PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

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Path Towards kHz Gravitational-Wave Astronomy

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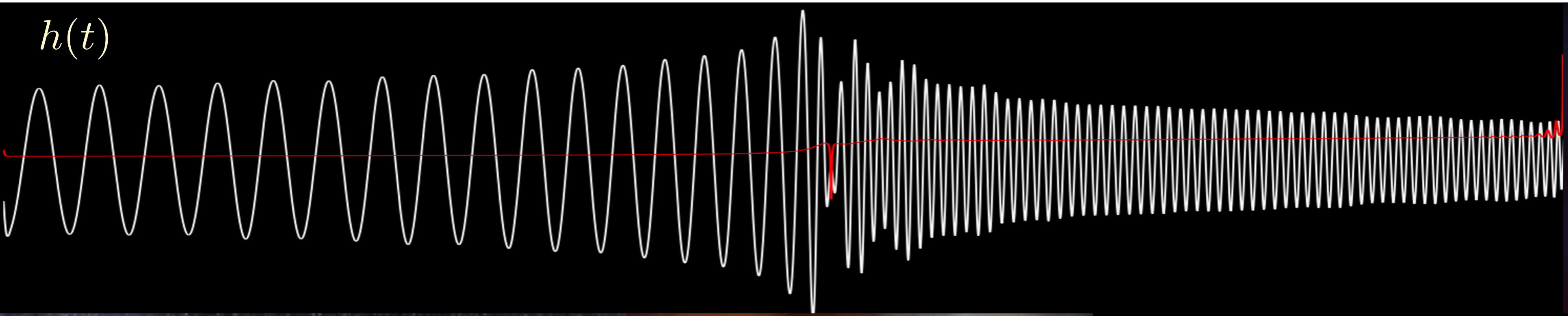
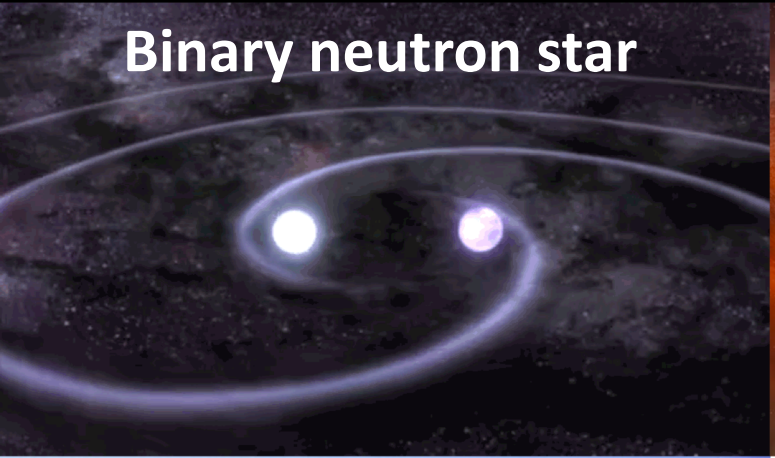
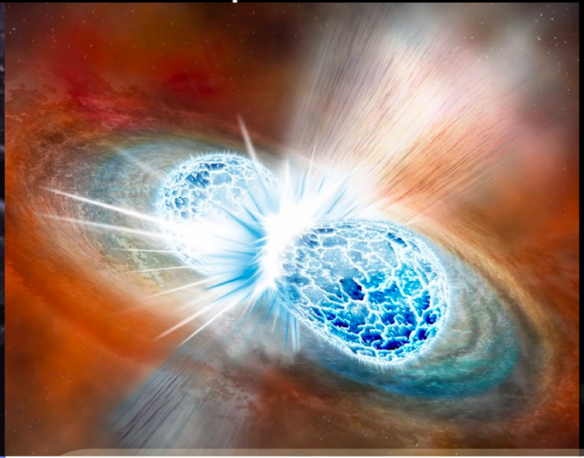
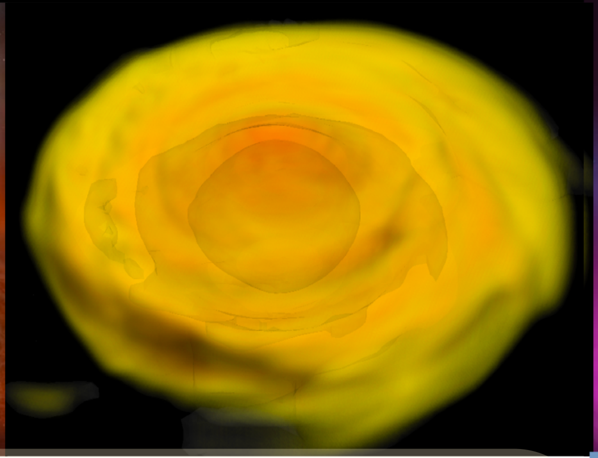
Based upon:

Denis Martynov, Haixing Miao, Huan Yang, Francisco Hernandez Vivanco, Eric Thrane, Rory Smith, Paul Lasky, William E. East, Rana Adhikari, Andreas Bauswein, Aidan Brooks, Yanbei Chen, Thomas Corbitt, Andreas Freise, Hartmut Grote, Yuri Levin, Chunnong Zhao, and Alberto Vecchio, *Exploring the sensitivity of gravitational wave detectors to neutron star physics*, arXiv:1901.03885 (2019)



