Detection of transient earthquake gravity signals using superconducting gravity gradiometer

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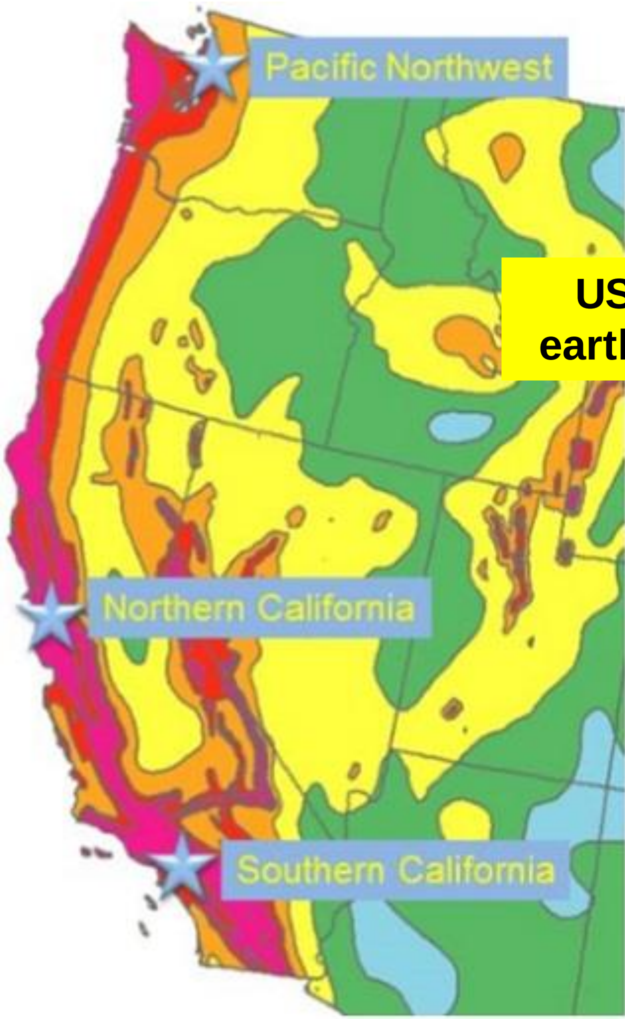
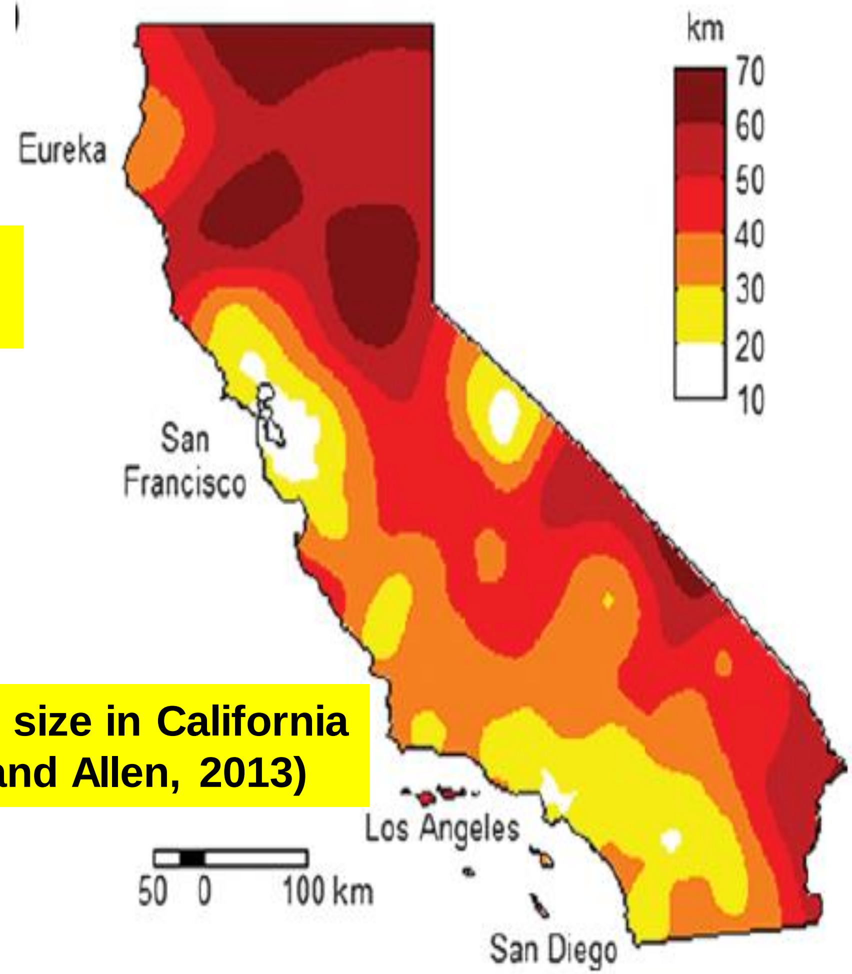
E-GRAAL
January 10, 2018

Blind zones of EEWS



US West Coast earthquake hazard

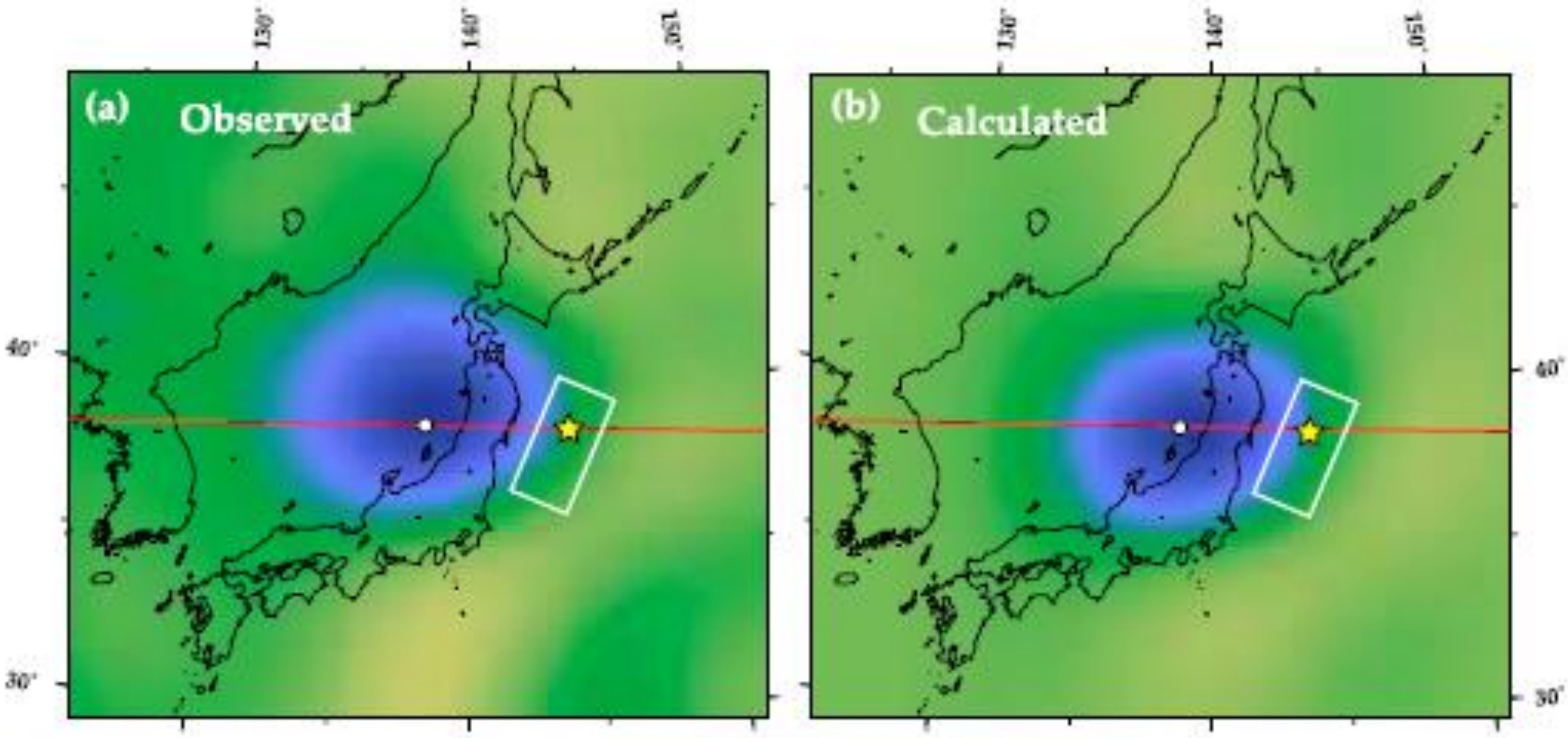


Blind zone size in California (Kuyuk and Allen, 2013)

- **To reduce the blind zone, can we use gravity signals that travel at *c*, 10^5 times faster than seismic waves?**

