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Superconducting tensor detector for mid-frequency gravitational waves: SOGRO

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in collaboration with

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Target science and a prototype design for a superconducting tensor detector for mid-frequency gravitational waves

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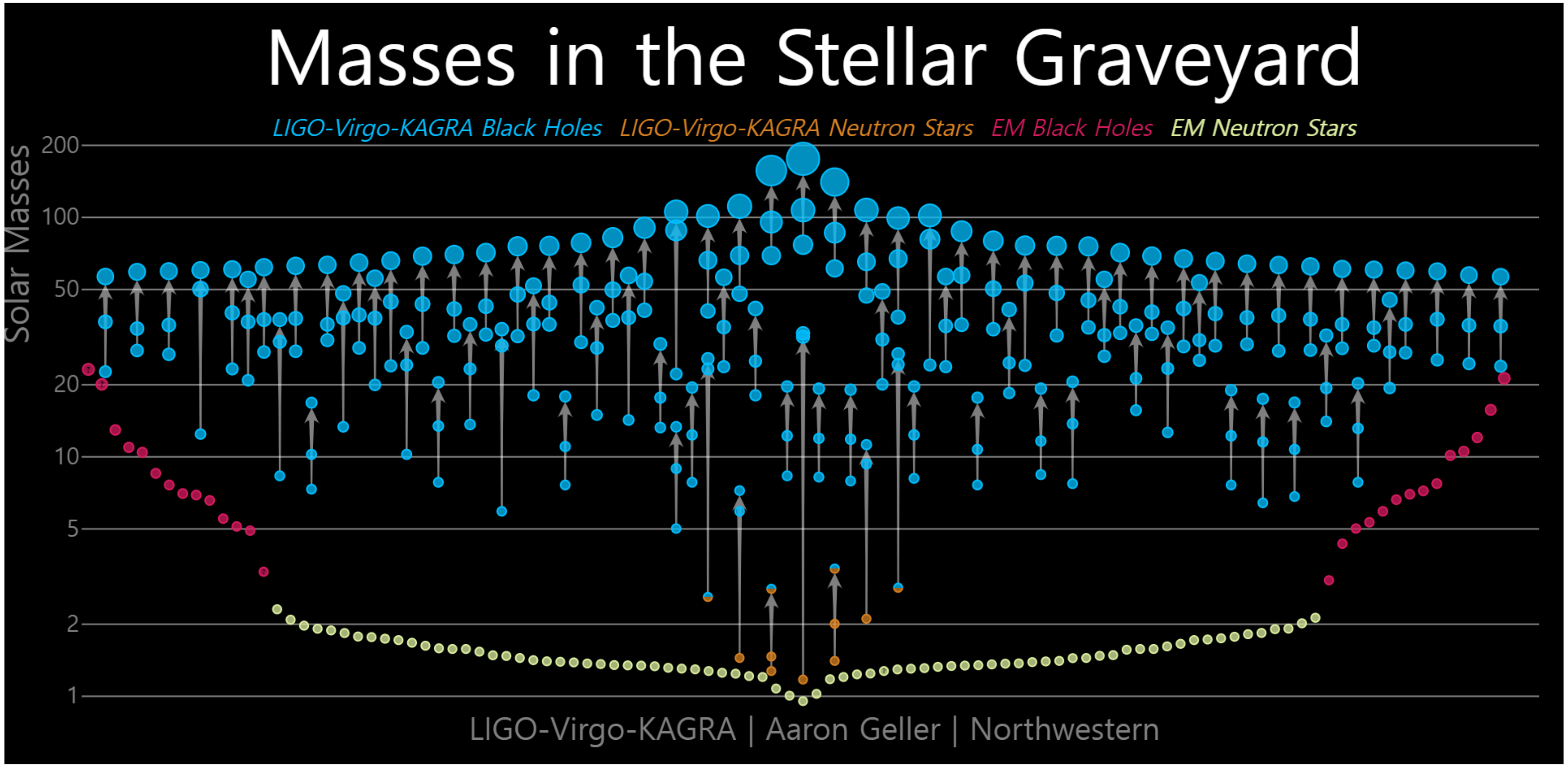
I. Introduction

✓ **GWs Observed:** O1 (2015.09.12~2016.01.19), O2 (2016.11.30~2017.08.25) & O3 (2019.04.01~2020.03.27)

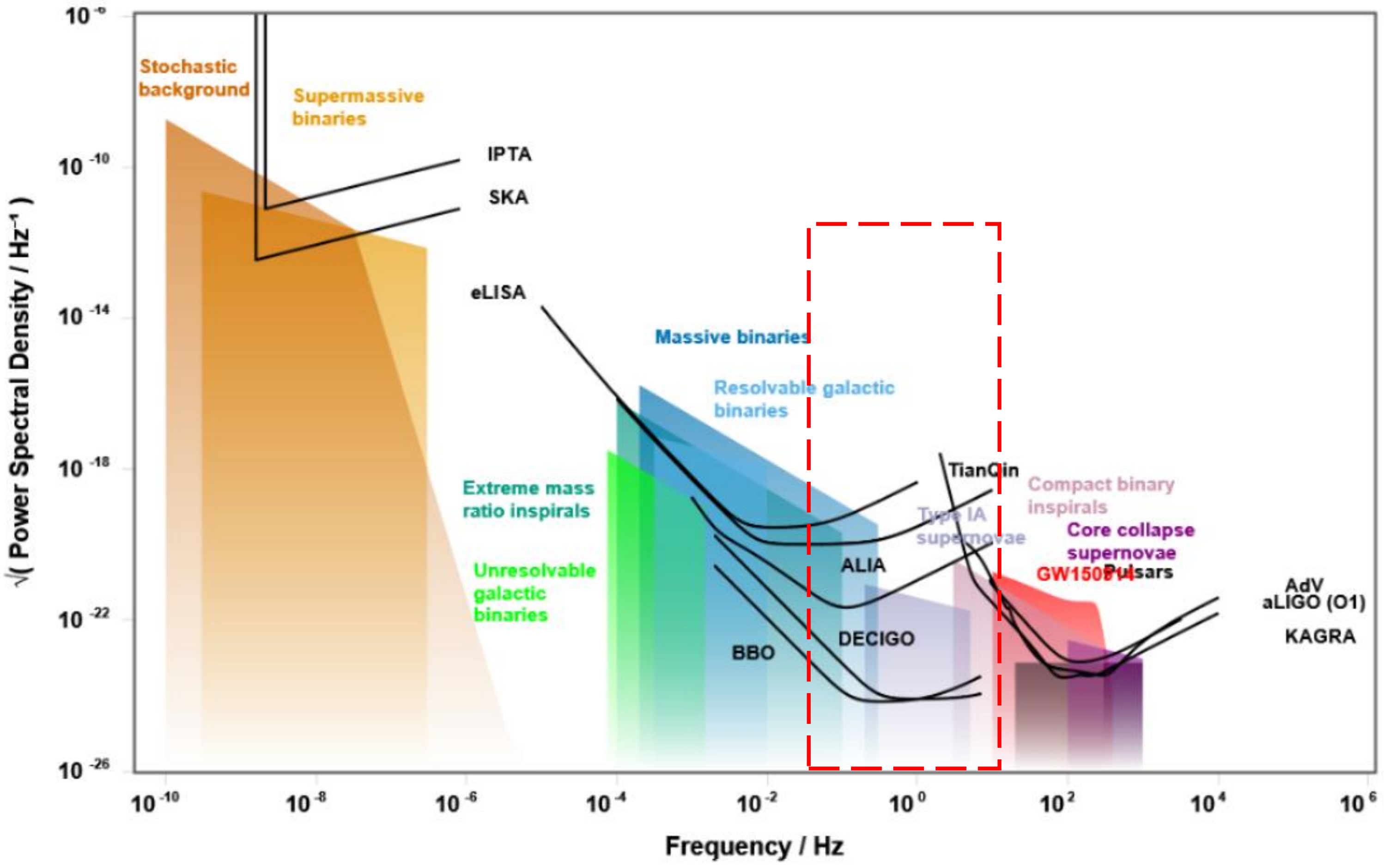


(Image credit: LIGO-Virgo/Aaron Geller/Northwestern)

✓ ~90 events in total from compact binary objects, e.g., BH-BH, NS-NS & BH-NS.

