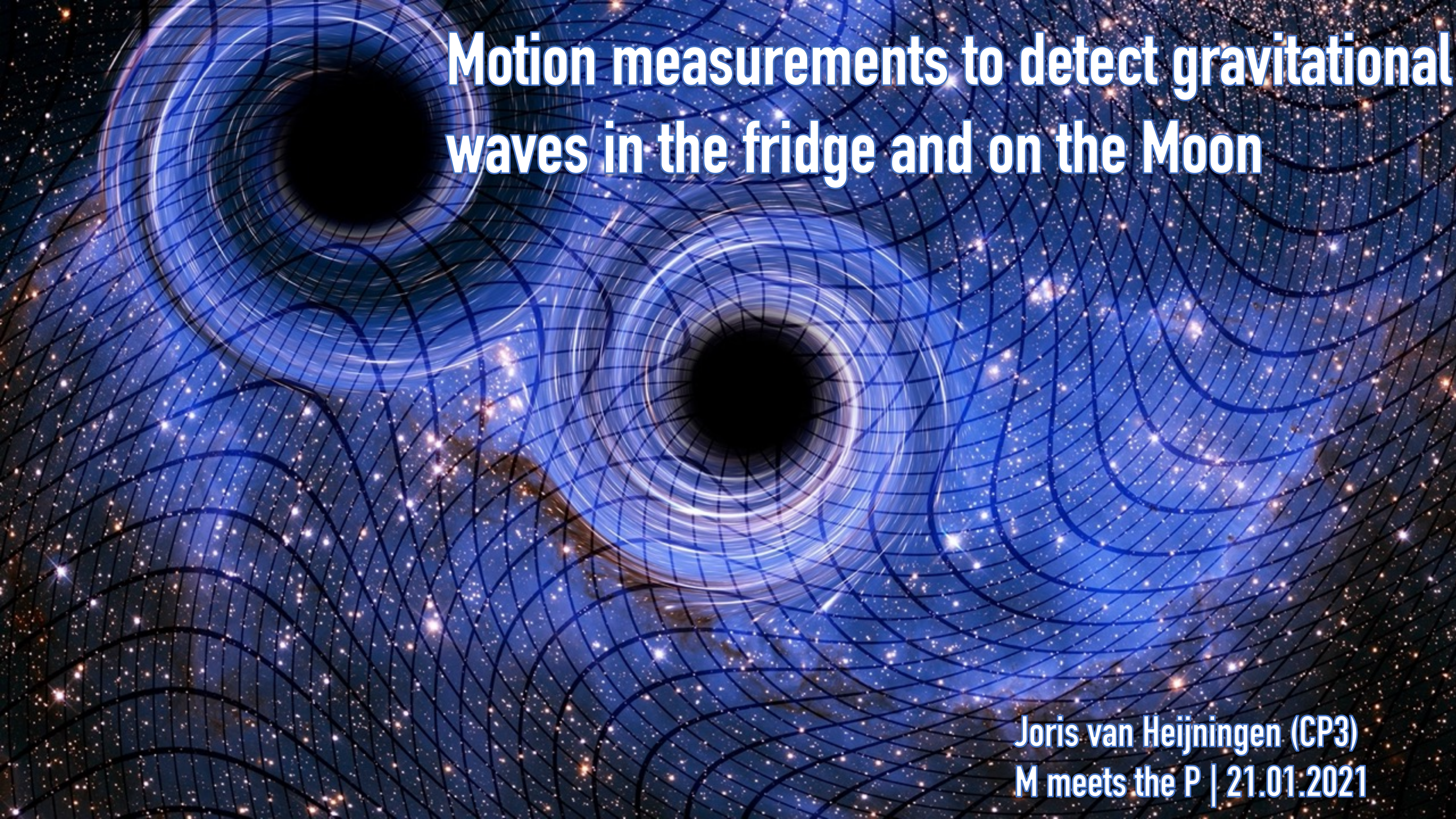
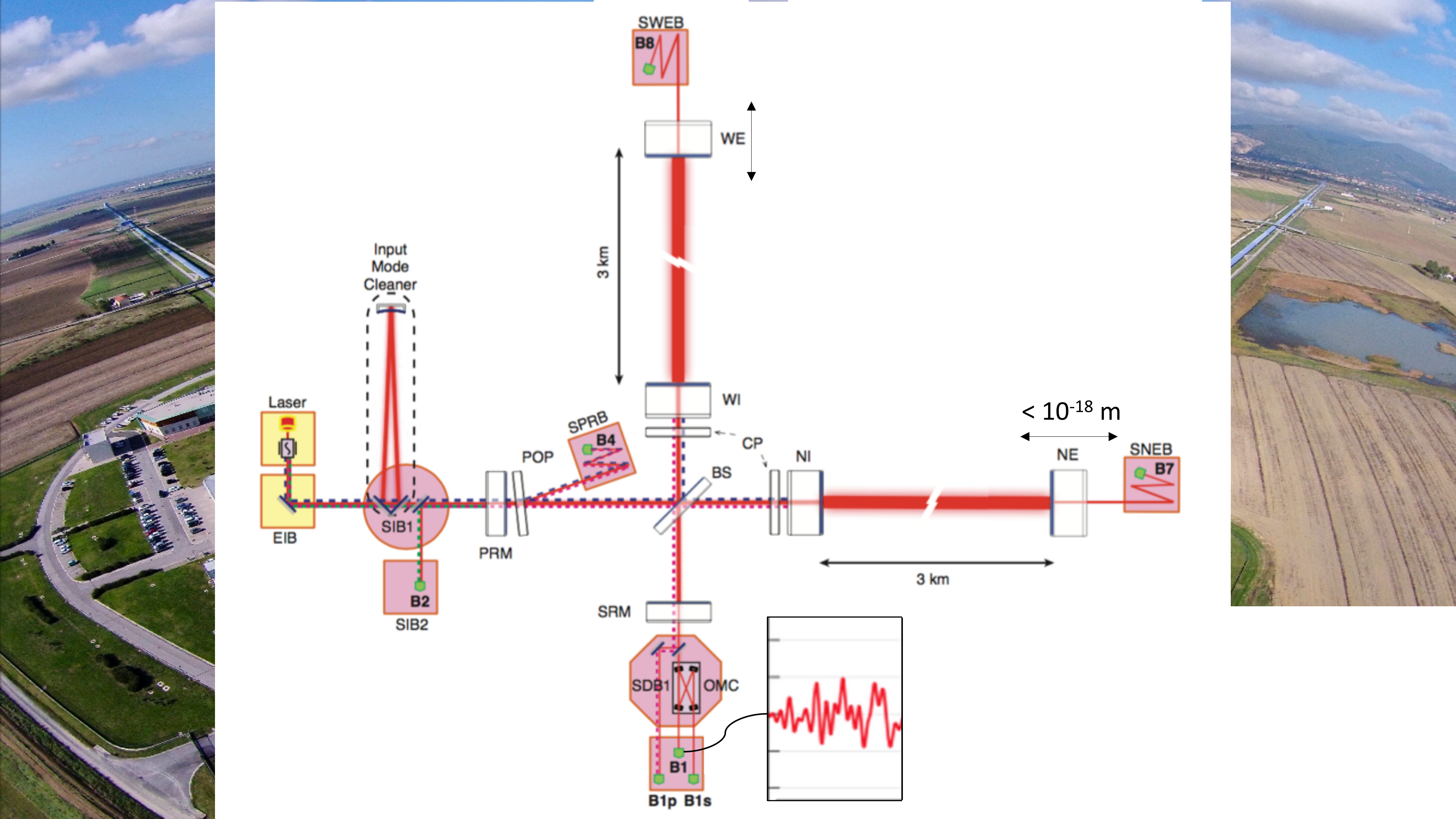


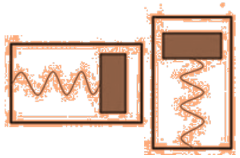
Motion measurements to detect gravitational waves in the fridge and on the Moon

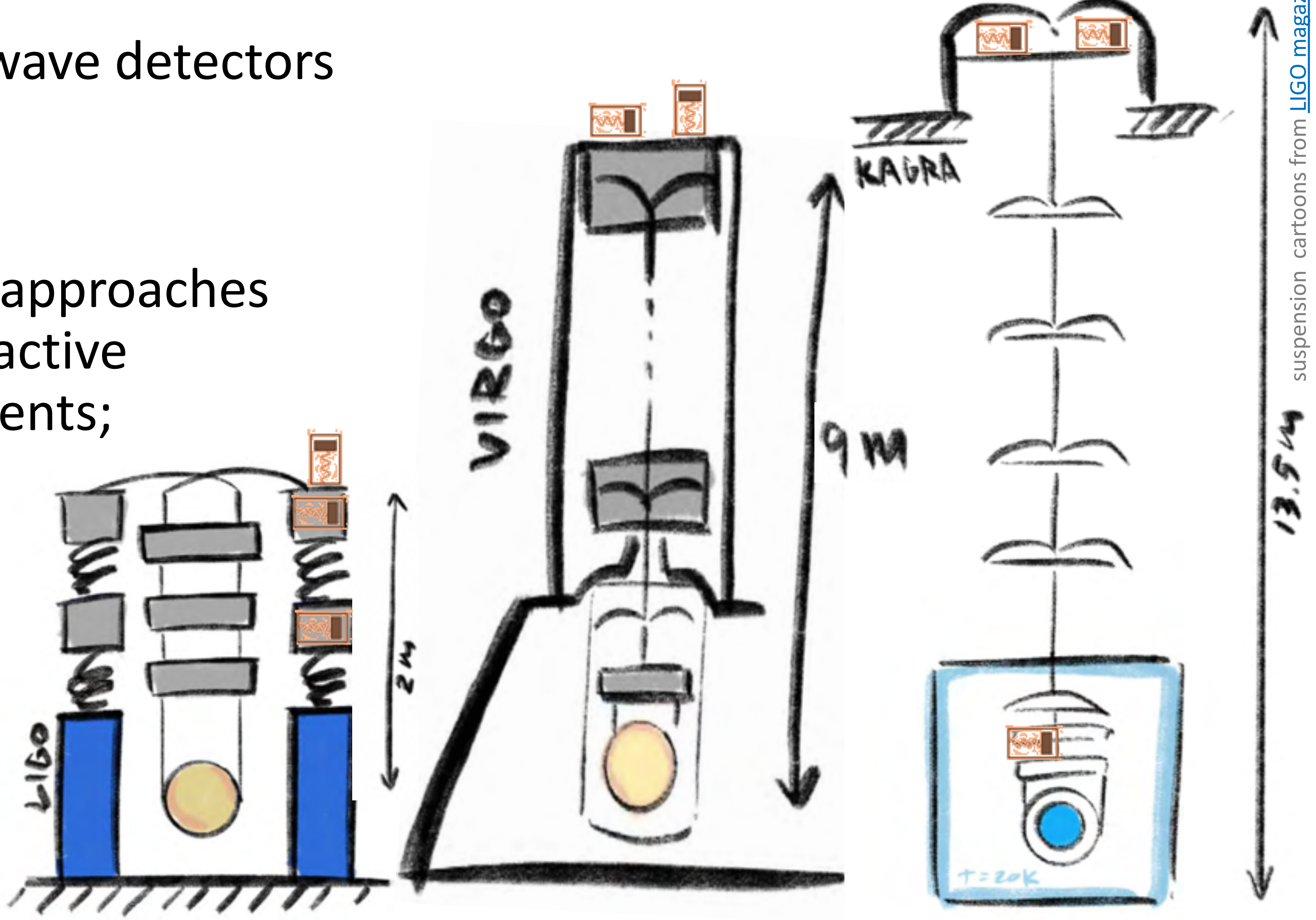
Joris van Heijningen (CP3)
M meets the P | 21.01.2021


SWEB
B8
WE
3 km
Input
Mode
Cleaner
Laser
EIB
SIB1
B2
SIB2
PRM
POP
SPRB
B4
WI
CP
BS
NI
NE
SNEB
B7
< 10^-18 m
3 km
SRM
SDB1
OMC
B1
B1p B1s

Different detectors, different suspensions

- ➢Different gravitational wave detectors use different strategies;
- ➢But, they are all hybrid approaches combining passive and active vibration isolation elements;
- ➢All approaches need good inertial sensors.

