Scientific and technological challenges of Advanced VIRGO

Andrea Chincarini
INFN - Genova
the VIRGO collaboration

Presentation overview

- brief intro to GW
- light as ruler: interferometers
- main noises and the sensitivity curve
- case study: noise from magnetic coupling
- elements of data analysis

14 Sep 2015: First detection of Gravitational Waves!

229,000 paper downloads
from APS in the first 24 hours,
servers down!

[Phys. Rev. Lett. 116, 061102 (2016)]

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

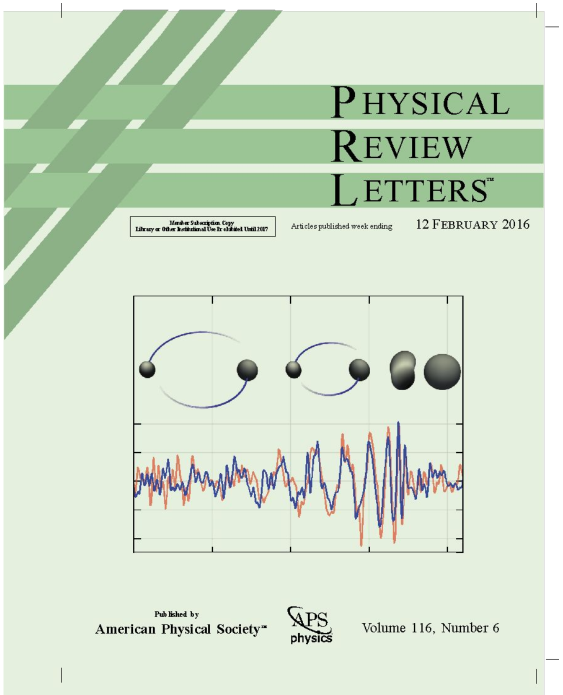
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in



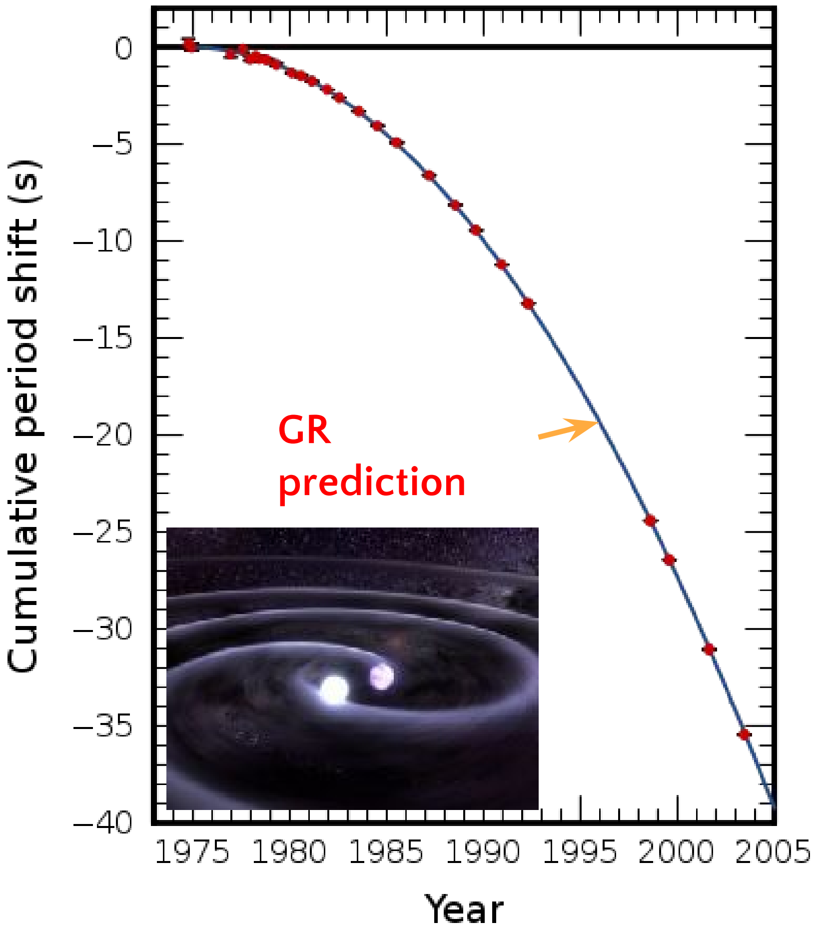
Binary black holes do exist!
and we can listen to them coalesce

This is the birth of gravitational wave astronomy

How did we know GWs exist?

The Nobel Prize in Physics 1993
Russell A. Hulse, Joseph H. Taylor Jr.

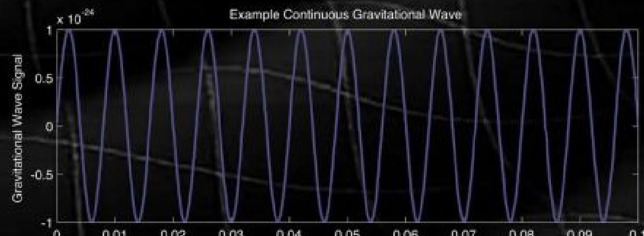
Binary Pulsar 1913+16



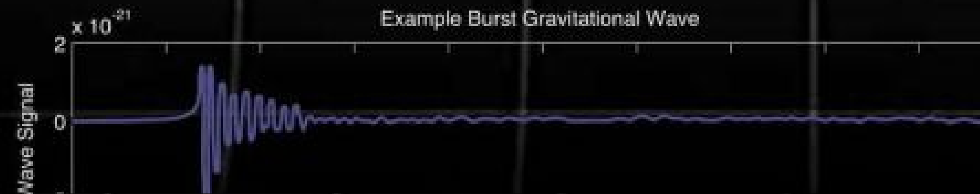
J. M. Weisberg, J. H. Taylor,
http://arxiv.org/abs/astro-ph/0407149

Ok, but how to *directly* detect it?

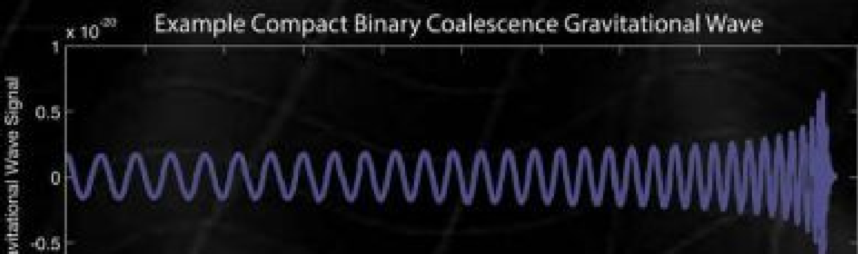
Continuous Wave Sources



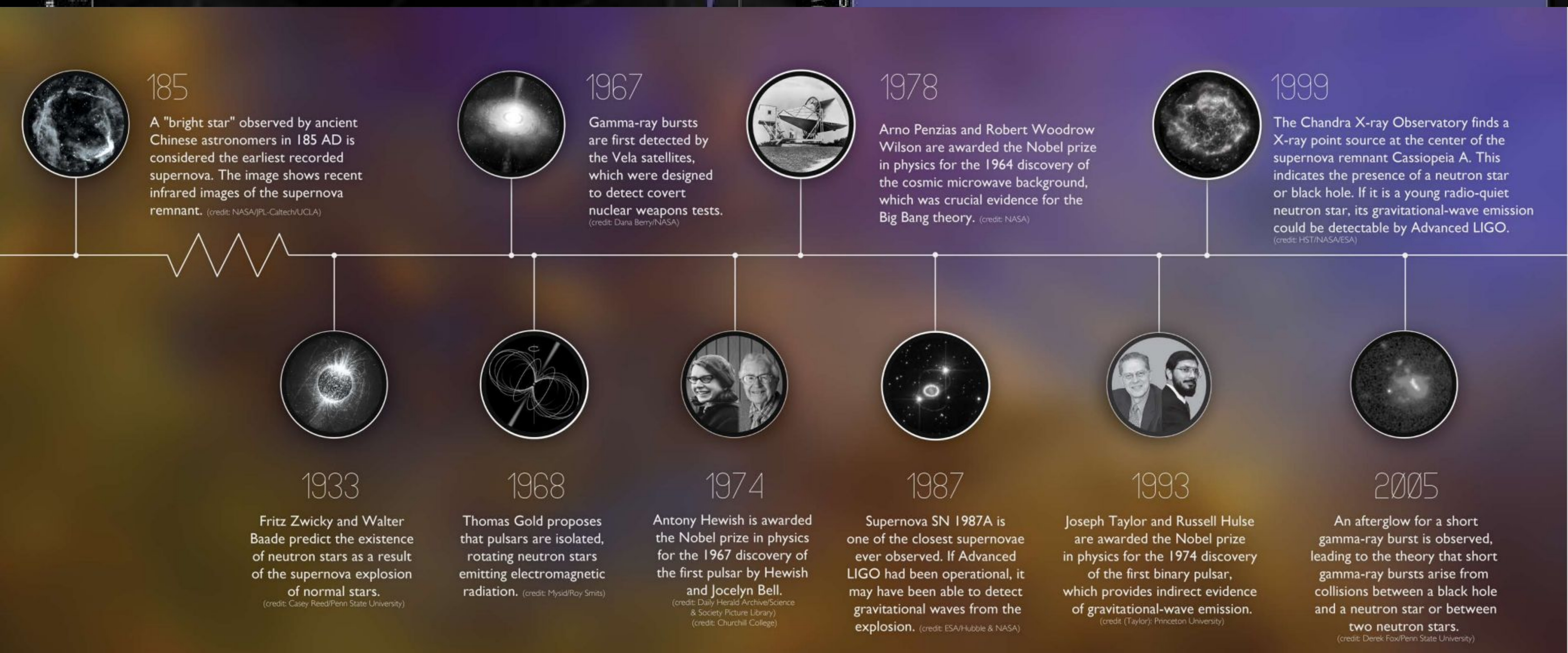
Burst Sources



Coalescing Compact Binaries



Stochastic Backgrounds



1st challenge: gravitational waves are very very… very weak

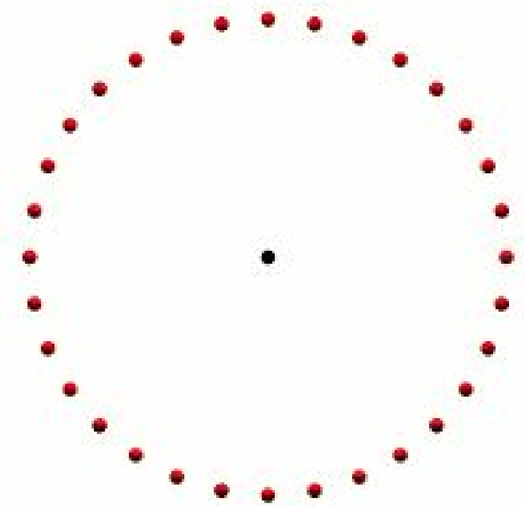
What is the Effect of GWs?

Squeeze and stretch the space [and time] in the directions perpendicular to the propagation

strain h = **ΔL/L**

What is the plausible "strain"?

Even for the most tremendous events in Universe, $h \sim 10^{-21}$



media-06

Ocean surface:

70% x 4pi x R_earth^2 = 0.7 x 4 x 3.14 x $(6.37 \times 10^6\ m)^2$

~ $3.6 \times 10^{14}\ m^2$

Glass volume:

~ $0.25 \times 10^{-3}\ m^3$

10 Drops of water:

~ $5 \times 10^{-7}\ m^3$

Ocean rise:

delta_h~

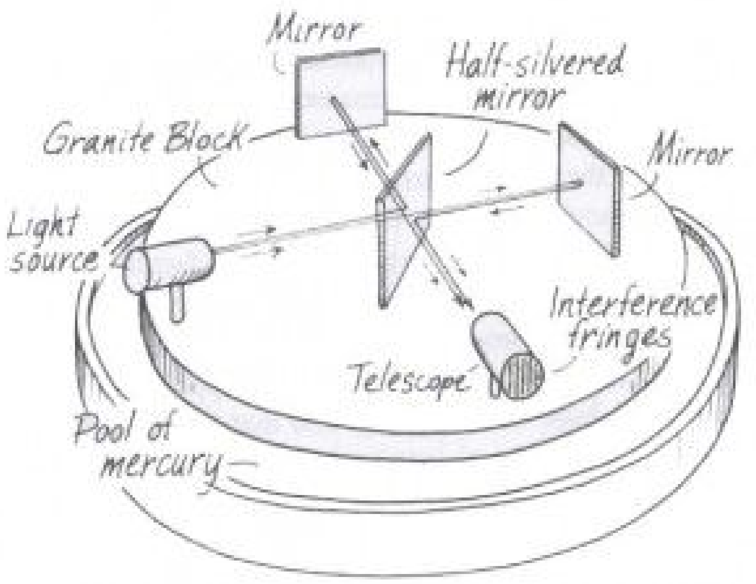
V_drops/Ocean surface ~ **1×10^{-21}m**

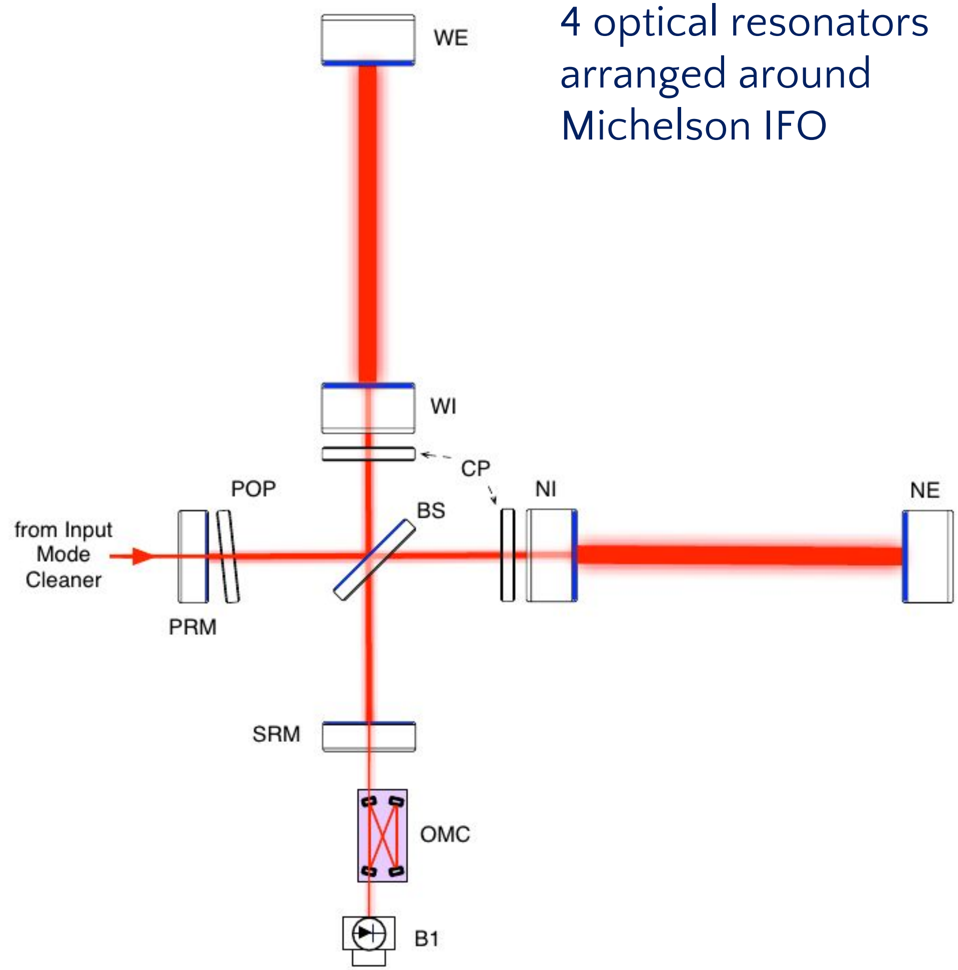
V_glass/Ocean surface ~ **1×10^{-18}m**

This is the kind of displacement we need to detect

light as ruler: interferometers

Michelson (with additions)





