The need for a Xylophone of GW interferometers

Riccardo DeSalvo

The need for xylophones

- Future GW astronomy and astrophysics require observatories sensitive to lower frequencies

- Underground Observatories may allow sensitivity to intermediate frequency range,

  down to 1 Hz and

  maybe even 0.1 Hz.

The need for xylophones

- Everybody talks about the
  next generation Detectors
- Wrong!

- We have better talk about the
  next generation Facilities

The need for xylophones

- The human eye covers the frequency span between 380 to 750 nm,

  not even an octave

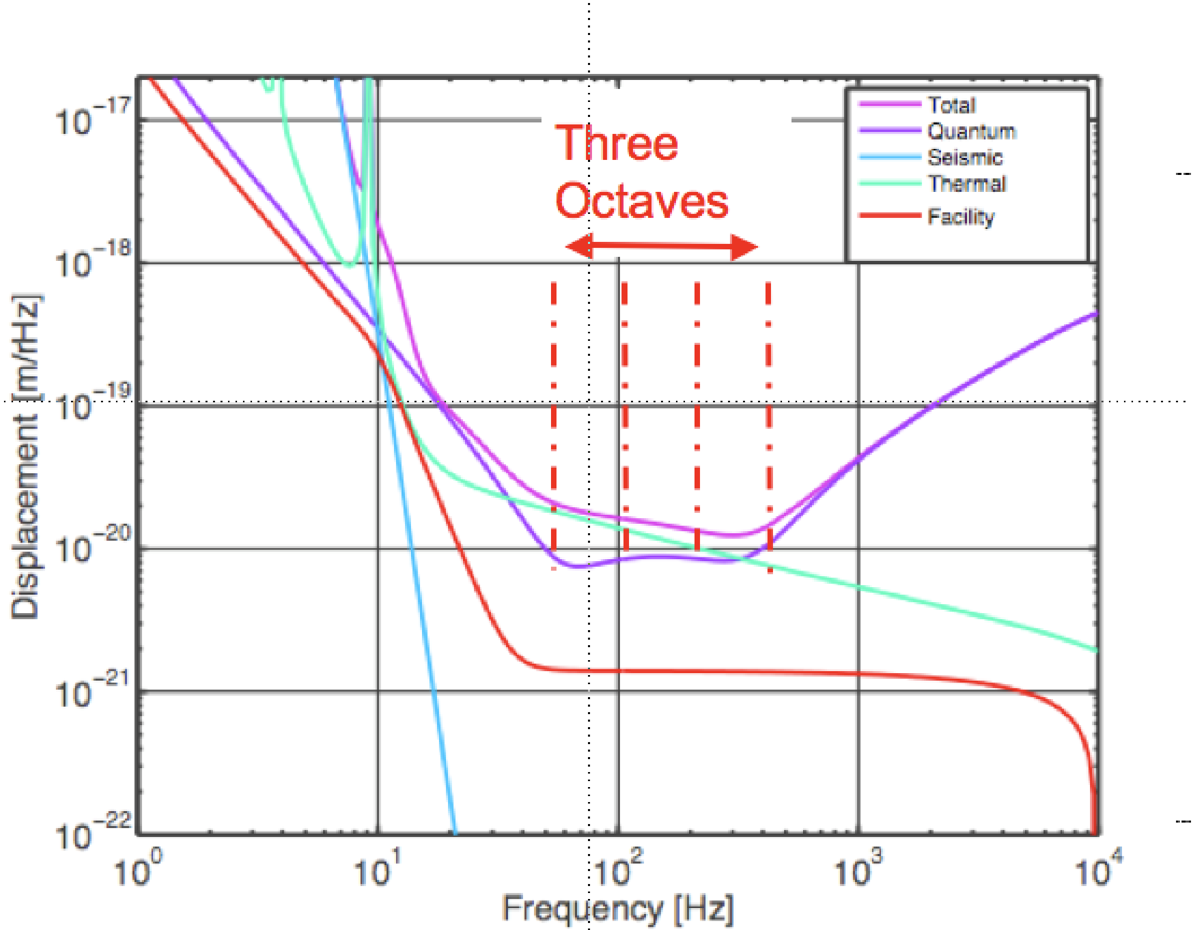
- Electromagnetic wave observatories use

  a host of different detectors

  to cover wider frequency spans

The need for xylophones

- Advanced LIGO and Virgo already cover much more than an Octave ! ! !



Why xylophones?

- From 1 kHz to 1 Hz (or to 0.1 Hz)

  there are 10 Octaves (or 13 Octaves)

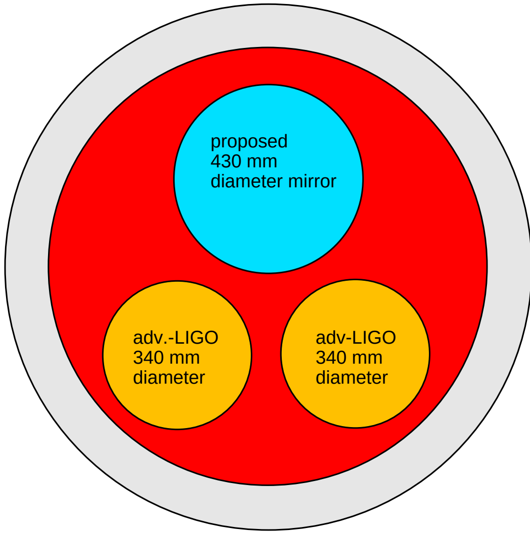
- Covering the frequency range between Advanced LIGO and the limits of Earth based detection

  will require a

  Xylophone of **frequency-specialized** instruments

Beginning xylophones (surface)

- "Proposal for lower frequency companions for the advanced LIGO Gravitational Wave Interferometric Detectors"



