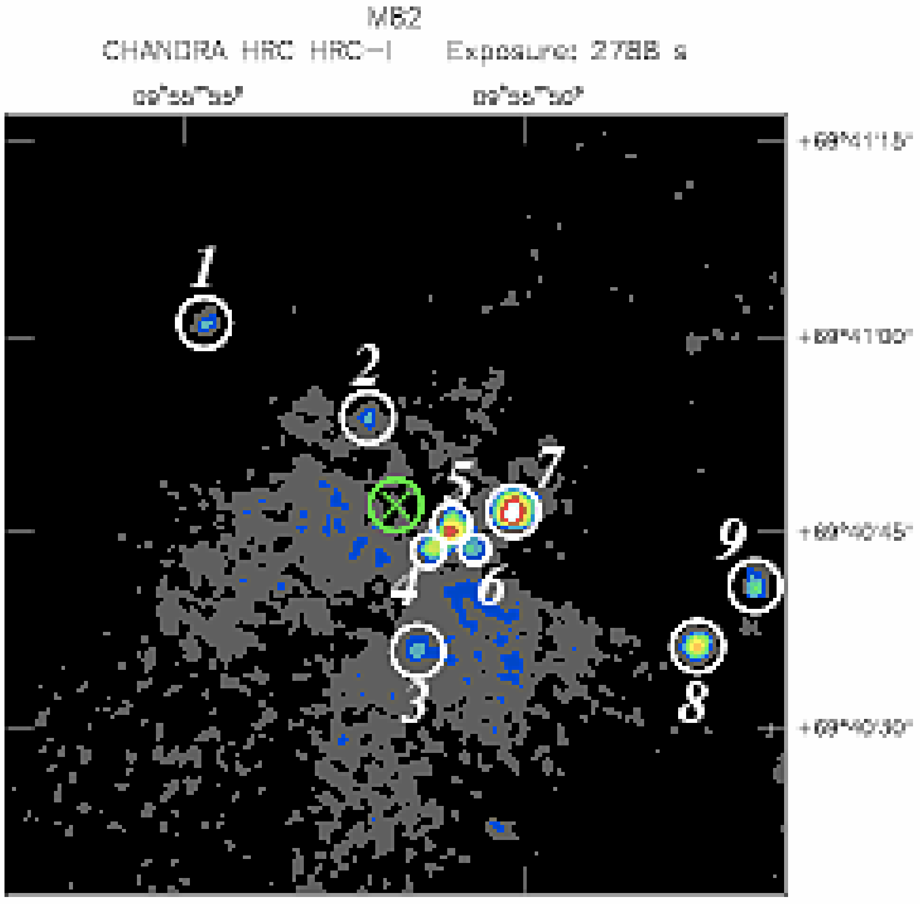
Gravitational Wave Detectors

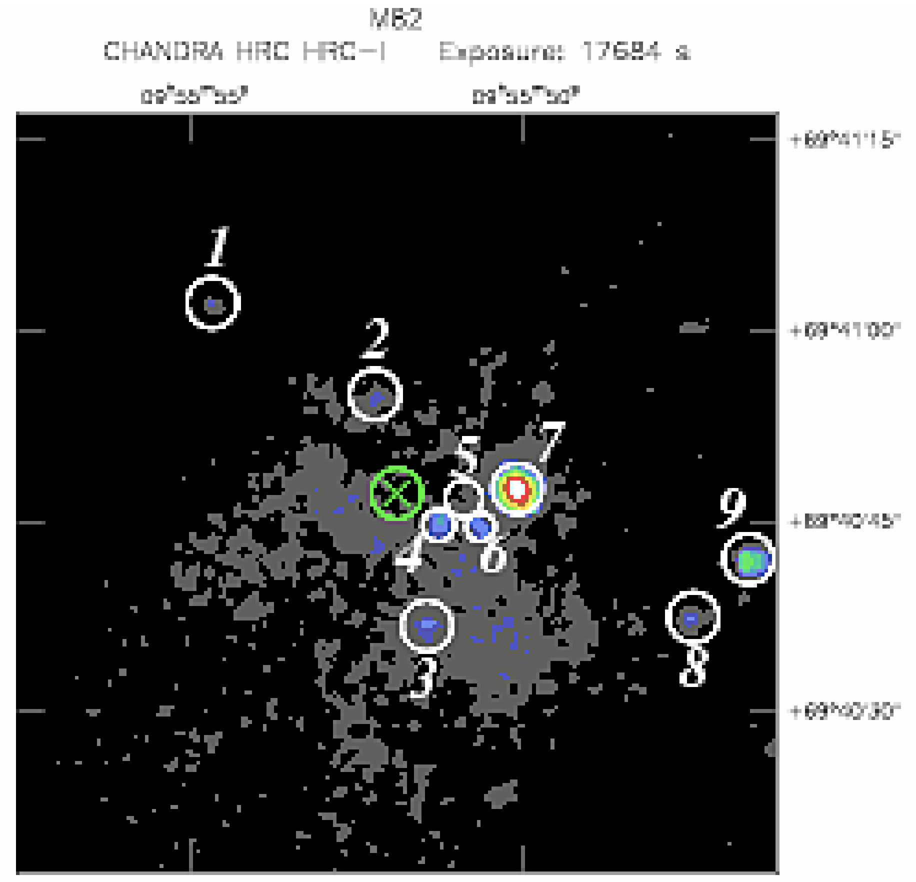
The challenge of Low Frequency G. W. Detection

Riccardo DeSalvo
LIGO laboratory
California Institute of Technology

Chandra's observations show plenty of Black holes in clusters



M82-28 October 1999



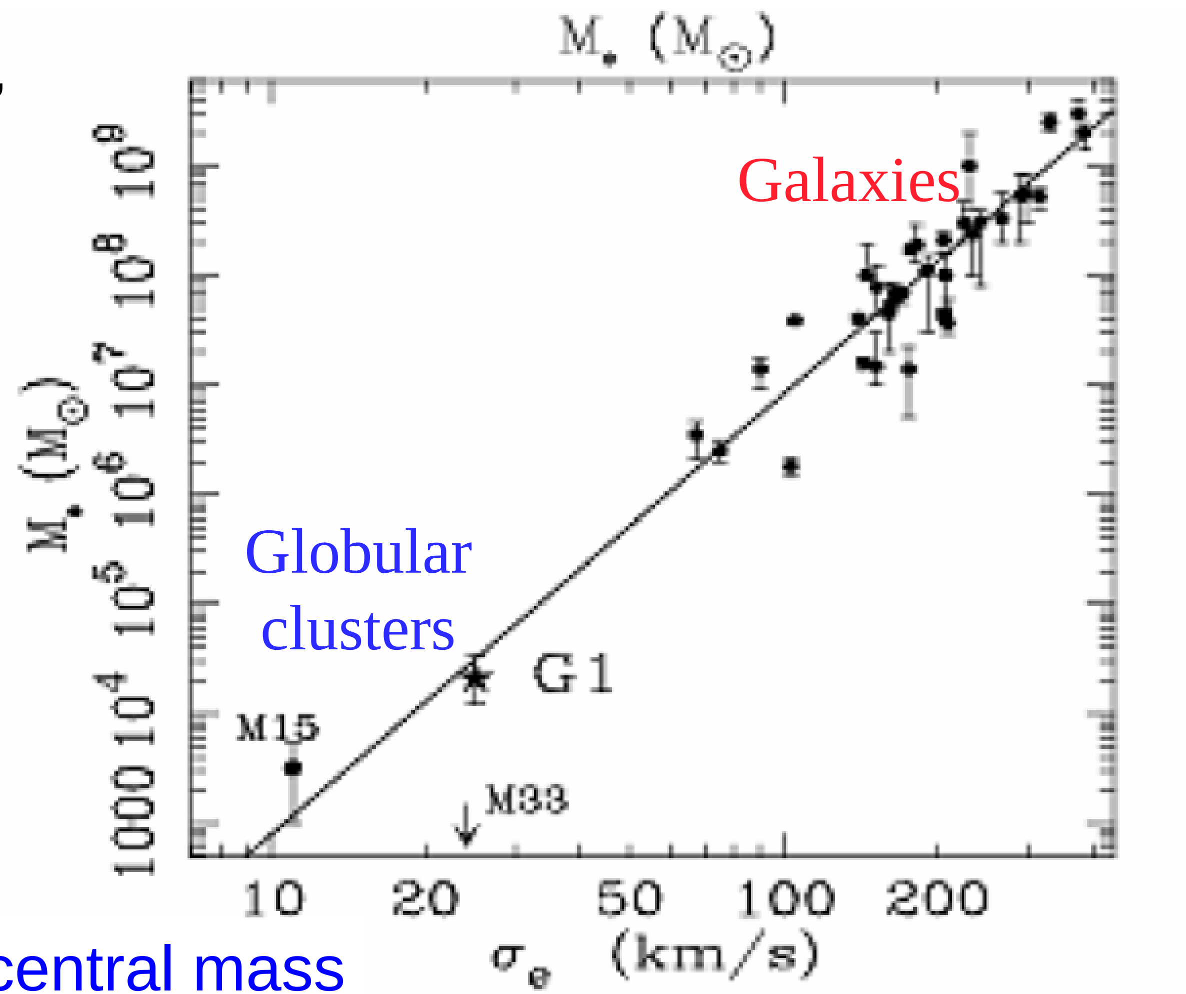
M82-20 January 2000

Central mass M - σ relation

- Formation of structures, from globular clusters to Galaxies, require central collapse of mass

- Thermalization of star motions produce such concentration

- =>Concentration and inspirals of Black Holes



σ <=> central mass

lower frequency sensitivity needed to study their dynamics

- Inspiral final chirp frequency :
- f ~ 4.4/ (M) kHz/M_{sun}
  - 100 M_{sun} systems stop @ 44 Hz
  - 1,000 M_{sun} systems stop@ 4.4 Hz

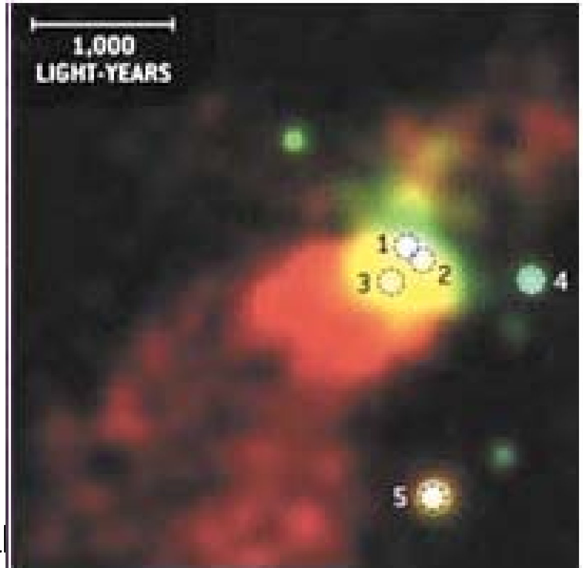
- Kerr BH post-merger ringdown frequency :
- f ~ 32/M kHz/M_{sun}
  - 1,000 M_{sun} BH ring @ ~ 32 Hz.
  - 10,000 M_{sun} BH ring @ ~ 3.2 Hz.

Physics waiting for Low-Frequency ground-based GWIDs

- Explore population of Intermediate Mass Black Holes on their merging way to galactic size BH

- Sensitivity reach of cosmological interest (red shift >1) is achievable

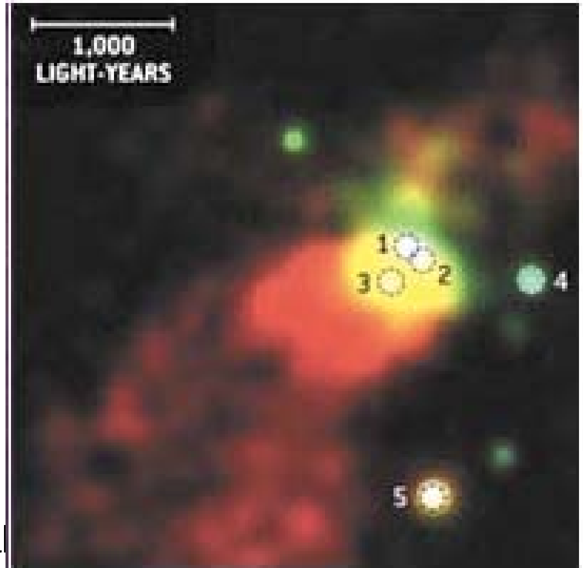
- Fill the frequency gap to LISA



Pushing the Low Frequency Limit of ground based GWIDs

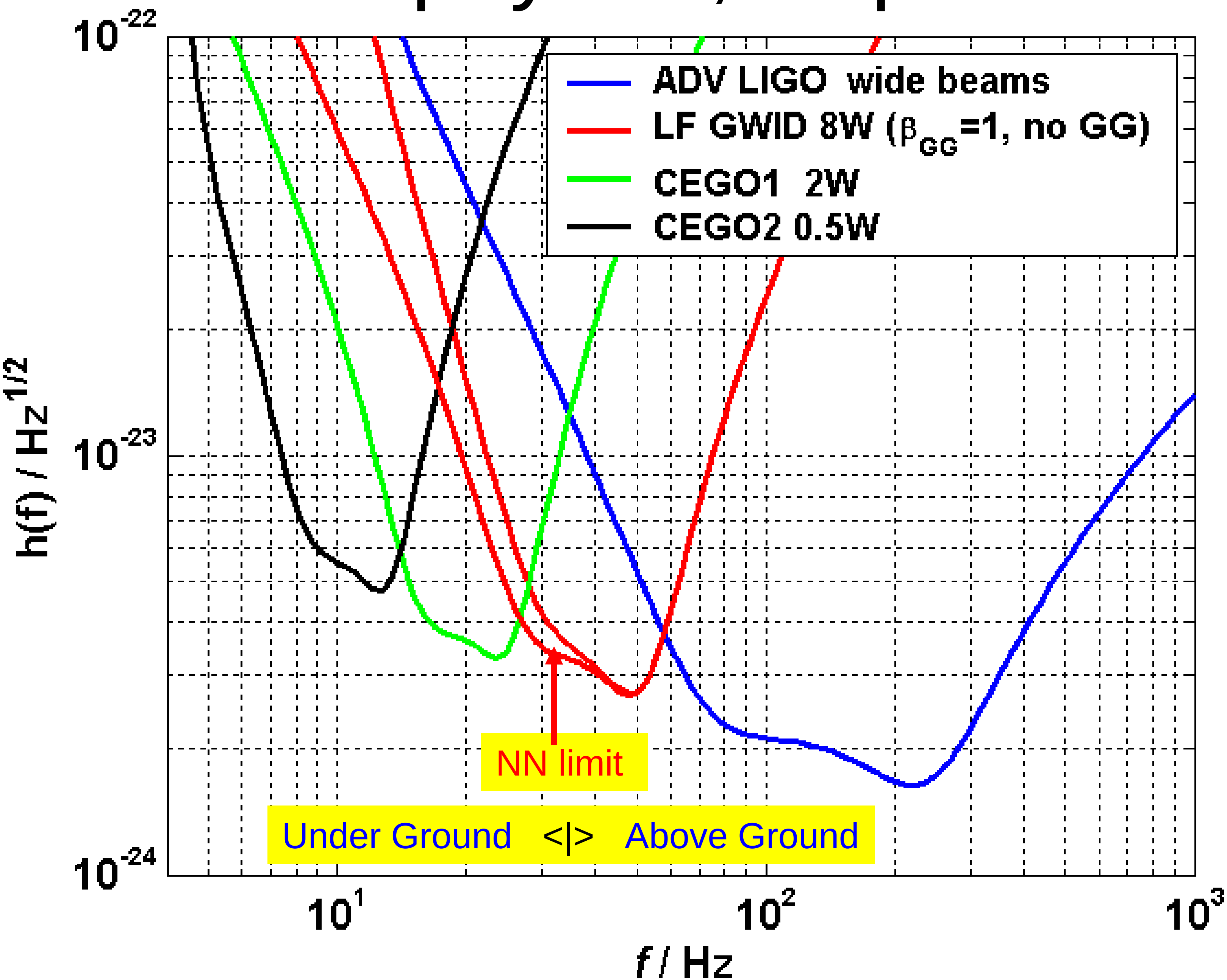
- limiting noise sources impede GWID at Low Frequency
  1. Newtonian Noise (NN)
  2. Suspension Thermal Noise (STN)
  3. Radiation Pressure Noise (RPN)
  4. Seismic noise

