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SOGRO: Superconducting Tensor Gravitational Wave Detector for Mid-Frequencies

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National Institute for Mathematical Sciences

Outline

I. Introduction

II. Design and Principle

III. Detector Sensitivity

IV. Science with SOGRO

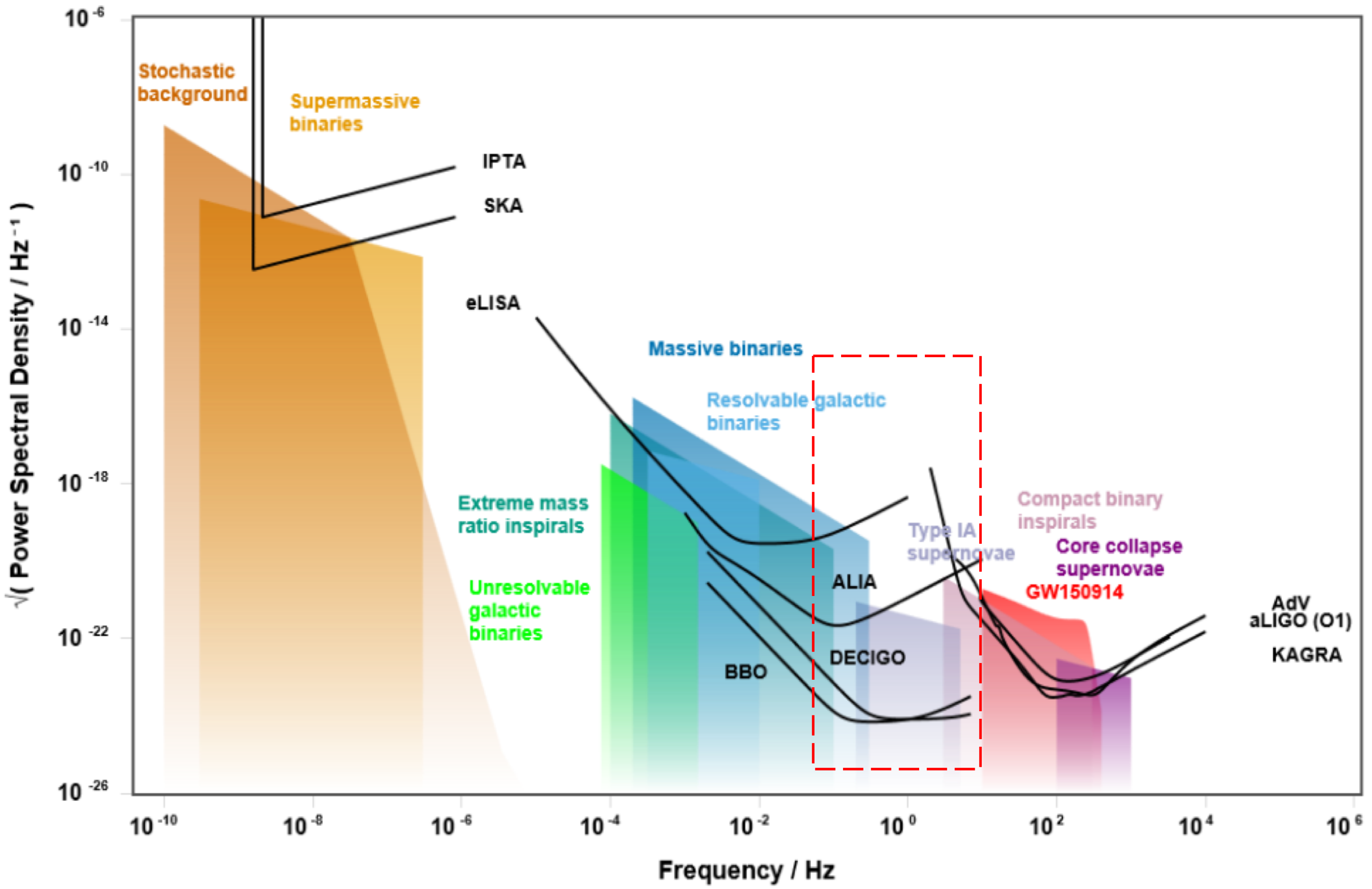
V. Summary and Outlook

I. Introduction

- Detections of GWs in LIGO:
  - 5 BBH & 1 BNS events
- Plans to improve sensitivity:
  - A+ (~22), Voyager (~25), Einstein Telescope (~23), Cosmic Explorer (~27), AAGO, TAIJI, TianQin, etc.
- **Covers 10~1000 Hz only!**
- Multi-wavelength GW astronomy
- Mid-Frequencies (0.1~10 Hz):
  - Space: DECIGO ('01), BBO, ALIA, AMIGO
  - Ground: TOBA ('10), MIGA, ZAIGA

+ "SOGRO" (~'13)

✓ Gravitational wave spectrum:

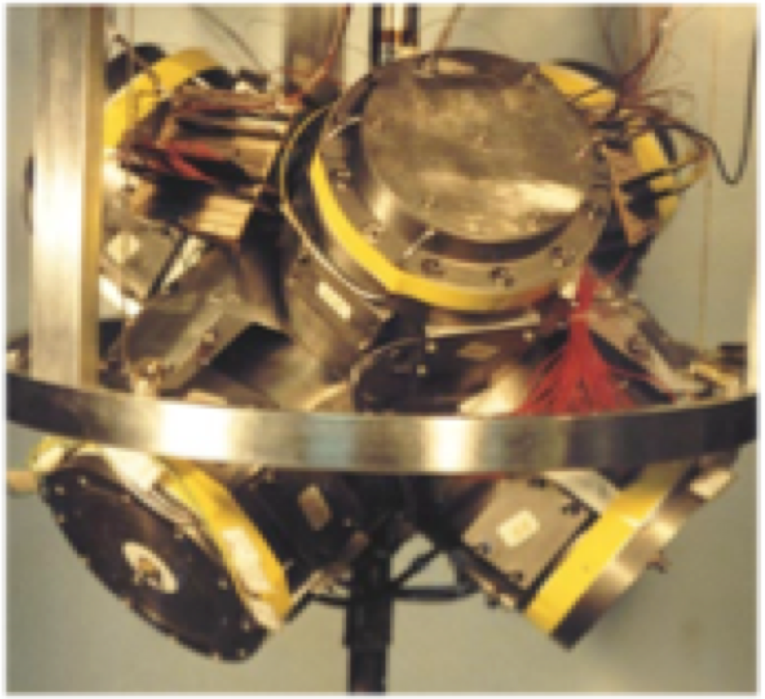


Based on http://rhcole.com/apps/GWplotter/ by Moore, Cole & Berry

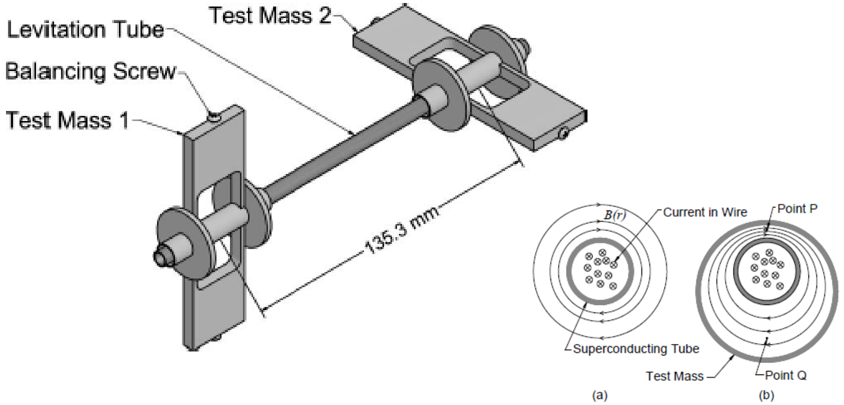
✓ History of SOGRO:

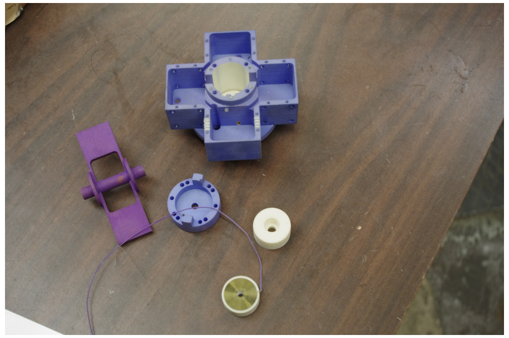
- Wagoner, Will & Paik: 1979
- Superconducting Gravity Gradiometer (SGG):

Ho Jung Paik



Moody, Paik, & Caravan (2002)



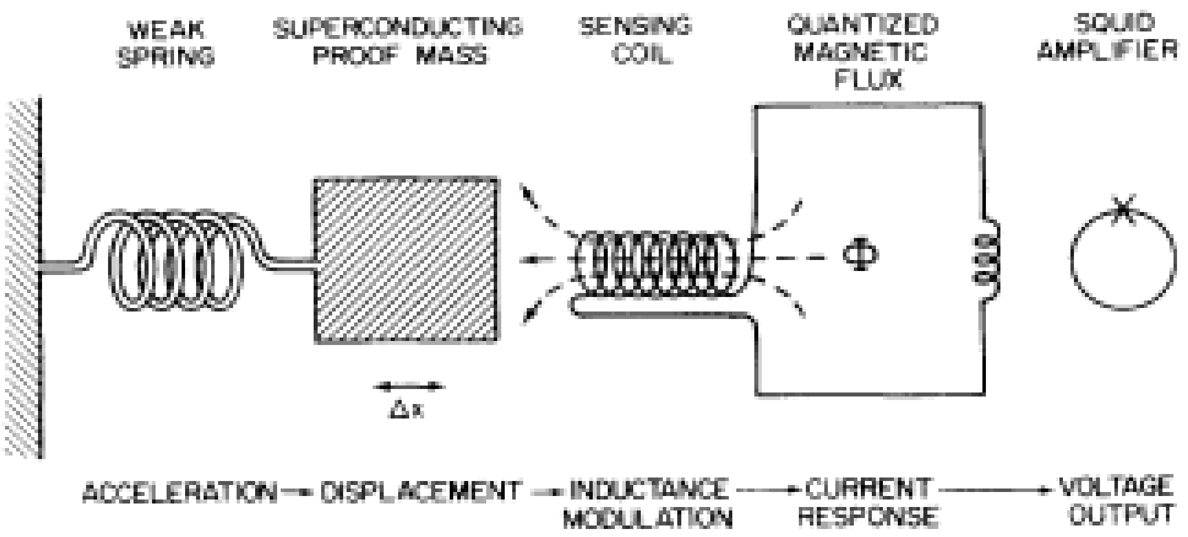


(Picture credit: H-M. Lee)

