Cryogenic Challenges for Third Generation Gravitational Wave Interferometers

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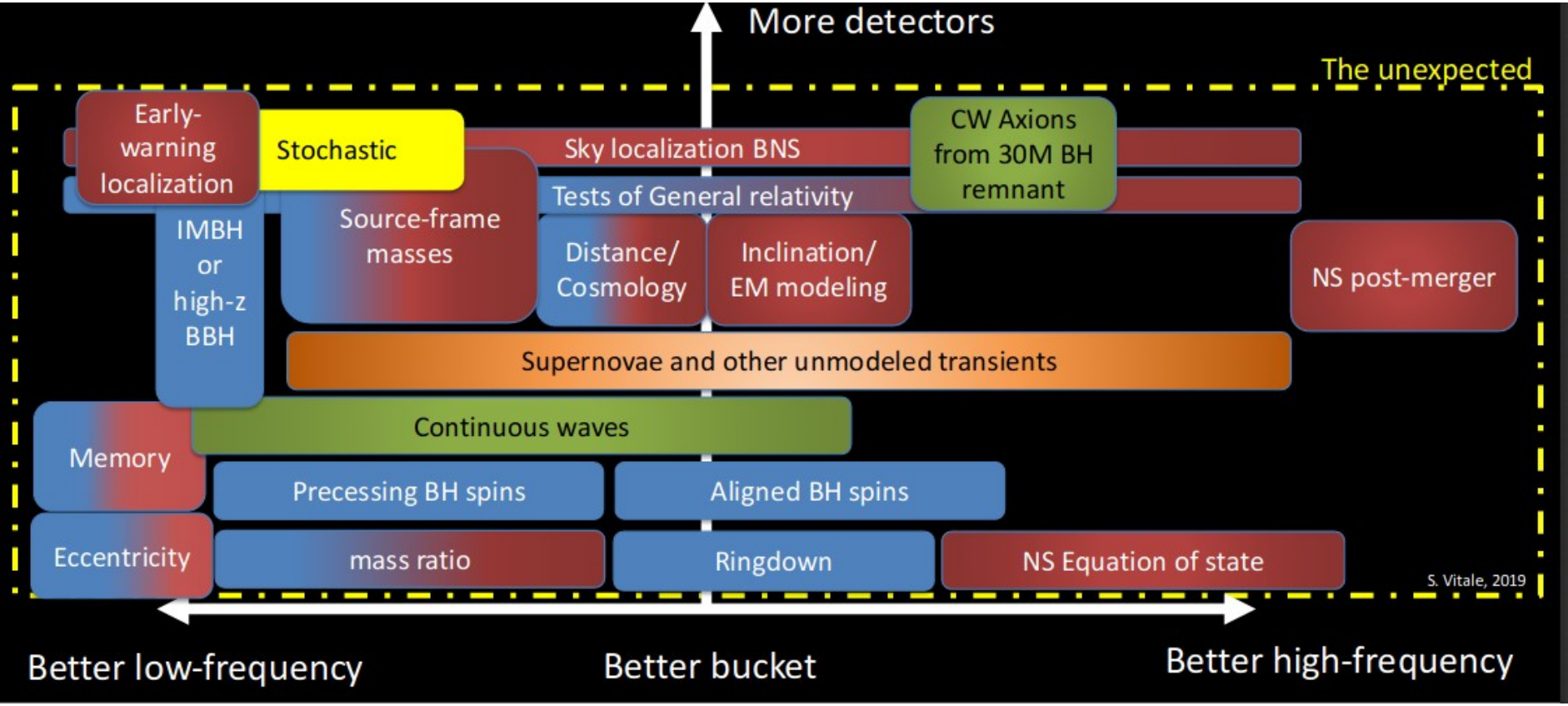


S. Vitale, G1900660

Suspension systems and thermal noise

Thermal noise power spectral density (Saulson 1990):

$$x^2(\omega) = \frac{4k_B T k \phi(\omega)}{\omega[(k - m\omega^2)^2 + k^2\phi^2]}$$

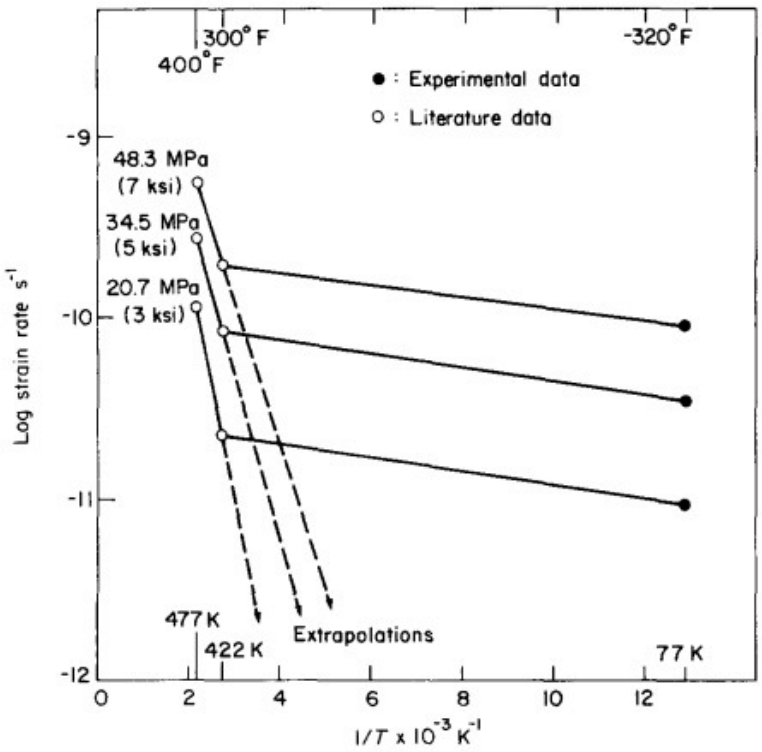
Materials with low mechanical loss

Operation at low temperatures

Materials, components and systems → UHV and cryogenic compatible

Large scale apparatus

Behavior of materials at cryogenic temperatures generally cannot be extrapolated from the room temperature properties →
Long term testing at the operation temperature



