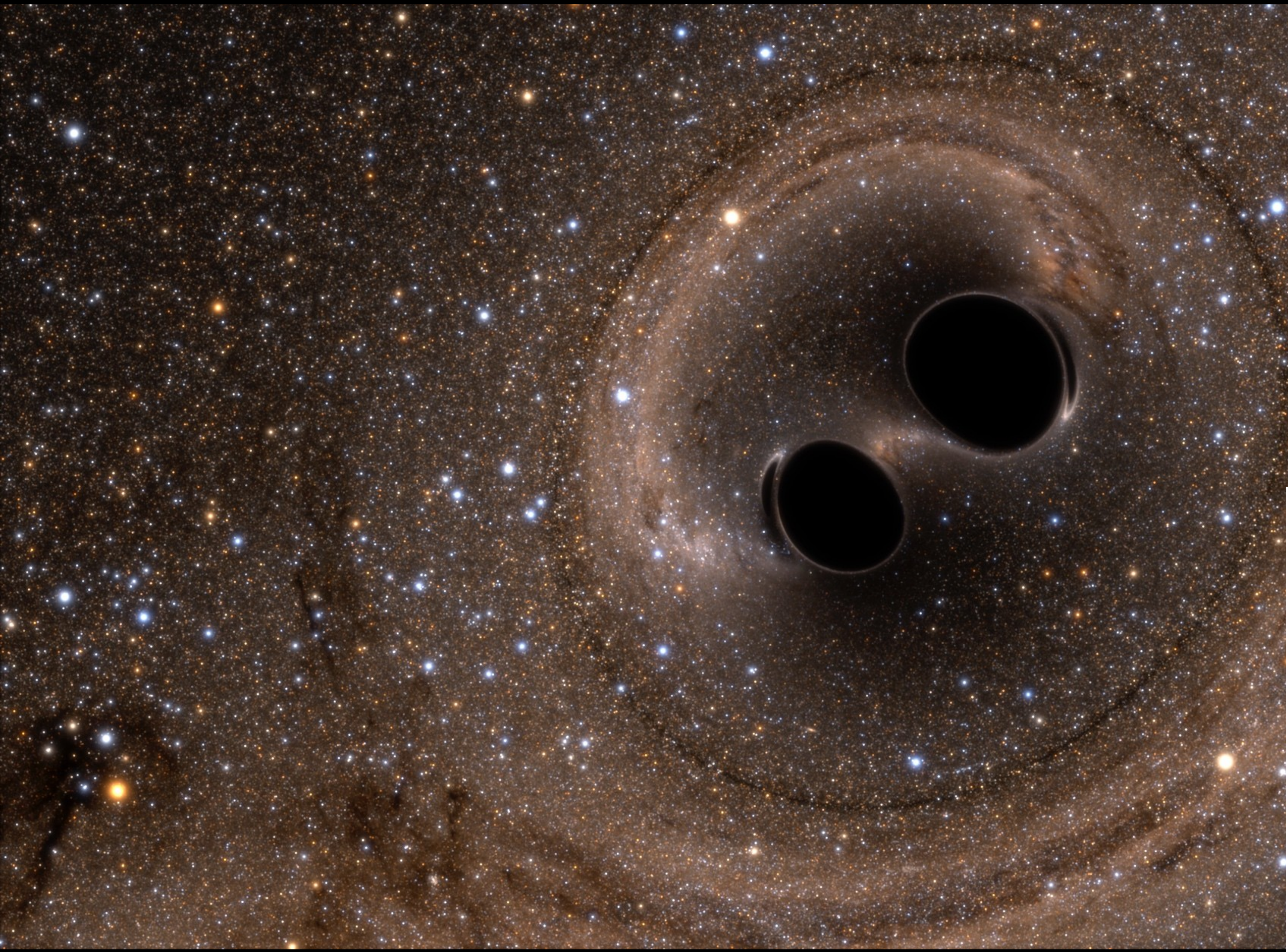
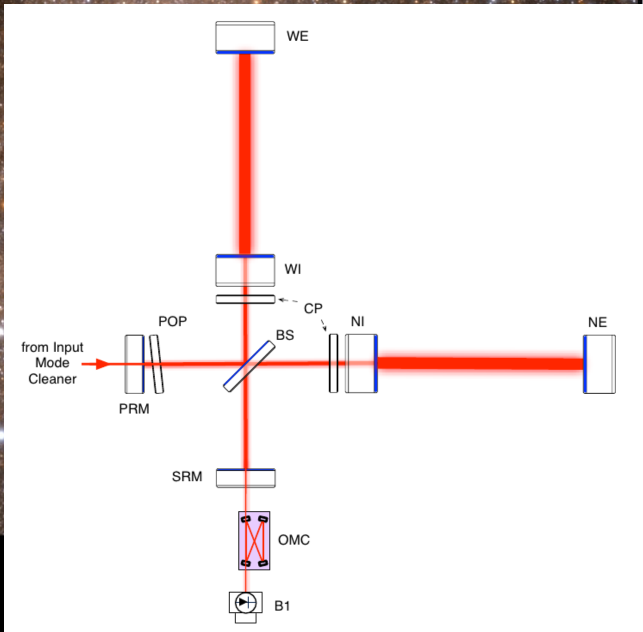
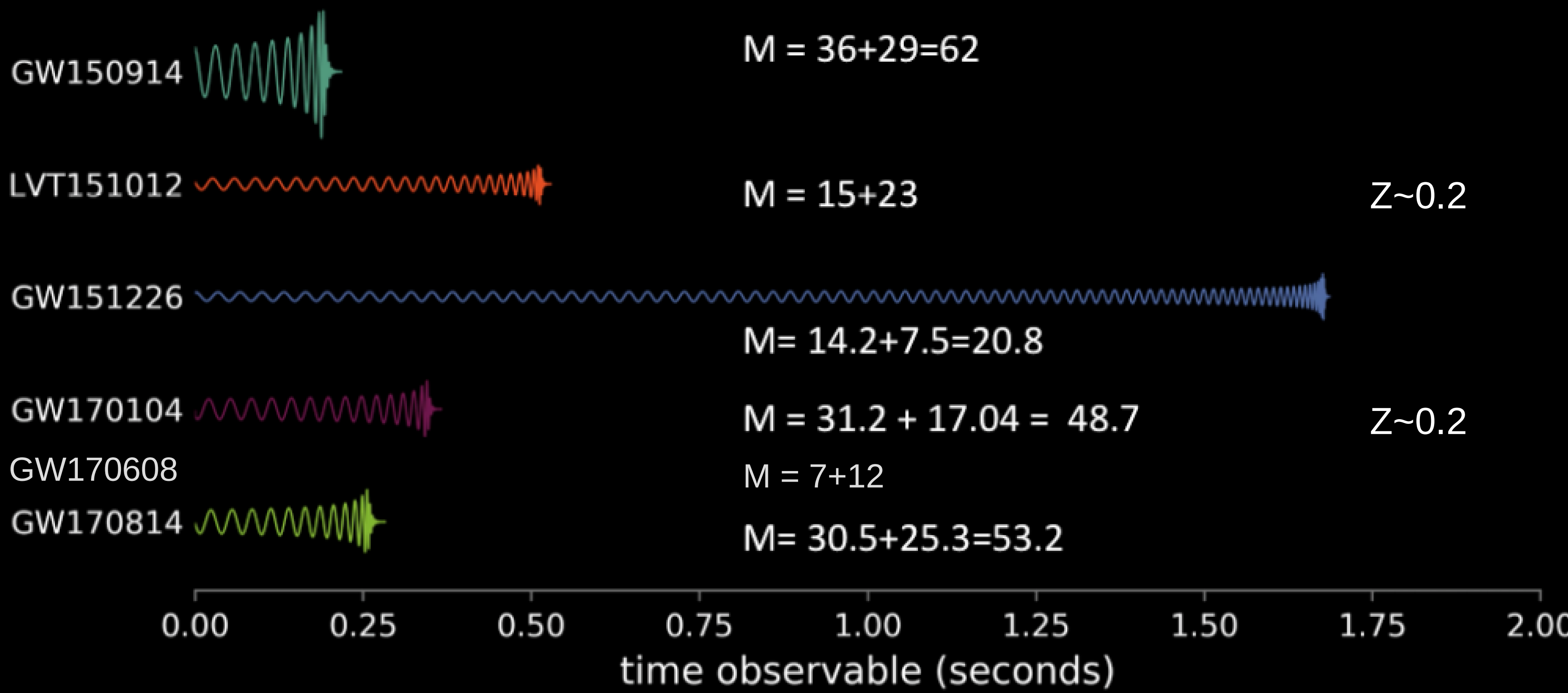
The Road Ahead:
Challenges for Future Gravitational Wave Detectors





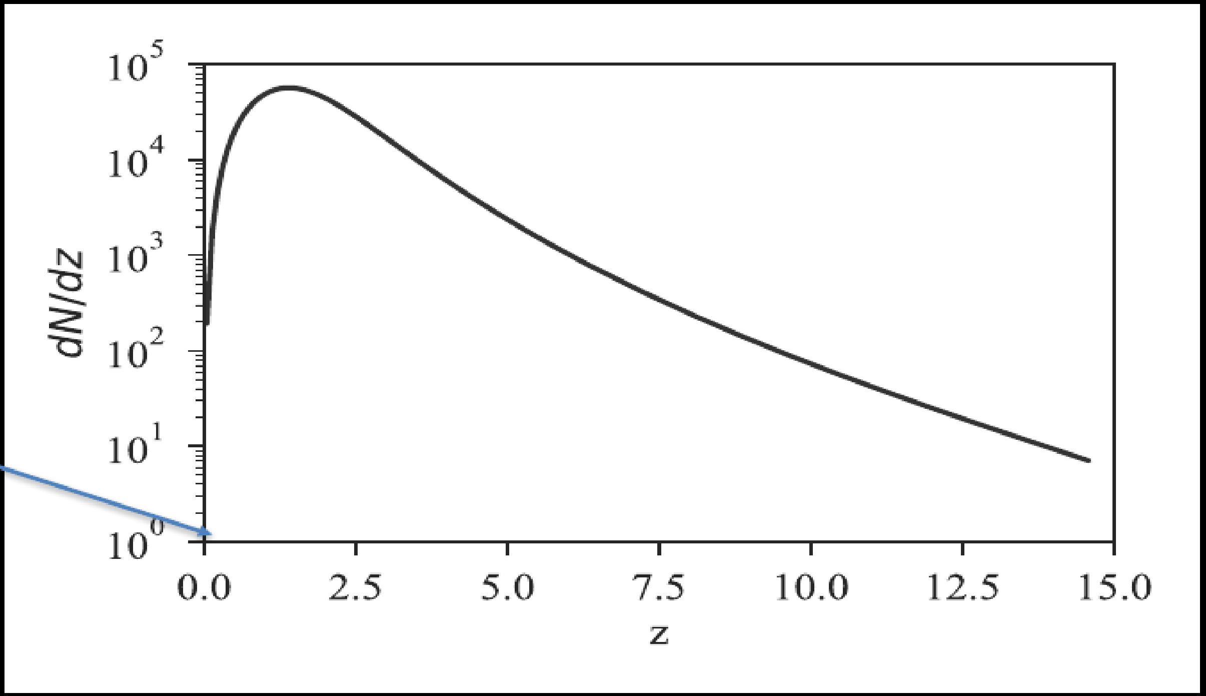
Hartmut Grote
Cardiff University
UK

Fermilab Colloquium, March 7^{th}, 2018


GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814
M = 36+29=62
M = 15+23
Z~0.2
M= 14.2+7.5=20.8
M = 31.2 + 17.04 = 48.7
Z~0.2
M = 7+12
M= 30.5+25.3=53.2
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
time observable (seconds)

This is only the beginning

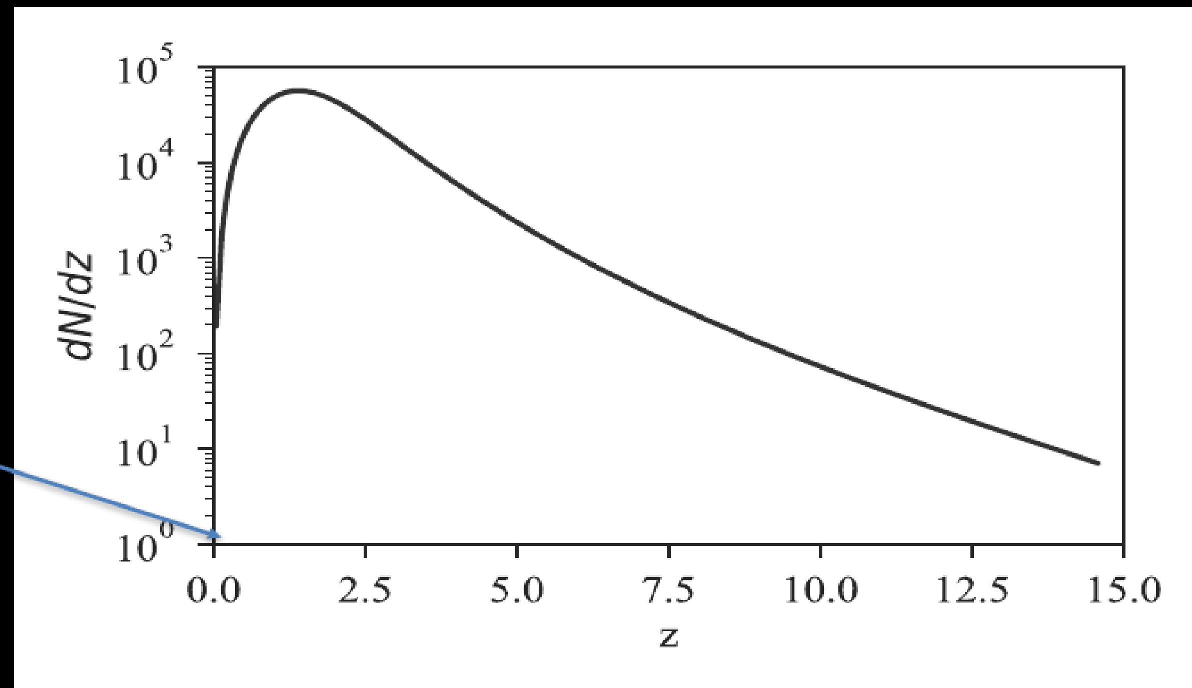
You are here!



