Potentials for Astronomical observations using Gravitational Waves

technological challenges, inventions and discoveries needed to get there

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Abstract

This seminar is divided into two parts. I will:

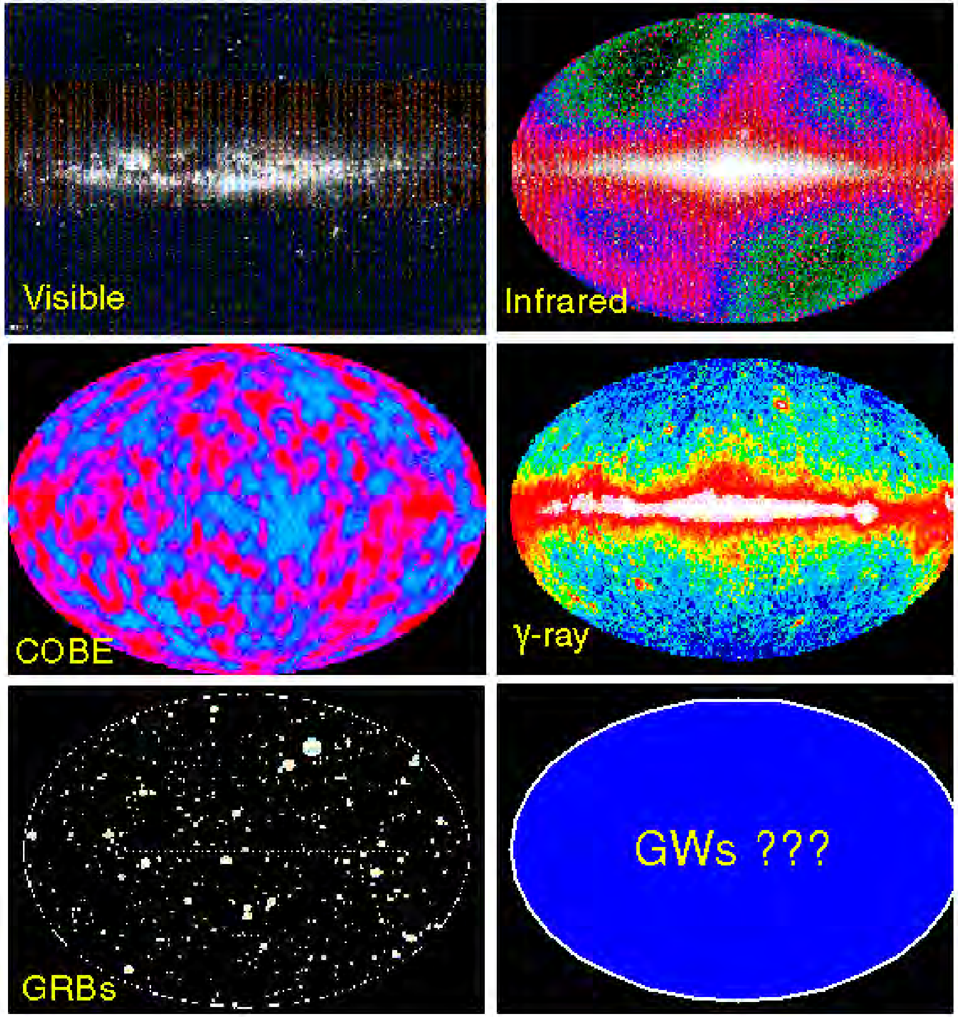
- Very briefly survey the interest and potentialities of GW astronomy, how do we detect gravitational waves and what it takes to turn detection into astronomical observations.
- make the point of where do we stand, what was achieved with the first generation of detectors, outline how far we can get with the second generation presently being commissioned, and illustrate some aims of the third generation, presently being considered.
- illustrate what can and should be done to get to true gravitational wave astronomy,
- list some example of challenges and problems that we had to solve, and some that still get to be tackled to get there

The second part of the seminar will focus on seismic attenuation, one of the challenges that may appear of having been solved, but still has surprises. I will:

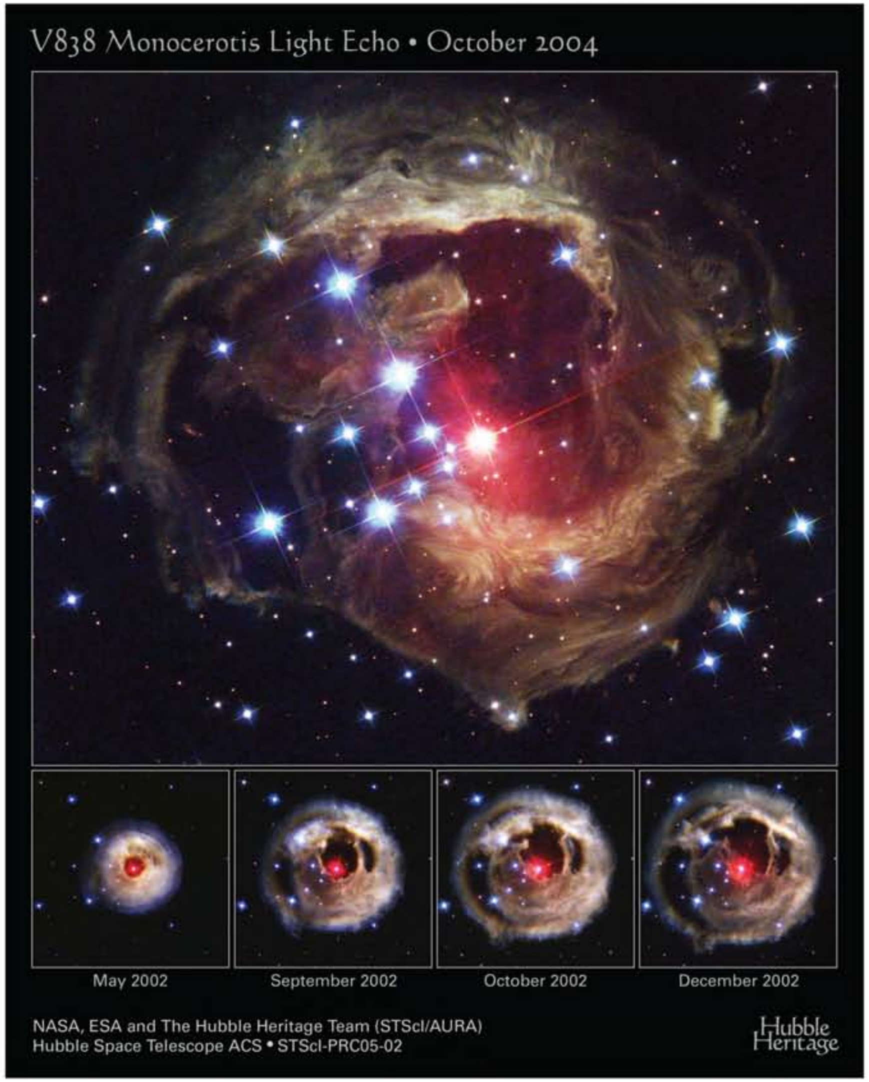
- tell the about the engineering problem that have been very successfully solved for the first and second generation of Gravitational wave detectors
- show how fundamental material problems emerged, how we solved some and discovered a completely new regime of dissipation and deviation from the laws of elasticity.
- starting from the Granato Lueck theory of elasticity and dislocations, we will get to dislocation entanglement and then to Bak's Self Organized Criticality behavior, non-causal response and a new 1/f mechanical noise mechanism.
- The new discovery, forced by the tight requirements of gravitational wave detectors, now guides the choice of better materials for the seismic attenuation for the third generation observatories, but also for metrology instruments, and many other vibration sensitive apparata,
- It also explains the source of mechanical noise in seismometers and other inertial sensors and will lead (it already has) to the design of better instruments for geophysics and diagnostics.

What electromagnetic observations have to tell

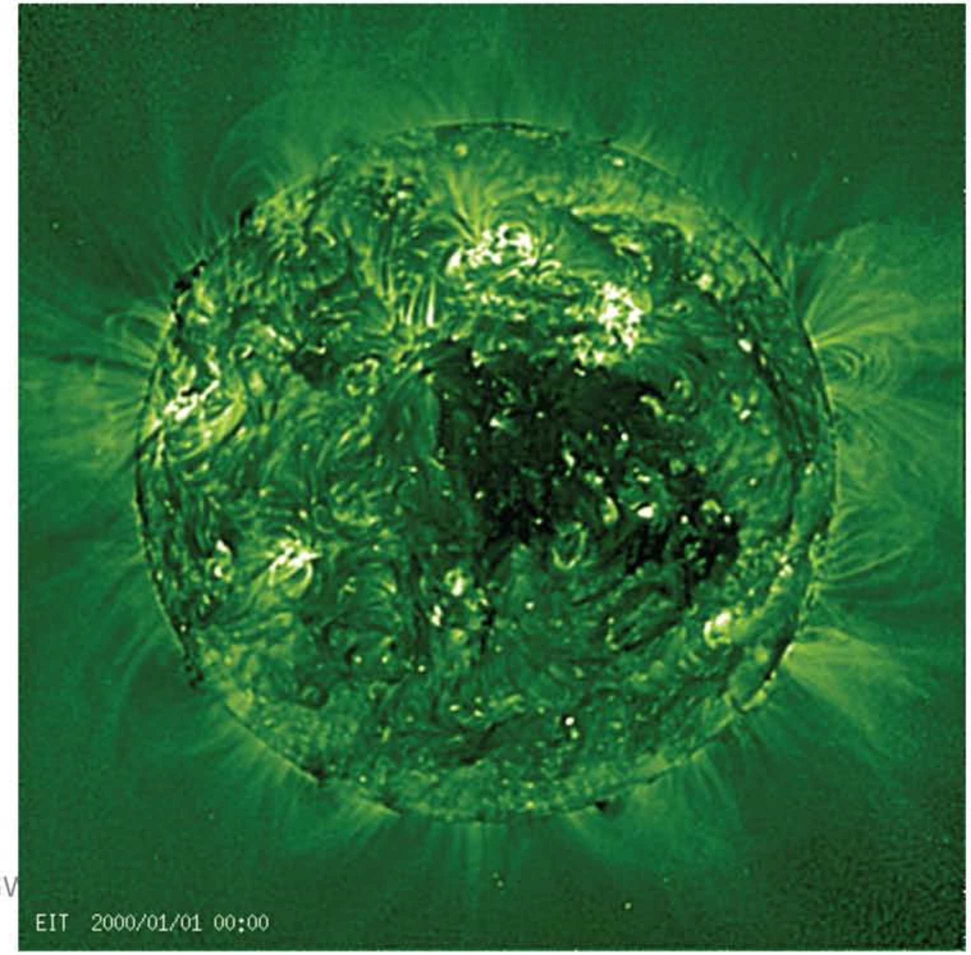
- Electro-magnetic observations give images of the instantaneous surface of objects
- We have to guess what happens inside
- E.m. radiation is absorbed by matter: ==> ==> dense structures are impenetrable



Only in rare case e.m. Observations show object dynamics



- Far UV Image of the sun



What Neutrinos have to tell?

Neutrinos:

- Register the power production of violent events
- Tell nothing about motion

What Gravitational Waves have to tell?

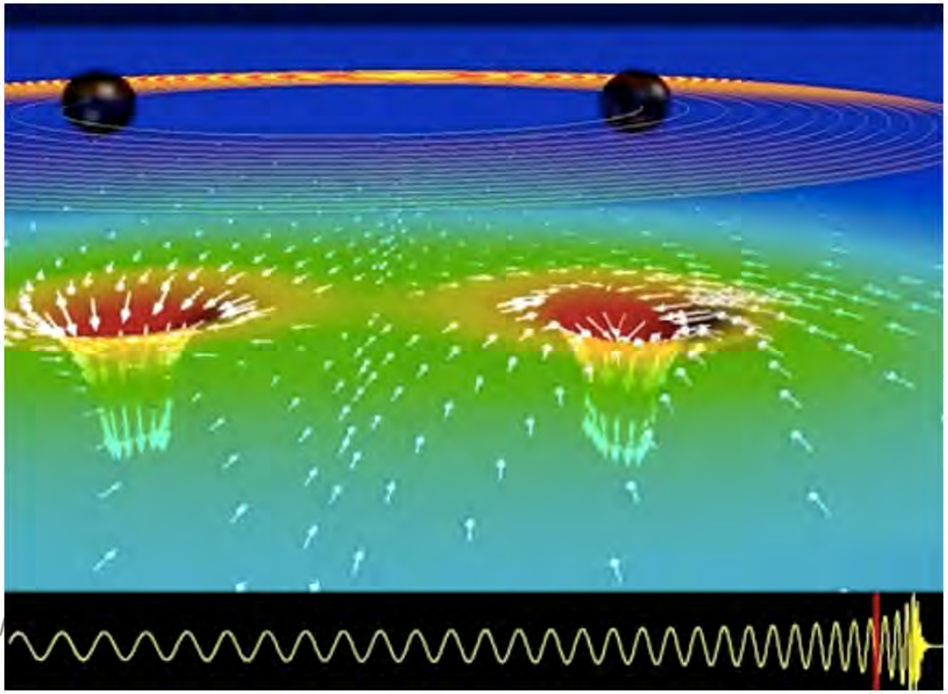
- Gravitational wave detection transduce the dynamics of violent events, tight relativistic orbits, et c.
  - They are sensitive only to motion
- Travel unaffected across the Universe
  - Everything is accessible !
- Copy the motion of

Orbiting Black Holes,

Neutron Stars,

dense stars, collapsing cores

- And plunges ! !



We already detected the emission of Gravitational Waves from binary Neutron Stars

Hulse

Taylor

Nobel Prize
Physics, 1993

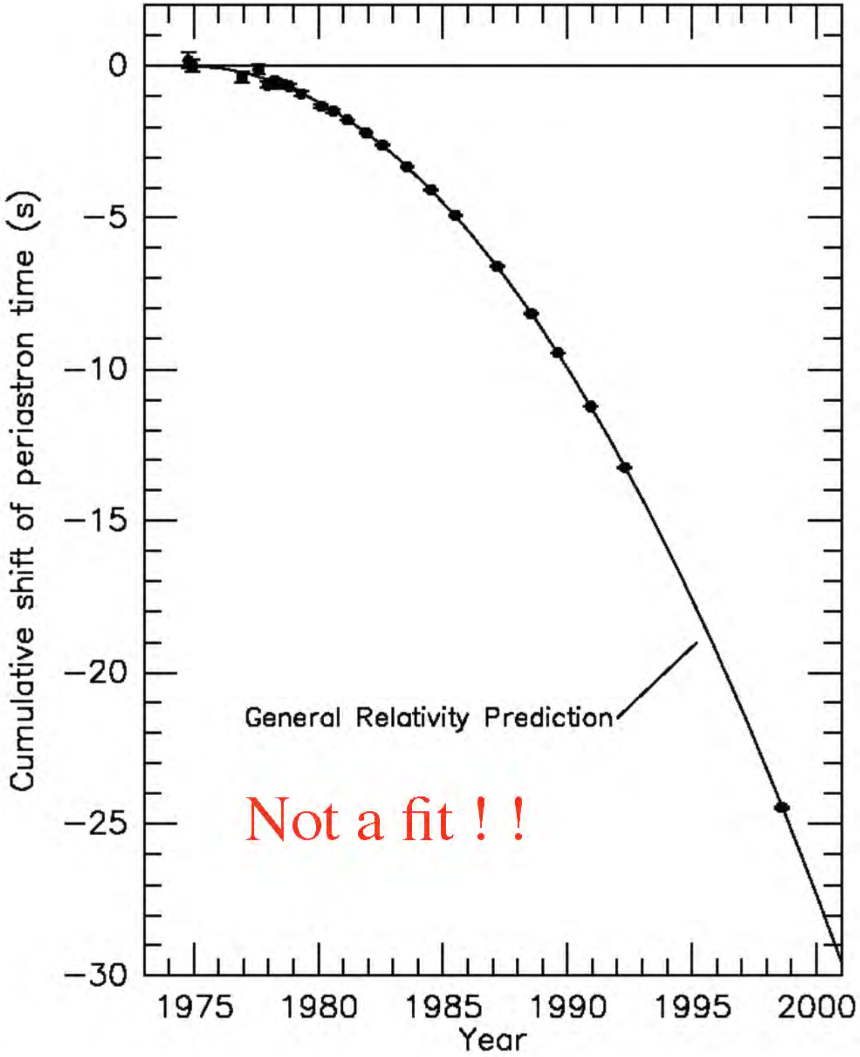
- Radio pulsar B1913+16

=>Binary neutron star

- Tight orbit =>GW emission

=> Orbital decay

- Matching GR prediction



Not a fit ! !

