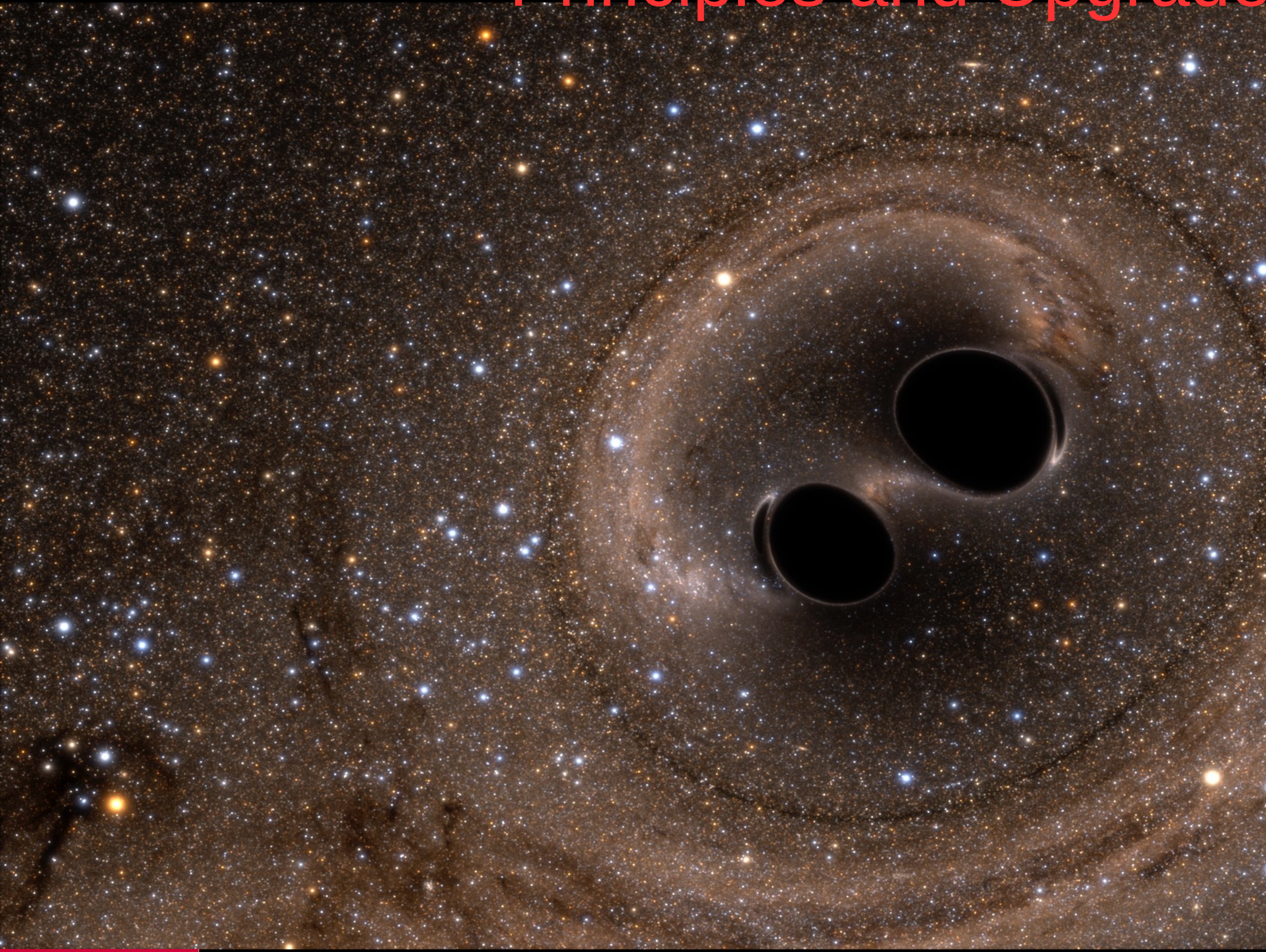
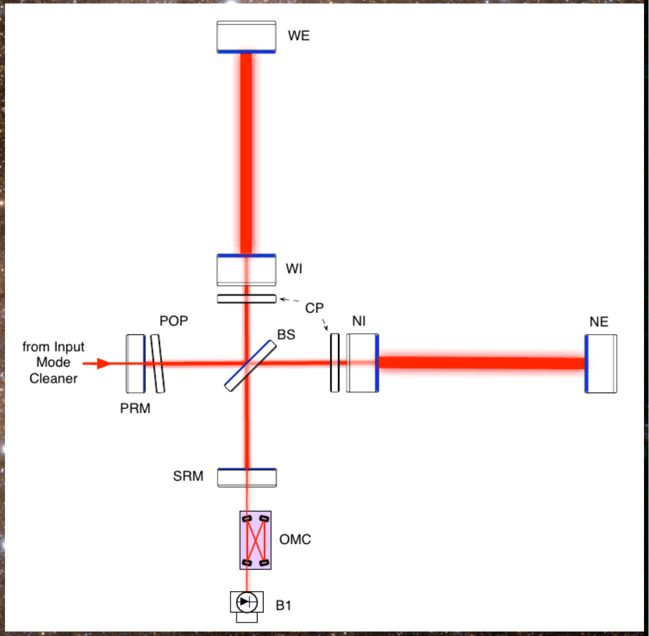
The Laser Interferometer Gravitational-wave Observatory LIGO: Principles and Upgrades

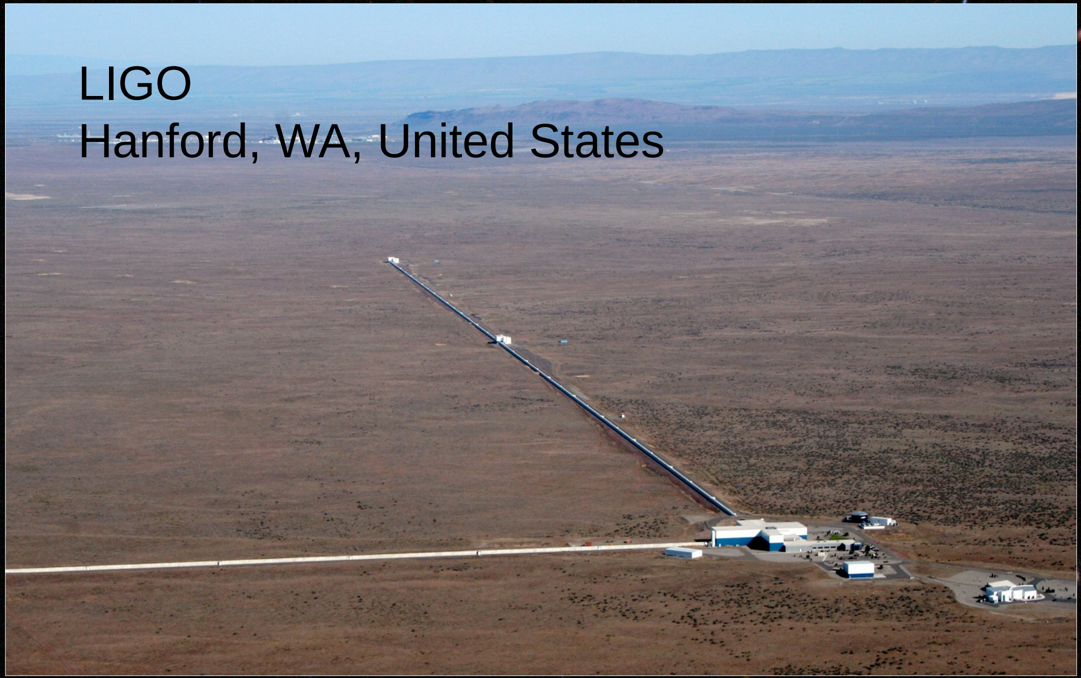




CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

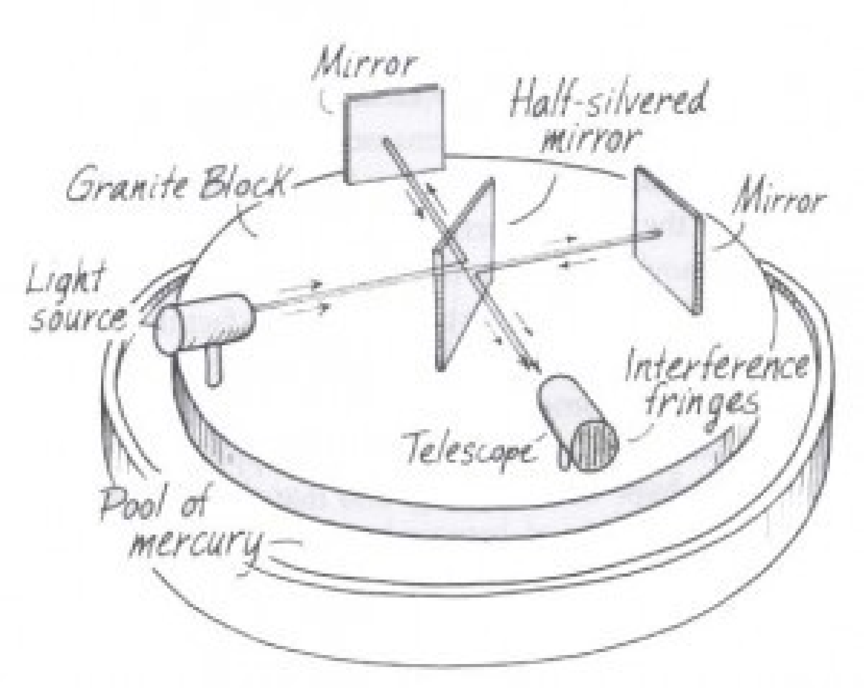
Hartmut Grote
Cardiff University, UK,
for the LIGO Lab and
Commissioning team

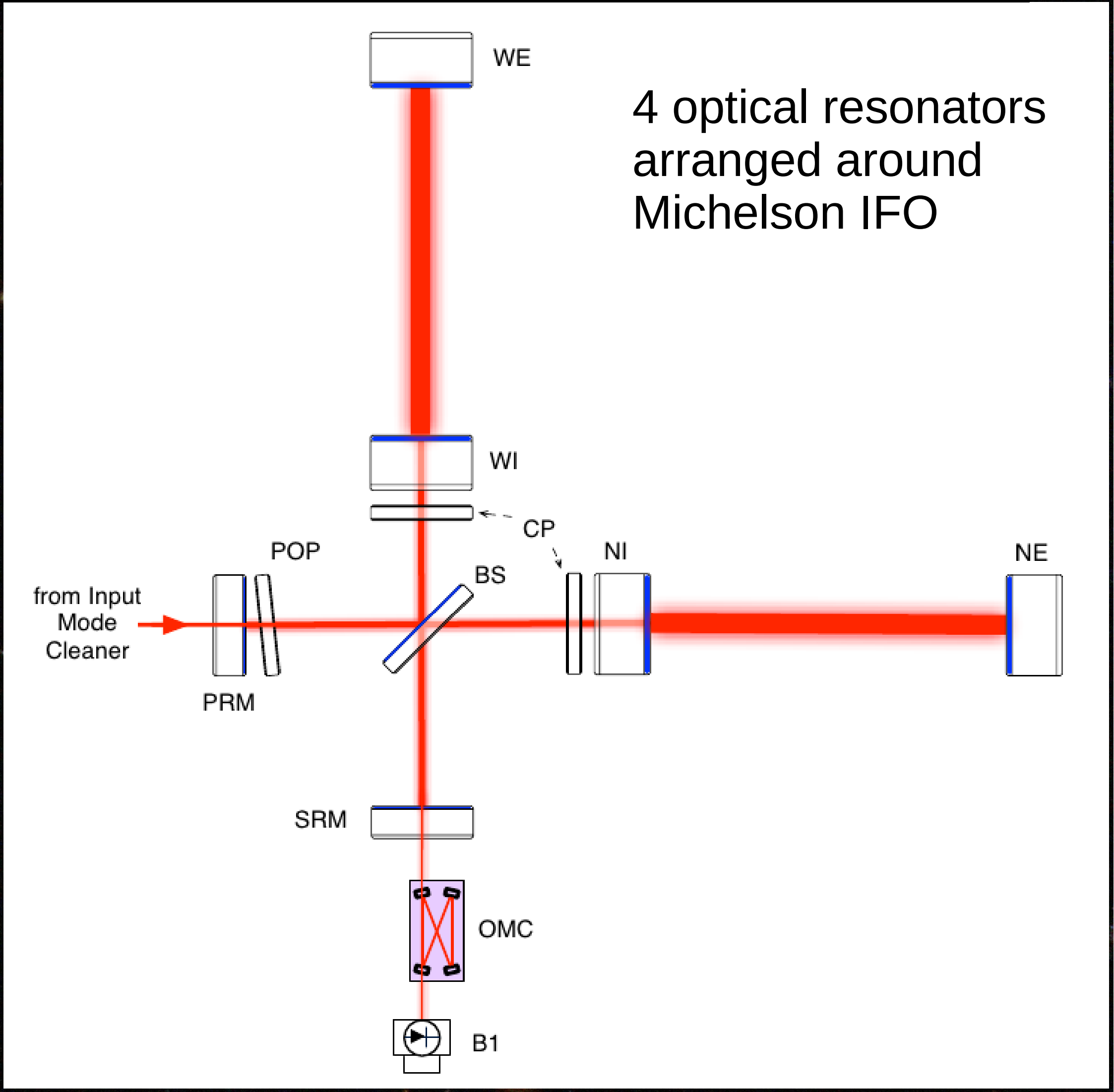
CHRIS 2018
June 18th-22nd, 2018
LIGO-G1801266


LIGO
Hanford, WA, United States


LIGO
Livingston, LA, United States

Michelson, with additions...