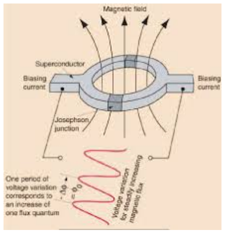
- ✓ Measure the **relative motion of test masses**
- ✓ Magnetic levitation, SQUID sensor
- ✓ Test mass: 25 kg, Size: ~15 cm
- ✓ Sensitivity: $\sim 2\times 10^{-11} s^{-2} Hz^{-1/2}$
- ✓ Developed for over 30 years at U. of Maryland

II. Design and Principle

✓ **Basic principle:** Chan & Paik ('87)

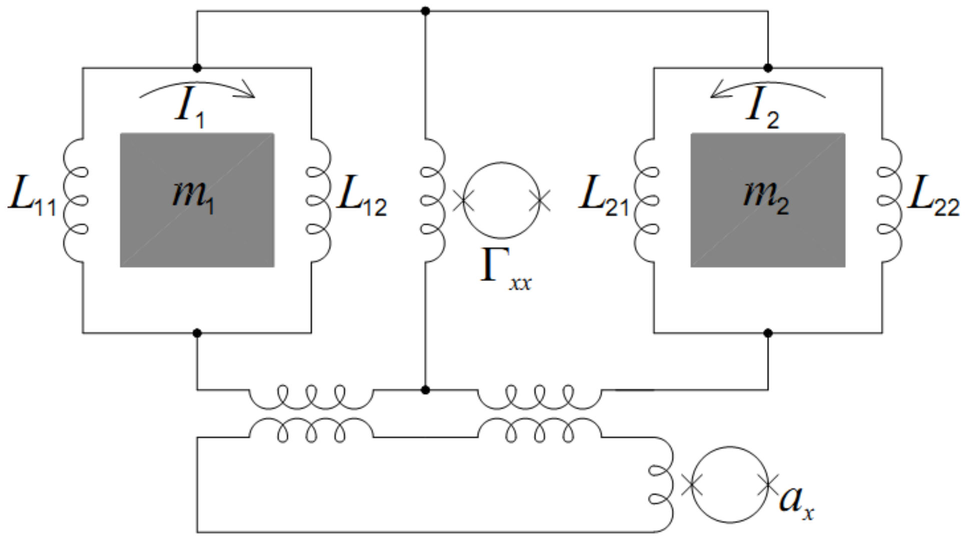


Test mass motion

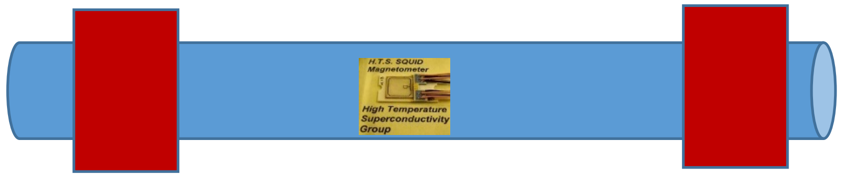


➔ Induced current at sensing coil

➔ Measure flux at SQUID

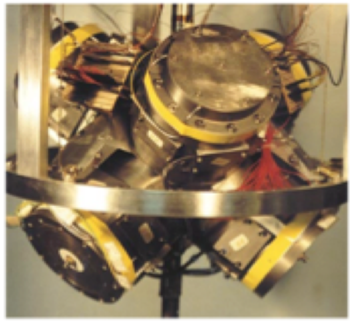


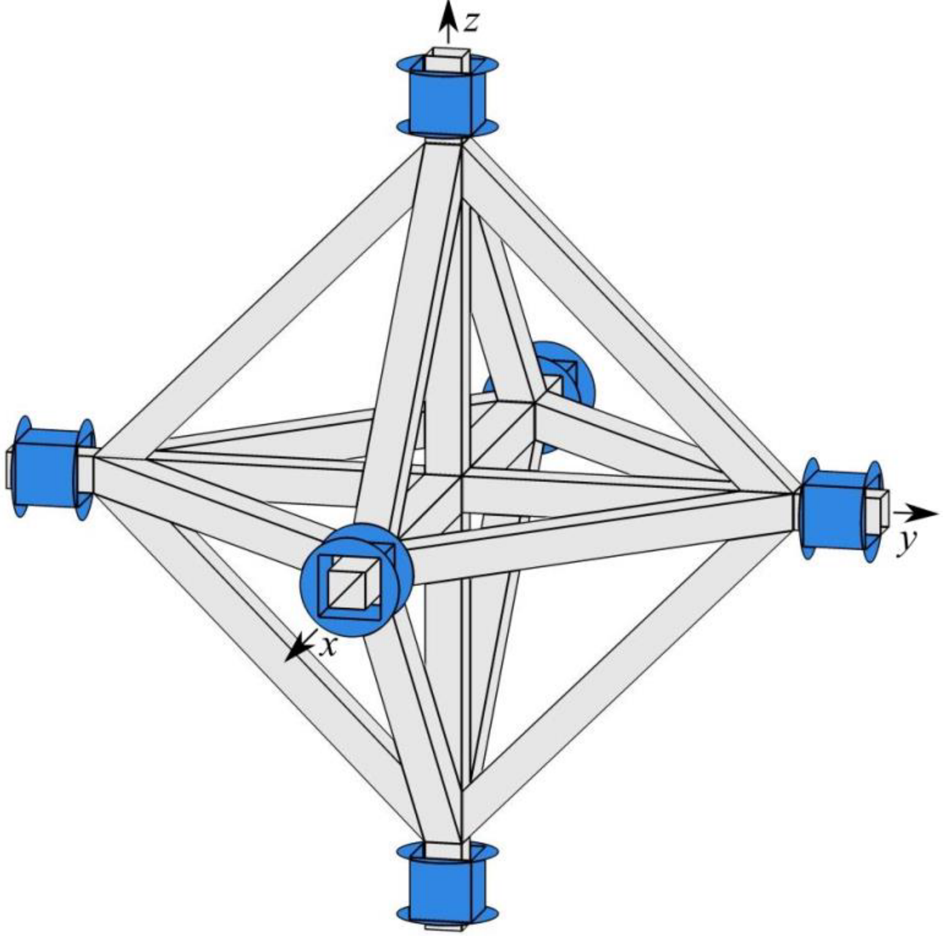
➔ **Sensitive to relative motions only!!**



- Sensing coils & SQUIDs are mounted on the rigid stick.
- Two masses are freely moving.

✓ **Platform design:**





- Combining 6 test masses, a tensor GW detector is formed;

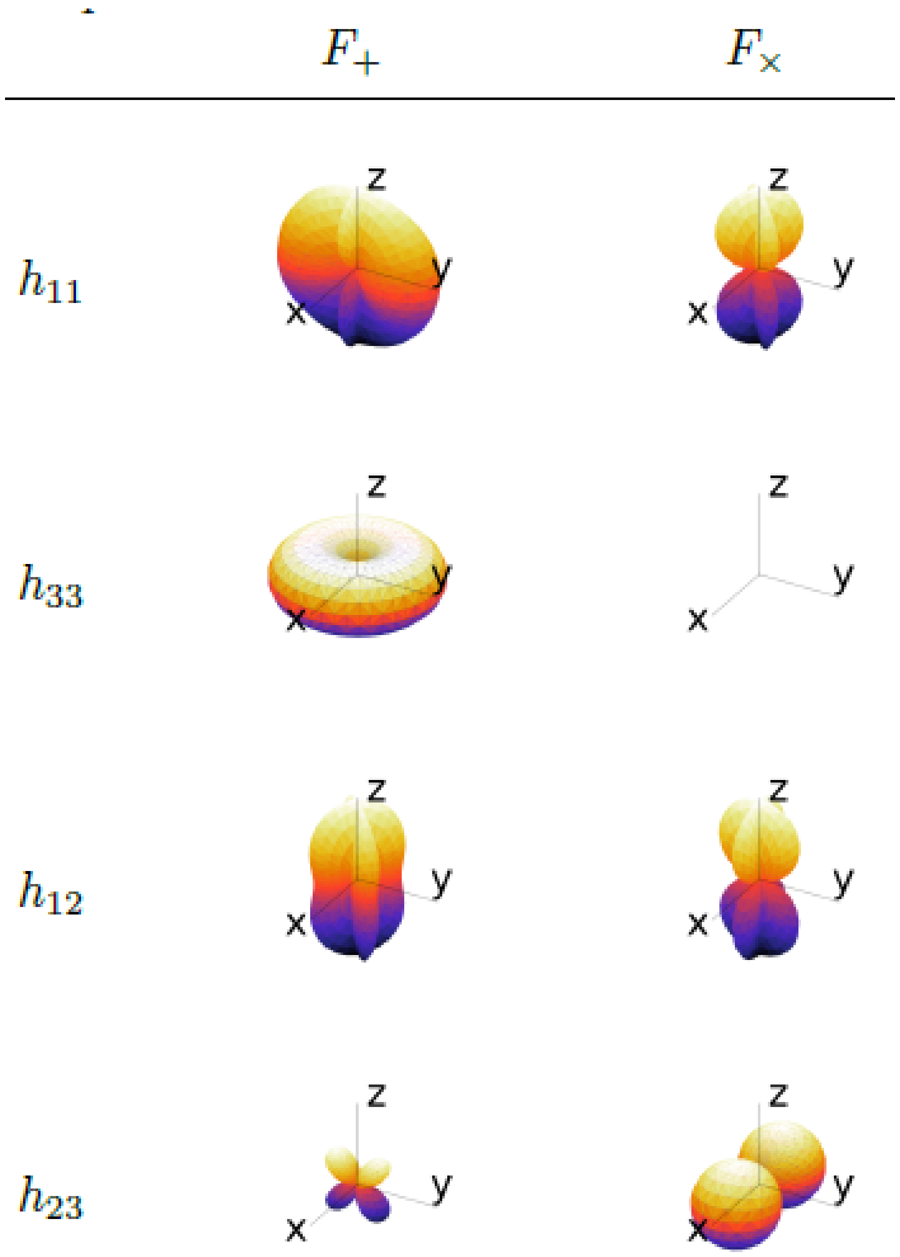
$$h_{ii}(t)=\frac{2}{L}\left[x_{+ii}(t)-x_{-ii}(t)\right]$$