From J. H. Taylor and J. M. Weisberg, unpublished (1998)

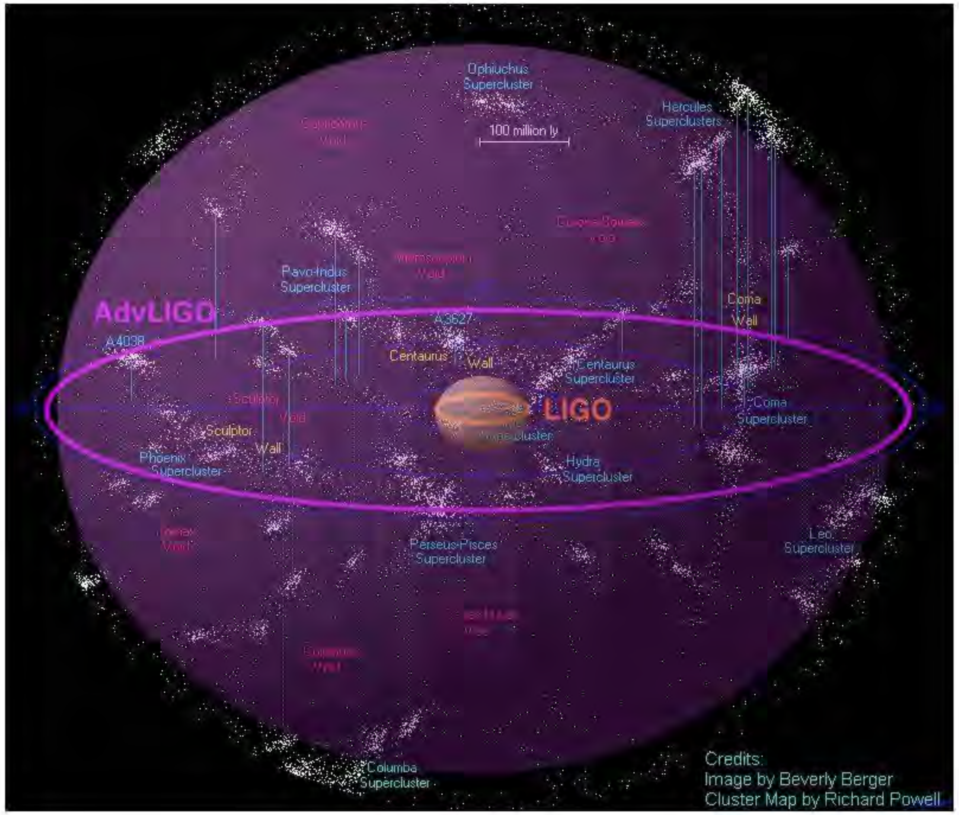
How many Binary Neutron Star inspiral event to be expected ?

- We observed already 4 binary pulsar systems and their gravitational wave decay
- We can calculate their time to inspiral (Myears)
- We know that many more Neutron Stars than visible stars must exist due to the observed amount of ordinary matter
- We can make estimations of the Inspiral rates with ~1 order of Magnitude error

Growing Sensitivity reach

- Virgo & LIGO were sensitive to Neutron Star inspirals up to ~ 20 MPc radius 3% event/year

- Advanced Virgo, LIGO & KAGRA will be listening to ~ 200 MPc
  - 1000 x detection frequency increase



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

What do we detect of Gravitational Waves ?

Measure the field, like radio telescopes:

- Detection reach grows ~1/noise
  - Vs. Optical telescopes ~ 1/√noise

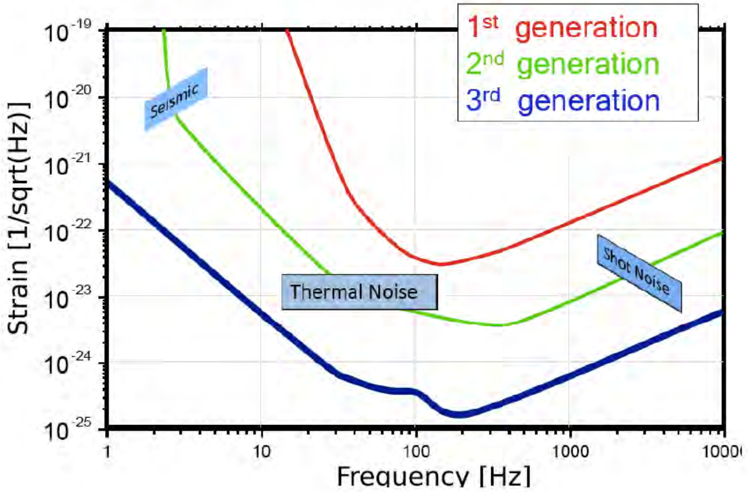
- We can expect rapid expansion of the GW detection reach with sensitivity improvements

Rapid growth of reach

- Detection reach for NS-NS inspiral

Observatory	Detection Reach M-parsec	Detection Reach g-light year	Fraction of Universe radius	Fraction of Universe volume	Event rate (est. error one order of mag.)
Present	20	0.05	0.3%	$2.5\ 10^{-8}$	~3%/year
Advanced	200	0.5	3. %	2.5 10-5	~30/year
Third-gen.	2,000	5	30%	2.5 %	80/day
Third-gen. +	7,000	17	100%	100%	10/hour

- Will be rapidly reaching the end of the Universe !



What can we learn from Gravitational Wave Astronomy ?

- Please check this interesting Compendium
- How Gravitational-wave Observations Can Shape the Gamma-ray Burst Paradigm
- I. Bartos, P. Brady, S. Marka LIGO P1200154 to appear in CQG And many references within

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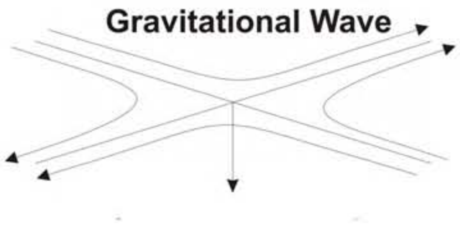
Gravitational Waves have an enormous Astrophysical potential

How do we detect them?

What needs to be done for the foundation of Gravitational Wave Astronomy ?

How do we measure Gravitational Waves

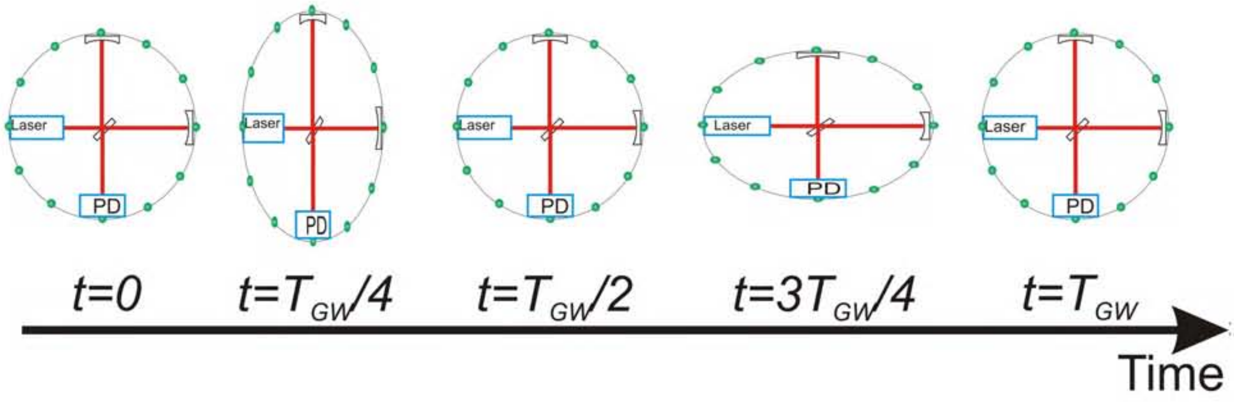


- Gravitational Waves are

  transversal quadrupolar waves

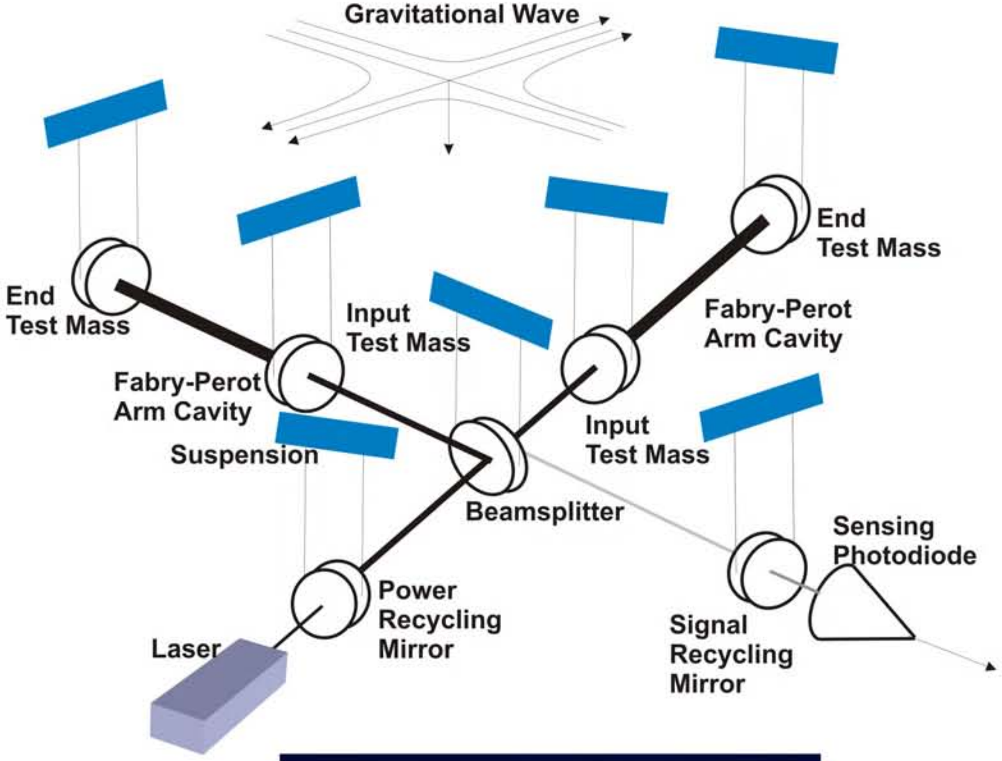
- => induce contraction on one axis, expansion in the other

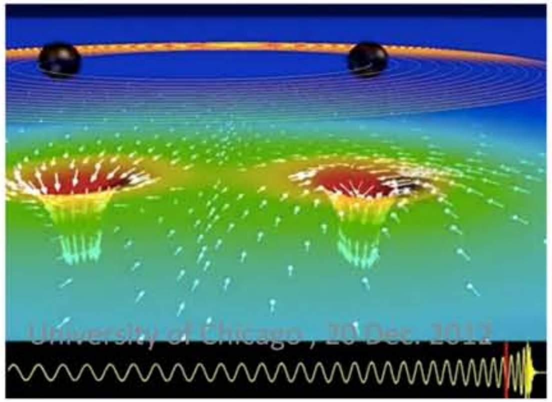
- => Michelson interferometer is the ideal detector for Gravitational Waves



Gravitational-wave interferometers

- Suspended test masses can be actuated by GW
- Fabry-Perot Enhanced Michelson interferometers used to increase sensitivity
  - LIGO, Virgo, KAGRA
- Passing GWs modulate the distance between the test masses
- The interferometer acts as a transducer, turning stellar-motion-induced GWs into photocurrent





Why Einstein predicted that we will never be able to detect GW ?

- We need to measure perturbations of 10^{-18}-10^{-19} m

(10^{-3}-10^{-4} of proton size) over lengths of few km !

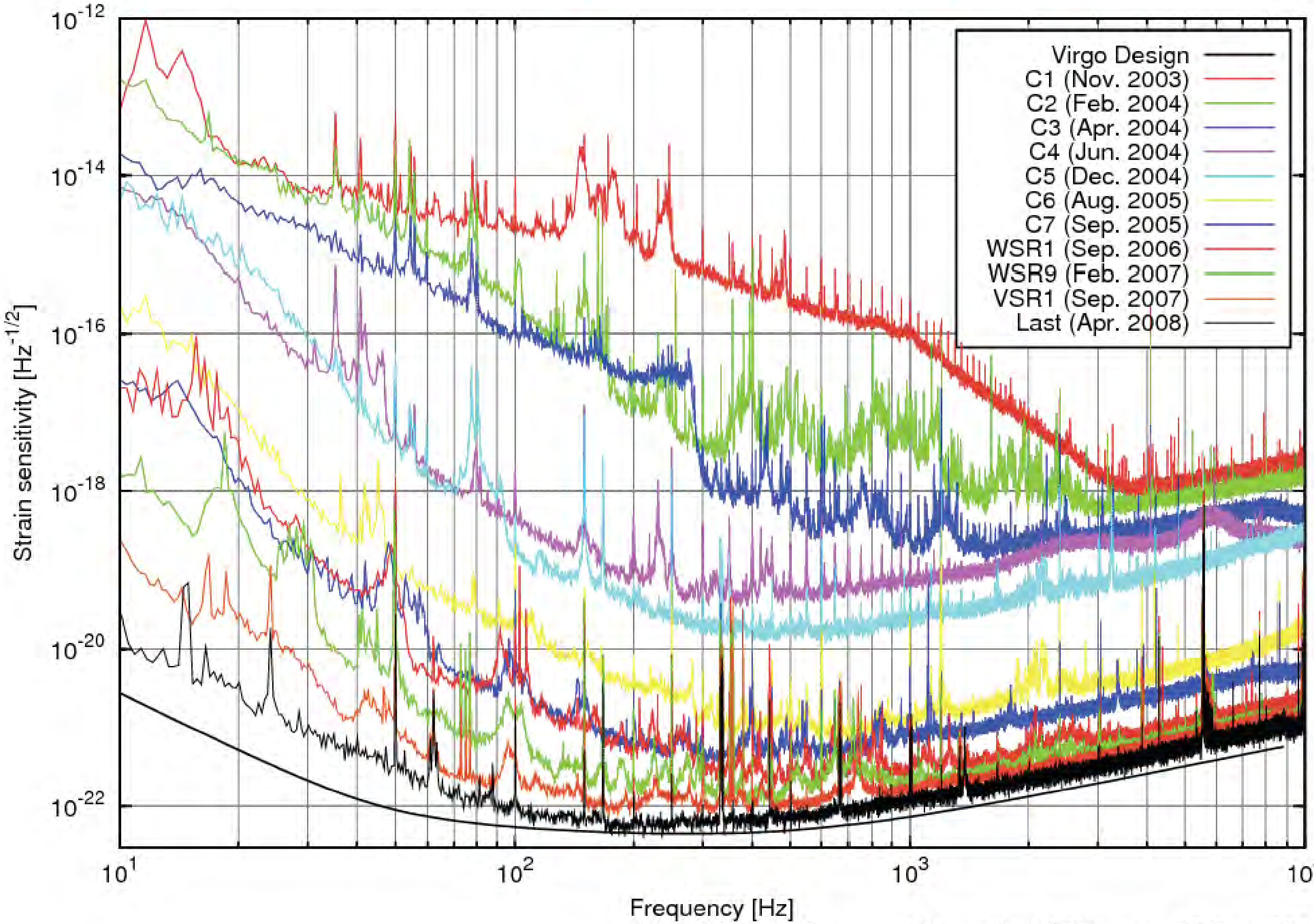
- Limits of optical length measurements require

