# LIGO 3 Strawman Design, Team Red


B. Barr[1], A. Bell[1], C. Bell[1], C. Bond[2], D. Brown[2], F. Brueckner[2], L. Carbone[2], K. Craig[1], A. Cumming[1], S. Danilishin[3], K. Dooley[4], A. Freise[2], T. Fricke[4], P. Fulda[2], S. Giampsis[5], N. Gordon[1], H. Grote[4], G. Hammond[1], J. Harms[6], S. Hild[1,*], J. Hough [1], S. Huttner[1], R. Kumar[1], H. Lück[4], N. Lockerbie[7], J. Macarthur[1], I. Martin[1], P. Murray[2], S. Reid[1], S. Rowan [1], D. Shoemaker[8], B. Sorazu[1], K. Strain[1], S. Tarabrin[4], K. Tokmakov[1] and N. Voronchev[3]

[1] SUPA, School of Physics and Astronomy, The University of Glasgow, Glasgow, G12 8QQ, UK

[2] University of Birmingham, Birmingham, B15 2TT, UK

[3] Moscow State University, Moscow, 119992, Russia

[4] Max–Planck–Institut für Gravitationsphysik and Leibniz Universität Hannover, D-30167 Hannover, Germany

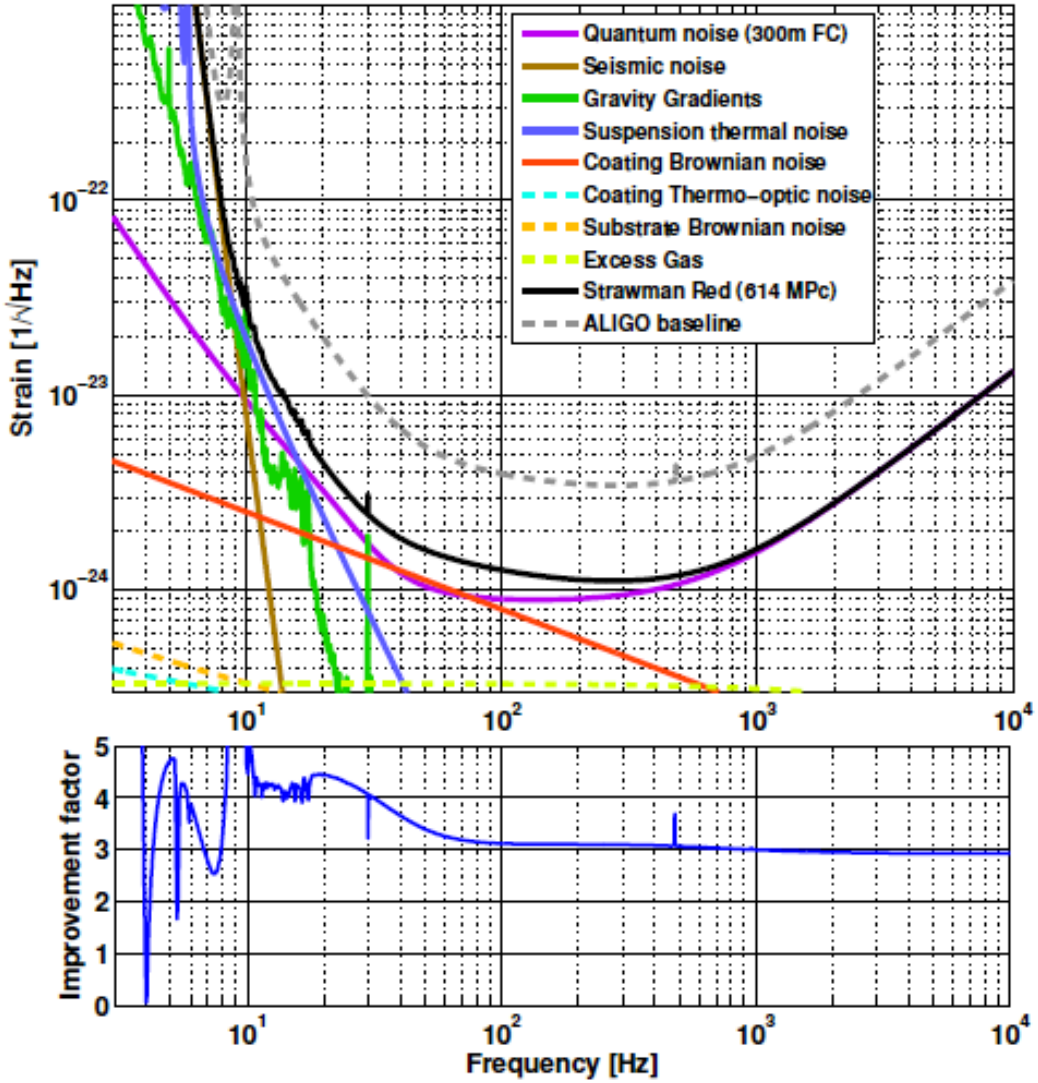
[5] University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA

[6] California Institute of Technology, Pasadena, California 91125, USA

[7] University of Strathclyde, Glasgow, G1 1XQ, UK

[8] Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

# 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 $\mu$m | 566 $\mu$m |
| Fibre Diameter at Bending Point | 800 $\mu$m | 1624 $\mu$m |
| **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 |

# Task description

Email from Eric Gustavson 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.*

# Some working assumptions

- 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.
- In addition we assumed that the seismic pre-isolation system is off limits, as replacing it would probably not fit within the targeted budget.
- 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.
- 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.
- 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.

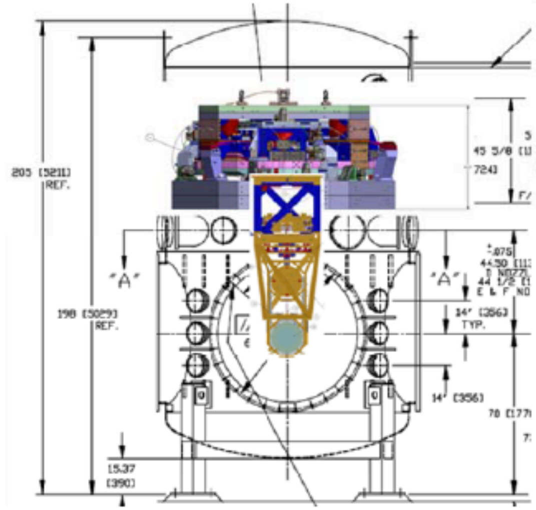
# To avoid misunderstandings …

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.

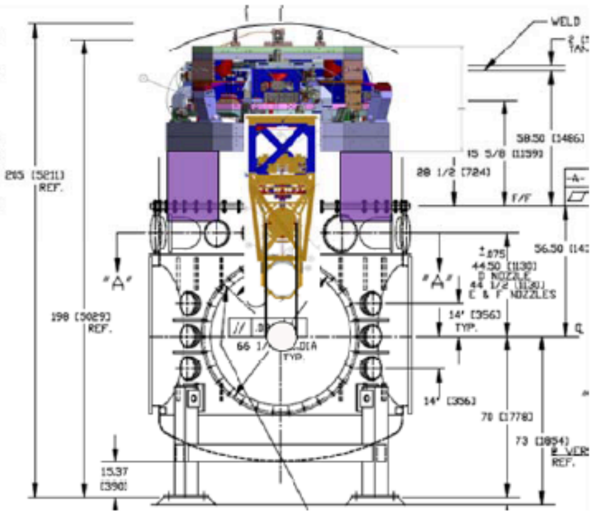
So please, see the rest of this document as an subjective example of what the Advanced LIGO upgrades **MAY** look like and not what they **WILL** or **WILL NOT** look like! The key task at the current stage of the progress is to identify and push forward the R&D required for allowing the advanced LIGO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

