An additional Low Frequency Gravitational Wave Interferometric Detector for Advanced LIGO?

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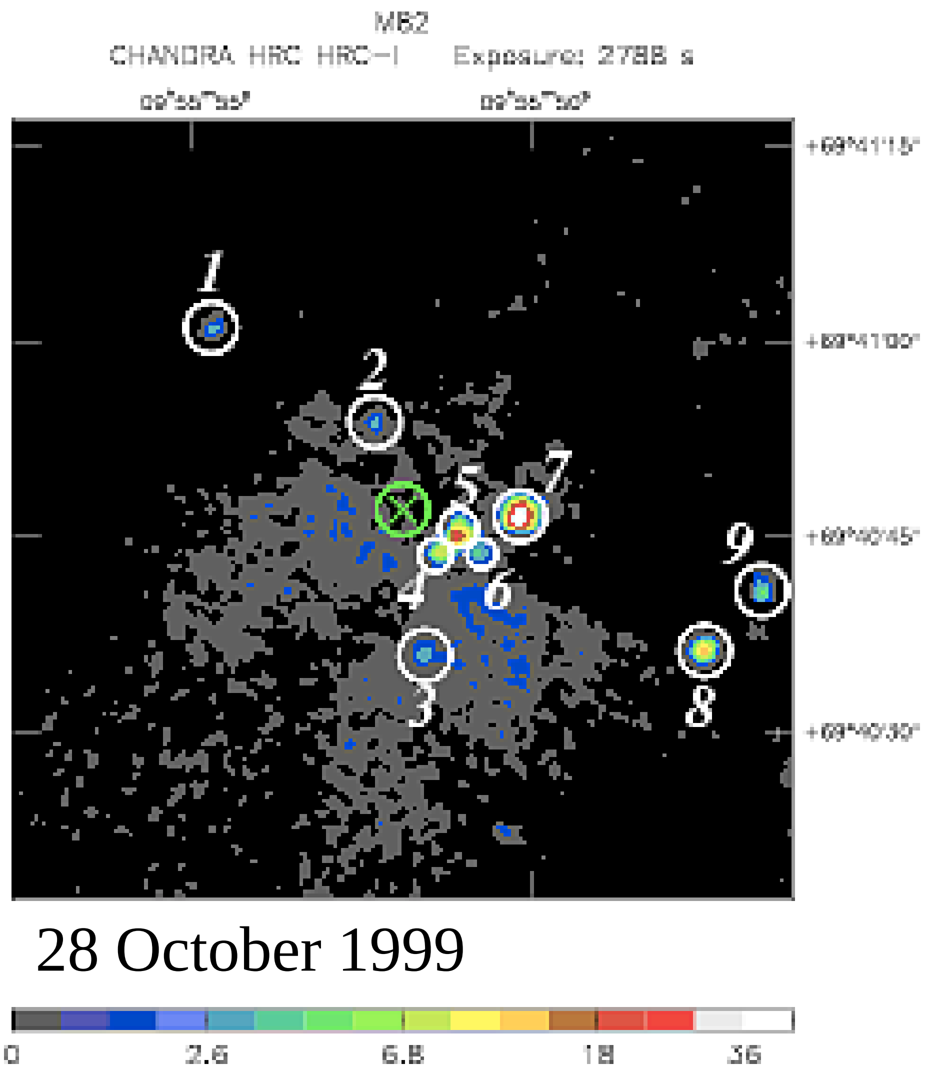
LIGO-G030165-00-R

Scientific motivations

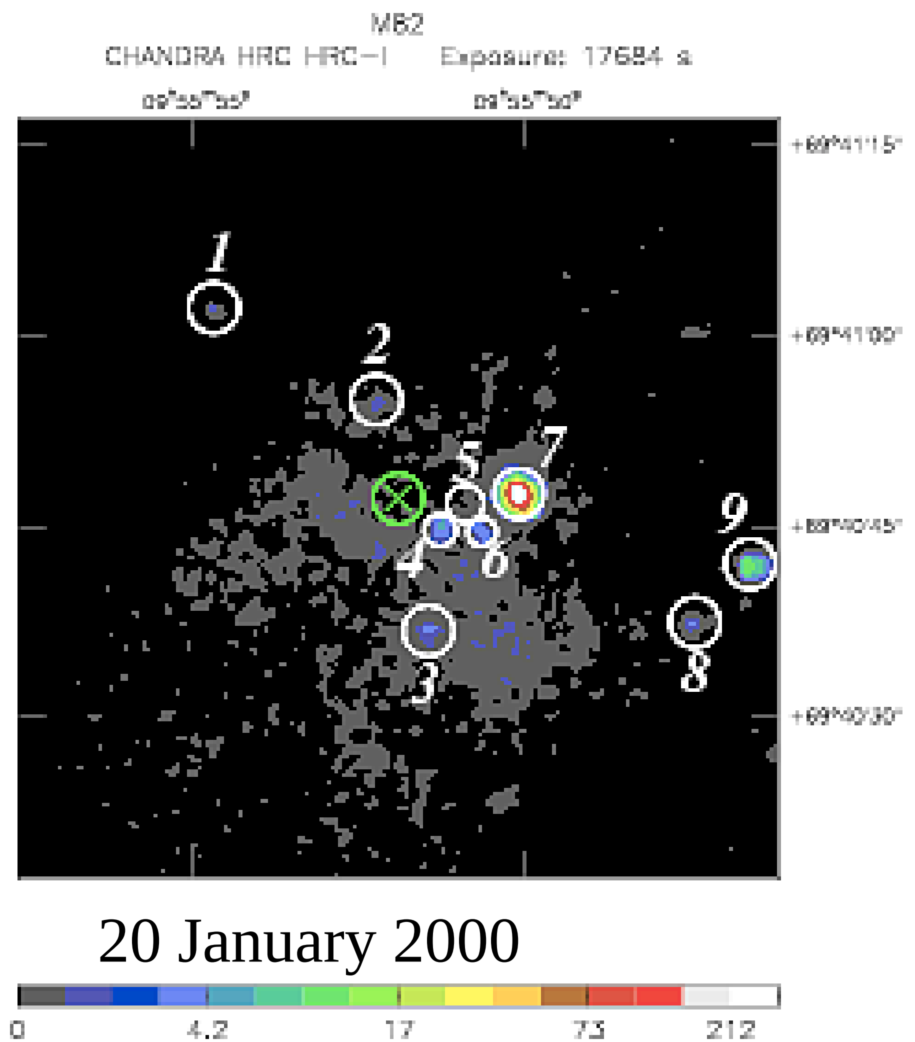
- New observations performed after the design of Adv-LIGO indicate the presence of new possible LF GW sources
- Data summary from Cole's Miller based on X-ray and optical observations of galaxies and globular clusters including Chandra's observations of X-ray sources

- http://www.astro.umd.edu/~miller/IMBH/
- http://online.kitp.ucsb.edu/online/bhole_c02/miller/oh/05.html

Chandra's observations of M82
Matsumoto et al.



28 October 1999



20 January 2000

Chandra's observations Matsumoto et al.

- Observed x-ray sources in globular clusters
- Eddington mass of sources 30~10^3 s.m.
- Emission implies a companion
- So many companions imply high density in the cluster (optically observed)
- High density implies frictional braking
  - Kinetic energy tend s to be equalized in encounters, fat guys get slowed
- Many clusters have the same pattern

What do I gather from globular cluster observations

- Stars above 50 s.m. directly evolve in BH (collapsars)
- Stars below 20-30 s.m. (above 8) rapidly (~10-15My) go supernova and leave behind 1.4 s.m. NS
  - (In between (30-50 s.m.) smaller BH are generated)

- <u>**Stars >50 s.m. slow down by dynamical friction**</u> (τ=10~50My) and sink to the center of the cluster where they may be induced to merge
  - In encounters kinetic energy gets equalised, heavy masses get slowed
  - Density of ~ million stars per cubic parsec observed
  - Mass segregation occurs

- Smaller stars (<8 s.m., including NSs) collect the kinetic energy, get accelerated and may be dispersed out of the cluster

What do I gather from globular cluster and galaxy observations

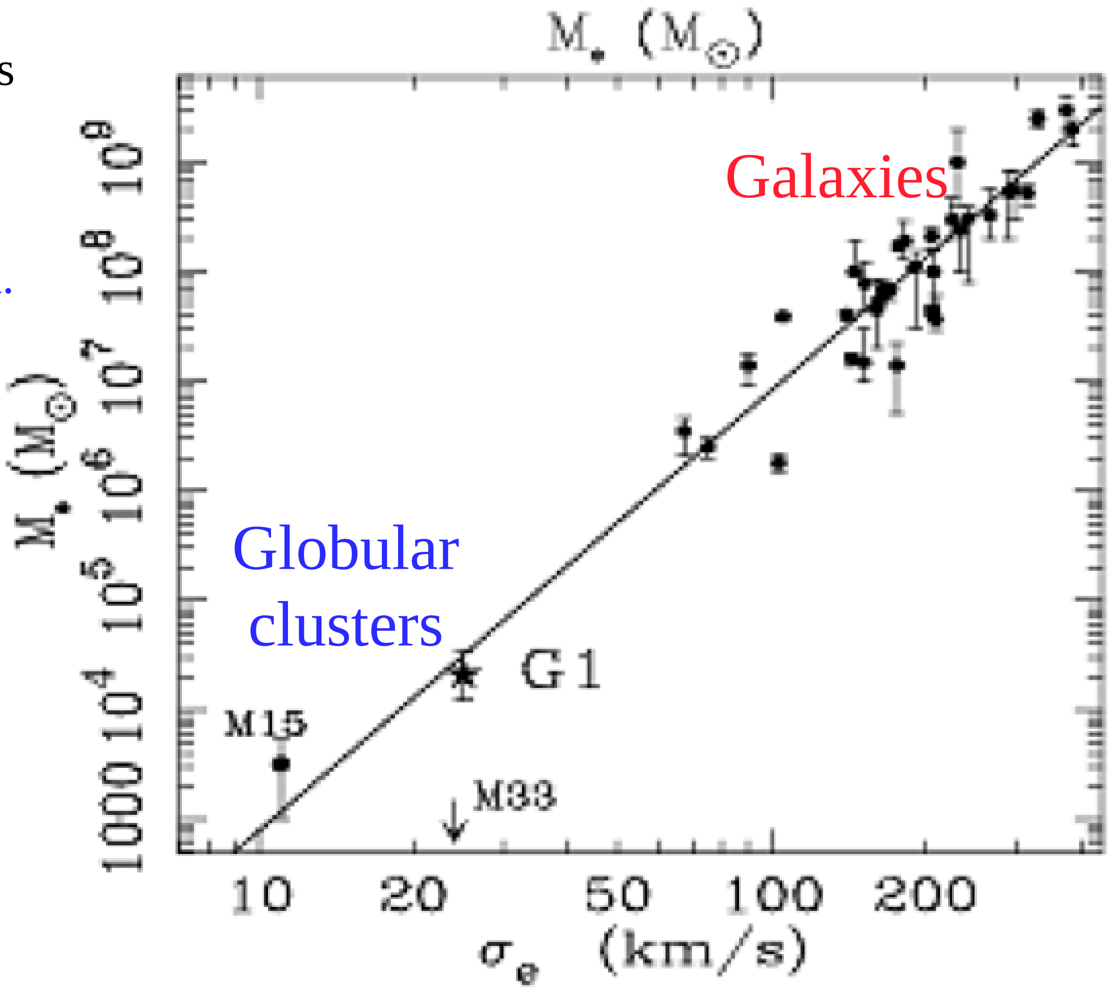
1. The only electromagnetically visible BH are those accreting from companion star.
   - The accretion stage is short (~10My)
   - Why so many are visible?
   - Frequent Encounters of binaries with singles tend to tie and tighten up the bigger guy and fling out the smaller of the three

2. X-ray sources compatible with several 30 to 1000 s.m. BH per galaxy are observed by Chandra and XMM, many more may lurk

3. Velocity dispersion in globular cluster centers imply presence of IMBH or BH clusters

Optical observations: inspirals may be ongoing at a catalyzed pace

- In some Globular clusters the speed distribution of stars is compatible with central concentrated and invisible mass ~10^3 s.m.
- Either a single, a binary or a cluster of BH must be at the center
- (Note: Statistics increased with respect to this figure)



LIGO Optical observations: inspirals may be ongoing at a catalyzed pace

- In some Globular clusters the speed distribution of stars is compatible with central concentrated and invisible mass ~10^3 s.m.