Mega Watts of standing laser light on the mirrors

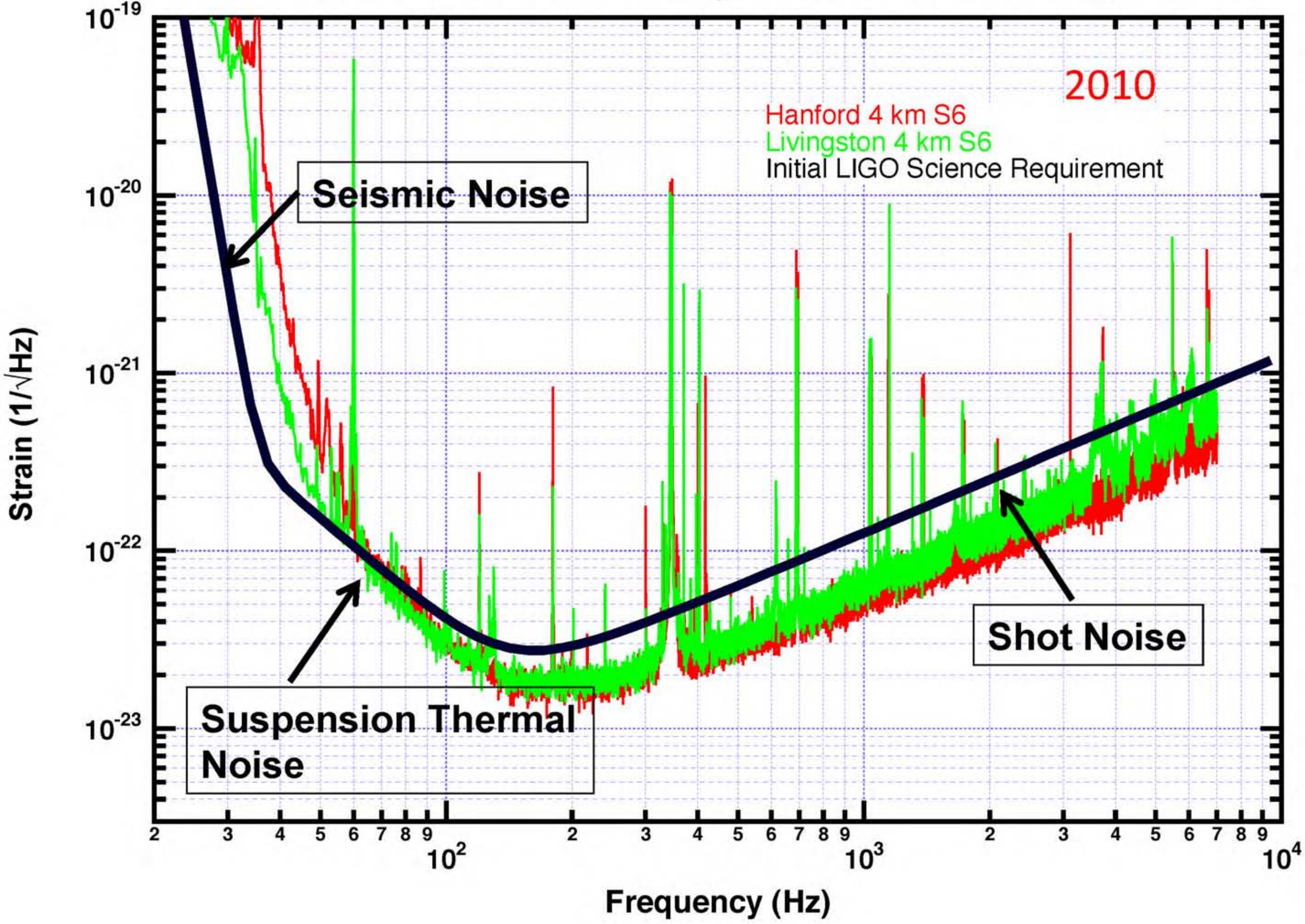
  - Radiation pressure

- E.M. measurement measures the surface of bodies, including mirrors
  - The surfaces of mirrors suffer random motion from thermal noise
- Micro-seismic noise is 10^{12} times larger than signal !
  - Newtonian noise
  - Suspension thermal noise
  - . . . . .

Getting to measure km distances with precision 1/1000 of the size of a proton !



Best Strain Sensitivity: S6 Science Run



2010

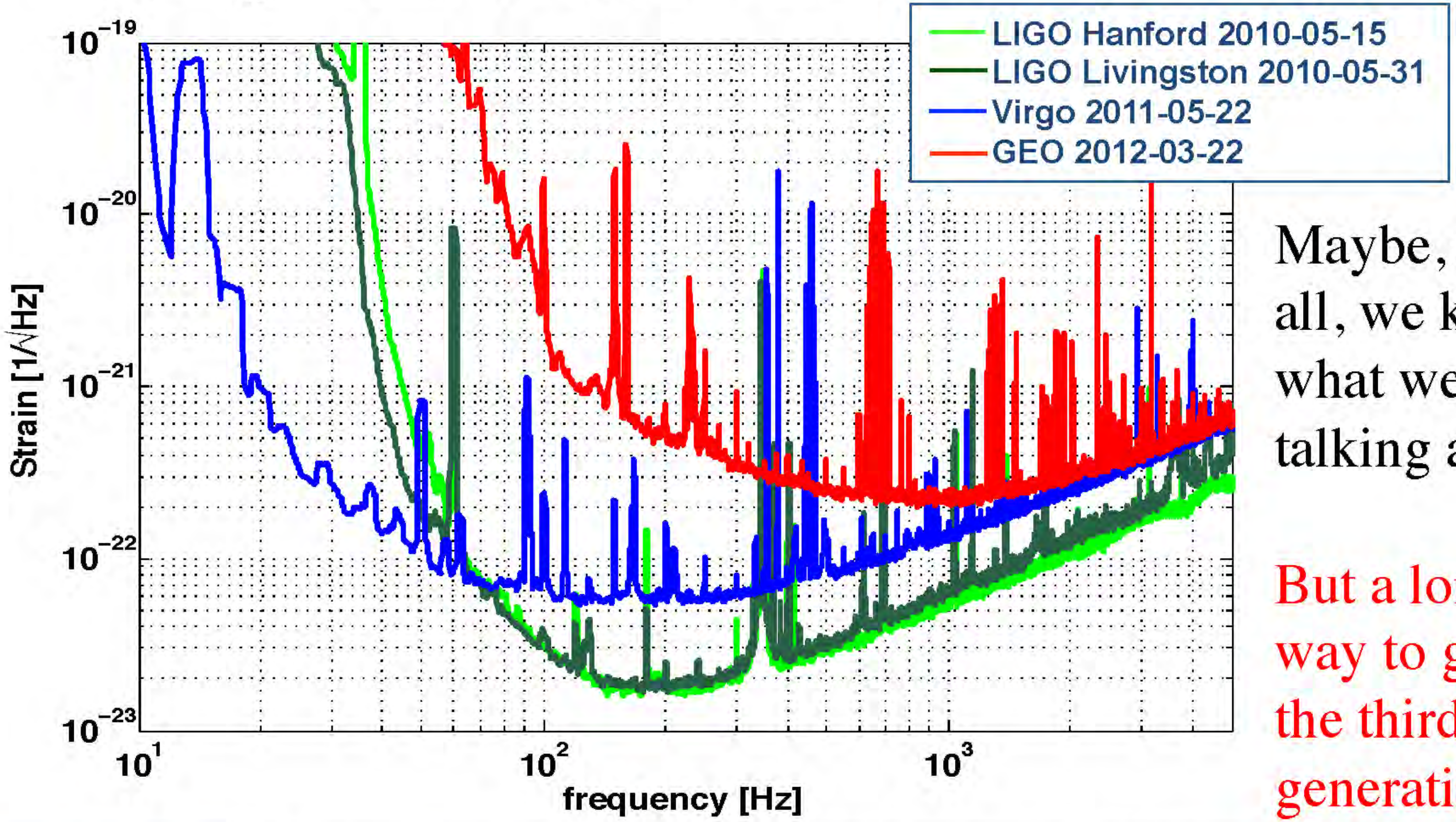
Seismic Noise

Suspension Thermal Noise

Shot Noise

Detectors' technical successes

- Design sensitivities were achieved !



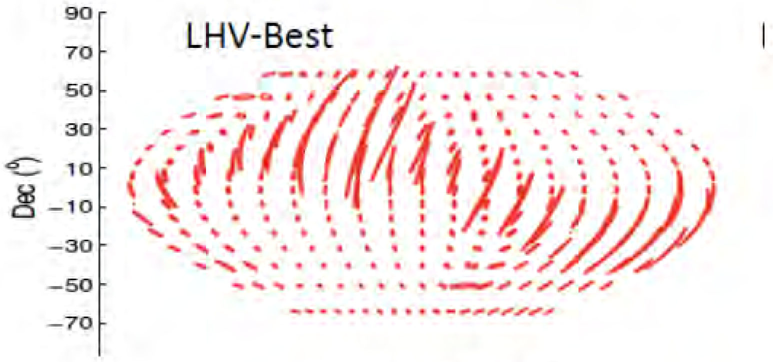
Maybe, after all, we know what we are talking about !

But a long way to go to the third generation ! !

LIGO Scientific Collaboration, *"LIGO: The Laser Interferometer Gravitational-Wave Observatory"*, Rep. Prog. Phys. 72 (2009) 076901
H. Grote (for the LSC), *"The Upgrade of GEO600"*, Class. Quantum Grav. 27, 084003 (2010)
T. Accadia, et al., *"Virgo: a laser interferometer to detect gravitational waves"*, J. Instrumentation 7, P03012 (2012)

Directionality of Gravitational Waves

- Gravitational Waves are like pressure waves
- With one observatory you can detect them, but cannot point to their origin
- We need a Global network for directionality



Virgo-LIGO

Courtesy of Linqing Wen

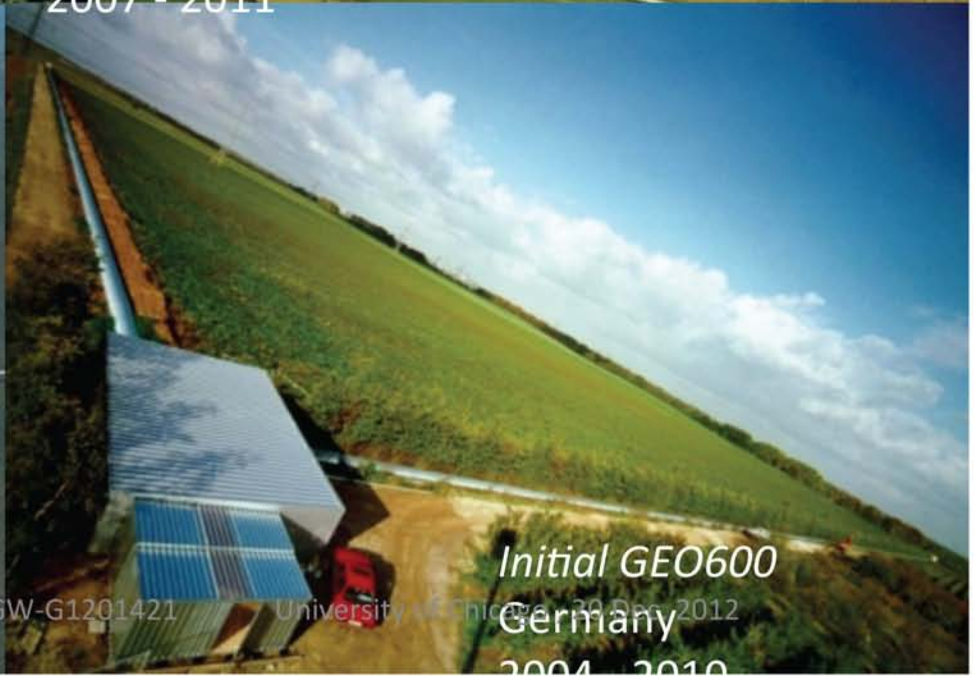
Virgo-LIGO-KAGRA-Indigo-ACIGA

First Generation Interferometer network

Initial LIGO
Louisiana,
USA
2002-2010

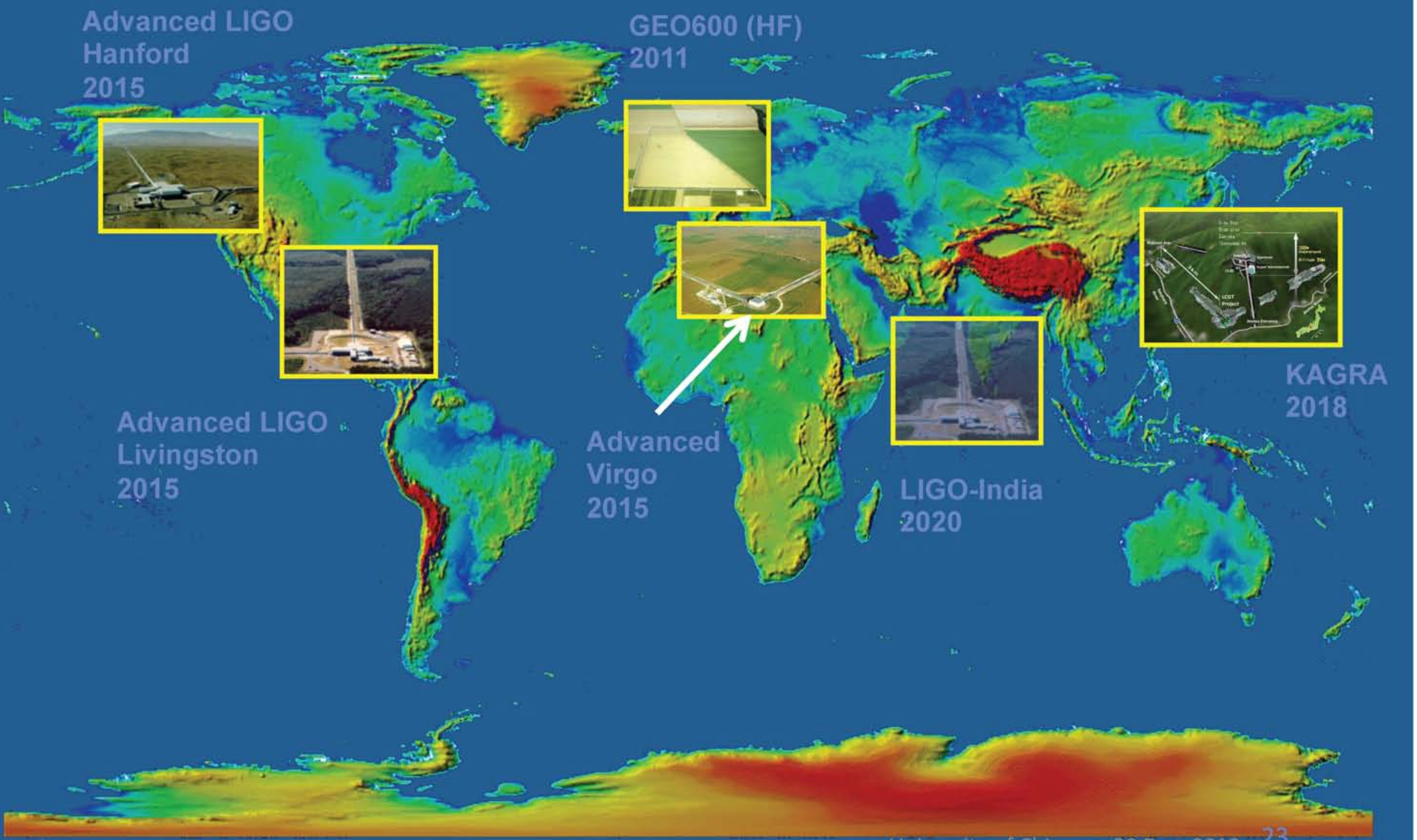
Initial VIRGO
Italy
2007 - 2011

Initial LIGO
Washington
, USA
2002-2010



Initial GEO600
Germany
2004 - 2010

The advanced GW detector network



Advanced LIGO
Hanford
2015

GEO600 (HF)
2011

Advanced LIGO
Livingston
2015

Advanced
Virgo
2015

LIGO-India
2020

KAGRA
2018

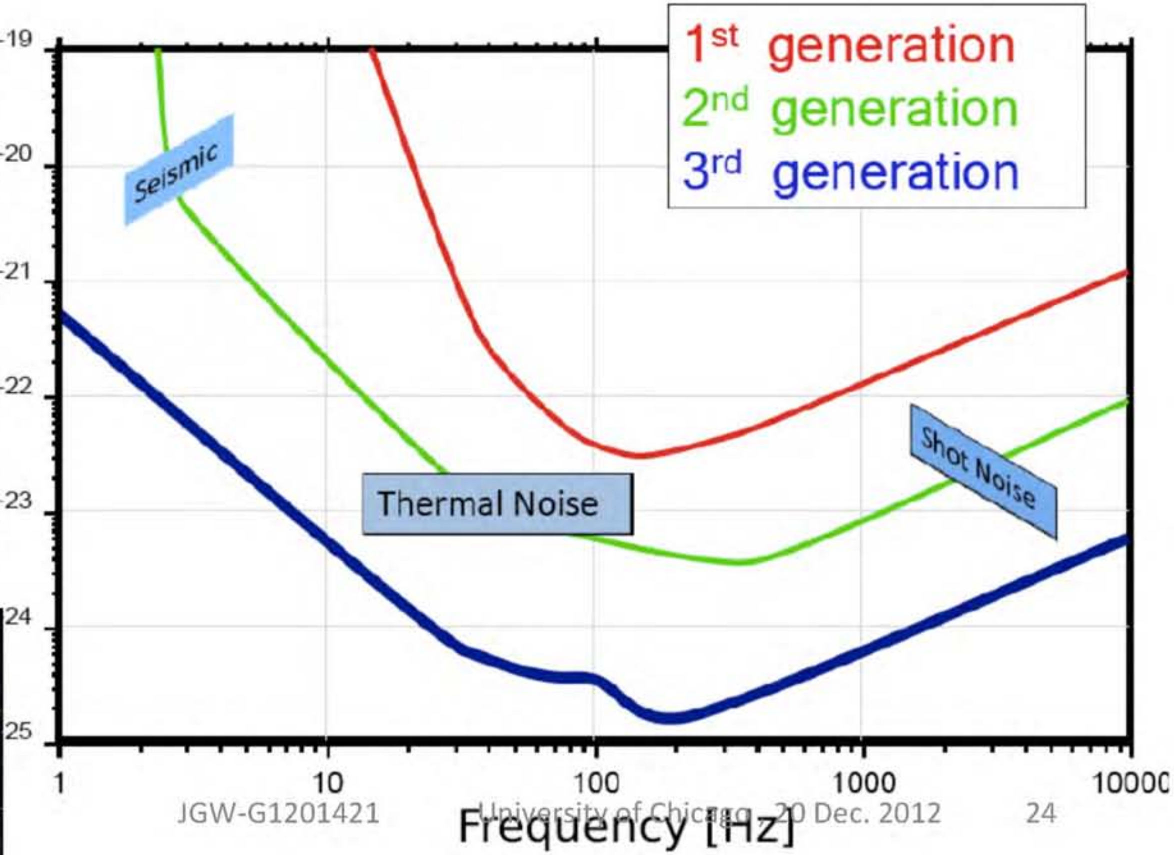
Credit D. Reitze

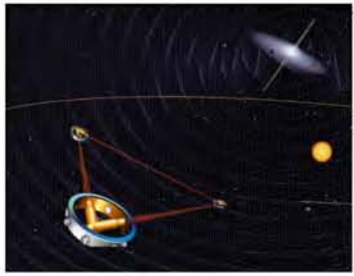
What do we need to do for Gravitational Wave Astronomy ?

