GWPPBSM2023@Osaka Metropolitan Univ. Nov 6-9, 2023

Gravitational Wave Constraints on Properties of Exotic Compact Objects

Λ $\delta\kappa$

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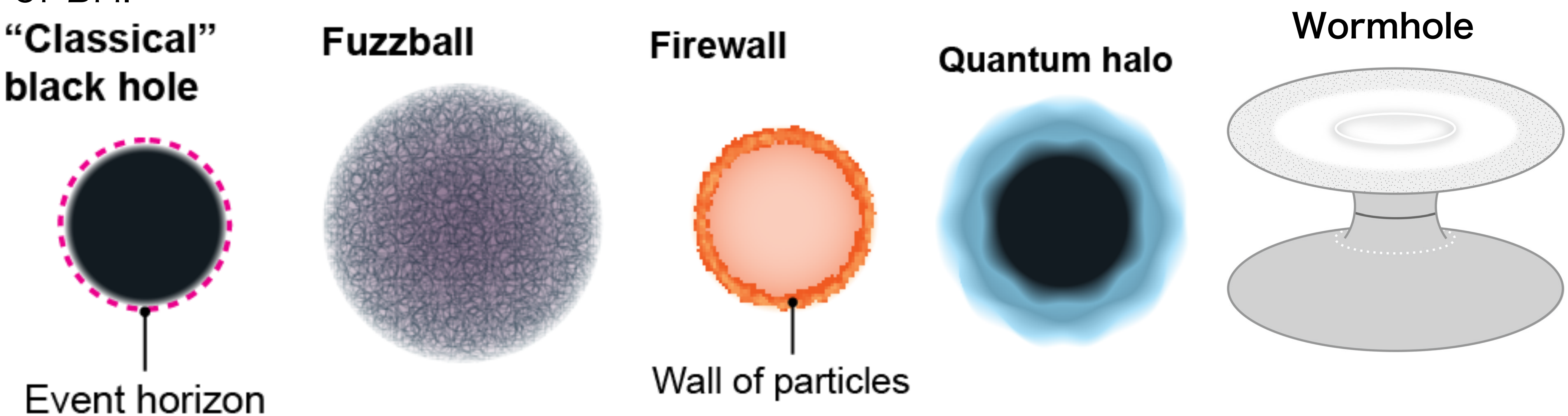
arXiv:2106.09193
Phys. Rev. D 104, 084056 (2021)

JGW-G2315375

Exotic compact objects (ECOs)

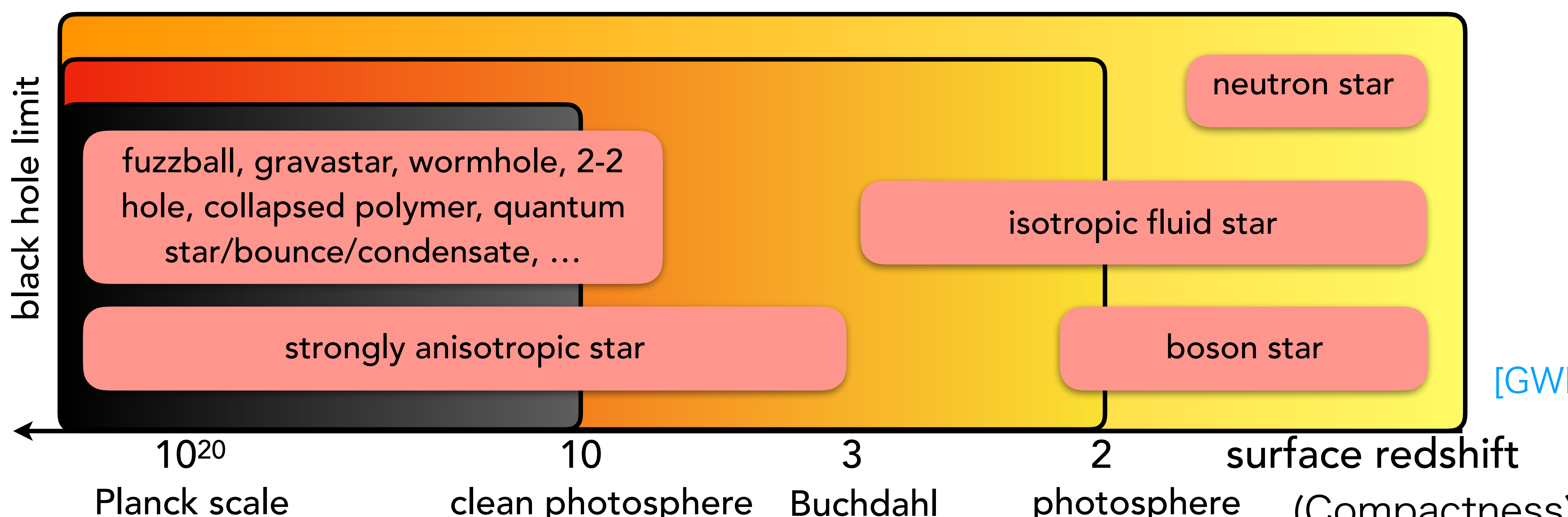
Alternatives to BH in GR

Motivation: avoid spacetime singularity in BH, and solve information loss problem of BH.



[Credit: Amanda Montanez, Scientific American, 2019]

[Cardoso, Pani, 2019]



[GWIC-3G science-case]

Properties of ECOs

Tidal deformability Λ **Spin-Induced Quadrupole Moment (SIQM)** $\delta\kappa$

ECOs have largely different values of Λ and $\delta\kappa$ from those of BHs.