Credit: S. Vitale, MIT

This is only the beginning

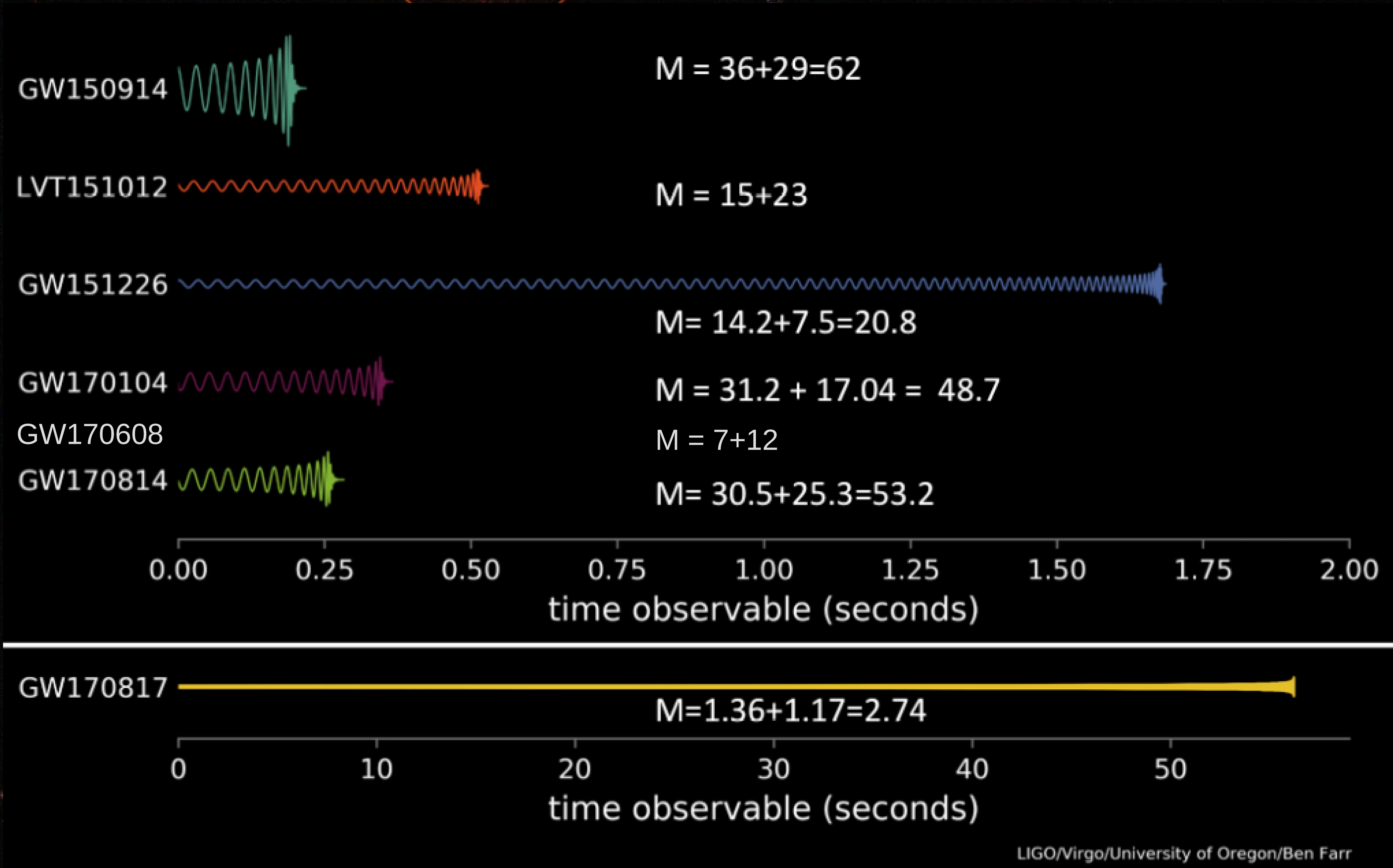
You are here!



Credit: S. Vitale, MIT

-BBH mass distribution and formation channels
-Precision tests of GR
-...

One BBH merger every ~5 minutes in the universe


GW150914
M = 36+29=62
LVT151012
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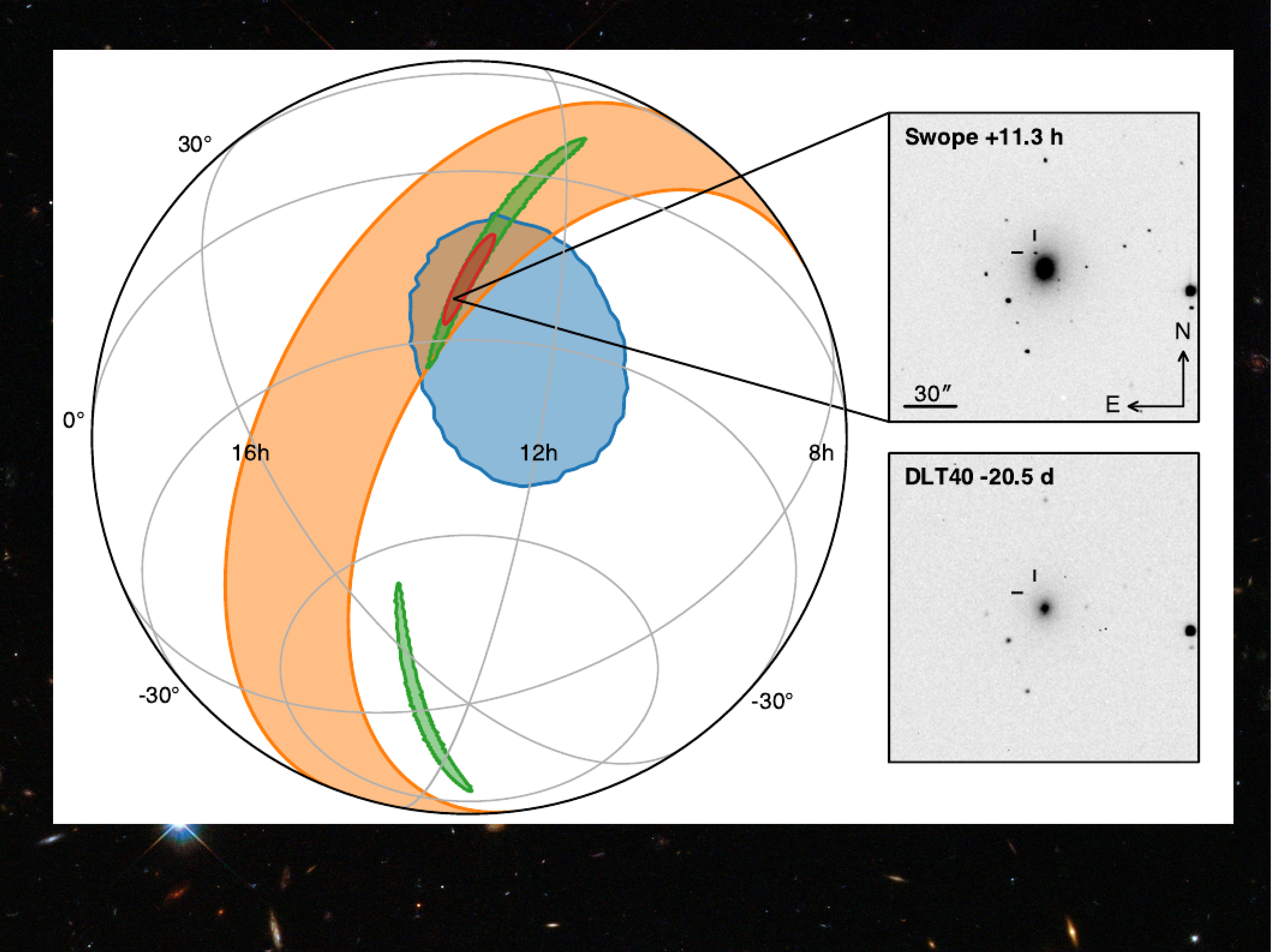
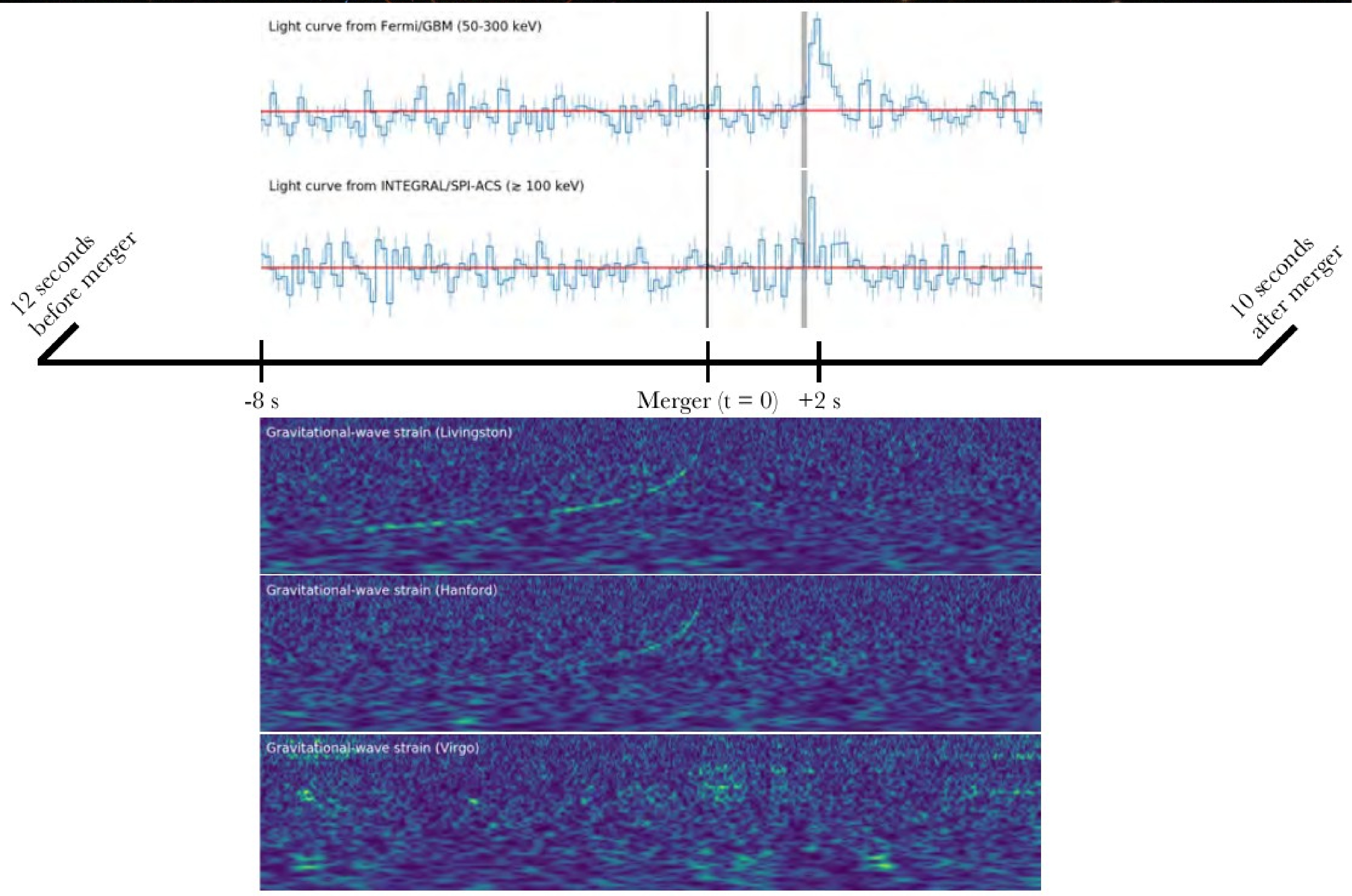
GW151226
M= 14.2+7.5=20.8
GW170104
M = 31.2 + 17.04 = 48.7
GW170608
M = 7+12
GW170814
M= 30.5+25.3=53.2
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
time observable (seconds)
GW170817
M=1.36+1.17=2.74
0
10
20
30
40
50
time observable (seconds)
LIGO/Virgo/University of Oregon/Ben Farr