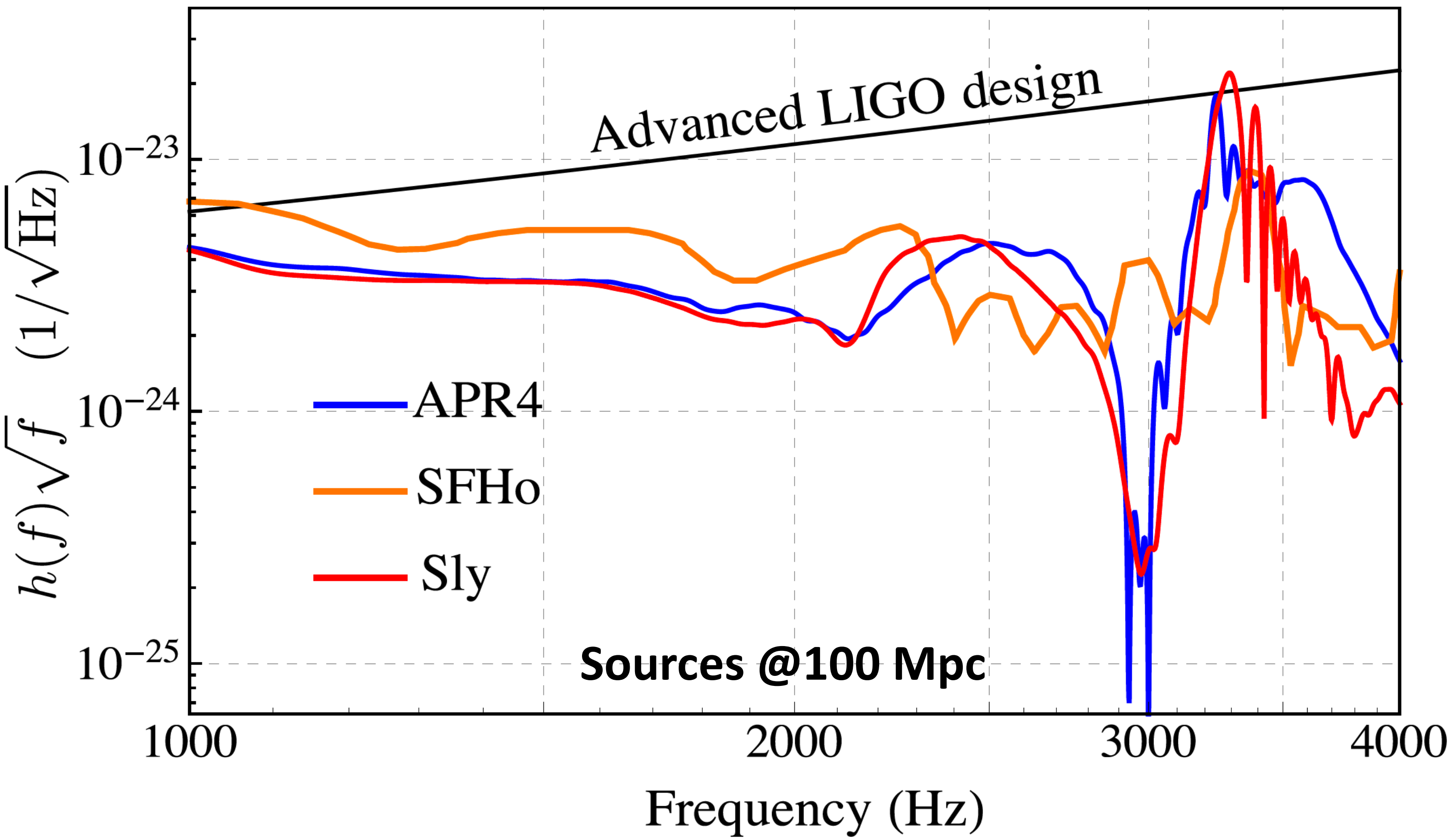






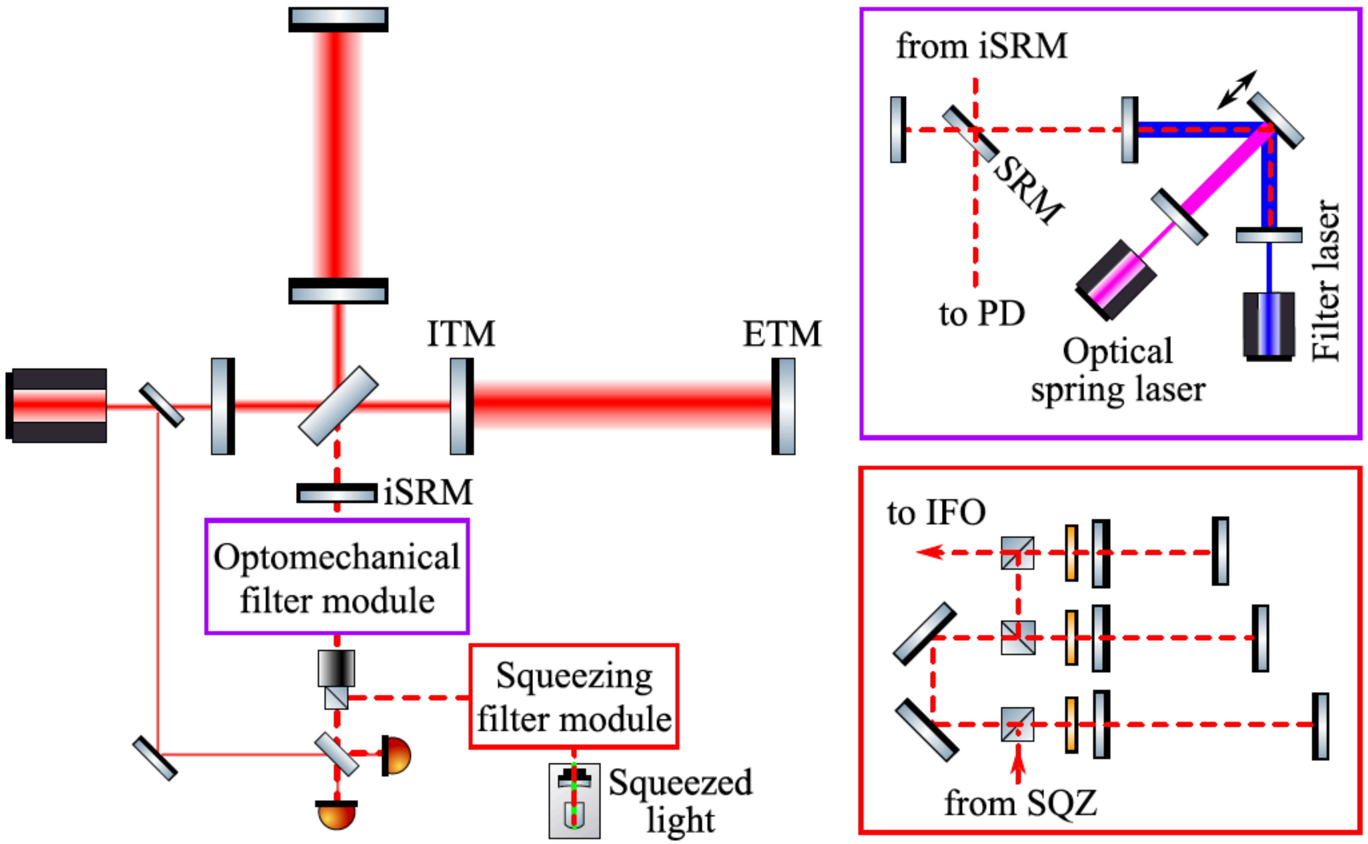
kHz GW detectors

Challenge of Detecting Post-merger Signals



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

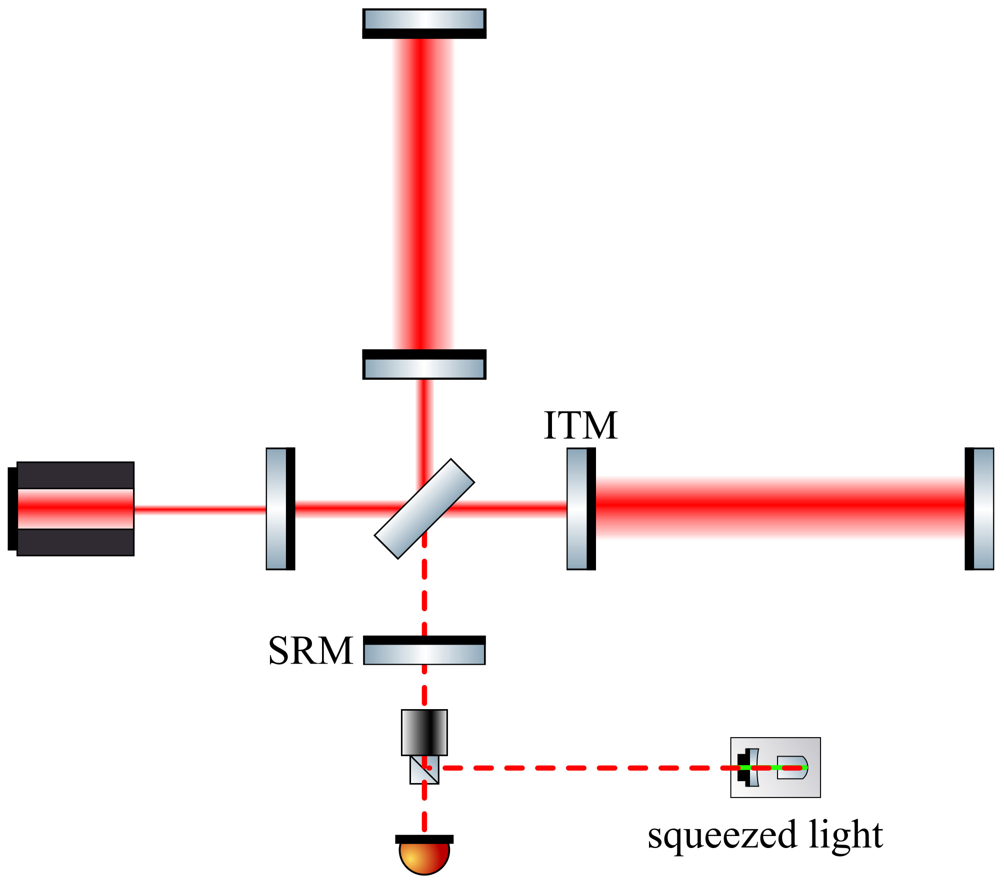
Reaching Target Sensitivity

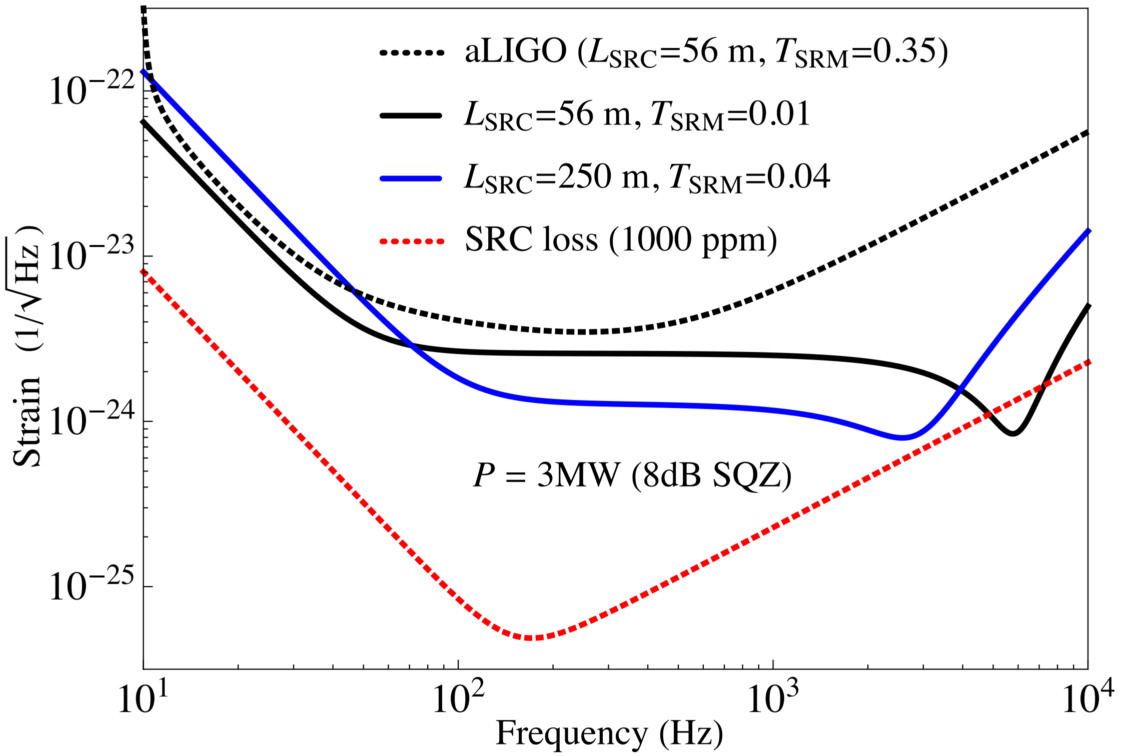


H. Miao, HY, D. Martynov, 2018

Reaching Target Sensitivity

Configuration:





Coupled SRC-arm-cavity resonance:

$$3\text{kHz}\sqrt{\left(\frac{T_{\rm ITM}}{0.015}\right)\left(\frac{250\,\rm m}{L_{\rm SRC}}\right)\left(\frac{4\,\rm km}{L}\right)}$$