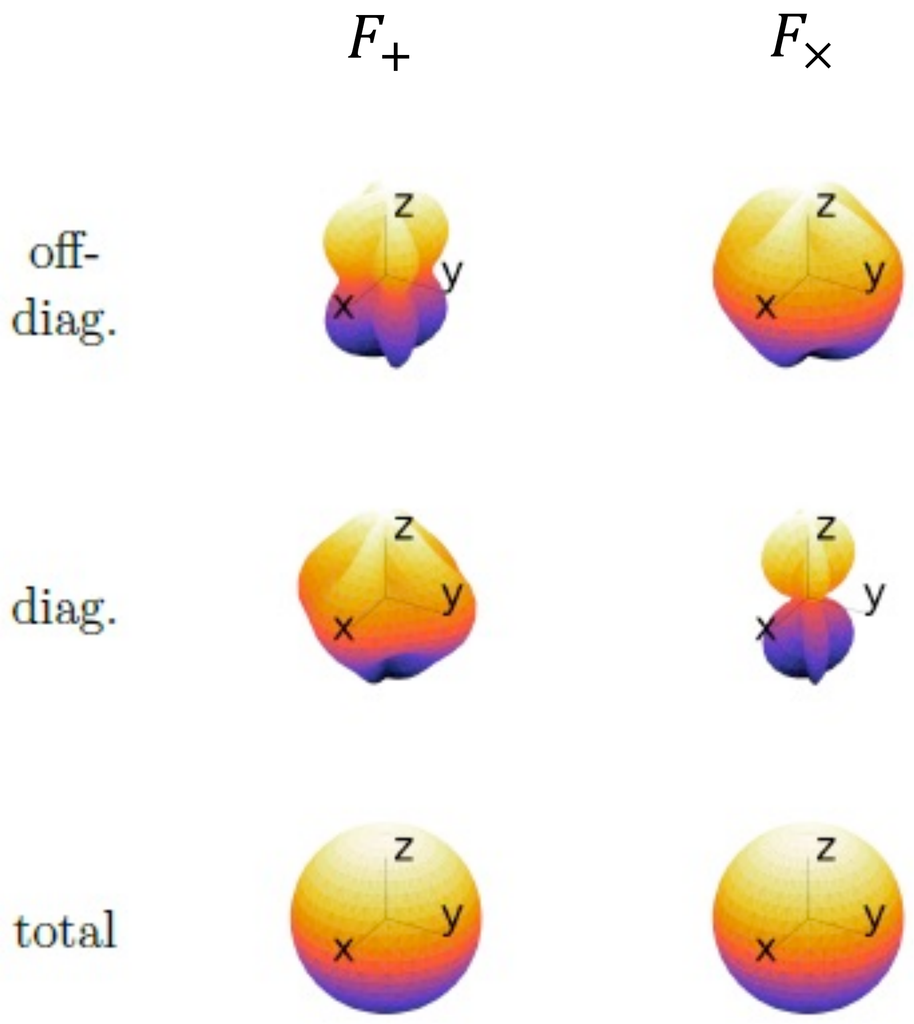
➔ "Diagonal" channel, "In-line component", or XX mode

$$h_{ij}(t)=\frac{1}{L}\left\{\left[x_{+ij}(t)-x_{-ij}(t)\right]-\left[x_{-ji}(t)-x_{+ji}(t)\right]\right\}, i \neq j$$

➔ "Off-diagonal" channel, "Cross component", or XY mode

✓ **Detector response:**



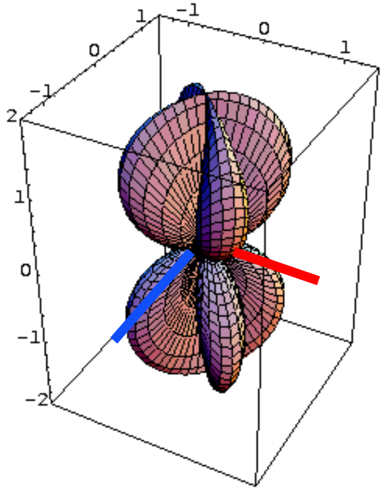


➔ NO LOSS OF INFORMATION IN SOGRO!