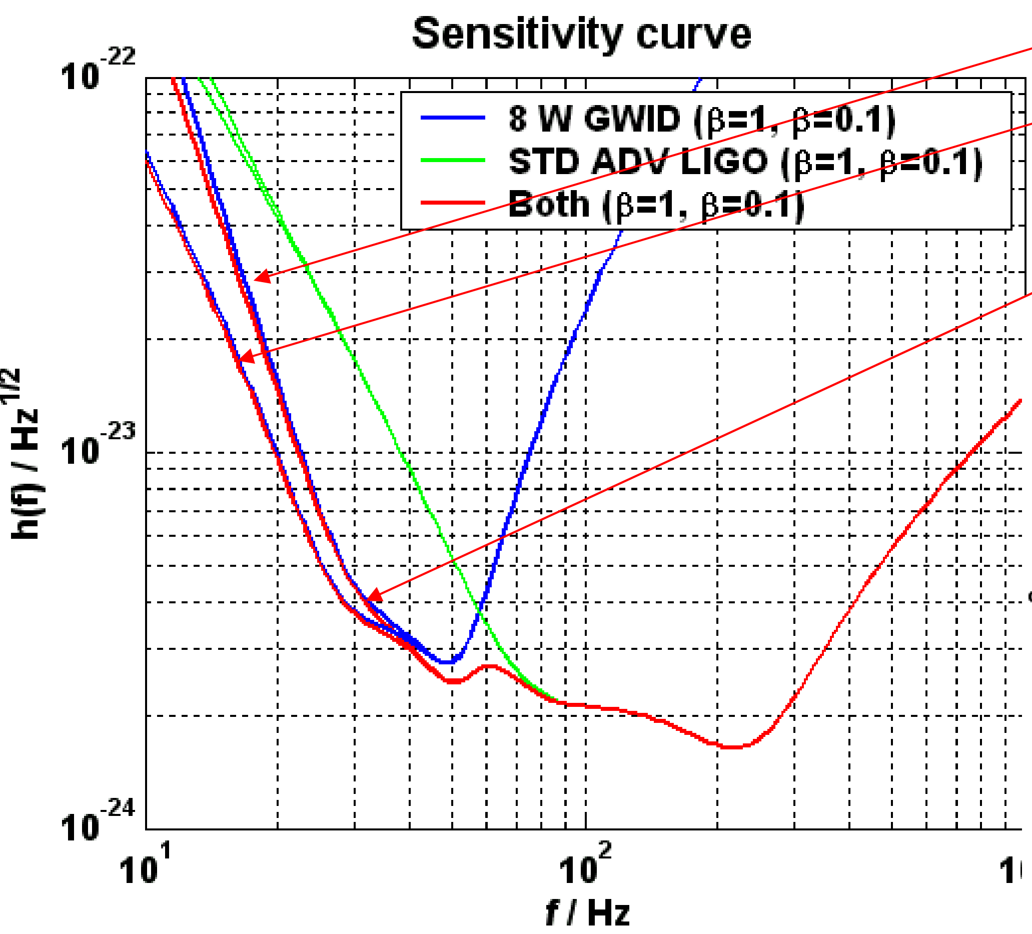
- Gianni Conforto, Riccardo DeSalvo
- Elba 2003

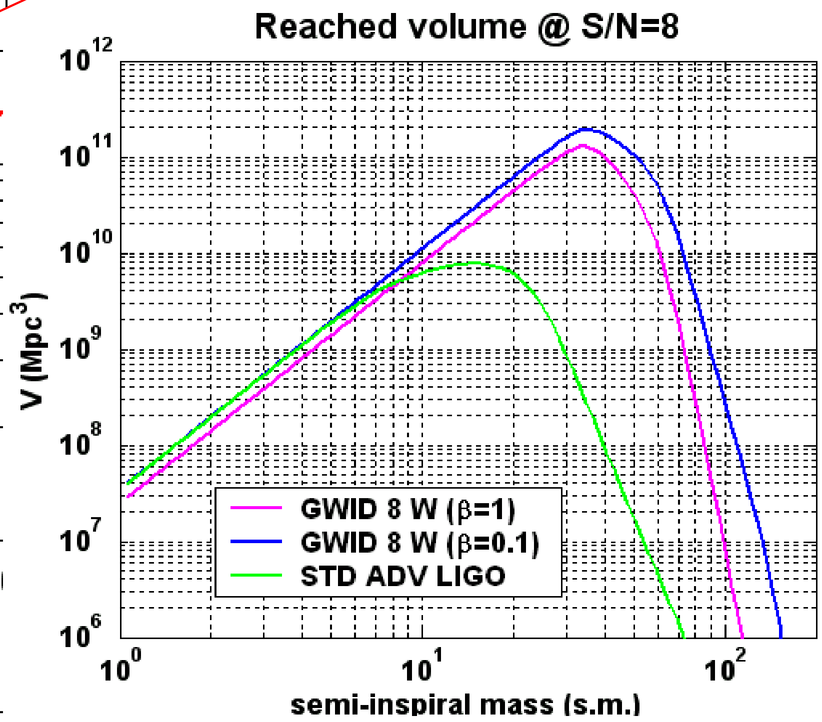
R.DeSalvo, Class. Quantum Grav. **21** S1145-S1154,(2004)
G. Conforto, Nucl.Instr.Meth. Vol 518/1-2 pp 228-232 (2004)

