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

Riccardo DeSalvo
California Institute of Technology

Livingston March 20th 2003

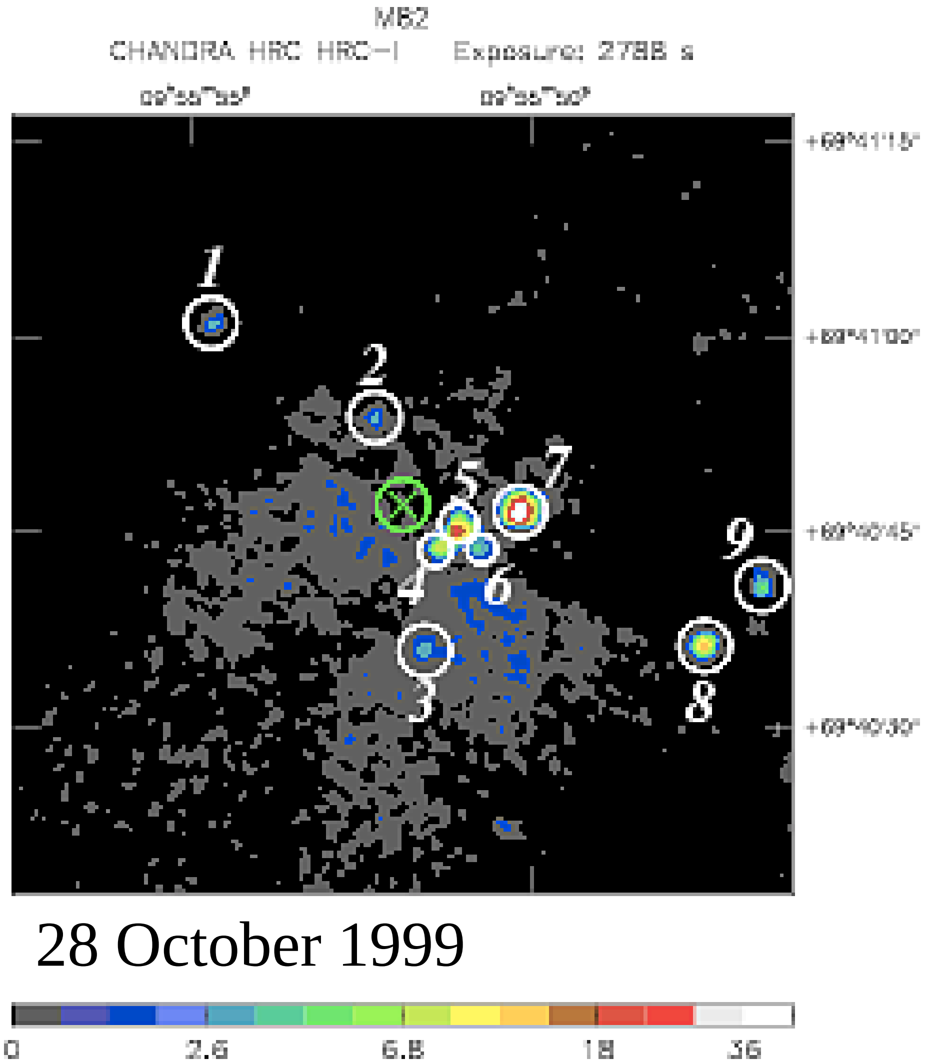
LIGO-G030086-00-R

Scientific motivations

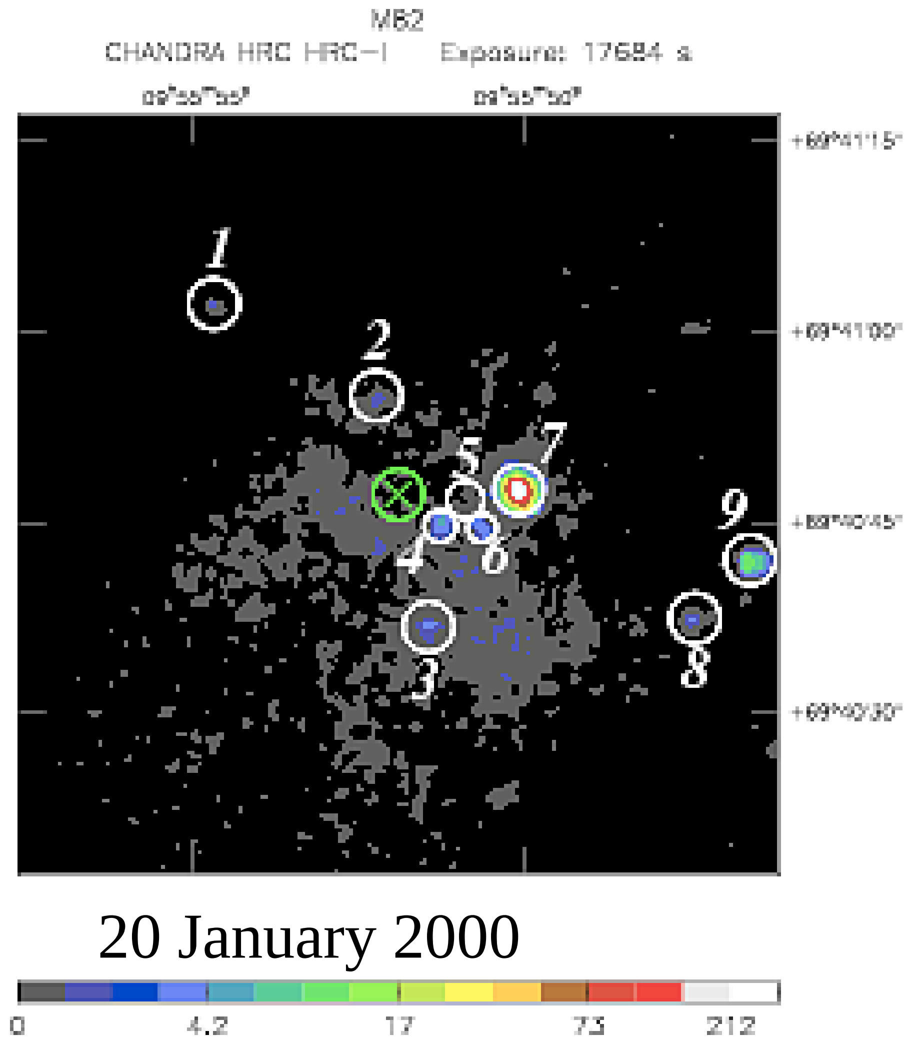
- Data summary from Cole's Miller based on X-ray and optical observations of galaxies and globular clusters including Chandra's observations of X-ray sources

- 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

- Other 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)

- Stars >50 s.m. slow down by dynamical friction (τ=10~50My) and sink to the center of the cluster where they may be induced to merge
  - Density of ~ million stars per cubic parsec observed
  - Mass segregation occurs

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

What do I gather from globular cluster and galaxy observations

- The only electromagnetically visible BH are those accreting from companion star
- Why so many are visible?
- Frequent Encounters of binaries with singles tie and tighten up the bigger guy and fling out the smaller guy (s.m. size ones)
- The feeding stage is short (~10My)
- X-ray sources compatible with several 30 to 1000 s.m. BH per galaxy are observed by Chandra and XMM, many more may lurk
- Velocity dispersion in globular cluster centers imply presence of IMBH

