aLIGO – key design choices

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Overview of the presentation

- **How the sensitivity goal was chosen**
- **Fixed points – infrastructure changes beyond the scope**
- **Some choices made during the design process**
  - shot noise and radiation pressure
  - arm cavity finesse, readout method, output mode cleaner
  - recycling cavity design
  - seismic noise and isolation
  - substrates, masses and fibres
  - thermal compensation
- **Keeping upgrade options in mind**

Point of View

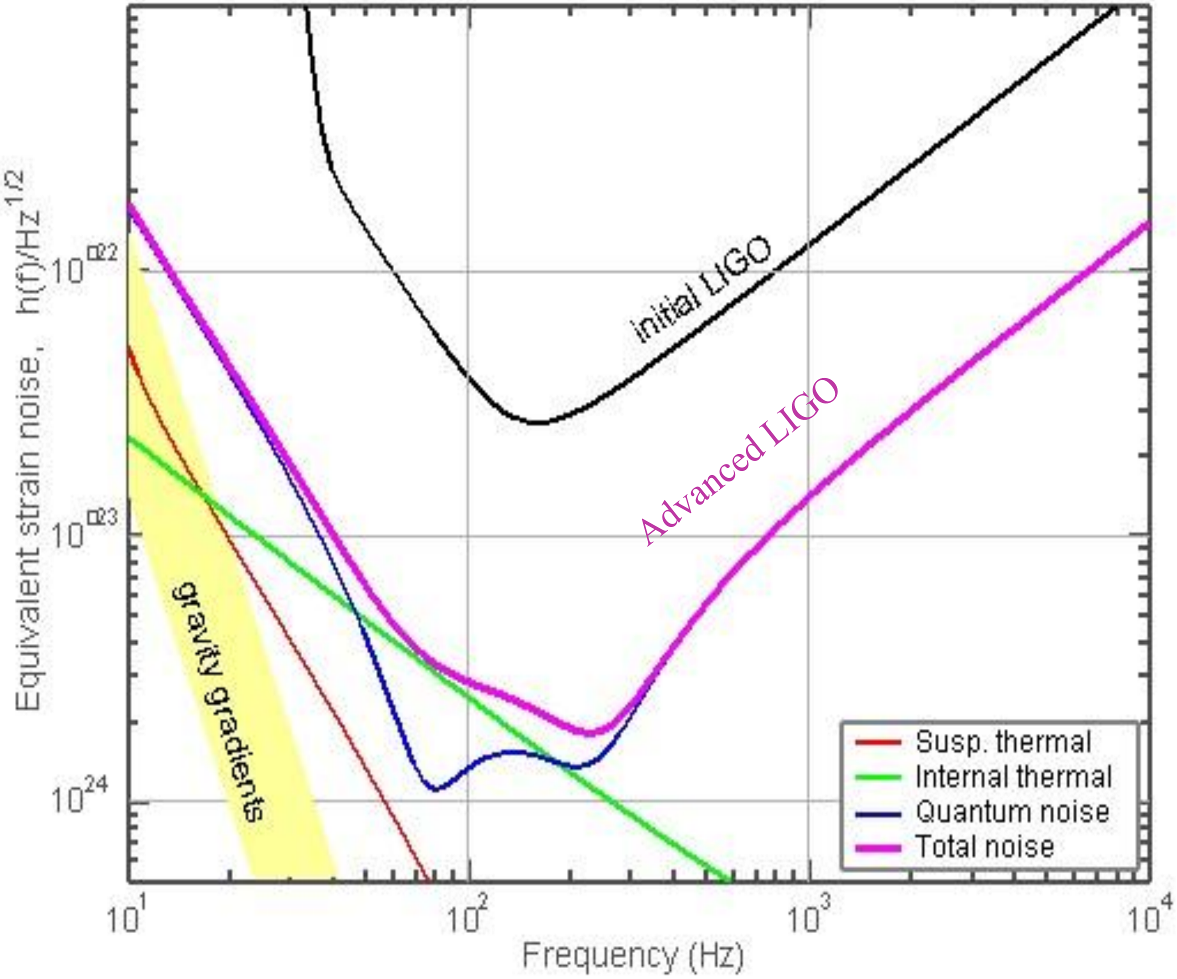
- Attempt to illustrate some of the major decisions that went into the baseline aLIGO design
- Generally based on knowledge available at the time the decision was made
  - but updated to reflect current values/thinking where appropriate
  - note that as a result some of the parameters included in this presentation are not exactly those of the current design

Beyond eLIGO – sensitivity choice

- Bench software (now GWINC) late 1990s versions
  - reasonable models for quantum noise in FPMI, thermal noise, seismic noise, and various approximations for gravity gradient noise
  - provided rapid simulation of NS:NS and other compact object inspirals – the primary benchmark used to refine the initial design concepts
  - focus still on discovery instrument, but alternative observing modes (post discovery) kept in mind
- Main areas of focus
  - mid-band, dominates NS:NS range, shot noise and mirror thermal noise
  - low frequency cutoff, important for BH, pulsars, radiation pressure and suspension thermal noise

Typical benchmark curve

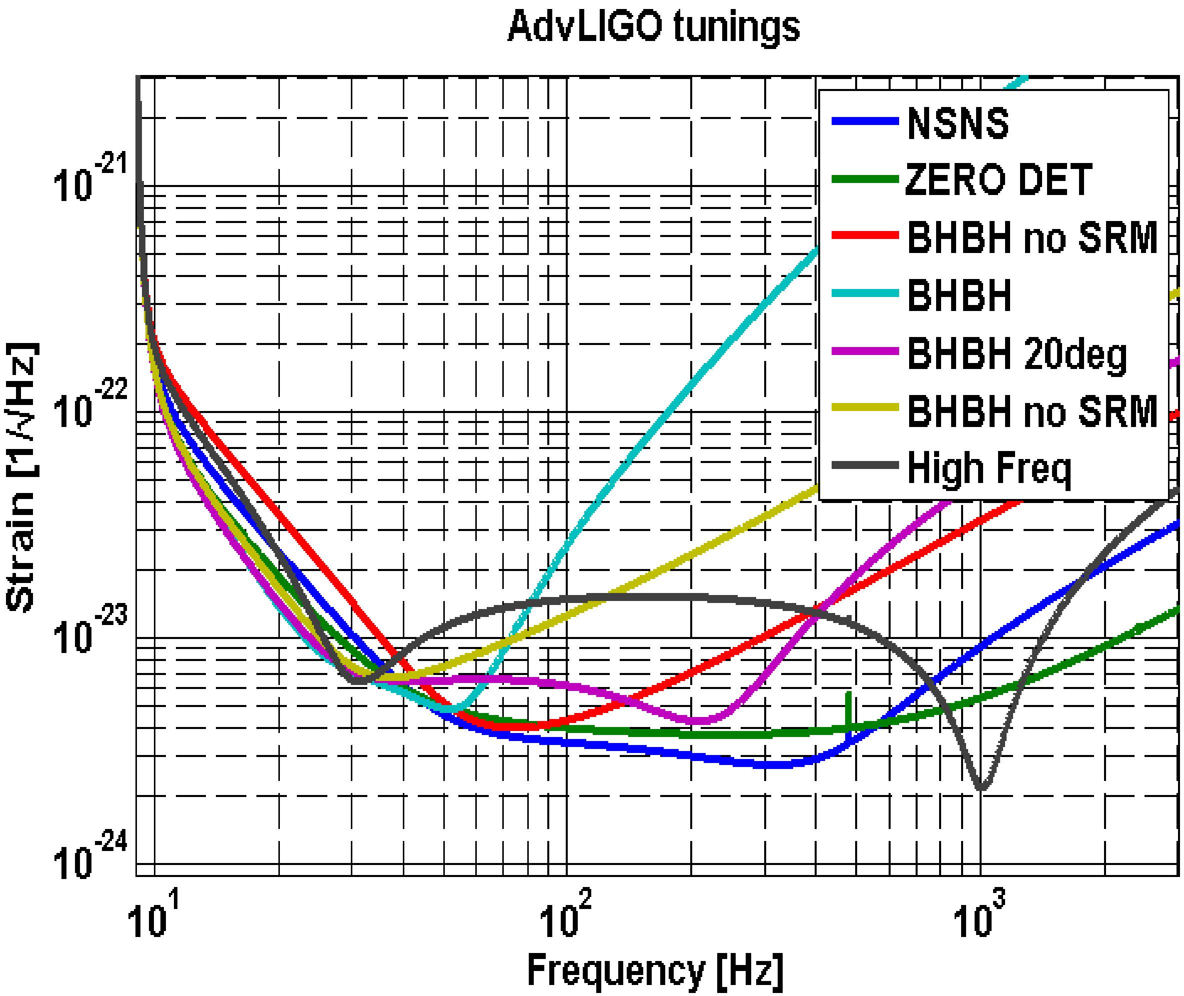
- Main features:
- 10x reduced shot noise
- Balance of thermal and quantum noise in mid-band/peak sensitivity
- Radiation pressure dominated at low frequency