Previous works: focusing on only one of Λ and $\delta\kappa$

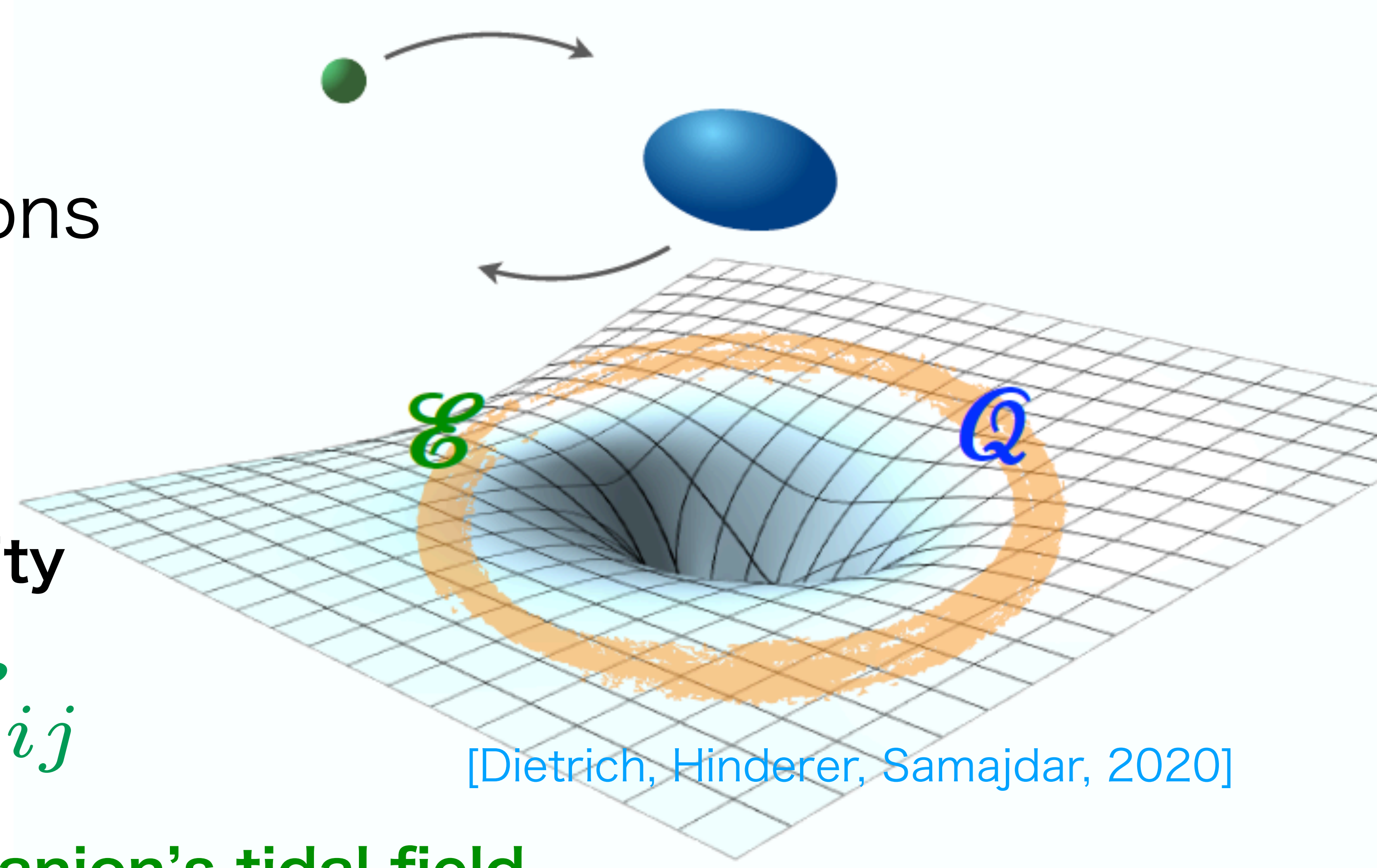
Aim of this work:
Focusing on both Λ and $\delta\kappa$.
Model-independent constraints on deviations from the BBH case by measuring Λ and $\delta\kappa$ via GWs.

Λ $\delta\kappa$

We report constraints on Λ and $\delta\kappa$ for six low-mass GWTC-2 events (long-inspiral regime): GW151226, GW170608, GW190707, GW190720, GW190728, GW190924

Tidal deformability

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



[Dietrich, Hinderer, Samajdar, 2020]

Tidal deformability

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

(Tidal-induced) Quadrupole moment

Companion's tidal field

Tidal deformability 1) affects GW phase, 2) characterizes compact objects

Binary tidal deformability

$$\tilde{\Lambda} = \frac{16}{13}\left[(1+11X_2)X_1^4\Lambda_1 + (1 \leftrightarrow 2)\right]$$

[Flanagan, Hinderer, 2007;
Hinderer 2008;
Vines, Flanagan, Hinderer 2011]

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

$X_{1,2} = m_{1,2}/(m_1 + m_2)$: mass ratio

Λ

Tidal deformability for different EOCs

$$\mathcal{Q}_{ij} = -\lambda \mathcal{E}_{ij} \qquad \Lambda_{1,2} = \lambda_{1,2}/m_{1,2}^5$$

Λ

$\Lambda = 0$: BH in GR

(Schwarzschild BH [Binnington, Poisson, 2009; Damour, Nagar, 2009],

Kerr BH [Poisson, 2015; Pani+, 2015; Landry, Poisson, 2015]),

$\Lambda \sim 100 - 1000$: Neutron Stars (NSs) [Lattimer, Prakash2004].

($\Lambda < 900$ by GW170817 [LVC 2018, Narikawa+2019])

$\Lambda \neq 0$: Exotic compact objects (ECOs),

boson stars, gravastars, wormhole, quantum correction to BH

For gravastars, $\Lambda < 0$. [Uchikata, Yoshida, Pani, 2016]

Previous works: focusing on only Λ

Tidal tests: Johnson-McDaniel+, 2020 (Constraints on Boson stars by future observations of binary ECOs)

Spin-induced quadrupole moment (SIQM)

Deformation due to compact object's spin

$\delta\kappa$

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

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

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

$\delta\kappa \sim \mathbf{10-150}$: **spinning boson stars** [Ryan 1997],

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

The leading effect on GW:

symmetric combination of SIQM parameters $\delta\kappa_{1,2}$:

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

Previous works: focusing on only $\delta\kappa$

SIQM tests: ① Krishnendu+, 2019 (GW151226 and GW170608);

② LVK, "O3a Tests of GR" (GWTC-2 events); "O3b Tests of GR" (GWTC-3 events)

Post-Newtonian GW phase

PN phase can efficiently describe the GW emission in the inspiral regime.