- LF Technical challenge

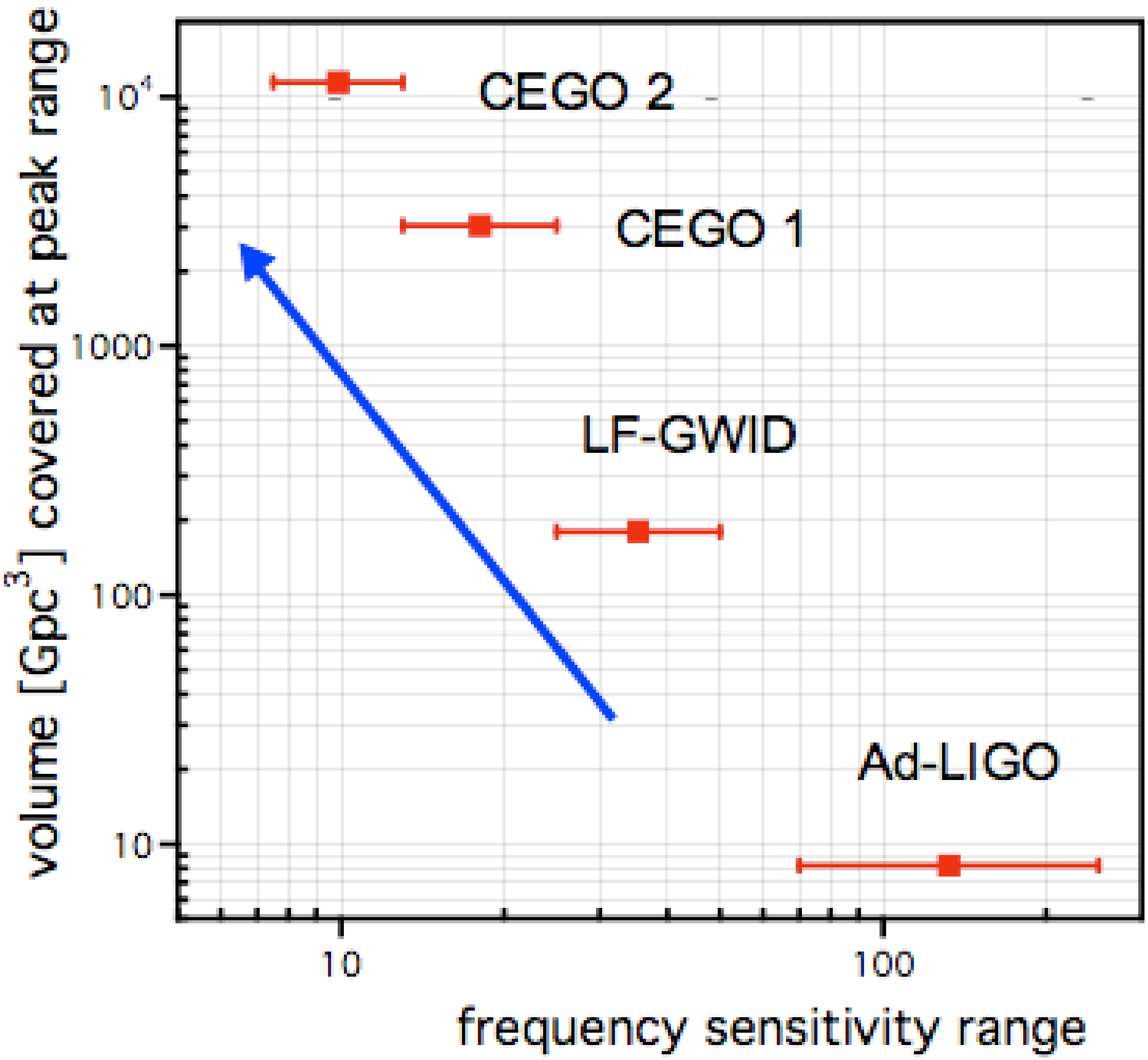


K. Weaver Astro-ph0108481/Sci. Am. July 2003

The physics, inspiral reach



The physics, Universe range



Under Ground

Above Ground

Taming Newtonian Noise by going underground

- NN derives from the varying rock density induced by seismic waves around the test mass
- It generates fluctuating gravitational forces indistinguishable from Gravity Waves

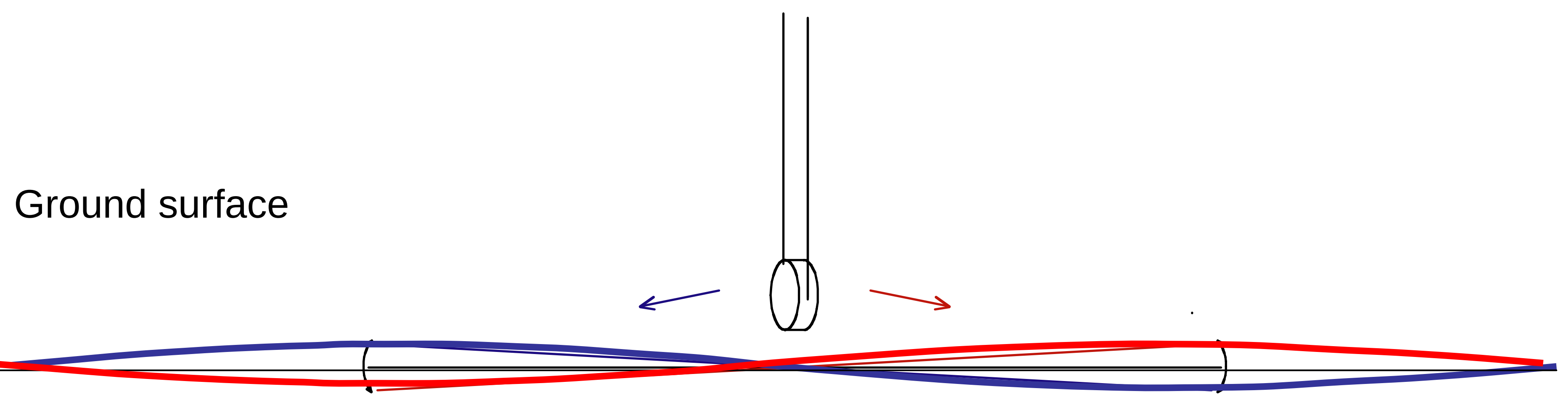
- NN has two sources,
  1. The movement of the rock surfaces or interfaces buffeted by the seismic waves
  2. The variations of rock density caused by the pressure waves

NN reduction underground

The dominant term of NN is the ground surface movement

- On the surface this edge is the flat surface of ground

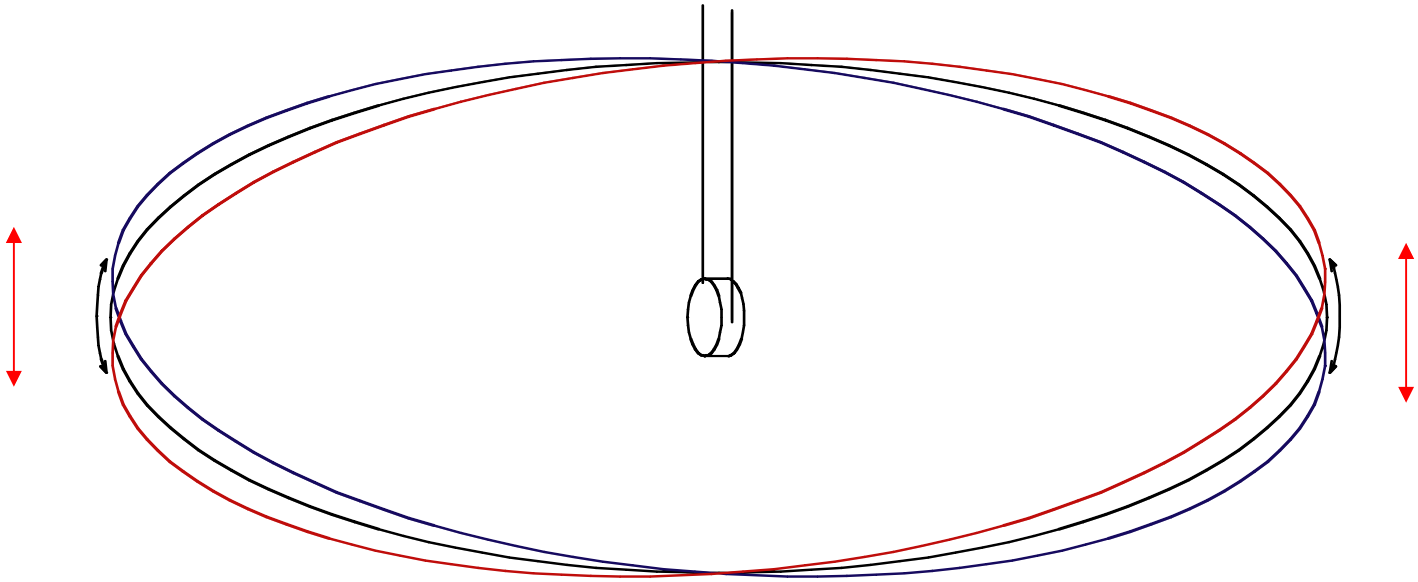
Ground surface



seismic motion tilting ground leads to fluctuating attraction force

NN reduction underground

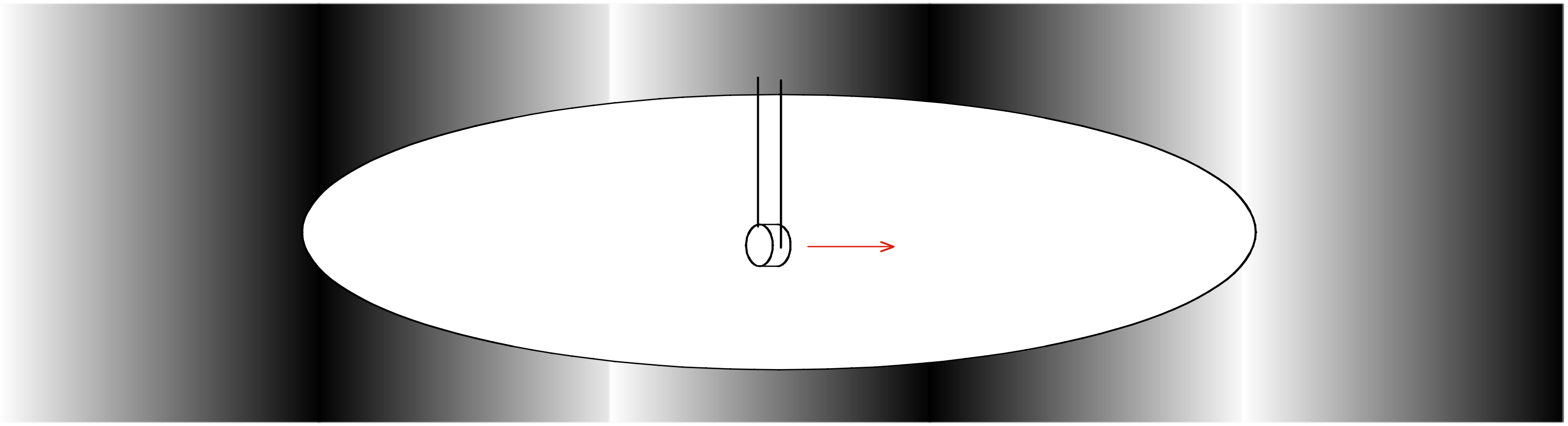
- Surface effects
- Symmetric caverns housing centered suspended test mass
  tilting and surface deformations, the dominant terms of NN, cancel out

