Measuring NS tidal deformability from LIGO observations of disruptive NSBH binaries

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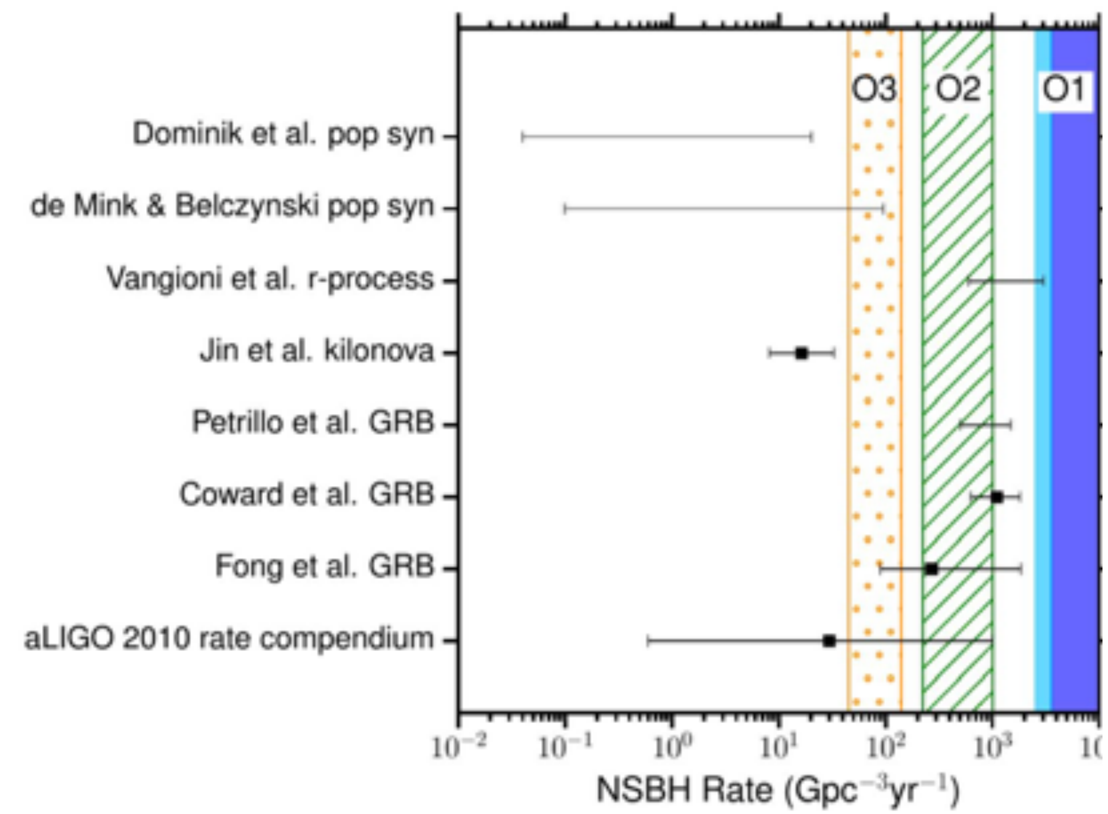
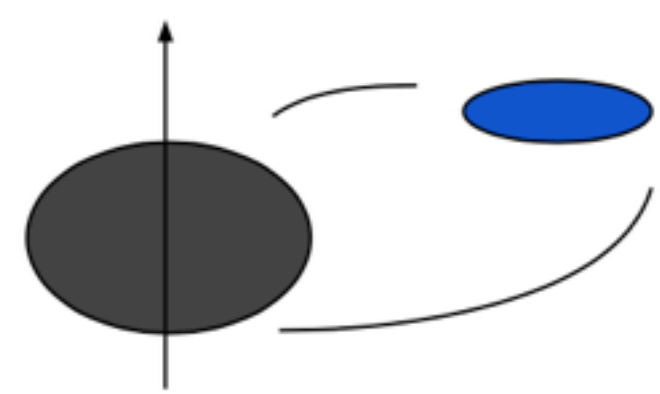
Motivation: NSBHs

- Neutron star - black hole (NSBH) binaries are promising sources for detection with LIGO
- In O1, we barely probed the range of predicted NSBH merger rates. First observations expected in O2 / O3.
- At design sensitivity, observation rate: 0.2 - 300 per year[1].
- In NSBH systems, neutron stars are deformed by the tidal field $E_{ij} \sim \partial_i \partial_j \phi$ of their companion
- The induced quadrupole moment $Q_{ij} = -\lambda(\mathrm{EOS}; m) E_{ij}$ depends on the bulk properties of the NS

LIGO O1 BNS/NSBH upper limits paper
ApJL 832, 2 (2016)

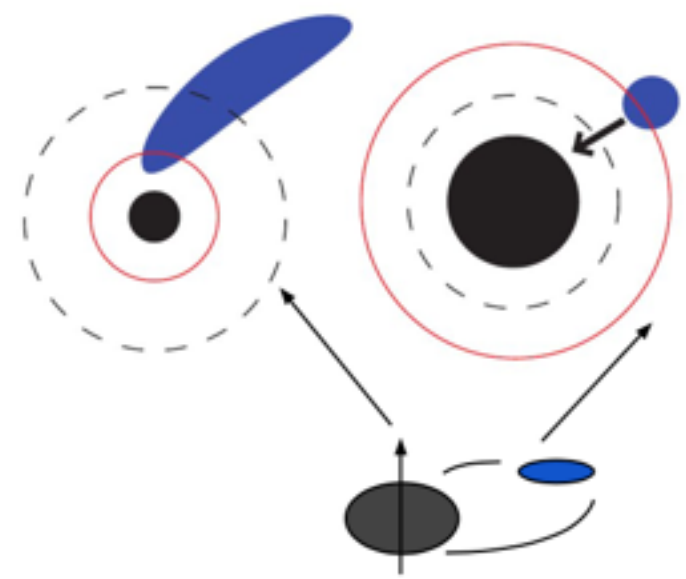




[1] Abadie et al (2010)

Motivation: NSBH merger

- During inspiral, the GW phasing is altered (weakly) at 5PN order, parametrized by the dimensionless tidal deformability parameter $\Lambda \sim \lambda/M^5 \sim (R/M)^5$. LIGO can (barely) resolve these effects for NSBHs[1-3].
- When BH size is comparable to the NS, its tidal field can disrupt the star during late inspiral.
- NS disruption can happen before/after reaching ISCO, depending on
  (a) mass ratio
  (b) black hole spin.