LF-GWID the lowest frequency feasible surface GW detector

Bad seismic day
Good seismic day

~30 Hz, possibly 20 Hz

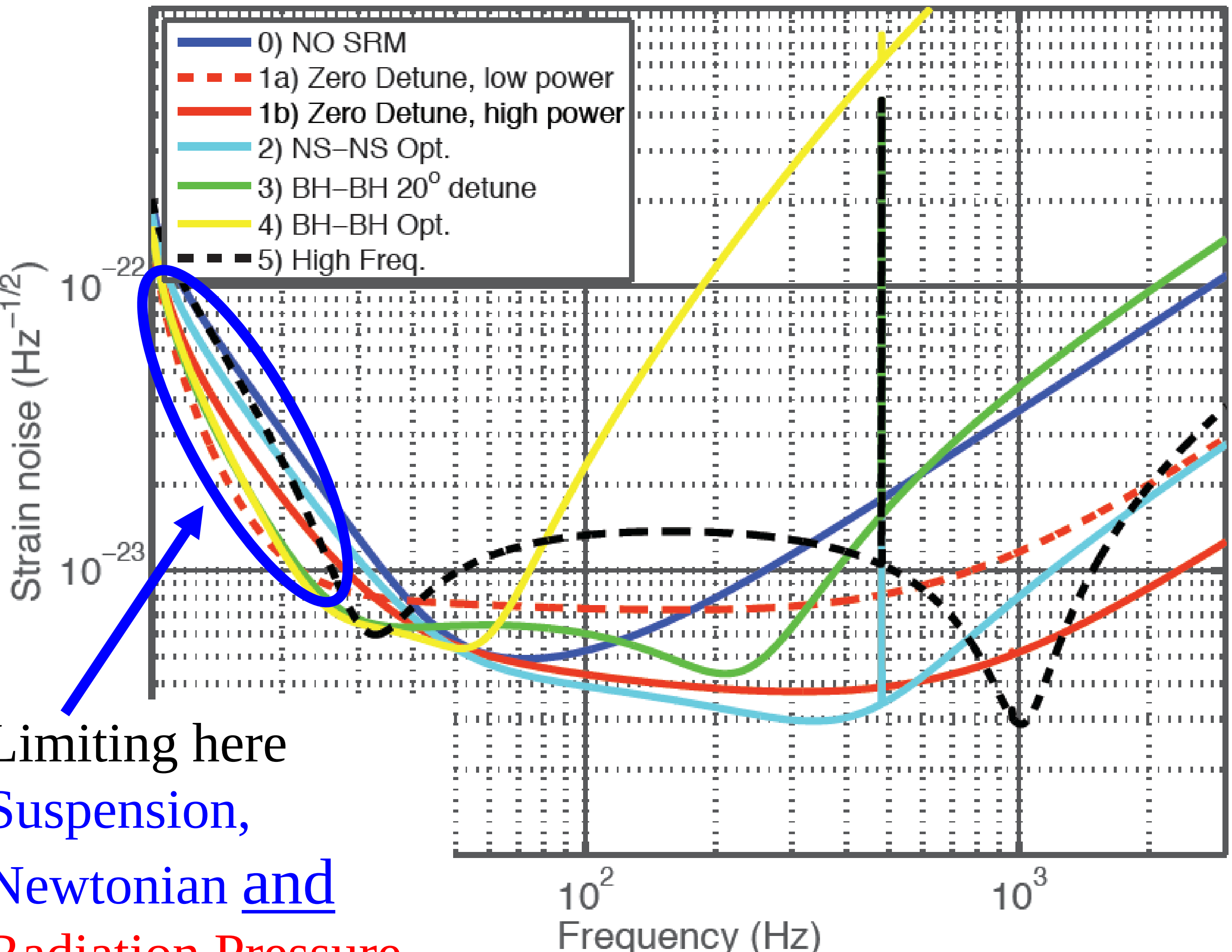




Note: T.N. estimation

"Before coating thermal noise times"

Sam Waldman



- The Lower Frequency Interferometer covers a Narrower bucket
- Little more than an Octave

Limiting here Suspension, Newtonian <u>and</u> Radiation Pressure noise

Surface xylophones

- Rana Adhikari, Caltech 2008

- Low power,
- Blue light

to reduce

Thermal noise

- Advanced

  LIGO

  mechanics

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

Surface xylophones (2)

- Blue light less Tantala, less TN,
- additional consequences
- Smaller diffraction-limited Gaussian beams
- Much wider mesa beams possible
- Additional TN Gain of 4-5
- 10-20 x more light required
- More radiation pressure noise

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

Radiation Pressure Limitation

- Blue light helps in lowering thermal noise and less required power for same length sensitivity
- But blue photons carry more momentum, not exactly the best to reduce the Radiation Pressure problem!

- Help is needed from Quantum Tricks to mitigate the quantum limit effects and minimize the number of separate interferometers in the xylophone
- For the moment only MUCH heavier masses would be a guaranteed solution

Underground Xylophones

Mining for gravitational waves

- Enrico Campagna
- Giancarlo Cella
- Riccardo DeSalvo
- Seiji Kawamura
- Aspen 2005