Annealed OFHC, Yen+ 1984

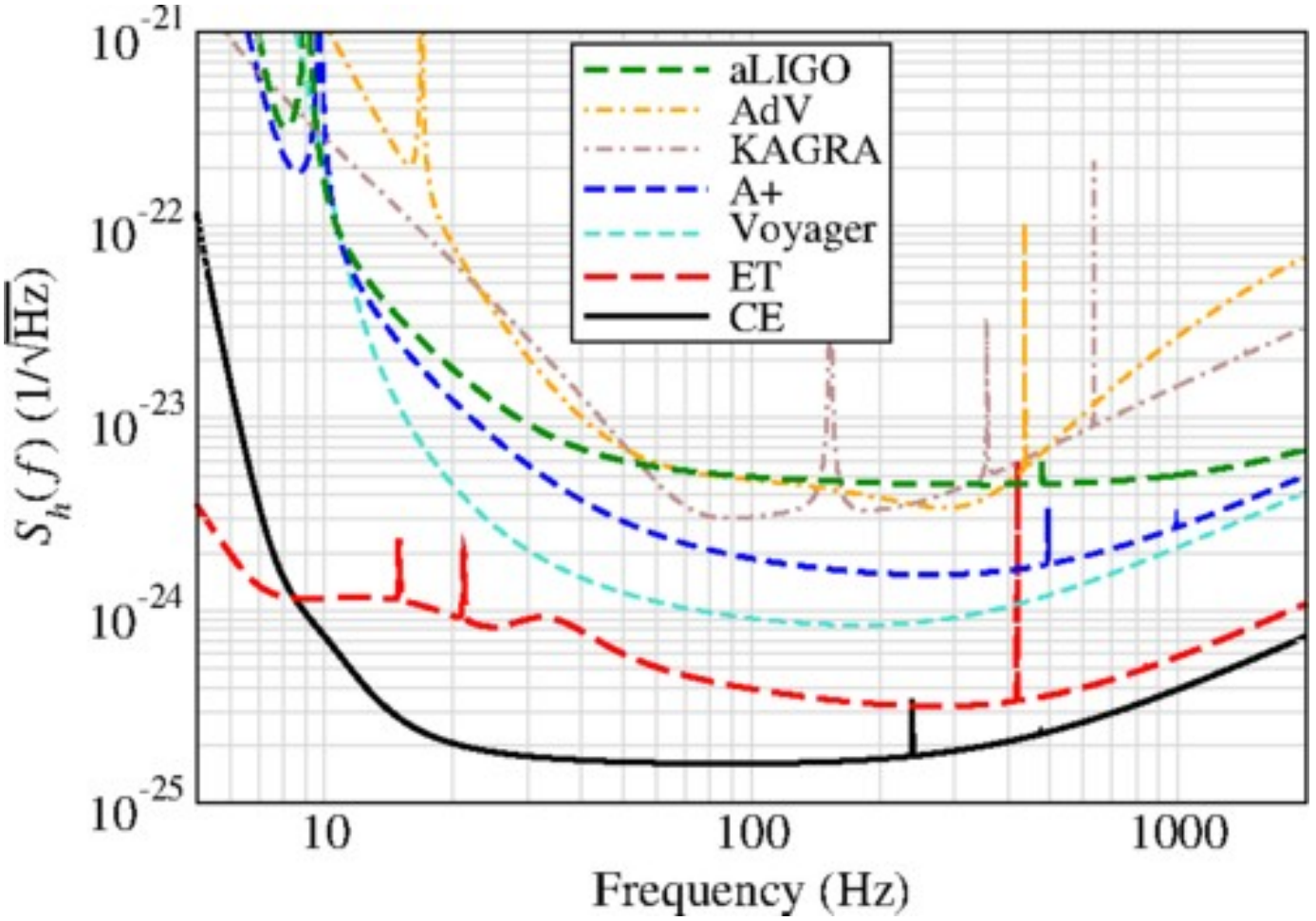
	aLIGO / AdV	A+/V+	KAGRA	CE 1	CE 2	ET-LF	ET-HF
Arm Length [km]	4 / 3	4	3	40	40	10	10
Mirror Mass [kg]	40 / 42	40	23	320	320	211	200
Mirror Material	silica	silica	sapphire	silica	silicon	silicon	silica
Mirror Temp [K]	295	295	20	295	123	10	290
Suspension Fiber	0.6m/0.7m SiO2	0.6m SiO2	0.35m Al2O3	1.2m SiO2	1.2m Si	2m Si	0.6m SiO2
Fiber Type	Fiber	Fiber	Fiber	Fiber	Ribbon	Fiber	Fiber
Input Power [W]	125	125	70	150	220	3	500
Arm Power [kW]	710 / 700	750	350	1400	2000	18	3000
Wavelength [nm]	1064	1064	1064	1064	1550	1550	1064
NN Suppression	1	1	1	10	10	1	1
Beam Size [cm]	(5.5/6.2) / 6	5.5/6.2	3.5/3.5	12/12	14/14	9/9	12/12
SQZ Factor [dB]	0	6	foreseen	10	10	10	10
F. C. Length [m]	none	300	unknown	4000	4000	10000	500

