Path Towards kHz Gravitational-Wave Astronomy

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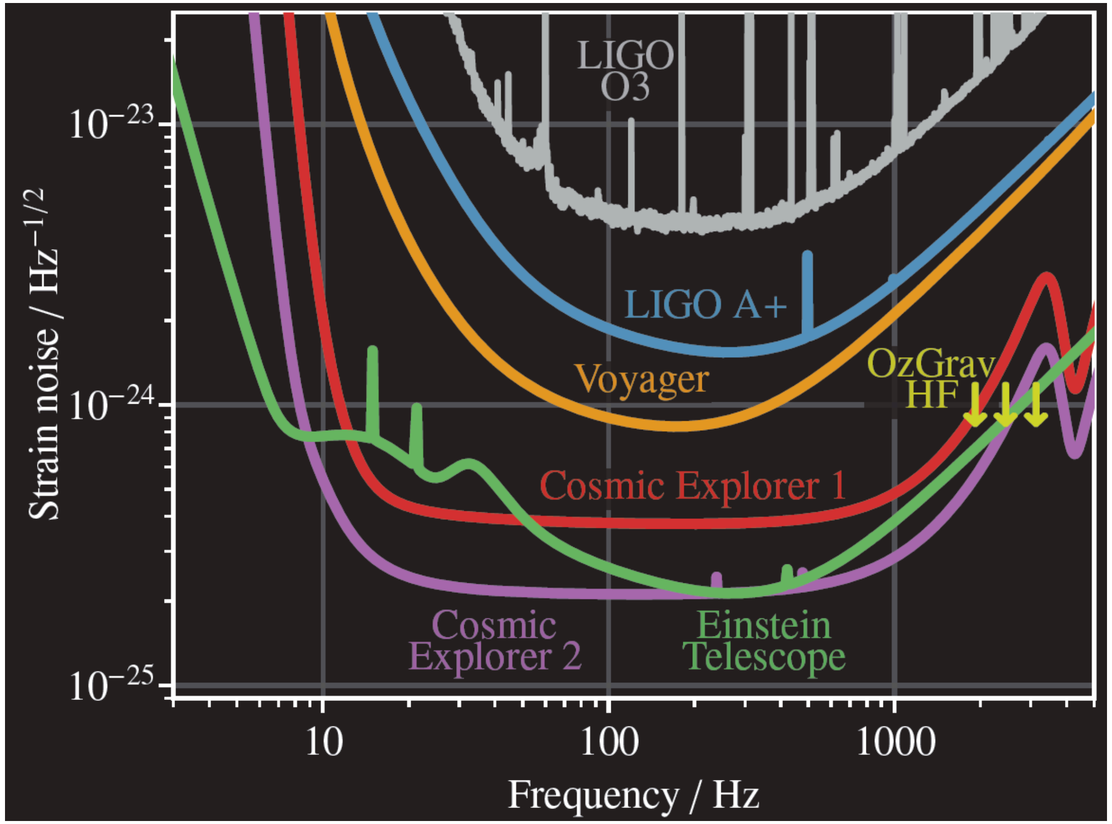
Based upon:

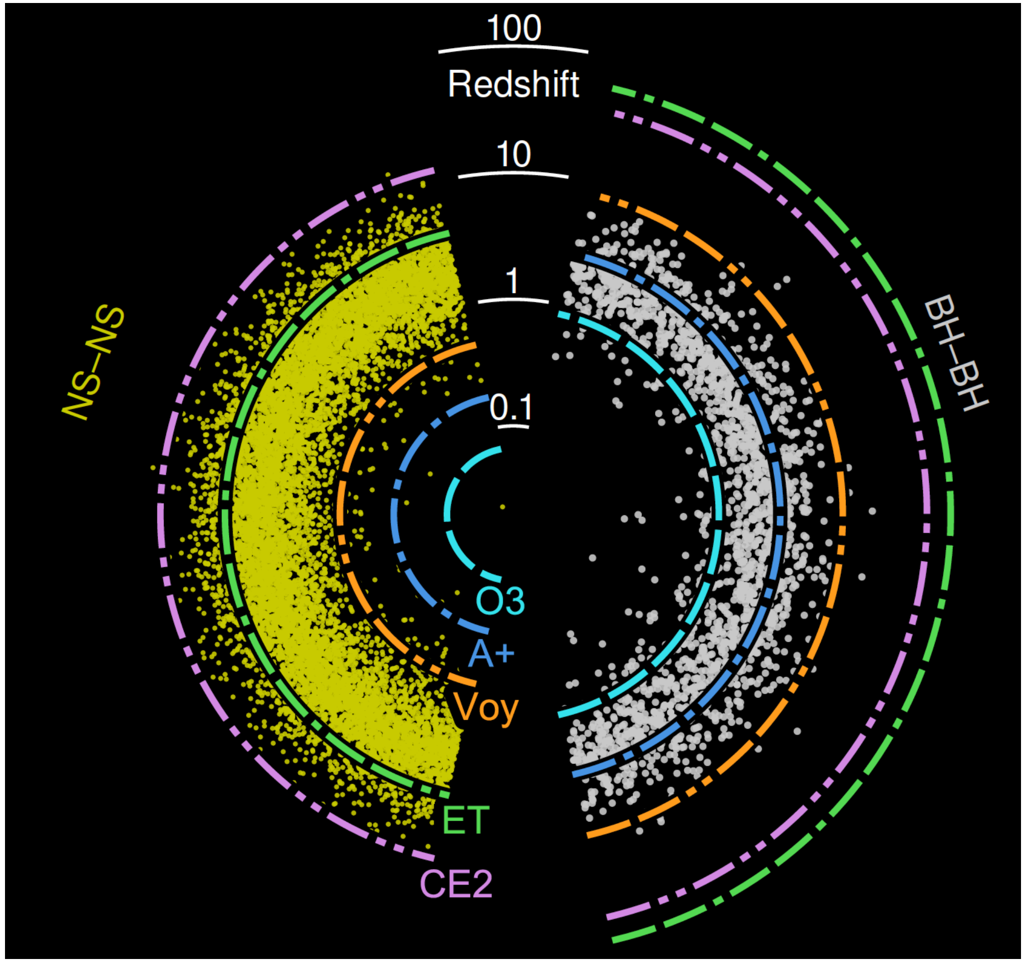
Haixing Miao, Huan Yang, Denis Martynov, PRD 98, 044044, (2018)

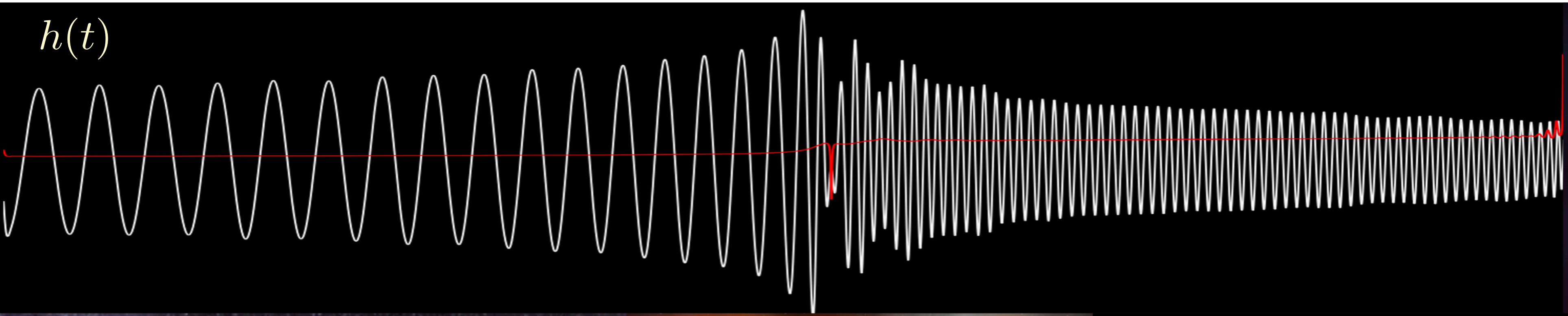
Denis Martynov, Haixing Miao, Huan Yang, et al, arXiv:1901.03885 (2019)

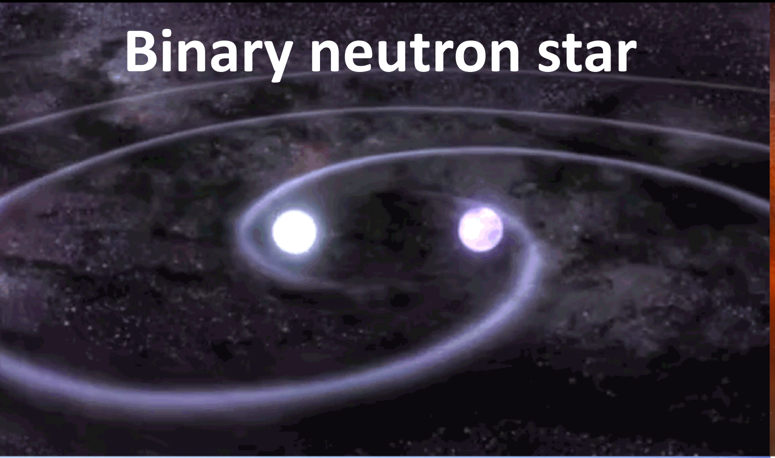
Proposed 3rd generation Gravitational-Wave Detectors