… but it is not so simple

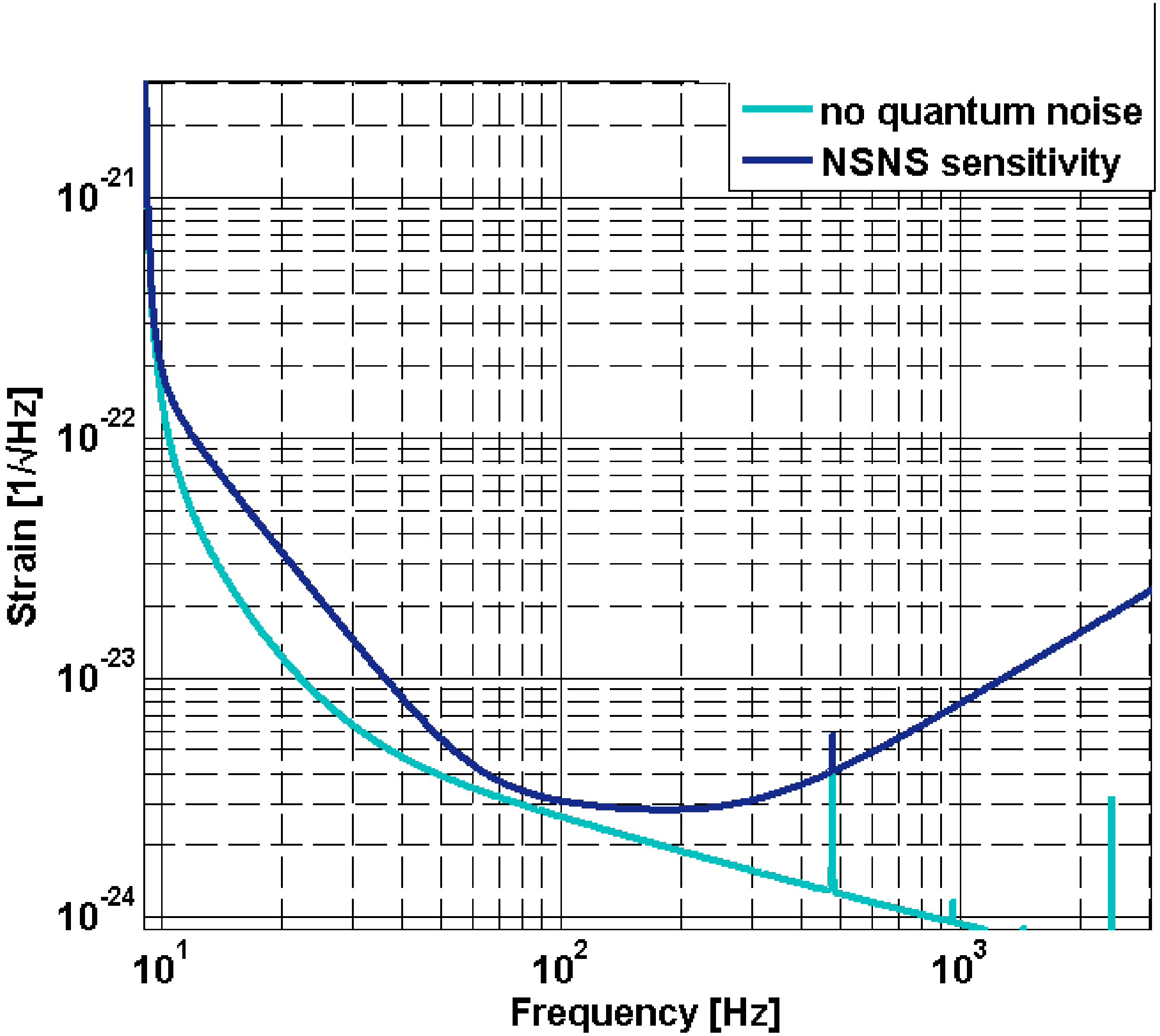
Even with most design parameters fixed there is a wide range of possible sensitivity curves depending on

- power in
- SR tuning
- SR reflectivity
- SR / no SR



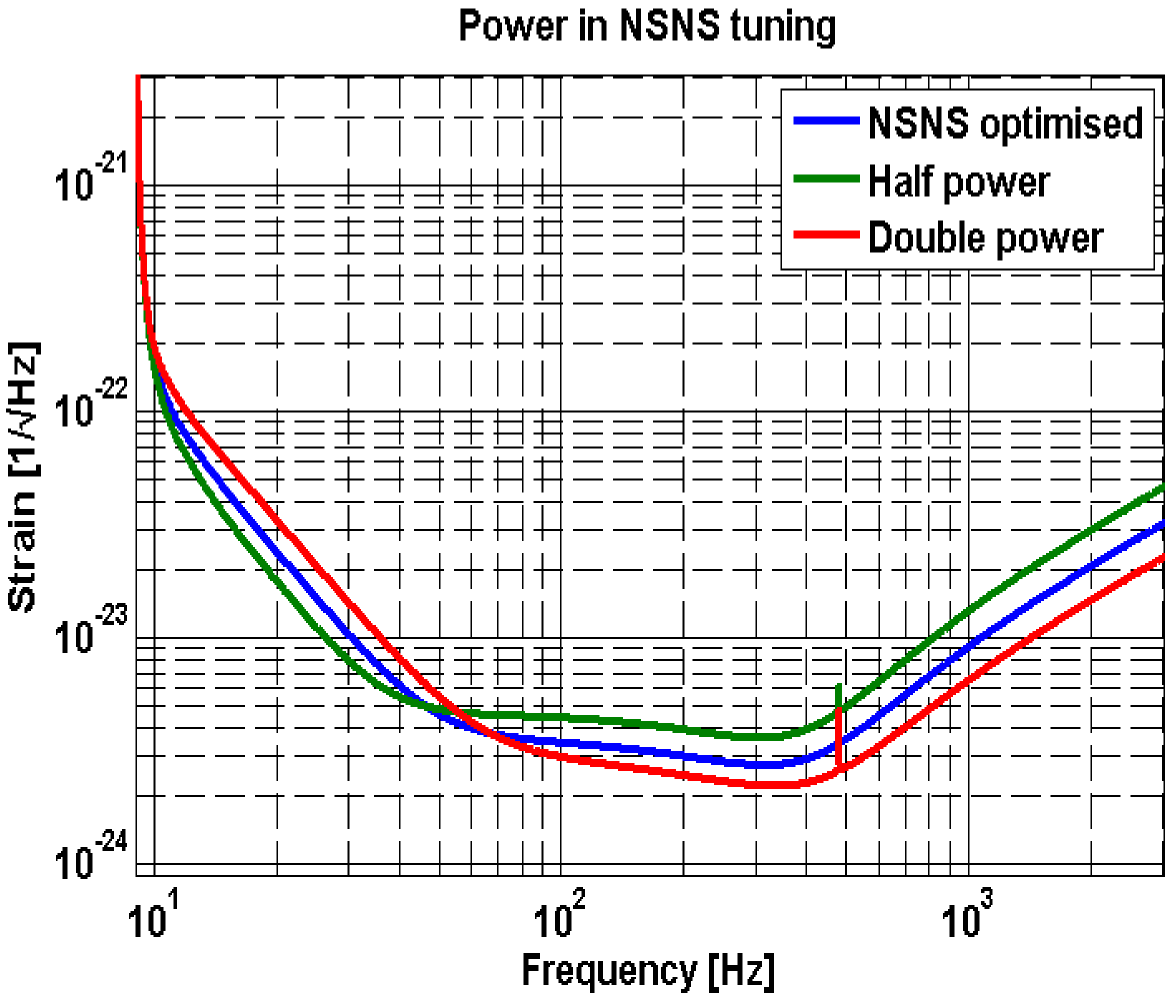
Quantum noise *vs.* other noise

- Significantly radiation pressure noise limited from~ 20-40Hz
- Significantly shot noise limited above ~200 Hz
- ~1.7x SQL near 75Hz



