# Tools for

# Low Frequency Gravitational Wave Interferometric Detectors

## Glassy Metal flex joints

## Are G.M. better than fused silica for mirror suspensions?

Riccardo DeSalvo et al.

22th of February 2002

# Reasons for a Low Frequency Gravitational Wave Interferometic Detector

- There are both scientific and technical reasons to develop a LF-GWID
- No time to show and discuss today, so I did hide many slides with the scientific motivations
- Please look for them in the DCC slide show
- Or ask me separately

# Reasons for a Low Frequency Gravitational Wave Interferometic Detector

- Scientific reasons, some old and well known:
  - Start closing the gap with LISA
  - All inspirallers start at low frequency
  - ……..
- Some new scientific reasons
  - 10 to 1000 S.M. black holes observed by Chandra
  - 1987-A non axisymmetric oblate NS, many more to see

# Reasons for a Low Frequency Gravitational Wave Interferometic Detector

- Also some technical reasons:

  As the mirror thermal floor is pushed low the canyon between
- radiation pressure noise and
- shot noise walls

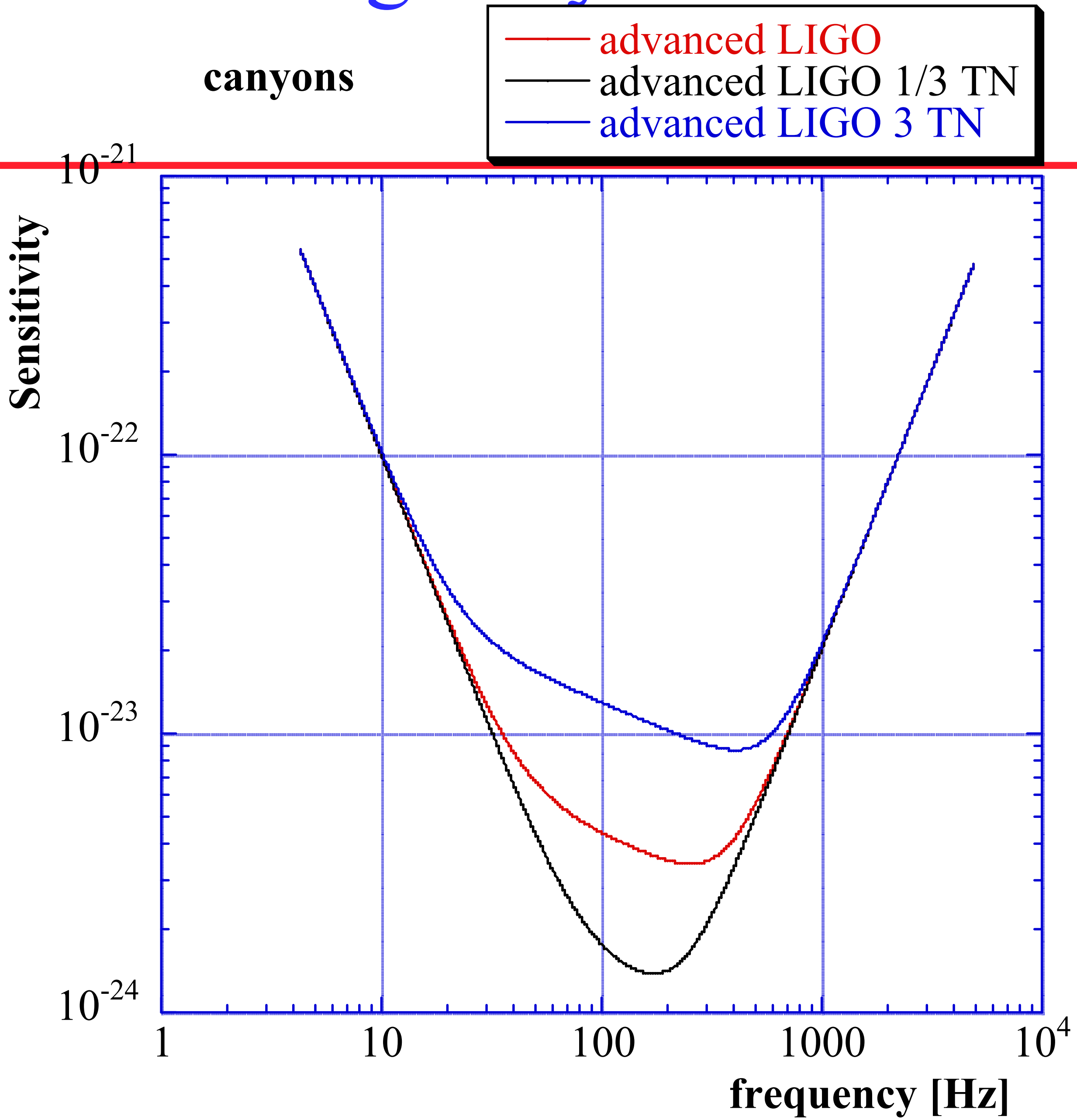
  becomes narrower

# Interest of LF-GWID

- As the mirror thermal floor is pushed low the canyon between radiation pressure noise and shot noise walls becomes narrower
- Stored beam power fixes location of canyon
- Although ns-ns inspirals peak at KHz level, BH-BH inspirals (10 and 1000 s.m.) have ISCO frequency between 4 and 400 Hz.

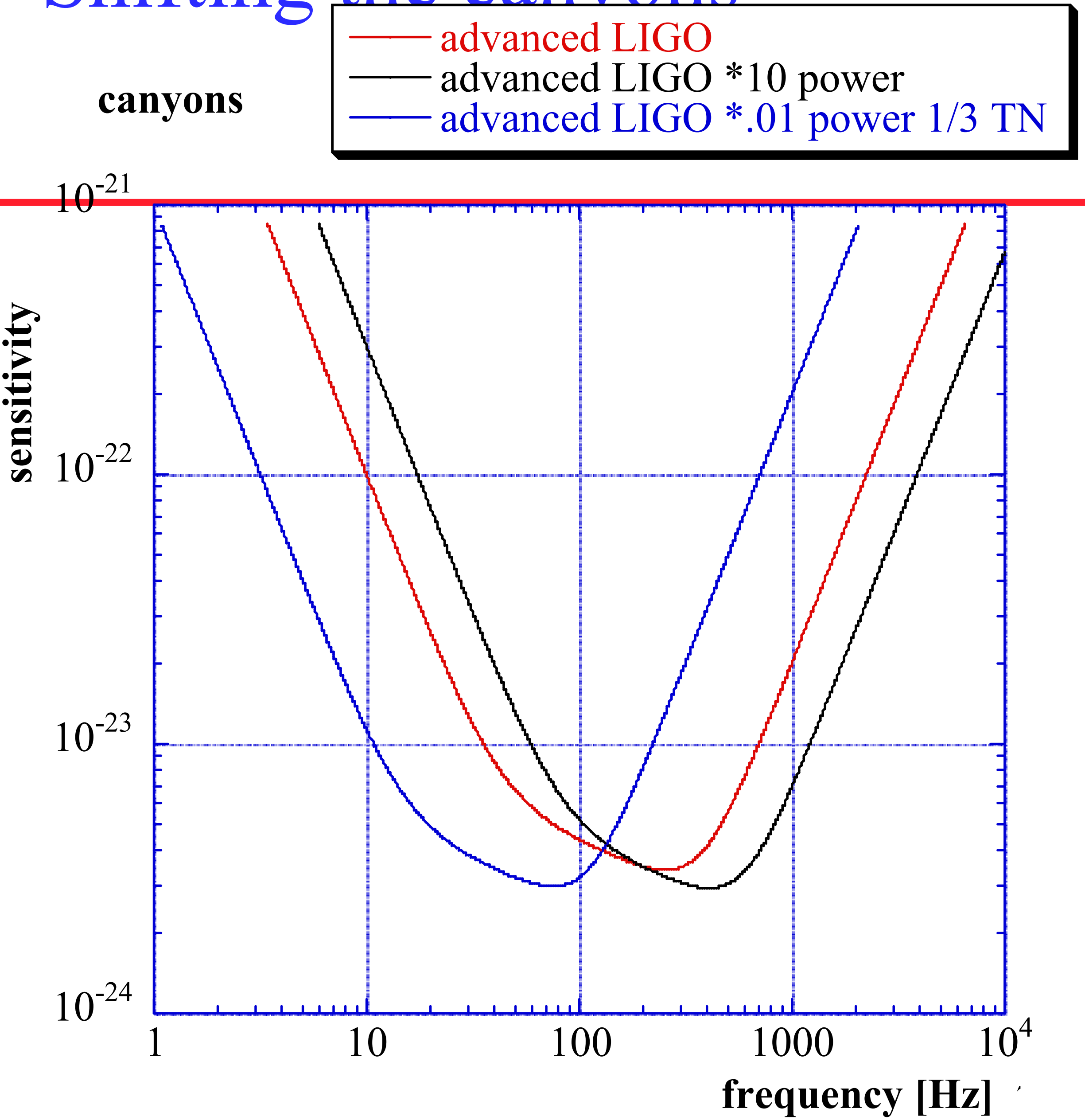
# Narrowing canyons

Any improvement of thermal noise narrows the sensitivity canyon



# Shifting the canyons

To efficiently cover a large frequency span it is necessary to build dedicated Interferometers each optimized at various frequency ranges

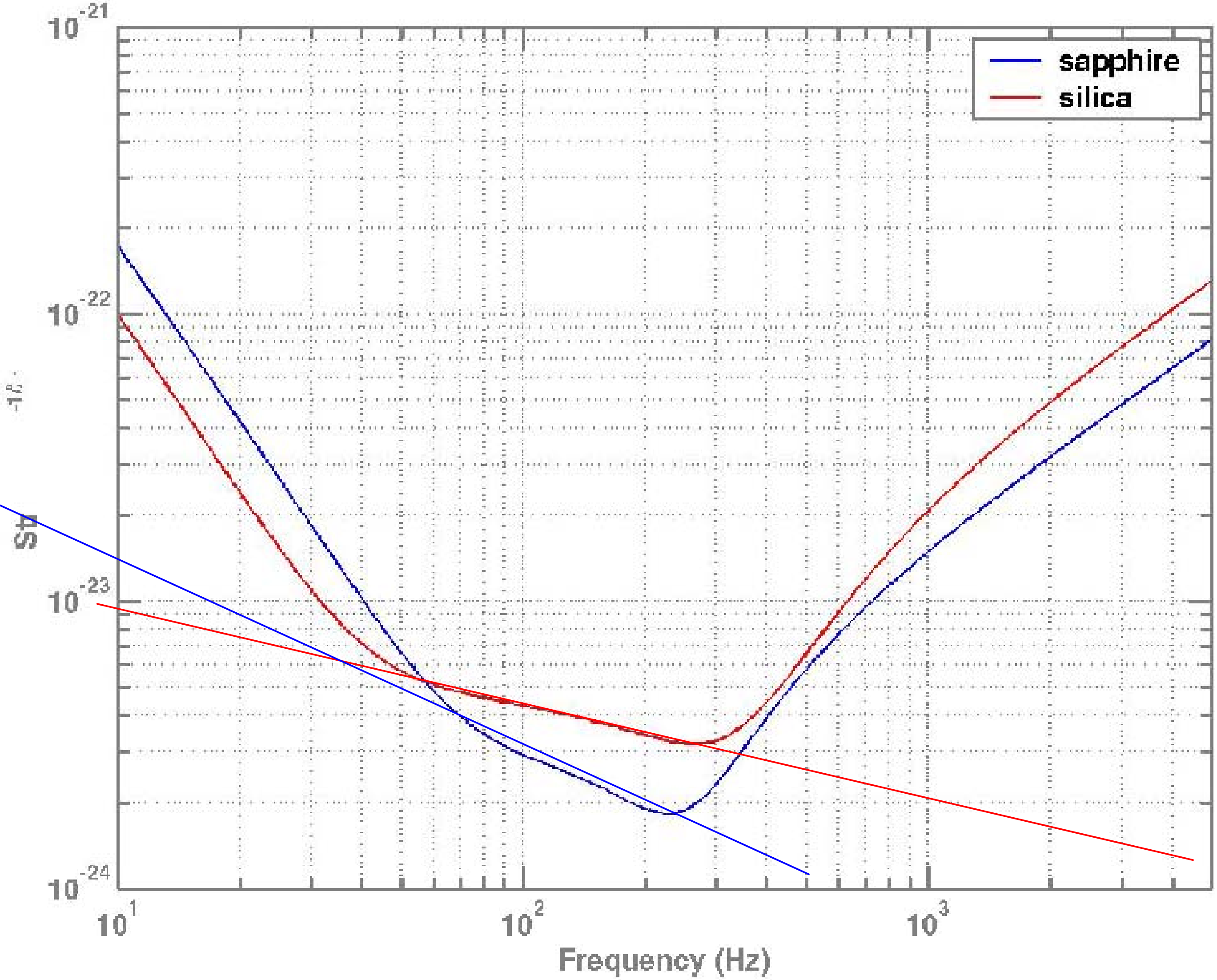


# Reasons for a Low Frequency Gravitational Wave Interferometic Detector

- Need to implement twin interferometers in the same vacuum enclosure
- Complementary in frequency range
- Separately cover the high and low frequency range

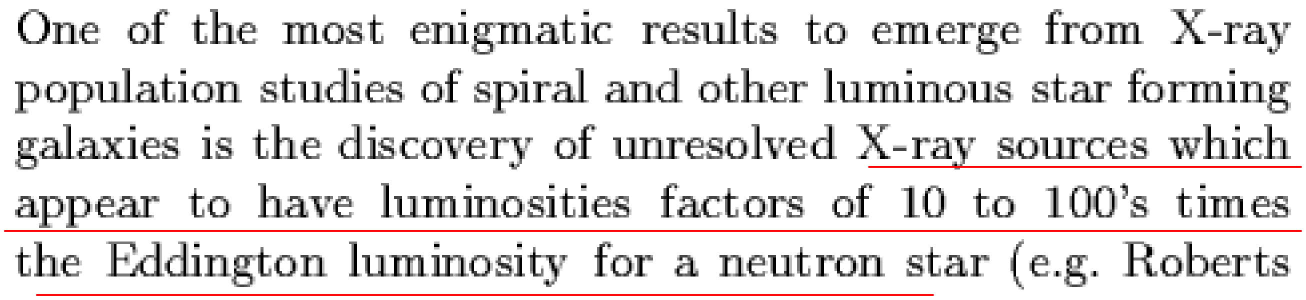
- Also at LF not having power limitations, fused silica is better than sapphire

# Comparing the canyons

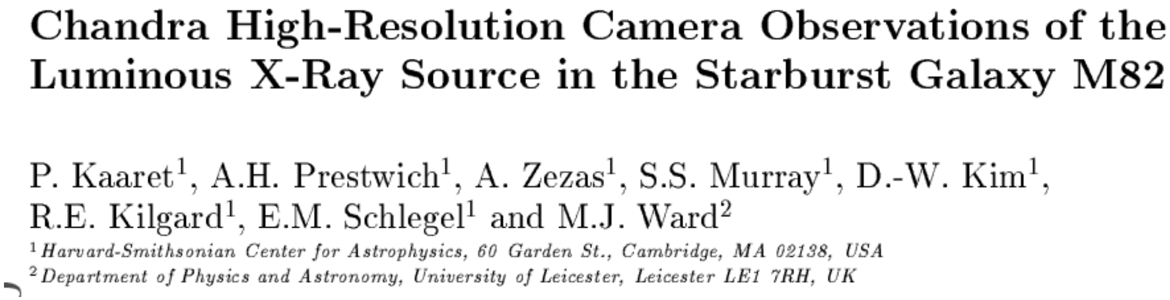


- DifferentTN slope of
- Sapphire
  - Best at high frequency
  - Also needed to dissipate high power
- and
- Fused Silica
  - Best at low frequency

# Intermediate mass BH



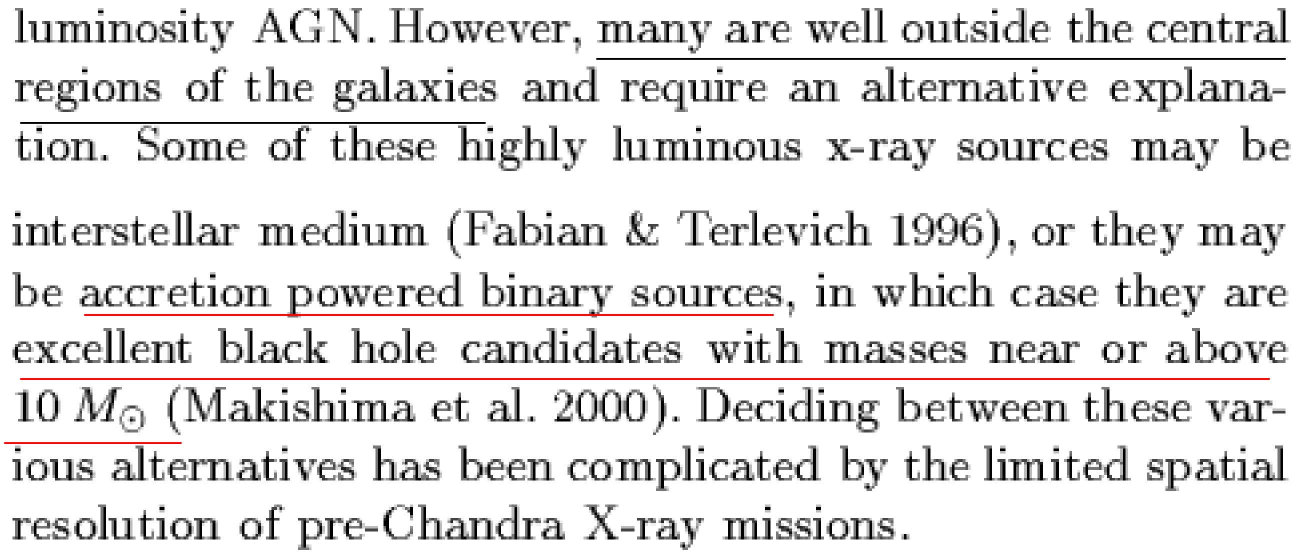
One of the most enigmatic results to emerge from X-ray population studies of spiral and other luminous star forming galaxies is the discovery of unresolved X-ray sources which appear to have luminosities factors of 10 to 100's times the Eddington luminosity for a neutron star (e.g. Roberts



**Chandra High-Resolution Camera Observations of the Luminous X-Ray Source in the Starburst Galaxy M82**

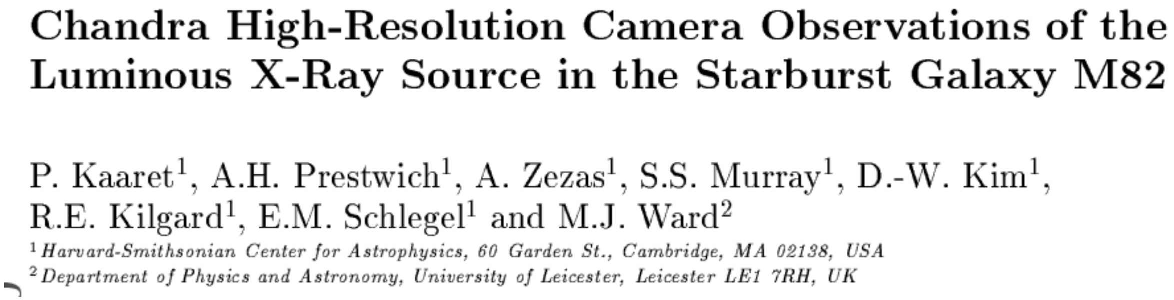
P. Kaaret[1], A.H. Prestwich[1], A. Zezas[1], S.S. Murray[1], D.-W. Kim[1],
R.E. Kilgard[1], E.M. Schlegel[1] and M.J. Ward[2]
[1] *Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA*
[2] *Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK*

# Intermediate mass BH



luminosity AGN. However, many are well outside the central regions of the galaxies and require an alternative explanation. Some of these highly luminous x-ray sources may be

interstellar medium (Fabian & Terlevich 1996), or they may be accretion powered binary sources, in which case they are excellent black hole candidates with masses near or above 10 $M_\odot$ (Makishima et al. 2000). Deciding between these various alternatives has been complicated by the limited spatial resolution of pre-Chandra X-ray missions.



