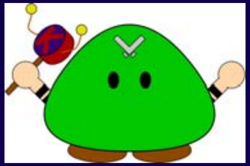


Overview on thermal noise reduction research for future GW detectors

G. Cagnoli, LMA

UNIVERSITÉ DE LYON

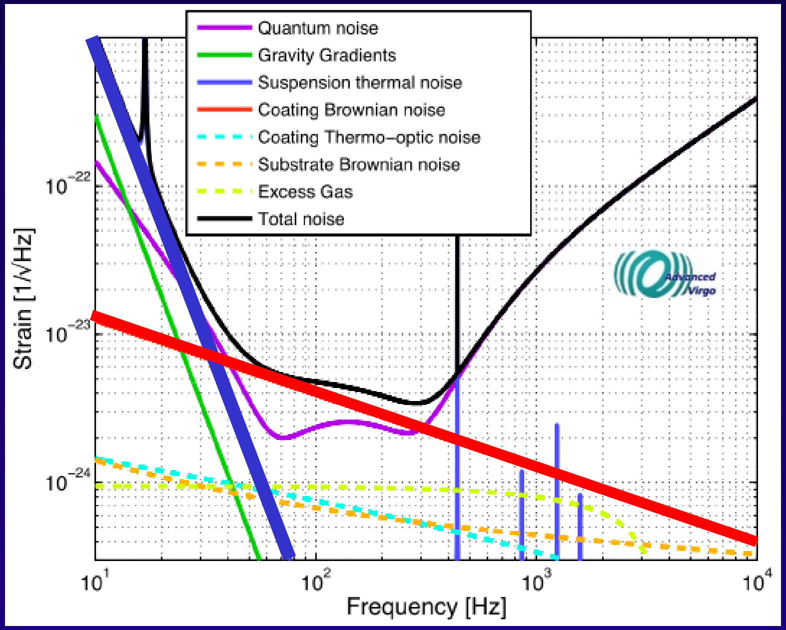
CNRS IN2P3 Les deux infinis

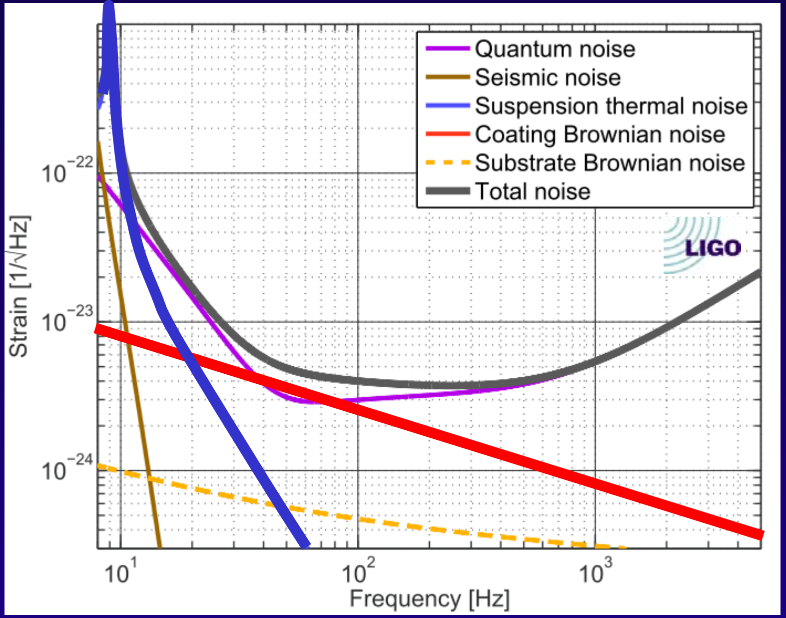
LIO Institut des Origines de Lyon
UNIVERSITE DE LYON

LMA LABORATOIRE MATÉRIAUX AVANCÉS

GWADW 2014
Takayama – 26 May 2014

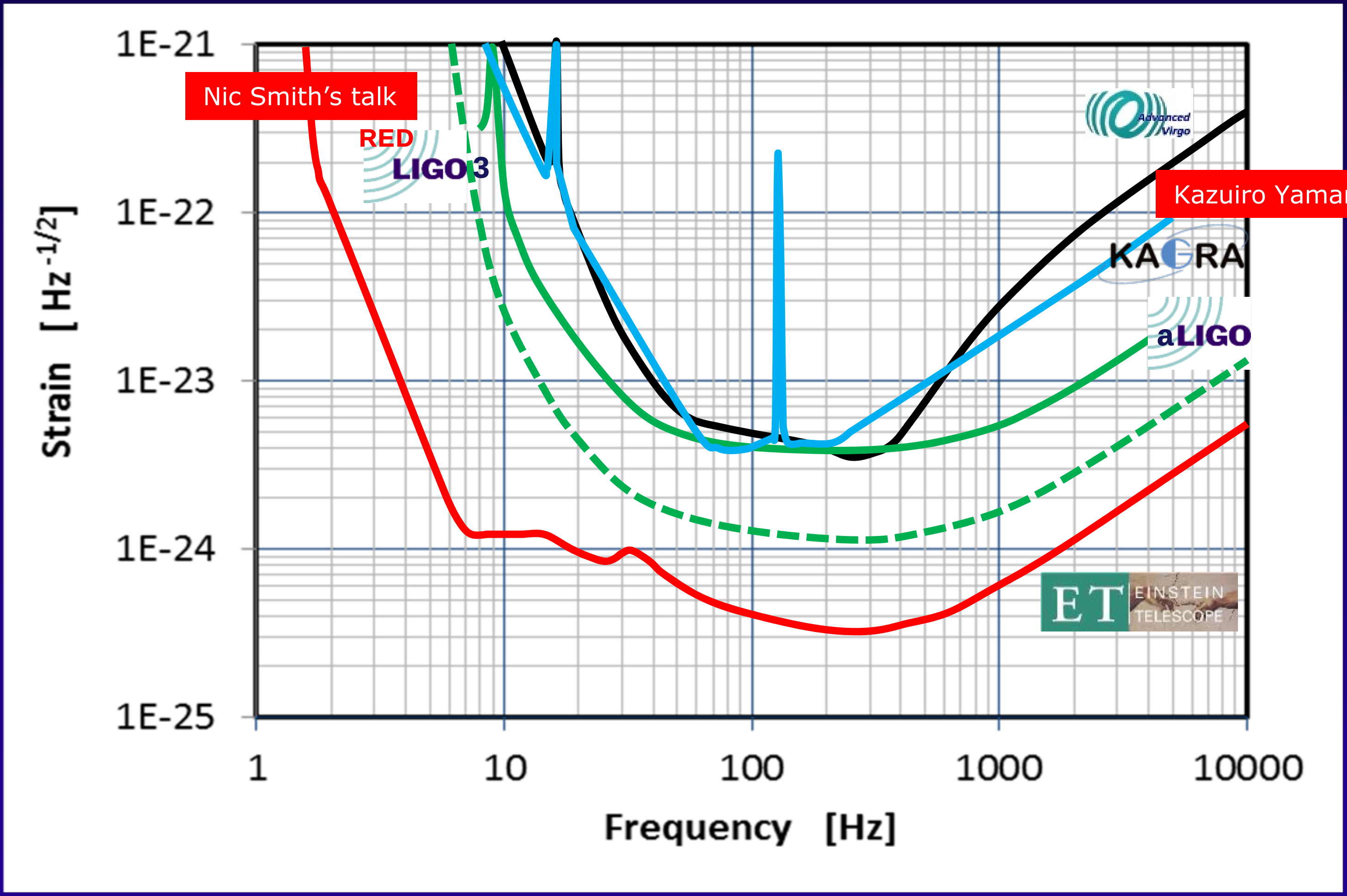
Sensitivity limits in Advanced Detectors



