Towards gravitational-wave astronomy

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The quest for the direct detection of gravitational waves

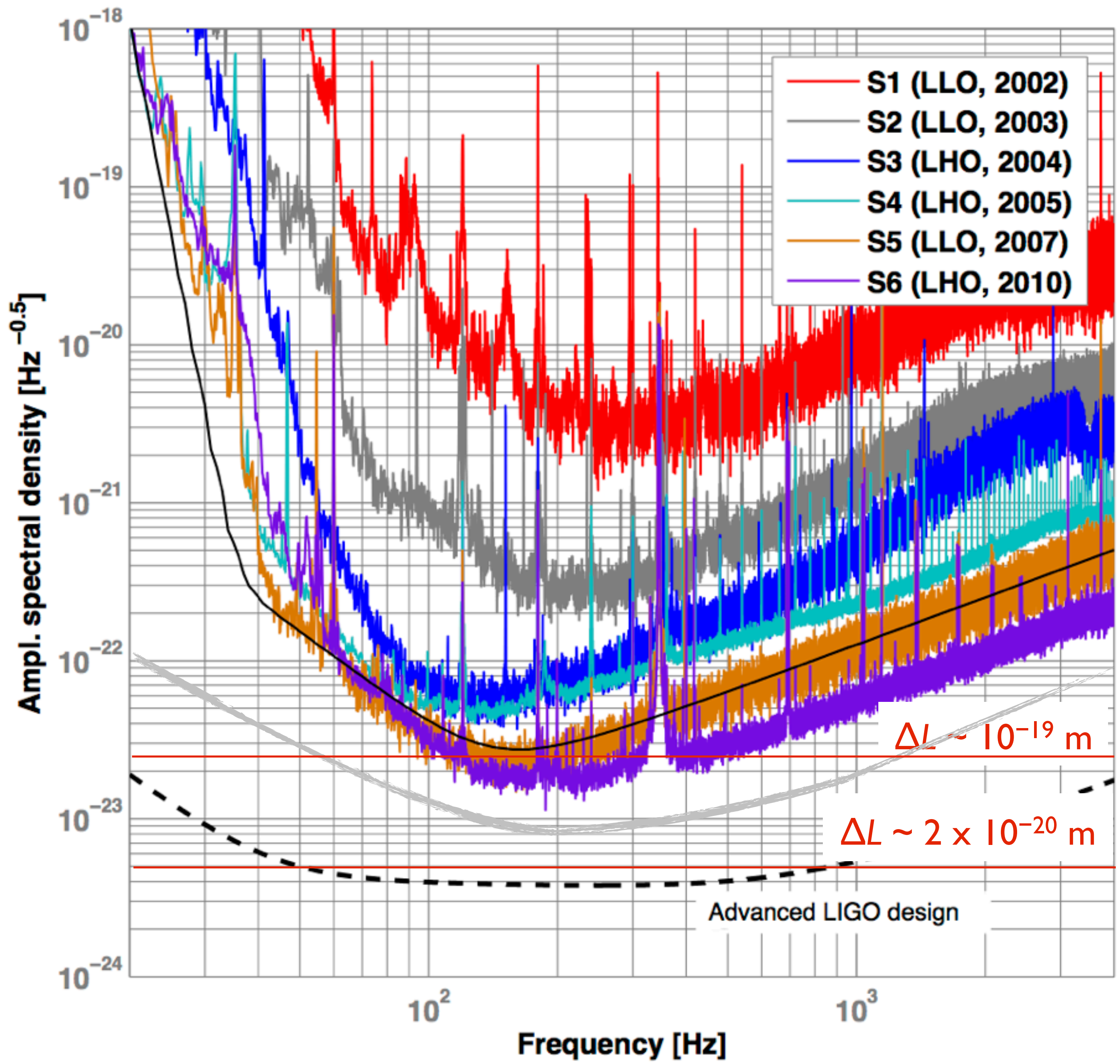
- A worldwide network of ground-based detectors has started an exciting search for GWs.


LIGO Observatories in Hanford and Livingston, USA

The quest for the direct detection of gravitational waves

- Initial LIGO detectors achieved their design sensitivity in 2007.
  - Non-detection is consistent with the astrophysical expectations.

[Keita Kawabe's talk]

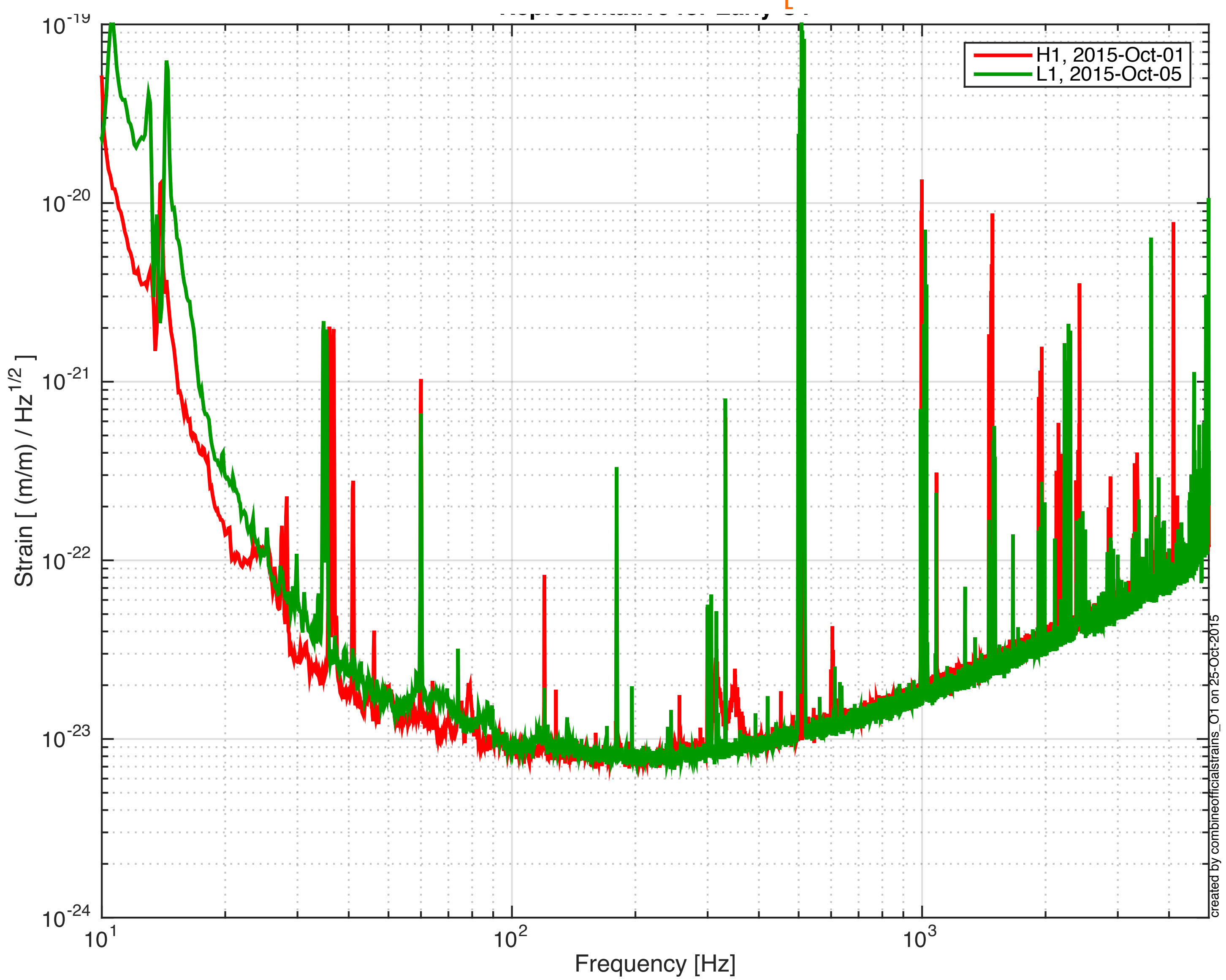


The quest for the direct detection of gravitational waves

- Initial LIGO detectors achieved their design sensitivity in 2007.
- Advanced LIGO detectors started operation in Sep 2015. With ~3-5x improved sensitivity as compared to Initial LIGO, ~30-100x improvement in the expected detection rates.
- Expected to achieve design sensitivity by 2018 (~10x compared to Initial LIGO).

[Keita Kawabe's talk]

[LIGO document: G1500632]



Representative noise spectrum from the ongoing observation run of Advanced LIGO.

The quest for the direct detection of gravitational waves

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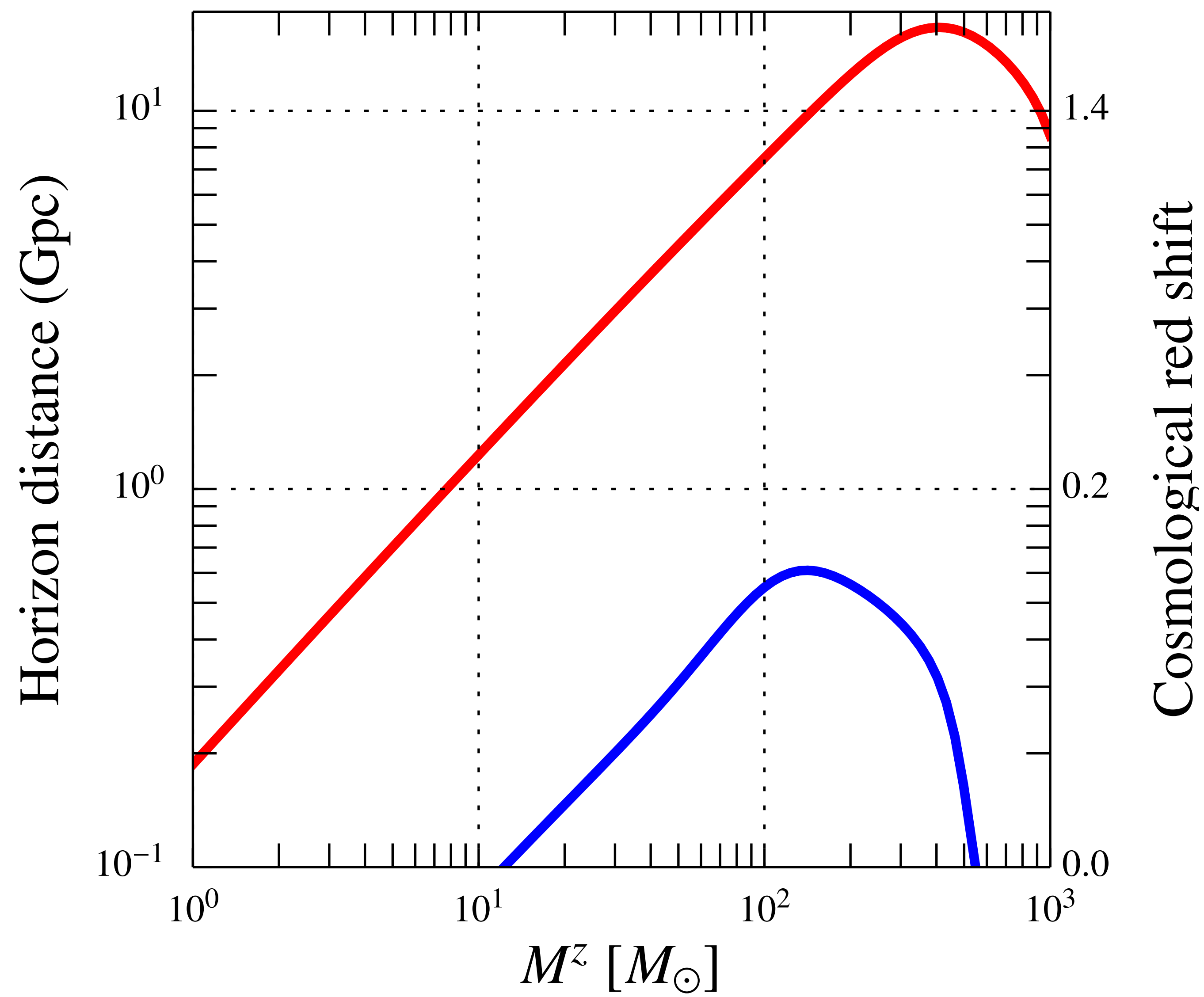


10x increase in the sensitivity → 1000x improvement in the event rates.

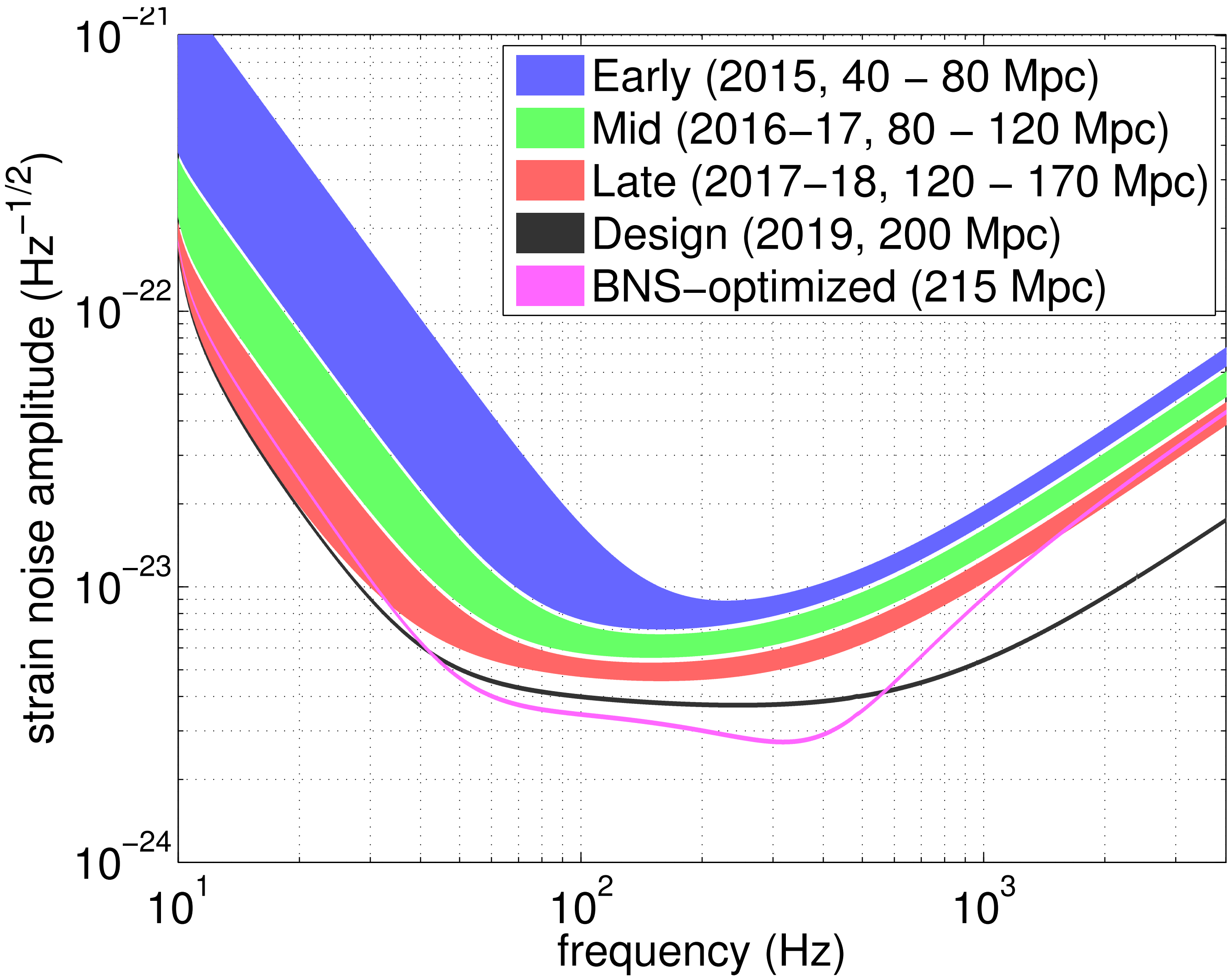
When can we expect the first detections?