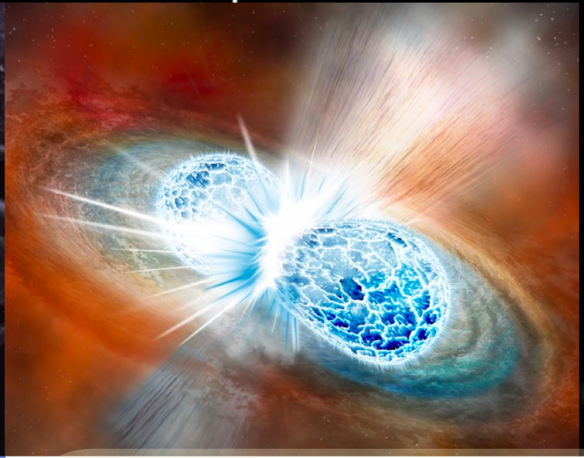


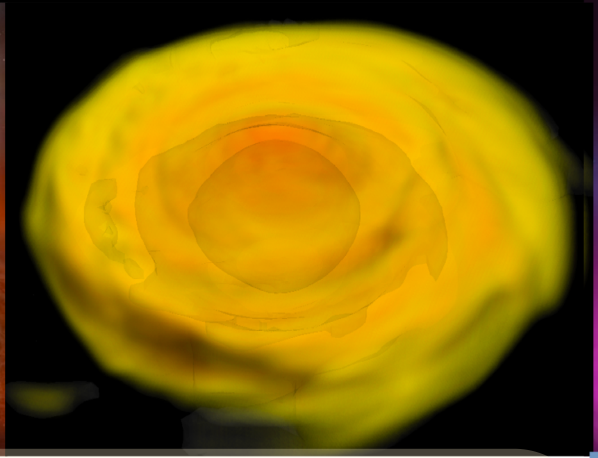
Courtesy of Evan Hall





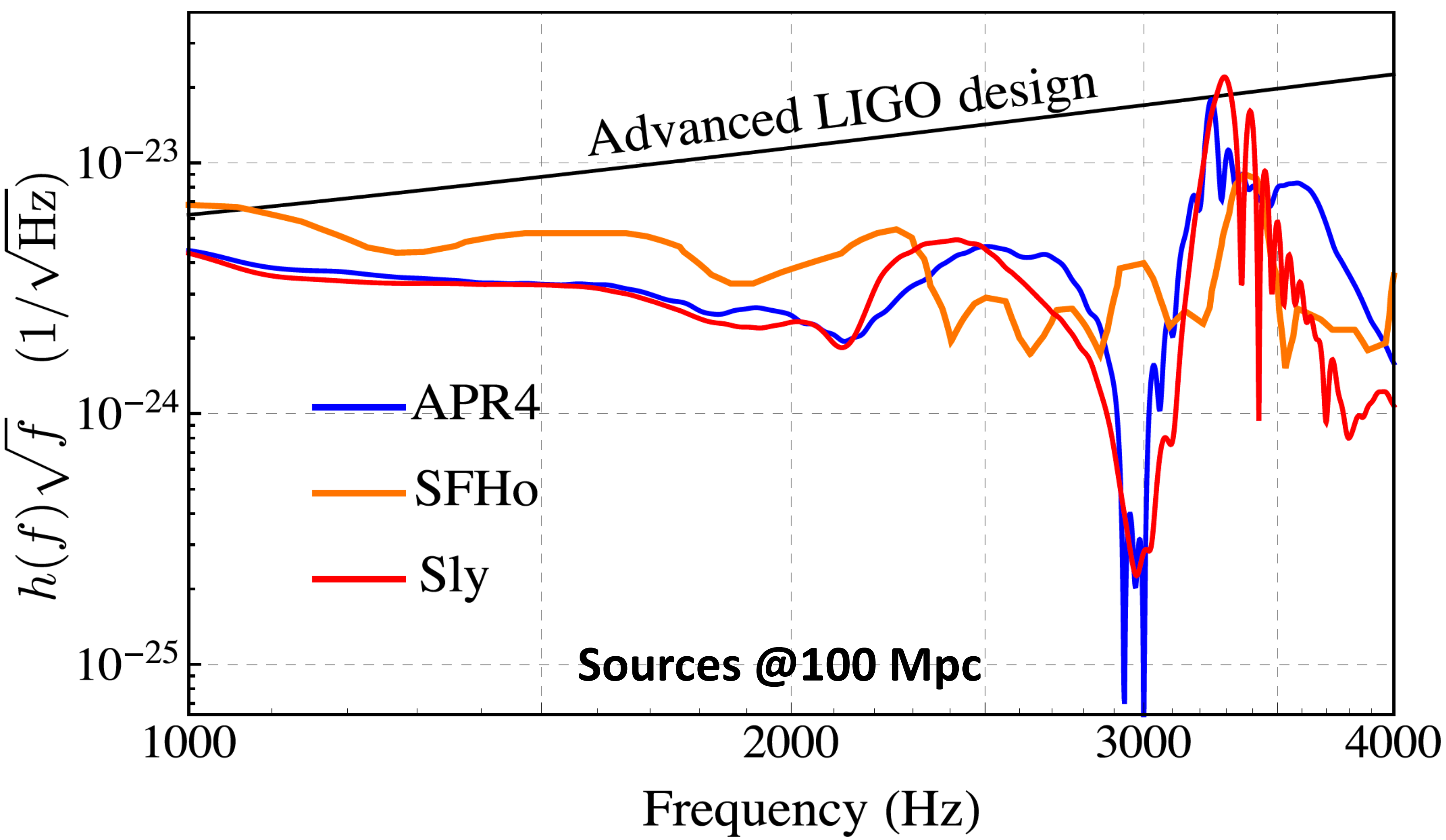






kHz GW detectors

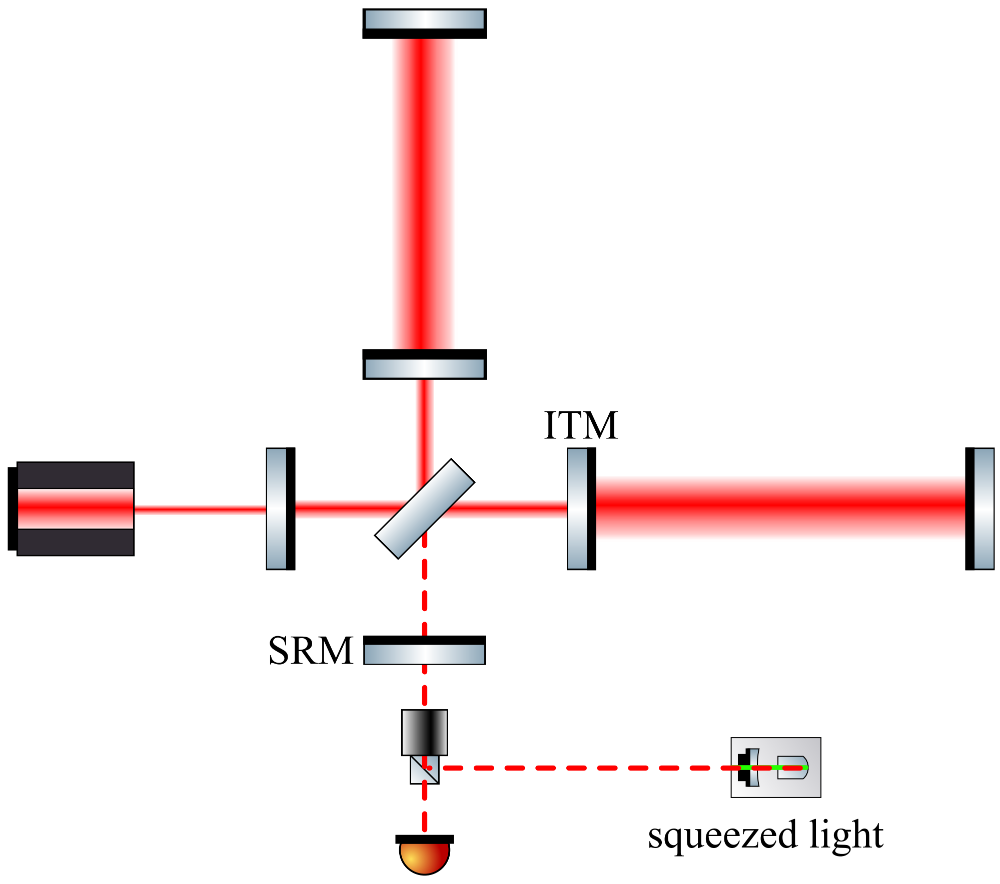
Challenge of Detecting Post-merger Signals



Making confident detections requires a sensitivity around 10^{-24} @ kHz

Reaching Target Sensitivity

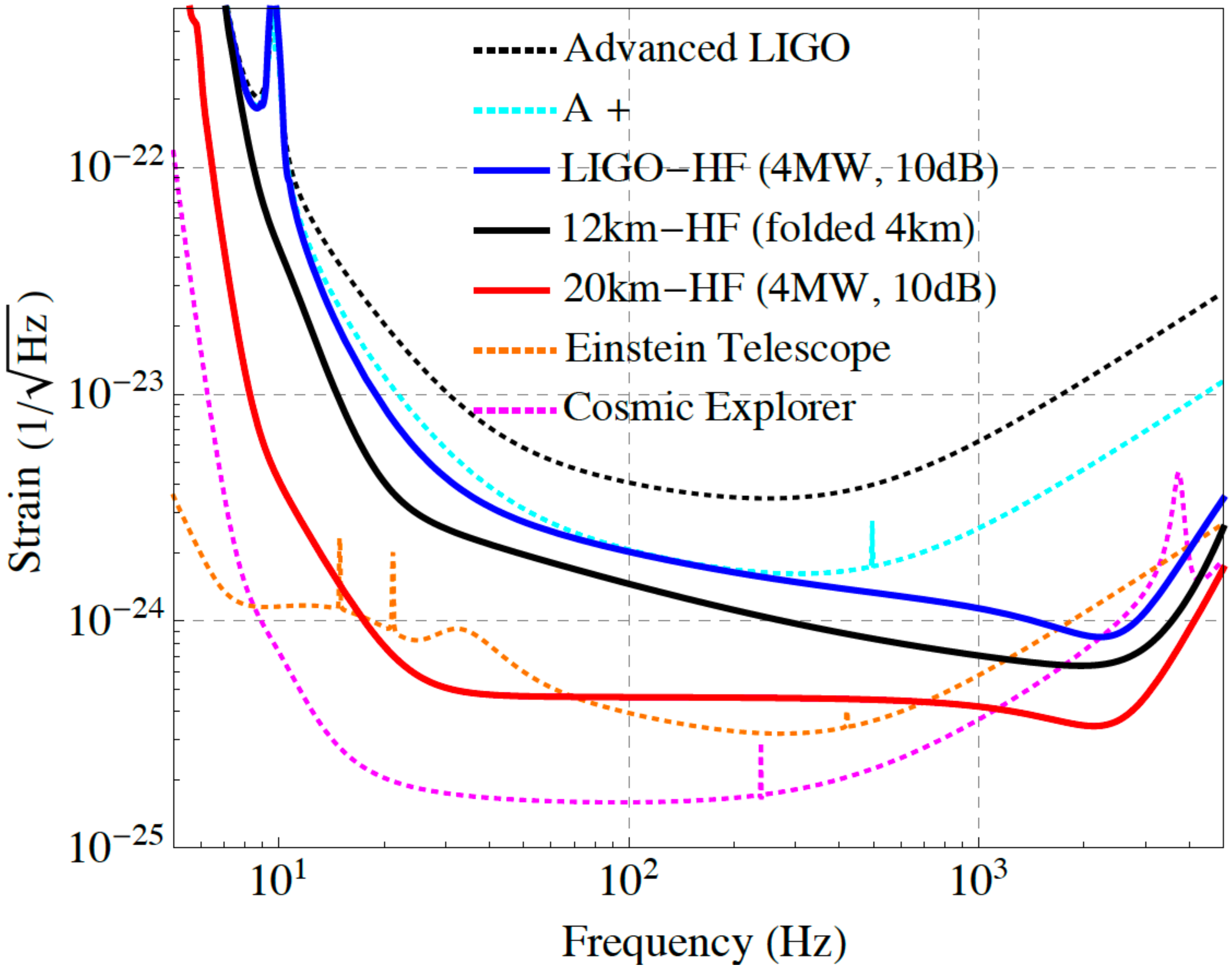
Configuration:



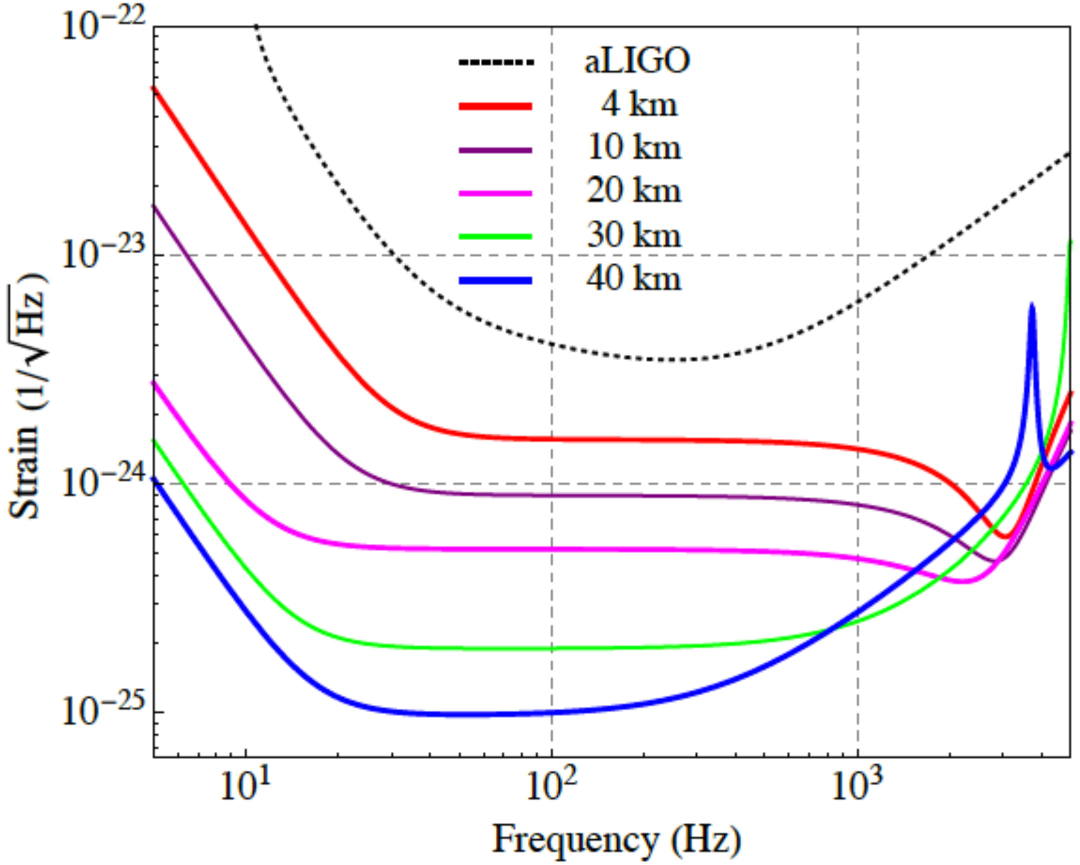
Different options:

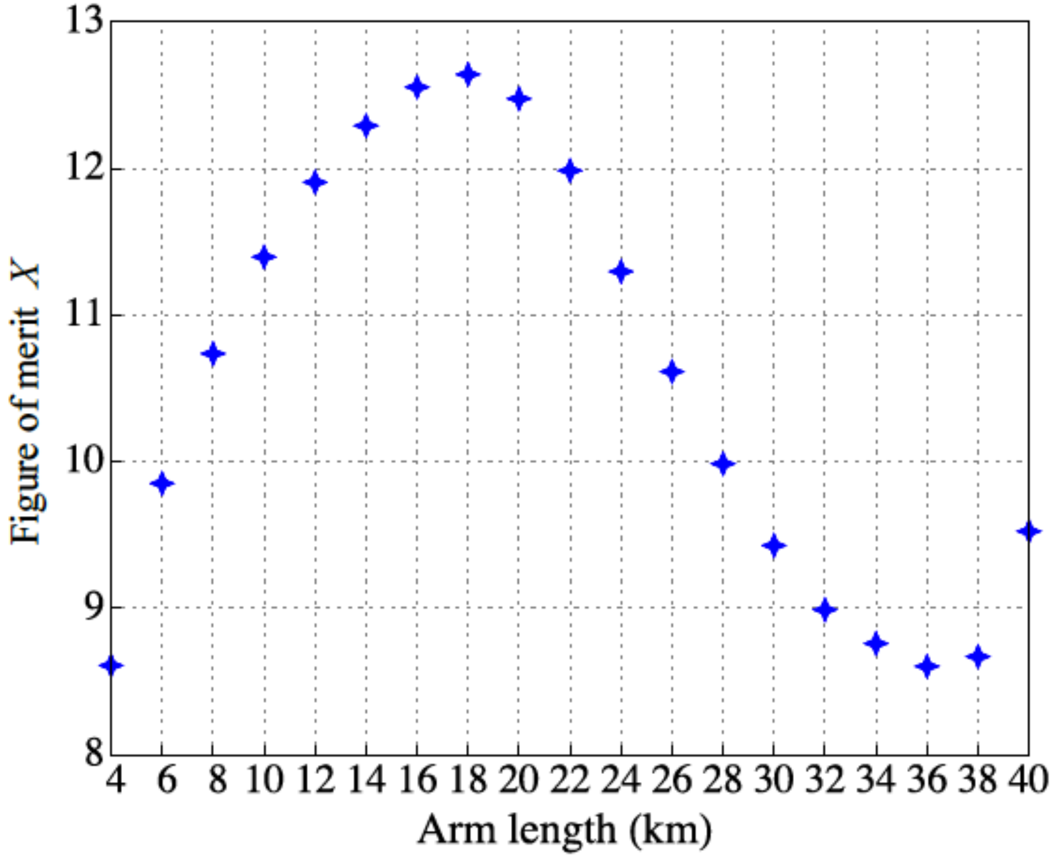
Arm length	SRC length	Power 1064 nm	Squeezing (observed)	Mirror Mass
4 km	356 m	4 MW	10 dB	40 kg
12km (fold)	200 m	4 MW	10 dB	87 kg
20 km	100 m	4 MW	10 dB	100 kg

Sensitivity Curve



Sensitivity Curve





$$X = \frac{1}{2\pi}\int_0^{\pi} d\theta \sin\theta \int_0^{2\pi} d\phi \sqrt{\int_{2\,\text{kHz}}^{4\,\text{kHz}} df \frac{h_0^2}{S_{hh}(f,\theta,\phi)}}$$