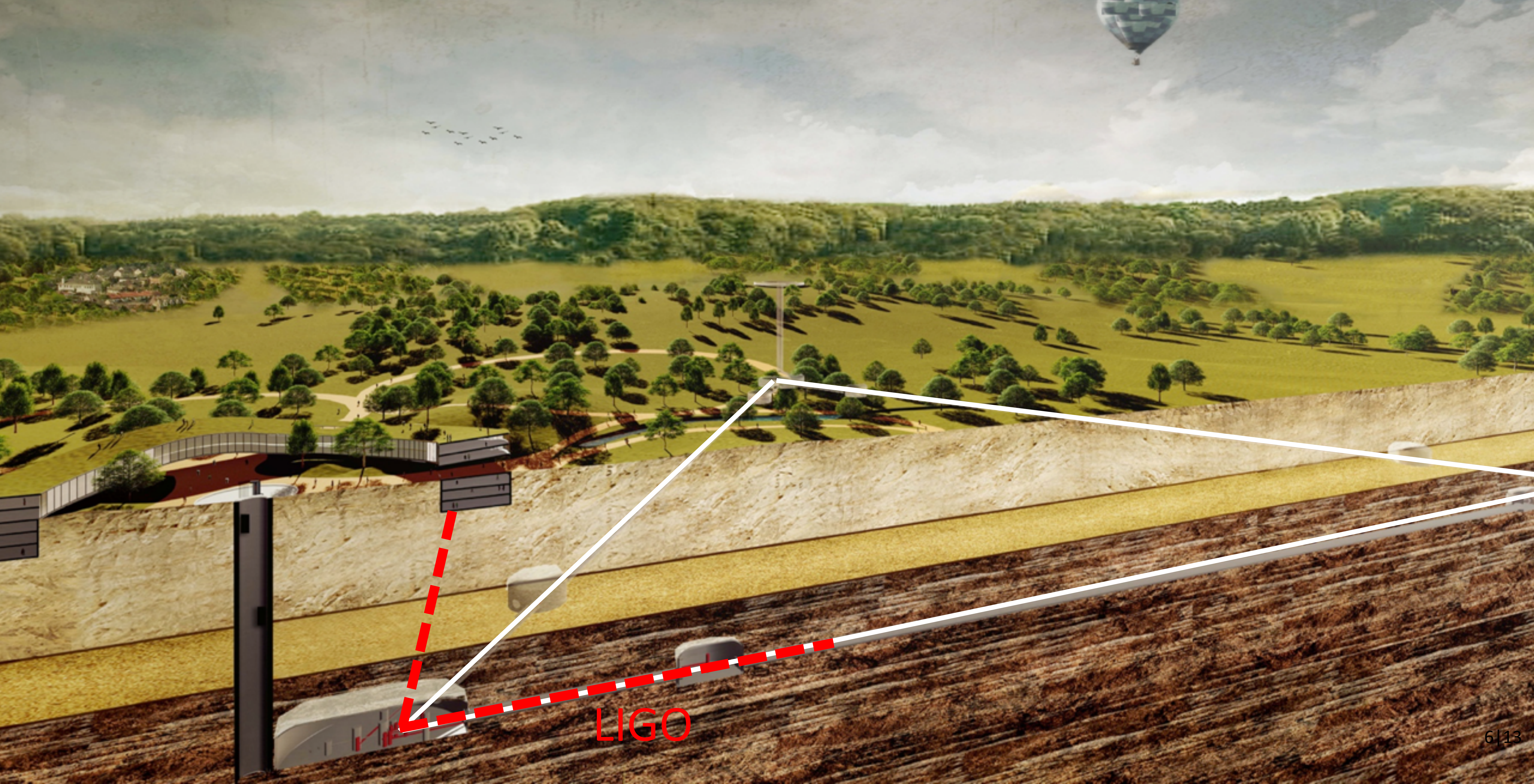




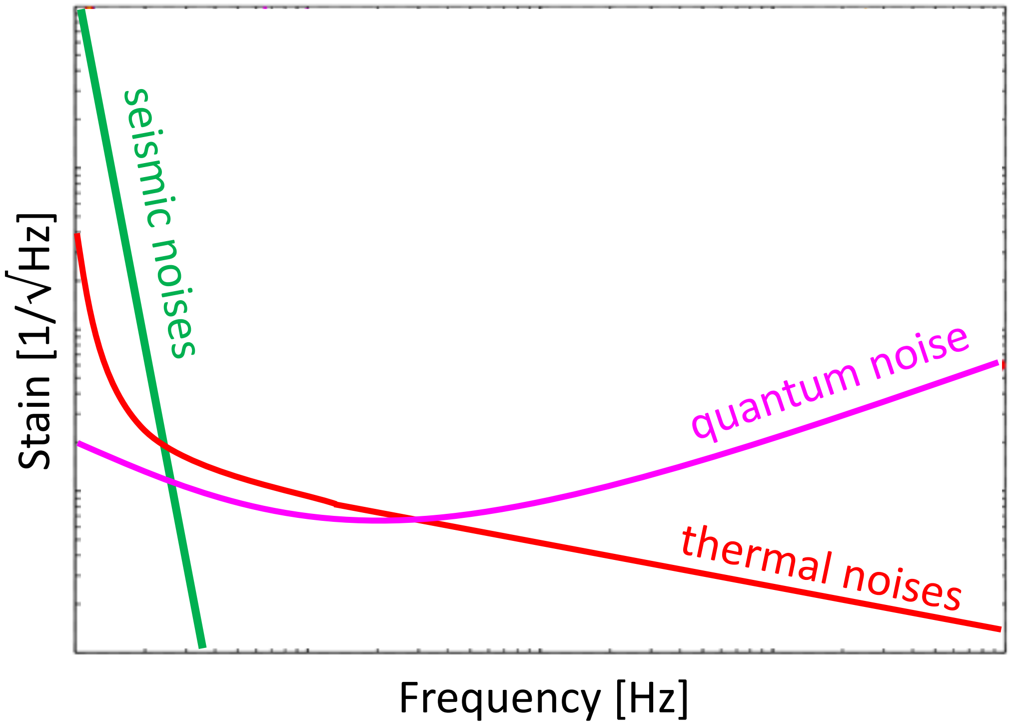
suspension cartoons from LIGO magazine 17

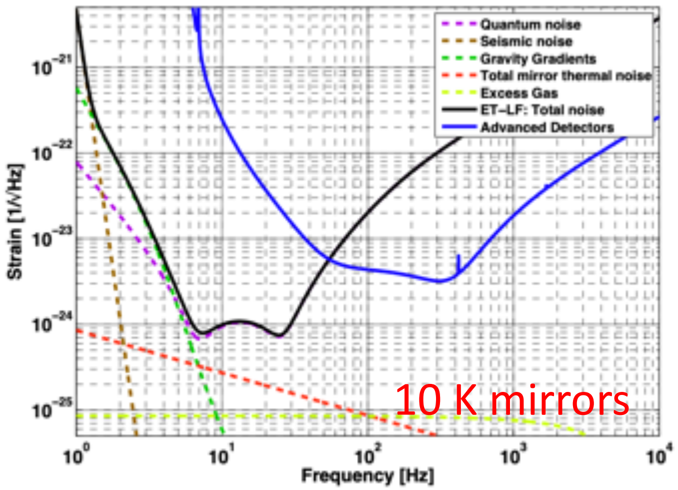

But what about the future?

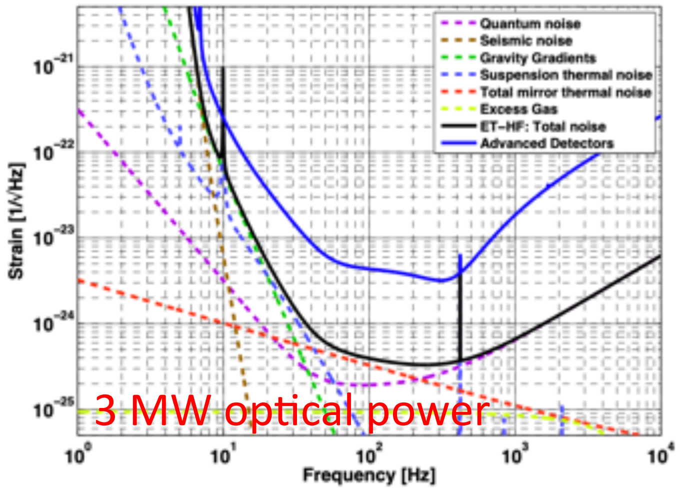
Einstein Telescope: a 10 km triangle



Xylophone concept to get the best of both worlds

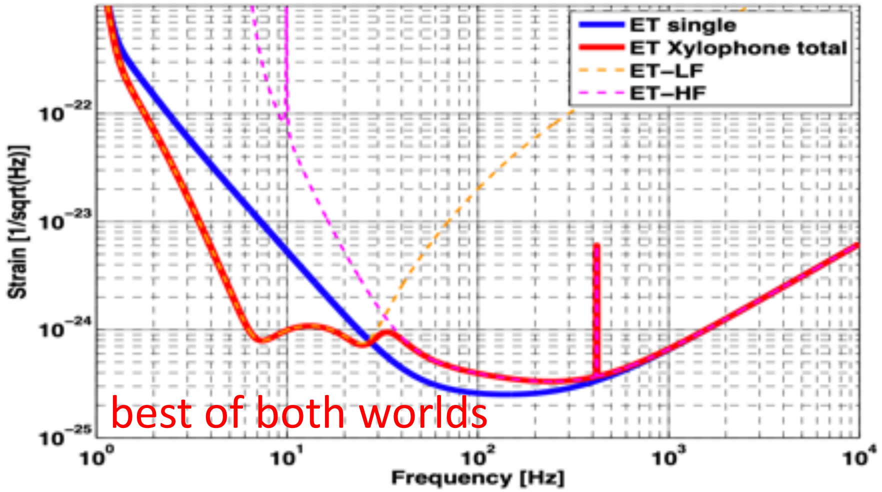




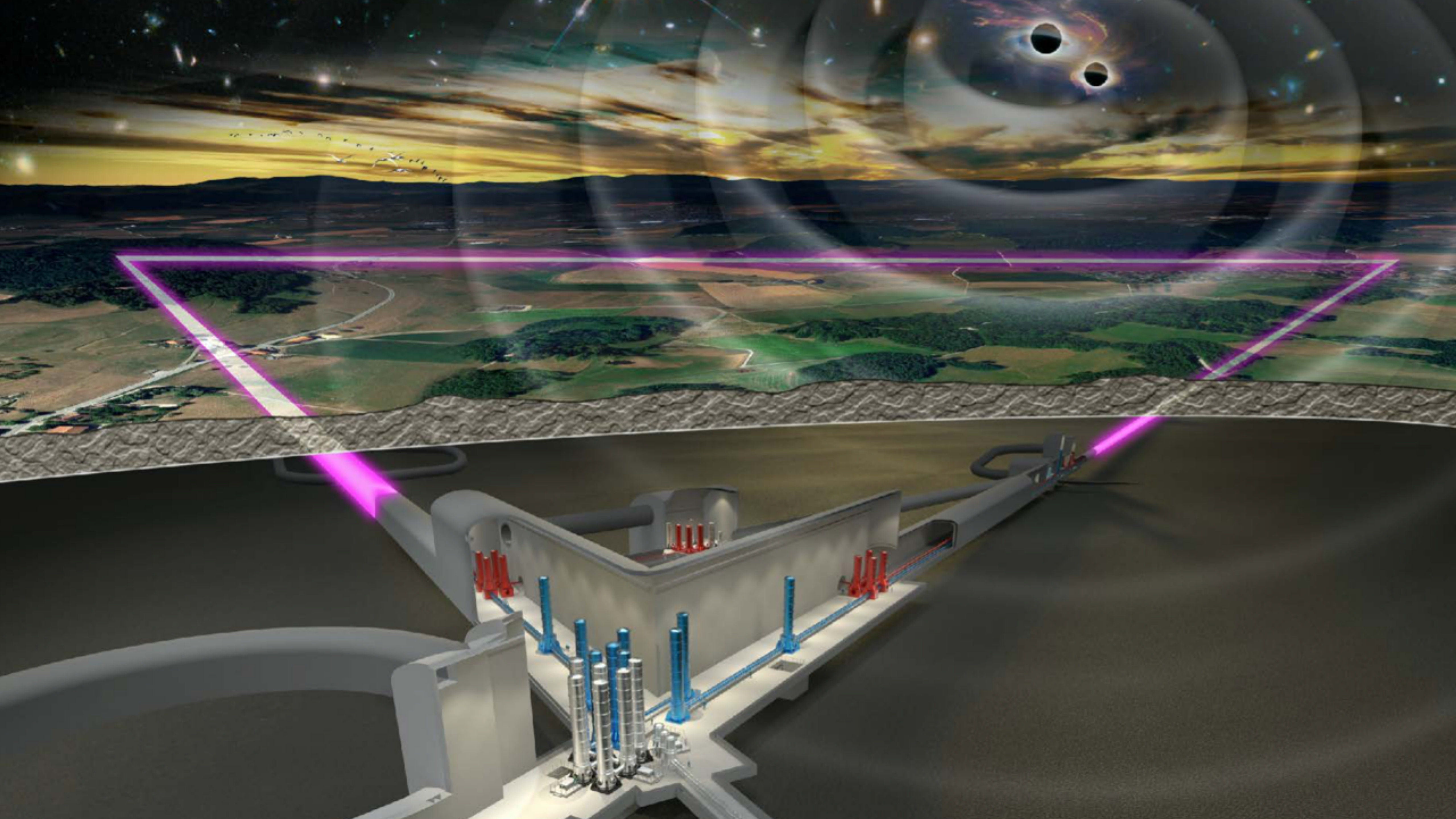


- 3 low-f and 3 high-f detectors make 3 broadband detectors.

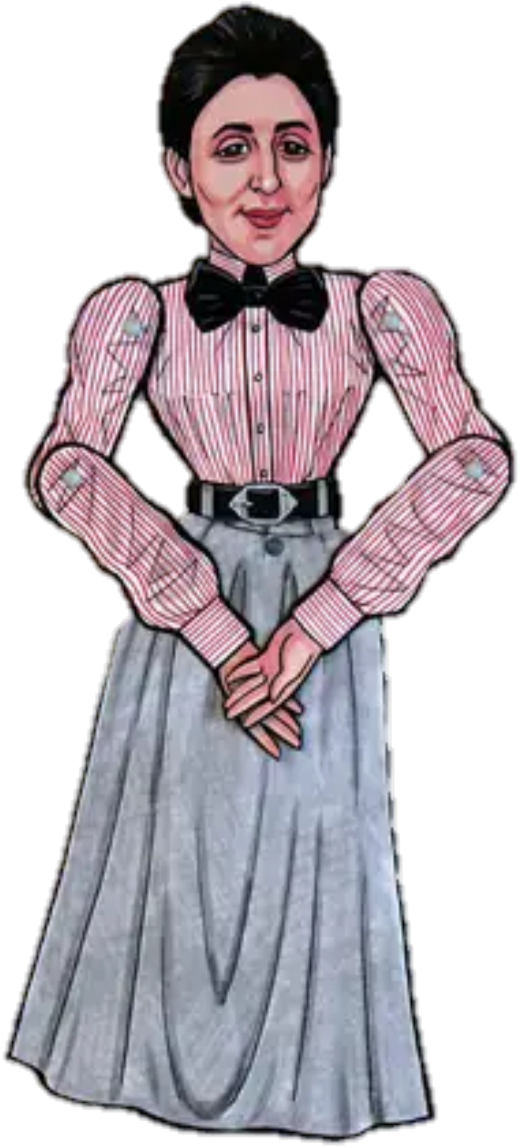
- Seismic noises depend on design ($);
- Higher P shift quantum noises ⏬, but 🌡️⏫;
- Thermal noise go down with 🌡️ ⏬, but then P ⏬ & the quantum noises go ⏫.



from S. Hild *et al.*, "A Xylophone Configuration for a third Generation Gravitational Wave Detector", Class. Quant. Grav. 27 015003 (2010)