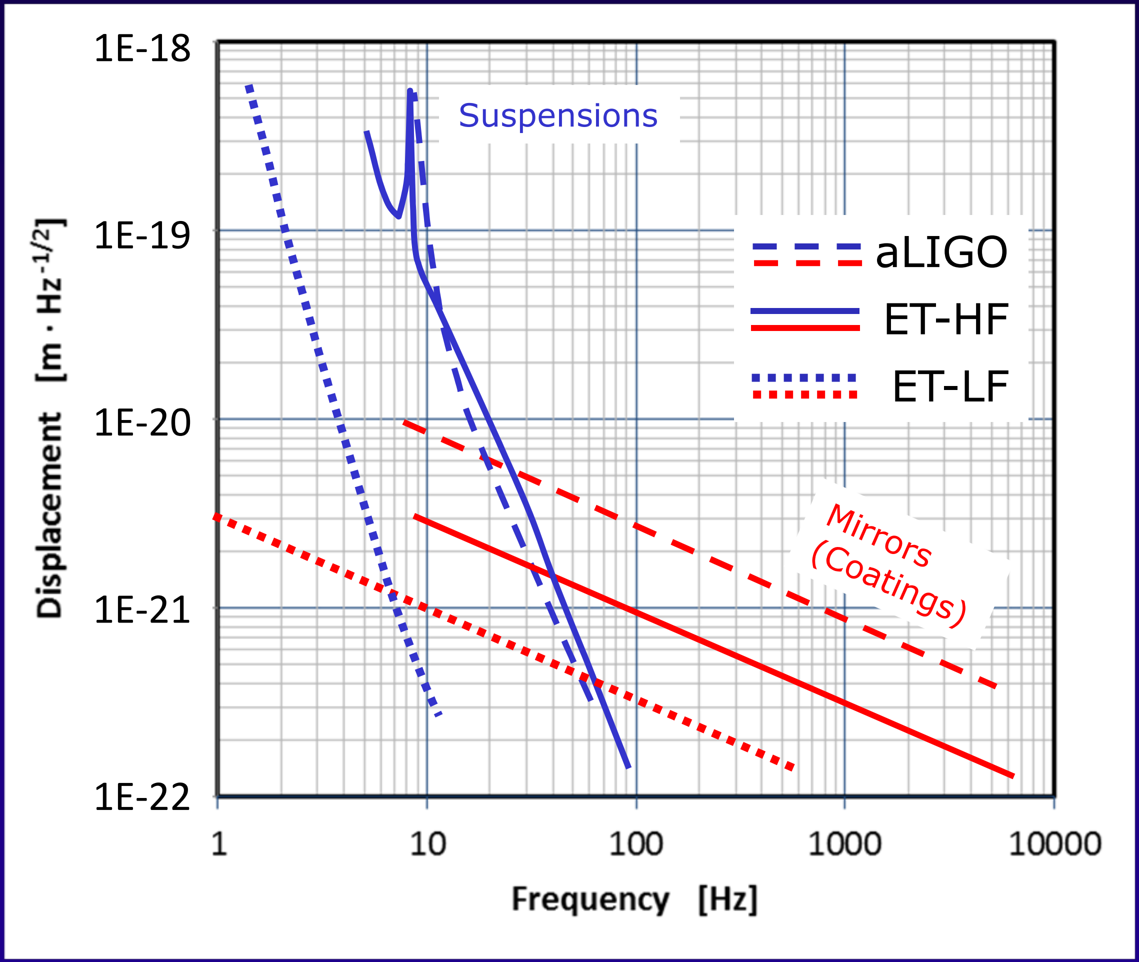


- Suspensions:
  - Silica fibres
  - Length <1m
  - Thermoelastic cancellation
  - Vertical mode frequency <10 Hz
- Substrates and Coatings:
  - Silica substrates
  - Optimal aspect ratio
  - Ti:Ta2O5/SiO2 coatings
  - Optimal coating design

Sensitivity curves beyond the Advanced detectors



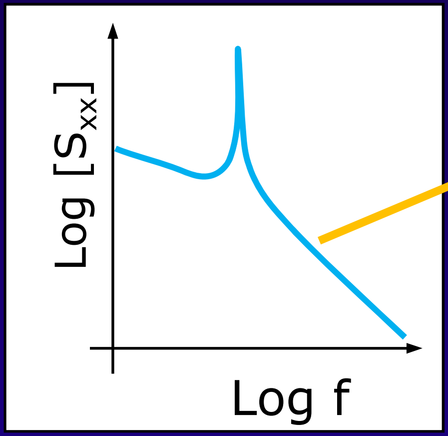
Comparison of thermal noise levels



- How do we go from Advanced to Future detectors?