- Difficult to make accurate predictions due to the uncertainties in the astrophysical event rates and challenges in the commissioning.

- **Plausible observing scenarios**

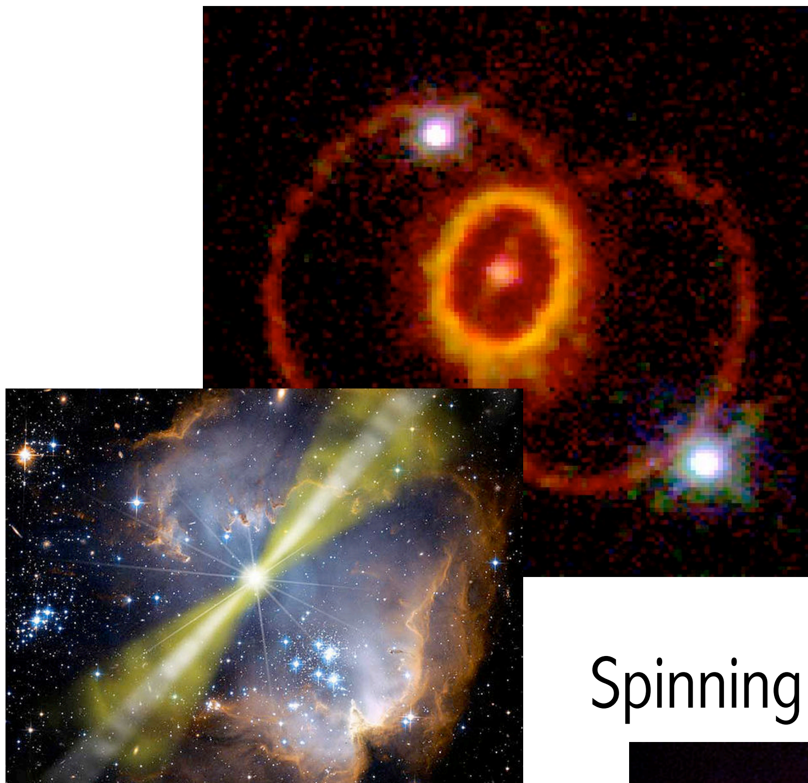
Epoch	Plausible BNS detections	% BNS located within 5 [20] sq deg
2015	0.0004 — 3	
2016-17	0.006 — 20	1 — 2 [10 — 12]
2017-18	0.04 — 100	
2019+	0.2 — 200	3 — 8 [8 — 28]
2022+ India	0.4 — 400	17 — [48]

[LIGO & Virgo Collab arXiv:1304.0670]



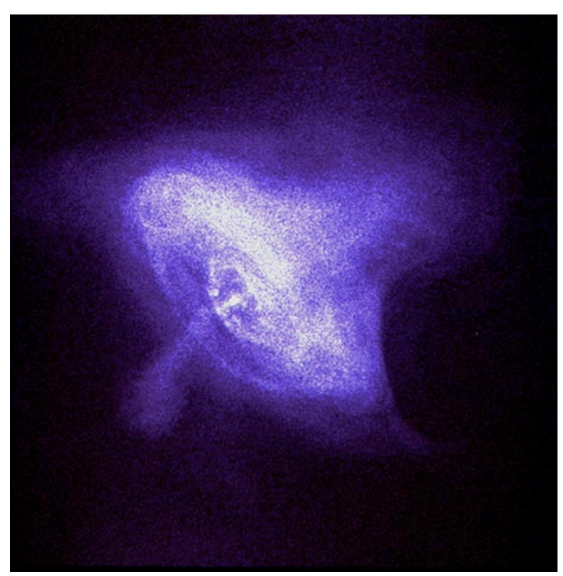
GW astronomy: Sources and science

Core-collapse and supernova

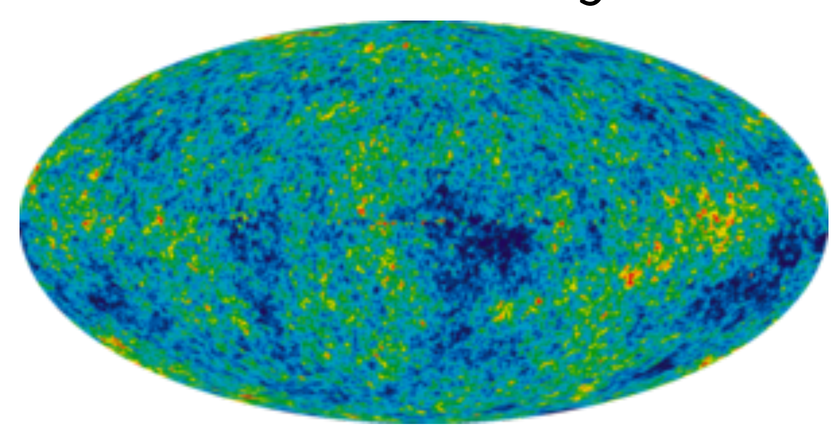


Coalescing compact binaries

Spinning neutron stars



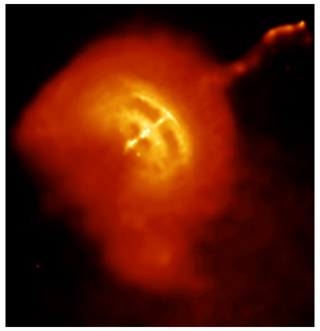
Stochastic GW background



Searches for spinning neutron stars

- **Known pulsars** phase evolution known; do fully coherent targeted search.
  - Initial LIGO upper limits for 174 known pulsars. For Crab/Vela, well below the "spindown" limit [Aasi et al 2014]
- **Unknown neutron stars** Computational constraints make coherent search unfeasible; need to do semi-coherent search, e.g. Einstein@Home .
- **Known neutron stars not seen as pulsars** (e.g., SN remnants, LMXBs); do directed search which still has to deal with residual parameter uncertainties.
  - Useful input from Astrosat x-ray data.

[Talk by John Whelan]



Spitzer/Hubble/Chandra

Searches for unmodeled transient sources

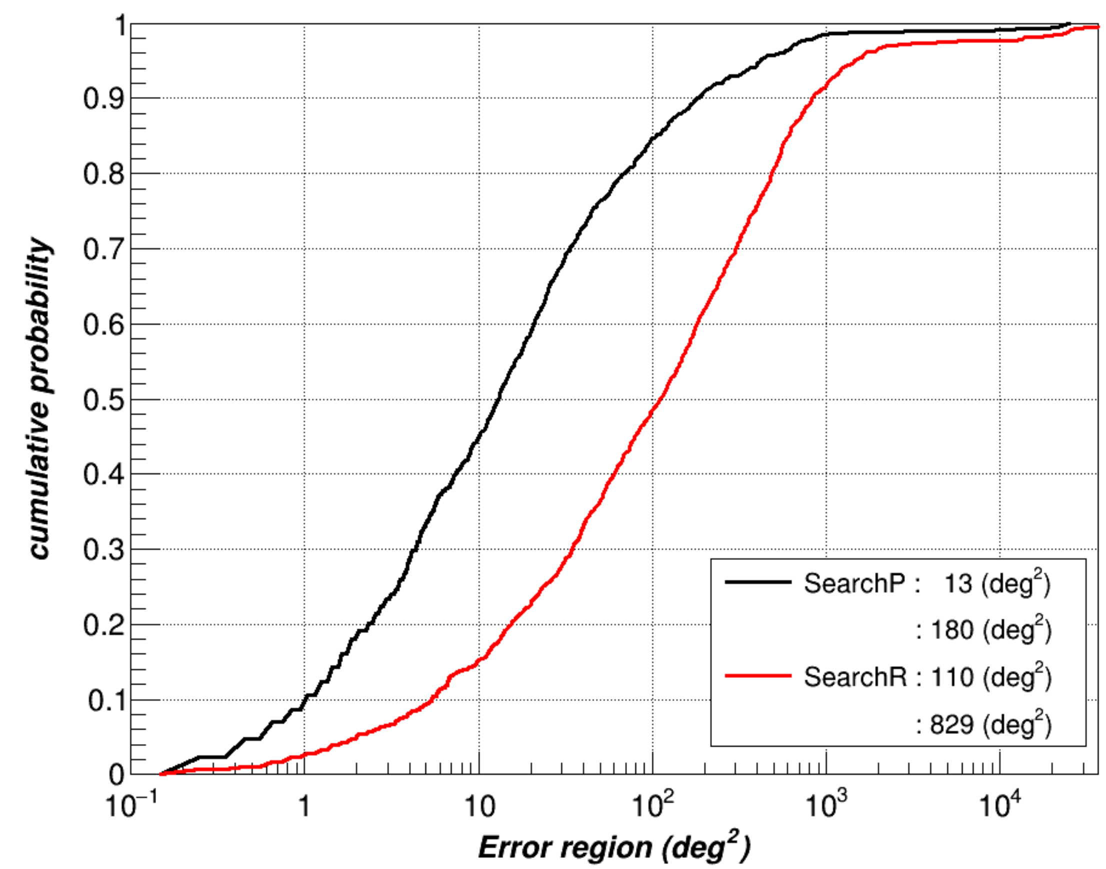
- **Searches for unmodeled transient sources**
  Search for excess power that is coherent in multiple detectors.

$$\eta = \sqrt{2E_{\mathrm{coh}}/(1 + E_{\mathrm{null}}/E_{\mathrm{coh}})}$$

  - Can add additional constraints to tune the search for different sources.

    [Poster by Atmajt]

[Klimenko et al 2015]

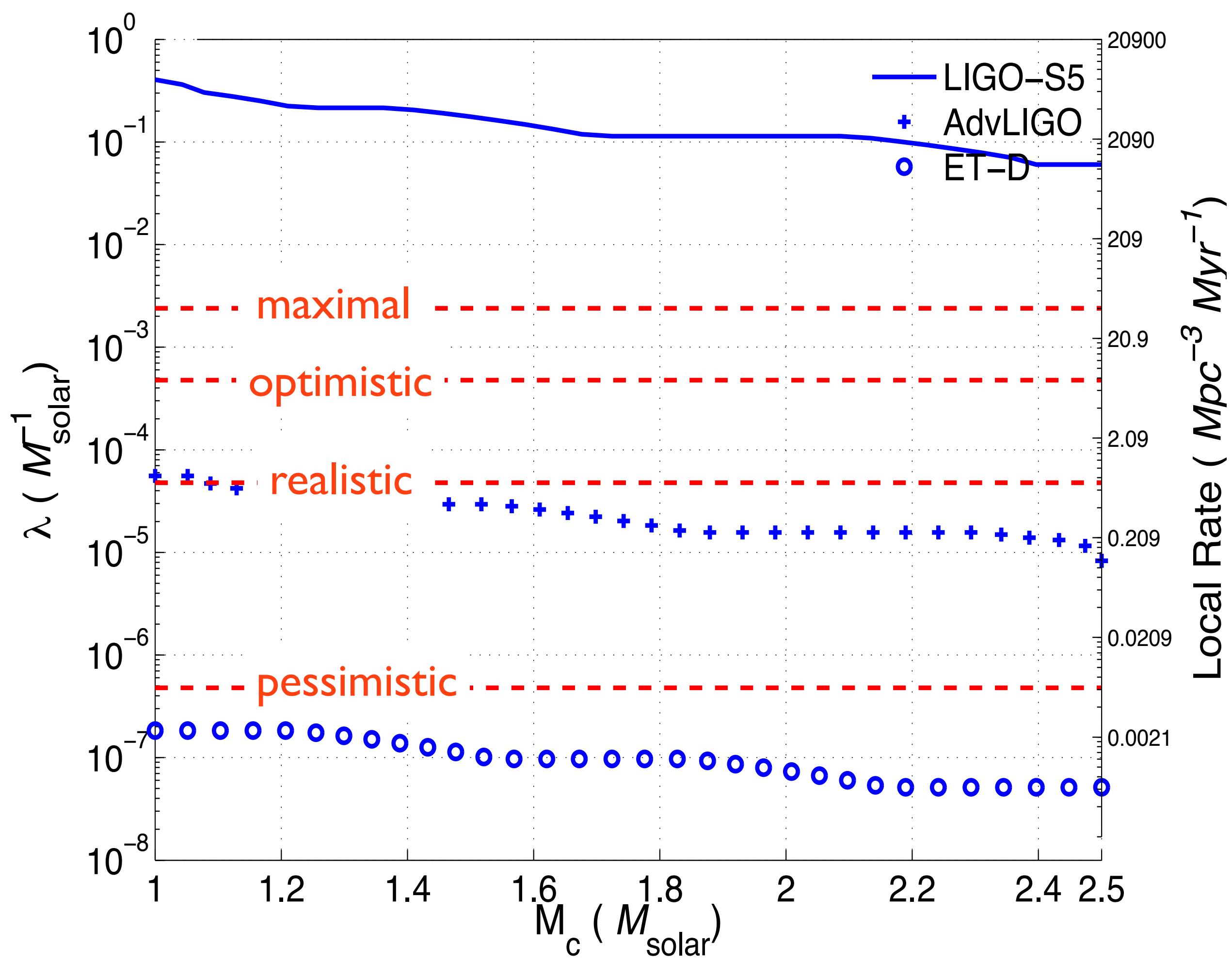


Searches for unmodeled transient sources, stochastic GW background

- **Searches for stochastic background**
  Produced by astrophysical or cosmological sources. Cross correlate the data from multiple detectors.
  - Potential for observing the stochastic background produced by astrophysical sources.

[Talk by Anirban Ain]

[Wu et al 2011]



compact binary coalescence

GW searches for CBCs: Matched filtering

- Signals are rare, weak, and buried in the noise. Need sophisticated data analysis techniques.