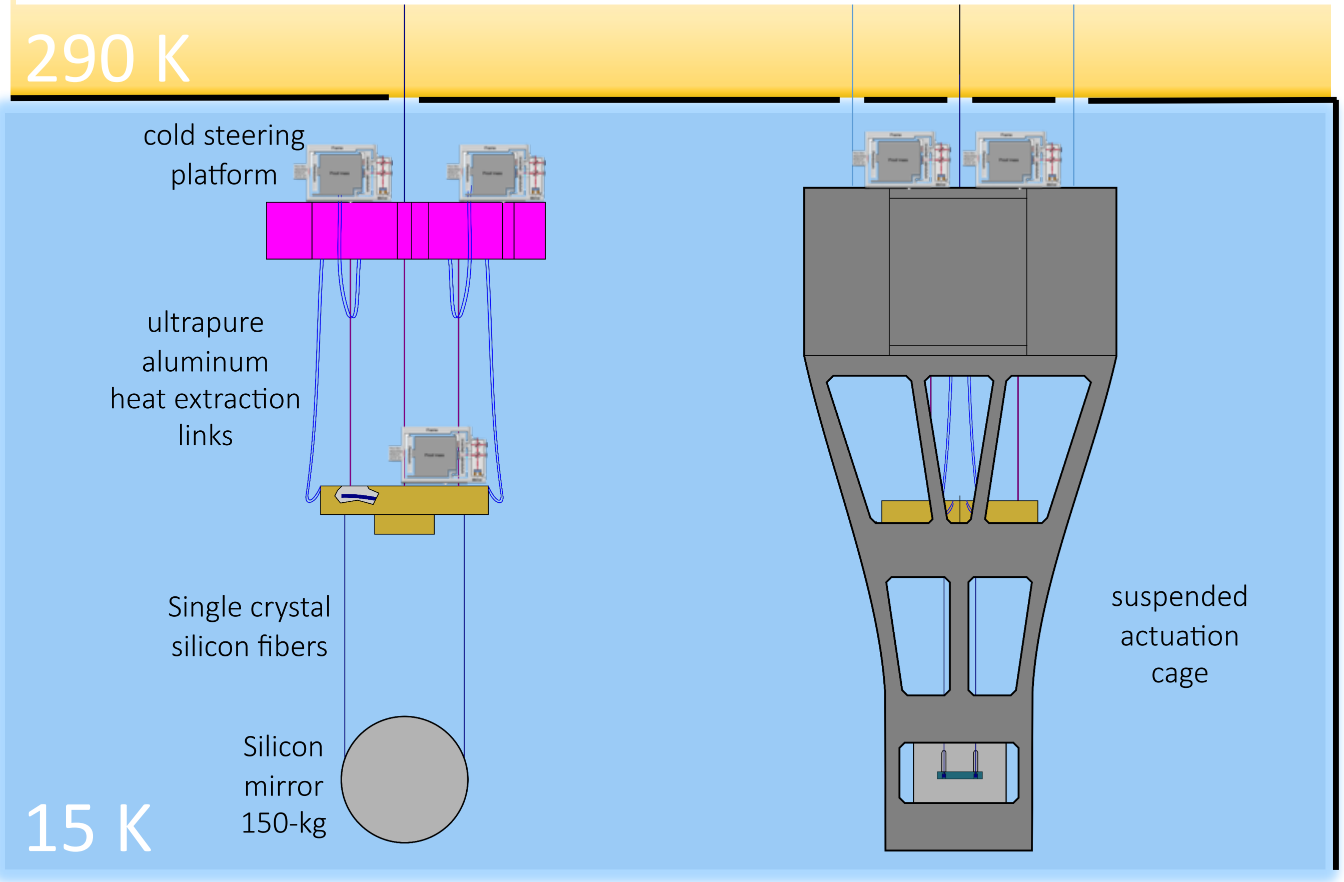
Making things cold typically means vibrations

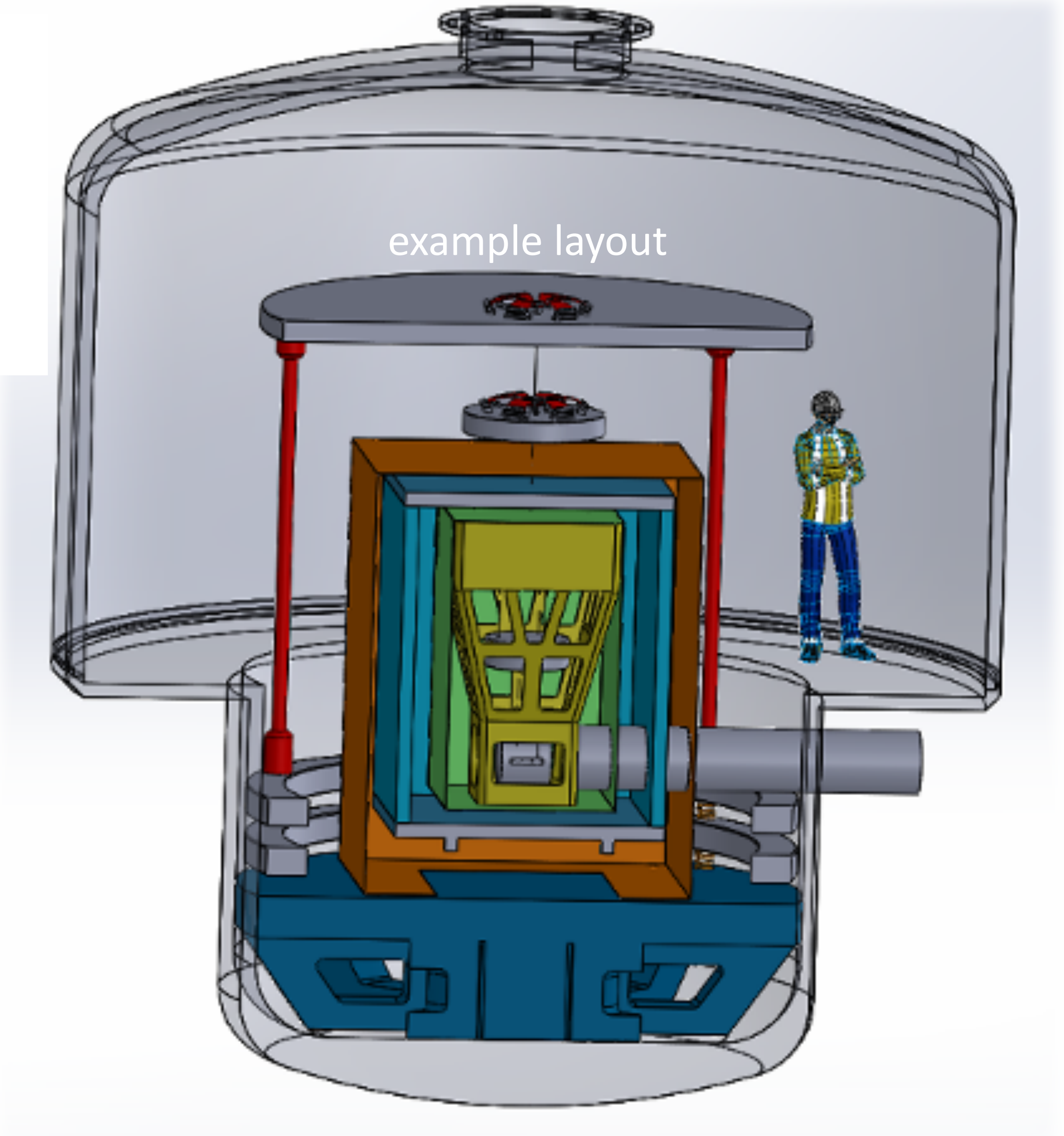


(Emmy Noether, 1882 – 1935)

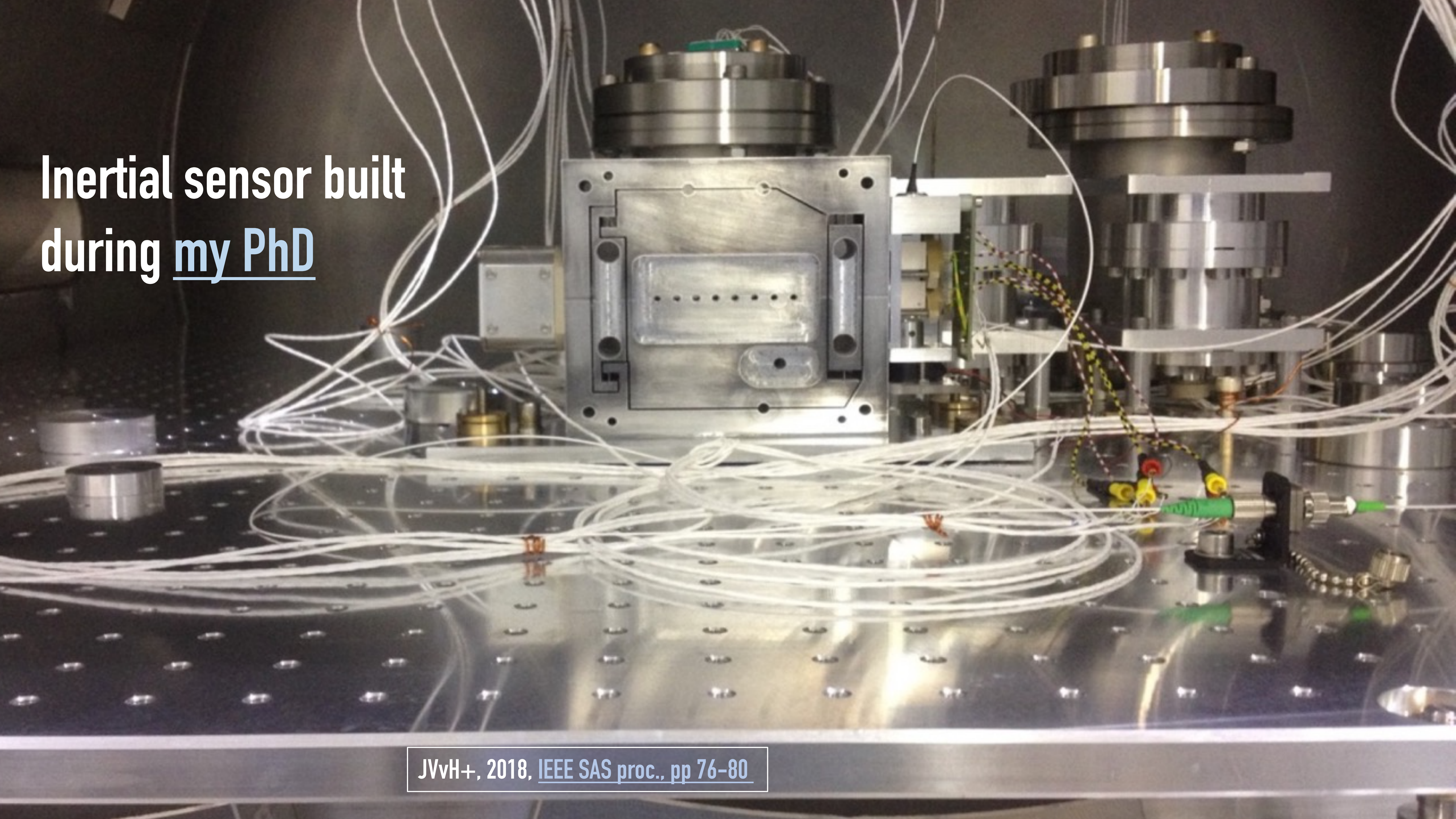
E-TEST (www.etest-emr.eu)

- One suspension: test hanging 100+ kg mirror;
- The 290 K (active) and cold 15 K suspension designed, fabricated in Liège (LIÈGE université & CSL);
- Testbed for new technologies, e.g. sensors.





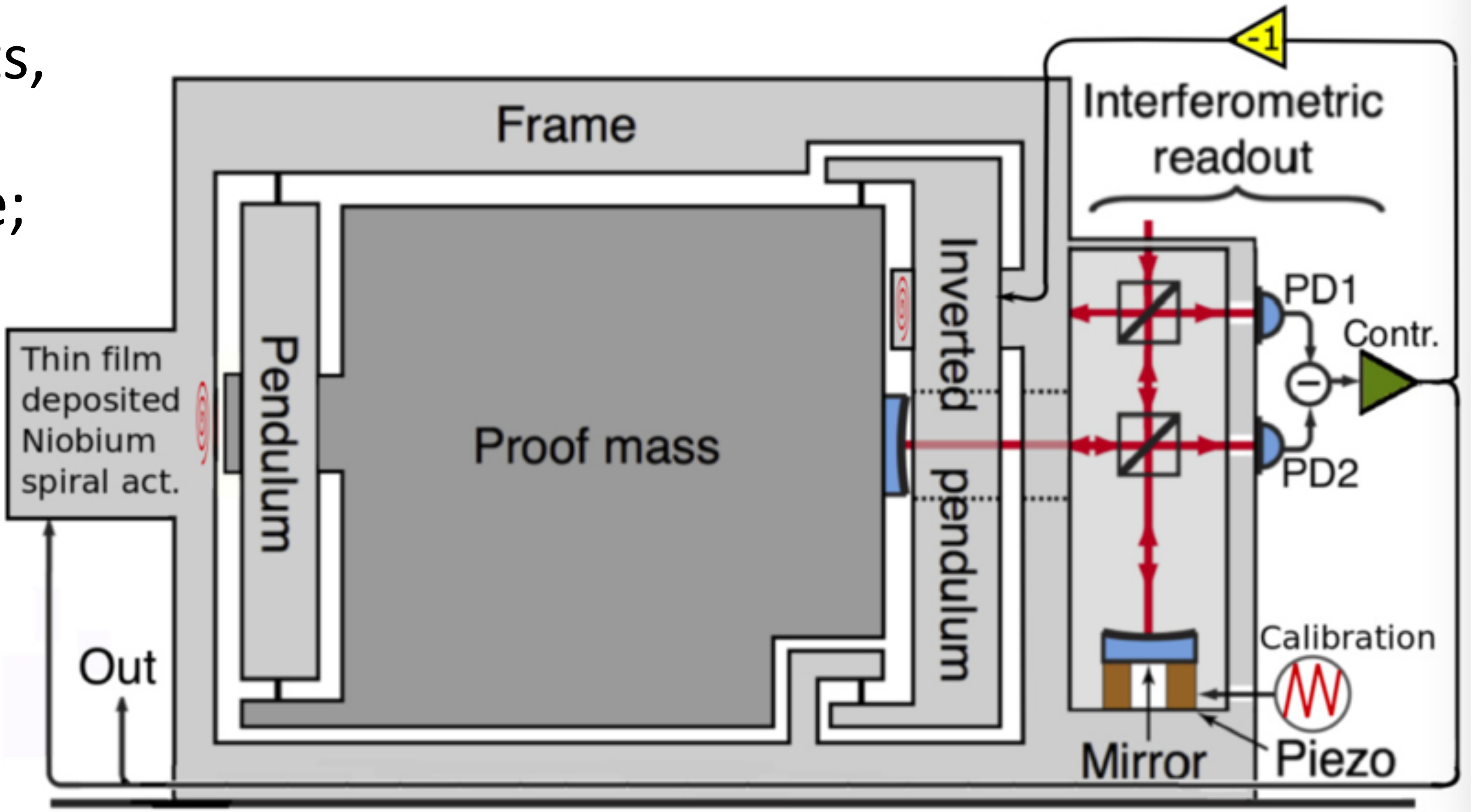
Inertial sensor built during my PhD



JVvH+, 2018, IEEE SAS proc., pp 76–80

Niobium mechanics with interferometric readout

- ➢Error signal from both ports, matched and subtracted to reject common mode noise;
- ➢Signal to actuators (which *lock* proof mass to frame) is sensor output;
- ➢Mechanics made out of Niobium (Nb), which is superconducting at T<9.2 K.

