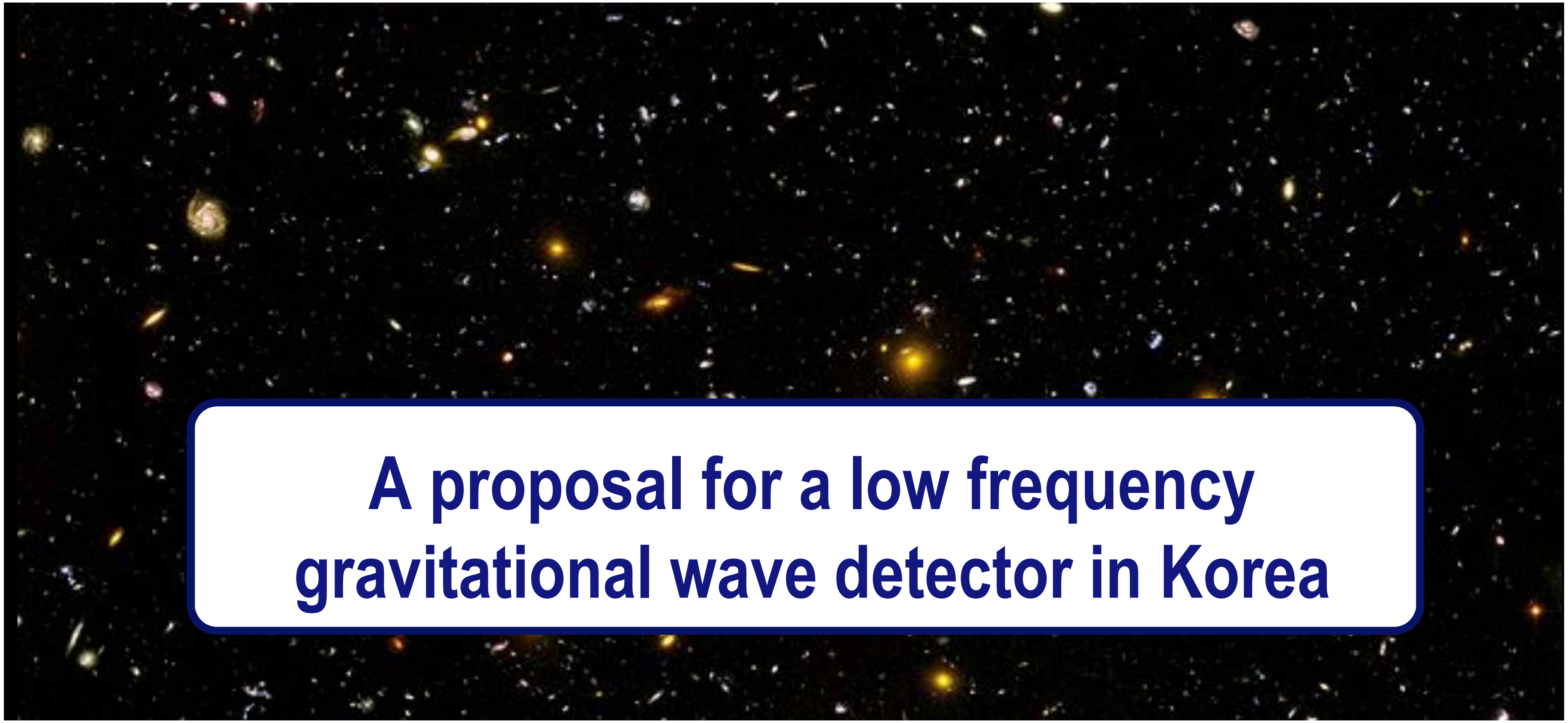
April 17, 2017 at CosKASI Conference 2017 in Daejeon, Korea



A proposal for a low frequency gravitational wave detector in Korea

Gungwon Kang (KISTI)
On behalf of the KKN Working Group

Korea Astronomy and Space Science Institute 한국천문연구원

KiSTi www.kisti.re.kr
한국과학기술정보연구원
Korea Institute of Science and Technology Information

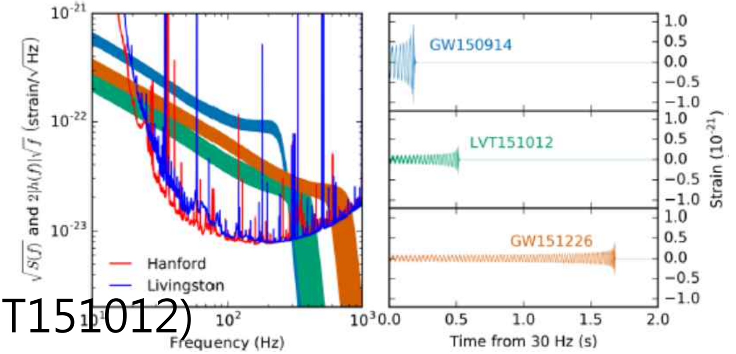
NIMS National Institute for Mathematical Sciences

Outline

I. Motivation
II. Design and Principle
III. Targets and Science
IV. Roadmap and Perspective
V. Summary

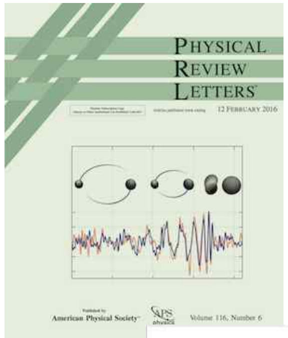
I. Motivation

1) Detection of GWs and current experiments



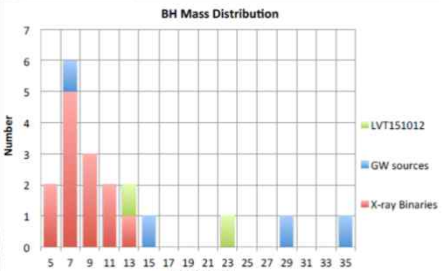
PRX ('16)

- aLIGO O1 (2015.09.12~2016.01.12): GW150914, GW151226, (LVT151012)
  O2 (2016.11.30~2017.08): 6 triggers as of Mar. 23 (FAR≲1/mon)
  O3 (2017~2018): 9 months
- aVirgo: will join to O2 around 2017.06~08
- bKAGRA: 2016~2019 for upgrade of iKAGRA and to operate ~2020
- LIGO-India: in construction currently and planned to operate ~2024
- eLISA: Path Finder (2015.12) and planned to install ~2029
- Pulsar Timing Array



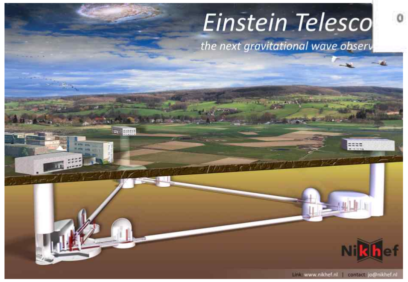
PRL ('16)

➔ Opened up a new window to the universe,
i.e., **"Gravitational Wave Astronomy"**

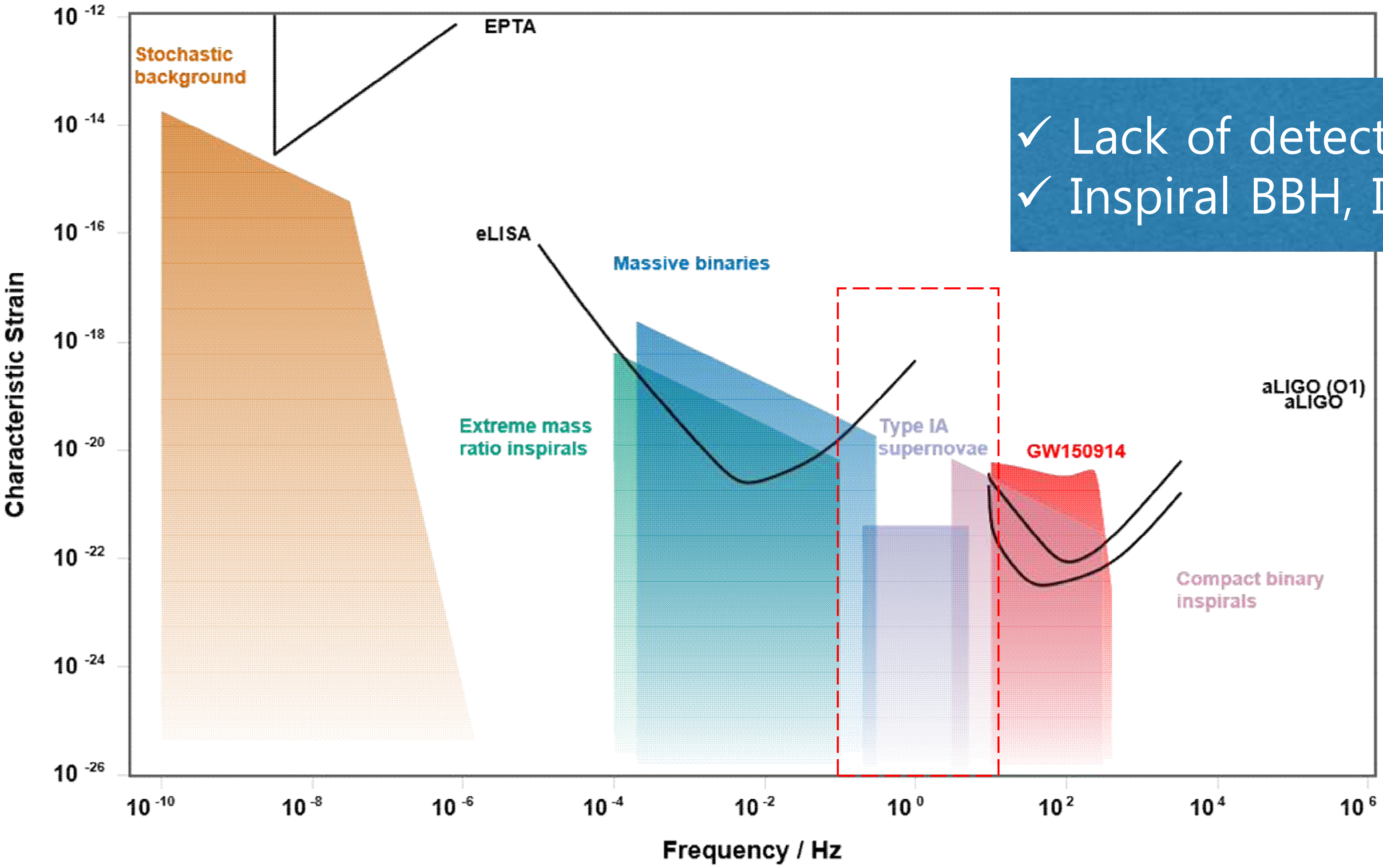


ApJL ('16)