Gravity signals from Tohoku earthquake

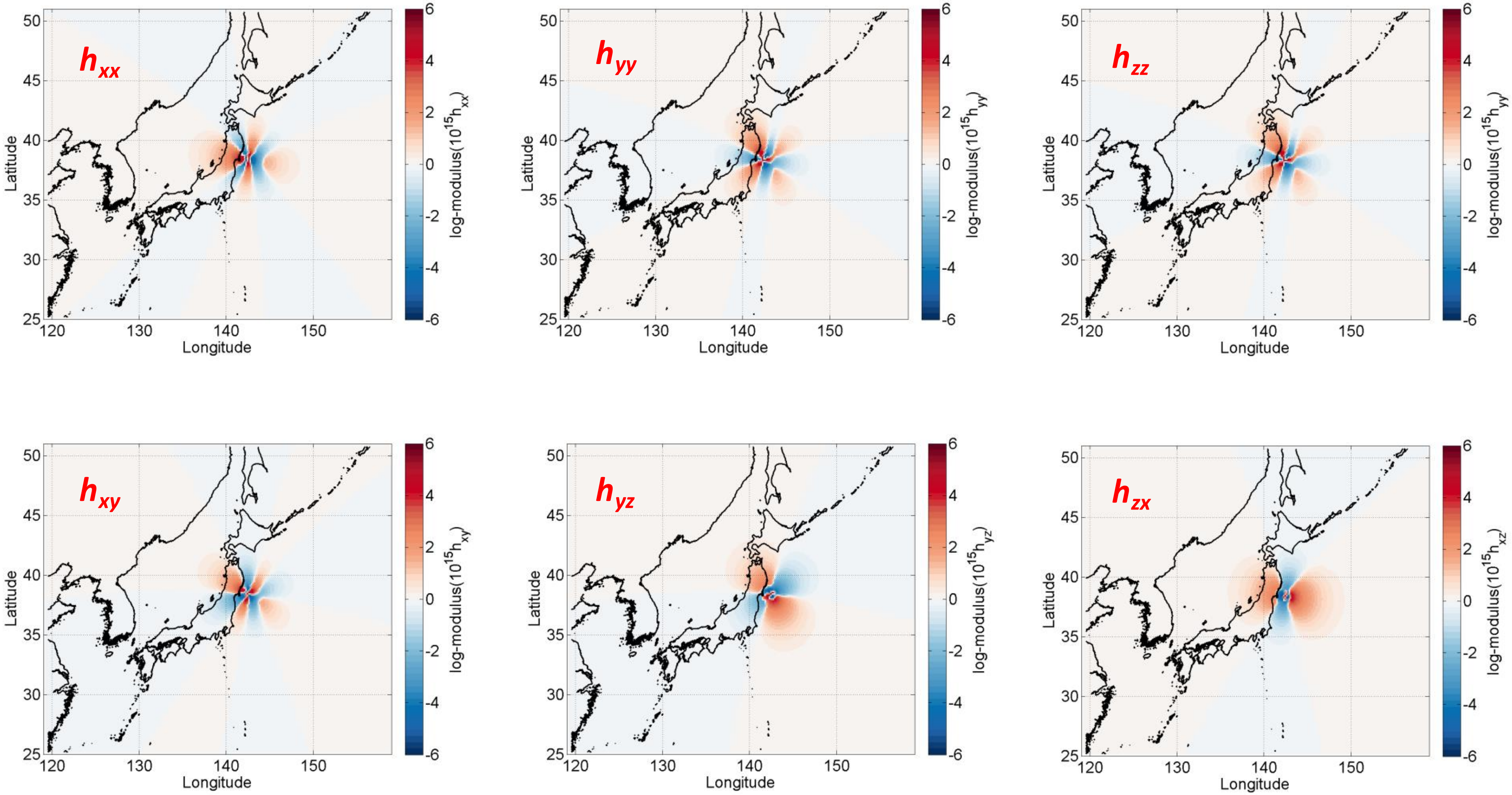
- **GRACE and GOCE missions have measured *static* gravity changes after vs before large earthquakes.**



- **Can *dynamic* gravity signals following fault rupture be measured quickly?**

From presentation by P. Ampuero (Caltech Seismolab)

GG signals from Tohoku earthquake

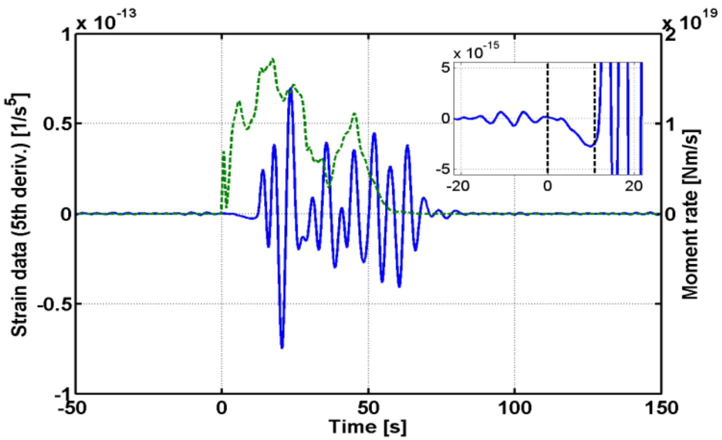


Courtesy of J. Harms

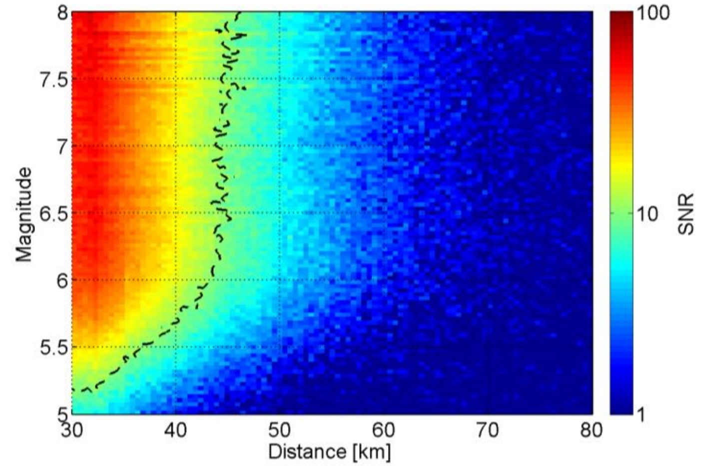
Expected dynamic gravity signal

Ampuero *et al*., Prompt detection of fault rupture for earthquake early warning (preprint)

Gravity signal following a rupture

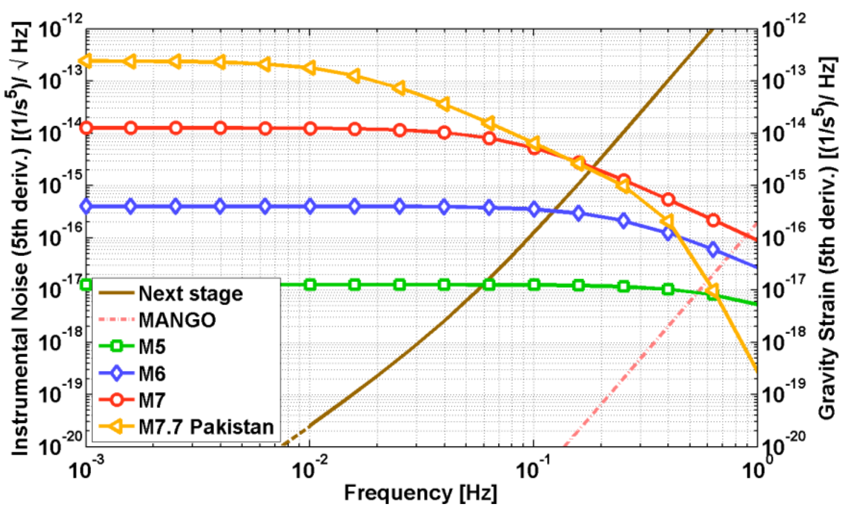


SNR after 5 s

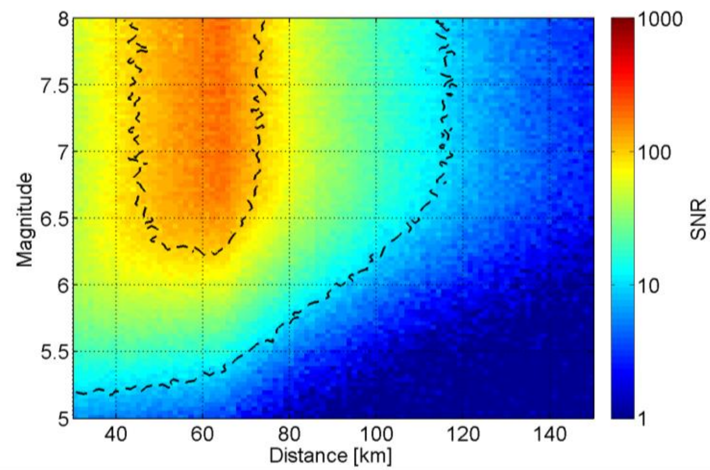


Epicentral distance = 70 km

Next stage: $h = 10^{-15}$ $\mathrm{Hz}^{-1/2}$, MANGO: $h = 10^{-20}$ $\mathrm{Hz}^{-1/2}$