4 optical resonators arranged around Michelson IFO

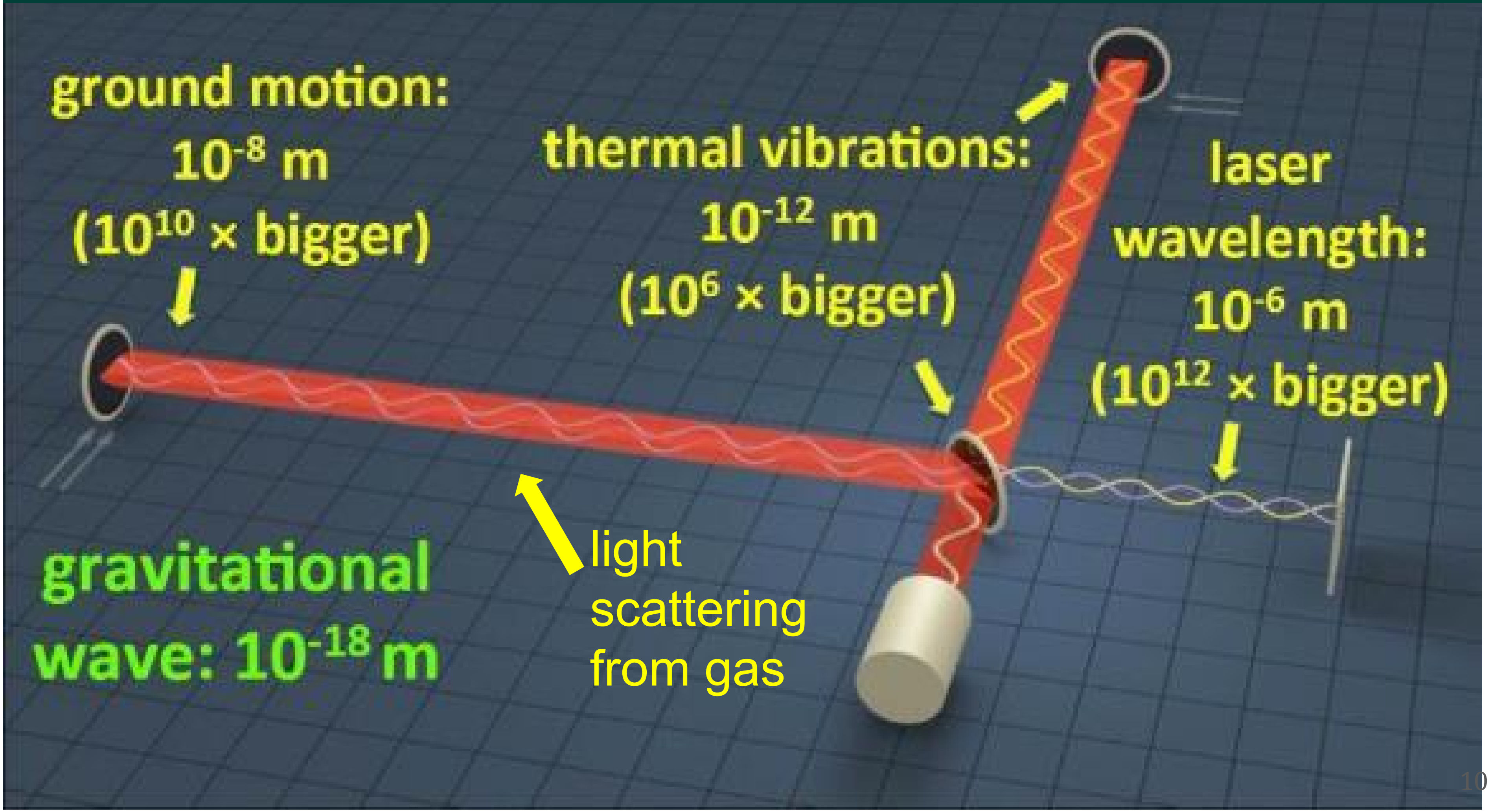
Michelson-Morley experiment (1887):
Accuracy: 10^{-8} m (10^{-9} relative)
10 m arm-length

Advanced Interferometer:
Accuracy: 10^{-19} m (~10^{-23} relative), 100Hz BW
3-4 km arm-length

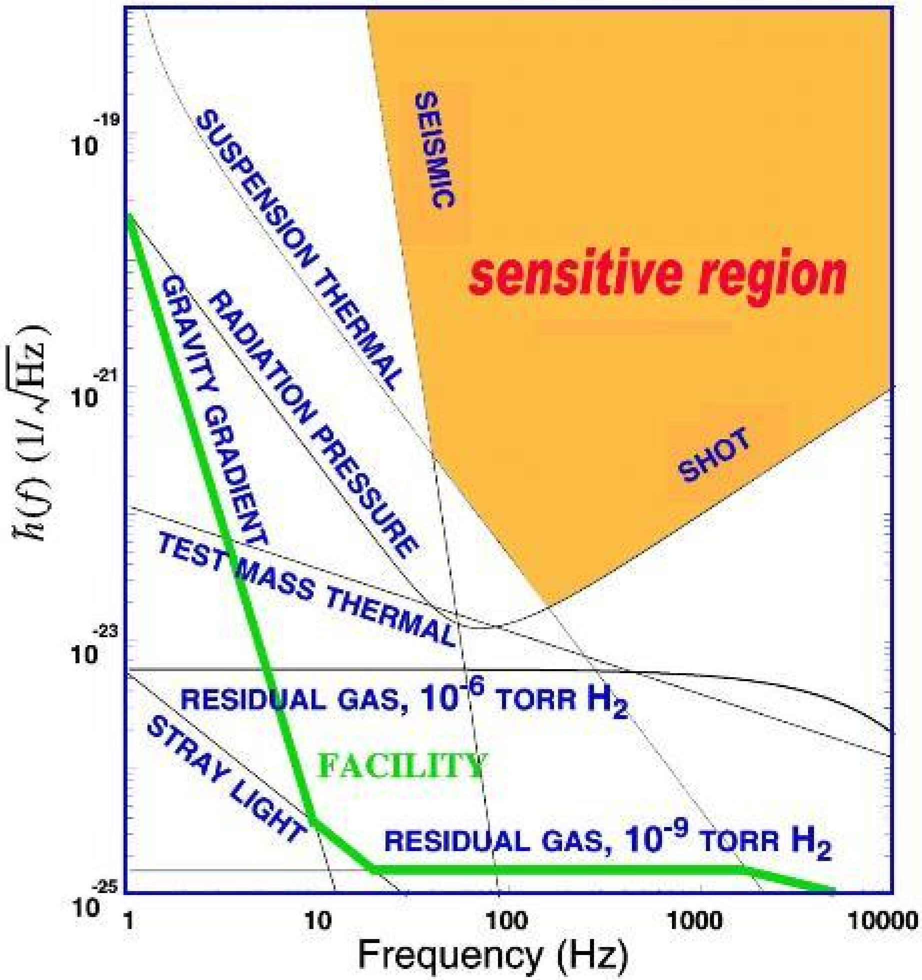
media-09

main noises

Doesn't matter how sensitive you are, if your noise is billions of times your signal



sensitivity curve and noises



Seismic noise limits low frequencies

Thermal Noise limits middle frequencies

Quantum nature of light (Shot Noise) limits high frequencies

Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals

components: optics

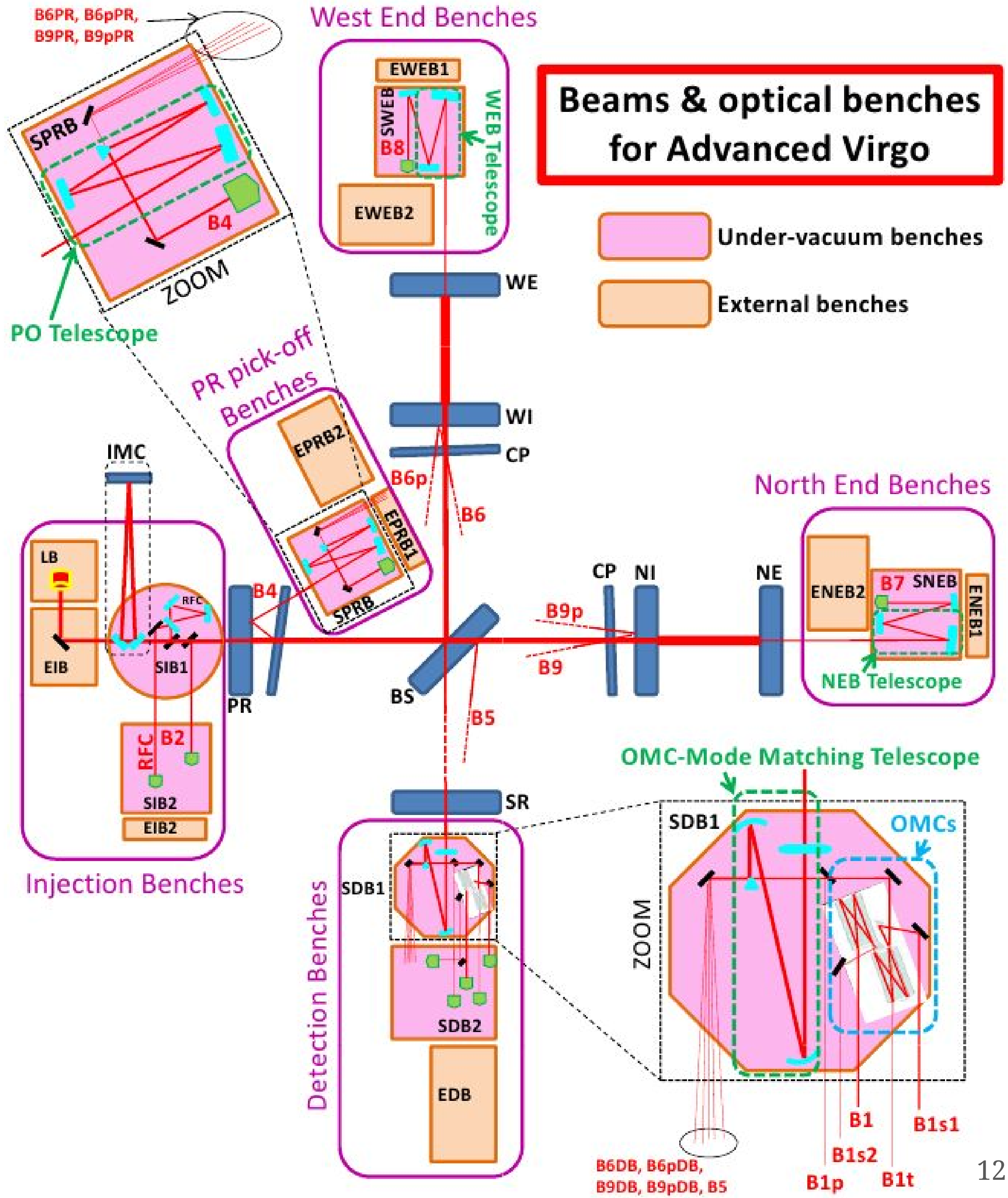
Laser & laser mode cleaner

mirrors & telescopes

modulators

scattering light stopper (baffles)

alignment & feedback



components: suspensions

mirrors and optical bench

superattenuators

seismic insulation

structural alignment

active feedback

IT infrastructure

low noise electronics

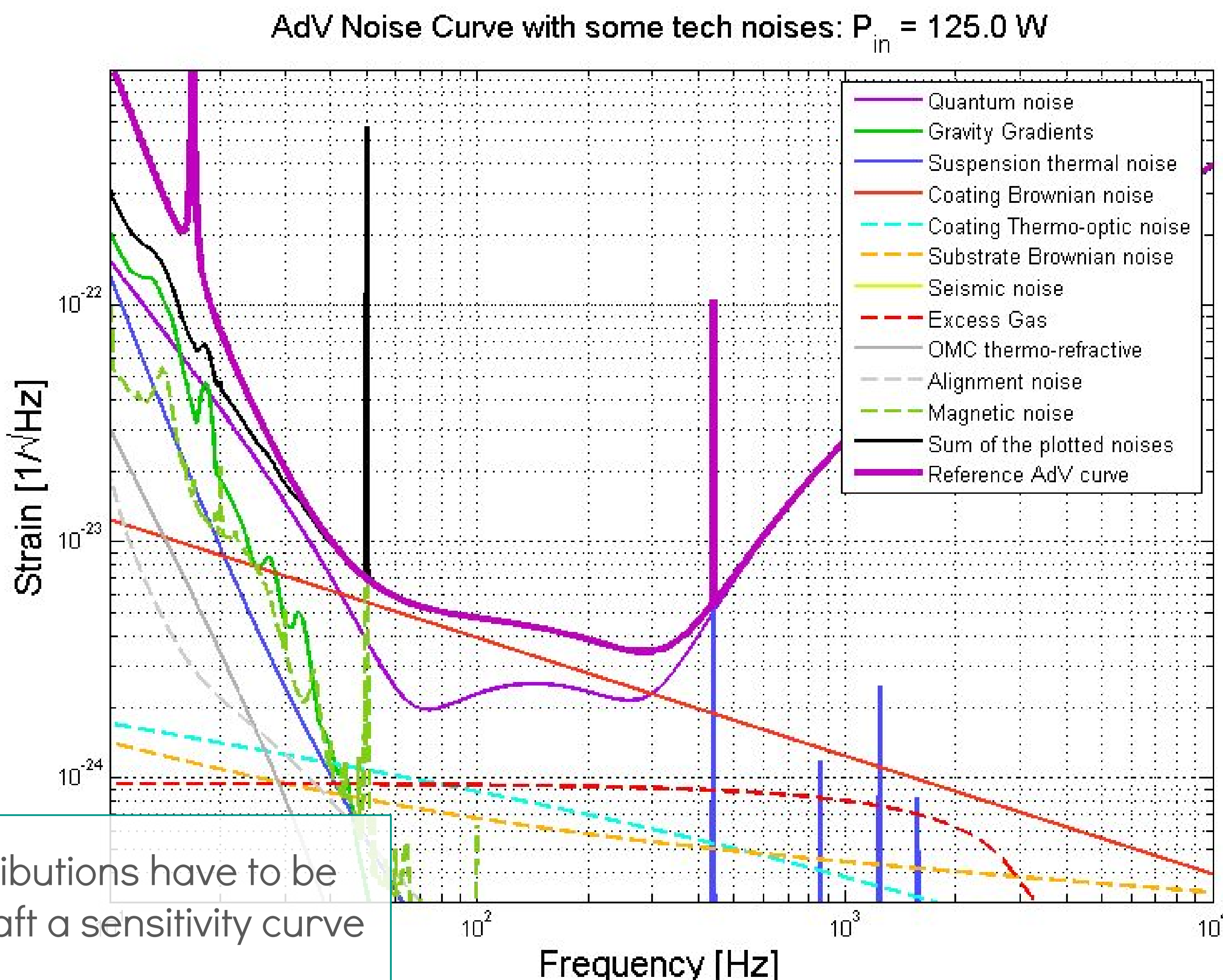
components: infrastructure

environmental control

vacuum

cryogenic

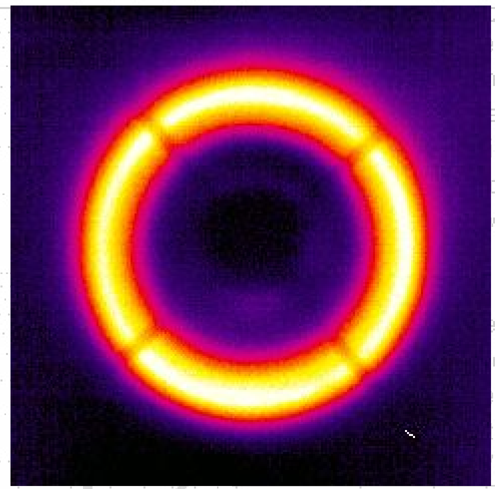
the sensitivity curve

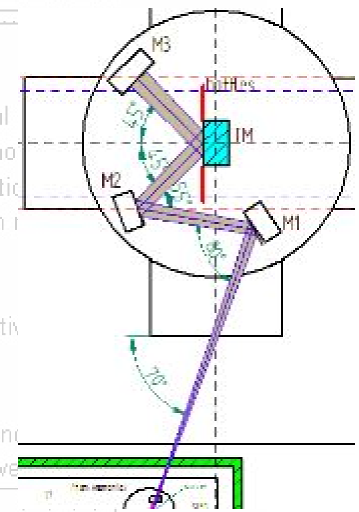


many more contributions have to be considered to draft a sensitivity curve

coping with noises: HF

High frequency range:
Dominated by laser shot noise.
Improved by increasing the power:
>100W input, ~1 MW in the cavities