# Suspension Thermal Noise

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



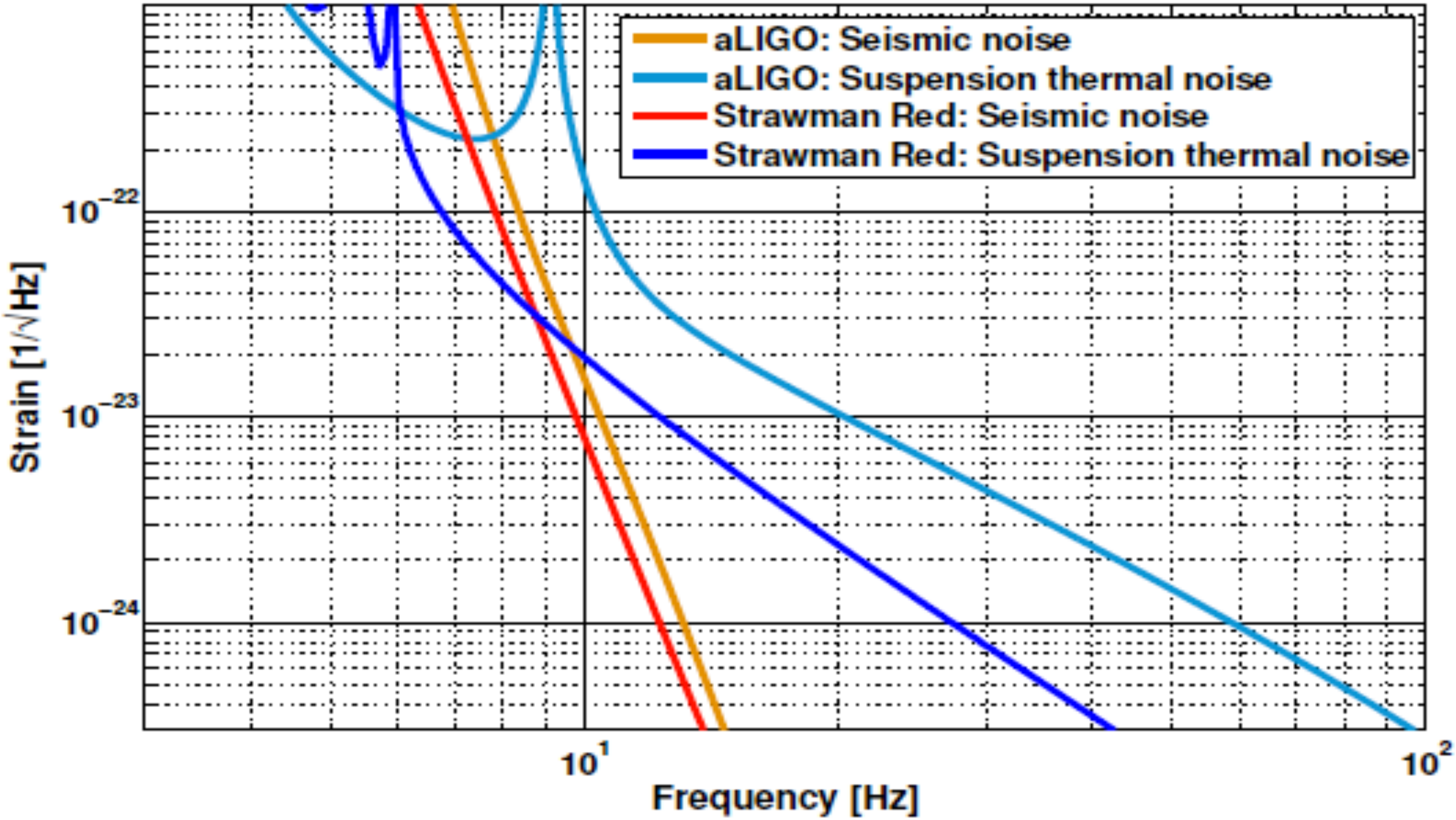
(a) aLIGO QUAD



(b) LIGO-3 QUAD

| 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 $\mu$m | 566 $\mu$m |
| Fibre Diameter at Bending Point | 800 $\mu$m | 1624 $\mu$m |

# 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.

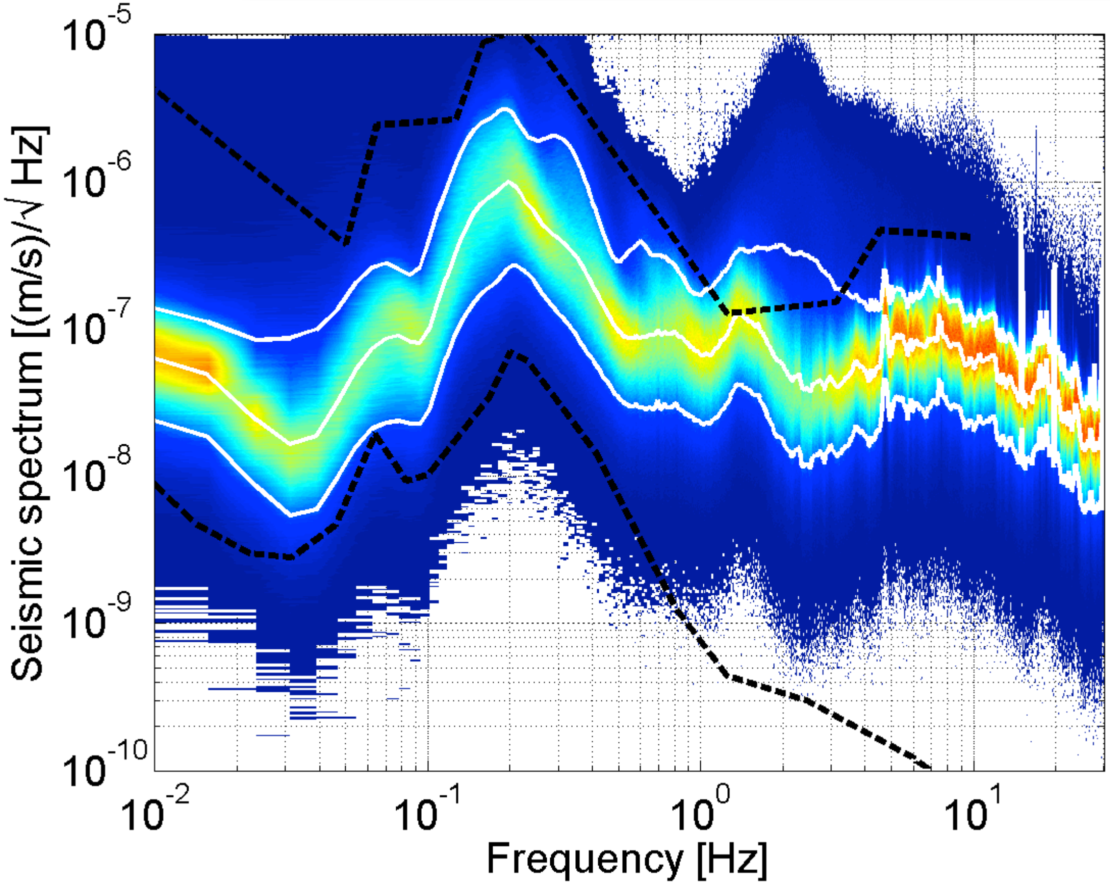
Used seismic from:

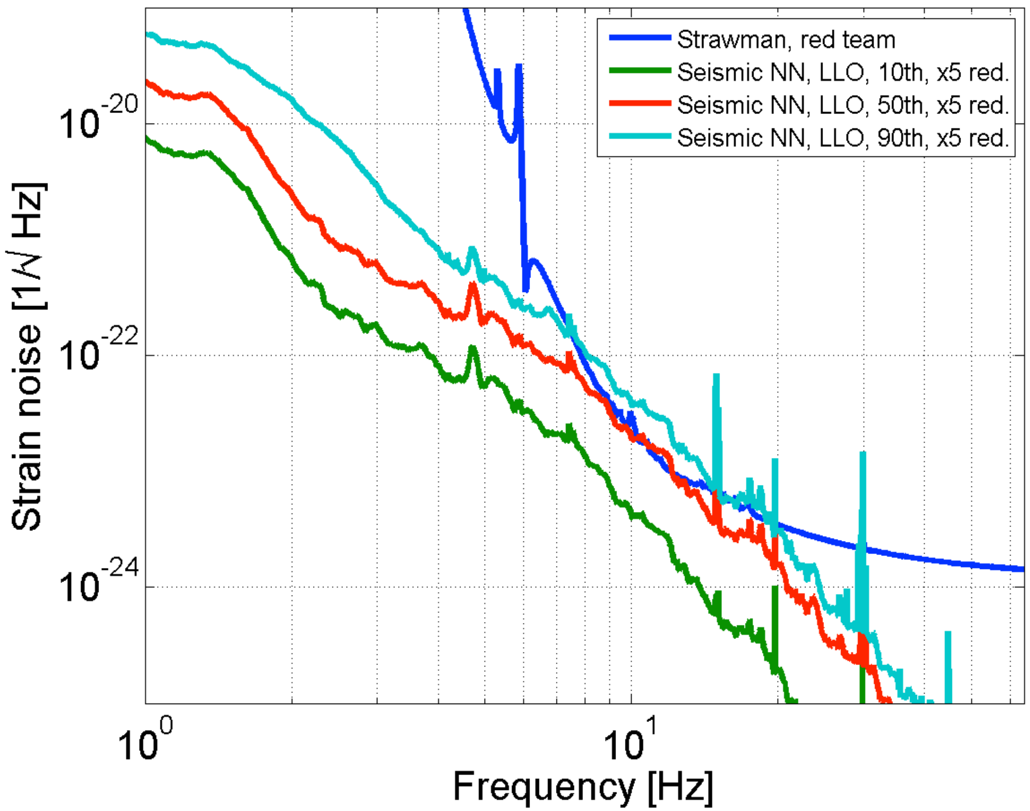
LIGO-T0900312-v1 *LIGO* June 26, 2009

**Reference Seismic Data for LLO**

P. Fritschel, S Waldman

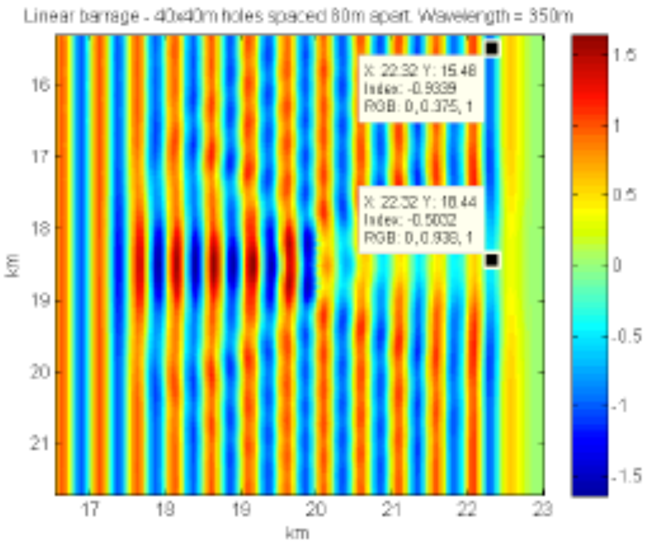
# Newer data from LLO

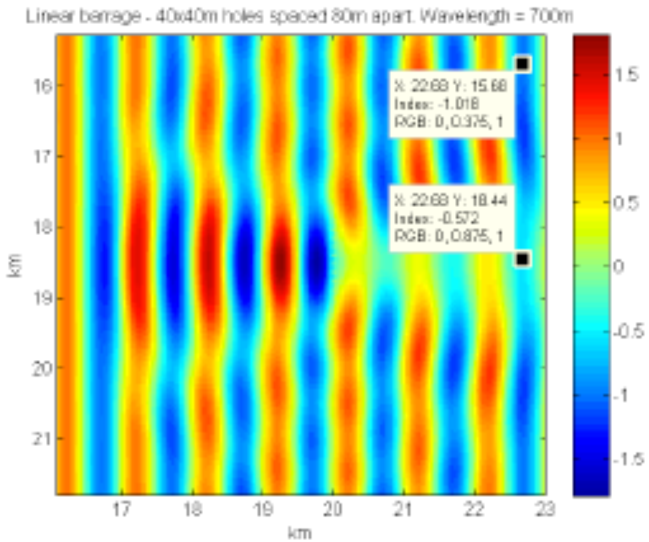


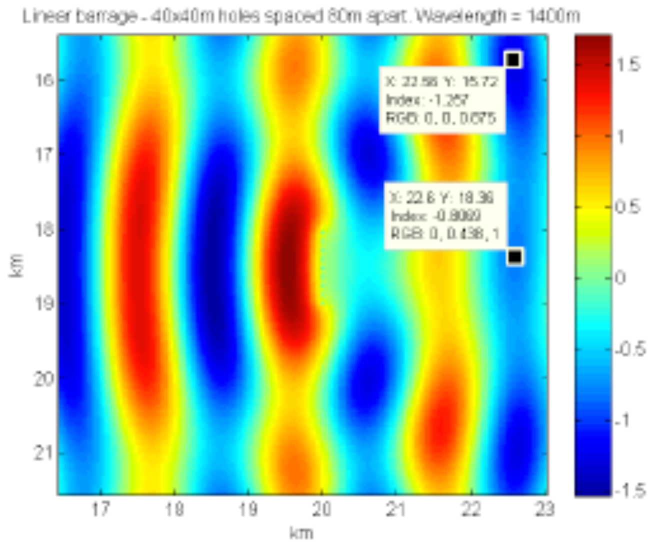




New data from LLO seem to suggest that Strawman red underestimates the GGN level by about a factor 2. Work in progress!

# Seismic barrages




- 2D finite-difference time-domain simulations for barrages of 40x40m.
- Attenuation of seismic by about a factor 2.