•Y. Chen, R. DeSalvo, 2004

•Study for CEGO China Einstein Gravitational wave Observatory

Pushing the Low Frequency Limit of ground based GWIDs

1. Newtonian Noise (NN)
2. Suspension Thermal Noise (STN)
3. Seismic noise

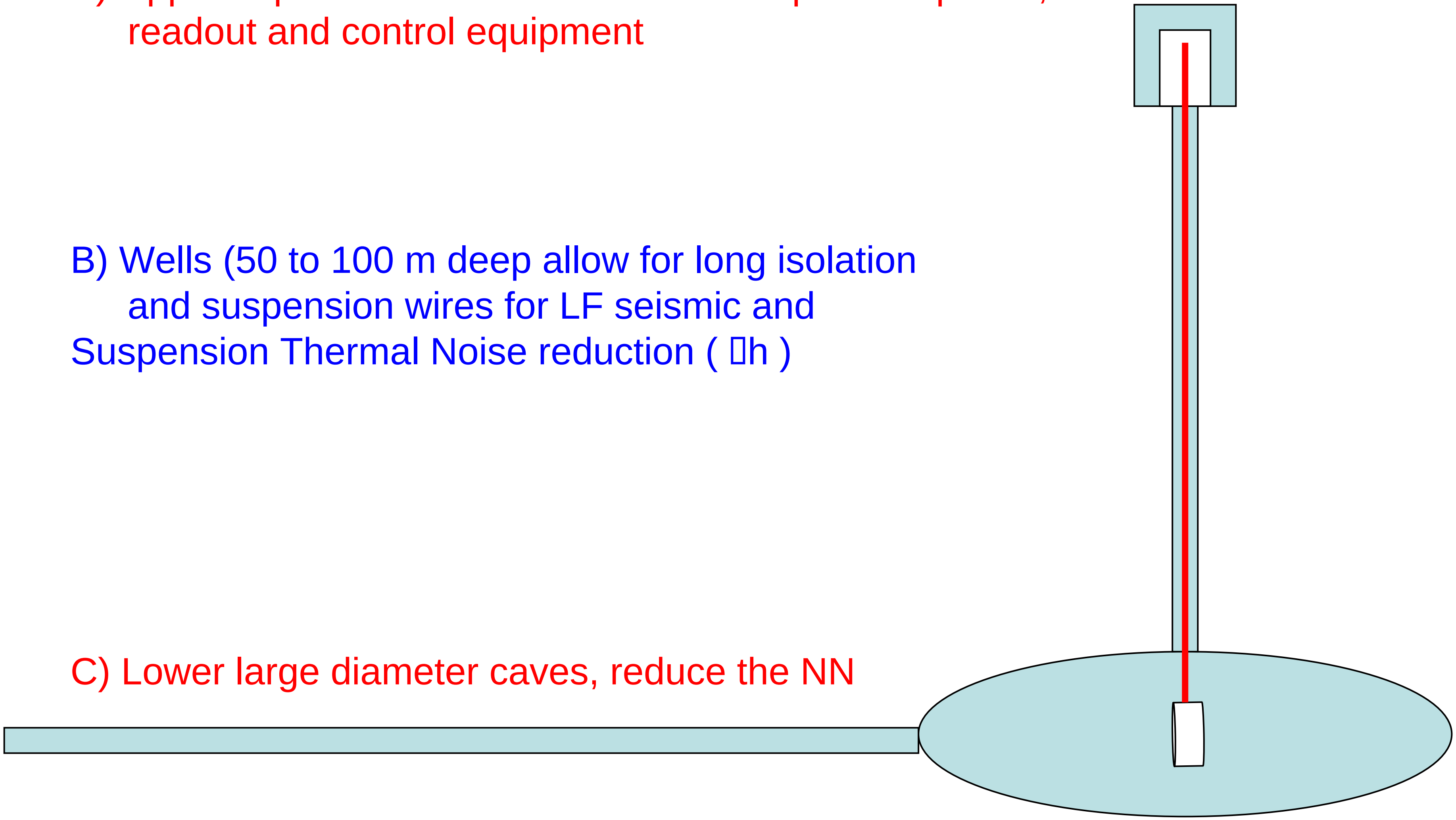
4. Radiation Pressure Noise ~ $I^{1/2}/(mf)^2$
5. Shot noise ~ $1/I^{1/2}$

Other problems more or less trivially solved

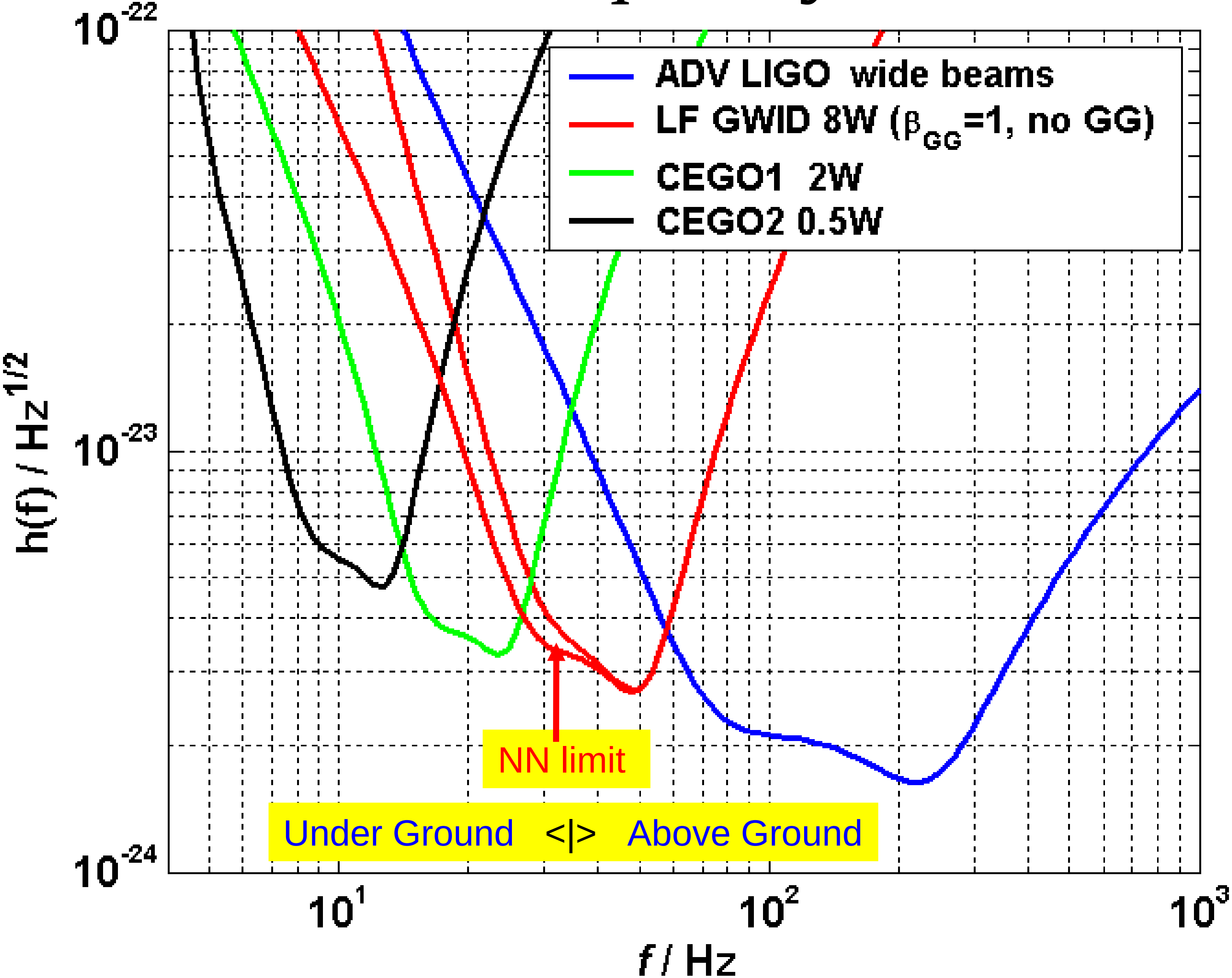
A) Upper experimental halls contain all suspension points,
readout and control equipment

B) Wells (50 to 100 m deep allow for long isolation
and suspension wires for LF seismic and
Suspension Thermal Noise reduction (□h)