4 optical resonators arranged around Michelson IFO

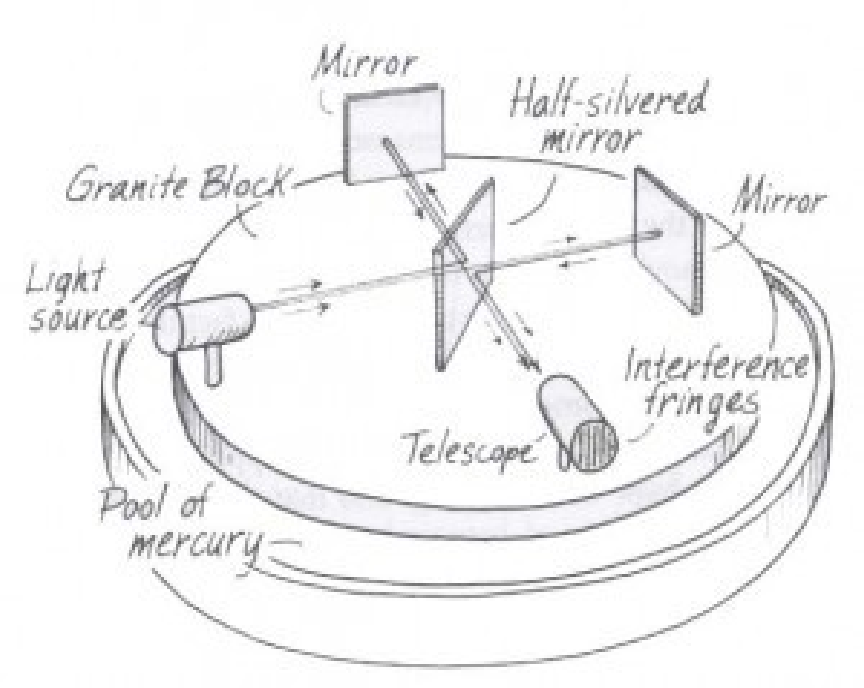
Michelson Morley experiment:
Accuracy: 10^-8 m (10^-9 relative)

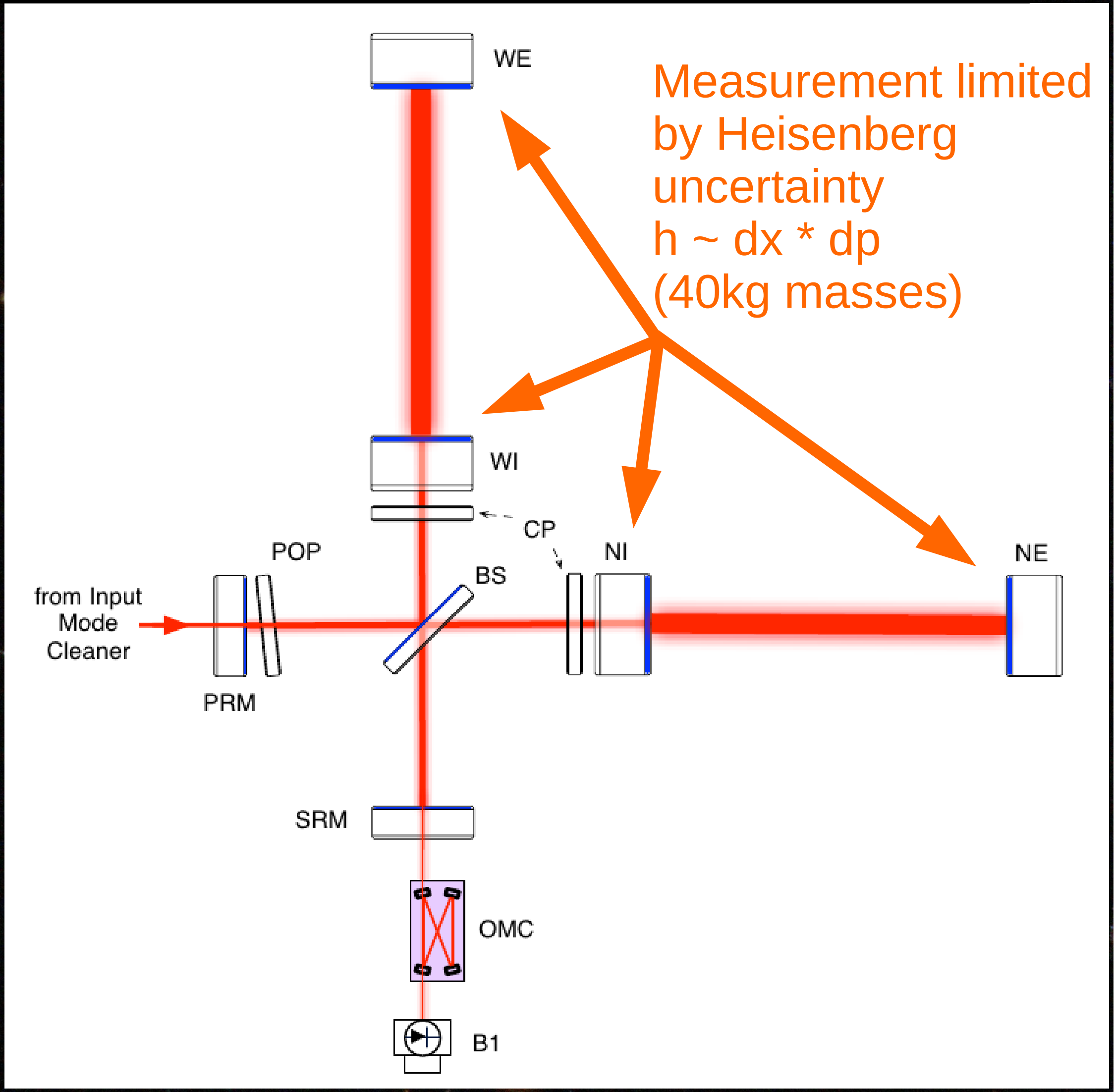
10m arm-length

Advanced Interferometer:
Accuracy: 10^-19 m (3 x 10^-23 relative), 100Hz BW

3-4 km arm-length

Michelson, with additions...





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Accuracy: 10^-8 m (10^-9 relative)

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Advanced Interferometer:
Accuracy: 10^-19 m (3 x 10^-23 relative), 100Hz BW

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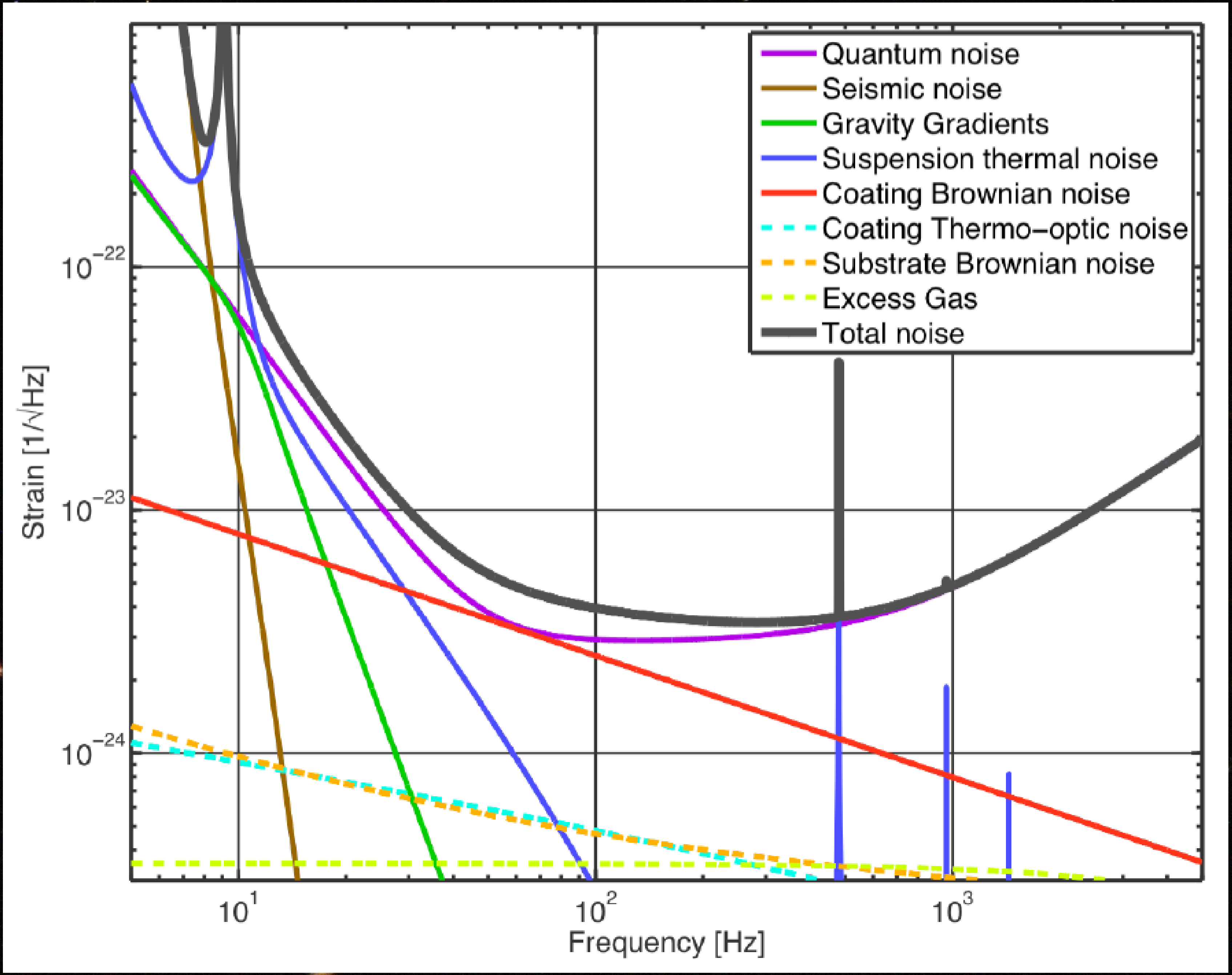
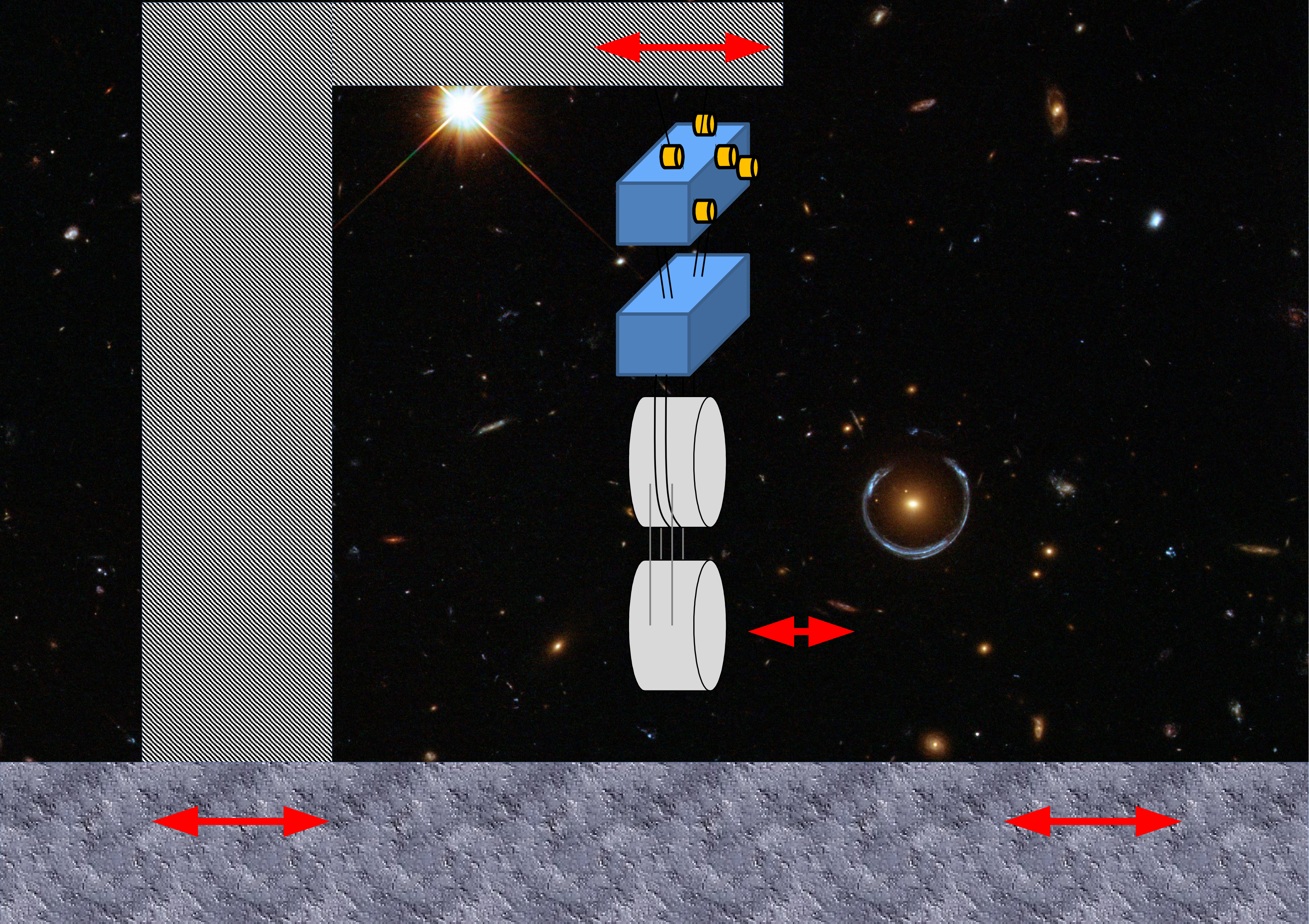
“2 G”

