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

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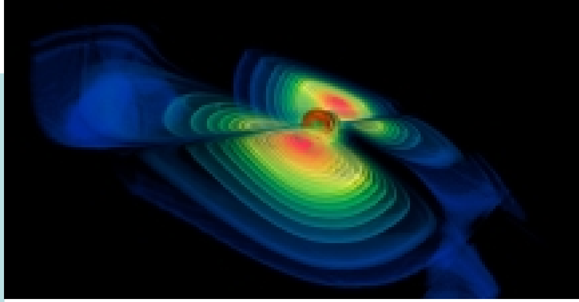
La Biodola 28th May 2003

LIGO-G030292-00-R

- In memory of Gianni
    - » Ω 20th of May 2003

- We conceived this idea together.

New Scientific motivations
Intermediate Mass Black Holes

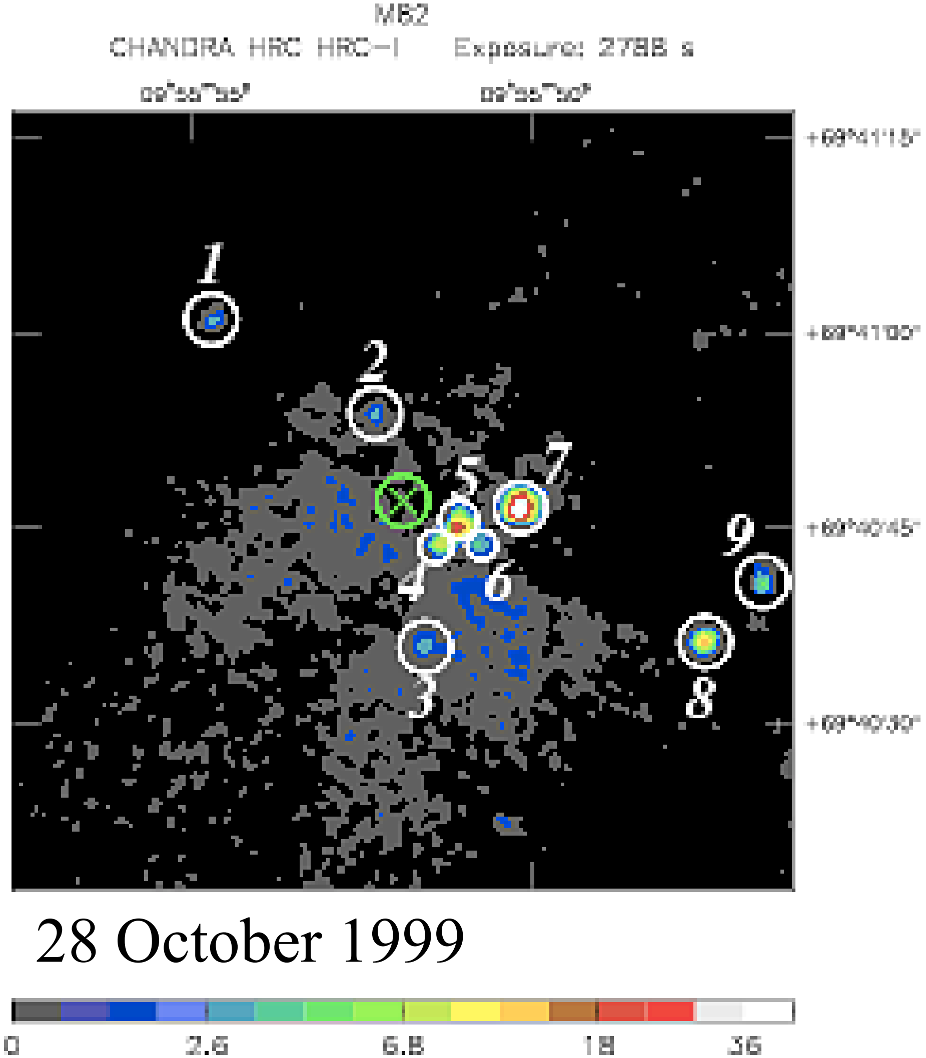


- Advanced LIGO was designed to detect ns-ns inspirals, mergers and inspirals
- New X-ray and optical observations performed after the design of Adv-LIGO indicate the presence of
- **new Lower Frequency GW sources**

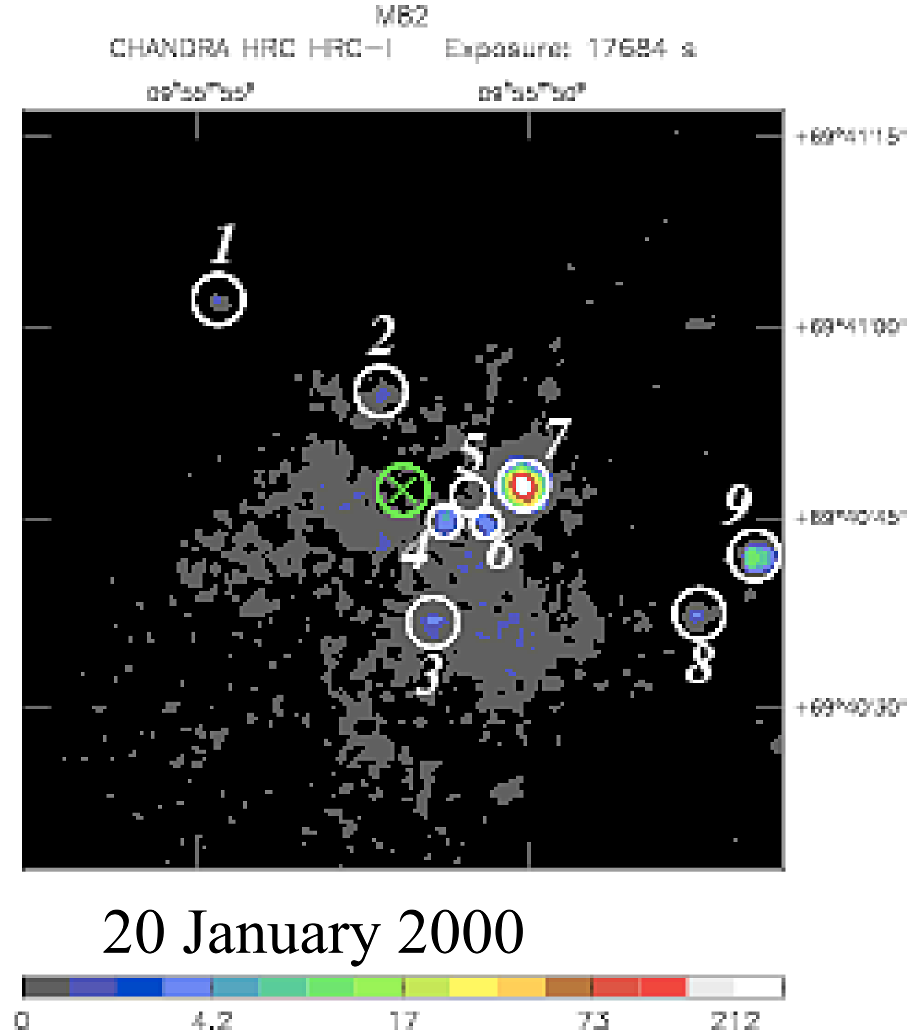
- Data summary from Cole's Miller, based observations of galaxies and globular clusters

- 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

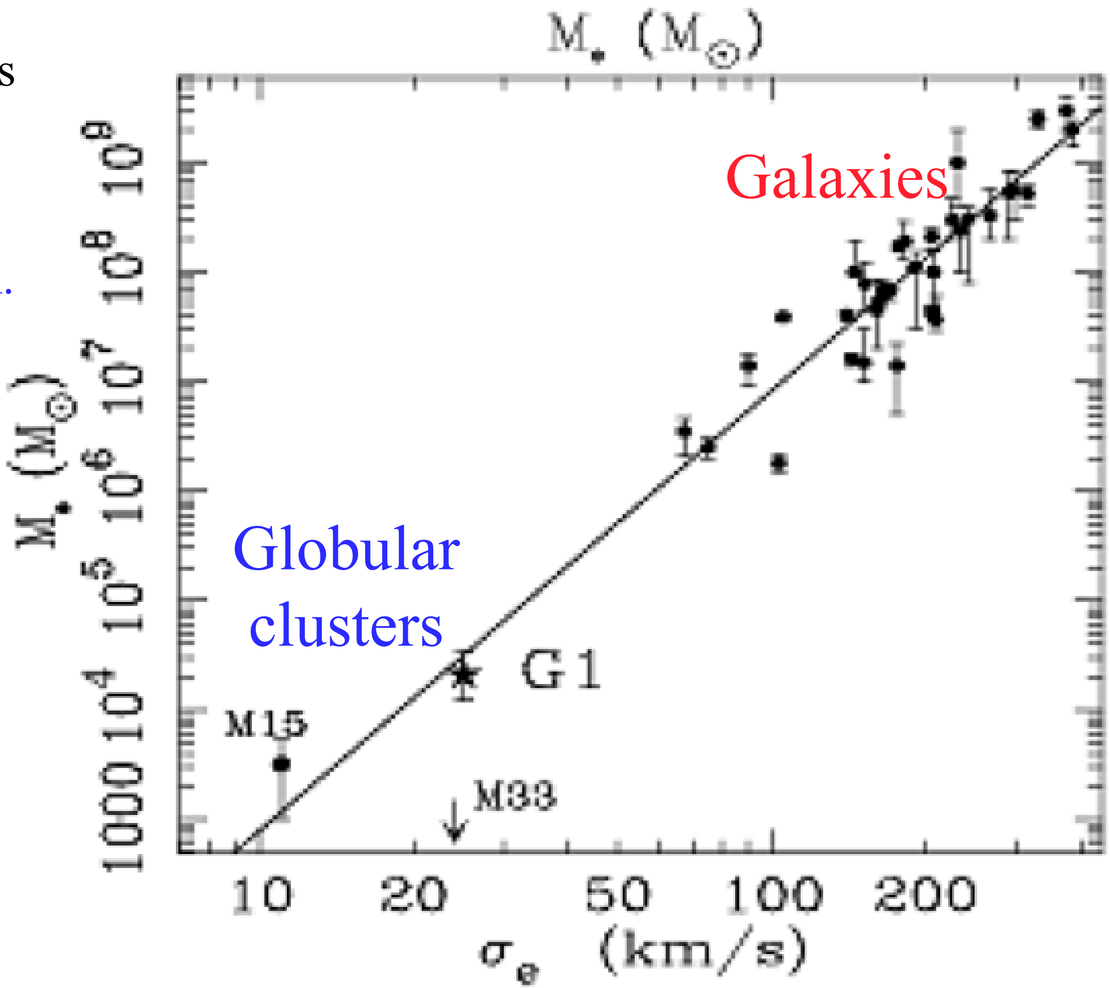


20 January 2000

Concurring evidence of IMBH

Central mass M - σ relation

- 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)



Observational facts

- Observed x-ray sources in globular clusters
- Eddington mass of sources 30~10^3 s.m.
- Emission implies a feeding companion
- So many couples imply high density in globular clusters (optically observed 10^6 stars/pc^3)

Optical observations: inspirals may be occurring at a catalyzed pace

- **Systems high high mass slow down by dynamical friction** (τ=10~50My) and sink to the center of the cluster
  where they are induced to merge

1. Density of ~ million stars per cubic parsec optically observed
2. Encounters tend to equalize kinetic energy, heavy masses get slowed
3. Mass segregation occurs

- Smaller stars collect **kinetic energy and angular momentum** and **export** them to the periphery or out of the cluster

- Encounters of binaries with singles tend to tie and tighten up the bigger guy and fling out the smaller of the three

Optical observations: Swirl in clusters

- **Swirl** is observed in the core stars around central hidden mass
- But
- Frictional braking would rapidly eliminate the observed swirl!
- Explanation (controversial but growing evidence)
- Core stars around central BH cluster can soak angular momentum while hardening massive BH binaries or clusters at the center

- Is swirl a catalyzed inspiral Smoking gun?