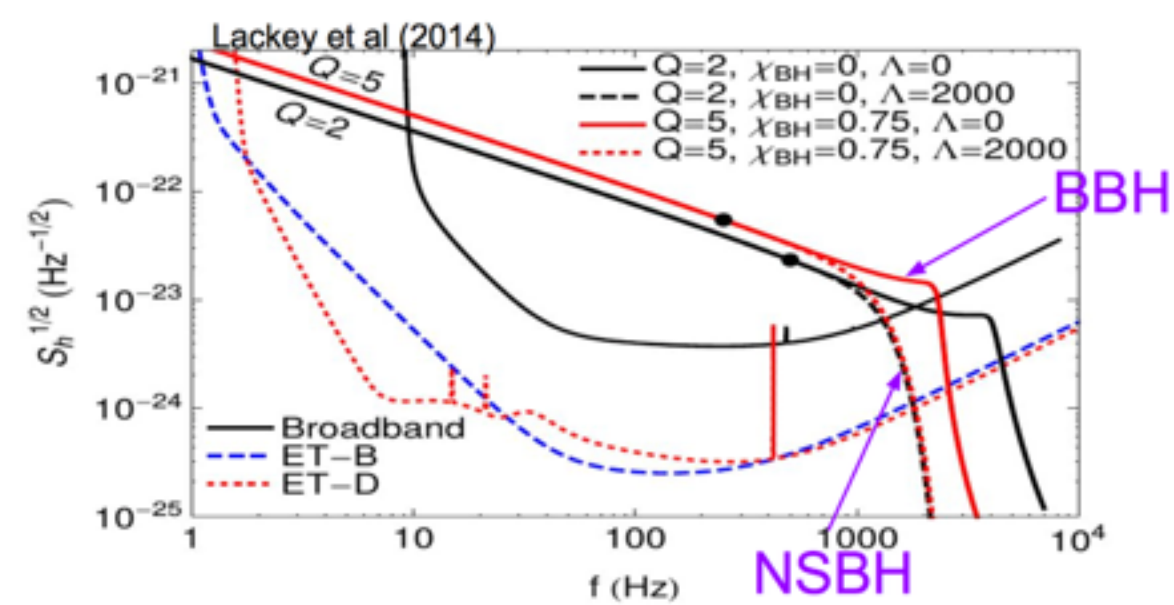


Illustration: Shibata & Taniguchi (2011) [1] Maseli et al (2013); [2] Yagi & Yunes (2014); [3] Lackey et al (2012)

Scope of this work

- We study the the measurability of Λ_{NS} with aLIGO, considering effects of NS distortion during inspiral, and disruption near merger
- We do so for both, single events and populations of observations of NSBH binaries

Waveform Model

- Aligned-spin waveform model for **disruptive** NSBH mergers[1]
- Calibrated to 134 NR simulations, 21 NS EoS (polytropic)
- Mass-ratio **2 <= q <= 5**; BH spin **-0.5 <= $\chi_{BH,z}$ <= +0.75**
- Reduced order effective-one-body[2,3] as the base BBH model.
  Intrinsic parameters **{ M, q, χ_{BH}, Λ_{NS} }**

$$\tilde{h}_{\rm NSBH}(f,\vec{\theta},\Lambda_{\rm NS}) = \tilde{h}_{\rm BBH}(f,\vec{\theta})A(f,\vec{\theta},\Lambda_{\rm NS})e^{i\Delta\Phi(f,\vec{\theta},\Lambda_{\rm NS})}$$

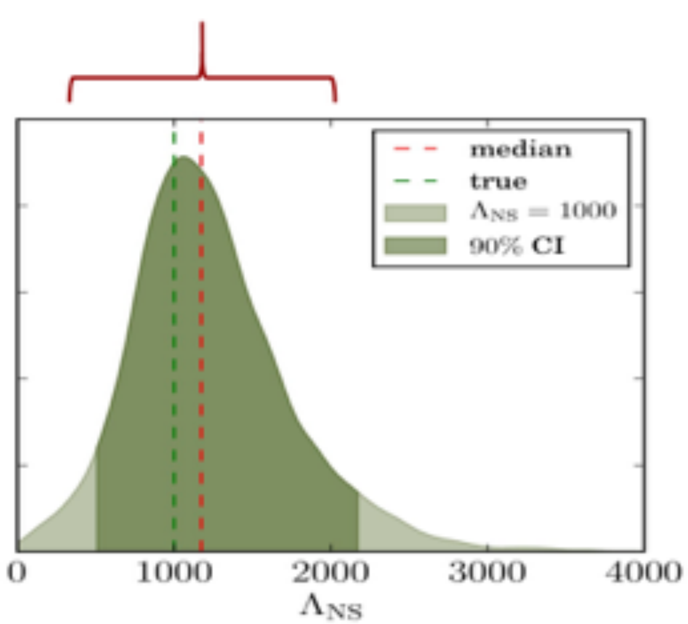
[1] Lackey et al (2014); [2] Pürrer (2016); [3] Taracchini et al (2014)

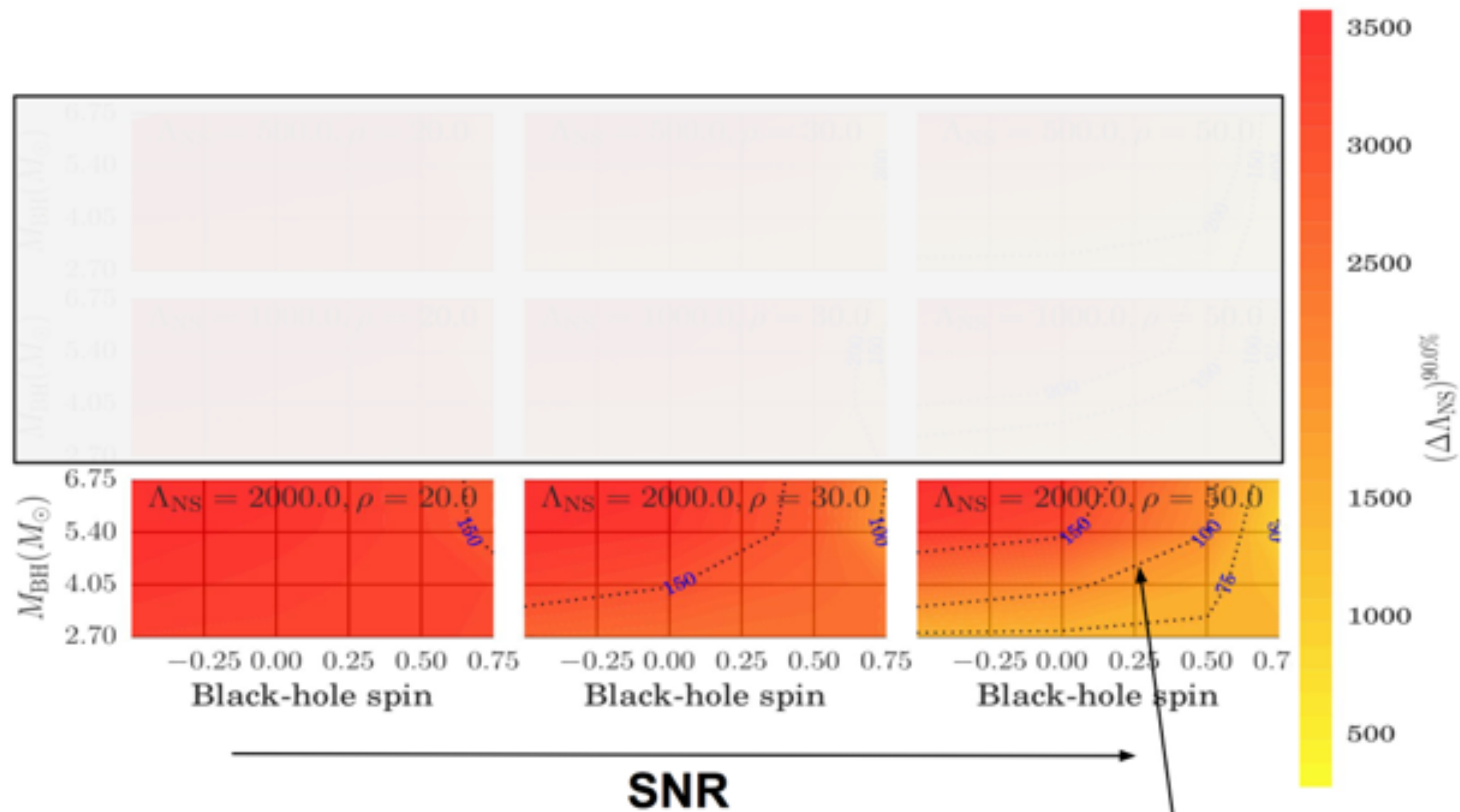
1. How well can we measure Λ_{NS} from a single event?