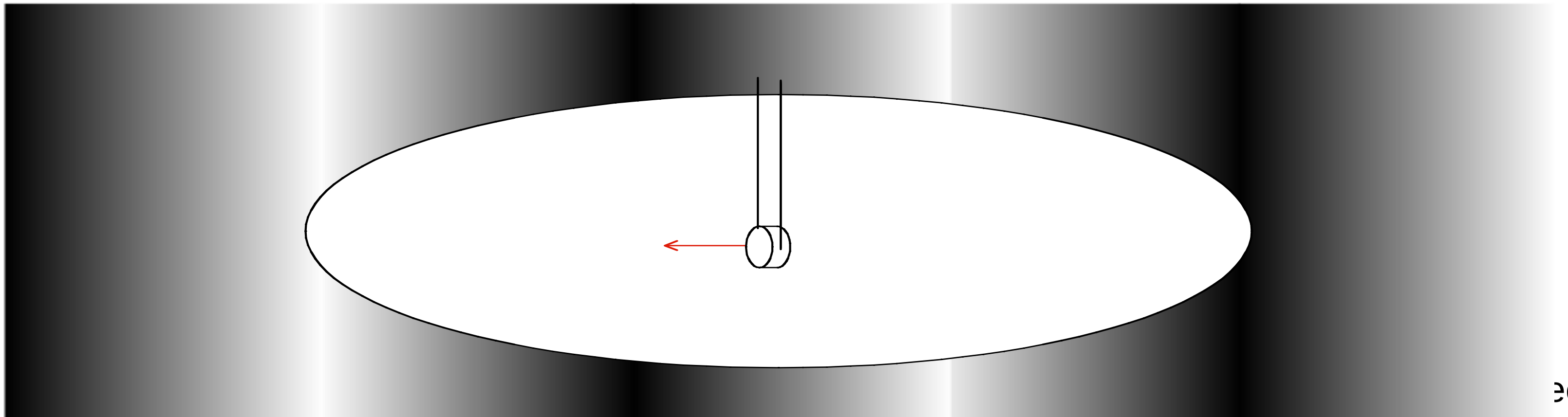


a tilting symmetrical cavern leads to
NO fluctuating attraction force

NN reduction underground

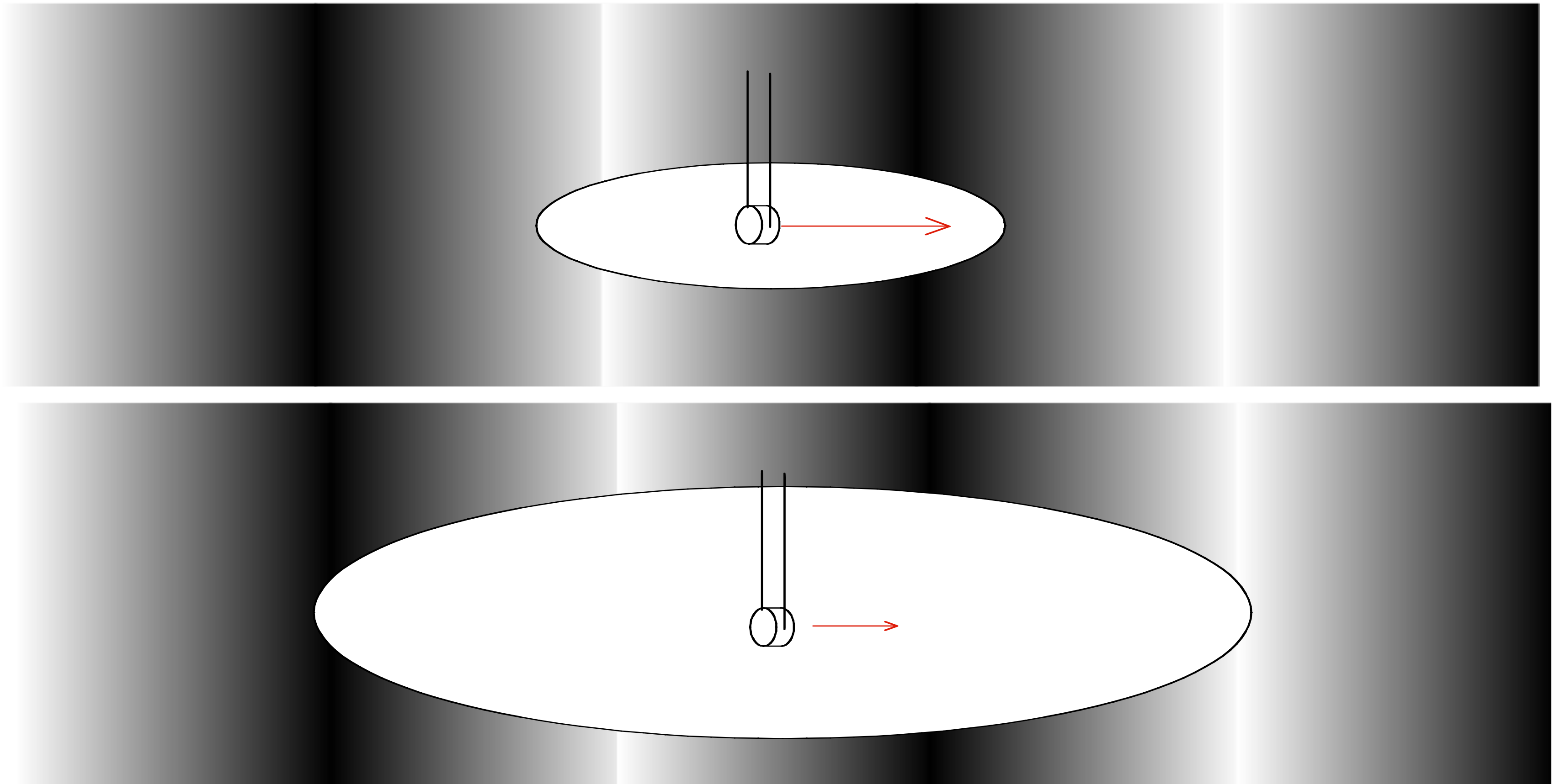
- Pressure seismic waves induce fluctuating rock density around the test mass
- Fluctuating gravitational forces on the test mass



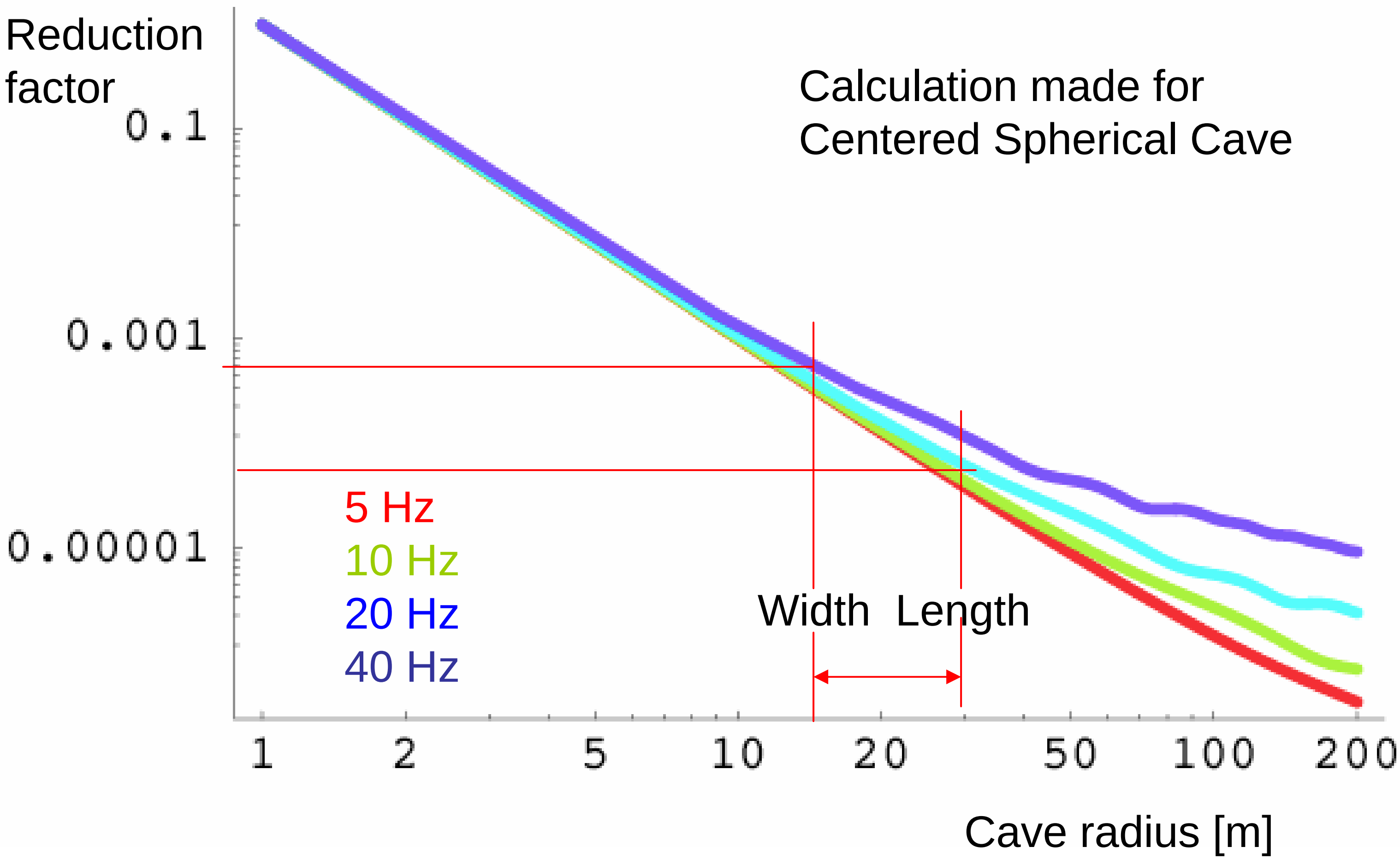


NN reduction underground

- Larger caves induce smaller test mass perturbations
- The noise reduction is proportional to $1/r^3$
- The longitudinal direction is more important =>elliptic cave



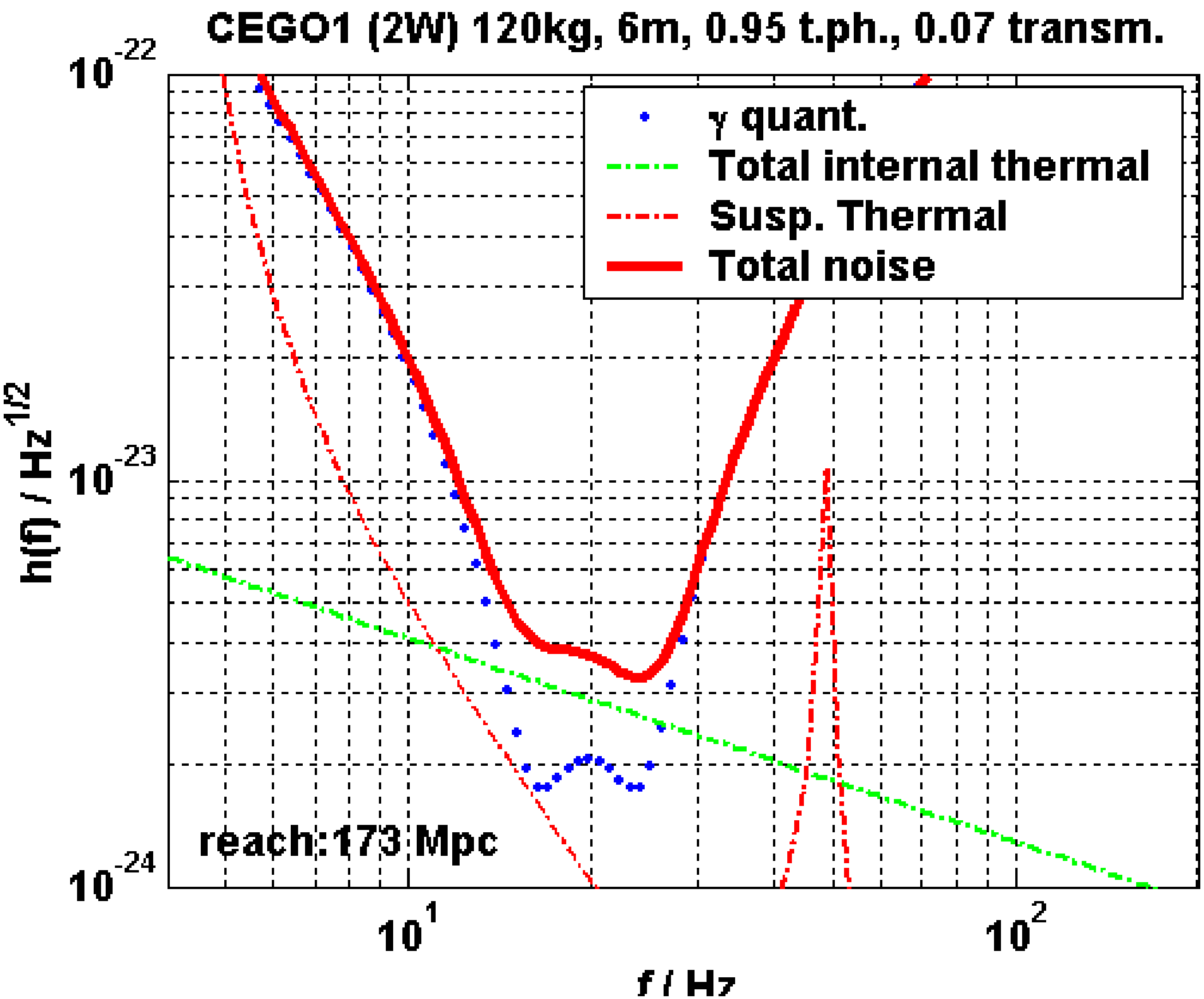
NN reduction from size



Newtonian Noise reduction

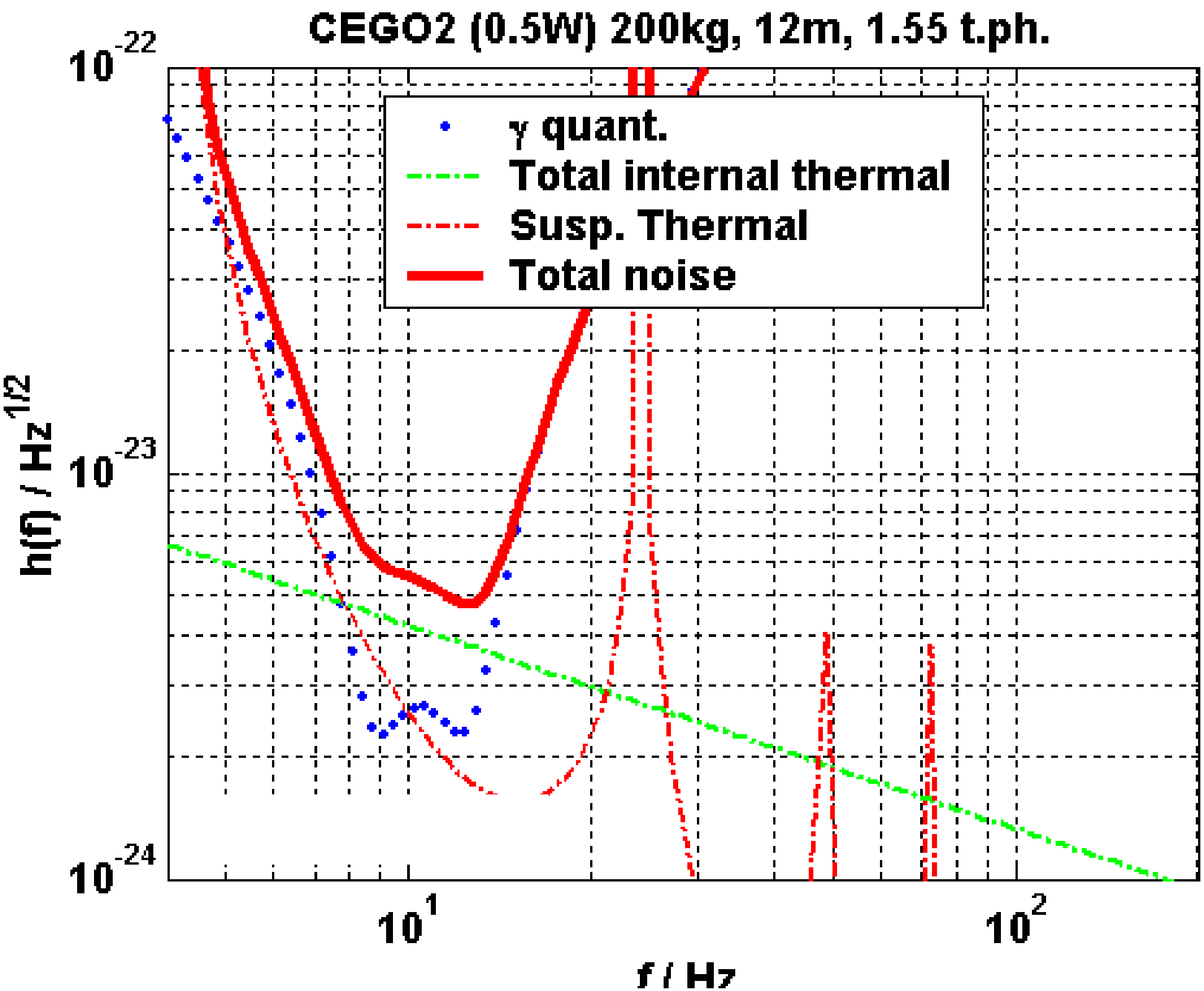
- NN can be reduced by an Amplitude factor $\sim 10^6$ by going underground
- At very LF some gain from coherence
- detect GW inside Earth towards 1 Hz