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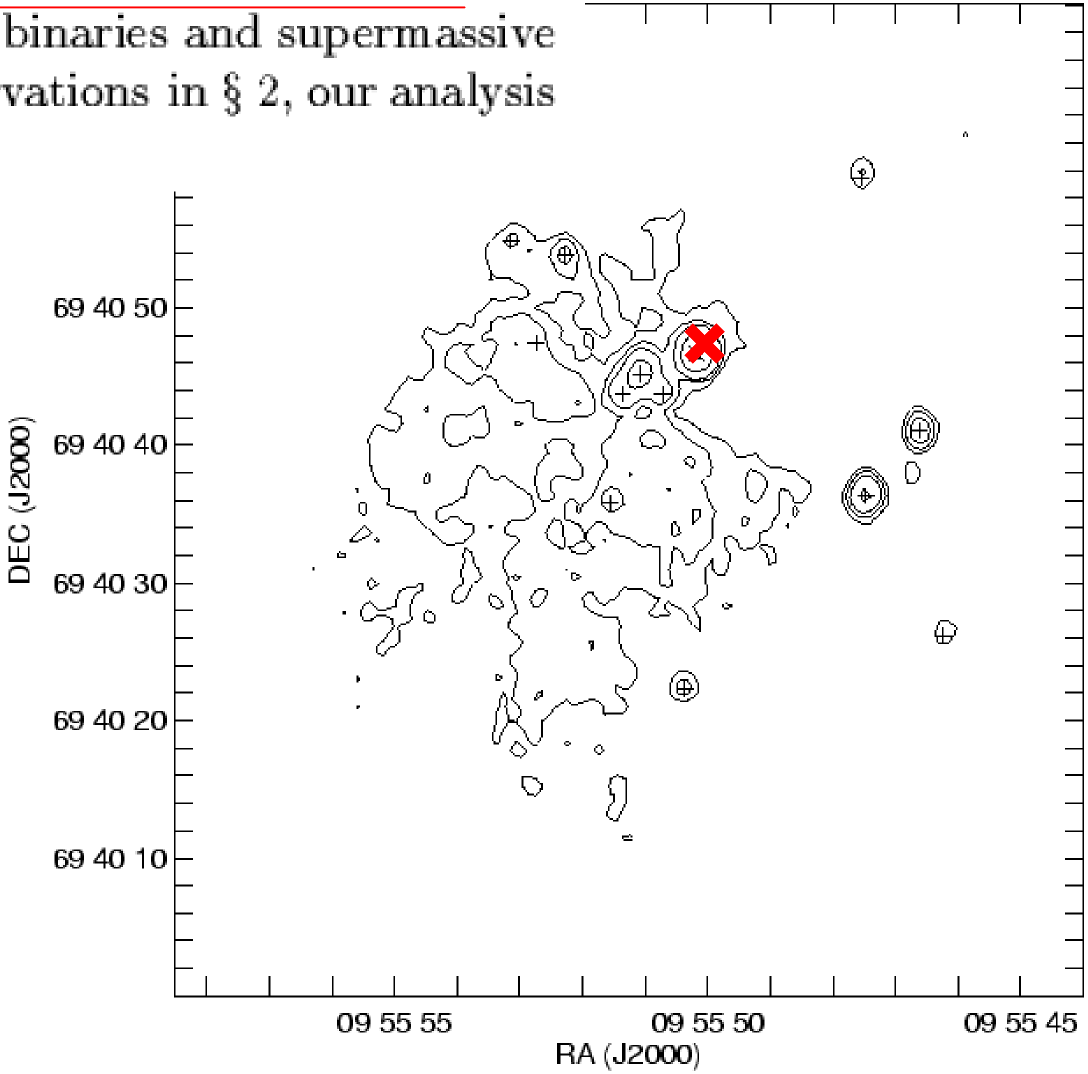
# Intermediate mass BH

the brightest Chandra source. Our results suggest that this source may be a black hole with a mass intermediate between stellar-mass Galactic x-ray binaries and supermassive black holes. We describe the observations in § 2, our analysis in § 3, and conclude in § 4.



# More on IMBH
# A short lived donor is needed

Massive Black hole with a giant companion star feeding mass :

- Necessity of a donor for visibility
- The short lifetime of donors and
- The possibility of beaming

makes for small observation probability
=> large unobserved population ! !

Observe BH-star binary,
How many of them are BH binaries?
How many are inspiralers?

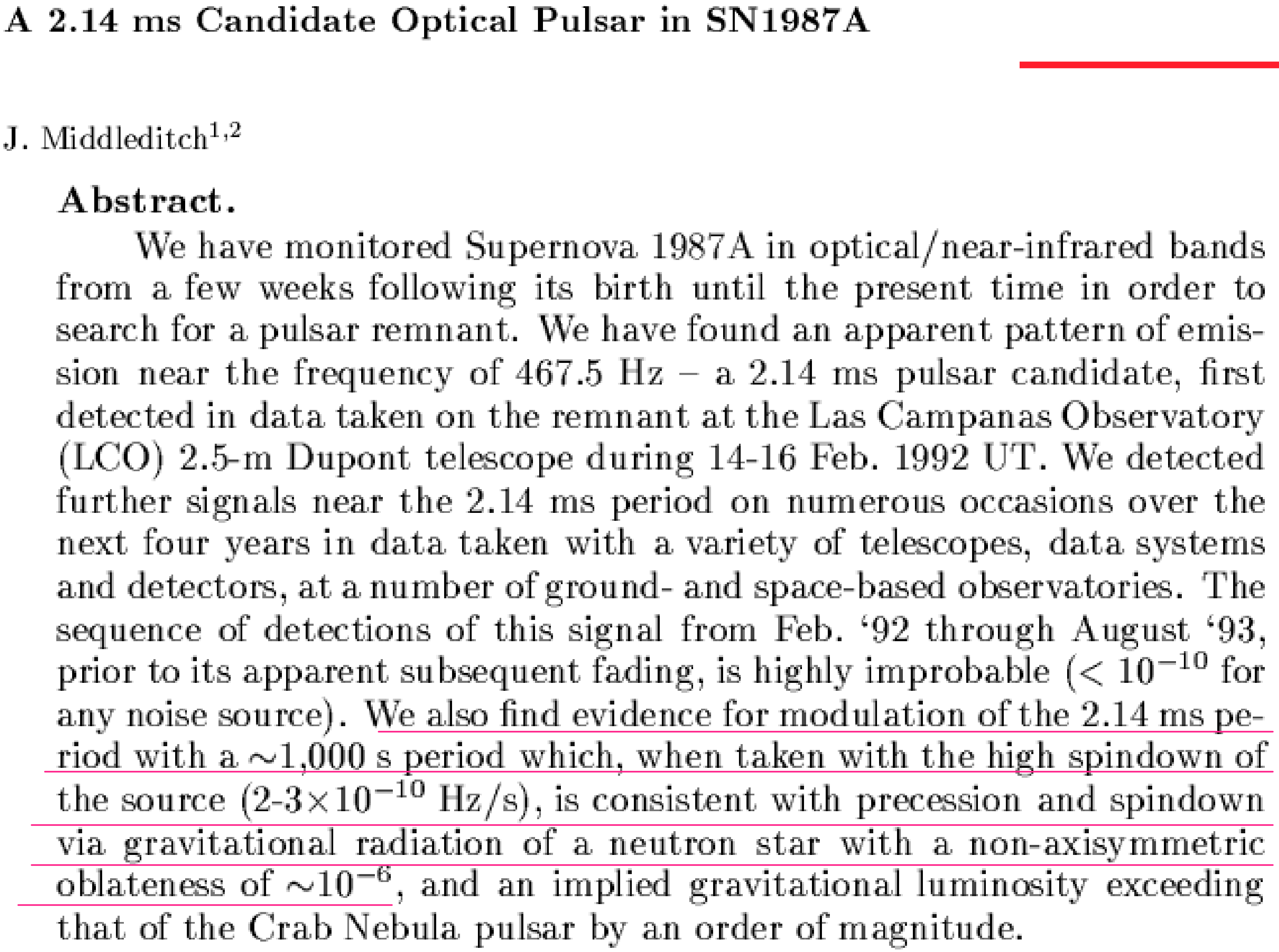
# Example reason for a LF-GWID

- 20+20 SM BH inspirallers merge at 100 Hz
- ISCO frequency $f_{GW} = 4467\ (M_{Sun}/M)$
- But may start deviating from the post Newtonian approximation at 40-50 Hz
- Stronger than NS-NS but
- No templates above 40 Hz to fish out signal
- Need LF interferometer to find signal
- Then follow the signal in the plunge phase

# A surprising reason for better coverage of high frequency range

- 1987-A oblated, spinning-down NS
- Spinning at 467.5 Hz, spinning down and precessing as compatible with GW emission from a $10^{-6}$ oblate NS
- Nautilus is being tuned and beefed up for detection, possibly within a year

# 1987-A oblated, spinning-down



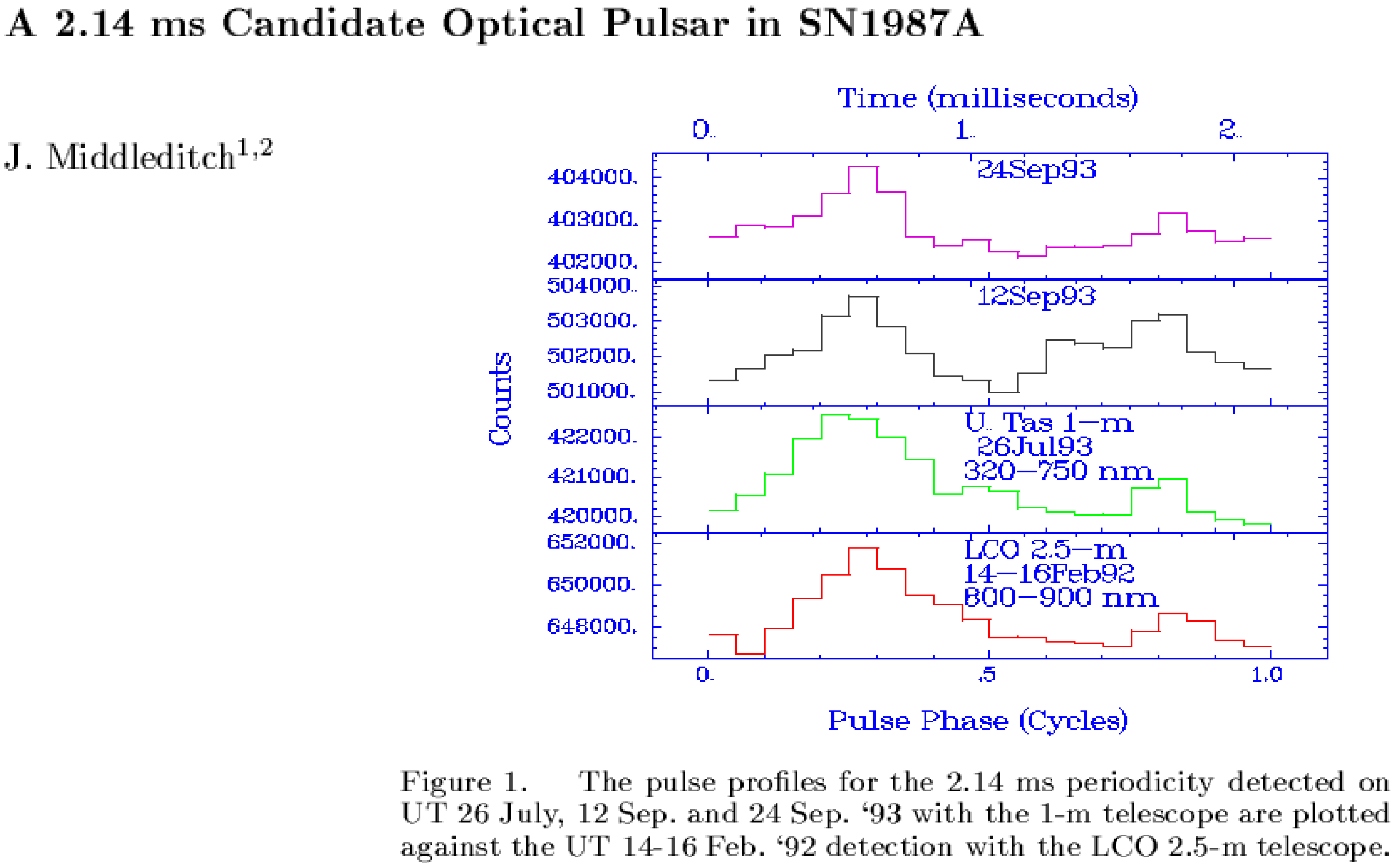
**A 2.14 ms Candidate Optical Pulsar in SN1987A**

J. Middleditch[1,2]

**Abstract.**

We have monitored Supernova 1987A in optical/near-infrared bands from a few weeks following its birth until the present time in order to search for a pulsar remnant. We have found an apparent pattern of emission near the frequency of 467.5 Hz – a 2.14 ms pulsar candidate, first detected in data taken on the remnant at the Las Campanas Observatory (LCO) 2.5-m Dupont telescope during 14-16 Feb. 1992 UT. We detected further signals near the 2.14 ms period on numerous occasions over the next four years in data taken with a variety of telescopes, data systems and detectors, at a number of ground- and space-based observatories. The sequence of detections of this signal from Feb. '92 through August '93, prior to its apparent subsequent fading, is highly improbable ($< 10^{-10}$ for any noise source). We also find evidence for modulation of the 2.14 ms period with a ~1,000 s period which, when taken with the high spindown of the source ($2\text{-}3 \times 10^{-10}$ Hz/s), is consistent with precession and spindown via gravitational radiation of a neutron star with a non-axisymmetric oblateness of $\sim 10^{-6}$, and an implied gravitational luminosity exceeding that of the Crab Nebula pulsar by an order of magnitude.

# 1987-A oblated, spinning-down



**A 2.14 ms Candidate Optical Pulsar in SN1987A**

J. Middleditch[1,2]

Figure 1. The pulse profiles for the 2.14 ms periodicity detected on UT 26 July, 12 Sep. and 24 Sep. '93 with the 1-m telescope are plotted against the UT 14-16 Feb. '92 detection with the LCO 2.5-m telescope.

# A surprising reason for better coverage of high frequency range

- 1987-A oblated, may be discovered by Nautilus
- If 1987-A is non axisymmetric oblate,
- many more lower frequency spinning NS
- might be lurking near us in our galaxy

# Ingredients for LF-GWID

- 1 Seismic Attenuation OK (see DCC slides)
- 2 Control schemes OK (see DCC slides)
- 3 Mirror suspensions (today's focus)
- 4 Mirrors
  - A Substrates probably OK
  - B Coatings to be seen
  - C Suspension points probably OK (see DCC slides)
- 5 Optical layout low power, will find solutions

# Next prioriry towards a LF-GWID

- All the above points seem soluble.
- The stumbling block for a Low Frequency Gravitational Wave Interferometer is Suspension Thermal Noise
- Absolutely need to find a clear solution for the suspension thermal noise limit at LF

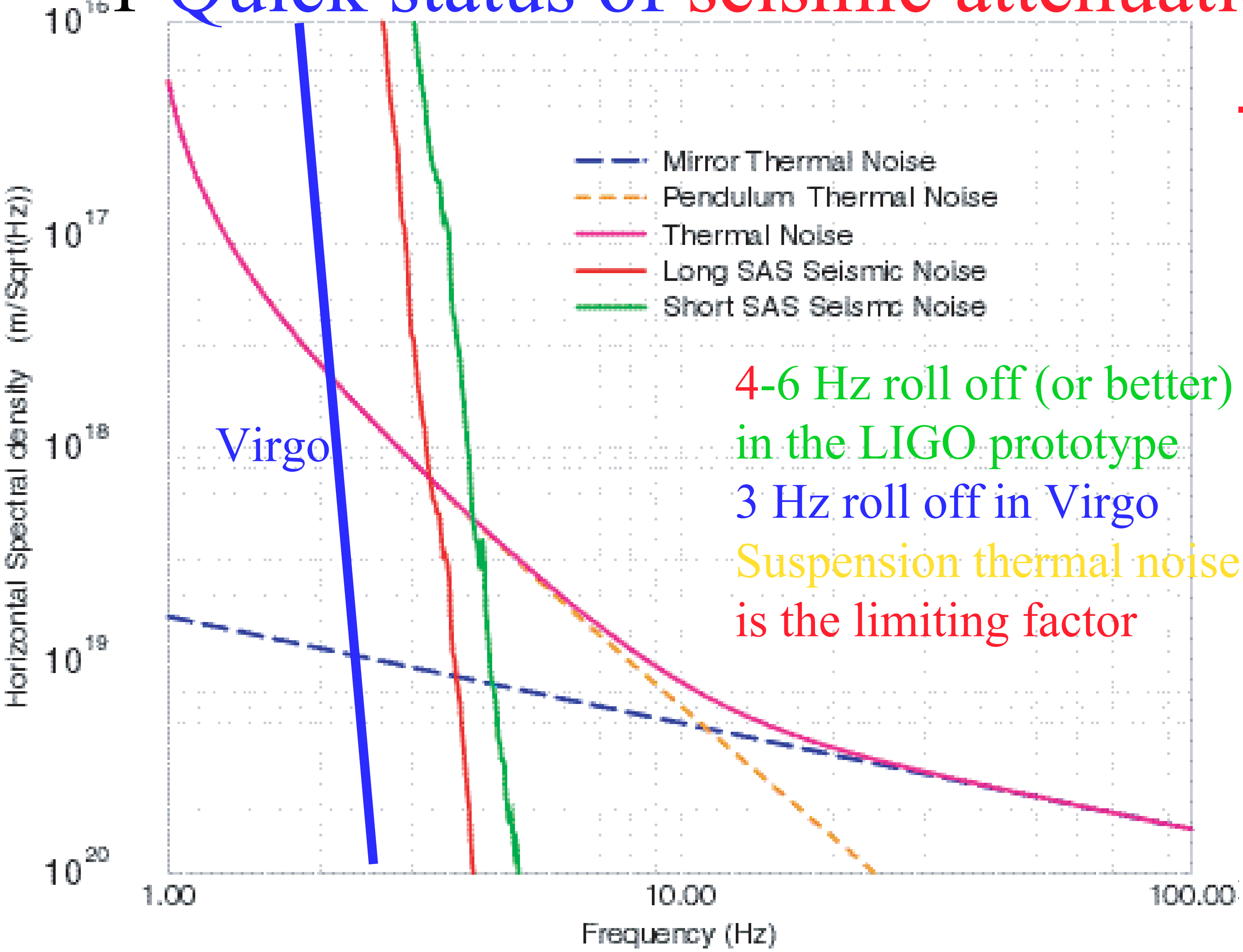
# 1 Quick status of seismic attenuation

- Virgo, installed and controls a three tower 12 m M&M interferometer with power recycling,
  - Seismic attenuation working
  - Inertial damping working
  - Length sensing to top stage feedback working
    - **Less than 70 nm/s residual velocity!**

# 1 Quick status of seismic attenuation

- TAMA 3 meter experiment
  - Two SAS towers assembled
  - 1 tower already operated locking to a ground bases M&M.
  - Second tower starting for F.P. operation
  - Scheduled implementation of SAS towers on all TAMA mirrors and benches

# Quick status of seismic attenuation



4-6 Hz roll off (or better)
in the LIGO prototype
3 Hz roll off in Virgo
Suspension thermal noise
is the limiting factor

# 1 Quick status of seismic attenuation

- Passive attenuation system well understood and ready for low frequency (>4-6 Hz) GWID operation
- Superattenuators used and tested in Virgo
- Advanced SAS scheduled to be implemented in TAMA
- Need no relevant further development

# 2 Quick status of mirror controls

- In Virgo
  - Hierarchical controls being operated and debugged
  - Operation of small PowerRec.  M&M  OK
  - L. F. Length sensing feed-back achieved

# 2 Quick status of mirror controls

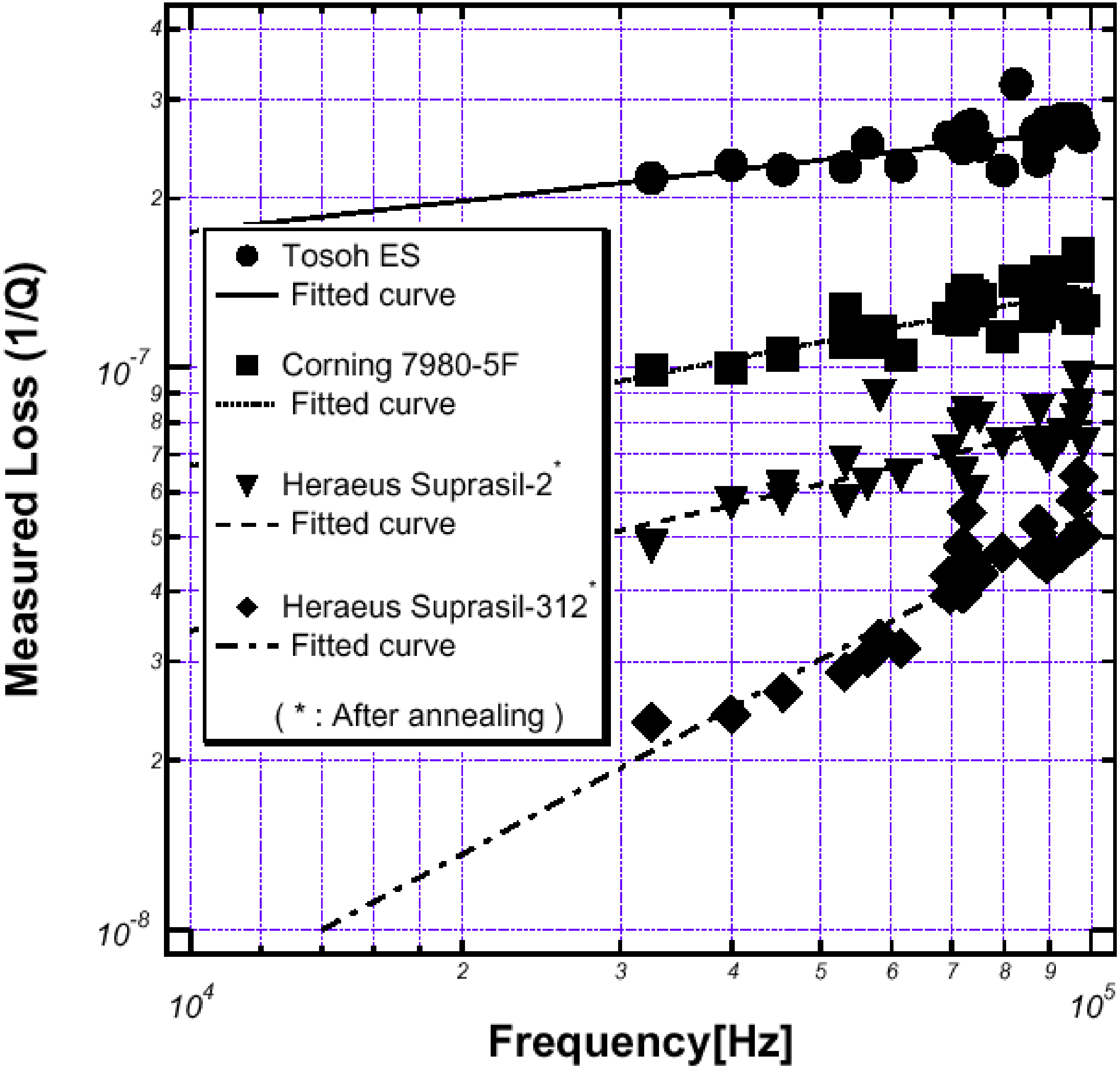
- In TAMA 3-meter experiment
  - Hierarchical controls being testes on a F.P.
  - Magnetic damping of control stage in testing
  - Starting operation of suspended F.P.