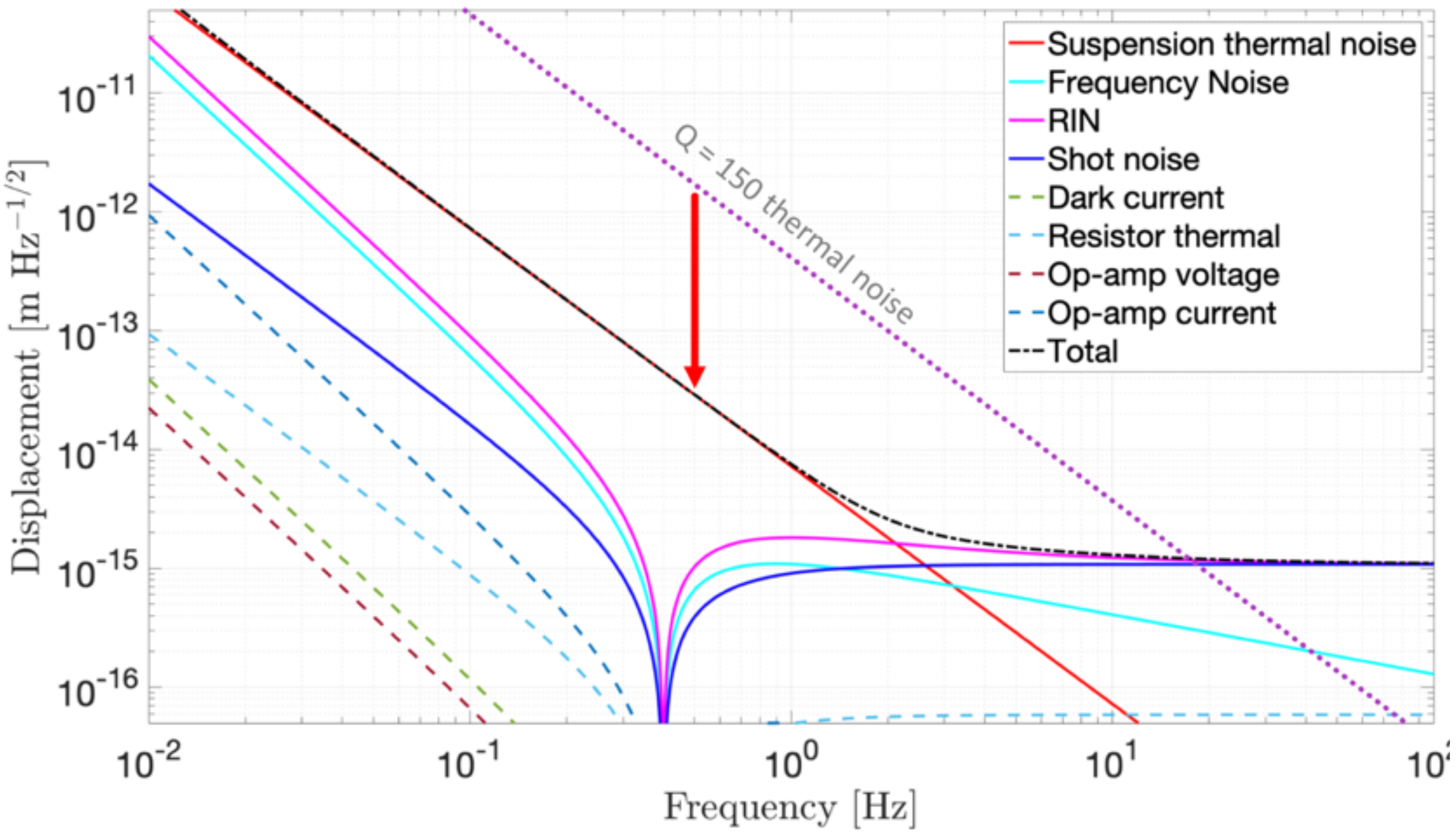


A. Bertolini et al.,2006, NIM A, 556, pp 616-623

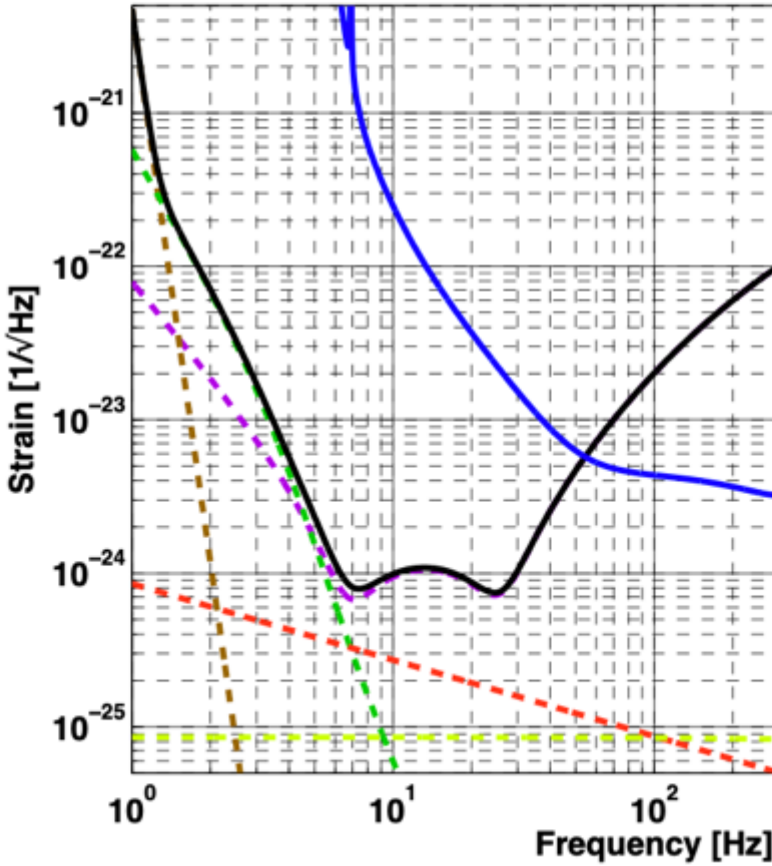
JVvH, 2020, JINST 15 P06034

M.B. Gray et al., 1999, Opt.Quant.Electron., 31, pp 571-582

How much more sensitive is this cold inertial sensor?



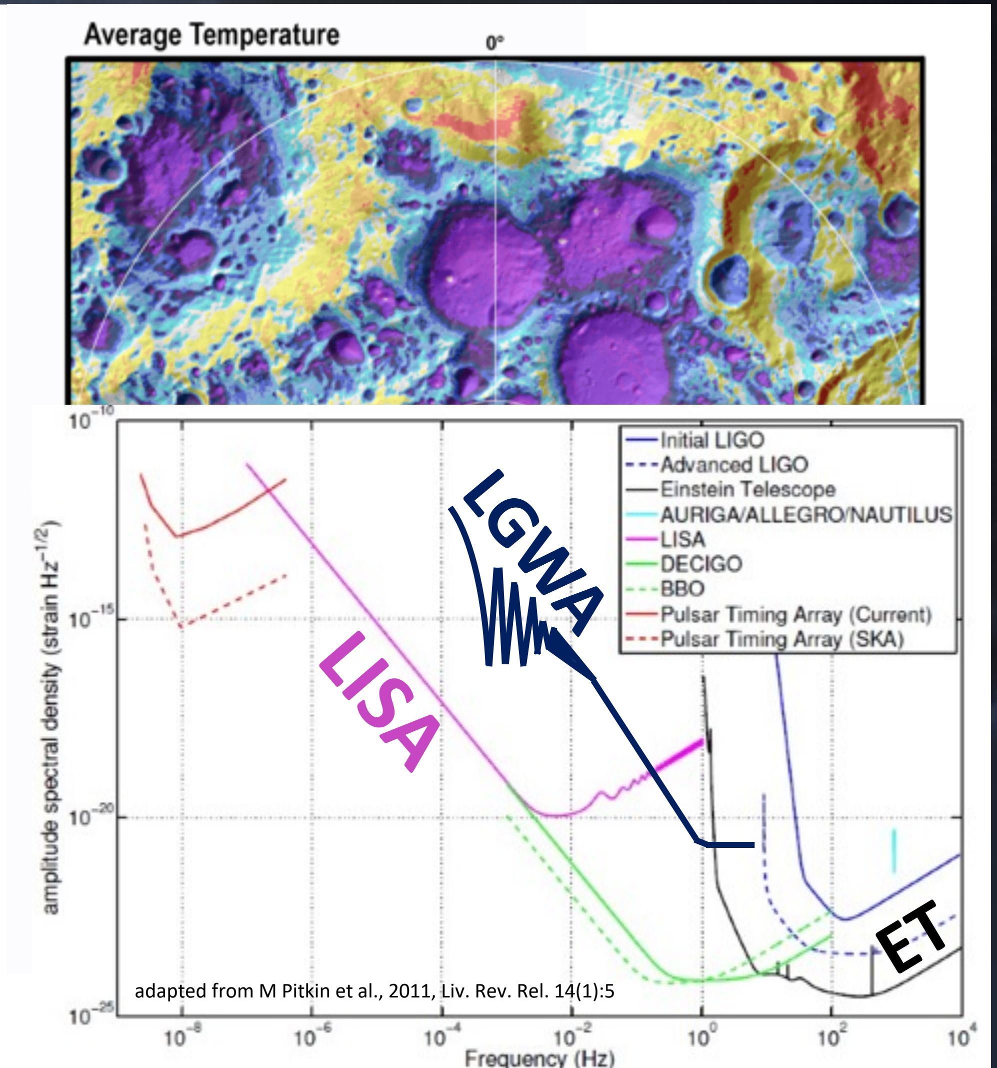
- ➢ Useful for ET low-f;



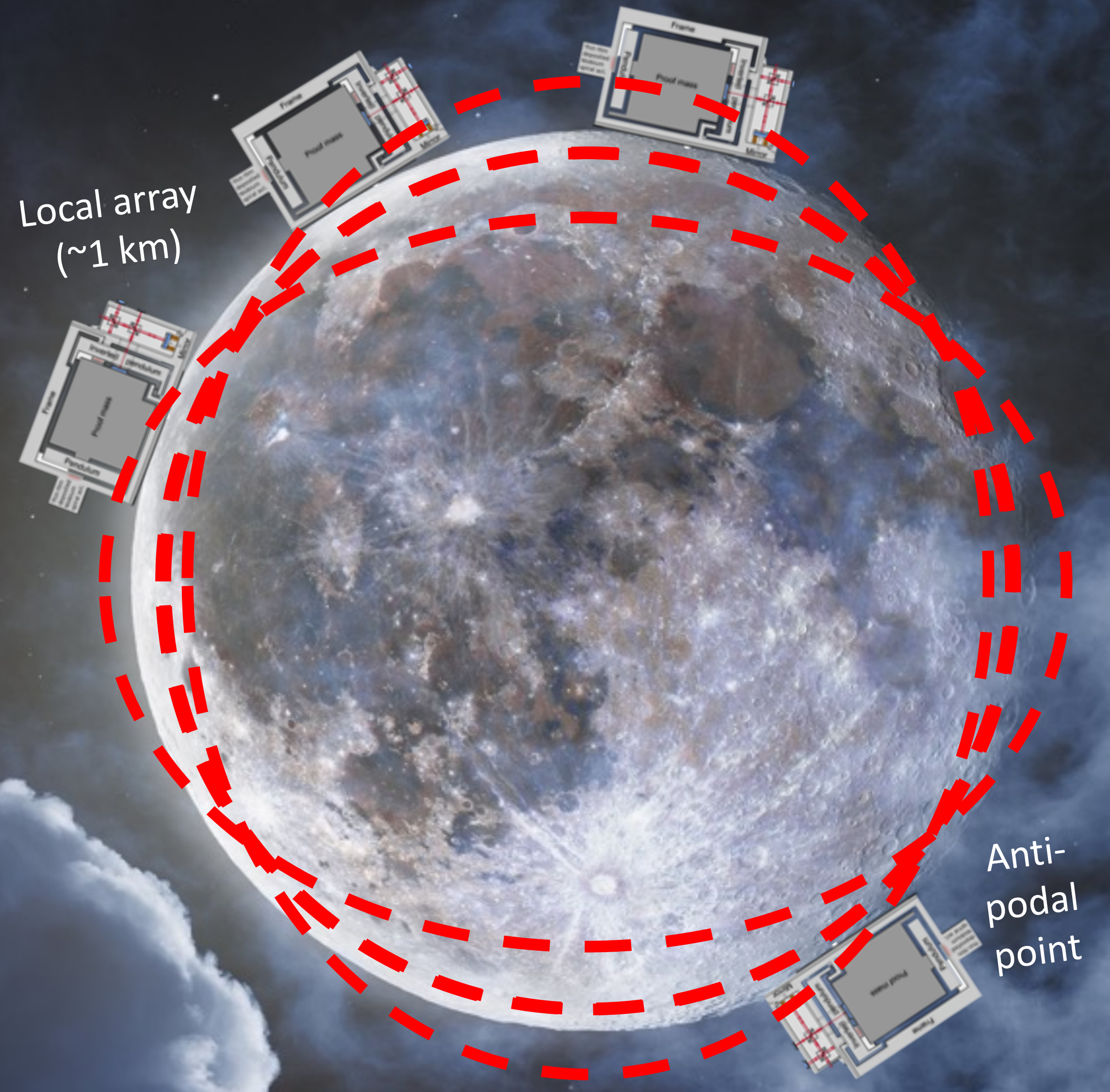
- ➢ Q is assumed much higher (Niobium & different actuator) and T is lower ➡ thermal noise 1/50th;
- ➢ And on the moon?!

Detecting gravitational waves on the moon

LGWA arXiv 2010.13726
(Lunar Gravitational Wave Antenna)



adapted from M Pitkin et al., 2011, Liv. Rev. Rel. 14(1):5



Bonus material for GW bingewatching in the lockdown

- LIGO: Journey of a G-Wave – Caltech
- Neutron star merger GWs and gamma rays – Veritassium
- Ripples of Gravity, Flashes of Light - Caltech
- How can we detect Gravitational Waves? – Nikhef
- Gravitational Waves research at Virgo: Lock Acquisition – Nikhef


Thank you!