Advanced LIGO Design

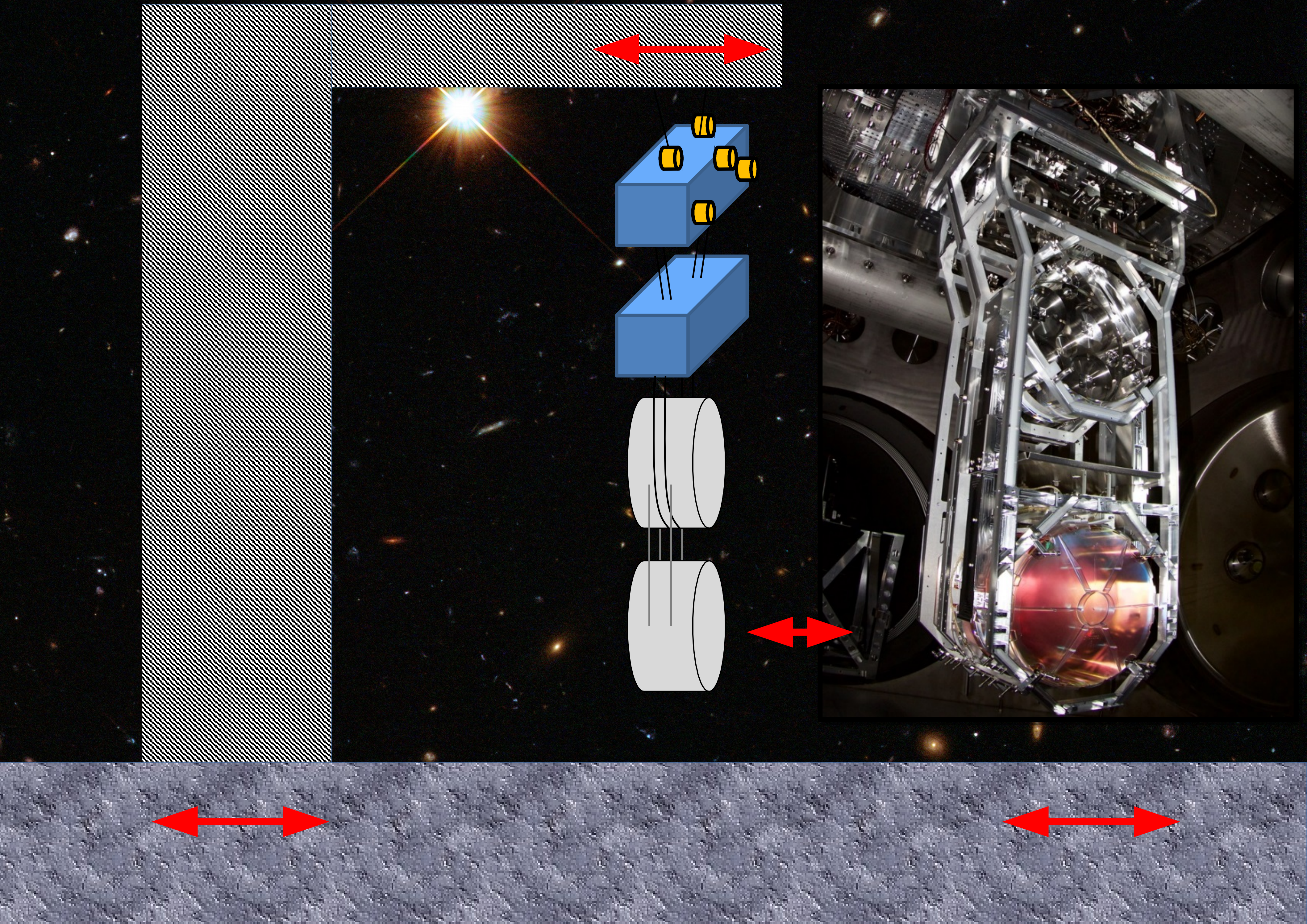
-seismic
-thermal
-quantum



Seismic input



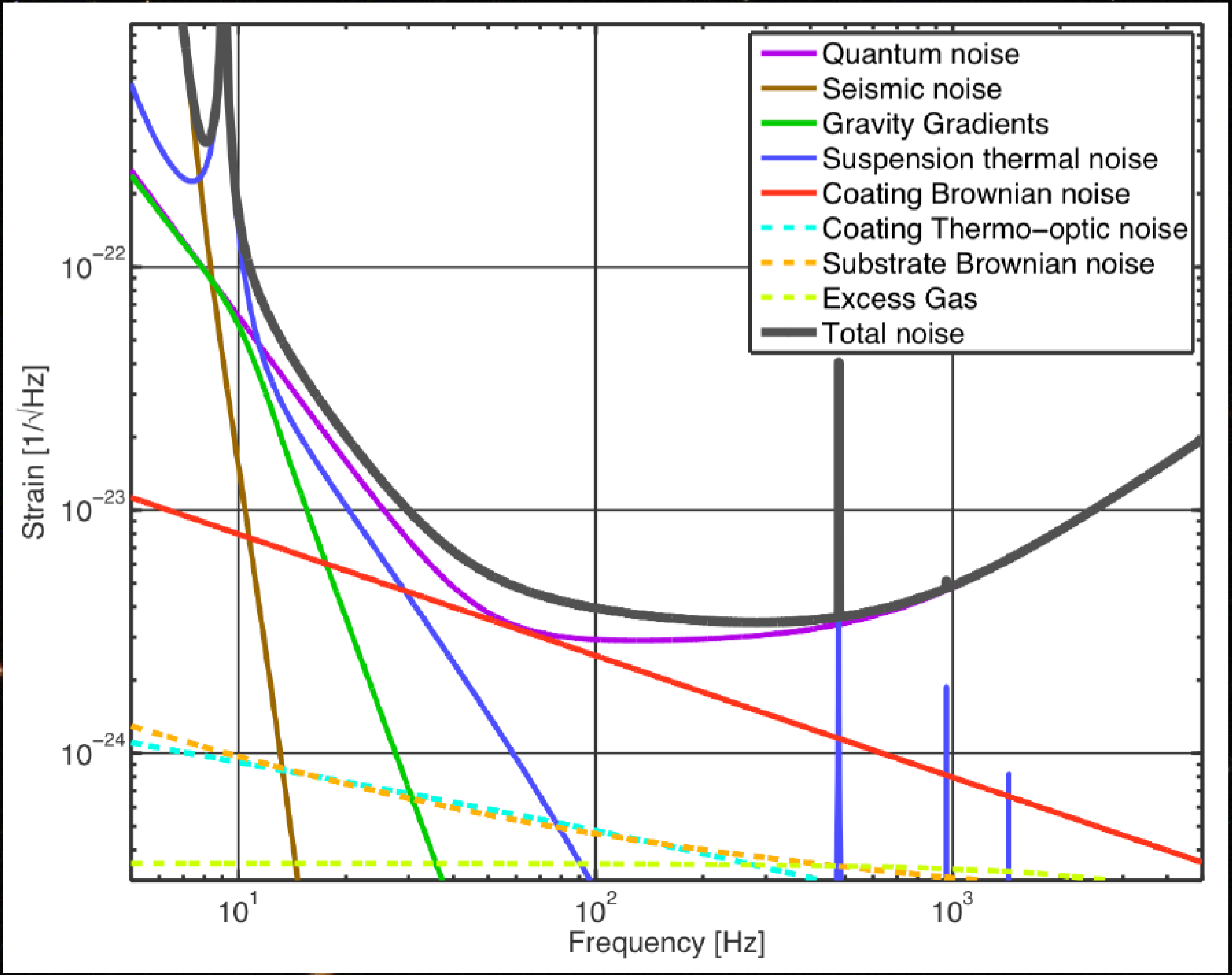
Seismic input

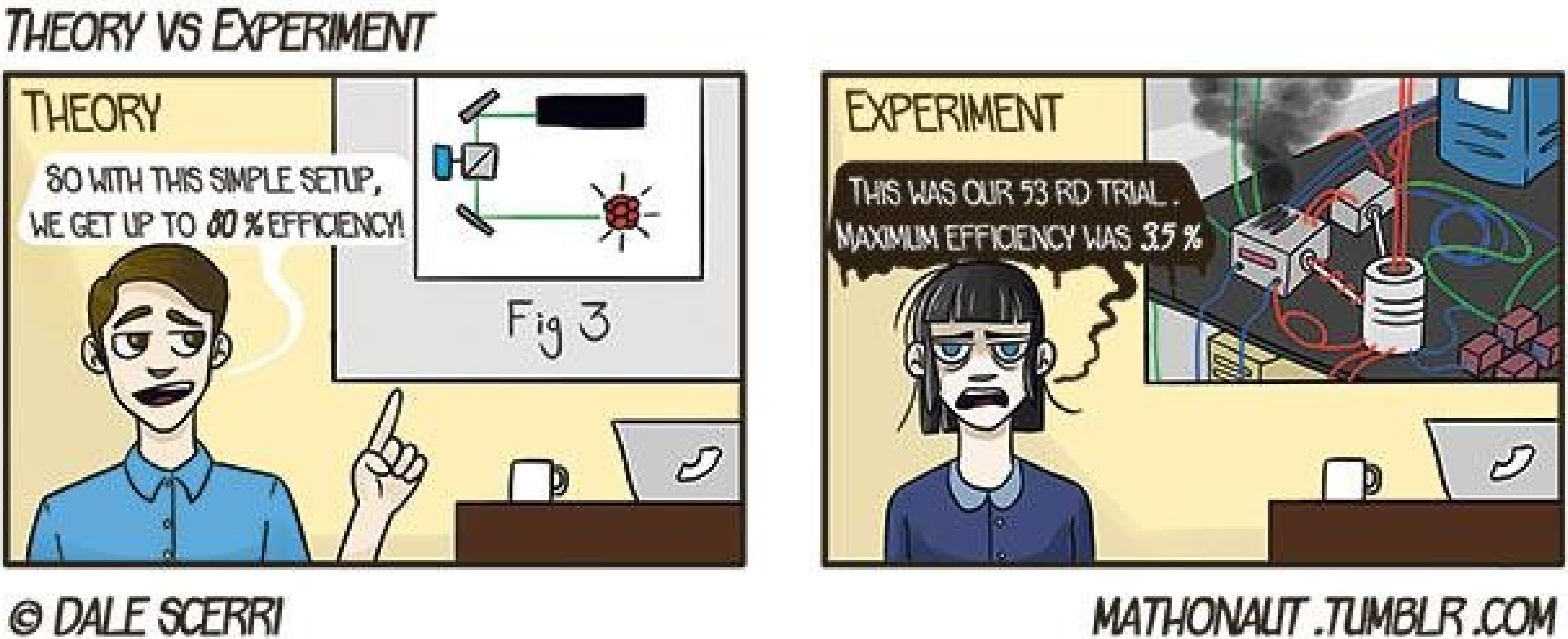


“2 G”