  - 3 meter experiment will upgrade to thermal noise interferometer  using the R&D Pasadena tower

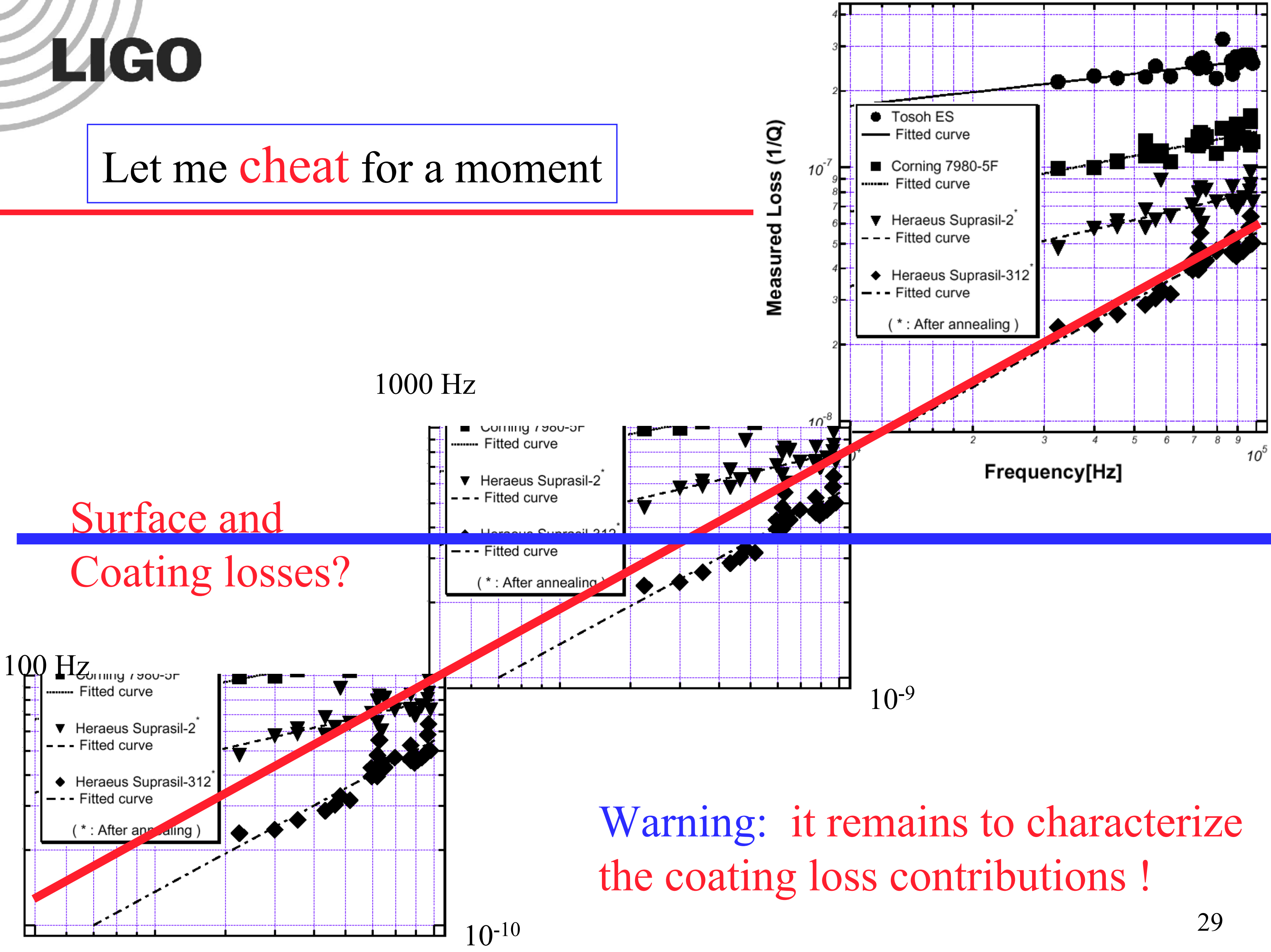
# LIGO 4 Status of Mirror's thermal noise
## A Substrates

- High internal Q factors (Kenji magnificent job!)
- May be good enough for next generation of LF-GWI already at room temperature!!!
  - At L.F. fused silica likely to be OK for long time
    - Low power densities
  - Substrates up to 75 Kg OK, more possible?

Annealing seems to expose the plunge to zero dissipation at zero frequency



# Let me cheat for a moment



Surface and
Coating losses?

Warning: it remains to characterize the coating loss contributions !

# 4 Status of Mirror’s thermal noise
# B Coatings

- Work in progress (shared between Virgo and LIGO).

- Possible surprises, will it be OK?
- Hint of at least one coated mirror with one mode at higher Q

- Can gain by 1/r of beam spot dimensions
  - Will gain fast

# 4 Status of Mirror's thermal noise

## C effects of dissipation on suspension points on reflected beam thermal noise

– Likely to be OK, (see Yamamoto's thesis) if make suspension reasonably carefully

– May not even need silicate bonding!

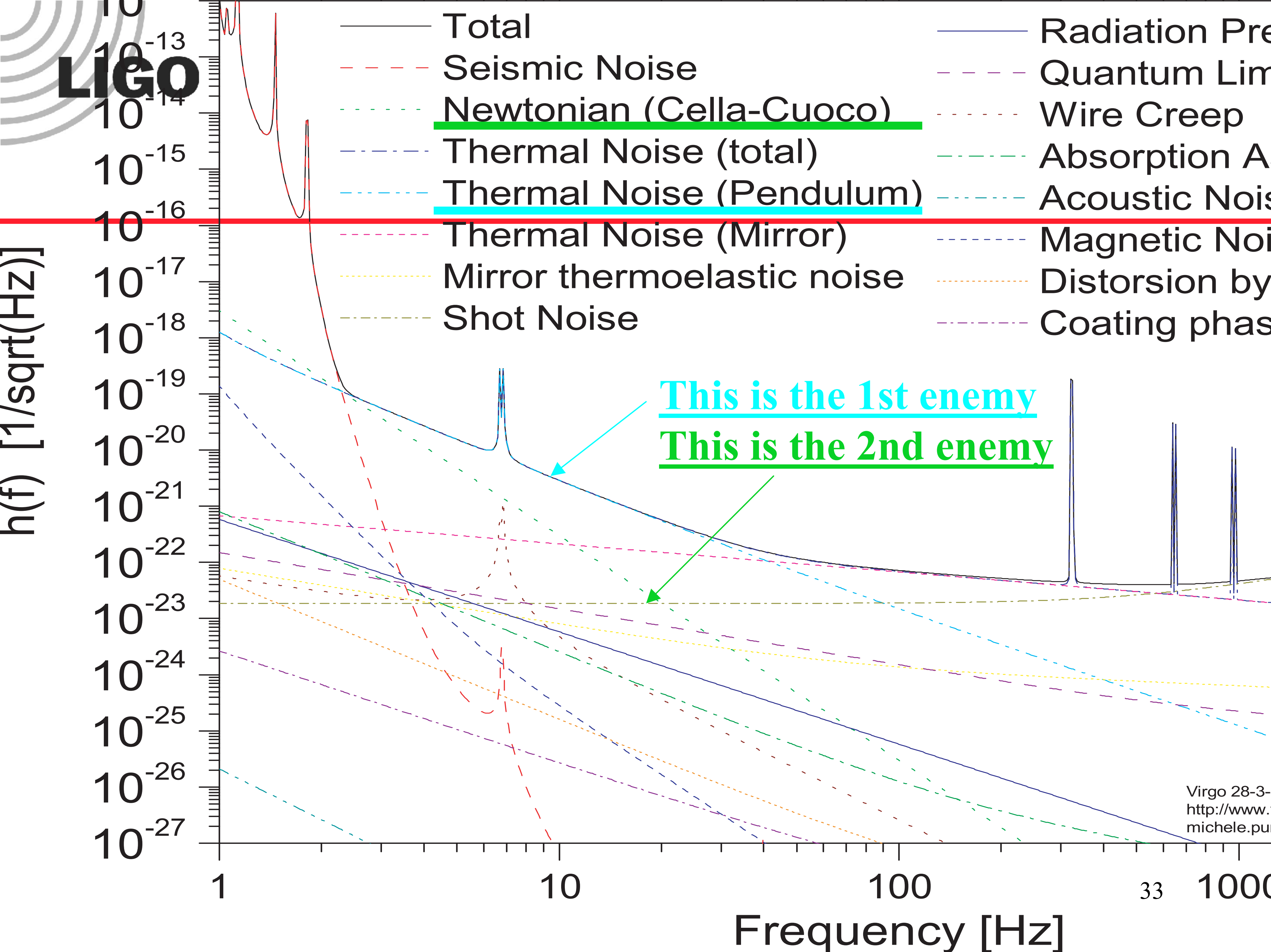
# 3 Suspension thermal noise

- Large advances are necessary and
  may be possible at Low Frequency

with Glassy metals

- Unsolved Suspension Thermal Noise would be the main limitations

- Urgent to solve !



This is the 1st enemy

This is the 2nd enemy

# 3 Suspension thermal noise

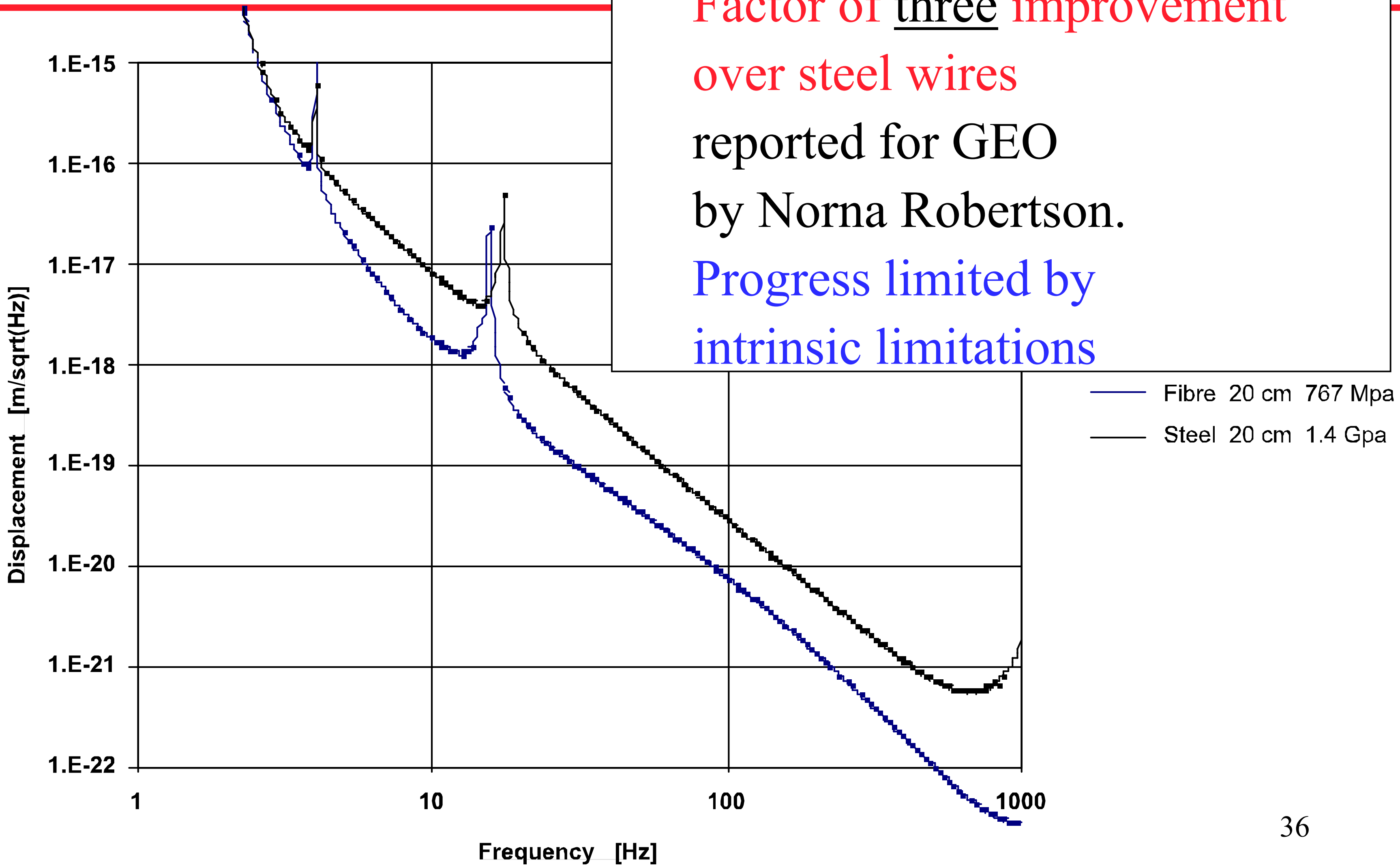
- Argument of presentation
- Three avenues explored by many scientists:

1. Quartz
2. Cryogenics
    - Fibers
    - Flex joints
3. <u>Alternative techniques</u>
    - Glassy metals (reduced thermal noise)
    - Alternative geometries (noise at lower Freq.)

# 3 Suspension thermal noise

- Quartz is being studied since a long time and by a large amount of physicists.
- Recently bearing some fruits

# Triple Pendulum: Thermal Noise



Factor of <u>three</u> improvement over steel wires reported for GEO by Norna Robertson.

Progress limited by intrinsic limitations

# 3 Suspension thermal noise

- Cryogenics, a tough but in the long term almost sure bet
- Very long term project, R&D time scale imposed by power dissipation requirements.

# 3 Suspension thermal noise

- Looking for alternative solutions, why? :
- Before investing a lot into cryogenics it is

  wise to explore the chance that

  alternative and easier technologies
  may steal much of the prize.

# Alternative Suspension Solutions metallic flex joints

- Metallic Flex joints have been evaluated in the past for mirror suspensions
- Extensive work by D. Blair et al.
- Flex joint have an edge because they allow large aspect ratio and large pendulum dilution factors
- Metals start disadvantaged with respect with glasses because of lower (<10,000 for metals) intrinsic Q-factors.
- Metals allow advanced mechanical geometries

# Why Fused Silica is not that good?

- The $10^7$-$10^8$ fused silica internal Q-factor

  is "internal"
- The surface in fibers is deteriorated by micron size scratches, defects and OH attack.
- Most of the suspension motion elastic energy is stored on the surface of fibers

# Fused Silica Limitations

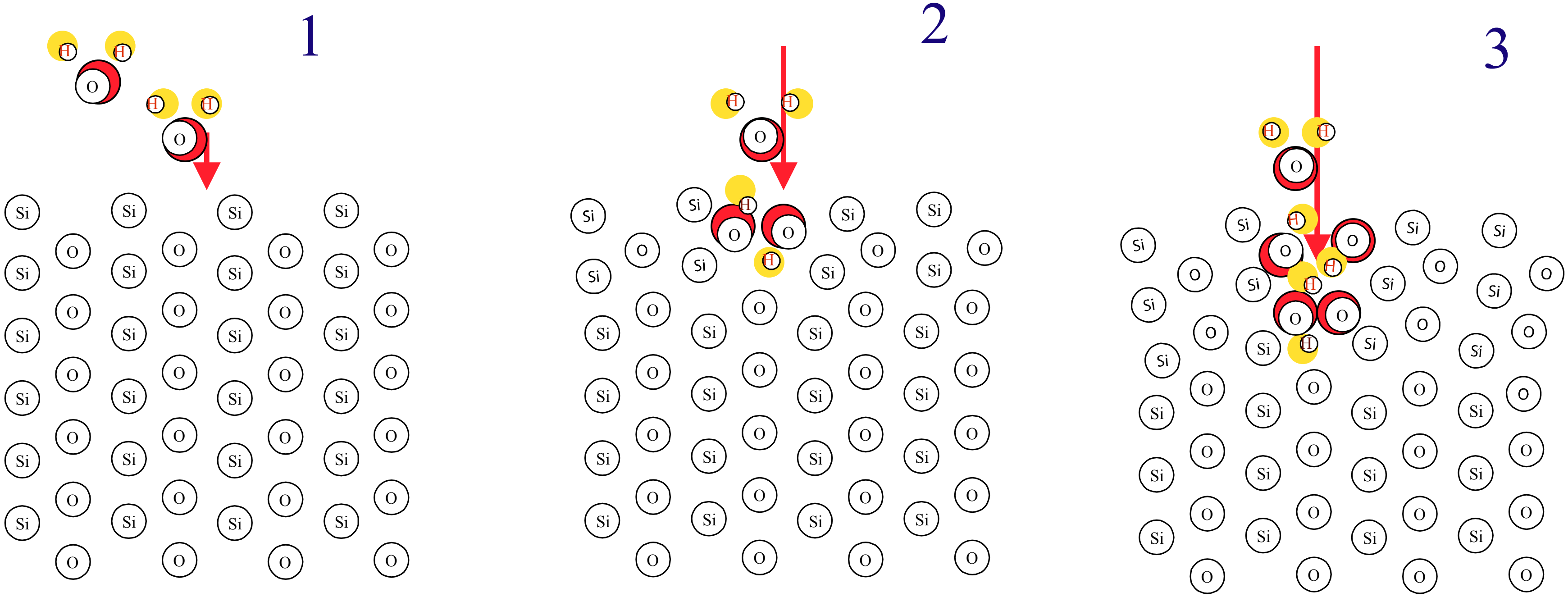
- A small scratch in a solid mirror surface would be widened and deepened infinitely by the OH wedging effect if the elastic pressure from the surrounding matter was not limiting the penetration.
- In fibers the volume beneficial effect is diminished by geometry (less volume vs. more surface)
- The ill effect of surface defects is further enhanced by operation under tension.
- Situation much worse with ribbons that are all surface and no volume to oppose the damage

# Why Fused Silica is not that good?

- In fused silica the critical defect size (below which the pressure of the surrounding material neutralise the defect is below the micron.
- During annealing processes the surrounding matter pressure helps healing defects below critical size.
- Flame polishing has some (limited) healing power.

# SiO +$H_2O$ scissor effect

- SiO + $H_2O$ = 2 SiOH
- scissor effect



# Fused Silica Limitations effects

- The effective fused silica Q-factor is often kept well below the theoretical ~$10^8$ by surface defects
- Allowable load in fused silica fibers is limited well below one GPa by
  - reliability considerations as well as
  - Thermo-elastic noise optimization

# Rekindled interest in metals

- Better understanding of glassy metals recently opened new opportunities
- Very interesting to explore this avenue to ascertain if glassy metals may give easier and better success or will be as tough as fused silica

# Why Glassy Metals ?

- Easy to shape and braze: allow the achievement of advanced engineering and mechanical geometries like metals.
- Naturally produced in thin films or ribbons.
- Not fragile
- Allow loads of 4, 5 or even 6 GPa!!!
- (Best steel limit at 1.8 Gpa, typical fused silica 0.7 GPa)
- Very large elasticity limit (2%)
- Some metallic glasses have low internal Q-factors but refractory metal glasses have large Q-factors that may be competing with fused silica.