Bonus slides

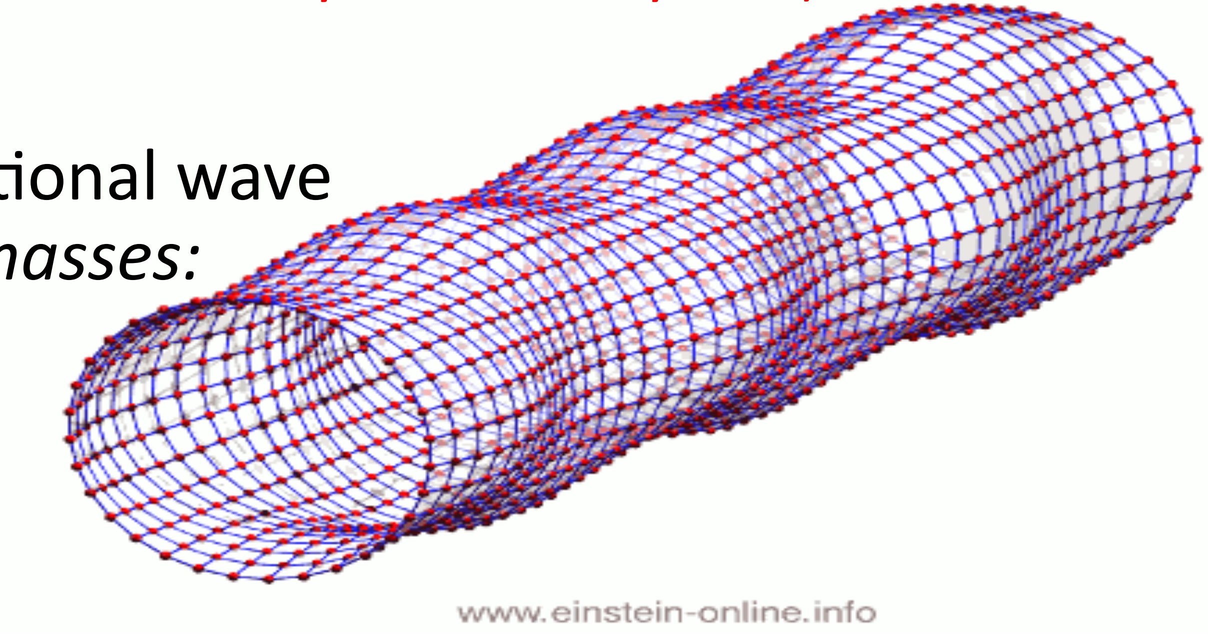
The effect of GWs on space-time and interferometers

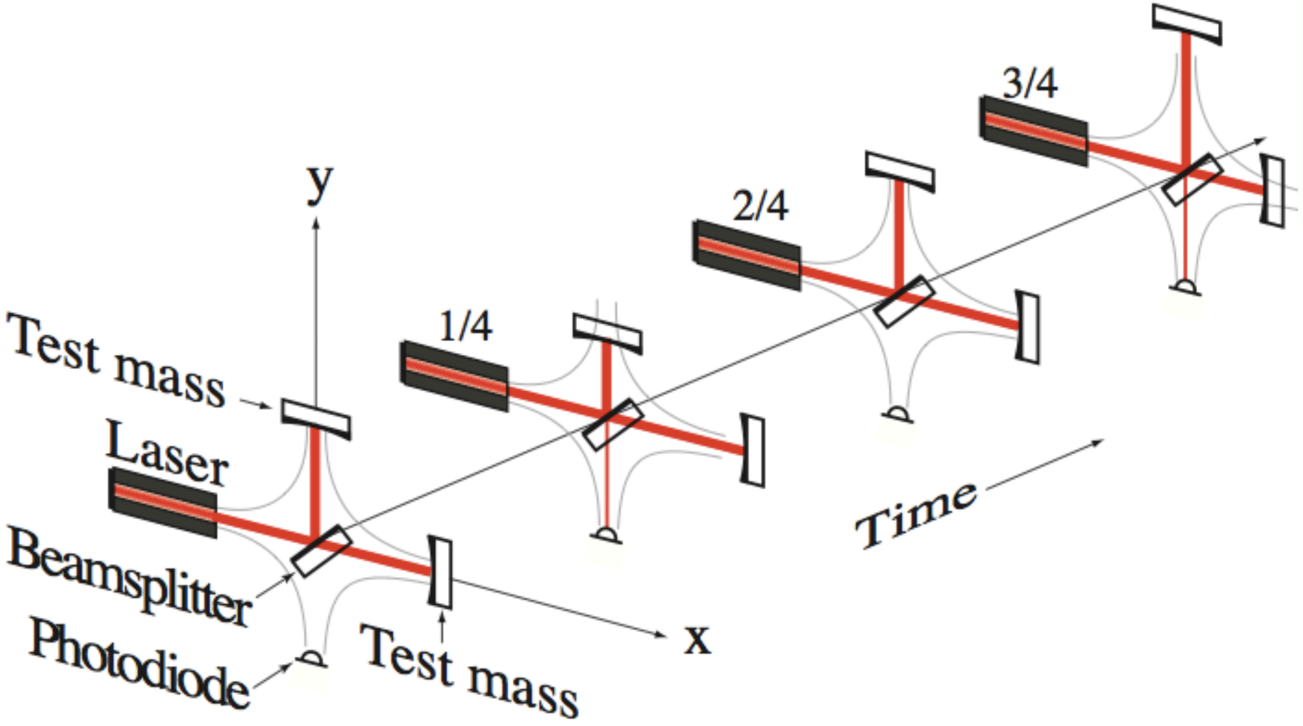
strain — quadrupole moment (accelerating masses in asymmertical system)

$$h \approx \frac{2G}{c^4}\frac{d^2Q}{dt^2}\frac{1}{d}$$, but

$$\frac{2G}{c^4} = 10^{-44}\, s^2 kg^{-1} m^{-1}$$

➢ Effect of a gravitational wave on a ring of *test masses:*

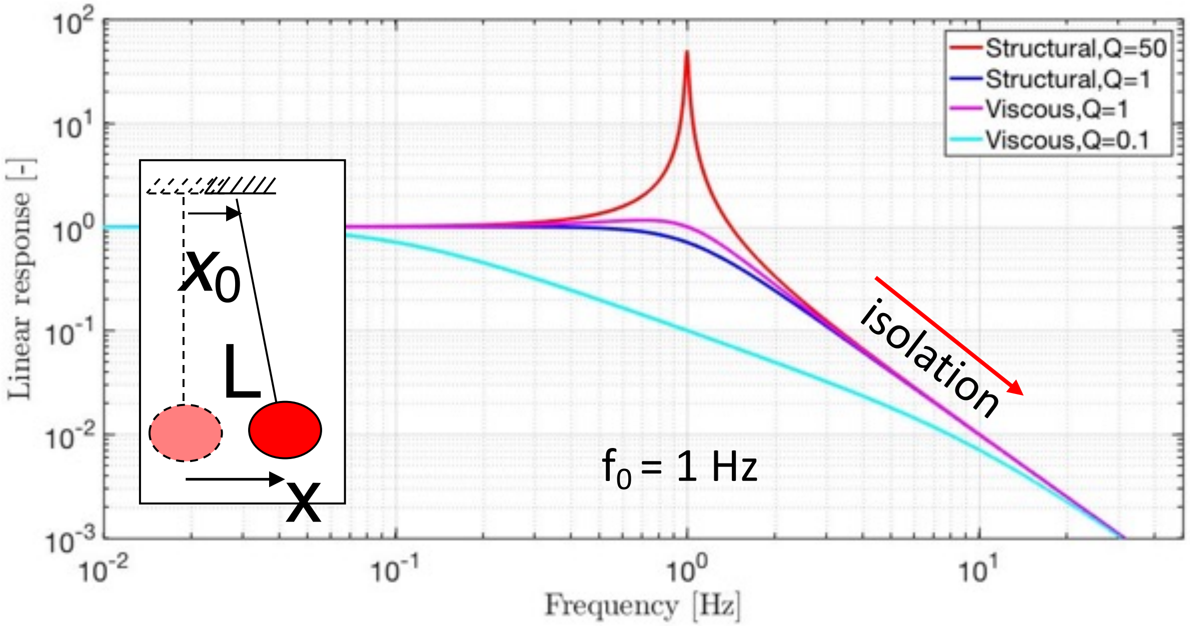


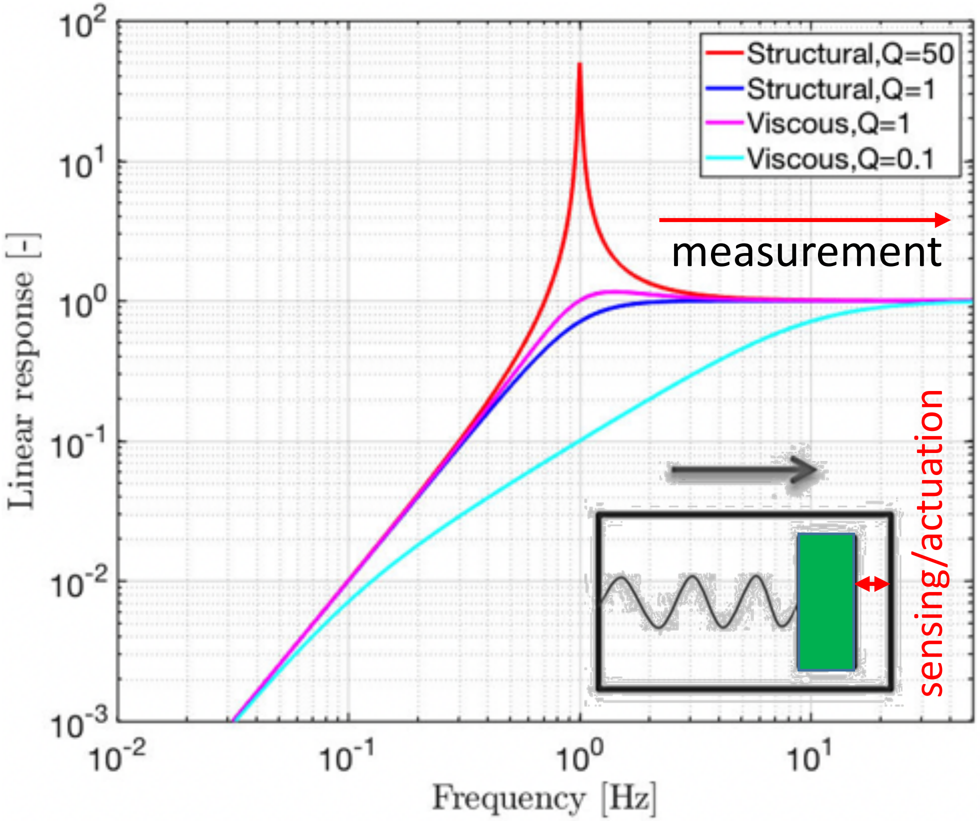


➢ Effect on an interferometer.

Seismic isolators and inertial sensors

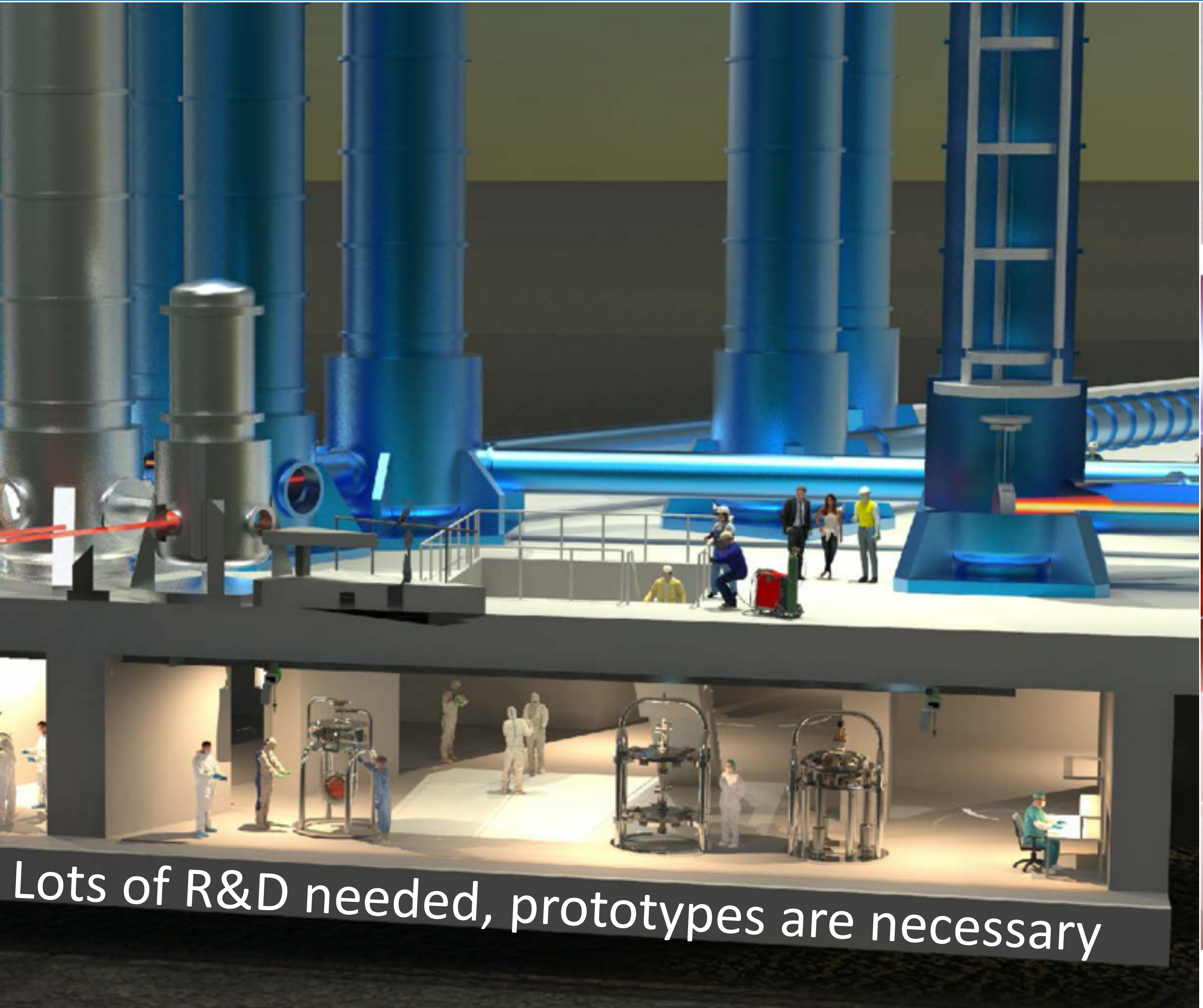
- ➢Seismic isolation and inertial sensors work as harmonic oscillators;
- ➢(Active) control is often needed to damp and DC position the suspended object;