Matched filter

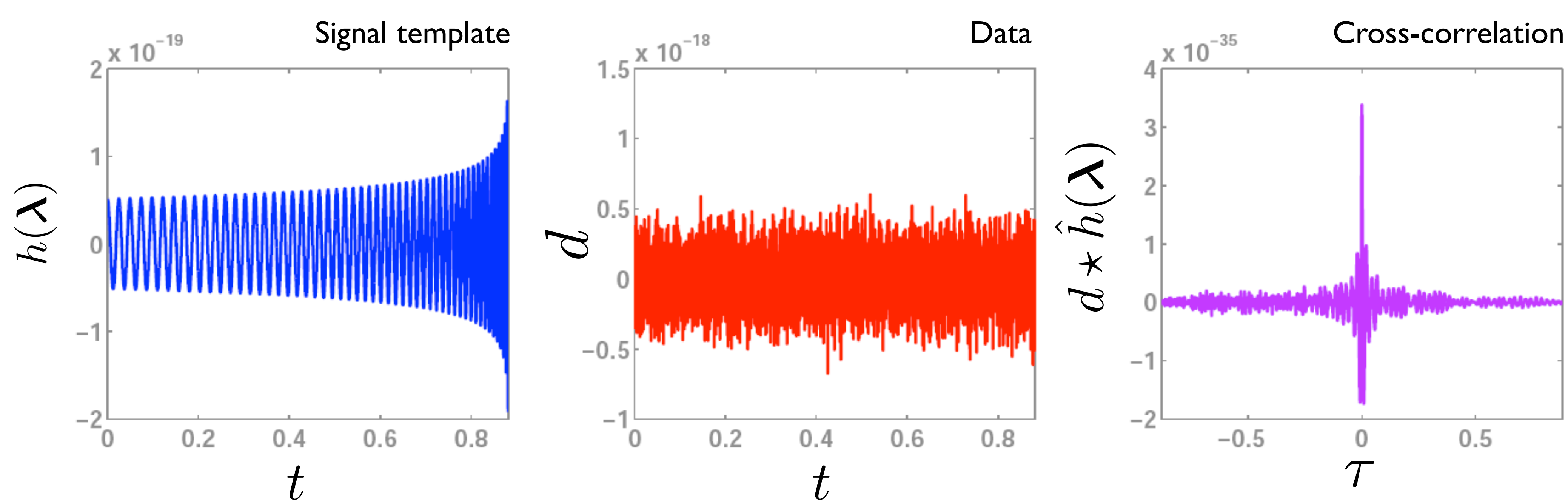
$$\rho \equiv \max_{\boldsymbol{\lambda}} \left[d \star \hat{h}(\boldsymbol{\lambda}) \right]$$

SNR

data

signal template

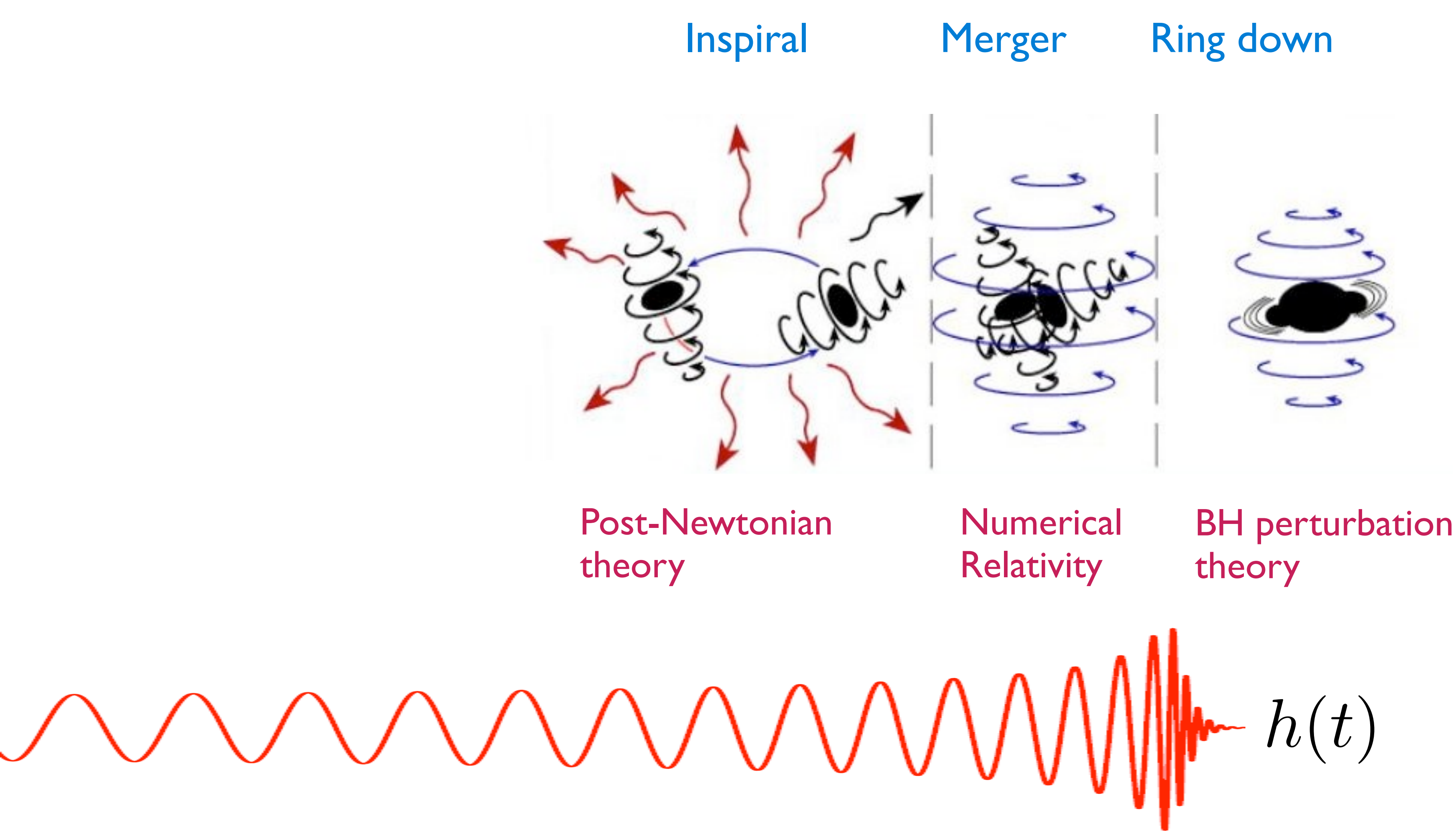
source parameters



GW searches for CBCs: Waveform templates

- The signal waveforms can be accurately computed by solving the Einstein equations (+ MHD in the case of neutron star binaries).

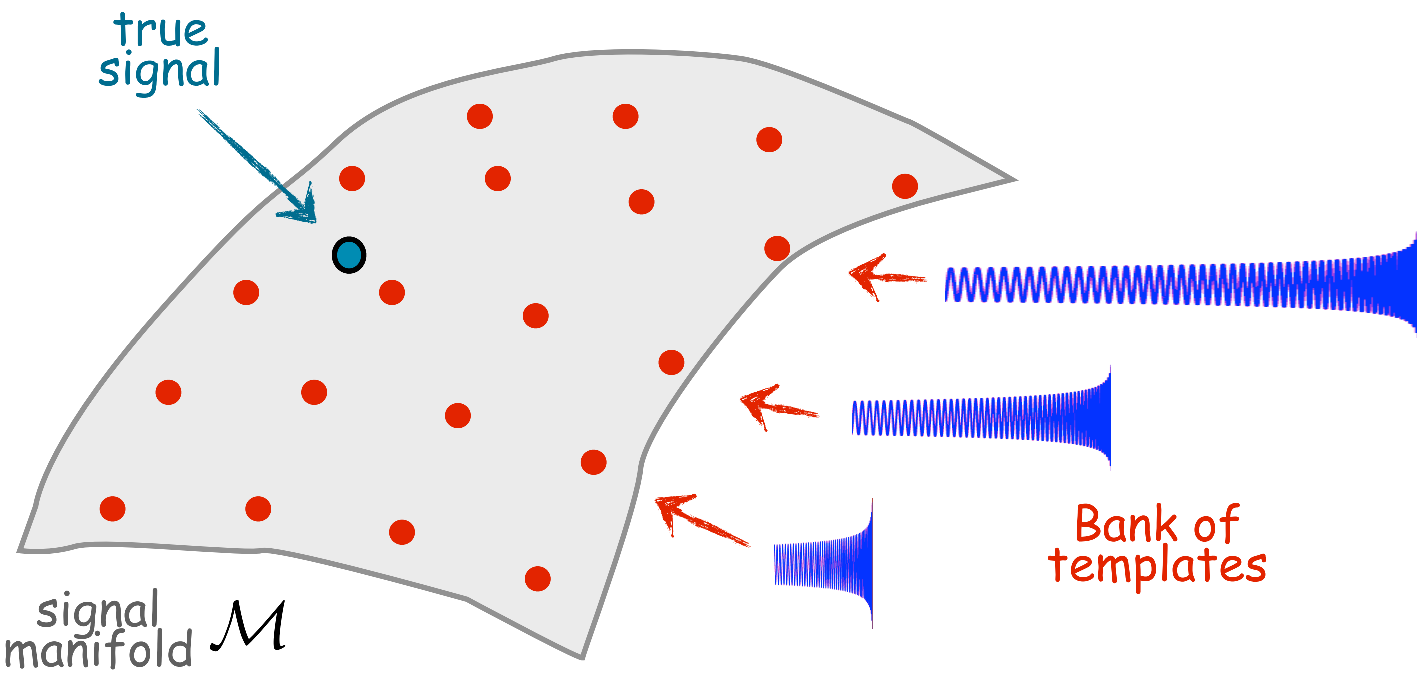
[Talks by Luc Blanchet, Harald Pfeiffer, Luca Baioti, Nathan Johnson McDaniel, Chandra Kant Mishra]



(Pic. K.Thorne)

GW searches for CBCs: Template banks

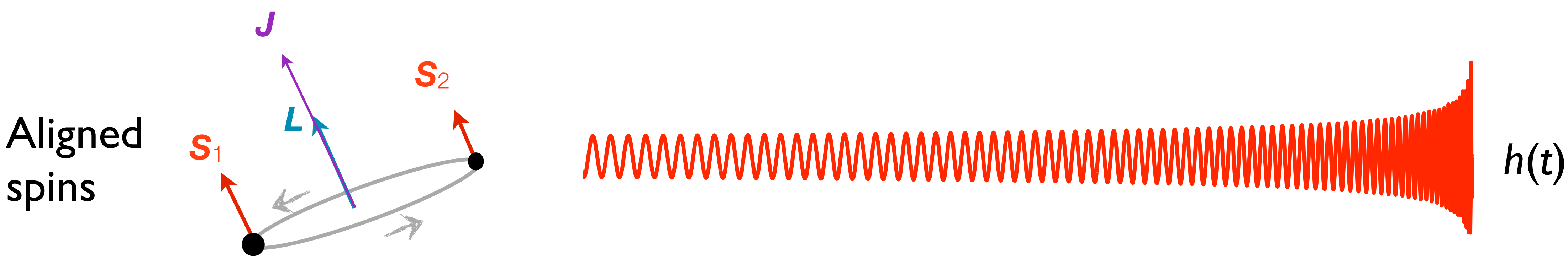
- Waveform depends on the (unknown) parameters of the system.
- Need to cross correlate the data with a bank of (~million) theoretical templates.
- Template banks are constructed in such a way that the signal manifold is (semi) optimally covered.

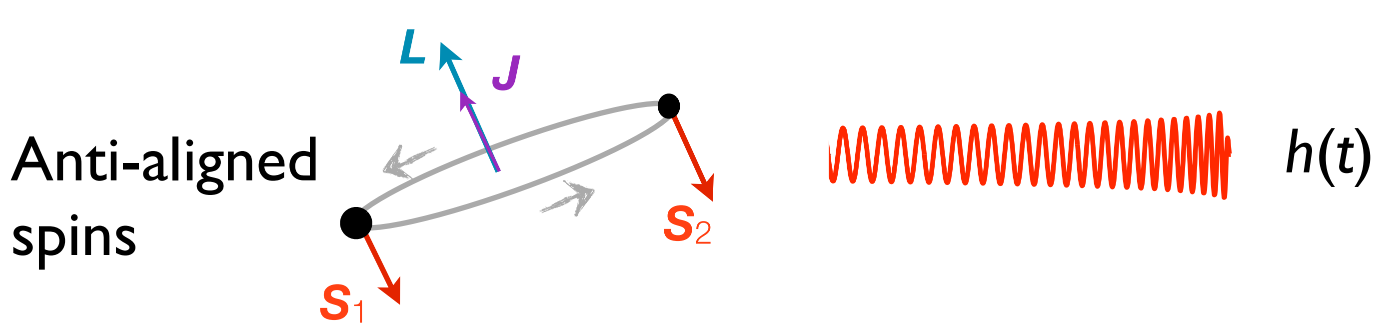


GW searches for CBCs: Template banks

- Current searches use inspiral, merger, ringdown templates including (non-precessing) spin effects of compact objects.

[Talks by Prayush Kumar, Swetha Bhagavat]





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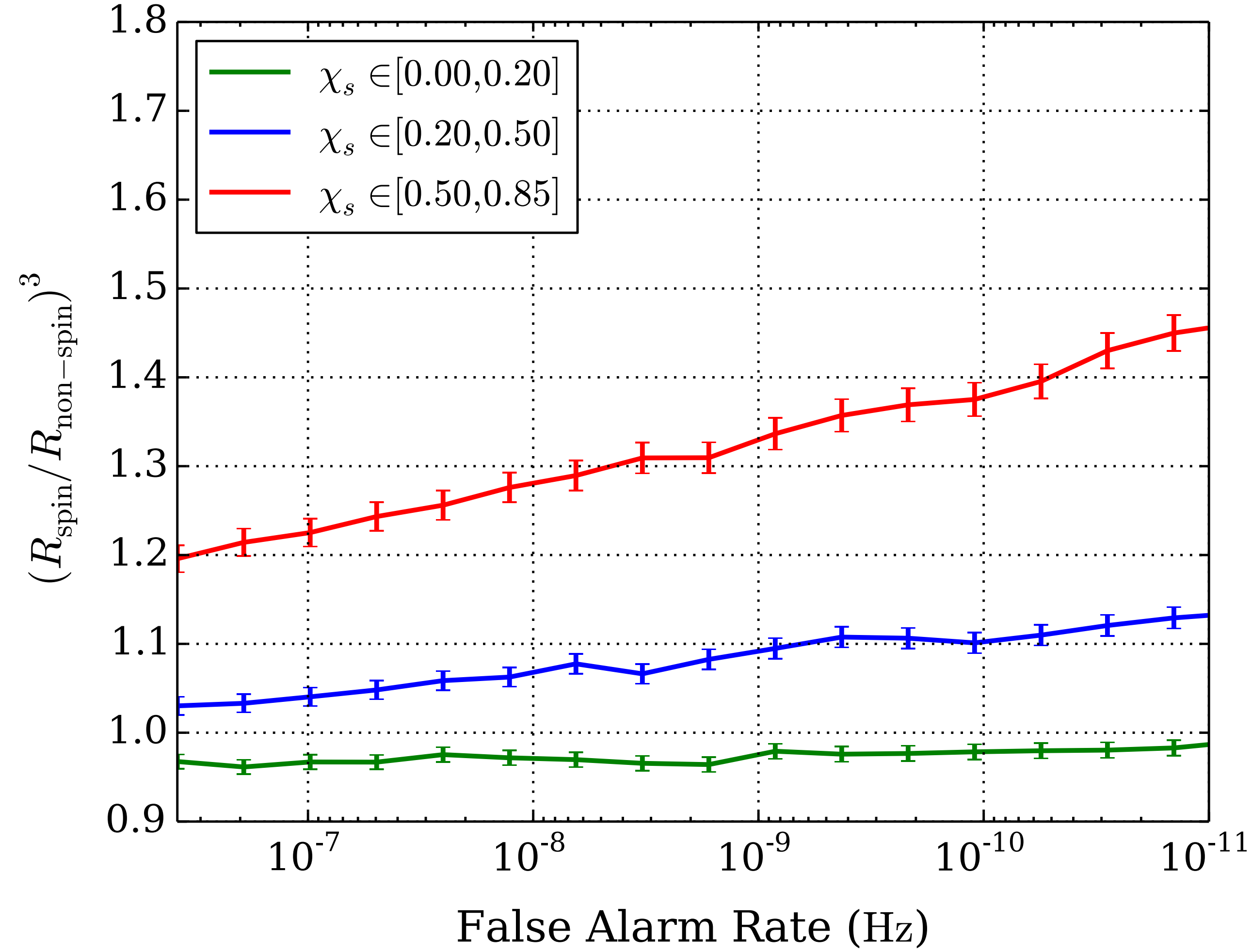
[Privitera et al (2014)]