C) Lower large diameter caves, reduce the NN



Frequency reach



Some design parameters

	ADV-LIGO wide beam	LF-GWID	CEGO1	CEGO2
Arm length (m)	4000	4000	4000	4000
Laser power (W)	125	8	2	0.5
Last susp. stage length (m)	0.6	1.5	6	12
Mirror mass (kg)	40	73.5	120	200
Mirror Q	$200\text{-}10^{6}$	$200\text{-}10^{6}$	$200\text{-}10^{6}$	$200\text{-}10^{6}$
Mirror coating phi	$2\text{-}10^{5}$	$2\text{-}10^{5}$	$2\text{-}10^{5}$	$2\text{-}10^{5}$
Mirror radius (cm)	15.7	21.5	24.8	24.8
Beam radius[3] (cm)	9.4	12	14	14
Signal recycling mirror transmit.	0.07	0.07	0.07	0.07
Signal recycling cavity detuning phase	0.12	0.52	0.95	1.55

Table 1A: list of optimization parameters of the four interferometers shown in Fig 2.

How to minimize the number of Xylophone elements?

- use the heaviest available test mass
  to widen the bucket

- starting with high frequency interferometers !

Radiation Pressure Limitation

- Radiation Pressure is probably the strongest limitating factor for LF interferometers

- Need much heavier test masses to avoid being forced to insufficient laser power on the mirrors to match thermal noise

- Insufficient mass makes the “bucket” narrower

How much heavier masses can we produce?

- Limits come from melting ovens and cooling times
- Larger masses require longer cooling times
- More internal stress, less purity
- Industrial trends moves towards heavier masses, which is good, but how far can we go? 1 ton?

- Might argue: Lower frequency means less power, which means more tolerance to impurities, maybe easier to make larger masses
- But best to use heavier masses early on
- Still need very good optical quality

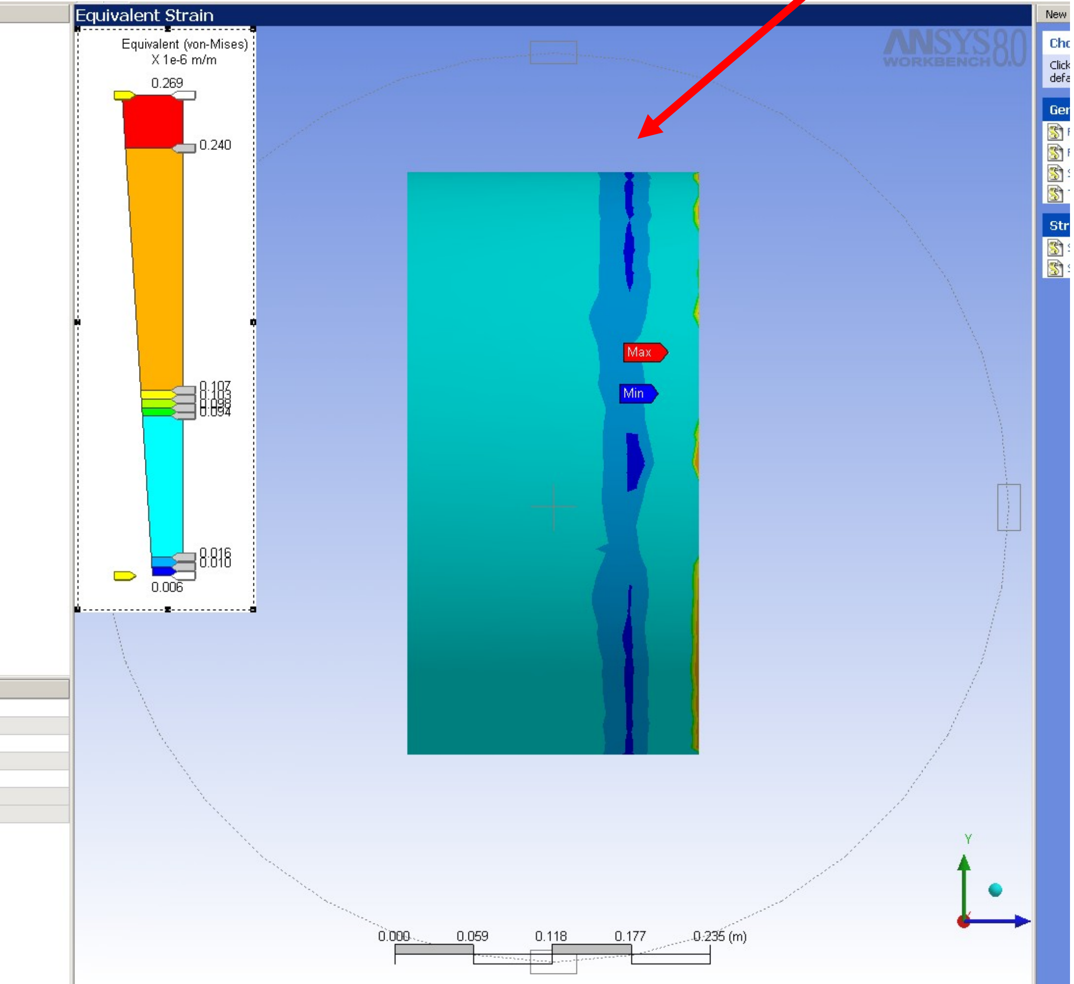
Composite masses are probably inescapable

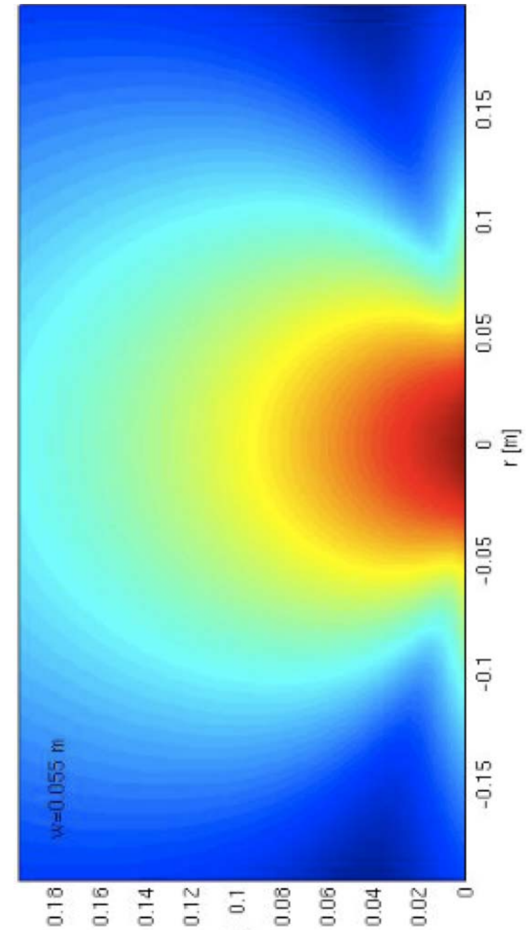
- Composite masses were proposed
- Good optical quality core and good mechanical properties in external ring
- Can we mount concentric masses without introducing other losses and causing Thermal Noise problems ? ? ?

