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Gravitational-Wave Constraints on GWTC-2 Events by Measuring Tidal Deformability and Spin-Induced Quadrupole Moment

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KIW8

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Introduction

spin-induced quadrupole moment

Λ $\delta\kappa$

Measuring tidal deformability Λ and SIQM $\delta\kappa$ by GW

→ Tests of GR

We report constraints on Λ for low-mass GWTC-2 events (long-inspiral regime):

GW151226, GW170608, GW190707, GW190720, GW190728, GW190924

Related works

Λ

- Tidal tests: Johnson-McDaniel+2018 (Constraints on Boson stars by future BBH detections)

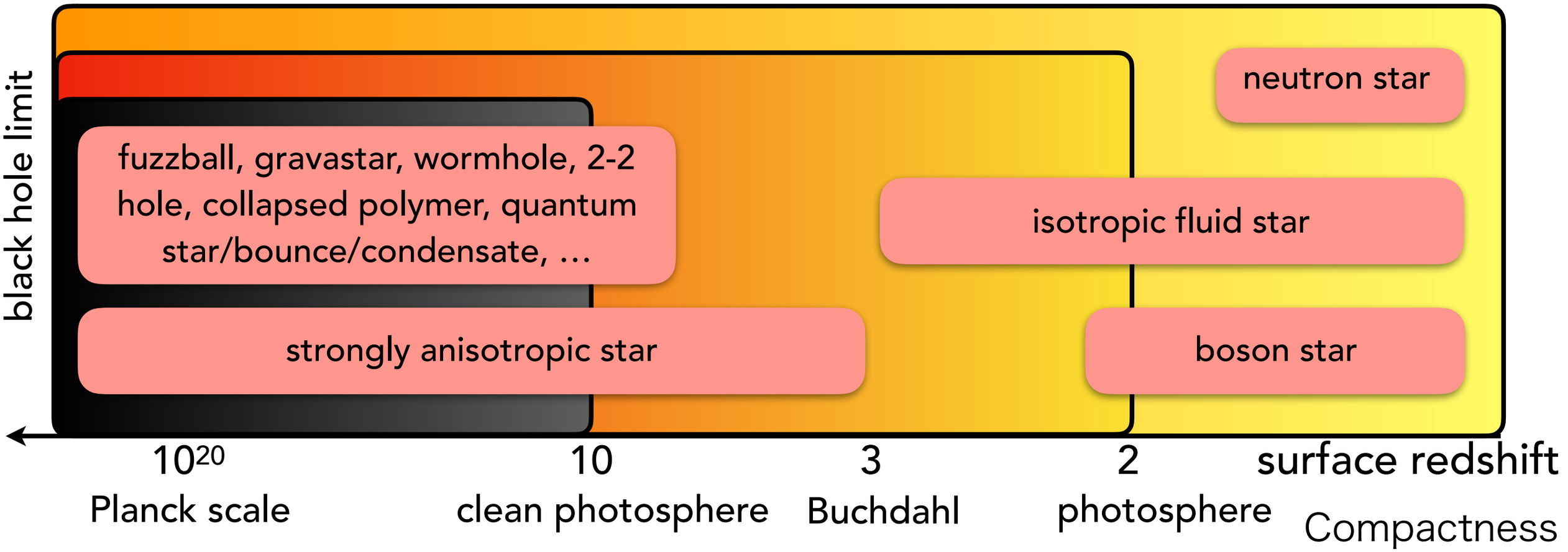
$\delta\kappa$

- SIQM tests: ① Krishnendu+2019 (GW151226 & GW170608); ② O3 TGR paper 2020 (GWTC-2 events)

Exotic compact objects (ECOs)

ECO: Alternatives to BH in GR

Motivation: Avoidance spacial singularity in BH, solution for information loss problem of BH [GWIC-3G_science-case]



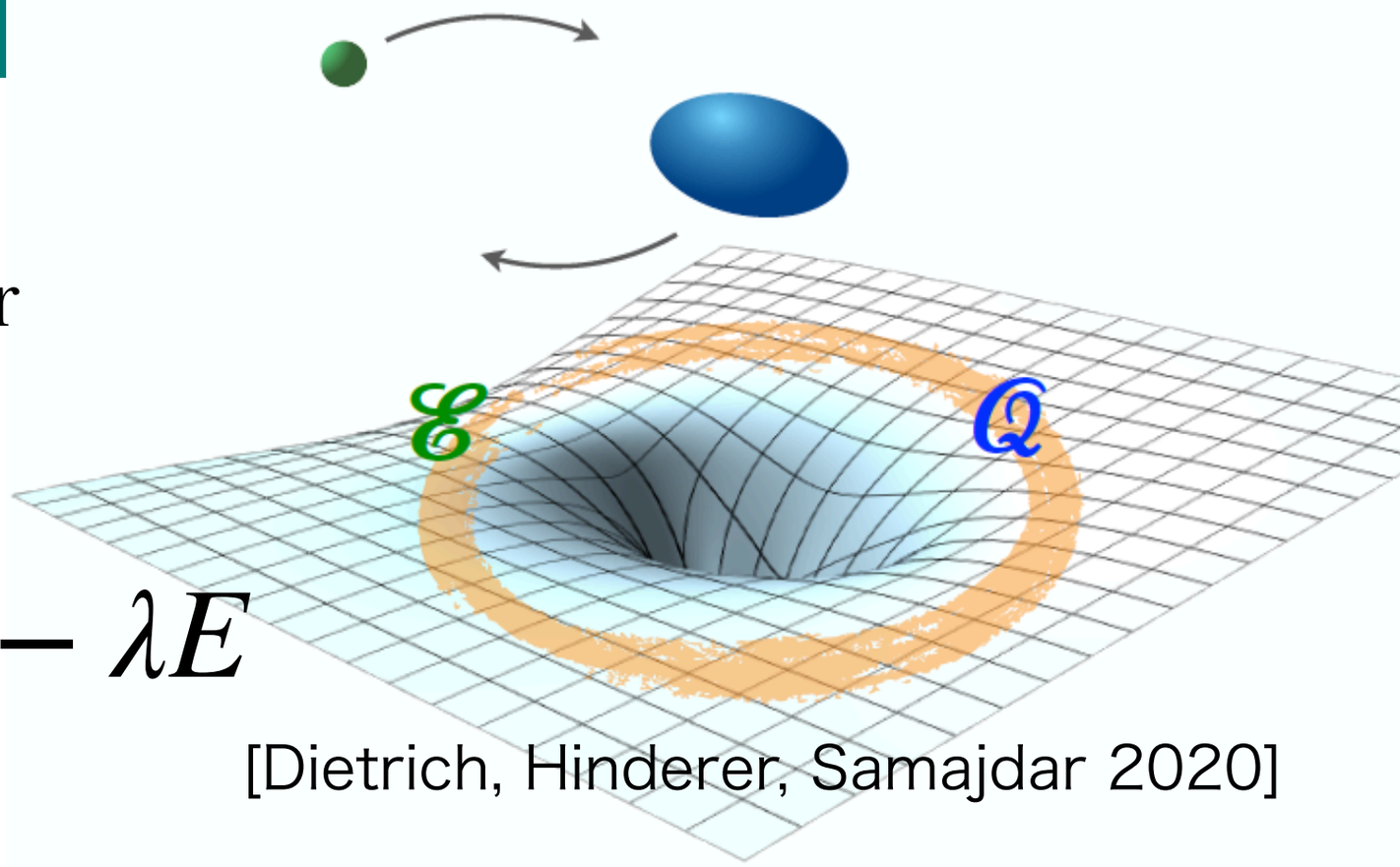
ECO modify GWs and tidal deformability and SIQM is useful to test deviation from BBH in GR ($\Lambda=0$ & $\delta\kappa=0$).