  Either a single, binary or cluster of BH must be at the center

  – (as well as the other BH observed farther away from the center)

- **Swirl** is observed in the core stars around that hidden mass
- But frictional braking would rapidly eliminate the observed swirl!

- Core stars around central BH cluster can be swirled up while hardening the massive binaries at the center (controversial but growing evidence)

- A BH cluster must be present and being hardened
- And will coalesce at rapid rate! << 10My !!!!
- Is this a Smoking gun?

What is relevant for GW observations

- Useful chirp for heavier masses ends at 30 to 100 Hz
  - Available signals start above 20+20 s.m.
  - – Close to ISCO the orbits are relativistic and difficult to make templates (still lower effective frequency range for detection)
  - L.F. sensitivity necessary to trigger with optimal filters
- ~10 of BH-BH inspiral events per year are expected
- GW Signals from massive BH will carry farther than NS
  - – We will map galaxy clusters farther away than NS-NS inspirals

Consequences

- Do we have evidence that low frequency sensitivity is of astrophysical interest?
- Of course yes!
- Is the present Advanced LIGO best suited to cover the new possible sources indicated by Chandra and other optical observations?

- **Not without some significant changes**
  - 10% power / different finesse
  - Fused Silica instead of Sapphire mirrors (bulk TN)
  - Supersized, double weight mirrors (coating TN)
  - Double length suspensions (susp. TN)

Consequences

- Note:
- Adv-LIGO is designed to be broadband and to cover a different class of sources and goes as low in frequency as practical as possible while focusing on the higher frequency end
- by specializing interferometer design is it possible to do better at either HF or LF than a single instrument in a single configuration can.
- It is practically impossible to optimally cover both ends with a single design
- Separate design lead to better optimizations.

Consequences

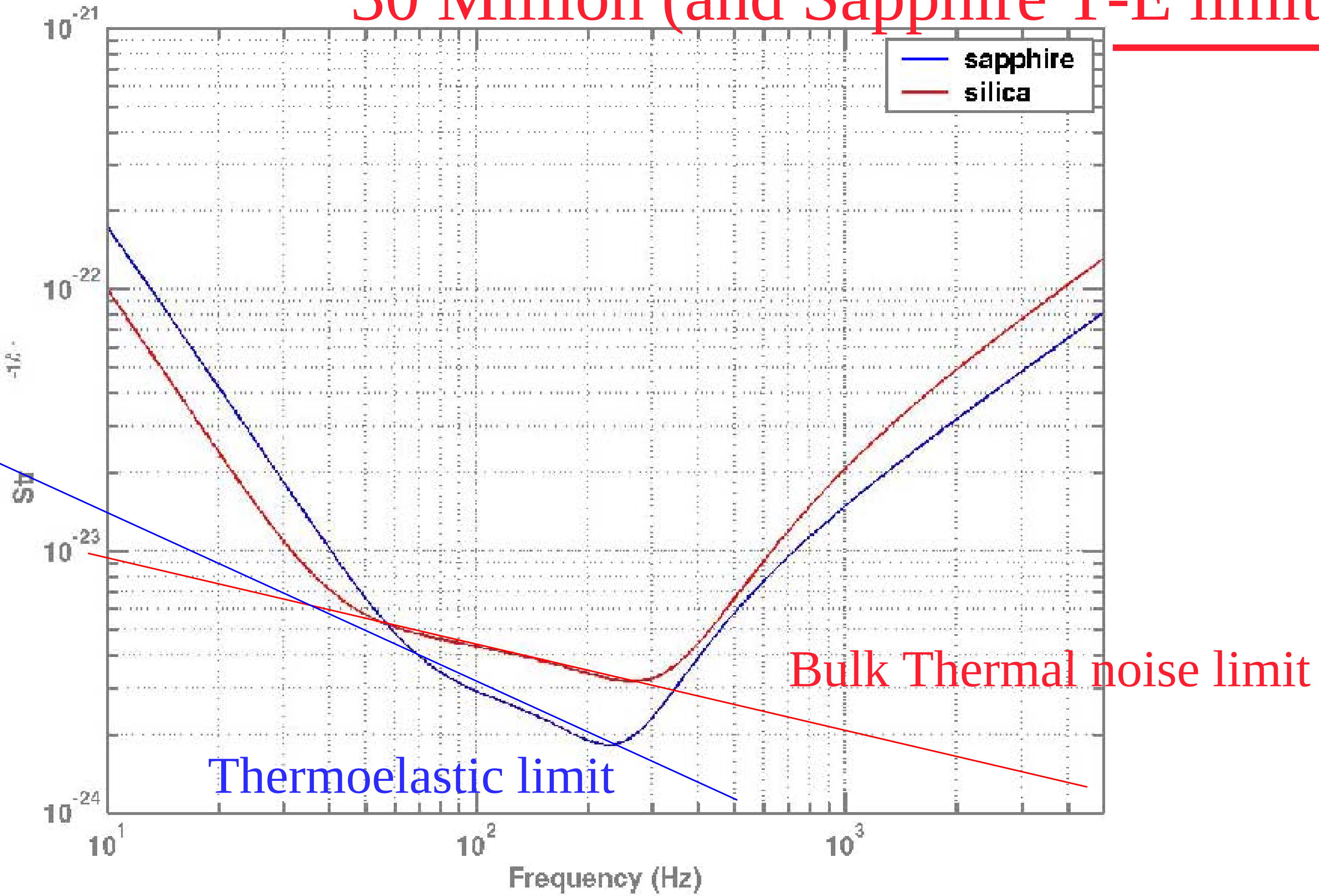
- Do we need a low frequency companion for Advanced LIGO to cover the new possible sources indicated by Chandra and other optical observations?

- Of course yes!
  - Note:
  - Adv-LIGO is designed to cover a different class of sources and goes as low in frequency as practical as possible while focusing on the higher frequency end
  - It is practically impossible to cover both ends with a single design
  - Separate design lead to better optimizations.

Question

- Can we technically build and operate an interferometer at Lower Frequency than Adv-LIGO?

This curve was drawn when Fused silica was believed to have a Q-factor of 30 Million (and Sapphire T-E limited)



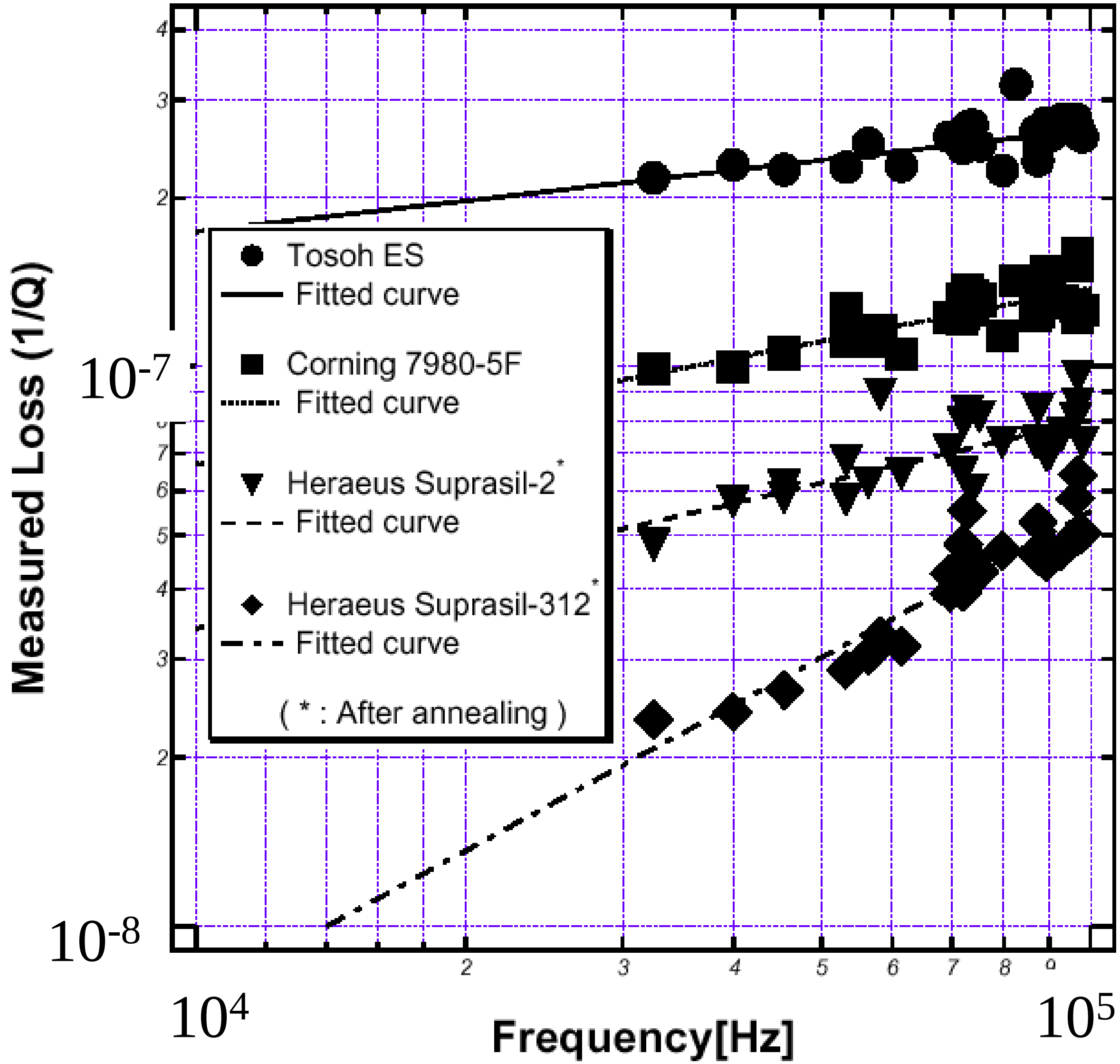
The new TN situation

- Now the bulk F.S. TN floor is crumbling.
- Two measurements:
- Kenji's Q- factor measurements
- Fused Silica have been observed to be capable of Q factors at and above 200 Million (Gregg Harry, Steve Penn)
  - Note: Sapphire show equally high Q factors but, unfortunately, the fact is irrelevant because of the thermo-elastic effect