- Proposed Solutions:

Calun Torrie, Ansys, Andri Gretarsson, Semi-analytical

- A clear lower action band is present on barrel

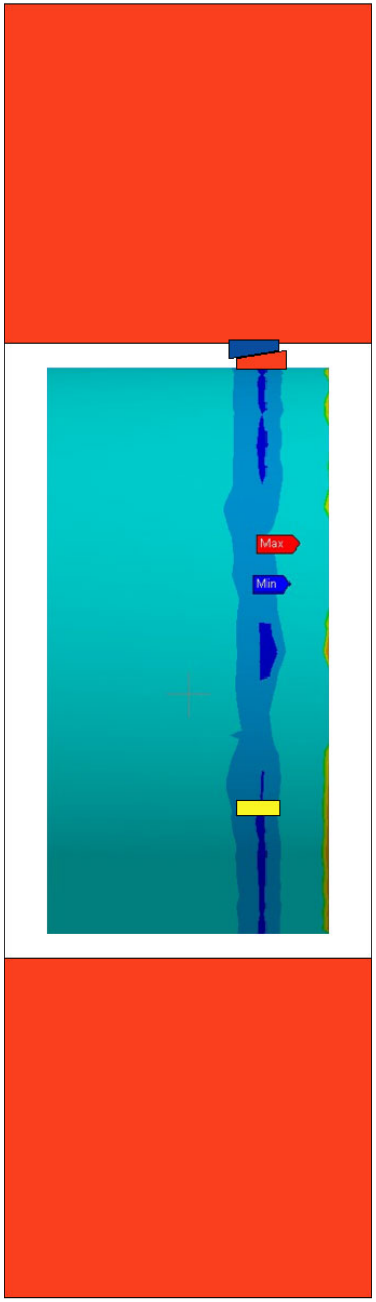




Encased mass

- Could mount the mirror holding from its neutral plane inside a heavier recoil mass

  Without spoiling its TN performance?



- Off center stresses
- Is this a killer ?

Suspended mass

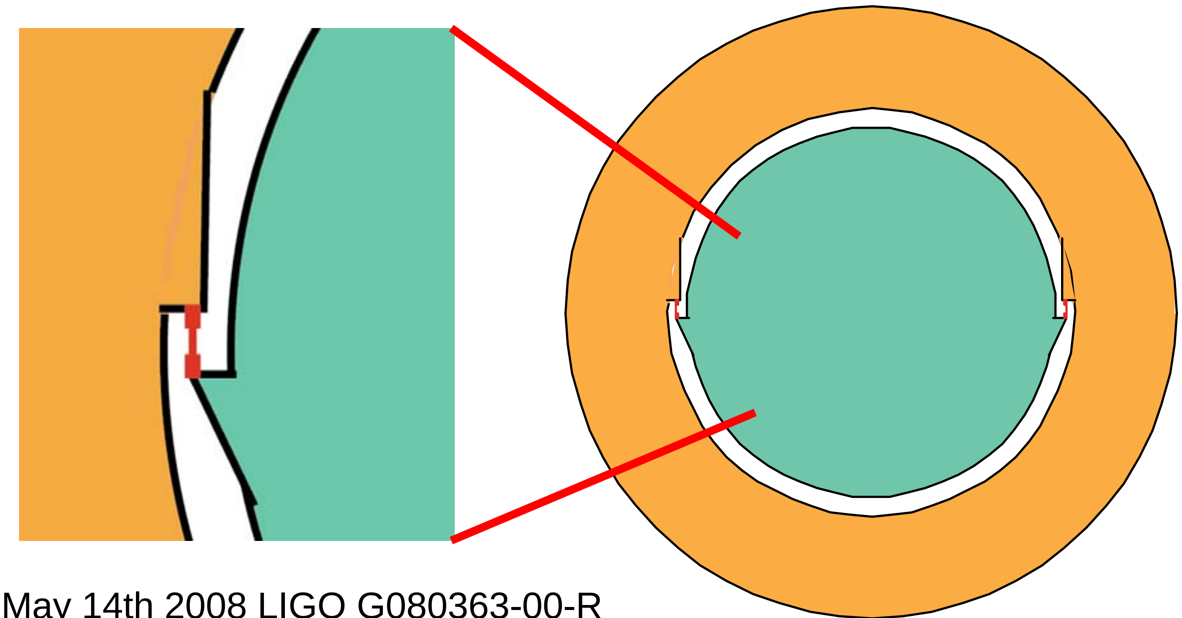
- We are fairly confident that we can suspend a mass without wrecking its TN performance

- Can we suspend it inside an external ring with sufficient rigidity to confer the effective mass of the heavier outer ring

  to the core mirror ? ?