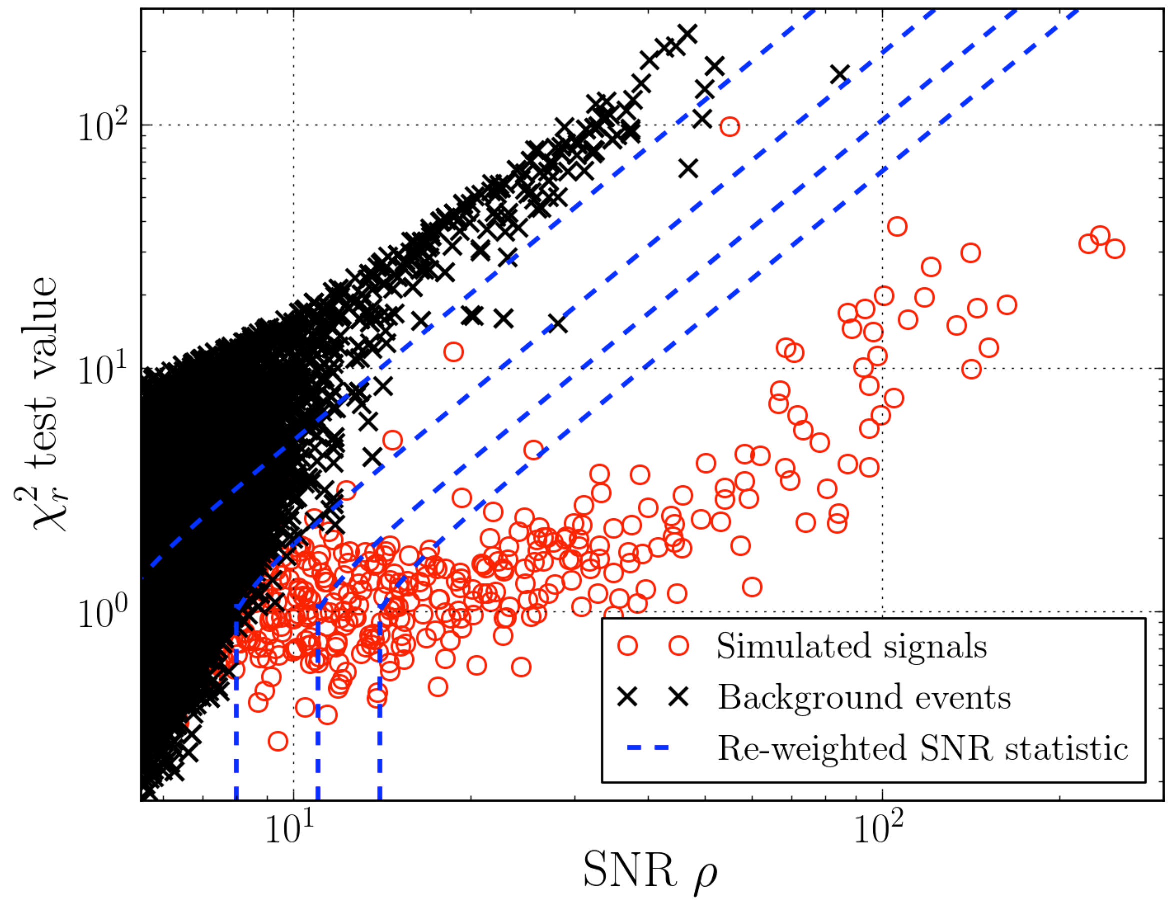
Expected increase in the observational volume of search using spinning templates Vs. a search using non-spinning templates in detecting spinning BH binaries (Iniital LIGO S5 data)

GW searches for CBCs: Data quality cuts

- In order to reduce the effect of noise transients, the frequency-distribution of power is compared against the expectation ("chi-square" test).
- Parameters of the triggers extracted from multiple detectors require to be consistent.
- Data quality cuts and vetoes using 10^5 auxiliary channels to minimize the effect of non-GW transients.

[Talk by Anuradha Gupta]

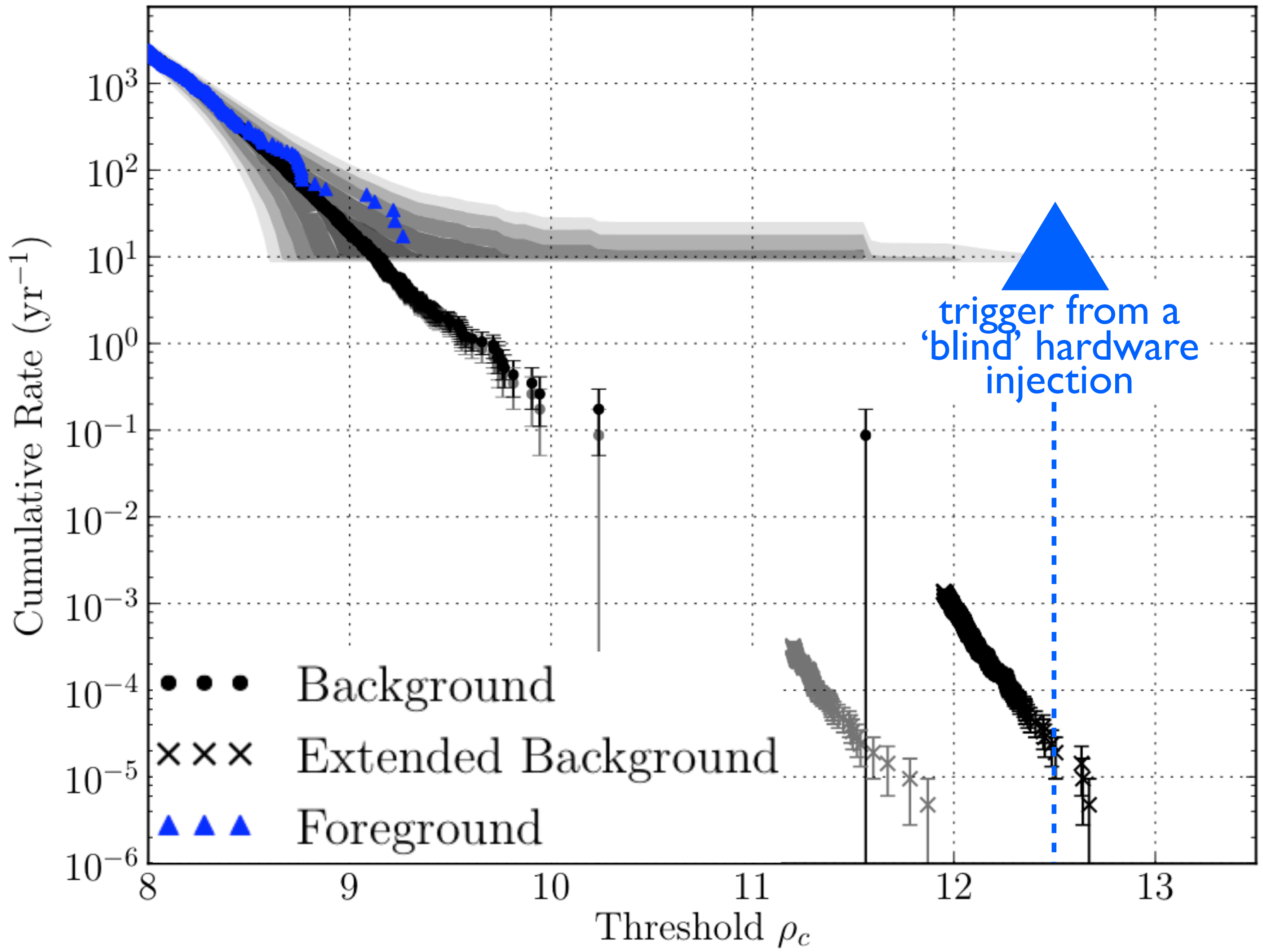
[Abadie et al (2012)]



GW searches for CBCs: Assessing the significance of the candidate events

- Background distribution is estimated by repeating the analysis on data with an artificial time-shift applied between two detectors.

[Abadie et al (2012)]

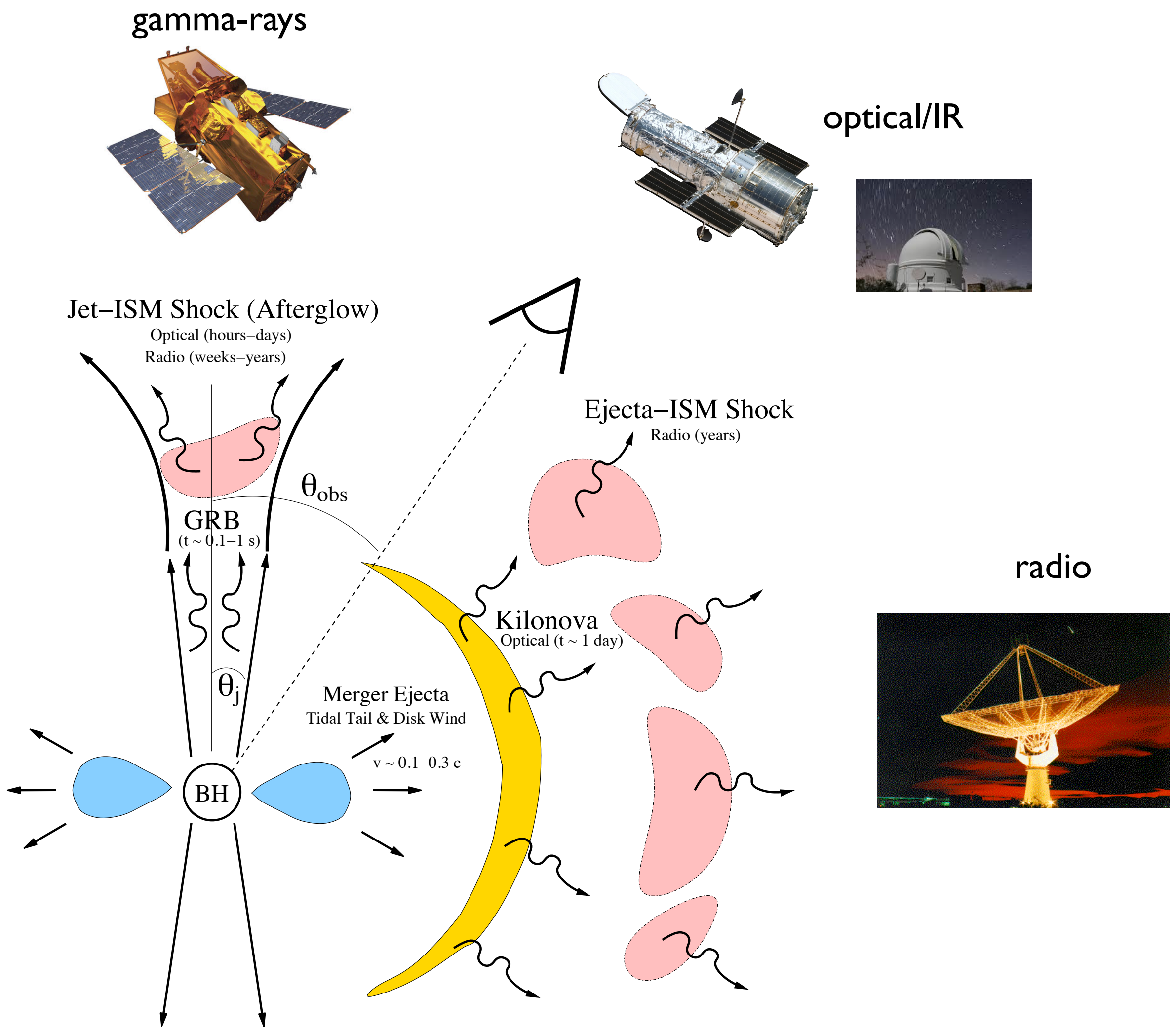


Distribution of the significance of the foreground and background triggers from the S6 analysis.

Low-latency data analysis for detection and "essential" parameter estimation

- Some GW events (e.g. merger of NS binaries) expected to produce EM counterparts. Need to alert EM telescopes with low-latency.

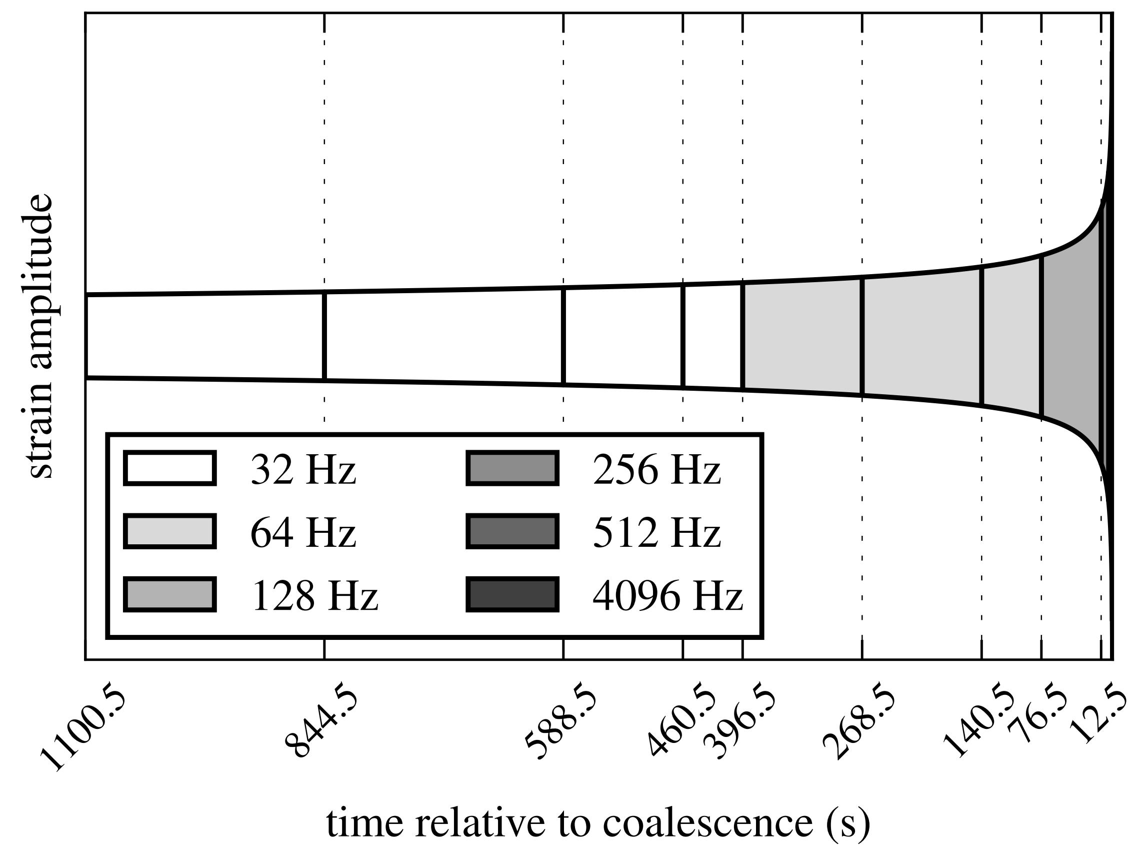
[Poonam Chandra's talk]



[Metzger & Berger (2011)]

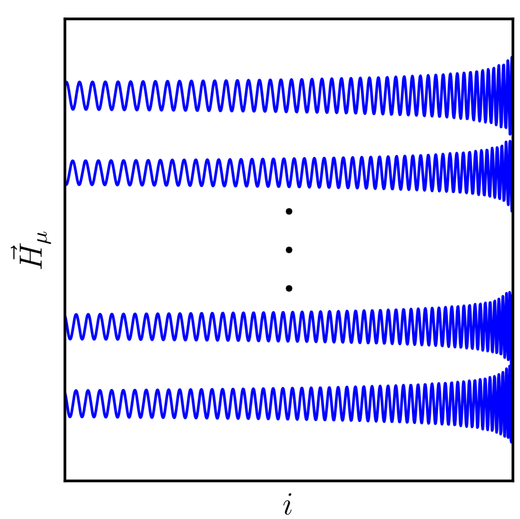
Low-latency data analysis for detection and "essential" parameter estimation

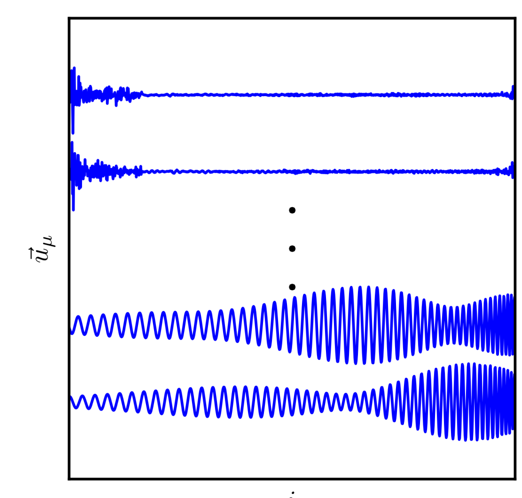
- Some GW events (e.g. merger of NS binaries) expected to produce EM counterparts. Need to alert EM telescopes with low-latency.
- Low-latency data analysis pipelines for detection and for "essential" parameter estimation.
  - Key techniques: multi-banding, orthogonalization of the template banks, etc.



