LIGO 3 Strawman Design, Team Red

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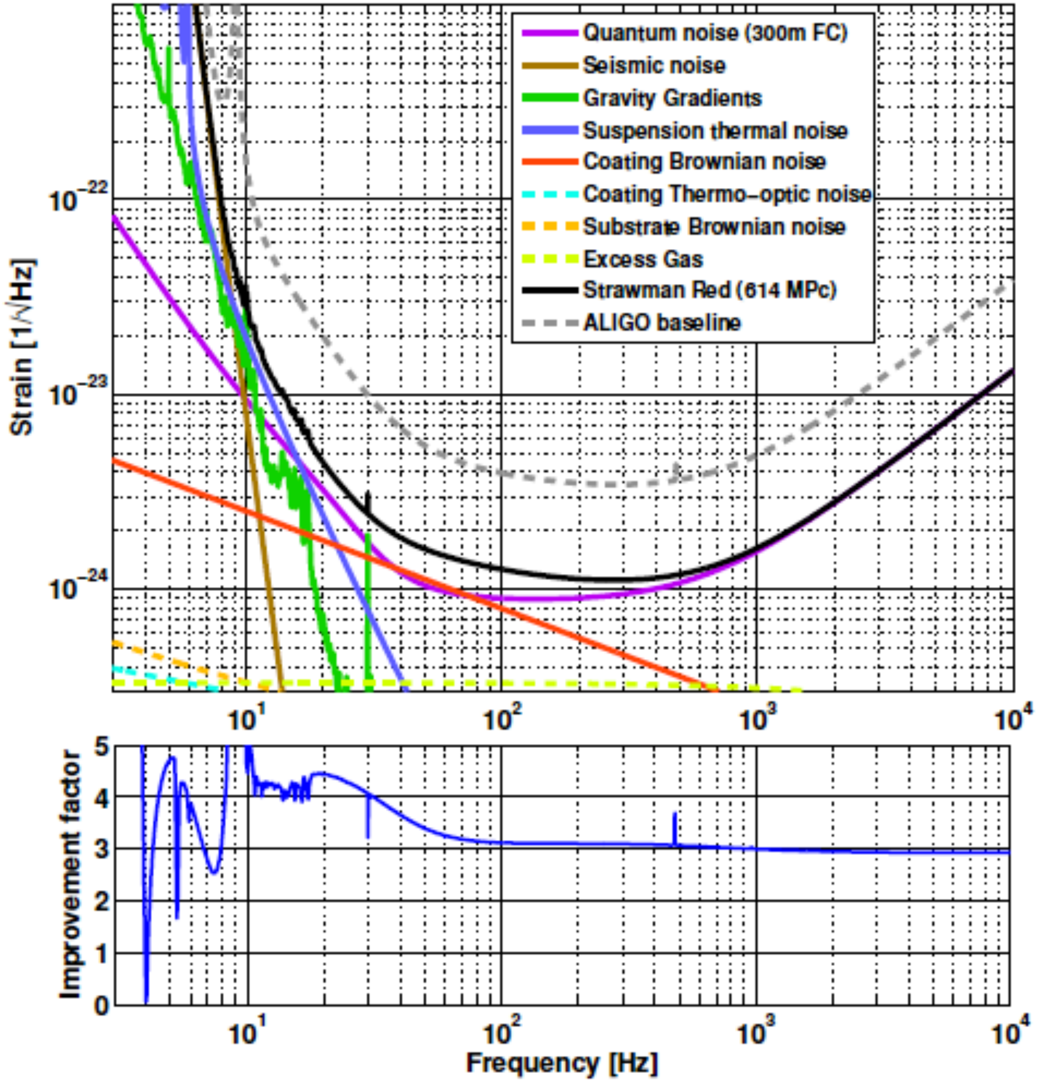
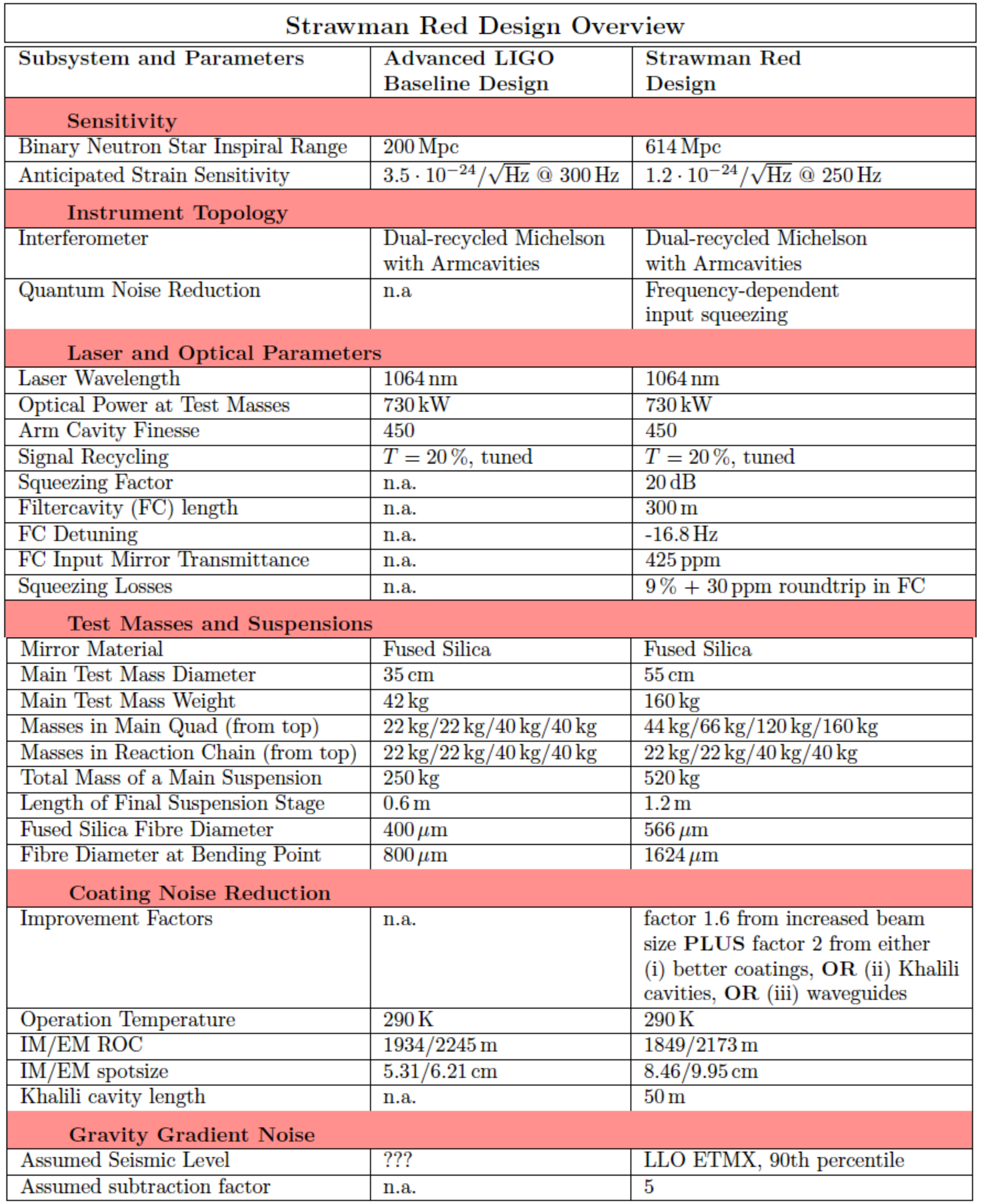
Overview





Strawman Red Design Overview		
Subsystem and Parameters	Advanced LIGO Baseline Design	Strawman Red Design
Sensitivity		
Binary Neutron Star Inspiral Range	200 Mpc	614 Mpc
Anticipated Strain Sensitivity	$3.5 \cdot 10^{-24}/\sqrt{\text{Hz}}$ @ 300 Hz	$1.2 \cdot 10^{-24}/\sqrt{\text{Hz}}$ @ 250 Hz
Instrument Topology		
Interferometer	Dual-recycled Michelson with Armcavities	Dual-recycled Michelson with Armcavities
Quantum Noise Reduction	n.a	Frequency-dependent input squeezing
Laser and Optical Parameters		
Laser Wavelength	1064 nm	1064 nm
Optical Power at Test Masses	730 kW	730 kW
Arm Cavity Finesse	450	450
Signal Recycling	$T = 20\,\%$, tuned	$T = 20\,\%$, tuned
Squeezing Factor	n.a.	20 dB
Filtercavity (FC) length	n.a.	300 m
FC Detuning	n.a.	-16.8 Hz
FC Input Mirror Transmittance	n.a.	425 ppm
Squeezing Losses	n.a.	9 % + 30 ppm roundtrip in FC
Test Masses and Suspensions		
Mirror Material	Fused Silica	Fused Silica
Main Test Mass Diameter	35 cm	55 cm
Main Test Mass Weight	42 kg	160 kg
Masses in Main Quad (from top)	22 kg/22 kg/40 kg/40 kg	44 kg/66 kg/120 kg/160 kg
Masses in Reaction Chain (from top)	22 kg/22 kg/40 kg/40 kg	22 kg/22 kg/40 kg/40 kg
Total Mass of a Main Suspension	250 kg	520 kg
Length of Final Suspension Stage	0.6 m	1.2 m
Fused Silica Fibre Diameter	400 μm	566 μm
Fibre Diameter at Bending Point	800 μm	1624 μm
Coating Noise Reduction		
Improvement Factors	n.a.	factor 1.6 from increased beam size **PLUS** factor 2 from either (i) better coatings, **OR** (ii) Khalili cavities, **OR** (iii) waveguides
Operation Temperature	290 K	290 K
IM/EM ROC	1934/2245 m	1849/2173 m
IM/EM spotsize	5.31/6.21 cm	8.46/9.95 cm
Khalili cavity length	n.a.	50 m
Gravity Gradient Noise		
Assumed Seismic Level	???	LLO ETMX, 90th percentile
Assumed subtraction factor	n.a.	5

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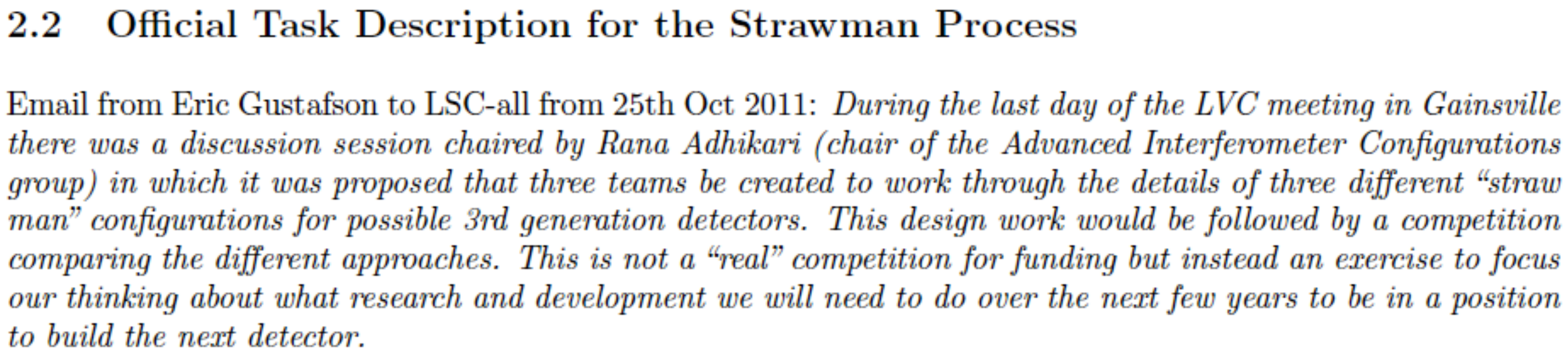
- Team Read
- Input parameters and working assumptions on with the Team Red design is based on.
- Description of the Team Red design and the required R+D:
  - Suspension Thermal noise
  - Newtonian noise
  - Coating Brownian noise
  - Quantum noise
- Rough estimate of the hardware costs
- Potential of a dual-Temperature xylophone?

Who is Team Red

- About 35 people from 8 institutions.
- In the period between Nov 2011 and Jan 2012 we had four telecons plus one F2F meeting (with 25 people attending in person) in Glasgow.
- Lots of PhD students involved.

Photos by A. Freise

Task description



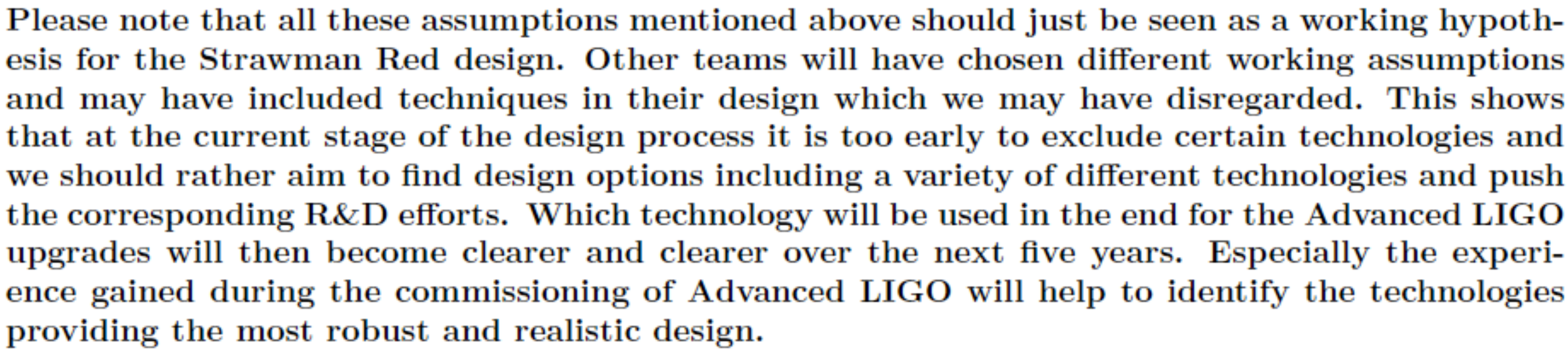
2.2 Official Task Description for the Strawman Process

Email from Eric Gustafson to LSC-all from 25th Oct 2011: *During the last day of the LVC meeting in Gainsville there was a discussion session chaired by Rana Adhikari (chair of the Advanced Interferometer Configurations group) in which it was proposed that three teams be created to work through the details of three different "straw man" configurations for possible 3rd generation detectors. This design work would be followed by a competition comparing the different approaches. This is not a "real" competition for funding but instead an exercise to focus our thinking about what research and development we will need to do over the next few years to be in a position to build the next detector.*

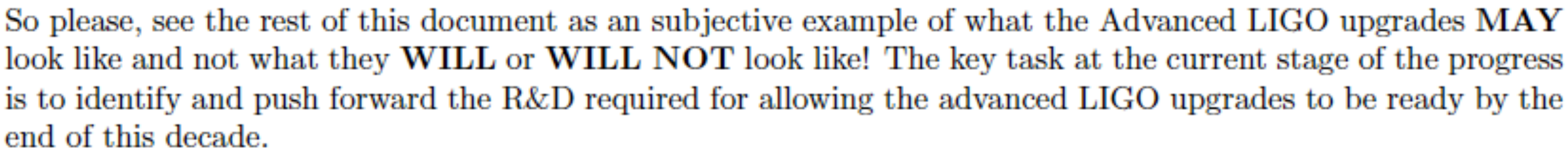
Input parameter and resulting working assumptions

INPUT		Working assumption
50-100 million $	The cost of the Advanced LIGO upgrade program was assumed to be limited to a maximum range of 50 to 100 million USD for all interferometers together.	
	From the previous point one can deduce, that the considered upgrades have to use to a large extend the same vacuum infrastructure as Advanced LIGO. Therefore we assumed that moderate changes of the vacuum system in the central and end stations will be possible, but assumed that no changes to the 4 km long vacuum tubes are possible.	**Stick to vacuum tube**
	In addition we assumed that the seismic pre-isolation system is off limits, as replacing it would probably not fit within the targeted budget.	**Keep ISI**
Available 2018	Regarding the anticipated timeline we assumed that all technologies included in our design should be mature enough to be compatible with an installation in 2018, assuming we start now with the required R&D and carry out the required prototyping over the next 5 years.	
	Another assumption we made was to keep the test masses and their suspensions at room temperature.	**T =290 K**
P = 800kW	Due to the current lack of practical experience with compensation of thermal lensing effects in the few hundred kilowatt range, we also assumed that the Advanced LIGO upgrades will initially not use any higher circulating light power as in the Advanced LIGO baseline.	
	Due to the limited time frame available for the strawman exerise we focussed our efforts nearly entirely on evaluating the 'fundamental' noise sources and in most cases did not consider implications on technical noise sources, such as control noise etc.	Only looked at Fundamental noise
	Since at the current stage our focus was sent on identifying useful technologies for advanced LIGO upgrades, so far we did not perform any detailed parameter optimisation (on the percent level), to 'squeeze' the last few MPc of binary neutron star inspiral range out of Strawman Red.	Not optimised on 10%level

To avoid misunderstandings …



Please note that all these assumptions mentioned above should just be seen as a working hypothesis for the Strawman Red design. Other teams will have chosen different working assumptions and may have included techniques in their design which we may have disregarded. This shows that at the current stage of the design process it is too early to exclude certain technologies and we should rather aim to find design options including a variety of different technologies and push the corresponding R&D efforts. Which technology will be used in the end for the Advanced LIGO upgrades will then become clearer and clearer over the next five years. Especially the experience gained during the commissioning of Advanced LIGO will help to identify the technologies providing the most robust and realistic design.