SNR after 10 s



Gravity gradients

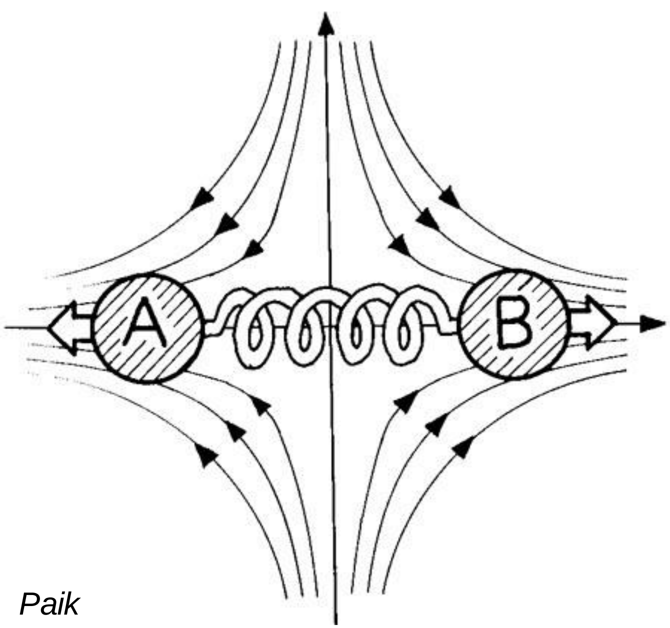
- **To measure gravity, field on two or more masses must be differenced.**
- **Gravity gradient Γ_{ij} is a symmetric 3×3 tensor:**

$$\Gamma_{ij} = -\frac{\partial^2 \phi}{\partial x_i \partial x_j} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} & \Gamma_{13} \\ \Gamma_{12} & \Gamma_{22} & \Gamma_{23} \\ \Gamma_{13} & \Gamma_{23} & \Gamma_{33} \end{pmatrix}.$$

$$\Gamma_{11} + \Gamma_{22} + \Gamma_{33} = -\nabla^2 \phi = 0$$

$\Rightarrow$ **5 independent components**

Γ_{ii} : "inline-component" Γ_{ij} ($j \neq i$): "cross-component"



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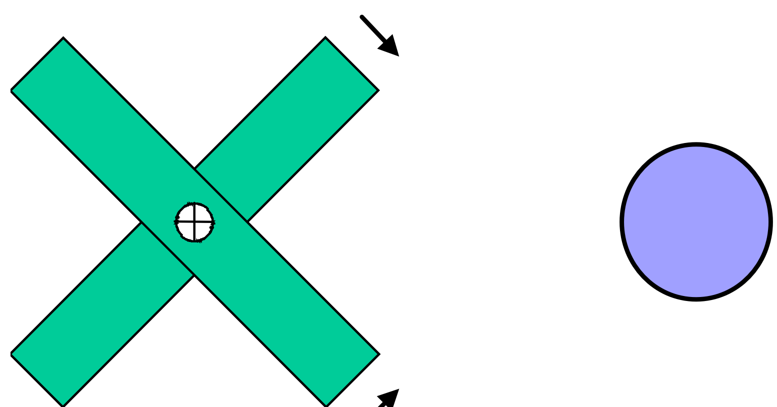
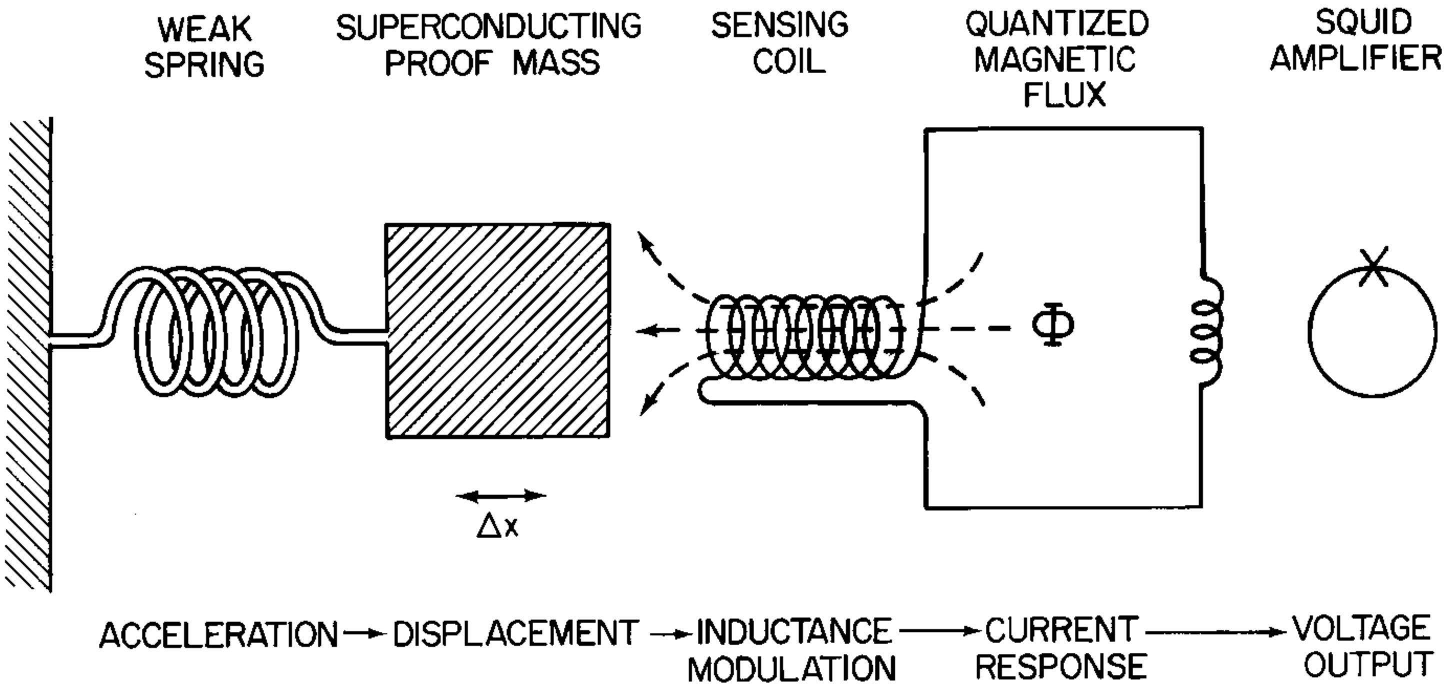


Superconducting accelerometer



- **Low noise:**

$$S_a(f) = \frac{4}{m}\left[k_B T\frac{\omega_0}{Q} + \frac{\omega_0^2}{2\beta\eta}E_A(f)\right]$$

- **Stable scale factors $\Rightarrow$ Sensitive differential measurement possible.**

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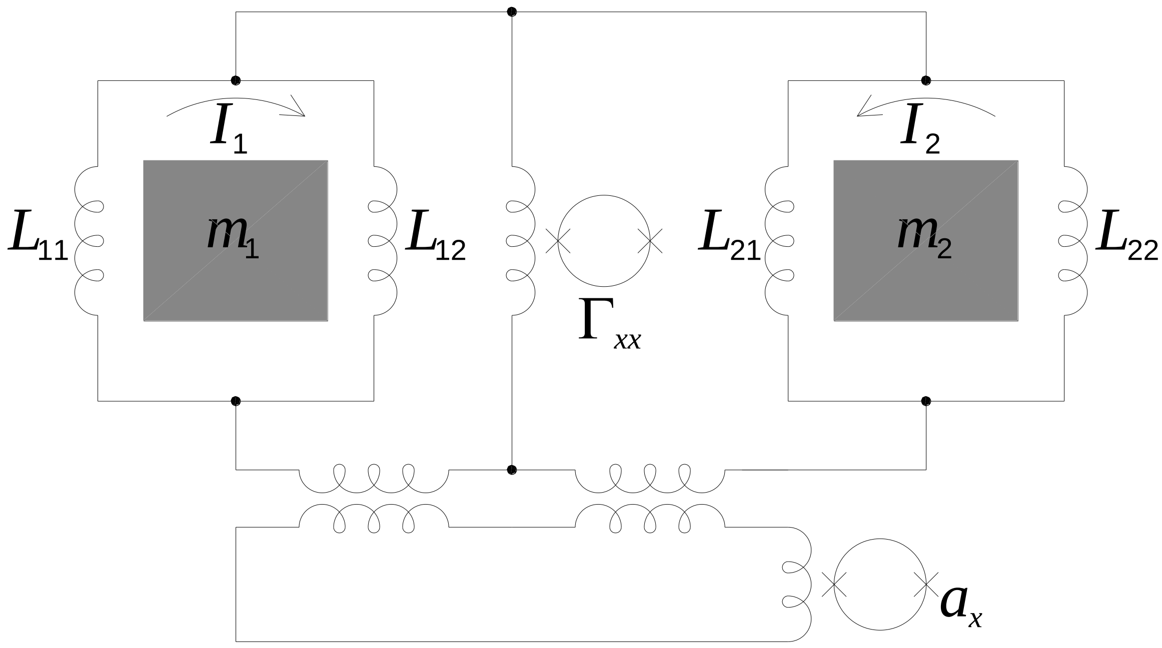
Superconducting Gravity Gradiometer (SGG)



