UNIVERSITY OF BIRMINGHAM

INSTITUTE OF GRAVITATIONAL WAVE ASTRONOMY

LIGO Scientific Collaboration

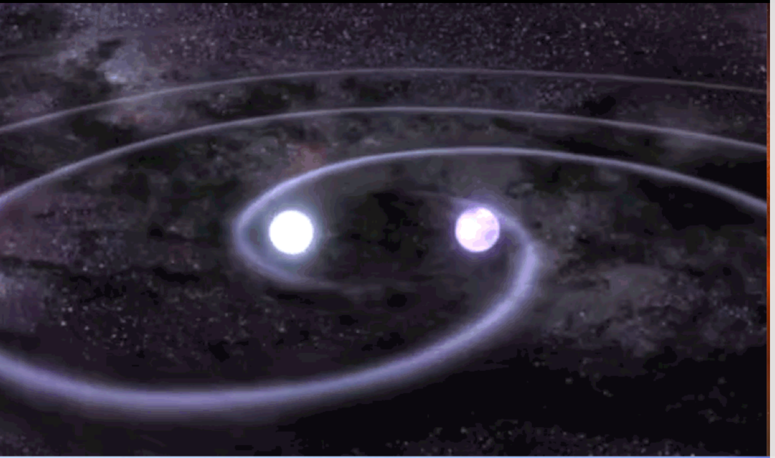
Path Towards kHz Gravitational-Wave Astronomy

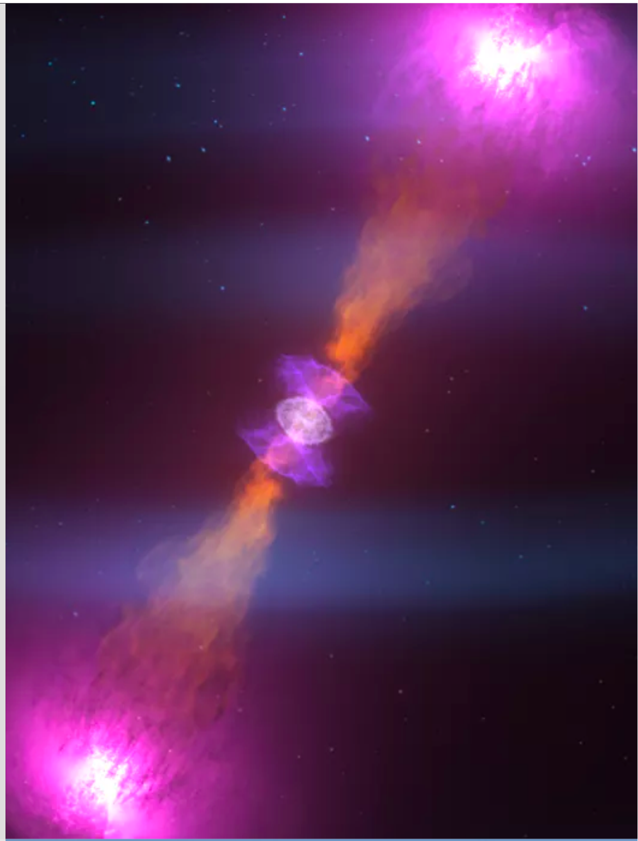
Denis Martynov, Haixing Miao, and Huan Yang

Based upon:

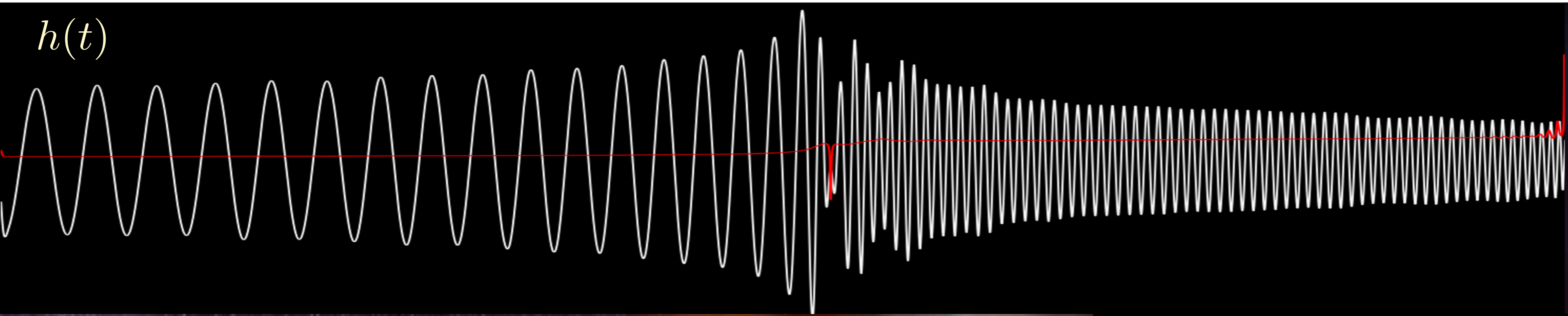
Denis Martynov, Haixing Miao, Huan Yang, Francisco Hernandez Vivanco, Eric Thrane, Rory Smith, Paul Lasky, William E. East, Rana Adhikari, Andreas Bauswein, Aidan Brooks, Yanbei Chen, Thomas Corbitt, Andreas Freise, Hartmut Grote, Yuri Levin, Chunnong Zhao, and Alberto Vecchio, *Exploring the sensitivity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

