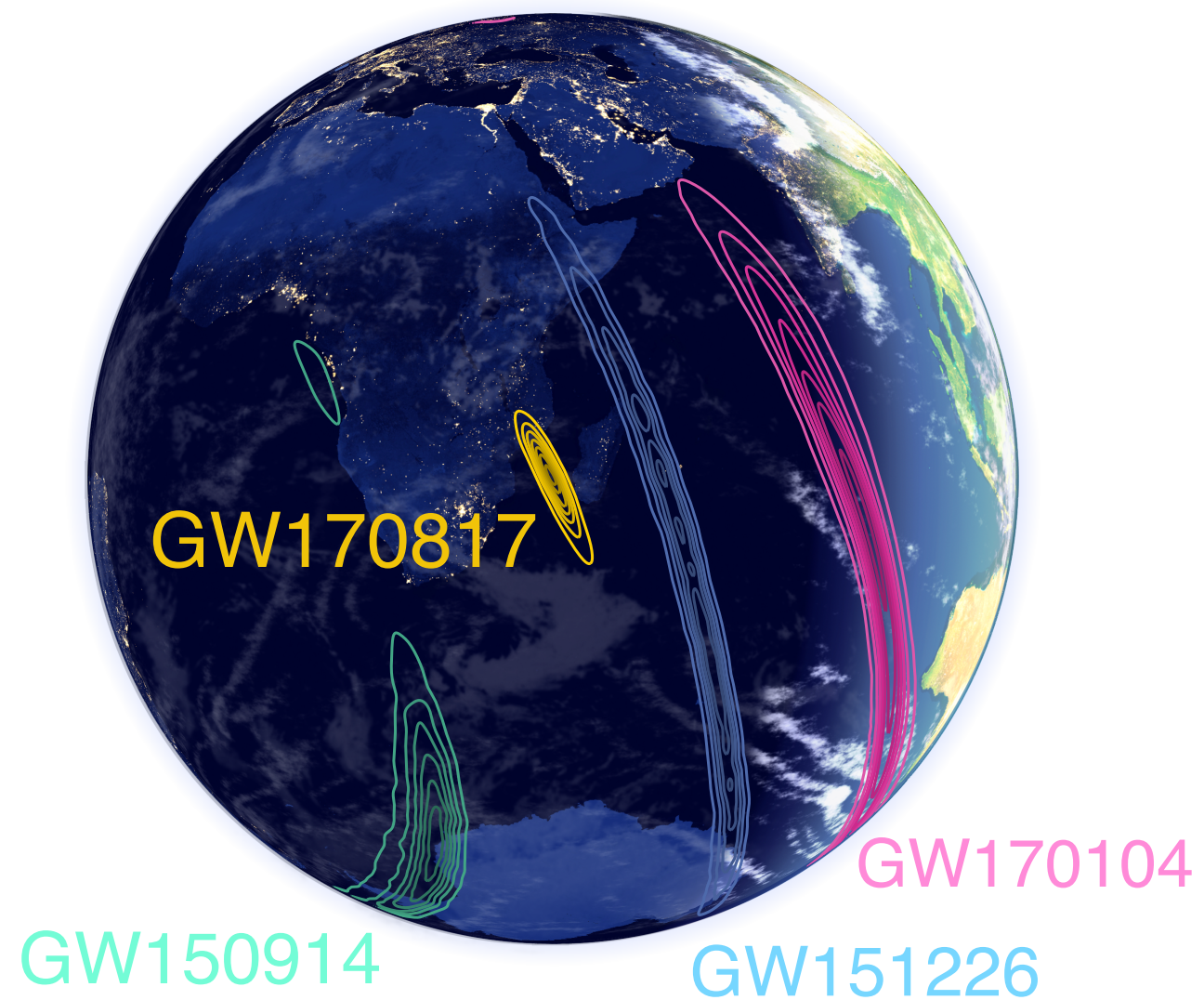
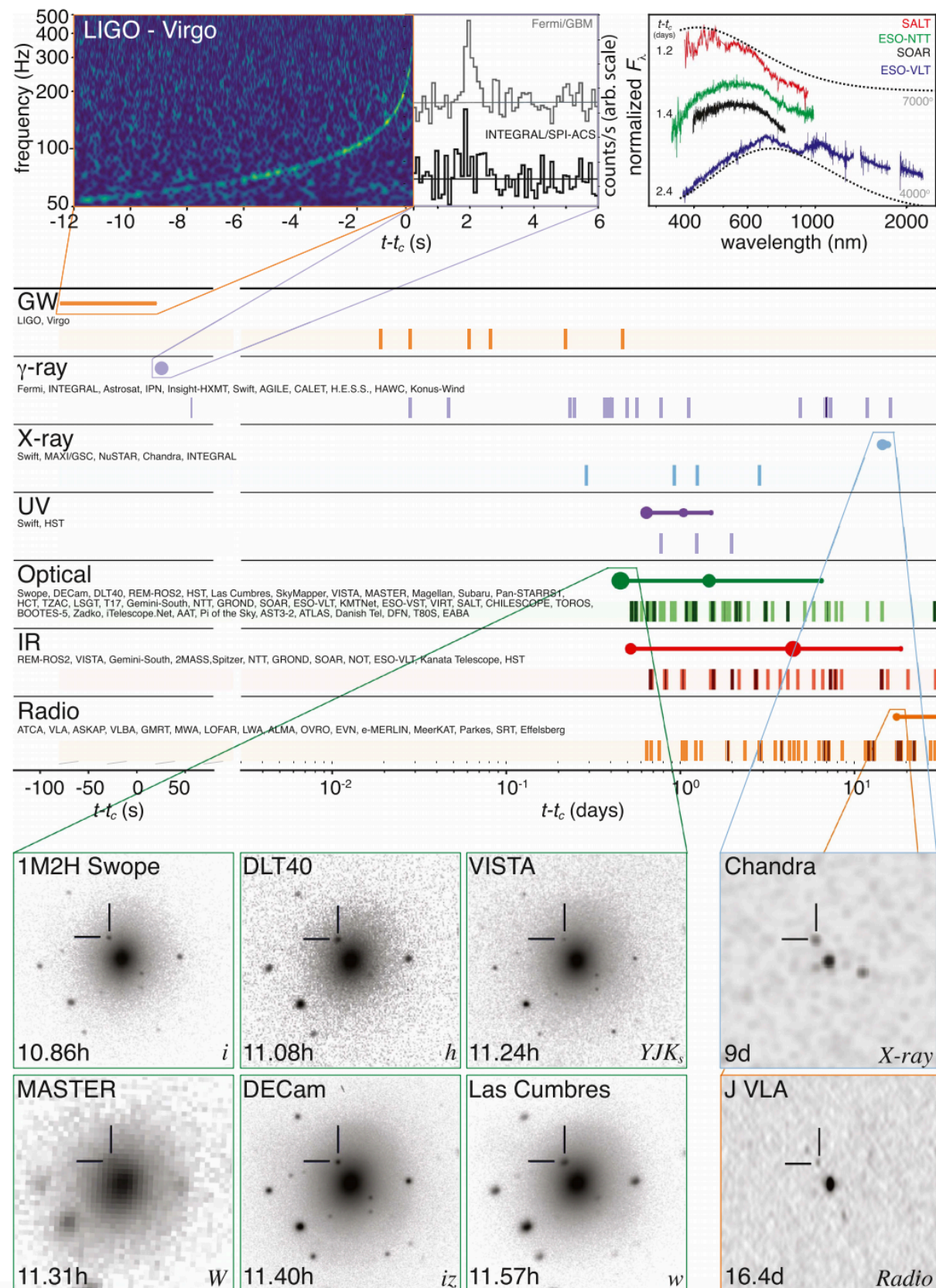
LIGO-VIRGO DATA: [HTTPS://DOI.ORG/10.7935/82H3-HH23](https://doi.org/10.7935/82H3-HH23)

WAVELET (UNMODELED)

EINSTEIN'S THEORY

IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

Multimessenger Astrophysics



Credit: LIGO/Virgo/NASA/Leo Singer

Gravitational wave open science center

Information about the data

From: **2016-11-30T16:00:00**
= GPS 1164556817

To: **2017-08-25T22:00:00**
= GPS 1187733618

Plot width: **8.82 months**
= 23176801 s

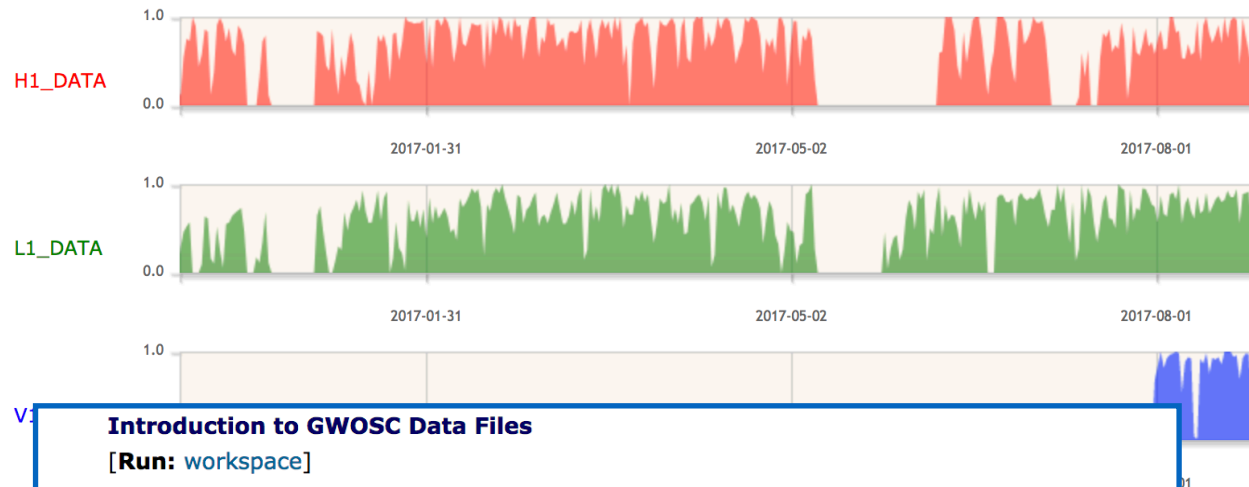
Sample time: **18.20 hours**

[Zoom out all the way](#) [Zoom out](#)

[Coarser resolution](#) [Finer resolution](#)

[URL for this view](#) | [Download this data](#)

To zoom by factor 2, click in any panel.



Introduction to GWOSC Data Files

[Run: workspace]

- Step 0) Software Setup
- Step 1) Download GWOSC Data
- Step 2) What's in a GWOSC Data File?
- Step 3) Working with Data Quality
- Step 4) Using the example API (readligo)

Working with Data

[Run: workspace]

- GWOSC Example API
- Working with Segment Lists
- FFTs, PSDs, and Spectrograms:
 - Lots of Plots tutorial
 - Browse the plot gallery
- LSC software stack and frame reading software
- See the structure of an HDF5 file
- Plot GW150914 data [**Now superseded by the BBH Event tutorial**]
 - HTML | Zip file with data

Searching for astrophysical sources

- Find an Inspiral
- Find an Inspiral Hardware Injection
- Find a Burst Injection: [Slides](#) | [Script](#)

Automated Downloads

- Discover and download GWOSC data
- Automatically discover and download GWOSC data
- Automatically download and process ALL the data

LIGO and Virgo Collaboration Members

- Get data on the LIGO Scientific Collaboration Data Grid: [Quickstart](#) | [Tutorial](#)

Tutorials

Strain Data

Next choose your gravitational wave detector:

- ☐ V1
- ☐ H1
- ☒ L1

Now choose the start and end time of the data that you want, either Universal time or GPS. Change either side and the other responds immediately.

	Universal Time (ISO8601)	GPS Time
Start Time	2016-11-30T16:00:00 🔗	1164556817 OK
End Time	2017-08-25T22:00:00 🔗	1187733618 OK

Choose your output format:

- ☒ Time series data in HDF5 and Frame files
- ☐ Time series data in HDF5 and Frame files, with data quality guide
- ☐ Includes statistics of each file: min/max, band-limited RMS, etc.

Associated Data Products

- **Catalog Paper and Figures:** [P1800307](#)
- **Parameter Estimation Samples:** [P1800370](#)
- **Skymaps (source localization):** [P1800381](#)
- **PSDs (noise model power spectra):** [P1900011](#)
- **Calibration uncertainty:** [P1900040](#)
- **Glitch Subtraction for GW170817:** [T1700406](#)
- **Rates and Populations:** [P1800324](#)
- **Audio Files:** [Example Audio Files](#) | [Sounds of Spacetime](#)
- **GCN Notices:** [GCN Notices](#)
- **GCN Circulars:** [GCN Circulars](#)

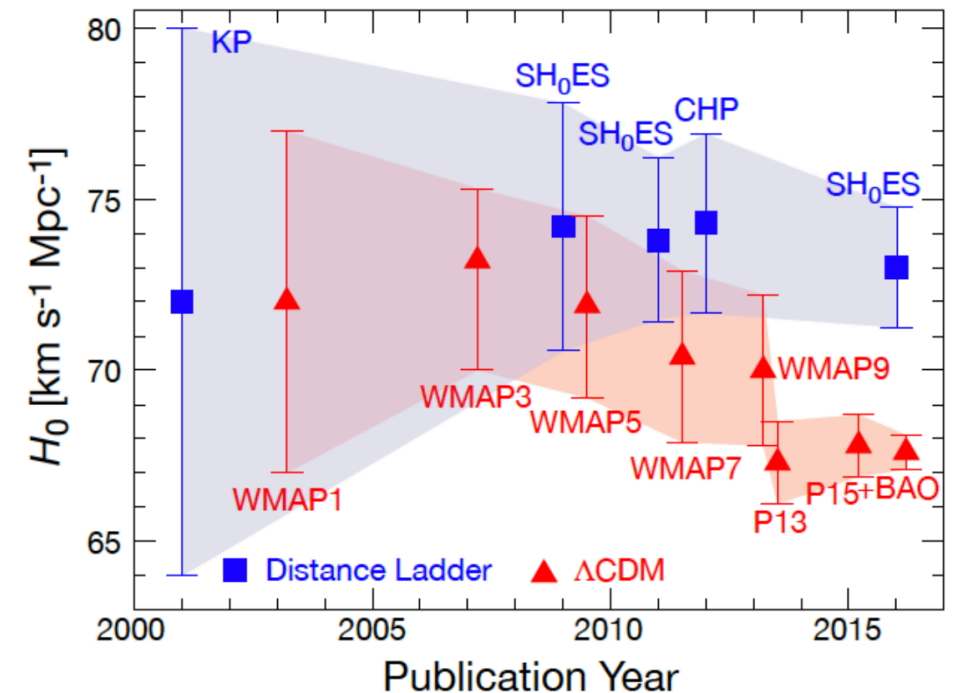
[GW150914](#) | [GW151012](#) | [GW151226](#) | [GW170104](#) | [GW170608](#)
[GW170809](#) | [GW170814](#) | [GW170817](#) | [GW170823](#)

Data products

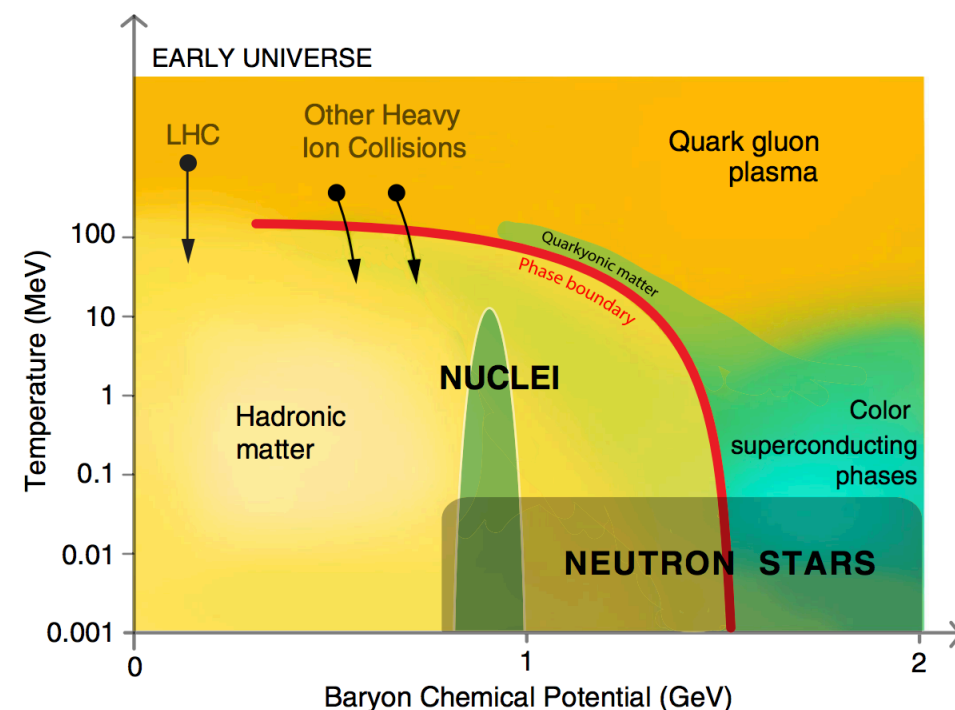
<https://www.gw-openscience.org/>

Unique opportunities

- Measurement of the **Hubble** constant with GWs
- Constraints on the properties of **supranuclear** matter
- Insights on **fundamental** physics



Freedman (arxiv:1706.02739)



Watts+ (arxiv:1602.01081)

Not covering:
origin of the elements,
properties of GRBs, neutrinos, etc.

Cosmology with gravitational waves

**GW measures the
luminosity distance**

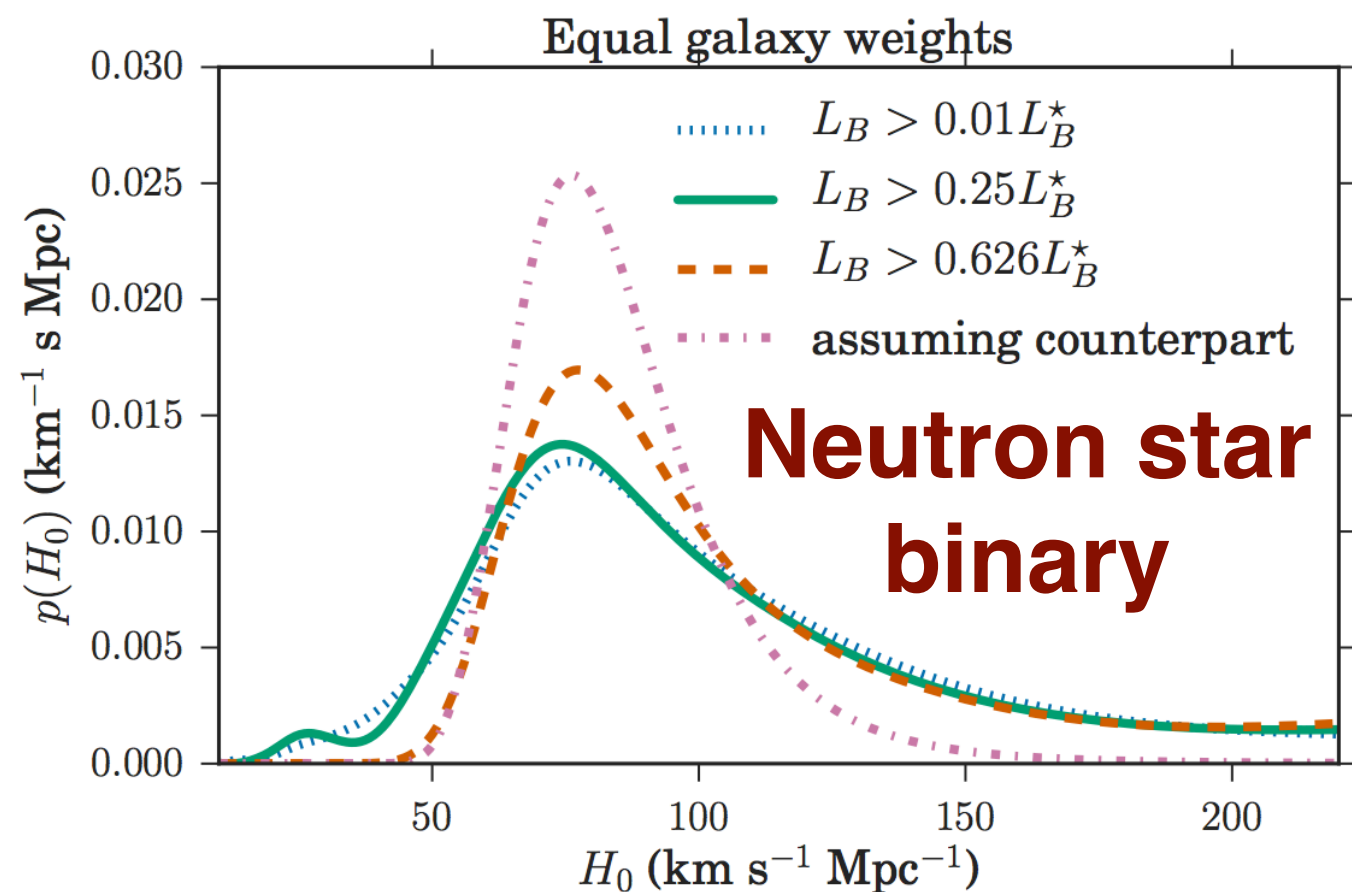
$$h \sim \frac{A(\text{mass, sky, inclination})}{D_L}$$

**Also need the
the redshift**

$$H_0 = \frac{cz}{D_L}$$

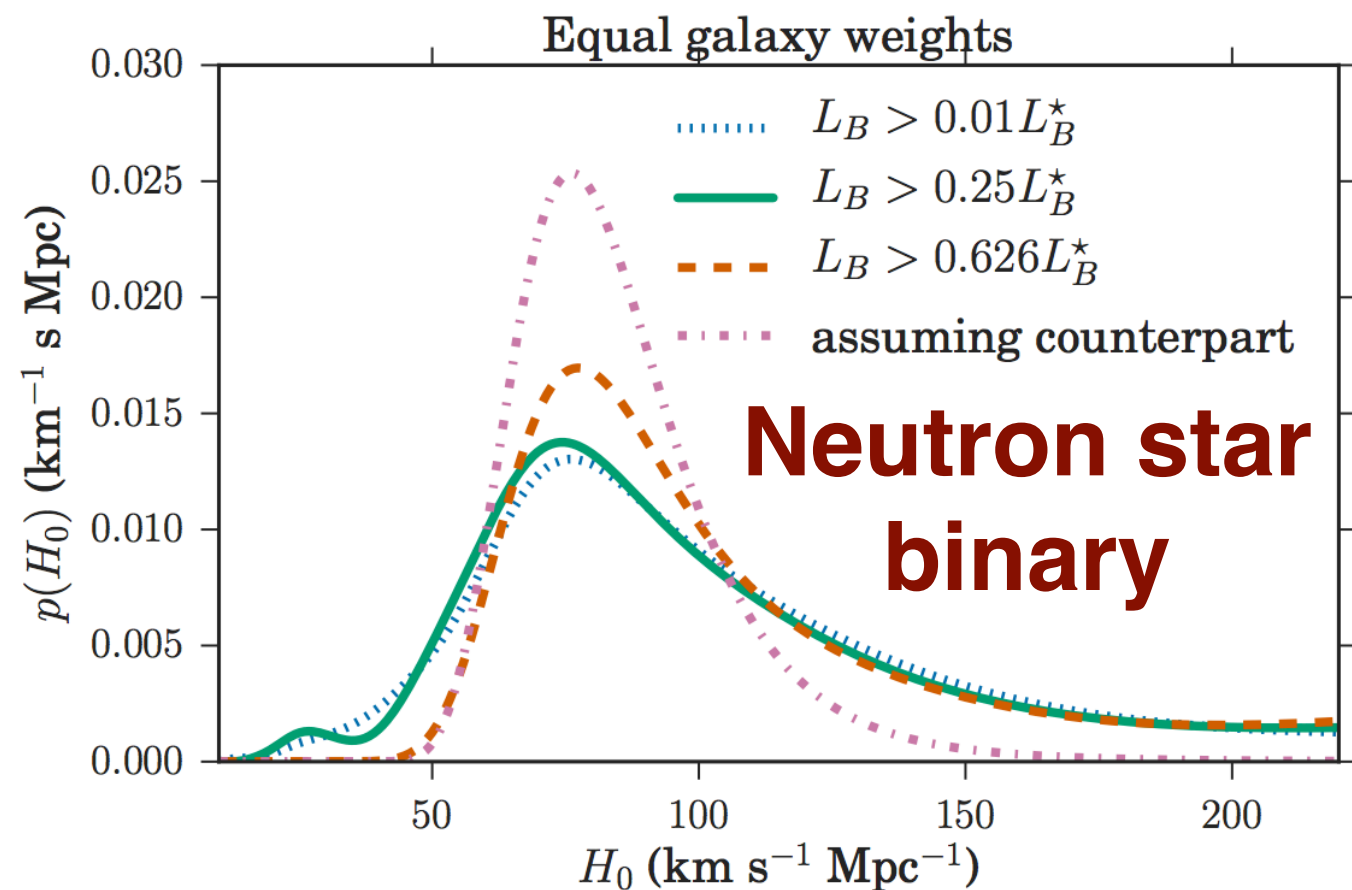
Statistical association between GW and its host galaxy

Statistical association between GW and its host galaxy

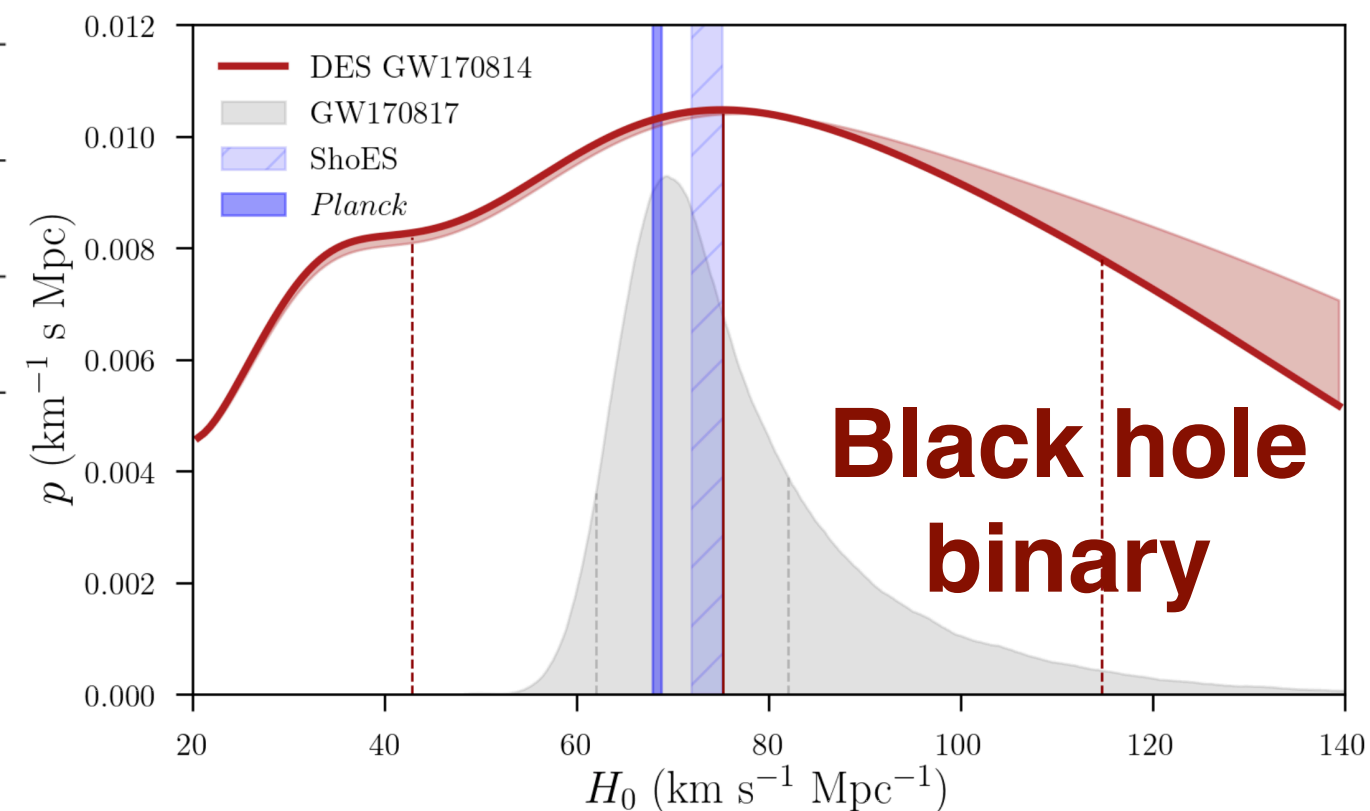


Fishbach+ (arxiv:1807.05667)

Statistical association between GW and its host galaxy



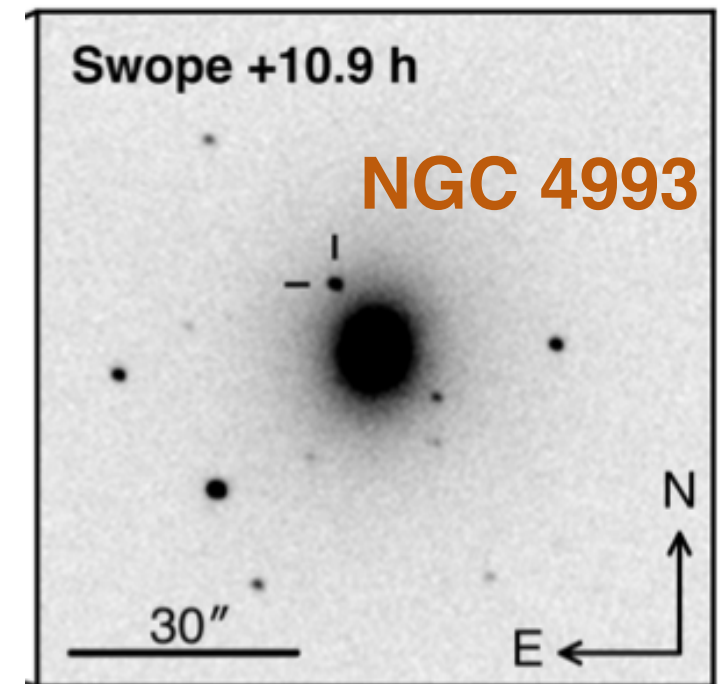
Fishbach+ (arxiv:1807.05667)



Soares-Santos+ (arxiv:1901.01540)

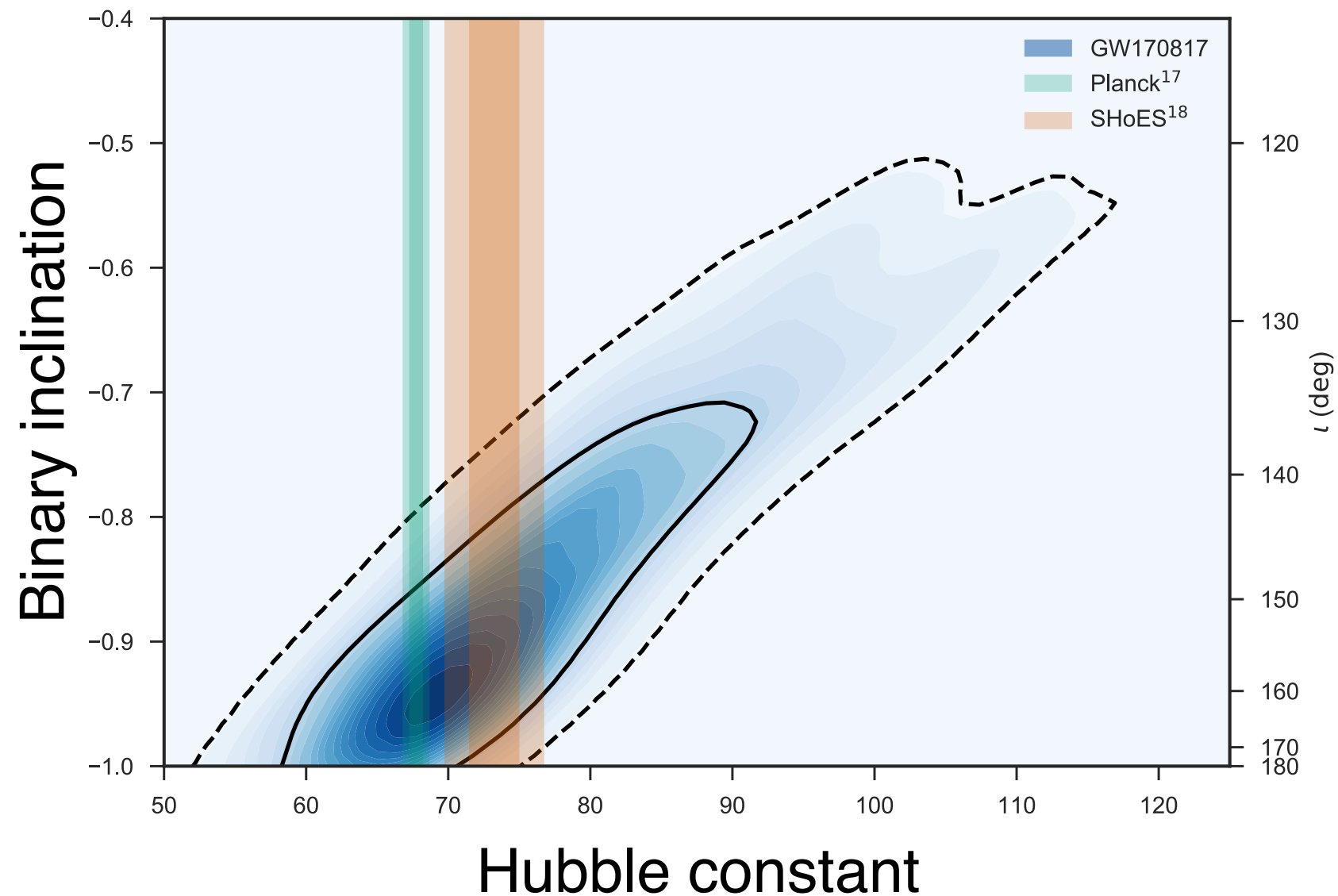
Standard Sirens: Schutz (Nature 1986)

Counterpart method

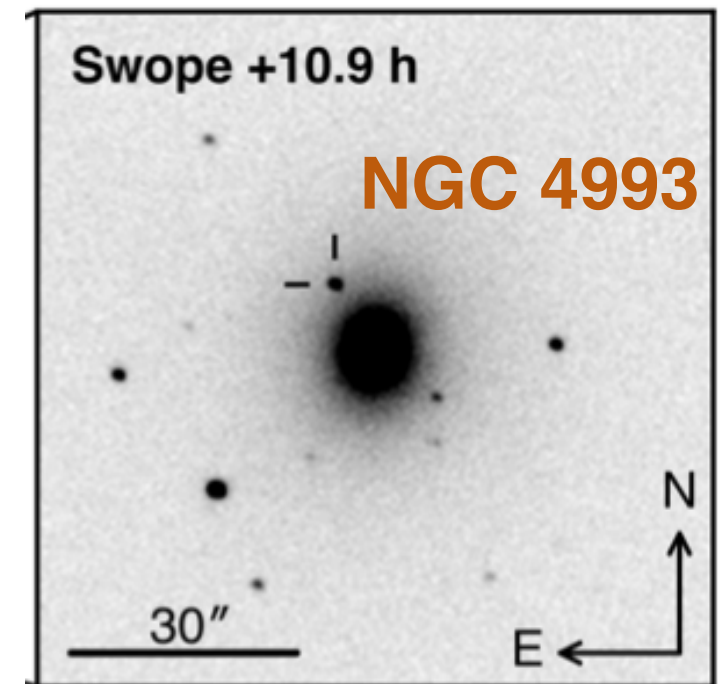


Standard Sirens:
Schutz (Nature 1986),
Holz and Hughes (astro-ph/0504616)

Counterpart method

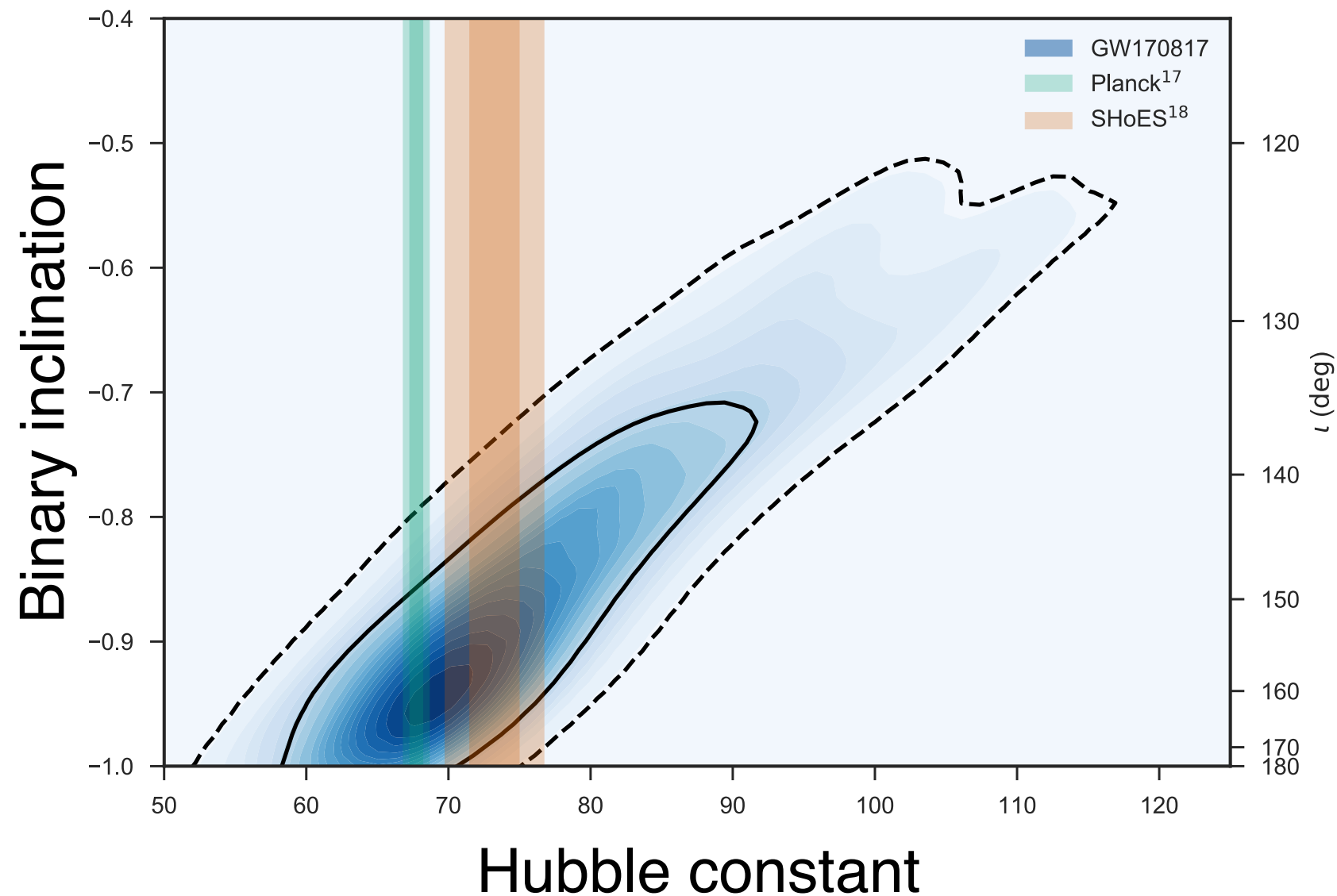


LVC & EM partners (arxiv:1710.05835)

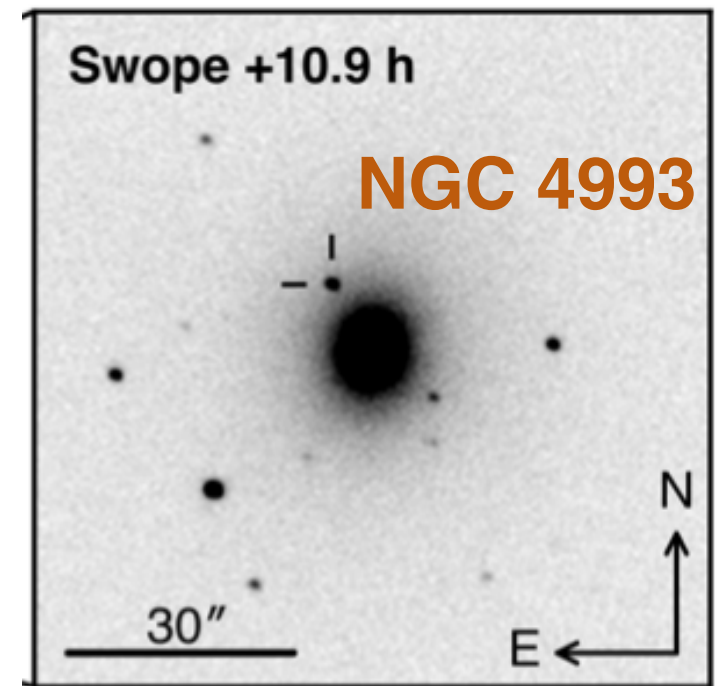


Standard Sirens:
Schutz (Nature 1986),
Holz and Hughes (astro-ph/0504616)

Counterpart method



LVC & EM partners (arxiv:1710.05835)



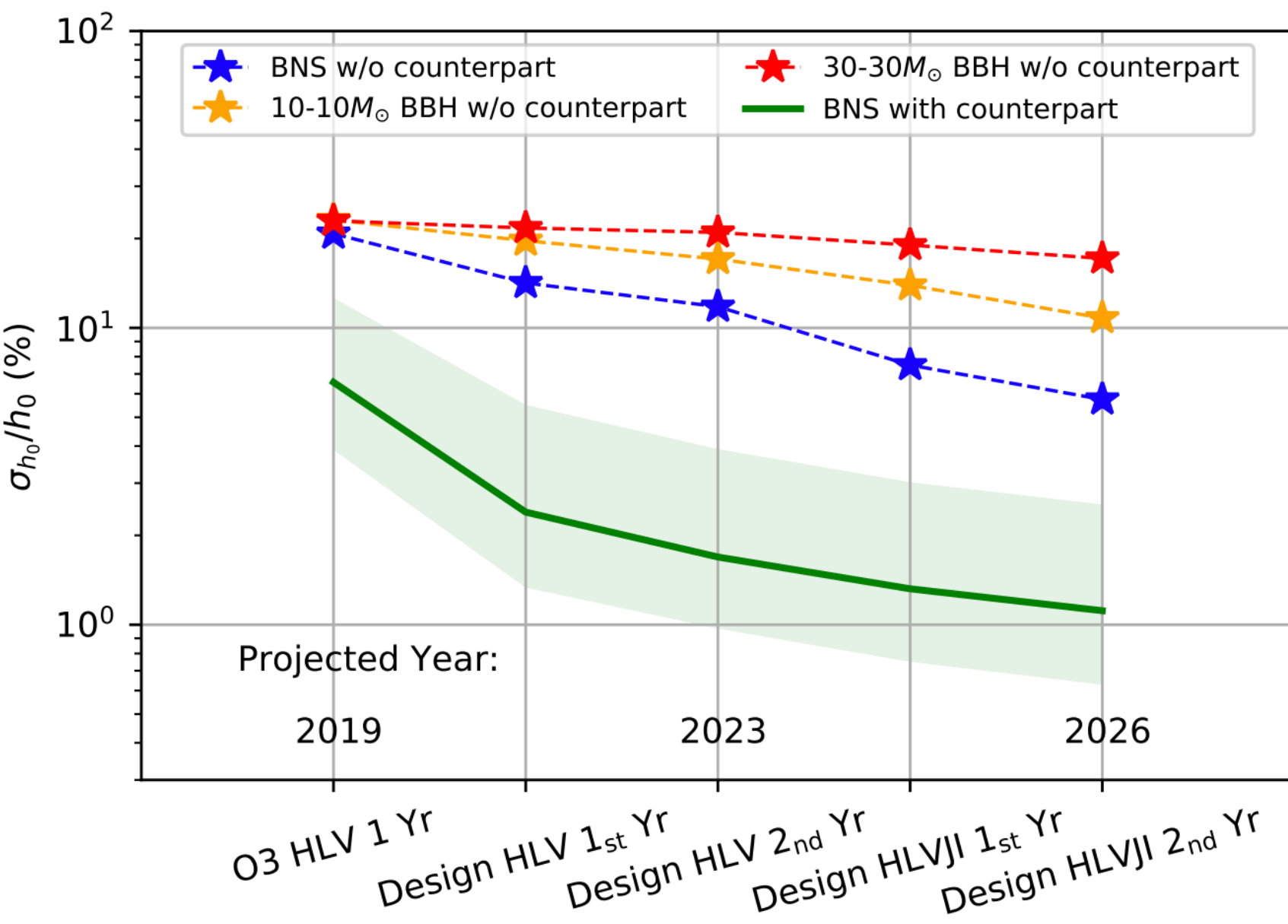
Consistent with
existing
measurements

Standard Sirens:

Schutz (Nature 1986),
Holz and Hughes (astro-ph/0504616)

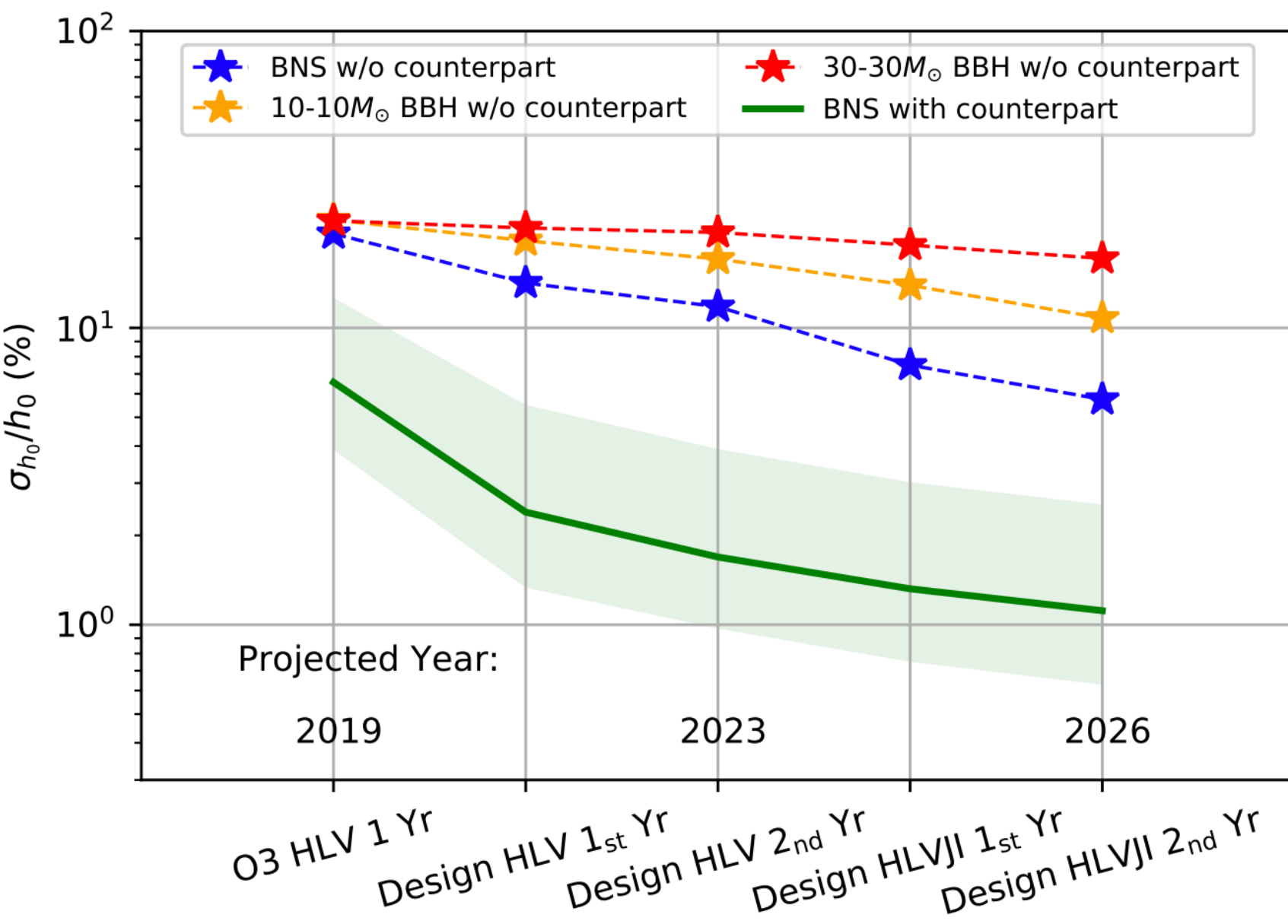
Hubble tension

Could help **resolve the H0 tension** with
~100 BNSs with EM counterparts



Hubble tension

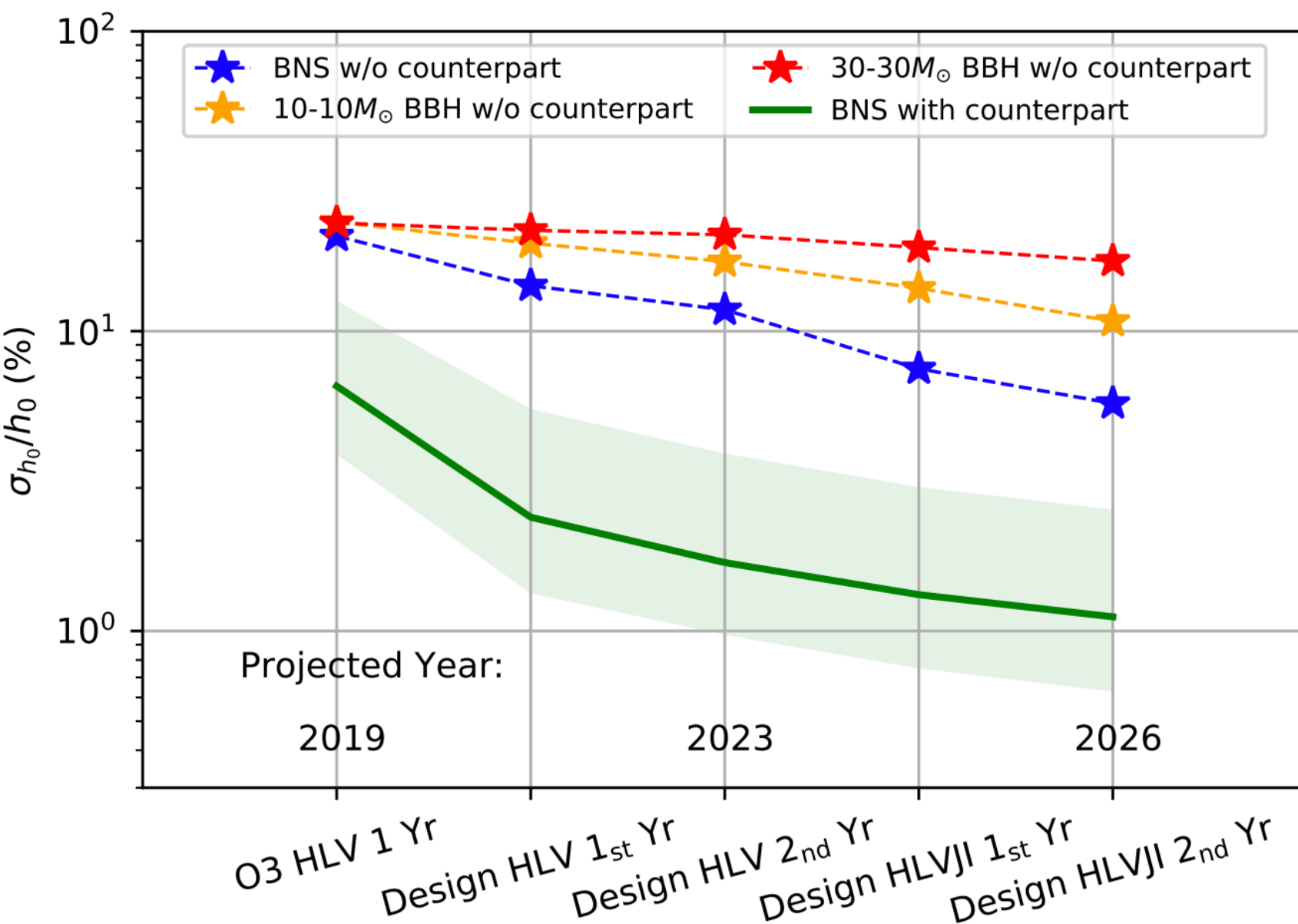
Could help **resolve the H0 tension** with
~100 BNSs with EM counterparts



Given current rate estimates, the **counterpart** method might **outperform** the **statistical** one

Hubble tension

Could help **resolve the H0 tension** with
~100 BNSs with EM counterparts



Given current rate estimates, the **counterpart** method might **outperform** the **statistical** one

Could be limited by **calibration** uncertainty, for O2 **3-5%** in amplitude

Length scale

GW/GR observations have **no intrinsic** length scale

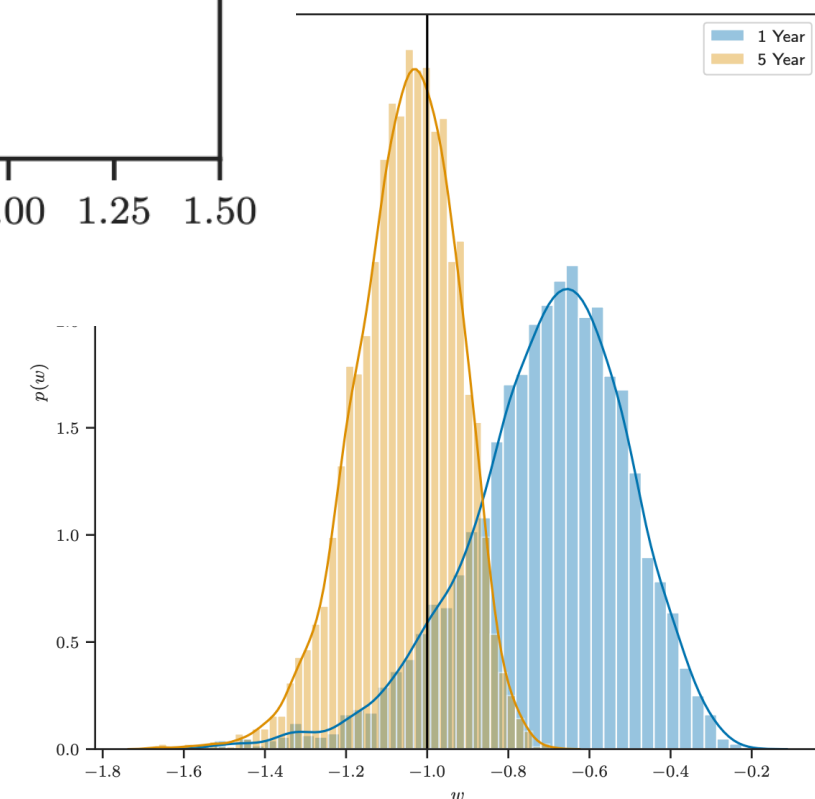
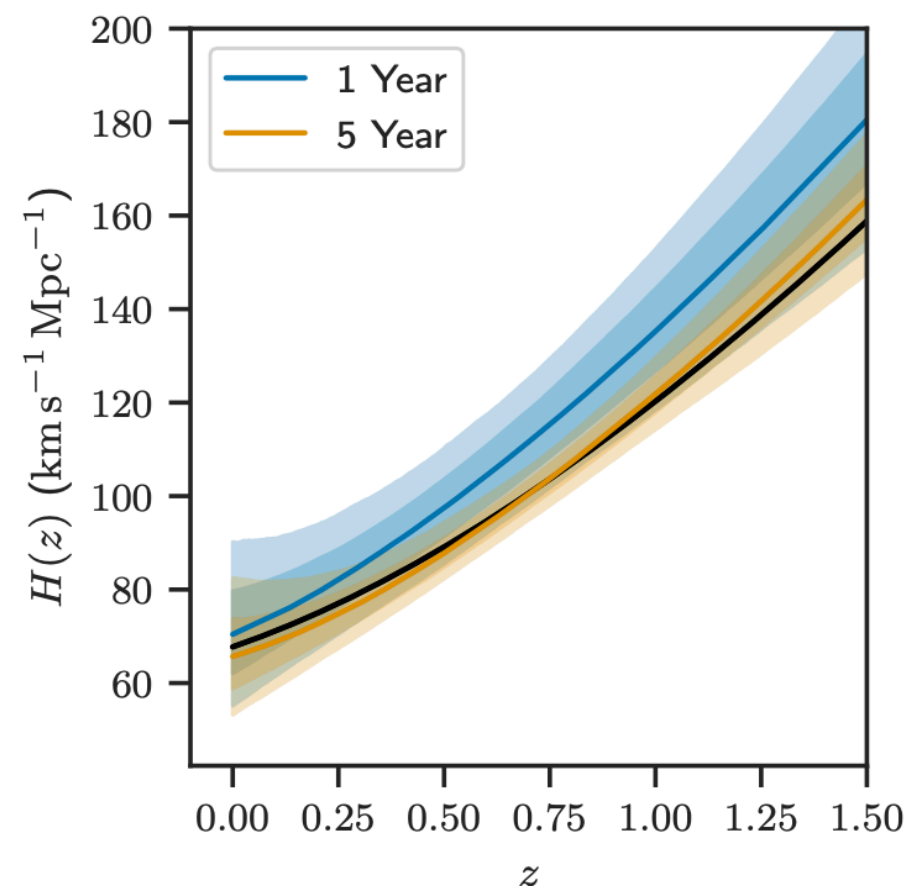
Need to include
astrophysical scales
(host galaxy redshift,
mass distribution,
NS equation of state)

Length scale

GW/GR observations have **no intrinsic** length scale

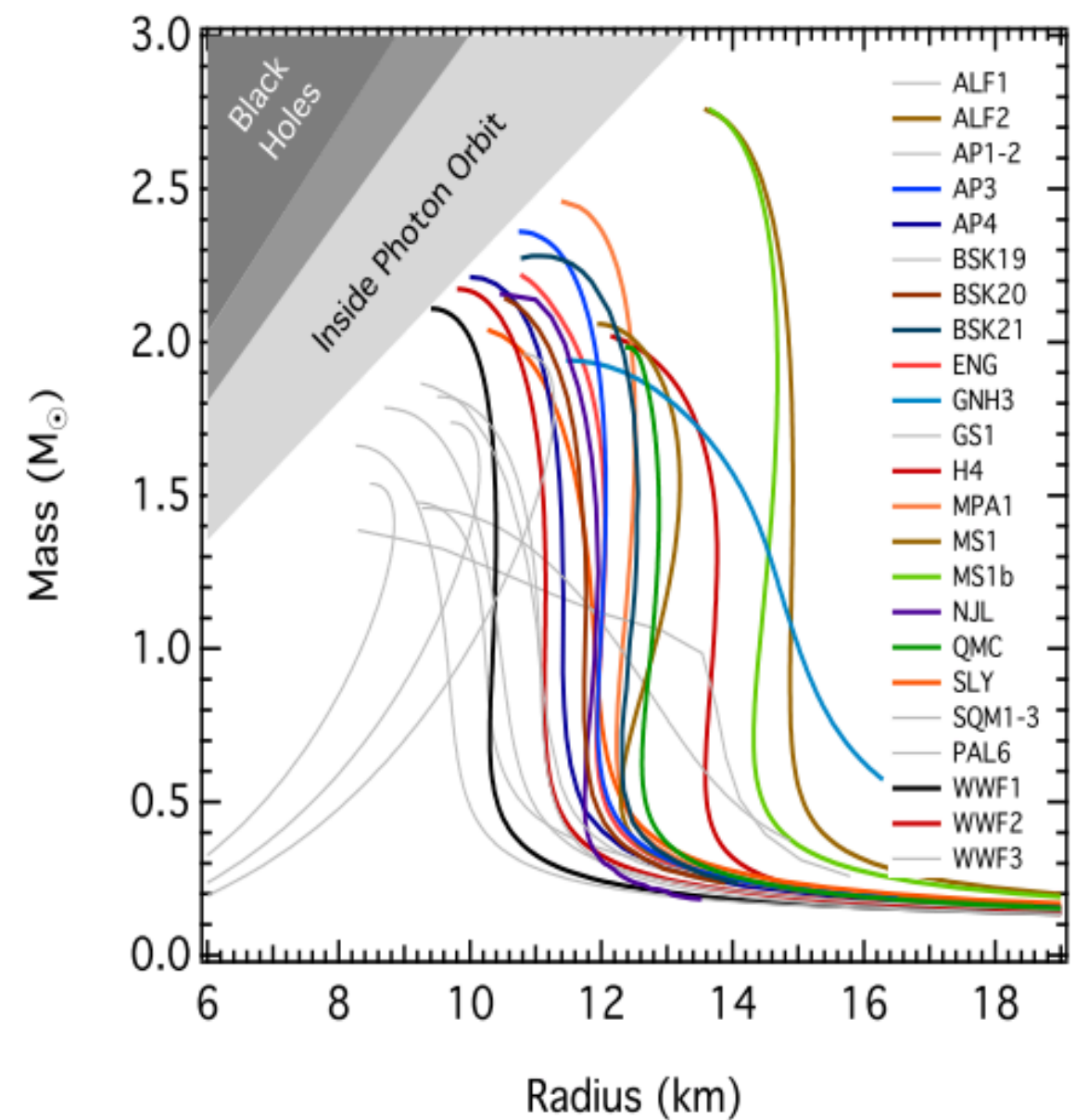
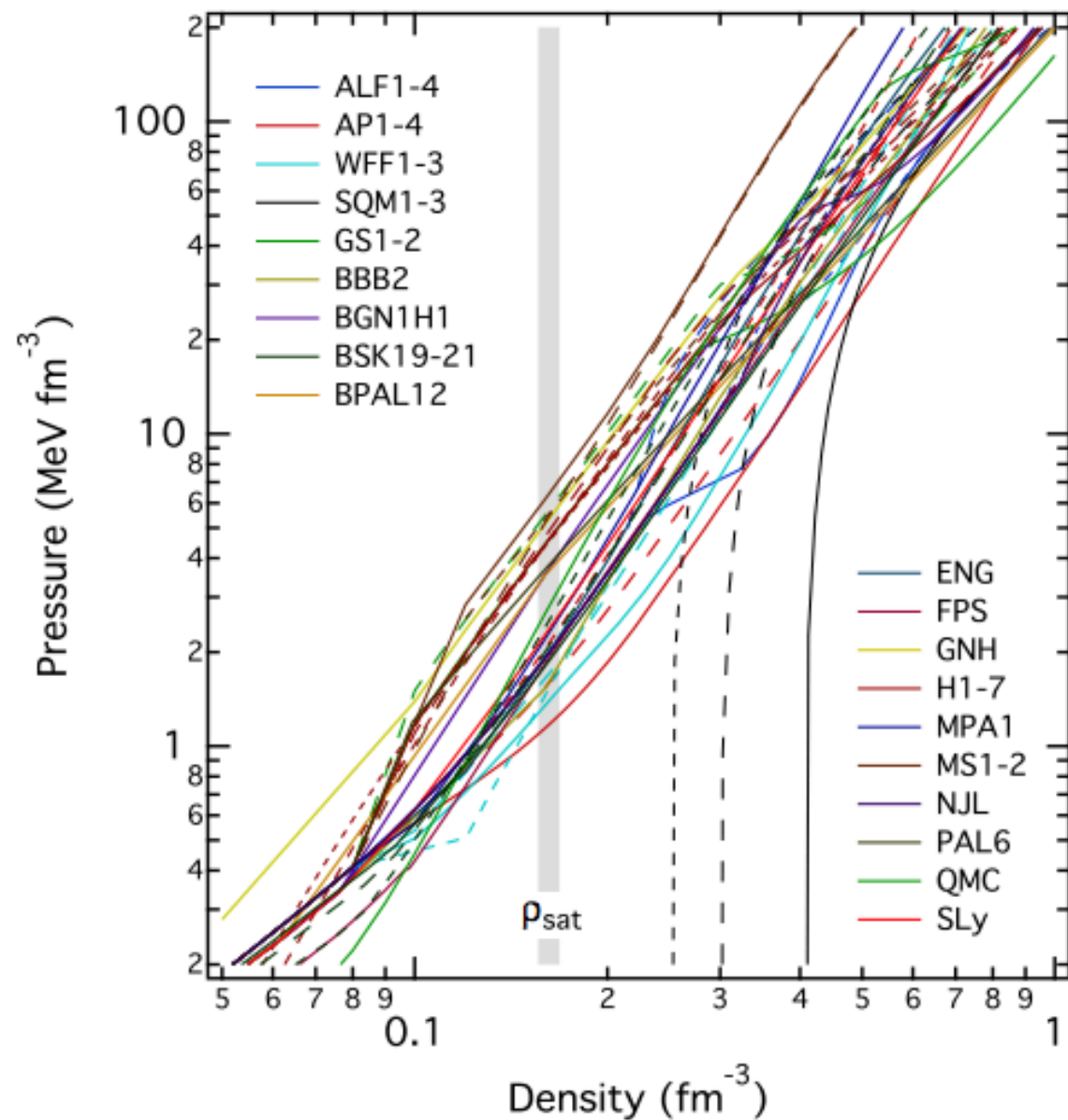
Need to include
astrophysical scales
(host galaxy redshift,
mass distribution,
NS equation of state)

This example: maximum BH
mass due to unstable
supernova processes

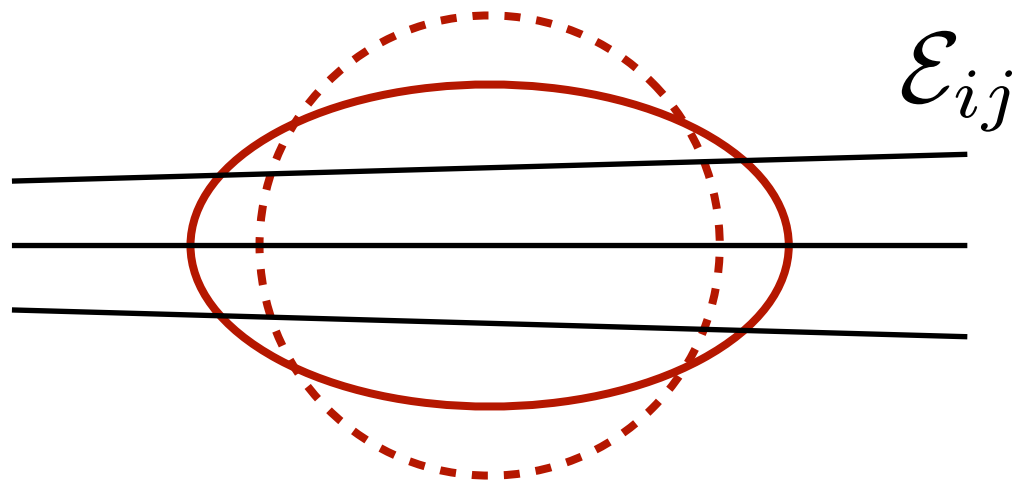


Equation of state of dense matter

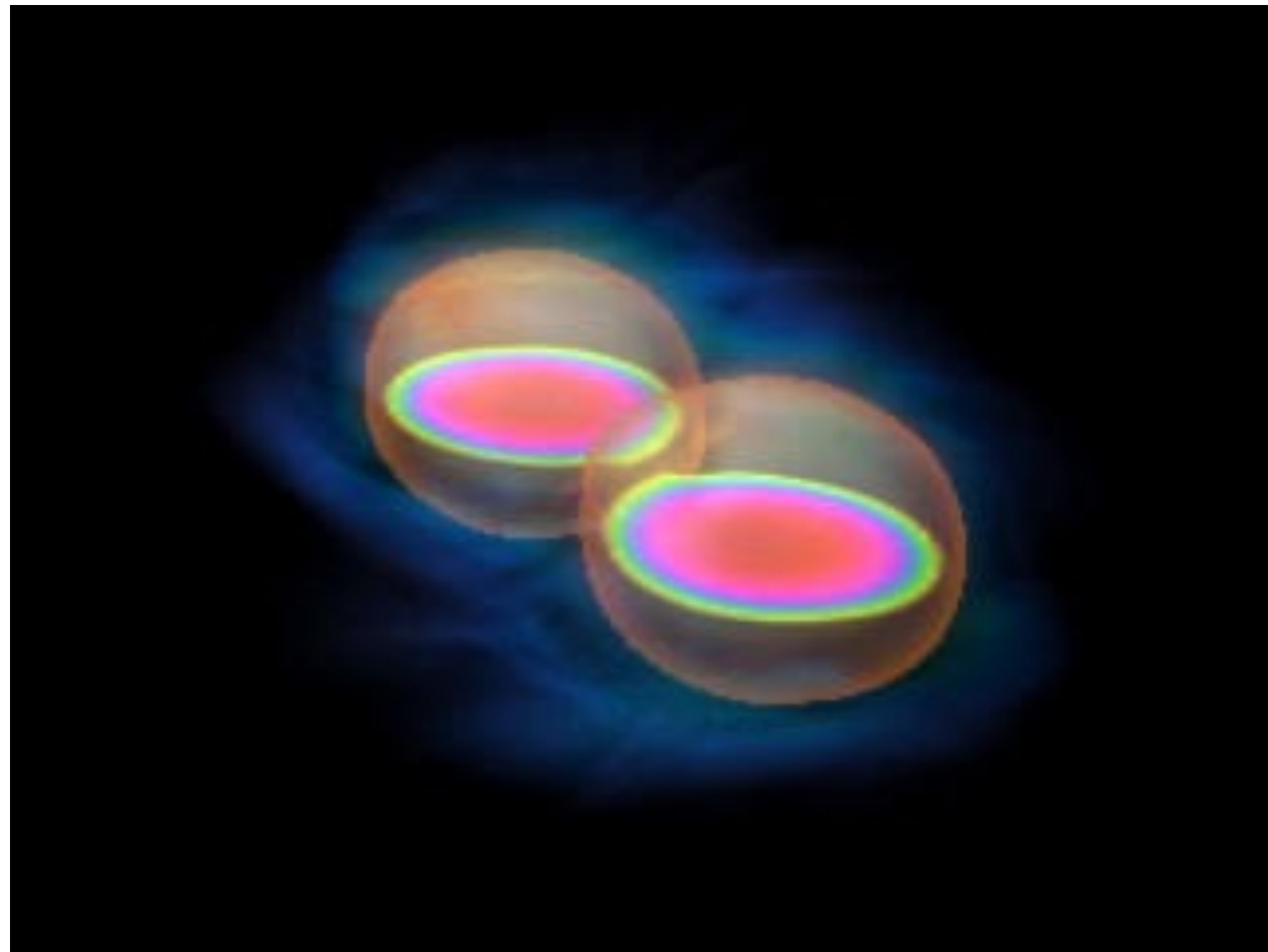
Neutron stars are extended bodies with structure



Tidal interactions

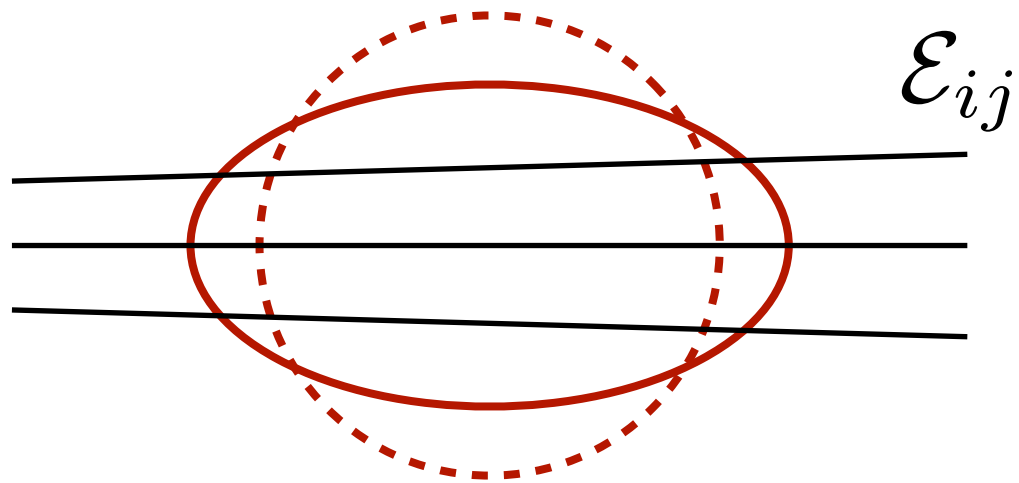


Credit: Aaron Zimmerman



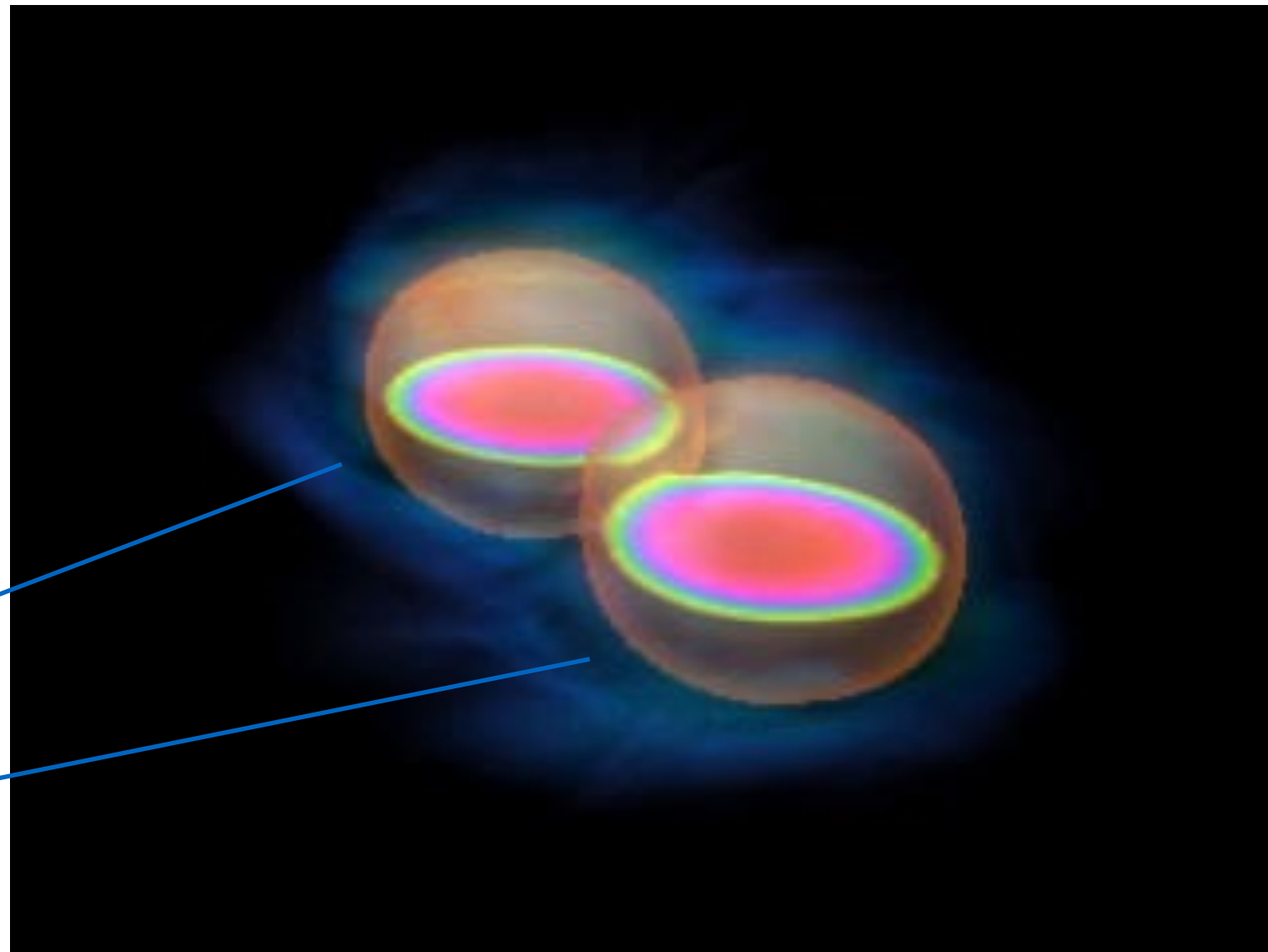
Calder

Tidal interactions



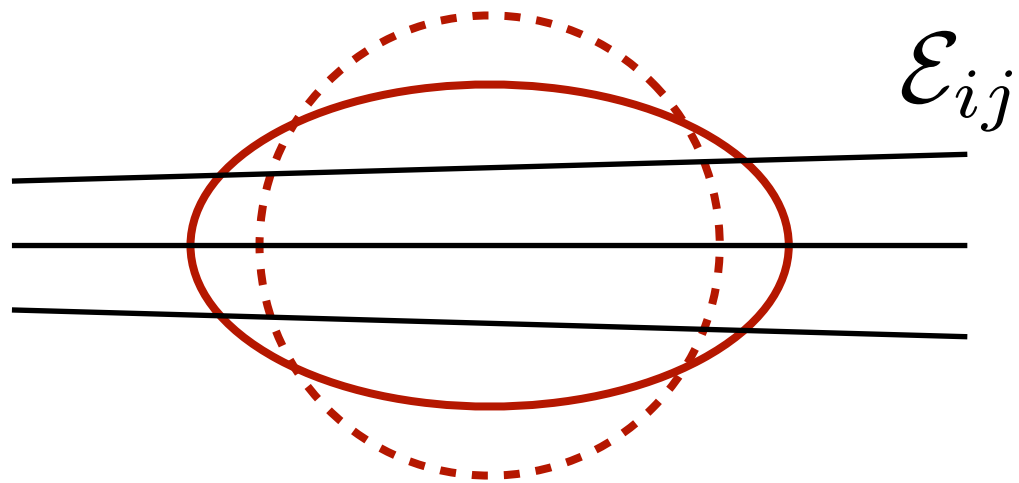
Credit: Aaron Zimmerman

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$



Calder

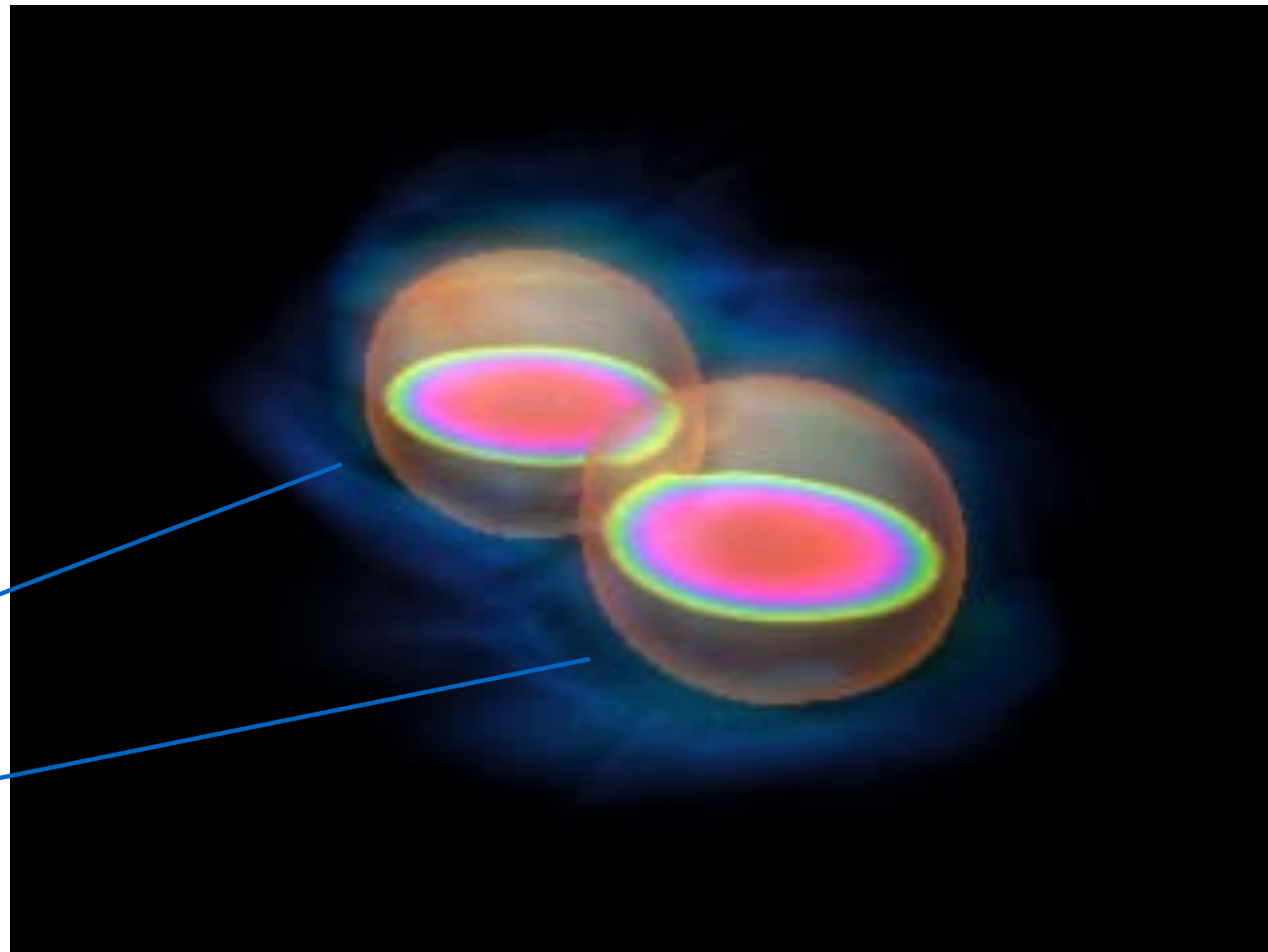
Tidal interactions



Credit: Aaron Zimmerman

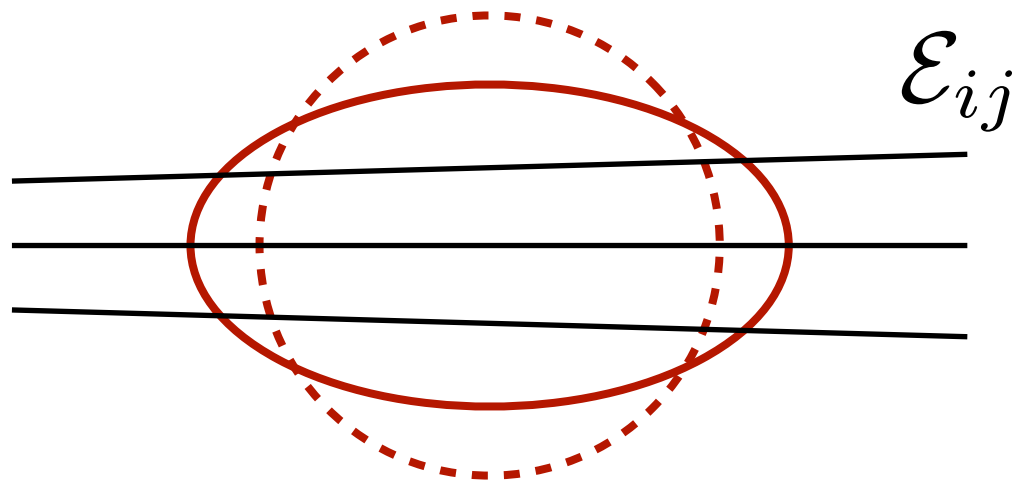
*Tidal deformability:
how easily a neutron
star is deformed*

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$



Calder

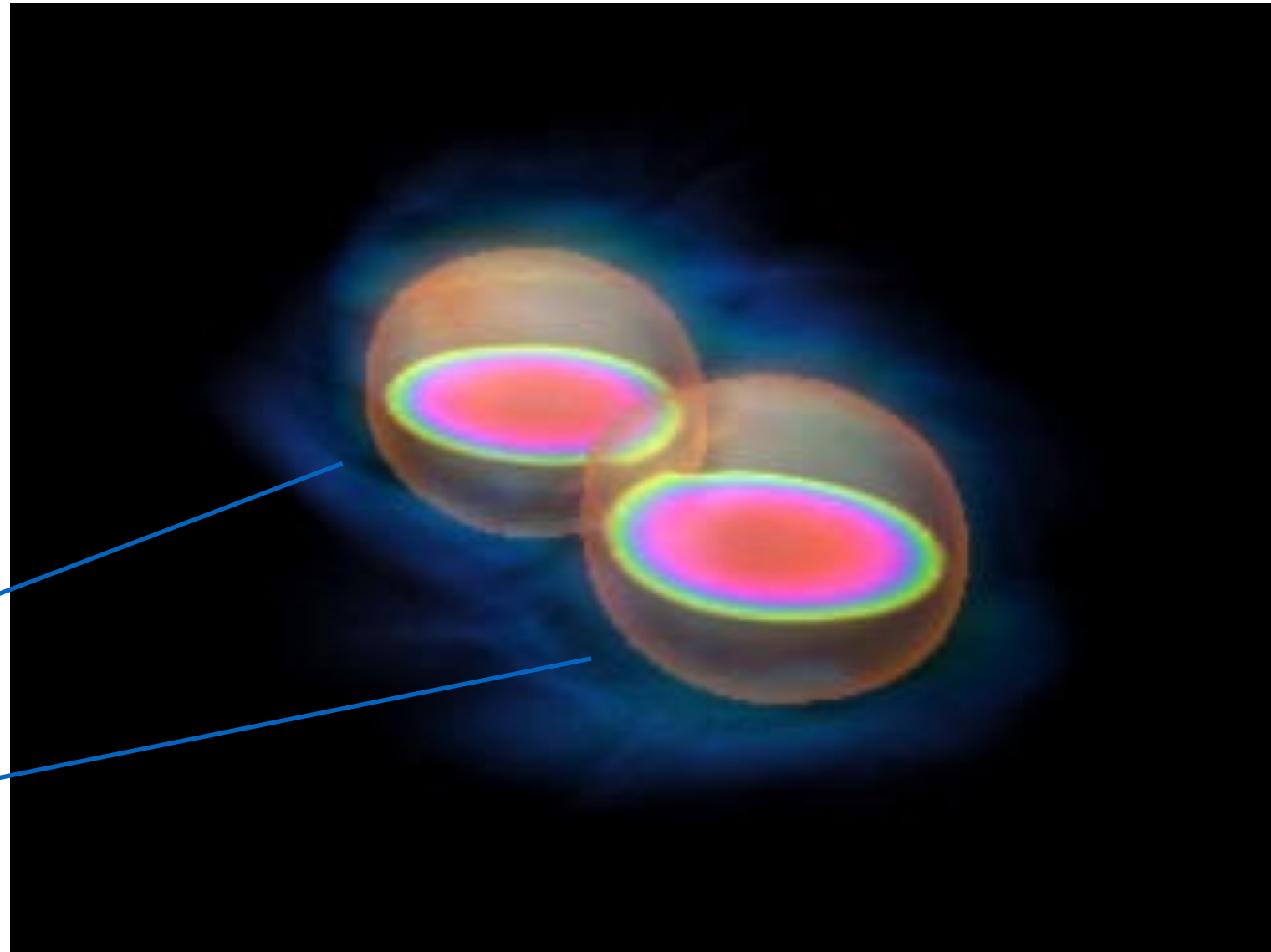
Tidal interactions



Credit: Aaron Zimmerman

*Tidal deformability:
how easily a neutron
star is deformed*

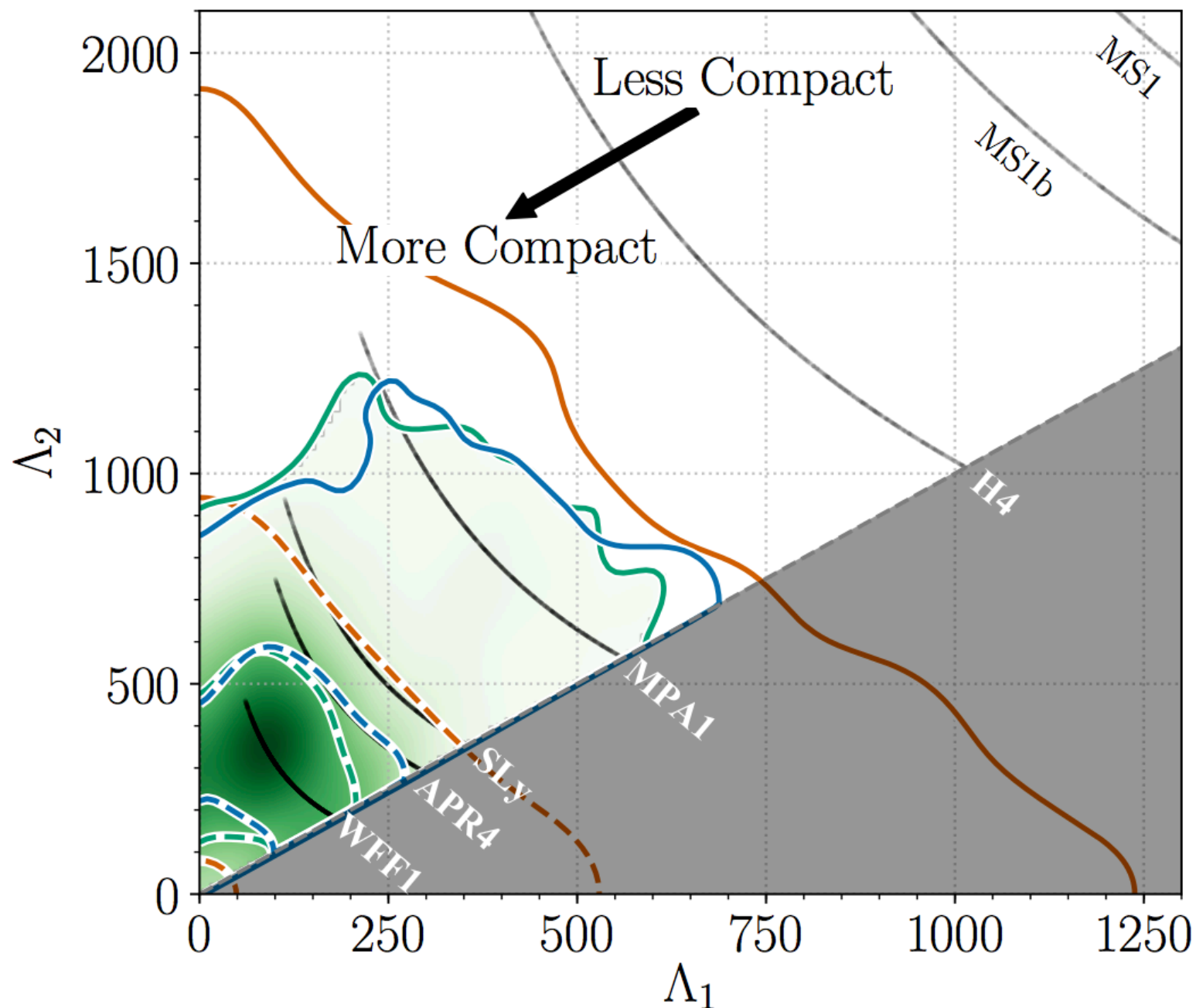
$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$



Calder

The tidal deformability depends on the EoS

GW170817 tides



Independent EoSs
Same hadronic EoS
**Spectral EoS
parametrization**

LVC (arxiv:1805.11581)

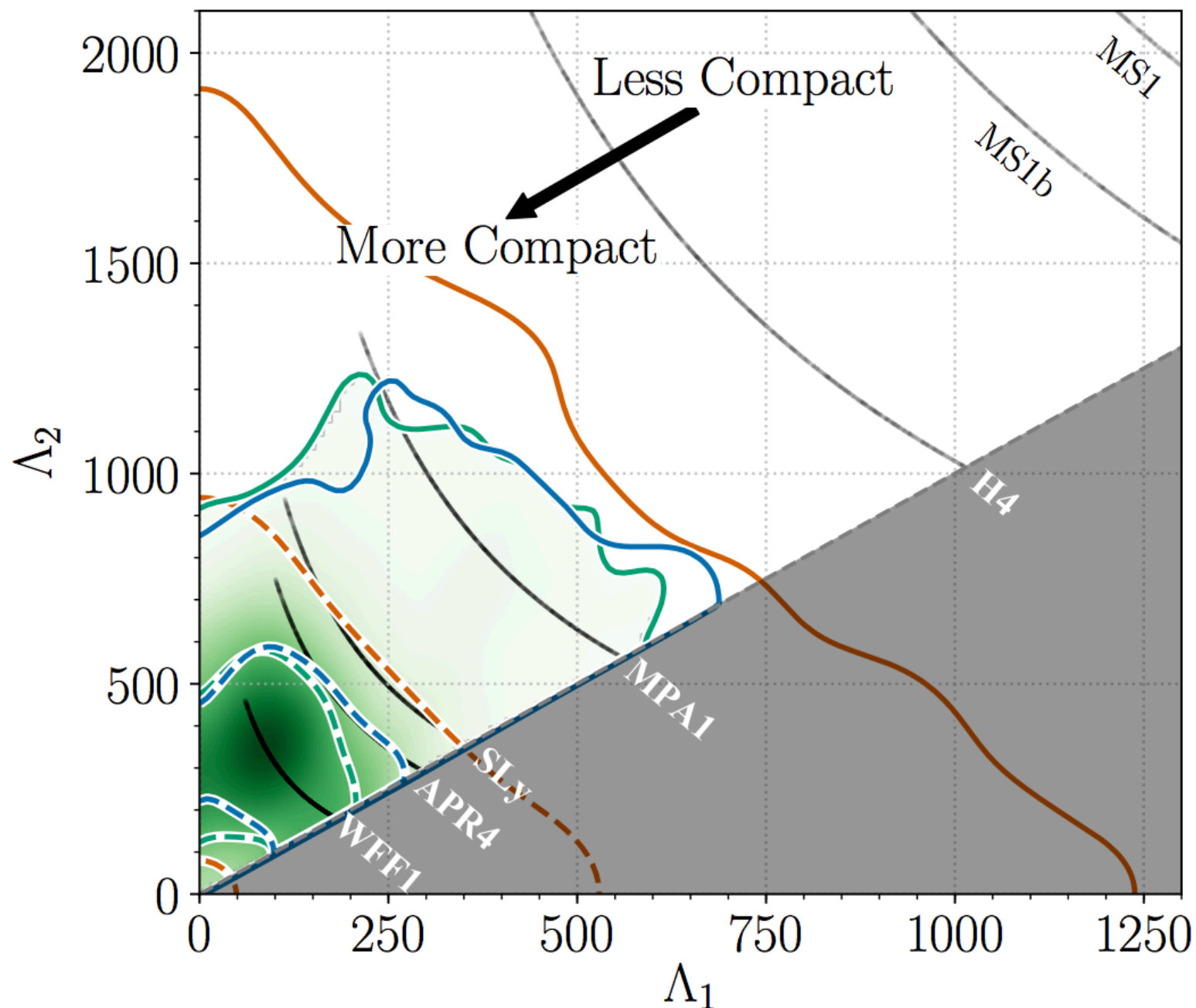
PE: Veitch+ (arxiv:1409.7215)

Waveform: Dietrich+ (arxiv:1804.02235)

Universal relations: Yagi and Yunes (arxiv:1512.02639), Chatziioannou+ (arxiv:1804.03221)

EoS Parametrization: Lackey and Wade (arxiv:1410.8866), Carney+ (arxiv:1805.11217)

GW170817 tides



Independent EoSs
Same hadronic EoS

**Spectral EoS
parametrization**

Rule out very large NSs

$$R \in [10.5, 13.3] \text{ km}$$

LVC (arxiv:1805.11581)

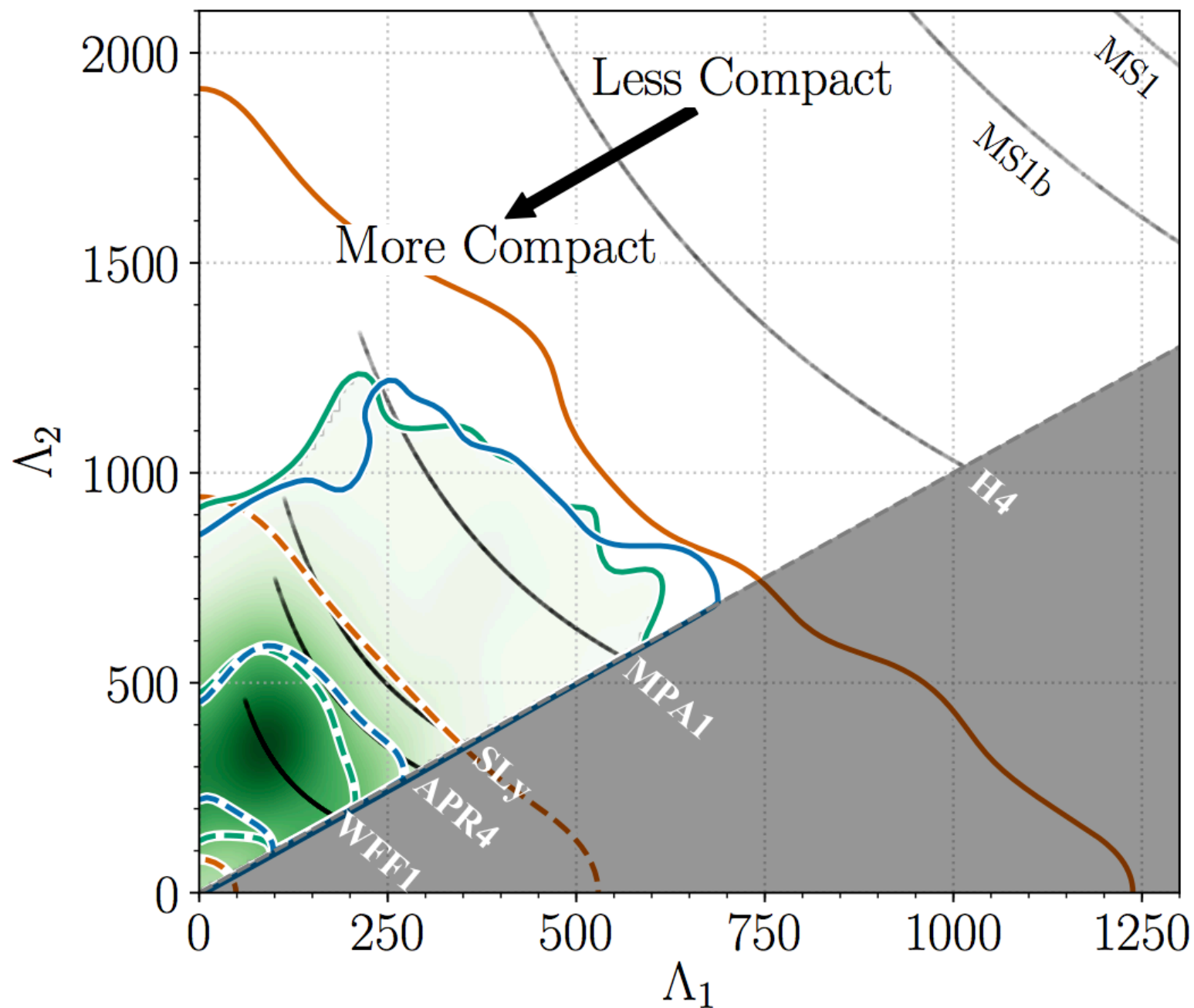
PE: Veitch+ (arxiv:1409.7215)