- **Low noise:**

$$S_\Gamma(f) = \frac{8}{m\ell^2}\left[k_B T \frac{\omega_0}{Q} + \frac{\omega_0^2}{2\beta\eta} E_A(f)\right]$$

- ***I*$_2$/*I*$_1$ are adjusted to balance out CM.** $\Rightarrow$ **Stable CM rejection > 10^7.**

$$S_\Gamma^{1/2}(f) \approx 2\times10^{-3}\,\mathrm{E\ Hz}^{-1/2}, 1\,\mathrm{E} \equiv 10^{-9}\,\mathrm{s}^{-2} (\Gamma_{zz,\mathrm{Earth}} \approx 3\times10^3\ \mathrm{E})$$

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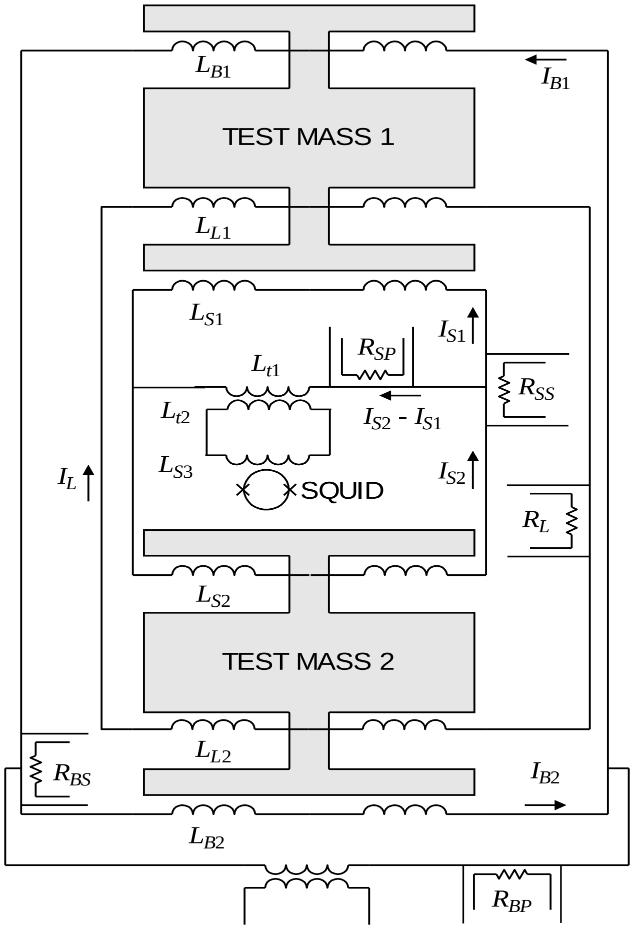
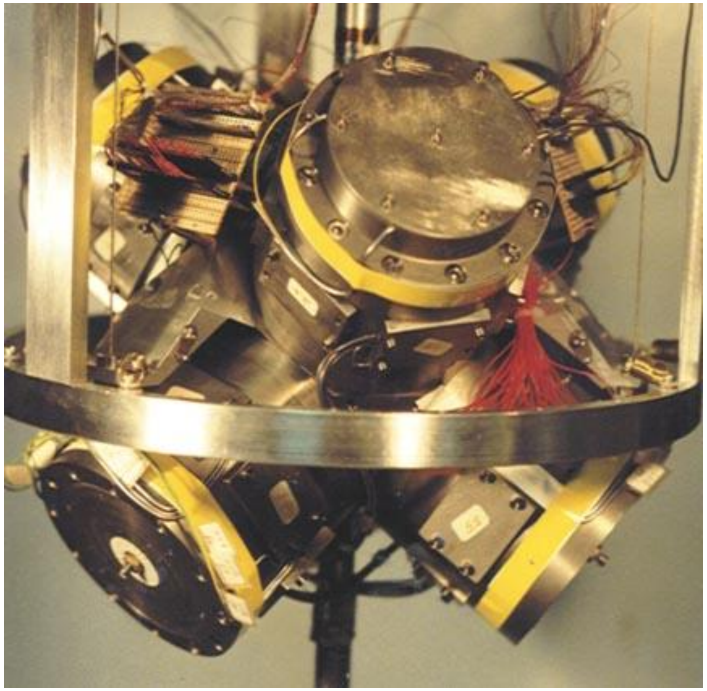
Model 2 SGG

- **Sensitive SGGs have been under development for over 30 years at UM.**



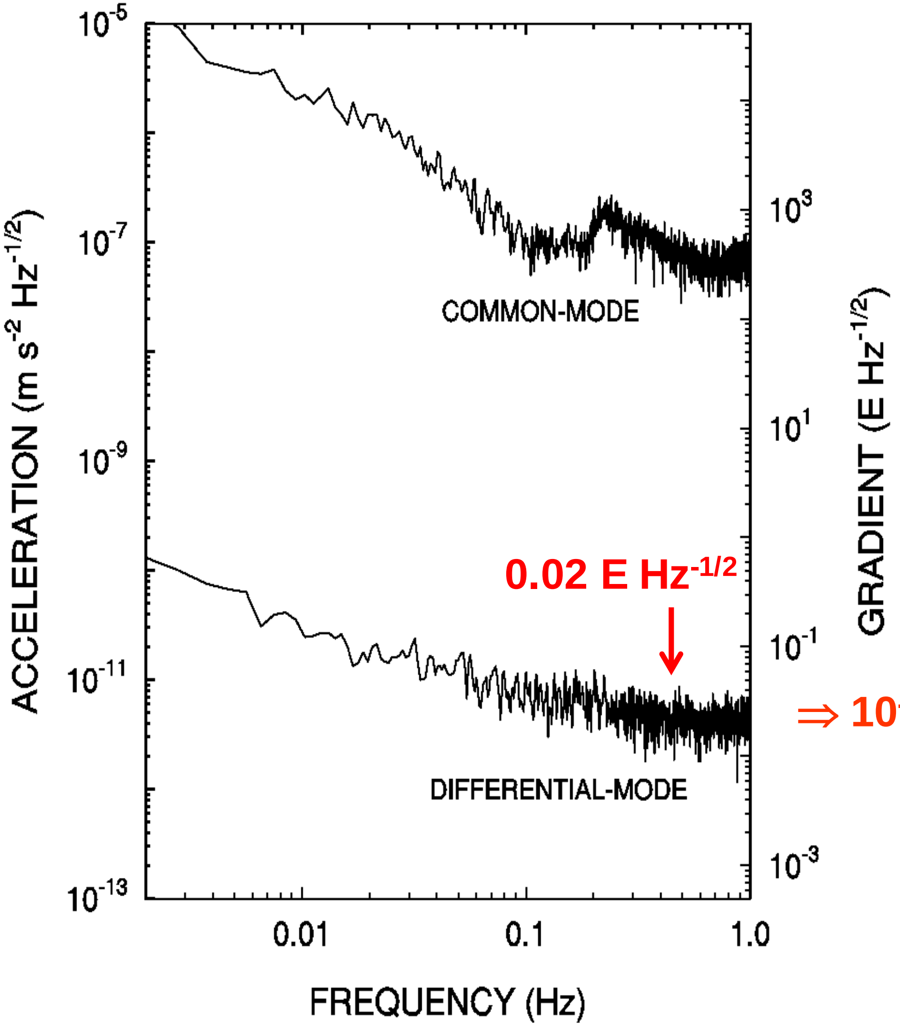


Moody *et al.*, *RSI* 73, 3957 (2002)

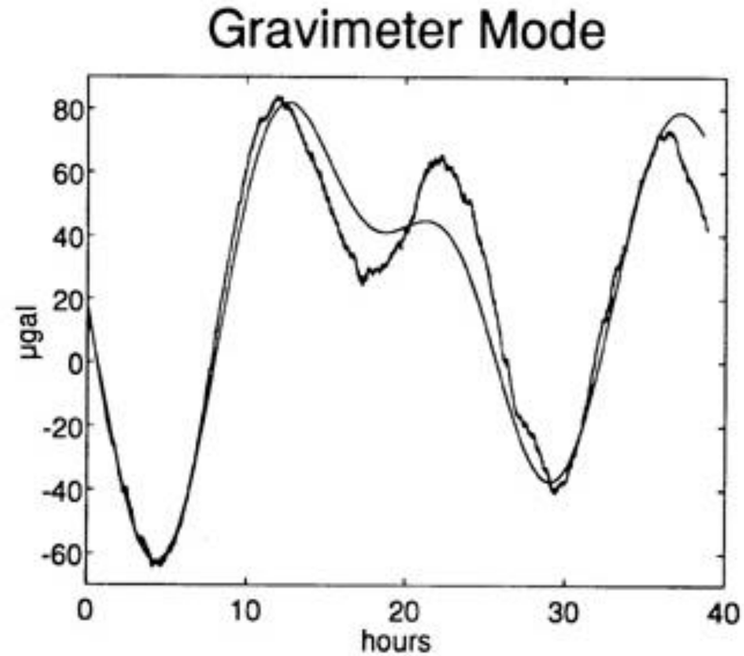
- **Test masses are mechanically suspended (f_{DM} ~ 10 Hz).**
- **CM platform vibration noise is *rejected* to 3 parts in 10^8.**