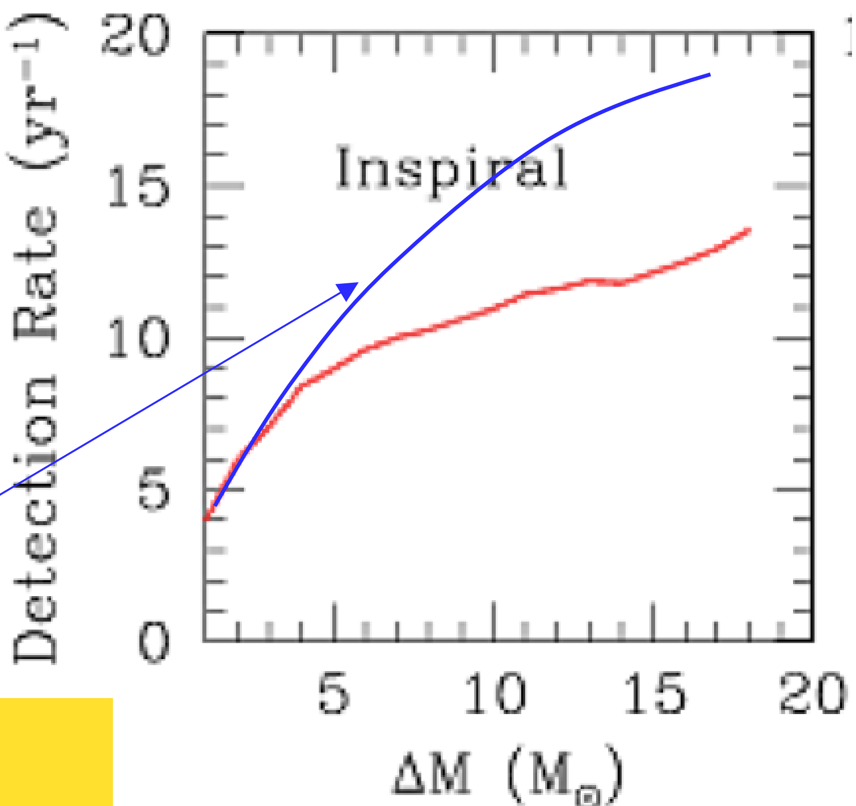
- Coalesce may ensue at rapid rate! ~ 10My not Gy !!!!

Signal Detection

- The G W signal from the above mentioned and other sources will be detected with Interferometric Detectors
- Study of Full Relativistic regimes (BH merger and ringdown) require sensitivity in the 100 Hz region.
- Detection of the signal in the inspiral phase require sensitivity in the 10 Hz region.

Predicted inspiral rate

- Assuming accretion of objects starting from a 10 M_{sun} BH
- Estimation for Adv-LIGO
- Adv-LIGO would preferentially see the initial accretions
- LF-GWID would see many more of these because of smaller effect of the merger frequency cutoff



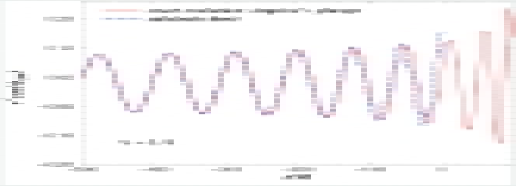
•Cole Miller

•Very preliminary

LIGO

Template difficulties

- Templates allow optimized filter matching only up to a certain frequency
- Templates fail close to mergers thus strongly reducing the S/N ratio
- The higher the inspiral mass, the lower the cutoff frequency thus reducing the template effectiveness and the effective detection range



- Number of templates must grow from

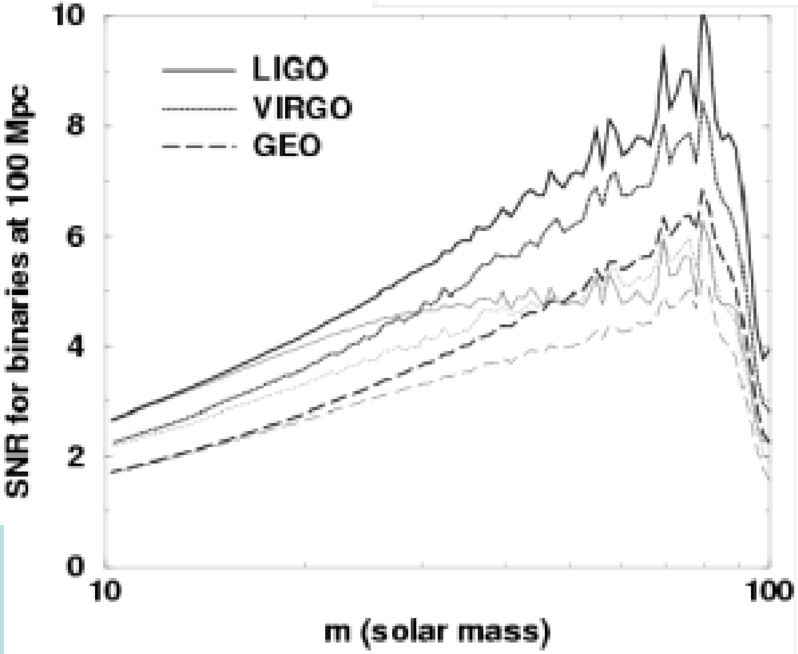
25 to 10,000 (not counting BH spins)

to recover the S/N from the last few orbits

- **Unfeasible without triggering**
- LF-GWID can trigger at LF
- Can apply all templates on

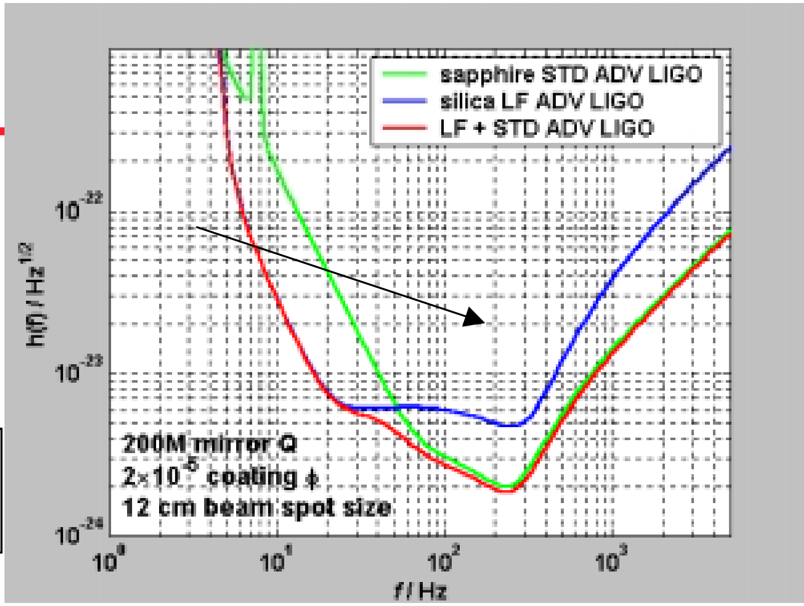
follow-up at HF measurements

of mergers and ringdowns



B. Iyer, T. D'Amour,
B.S.Sathyaprakash, P. Jaranowsky

In numbers



Integrating signal to noise with template, on full spectral range	Lost S/N
up to f_{max}=99 Hz/(1+z)*(20 M_{sol}/M)	

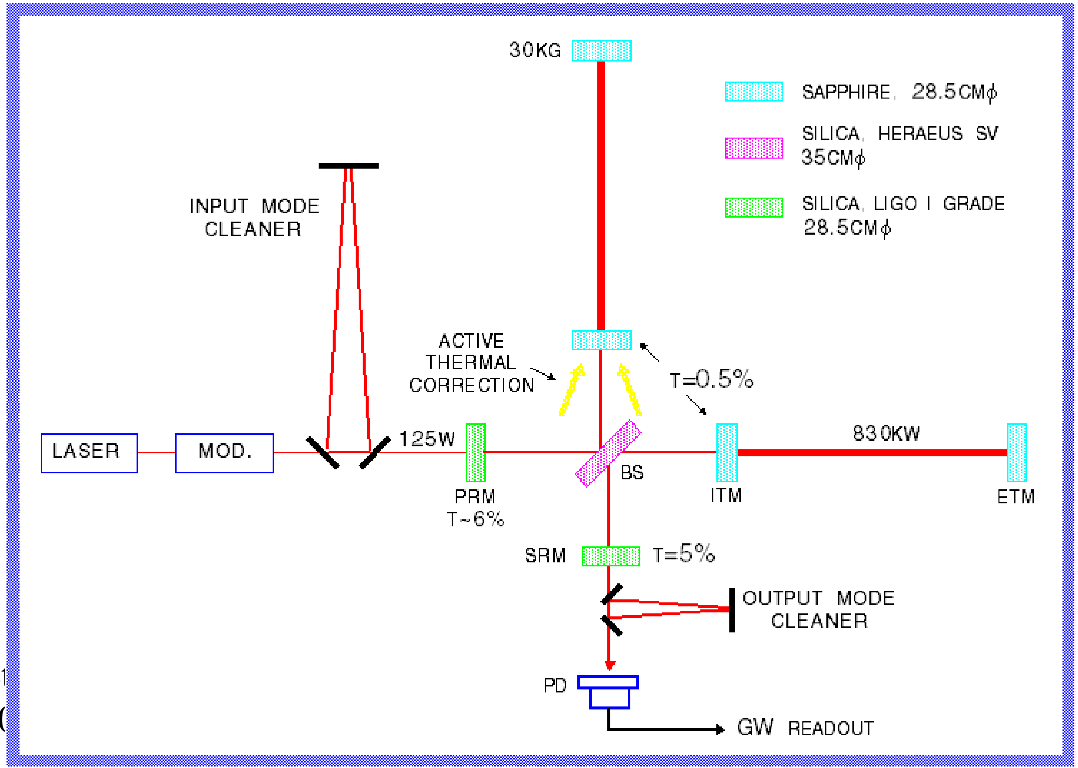
Inspiral mass	ADV-LIGO HF		LF GWID (w. SR)	
1.4+1.4	4.3	0 %	4.5	0 %
	4.4		4.6	
10+10	21.8	20 %	22.8	0 %
	17.5		22.9	
30+30	54.6	80 %	57.1	14%
	10.7		49	
50+50	83.5	95 %	87.4	31 %
	4.1		60	

Technical feasibility

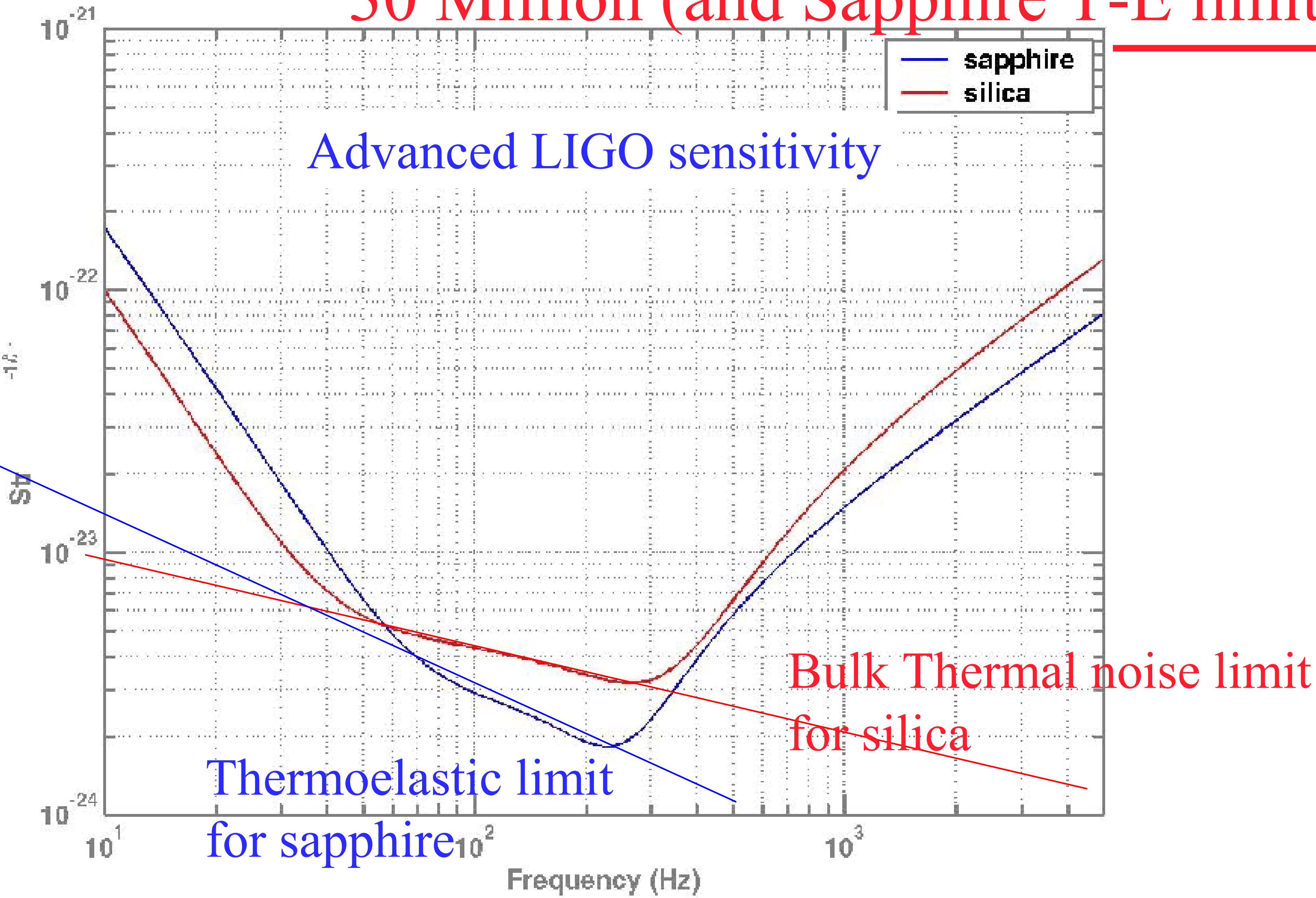
- **Low frequency GW sensitivity** is of great **astrophysical interest**
- Advanced LIGO is foreseen and optimized to cover HF signals should not be diverted
- **Cannot be optimized for LF without some significant changes**
  - Reduce beam power and different finesse (rad. Pressure)
  - Use Fused Silica instead of Sapphire mirrors (bulk TN)
  - Use Supersized, double weight, mirrors (coating TN, rad. Pr)
  - Use Double length suspensions (susp. TN)
- Need separate and specialized Low and High Frequency interferometers