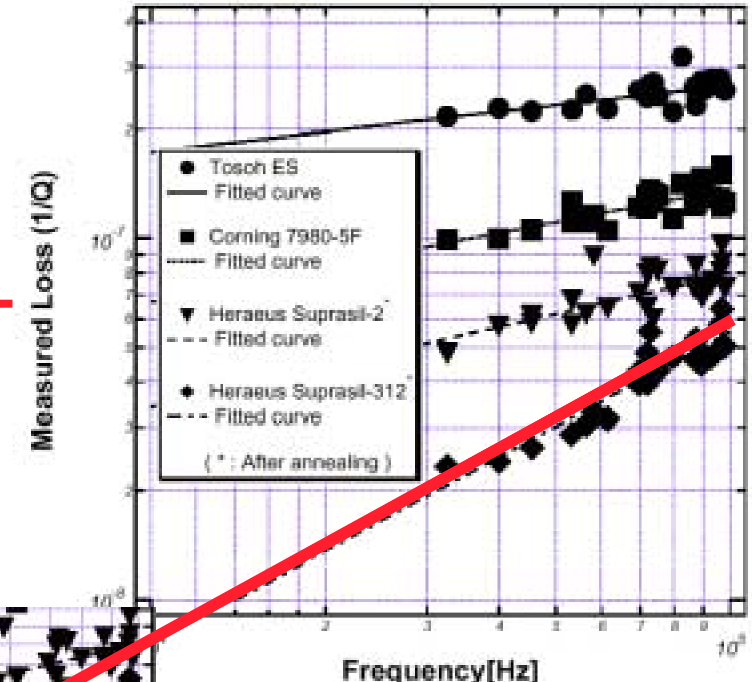
Kenji Numata results

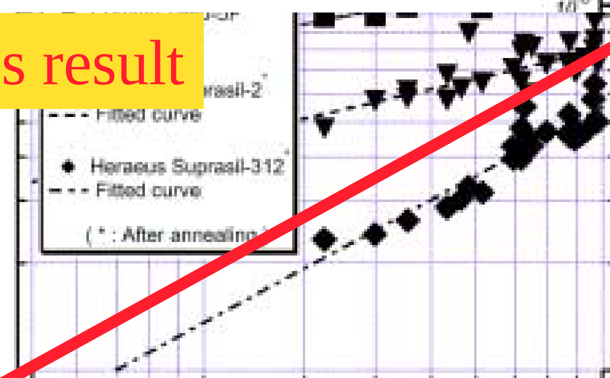
The Q-factor improves at lower frequency

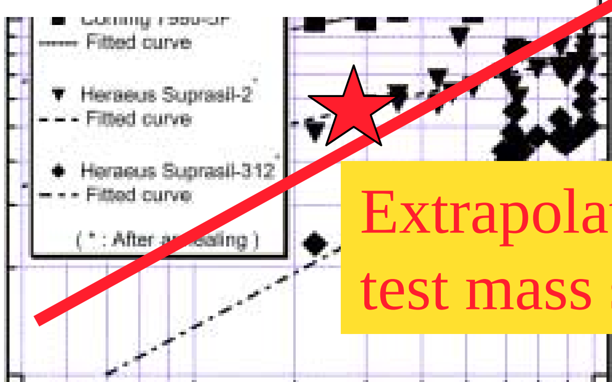
How much better does it gets at 100 Hz?



Let me cheat for a moment







10^3 Hz

Steve and Gregg's result

10^{-9}

10^4 Hz

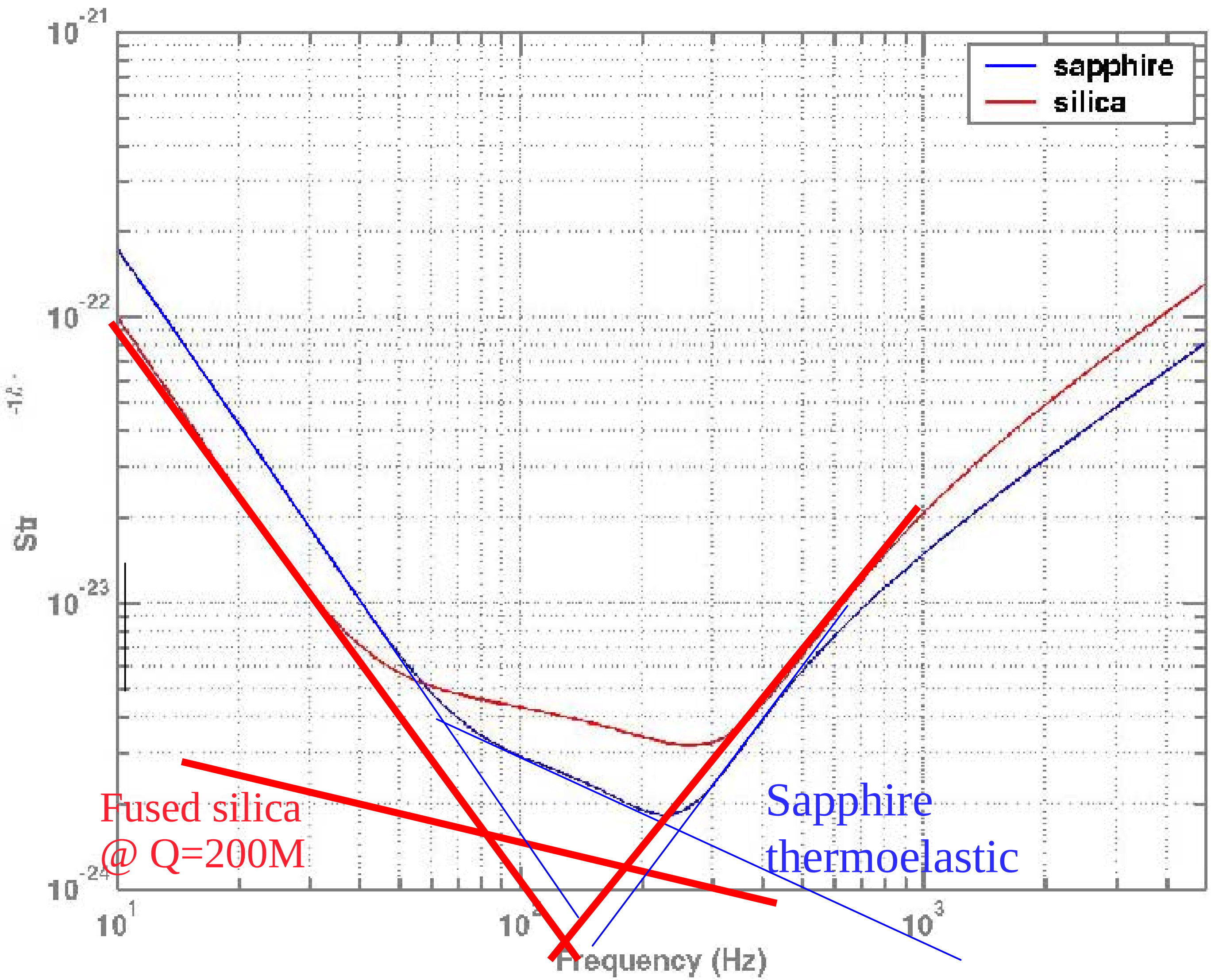
Extrapolated to test mass shape

10^{-10}

Surface and Coating losses?

Where are the substrate losses at f ~100 Hz?

What can we expect?.



Coating TN Disregarded!

This opens the road To LF

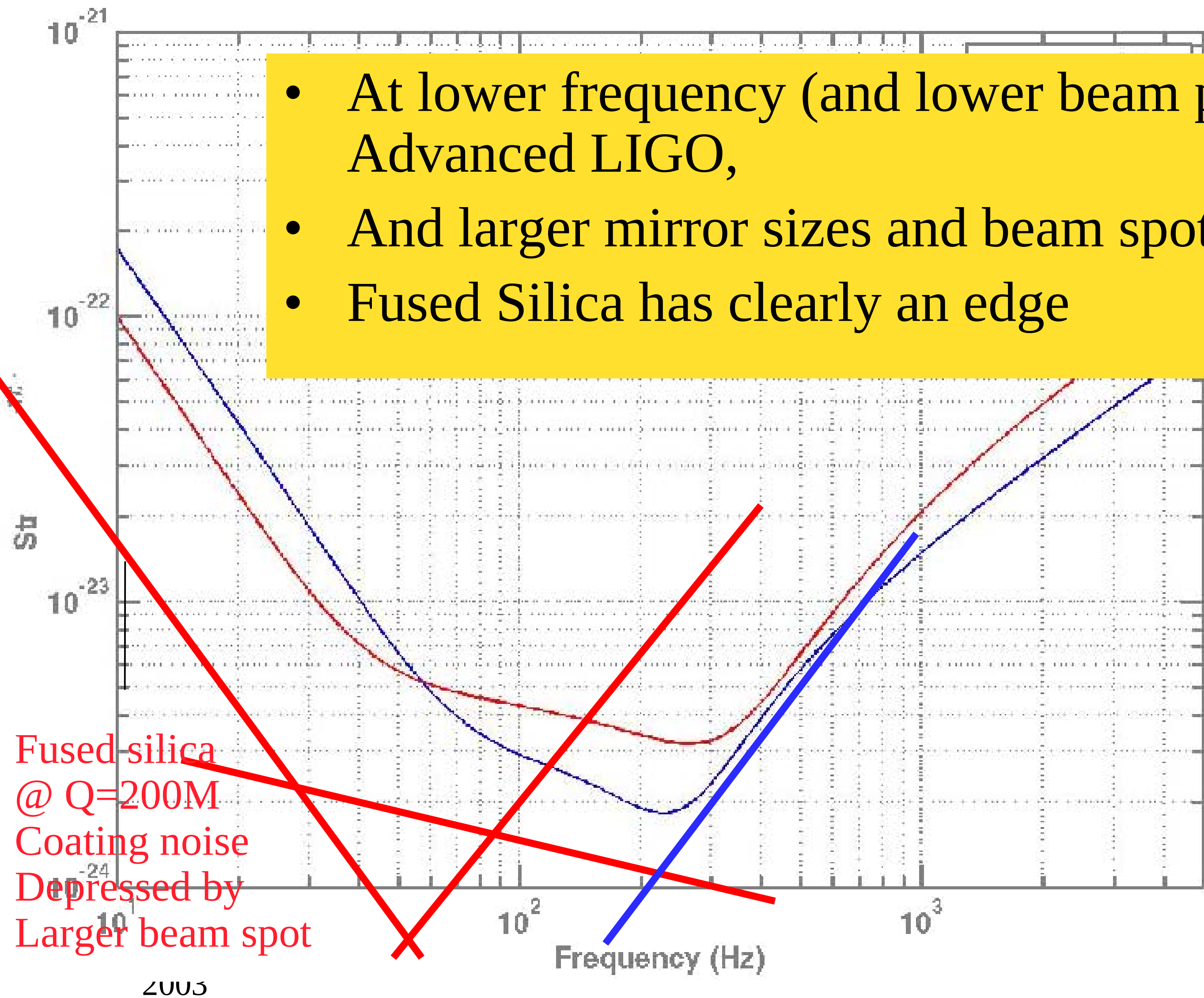
Note:At high Frequency Sapphire is preferable because of power dissipation limitations for Fused Silica

Implications at L.F.