[Canon et al (2011)]

original template bank



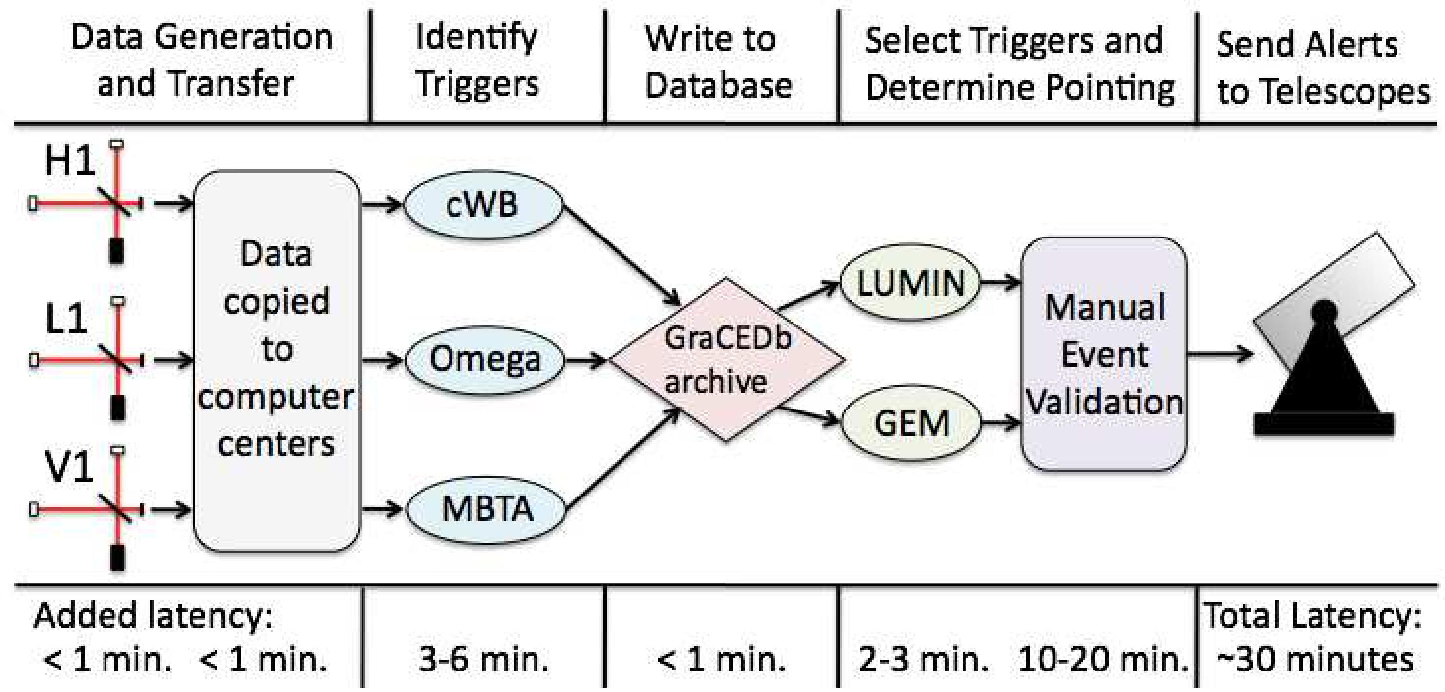


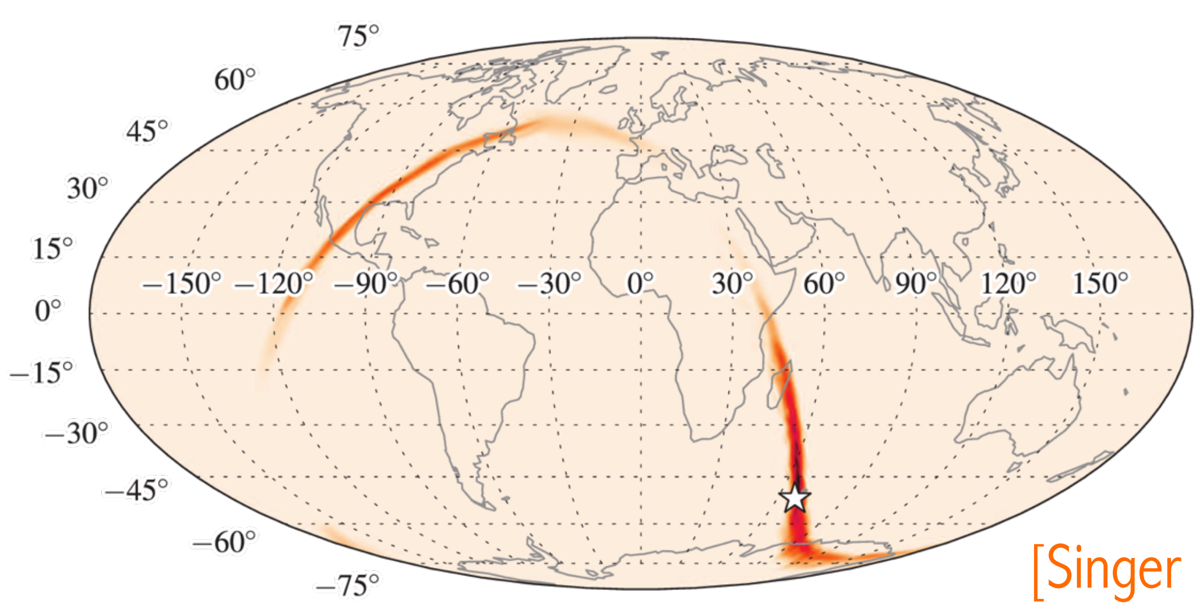
orthonormal basis

Low-latency data analysis for detection and "essential" parameter estimation

- During the S6 alerts from candidate GW triggers were sent with latency ~30 mins.

[LIGO+Virgo+others arXIv:1109.3498v2]





[Singer 2014]

[Talk by Poonam Chandra]

Estimating the source parameters from detected signals

- Posteriors on the source parameters computed from data (containing detected signals) using Bayesian inference.

posterior distribution of λ, given data d

prior distribution of parameter λ

likelihood of d, given λ

$$p(\boldsymbol{\lambda}|d) \propto p^0(\boldsymbol{\lambda})\, \mathcal{L}(d|\boldsymbol{\lambda})$$

Thomas Bayes (1702-1761)

Estimating the source parameters from detected signals

- Parameter space is large-D. Need to use stochastic techniques (MCMC, nested sampling) to sample the parameter space.

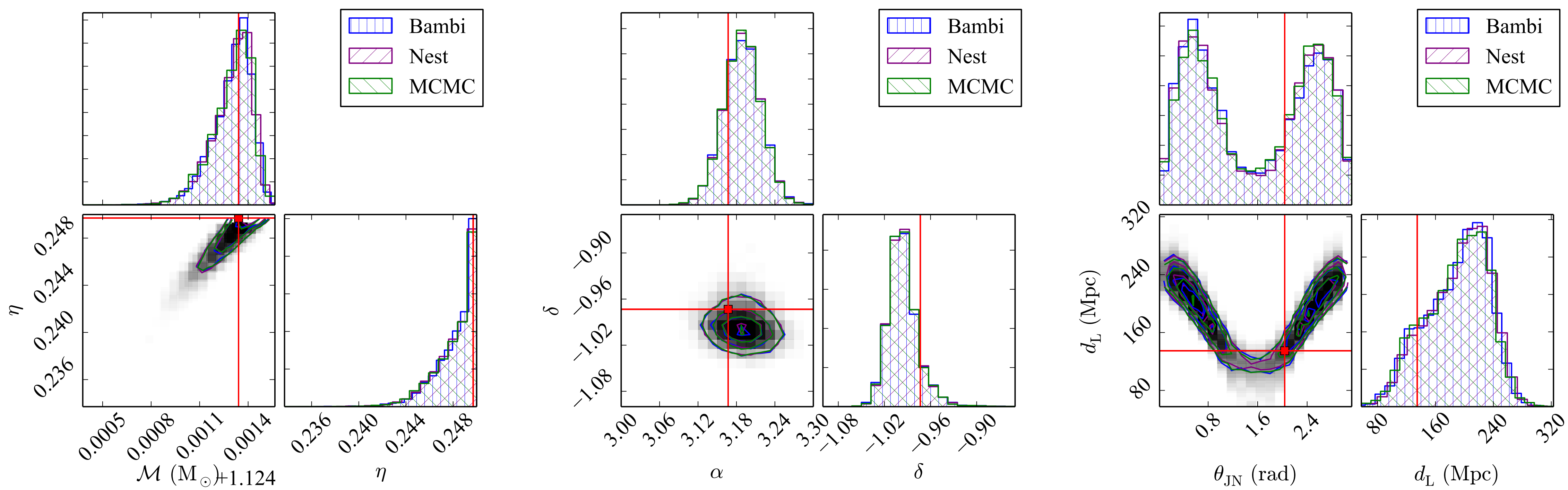
$m_1, m_2, \mathbf{S}_1, \mathbf{S}_2$ intrinsic parameters

α, δ, d_L location

ι, ψ orientation

t_0, φ_0 arrival time & phase

[Veitch et al 2014]



[Talk by Anuradha Samajdar]

Grid computing for gravitational-wave astronomy

["LSC Computing Plan", LIGO Document # LIGO-T050053]

- Data analysis performed at distributed computing sites part of the LIGO data grid (particle physics model).
- Current data analysis demands ~30K CPU cores. Will grow 10x by 2018.

LIGO Hanford — LIGO Caltech — LIGO Livingston

Tier 1 centers

- Storage & archival of 10,000s of channels (~800 TB/year).
- Storage of data products (~1.3 PB/year).
- Modest computing facility

Max Planck Institute | Wisconsin Milwaukee | Syracuse | XSEDE | EINSTEIN@HOME

Tier 2 centers

Major computing resource for the LSC. Preference to internal users.

AEI Potsdam | KISTI | Cardiff | Birmingham

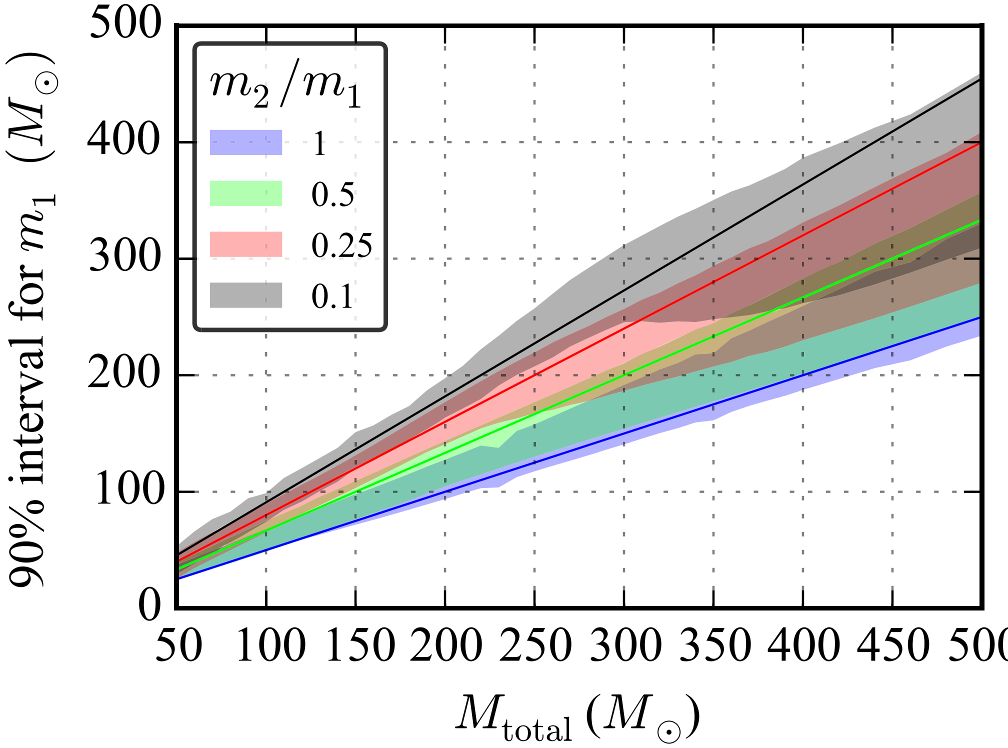
UTB | Penn State | ICTS-TIFR | IUCAA

Tier 3 centers

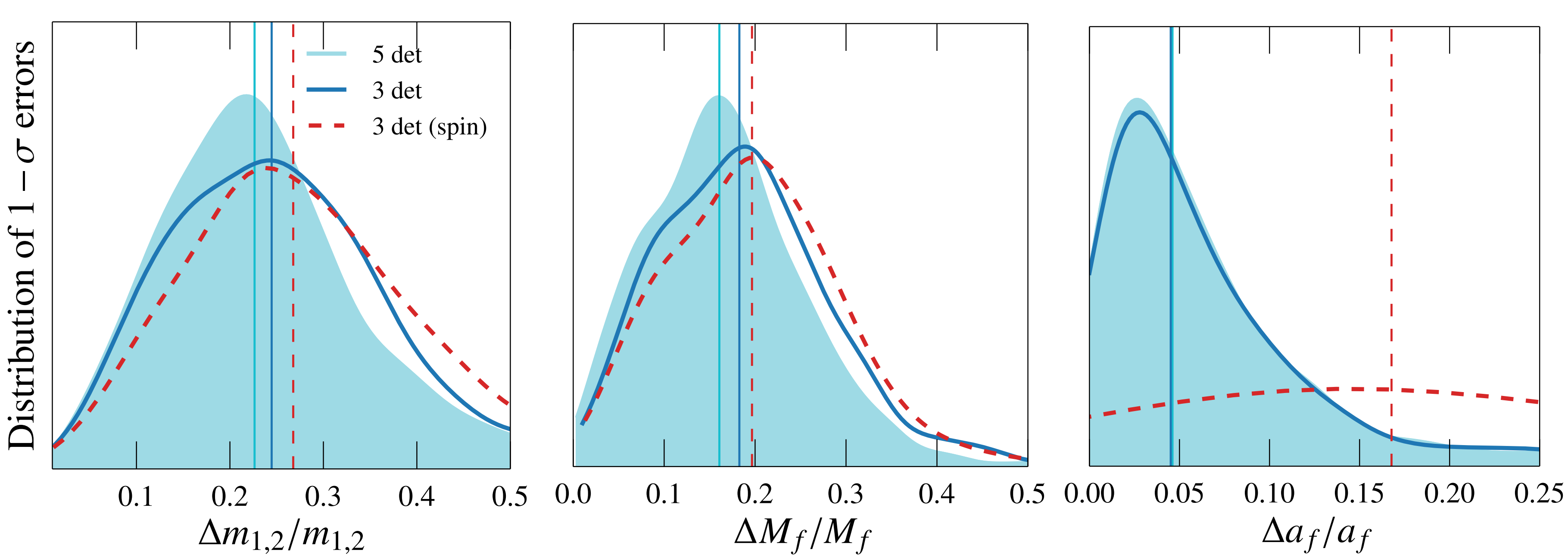
Computing resources for and by member institutions.