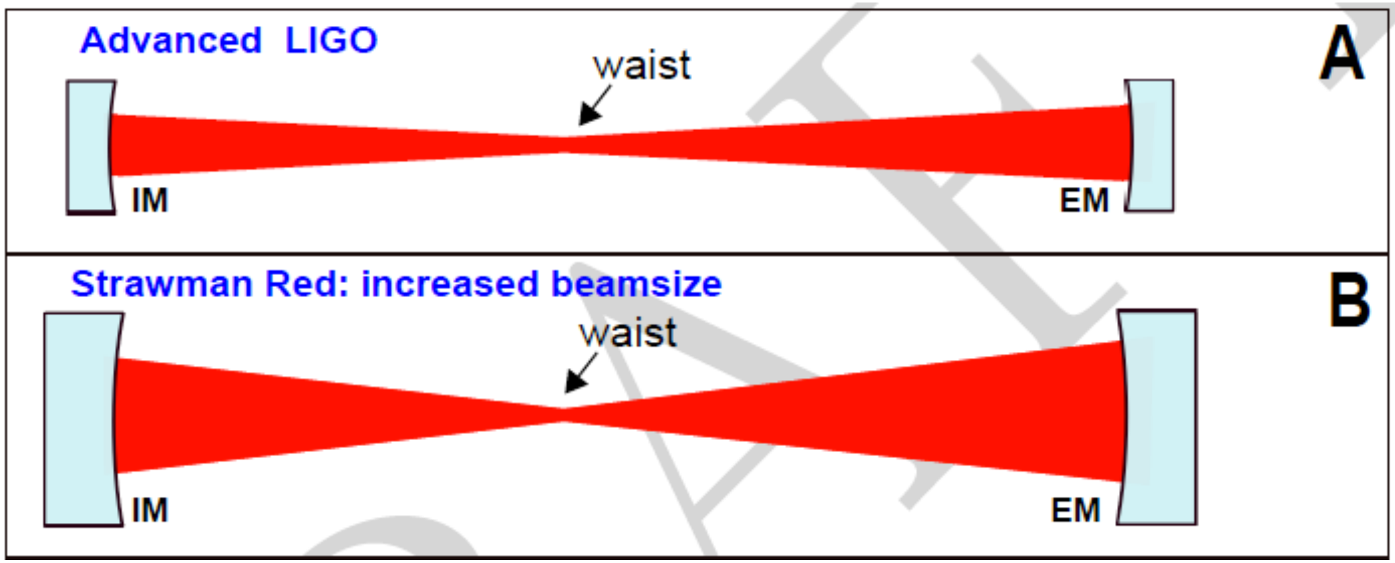
# Coating Brownian noise

- **Coating Thermal Noise:** We assumed an overall reduction of coating noise by a factor 3.2. Increasing the beam size by a factor 1.6 reduces the coating noise by a factor 1.6. In addition we assumed a further reduction of a factor 2 which can come from improved coatings or the application of Kahlili cavities or the use of waveguide mirrors or the application of alternative beam shapes.

# 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.

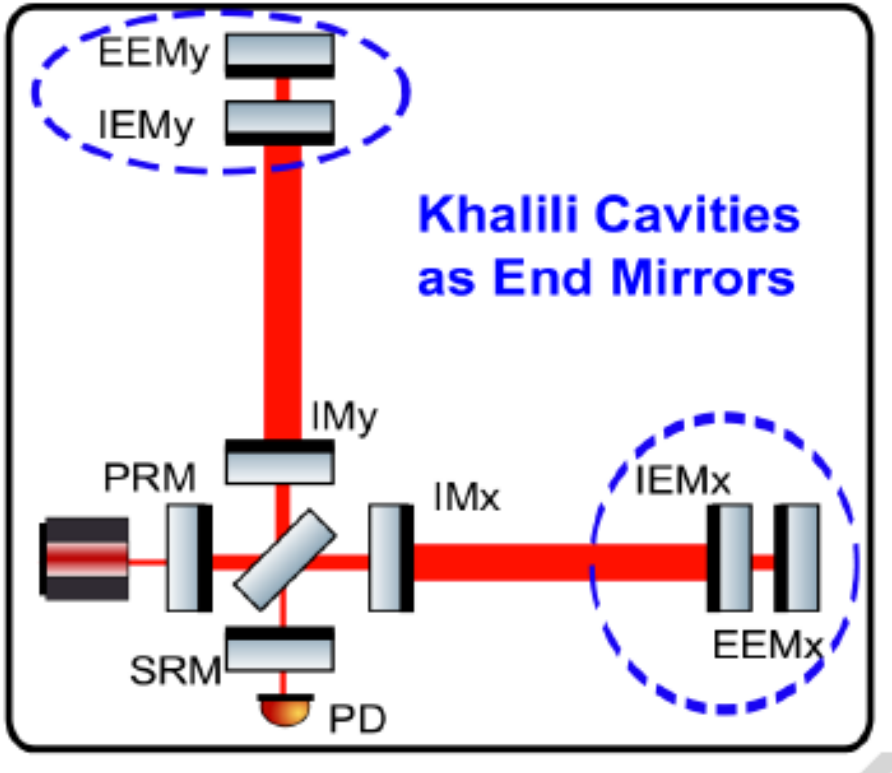
| Parameter | Advanced LIGO | Strawman Red Design |
|---|---|---|
| ROC of ITM [m] | 1934 | 1849 |
| ROC of ETM [m] | 2245 | 2173 |
| cavity length [m] | 3996 | 3996 |
| spot size at ITM [cm] | 5.31 | 8.46 |
| spot size at ETM [cm] | 6.21 | 9.95 |
| mirror diameter [cm] | 34 | 55 |
| waist position [m]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

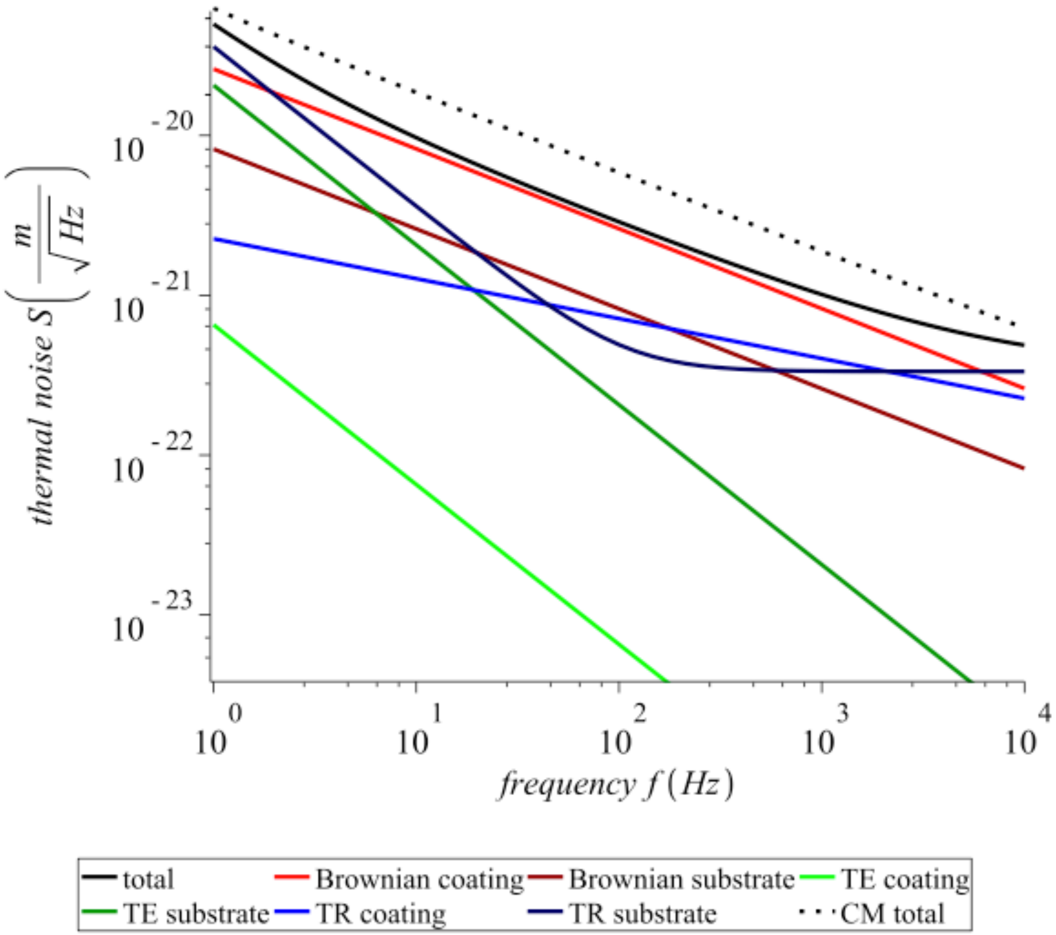


# Optical coatings with reduced thermal noise

- 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 = 4.6
  - Requires change of laser wavelength
- Crysatalline coatings (AlGaAs)