- Fused silica allows for much lower thermal noise floor at L. F. if coating problem is solved
- The lower beam power can be tolerated.
  - No need for the higher thermal conductivity of Sapphire.
- Fused silica marginal for Adv-LIGO mirror size and power level
- At frequencies lower than Adv. LIGO (and larger beam sizes) the beam power problem rapidly disappears $\sim 1/f^2$
- The limit will be given by coating thermal noise.
- Advanced coatings and Large spot sizes are the solution to offset this limit
  - Coating thermal noise ~ (spot diameter)$^{-1}$

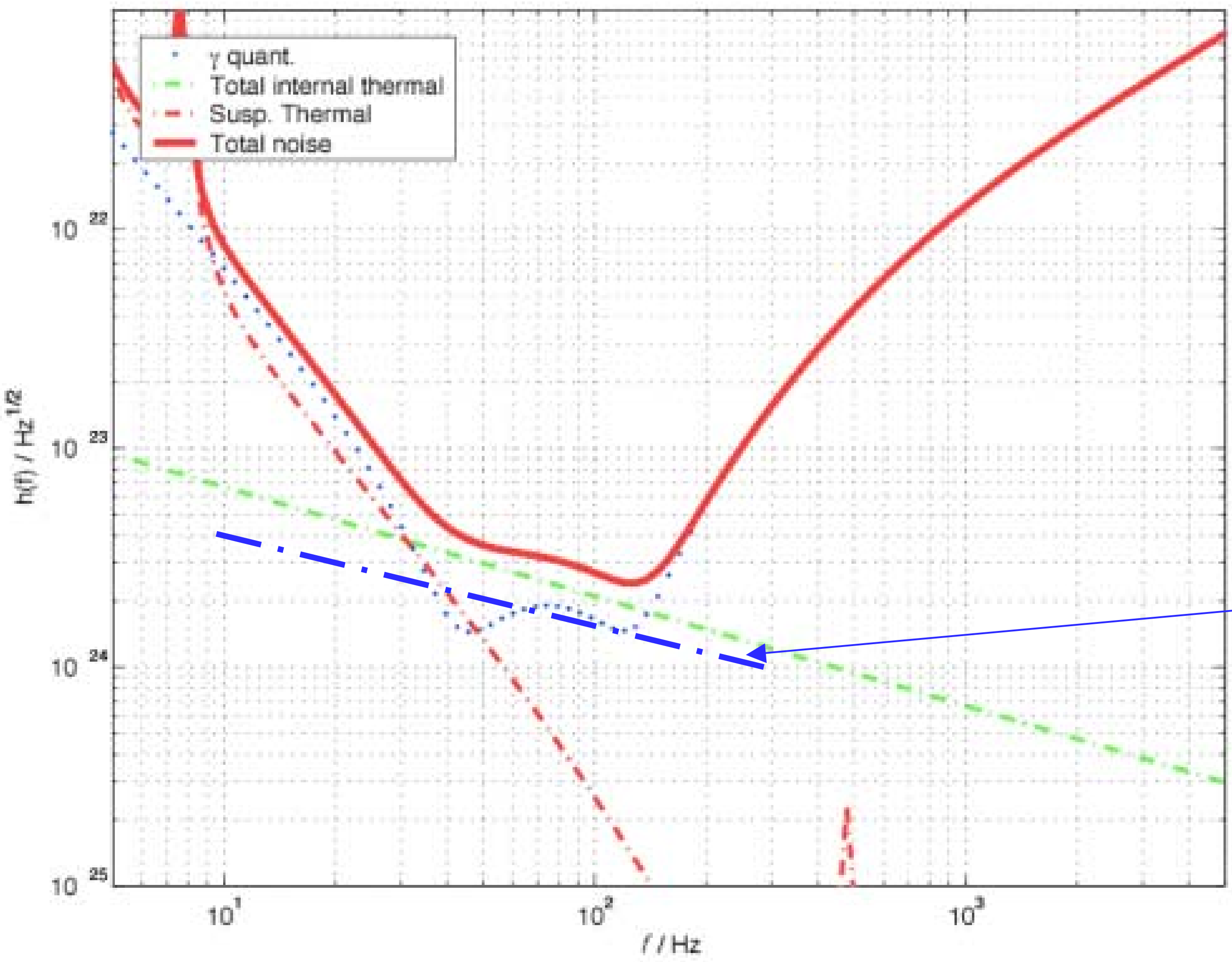
Resuming

- At lower frequency (and lower beam power) than Advanced LIGO,
- And larger mirror sizes and beam spots
- Fused Silica has clearly an edge



1/2 Freq.=>1/4 power
2x Spot=>1/4 p. dens.

Bench and Kenji's estimations



- 12 cm beam spot,
- 1 10^-4coating phi,
- 500 million silica Q,
- 5 Hz seismic wall

Coating TN limited

- In dashed: Kenji extimation for same parameters

Cosmic reach LF-LIGO

Spot cm	coating ϕ	silica Q Millions	BNS range Mpc
6	$5\ 10^{-5}$	100	166
6	$1\ 10^{-5}$	200	230
12	$1\ 10^{-4}$	500	234
12	$5\ 10^{-5}$	200	258

Cosmic reach

NS inspiral 100 Mpc

Adv.LIGO optimized for ns insp.	S/N 6
LF-LIGO Opt.for 30+30sm insp.	S/N 9

t.b.c.

30+30sm inspiral,
max reach at S/N 10

Adv.LIGO	770 Mpc
LF-LIGO	1150 Mpc

t.b.c.

Bench/G. Harry
Adv-LIGO standard Config.
Fused silica Q 200M

Parameter	LF LIGO	ADV LIGO
Seismic wall	6 Hz	10 Hz
Mass radius	215 mm	155 mm
Beam radius	12 cm	6 cm
Suspension l.	1.5 m	0.5 m

Signal to noise at 200 MPc

Inspiral mass	Adv LIGO S/N	LF LIGO S/N
1.4+1.4	4	4.4
30+30	51.5	57.1
50+50	78.9	87.4

Q silica 50M (conservative)
Coating Phi 2 10^{-5}

A-LIGO seis. Wall @ 10 Hz
Standard configuration

LF-L susp. Noise limited

Bench/Gregg Harry

- Assuming templates exist throughout the freq. range
  - At higher frequencies templates may not be available for the final merge and inspiral phase

Signal to noise at 200 MPc

Inspiral mass	Adv LIGO S/N	LF LIGO S/N
1.4+1.4	4	4.4
30+30	51.5	57.1
50+50	78.9	87.4

But much larger S/N are possible if the signal of both interferometers is combined!!

- Kip is running his own independent evaluation of merit for a LF LIGO companion.

- To be cross checked

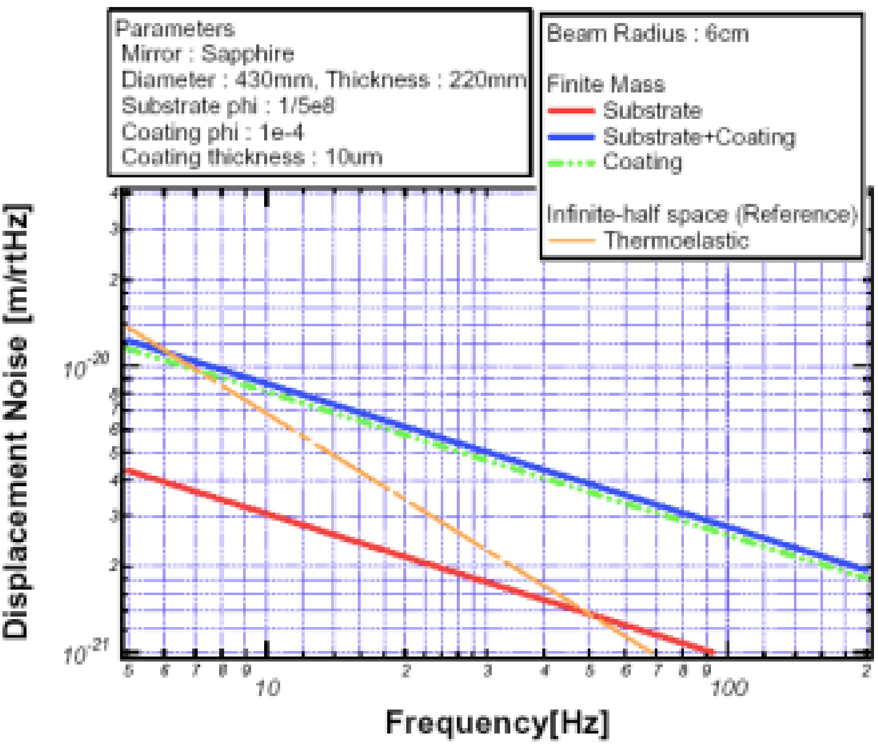
Implications

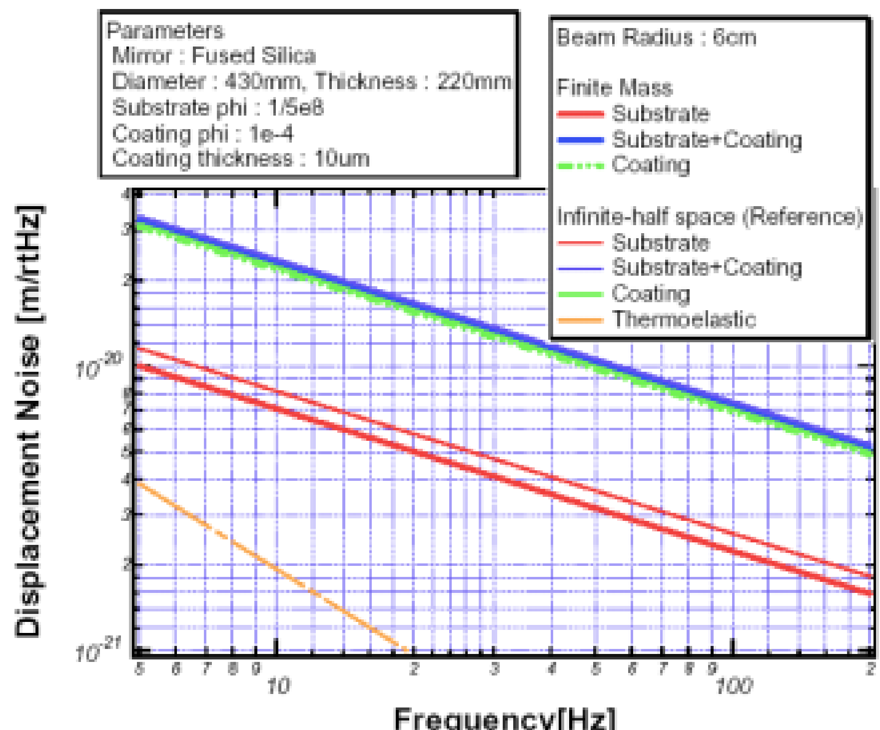
- A Virgo-like interferometer to cover the low frequency region at LIGO would be mostly welcome
- Advantages
- lower frequency region is better covered
- Splitting up the frequency range between two different interferometers eases lots of design constraints and allows better performance from each
- Advanced LIGOs are free to be narrow banded
- For heavy massers, Adv.LIGO would be “triggered” by the LF optimal filter detection and can start disentangling final inspiral and merge signals

LIGO Is Fused Silica better than Sapphire at low frequency?

- If we consider same geometrical size mirrors
- Sapphire is unbeatable!

Data from Kenji





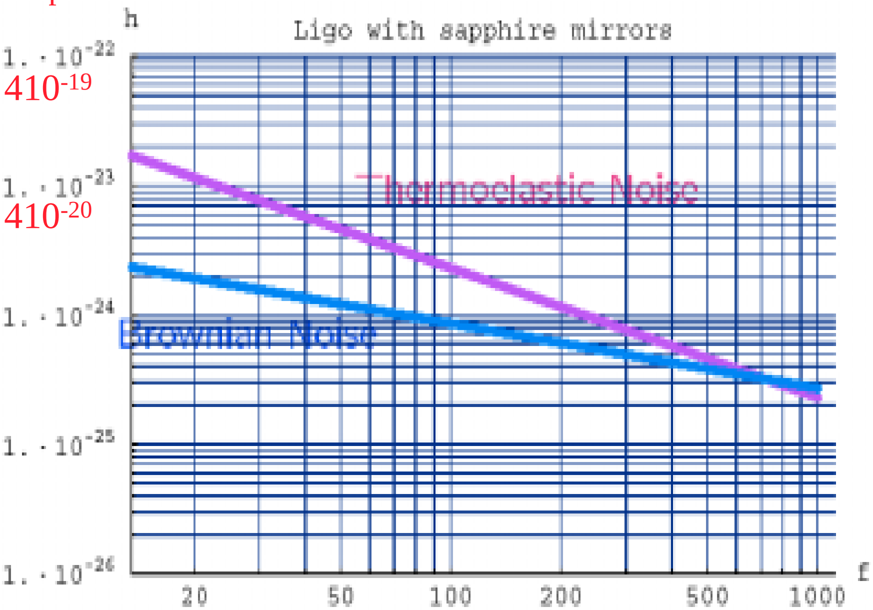
LIGO Is Fused Silica better than Sapphire at low frequency?