Inject tidal signals into zero noise and recover with tidal templates.

Prior: Λ_{NS} flat in [0, 4000]

Quantify the measurability of Λ_{NS} using the full width of its recovered 90% credible intervals $(\Delta\Lambda_{NS})^{90\%}$





Contours of $\Delta\Lambda_{NS} / \Lambda^{true}_{NS}$ = 50%, 75% ..

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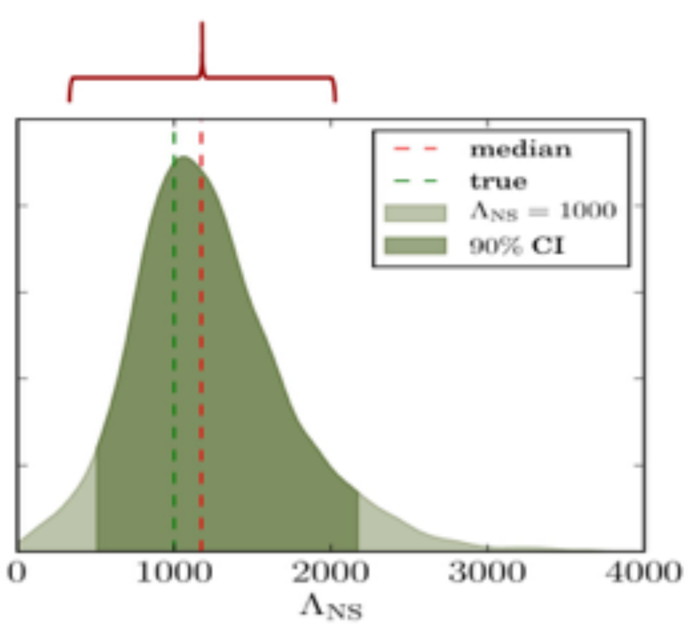