Building a LF optimized interferometer

- Choice of materials and technologies



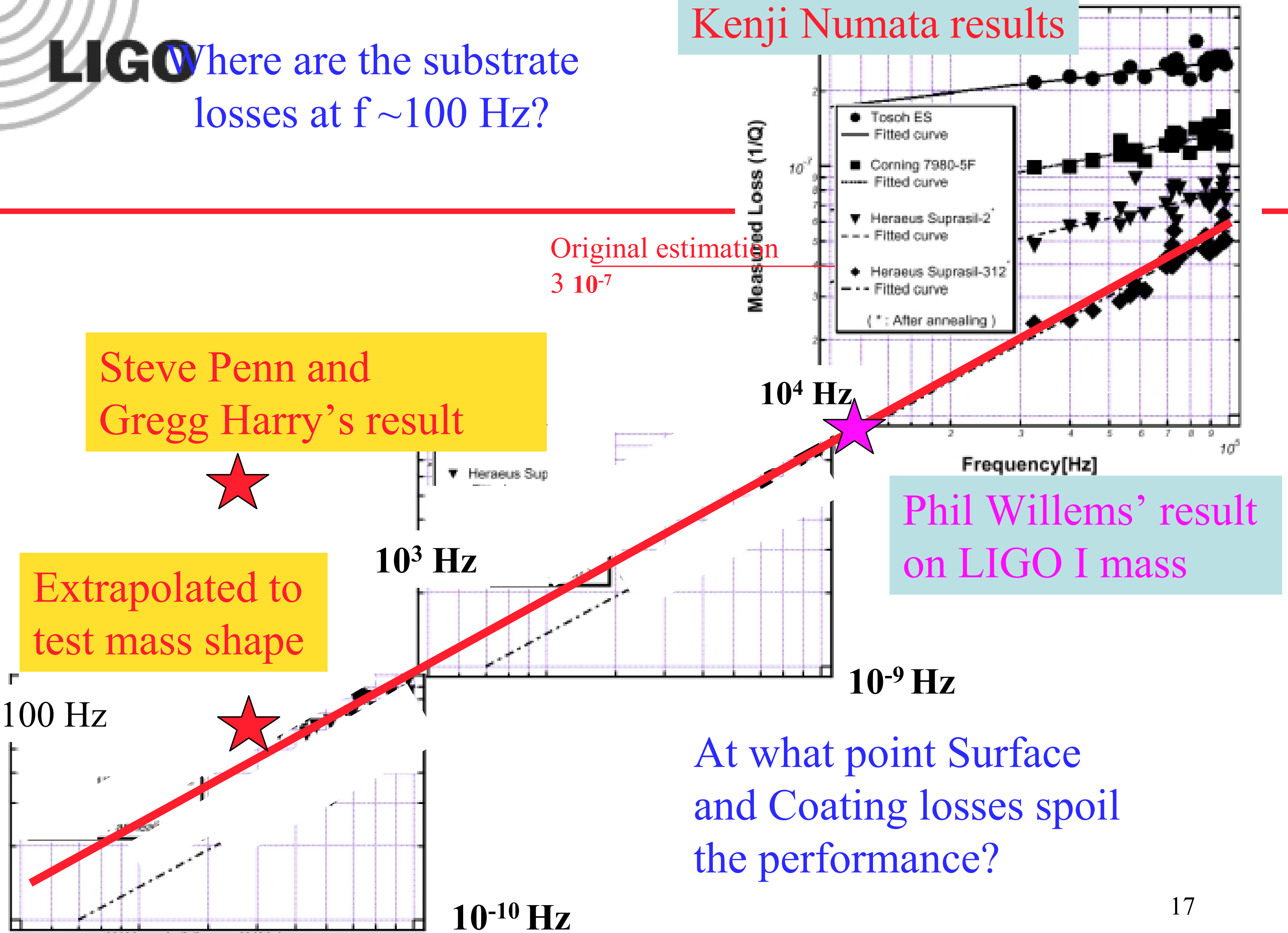
This curve was drawn when Fused silica was believed to have a Q-factor of 30 Million (and Sapphire T-E limited)



The new TN situation

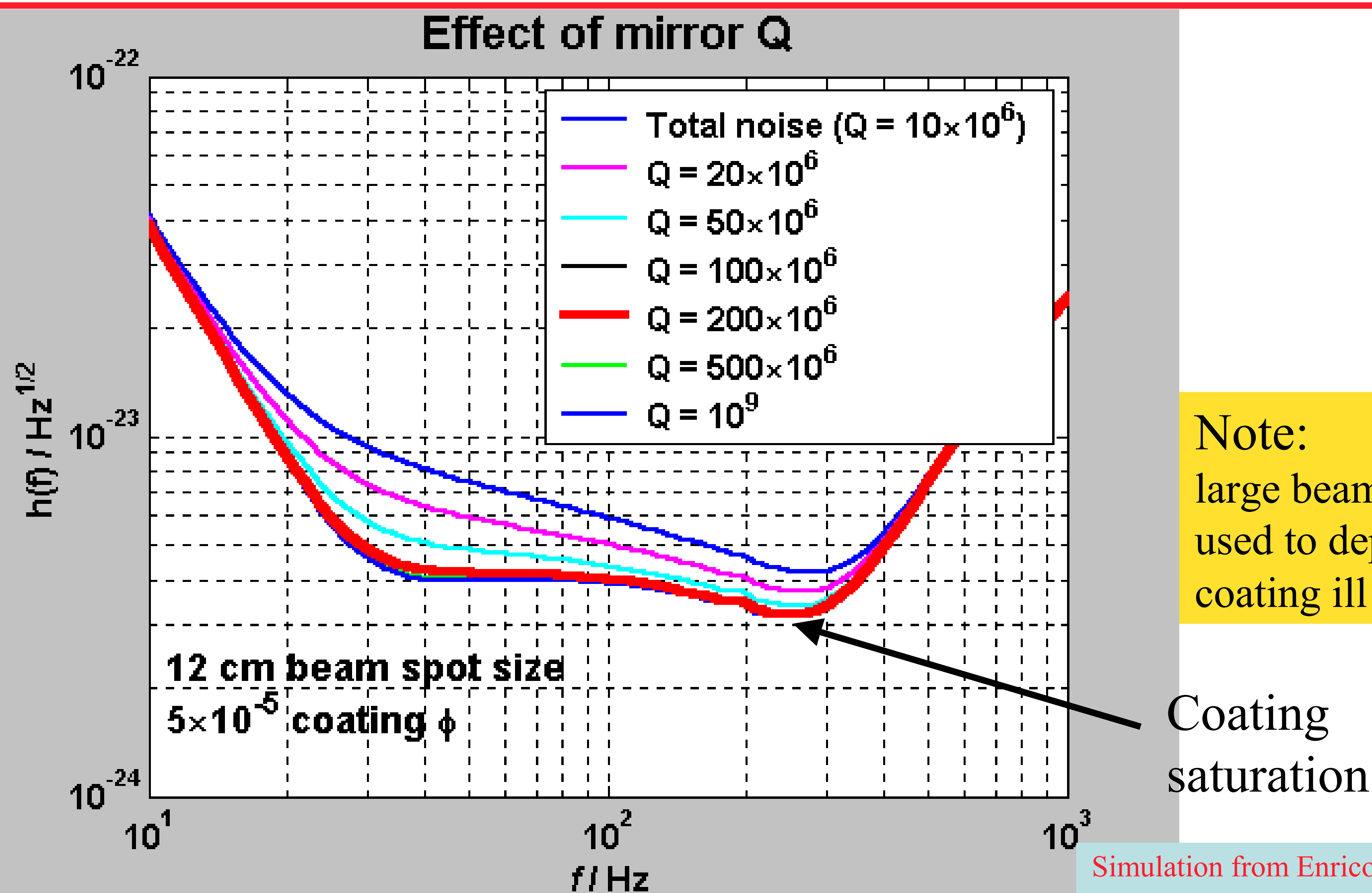
- Now the bulk F.S. TN floor is crumbling.
- Three new measurements:
- Kenji's Q- factor measurements
- Gregg Harry, Steve Penn observed Fused Silica Q factors at and above 200 Million
  - Note: Sapphire show equally high Q factors but, unfortunately, the fact is irrelevant because of the thermo-elastic effect
- Phil's measurement of old LIGO test mass

Where are the substrate losses at f ~100 Hz?



At what point Surface and Coating losses spoil the performance?

What can we expect?
Effect of substrate's Q factor.



Note:
large beam size used to depress coating ill effects

Simulation from Enrico Campagna

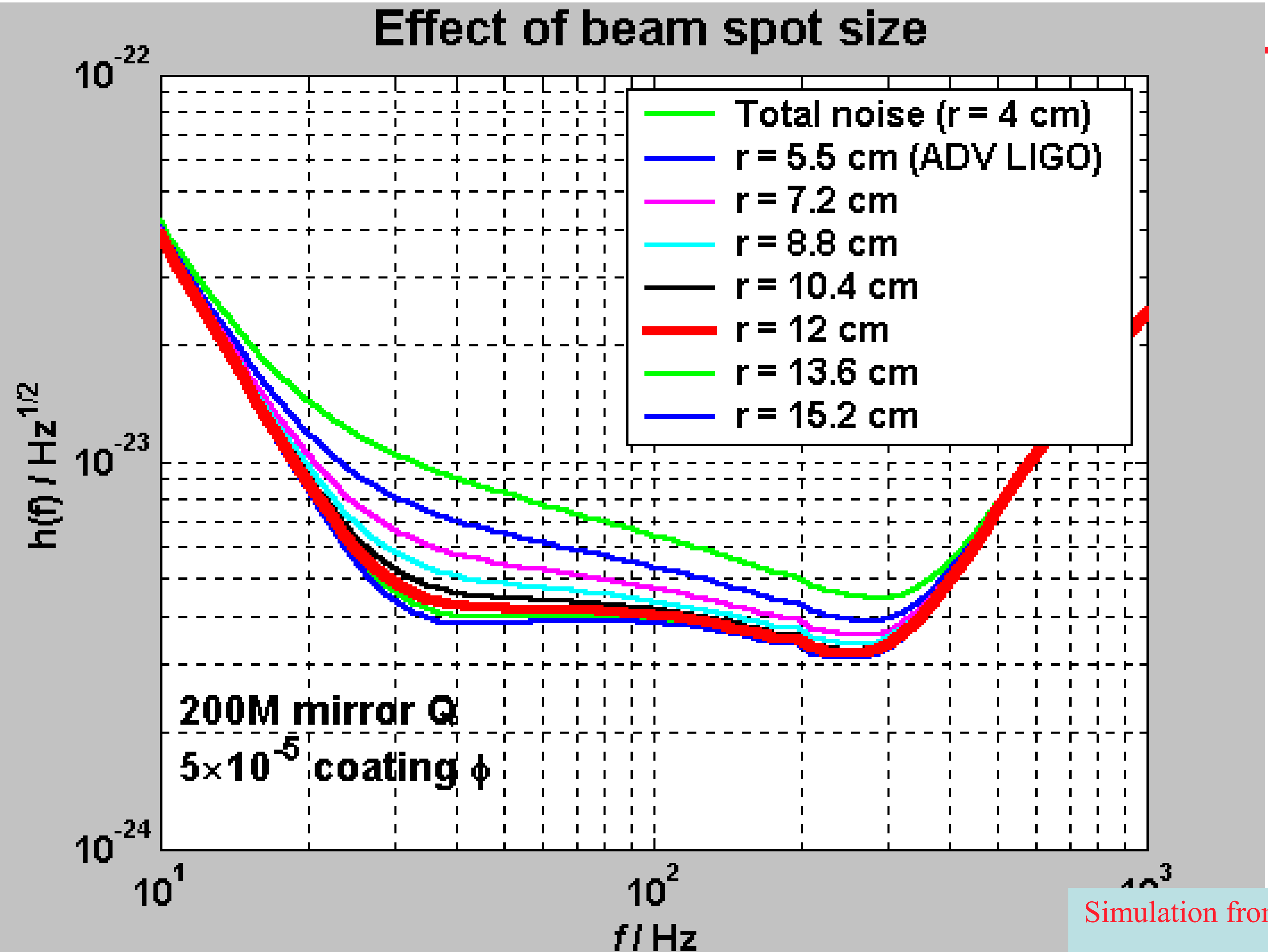
Implications at L.F.