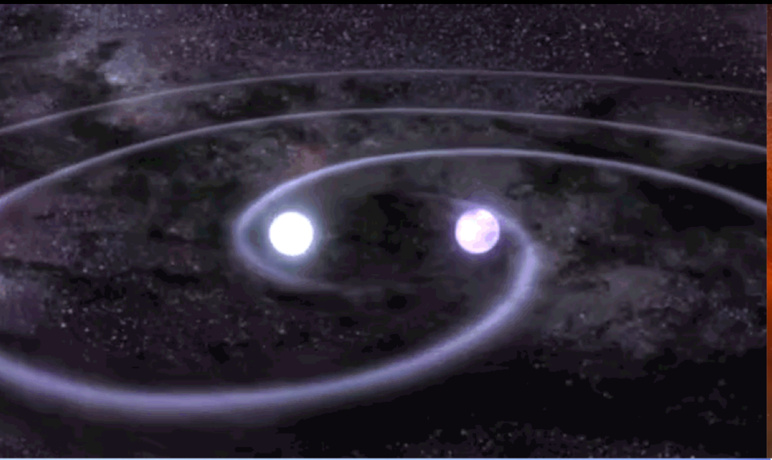
GW170817

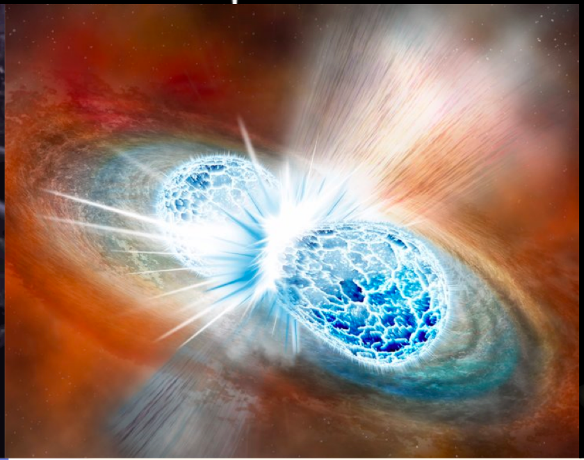


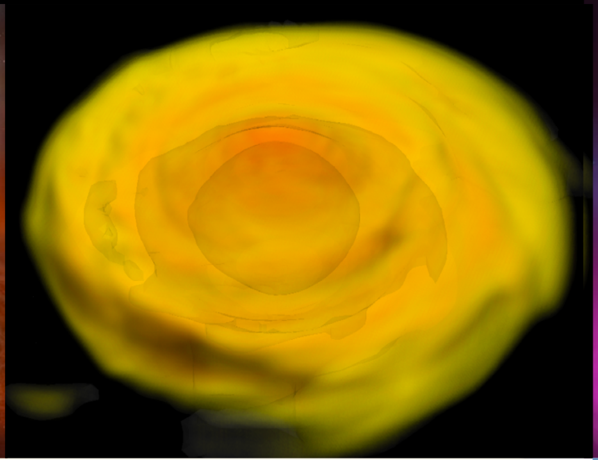


GW170817



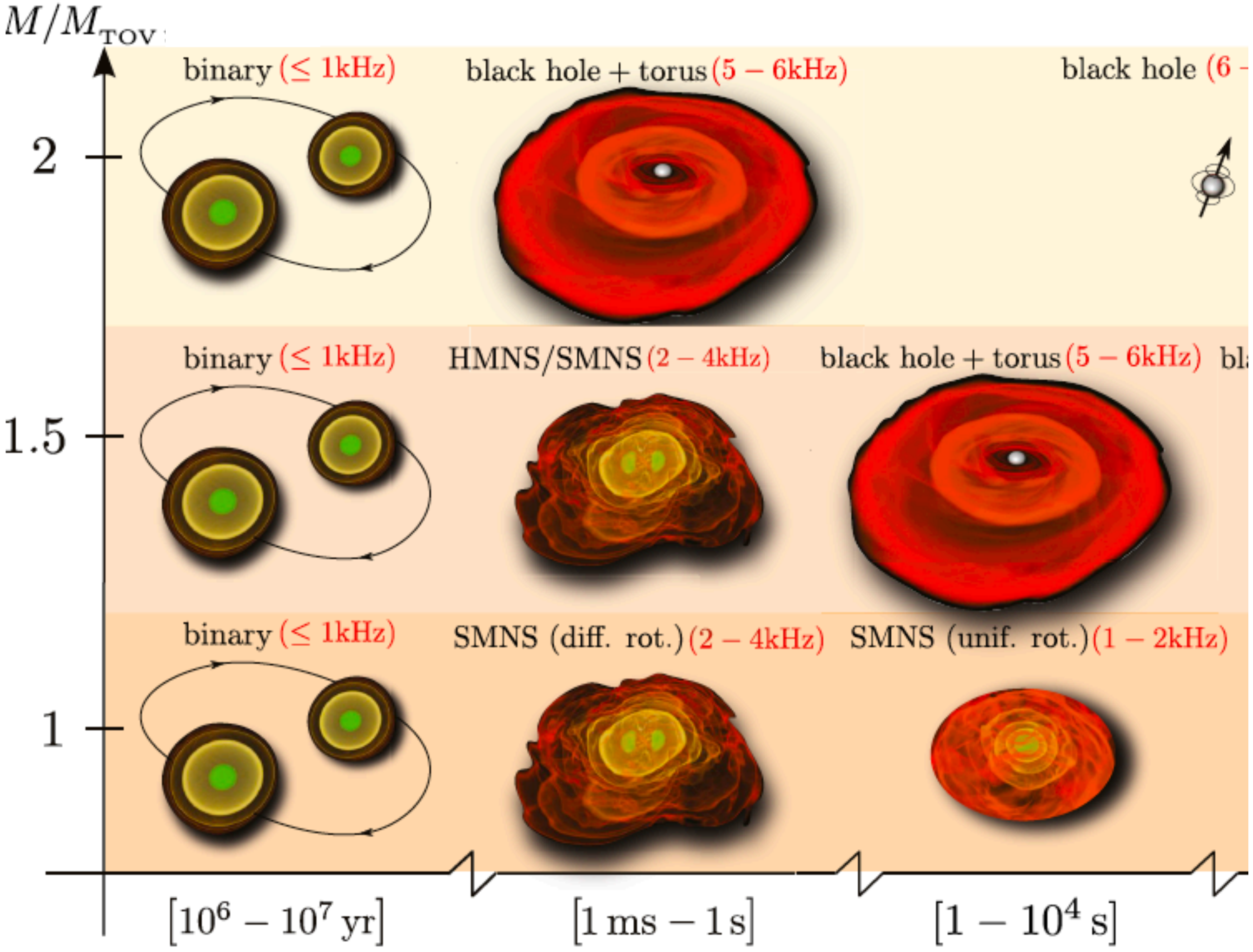


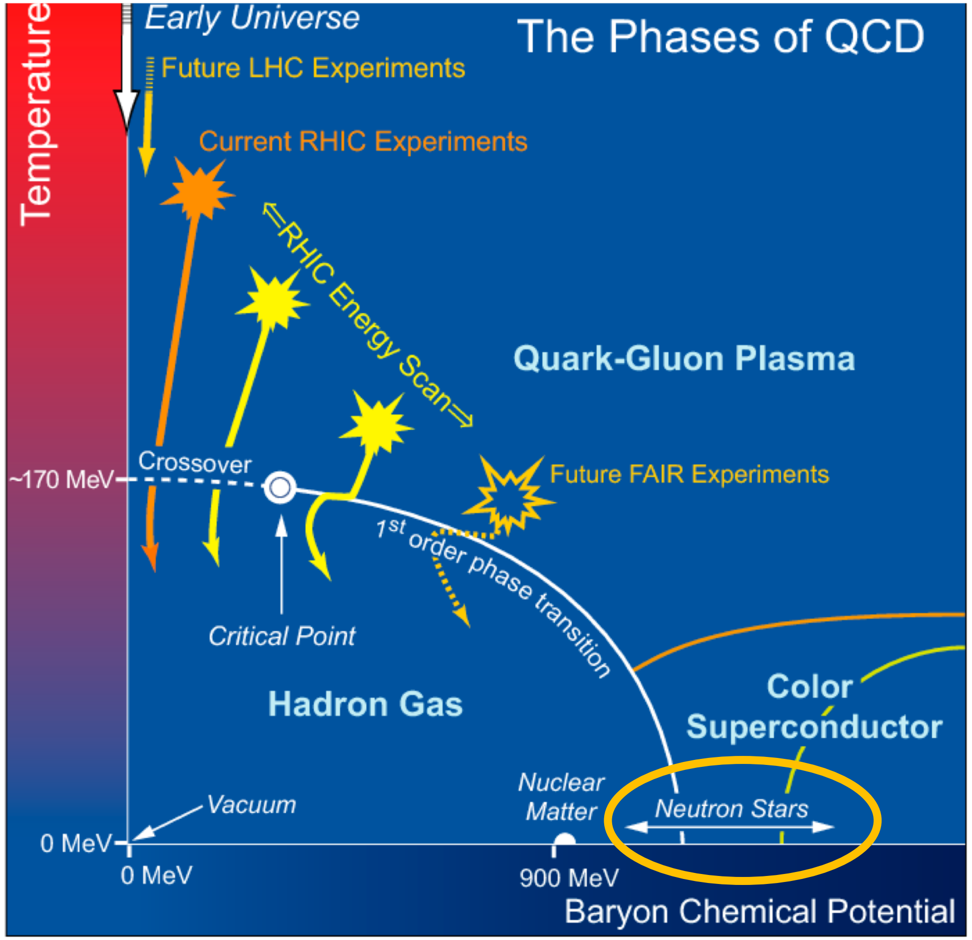




kHz GW detectors

Exploring New Physics at Merger and Post-merger

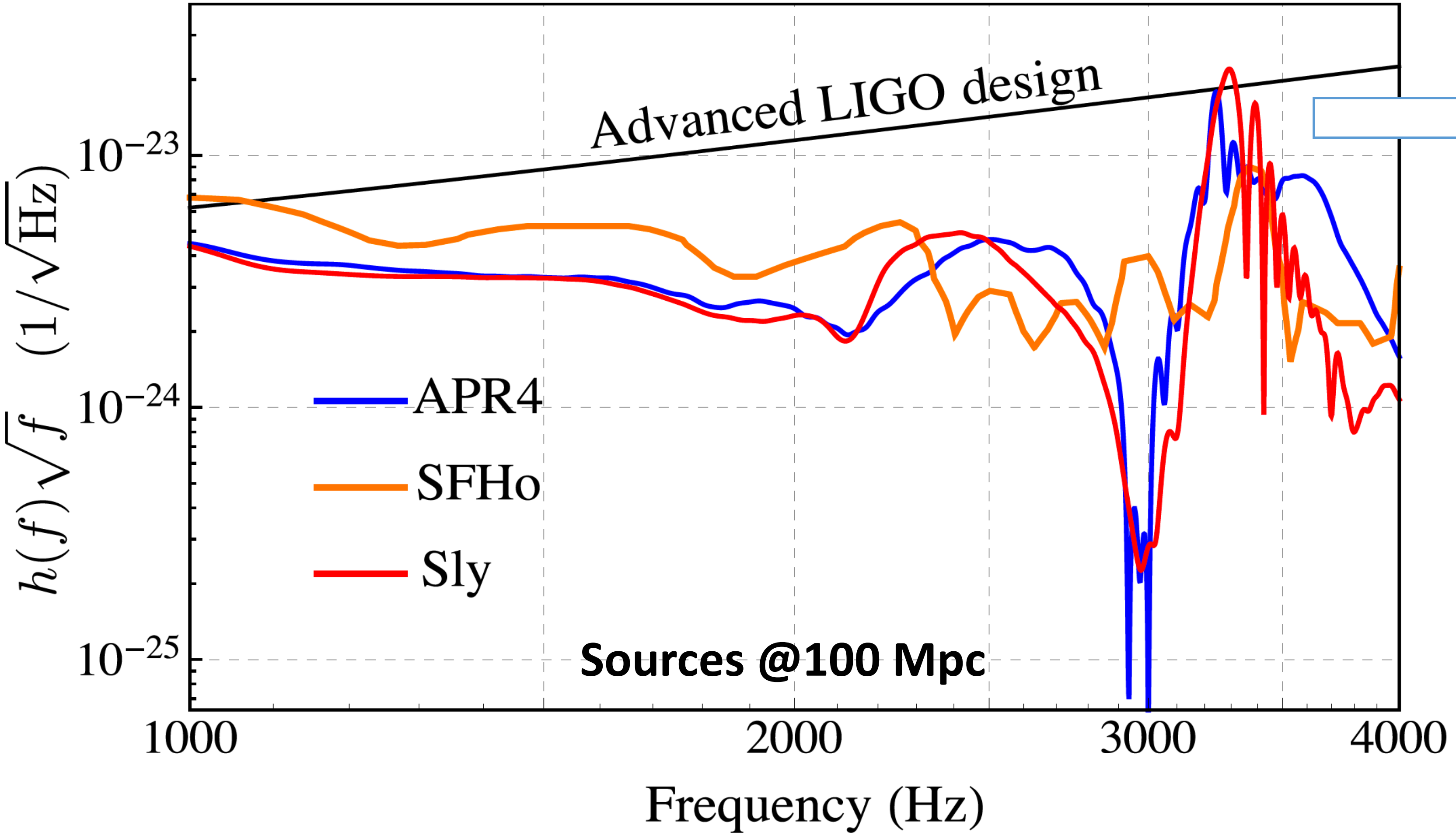


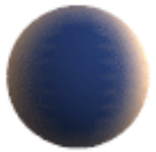


L. Baiotti, and L. Rezzolla, *Binary neutron star mergers: a review of Einstein's richest laboratory*, Rep. Prog. Phys. **80**, 096901 (2017).