- Future detectors: A+ (~2022), AdV+, Voyager (~2025), Einstein Telescope (~2023), Cosmic Explorer (~2027), DECIGO (~2027), TianQin (?), …



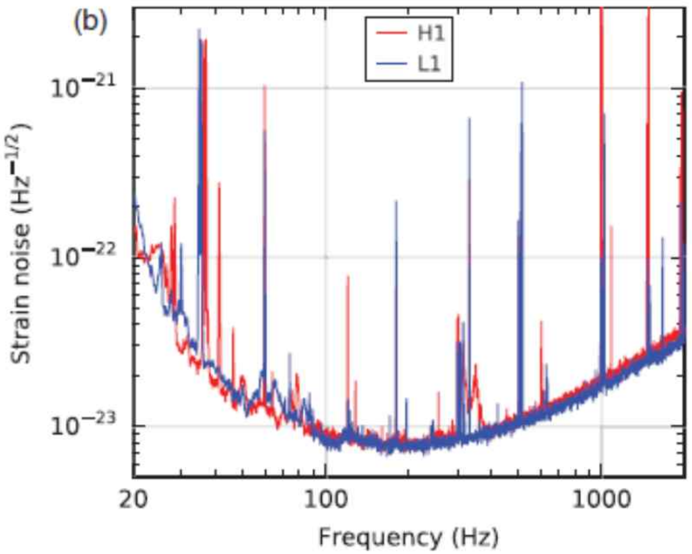
2) Gravitational wave spectrum, detectors and sources



- ✓ Lack of detector for 0.1~10Hz
- ✓ Inspiral BBH, IMBH, WDB, …

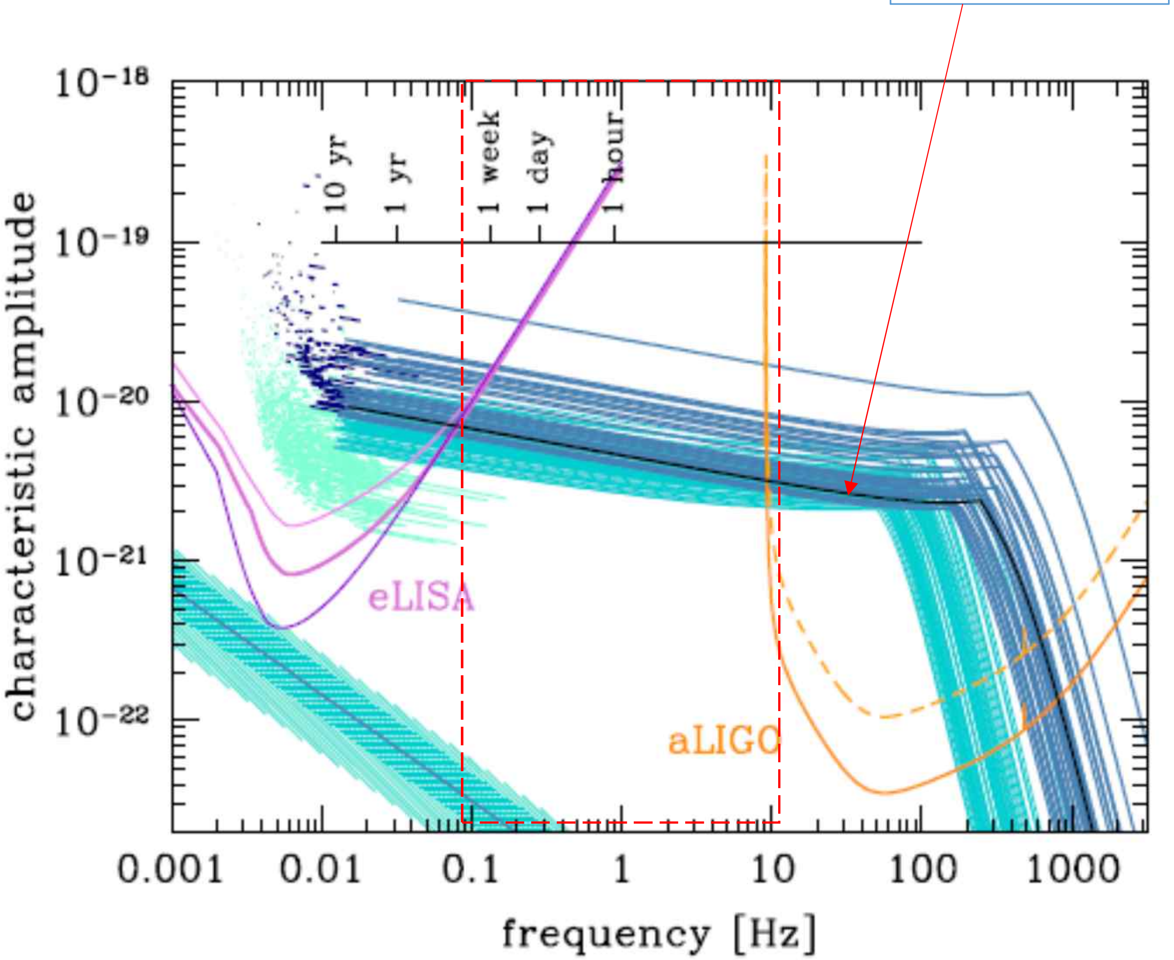
http://rhcole.com/apps/GWplotter/
by Moore, Cole & Berry

3) Low frequency (*e.g.,* 0.1~10Hz) GWs and obstacles



aLIGO O1 sensitivity

Mainly due to
- ✓ Seismic noise
- ✓ Newtonian gravity noise

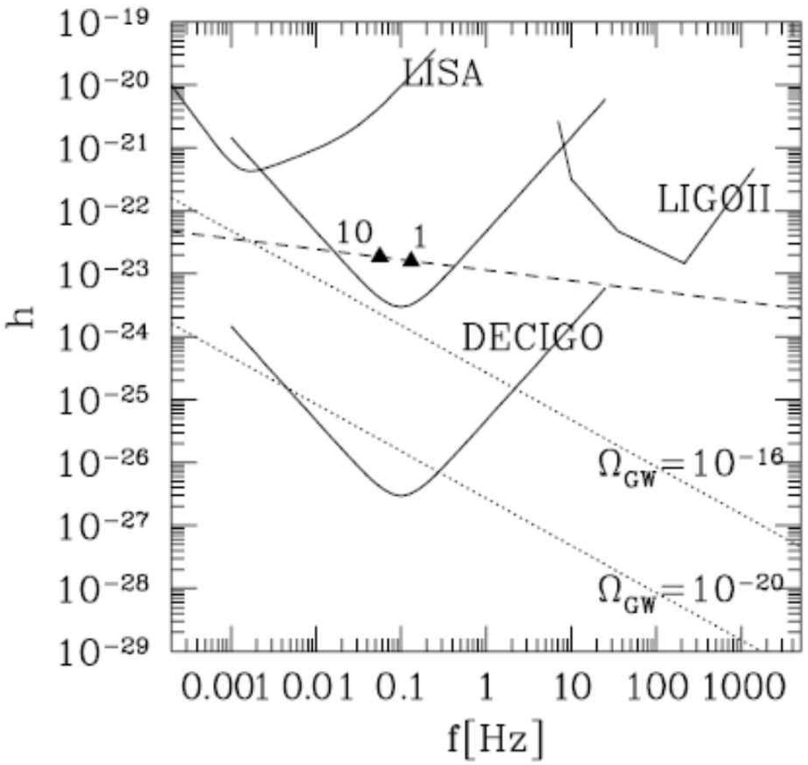


GW150914

Sesana (2016)

4) DECIGO (Deci-hertz interferometer Gravitational-wave Observatory)

- ✓ Same interferometer detector, but put it into space to avoid such noises!
- ✓ ~2027



Seto, Kawamura & Nakamura (2001)

Roadmap (Slide credit: M. Ando 2012)