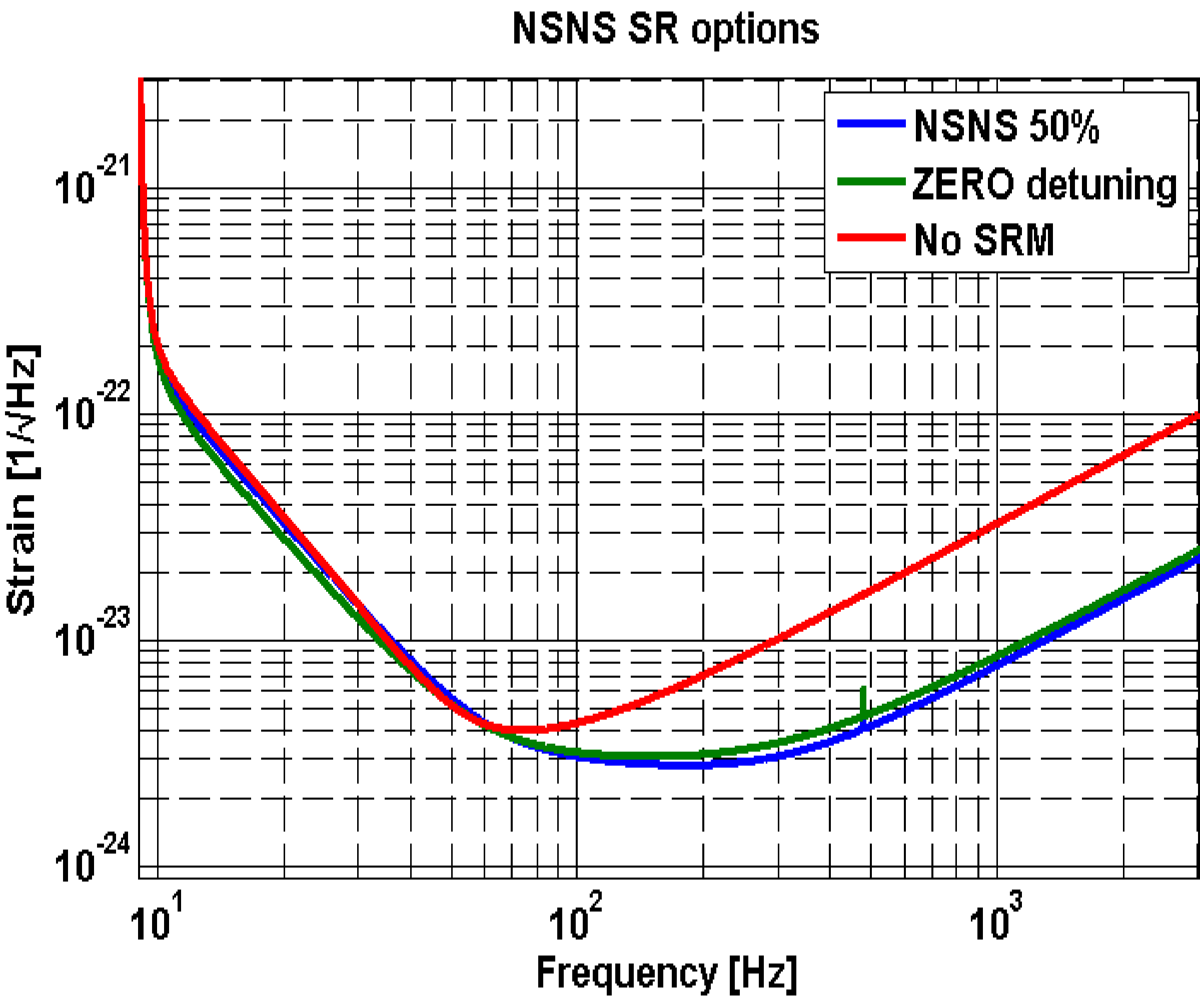
Vary power from NSNS “optimum”

- Note: SR not re-optimised (for clarity)
- Expected trade-off between shot noise and QRP noise
- Performance saturates in mid-band (thermal noise)



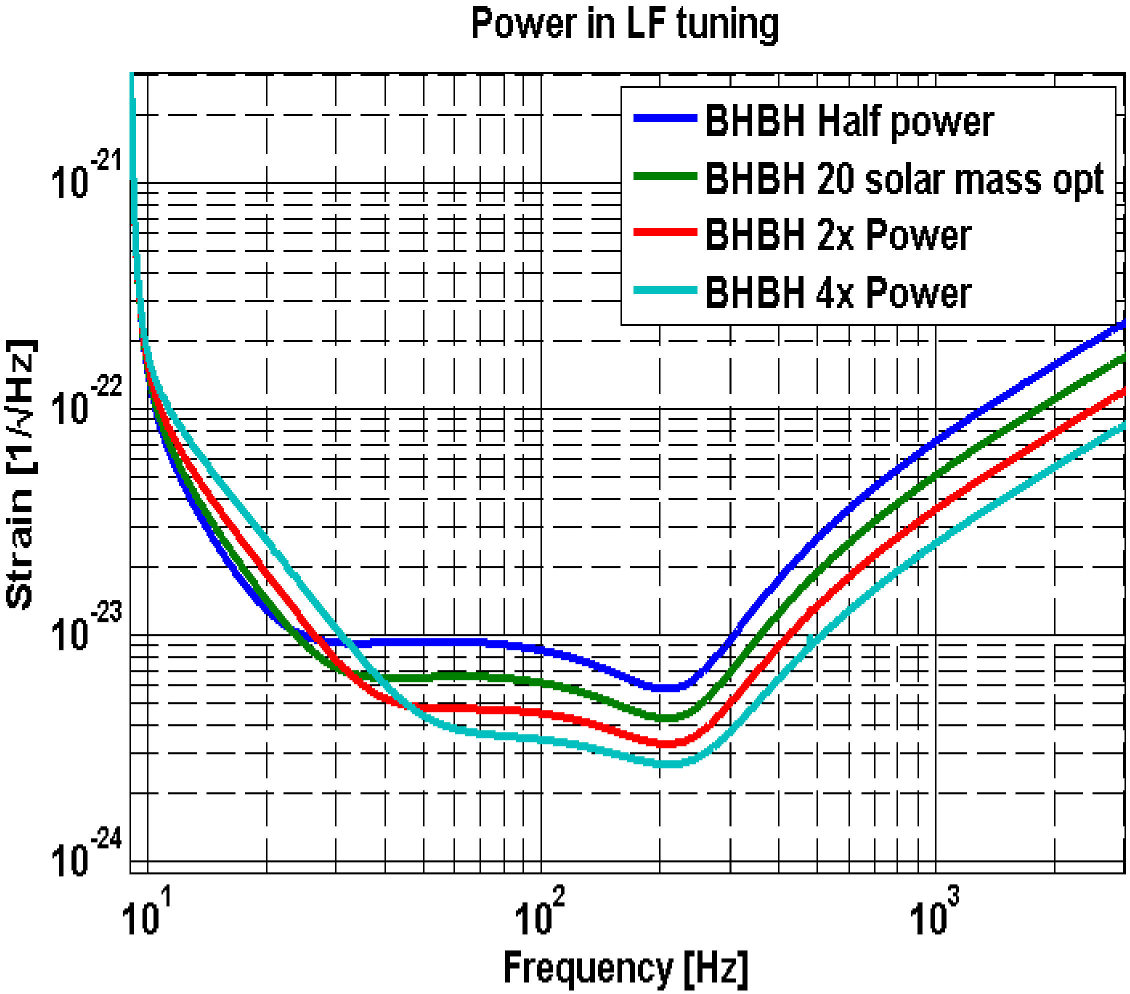
Value of Signal Recycling (NSNS)