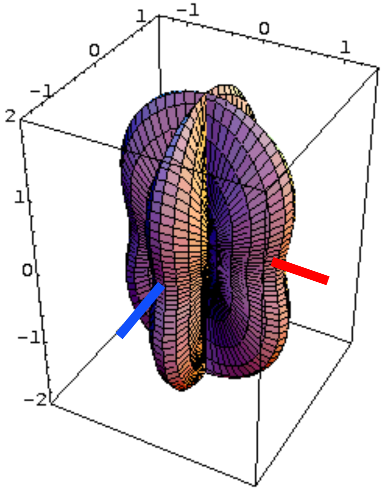
Antenna pattern

LIGO

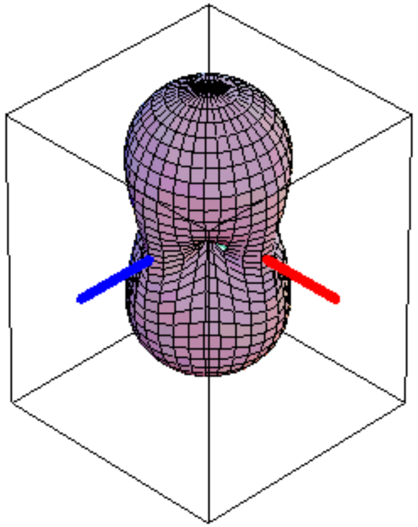
× polarization



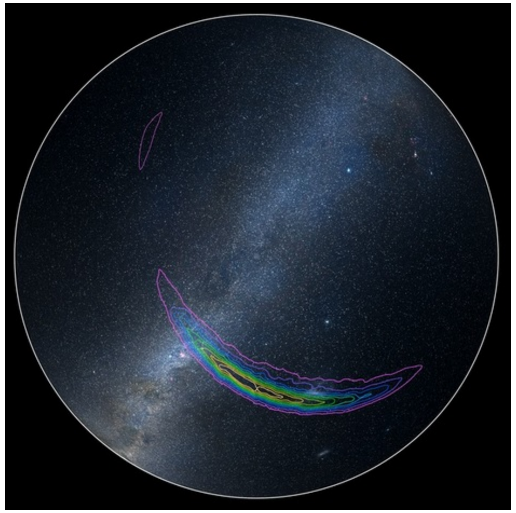
+ polarization



rms sensitivity

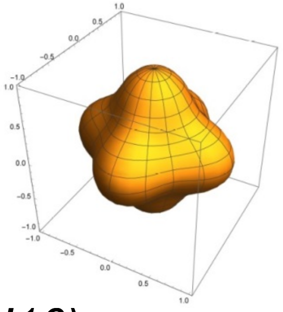


Sky location of GW150914

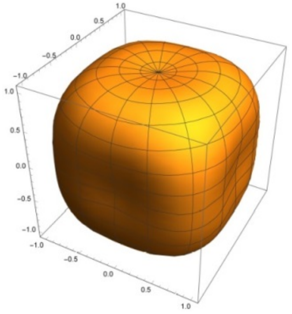


SOGRO

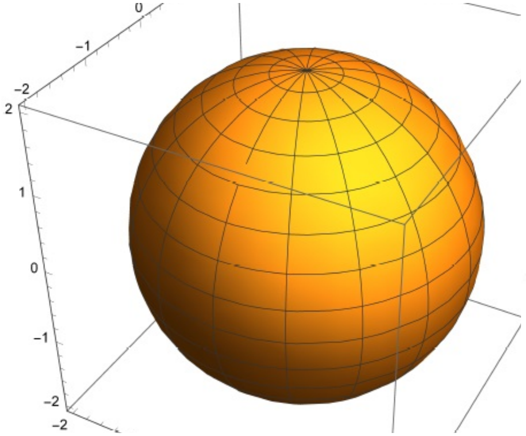
Diagonal



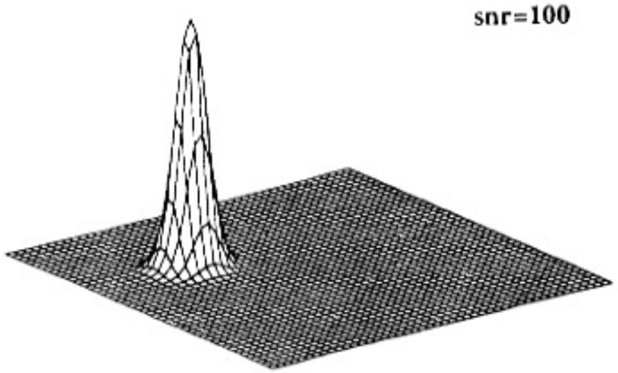
Off-diagonal



Total



Sky location by SOGRO

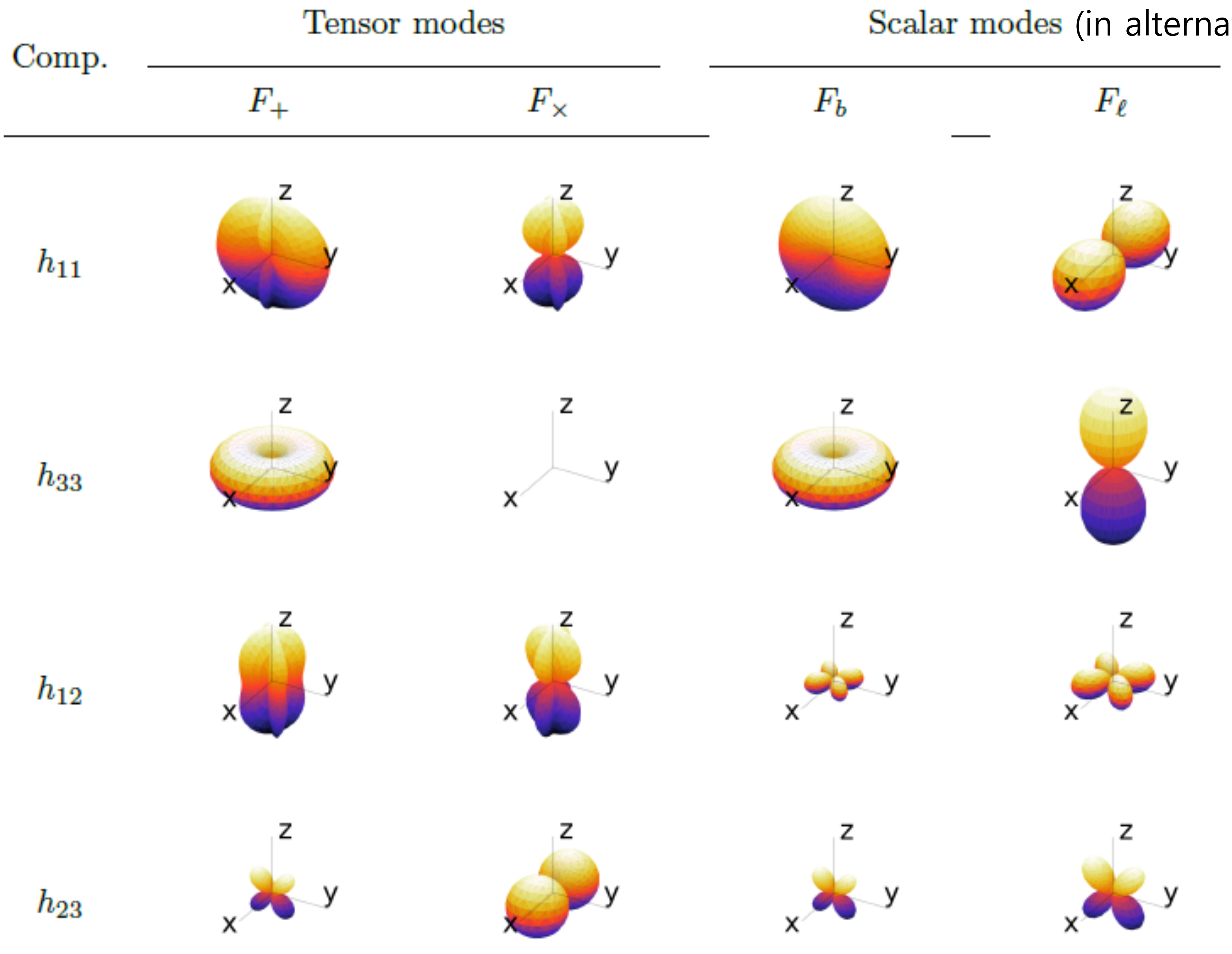


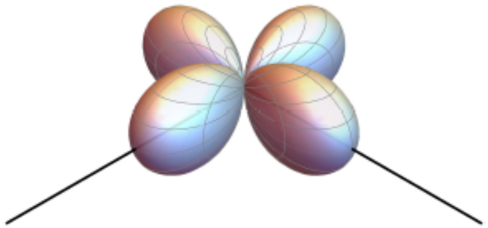
(Slide credit: Paik '16)

- Thus, the source direction $(\theta, \emptyset)$ and GW polarizations can be determined by a single antenna.

➔ **“Spherical Antenna”**

- **SOGRO**: **S**uperconducting **O**mni-directional **G**ravitational **R**adiation **O**bservatory



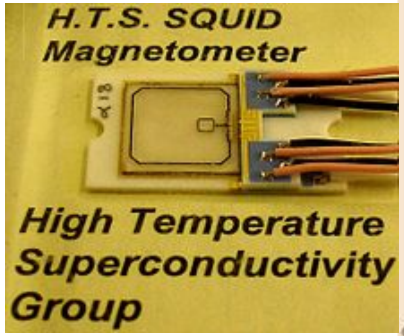


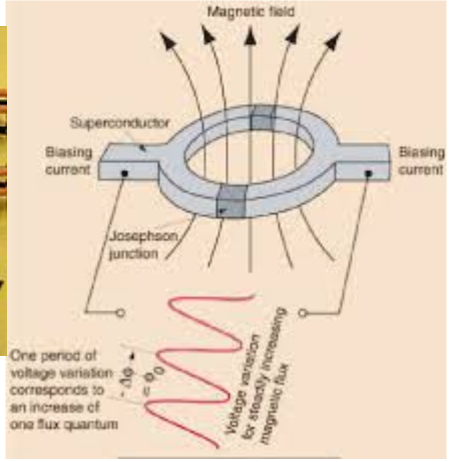
- ✓ Degeneracy for Breathing and Longitudinal modes in LIGO: Isi, Pitkin & Weinstein ('17)
- ✓ LIGO $\equiv h_{11} - h_{22}$

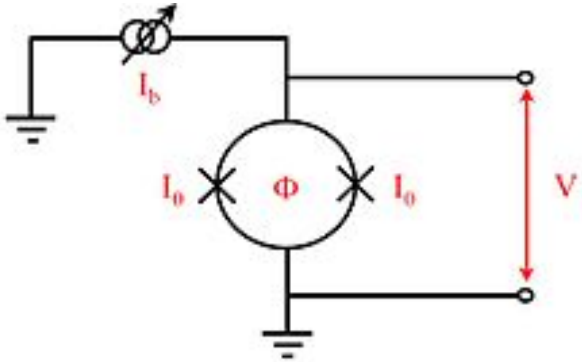
III. Detector Sensitivity

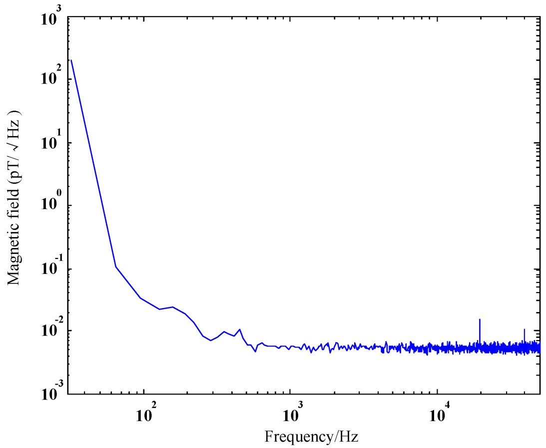
- ✓ **Variance:** $\Delta L \sim 10^{-20} \times 50m = 5\times10^{-19}\ m$
- ✓ **SQUID**

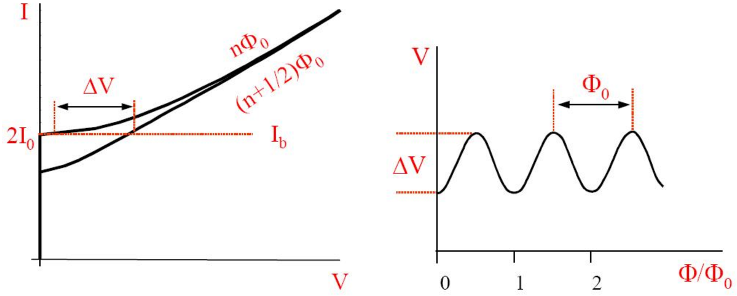
"SQUIDs are sensitive enough to measure fields as low as 5 aT (5×10^{-18} T) with a few days of averaged measurements. Their noise levels are as low as 3 fT·Hz−½."







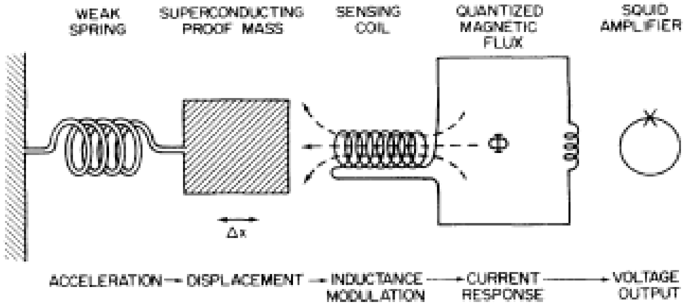




$$\Delta V = \frac{R}{L}\cdot\Delta\Phi$$

From Wikipedia

✓ Main noise sources:



- Antenna noise: Test mass
- Amplifier noise: SQUID

$$S_h(f) = \frac{32}{ML^2\omega^4}\left\{ \frac{k_B T \omega_D}{Q_D} + \frac{\left|\omega^2 - \omega_D^2\right|}{2\omega_p}\left(1 + \frac{1}{\beta^2}\right)^{1/2} k_B T_N \right\},\ k_B T_N = n\hbar\omega_p$$

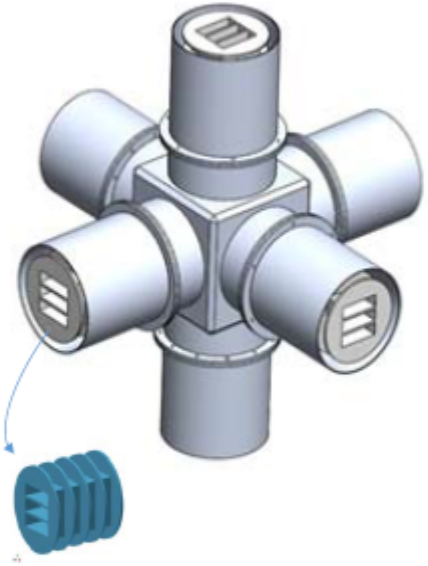
- Platform thermal noise

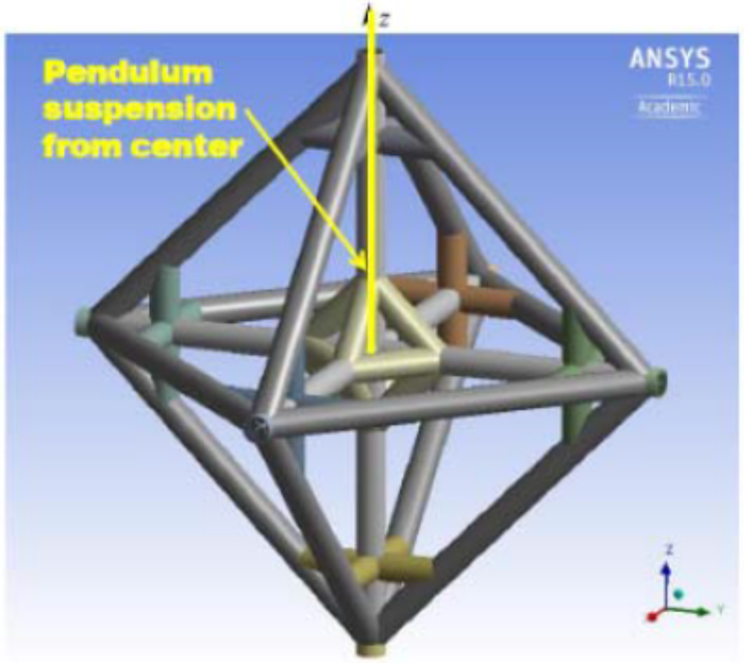
$$S_{\xi,\omega_0}(f) = \frac{16}{m_{\rm eff} L^2 \omega_0^2 Q_{\rm pl}\omega} \frac{4k_B T_{\rm pl}}{(1-\omega^2/\omega_0^2)^2 + 1/Q_{\rm pl}^2}. \qquad S_\xi(f) = \sum_i S_{\xi,\omega_{0i}}(f)$$