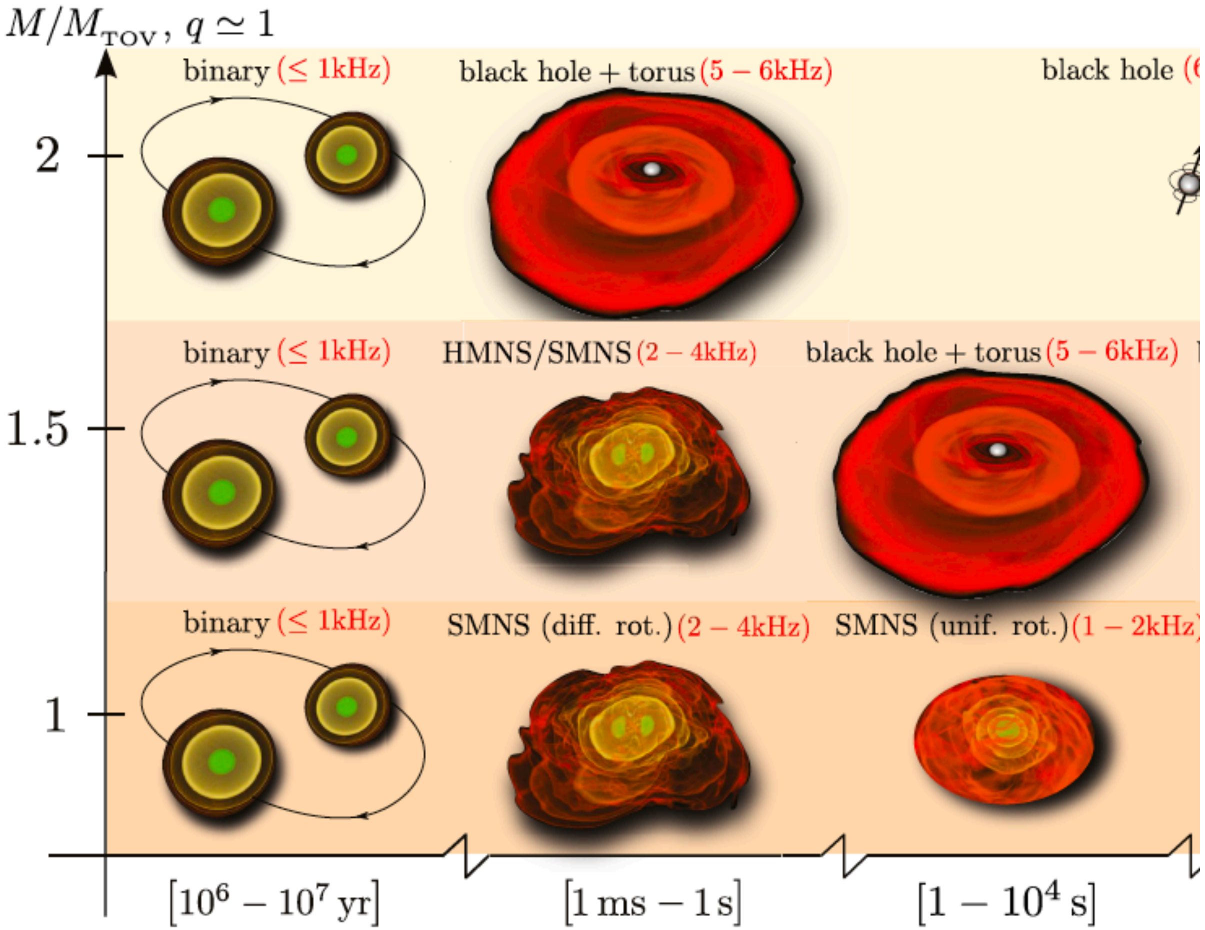
Science opportunities @ high frequency

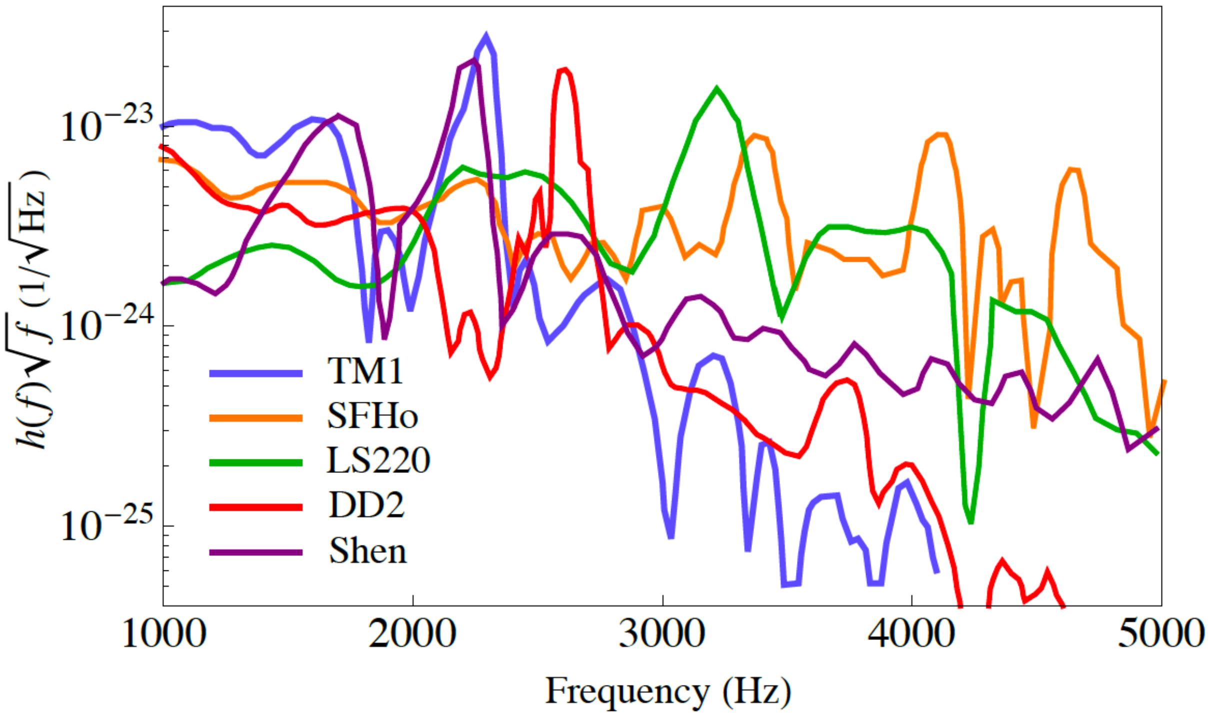
- **Neutron star physics:**
    1. **Post-merger binary neutron stars**
    2. **neutron star-black hole mergers**
    3. **highly eccentric binary neutron star encounters**

- **Cosmology: measuring H0 without electromagnetic counterpart**

- **Test gravity with low-mass black holes**

Post merger neutron stars





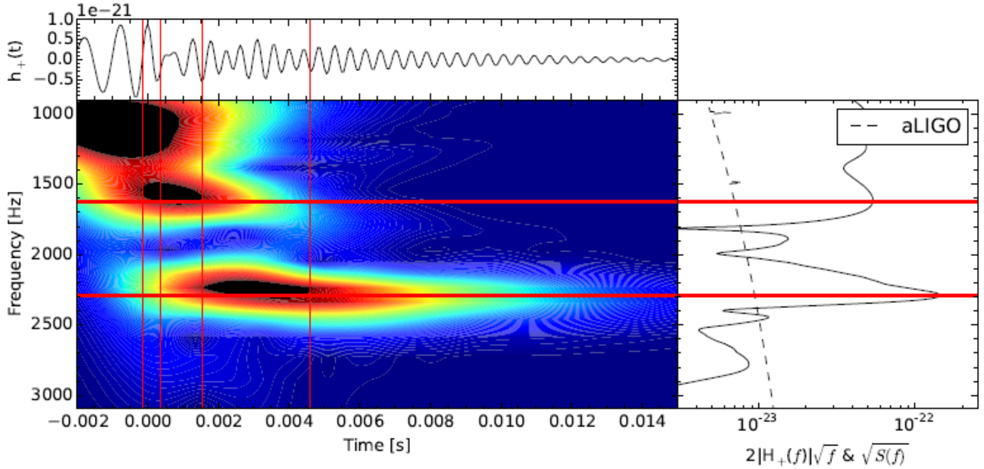
L. Baiotti, and L. Rezzolla (2017)

Post merger neutron stars

1. Direct connection to EM observables and many important problems in transient astronomy: Shot Gamma-Ray burst, Kilonova (Daniel's talk)

2. Numerical simulations contain large theoretical uncertainties: results do not converge with different resolution; missing physics (e.g., neutrino transport, fully resolved magneto-hydrodynamics); parameter space poorly researched (eccentricity, mass ratio, magnetic field configuration, spin, EOS…)

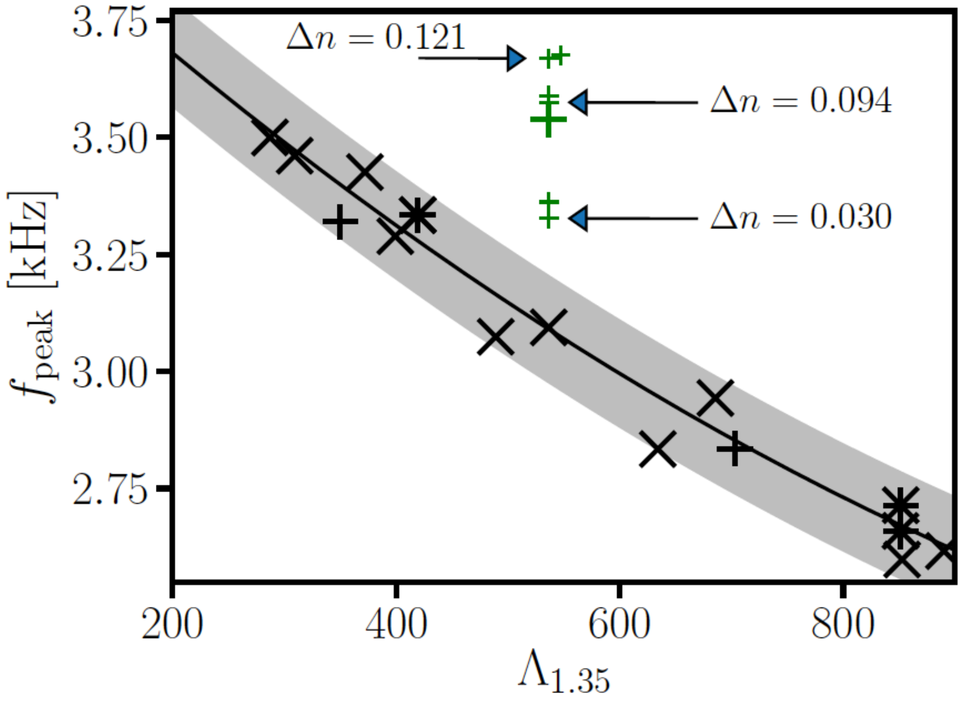
3. Waveforms cannot be used for matched-filter analysis. Peak mode robust.