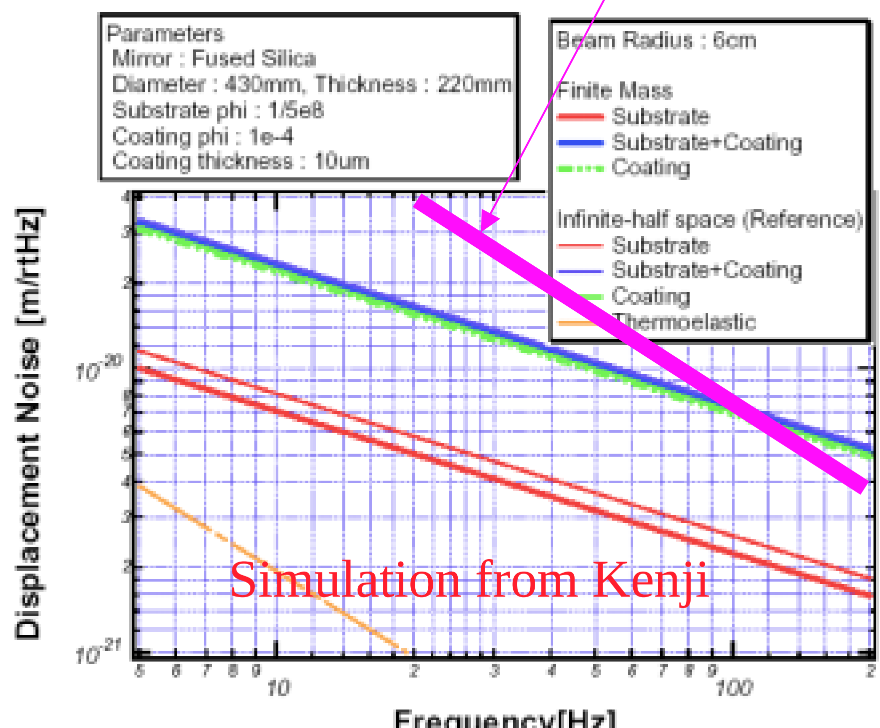
- However, as soon as we consider reasonable sizes of sapphire (advanced-LIGO sizes)

  Fused Silica immediately becomes competitive at LF

Thermo-elastic noise of adv. LIGO mirrors Gauss spot (Erika)

Displacement noise





Adv,LIGO simulation from Erika
6 cm spot

$$Q_{sapphire} = 2 \times 10^8$$

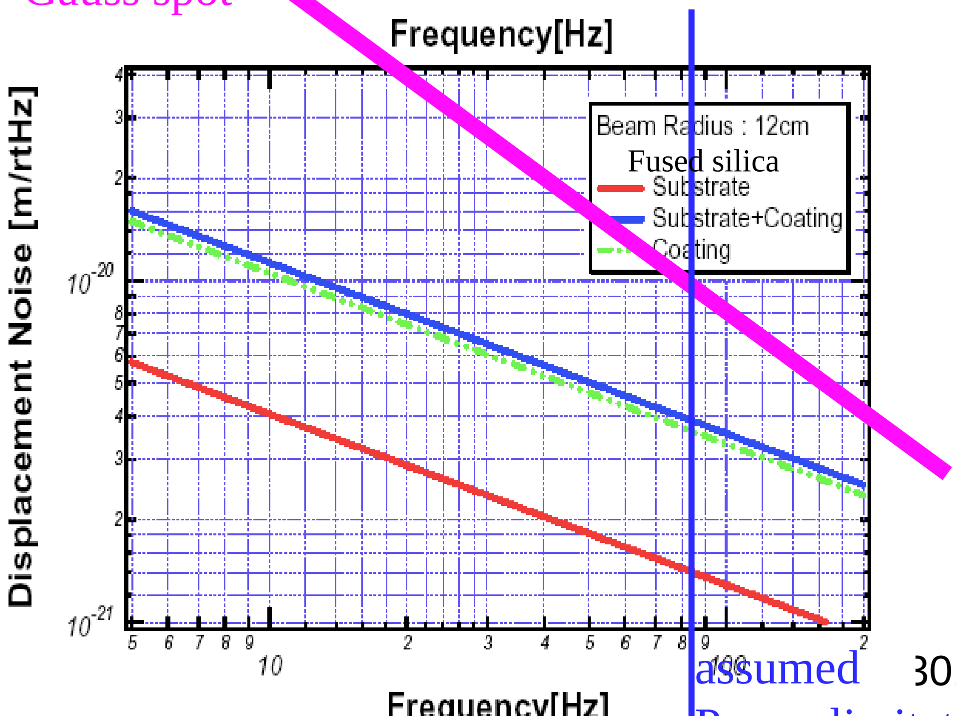
030

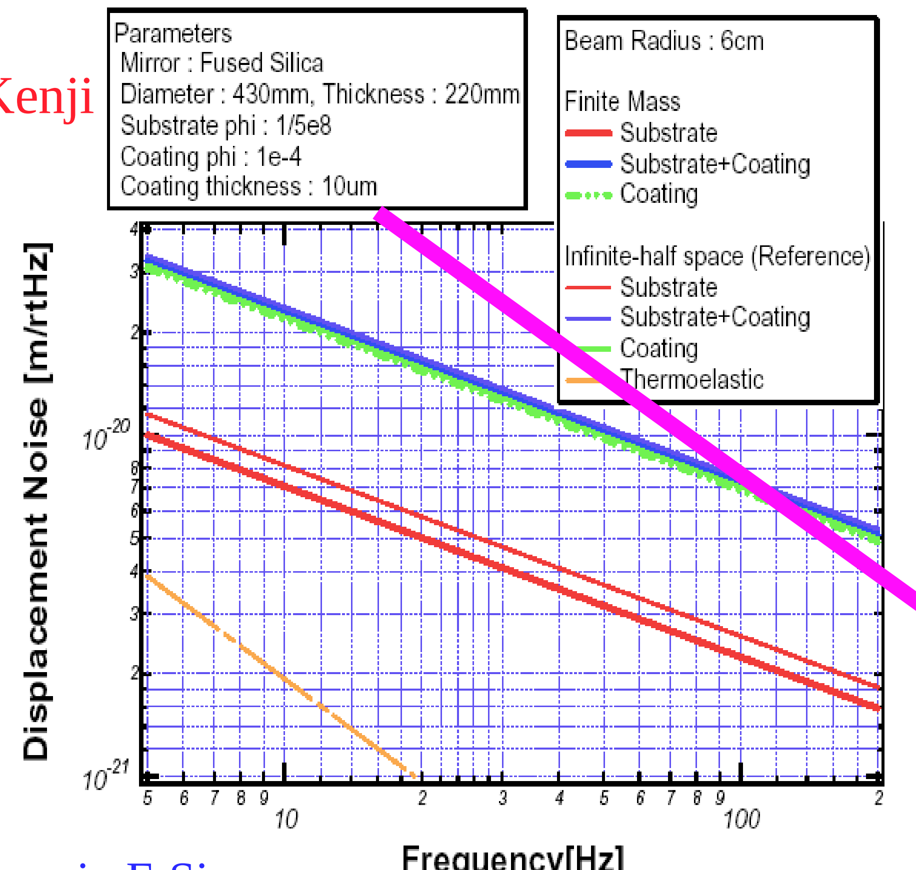
Is Fused Silica better than Sapphire at low frequency?

- Even better with **larger spot sizes** allowable by larger fused silica mirrors and softer suspensions

Thermo-elastic noise of
adv. LIGO mirrors
Gauss spot

Simulation from Kenji





assumed
Power limitations in F-Si

How to mitigate the coating noise problem

- Can use **bigger masses** and **larger beam spots** to counter both coating thermal noise and power limitations (and depress radiation pressure fluctuations)

- Bonus: larger bottom of the canyon
- Tighter alignment requirements are possible with lower frequency suspensions and hierarchical controls (Virgo scheme).

- Note, possible advances in coating loss angle not included

How to mitigate the coating noise problem 2

Ligo Seminar
February 2003

Erika D'Ambrosio
Ligo Laboratories, Caltech

Scaling law for w

Standard Thermal Noise: $S_{coupled}(f) \sim w^{-1}$

Thermodynamical Fluctuations:

$$S_{coupled}(f) \sim w^{-3} \Longleftarrow < \delta x^2 > = \alpha^2 \delta T^2 \left[\frac{K_{th}}{C_p} \tau \right]$$

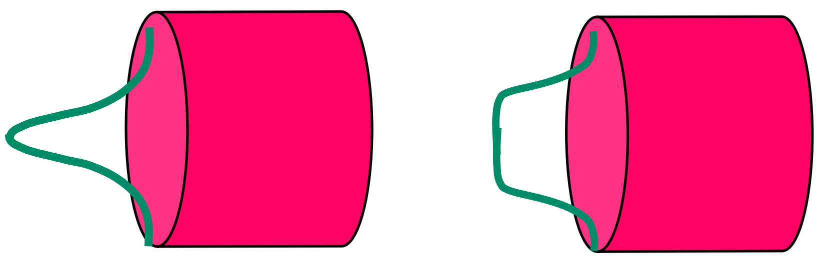
Coating Mechanical Loss: $S_{coupled}(f) \sim w^{-2}$

How to mitigate the coating noise problem 3

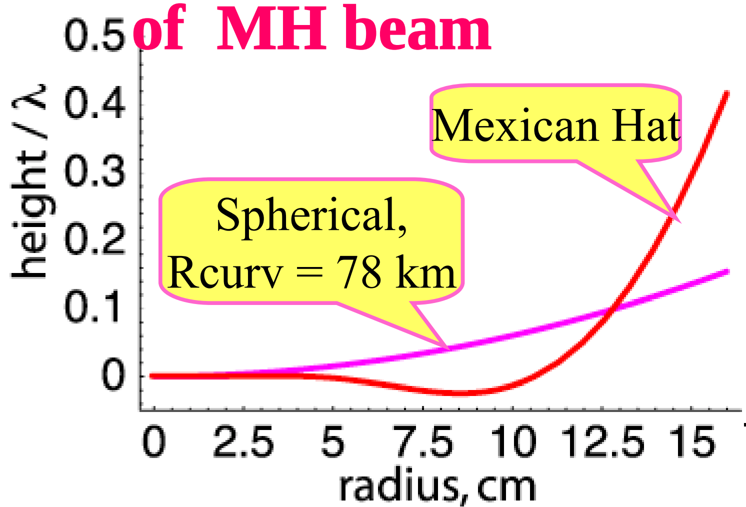
Mexican hats proposed by Kip Thorne et al. are a solution

http://www.ligo.caltech.edu/docs/G/G030137-00/

- A Flat-topped beam averages over bumps much more effectively than a Gaussian beam.