- **Fused silica is the ideal choice for LF interferometers**

- The thermal noise limit from coating thermal noise.
- Solutions
- Advanced coatings may be in future
- Large spot sizes possible now
  - Spot size effects:
  - Bulk thermal noise ~ (spot diameter)$^{-1/2}$
  - Coating thermal noise ~ (spot diameter)$^{-1}$
  - Thermo-elastic noise ~ (spot diameter)$^{-3/2}$

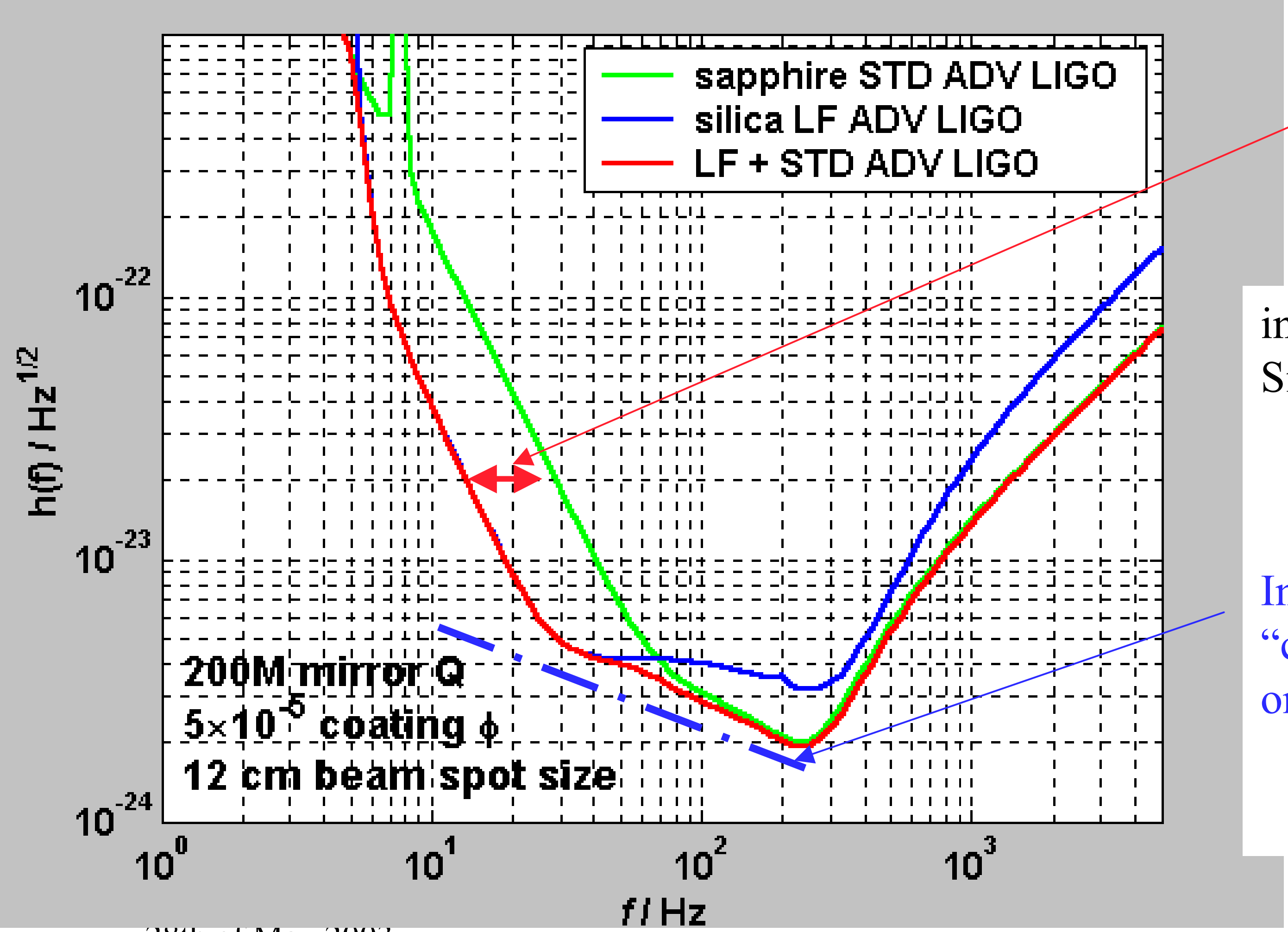
- Large spot sizes are required

Effect of spot size



Simulation from Enrico Campagna

Bench and Kenji's estimations



x 2 gain from longer Suspensions, higher mass, and lower stored beam power

in solid Gregg and Enrico's Simulations on Bench

In blue dashes Kenji's "complete" TN simulation on Ansys (10^{-4} coating ϕ)

Signal to noise at 200 MPc

Inspiral mass	AdvLIGO S/N	LF LIGO S/N	Tandem S/N
1.4+1.4	4	4.4	>6
30+30	51.5 ★	57.1 ★	>80
50+50	78.9 ★	87.4 ★	>120

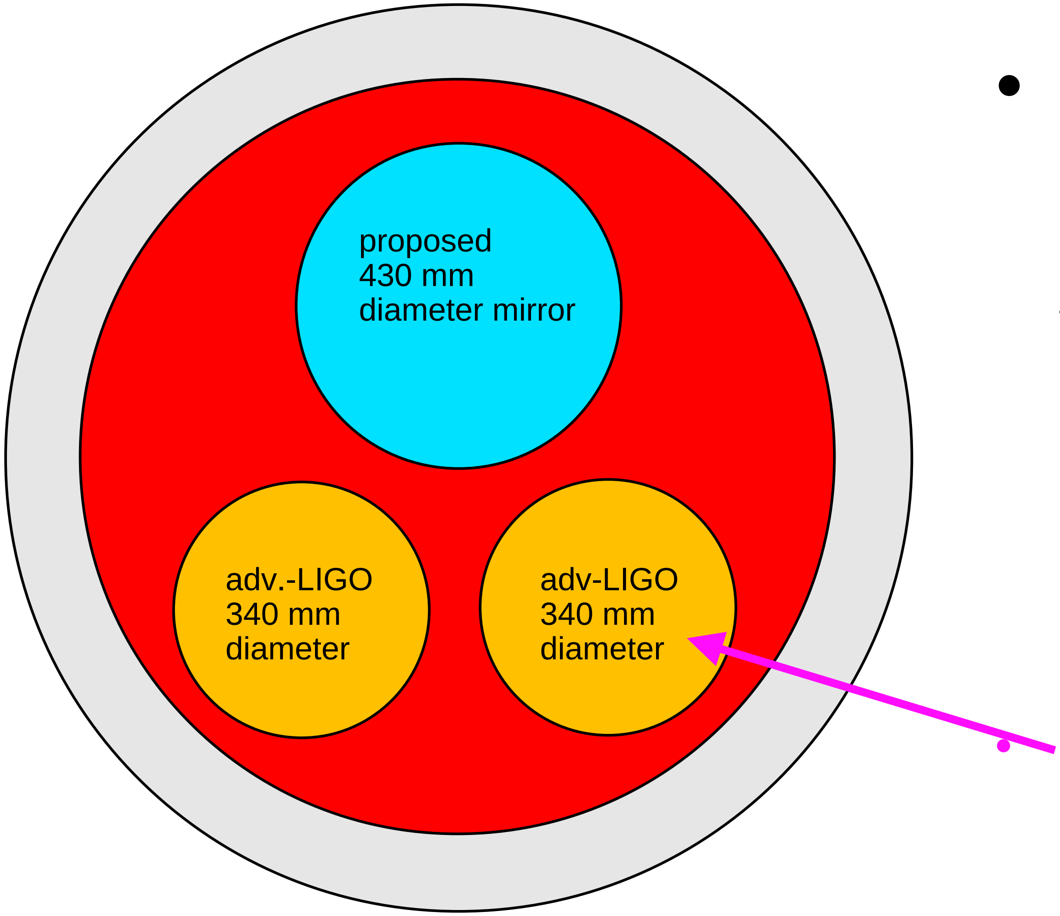
Tandem configuration allows much larger S/N (between √2 [equal range IFO] and 2 [fully separated f ranges]) !!

★ Assuming templates applicable throughout the frequency range, see Iyer et al. **afterLF trigger and follow up at HF to <u>recover full S/N</u> for high mass objects merging in Adv-LIGO bandwidth**

At LF twice or more the effective signal to noise =>

⇒ ~1 order of magnitude in observed volume for high mass obj.s

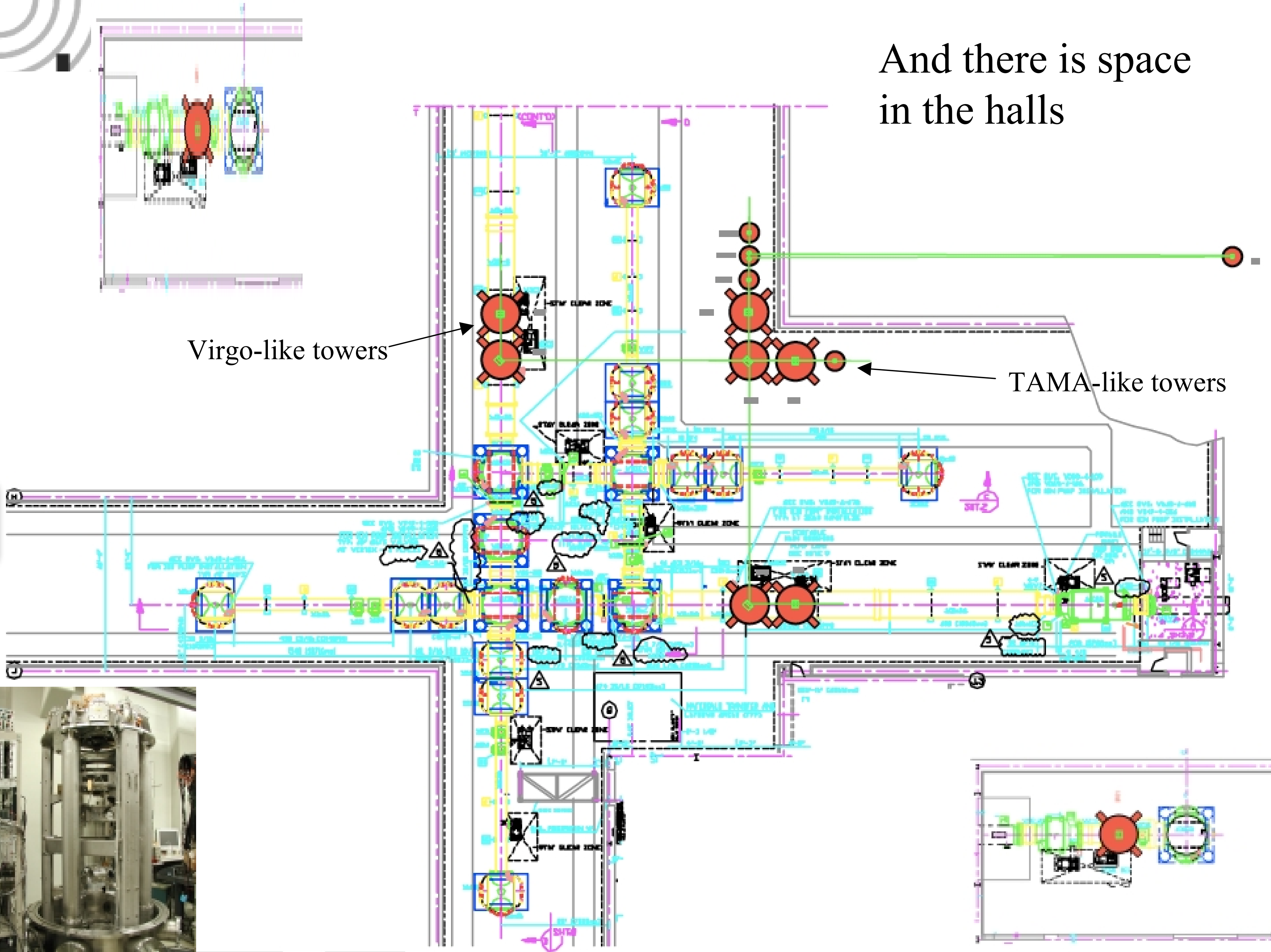
Can we accommodate a LF interferometer next to Adv-LIGO



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

- Advanced LIGO nominal beam positions

And there is space in the halls



Resuming

- A Virgo-like interferometer to cover the low frequency region at LIGO would be greatly desireable
- Advantages
- Lower frequency region is better covered (Explored volume >*3)
- 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 allow disentangling final inspiral and merge signals and recover S/N

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**
- Optimized LF sensitivity allows
  - study of the genesis of the large galactic BH believed to be central to the dynamics of galaxies and
  - mapping the globular clusters in our neighborhood
  - Enhancement of the performance of both Virgo and LIGO
- At LIGO with roughly a 10% increase of the projected costs the explored volume in the Universe can be increased by at least a factor of 3 for ns-ns inspirals, and much more for heavier mass objects.
- Similarly, but at a higher cost, at Virgo

LIGO

The End !