Suspension Thermal Noise

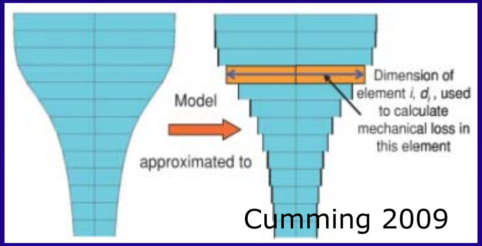
- In the detection bandwidth, interferometers work above the pendulum resonant frequency



$$S_{xx} \propto T \cdot \frac{1}{m f^5} \cdot \frac{g}{L} \cdot Dil \cdot \varphi_{fibre}$$

$$Dil = \frac{r^2}{L}\sqrt{\frac{\pi Y}{m g}}$$

- For fibres with a neck the dilution is almost independent on mass

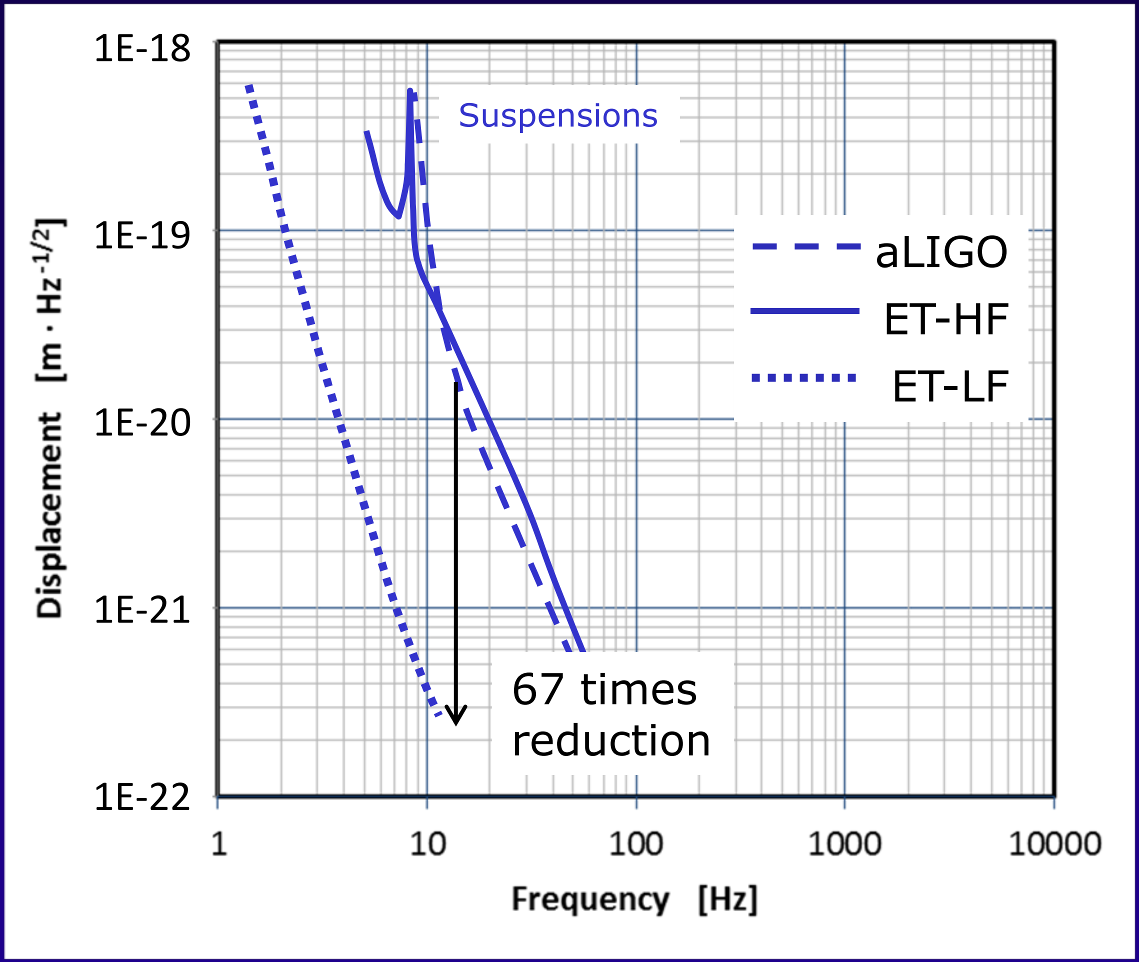


- Fixing the fibres radius
  - Thermo-elastic cancellation in silica (~190Mpa)
  - Sufficient heat conduction for sapphire and Si
  - Dil in ET-LF = 2.6 x Dil in aLIGO