Which knobs to turn for low frequency



- INGREDIENTS
- Longer suspension, advanced materials or cryogenics for Suspension TN
- Heavier mirrors and Lower laser power for Radiation Pressure N
- LF seismic attenuation
- Large beam spots for Thermal Noise

Which knobs to turn for low frequency



- INGREDIENTS
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- LF seismic attenuation
- Large beam spots for Thermal Noise

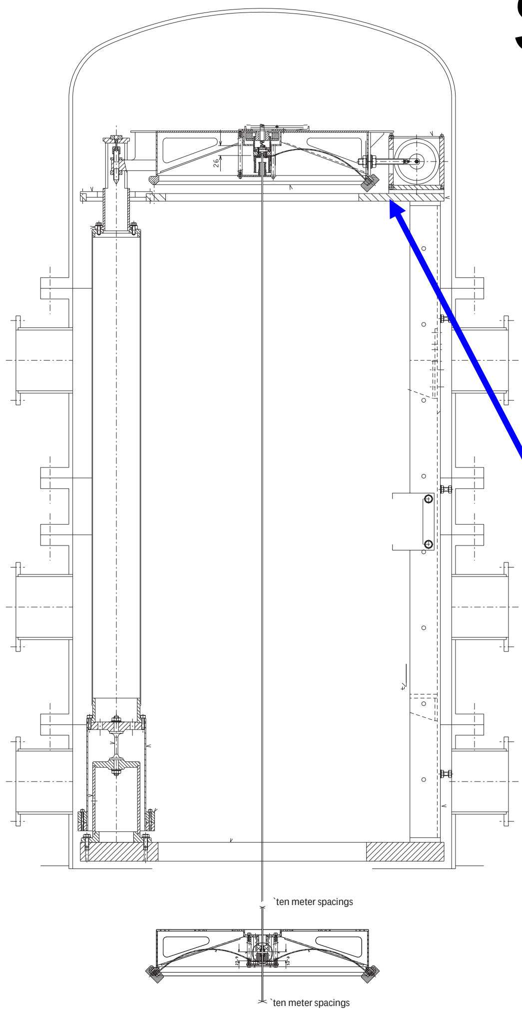
Focus on

- Advanced seismic attenuation
- Composite masses for Radiation Pressure noise

- Some Comments on Advanced materials or Cryogenics for suspension Thermal Noise reduction

- Where to do underground GW D

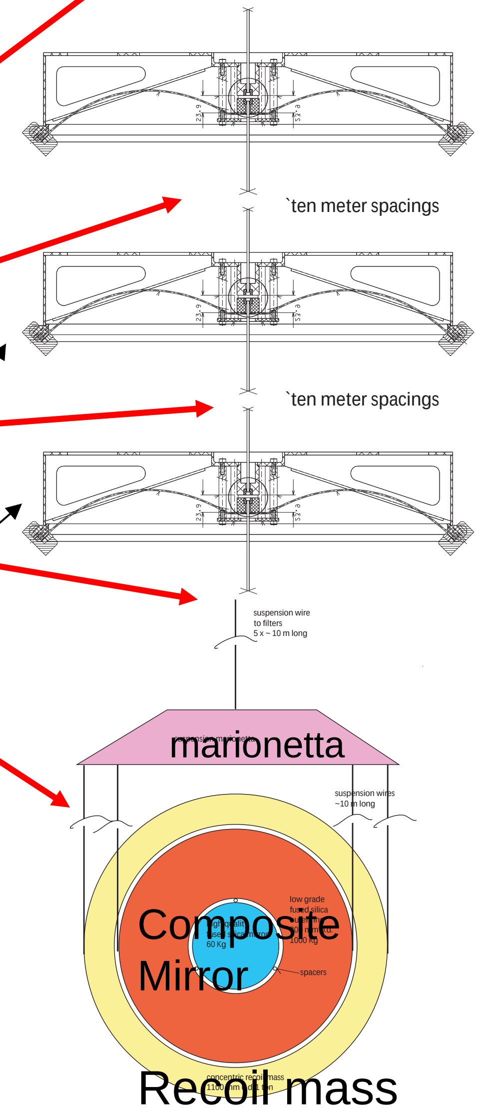
Suspension and Seismic Isolation schematics



10-20 meter pendula
Between all stages

short
Pre-isolator
In upper
cave

LF Vertical filters



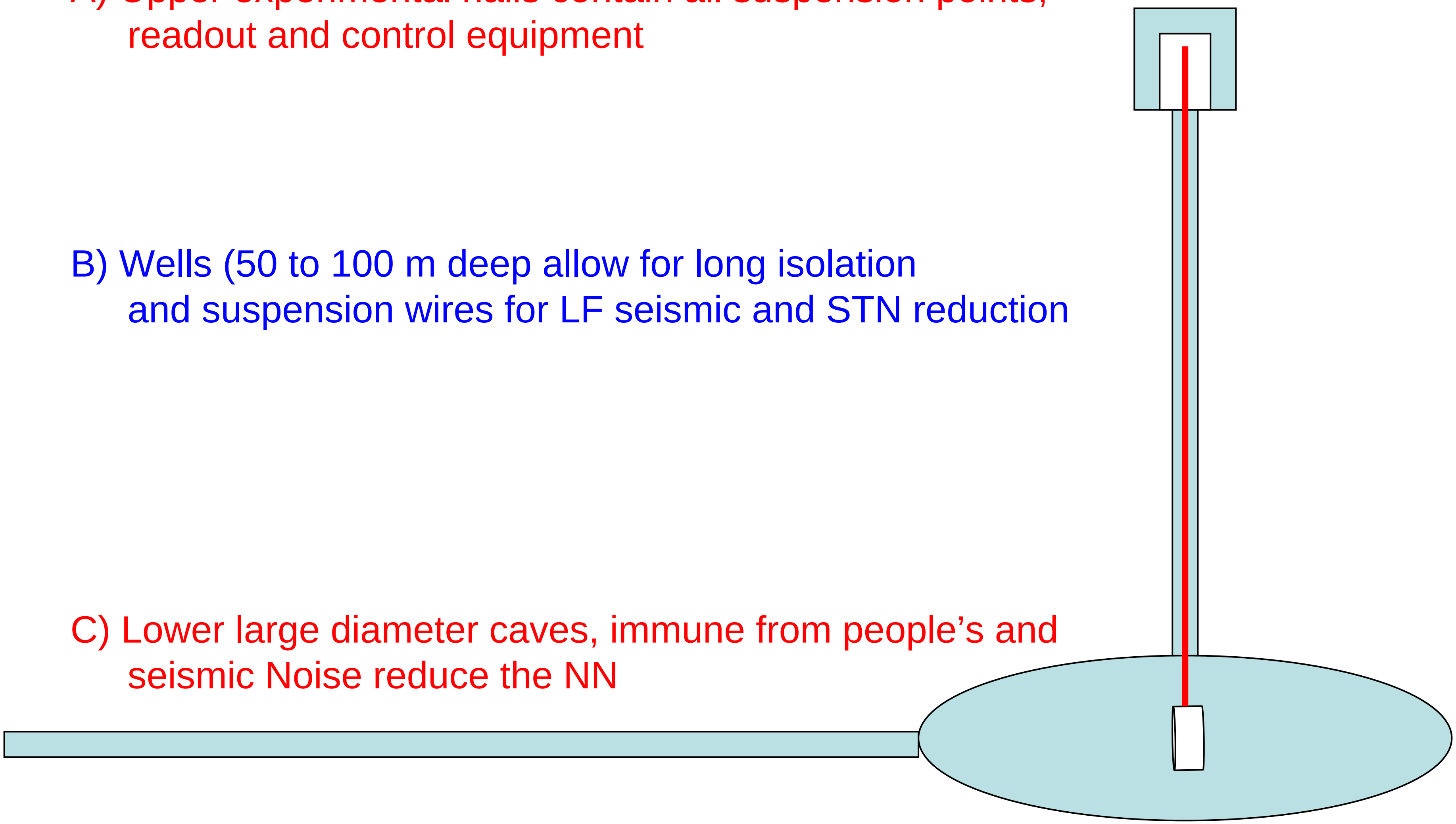
Attenuation filters in well

Vertical cross section

A) Upper experimental halls contain all suspension points, readout and control equipment

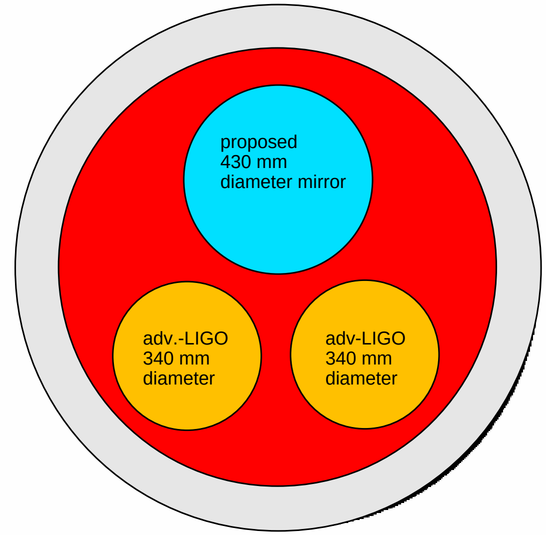
B) Wells (50 to 100 m deep allow for long isolation and suspension wires for LF seismic and STN reduction

C) Lower large diameter caves, immune from people’s and seismic Noise reduce the NN



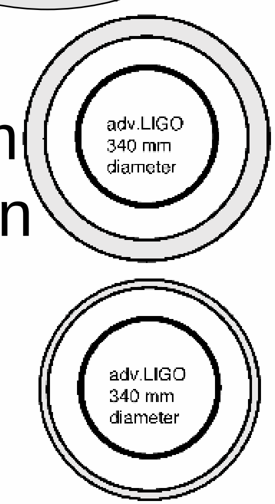
Avoid repeating Virgo and LIGO mistakes

- the beam pipes does not need to be much bigger than the mirrors



- Half size means
- half surface,
- half thickness of material and weld
- => less than half the cost
- Additional diameter and installation savings by replacing baffles with a spiral band saw co-welded in place
- Independent interferometers

2x500 mm
Better than
1200 mm



Seismic attenuation desired new developments

- Premium in attenuation factor per stage
- Premium in low frequency resonant frequency

- Horizontal direction probably OK
- Vertical direction need further improvements

Horizontal direction

- IP filters
  - Always have been good to ~20 mHz
  - Can deliver > 80 dB per stage

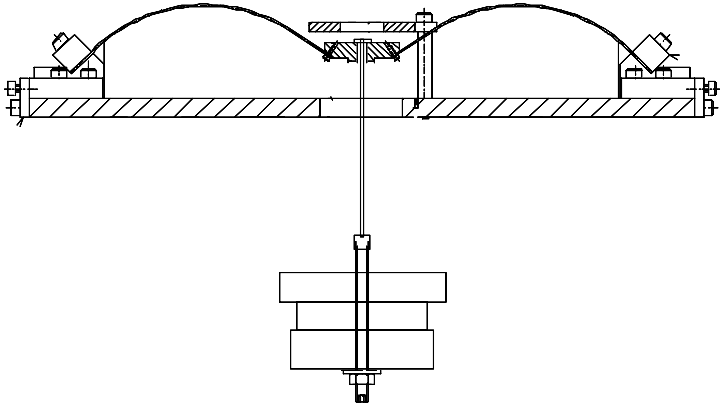
- Nobody doubts wires
  but f~□length
  can do better?

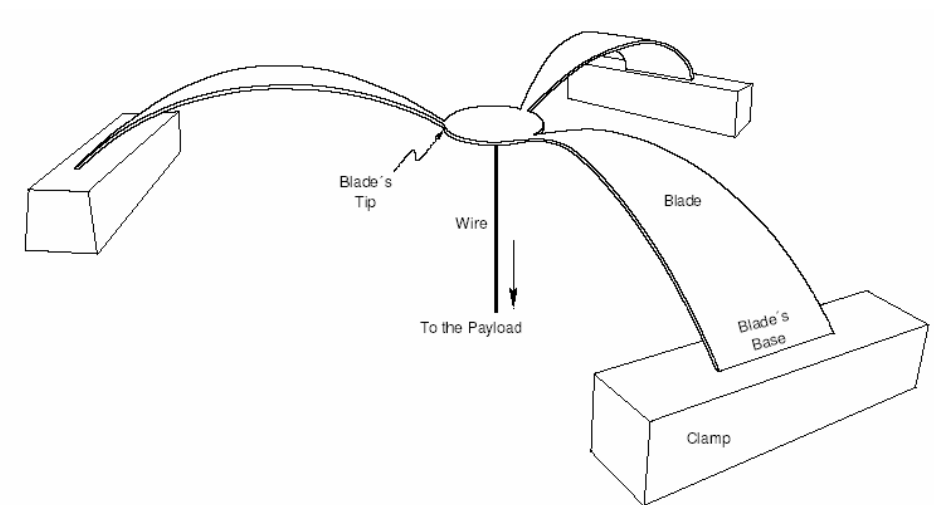
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Vertical direction

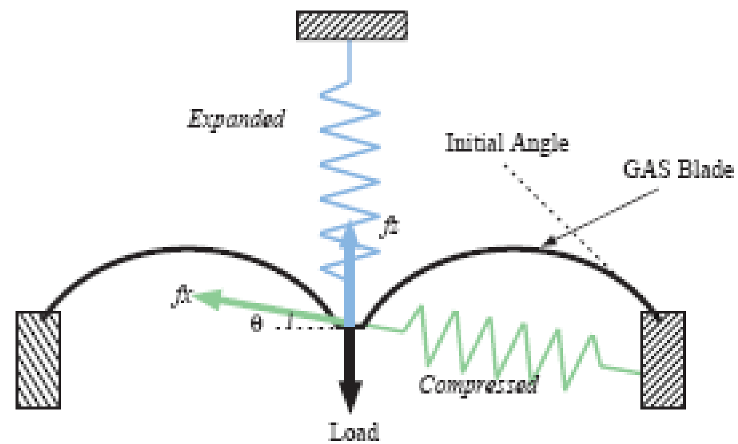
- GAS filters
  - Used to be limited to > 200 mHz
  - Used to be limited to 60 dB per stage
- Euler springs - Lacoste
- All limited by distributed mass (inertia) and dissipation in materials