# Why Glassy Metals were overlooked ?

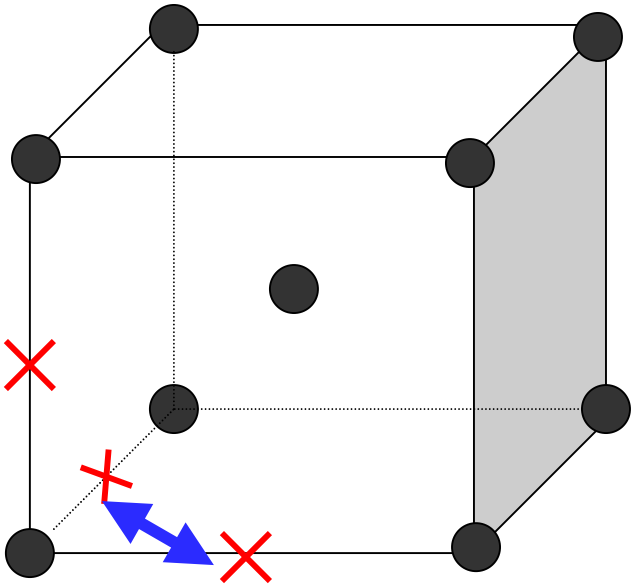
- Available glassy metals:
- Developed mainly as iron based ferrometallic alloys for transformer cores
- Developed as braze materials because of very low eutectic melting point

- Both characteristics make them bad for suspensions

# Why Glassy Metals were overlooked ?

- Ferrometallic alloys are based on Iron, Nickel and Cobalt
- All of them like
  - to make locally cubic structure
  - to absorb hydrogen
  - to store H in one of the orbitals between Iron atoms
- Under varying stresses the hydrogen continuously jumps from the compressed to the stretched links
- Energy dissipation ensues with a Debye peak near room temperature (300 to 400 Kelvin)
- Low mechanical Q-factors are produced
- refractory metals do not absorb hydrogen!!!

# Hydrogen flipping losses



● **= Metal Atom**

✕ **= Hydrogen location**

Hydrogen atom flip-flop with changing stresses

# Why Glassy Metals were overlooked ?

- The braze materials also have low mechanical Q-factors
- In all glasses (metal or not),

barring all other spurious loss factors like hydrogen,

the mechanical Q-factor is proportional to the ratio between melting and room temperature.

- (optical glass has lower Q than fused silica)
- Low melting point of braze glassy metals means low mechanical Q-factors

# Which Glassy Metals are promising

- Glassy metals can be manufactured
  - Starting from many metals,  recipe:
  - Mix  two close relative metal
  - Add Boron or Silicon to frustrate the formation of crystalline structures
  - Cool rapidly
- Molybdenum or Tungsten mixed with Ruthenium or Rhenium and additioned with Boron and/or Silicon)

# Which Glassy Metals are promising

- Molybdenum or Tungsten Ruthenium or Rhenium Boron and Silicon

do not absorb hydrogen

and have

very high melting points

(similar or higher than Fused Silica)

# Melting points

| **Element** | **Melting Point (${}^{0}$C)** |
|---|---|
| Mo | 2617 |
| Ru | 2310 |
| B | 2300 |
| W | 3410 |
| Re | 1966 |
| Si | 1410 |

| **Glass** | **Melting Point (${}^{0}$C)** |
|---|---|
| MoRuB | 1400-1450 |
| WReSiB | 1600-1700 |

do not absorb hydrogen

# Which Glassy Metals are promising

- There is no qualitative difference between
- Quartz/Fused Silica and
- Crystalline metals/Glassy metals

- Crystallization time
  - Hours for Fused Silica
  - Seconds for Glassy Metals

# Which Glassy Metals are promising

- In metallic glasses the Mo-Ru or W-Re bond play same role as the Si-O bond in Fused Silica, both in determining the melting temperature the dissipation processes and the damage processes

- There is no equivalent of the OH problem
- No fragility ! ! !

# Which Glassy Metals are promising

- As in Fused Silica purity and annealing conditions will play a determinant role

- Unless unknown (and so far unexpected) loss mechanisms are observed **MoRuB** and **WReBSi** should have Q-factors comparable to fused silica

- But intrinsic Q factor is <u>less important</u> because of the much more advantageous possible geometries

# Which Glassy Metals are promising

- While fused silica inherits from Quartz and has and has small critical defect size (<μm),
- Glassy metals inherit from metals and their their critical defect size is measured in tens of tens of μm.
- Defects will be visible if present
- In absence of visible defects the material can be can be safely loaded to close to its limit breaking point which was measured is
- 4-5 GPa for MoRuB and
- 5-7 GPa for WReBSi.

# Estimated MoRuB glass properties

- Mo49Ru33B18 in atomic percent.
- density, 9.5 g/cc
- heat conductivity, 10 Watts/m-K
- heat capacitance, 30 J/mole-K
- linear thermal expansion coeff., 5-6 x $10^{-6}$ ($K^{-1}$)
- elastic modulus, 250 GPa
- Poisson modulus, 0.36-0.38
- breaking point 5 GPa
  (not fragile, loadable to > 4GPa)
- - These numbers should be accurate to +/- ~20%

# MoRuB sample

# Estimated MoRuB glass properties

- Q factor >>$10^4$, probably > $10^5$

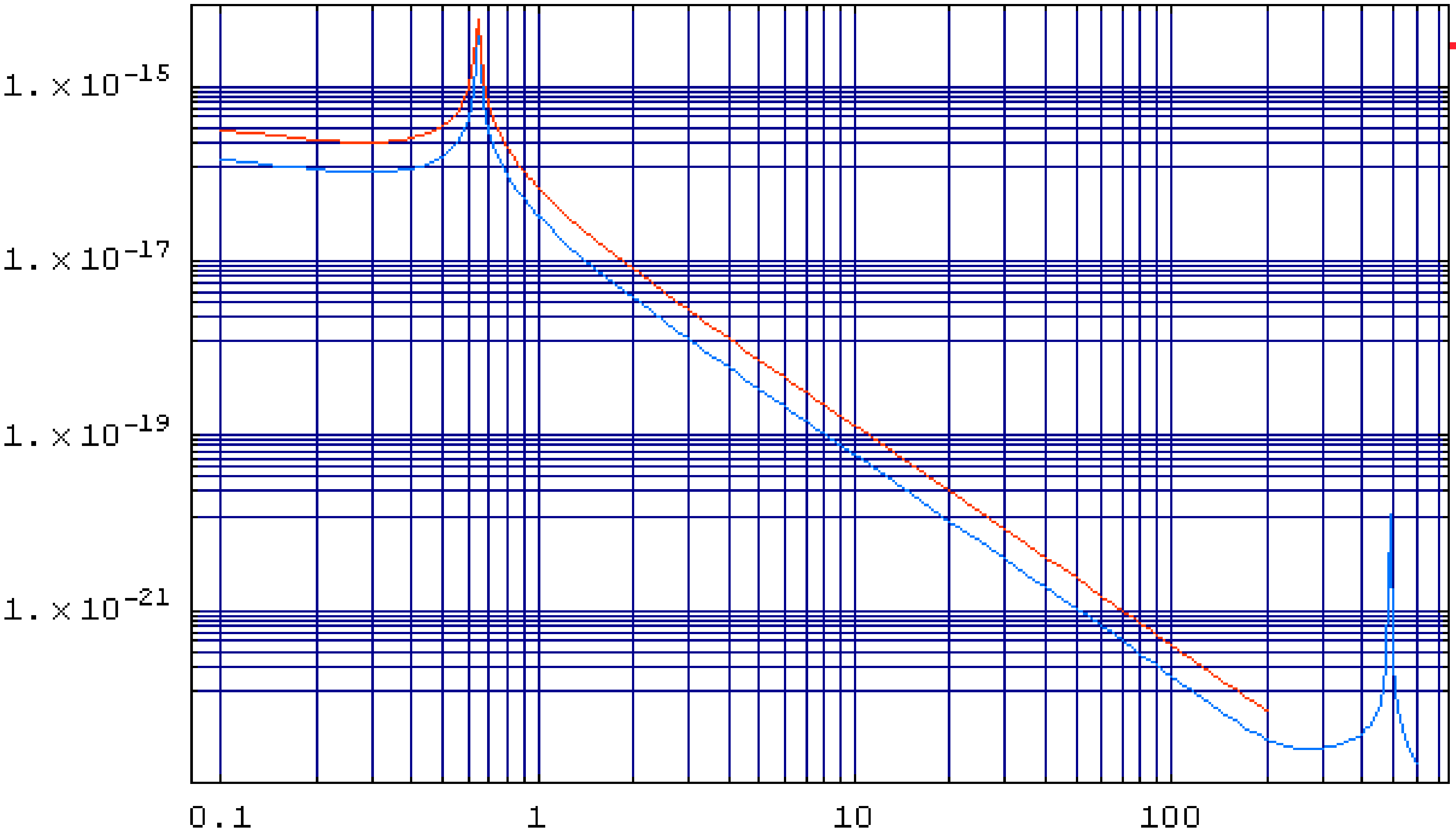
- All of these numbers

  necessary to calculate thermal and thermo-elastic noise

  need to be measured soon

Ready to start measuring

# Thermal noise of MoRuB flex joints



Glassy metal Q=$10^4$, Fused $SiO_2$ dumb bell shaped fiber Q=$8.4*10^8$,
10*3000 = 30,000 μ$m^2$, 357 μm diameter, 100,000 μ$m^2$,
60 Kg mirror, 40 Kg mirror

# WReBSi glass properties

- Stronger than MoRuB
- Higher loads possible (6 GPa instead of 4 GPa)
- Higher still possible Q-Factors

  (>$10^6$ instead of >$10^5$)
- More difficult to manufacture

# What's being done to explore possibilities?

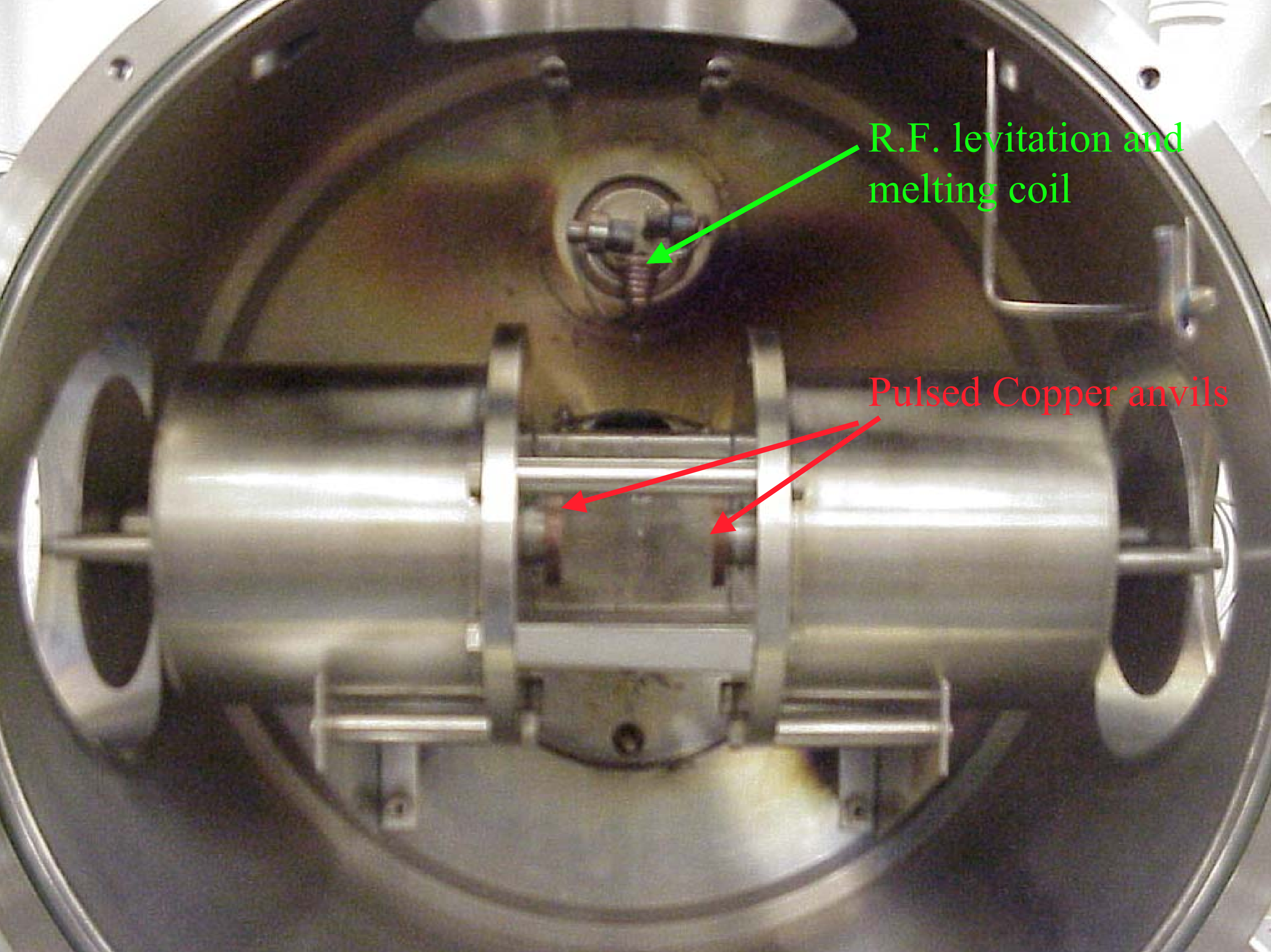
- Make several samples of different compositions
- Measure physical properties
  - Yield point,
  - Elastic constant
  - Poisson ratio
  - Thermal capacity
  - Thermal conductivity
  - Thermal expansion coefficient . . . . . . . .
- **Measure** reed (diving board) **Q-factors** of samples

# What else to do to explore the possibilities?

- Demonstrate feasibility of fabrication of suspension structures
- Demonstrate feasibility of attachments to mirrors without significant loss of mirror Q-factor
- Test suspension Q-factors ($>10^8$) with macroscopic mirrors

# What is being done?

- Make several samples of different compositions
- Samples are made in Caltech Metallurgy department (splat cooling)


R.F. levitation and melting coil
Pulsed Copper anvils

# What does splat cooling produce?

- The end product is a disk
  - 50 µm thick,
  - 15 mm in diameter
- The surface copies the (electropolished) anvil’s surface to optical accuracy
- Only 3*6 mm platelets are required

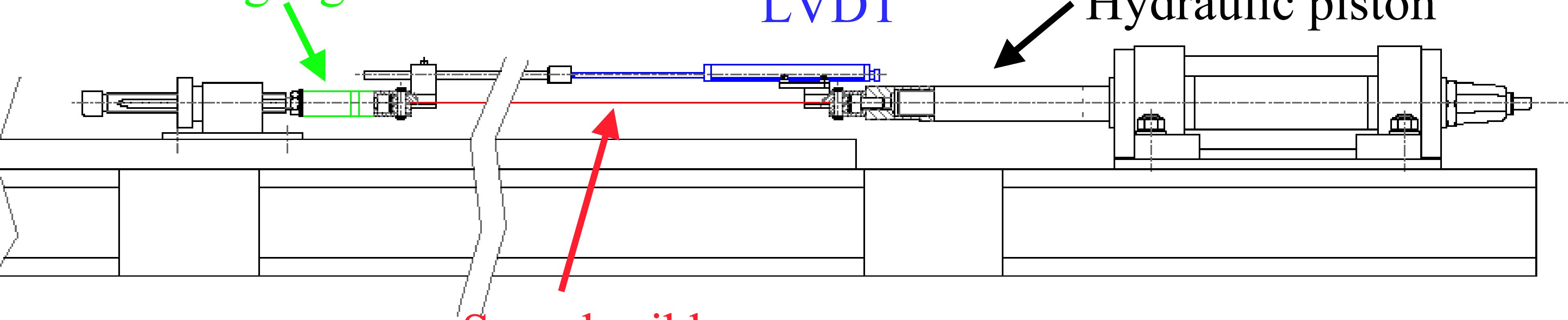
# What is being done?

- Measure physical properties

  At room temperature
  - Yield point,
  - Elastic constant
  - Poisson ratio
  - Hysteresis