- We need a Third generation Gravitational Wave

Observatories with:

- Higher sensitivity
- Larger Bandwidth
- Eventually in space



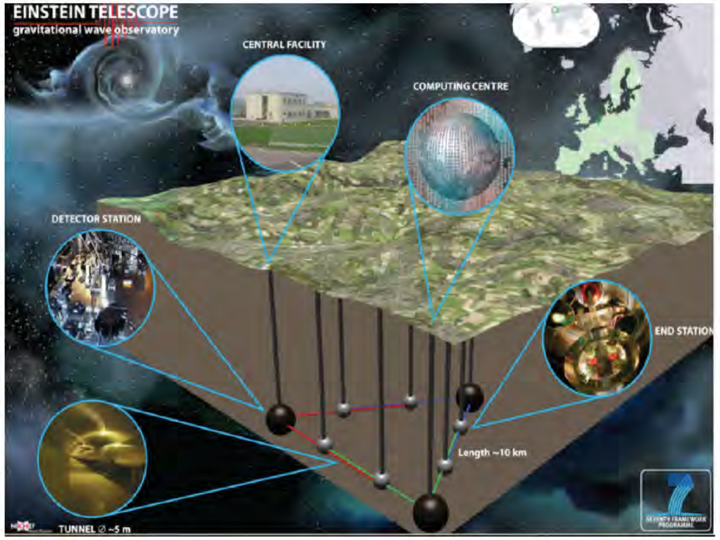


Third generation Gravitational Wave observatory
to do list: technical-scientific challenges

- Low frequency seismic noise
- Suspension thermal noise
- Radiation pressure noise
- Newtonian noise
- Coating thermal noise
- Mirror substrate thermal noise
- Length sensing shot noise

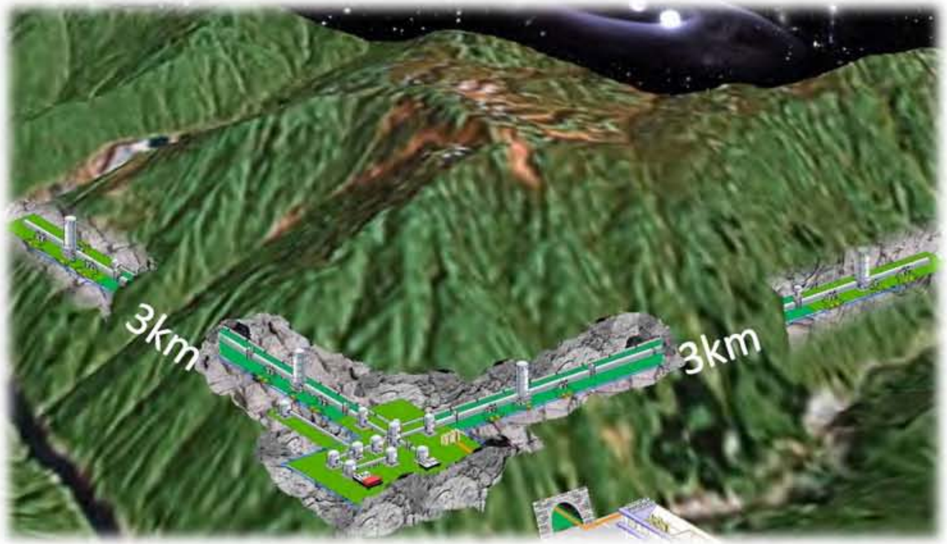
Third generation Gravitational Wave observatory
to-do list: Engineering challenges

- Underground operations
- Operate xylophone interferometers
- Cryogenic operation
- Isolate cryo-chiller noise
  down to 10^{-20}m
- . . . . .



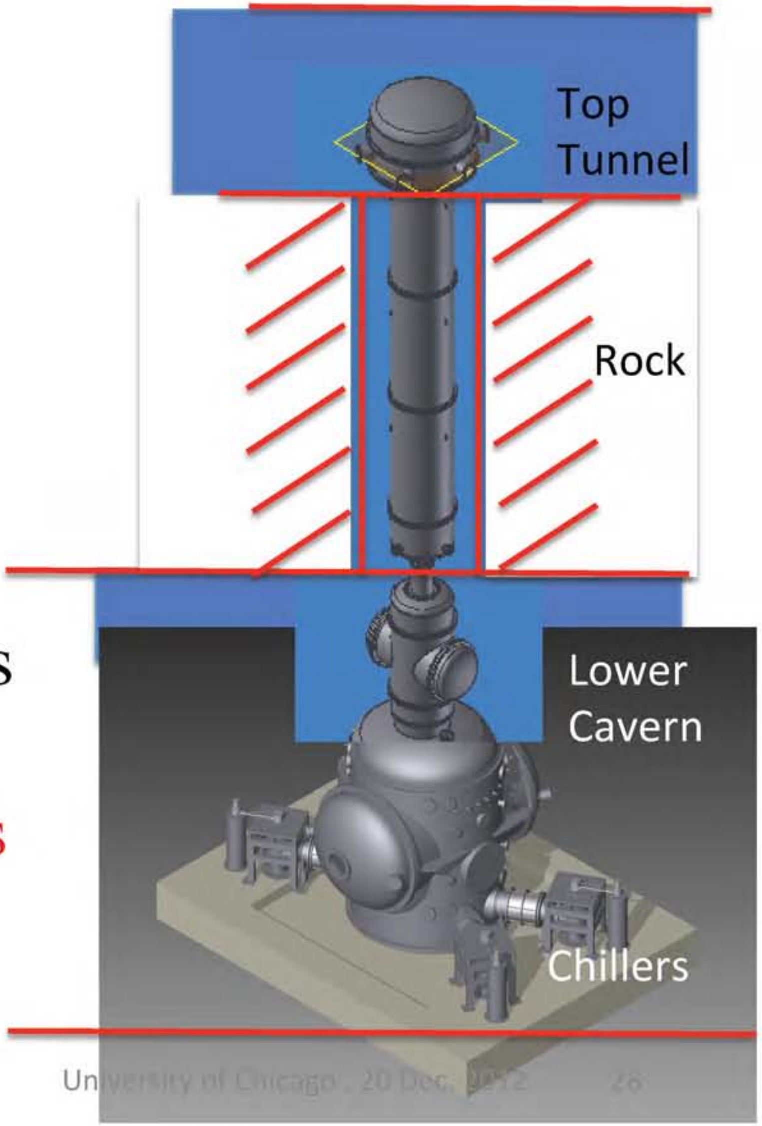
KAGRA the ground-breaker

- KAGRA is 2nd generation observatory
- First one <u>underground</u> and <u>cryogenic</u>
- Potential for lower frequency operation
- Many of the third generation challenges are already present
- Natural lab for the development of 3rd gen. instruments



Mining developments @ KAGRA

- Think in 3D take advantage of elevation in wells to:
- minimize digging,
- maximize stability,
- allow extra long suspensions for low frequency attenuation
- allow use of local pulse tube chillers to avoid Helium leak risks
- separate mechanical noise of chillers from the suspended optics



KAGRA, ET and 3rd generation

- Both KAGRA and ET need radically new technologies to push the envelope of GW detection
- Some solutions that will be used in ET and KAGRA look like science fiction today, but
- Many of the technologies that we use in 2nd gen. only a short time ago seemed like Science Fiction

US and 3rd generation

- With the Homestake initiative the United States got an early, but small, start
- Europe and Japan are moving ahead
- The United States urgently need to vigorously embark into a 3rd generation Gravitational Wave Detector development !

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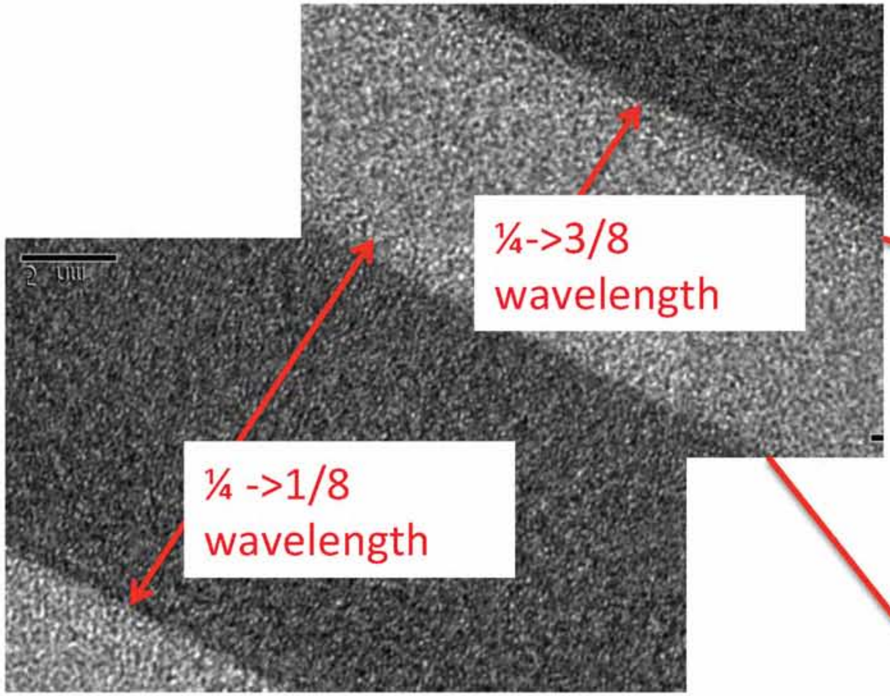
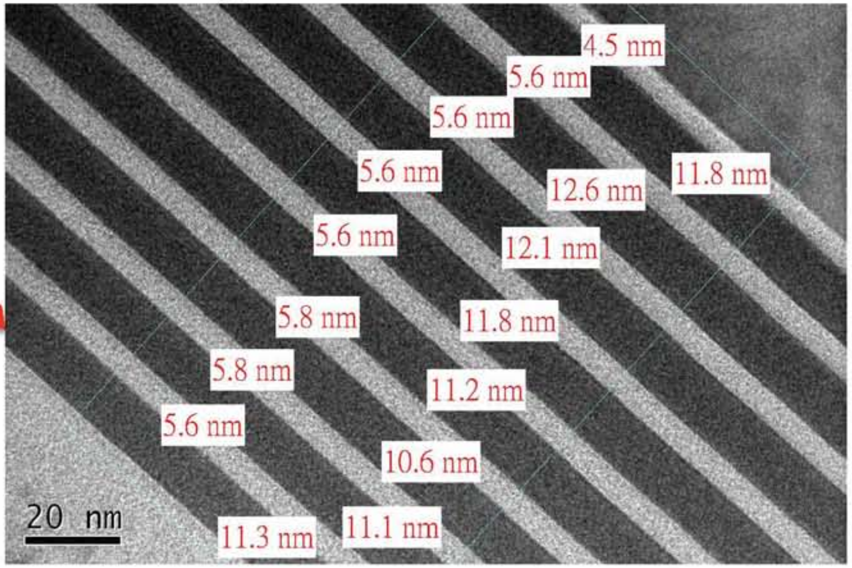
Illustrating some present and future Technical and Scientific Challenges

- I could tell many stories of problems and found and/or possible answers
- Will mention some,
- Will focus on one only!

I will not tell about



- how we reduced the thermal noise of mirrors by optimizing coating structure and how we will further optimize them

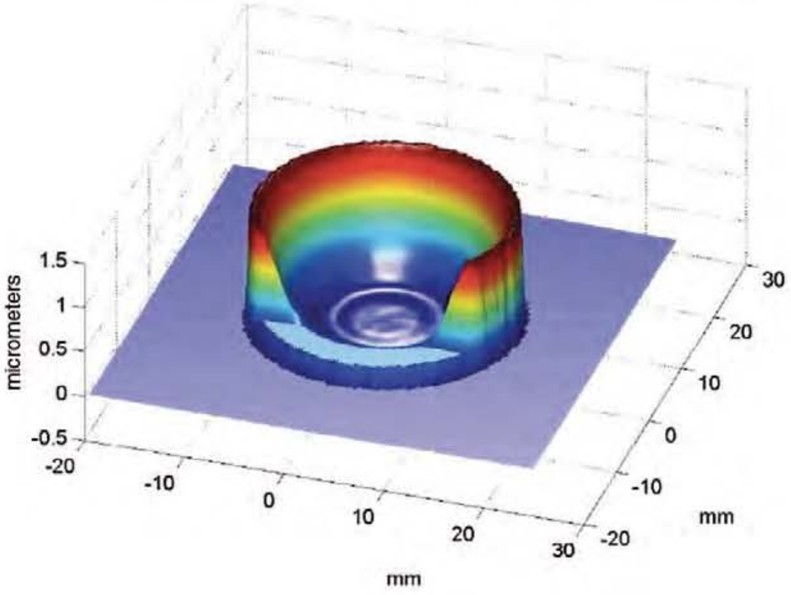


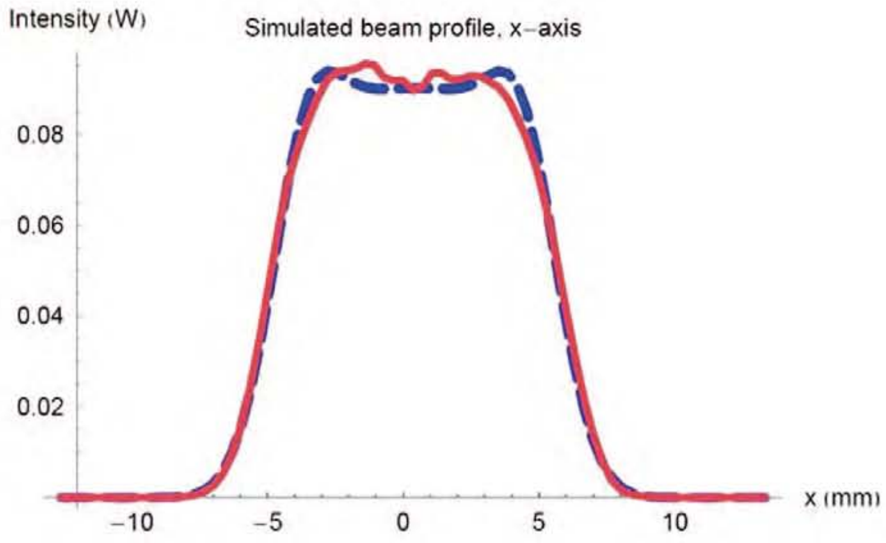
by developing nano-layer coating technology

Akira E. Villar,et al. Measurement of thermal noise in multilayer coatings with optimized layer thickness, PHYSICAL REVIEW D 81, 122001 (2010)

I will not tell about

- How to optimize stored beam shapes to reduce the effects of mirror Thermal noise on length sensing