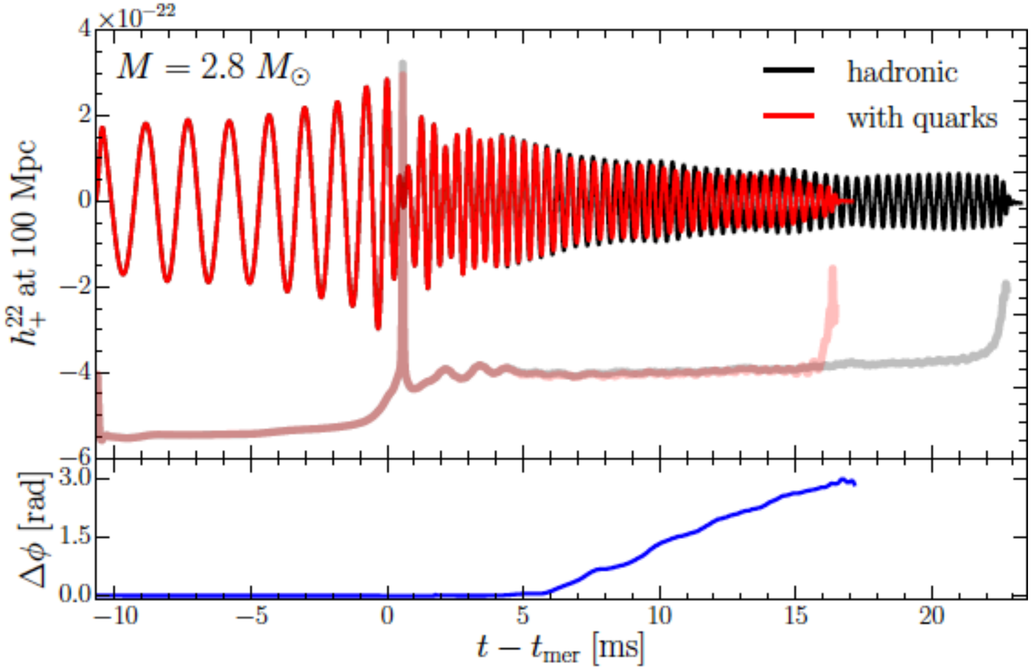
J. Cark et al, 2014

Probing quark core within neutron stars

- First order phase transition in the neutron star equation of state can be probed by measuring the tidal love number and post-merger mode frequency:

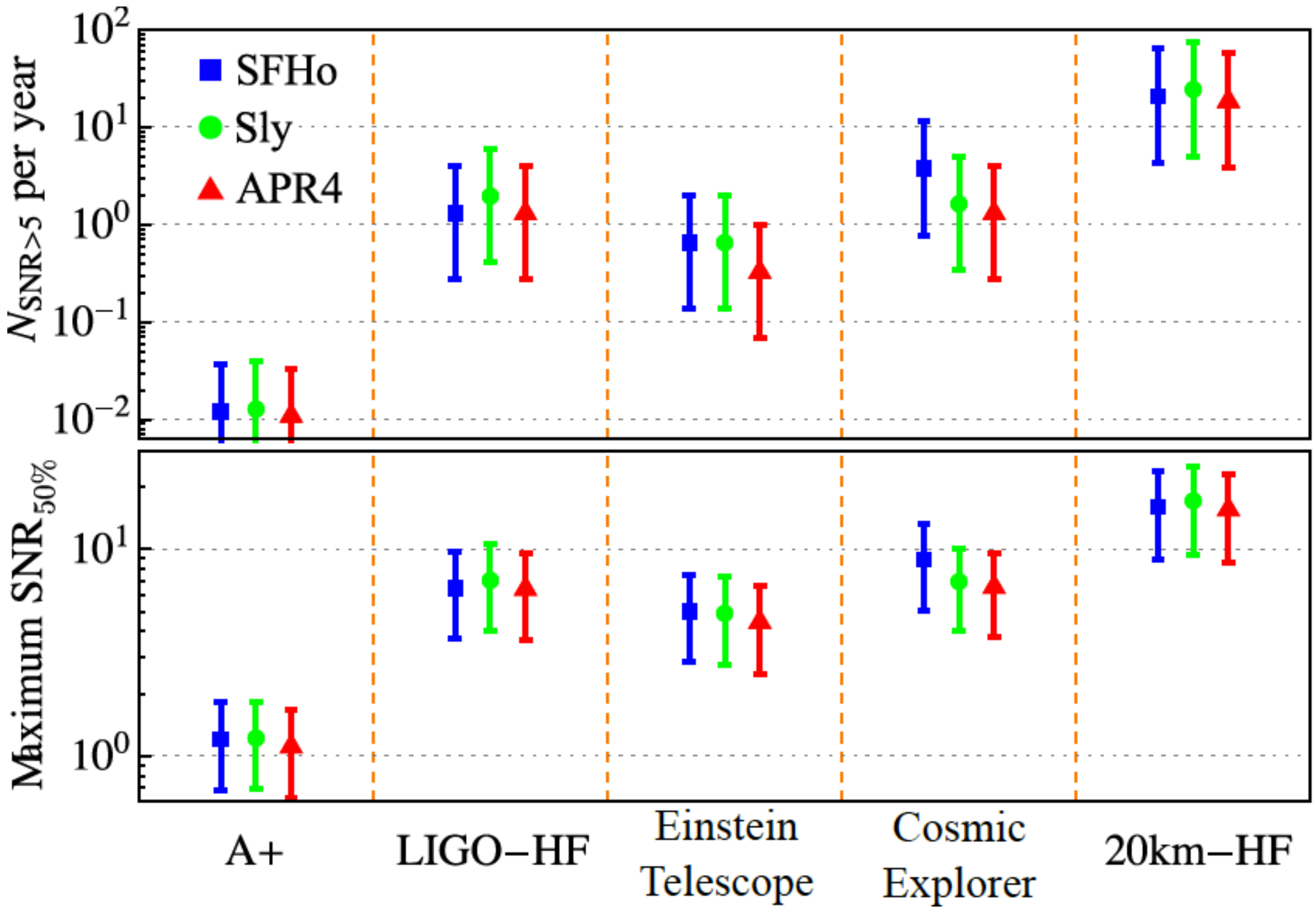


A. Bauswein et al, PRL 2019



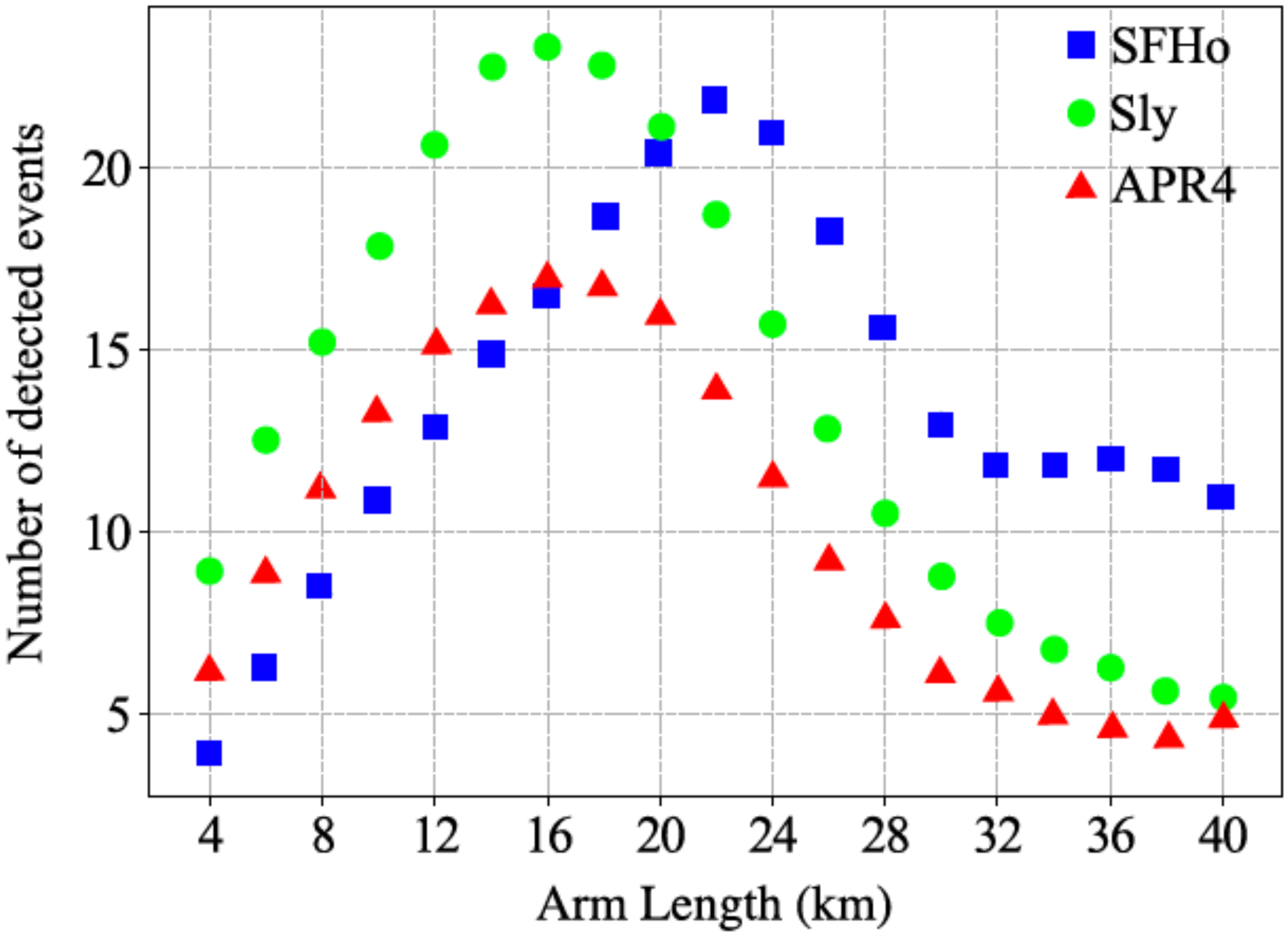
E. Most et al, PRL 2019

Event SNR



SFHo
Sly
APR4
$N_{SNR>5}$ per year
Maximum $SNR_{50\%}$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^1
10^0
A+
LIGO−HF
Einstein Telescope
Cosmic Explorer
20km−HF

Event SNR


SFHo
Sly
APR4
Number of detected events
5
10
15
20
4
8
12
16
20
24
28
32
36
40
Arm Length (km)