Extracting science: Black hole astrophysics

- Component masses of BHs measured with ~25% median accuracy. Mass & spin of the final BH measured with better accuracy.
    - Can point to the existence of IMBHs.
      [Veitch et al 2015, Graff et al 2015]



[Veitch et al 2015]

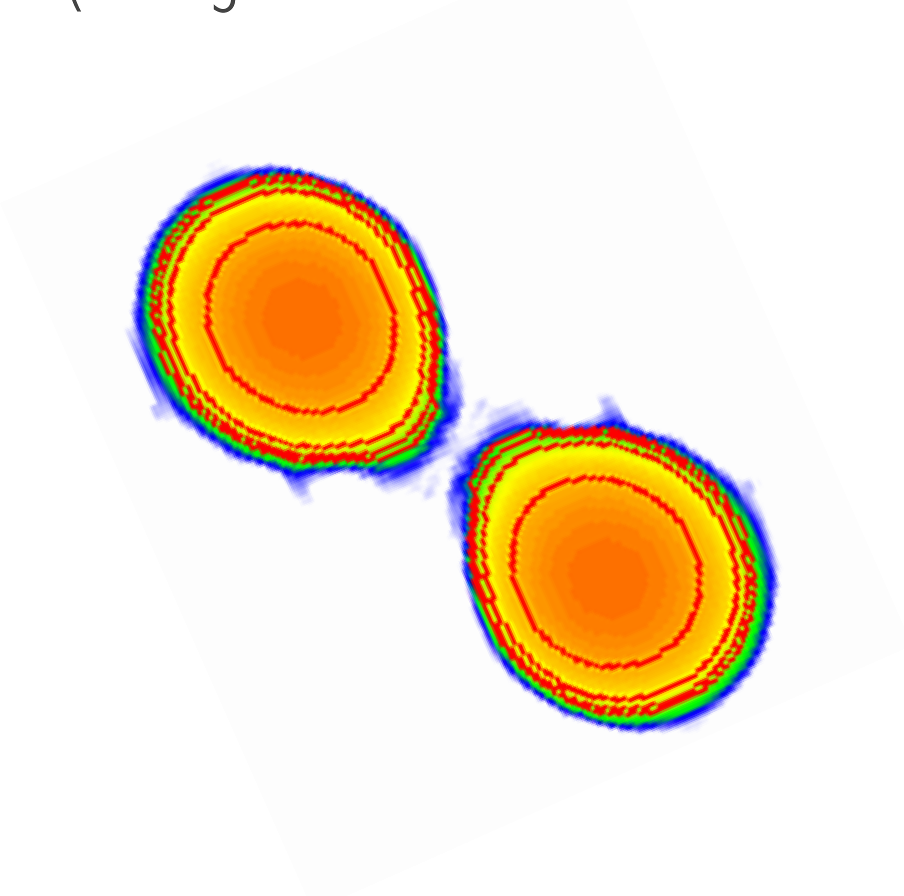


Distribution of the 1-σ error in measuring the parameters of BBHs by Adv LIGO. Sources are distributed uniformly in co-moving volume.

[Ghosh et al 2015]

Extracting science: Measuring equations of state

- BNS/NSBH inspiral signals contain imprint of the NS EoS (through tidal deformation of the NS).



$$\lambda(m) = (2/3)\, k_2\, R^5(m)$$

tidal deformability

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

induced quadrupole moment of the star

external tidal field

[Talk by B. Sathyaprakash]

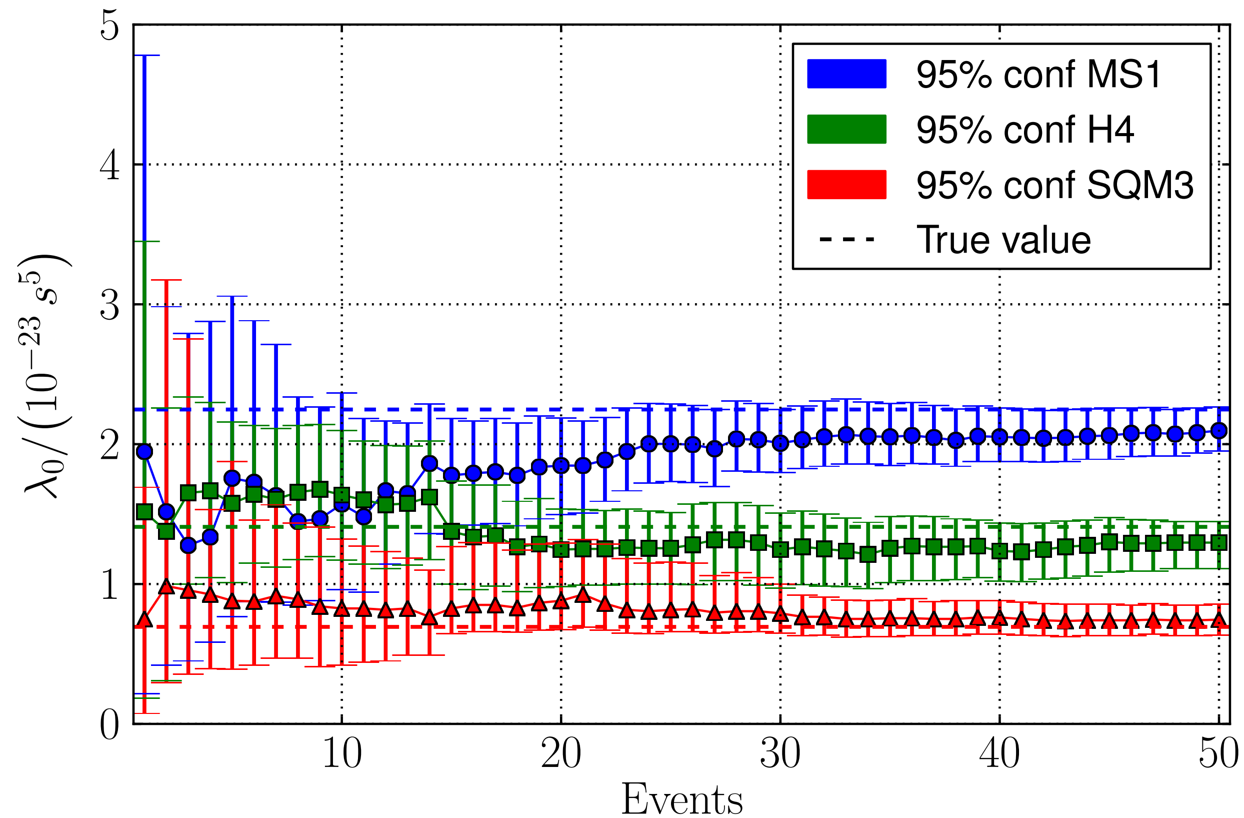
Extracting science: Measuring equations of state

- BNS/NSBH inspiral signals contain imprint of the NS EoS (through tidal deformation of the NS).

Merger/ring-down part expected to have clearer signature. NR simulations are getting mature to explore this.

[Talk by A. Mukherjee, Poster by Kabir]

[Del Pozzo et al (2013)]

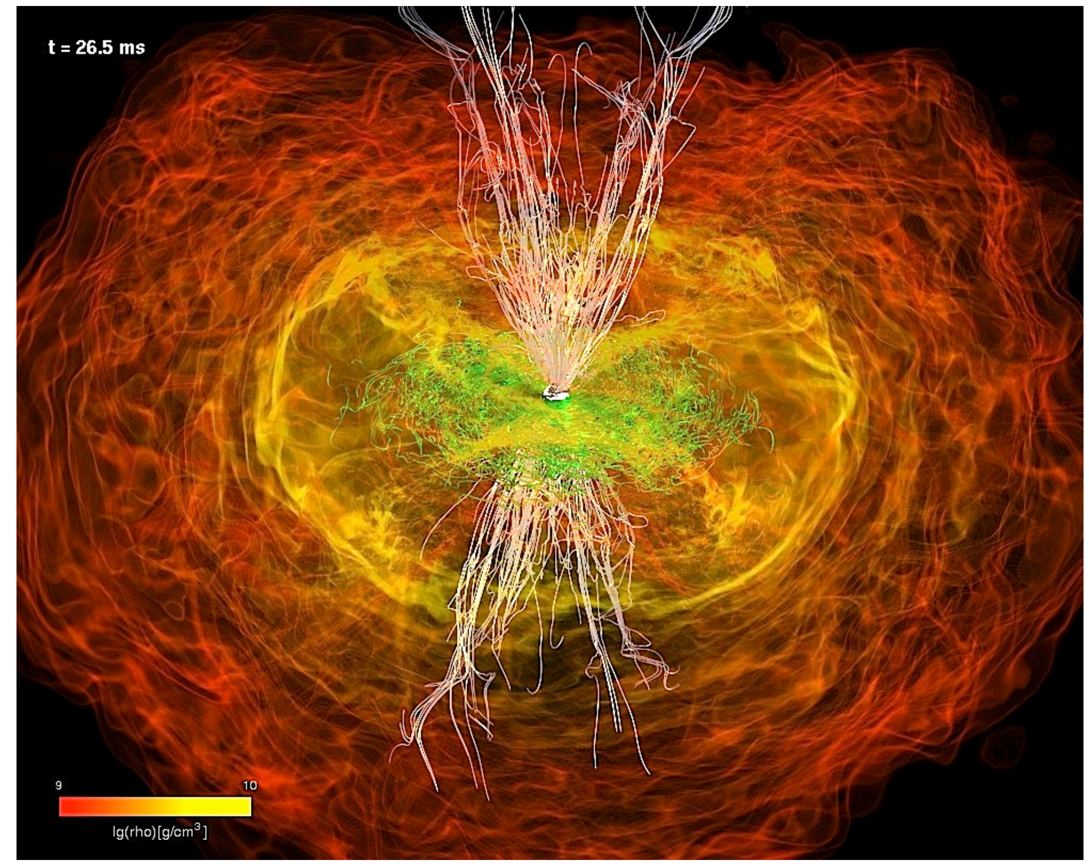


Median and 95% confidence interval for the estimation of the tidal deformability parameter as a function of the number of simulated BNS observations (with a narrow mass function).

Extracting science: Measurement of cosmological parameters

- **CBCs are standard sirens** Self calibrating sources → cosmic expansion rate. [Schutz (1986)]

[Rezzolla et al (2011)]



GWs

absolute determination of the luminosity distance

EM counterpart

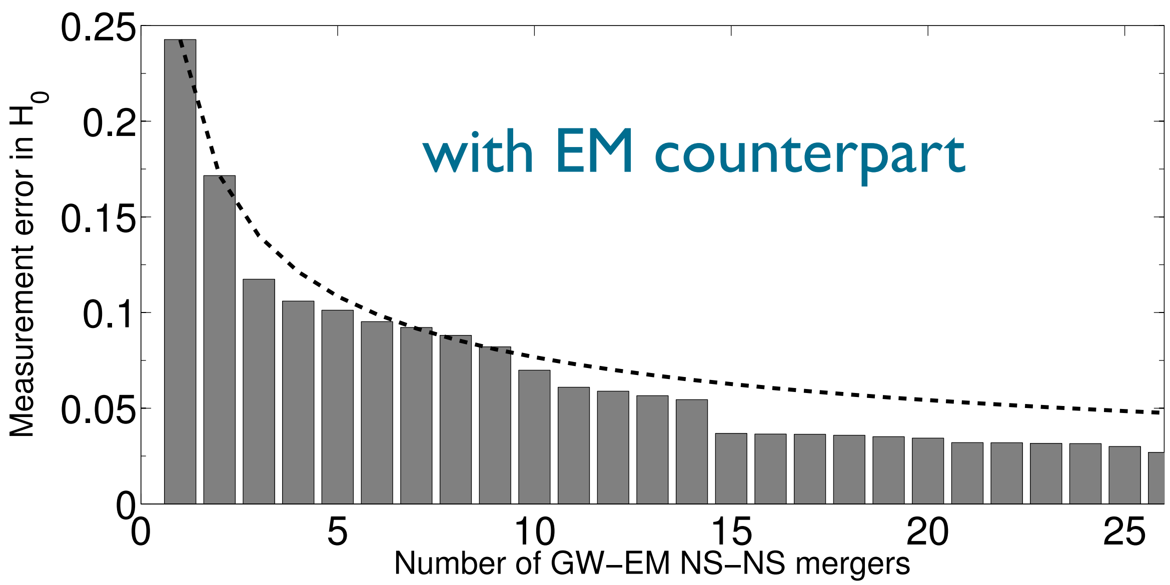
e.g. GRB afterglow → red-shift information

Numerical simulation of the merger of NS-BH binary. Magnetic fields can support GRB jets.

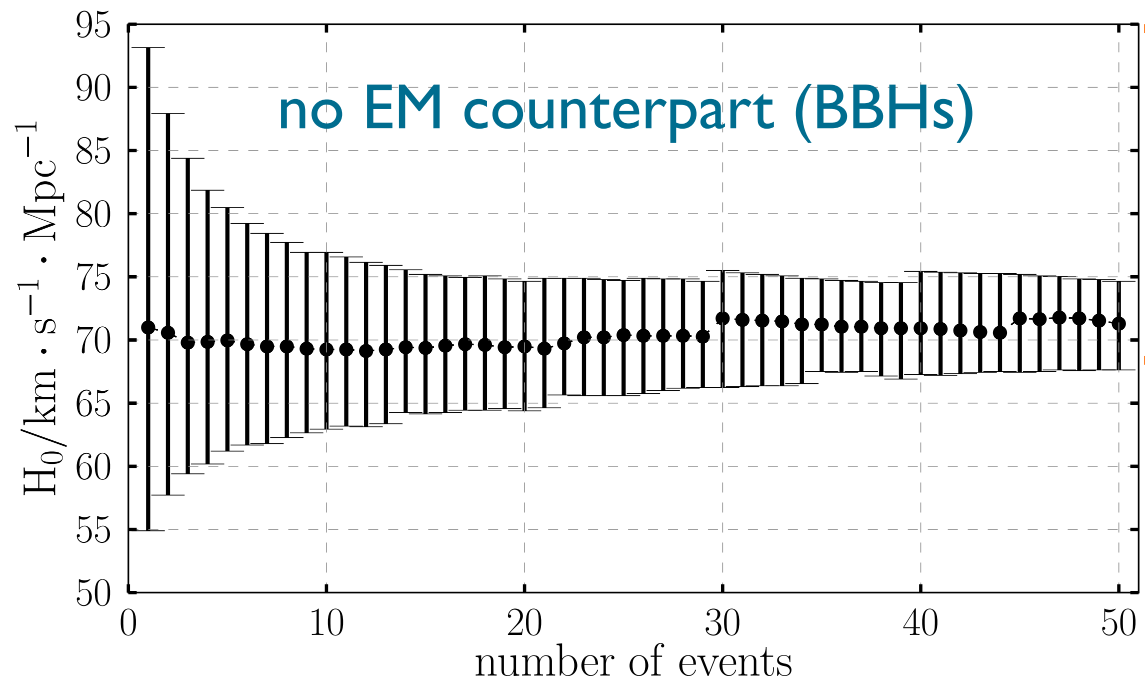
Extracting science: Measurement of cosmological parameters

- **CBCs are standard sirens** Self calibrating sources → cosmic expansion rate. [Schutz (1986)]
  - 2G network: modest measurement of H_0.