PN approximation: solve the Einstein eqs. by a series in v/c.

Newton gravity + GR correction: $\mathcal{O}((v/c)^0) + \mathcal{O}((v/c)^2) + \mathcal{O}((v/c)^3) + \cdots$.

(valid for slow motion $v/c \ll 1$ and weak field $GM/Rc^2 \ll 1$. Hereafter, c=G=1.)

$$\Psi_{\mathrm{ECO}}(f) = \Psi_{\mathrm{BBH}}(f) + \Psi_{\mathrm{SIQM}}(f) + \Psi_{\mathrm{Tidal}}(f)$$

0-5.5PN **2-3PN** **5-7.5PN**

η: symmetric mass ratio
Difficult to measure well

χ_{eff}: spin
Difficult to measure well

$$\sim \mathcal{M}^{-5/3} f^{-5/3} \left[1 + a_{1\mathrm{PN}}(\eta) x^2 + a_{1.5\mathrm{PN}}(\eta, \chi_{\mathrm{eff}}) x^3\right.$$

$\mathcal{M}$: chirp mass
Measurable very well

$$\left. + a_{2\mathrm{PN}}(\eta, \chi_i^2, \kappa_s) x^4 + \ldots + a_{5\mathrm{PN}}(\eta, \tilde{\Lambda}) x^{10} + \ldots \right]$$