- No SR and/or zero detuning could be easier to operate
- But No SR represents significant loss of range
- Zero detune is a good starting point



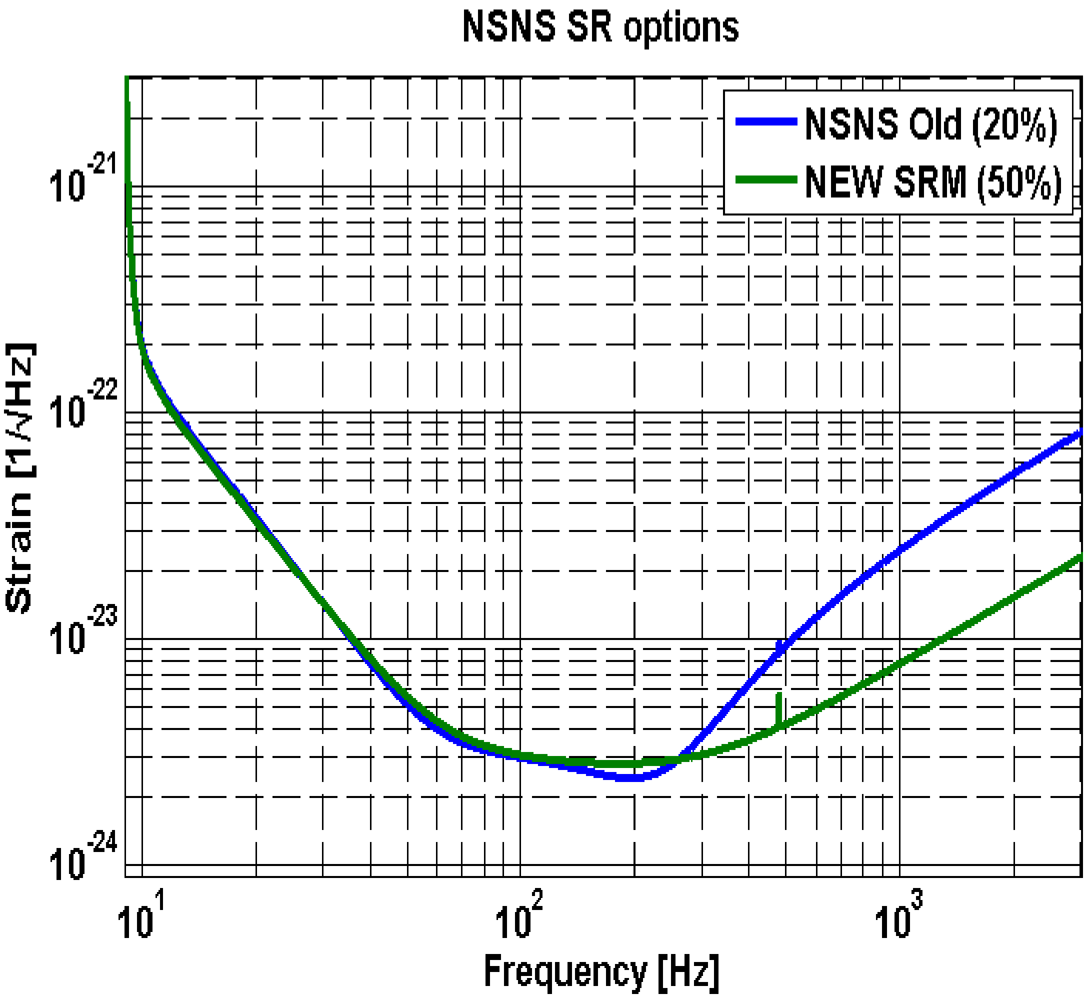
BH Opt. is close to lowest power

- Reducing power below BH optimum gains very little
- Increasing power gains NSNS range in rough proportion to reduction in BHBH range

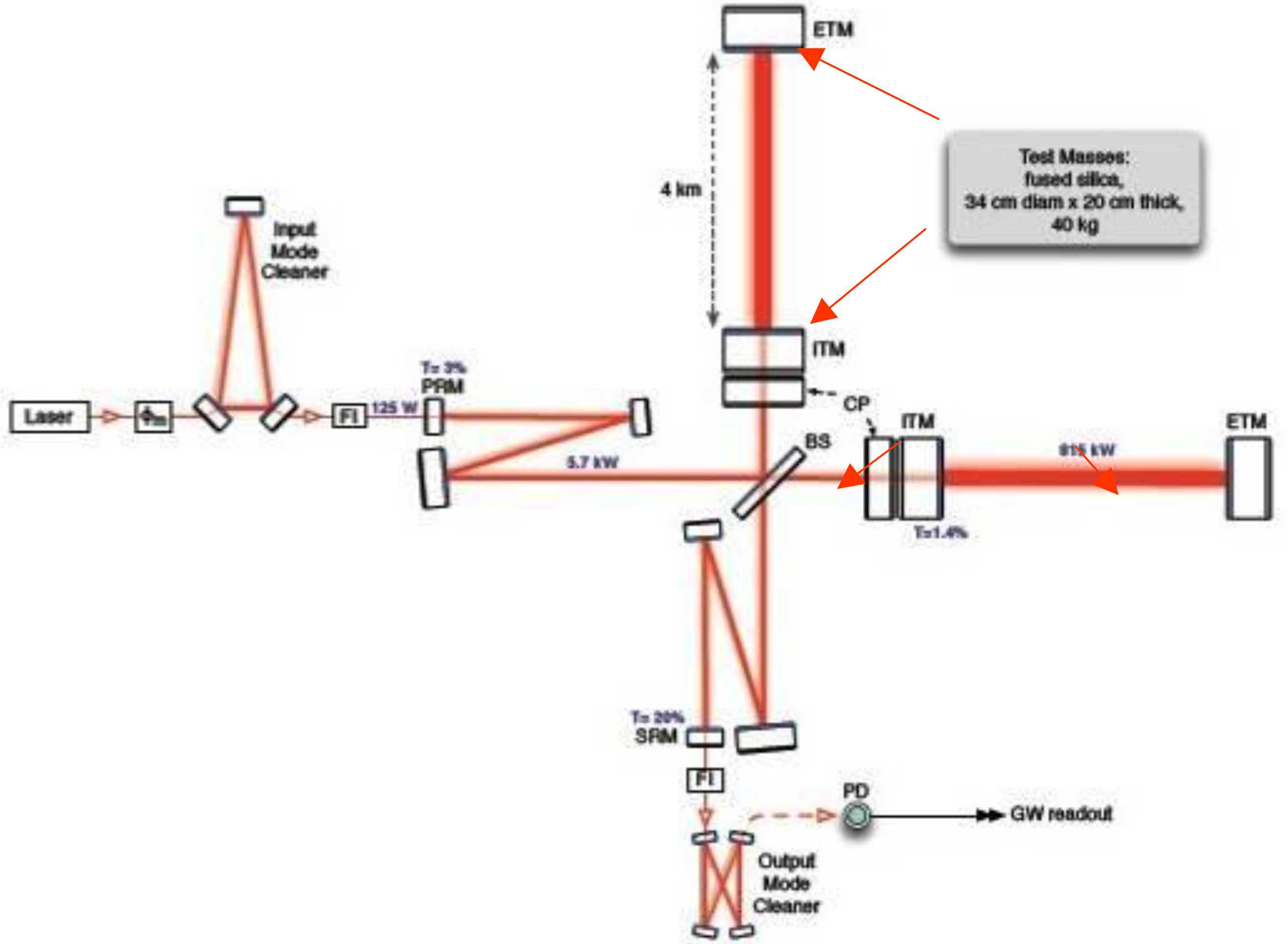


Recent change to 50% SRM

- Almost same NS:NS range and BH:BH range
- Better HF response (mergers, bursts)
- Quite tolerant of parameter variation (tuning etc.)
  - simpler control