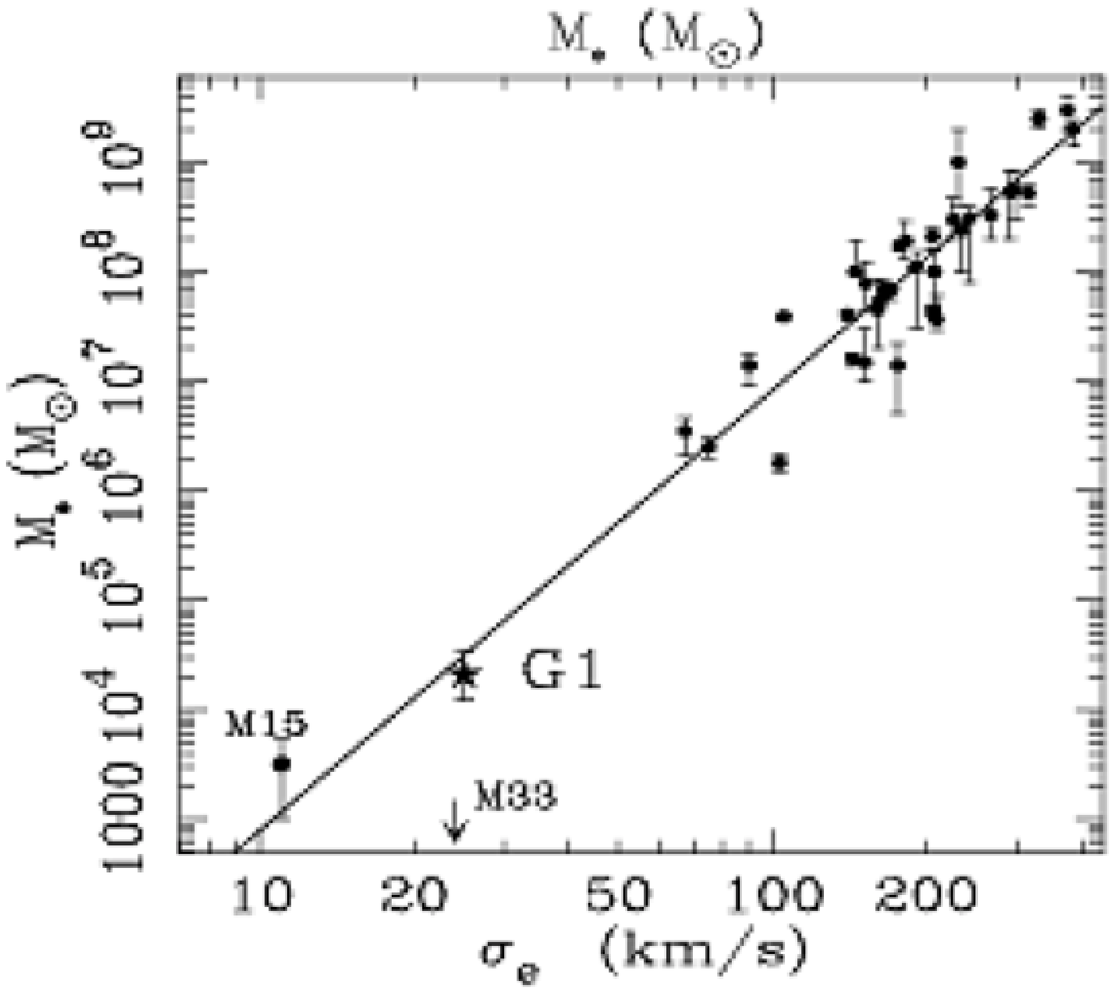
What do I gather from globular cluster observations

- 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

Hubble 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



Hubble 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.
  - (as well as the other BH observed farther away)

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

- A BH cluster must be present and being hardened
- And will coalesce at rapid rate! << 10My !!!!

Consequences

- Do we need a low frequency companion for Advanced LIGO to cover the new Chandra observations?

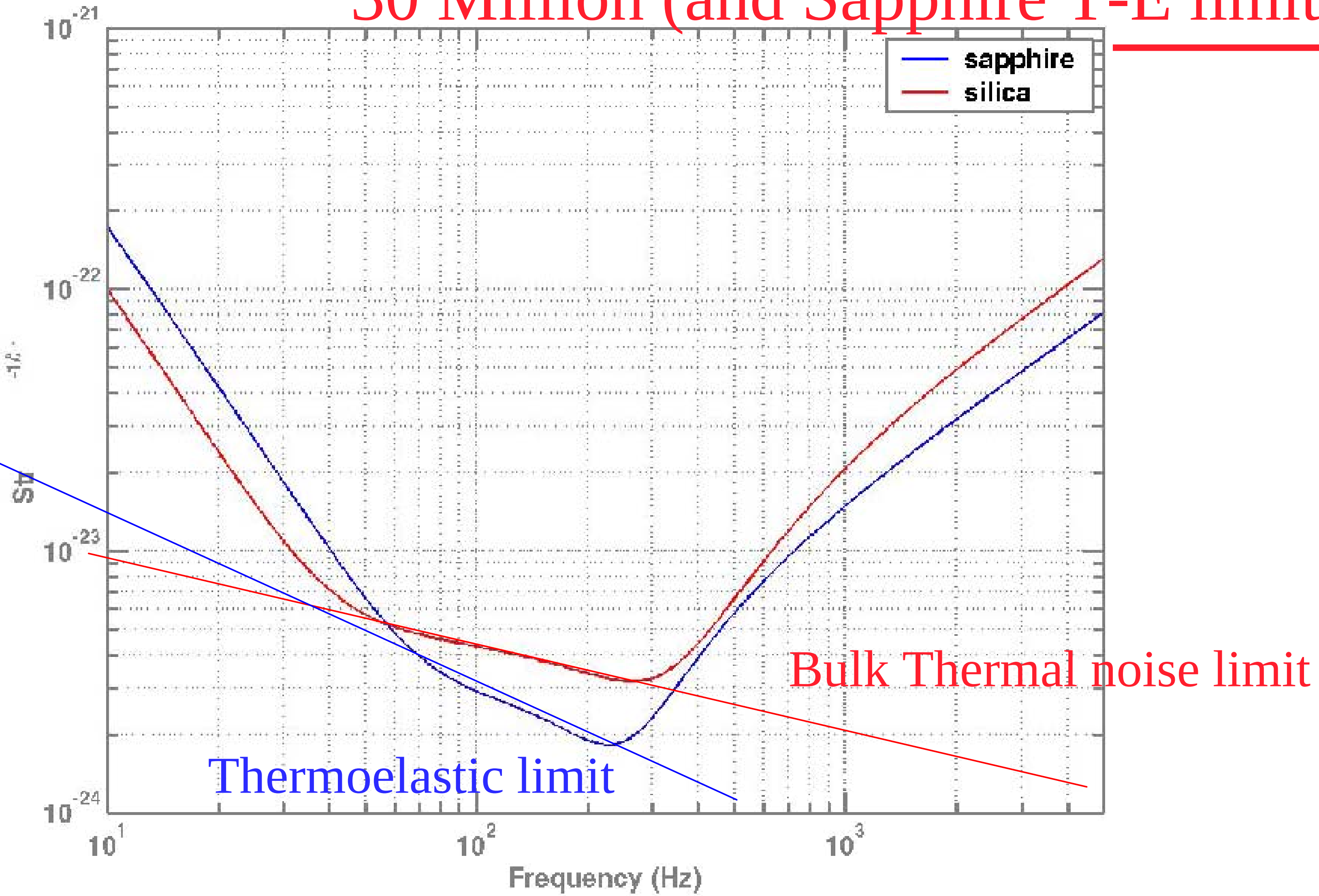
- Of course yes!
  - Note: Advanced LIGO is designed to go as low in frequency as practical while focusing on the higher frequency end
  - separated design lead to better optimizations.