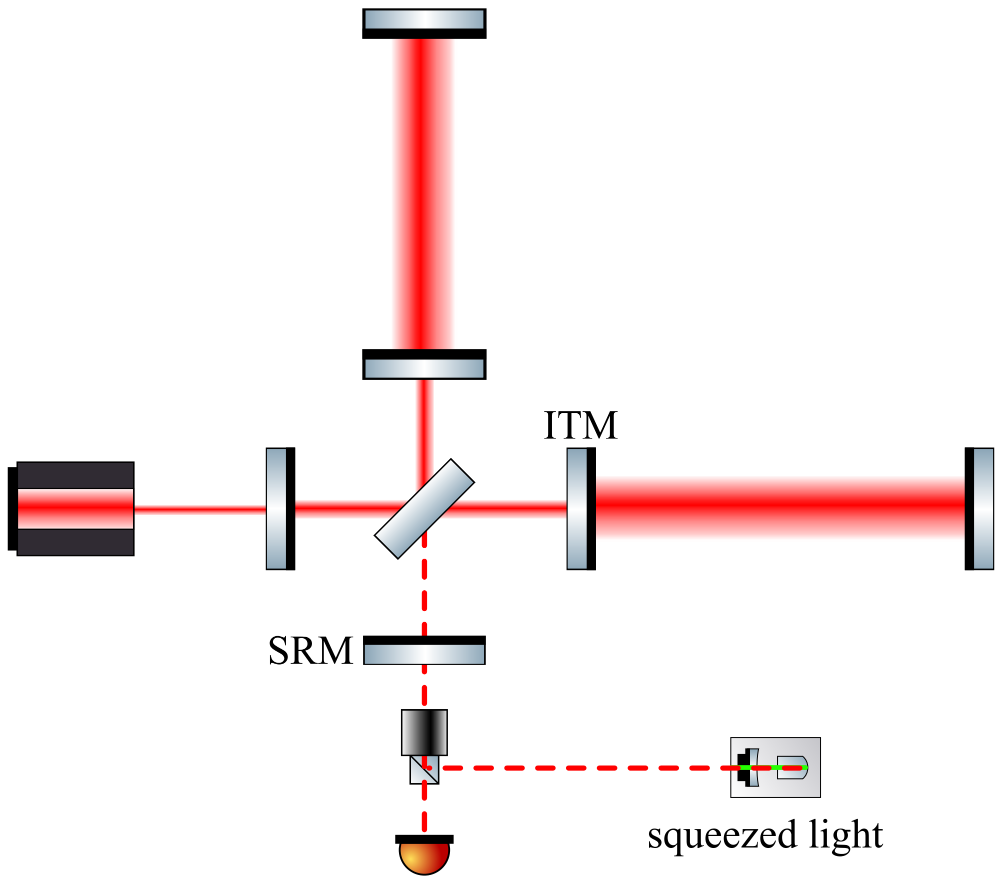
Same principle as twin-signal-recycling

A. Thüring, R. Schnabel, H. Lück, K. Danzmann (2007)

SRC loss due to thermal effect is the limiting factor.

Reaching Target Sensitivity

Configuration:



Coupled SRC-arm-cavity resonance:

$$3\text{kHz}\sqrt{\left(\frac{T_{\text{ITM}}}{0.015}\right)\left(\frac{250\,\text{m}}{L_{\text{SRC}}}\right)\left(\frac{4\,\text{km}}{L}\right)}$$

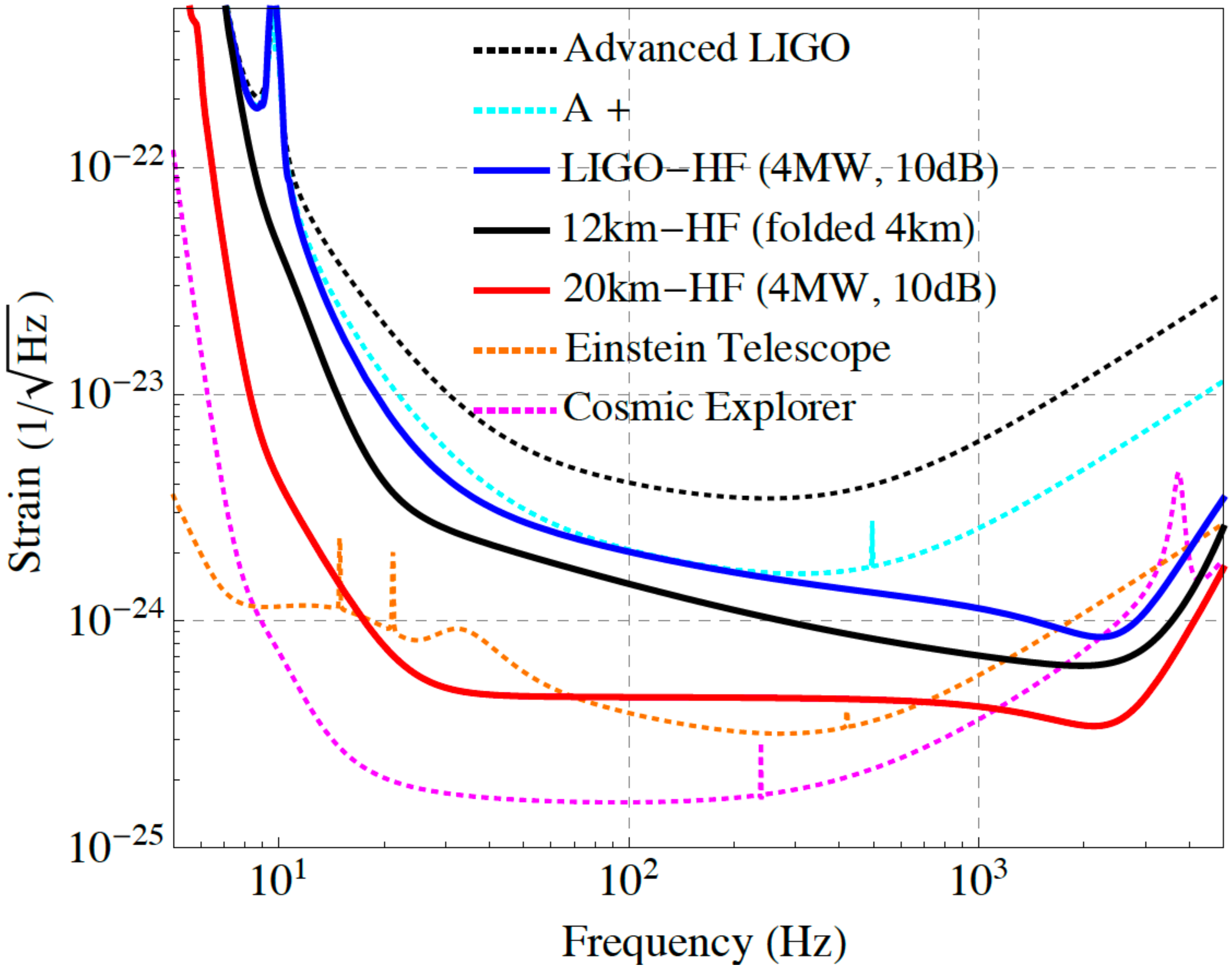
Shot-noise level (without SRC loss*):

$$\frac{10^{-24}}{\sqrt{\text{Hz}}}\sqrt{\left(\frac{3\,\text{MW}}{P}\right)\left(\frac{\lambda}{1064\,\text{nm}}\right)\left(\frac{\gamma/2\pi}{2\,\text{kHz}}\right)\left(\frac{4\,\text{km}}{L}\right)\left(\frac{10^{0.8}}{e^{2r_{\text{sqz}}}}\right)}$$

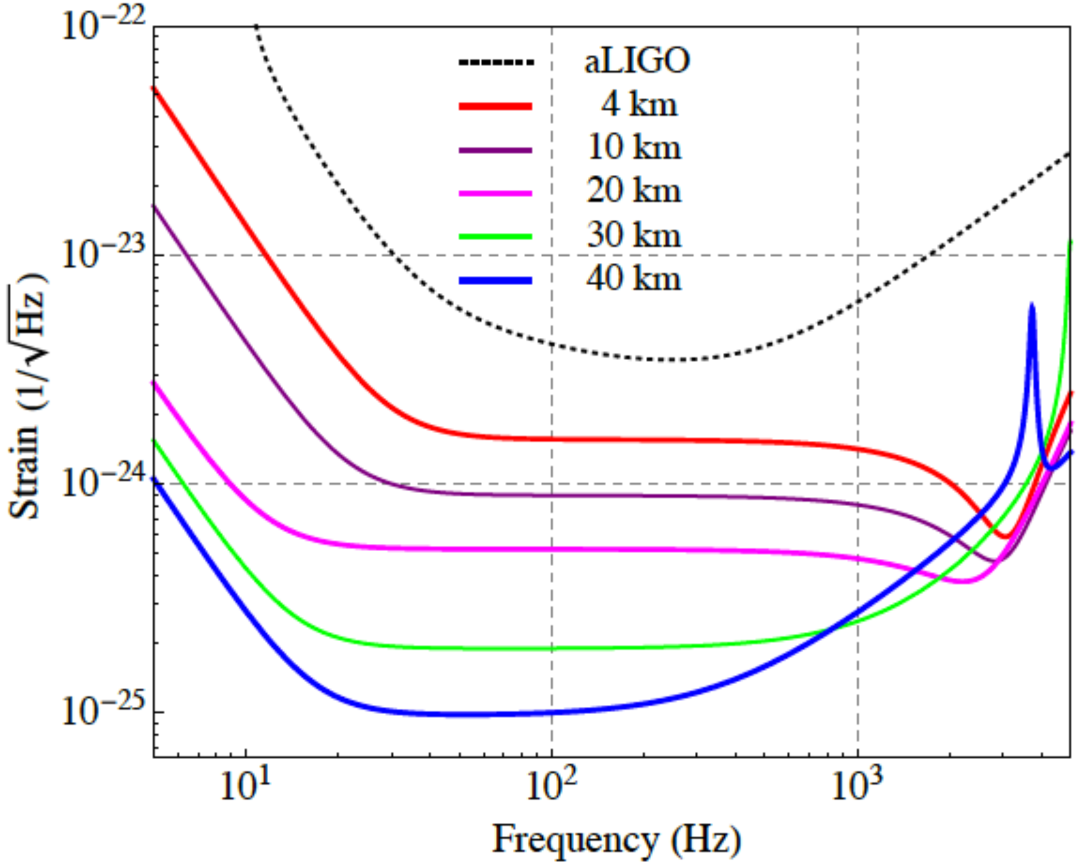
Different options:

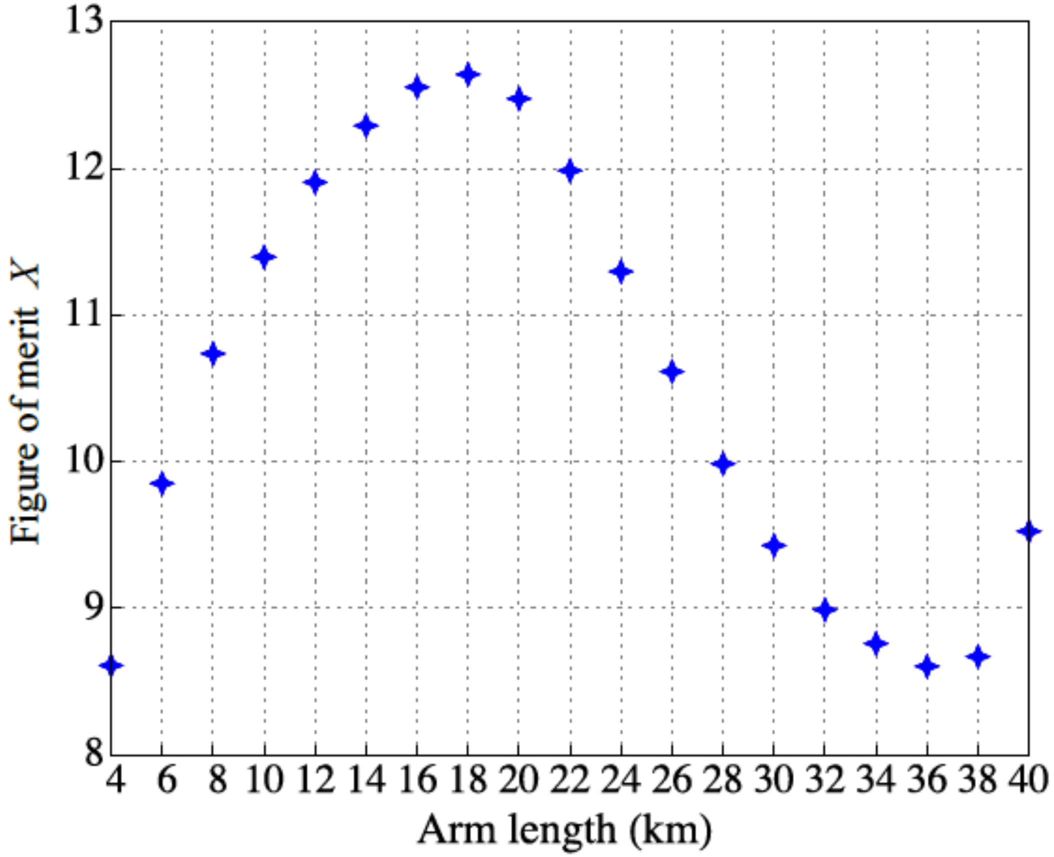
Arm length	**SRC length**	**Power** 1064 nm	**Squeezing (observed)**	**Mirror Mass**
4 km	356 m	4 MW	10 dB	40 kg
12km (fold)	200 m	4 MW	10 dB	87 kg
20 km	100 m	4 MW	10 dB	100 kg

Sensitivity Curve



Sensitivity Curve





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

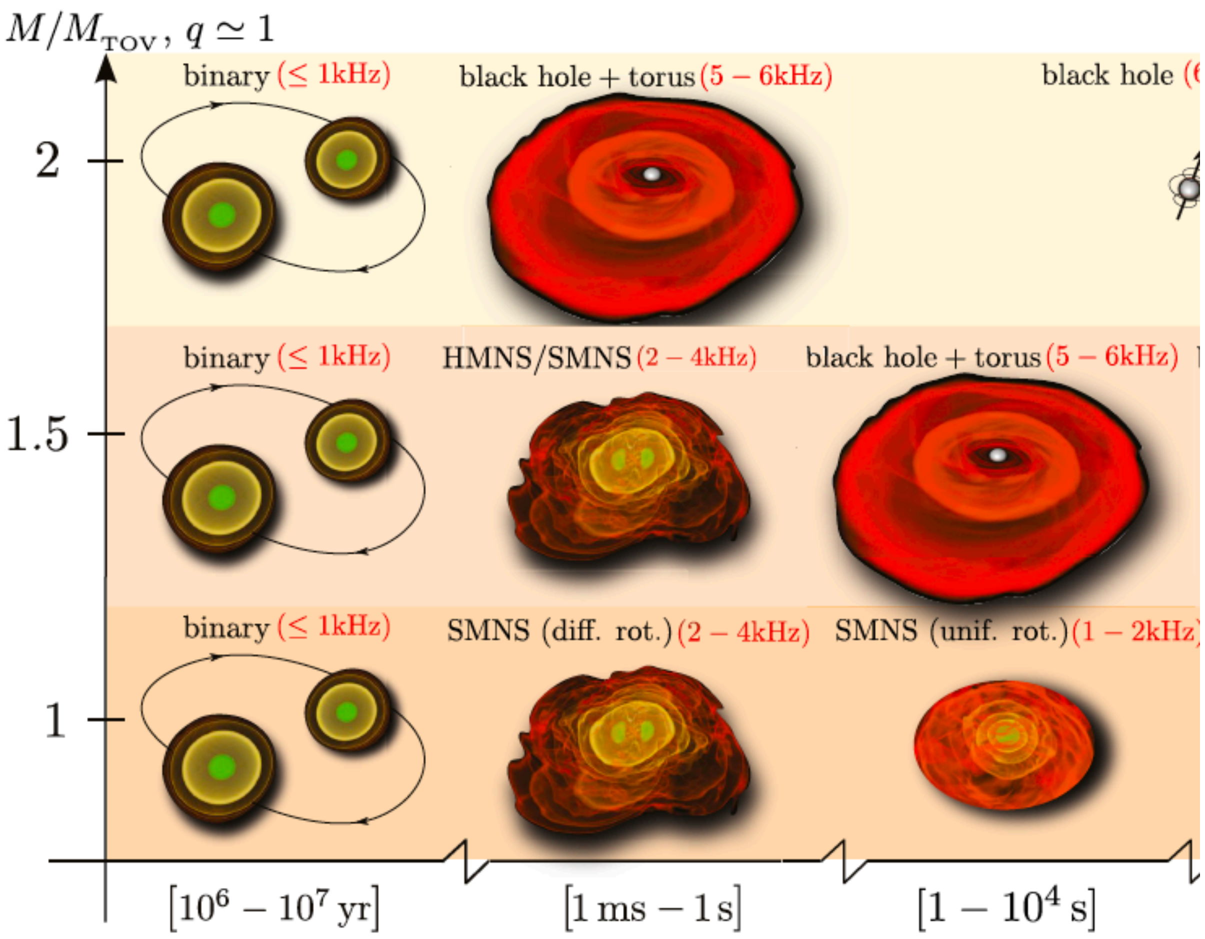
Science opportunities @ high frequency

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

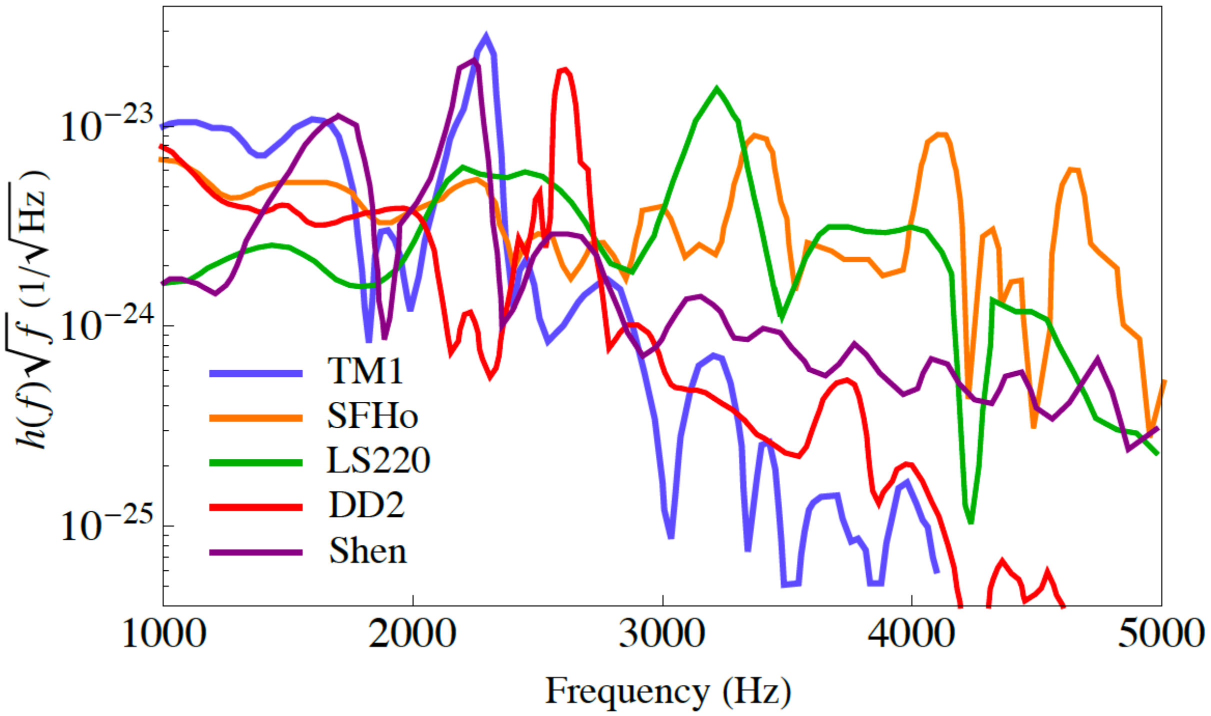
- **Cosmology: measuring H0 without electromagnetic counterpart**