A cosmic collider

Challenge of Detecting Post-merger Signals



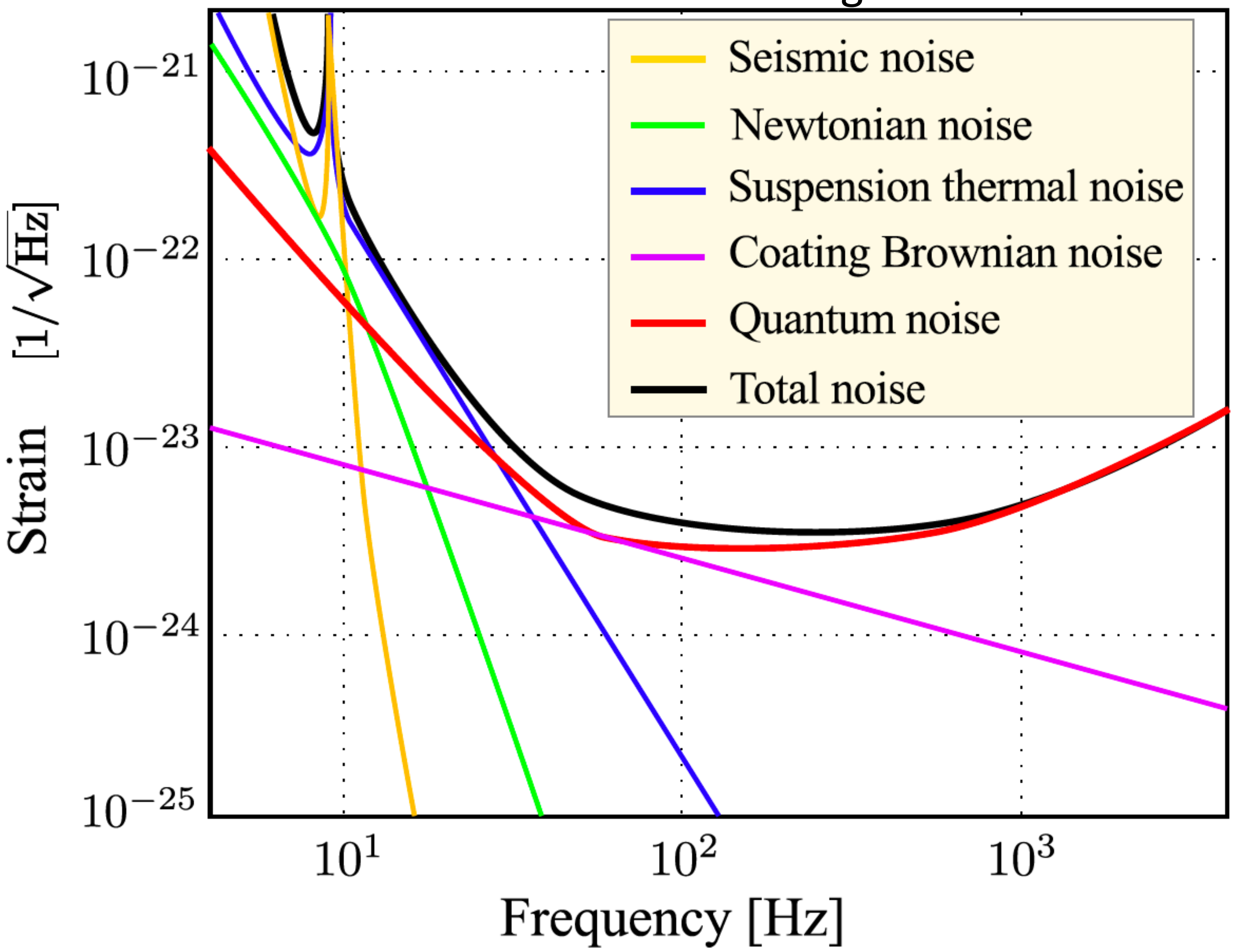


Fundamental (2, 2) mode of post-merger remnants

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

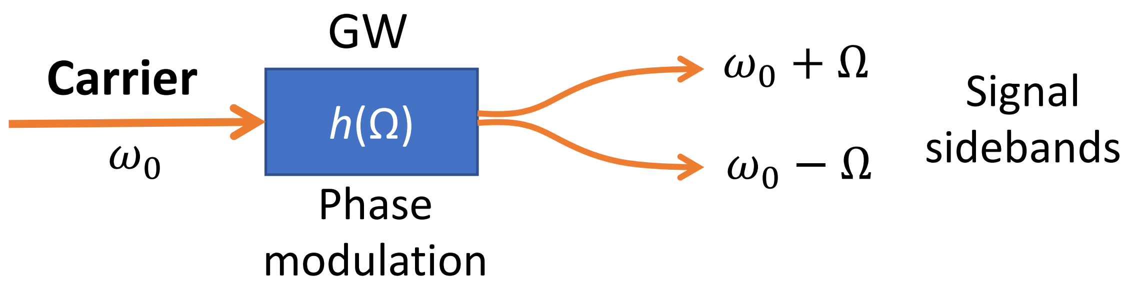
Limiting Fundamental Noises Above 1kHz

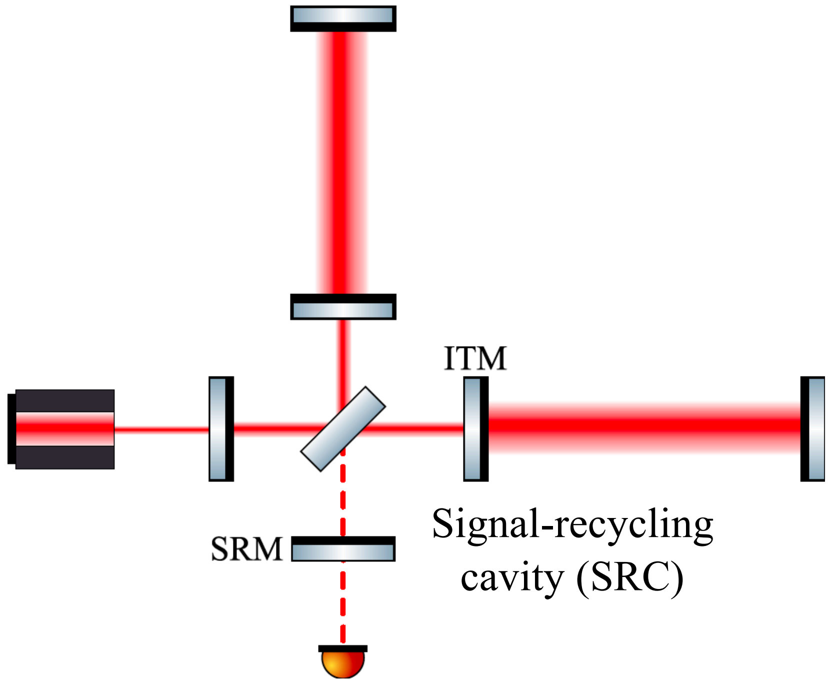
Advanced LIGO design



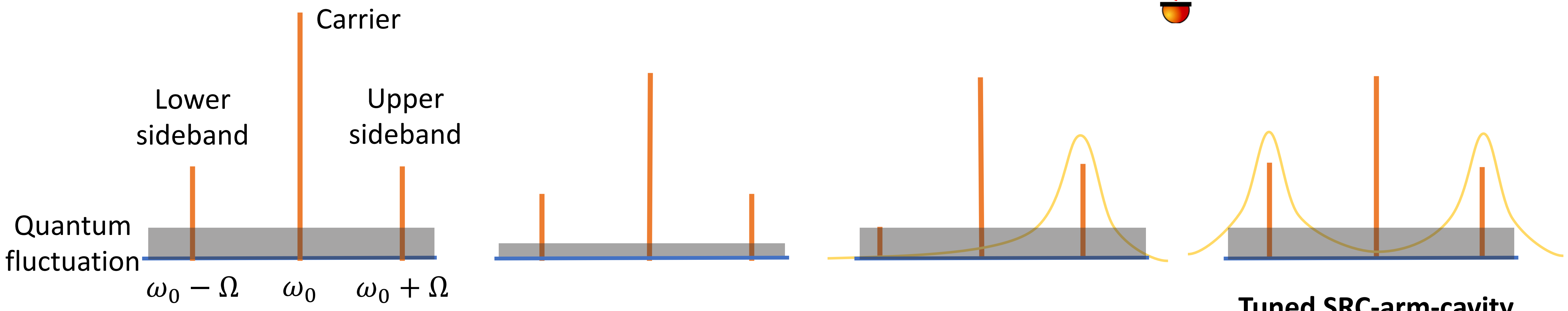
coating thermal noise and **shot noise**

How to Reduce Shot Noise





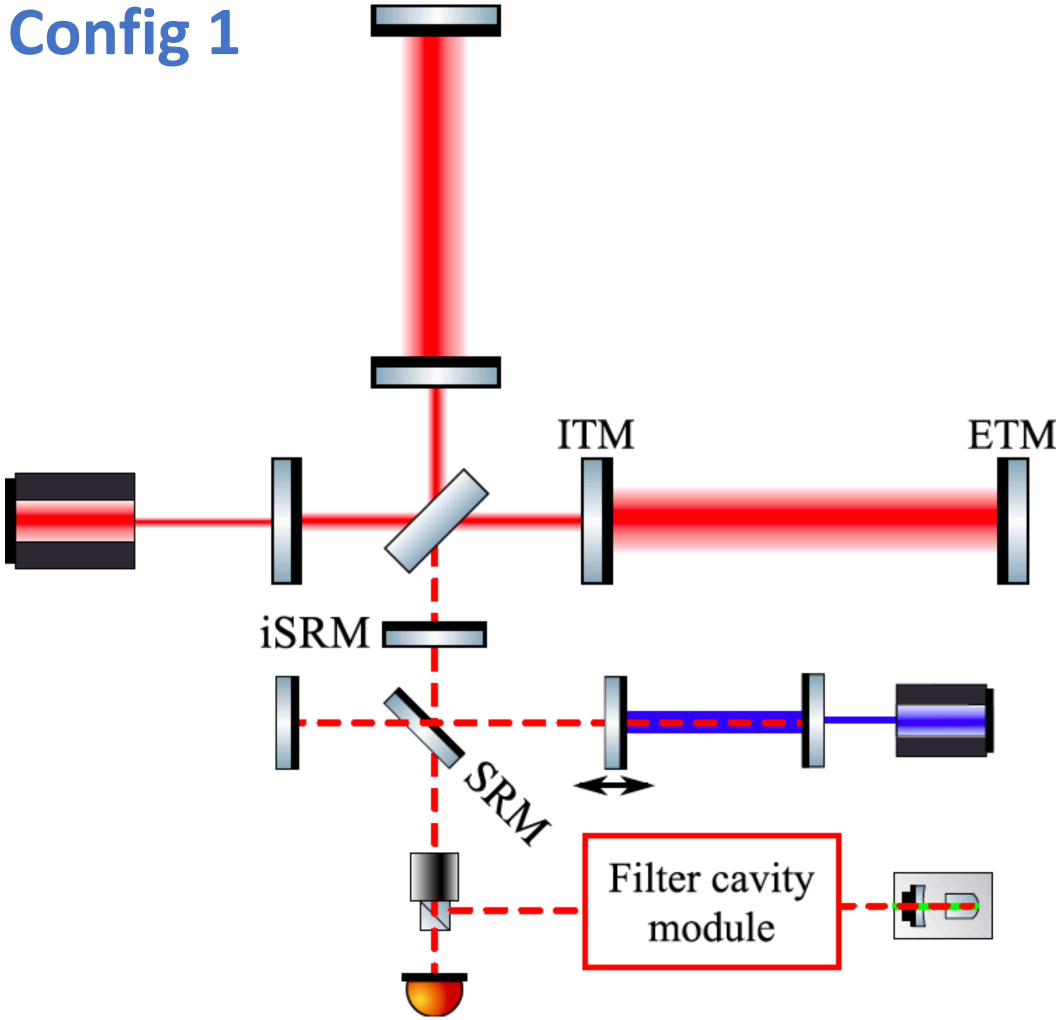
Different approaches:



Increase power **Squeezing** **Detuned SRC** **Tuned SRC-arm-cavity coupled resonance**

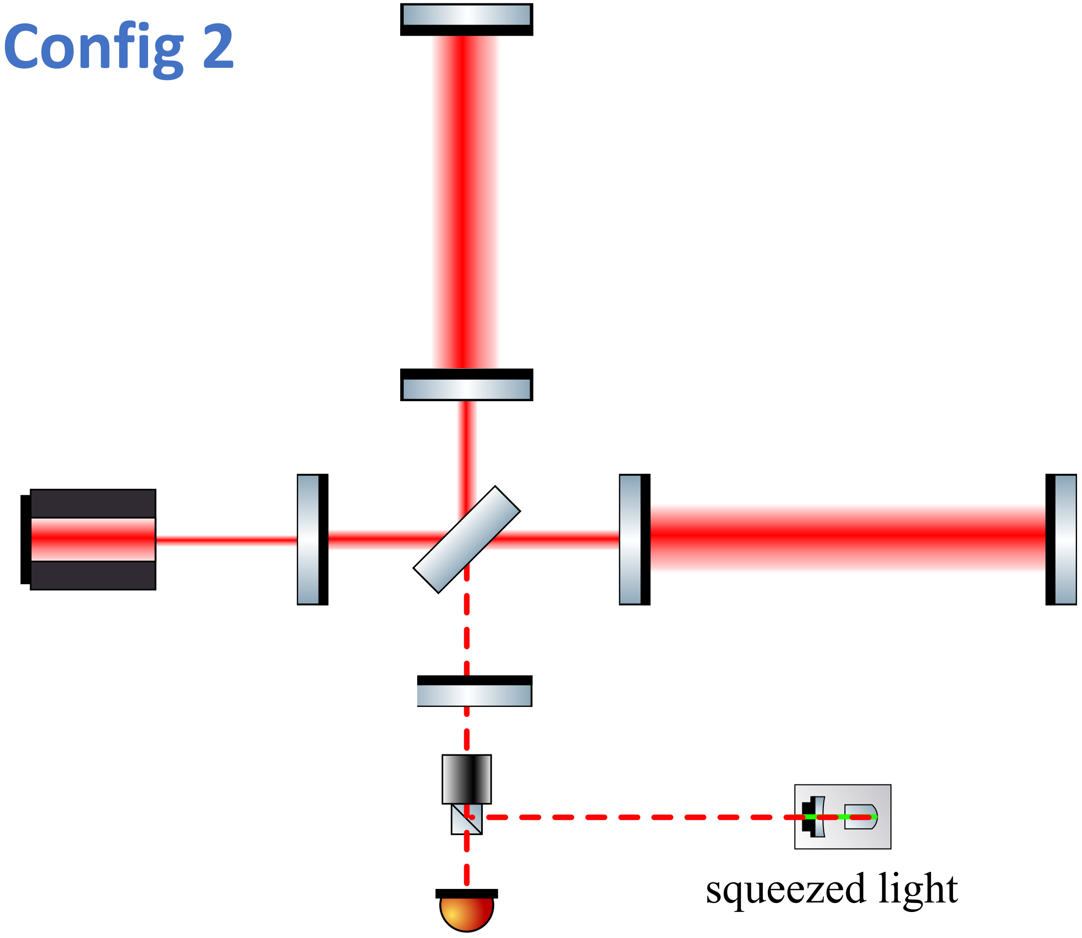
How to Reduce Shot Noise

Config 1



Detuned SRC with active optomechanical filter
[Phys. Rev. D **98**, 044044 (2018)]