So please, see the rest of this document as an subjective example of what the Advanced LIGO upgrades **MAY** look like and not what they **WILL** or **WILL NOT** look like! The key task at the current stage of the progress is to identify and push forward the R&D required for allowing the advanced LIGO upgrades to be ready by the end of this decade.

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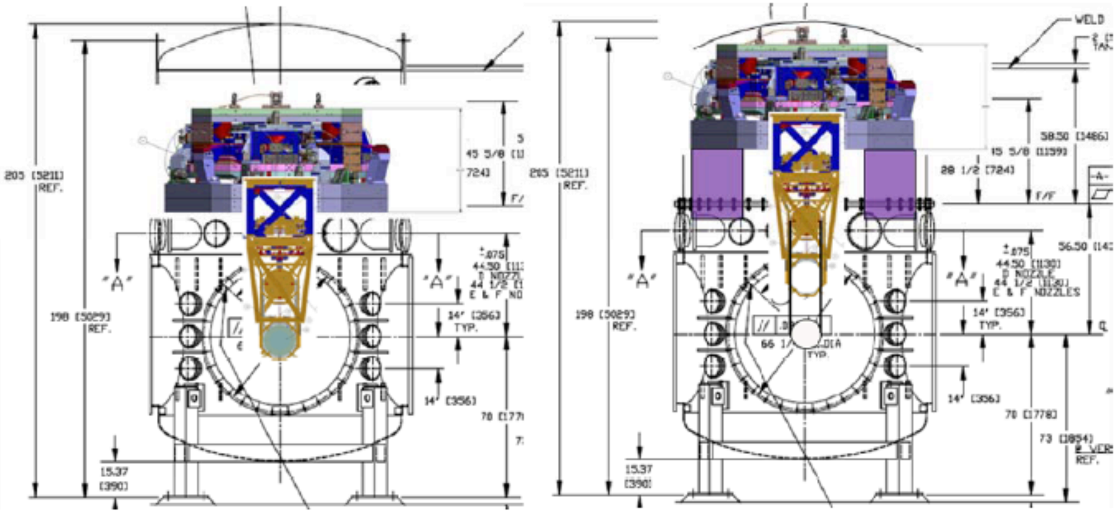
Suspension Thermal Noise

- Boosted aLIGO Quad with 1.2m long last stage and 160kg test masses.



Test Masses and Suspensions		
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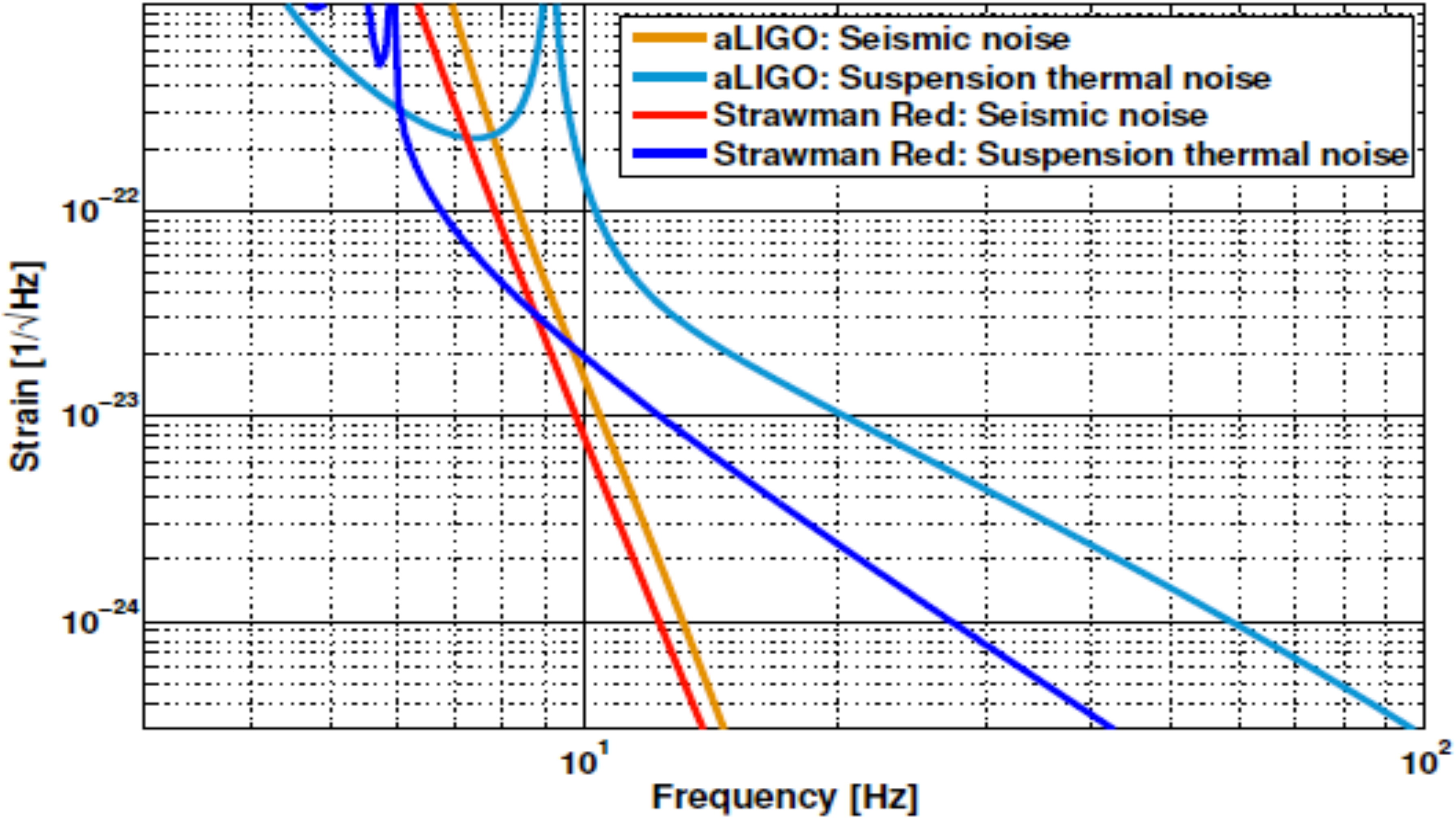
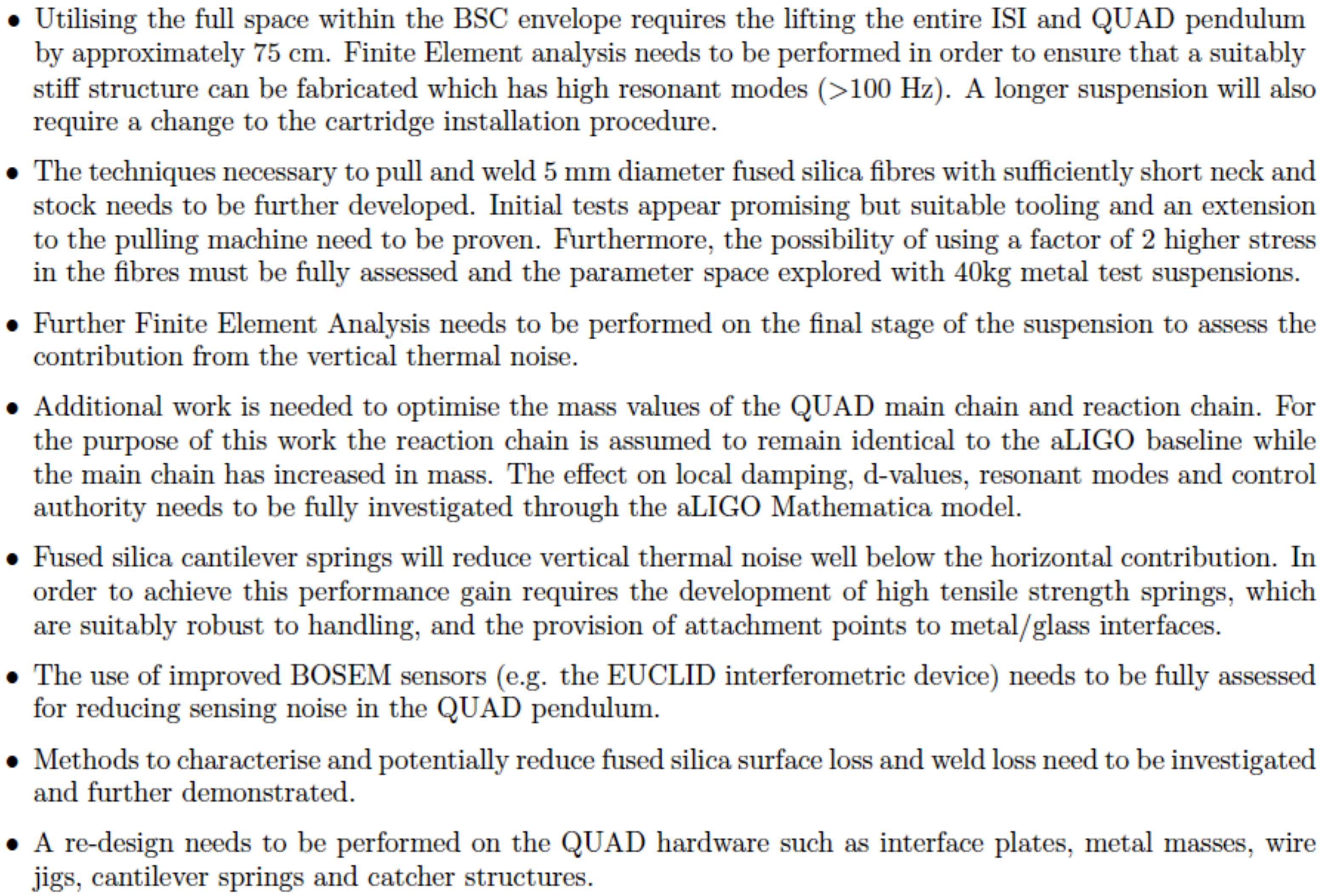
Suspension Thermal Noise



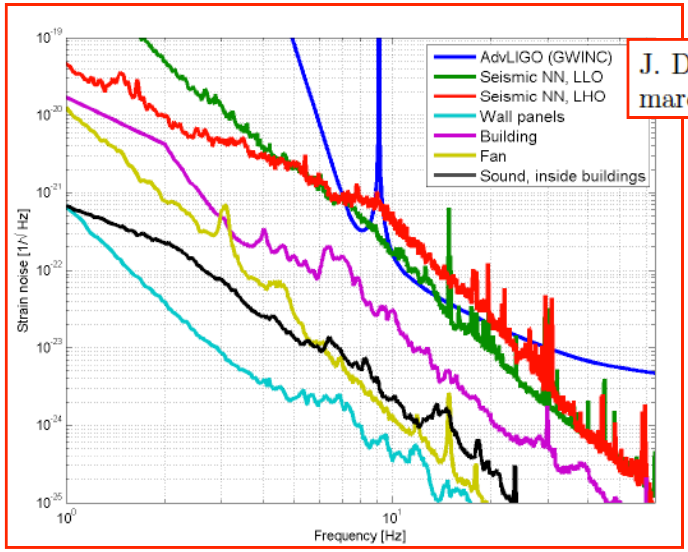
Suspension R&D



- Utilising the full space within the BSC envelope requires the lifting the entire ISI and QUAD pendulum by approximately 75 cm. Finite Element analysis needs to be performed in order to ensure that a suitably stiff structure can be fabricated which has high resonant modes (>100 Hz). A longer suspension will also require a change to the cartridge installation procedure.
- The techniques necessary to pull and weld 5 mm diameter fused silica fibres with sufficiently short neck and stock needs to be further developed. Initial tests appear promising but suitable tooling and an extension to the pulling machine need to be proven. Furthermore, the possibility of using a factor of 2 higher stress in the fibres must be fully assessed and the parameter space explored with 40kg metal test suspensions.
- Further Finite Element Analysis needs to be performed on the final stage of the suspension to assess the contribution from the vertical thermal noise.
- Additional work is needed to optimise the mass values of the QUAD main chain and reaction chain. For the purpose of this work the reaction chain is assumed to remain identical to the aLIGO baseline while the main chain has increased in mass. The effect on local damping, d-values, resonant modes and control authority needs to be fully investigated through the aLIGO Mathematica model.
- Fused silica cantilever springs will reduce vertical thermal noise well below the horizontal contribution. In order to achieve this performance gain requires the development of high tensile strength springs, which are suitably robust to handling, and the provision of attachment points to metal/glass interfaces.
- The use of improved BOSEM sensors (e.g. the EUCLID interferometric device) needs to be fully assessed for reducing sensing noise in the QUAD pendulum.
- Methods to characterise and potentially reduce fused silica surface loss and weld loss need to be investigated and further demonstrated.
- A re-design needs to be performed on the QUAD hardware such as interface plates, metal masses, wire jigs, cantilever springs and catcher structures.

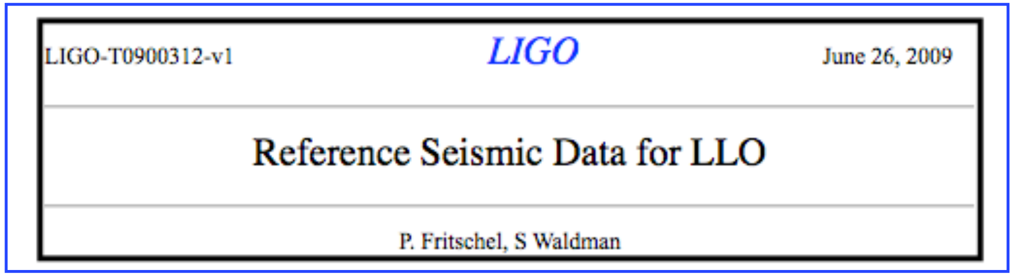
Newtonian Noise

- The seismic data is from LLO only.
- The current NN plot is calculated from seismometer data at the ETMX station.
- The 90th percentile is currently shown.
- A subtraction factor of 5 is assumed currently. This estimate comes from the fact that the seismically driven NN level is expected to be around a factor of 5 above the level of the other NN sources, such as the vibrations of the building itself (see figure 5). In order to get more than a factor of 5 subtraction of NN, it would be therefore be necessary to accurately measure the motion of these additional sources. For this reason we assume the cautious estimate that we can just substract the seismically driven NN, resulting in roughly a factor 5 reduction in total NN.