- Newtonian noise

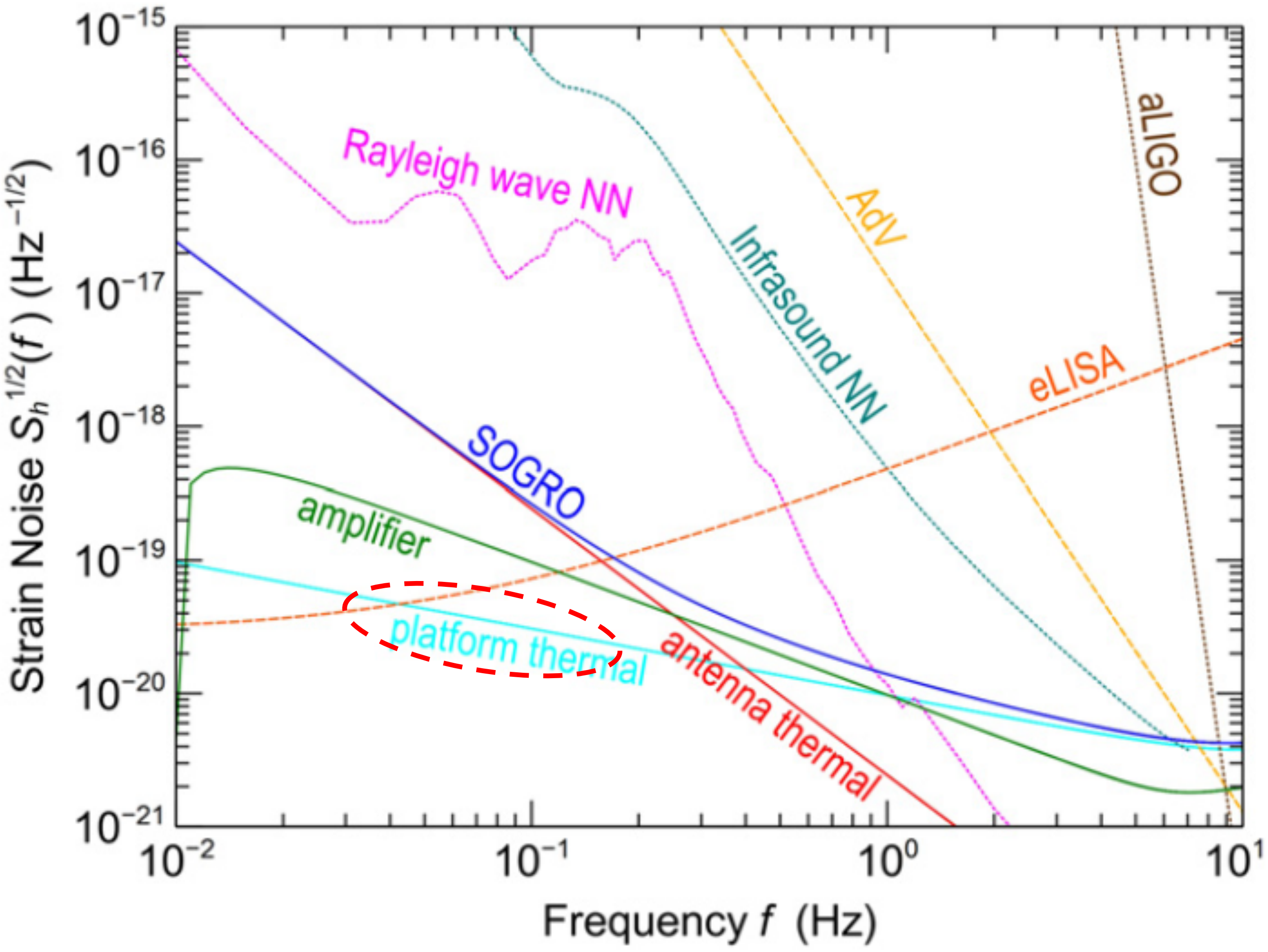
✓ Design parameters:

Parameter	pSOGRO	aSOGRO	Method employed
Each test mass M	100 kg	5 ton	Multiple-layer Nb shell
Arm-length L	2 m	50 m	Rigid platform
Antenna temperature T	0.1 K	0.1 K	$He^3 - He^4$ dilution refrigerator
Platform temperature T_{pl}	0.1 K	4.2 K	Large cryogenic chamber and cooling system
Platform quality factor Q_{pl}	10^6	10^7	Al platform structure
DM frequency f_D	0.01 Hz	0.01 Hz	Magnetic levitation (horizontal only)
DM quality factor Q_D	10^8	10^8	Surface polished pure Nb
Pump frequency f_p	50 kHz	50 kHz	Tuned capacitor bridge transducer
Amplifier noise no. n	5	2	Two-stage dc SQUID
Detector noise $S_h^{1/2}(f)$	8×10^{-19} Hz$^{-1/2}$	4.5×10^{-21} Hz$^{-1/2}$	Best sensitivity at 1Hz





✓ Noise budget:

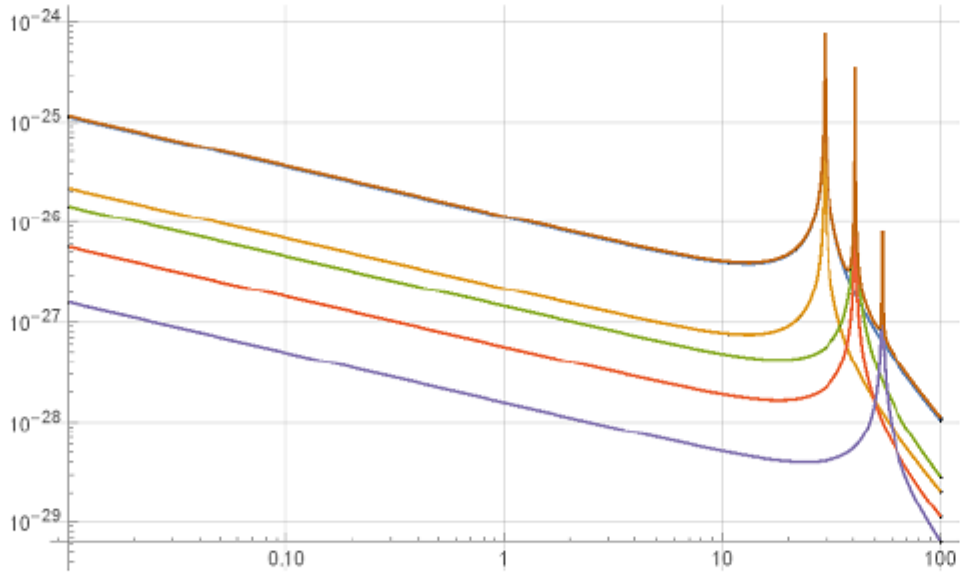


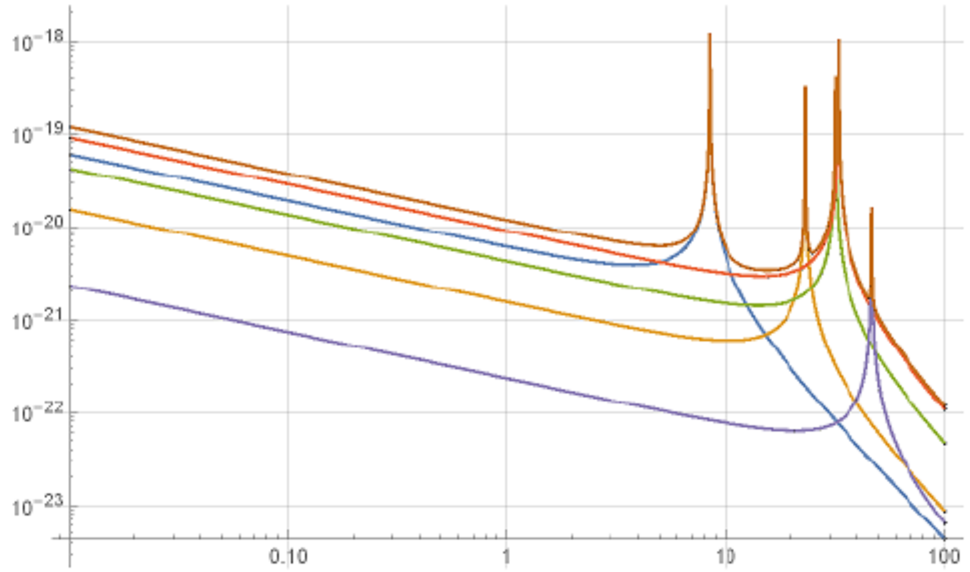
- Understanding its characteristic features is essential for designing the whole experiments.
- Goal: Find out the optimal design(s) for the platform which satisfies (all) desired requirements.

- So, we have investigated the thermal noise features of various SOGRO platforms, and report some preliminary results.