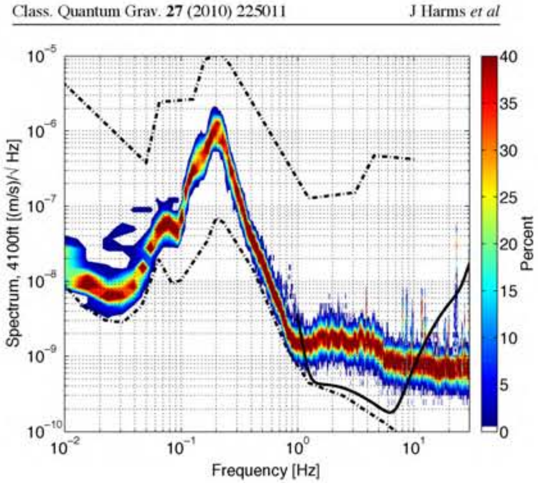


- Or how to dope coating materials to reduce dissipation and thermal noise

Generation of a flat-top laser beam for gravitational wave detectors by means of a nonspherical Fabry–Perot Resonator, Applied Optics, Vol. 4
Measurement of thermal noise in multilayer coatings with optimized layer thickness PHYSICAL REVIEW D 81, 122001 (2010)

I will not tell about

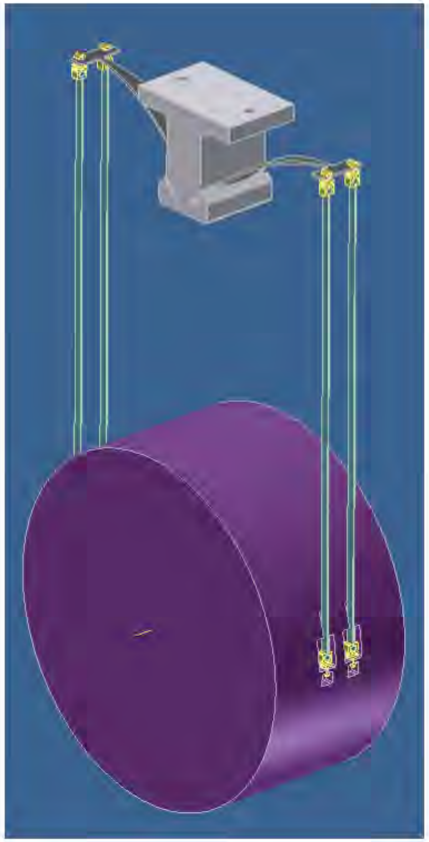
- How to reduce the perturbations on the test masses by the fluctuations of Earth's Newtonian gravitational attraction



Gravity-Gradient Subtraction in 3rd Generation Underground Gravitational-Wave Detectors in Homogeneou
Simulation of underground gravity gradients from stochastic seismic fields, PHYSICAL REVIEW D 80, 122001
Characterization of the seismic environment at the Sanford Underground Laboratory, South Dakota, Class. C

I will not tell about cryogenics

- How to build cryogenic suspensions out of mono-crystalline silicon and sapphire
- How to isolate the noise from the cryogenic chillers



I chose to tell you some about the great challenge of seismic attenuation

- How it pushed the limit of engineering and :
- Lead to discovered new limits of elasticity
- Lead to discovery of a new regime of

dissipation in condensed matter dominated by entanglement of dislocations and

their Self Organized Criticality behavior

- How this new knowledge will allow advanced seismometers and inertial sensors

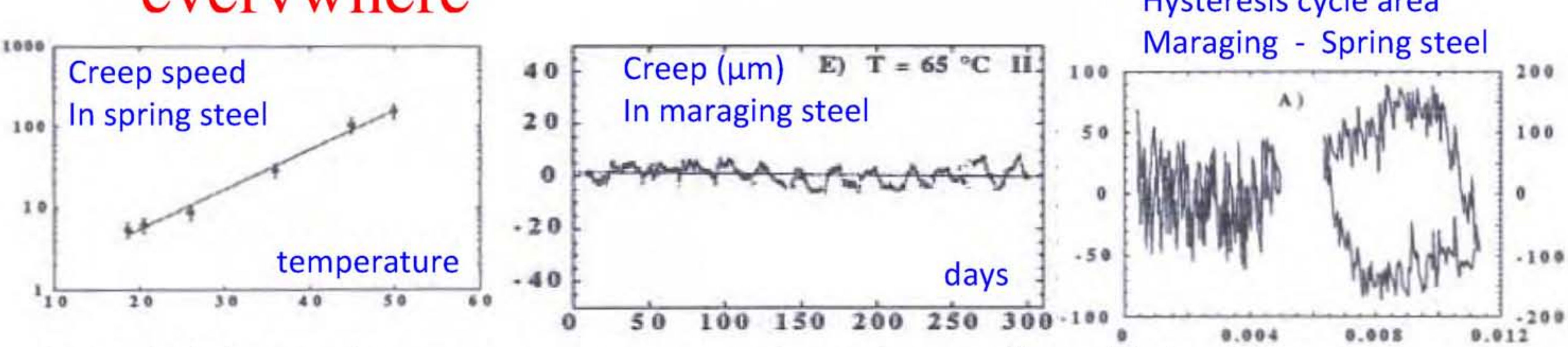
When I was asked to engineer the Virgo superattenuators

- I immediately realized that they were not feasible with common spring steel
- Creep would rapidly overwhelm them
- Your car springs will droop ~1 mm over its lifetime, that is OK
- A spring 1000x softer will droop 1 meter
- Mission impossible!

How we made the Virgo superattenuators ?

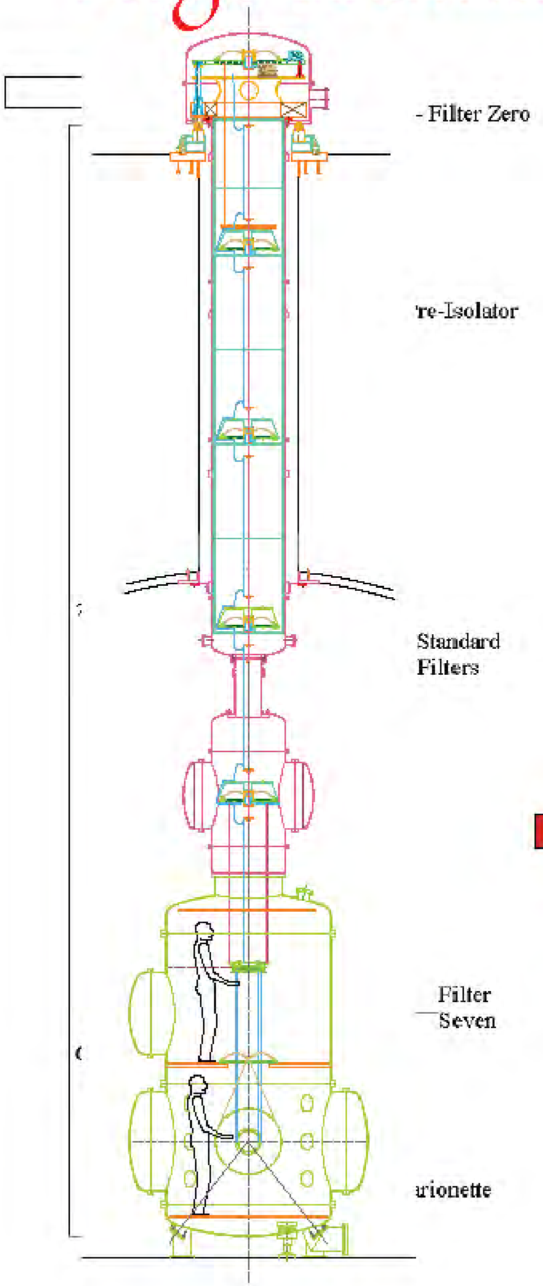
- R. Valentini, R.D.S. (and my dad) introduced Maraging Steel cantilever springs

  to GW Seismic Attenuation Systems
- Maraging steel was a great enabler, adopted everywhere

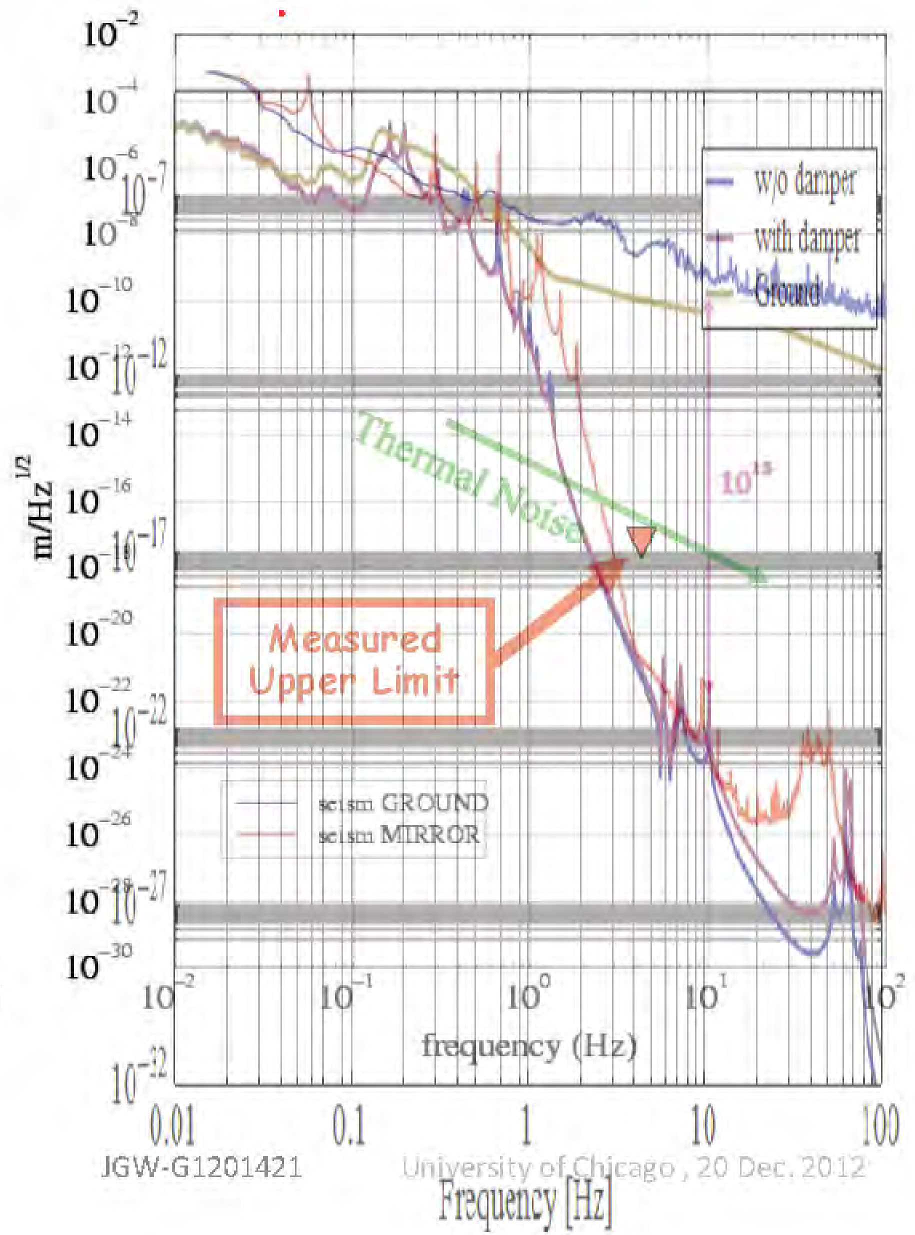


Extended-time-scale creep measurement on Maraging cantilever blade springs, Nicole Virdone, Nuclear Instruments and Methods in Physics Research A 593 (2008) 597–607

Virgo seismic Passive attenuation 10^{-18} @ 5 Hz



courtesy
F. Frasconi

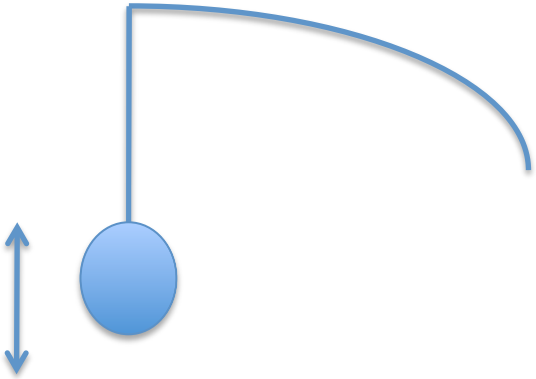


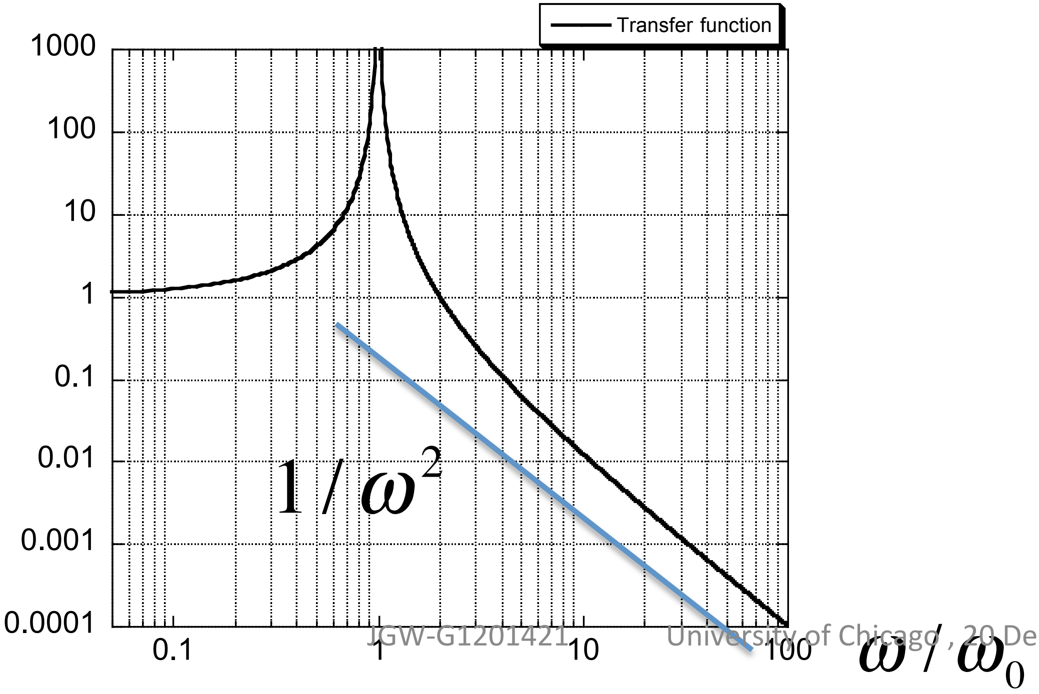
How was this achieved ?