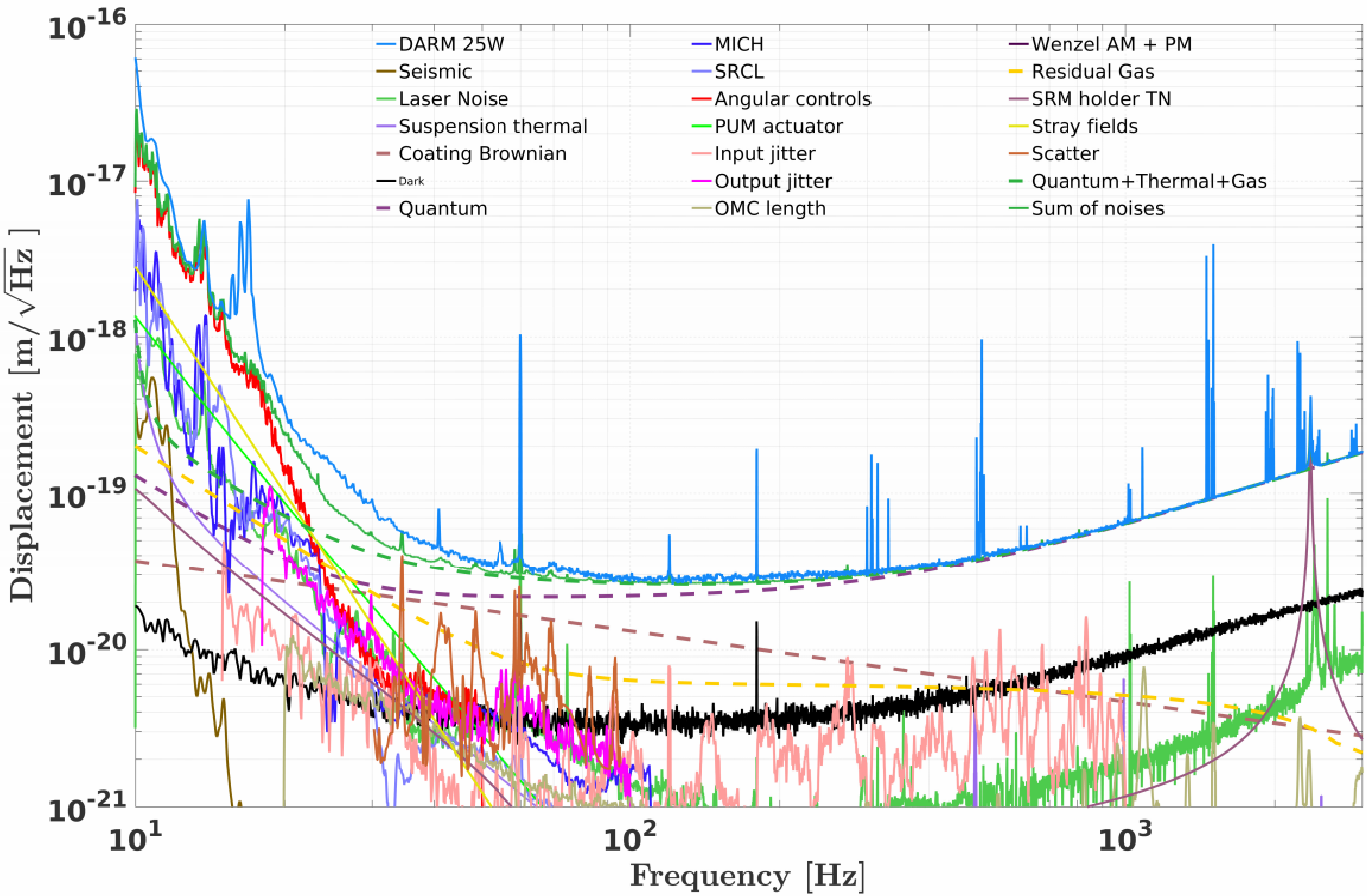
Advanced LIGO Design

-seismic
-thermal
-quantum

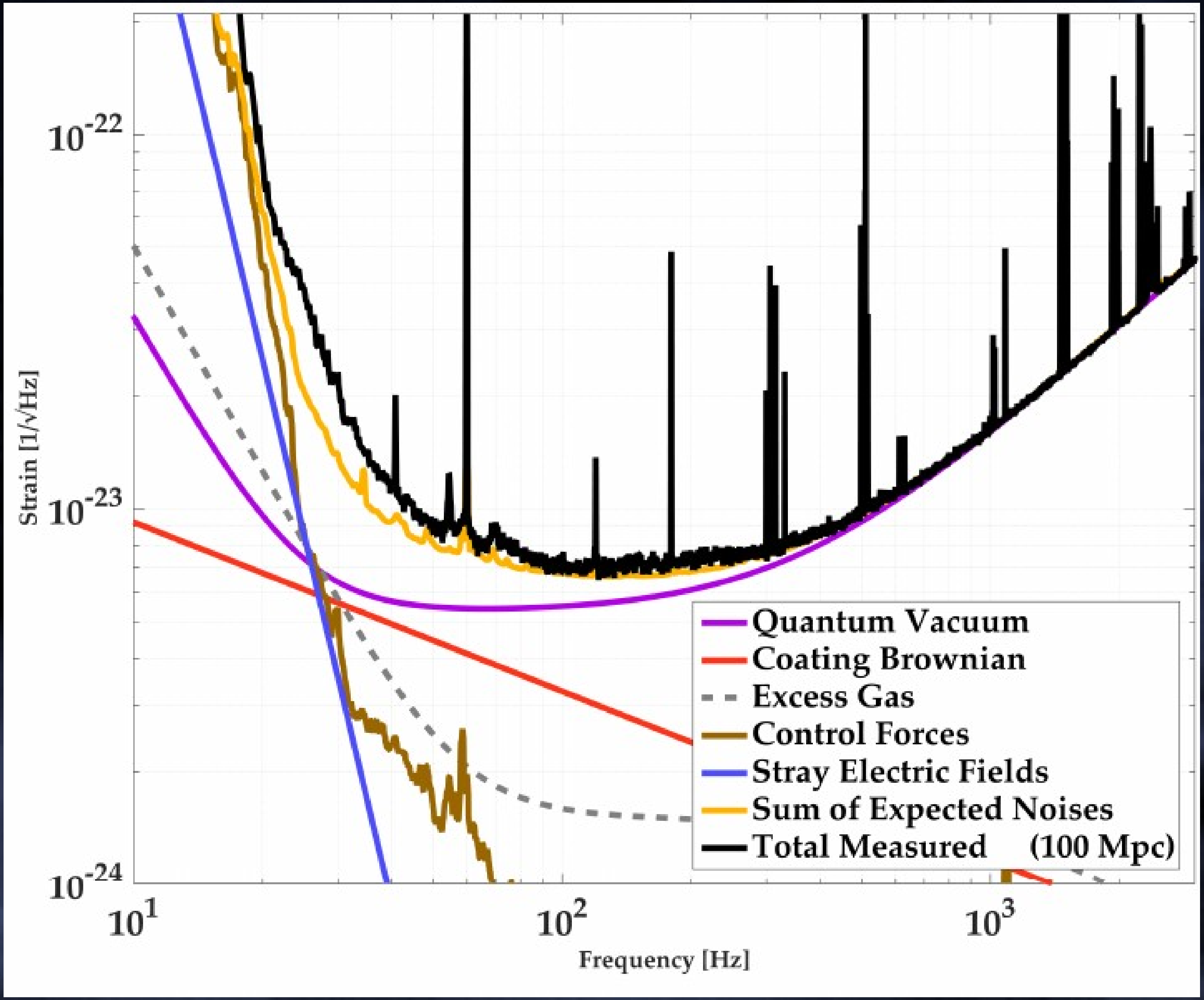



THEORY VS EXPERIMENT
THEORY
SO WITH THIS SIMPLE SETUP, WE GET UP TO 80 % EFFICIENCY!
Fig 3
EXPERIMENT
THIS WAS OUR 53 RD TRIAL. MAXIMUM EFFICIENCY WAS 3.5 %
© DALE SCERRI
MATHONAUT.TUMBLR.COM

LIGO noise budget (LLO, Aug. 2017)



Coating, Excess gas, Control noise, Stray electric fields, ...