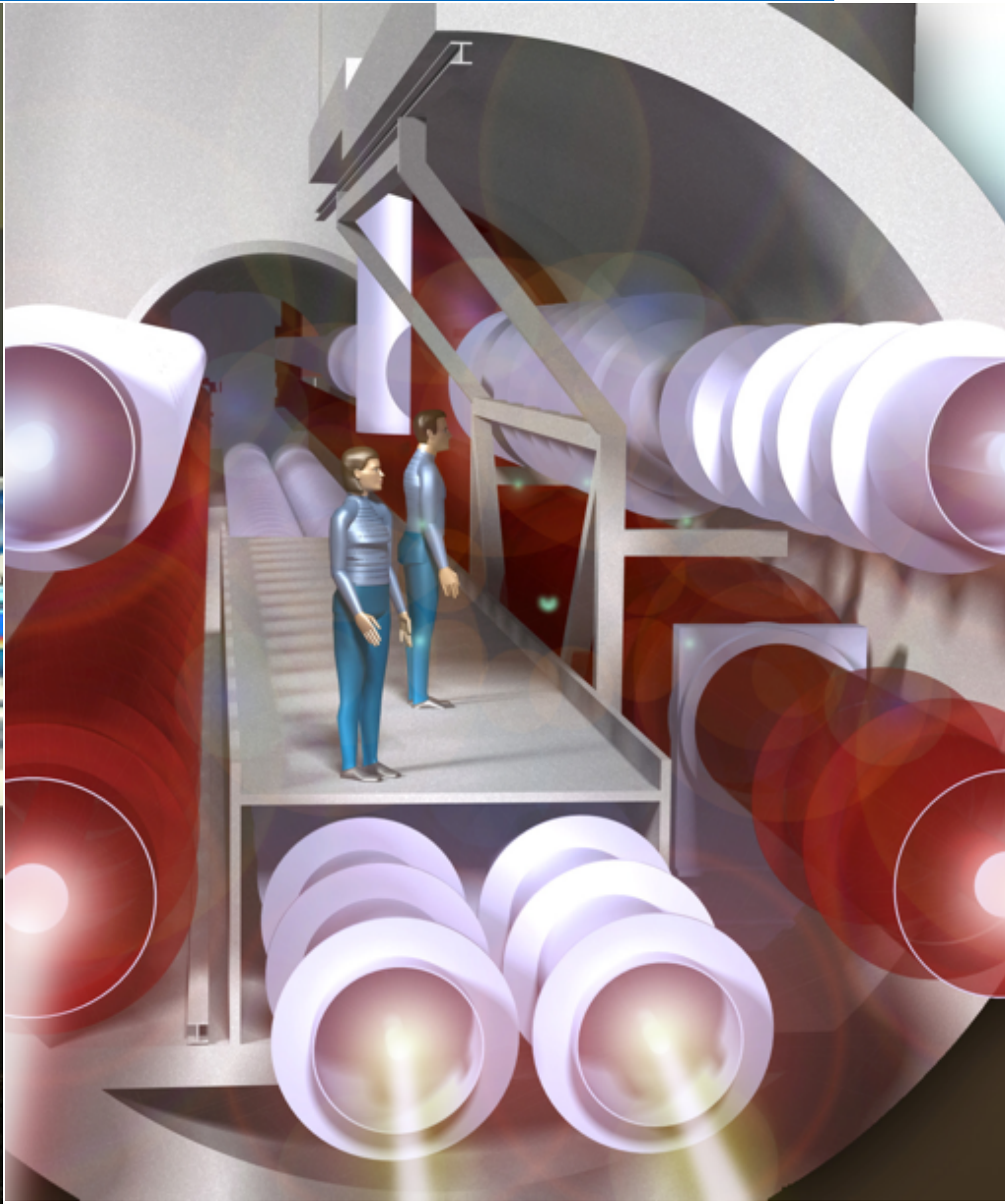




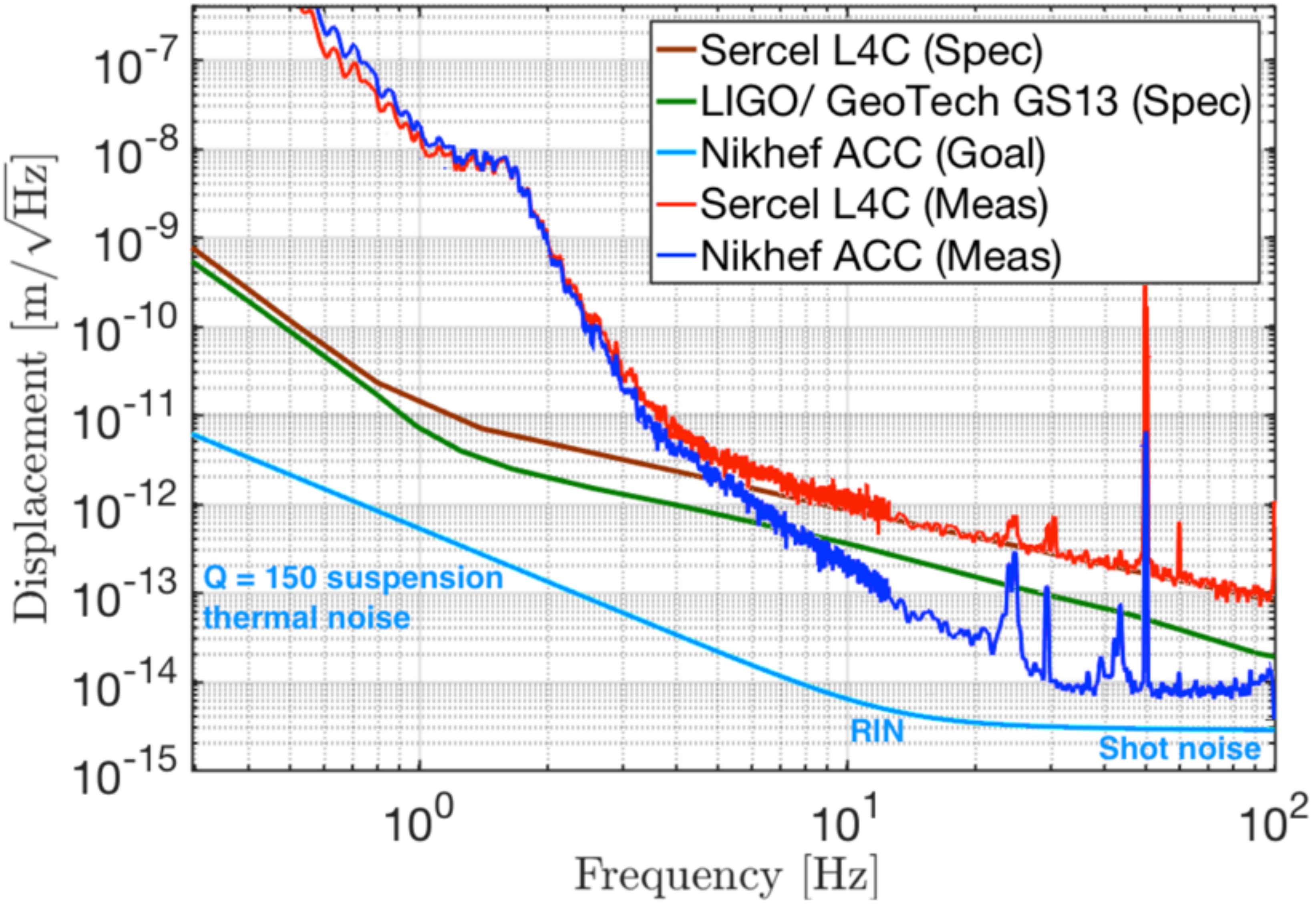
- ➢Looking at the relative motion between 'proof'-mass and frame, we see 1-to-1 meaurement amplitude above f_0;

Tunnels and Caverns





Room temperature version on suspensed bench



JVvH+, 2018, IEEE SAS proc., pp 76-80

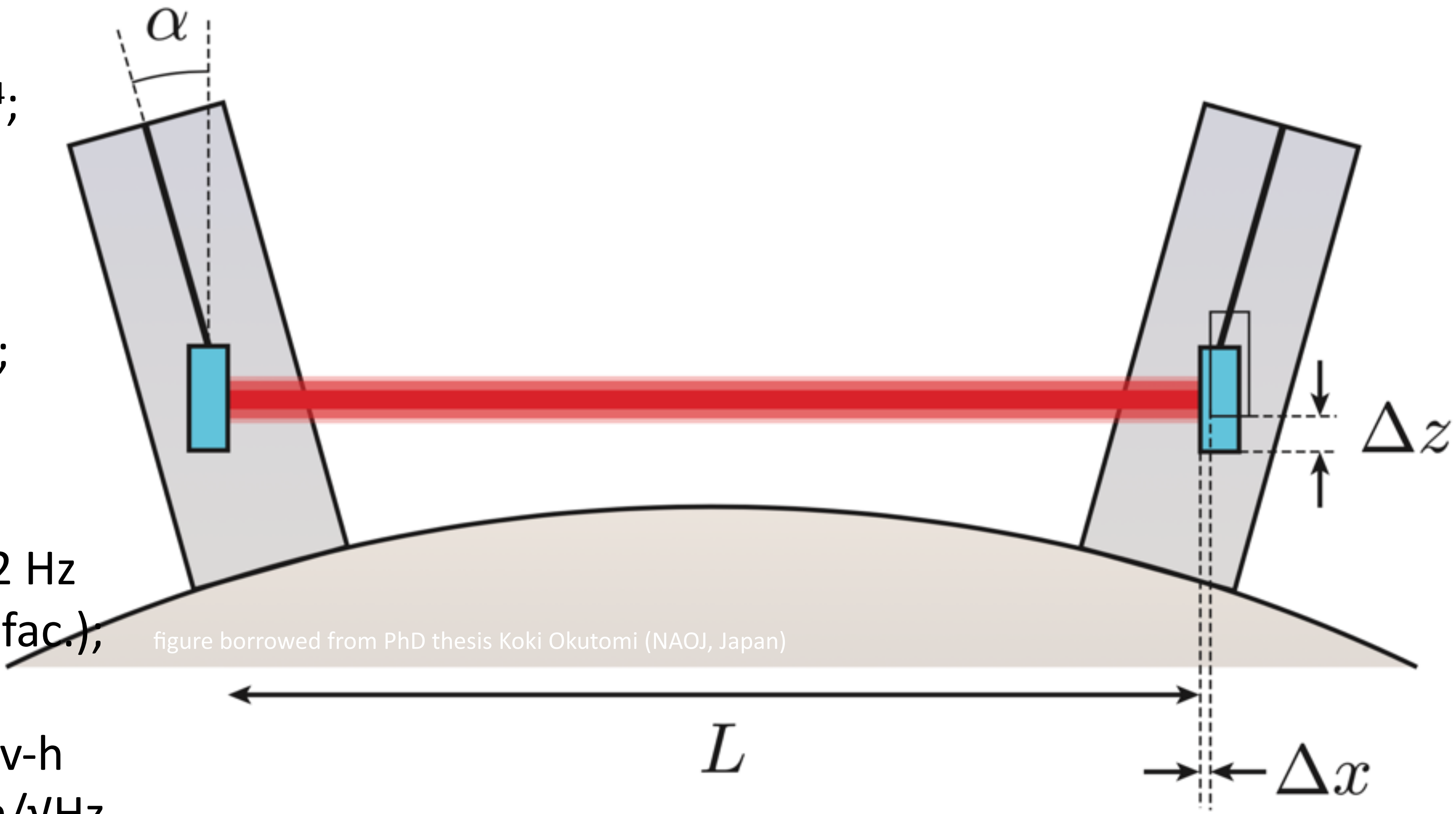
- Measurement done on bench MultiSAS prototype at Nikhef;

JVvH+, 2019, CQG 36 075007

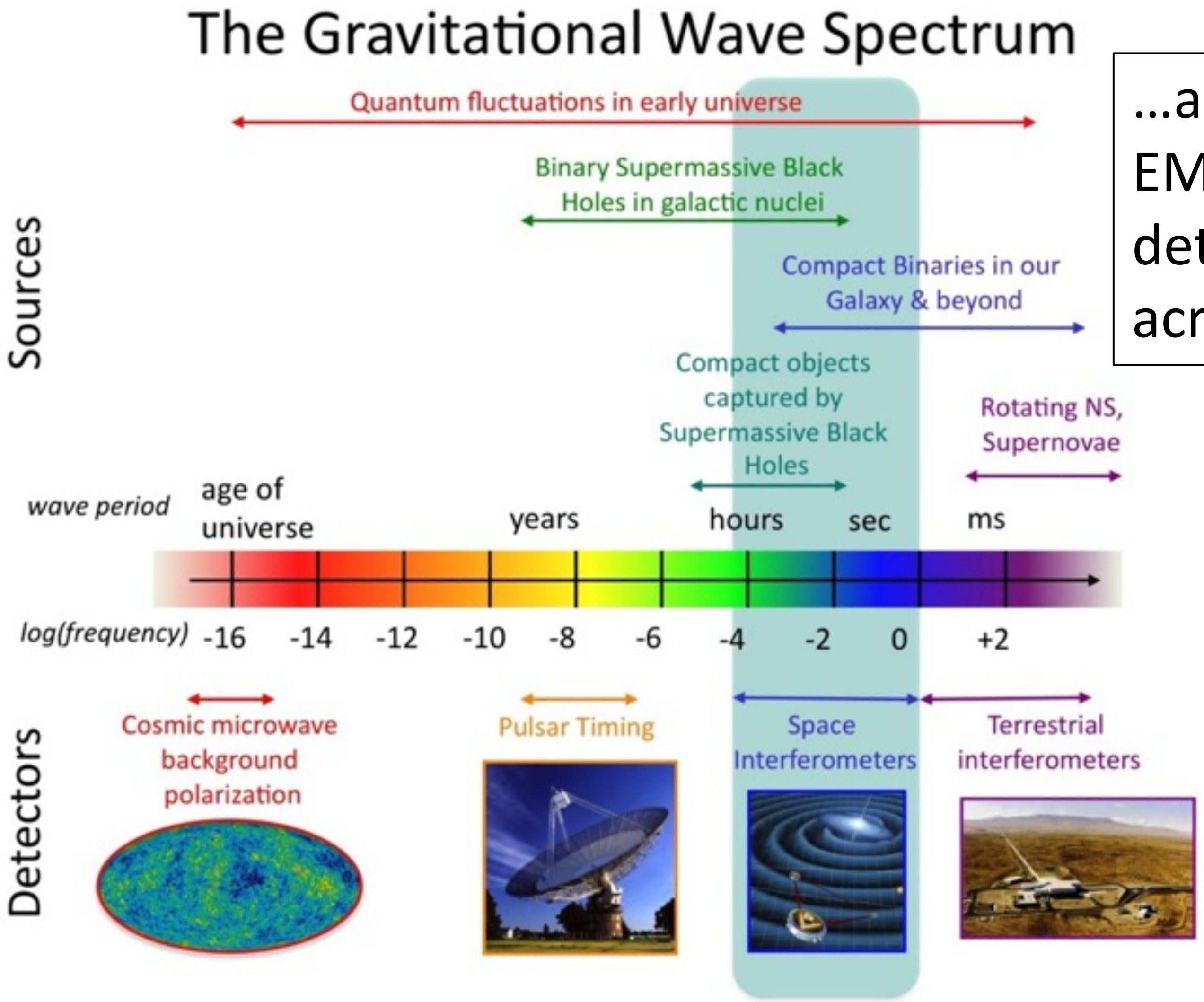
- 8 fm/√Hz observed sensitivity from 30 Hz onwards;
- Expected noise not reached and high thermal noise.