Waveform: Dietrich+ (arxiv:1804.02235)

Universal relations: Yagi and Yunes (arxiv:1512.02639), Chatziioannou+ (arxiv:1804.03221)

EoS Parametrization: Lackey and Wade (arxiv:1410.8866), Carney+ (arxiv:1805.11217)

GW170817 tides



Independent EoSs

Same hadronic EoS

**Spectral EoS
parametrization**

Rule out very large NSs

$$R \in [10.5, 13.3] \text{ km}$$

and very stiff EoSs

$$p_{\text{nuc}} = 3.5^{+2.7}_{-1.7} \times 10^{34} \text{ dyn cm}^{-2}$$

LVC (arxiv:1805.11581)

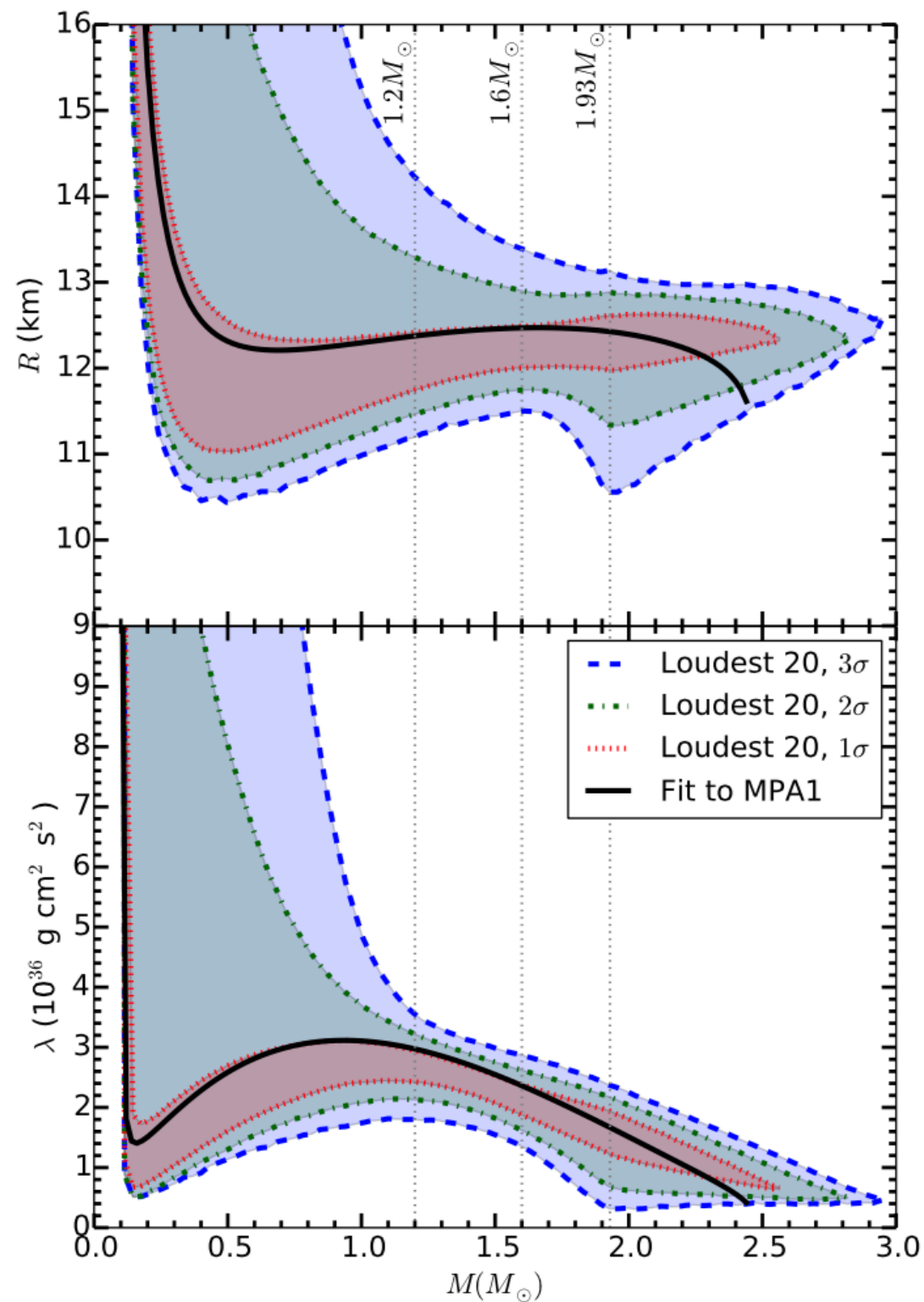
PE: Veitch+ (arxiv:1409.7215)

Waveform: Dietrich+ (arxiv:1804.02235)

Universal relations: Yagi and Yunes (arxiv:1512.02639), Chatziioannou+ (arxiv:1804.03221)

EoS Parametrization: Lackey and Wade (arxiv:1410.8866), Carney+ (arxiv:1805.11217)

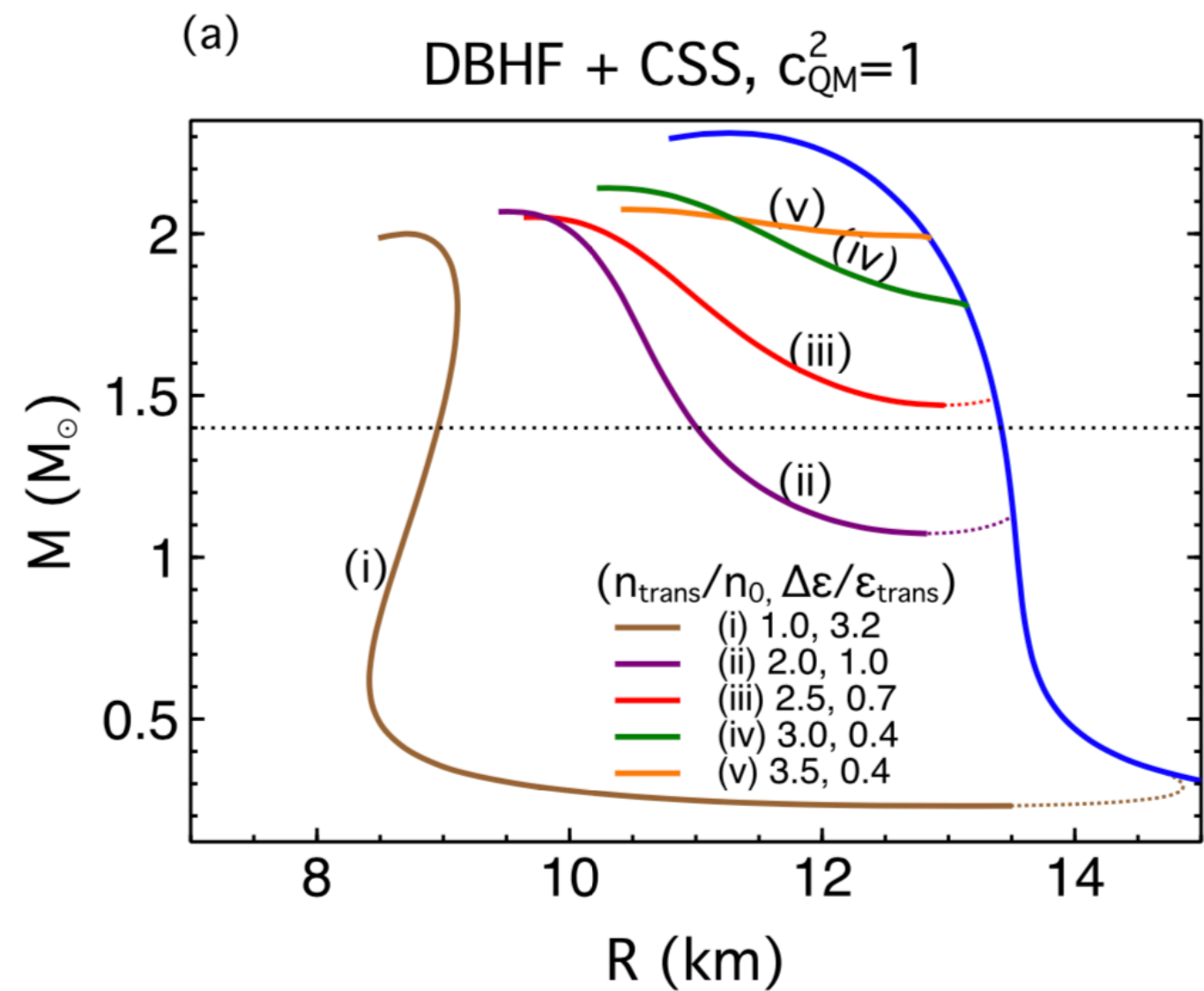
Future observations



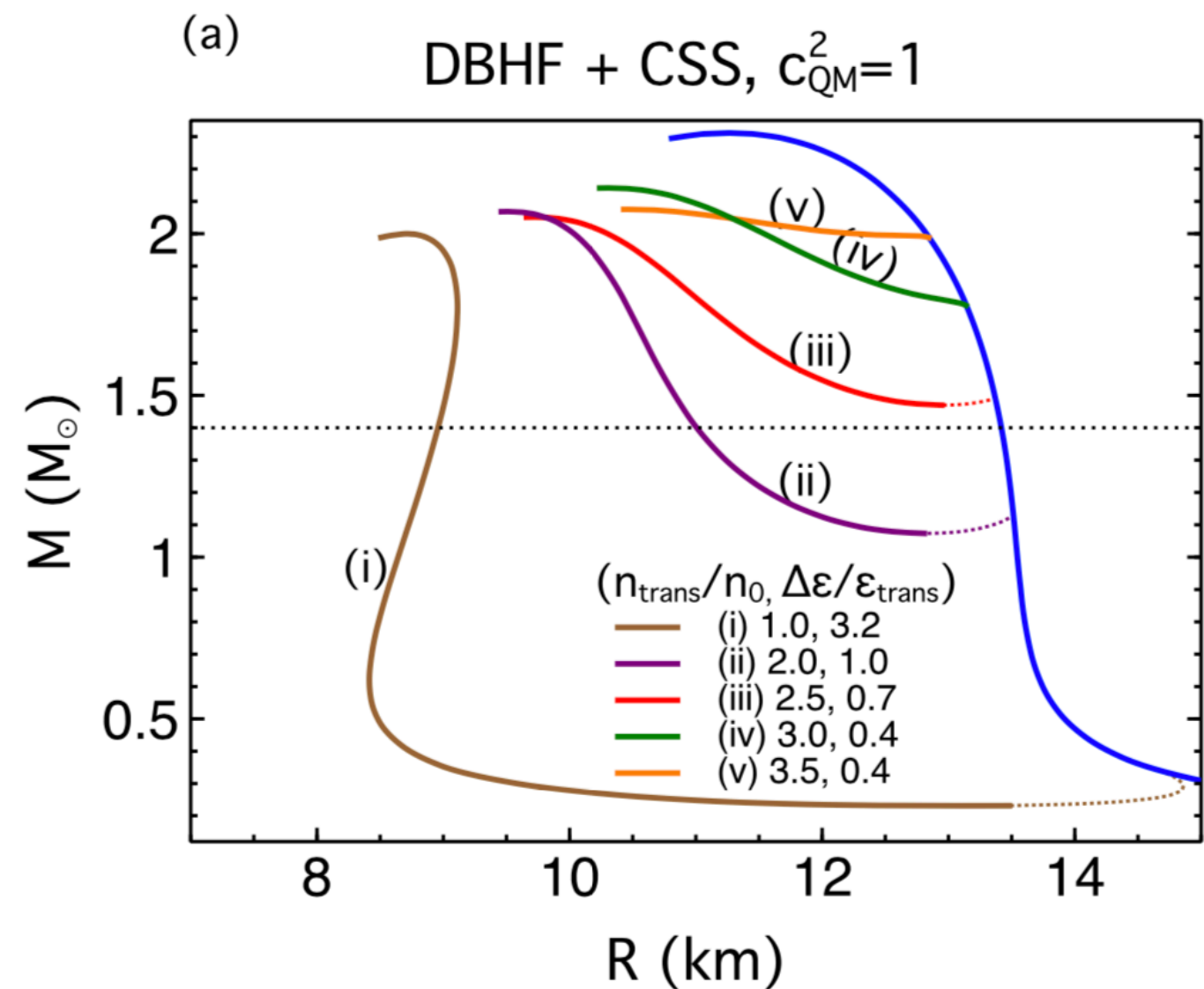
One year of detector data
 ~ 40 BNS detections

Constraints driven
by loudest events
 $R \sim 1\text{-}2\text{ km}$

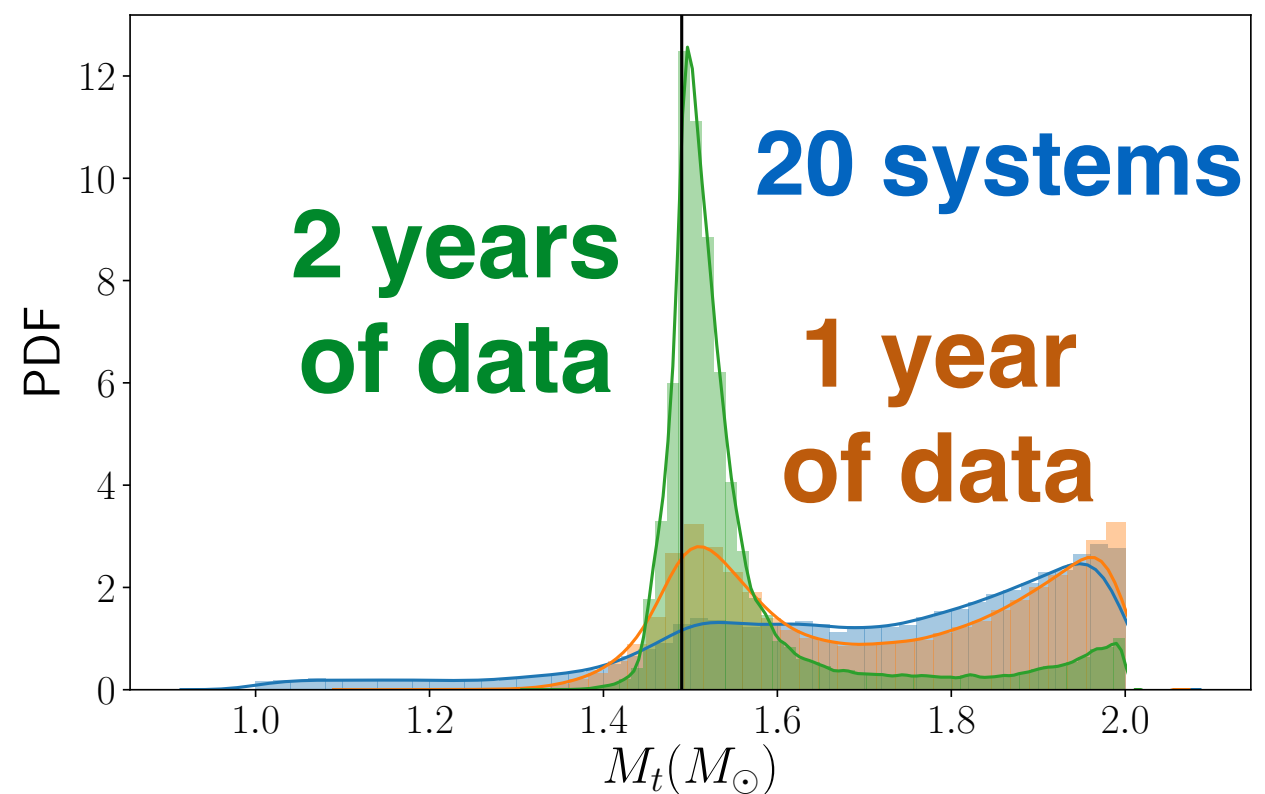
Quark matter phase transitions



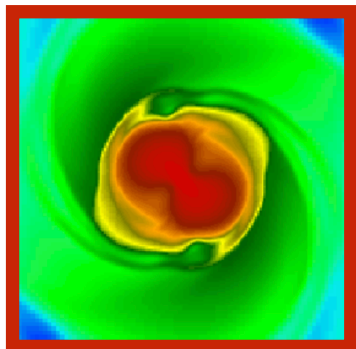
Quark matter phase transitions



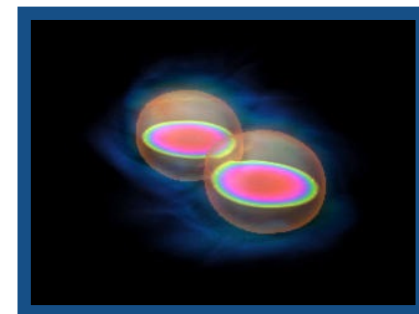
A population of BNSs
can lead to an
estimate of the
transition mass/density



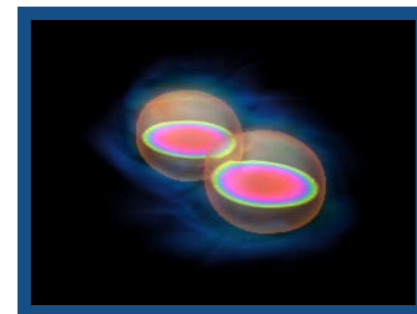
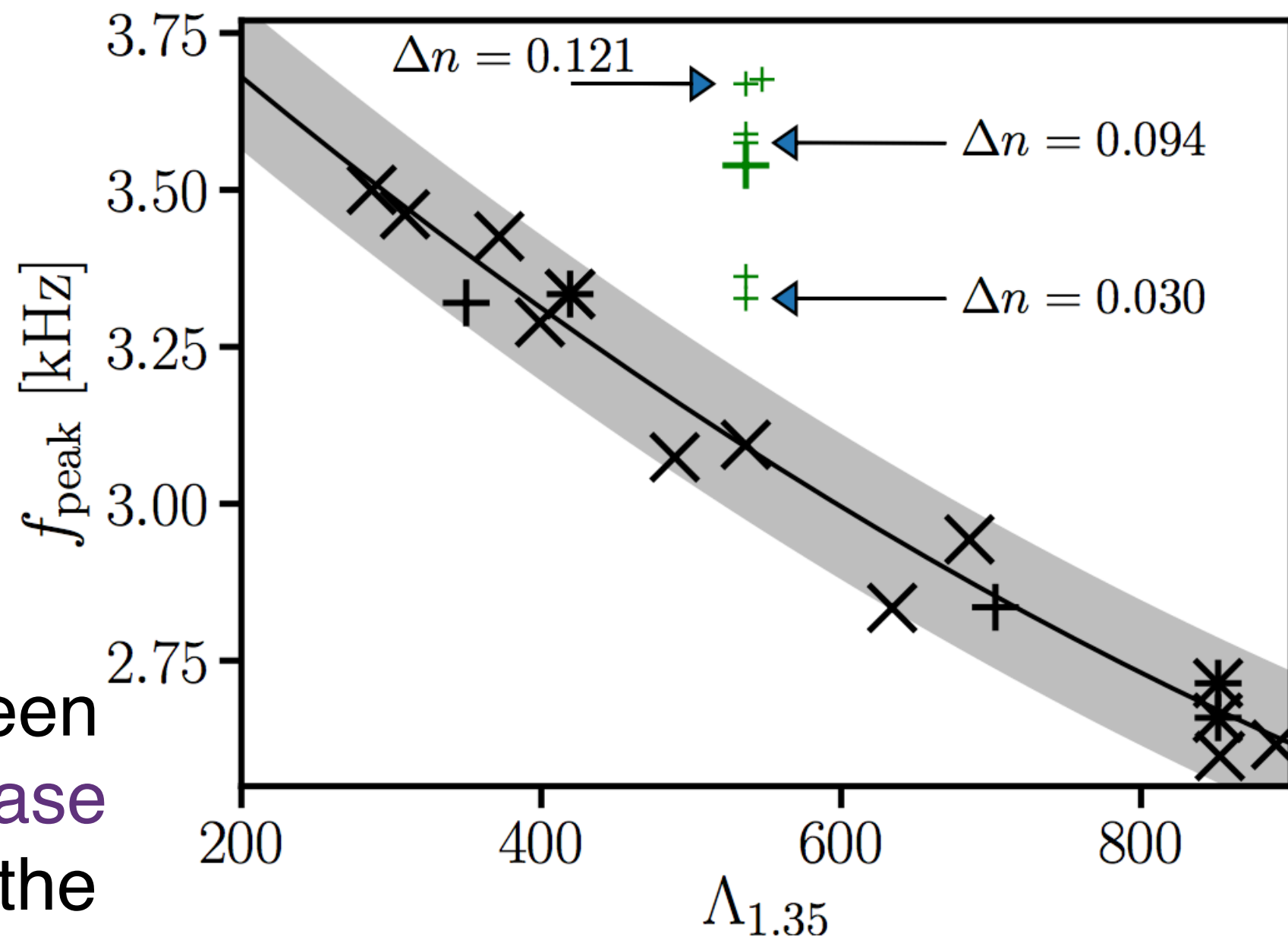
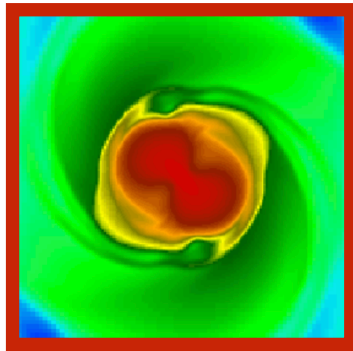
Complementary information



Inconsistencies between
the binary **inspiral phase**
and the properties of the
merger remnant could also
indicate the presence of
strong phase transitions

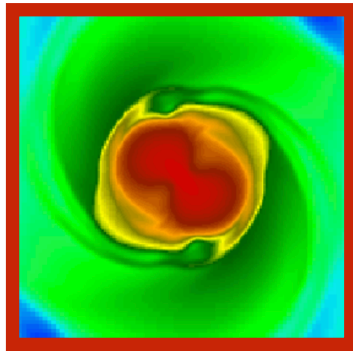


Complementary information

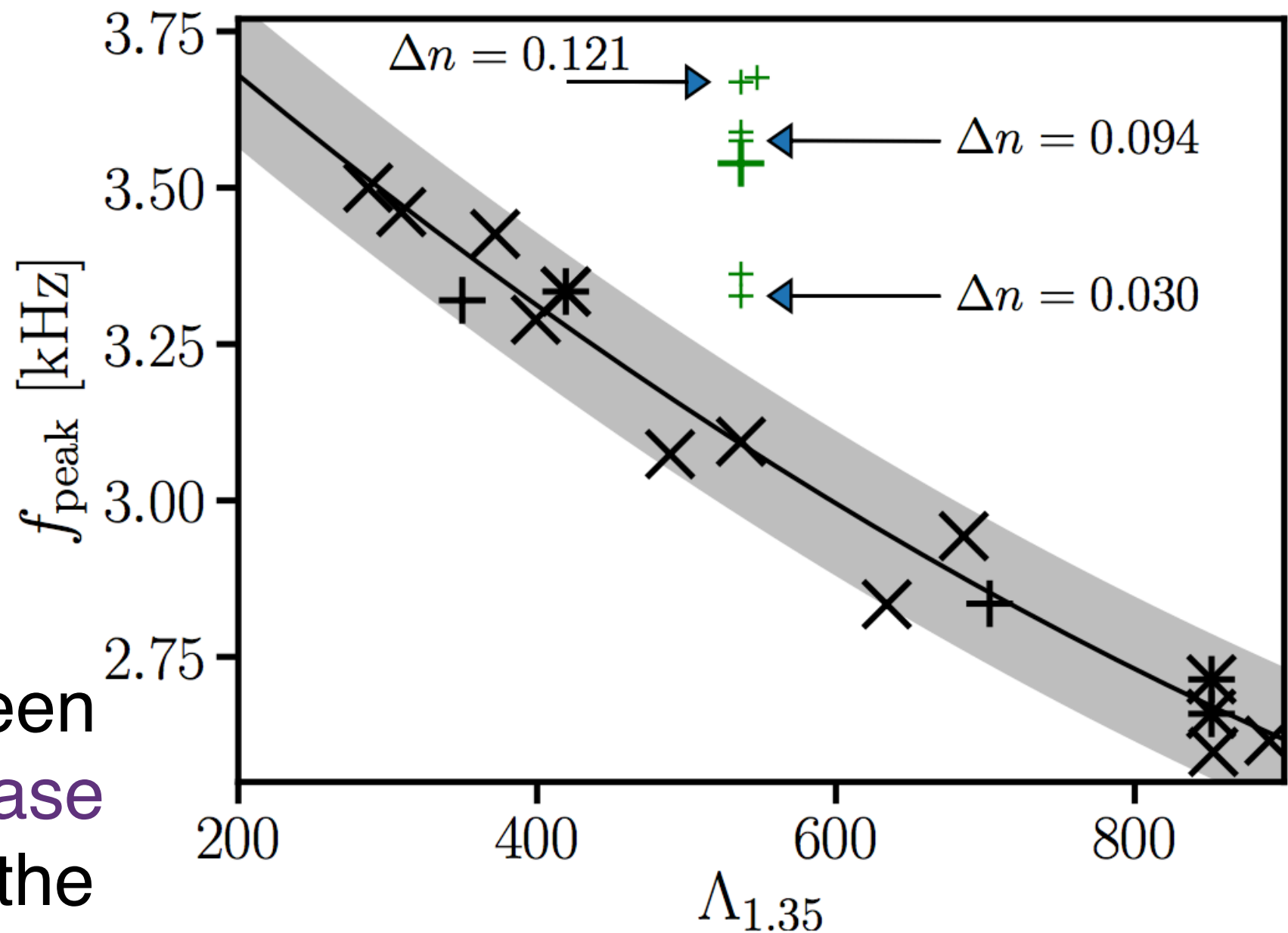


Inconsistencies between the binary **inspiral phase** and the properties of the **merger remnant** could also indicate the presence of **strong phase transitions**

Complementary information

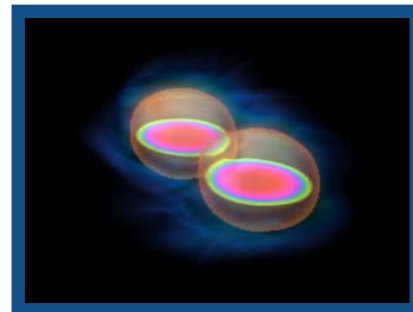


Measure from
post merger



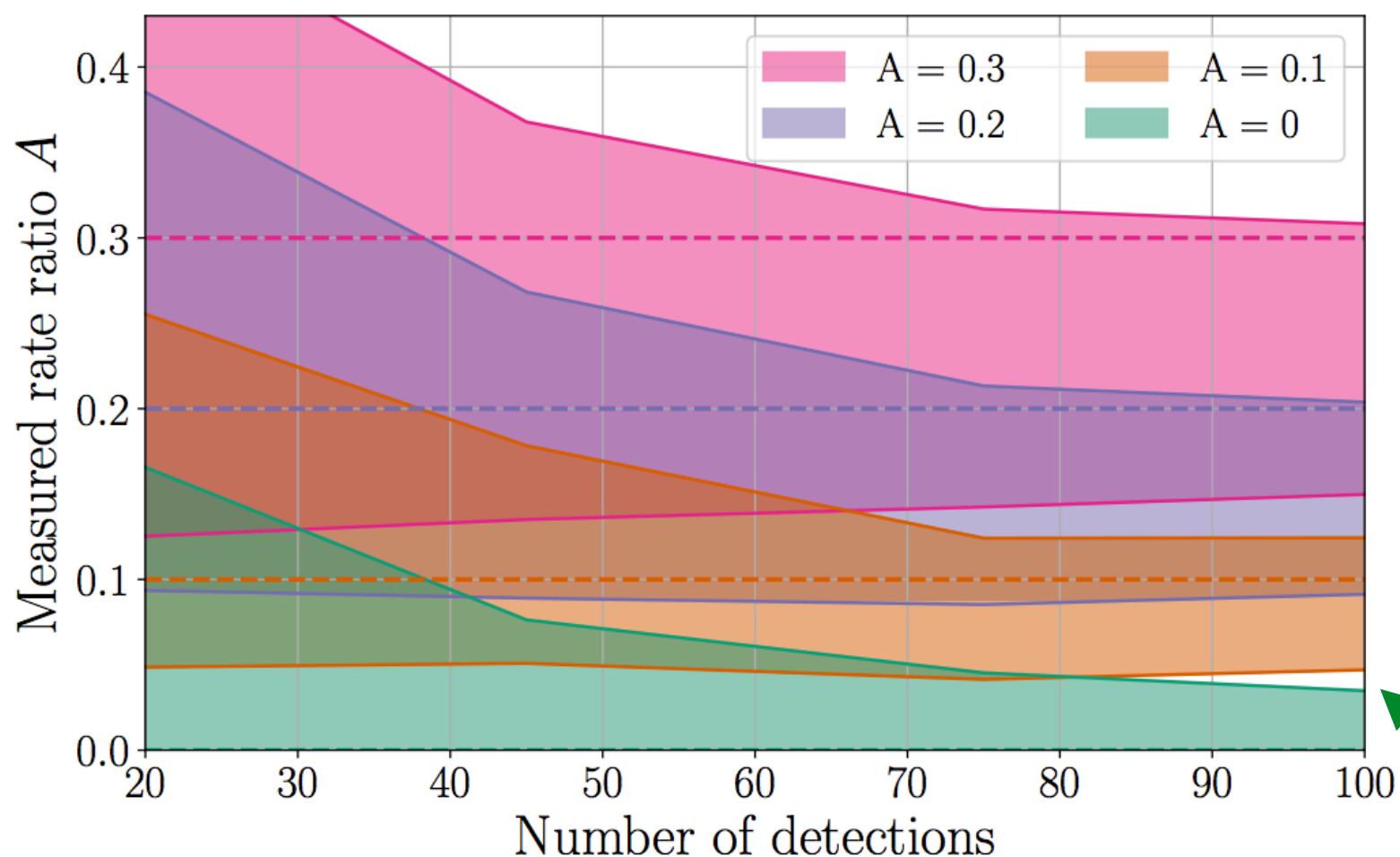
Inconsistencies between the binary **inspiral phase** and the properties of the **merger remnant** could also indicate the presence of **strong phase transitions**

Measure from
pre merger



Low mass black holes

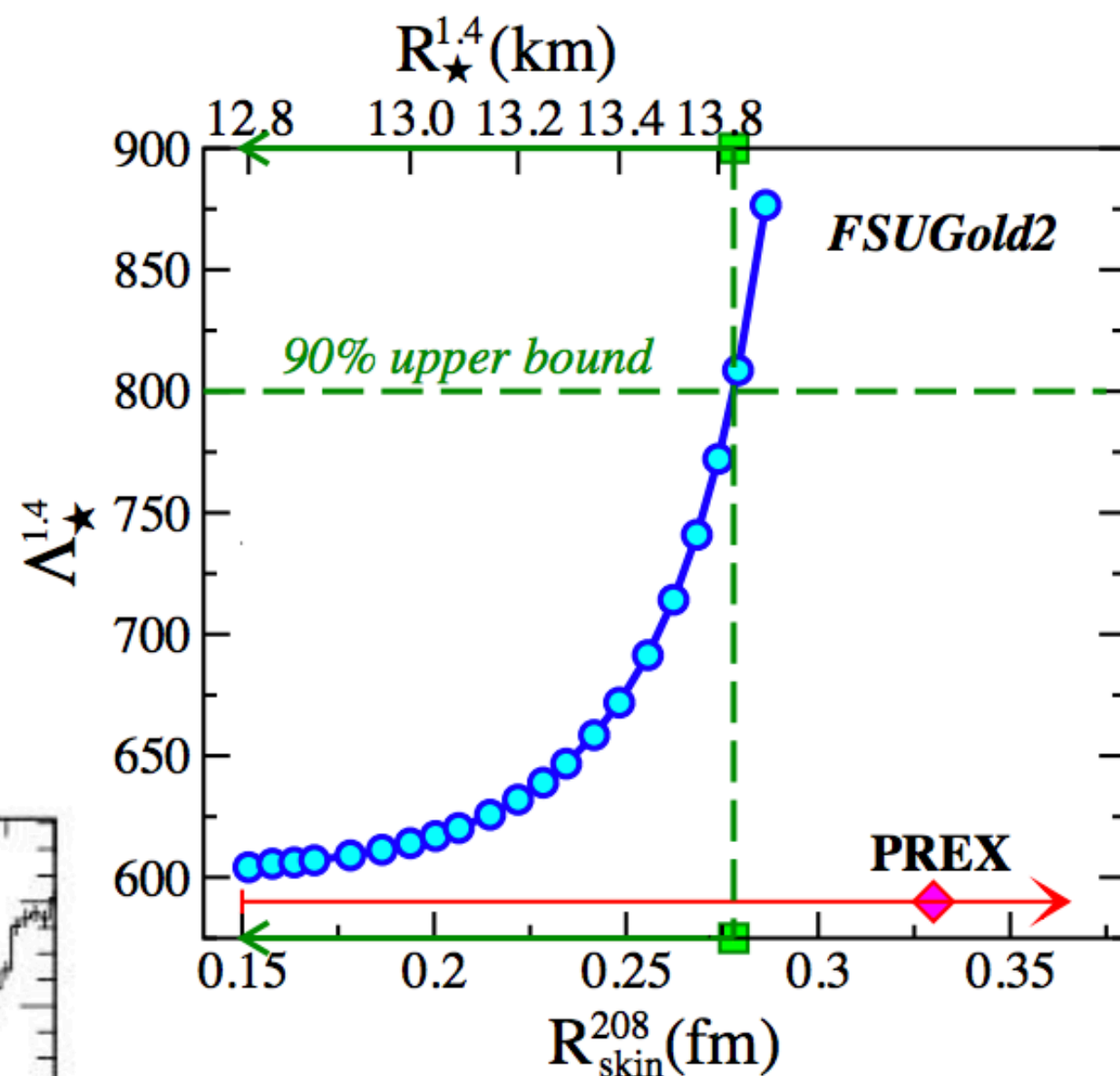
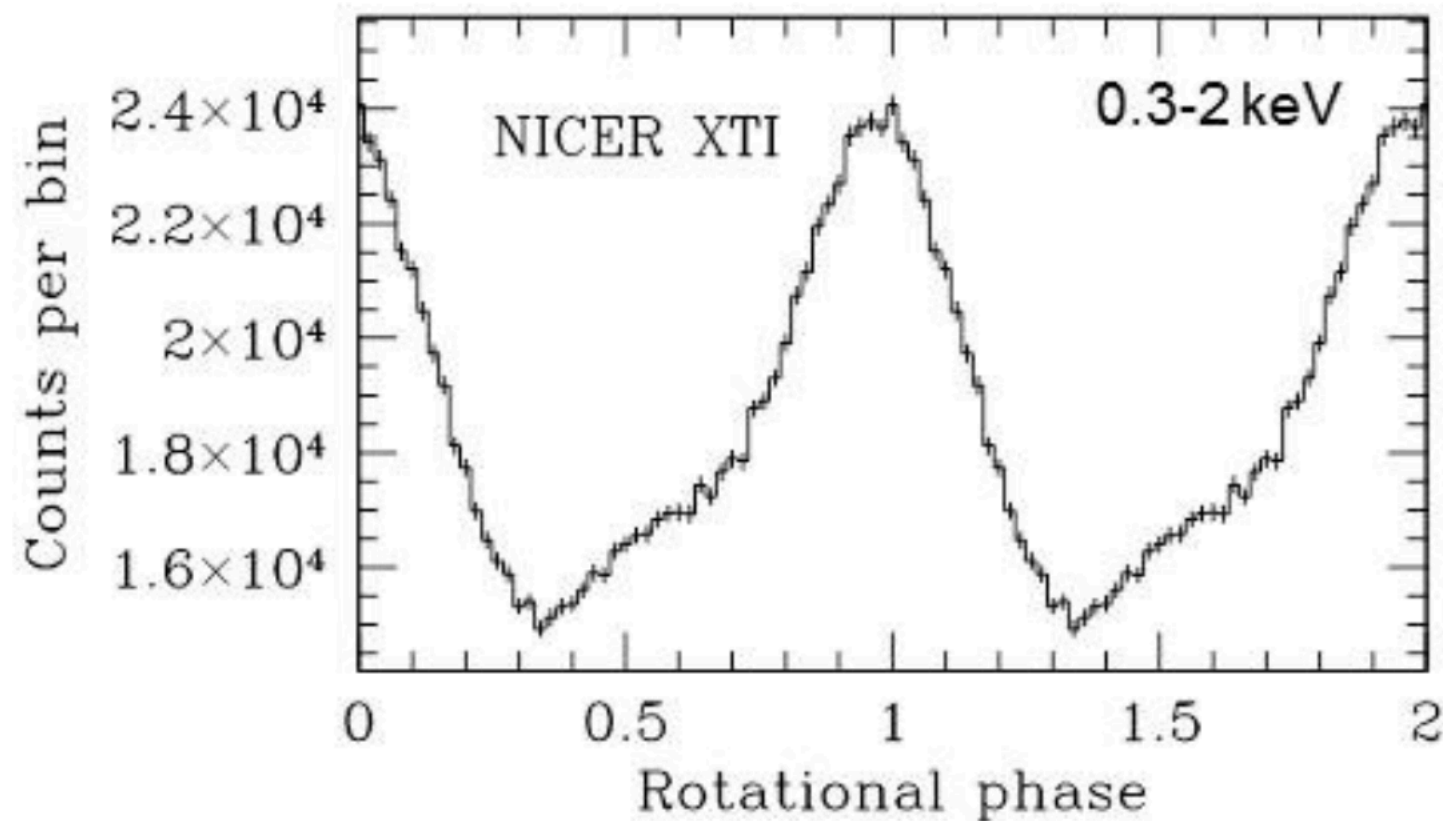
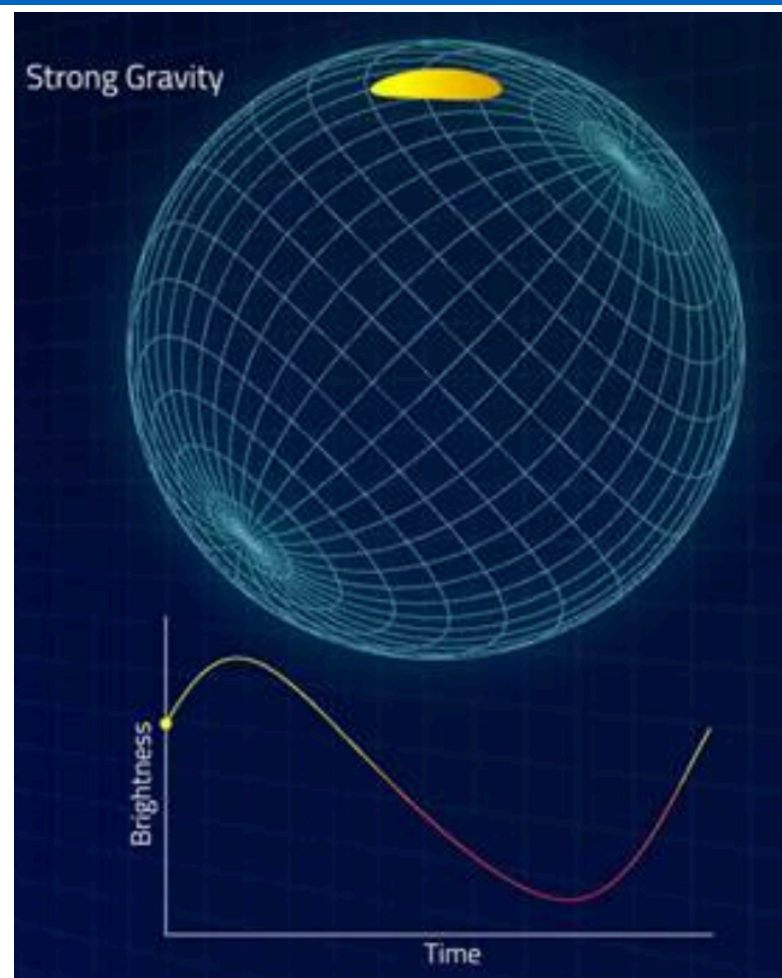
We interpret 1-2 solar mass objects as NSs. Tidal interactions could help identify such low mass BH (primordial?)



Measure the ratio of NSBH to BNS to **0.16**(**0.11**)[**0.08**] with 100 detections if the true ratio is **0.3**(**0.2**)[**0.1**]

With 100 events (design sensitivity) we can constrain the ratio of NSBH to BNS to **~0.03**

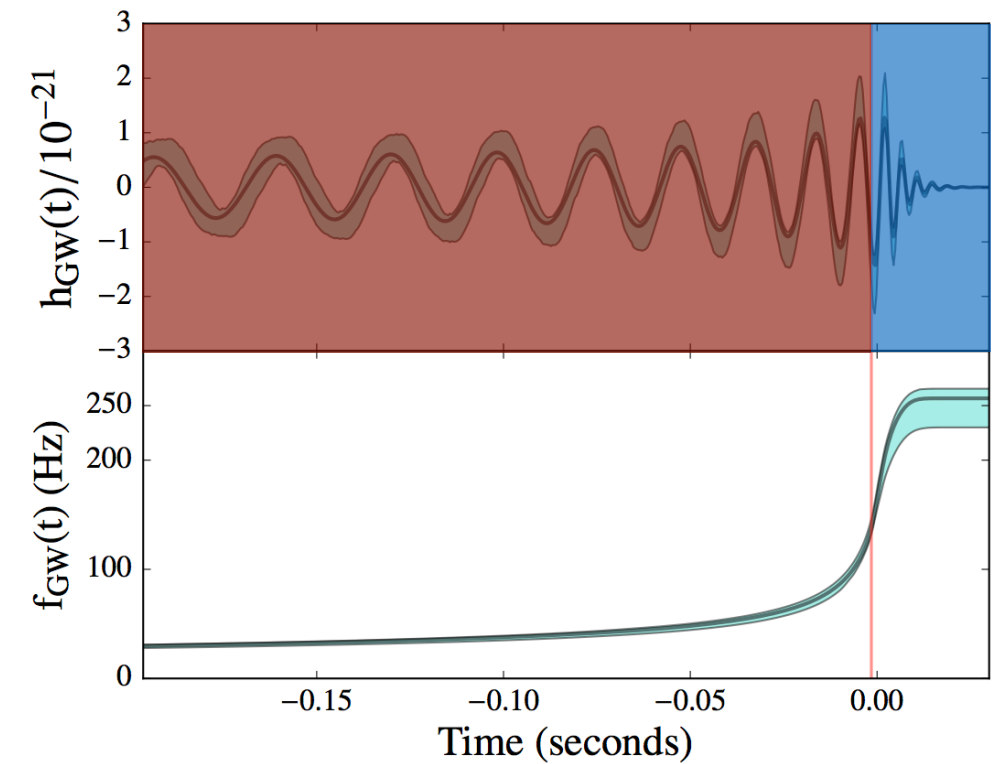
Nuclear experiment and astrophysics



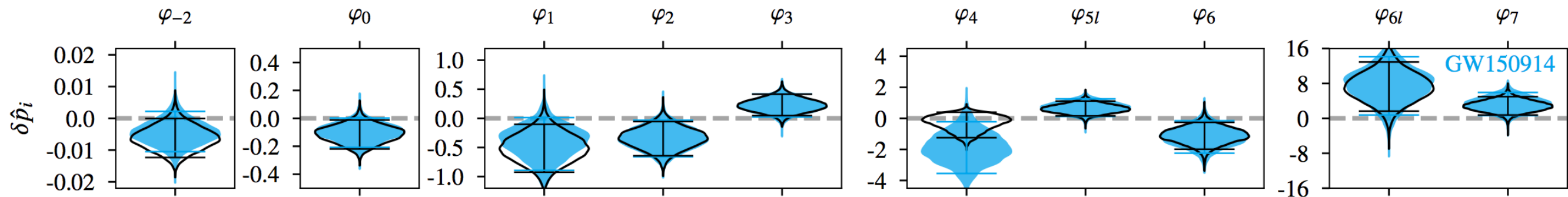
Fattoyev+ (arxiv:1711.06615)

Probes of fundamental physics (testing GR)

- No residual power
- Parametric deviations
- IMR consistency
- Wave propagation
- Polarization content
- Echoes
- Extra dimensions
- Speed of gravity



LVC (arxiv:1602.03841)



LVC (arxiv:1903.04467)

IMR consistency: Ghosh+ (arxiv:1602.02453)

Parametric deviations: Yunes+ (arxiv:0909.3328), Meidam (arXiv:1712.08772)

Propagation: Mirshekari+ (arxiv:1110.2720)

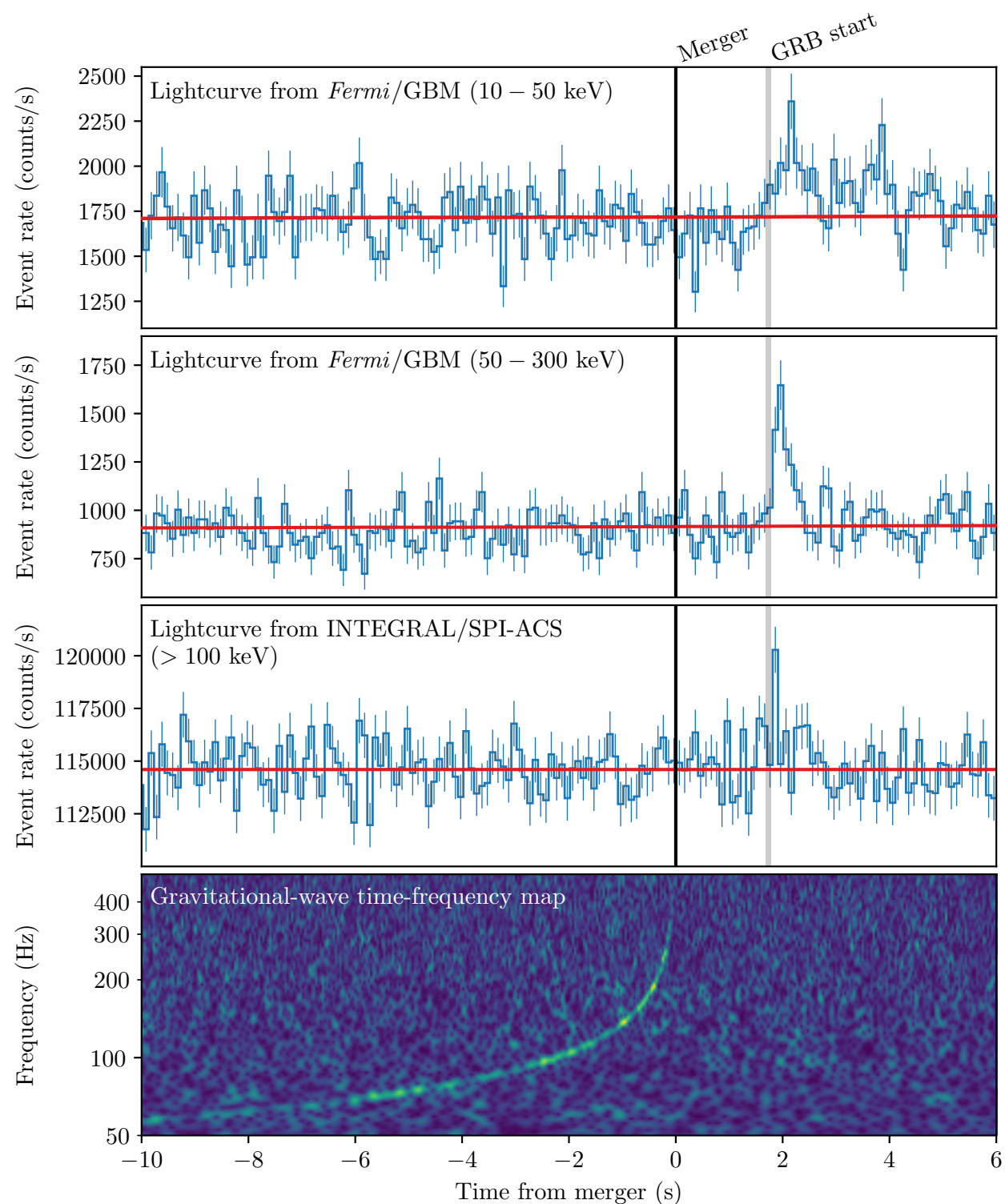
Polarization: Isi+ (arxiv:1710.03794), Hagihara (arxiv:1904.02300)

Echoes: Cardoso+ (arxiv:1608.08637)

Extra dimensions: Pardo+ (arxiv:1801.08160)

Speed of gravity: LVC/Fermi/INTEGRAL (arxiv:1710.05834)

Speed of gravity



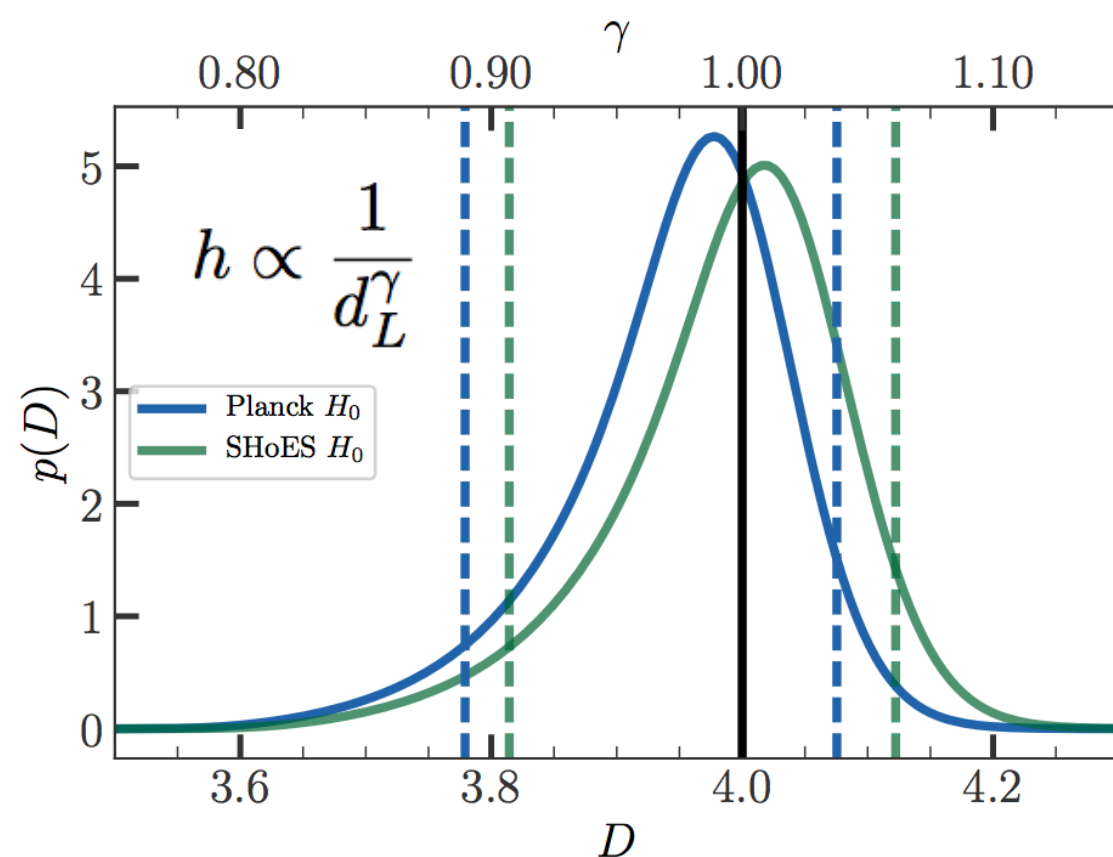
Independent detection,
but more than 4σ association
between GRB and GW

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\text{EM}}} \leq +7 \times 10^{-16}$$

Stringent constraints
on certain classes
of beyond-GR theories

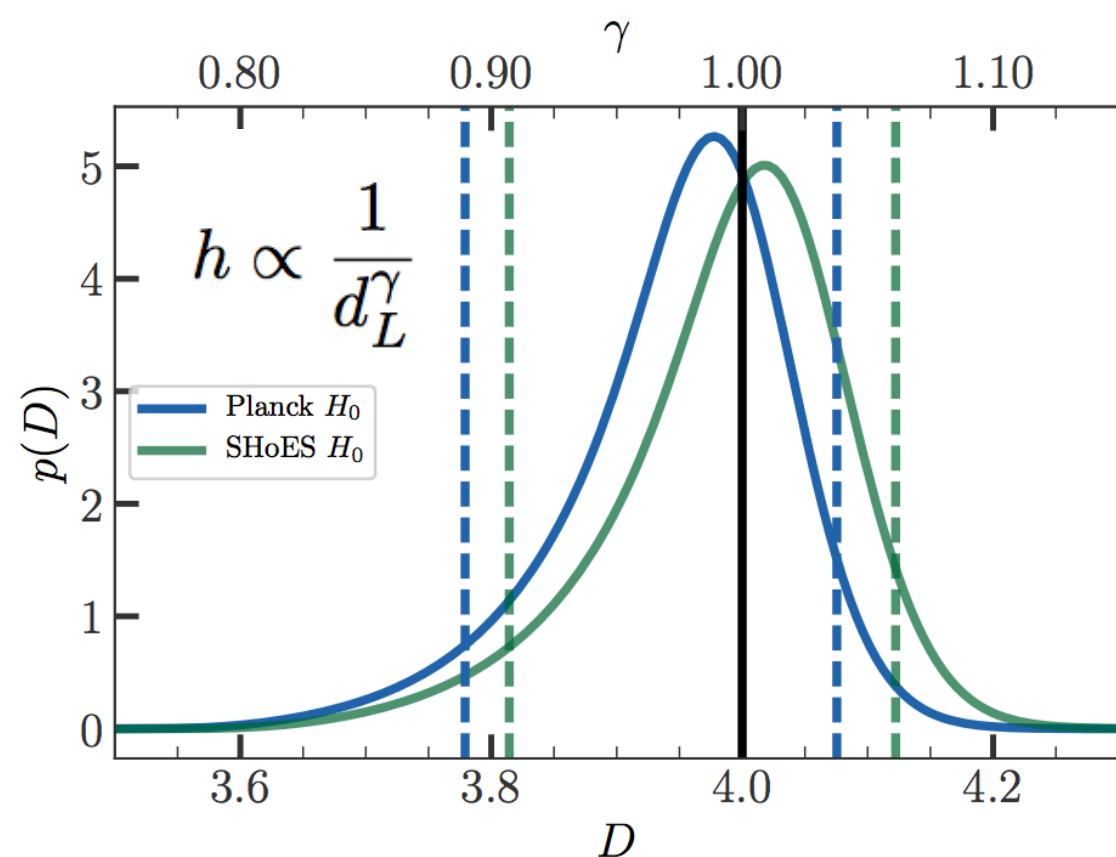
Extra dimensions

Test if the EM and GW signals propagate in the same number of dimensions (4)



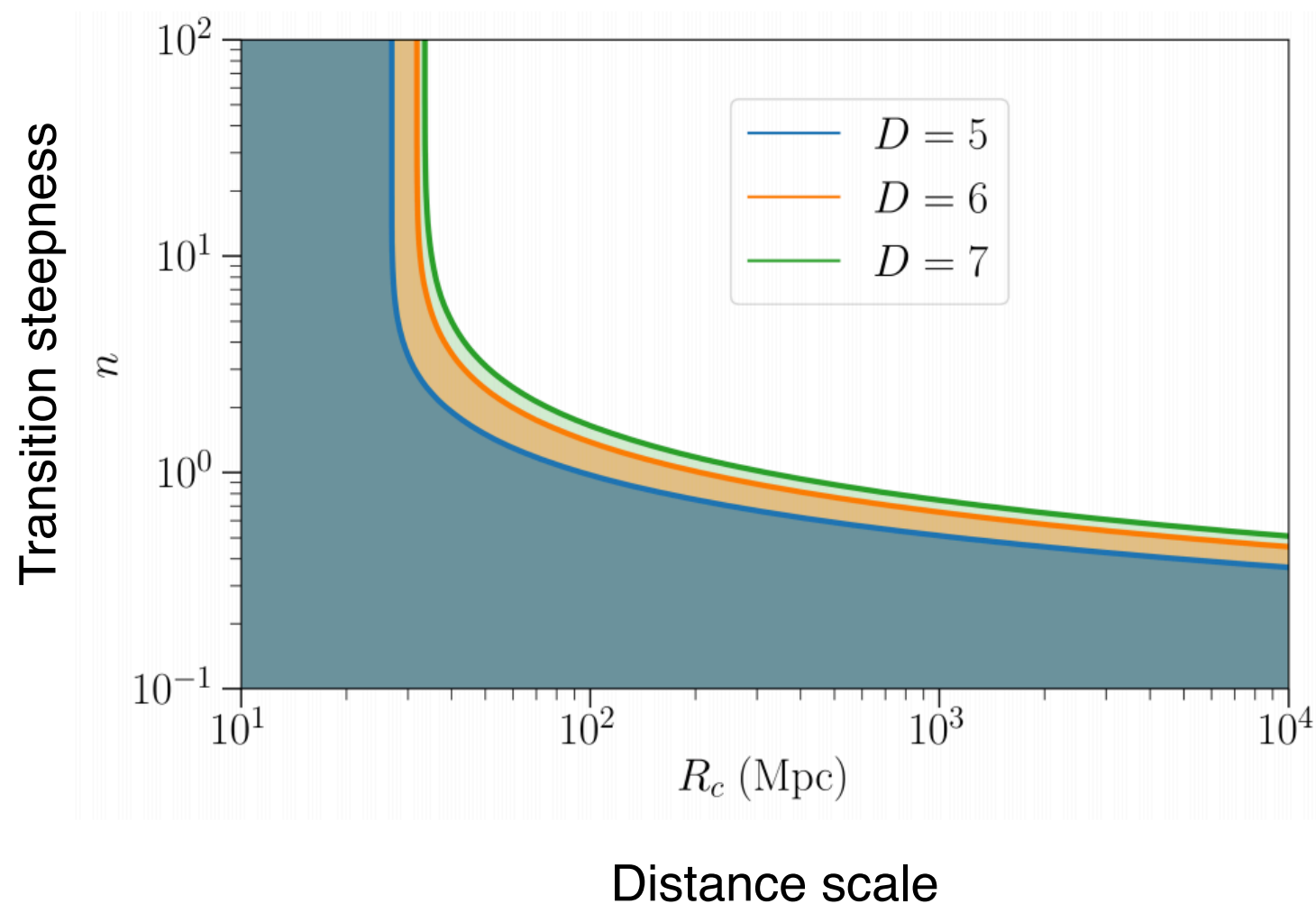
Extra dimensions

Test if the EM and GW signals propagate in the same number of dimensions (4)



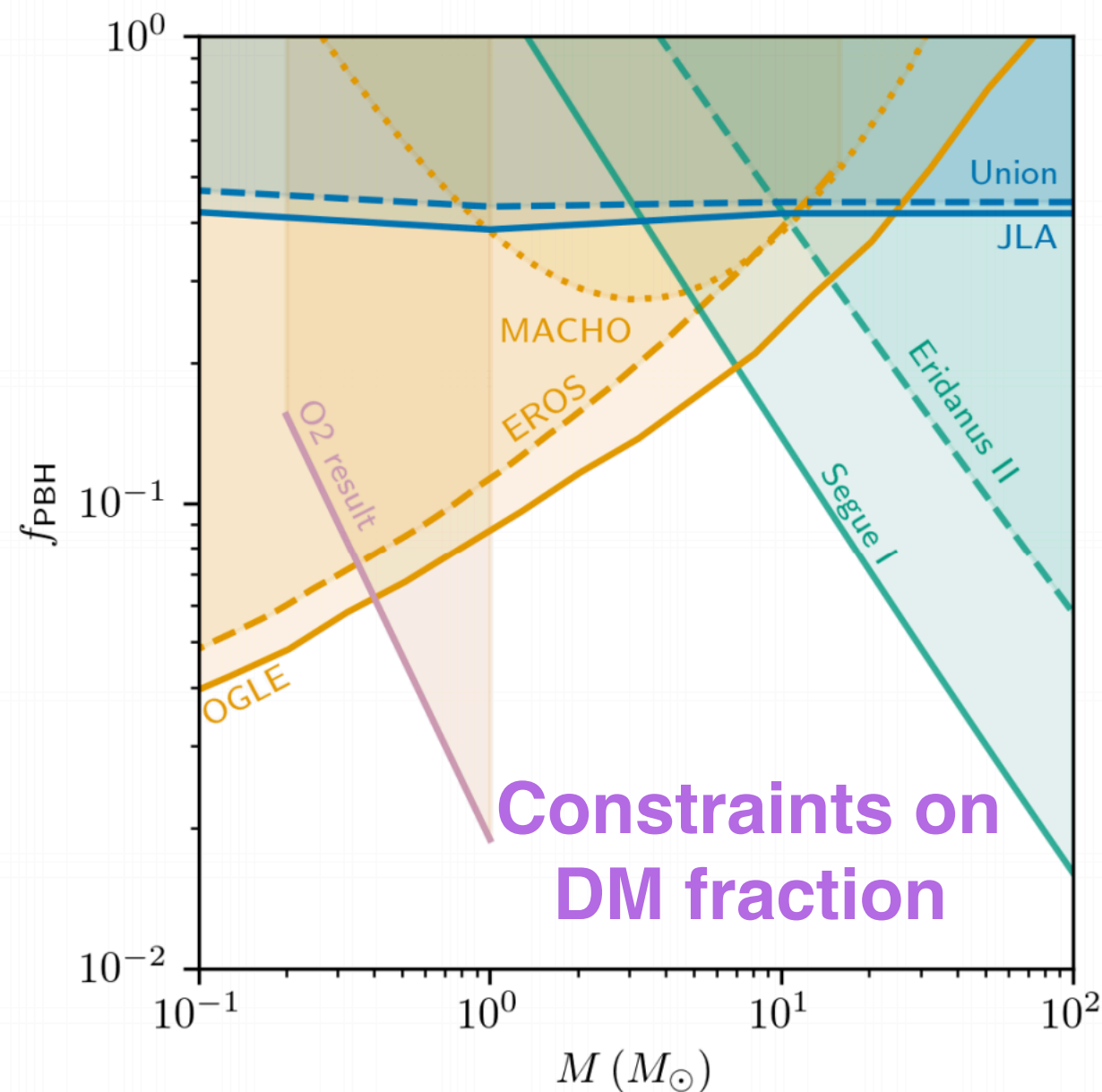
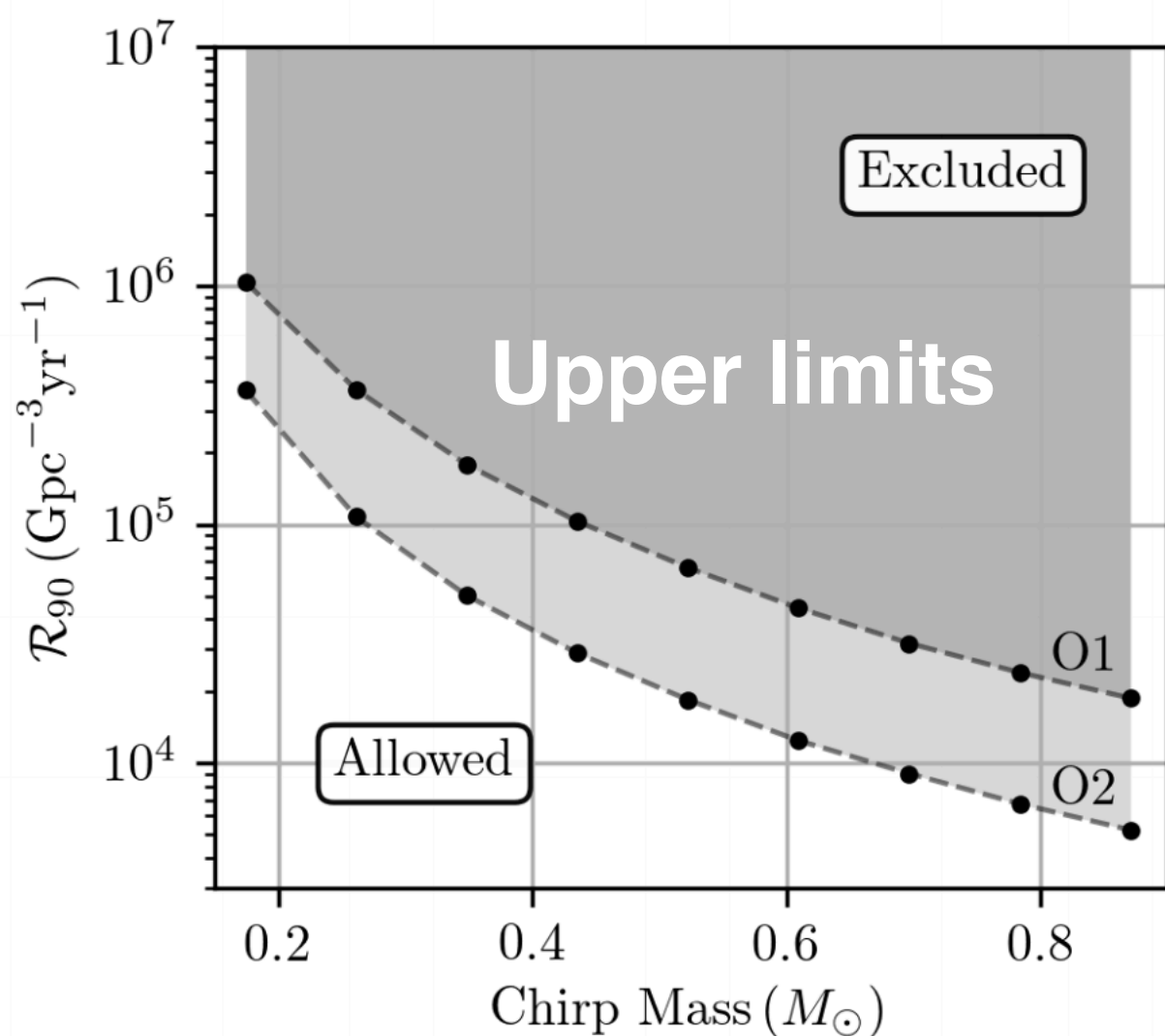
Screening mechanism

$$h \propto \frac{1}{d_L^{\text{GW}}} = \frac{1}{d_L^{\text{EM}}} \left[1 + \left(\frac{d_L^{\text{EM}}}{R_c} \right)^n \right]^{-(D-4)/(2n)}$$



Subsolar mass black holes

Astrophysically **challenging** to make such light BHs: **primordial origin**



LVC (arxiv:1904.08976)

Methods: Magee+ (arxiv:1808.04772)

Ultra light bosons

LIGO's black holes can be used to probe boson masses

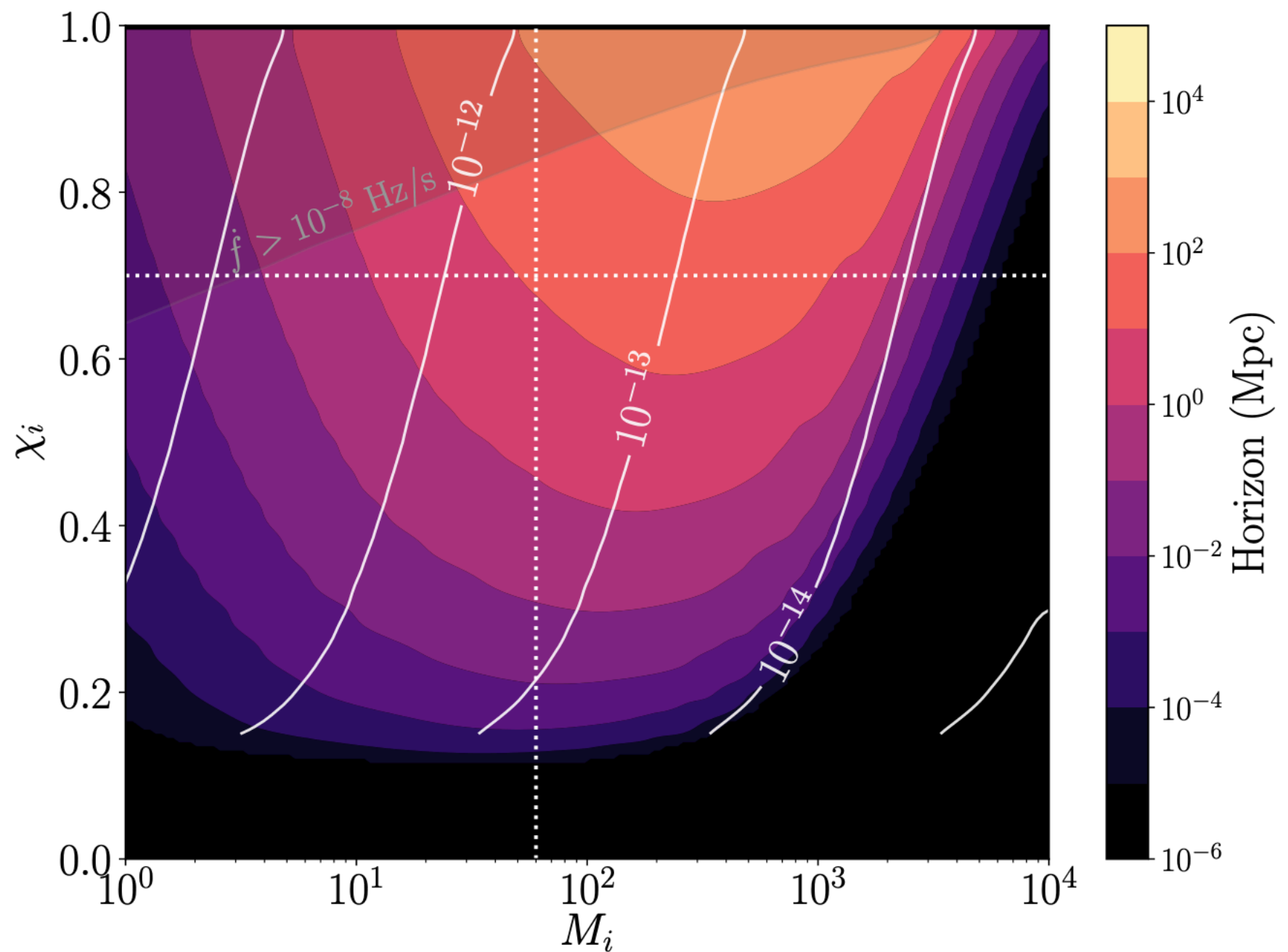
$$10^{-15} \text{ eV to } - 10^{-11} \text{ eV}$$

Ultra light bosons

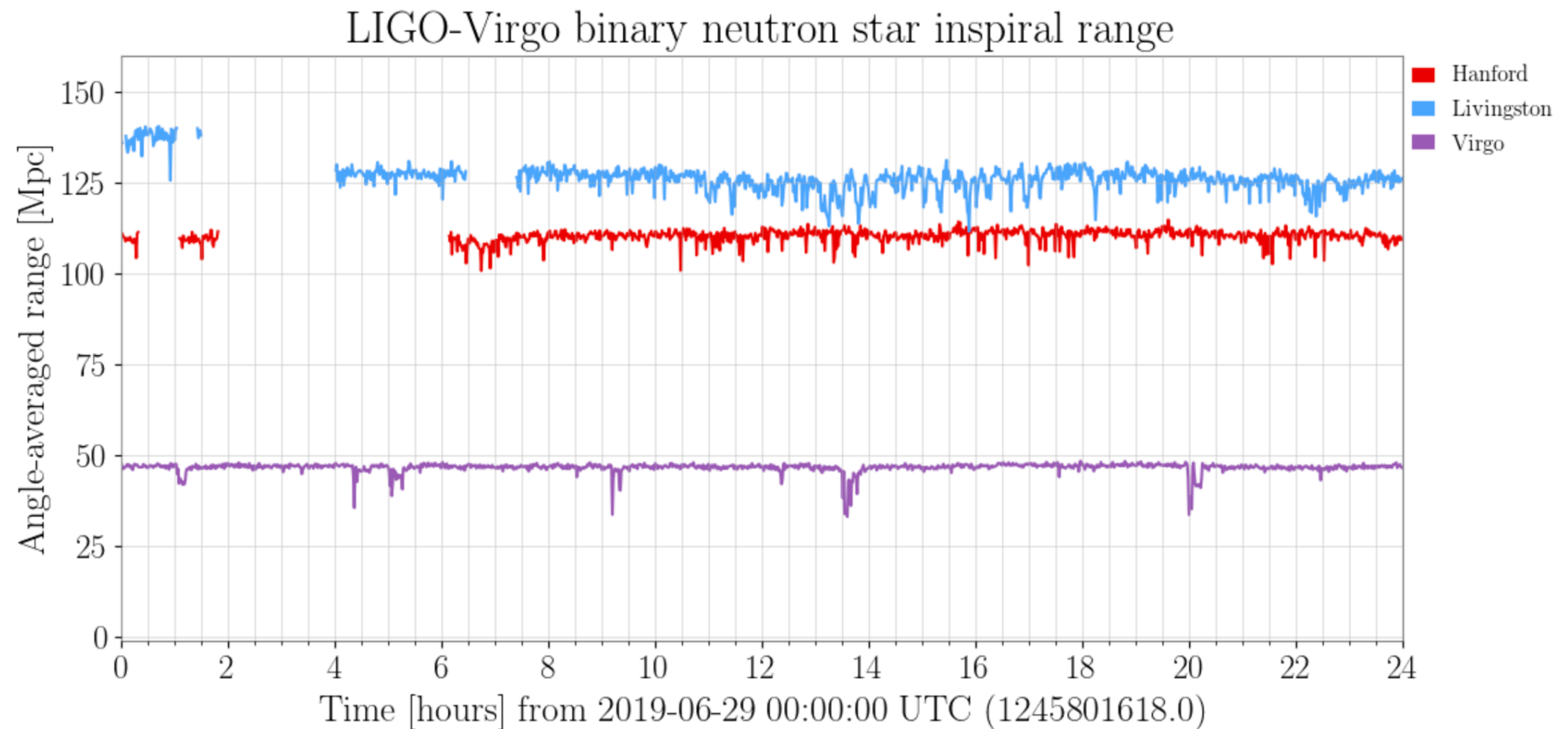
LIGO's black holes can be used to probe boson masses

10^{-15} eV to 10^{-11} eV

Detection horizon
after 1 year of
observations at
design sensitivity
(c. 2022)



Current status: half-way through O3



https://www.gw-openscience.org/detector_status

Binary black holes: 1/month to 1/week of data taken

Binary neutron stars: Up to 1/month, median is 2/year. Median 90% localization 120-180 deg²; 12-21% localized <20 deg²

Neutron star black hole binaries: ?

GraceDB — Gravitational-Wave Candidate Event Database

HOME	PUBLIC ALERTS	SEARCH	LATEST	DOCUMENTATION		LOGIN
------	---------------	--------	--------	---------------	--	-------

Latest — as of 23 September 2019 23:40:17 UTC

Test and MDC events and superevents are not included in the search results by default; see the [query help](#) for information on how to search for events and superevents in those categories.

Query:

Search for:

Superevent

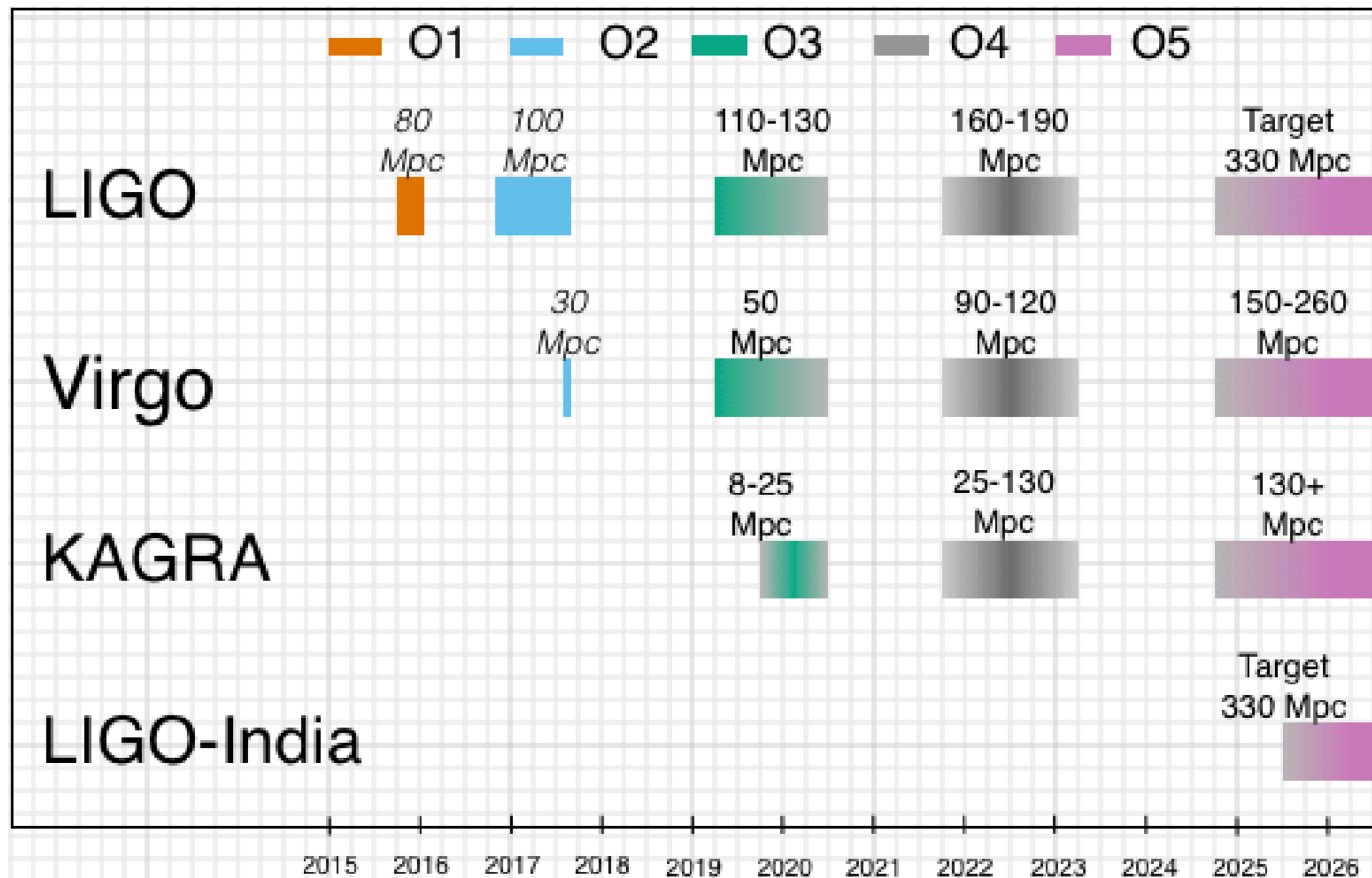
Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
S190923y	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253278576.645077	1253278577.645508	1253278578.654868	4.783e-08	2019-09-23 12:56:22 UTC
S190915ak	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252627039.685111	1252627040.690891	1252627041.730049	9.735e-10	2019-09-15 23:57:25 UTC
S190910h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252139415.544299	1252139416.544448	1252139417.544448	3.584e-08	2019-09-10 08:30:21 UTC
S190910d	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252113996.241211	1252113997.242676	1252113998.264918	3.717e-09	2019-09-10 01:26:35 UTC
S190901ap	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251415878.837767	1251415879.837767	1251415880.838844	7.027e-09	2019-09-01 23:31:24 UTC
S190829u	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251147973.281494	1251147974.283940	1251147975.283940	5.151e-09	2019-08-29 21:06:19 UTC
S190828l	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251010526.884921	1251010527.886557	1251010528.913573	4.629e-11	2019-08-28 06:55:26 UTC
S190828j	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251009262.739486	1251009263.756472	1251009264.796332	8.474e-22	2019-08-28 06:34:21 UTC
S190822c	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1250472616.589125	1250472617.589203	1250472618.589203	6.145e-18	2019-08-22 01:30:23 UTC
S190816i	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249995888.757789	1249995889.757789	1249995890.757789	1.436e-08	2019-08-16 13:05:12 UTC
S190814bv	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249852255.996787	1249852257.012957	1249852258.021731	2.033e-33	2019-08-14 21:11:18 UTC
S190808ae	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249338098.496141	1249338099.496141	1249338100.496141	3.366e-08	2019-08-08 22:21:45 UTC
S190728g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248331527.497344	1248331528.546797	1248331529.706055	2.527e-23	2019-07-28 06:45:27 UTC
S190727h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248242630.976288	1248242631.985887	1248242633.180176	1.378e-10	2019-07-27 06:03:51 UTC
S190720a	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1247616533.703127	1247616534.704102	1247616535.860840	3.801e-09	2019-07-20 00:08:53 UTC
S190718y	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1247495729.067865	1247495730.067865	1247495731.067865	3.648e-08	2019-07-18 14:35:34 UTC
S190707g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246527223.118398	1246527224.181226	1246527225.284180	5.265e-12	2019-07-07 09:33:44 UTC
S190706ai	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246487218.321541	1246487219.344727	1246487220.585938	1.901e-09	2019-07-06 22:26:57 UTC
S190701ah	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246048403.576563	1246048404.577637	1246048405.814941	1.916e-08	2019-07-01 20:33:24 UTC
S190630ag	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1245955942.175325	1245955943.179550	1245955944.183184	1.435e-13	2019-06-30 18:52:28 UTC
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
S190524g	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

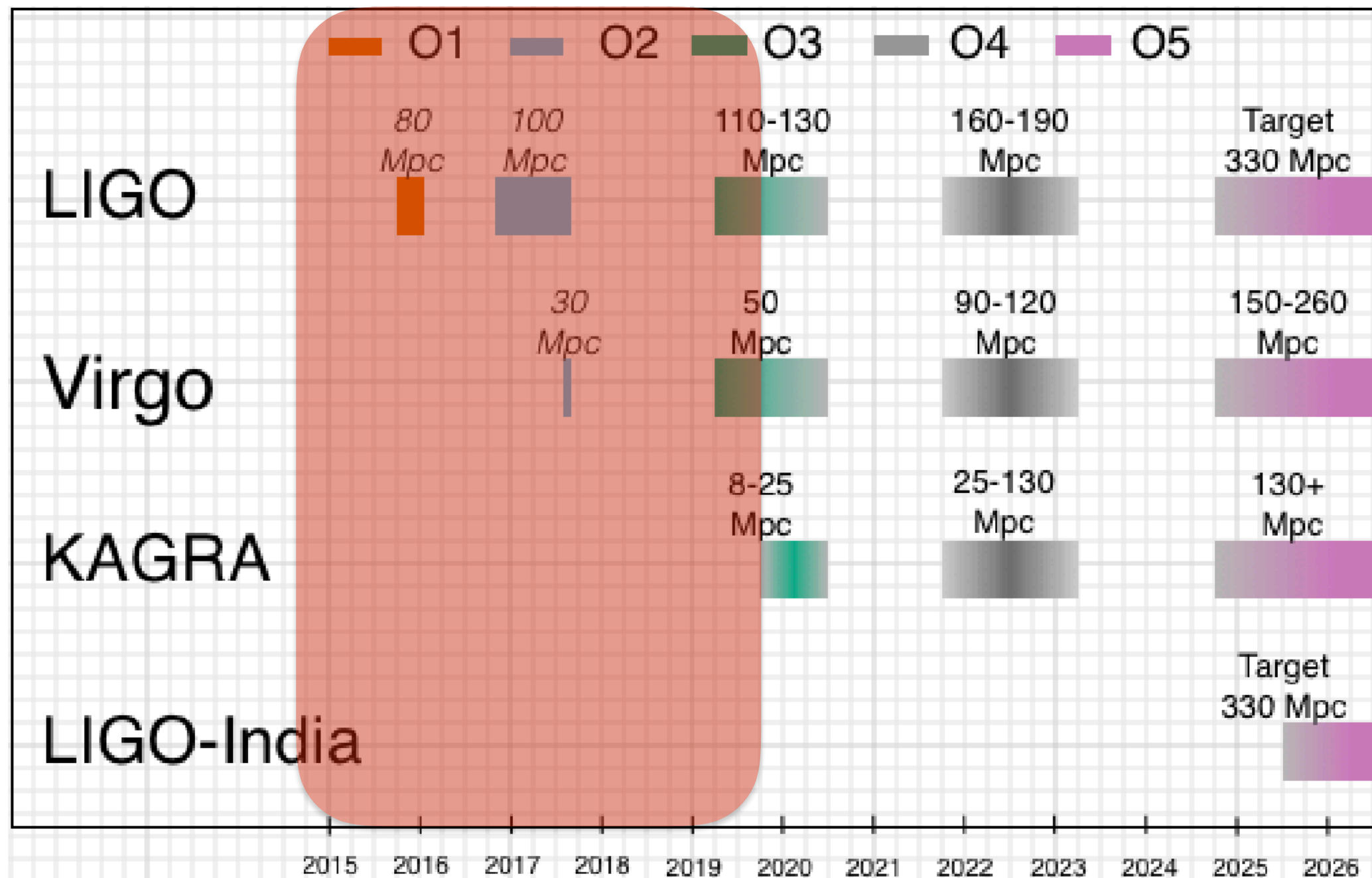


<https://gracedb.ligo.org/latest/>

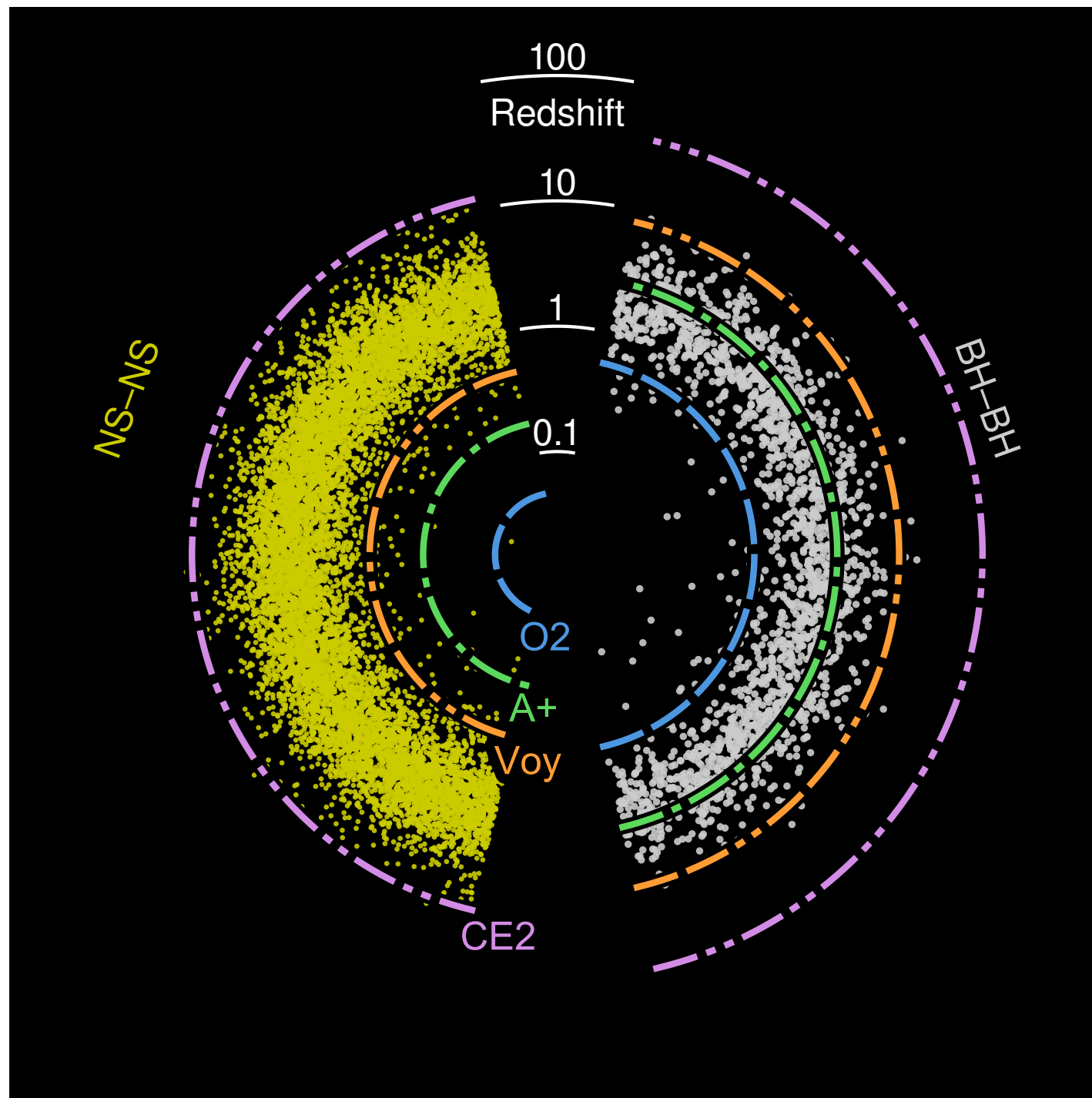
Looking ahead



Looking ahead



Even further ahead



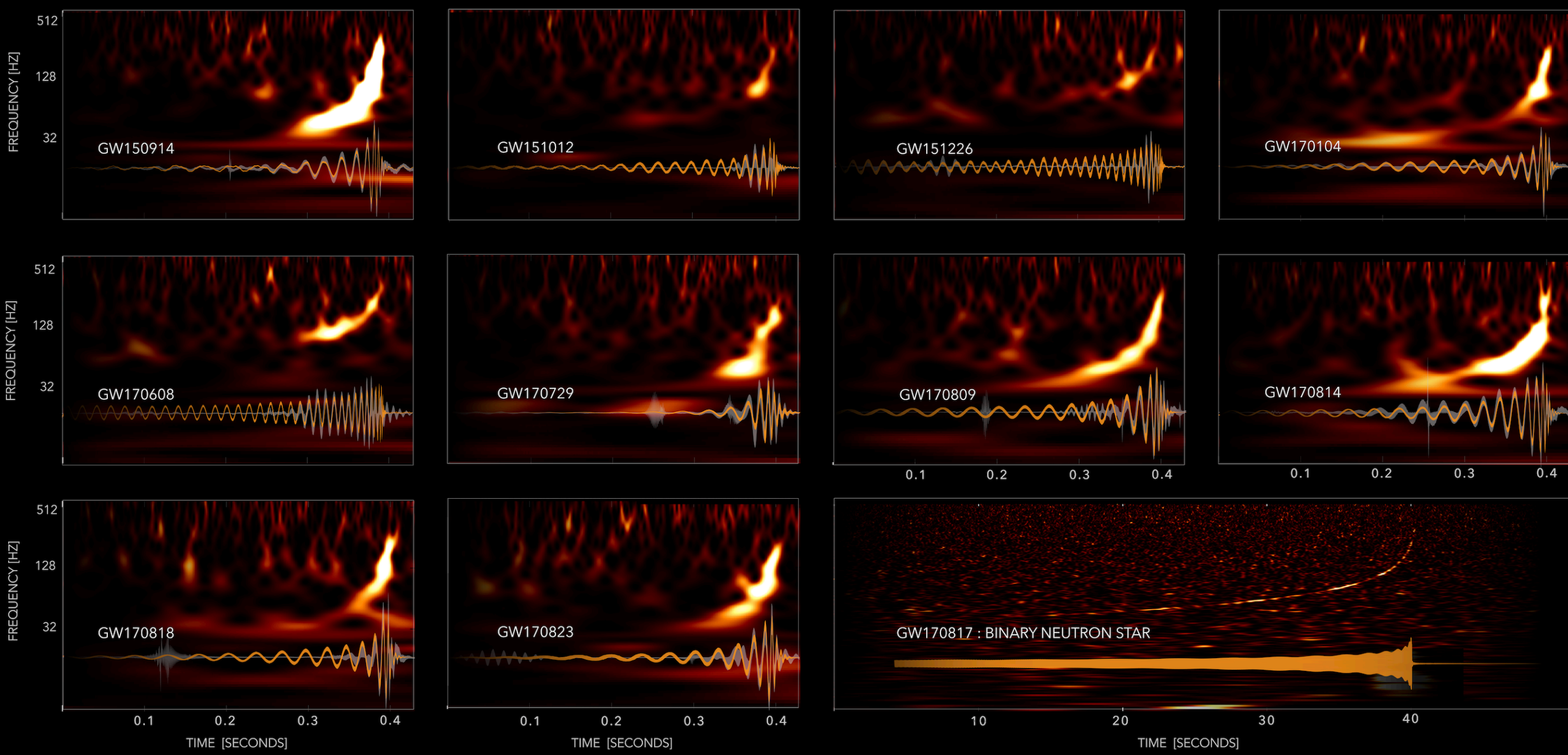
O2: 10 BBHs, 1 BNS

A+: 2xDS, funded

**Voyager: ceiling for
current sites**

**CE2: 3rd gen detectors,
science case**

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: [HTTPS://DOI.ORG/10.7935/82H3-HH23](https://doi.org/10.7935/82H3-HH23)

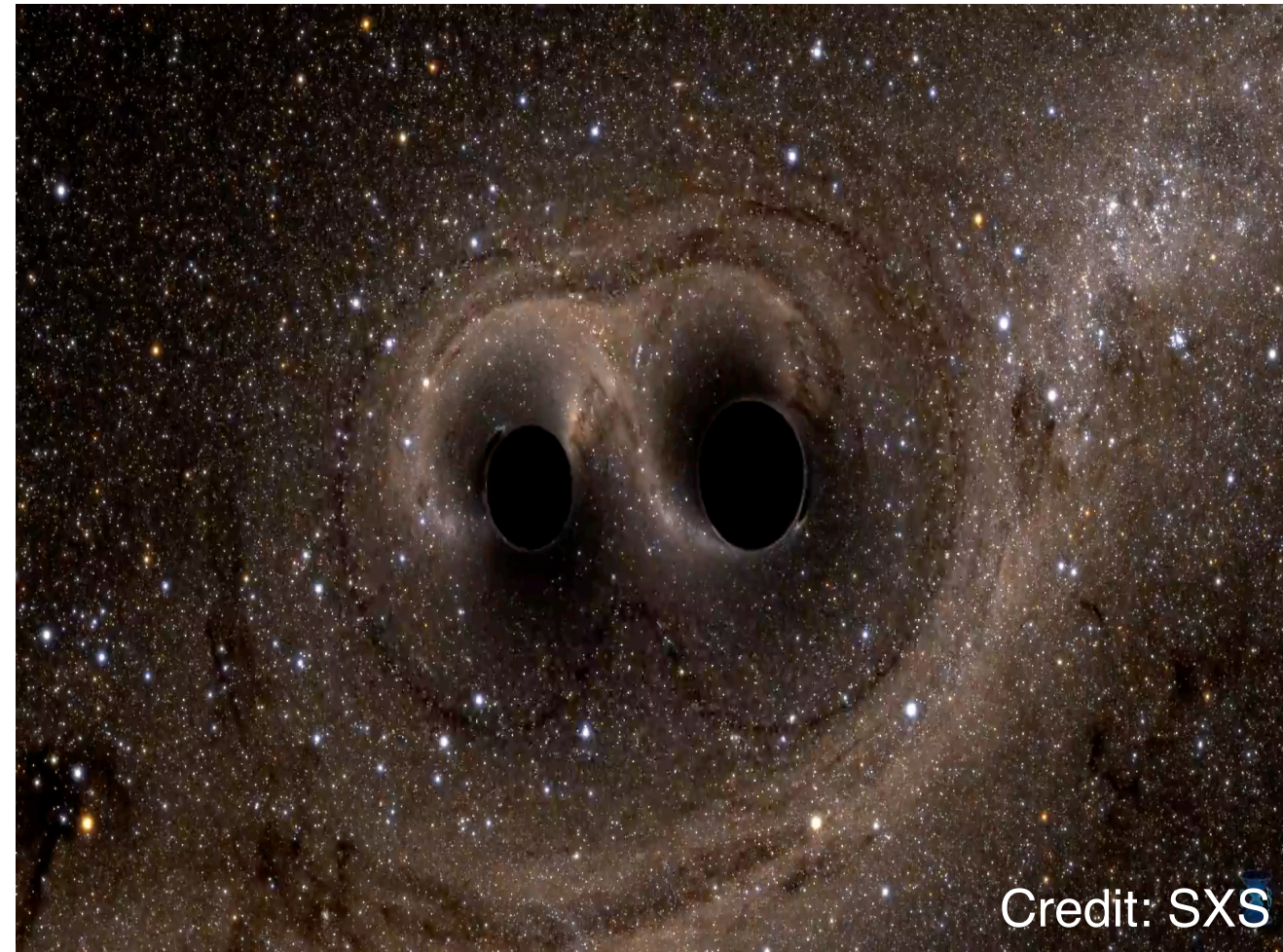
WAVELET (UNMODELED)