- Summing them up:
  - 1/30 from T – 1/3 from L
  - 1/5 from m – 1/10 from φ

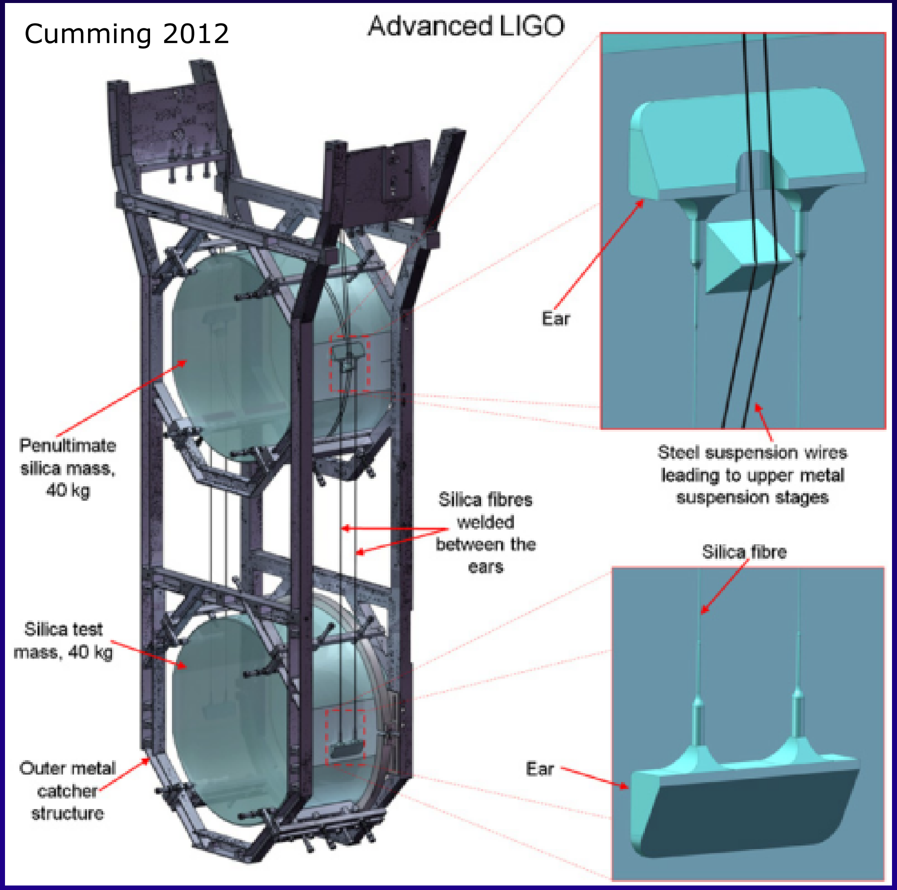
$\sqrt{S_{xx}}$ may decrease 67 times

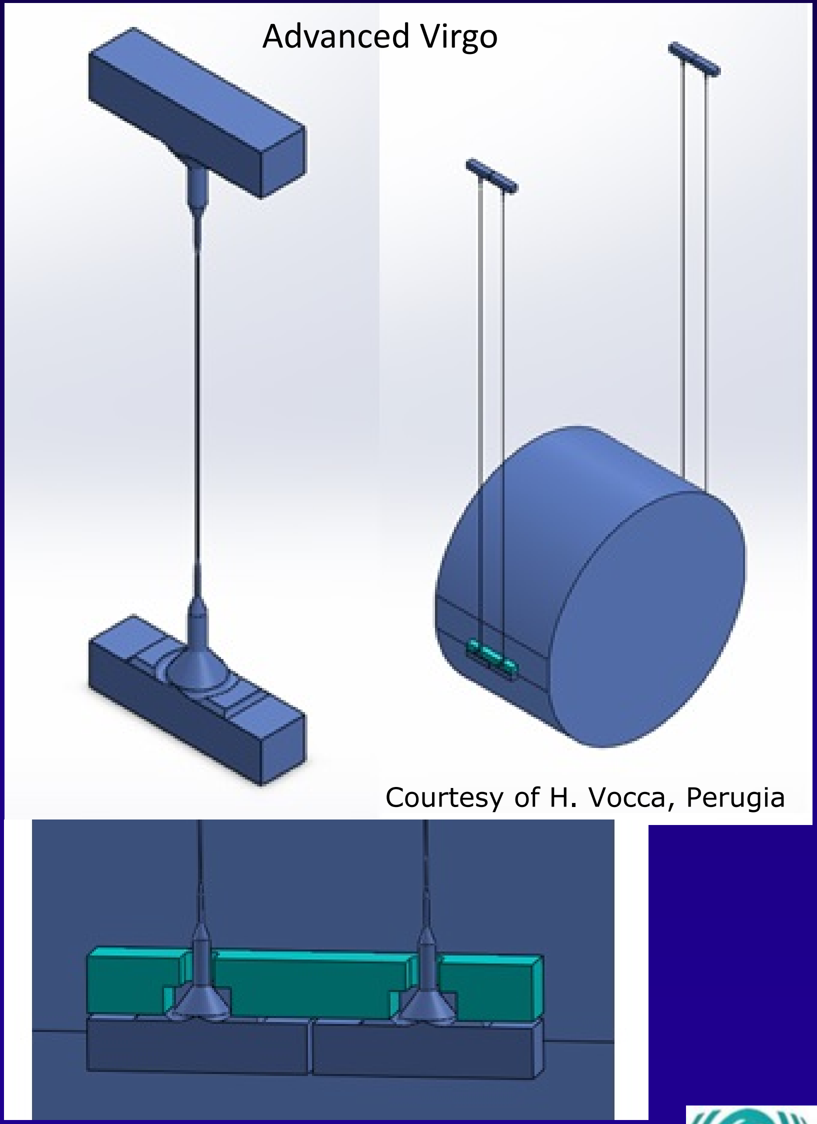
Comparison of thermal noise levels



- What scientific and technological advancements are needed to secure the result?