[Talk by Archisman Ghosh]



[Nissanke et al 2013]



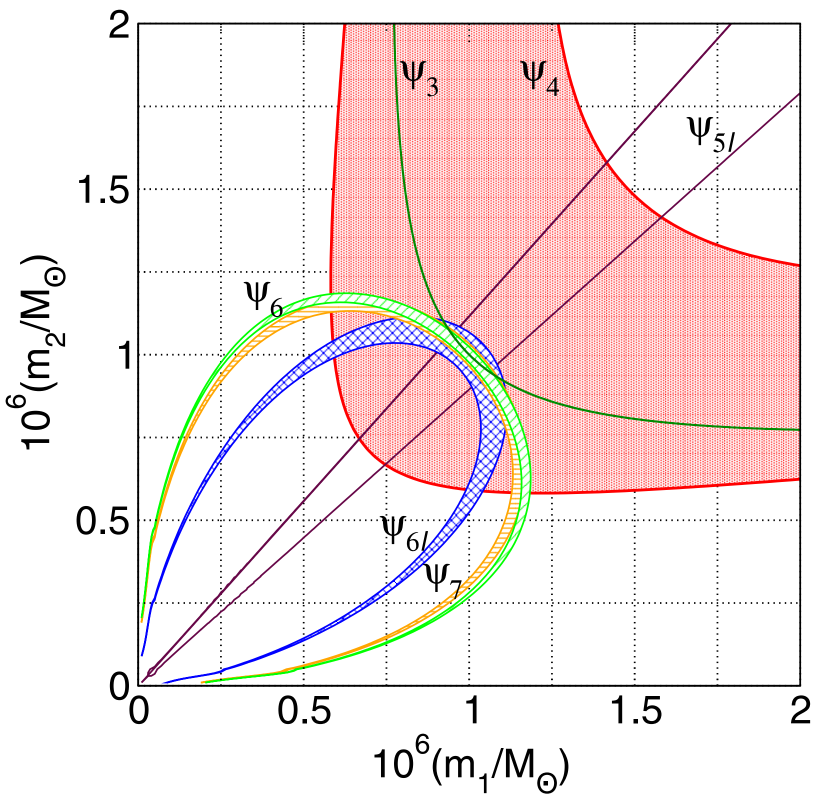
[Del Pozzo 2011]

H_0 measurement vs number of observations by LIGO-Virgo network.

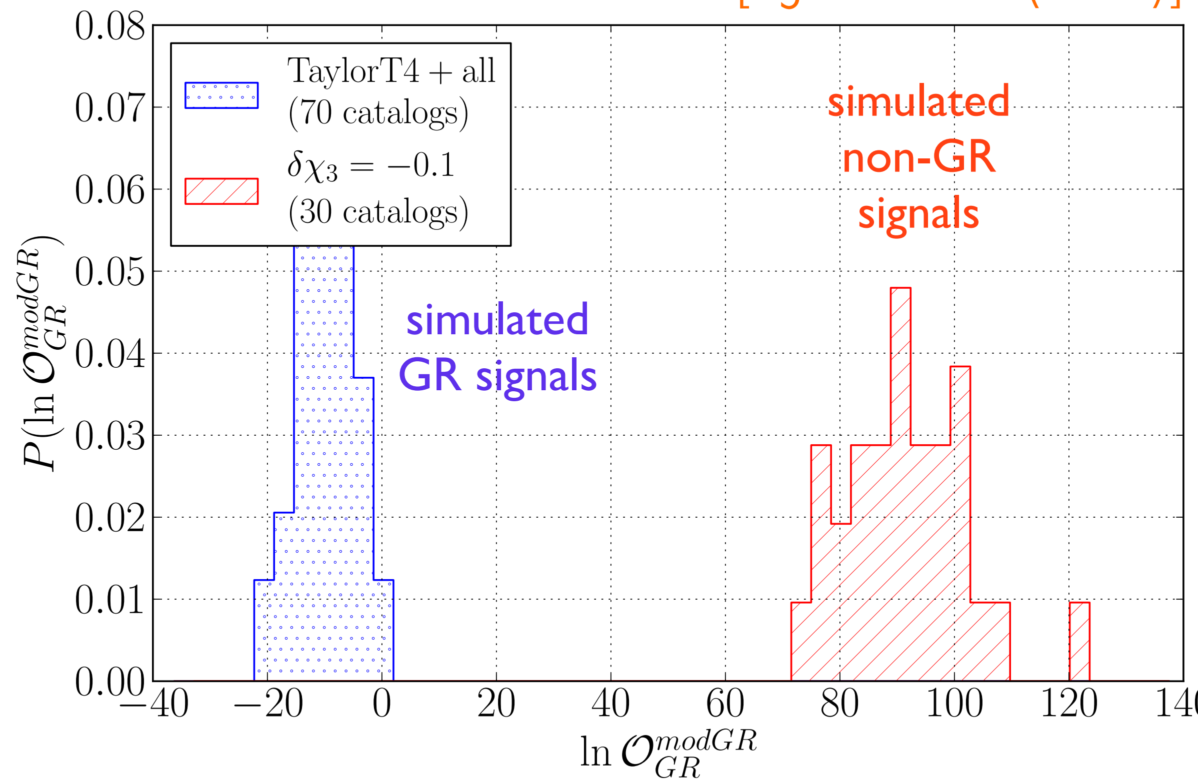
Extracting science: Tests of general relativity

- **Testing parameterized deviations from GR**
  Measure the PN coefficients independently from the waveform. Are they consistent with the GR prediction?

[Arun et al (2006)]



[Agathos et al (2014)]

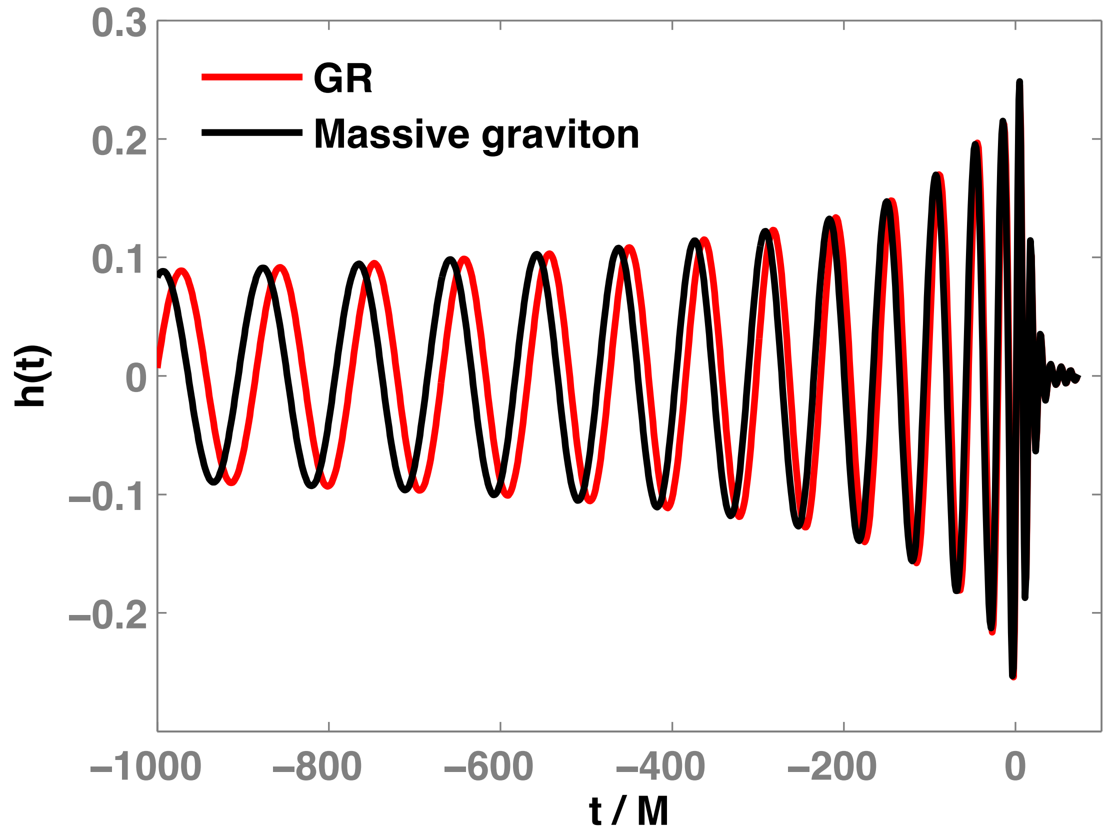


Distribution of the odds ratios between a model where at least one PN coefficient is different from the GR prediction against the GR model.

[Talk by B. Sathyaprakash]

Extracting science: Tests of general relativity

- **Mass of the "graviton" from the propagation of GWs** A massive graviton will produce an non-trivial dispersion relation for GWs. Different frequency components travel with different speeds ⇛ characteristic deformation in the observed waveform [Will 1998]



hf$_{GW}$

$$v_g^2/c^2 = 1 - m_g^2\, c^4/E_g^2$$

Extracting science: Tests of general relativity

[Del Pozzo et al (2011)]

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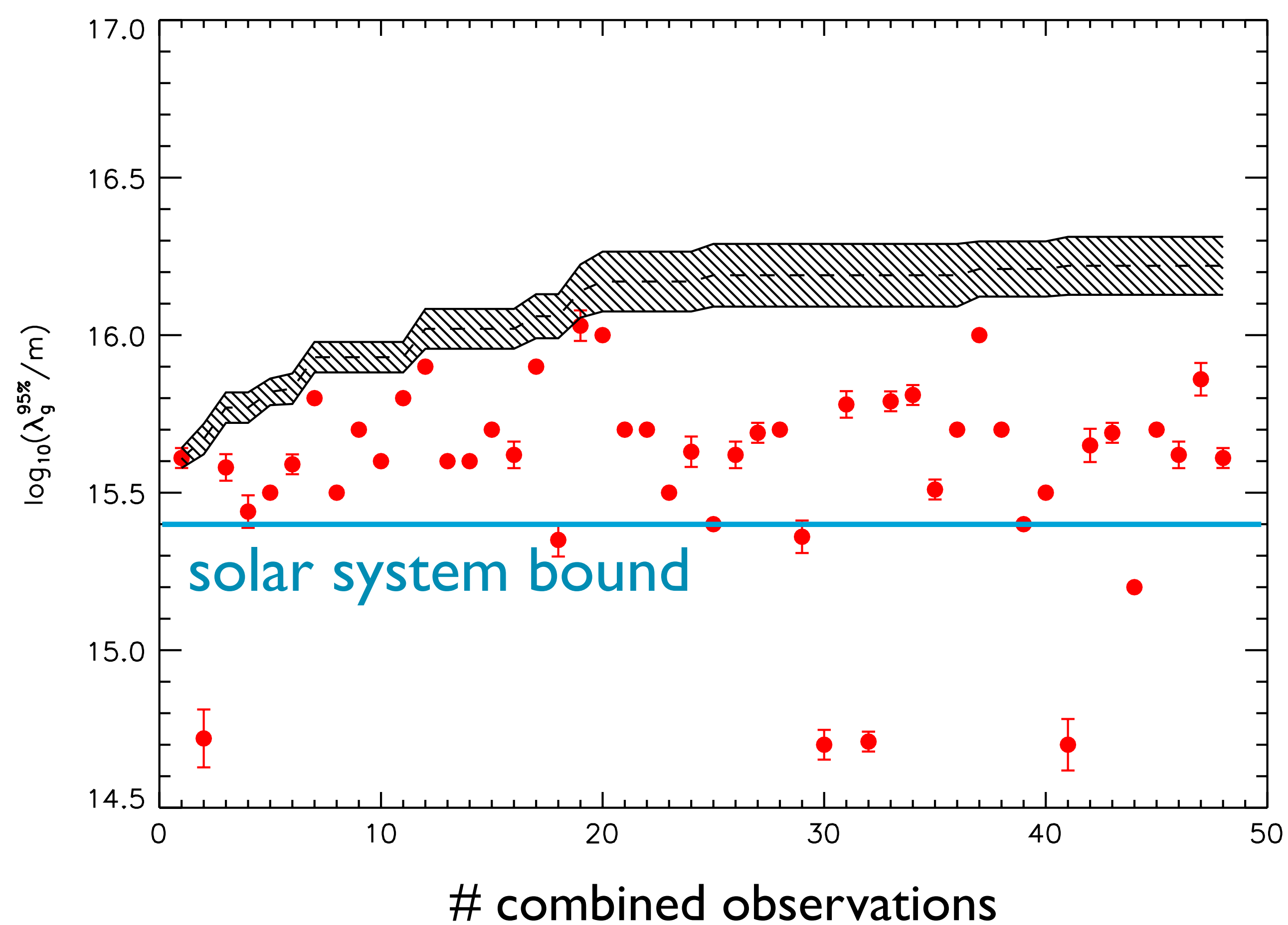
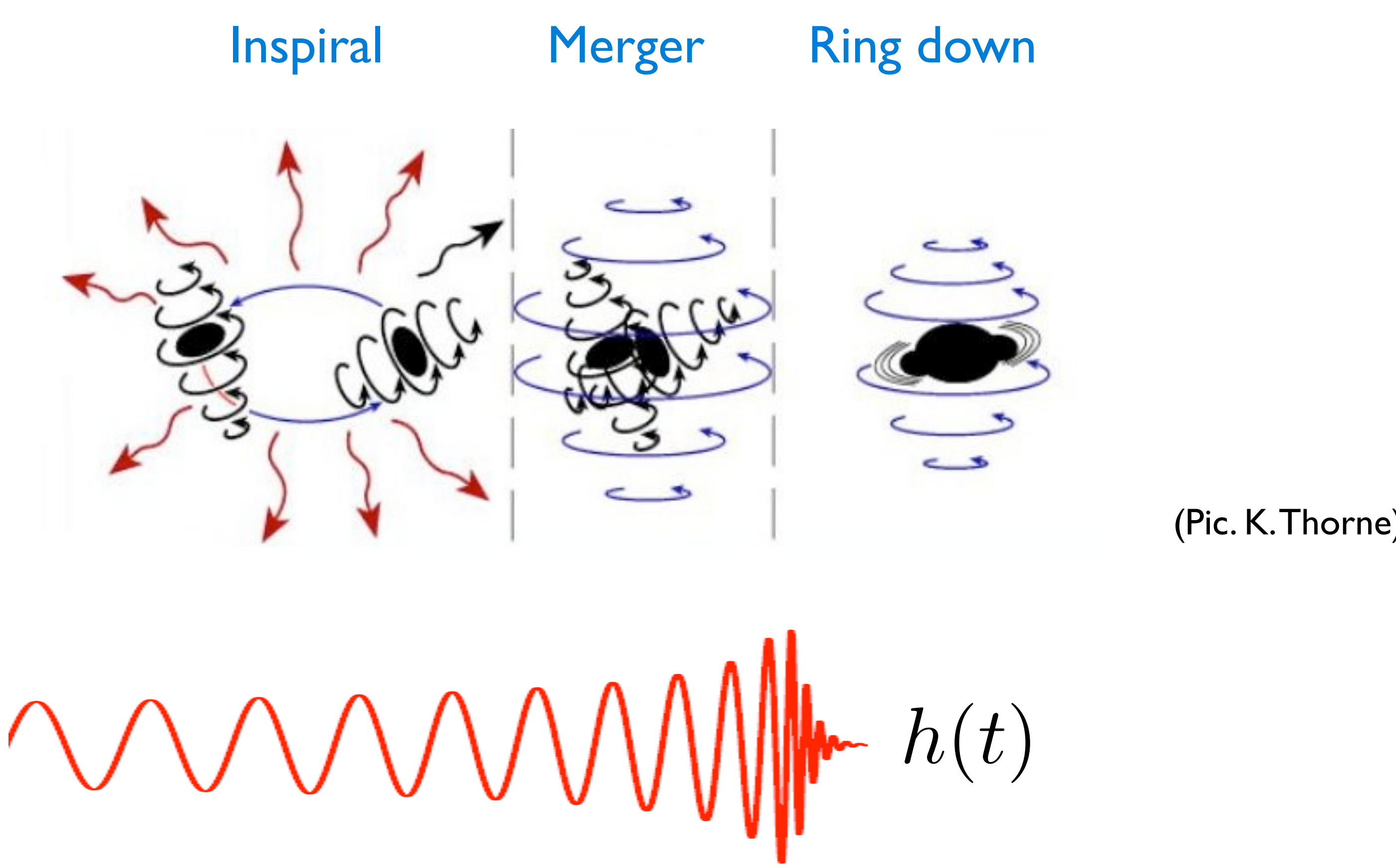


Expected bounds on the Compton wavelength of the graviton from Advanced LIGO observations of binary black holes.