If we find deviation from BBH, which provides evidence for existence of ECO and hint for new physics.

Tidal deformation

When binary orbital separations are small, each star is tidally distorted by its companion.

$$Q = -\lambda E$$



[Dietrich, Hinderer, Samajdar 2020]

tidal deformability: λ **=-** **Q: (tidal induced) quadrupole moment / ε : companion's tidal field**

binary tidal deformability, mass-weighted combination of $\Lambda_{1,2}$

$$\tilde{\Lambda} = \frac{8}{13}\left[(1+7\eta-31\eta^2)(\Lambda_1+\Lambda_2)+\sqrt{1-4\eta}(1+9\eta-11\eta^2)(\Lambda_1-\Lambda_2)\right]$$

[Flanagan & Hinderer 2007; Damour, Nagar, Villain 2012]

$\Lambda_{1,2} = \lambda_{1,2}/m_{1,2}^5$: individual ones

Tidal deformability

Λ=0: BH in GR

(Schwarzschild BH [Binnington&Poisson2009; Damour&Nagar2009],
Kerr BH [Poisson2015; Pani+2015; Landry&Poisson2015]),

Λ=100-1000: Neutron Stars (NSs) [Lattimer&Prakash2004].
(<900 by GW170817 [LVC 2018])

Λ≠0: exotic compact objects (ECOs),
boson stars, gravastars, wormhole, quantum correction to BH

For gravastar Λ<0. [Uchikata, Yoshida, Pani 2016]

Tidal tests: Johnson-McDaniel+2018 (Constraints on Boson stars by future BBH detections)

Spin-induced quadrupole moment (SIQM)

deformation due to compact object's spin

$\delta\kappa$

$$Q = -(1+\delta\kappa)\chi^2 m^3$$

$\delta\kappa$ =0: BH [Poisson 1998],

$\delta\kappa$ ~2-20: spinning NS [Laarakkers 1997; Pappas 2012],

$\delta\kappa$ ~10-150: spinning boson stars [Ryan 1997],

For gravastar $\delta\kappa < 0$ is possible [Uchikata+2016].

$$\delta\kappa_s = (\delta\kappa_1 + \delta\kappa_2)/2$$

SIQM tests: ① Krishnendu+2019 (GW151226 & GW170608); ② O3 TGR paper 2020 (GWTC-2 events)

Our analysis

- **Post-Newtonian inspiral waveform model:**
  TaylorF2-5.5PN (TF2g) + Tidal + SIQM

Λ $\delta\kappa$

  - Phase $\Psi(f) = \Psi_{\rm BBH} + \Psi_{\rm SIQM} + \Psi_{\rm tidal}$

    - **Point-particle (TF2g): 0-5.5 PN,**
    - Spin (aligned-spin): 1.5-3 PN, **SIQM: 2-3PN,**
    - **Tides: 5-7.5 PN.**

adding higher-order PN terms to prevent $\tilde{\Lambda}$ biasing

spin terms at other PN orders help to break degeneracies, e.g., $q - \chi_{\rm eff}$

  - Amplitude up to 3PN for BBH (PP & spin)

- Priors: uniform in [-3000, 3000] on $\tilde{\Lambda}$ and $\delta\tilde{\Lambda}$, uniform in [-200, 200] on $\delta\kappa_{1,2}$

- Bayesian inference library: Nested sampling in LALSUITE

Refs.
- TF2-5.5PN [Messina, Dudi, Nagar, Bernuzzi, 2019]
- SIQM [Krishnendu+ 2017]
- PNTidal [Damour, Nagar, Villain, 2012; Henry, Faye, Blanchet, 2020]