κ: spin-induced QM
Compact objects

Λ: tidal deformability
Compact objects

v: orbital velocity

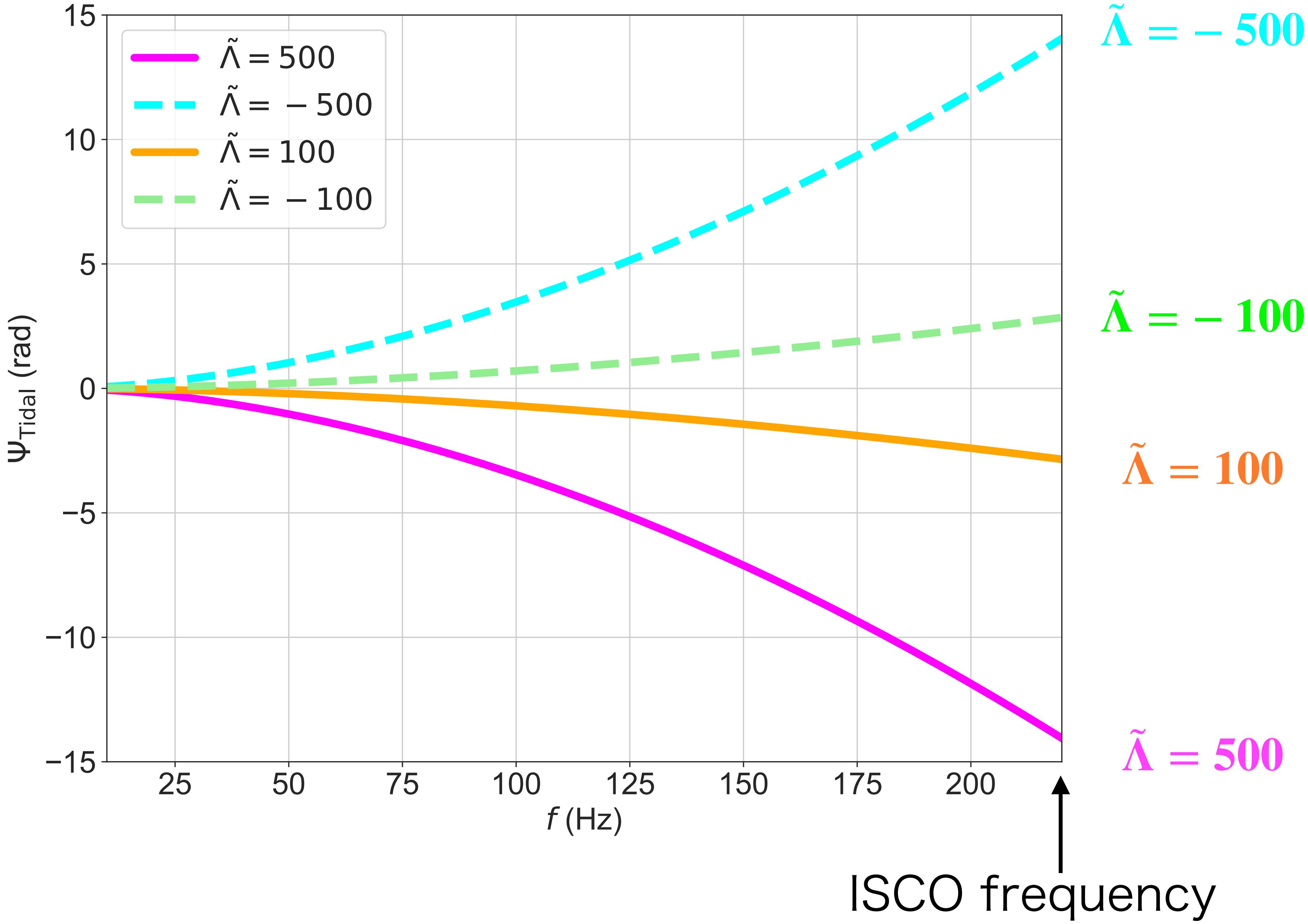
$$x = (\pi M f)^{2/3} = v^2$$

Tidal phase evolution

for unequal mass binary ECO with (12, 8) Msun

Demonstration of tidal phase evolution for binary ECO

$$a_{\rm Tidal}^{\rm 5PN} = -\frac{39}{2}\tilde{\Lambda}$$

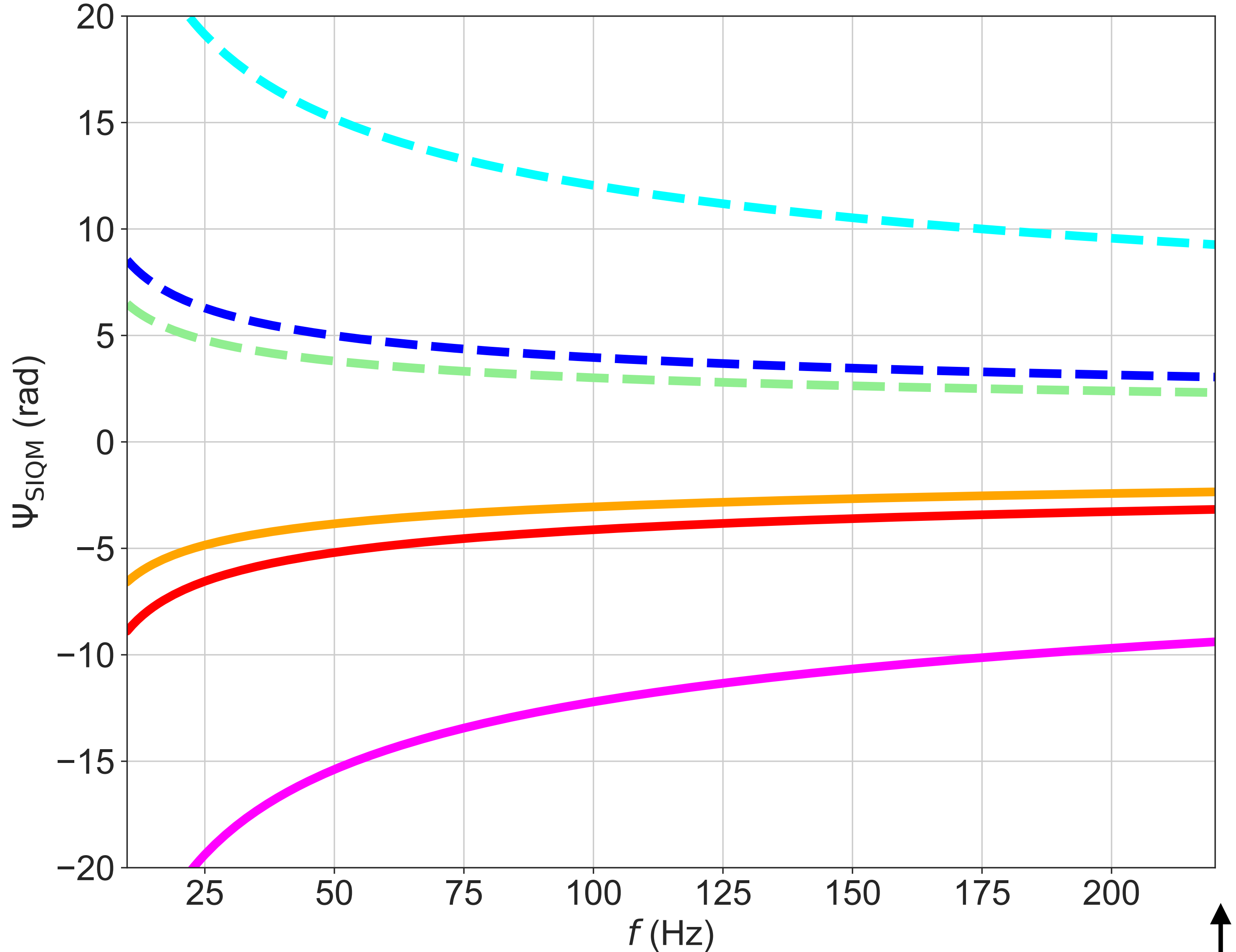


Large phase effects ~15 rad around ISCO frequency for Λ=500.

SIQM phase evolution

for unequal mass binary ECO with (12, 8) Msun

Demonstration of SIQM phase evolution for binary ECO



$$a^{\rm 2PN}_{\rm SIQM} = -50\chi_s^2(1-2\eta)(1+\delta\kappa_s)+\ldots$$

$\chi_{\rm eff} = \mathbf{0.1},\ \delta\kappa_{\rm s} = \mathbf{-150}$

$\chi_{\rm eff} = \mathbf{0.1},\ \delta\kappa_{\rm s} = \mathbf{-50}$

$\chi_{\rm eff} = \mathbf{0.05},\ \delta\kappa_{\rm s} = \mathbf{150}$

$\chi_{\rm eff} = \mathbf{0.05},\ \delta\kappa_{\rm s} = \mathbf{150}$

$\chi_{\rm eff} = \mathbf{0.1},\ \delta\kappa_{\rm s} = \mathbf{50}$

$\chi_{\rm eff} = \mathbf{0.1},\ \delta\kappa_{\rm s} = \mathbf{150}$

ISCO frequency

Large phase effects ~10 rad for $\chi_{\rm eff} = \mathbf{0.1},\ \delta\kappa_{\rm s} = \mathbf{150}$.

SIQM effect is strongly degenerate with spins.