J. Driggers and J. Harms, "Results of phase 1 newtonian noise measurements at the ligo sites, february-march 2011," *LIGO DCC*, vol. T1100237, 2011.

Used seismic from:

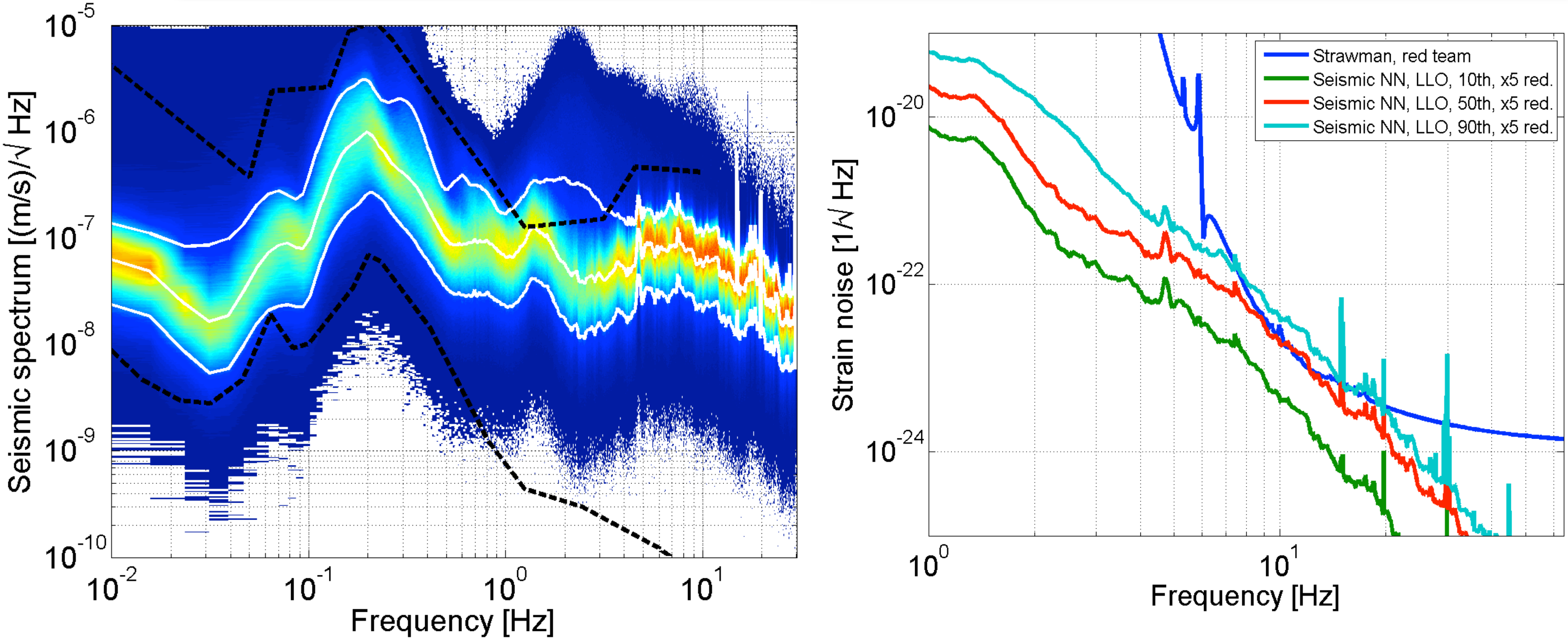


LIGO-T0900312-v1 *LIGO* June 26, 2009

Reference Seismic Data for LLO

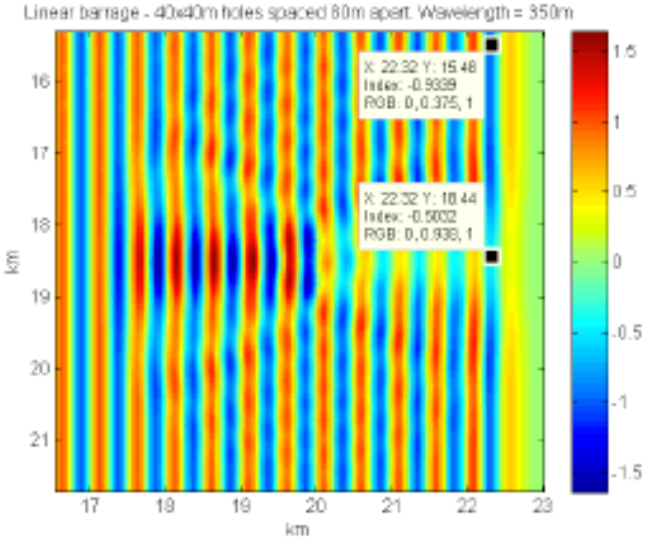
P. Fritschel, S Waldman

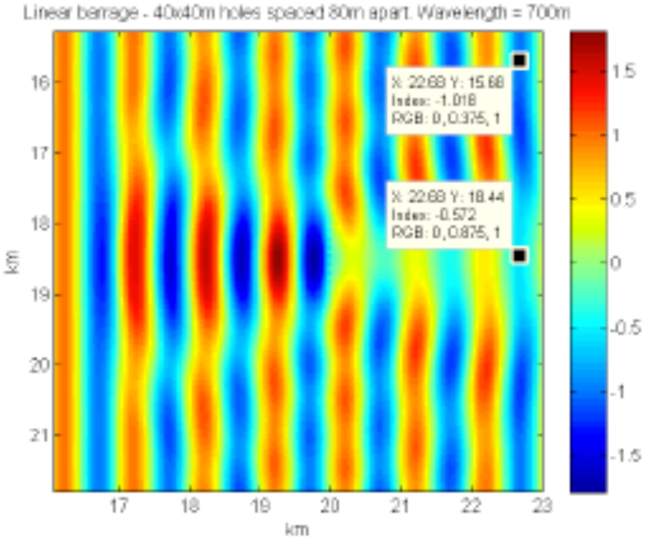
Newer data from LLO

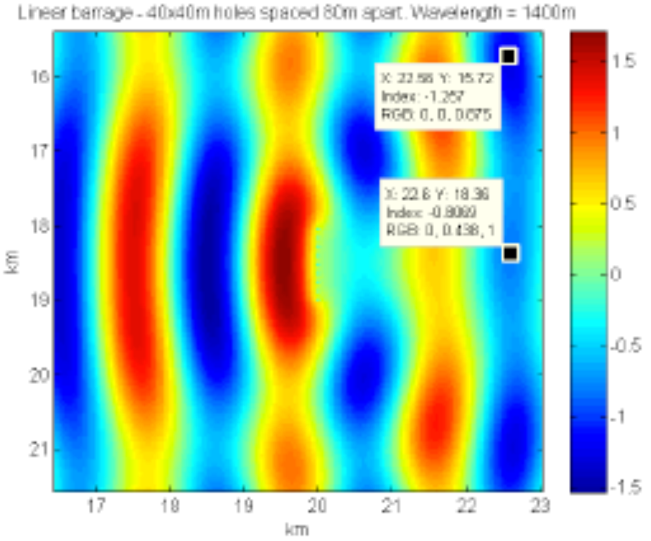


New data from LLO seem to suggest that Strawman red underestimates the GGN level by about a factor 2.

Side note: Seismic barrages


Linear barrage - 40x40m holes spaced 80m apart. Wavelength = 350m


Linear barrage - 40x40m holes spaced 80m apart. Wavelength = 700m


Linear barrage - 40x40m holes spaced 80m apart. Wavelength = 1400m

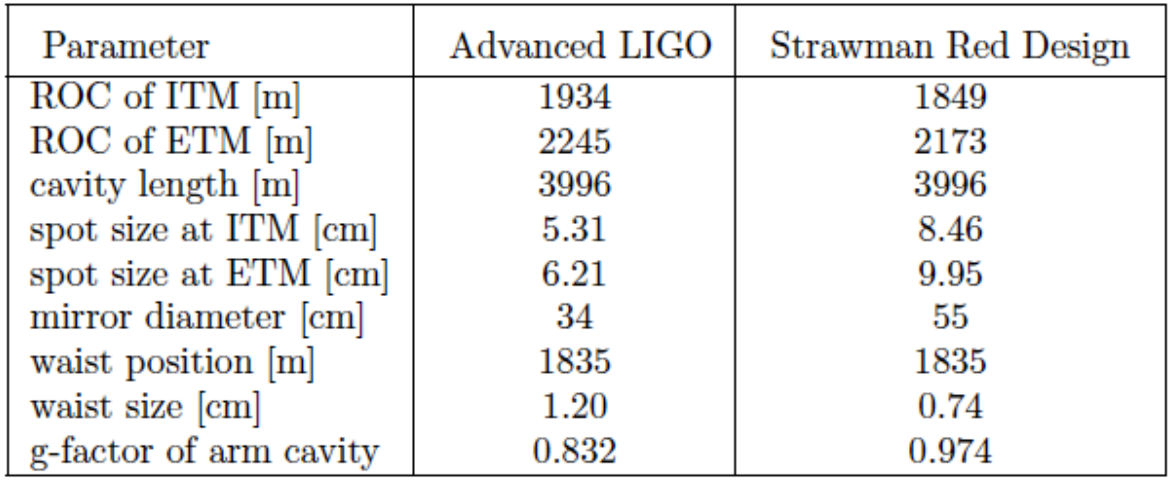
- 2D finite-difference time-domain simulations for barrages of 40x40m.
- Attenuation of seismic by about a factor 2.
- Seismic barrages are not included in the Strawman Red sensitivity curve.

Coating Brownian noise

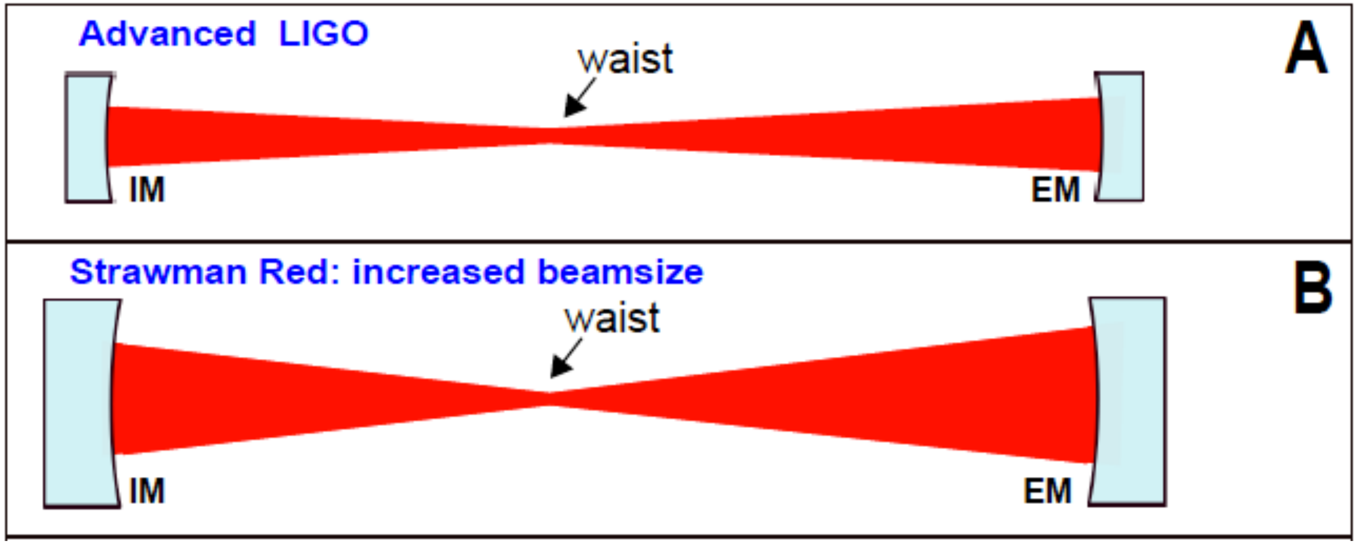
- Assumed and overall improvement by a factor **3.2**.
- Factor **1.6** from increased beam sizes.
- Another factor of **2** on top of this from either:
  - Better coatings
  - Khalili cavities
  - Resonant waveguide mirrors

Increasing the beam size

- Assume an increase of beam size by a factor 1.6.
- Keep aspect ratio of test masses as it is => 160kg.



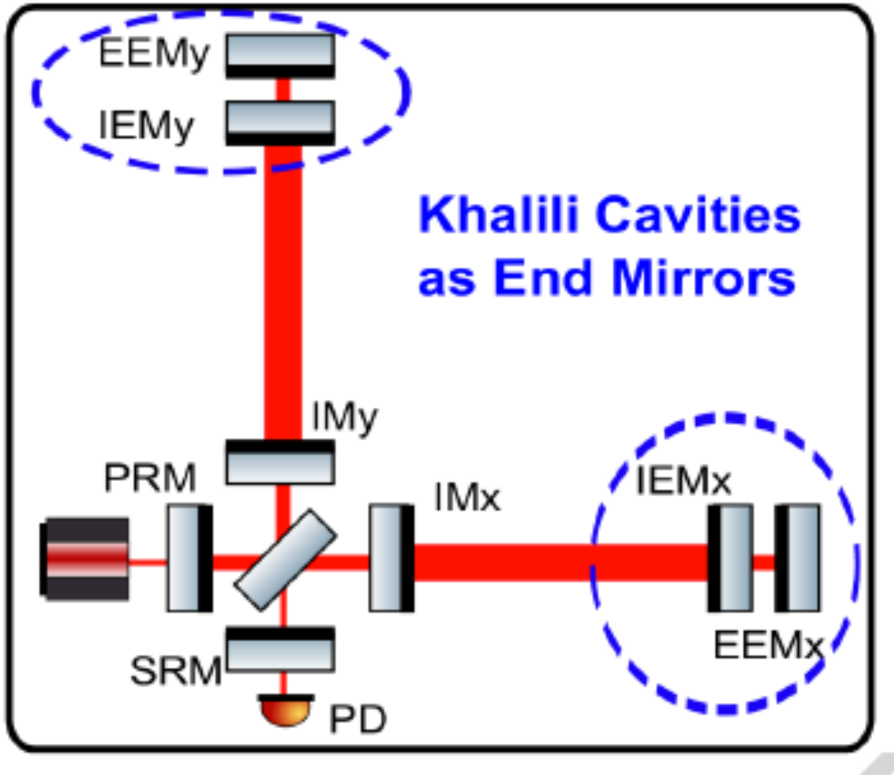
Parameter	Advanced LIGO	Strawman Red Design
ROC of ITM [m]	1934	1849
ROC of ETM [m]	2245	2173
cavity length [m]	3996	3996
spot size at ITM [cm]	5.31	8.46
spot size at ETM [cm]	6.21	9.95
mirror diameter [cm]	34	55
waist position [m]	1835	1835
waist size [cm]	1.20	0.74
g-factor of arm cavity	0.832	0.974