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

Post merger neutron stars



L. Baiotti, and L. Rezzolla (2017)

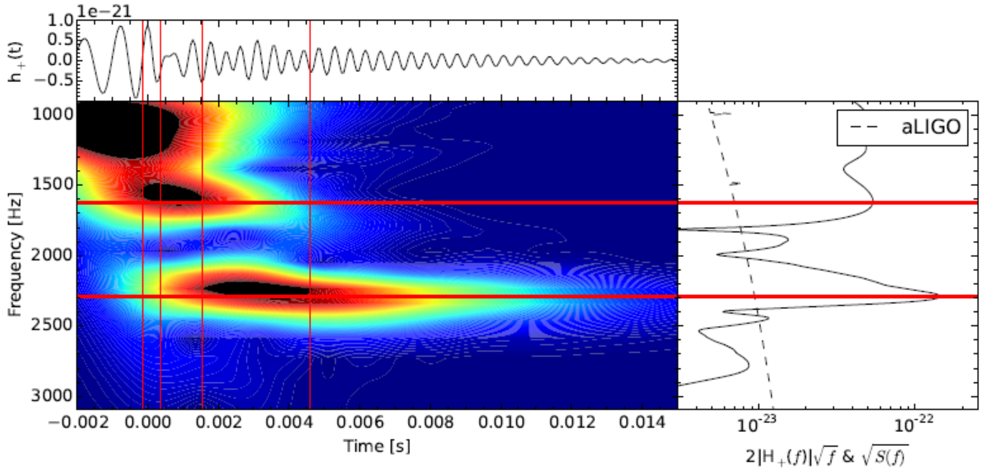


Post merger neutron stars

1. Direct connection to EM observables and many important problems in transient astronomy: Shot Gamma-Ray burst, Kilonova

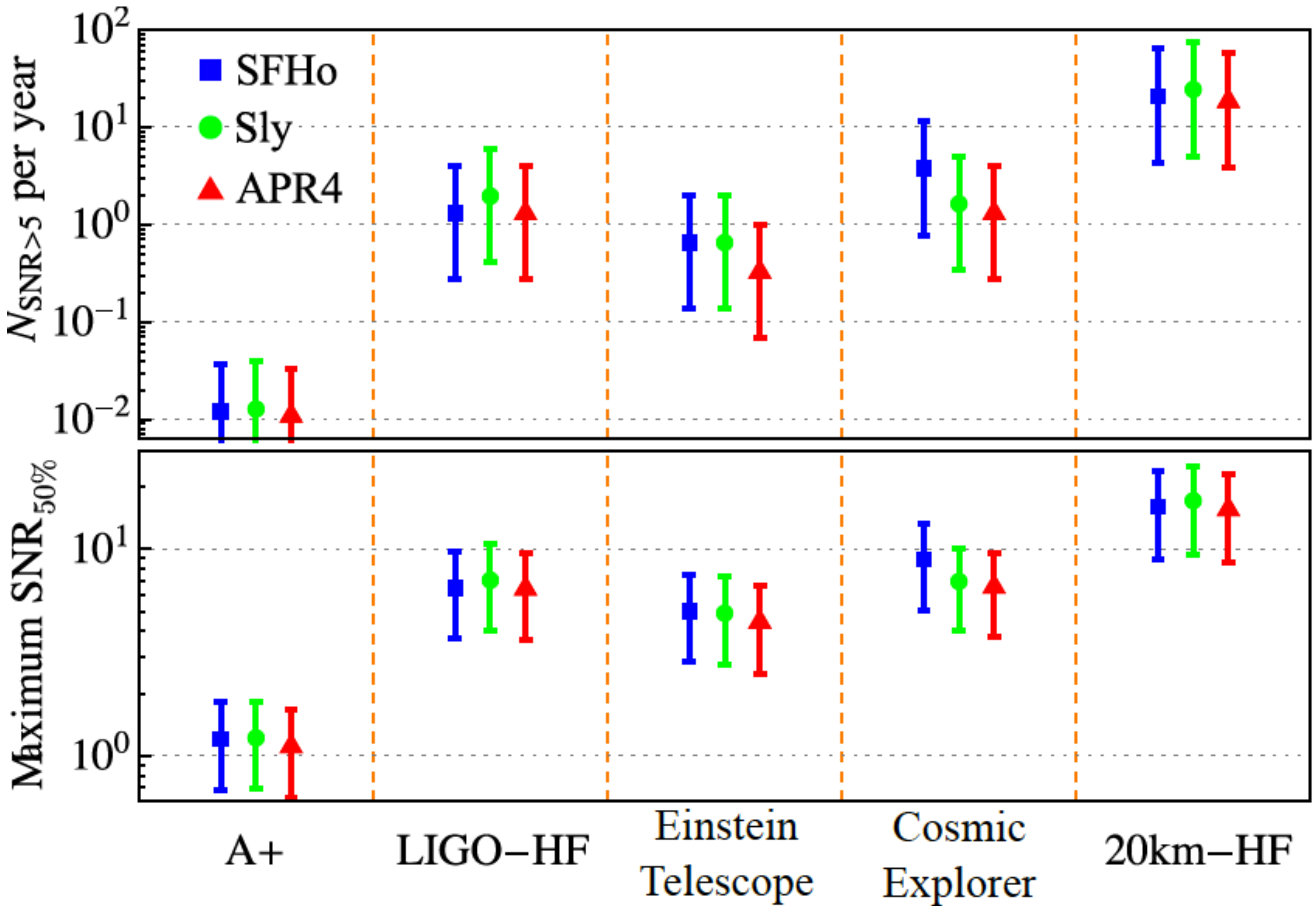
2. Numerical simulations contain large theoretical uncertainties: results do not converge with different resolution; missing physics (e.g., neutrino transport, fully resolved magneto-hydrodynamics); parameter space poorly researched (eccentricity, mass ratio, magnetic field configuration, spin, EOS…)