- ✓ It opened up a new window to the universe: GW astronomy.
- ✓ Already gave lots of implications to gravitational physics and fundamental physics, e.g., test of GR in strong field ($\dot{P}_{orb} \sim -(10^{-14} \sim 10^{-12})$ ➔ $(0.1 \sim 1)$), origin of heavy elements including Ag, Hubble tension, …

✓ Gravitational Wave Spectrum:



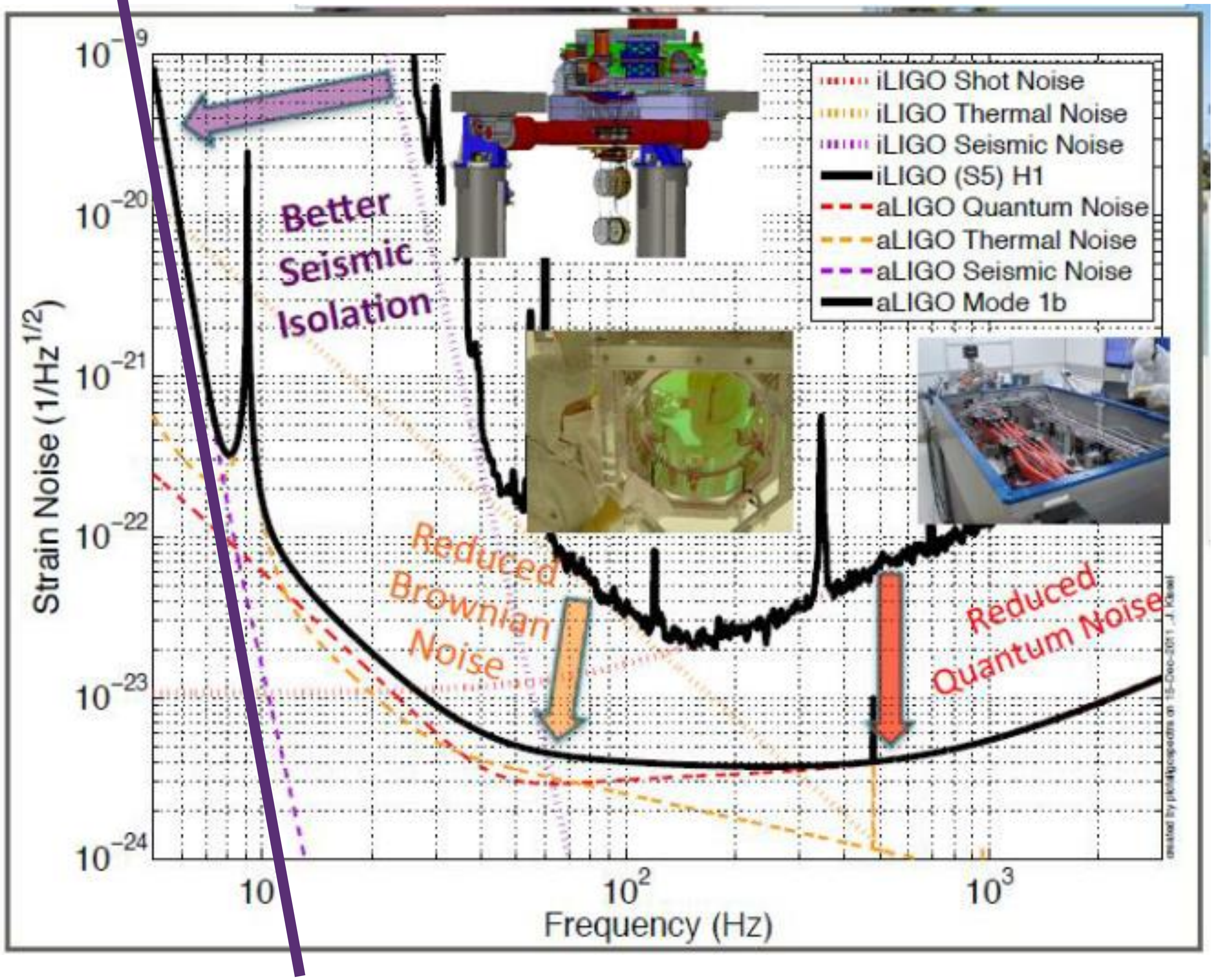
Based on http://rhcole.com/apps/GWplotter/ by Moore, Cole & Berry

- Interferometer-type detectors:
  - aLIGO, aVirgo, KAGRA, eLISA, INDIGO
- Plans to improve sensitivity:
  - A+ (~22), Einstein Telescope (~23), Cosmic Explorer (~27), AAGO, TAIJI, TianQin, etc.
- **Terrestrial ones cover 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~)

✓ Obstacles to observe GWs below $\sim\vartheta(10)Hz$ on the ground:

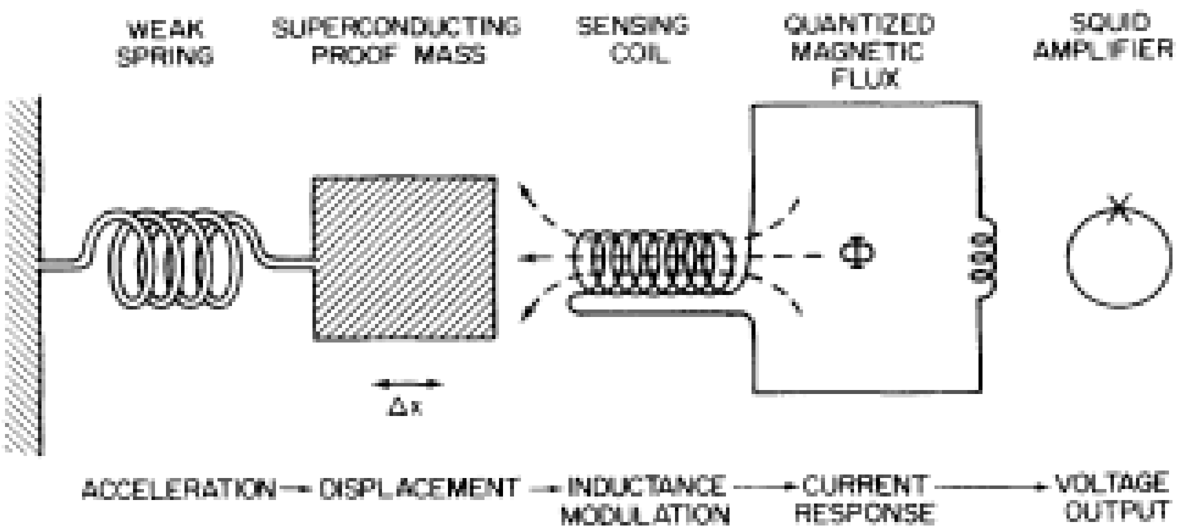
Big barrier due to (Seismic +Newtonian) noises!