Optical coatings with reduced thermal noise

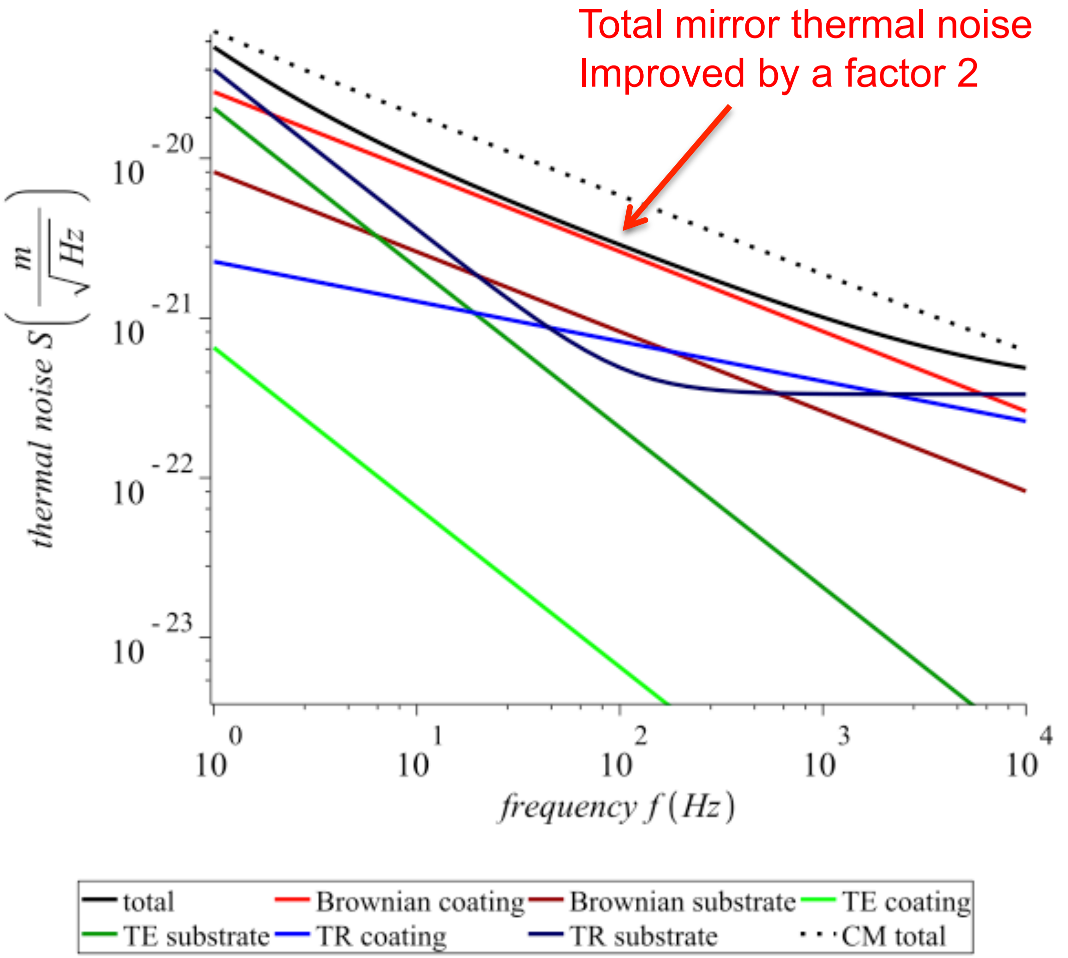
- Continued improvement of tantala coatings.
  - Loss related to local atomic structure of material
- High-temperature annealing of coatings.
  - Heat treatment in the range of 500-1000 degrees centigrade
- Amorphous silicon as a high-index coating material
  - n=3.5 => quarter-wave layer is thinner. In addition need fewer layers.
  - Potential improvement = 2.3 (in amplitude)
  - Requires change of laser wavelength
- Crystalline coatings (eg AlGaAs or AlGaP)

Khalili cavities



Reducing thermal noise in future gravitational wave detectors by employing Khalili etalons

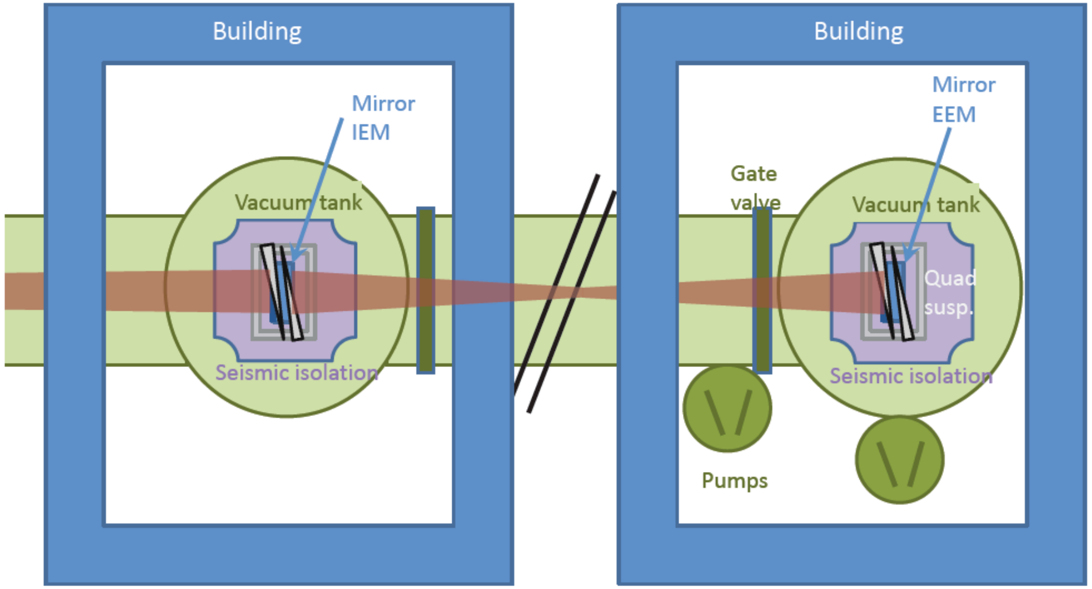
Alexey G. Gurkovsky[a], Daniel Heinert[b], Stefan Hild[c], Ronny Nawrodt[b], Kentaro Somiya[d, e], Sergey P. Vyatchanin[a], Holger Wittel[f]

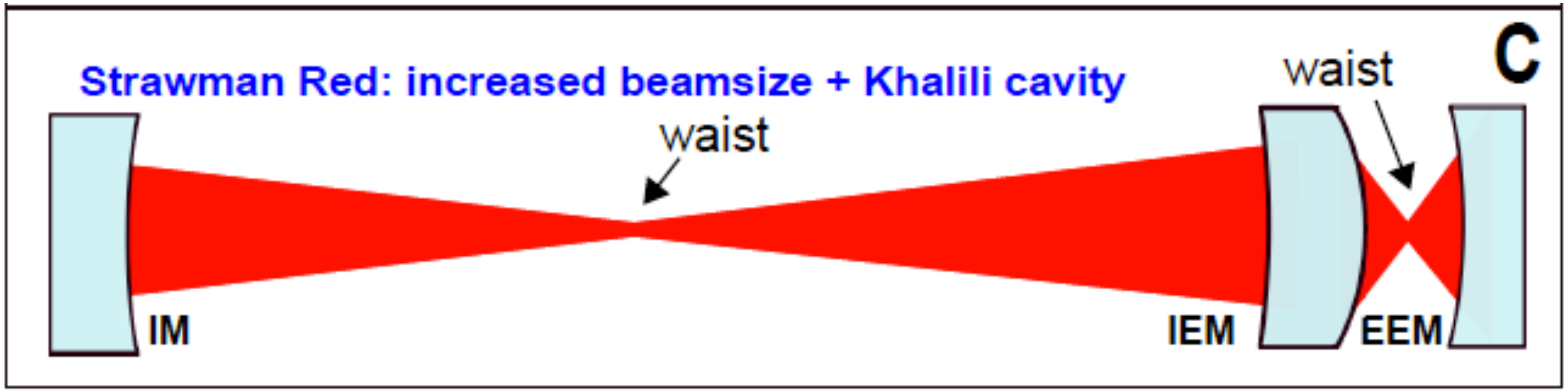


Total mirror thermal noise
Improved by a factor 2

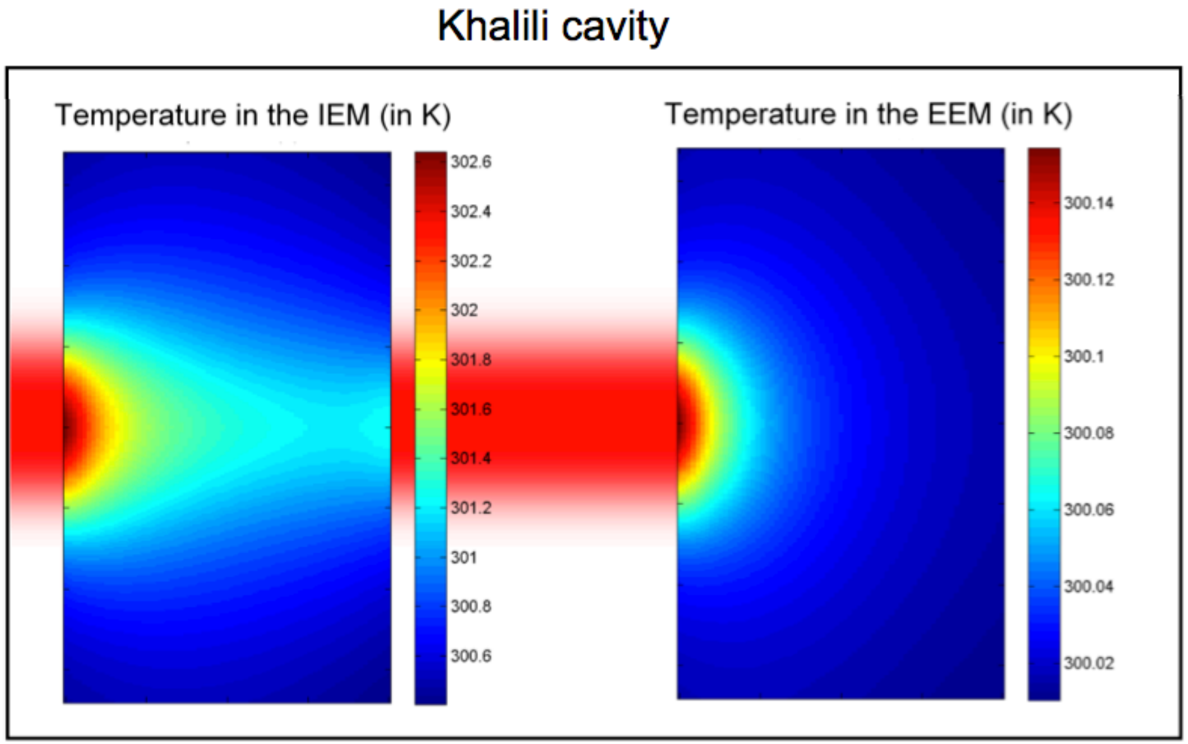
Khalili cavities

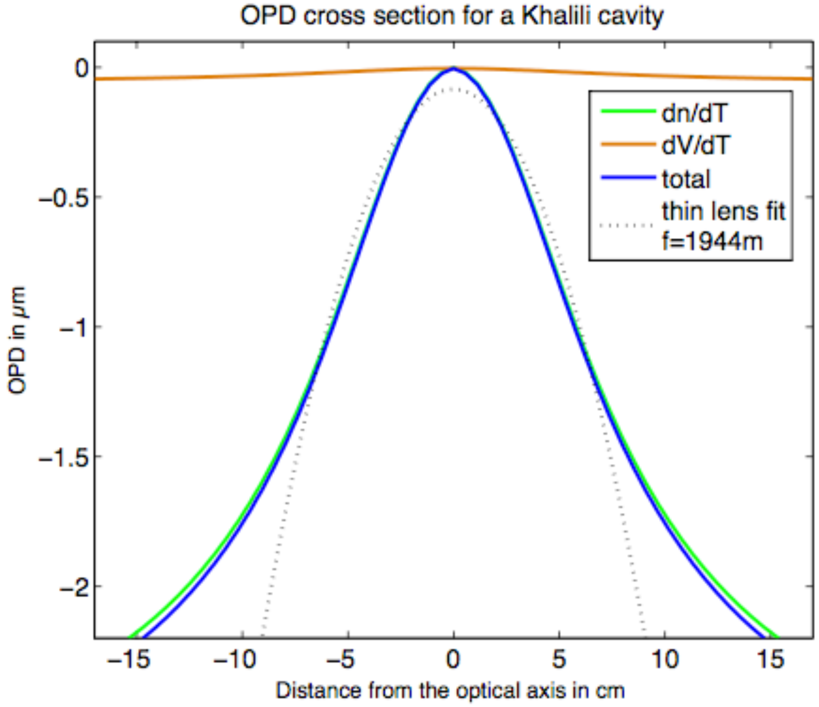
- Extremely hardware intensive.
- Lots of technical challenges:
    - Thermal lensing
    - Cavity stability
    - Control





Thermal lensing in K-cavity





Reducing thermal noise in future gravitational wave detectors by employing Khalili etalons

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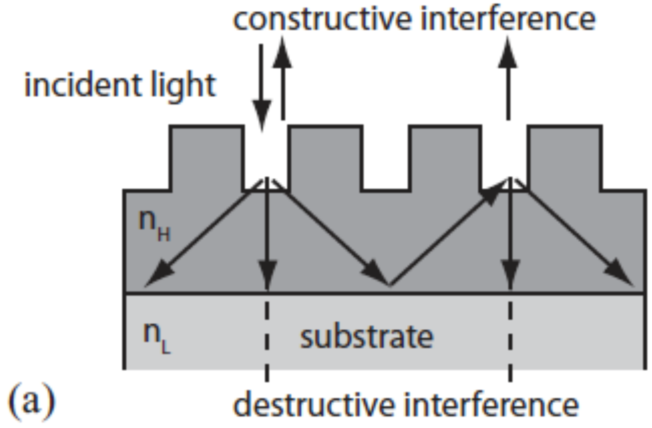
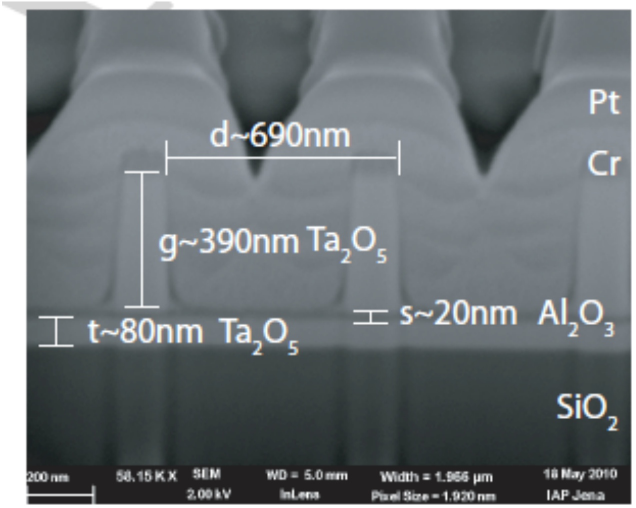
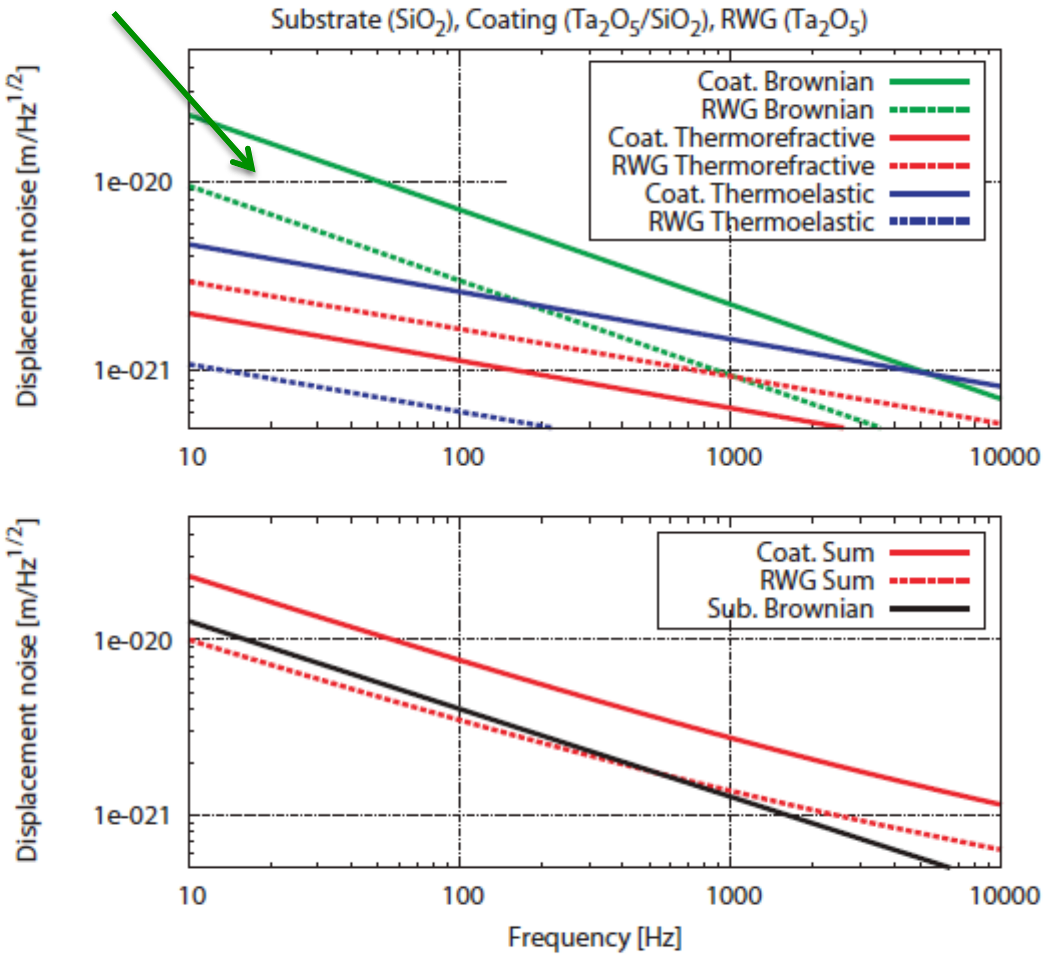
Waveguide mirrors