- Frequently Asked Questions (for offline discussions)
  - Comments for LIGO
  - Comments for Virgo
  - Are wide beams feasible?
  - Is gravity gradient a problem
  - Do we need a new design?
  - When and where to implement LF-GWIDs?
  - Can we afford LF-GWID?
  - LF-GWID Characteristics
  - How big a mirror can we make?
  - Is Virgo an optimized LF-GWID?
  - Is there space in Virgo for a HF companion?
  - What would be the interest for Virgo in LF companions?
    - Are LF interferometers in the LIGO facilities adequate LF companions for Virgo
    - Should EGO push to build Low Frequency companion(s) for LF coincidence detection in the LIGO facilities?
  - Effect of spot size and better catings
  - More on event rates

Comments for LIGO

- Adv-LIGO is designed for broadband 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!

Comments for Virgo

- Virgo needs matching LF coincidence partner(s) to optimize its science goals
- Adv-LIGO is unlikely to be optimized for the low frequency range and would profit greatly both in reach and scientific scope from LF companions
- Building the LF GWIDs in the LIGO vacuum pipes is cost effective
- The relative orientations makes that two Virgo-likes in the LIGO pipes allow **both** coincidence detection **and** coverage of both emission polarizations.

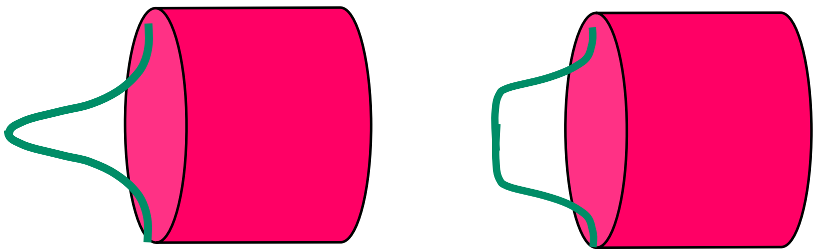
LIGO

How to reduce the coating noise problem

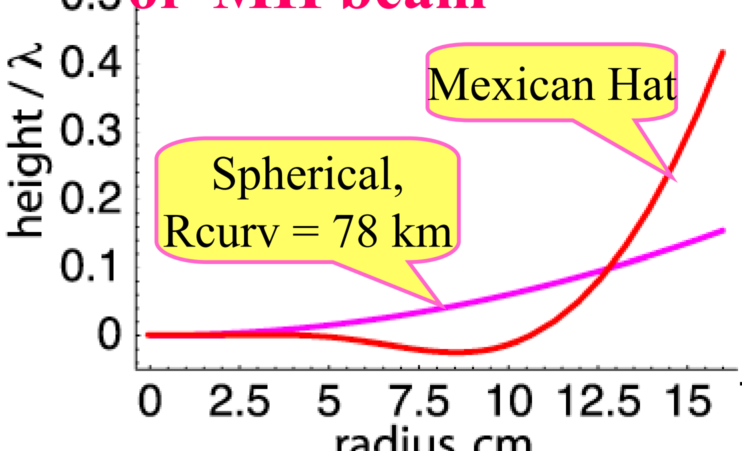
Mexican hats proposed by Kip Thorne et al. are a solution

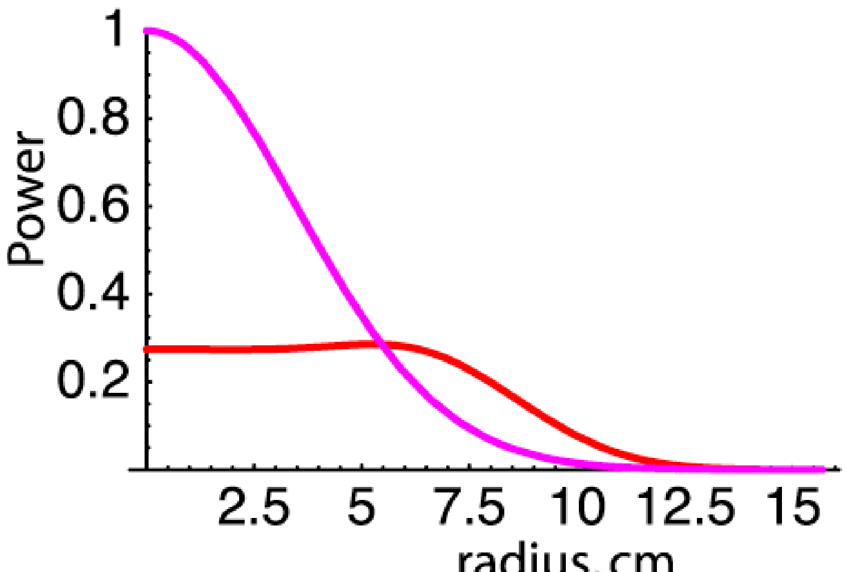
http://www.ligo.caltech.edu/docs/G/G030137-00/

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



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





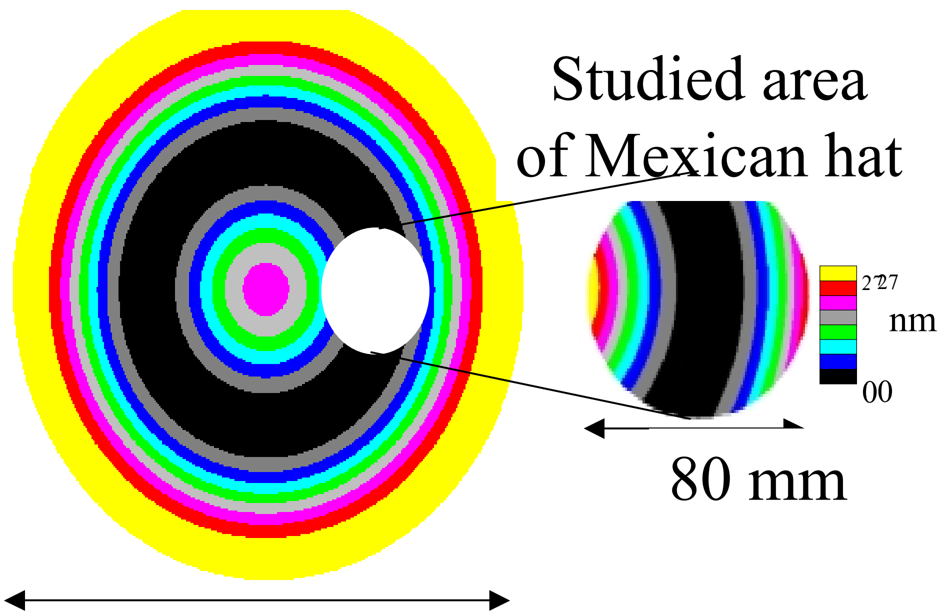
Mexican hats are feasible

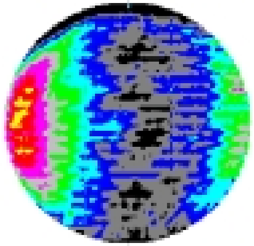
And J.M. Mackowsky shows that they are relatively easy to make

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

Theoretical mexican hat

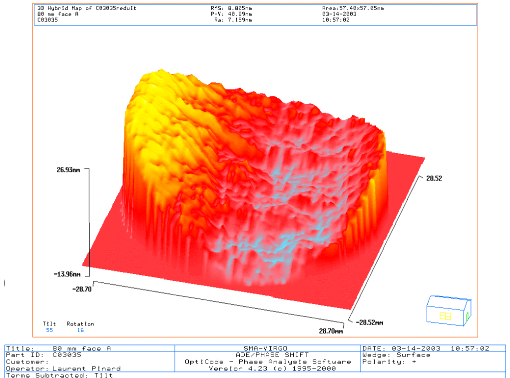
Top view of a Mexican hat

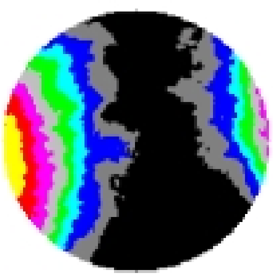




Simulation of the corrective coating

Experimental mexican hat





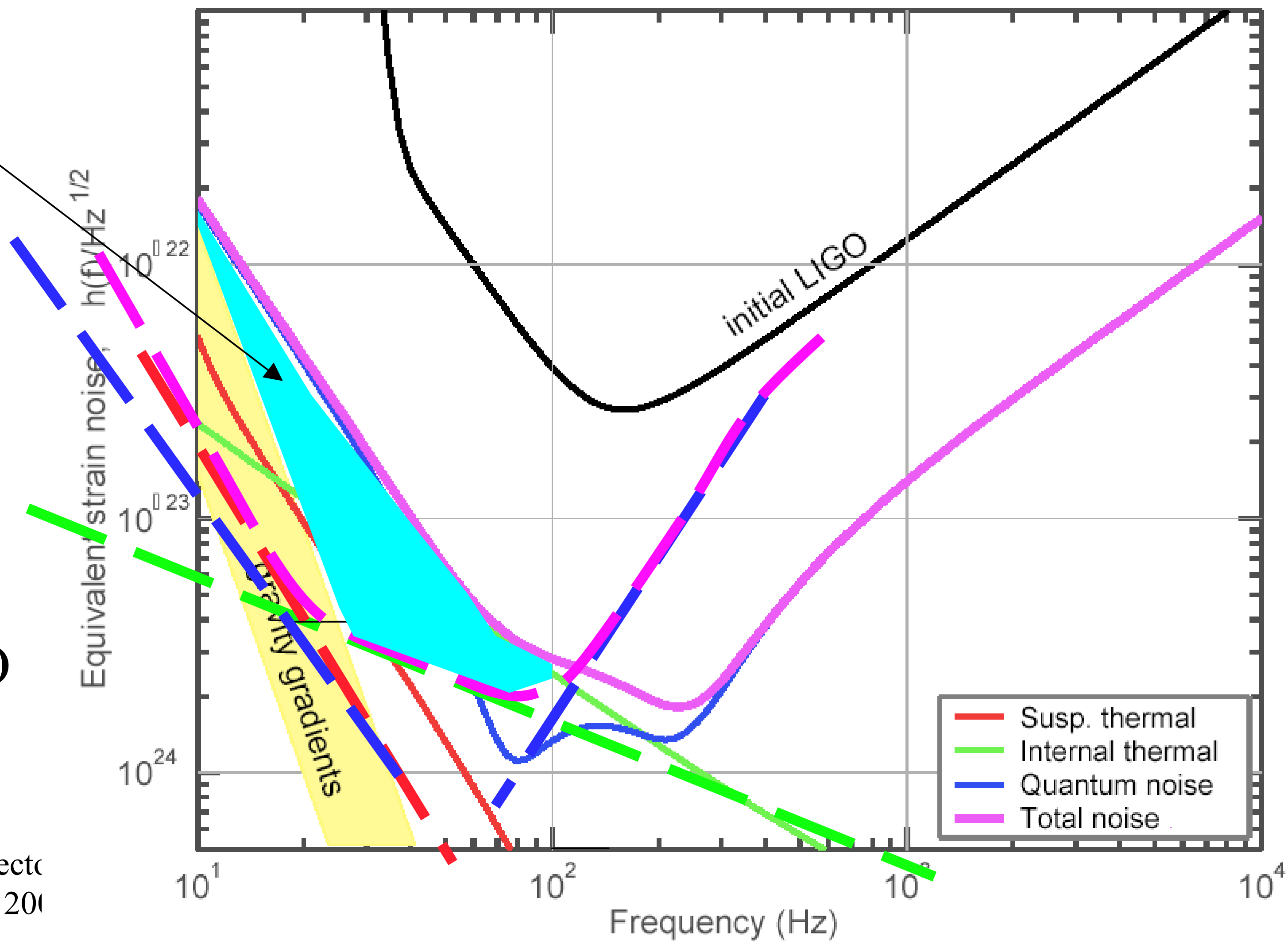
350 mm

Is gravity gradient going to stop us?