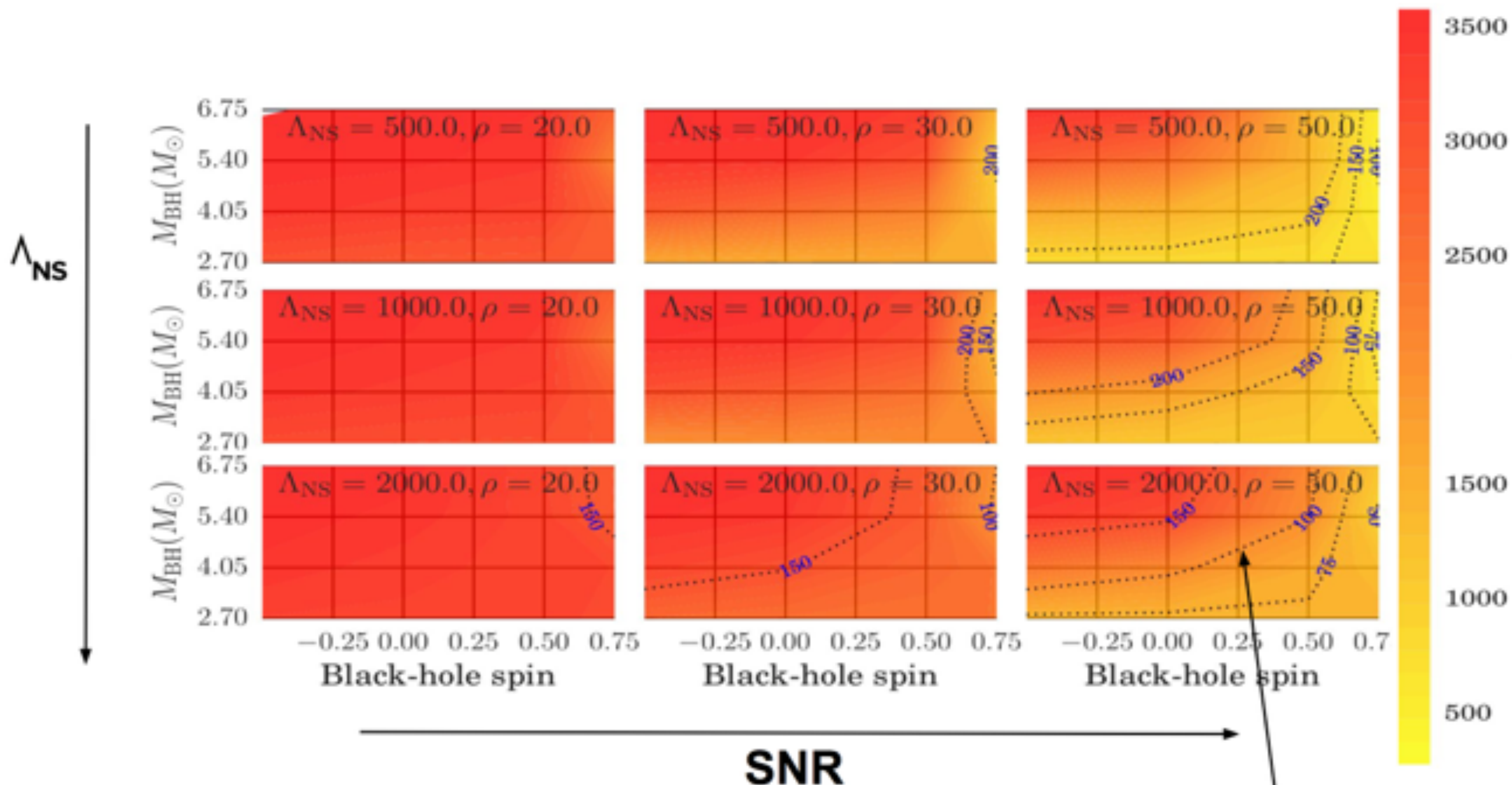

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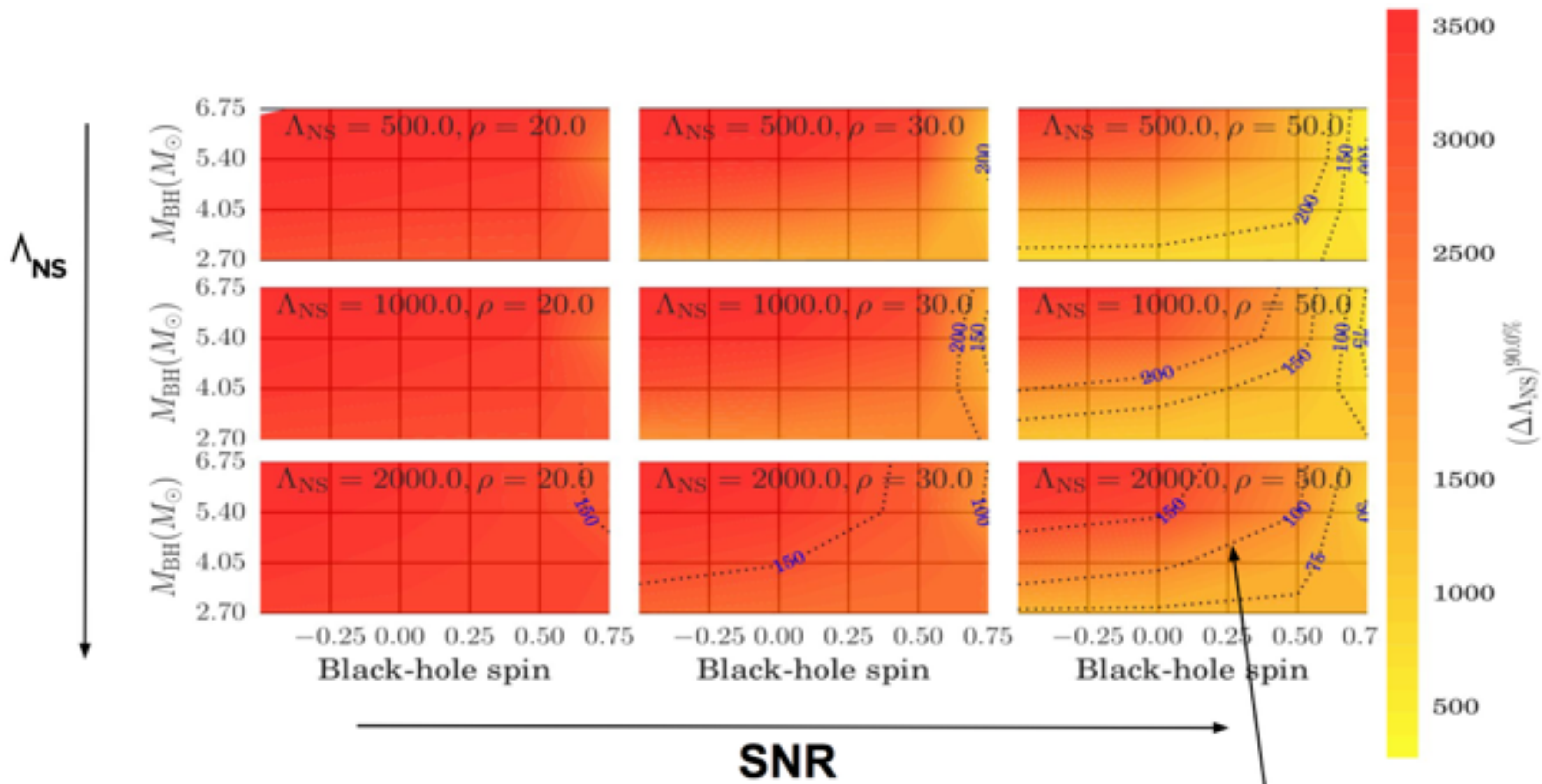

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1) Below SNR ~ 30, our measured PDF for Λ_{NS} spans the entire prior range!
2) Only when the BH is small with positive spins, and/or the NS is fairly deformable can we constrain Λ_{NS} to better than ±50% of its true value.

2. How about multiple realistic observations?

- We combine information for populations of multiple independent disruptive NSBH mergers
- To fix EOS per population:
  - ✦ M_{NS} = 1.35 $M_\odot$, χ_{NS} = 0
  - ✦ Λ_{NS} = {500, 800, 1000, 1500, 2000}
- Events in the population are generated by sampling remaining NSBH parameters:
  - ✦ Mass-ratio: 2 <= q <= 5,
  - ✦ BH spin: 0 <= $\chi_{BH,z}$ <= 1,
  - ✦ source location: uniform in volume,
  - ✦ source orientation: uniform on a 2-sphere.

$$p(\Lambda_{\rm NS}|d_1, d_2, \cdots, d_N; K) = p(\Lambda_{\rm NS}|K)^{1-N} \prod_{i=1}^{N} p(\Lambda_{\rm NS}|d_i, K).$$

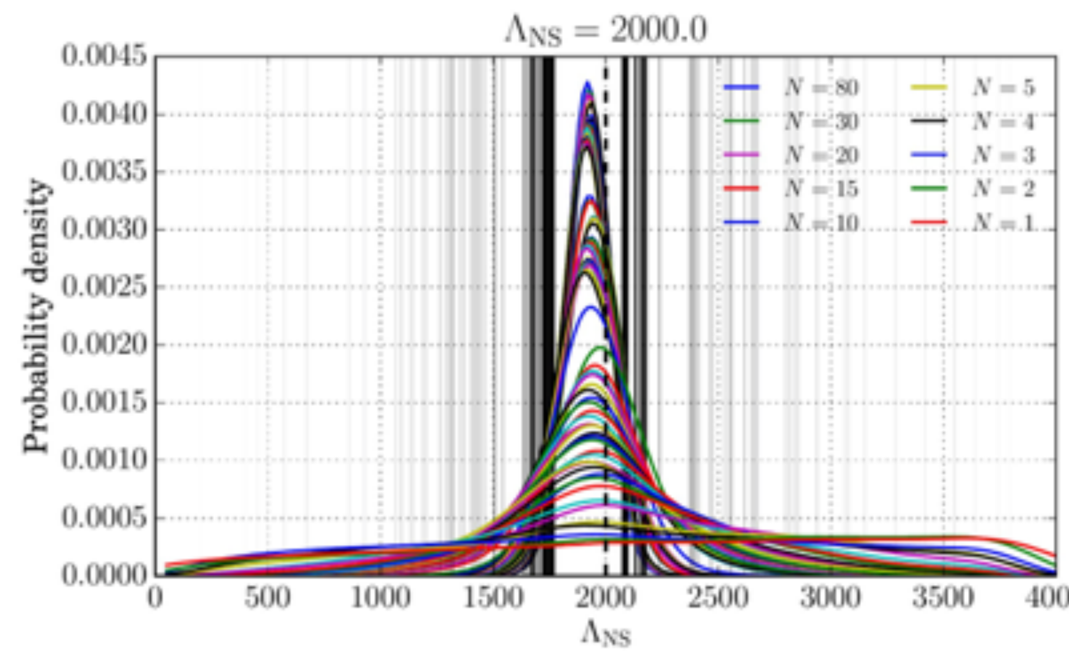
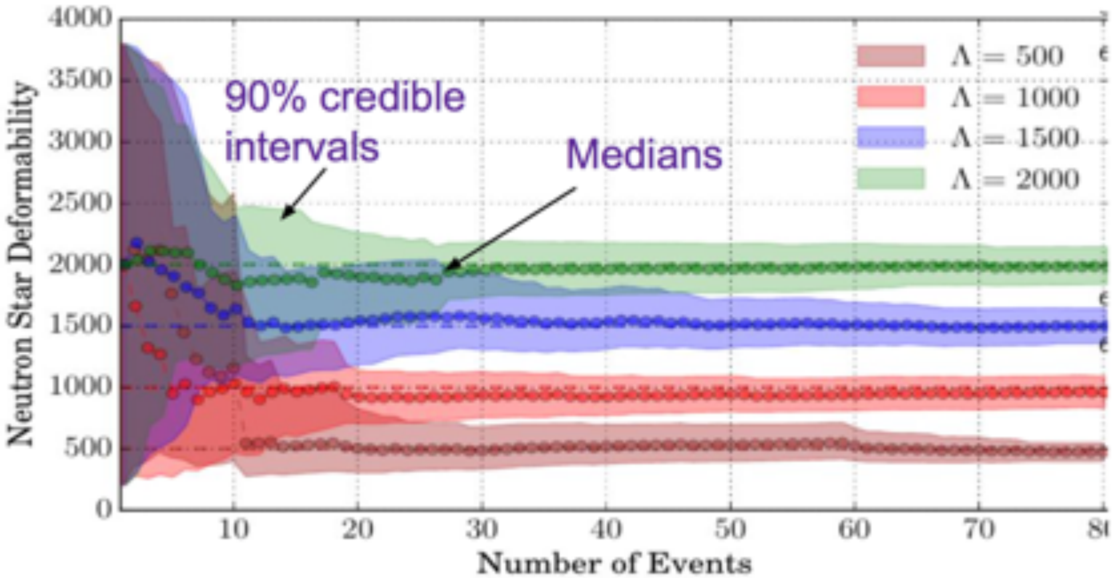