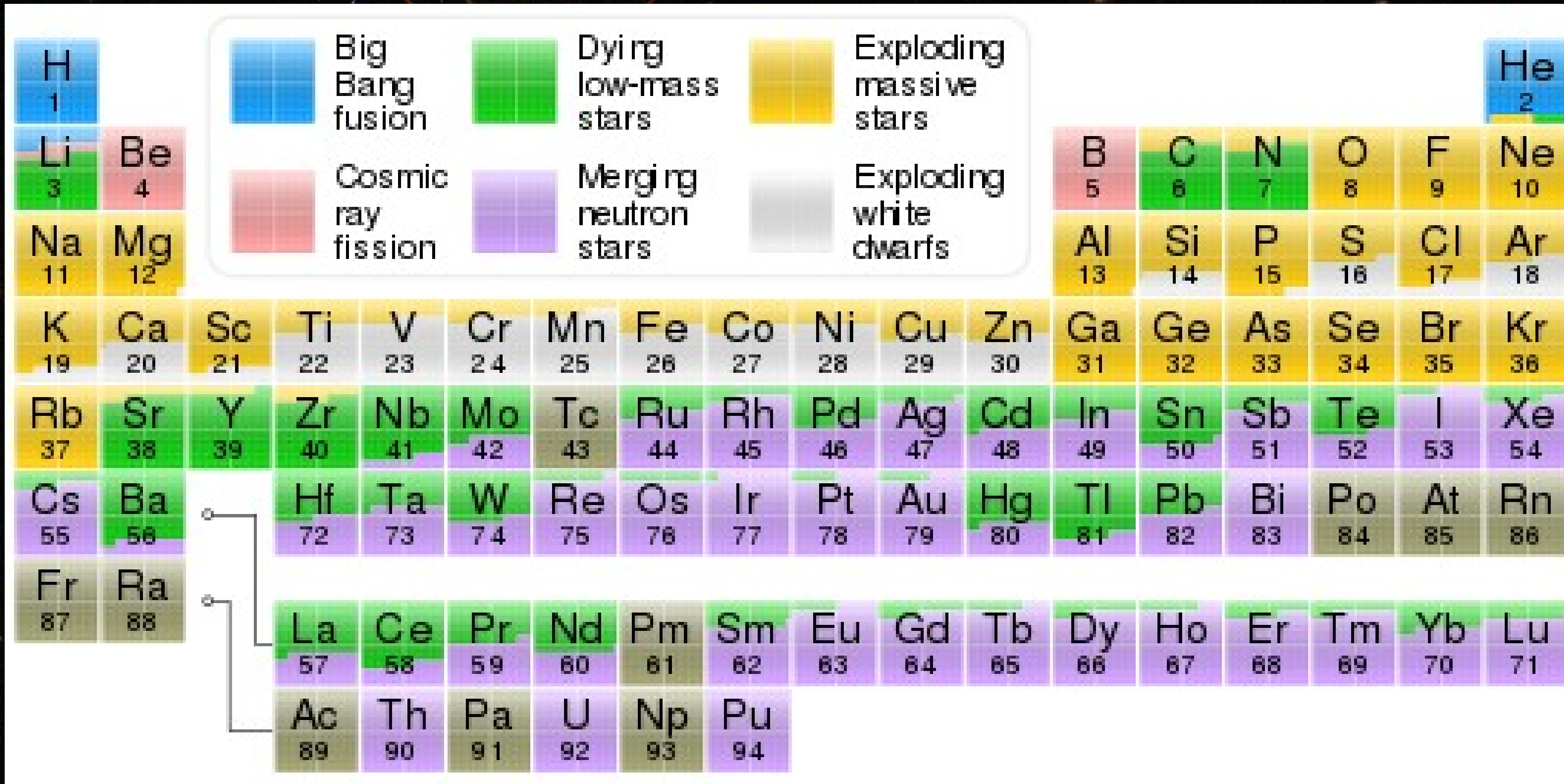

220



30°
0°
16h
12h
8h
-30°
-30°
Swope +11.3 h
N
30″
E
DLT40 -20.5 d



Light curve from Fermi/GBM (50-300 keV)
Light curve from INTEGRAL/SPI-ACS (≥ 100 keV)
12 seconds before merger
10 seconds after merger
-8 s
Merger (t = 0)
+2 s
Gravitational-wave strain (Livingston)
Gravitational-wave strain (Hanford)
Gravitational-wave strain (Virgo)



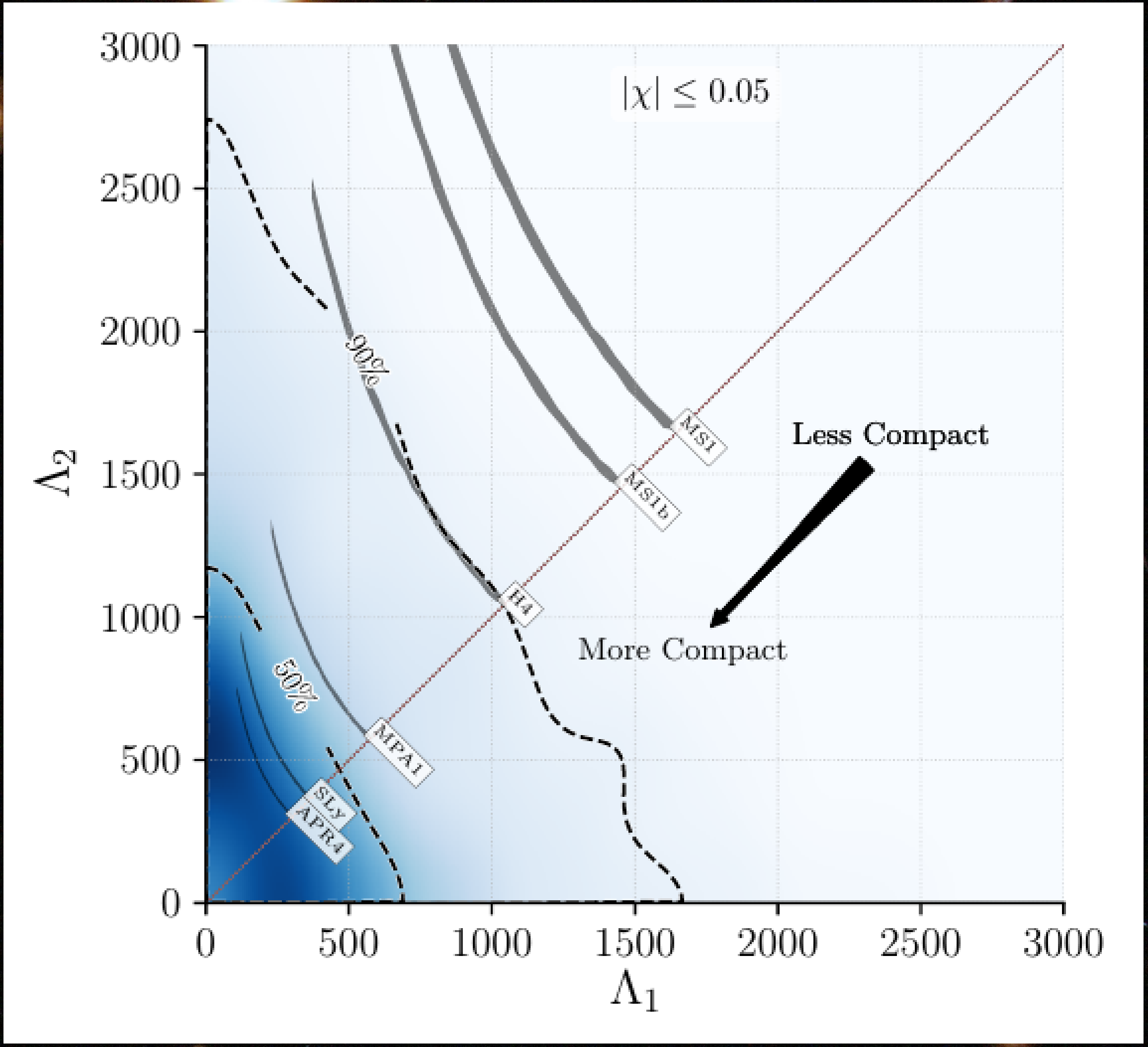
Nucleosynthesis of heavy elements:
More than the mass of earth in gold

Binary neutron star observations...

-nuclear equation of state
-hubble constant
-more tests of GR (speed of Gws…)
-multi-messenger astronomy
-...

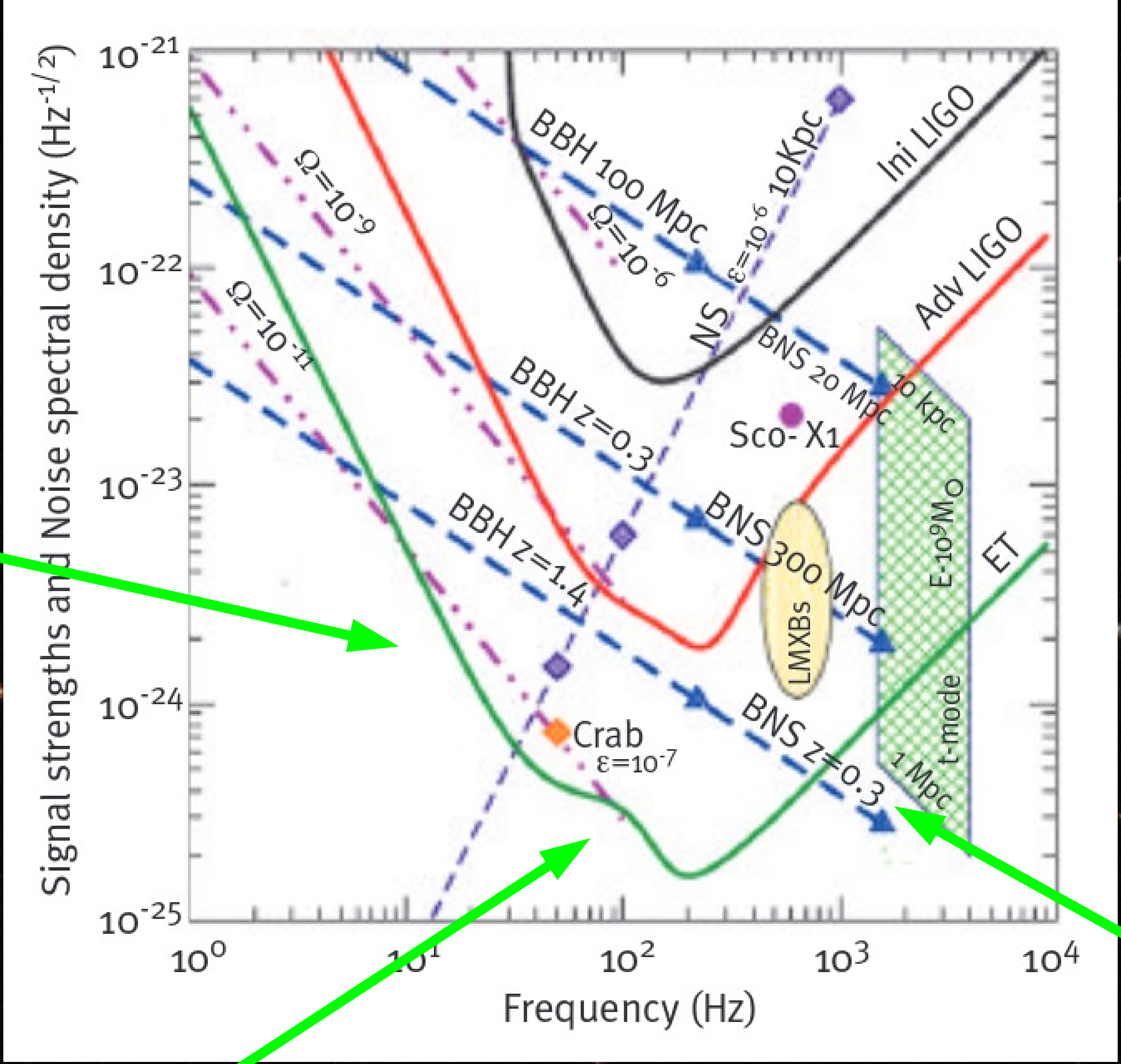
One BNS merger every 15 seconds in the universe

Constraints on Nuclear Equation of State from GW170817



Need more signal to noise and/or more events (stacking possible)