Question

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

LIGO

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



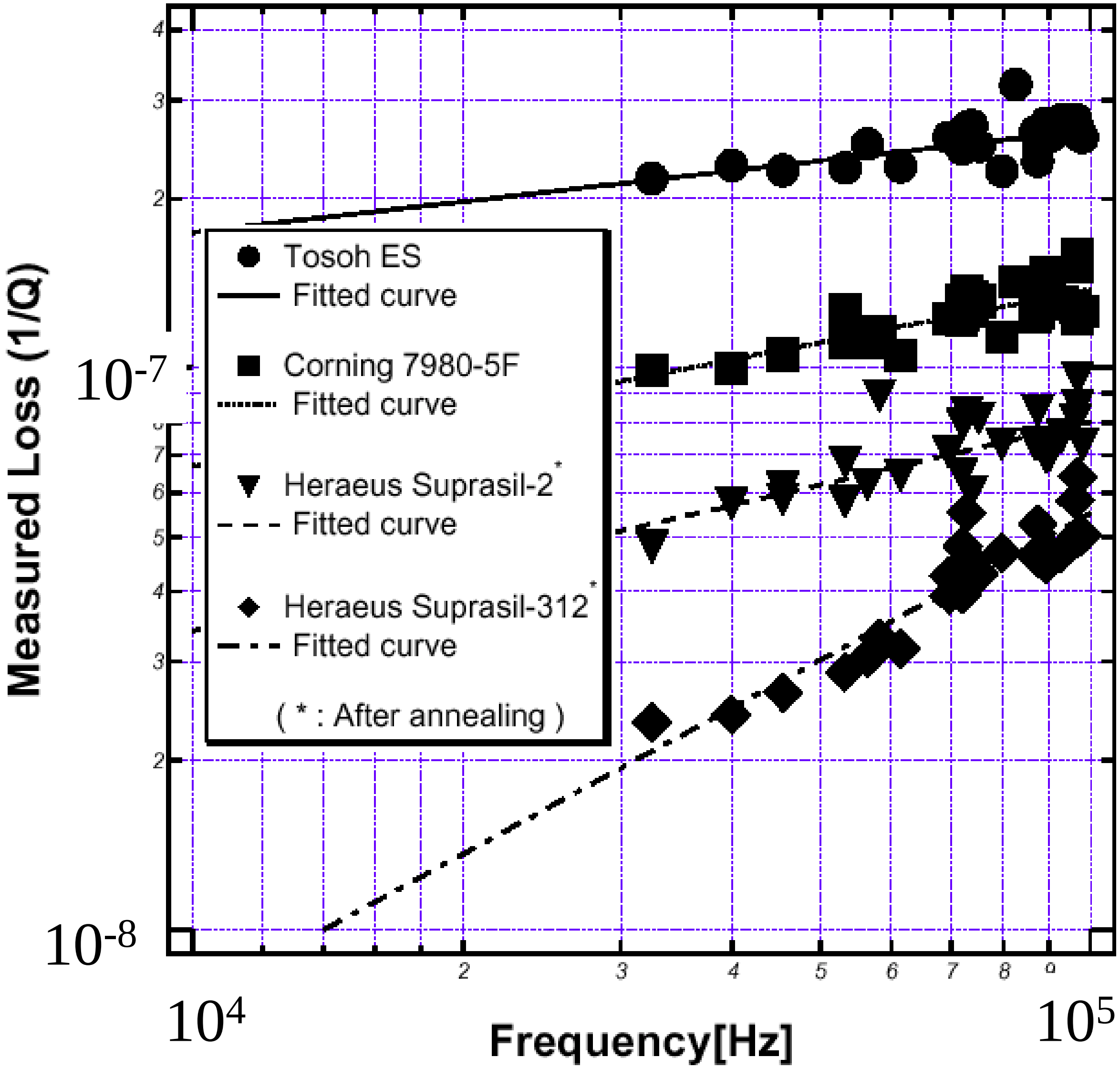
The new TN situation

- Now the bulk TN bottom may have fallen.
- 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)
  - Sapphire show equally high Q factors but, unfortunately, the fact is irrelevant because of the thermo-elastic effect

Kenji Numata results

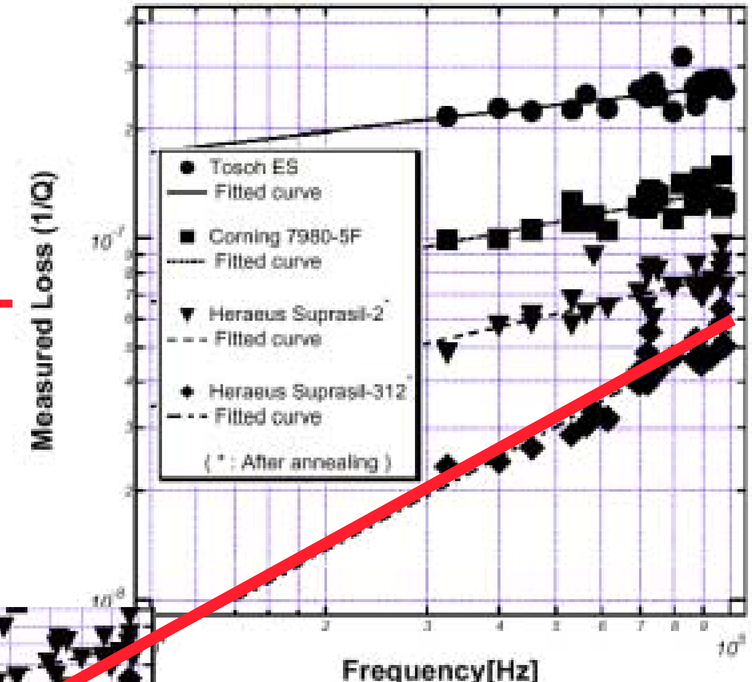
The Q-factor improves at lower frequency

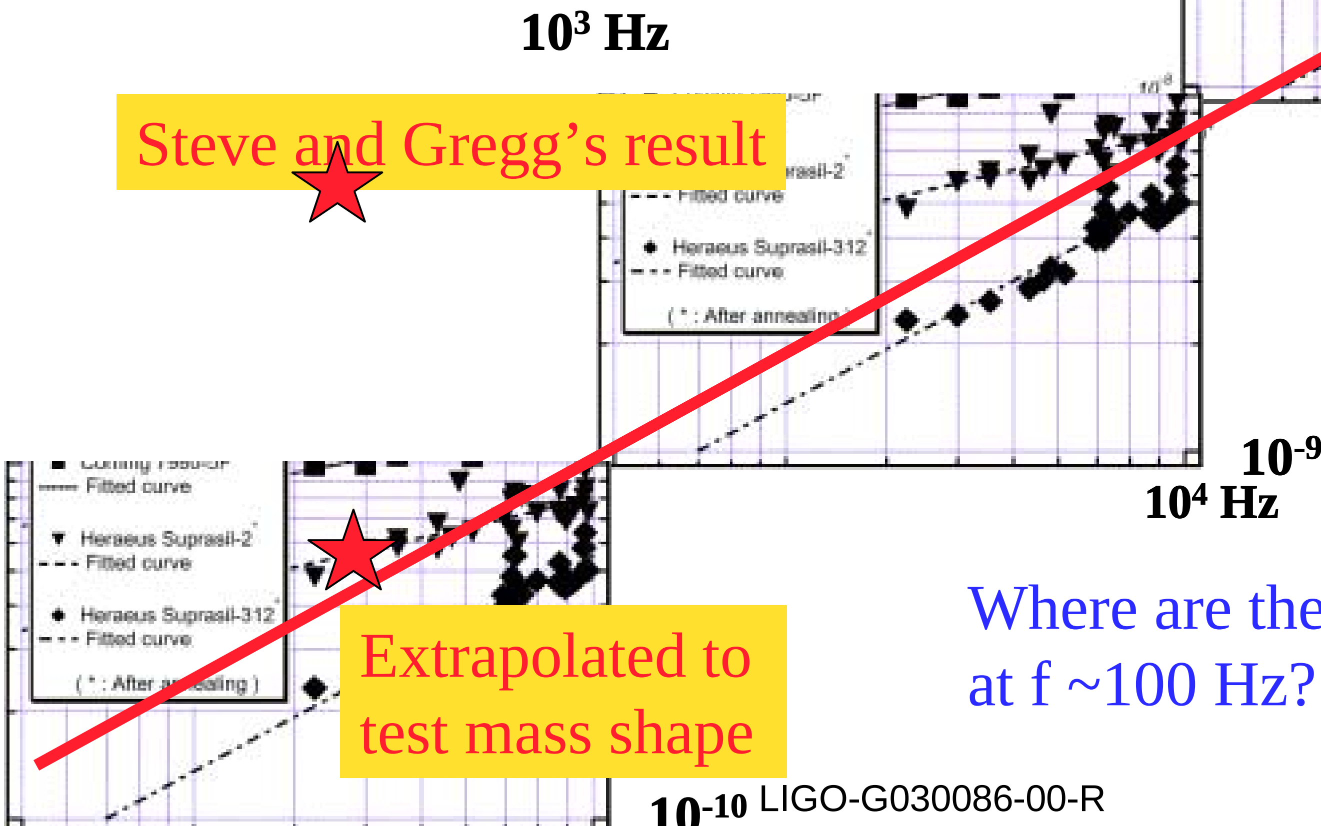
How much better does it gets at 100 Hz?