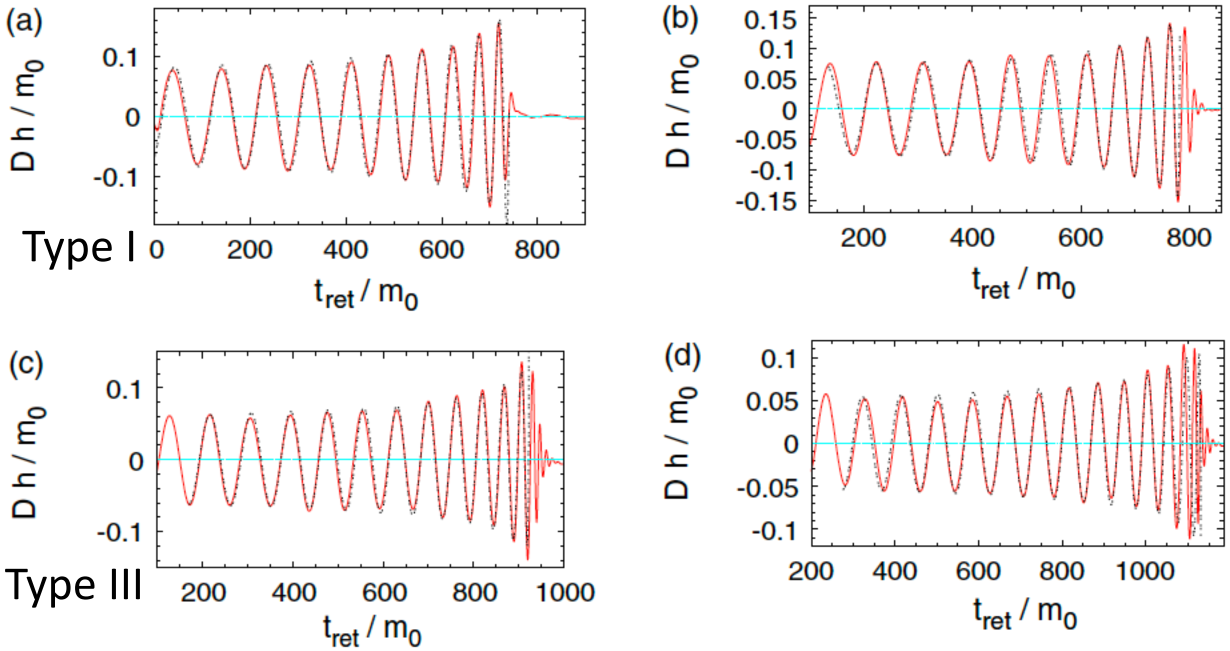
Neutron star-black hole merger

1. Generic mergers can be classified into three categories

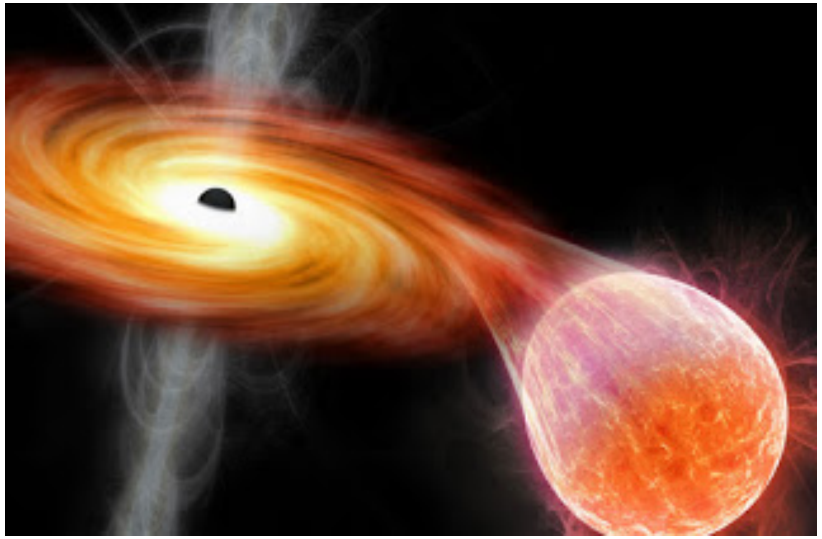
I. Tidal disruption outside ISCO.

II. Tidal disruption within ISCO.

III. No tidal disruption, only black hole ringdown.



Type II



M. Shibata, K. Kyutoku, T. Yamamoto, K. Taniguchi, 2009

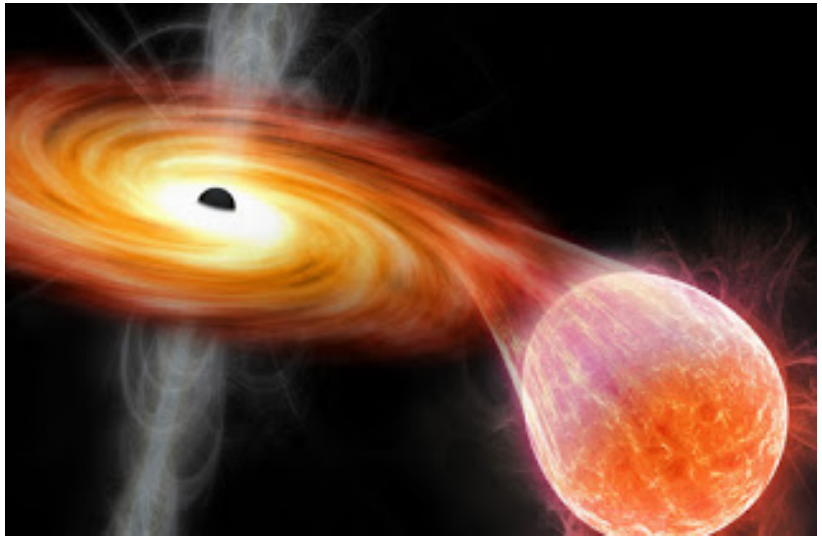
Type III

2. Nontrivial electromagnetic emission associated with the tidal disruption.

Neutron star-black hole merger

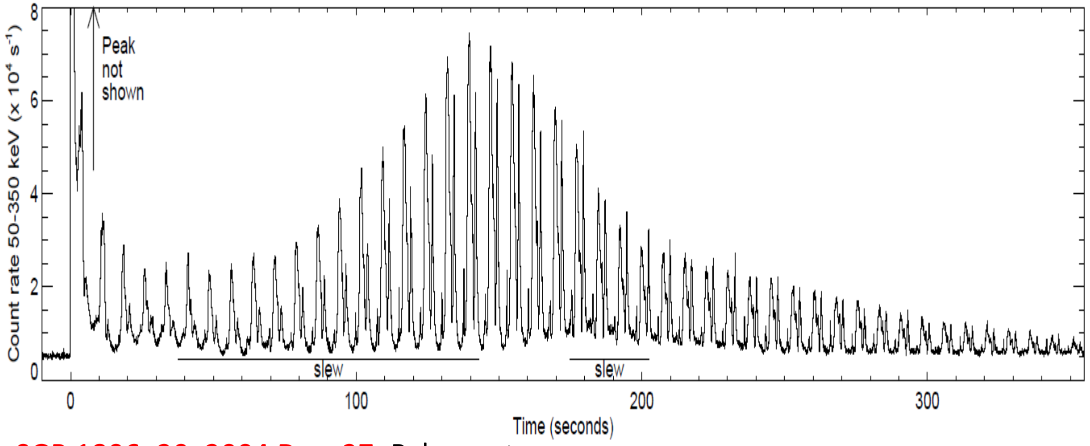
	Type I	Type II	Type III
LIGO-HF	1.59	3.65	4.05
Einstein Telescope	1.37	2.44	2.98
Cosmic Explorer	2.00	3.27	4.18
20 km-HF	4.86	10.98	12.61

SNR starting from tidal disruption @100 Mpc



f-mode excitation in eccentric binary neutrons stars

- The only (EM) observation of neutron star oscillations comes from Magnetar giant flares, where the crust modes show up in Quasi-Periodic Oscillation of gamma rays. The Magnetar eigenvalue problem, *"hearing the shape of a drum"*.



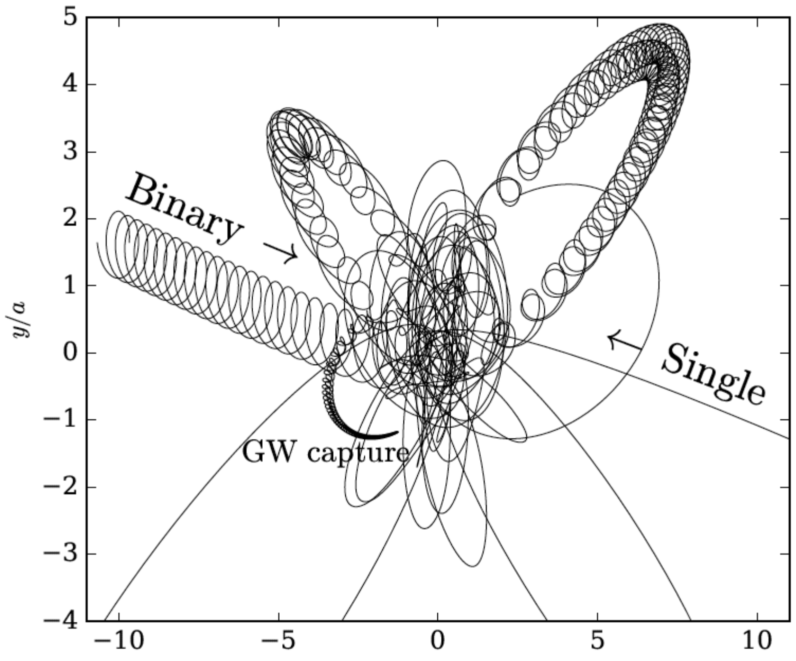
SGR 1806+20, 2004 Dec. 27; Palmer et al. Nature 2005

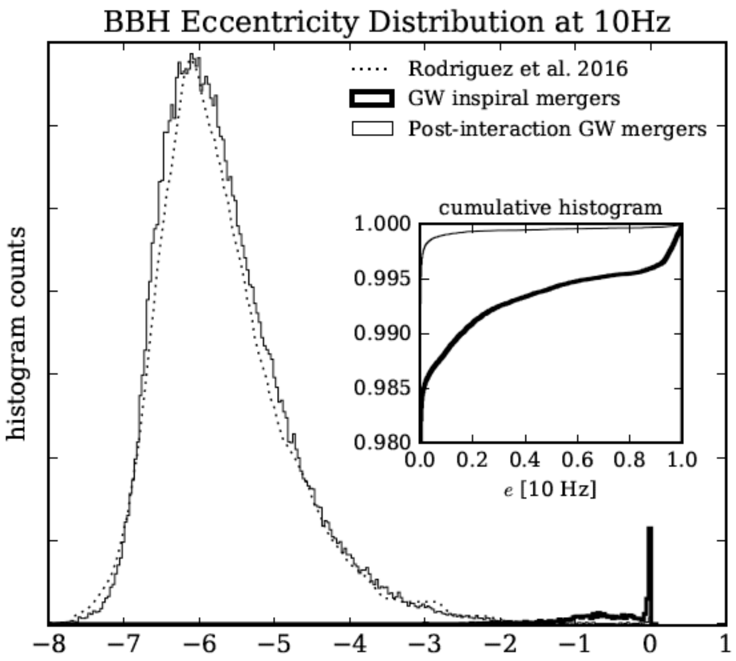
R. Duncan, ApJL 498, L45, 1998
A. Piro. ApJL 634, L153, 2005
K. Glampedakis et al., MNRAS 371, L74, 2006
C. Thompson, HY, N. Ortiz, ApJ 841, 54, 2017
…