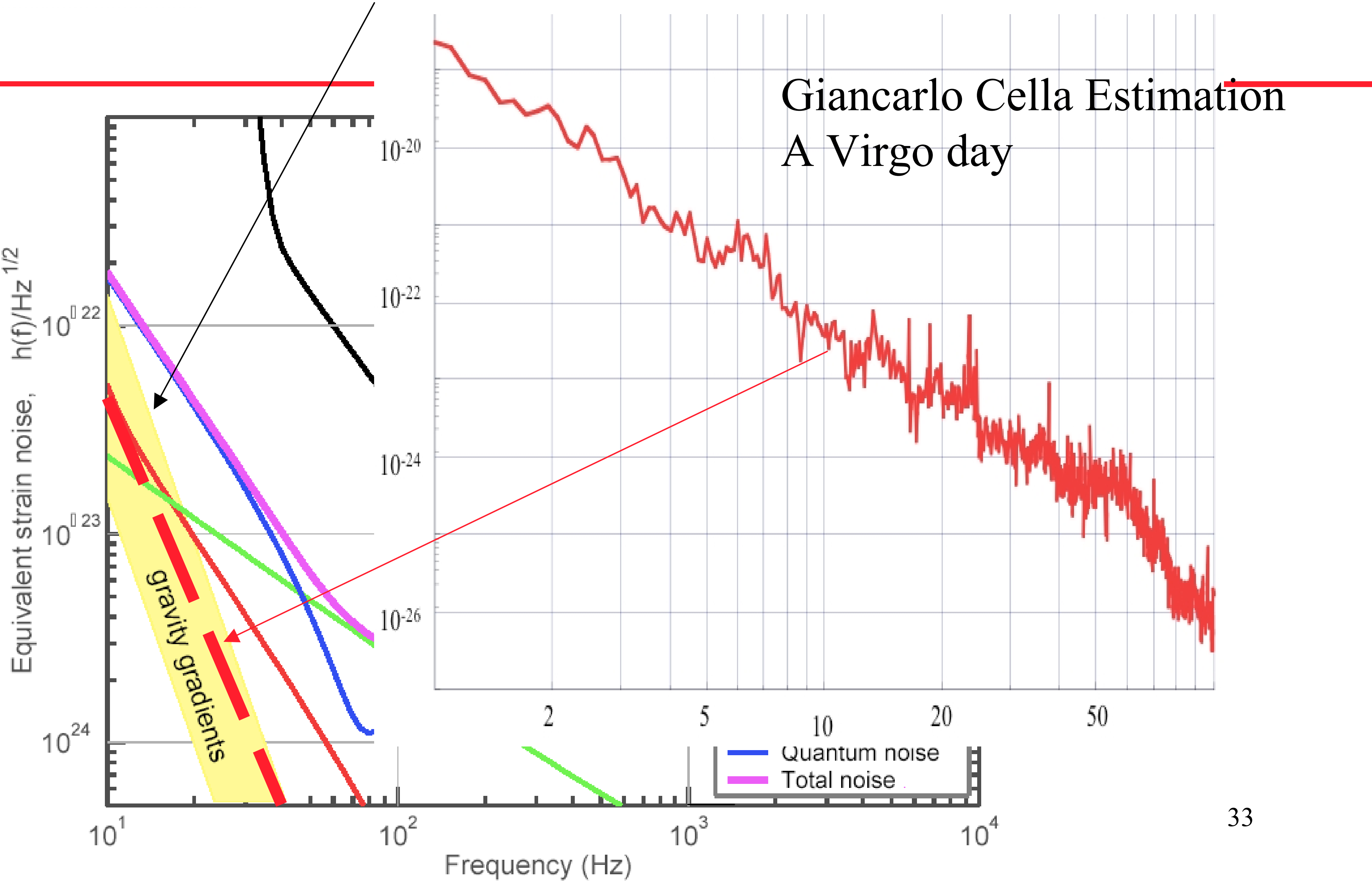
Minimal Additional Phase space

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

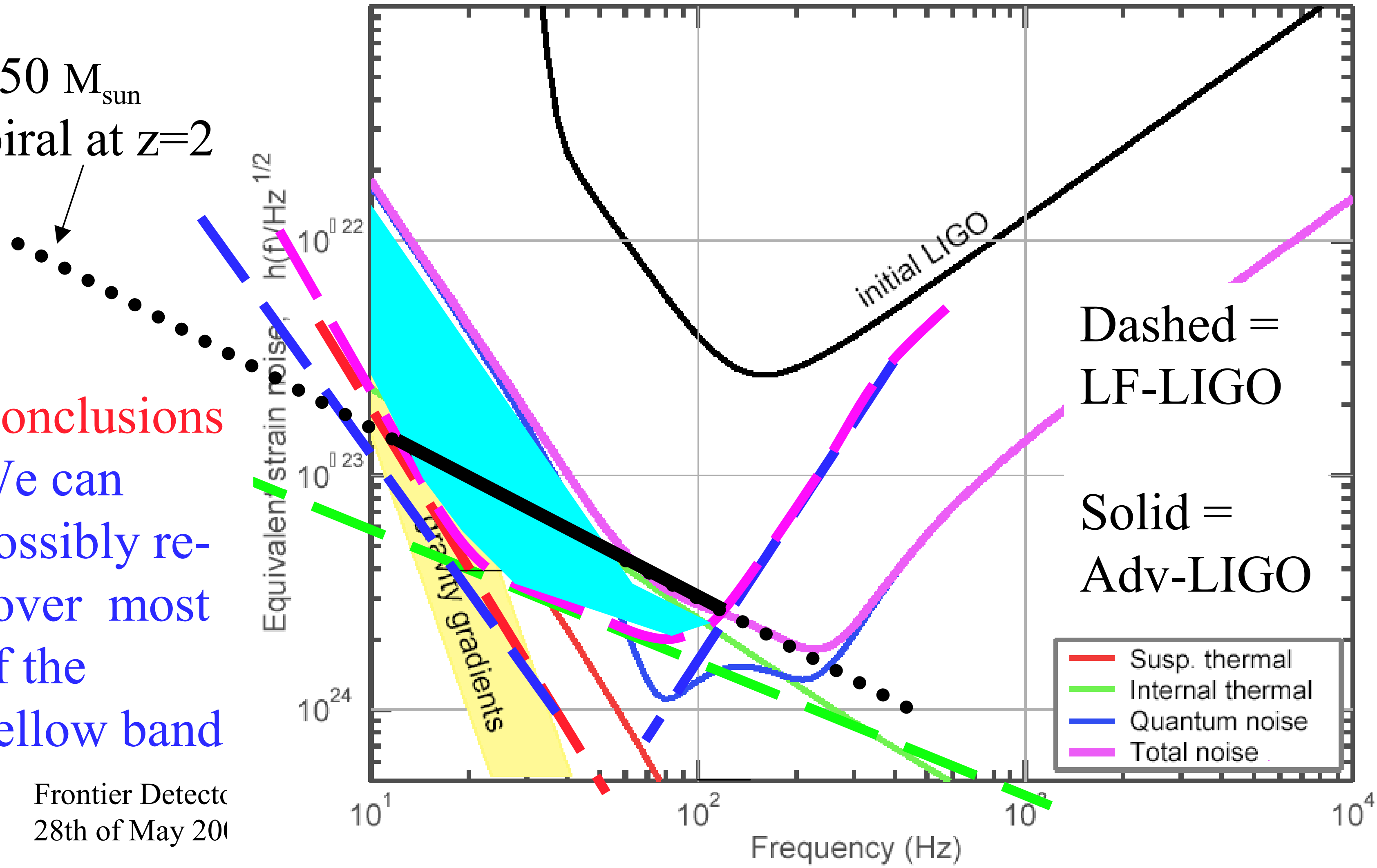
- Even if the GG was to be low only in windless nights, it would be worth having the listening capability 50% of the time
- LF-LIGO would give us the opportunity to test GG subtraction techniques

Does gravity gradient negate the advantages?

- With longer mirror suspensions (1-1.5m) the suspension thermal noise is pushed at lower frequency
- Gravity gradient limitations get uncovered
- Can start testing GG subtraction techniques
  - Note: Clearly for the future will need to go underground to fight GG
- Even aboveground there is so much clear frequency range to allow substantial detection improvements

Is gravity gradient going to stop us?

50+50 M_{sun} inspiral at z=2



Conclusions

We can possibly re-cover most of the yellow band

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 GWID?

- 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 LF GWIDs

- LSC and Advanced LIGO have decided not to pursue the L.F. option to focus on different 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.
- 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 small buildings for mode cleaner end towers if needed.

Can we afford a LF GWID

- 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.
6 needed	0.6 Meu	
New building for mode cleaner, and 150 m vac pipe:	0.5 MUS$	Est. F. Asiri
Design	0.5 Meu	Est./A.C.
Various	3.0 Meu	Est.
Total per interferometer	14.5 Meu	
Spares (1 set optics)	4.0 Meu	

Can we afford a LF-GWID

- We are talking of 15 M US$
- per interferometer for components

  \+ for spares 5 MUS$
- Manpower estimated staff of
- 20 persons for 5 years for 1 interferometer,
- 30 persons for 2 interferometers
  - at100,000US$ per person/year, for 1 interferometer 10 MUS$

    for 2 interferometers 15 MUS$
- Estimated Grand Total
- for one interferometer 30 MUS$
- for two interferometers 50 MUS$

L F GWID Characteristics

- Shortened SAS to fit under roof
- 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

How big a mirror can we get?

- larger mirrors are feasible today
  - 75 Kg fused silica
  - 430 mm diameter
  - (Heraeus bid)

Is Virgo an optimized LF GWID?

- Mostly yes, but needs its scheduled upgrades
  - Monolithic Fused Silica suspensions for suspension thermal noise
  - New mirrors, (including to replace the low-Q Herasyl mirrors at the end stations) possibly heavier ones.
- Mexican hat mirrors would be necessary to reduce the coating thermal noise problem
  - And a new injection telescope to match the wider beam

Is there space in Virgo for a HF companion?

- A new L building should be built in front of the central building to house the companion, as well as new or enlarged end stations.
- The Virgo beam is in the center of the beam pipe; during the Virgo upgrade the fused silica suspensions should be made longer to lower the beam line and make space for an HF companion.
- Given the location of the present gate valves, venting of the 3 Km pipes would be necessary to install the companion vacuum tanks.

What would be the interest of Virgo in a Low Frequency companion?

- Virgo is already focusing on low frequencies where the new observed possible sources may emit.
- Why should it need a companion?
- Present LIGO has essentially no LF capabilities
- Adv-LIGO will have broad-band capabilities but it will run optimized for high frequency narrow-banding,
-
- The LF range may not be sufficiently covered by LIGO to provide optimized coincidence

Should EGO push to build Low Frequency companion(s) for LF coincidence detection in the LIGO facilities?

- Economically it makes lots of sense,
- Two independent interferometers can be built without having to build new facilities
- No new concepts or difficult developments are needed
  - The Virgo concept is perfectly adequate

Are LF interferometers in the LIGO facilities adequate LF companions for Virgo

- The LIGO facilities are not well aligned with Virgo,
- But two of them are available
- Coincidence running **and** coverage of both source polarizations are possible if two LF-GWID are implemented!!!
- Three point observation gives the best pointing capabilities.