Einstein Telescope Pathfinder

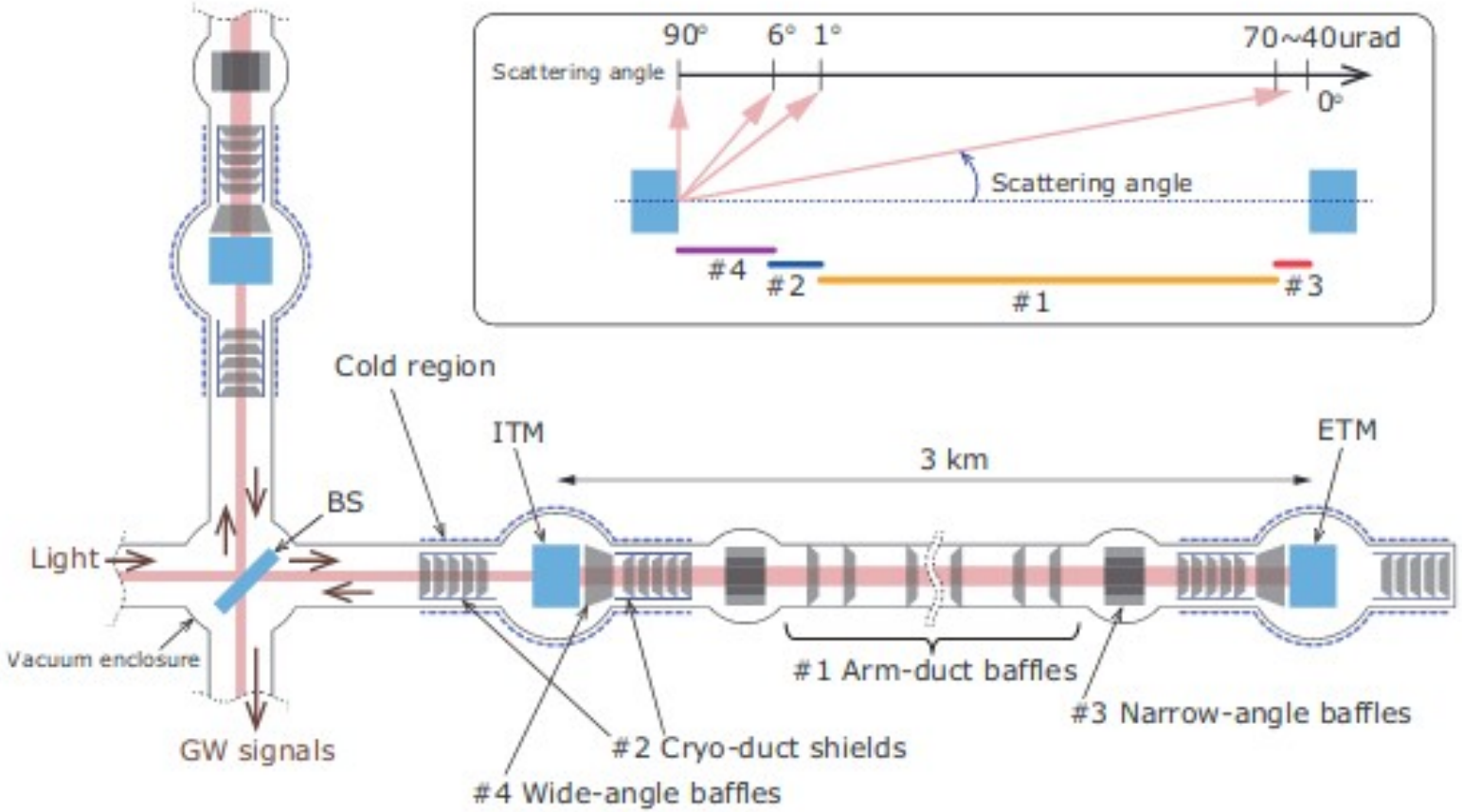
Lueck, GWADW2019

40 m Caltech interferometer

Different cryogenic regimes → 10K, 20K, 120 K



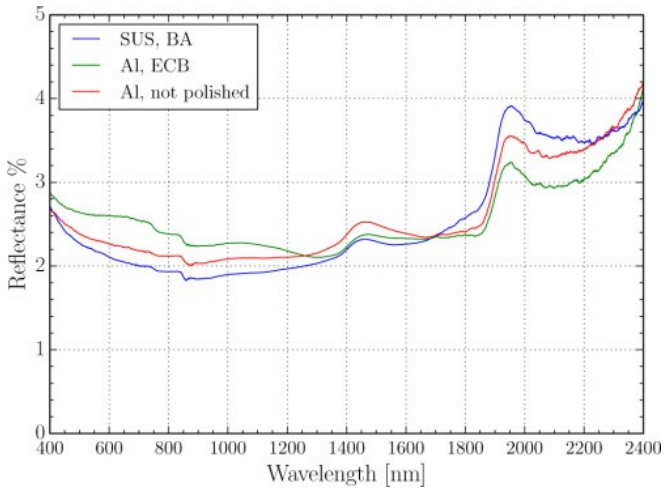
PRL 118 (2017) 151105

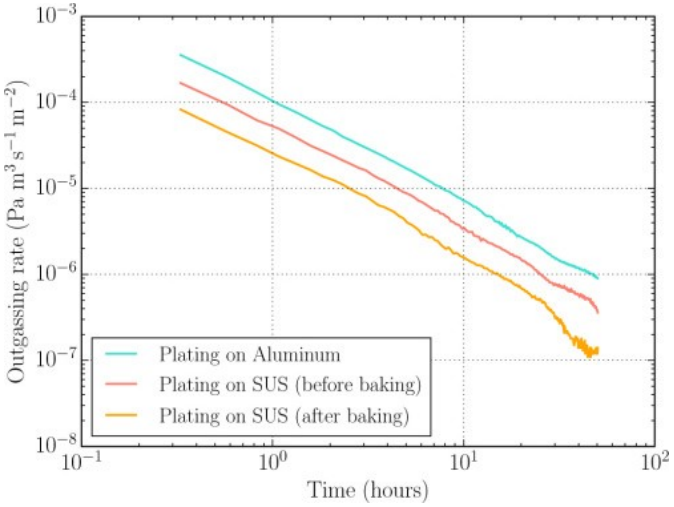

90°
6°
1°
70~40urad
Scattering angle
0°
Scattering angle
#4
#2
#1
#3
Cold region
ITM
3 km
ETM
BS
Light
Vacuum enclosure
GW signals
#1 Arm-duct baffles
#3 Narrow-angle baffles
#2 Cryo-duct shields
#4 Wide-angle baffles