LIGO

Let me cheat for a moment

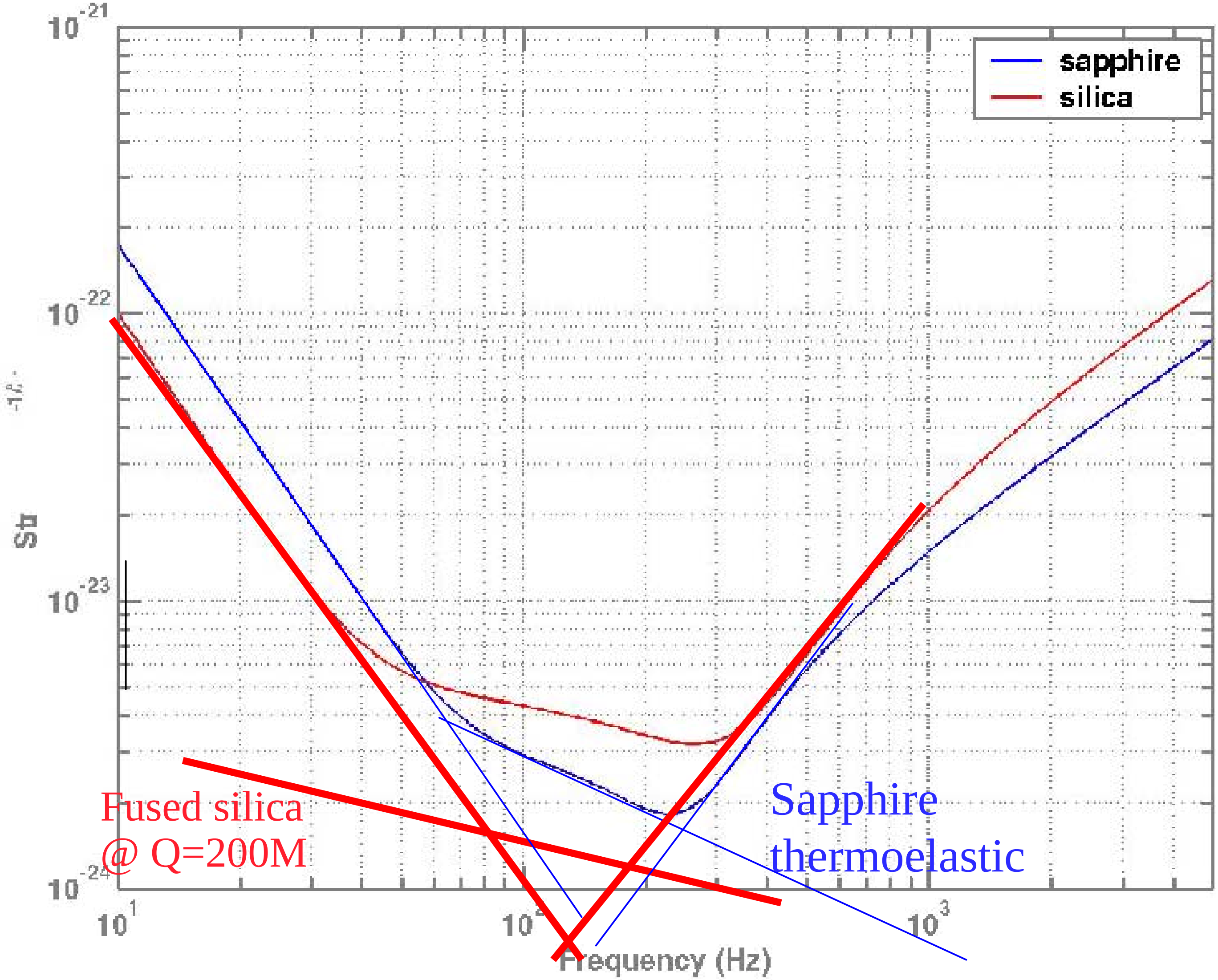




Surface and Coating losses?

Where are the substrate losses at f ~100 Hz?

What can we expect?.



Coating TN Disregarded!

This opens the road
To LF

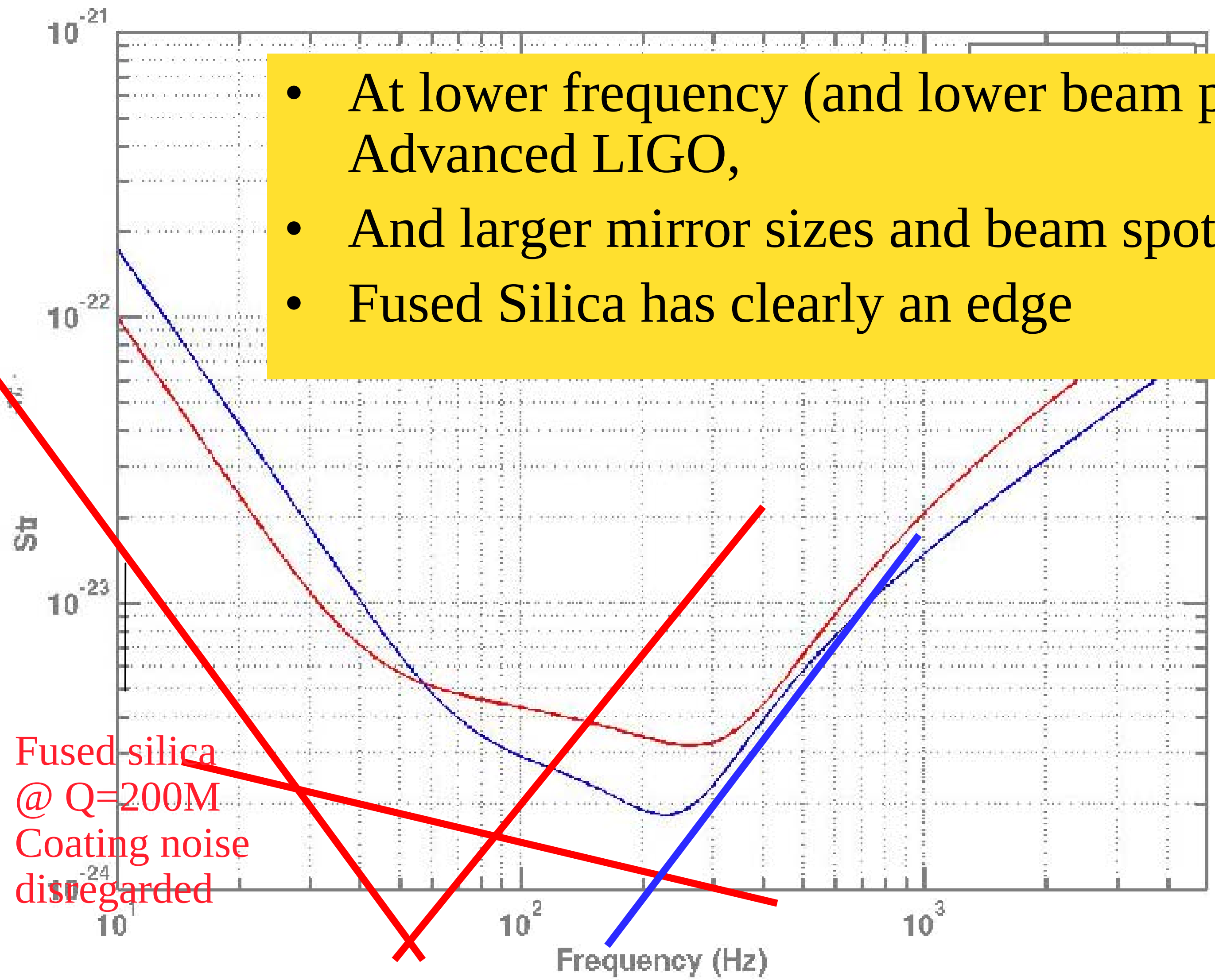
At high F
Power limitations
For Fused silica

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
- 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)$^{-1}$