Sources and Detector Generations

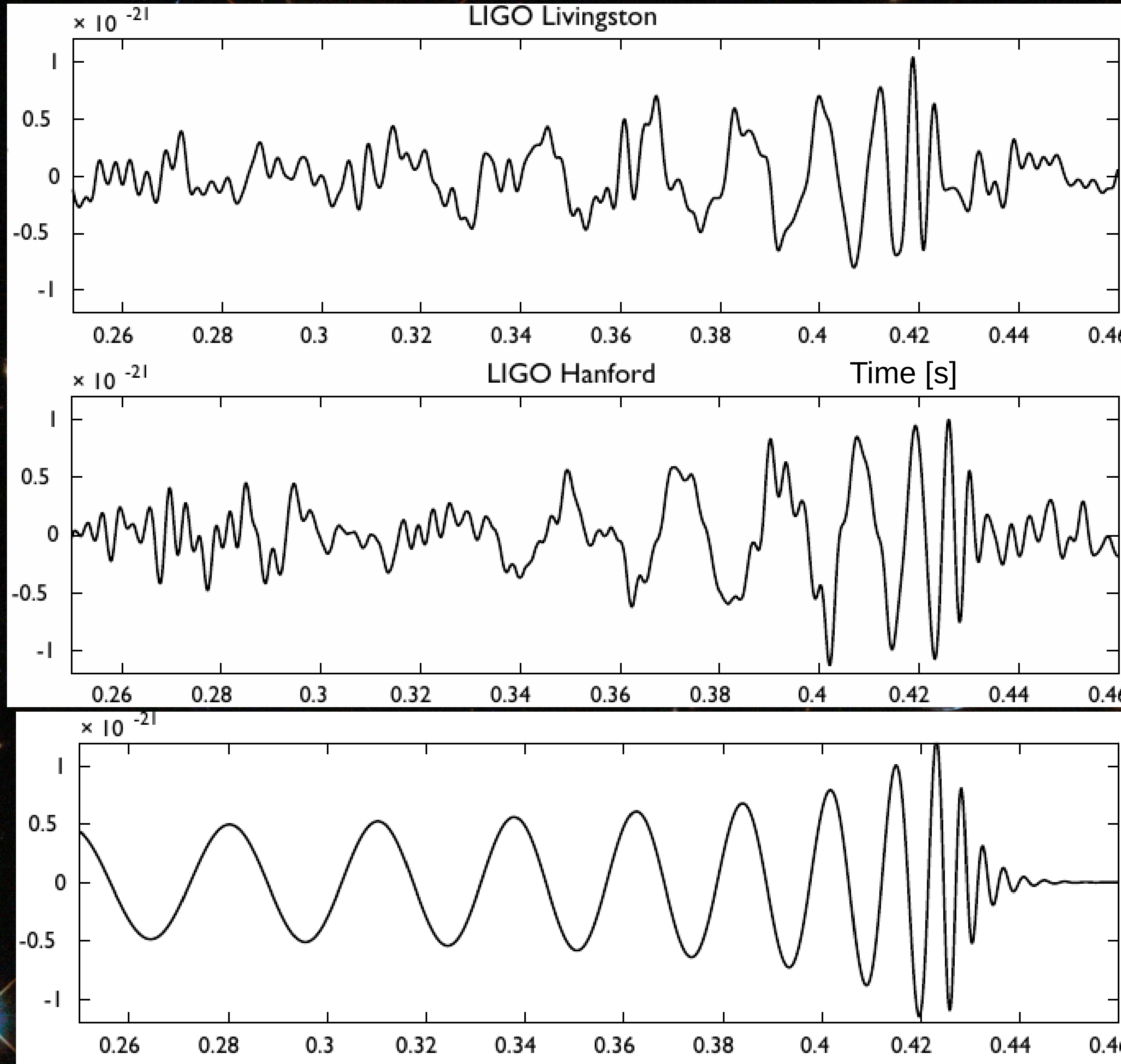


Higher BH masses

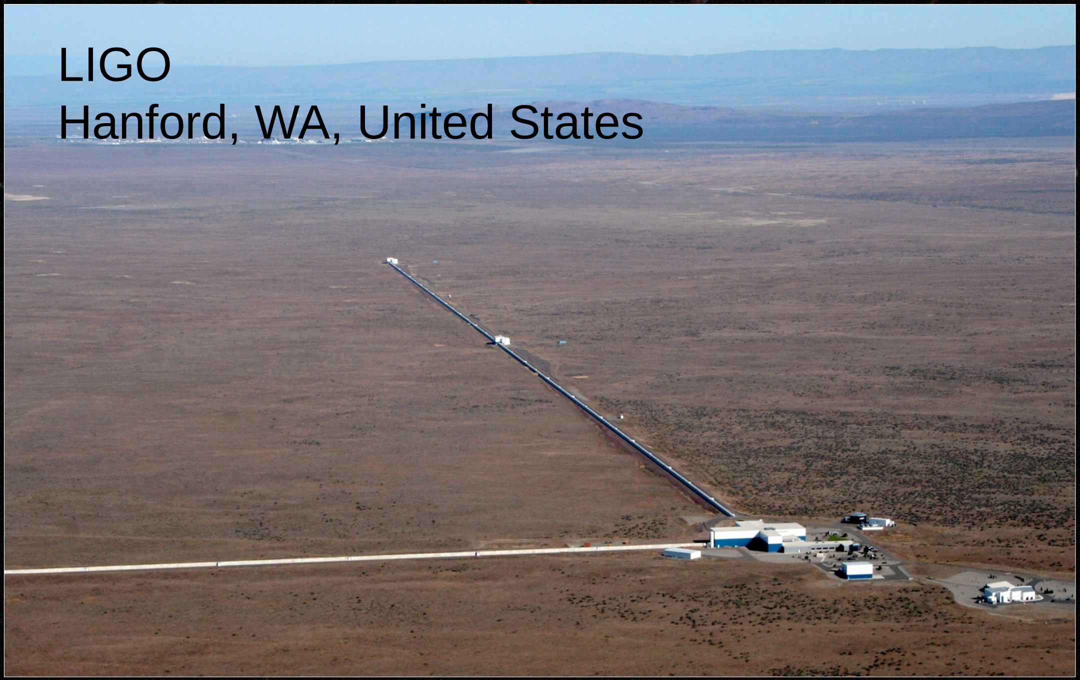
Higher SNR's

Neutron star physics

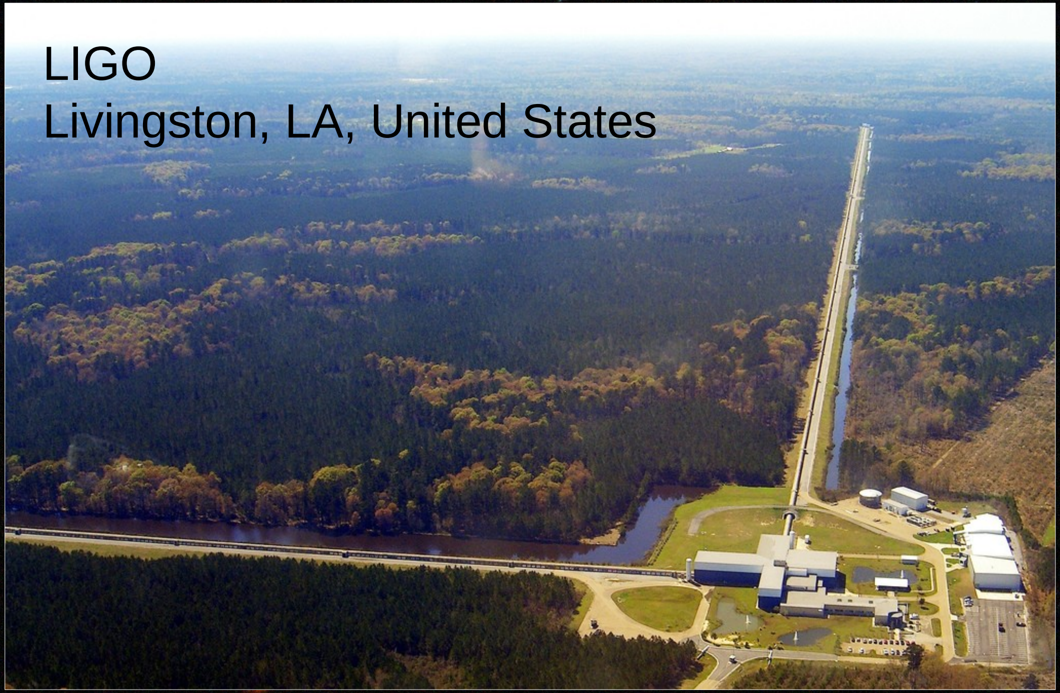
Really Really Really a Black Hole?



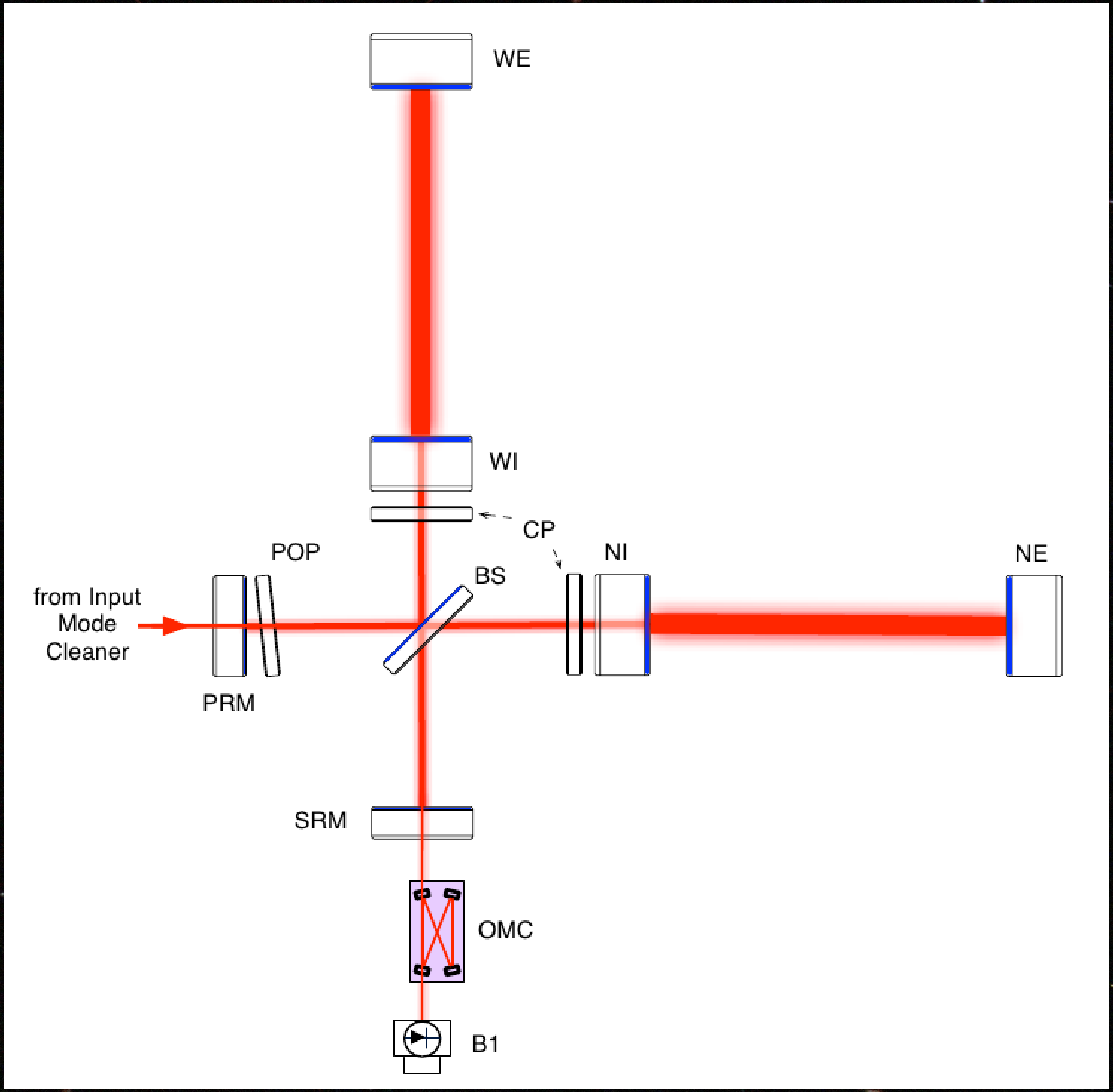
Need higher SNR to resolve BBH ringdown:

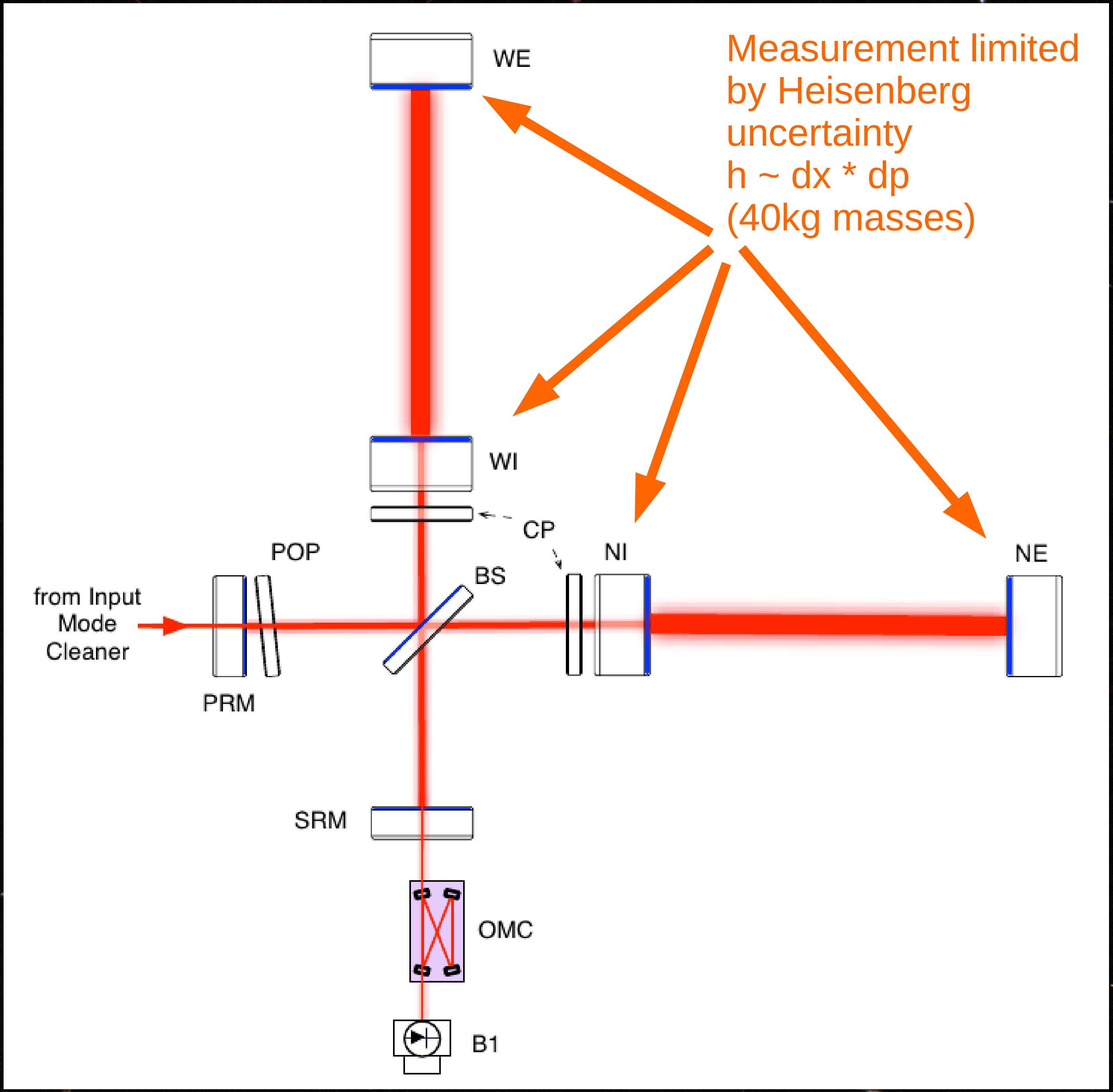

LIGO
Hanford, WA, United States


Virgo, Italy


LIGO
Livingston, LA, United States


KAGRA, Japan
池ノ山
Google


WE
WI
CP
POP
NI
NE
BS
from Input Mode Cleaner
PRM
SRM
OMC
B1

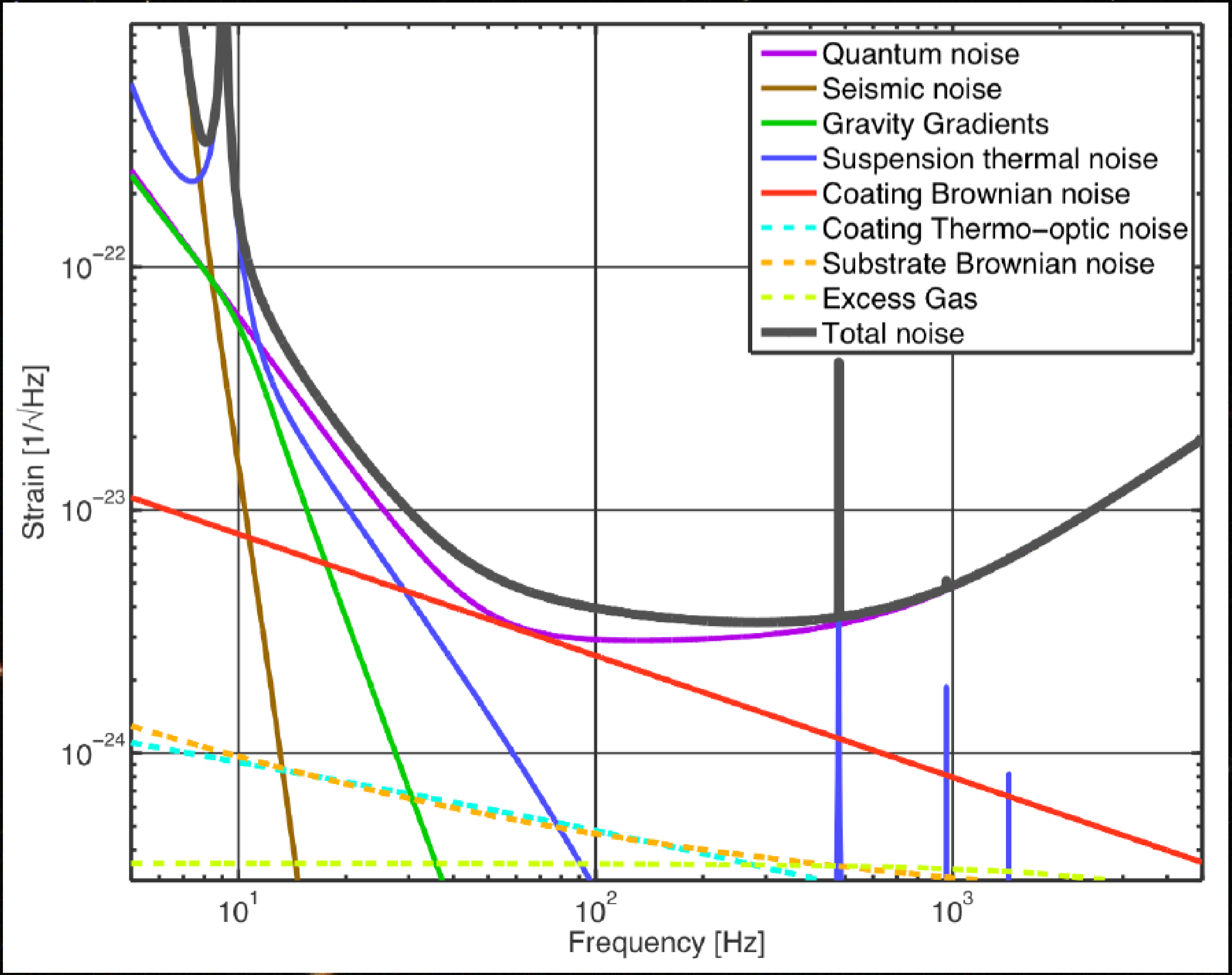


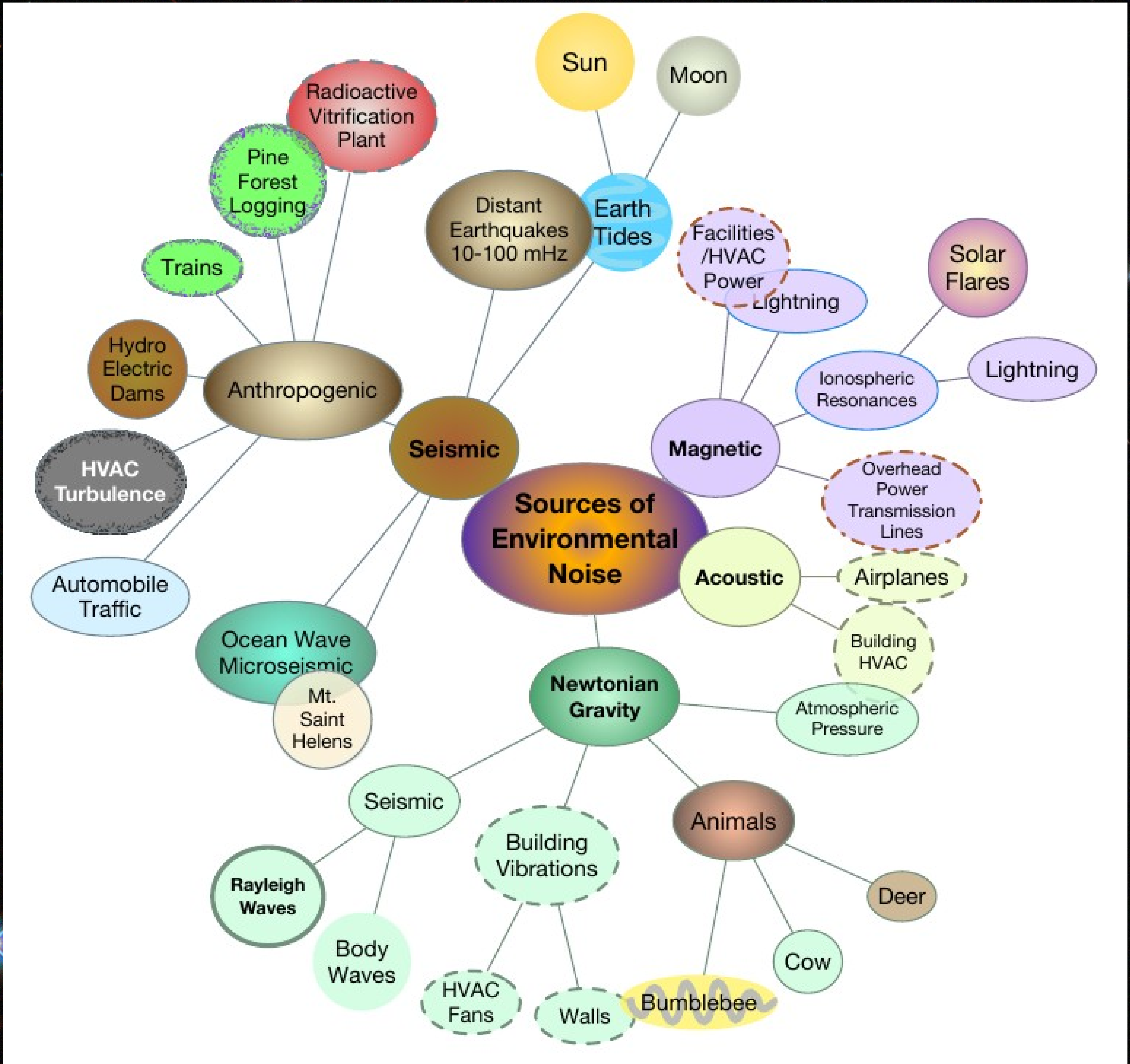
State of the art: ~10^{-20} m/rt(Hz) @ 100Hz position measurement

“2 G”