Optical layout



Test Masses:
fused silica,
34 cm diam x 20 cm thick,
40 kg

Choices – arm cavity finesse

- SR and/or RSE provide freedom to choose arm cavity finesse yet still achieve the desired system bandwidth
    - within limits: loss in the BS/recycling mirror region prevents full recovery of shot noise performance in the case of strong RSE
    - not a concern for aLIGO as the required RSE turns out to be quite weak (SR mirror: 20% to 50% transmission)
- This allows rebalancing of
    - effective system losses to approach the optimal quantum noise
    - thermal load to permit the highest possible stored energy
- The latter is more important in aLIGO

Choices – arm cavity & thermal load

- Balance two sources of thermal distortion at the ITM
  - from coating absorption: e.g. 0.5 ppm x intra-cavity power
  - from ITM substrate heating e.g. 0.5 ppm/cm x 2 x 20 cm x power in beam-splitter region (plus allowance for beam-splitter itself)
  - leads to compromise finesse such that coating absorption dominates somewhat
- Thermal distortion differs between substrate and coating (needs numerical integration)
  - initially modelled using MELODY (MATLAB) by Ray Beausoleil
  - compromise finesse chosen (~450)

Readout – RF?

- The options:
  - standard RF/heterodyne readout with ~10MHz modulation
  - DC readout using light obtained by slightly offsetting the arms
- RF
  - PRO: familiar, tested (iLIGO etc. etc.)
  - CON: extreme requirement on oscillator phase noise (in particular 30 to 100Hz sidebands), practical restriction to sinusoidal modulation reduces maximum *SNR* and complicates potential squeezing, by mixing in noise from mixing in noise from optical frequency +/- twice the RF frequency

Or DC?

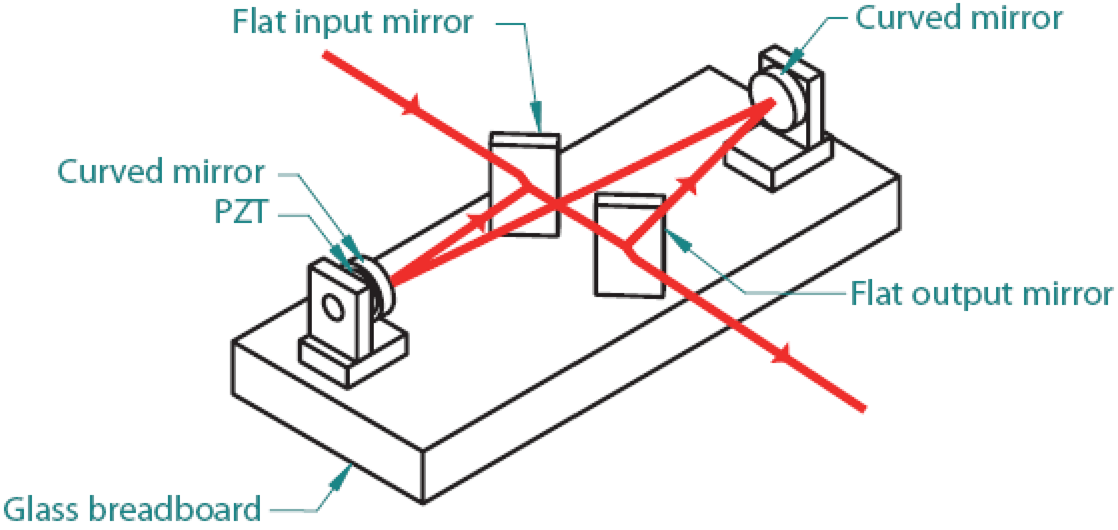
- DC
  - CON: unfamiliar (at the time, though planned for GEO600), potential to couple amplitude noise
  - PRO: close to ideal *SNR* in principle
- Setting the quadrature: junk light
  - ideally no light apart from the desired local oscillator field at the dark port, but there is always some junk due to imperfect overlap of fields from two arms
  - the fundamental-mode component of this comes from a loss mismatch between the two arms (amplitude quadrature)
  - by offsetting the arms by the required amount the resulting LO can be set to (nearly) any phase

DC readout

- aLIGO favours DC in a number of ways
  - lower loss optics provides a longer storage time and provides passive filtering of stored light (~1s time constant)
  - high quality optics, effective TCS, reasonably high finesse arms, all lead to good fringe contrast – adding an output mode-cleaner leads to excellent fringe contrast (few mW of fundamental-mode out per MW in arms)
  - technical radiation pressure effects demand that the ingoing light power is stabilised (shot noise in ~1W)
  - requirements for RF system only get tougher than earlier detectors (and no commercial solution known)
- to make DC readout work on aLIGO requires an OMC.

Output Mode Cleaner

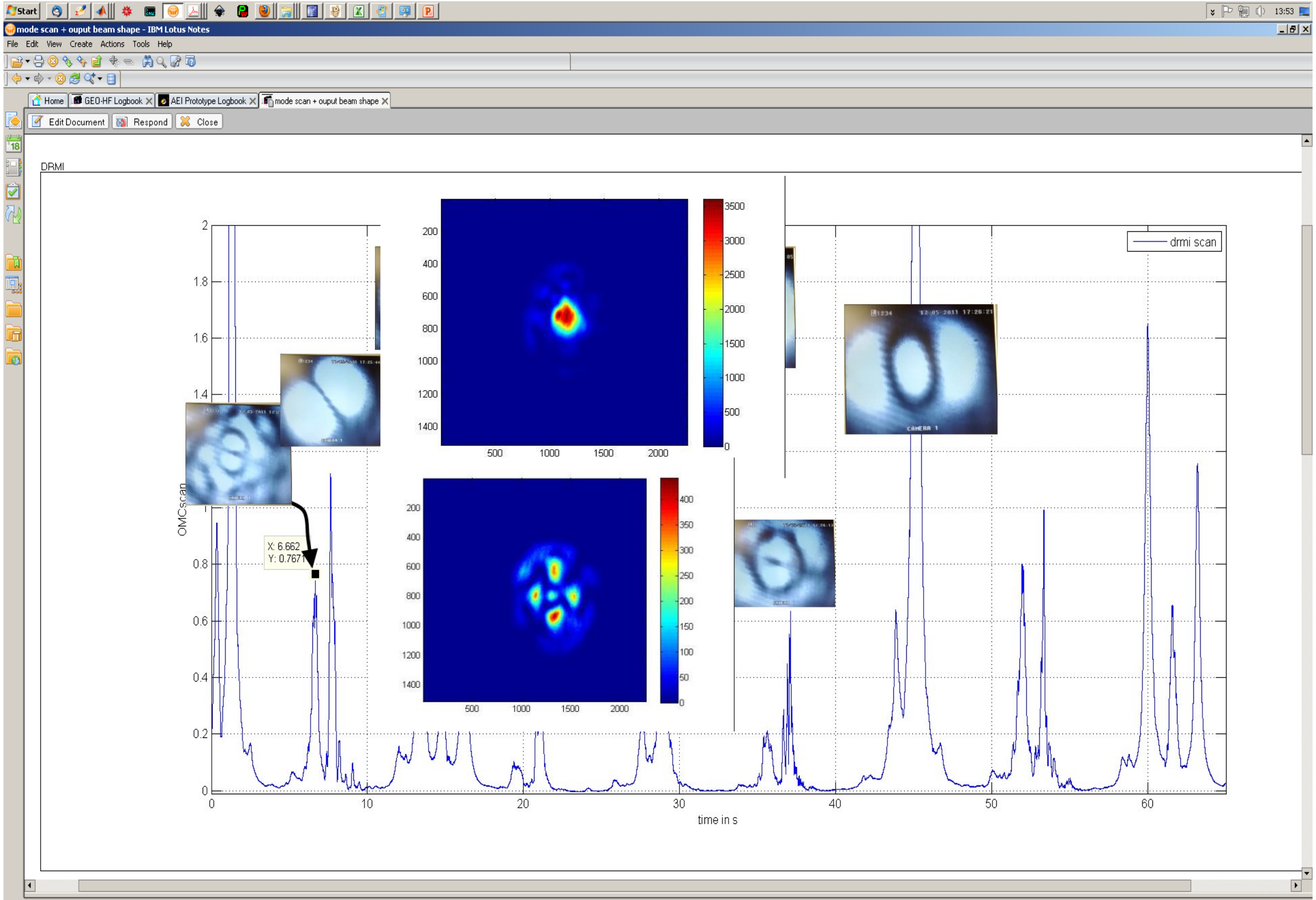
- Moderate finesse ring cavity
  - to suppress non-resonant modes
  - to filter as many higher order mode components as possible (~pi/finesse modes are not suppressed)
  - should be low loss for detection efficiency and squeezing
- GEO OMC shown (annotated CAD, Prijatelj *et al*)