J. Driggers/
A. Effler

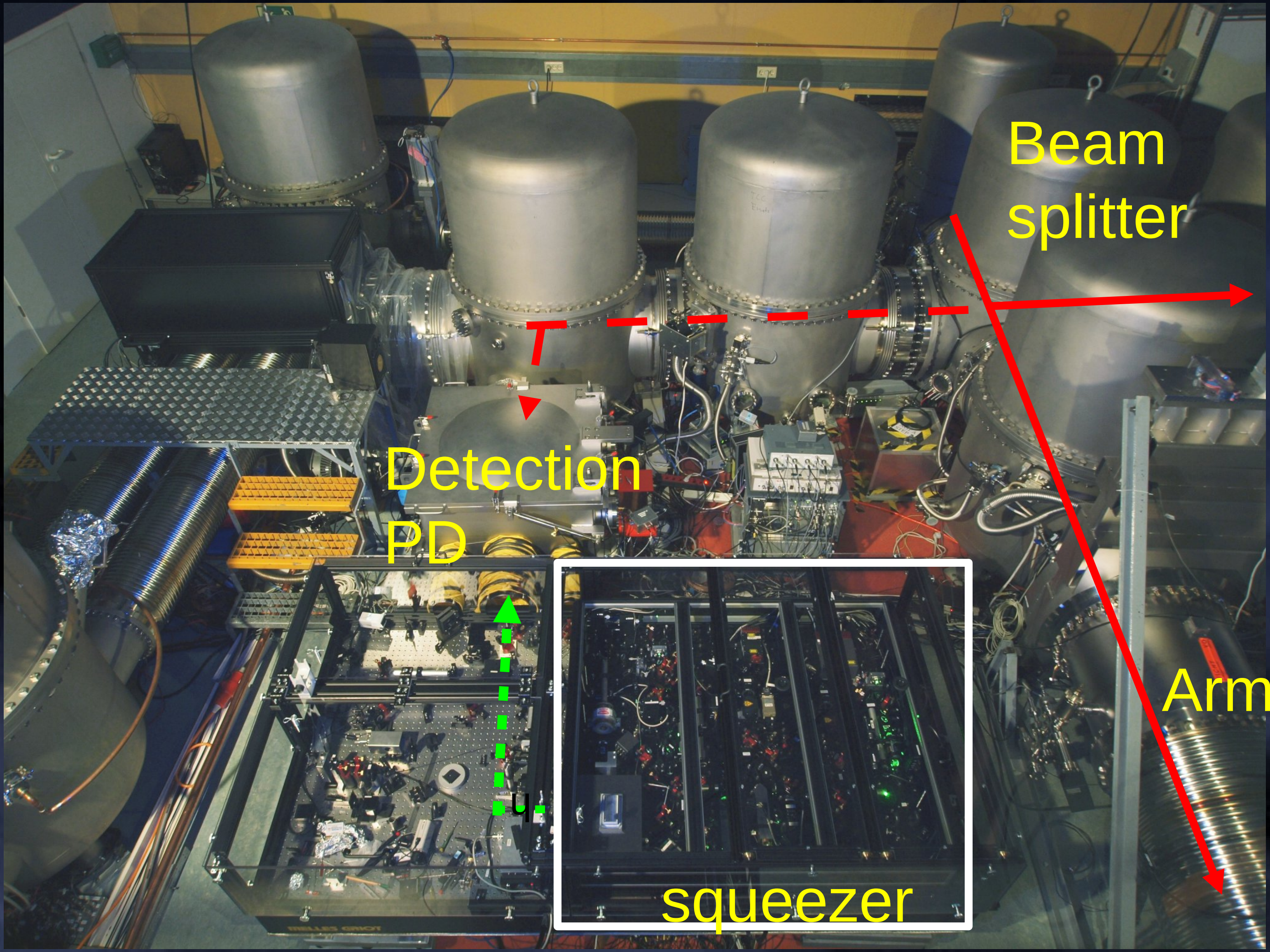
Fundamental, Technical, Robust

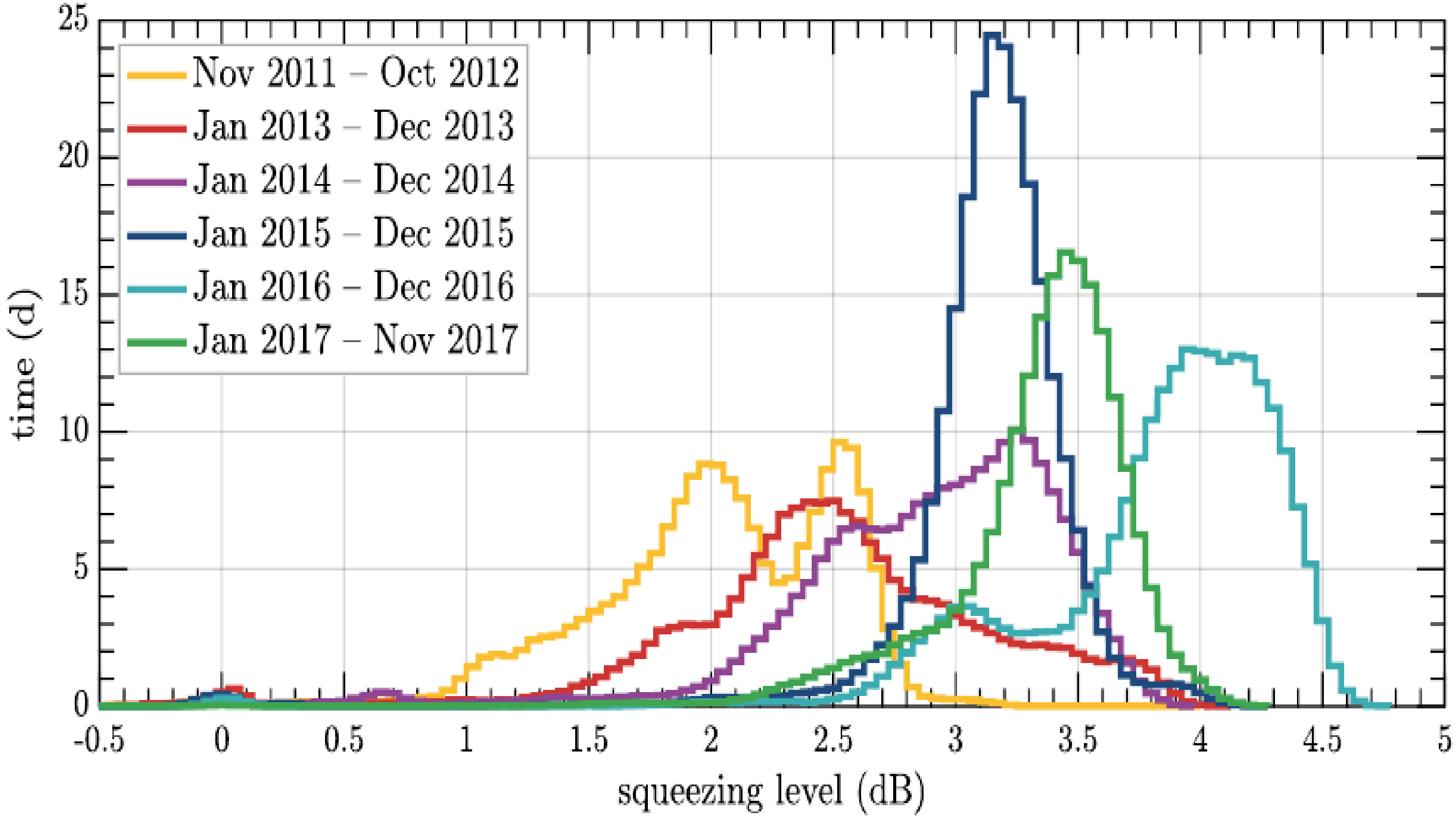
LIGO: from O2 to O3

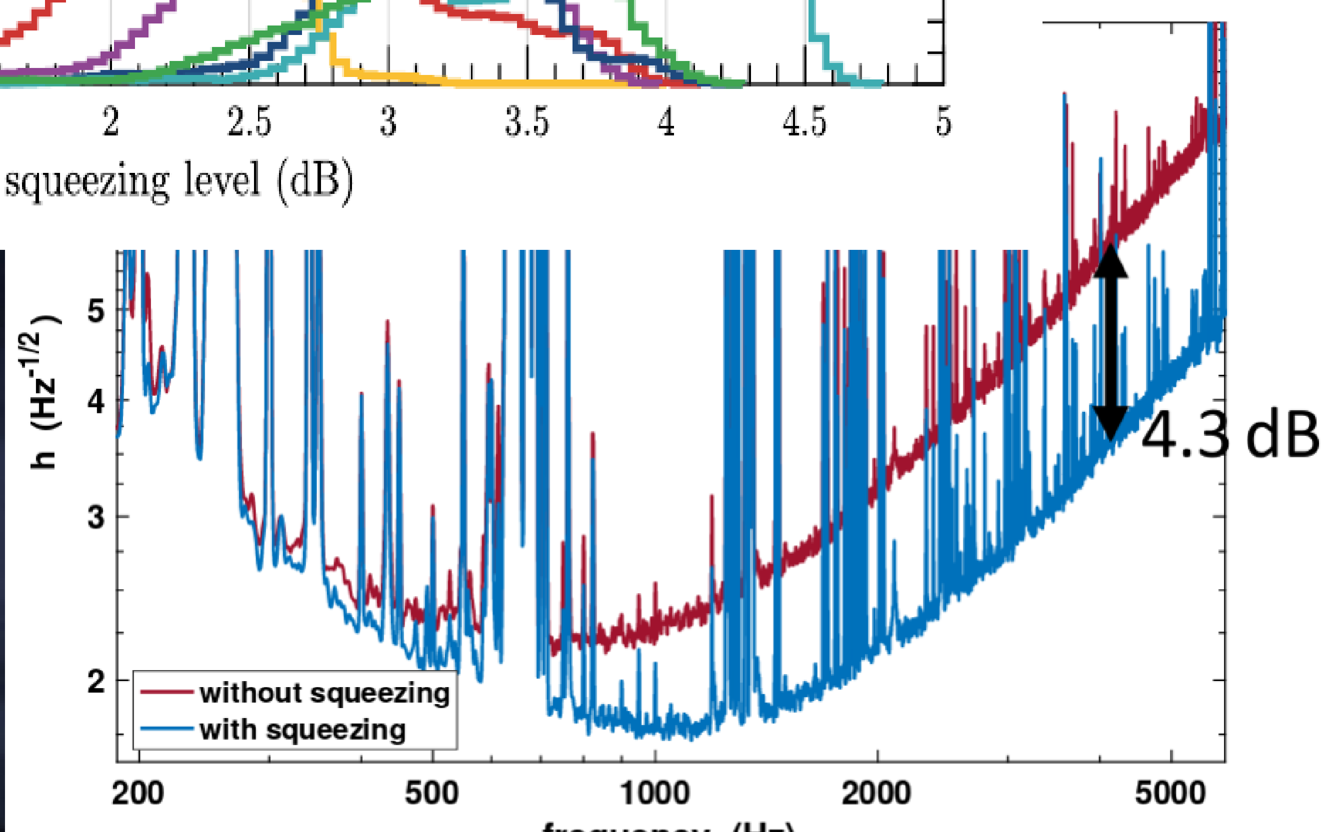
- Higher laser power and squeezing implementation to reduce shot noise

GEO 600

Quantum noise reduction: Squeezing the EM-vacuum state




Nov 2011 – Oct 2012
Jan 2013 – Dec 2013
Jan 2014 – Dec 2014
Jan 2015 – Dec 2015
Jan 2016 – Dec 2016
Jan 2017 – Nov 2017
time (d)
25
20
15
10
5
0
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
squeezing level (dB)

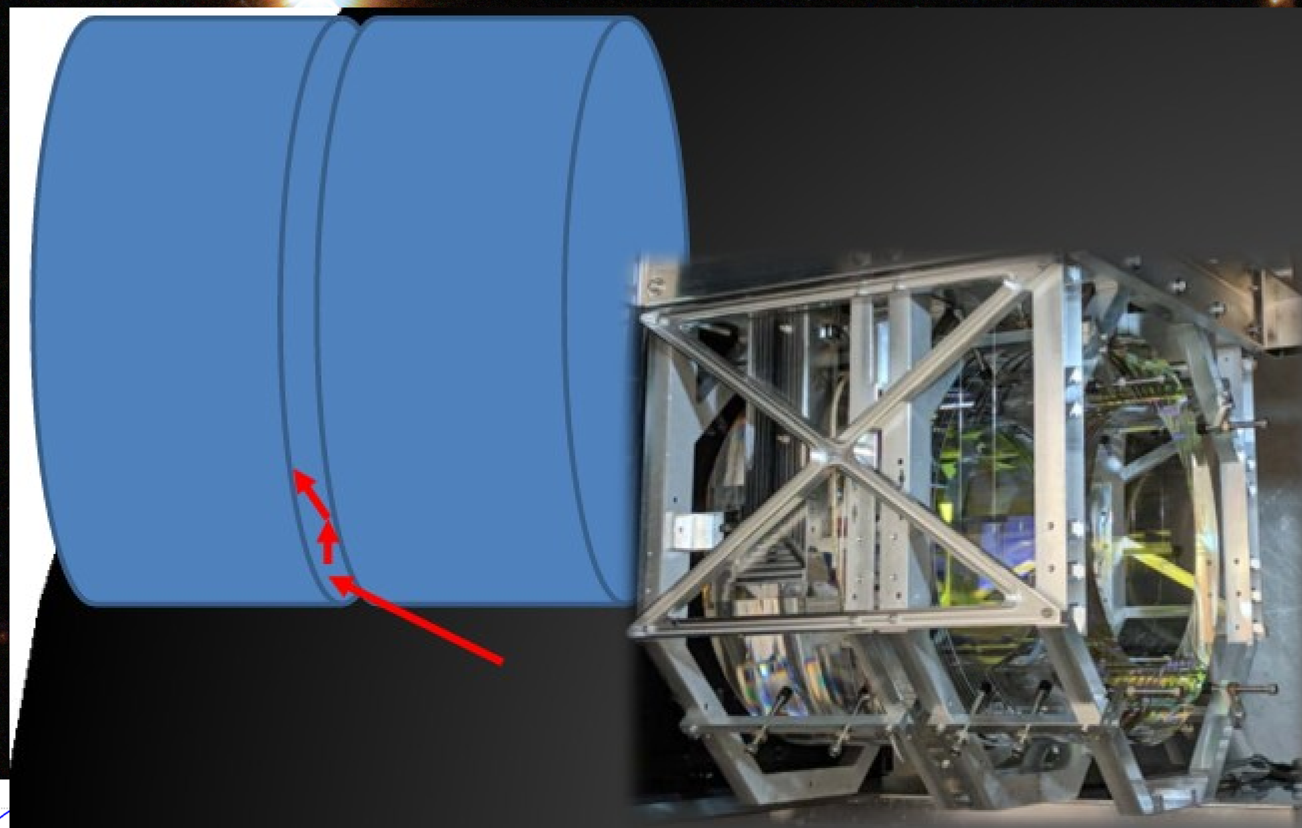

h (Hz^-1/2)
5
4
3
2
200
500
1000
2000
5000
without squeezing
with squeezing
4.3 dB

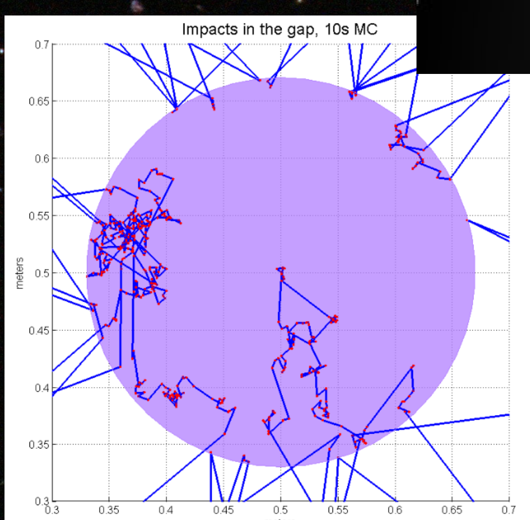
LIGO: from O2 to O3

-Higher laser power and squeezing implementation
to reduce shot noise

-Improved reaction masses
to lower squeeze film damping

Squeeze Film Damping:
Excess noise from ‘trapped gas molecules’





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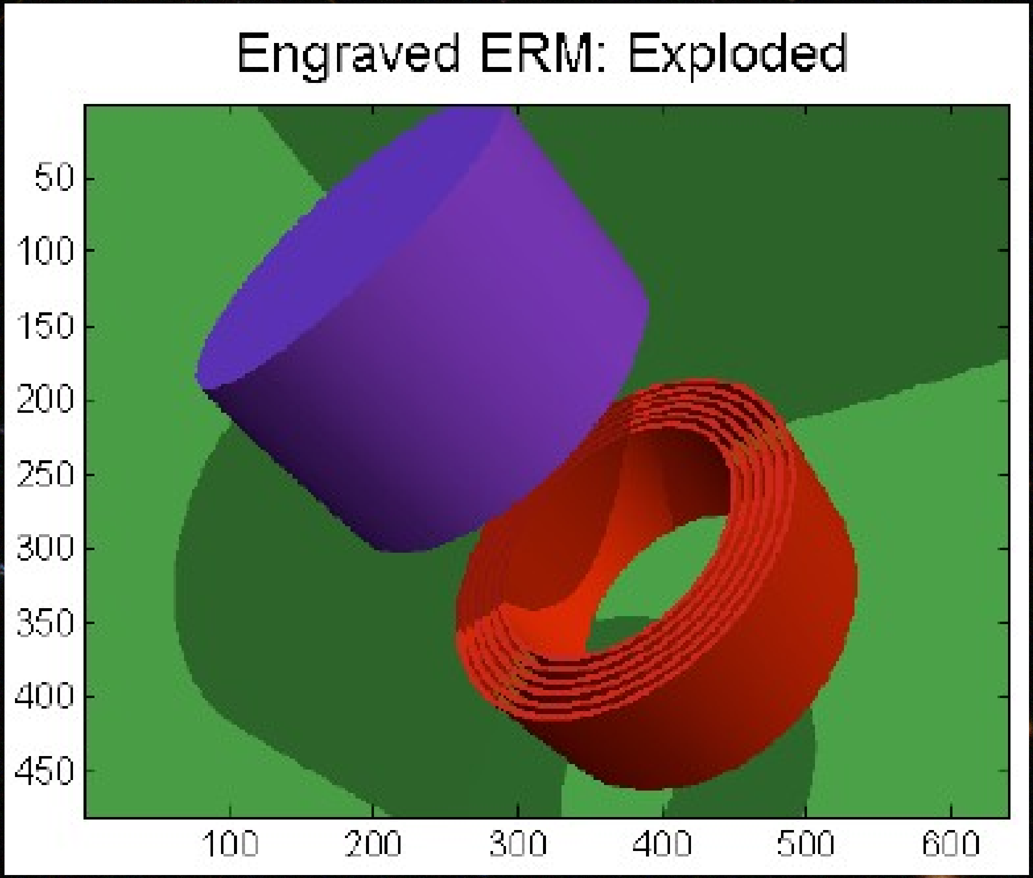
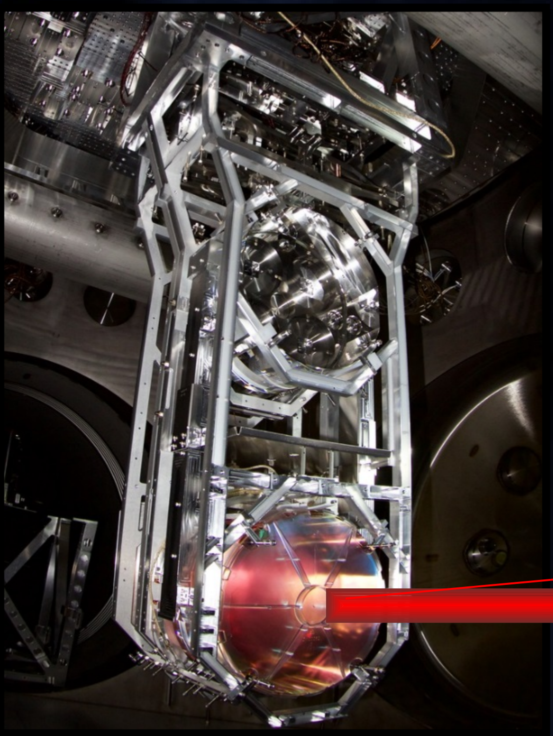