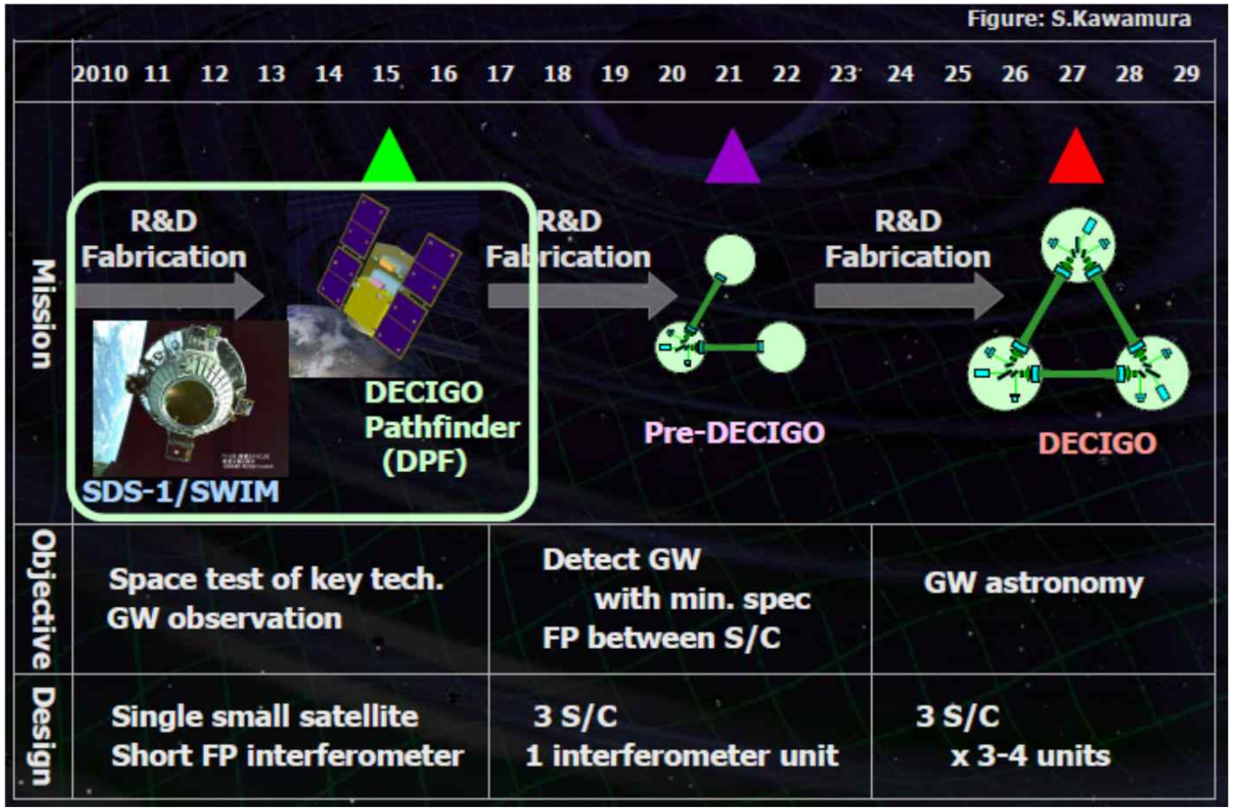


Figure: S.Kawamura

2010 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29

Mission

R&D Fabrication → SDS-1/SWIM, DECIGO Pathfinder (DPF)

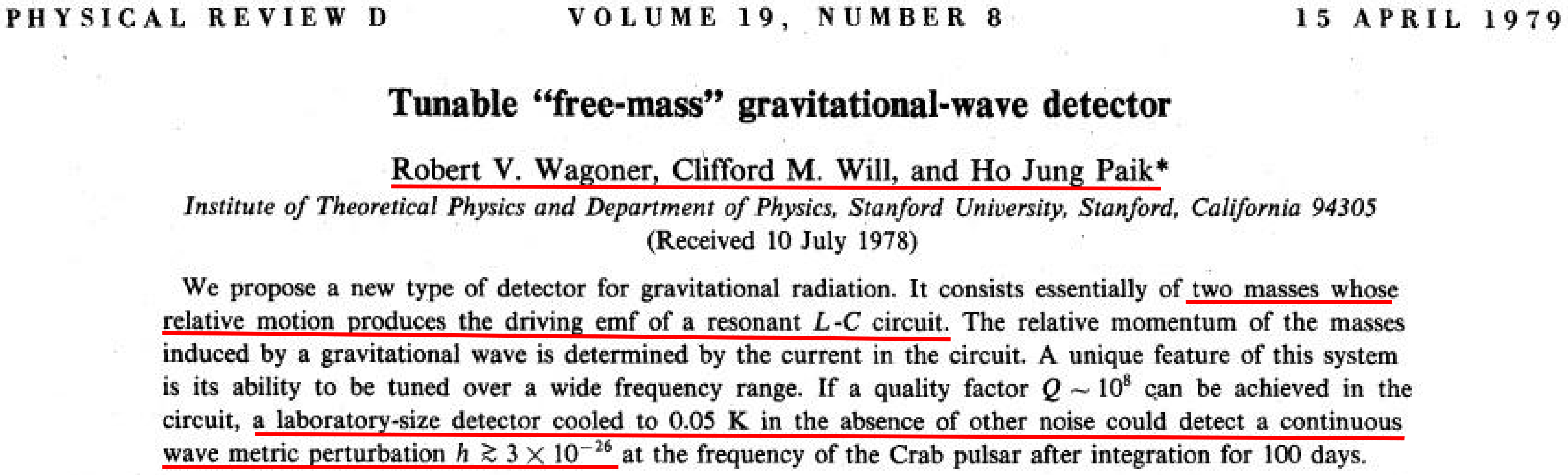
R&D Fabrication → Pre-DECIGO

R&D Fabrication → DECIGO

Objective	Space test of key tech. GW observation	Detect GW with min. spec FP between S/C	GW astronomy
Design	Single small satellite Short FP interferometer	3 S/C 1 interferometer unit	3 S/C x 3-4 units

5) Terrestrial antenna?


Ho Jung Paik



PHYSICAL REVIEW D VOLUME 19, NUMBER 8 15 APRIL 1979

Tunable "free-mass" gravitational-wave detector

Robert V. Wagoner, Clifford M. Will, and Ho Jung Paik*

Institute of Theoretical Physics and Department of Physics, Stanford University, Stanford, California 94305

(Received 10 July 1978)

We propose a new type of detector for gravitational radiation. It consists essentially of two masses whose relative motion produces the driving emf of a resonant L-C circuit. The relative momentum of the masses induced by a gravitational wave is determined by the current in the circuit. A unique feature of this system is its ability to be tuned over a wide frequency range. If a quality factor $Q \sim 10^8$ can be achieved in the circuit, a laboratory-size detector cooled to 0.05 K in the absence of other noise could detect a continuous wave metric perturbation $h \gtrsim 3 \times 10^{-26}$ at the frequency of the Crab pulsar after integration for 100 days.

- SGG (Superconducting Gravity Gradiometer):

Moody, Paik, & Caravan (2002)

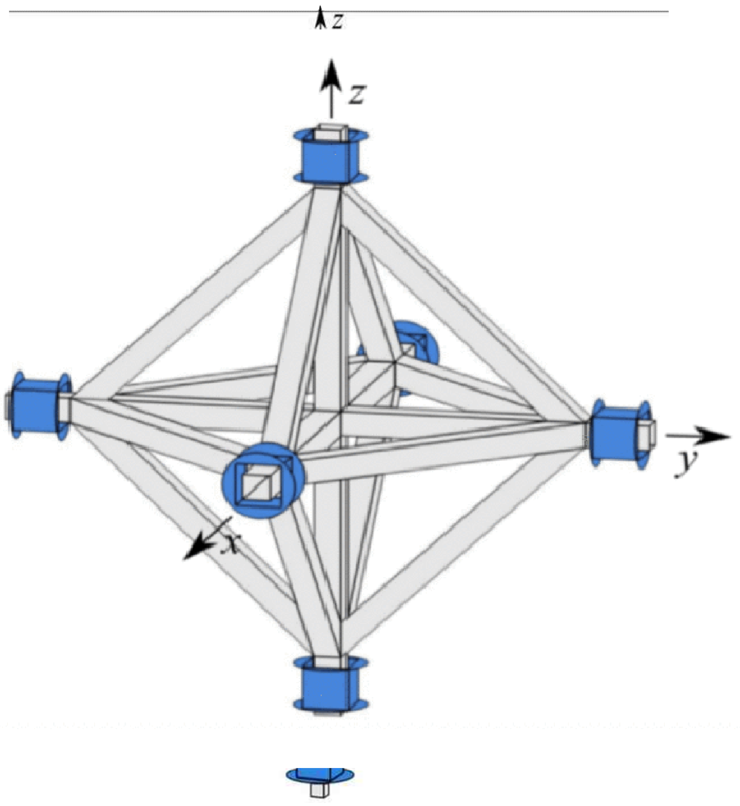
- ✓ Sensitivity: $\sim 2 \times 10^{-11} s^{-2} Hz^{-1/2}$
- ✓ Magnetic levitation
- ✓ SQUID sensor
- ✓ Test mass: 25kg, Size: 30cm
- ✓ Sensitive SGGs have been developed for over 30 years at U. of Maryland.

➔ JUST SCALE-UP THE SGG and improve sensitivities of main parts!

“SOGRO” (Superconducting Omnidirectional Gravitational Radiation Observatory)

- ✓ $2 \times 10^{-19} s^{-2} Hz^{-1/2}$ is required for the detection of GWs!