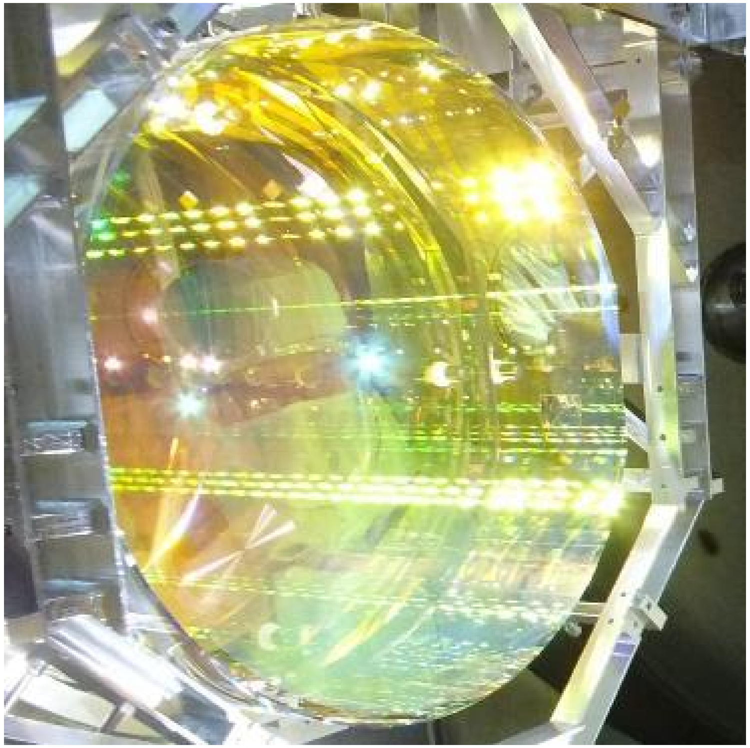


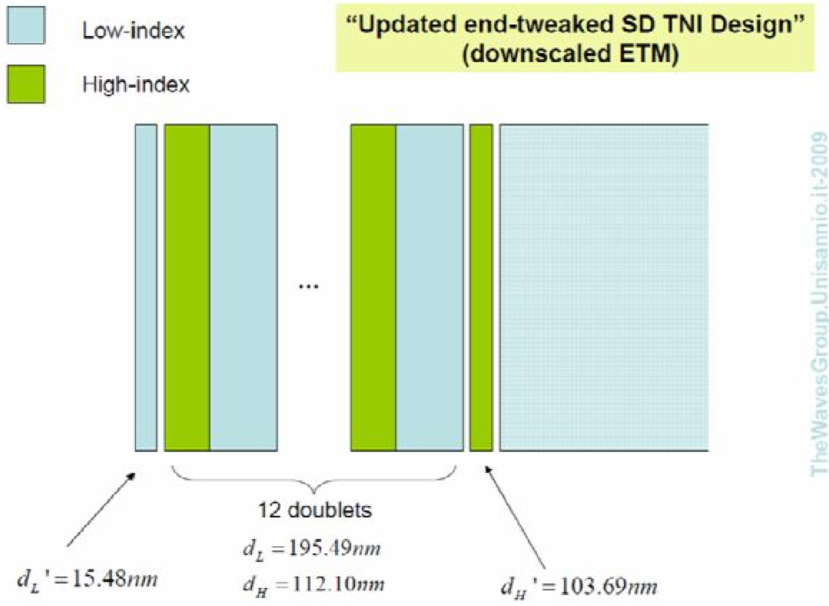
Requires:

- New laser amplifiers (solid state, fiber)
- Heavy, low absorption optics (substrates, coatings)
- Sophisticated systems to correct for thermal aberrations

coping with noises: MF

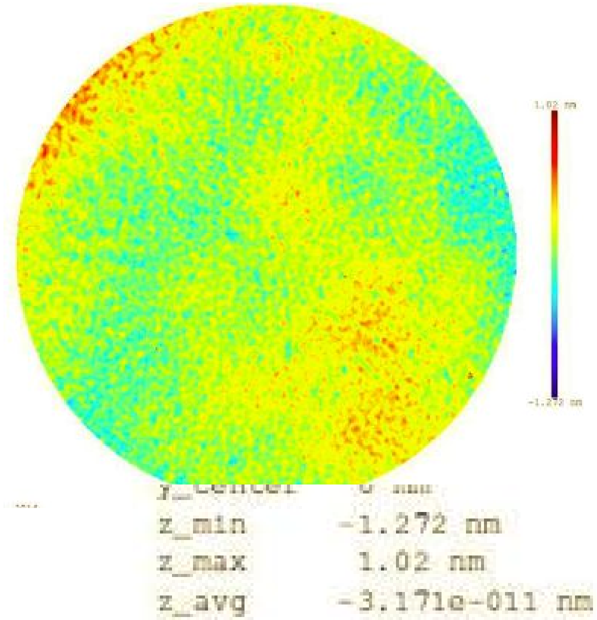
Intermediate frequency range:
Dominated by thermal noise of mirror coatings and suspension
Coating performance is critical! optimized $Si0_2$ + doped Ta_2O_5 to minimize mech. losses

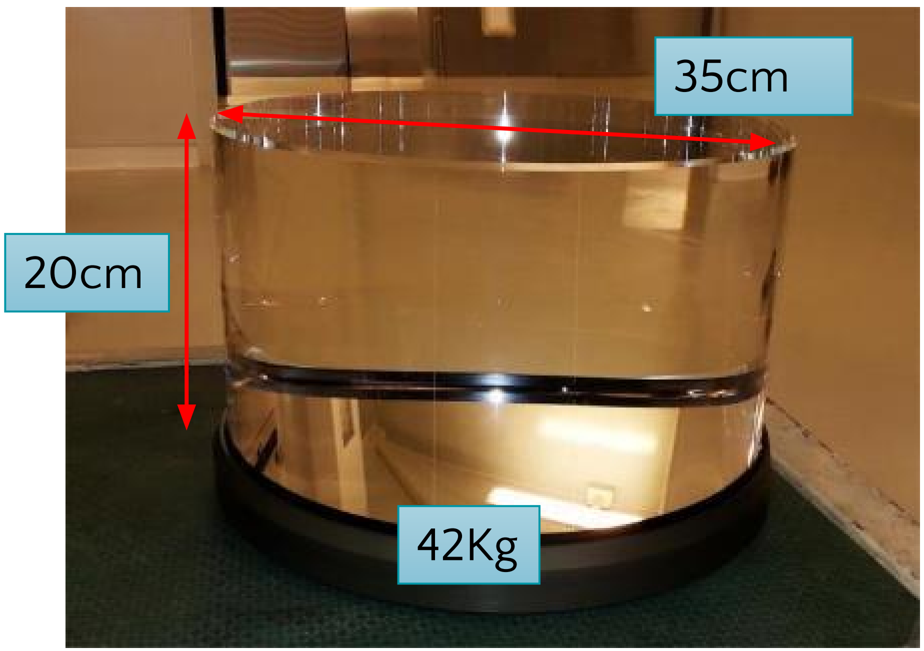


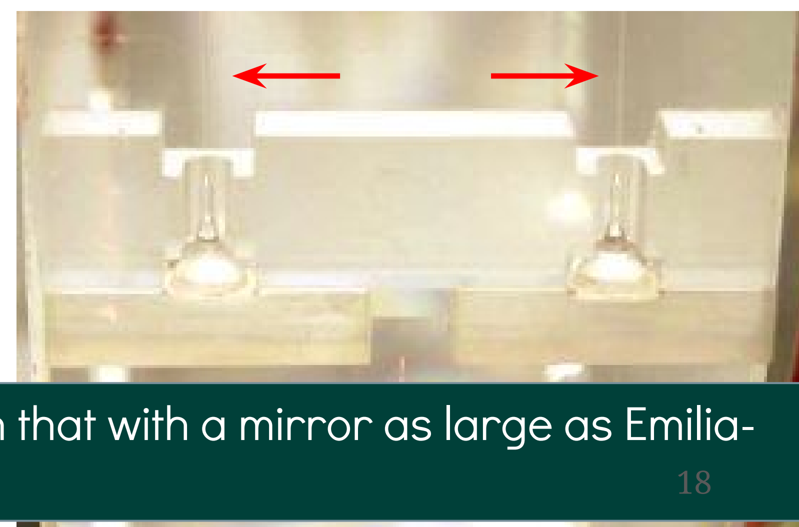


coping with noises: MF

Reduced by:
Larger beam spot (sample larger mirror surface)
Test masses suspended by fused silica fibers (low mechanical
Mirror coatings engineered for low losses
(curing, annealing, optimized thickness, etc..)







The surface figure of the polished test masses is such that with a mirror as large as Emilia-Romagna, ***highest mountain would be 1mm***

coping with noises: LF

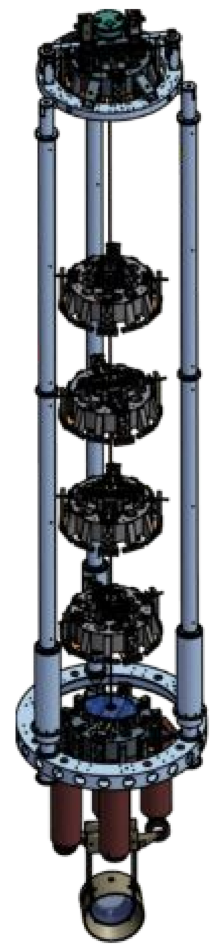
Low frequency range:

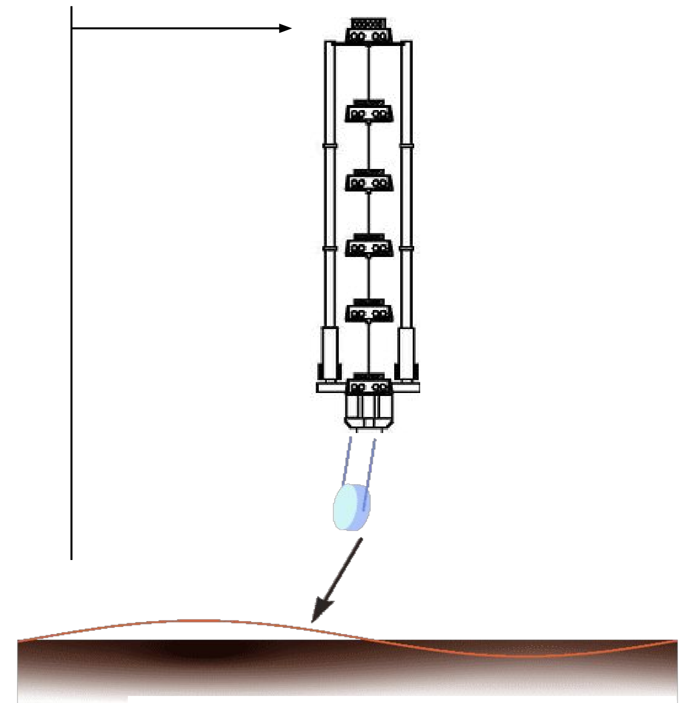
Dominated by seismic noise

Managed by suspending the mirrors from extreme vibration isolators (attenuation > 10^{12})

Technical noises of different nature are the real challenge in this range

Ultimate limit for ground-based detectors: gravity gradient noise





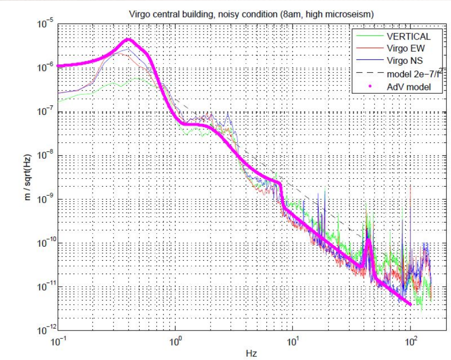


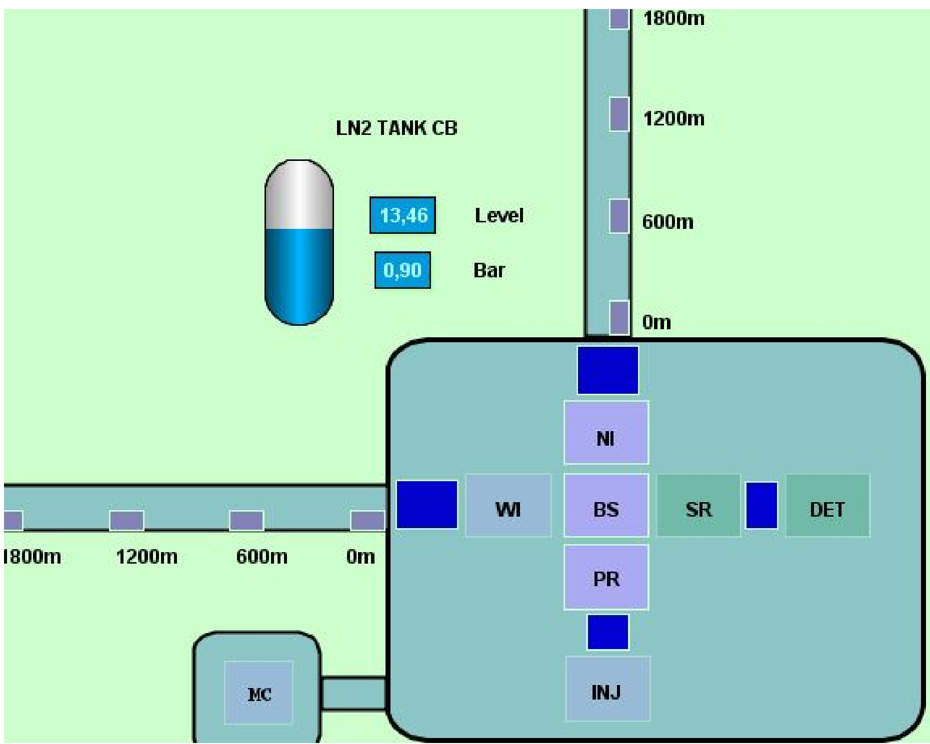
Figure 4: Seismic noise in the Virgo CB [7], in a condition of **noisy** μ–seism. The green curve shows the spectral amplitude of the vertical seismic red curve the East–West horizontal vibration and the blue curve the North–South horizontal seismic vibration. The dashed black line is the $10^{-7}/f^2$ simple model. The magenta markers shows the prediction of Eq.1, computed with the high noise parameters.