Performance of Model 2 SGG

Gravity gradient noise PSD



$\Rightarrow 10^{-12}\ g_E\ Hz^{-1/2}$



10^3 times more sensitive than GWR gravimeter

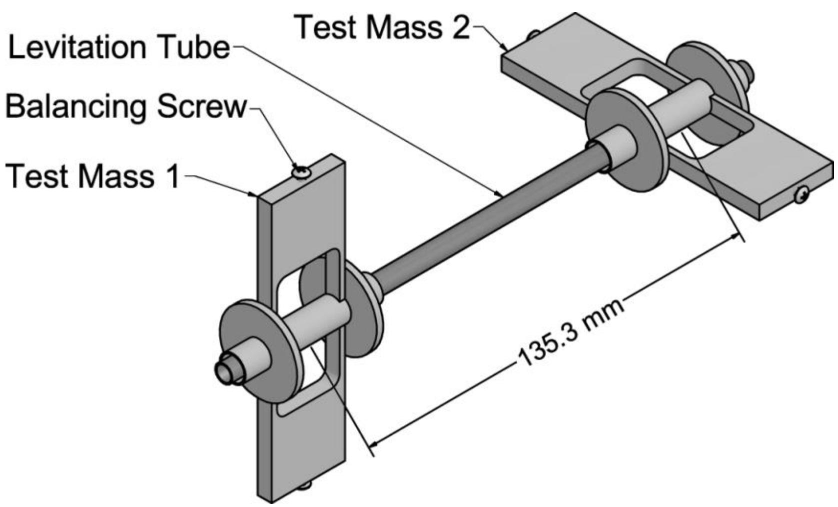
By early 1990's, SGG achieved sensitivity 10^3 times better than atom interferometers to date.

Demonstration of Model 2 SGG

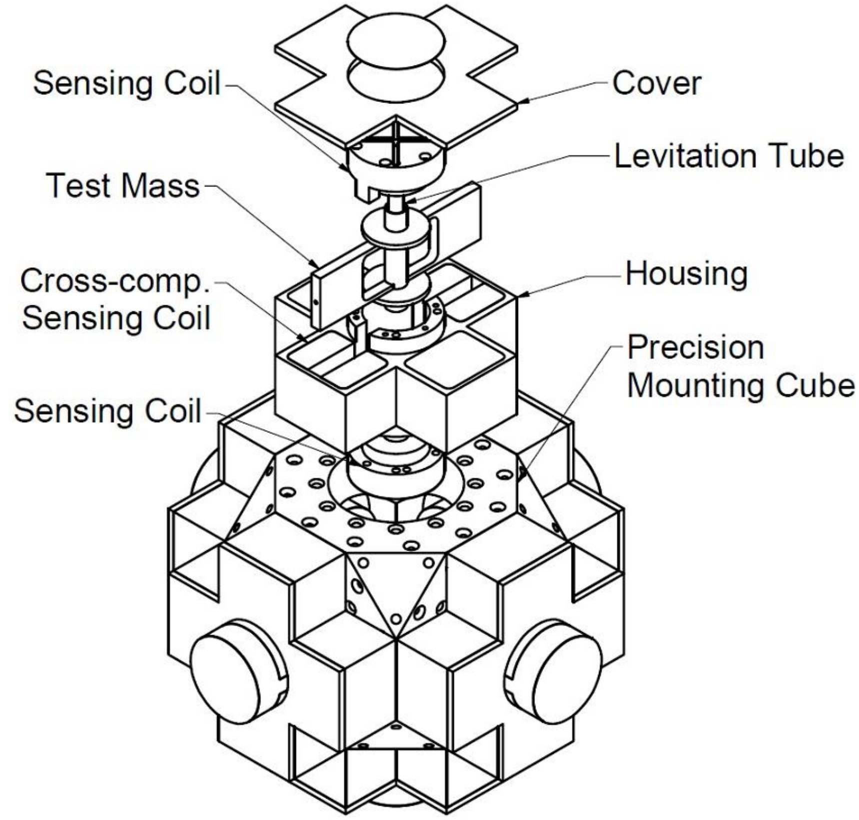
http://www.physics.umd.edu/GRE/SGG_video.htm

Tensor SGG with levitated test masses

- **More sensitive SGG is under development with NASA support.**
- **Test masses are magnetically suspend (f_{DM} ~ 0.01 Hz).**
  ⇨ **10^2-10^3 times higher sensitivity**



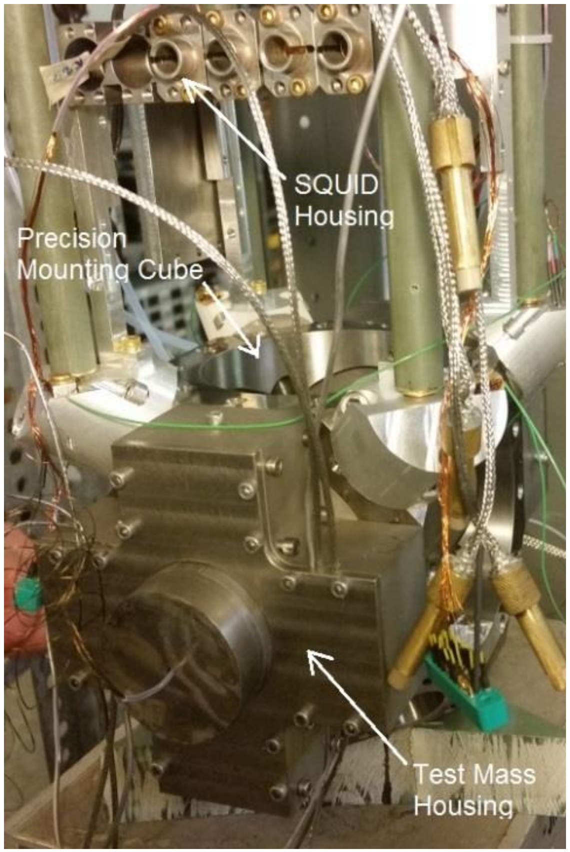
Test masses (100 g each) are levitated by a current induced along a tube.



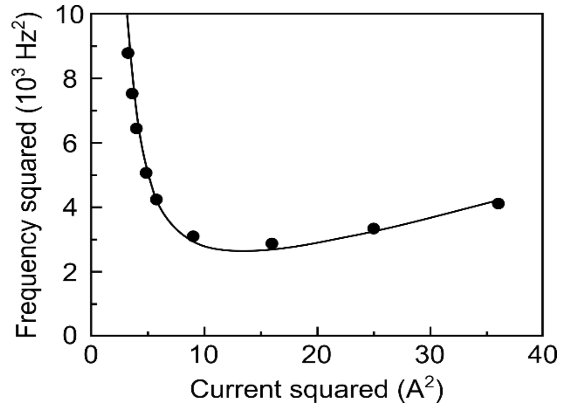
Six test masses mounted a cube form a tensor gradiometer.