✓ Platform strain noise: Pre-stressed modal analyses using ANSYS

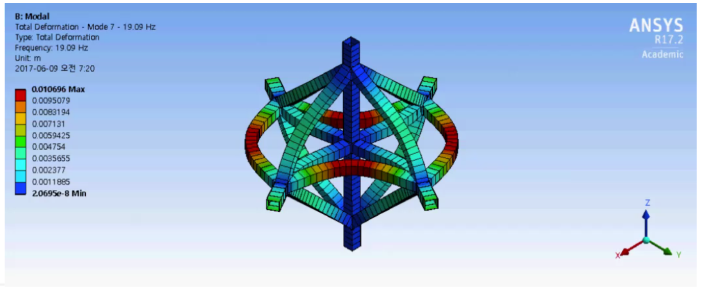
aSOGRO



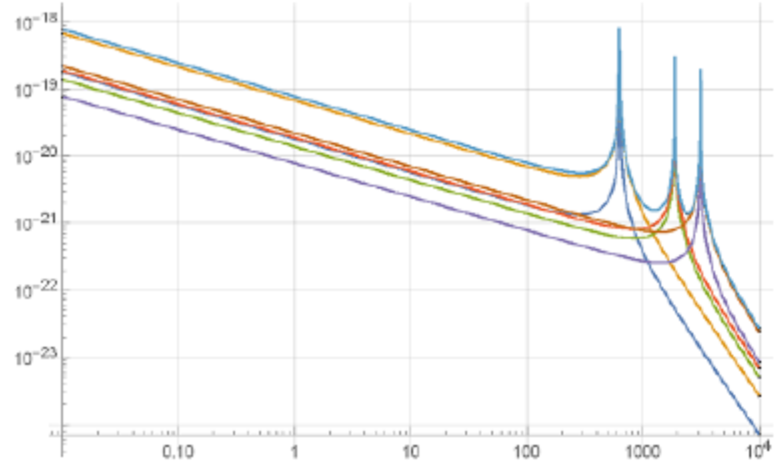


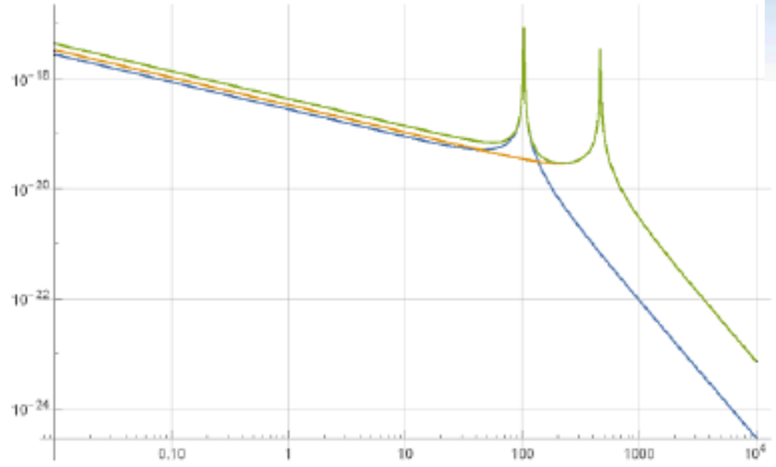
XX-Modes

XY-Modes



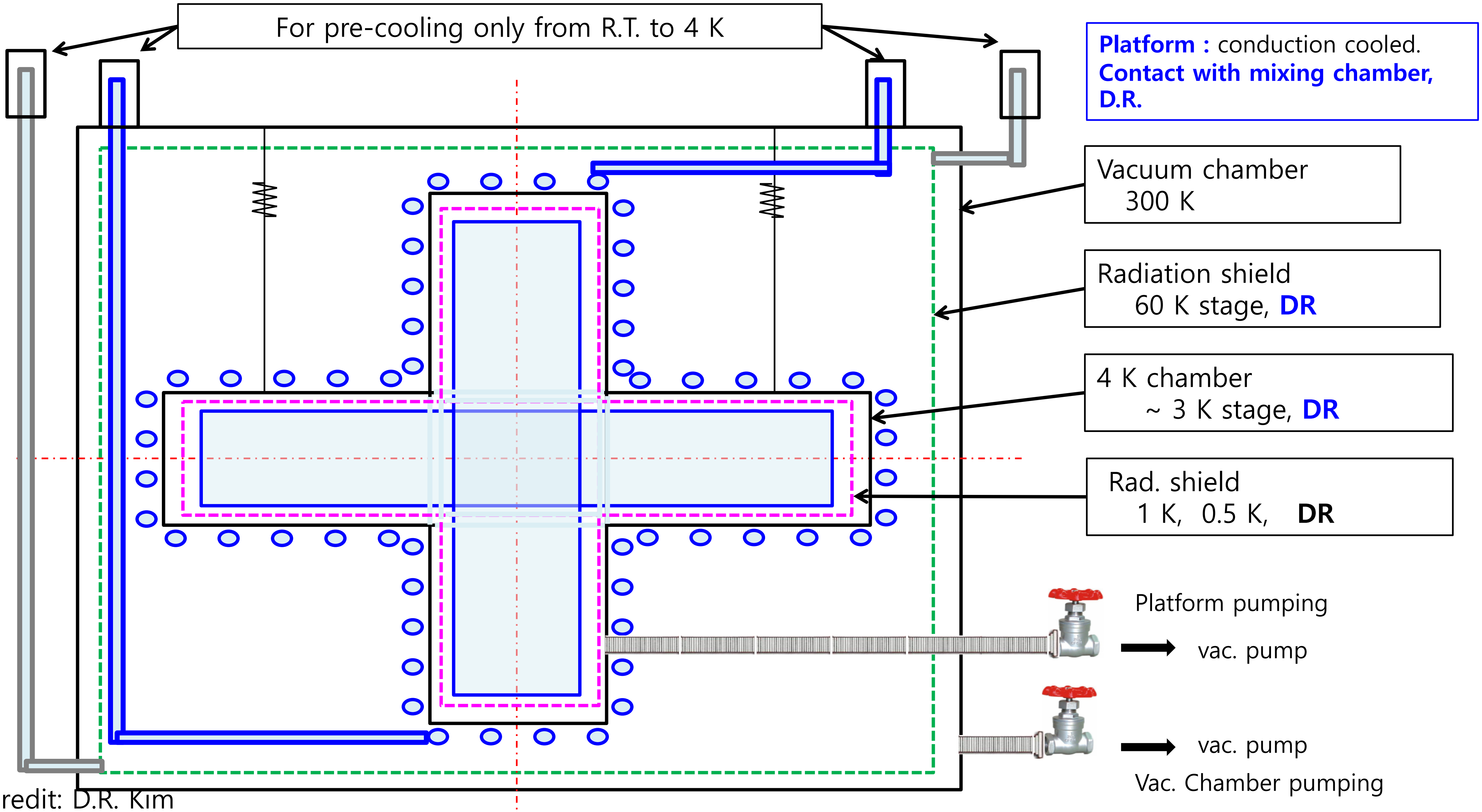
Mode 7 @ 19.09Hz : Scissor mode





pSOGRO

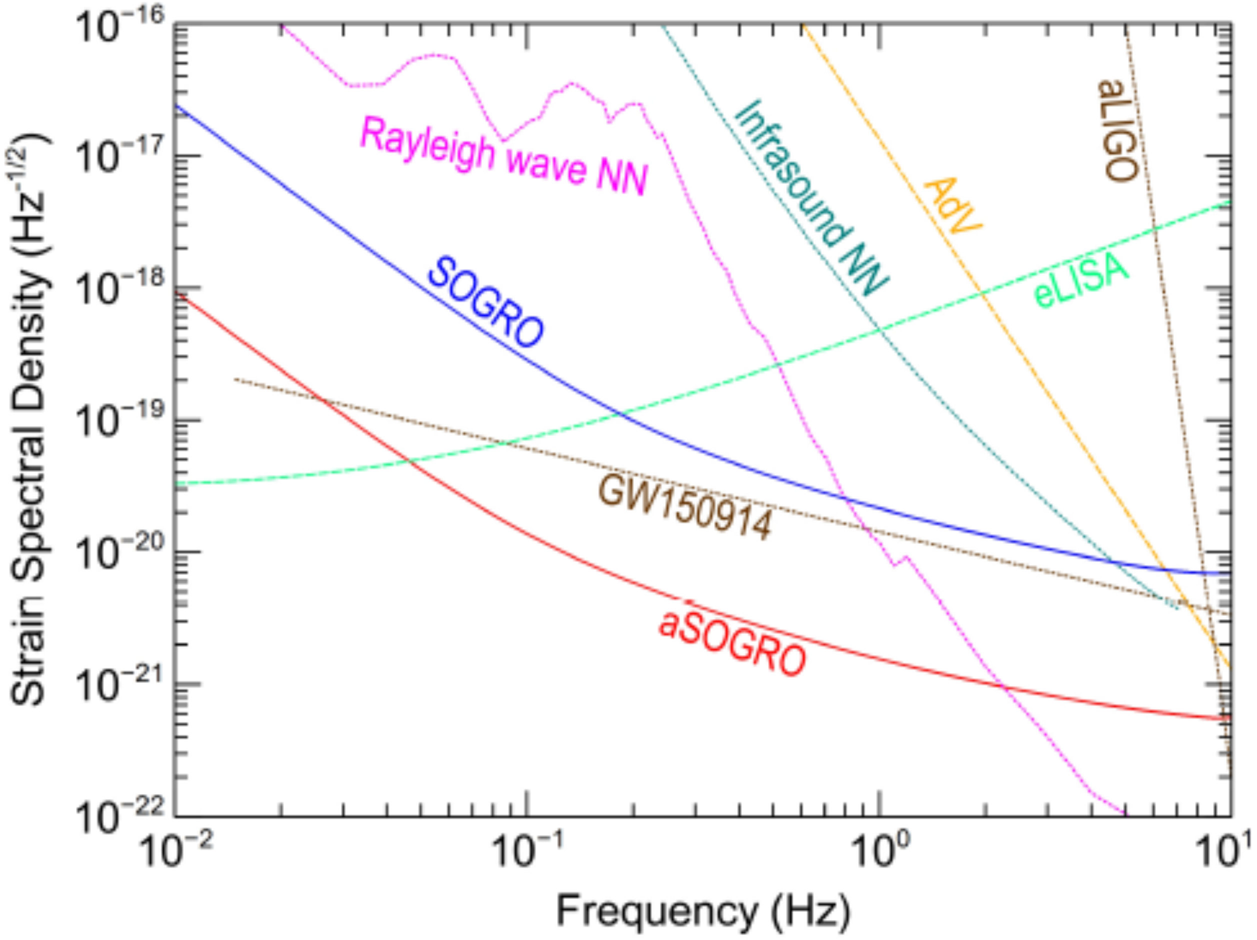
✓ Concept for Cooling SOGRO System – 2nd Stage : 0.1 K

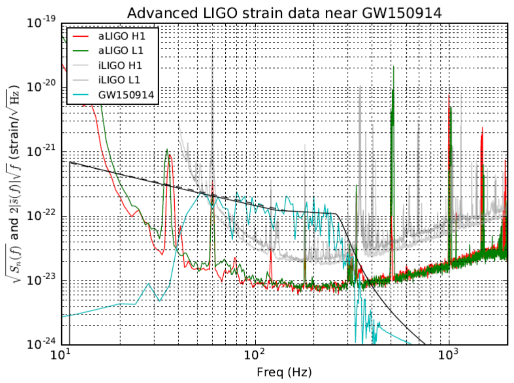


Slide credit: D.R. Kim

IV. Science with SOGRO

1) Inspiralling BBH:

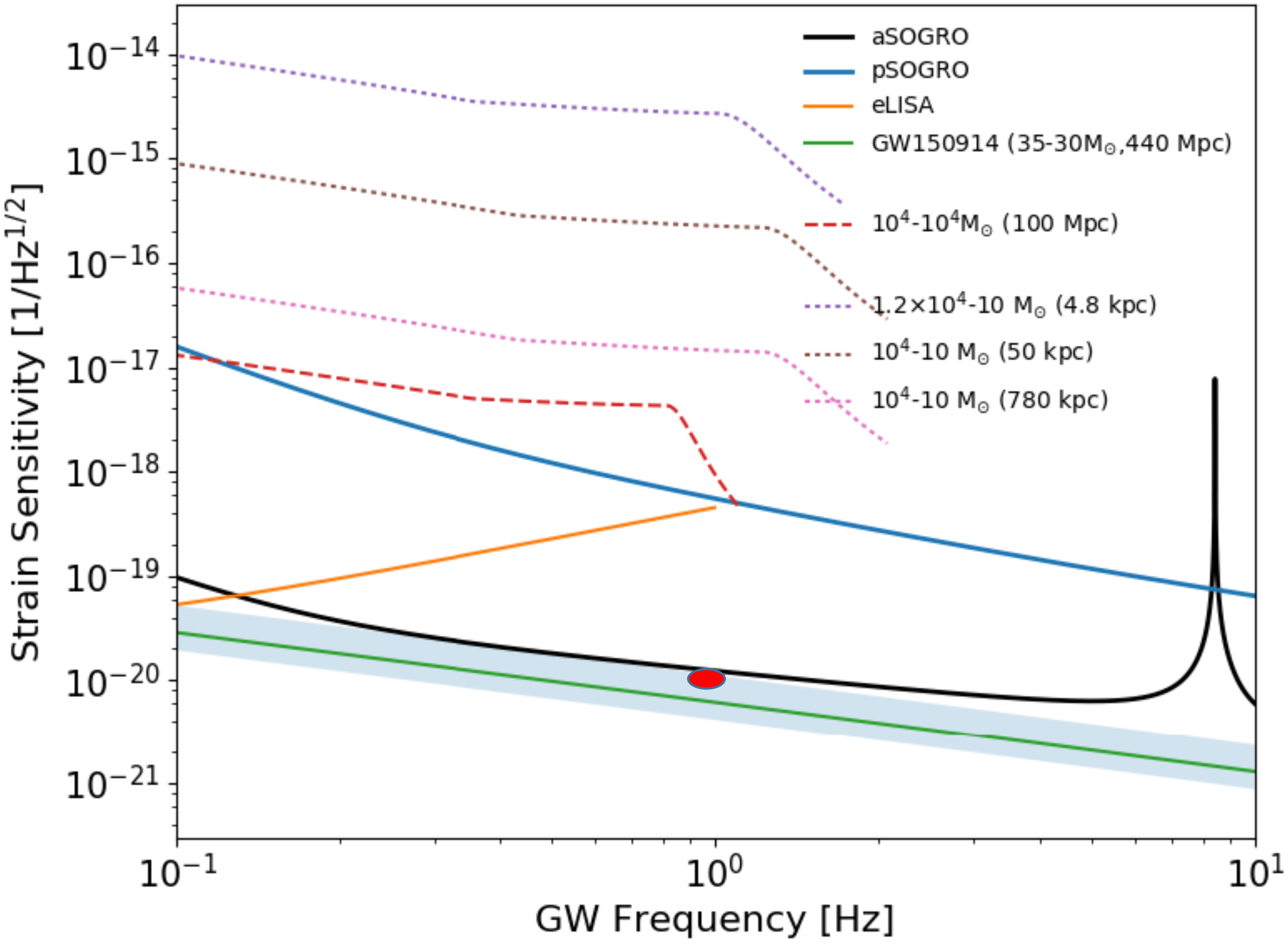




~ 10 days

Observed for ~.2s

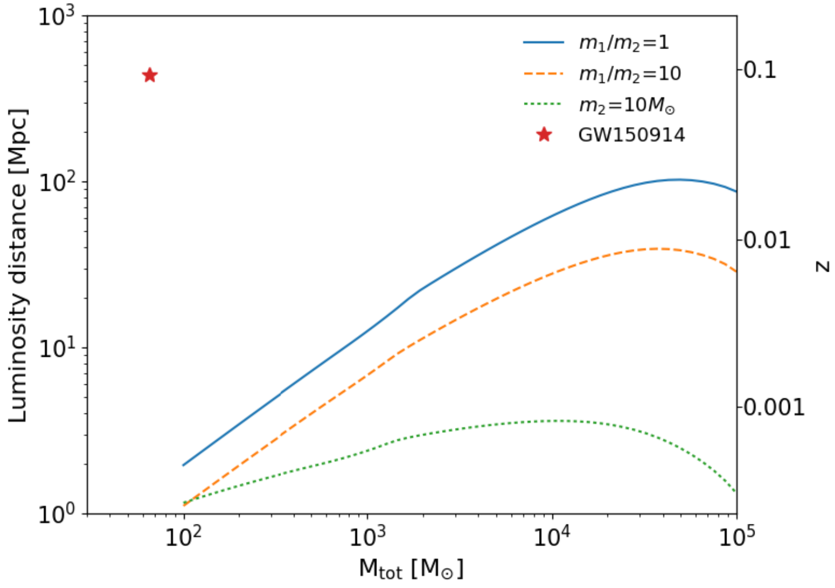
2) IMBH binary inspirals and mergers:



$$f_{ISCO,GW} = \frac{1}{\pi}\left(\frac{1}{6}\right)^{1.5}\frac{c^3}{GM} \sim \frac{4396}{M/M_\odot}\ [\text{Hz}]$$

✓ Obs. Time: 0.5 hrs ~ 1.2 days

✓ Event rate: 0.001~4.8 per yr



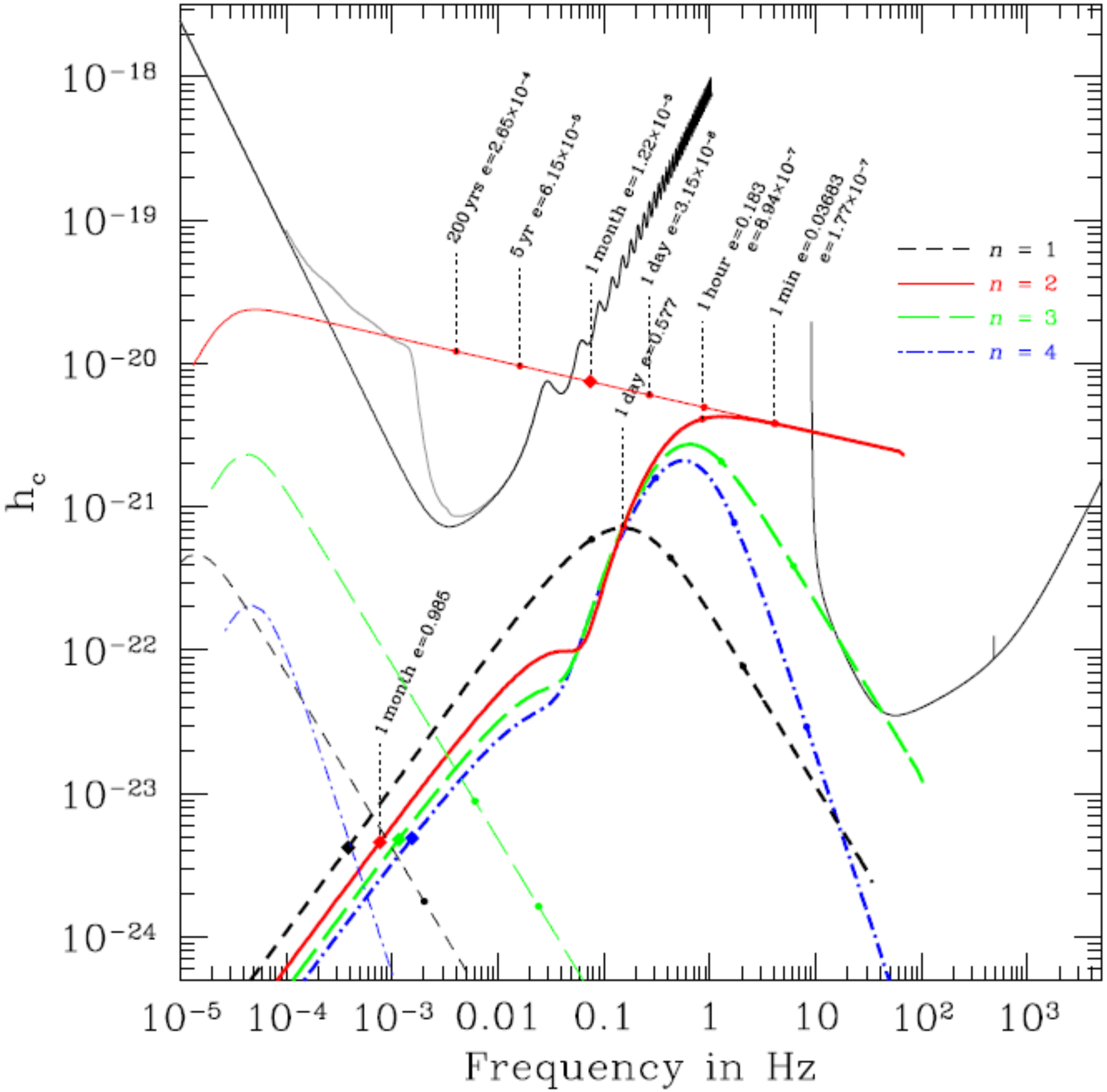
✓ X. Chen & P. Amaro-Seoane ('17):

"Formation of stellar-mass binary black holes"