II. Design and Principle



(Movie credit: C. Kim)

- Each Nb test mass is magnetically levitated on a rigid Al mounting tube, and so has 3 DOF in motion.
- Relative motions of two test masses are measured by SQUID sensors.
- Combining 6 test masses, a tensor GW detector is formed;

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

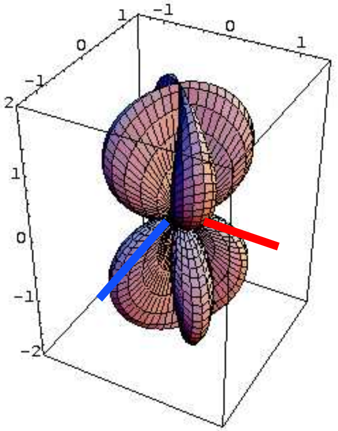
$$h_{ij}(t) = \frac{1}{L}\left\{\left[x_{+ij}(t) - x_{-ij}(t)\right] - \left[x_{-ji}(t) - x_{+ji}(t)\right]\right\}, i \neq j$$

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

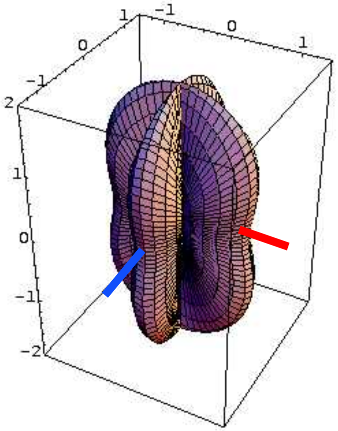
Antenna pattern

LIGO

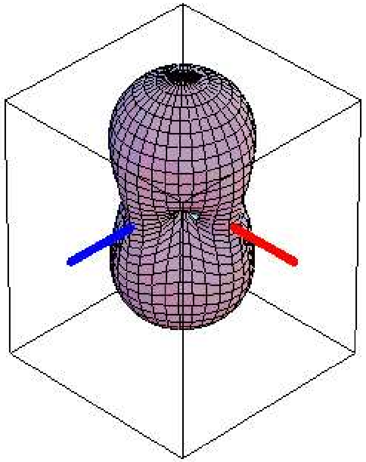
× polarization



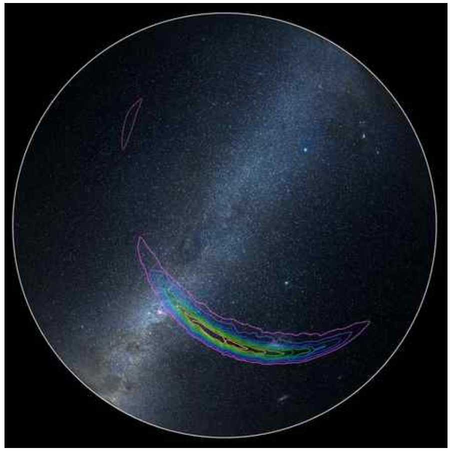
+ polarization



rms sensitivity

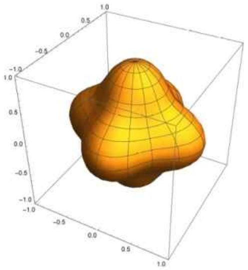


Sky location of GW150914

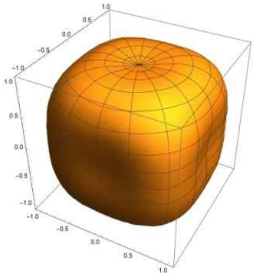


SOGRO

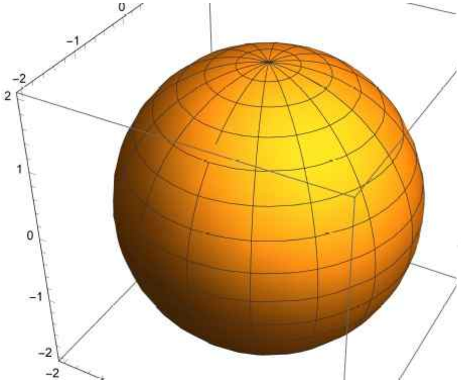
Diagonal



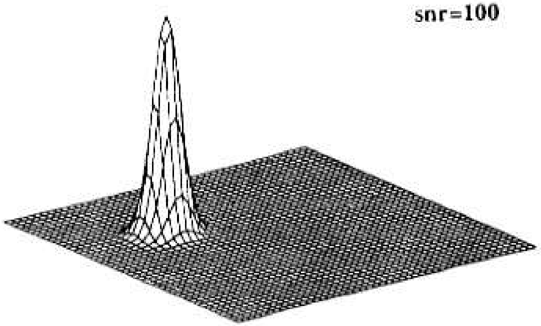
Off-diagonal



Total

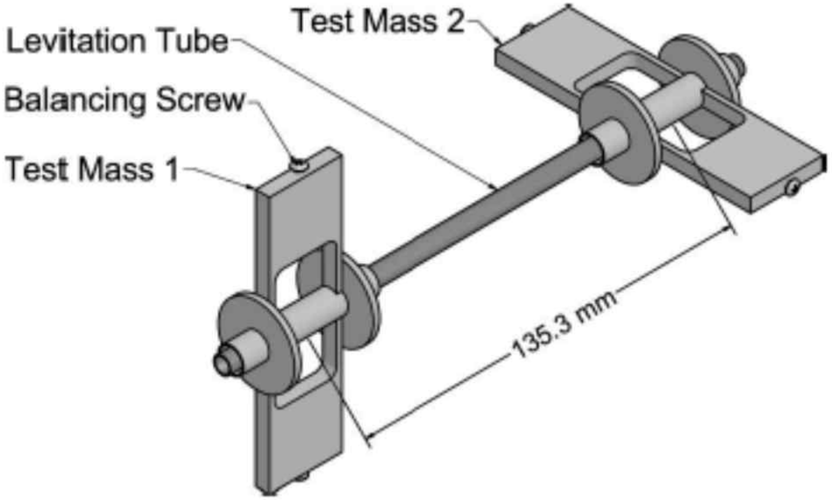


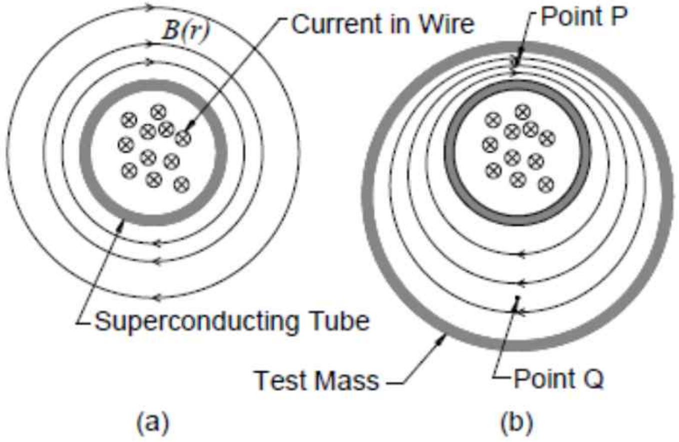
Sky location by SOGRO

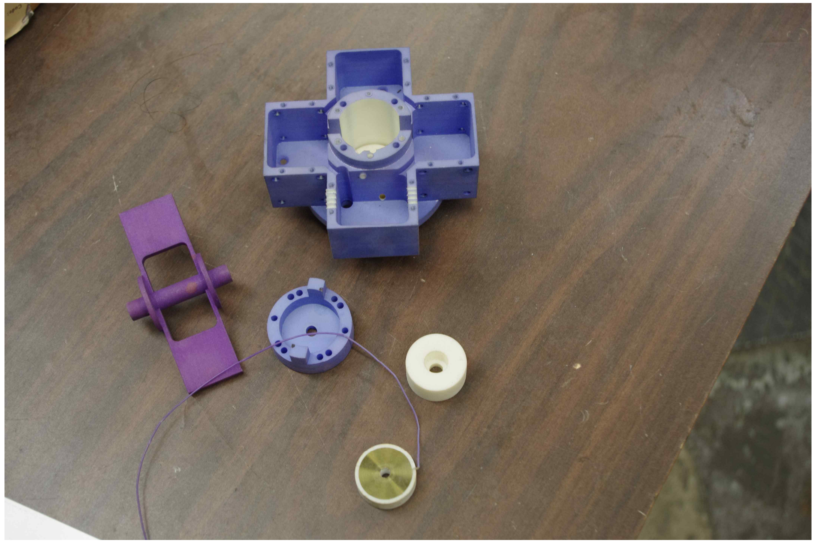


(Slide credit: Paik ’16)

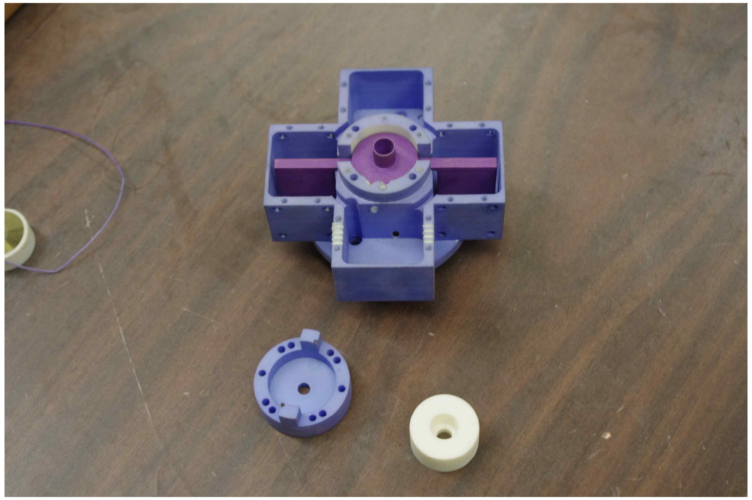
Structure of a single axis in SGG

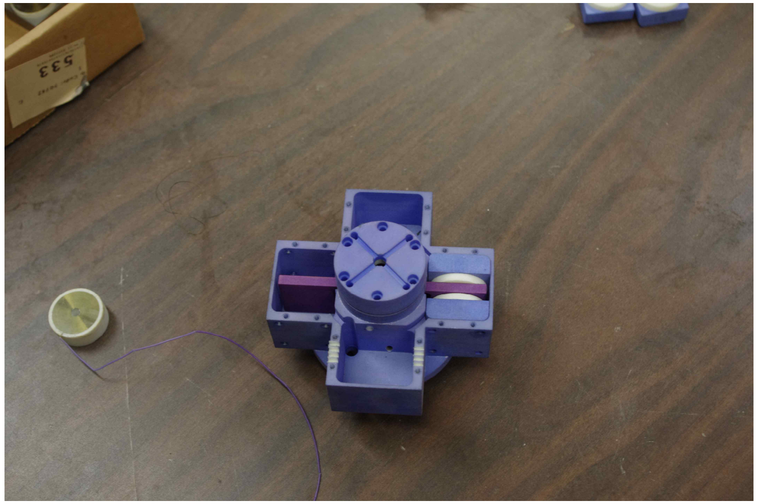






(Picture credit: H-M. Lee)