EINSTEIN'S THEORY

IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH

Extra slides

Gravitational Waves

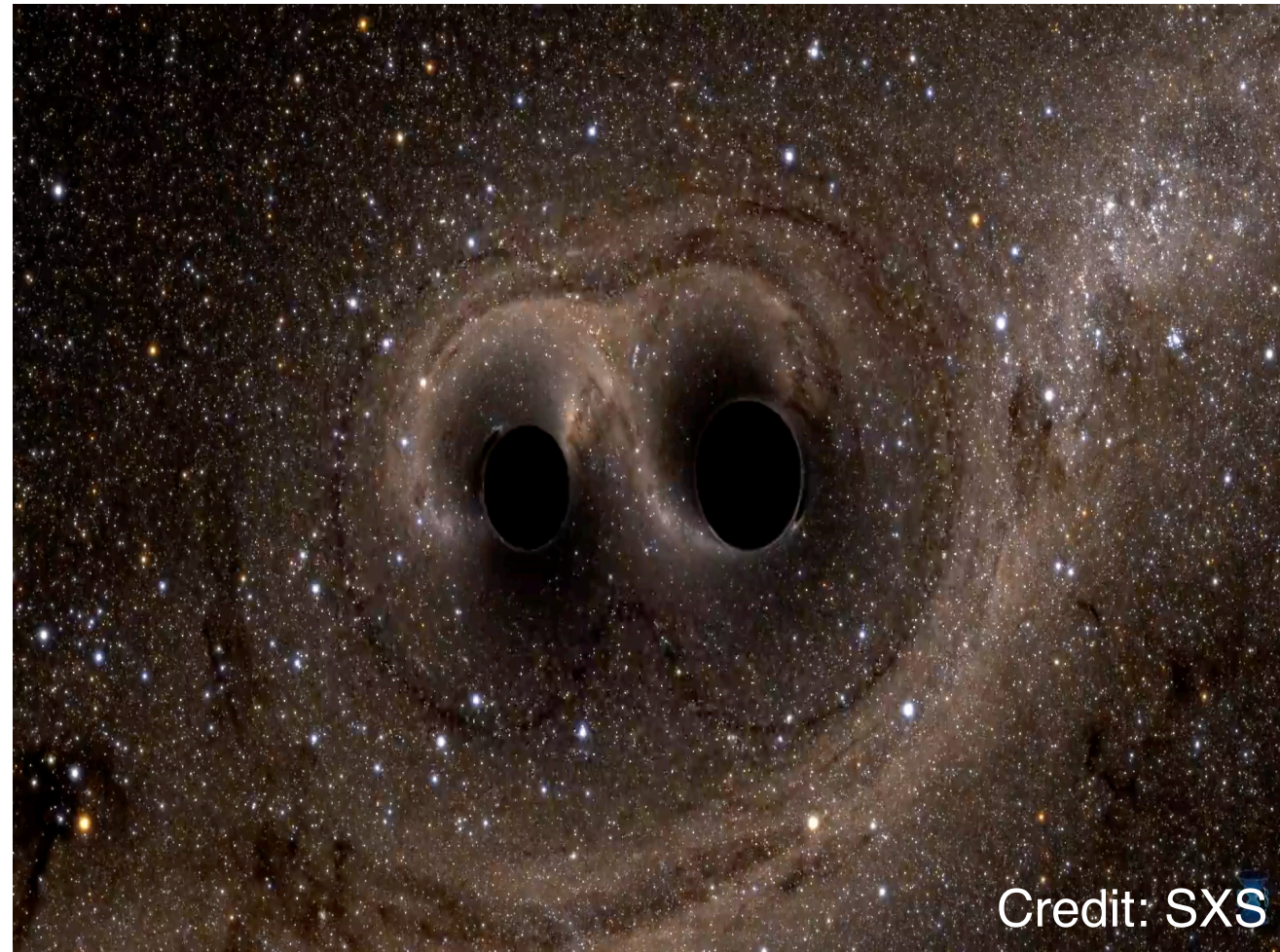


Credit: SXS

Gravitational Waves

Definition: Wave-like perturbation of the gravitational field

$$\square h_{\mu\nu} = T_{\mu\nu}$$



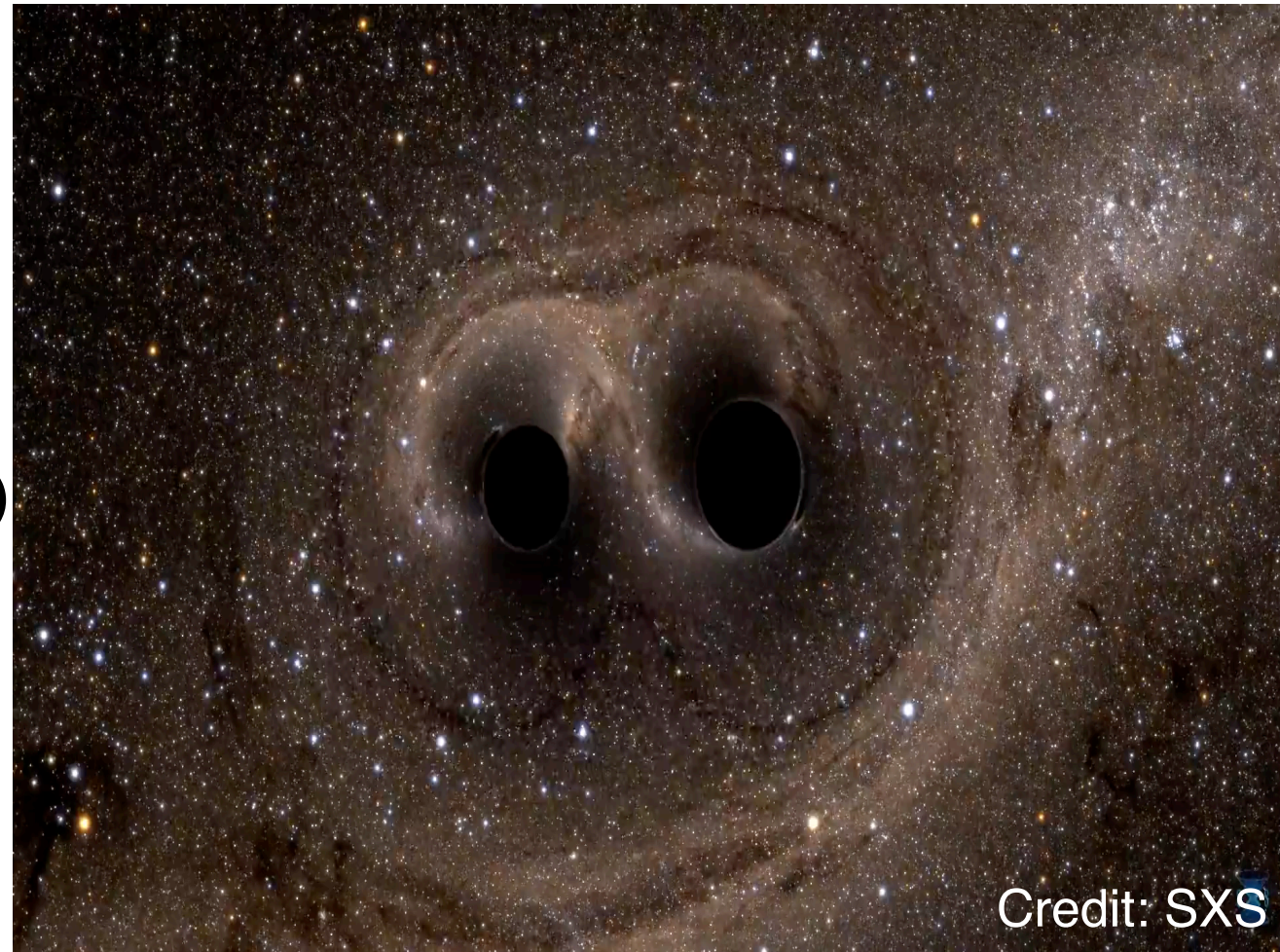
Gravitational Waves

Definition: Wave-like perturbation of the gravitational field

$$\square h_{\mu\nu} = T_{\mu\nu}$$

Generation: Accelerating masses (changing quadrupole and higher multipole moments)

$$h_{ij} \sim \frac{1}{R} \frac{d^2 Q_{ij}}{dt^2}$$



Credit: SXS

Gravitational Waves

Definition: Wave-like perturbation of the gravitational field

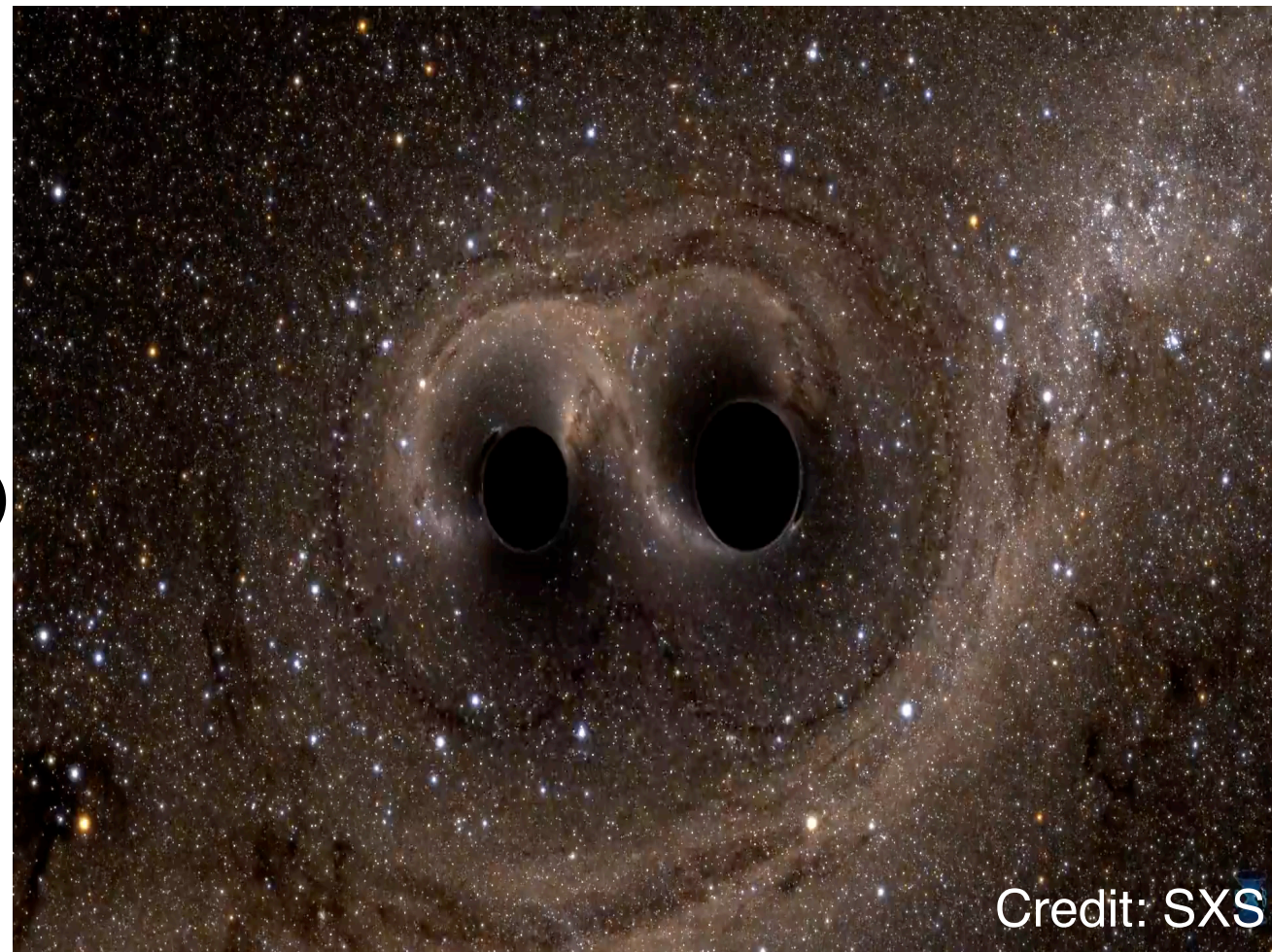
$$\square h_{\mu\nu} = T_{\mu\nu}$$

Generation: Accelerating masses
(changing quadrupole and higher multipole moments)

$$h_{ij} \sim \frac{1}{R} \frac{d^2 Q_{ij}}{dt^2}$$

Amplitude: Small

$$h \sim \frac{G}{c^4} \frac{mu^2}{R} \sim 10^{-22}$$



Gravitational Waves

Definition: Wave-like perturbation of the gravitational field

$$\square h_{\mu\nu} = T_{\mu\nu}$$

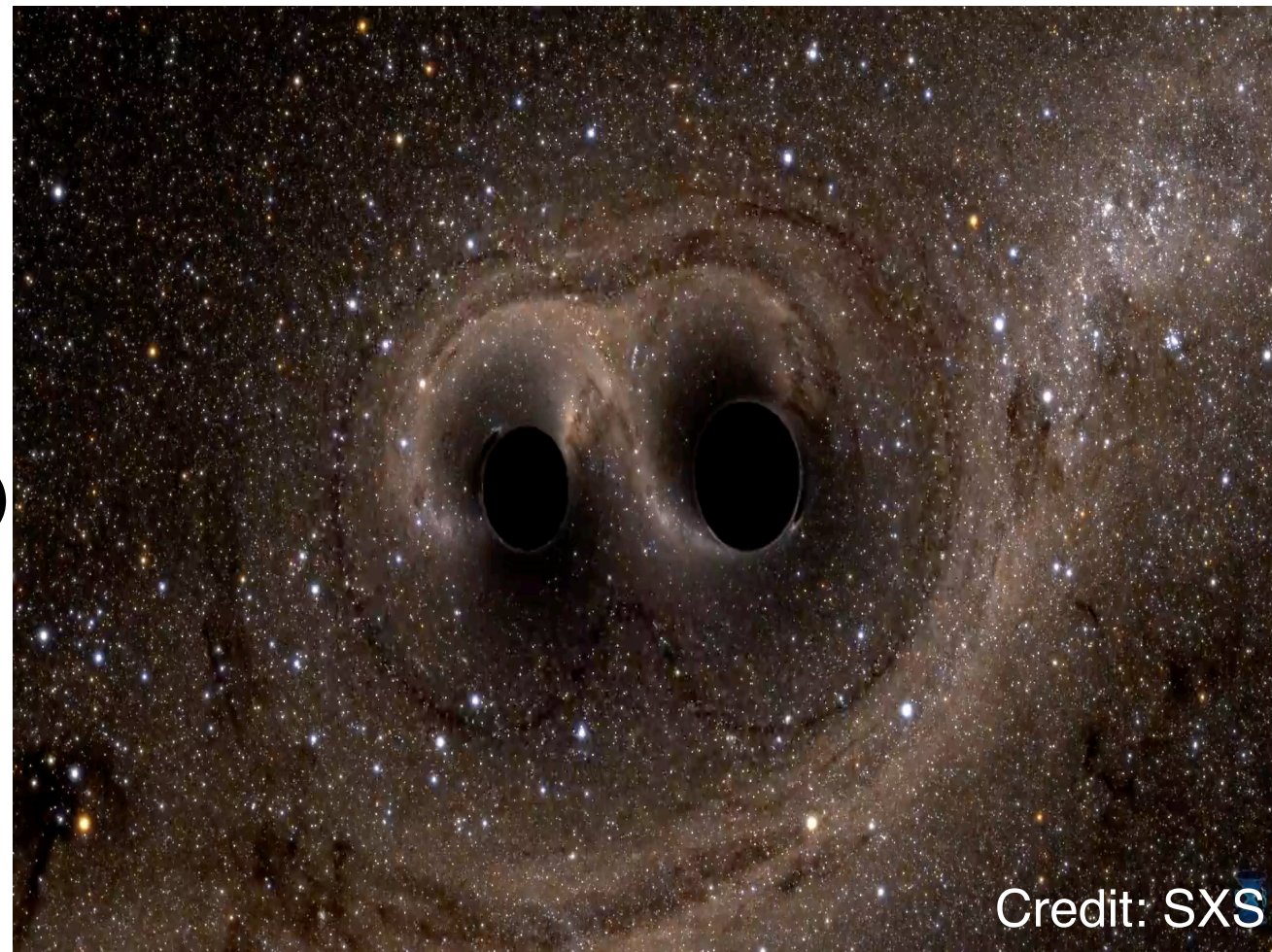
Generation: Accelerating masses (changing quadrupole and higher multipole moments)

$$h_{ij} \sim \frac{1}{R} \frac{d^2 Q_{ij}}{dt^2}$$

Amplitude: Small

$$h \sim \frac{G}{c^4} \frac{mu^2}{R} \sim 10^{-22}$$

Propagation: Light speed, weakly interacting



Gravitational Waves

Definition: Wave-like perturbation of the gravitational field

$$\square h_{\mu\nu} = T_{\mu\nu}$$

Generation: Accelerating masses (changing quadrupole and higher multipole moments)

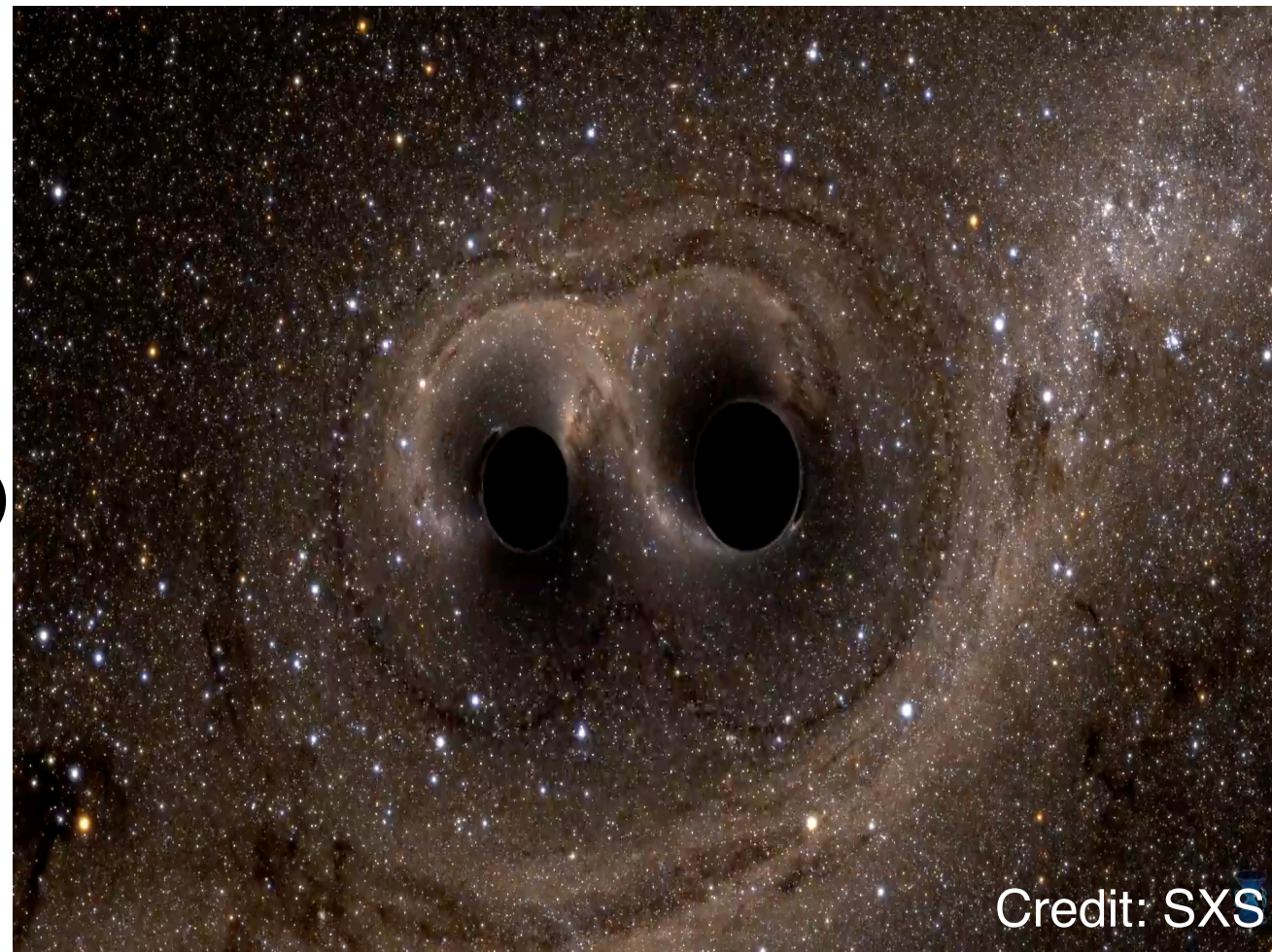
$$h_{ij} \sim \frac{1}{R} \frac{d^2 Q_{ij}}{dt^2}$$

Amplitude: Small

$$h \sim \frac{G}{c^4} \frac{mu^2}{R} \sim 10^{-22}$$

Propagation: Light speed, weakly interacting

Spectrum: Kepler 3rd Law: $f \sim \sqrt{\frac{m}{r_{12}^3}} \sim \frac{1}{m}$, $E_{rad} \sim \%m$



Gravitational Waves

Definition: Wave-like perturbation of the gravitational field

$$\square h_{\mu\nu} = T_{\mu\nu}$$

Generation: Accelerating masses (changing quadrupole and higher multipole moments)

$$h_{ij} \sim \frac{1}{R} \frac{d^2 Q_{ij}}{dt^2}$$

Amplitude: Small

$$h \sim \frac{G}{c^4} \frac{mu^2}{R} \sim 10^{-22}$$

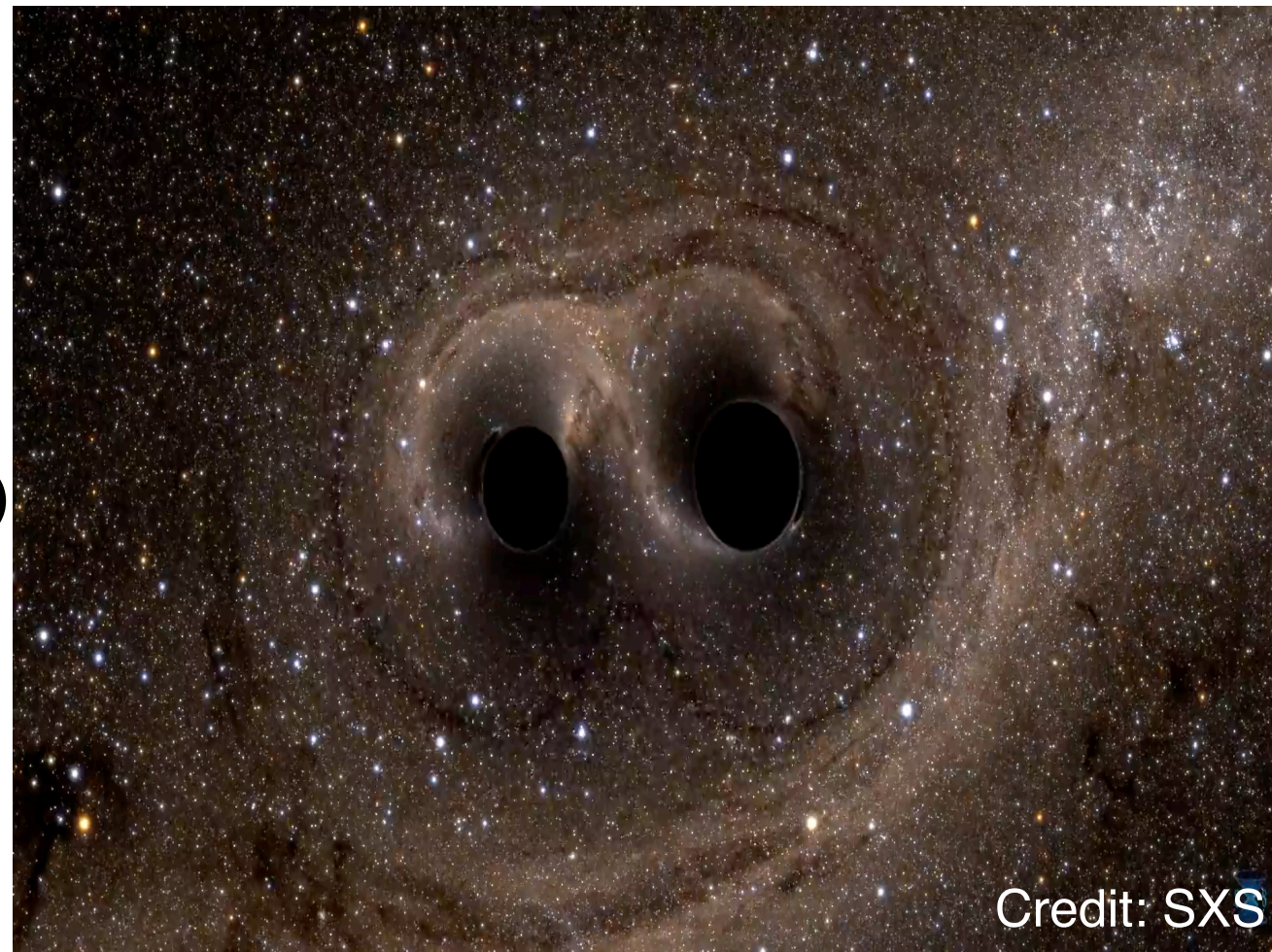
Propagation: Light speed, weakly interacting

Spectrum: Kepler 3rd Law: $f \sim \sqrt{\frac{m}{r_{12}^3}} \sim \frac{1}{m}$, $E_{rad} \sim \%m$

Example: for GW150914,

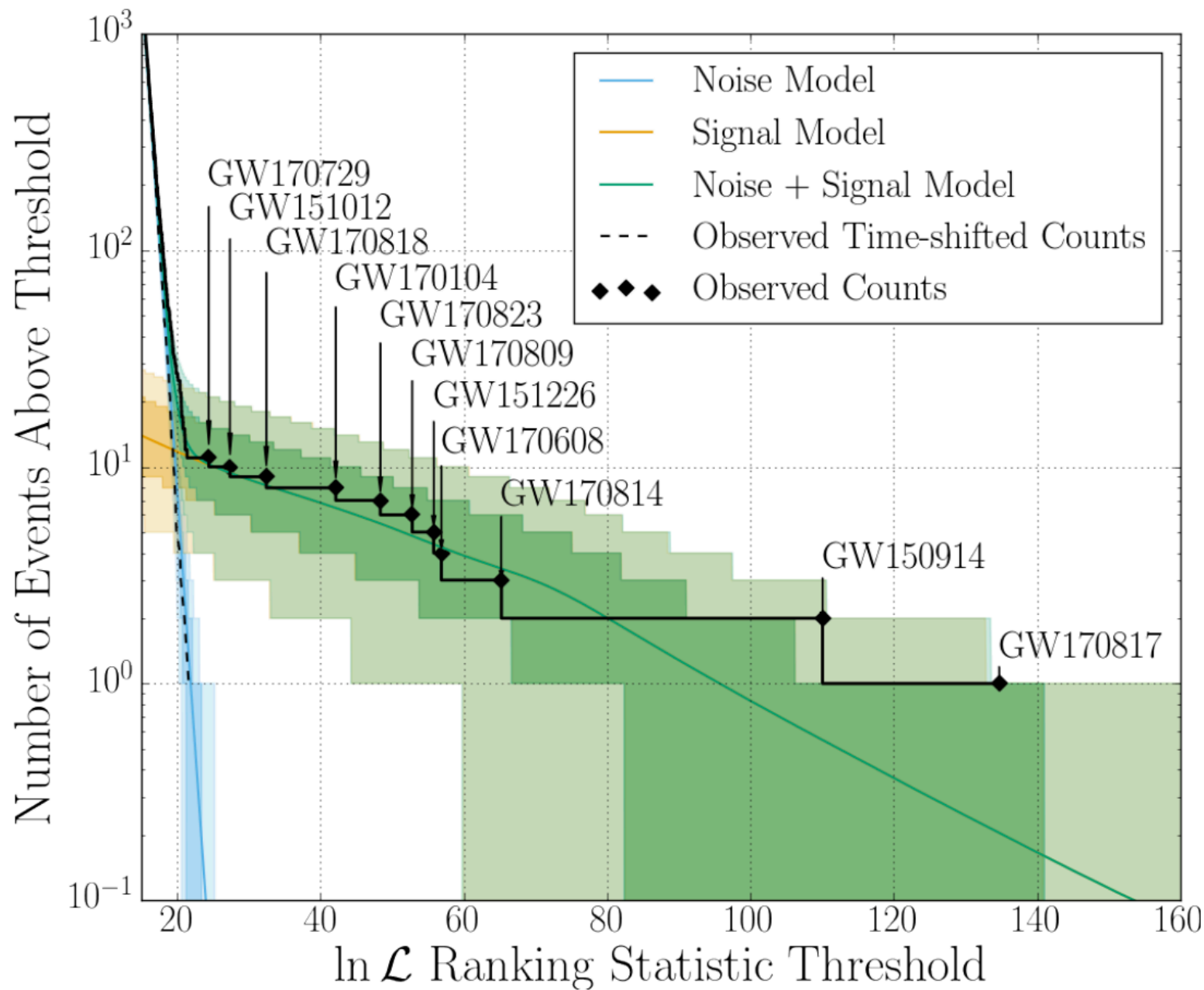
$$E_{GW} \sim 3M_{\odot}$$

More luminous than the entire EM universe



Credit: SXS

The story so far



- 10 black hole binaries
- 1 neutron star binary
- Many marginal triggers that (probably) include a few binaries

LVC (arxiv:1811.12907)

Searches:

GstLAL — Messick+ (arxiv:1604.04324),
PyCBC — Usman+ (arxiv:1508.02357),
cWB — Klimenko+ (arxiv:1511.05999)

Source properties

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_f/M_\odot$	a_f	$E_{\text{rad}}/(M_\odot c^2)$	$\ell_{\text{peak}}/(\text{erg s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\text{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	180
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.05}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

LVC (arxiv:1811.12907)

This and more available at
<https://www.gw-openscience.org/>

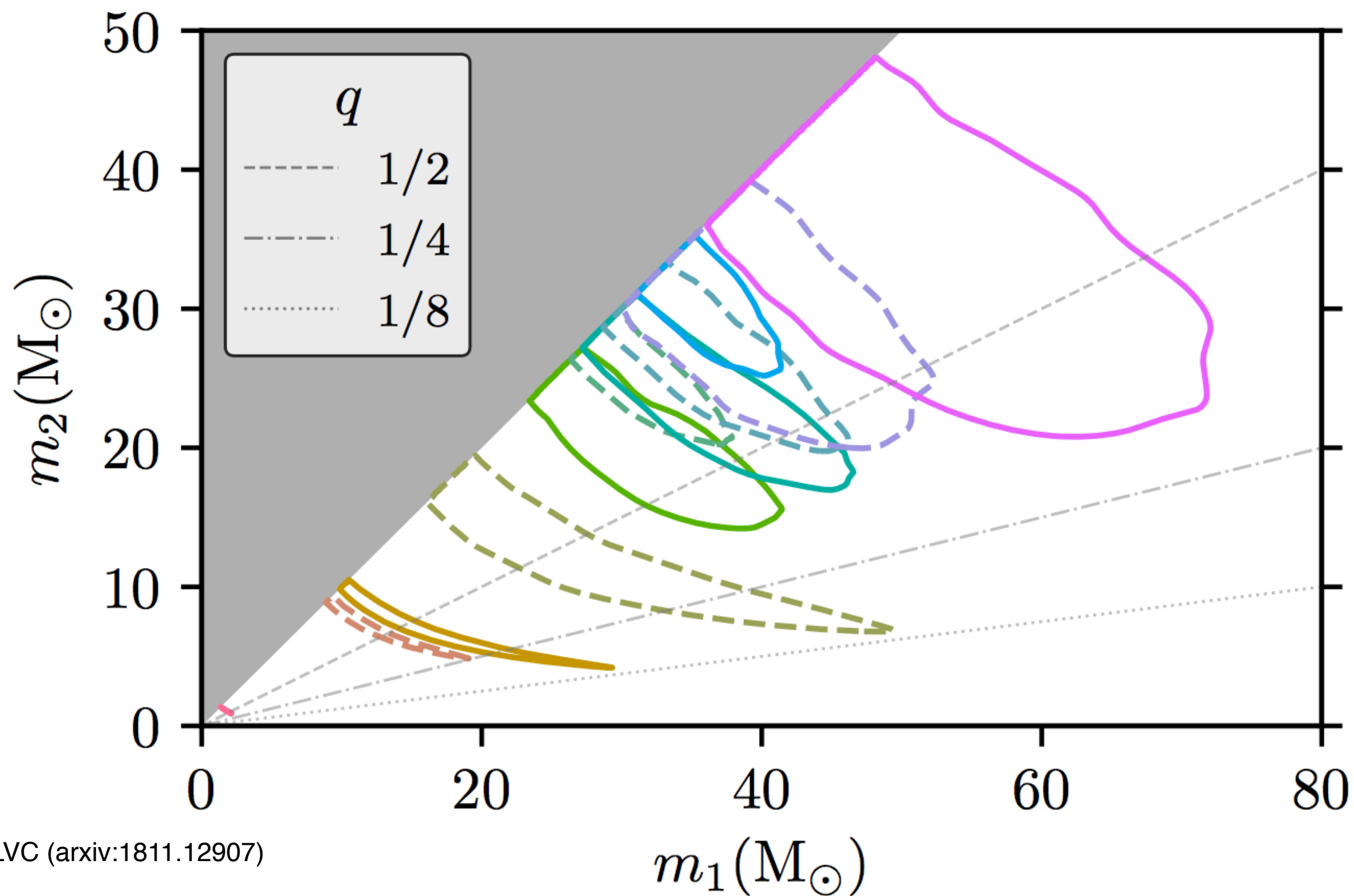
Source properties

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	χ_{eff}	$M_f/M_\odot$	a_f	$E_{\text{rad}}/(M_\odot c^2)$	$\ell_{\text{peak}}/(\text{erg s}^{-1})$	d_L/Mpc	z	$\Delta\Omega/\text{deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	180
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.6}_{-0.5}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.5}_{-0.5}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

LVC (arxiv:1811.12907)

This and more available at
<https://www.gw-openscience.org/>

Masses of black holes in binaries



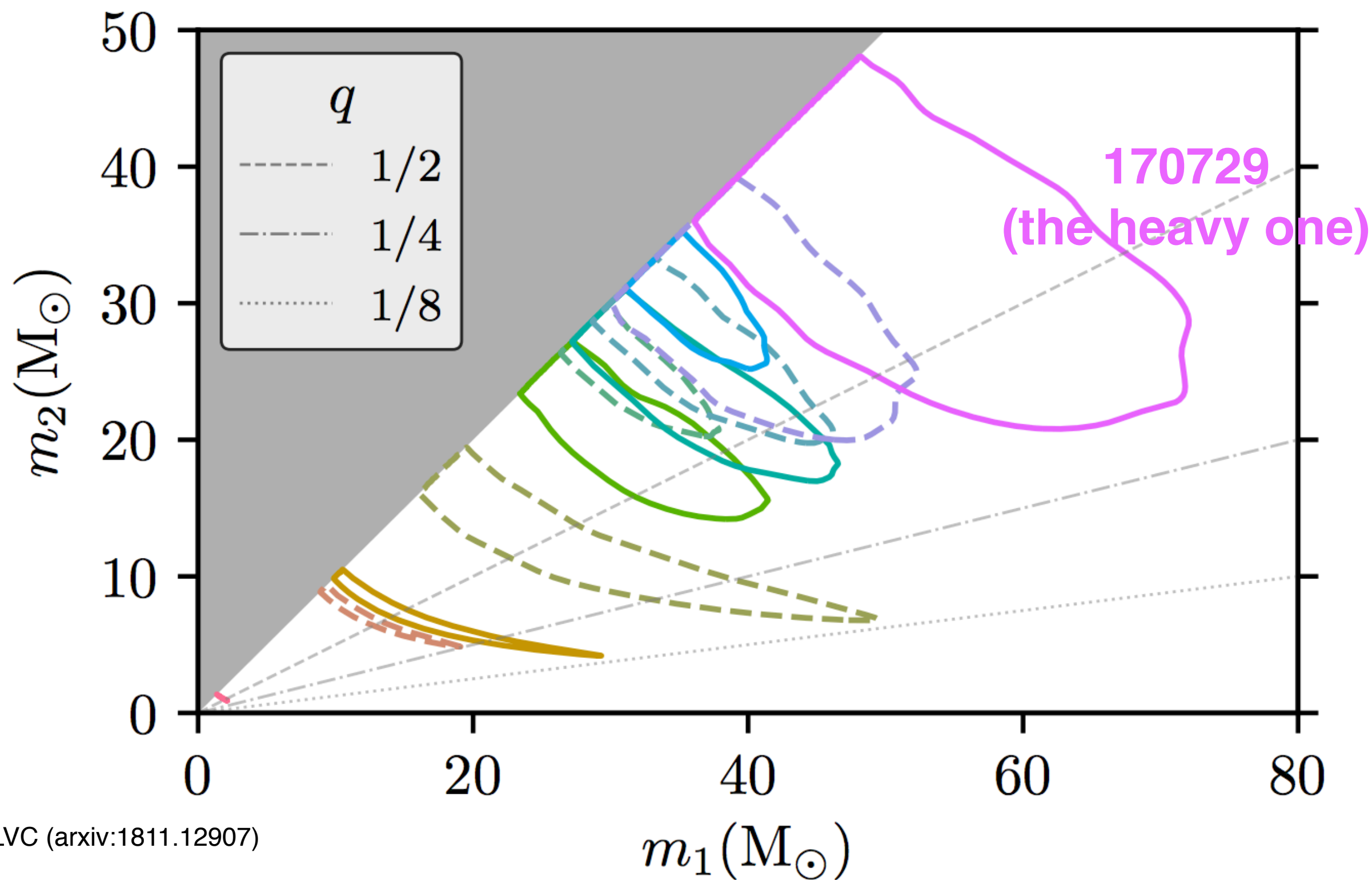
LVC (arxiv:1811.12907)

PE: LALInference — Veitch+ (arxiv:1409.7215)
PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Waveforms:

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

Masses of black holes in binaries



LVC (arxiv:1811.12907)

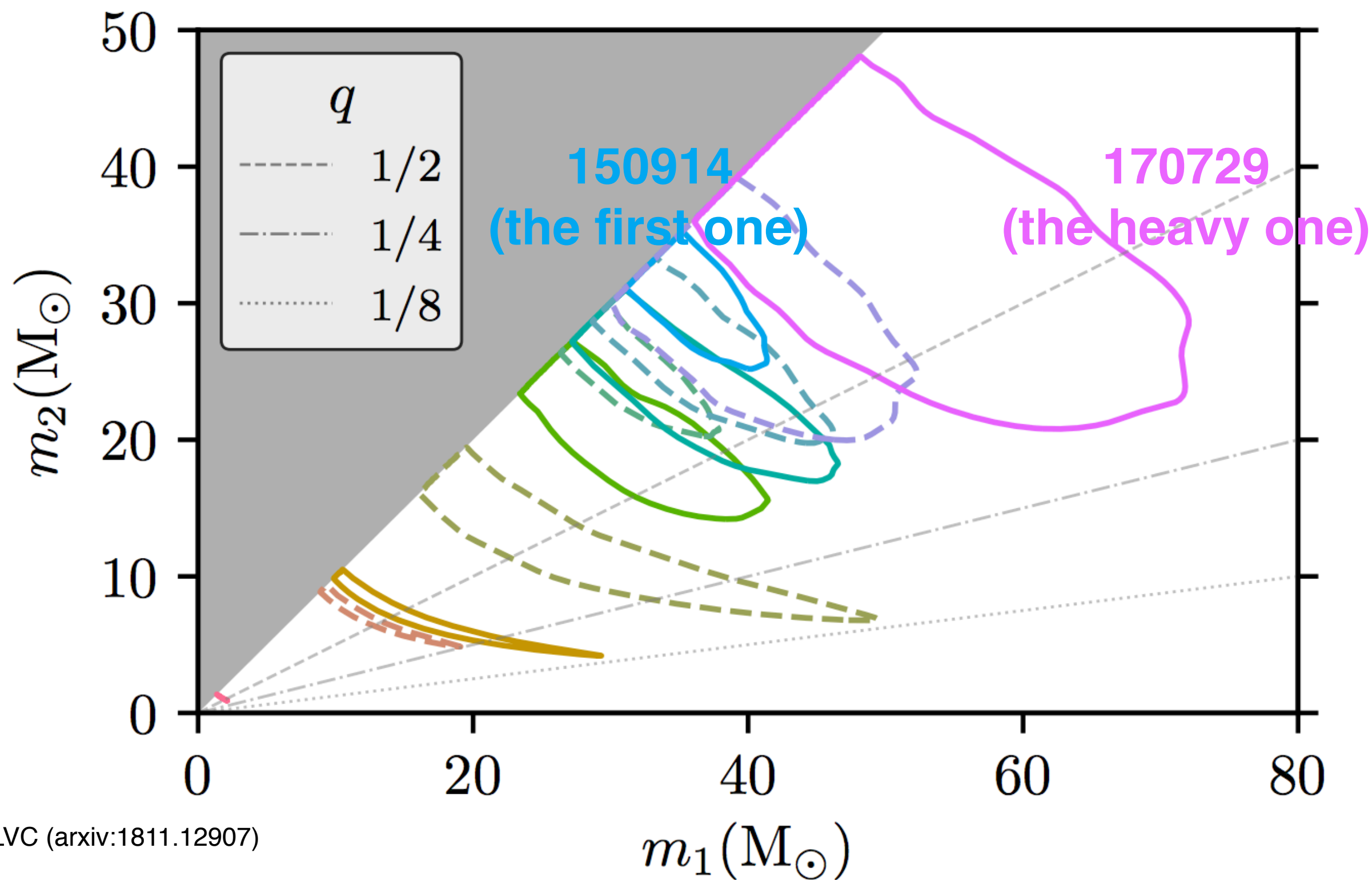
PE: LALInference — Veitch+ (arxiv:1409.7215)

PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Waveforms:

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

Masses of black holes in binaries



LVC (arxiv:1811.12907)

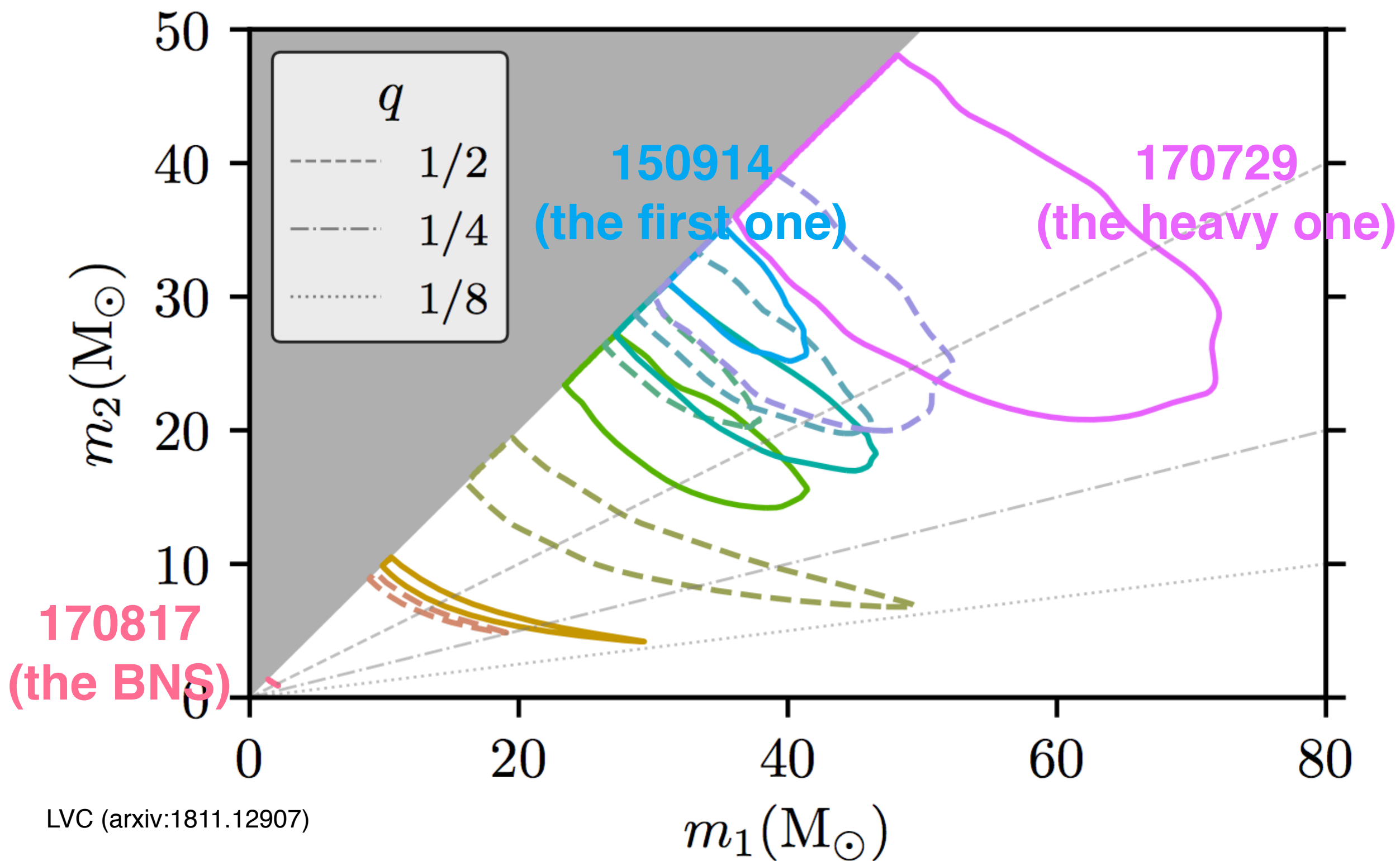
Waveforms:

PE: LALInference — Veitch+ (arxiv:1409.7215)

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Masses of black holes in binaries

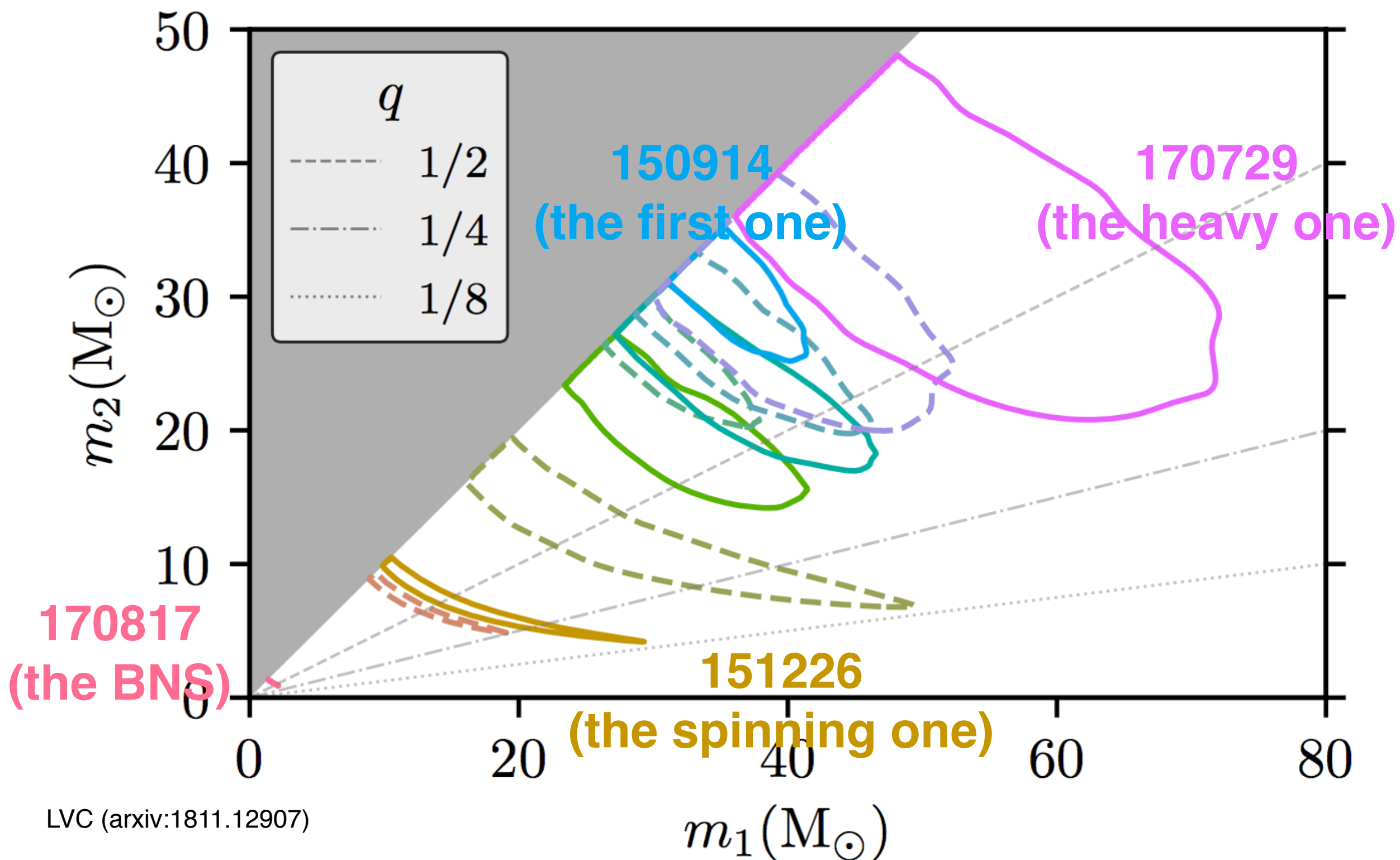


Waveforms:

PE: LALInference — Veitch+ (arxiv:1409.7215)
PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

Masses of black holes in binaries

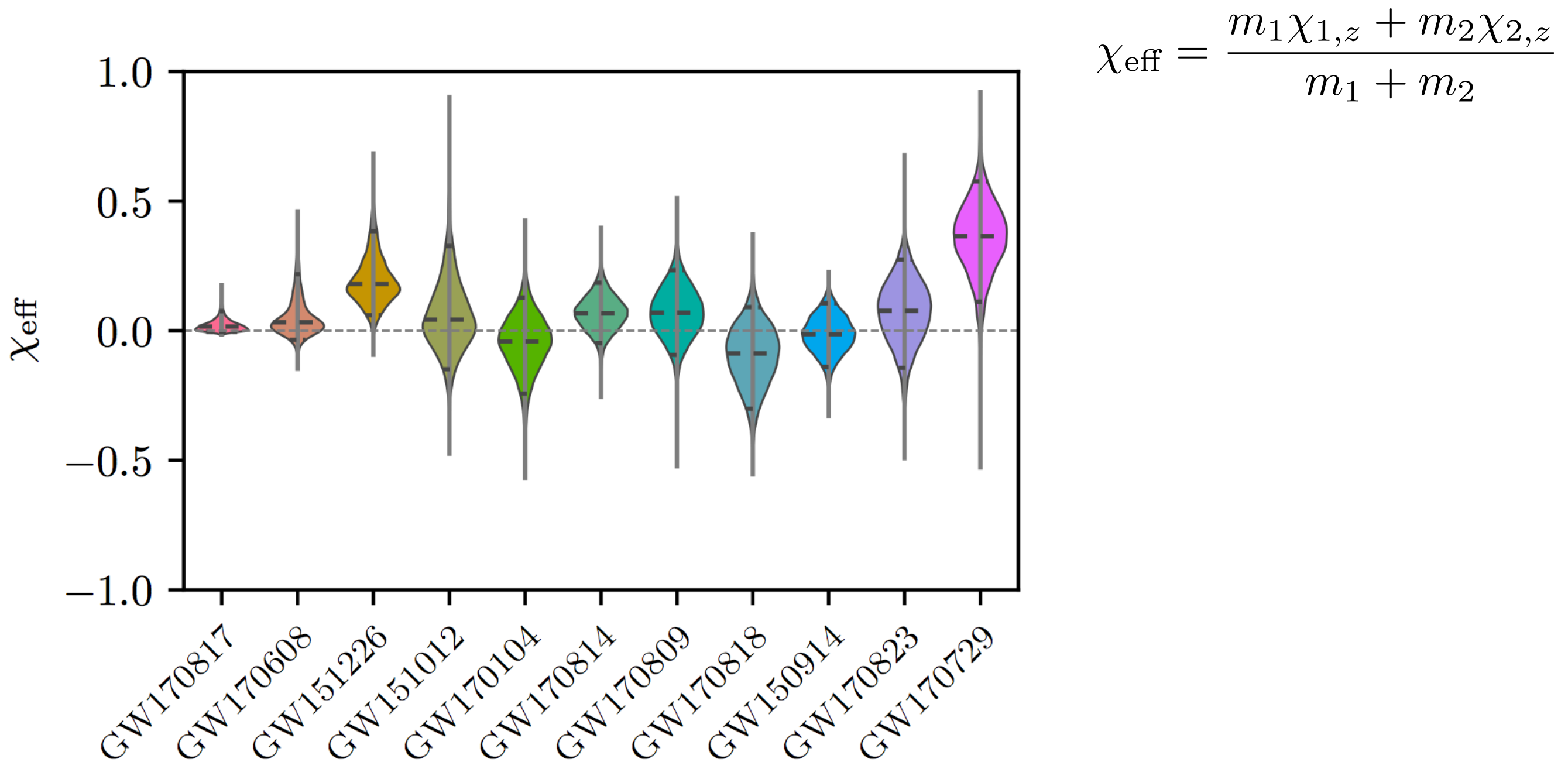


Waveforms:

PE: LALInference — Veitch+ (arxiv:1409.7215)
PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

Spins of black holes in binaries



LVC (arxiv:1811.12907)

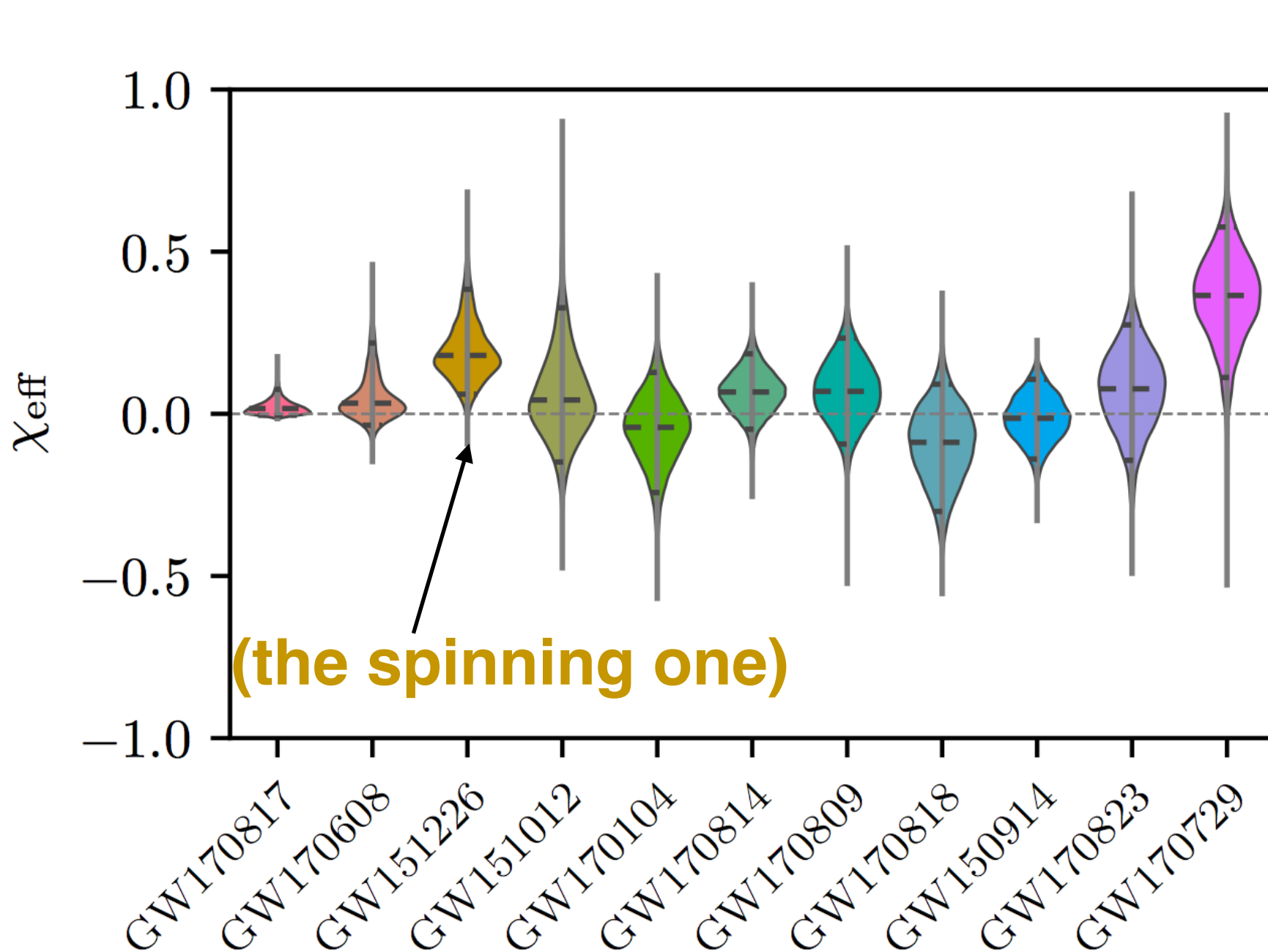
PE: LALInference — Veitch+ (arxiv:1409.7215)

PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Waveforms:

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

Spins of black holes in binaries



$$\chi_{\text{eff}} = \frac{m_1 \chi_{1,z} + m_2 \chi_{2,z}}{m_1 + m_2}$$

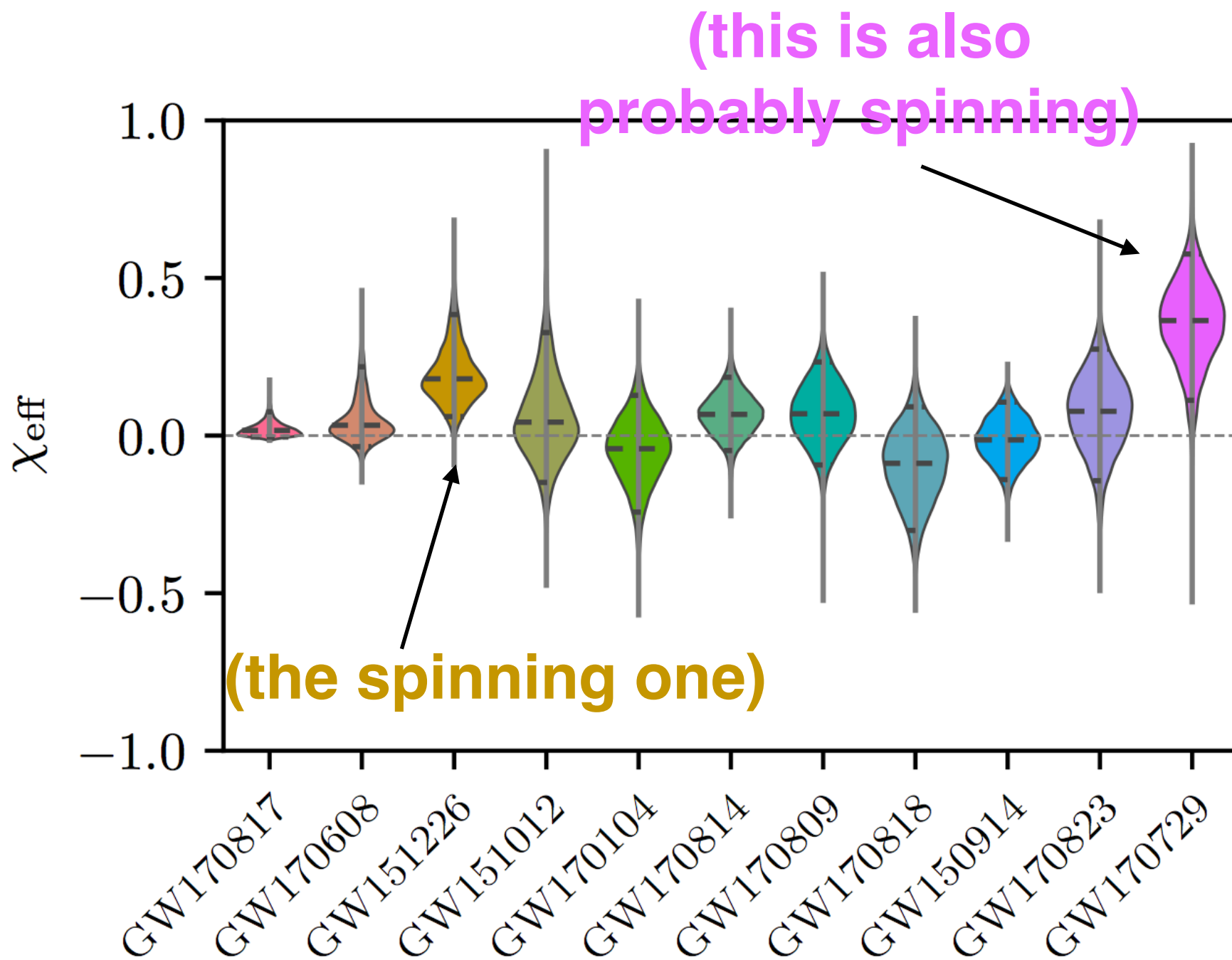
Effective spin > 0.05

LVC (arxiv:1811.12907)

PE: LALInference — Veitch+ (arxiv:1409.7215)
PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Waveforms:
IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

Spins of black holes in binaries



$$\chi_{\text{eff}} = \frac{m_1 \chi_{1,z} + m_2 \chi_{2,z}}{m_1 + m_2}$$

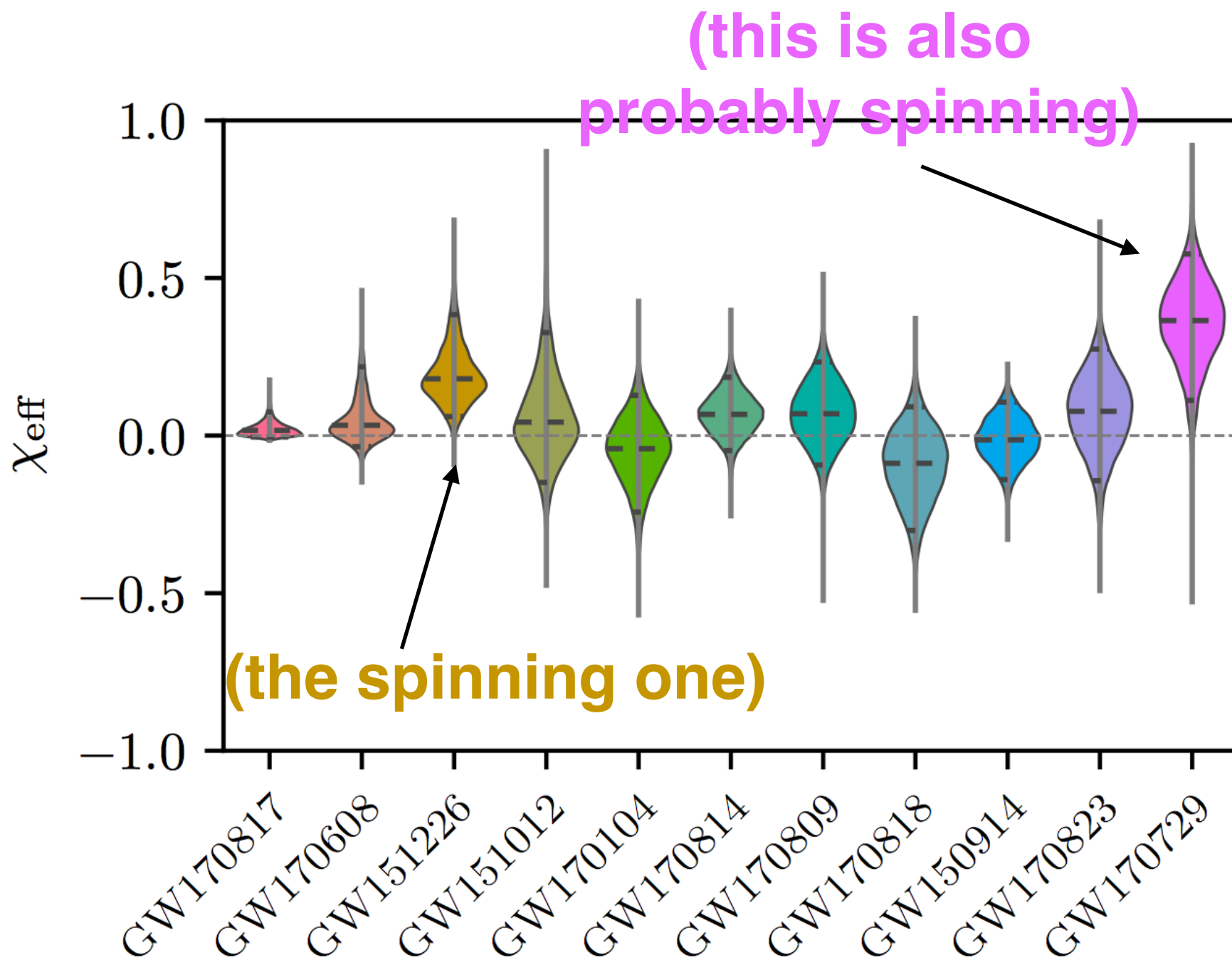
Effective spin > 0.05
Effective spin > 0.1

LVC (arxiv:1811.12907)

PE: LALInference — Veitch+ (arxiv:1409.7215)
PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Waveforms:
IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

Spins of black holes in binaries



$$\chi_{\text{eff}} = \frac{m_1 \chi_{1,z} + m_2 \chi_{2,z}}{m_1 + m_2}$$

Consistent with
moderate spins

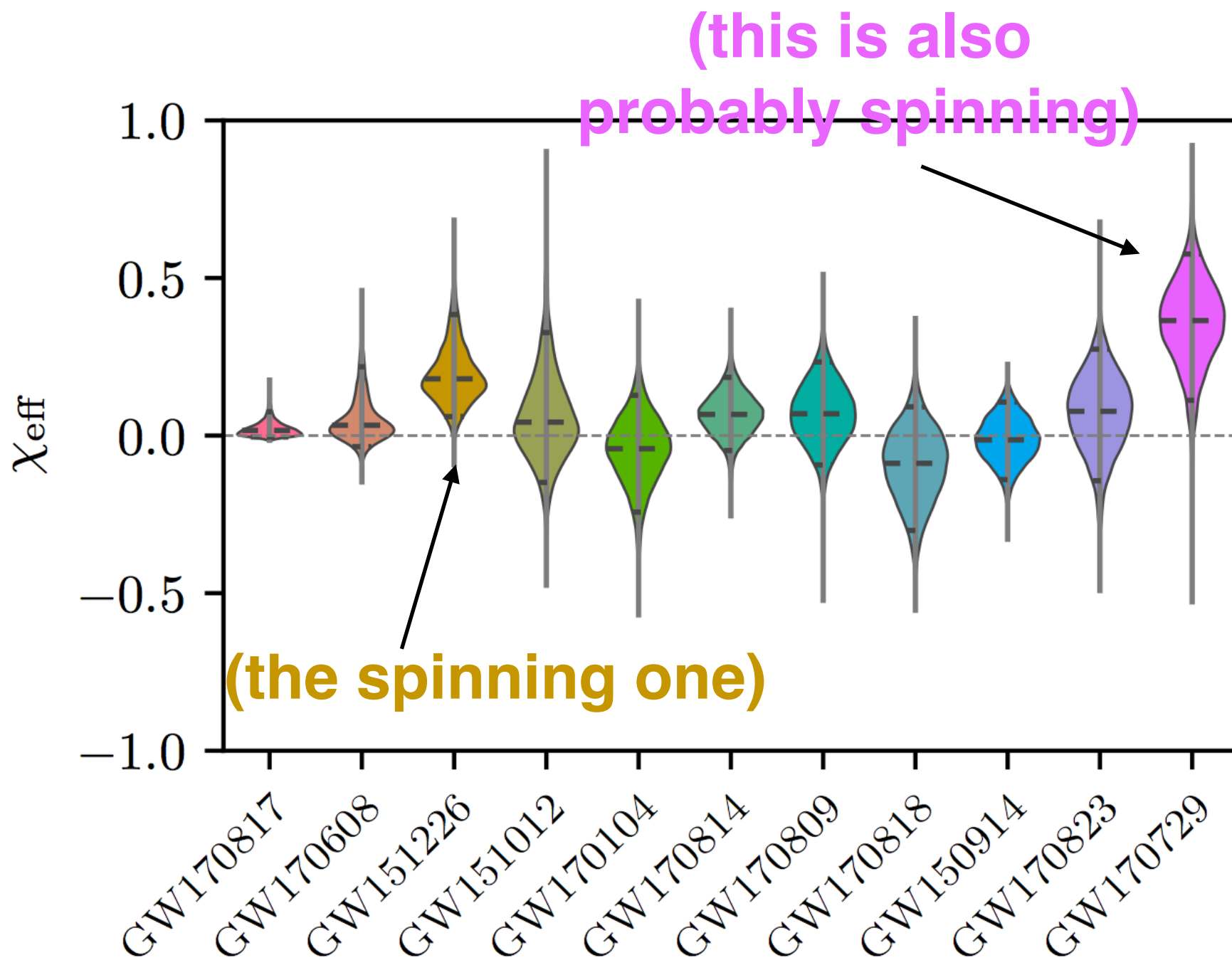
Effective spin > 0.05
Effective spin > 0.1

LVC (arxiv:1811.12907)

PE: LALInference — Veitch+ (arxiv:1409.7215)
PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Waveforms:
IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

Spins of black holes in binaries



$$\chi_{\text{eff}} = \frac{m_1 \chi_{1,z} + m_2 \chi_{2,z}}{m_1 + m_2}$$

Consistent with
moderate spins

No evidence for
spin-precession

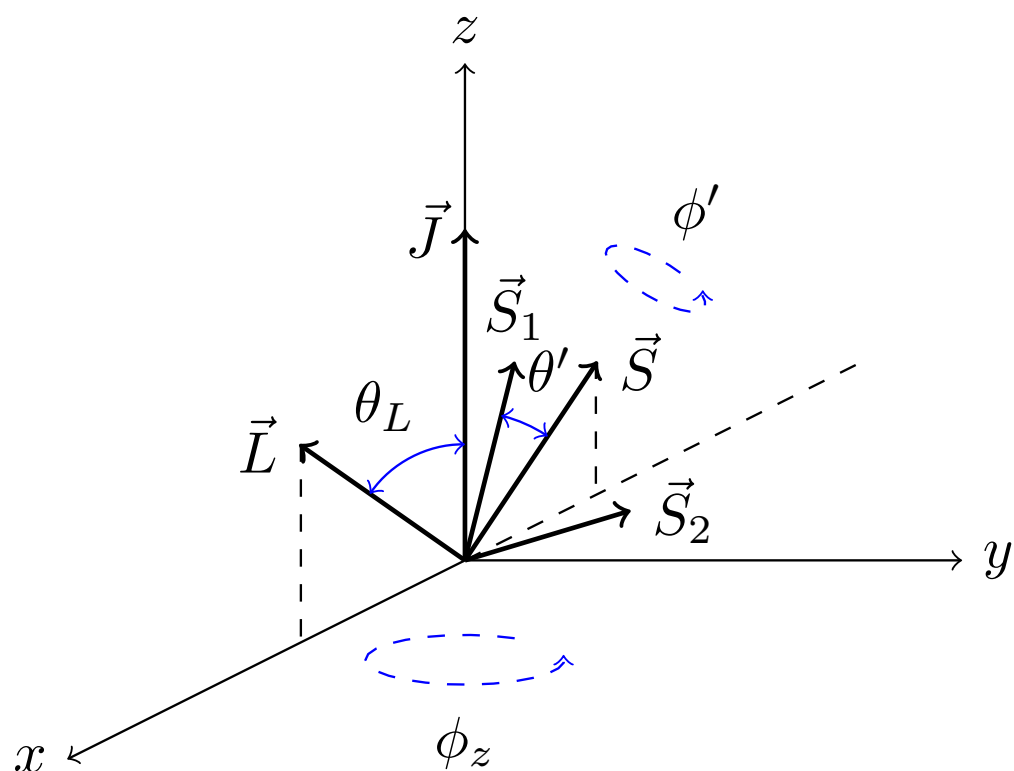
Effective spin > 0.05
Effective spin > 0.1

LVC (arxiv:1811.12907)

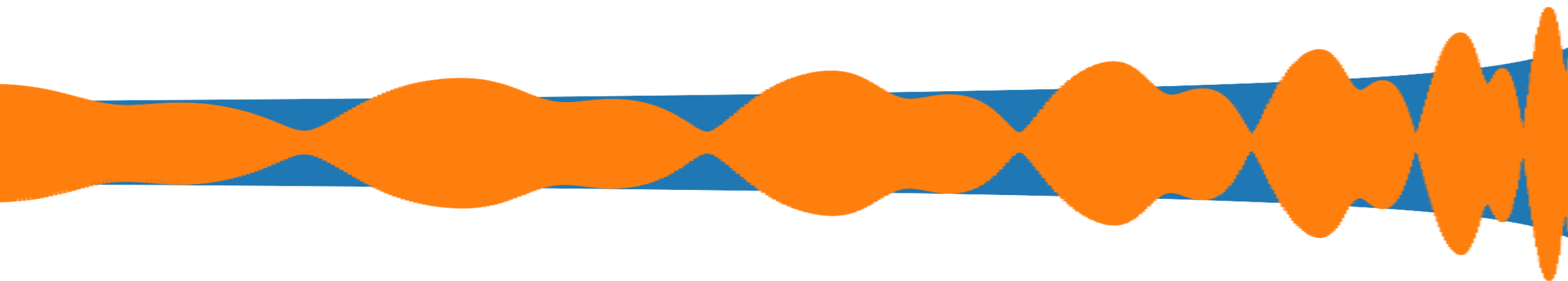
PE: LALInference — Veitch+ (arxiv:1409.7215)
PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Waveforms:
IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

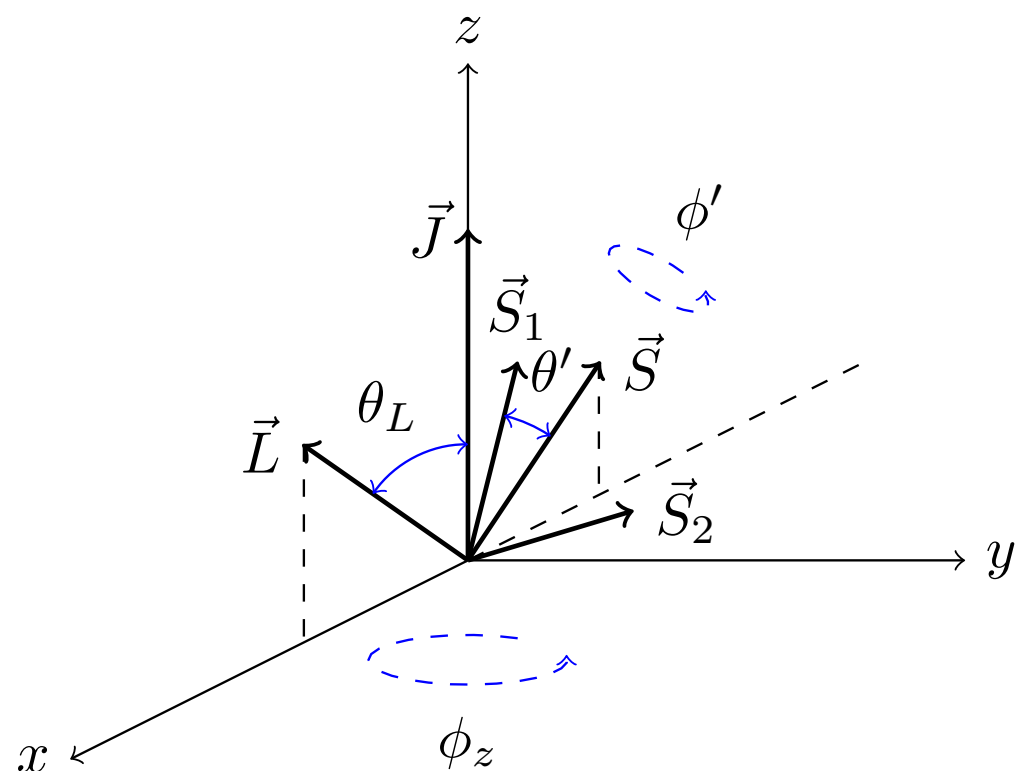
Precession: no evidence



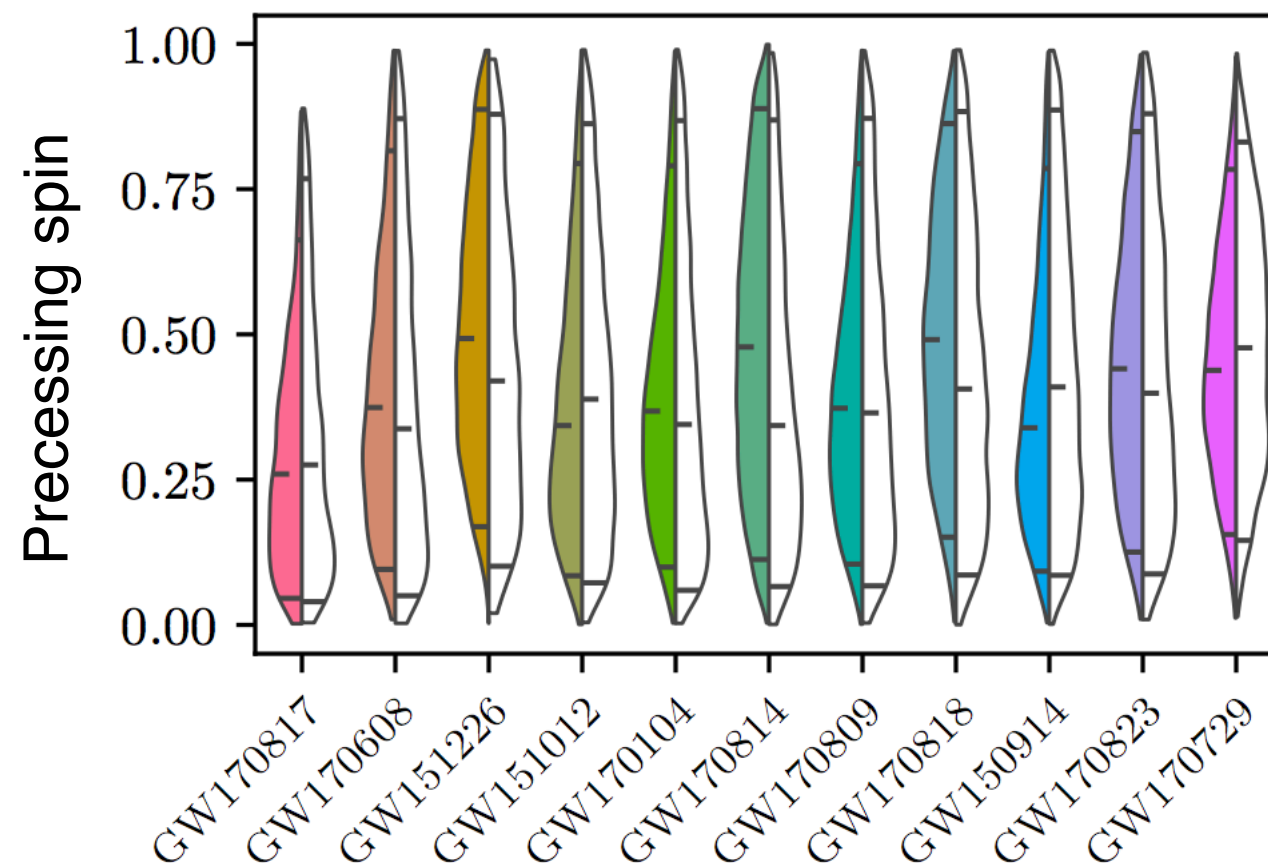
Chatziioannou+ (arxiv:1703.03967)



Precession: no evidence

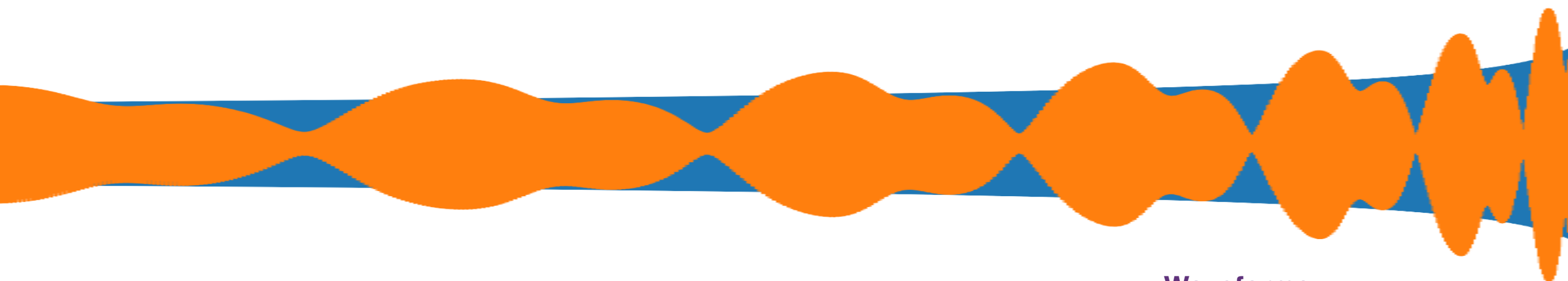


Chatziioannou+ (arxiv:1703.03967)



LVC (arxiv:1811.12907)

Precessing spin — Schmidt+ (arxiv:1408.1810)



Waveforms:

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

PE: LALInference — Veitch+ (arxiv:1409.7215)

PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Higher modes: small evidence

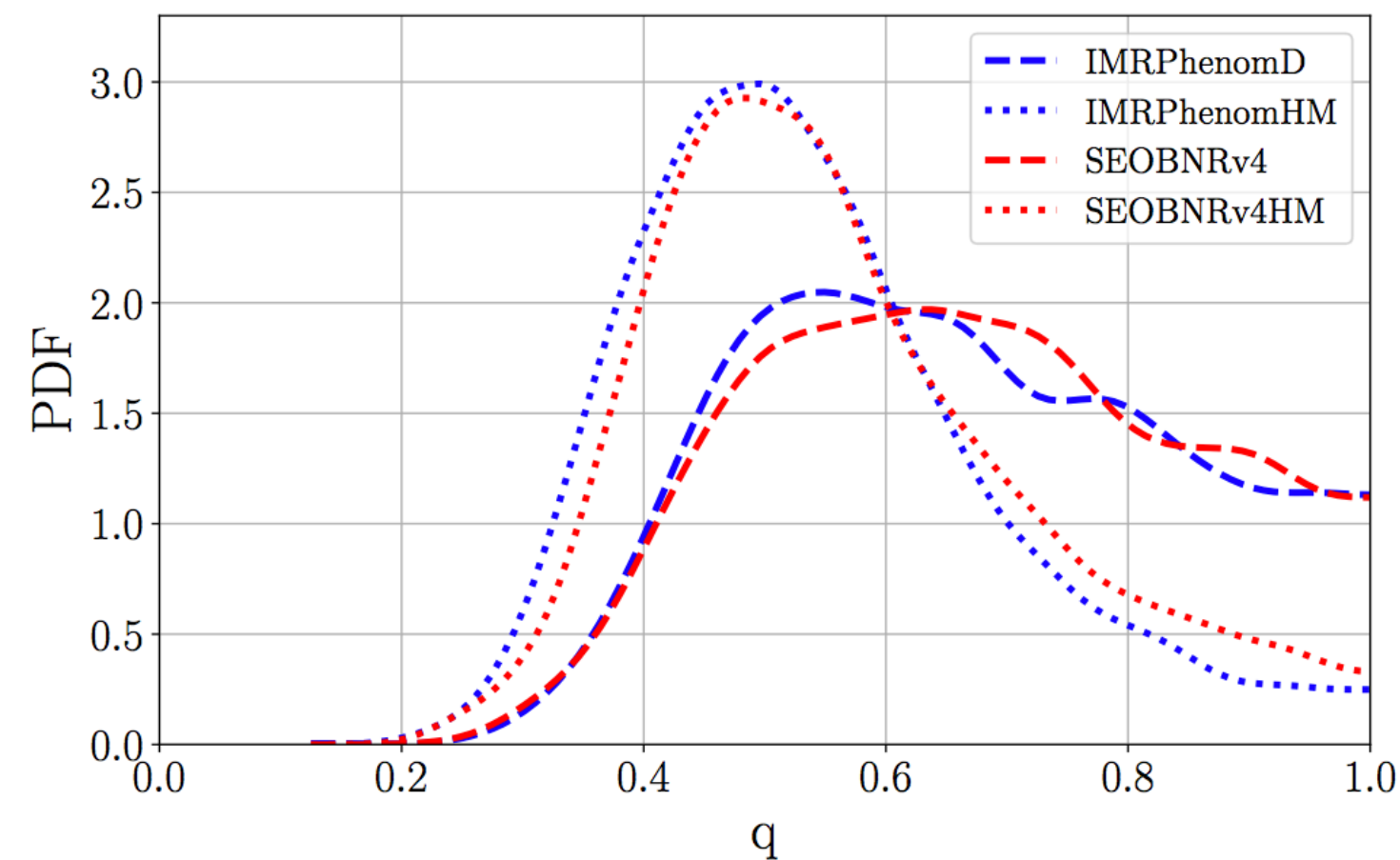
$$h \equiv h_+ - ih_\times = \sum_{\ell,m} Y_{\ell,m}^{-2}(\iota, \varphi) h_{\ell,m}(t, \vec{\theta})$$

Quadrupolar waves: $\ell=2$, Quasicircular mergers: $|m|=2$

Higher modes: small evidence

$$h \equiv h_+ - ih_\times = \sum_{\ell,m} Y_{\ell,m}^{-2}(\iota, \varphi) h_{\ell,m}(t, \vec{\theta})$$

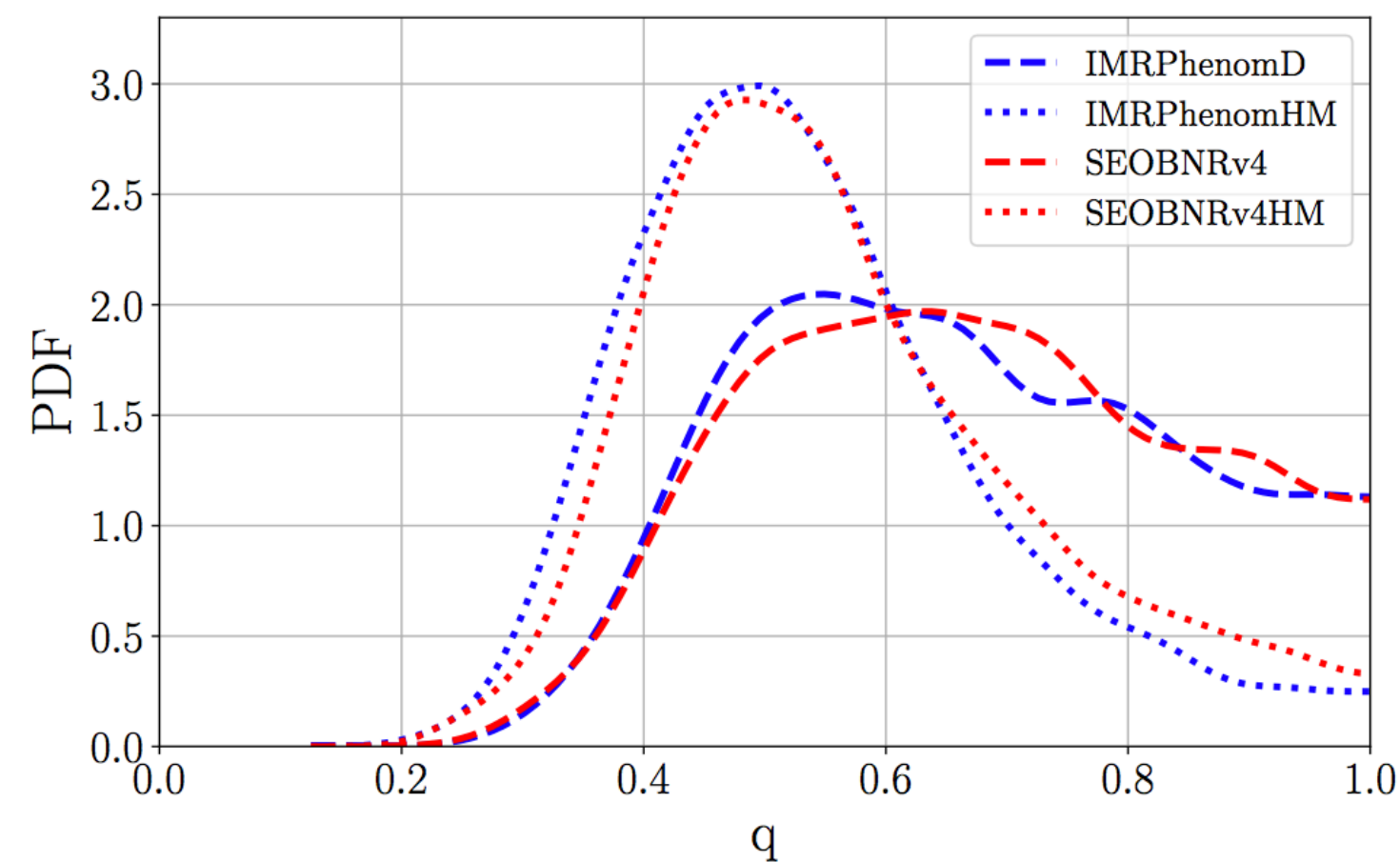
Quadrupolar waves: $\ell=2$, Quasicircular mergers: $|m|=2$



Higher modes: small evidence

$$h \equiv h_+ - ih_\times = \sum_{\ell,m} Y_{\ell,m}^{-2}(\iota, \varphi) h_{\ell,m}(t, \vec{\theta})$$

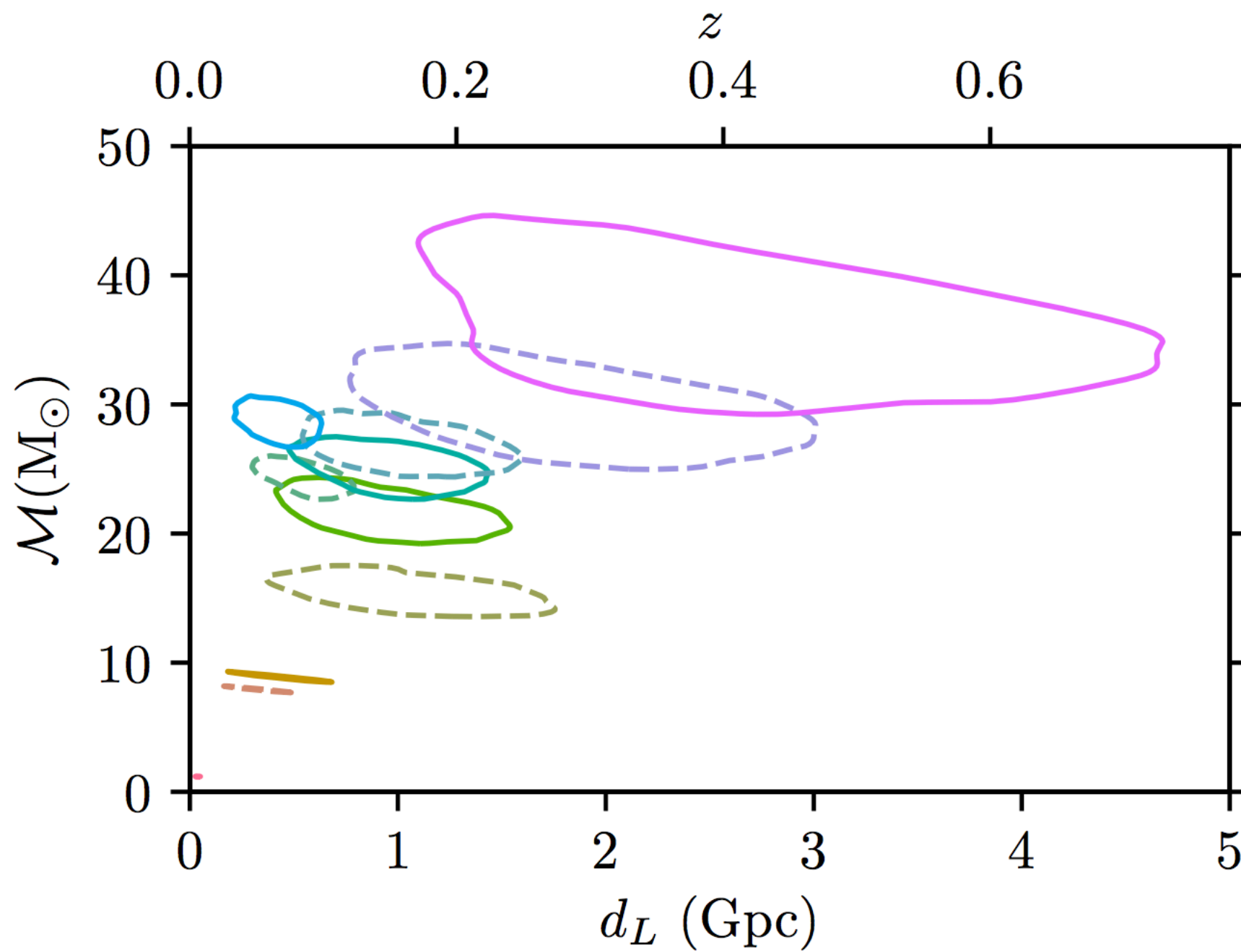
Quadrupolar waves: $\ell=2$, Quasicircular mergers: $|m|=2$



Strongest evidence
for **unequal** masses

GR predicts the presence
of higher modes;
Small evidence for their
(inevitable) presence in the
heaviest BBH GW170729

Distance



LVC (arxiv:1811.12907)

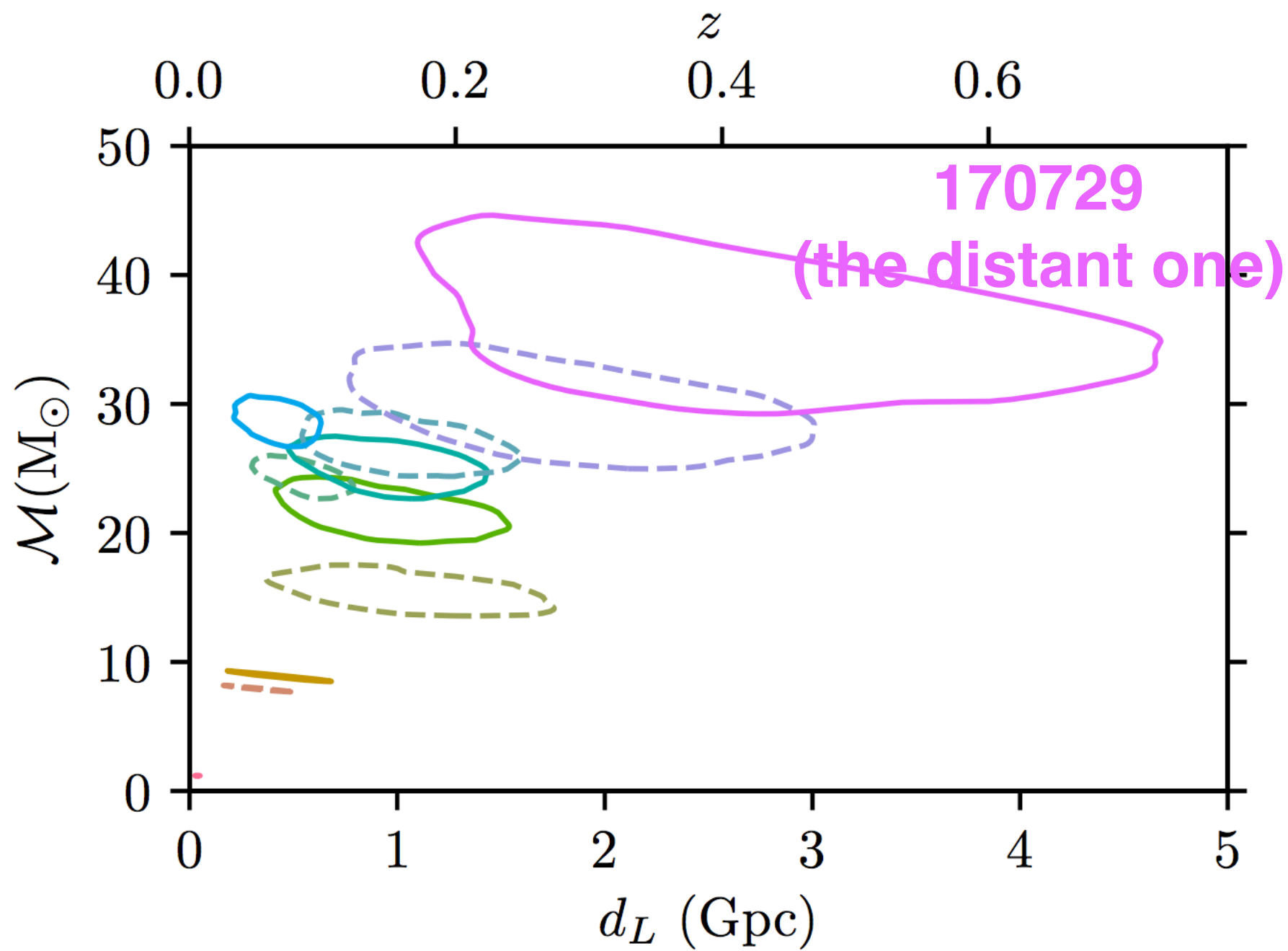
Waveforms:

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

PE: LALInference — Veitch+ (arxiv:1409.7215)

PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Distance



LVC (arxiv:1811.12907)

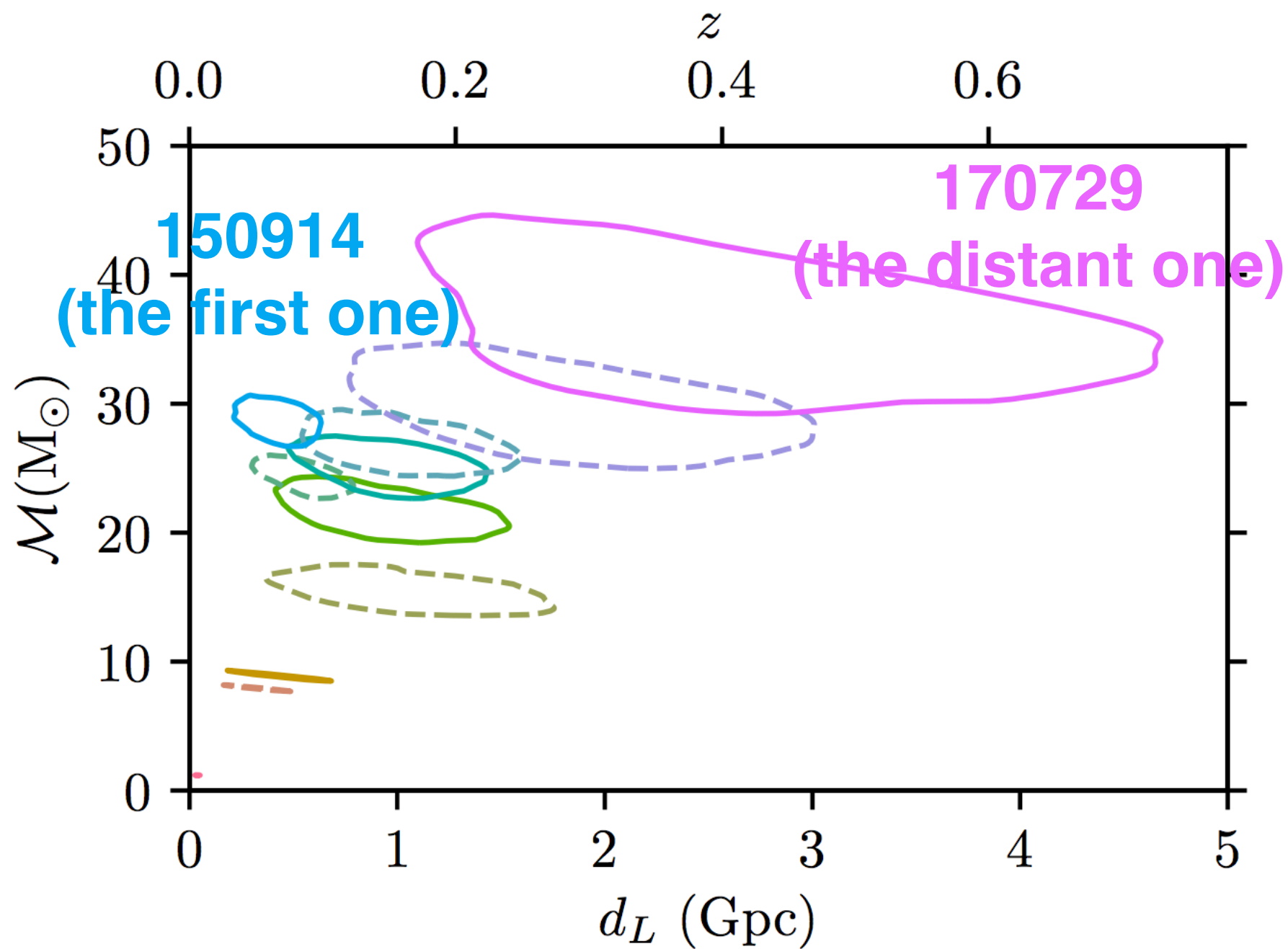
Waveforms:

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

PE: LALInference — Veitch+ (arxiv:1409.7215)

PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Distance



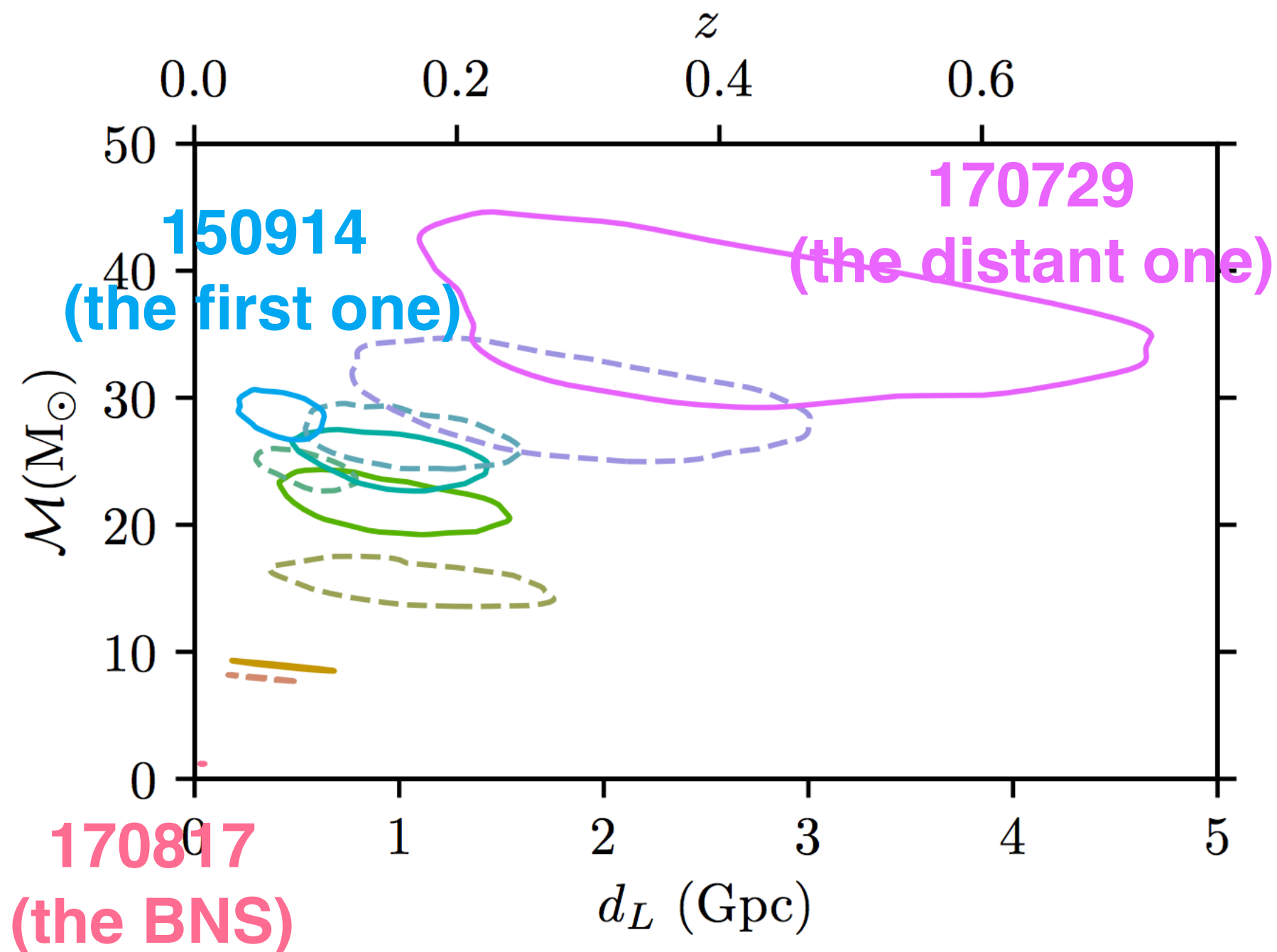
LVC (arxiv:1811.12907)

PE: LALInference — Veitch+ (arxiv:1409.7215)
PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Waveforms:

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

Distance



LVC (arxiv:1811.12907)

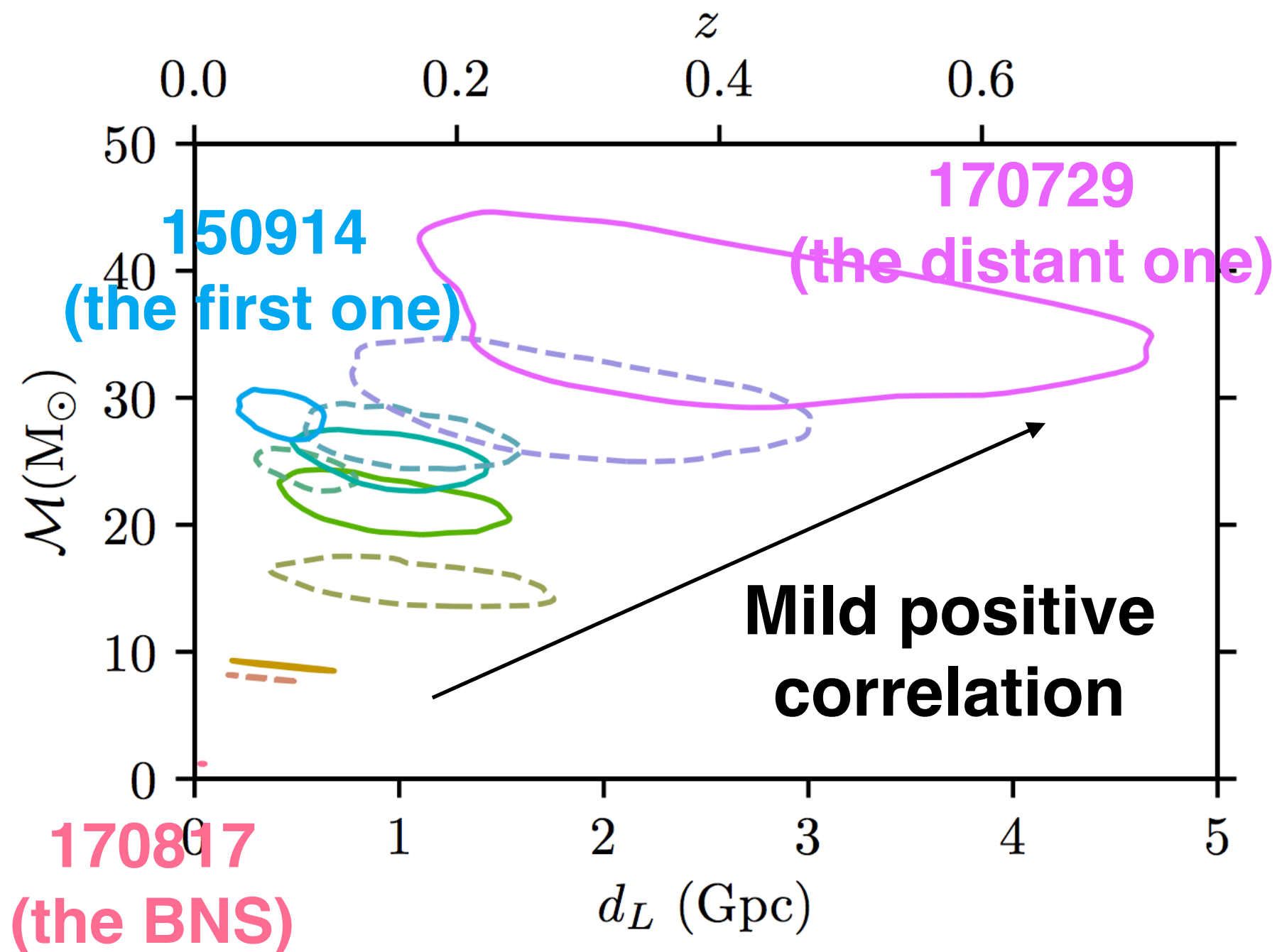
Waveforms:

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

PE: LALInference — Veitch+ (arxiv:1409.7215)

PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Distance



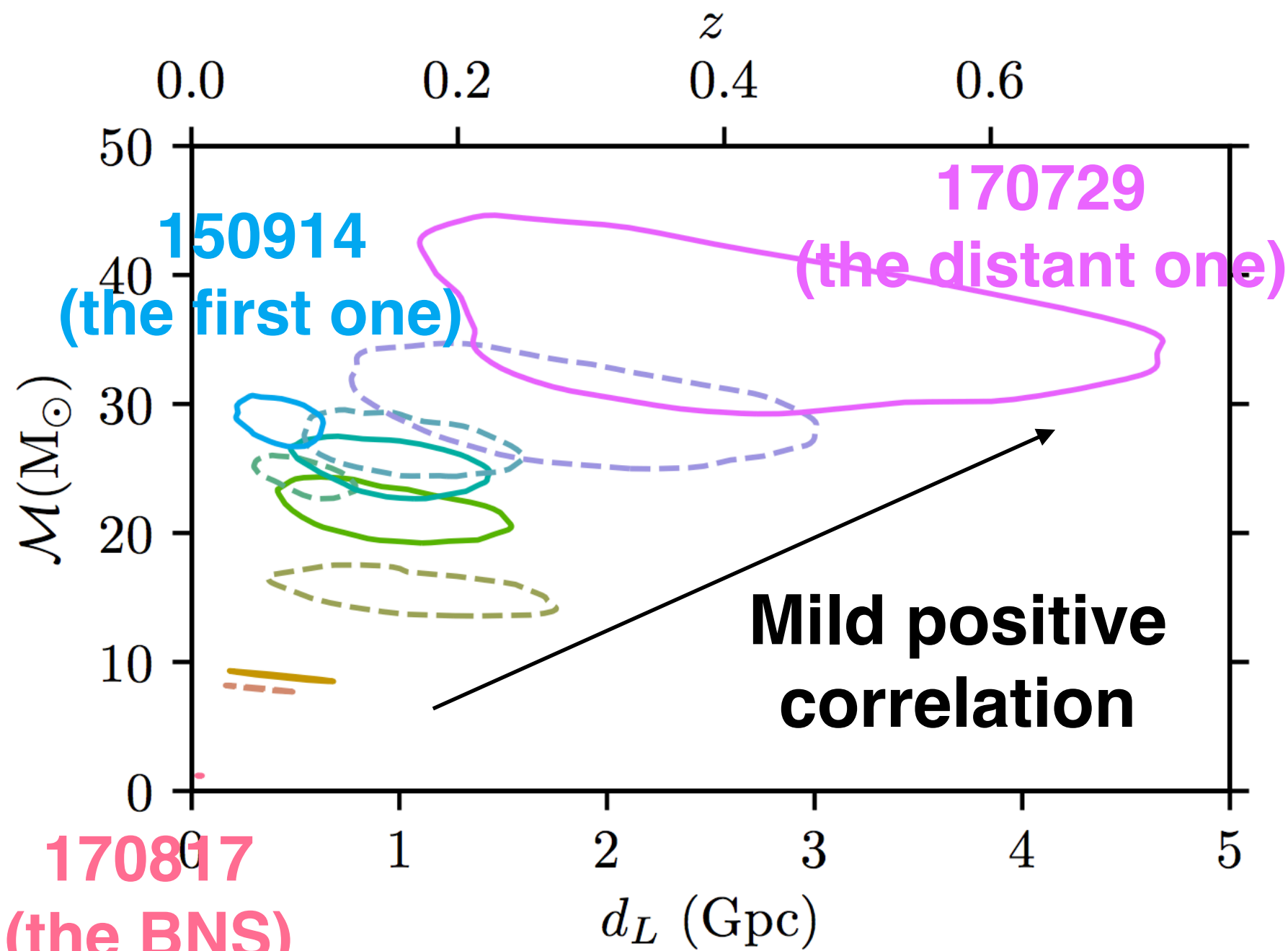
LVC (arxiv:1811.12907)

Waveforms:

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

PE: LALInference — Veitch+ (arxiv:1409.7215)
PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

Distance



No compelling evidence for lensing

Hannuksela+ (arxiv:1901.02674)

LVC (arxiv:1811.12907)

Waveforms:

IMRPhenomPv2 — Hannam+ (arxiv:1308.3271),
SEOBNRv3 — Taracchini+ (arxiv:1311.2544)

PE: LALInference — Veitch+ (arxiv:1409.7215)
PSD: BayesLine — Littenberg+ (arxiv:1410.3852)

The sirens of August

5 detections in August 2017, 6 in the preceding 9 months of O2/O1
Poisson draw: (1,1,1,1,0,0,0,1,1,5)

The sirens of August

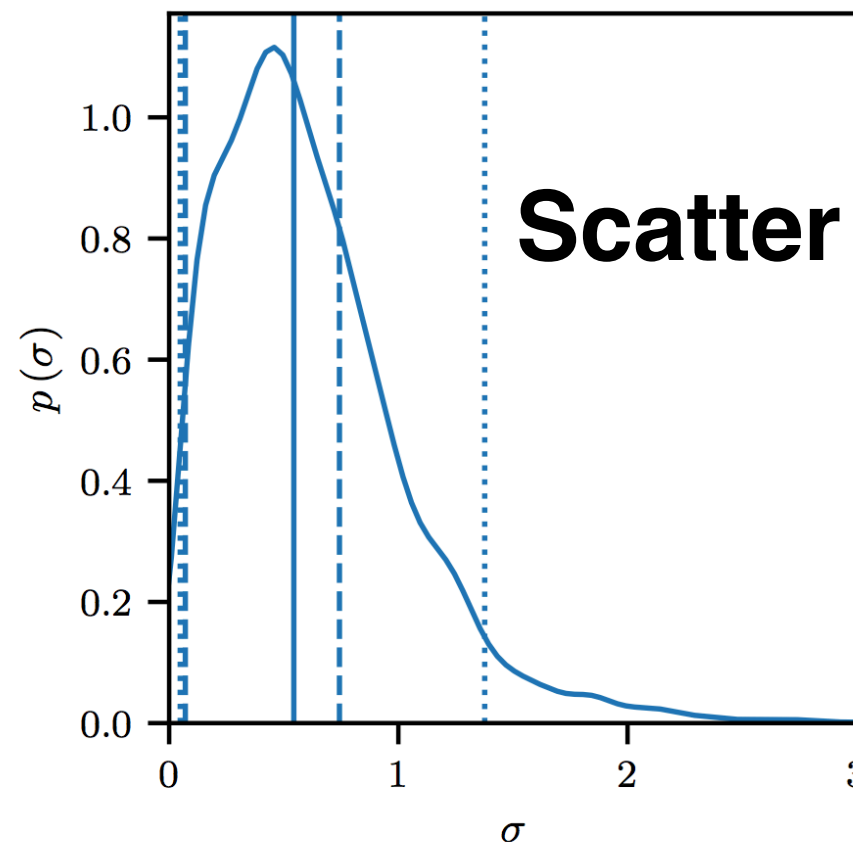
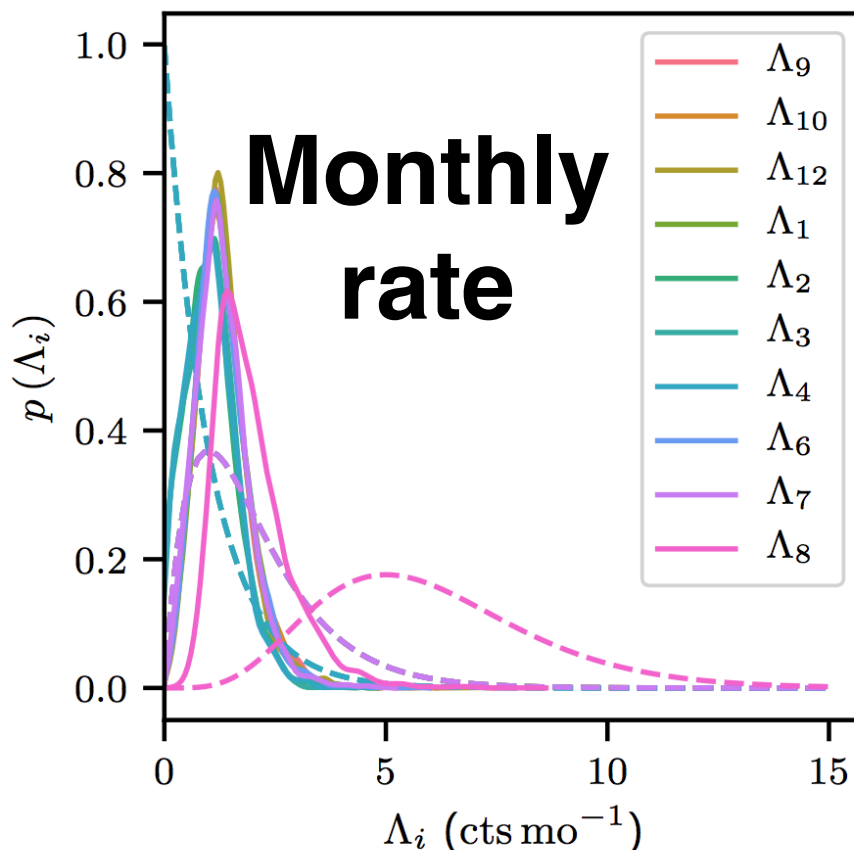
5 detections in August 2017, 6 in the preceding 9 months of O2/O1
Poisson draw: (1,1,1,1,0,0,0,1,1,5)

- Poisson process with a mean of 11(detections)/10(months)
- Probability of 5 or more in one month: 0.54%
- Probability of August 2017 after observing for 10 months: 5.4%

The sirens of August

5 detections in August 2017, 6 in the preceding 9 months of O2/O1
Poisson draw: (1,1,1,1,0,0,0,1,1,5)

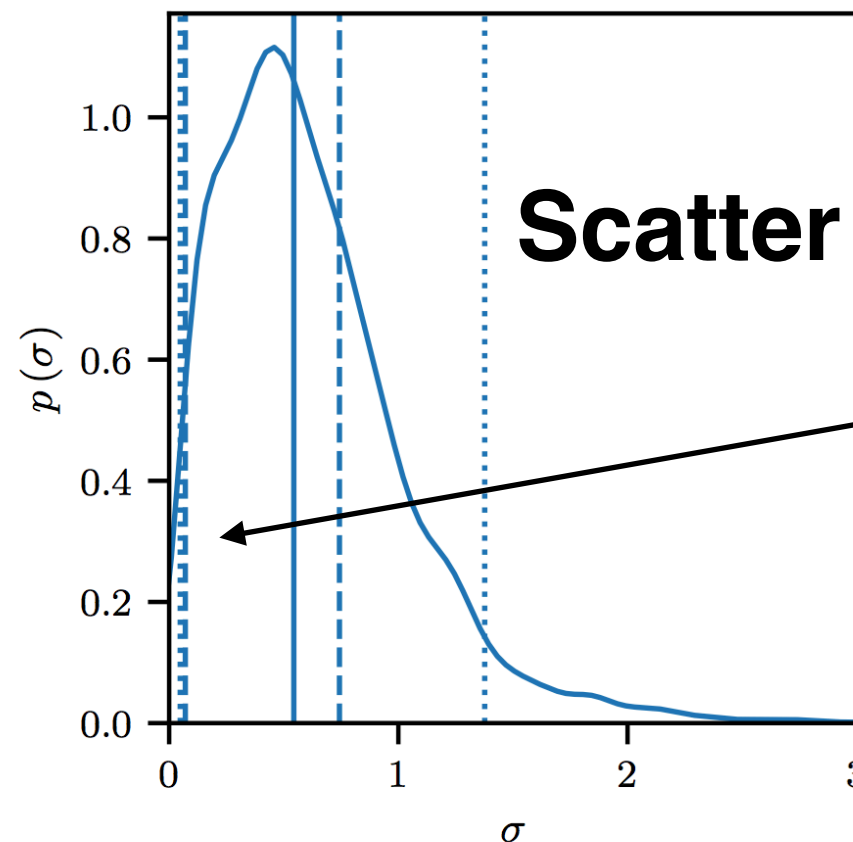
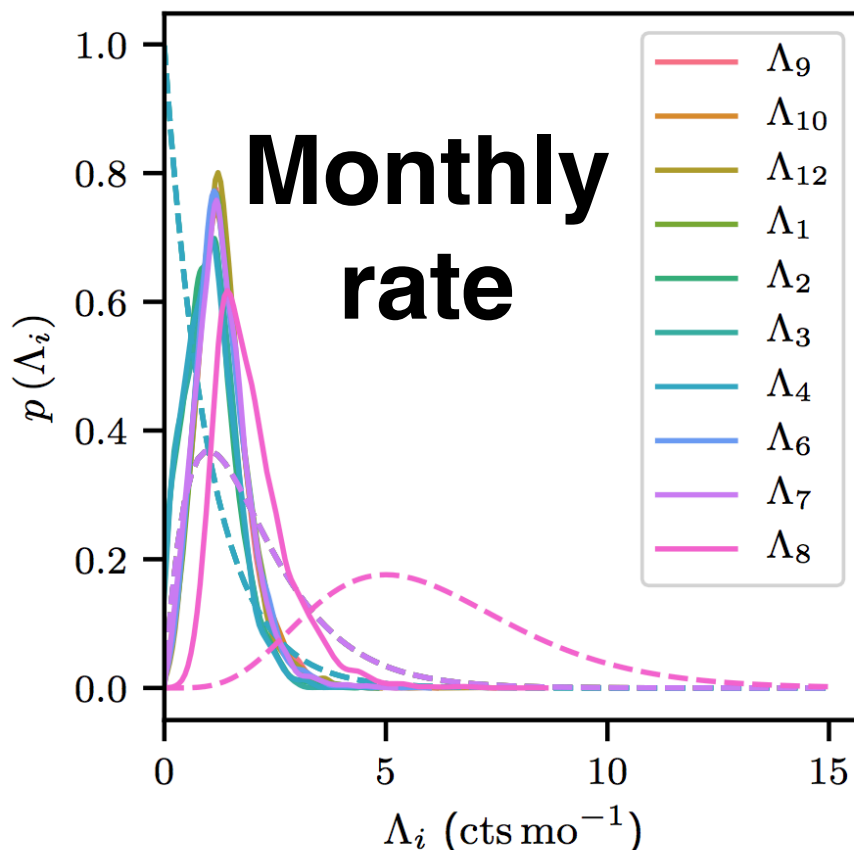
- Poisson process with a mean of 11(detections)/10(months)
- Probability of 5 or more in one month: 0.54%
- Probability of August 2017 after observing for 10 months: 5.4%



The sirens of August

5 detections in **August** 2017, 6 in the preceding 9 months of O2/O1
Poisson draw: (1,1,1,1,0,0,0,1,1,5)

- Poisson process with a mean of 11(detections)/10(months)
- Probability of 5 or more in one month: 0.54%
- Probability of August 2017 after observing for 10 months: 5.4%

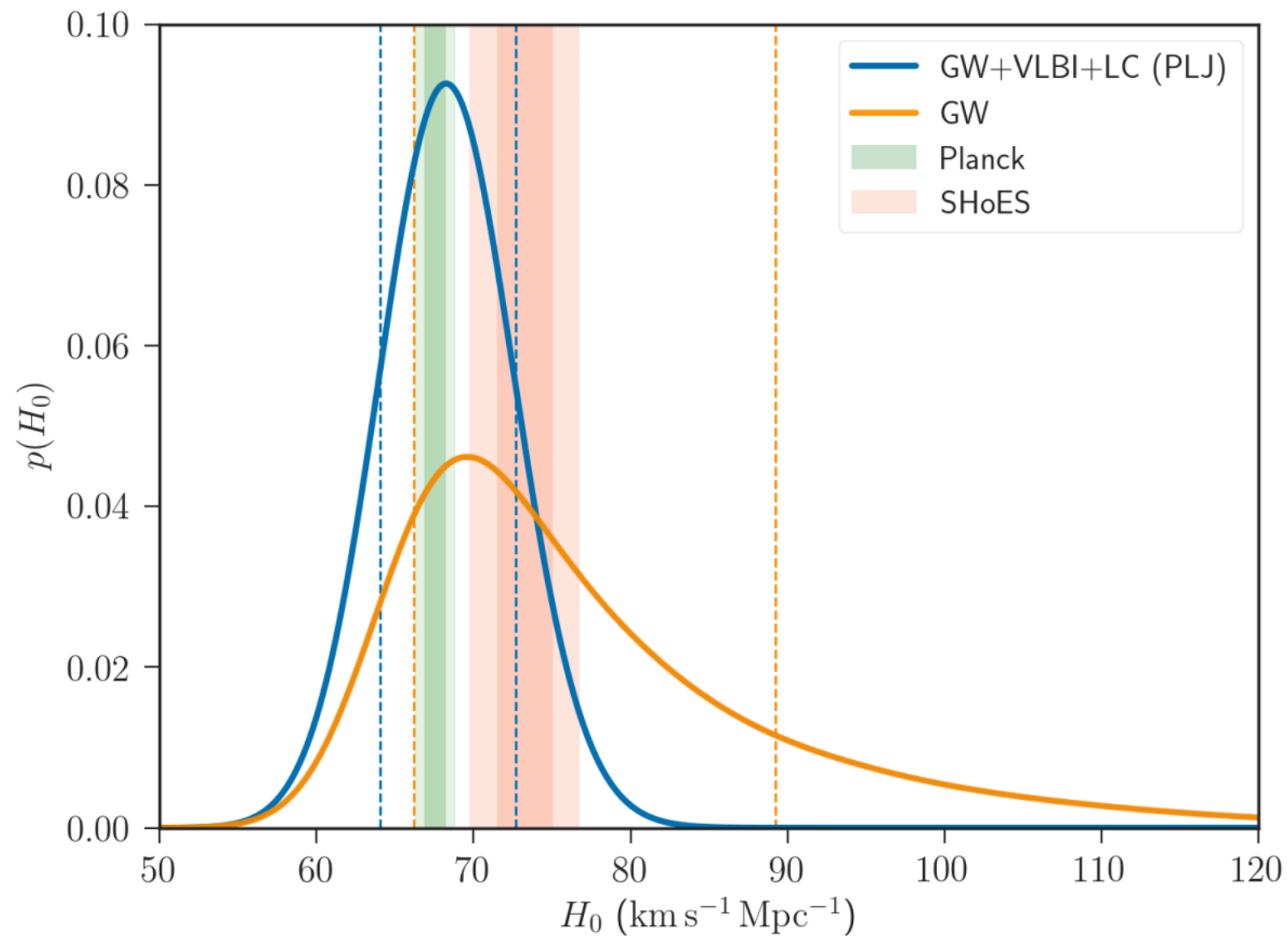


Consistent with
a constant rate
per month

Inclination

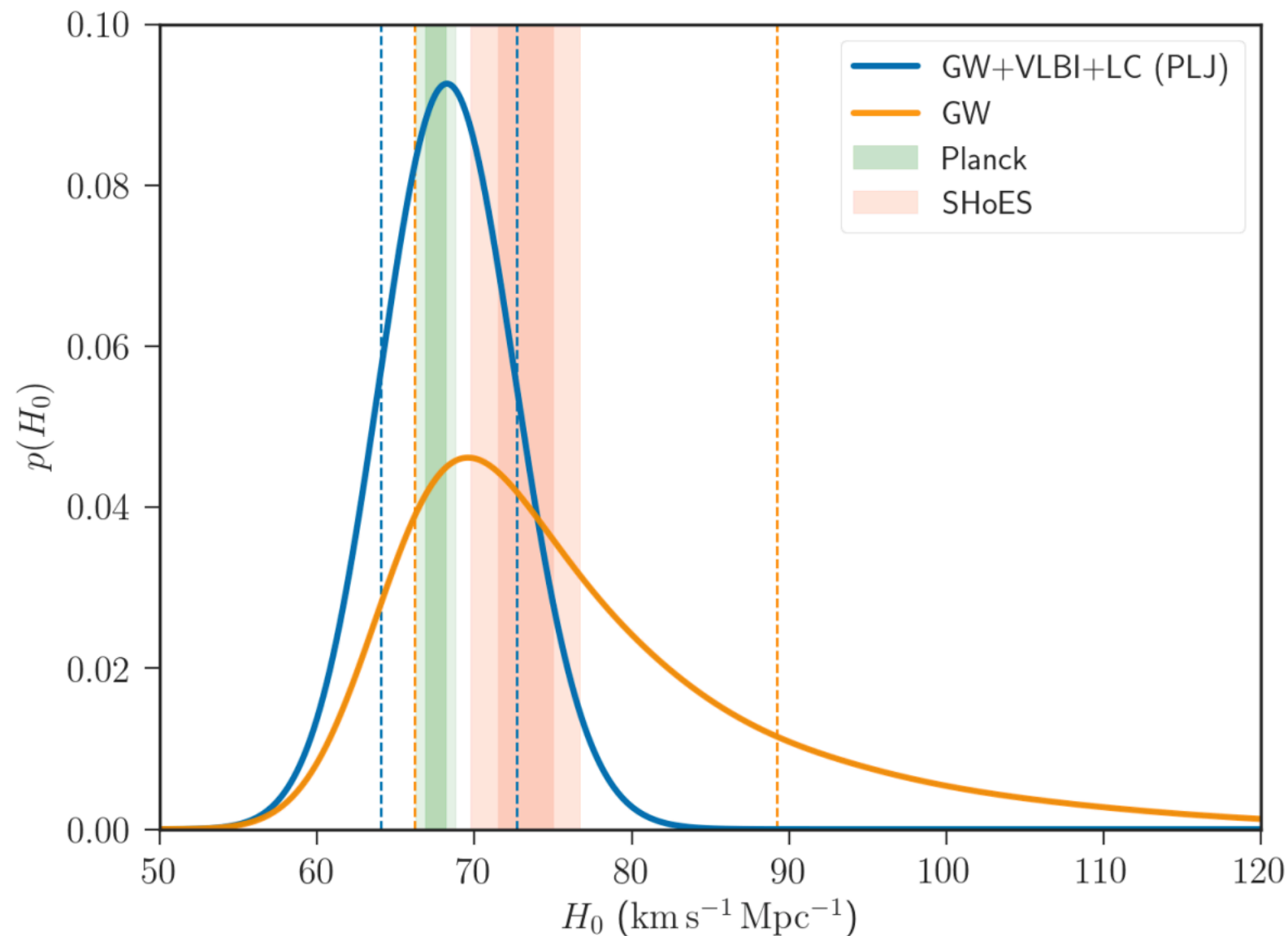
Non GW constraints
to the **inclination**
from counterpart
interpretation
(radio afterglow)

Inclination



Non GW constraints
to the **inclination**
from counterpart
interpretation
(radio afterglow)

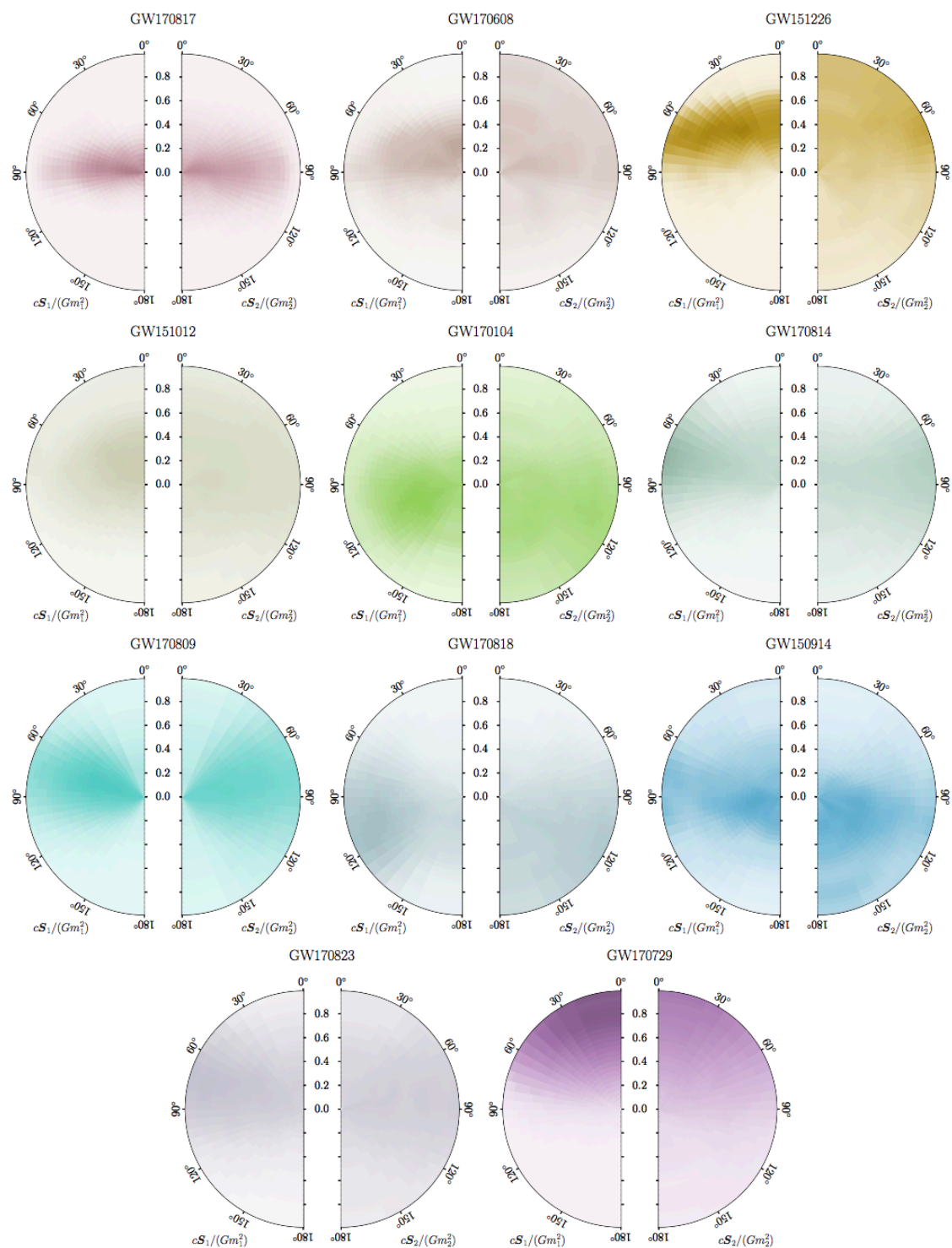
Inclination



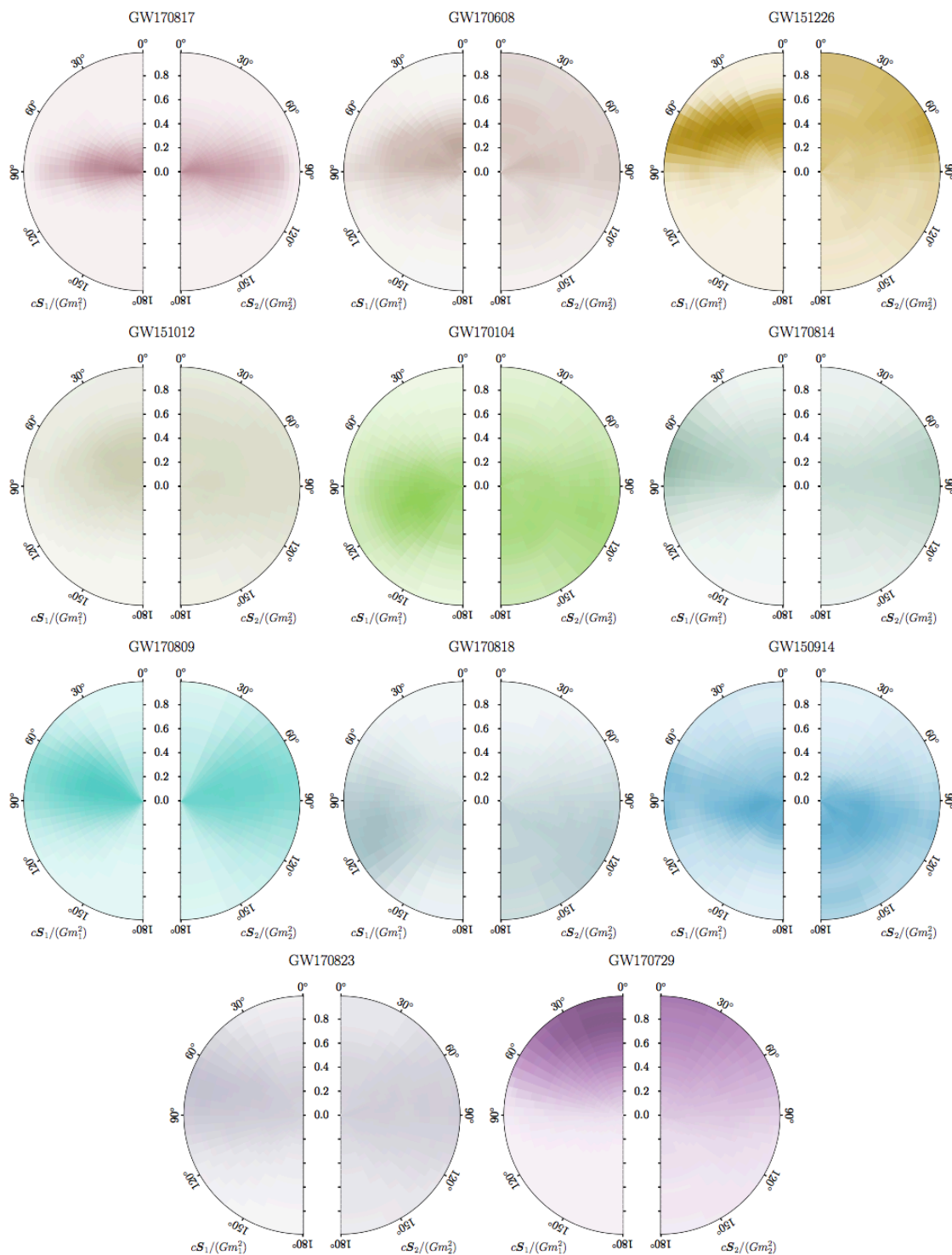
Non GW constraints
to the **inclination**
from counterpart
interpretation
(radio afterglow)

$$H_0 = 68.9^{+4.7}_{-4.6} \text{ km/s/Mpc}$$

Population properties

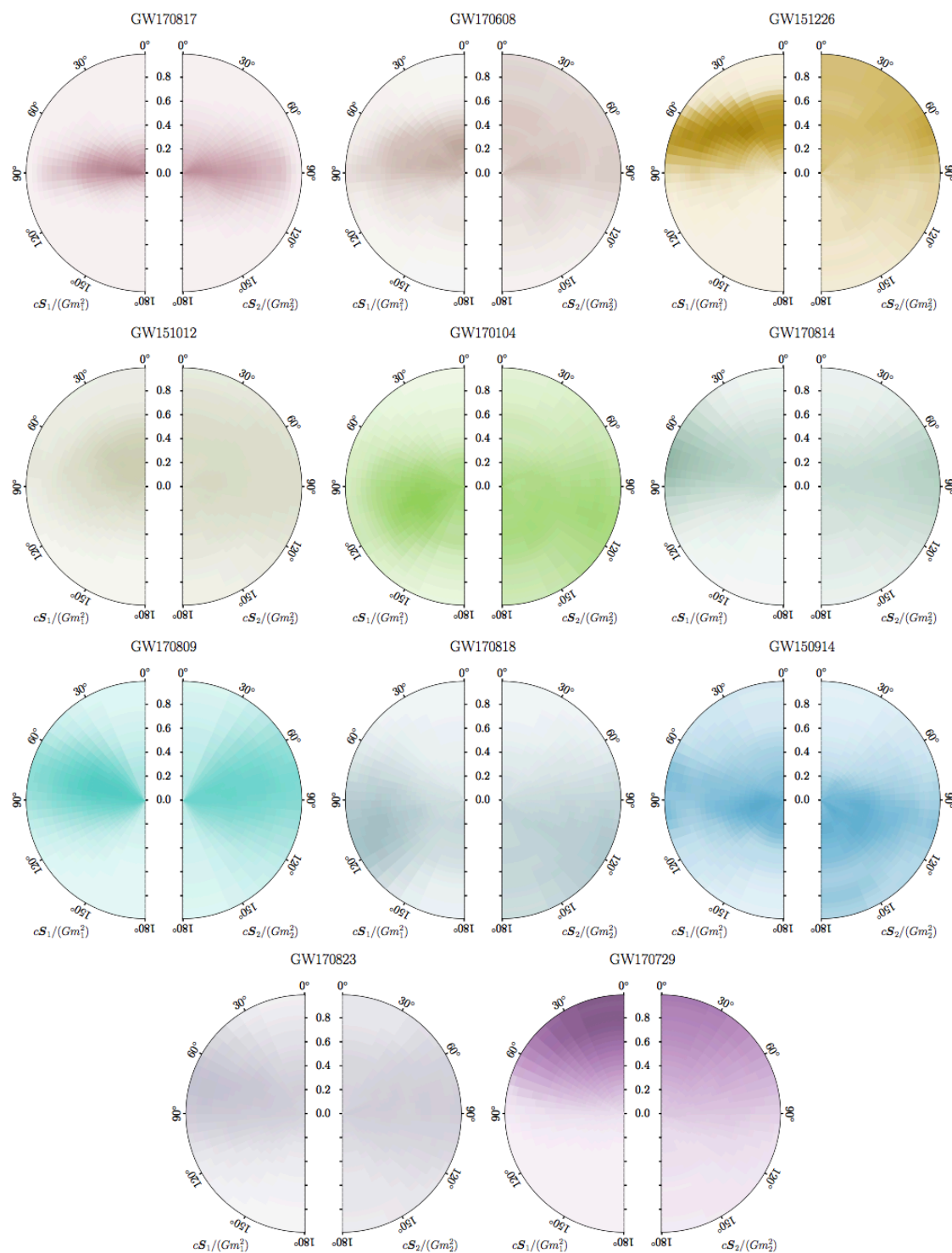


Population properties



- Isolated binaries in the field
- Chemically homogeneous evolution
- Dynamical interactions in clusters
- Galactic nuclei
- Hierarchical triples
- Disks around supermassive black holes
- Primordial
- etc.

Population properties



- Isolated binaries in the field
- Chemically homogeneous evolution
- Dynamical interactions in clusters
- Galactic nuclei
- Hierarchical triples
- Disks around supermassive black holes
- Primordial
- etc.

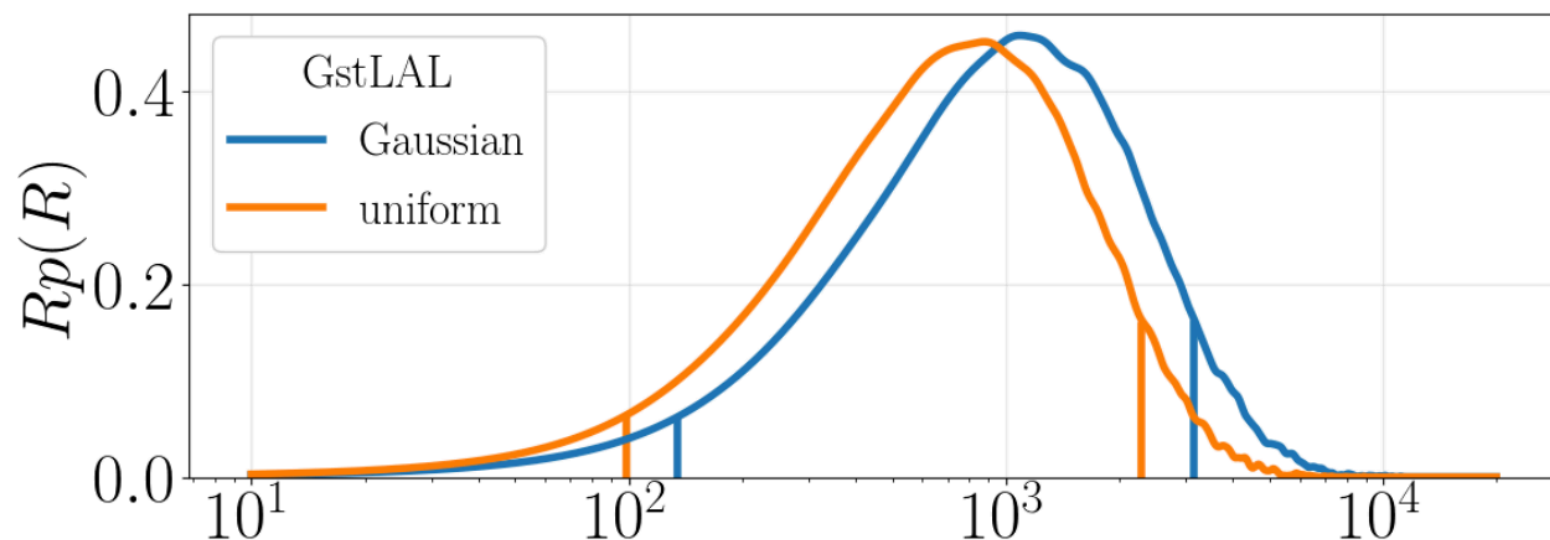
Distinguish between them
through the population
properties of mergers:
rates, **masses**, **spins**

Rates for neutron stars

170817 is a population of one

Rates for neutron stars

170817 is a population of one



$$110 - 3840 \text{ Gpc}^{-3} \text{ y}^{-1}$$

With more BNSs
we can start inferring
the mass model too,
now consistent with
galactic binaries

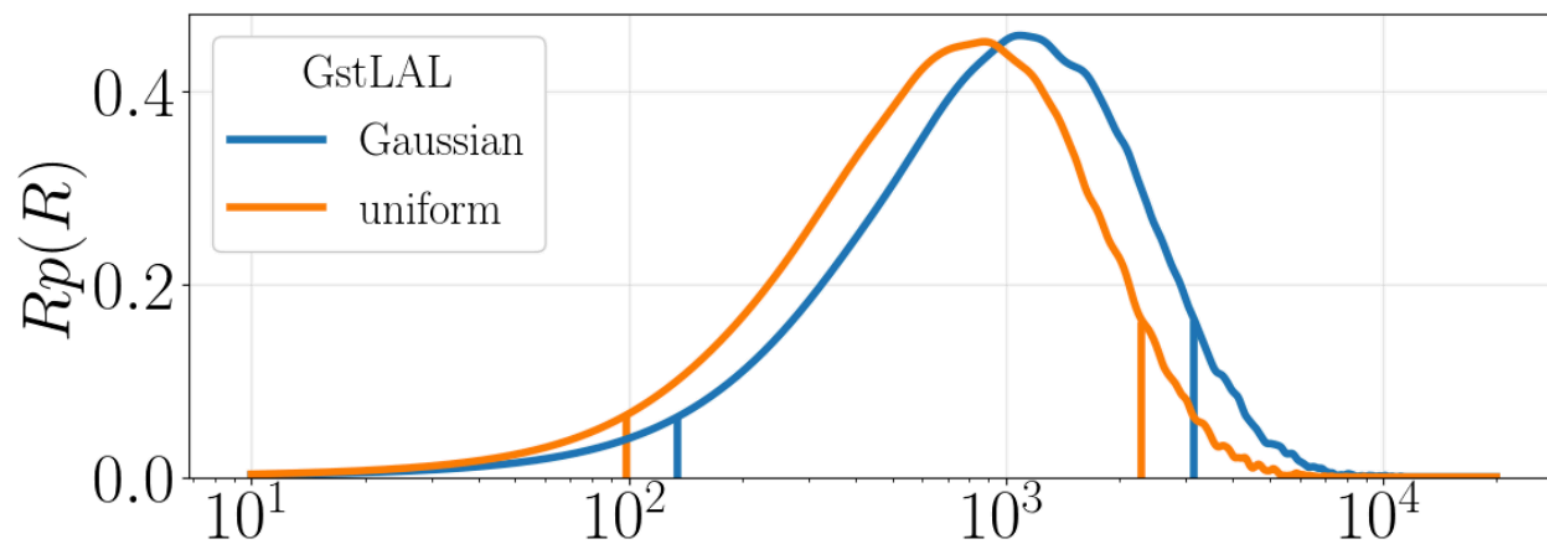
LVC (arxiv:1811.12907)

Multicomponent population:

Farr+ (arXiv:1302.5341),
Kapadia+ (arxiv:1903.06881)

Rates for neutron stars

170817 is a population of one



$$110 - 3840 \text{ Gpc}^{-3} \text{ y}^{-1}$$

With more BNSs
we can start inferring
the mass model too,
now consistent with
galactic binaries

$$610 \text{ Gpc}^{-3} \text{ y}^{-1}$$

With no NSBHs, we only have upper limits

LVC (arxiv:1811.12907)

Multicomponent population:

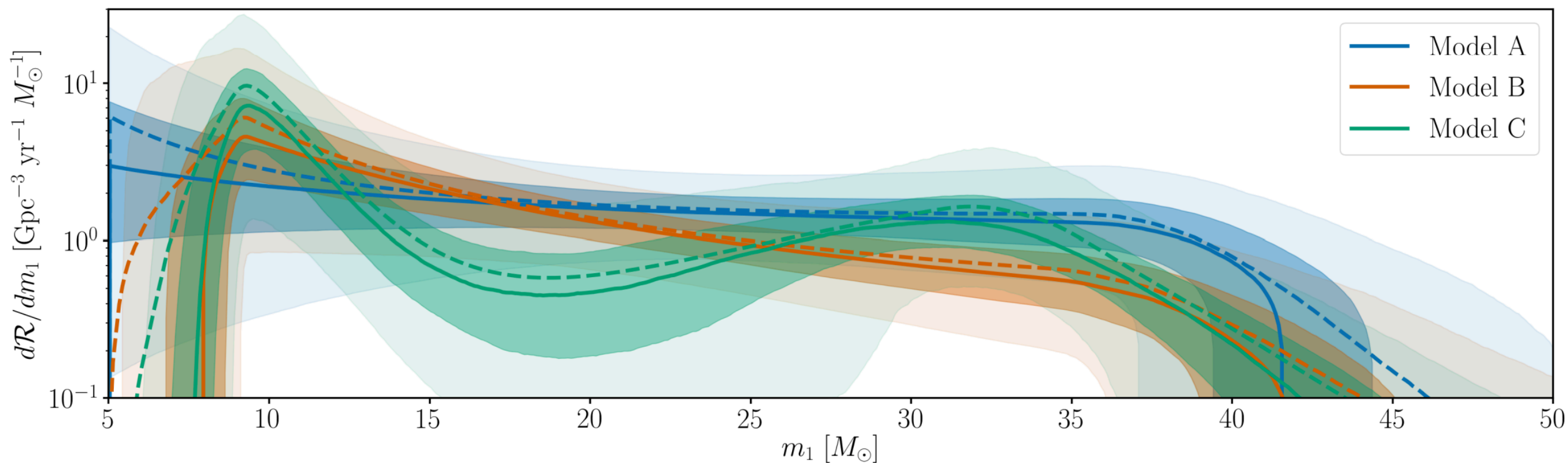
Farr+ (arXiv:1302.5341),
Kapadia+ (arxiv:1903.06881)

Mass distribution

Model A: power law for the primary mass and a maximum mass cut off

Model B: power law for both masses and maximum/minimum mass cut off

Model C: mixture of power law and a high-mass gaussian



Model A: Fishbach+ (arxiv:1709.08584)

Model B: Kovetz+ (arxiv:1611.01157)

Model C: Talbot+ (arxiv:1801.02699)

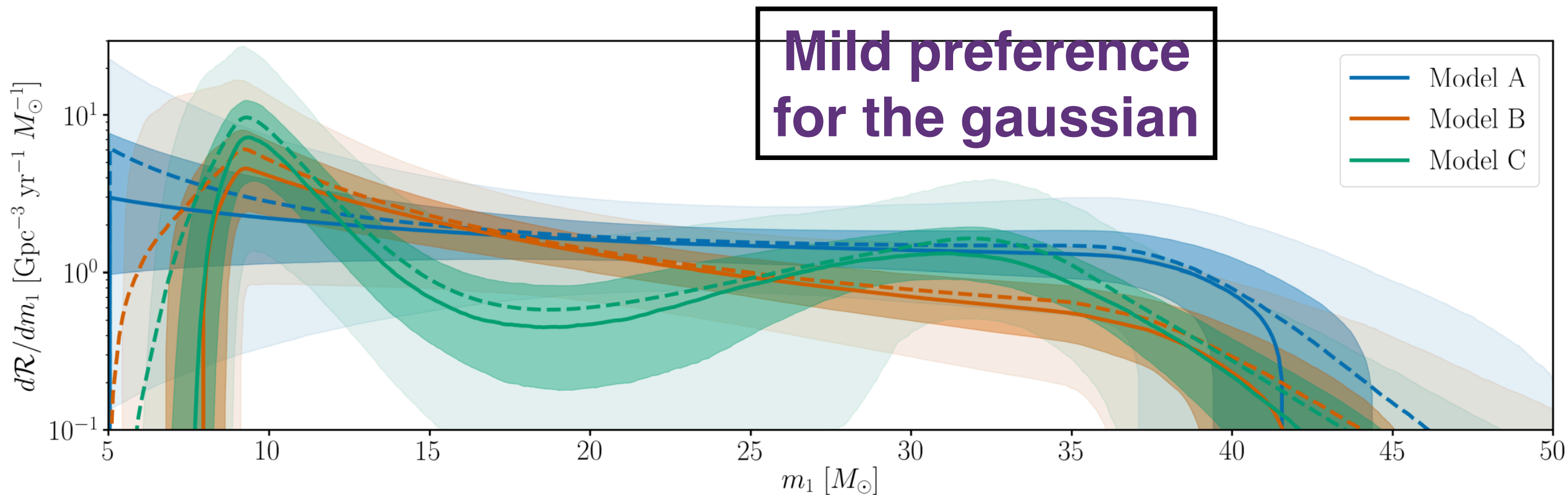
LVC (arxiv:1811.12940)

Mass distribution

Model A: power law for the primary mass and a maximum mass cut off

Model B: power law for both masses and maximum/minimum mass cut off

Model C: mixture of power law and a high-mass gaussian



Model A: Fishbach+ (arxiv:1709.08584)

Model B: Kovetz+ (arxiv:1611.01157)

Model C: Talbot+ (arxiv:1801.02699)

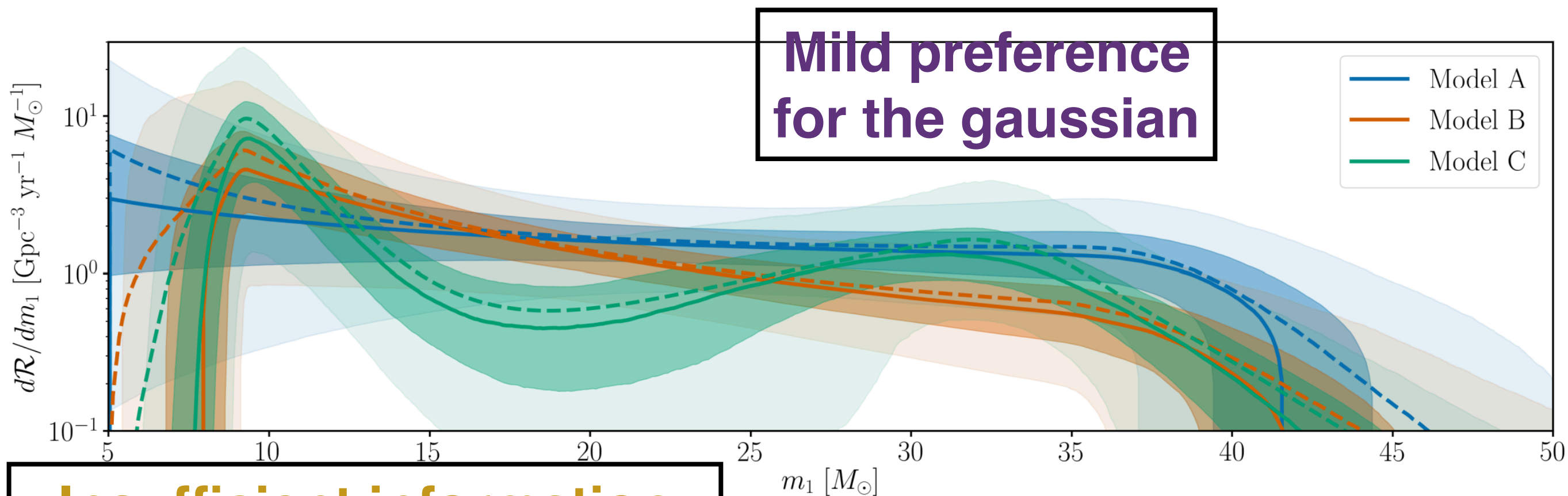
LVC (arxiv:1811.12940)

Mass distribution

Model A: power law for the primary mass and a maximum mass cut off

Model B: power law for both masses and maximum/minimum mass cut off

Model C: mixture of power law and a high-mass gaussian



**Insufficient information
about the lower mass gap
(drop in sensitivity)**

Model A: Fishbach+ (arxiv:1709.08584)

Model B: Kovetz+ (arxiv:1611.01157)

Model C: Talbot+ (arxiv:1801.02699)

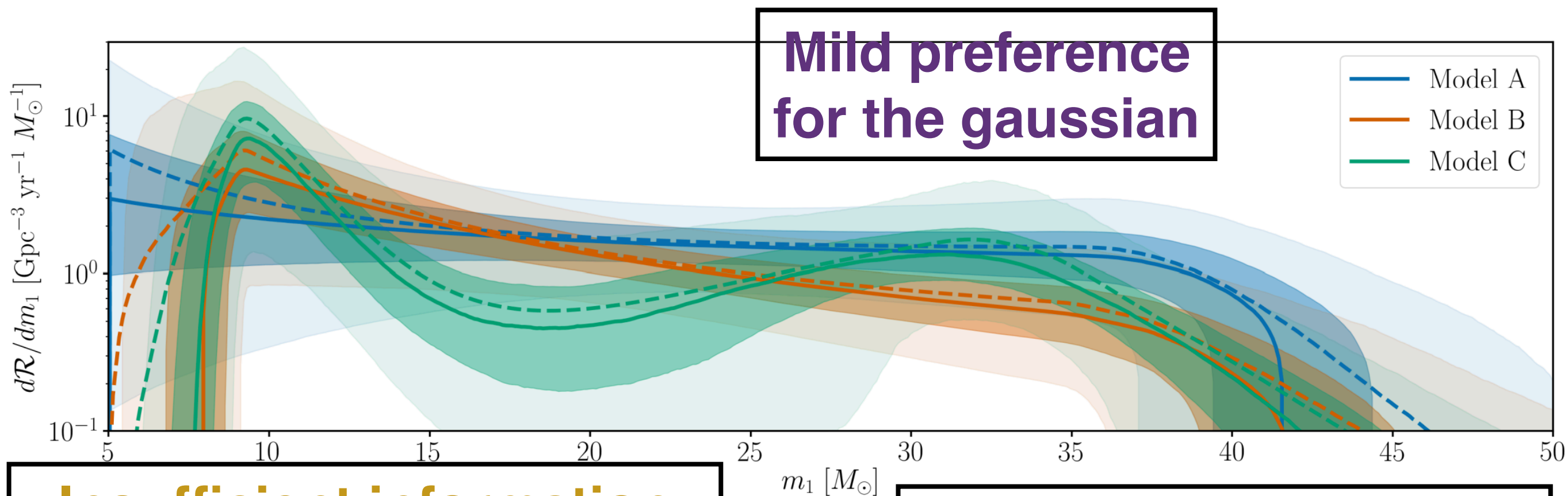
LVC (arxiv:1811.12940)

Mass distribution

Model A: power law for the primary mass and a maximum mass cut off

Model B: power law for both masses and maximum/minimum mass cut off

Model C: mixture of power law and a high-mass gaussian



Model A: Fishbach+ (arxiv:1709.08584)

Model B: Kovetz+ (arxiv:1611.01157)

Model C: Talbot+ (arxiv:1801.02699)

LVC (arxiv:1811.12940)

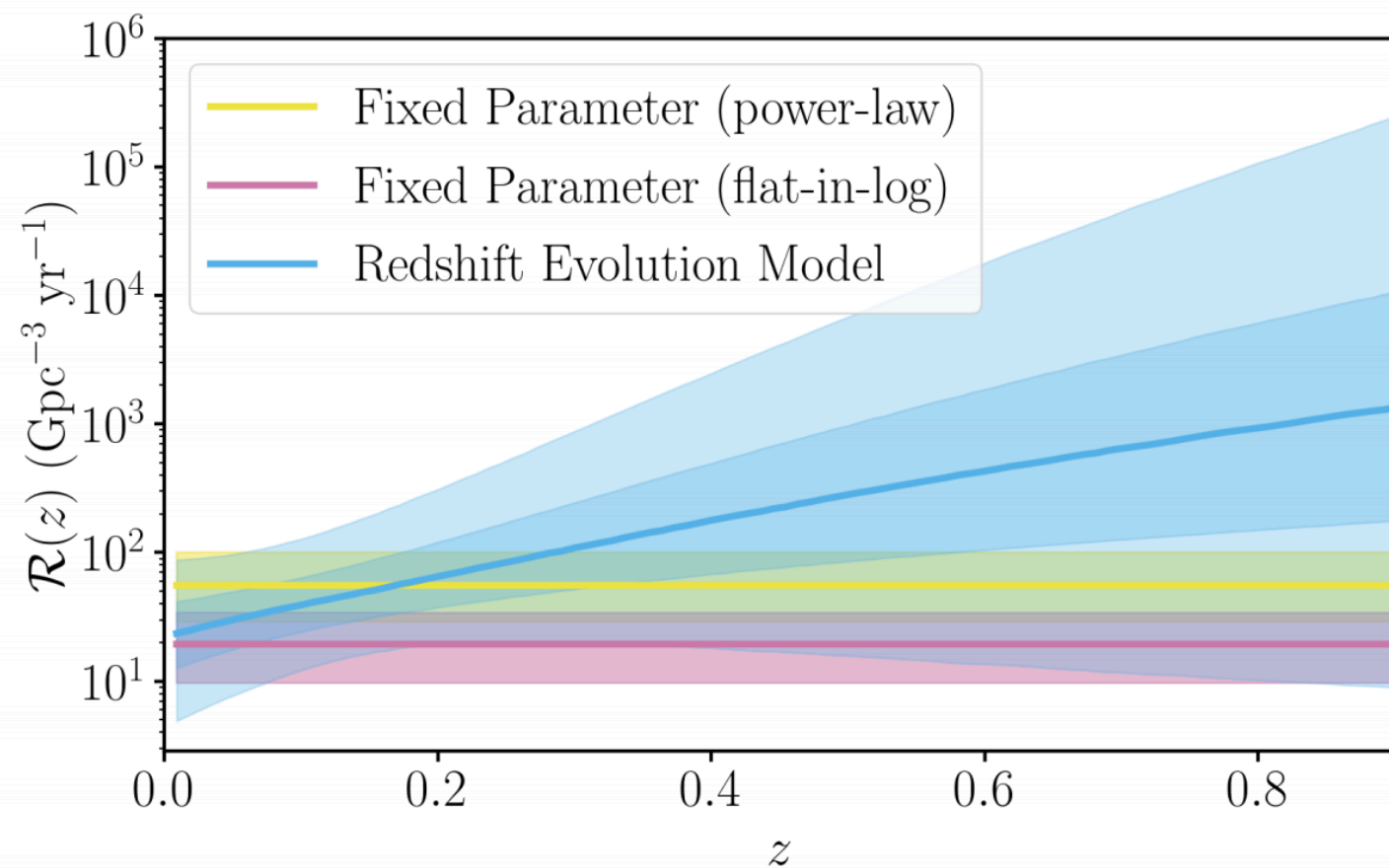
Rates for black hole binaries

$$R = 53.2^{+58.5}_{-28.8} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

Rates for black hole binaries

$$R = 53.2^{+58.5}_{-28.8} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

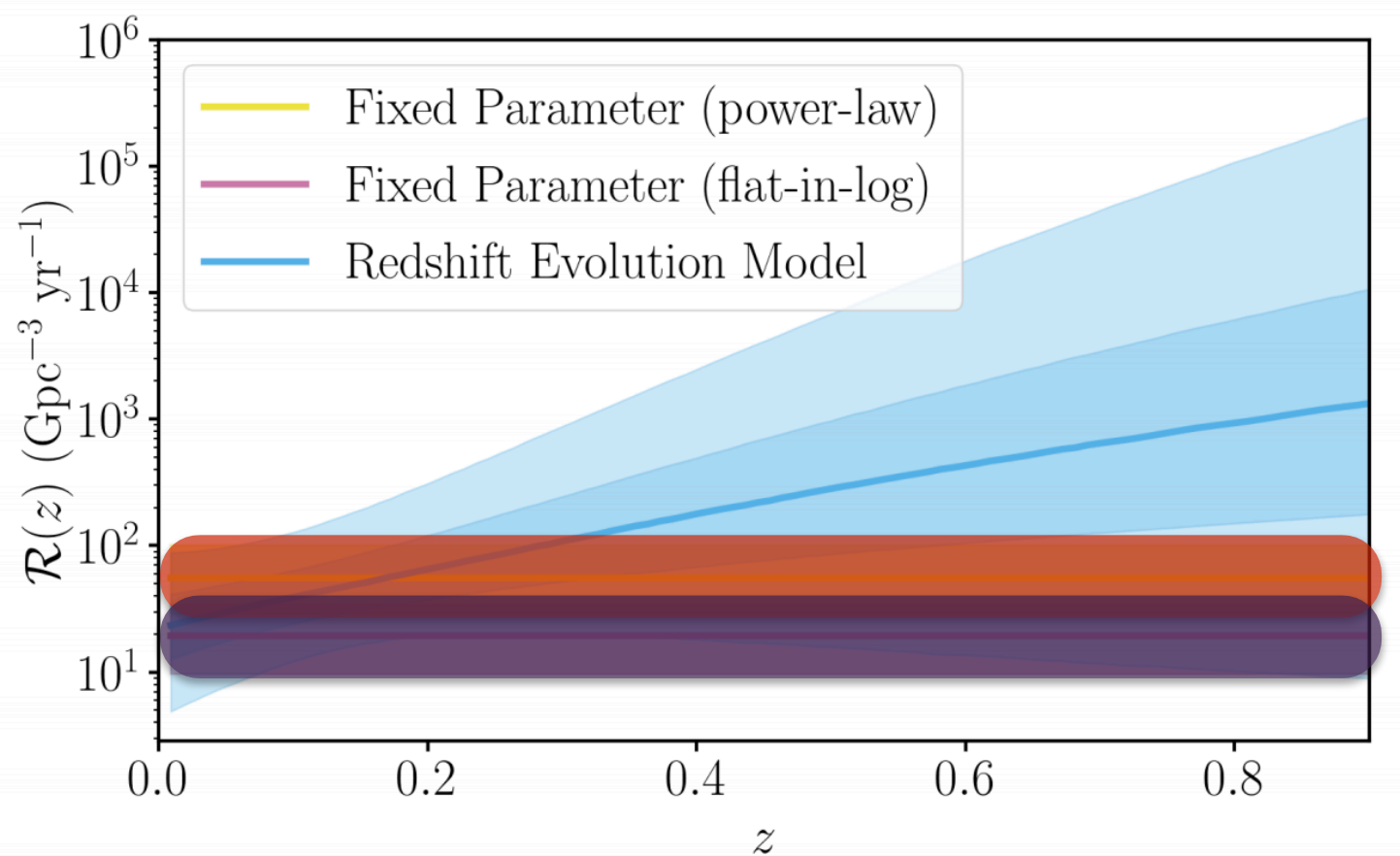
Depends on mass distribution



Rates for black hole binaries

$$R = 53.2^{+58.5}_{-28.8} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

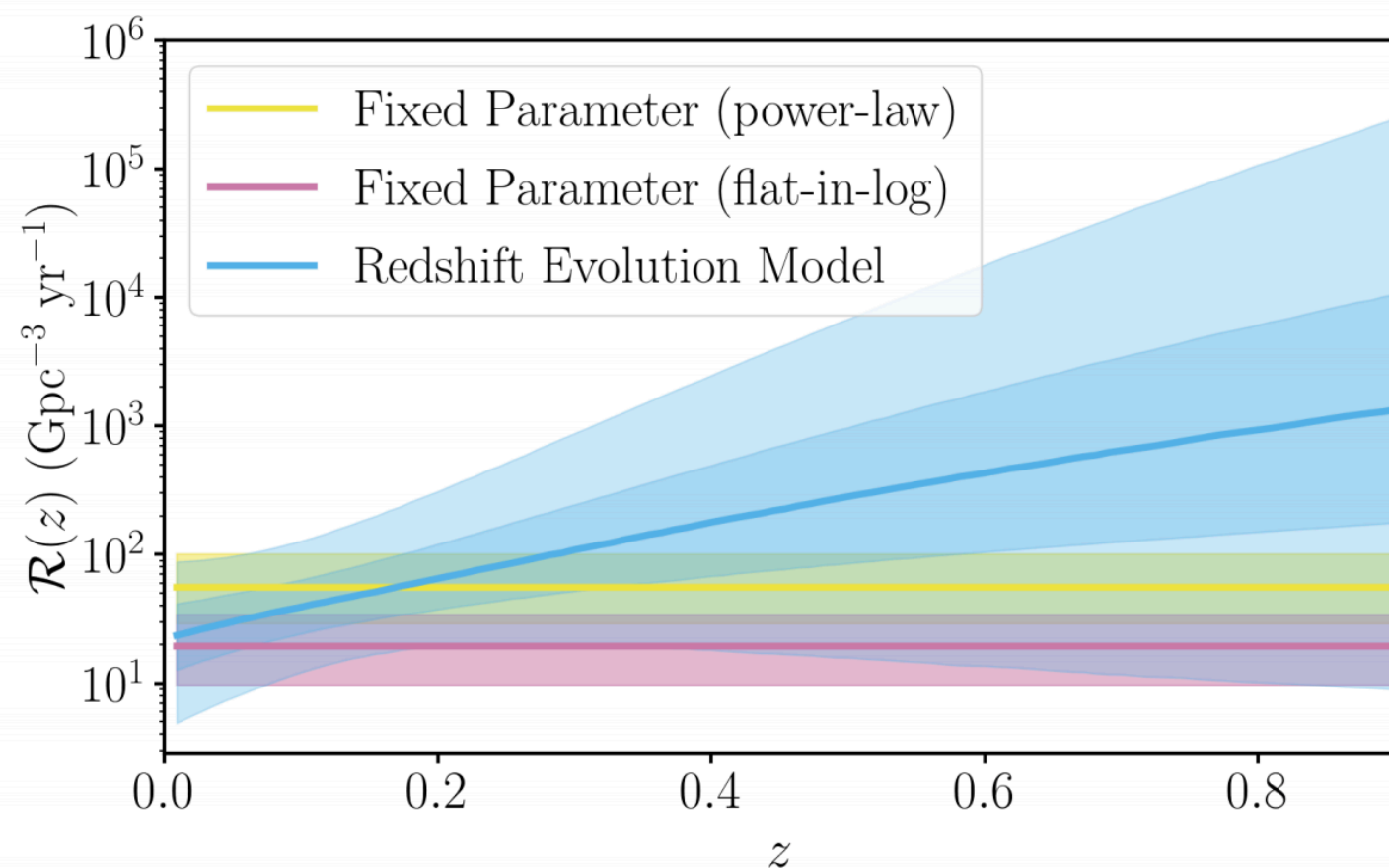
Depends on mass distribution



Rates for black hole binaries

$$R = 53.2^{+58.5}_{-28.8} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

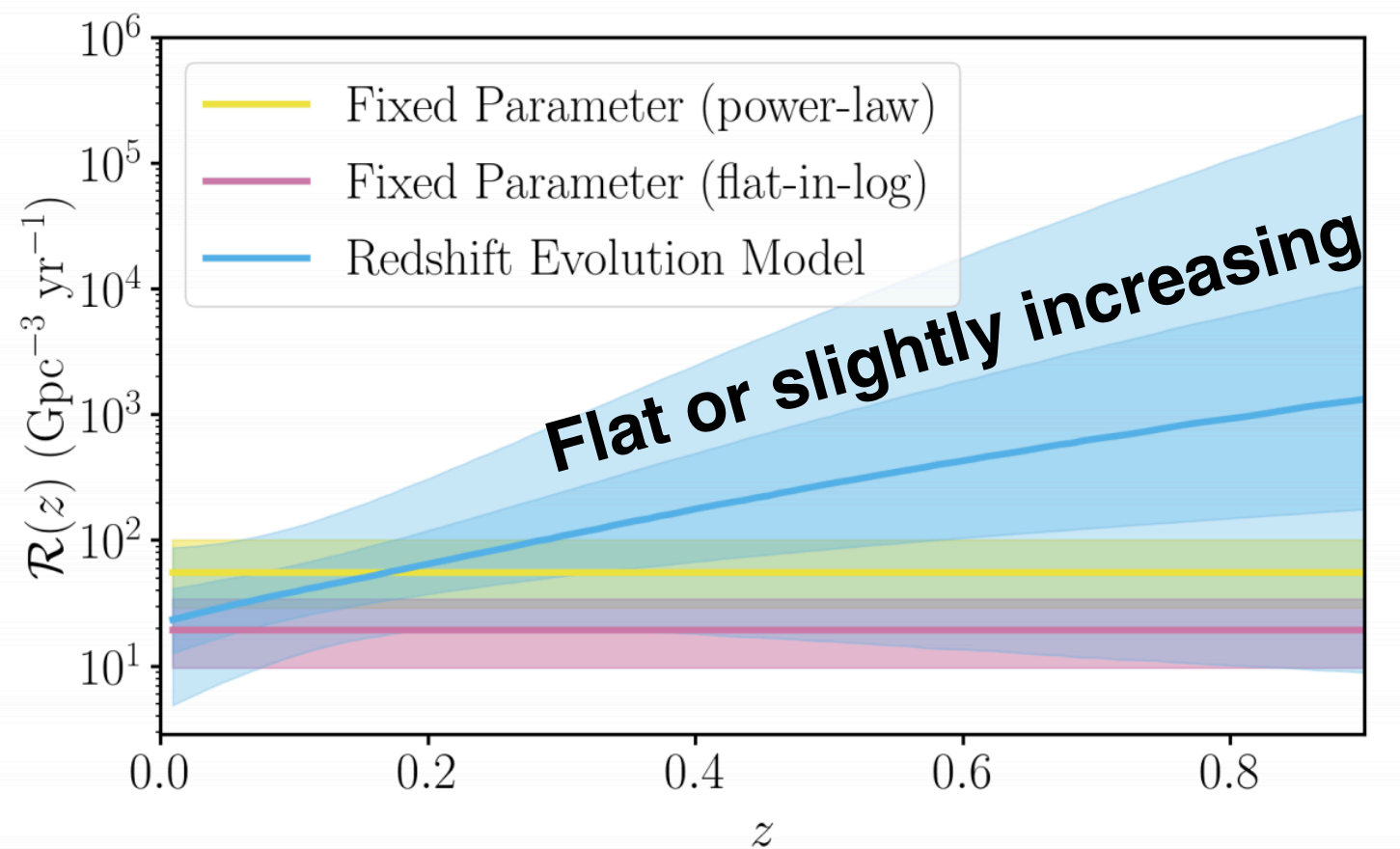
Depends on mass distribution



Rates for black hole binaries

$$R = 53.2^{+58.5}_{-28.8} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

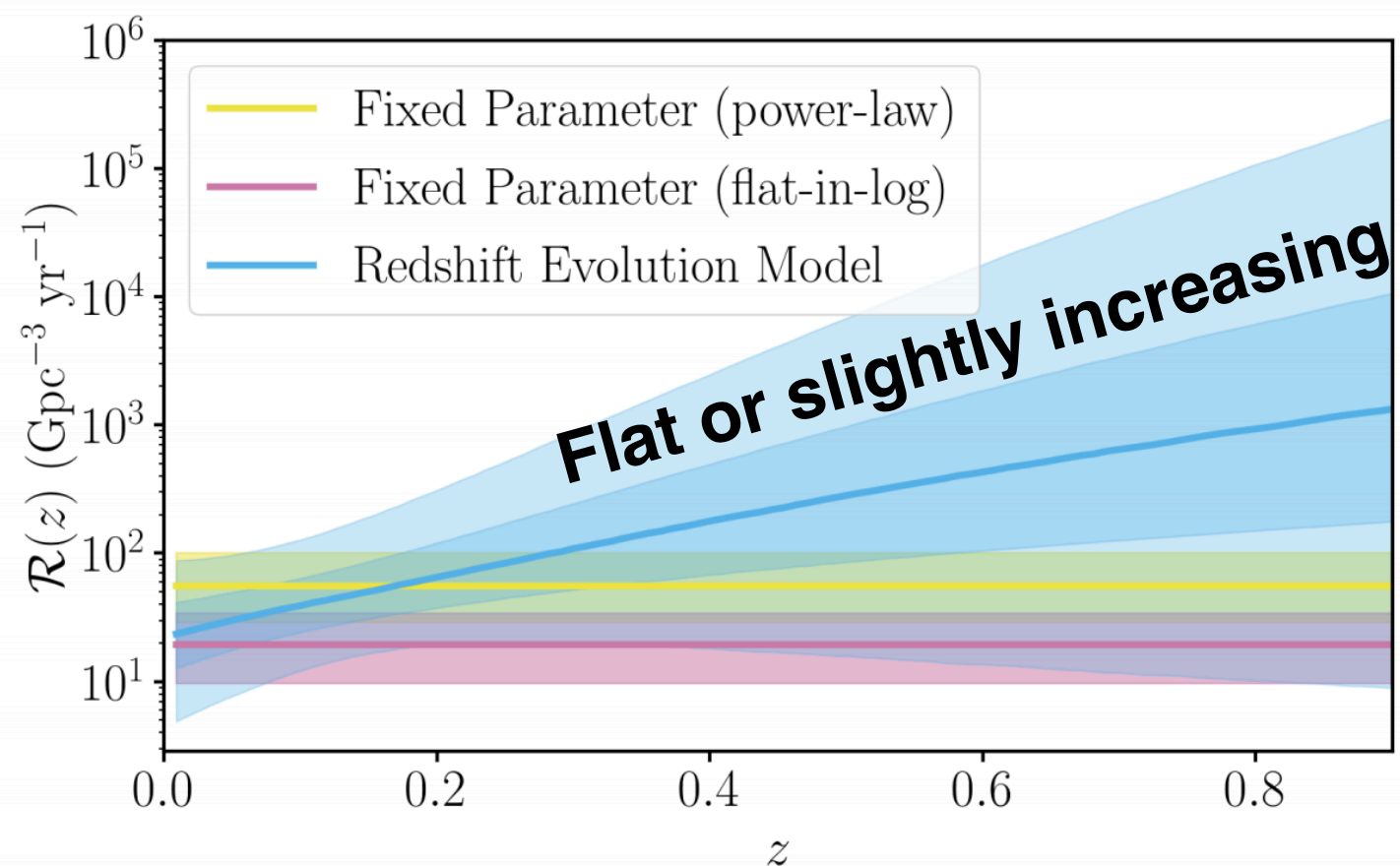
Depends on mass distribution



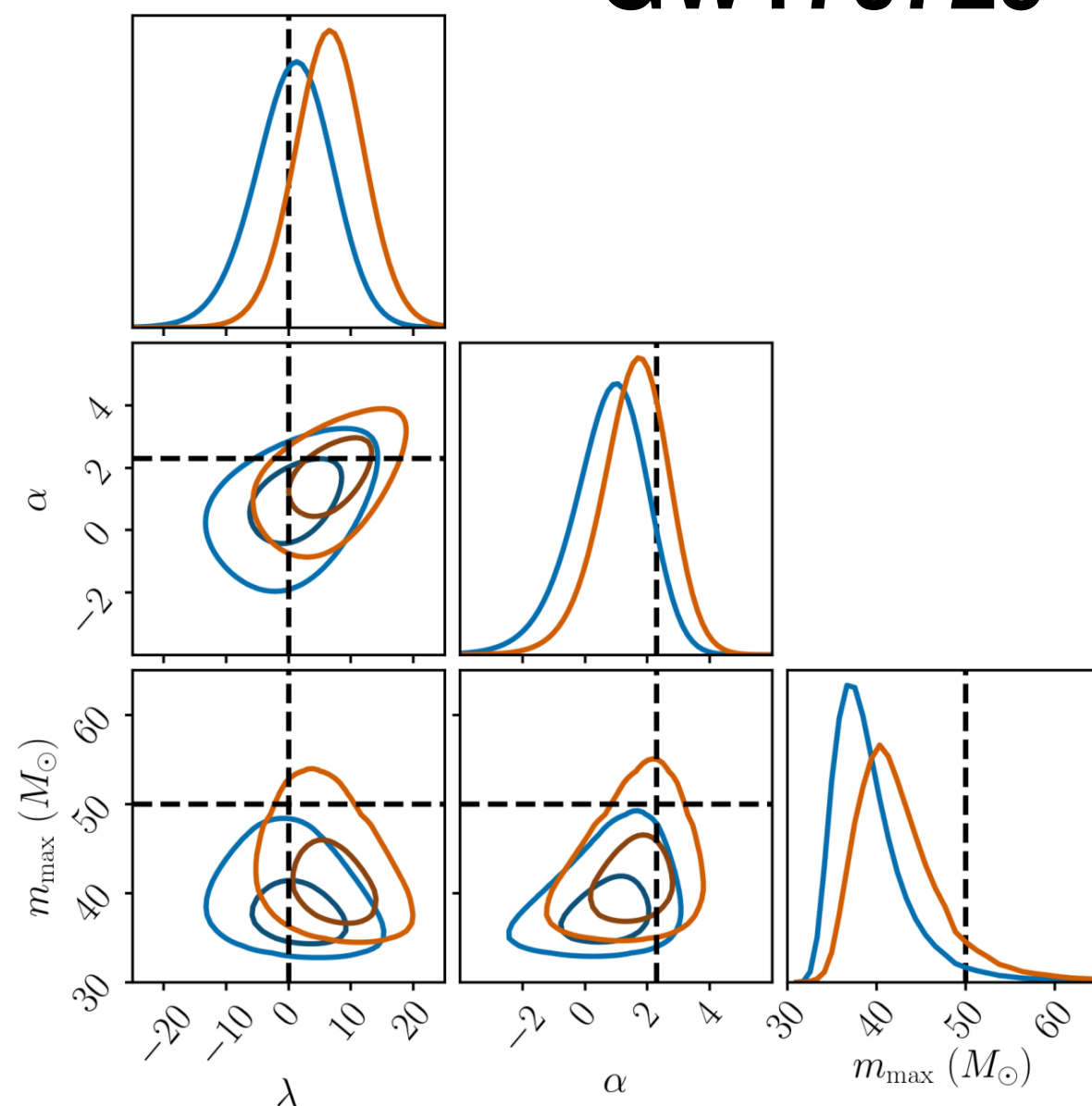
Rates for black hole binaries

$$R = 53.2^{+58.5}_{-28.8} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

Depends on mass distribution



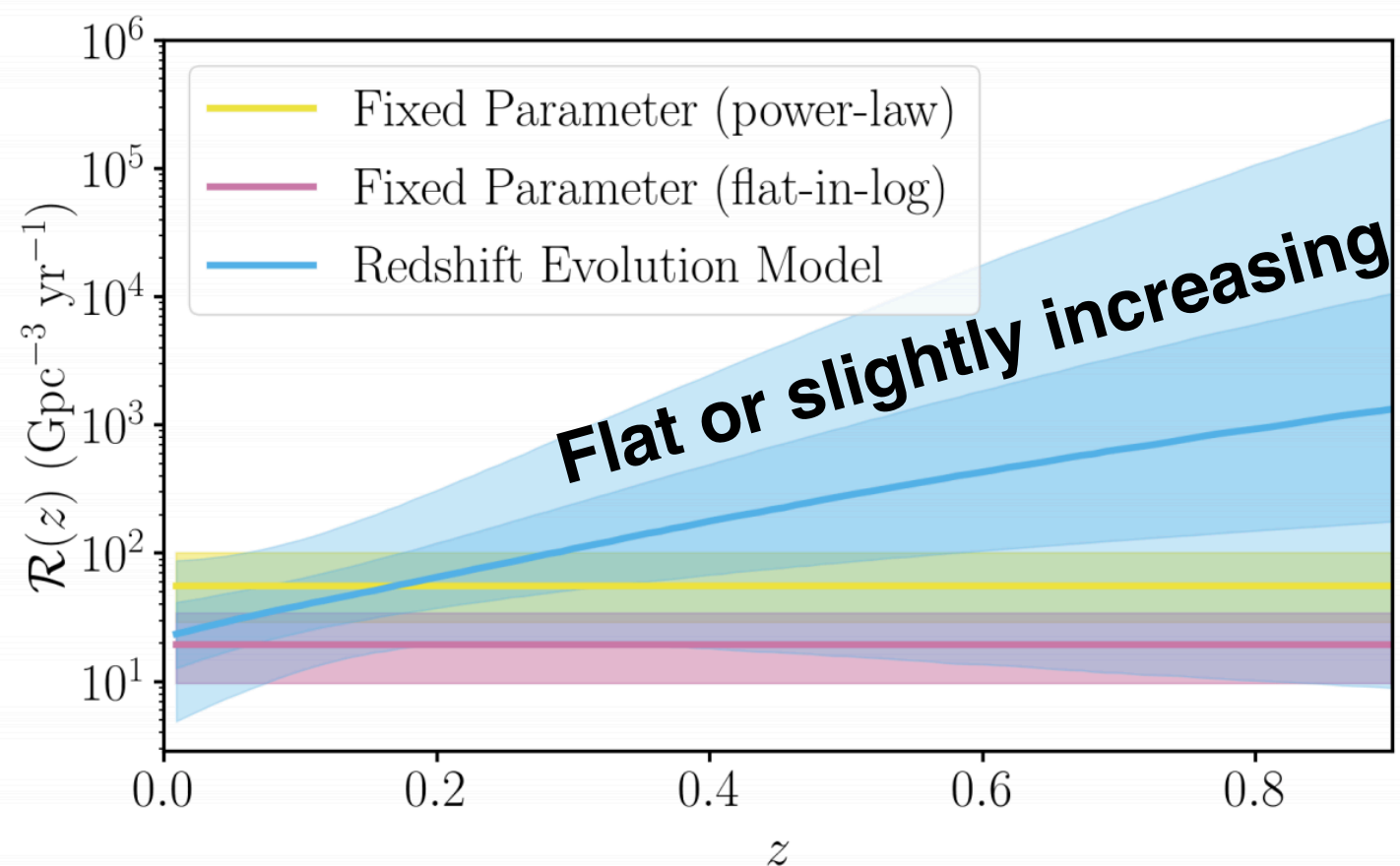
**With/without
GW170729**



Rates for black hole binaries

$$R = 53.2^{+58.5}_{-28.8} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

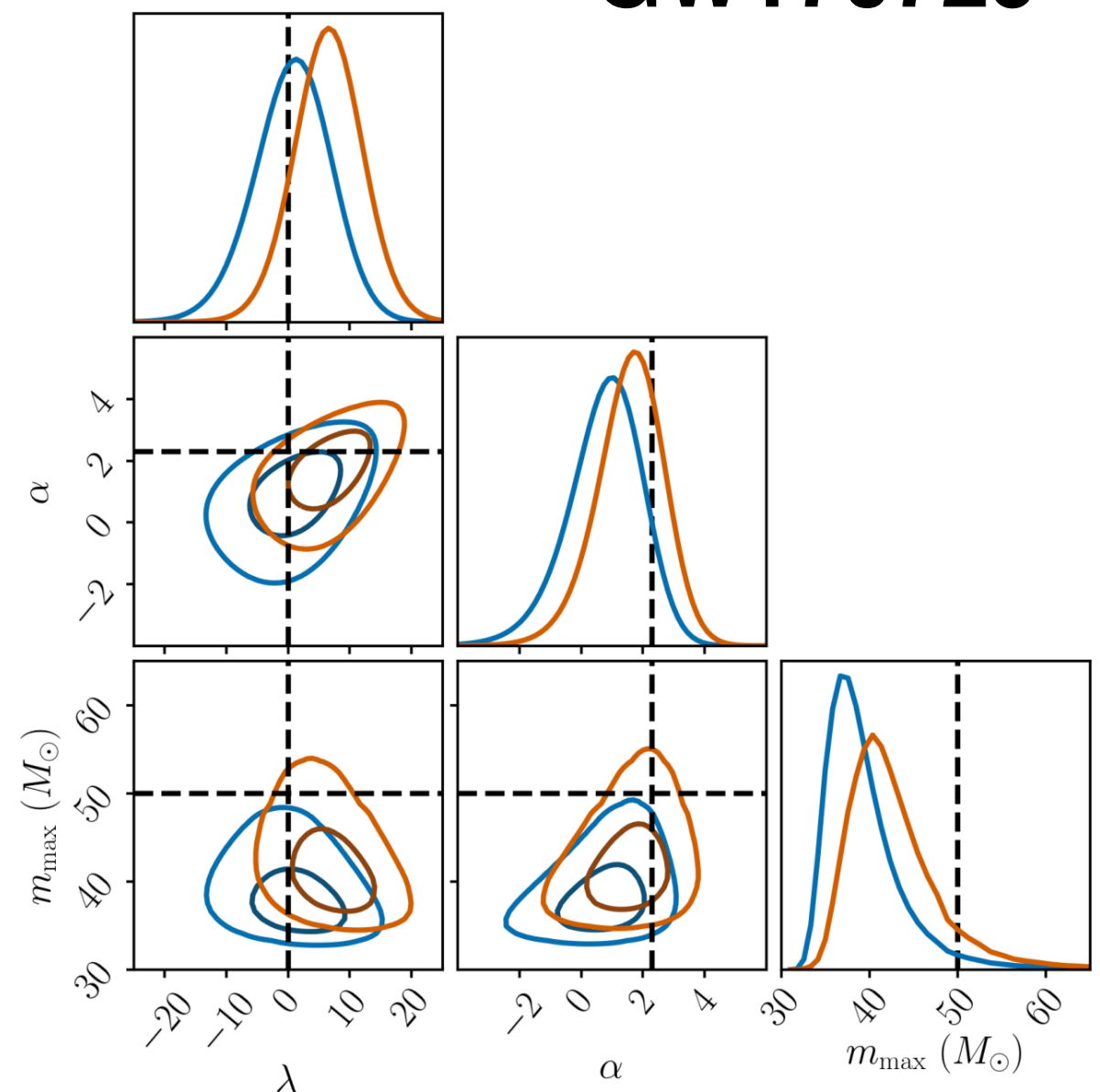
Depends on mass distribution



Model: Fishbach+ (arxiv:1805.10270)

Redshift
evolution

**With/without
GW170729**

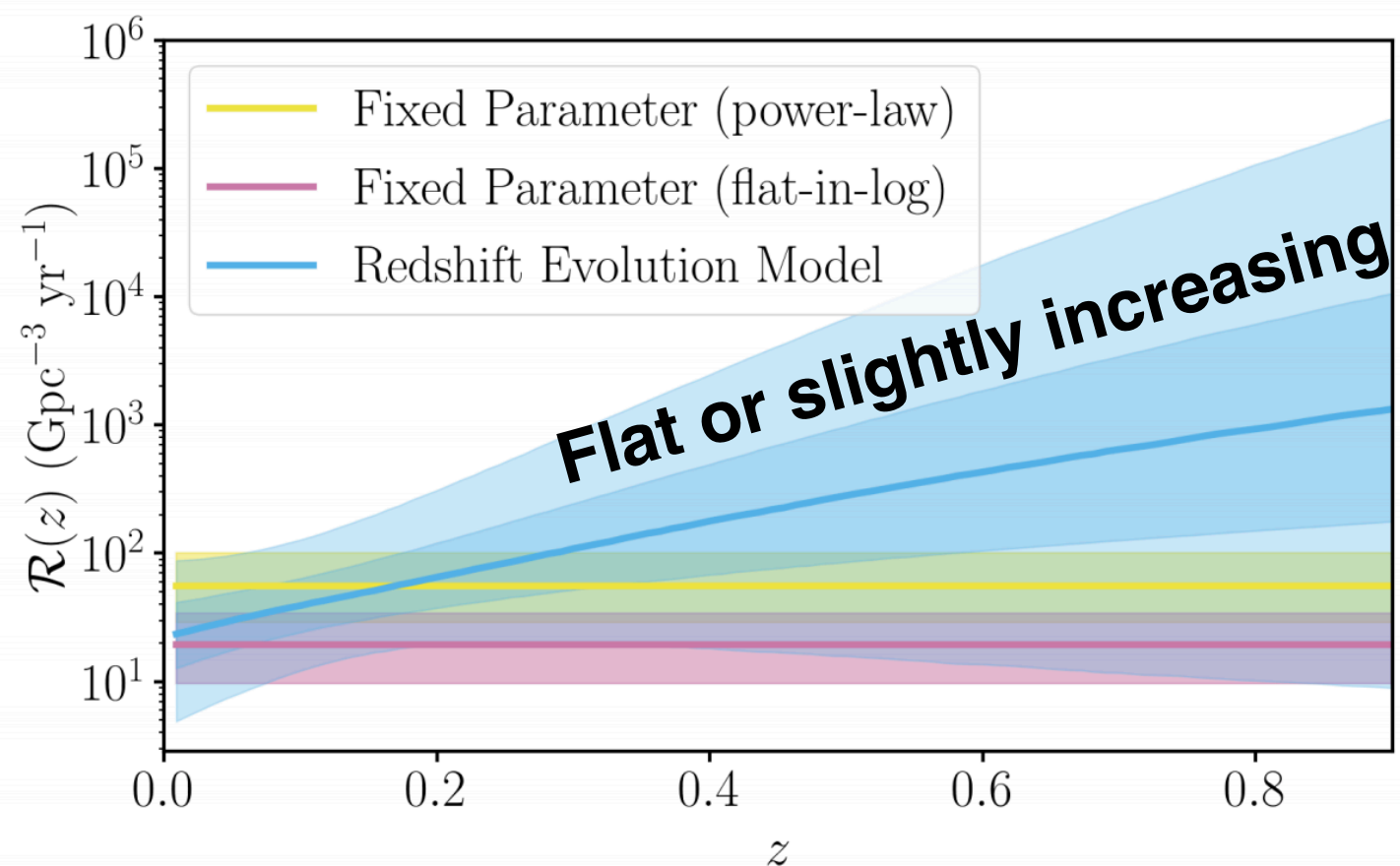


LVC (arxiv:1811.12940)

Rates for black hole binaries

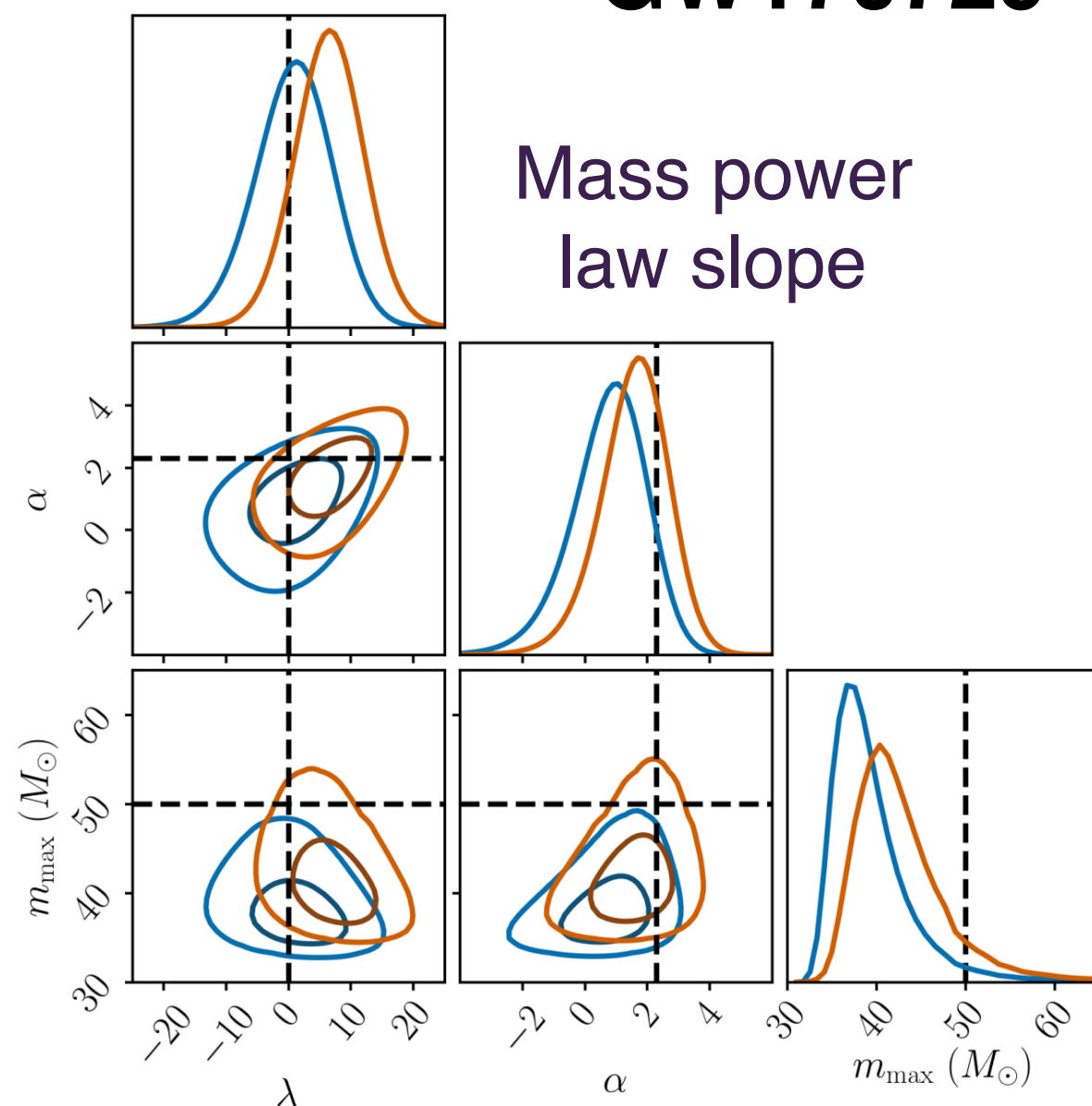
$$R = 53.2^{+58.5}_{-28.8} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