$$x_{\rm seism} = a_1 \cdot \left| \prod_{j=1,3} \left(f^2 - f_j^2 + i\frac{f_j f}{Q_j} \right)^{p_j} \right| + a_2 \cdot \sum \text{bumps}$$

vacuum, cryogenics

Cryopumps to improve vacuum in tubes and near mirrors

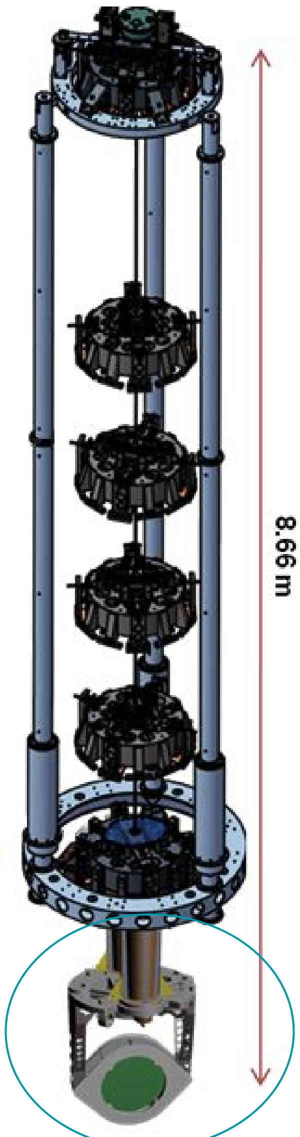
Low-noise pumping system (magnetically suspended turbo pumps + ionic pumps)

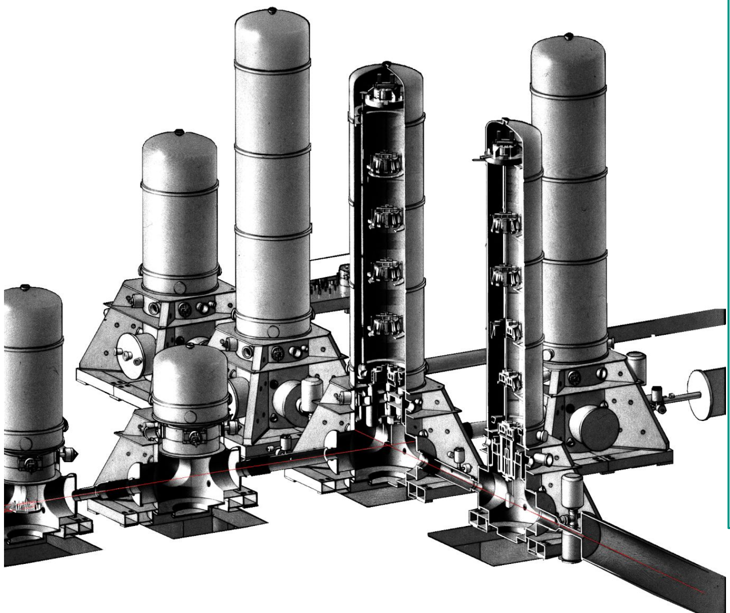


case study:

magnetic coupling noise budget estimation

adv. VIRGO payloads in a nutshell

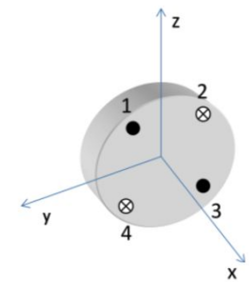




mirror alignment

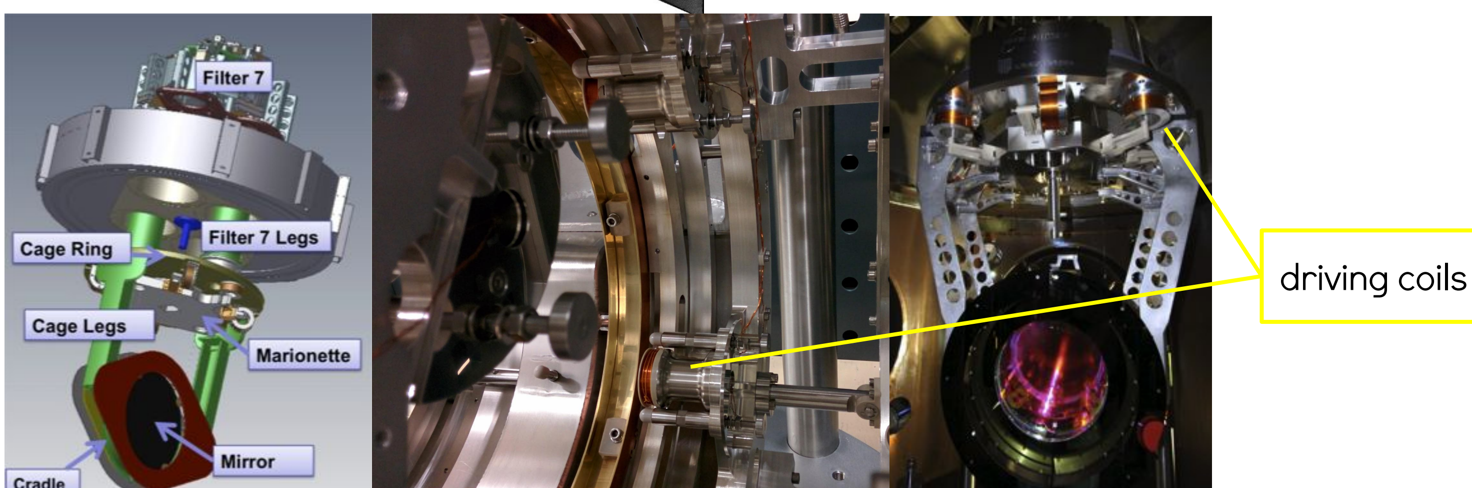
4 magnets (antiparallel conf.)

μ =(2.2 ± 3.3) x 10^{-2} Am^2



8 magnets on the marionette

2 input + 2 end PAYload designs



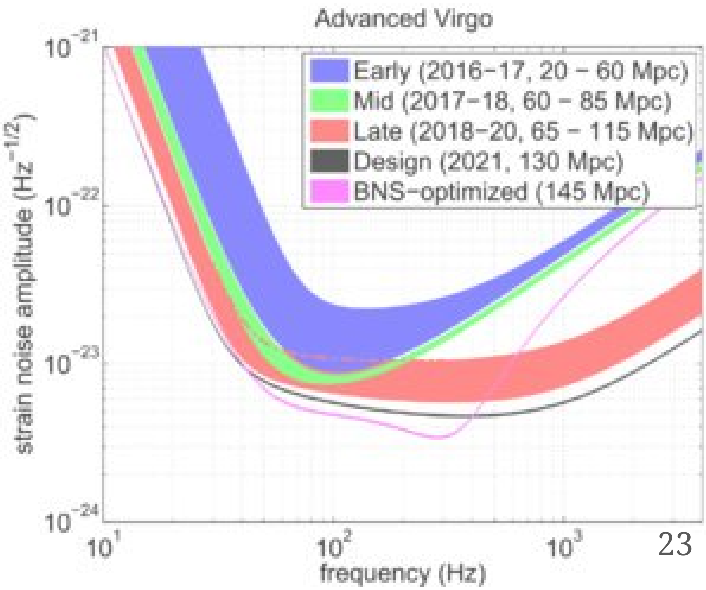
$$\mathbf{F} = \nabla(\boldsymbol{\mu} \cdot \mathbf{B})$$

any $\nabla \mathbf{B}$ can generate a force on the magnets

$$h = \frac{\sum F}{M L_0 (2\pi f)^2}$$

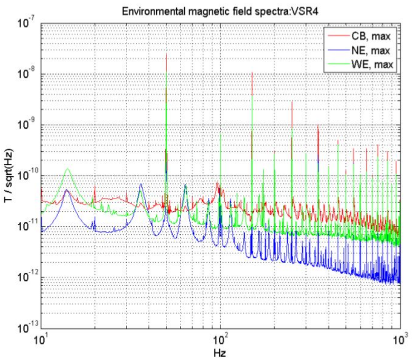
posing the problem

estimate the contribution to the adv VIRGO noise budget due to the coupling of the payload magnets with an environmental [noisy] magnetic field



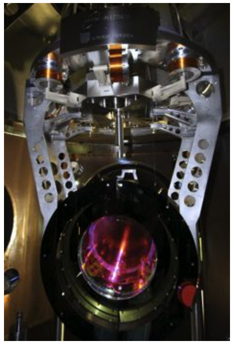
magnetic coupling

environmental B



+

metallic frame



=

Faraday-Neumann-Lenz

$$\xi = -\frac{\partial \phi(\mathbf{B})}{\partial t}$$

$$I_{eddy} = \xi / R$$

induced B

locally warped field lines even in presence of a spatially uniform external field

in principle F = 0 (anti-parallel conf.) ...

how can we estimate the effect since:

- gradients that small can hardly be measured on site and in working conditions
- it is impractical to make an actual 3D map of the B field
- environment (cables, electronics, ...) still undergoes significant changes

A.Chincarini

model BUILDING

harmonic FEA of a structure in a user-defined magn. field

model VALIDATION

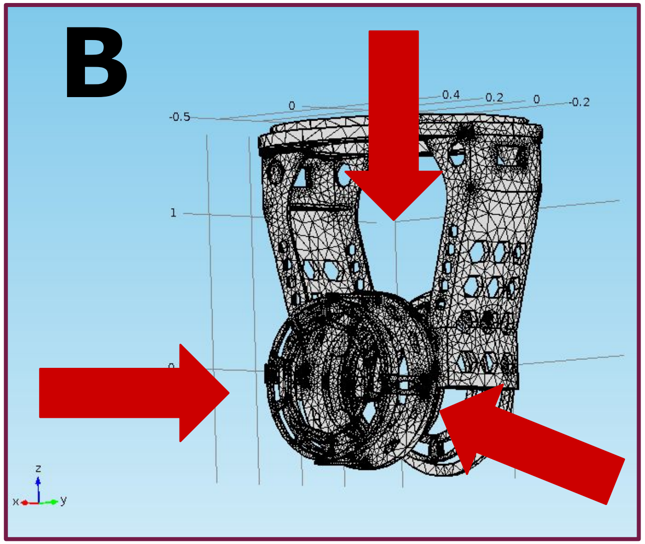
known conditions
experimental measures &
optimization

application of a real external field + force calculation

strain estimation

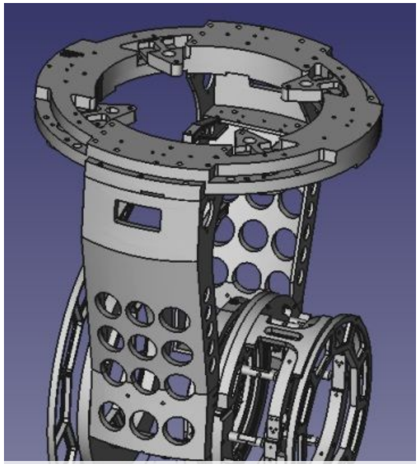
mitigation strategies

approaching the solution

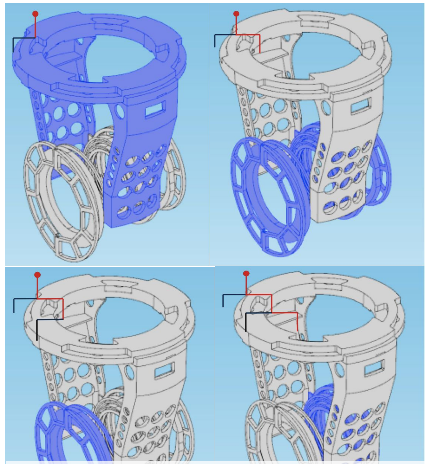


structure complexity doesn't suggest a direct (i.e. from CAD) modeling

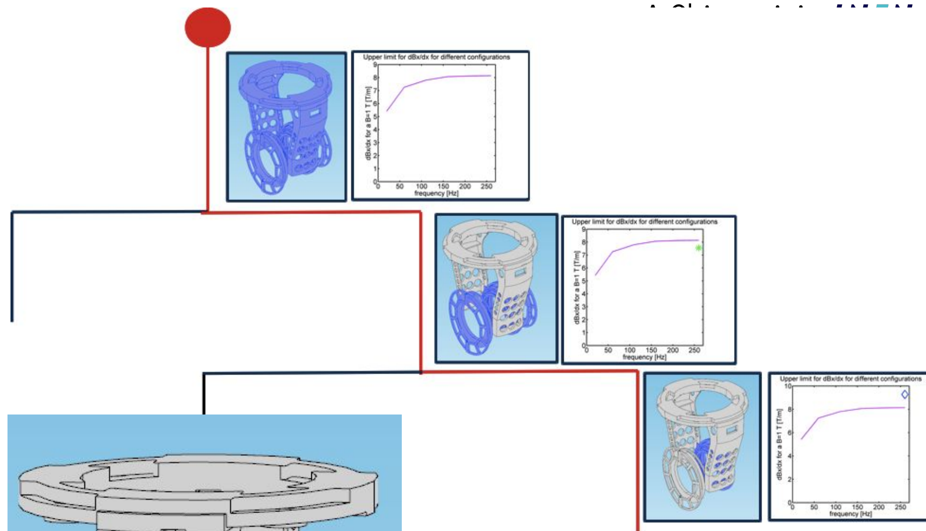
simplification and validation steps are required to get a "magnetic transfer function"

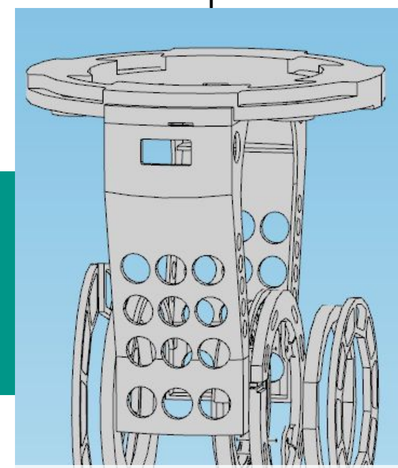


CAD import



hierarchical decomp.