Event selection

Low-mass events:
higher cutoff frequency > 120 Hz
and larger inspiral SNR > 9

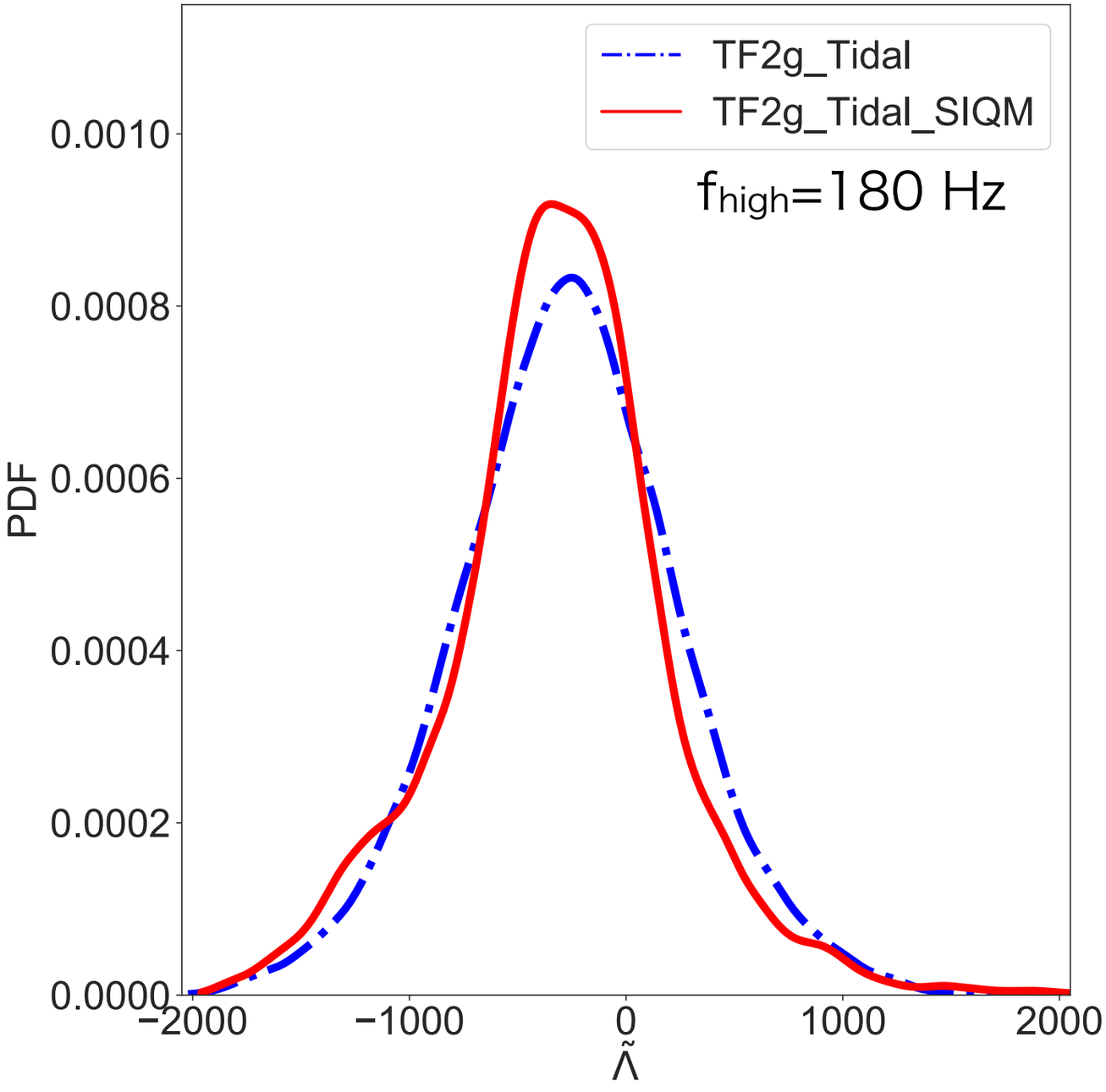
Event	f_{high} [Hz]	ρ_{insp}
GW151226	150	11.1
GW170608	180	14.8
GW190707	160	12.2
GW190720	125	9.2
GW190728	160	11.4
GW190924	175	11.8

f_{high} denotes the cutoff frequency divide the inspiral and post-inspiral regimes.

See Table V in O3a Test of GR paper 2010.14529

Results for the largest SNR event GW170608

Tidal constraints on GW170608

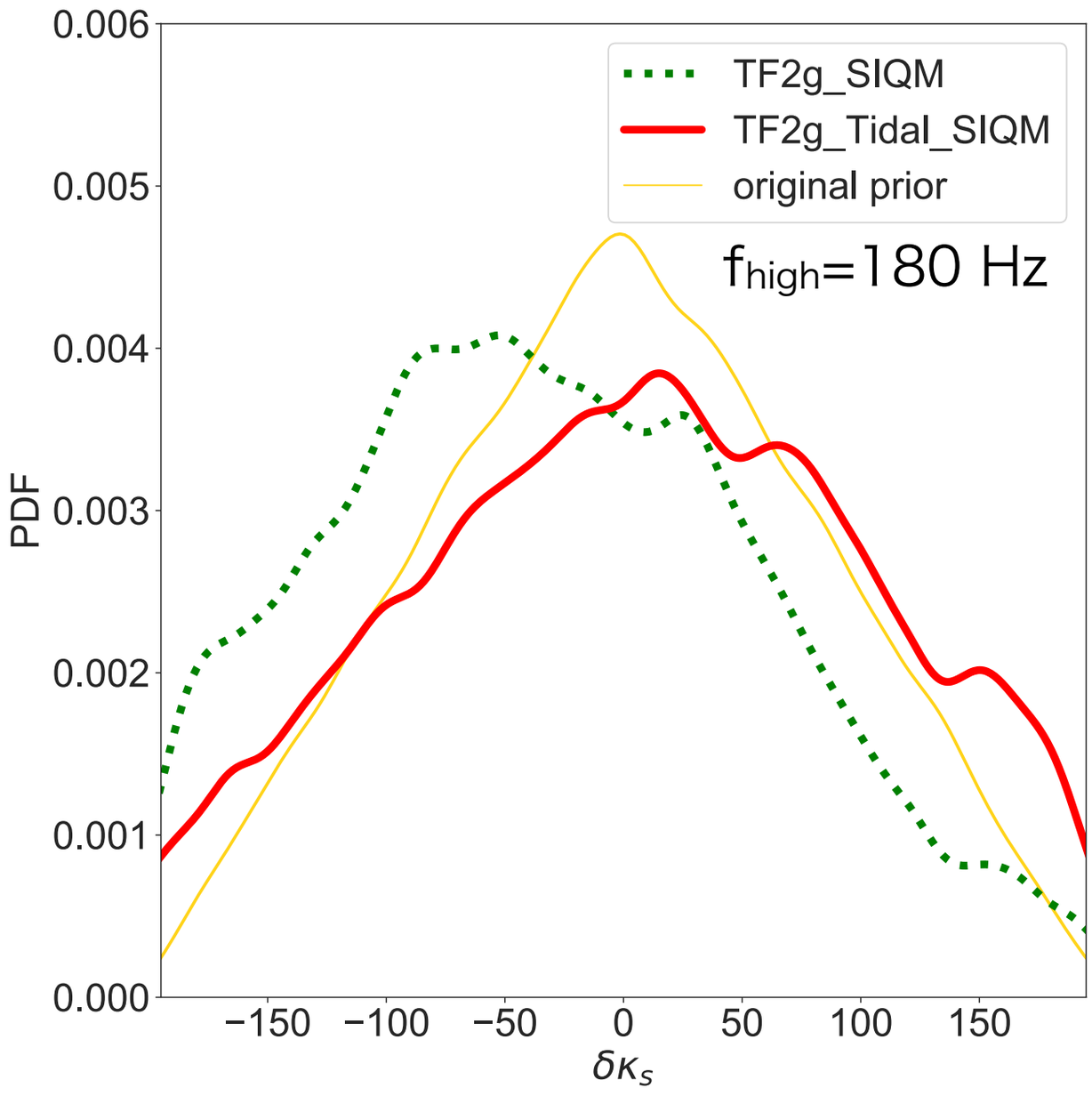


Almost no change for $\tilde{\Lambda}$ by adding SIQM parameters

Consistent with GR, $\tilde{\Lambda} = 0$ at the 90% CR

The 90% symmetric credible range of $\tilde{\Lambda}$: [-1213, 523]