Illustration: Recovered Λ_{NS} probability distributions for different number of events

2. Measuring Λ_{NS} from a realistic population



Λ_{NS} measurements from NSBH populations with different NS deformabilities.

We can distinguish between soft and hard EOSs with ~20 disruptive NSBH observations.

These results are valid for specific population realizations. We marginalize our results over the population generation process.

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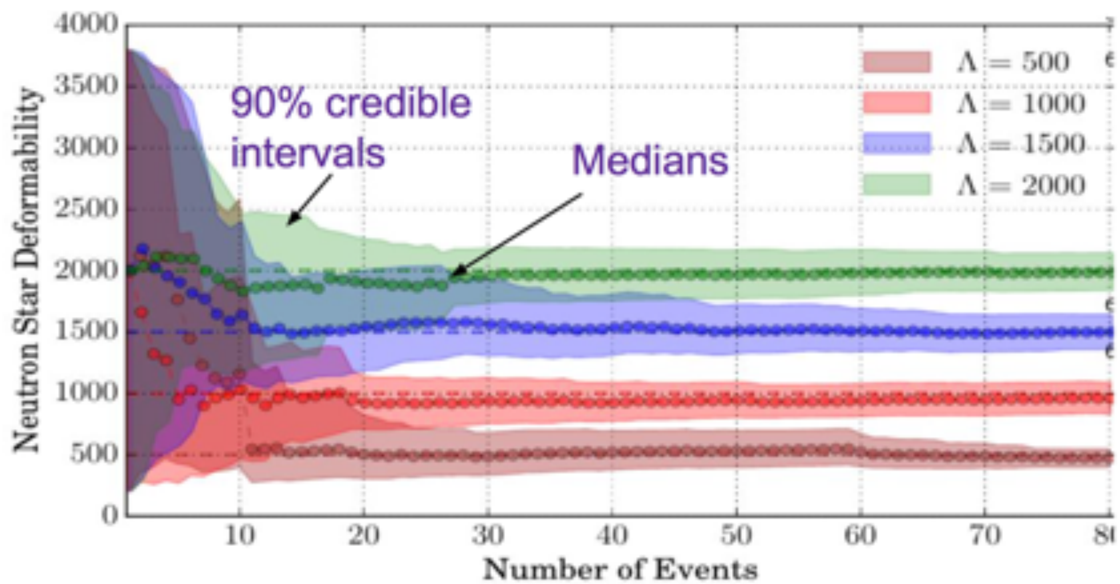