simplified model

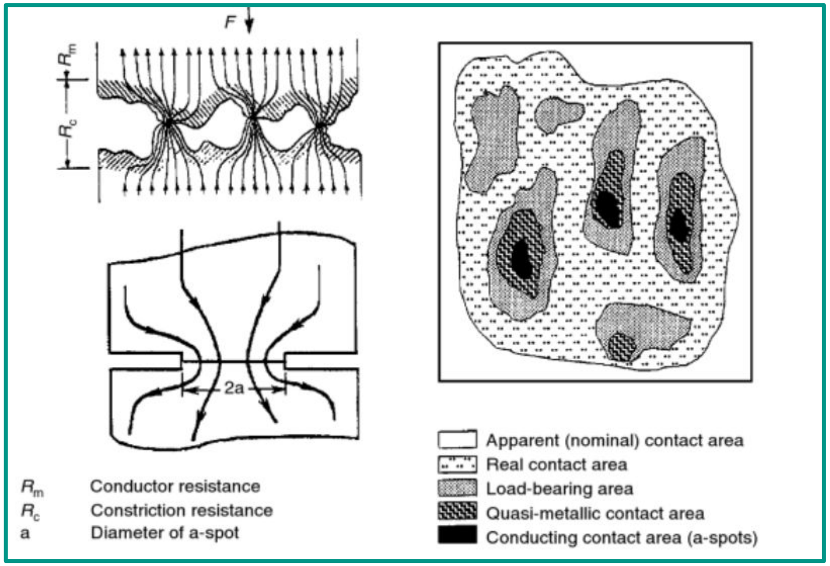
model building

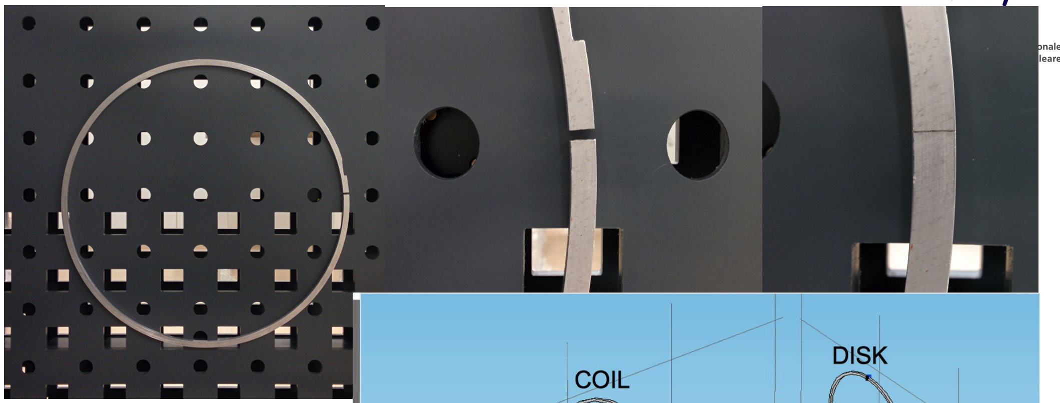
composite & complex object with very varied details

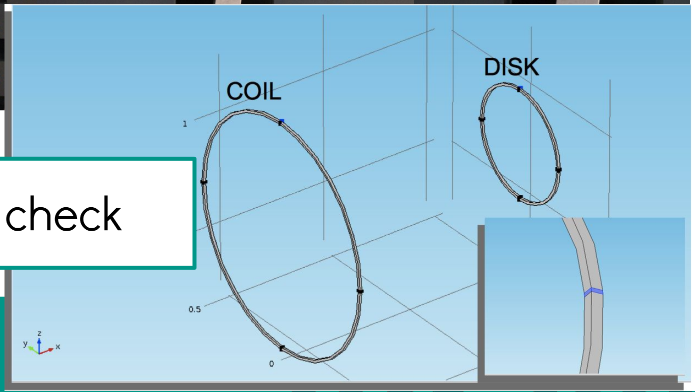
materials: Al (alloy), Ti, steel → only Al is modeled (highest conductivity)

meshing [solving time] calls for geometry simplification

geometry simplification is guided by relative impact on B gradient near the magnets

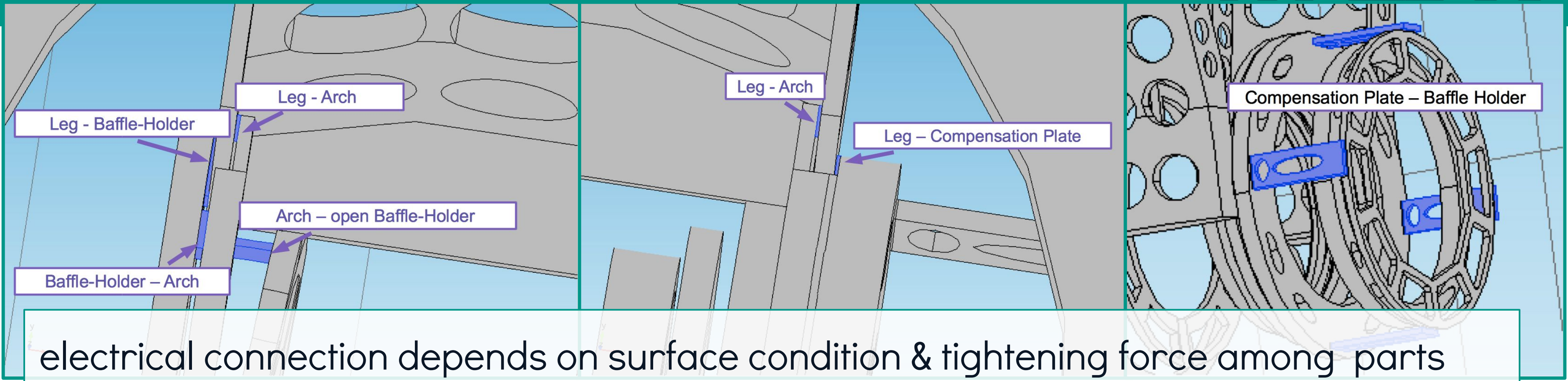






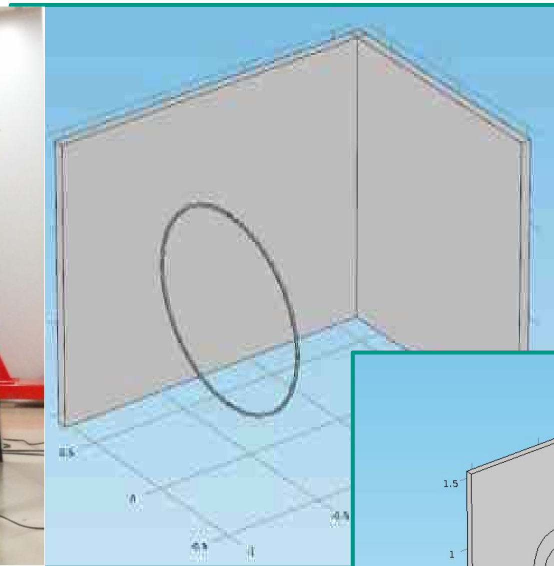
Experimental check

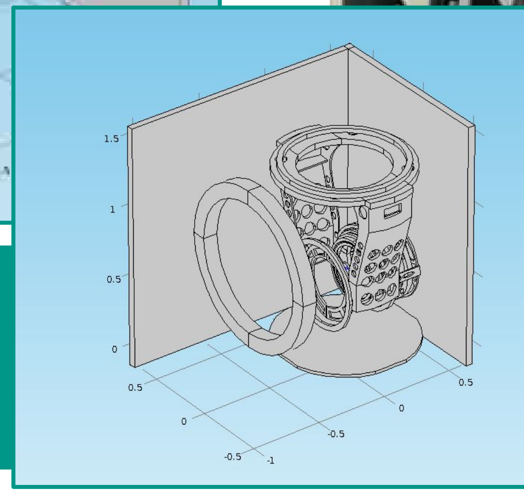
connections & contacts



electrical connection depends on surface condition & tightening force among parts

7 electrical connection points identified = 2^7 possible model configurations



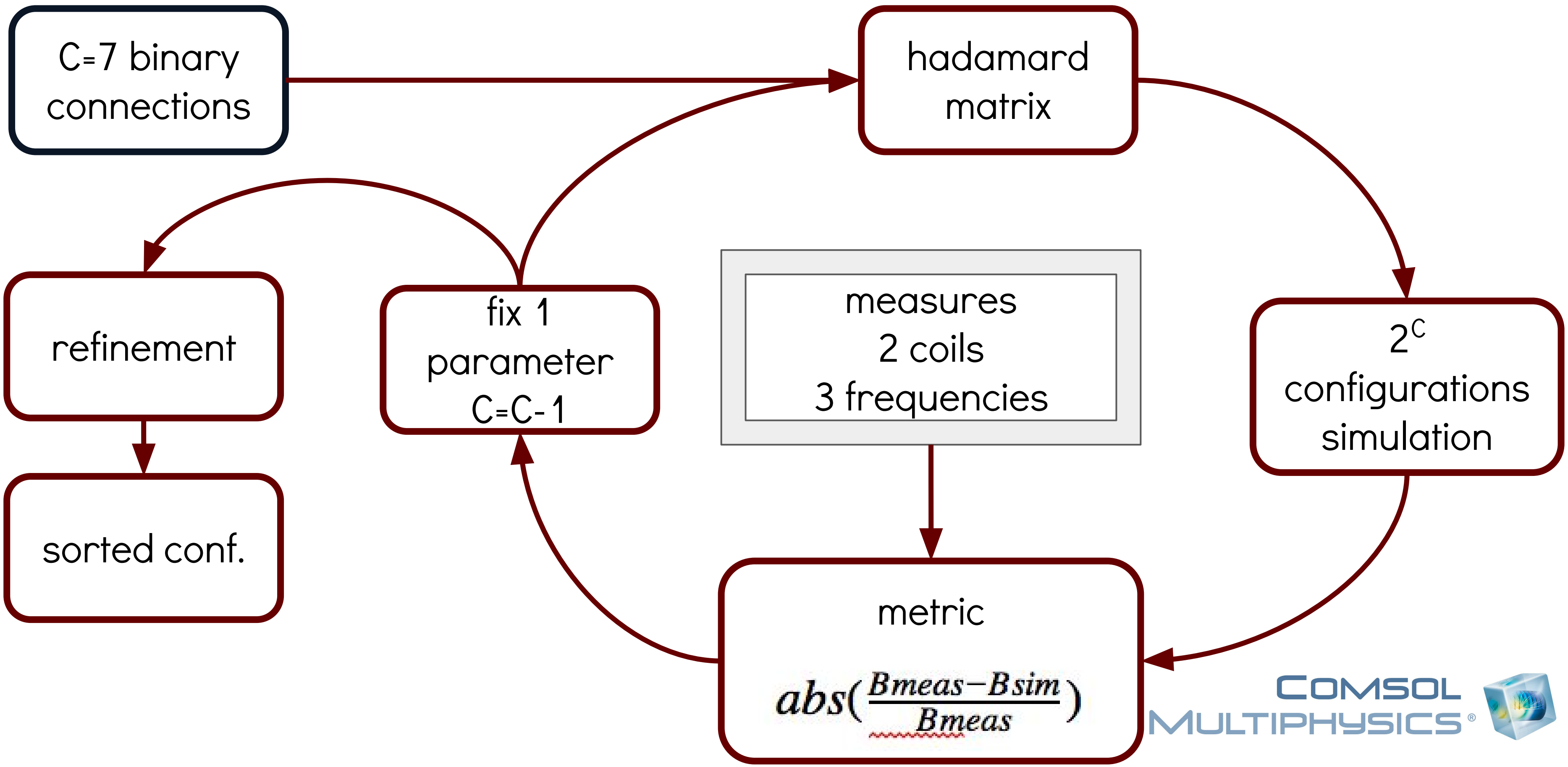


model validation

geometry simplification and multiple electrical connections choices call for model validation

clean room setup with 2 driving coils + abs cage with multiple measuring sites, ensuring reproducible placing of a 3-axial high-sensitivity B-field gauge.

simulations & measures

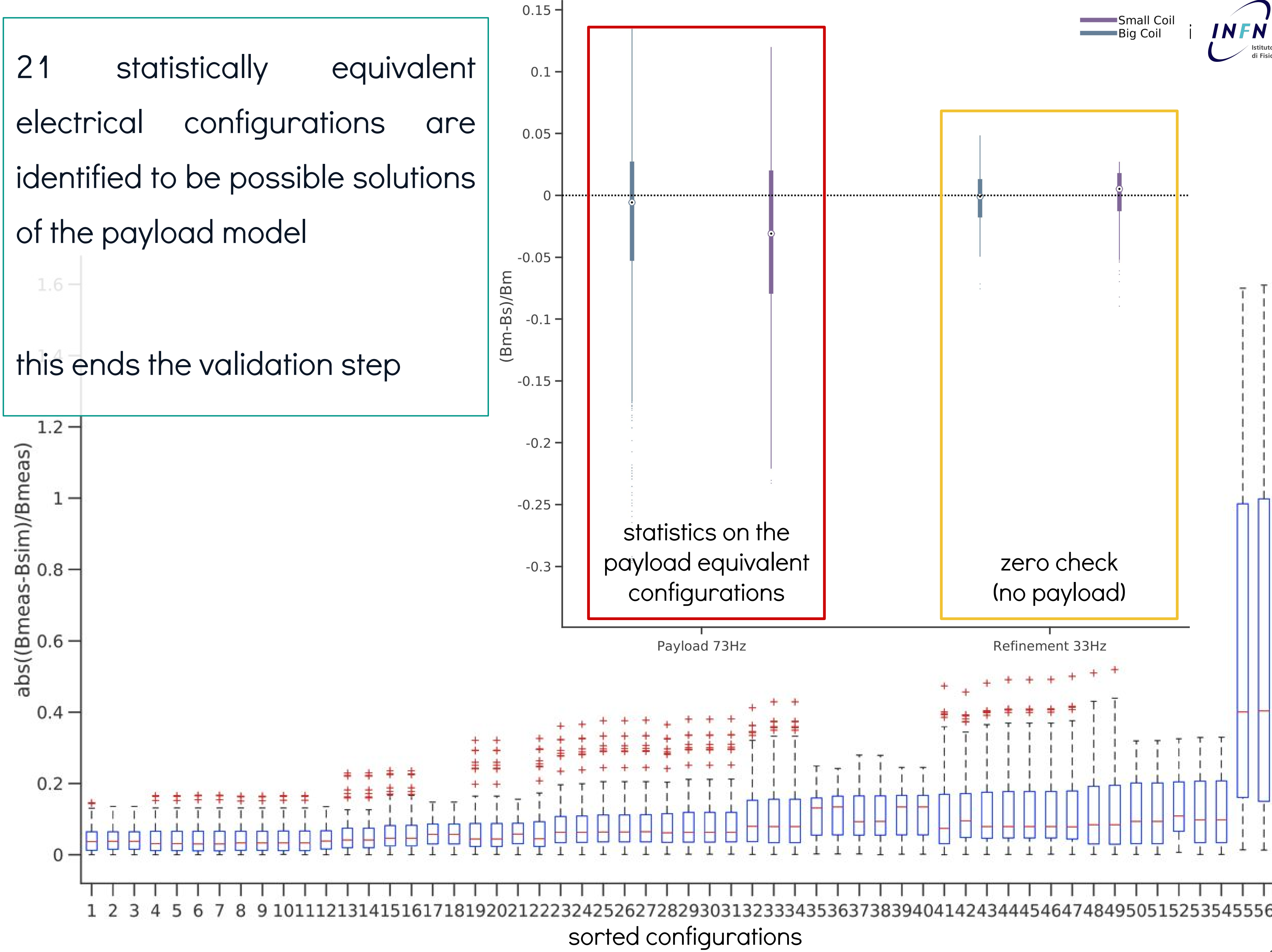


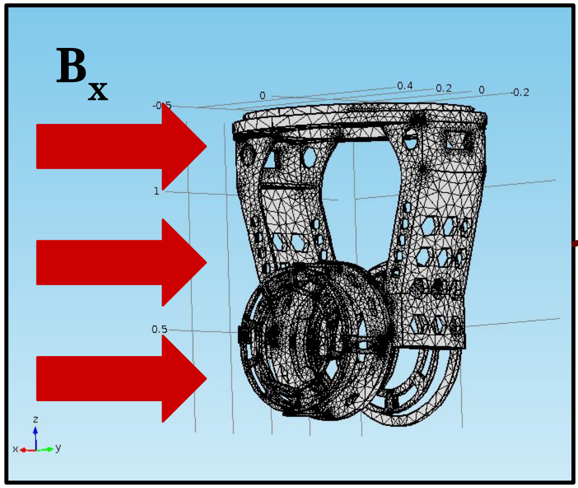
recursive hadamard matrix to take into account maximum number of interactions