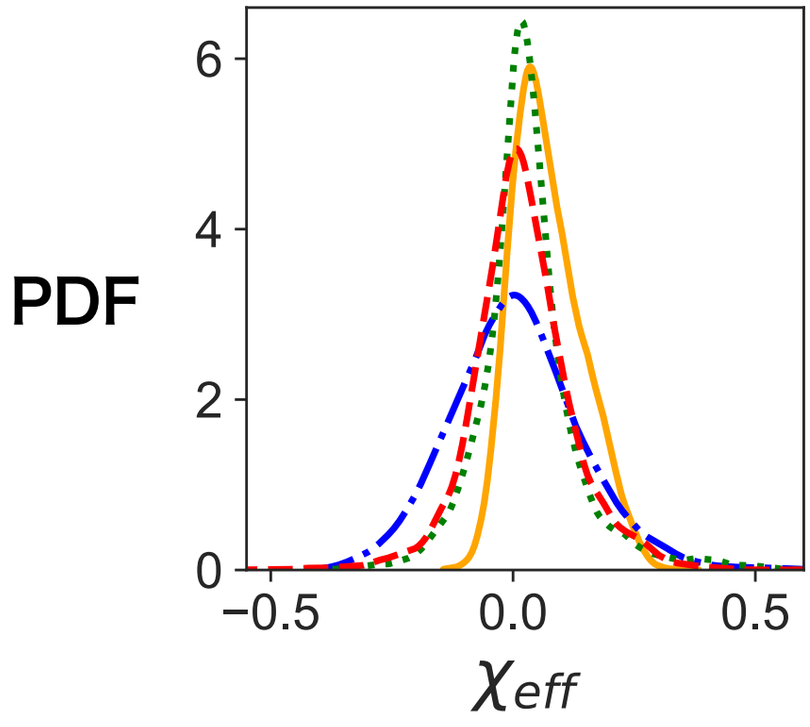
SIQM constraints on GW170608



Consistent with GR,
$\delta\kappa_s = 0$ at the 90% CR

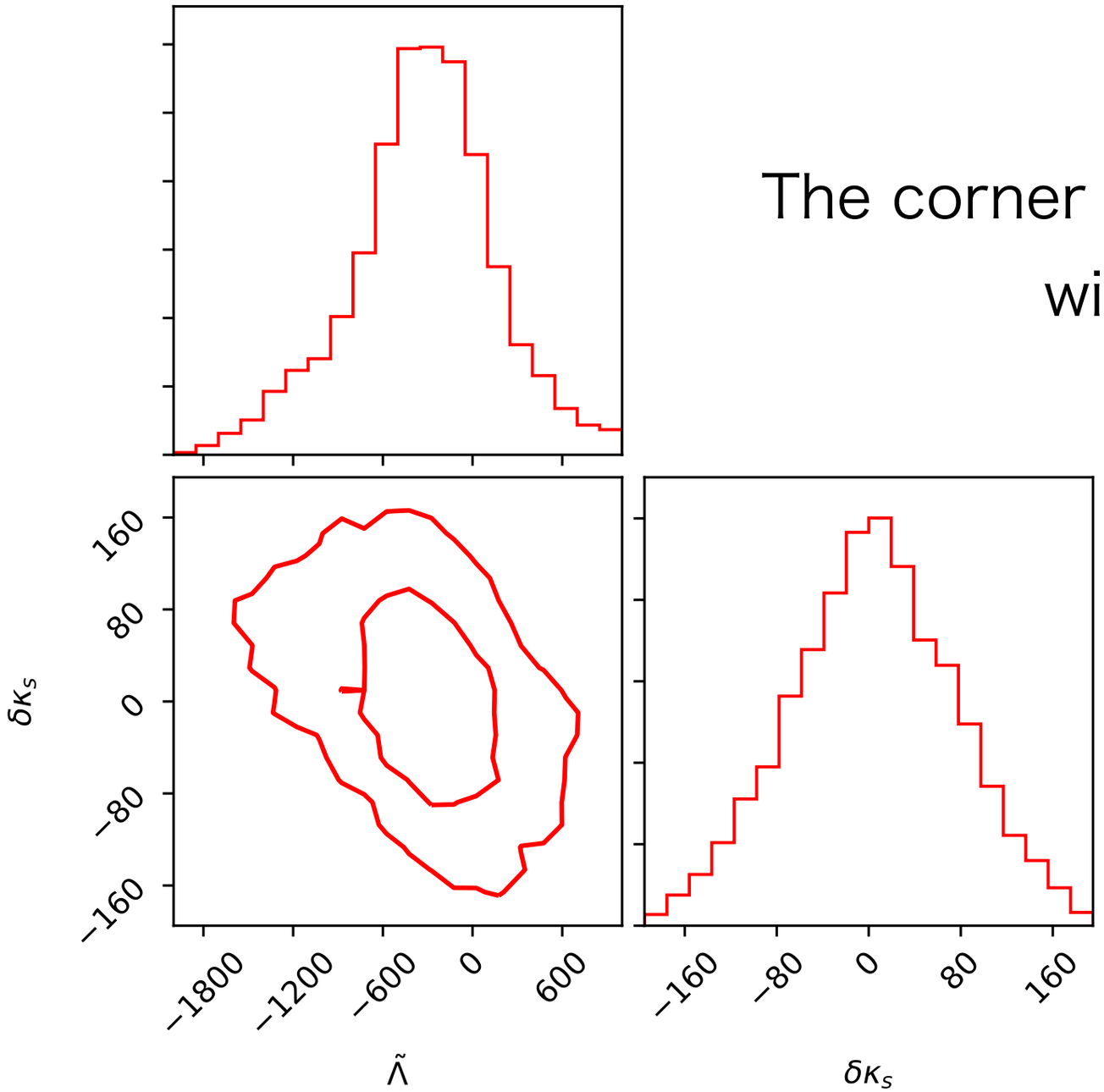
They are weighted by dividing the original prior: uniform on $\delta\kappa_{1,2}$.