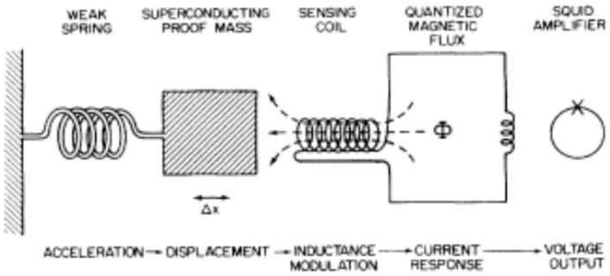


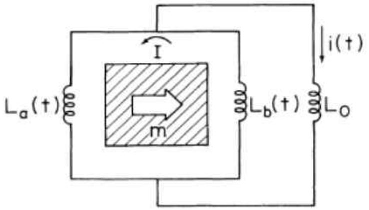


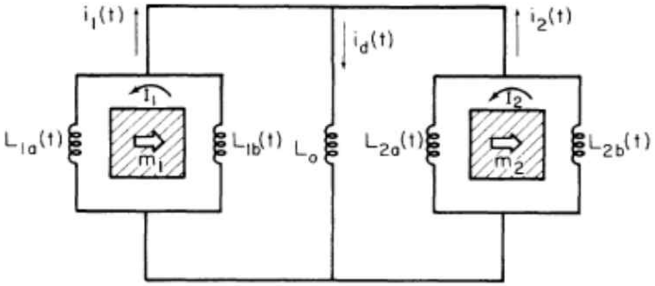
(Picture credit: H-M. Lee)

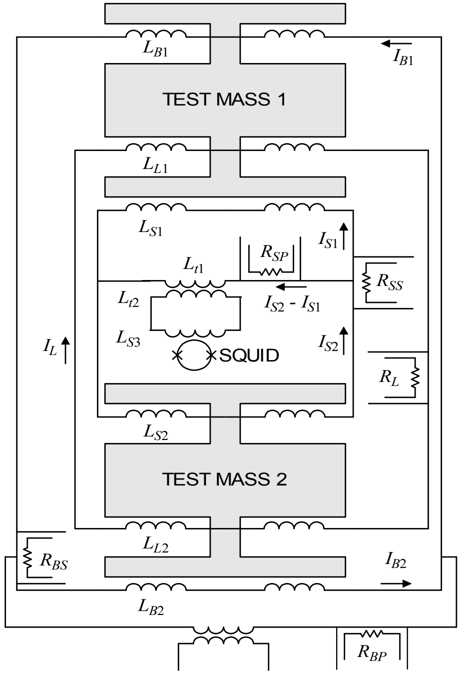
(Picture credit: H-M. Lee)

❖ Chan & Paik, PRD (1987):









$$\ddot{x}'(t)+\omega_M{}^2 x'(t)+\frac{\Lambda}{m}\left[I+\tfrac{1}{2}\frac{L_a(t)-L_b(t)}{L_a+L_b}i(t)\right]i(t) = \hat{\mathbf{n}}\cdot\mathbf{g}'(\mathbf{r},t)\ ,$$

$$x'(t)\equiv x_0+x(t)\ ,$$

$$\mathbf{g}'(\mathbf{r},t)\equiv\mathbf{g}_E(\mathbf{r})+\mathbf{g}'_P(\mathbf{r},t)\ ,$$

$$x_0=-\frac{g_E\cos\theta_n}{\omega_M{}^2}\frac{\Lambda}{m\omega_M{}^2}\left[I+\frac{1}{2}\frac{L_a-L_b}{L_a+L_b}i\right]i$$

$$\left[-\omega^2+\omega_M{}^2+\frac{\Lambda^2 i^2}{mL_s}\right]x(\omega)+\frac{\Lambda I'}{m}i(\omega)=g(\omega)$$

$$\Lambda I' x(\omega)=(L_0+L_p)i(\omega)$$

$$\omega_0{}^2\equiv\omega_M{}^2+\frac{\Lambda^2 i^2}{mL_s}+\frac{\Lambda^2 I'^2}{m(L_0+L_p)}$$

$$\left[-\omega^2+\omega_{kM}{}^2+\frac{\Lambda^2 i_k{}^2}{m_k L_{ks}}\right]x_k(\omega)+\frac{\Lambda I'_k}{m_k}\frac{1}{2}i_d(\omega)+(-1)^k\frac{\Lambda I'_k}{m_k}i_c(\omega)=(-1)^k\tfrac{1}{2}g_d(\omega)+g_c(\omega)$$

Achievable detector noise

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

Parameter	SOGRO	aSOGRO	Method employed (/aSOGRO)
Each test mass M	5 ton	10 ton	Nb square shell
Arm-length L	30 m	100 m	Over "rigid" platform
Antenna temp T	1.5 K	0.1 K	Liquid He / He^3-He^4 dilution refrigerator
Platform temp T_{pl}	1.5 K	1.5 K	$Q_{pl} = 5 \times 10^6 / 10^7$
DM frequency f_D	0.01 Hz	0.01 Hz	Magnetic levitation (horizontal only)
DM quality factor Q_D	5×10^8	10^9	Surface polished pure Nb
Signal frequency f	0.1-10 Hz	0.1-10 Hz	
Pump frequency f_p	50 kHz	50 kHz	Tuned capacitor bridge transducer
Amplifier noise no. n	20	2	Two-stage dc SQUID
Detector noise $S_h^{1/2}(f)$	2×10^{-20} Hz$^{-1/2}$	2×10^{-21} Hz$^{-1/2}$	Computed at 1 Hz

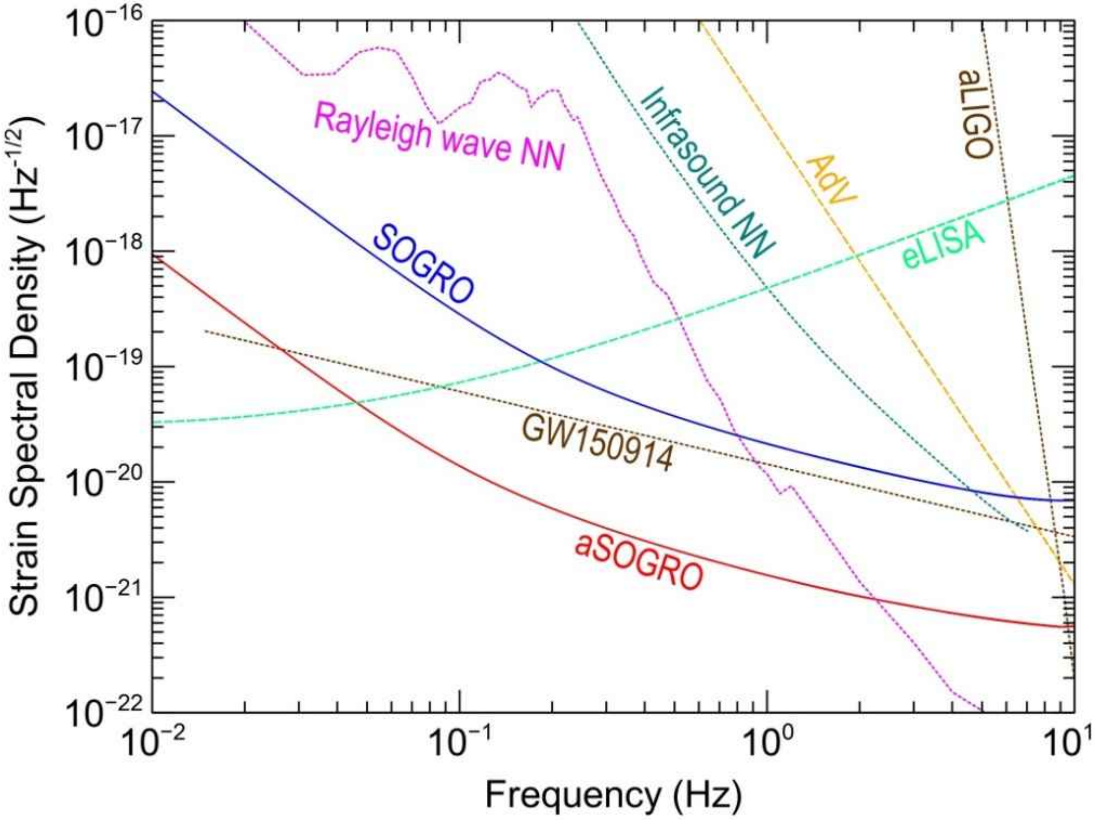
Technical Challenges:

- ✓ Platform design
- ✓ Cryogenic coolling to extremely low temperatures
- ✓ Highly purified test mass with surface polished
- ✓ Improve SQUID sensitivity

- **SOGRO requires $Q_D \sim 10^9$ for test masses and $Q_{pl} \sim 10^7$ for the platform.**
- **By using two-stage dc SQUIDs, $120\hbar$ and $10\hbar$ have been demonstrated at 1.5 and 0.1 K, respectively. (Falferi *et al.*, 2003; 2008)**
  ⇨ SOGRO requires improvement by a factor of 5-6.