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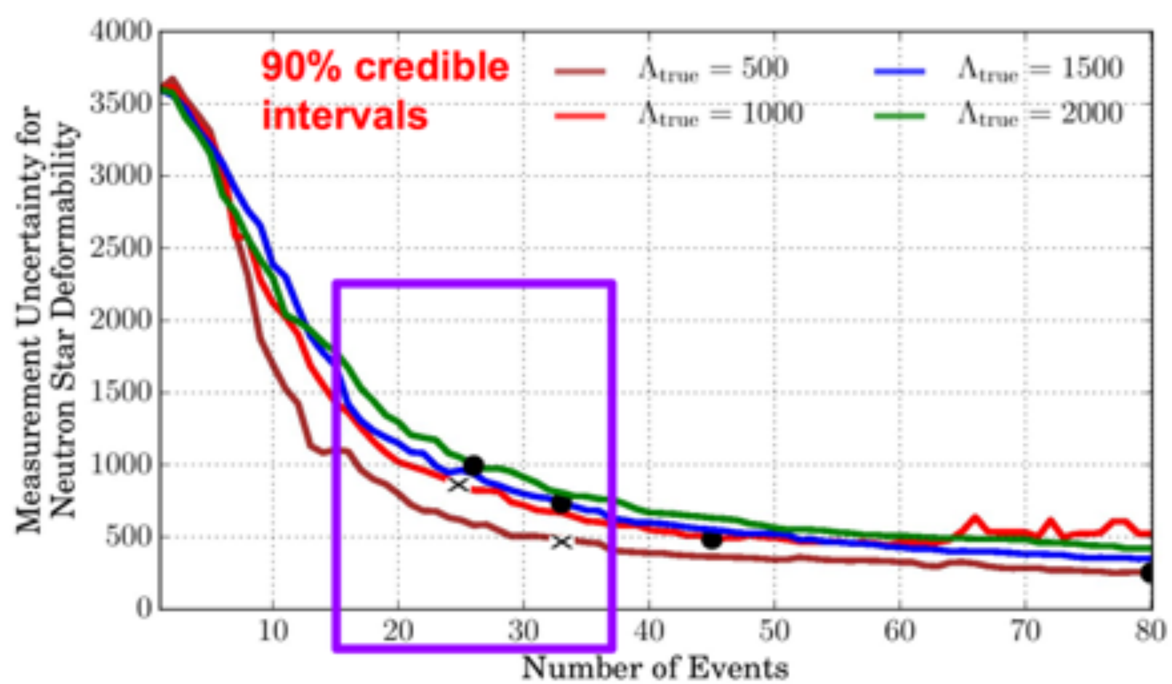
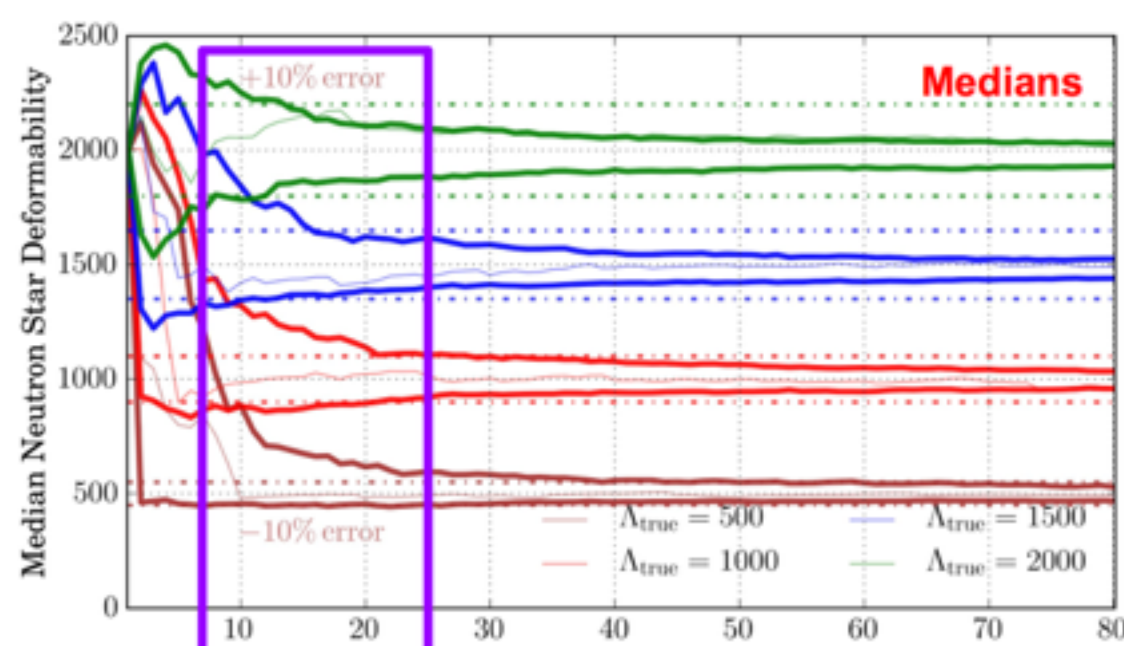
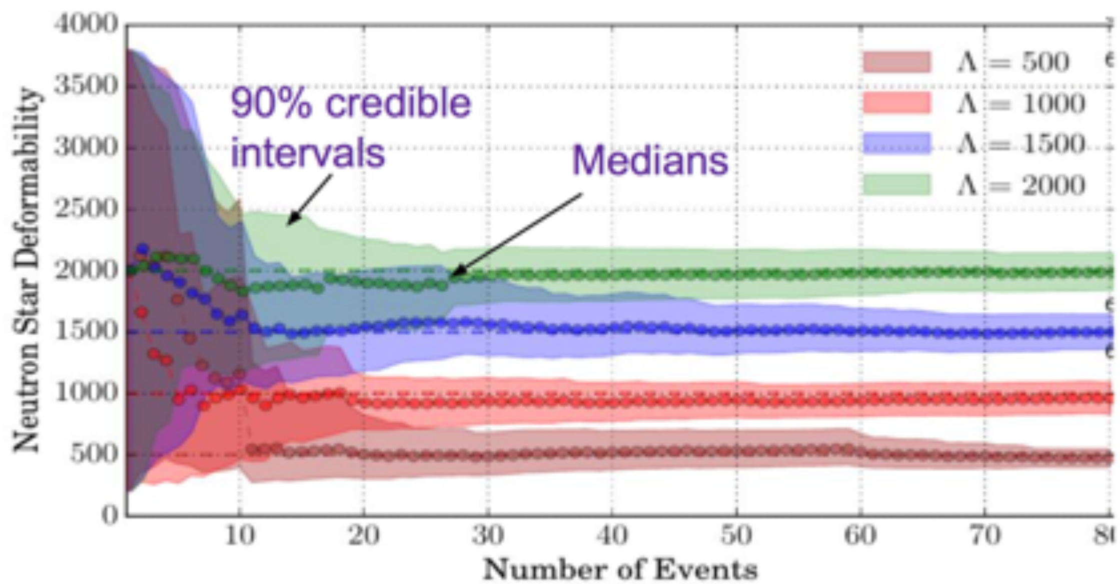




With 20-35 observations: Λ_{NS} measurement will have ±25% error-bars for $\Lambda^{true}_{NS} > 1000$ (black circles), and ±50% error-bars for $\Lambda^{true}_{NS} < 1000$ (black crosses)

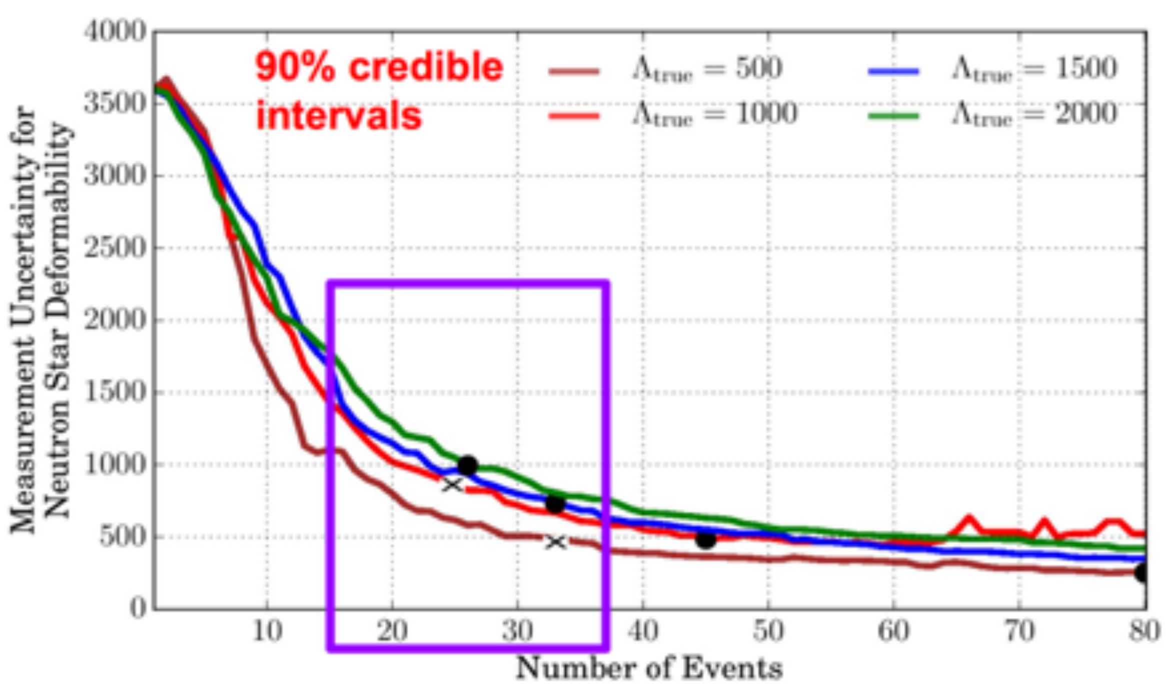
With 10-20 observations: median Λ_{NS} will be within ±10% of Λ^{true}_{NS}