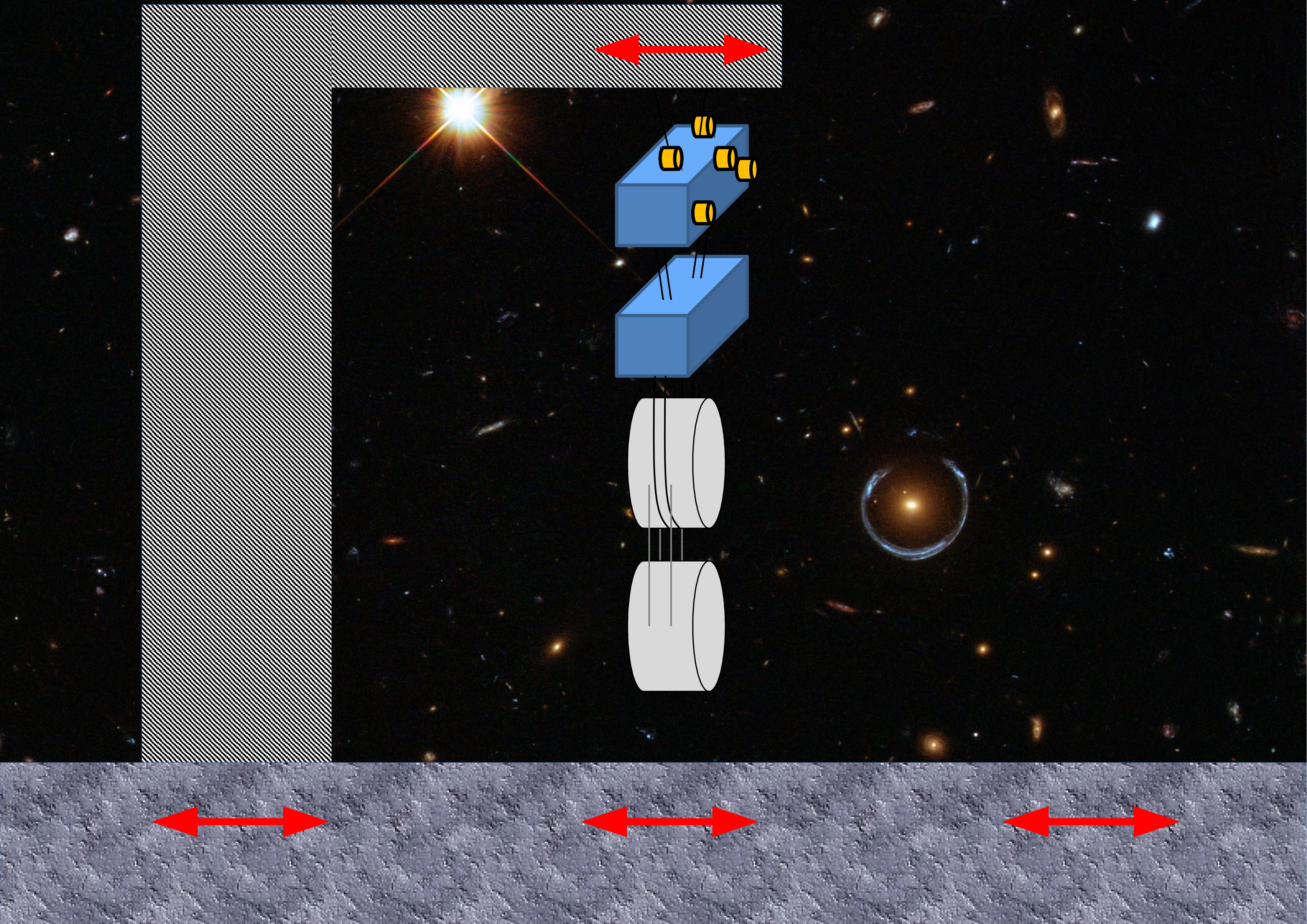
Advanced LIGO Design

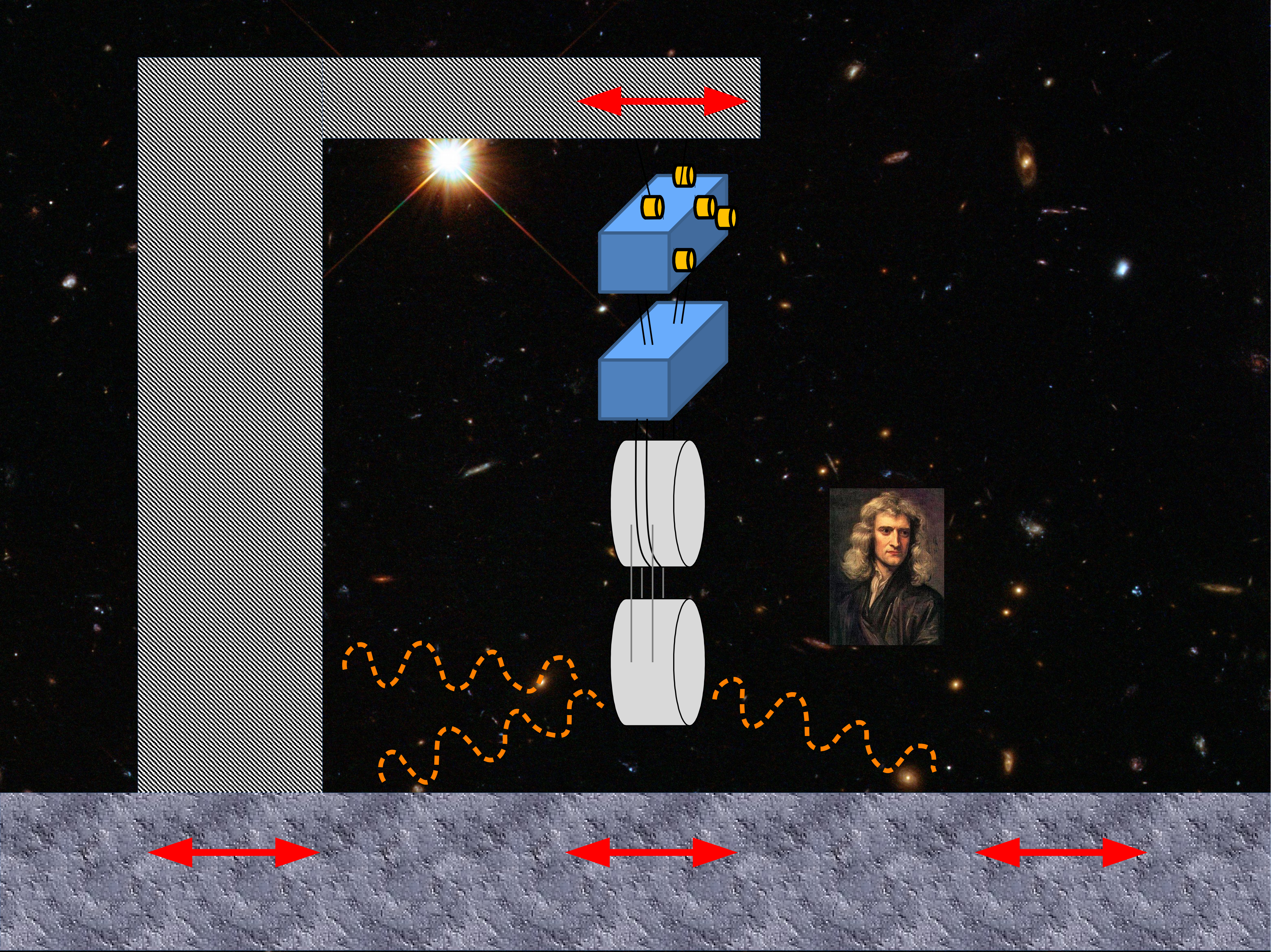
-seismic
-thermal
-quantum

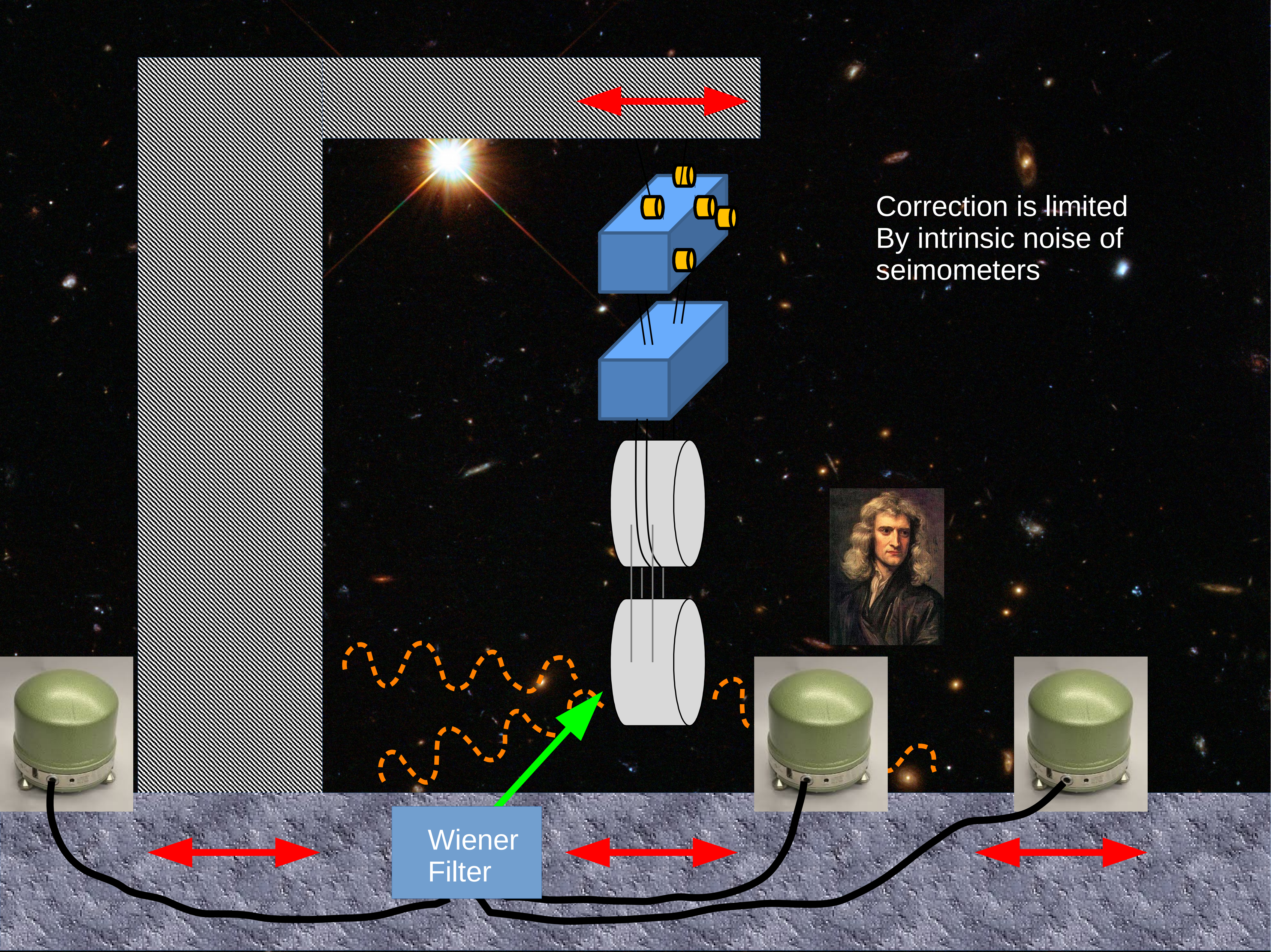


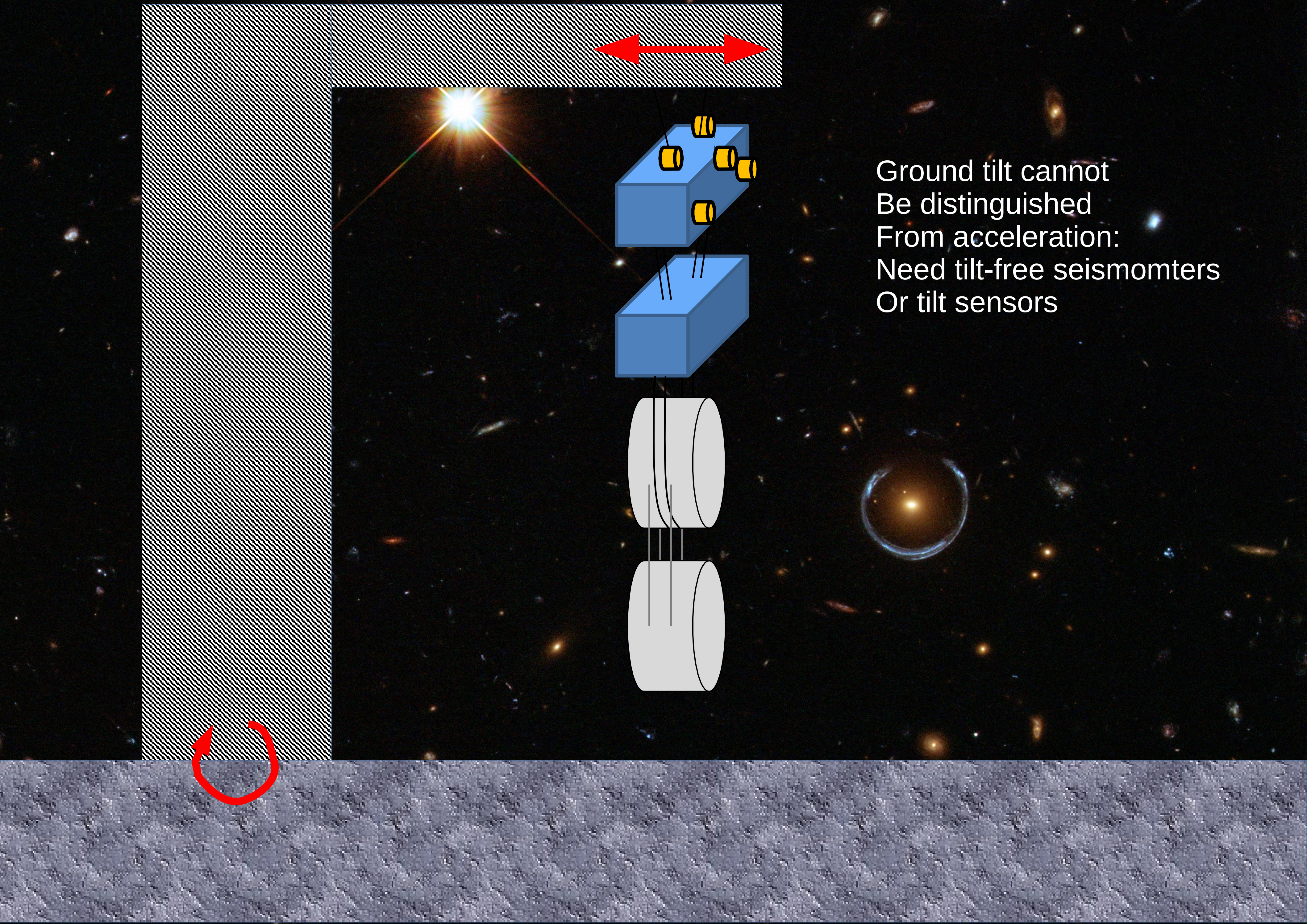

Sources of Environmental Noise
Seismic
Anthropogenic
Radioactive Vitrification Plant
Pine Forest Logging
Trains
Hydro Electric Dams
HVAC Turbulence
Automobile Traffic
Distant Earthquakes 10-100 mHz
Earth Tides
Sun
Moon
Ocean Wave Microseismic
Mt. Saint Helens
Magnetic
Facilities /HVAC Power
Lightning
Ionospheric Resonances
Solar Flares
Lightning
Overhead Power Transmission Lines
Acoustic
Airplanes
Building HVAC
Newtonian Gravity
Atmospheric Pressure
Seismic
Rayleigh Waves
Body Waves
Building Vibrations
HVAC Fans
Walls
Animals
Bumblebee
Cow
Deer

Seismic input



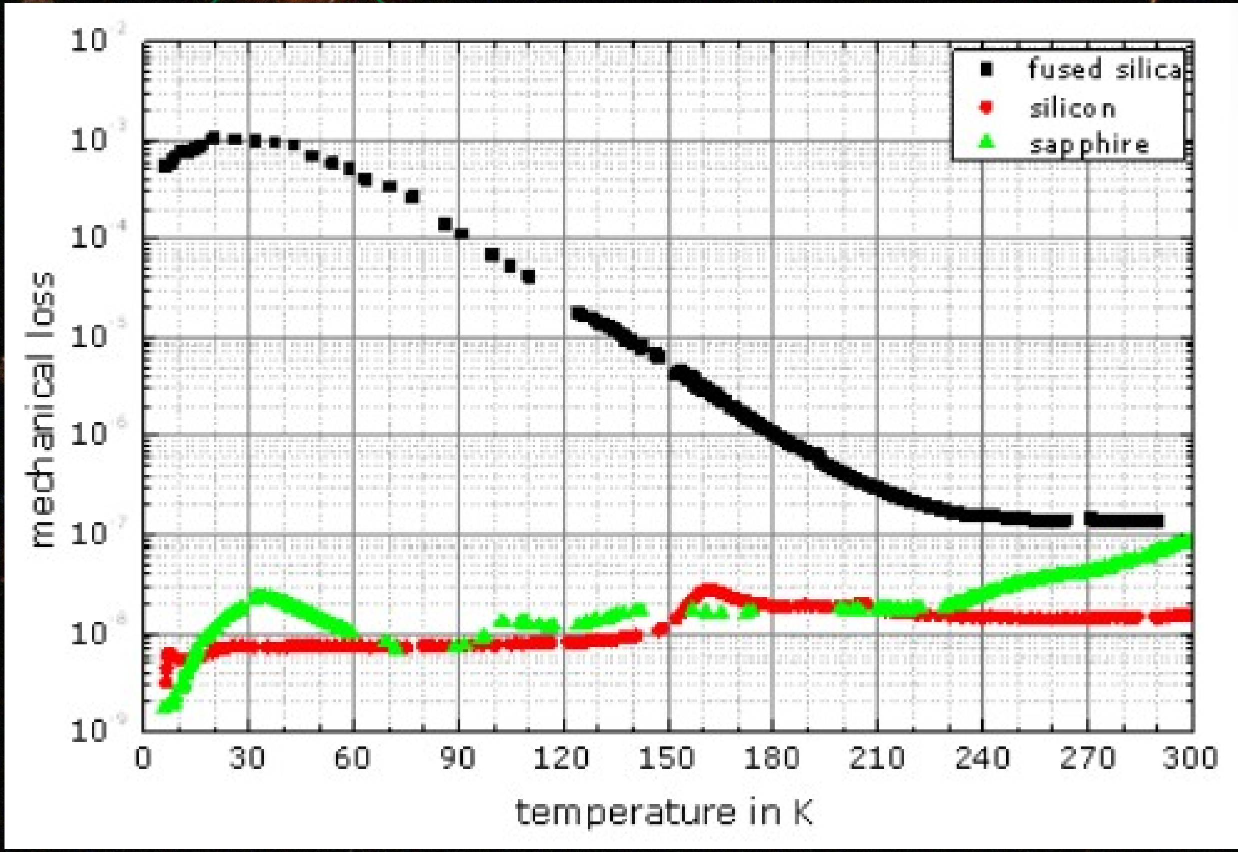



Correction is limited
By intrinsic noise of
seimometers
Wiener
Filter



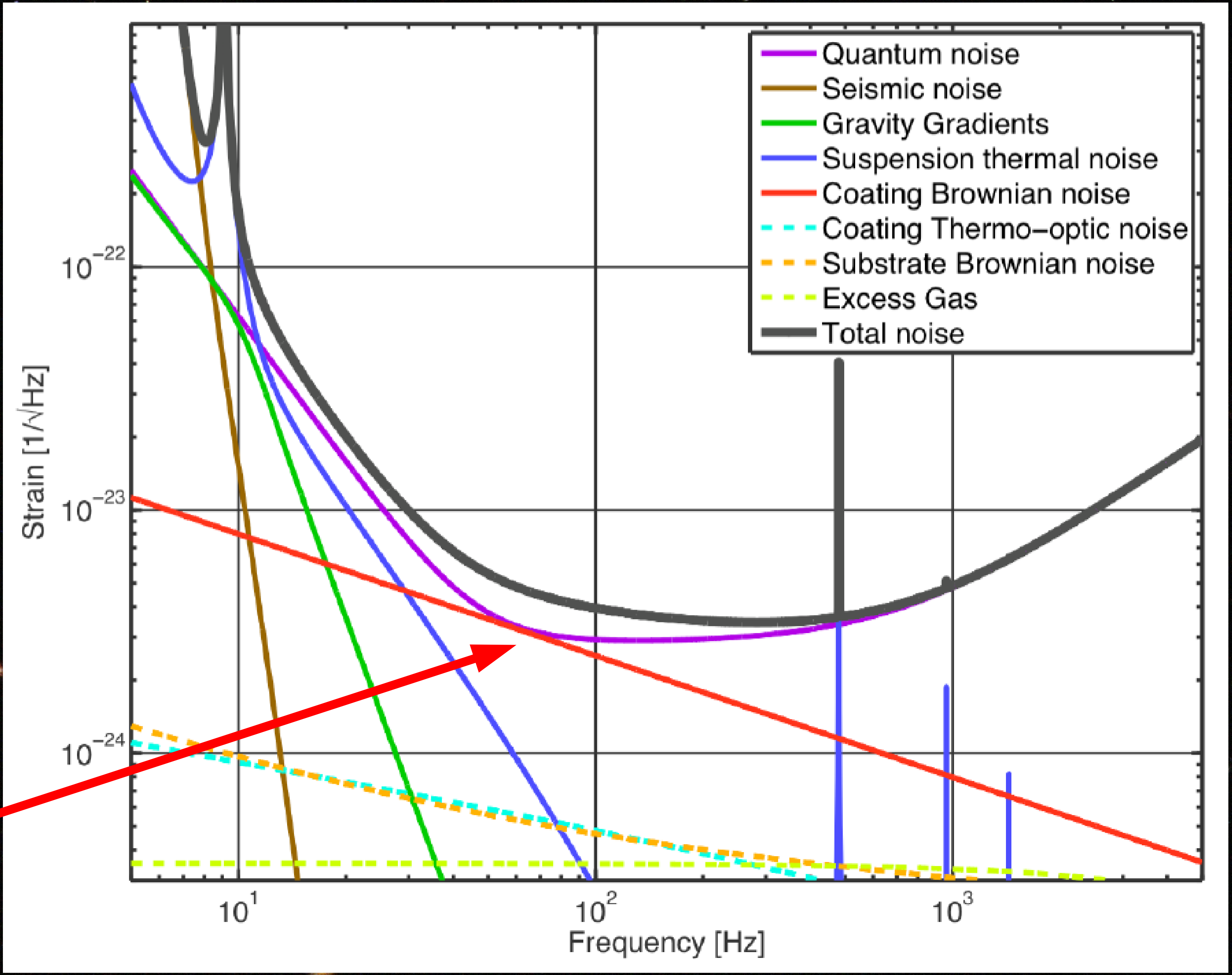
Ground tilt cannot
Be distinguished
From acceleration:
Need tilt-free seismomters
Or tilt sensors