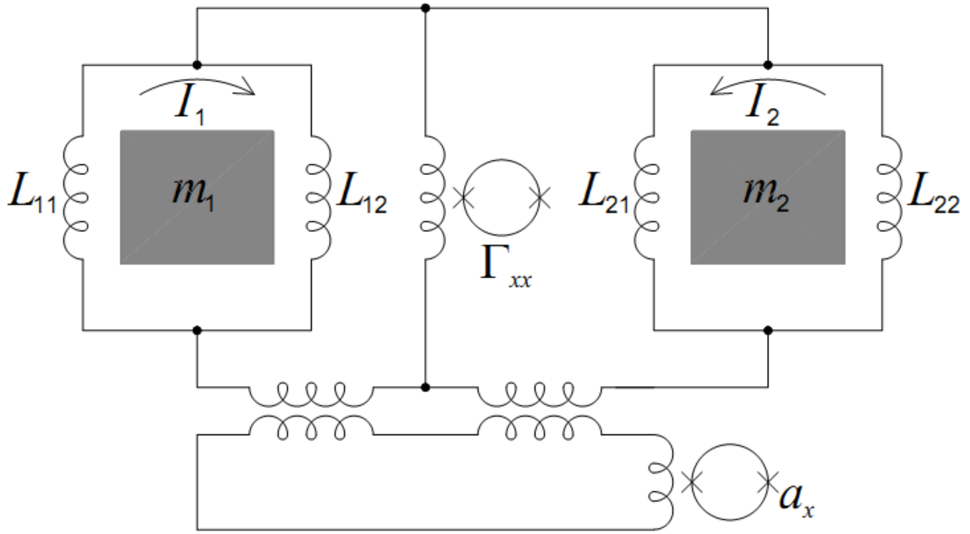


LIGO-G1600341

II. Basic Principle and Designs

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



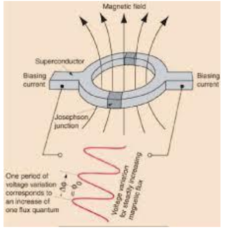


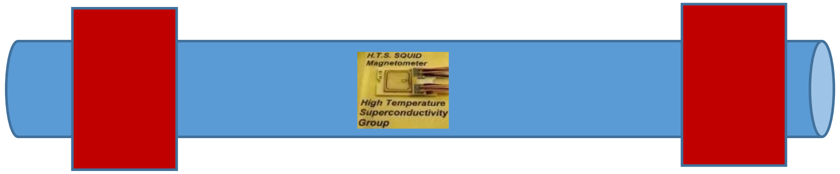
➔ **Only relative motions matter!!**

Test mass motion

➔Induced current at sensing coil

➔Measure flux at SQUID



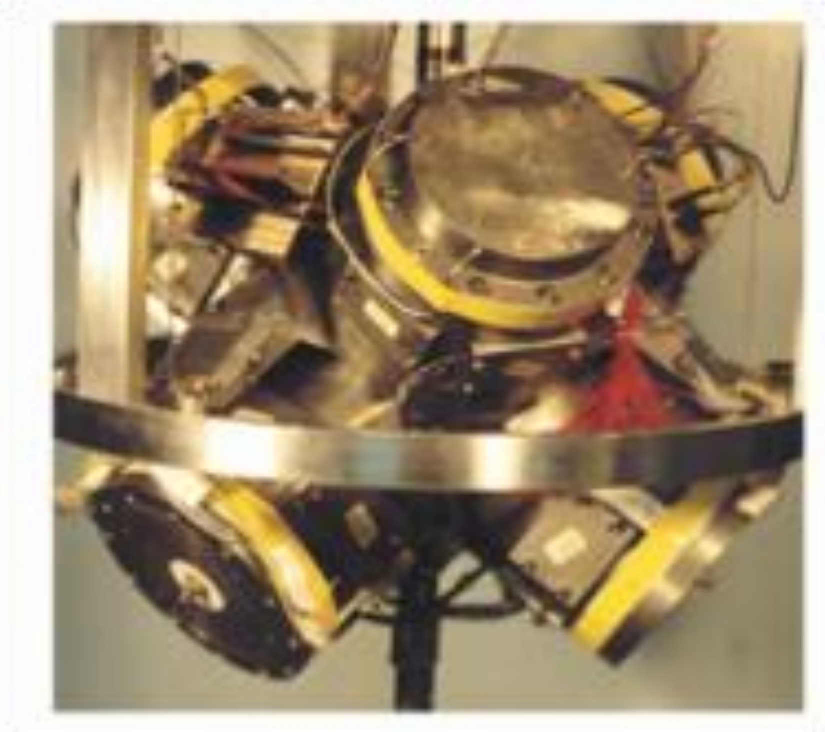


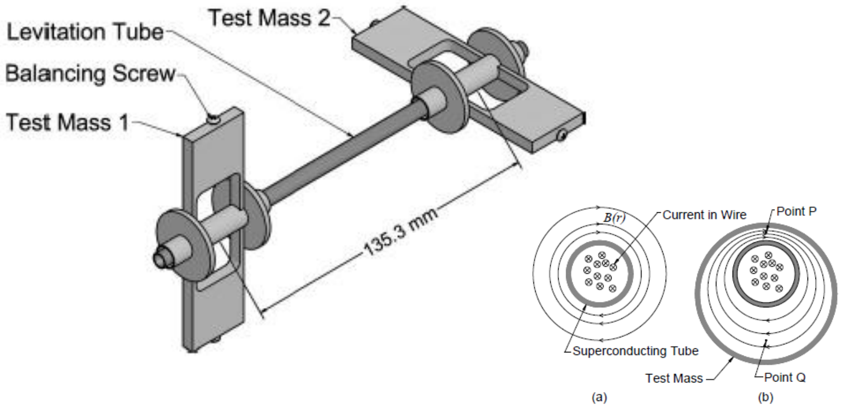
- Sensing coils & SQUIDs are mounted on the rigid stick.
- Two masses are freely moving.

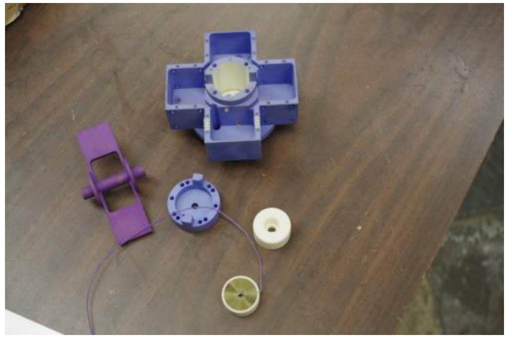
✓ A Bit of History for SOGRO:

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

Ho Jung Paik





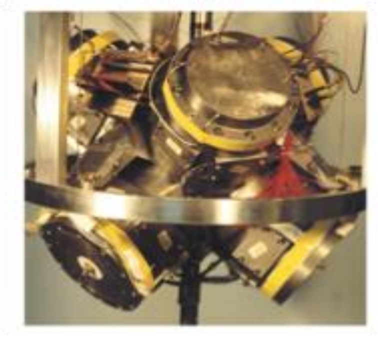


(Picture credit: H-M. Lee)

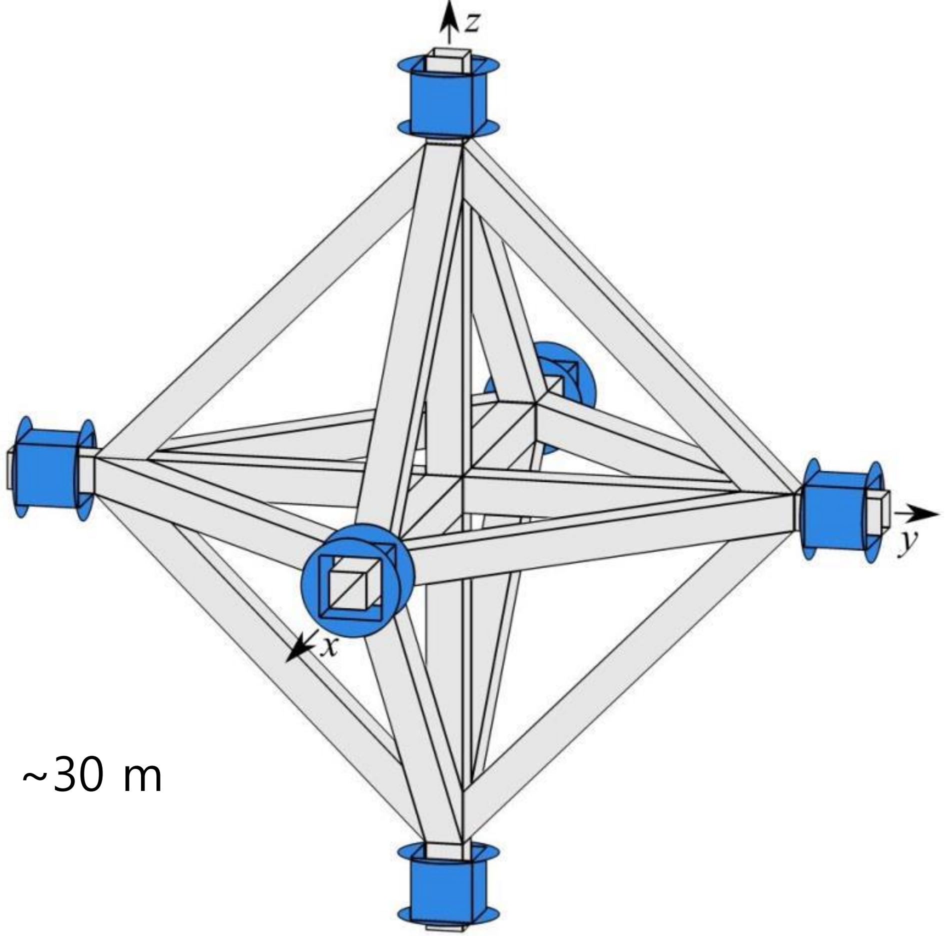
Moody, Paik, & Caravan (2002)

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

✓ Make it large!