OMC control

- Require locking and alignment sidebands/subcarriers
  - should be reliably in same mode as carrier in IFO arms (common mode) to ensure OMC aligned to correct spatial mode
  - one approach is to add beacons (kHz sidebands added in IFO), and dither alignment (few Hz)
- Optimising OMC control is tricky

From GEO (Wittel/Prijatelj)



Thermal Compensation

- Arm-cavity power is main determinant of NSNS range
- Push injected power as high as practicable
  - 180W laser, efficient injection optics, thermal compensation in Faraday rotators, power tolerant EOM crystals (e.g. RTP *rubidium titanyl phosphate*)
- Try to keep optical loss as low as possible
  - scattering: to allow maximum cavity power
  - absorption: to reduce thermal load
  - still leaves ~1W absorbed in BS, ITMx, ITMy
  - significantly above the threshold for significant degradation of mode-matching and interference quality

TCS requirements

- Spherical correction at ITMs
- Astigmatic (toric) correction at BS
- Possibly local correction of inhomogeneous absorption
  - was a concern with sapphire, samples showed inhomogeneity
- Require most correction near beam axis, can tolerate poorer correction where light field is smaller
  - needs a little over 1 order of magnitude increase in power tolerance
  - allowing moderate degradation uncompensated designs work to ~10W input
  - with compensation require little degradation at 125W input

TCS strategies

- Ring heaters
  - tried on GEO600, work well for symmetric case in centre of optic, but hard to get good match to thermal lens
  - fitted to ITM suspensions
- Side heaters
  - recently introduced in GEO600, for control of astigmatism (greater relative astigmatism in GEO)
- Laser heating
  - can project (with raster scanning) an IR heating beam on to a thermal compensation plate (suspended between BS and both ITMs to reduce scanning noise)
  - investigated in-depth by Ryan Laurence (MIT)
  - works best in combination with ring heater, allowing near-ideal sensitivity at 125W input

Choices: isolation (brief)

- Passive isolation (Virgo technology and GAS)
  - PRO: dynamically stable, relatively compact, fine engineering of flexures but otherwise nominally straightforward
  - CON: thermal drift (~mm/K), very intolerant of load variation (~10mm/kg), hard to fix if something is not built within often narrow tolerance
- Active isolation
  - PRO: can shape optical table displacement spectrum to meet needs of project (small drift, good attenuation near 10Hz), tolerant of spring-rate errors, stiff and temperature stable, fixing it often means changing control coefficients rather than exchanging or adjusting hardware
  - CON: potentially unstable, sensitive to load dynamics
- Active isolation chosen as lower risk approach

Choices: substrates

- Initial view: silica
  - absorption: usually few ppm/cm -> thermal problem might require too much TCS effort to tolerate required power
  - thermal noise: regarded as sub-optimum compared to crystalline materials
  - reliable availability and known cost
- Initial view: sapphire
  - high thermal conductivity seen as a primary defence against thermal problems
  - mechanical properties and some measurements point to low thermal noise
  - uncertain availability as 30kg+ single crystals
  - uncertain problems with birefringence

Choices: substrates

- Down-select view: silica
  - absorption: promise of lower–absorption silica (piloted on GEO beamsplitter), good homogeneity therefore even strong thermal distortion can be compensated (how well?)
  - thermal noise: closer analysis of many samples suggests surface loss was influencing estimates (small in 30+kg piece)
  - still reliable availability and known cost
- Down-select view: sapphire
  - test pieces not so homogeneous, thermal distortion could be patch and hard to correct
  - good understanding of thermo-elastic noise developed
  - still uncertain availability as 30kg+ single crystals
  - birefringence not viewed as a problem (though birefringence inhomogeneity could be)

Choices: substrates

- Final view: silica (40kg – improved BHBH response)
  - Heraeus 3000 series fused silica offers reliable reduced absorption
  - Thermal noise well understood, and less important than coating noise
  - TCS techniques investigated at MIT and thought adequate
- Final view: sapphire
  - Still offers possibility of a back-up material
  - Risk of producing large volumes (with spares ~1 tonne) to the required quality seen to be considerably higher than the risk associated with fused silica
- Down-selected silica, which still seems the correct choice.

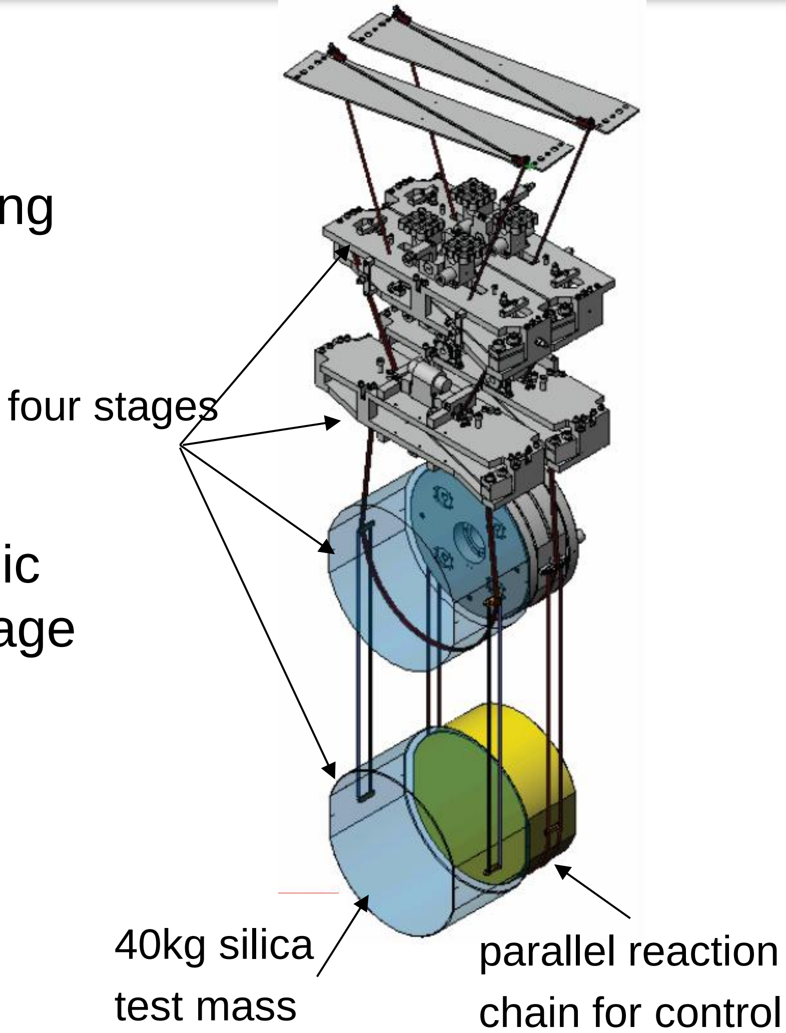
Masses and Suspensions

- Here we consider only a few of the key design decisions
  - since the majority of the suspension technology was a UK contribution, the list of questions the UK team could consider is almost unending

- Key points
  - 40 kg
  - 4 stages
  - ribbons or round fibres
  - approach to local and global control