The median of $\delta\kappa_s$ is shifted zero by adding tidal deformability, since spins become unmeasurable.



Tidal and SIQM constraints on GW170608

Λ $\delta\kappa$



The corner plots of $\tilde{\Lambda}$ and $\delta\kappa_s$ from GW170608 with uniform priors on $\tilde{\Lambda}$, $\delta\tilde{\Lambda}$ and $\delta\kappa_{1,2}$.

Consistent with GR, $\tilde{\Lambda} = 0$ and $\delta\kappa_s = 0$ at the 90% CR

$\delta\kappa_s$-$\tilde{\Lambda}$ degeneracy:

slightly negative correlation

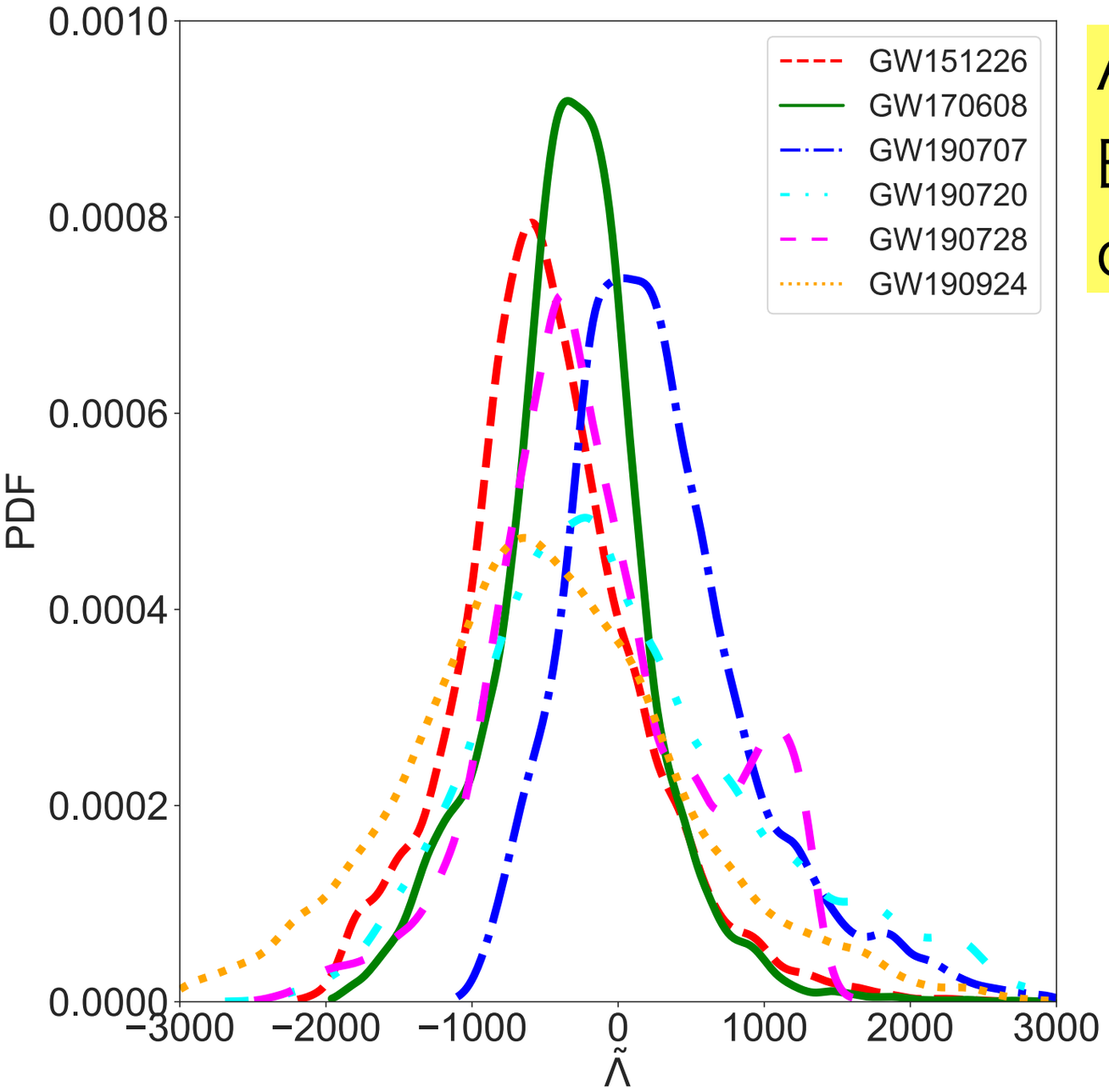
— TF2g_Tidal_SIQM
f_{high}=180 Hz

Results for low-mass GWTC-2 events:

GW151226, GW170608, GW190707, GW190720, GW190728, and GW190924

Tidal constraints on six events

The corner plots of $\tilde{\Lambda}$ and $\delta\kappa_s$ from six low-mass events.