~0.3 m



~30 m

- 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

✓ Responses:

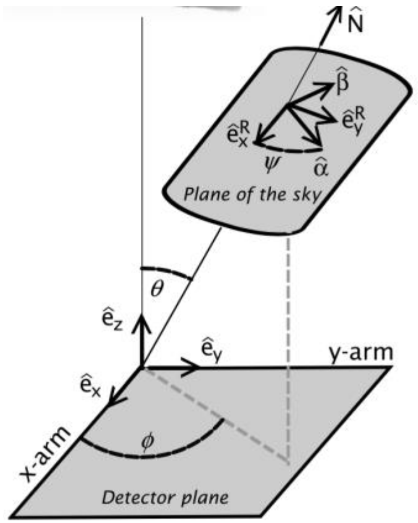
SOGRO is omni-directional!

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

6 channels in total: Multi-channel (tensor) detector!

able to distinguish breeding and longitudinal signals!

✓ Sky localization (Simple estimation with Gaussian noise):



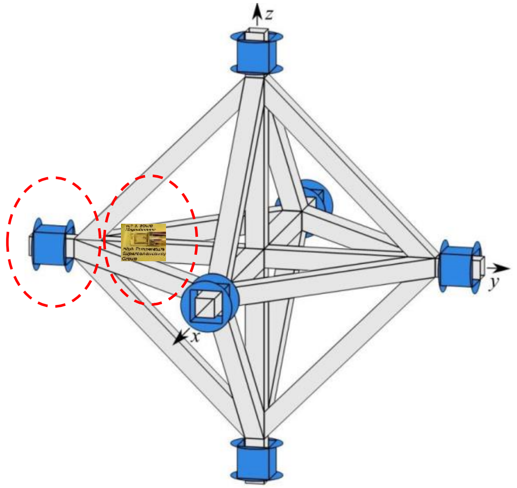
$$h_+ = h_{11}\sin^2\phi - h_{12}\sin(2\phi) + h_{22}\cos^2\phi,$$

$$h_\times = (h_{23}\cos\phi - h_{13}\sin\phi)\sin\theta + \left(\frac{1}{2}(h_{11} - h_{22})\sin(2\phi) - h_{12}\cos(2\phi)\right)\cos\theta,$$

$$0 = (h_{11} + h_{22})\cos\theta - (h_{13}\cos\phi + h_{23}\sin\phi)\sin\theta,$$

$$0 = (h_{11}^2 - h_{22}^2 + h_{13}^2 - h_{23}^2)\sin(2\phi) - 2[h_{12}(h_{11} + h_{22}) + h_{13}h_{23}]\cos(2\phi).$$

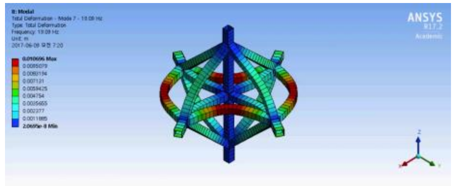
✓ Main noise sources:



- 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



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

- Newtonian noise

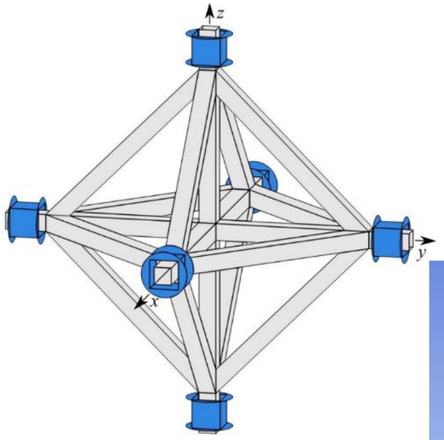
✓ **Platform strain noise:** Pre-stressed modal analyses using ANSYS

aSOGRO

pSOGRO

✓ Design parameters:

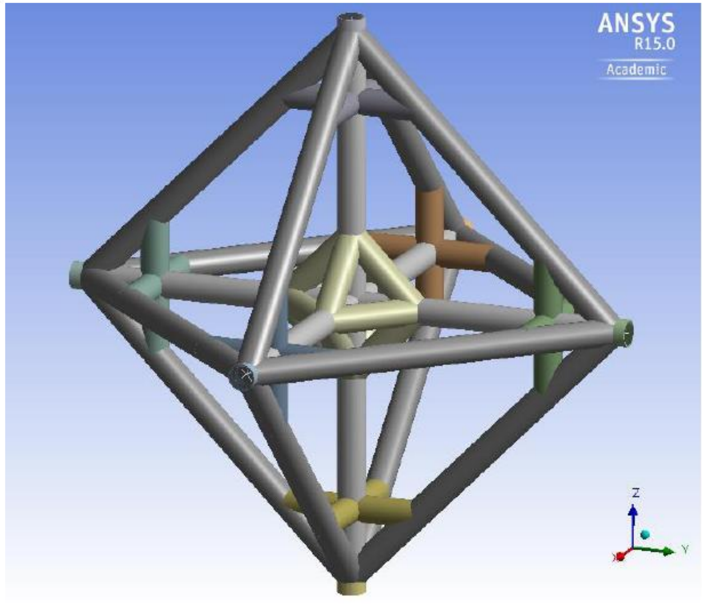
Bae+’22   Paik+ ’16 & Paik+‘20



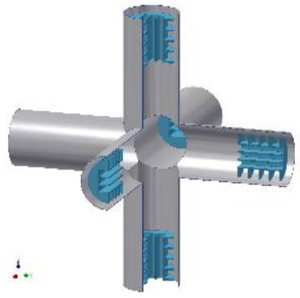
SOGRO/aSOGRO

(30 m, 50 m, 100 m)