Our analysis setup - parameter estimation

- **Post-Newtonian (PN) inspiral waveform model:**
  ECO = BBH + Tidal + SIQM

Λ $\delta\kappa$

- Bayesian inference library: Nested sampling in LALSUITE (LALInferenceNest)

Bayes's theorem $$p(\theta|d) = \frac{\mathcal{L}(d|\theta)\pi(\theta)}{\mathcal{Z}},$$

d: data

θ ={m1, m2, Λ, $\delta\ \kappa$,$\cdots$}

Likelihood $$\mathcal{L}(d|\theta) \propto \exp\left[-\frac{\langle d-h(\theta)|d-h(\theta)\rangle}{2}\right]$$

$$\tilde{h}(f) = \mathscr{A}(f)e^{i\Psi(f)}$$

Noise-weighted inner product $$\langle a|b\rangle := 4\mathrm{Re}\int_{f_{\rm low}}^{f_{\rm high}} df\, \frac{\tilde{a}^*(f)\tilde{b}(f)}{S_n(f)},$$

Evidence $$\mathcal{Z} = \int d\theta \mathcal{L}(d|\theta)\pi(\theta).$$

Bayes factor $$\mathrm{BF}^{\rm ECO}_{\rm BBH} = \frac{\mathcal{Z}_{\rm ECO}}{\mathcal{Z}_{\rm BBH}}.$$

- Priors: uniform on $\tilde{\Lambda}$ and $\delta\tilde{\Lambda}$ for tidal, uniform on $\delta\kappa_{1,2}$ for SIQM.

Selected events from GWTC-2 events

Low-mass events (long inspiral):
higher cutoff frequency ≧ 120 Hz
and larger inspiral SNR ≧ 9

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

Event	f_{high} [Hz]	$SNR_{inspiral}$
GW151226	150	10.7
GW170608	180	14.7
GW190707	160	11.2
GW190720	125	9.3
GW190728	160	12.1
GW190924	175	11.4

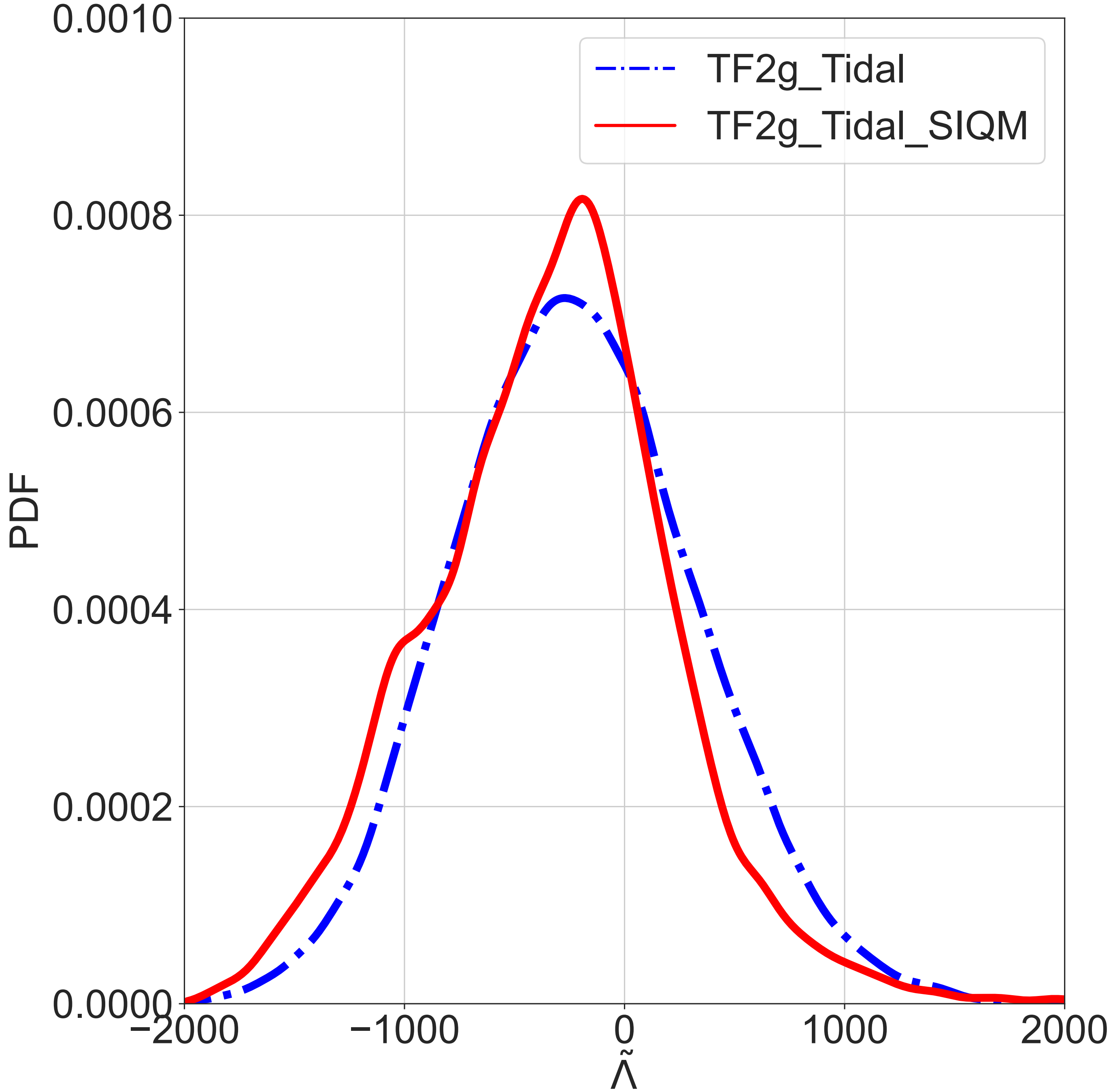
← the loudest inspiral SNR

First, we present the results for GW170608 in detail.