KAGRA

Baffles

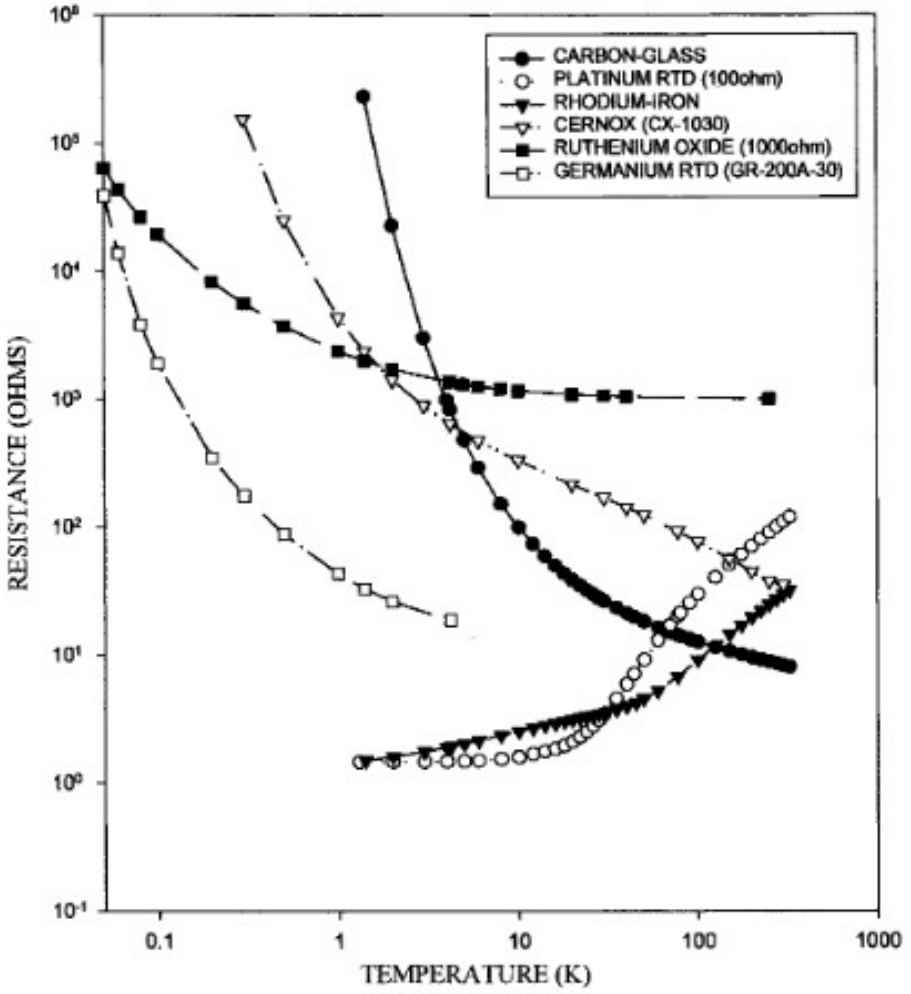
Requirements: low reflectance, low scattering and low outgassing, usable down to 20 K





Akutsu+ 2016, electroless NiPW plating

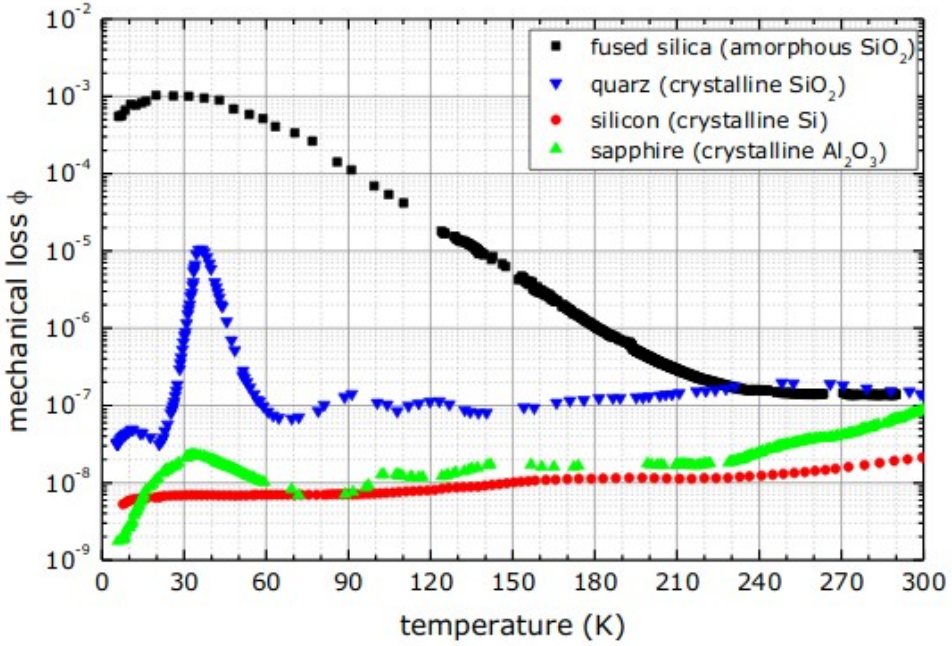
Thermometry



Yeager & Courts 2001

Mirrors and coatings

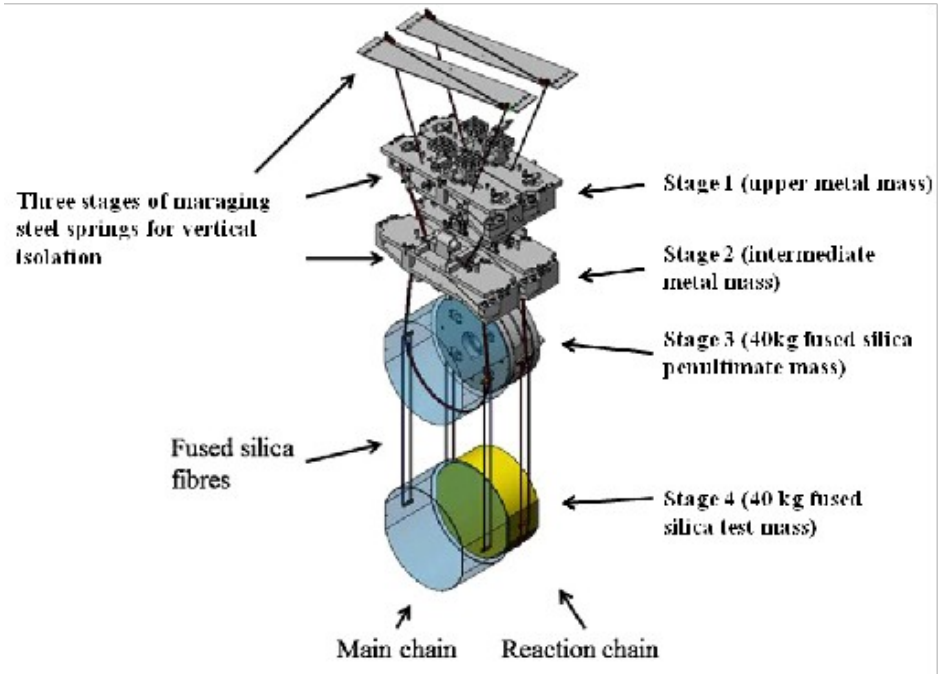
Bulk thermal noise: Brownian noise, thermoelastic noise