Why do we need vertical vibration isolation?

- For 3 km, $\alpha \backsim 2.4 \times 10^{-4}$;
- For 10 km, $\alpha \backsim 8 \times 10^{-4}$ (we can hold on to a 0.1% typical coupling);
- ET design requires at 2 Hz h = 10^{-23} 1/√Hz (10 sft.fac.);
- 10 km arms and 0.1% v-h coupling yields 10^{-16} m/√Hz.



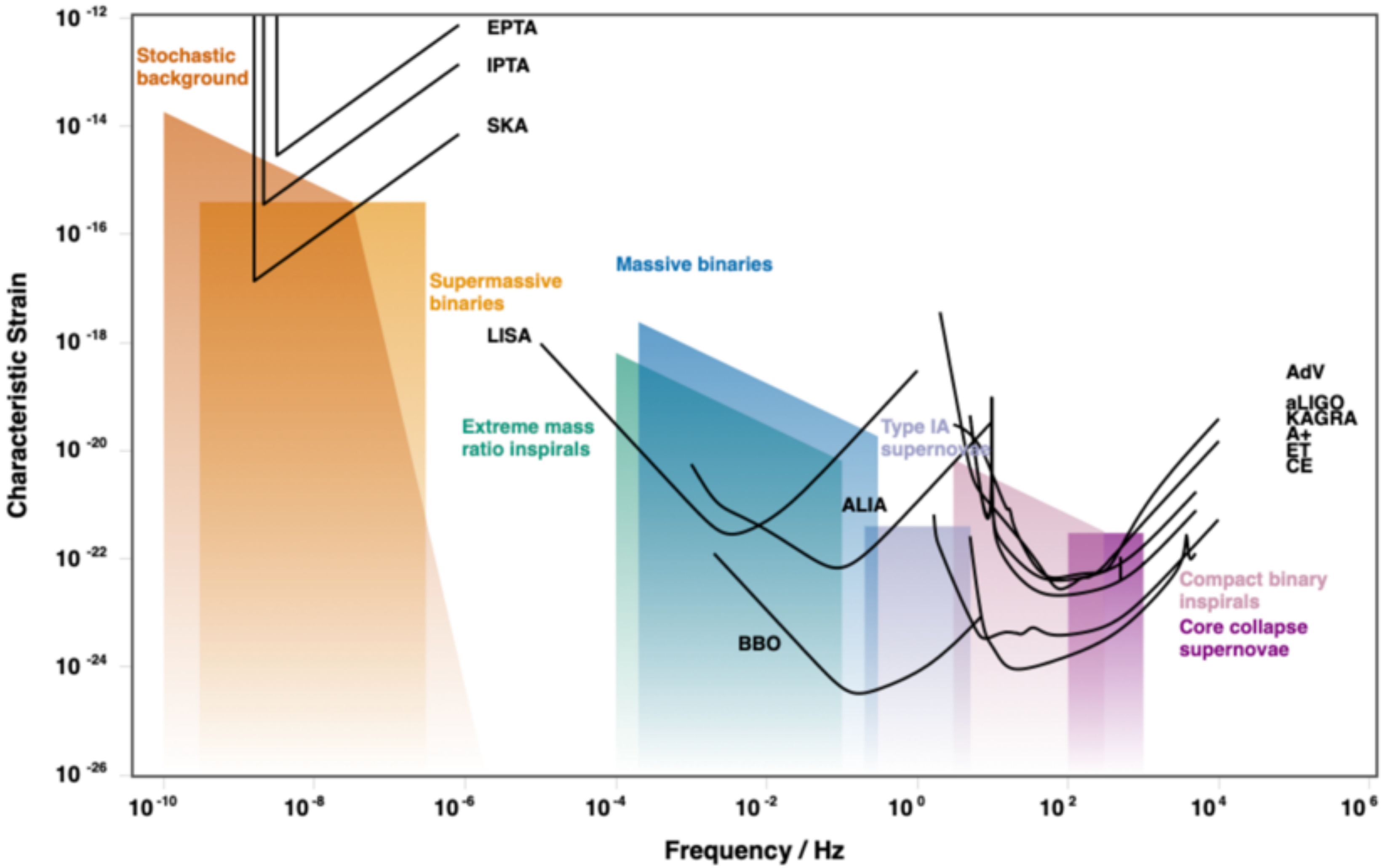
Just like EM waves, GWs have a spectrum



…and like the different EM waves, different detectors are used across the spectrum

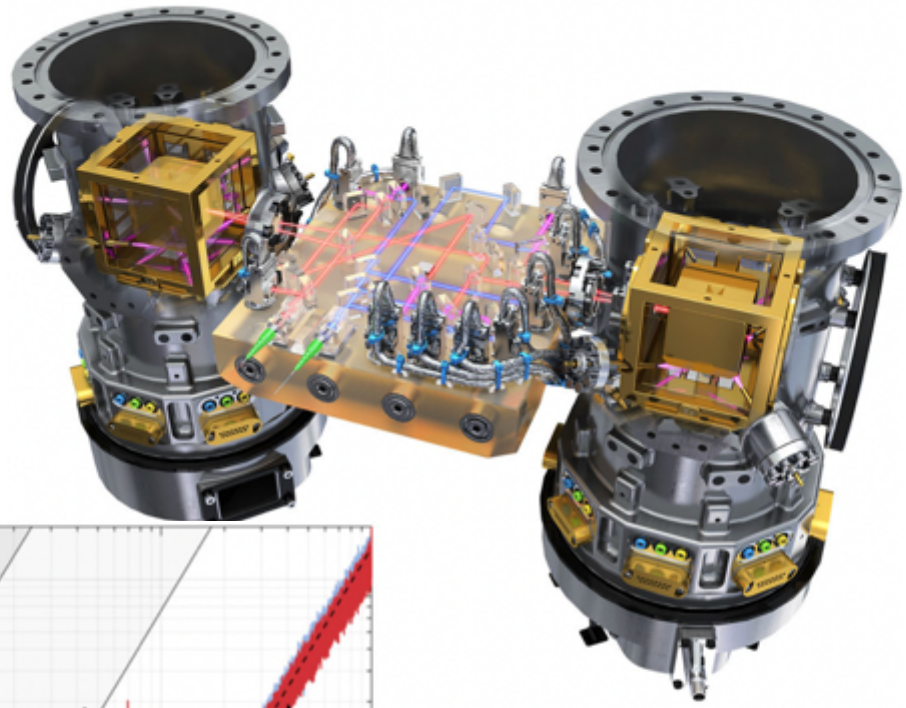
Different frequencies, different sources

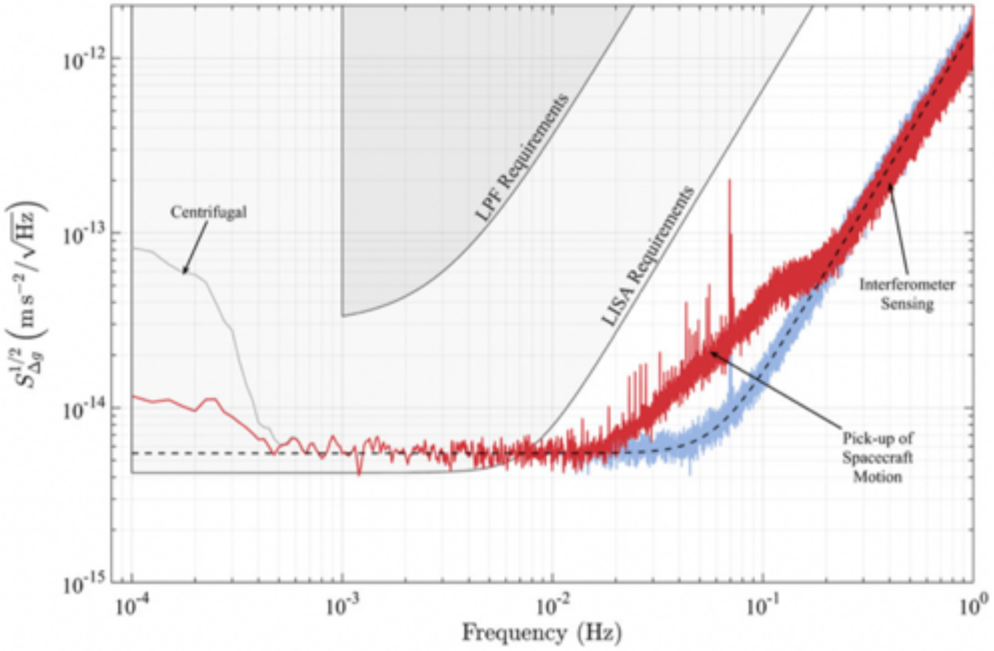
➢Make your own such plot at gwplotter.com



LISA path finder

- ➢Technology demonstrator for LISA – a huge success!
- ➢Surpassed path finder reqs and almost made LISA reqs!
- ➢After subtraction of centrifugal force and space craft motion, clean blue trace remains in acceleration spectrum

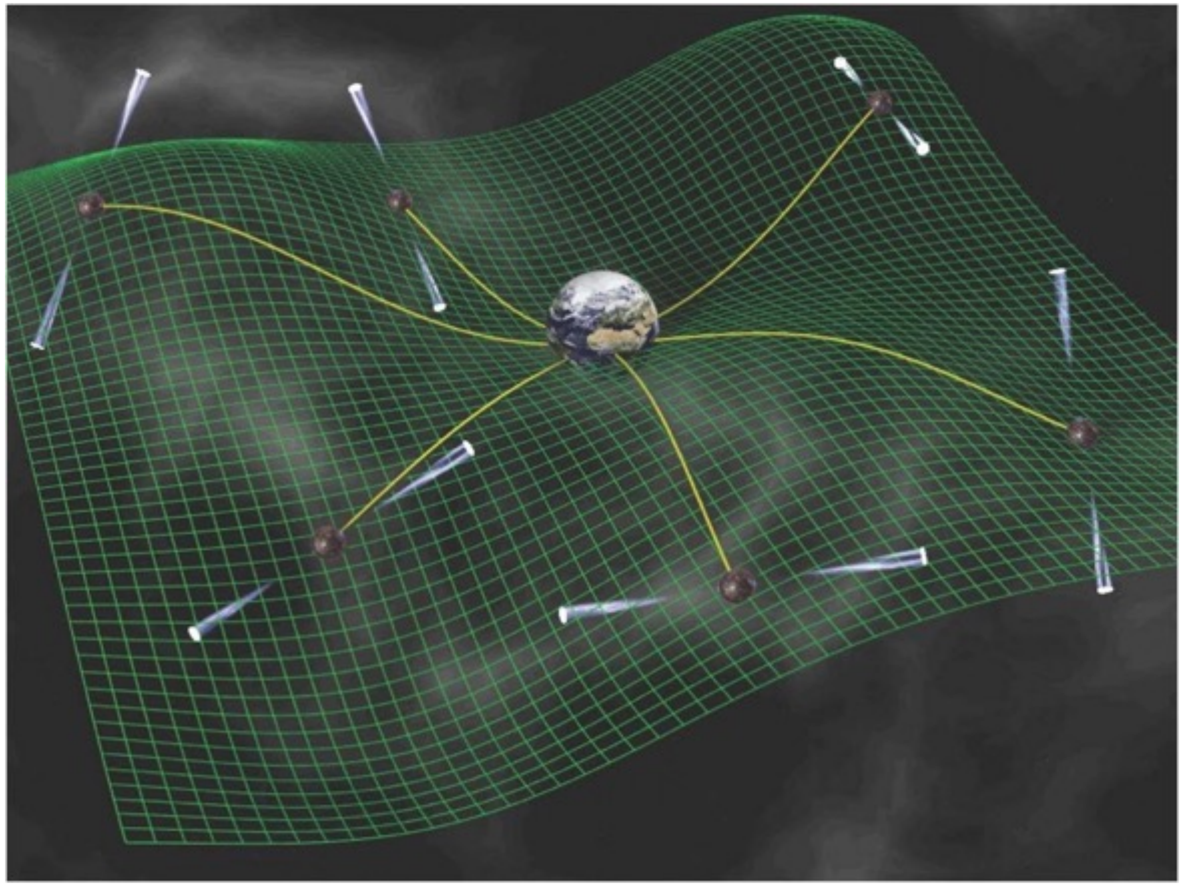


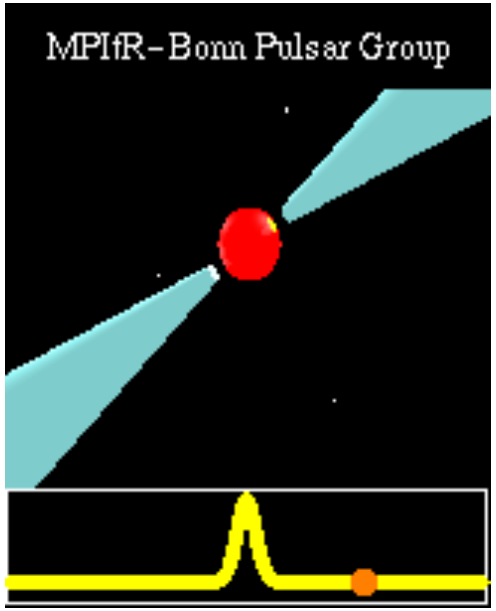


Optical setup with two TM cubes pack-aged in spacecraft

Even lower frequency: Pulsar timing arrays

- 1982: the first millisecond pulsar is discovered
- Foster & Backer (1990) showed how a comparison in timing from *multiple* millisecond pulsars could detect GWs