Constraints on Tidal: GW170608

The posterior PDF of $\tilde{\Lambda}$

f_{high}=180 Hz



The 90% symmetric credible range of $\tilde{\Lambda}$: [-1265, 565]

Consistent with GR ($\tilde{\Lambda} = 0$) at the 90% CL

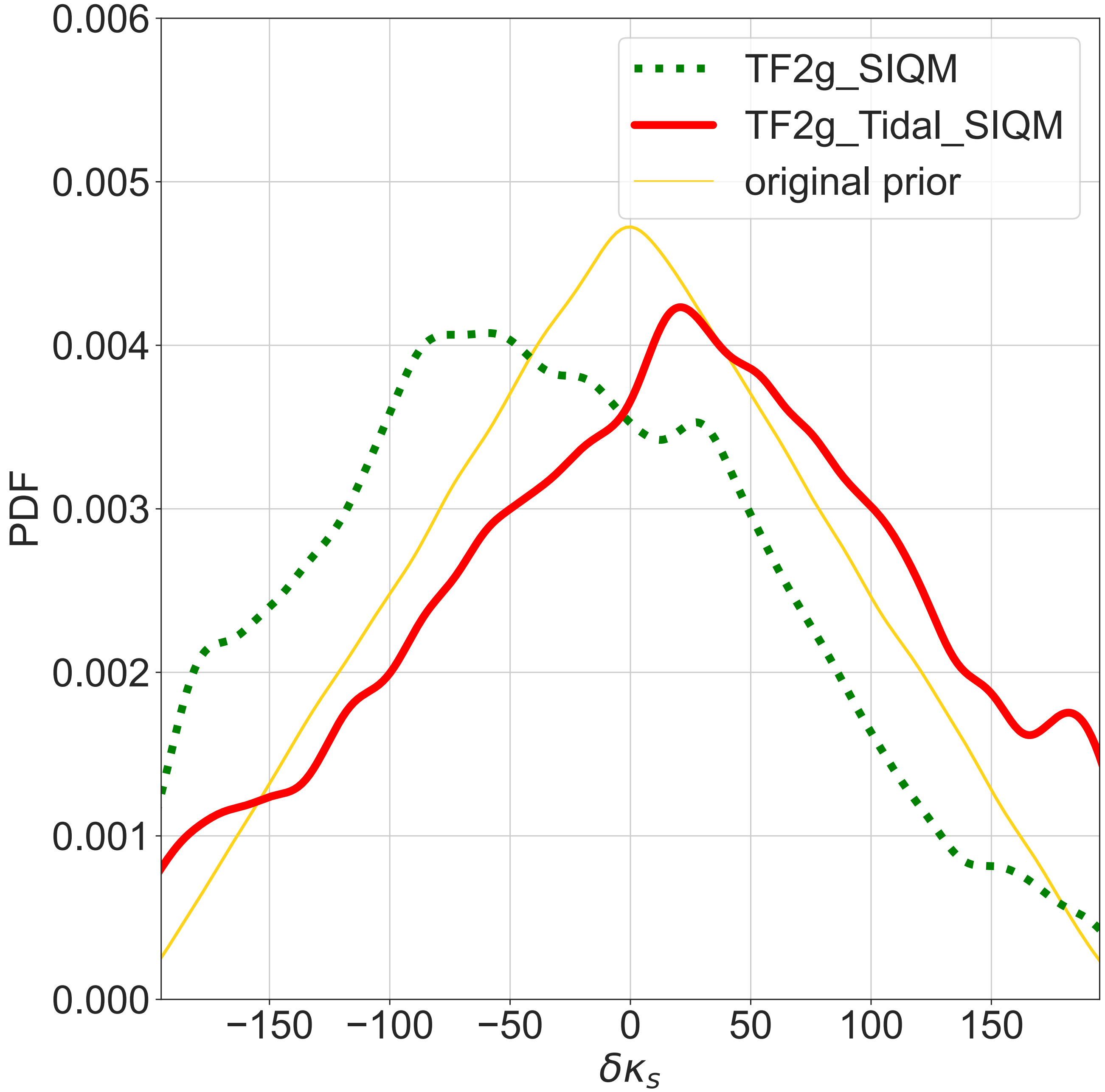
Adding the SIQM terms do not affect the constraint on the tidal deformability $\tilde{\Lambda}$.