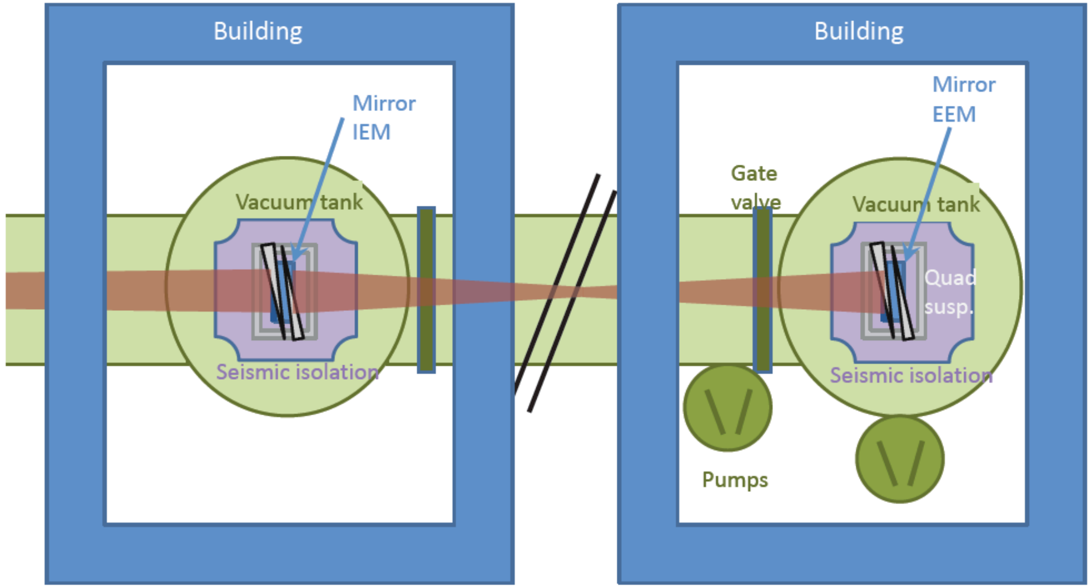
# Khalili cavities

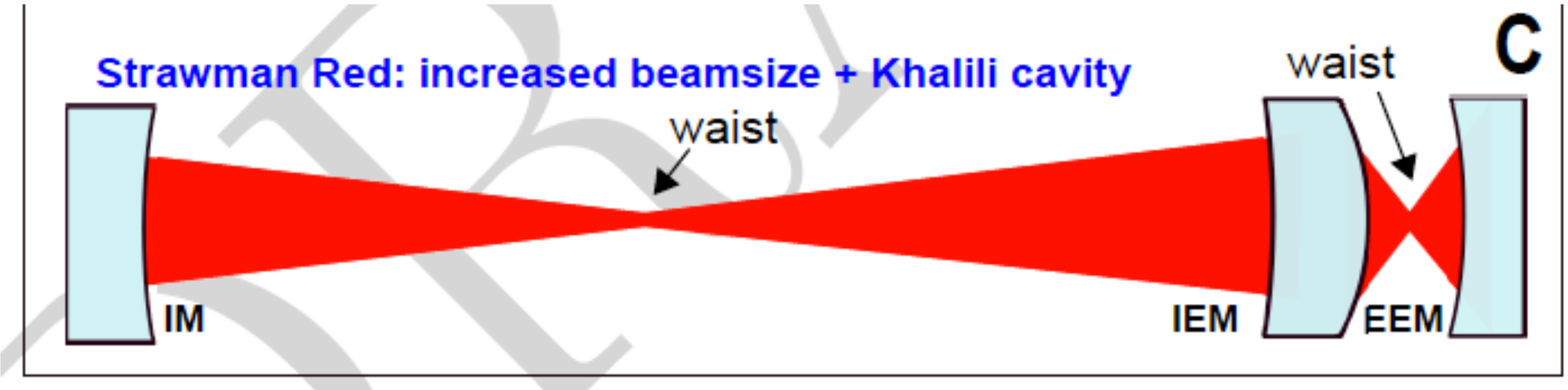


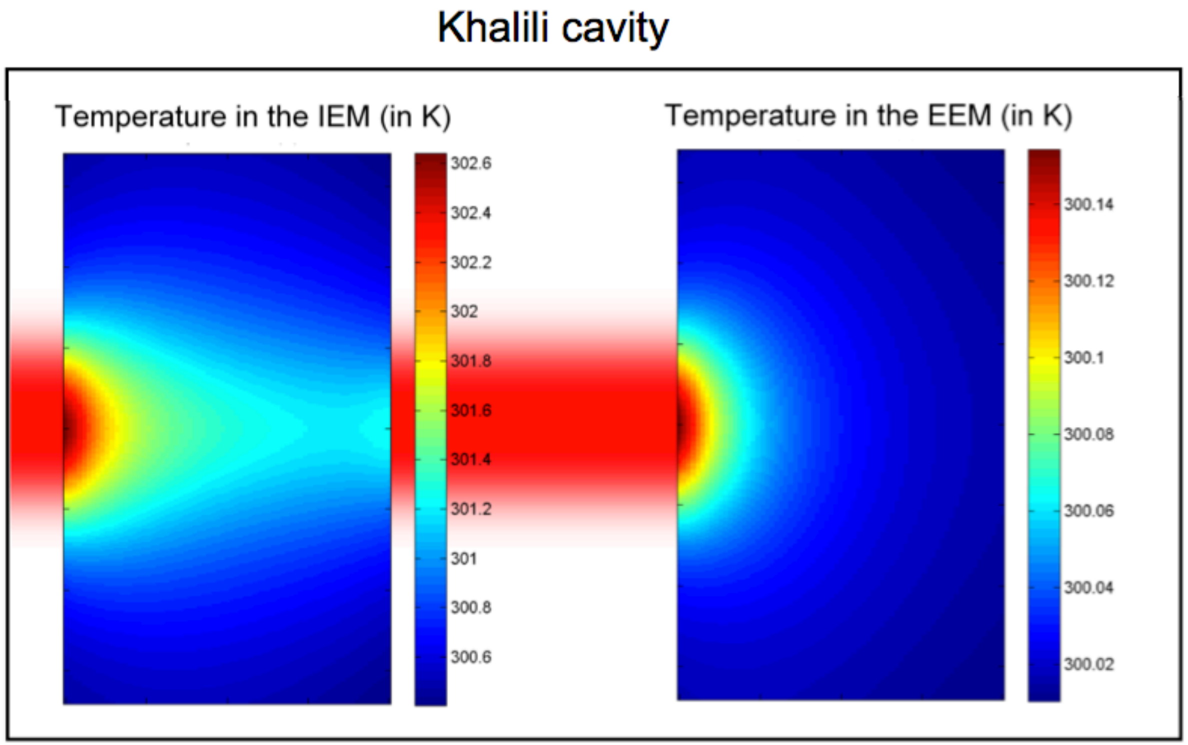
# Khalili cavities

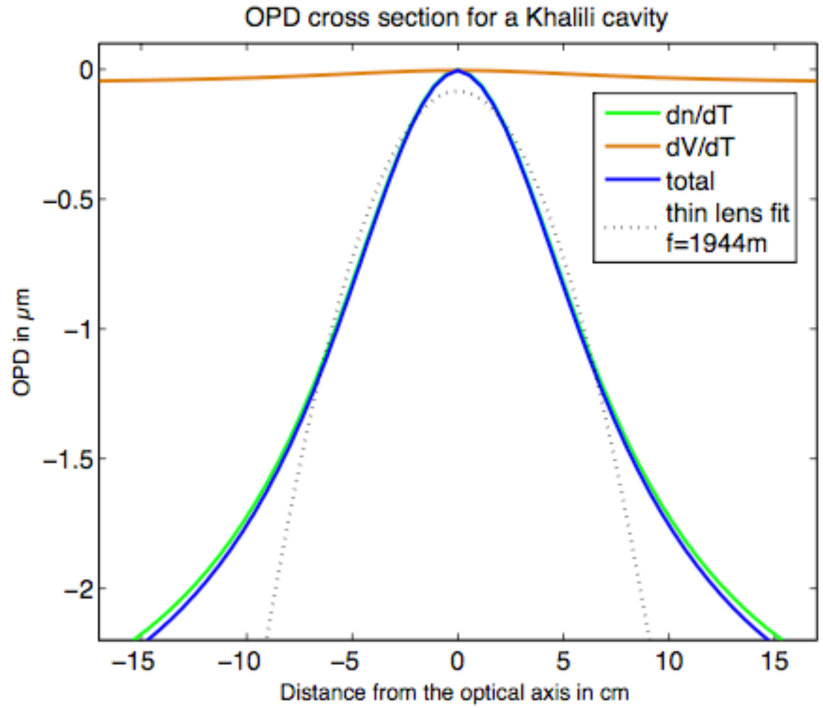
- Extremely hardware intensive.
- Lots of technical challenges:
  - Thermal lensing
  - Cavity stability
  - Control