Seismic attenuation filters

- Alternating horizontal and vertical oscillators

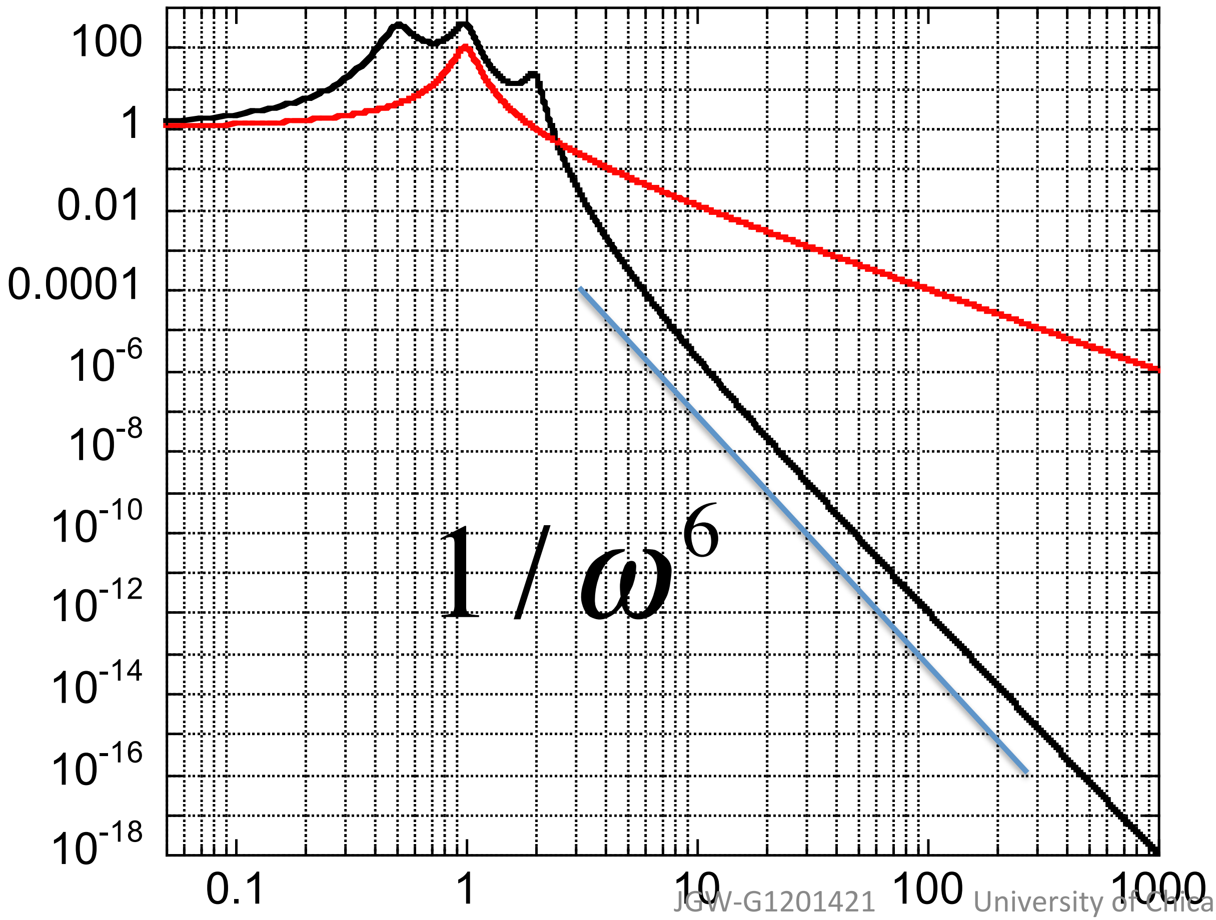
$$H(\omega) = \frac{\omega_0^2}{(\omega_0 - \omega)^2}$$

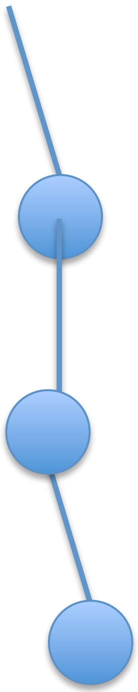


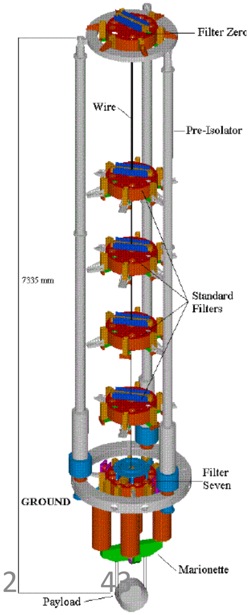


Chaining filters

- Multiply attenuation factors

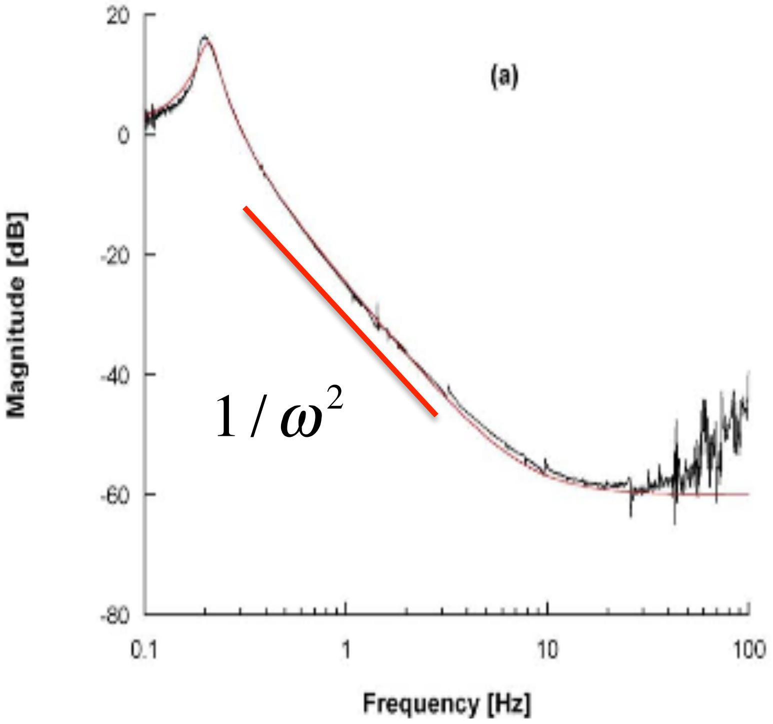






Vertical attenuation:
The tough part

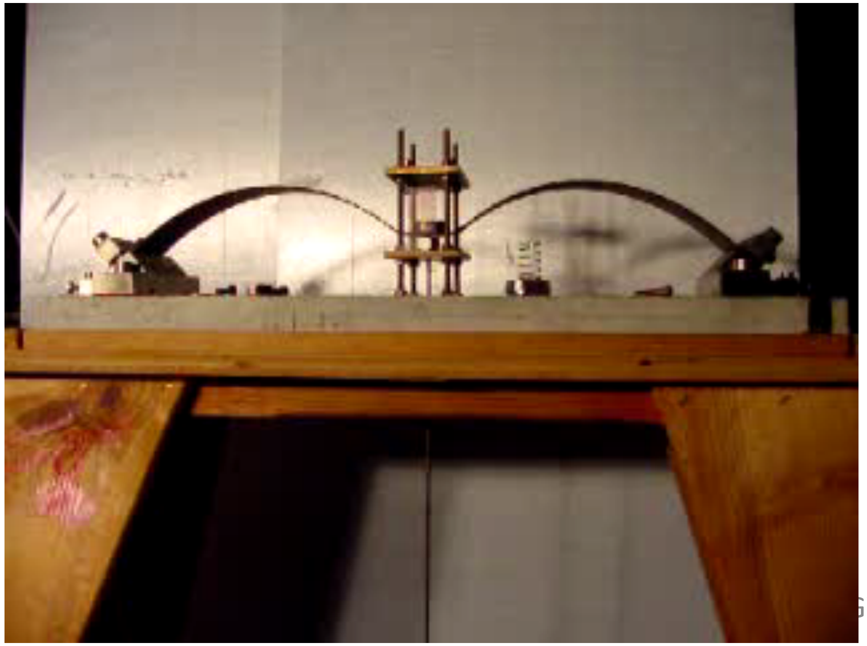
- The problem is the vertical filter:
- The difficulty is to build a compact mechanical oscillator at <u>sufficiently low frequency</u>
  - Cantilever blades
  - Magnetic Anti-Springs
  - Geometric A-S
  - Electro-magnetic A-S

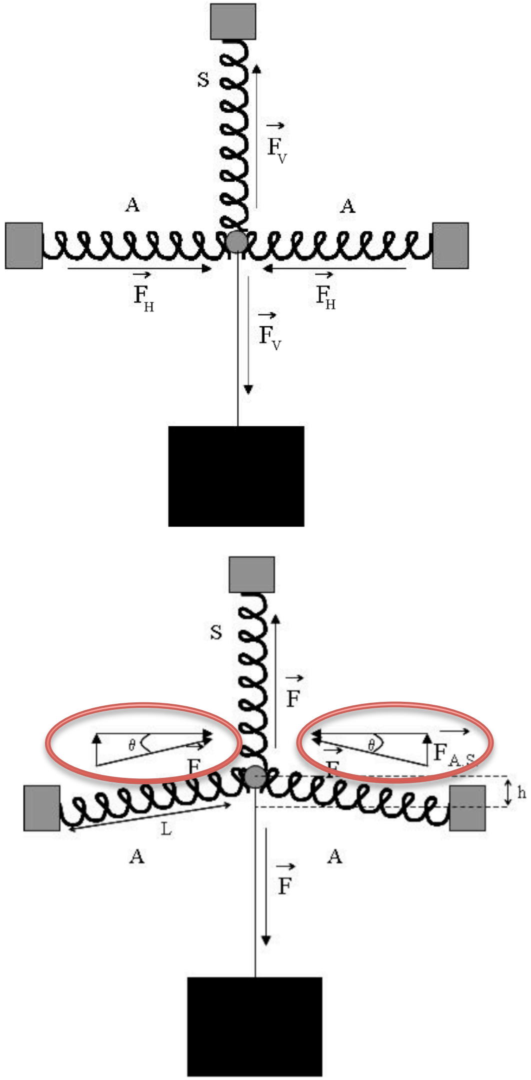


Beccaria,et al., Extending the VIRGO gravitational wave detection band down to a few Hz: metal blade springs and magnetic antisprings, NIM-A 39
Bertolini, et al. Seismic noise filers, vertical resonance frequency reduction with geometric anti-springs: a feasibility study, NIM-A 435 (1999) 475-
DeSalvo, Passive, Nonlinear, Mechanical Structures for Seismic Attenuation, Journal of Computational and Nonlinear Dynamics Vol. 2, OCTOBER 2
Mantovani, DeSalvo, One hertz seismic attenuation for low frequency gravitational waves interferometers, NIM-A 554 (2005) 546–554

Solution: Geometric Anti Springs

- Theoretically, the radial compression allows to null the resonant frequency
- Seemingly the perfect solution

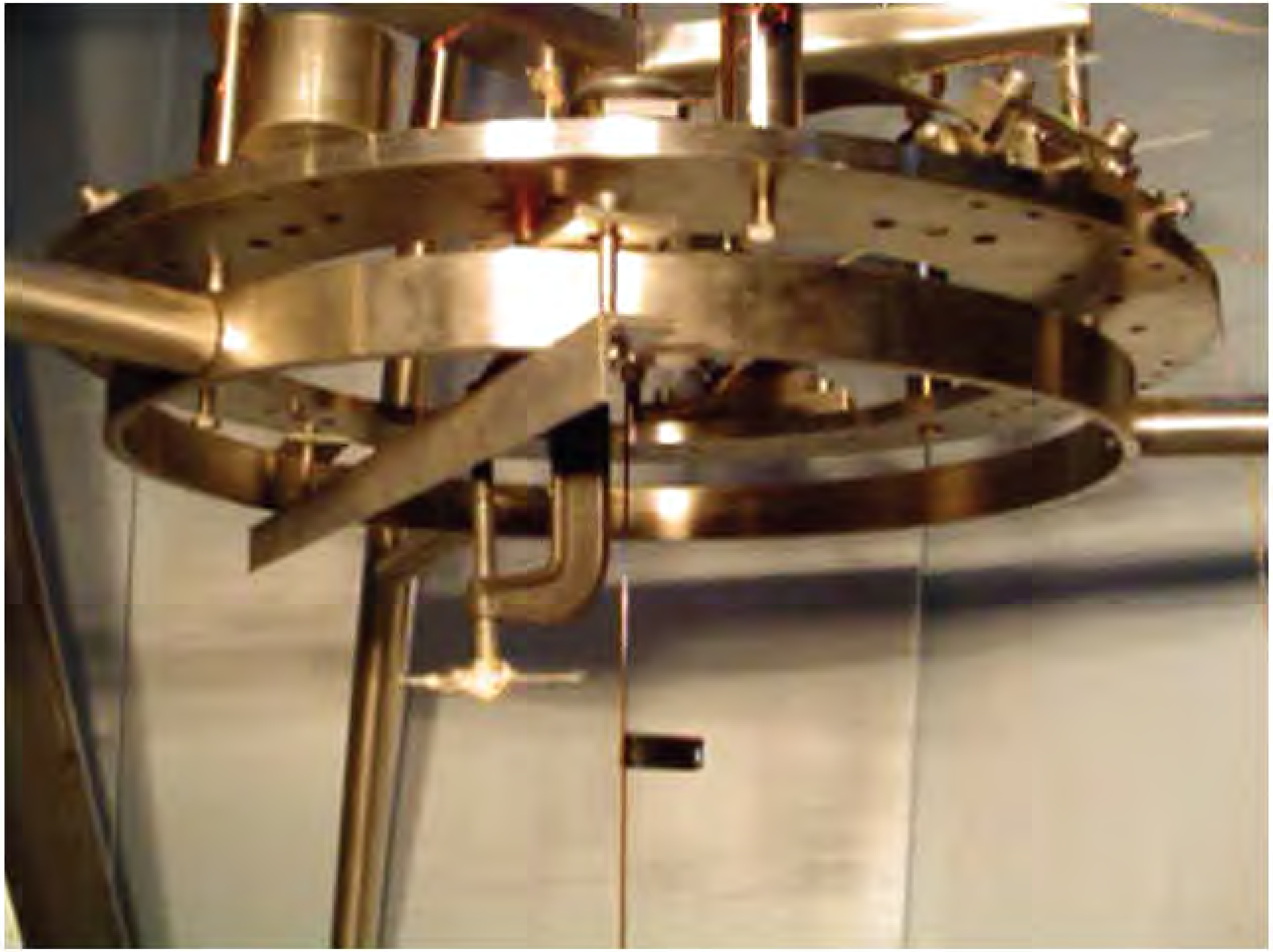




Desalvo, Passive, Nonlinear, Mechanical Structures for Seismic Attenuation, Journal of Computational and Nonlinear Dynamics, 2007, 290- 298

How good a filter can we build?

Attenuation filter in action



65 kg hanging in here

up to 90 dB attenuation achieved

Success?

- As much attenuation as desired was achieved (>10 Hz)
- Variations of this scheme (blades with Geometric Anti-Springs, Magnetic Anti-Springs, ElectroMagnetic Anti-Springs, or no Anti-Springs) are used in all Gravitational Wave observatories and development labs in the world !

- It feels good to conquer the entire World, but
- An underlying mystery spoils the pleasure and closes the path to the future

What is missing?

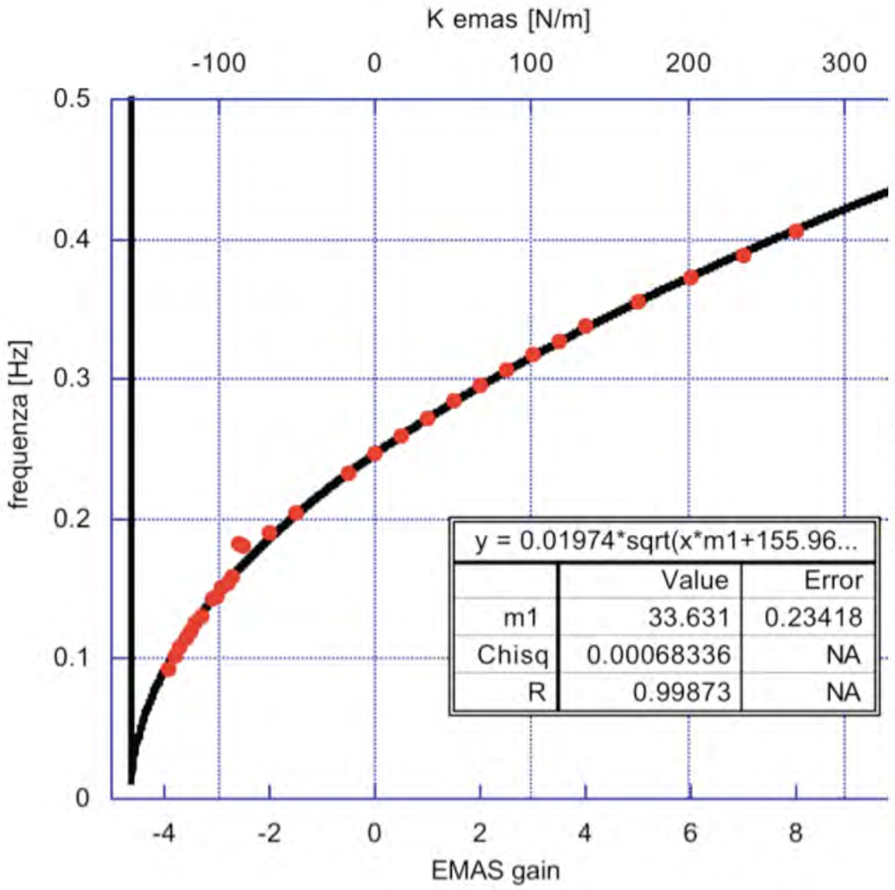
- The future requires lower frequency Gravitational Wave detectors