  - All in Virgo’s stress-strain machine

# Yield point, Elastic constant, Poisson ratio



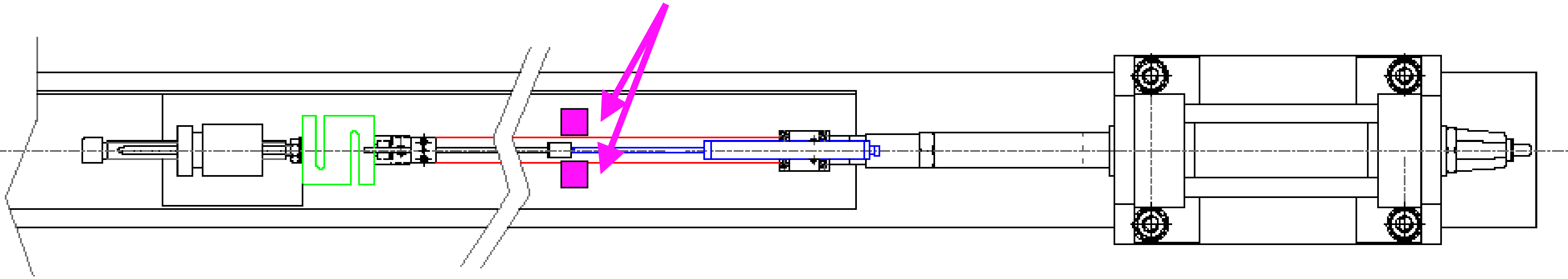
Strain gauge

LVDT

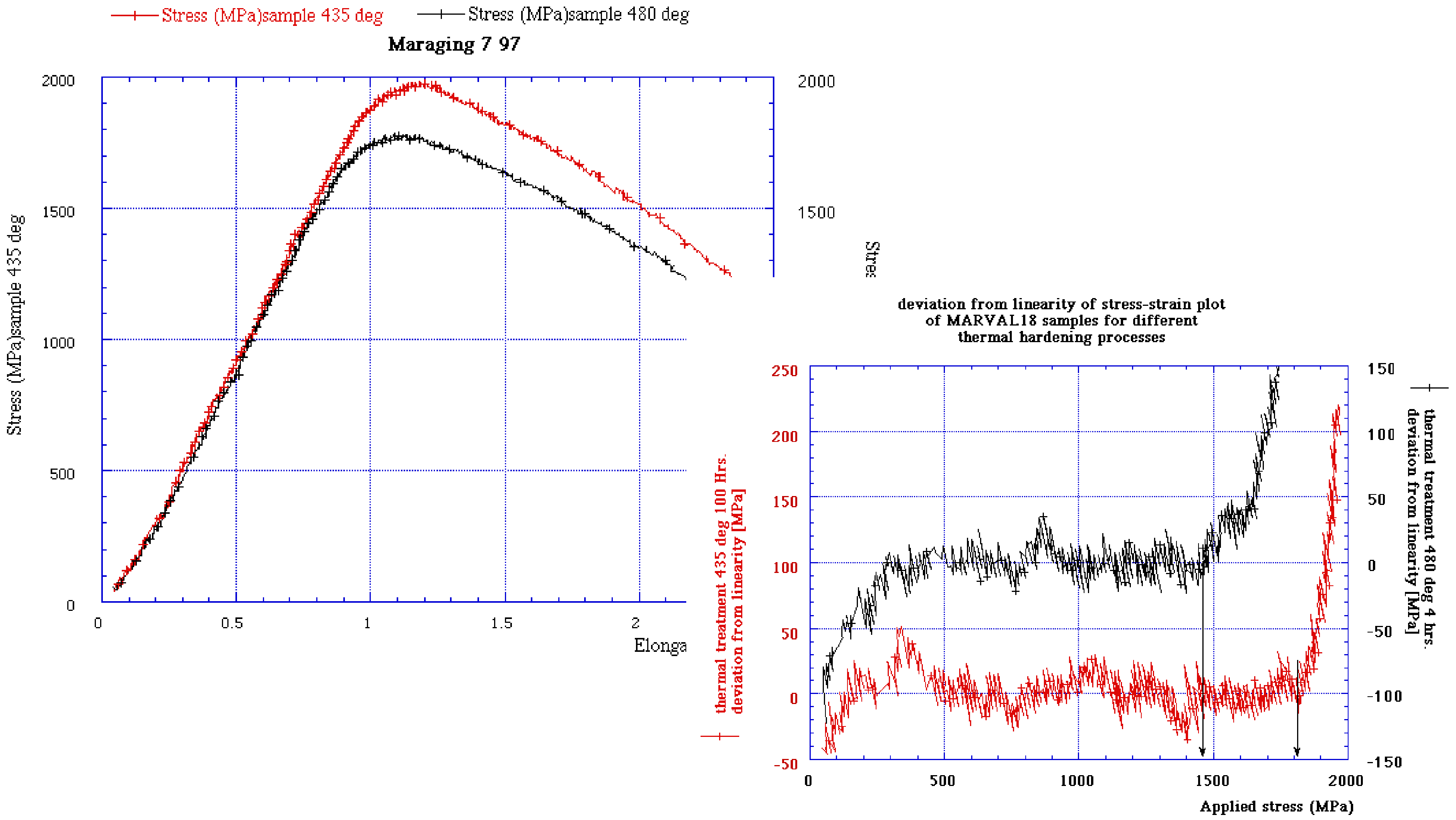
Hydraulic piston

Sample ribbon

Shadow meters mounted on the side of the ribbon to measure Poisson factor



# Yield point, Elastic constant, Poisson ratio



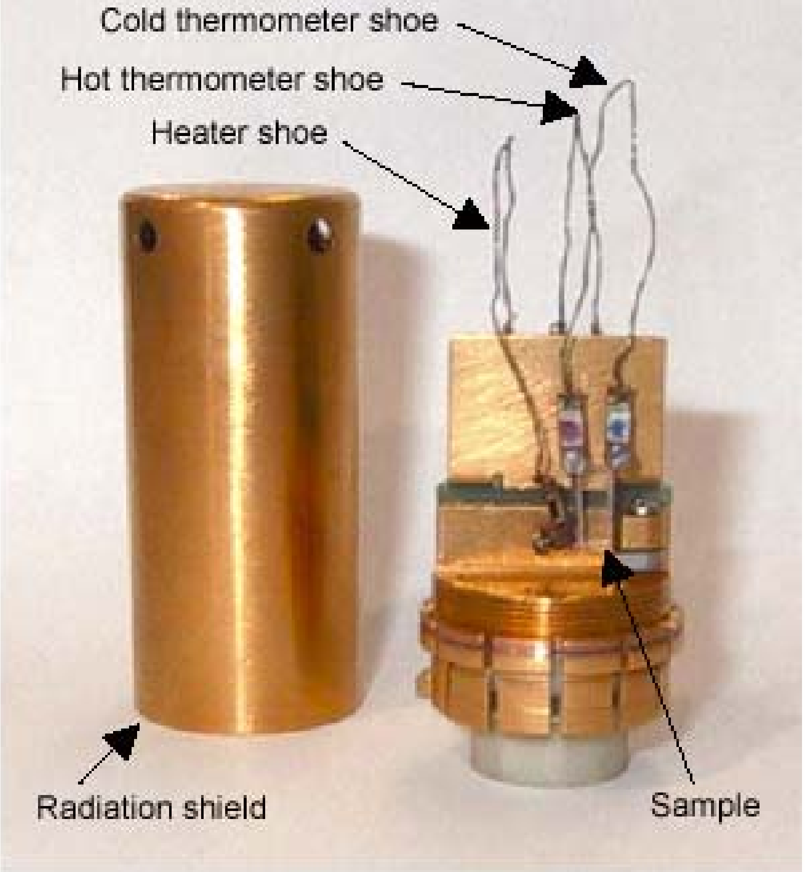
# What is being done?

- Measure physical properties

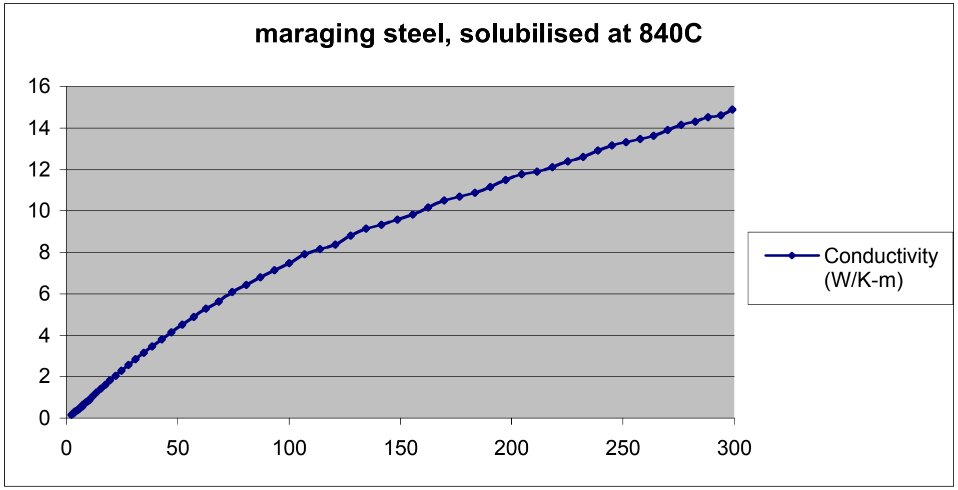
  Continuously between 2 and 400 Kelvin
  - Thermal capacity
  - Thermal conductivity

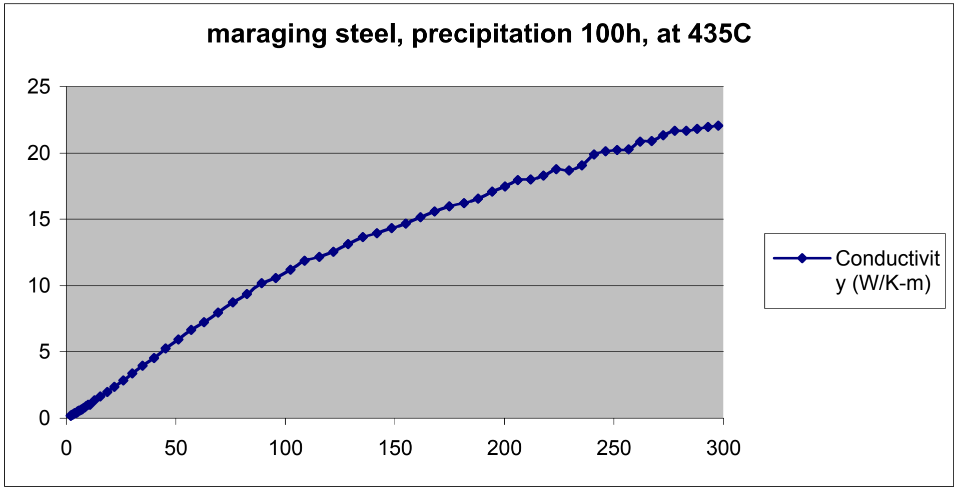
  - Into LIGO's programmable cryostat

# Thermal capacity,Thermal conductivity

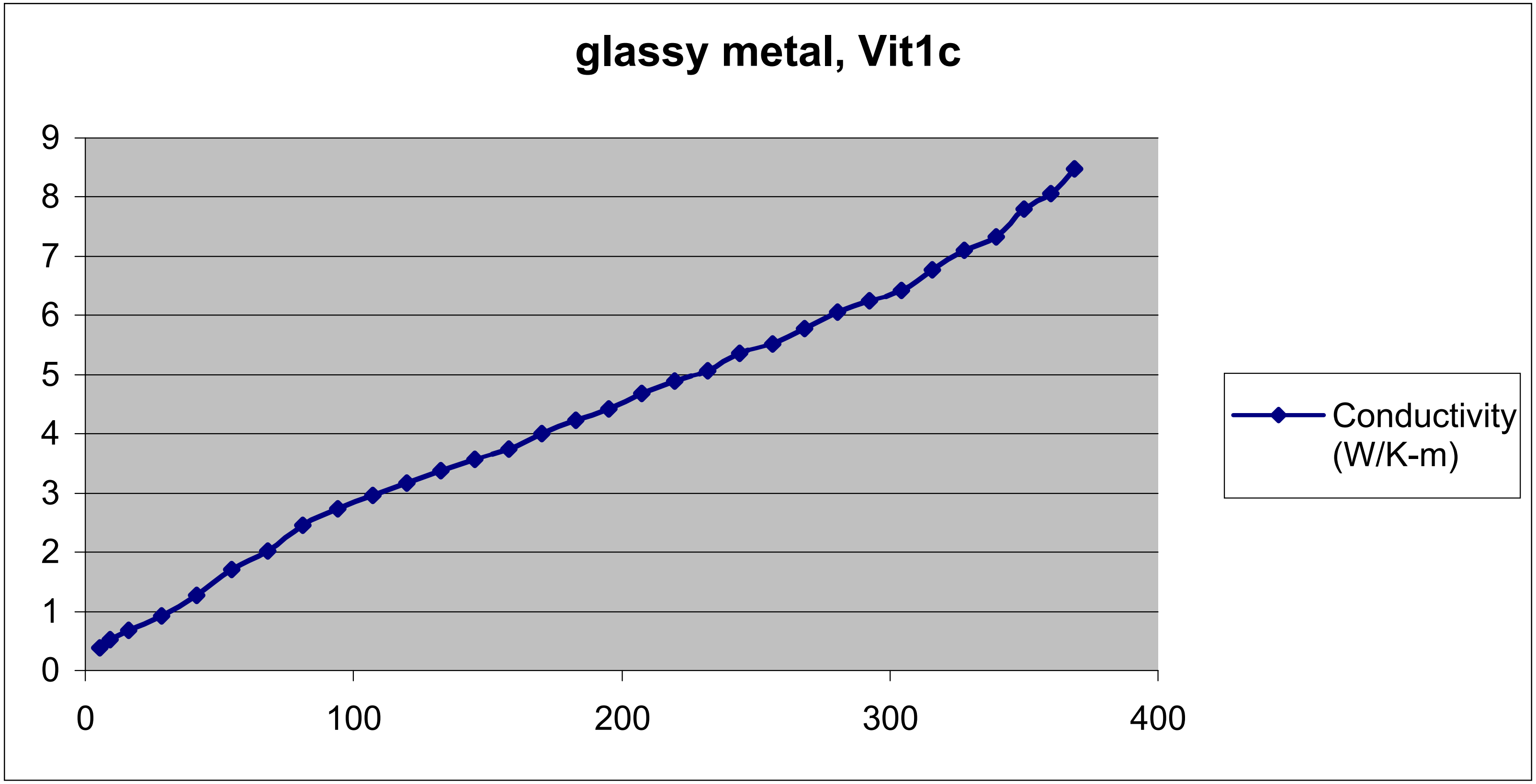


# Thermal conductivity sample measurements

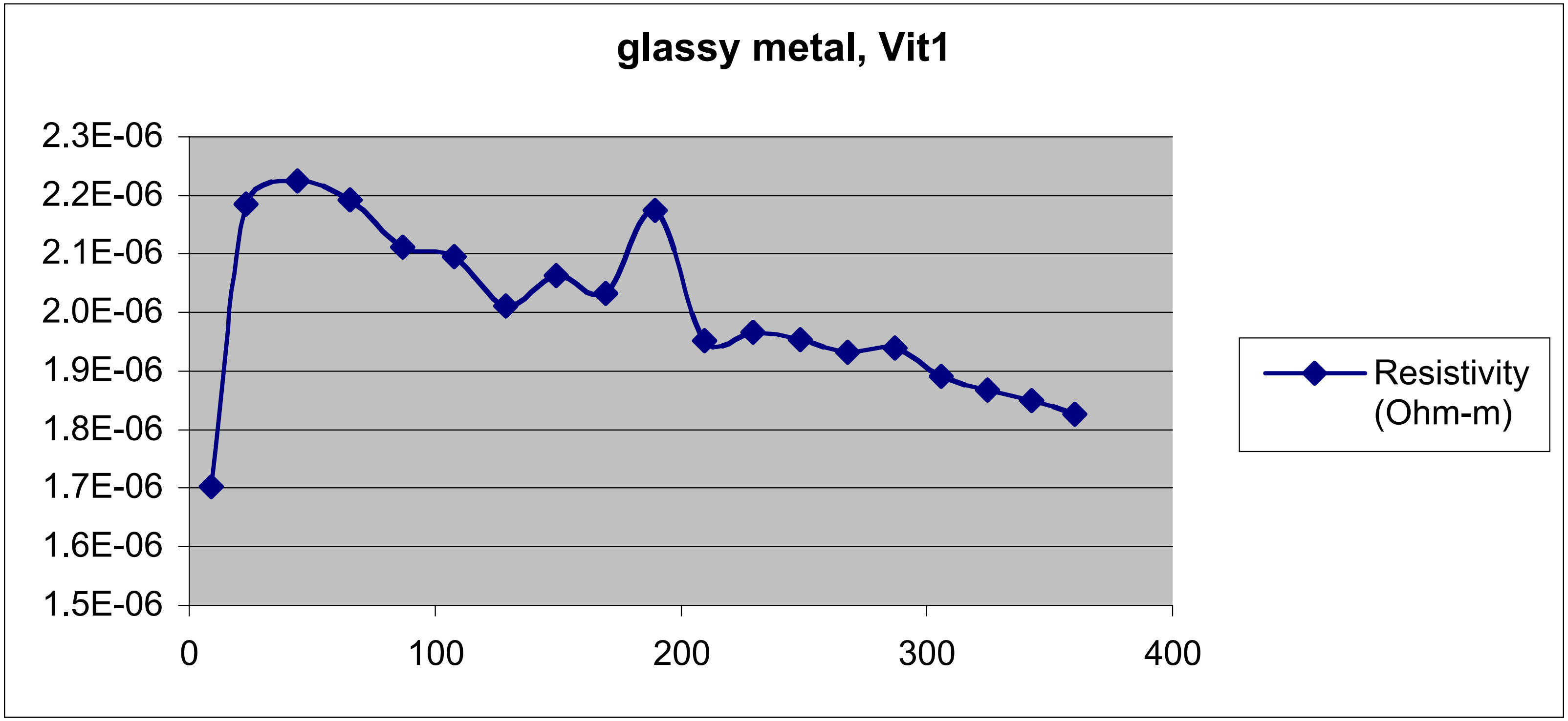




# Thermal conductivity sample measurements



# Thermal conductivity sample measurements



# Thermal capacity
## sample measurements

- Calorimeter puck

# What is being done?

- Measure physical properties
  - Thermal expansion coefficient

    Continuously between 300 and 500 Kelvin (if necessary between 70 and 500 Kelvin)
  - At Caltech's metallurgy estensometer

# What is being done?

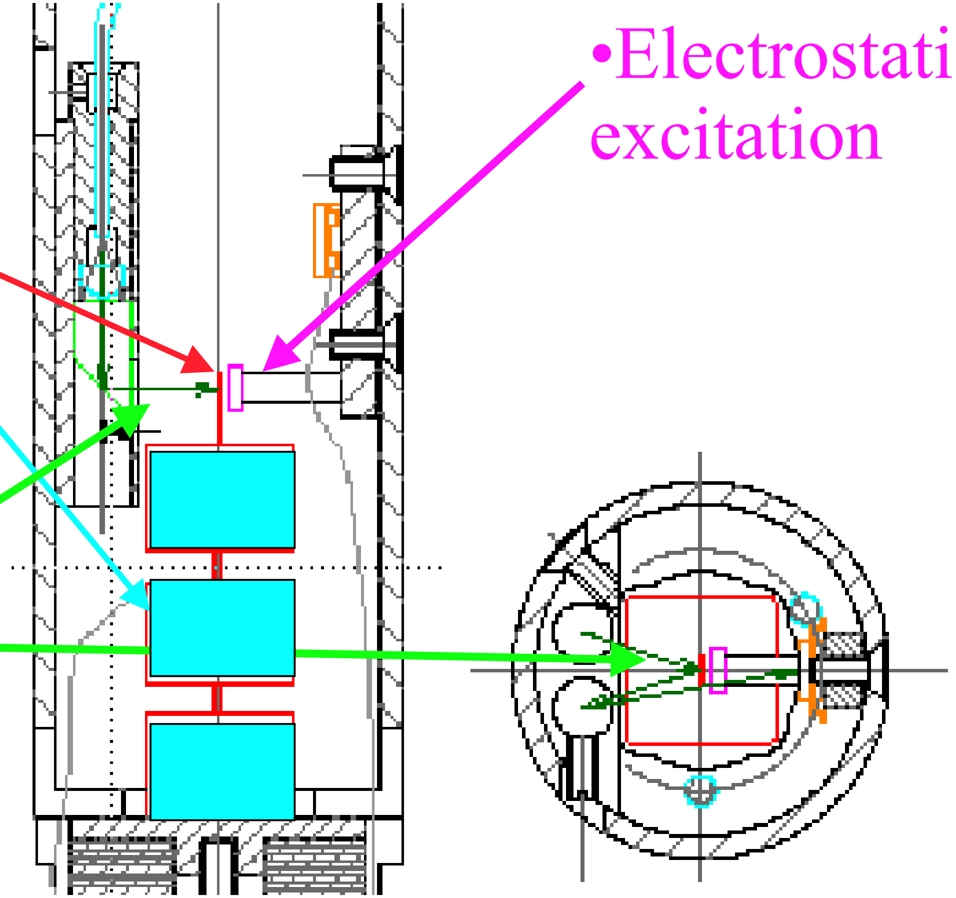
- Measure diving board Q-factors of samples

- At all temperatures between 2 and 400 Kelvins

- In Caltech's programmable cryostat
- Temperature in wide thermal range will

allow identification and location
of possible Debye peaks and
estimate impurity ill effects

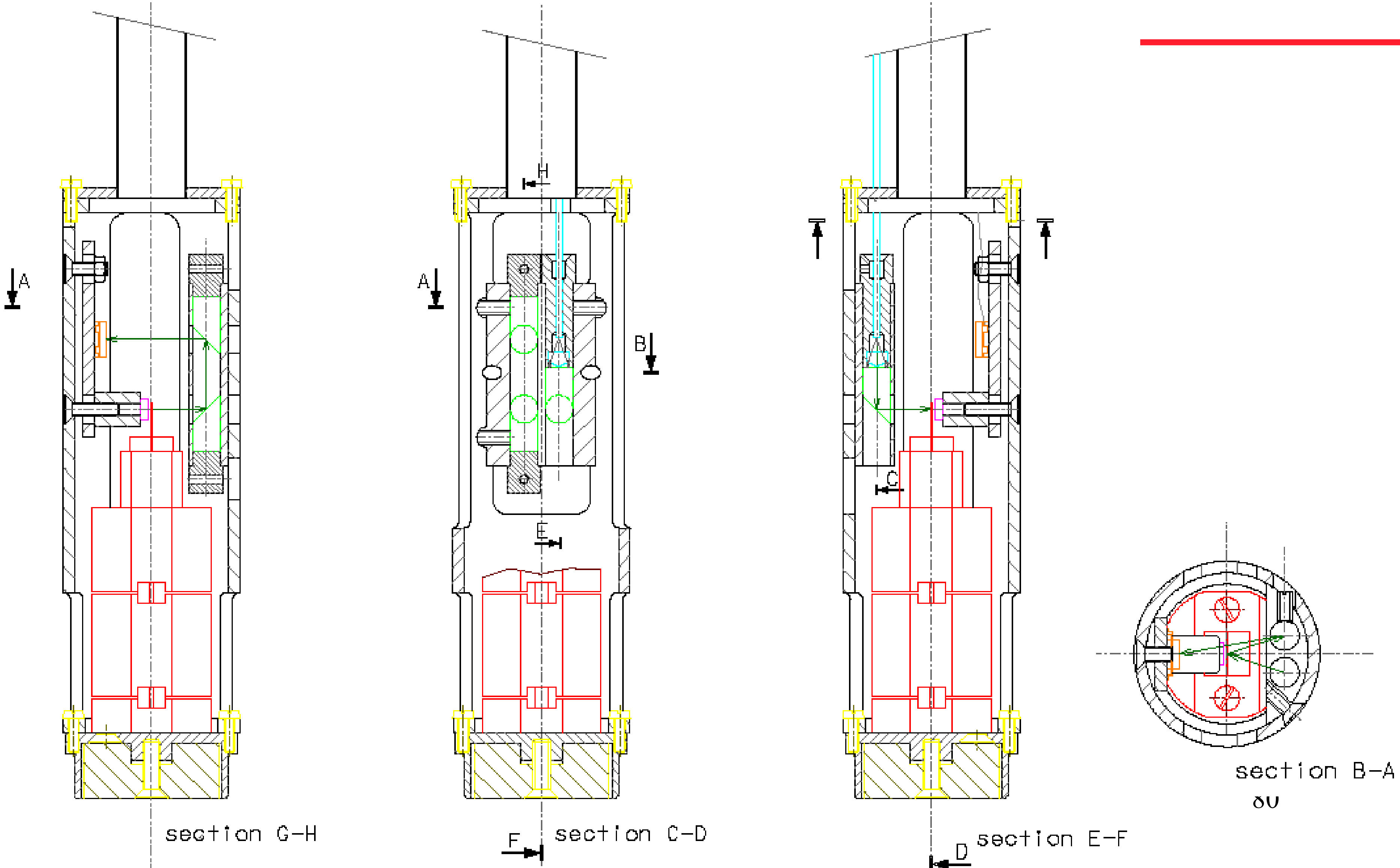
# Measure reed Q-factors



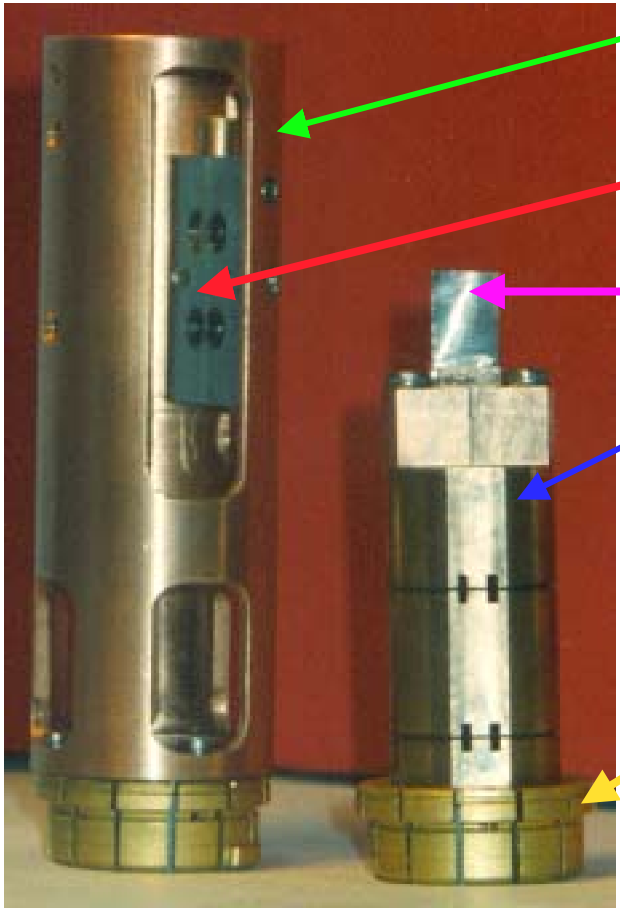
- Reed mounted on an isolation stack to isolate it from cryostat dissipation.
- Optical lever readout of ringdown