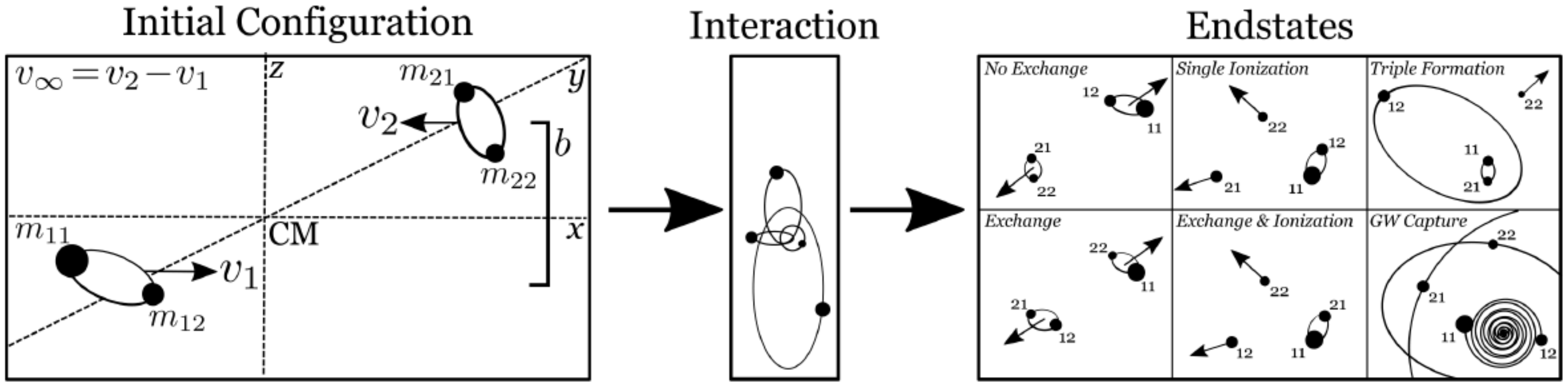
- Hearing the shape of a neutron star through gravitational waves. The f mode (1.5~2 kHz) has strongest coupling to gravity.

- Neutron stars as driven oscillators in the binary inspiral stage

f-mode excitation in eccentric binary neutrons stars



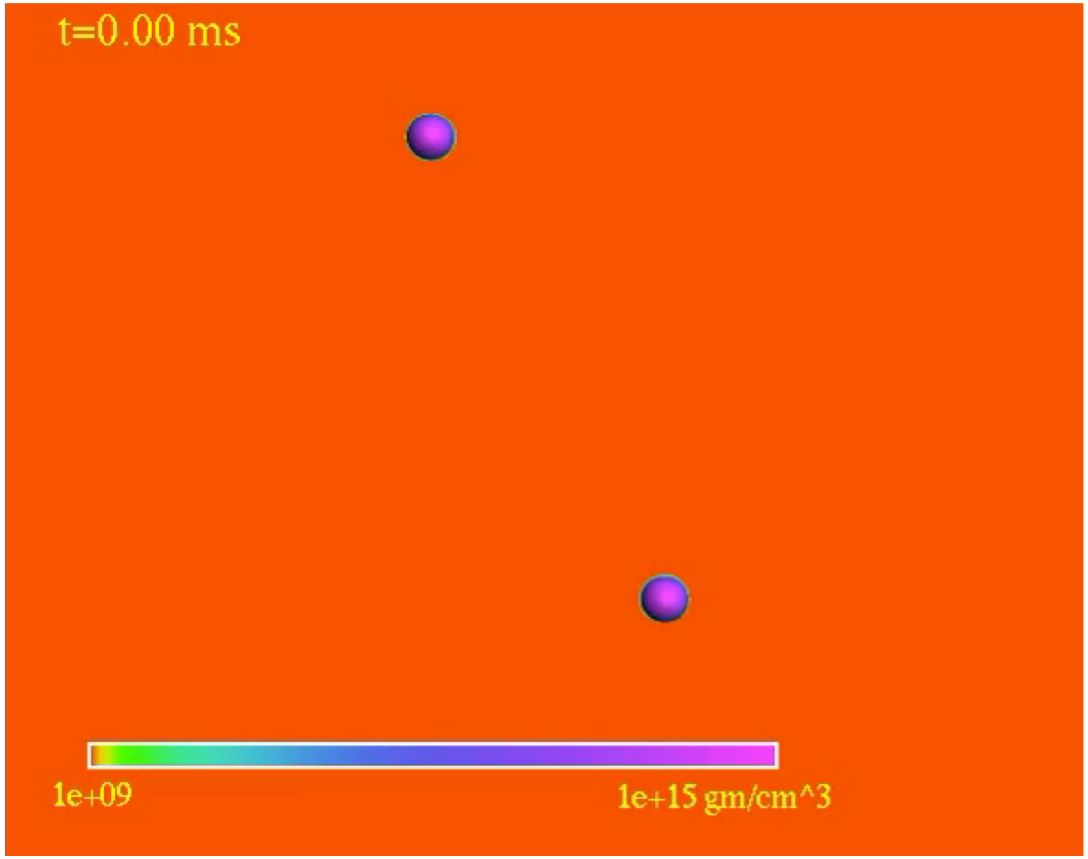


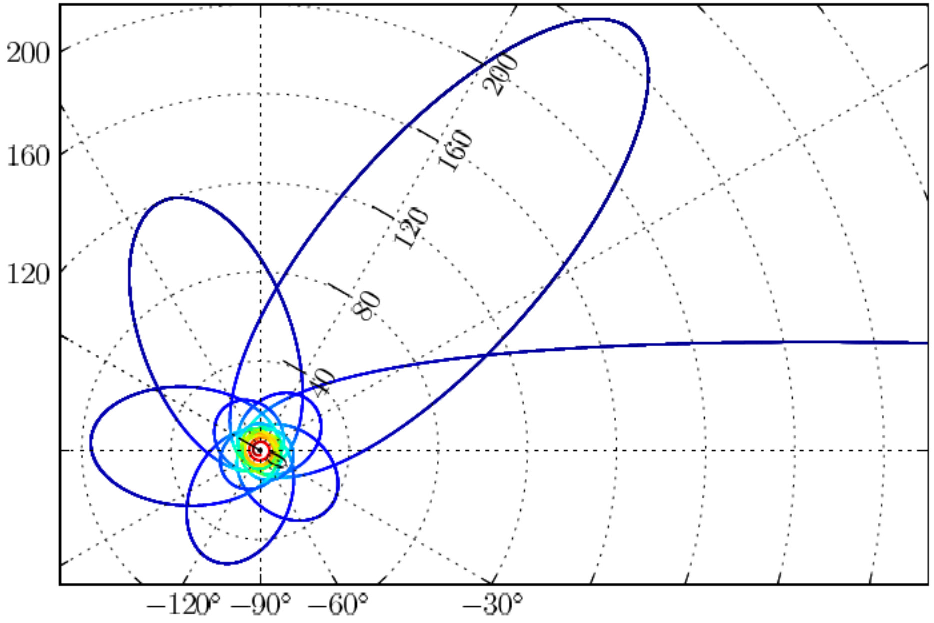


J. Samsing, E. Ramirez-Ruiz, ApJL 840, L14, 2017
Zevin et al., ApJ 871, 1, 2019

f-mode excitation in eccentric binary neutrons stars

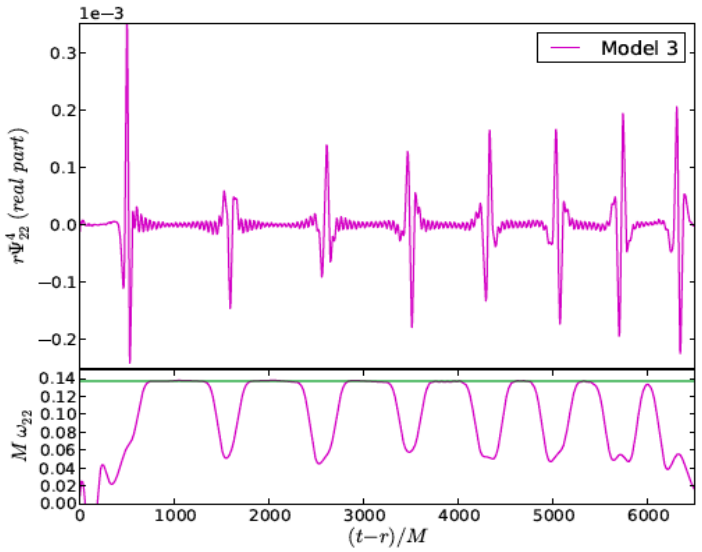
- Eccentric binaries can be produced by:
  - Dynamic capture.
  - Hierarchical triples with Kozai-Lidov mechanism.
  - Binary-binary/binary-single interaction, dynamical scattering or exchange …