- **MH mirror shape: matches phase fronts of MH beam**



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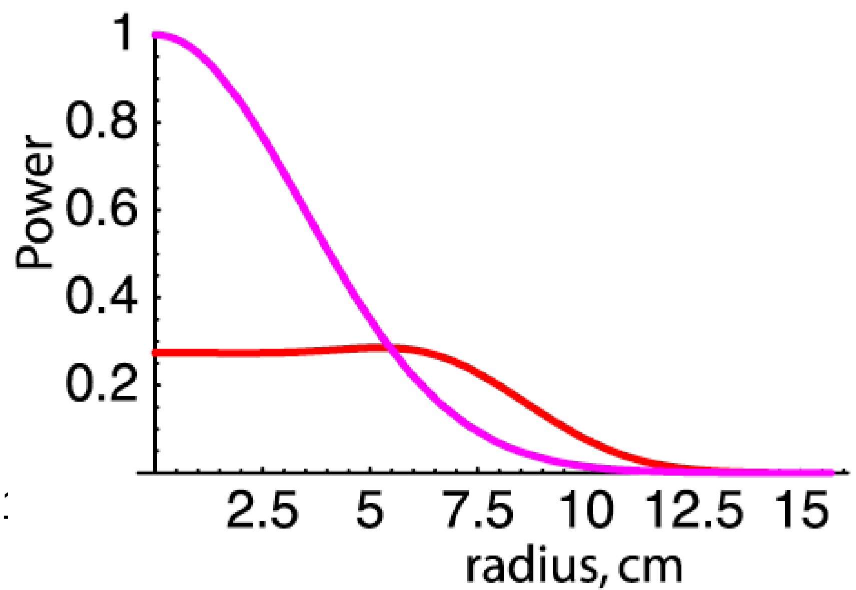
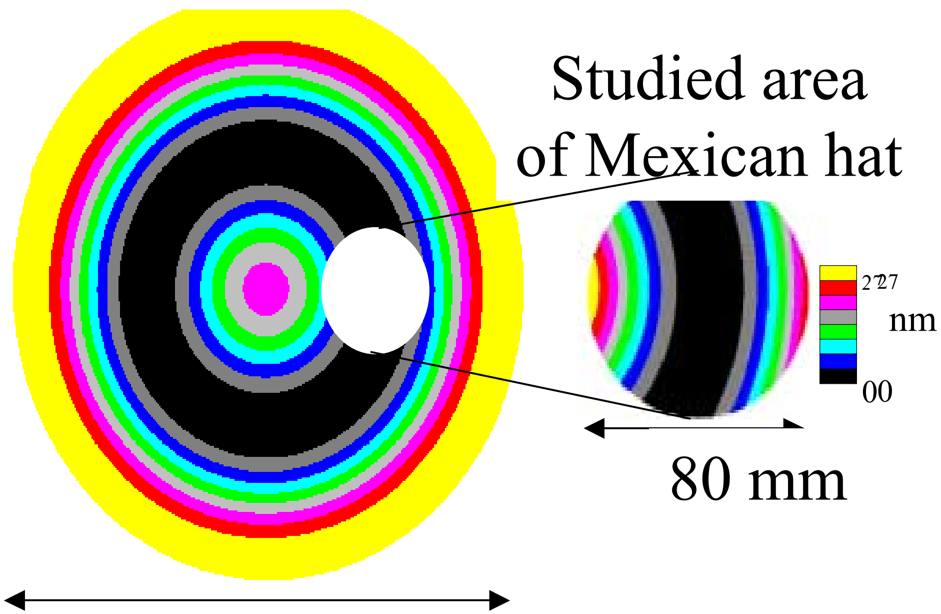


How to mitigate the coating noise problem 4

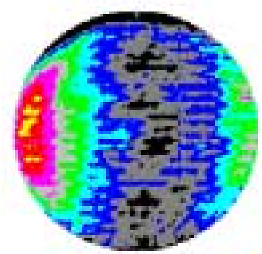
And J.M. Mackowsky shows that they are relatively easy to make

http://www.ligo.caltech.edu/docs/G/G030115-00/

Top view of a Mexican hat

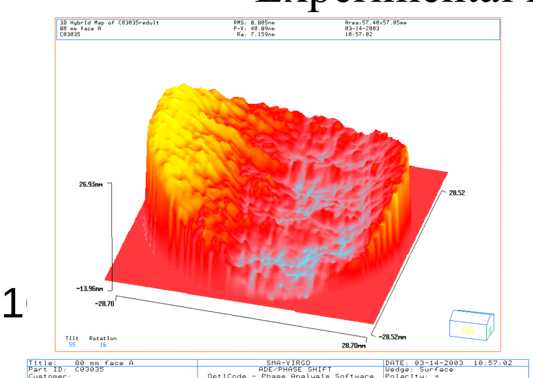


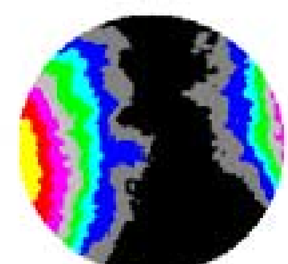
Theoretical mexican hat



Simulation of the corrective coating

Experimental mexican hat





How much larger?

- The larger mirrors discussed are feasible today
  - 75 Kg fused silica
  - 430 mm diameter
  - Have a bid from Heraeus

Does gravity gradient negate the advantages?

- With longer mirror suspensions (1-1.5m) the suspension thermal noise is pushed at lower frequency
- Gravity gradient gets uncovered
- Can start testing GG subtraction techniques
- Note:

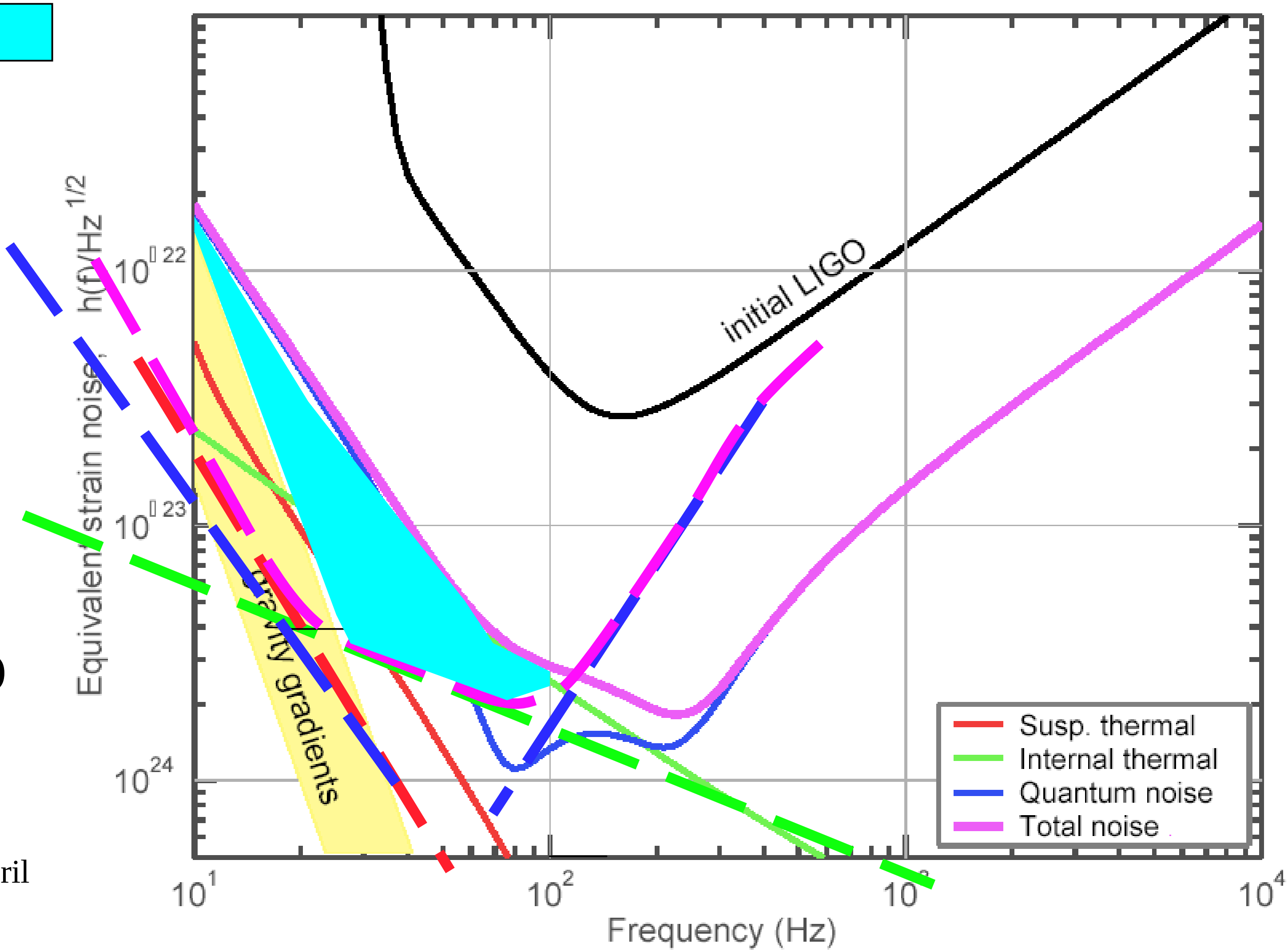
  Clearly for the future will need to go underground to fight GG
- But even aboveground there is so much clear frequency range to allow substantial detection improvements

Is gravity gradient going to stop us?

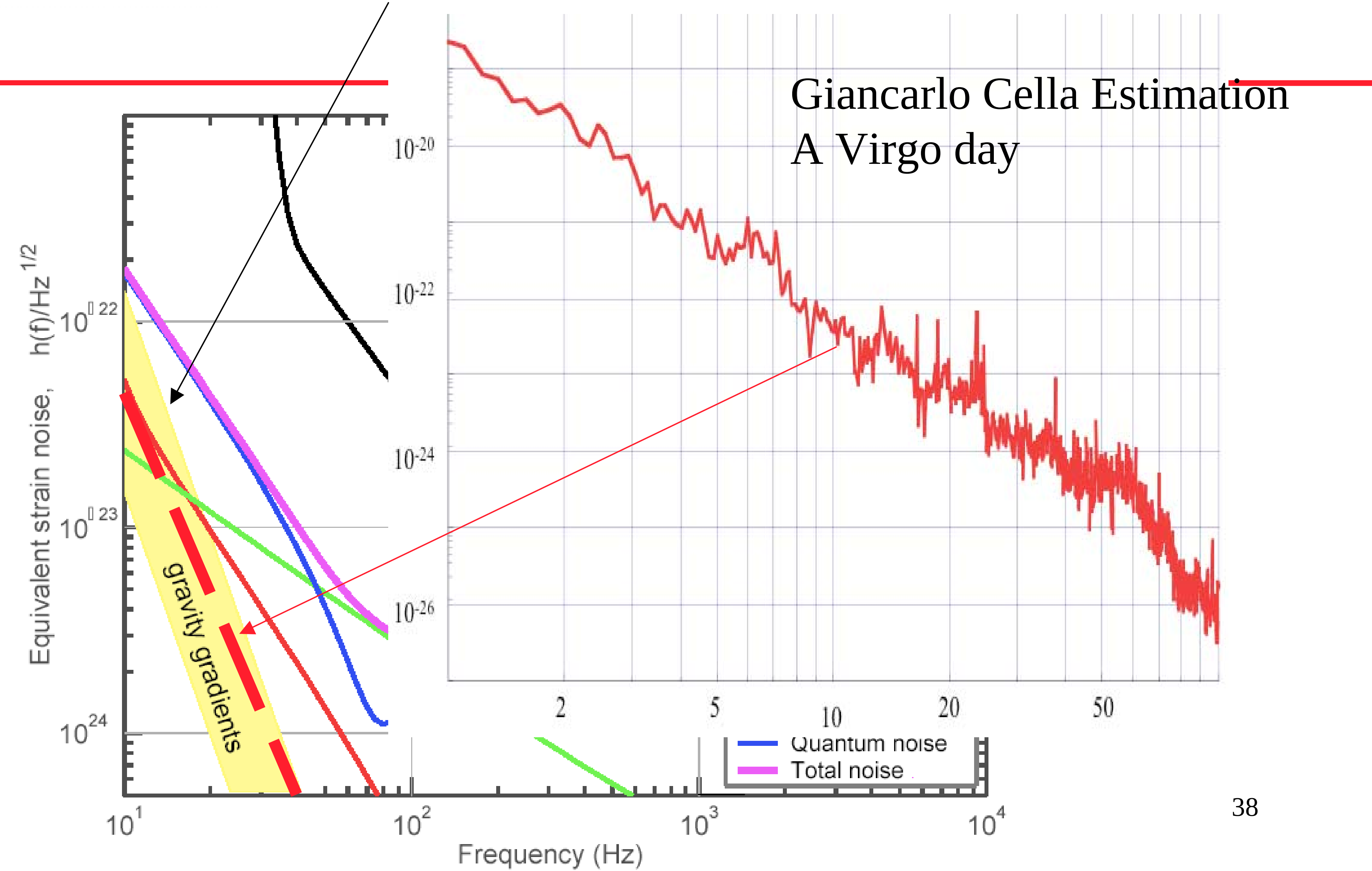
Minimal Additional Phase space

Dashed = LF-LIGO

Solid = Adv-LIGO



Adv-LIGO estimation based on worse of best 90%
Of data stretches, including transients!