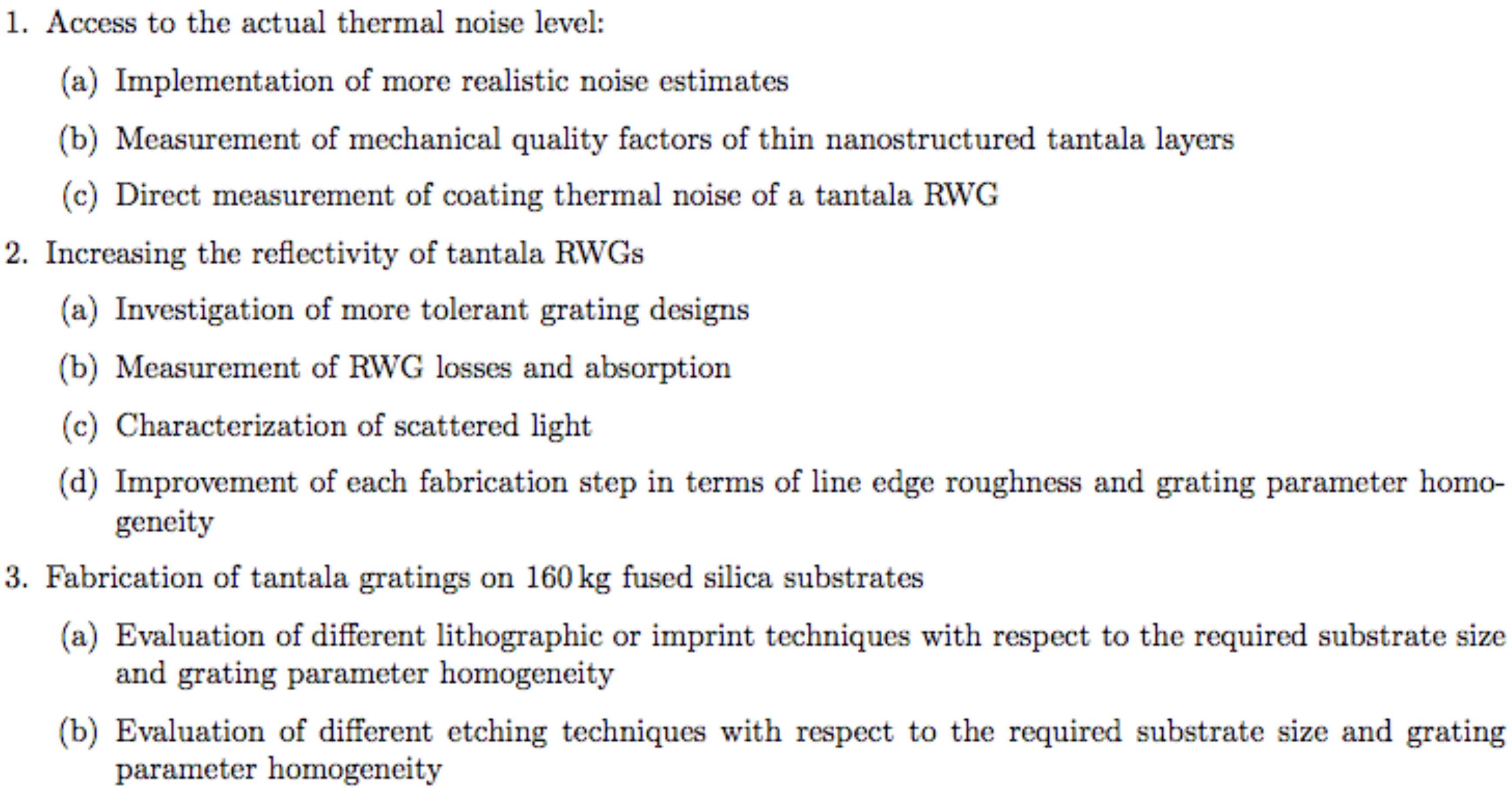


Factor of 2 lower total noise



From D. Friedrich PhD thesis

R+D required for waveguide mirrors



1. Access to the actual thermal noise level:
    - (a) Implementation of more realistic noise estimates
    - (b) Measurement of mechanical quality factors of thin nanostructured tantala layers
    - (c) Direct measurement of coating thermal noise of a tantala RWG
2. Increasing the reflectivity of tantala RWGs
    - (a) Investigation of more tolerant grating designs
    - (b) Measurement of RWG losses and absorption
    - (c) Characterization of scattered light
    - (d) Improvement of each fabrication step in terms of line edge roughness and grating parameter homogeneity
3. Fabrication of tantala gratings on 160 kg fused silica substrates
    - (a) Evaluation of different lithographic or imprint techniques with respect to the required substrate size and grating parameter homogeneity
    - (b) Evaluation of different etching techniques with respect to the required substrate size and grating parameter homogeneity

Quantum noise

- **Quantum noise:** We assumed the same interferometer configuration and optical power as for aLIGO. The quantum noise improvements originate from an increased test mass weight of 160 kg and the injection of frequency dependent squeezed light. We consider an initial squeezing level of 20 dB and losses of 9 % plus the roundtrip loss in the filter cavity. The filtercavity has a length of 300 m and a roundtrip loss of 30 ppm.

Laser and Optical Parameters		
Laser Wavelength	1064 nm	1064 nm
Optical Power at Test Masses	730 kW	730 kW
Arm Cavity Finesse	450	450
Signal Recycling	$T = 20\,\%$, tuned	$T = 20\,\%$, tuned
Squeezing Factor	n.a.	20 dB
Filtercavity (FC) length	n.a.	300 m
FC Detuning	n.a.	-16.8 Hz
FC Input Mirror Transmittance	n.a.	425 ppm
Squeezing Losses	n.a.	9 % + 30 ppm roundtrip in FC

Squeezing losses

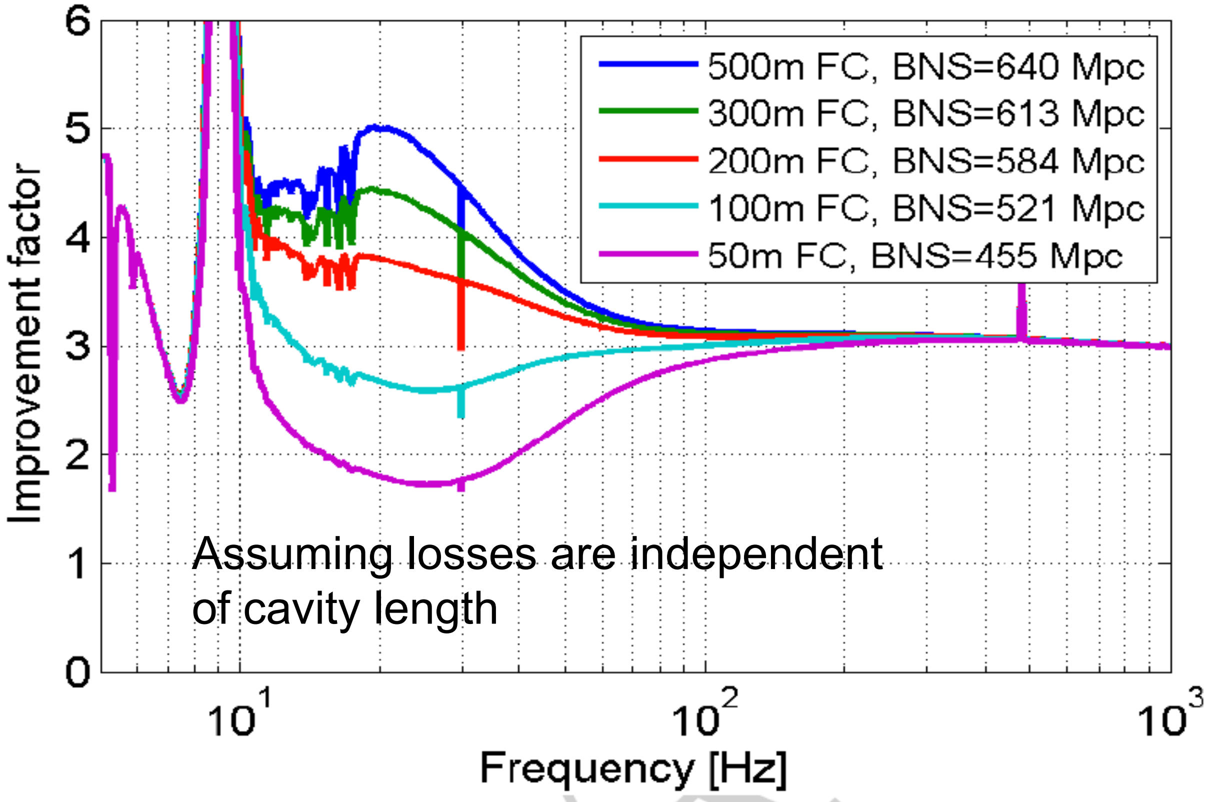
- Generation of squeezing: 3 %
- Optical isolation: 3 x 0.8 %
- Mode matching to IFO and to OMC: 2 x 1 %
- OMC loss and QE of PD: 2 x 0.5 %
- Mode matching to filter cavity: 1 %

= 9% in total

Cavity losses in literature

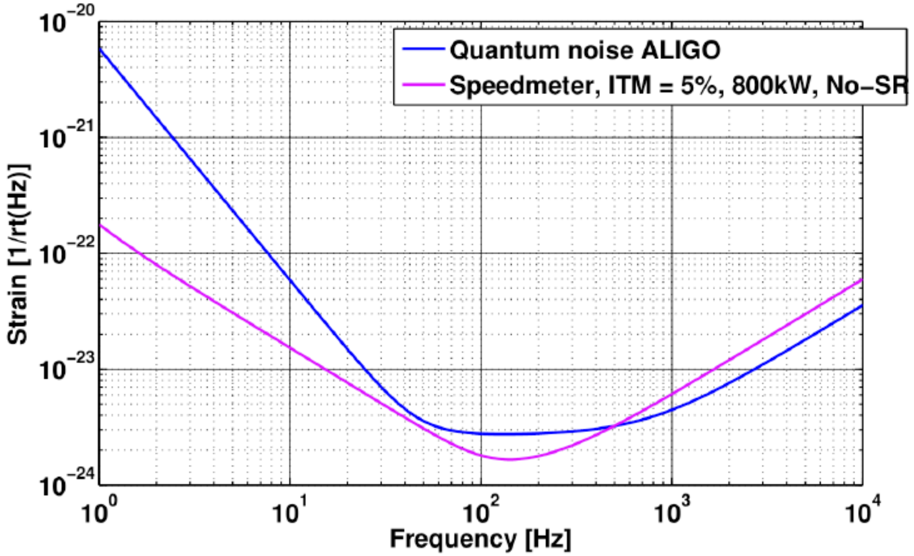
Length [m]	Loss per mirror [ppm]	Year
10	60	1984 [61]
0.004	1.1	1992 [62]
0.202	1.5	1996 [63]
0.202	1.6	1998 [64]
20	30	1999 [?]

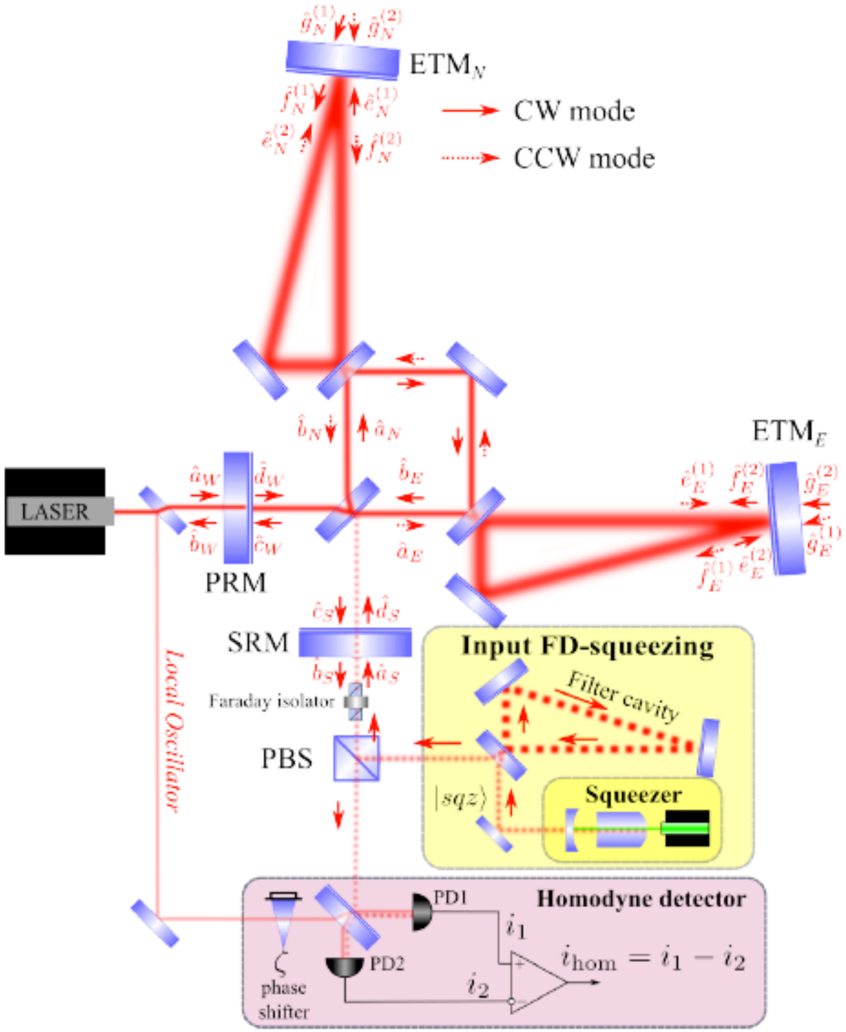
Filter cavity length [m]	500	300	200	100	50
Input mirror power transmittance [ppm]	704	422	281	141	70
Binary neutron star inspiral range [MPc]	640	613	584	521	455



Assuming losses are independent of cavity length

Speedmeter an alternative?