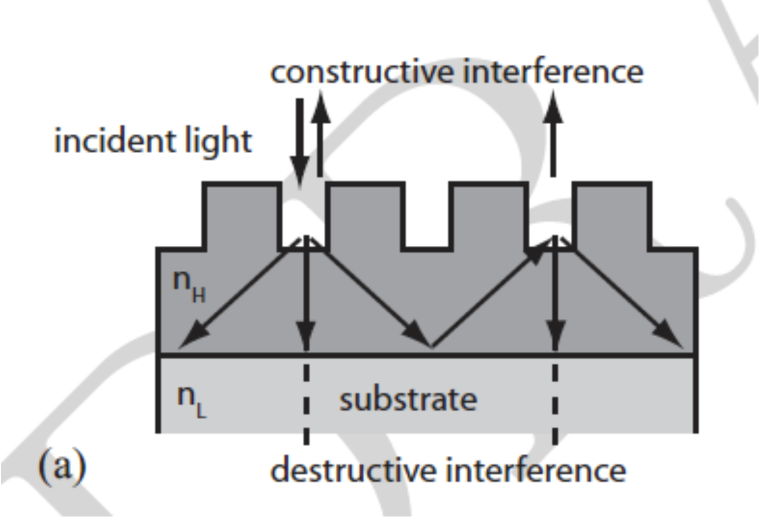



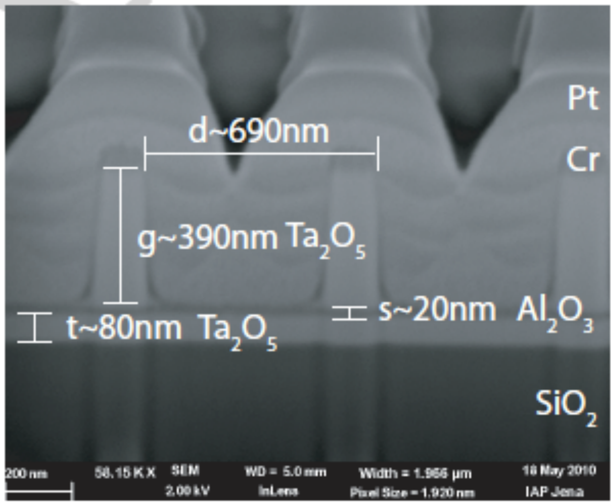
# Thermal lensing in K-cavity

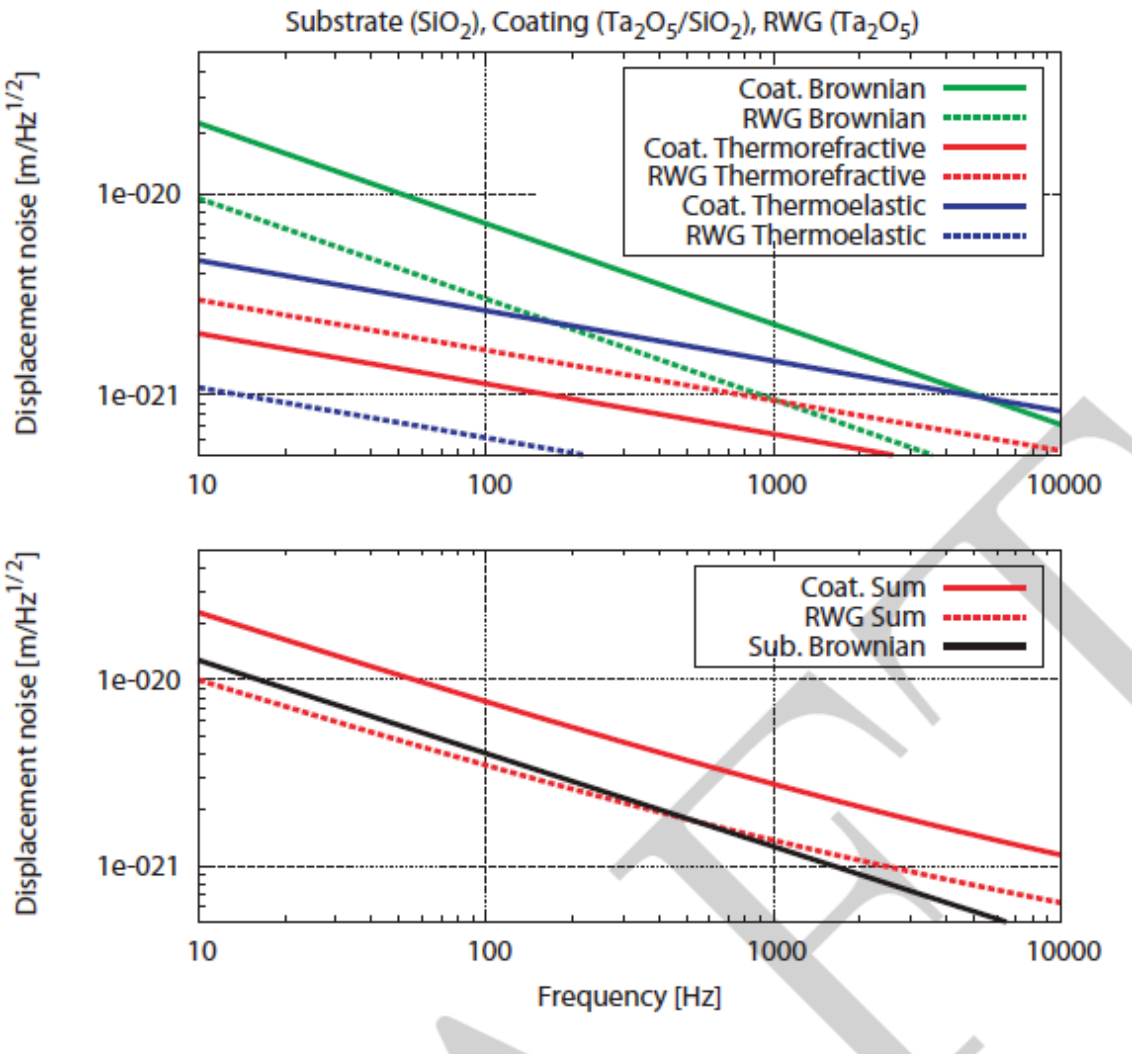


# Waveguide mirrors



# 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.

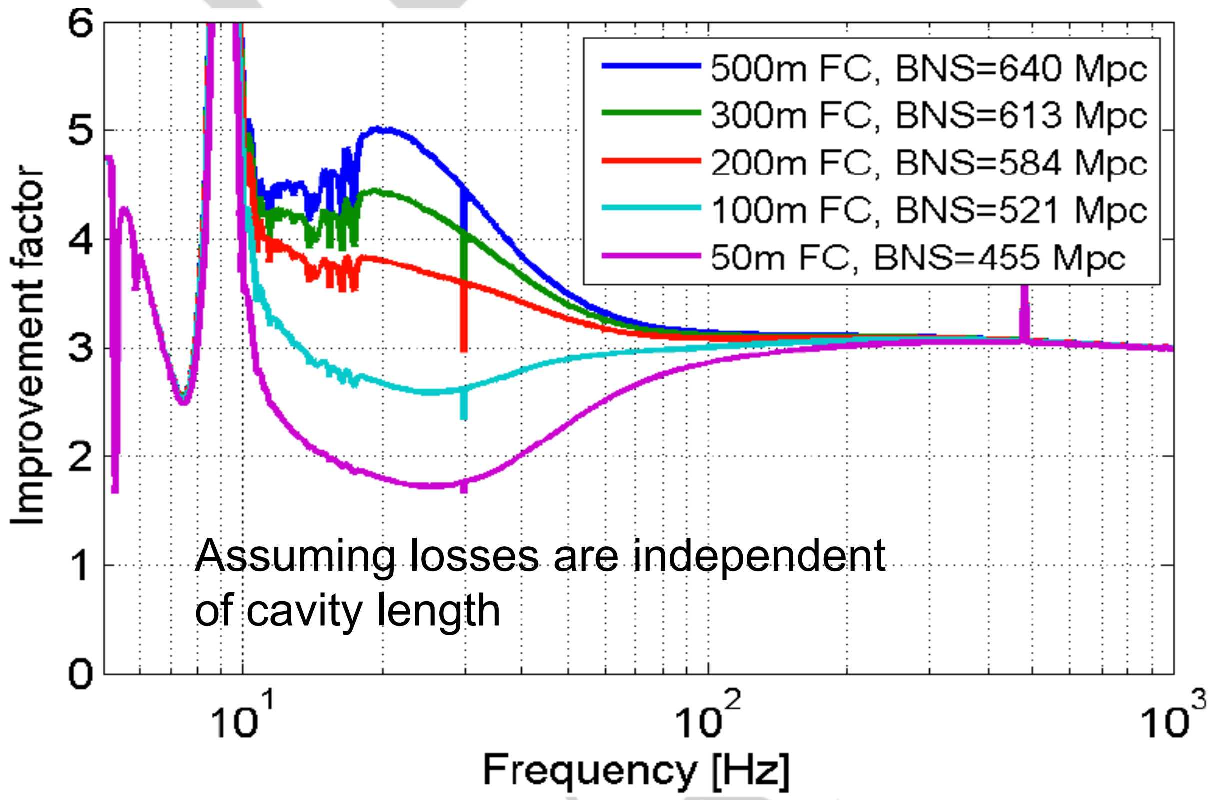
| **Laser and Optical Parameters** | | |
|---|---|---|
| Laser Wavelength | 1064 nm | 1064 nm |
| Optical Power at Test Masses | 730 kW | 730 kW |
| Arm Cavity Finesse | 450 | 450 |