Constraints on SIQM: GW170608

$\delta\kappa$

The posterior PDF of $\delta\kappa_s$

f_{high}=180 Hz



Consistent with GR ($\delta\kappa_s = 0$) at the 90% CL

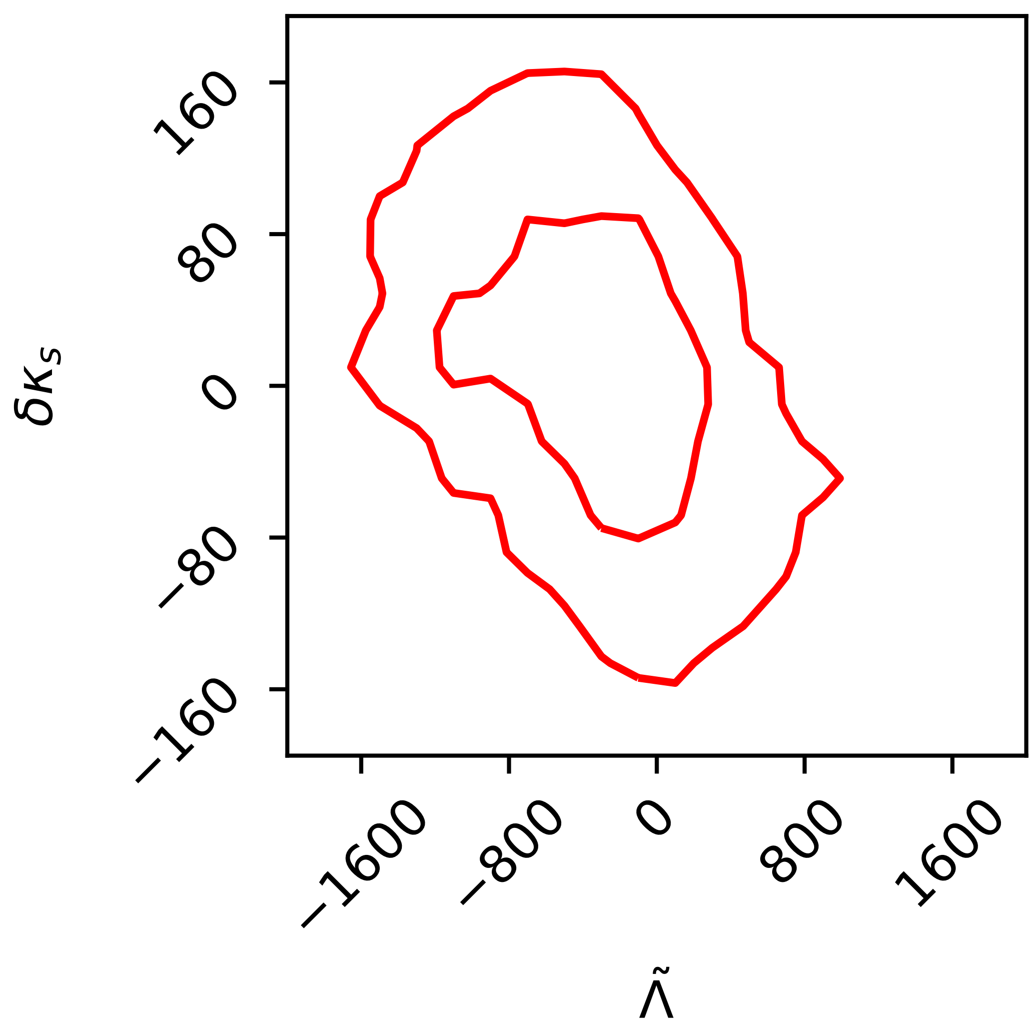
$\delta\kappa_s$ is poorly constrained for both waveform templates, which is consistent with the results shown in the previous studies by LIGO-Virgo.

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

Constraints on Tidal and SIQM: GW170608

The corner plots of $\tilde{\Lambda}$-$\delta\kappa_s$ plane. (50% and 90%)

Λ $\delta\kappa$



Consistent with GR
($\tilde{\Lambda} = 0$ and $\delta\kappa_s = 0$)
at the 90% CL

We find weak negative correlation between $\tilde{\Lambda}$ and $\delta\kappa_s$.

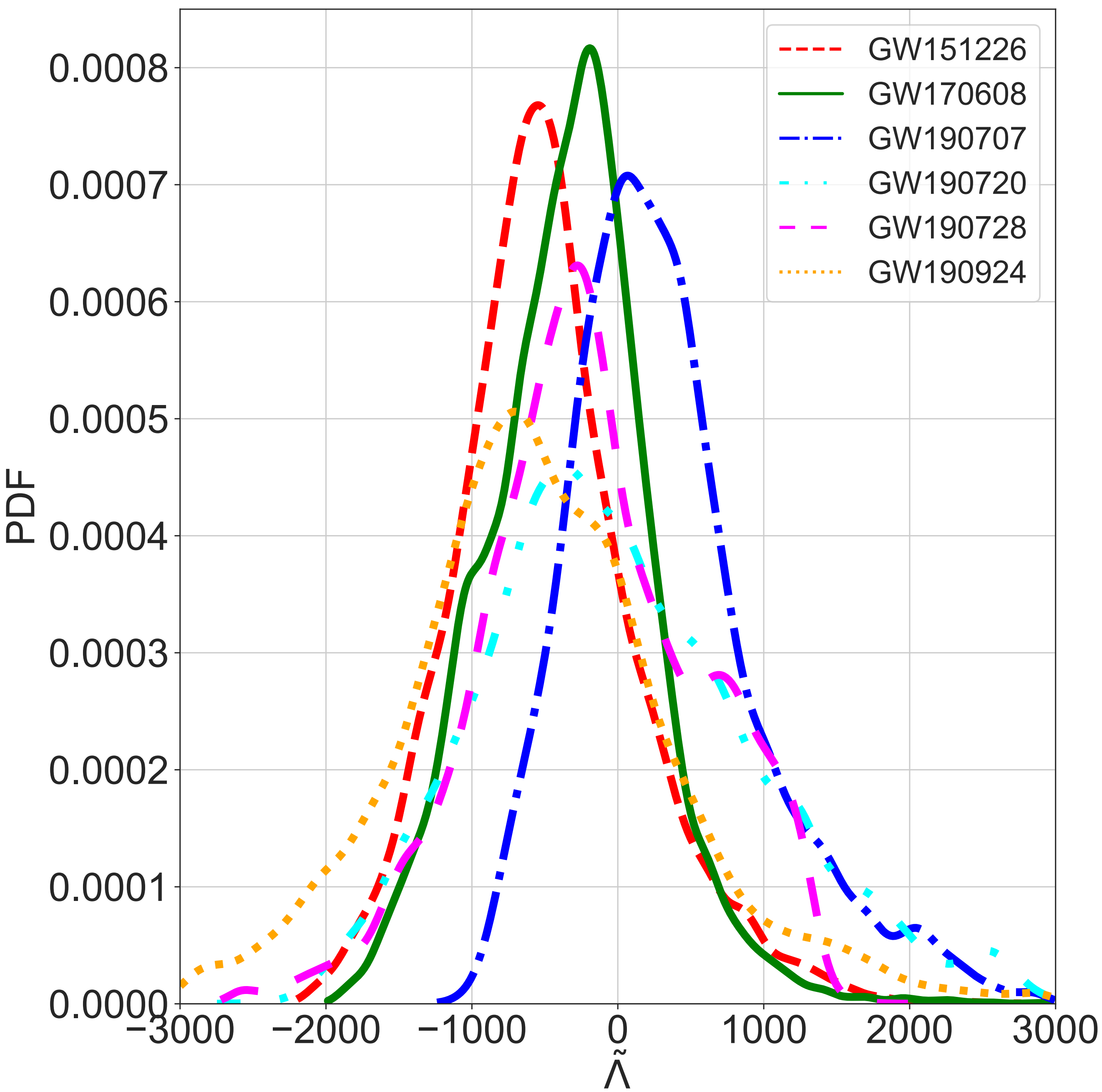
uniform priors on $\tilde{\Lambda}$, $\delta\tilde{\Lambda}$ and $\delta\kappa_{1,2}$.