(Slide credit: Paik '16)

Potential sensitivities of SOGRO



- **SOGRO would fill frequency gap 0.1 to 10 Hz between the terrestrial and future space interferometers.**

(Slide credit: Paik '16)

Newtonian gravity noise

- **Seismic and atmospheric density fluctuations produce NN.**
- **GWs are transverse whereas near-field Newtonian gradient is not.**

  ⇨ **Could GW signal be separated out from NN?**

In the GW coordinate system,

$$h'(\omega)=\begin{pmatrix} h_+(\omega)+h'_{N11}(\omega) & h_\times(\omega)+h'_{N12}(\omega) & h'_{N13}(\omega) \\ h_\times(\omega)+h'_{N12}(\omega) & -h_+(\omega)+h'_{N22}(\omega) & h'_{N23}(\omega) \\ h'_{N13}(\omega) & h'_{N23}(\omega) & h'_{N33}(\omega) \end{pmatrix},\ \text{where}$$

$$h'_{N11}(\omega)=\sum_i\left[a(\omega)\xi_i(\omega)+b(\omega,\vartheta_i)\delta\rho_i(\omega)\right][\cos(\psi_i-\phi)\cos\theta+i\sin\theta]^2$$

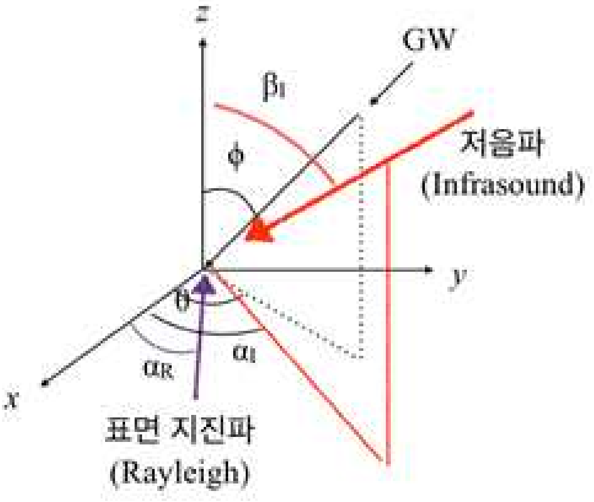
$$h'_{N22}(\omega)=\sum_i\left[a(\omega)\xi_i(\omega)+b(\omega,\vartheta_i)\delta\rho_i(\omega)\right]\sin^2(\psi_i-\phi)$$

$$h'_{N33}(\omega)=\sum_i\left[a(\omega)\xi_i(\omega)+b(\omega,\vartheta_i)\delta\rho_i(\omega)\right][\cos(\psi_i-\phi)\sin\theta-i\cos\theta]^2$$

$$h'_{N12}(\omega)=\sum_i\left[a(\omega)\xi_i(\omega)+b(\omega,\vartheta_i)\delta\rho_i(\omega)\right]\sin(\psi_i-\phi)[\cos(\psi_i-\phi)\cos\theta+i\sin\theta]$$

$$h'_{N23}(\omega)=\sum_i\left[a(\omega)\xi_i(\omega)+b(\omega,\vartheta_i)\delta\rho_i(\omega)\right]\sin(\psi_i-\phi)[\cos(\psi_i-\phi)\sin\theta-i\cos\theta]$$

$$h'_{N13}(\omega)=\sum_i\left[a(\omega)\xi_i(\omega)+b(\omega,\vartheta_i)\rho_i(\omega)\right][\cos(\psi_i-\phi)\cos\theta+i\sin\theta][\cos(\psi_i-\phi)\sin\theta-i\cos\theta]$$



(Figure Credit: H-M. Lee '17)

- **Tensor measurement is insufficient to remove NN from multiple waves.**

  ⇨ **Still requires external seismometers and microphones.**

(Credit: Paik '16)

Extraction of GWs: Harms & Paik PRD ('16)

$$h_+ = h'_{11} - 2\cot(\theta)h'_{13} + \cot^2(\theta)h'_{33}$$

$$+ \csc^2(\theta)2\pi\gamma G\rho_0\frac{k}{\omega^2}\sum_i \xi_i(\omega),$$

➔ Effect due to Rayleigh-wave

$$+ \csc^2(\theta)\frac{4\pi}{\omega^2}\frac{G\rho_0}{\gamma p_0}\sum_i \delta p_i(\omega)\sin^2(\beta_i)$$

➔ Effect due to Infrasound-wave

$$h_\times = h'_{12} - \cot(\theta)h'_{23}$$

$$+ \mathrm{i}\csc(\theta)2\pi\gamma G\rho_0\frac{k}{\omega^2}\sum_i \xi_i(\omega)\sin(\alpha_i - \phi)$$

➔ Effect due to Rayleigh-wave

$$+ \mathrm{i}\csc(\theta)\frac{4\pi}{\omega^2}\frac{G\rho_0}{\gamma p_0}\sum_i \delta p_i(\omega)\sin^2(\beta_i)\sin(\alpha_i - \phi)$$

➔ Effect due to Infrasound-wave

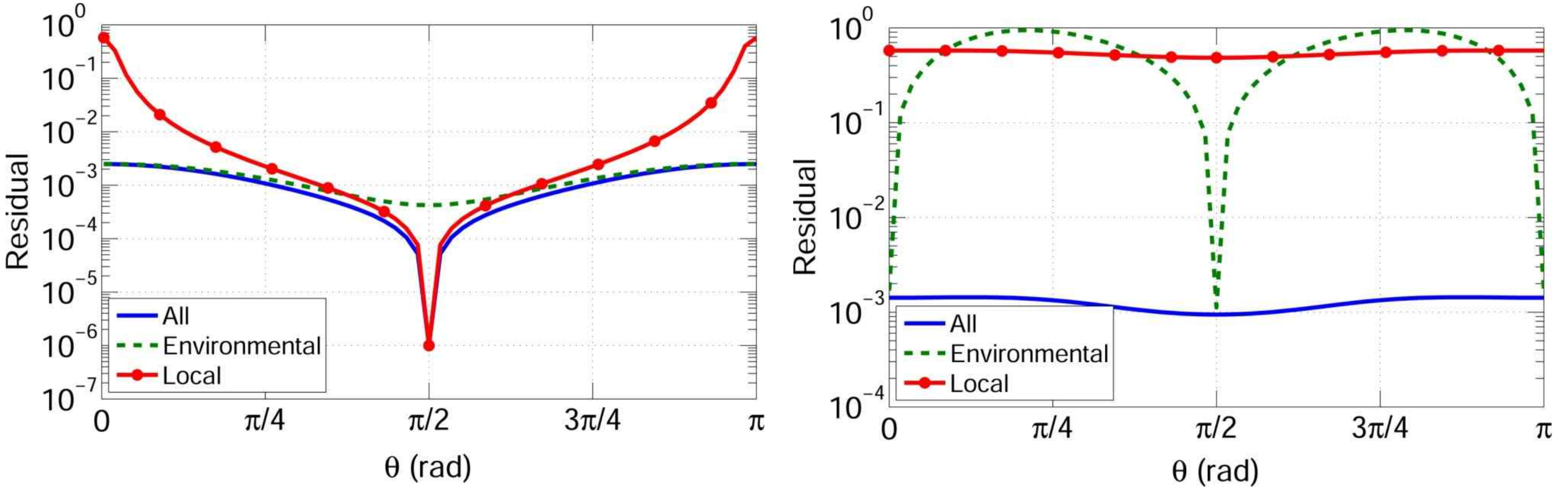
And use Wiener Filter ……

$$r(\omega) = 1 - \frac{\vec{C}_{\mathrm{RT}}^{\top}(\omega)\cdot(C_{\mathrm{RR}}(\omega))^{-1}\cdot\vec{C}_{\mathrm{RT}}(\omega)}{C_{\mathrm{TT}}(\omega)}.$$

Mitigation of NN

NN due to Rayleigh waves removed by using h'_{13}, h'_{23}, h'_{33}, a_z (CM), plus 7 seismometers with SNR = 10^3 at the radius of 5 km.

NN due to infrasound removed by using h'_{13}, h'_{23}, h'_{33} and 15 mikes of SNR = 10^4, 1 at the detector, 7 each at radius 600 m and 1 km.