Demonstration of levitated SGG

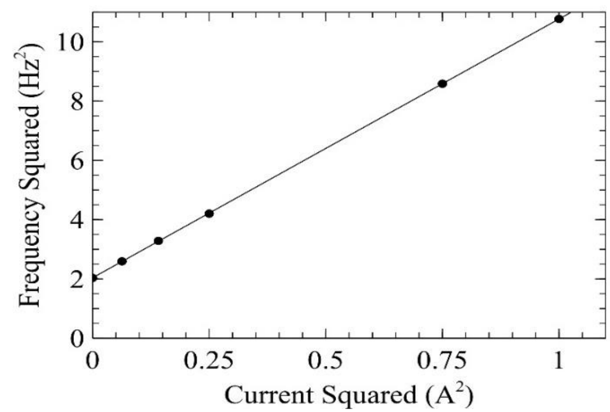
- **Two-component SGG with levitated test masses has been demonstrated.**



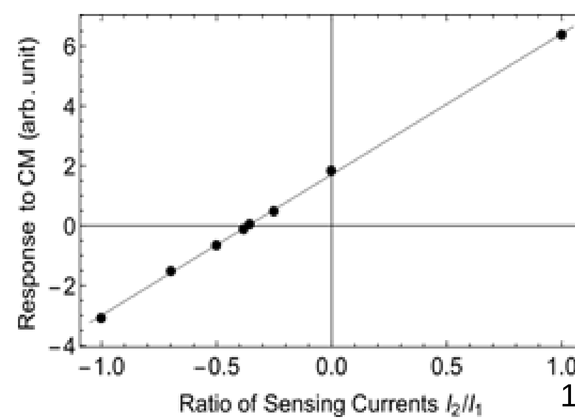
Levitation



Frequency tuning



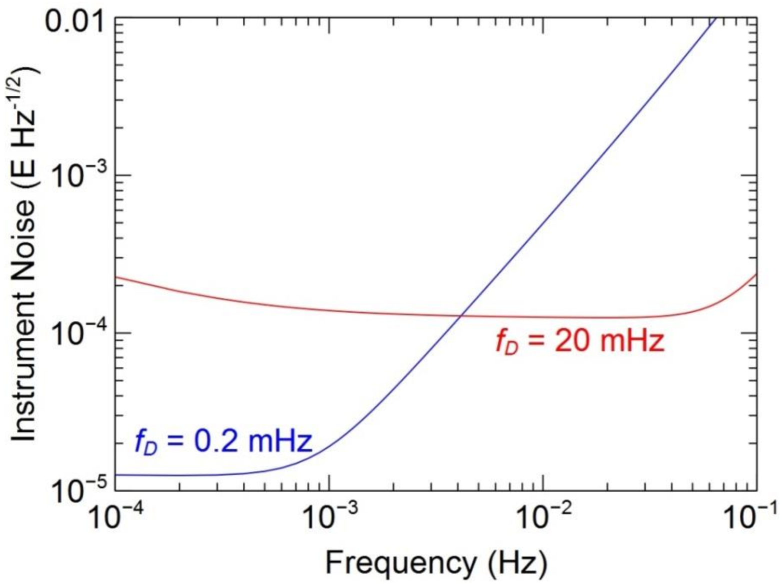
Common-mode balance



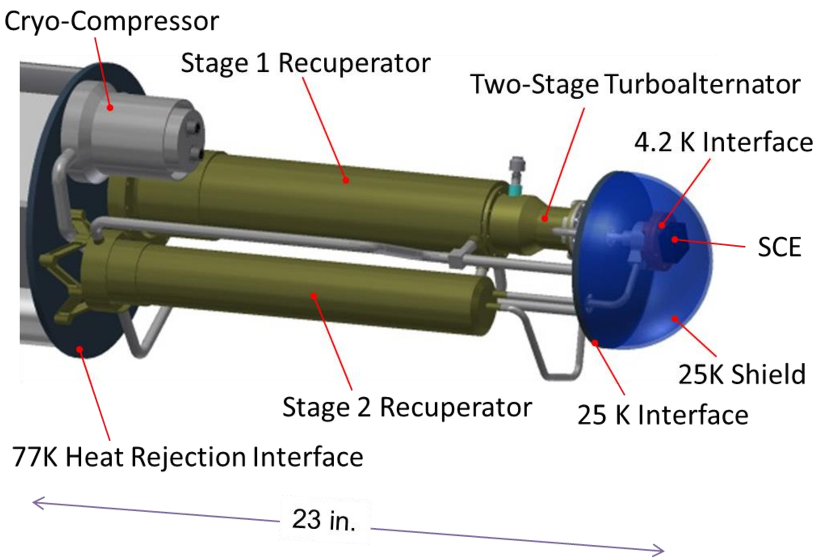
Griggs *et al.*, *Phys. Rev. Applied*, 064024 (2017)

SGG for planetary science mission

- **Tensor SGG with sensitivity 2 x 10^{-4} E $Hz^{-1/2}$ over 0.1 ~ 100 mHz.**
- **SGG could be *tuned* during the mission to yield higher sensitivity at low frequencies where time-variable gravity signals are.**
- **Cryocooler will permit 5-10 year mission lifetime.**

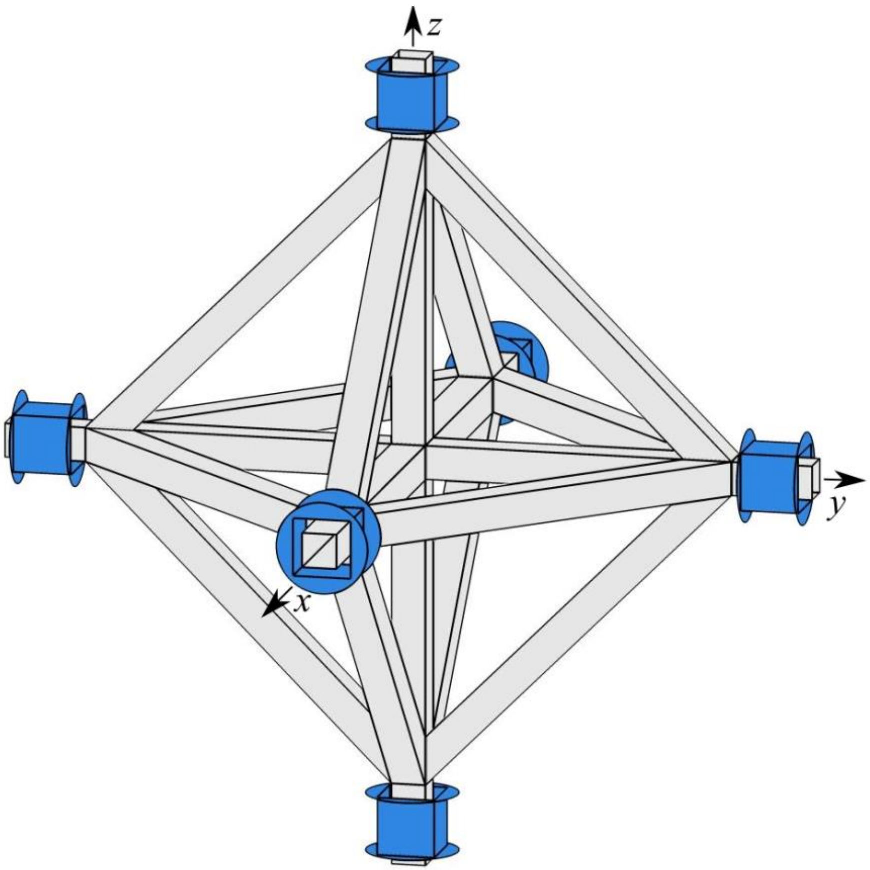


Instrument noise spectral density



Creare two-stage turbo-Brayton cryocooler

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



- **Each test mass has 3 DOF.**
- **Combining six test masses, tensor GW detector is formed.**

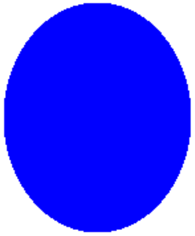
$$h_{ii}(t) = \frac{2}{L}\left[x_{+ii}(t) - x_{-ii}(t)\right]$$

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

- **Source direction (θ, ϕ) and wave polarization (*h+*, *h*×) can be determined by a single antenna.**

⇨ **"Spherical" Antenna**

Paik *et al.*, *Class. Quantum Gravity* 33, 075003 (2016)