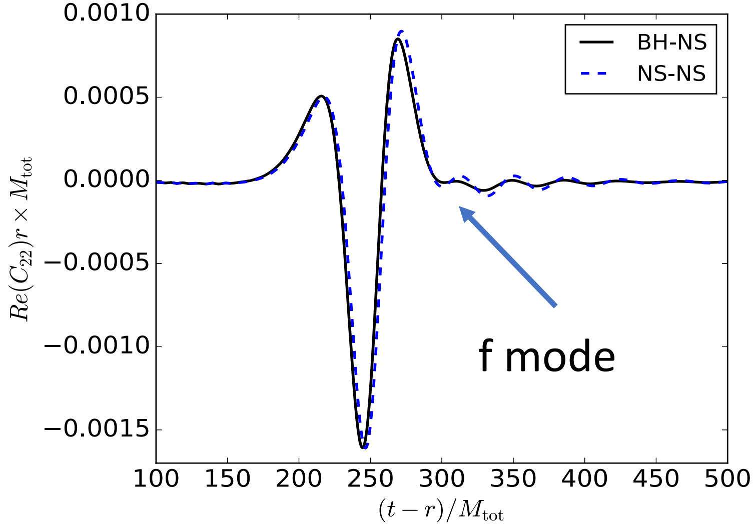




Courtesy of William East

f-mode excitation in eccentric binary neutrons stars





R. Gold et al, PRD 86, 121501, 2012
HY et al., PRD 98, 044007, 2018

- Star oscillation excited after each pericentre passage.
- f-mode emission follows the main bursts. Orbital energy transfers to the star oscillations and GW emissions.
- Waveform not available. The expected f-mode SNR assuming perfect stacking of post-encounter f-mode emissions:

$$\mathrm{SNR} \sim 30 \left(\frac{2E_{\rm mode}}{E_{\rm GW}}\right)^{1/2} \left(\frac{50Mpc}{d}\right) \left(\frac{5\times10^{-25}\mathrm{Hz}^{-1/2}}{\sqrt{S_n}}\right) \left(\frac{2000\mathrm{Hz}}{f}\right)$$

H0 measurement without EM counterpart

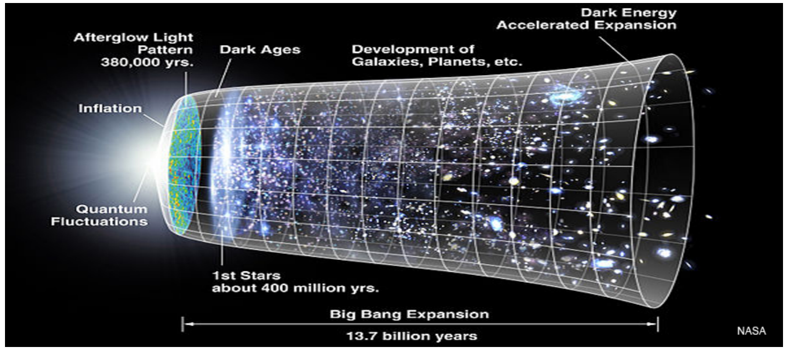
- Comparing the inspiral and post merger waveform: extract redshift information

$$f_{\rm inspiral} \propto \frac{1}{M(1+z)} \qquad f_{\rm peakmode} \propto \frac{M}{(1+z)}$$

- The accuracy of this method depends on the resolution/sensitivity of the post-merger peaks. Similarly for tidal measurements.

- An estimate of the accuracy:

$$\frac{\delta H_0}{H_0} \sim 0.1 \frac{1}{\sqrt{N}}$$

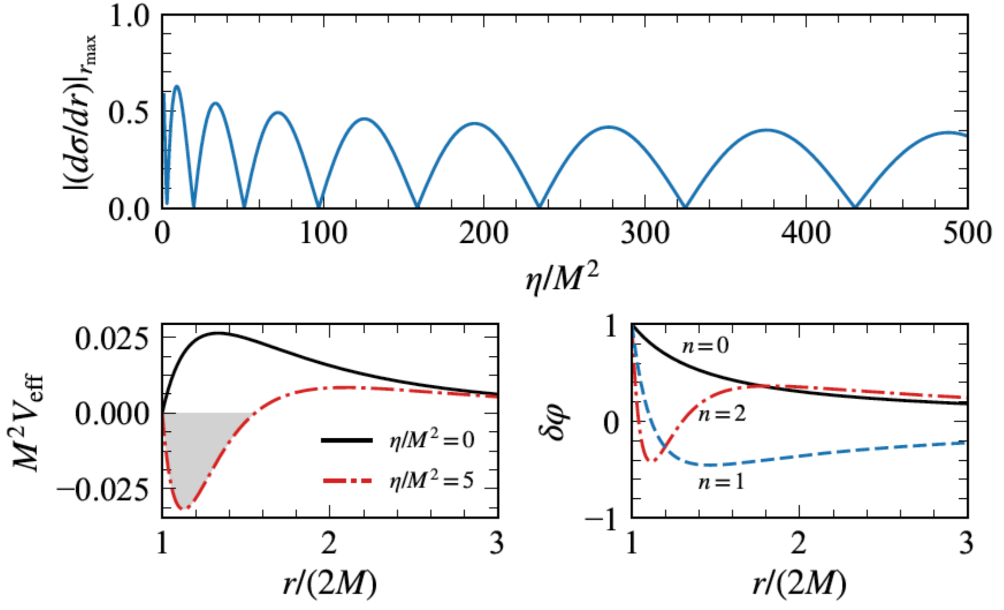


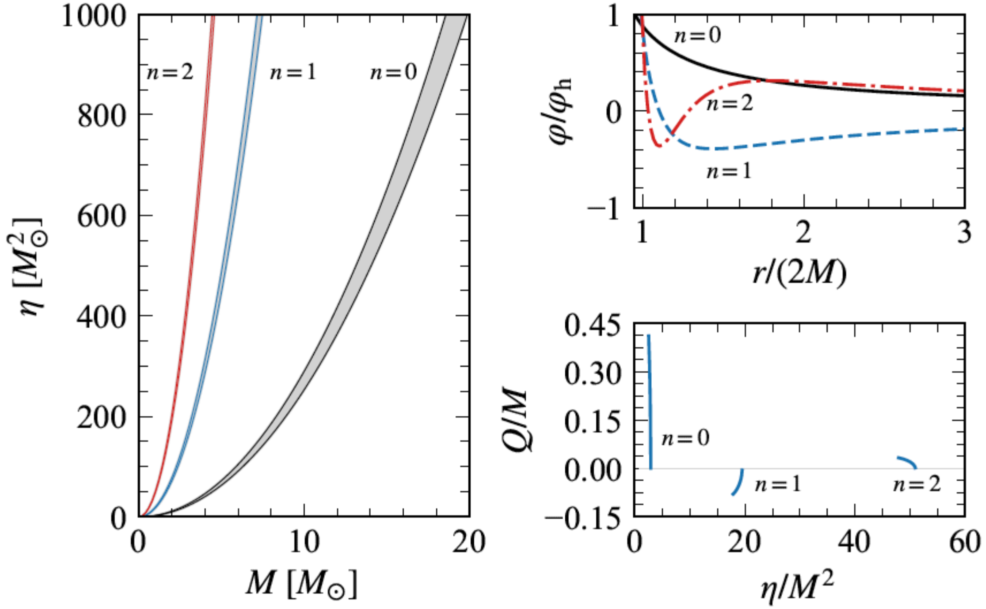
Test gravity with low-mass black holes

- Modified gravity theories contain coupling parameters with length dimensions:

$$S = \int d^4x\sqrt{-g}\left\{R + \alpha_{\rm CS} R_{\mu\nu\rho\sigma}{}^{*}R^{\mu\nu\rho\sigma} - \frac{\beta_{\rm CS}}{2}\left[\nabla_\nu\theta\nabla^\nu\theta + 2V(\theta)\right]\right\} \qquad \xi_{\rm CS} \propto \frac{\alpha_{\rm CS}^2}{\beta_{\rm CS}[{\rm Mass}]^4}$$

- Certain behavior only happens for low-mass black holes, e.g., spontaneous scalarization in Gauss-Bonnet gravity:

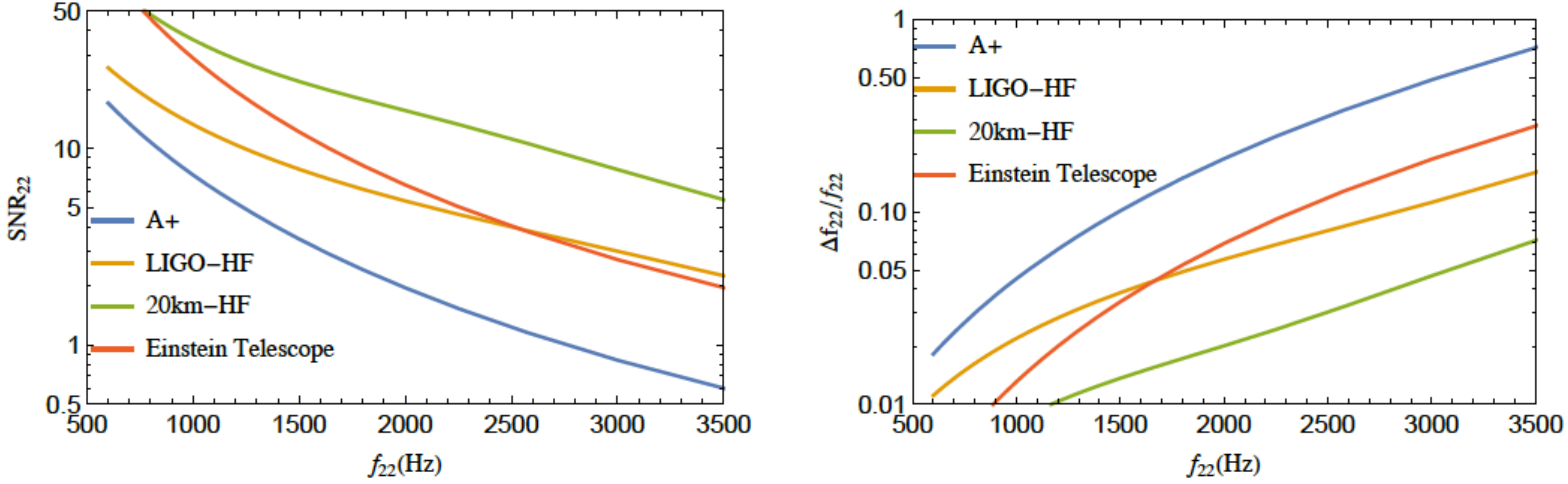




H. Silva, J. Sakstein, L Gualtieri, T. Sotiriou, E. Berti, PRL 2018

Test gravity with low-mass black holes

- Better to constrain with low-mass black holes @ high frequencies. Ringdown measurements:



Binary Black Hole ringdown @200 Mpc

Conclusions

1. We have discussed one possible realization of high-frequency gravitational-wave detector(s). Many technology developments required, high power issues, etc.

2. Kilohertz gravitational waves encode important information about neutron stars, that are difficult to probe by other means.

3. Kilohertz gravitational waves are also important for testing modified gravity theories with higher derivatives.

4. Applications to cosmology.