Thermal noise



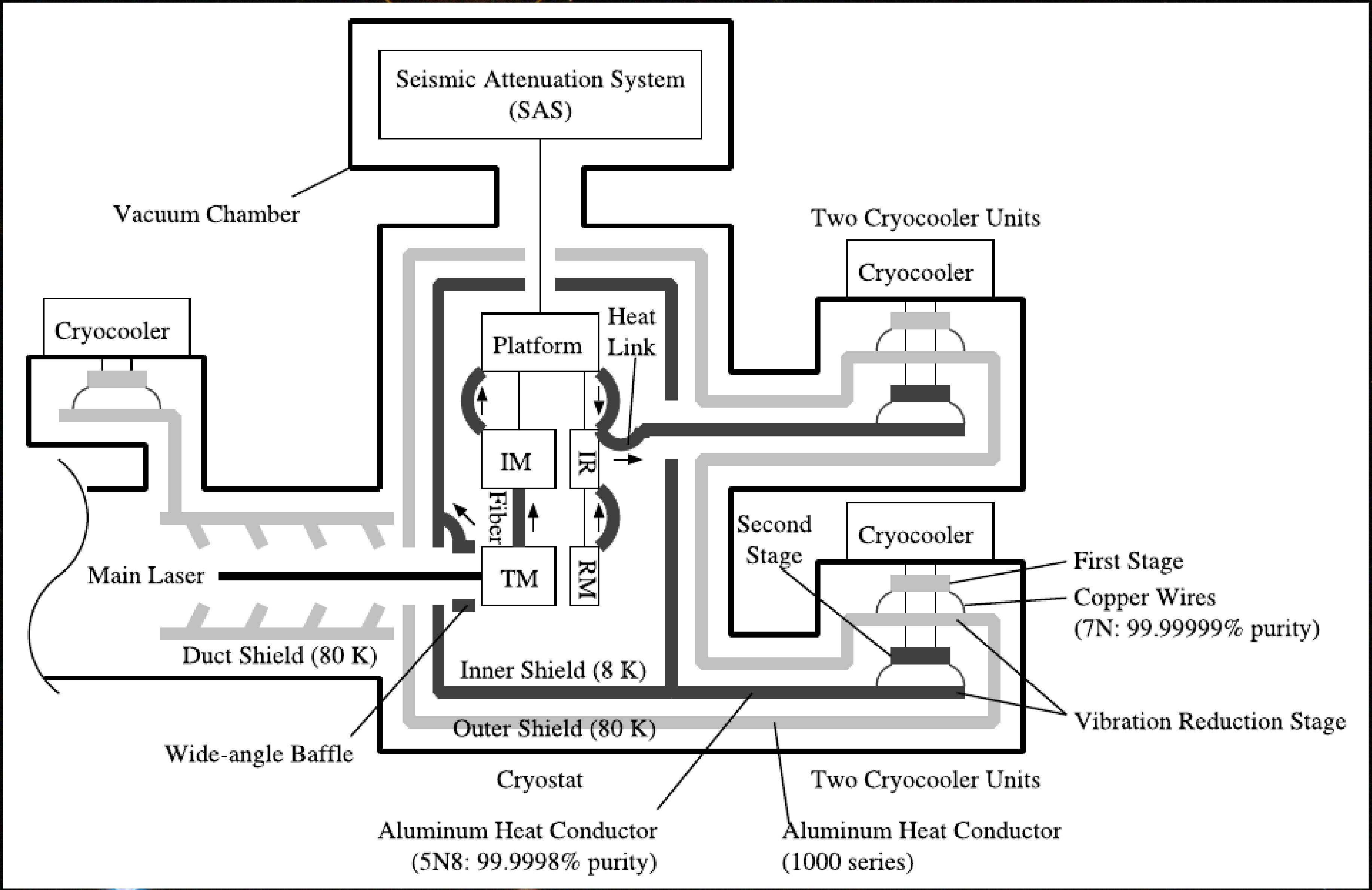
Which material for mirrors and suspension?
Silicon and Sapphire being researched

Optical Coatings Limiting: Ion-beam Sputtered Coatings With lossy High-n layers



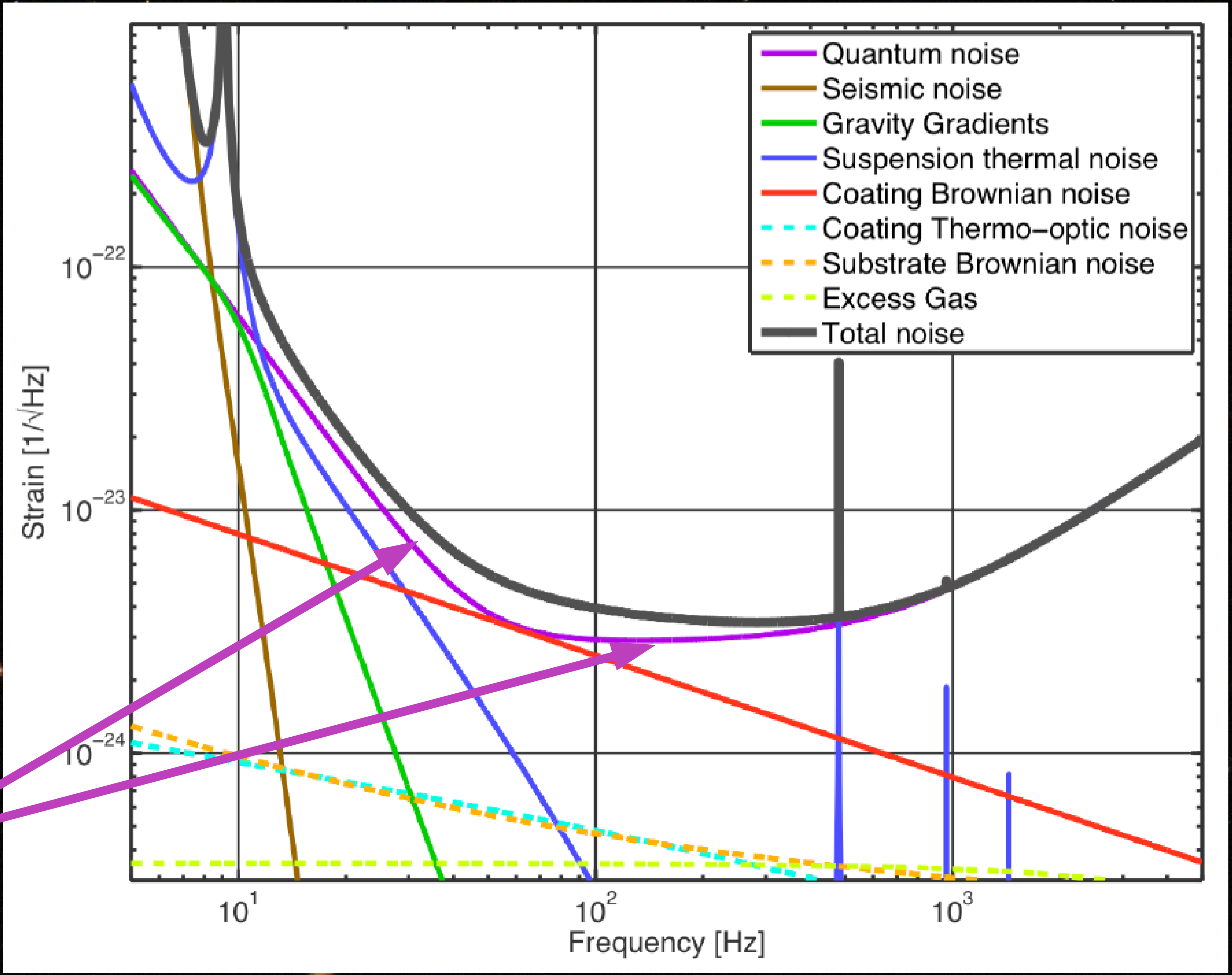
Coating reseach: low-loss high-n materials, crystaline coatings

Cooling: under way at KAGRA



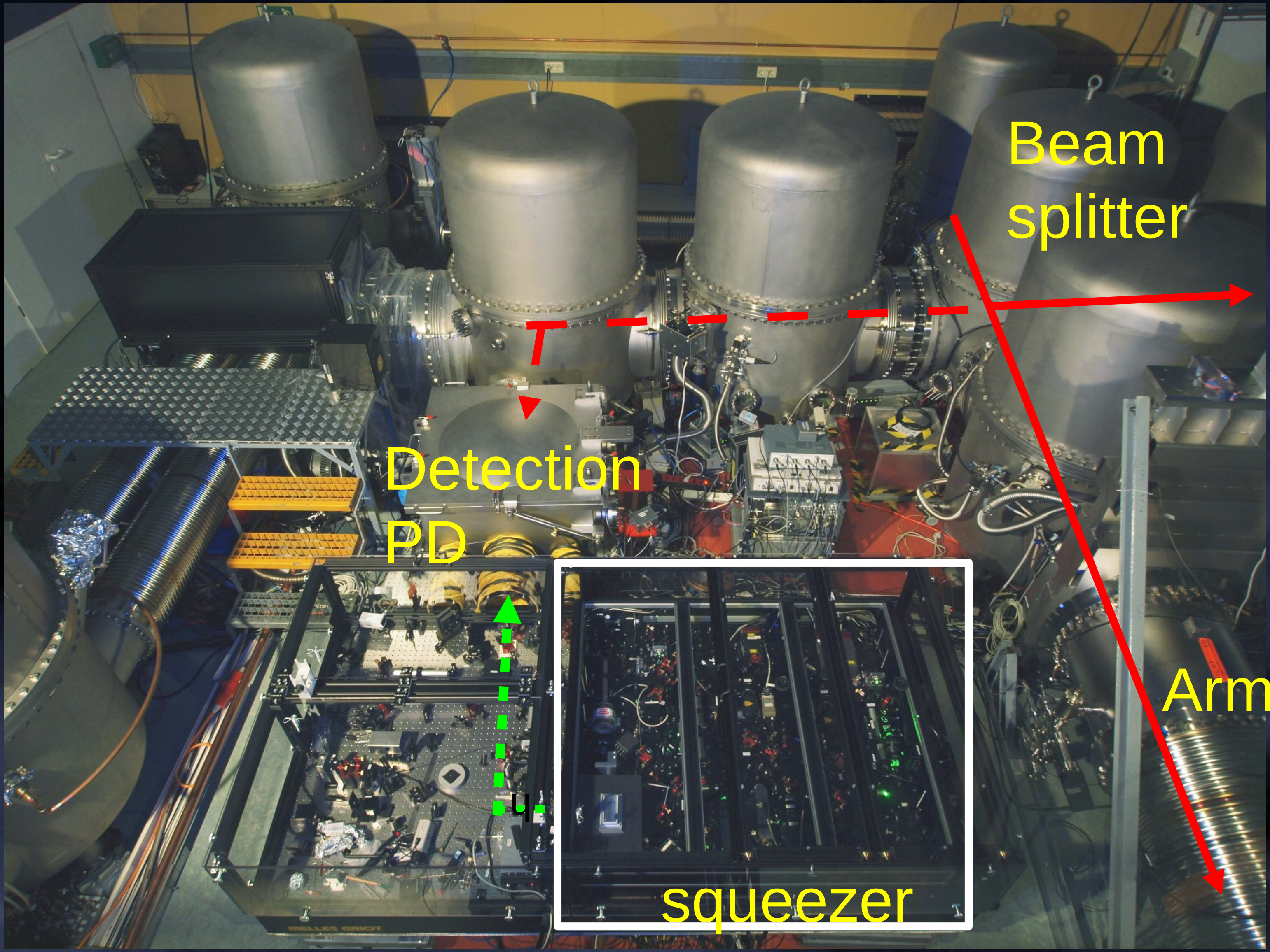
Challenging: seismic attenuation and mirror heat load
Using Sapphire mirrors