Comments on GG

- G.C. Cella evaluations give similar results

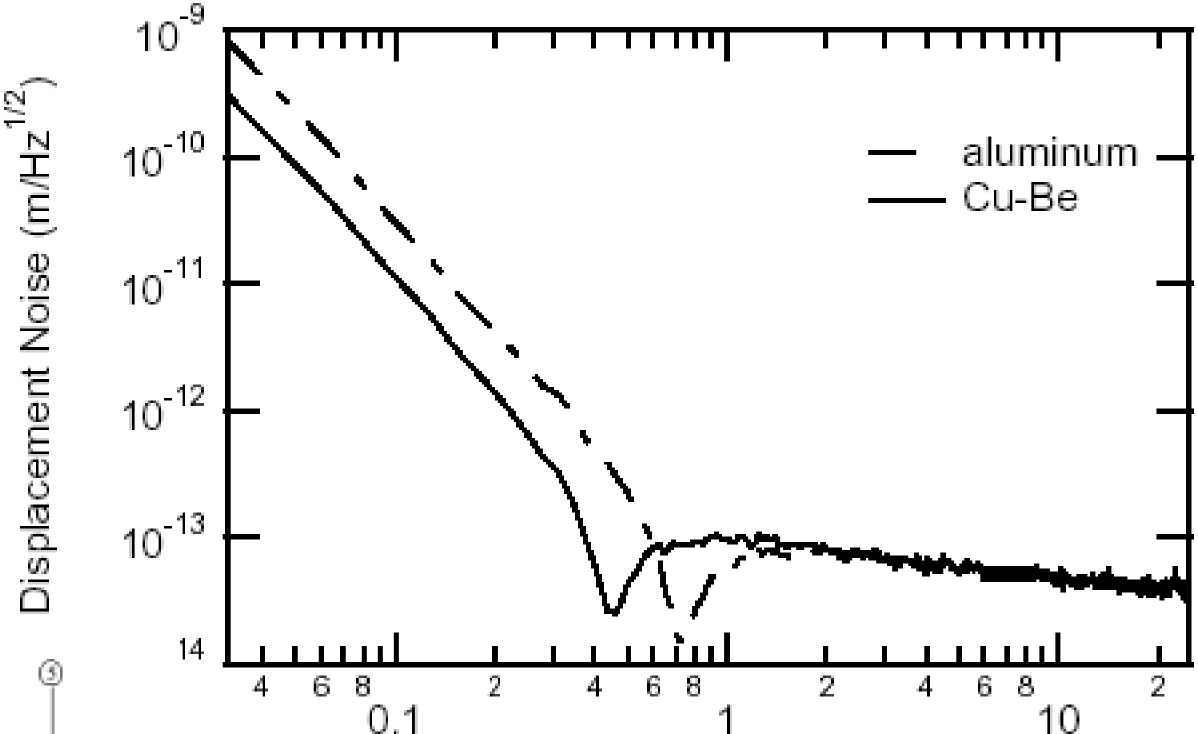
- Even if the GG was to be low only in windless nights, it would be worth having the listening capability 50% of the time
- LF-LIGO would give us the opportunity to test GG subtraction techniques

Comments on GG

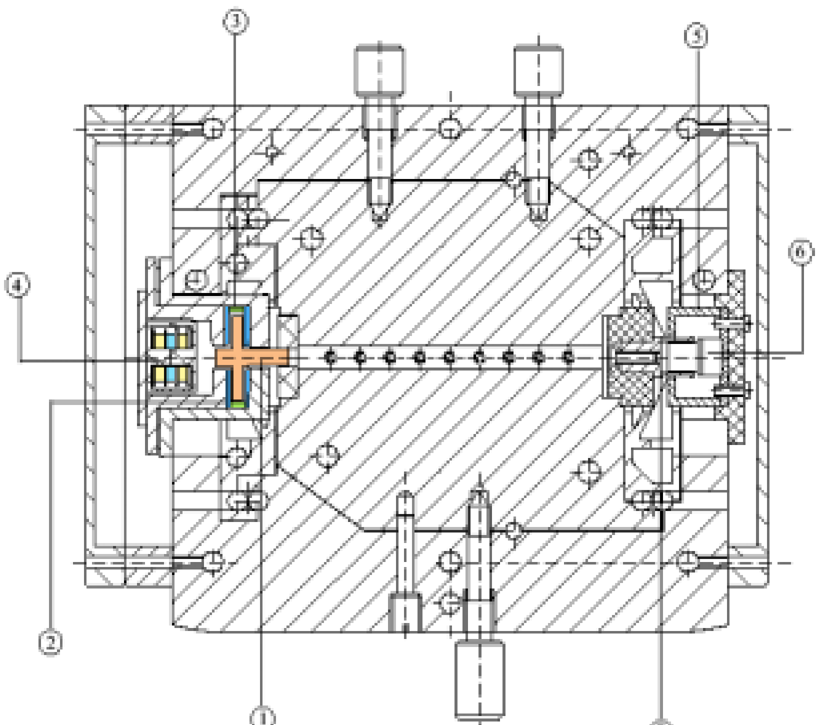
- Main contribution to GG is the moving soil/air interface.

- Simple matrix of surface accelerometers can allow up to x10 improvement
  - (work in Pisa)

- Then more difficult

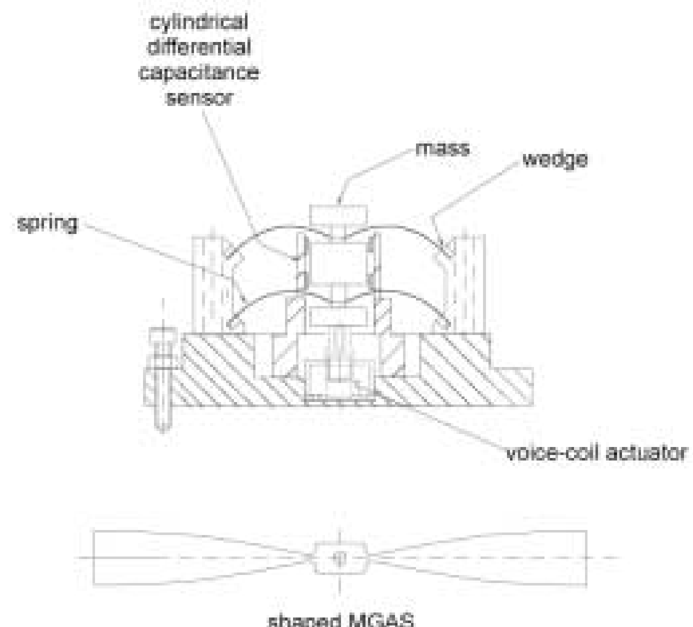


Displacement Noise (m/Hz$^{1/2}$)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
14
aluminum
Cu-Be
4 6 8 0.1 2 4 6 8 1 2 4 6 8 10 2



1
2
3
4
5
6
7

-G030165-



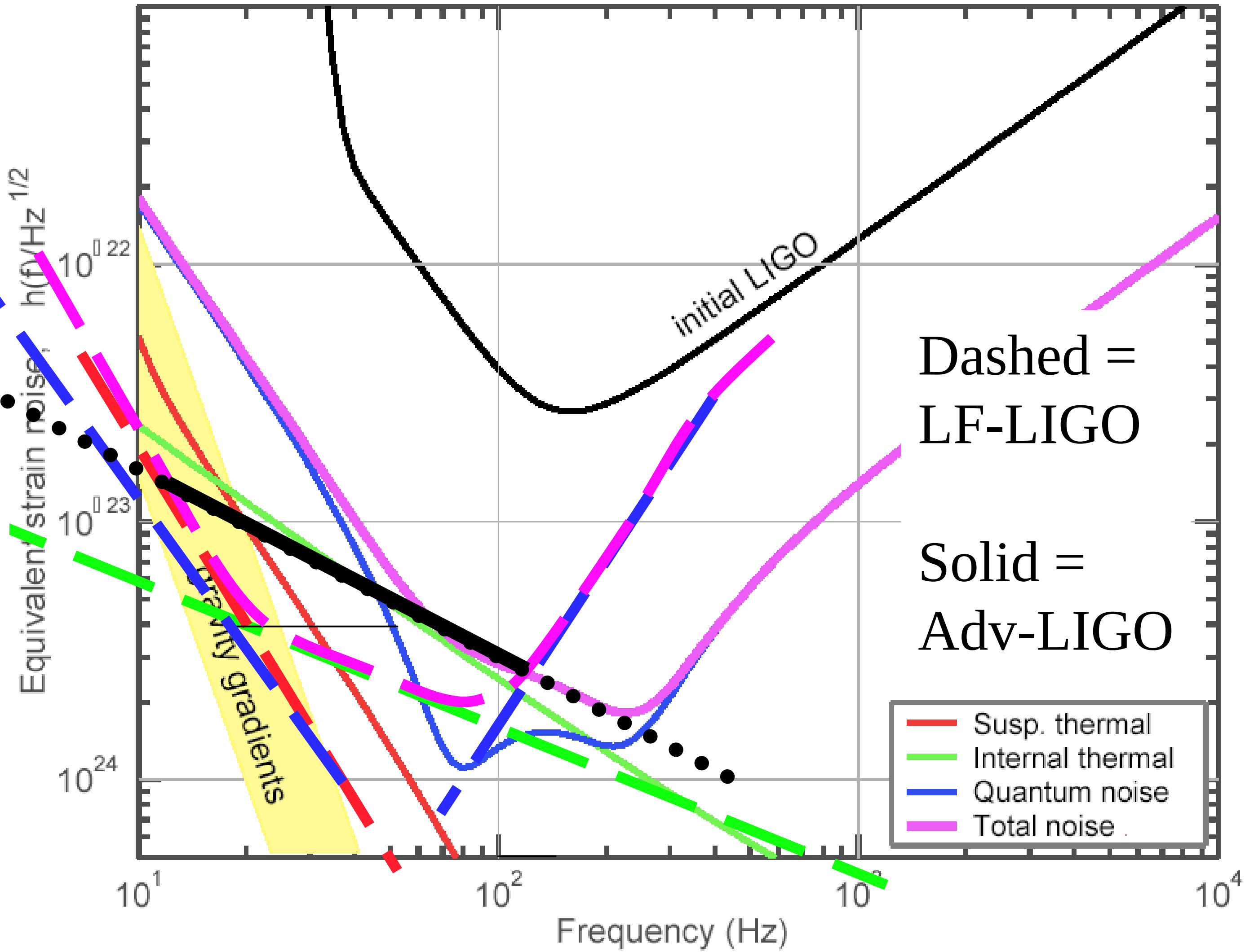
cylindrical differential capacitance sensor
mass
wedge
spring
voice-coil actuator
shaped MGAS