Depends on mass distribution



Redshift evolution

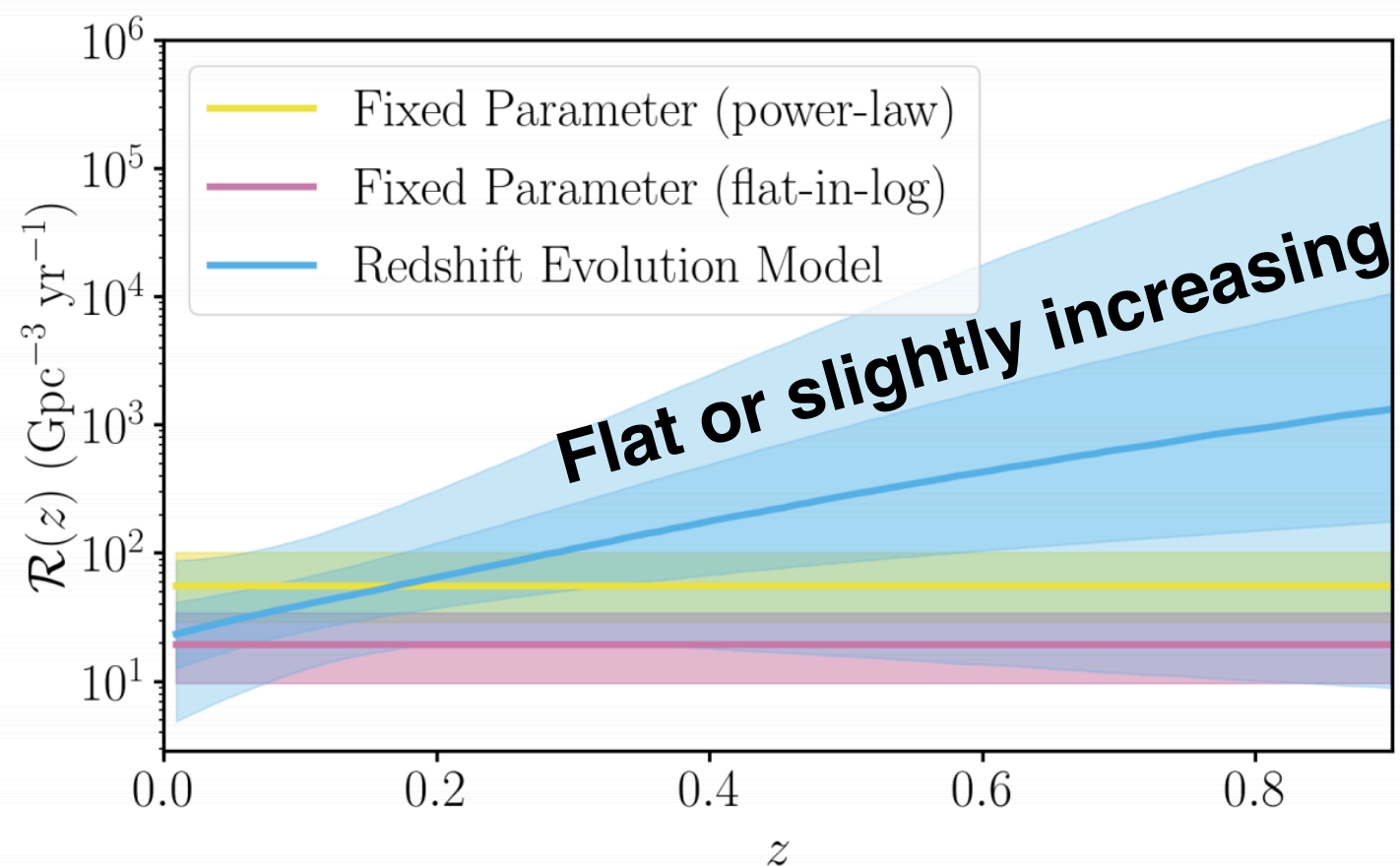
With/without GW170729



Rates for black hole binaries

$$R = 53.2^{+58.5}_{-28.8} \text{ Gpc}^{-3} \text{ yr}^{-1}$$

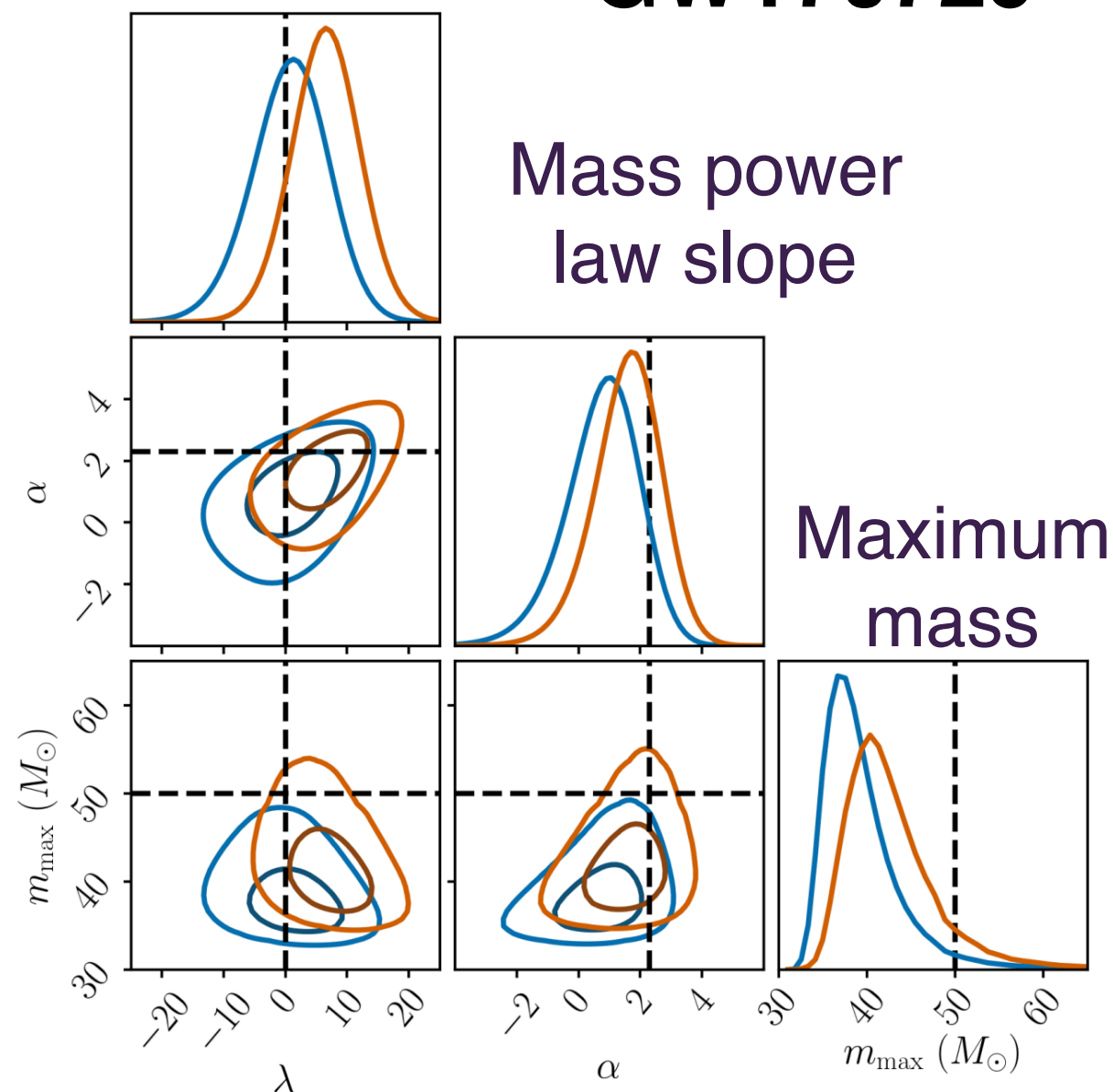
Depends on mass distribution



Model: Fishbach+ (arxiv:1805.10270)

Redshift
evolution

**With/without
GW170729**



LVC (arxiv:1811.12940)

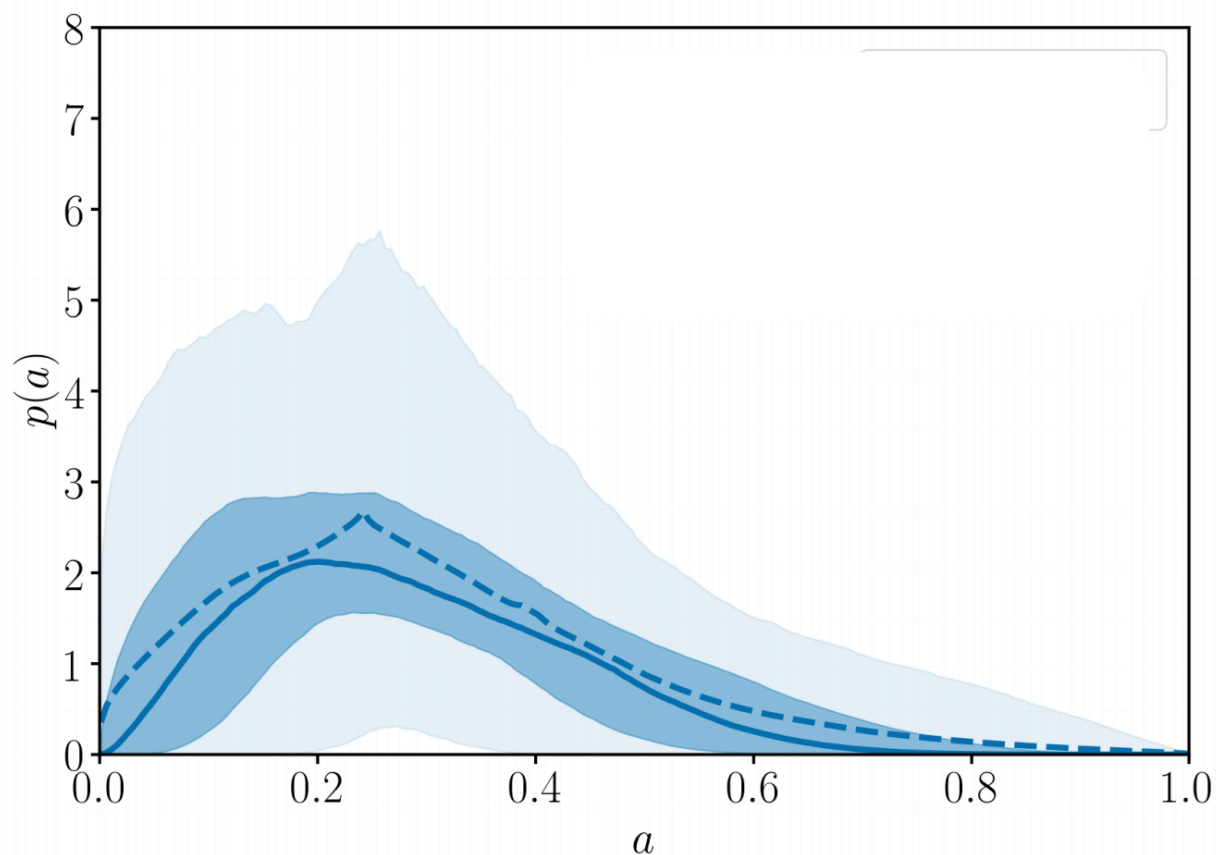
Spin distribution

Rule of thumb

Dynamical formation: isotropic spins

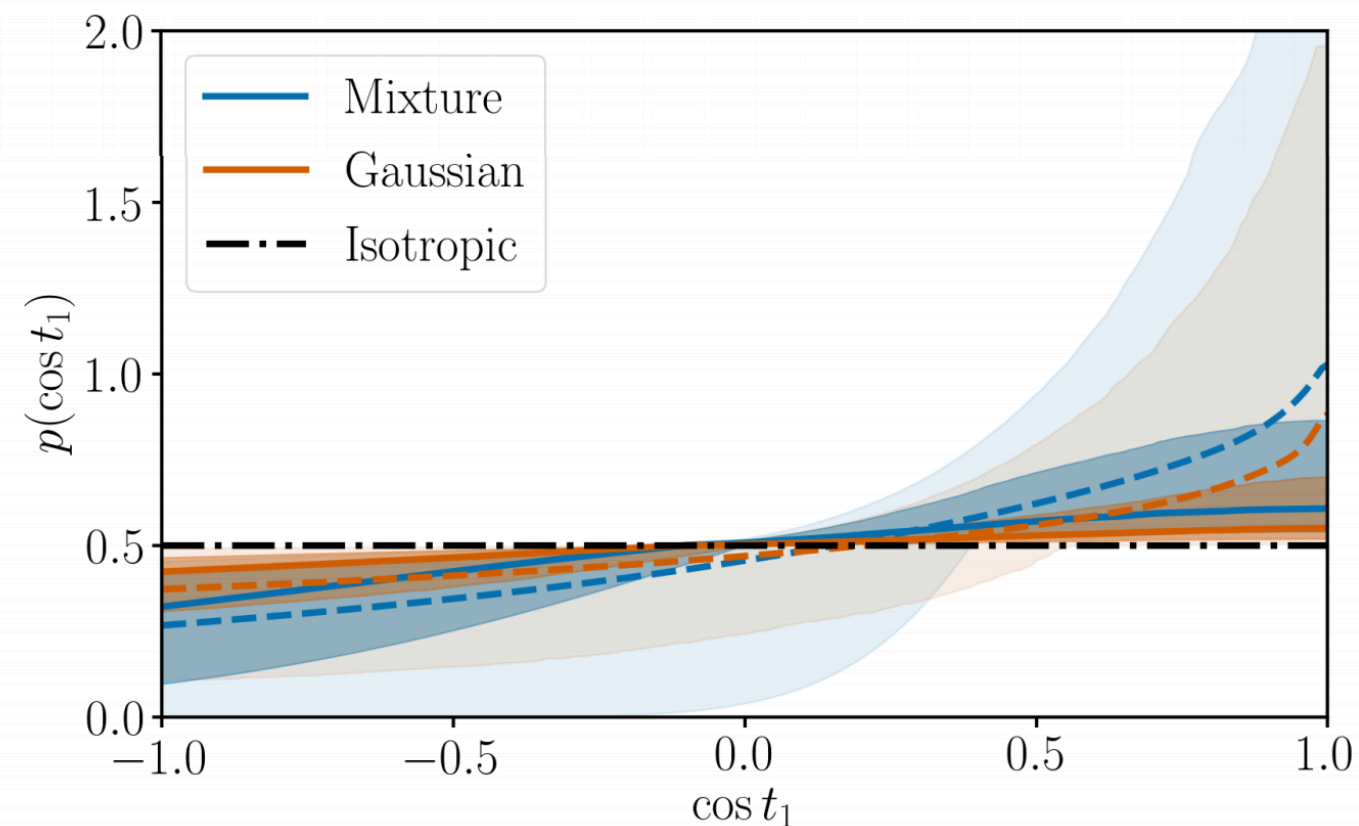
Field evolution: aligned spins

Parametric model on the spin magnitude



Model: Wysocki+ (arxiv:1805.06442)

Mixture of isotropic (dynamical)
and gaussian (field) component

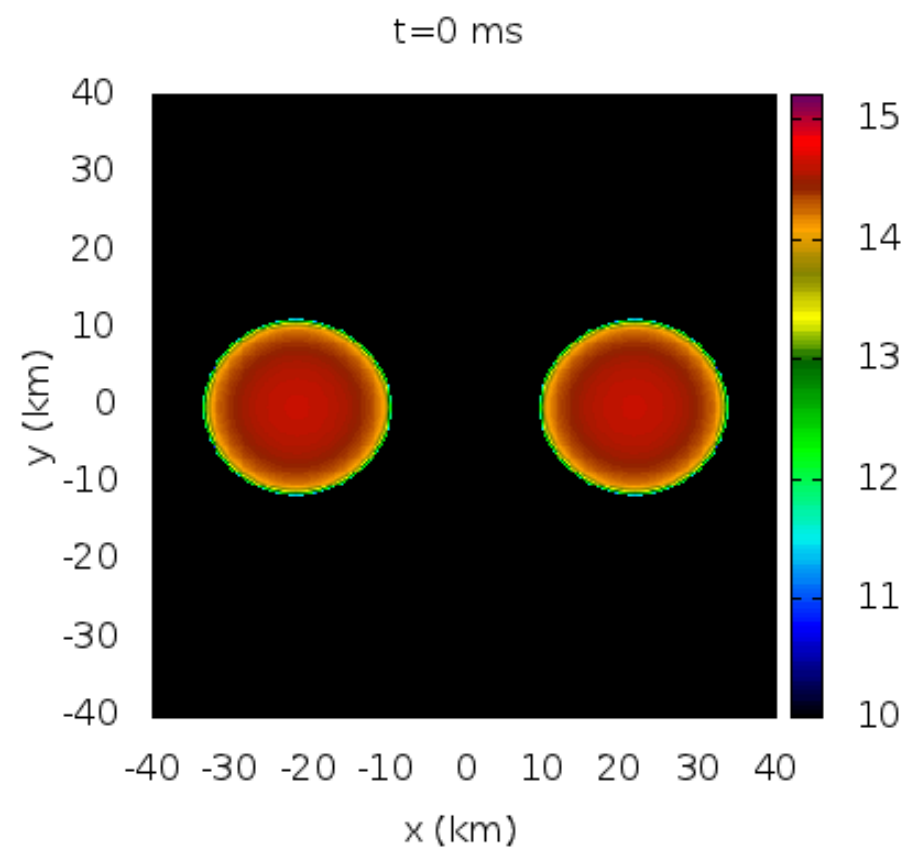


Model: Talbot+ (arxiv:1704.08370)

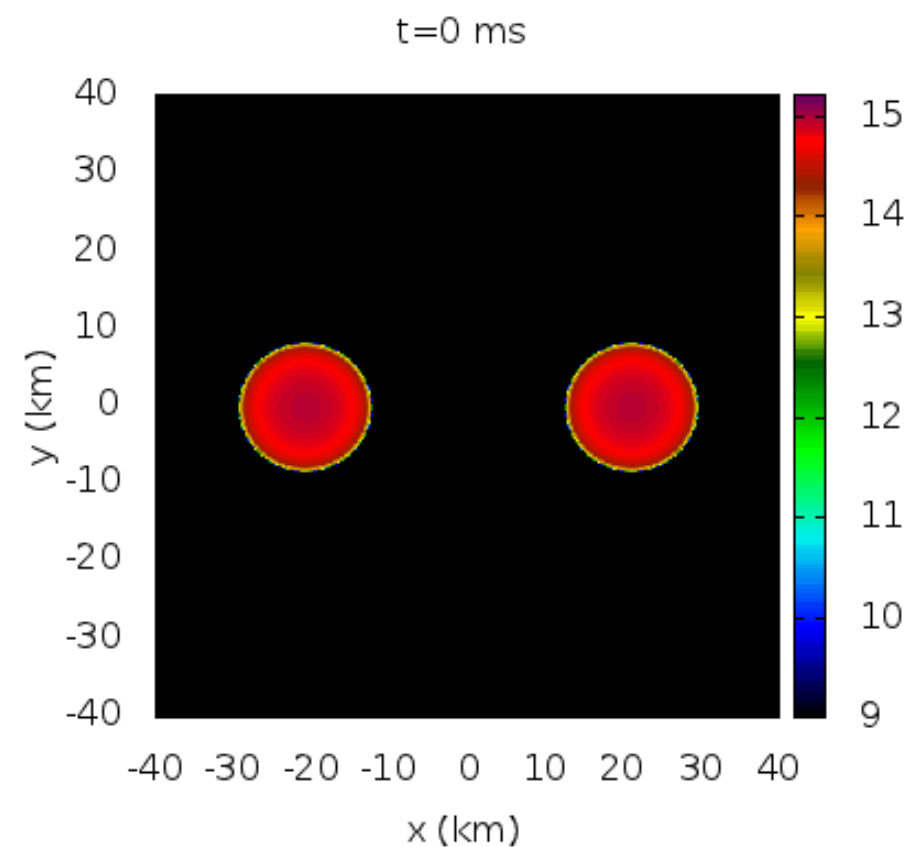
Disfavor large
aligned spins

Effect of internal structure

**Larger NSs emit
energy faster,
accelerating the
inspiral**

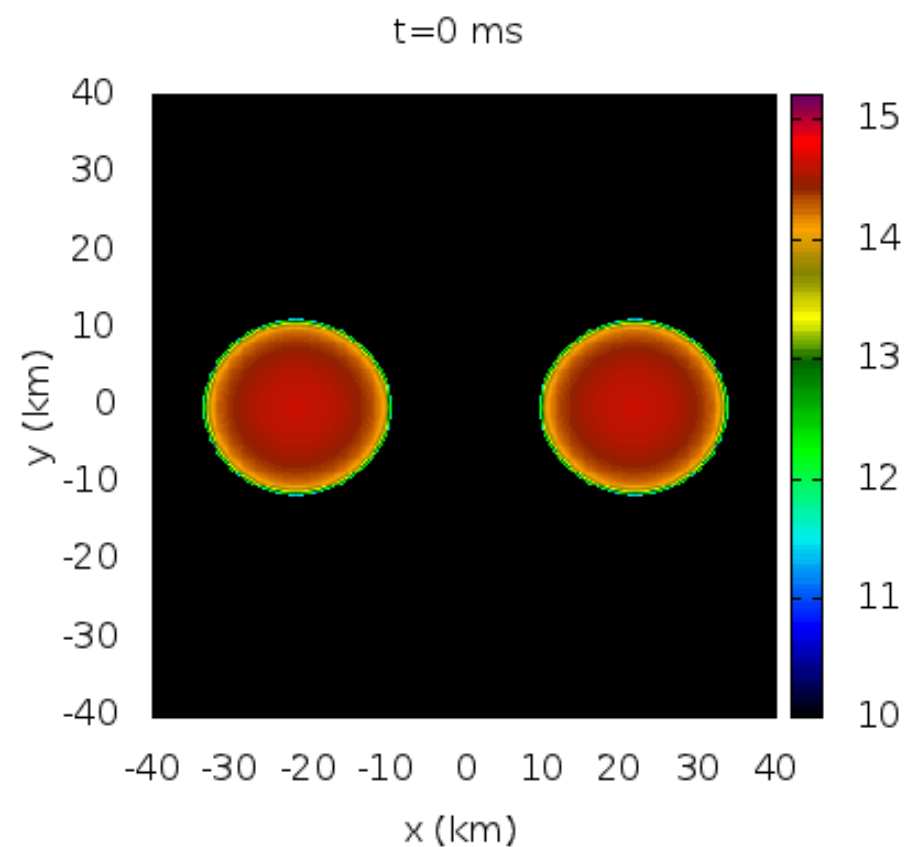


**Smaller NSs take
longer to merge**

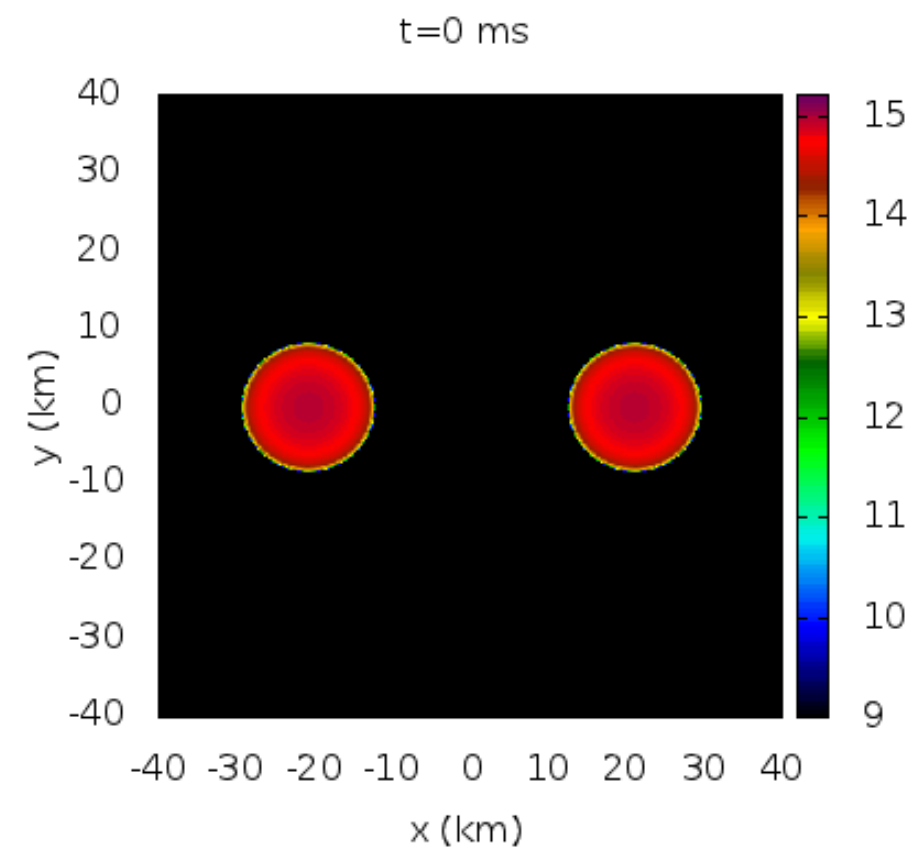


Effect of internal structure

**Larger NSs emit
energy faster,
accelerating the
inspiral**



**Smaller NSs take
longer to merge**

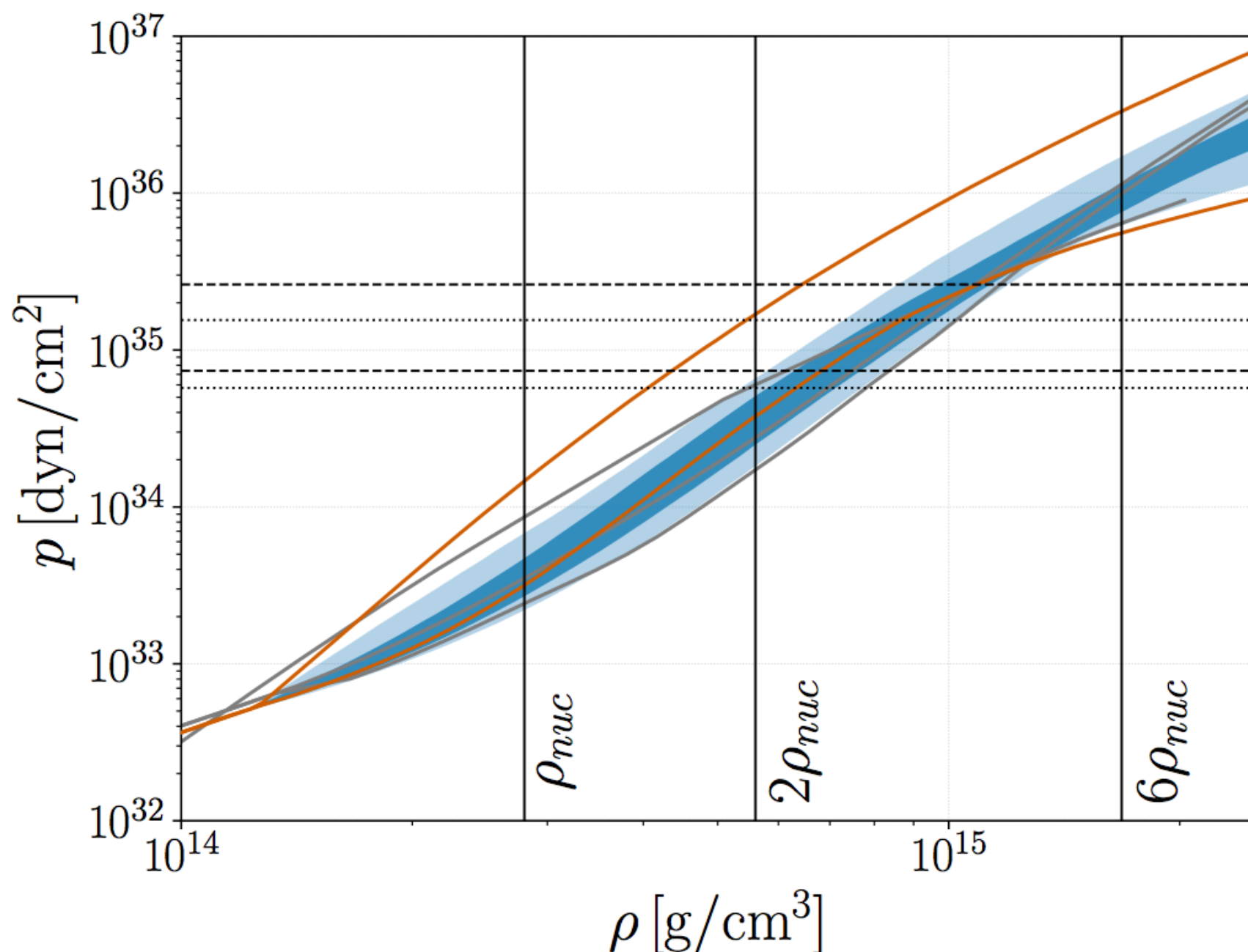


GW170817 EoS

Parametrize the EoS directly
(spectral approach)

$$P \sim \epsilon^{\Gamma(x)}$$
$$\Gamma(x) = \exp\left(\sum_k \gamma_k x^k\right)$$

Lindblom and Indik (arxiv:1207.3744)



LVC (arxiv:1805.11581)

PE: Veitch+ (arxiv:1409.7215)

Waveform: Dietrich+ (arxiv:1804.02235)

EoS Parametrization:

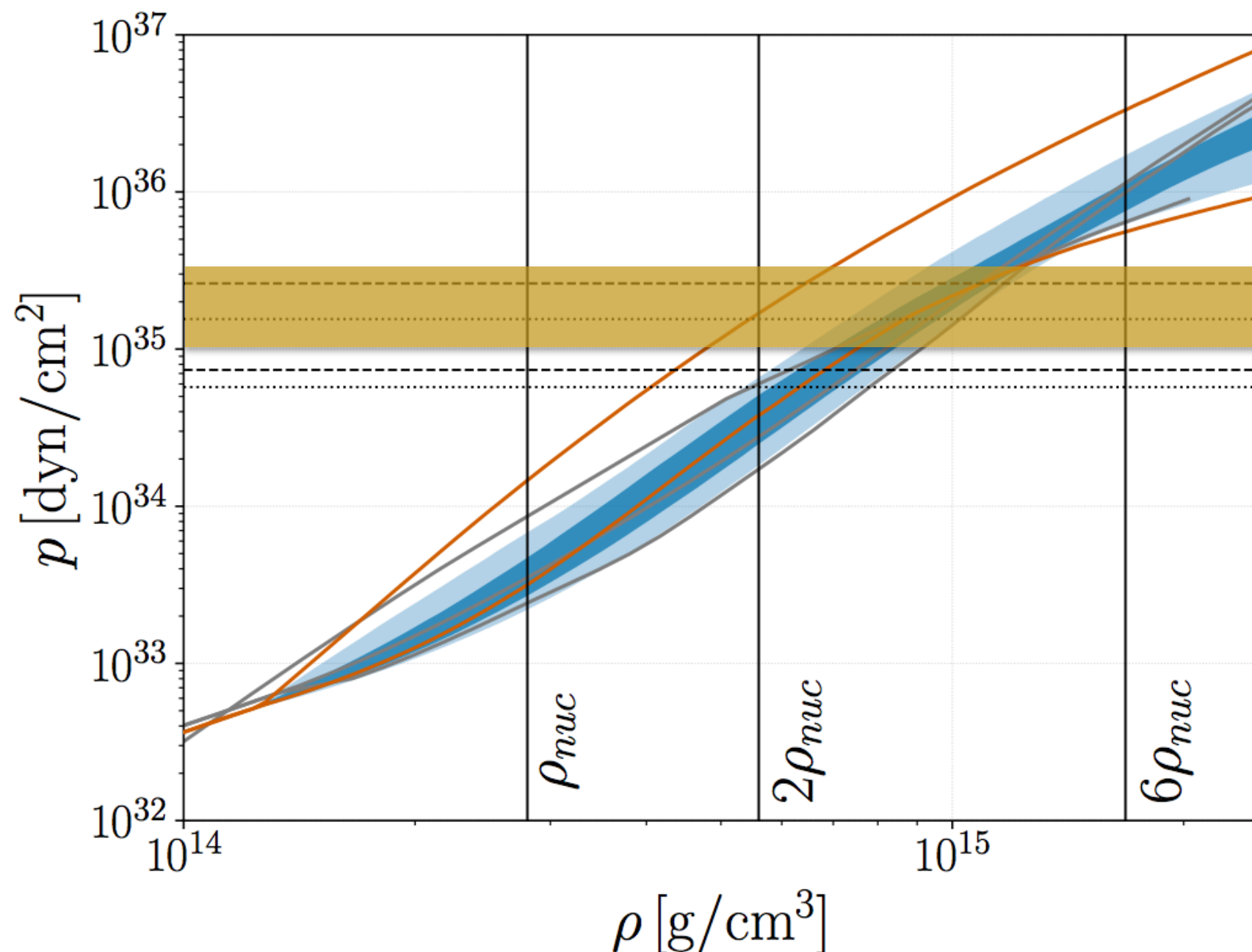
Lackey and Wade (arxiv:1410.8866),
Carney+ (arxiv:1805.11217)

GW170817 EoS

Parametrize the EoS directly
(spectral approach)

$$P \sim \epsilon^{\Gamma(x)}$$
$$\Gamma(x) = \exp\left(\sum_k \gamma_k x^k\right)$$

Lindblom and Indik (arxiv:1207.3744)



LVC (arxiv:1805.11581)

PE: Veitch+ (arxiv:1409.7215)

Waveform: Dietrich+ (arxiv:1804.02235)

EoS Parametrization:

Lackey and Wade (arxiv:1410.8866),

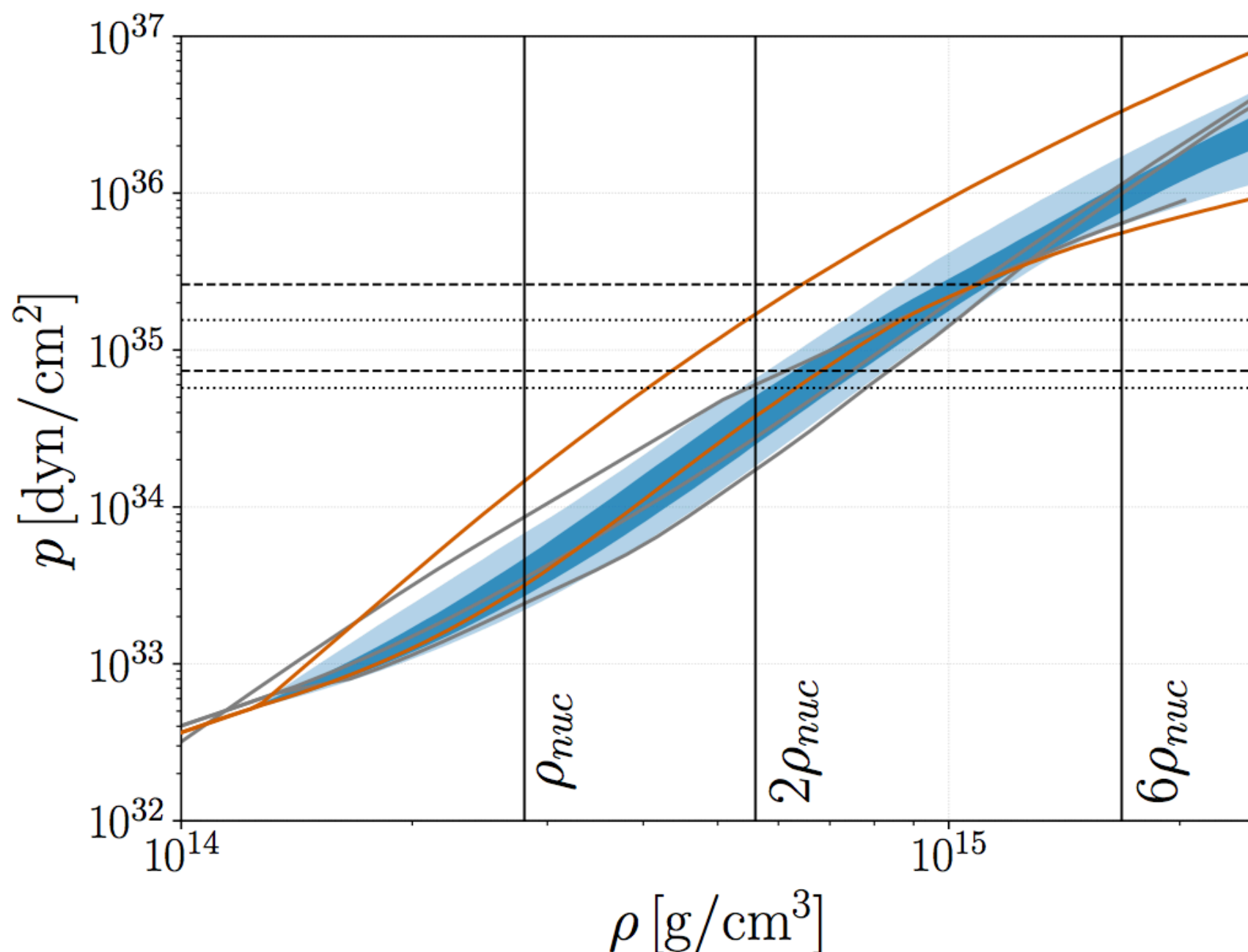
Carney+ (arxiv:1805.11217)

GW170817 EoS

Parametrize the EoS directly
(spectral approach)

$$P \sim \epsilon^{\Gamma(x)}$$
$$\Gamma(x) = \exp\left(\sum_k \gamma_k x^k\right)$$

Lindblom and Indik (arxiv:1207.3744)



LVC (arxiv:1805.11581)

PE: Veitch+ (arxiv:1409.7215)

Waveform: Dietrich+ (arxiv:1804.02235)

EoS Parametrization:

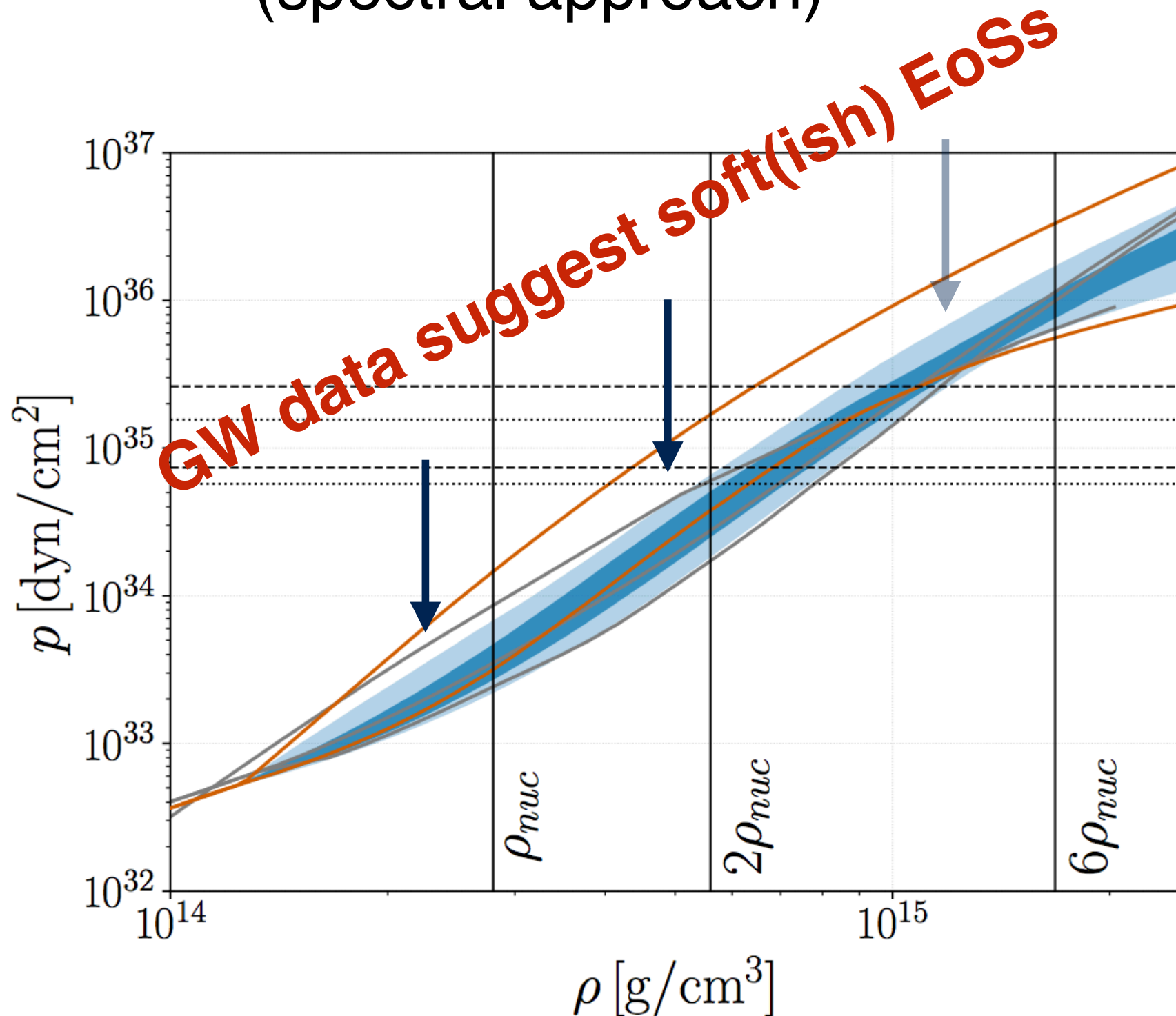
Lackey and Wade (arxiv:1410.8866),
Carney+ (arxiv:1805.11217)

GW170817 EoS

Parametrize the EoS directly
(spectral approach)

$$P \sim \epsilon^{\Gamma(x)}$$
$$\Gamma(x) = \exp\left(\sum_k \gamma_k x^k\right)$$

Lindblom and Indik (arxiv:1207.3744)



LVC (arxiv:1805.11581)

PE: Veitch+ (arxiv:1409.7215)

Waveform: Dietrich+ (arxiv:1804.02235)

EoS Parametrization:

Lackey and Wade (arxiv:1410.8866),

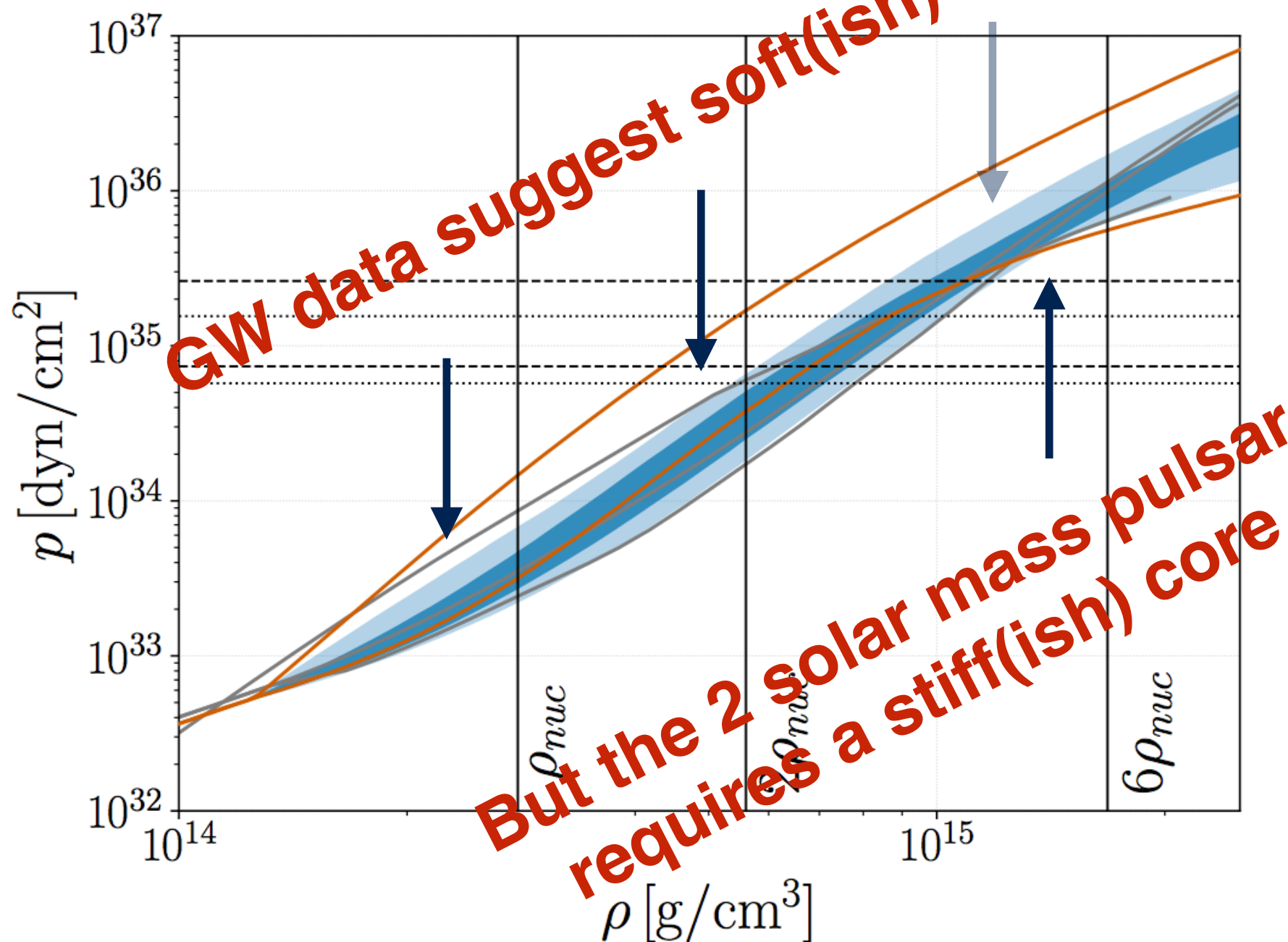
Carney+ (arxiv:1805.11217)

GW170817 EoS

Parametrize the EoS directly
(spectral approach)

$$P \sim \epsilon^{\Gamma(x)}$$
$$\Gamma(x) = \exp\left(\sum_k \gamma_k x^k\right)$$

Lindblom and Indik (arxiv:1207.3744)



LVC (arxiv:1805.11581)

PE: Veitch+ (arxiv:1409.7215)

Waveform: Dietrich+ (arxiv:1804.02235)

EoS Parametrization:

Lackey and Wade (arxiv:1410.8866),

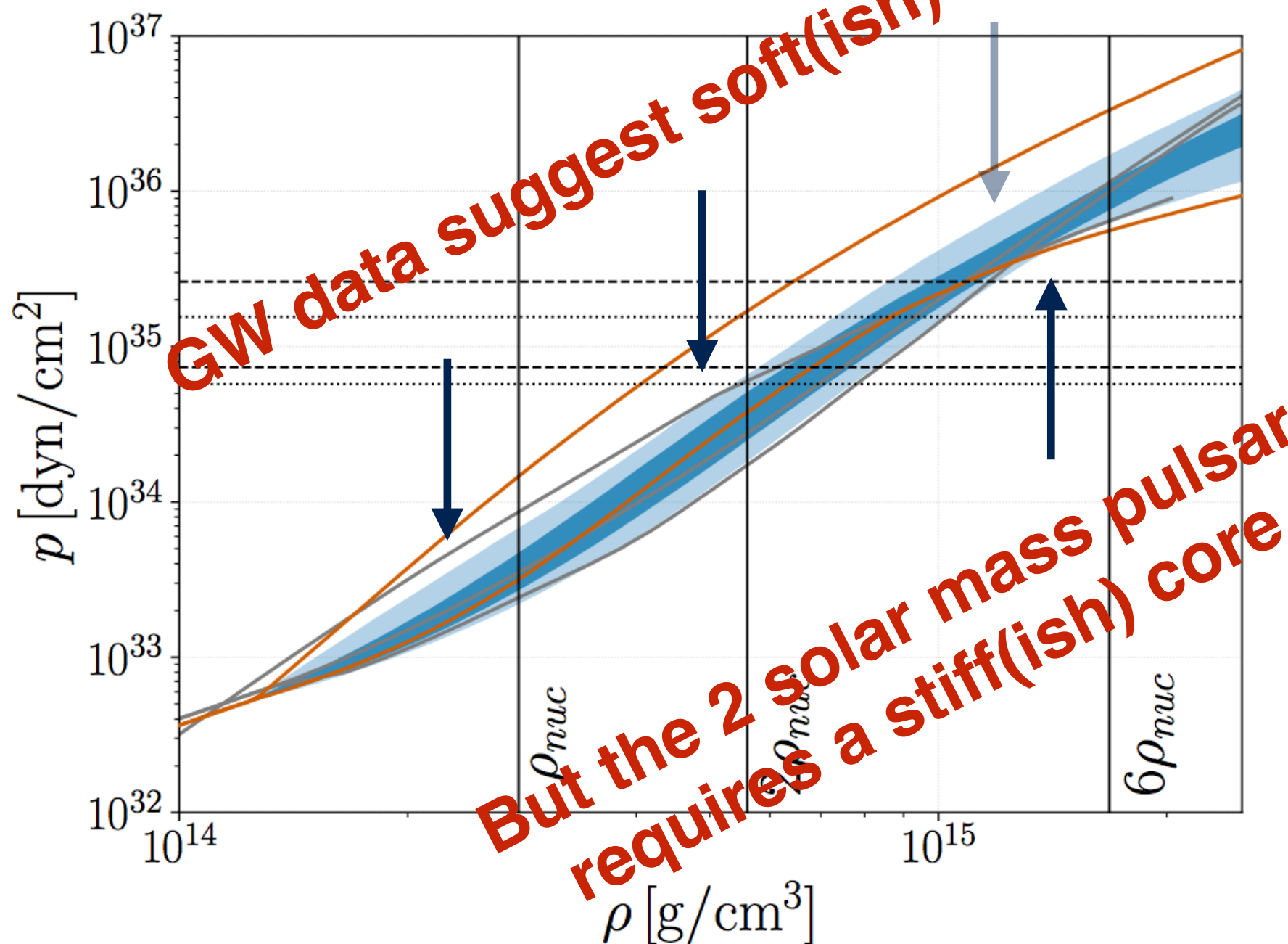
Carney+ (arxiv:1805.11217)

GW170817 EoS

Parametrize the EoS directly
(spectral approach)

$$P \sim \epsilon^{\Gamma(x)}$$
$$\Gamma(x) = \exp\left(\sum_k \gamma_k x^k\right)$$

Lindblom and Indik (arxiv:1207.3744)



Overall

$$R \in [10.5, 13.3] \text{ km}$$

LVC (arxiv:1805.11581)

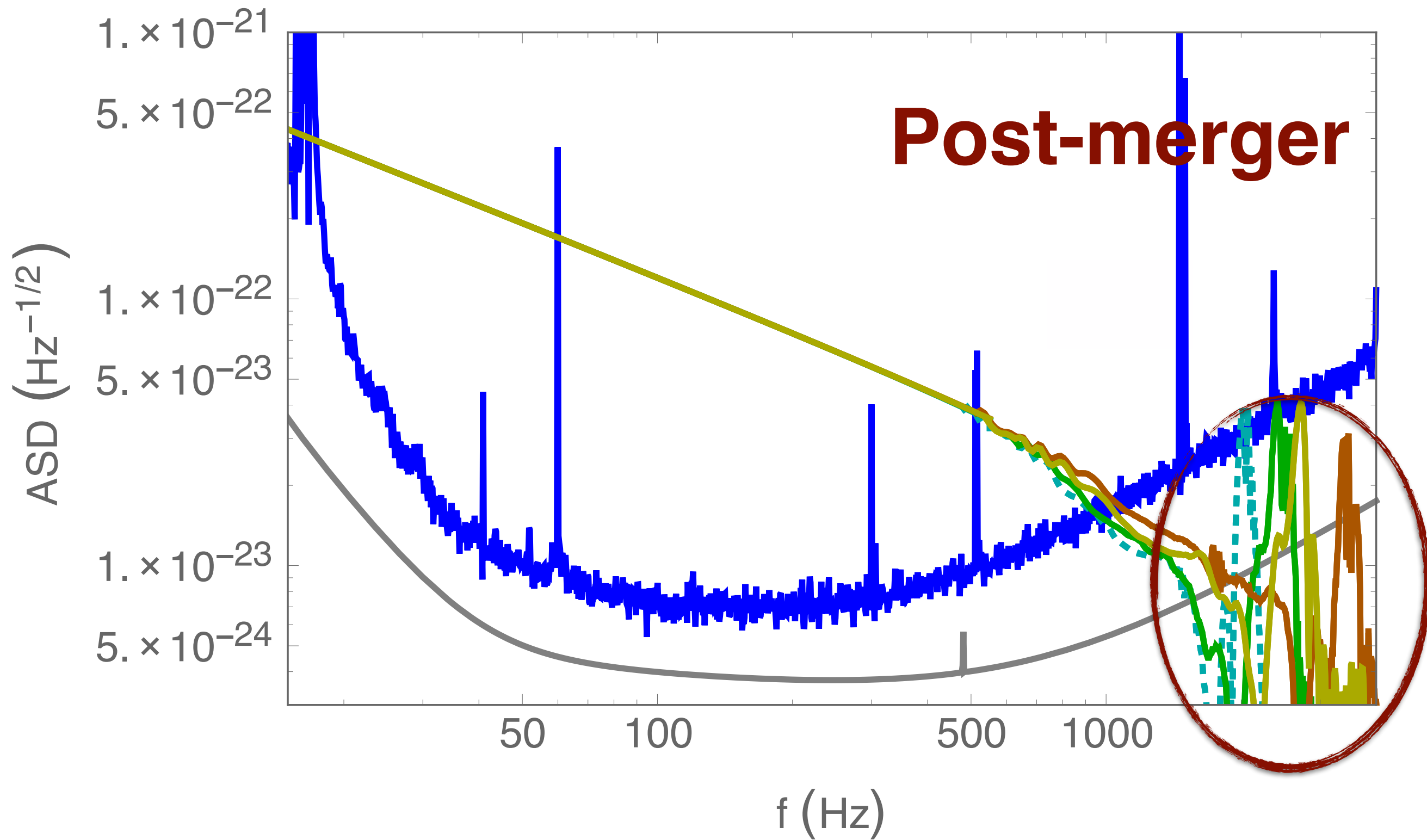
PE: Veitch+ (arxiv:1409.7215)

Waveform: Dietrich+ (arxiv:1804.02235)

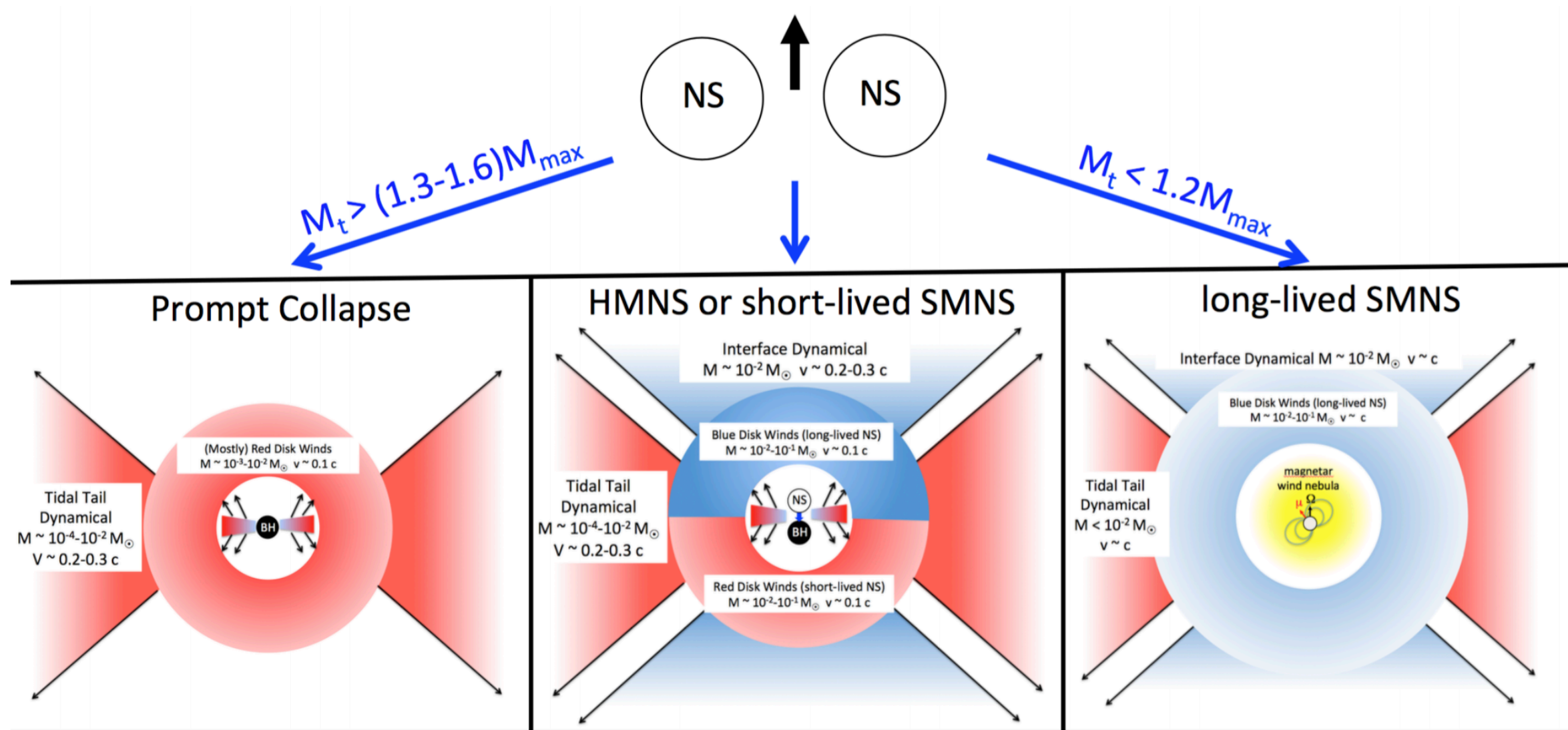
EoS Parametrization:

Lackey and Wade (arxiv:1410.8866),
Carney+ (arxiv:1805.11217)

Post-merger phase



Remnant star



Margalit, Metzger (arxiv:1710.05938)

~6kHz ringdown

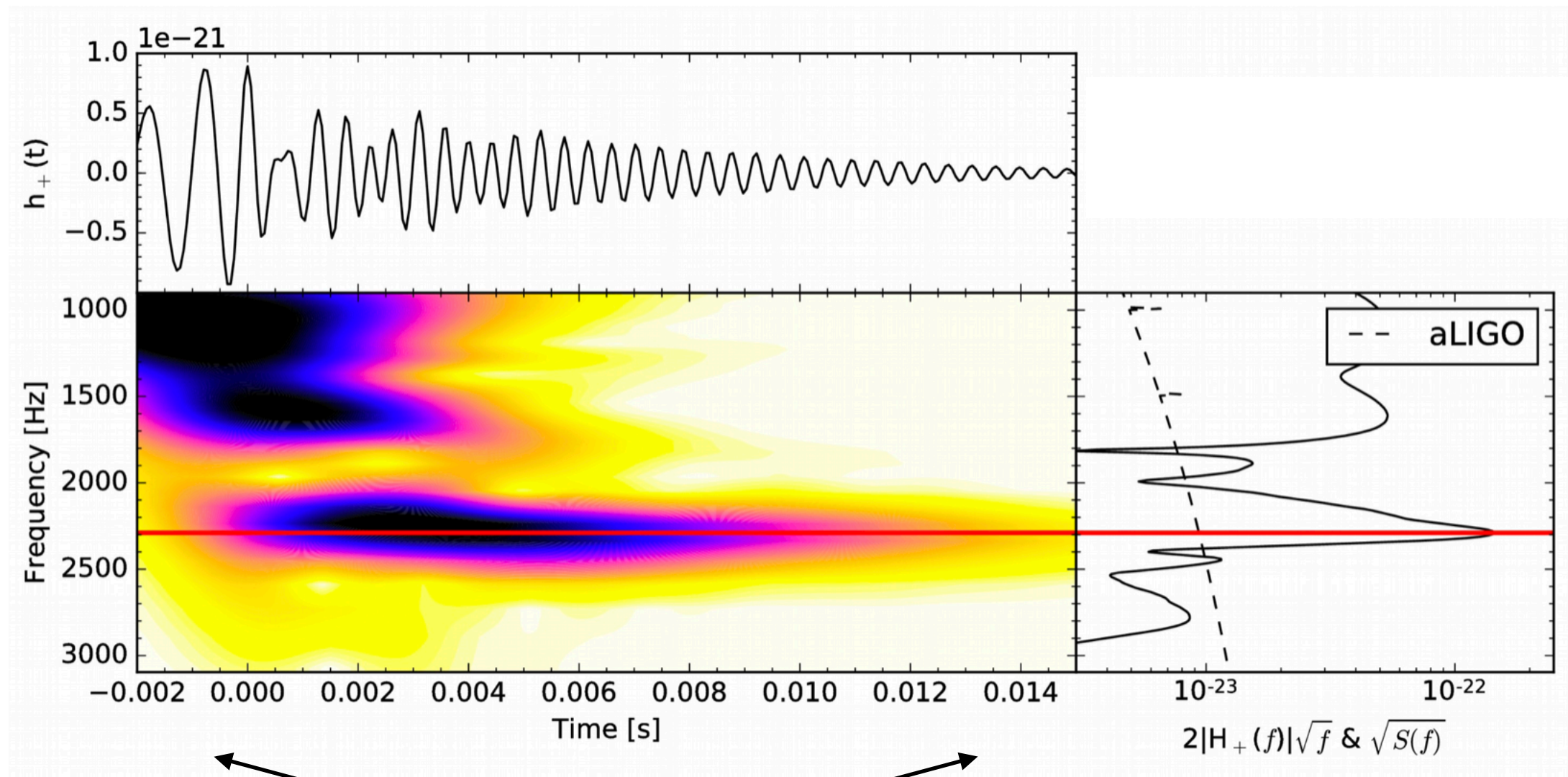
**Short duration
signal at ~2-4kHz**

**Long duration
signal**

Post-merger signal

complicated morphology

high frequency



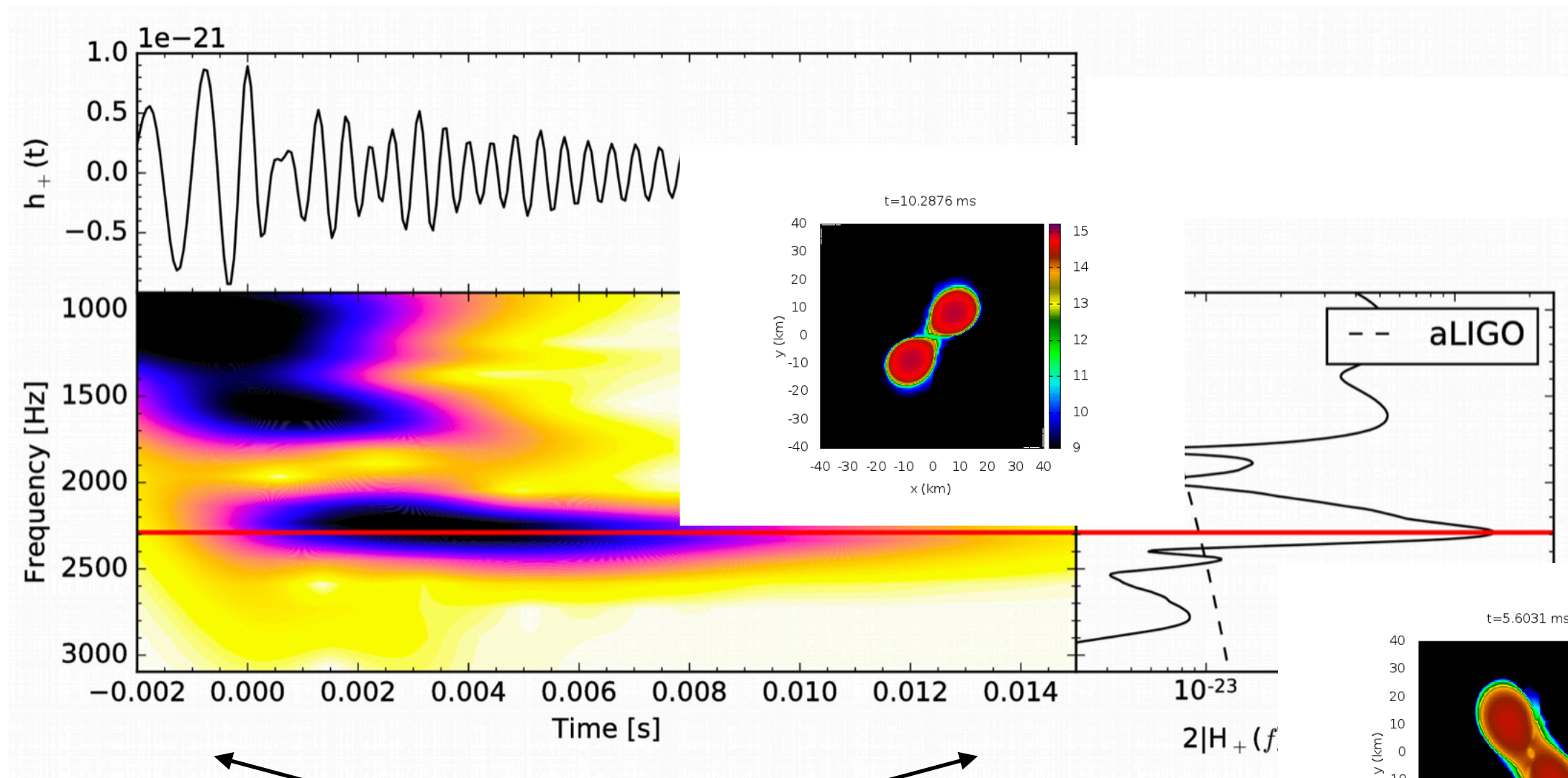
characteristic peak

short duration

Post-merger signal

complicated morphology

high frequency



characteristic

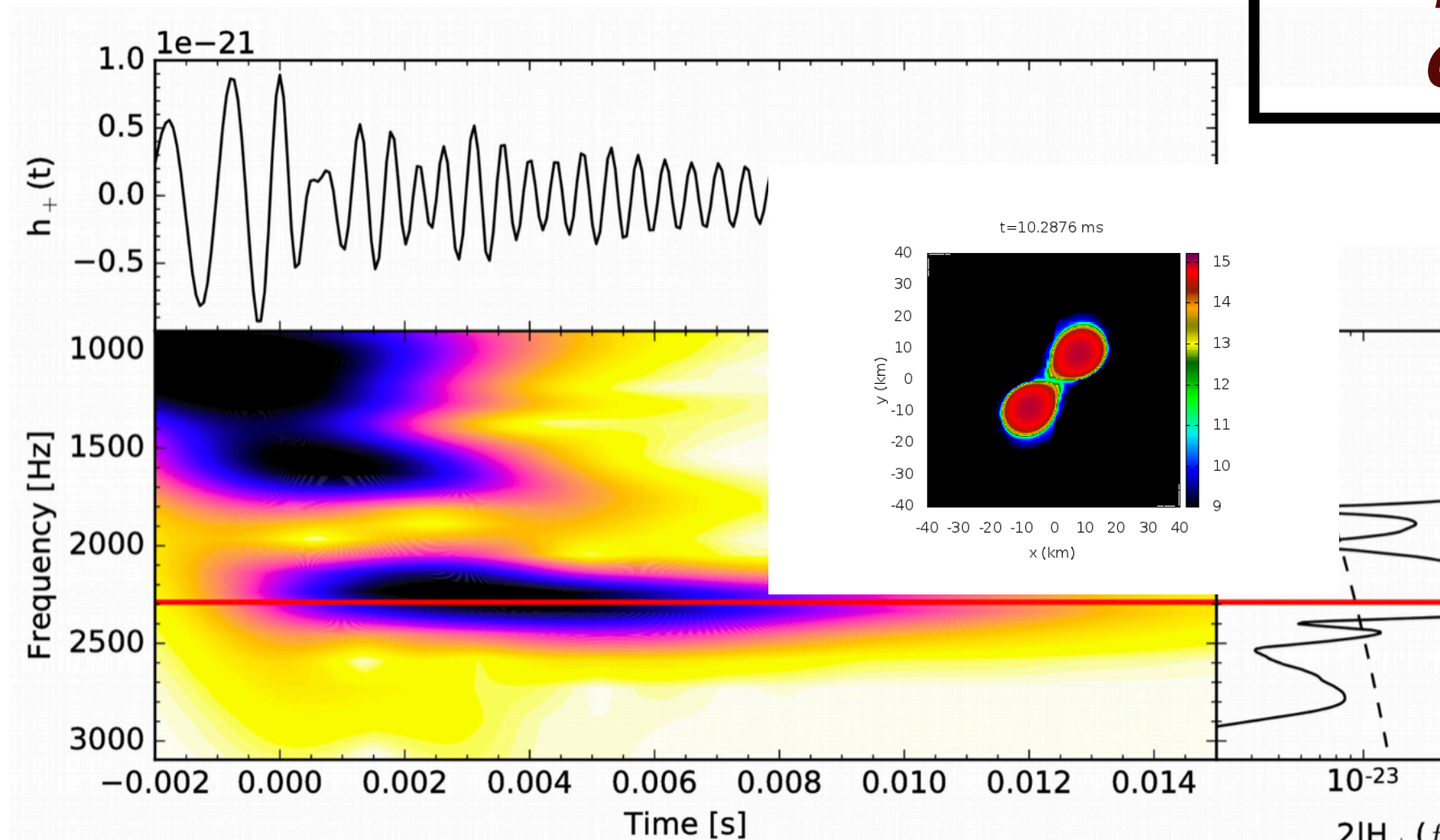
short duration

Post-merger signal

complicated morphology

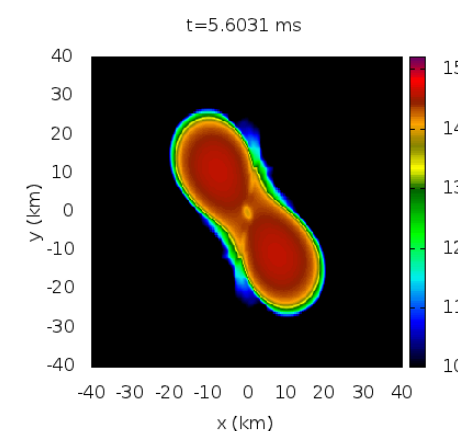
*The location of
the peak depends
on the EoS*

high frequency



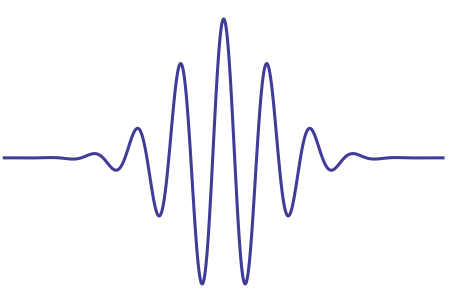
characteristic

short duration



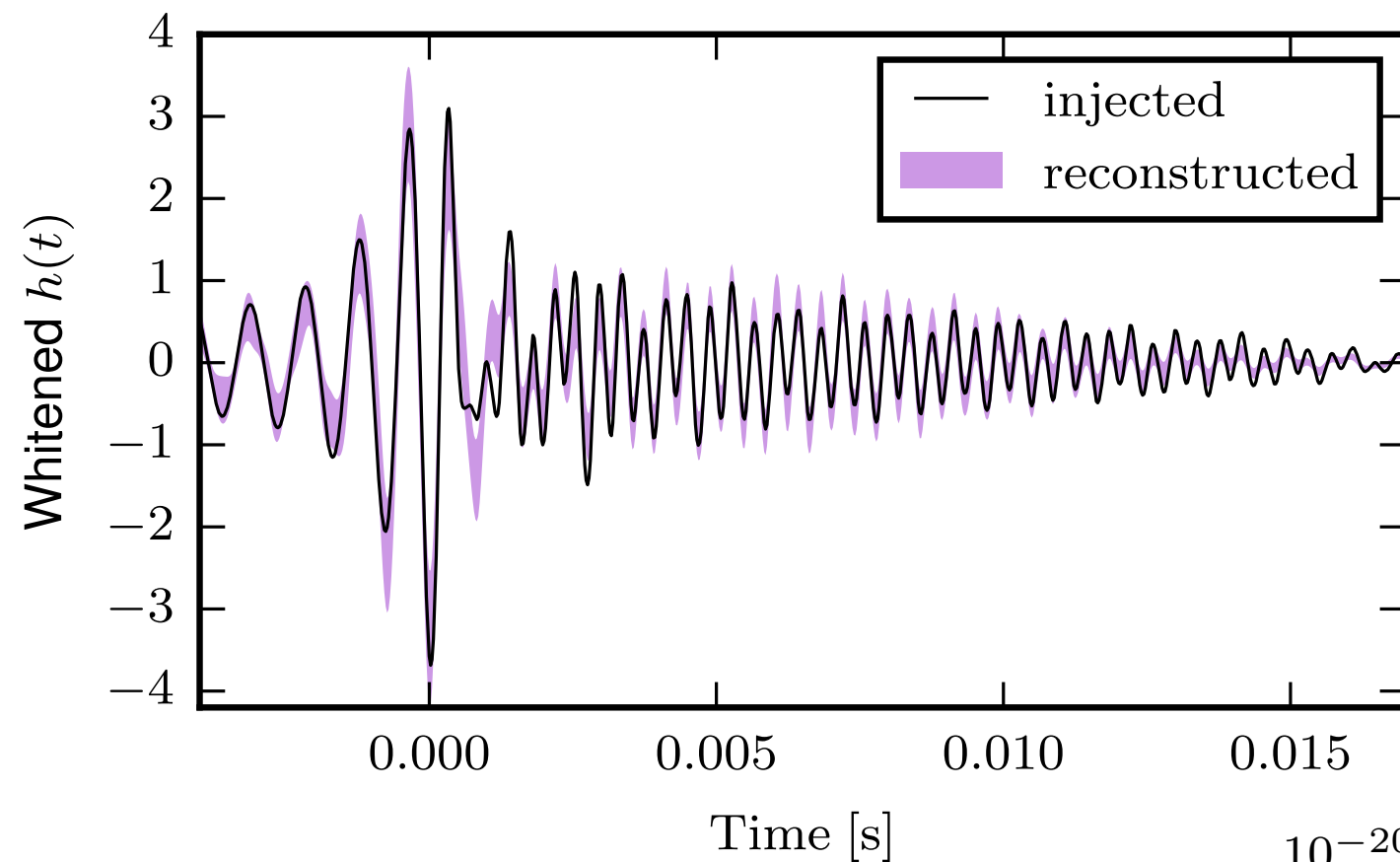
Clark+ (arxiv:1509.08522)

Reconstruction

$$h' \rightarrow \sum^N$$


Cornish, Littenberg (arxiv:1410.3835)

Reconstruction

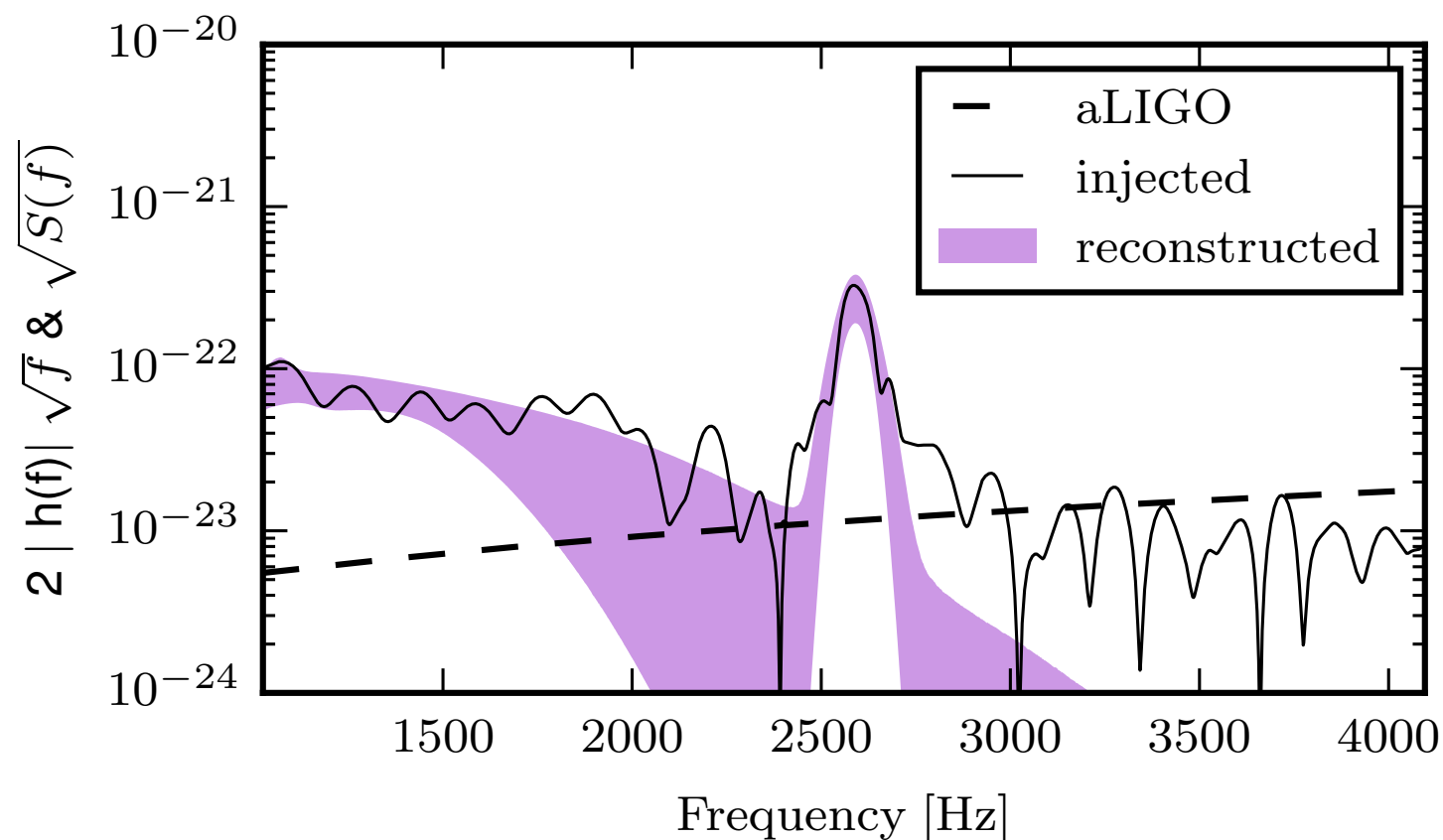


$$h' \rightarrow \sum^N$$

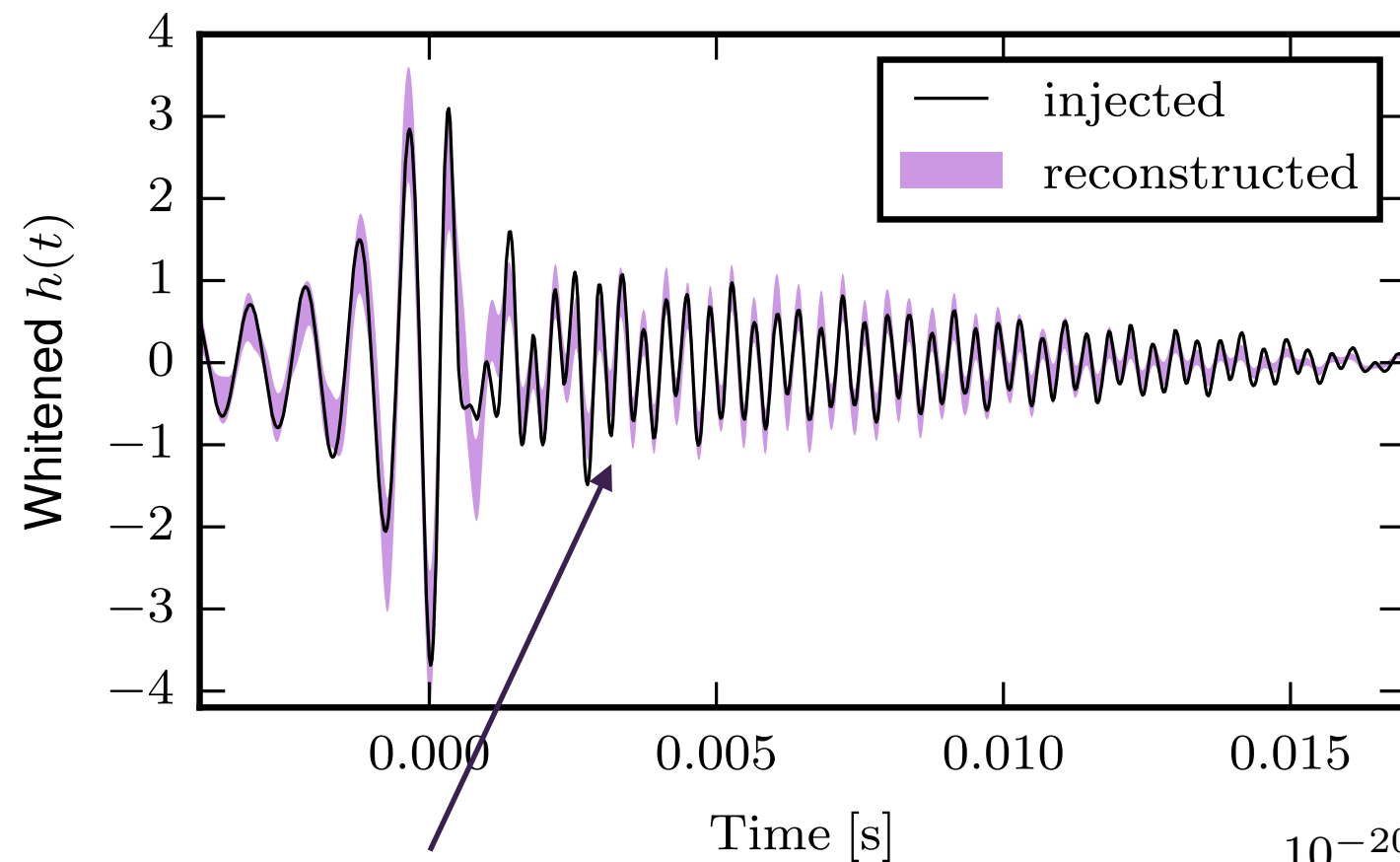
A diagram illustrating the reconstruction process. It shows the equation $h' \rightarrow \sum^N$ followed by a blue waveform representing a single component of the sum. The waveform is a high-frequency oscillation with a decaying amplitude.

Cornish, Littenberg (arxiv:1410.3835)

Chatziioannou+ (arxiv:1711.00040)
with numerical data from
Bauswein+ (arxiv:1204.1888)



Reconstruction



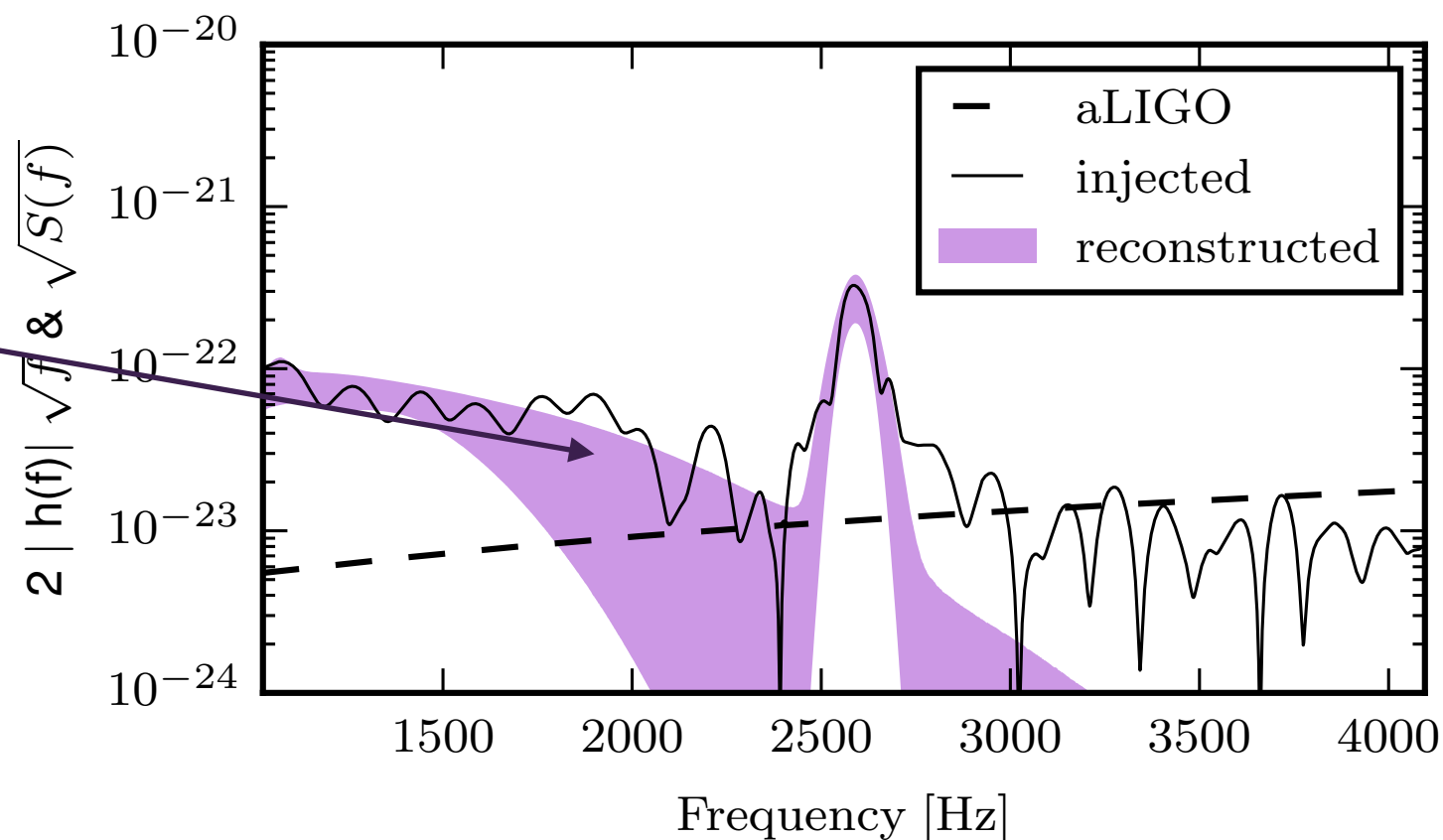
**90% credible
intervals for the
waveform**

Chatziioannou+ (arxiv:1711.00040)
with numerical data from
Bauswein+ (arxiv:1204.1888)

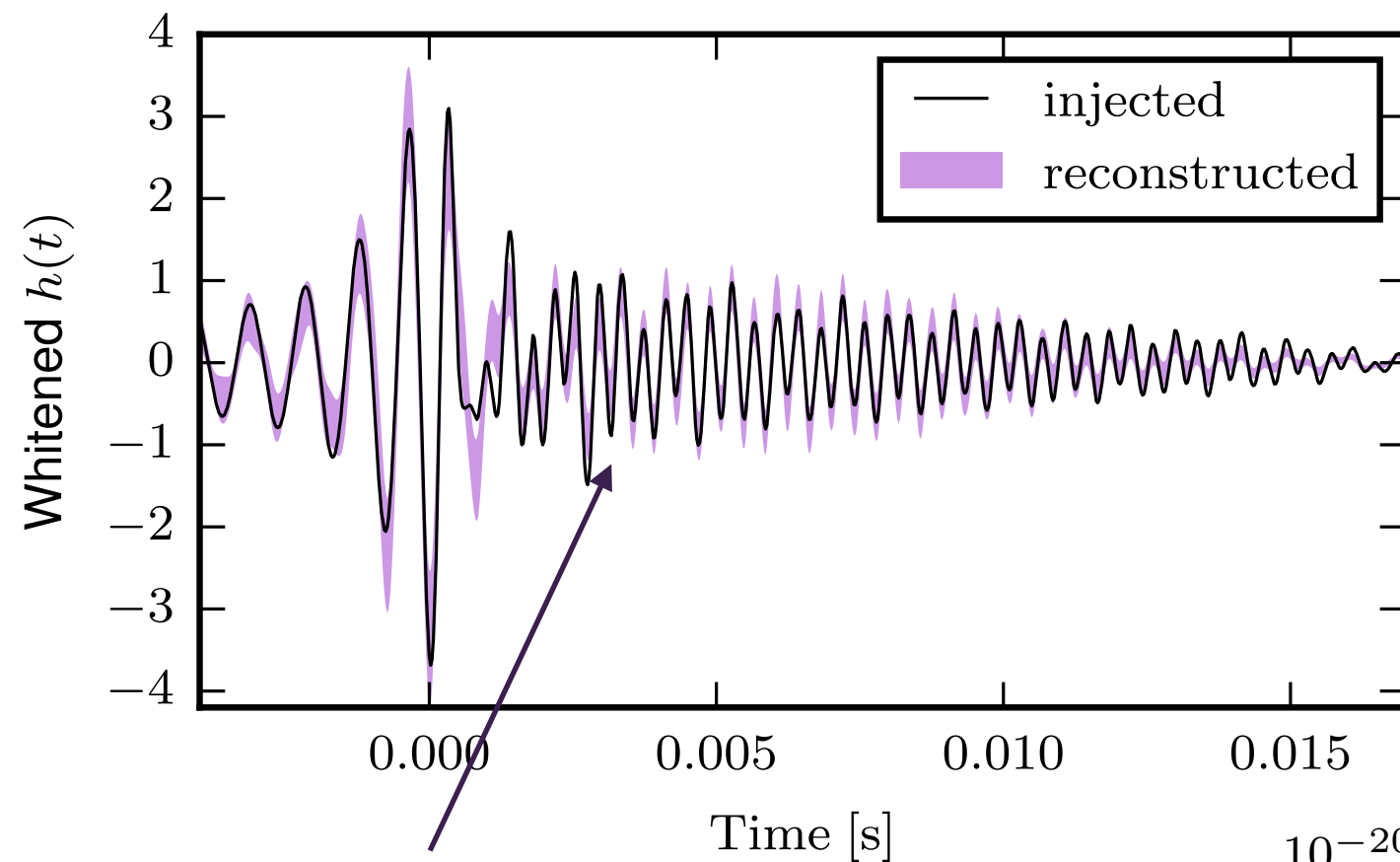
$$h' \rightarrow \sum^N$$

The diagram shows a blue waveform representing the sum of N components, as indicated by the equation $h' \rightarrow \sum^N$.

Cornish, Littenberg (arxiv:1410.3835)



Reconstruction



**90% credible
intervals for the
waveform**

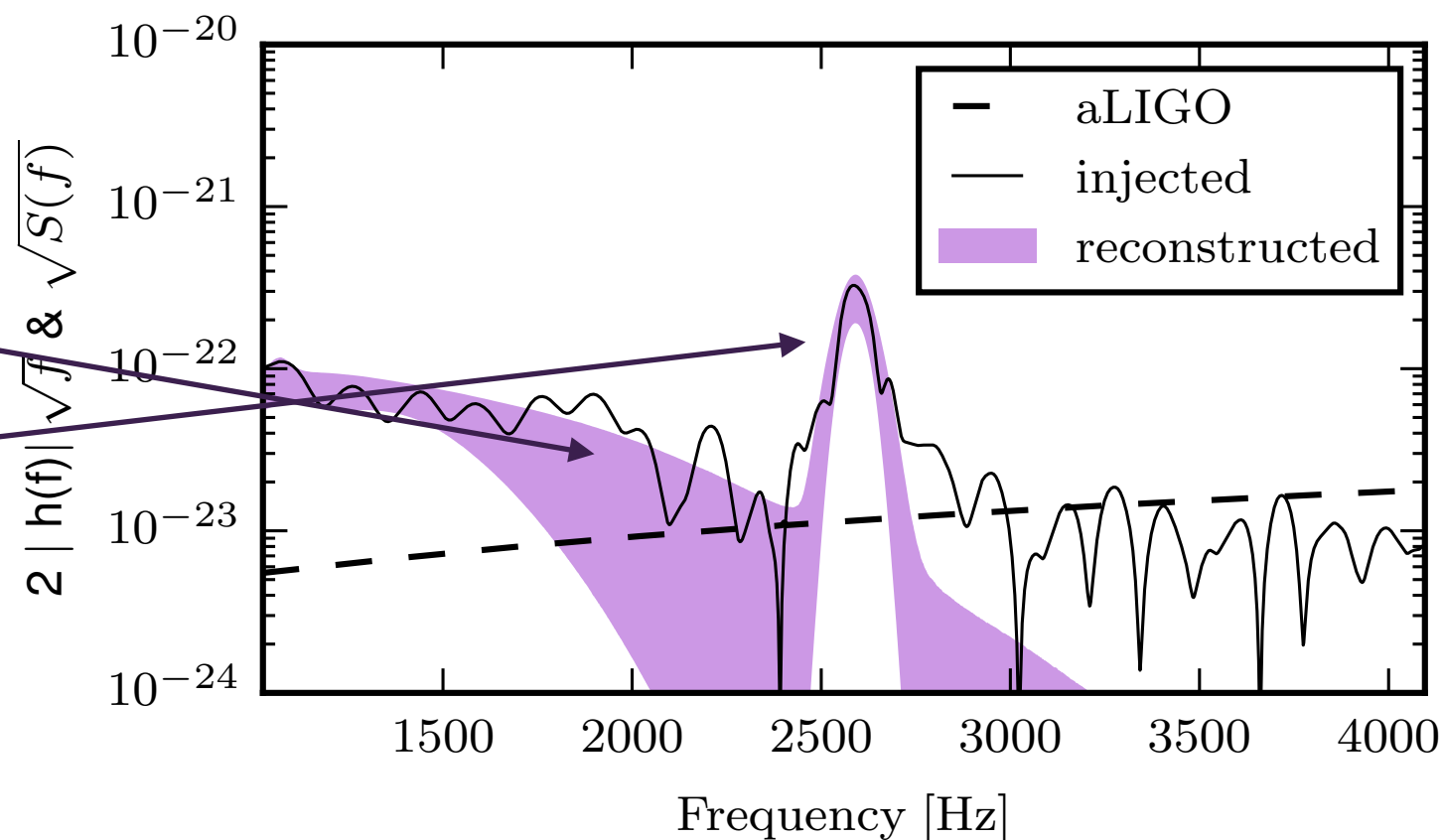
**Reconstruction of the
main peak**

Chatziioannou+ (arxiv:1711.00040)
with numerical data from
Bauswein+ (arxiv:1204.1888)

$$h' \rightarrow \sum^N$$

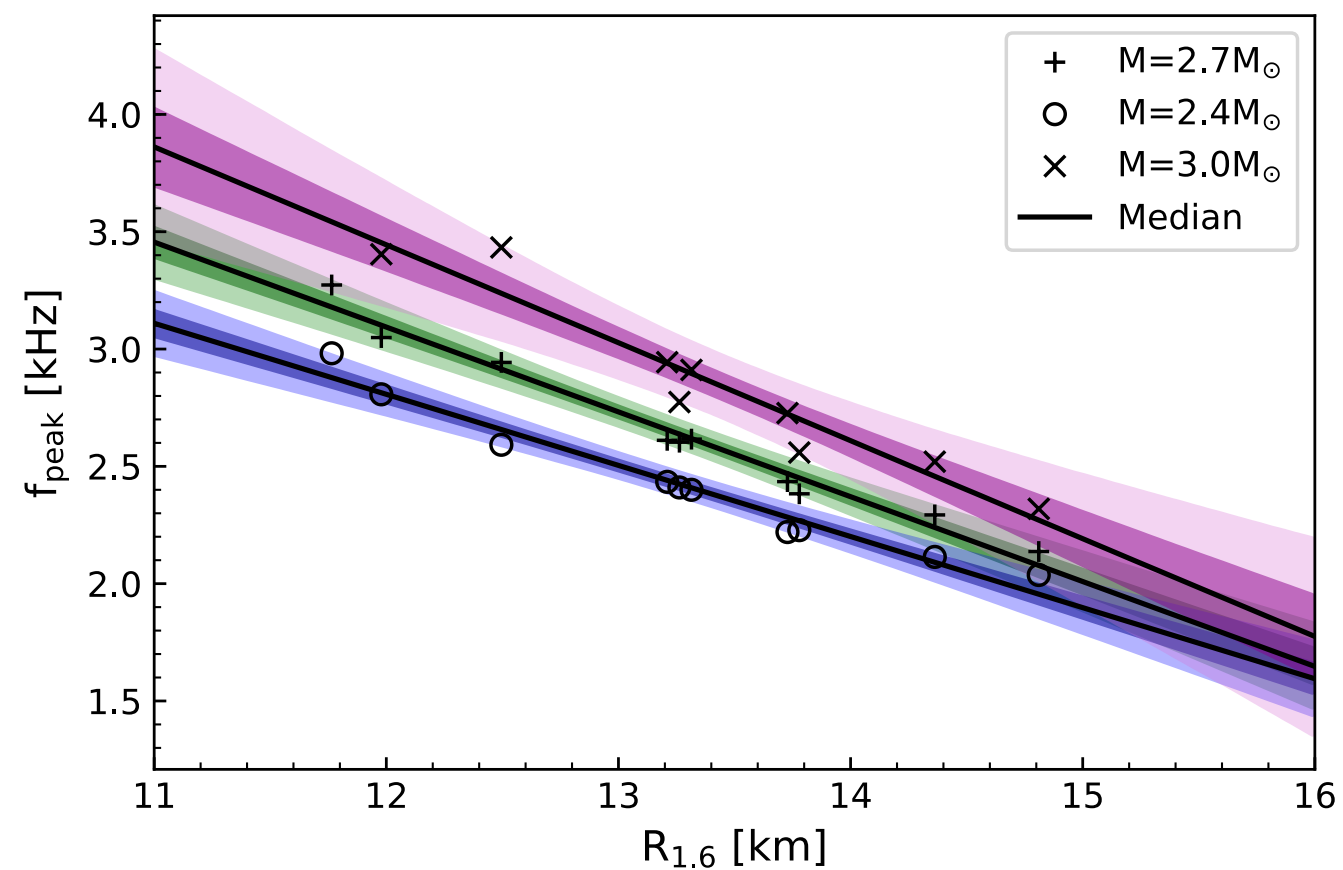
The diagram shows the equation $h' \rightarrow \sum^N$ followed by a blue waveform. This represents the reconstruction of a signal h' as a sum of N individual waveforms.