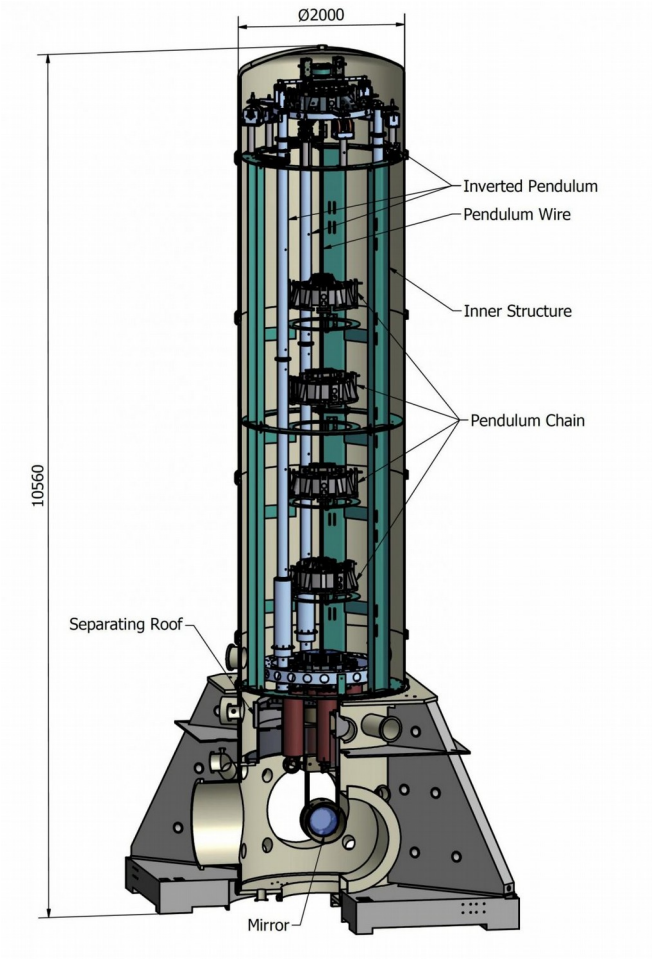


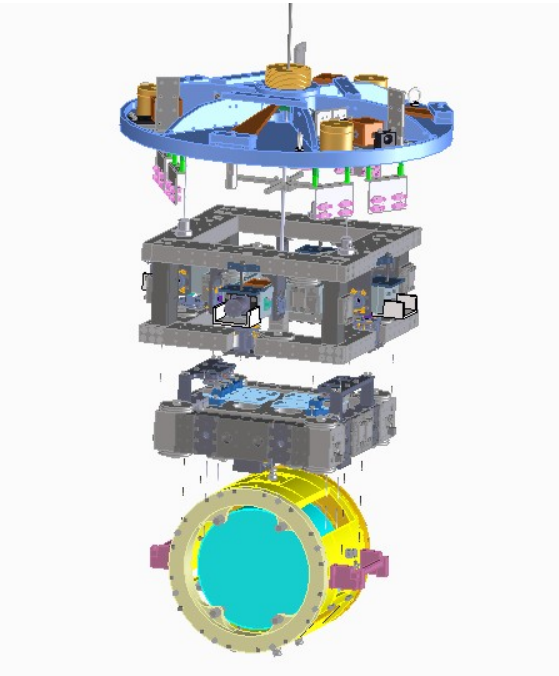
Hofmann GWADW2013

Coating thermal noise: Brownian, thermo-refractive, thermoelastic

Several coating solutions under investigation (talks at this conference)