TF2g_Tidal_SIQM

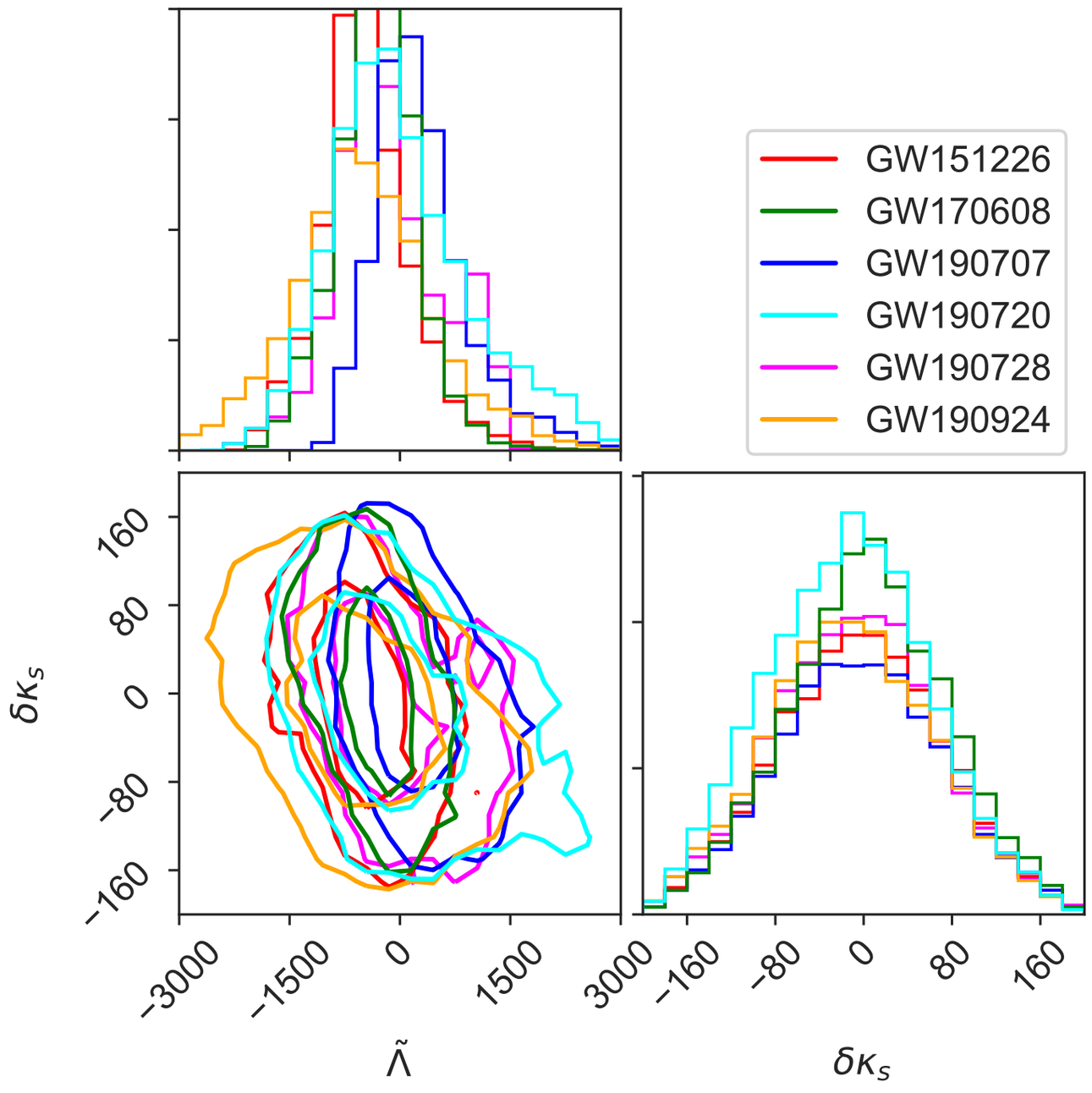
All events are consistent with BBH in GR ($\tilde{\Lambda} = 0$), no evidence of deviation from GR

Event	$\tilde{\Lambda}$
GW151226	$[-1466,\ 623]$
GW170608	$[-1213,\ 522]$
GW190707	$[-593,\ 1556]$
GW190720	$[-1366,\ 1880]$
GW190728	$[-1250,\ 1159]$
GW190924	$[-2022,\ 1210]$

Tidal and SIQM constraints on six events

The corner plots of $\tilde{\Lambda}$ and $\delta\kappa_s$ from six low-mass events.

Λ $\delta\kappa$



TF2g_Tidal_SIQM

All events are consistent witn BBH in GR ($\tilde{\Lambda} = 0$ and $\delta\kappa_s = 0$)

Event	$\log_{10} \mathrm{BF}^{\mathrm{ECO}}_{\mathrm{BBH}}$
GW151226	-0.52
GW170608	-2.1
GW190707	-2.1
GW190720	-1.2
GW190728	-1.9
GW190924	-2.2
Combined	-10.1

The non-GR model (with Tidal and SIQM) is disfavored compared to GR.

Conclusion

Λ $\delta\kappa$

- We are implementing the tidal deformability, Λ, and spin-induced quadrupole moments (SIQMs), $\delta\kappa$, in TF2g.
- Analysis on six low-mass GWTC-2 events: GW151226, GW170608, GW190707, GW190720, GW190728, and GW190924 with TF2g_Tidal_SIQM.
- **We find that all events that we have analyzed to be consistent with BBH mergers in GR ($\tilde{\Lambda} = 0$ and $\delta\kappa_s = 0$).**
- **The non-GR model (with Tidal and SIQM parameters) is disfavored compared to GR.**

Future work

- Improvement of waveform model by extension to post-inspiral regimes of binary ECOs