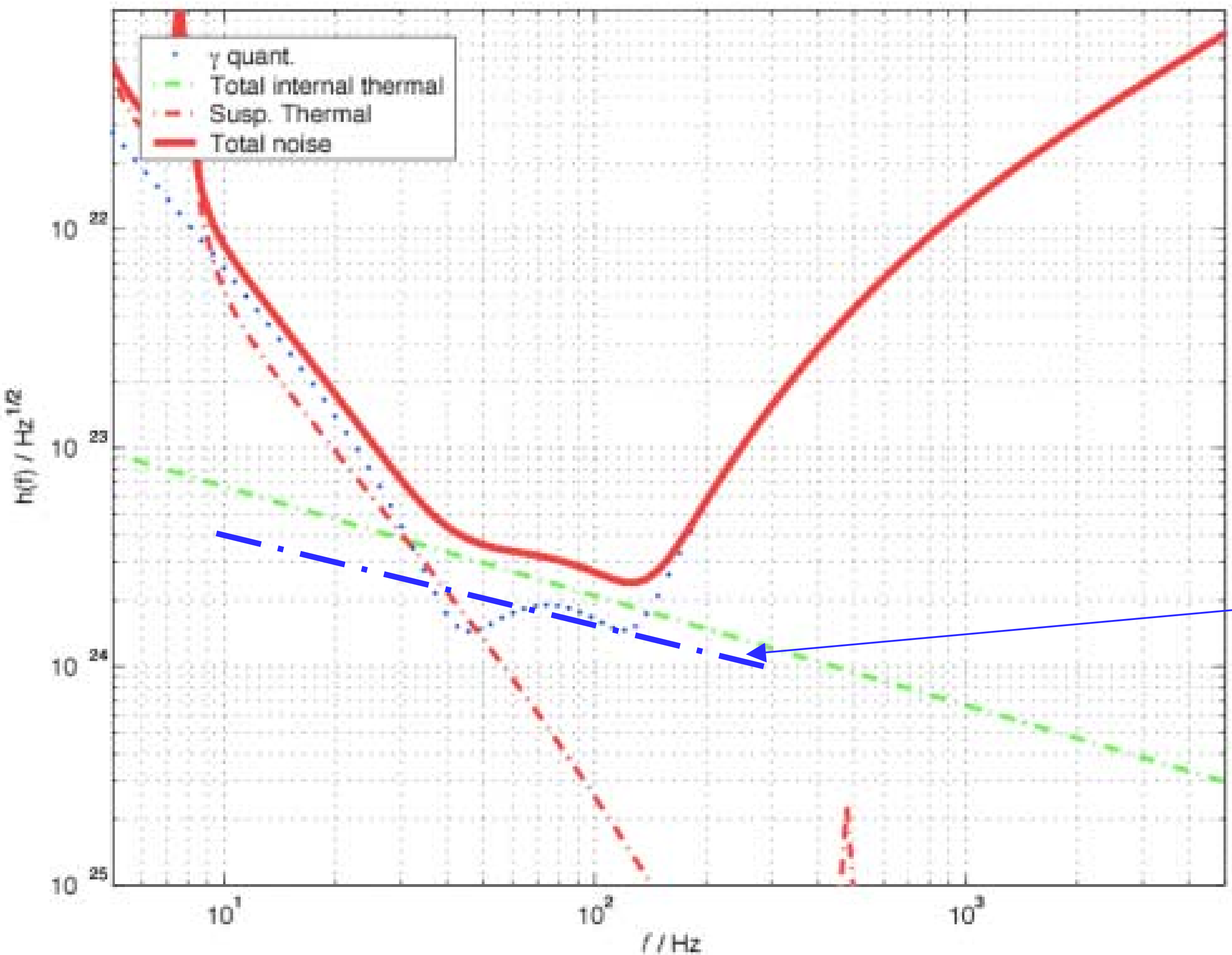
Resuming

- 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

- In dashed: Kenji extimation for same parameters

Cosmic reach

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

Implications

- Need a Virgo-like interferometer to cover the low frequency region at LIGO

- Advantages
- lower frequency region is better covered

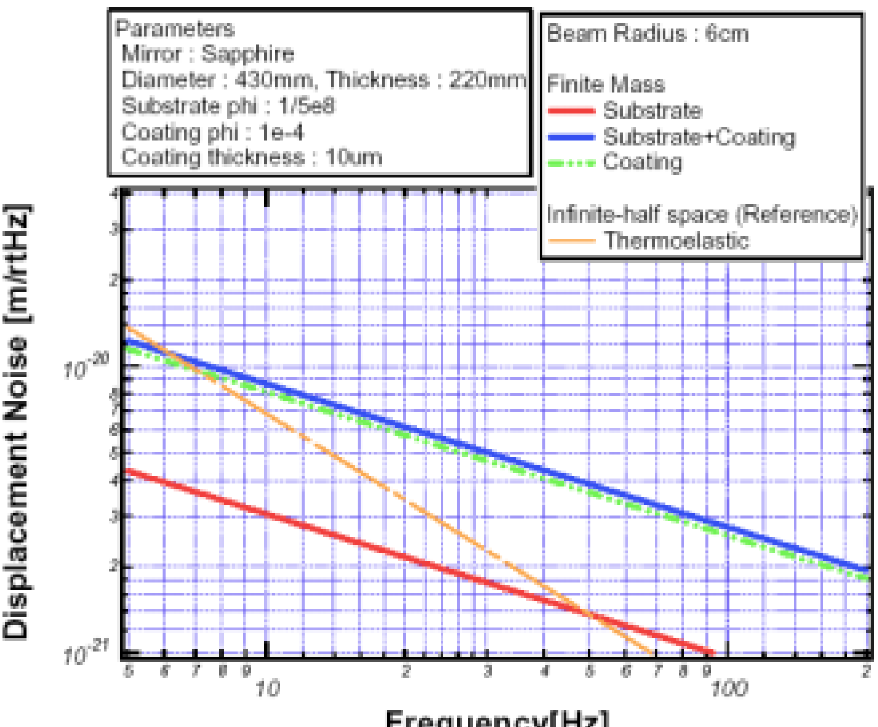
- Splitting up the frequency range between two different interferometers eases lots of design constraints and allows better performance from each

- Advanced LIGOs free to be narrow banded

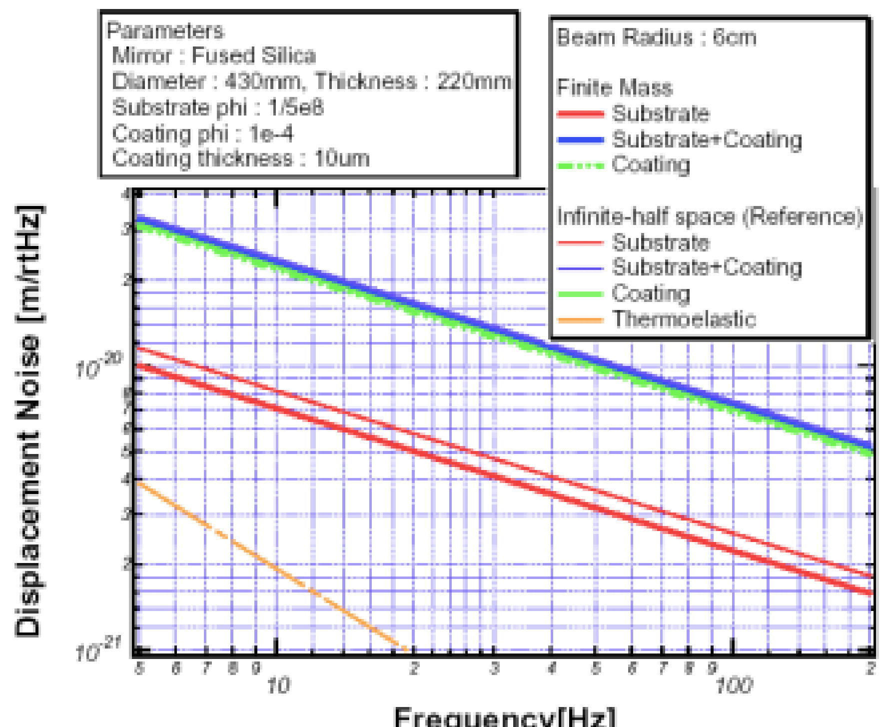
LIGO Is Fused Silica better than Sapphire at low frequency?