3. Waveforms cannot be used for matched-filter analysis.



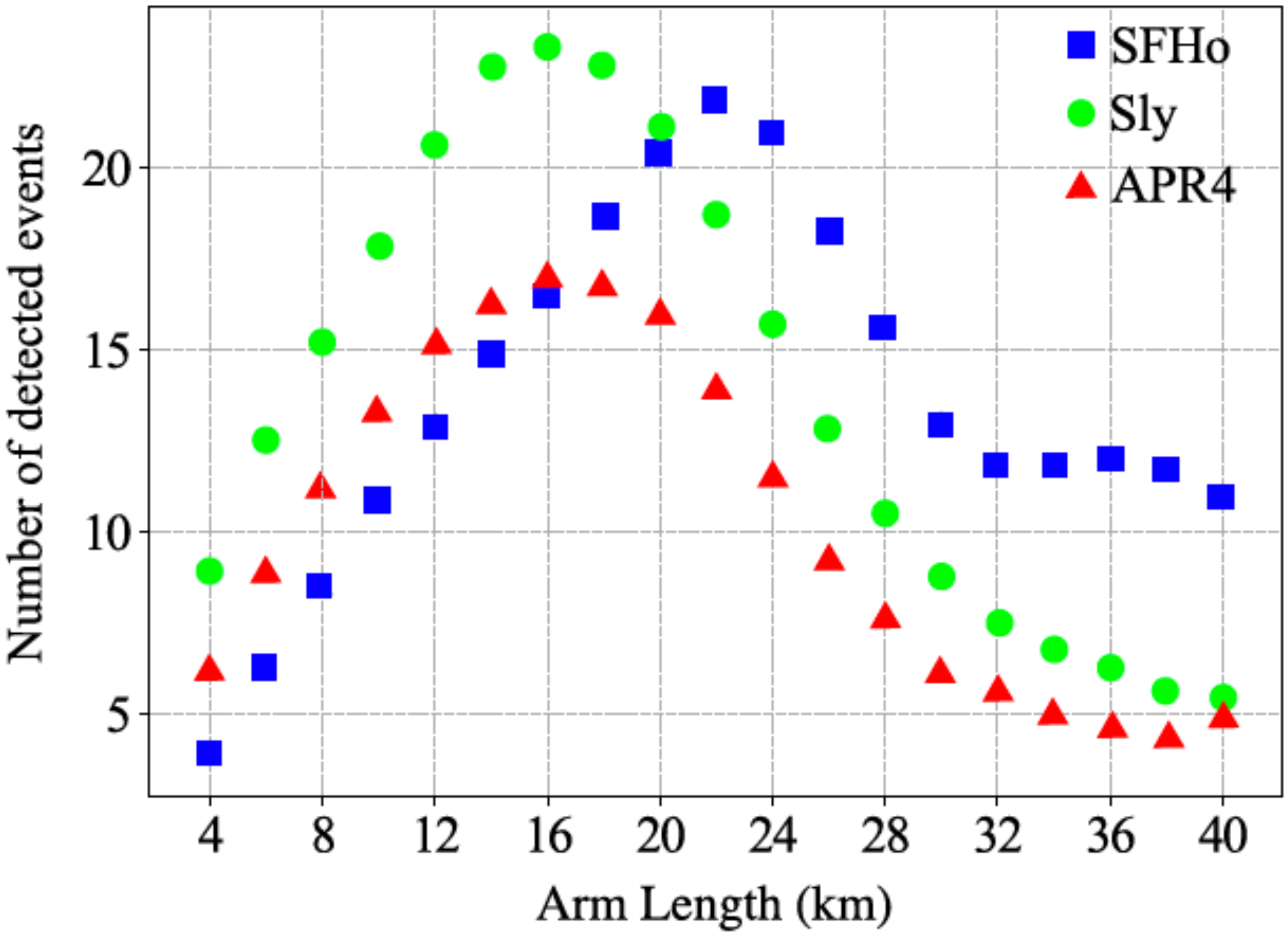
J. Cark et al, 2014

Event SNR



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

Event SNR



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

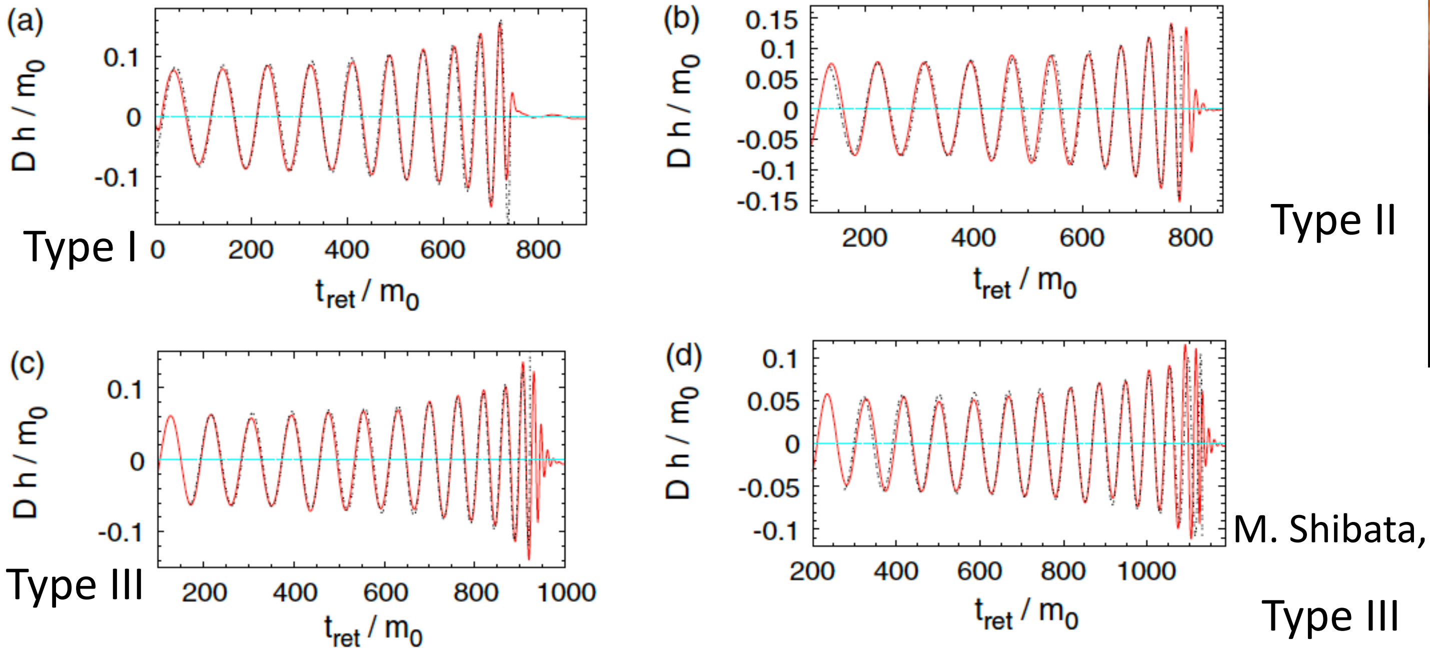
Neutron star-black hole merger

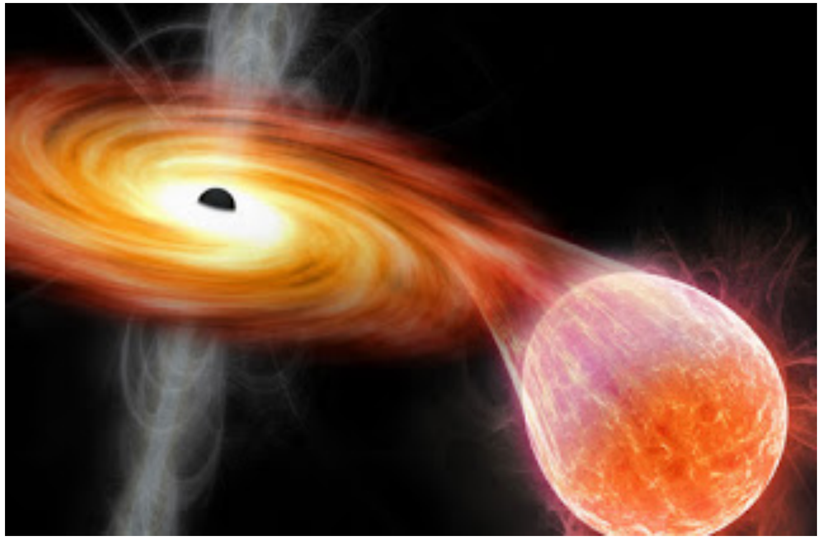
1. Generic mergers can be classified into three categories

I. Tidal disruption outside ISCO.

II. Tidal disruption within ISCO.

III. No tidal disruption, only black hole ringdown.



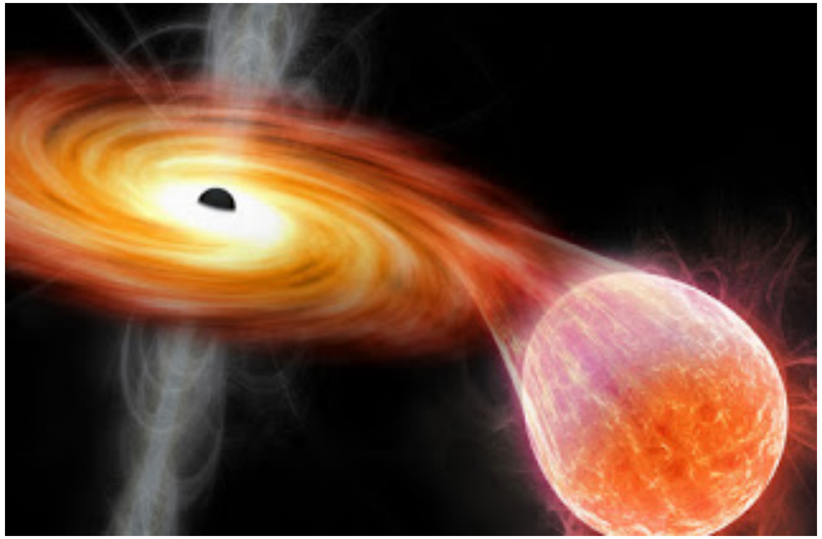


M. Shibata, K. Kyutoku, T. Yamamoto, K. Taniguchi, 2009

2. Nontrivial electromagnetic emission associated with the tidal disruption.

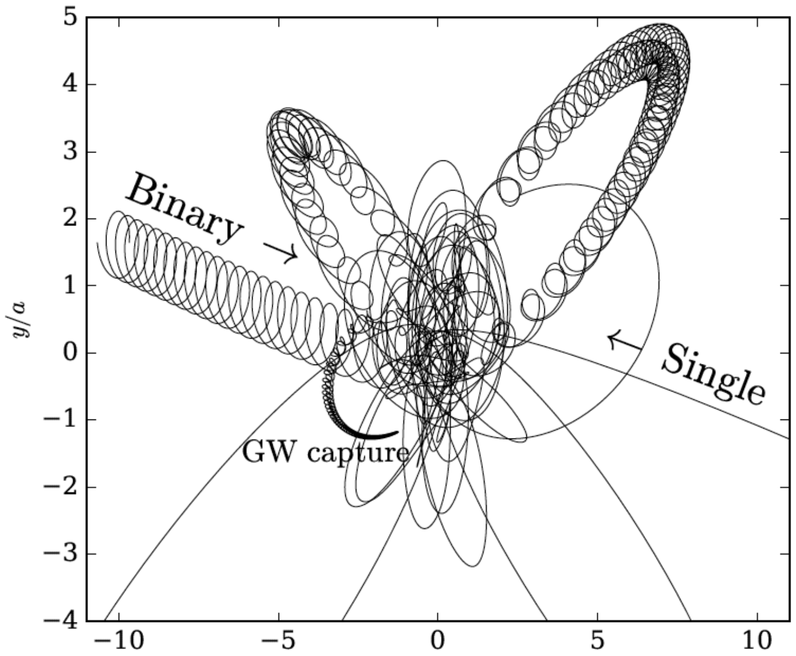
Neutron star-black hole merger

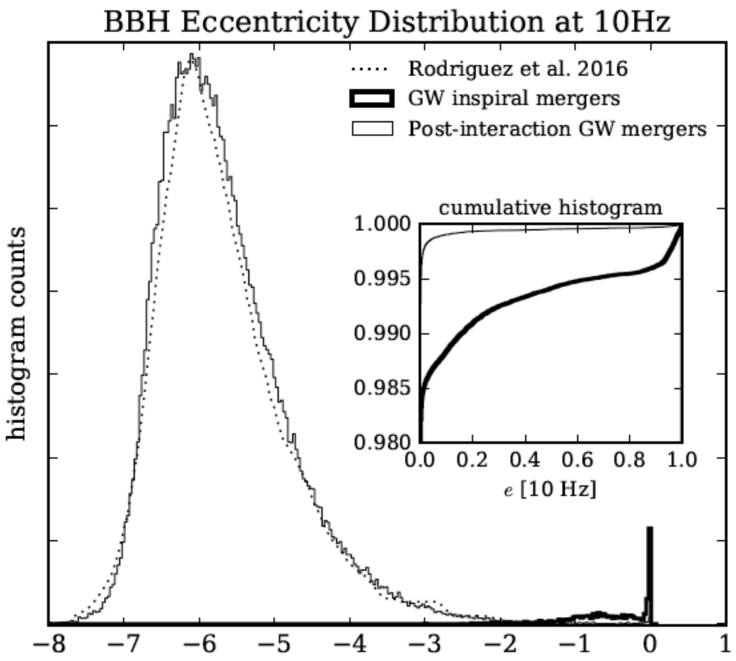
	Type I	Type II	Type III
LIGO-HF	1.59	3.65	4.05
Einstein Telescope	1.37	2.44	2.98
Cosmic Explorer	2.00	3.27	4.18
20 km-HF	4.86	10.98	12.61