Two concepts for warm suspensions

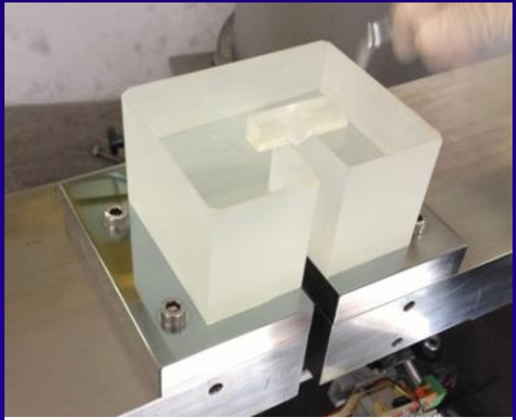




Technologies for warm suspensions

- Fused silica fibres
  - Heavier masses require thicker fibres
  - Breaking strength is related to the probability to have a flaw in the fibre, which is proportional to the volume
- Tapering
  - A sharp neck increases the dilution factor
- Bonding
  - Shear or compressive stress
  - Bonding silica to silica coated steel
- Cantilever blades
  - DLC protective coating increases handling

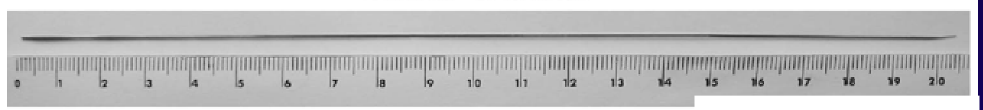
Ross Birney's talk



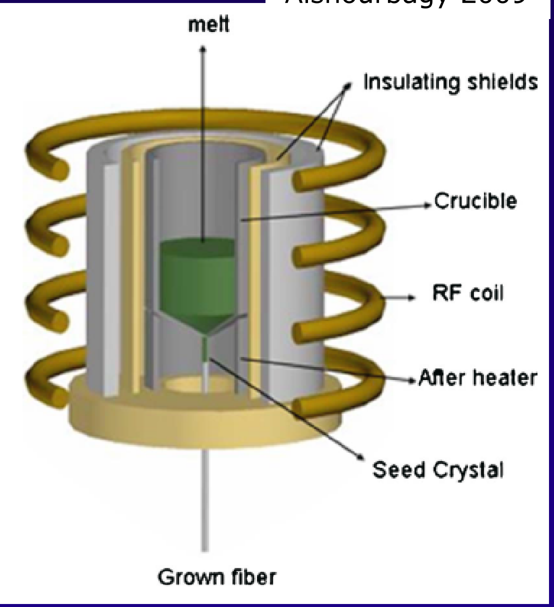
Courtesy of H. Vocca, Perugia

Technologies for cold suspensions - 1

- Crystalline fibres
  - µpulling
  - Vertical growth
  - Machining



Alshourbagy 2009



- Bonding

M. Van Veggel's talk and poster

  - New challenges come from:
    1) the cryogenic environment
       - Thermal cycling

    2) Sapphire and silicon bonding

Sapphire bonded samples which broke across the bond surface, but with damage to the bulk sapphire. Strengths 60-80MPa at 77K

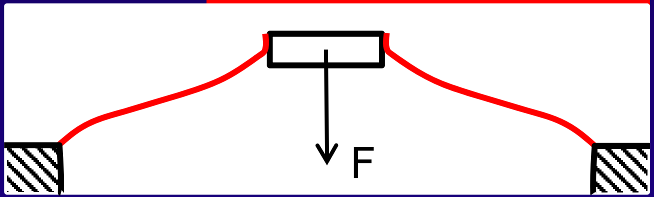
S. Rowan's talk, GWADW 2013

3) Indium bonding?

Technologies for cold suspensions - 2

- Crystalline LF vertical suspensions
  - Cantilevers
  - Elements under compression

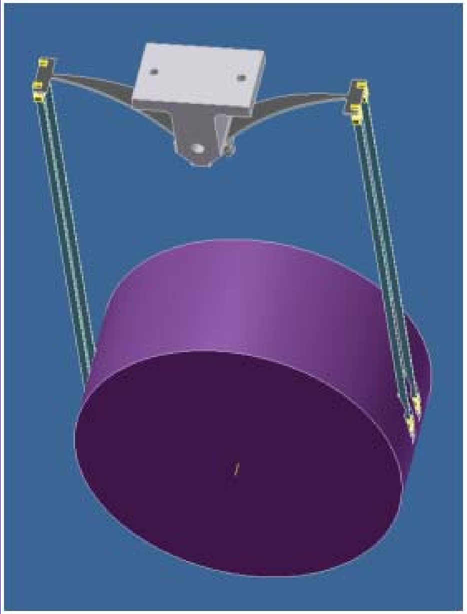
Eric Hennes's posters



G. Hammond's poster on breaking stress of sapphire

A. Cumming's talk, 5th ET Symposium

Mode	Frequency no spring Hz	Frequency spring Hz
Pendulum	0.89	0.89
Vertical bounce	106	15.3
Violin	221	221



E. Majorana's talk, GWADW 2013

- Cradles

Raul Kumar's talk

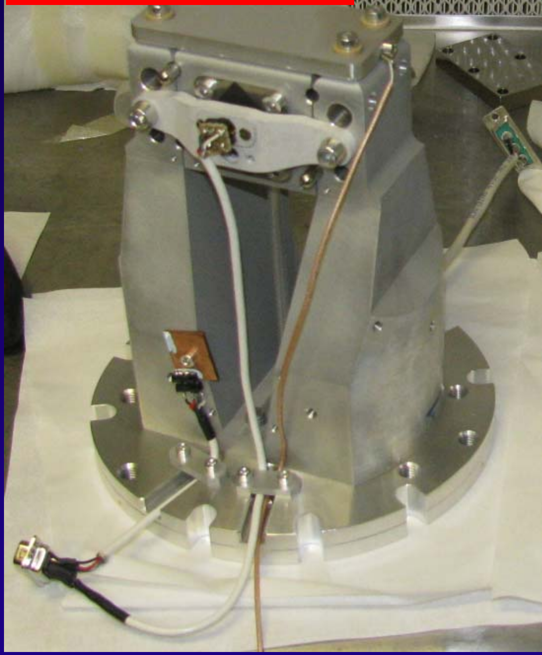
Scientific investigations

- Thermal noise under heat currents

Giles Hammond's poster on Johnson noise

Daniel Heinert's poster on non-eq. Th.Ns.