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

Data from Kenji



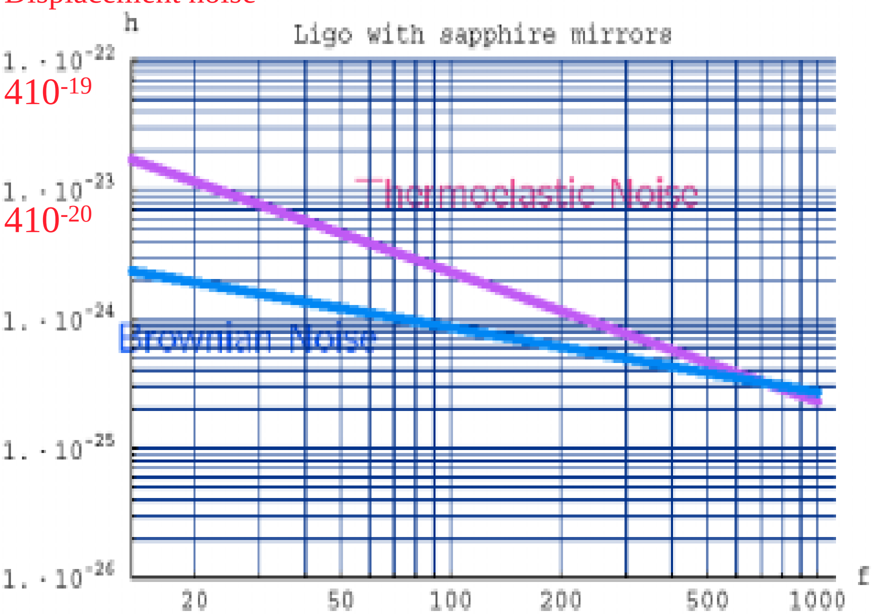
030(



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

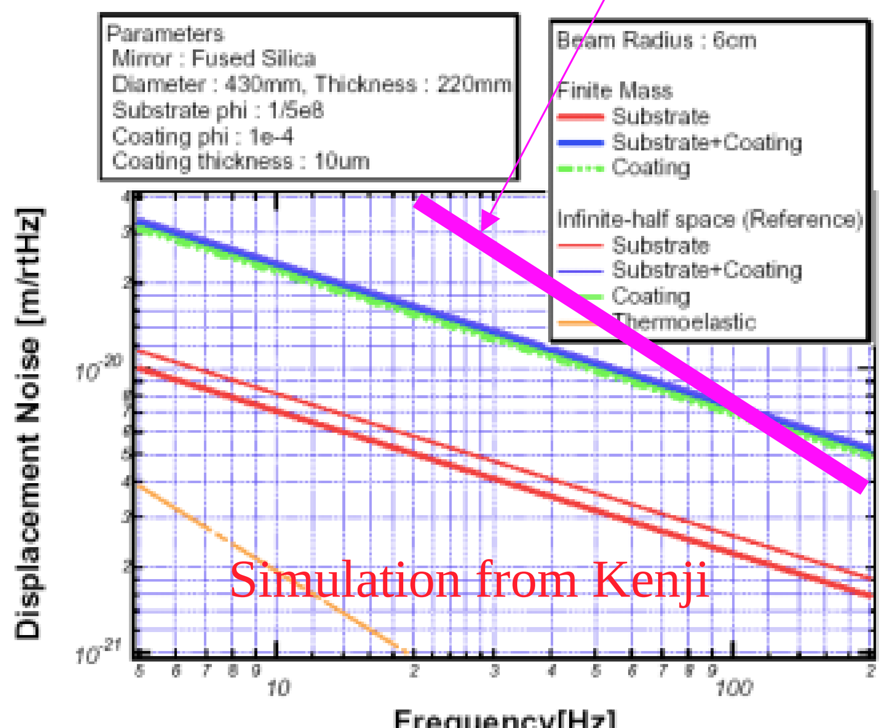
Displacement noise



Adv,LIGO simulation from Erika
6 cm spot $Q_{sapphire} = 2 \times 10^8$

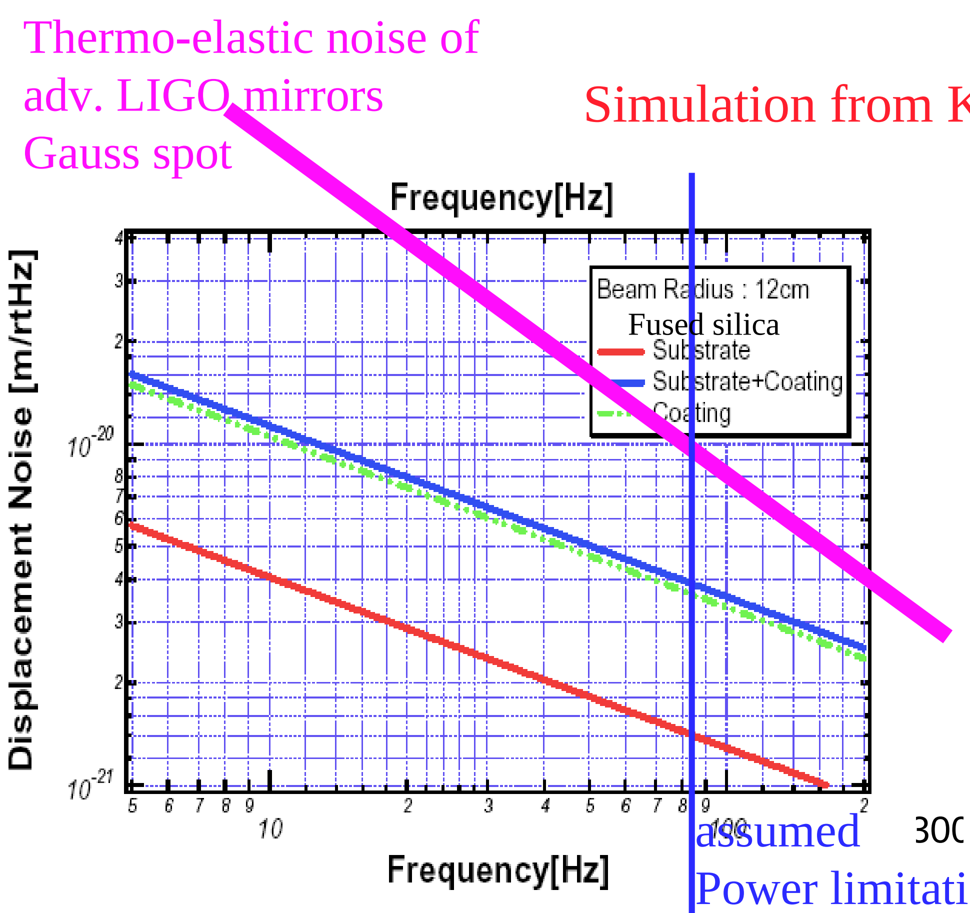
0300

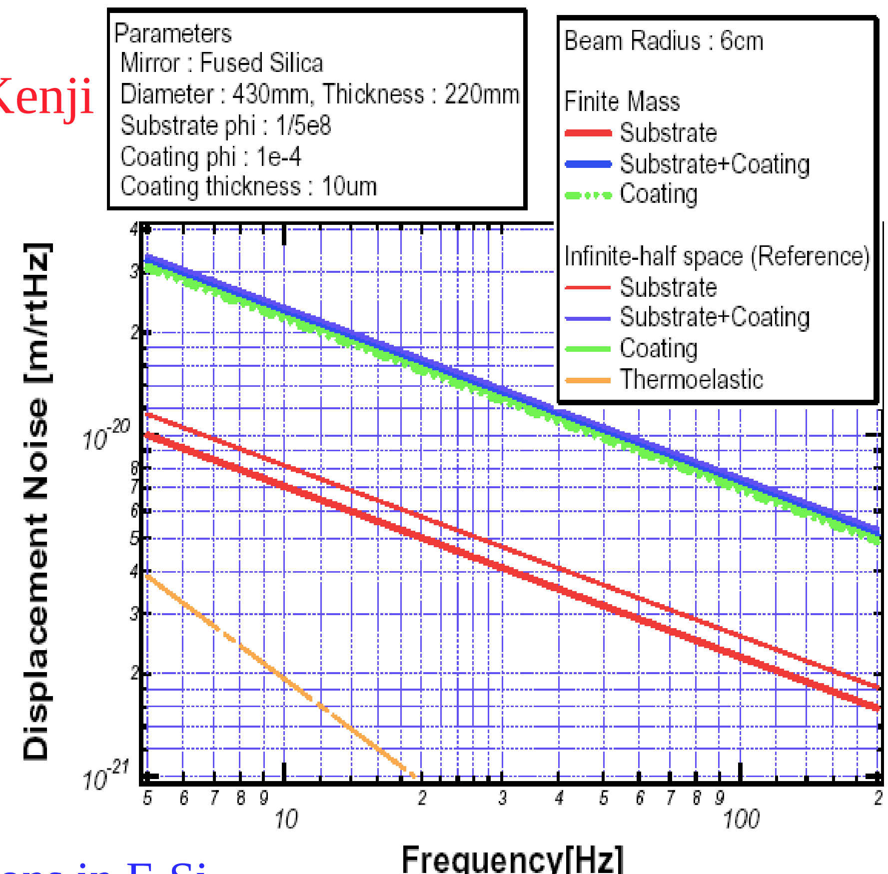
Thermo-elastic noise of adv. LIGO mirrors Gauss spot



Is Fused Silica better than Sapphire at low frequency?

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





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).

How much larger?

- Larger mirrors feasible today
  - 75 Kg fused silica
  - 430 mm diameter
  - 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:

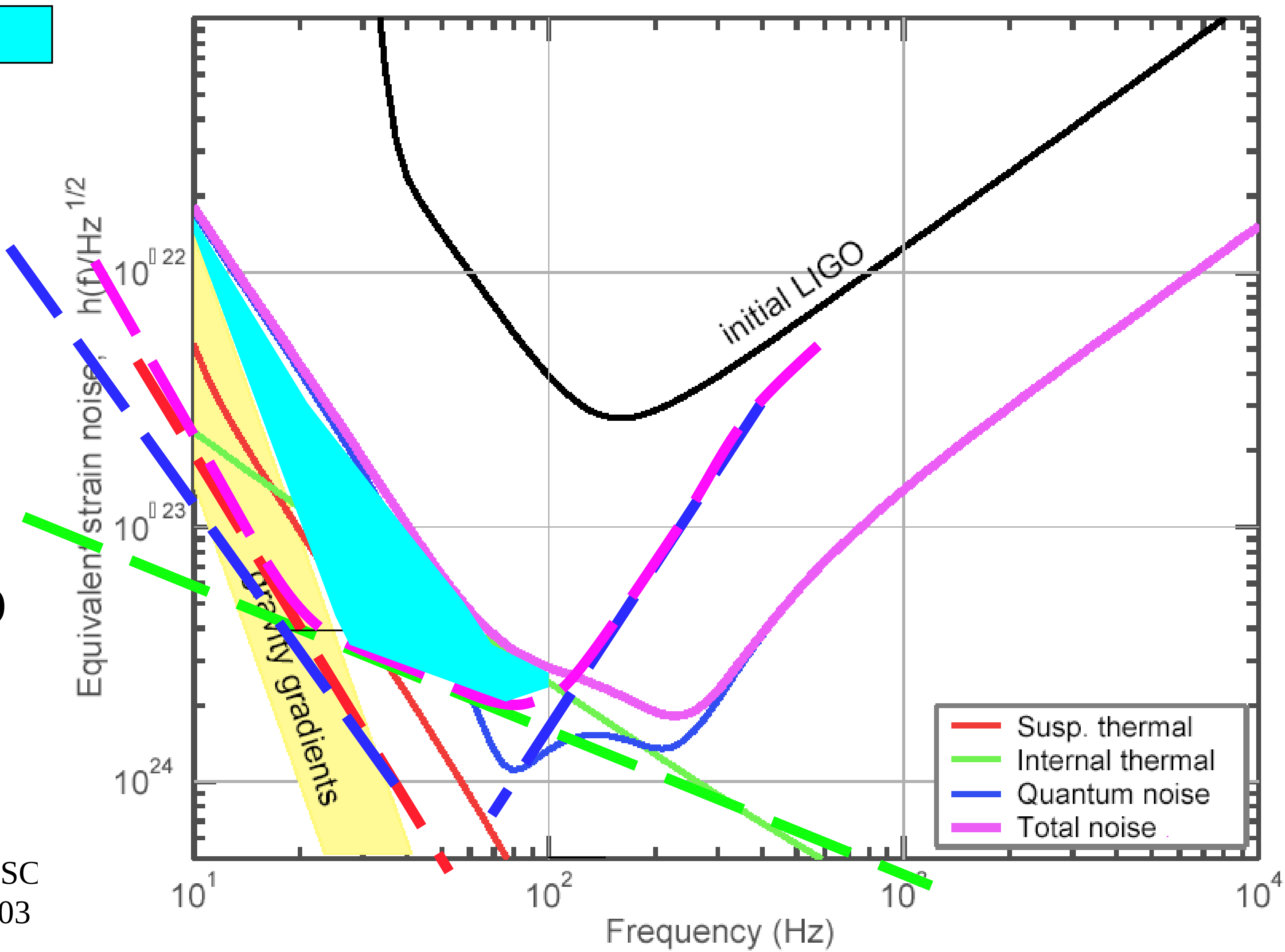
  Clearly for the future will need to go underground