•Electrostatic excitation

# Measure reed Q-factors



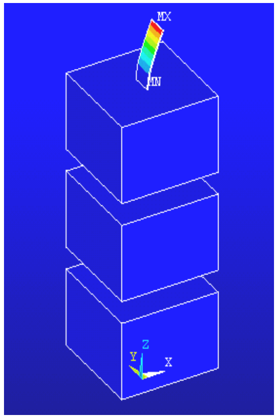
# Measure reed Q-factors



Cryo puck case,
without Q-factor probe
with periscope housing

Test reed on
Q-factor probe on puck

# Measure reed Q-factors



| | Frequency (Hz) | Mode Shape |
|---|---|---|
| **$F_1$** | **66** | Rotation around **y**, at lowest blade |
| $F_2$ | 129 | Rotation around **x**, at lowest blade |
| $F_3$ | 250 | Twist around **z**, at lowest blade |
| **$F_4$** | **388** | 2 nodes oscillation around **y** |
| $F_5$ | 694 | 2 nodes twist around **z** |
| $F_6$ | 751 | 2 nodes oscillation around **x** |
| **$F_7$** | **896** | 3 nodes oscillation round **y** |
| $F_8$ | 1001 | 3 nodes twist around **z** |
| $F_9$ | 1730 | 3 nodes oscillation around **x** |
| **$F_{10}$** | **3222** | Rotation around **y** of the reed |

(10 micron thick reed)

# Measure reed Q-factors

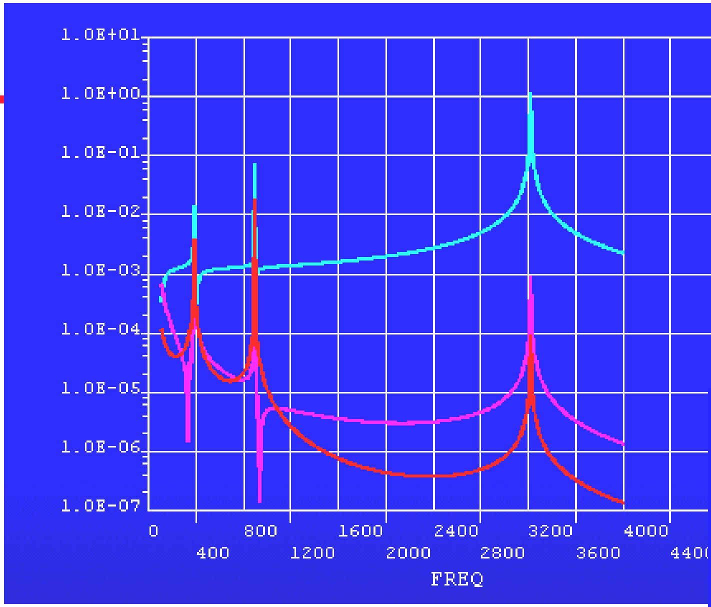
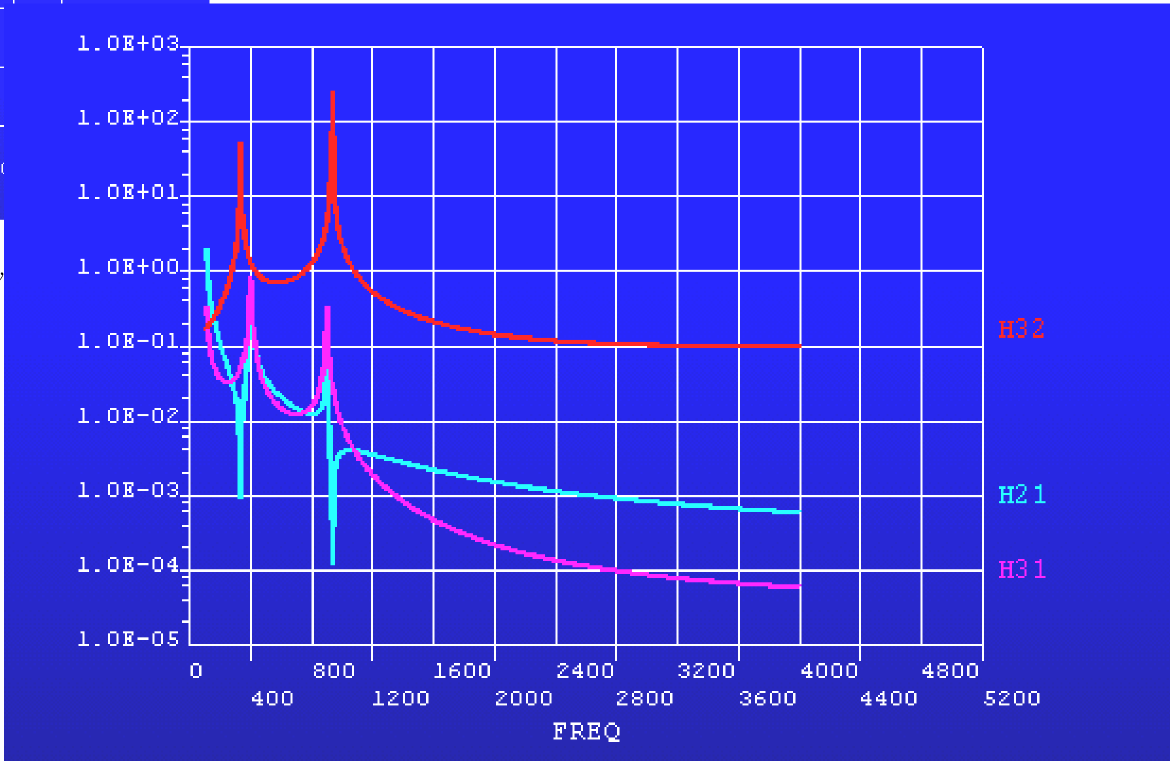


*Fig.XXX: displacements at points 1, 2 and 3 versus frequency*

Calculated Chain
isolation power
Charlotte Py



# What to be done next?

- Need to

- Demonstrate feasibility of employing Glassy Metals to fabricate mirror suspensions with record Q-factor

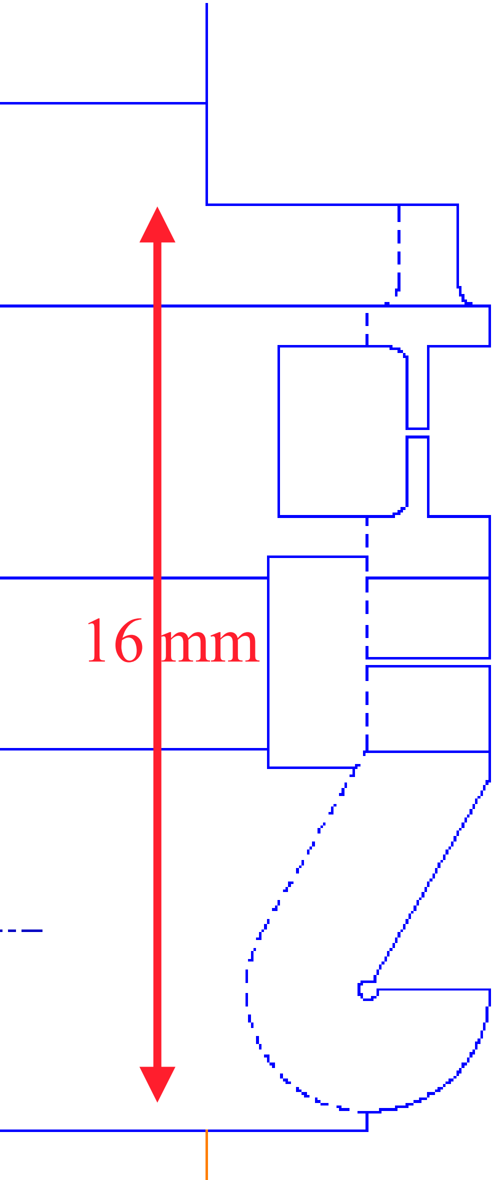
# What to be done next?

- Demonstrate feasibility of employing Glassy Metals to fabricate mirror suspensions with record Q-factor
- Ingredients
  - Suspension rigid structure carved by EDM
  - Glassy metal Flex joints brazed to the rigid structure
  - Flex joint structure brazed to a wire
  - Hook bonded to a ledge in the mirror

# What is being done?

- Fabricate test hook flex joint and wire units,
  - initially with available iron-based glassy metals
  - Later with materials of choice (MRuB, WReSiB, ..)
- Can Use Wire with low Q to eliminate violin resonance problems

# Fabricate the Flex Joint

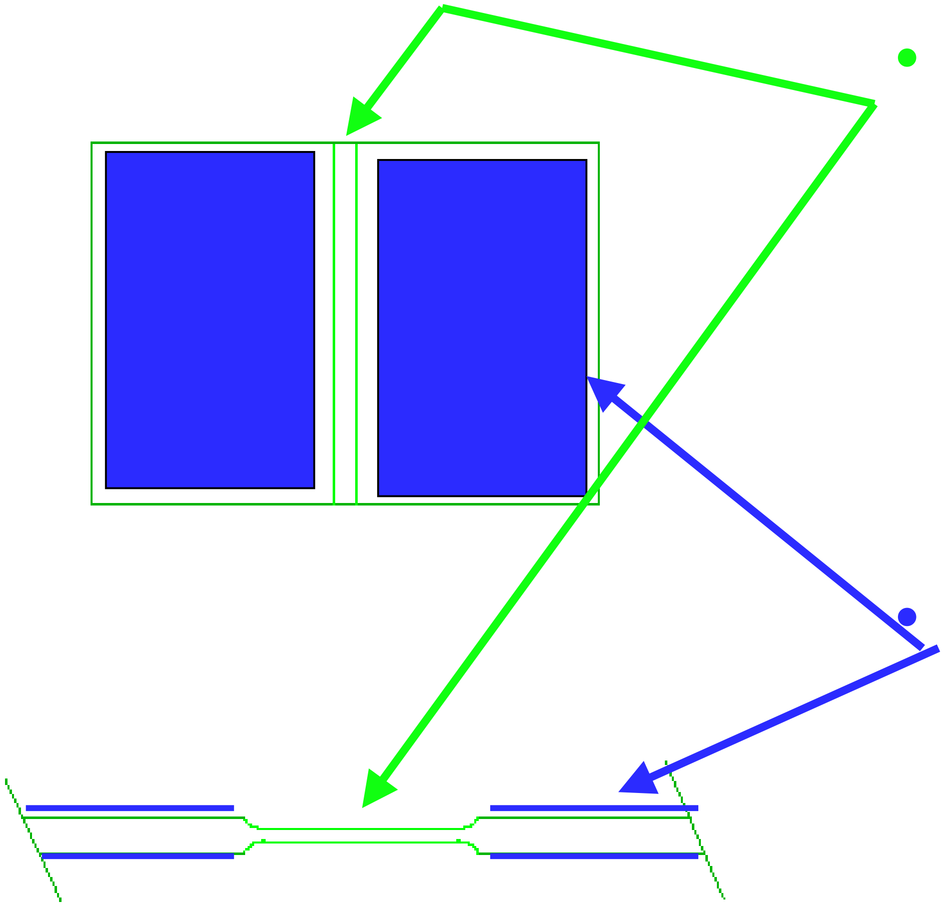


EDM carve half of the Flex Joint structure out of a single piece of material

The Flex Joint structure will be finished at the very end of the process by cutting the dashed lines

All the surfaces on which to braze the flex joint are aligned by birth!

# Fabricate the Flex Joint



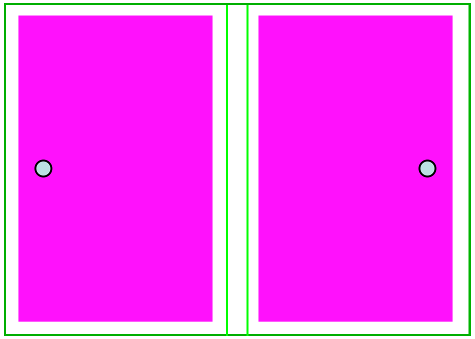
- The Flex Joint is obtained from a ribbon of glassy metals by thinning it from 50 to 10 µm by through-mask electrochemical micromachining (IBM patent)
- The thick blue parts will be brazed to the rigid structure with AuSn Bronze

# Fabricating the Flex Joint

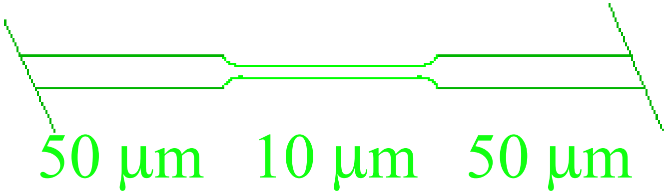
- The Flex Joint

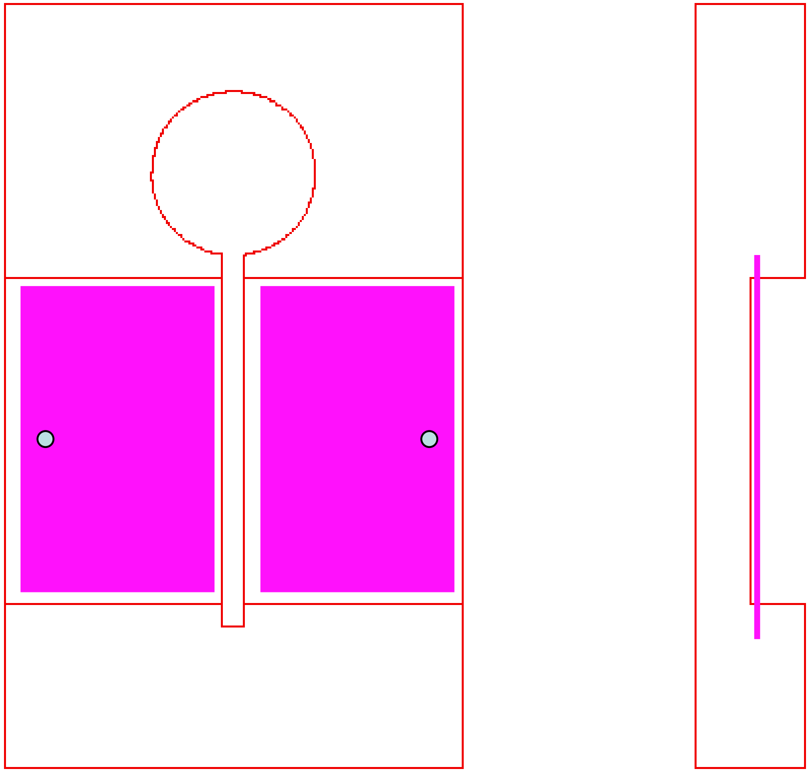
Is positioned by a ”Cavalier”, with a slot to house the thin part of flex joint

The flex joint and cavalier brazing surfaces are shown in magenta



The small holes in the joint and the cavalier are the reservoires for the AuSn bronze braze

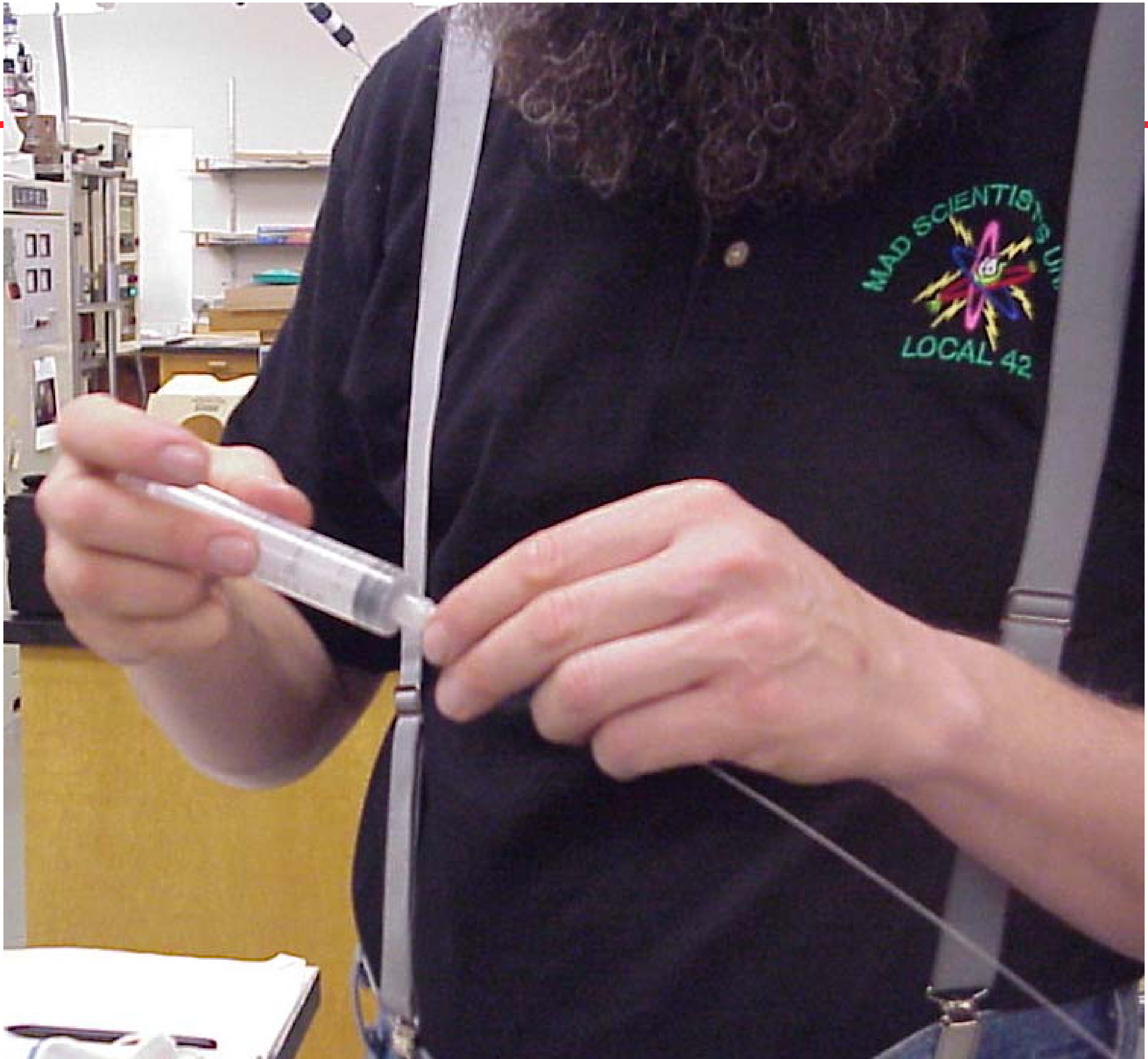




# Preparing the braze

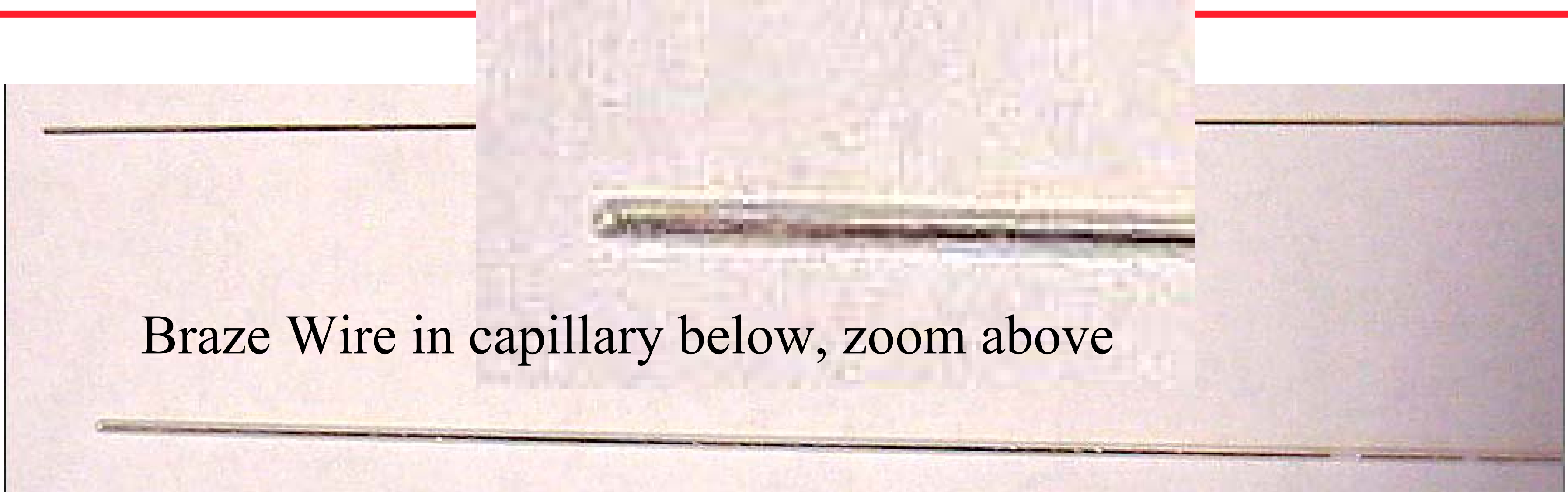
- The AuSn braze has to be prepared in 0.5 mm diameter wires to fit in the reservoir in the cavalier.
- The wire is obtained sucking the molten bronze in a fused silica capillary tube
- The capillary is then shattered to free the braze wire
- The wire is cut to length to fit in the reservoire.