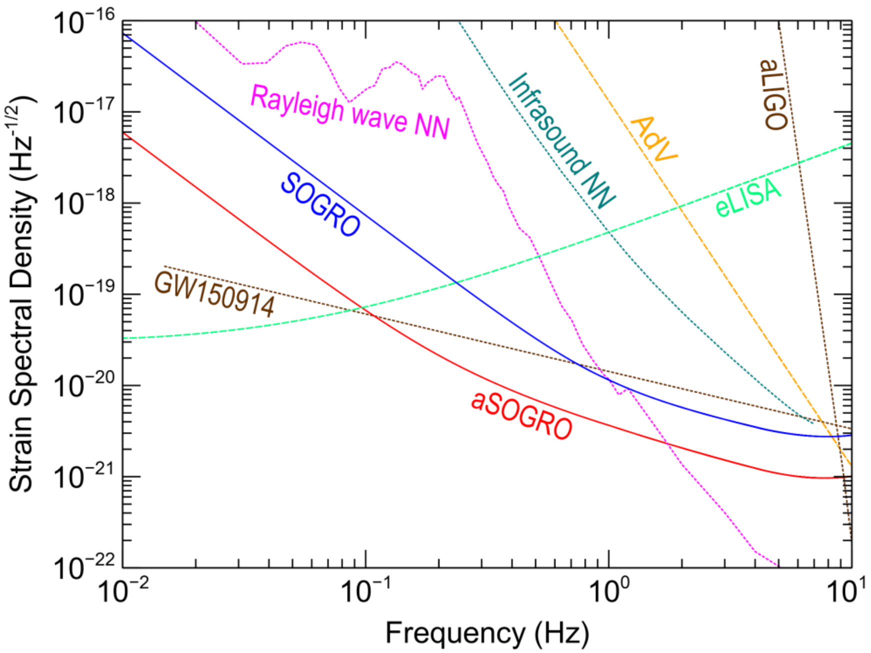


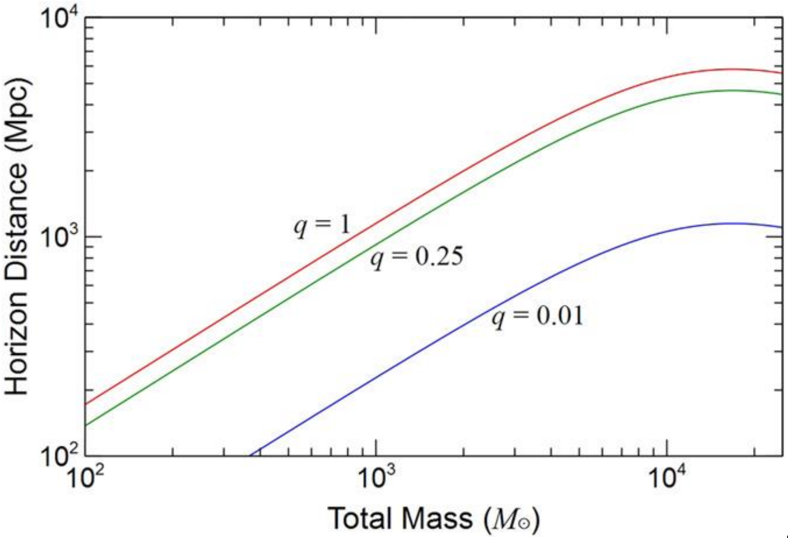
+ polarization

x polarization

Astrophysics with SOGRO

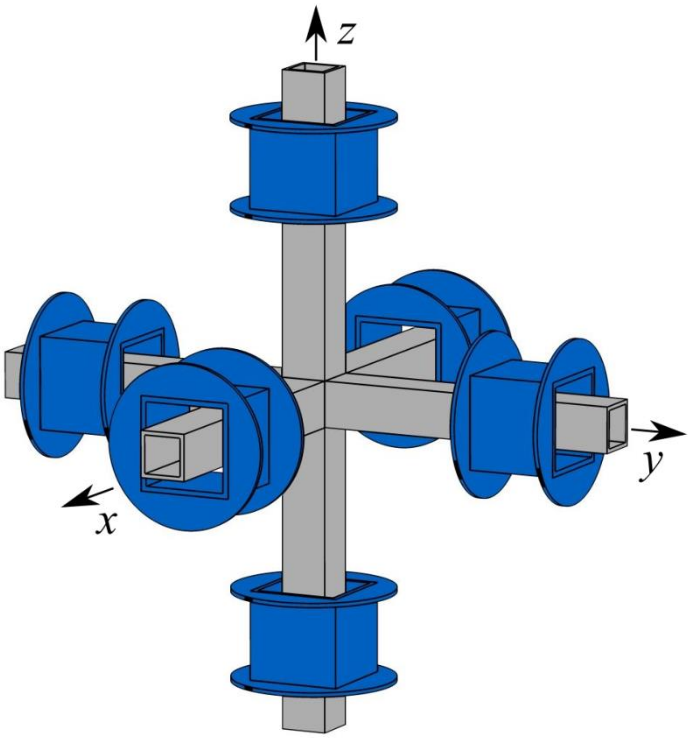
- **SOGRO would fill 0.1-10 Hz frequency gap between the terrestrial and future space interferometers.**
- **aSOGRO would be able to detect stellar mass BH binaries like GW150914 and alert interferometers days before merger.**
- **SOGRO could detect IMBH binaries with 10^3-$10^4 M_\odot$ at a few billion light years away, and WD binaries within the Local Group.**



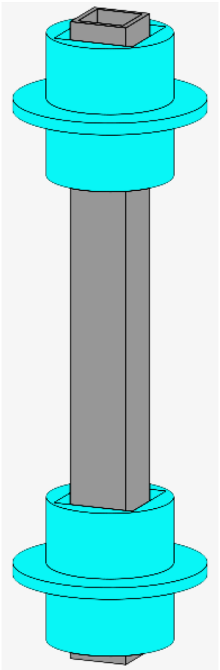


EEW instrumentation options

Full Tensor



Two-axis

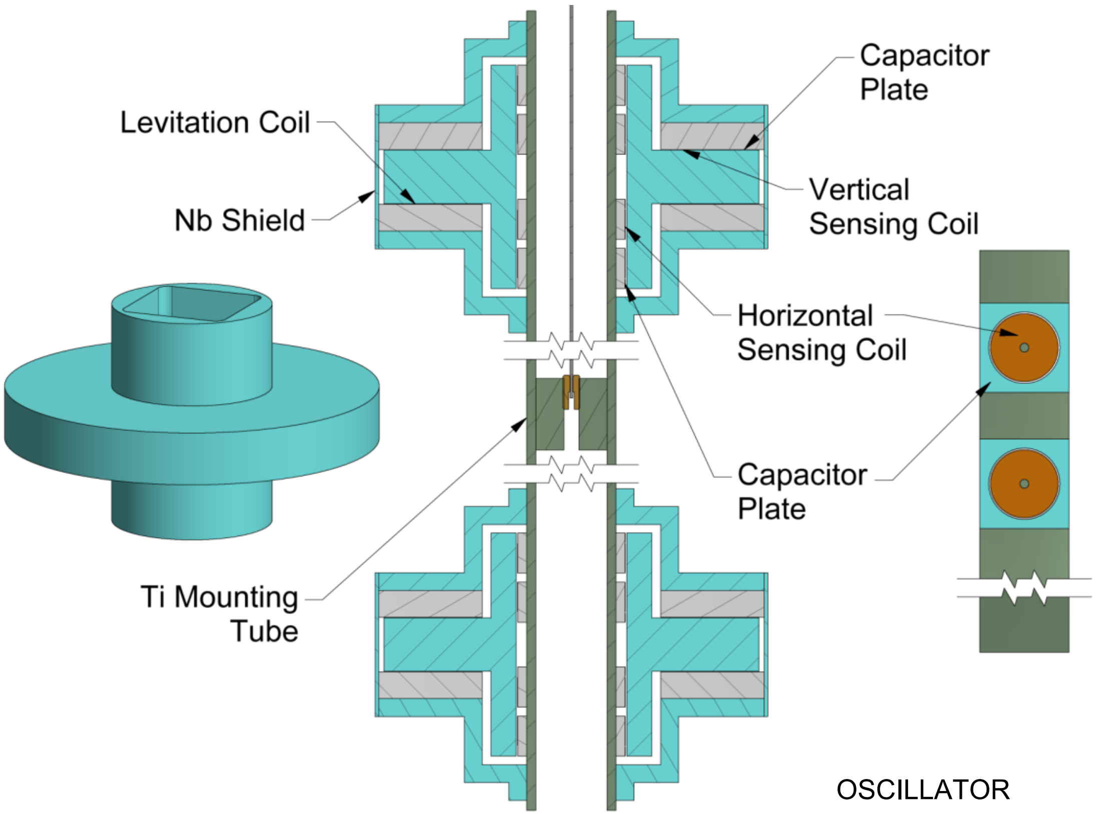


- **More information can be obtained but too large a cryostat is required.**
- **Vertical accelerometers are noisier due to higher resonance frequency.**
- **By suspending as a pendulum, the platform is isolated from ground tilt.**
  - ⇨ Γ_{xz} **and** Γ_{yz} **can be measured from horizontal motions of two test masses only.**

$$\Gamma_{xz} = \frac{1}{\ell}\left[\left(a_{x2} - a_{x1}\right) + \left(a_{z2} - a_{z1}\right)\right] = \frac{2}{\ell}\left(a_{x2} - a_{x1}\right)$$

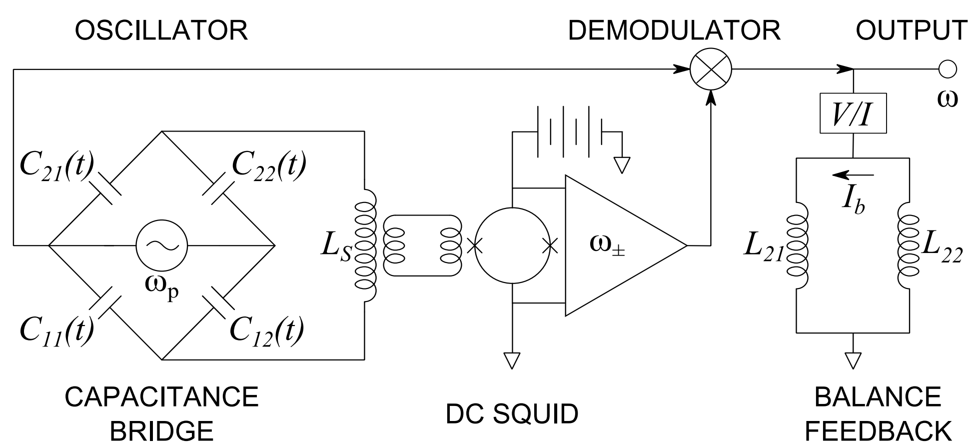
$$\Gamma_{yz} = \frac{1}{\ell}\left[\left(a_{y2} - a_{y1}\right) + \left(a_{z2} - a_{z1}\right)\right] = \frac{2}{\ell}\left(a_{y2} - a_{y1}\right)$$