- (100~250) tons
- ≤ 4 K
- Underground: ~200 m



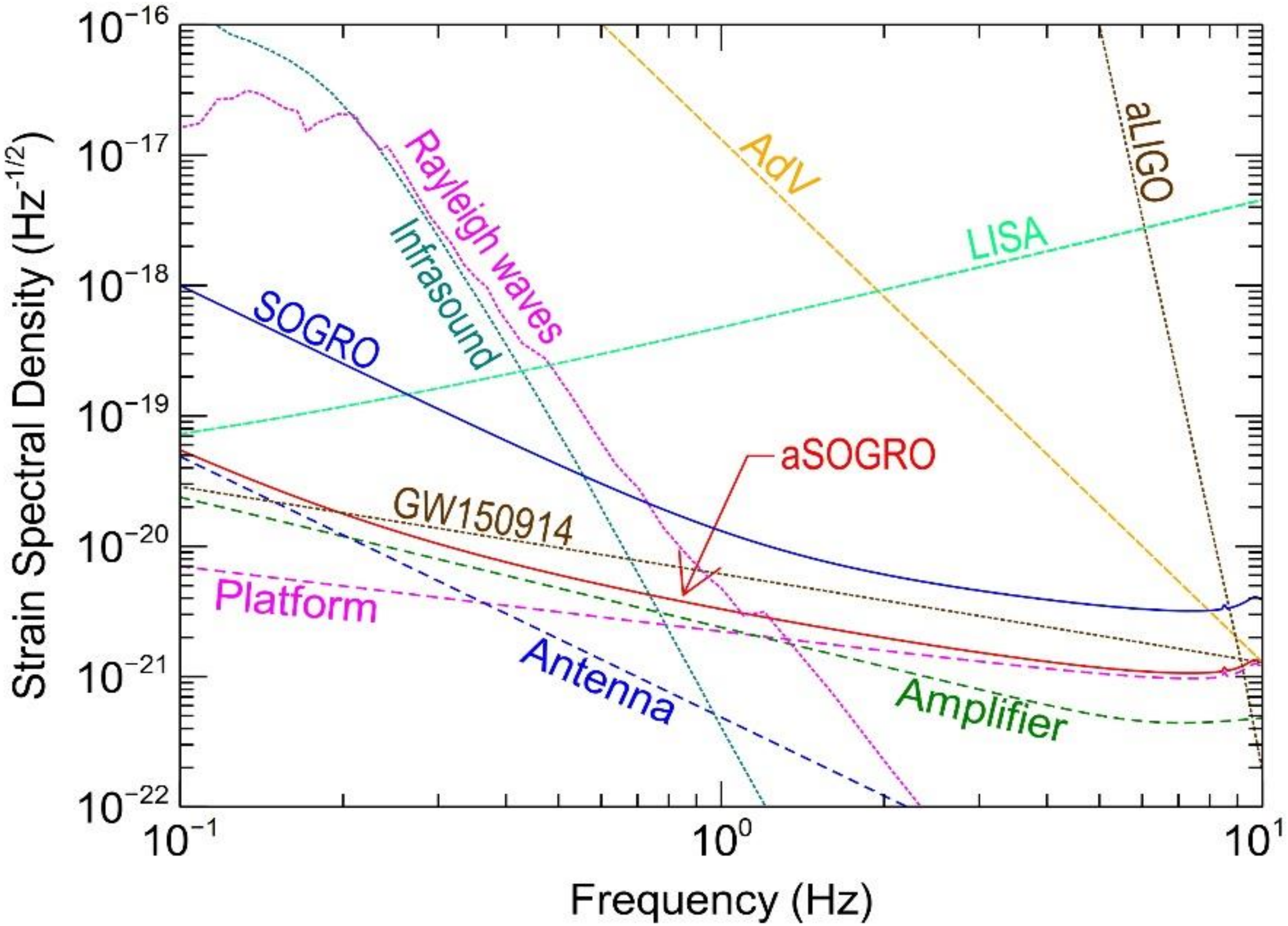
pSOGRO



2 m, 1 ton

✓ Sensitivity of SOGROs:

$$S_{h,\Sigma}(f) = \frac{16}{3ML^2\omega^4}\left[\frac{k_B T \omega_D}{Q_D} + \frac{|\omega^2-\omega_D^2|}{\omega_p}\left(1+\frac{1}{\beta^2}\right)^{1/2} k_B T_N\right], \quad k_B T_N = n\hbar\omega_p, \ \Sigma \text{ over 5 channels}$$



$$\delta\phi_{\rm Rf}(\vec{\varrho}, z, \omega) = -2\pi\frac{\gamma G\rho_0}{k}\xi(\omega)e^{-zk}e^{i\vec{k}\cdot\vec{\varrho}}$$

(Harms & Paik '15)

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

✓ Cooling of SOGRO System:

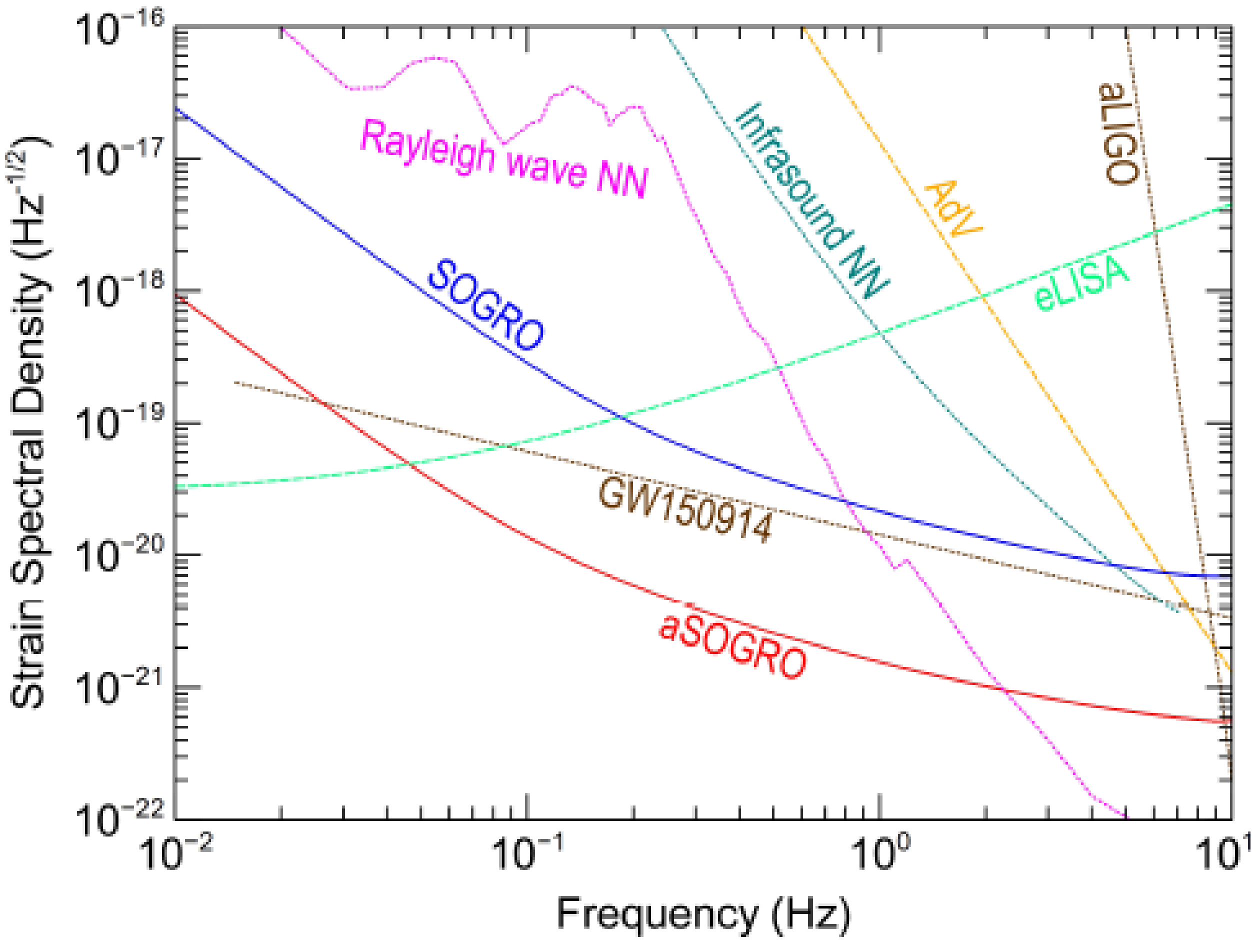
@ SNU workshop (2017/8/1)

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

Slide credit: D.K. Kim

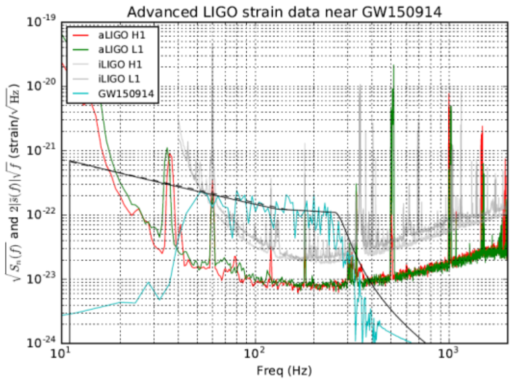
III. Science with SOGRO

1) Inspiralling BBH: "Stellar-mass binaries"