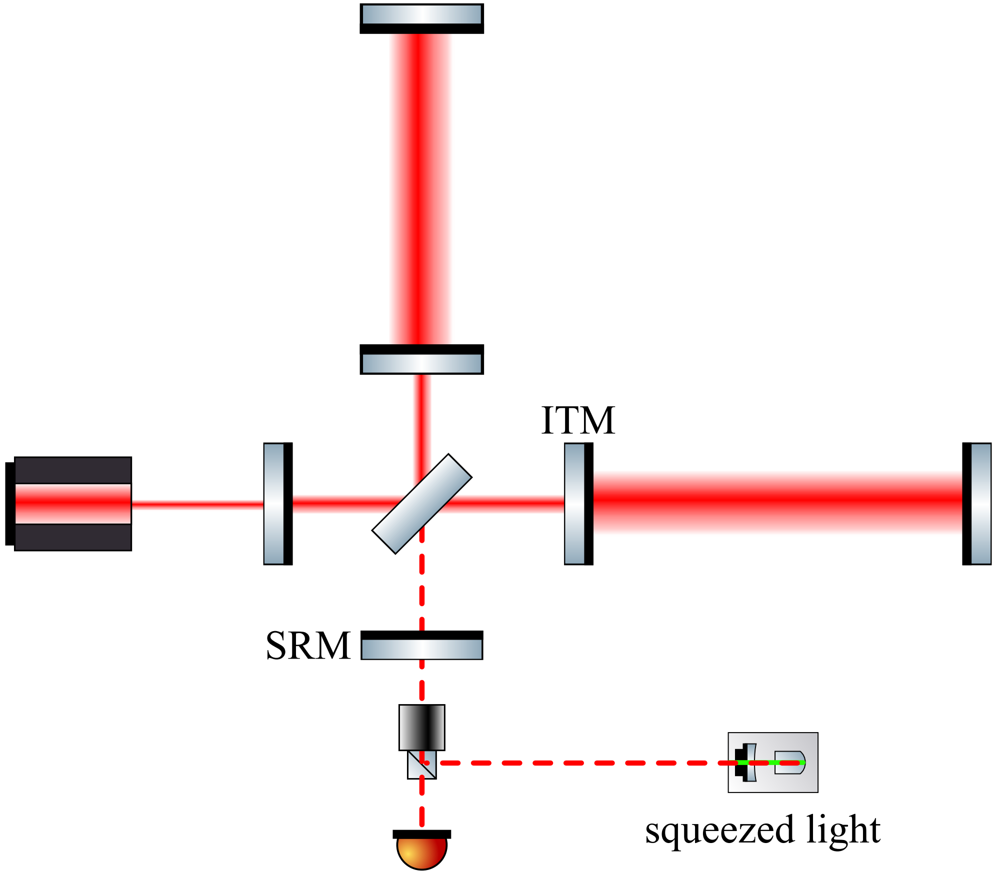
Config 2

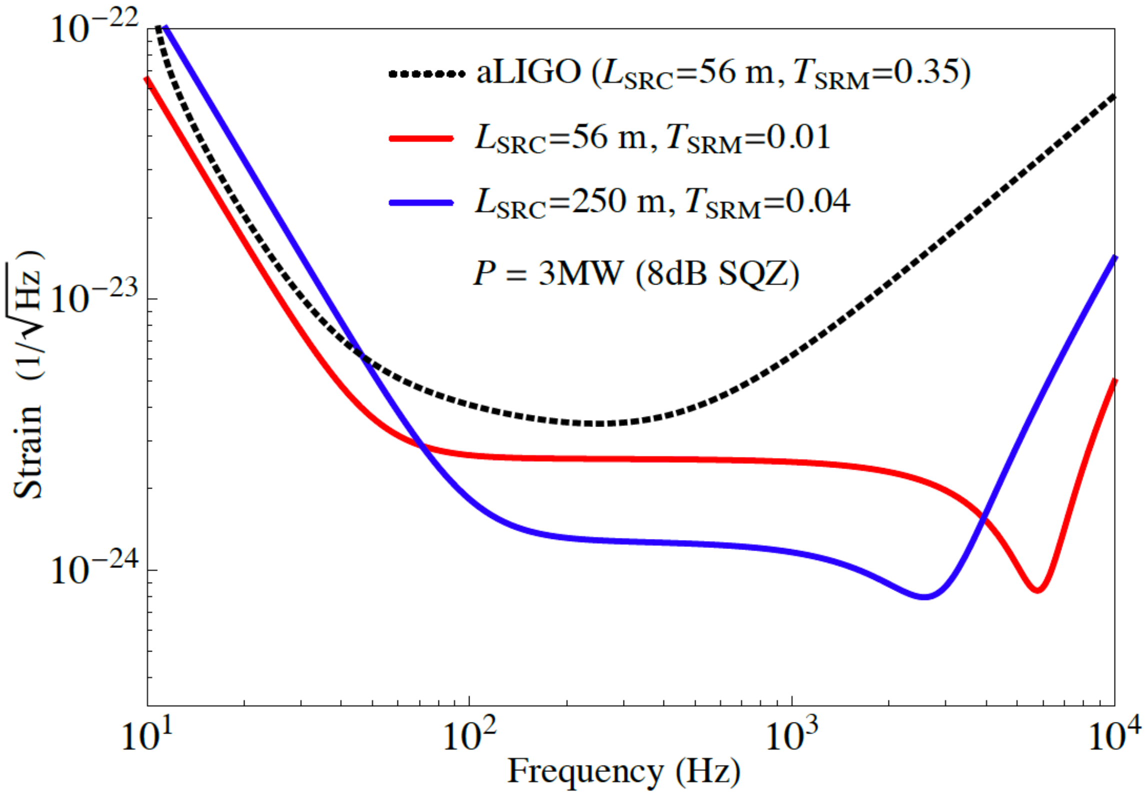


Tuned SRC
(coupled SRC-arm-cavity resonance)

Tuned Configuration

Configuration:





Same principle as twin-signal-recycling

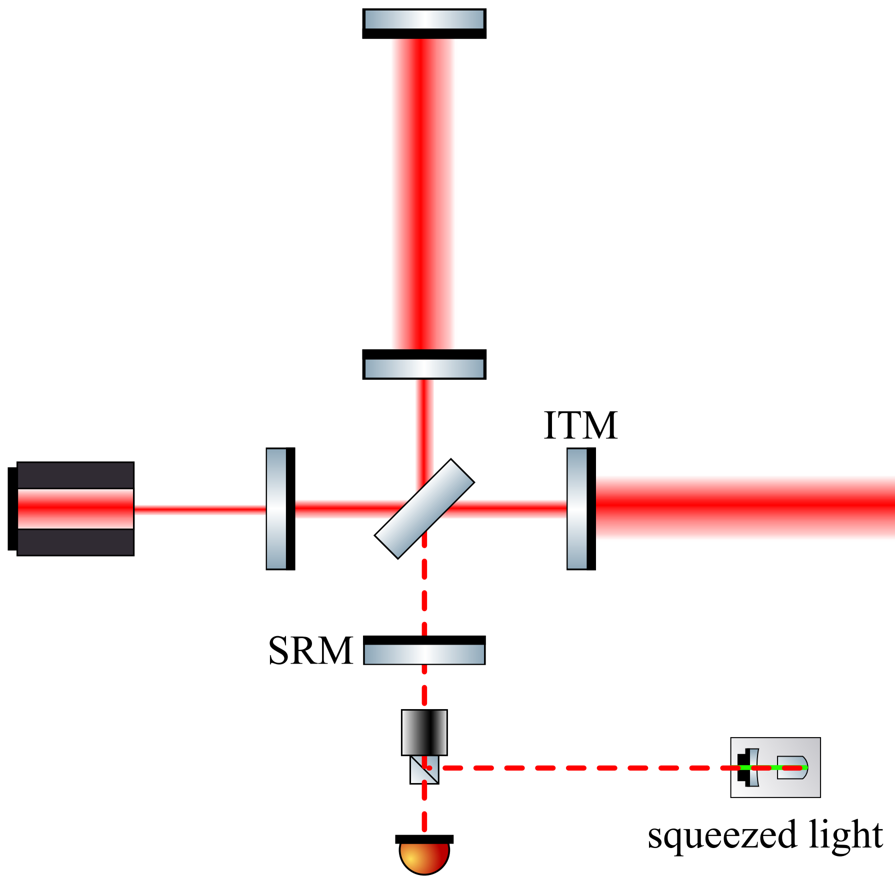
A. Thüring, R. Schnabel, H. Lück, K. Danzmann (2007)

Coupled SRC-arm-cavity resonance:

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

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:

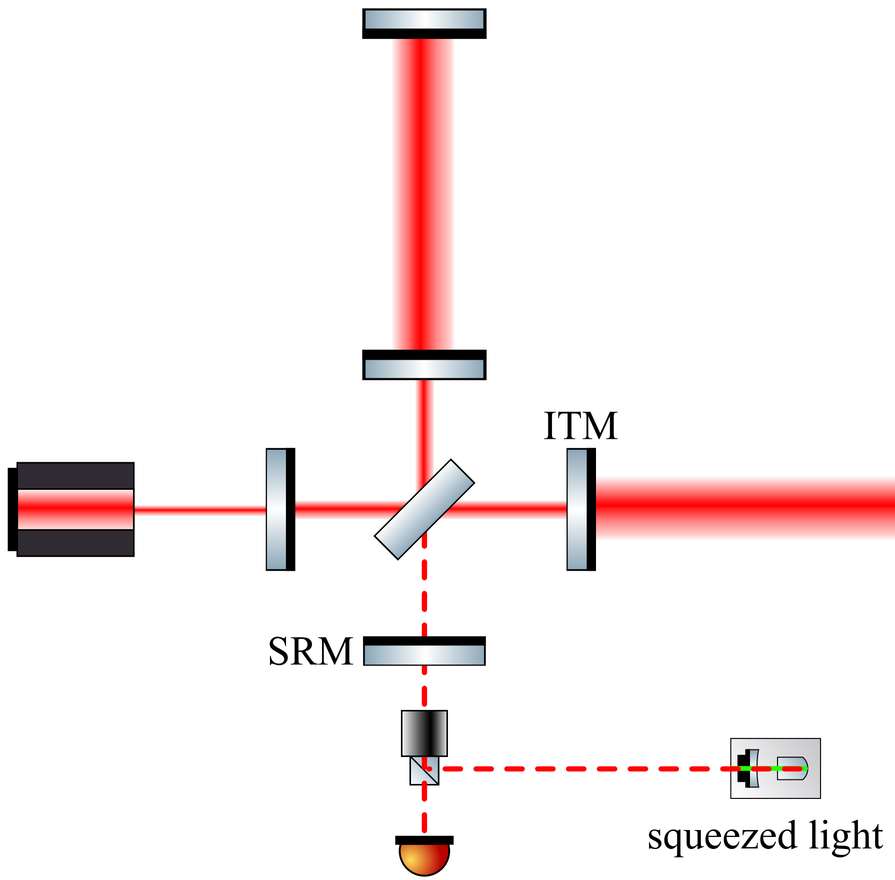
$$\frac{10^{-24}}{\sqrt{\text{Hz}}}\sqrt{\left(\frac{3\,\text{MW}}{P}\right)\left(\frac{\lambda}{1064\,\text{nm}}\right)\left(\frac{\gamma/2\pi}{2\,\text{kHz}}\right)\left(\frac{4\,\text{km}}{L}\right)\left(\frac{10^{0.8}}{e^{2r_{\text{sqz}}}}\right)}$$

Different options:

Arm length	SRC length	Power	Squeezing
2 km	500 m	4 MW	10 dB
4 km	250 m	3 MW	8 dB
6 km	150 m	2 MW	8 dB

Reaching Target Sensitivity

Configuration:



Coupled SRC-arm-cavity resonance:

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

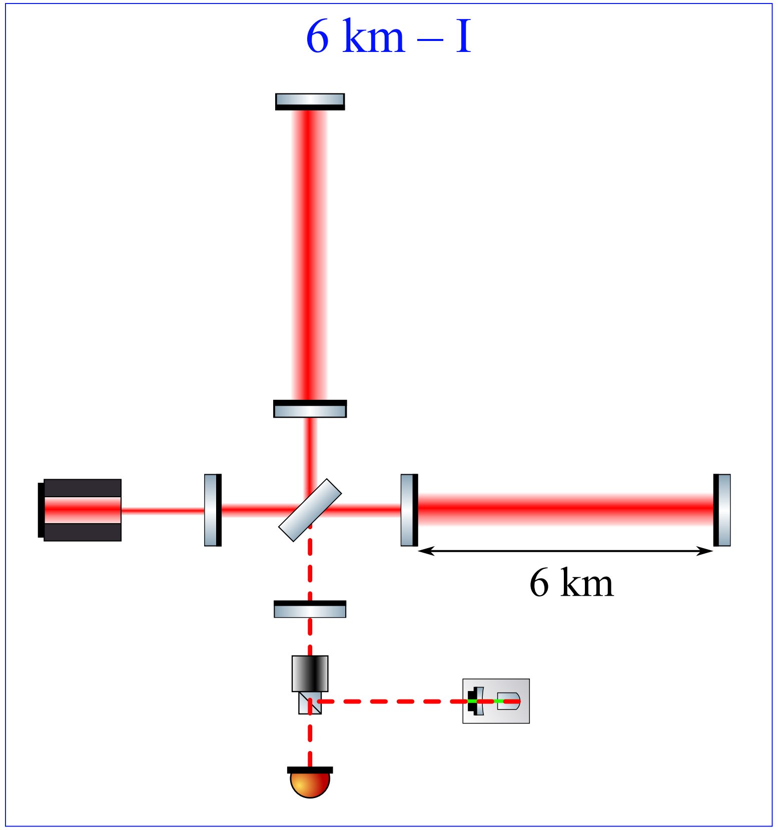
Shot-noise level:

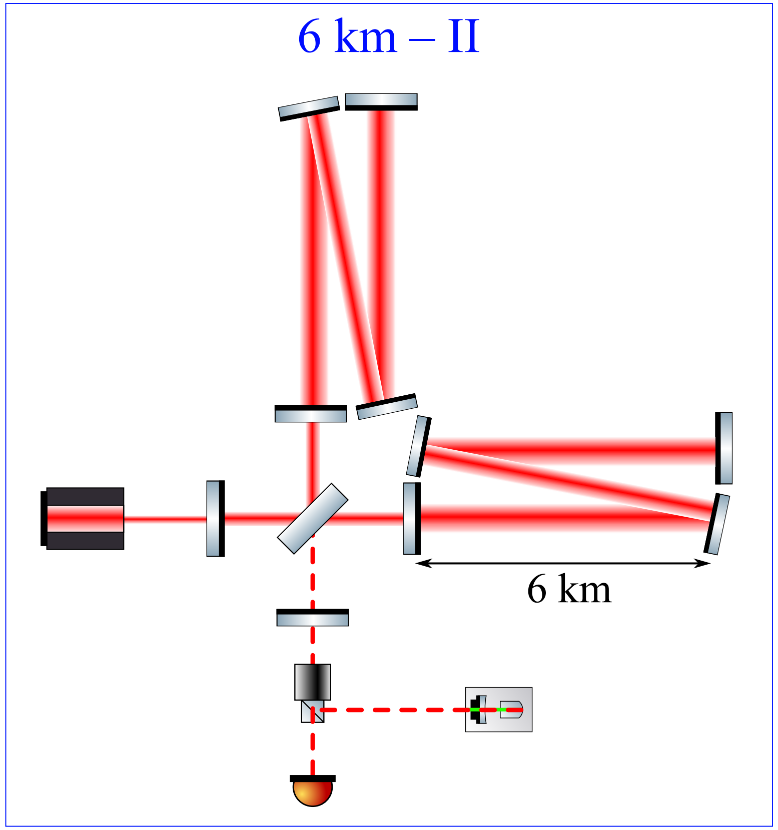
$$\frac{10^{-24}}{\sqrt{\mathrm{Hz}}}\sqrt{\left(\frac{3\,\mathrm{MW}}{P}\right)\left(\frac{\lambda}{1064\,\mathrm{nm}}\right)\left(\frac{\gamma/2\pi}{2\,\mathrm{kHz}}\right)\left(\frac{4\,\mathrm{km}}{L}\right)\left(\frac{10^{0.8}}{e^{2r_{\mathrm{sqz}}}}\right)}$$

Different options:

Arm length	SRC length	Power	Squeezing
2 km	500 m	4 MW	10 dB
4 km	250 m	3 MW	8 dB
6 km	150 m	2 MW	8 dB

6 km design





Phase-I

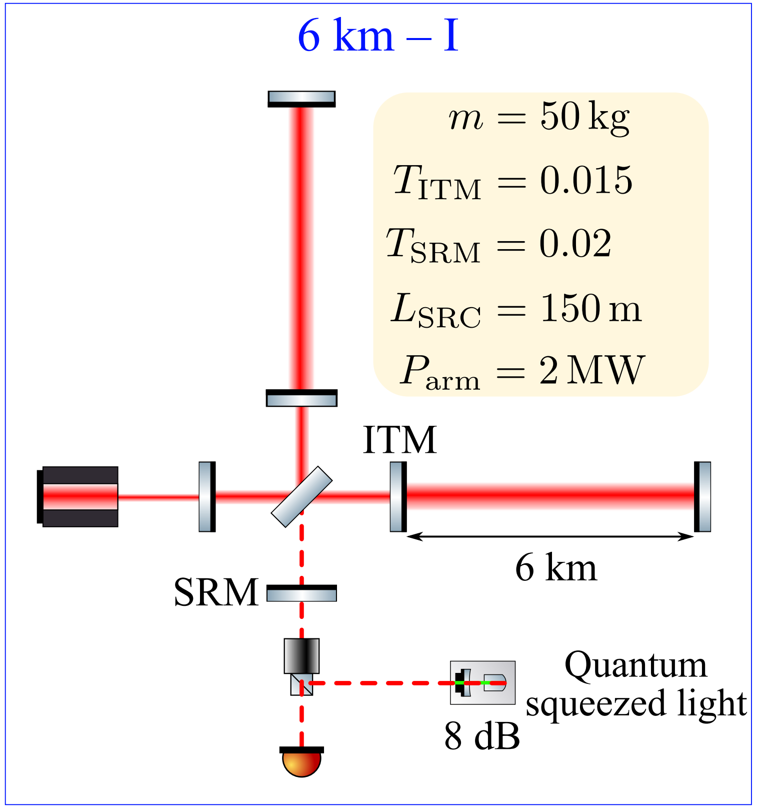
A balance of different physical requirements and being a 2.5G detector

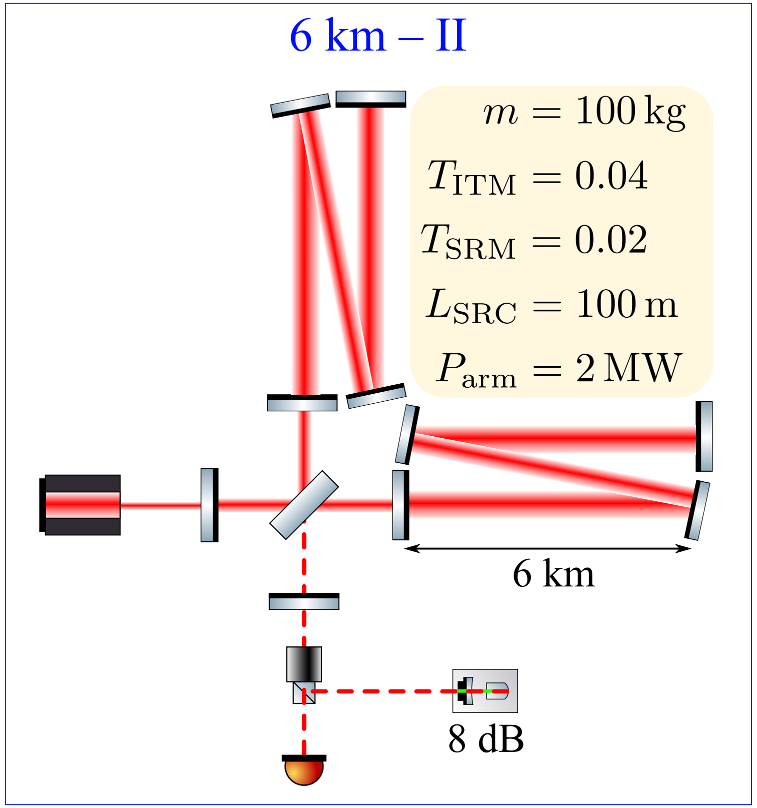
Phase-II

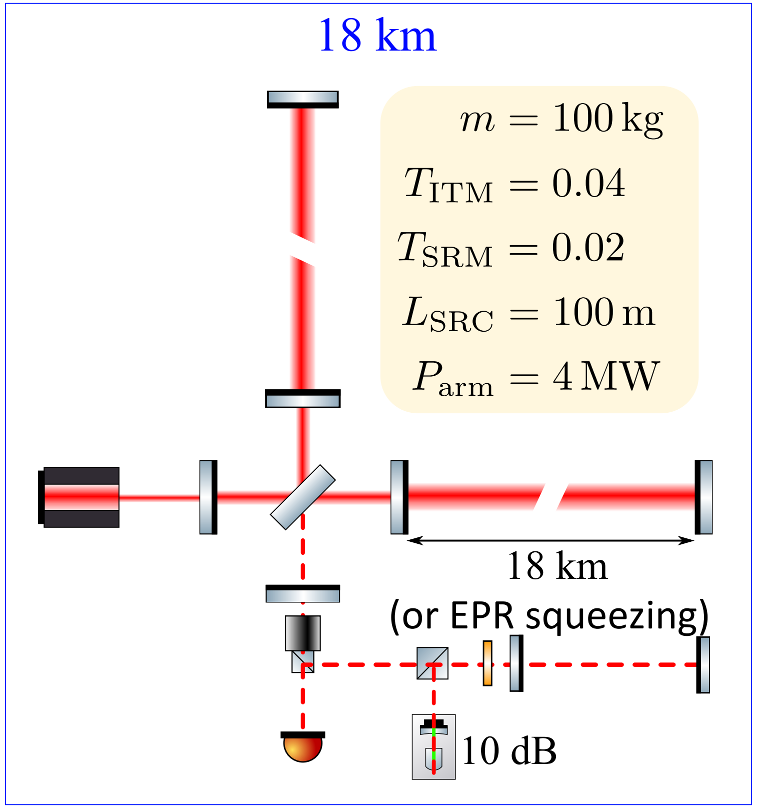
Realizing a 18km facility (the optimal* arm length) and being a 3G high-frequency detector

*for detecting post-merger remnants with fundamental-mode frequency at 2 – 4 kHz [arXiv:1901.03885]