Cornish, Littenberg (arxiv:1410.3835)

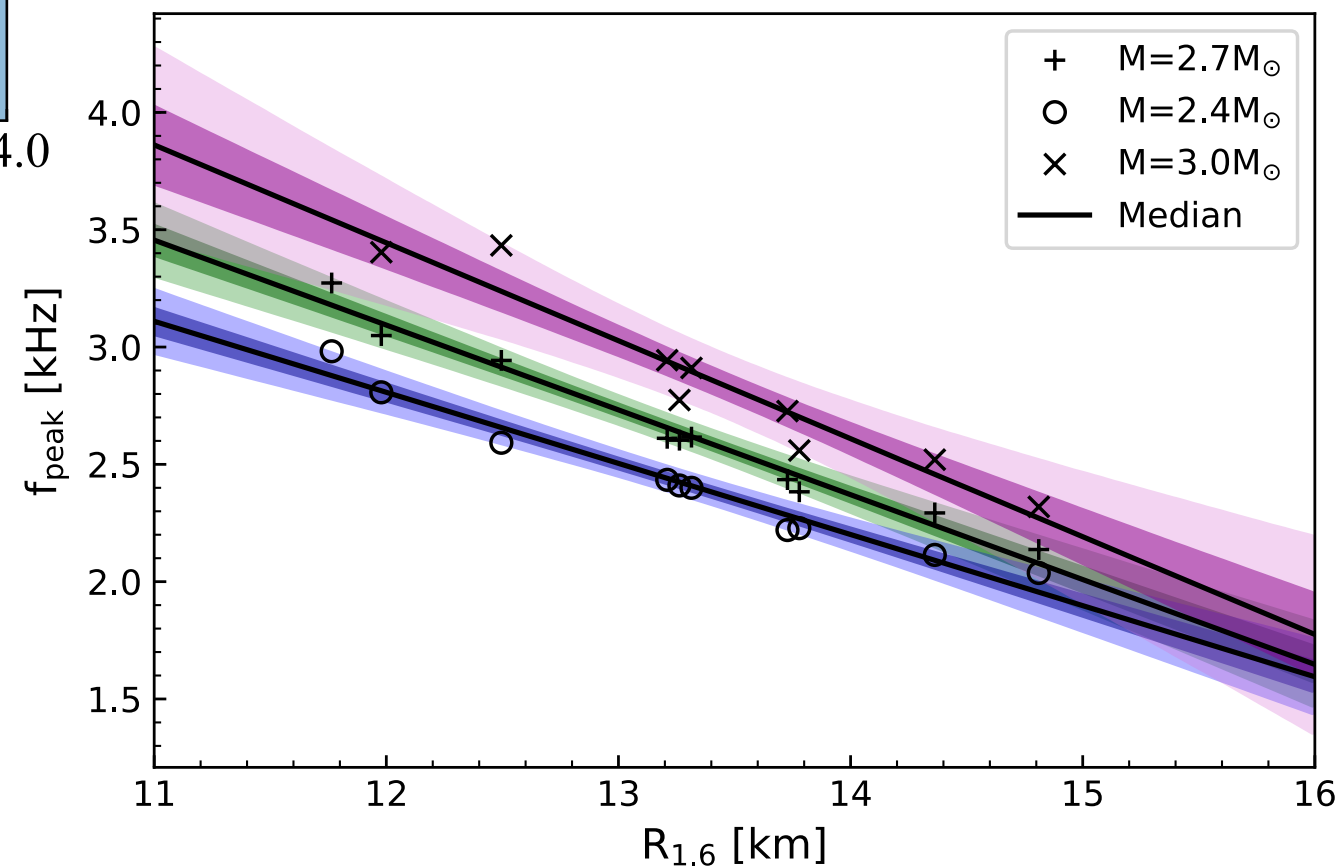
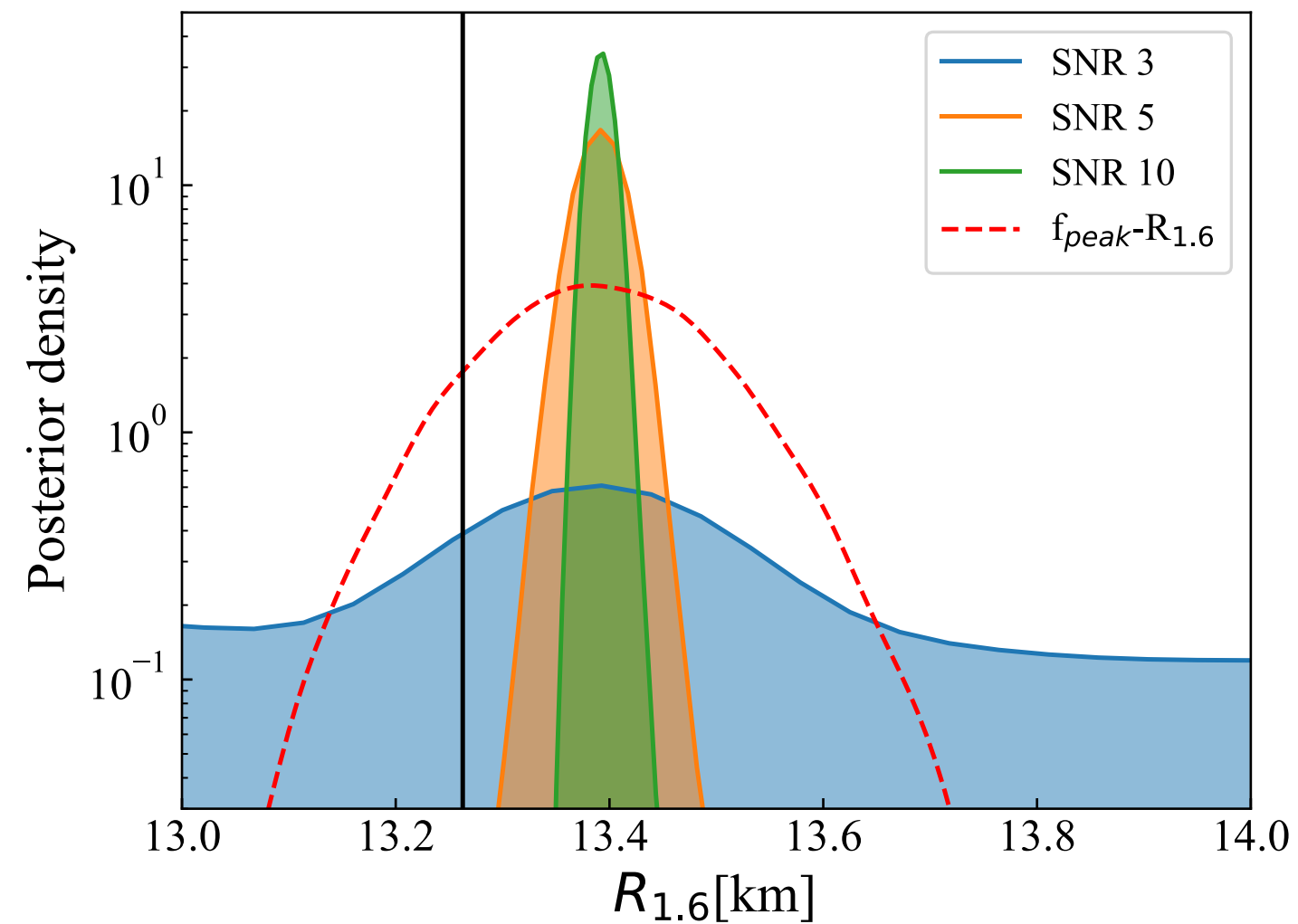


Neutron star radius

Chatziioannou+ (arxiv:1711.00040)
with numerical data from
Bauswein+ (arxiv:1204.1888)

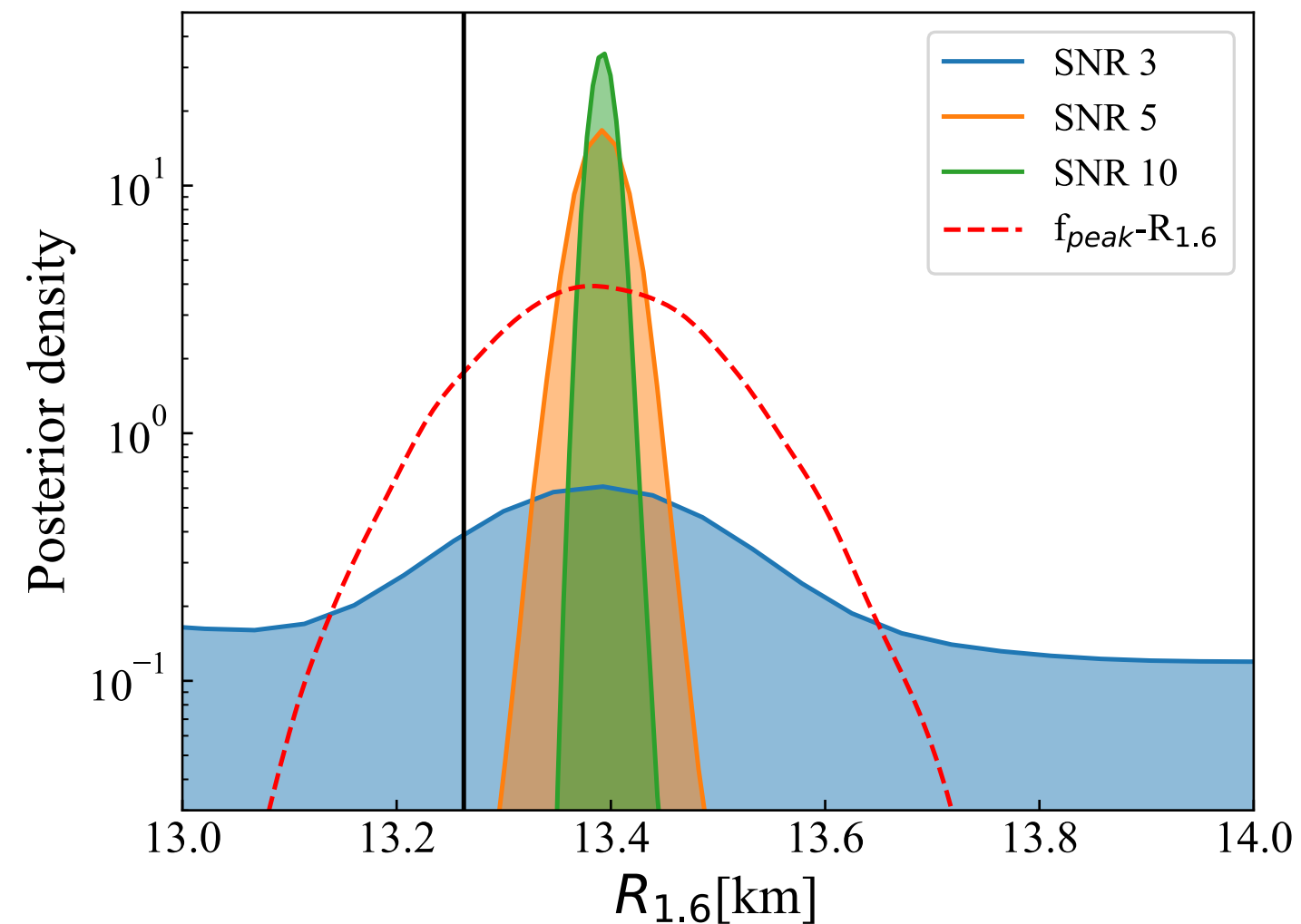


Neutron star radius

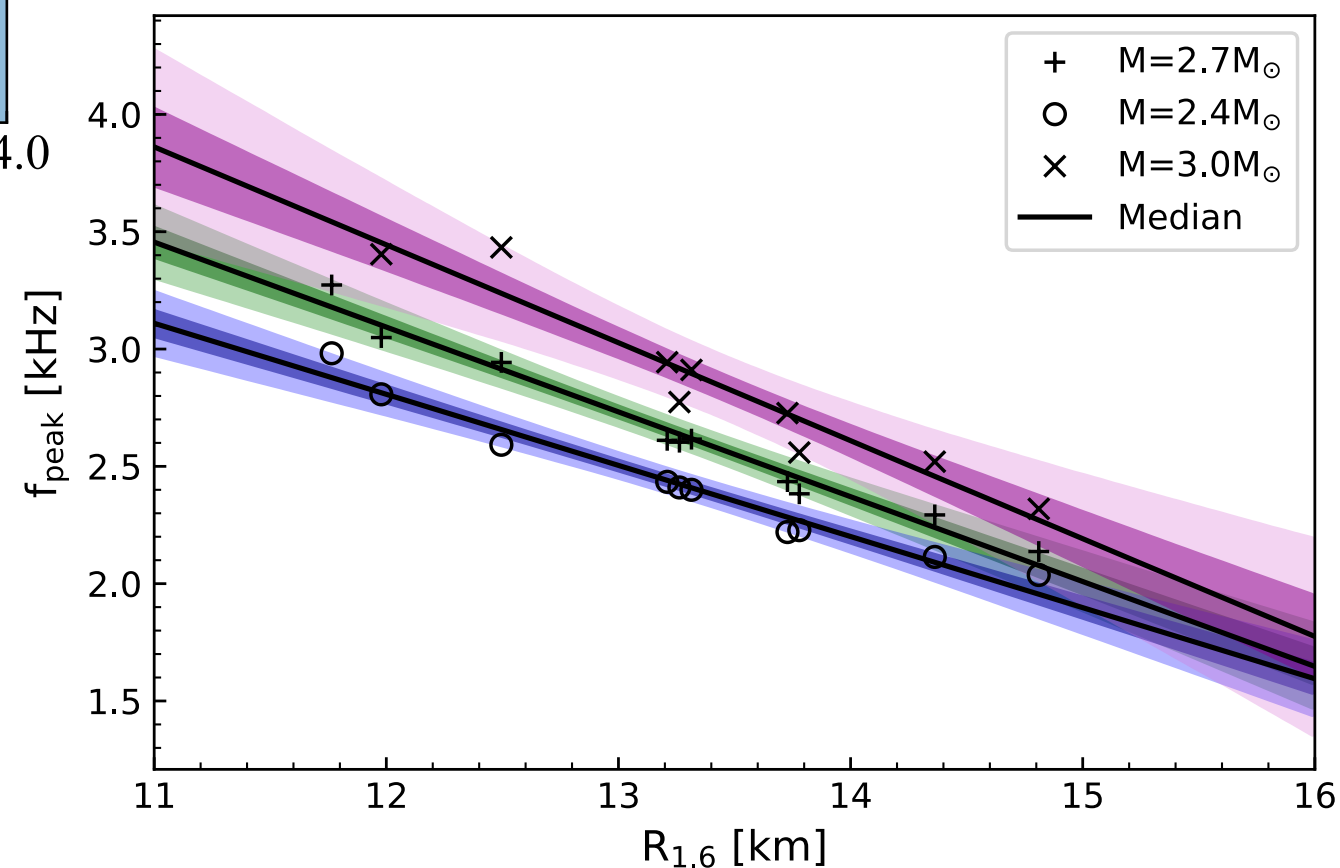


Chatziioannou+ (arxiv:1711.00040)
with numerical data from
Bauswein+ (arxiv:1204.1888)

Neutron star radius



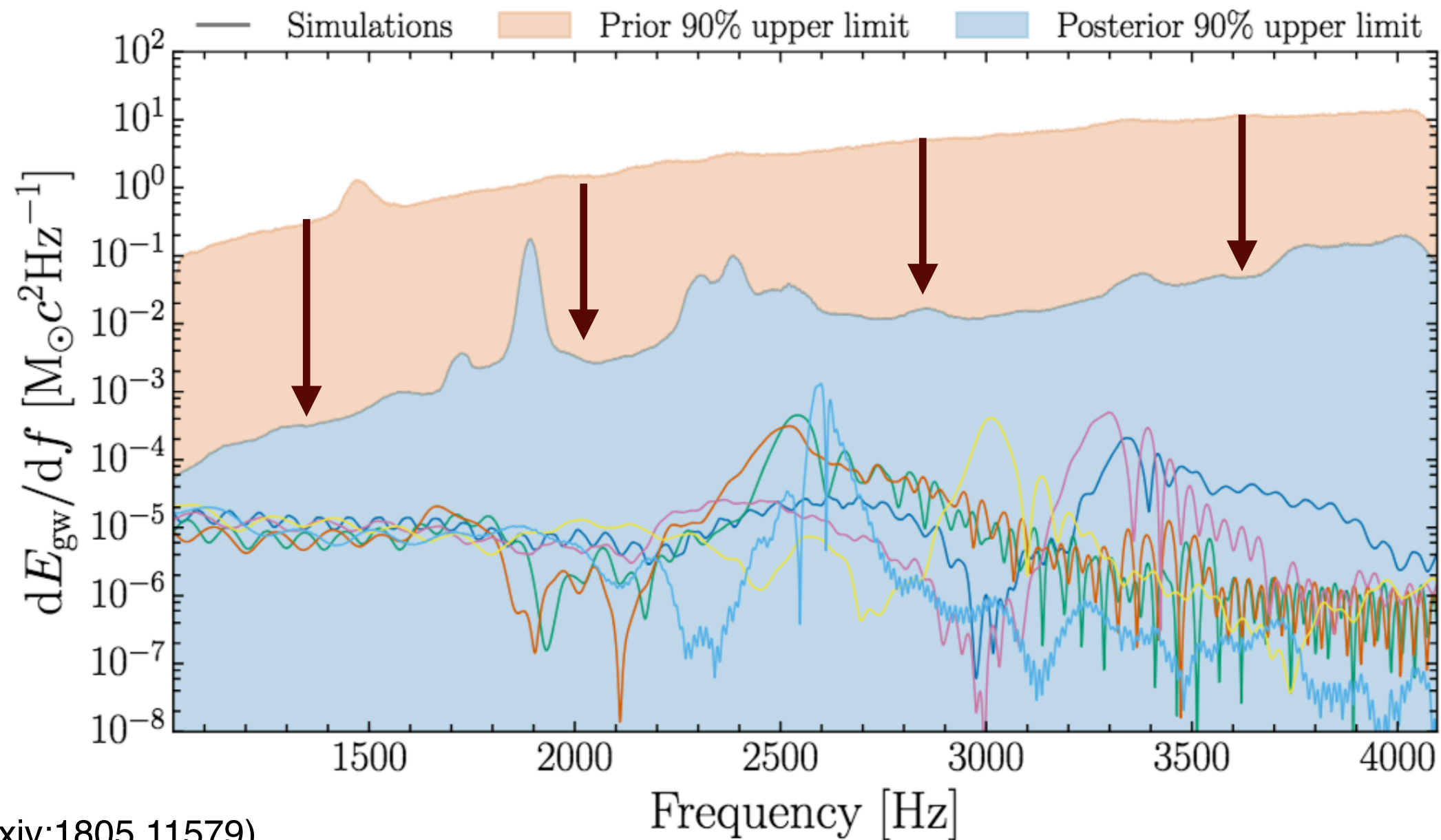
***Radius
measurement to
 $\sim(300-700)m$***



Chatziioannou+ (arxiv:1711.00040)
with numerical data from
Bauswein+ (arxiv:1204.1888)

GW170817

No detectable post-merger emission, upper limits



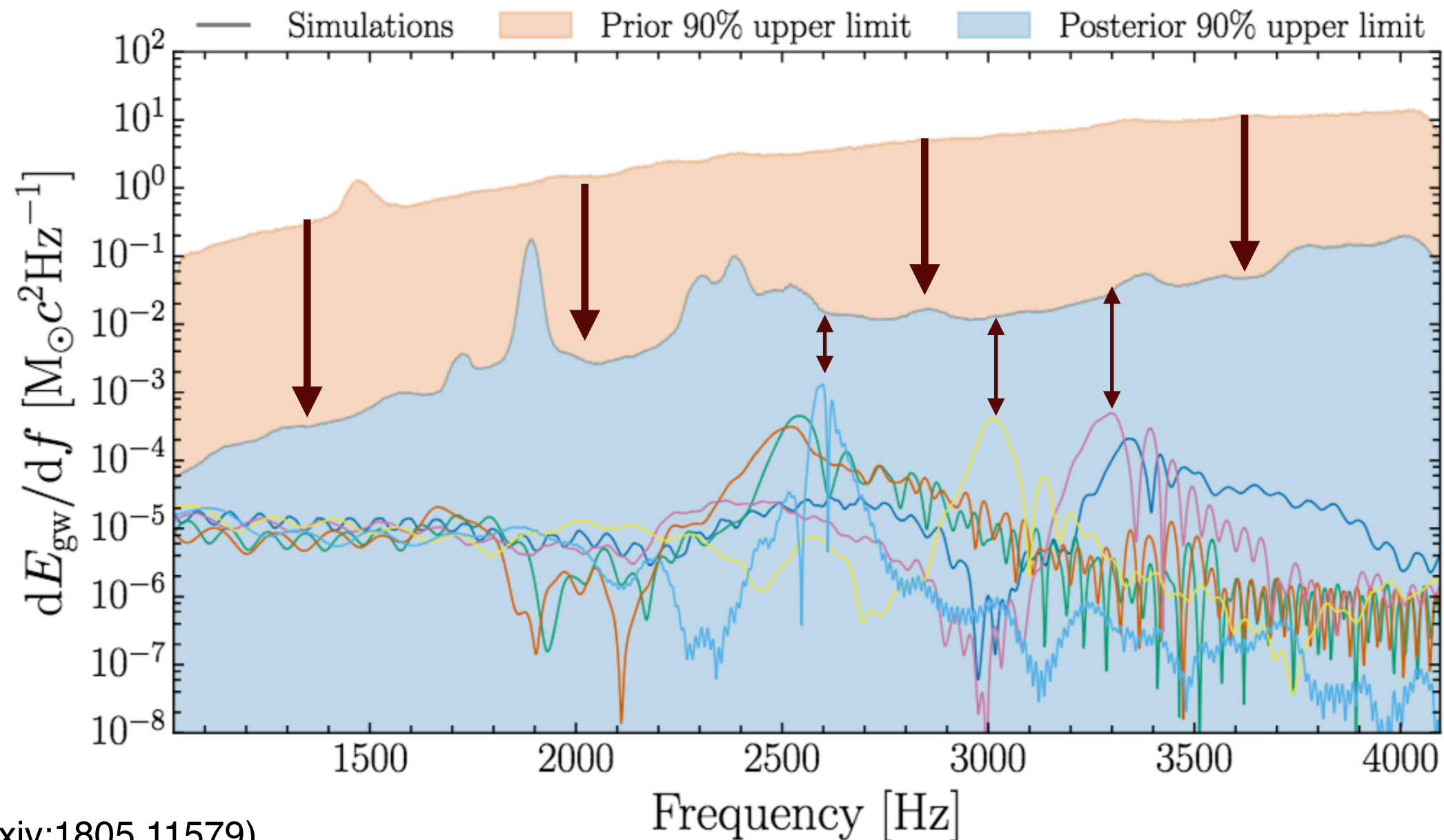
LVC (arxiv:1805.11579)

Analysis: Chatziioannou+ (arxiv:1711.00040)

Simulations: Bauswein+ (arxiv:1204.1888)

GW170817

No detectable post-merger emission, upper limits



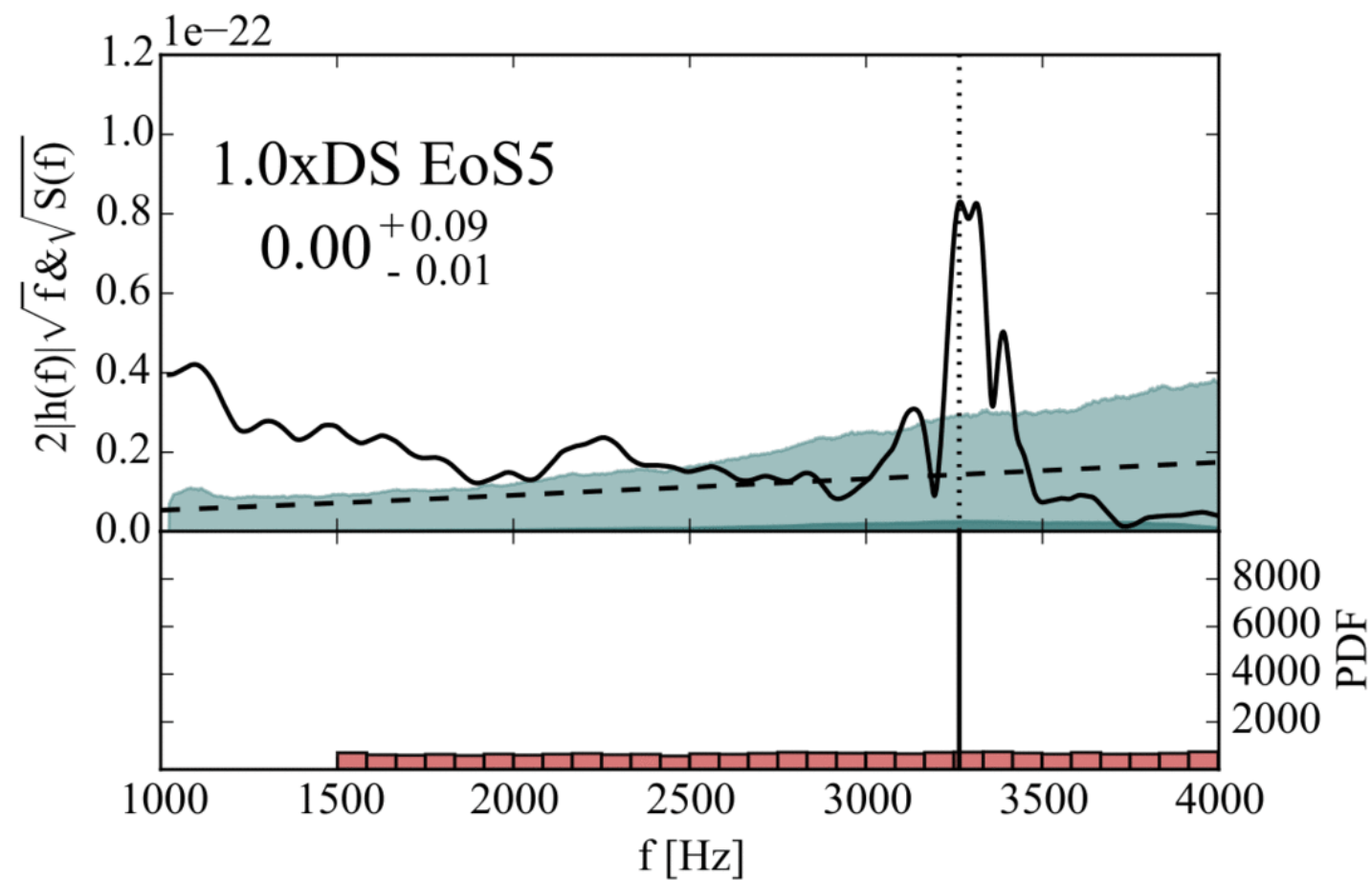
LVC (arxiv:1805.11579)

Analysis: Chatziioannou+ (arxiv:1711.00040)

Simulations: Bauswein+ (arxiv:1204.1888)

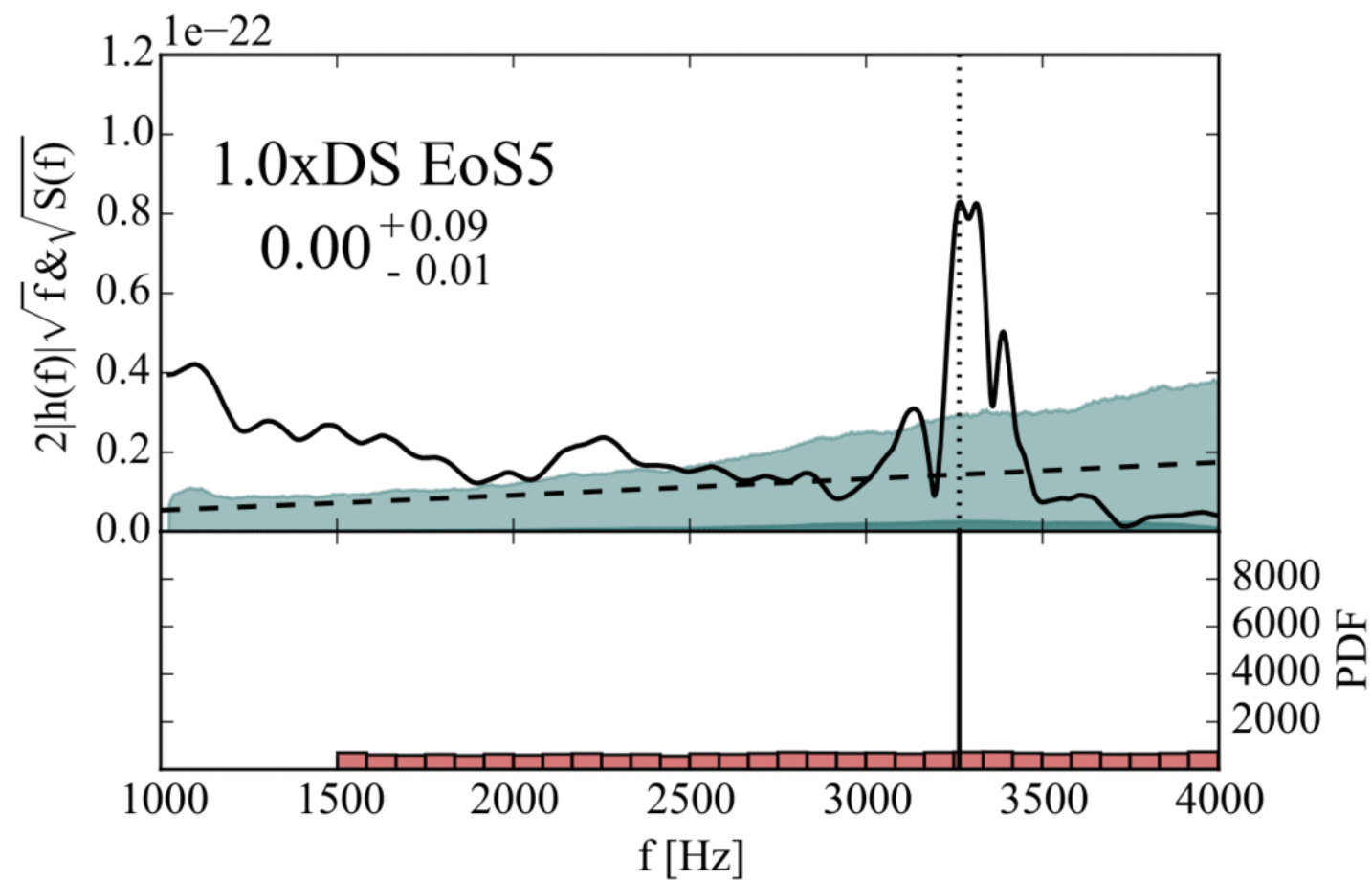
We need a 3-10 improvement in high frequencies

Instrumental upgrades



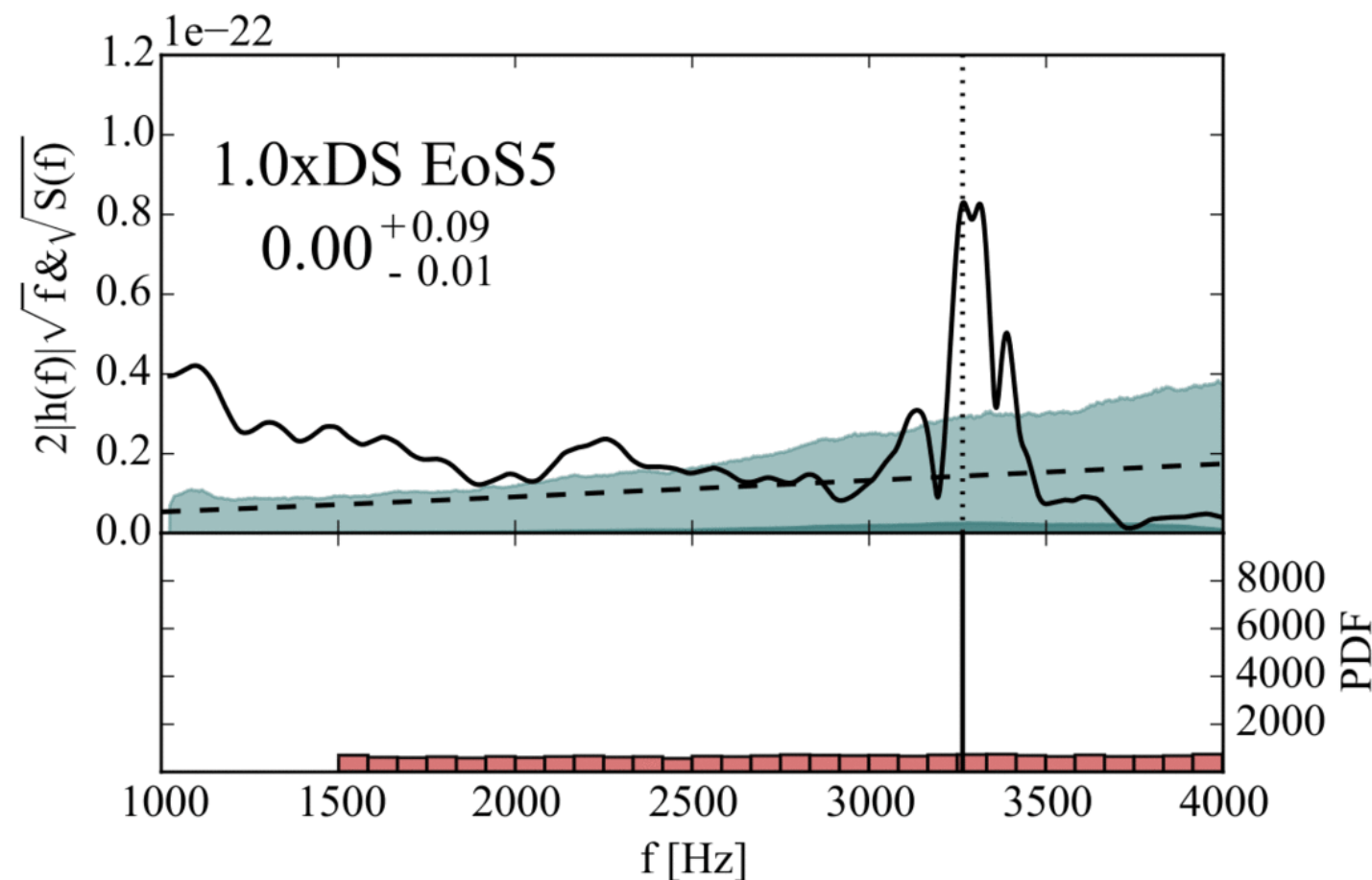
Torres-Rivas+ (including KC) (arxiv:1811.08931)

Instrumental upgrades



Torres-Rivas+ (including KC) (arxiv:1811.08931)

Instrumental upgrades

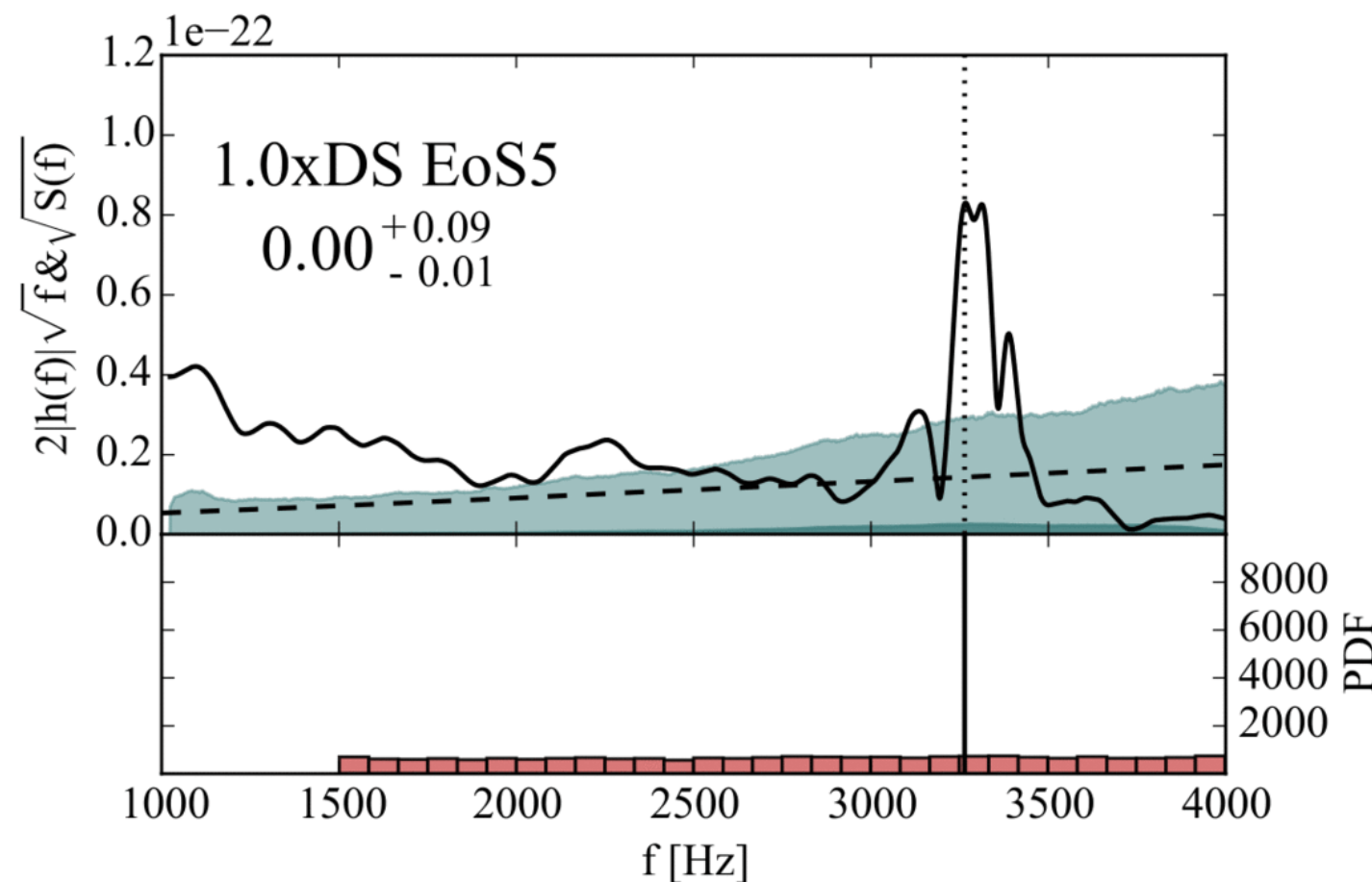


An instrument **2-3 times** better than aLIGO would have observed the GW170817 post-merger

Within reach of proposed and/or funded instruments

Torres-Rivas+ (including KC) (arxiv:1811.08931)

Instrumental upgrades



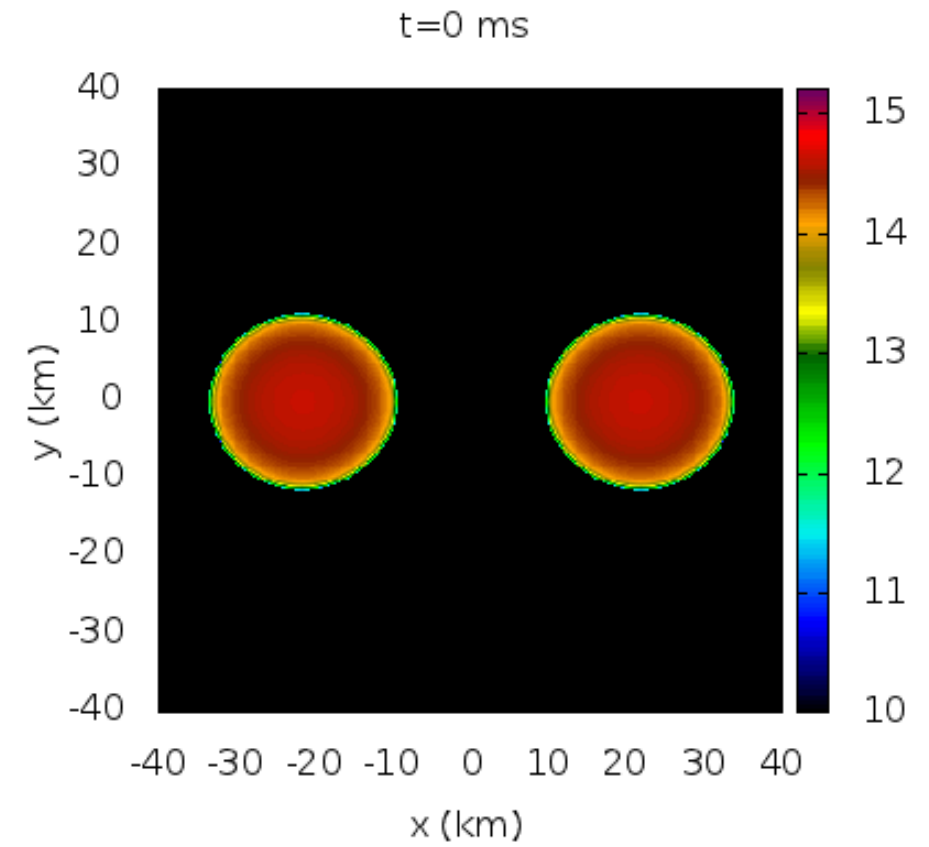
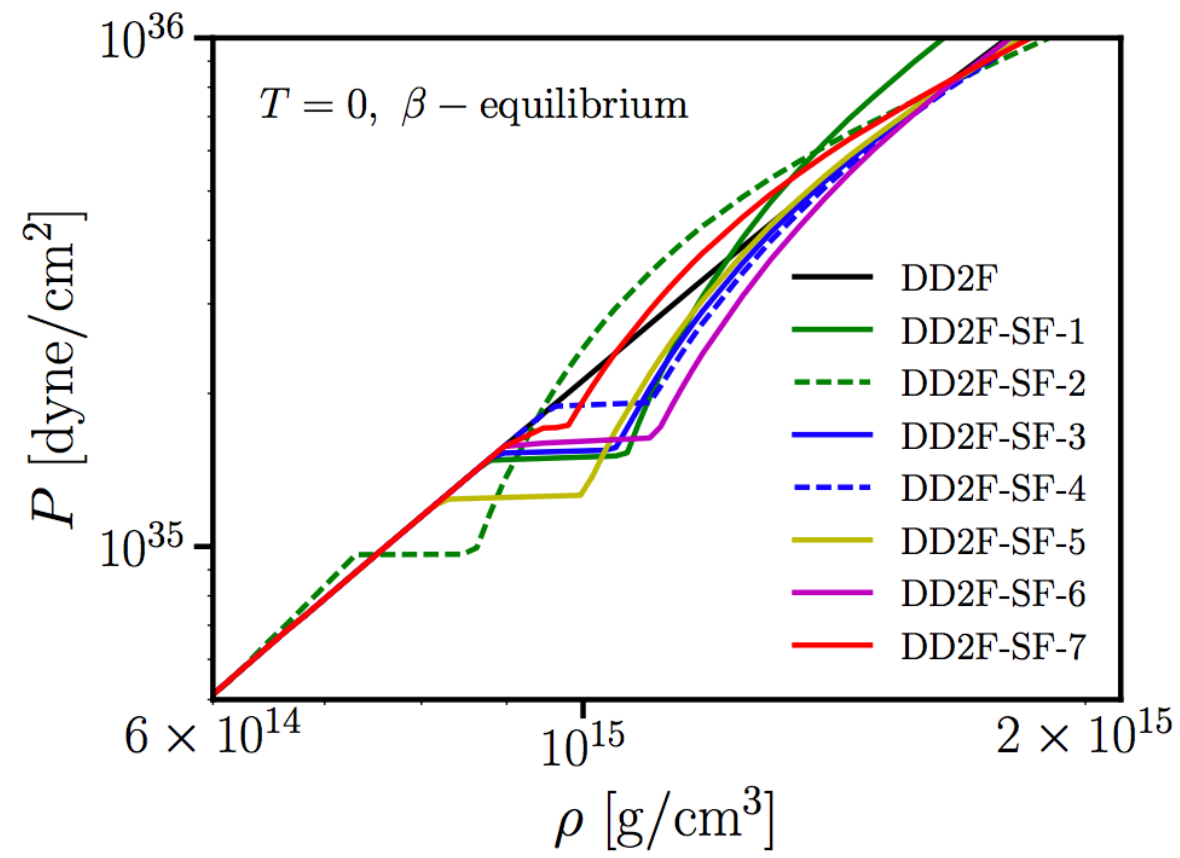
An instrument **2-3 times** better than aLIGO would have observed the GW170817 post-merger

Within reach of proposed and/or funded instruments

Torres-Rivas+ (including KC) (arxiv:1811.08931)

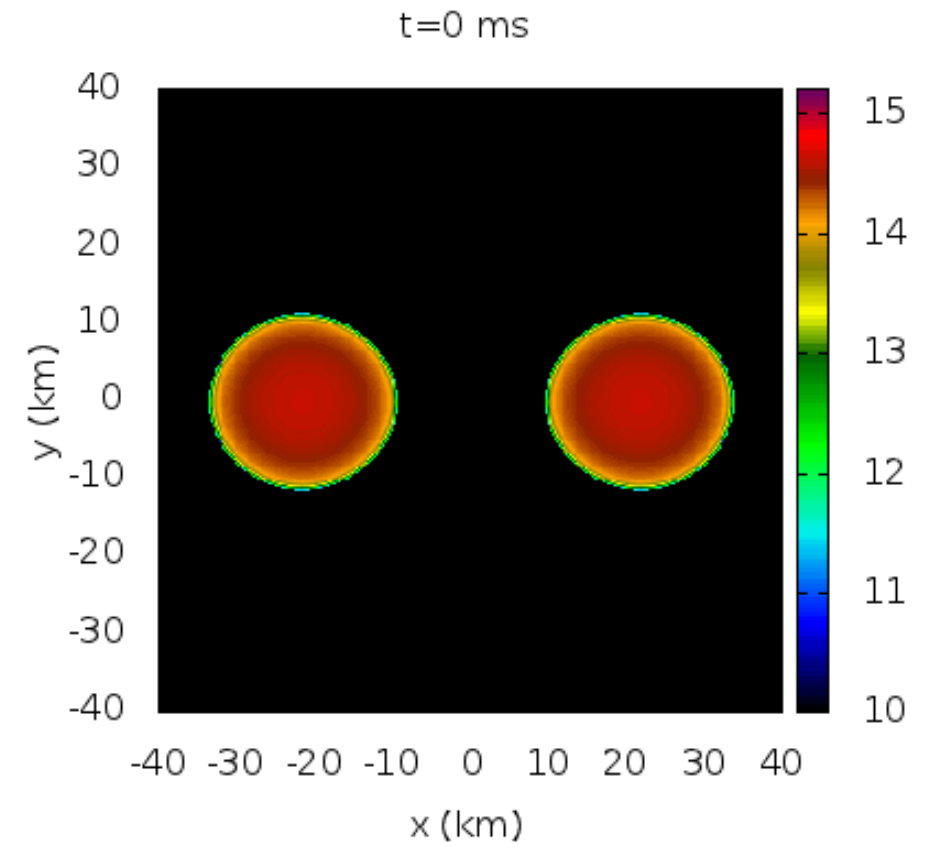
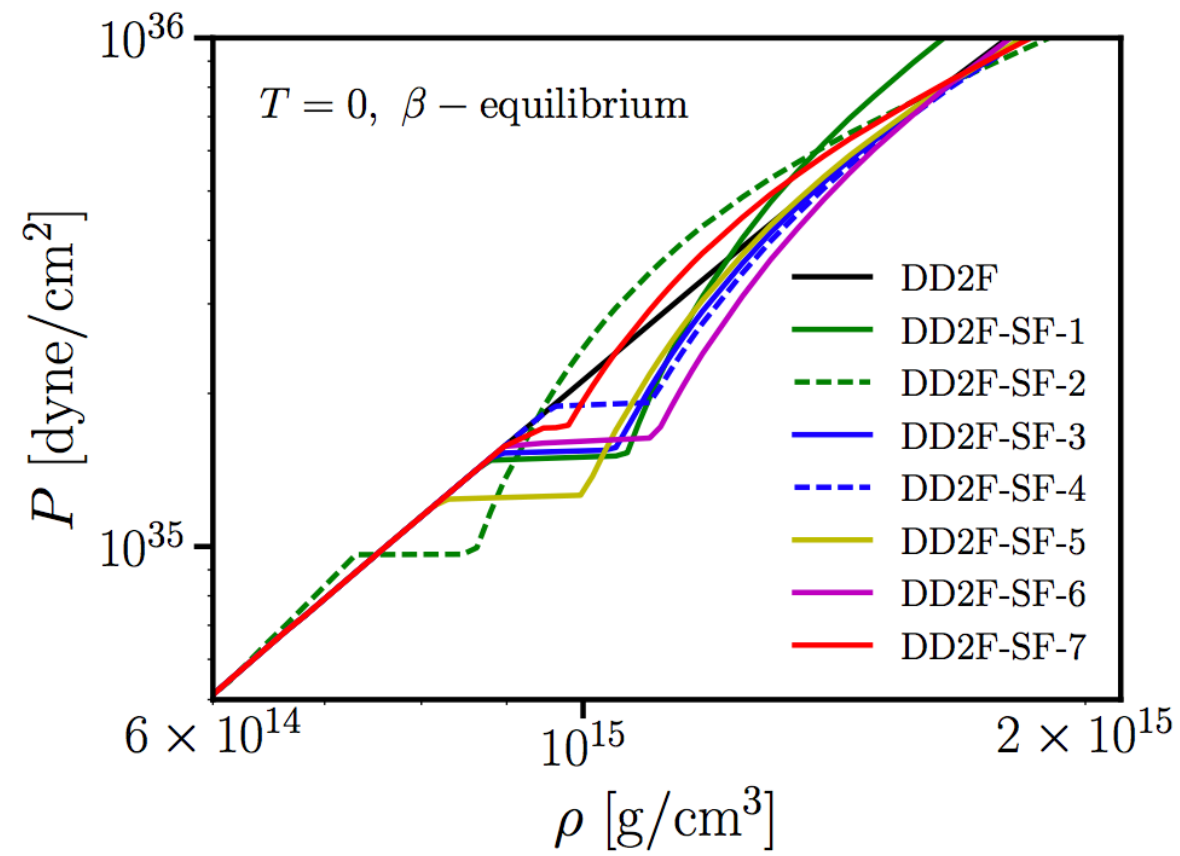
Analysis improvements can also reduce the time to detection (under construction)

Quark phase transition



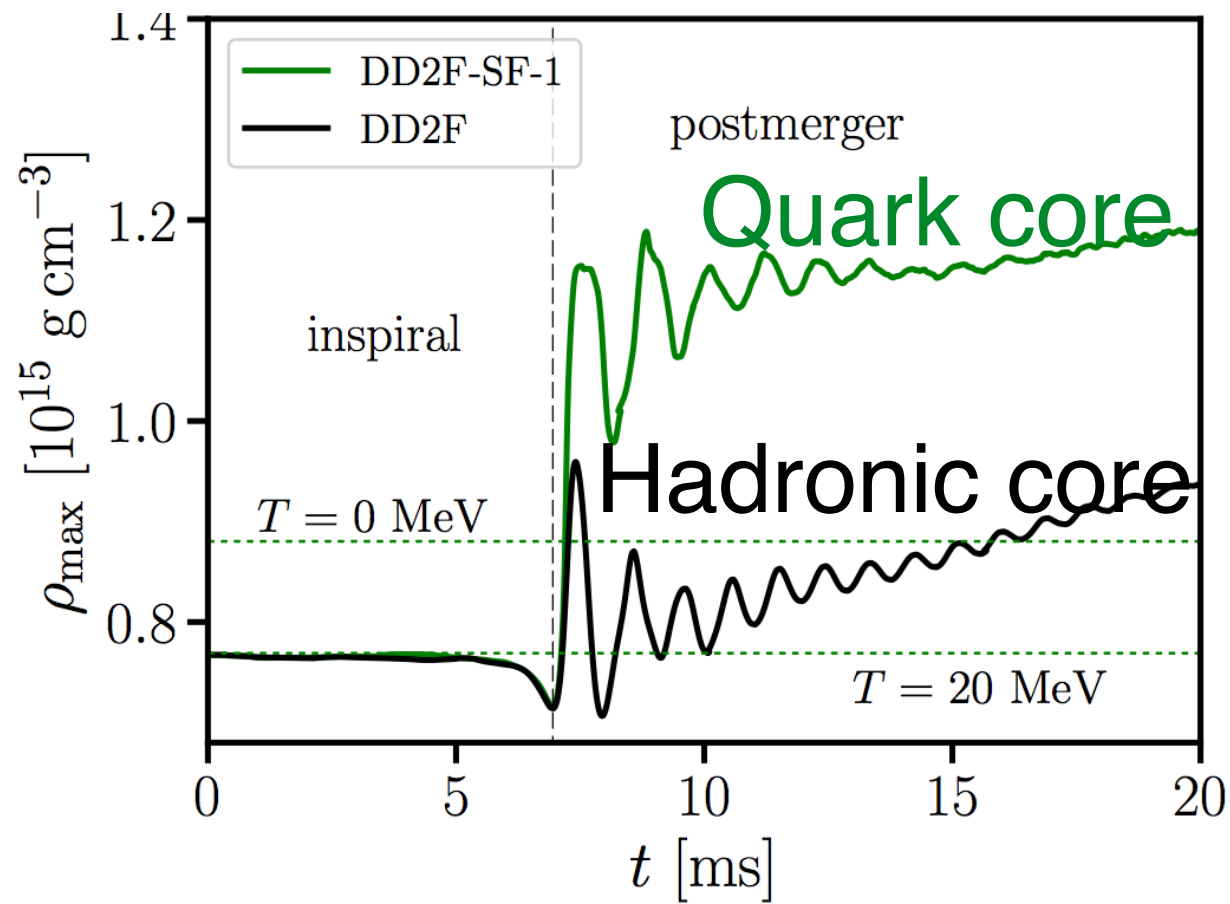
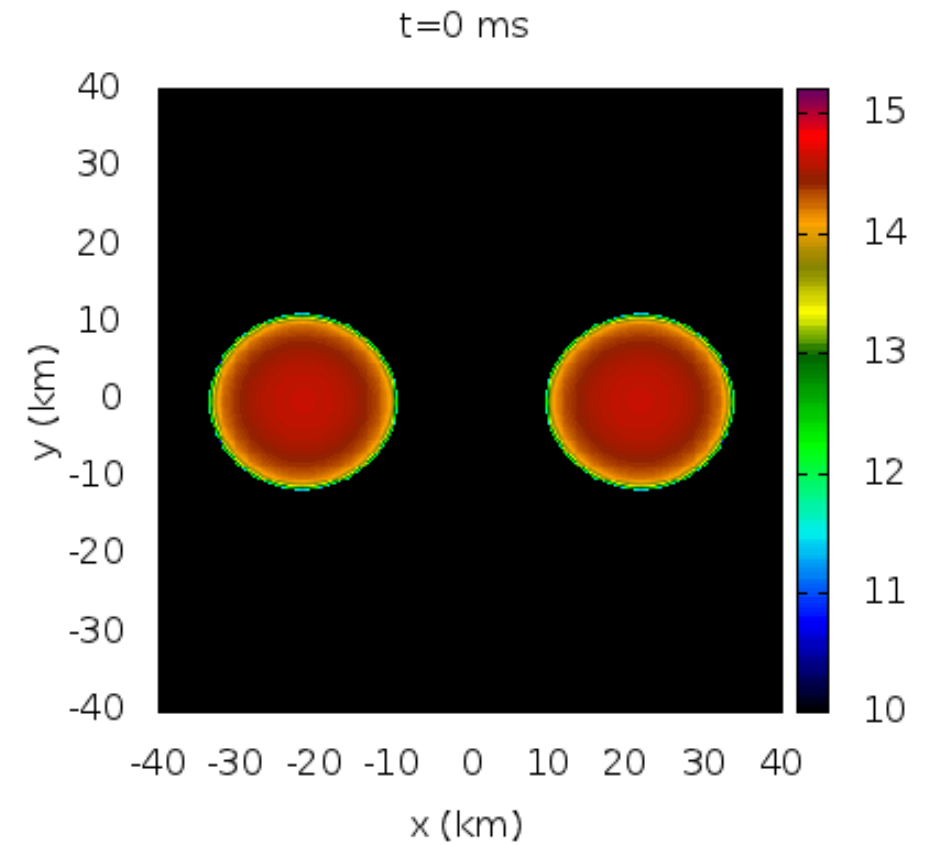
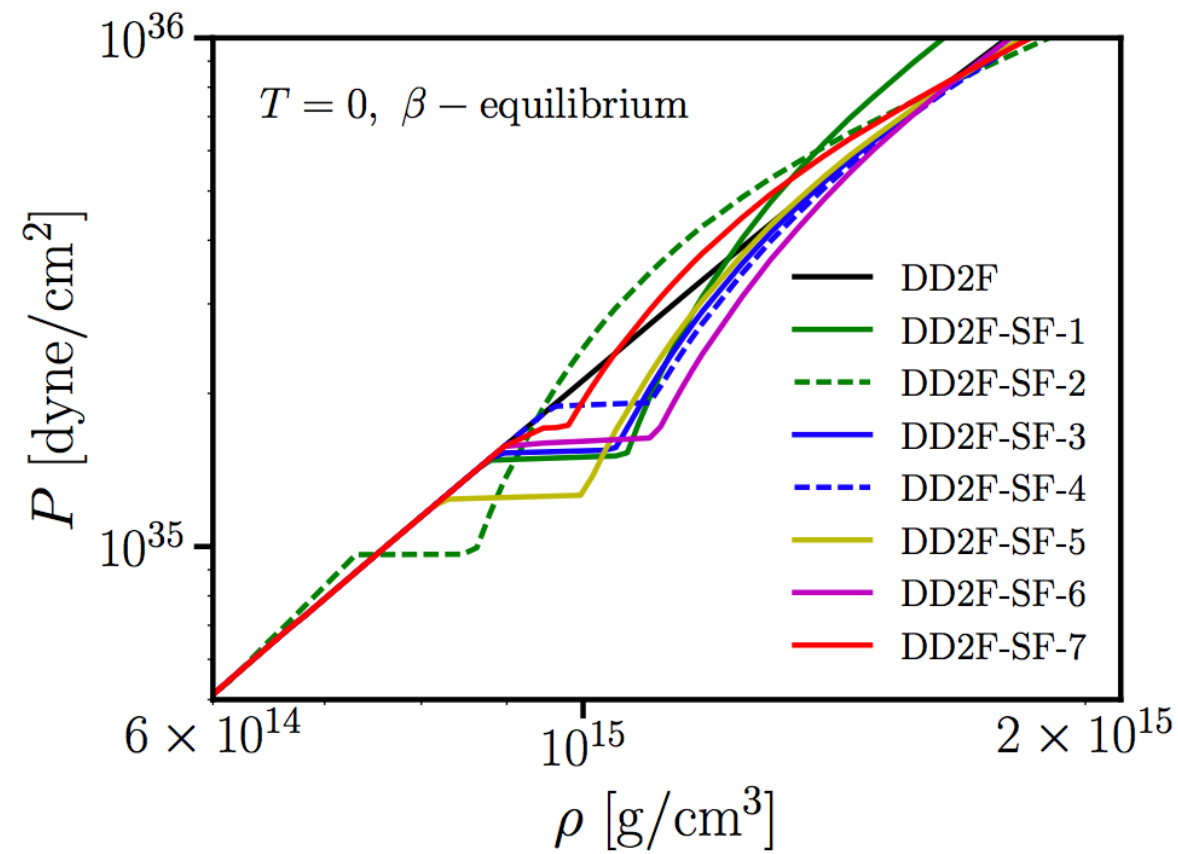
Simulations by Kenta Hotokezaka

Quark phase transition



Simulations by Kenta Hotokezaka

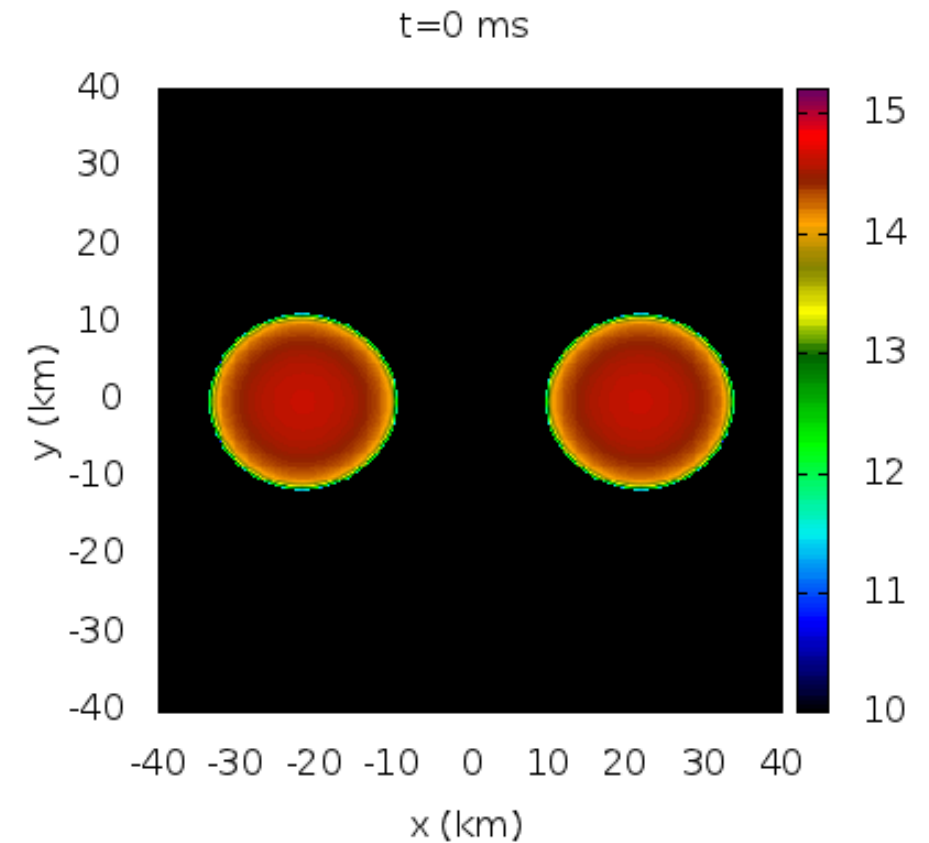
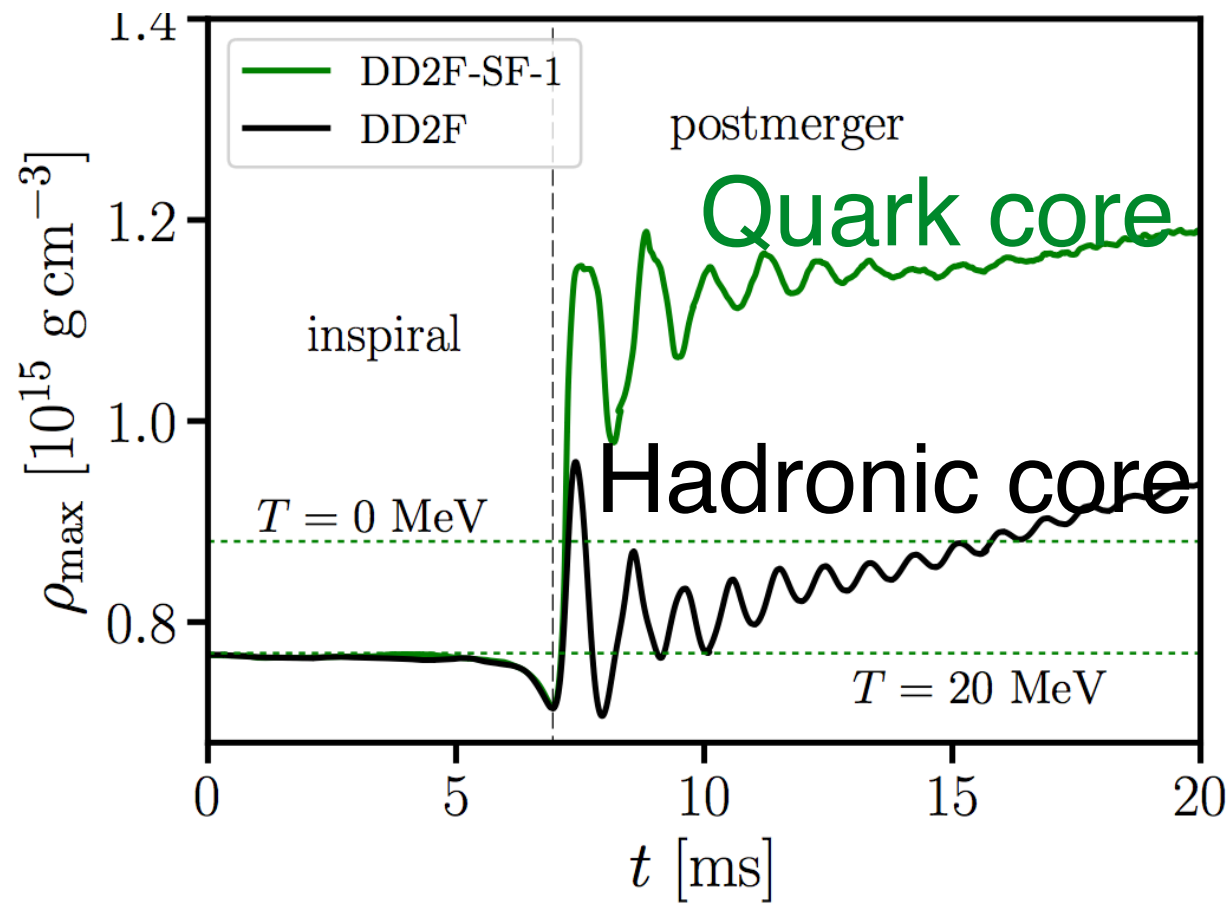
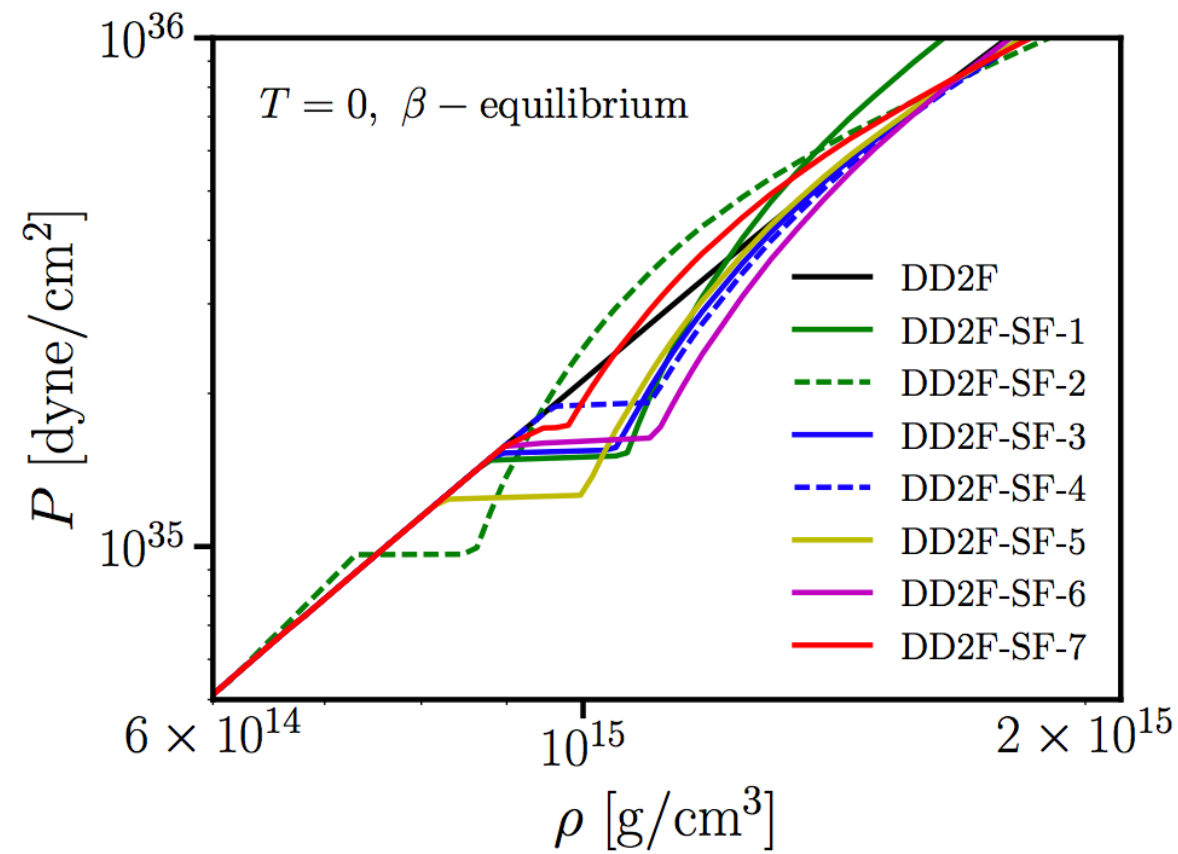
Quark phase transition



Simulations by Kenta Hotokezaka

Bauswein+ (including KC) (arxiv:1809.01116)

Quark phase transition

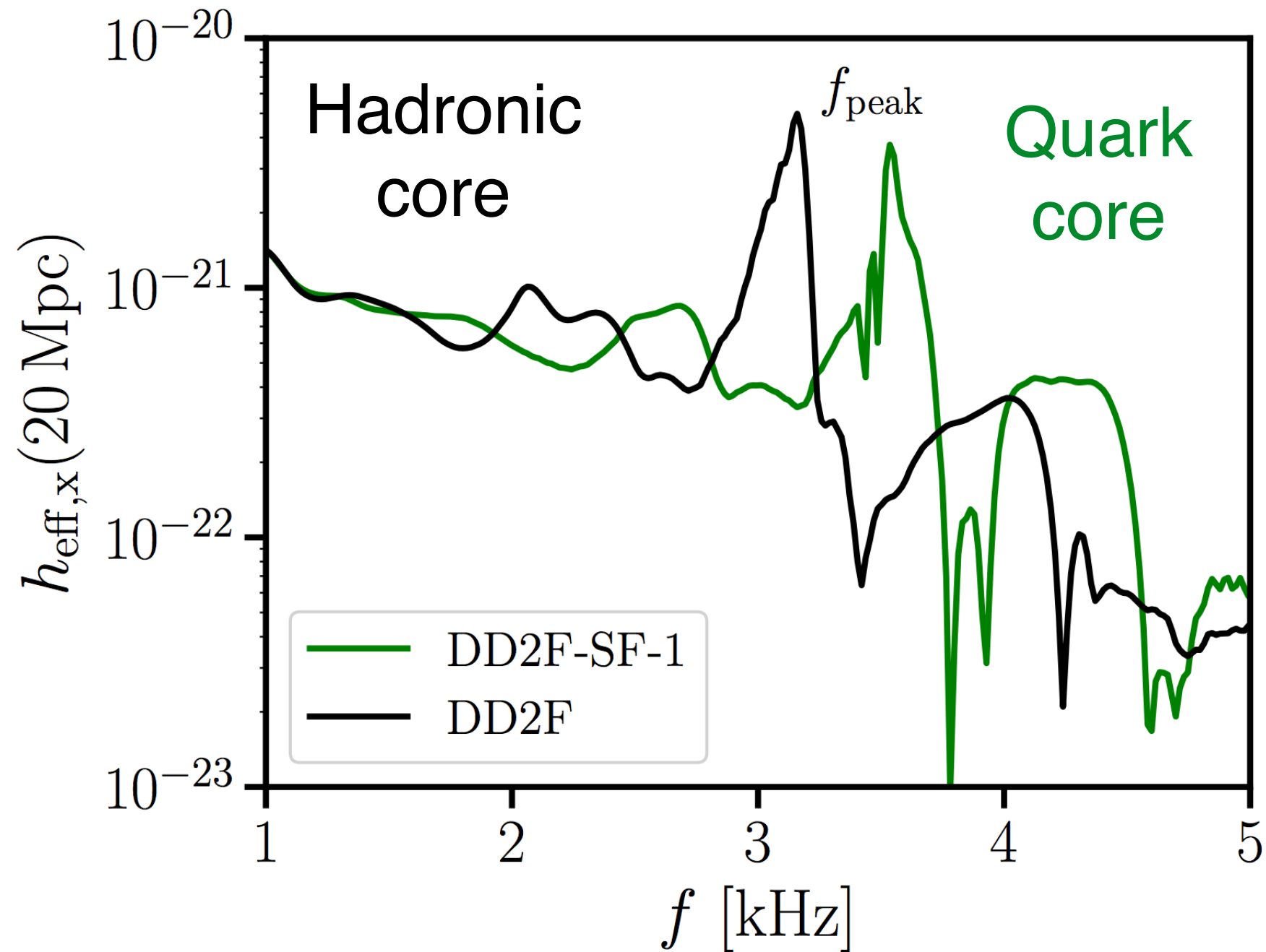


Simulations by Kenta Hotokezaka

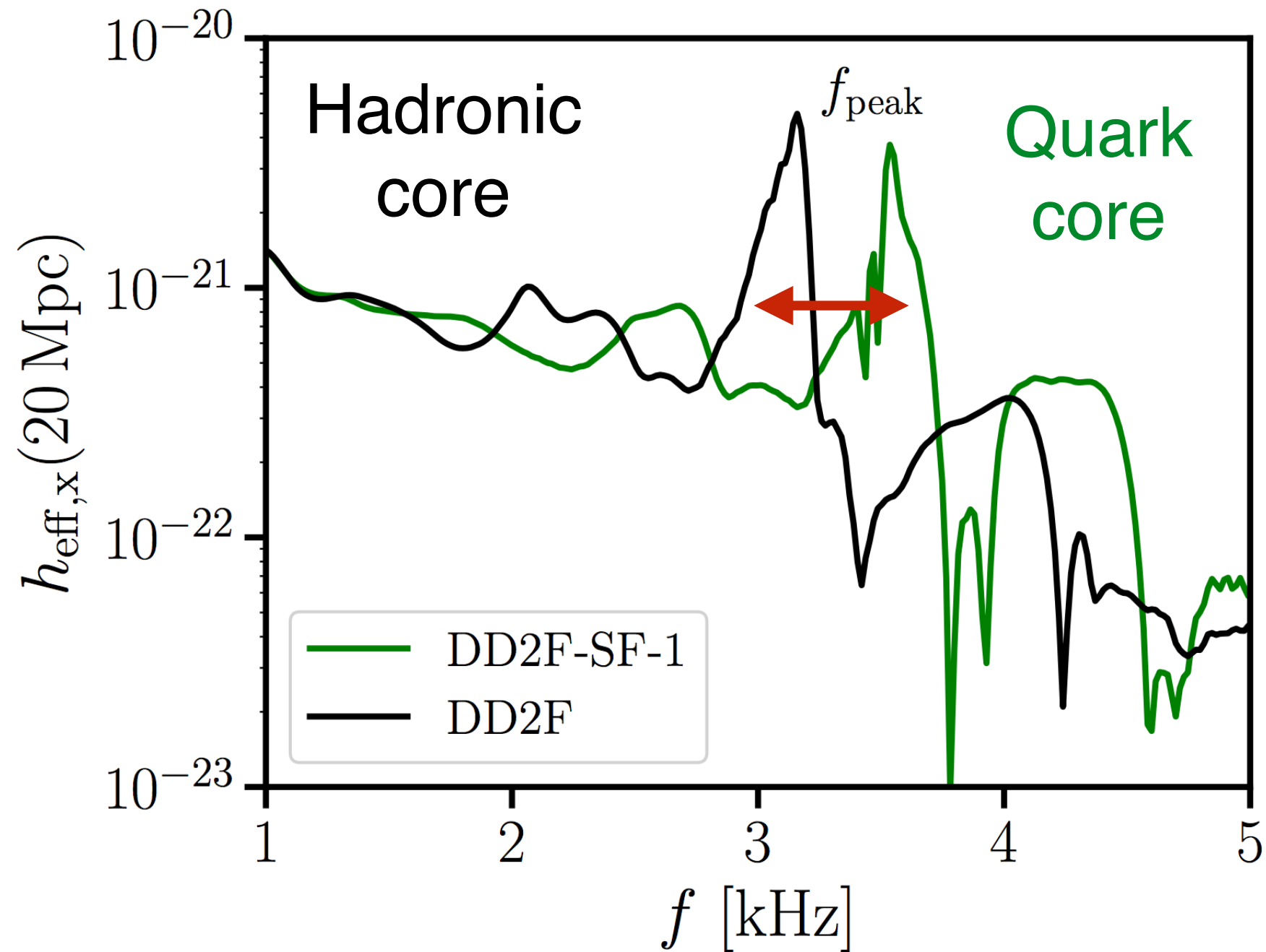
The merger remnant exceeds the threshold density for the phase transition, and ‘develops’ a **dense quark core**

Bauswein+ (including KC) (arxiv:1809.01116)

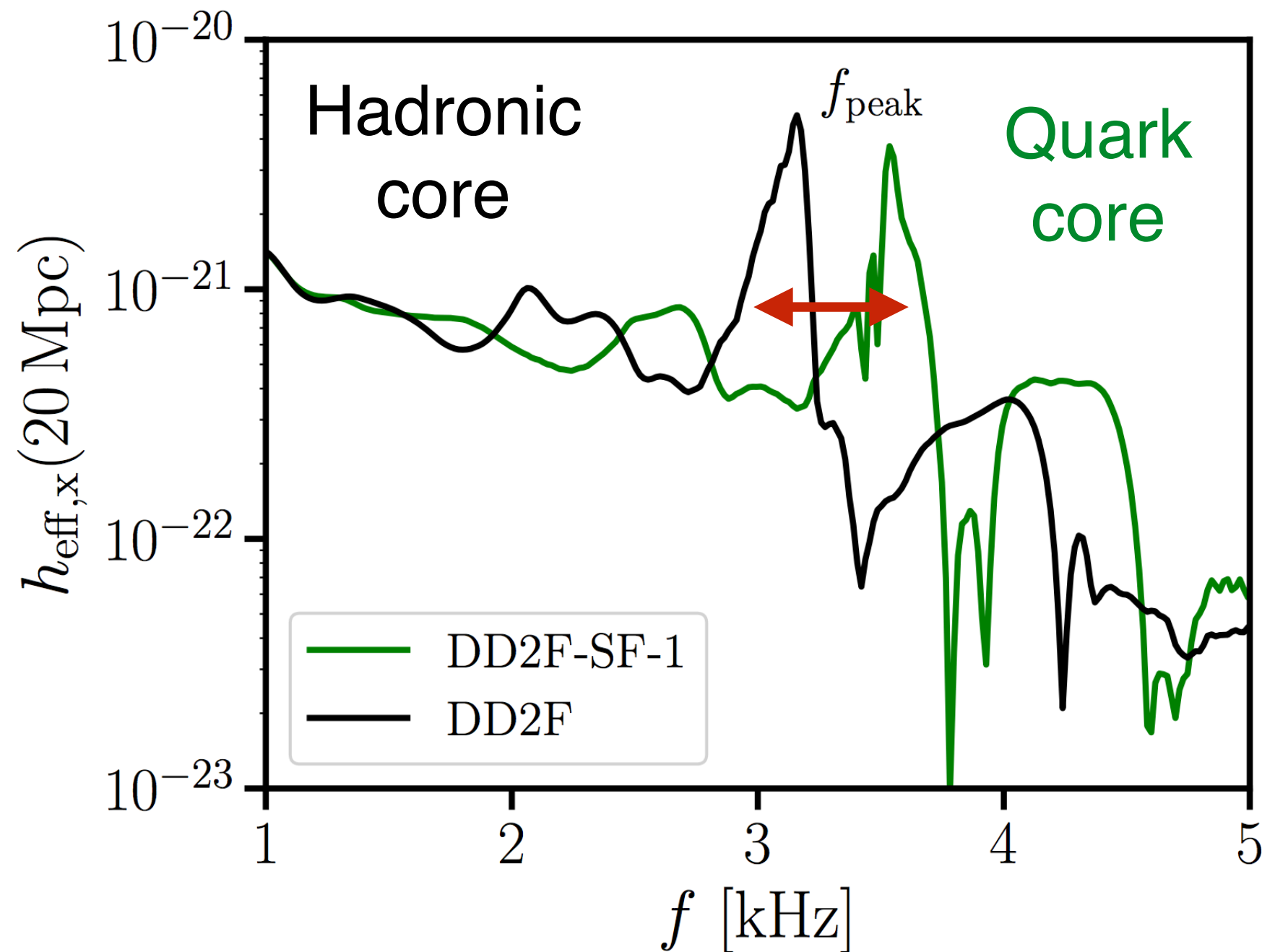
Observational effect



Observational effect

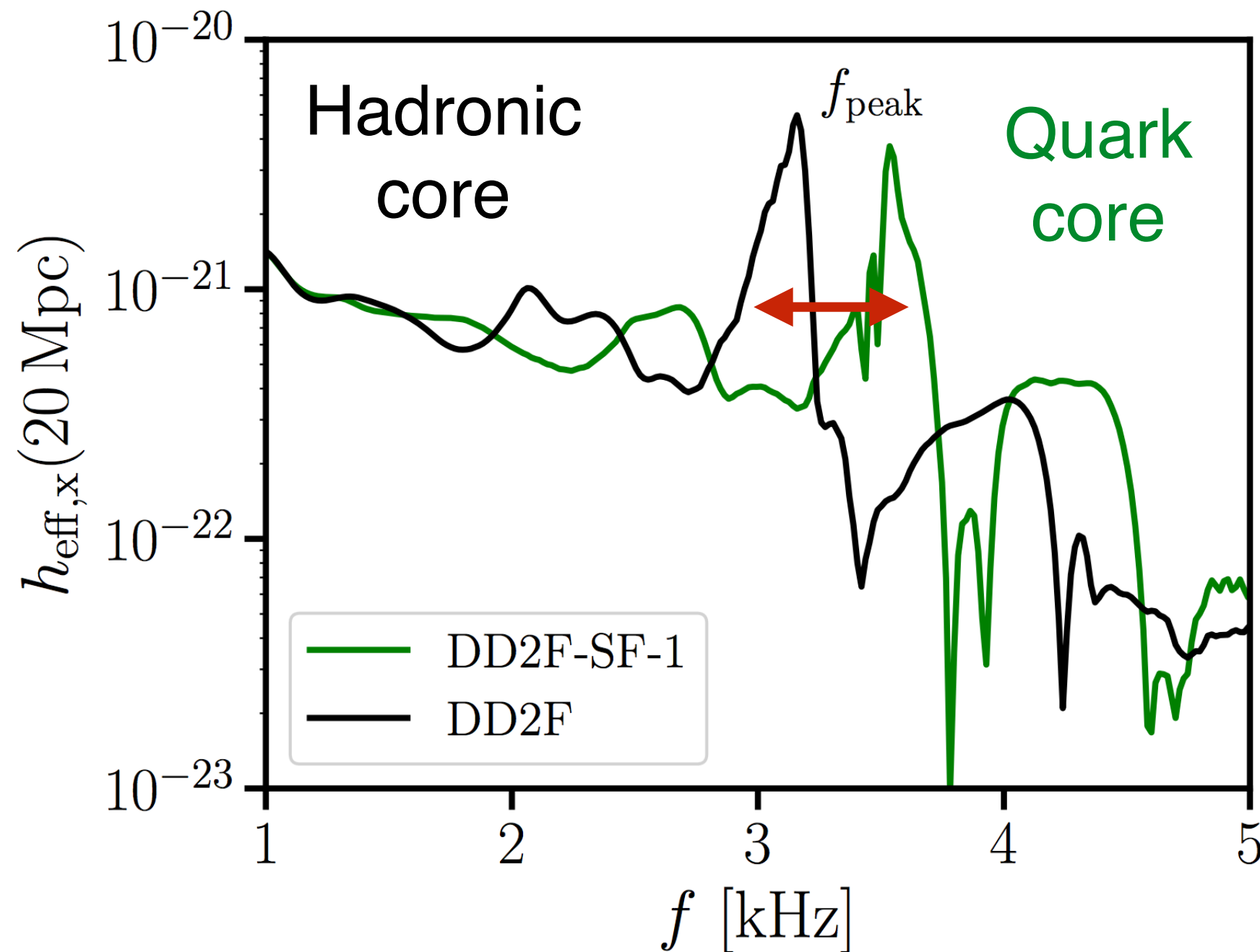


Observational effect



The characteristic peak moves to higher frequencies

Observational effect



The characteristic peak moves to higher frequencies

Degenerate with the softness of the hadronic EoS

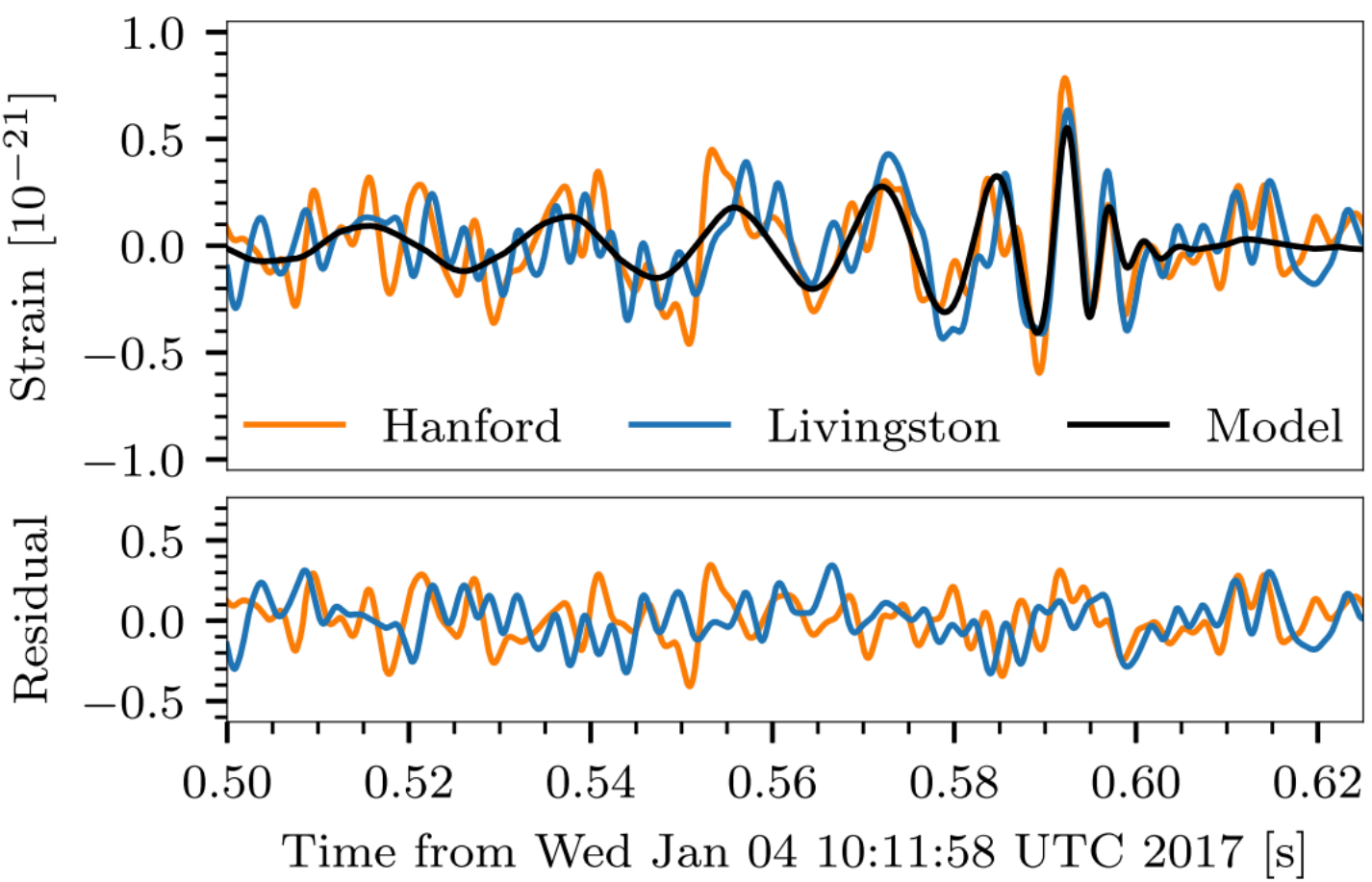
Tests of General Relativity

Test of wave **generation** and tests of wave **propagation**

- Inspiral-merger-ringdown consistency
- Parametric waveform deviations
- Lorenz invariance
- Polarization content
- Post-merger echoes
- Merger properties
- Extra dimensions (with neutron stars)
- Speed of gravity (with neutron stars)

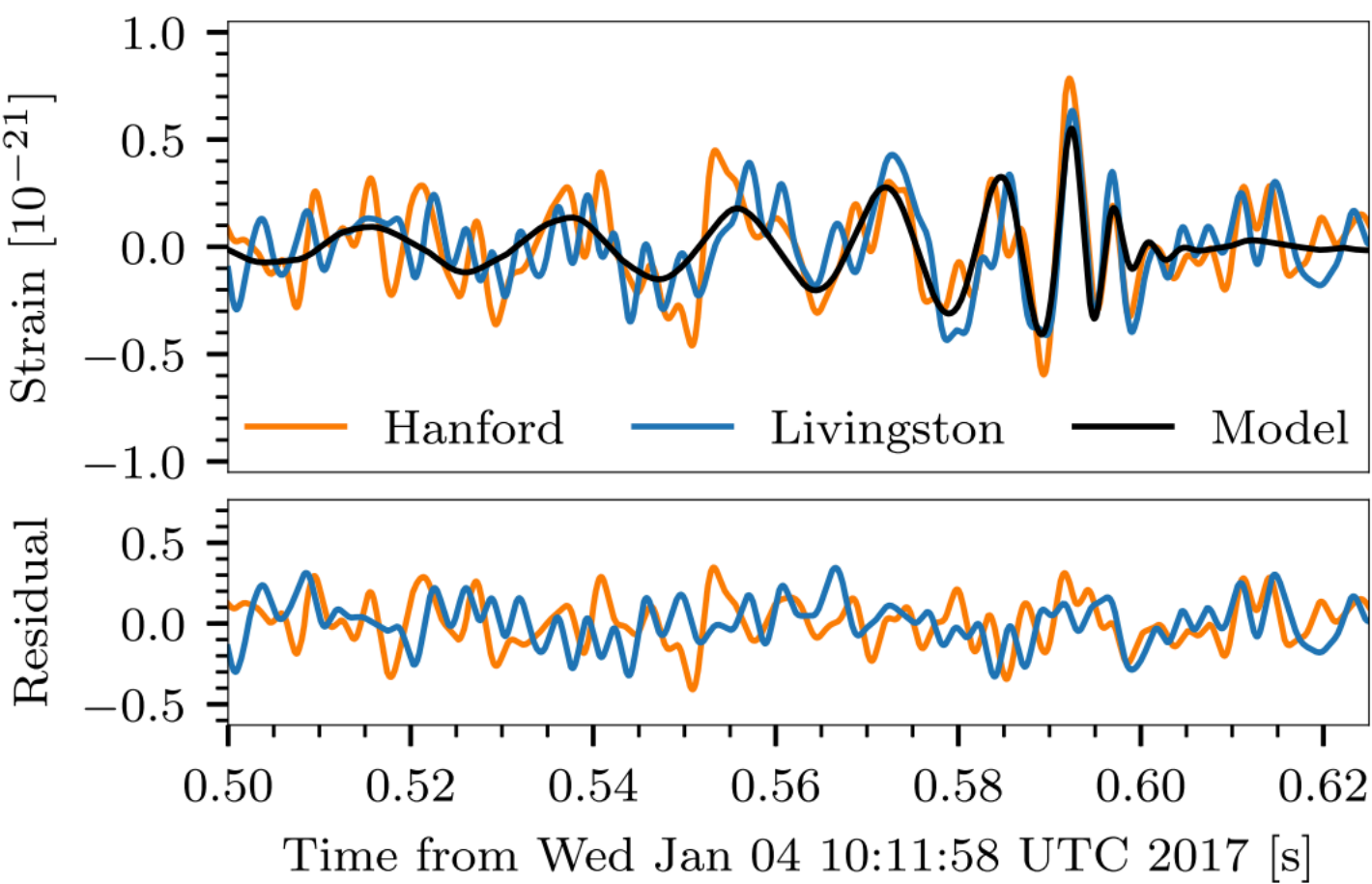
IMR consistency: Ghosh+ (arxiv:1602.02453), **Parametric deviations:** Yunes+ (arxiv:0909.3328), Chatziioannou+ (arXiv:1204.2585), **Propagation:** Mirshekari+ (arxiv:1110.2720), **Polarization:** Isi+ (arxiv:1710.03794), Hagiwara (arxiv:1904.02300), **Echoes:** Cardoso+ (arxiv:1608.08637), **Extra dimensions:** Pardo+ (arxiv:1801.08160), **Speed of gravity:** LVC/Fermi (arxiv:1710.05834)

Consistency

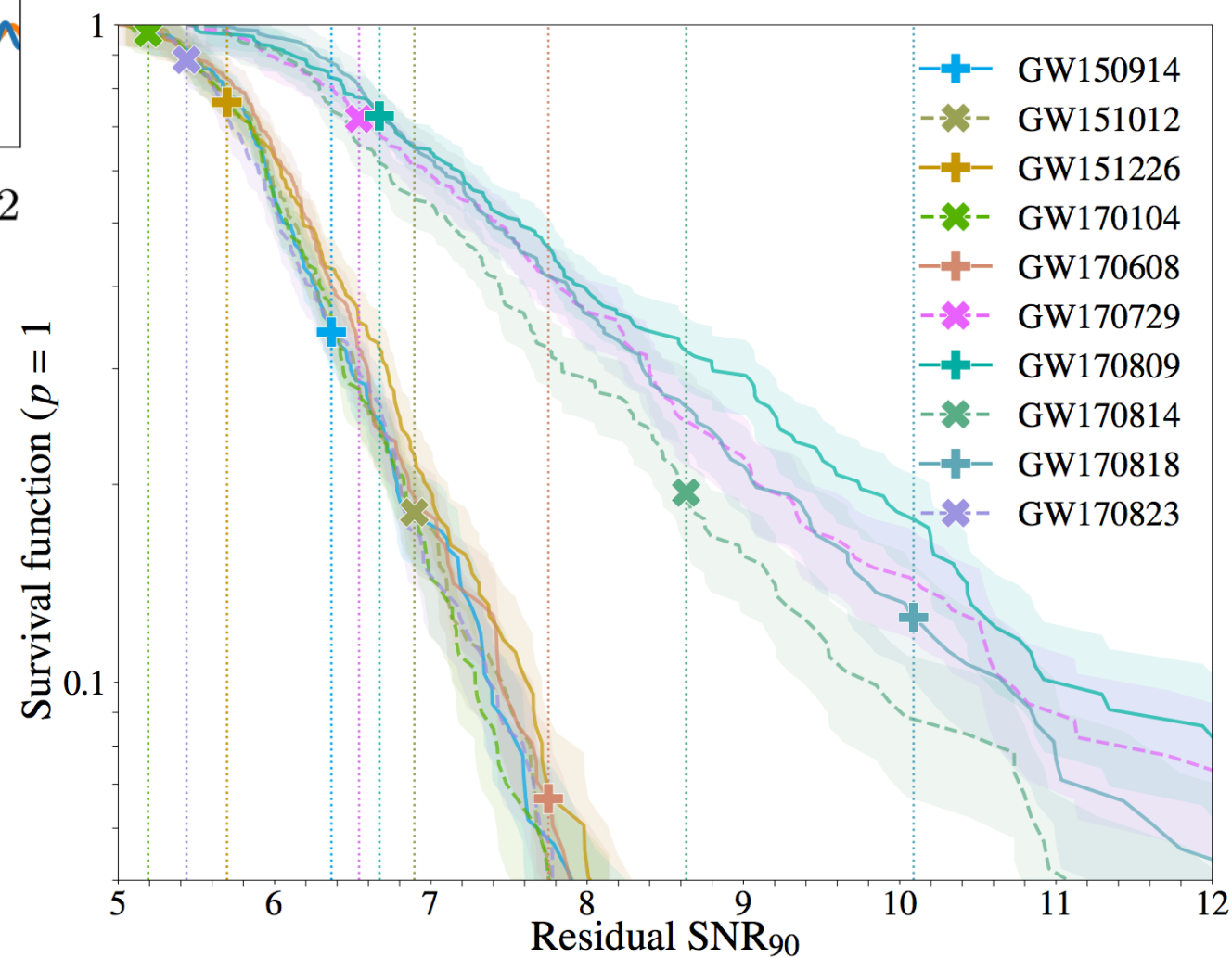


LVC (arxiv:1706.01812)

Consistency



LVC (arxiv:1706.01812)