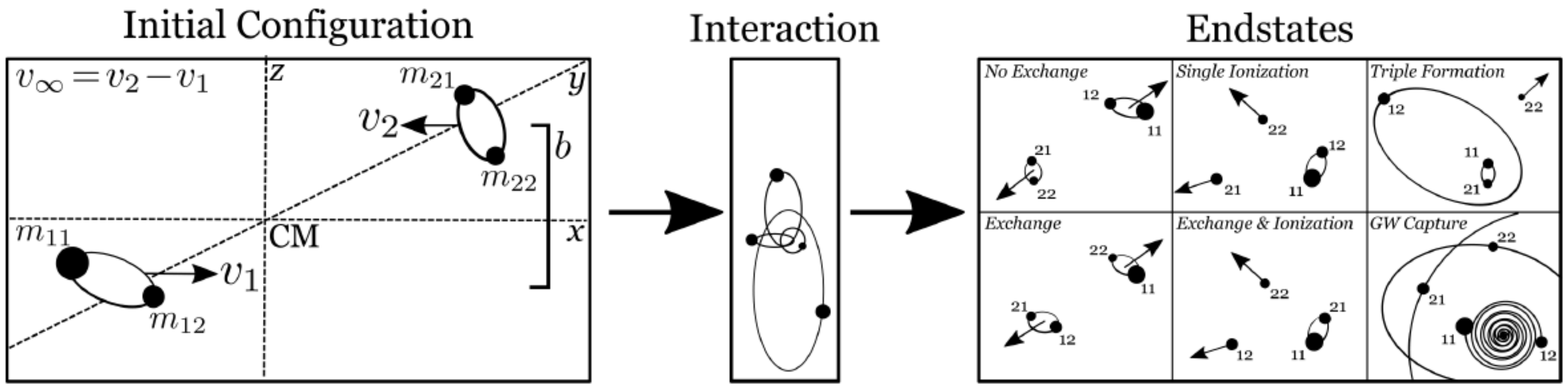


SNR starting from tidal disruption @100 Mpc

f-mode excitation in eccentric binary neutrons stars



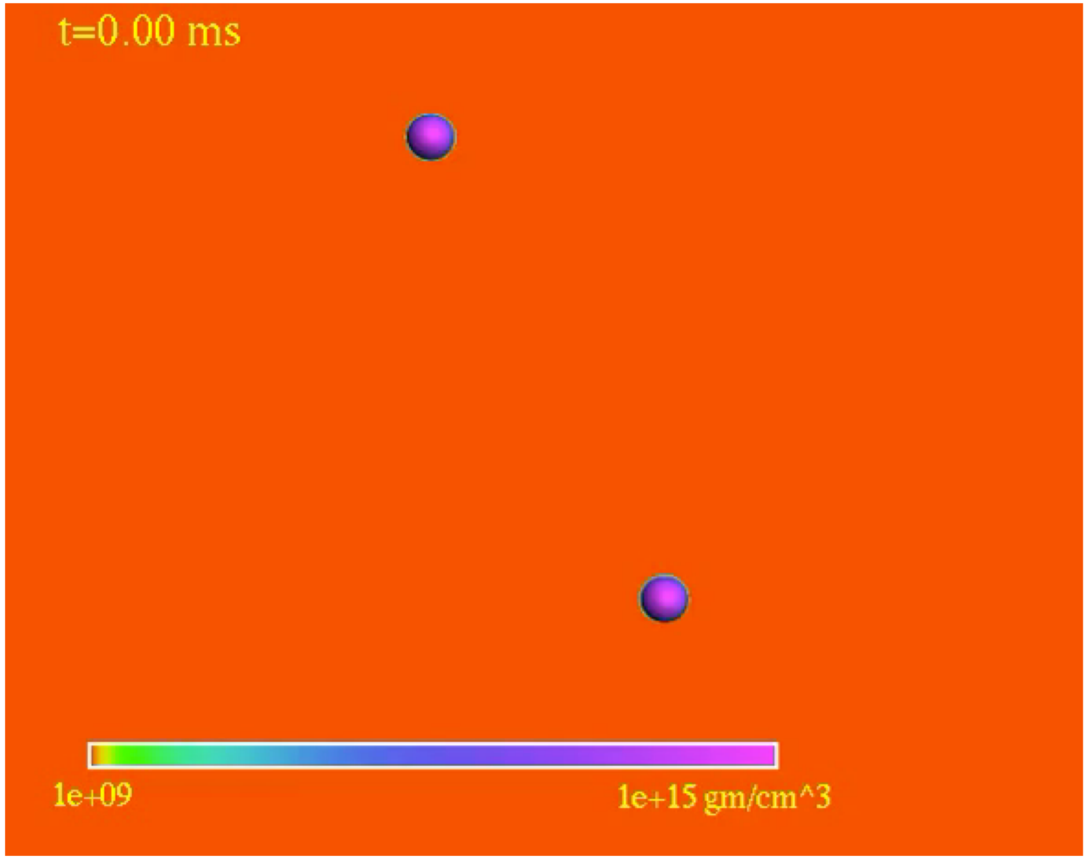


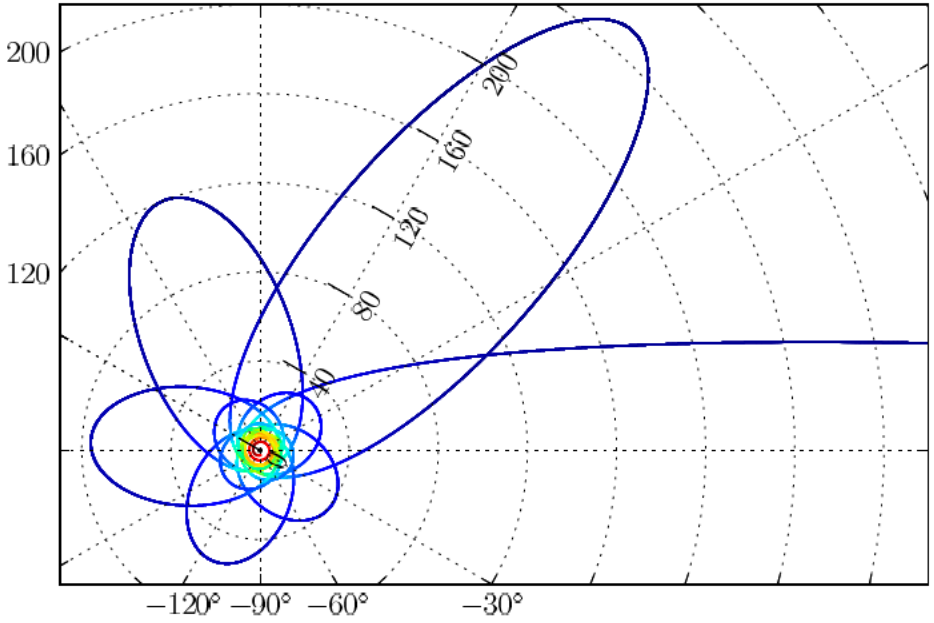


J. Samsing, E. Ramirez-Ruiz, ApJL 840, L14, 2017
Zevin et al., ApJ 871, 1, 2019

f-mode excitation in eccentric binary neutrons stars

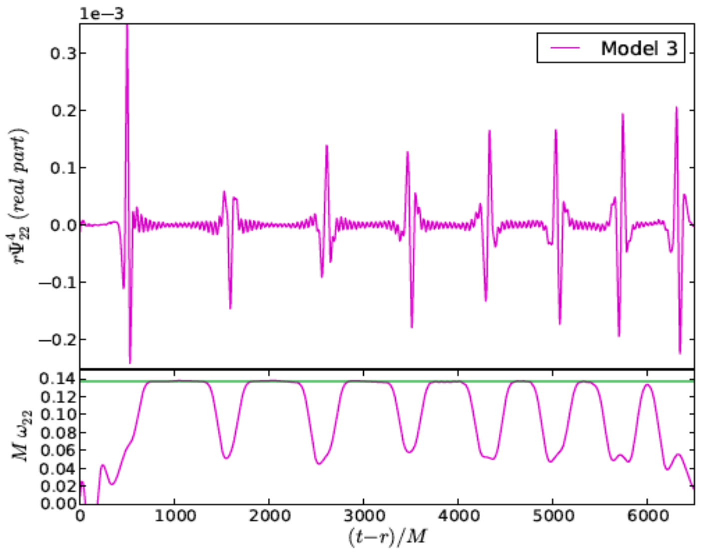
- Eccentric binaries can be produced by:
  - Dynamic capture.
  - Hierarchical triples with Kozai-Lidov mechanism.
  - Binary-binary/binary-single interaction, dynamical scattering or exchange …

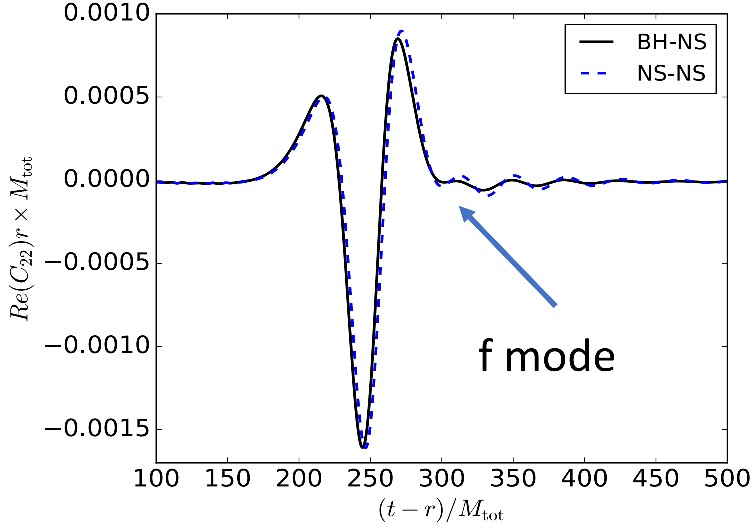




Courtesy of William East

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:

$$\mathrm{SNR} \sim 30 \left(\frac{2E_{\rm mode}}{E_{\rm GW}}\right)^{1/2} \left(\frac{50Mpc}{d}\right) \left(\frac{5\times 10^{-25}\mathrm{Hz}^{-1/2}}{\sqrt{S_n}}\right) \left(\frac{2000\mathrm{Hz}}{f}\right)$$

H0 measurement without EM counterpart

- Binary neutron star waveforms are similar to binary black hole waveforms, except tidal effects + post-merger emission.