Parameter	Description	Value (4-km filter cavity)	Value (100-m filter cavity)
M	Mirror mass	40 kg	40 kg
L	Arms length	3995 m	3995 km
λ_0	Laser wavelength	1.064 μm	1.064 μm
P_c	Power in arms	2×750 kW	2×750 kW
η	quantum efficiency of PD	95%	95%
$\epsilon_{\rm arm}$	round-trip loss in arms	40 ppm	40 ppm
$\epsilon_{\rm FC}$	round-trip loss in FC	40 ppm	40 ppm
ζ	optimal homodyne angle	6.43 degrees	15 degrees
e^{2r}	squeezing factor	10 dB	10 dB
ψ_0	constant squeezing phase shift	6.46 degrees	15.5 degrees
$T_{\rm ITM}$	ITM power transmissivity	0.052	0.06
$T_{\rm SRM} = 1 - \rho_{\rm SR}^2$	SRM power transmissivity	0.89	0.9
$\phi_{\rm SRC}$	SR cavity detune phase	90	73.7 degrees
T_f	FC input mirrot power transmissivity	0.017	0.023
L_f	FC length	3.995 m	100 m
$\gamma_f = \frac{cT_f}{4L_f}$	FC half-bandwith	$2\pi \times 49$ sec^{-1}	$2\pi \times 540$ sec^{-1}
δ_f	FC detuning	$2\pi \times 32$ sec^{-1}	$2\pi \times 255$sec^{-1}

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Strawman Red Costs

On the following two pages a dummy-costing for the here presented Strawman-Red design can be found. The principal elements of the design were interpreted in terms of the hardware required to realize them, and then estimates made where ever possible as increments upon the Advanced LIGO parts to base them in reality. Others were based on relatively recent data from Advanced Virgo or the ET design exercise. Please note that the quality of the given numbers varies significantly as some are based on up-to-date quotes, some are scaled or based on outdated quotes, and some are educated guesses. Therefore, these numbers should only be considered as ballpark, but they are probably good enough for the purpose at hand. For equipment, the total estimated cost, per interferometer, is roughly censored

In the table, for most elements, the following manpower-intensive items are not included:

- Design costs
- Conditioning (cleaning)
- Assembly
- Test
- Installation
- Shakedown
- Contingency (was an average of about 25 % for aLIGO)

For aLIGO, the labor costs post-design were about 2/3 the cost for the labor-intensive equipment. Since much of the expense of the Strawman Red design however is not labor intensive (a large portion of the cost is in Suprasil and figuring by others, beam tubes and vacuum chambers, buildings), we might expect censored USD for labor (US accounting, benefits but no overhead) on top of the about censored for components (shown in Figure 17), **thus yielding a total cost of about censored dollars per interferometer. Contingency would be in addition.**

Strawman red Dummy costing v0.4

	Item	Description	Price/item [k$]	Number required for one interferometer	Total price per single IFO [k$]	source for the price	Remarks
Injection of frequency dependent squeezing	1	Low-loss, large aperture Faraday isolator	[redacted]	3	[redacted]	Hartmut, From GEO faraday	1x FI for squeezing injection, 2x FI for
	2	Squeezing source	[redacted]	1	[redacted]	Henning, from GEO squeezer	
	3	Filter cavity mirrors (ALIGO recycling mirror dimensions), super-polished, various coatings	[redacted]	2	[redacted]	RM/dhs	aLIGO RM
	4	Filter cavity suspensions (same as ALIGO recycling mirror)	[redacted]	2	[redacted]	DHS	aLIGO mech+elec
	5	Small vacuum tank (1.2m diameter) for filtercavity suspension	[redacted]	2	[redacted]	DHS	Scaled from BSC
	6	End building for filter cavity (5x5m)	[redacted]	1	[redacted]	DHS	LIGO Australia estimates
	7	300 meter of vacuum tube (50cm diameter) for filter cavity, pumping, instrumentation	[redacted]	1	[redacted]	JW/dhs/MEZ	scaled from LIGO-Aus. BT
	8	Acoustic enclosure with cleanroom 4mx4m (similar to ALIGO laser or detection room) for the squeezing source and the injection of the squeezed light into the filtercavity.	[redacted]	1	[redacted]	JW/dhs	aLIGO, scaled down a bit
	9	CDS for squeezing control (about 50 channels)	[redacted]	1	[redacted]	dhs	guess from aLIGO ISC
		Total cost of quantum noise upgrades			[redacted]		
GGN	10	3x Geophone based seismometer	[redacted]	120	[redacted]	Jan	30x 3-axis seismometers per main testmass
	11	power, ADC + recording of 30 slow (f<50Hz) channels	[redacted]	4	[redacted]	dhs	guess
		Total cost of Newtonian noise upgrades			[redacted]		
Suspension upgrades	12	Suprasil 312 rectangular fused silica penultimate mass (54cm long, 26cm wide, 26 cm thick, 1/10 polished side faces)	[redacted]	4	[redacted]	dhs	scaled from costs for line 21, per GLB
	13	EUCLID interferometers	[redacted]	24	[redacted]	Stefan, from recetly bought Euclid	
	14	Redesign/Fabrication of QUAD main chain/reaction chain structure to accommodate 1.2m long suspension	[redacted]	4	[redacted]	DHS - new fabrication	Scaled from ALUK plus LIGO elect.
	15	Redesign/Fabrication of ISI metal cantilever springs and flexures to support higher QUAD load	[redacted]	4	[redacted]	FM	aLIGO
	16	Redesign/Fabrication of new intermediate and upper intermediate metal masses	[redacted]	4	[redacted]	DHS	
	17	Redesign/Fabrication of QUAD metal cantilever springs to support total loads of 85kg/spring (stage 0), 72kg/spring (stage 1) and 60kg/spring (stage 2).	[redacted]	4	[redacted]	DHS	

	18	Design/Fabrication of pillars to lift ISI/QUAD by approximately 30"	[redacted]	4	[redacted]	DHS	guess
	19	Extension of the pulling machine ballscrew unit to 1.5m	[redacted]	1	[redacted]	DHS	guess
		Total cost of suspension upgrades			[redacted]		
Beamsize increase of 1.6	20	Input test masses, 160kg Suprasil 3002 (cylindrical: 54cm diameter, depth 32.4cm, λ/10 polished flats of size 32.4cmx 16.2cm.)	[redacted]	2	[redacted]	Harald from 200kg ET quote: 3.0k€ /kg	
	21	End test masses, 160kg Suprasil 312 (cylindrical: 54cm diameter, depth 32.4cm, λ/10 polished flats of size 32.4cmx 16.2cm.)	[redacted]	2	[redacted]	1.58k€/kg based on Adv. Virgo estimate	
	22	Polishing of a main mirror	[redacted]	4	[redacted]	Harald	
	23	Coating runs for main test masses (2xHR, 1xAR)	[redacted]	3	[redacted]	Harald	
	24	Beam splitter, 21kg, 55cm diamter, 6cm dept, Suprasil 3001	[redacted]	1	[redacted]	Harald from 200kg ET quote: 3.5k€ /kg	
	25	Modified beam splitter suspension	[redacted]	1	[redacted]	DHS	aLIGO
	26	Modified recycling cavity telescope mirrors and suspensions (PR+SR) to allow 1.6 times larger beam size in the arm cavities.	[redacted]	1	[redacted]	DHS	Half of the aLIGO IO optics plus susp.
		Total cost of increasing beamsize by 1.6			[redacted]		
Khalili cavities	27	Additional end station (10x10m) with crane	[redacted]	2	[redacted]	Harald: 5k$/m^2	
	28	50 m beam tube + enclosure + road etc	[redacted]	2	[redacted]	Harald: 10k$/m^2	
	29	BSC Vacuum vessel	[redacted]	2	[redacted]	JW/dhs	LIGO Australia estimates
	30	gate valve (tube diameter)	[redacted]	2	[redacted]	JW/dhs	LIGO Australia estimates
	31	Vacuum pumps and control for additional chamber	[redacted]	2	[redacted]	JW	LIGO Australia estimates
	32	Active seismic isolation system for main mirror	[redacted]	2	[redacted]	DHS, Scaling	aLIGO
	33	Full Quad-suspension for EETM of 160 kg	[redacted]	2	[redacted]	DHS	aLIGO/ALUK
	34	IETM, 160kg Suprasil 3002 (cylindrical: 54cm diameter, depth 32.4cm, λ/10 polished flats of size 32.4cmx 16.2cm.)	[redacted]	2	[redacted]	same as 20	
	35	Polishing of IETM	[redacted]	2	[redacted]	same as 22	
	36	Coating runs for main test masses (1xHR, 1xAR)	[redacted]	2	[redacted]	same as 23	
	37	Control systems for 2 additional LSC and ASC degrees of freedom	[redacted]	1	[redacted]	DHS - scaling	aLIGO
		Total cost of Khalili cavities			[redacted]		
Opt 1	38	Change the wavelength to 1550nm (or similar), i.e. Replace all optical components and coatings, buy new 200W lasers etc.	[redacted]	1	[redacted]	dhs	aLIGO: COC + IO + Laser = $28.2M. Need a bit more. So $10M/IFO
		Total estimated cost of components Strawman Red for a single interferometer [k$]			[redacted]		

More Details of the Team Red Design

- For details please see documents on the DCC:
- 50 page long description of the Team Red Design can be found at https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=78100
- The sensitivity data for the Team Red design are available at https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=86562

LIGO 3 Strawman Design, Team Red

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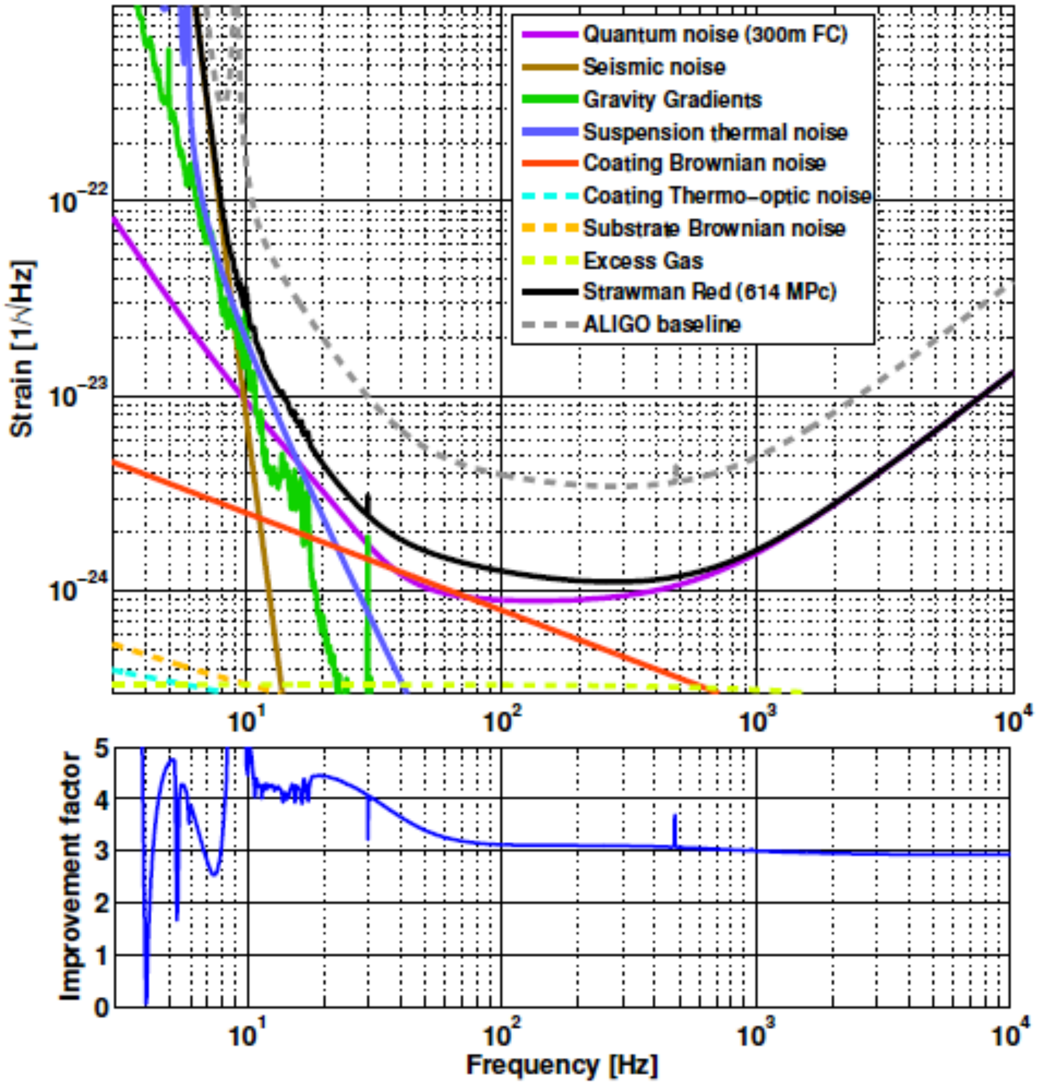
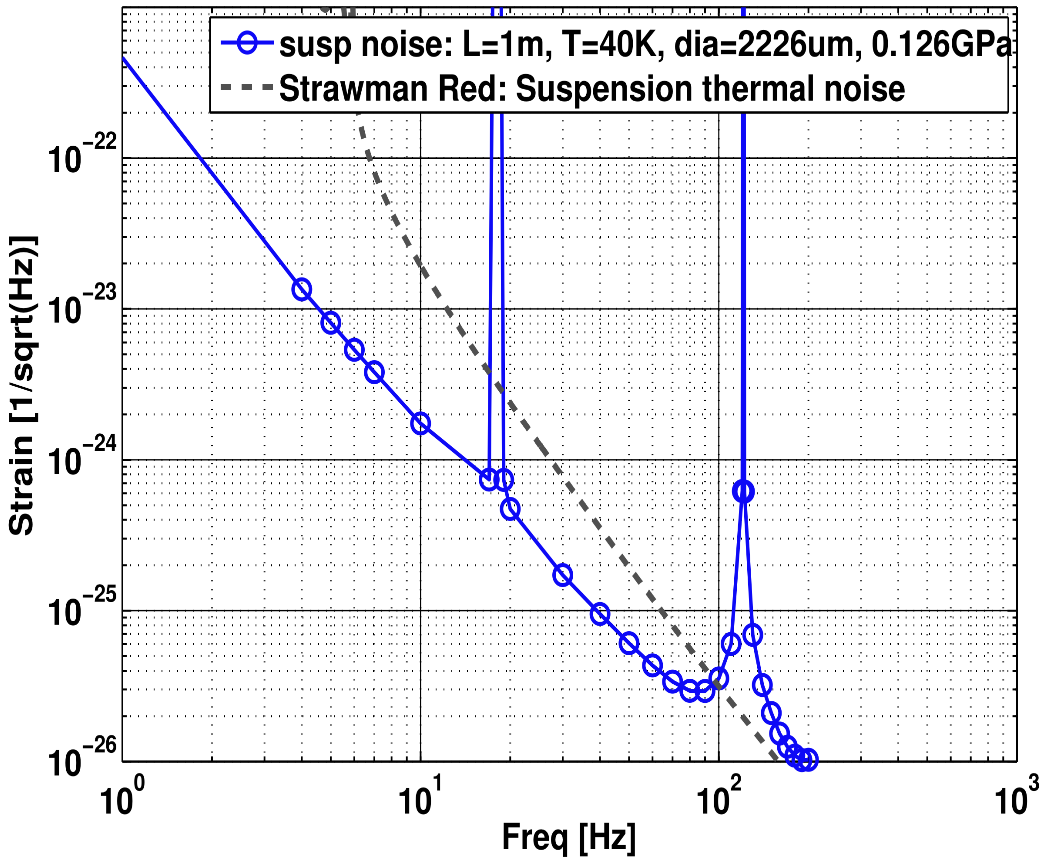
Benefits of a (modified) Strawman red H1 with a cryogenic H2 ?