~ 10 days

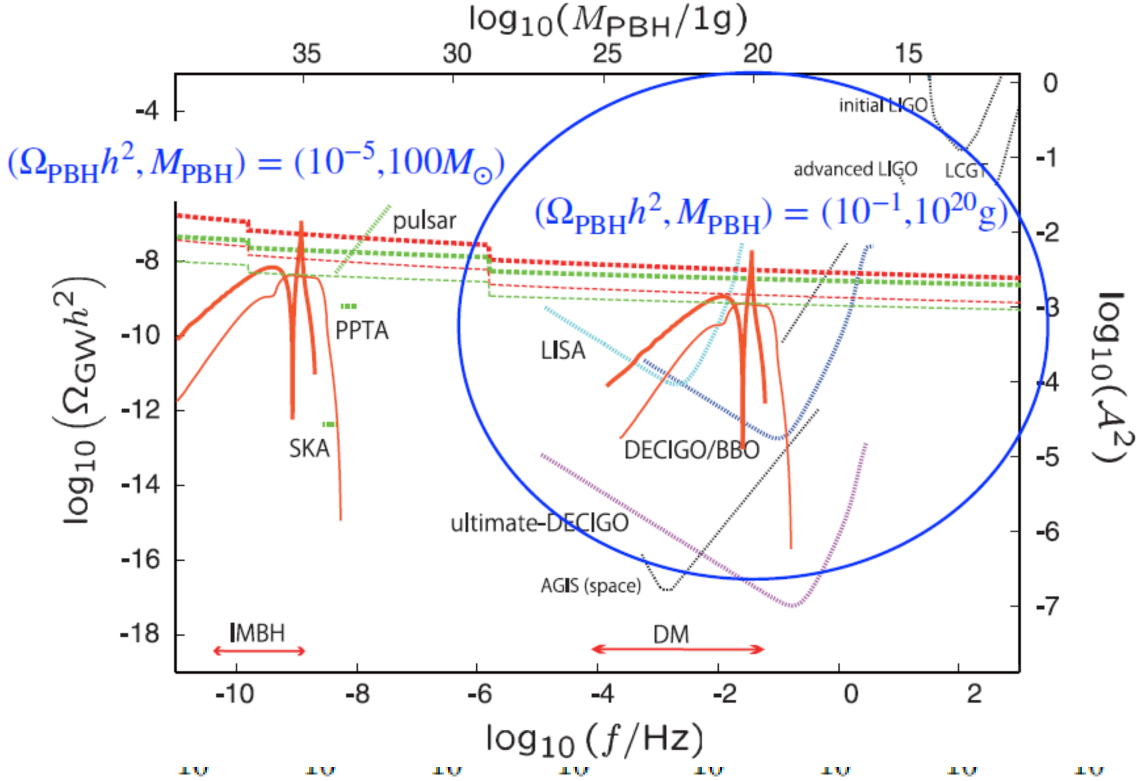
- Accurate measurements of inspiral phase
- Early notification to LIGO/Virgo/KAGRA



Observed for ~.2s

2) IMBH binary inspirals and mergers:

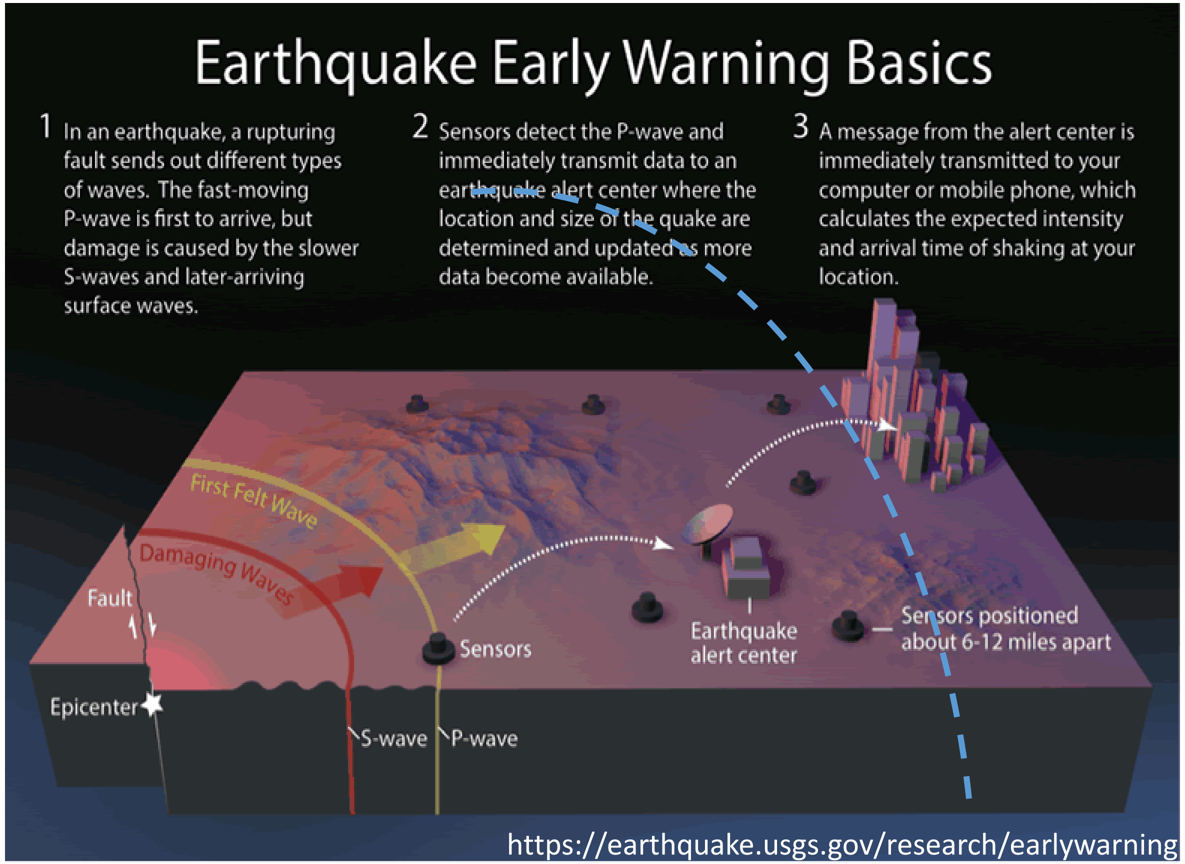
3) Stochastic Gravitational Wave Background



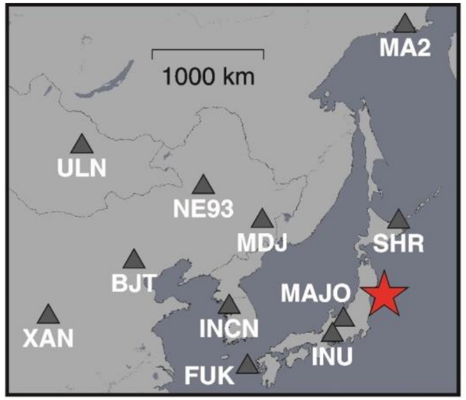
- Sasaki, Zhang & Pi ('18): Scalaron
- Espinosa, Racco & Riotto ('18): "SM Higgs instability"

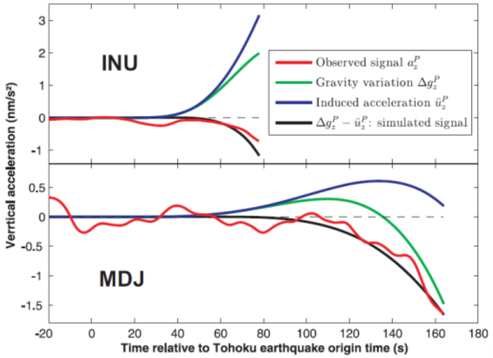
✓ **Build multi detectors!!**

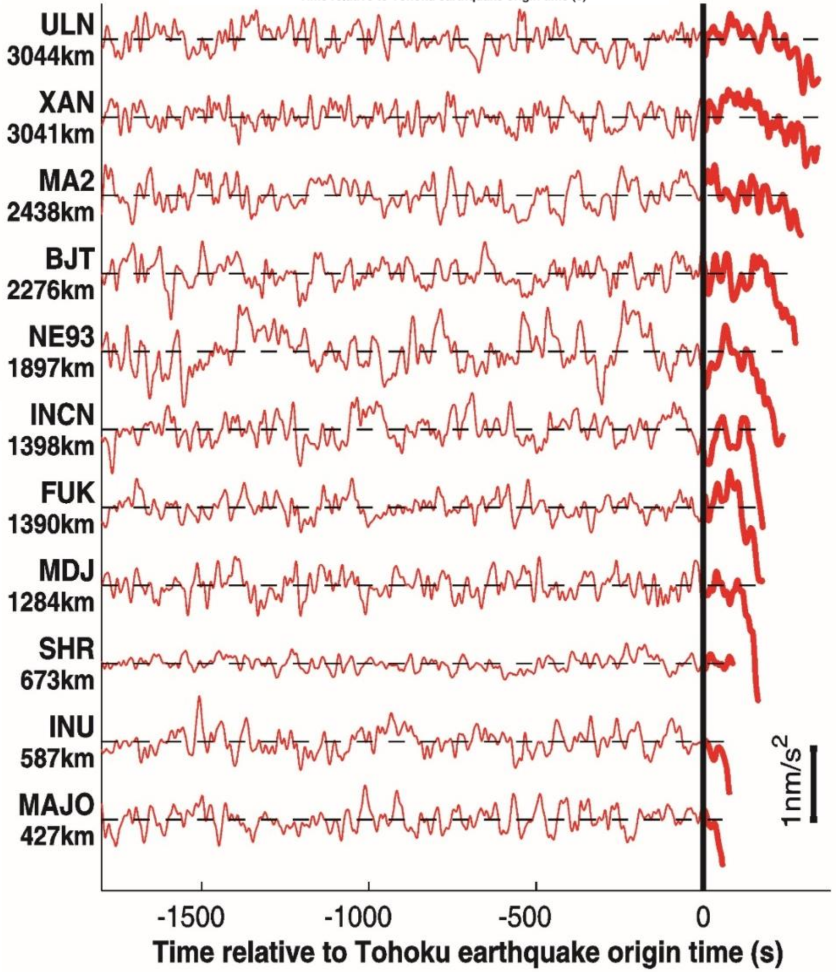
4) Earthquake Early Warning:



2011 Tohoku earthquake





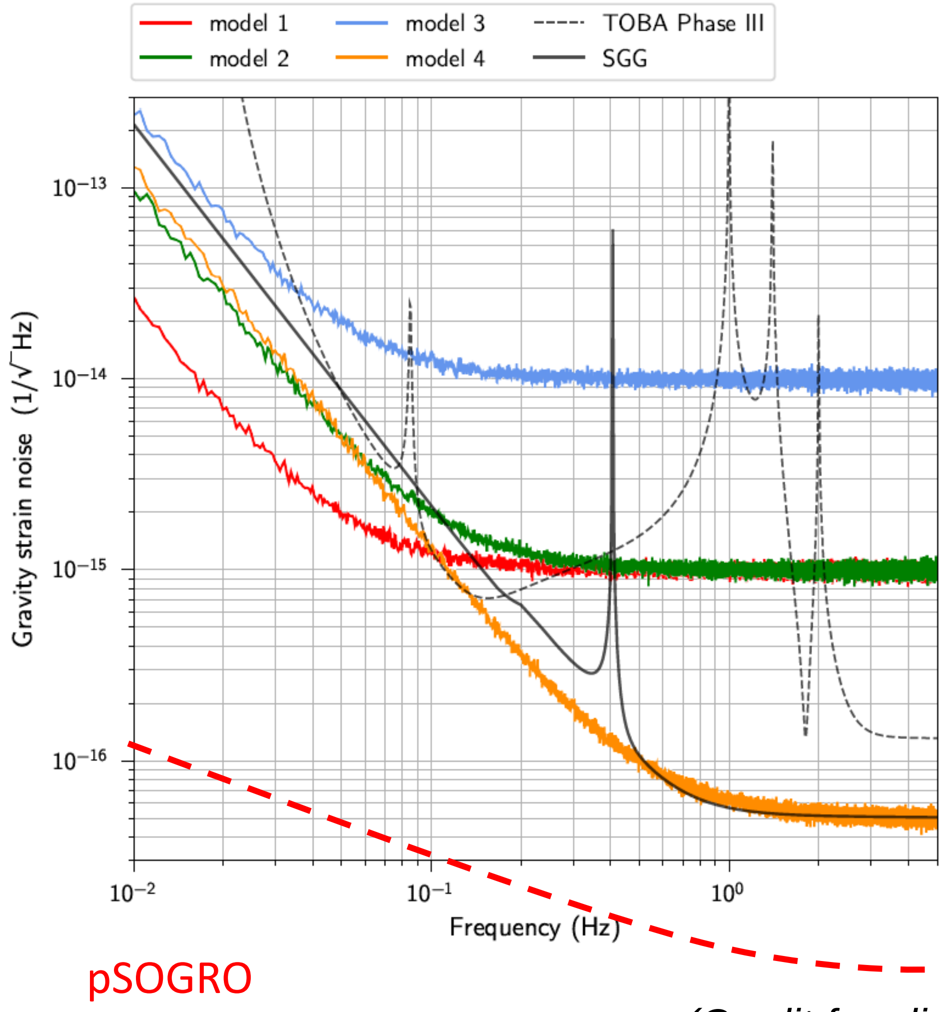


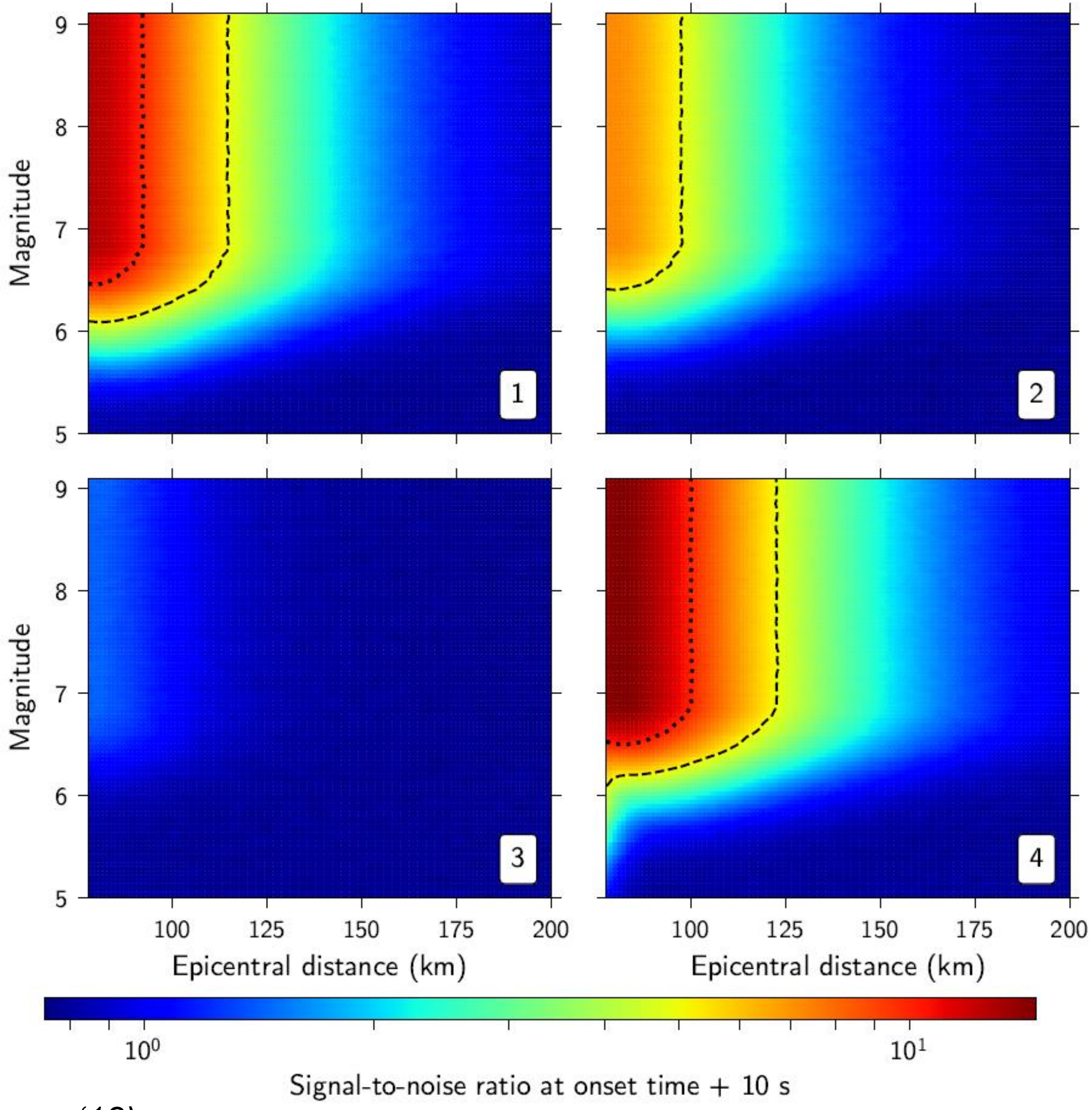
✓ **Saves ~10 s for Kyungjoo-Busan (~76 km)**