Pendulum TF flat below its resonance

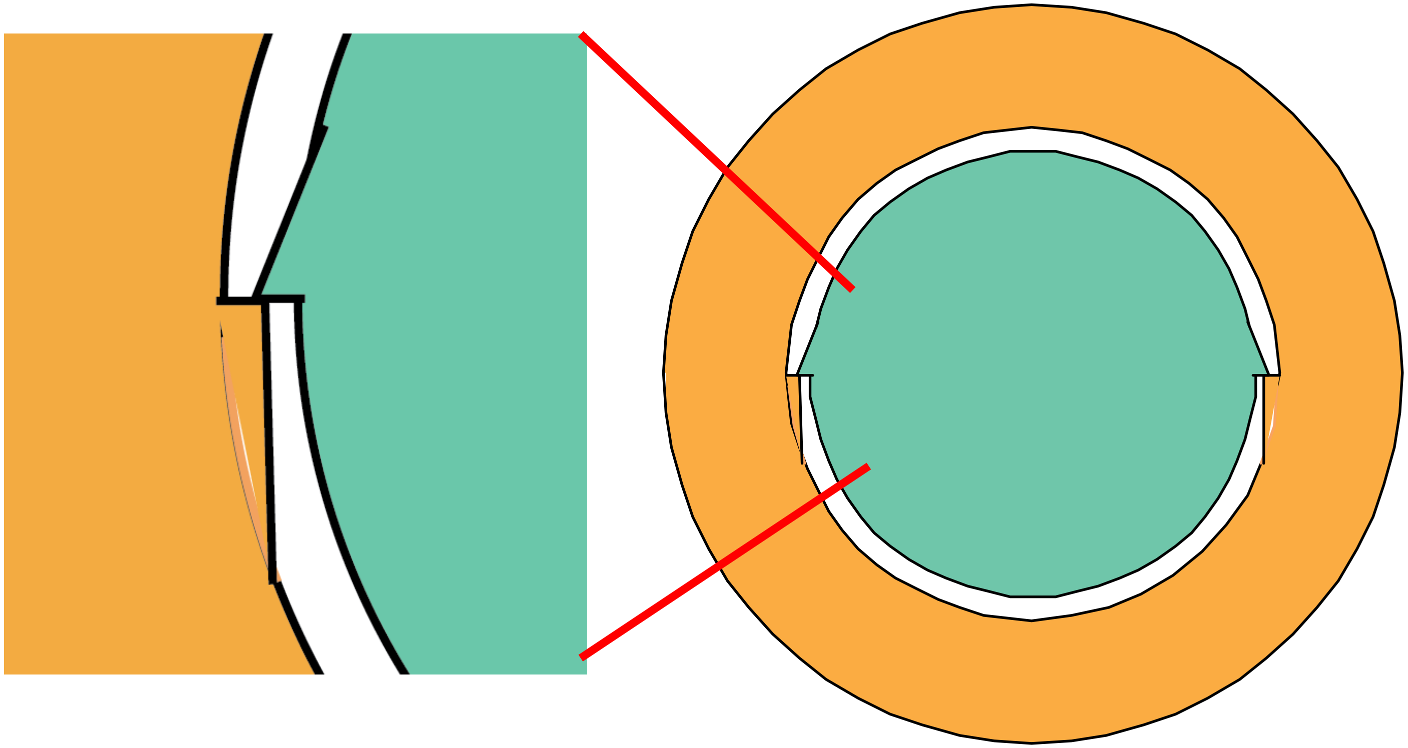
- Suspend concentric mass with very short (1 cm pendulum = 5 Hz) suspensions with pendulum resonance "above" the GW frequency of interest?



- If it works we solved the problem below, say, 5 Hz

- Tough to make suspensions shorter than 1 cm

- Can we simply support the mirror from a shelf in the annular ring?



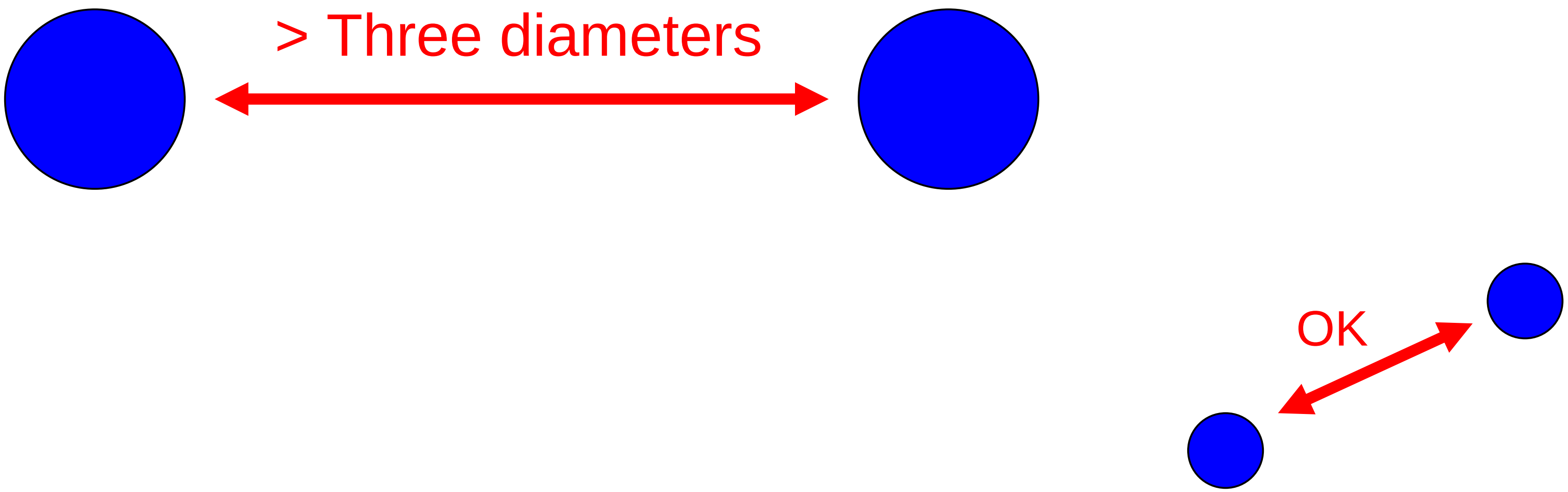
A different question

- How can we fit a xylophone of interferometers in an underground facility?

tunnel digging in hard rock

- Digging with Tunnel Boring Machine
- Cheapest tunnel diameter
  > 5 meters
- The size is dictated by the trucks that must evacuate the rock, air piping, equipment movement, . . .