- This development could be made while developing new generation IF in new facilities

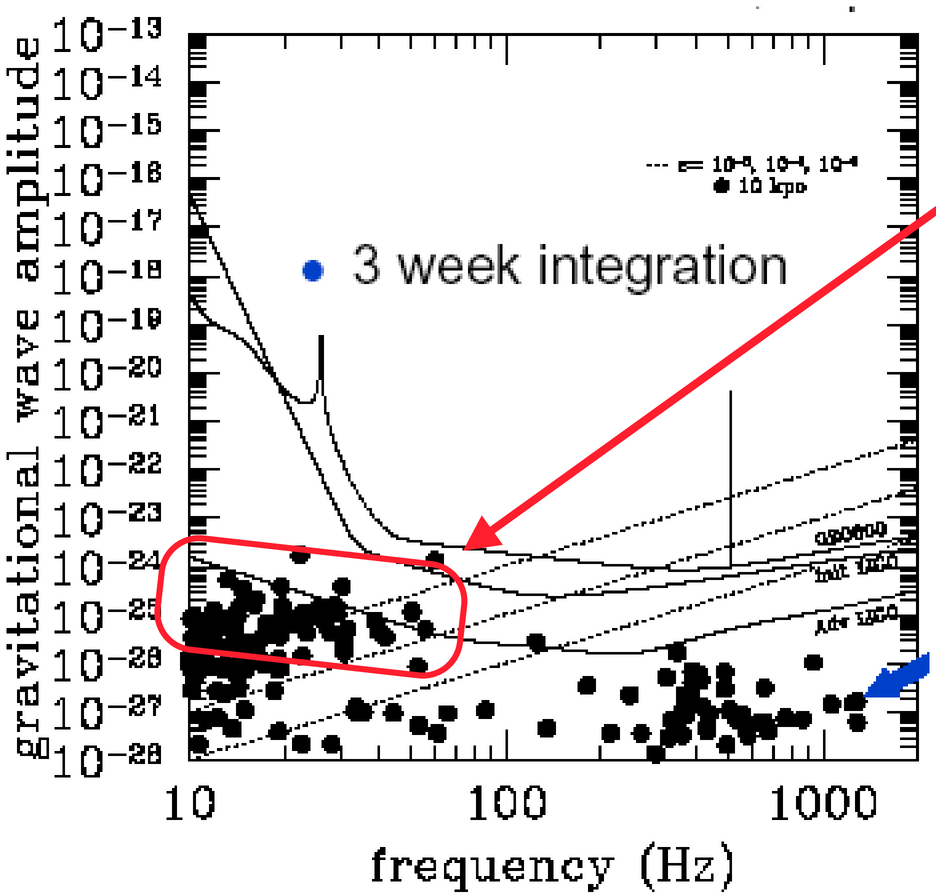
Interesting question.

Matthew Benacquista

- How did the inferred 1000 s.m. BH get in cores of globular clusters?
- Star merger in cluster core + direct collapse?
- Or
- Sequential accretion of ~10 s.m. BH?

- Presence or absence of GW signal give the answer
-

Older motivations?



- A LF-GWID would allow exploration of a much richer ns population than an HF-GWID
- Teviet Creighton http://cajagwr.caltech.edu/scripts/seminars.html

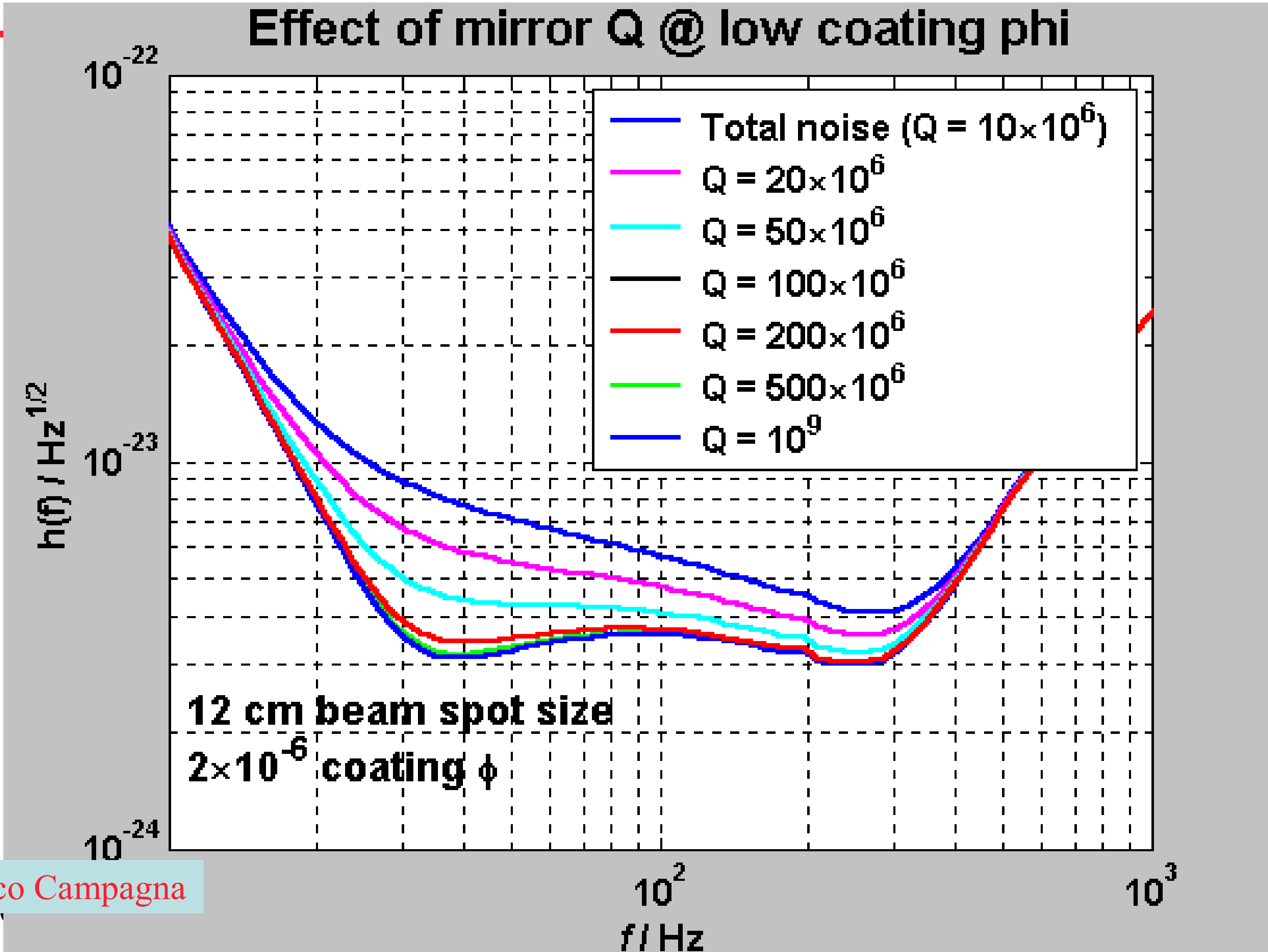
Other motivations? Cosmic background

- The sensitivity to GW cosmic background (if the background is flat in frequency) would increase at LF with $f^{-3/2}$ and

- The GW background signal coherence of LF interferometers would be almost perfect

- Albert Lazzarini http://www.ligo.caltech.edu/docs/G/G030242-01/

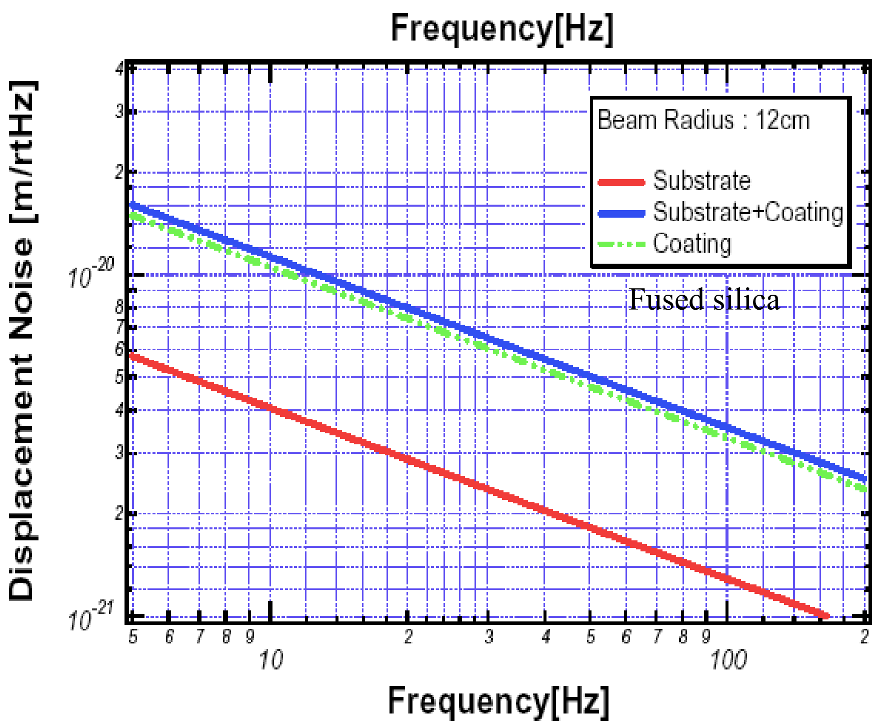
What happens if one could have a better coating Q-factor!