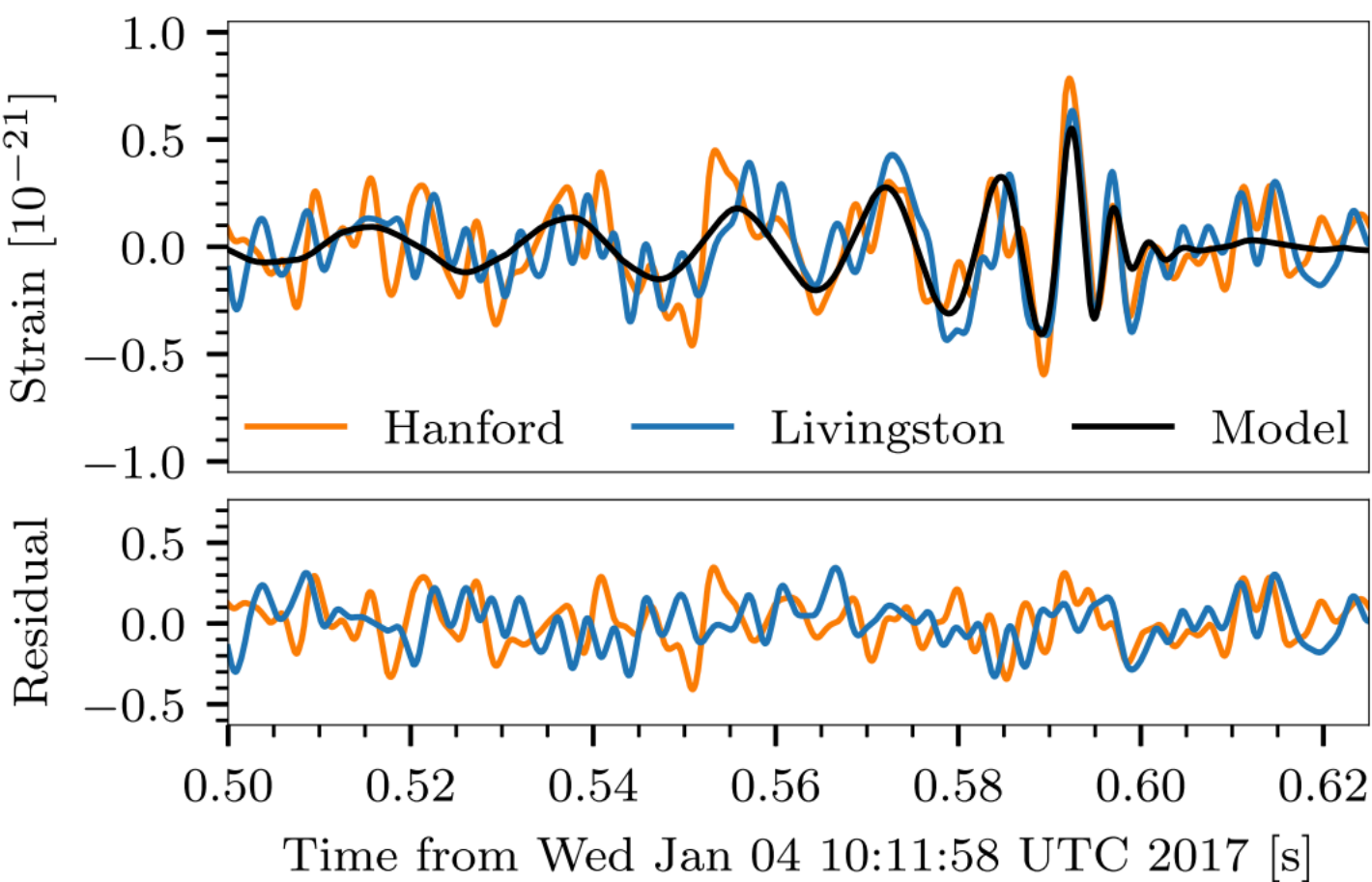


LVC (arxiv:1903.04467)

Waveform: IMRPhenomPv2 — Hannam+ (arxiv:1308.3271)

BayesWave — Cornish and Littenberg (arxiv:1410.3835)

Consistency



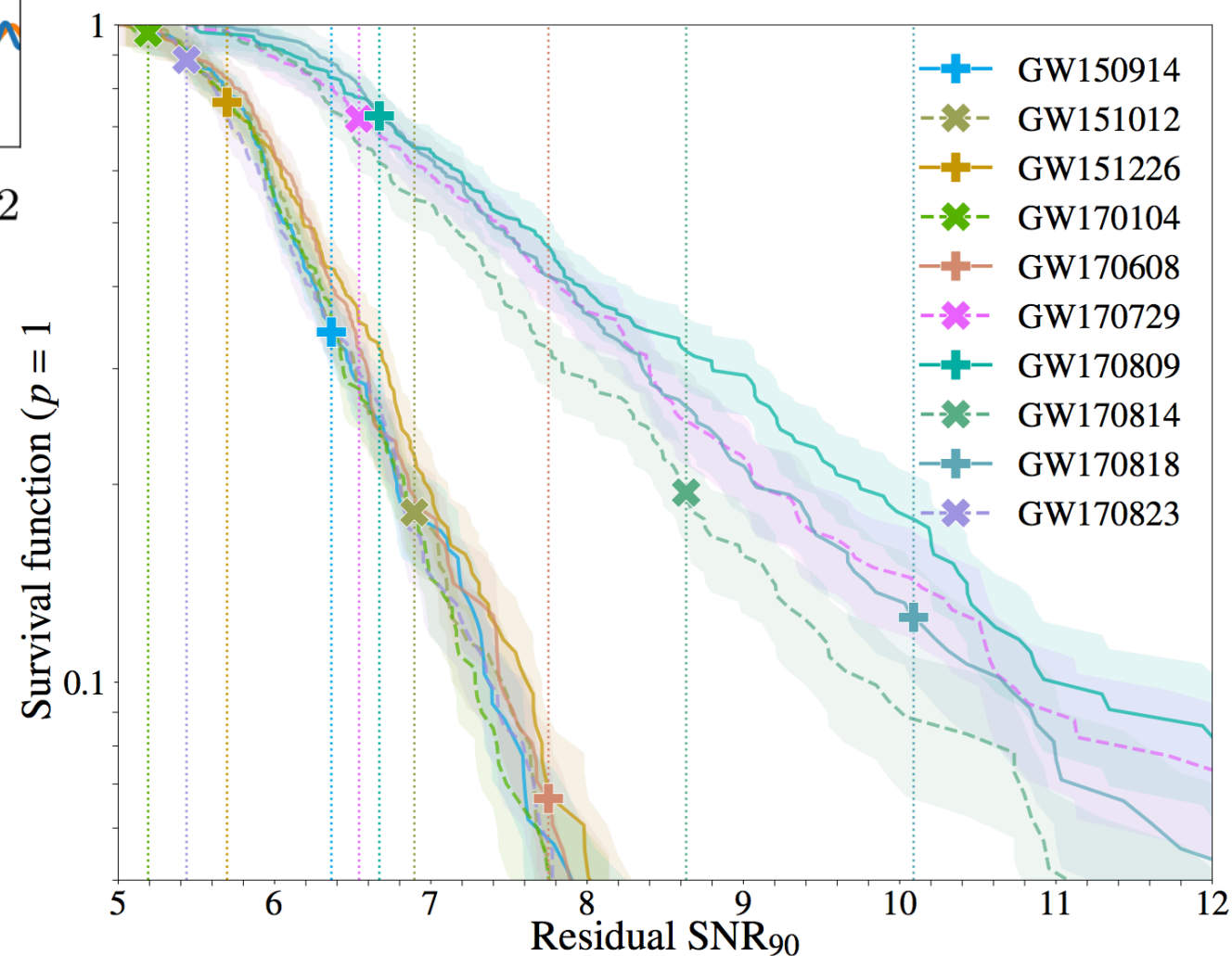
LVC (arxiv:1706.01812)

**Consistency test of both GR
and the overall analysis**

Waveform: IMRPhenomPv2 — Hannam+ (arxiv:1308.3271)

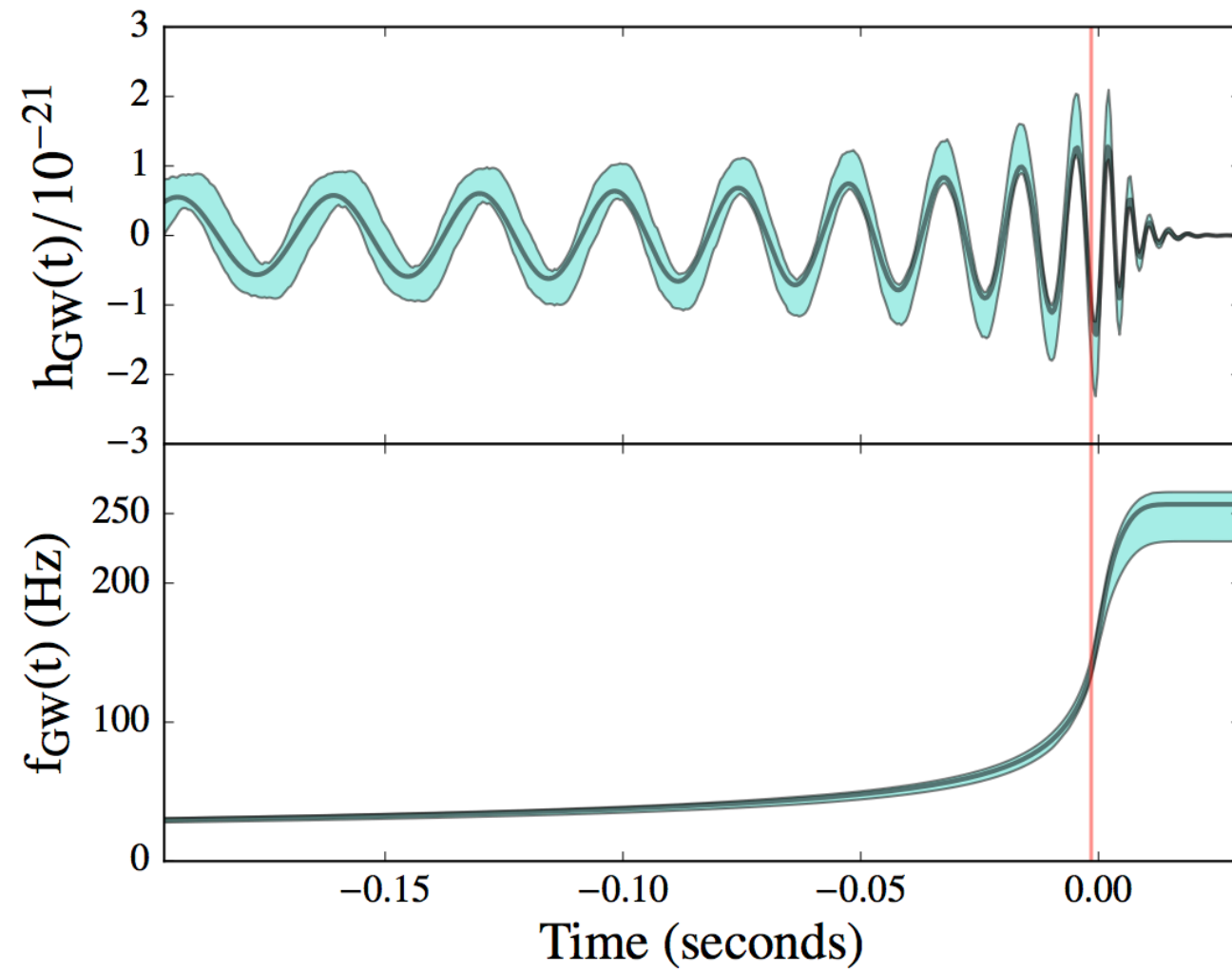
BayesWave — Cornish and Littenberg (arxiv:1410.3835)

**No statistically
significant residual power
after subtracting the best-fit
GR waveform**



LVC (arxiv:1903.04467)

Merger consistency

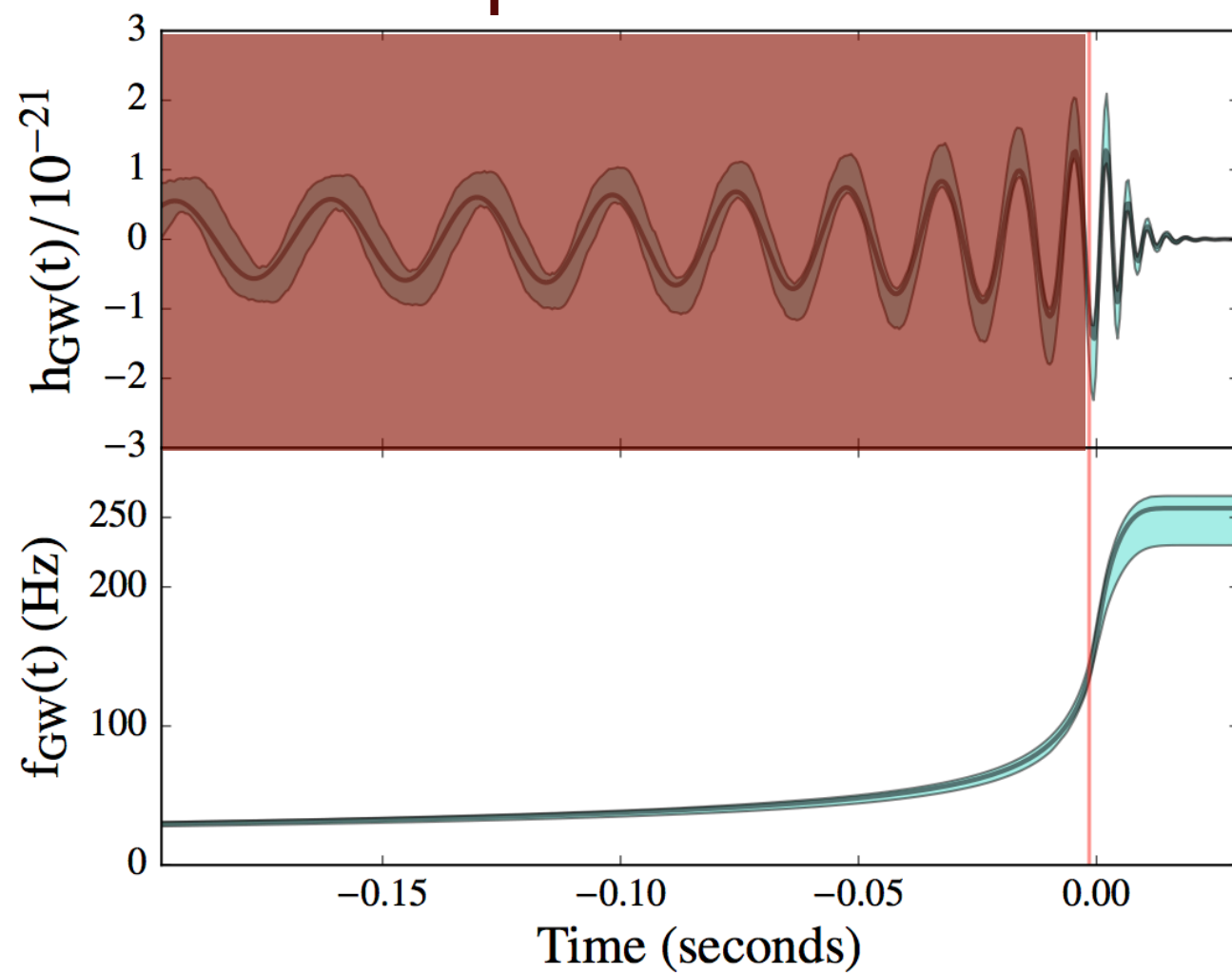


LVC (arxiv:1602.03841)

IMR consistency: Ghosh+ (arxiv:1602.02453)

Merger consistency

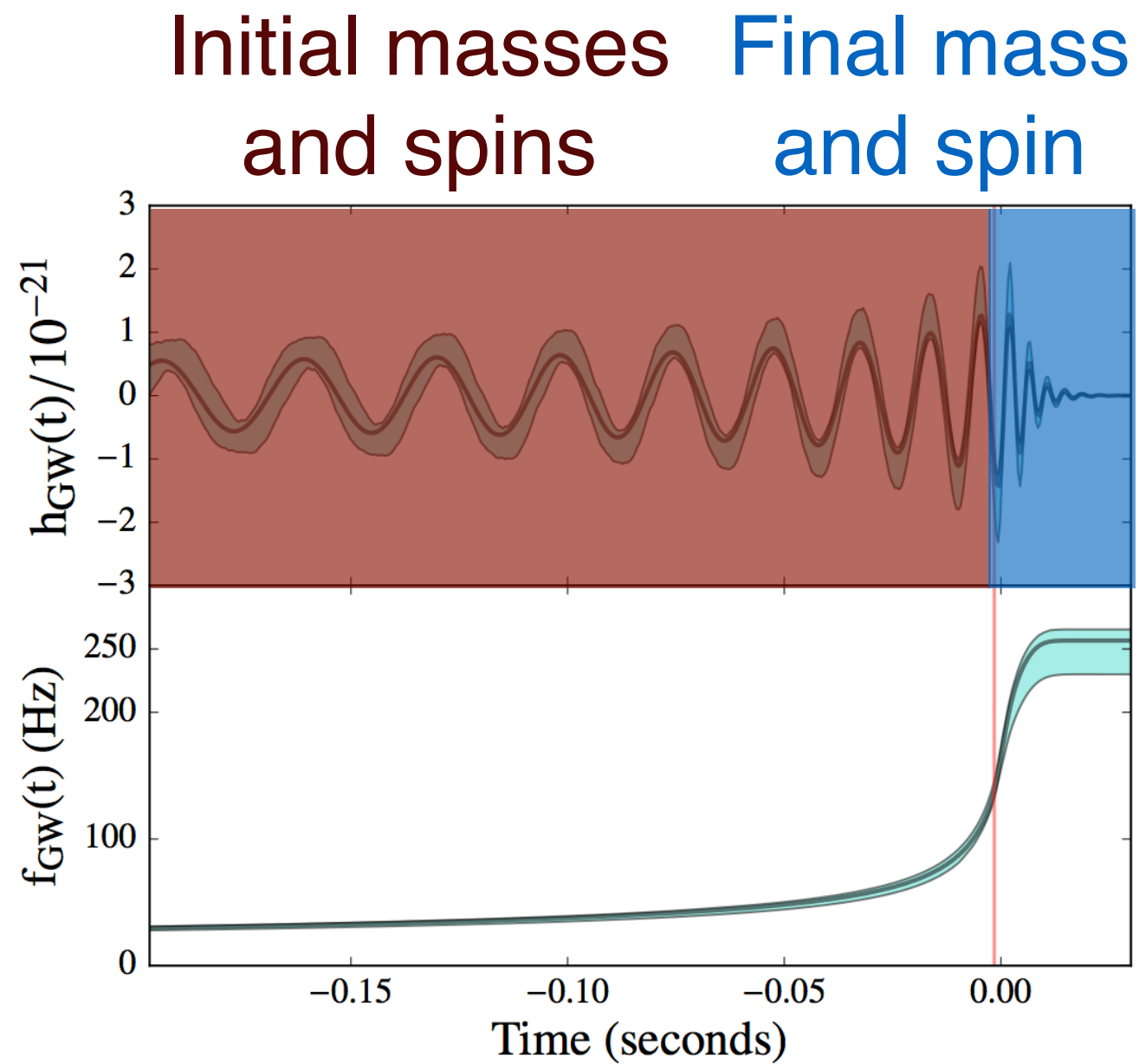
Initial masses
and spins



LVC (arxiv:1602.03841)

IMR consistency: Ghosh+ (arxiv:1602.02453)

Merger consistency

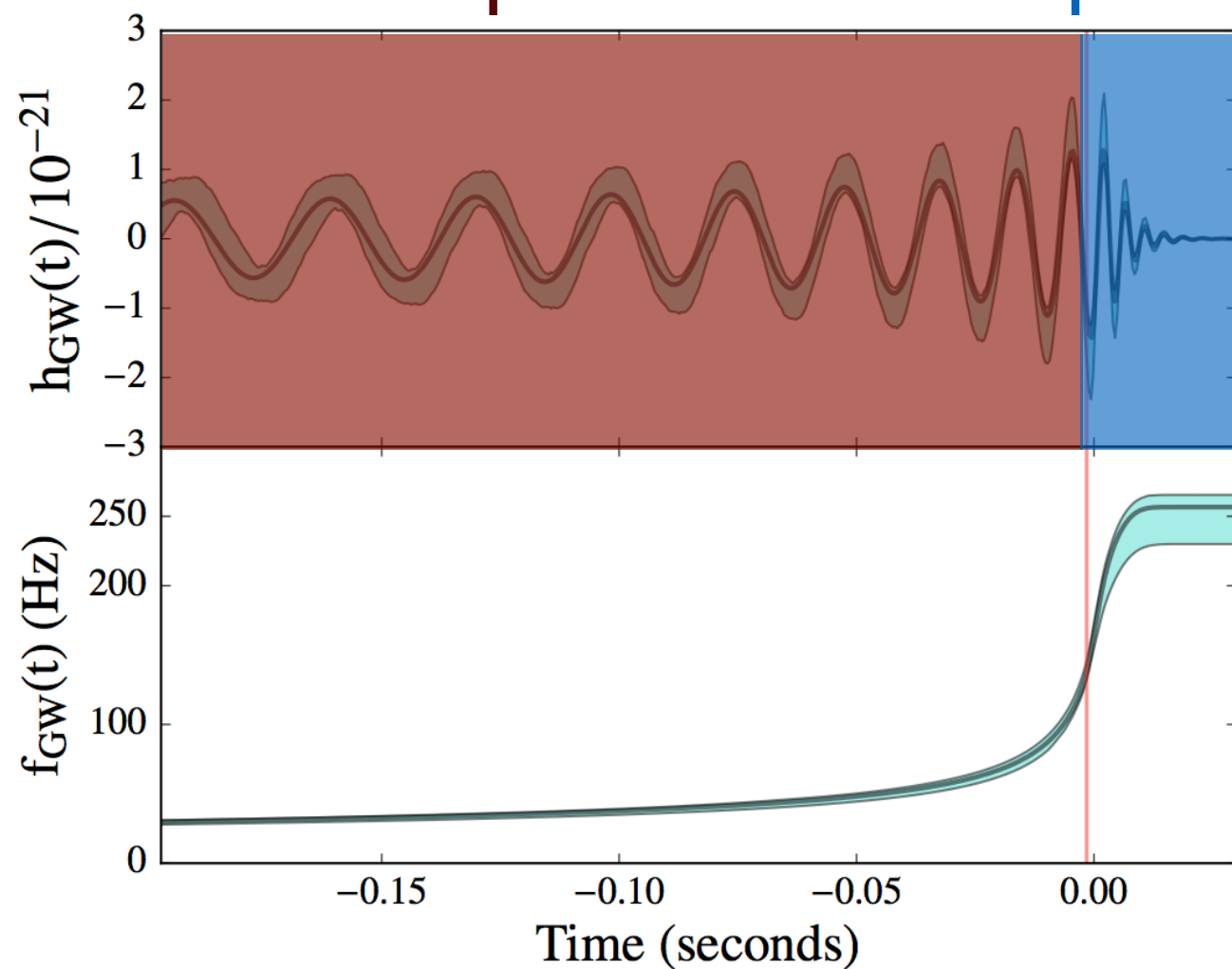


LVC (arxiv:1602.03841)

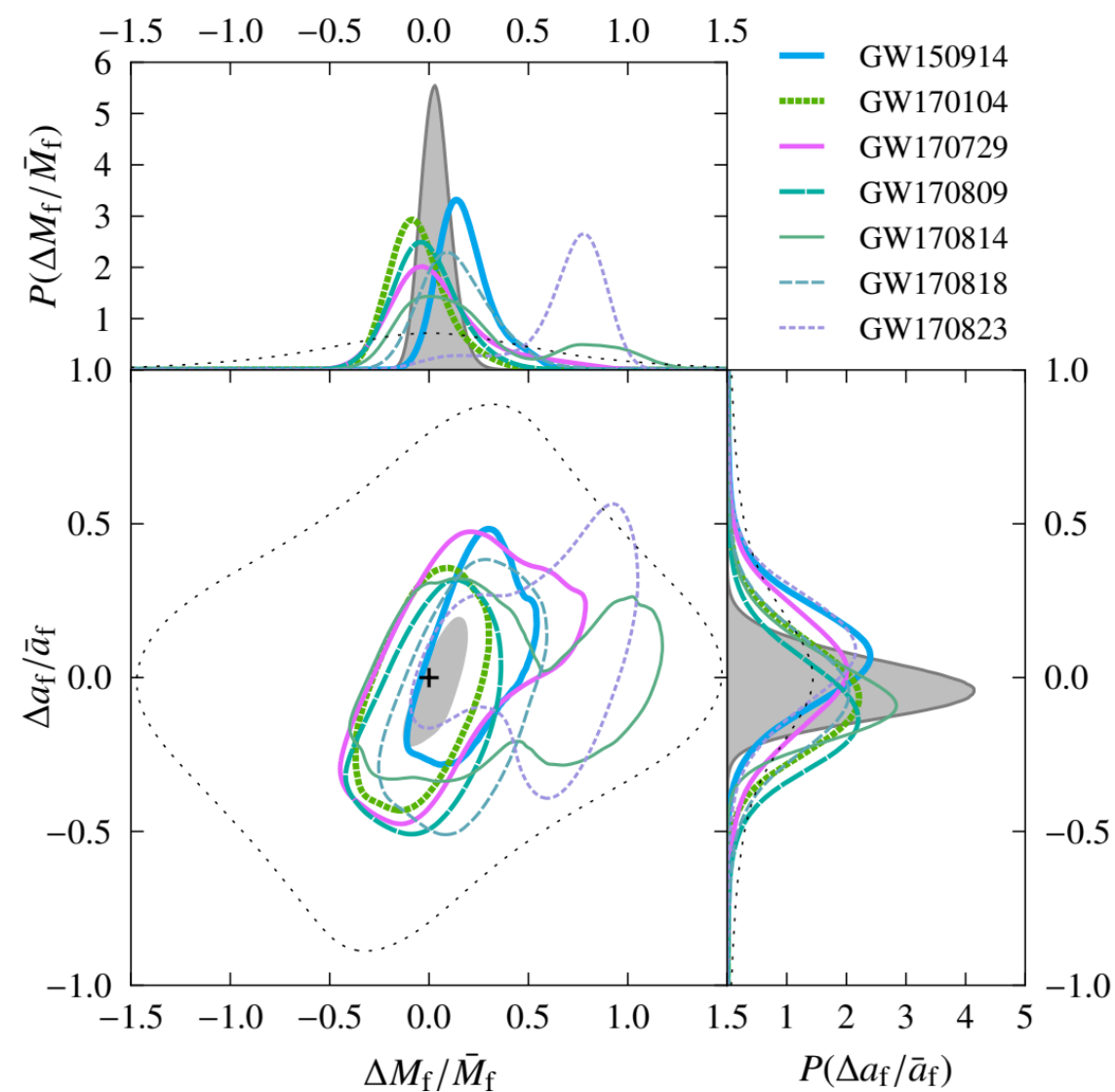
IMR consistency: Ghosh+ (arxiv:1602.02453)

Merger consistency

Initial masses and spins Final mass and spin



LVC (arxiv:1602.03841)

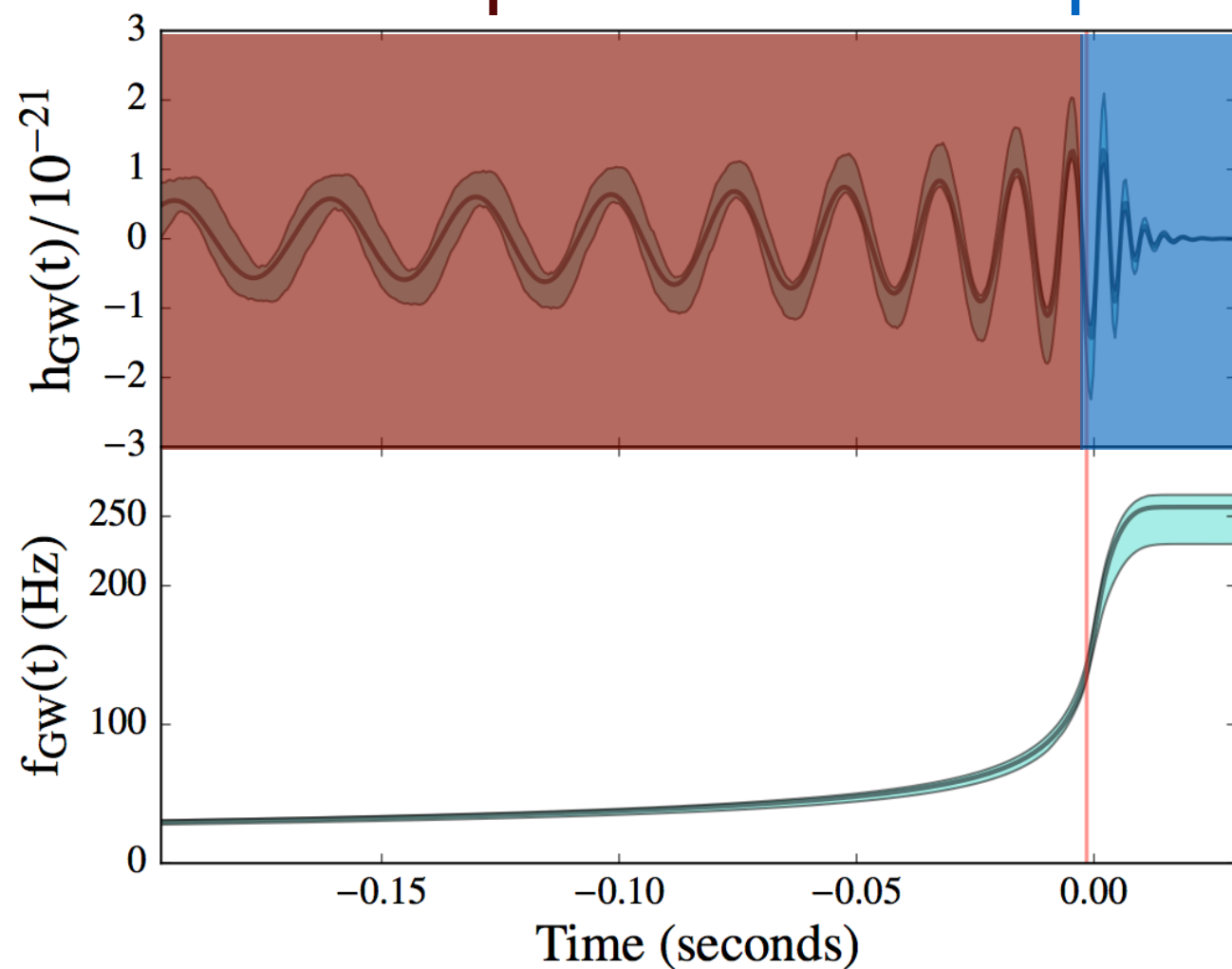


LVC (arxiv:1903.04467)

IMR consistency: Ghosh+ (arxiv:1602.02453)

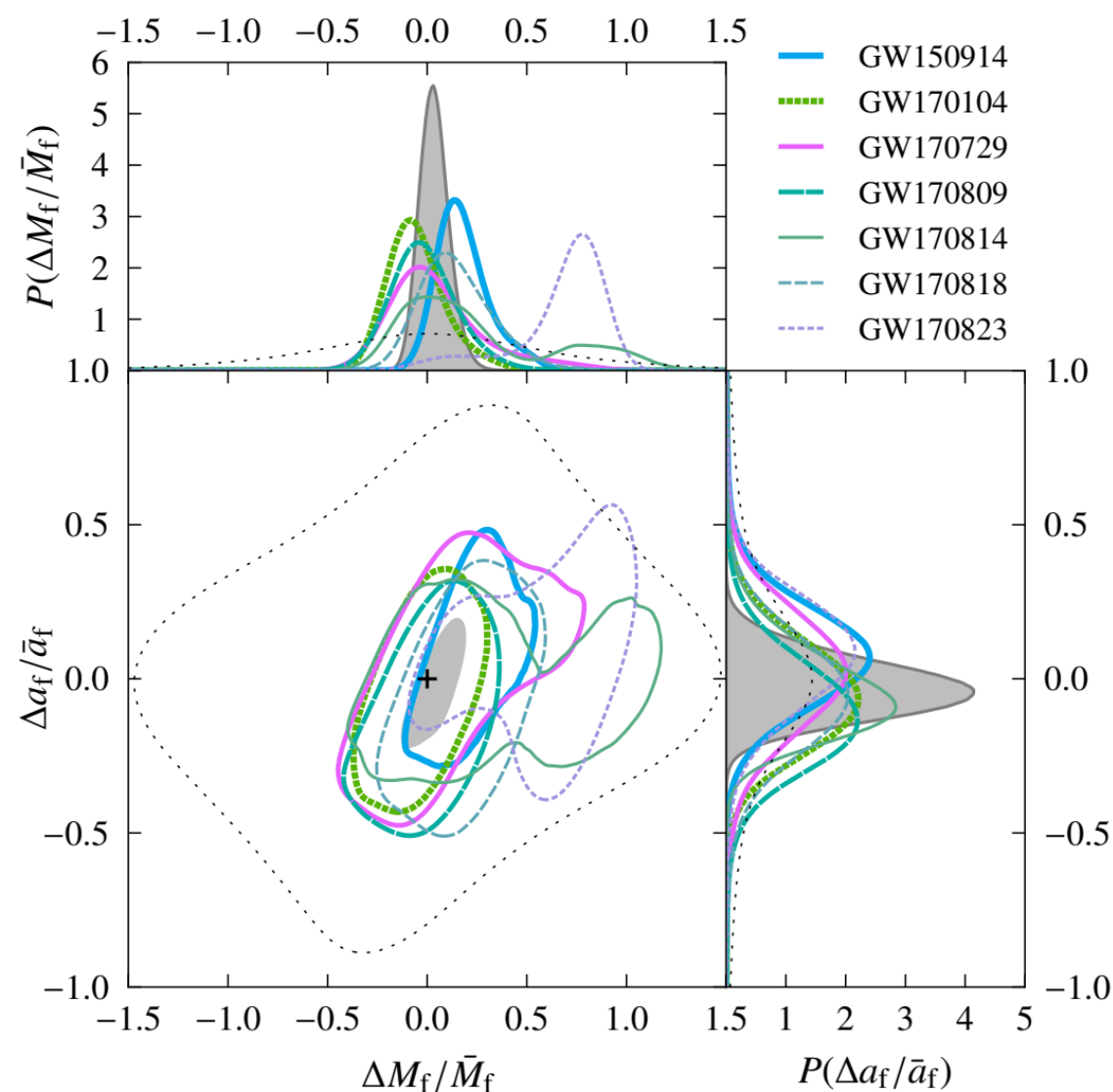
Merger consistency

Initial masses and spins Final mass and spin



LVC (arxiv:1602.03841)

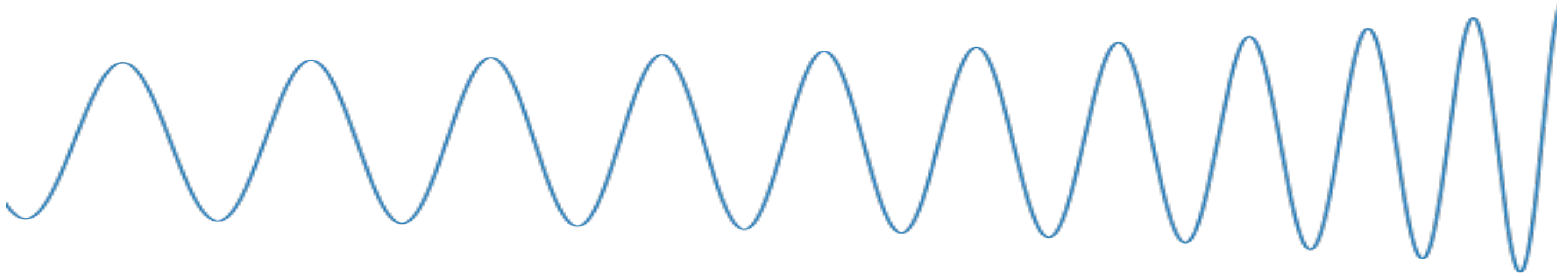
The non-linear, dynamical part of the merger that creates the final black hole is consistent with GR



LVC (arxiv:1903.04467)

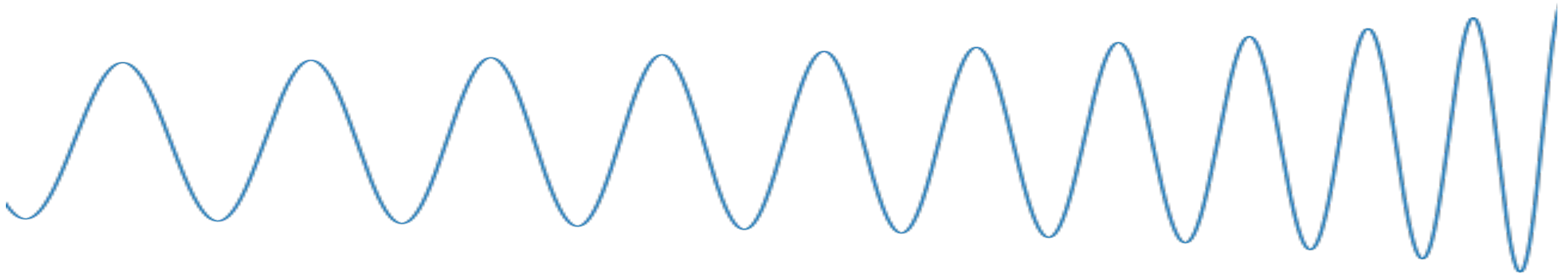
IMR consistency: Ghosh+ (arxiv:1602.02453)

Parametric deviations



$$\tilde{h} \sim \tilde{A}(f; \vec{\theta}_{GR}) e^{i \sum_j p_{j/3}(\vec{\theta}_{GR}) f^{j/3}}$$

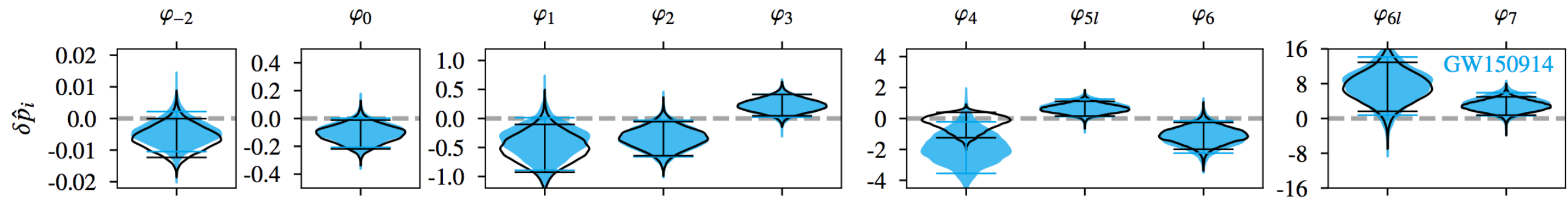
Parametric deviations



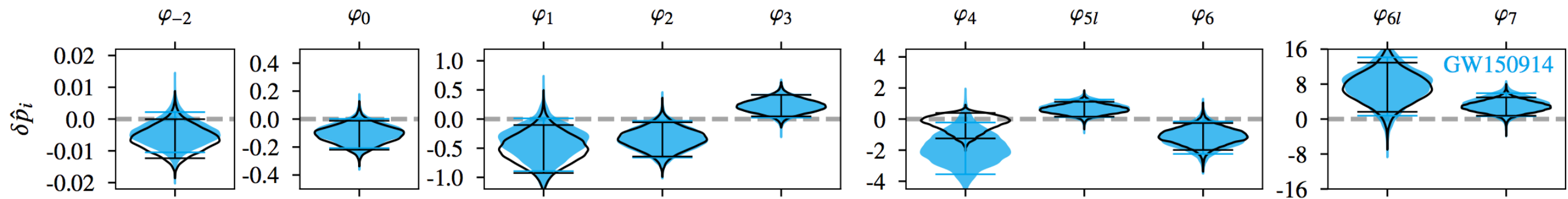
$$\tilde{h} \sim \tilde{A}(f; \vec{\theta}_{GR}) e^{i \sum_j p_j / 3} (\vec{\theta}_{GR}) f^{j/3}$$

$$p_i \rightarrow p_i (1 + \delta p_i)$$

Parametric deviations



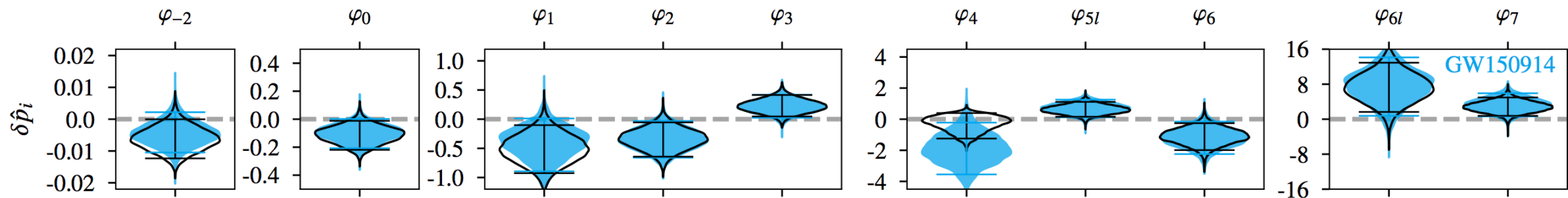
Parametric deviations



Dipole emission

Parametric deviations

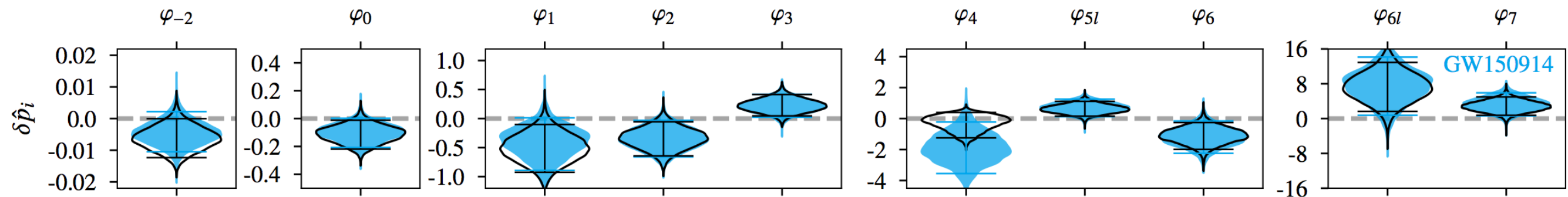
Vector field



Dipole emission

Parametric deviations

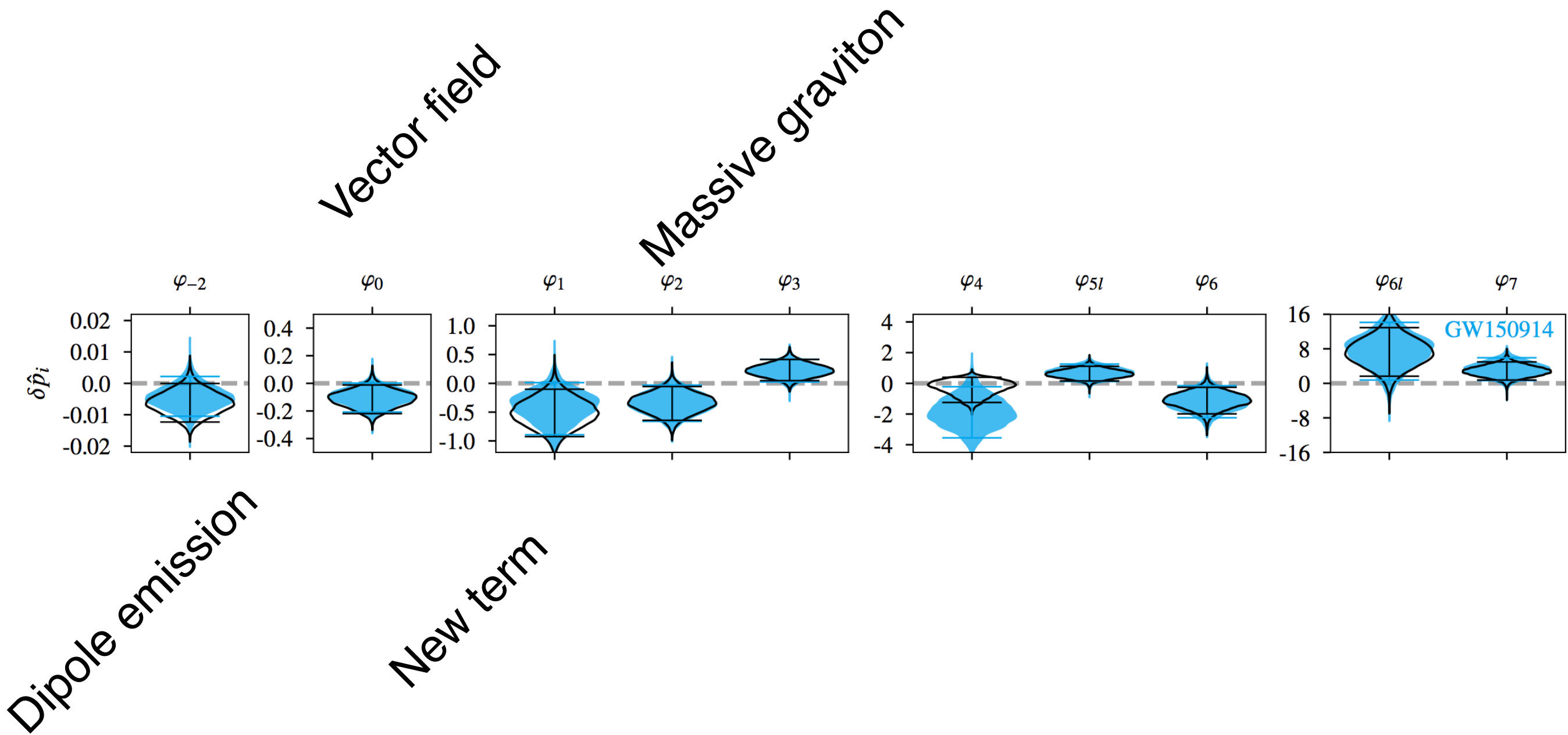
Vector field



Dipole emission

New term

Parametric deviations

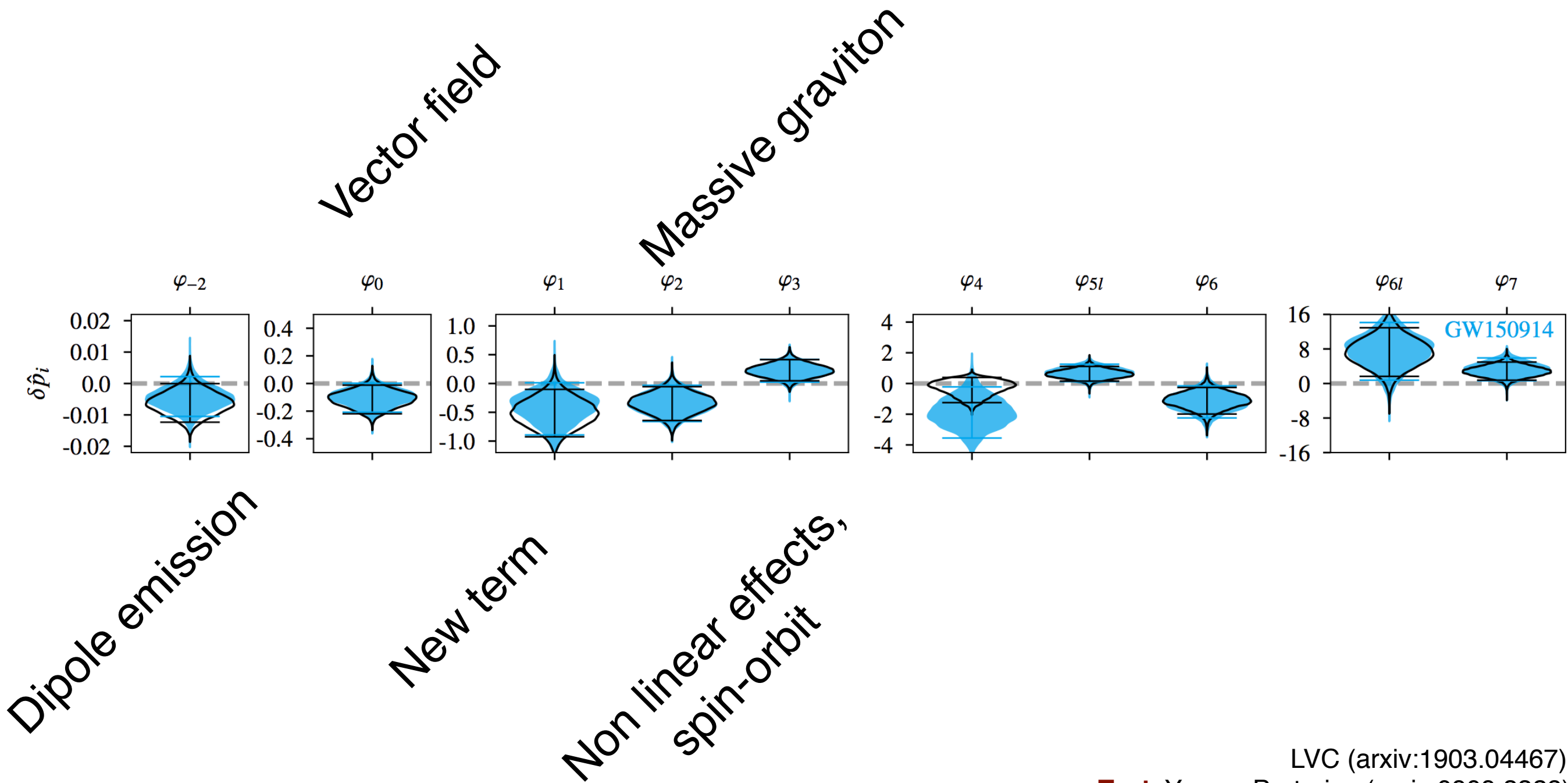


LVC (arxiv:1903.04467)

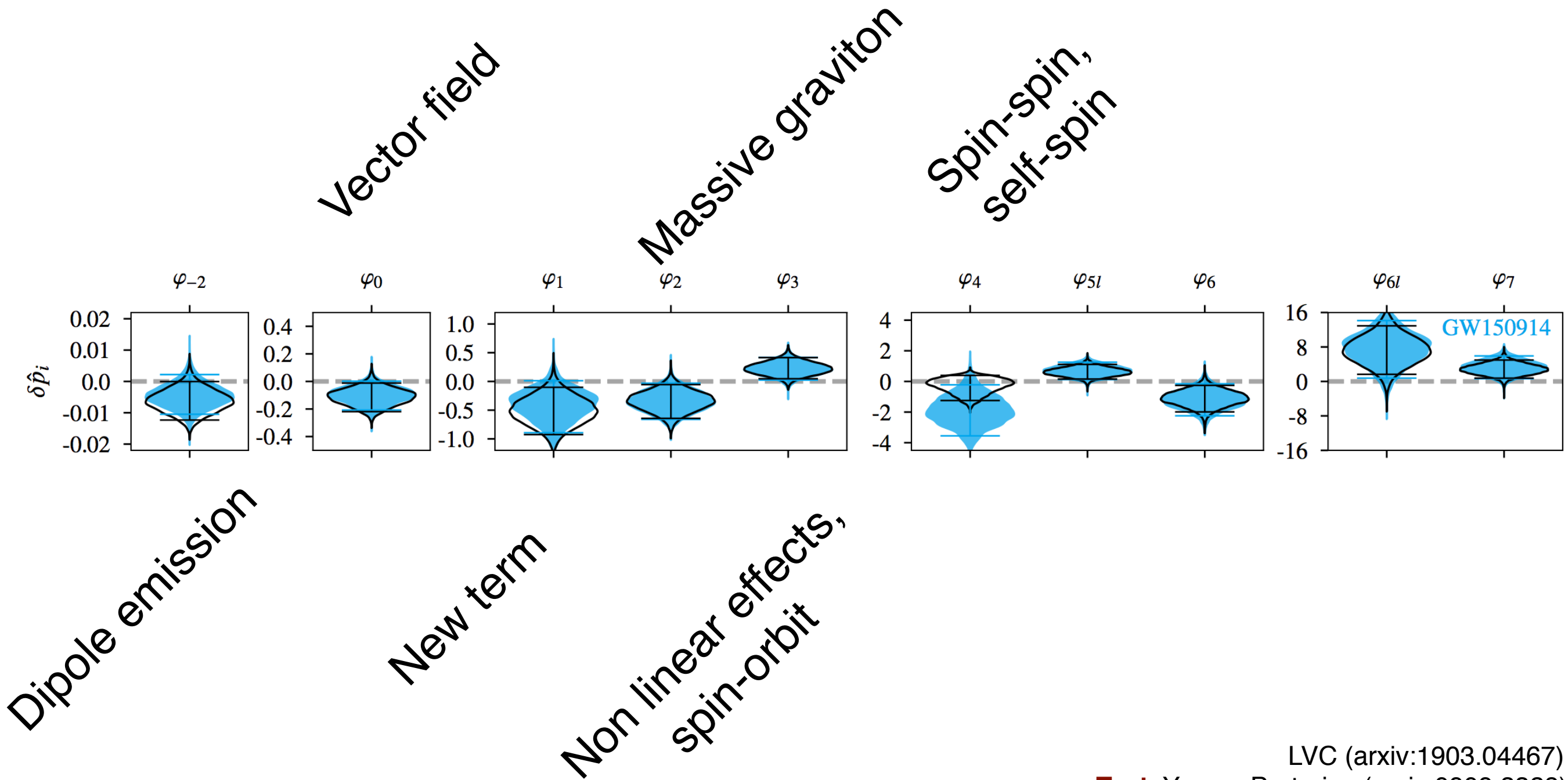
Test: Yunes, Pretorius (arxiv:0909.3328)

Implementation: Meidam (arxiv:1712.08772)

Parametric deviations



Parametric deviations

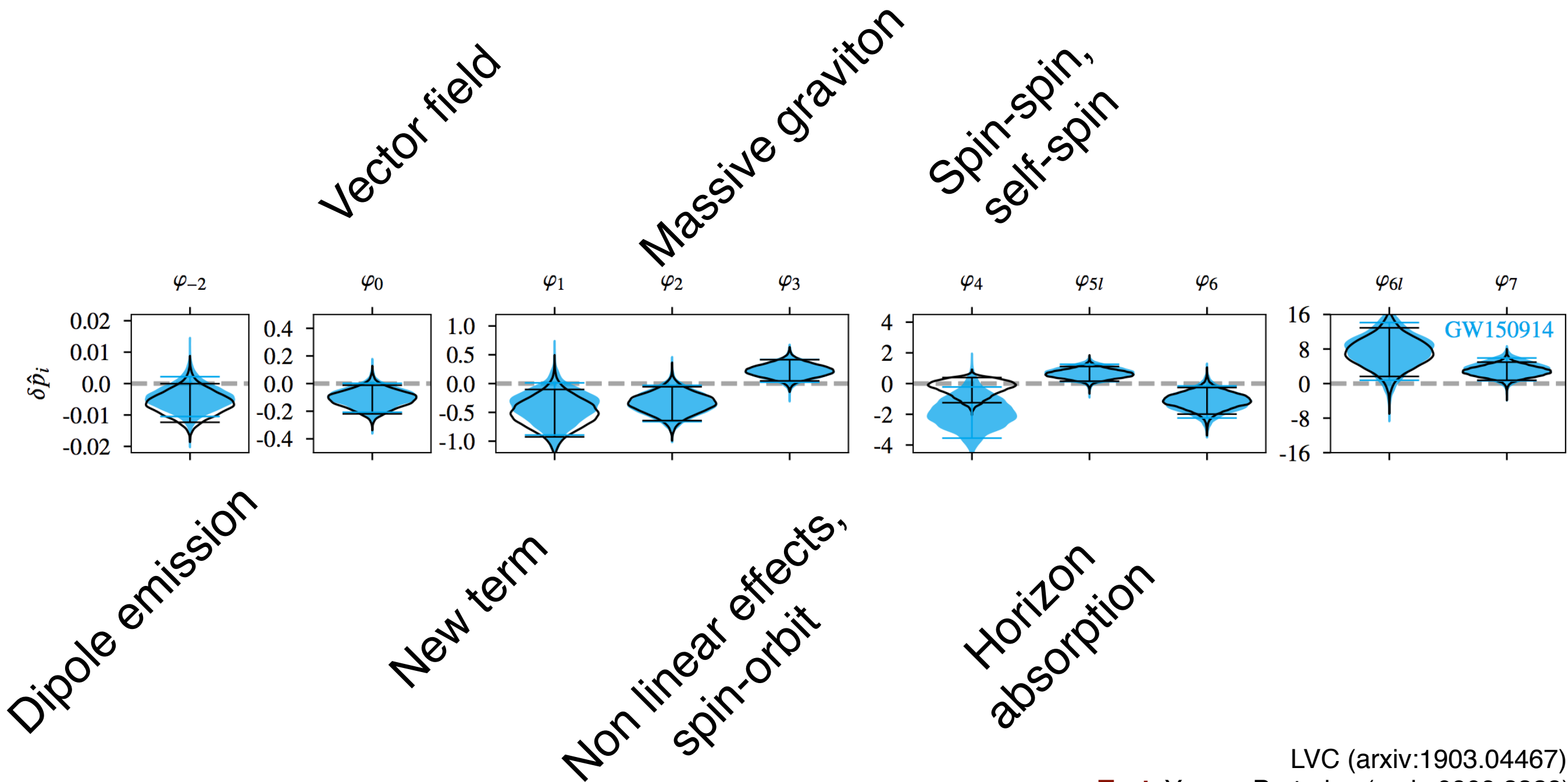


LVC (arxiv:1903.04467)

Test: Yunes, Pretorius (arxiv:0909.3328)

Implementation: Meidam (arxiv:1712.08772)

Parametric deviations

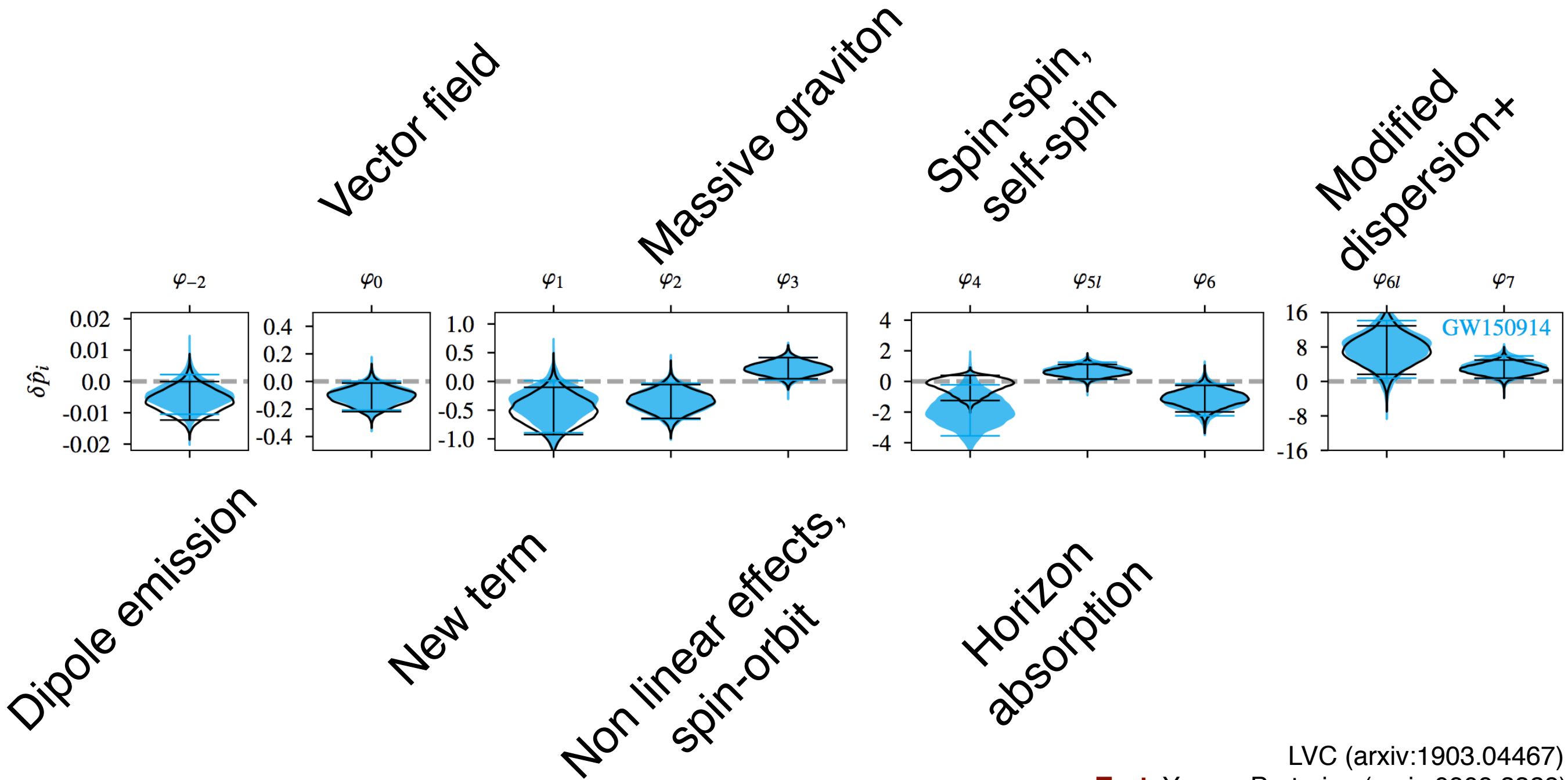


LVC (arxiv:1903.04467)

Test: Yunes, Pretorius (arxiv:0909.3328)

Implementation: Meidam (arxiv:1712.08772)

Parametric deviations

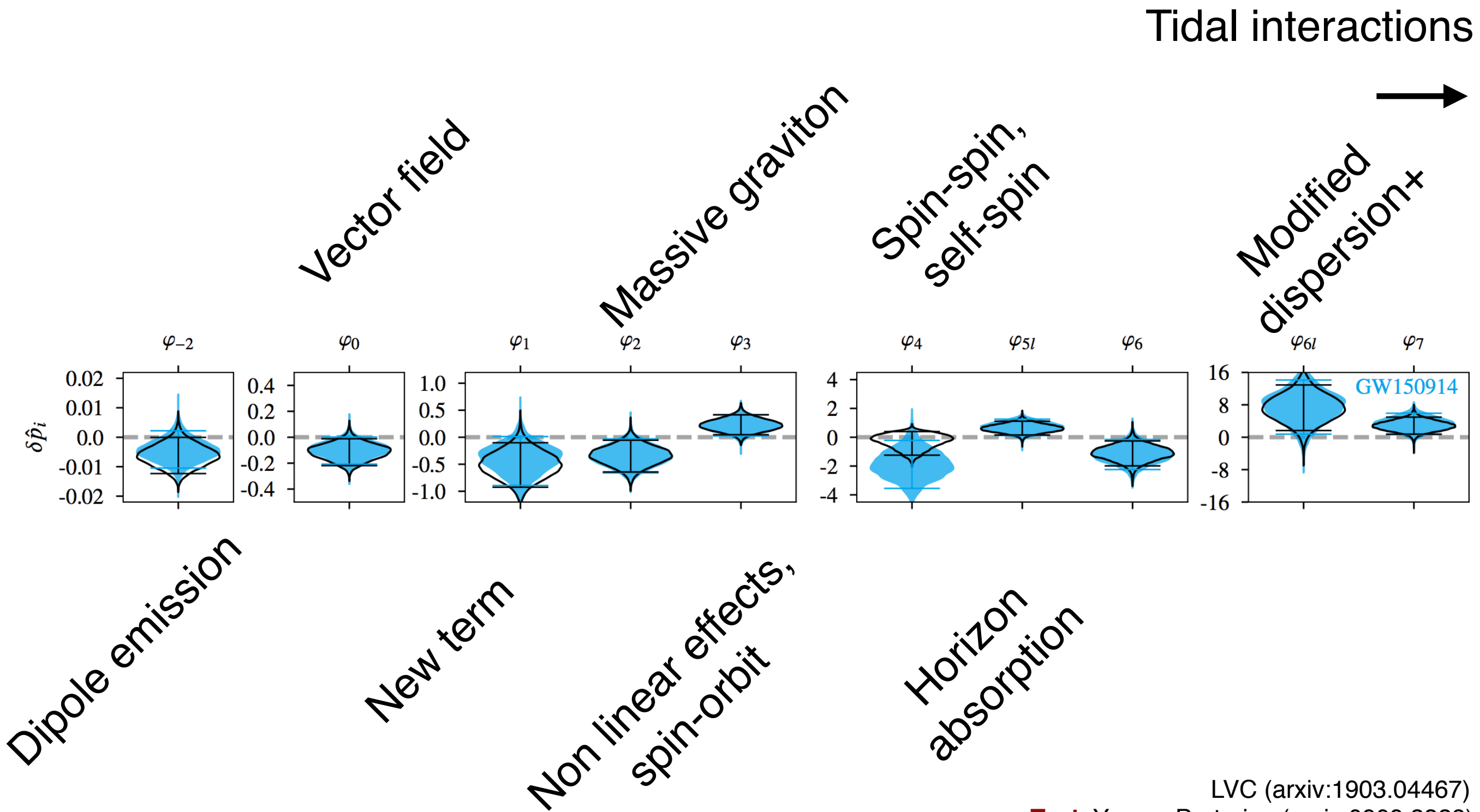


LVC (arxiv:1903.04467)

Test: Yunes, Pretorius (arxiv:0909.3328)

Implementation: Meidam (arxiv:1712.08772)

Parametric deviations



LVC (arxiv:1903.04467)

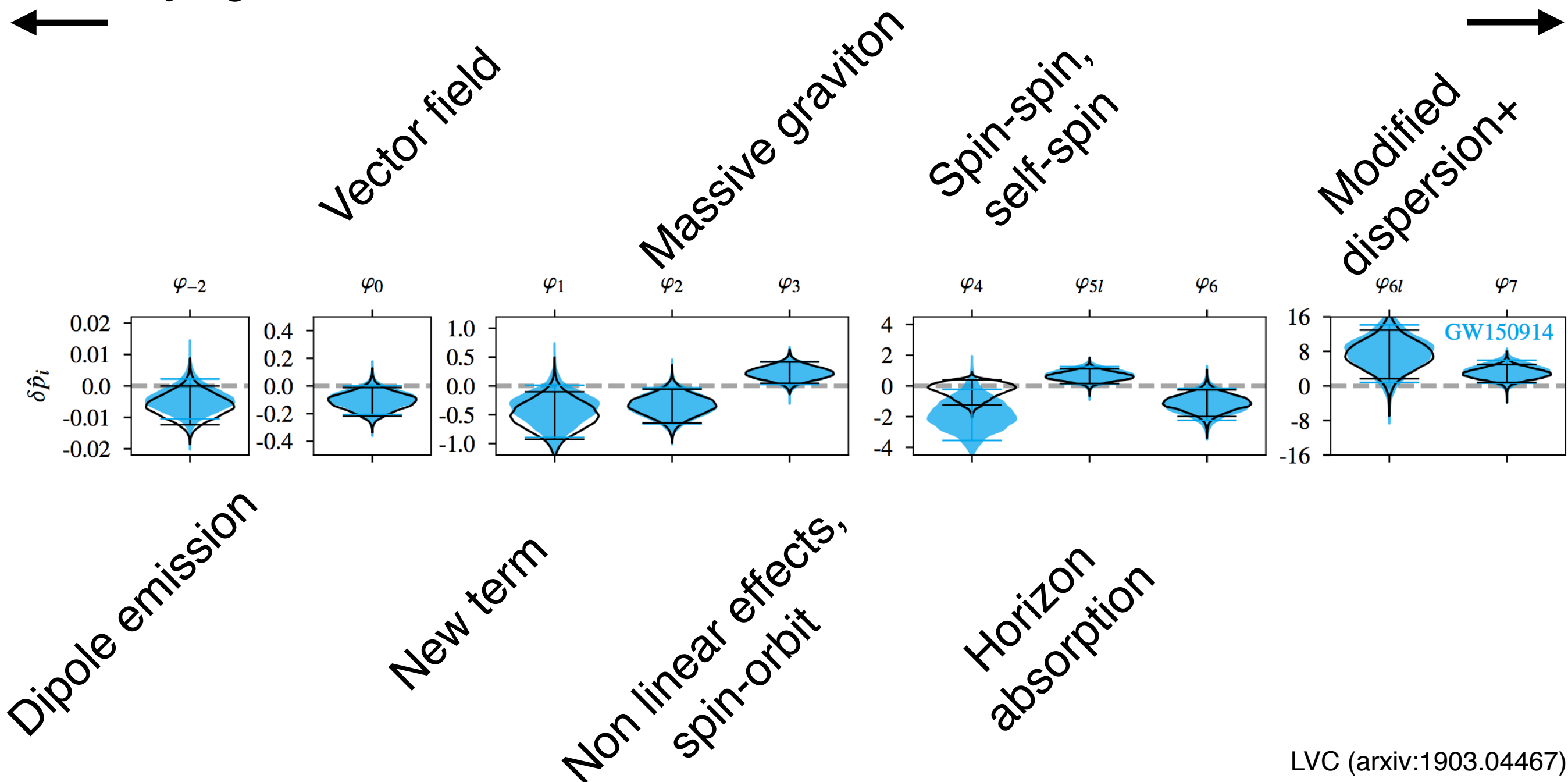
Test: Yunes, Pretorius (arxiv:0909.3328)

Implementation: Meidam (arxiv:1712.08772)

Parametric deviations

Extra dimensions,
Varying G

Tidal interactions



LVC (arxiv:1903.04467)

Test: Yunes, Pretorius (arxiv:0909.3328)

Implementation: Meidam (arxiv:1712.08772)

Population of binary black holes

How do you combine constraints from 10 binaries **without restricting** to a specific modified gravity theory?

Population of binary black holes

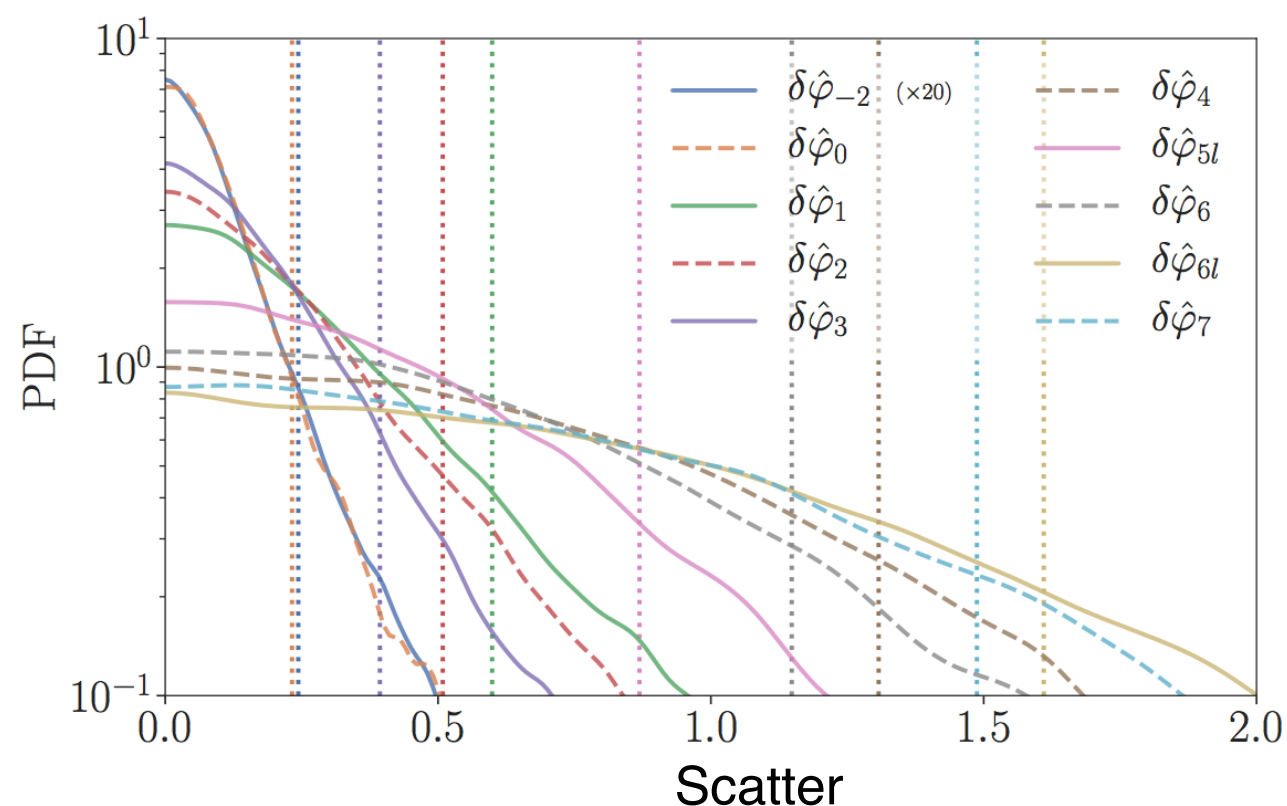
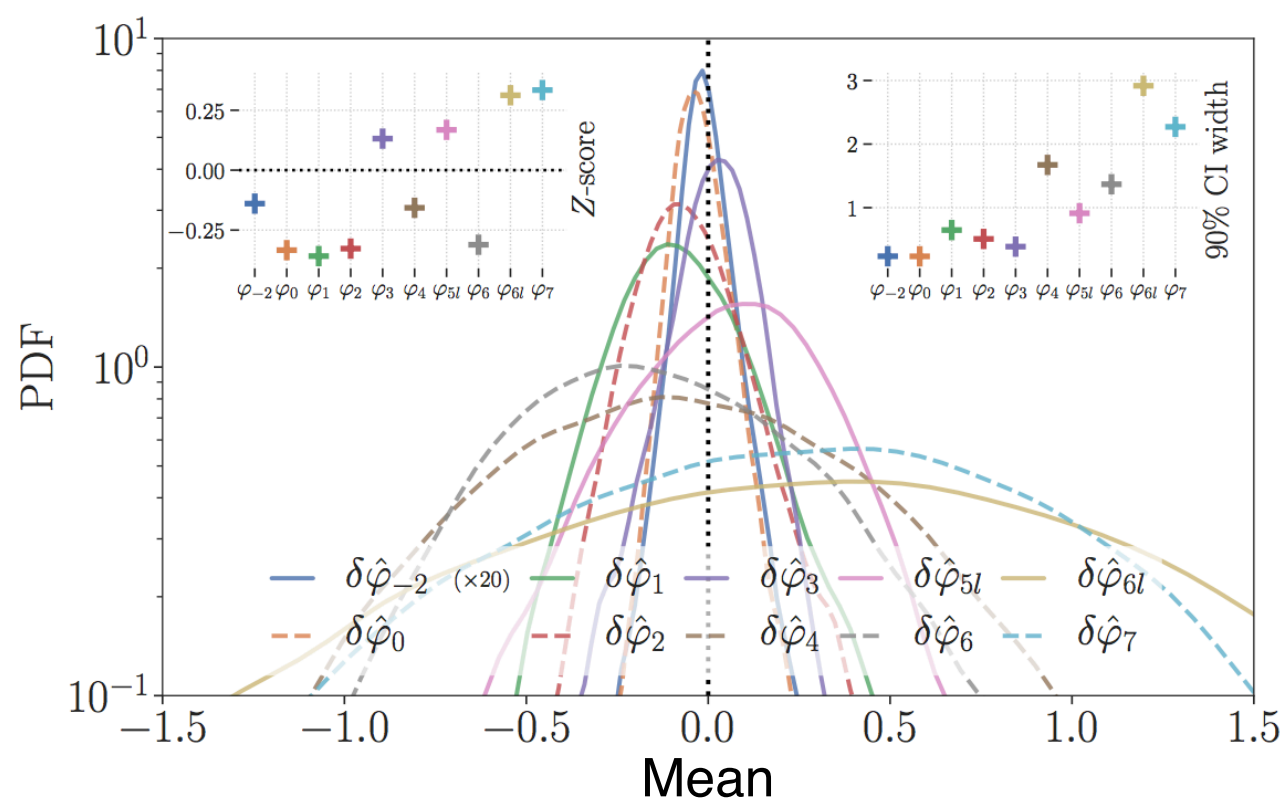
How do you combine constraints from 10 binaries **without restricting** to a specific modified gravity theory?

Parametrize the population distribution and **constrain** it

Population of binary black holes

How do you combine constraints from 10 binaries **without restricting** to a specific modified gravity theory?

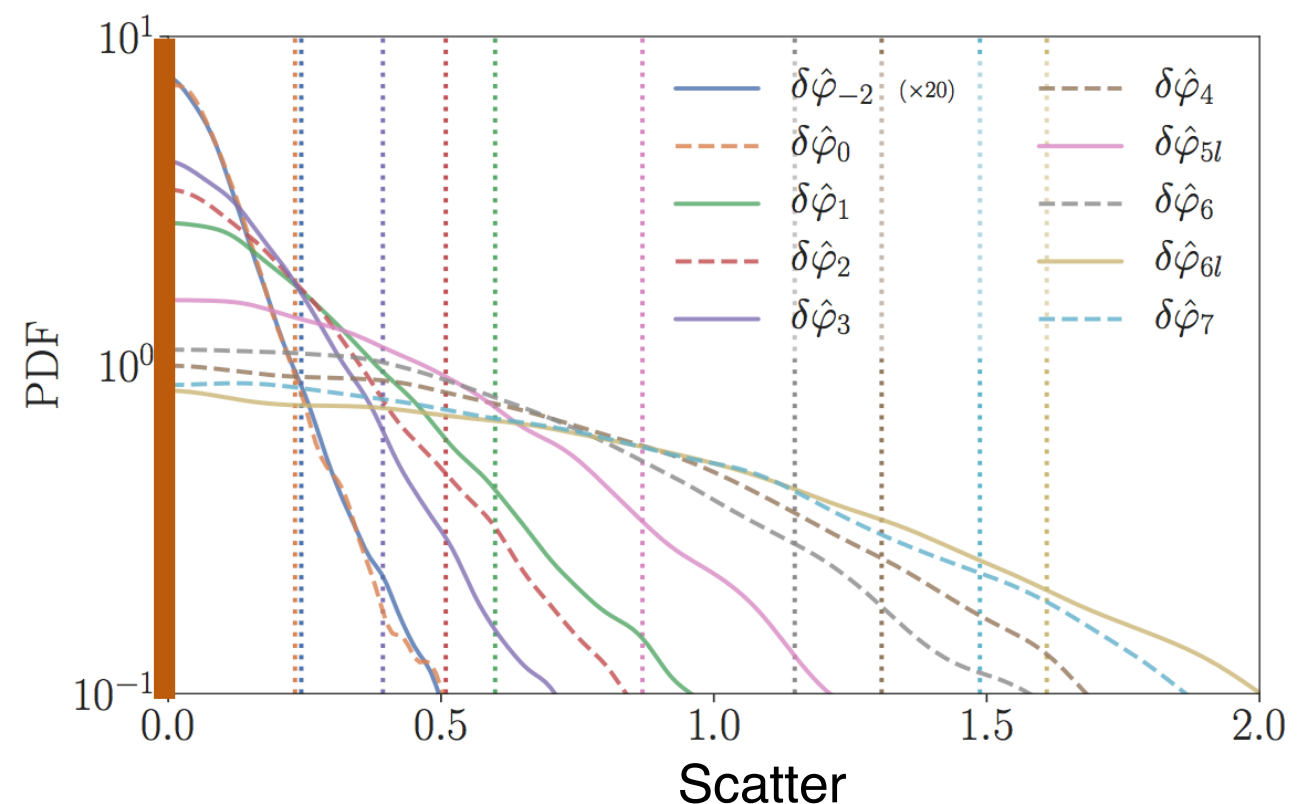
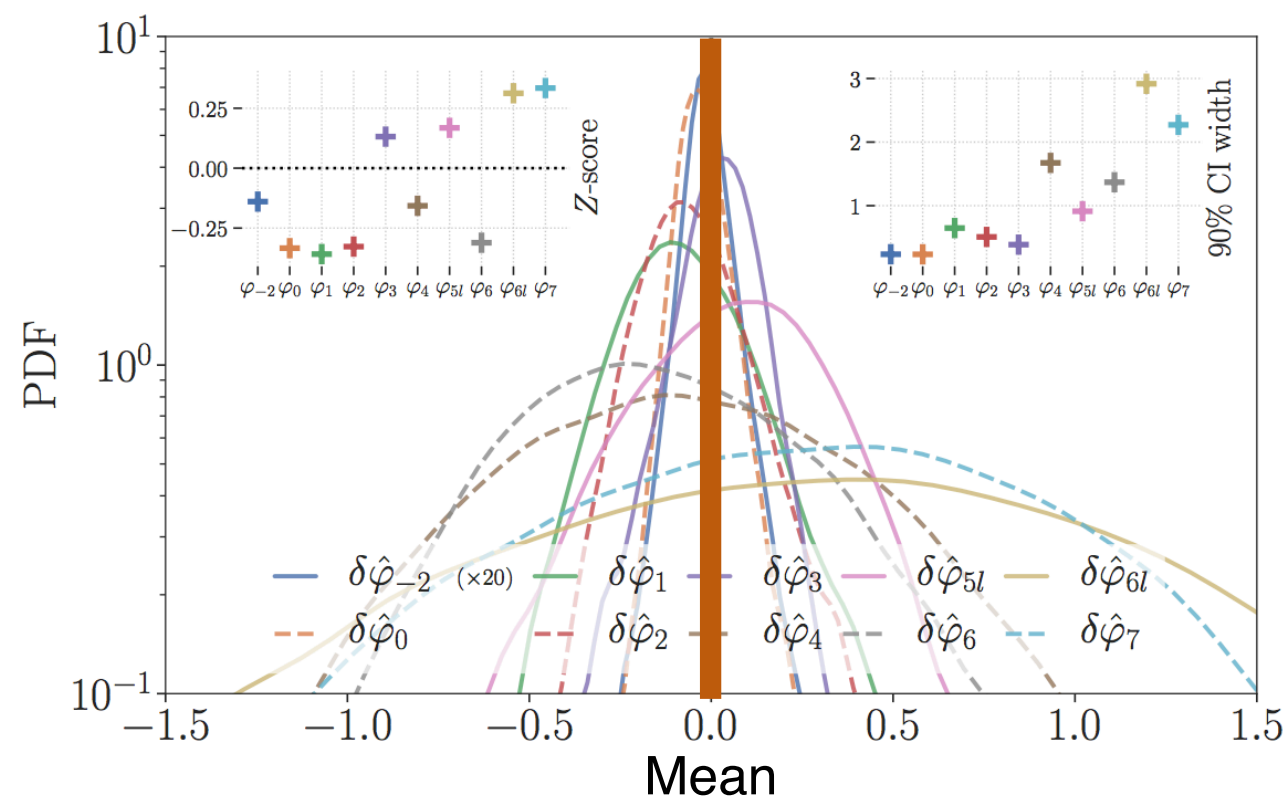
Parametrize the population distribution and **constrain** it



Population of binary black holes

How do you combine constraints from 10 binaries **without restricting** to a specific modified gravity theory?

Parametrize the population distribution and **constrain** it



Propagation effects

Modified dispersion arises when Lorentz invariance is violated

Propagation effects

Modified dispersion arises when Lorentz invariance is violated

$$E^2 = p^2 c^2 + A p^\alpha c^\alpha$$

Propagation: Mirshekari+ (arxiv:1110.2720)

Propagation effects

Modified dispersion arises when Lorentz invariance is violated

$$E^2 = p^2 c^2 + A p^\alpha c^\alpha$$

Propagation: Mirshekari+ (arxiv:1110.2720)

$$\delta v_g \sim \frac{\text{GW period}}{\text{travel time}} \sim \frac{\text{GW wavelength}}{\text{distance}}$$

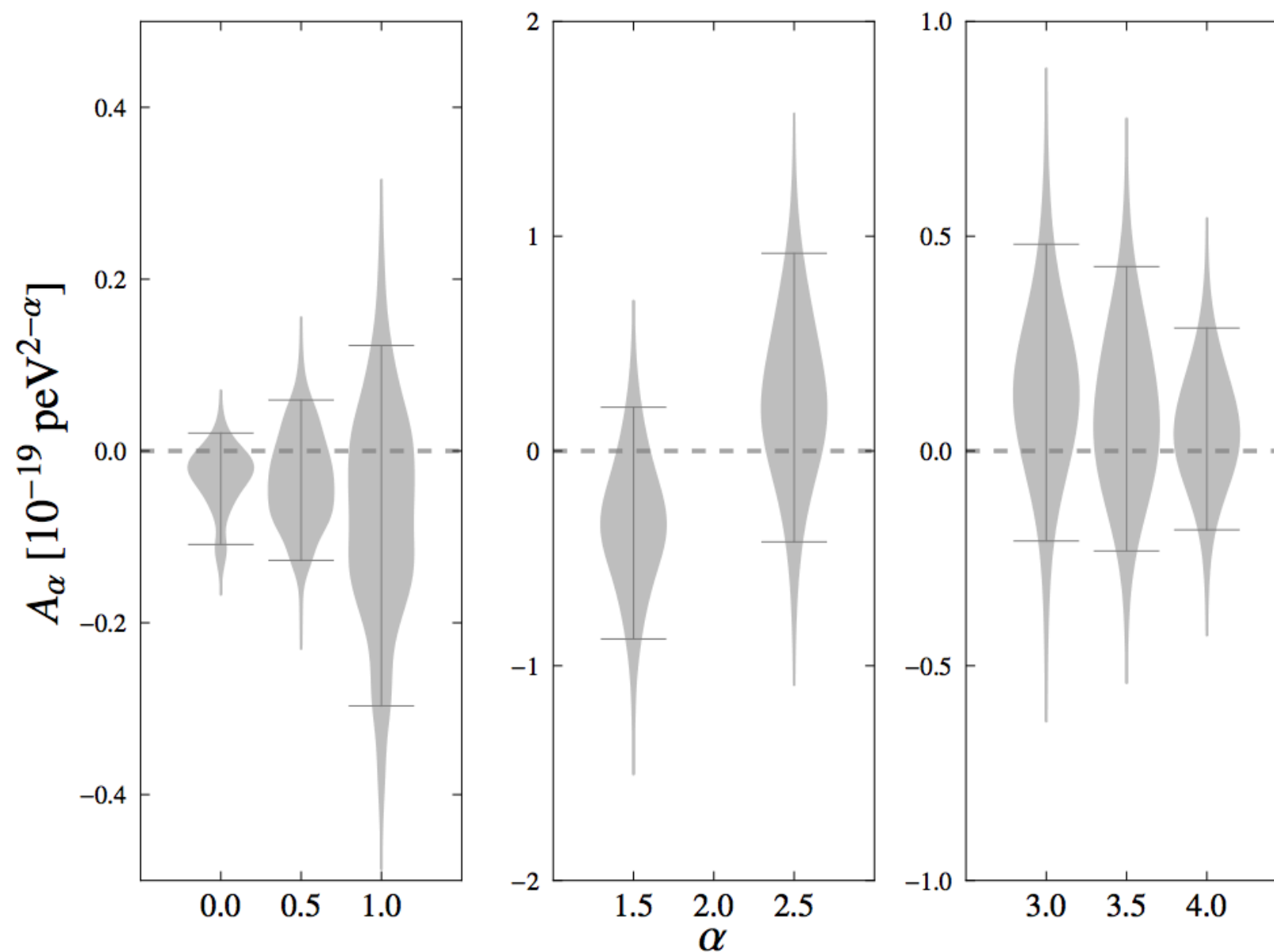
For 800Mpc and 250Hz, $\delta v_g \sim 5 \times 10^{-20}$

Modified dispersion

$$\delta v_g \sim AE^{\alpha-2} \Rightarrow A \sim \delta v_g E^{2-\alpha} \sim \delta v_g (h_{\text{P1}} f)^{2-\alpha} \sim 10^{-20} \text{peV}^{2-\alpha}$$

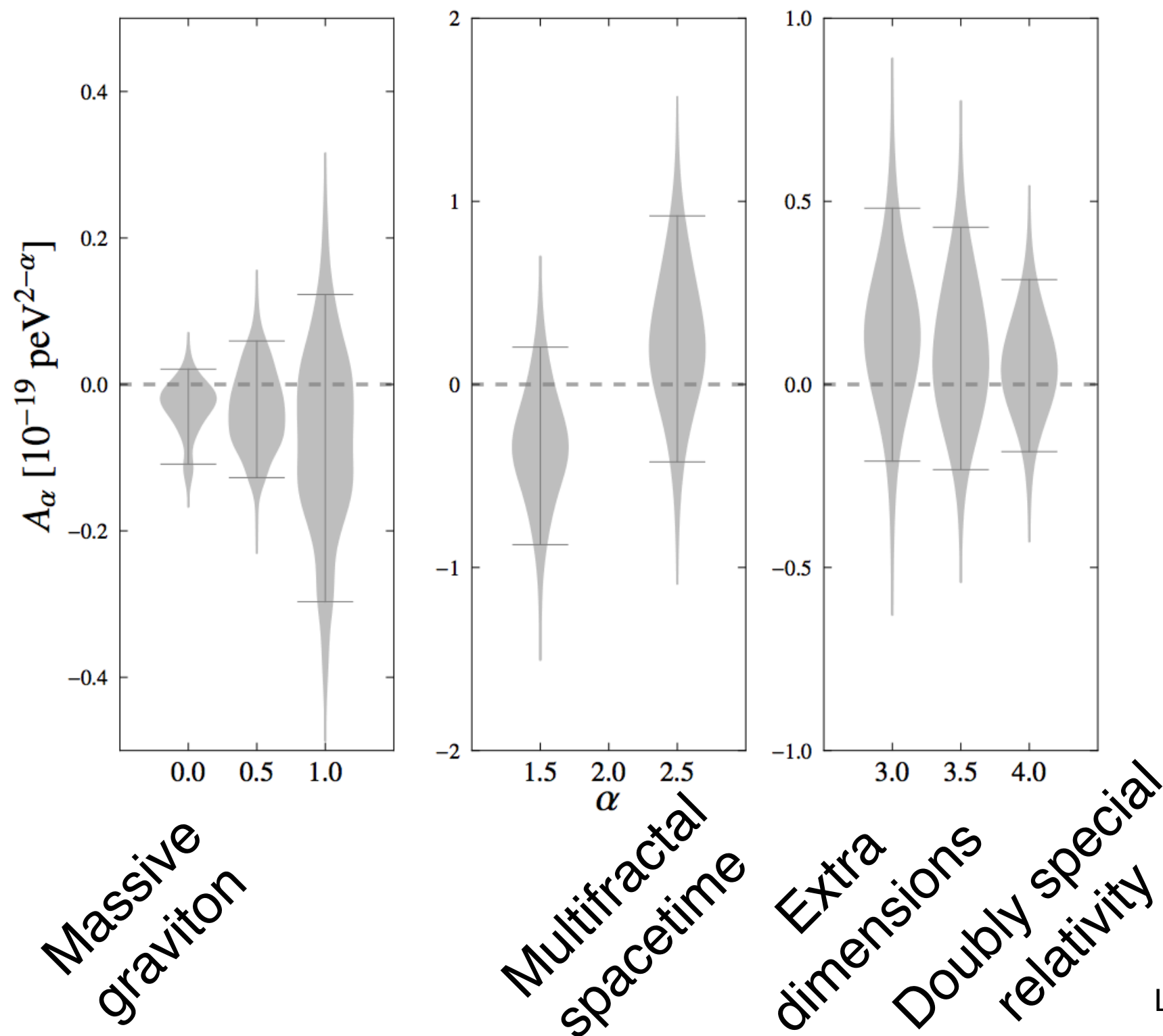
Modified dispersion

$$\delta v_g \sim A E^{\alpha-2} \Rightarrow A \sim \delta v_g E^{2-\alpha} \sim \delta v_g (h_{\text{Pl}} f)^{2-\alpha} \sim 10^{-20} \text{peV}^{2-\alpha}$$

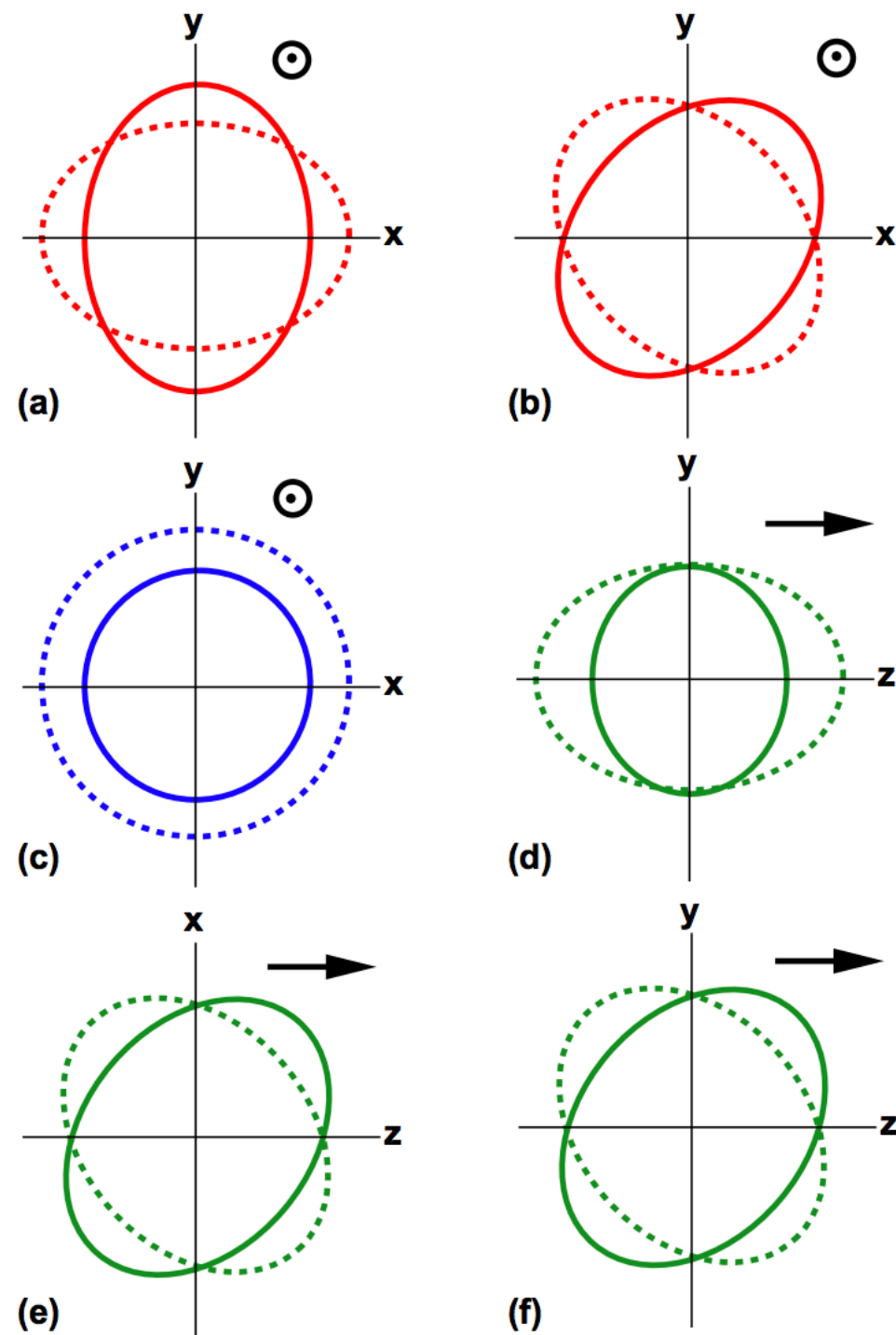


Modified dispersion

$$\delta v_g \sim A E^{\alpha-2} \Rightarrow A \sim \delta v_g E^{2-\alpha} \sim \delta v_g (h_{\text{Pl}} f)^{2-\alpha} \sim 10^{-20} \text{peV}^{2-\alpha}$$



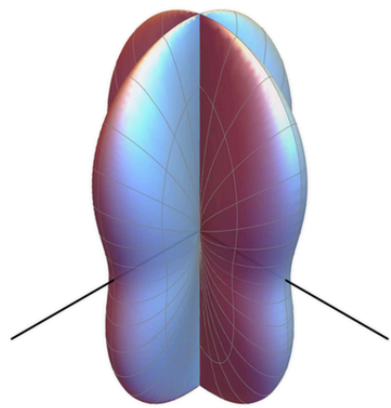
Gravitational wave polarization



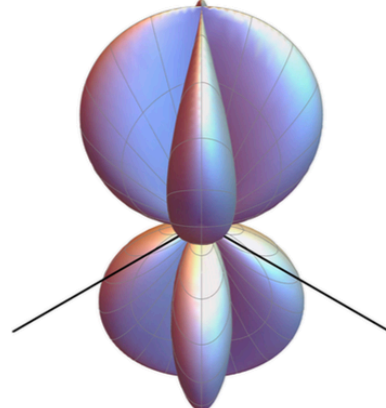
General Relativity
possesses only **two**
propagating
degrees of freedom

$$[h_{ij}] = \begin{pmatrix} h_b + h_+ & h_{\times} & h_{\times} \\ h_{\times} & h_b - h_+ & h_y \\ h_{\times} & h_y & h_l \end{pmatrix}$$

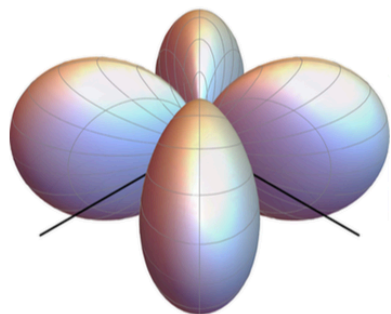
Detector response



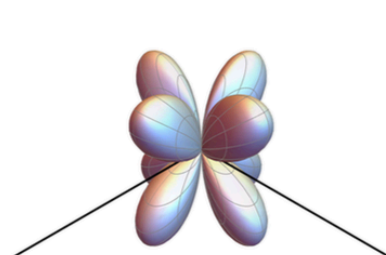
(a) Plus (+)



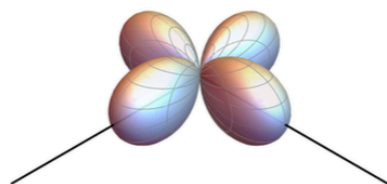
(b) Cross (x)



(c) Vector-x (x)



(d) Vector-y (y)

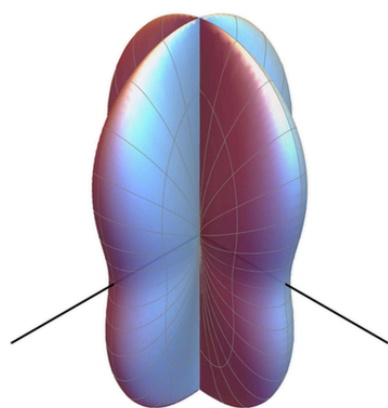


(e) Scalar (s)

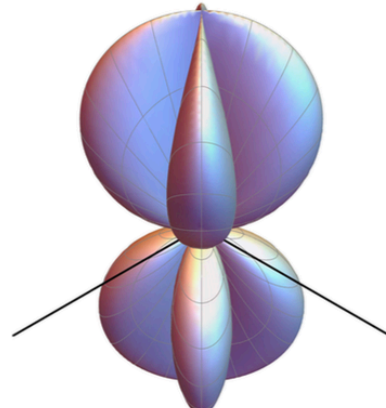
The wave polarization
affects the inferred sky location

Inconclusive test with 2 detectors,
most promising with neutron star
binaries whose **sky location is known**