Path Forward





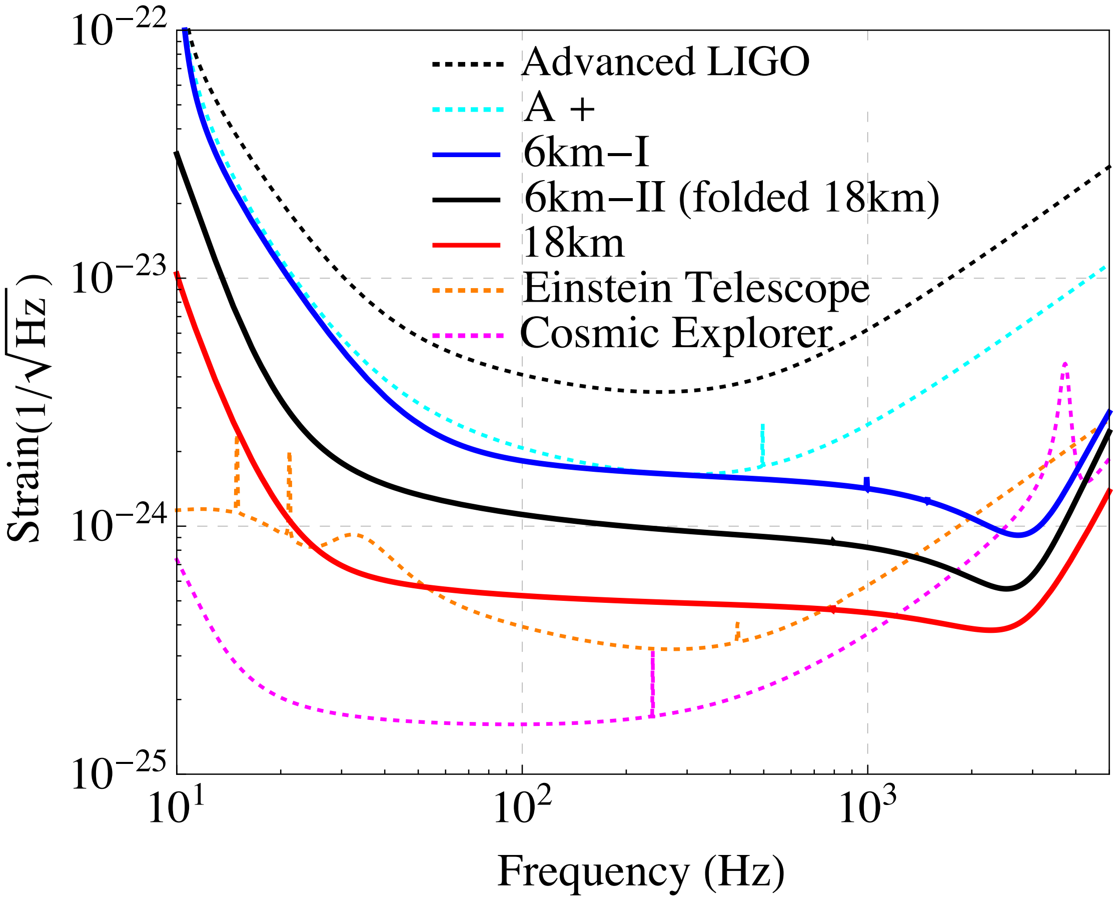


Goal: direct observation of post-merger signals.

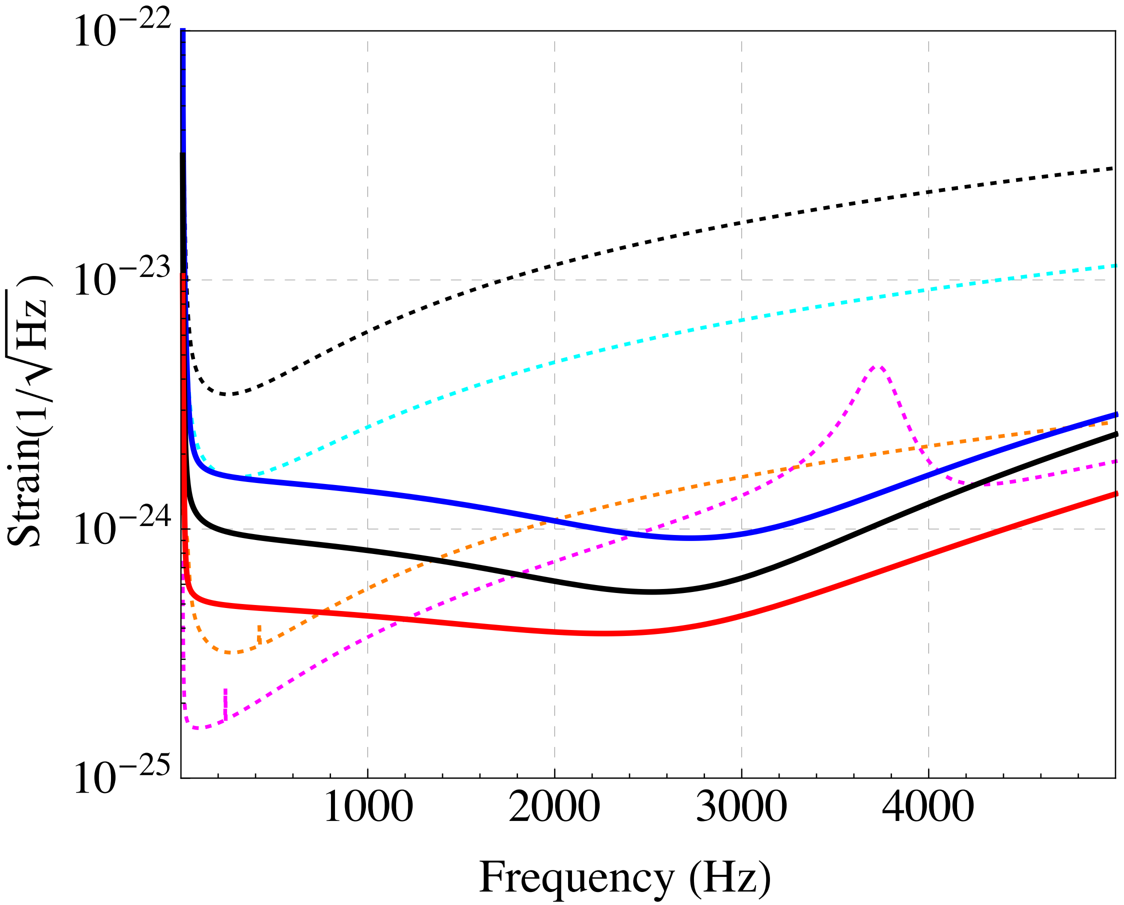
Goals: (1) precision measurement of the fundamental oscillation mode; (2) a pathfinder for the long facility.

Goal: kHz GW astronomy.

Sensitivity Curves

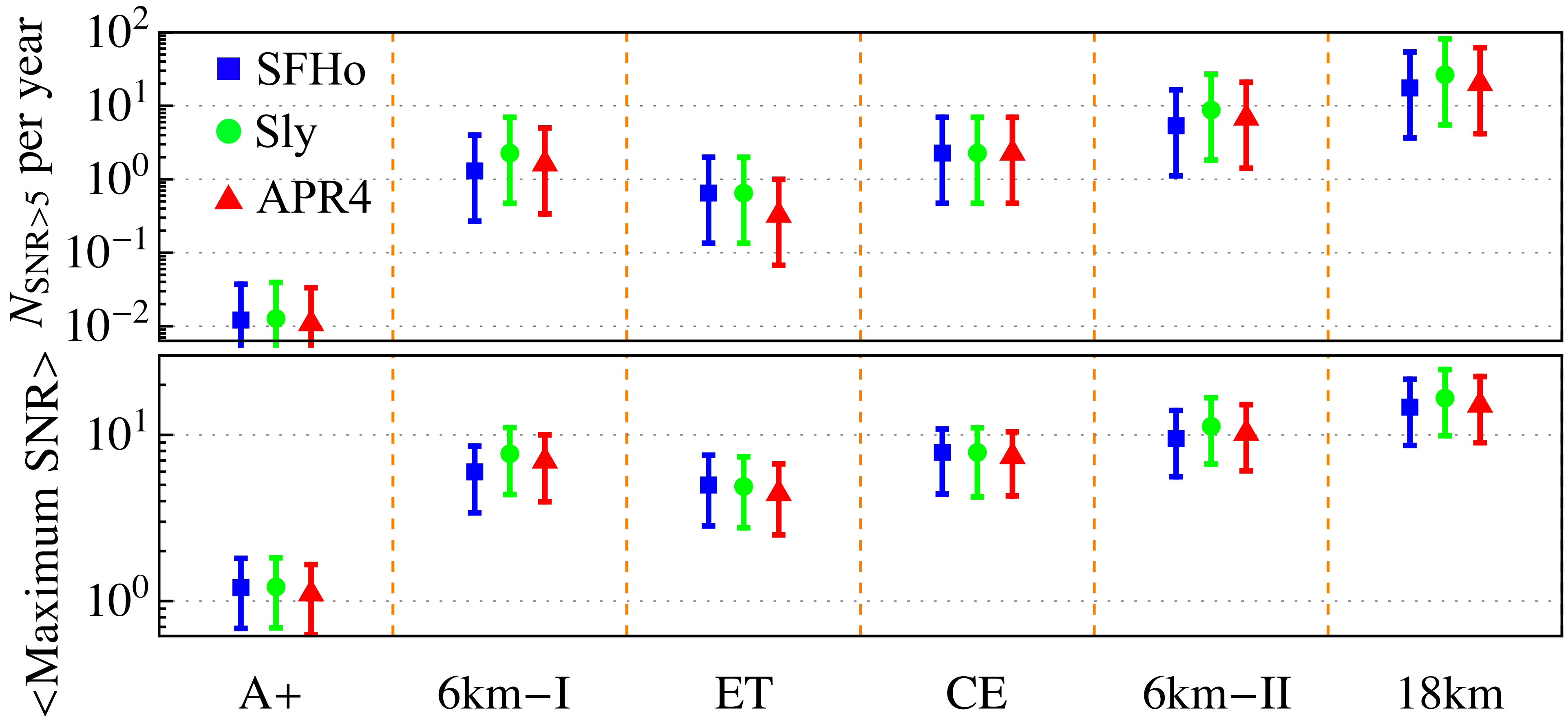


Log-log scale



Log-linear scale

Science Case: Detecting Post-merger Signal



Error bar comes from the current uncertainty in the BNS merger rate

Joint observation with space-based detectors and also low-frequency detectors can further constrain the new physics at the merger.