  To go after heavier Black Holes

- We need to push springs to Lower frequency

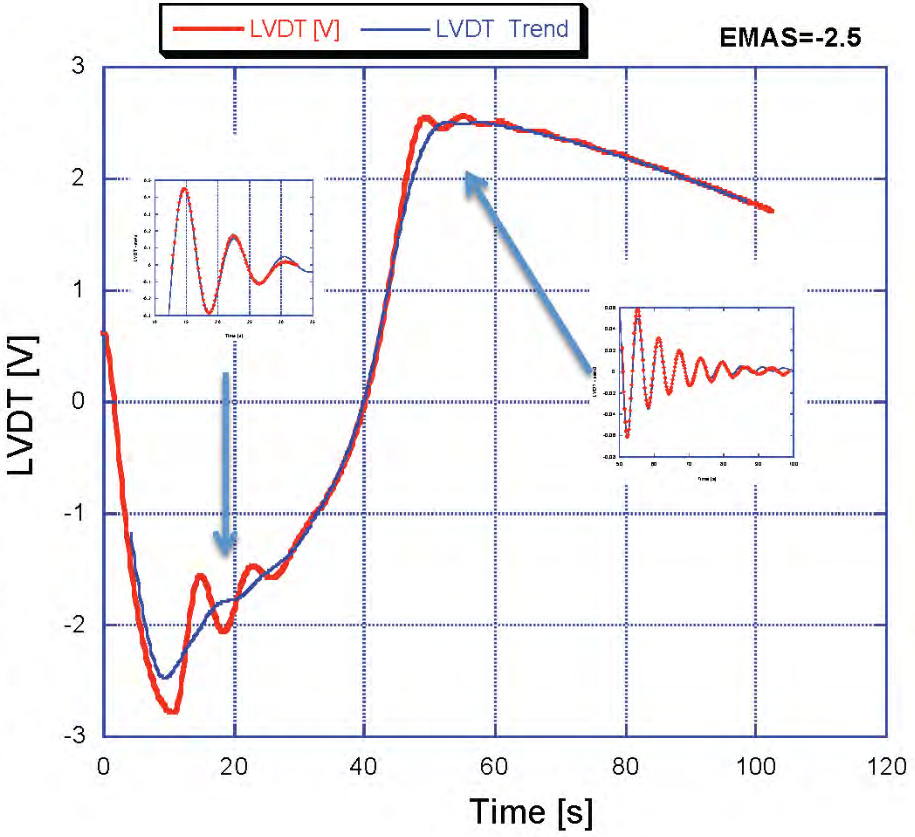
Pushing down the frequency limit

- Instabilities encountered starting below 0.2 Hz



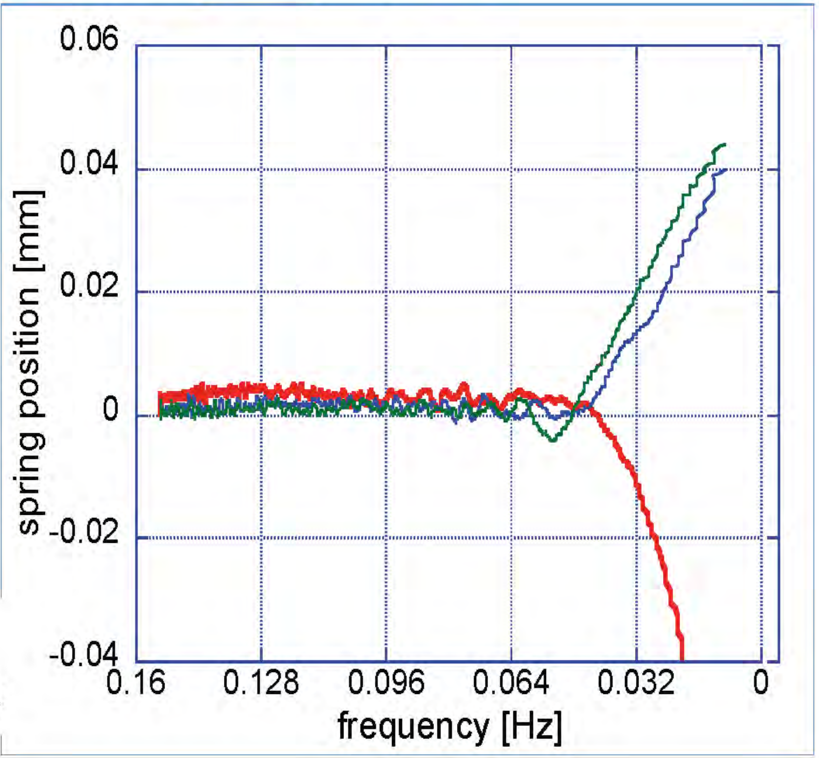
y = 0.01974*sqrt(x*m1+155.96...

	Value	Error
m1	33.631	0.23418
Chisq	0.00068336	NA
R	0.99873	NA



Low Frequency Filter Instability

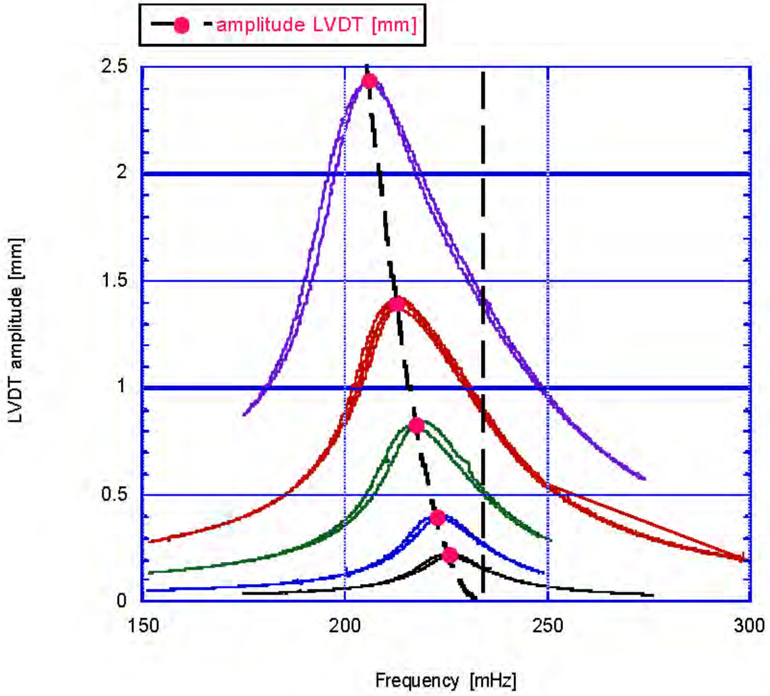
- After some time the springs spontaneously runs off (collapse)
- Half of the times the mass falls "UP" ! ! !
  - No gravity-induced effect
- Reversible collapse
  - No creep-induced effect
- First observed by Saulson

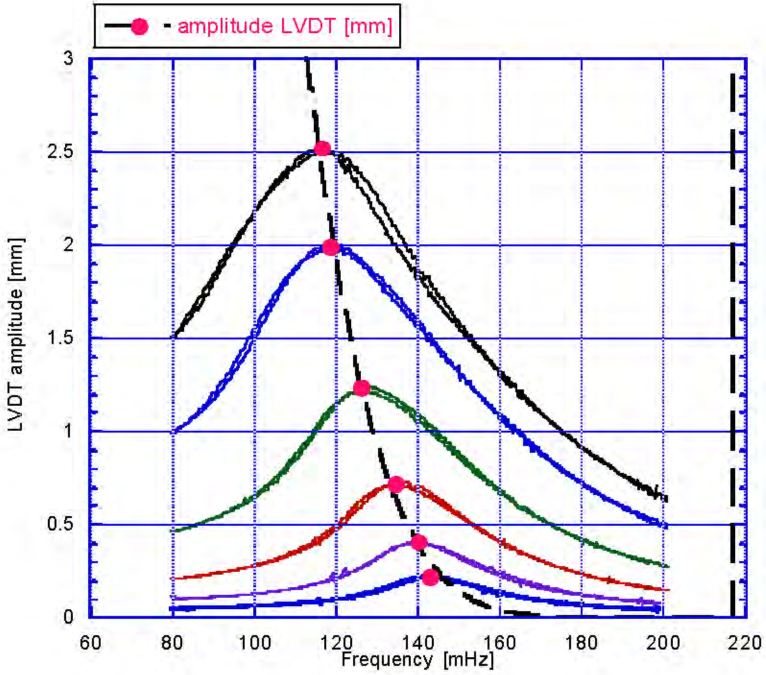


The inverted pendulum as a probe of anelasticity
Saulson Rev. Sci. Instrum. 85 (I), January 1994, p 184

Observed Instability of Young's modulus ! ! !

- Found an amplitude dependence of elasticity !



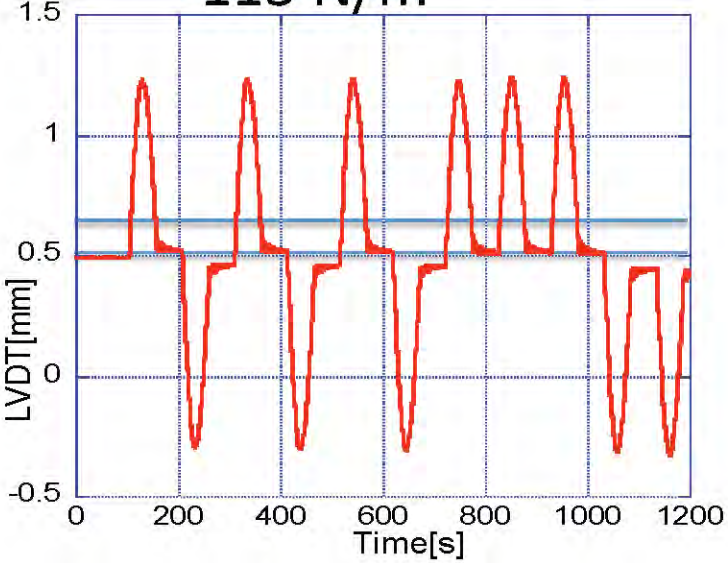


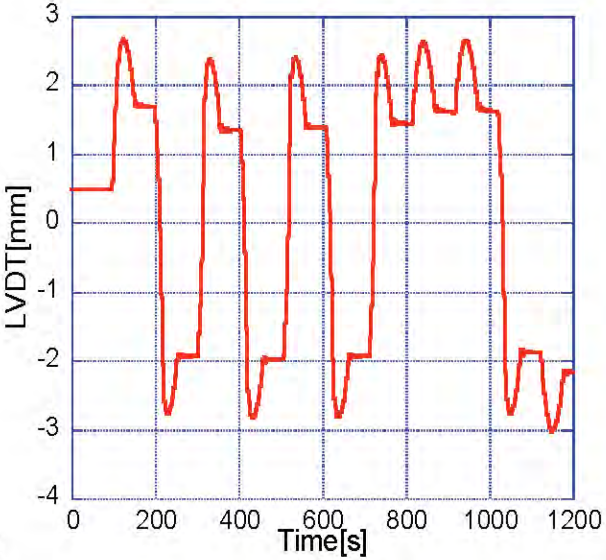
Strongly non linear hysteresis

- Hysteresis seems to grow orders of magnitudes at low frequency tune, for just small changes of spring elastic constant
- Response completely not proportional to the excitation

frequency 0.21 Hz

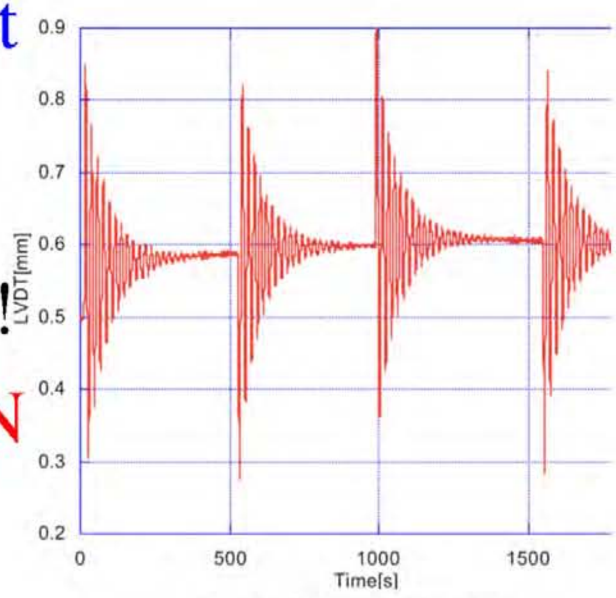
113 N/m

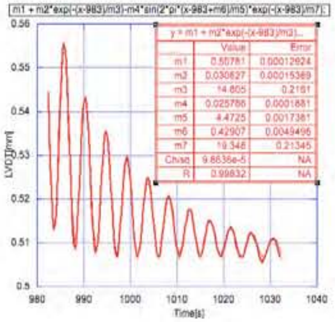




Funny hysteresis

- Miscellaneous Observations
  - Completely reversible hysteresis, not accompanied by work hardening
  - Found that hysteresis could be eliminated by oscillation cycling ! ! !
  - Observed hysteresis (in force) EVEN in absence of actual motion ! ? ! ?
  - Anelasticity observed as well.

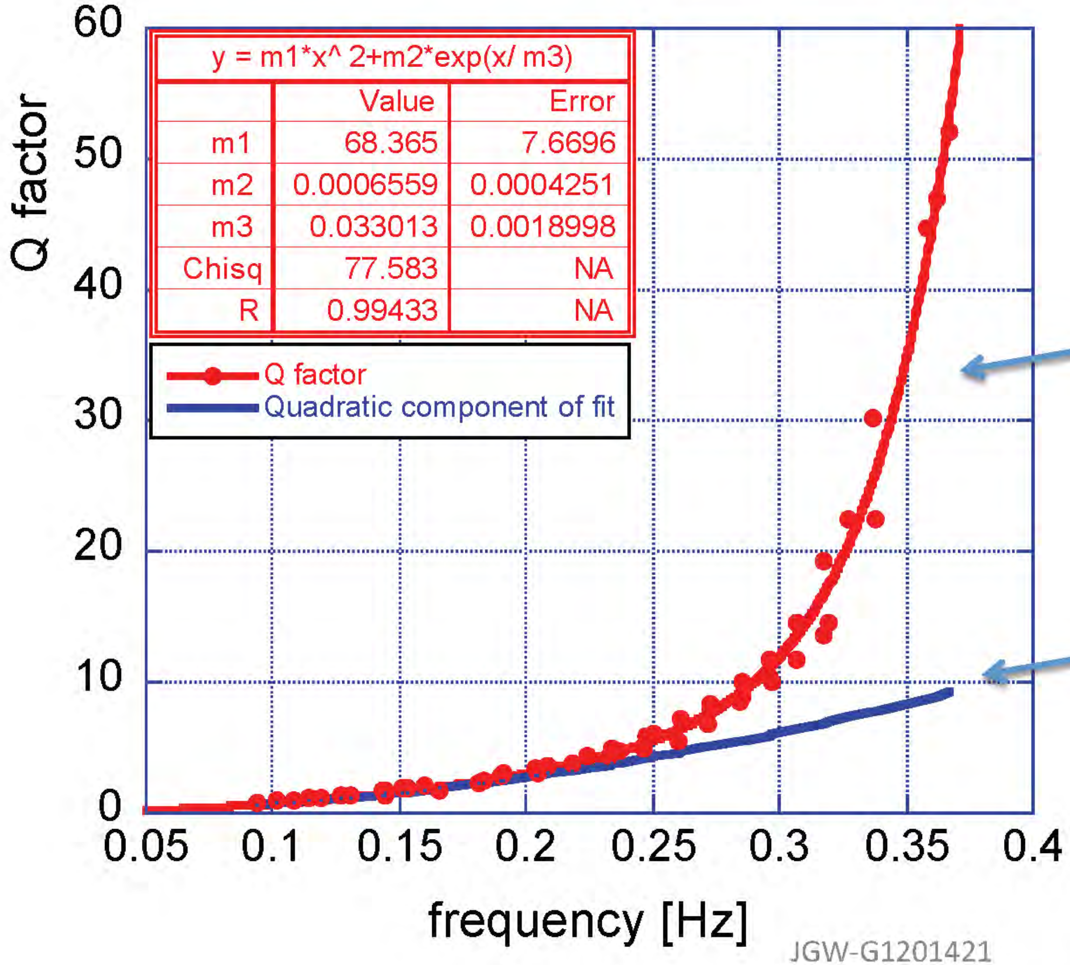




y = m1 + m2*exp(-(x-983)/m3)...