- But there is so much clear frequency range to allow substantial detection improvements

Is gravity gradient going to stop us?

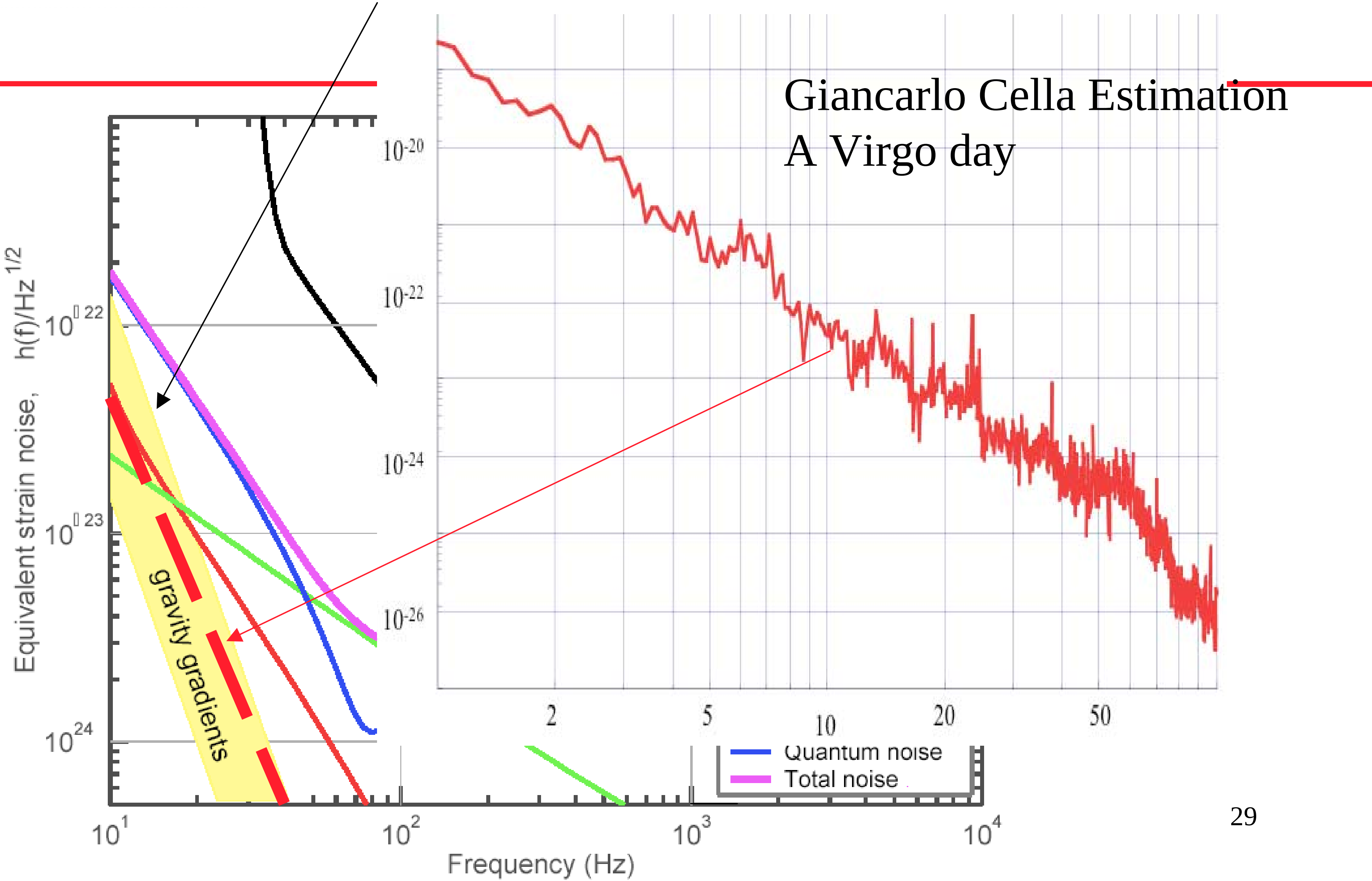
Additional Phase space

Dashed = LF-LIGO
Solid = Adv-LIGO



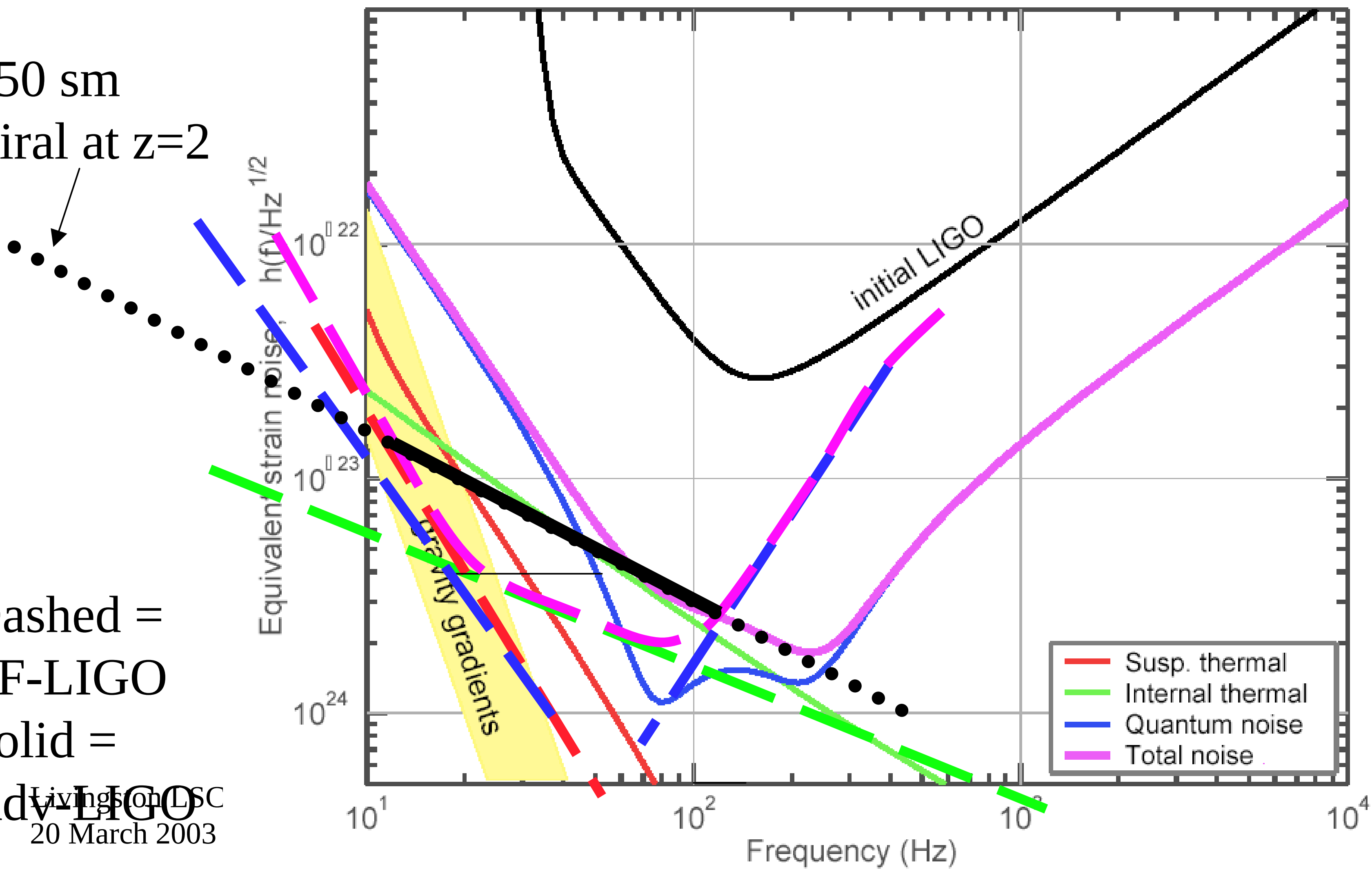
Livingston LSC
20 March 2003

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



Is gravity gradient going to stop us?