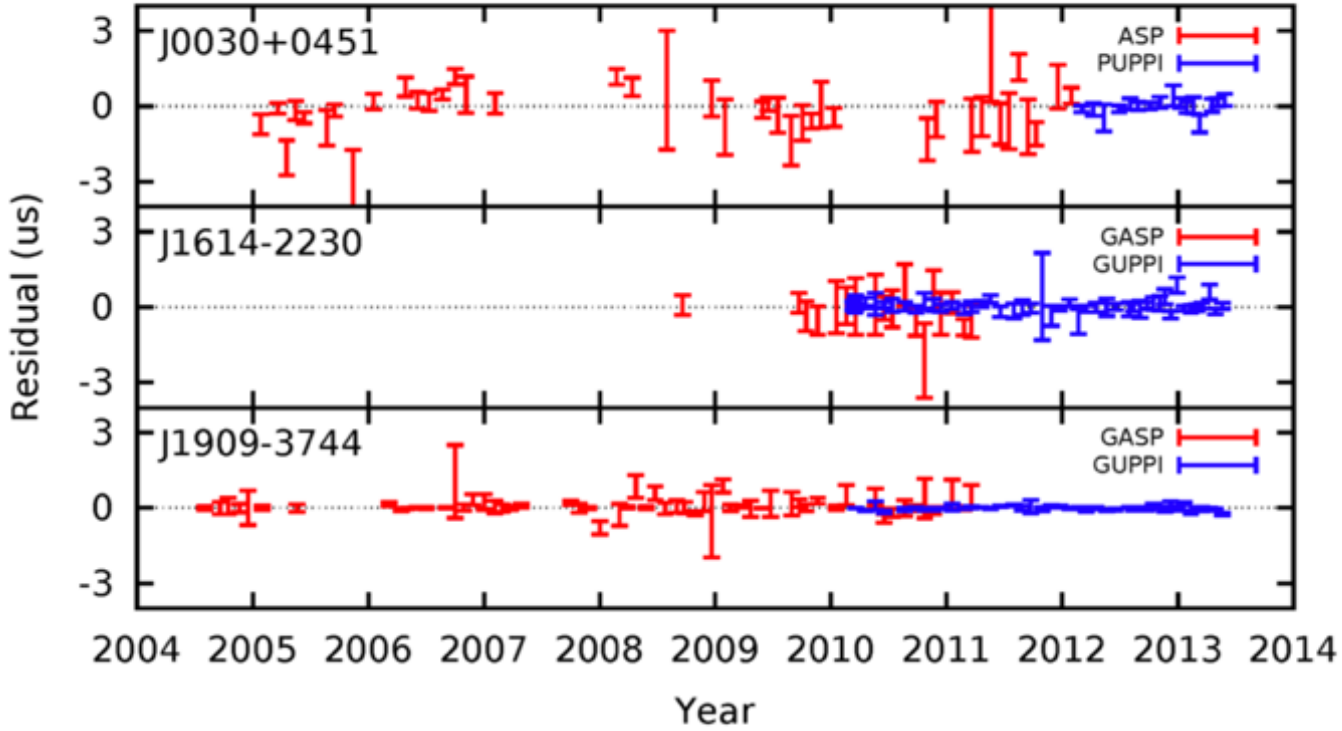




Timing should be extremely precise, but passing GW could influence arrival times of pulse

International Pulsar Timing Array (IPTA)

- ➢Parkes PTA (PPTA), European PTA (EPTA) and North American Nanohertz Observatory for Gravitational Waves (NANOGrav)
- ➢Combined array of about 30 millisecond pulsars, as spread over the sky as possible

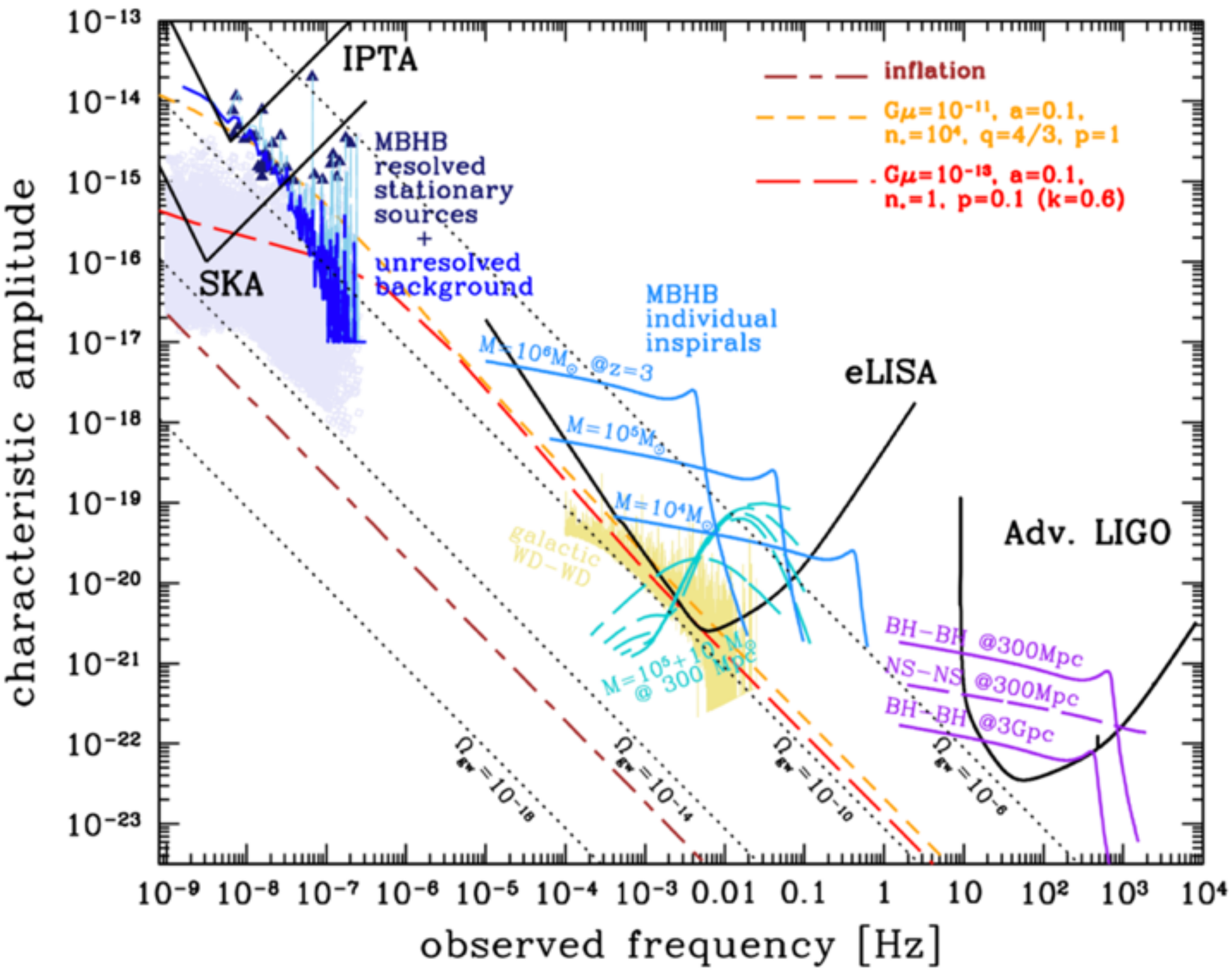


- ➢Frequency: upper limit set by cadence of observation (Nyquist theorem); lower limit by timespan of observations

What can we do with PTAs?

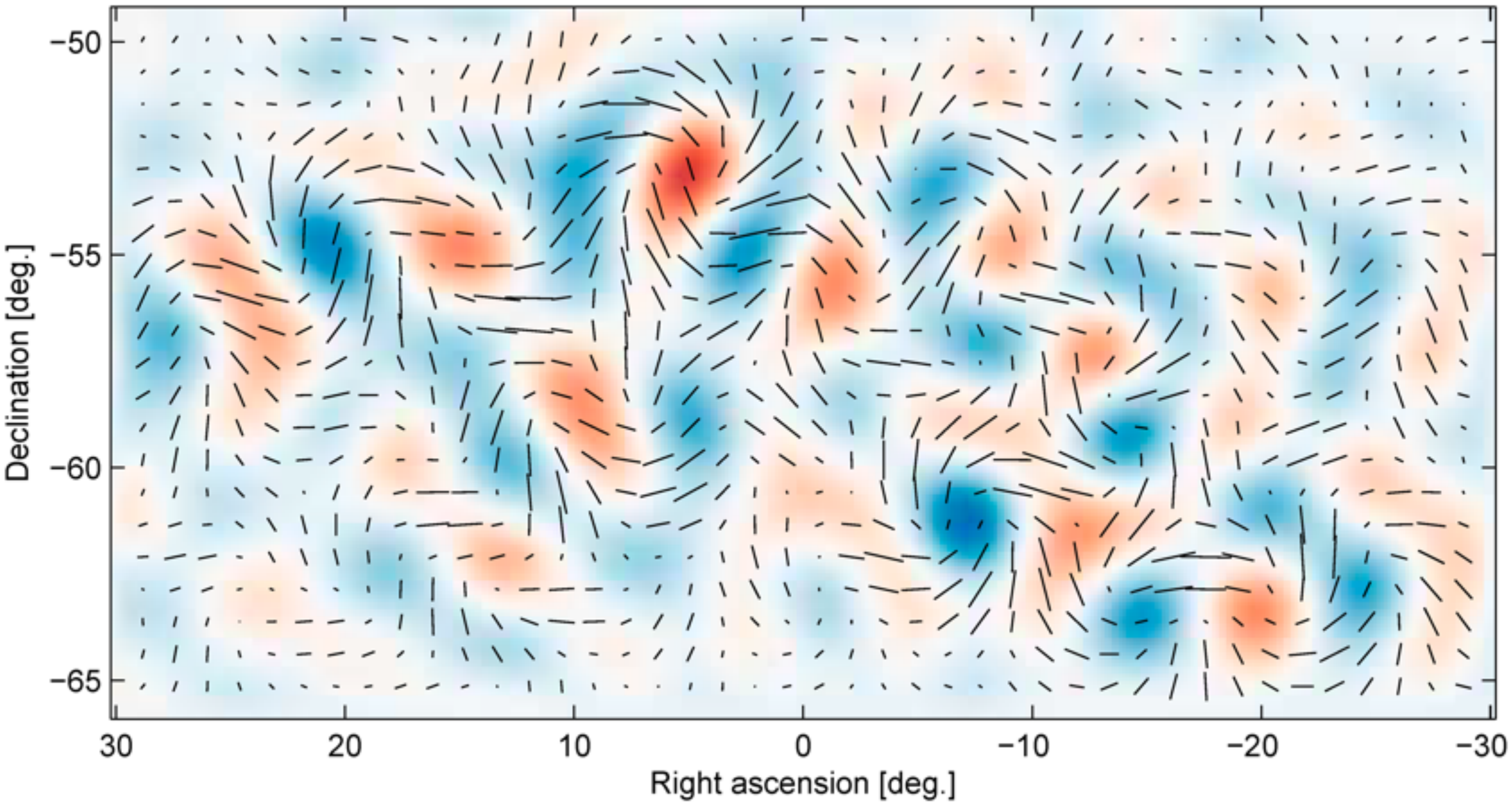
- ➢ 10^{-6} – 10^{-9} Hz (weeks to years)
- ➢ Supermassive BBH inspirals (>10^{7} M_{sol})
- ➢ Stochastic background supermassive inspirals

- ➢ You see the GW community is also waiting for SKA to come online!



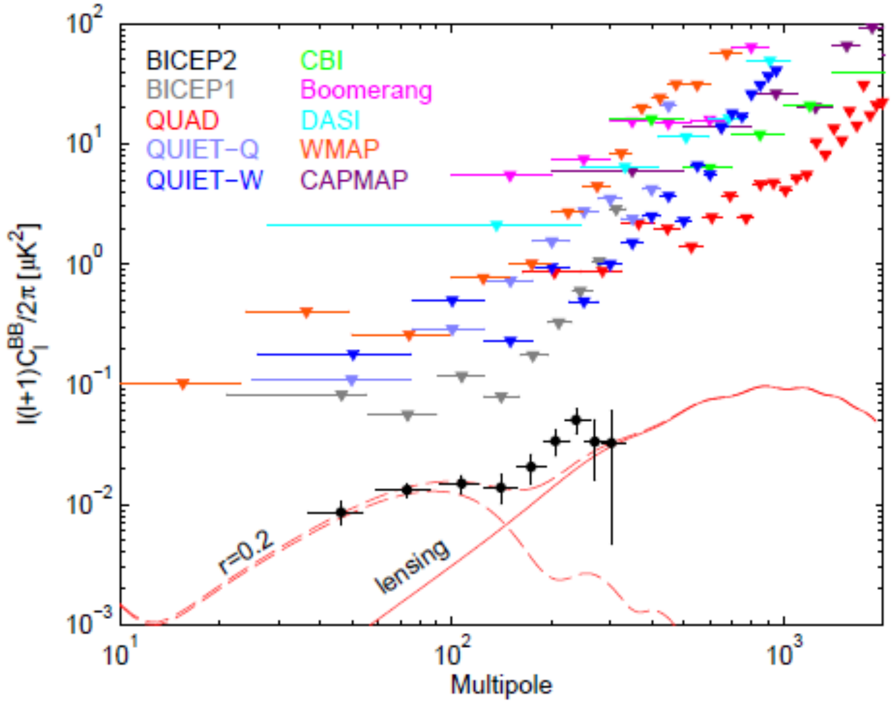
Imprints of inflation: CMB polarization

- Polarization from density perturbations in the early Universe
- Seen in so called B-modes (curl) in polarization maps



Was this not already found in 2014?

- ➢BICEP2, a telescope on the South pole claimed GW detection
- ➢Models of inflation predict that gravitational waves will source B-modes at angular scales of a degree or larger



- ➢Turned out to be the effect of interstellar dust when properly studying the PLANCK data (they didn't wait for that, lesson learned)

What signals do we find in the MHz regime?

- Thermal gravitational radiation from stars
- GWs from low mass primordial black holes
- GW background from quintessential inflation
- Parametric resonance at the end of inflation or preheating
- Clouds of axions