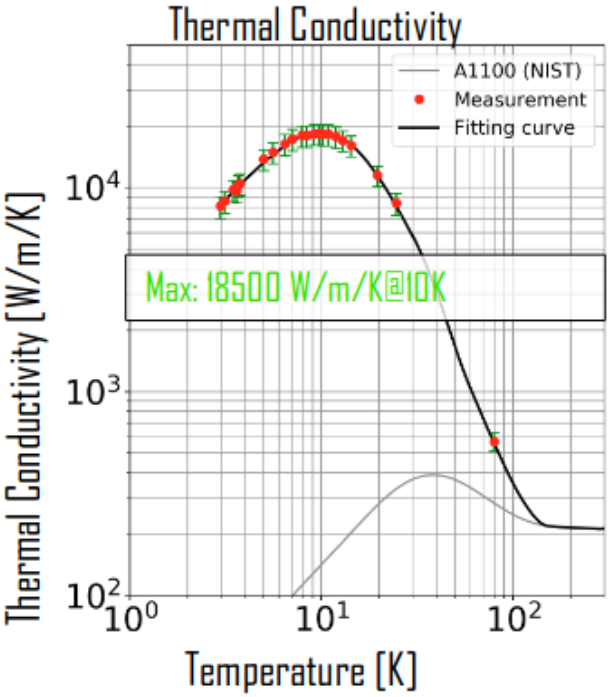


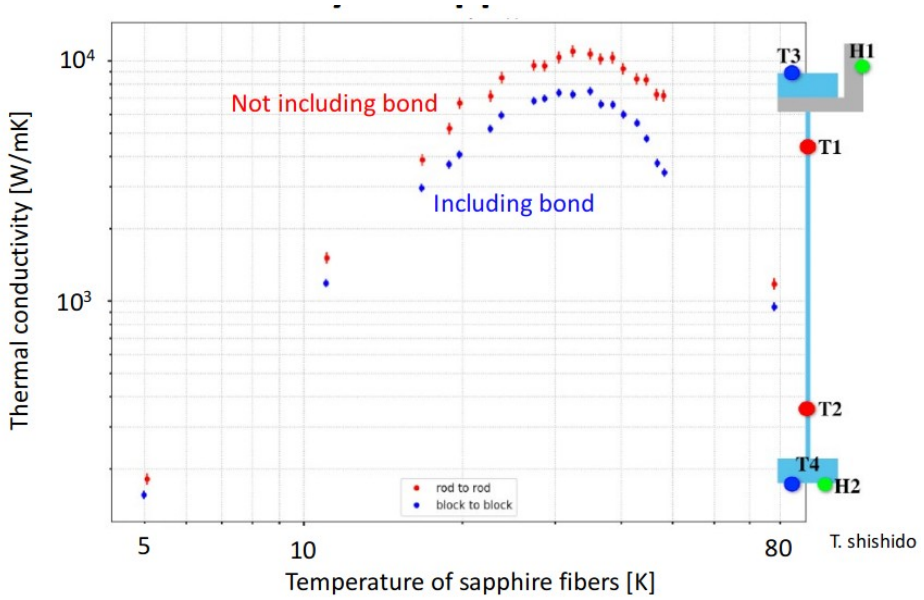


Suspension systems: pendulums, cantilevers, actuators, coils, glued magnets, cables (RP, ET-026-09)

Fundamental properties of materials

Thermal conductivity: heat link, fiber





KAGRA, GWADW2019

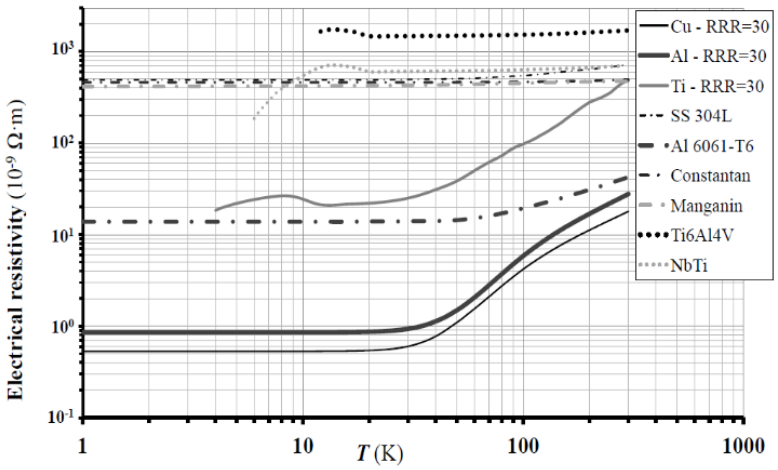
Thermal expansion: mechanical stress, mirror heating, different expansion of bonded components

Cabling

Signal cabling, power cabling, coils, LVDTs….

Requirements: low thermal conductivity, low electrical resistivity, high flexibility, low outgassing, robustness against thermal cycling

Conductors



Insulation: Kapton, Pyre-ML, Gore-Tex, alumina (tested in Virgo at RT)

Optimization of conductor size

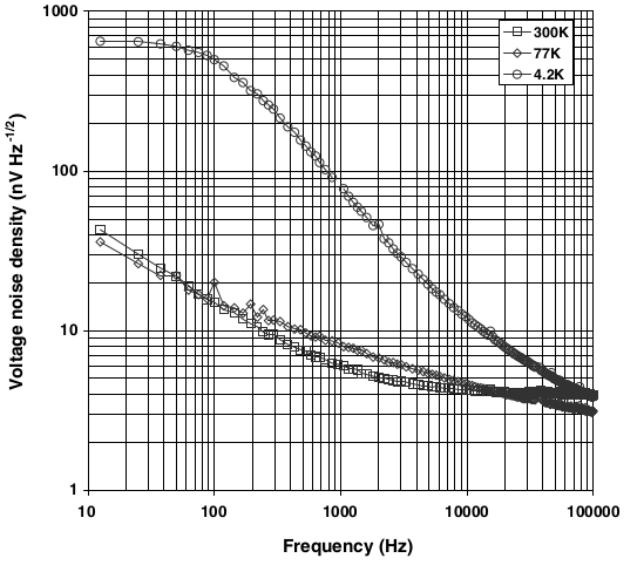
$$\frac{L}{A} = \int_{T_L}^{T_H} \frac{k(T)dT}{\sqrt{Q_H^2 + I^2 \int_T^{T_H} 2\rho(\tau)k(\tau)d\tau}}$$

Mechanical modeling necessary, as in T0900627

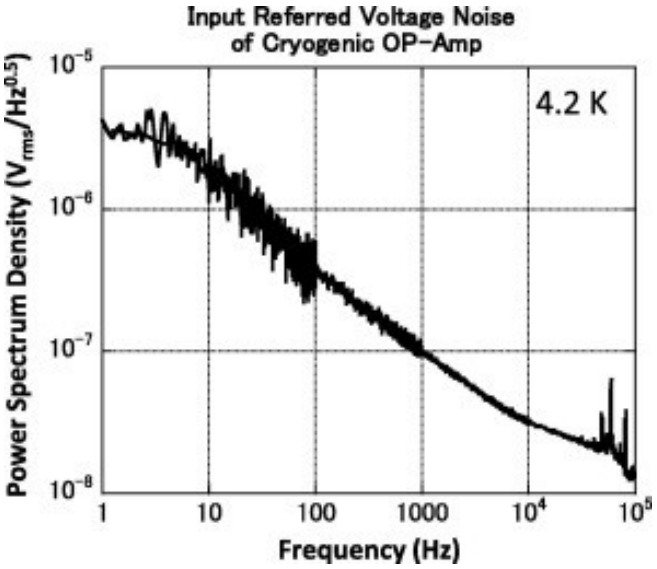
Low temperature electronics

Requirements: low dissipation, low outgassing, robustness against thermal cycling