LIGO

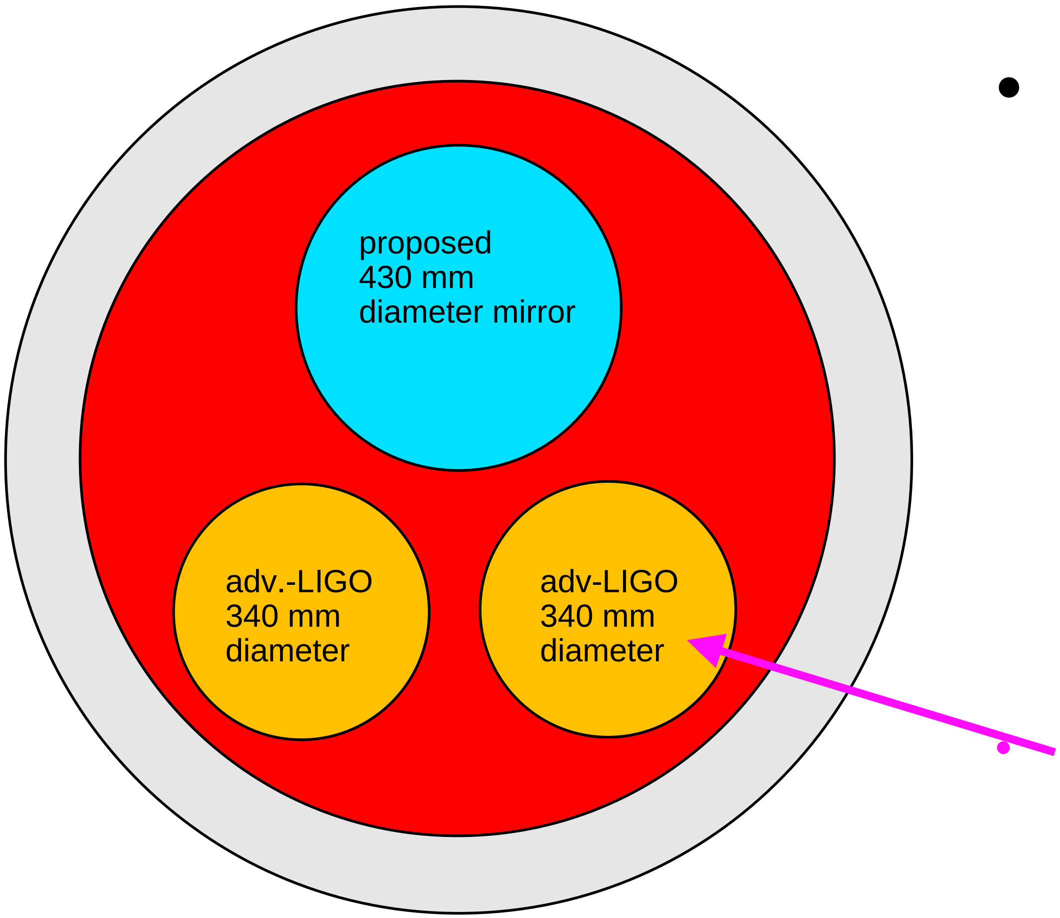
Is gravity gradient going to stop us?

50+50 sm inspiral at z=2

We can possibly re-cover all the yellow band



Can we accommodate a LF Adv-LIGO

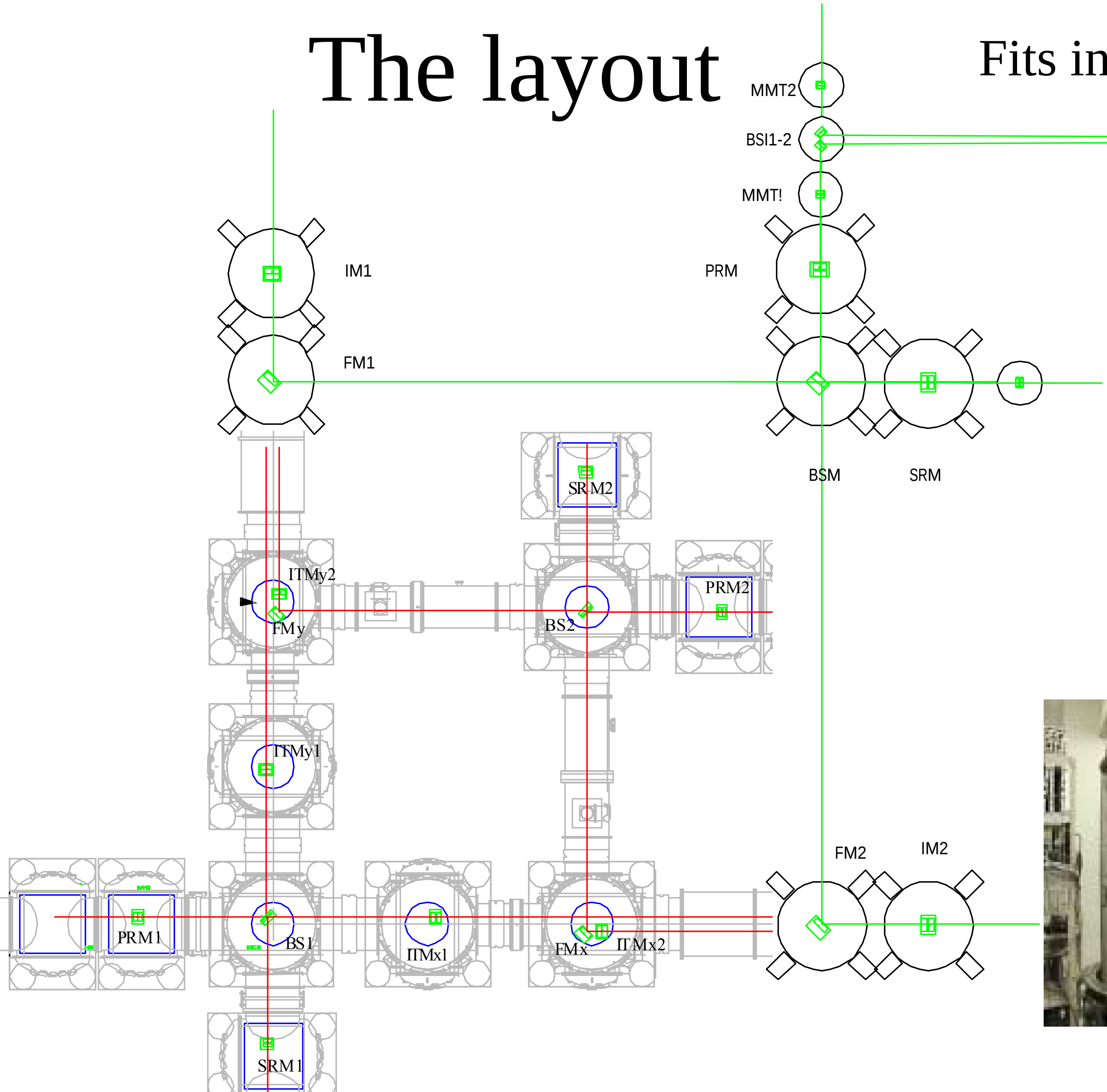


- There is space in the beam pipe just above and forwards of the Adv-LIGO mirrors

- Advanced LIGO nominal beam positions

The layout

Fits in LVEA



- Technical solutions:
- Advanced-LIGO SAS suspensions for large optics
- TAMA-SAS suspensions for small optics

L F Int. Characteristics

- Shorter SAS
- Longer mirror suspensions
  - Suspension T.N. freq. cut ~ $1/\sqrt{L}$
- Everything hanging down

Auxiliar suspended tables above beam line for pickoff, etc.

- Stay out of the way of Adv. LIGO

Do we need a new design?

- Virgo optical and control design is nearly optimal,
  - The Virgo interferometer is (or soon will be) fully validated.
  - Will only needs minor improvements and some simplifications
- Laser can be the same as LIGO (lower power)
- Seismic Attenuation and Suspensions
  - large optics: already developed for advanced LIGO (downselected at the time)
  - Small optics: use TAMA-SAS design
  - Both well tested

All components off the shelf and tested.

Technically we can build it almost immediately

When and where to implement LF LIGO?

- Cannot disrupt Adv-LIGO operations
- Above the Adv.-LIGO beamline => must be installed forward of Adv-LIGO
- At least all the main mirror vacuum tanks must, but probably all of the interferometer should, be installed at the same time as Adv-LIGO

Can we afford a LF Adv-LIGO

- LSC and Advanced LIGO have decided not to pursue the L.F. option to focus on differen possible sources, and dedicated all available sources to it
- A L.F. interferometer can be done only with external support
- A LF brother for Adv-LIGO would be a simpler and cheaper interferometer.
- There may be interest for EGO to make new interferometers in the LIGO facility before making a new generation IF in a new facility.
- Seismic and suspension design is available using the inexpensive, existing, and well validated, SAS and Virgo concept
- There is space in the existing facilities,
  - except the end stations at Hanford and small buildings for mode cleaner.

Can we afford a LF Adv-LIGO

- Estimation of project costs:

Color code: Prices per unit Price per interferometer		Cost source
Large Vacuum tanks (2 m diameter ~Virgo design)	0.4 Meu	Actual Cost
Large SAS tower (including control electronics)	.25 Meu	A.C./Bids
Mirrors	0.3 Meu	Bids
7 or 8 systems(vacuum+SAS+mirror) per interferometer	7.6 Meu	
Small vacuum tank and TAMA-SAS suspensions	0.2 Meu	A. C. + Bids
6 to 8 needed per interferometer	1.6 MeU	
Small optics	0.2 Meu	Est.
Laser	0.5 Meu	rec. LIGO
Gate valves	0.1 Meu	A.C.
4 to 6 needed	0.6 Meu	
New buildings for end station and mode cleaner, each:	0.5 MUS$	Est. F. Asiri
1 needed in LA (MC), 3 in WA (end station and MC)	1.0 MUS$	
Design	0.3 Meu	Est./A.C.
Various	3.0 Meu	Est.
Total per interferometer	14.8 Meu	
Spares (1 set optics)	4.0 Meu	

Can we afford a LF Adv-LIGO

- We are talking of 15 to 20 M US$ per interferometer for components
- Manpower we can estimate a staff of 20 persons for 5 years for one interferometer, 30 persons for 2 interferometers
  - Partly from Europe in part from the States.
  - 100,000US$ per person/year, for 1 interferometer 10 MUS$
    for 2 interferometers 15 MUS$
- Estimated Total
- for one interferometer 30 MUS$
- for two interferometers 50 MUS$

Can we afford not to introduce a LF brother for Adv-LIGO

- Clearly **the newly observed BH are important and compelling potential GW sources for a LF interferometer**

- Not going LF means forgoing the study of the genesis of the large galactic BH believed to be central to the dynamics of galaxies and forgoing mapping the globular clusters in our neighborhood

Conclusions

- Adv-LIGO is designed for bradband over a different set of possible sources and consequently does not cover well the Low Frequency range as well as an IFO exclusively targeted at this range
- Ignoring the LF range could be dangerous because it contains many juicy, and observed, GW signal generator candidates
- Redesigning Adv-LIGO to cover it would be awkward and take too long and it would uncover the equally important High Frequency range
- Adding a simple Low Frequency interferometer is the simplest and best choice!

Implementation strategy

- Gather a composite study group
- Since the resources will have to be both external and harmonized to the A-LIGO program
  the study group would have to be initially independent from LSC.

- Go around the world with a hat
  see how many collaborators and additional millions of $/Euro I manage to collect