Livia Conti's talk



- Surface relaxations in mechanical losses of amorphous and crystalline materials

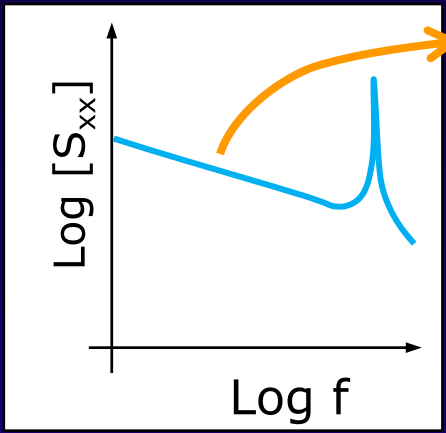
Dmitry Koptov's poster on the ESD effect on test masses

Zach Korth's poster on silicon ribbons noise

Nic Smith's poster on continous measurement of Q

- Can we have a factor 10 gain over fused silica losses?

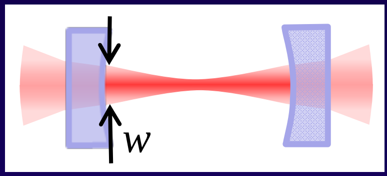
Mirror thermal noise



Mirror noises are always below resonance: little gain from substrate Young's modulus

$Y_{Sapphire} \sim 2.9 \times Y_{Silicon} \sim 2.2 \times Y_{Silica}$

Granata 2013



- Substrate Brownian $$S_{xx} \propto T \cdot \frac{1}{Y} \cdot \frac{1}{w\, f} \cdot \varphi_S$$
- Substrate thermo-elastic $$S_{xx} \propto T^2 \cdot \frac{\alpha^2 \cdot \kappa}{(C \cdot \rho)^2} \frac{1}{w^3 f^2}$$
- Coating Brownian $$S_{xx} \propto T \frac{1}{Y} \cdot \frac{d}{w^2 f} \cdot \varphi_C$$

DOMINANT TERM SO FAR

$$S_{xx} \propto T^2 \cdot \frac{1}{\sqrt{C_s \cdot \rho_s \cdot \kappa}} \cdot \frac{1}{w^2 \sqrt{f}} \cdot \left(\alpha_c \cdot d - \alpha_s \cdot d \frac{C_c \cdot \rho_c}{C_s \cdot \rho_s} - \beta_C \cdot \lambda \right)^2$$

- Coating thermo-optic

Playing with numbers

– 1/30 from T
– $1/1.7^2$ from w
– 1/x from φ

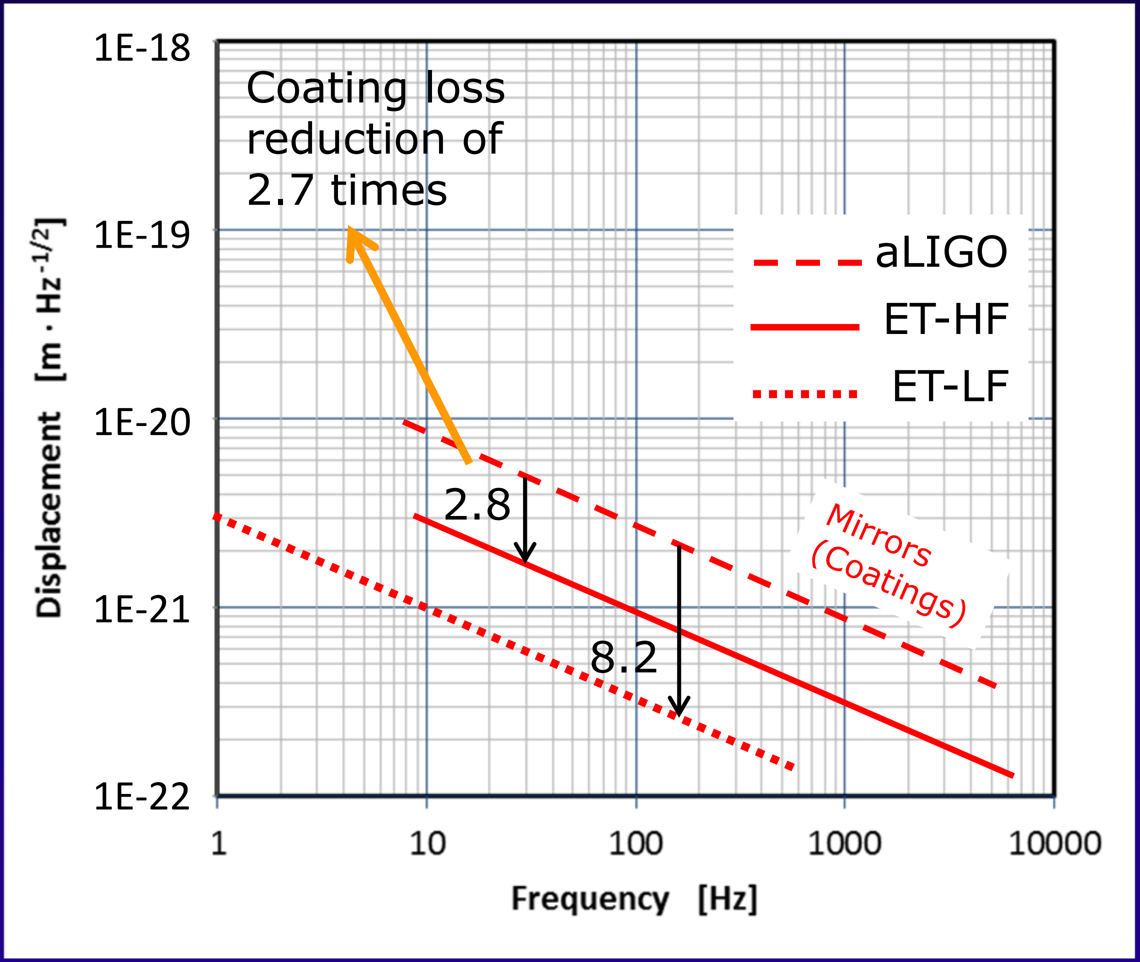
$\sqrt{S_{xx}}$ may decrease:

$1.7 \cdot \sqrt{x}$ times @ 300 K

$9.3 \cdot \sqrt{x}$ times @ 10 K

The 1.7 factor may increase further if the LG33 mode replaces the TEM00 in the cavities

Alberto Gatto's talk



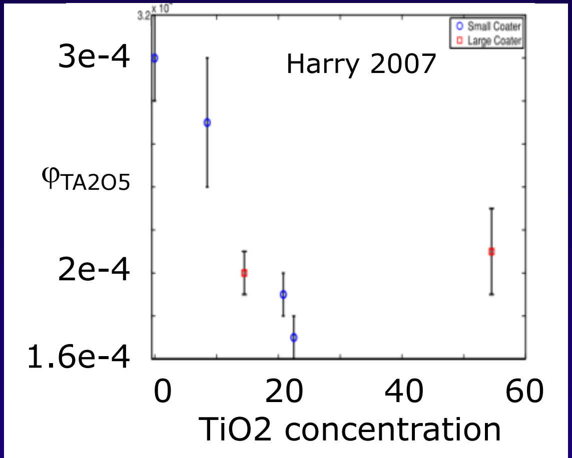
The factor x in the Amorphous Coatings

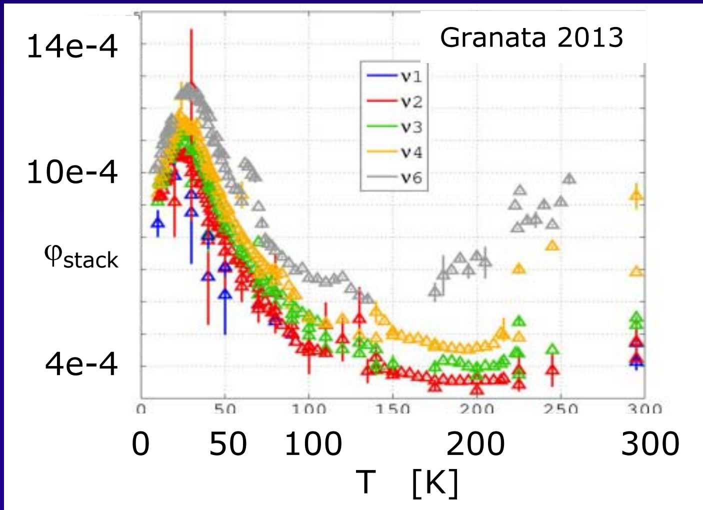
- Room temperature:
  - Doping of Ta_2O_5 with Ti developed at LMA
  - Heat treatment
    - Effects at low T
    - At room T
  - New materials and new doping
    - Steve Penn's research on Zr02
  - Nano-structured layers

Martin 2010

Massimo Granata's talk

Innocenzo Pinto's talk





- Low temperature
  - . φ_{coat} (10K) is ~2 x φ_{coat} (300K)

Structural studies

- To understand which are the relaxations responsible of thermal noise in amorphous materials

LIGO-Virgo meeting
August 29th - Stanford

6th ET Symposium
November 20th - Lyon

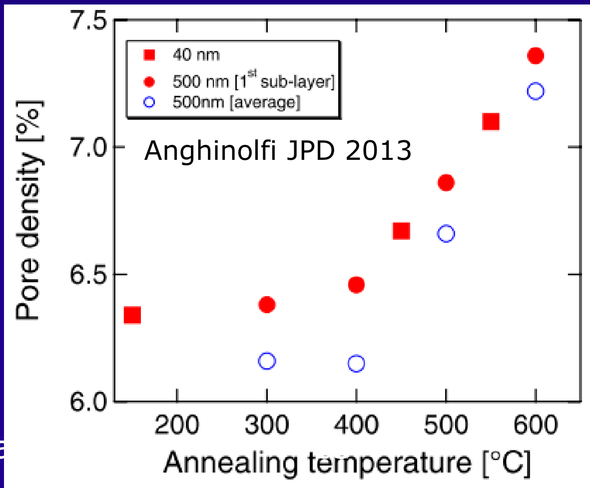
- The intelligent design of coatings follows
- Strategy

Riccardo Bassiri's talk

  - Multi-technique analysis of static structure (x-rays and electronic diffraction) or dynamic (Raman)

M. Granata's talk

  - Correlation studies with mean properties like mechanical losses or refractive index
  - Molecular dynamics models
  - Controlled alteration of coatings



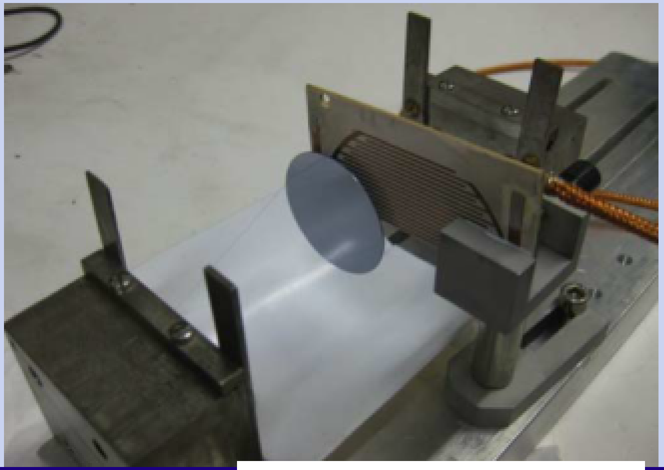
Crystalline coatings

- Low temperature operation
  - AlGaP grown on Si
  - AlGaAs grown on GaAs and lift off onto substrates

Iain Martin's talk

- Room temperature operation
  - Lift off technique
  - Thermo-optic noise seems under control
- Optical properties
  - 5 to 13ppm absorp. measured on Cole's coatings
  - Point like defects are sometimes present
  - Scattering measurements