TF2g_Tidal_SIQM
f_{high}=180 Hz

Constraints on Tidal: six events

Λ

The posterior PDF of $\tilde{\Lambda}$ for six low-mass events.



TF2g_Tidal_SIQM waveform model

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

Event	$\tilde{\Lambda}$
GW151226	[-1441, 649]
GW170608	[-1265, 565]
GW190707	[-590, 1661]
GW190720	[-1445, 1768]
GW190728	[-1432, 1078]
GW190924	[-2041, 1118]

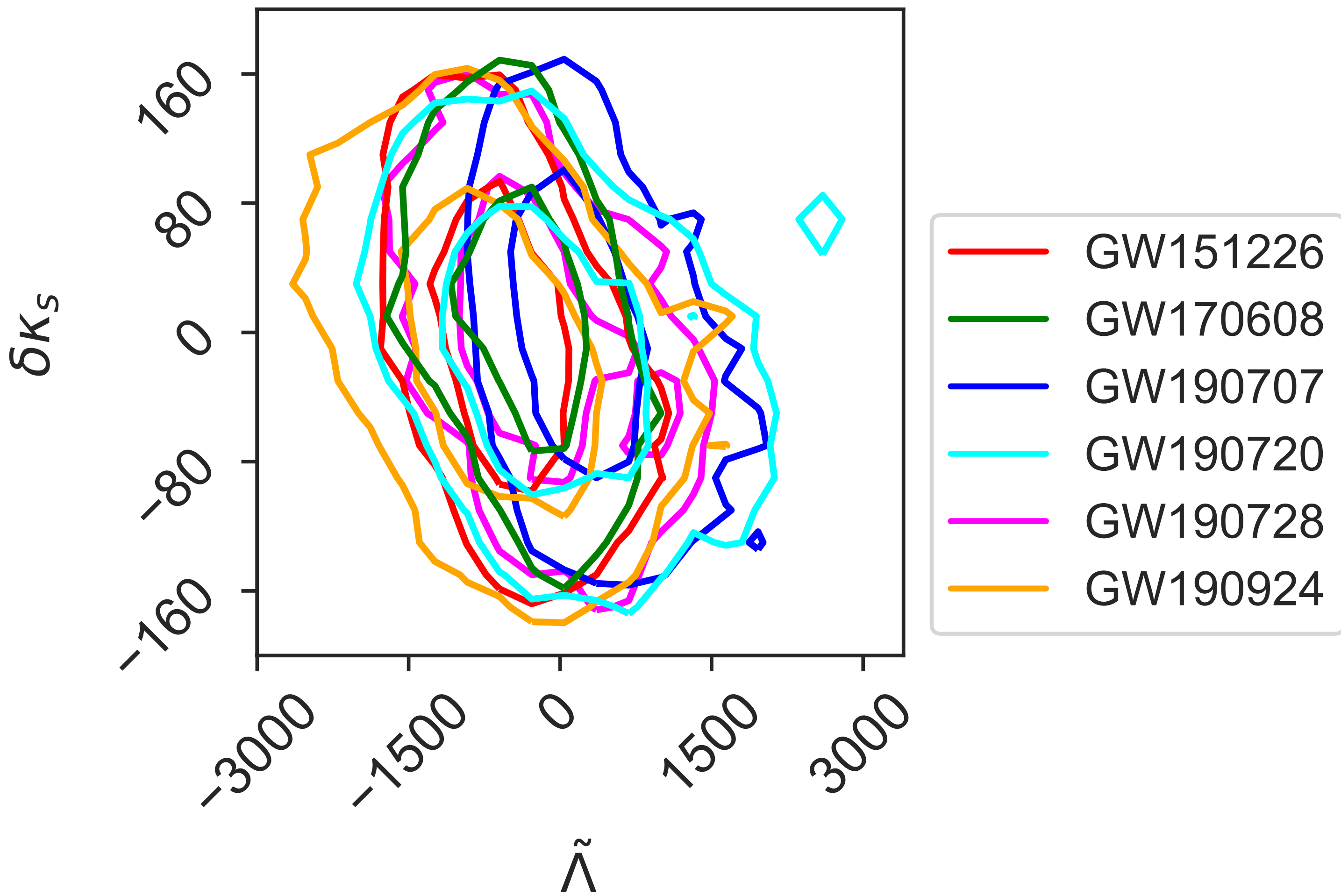
90% symmetric intervals

Constraints on Tidal and SIQM: six events

Λ $\delta\kappa$

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

TF2g_Tidal_SIQM waveform model



Event	$\log_{10} \mathrm{BF}^{\mathrm{ECO}}_{\mathrm{BBH}}$
GW151226	**-0.45**
GW170608	**-2.08**
GW190707	**-2.07**
GW190720	**-1.77**
GW190728	**-1.98**
GW190924	**-2.03**
Combined	-10.38

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

The binary ECO model (with Tidal and SIQM) is disfavored compared to the BBH in GR.

We find weak negative correlation between $\tilde{\Lambda}$ and $\delta\kappa_s$.

Conclusion

Λ $\delta\kappa$

- We analyzed six low-mass GWTC-2 events using the post-Newtonian waveform model.
- **The first constraints on $\tilde{\Lambda}$ of events classified as BBH**
- **We found that all events that we have analyzed are consistent with BBH mergers in GR ($\tilde{\Lambda} = 0$ and $\delta\kappa_s = 0$).**
- **The binary ECO model (with tidal and SIQM terms) is disfavored compared to the BBH in GR.**

Future work

- Results of GWTC-3 events will appear soon.