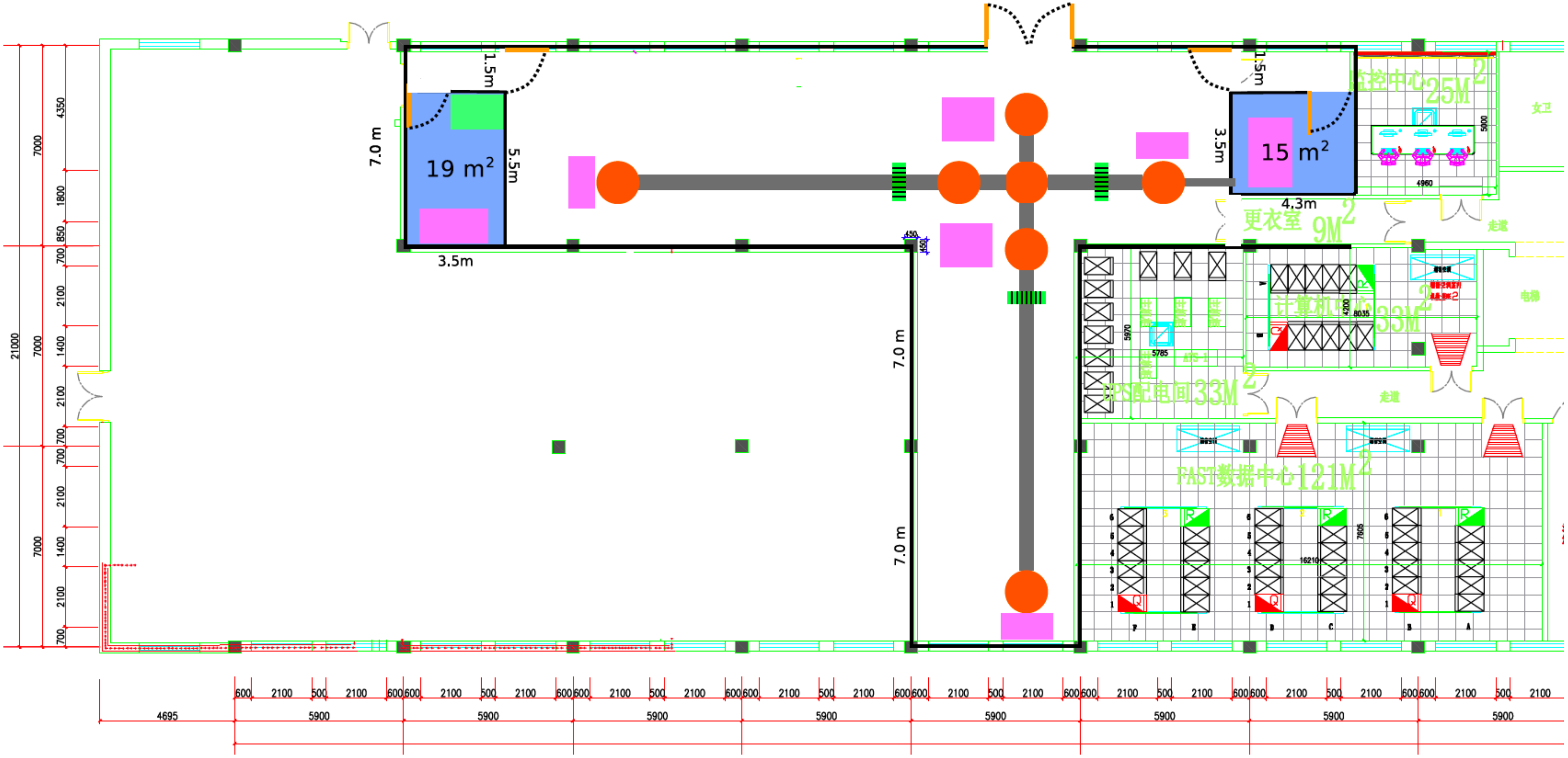
Beijing Normal University Prototype

Fan Zhang and Haixing Miao

Team (current):

Yikang Chen, Bingjie Liu, Jian Liu, Jianyu Liu, Yubo Ma, Denis Martynov, Haixing Miao, Haibo Wang, Haoyu Wang, Mengyao Wang, Wenjie Yu, Zehui Zhai, Fan Zhang, and Zonghong Zhu

Floor plan



19 m²
15 m²
1.5m
5.5m
7.0 m
3.5m
4.3m
监控中心25M²
更衣室 9M²
计算机中心33M²
UPS配电间33M²
FAST数据中心121M²
走道
电梯
女卫

Objectives

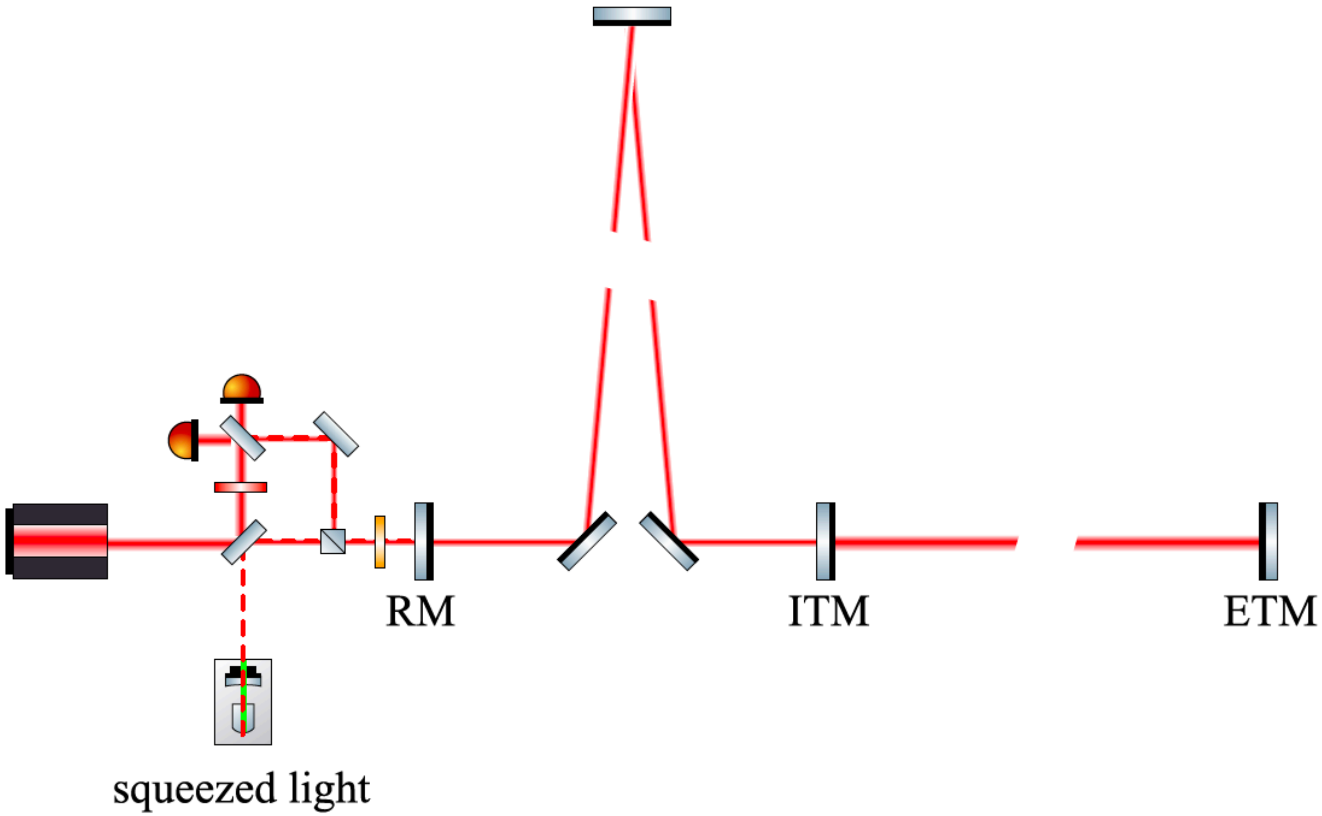
General: training

- ❖ Learn sensing and control, and precision measurement techniques.
- ❖ Build an instrumentation team on the ground-based GW laser interferometry.

Scientific: towards kHz GW detectors

- ❖ Demonstrate coupled-cavity resonance @ tens of kHz.
- ❖ Reduce shot noise at the coupled-cavity resonance using squeezed light.
- ❖ Study Einstein-Podolsky-Rosen (EPR) squeezing idea with coupled cavity.
- ❖ Study high-power effects.

Preliminary design



Parameters:

$m = 0.1$ kg $\quad L_{RC} = 36$ m $\quad L_{arm} = 12$ m

$T_{RM} = 0.04 \quad T_{ITM} = 0.002$

$P_{in} = 1$ mW (squeezing experiment)

$= 6$ W (high-power and 10 kW in arm)

$\omega_s/(2\pi) = 50$ kHz

Requirements (for 6dB SQZ):

Mode mismatch $< 5\%$

$\mathrm{Loss}_{RC} < 500$ ppm

$\mathrm{Loss}_{arm} < 200$ ppm

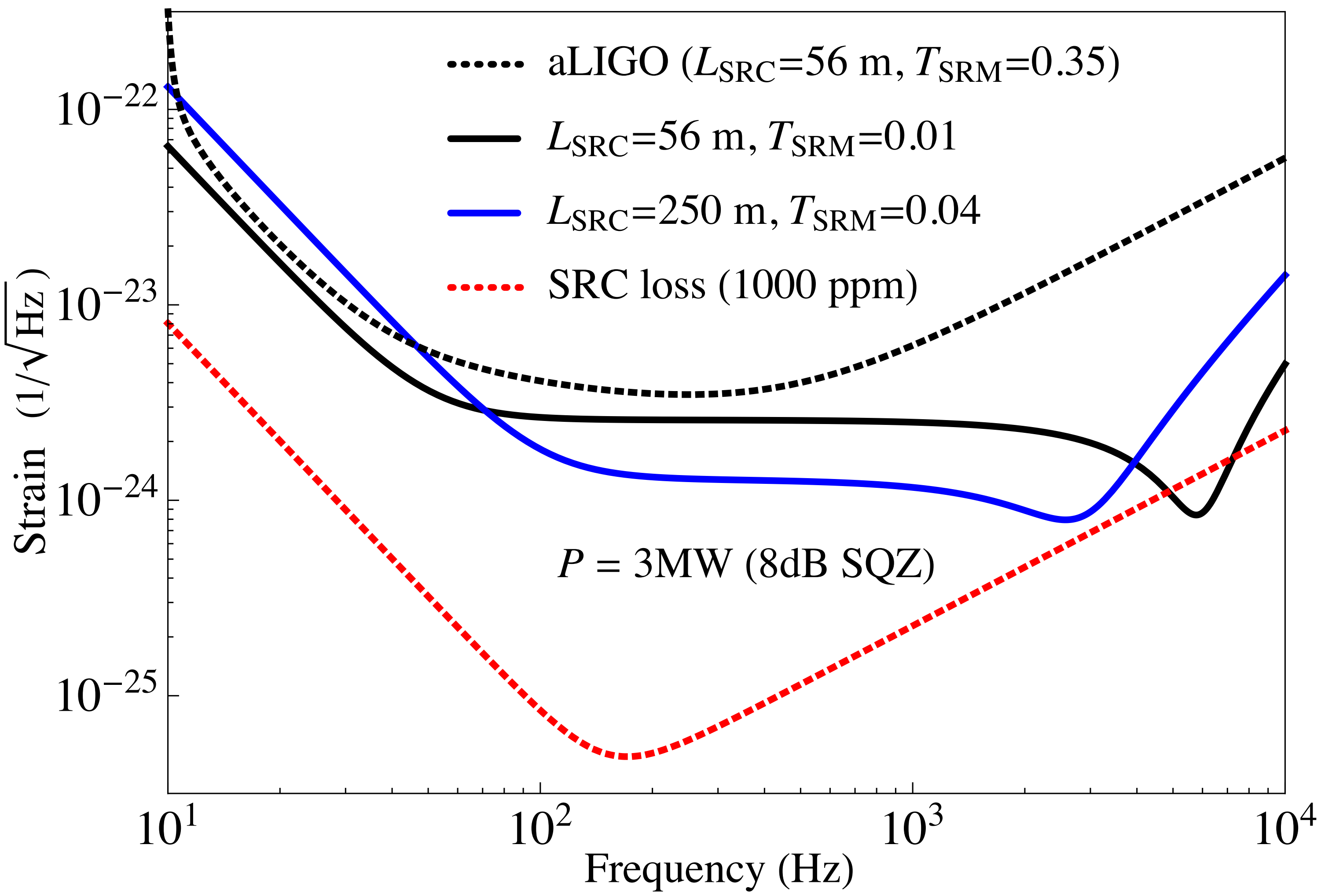
$S_{ff}^{1/2} \leq 4.0\times10^{-4}\ \mathrm{Hz}^{1/2}$ @ 50 kHz

(frequency stabilization and mode cleaners)

Control scheme:

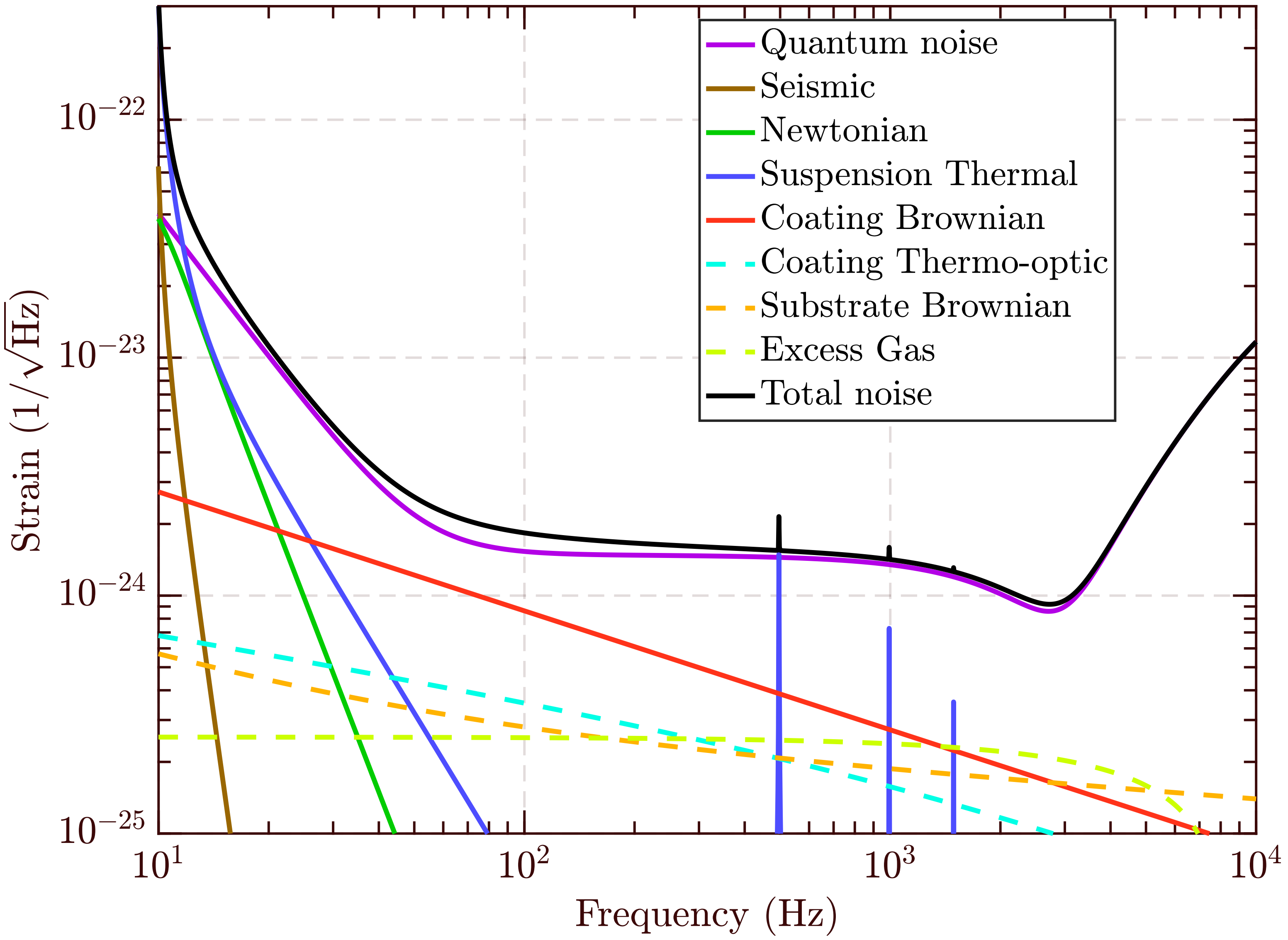
[1] K. Arai, M. Ando, S. Moriwaki, K. Kawabe, and K. Tsubono, Phys. Lett. A **273**, 15 (2000).
[2] S. Huttner, B. Barr, M. Plissi, J. Taylor, B. Sorazu and K. Strain, Class. Quantum Grav. **24**, 3825 (2007).

Effect of SRC Optical Loss



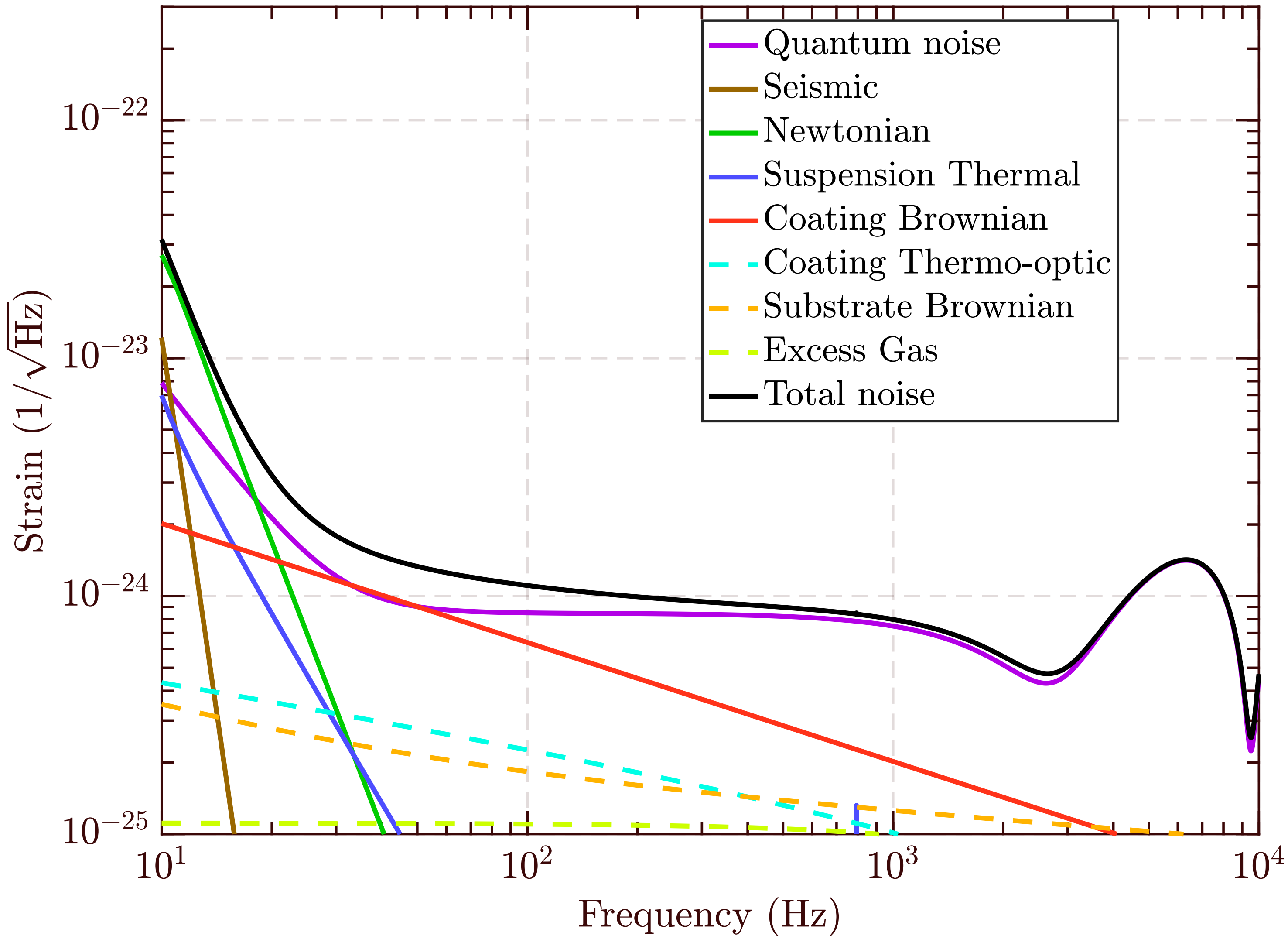
SRC loss is the limiting factor [PRX 9, 011053 (2019)]

6km-I



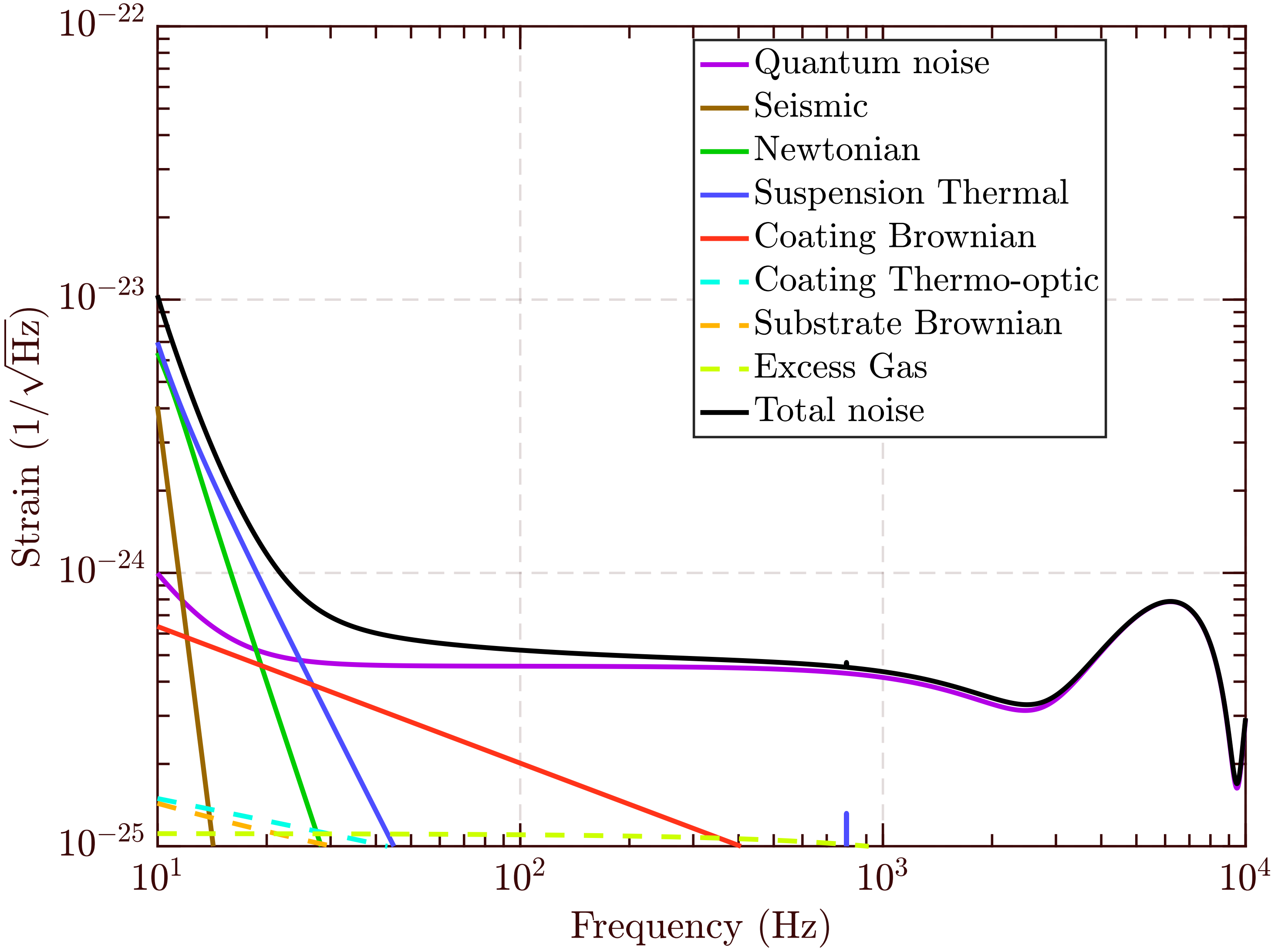
Quantum noise
Seismic
Newtonian
Suspension Thermal
Coating Brownian
Coating Thermo-optic
Substrate Brownian
Excess Gas
Total noise
Strain (1/√Hz)
Frequency (Hz)
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{1}
10^{2}
10^{3}
10^{4}

6km-II



Antenna response not included

18km



Antenna response not included