(linear integer programming not suitable for repeated simulations with COMSOL)

21 statistically equivalent electrical configurations are identified to be possible solutions of the payload model

this ends the validation step





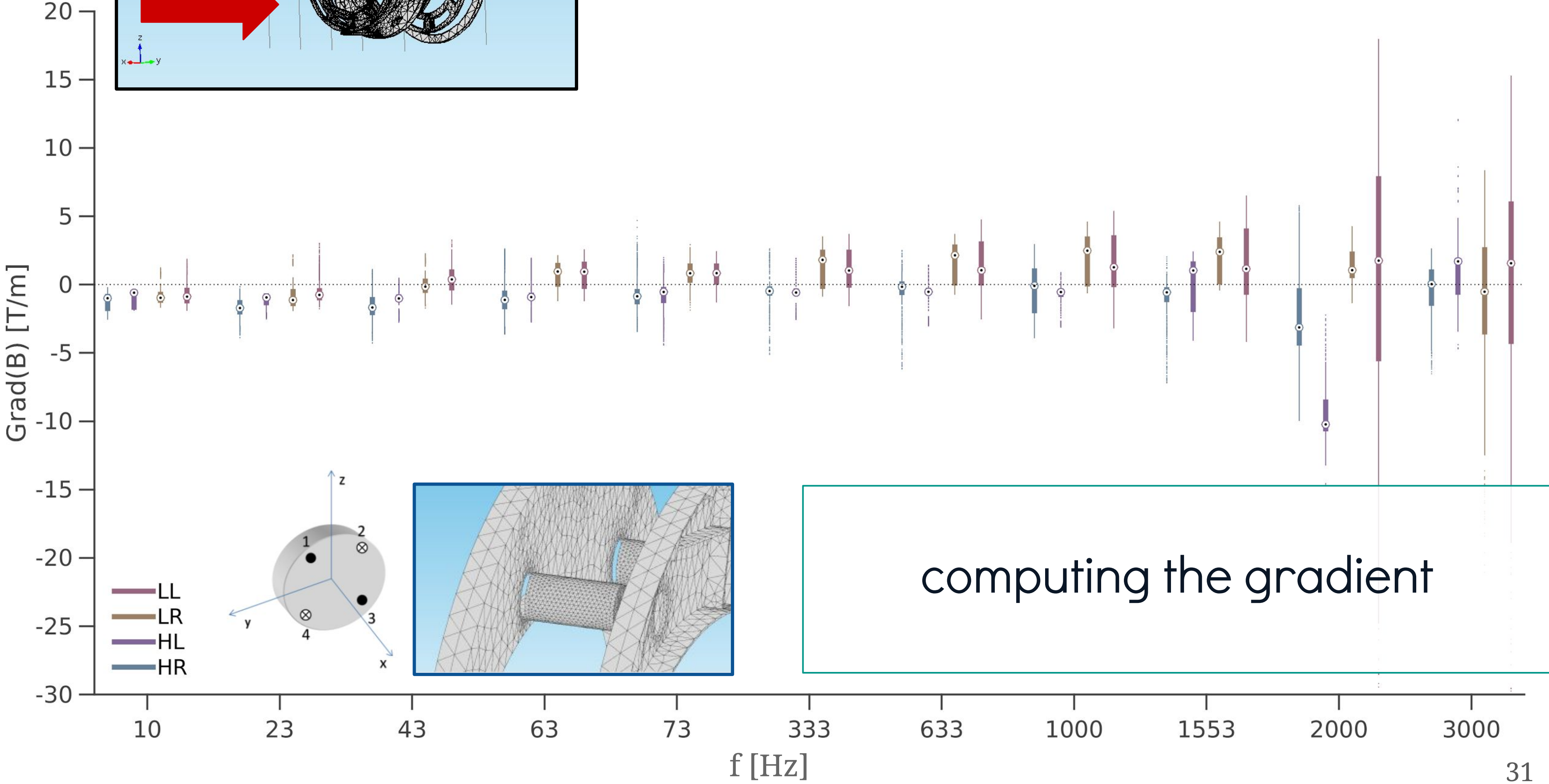
1T uniform field
Bx, By, Bz
10 Hz - 3.0 kHz
21 configurations

refined mesh around magnets

numerical gradient

$\Delta B/\Delta x$

grouped by freq.



computing the gradient

grad B can assume different values on magnets

magn. moment is not equal for all magnets

magnet positioning with respect to payload frame with a tolerance

MonteCarlo simulations on

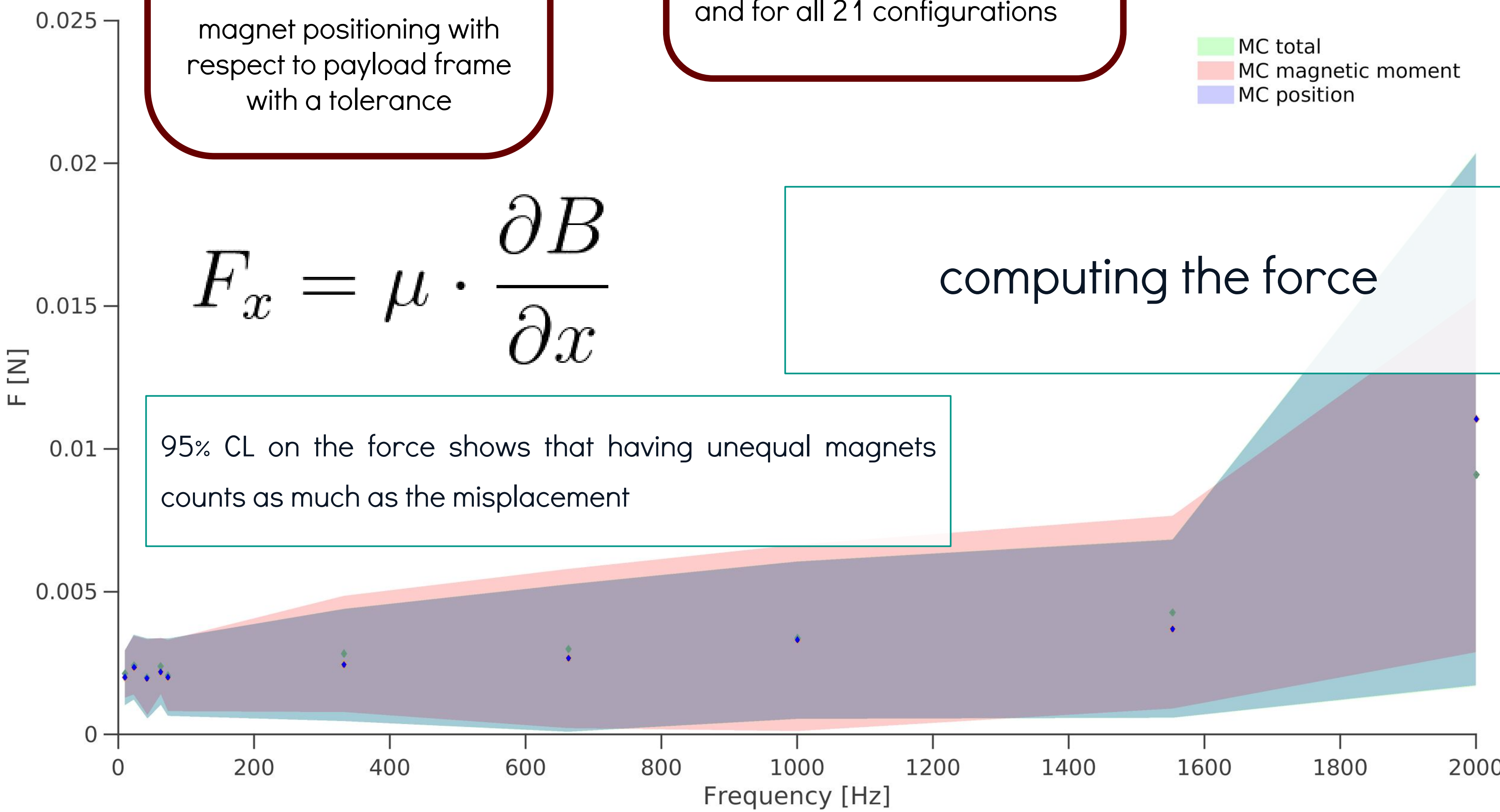
$\mu = (2.2 \pm 0.3) \times 10^{-3}$ Am^2
dx = ± 2 mm

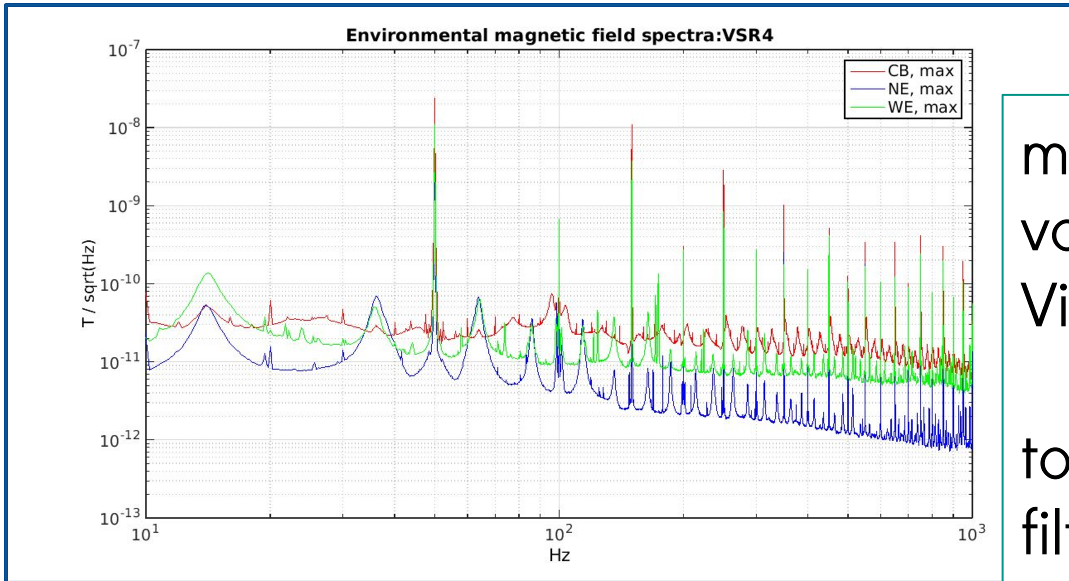
and for all 21 configurations

computing the force

$$F_x = \mu \cdot \frac{\partial B}{\partial x}$$

95% CL on the force shows that having unequal magnets counts as much as the misplacement





measures near & inside vacuum towers during VSR4 Virgo+

towers act as a 1-pole low-pass filter @ 15 Hz

$$B_{env} = \frac{\sqrt{B_{CB}^2 + B_{CB}^2 + B_{NE}^2 + B_{WE}^2}}{\sqrt{1 + (f/f_{pole})^2}}$$