| Signal Recycling | $T = 20\,\%$, tuned | $T = 20\,\%$, tuned |
| Squeezing Factor | n.a. | 20 dB |
| Filtercavity (FC) 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

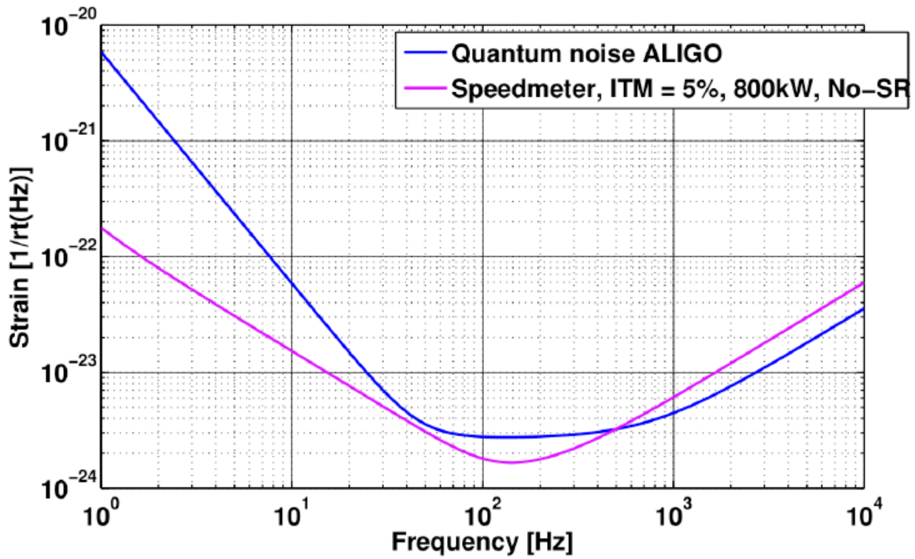
| Filter cavity length [m] | 500 | 300 | 200 | 100 | 50 |
|---|---|---|---|---|---|
| Input mirror power transmittance [ppm] | 704 | 422 | 281 | 141 | 70 |
| Binary neutron star inspiral range [MPc] | 640 | 613 | 584 | 521 | 455 |