- Building a cryogenic xylophone can in principle allow reduction of thermal noise and radiation pressure noise and therefore improve the low frequency sensitivity.
- However, looking at the Strawman Red noise budget we see that to do this GGN needs to be subtracted - important R&D area.
- For the following investigations we assumed that seismic and GGN could be significantly reduced by subtraction, feedforward or similar techniques. (For simplicity we completely exclude them for the moment.)



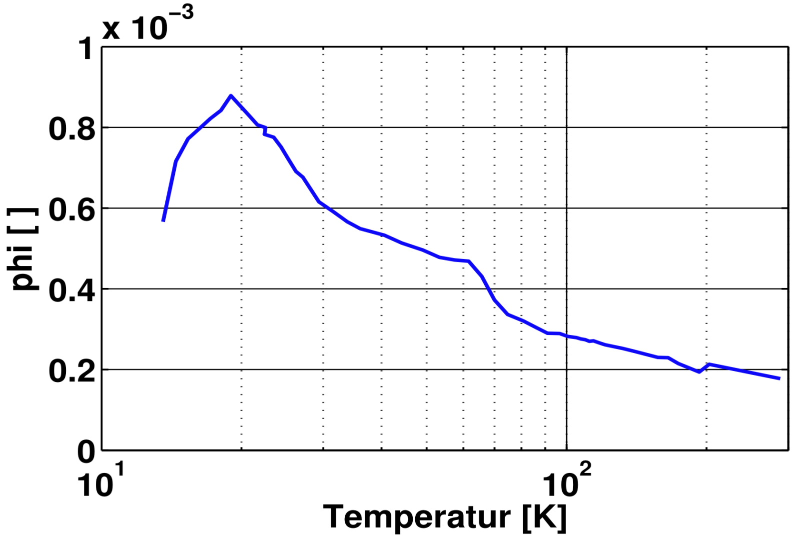
Suspension TN

- Allows to extract the power similar to ET-D-LF: 18kW * 1ppm = 18mW
- Cryogenic silicon suspension at 40K.
- Improvement of about factor 10 at 10Hz.
- Stress was chosen to be half of the current (quick) lab measurement.
- Temperature was chosen as a compromise of heat extraction and TN performance.

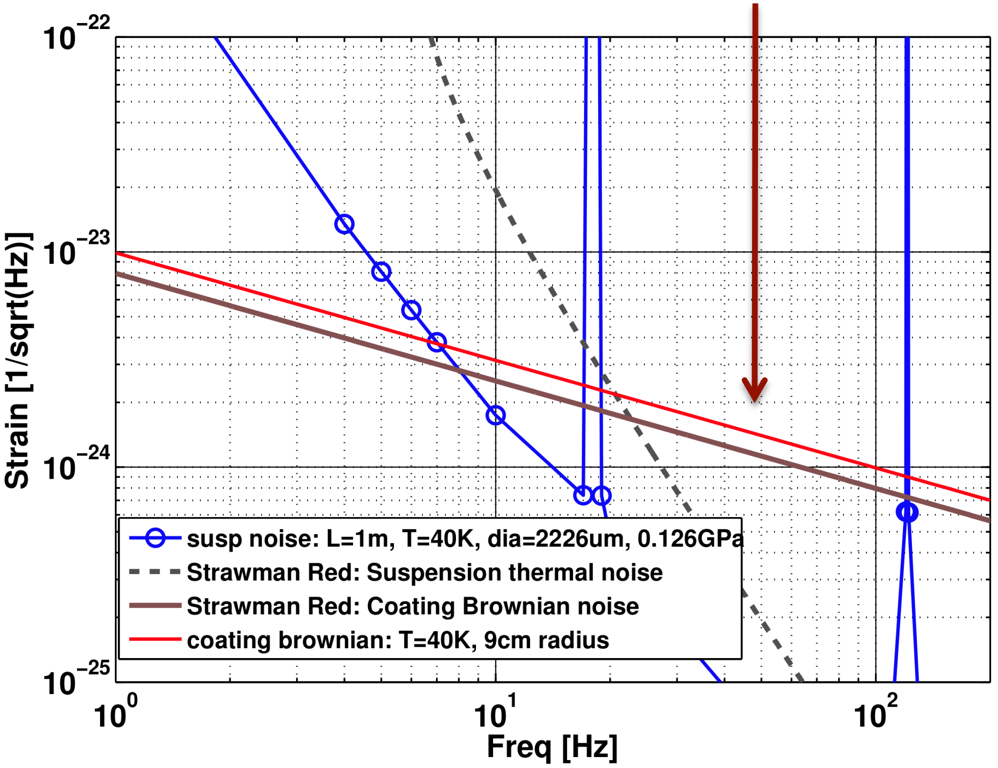


Coating noise

- **Assumes no better than tantala/silica coating on silicon substrate (conservative choice)**
- Uses measured phi values.
- Beam radius of 9 cm was assumed (same as ET-D-LF).



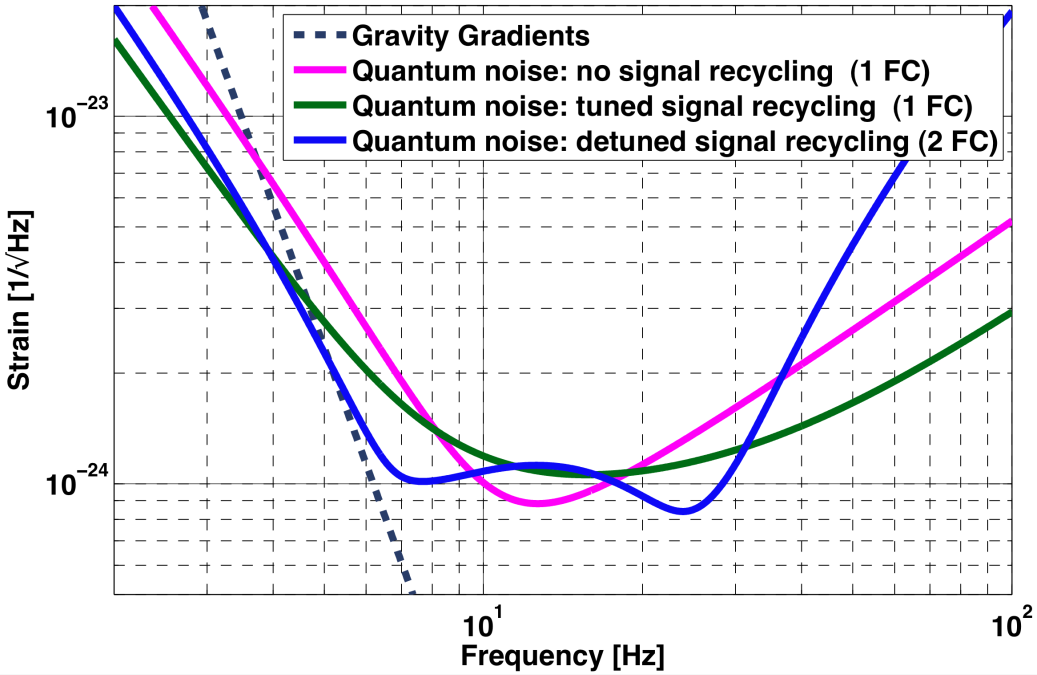
Please note: Strawman red includes a factor 2
From Khalili cavities and is therefore slightly better



Quantum noise

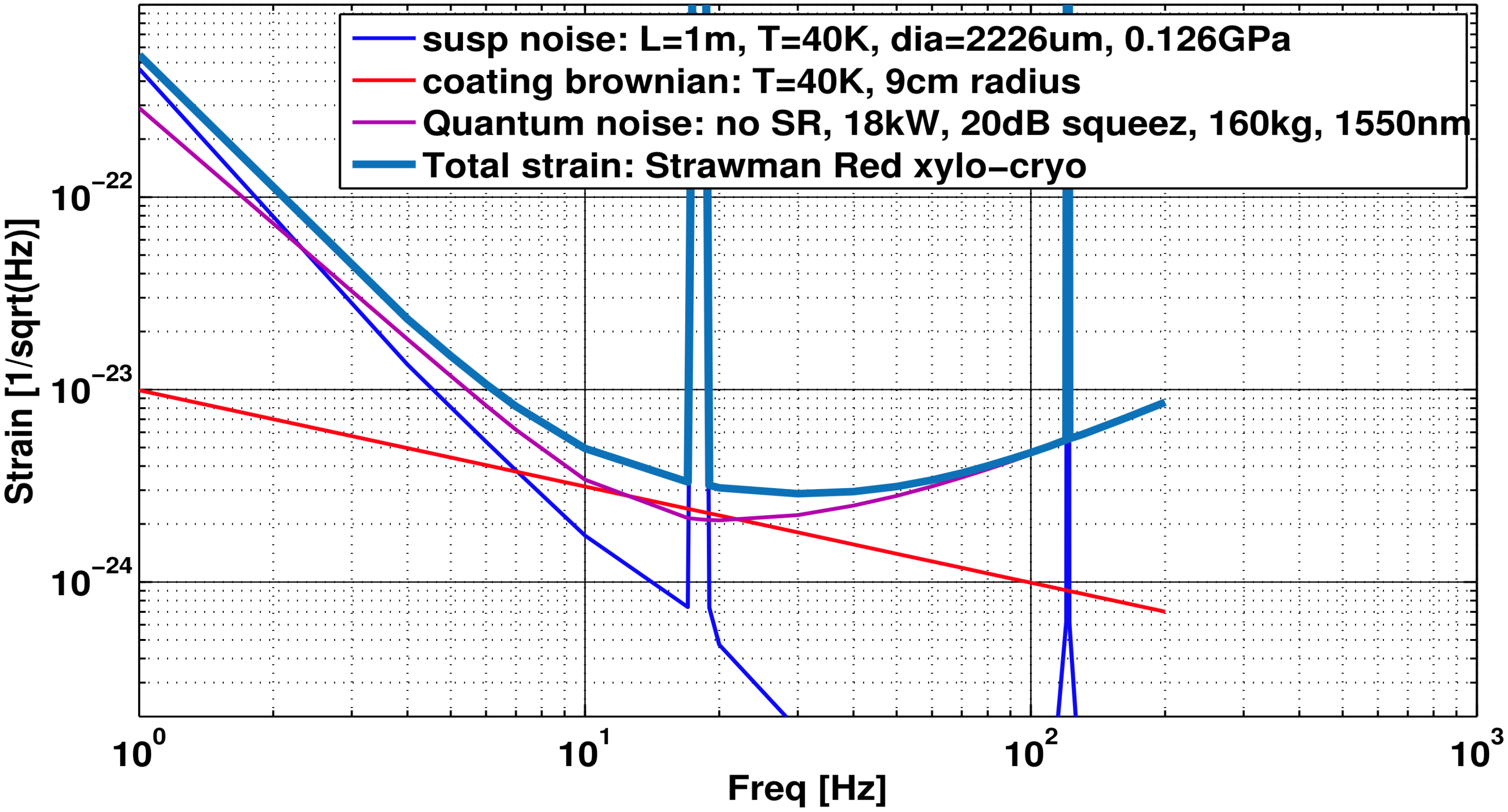
- Assumed 18kW of circulating power. 1550nm and test masses of 160kg. Squeezing of 20dB plus similar losses as for Strawman Red baseline, i.e. an improvement factor of 2.9 (nearly 10dB) in amplitude.
- Can optimise the SR configuration.
- For the moment we have chosen a FPMI without Signal recycling to give best sensitivity around 10Hz.
- This allows to get away with a short filtercavity

Examples of different SR configurations from ET-D_LF

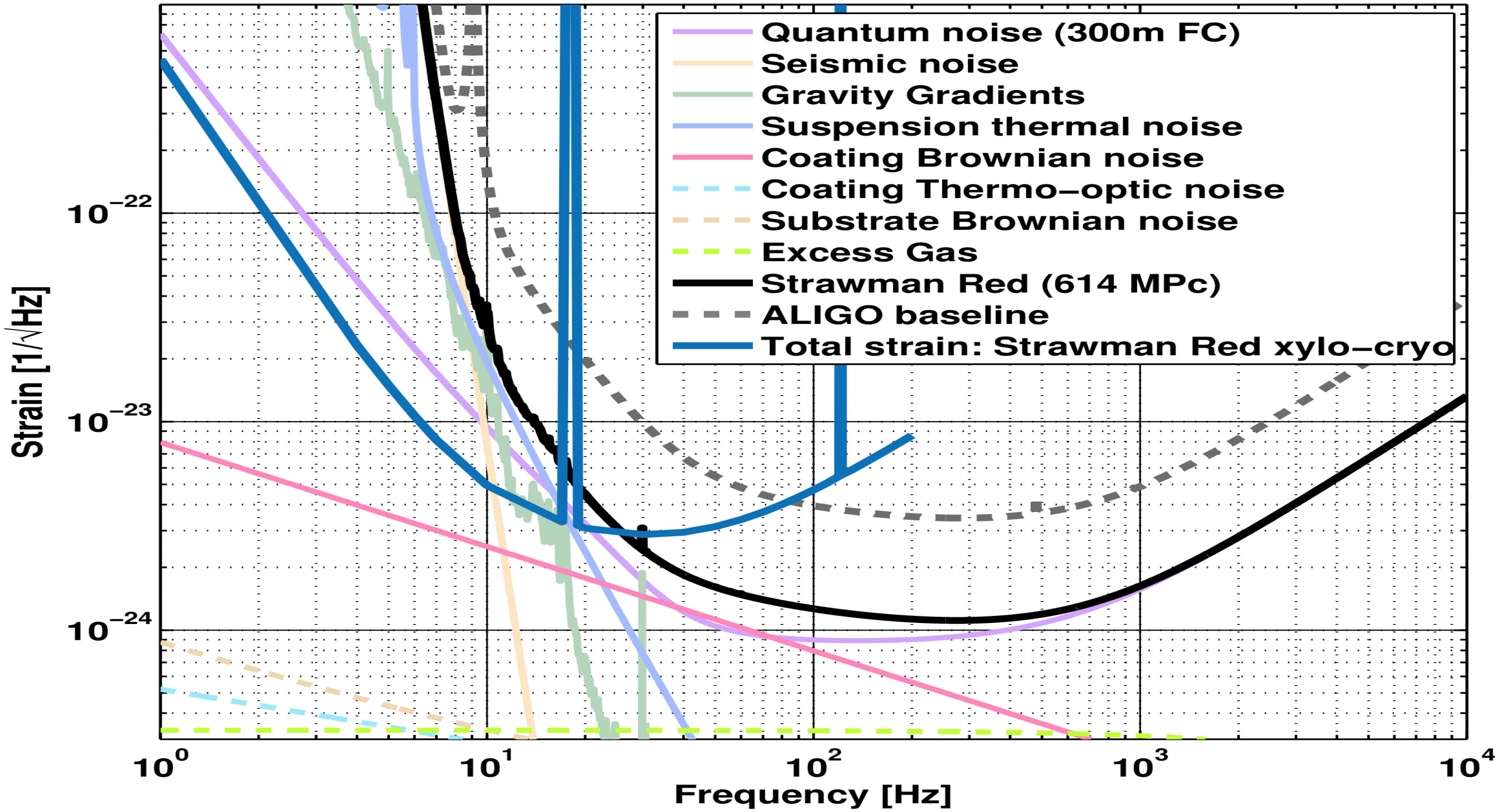


The Cryo noise budget

Please note: No GGN or seismic noise or any control noises are included here !!