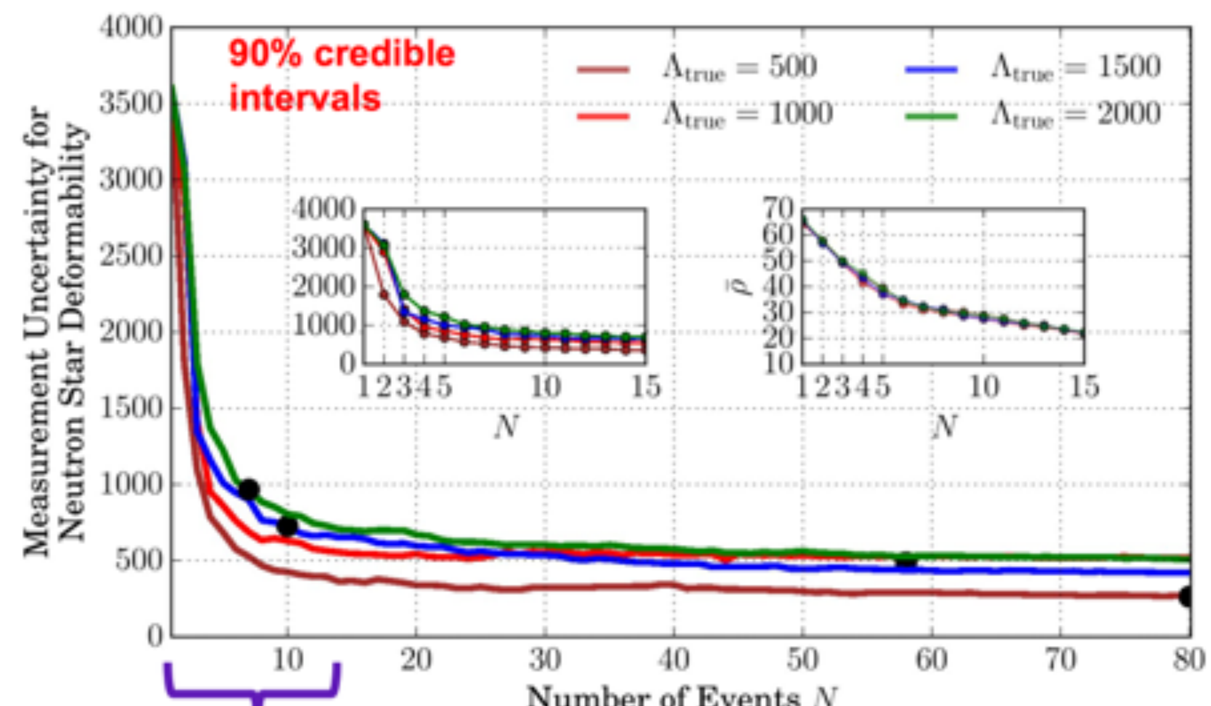
2. Measuring Λ_{NS} from a realistic population



Q: Does most of the tidal information come from all low-SNR events together or a few loud ones?

The loudest 10 events with SNR > 20 contribute the most, and will be interesting for detailed follow-ups.