Quadruple suspension overview

- Seismic isolation: use quadruple pendulum with 3 stages of maraging steel blades for enhanced vertical isolation
- Thermal noise reduction: monolithic fused silica suspension as final stage - low pendulum thermal noise and preservation of high mirror quality factor
  - *silica fibre loss angle ~ $3 \cdot 10^{-7}$,*
  - *c.f. steel ~$2 \cdot 10^{-4}$*



Ribbons or round-section fibres

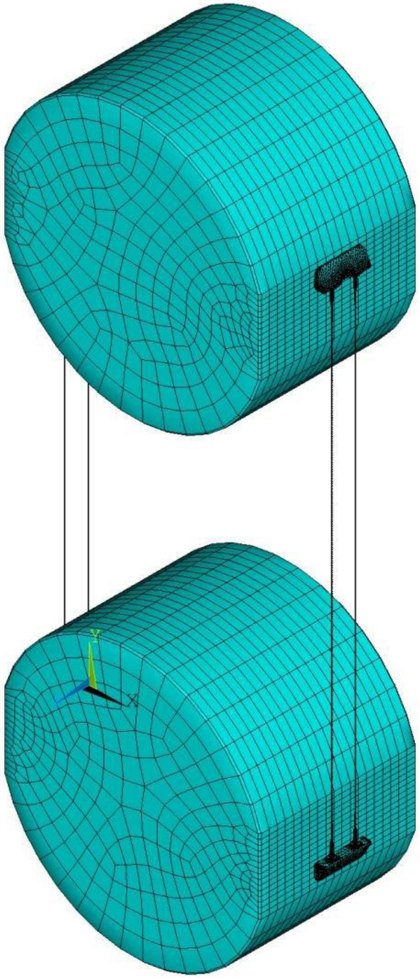
- Initial view:
  - ribbons attractive as, for a given x-section they can be softer in the sensitive direction: potentially lower thermal noise
  - but are ribbons strong enough, what is the best way to interface these to the ears?
  - ribbons were initial baseline
  - round fibres were proven to be strong, and had been welded successfully in GEO, but may have too much thermo-elastic noise in the 10s of Hz range for aLIGO
- New information
  - thermo-elastic noise cancellation led to alternative fibre designs (Willems/Cagnoli/Cumming and others)

Thermal noise calculation

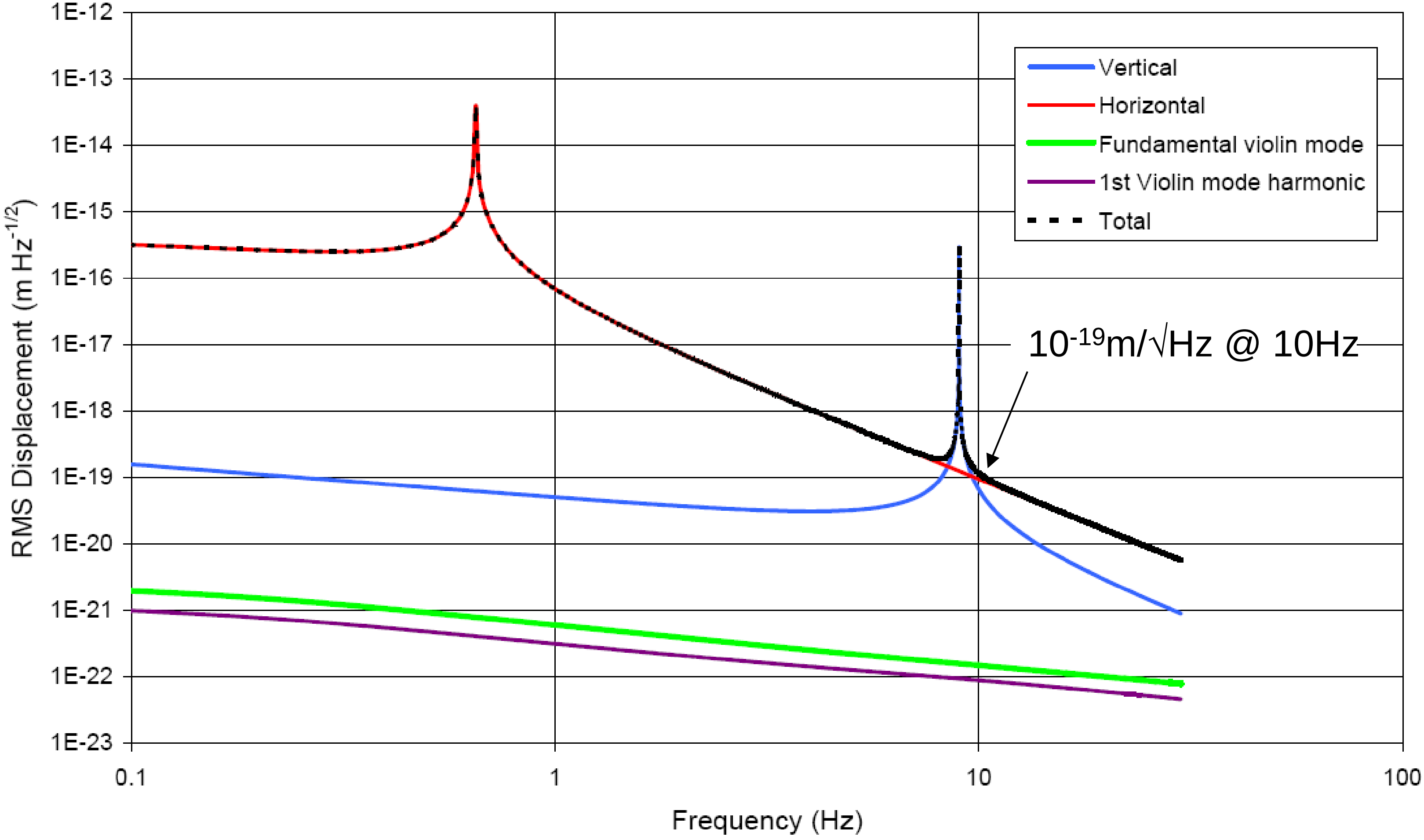
- Calculation as in Cumming et al., Class. Quantum Grav 26 (2009) 215012 (P0900084)

- Method: FEA estimate of loss weighted by elastic energy density

- Thermal noise found from loss
- Also predicts violin-mode loss which was confirmed accurate at LASTI/MIT



aLIGO Final Stage Noise (Single Test Mass)



A. Cumming et al., Class. Quant. Grav., 2011

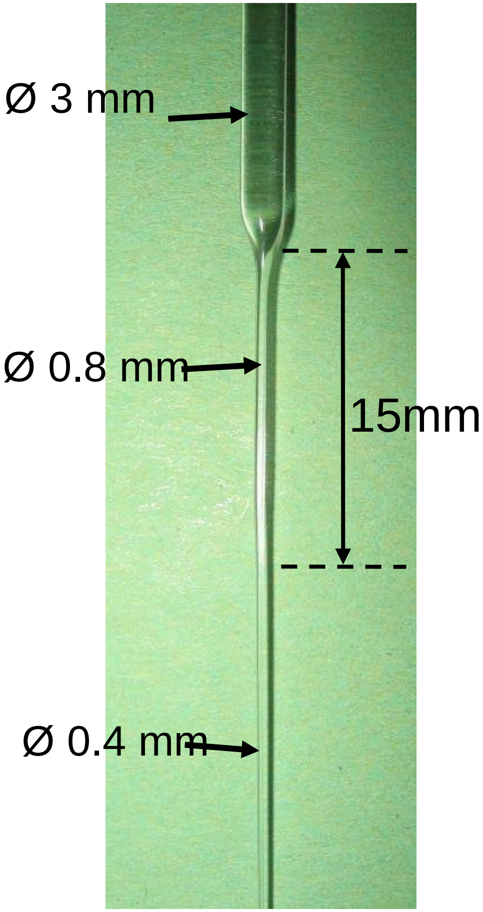
Ribbons or round-section fibres

- Final view:
  - it is hard to see how to weld ribbons while preserving strength and maintaining low noise
  - round fibres with thicker end-sections meet the noise target set for ideal ribbons
  - this includes making an allowance for loss in the weld