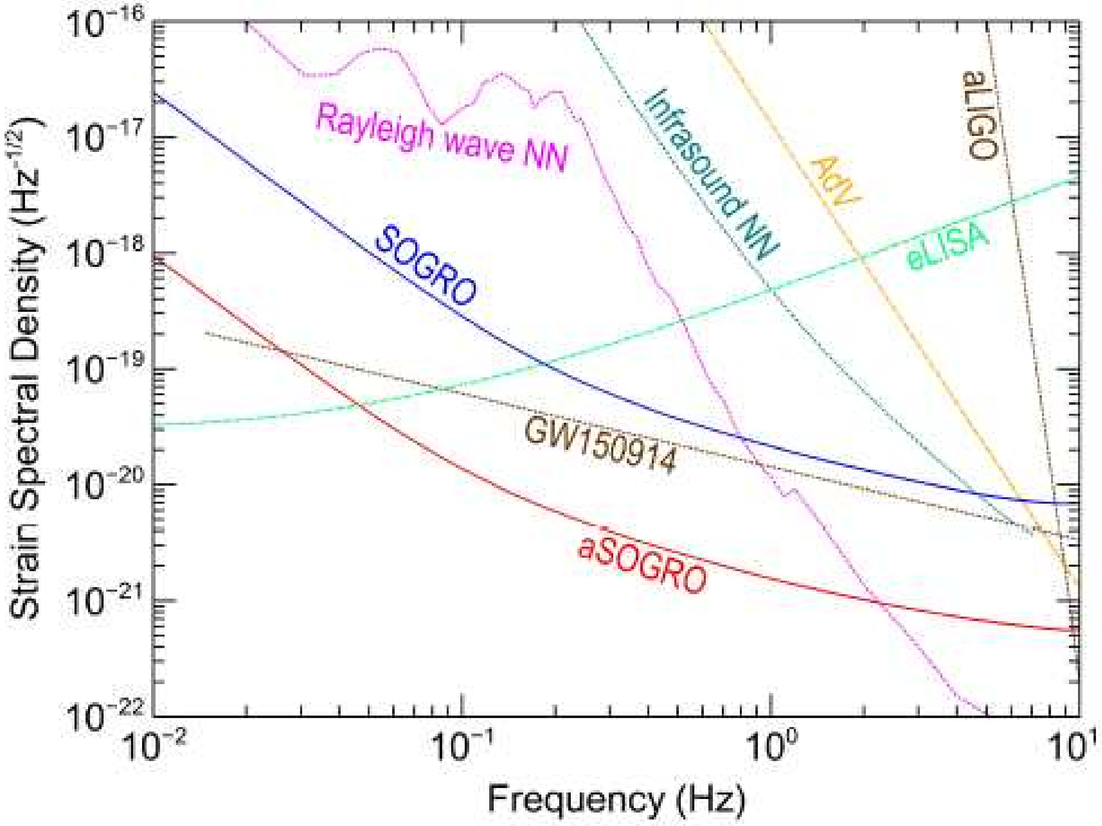
- **First remove Rayleigh NN by using seismometers only, then remove infrasound NN by using microphones and cleaned up SOGRO outputs.**
- **Unlike TOBA and laser interferometer, SOGRO can remove NN from infrasound for *all* incident angles.**

Harms and Paik, *PRD* 92, 022001 (2015)

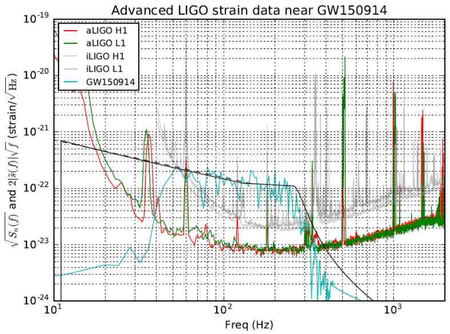
(Slide credit: Paik '16)

III. Targets and Science

1) Inspiralling BBH:

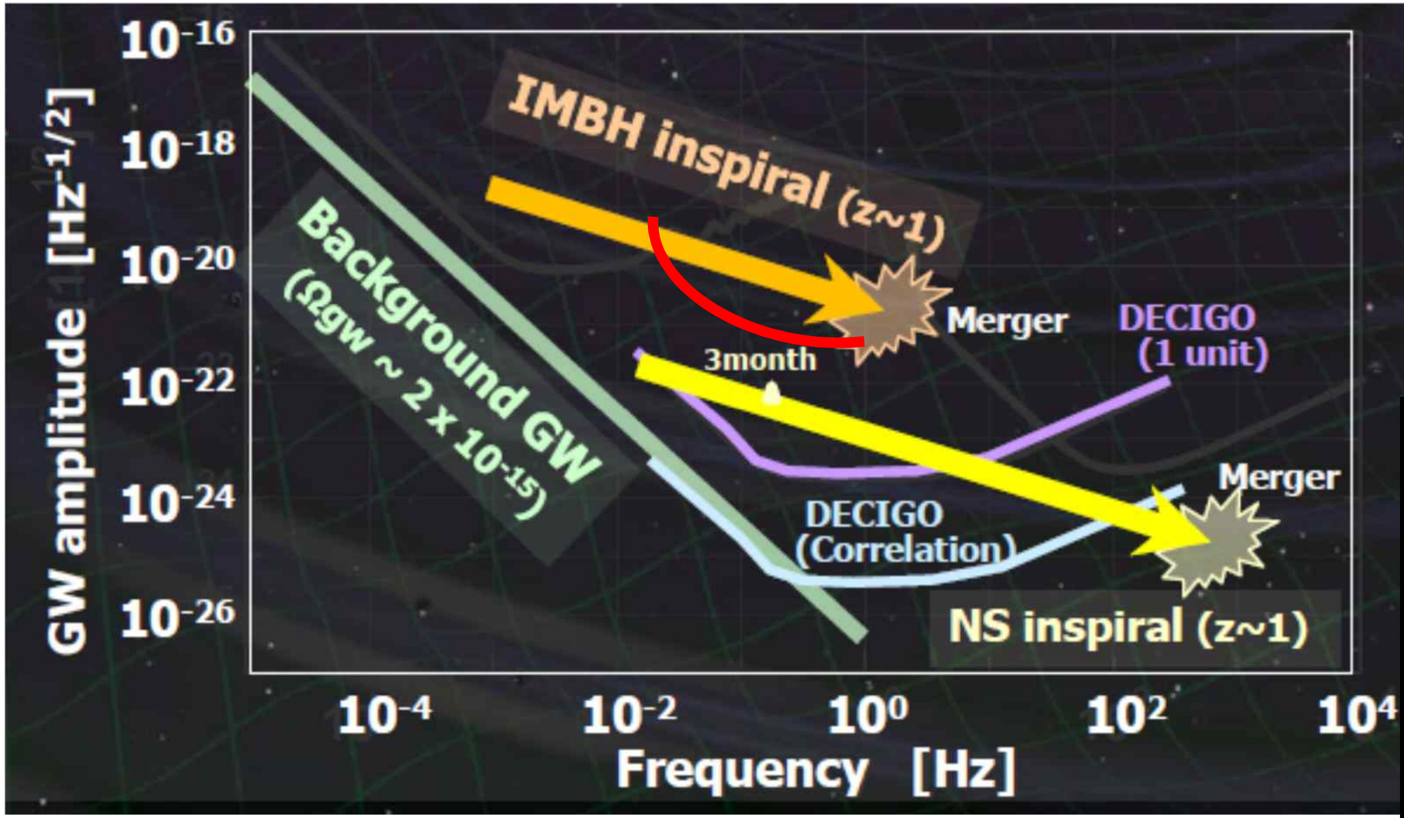


~ 10 days



Observed for ~.2s

2) IMBH binary inspirals and mergers:



(Figure credit: C. Kim ’17)

(Figure credit: M. Ando ’12)

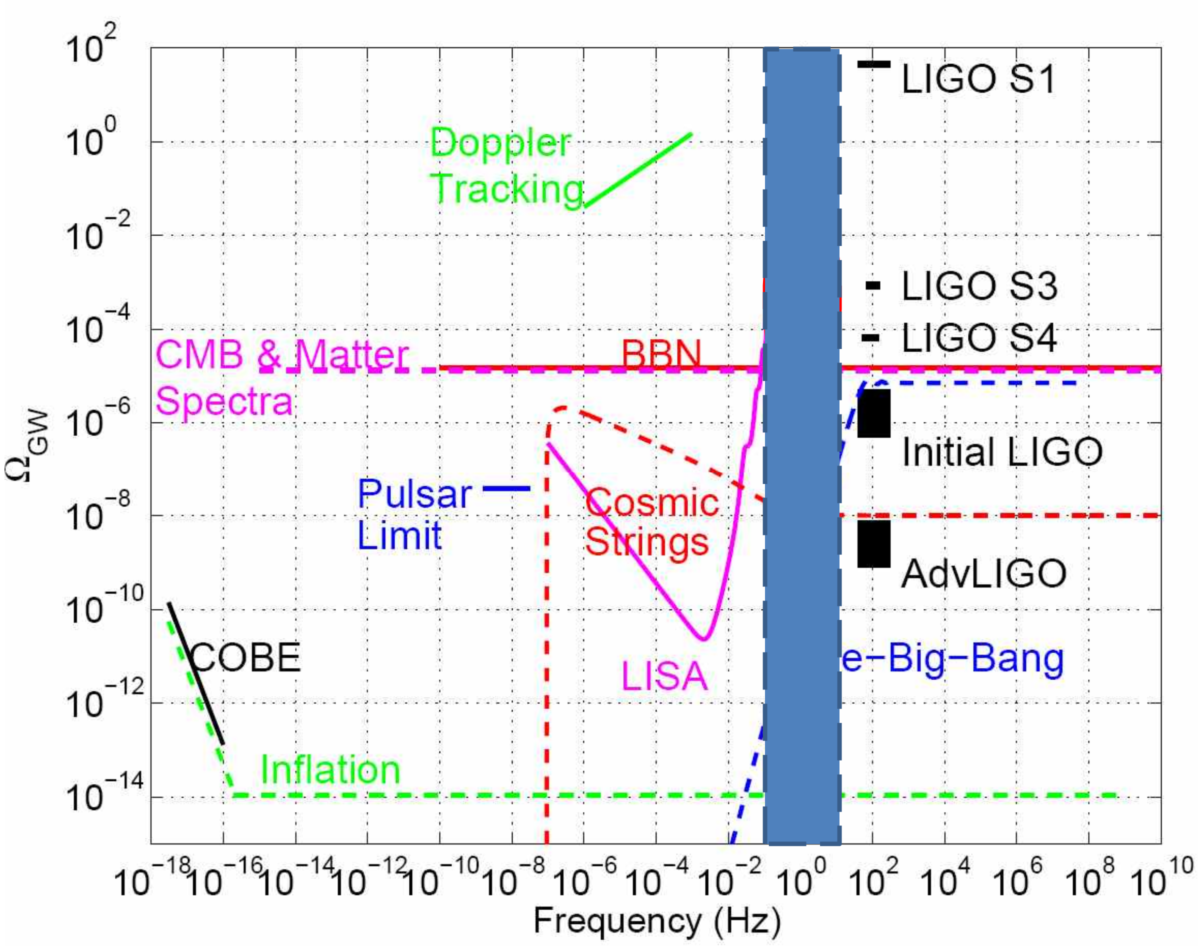
3) Stochastic Gravitational Wave Background:

$$\Omega_{GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

$$S_{\rm gw}(f) = \frac{3H_0^2}{10\pi^2}\, f^{-3}\Omega_{\rm gw}(f)$$

$$h(f) = S_{\rm gw}^{1/2}(f) = 5.6\times10^{-22}\, h_{100}\sqrt{\Omega_0}\left(\frac{100\mathrm{Hz}}{f}\right)^{3/2}\mathrm{Hz}^{1/2}$$