MGAS Filter





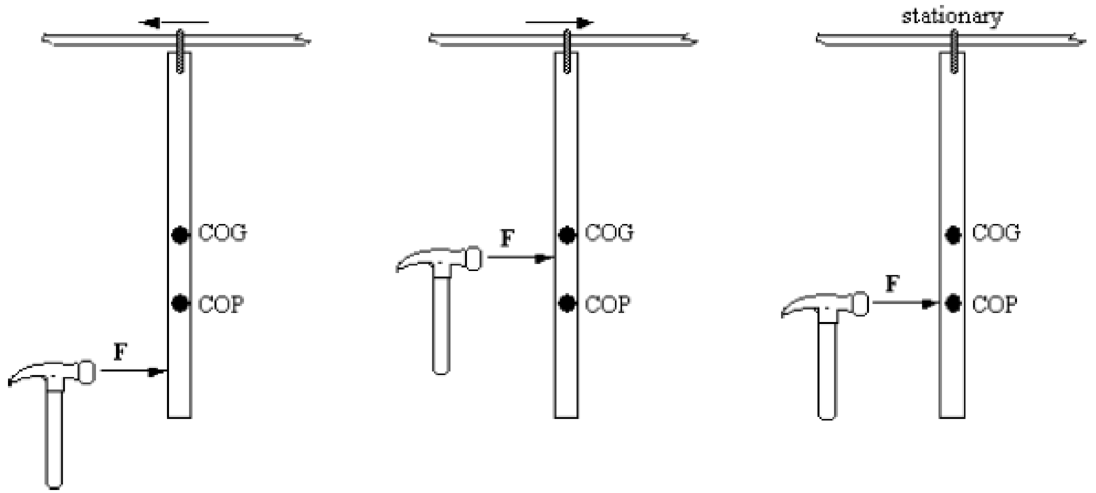
Linear Model for GAS Springs

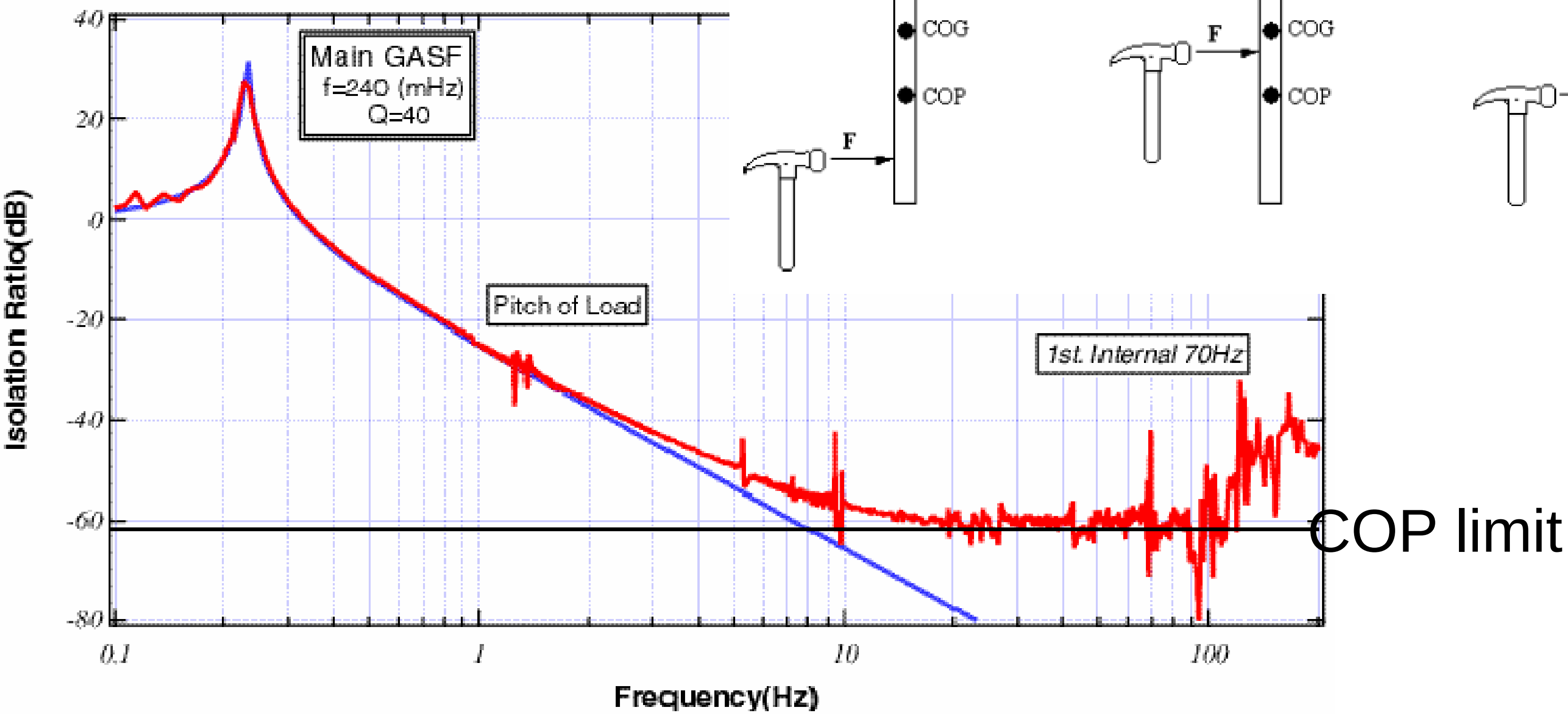


Illustrating the GAS filter

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

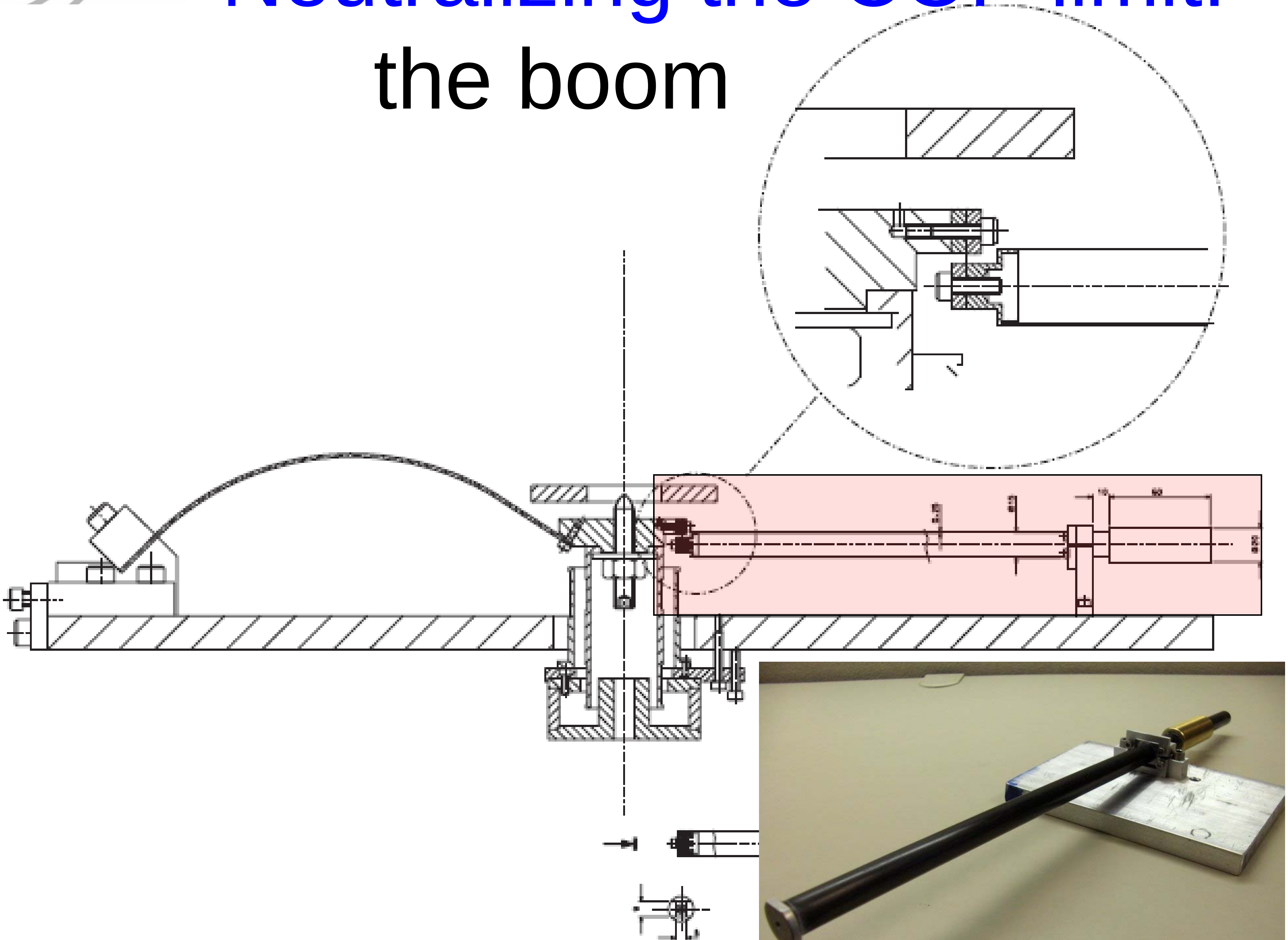
GAS Filter Limit



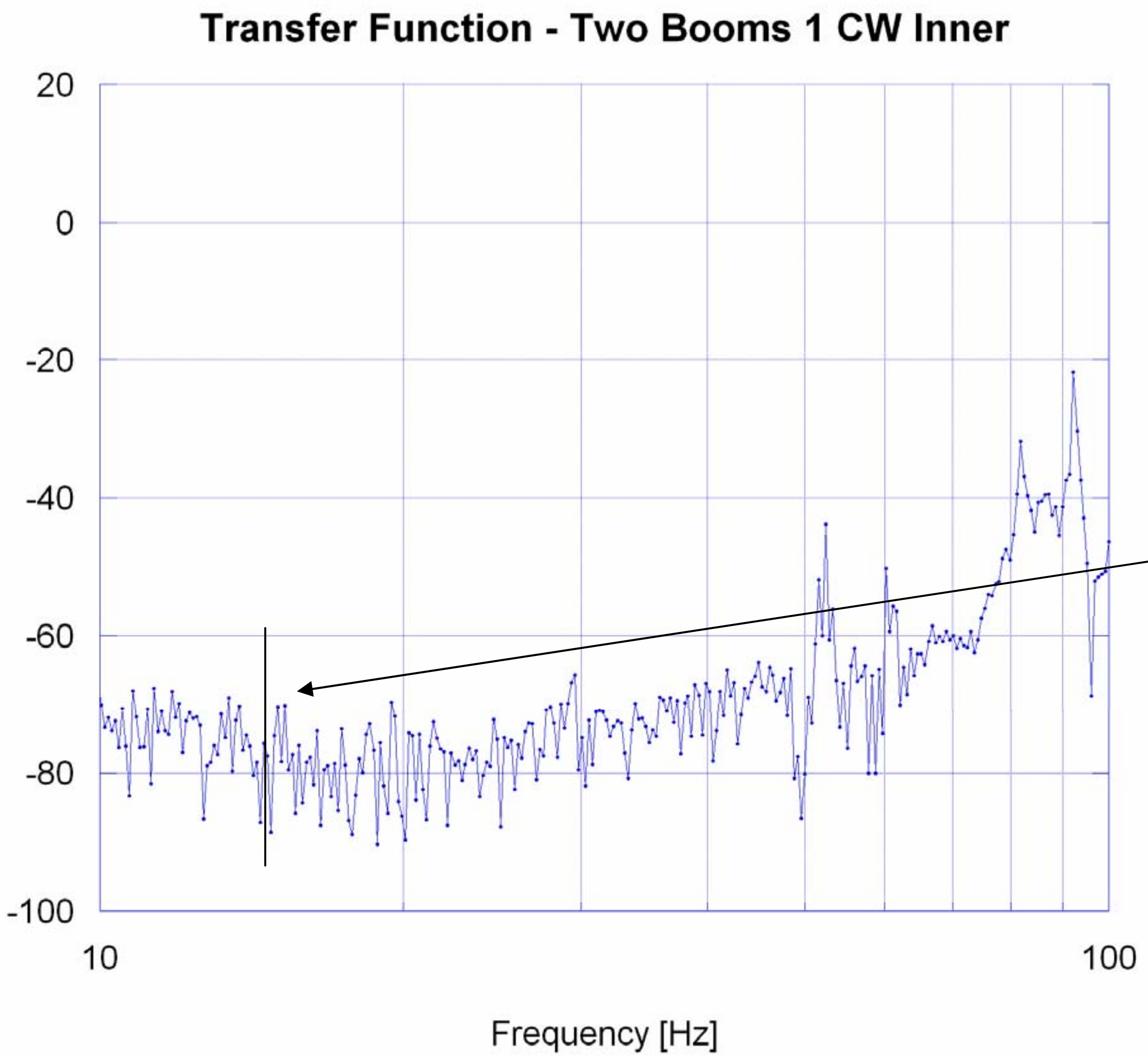


Neutralizing the COP limit:

the boom

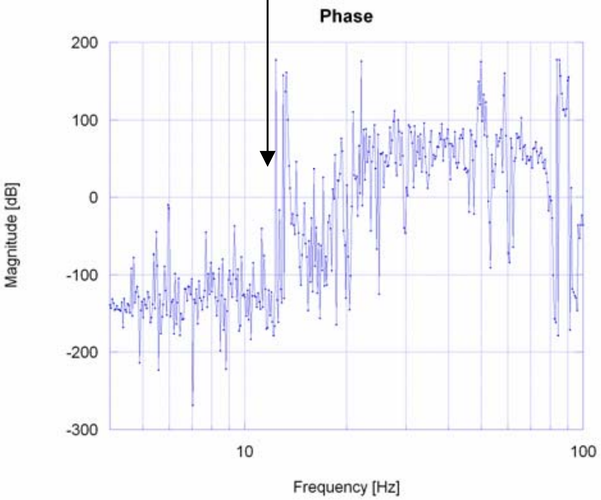


The Boom effect



- 80 Db per filter (or better) is possible

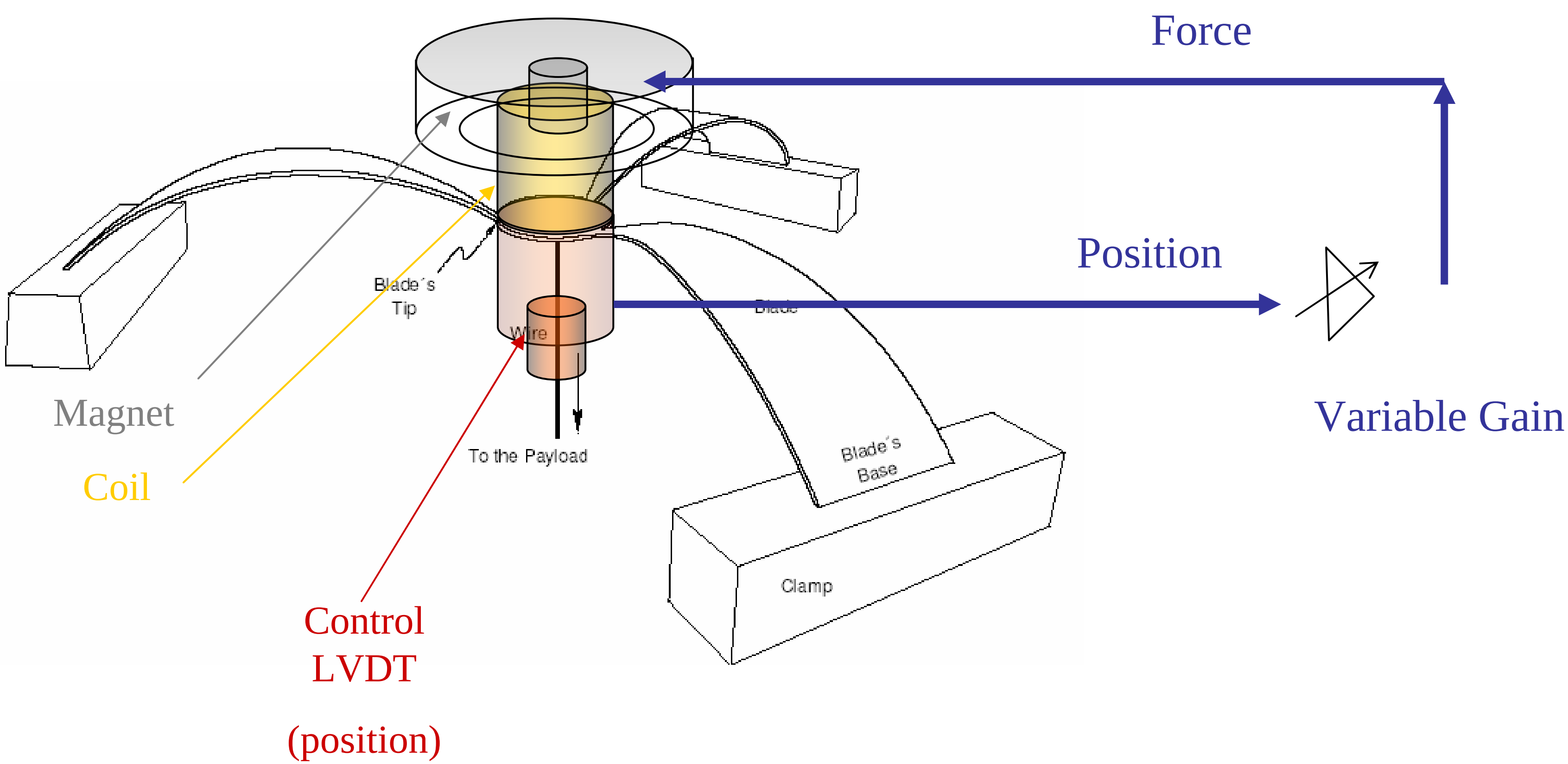
overcompensation



Tuning GAS springs to 30 mHz

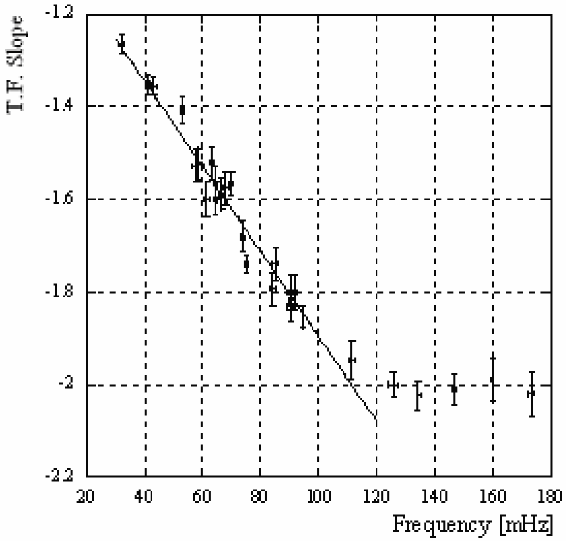
resonance frequency limited at >200 mHz

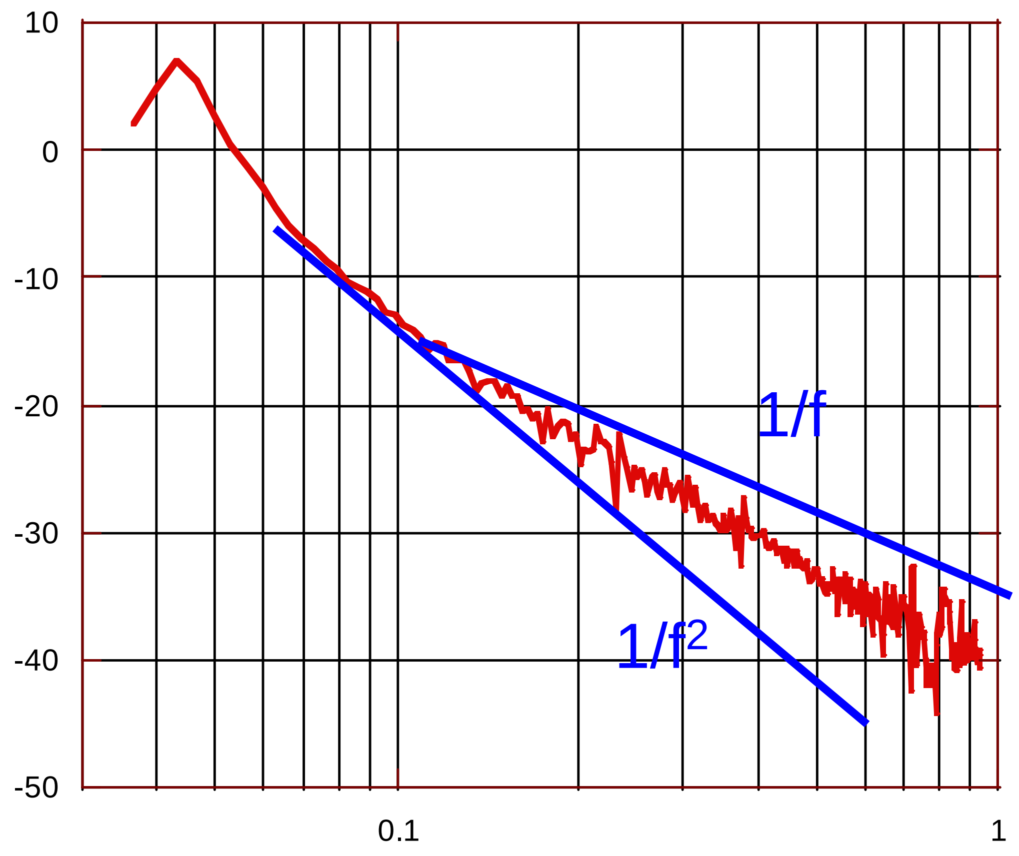
lowered < 100 mHz with E.M. springs



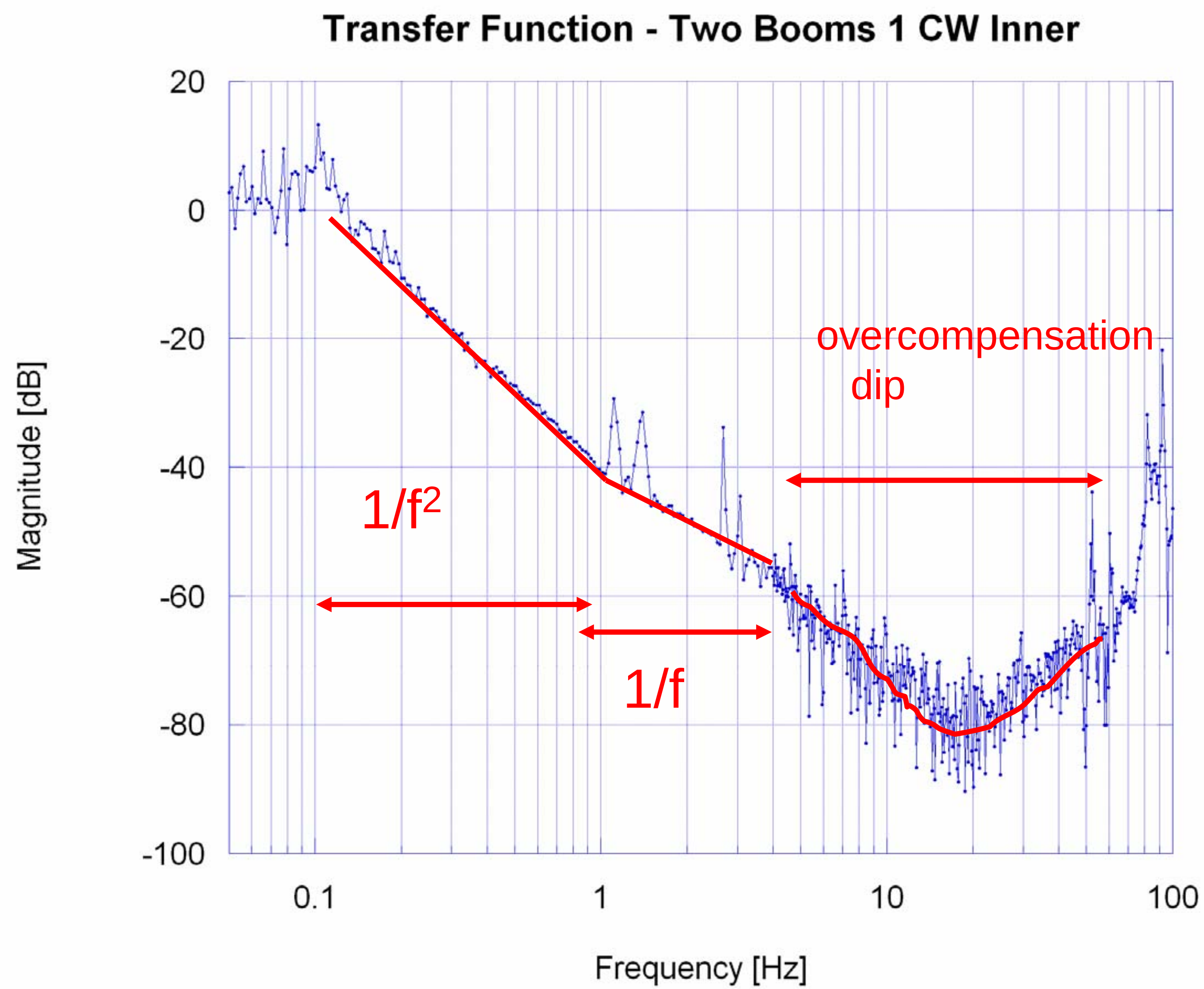
The hysteresis limit?

- at 30 mHz tuning the slope turns even closer to a 1/f slope
- Is a 1/f tail being uncovered or a gradual slope change?





The hysteresis limit?



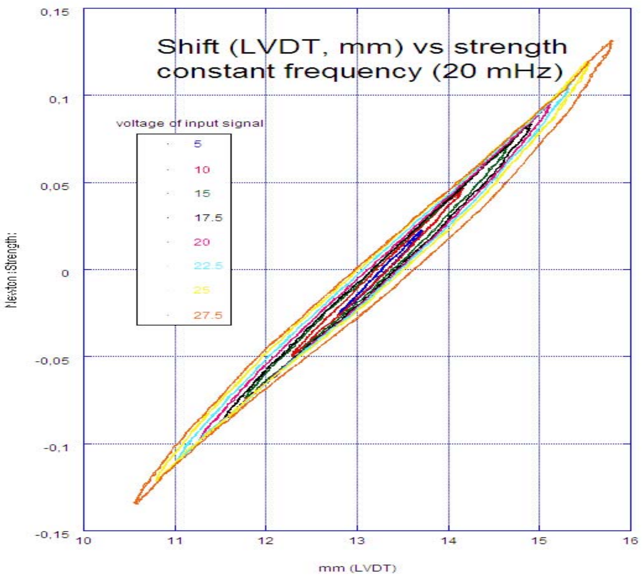
100 mHz
resonance

Understanding the 1/f degradation

- As the restoring force is tuned to zero

Hysteresis becomes the dominant effect

- Hysteresis $\propto \int past$
-



Understanding the 1/f degradation

- Viscous dissipation generates 1/f attenuation behavior

- Intrinsic dissipation generates $1/f^2$ attenuation behavior

Understanding the 1/f degradation

- Hysteresis ~ $\int \sin(t) = -\cos(t)$
- Viscous dissipation ~ - $\frac{\partial \sin(t)}{\partial t} = \cos(t)$

- Identical behavior ! !
- Both generate 1/f attenuation behavior

- At LF Hysteresis becomes dominant effect explains the observed effect

Two possible solutions

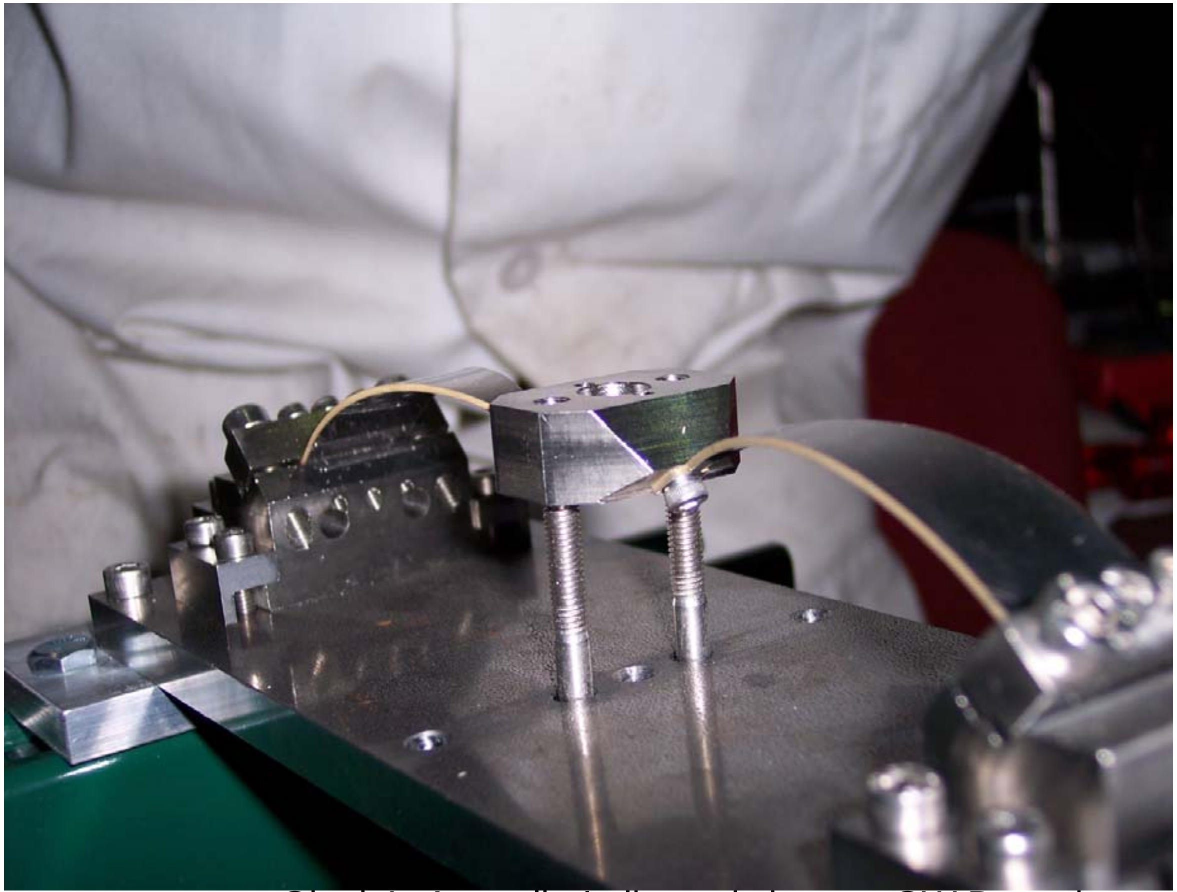
- Correcting the hysteresis by adding a

force $\propto \int past$??