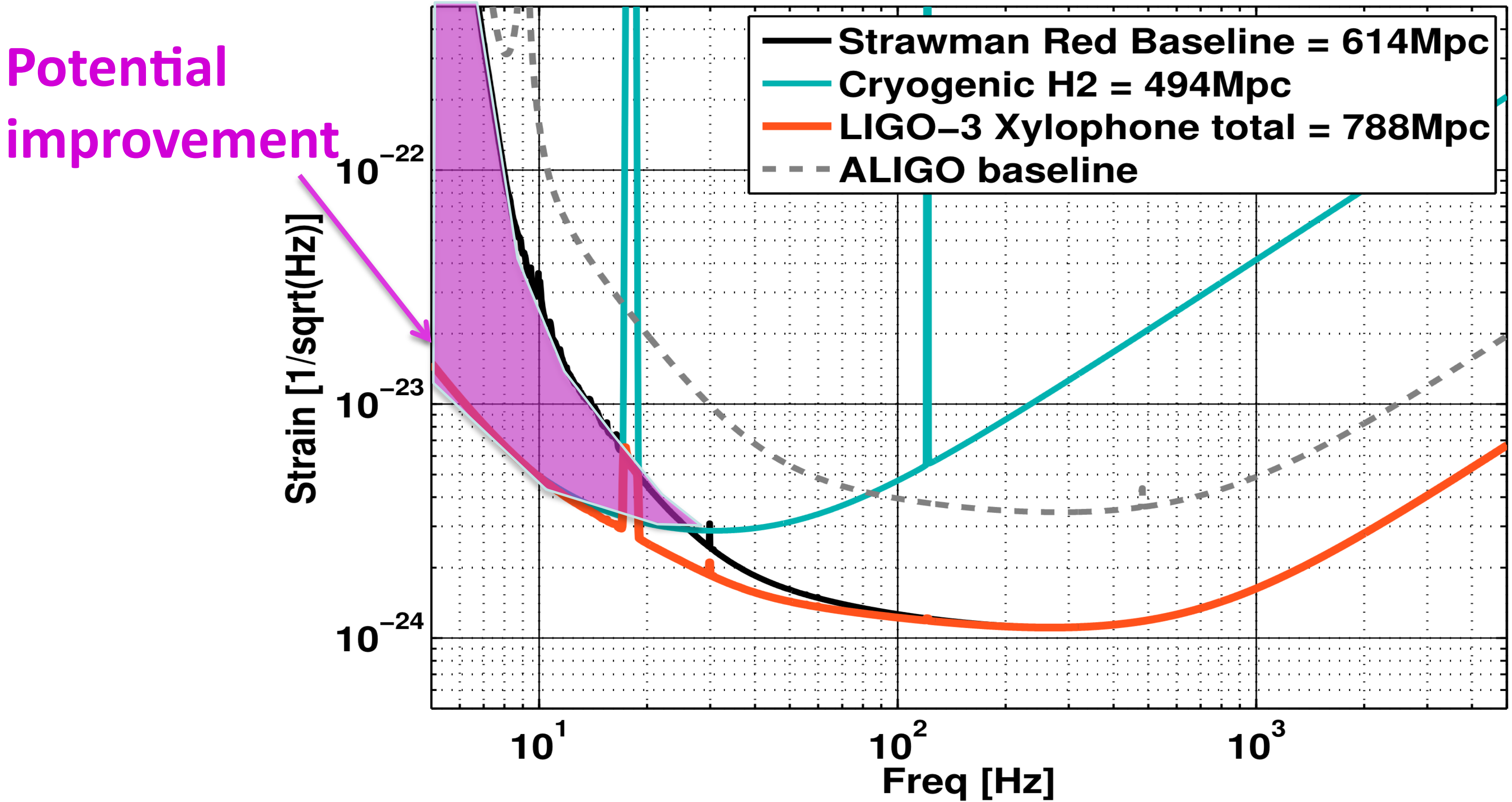
Cryogenic IFO plus room temperature Strawman Red



Please note: No GGN or seismic noise or any control noises are included in the LF detector noise budget !!

The full xylophone

Please note: No GGN or seismic noise or any control noises are included in the LF detector noise budget !!

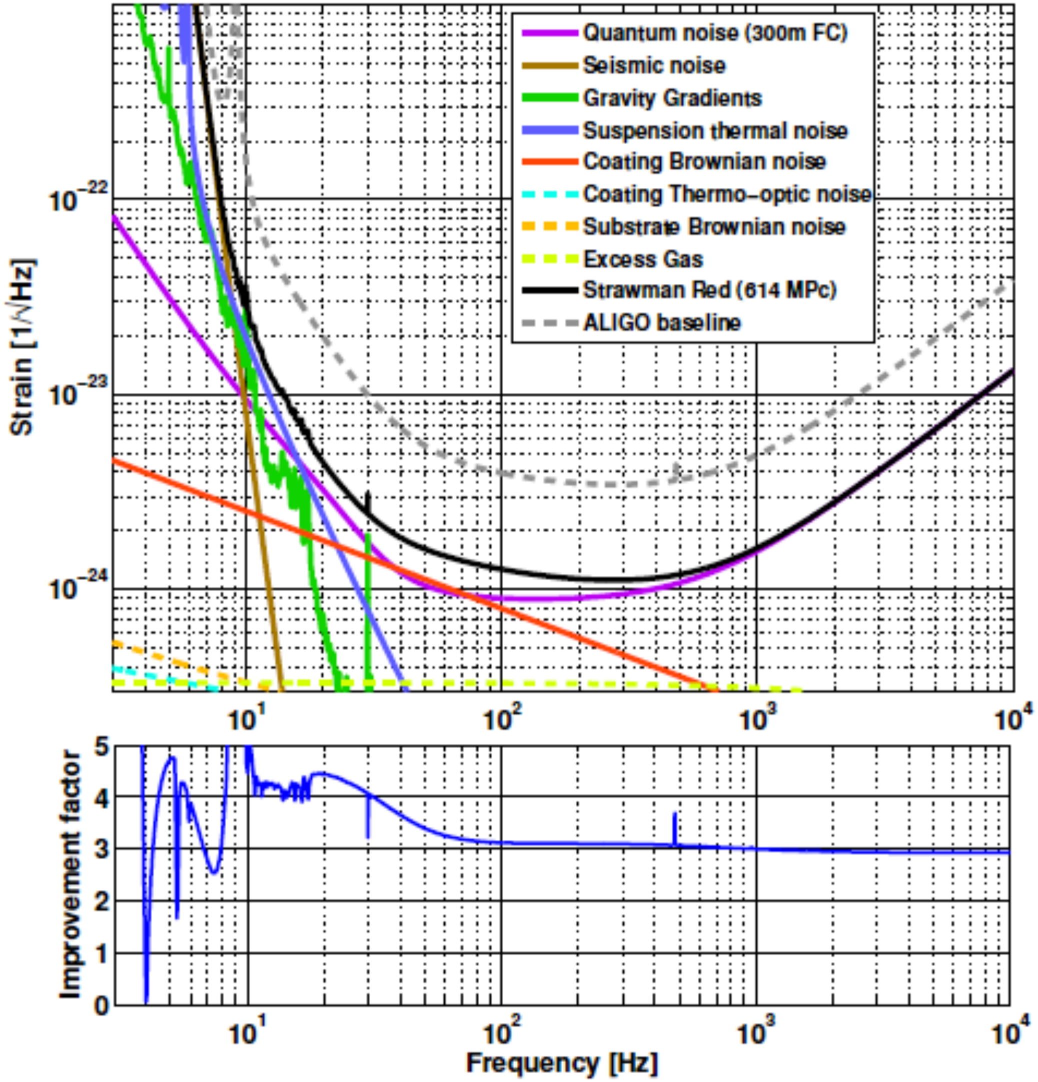


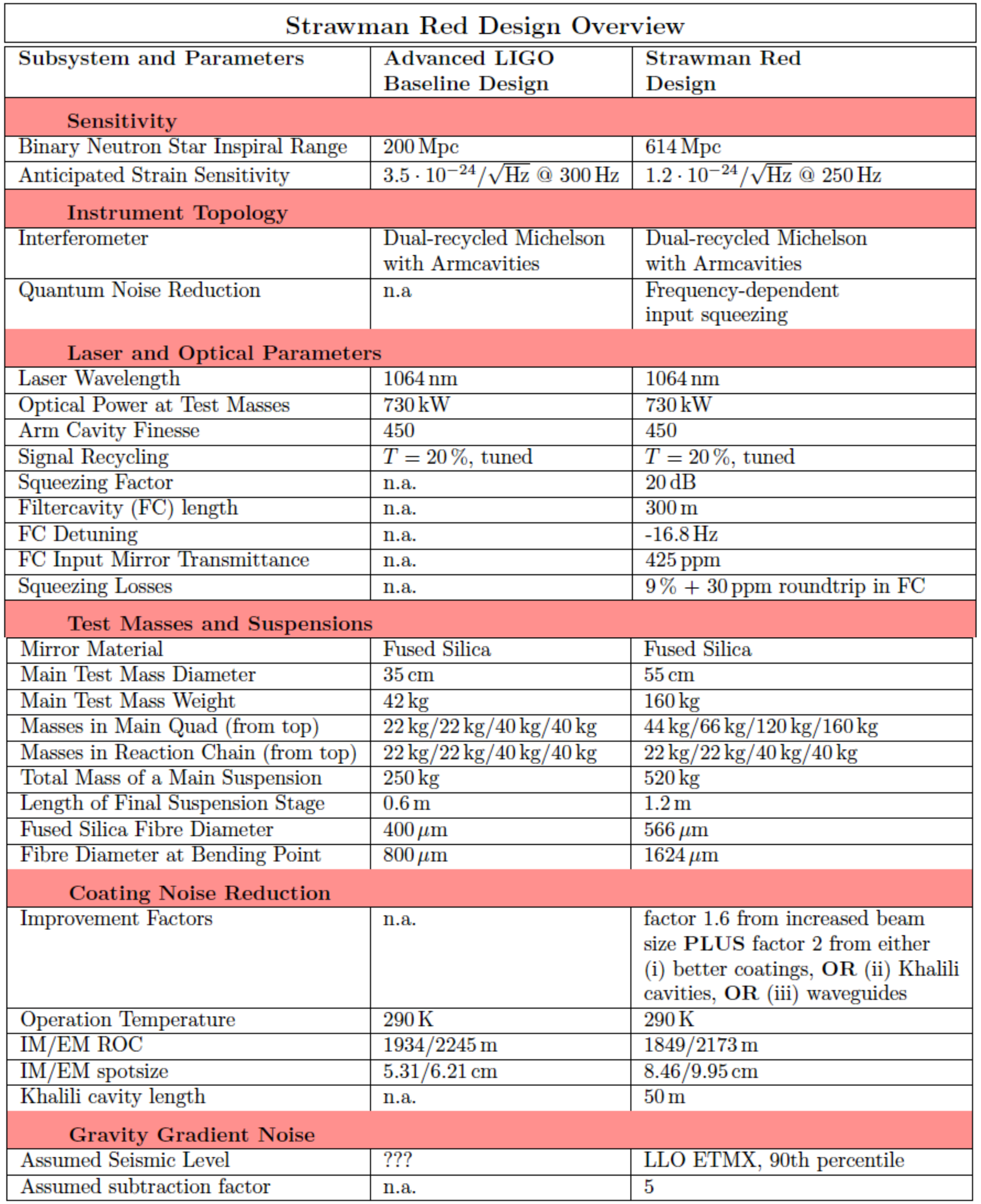
Numbers given in the legend refer to binary neutron star inspiral range.
A lower cut-off frequency of 5Hz was chosen.

What are the benefits of a xylophone?

- If gravity gradient noise and seismic noise can be mitigated, a cryogenic instrument accompanying a RT partner could make a significant low frequency sensitivity improvement
- Using a xylophone can allow simplifying the accompanying room temperature upgrade (for instance shorter suspensions etc)
- Going for a full xylophone (with test masses temperatures in 20-40K region) can give all the benefits of a cryogenic, low-power interferometer to cover the low frequency range while AT THE SAME TIME give the full benefit of a not too complex high-power interferometer covering the high frequency end.
- So we suggest exploring xylophone options in the R+D plans for LIGO-3.

Overview





Strawman Red Design Overview

Subsystem and Parameters	**Advanced LIGO Baseline Design**	**Strawman Red Design**
Sensitivity		
Binary Neutron Star Inspiral Range	200 Mpc	614 Mpc
Anticipated Strain Sensitivity	$3.5 \cdot 10^{-24}/\sqrt{\mathrm{Hz}}$ @ 300 Hz	$1.2 \cdot 10^{-24}/\sqrt{\mathrm{Hz}}$ @ 250 Hz
Instrument Topology		
Interferometer	Dual-recycled Michelson with Armcavities	Dual-recycled Michelson with Armcavities
Quantum Noise Reduction	n.a	Frequency-dependent input squeezing
Laser and Optical Parameters		
Laser Wavelength	1064 nm	1064 nm
Optical Power at Test Masses	730 kW	730 kW
Arm Cavity Finesse	450	450
Signal Recycling	$T = 20\,\%$, tuned	$T = 20\,\%$, tuned
Squeezing Factor	n.a.	20 dB
Filtercavity (FC) length	n.a.	300 m
FC Detuning	n.a.	-16.8 Hz
FC Input Mirror Transmittance	n.a.	425 ppm
Squeezing Losses	n.a.	9 % + 30 ppm roundtrip in FC
Test Masses and Suspensions		
Mirror Material	Fused Silica	Fused Silica
Main Test Mass Diameter	35 cm	55 cm
Main Test Mass Weight	42 kg	160 kg
Masses in Main Quad (from top)	22 kg/22 kg/40 kg/40 kg	44 kg/66 kg/120 kg/160 kg
Masses in Reaction Chain (from top)	22 kg/22 kg/40 kg/40 kg	22 kg/22 kg/40 kg/40 kg
Total Mass of a Main Suspension	250 kg	520 kg
Length of Final Suspension Stage	0.6 m	1.2 m
Fused Silica Fibre Diameter	400 μm	566 μm
Fibre Diameter at Bending Point	800 μm	1624 μm
Coating Noise Reduction		
Improvement Factors	n.a.	factor 1.6 from increased beam size **PLUS** factor 2 from either (i) better coatings, **OR** (ii) Khalili cavities, **OR** (iii) waveguides
Operation Temperature	290 K	290 K
IM/EM ROC	1934/2245 m	1849/2173 m
IM/EM spotsize	5.31/6.21 cm	8.46/9.95 cm
Khalili cavity length	n.a.	50 m
Gravity Gradient Noise		
Assumed Seismic Level	???	LLO ETMX, 90th percentile
Assumed subtraction factor	n.a.	5