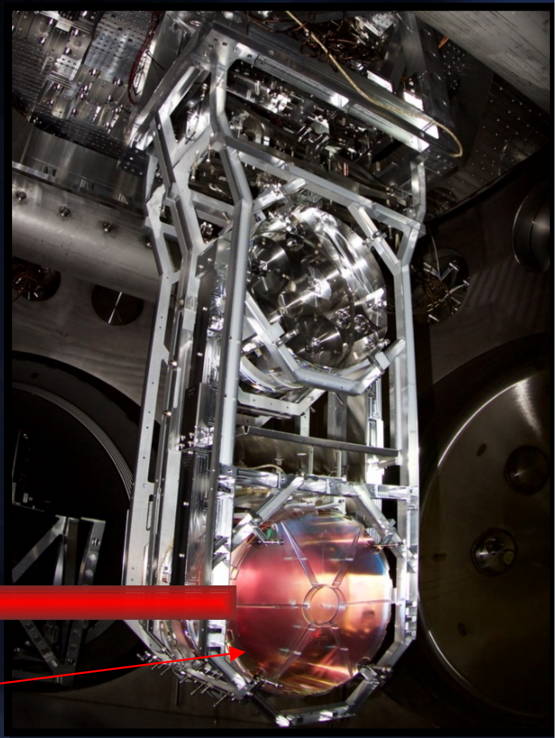
LIGO: from O2 to O3

- Higher laser power and squeezing implementation to reduce shot noise
- Improved reaction masses to lower squeeze film damping
- Scattered light reduction with more and improved baffles

Not easy to budget: Scattered Light

Mitigation strategies:
1) Reduce amplitude of light in spurious path
2) Reduce motion of scattering objects





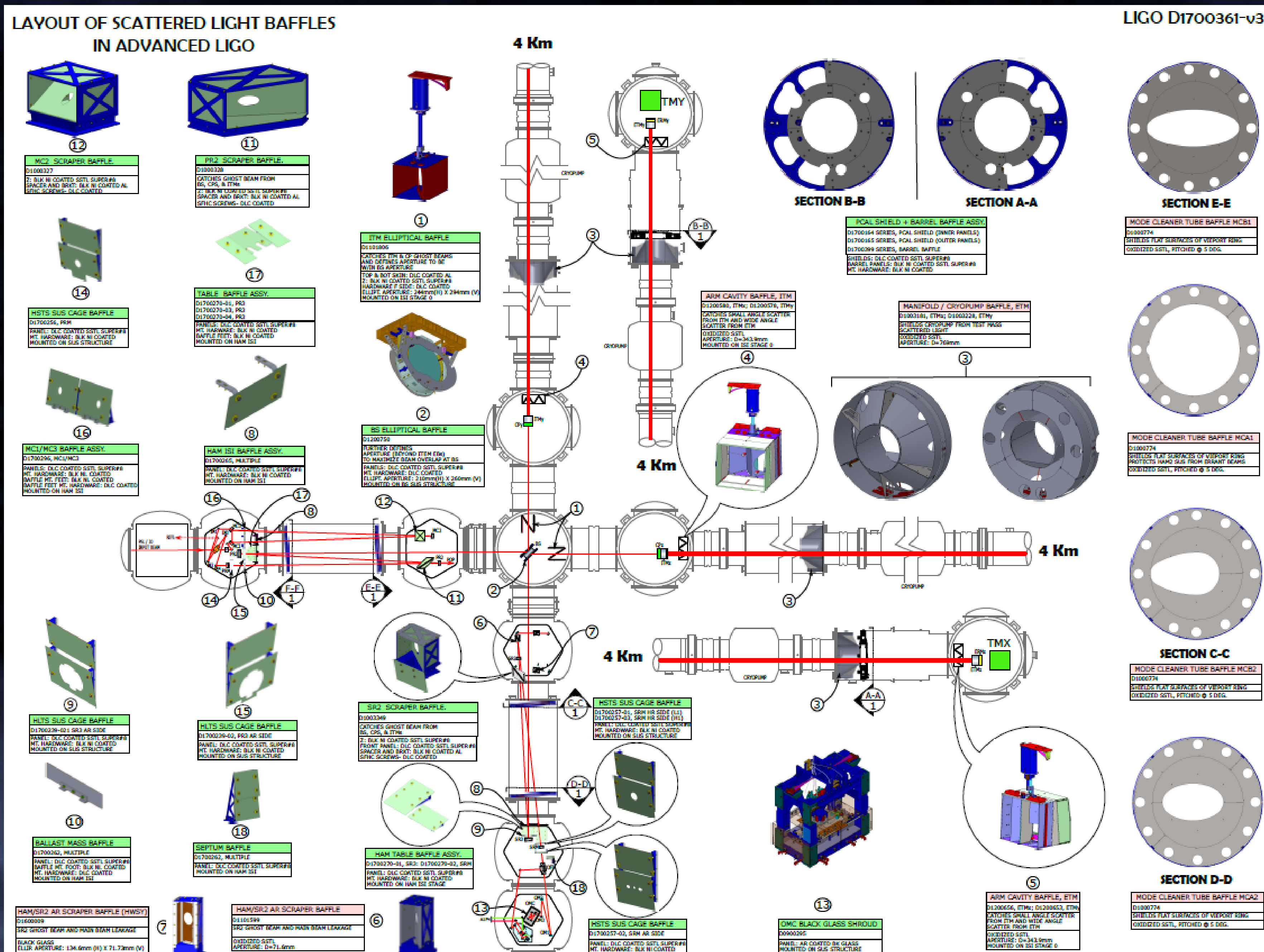
2) Scatters off of less well isolated objects (baffles)

1) Light scatters out of main interferometer beam (Anti reflection coatings, imperfections in optics)

3) Light re-enters interferometer creating spurious interferometer Or acting via rad. pressure

Credit: S. Dwyer

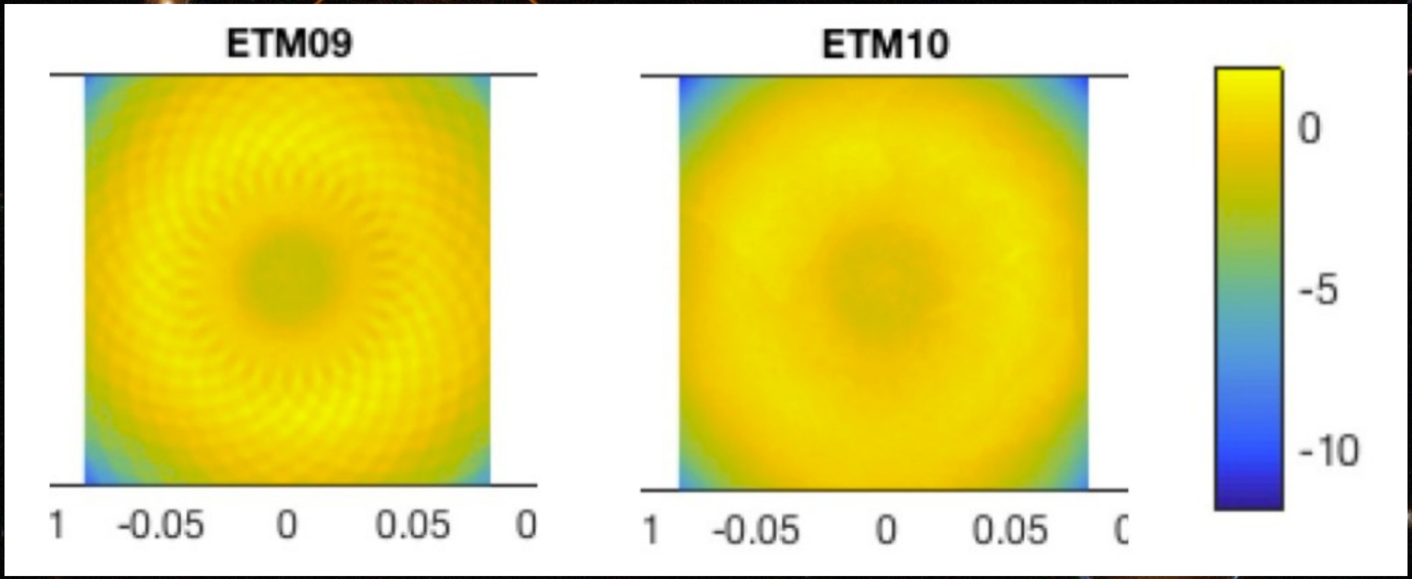
...and how to fight scattered light



LIGO: from O2 to O3

-Higher laser power and squeezing implementation
  to reduce shot noise
-Improved reaction masses
  to lower squeeze film damping
-Stray light reduction with more and improved
  baffles
-Improved coatings for less stray light and
  to make lock acquisition more robust

Replaced test masses:
Improved coatings for less stray light



LIGO: from O2 to O3

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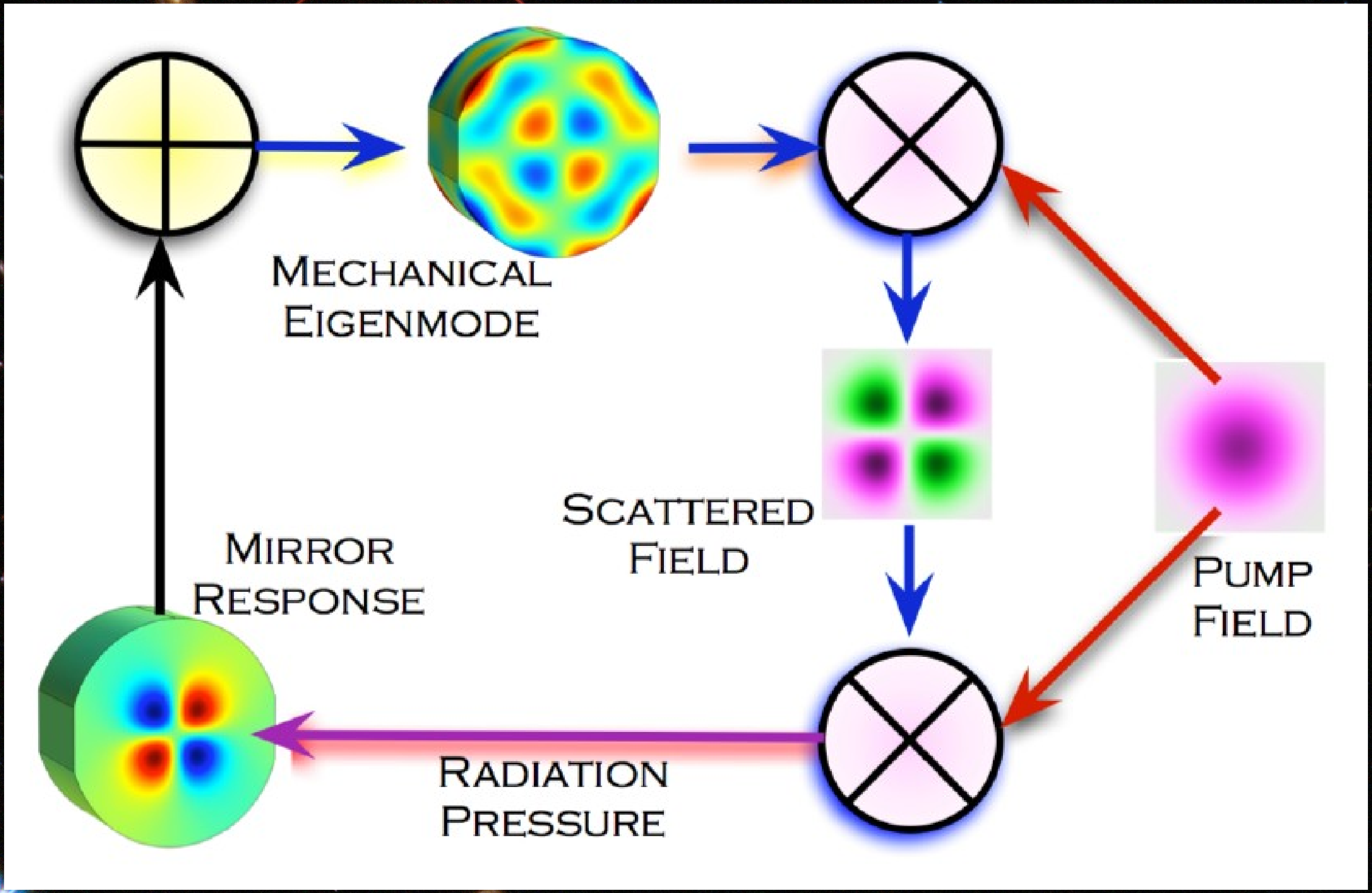
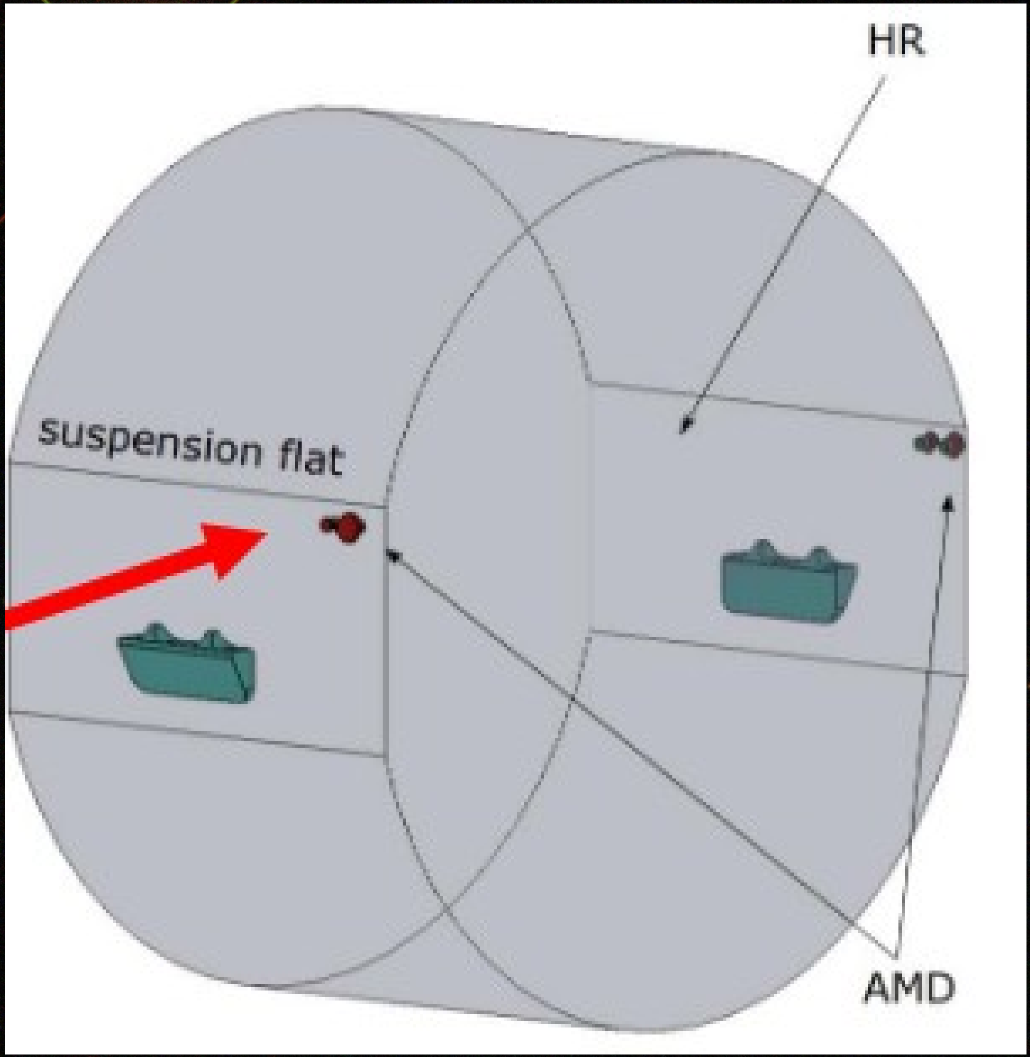
to make lock acquisition more robust
-Test mass dampers to reduce
parametric instabitlity problems