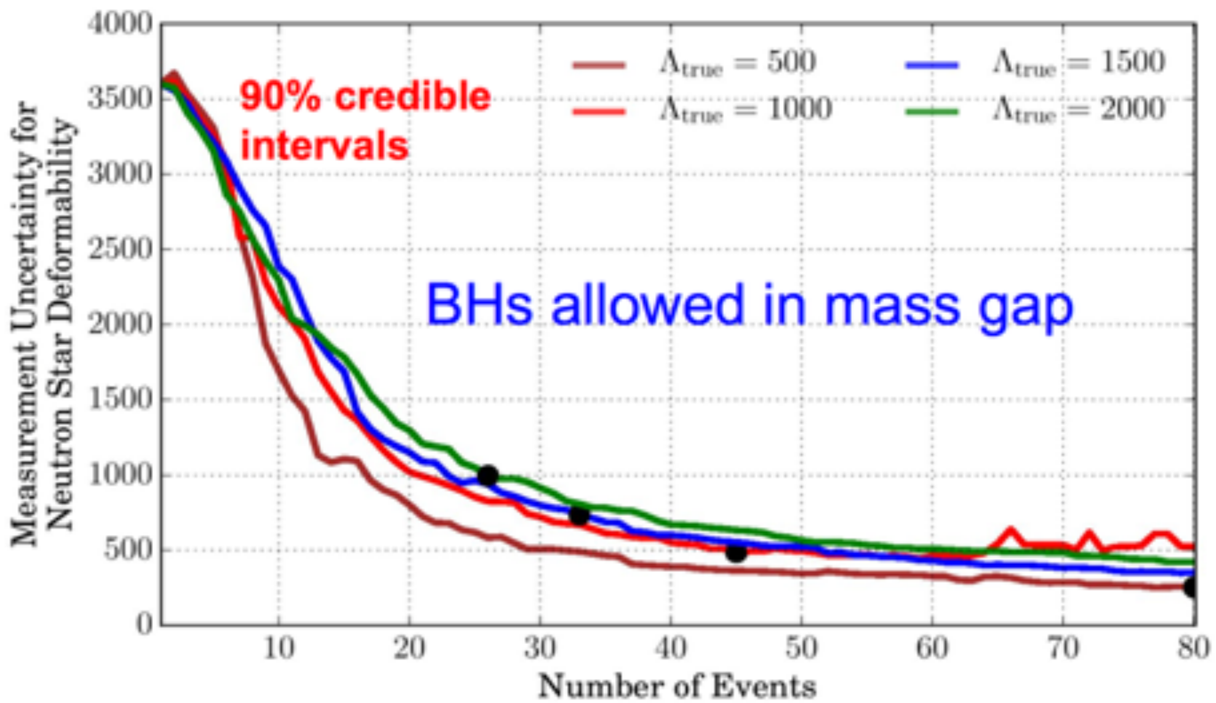


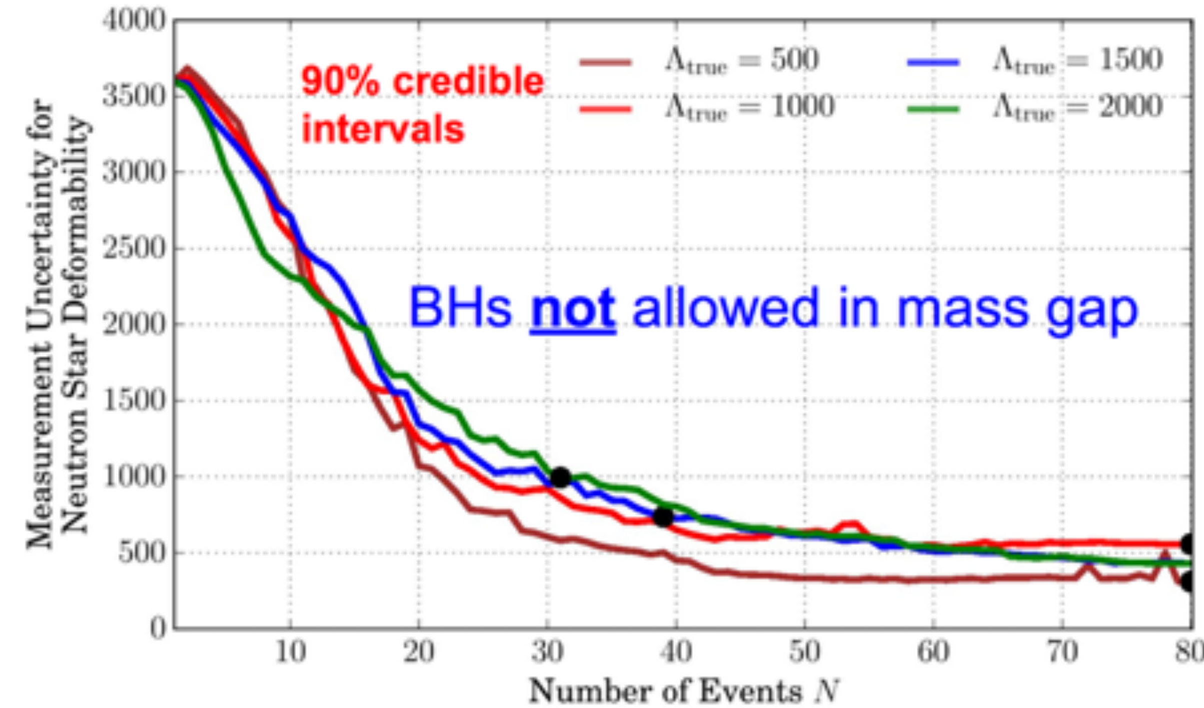


Loudest 10-15 events

With 20-35 observations: Λ_{NS} measurement will have ±25% error-bars for $\Lambda^{true}_{NS} > 1000$ (black circles), and ±50% error-bars for $\Lambda^{true}_{NS} < 1000$ (black crosses)

2. Measuring Λ_{NS} from realistic populations: Mass gap vs no-Mass gap





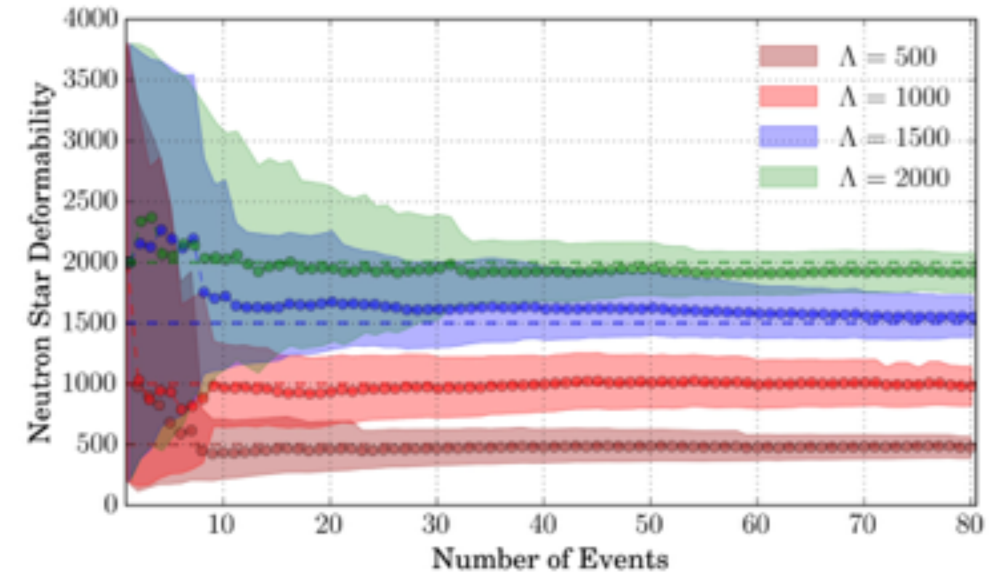
If BH masses are outside the astrophysical mass-gap (~ 2-5 $M_\odot$), Λ_{NS} measurement gains accuracy more slowly, requiring 25+% additional events to attain the same accuracy.

Conclusions

Λ_{NS} error bars

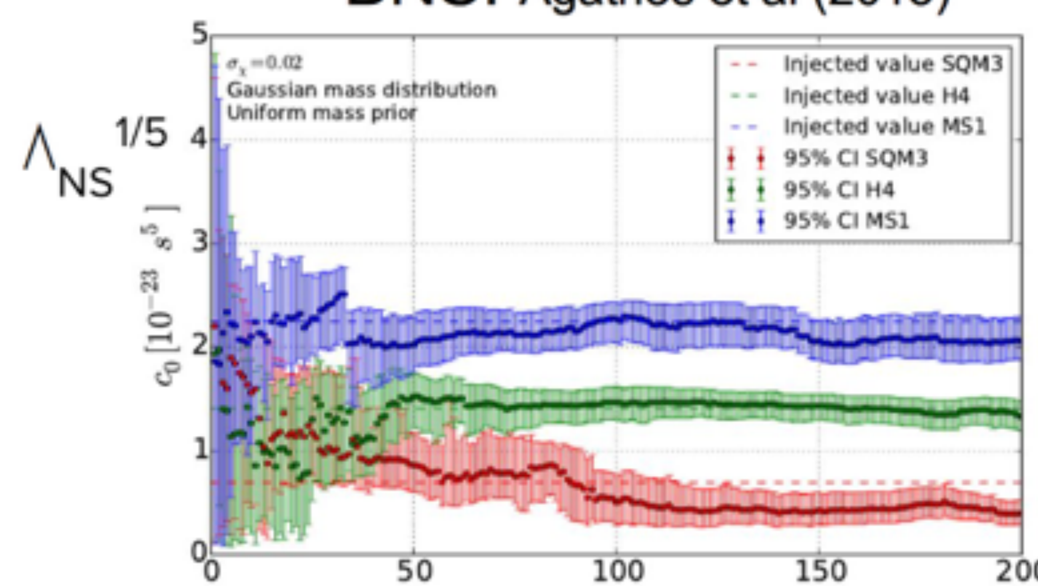
#Events	Λ_{NS} > 1000 (MG)	Λ_{NS} <= 1000 (MG)
10 - 20	±50% (±60%)	-
20 - 35	±20% (±35%)	±40% (±50%)
70+	±15% (±25%)	±25% (±30%)

*MG = Mass-gap respected



NSBH: this study

BNS: Agathos et al (2015)



- Disruptive NSBH binaries are as good probes as BNS for constraining the NS tidal deformability, and distinguishing between NS candidate EOSs.
- With the first 10-20 events, we may begin to place factor of 1-2 bounds on Λ_{NS}. With 30-40 events we can constrain Λ_{NS} to within a few 10s of percent.
- The loudest 10 events (SNR > 20) provide most of tidal information, with little furnished by other low-SNR events.
- Accounting for the reduced size of the disruptive NSBH parameter space, we can see up to 30 of such sources a year with design aLIGO. Therefore all of the above is possible within a few years of aLIGO's operation.

Followup study

H. Fong, P. Kumar, MP, V. Raymond, S. Field

- Assess **systematic errors** in LEA+ waveform model by comparing against TEOB-NR hybrids
- Study accumulation of information on tidal deformability in **detector noise**.
- Fast PE in noise: leverage LEA+ **reduced order quadrature** (S. Field, MP).