# Preparing the braze

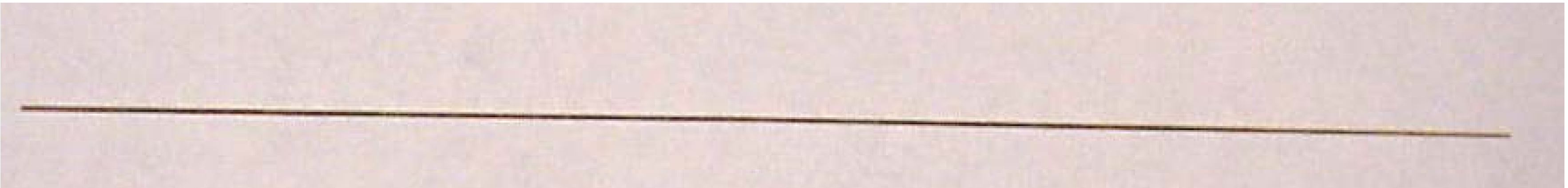


# Preparing the braze

# Preparing the braze
# fused silica at its best !!



Braze Wire in capillary below, zoom above



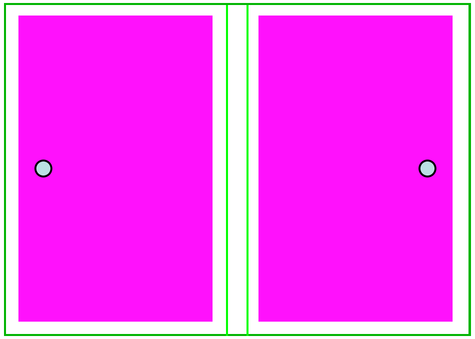
0.5 mm diameter wire after shattering the capillary tube

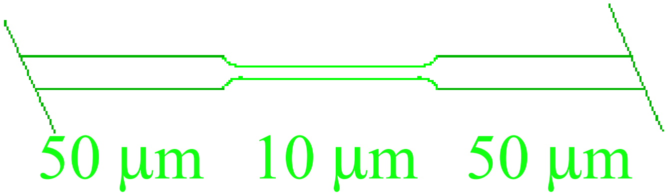
# Fabricating the Flex Joint

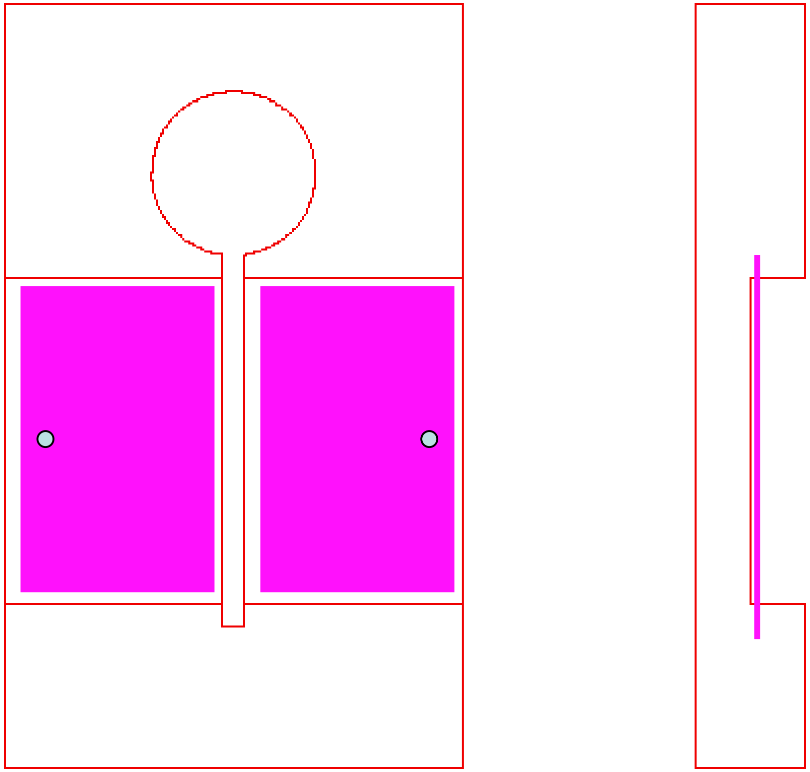
- The Flex Joint

Is positioned by a "Cavalier", with a slot to house the thin part of flex joint

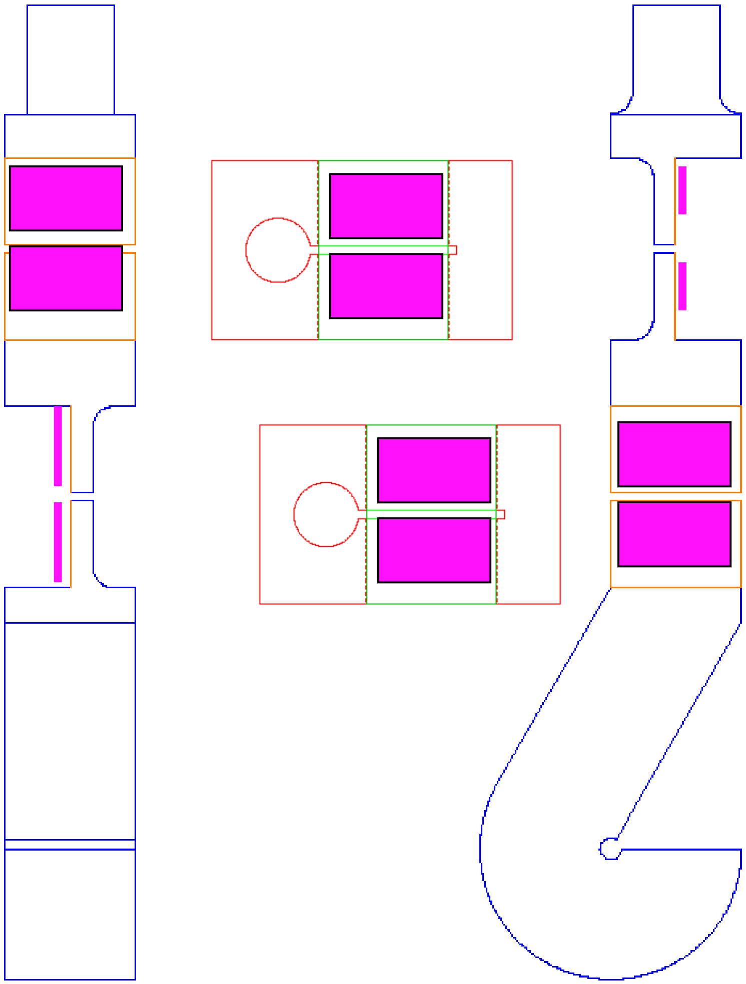
The flex joint and cavalier brazing surfaces are shown in magenta





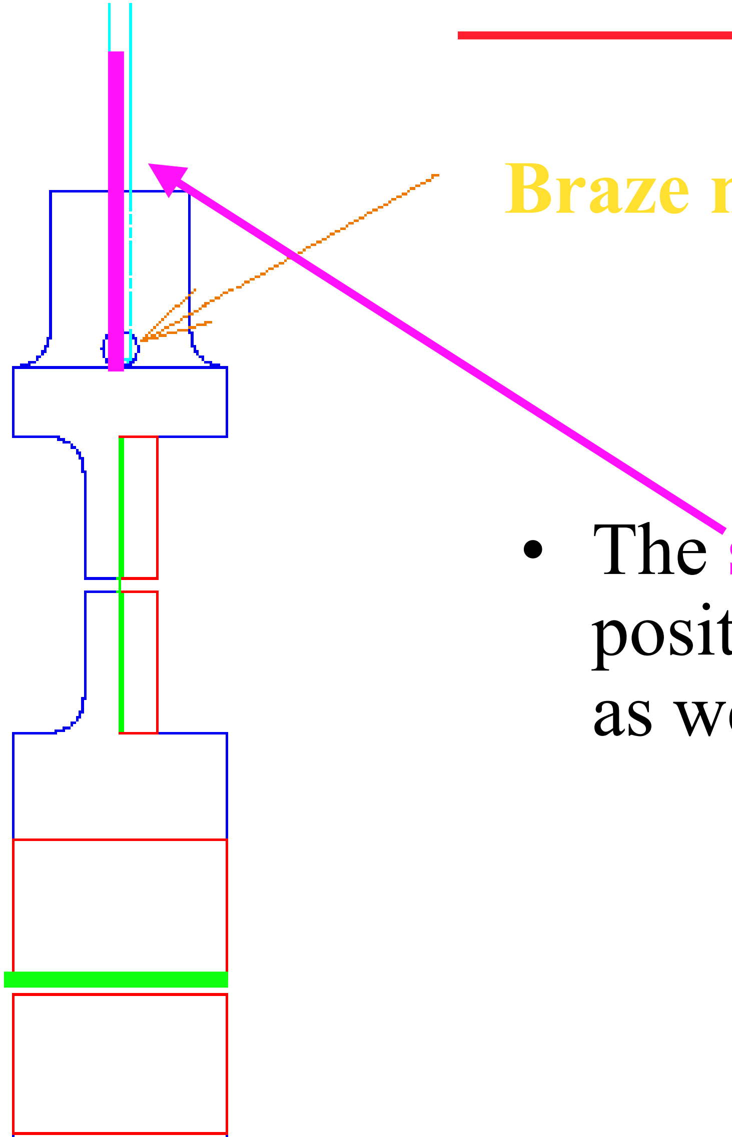


# Fabricate the Flex Joint



- For positioning the flexure two cavaliers encasing a flex joint are mounted straddling the main structure
- (Note: The flex joint structure is still monolithically attached to the structure)

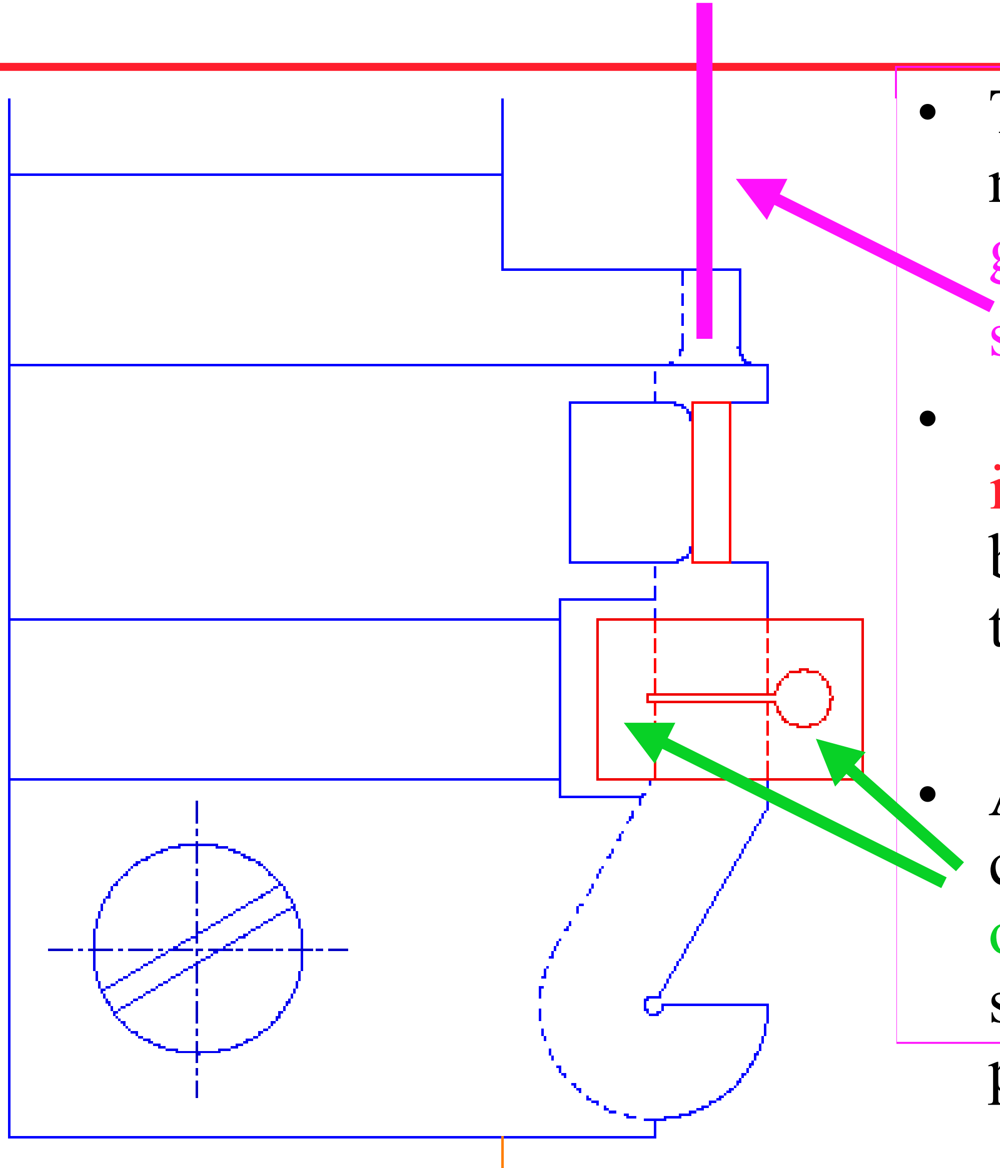
# Fabricate the Flex Joint



**Braze material**

- The suspension wire is positioned to be brazed as well

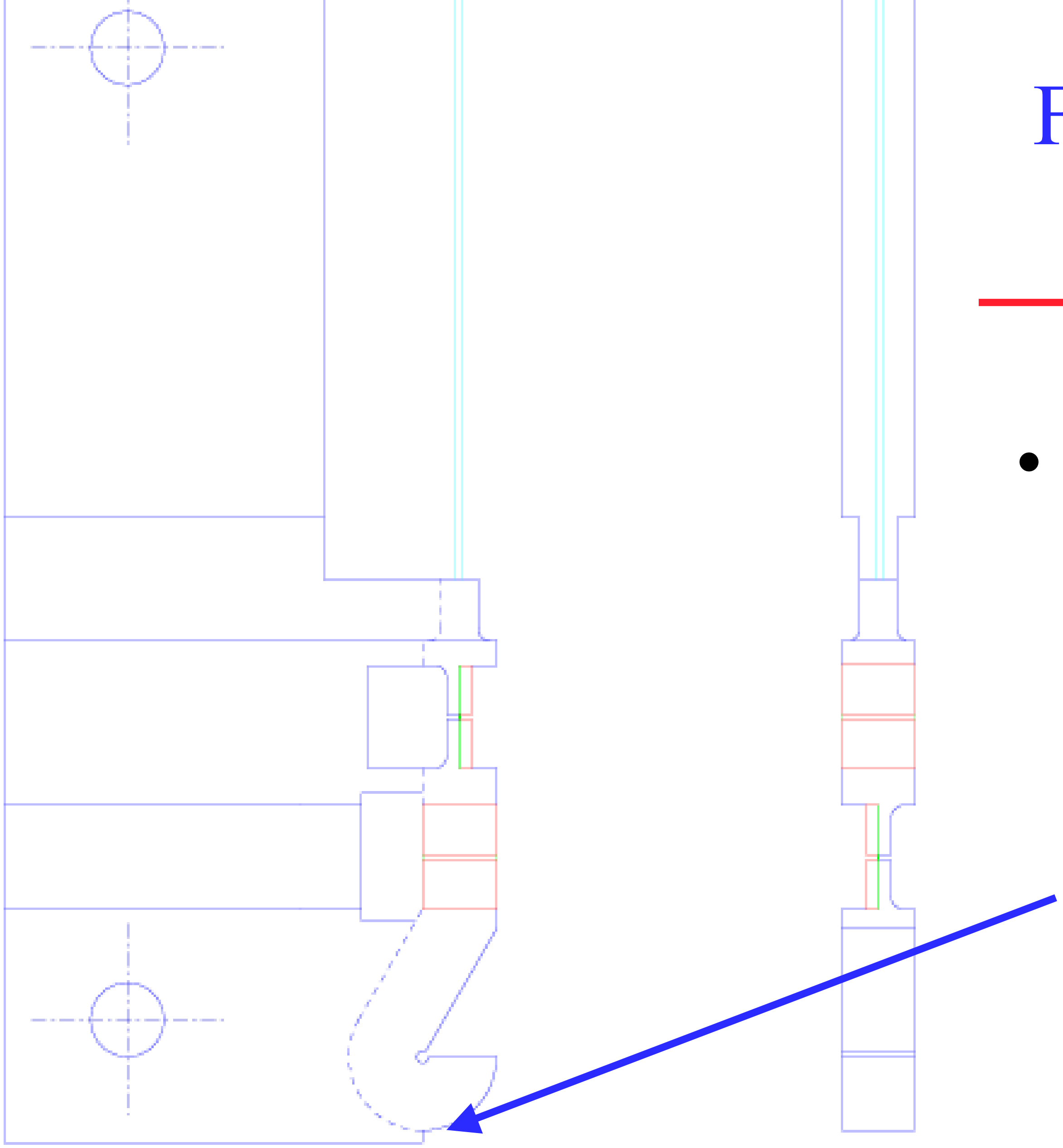
# Fabricate the Flex Joint



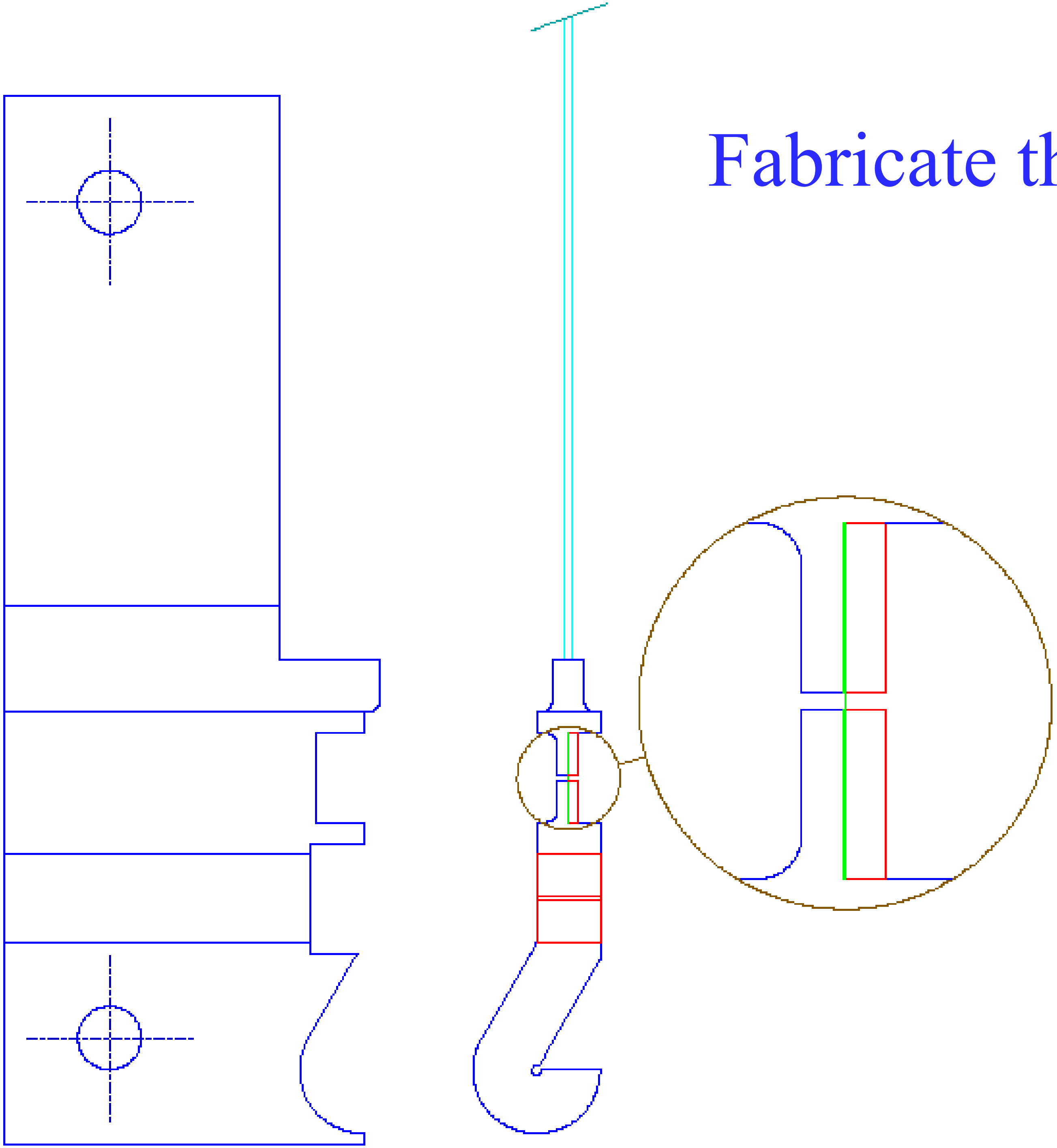
- The flex joint structure, is now provided with the glassy metal

  suspension wire
-  The thin flex joints, are still imprisoned by the cavaliers both are brazed together by the baking process
- After brazing the ears of the cavaliers are EDM chopped off before separating the structure from its mother plate