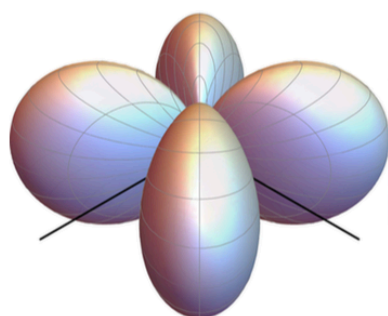
Detector response



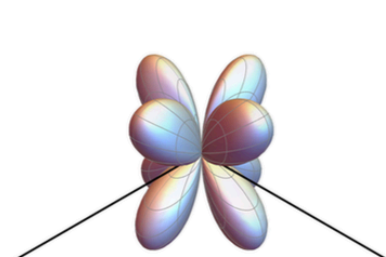
(a) Plus (+)



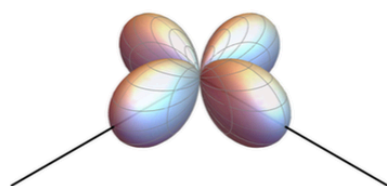
(b) Cross (x)



(c) Vector-x (x)



(d) Vector-y (y)



(e) Scalar (s)

The wave polarization
affects the inferred sky location

Inconclusive test with 2 detectors,
most promising with neutron star
binaries whose **sky location is known**

**Very strong evidence in favor
of **tensor** modes compared
to **vector** or **scalar****

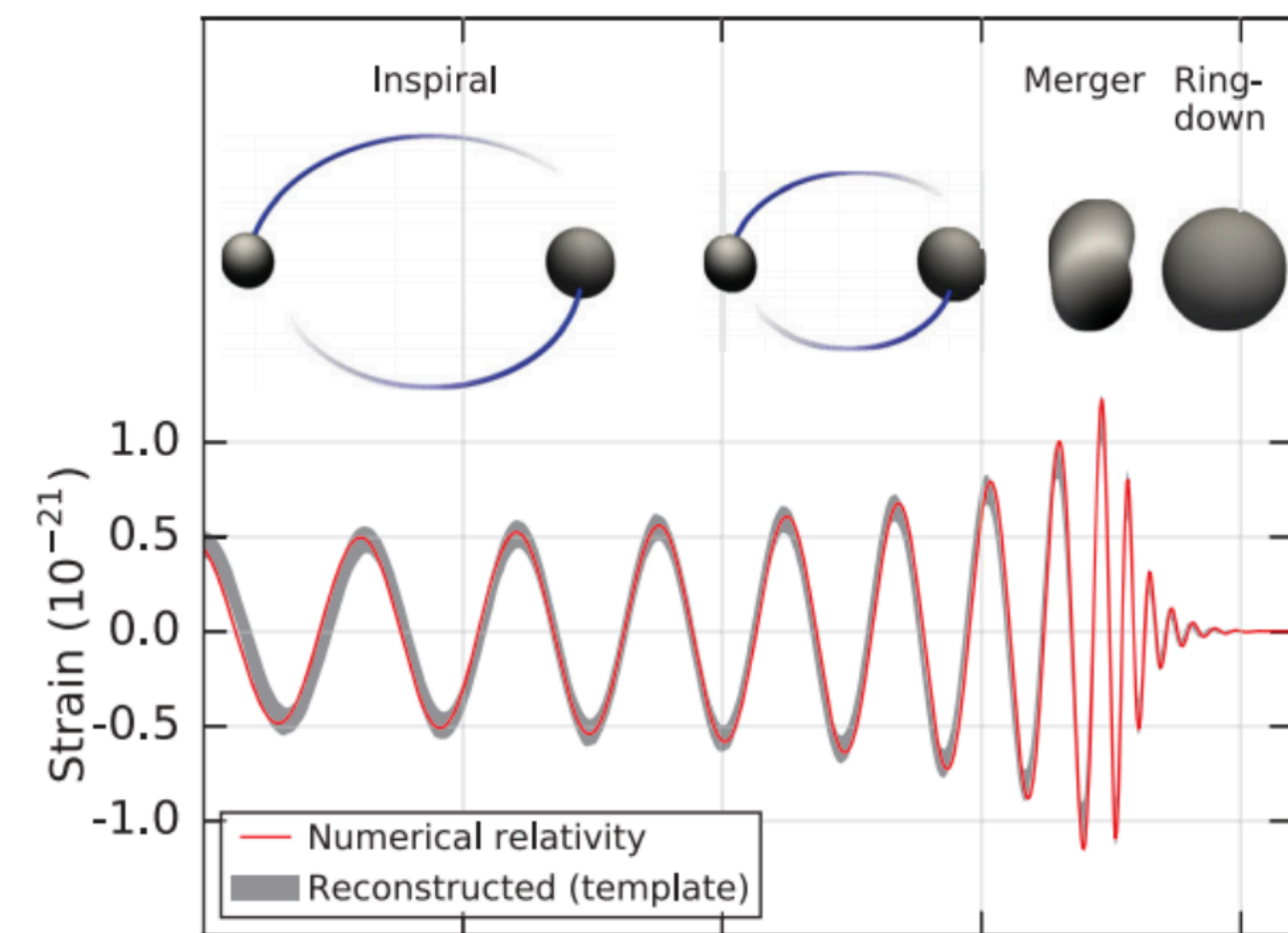
Indications that the linear regime starts “early”

Price and Pullin (arxiv:gr-qc/9402039)

Merger properties

Indications that the linear regime starts “early”

Price and Pullin (arxiv:gr-qc/9402039)

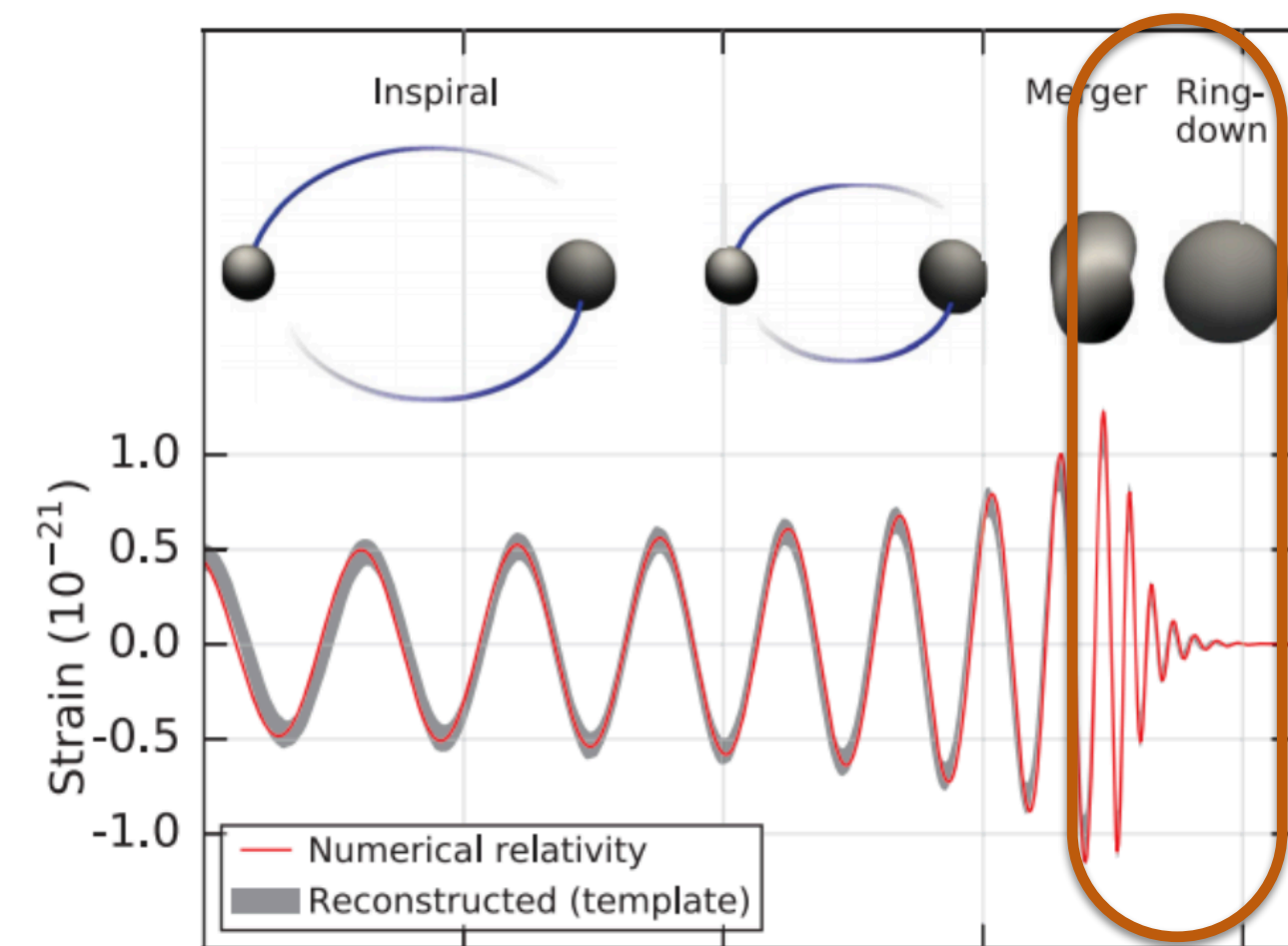


Merger properties

Indications that the linear regime starts “early”

Price and Pullin (arxiv:gr-qc/9402039)

Ringdown: black hole
perturbation theory



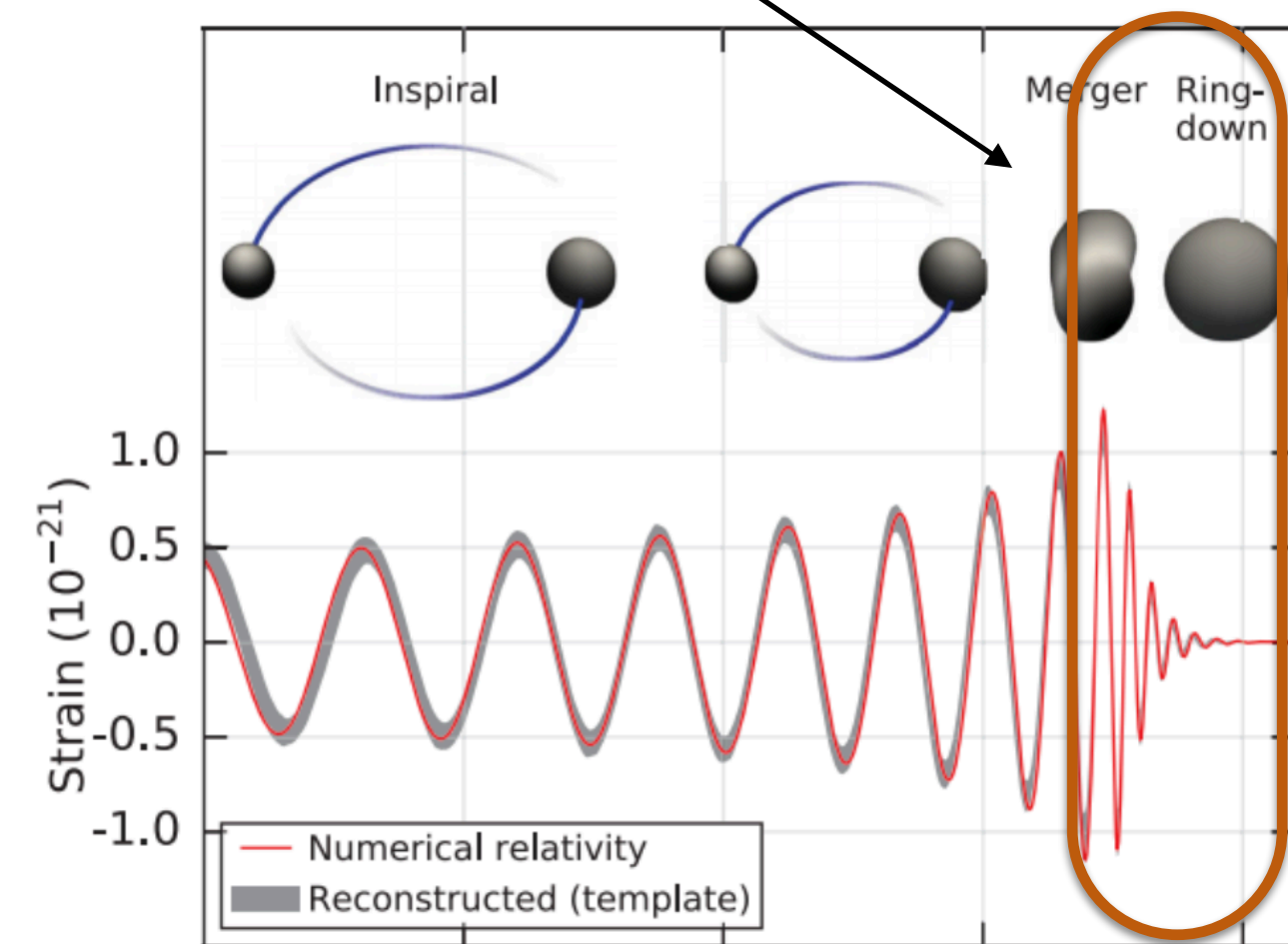
Merger properties

Indications that the linear regime starts “early”

Price and Pullin (arxiv:gr-qc/9402039)

Can be described as
one perturbed BH

Ringdown: black hole
perturbation theory



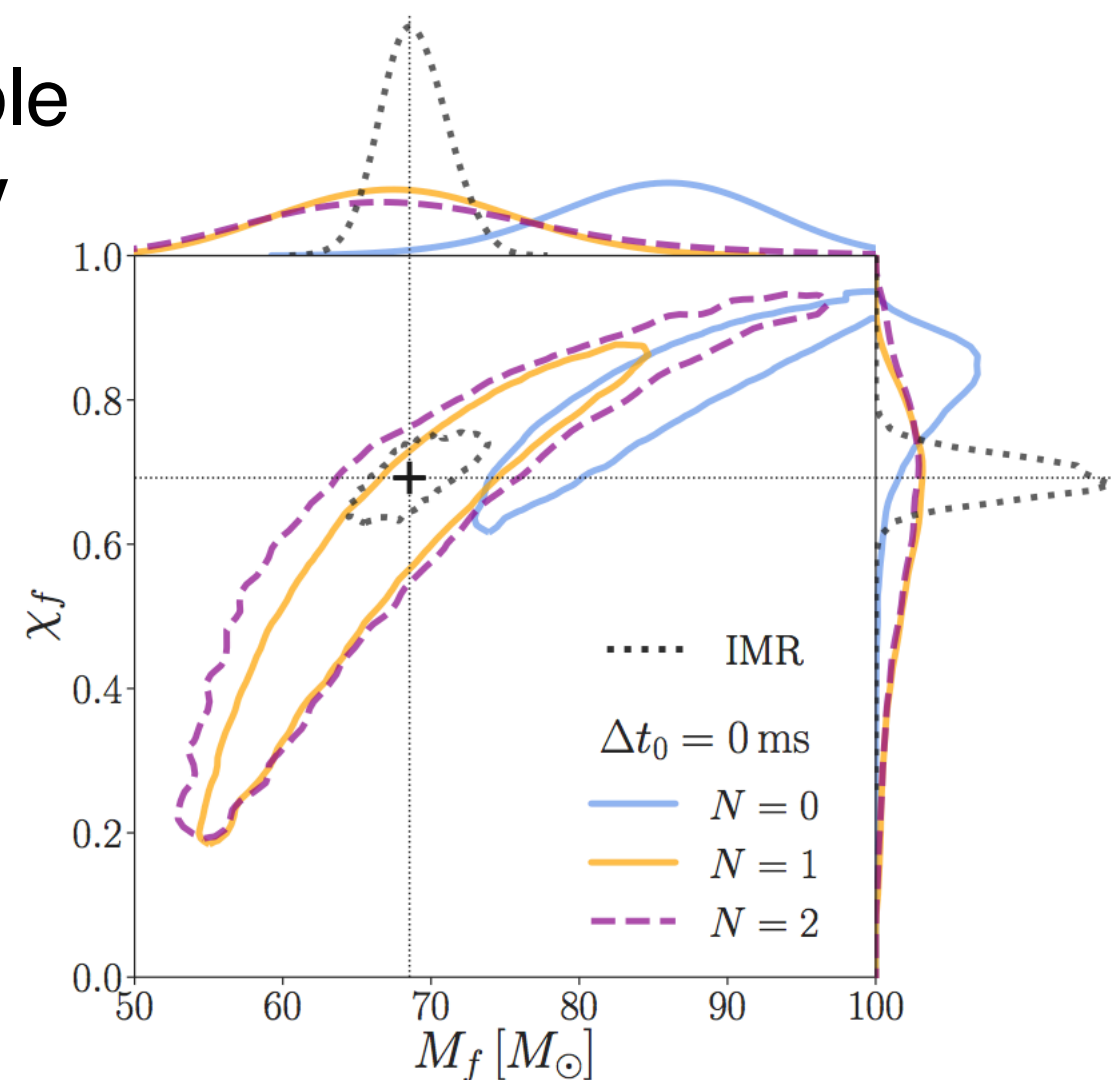
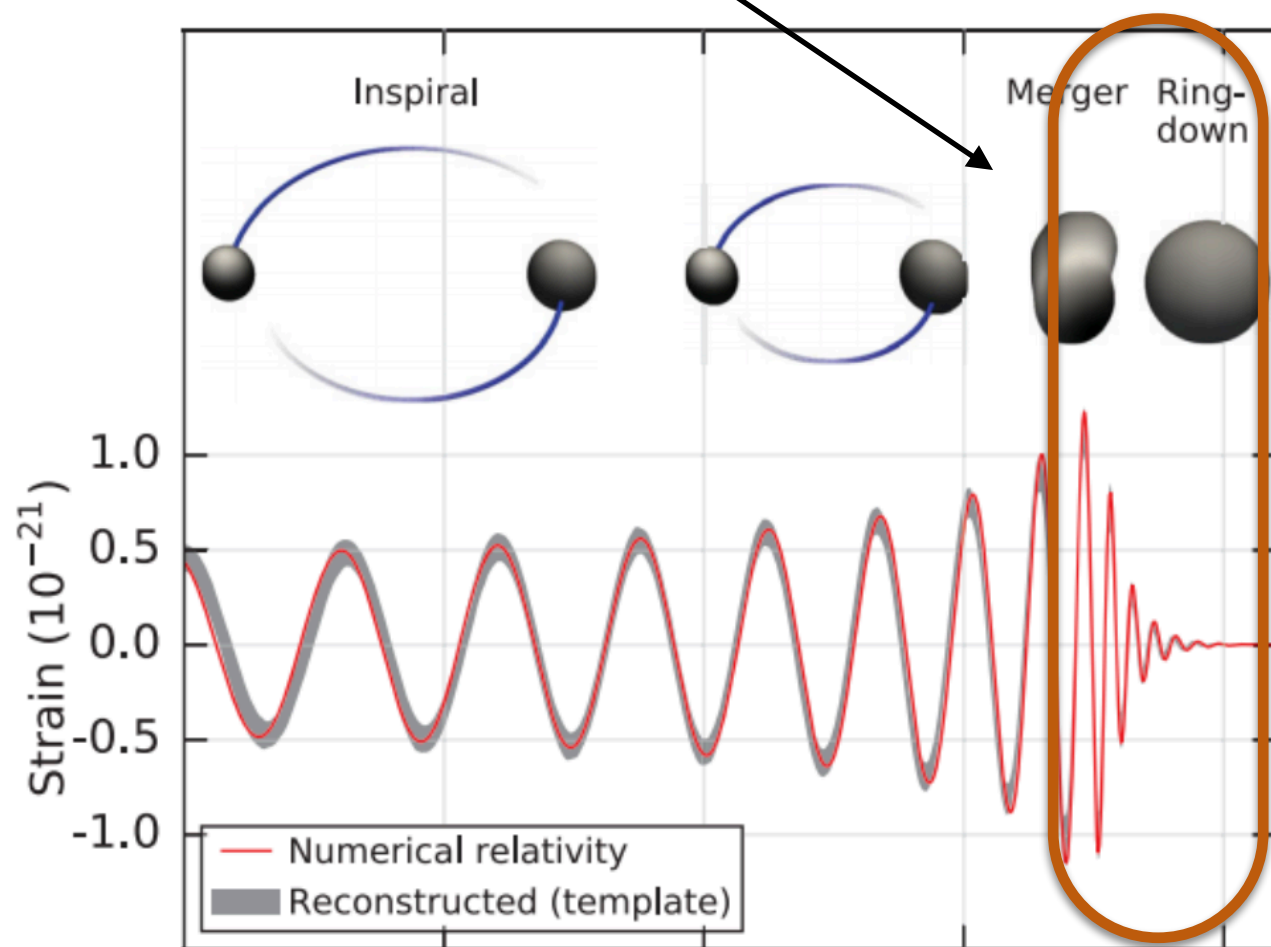
Merger properties

Indications that the linear regime starts “early”

Price and Pullin (arxiv:gr-qc/9402039)

Can be described as
one perturbed BH

Ringdown: black hole
perturbation theory

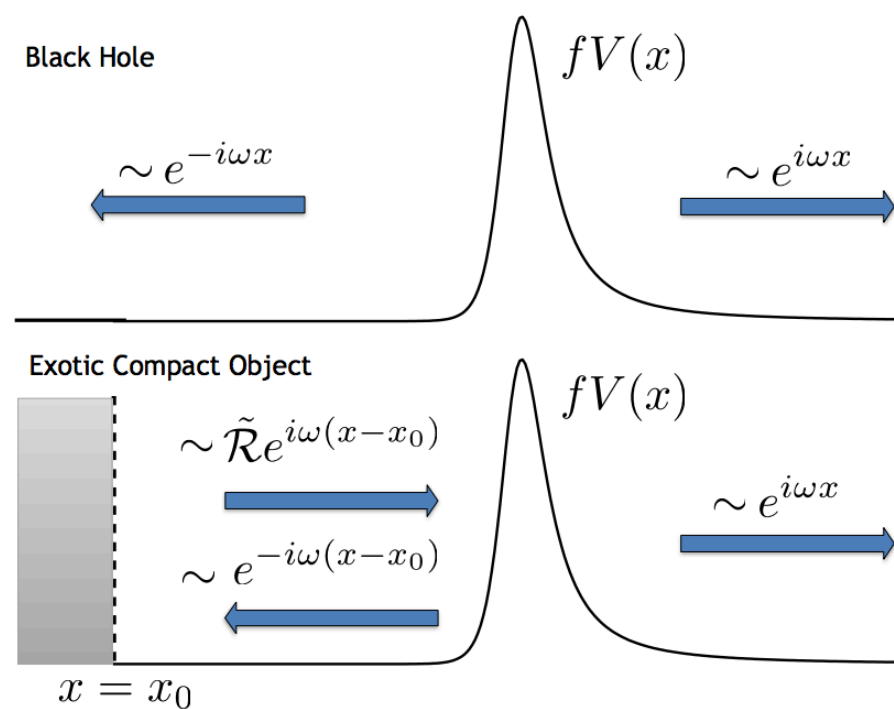
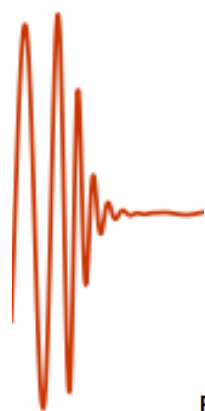


3.6 σ evidence for the presence
of a ringdown overtone mode

Giesler+ (arxiv:1903.08284)

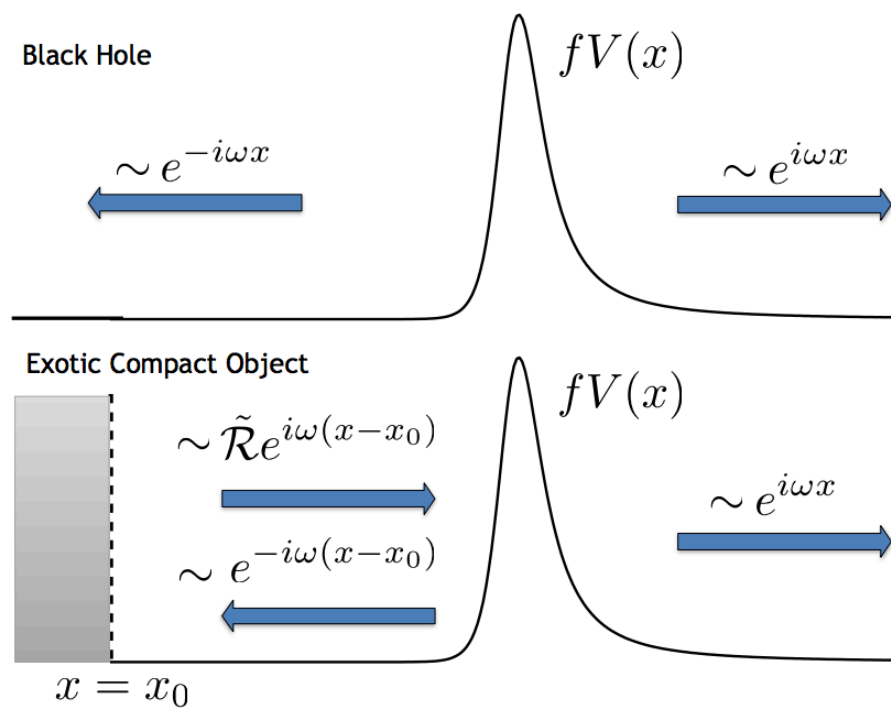
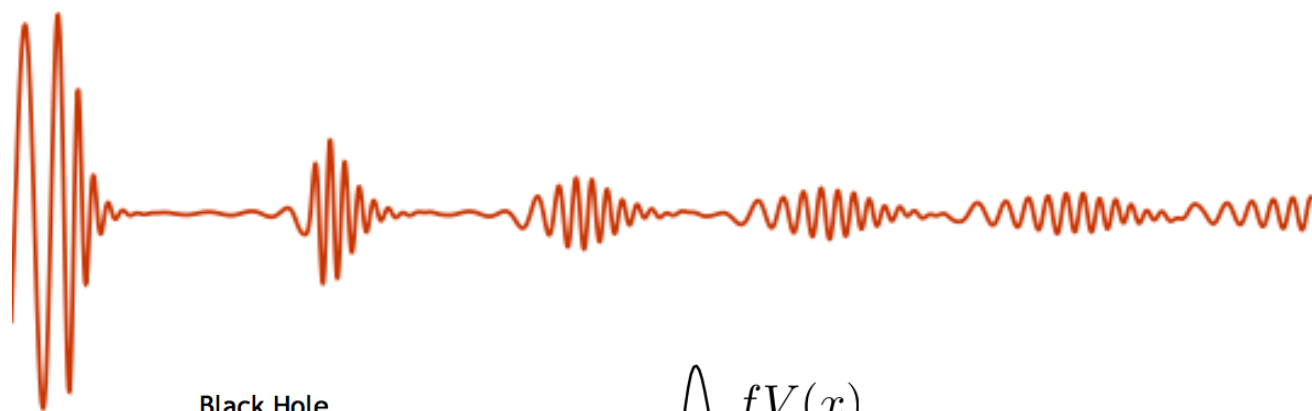
Isi+ (arxiv:1905.00869)

Horizon(less) objects: echoes?



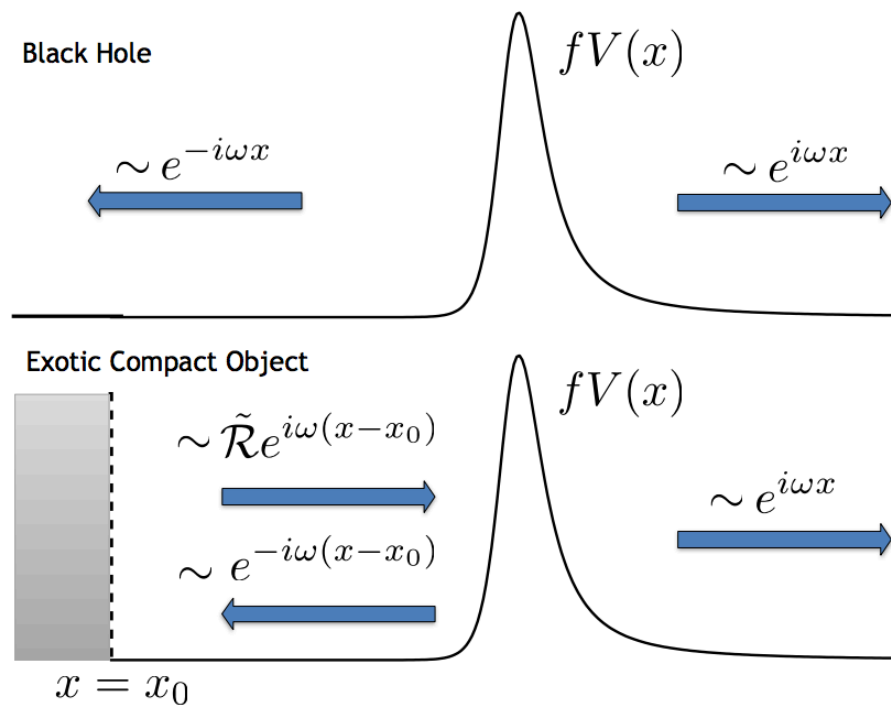
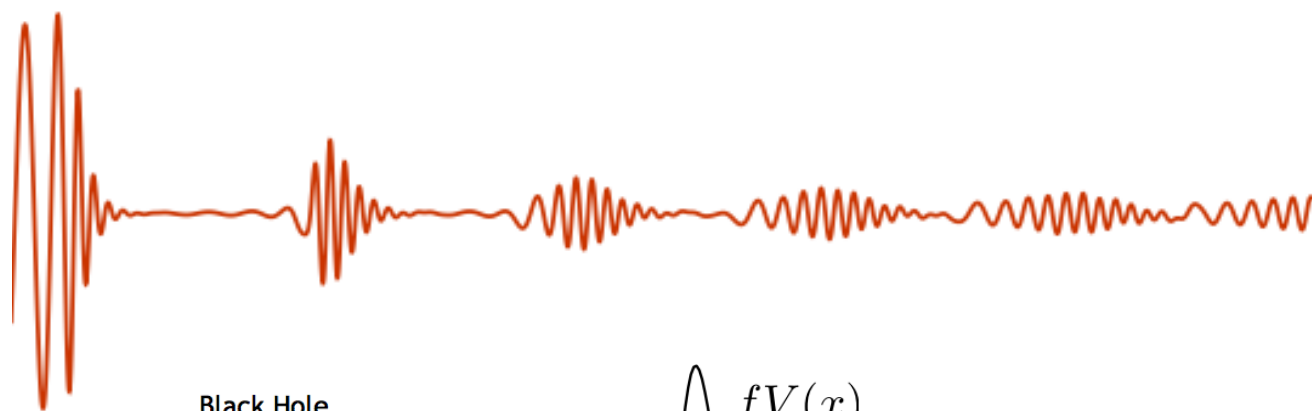
Mark+ (arxiv:1706.06155)

Horizon(less) objects: echoes?

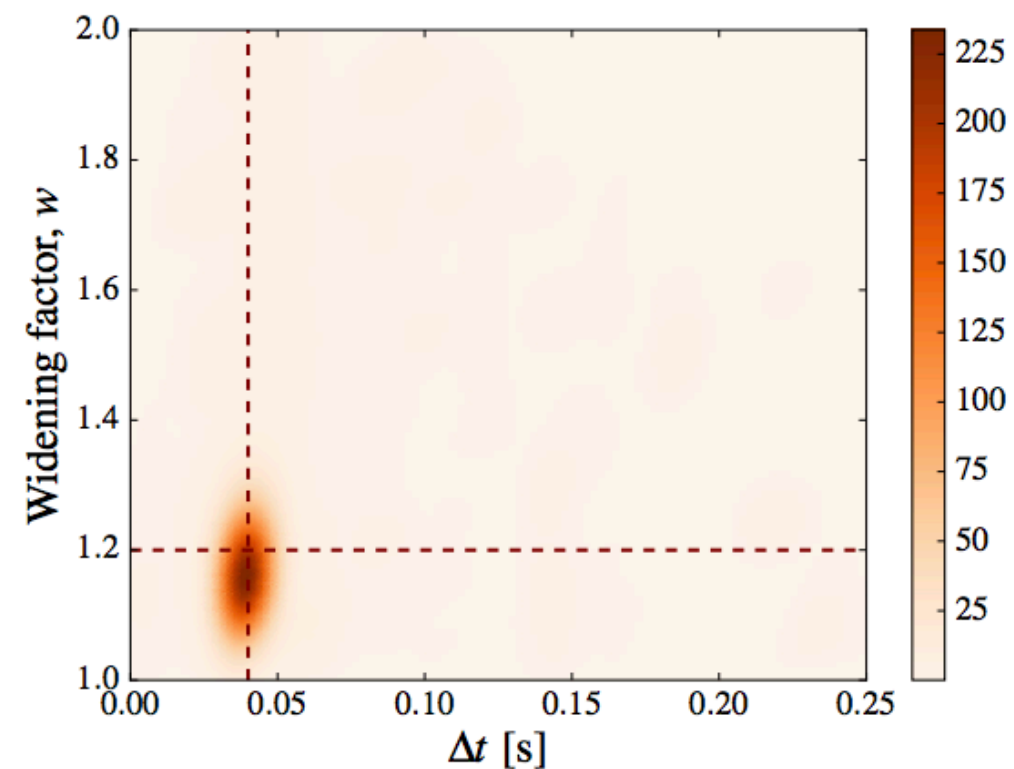
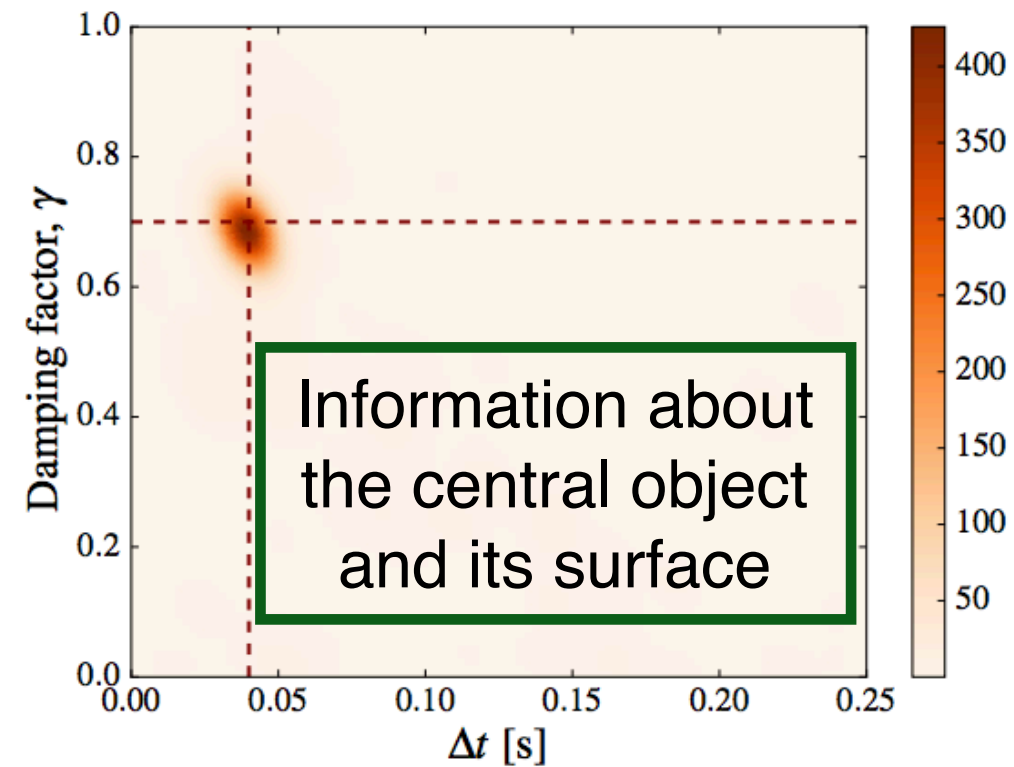


Mark+ (arxiv:1706.06155)

Horizon(less) objects: echoes?

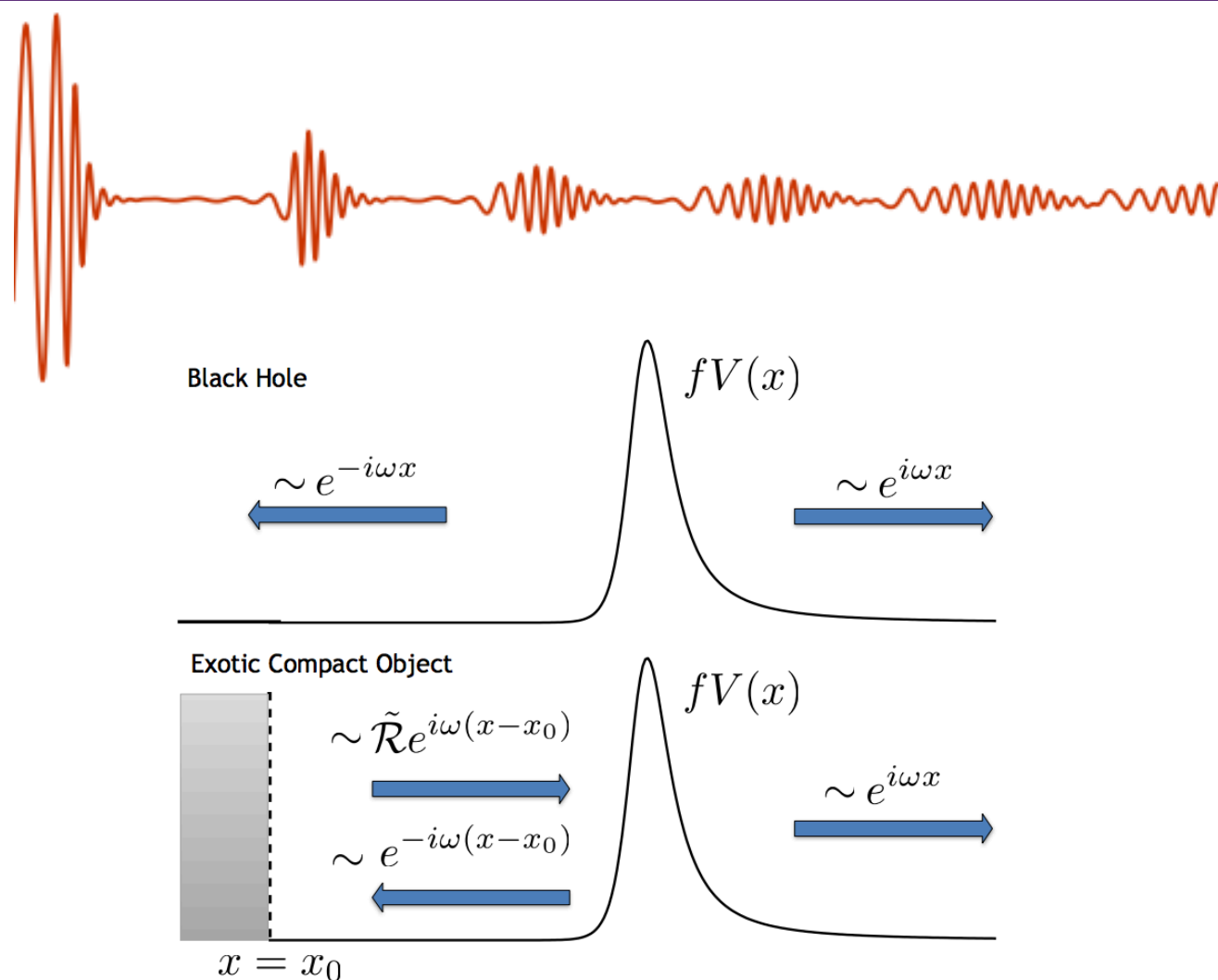


Mark+ (arxiv:1706.06155)



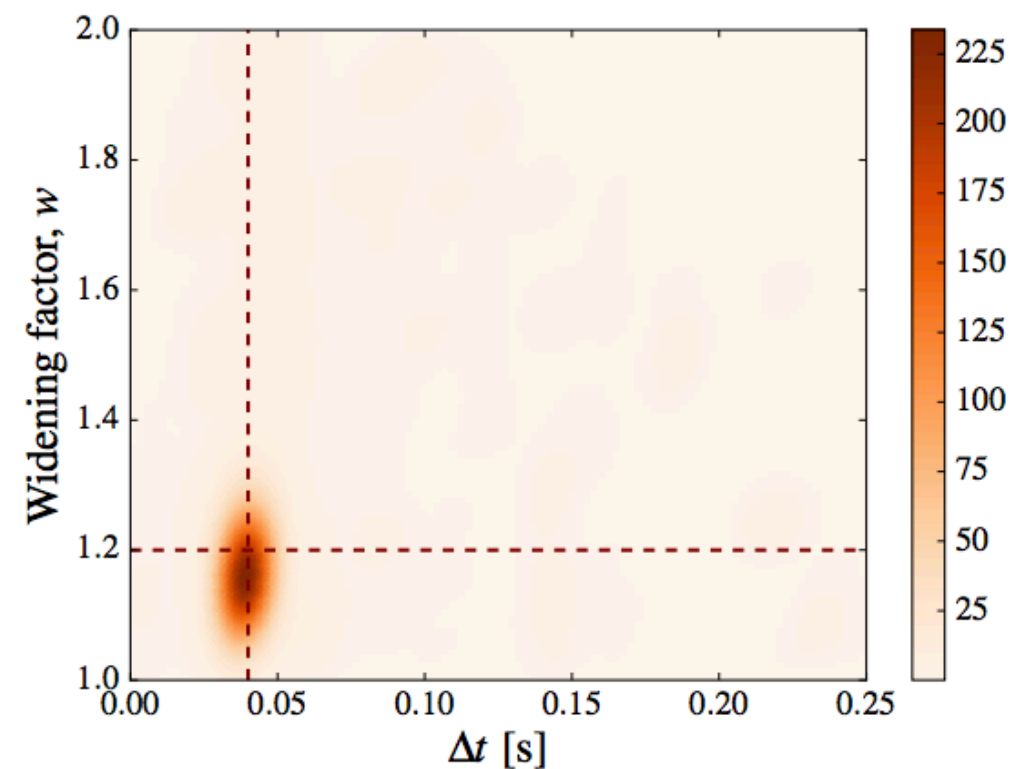
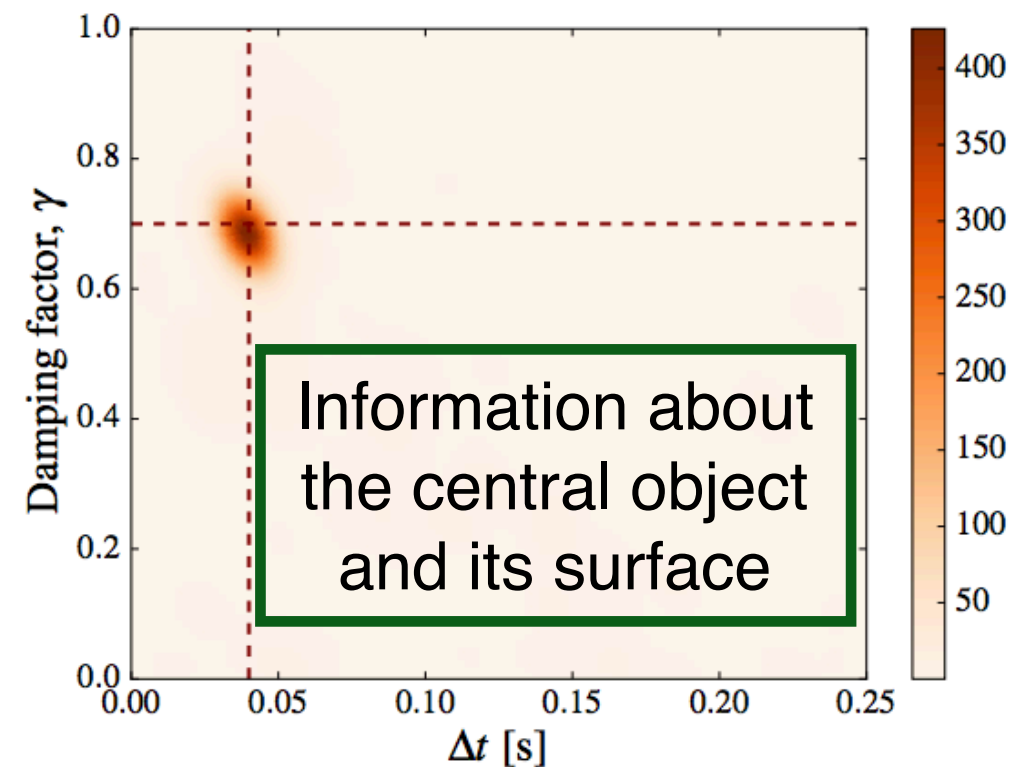
Tsang+ including KC (arxiv:1804.04877)

Horizon(less) objects: echoes?



Mark+ (arxiv:1706.06155)

No statistically significant
evidence for echoes after
the observed signals

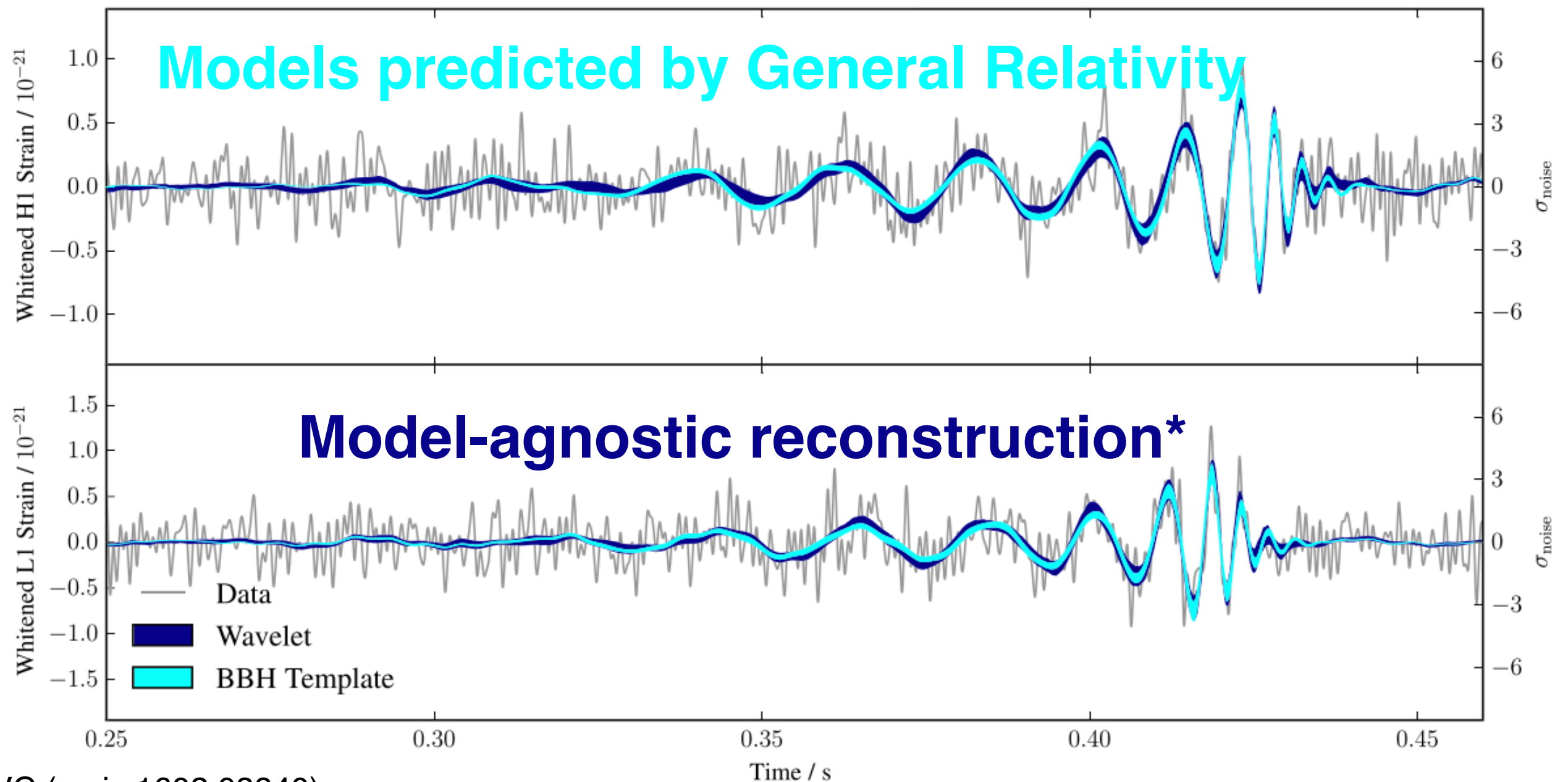


Tsang+ including KC (arxiv:1804.04877)

Westerweck+ (arxiv:1712.09966)

Nielsen+ (arxiv:1811.04904)

The data

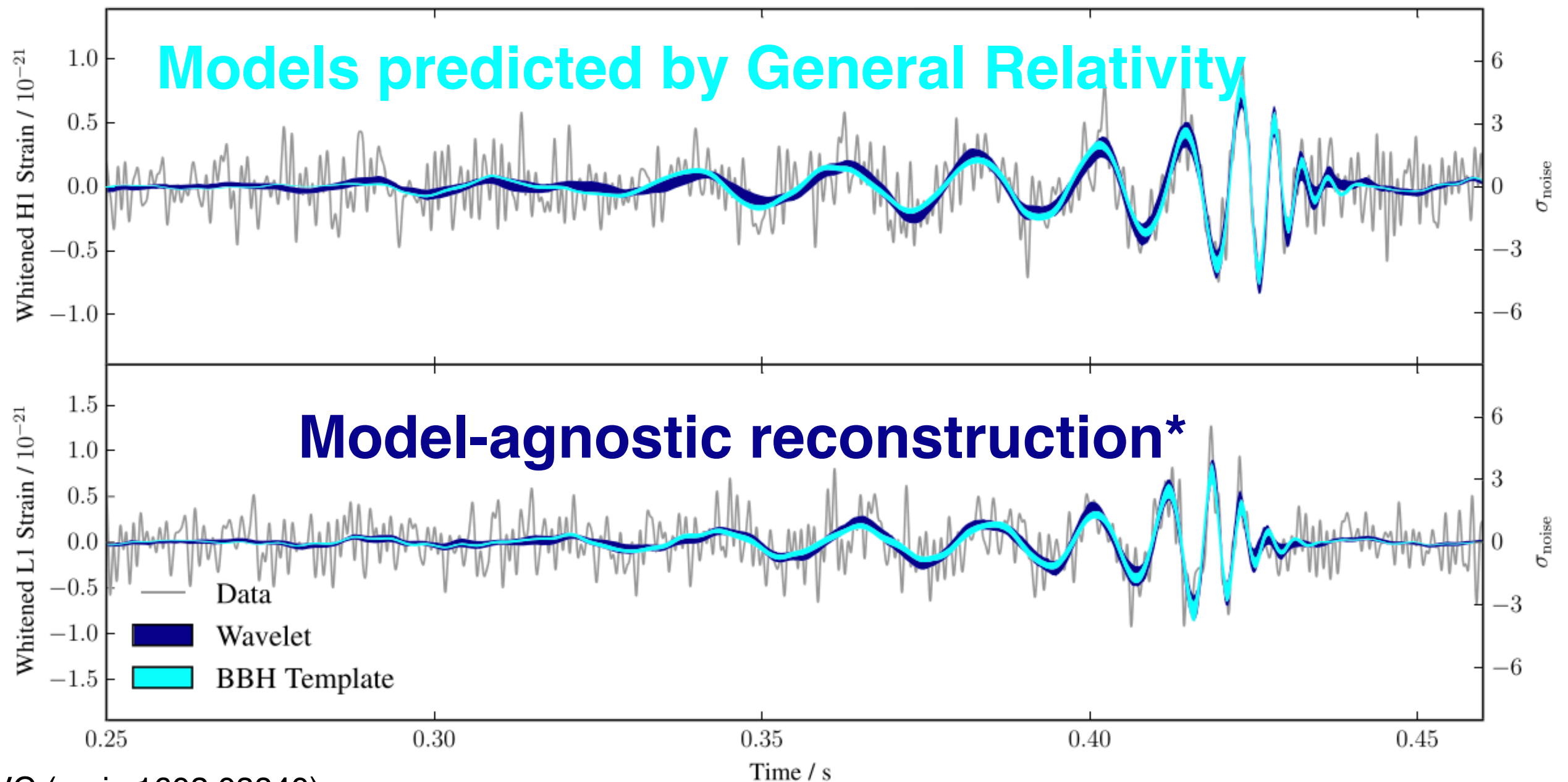


LVC (arxiv:1602.03840)

*Elliptical polarization,
speed-of-light propagation,
no decoherence

PE: LALInference — Veitch+ (arxiv:1409.7215)

The data



LVC (arxiv:1602.03840)

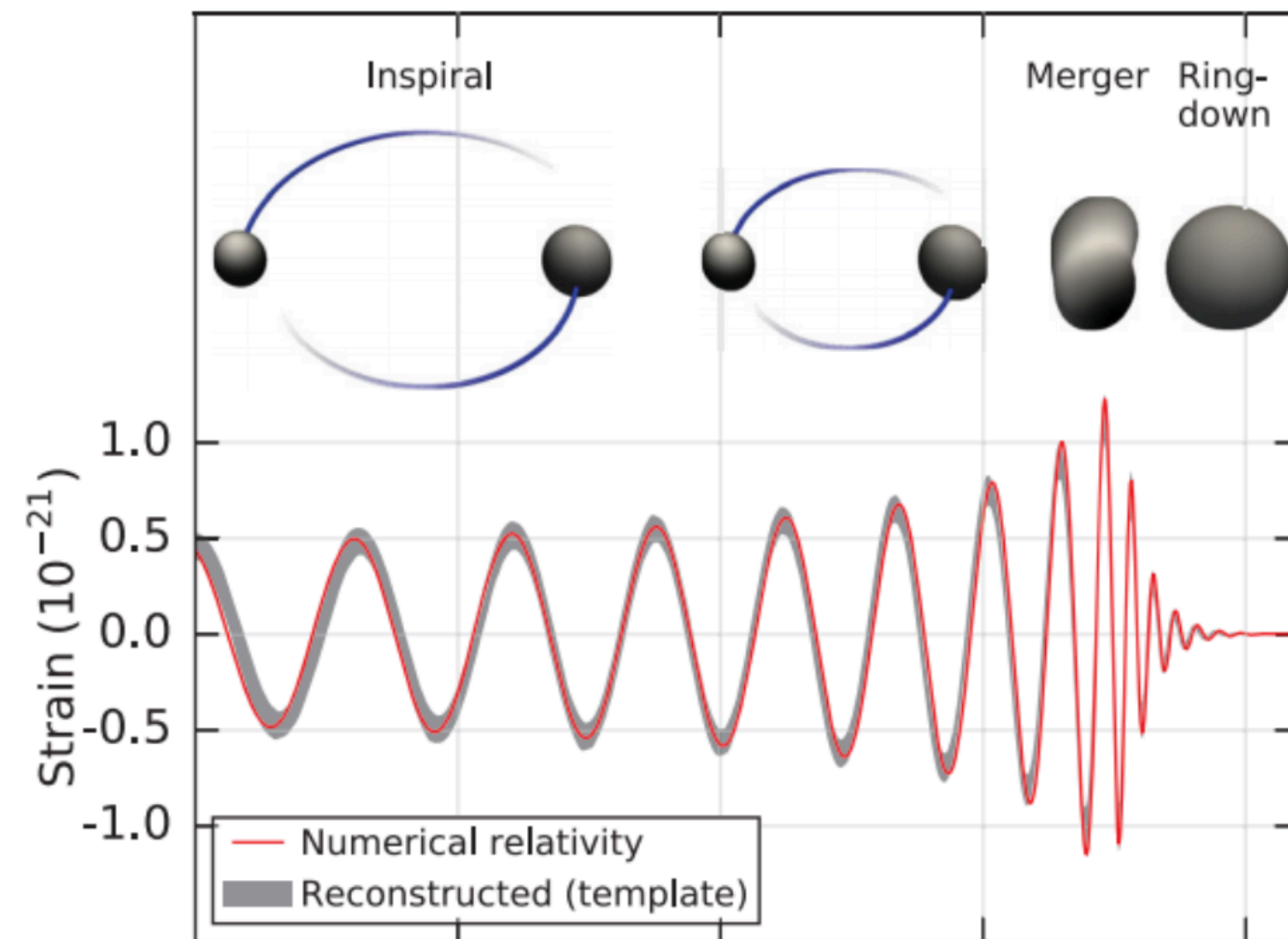
*Elliptical polarization,
speed-of-light propagation,
no decoherence

PE: LALInference — Veitch+ (arxiv:1409.7215)

Waveform: IMRPhenomPv2 — Hannam+ (arxiv:1308.3271)

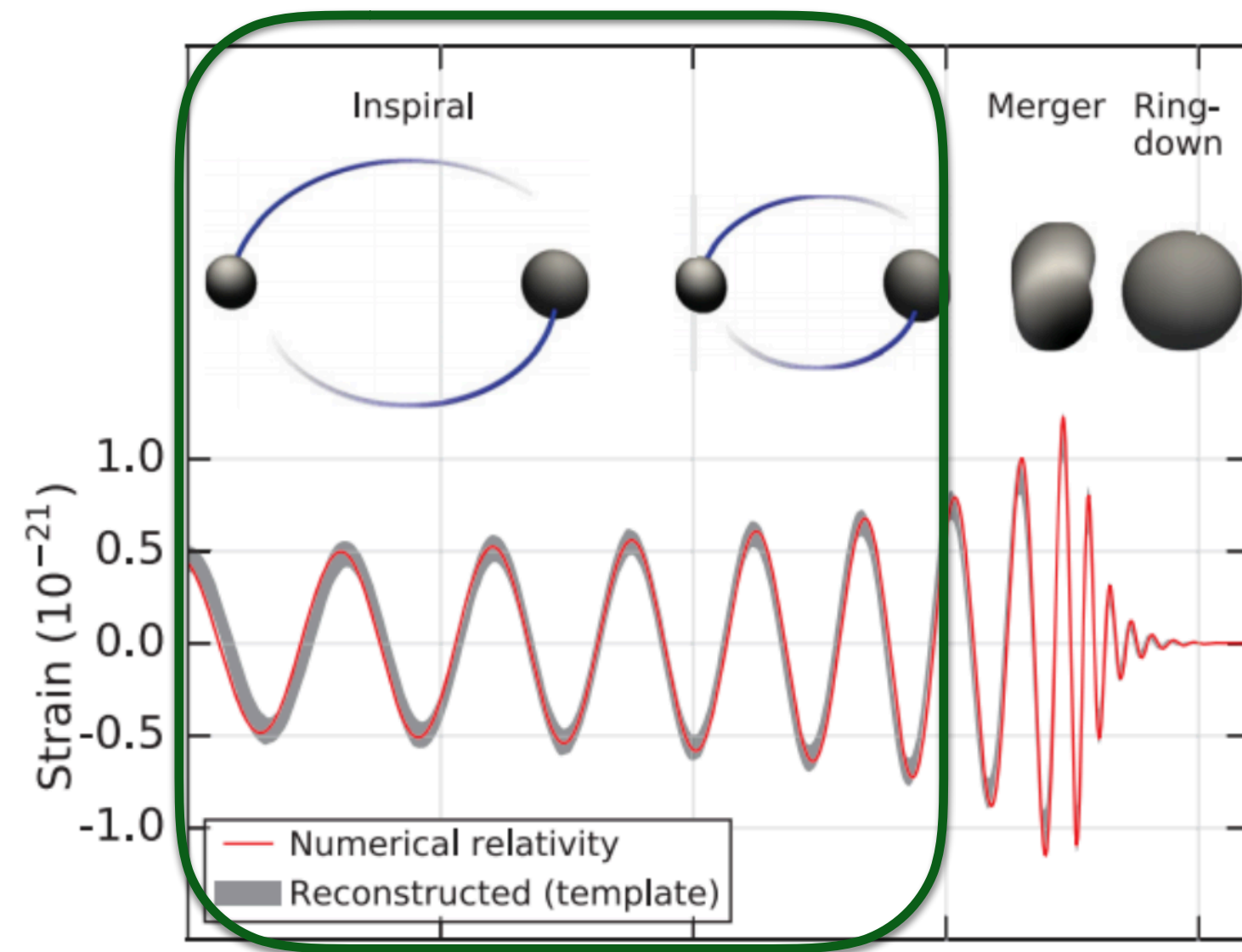
Model-agnostic: BayesWave — Cornish and Littenberg (arxiv:1410.3835)

General Relativity models



General Relativity models

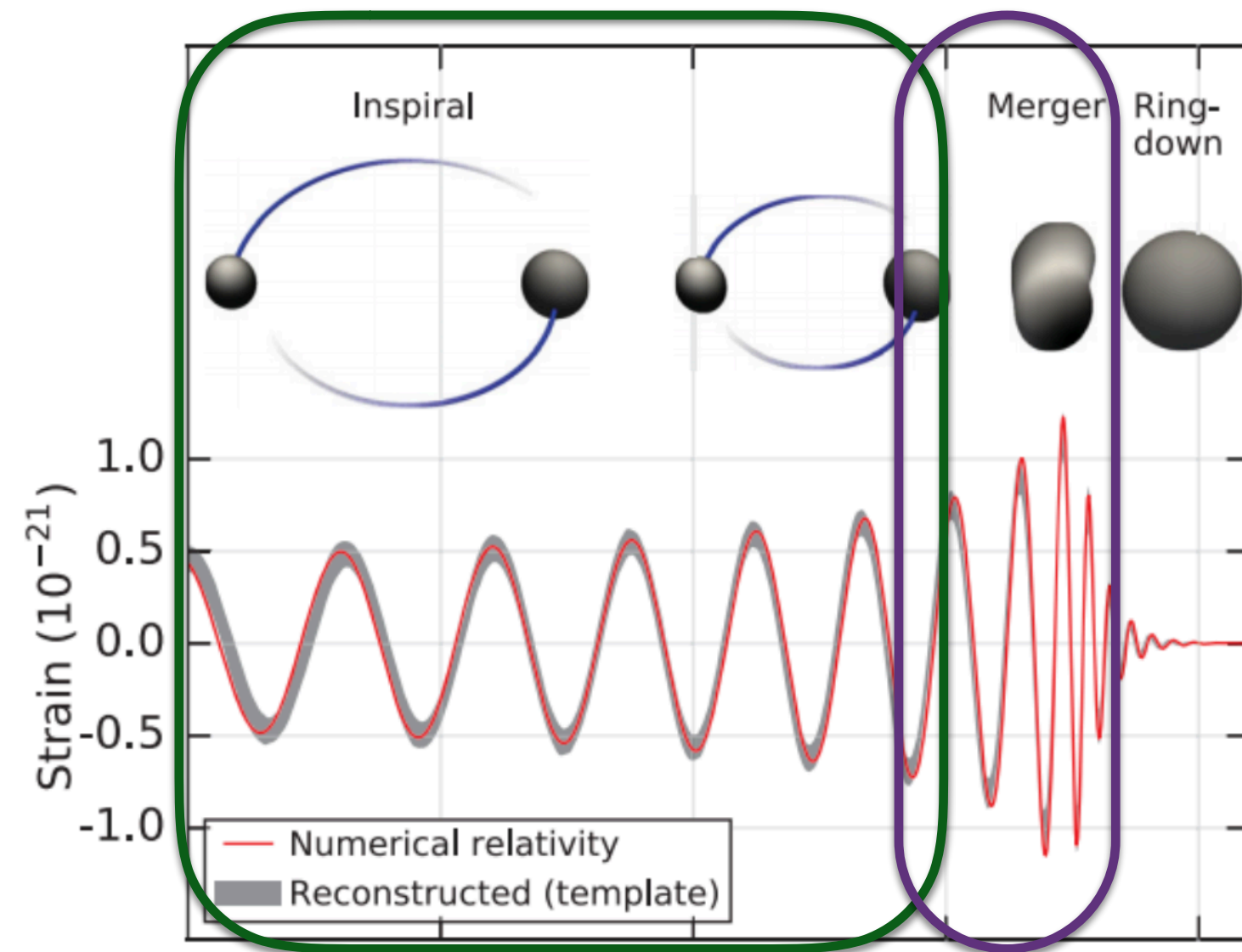
Inspiral: post-Newtonian theory, expansion in powers of the velocity



General Relativity models

Inspiral: post-Newtonian theory, expansion in powers of the velocity

Merger: dynamical and nonlinear, full numerical simulations

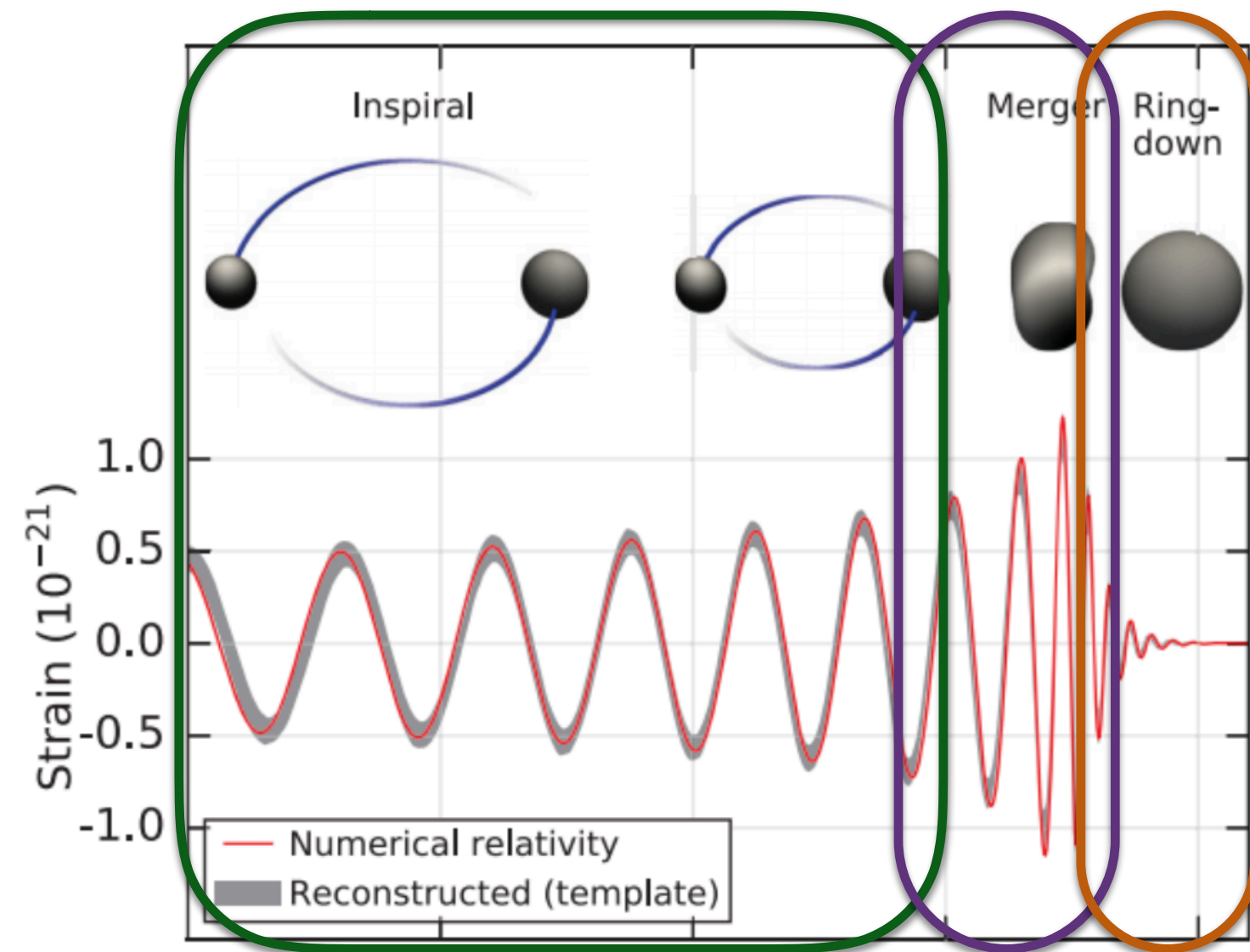


General Relativity models

Inspiral: post-Newtonian theory, expansion in powers of the velocity

Merger: dynamical and nonlinear, full numerical simulations

Ringdown: black hole perturbation theory

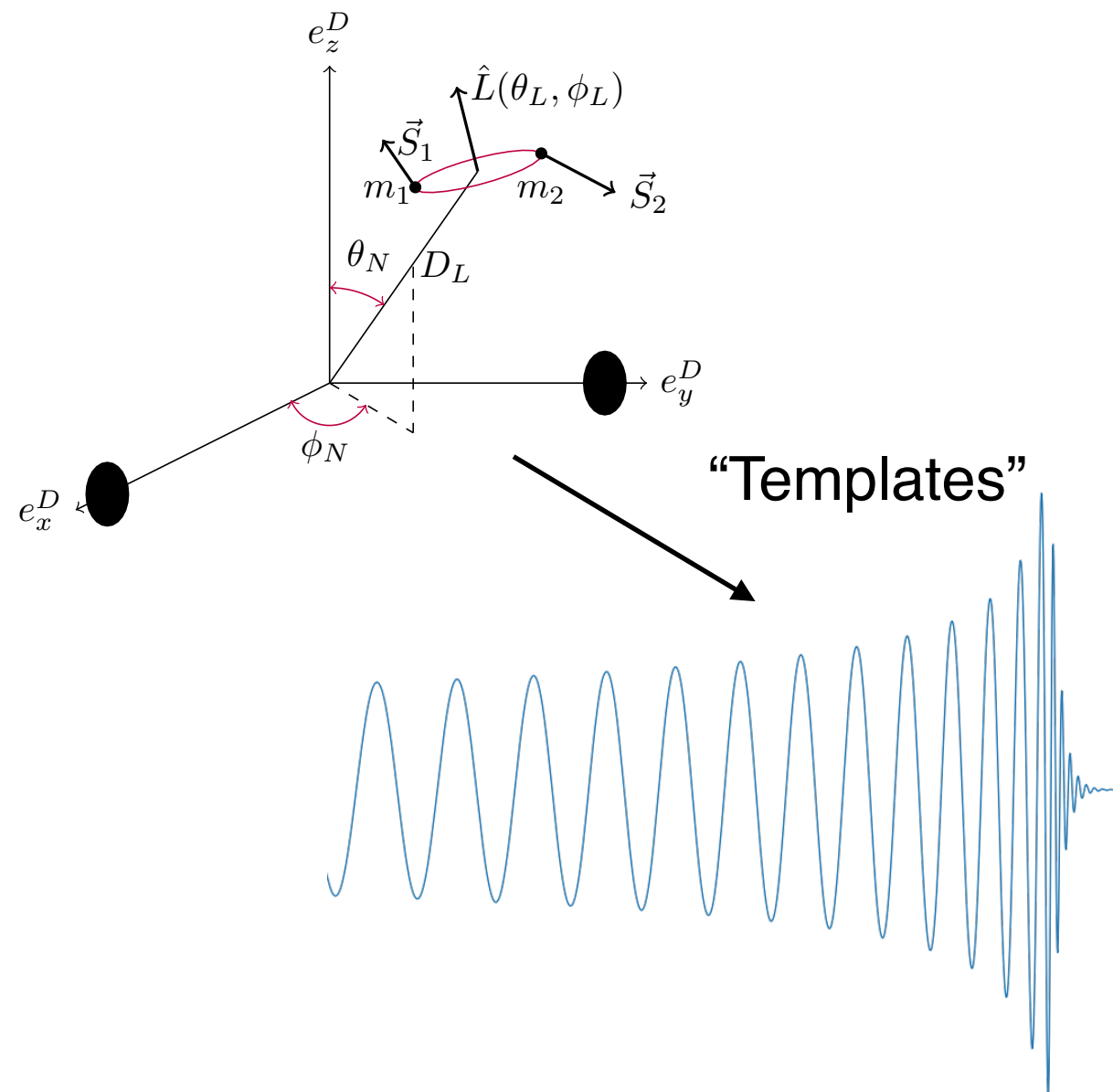
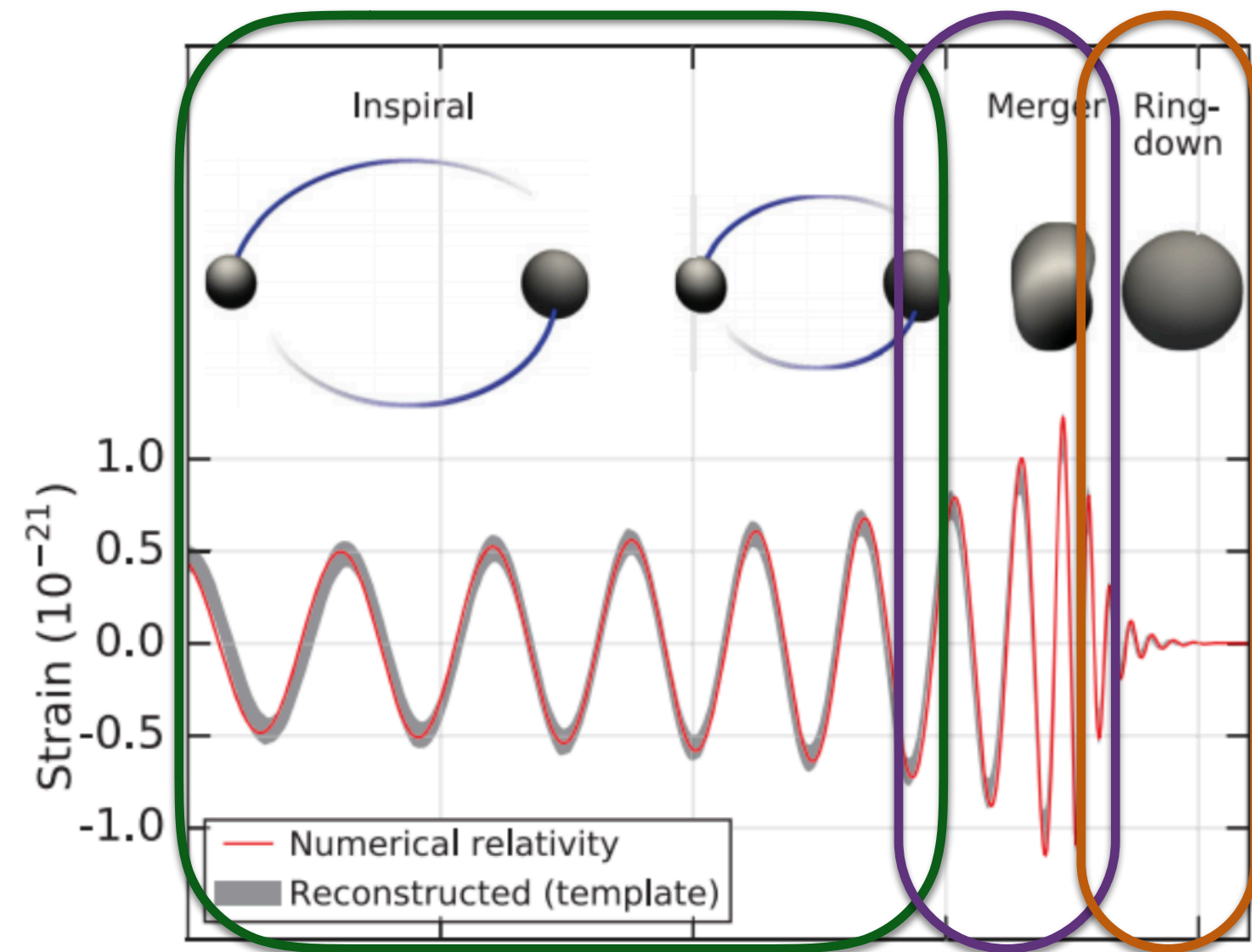


General Relativity models

Inspiral: post-Newtonian theory, expansion in powers of the velocity

Merger: dynamical and nonlinear, full numerical simulations

Ringdown: black hole perturbation theory



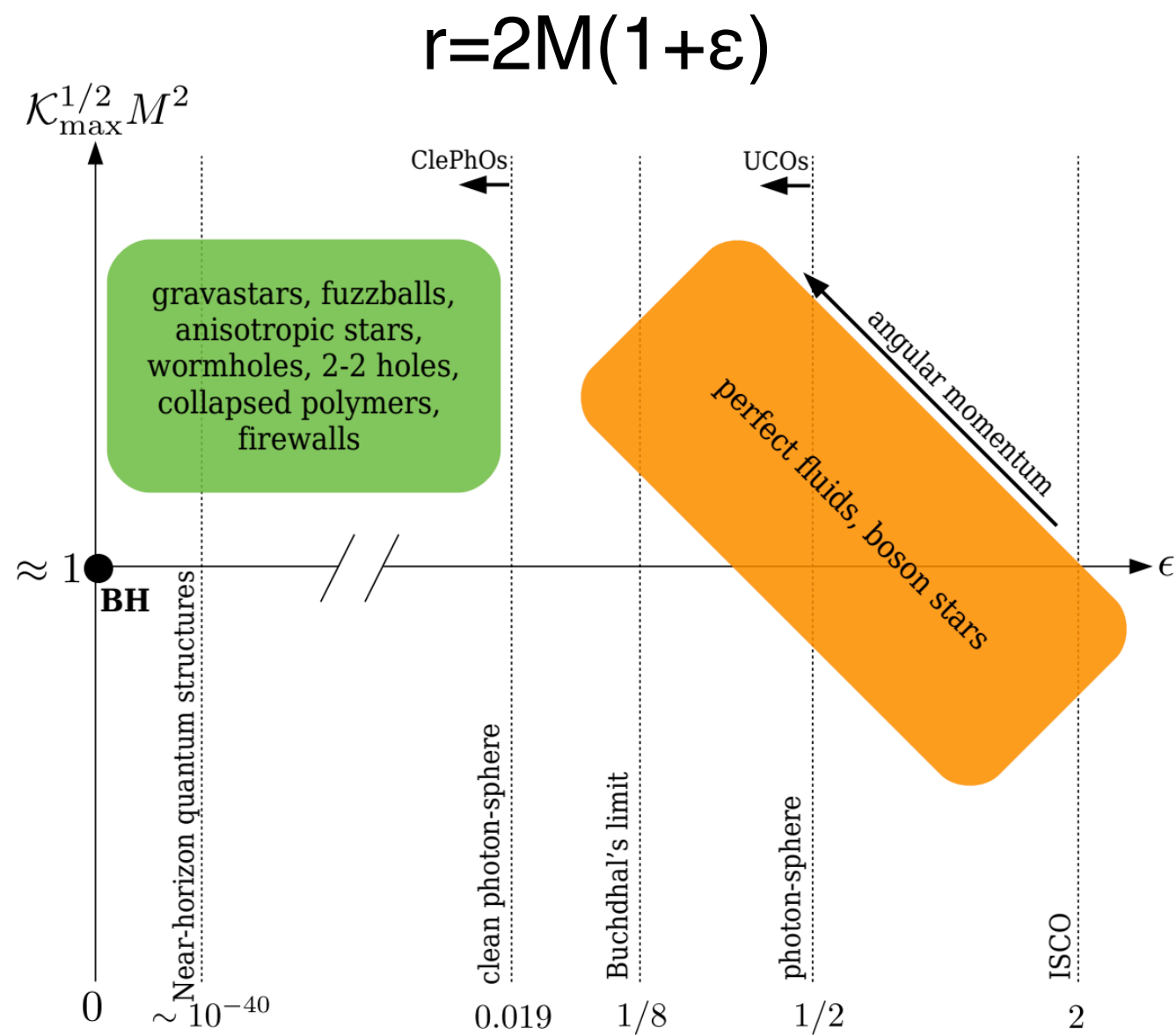
What exactly are we probing?

What exactly are we probing?

Not the black hole horizon

What exactly are we probing?

Not the black hole horizon

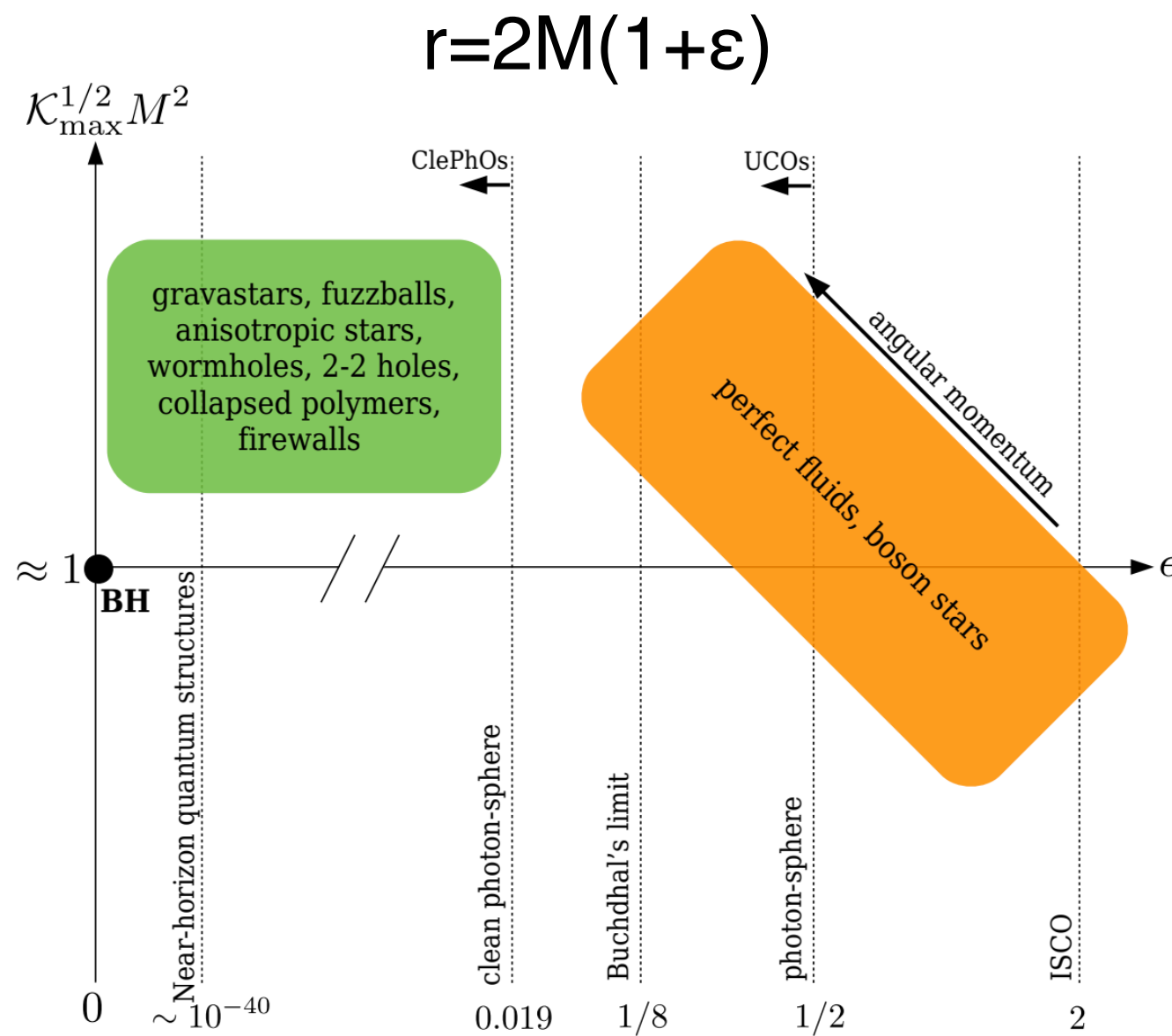


What exactly are we probing?

Not the black hole horizon

Quantum gravity effects

$$\ell_P \sim \sqrt{G\hbar/c^3} \sim 10^{-35} \text{ meters}$$

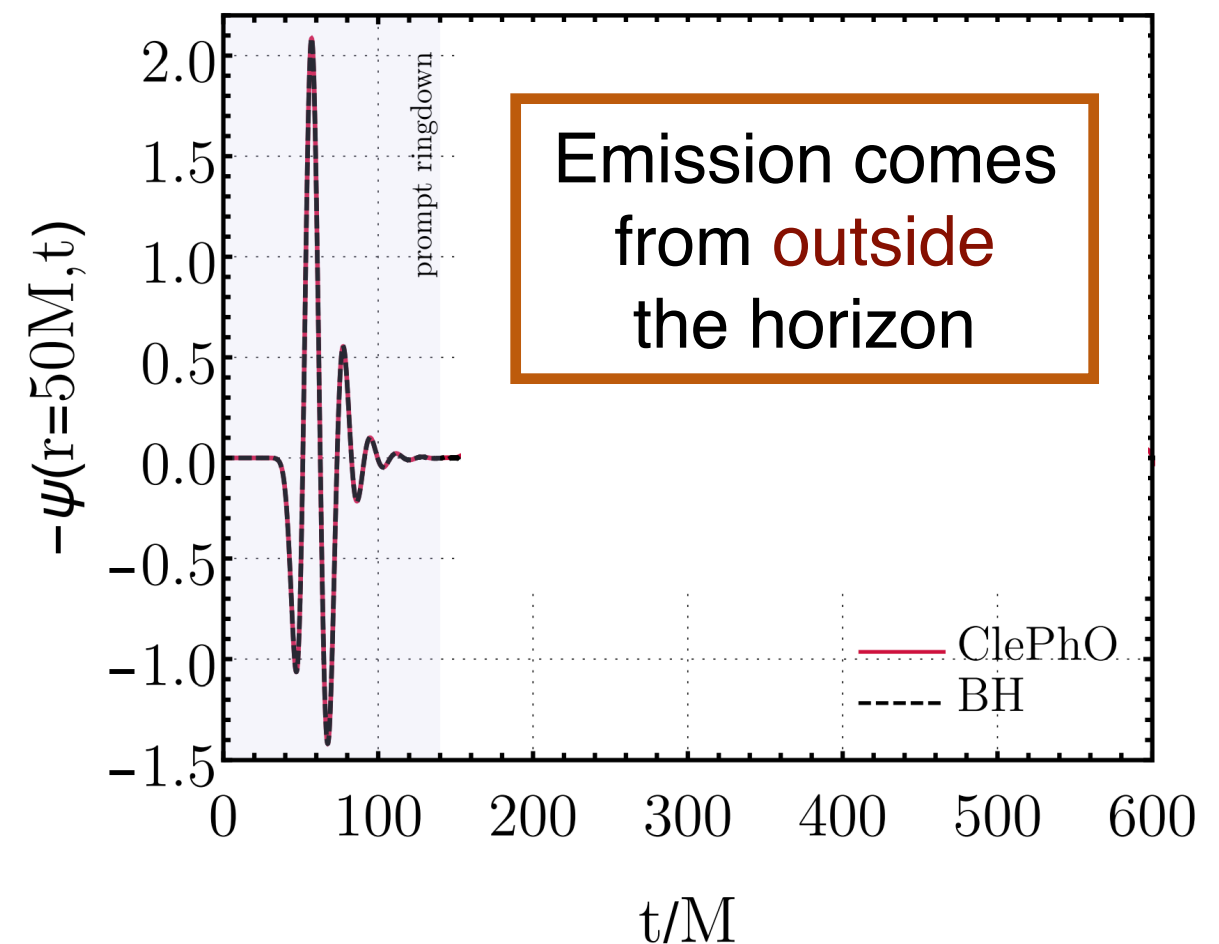
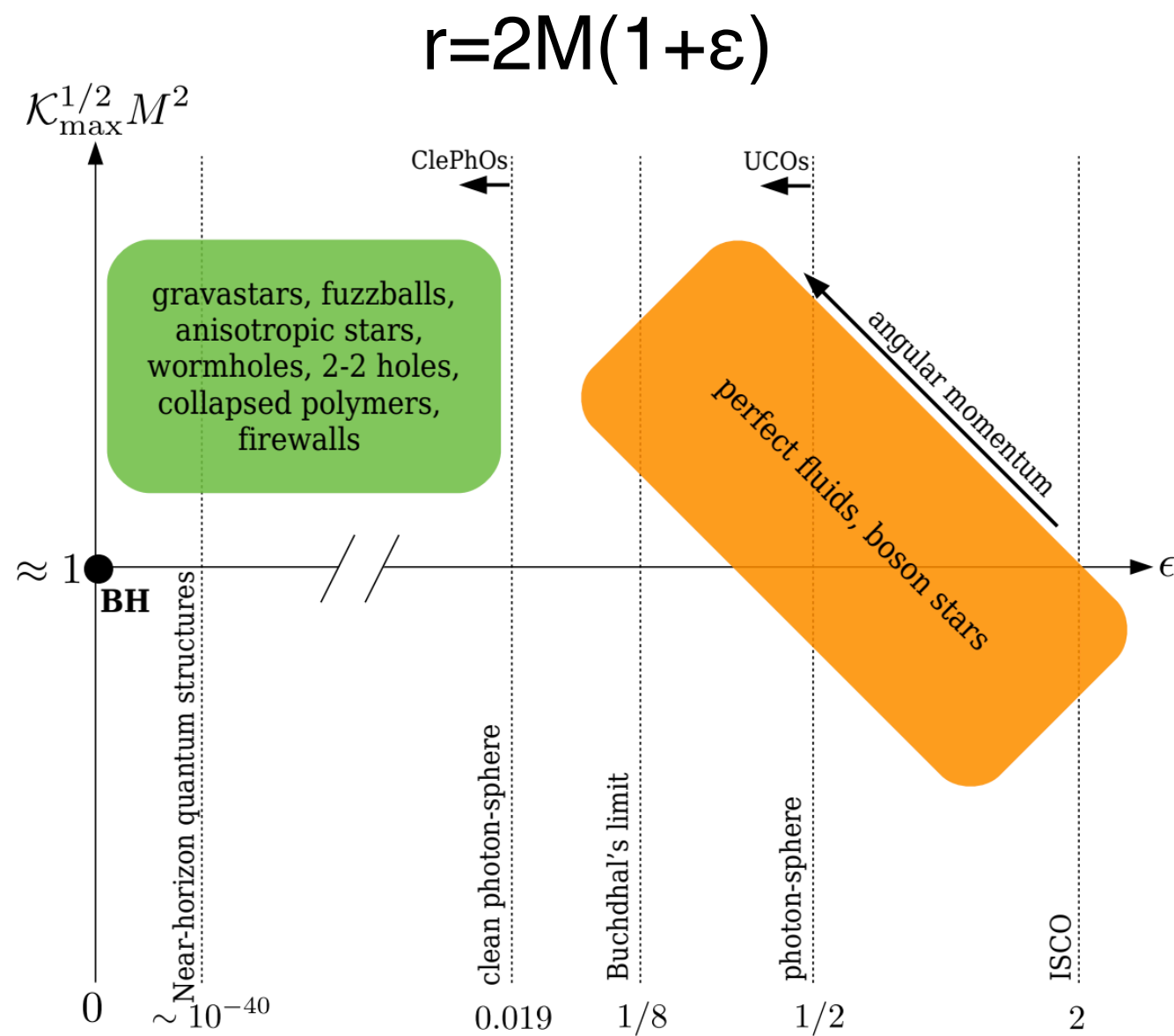


What exactly are we probing?

Not the black hole horizon

Quantum gravity effects

$$\ell_P \sim \sqrt{G\hbar/c^3} \sim 10^{-35} \text{ meters}$$



Logarithmic corrections

For some “black hole mimickers”

$$\delta = r_0 - r_H = r_H e^{-1/k}$$

Logarithmic corrections

For some “black hole mimickers”

$$\delta = r_0 - r_H = r_H e^{-1/k}$$

Tidal deformability,
identically **zero** for BHs

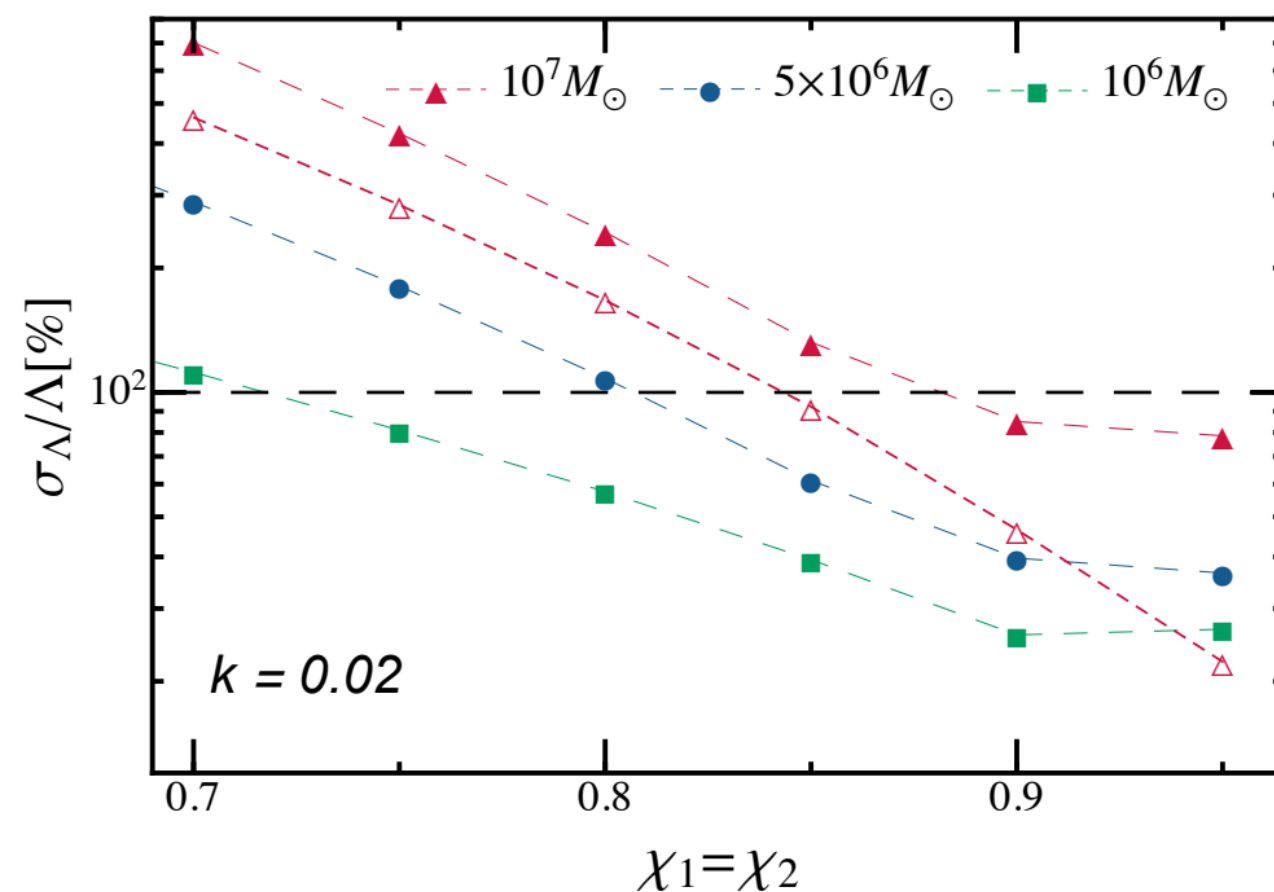
Logarithmic corrections

For some “black hole mimickers”

$$\delta = r_0 - r_H = r_H e^{-1/k}$$

Tidal deformability,
identically **zero** for BHs

Possible to get the required
Planck-level accuracy with **LISA**
(quantum limit)

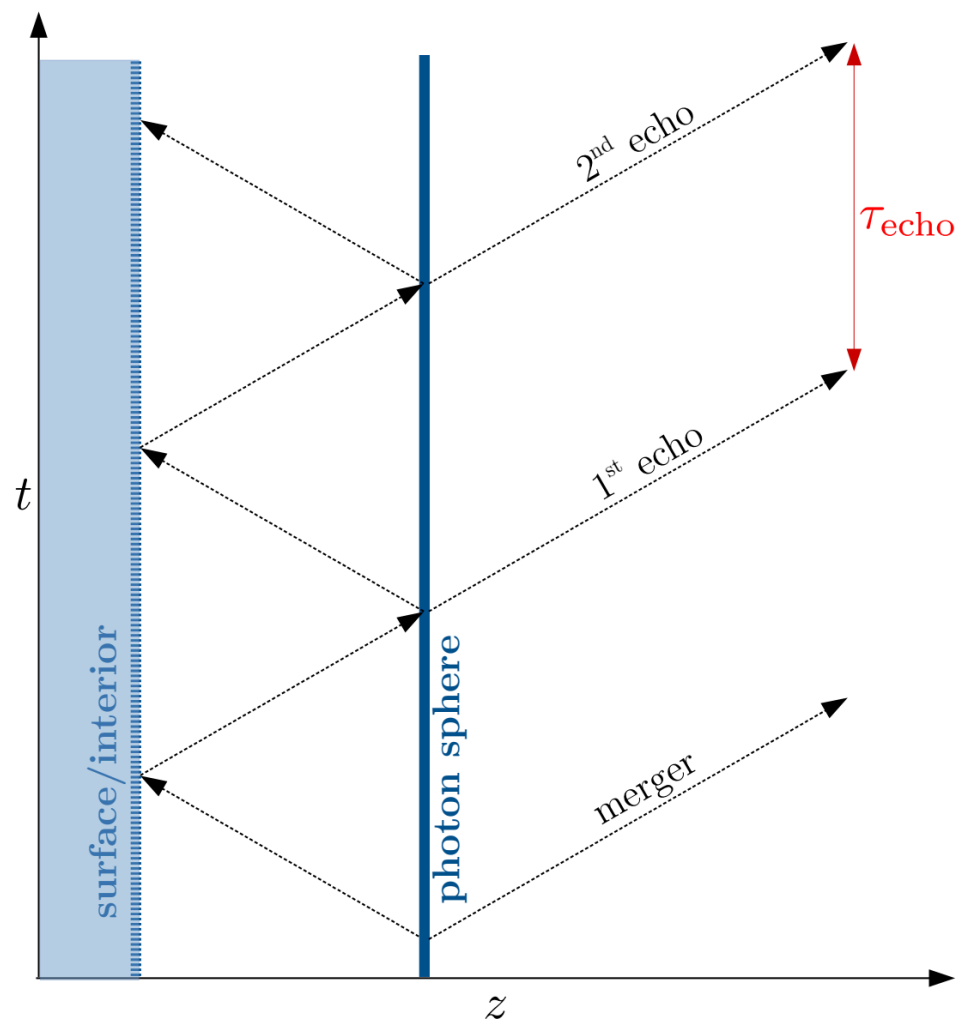


Maselli+ (arxiv:1703.10612)

Addazi+ (arxiv:1810.10417)

Echoes: $O(1)$ effect

A surface changes the boundary conditions of perturbations that propagate in the spacetime



Echoes: $O(1)$ effect

A surface changes the boundary conditions of perturbations that propagate in the spacetime