(Credit for slides: Ampuero '18)

Vallée et al., Science, 2017

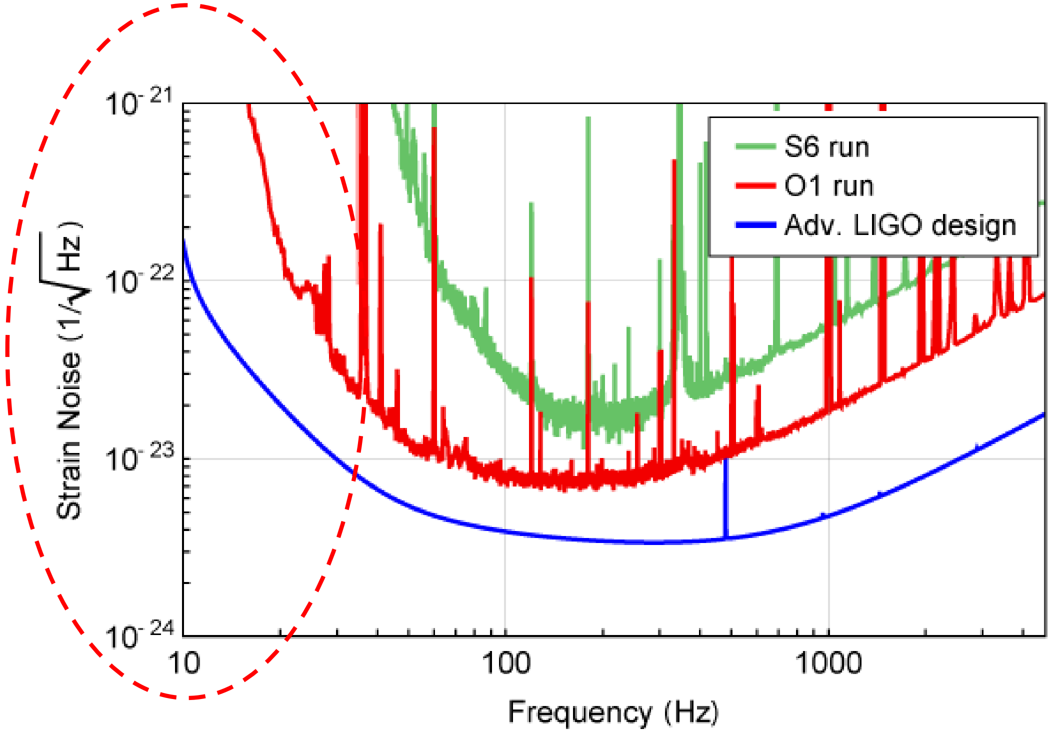
SNR of matched filter detection



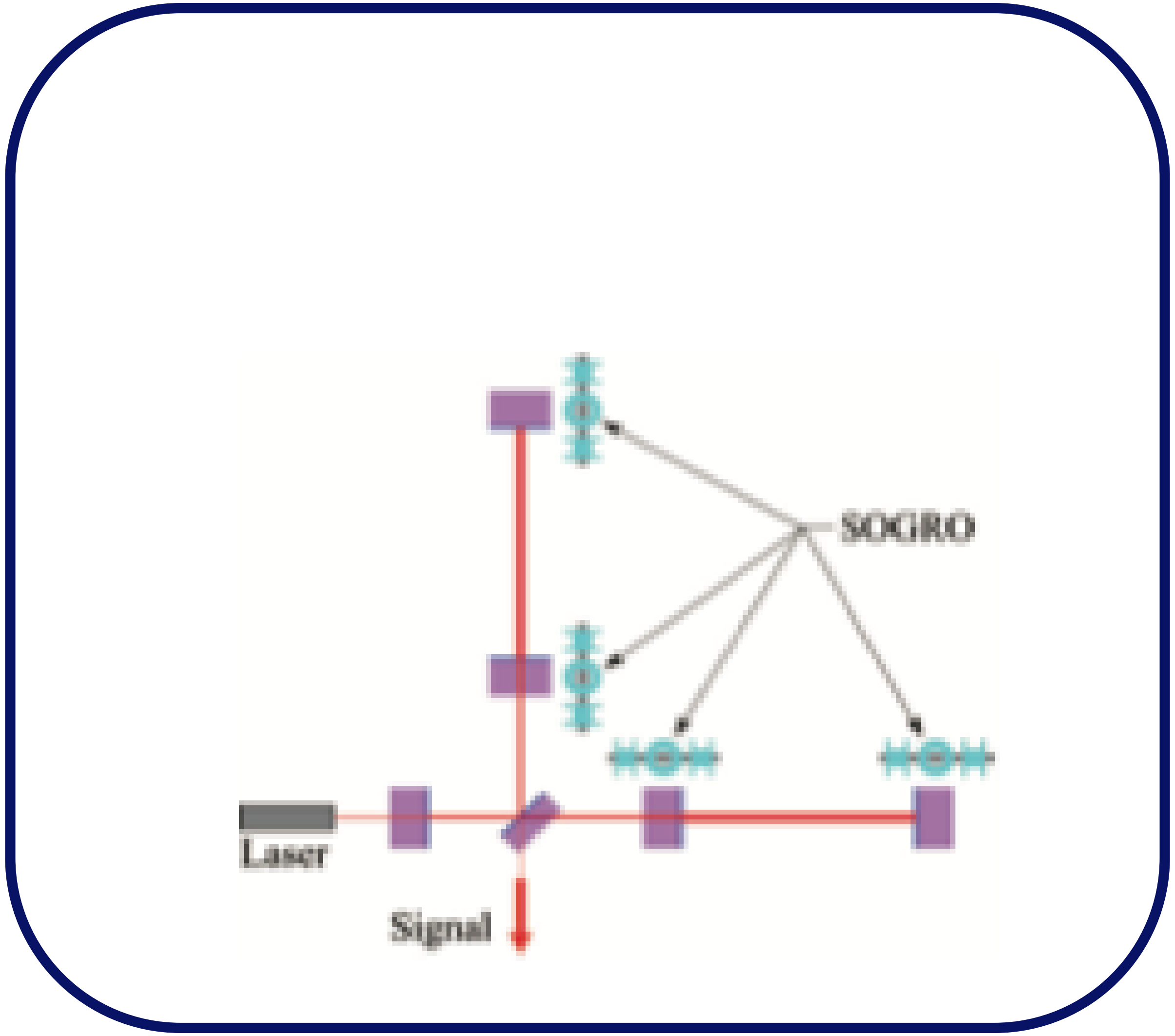


(Credit for slide: Ampuero '18)

5) Improve aLIGO sensitivity at low freqs:



https://www.advancedligo.mit.edu/



(Credit for figure: H. Paik)

IV. Summary and Outlook

- Brief introduction to SOGRO and its target sciences in $(0.1 \sim 10)Hz$

- There still remain many technical and theoretical challenges, in particular, Newtonian noise reduction and civil engineering.

✓ **Budget estimated for the pSOGRO:**

Status in Asian Regions for GW Experiments

	Statements in 2019
Japan	• KAGRA • R&Ds for B-DECIGO (2020s), DECIGO, TOBA
India	• LIGO-India
China	• Collaboration with KAGRA • Space projects (TianQin and Taiji) • ZAIGA (Terrestrial), AIGSO (Space)
Korea	• Collaboration with KAGRA and $LIGO^{(*3)}$ • Contribution to KAGRA+ (*1) • R&Ds for a 0.1-10Hz detector (SOGRO)
Taiwan	• Collaboration with KAGRA • Contribution to KAGRA+ (*2) • Joining LISA consortium
Australia	• OzGrav

(Based on K. Somiya's slide)

(*1) Squeezing experiment
(*2) High power laser, squeezing
(*3) Added by GK

✓ SOGRO in Space

- We strongly believe that the SOGRO experiment will bring lots of fruitful sciences and new chances in the future.

  - I was told that a Korean experimentalist visited UMD group and learned the SGG from A to Z……

- **We hope that our pilot study will be a milestone of detector developments for GW astronomy in Korea.**

1/10^(−21) OF THANKS!