Commercial components available



Vindrych+ 2008, AD8651 CMOS amplifier



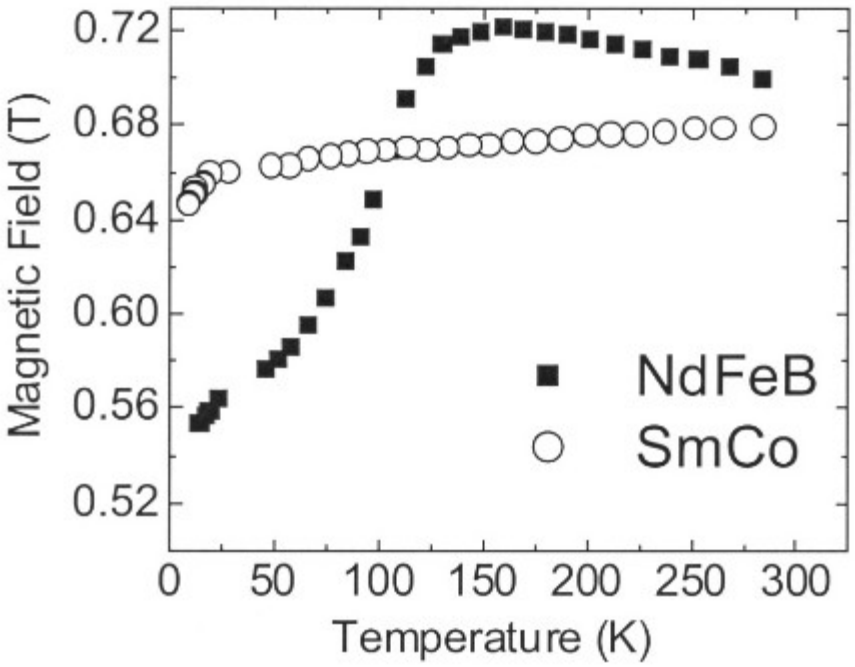
Hibi+ 2016, GaAs JFET

Magnets

Coil-magnet actuators, antisprings..

But: Barkhausen noise

Candidate material: SmCo (ET-0004A-11)



Strnat+ 1985

Adhesives

Requirements: bond strength, differential thermal expansion, outgassif, robustness against thermal cycling, aging

Ceramic (Ceramabond 571): used down to a few Kelvin (Lee+ 2005, Gerstl+ 2014)

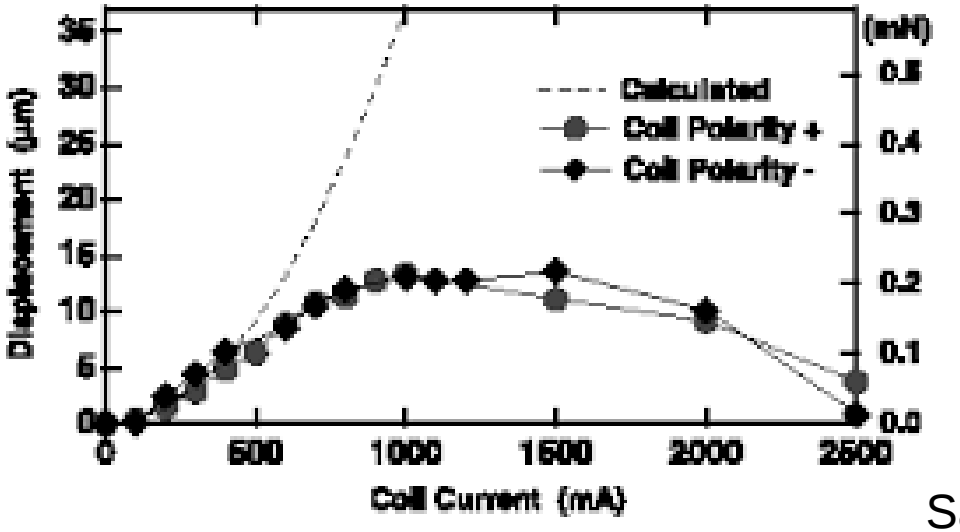
Epoxies: bonding strength increases after degassing, cure temperature and time relevant; tested down to LN2 temperature (Silvera+ 2001)

Suggested test: cryogenic evaluation of bond strength

Actuation

Technical solutions available down to a few Kelvin:

- stepper motors
- piezoelectric motors
- superconducting film actuators



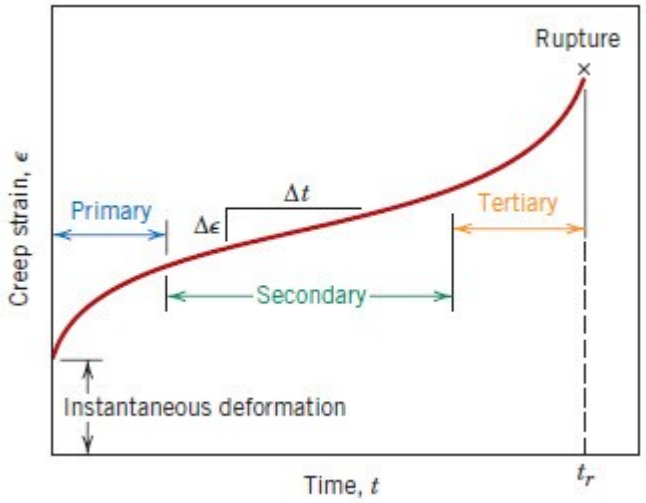
Sato 2003

Solid state lubrication

Creep at cryogenic temperatures

Suspension wires, cantilever blades…

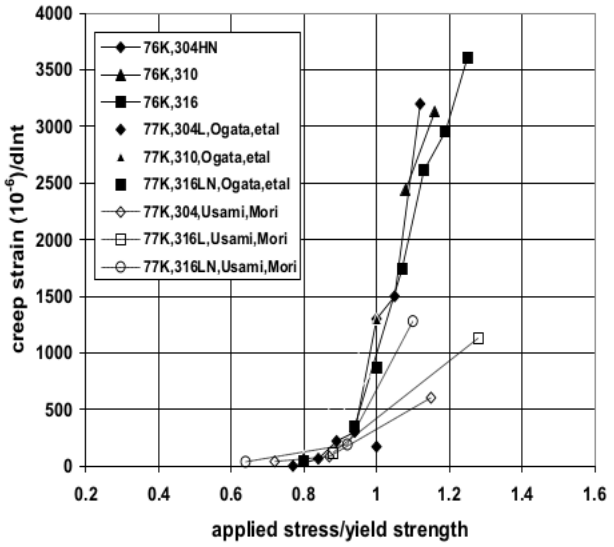
Candidate materials: steel (ET-0102A-10), CuBe ...