# Fabricate the Flex Joint



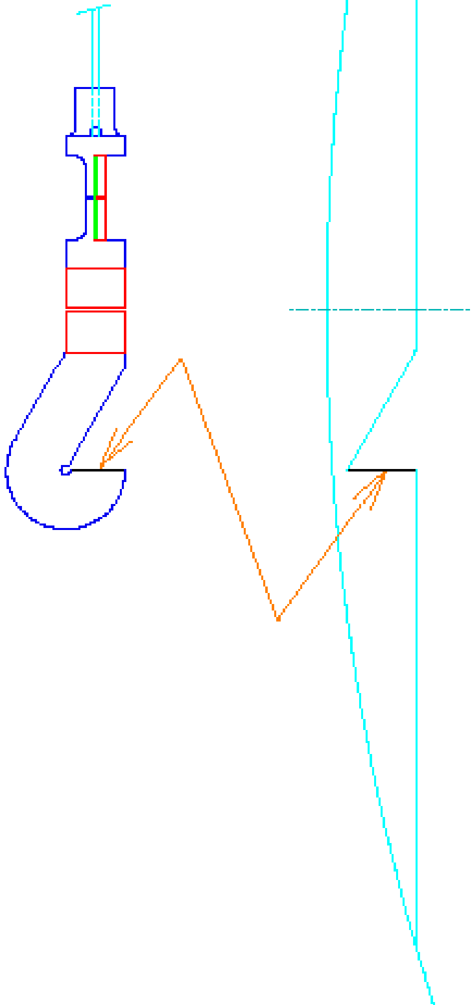
- The finished flex joint is ready to be cut away from the mother plate



# Fabricate the Flex Joint

The finished flex joint is finally ready for attachment to the mirror's ledges

# Fabricate the Flex Joint



- The mating surfaces of the flex joint and of the mirror's ledge are indium coated to provide an excess-noise-free connection

# Why using ledges

- The use of ledges and low temperature brazing eliminated all shear efforts
- Can be assembled and disassembled by simply warming up the indium

# What else needs to be done?

To obtain ledge attachments on the mirrors

- Silicate bond ledges to mirror sides

  or

- Ultra Sound machine (new advances)
  - Machine ledge-in-groove in sides of mirrors

# What more to be done?

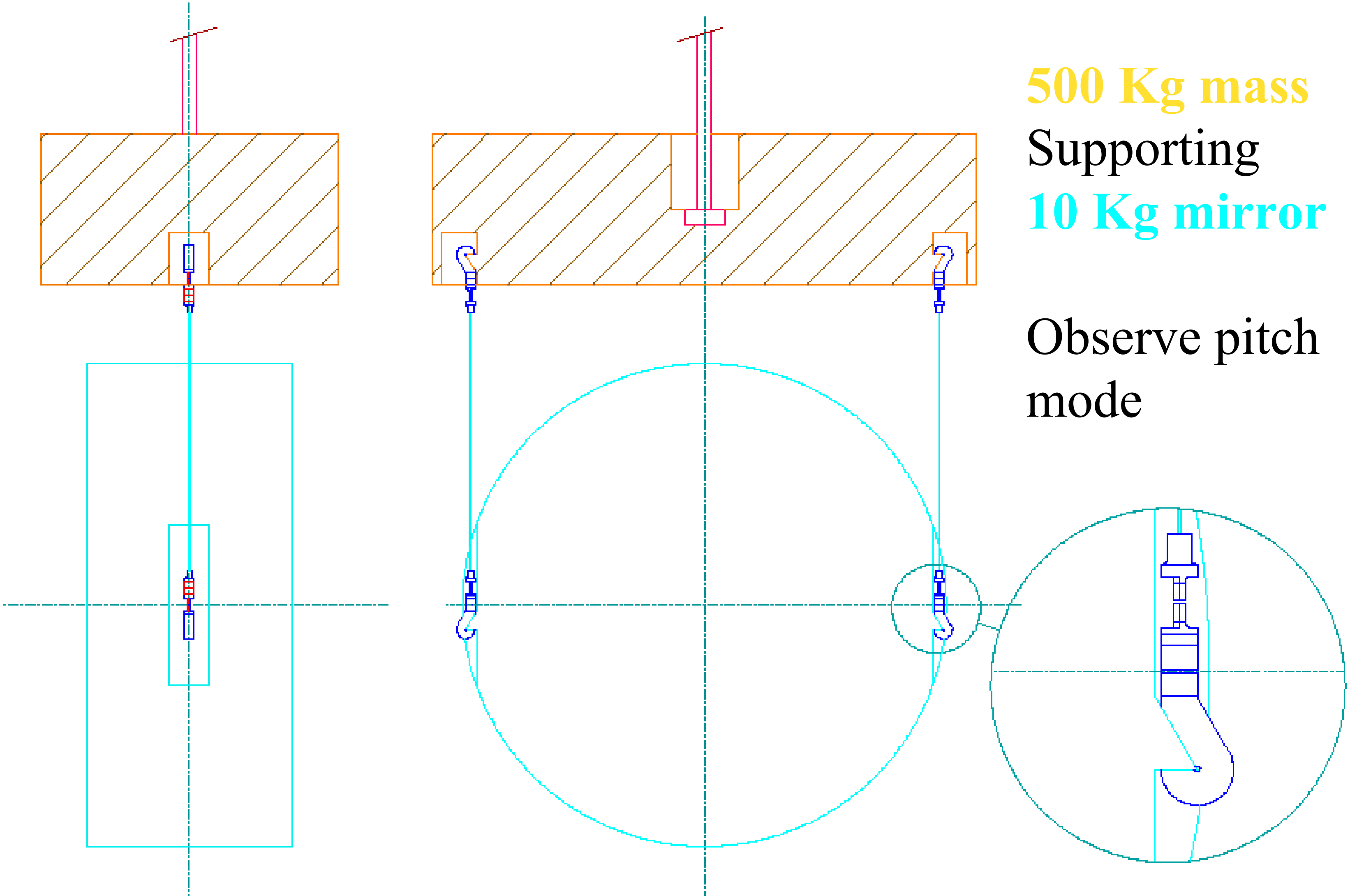
- Demonstrate feasibility of attachments to mirrors without significant loss of mirror Q-factor
- Will use assistance from Kenji Numata’s setup to measure the localized loss of Q-factor and from Kazuhiro Yamamoto to evaluate its effect on mirrors’ performance

# To physically measure suspension Q-factors (>$10^8$) with macroscopic mirrors

Propose to use Opposite philosophy of all existing facilities

- Do not look for biggest available rock !
- Build softest available support to decouple ground losses from mirror suspensions under test
- Build mirror suspension test facility taking advantage of existing Ad-LIGO test tower
- Measure pendulum or, better, pitch mode

# What is being done?



**500 Kg mass**

Supporting

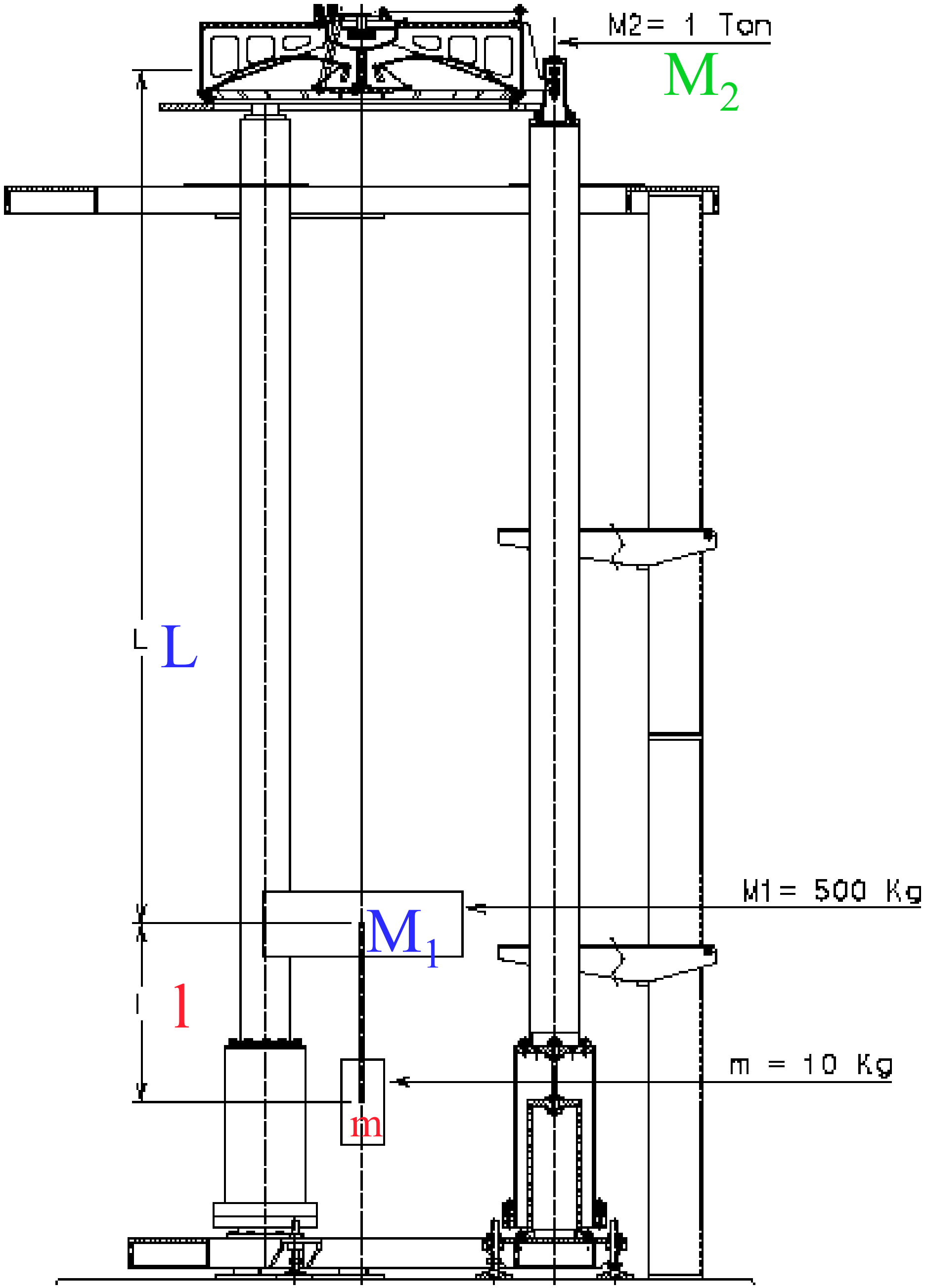
**10 Kg mirror**

Observe pitch mode

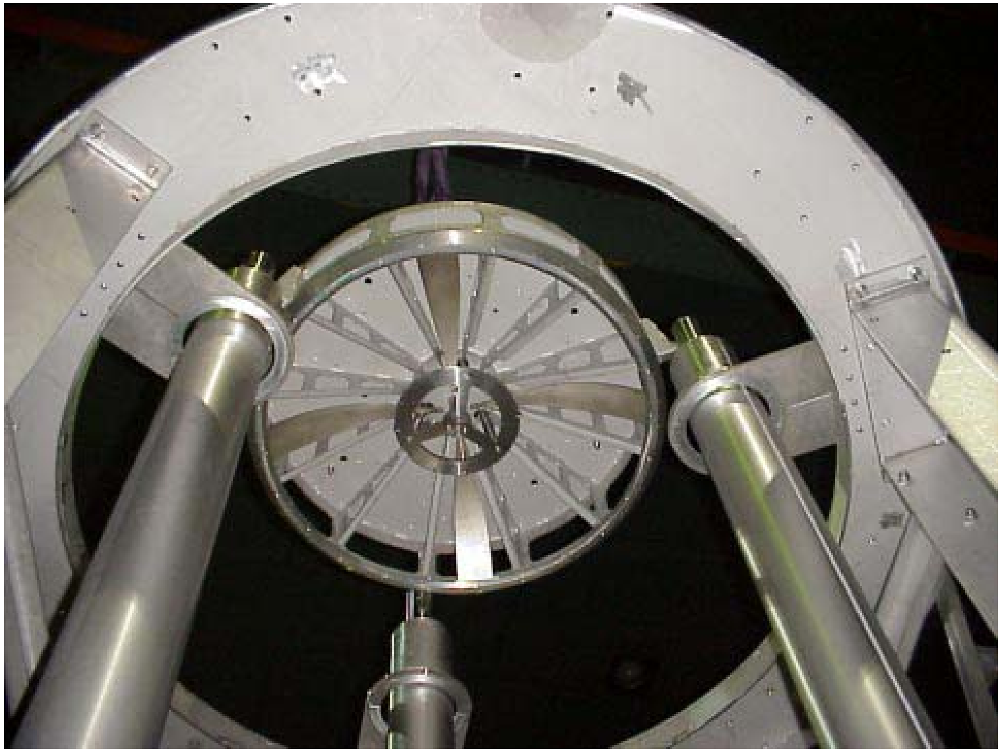
# What is being done?

- Losses to ground decoupling factors:
- Measure pitch decay $M_2$
- $\Delta\theta/x$ (depending on balance) 50?
- $\Delta m/M_1$ 10/500 50
- $\Delta m/M_2$ 10/1000 100
- $\Delta l/L$ 20/400 20
- IP isolation factor ?

- Total > $5\ 10^6$
- Facility should be able to measure oscillation Q >>$10^8$



# What is being done?

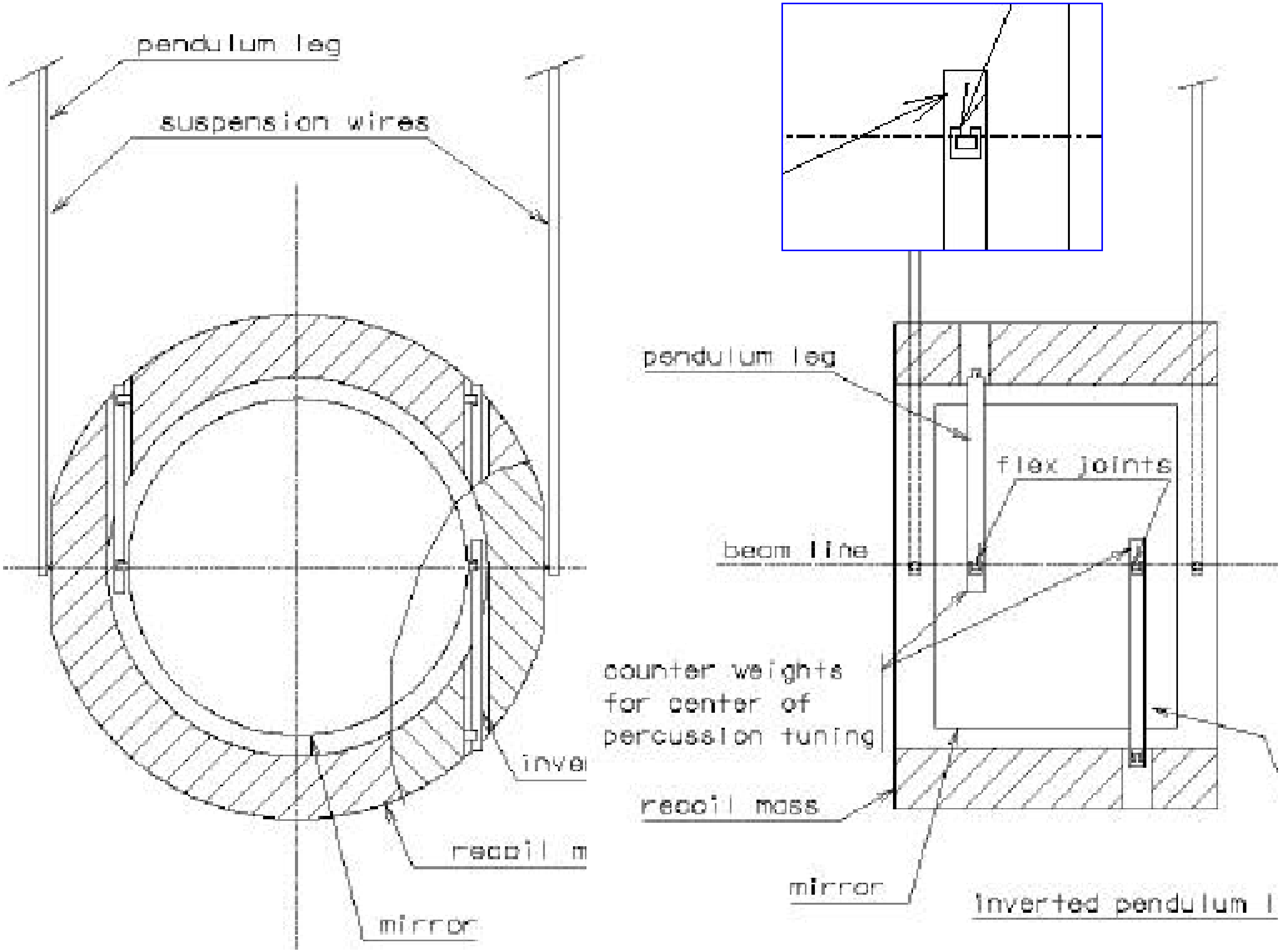


# Advanced geometries, an Additional safety solution

- Can achieve good thermal noise performance by working at lower suspension pendulum frequency
- Above resonance T.N. proportional to $f^{-5/2}$
- A 500 m tall suspension would do just fine

- How to build a 500 m tower within 500 mm?

# Advanced geometry, folded pendulum



# Additional safety solution

- Folded pendulum can be tuned to mimic a 500 m tall pendulum
- Well feasible with metal mechanics
- Vertical thermal noise filtered with MGASF
- Thermo-optical pitch control

- Suspension thermal noise << 5 Hz

# Conclusions

- Ingredients for next generation of LF GWID
- 1 Seismic Attenuation OK at r.t.
- 2 Control schemes OK at r.t.
- 4 Mirrors
  - A **Substrates** **probably OK at r.t.**
  - B **Coatings** **to be tested**
  - C **Suspension points** **probably OK at r.t.**
- 3 Mirror suspensions may become OK
- This scheme eats a lot of the cryogenic grass ! ! !
- Life is easier at room temperature ! ! !