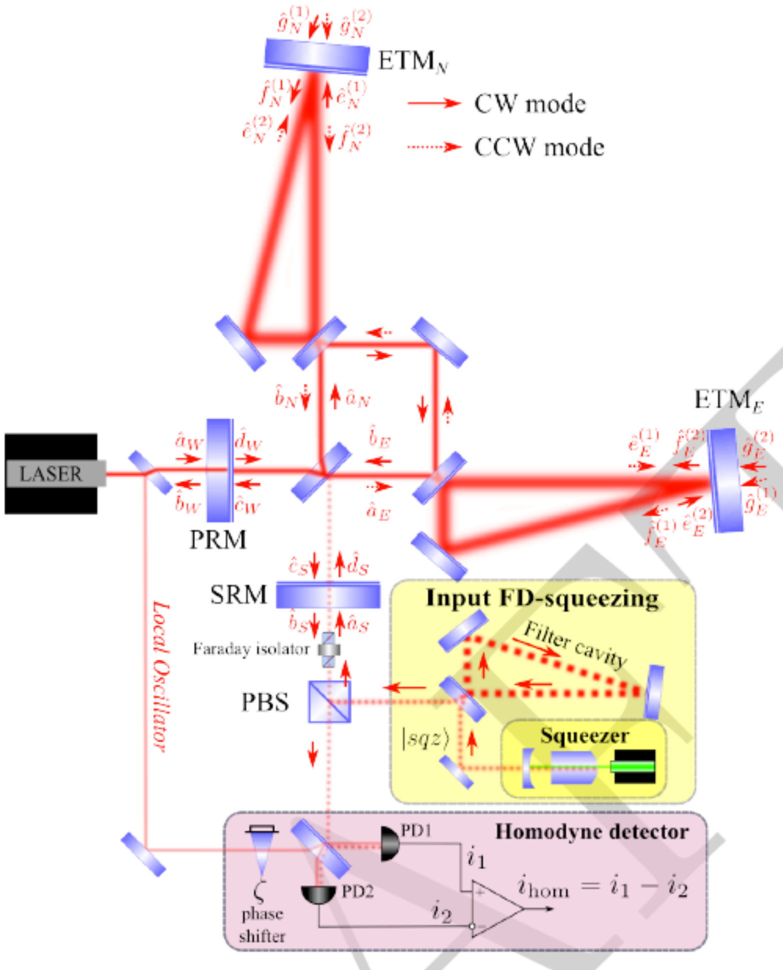



## Cavity losses in literature

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

# 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 |
| $\lambda_0$ | Laser wavelength | 1.064 $\mu$m | 1.064 $\mu$m |
| $P_c$ | Power in arms | $2 \times 750$ kW | $2 \times 750$ kW |
| $\eta$ | 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 |
| $\zeta$ | optimal homodyne angle | 6.43 degrees | 15 degrees |
| $e^{2r}$ | squeezing factor | 10 dB | 10 dB |
| $\psi_0$ | 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$^{-1}$ |
| $\delta_f$ | FC detuning | $2\pi \times 32$ sec$^{-1}$ | $2\pi \times 255$sec$^{-1}$ |

# 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 signicantly 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 USD.

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 about USD for labor (US accounting, bene

fits but no overhead) on top of the about USD for components (shown in Figure 17), **thus yielding a total cost of about dollars per interferometer. Contingency would be in addition.**

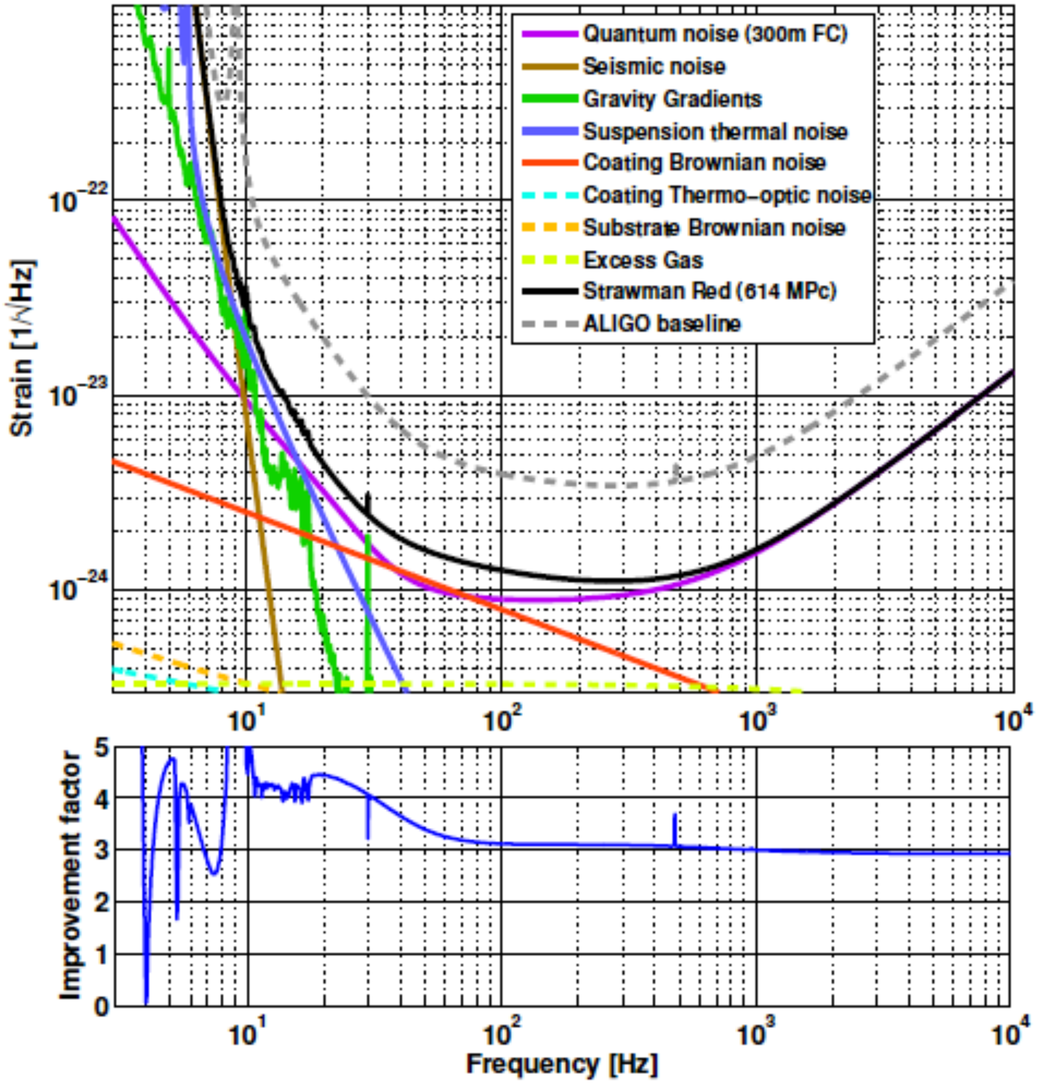
# Strawman red Dummy costing v0.4

| | 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 | | | | Hartmut, From GEO faraday | 1x FI for squeezing injection, 2x FI for |
| | 2 | Squeezing source | | | | Henning, from GEO squeezer | |
| | 3 | Filter cavity mirrors (ALIGO recycling mirror dimensions), super-polished, various coatings | | | | RM/dhs | aLIGO RM |
| | 4 | Filter cavity suspensions (same as ALIGO recycling mirror) | | | | DHS | aLIGO mech+elec |
| | 5 | Small vacuum tank (1.2m diameter) for filtercavity suspension | | | | DHS | Scaled from BSC |
| | 6 | End building for filter cavity (5x5m) | | | | DHS | LIGO Australia estimates |
| | 7 | 300 meter of vacuum tube (50cm diameter) for filter cavity, pumping, instrumentation | | | | 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. | | | | JW/dhs | aLIGO, scaled down a bit |
| | 9 | CDS for squeezing control (about 50 channels) | | | | dhs | guess from aLIGO ISC |
| | | **Total cost of** | | | | | |
| GGN | 10 | 3x Geophone based seismometer | | | | Jan | 30x 3-axis seismometers per main testmass |
| | 11 | power, ADC + recording of 30 slow (f<50Hz) channels | | | | dhs | guess |
| | | **Total cost of N** | | | | | |
| Suspension upgrades | 12 | Suprasil 312 rectangular fused silica penultimate mass (54cm long, 26cm wide, 26 cm thick, 1/10 polished side faces) | | | | dhs | scaled from costs for line 21, per GLB |
| | 13 | EUCLID interferometers | | | | Stefan, from recetly bought Euclid | |
| | 14 | Redesign/Fabrication of QUAD main chain/reaction chain structure to accommodate 1.2m long suspension | | | | DHS - new fabrication | Scaled from ALUK plus LIGO elect. |
| | 15 | Redesign/Fabrication of ISI metal cantilever springs and flexures to support higher QUAD load | | | | FM | aLIGO |
| | 16 | Redesign/Fabrication of new intermediate and upper intermediate metal masses | | | | 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). | | | | DHS | |

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

# 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 $\mu$m | 566 $\mu$m |
| Fibre Diameter at Bending Point | 800 $\mu$m | 1624 $\mu$m |
| **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 |

- For details please see document on the DCC:
- https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=78100