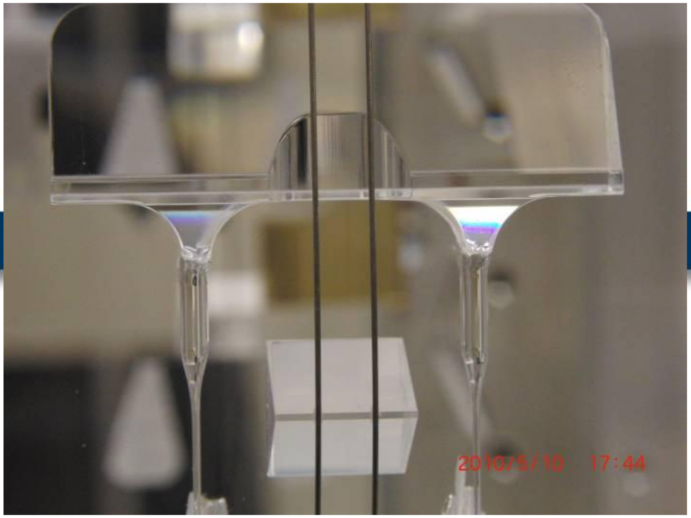
Optimin fibre design

Manufacturing and characterising the fibres

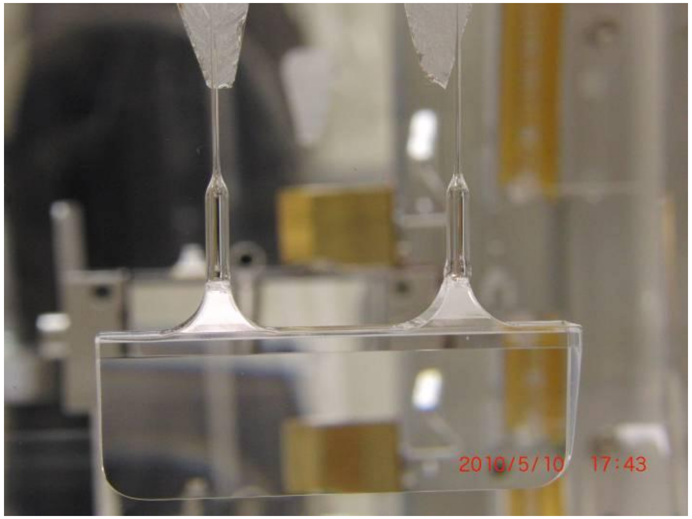
- Pull fibres with a laser pulling machine
  - Dumbbell shape for thermo-elastic noise optimisation*



*Cumming et al. Classical and Quantum Gravity 26 (2009) 215012



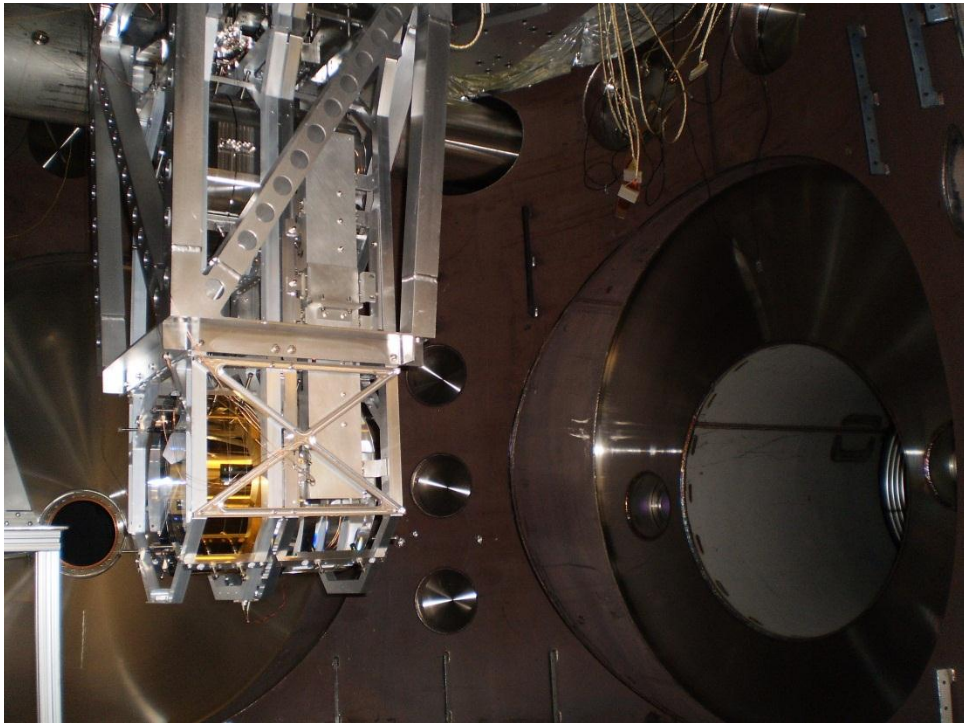
Upper ear, welded fibres, break-off prism & wires



Lower ear, welded fibres

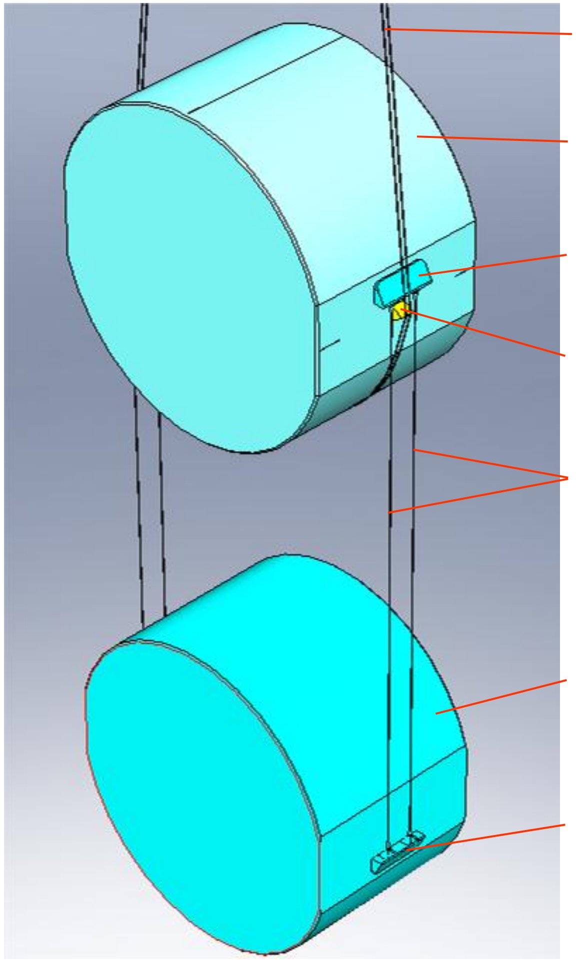
Quadruple Suspension

- Make quadruple out of monolithic and upper stages
- Marry chains again
- Back into tank



4 stages – lower two

- Extension of GEO600 triple-pendulum design (was 3 x 6kg stages)
  - lower two stages fused silica, cylinders with flats (see right),
  - connected by silica fibres welded onto ears that are bonded to the flats
  - all motion coupled "marionette style"
  - double wire loop from upper stage(s)



4 stages – upper two

- Limited by vertical isolation (and cross-coupling to horizontal)
  - upper two stages include 3 layers of springs for vertical isolation,
  - cf GEO: larger springs, higher stress (~800MPa), and extra stage, to meet performance target at 10 Hz (very roughly 10^{-7} horizontal, 10^{-4} vertical)
  - still coupled “marionette style”
- Reaction chain provides actuation at all but top stage

40kg

- Original concept designed for sapphire masses
  - 4 stages of 20, 20, 30 and 30 kg (top-down)
- 40kg test mass leads to direct reduction of quantum radiation pressure noise
  - just fits within mass budget
  - end up with about 22, 22, 40, 40kg
  - still meets all mode-frequency and control requirements
- Chosen as baseline