SEED (Superconducting Earthquake Early Detector)



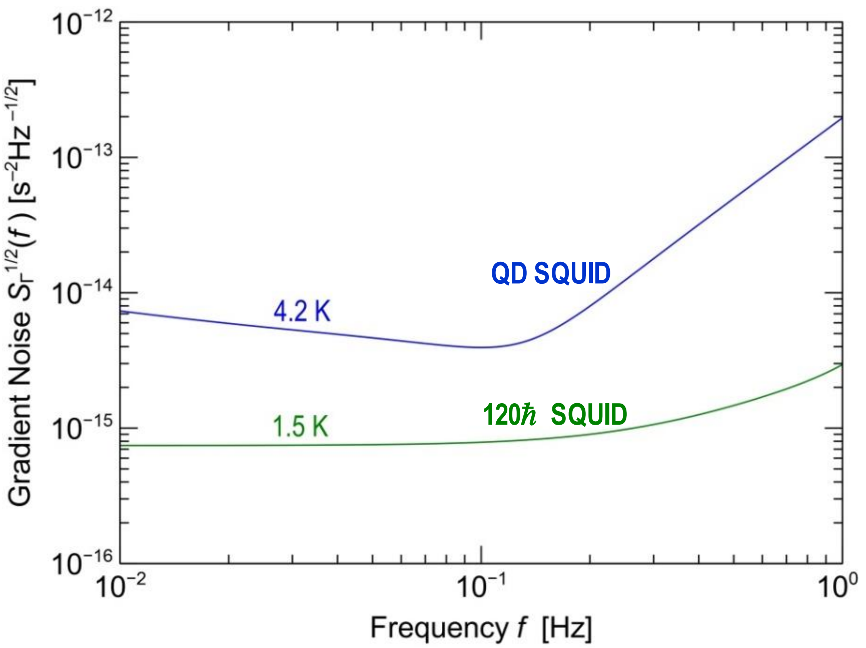
- **Two Nb test masses weighing M = 10 kg each are separated by L = 50 cm along z axis.**
- **SEED measures Γ_{xz} and Γ_{yz} with high sensitivity, and Γ_{zz} and g_z with 10 times lower sensitivity.**

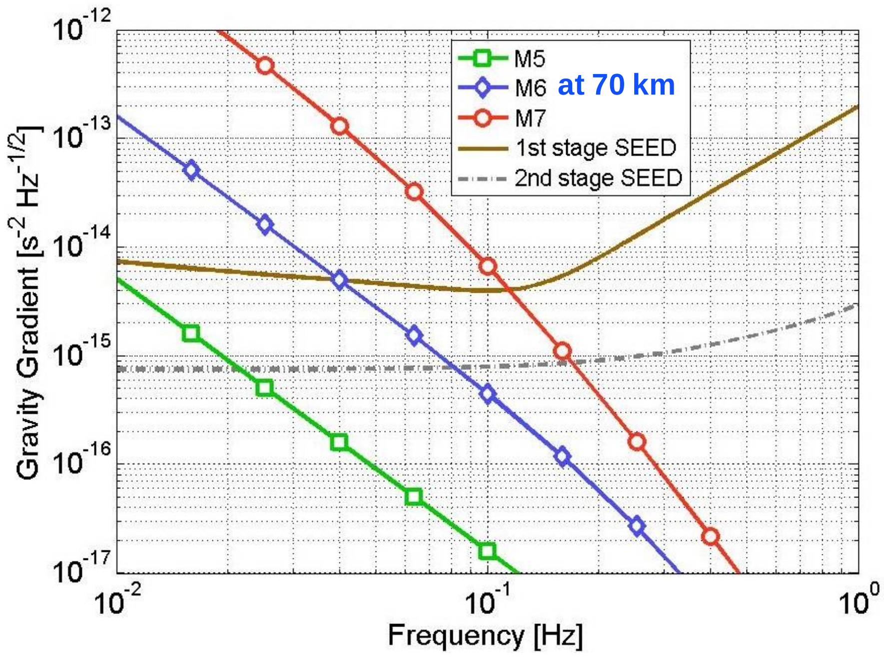
- **For higher sensitivity, test masses are cooled to 1.5 K and coupled to a two-stage SQUID (120$\hbar$ noise) via capacitor bridge transducer.**



Expected sensitivity of SEED

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

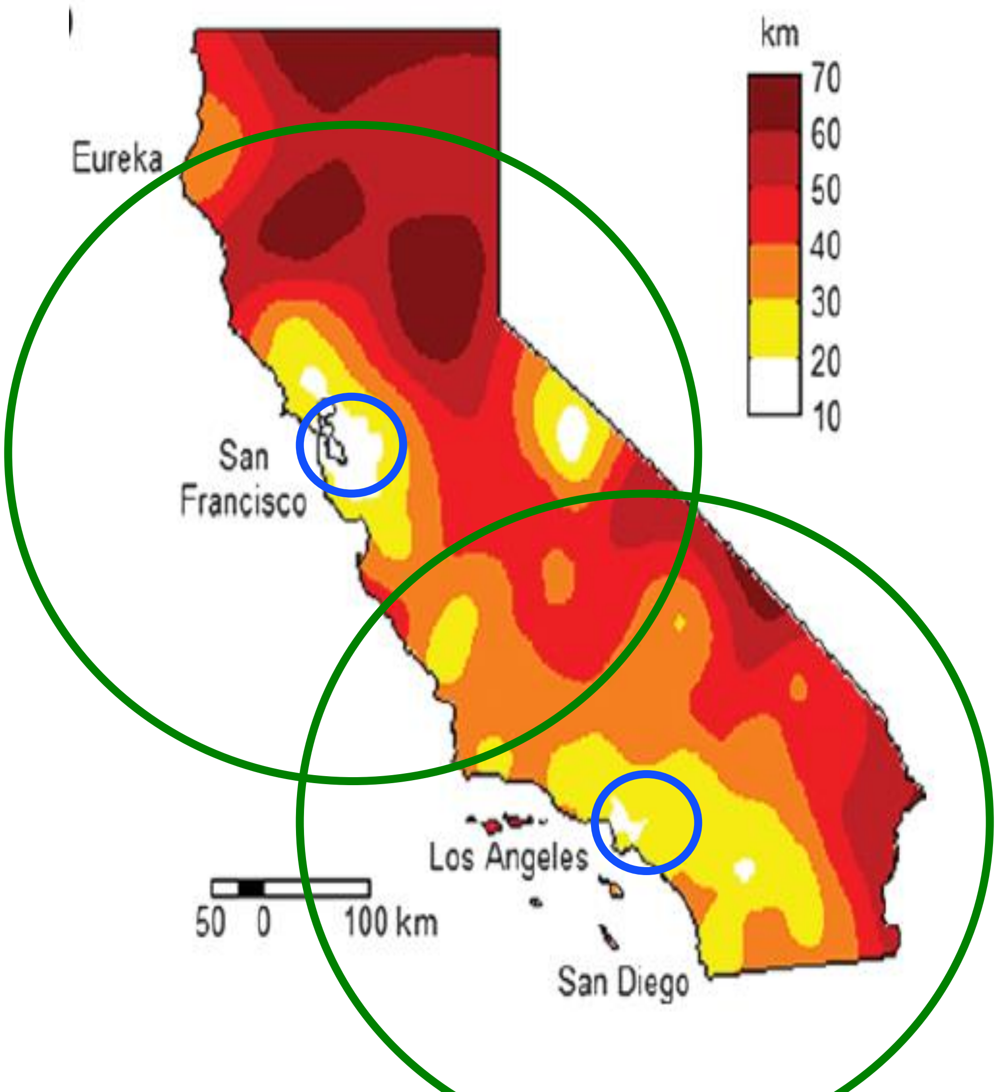




- **To reject the seismic noise to below the intrinsic noise, CMRR = 10^9 is achieved.**

Detection range of SEED and SOGRO

- SEED has a range of 50 km for M6 earthquake.
- SOGRO has a range of 350 km for M6 earthquake.



Deployment of SEED

- **SEED requires improvement in sensitivity by a factor of 200 beyond the SGG under development.**
  - ⇨ **A factor of 40 comes from scaling up and a factor of 5 from using a lower noise SQUID.**
- **It is highly desirable to use cryocoolers to cool and operate SEEDs.**
  - ⇨ **Pulse-tube cryocoolers are not quiet enough. Vibration-free 4-K turbo-Brayton cryocoolers are under development.**
- **To cover the West Coast of the United States, a few 10s of SEEDs, one sensor every ~50 km near major faults may be required.**
  - ⇨ **We need to perform a systematic cost-benefit analysis of SEED in comparison with conventional EEWS.**