- Constraints from tidal love number:

	SLY	APR4	SFHo
A+	0.147	0.173	0.148
LIGO-HF	0.055	0.064	0.056
Einstein Telescope	0.038	0.043	0.038
Cosmic Explorer	0.027	0.032	0.03
20 km-HF	0.017	0.020	0.017

Love number accuracy @ 100 Mpc

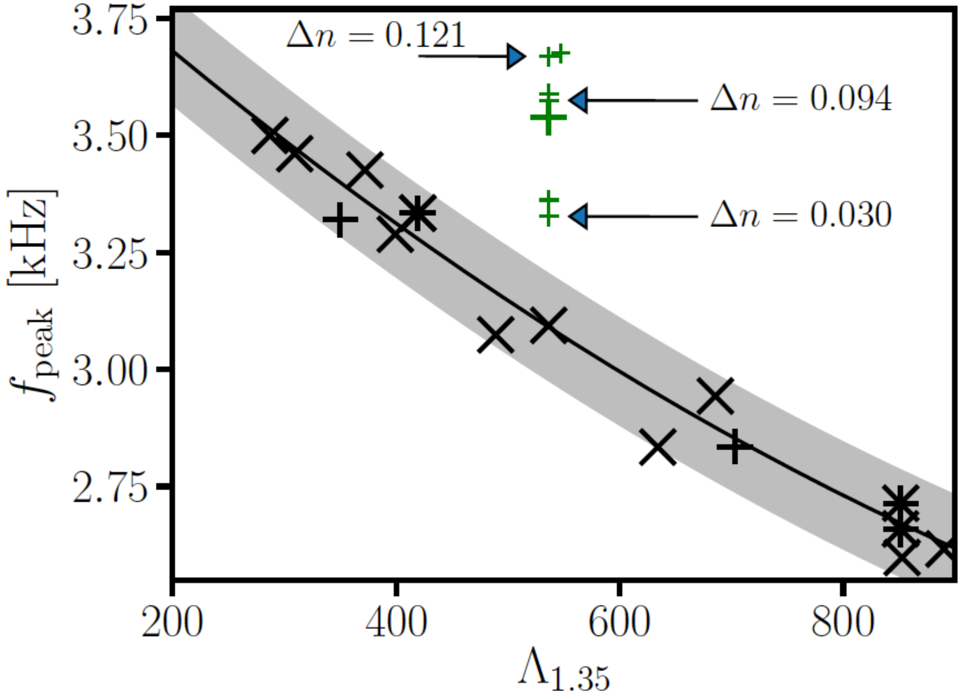
	SLY	APR4	SFHo
A+	1.009	1.206	1.008
LIGO-HF	0.384	0.448	0.383
Einstein Telescope	0.259	0.310	0.259
Cosmic Explorer	0.187	0.195	0.186
20 km-HF	0.119	0.139	0.119

Redshift accuracy @ z=0.01

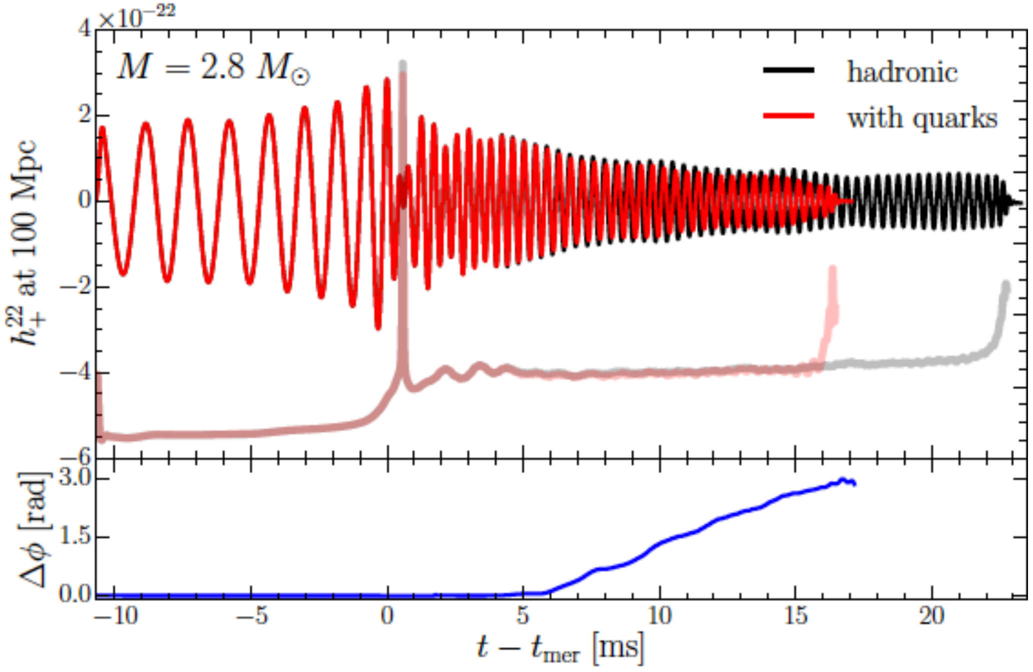
- Constraints from post-merger signal is comparable (within a factor of 2).

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



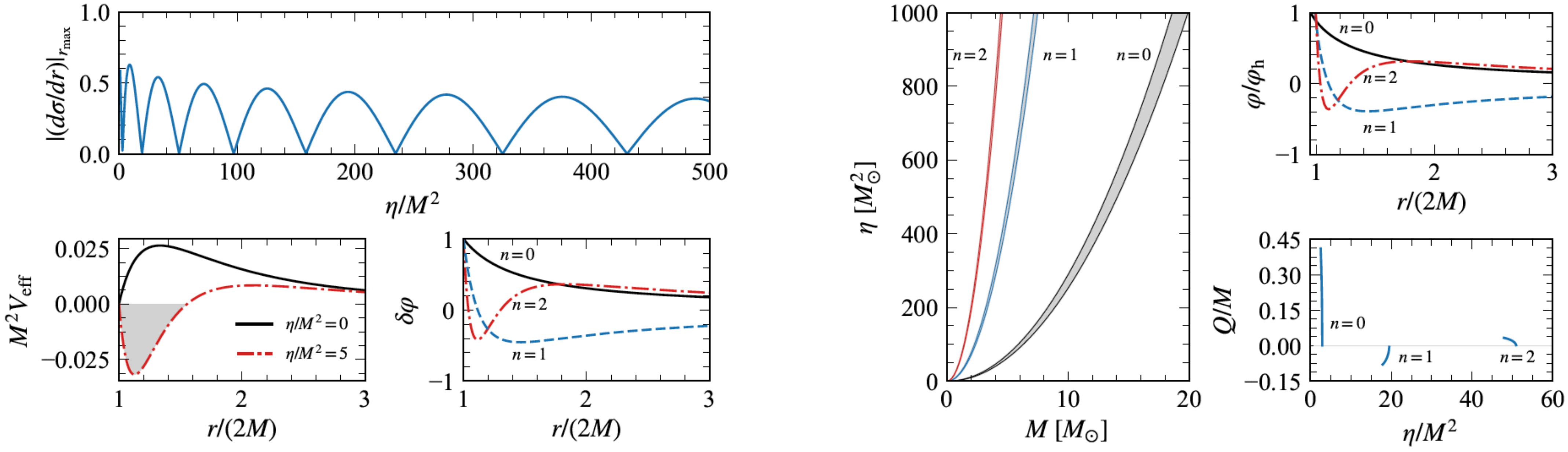
E. Most et al, PRL 2019

Test gravity with low-mass black holes

- Modified gravity theories contain coupling parameters with length dimensions:

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

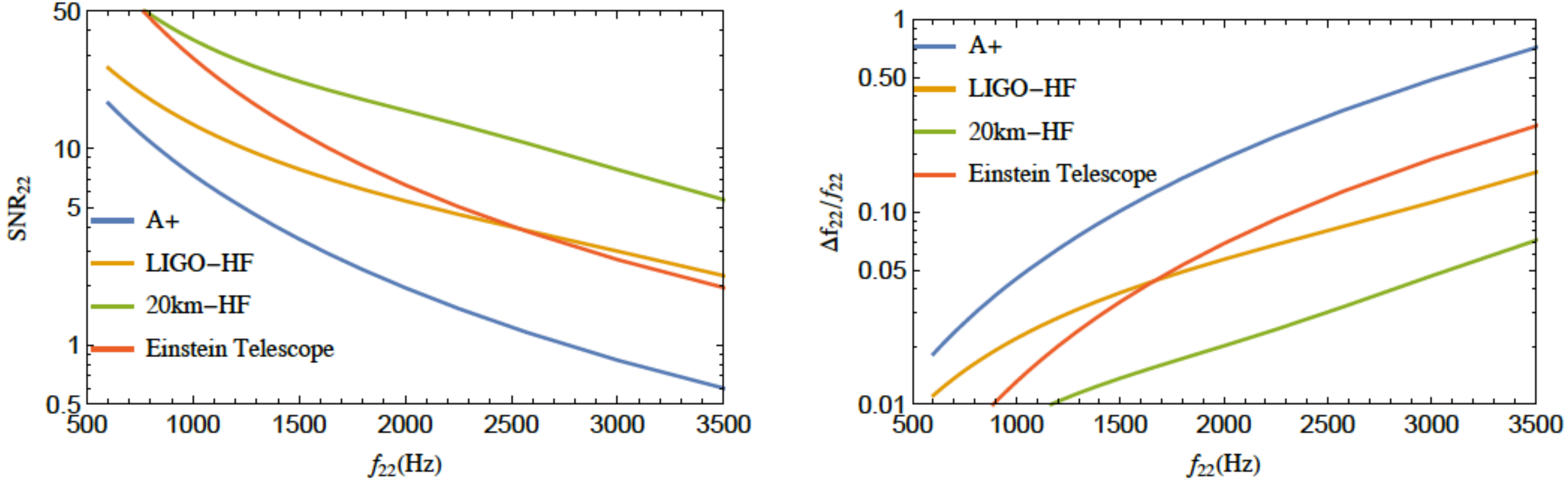
- Certain behavior only happens for low-mass black holes, e.g., spontaneous scalarization in Gauss-Bonnet gravity:



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.