50+50 sm inspiral at z=2



Dashed = LF-LIGO
Solid = Adv-LIGO

Comments on BB

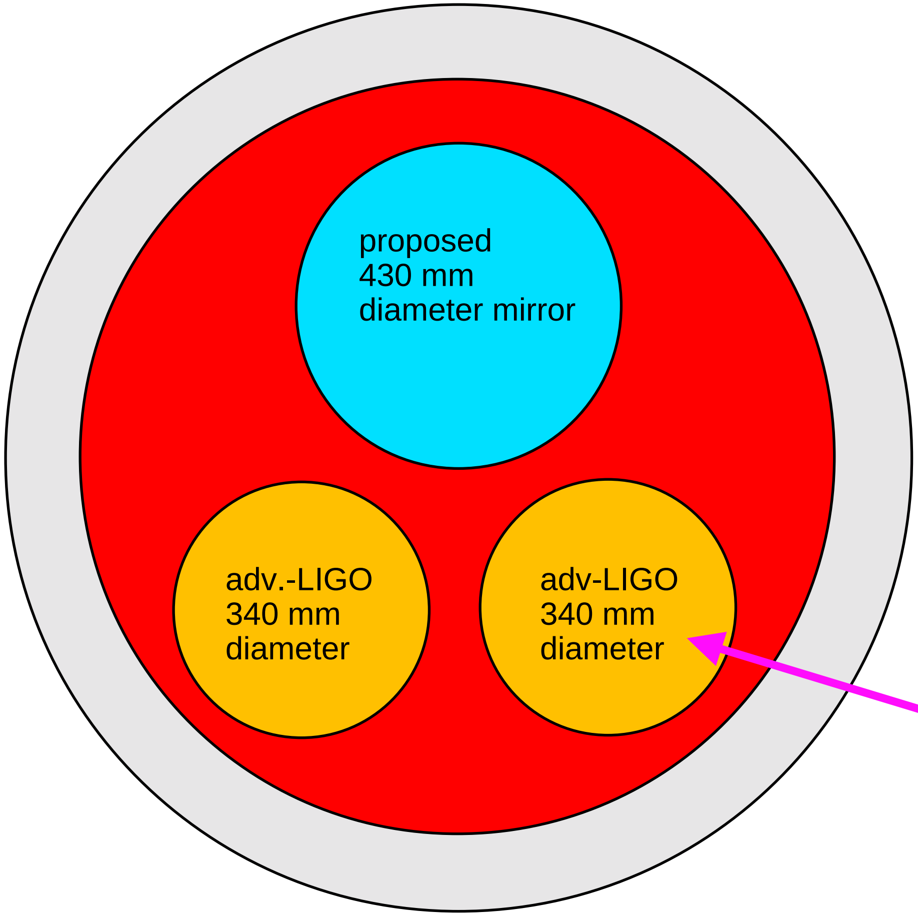
- G.C. Cella evaluations give similar results

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

Comments on BB

- Main contribution to GG is the moving soil/air interface.
- Simple matrix of surface accelerometers can allow up to x10 improvement
- Then more difficult

Can we accommodate a LF Adv-LIGO

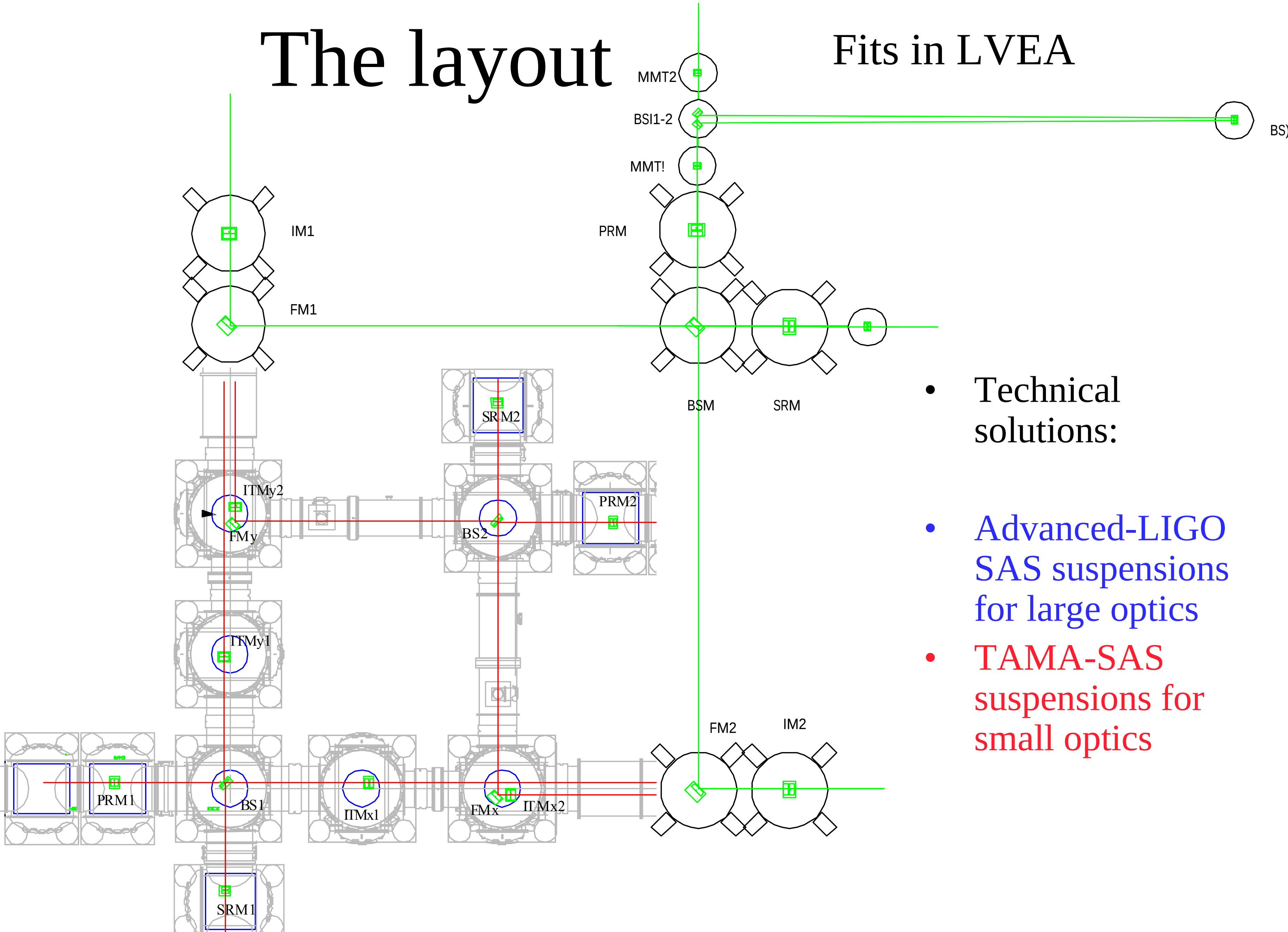


- There is space in the beam pipe just above and forwards of the Adv-LIGO mirrors

- 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 Adv.-LIGO (lower power)
- Seismic Attenuation and Suspensions
  - large optics: already developed for advanced LIGO (downselected)
  - 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 in 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
- 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 before making a new facility, possibly in the LIGO facility.
- Seismic and suspension design using inexpensive, existing, 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

		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	2.0 Meu	Adv. 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	2.0 Meu	Est.
Total per interferometer	15.3 Meu	
Spares (1 laser, 1 set optics, common if two interferometers)	4.5 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 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

Implementation strategy

- Get together 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 somehow, but not completely, independent from LSC

- Go around the world with a hat

  see how many millions of $/Euro and collaborators I manage to collect