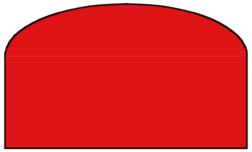
- Comment:
- Long distance tunneling will likely require dual bore with crossings (safety laws)



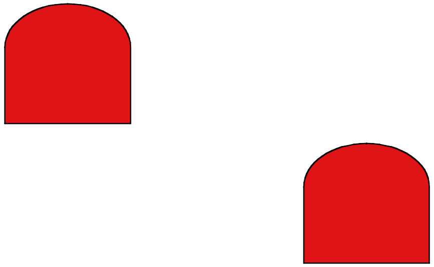
tunnel digging in salts

- Digging with continuous miners
- (flat bottom rounded top profile)

- One tunnel option
- Cheapest option tunnel 5x7m
- Evacuation: conveyor belts

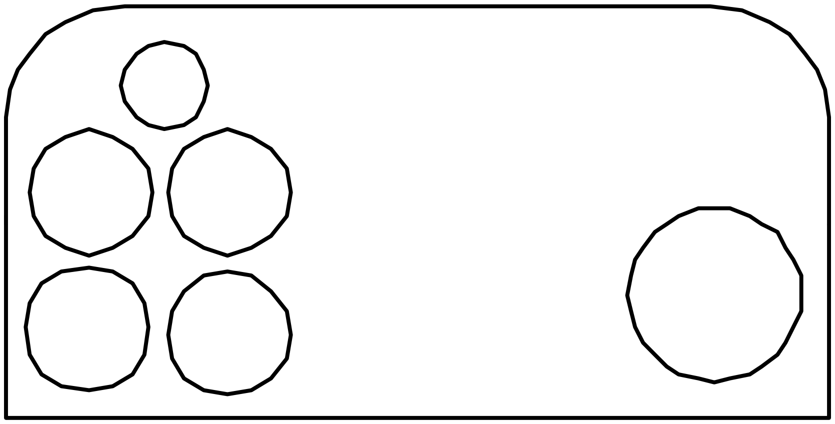


- Dual tunnel option
- Cheapest option twin tunnels 2 x 3.5*3.5m
- Evacuation: trains

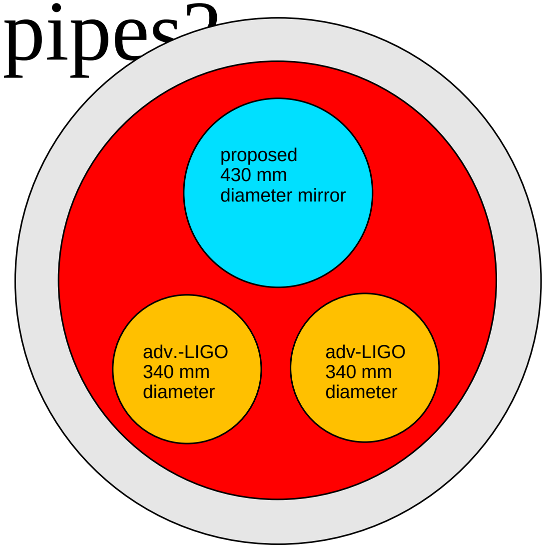


Tunnel space

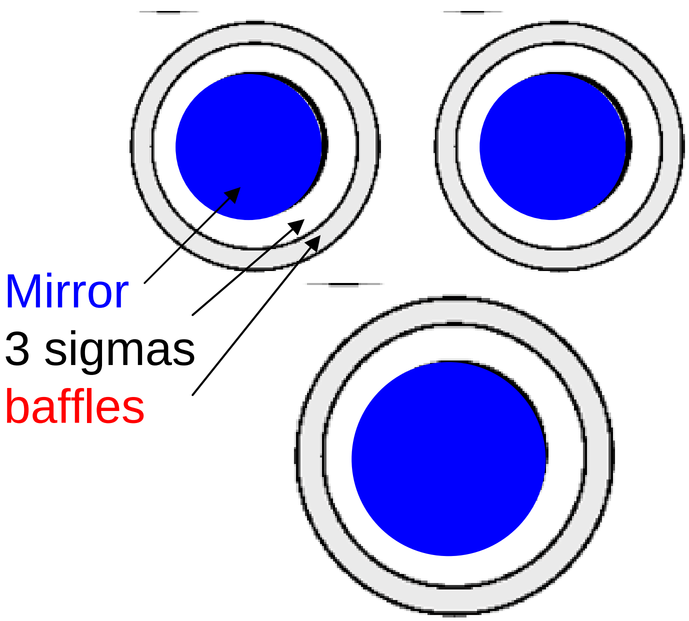
- The cheapest tunnels offer at least 35 square meters of cross section
- Can put several pipes in a tunnel



Larger pipes, smaller pipes?

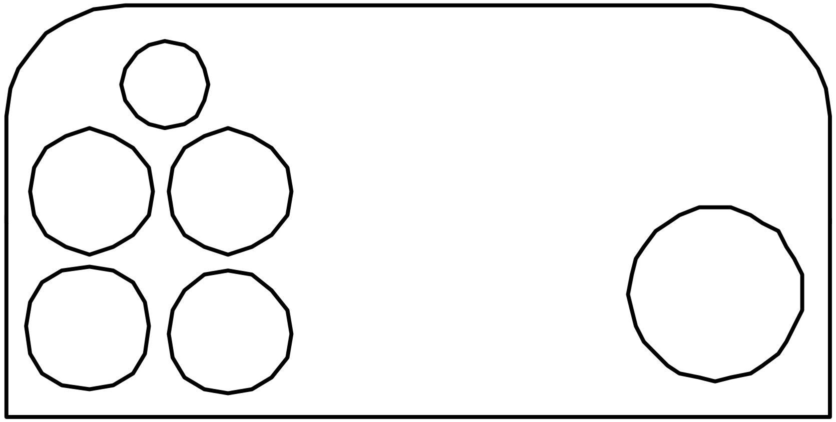


- May either fit more interferometers in same pipe or more pipes in a tunnel
- More reliable, less cross correlation and maybe cheaper to fit single beams in smaller pipes
- The beam pipes do not need to be much wider than the mirrors
- Note, larger diameter mirrors will likely be used, but not enormous ones if we recur to composite masses



Conclusions

- An underground facility requires large cross section tunnels, which automatically yield sufficient space for a xylophone



- “There is plenty of space at the bottom”