Extracting science: Tests of general relativity

- **Consistency between the inspiral, merger and ringdown in BBH signals**

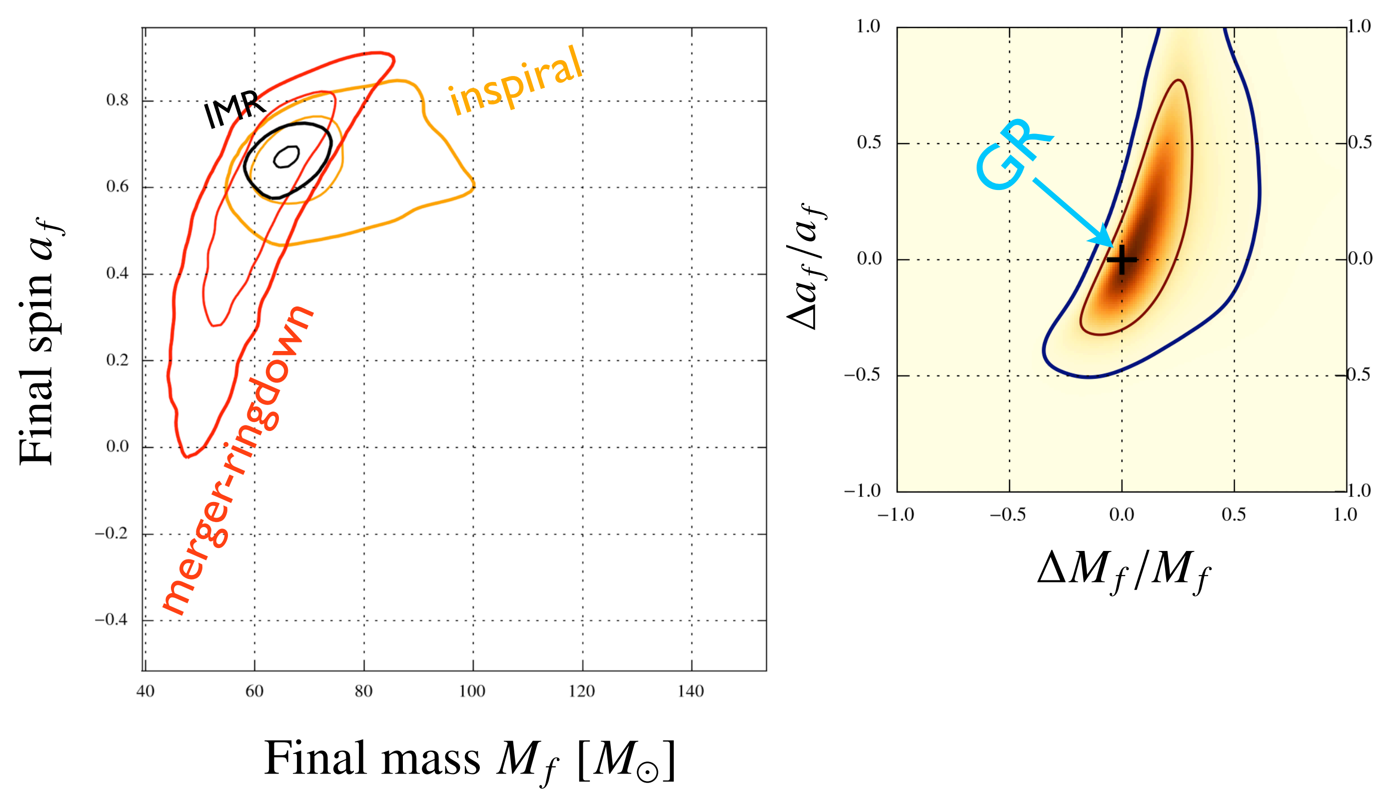


Source parameters can be extracted independently from the inspiral and the merger-ringdown parts of the signal. If the signal is consistent with GR, the two estimations have to be mutually consistent.

Extracting science: Tests of general relativity

[Talk by Abhirup Ghosh]

- **Consistency between the inspiral, merger and ringdown**



Expected results from a GR signal.

Extracting science: Tests of general relativity

[Talk by Abhirup Ghosh]

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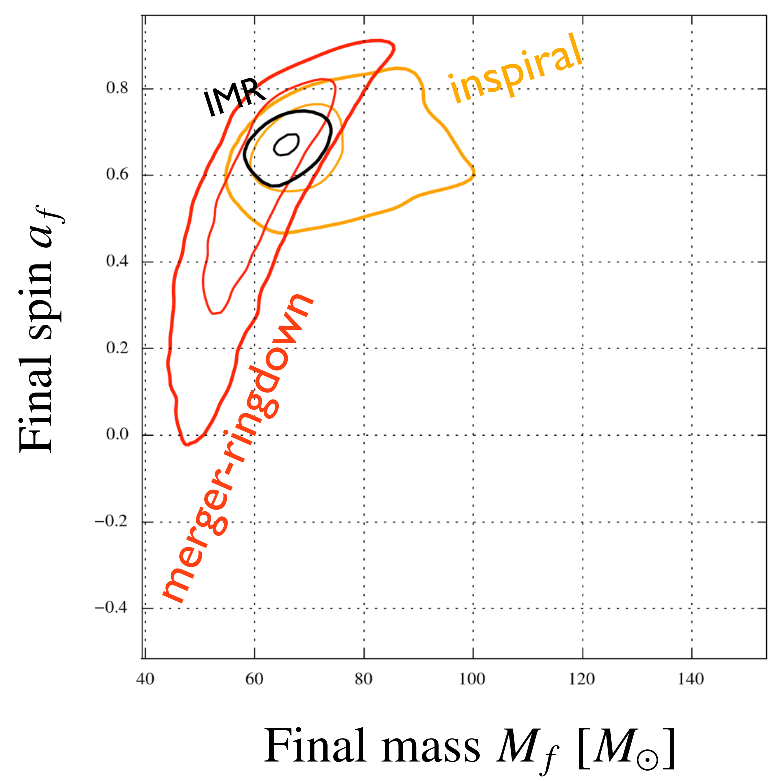
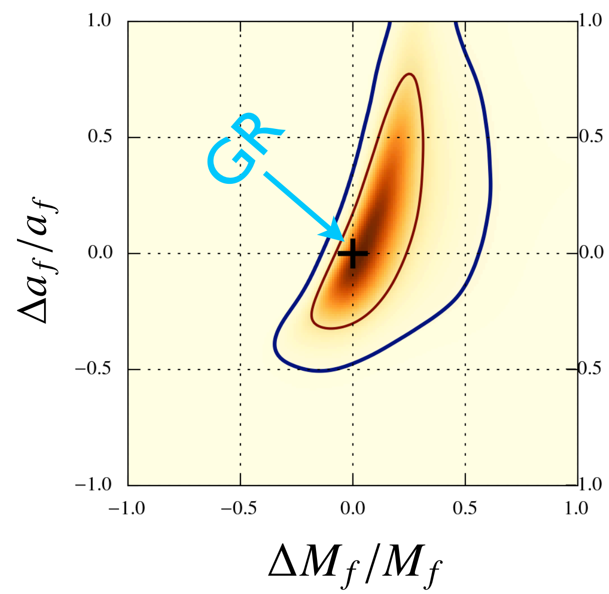
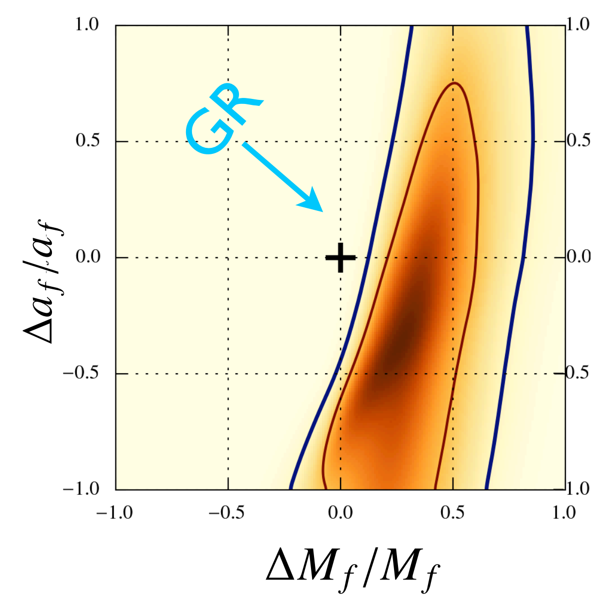
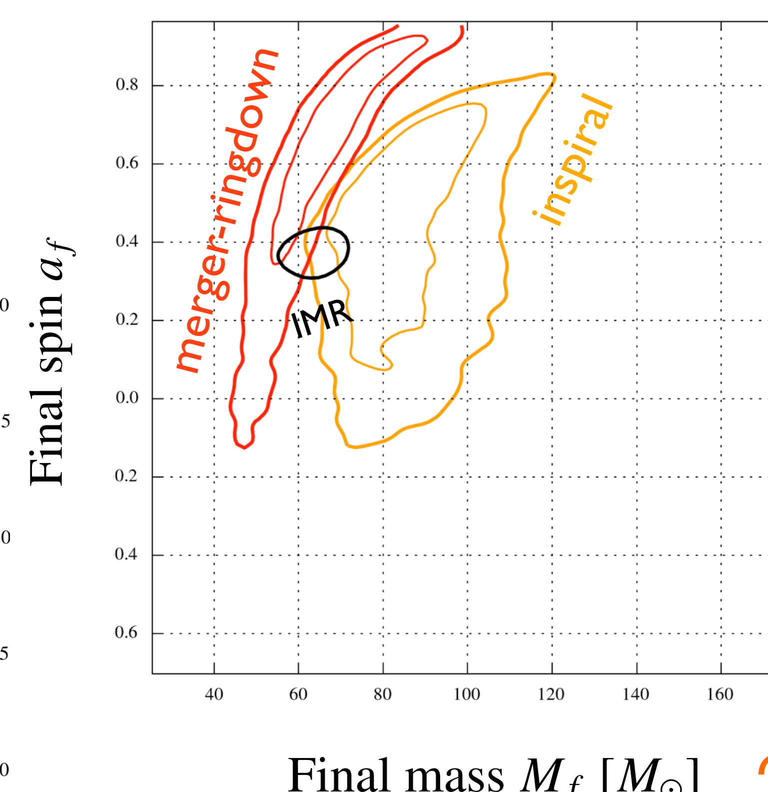




Expected results from a modified GR signal where the energy and ang momentum loss differs from the GR prediction

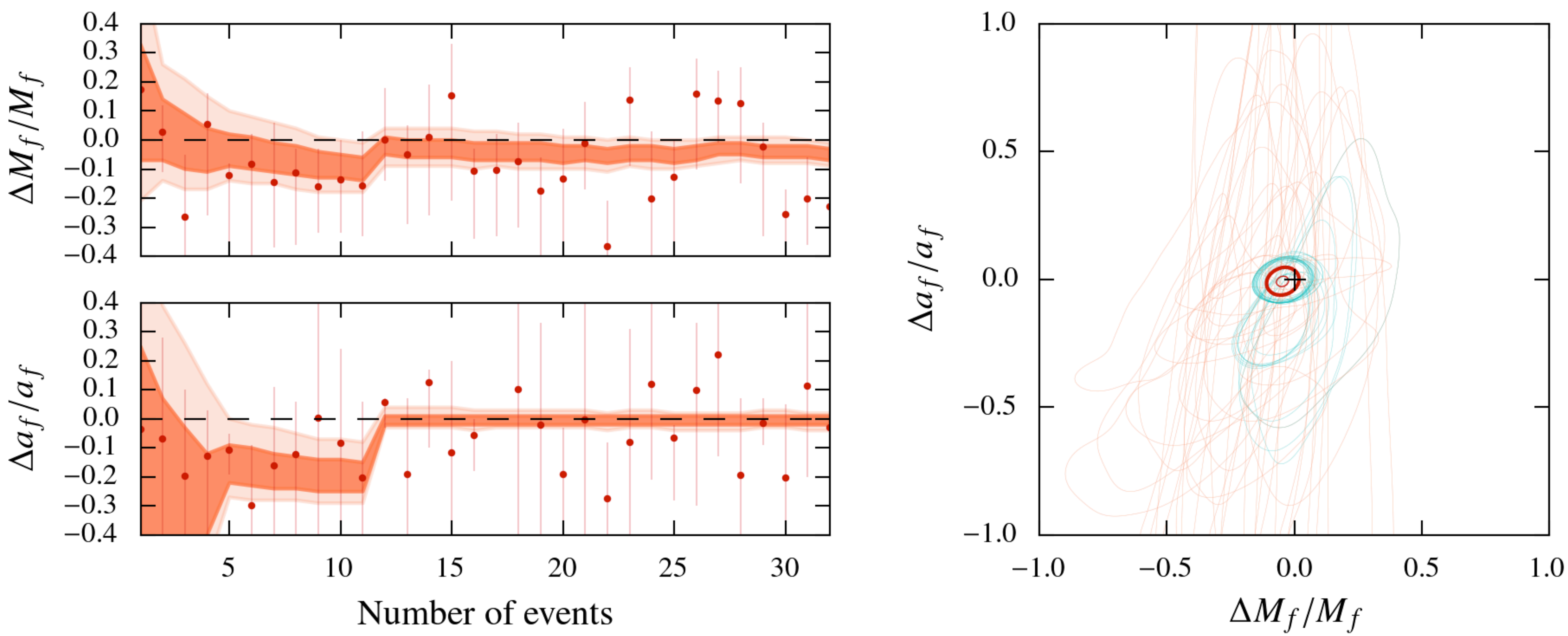




Extracting science: Tests of general relativity

- **Consistency between the inspiral, merger and ringdown**

[Talk by Abhirup Ghosh]



Multiple observations could be combined to produce tighter constraints on deviations.

Summary

- GW astronomy has come of age. Instruments, source modeling as well as data analysis techniques for detection, parameter estimation and extraction of the science.
  - Data analysis pipelines are mature to make detections without significant loss of sensitivity, and to estimate the source parameters without significant systematic errors, over most regions in the parameter space.
  - Work is ongoing to prepare for "precision astronomy".
- All we need is a signal. Stay tuned!