estimating the strain

$$h = \frac{\Delta L}{L_0}$$

$$h = \frac{2D\tau_y}{I_{yy}L_0\omega^2} + \frac{2D\tau_z}{I_{zz}L_0\omega^2}$$

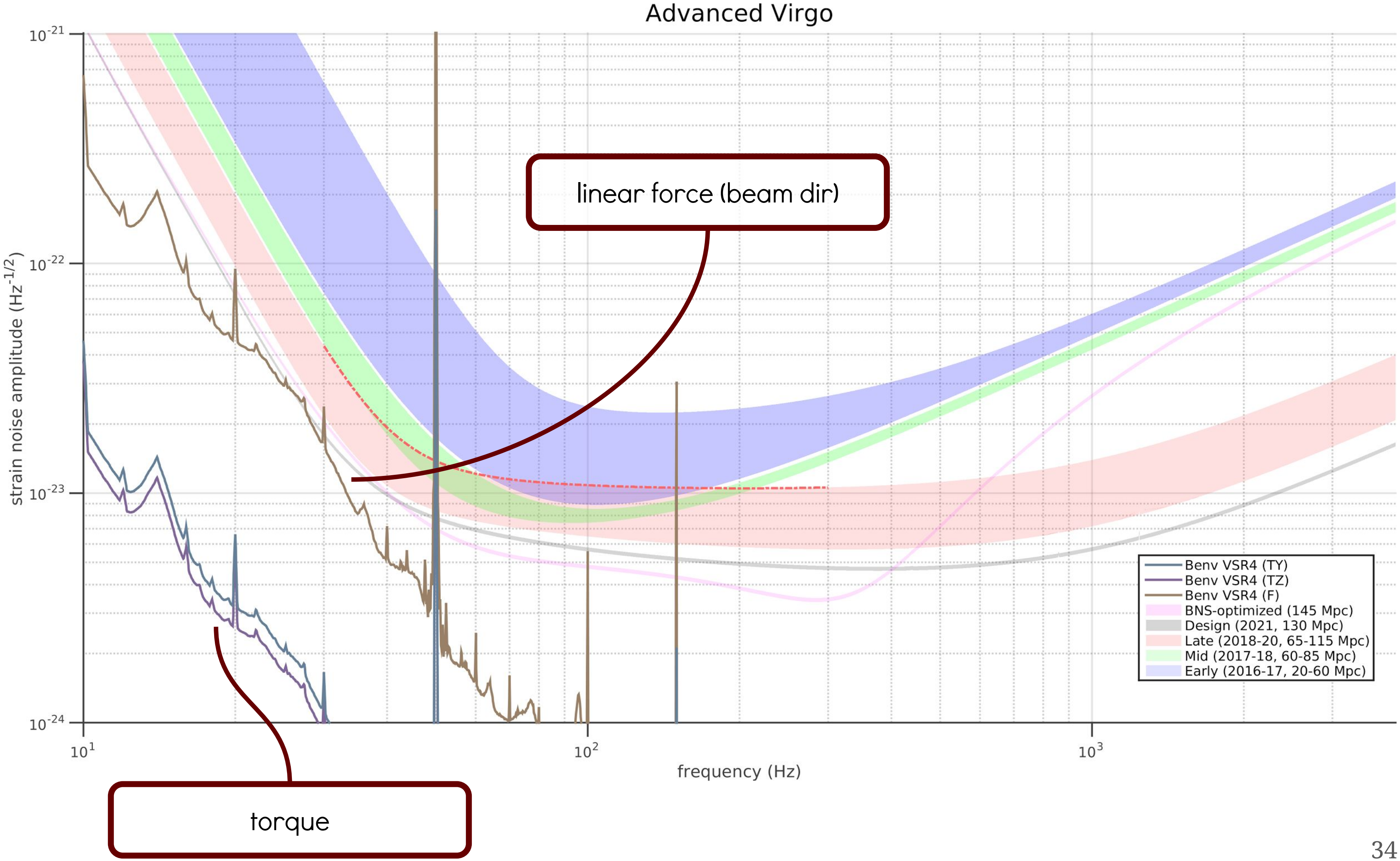
torque

$$h = \frac{2F}{mL_0\omega^2}$$

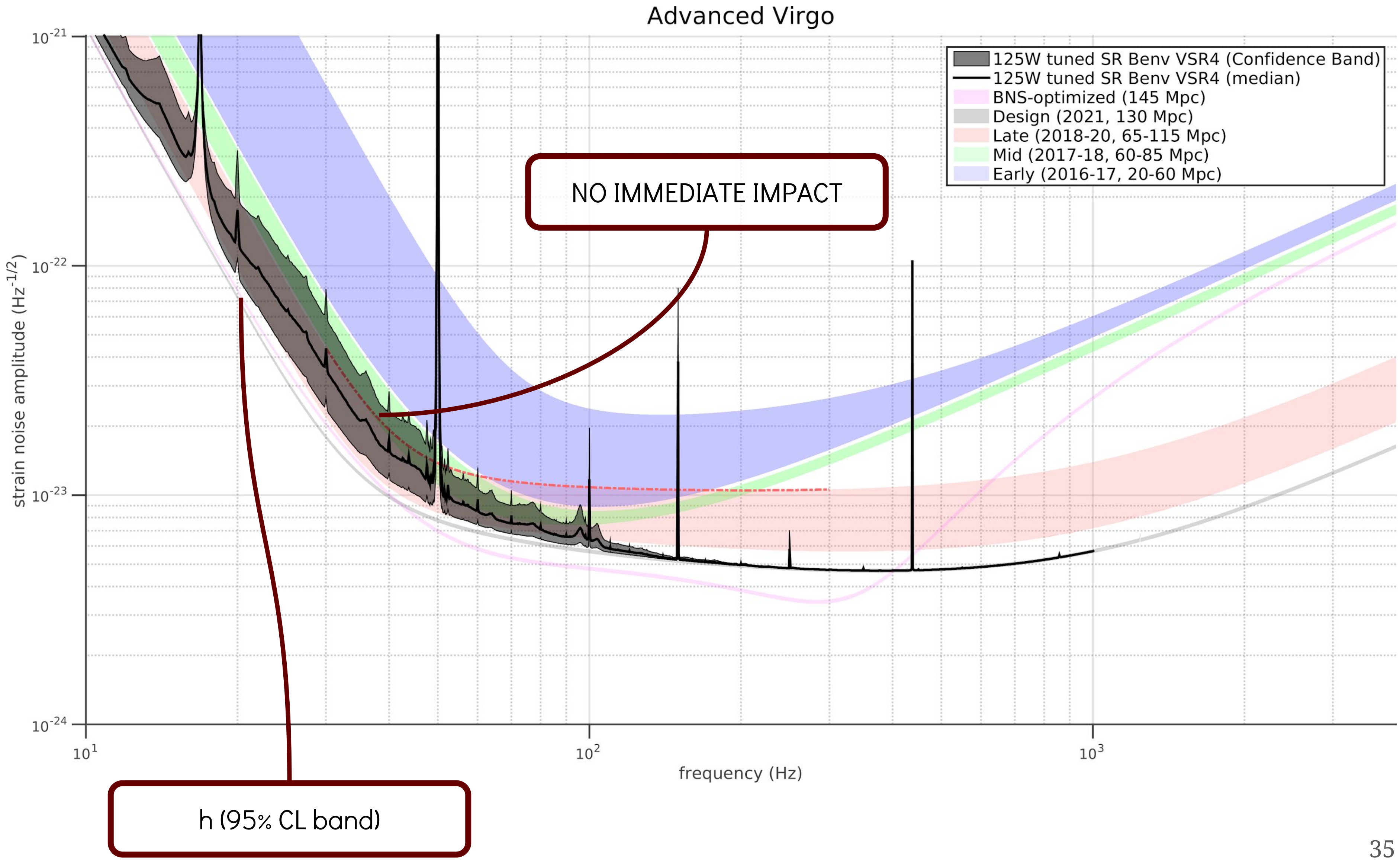
linear force

$$h = \frac{2F}{mL_0\omega^2} + \frac{2D}{IL_0\omega^2}(\tau_y + \tau_z)$$

linear vs. torque



estimated impact with VIRGO power supply



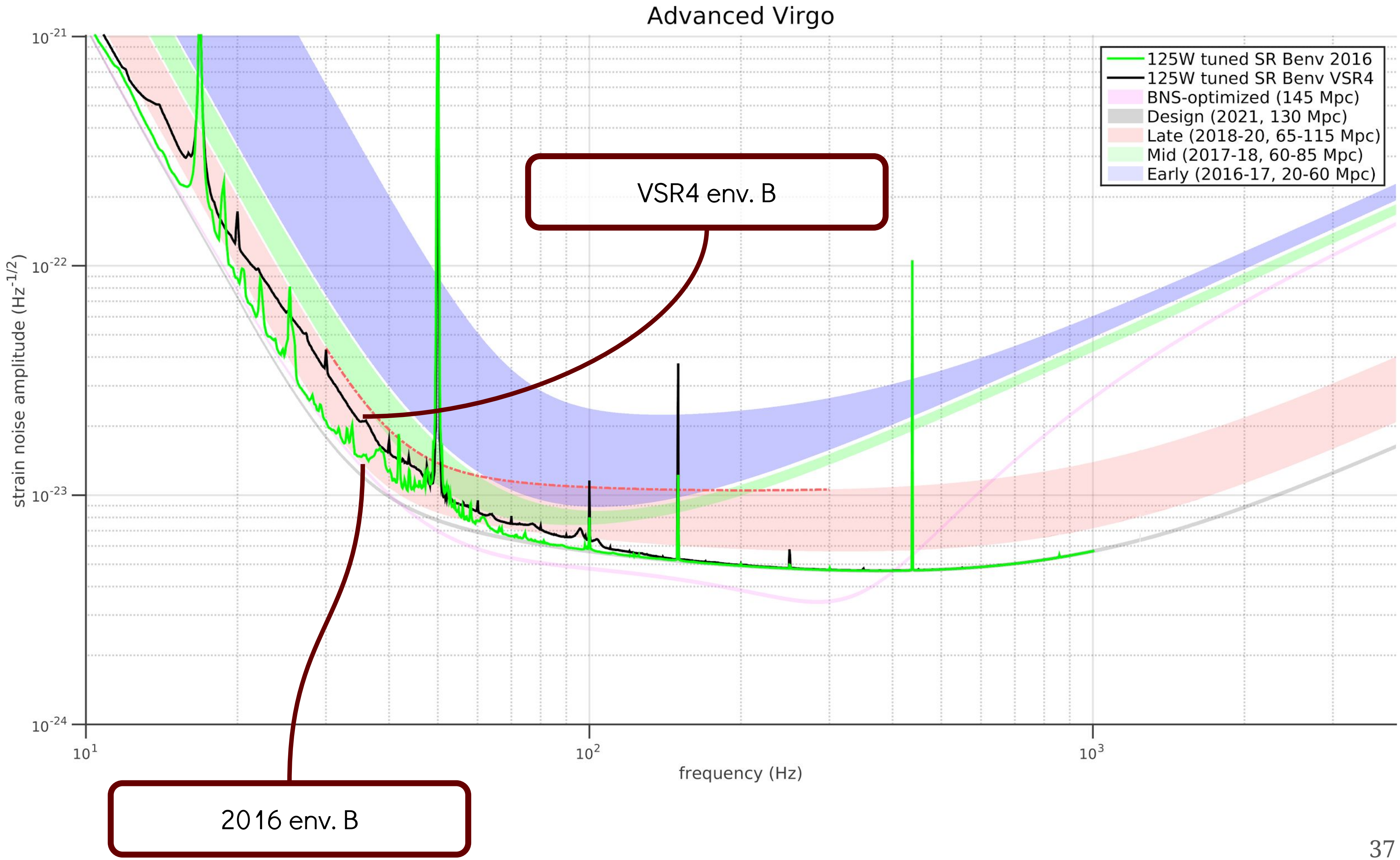
mitigation strategies

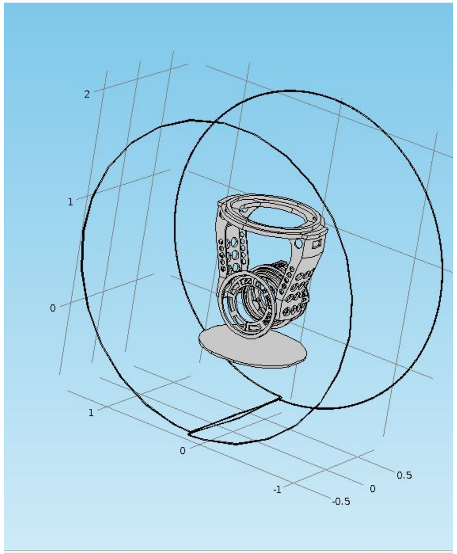
- tame the external sources
  (UPS, cabling, electronics, ...)
- install Helmholz coils
- lower the total magn. moment

.. and if nothing helps

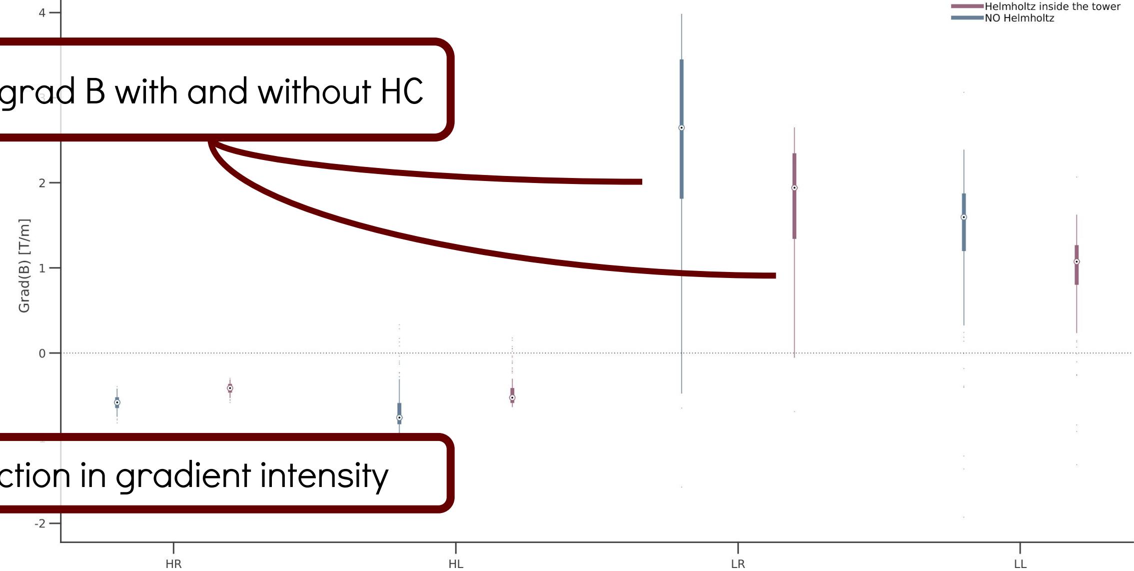
- redesign / material selection of some payload components

lowering the environmental noise





grad B with and without HC

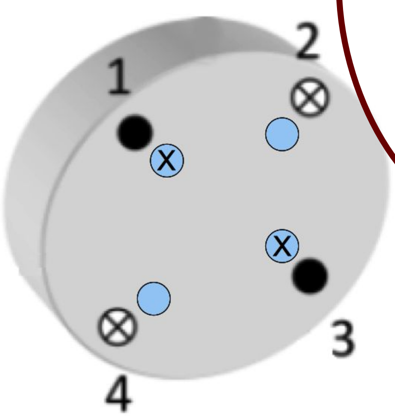


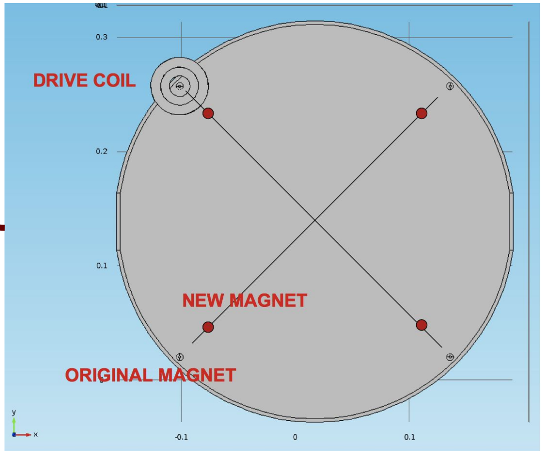
20% - 30% reduction in gradient intensity

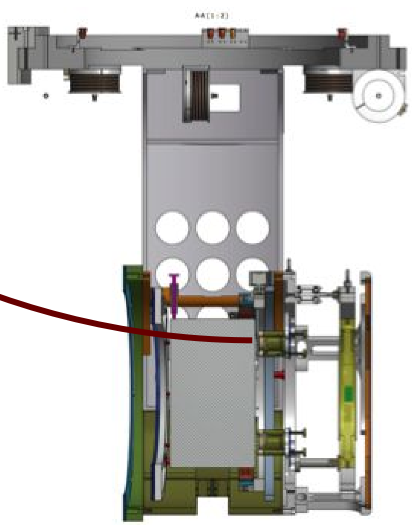
other solutions

reduce overall moment

technical rings redesigning





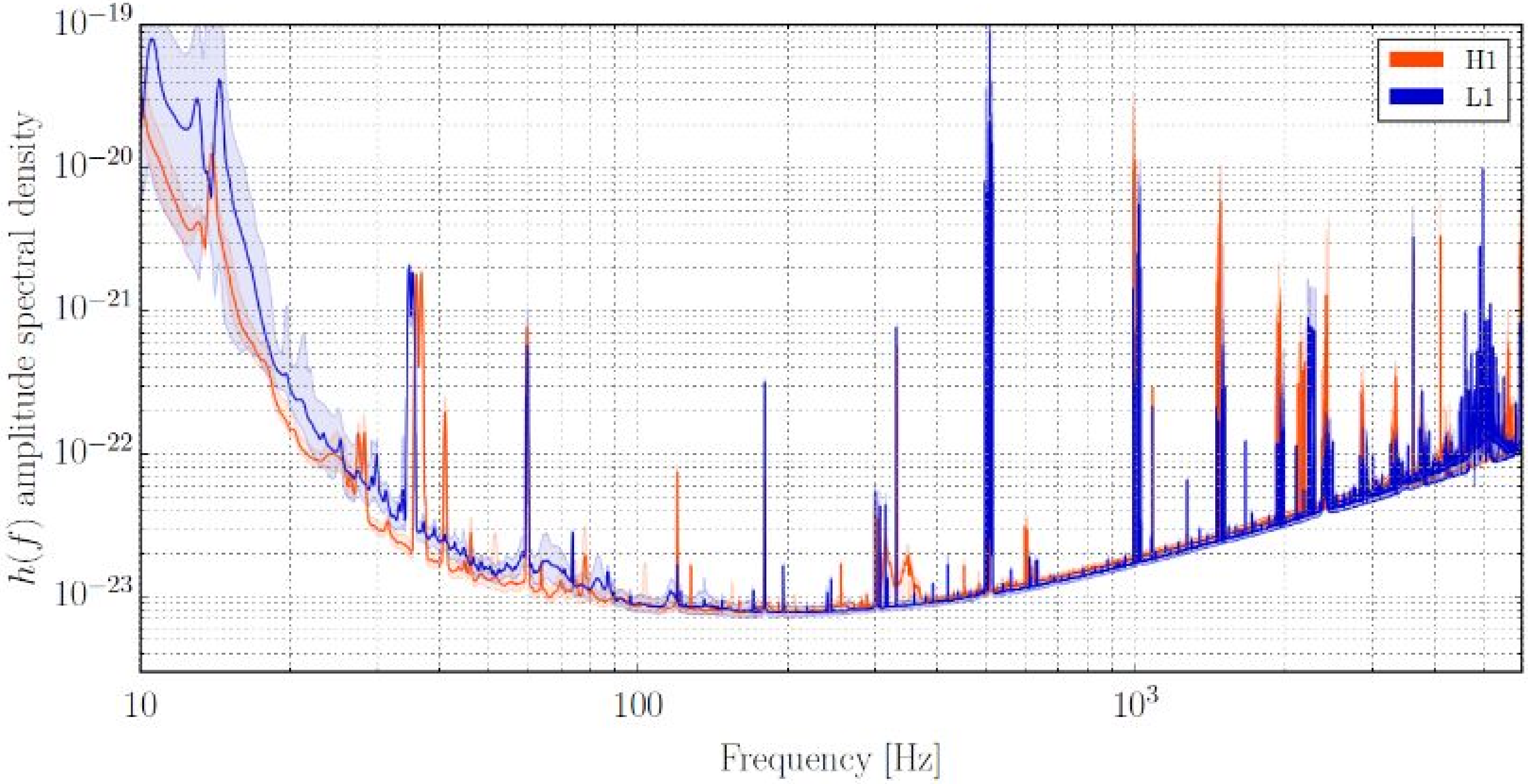


wrapping up

- the simulated transfer function of the adv.VIRGO payload allows us to estimate the magnetic noise budget
- simulations are not straight-forward: geometry, electrical configurations, magnets positioning and intensity are all sources of uncertainty
- a validation step in known circumstances is mandatory
- this study allows us to estimate the impact of different mitigation strategies
- an actual test during adv. VIRGO commissioning is scheduled to consolidate results