Of course there is more:
e.g. Parametric Instability



Can prevent laser power increase

Resonant damper



S.Gras, S. Biscans

LIGO: from O2 to O3

-Higher laser power and squeezing implementation
to reduce shot noise
-Improved reaction masses
to lower squeeze film damping
-Stray light reduction with more and improved
baffles
-Improved coatings for less stray light and
to make lock acquisition more robust
-Test mass dampers to reduce
parametric instabitlity problems
-and more…
-goal is to have at least 120 Mpc on both LIGO's

Post-O3 plans:

The A+ program (2019-2022):

-filter cavities to squeeze rad. Pressure noise (amplitude quadrature)
-better coatings / new testmasses
-Larger beam splitter, improved control
-should yield factor 4 to 7 increase in volume range

LIGO Beyond A+

LIGO Voyager:

-new materials and cryogenics:
Silicon (120K)
-higher power lasers
(3MW in IFO arms)

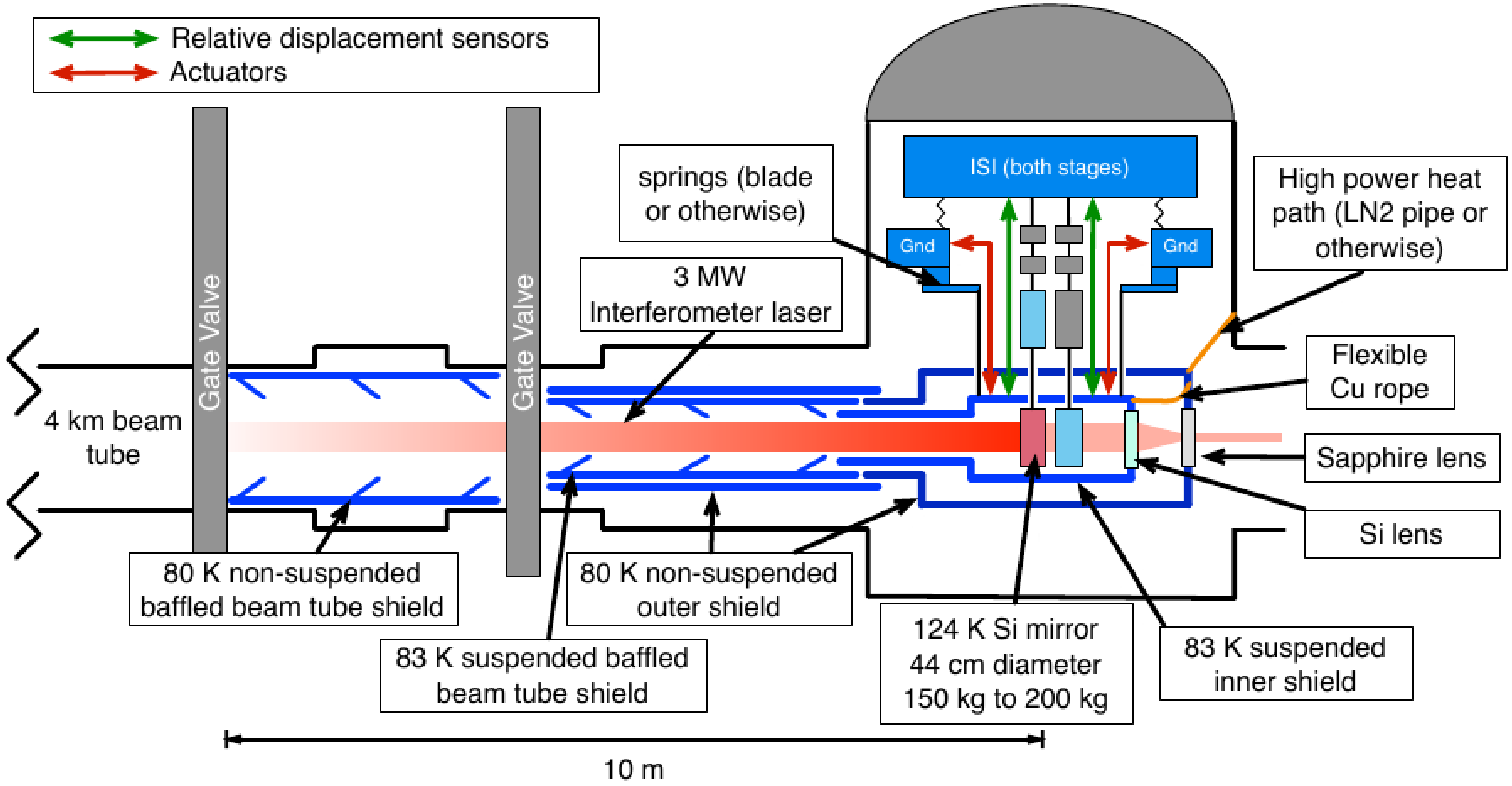
LIGO HF?:

-Detector optimised for 1-4kHz
Range: NS physics
-higher power lasers
(3MW in IFO arms)

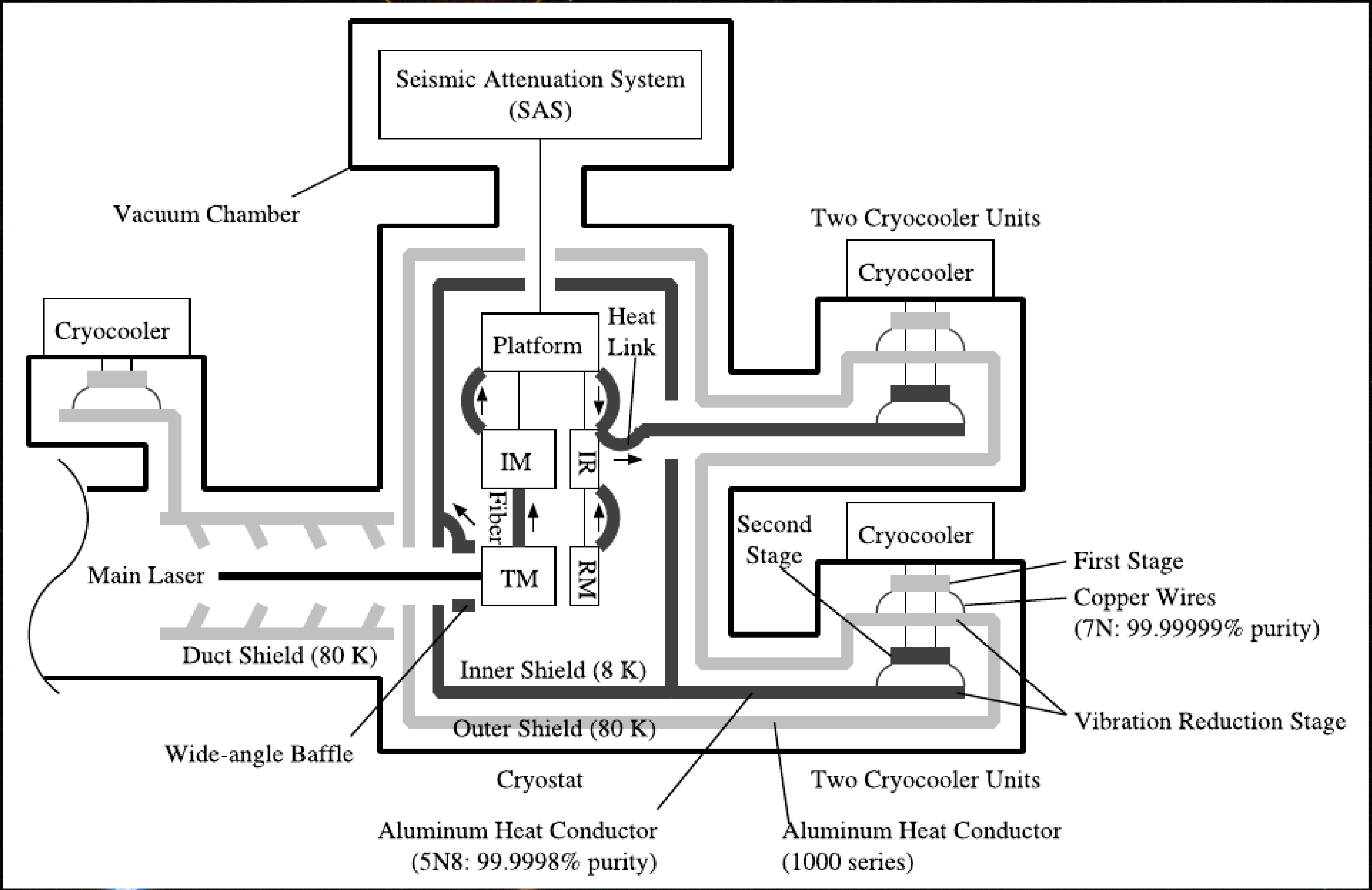
Cosmic Explorer:

-new facilities: longer arms
-heavier test masses, larger beams, longer suspensions
-new materials and cryogenics:
Silicon (120K ?)
-higher power