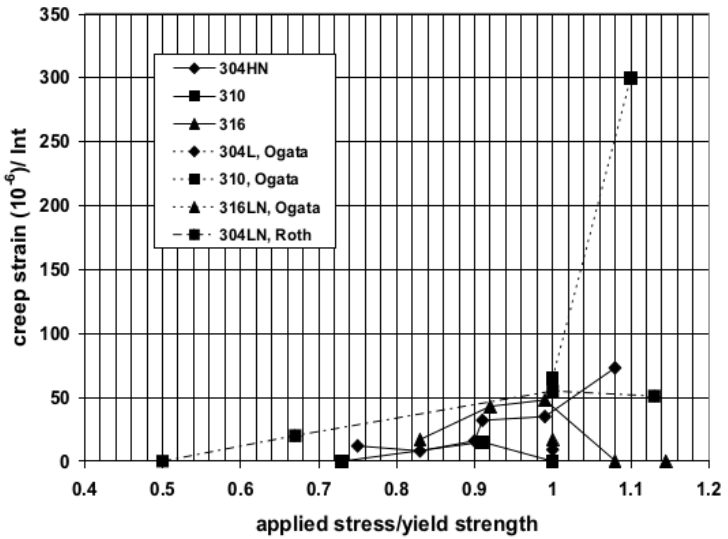


$$\varepsilon = \alpha \ln(\gamma t + 1)$$

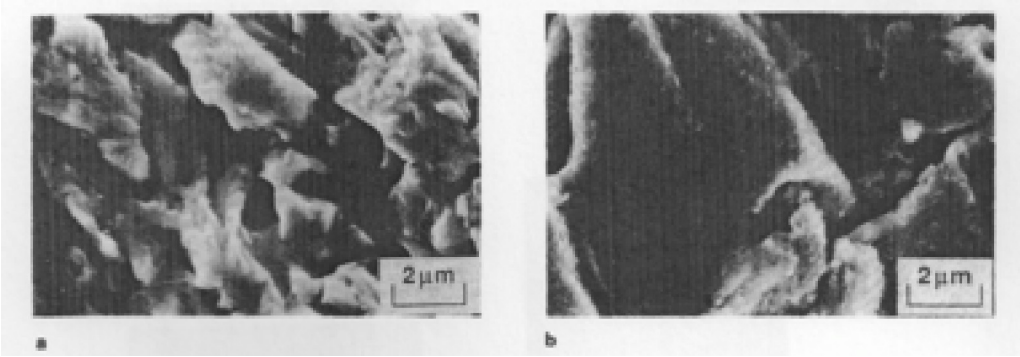
Generally transient creep investigated in literature → Long term testing necessary (RP, ET-0102A-10)

Creep at cryogenic temperatures





Reed, Walsh 2017, 77K and 4 K, 0.1 to 4 x 10^4 min



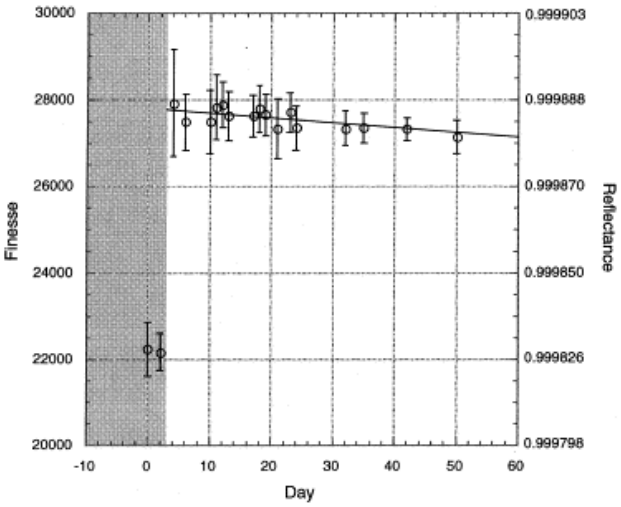
Wagner 1991, 18Ni 200 grade maraging at RT and at -170 ^{0}C

Contamination

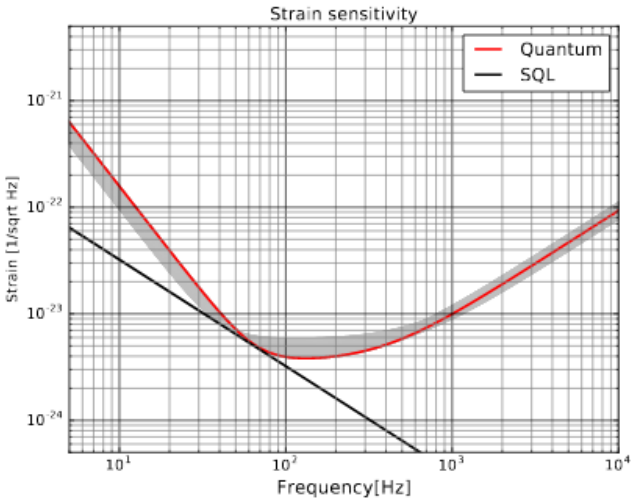
Miyoki+ 2000: 10 K mirror reflectance constant within ±5 ppm over 1 mo

Miyoki+ 2001: 10 K mirror reflectance decreasing at 0.12 ppm/day over 2mo

Hasegawa+2019: molecular adsorbed layer formation (H_20), 27±1.9 nm/day



Miyoki+ 2001



Hasegawa+ 2019

Conclusions

Several ongoing R&D efforts for 3G detectors

Suspensions operating at cryogenic temperatures topics: materials and possible solutions

Long term testing at the operation temperature