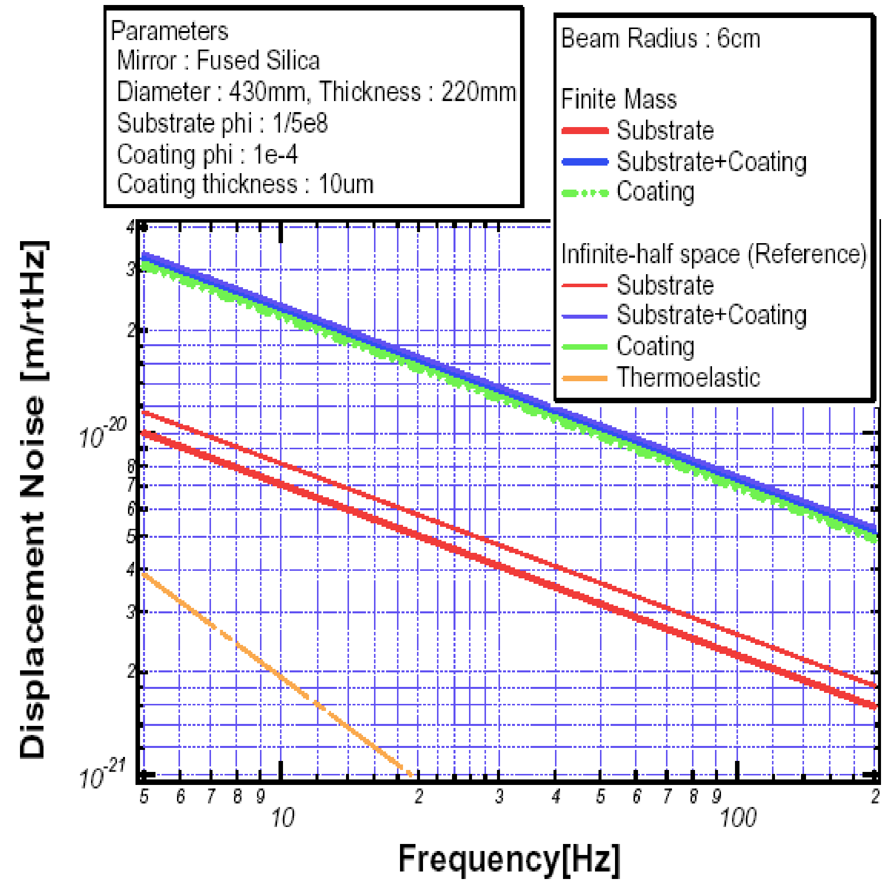


Simulation from Enrico Campagna

Effect of spot size

ANSYS "complete" Simulation
from Kenji Numata





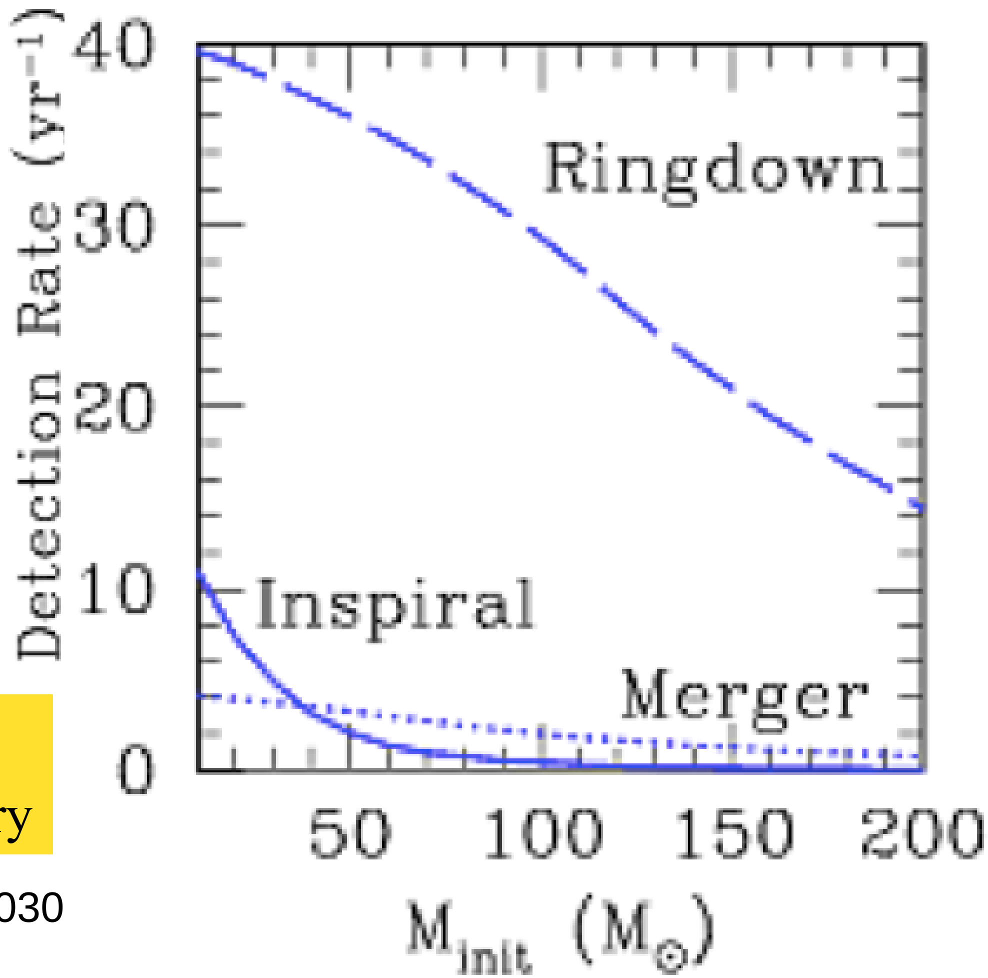
For spot size effects on sapphire, see Erika D'ambrosio, ref.

LIGO

Predicted inspiral rate

- If central BH initial mass is higher, the Adv-LIGO detection rate is strongly depressed by
  LF and template limitations.

- a LF-GWID inspiral would recover the high detection rate by a large factor



•Cole Miller

•Very preliminary

Predicted inspiral rate

- ΔM assumed to be ΔM=10 M_{sun}

- If accretion was with bigger increments (say ΔM=30 M_{sun})
  - (Heavier masses are slowed down first)
- Number of accretion events ~ $1/\Delta M$
- But signal amplitude and detectable range ~ΔM

- Number of detectable events ~ΔM^2

- If lower frequency sensitivity is available

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 applicable throughout the frequency range, see Iyer et al.

What is relevant for LF-GW observations

- Tens of BH-BH detectable inspiral events per year are expected Coleman Miller. Astrophysics Journal 581: 438-450, Dec 2002

- GW Signals from massive BH will carry farther than NS
  - Signal amplitude roughly proportional to mass
  - Can reach much farther M^3 (if not limited in freq.)

- BUT
- Most signals start above 20+20 M_{sun}.
  - Close to ISCO difficult to make templates

Other motivations?
BH chirp and ringdown

- final chirp frequency can be approximated by:
- f ~ 4.4/ (M/M_{sun}) kHz
  - 100 M_{sun} systems at 44 Hz,
  - 1000 M_{sun} systems at 4.4 Hz

- Kerr BH ringdown frequency after merger for mass M:

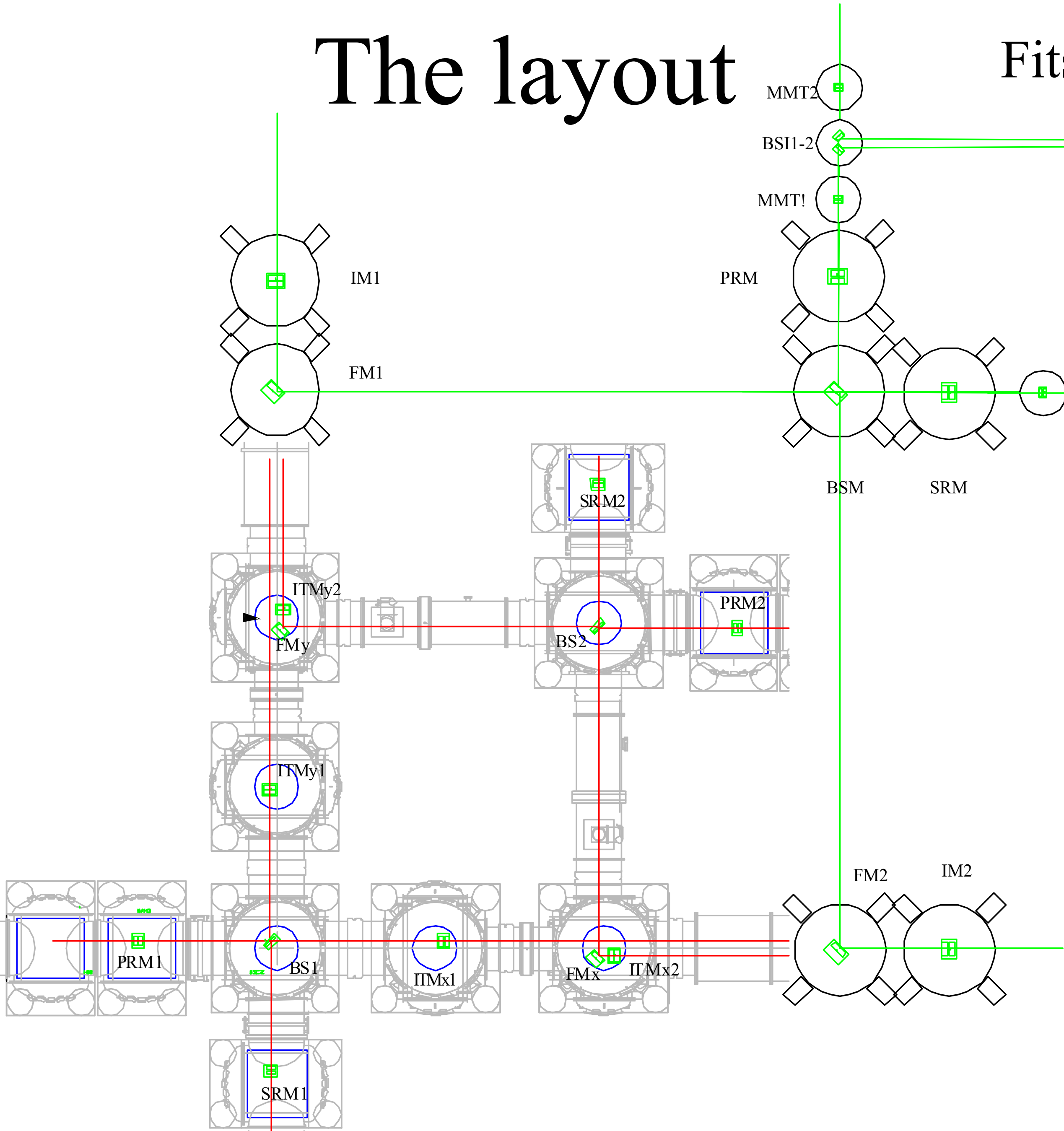
  f ~ (32/M) kHz

  » (J. Creighton, gr-qc/9712044 or F. Echeverria, PRD 40, 3194 (1989))
- ringdown for a 1000 M_{sun} BH at ~ 32 Hz.

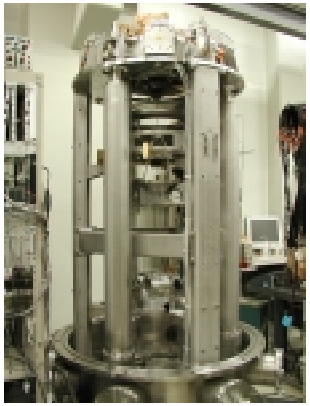
Matthew Benacquista

The layout

Fits in LVEA



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

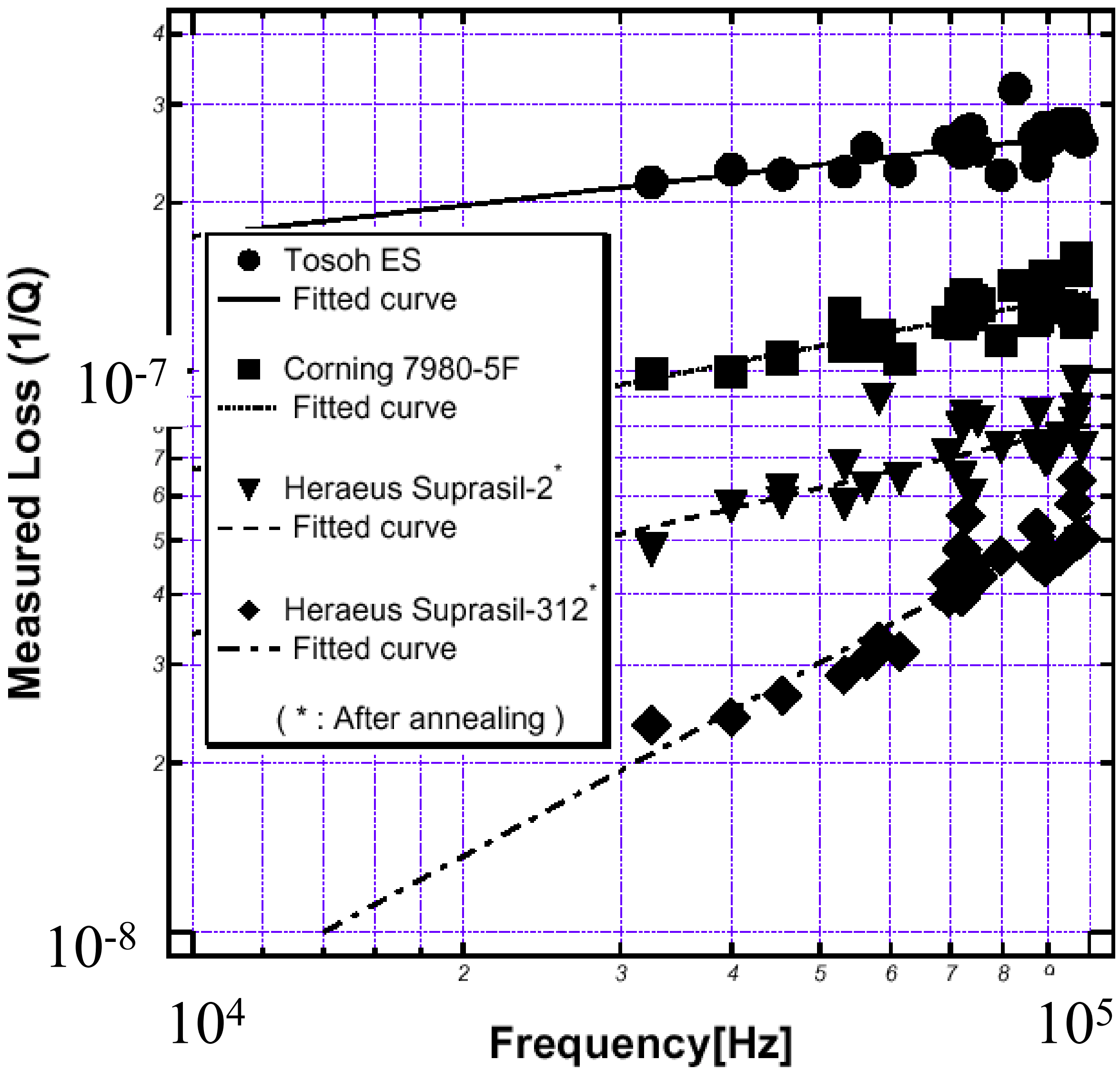


LIGO

Kenji Numata results

The Q-factor improves at lower frequency

How much better does it gets at 100 Hz?



Implications at L.F.

- Fused silica allows for much lower thermal noise floor at L. F. (if coating problem is solved)
- Fused Silica only tolerates “lower” beam power
- At lower frequencies much lower power is required ($\sim 1/f^2$)
- larger beam sizes => less beam power problem
- **Fused silica is the ideal choice for LF interferometers**