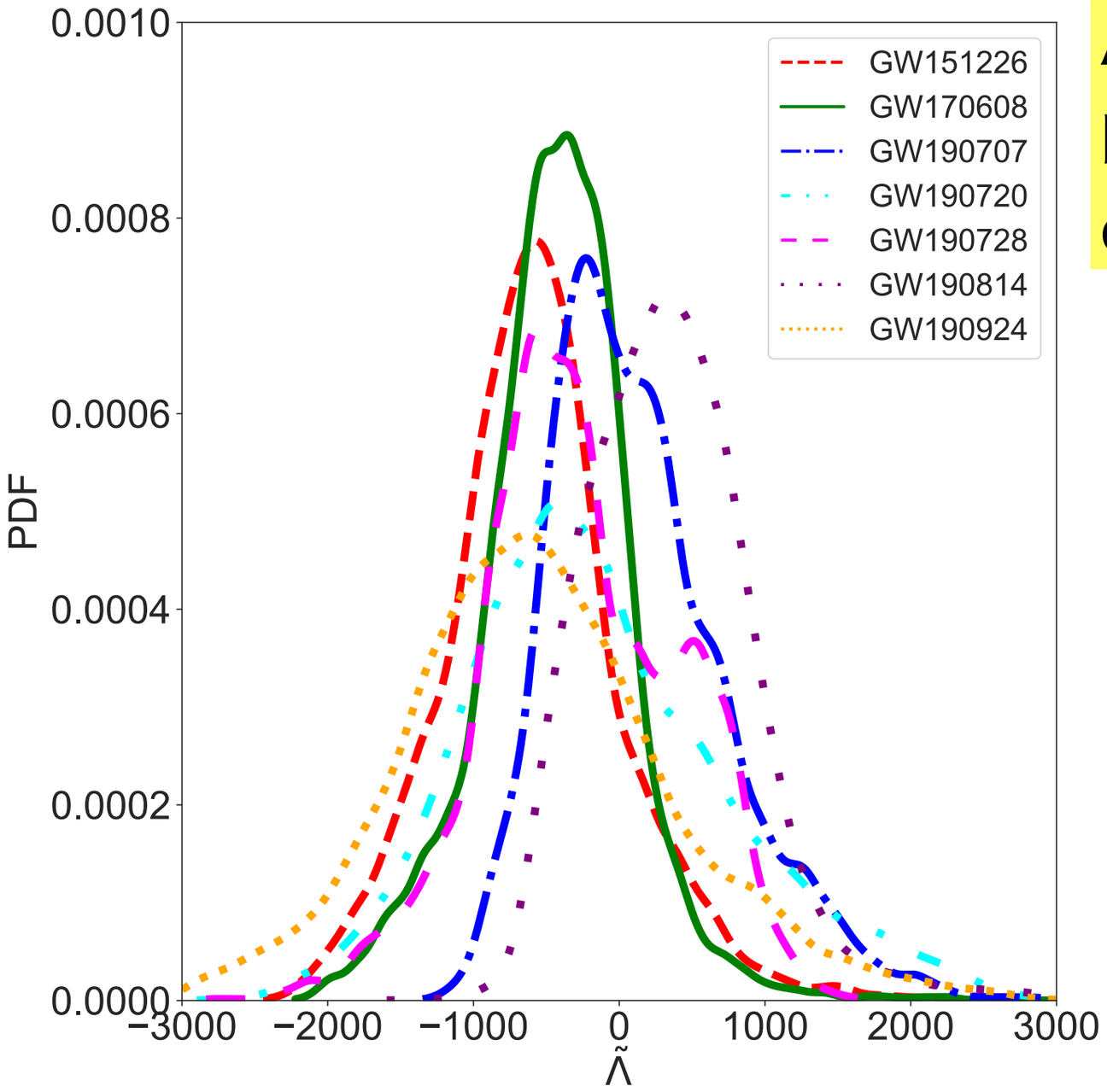
Back up slides

Tidal and SIQM constraints

$\log BF_{ECOvsBBH}$	fhigh	TF2g_Amp	TF2_Amp
GW151226	150	-0.52	-0.67
GW170608	180	-2.11	-1.65
GW190707	160	-2.1	-1.95
GW190720	125	-1.24	-1.31
GW190728	160	-1.92	-1.89
GW190814	140	×	-3.81
GW190924	175	-2.18	-2.13
Combined	-	-10.07	-13.41

Tidal constraints with TF2_Tidal_SIQM

The corner plots of $\tilde{\Lambda}$ and $\delta\kappa_s$ from seven low-mass events.



TF2_Tidal_SIQM

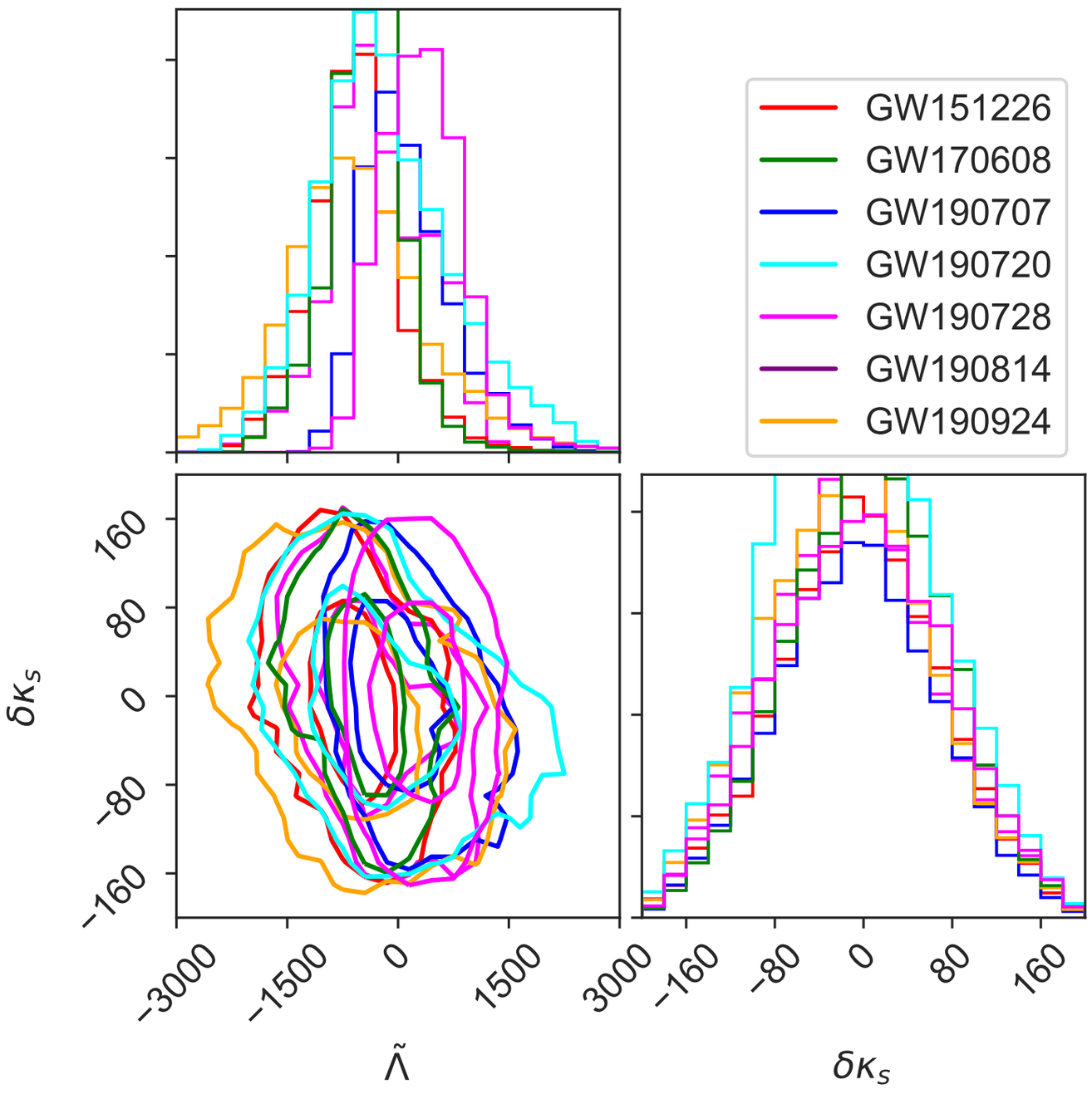
All events are consistent with BBH in GR ($\tilde{\Lambda} = 0$), no evidence of deviation from GR