	Value	Error
m1	0.50781	0.00012924
m2	0.030627	0.00015369
m3	14.605	0.2161
m4	0.025786	0.0001881
m5	4.4725	0.0017381
m6	0.42907	0.0049496
m7	19.348	0.21345
Chisq	9.8636e-5	NA
R	0.99832	NA

Most striking:
Q-factor vs. Frequency !



y = m1*x^ 2+m2*exp(x/ m3)

	Value	Error
m1	68.365	7.6696
m2	0.0006559	0.0004251
m3	0.033013	0.0018998
Chisq	77.583	NA
R	0.99433	NA

10^4Q maraging limit
Reached by 0.5 Hz
(fit extrapolation)

Exponential growth of Q
losses in material
growing exponentially
with time until saturation

Quadratic Q behavior
Hysteretic behavior
Frequency-independent
losses

Looks like a
phase transition

All effects mysteriously frequency-dependent

- All anomalies were connected with low frequency operation,

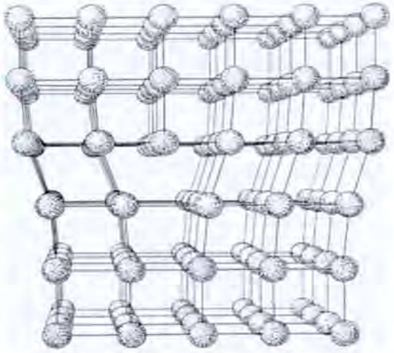
independently on how the system got there

  - Geometric Anti Springs - Magnetic Anti Springs
  - Inverted pendulum - Electro-Magnetic Anti Springs

- Almost hundred students and young scientists, over 15 years, in one way or another got involved in this puzzle, initially not even realizing there was a serious problem

Slowly Solving the puzzle

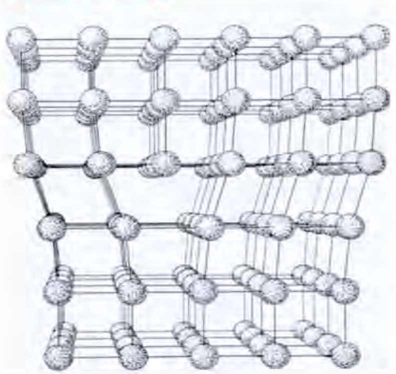
- Dislocations with length longer than the distance to the moon are present in a cubic centimeter of iron
- Dislocations are free to move and induce plasticity
- Perfect crystals are perfectly elastic
- The presence of dislocations produce the observed elastic "modulus defect"
- Work hardening entangles dislocations so that the modulus defect is reduced



Granato, Luecke, Theory of Mechanical damping due to Dislocations, J. od app..Phys., 27-6, p. 583, 1956

Slowly Solving the puzzle: going beyond Granato Lueck

- Dislocations with length longer than the distance to the moon are present in a cubic centimeter of iron
- Dislocations are free to move and induce plasticity
- Defects and impurities are introduced to pin dislocations and produce elastic steel



- Dislocations cannot cross each other
- Ergo
- Dislocations are much likely to be entangled than to be pinned

D.O. Thompson, "The effects of neutron irradiations on the Young's modulus of copper single crystals", Jour. Appl. Phys., **27**-7, p 713-723, 1956

Self Organized Criticality
to the rescue !

- Entangled dislocations act collectively
- They can dis-entangle !
- Collective action takes long time
  - Explain the low frequency effects
- Motion happens via avalanches
  - Explain random effects
- During disentanglement:
  - Modulus is weak!

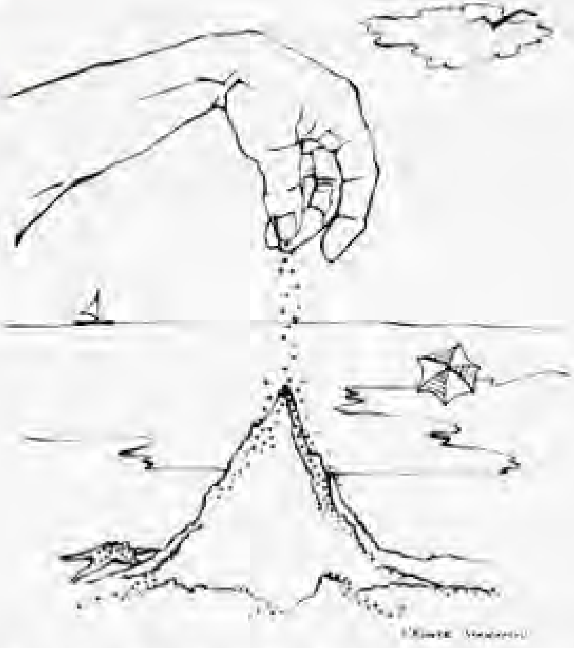
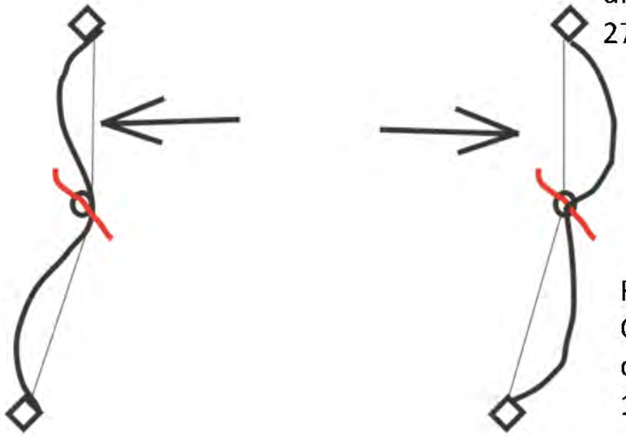


Figure 1. Sandpile (Drawing by Ms. Elaine Wiesenfeld.)

Per Bak 1996, How nature works:
The Science of Self-Organized Criticality

Self Organized criticality to the rescue !

- A phase transition from structural damping to a chaotic, avalanche-dominated dissipation regime is predicted when there the movement is sufficiently slow that dislocations can act collectively and abandon the Granato-Lueck pinned-string dissipation regime



A. Granato, et al., "Theory of mechanical damping due to dislocations", Jour. Of Appl. Phys., vol 27, n 6, p583-593, 1956

Per Bak 1996
How nature works: The Science of Self-Organized Criticality

Riccardo DeSalvo, et al., The role of Self-Organized Criticality in elasticity of metallic springs: Observations of a new dissipation regime, Eur. Phys. J. Plus (2011) 126: 75

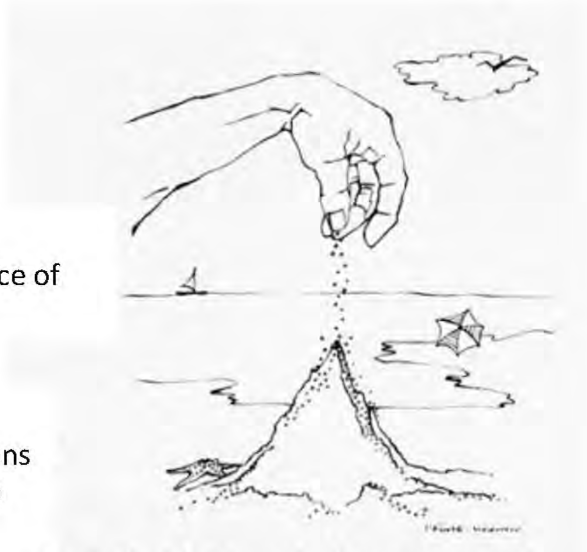


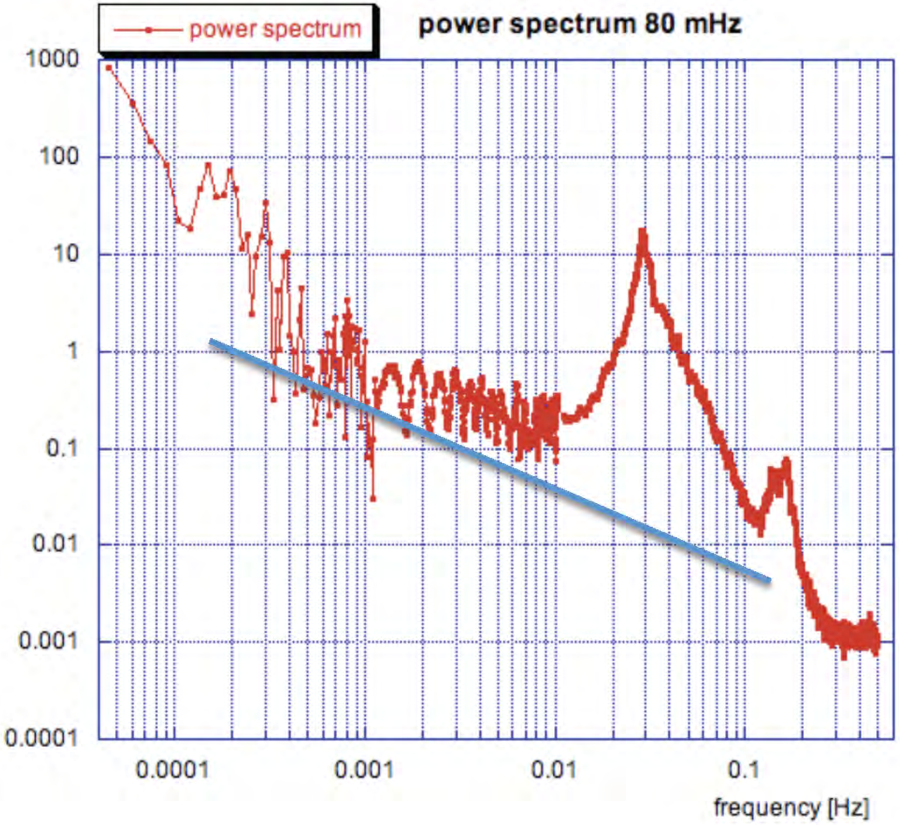
Figure 1. Sandpile. (Drawing by Ms. Elaine Wiesenfeld.)

A new noise regime predicted

- *SOC predicts 1/f noise*

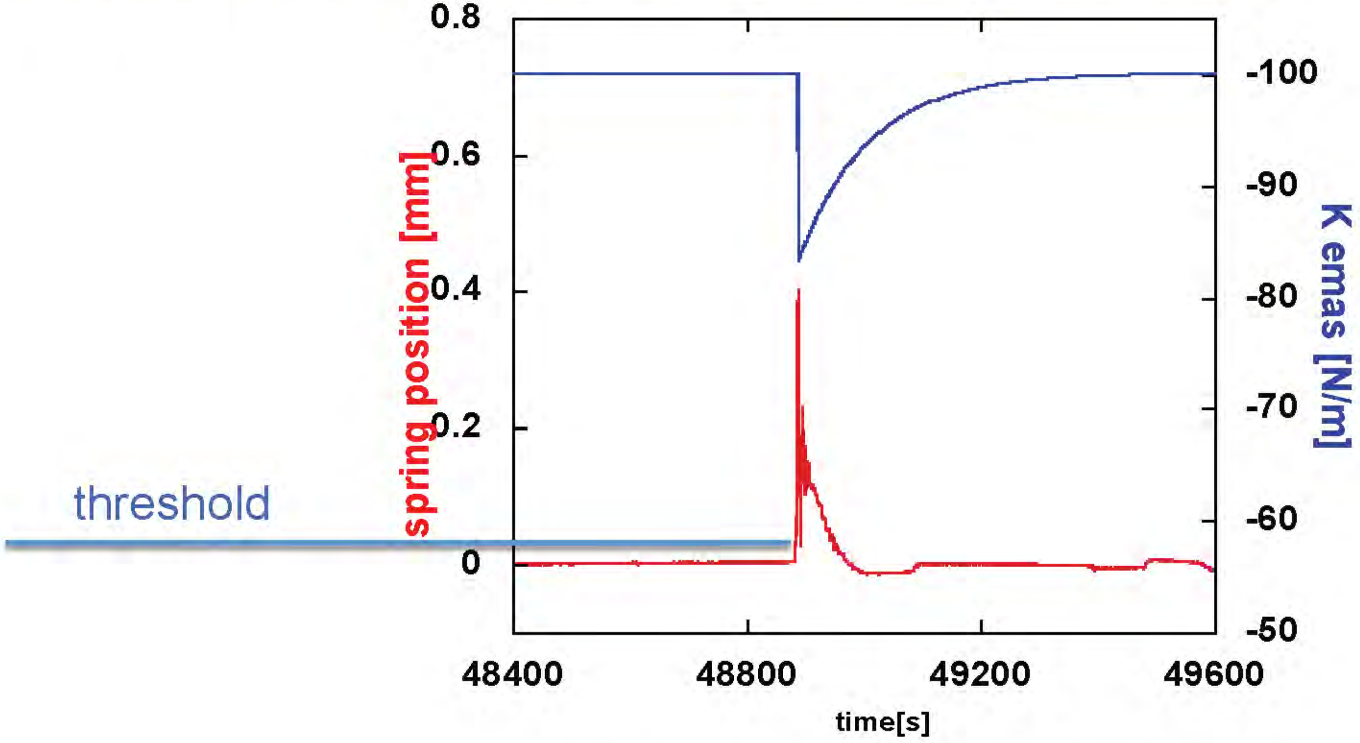
- Which is

  observed !



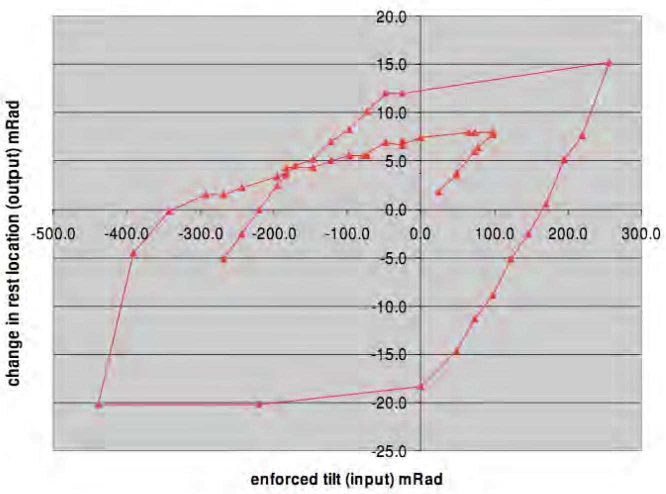
Internal proof of dislocation SOC

- We predicted a run-off control method
- The method observed to work as predicted



External proof of dislocation SOC

- We predicted
  - Hysteresis in LIGO suspensions
- We predicted
  - That it could be eliminated with damped oscillation motion



variation of offset in rest location vs enforced tilt

- Both predictions were observed !

External Proof

- The Virgo group at NIKHEF built a spring tuned at 320 mHz

- They observed its resonant frequency shifting down from 300 to 250 mHz when the spring was excited with a 11 Hz vibration. ! ! ! ! ! !

Private communication Eric Hennes, still unpublished

Dislocation SOC elsewhere

- Transient noise explainable by Self Organized Criticality of Entangled Dislocations was recognized in tungsten wire suspension of some torsion pendula, as well as other inertial sensors made with different metals
- Glitch noise in low frequency seismometers
- Independent random walk was observed in the Virgo Inverted Pendulums when excited by storm vibrations

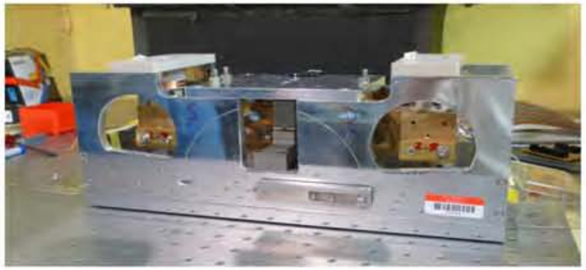
Consequences and conclusions

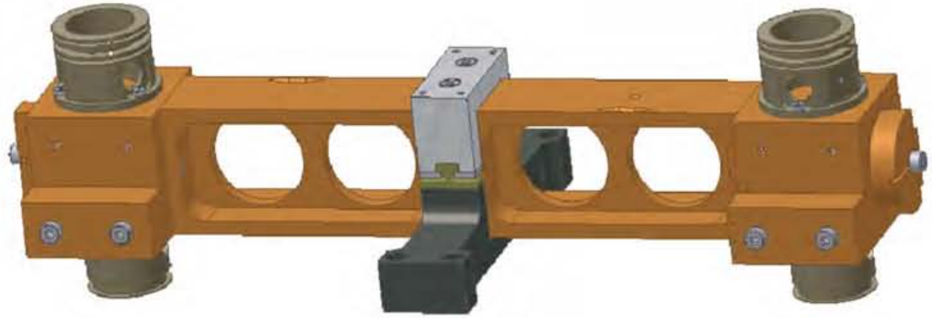
- The discovery of Self organized criticality of entangled dislocations explains the empirically proven superiority of fused silica and other glass flexure for seismic isolation or inertial sensors
- It guides the way for the design of better instruments
- For example using glassy metals or ceramics flexures
- or adopting engineering solutions that mitigates or avoid the problem altogether

Consequences and Conclusions

With the guidance of the new knowledge:

- A new kind of tiltmeter was designed with a knife-edge hinge (learning from our forefathers), which showed 1000x better sensitivity that any other built with metallic flexures
- Similar advances in seismometers can be expected
- And we will be able to build the seismic attenuators for the third generation Gravitational Wave Observatories





How?

- Glassy metal springs (no dislocations)
- Ceramic crystalline springs (no dislocation movement)
- Other ideas?