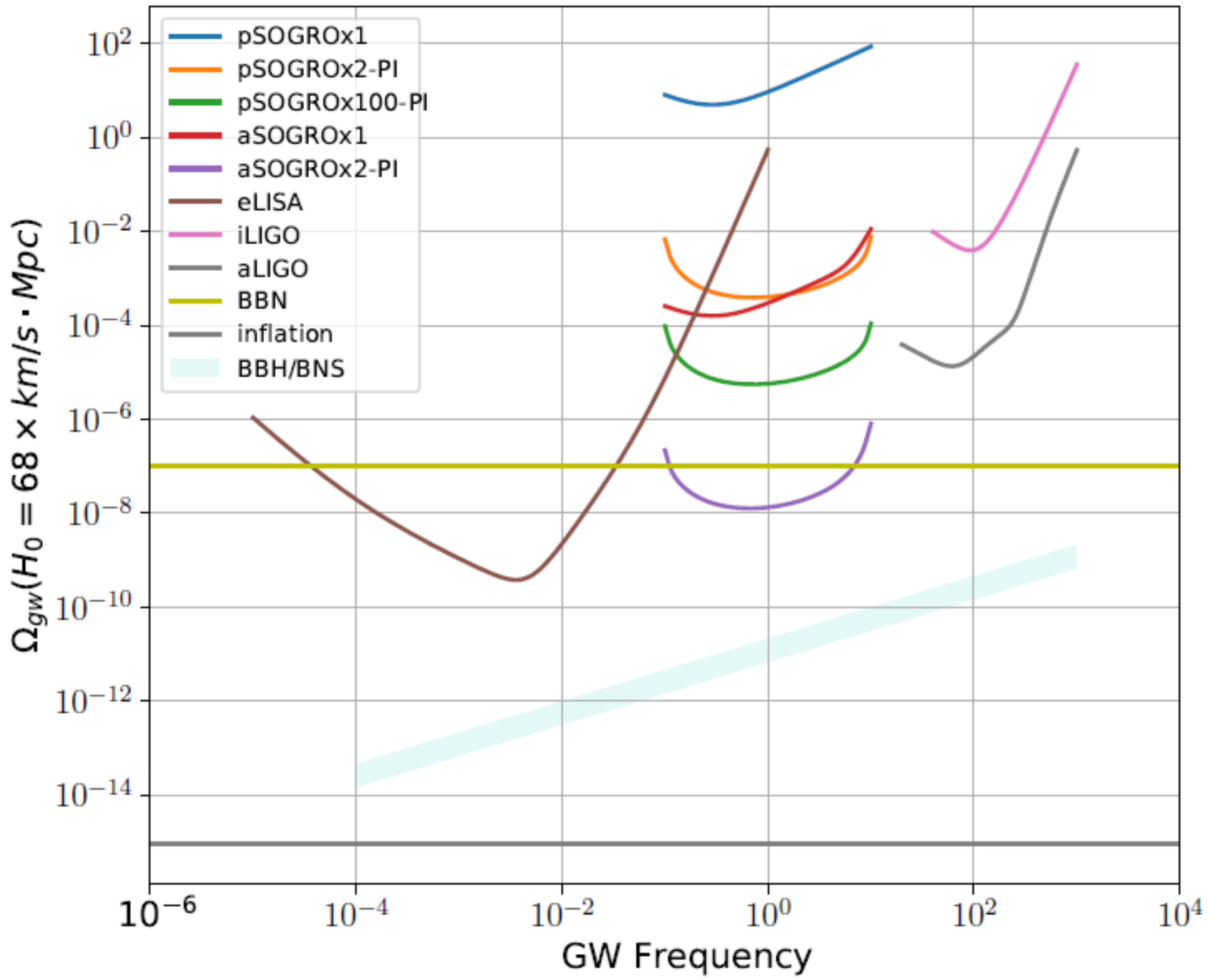
Binary star evolution

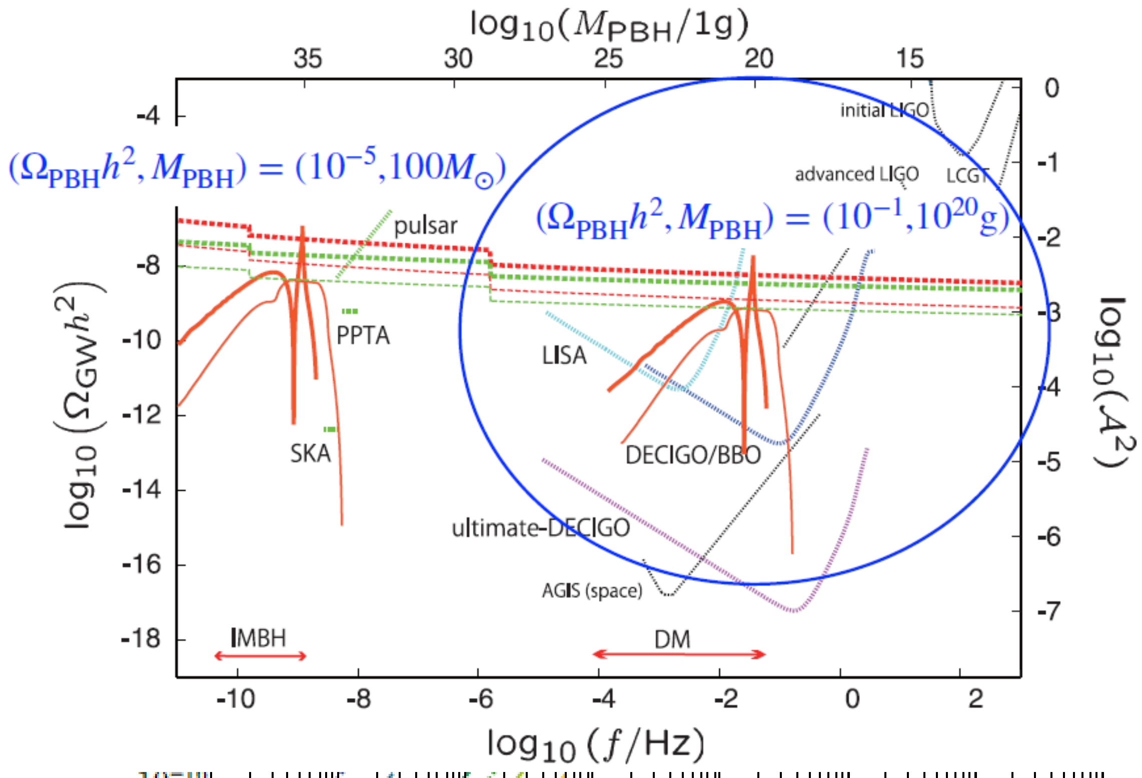
vs

Dynamical interactions in dense stellar systems



3) Stochastic Gravitational Wave Background:



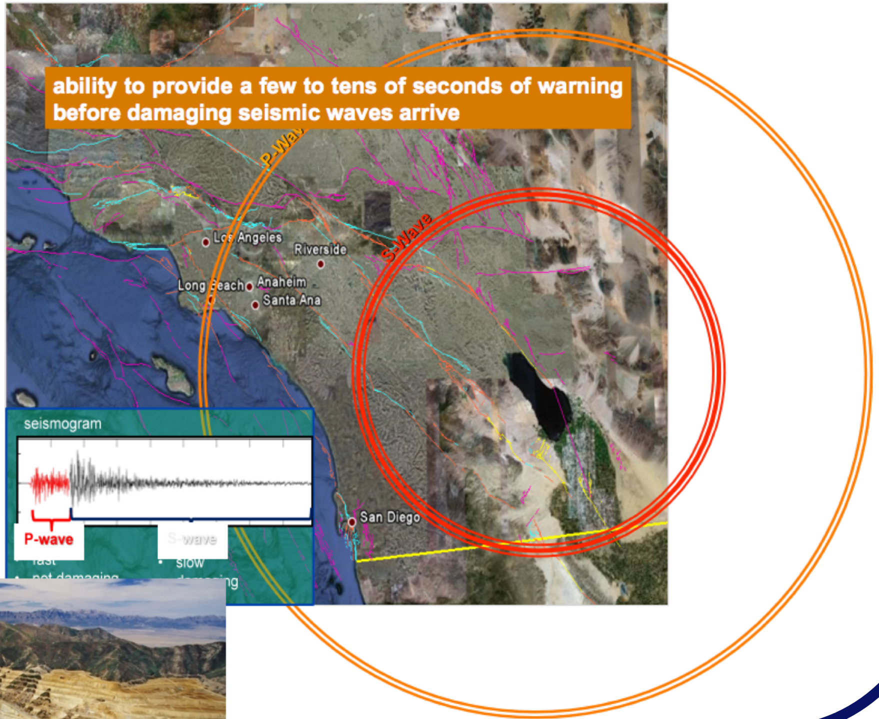


- Sasaki, Zhang & Pi ('18): Scalaron
- Espinosa, Racco & Riotto ('18): "SM Higgs instability"

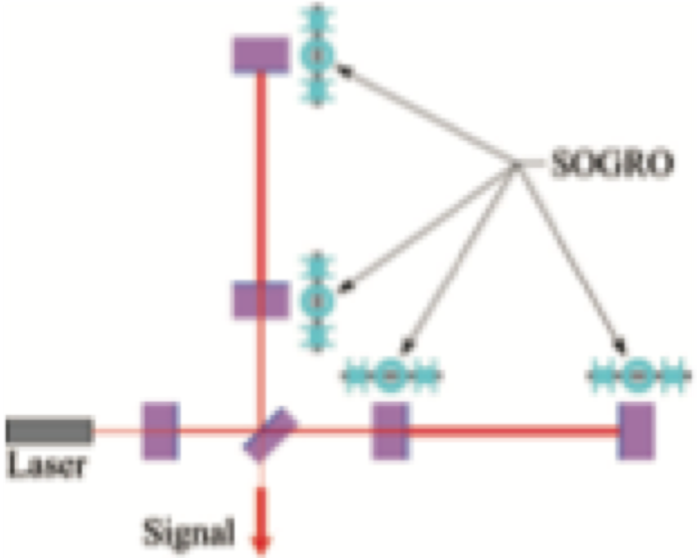
✓ **Build multi detectors!!**

4) Other applications:

Fastest Earthquake Early Warning



Improve aLIGO sensitivity at low freqs.



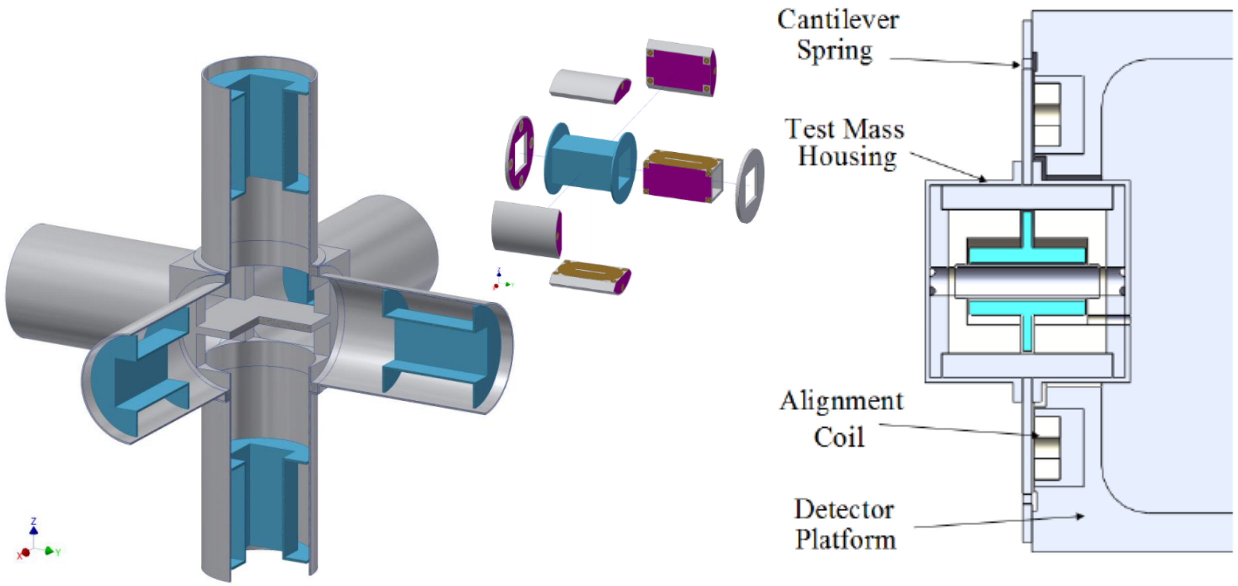
- ✓ **Saves ~10 s for Kyungjoo-Busan (~76 km)**

(Based on figures by H. Paik & C. Kim)

V. Summary and Outlook

- Design, principles and sciences are briefly introduced for the project of developing a superconducting mid-frequency gravitational wave telescope (SOGRO).
- Although our pilot study shows some feasibility of SOGRO, there remain many technical and theoretical challenges.
- Budget estimation for pSOGRO:

  ~30 M$ in total for 6 years
- We hope that it should be realized sometime in the future.



1/10^(-21) OF THANKS!