Event	$\tilde{\Lambda}$
GW151226	$[-1580,\ 471]$
GW170608	$[-1336,\ 344]$
GW190707	$[-691,\ 1313]$
GW190720	$[-1506,\ 1557]$
GW190728	$[-1341,\ 807]$
GW190814	$[-475,\ 1268]$
GW190924	$[-2005,\ 1111]$

Tidal and SIQM constraints with TF2_Tidal_SIQM

The corner plots of $\tilde{\Lambda}$ and $\delta\kappa_s$ from seven low-mass events.

Λ $\delta\kappa$



TF2_Tidal_SIQM

All events are consistent with BBH in GR ($\tilde{\Lambda} = 0$ and $\delta\kappa_s = 0$)

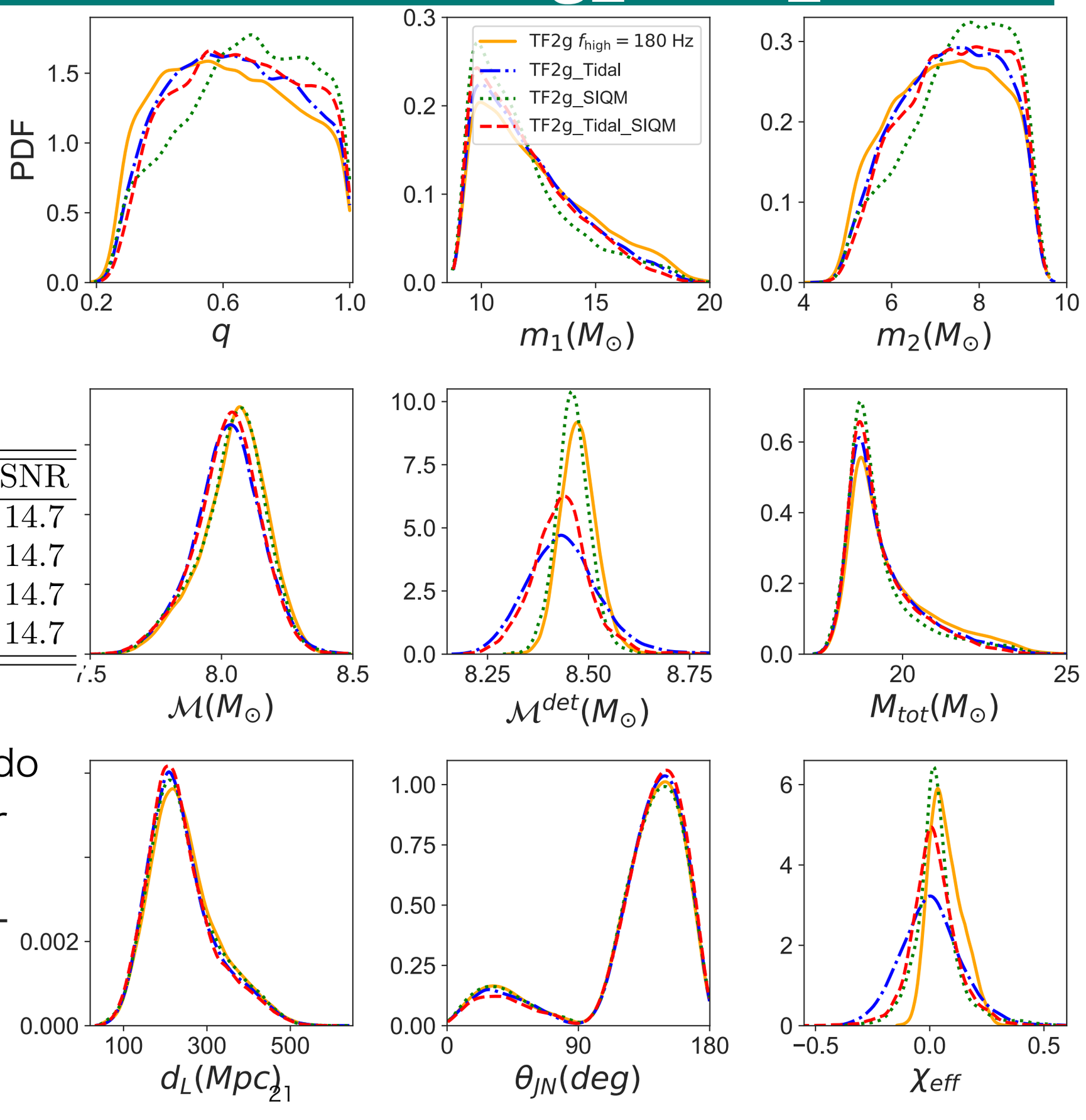
Event	$\log_{10} \mathrm{BF}^{\mathrm{ECO}}_{\mathrm{BBH}}$
GW151226	-0.67
GW170608	-1.7
GW190707	-2.0
GW190720	-1.3
GW190728	-1.9
GW190814	-3.8
GW190924	-2.1
Combined	-13.4

The non-GR model (with Tidal and SIQM) is disfavored compared to GR.

Results of GW170608 with TF2g_Tidal_SIQM

	$\log_{10}\mathrm{BF}_{s/n}$	SNR
TF2g (BBH in GR)	71.3	14.7
TF2g_Tidal	69.9	14.7
TF2g_SIQM	70.4	14.7
TF2g_Tidal_SIQM	69.2	14.7

The tidal and SIQM terms do not affect the Bayes factor and SNR.



Results of GW170608 with TF2g

GR	$\log_{10}BF_{s/n}$	SNR
PhenomD fhigh180	71.51	14.71
TF2g_Amp fhigh180	71.34	14.67