- Using materials advanced with no hysteresis
  - Glassy metals

Glassy metal tests

- First Glassy metal GAS spring under test!!



Reducing the radiation pressure noise

The composite Mirror concept

- A heavy mirror is necessary to widen the radiation pressure/shot noise canyon
- > One ton inertial mass desired
- High transparency mirrors available only up to 200 Kg

Composite Mirror concept

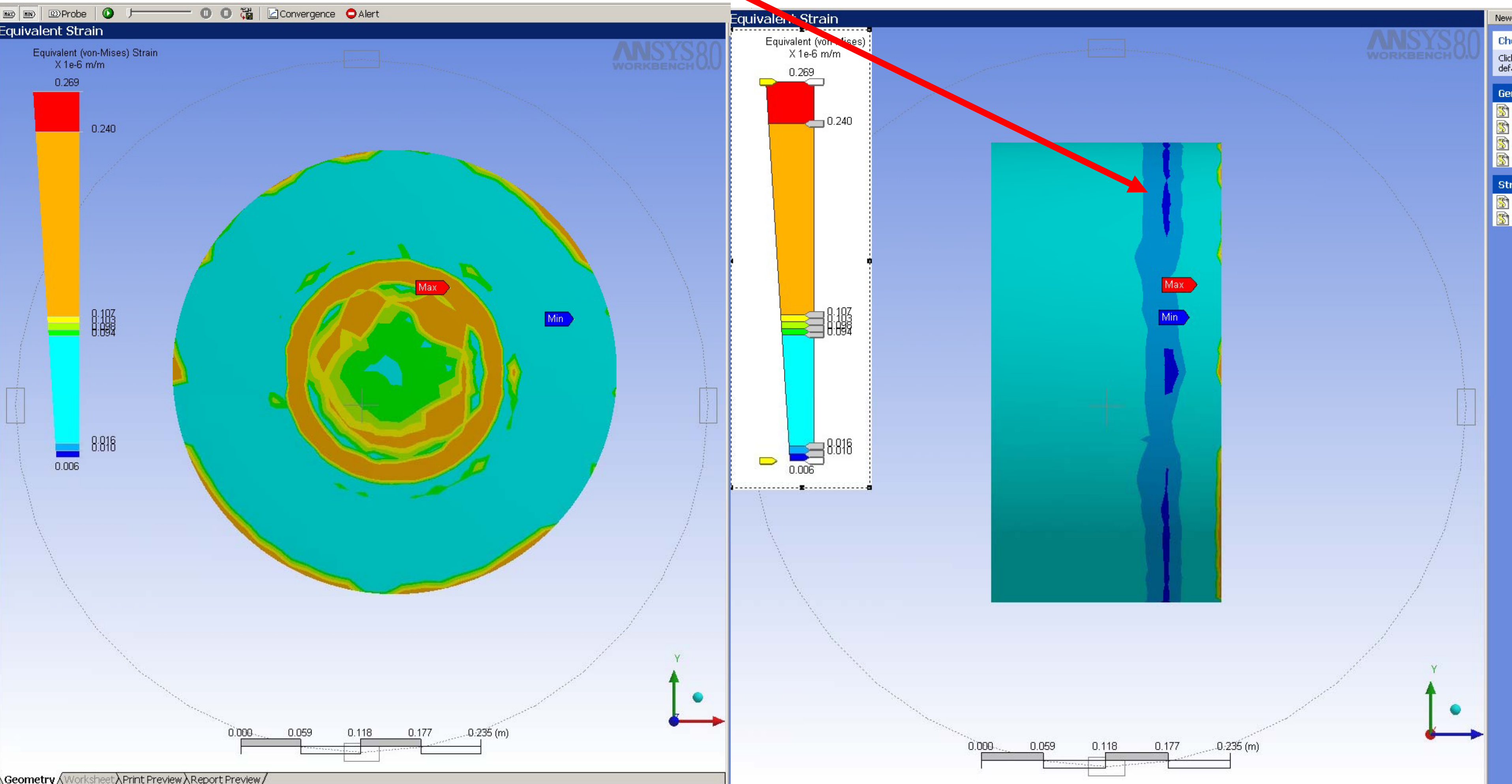
- Kenji Numata has proven that you can support a mirror from the nodes of a mode without affecting its Q-factor performance.
- Kazuhiro Yamamoto (Levin's theorem) has shown that:
  - if you consider the action of a pressure with the same profile of the laser beam and
  - support the mirror from points where this pressure has no action,
  - the thermal noise performances of the mirror is not affected.

Mirror concept

- Calum Torrie Using Ansys simulations and Andri Gretarsson with semi analitic means, both using Levin's recipe
- applied a beam profile pressure on a mirror
- found null action areas on the mirror outer surface

Ansys, Calun

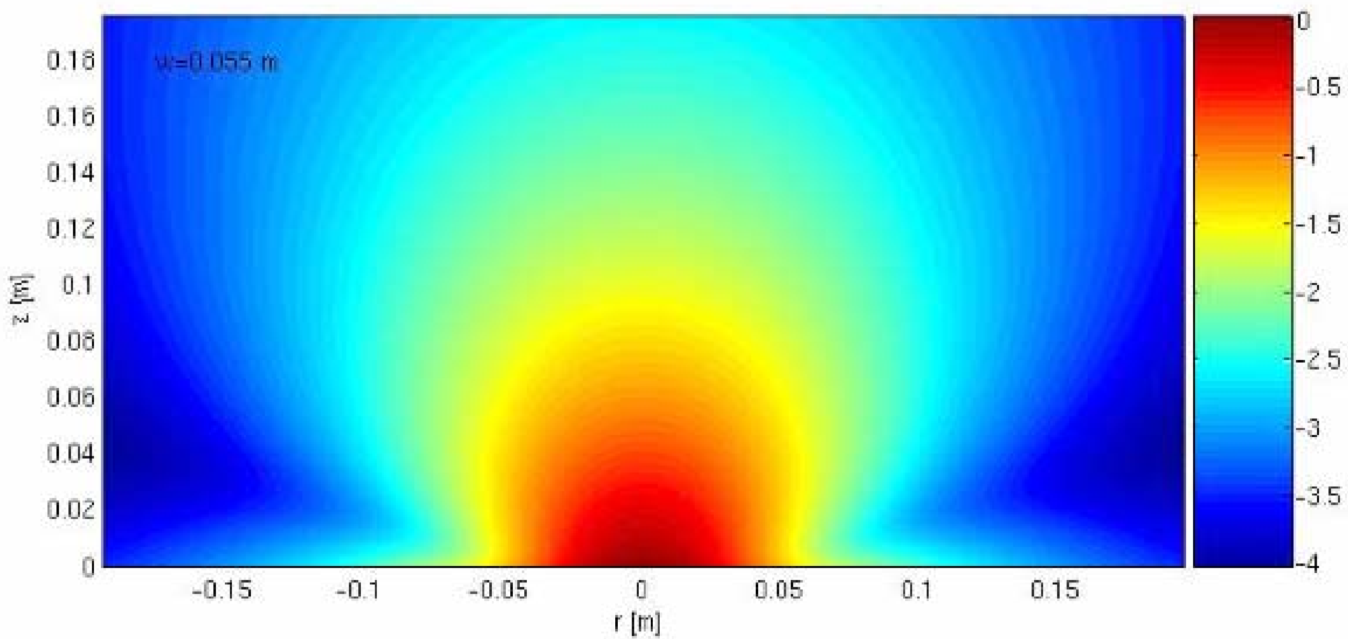
- A clear no action band is present



Semi-analytical, Andri Gretarsson

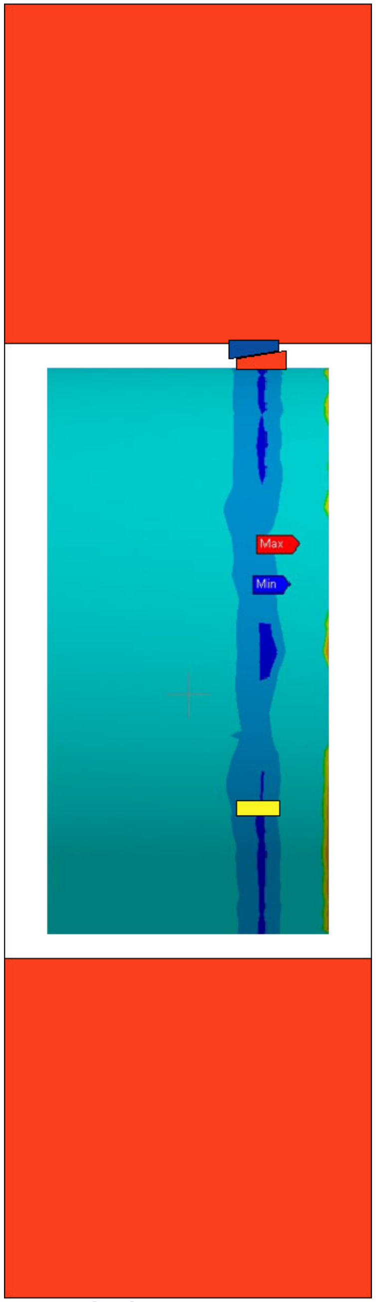
Null action band

$<10^{-4}$ effect



Mirror design consequences

- can mount the mirror from its neutral plane inside a heavy recoil mass
- negligible losses for the beam pressure action
- probably no TN degradation
- Forthcoming Tests at TNI



Mirror suspensions

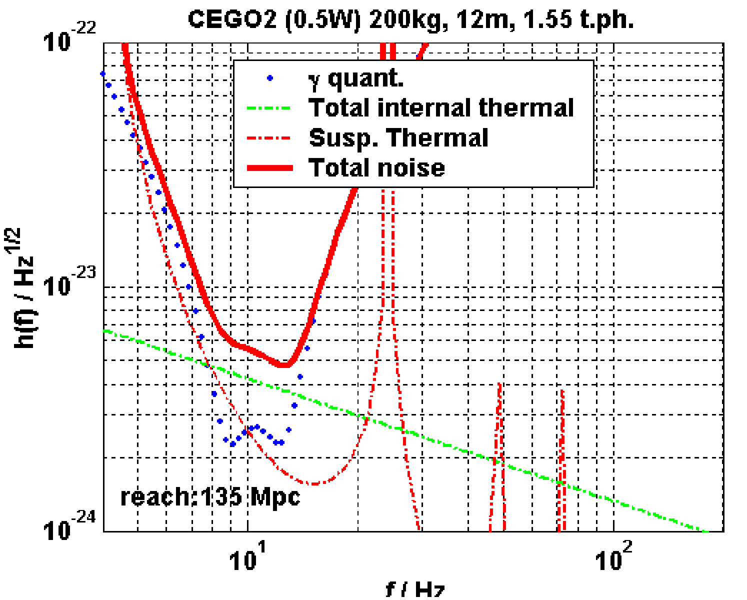
The longer suspension wires will push the suspension thermal noise to lower frequencies

Need to worry about violin modes

Need damping strategies?

Can use advanced materials to get lower STN with shorter wires?

Is Low Frequency the right place for cryogenics?



Where to dig an underground GWID?

- Need uniform rock to dig the mirror caverns for NN suppression
- Easy to dig and self supporting rock for cheapness
- Salt beds?
- Solid rock?

Where to do it?

- Salt beds
  - cheapest dig, but
  - problems with convergence, may need periodic shavings, also
  - access costs may be comparable with tunnel and cavern cost itself
- Solid rock
  - more expensive to dig, but
  - more stable, also
  - faster seismic wave speed,
  - may have crack problems if a crack is found at the mirror cavern point
- Examples?

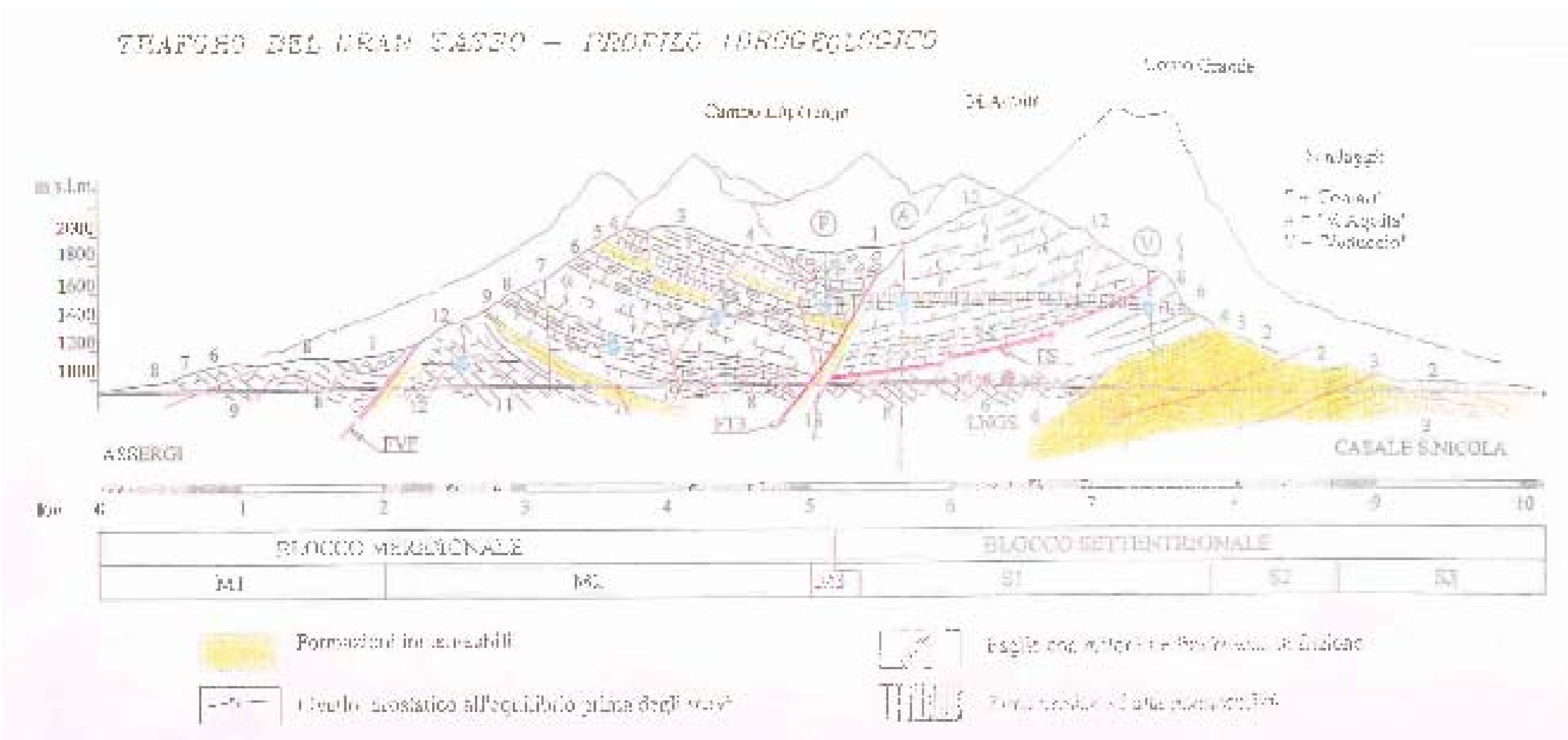
Digging in salts is made by means of continuous mining machines like this one