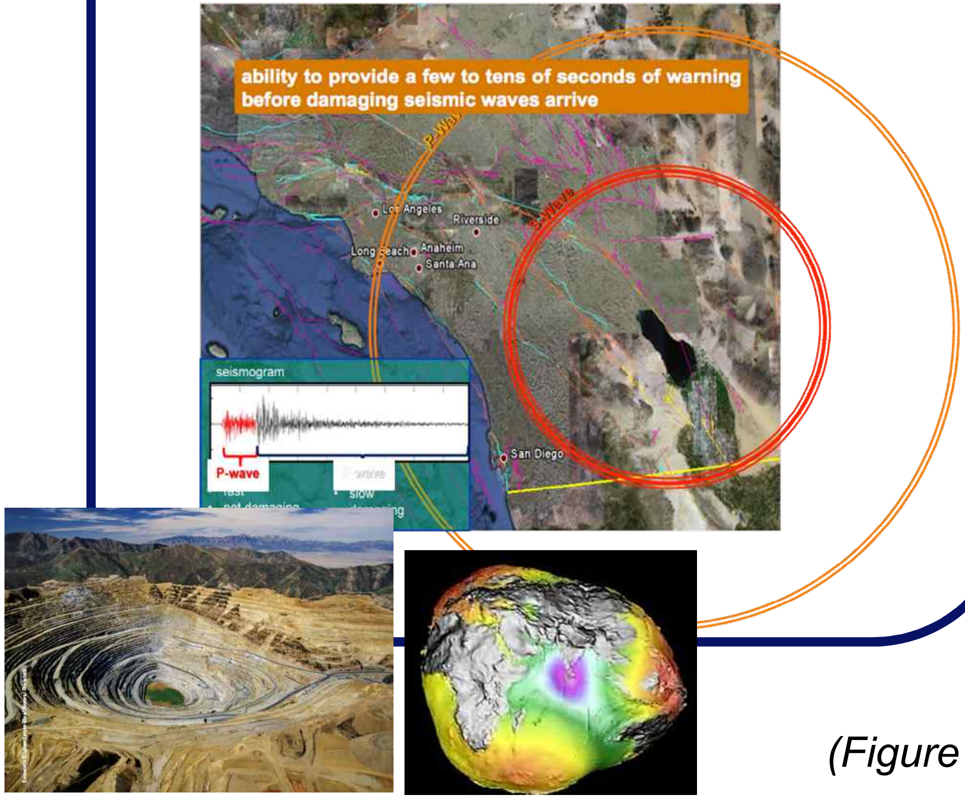
Build two detectors?!



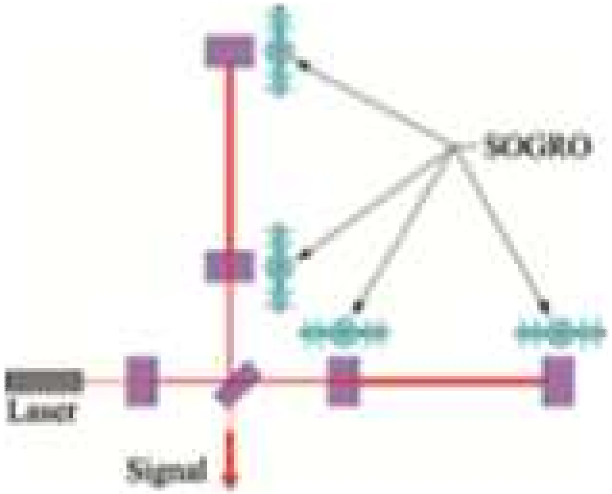
(Figure credit: G. Gonzalez '08)

4) Other applications:

Earthquake Early Warning



Improve aLIGO sensitivity at low freqs.

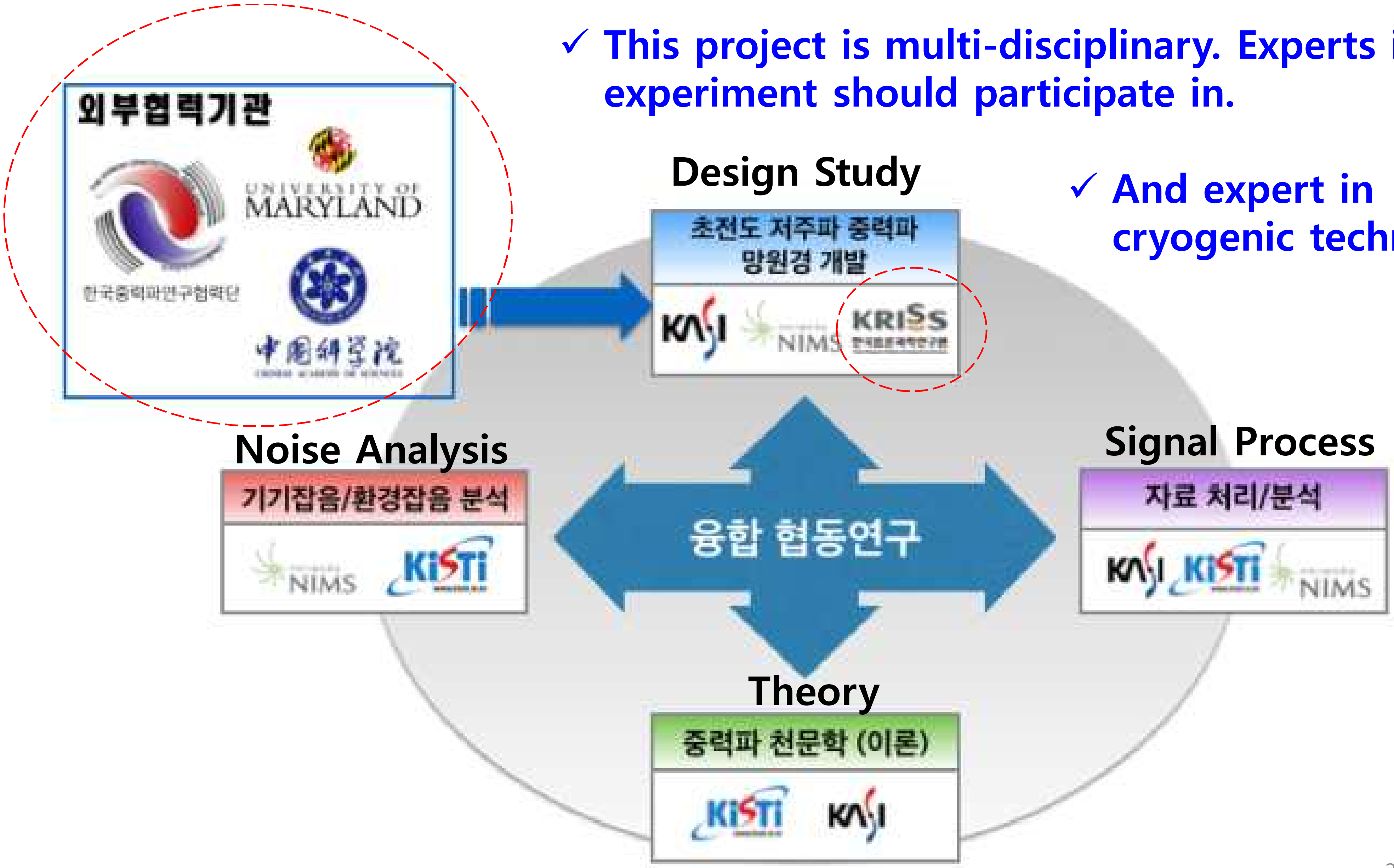


(Figure credit: C. Kim ’17)

IV. Roadmap and Perspective

1) Pilot study for Superconducting Low-frequency Gravitational-wave Telescope

- ✓ 2017.03.01~12.31
- ✓ ~0.2M$
- ✓ (9 members + More) in KASI, NIMS & KISTI
- ✓ Feasibility studies



- ✓ **This project is multi-disciplinary. Experts in experiment should participate in.**

Design Study

- ✓ **And expert in cryogenic technology!**

Noise Analysis

Signal Process

Theory

2) Then, apply for a larger project:

- ✓ ~10M$/year
- ✓ 3+3 = 6 years
- ✓ Develop a prototype SOGRO
- ✓ Then SOGRO 30 or aSOGRO

V. Summary

- Design, principles, sciences, challenges and roadmap are briefly introduced for the project of developing a superconducting low-frequency gravitational wave telescope.
- We do not know as yet if this project will be successful although we are doing our best for it.
- But, we strongly believe that it will bring lots of fruitful sciences and new chances in the future.

- Lots of interest, support and active participation of other people in various fields are essential.
- We hope that KASI takes a leadership for opening up the GW Astronomy in Korea!

1/10^(-21) OF THANKS!