Coatings on Si disks: nodal support technique supported by 50 μm wires



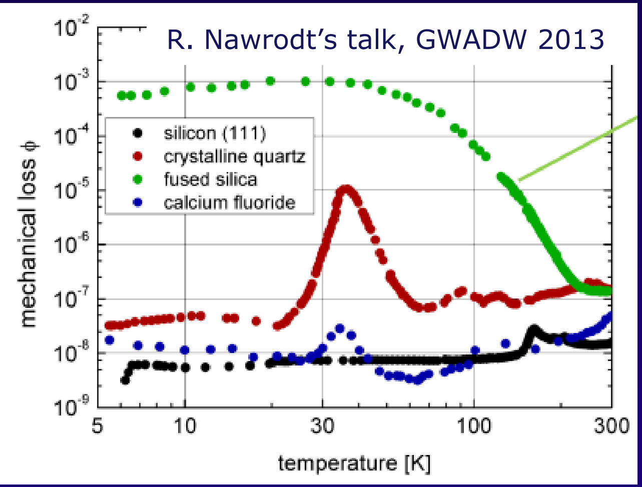
A. Lin's talk, GWADW 2013

Average coating loss (at 12K) calculated to be 1.4×10^{-5}

→ A factor of 45x lower than AdvLIGO SiO_2/doped-Ta_2O_5 coating loss at 12K

Crystalline substrates

- Silicon
  - CZ vs FZ
  - Homogeneity of impurities and of thermo-optical and mechanical parameters
  - Effect of crystalline axis orientation

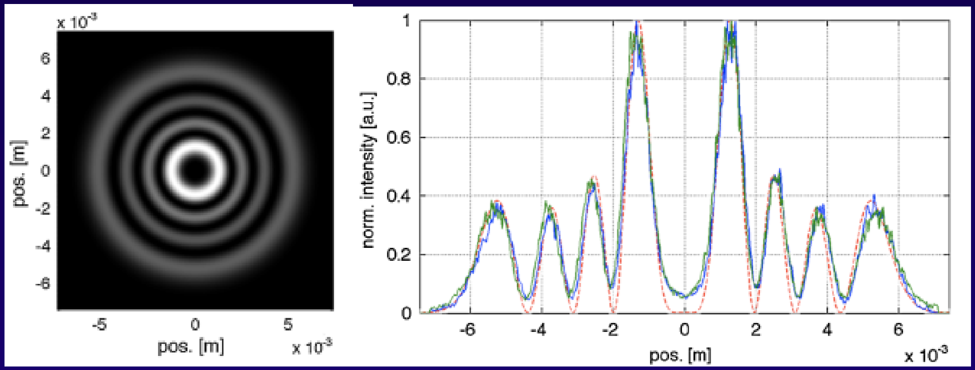


Gerd Hofmann's talk

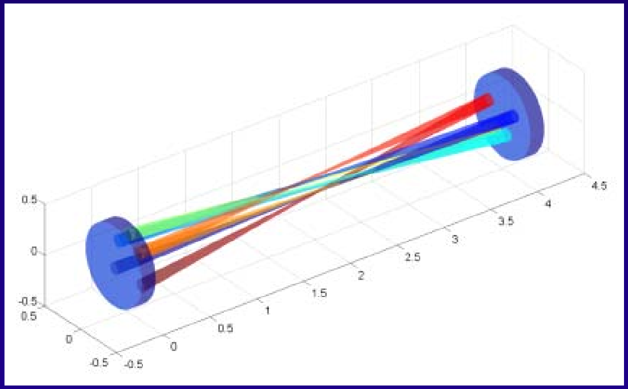
- Sapphire
  - Absorption

Advancements in optics

- LG33 Alberto Gatto's talk
  - Results from the latests experiments



- Folded FP cavities Stefan Balmer's talk
  - The history kicks back!
  - Sampling ideally the whole mirror surface



- Centre of Mass detection

Parameters for different generations

	Virgo	AdV	LIGO	aLIGO	KAGRA	LIGO 3-R	ET-LF	ET-HF
Suspension material	Steel	Silica	Steel	Silica	Sapphire	Silica	Silicon	Silica
Suspension length, m	0.7	0.7	0.25	0.6	0.3	1.2	2	0.7
Wire diameter, μm	300	400	300	400	1600	566	3000	920
Bending p diameter, μm	300	800	300	800	1600	1624	?	1900
End mirror mass, kg	21	40	11	40	23	160	200	211
Input beam radius, mm	20	49	22	53	35	85	90	72
End beam radius, mm	55	58	22	62	35	100	90	72
Temperature, K	300	300	300	300	20	300	10	300

		Y [Mpa]	dE/E dT [1/K]	ρ [g/cm^3]	α [1/K]	κ [W/K m]	C [J/K kg]	n	dn/n dT [1/K]	φ structural
Steel		210	-1.32E-04	7.85	1.23E-05	58	480			1.80E-04
Fused silica		72	1.60E-04	2200	4.10E-07	1.38	716	1.45	8.00E-06	5.00E-09
Sapphire	300 K	392	-1.24E-04	3.99	5.49E-06	70	780			3.00E-09
	20 K	398	-1.41E-05		-2.91E-07	1000	0.71			
Silicon	300 K	130 / 188	-5.42E-05	2330		120				1.00E-08
	10 K					2200				3E-9 / 5E-9
Ta2O5 doped	300 K	140		und. 7390	3.60E-06	33	280	2.06	1.40E-05	2.44 E-4
	10 K									
SiO2	300 K	70		2470	5.00E-07	1.38	745	1.45	8.00E-06	4.60E-05
	10 K									
GaAs	300 K	85.5 / 140		5.32	5.80E-06	51	327	3.3	4.50E-05	Mirror 2.5E-5
	10 K				-3.84E-09	2000	14.6			
GaP	300 K	103		6.15	4.73E-06	110	444	3.05		
	10 K									Mirror 1.4E-5

Conclusion

- Progresses are constants
- There are good chances to reach the expected noise levels for future detectors
- A POSITIVE COMPETITION BETWEEN MATERIAL RESEARCH AND OPTICS IS NECESSARY