Cryogenics a la Voyager

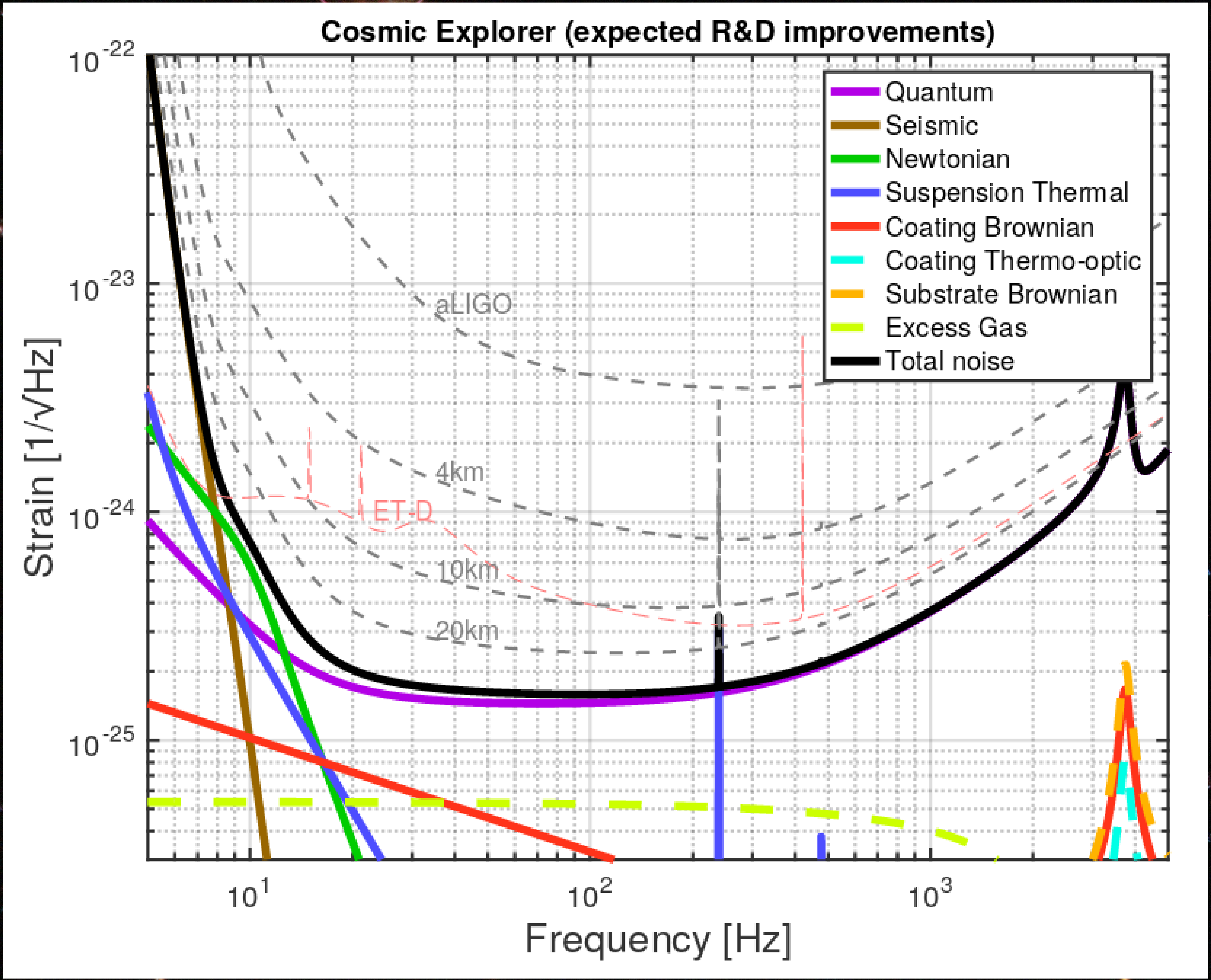


Cryogenics under way at KAGRA



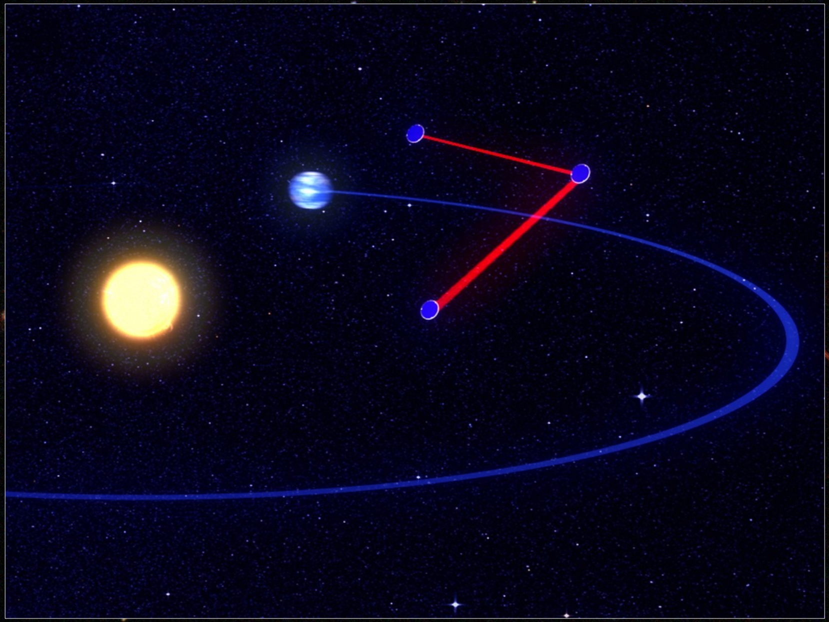
Challenging: seismic attenuation and mirror heat load
Using Sapphire mirrors

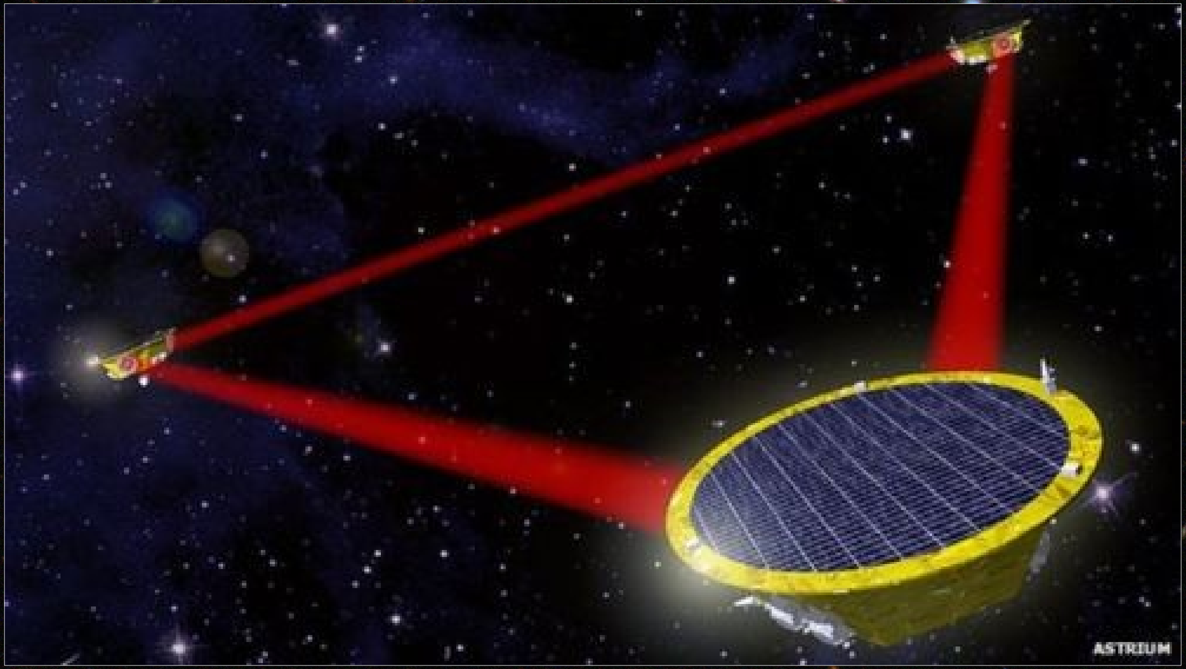
Longer arms



Cosmic Explorer (expected R&D improvements)
Strain [1/√Hz]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{1}
10^{2}
10^{3}
aLIGO
4km
ET-D
10km
20km
Quantum
Seismic
Newtonian
Suspension Thermal
Coating Brownian
Coating Thermo-optic
Substrate Brownian
Excess Gas
Total noise

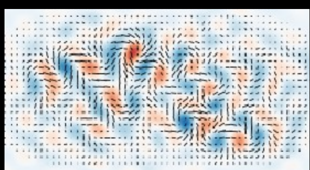
LISA



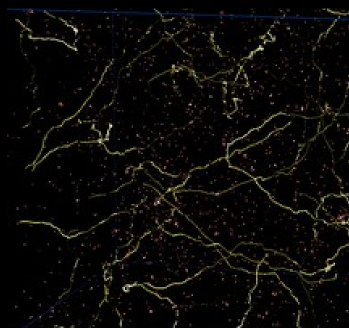


Das Gravitationswellen-Spektrum

Primordial GWs



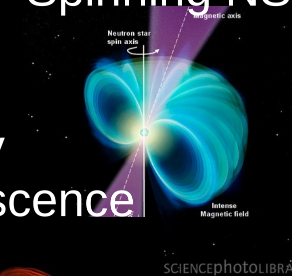
Cosmic strings



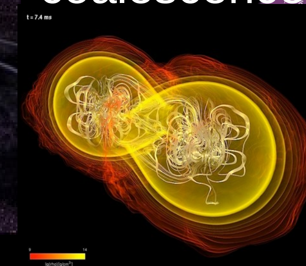
Supermassive BH binaries

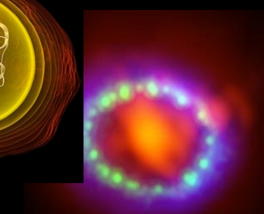
BH and NS binaries

Spinning NS



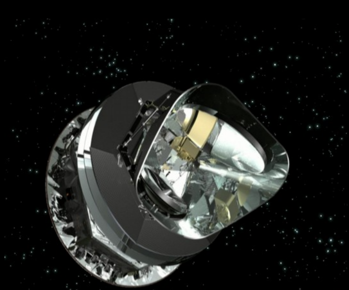
Binary coalescence





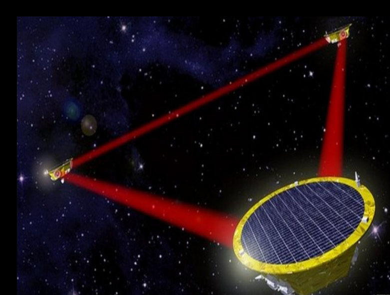
Supernovae

10^{-16} 10^{-8} 10^{-3} 10^{0} 10^{3} Hz



Inflation probe

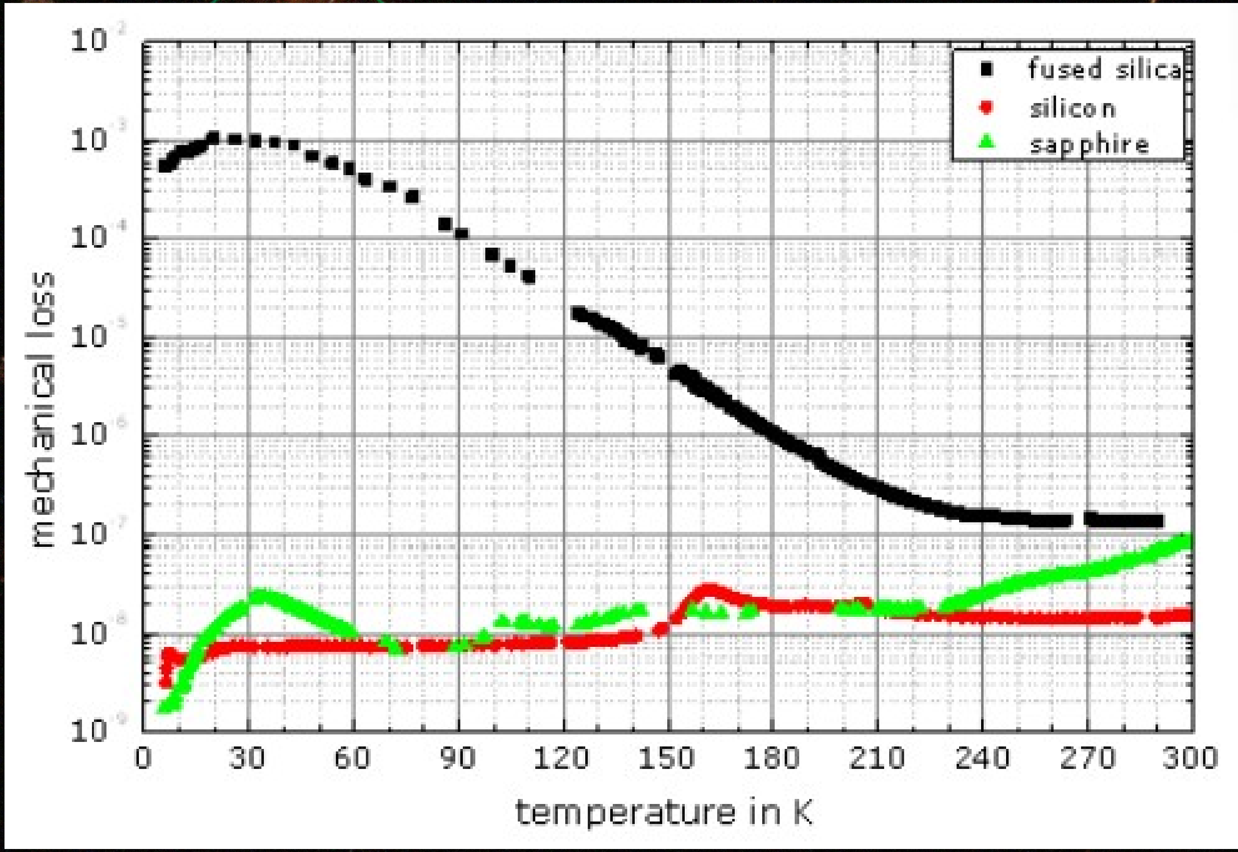
Pulsar timing



Interferometers In space

Ground-based interferometers

Thermal noise



Which material for mirrors and suspension?
Silicon and Sapphire being researched