Arbitrary cave shapes are possible within the rock stability limits (30-50-even 100 m depending on salt quality)

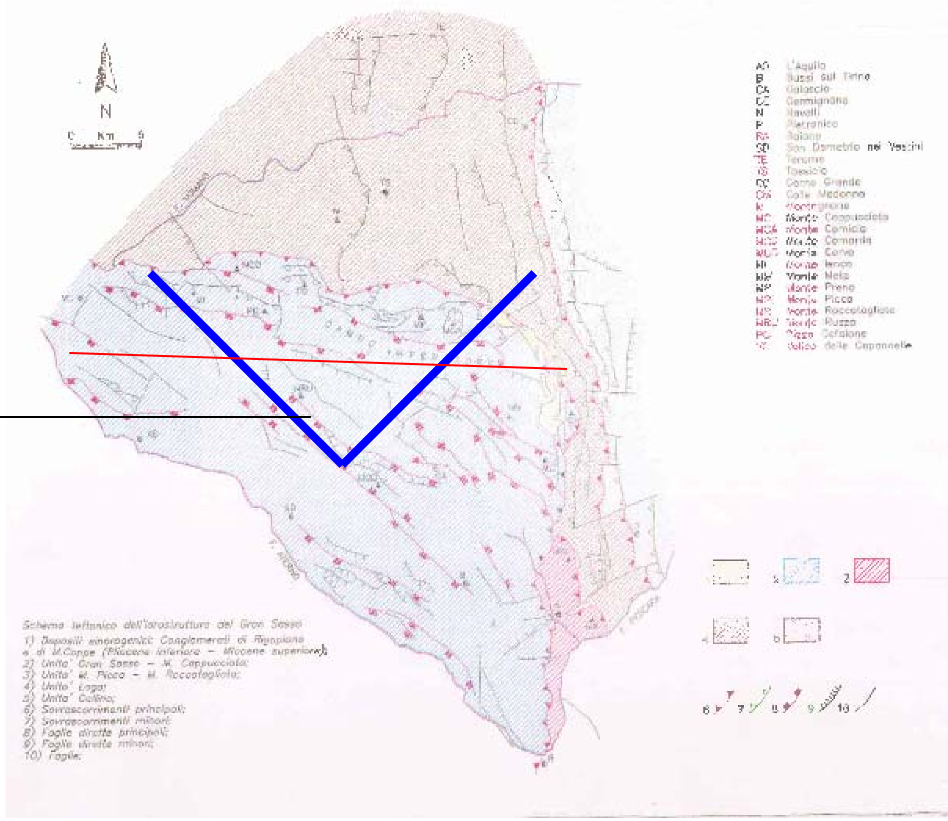
Kamioka?

- Is LCGT looking in the wrong frequency range?
- Going underground is expensive and is best justified for a bigger challenge
- Should a Low Frequency Observatory be considered on the side of LCGT?

Could it be done in Gran Sasso?

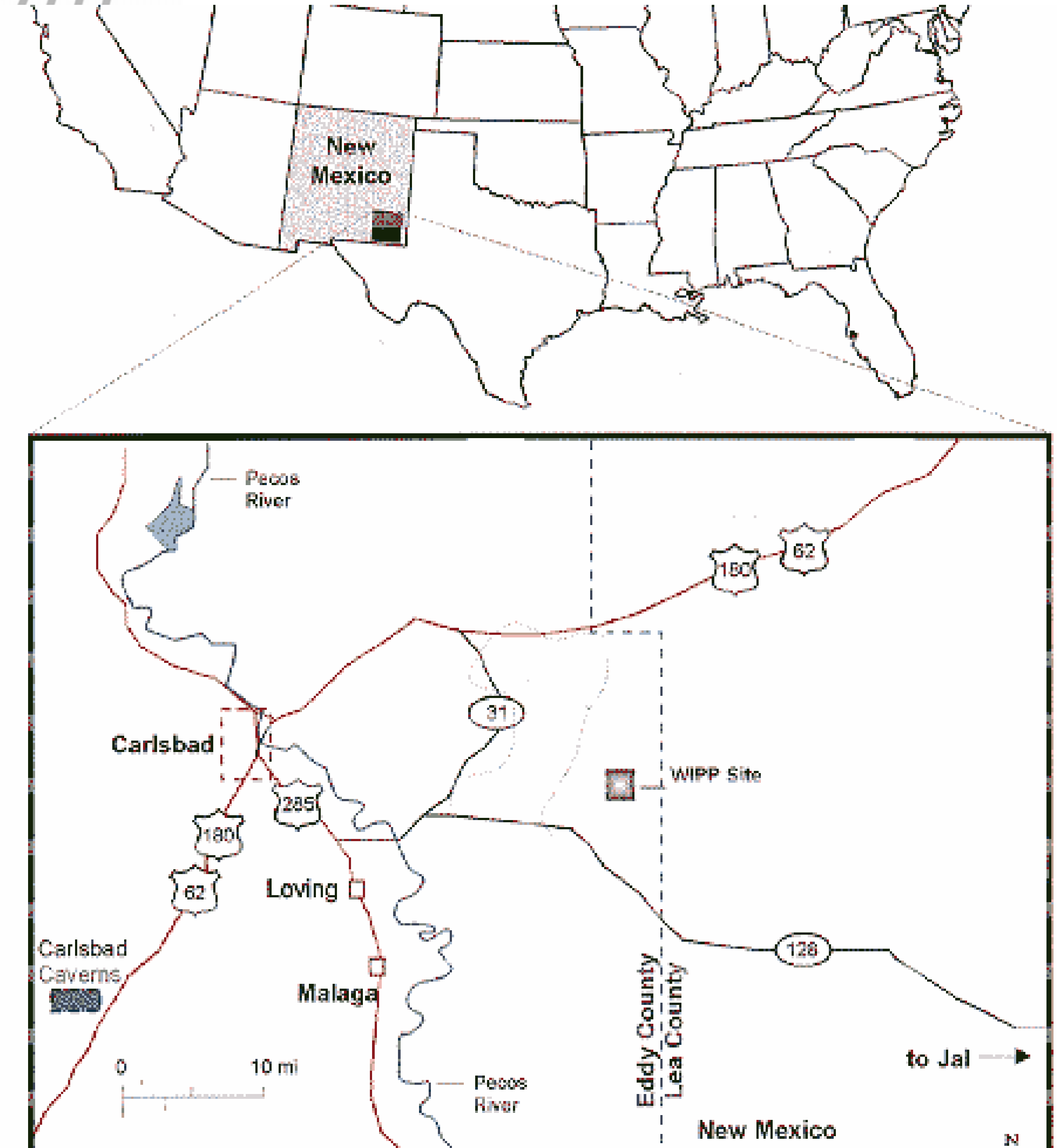


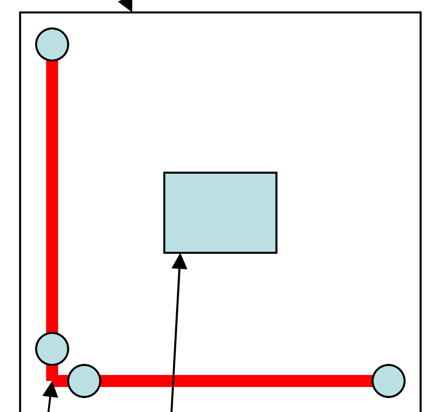
- Double access from the tunnel
- Beam splitter and end point far from noisy highway
- Pre-existing facilities
- Space for 2x6 maybe even 2x10 Km tunnels

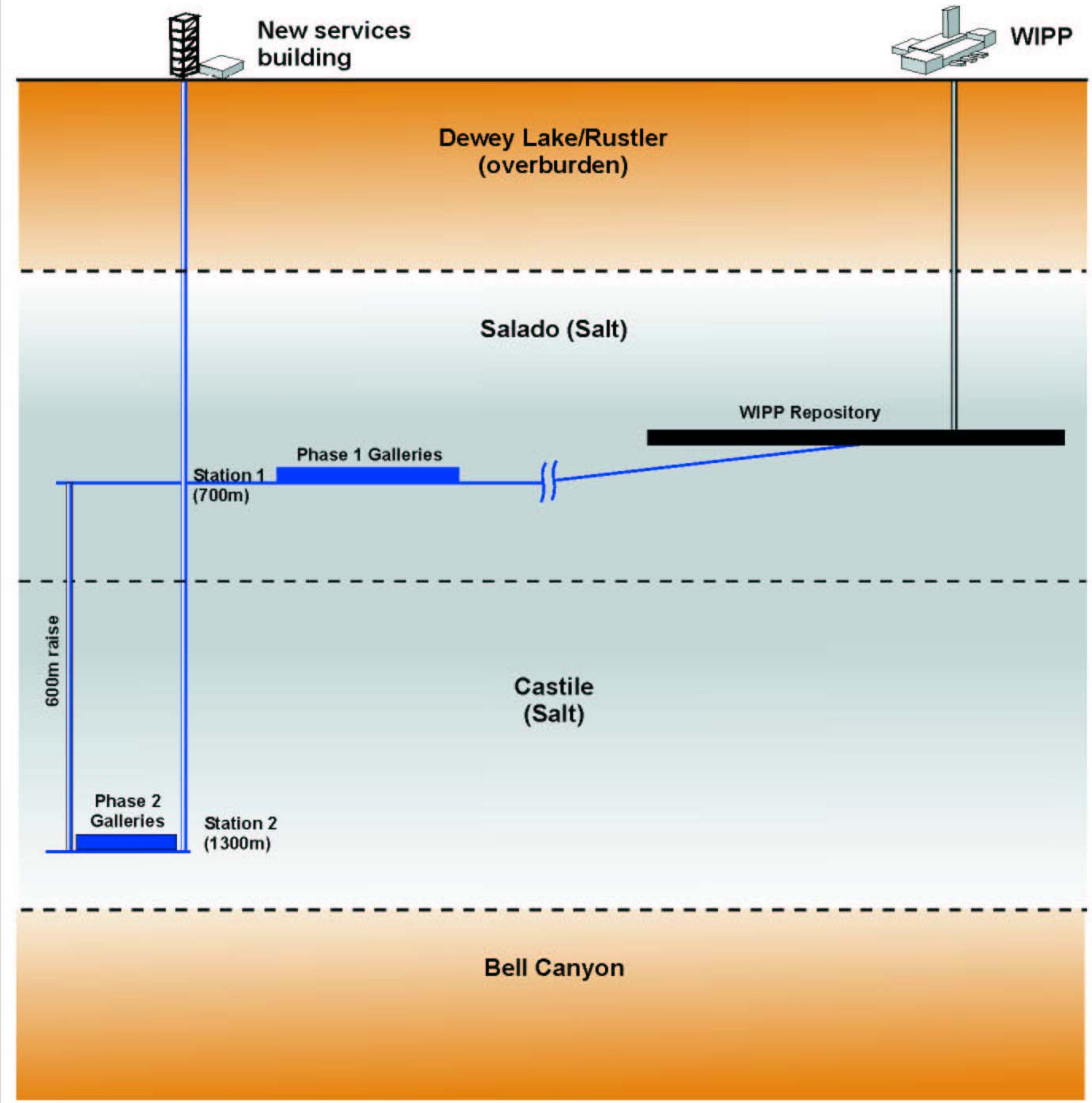


Could it be done at WIPP?

- Large salt beds available
- Land interdicted to commercial exploitation
- Local facilities
- Possibly access tunnels already available


New Mexico
Pecos River
62
180
31
Carlsbad
WIPP Site
285
180
62
Loving
Carlsbad Caverns
Malaga
128
Eddy County
Lea County
0
10 mi
to Jal
Pecos River
New Mexico
N

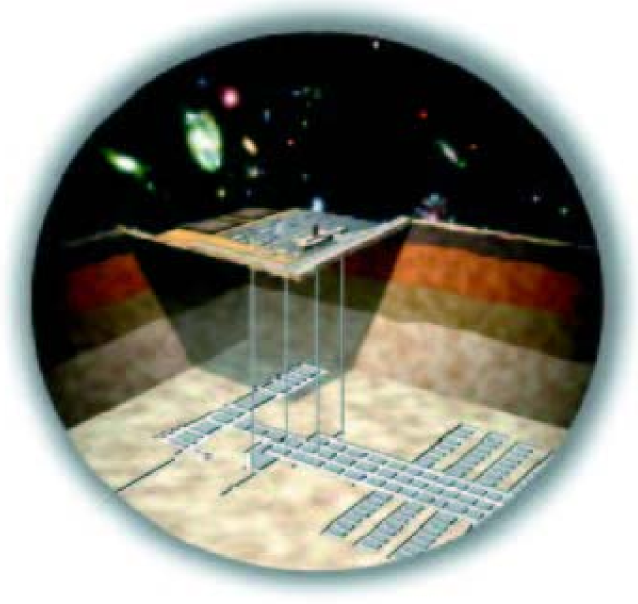

6.4*6.4 Km
WIPP land withdrawal area
(no commercial mining allowed)
1.5*2 Km
WIPP facility area
5*5 Km
interferometer



Chlorides
Dens. 2.1
More conv.

Sulfides
Dens. 2.3
Less conv.

Summarizing



Newtonian,

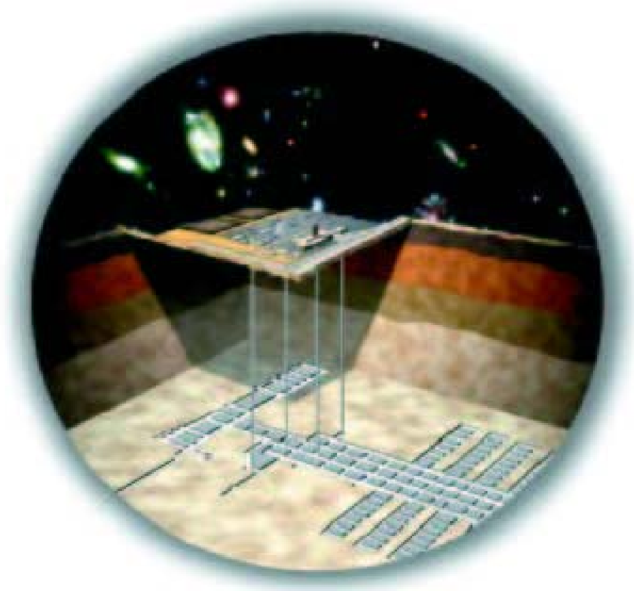
Suspension Thermal and

Radiation Pressure Noise

the three main limitations for Low Frequency operation of GWIDs

An underground facility would permit to overcome or reduce them

Summarizing



- Going underground is the next option to explore the

  Intermediate Mass BH Universe

it is time to start seriously thinking about it ! !