elements of data analysis

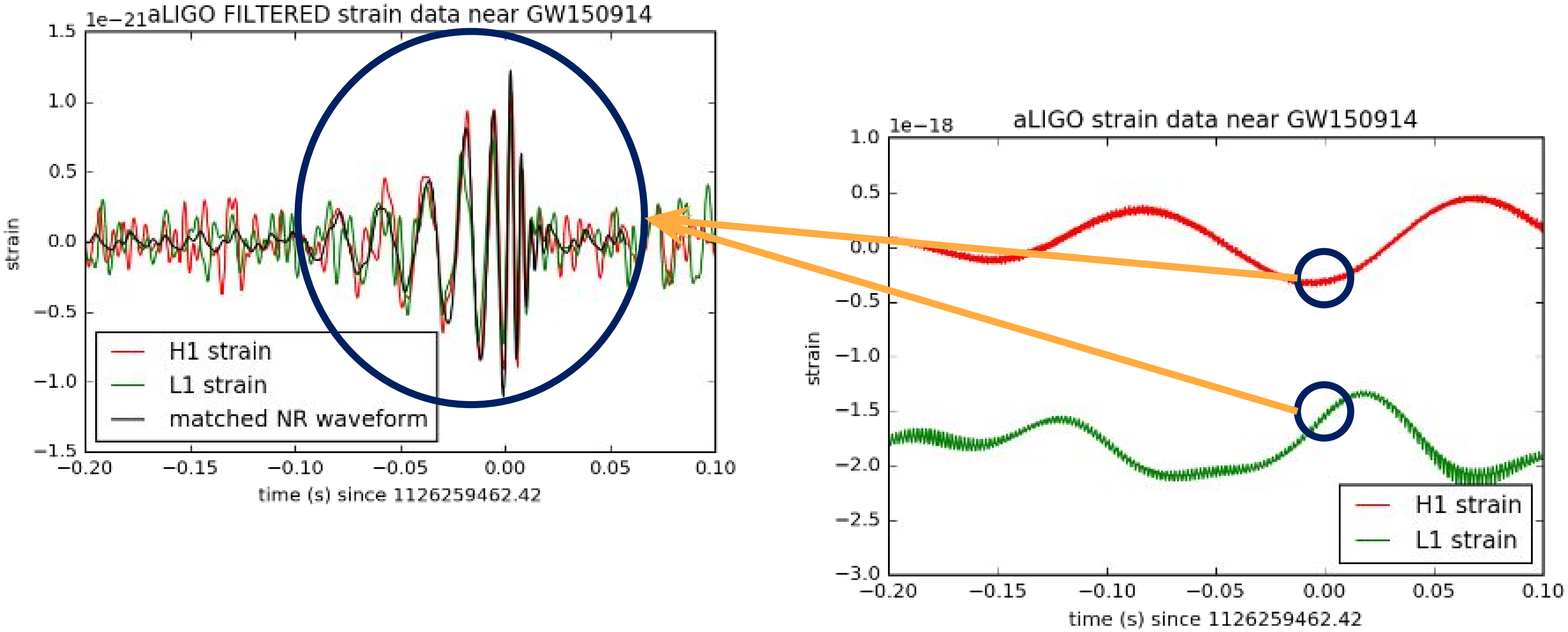
O1 sensitivity



average measured strain-equivalent noise, of the Advanced LIGO detectors during the time analyzed to determine the significance of GW150914 (Sept 12 - Oct 20, 2015)

signal ≤ noise

Despite all the efforts, signal still buried in noise.
How do you extract the signal from noise?



Finding a weak signal in noise

“Matched filtering” lets us find a weak signal submerged in noise

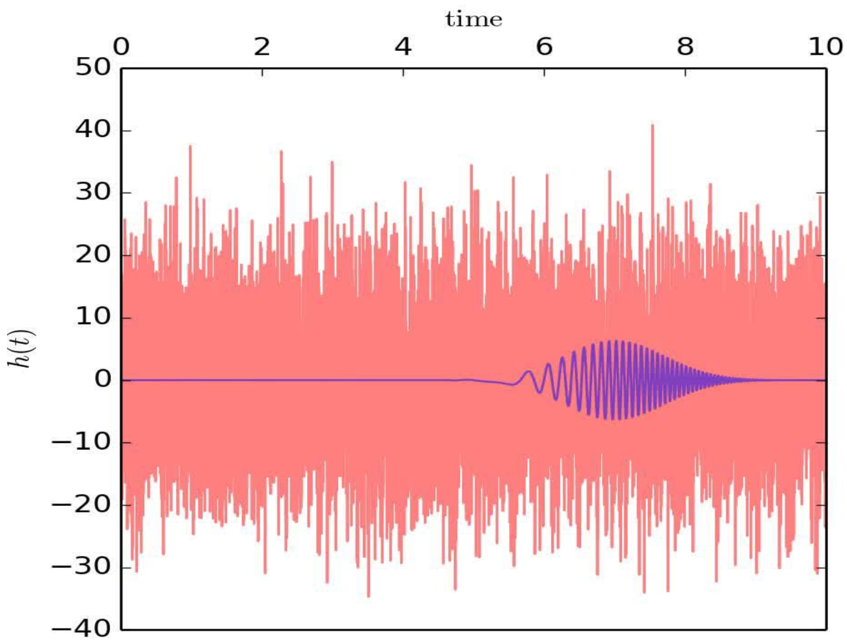
in a nutshell:
take a waveform, multiply it by the data, for all possible times when the signal might have arrived

When there’s a match, you can see it BUT…

you HAVE TO KNOW your signal in advance
to be able to detect it in a noisy data

and

noise MUST BE stationary

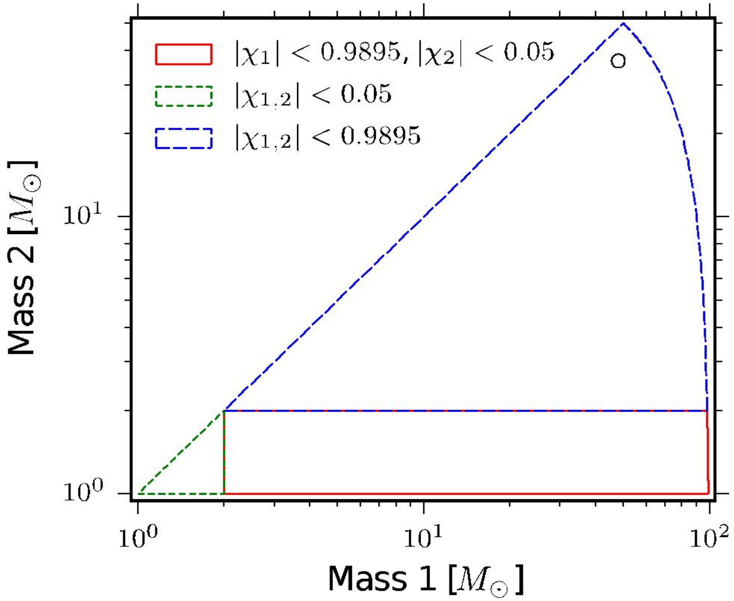


Transient Event Searches

Binary Coalescence search:

Targets searches for GW emission from binary sources

arXiv:1602.03839



Component masses 1 to 99 solar masses;

total mass, up to 100 solar masses

dimensionless spin < 0.99

~250,000 waveforms, calculated using analytical and numerical methods, are used to cover the parameter space

caveats

Background estimation in gravitational wave searches is different than particle physics experiments

Gravitational wave detectors observe a high rate of loud, short-duration noise transients, much higher than would be expected from Gaussian noise alone
(glitches: environmental noise and instrument artefacts)

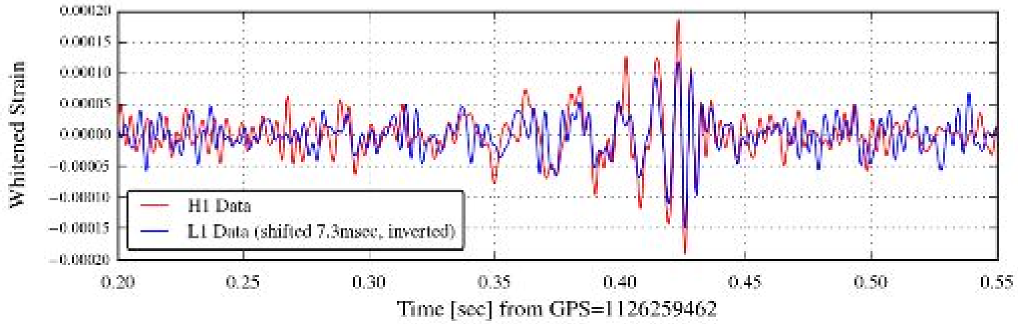
We reject glitches by requiring exact coincidence between the detectors, as well as agreement with particular models for gravitational wave signals (for example, the famous chirp from the merger of compact objects)

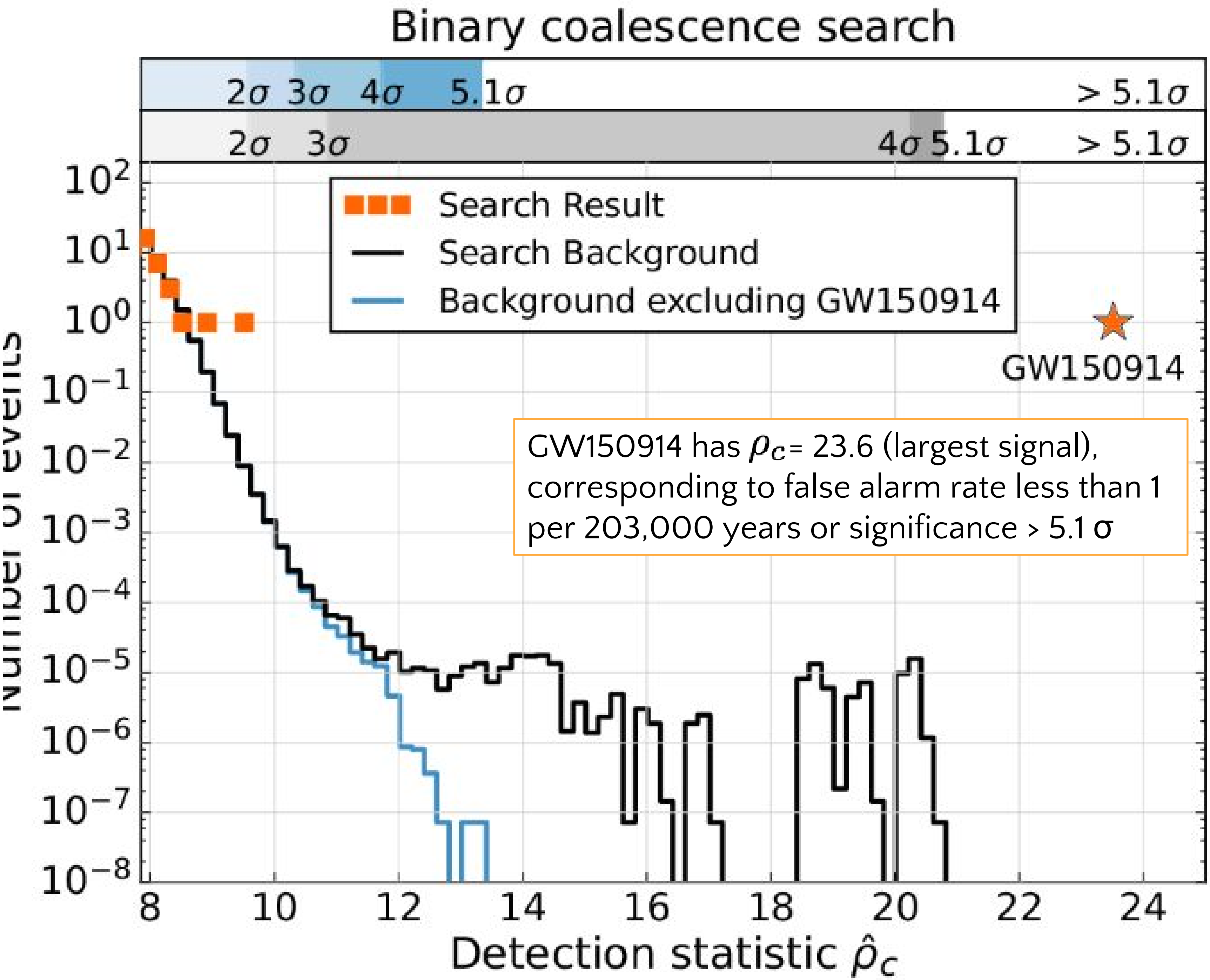
consequences

The background due to glitches cannot be modeled analytically, so we estimate it empirically using a time-slide technique

For each analysis, the data are re-analyzed, using the time-series from Hanford compared with the time-series from Livingston from, for example, five seconds later - much longer than the time it takes a gravitational wave to travel between the sites

The analysis is repeated for $O(10^6)$ time steps to calculate how frequently the noise fluctuations in the detectors might align to generate an event, purely from chance





Binary coalescence search
2σ 3σ 4σ 5.1σ > 5.1σ
2σ 3σ 4σ 5.1σ > 5.1σ
Search Result
Search Background
Background excluding GW150914
GW150914
GW150914 has ρ_c= 23.6 (largest signal), corresponding to false alarm rate less than 1 per 203,000 years or significance > 5.1 σ
Number of events
Detection statistic $\hat{\rho}_c$

thank you

Correlated noise

- Possible electromagnetic noise sources
  - Lightning, solar events, Schumann resonances.
  - Would be picked up in radio receivers, magnetometers
  - Nothing at time of event

- Cosmic ray showers
  - Not correlated on 3,000 km scales
  - Cosmic ray detector at Hanford – no events

Monitoring channels

- Interferometer monitoring
  - Transmitted light beams, optics alignment sensors, feedback signal
- Environmental monitoring
  - Seismic sensors, microphones, magnetometers, radio-frequency antennas, cosmic rays detectors
- Detailed study of the couplings between auxiliary channels/environmental disturbances and detector output
  - Injections of external disturbances
- Potential noise sources
  - Anthropogenic noise, Earthquakes, Radio Frequency noise
  - Lightning, Cosmic rays

Calibration

- The detector output is calibrated in strain by measuring its response to test mass motion induced by photon pressure from a modulated calibration laser beam
- Calibration uncertainty (1σ) less than 10% in amplitude and 10 degrees in phase
- Continuously monitored with calibration laser excitations at selected frequencies.
  - Two alternative methods are used to validate the absolute calibration
    - main laser wavelength
    - radio-frequency oscillator