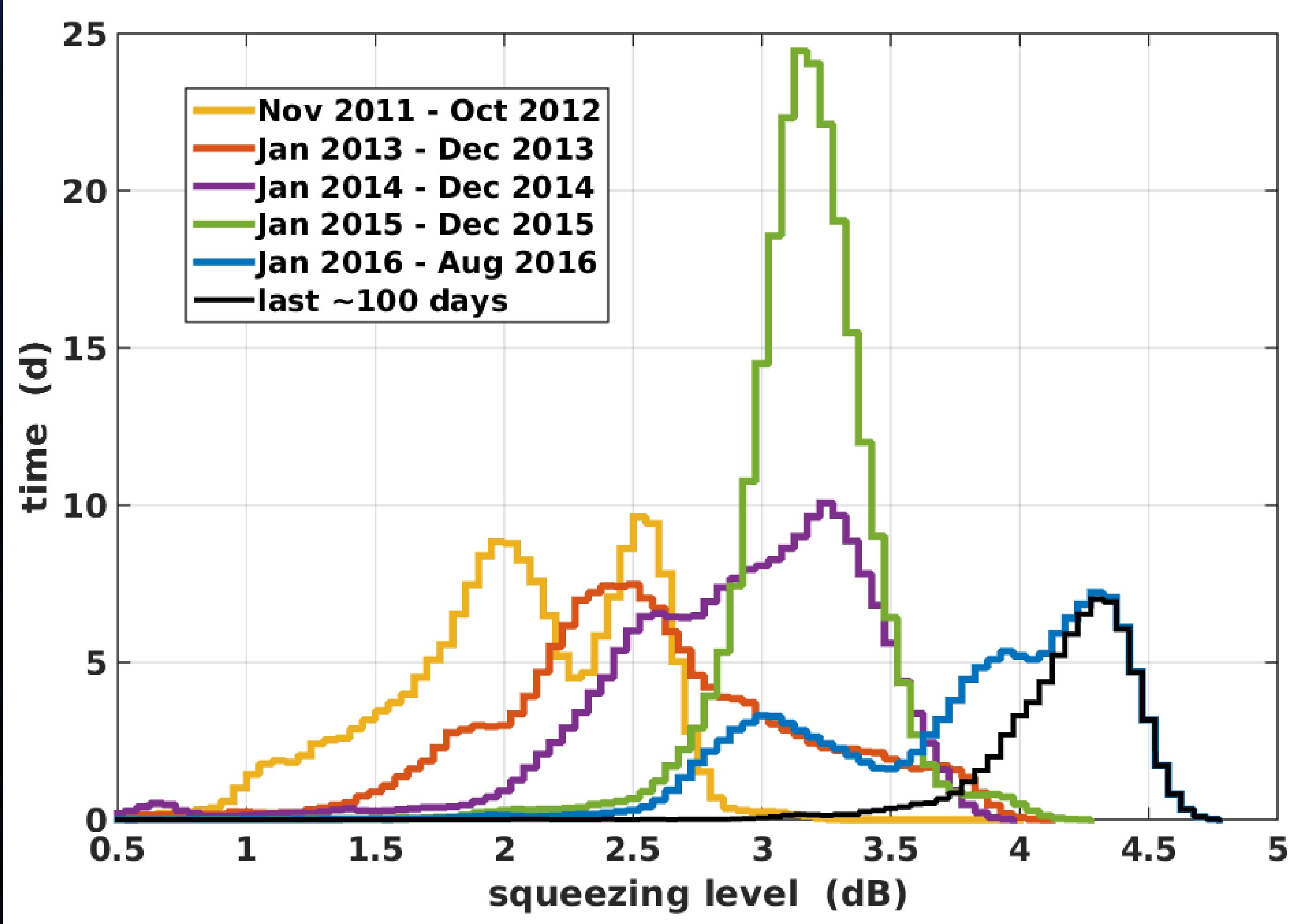
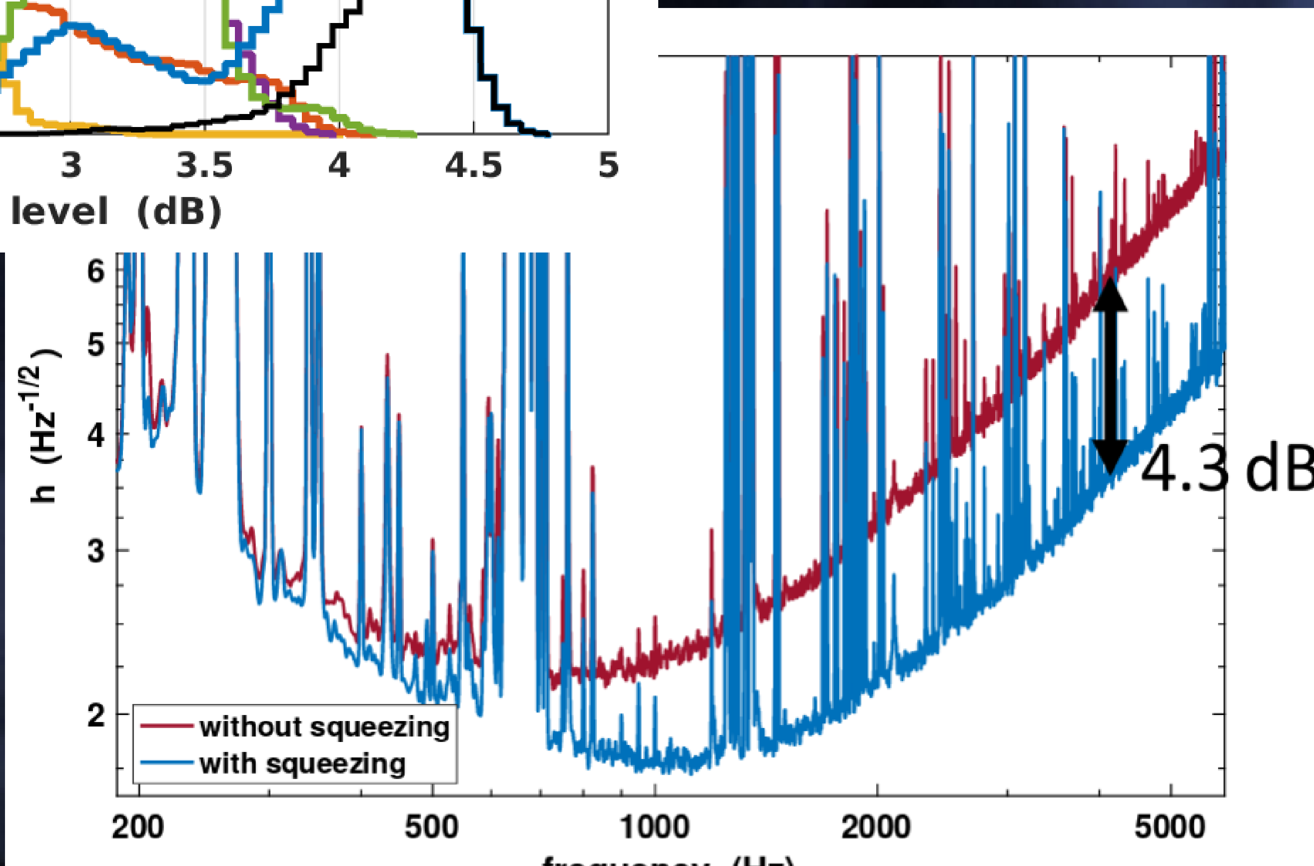
To reduce shot noise: increase laser power. Soon optimal!

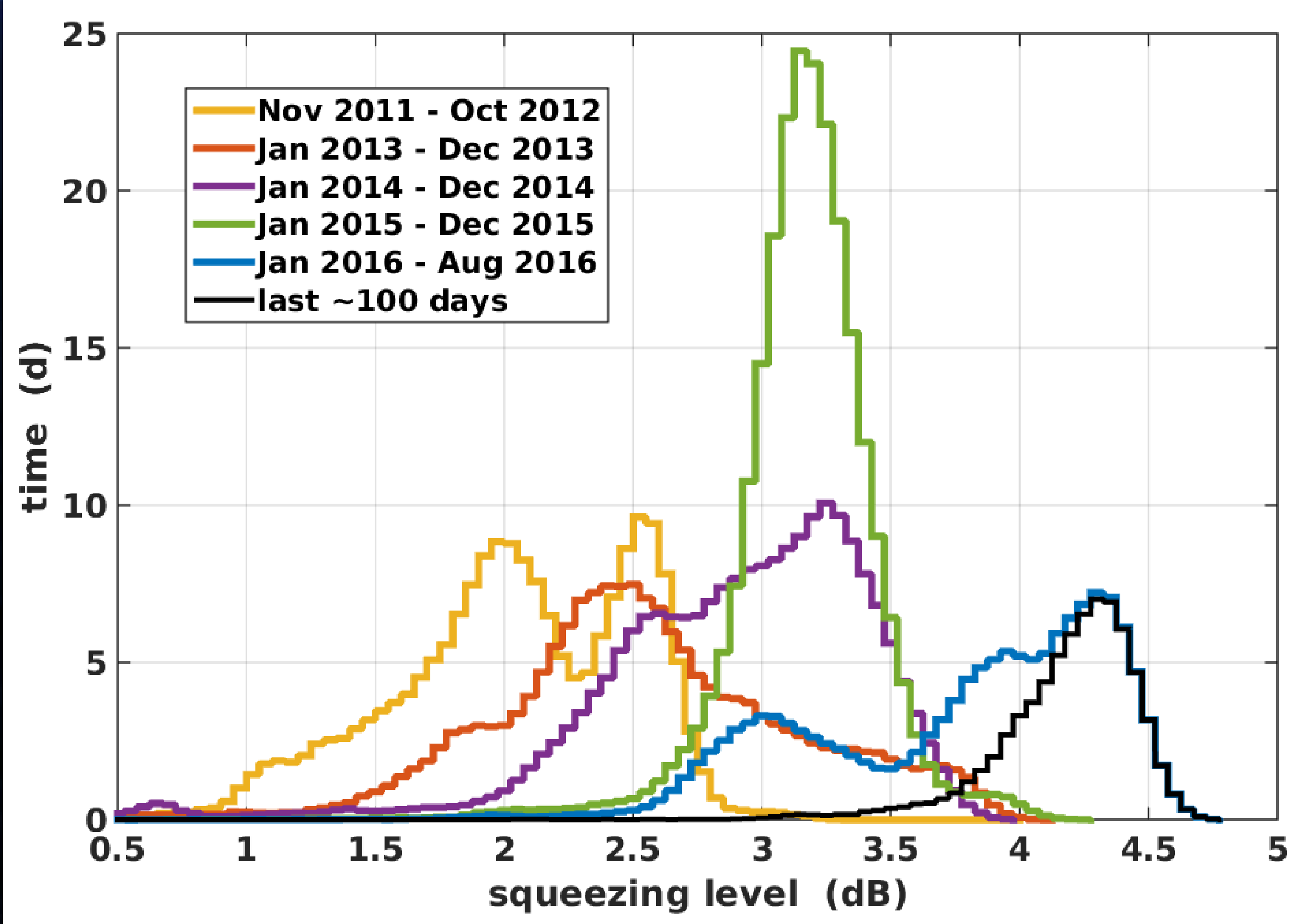


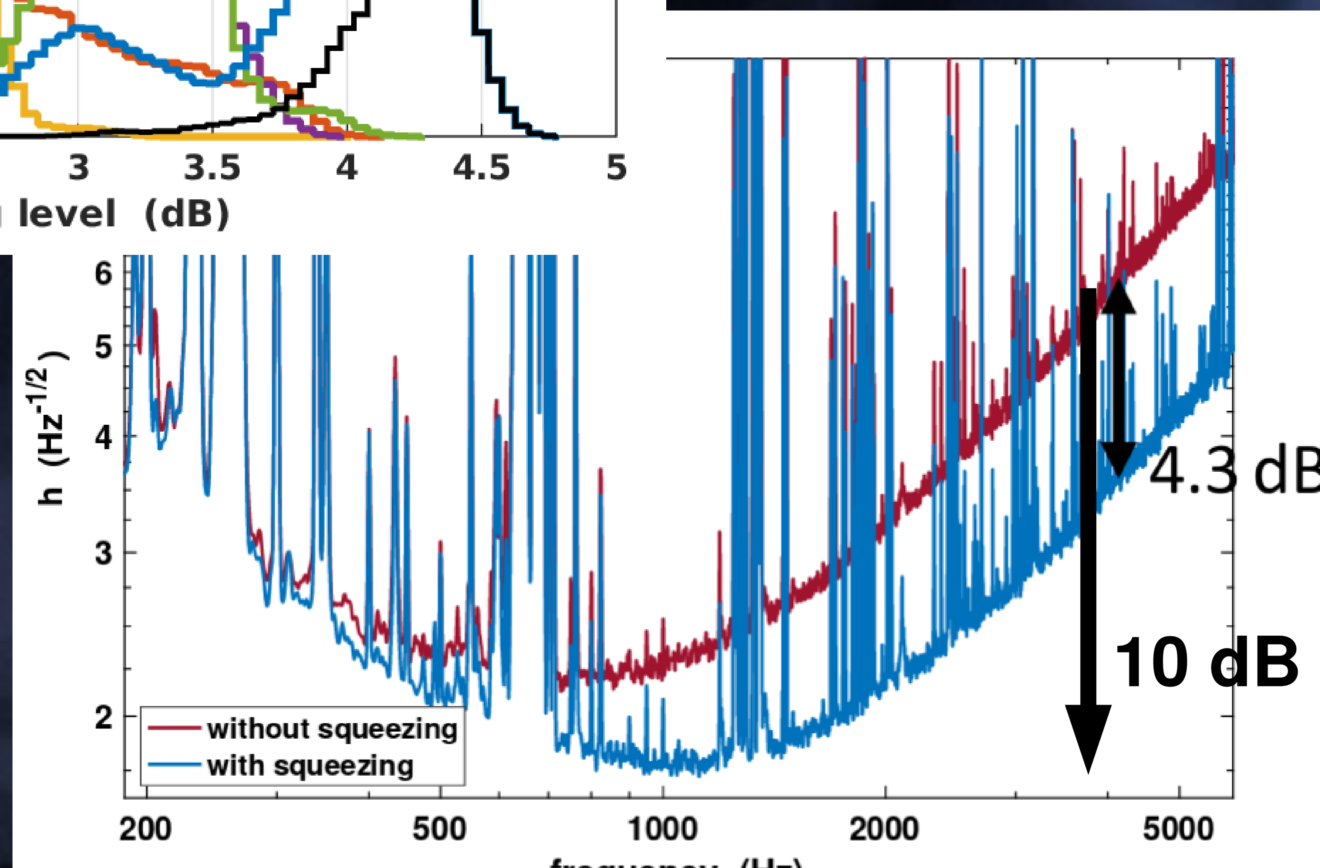
Shot noise and rad. Press. Noise: two quadratures of vacuum fluctuation
Entering the interferometer [Caves 1981]

Quantum noise reduction: Squeezing the EM-vacuum state



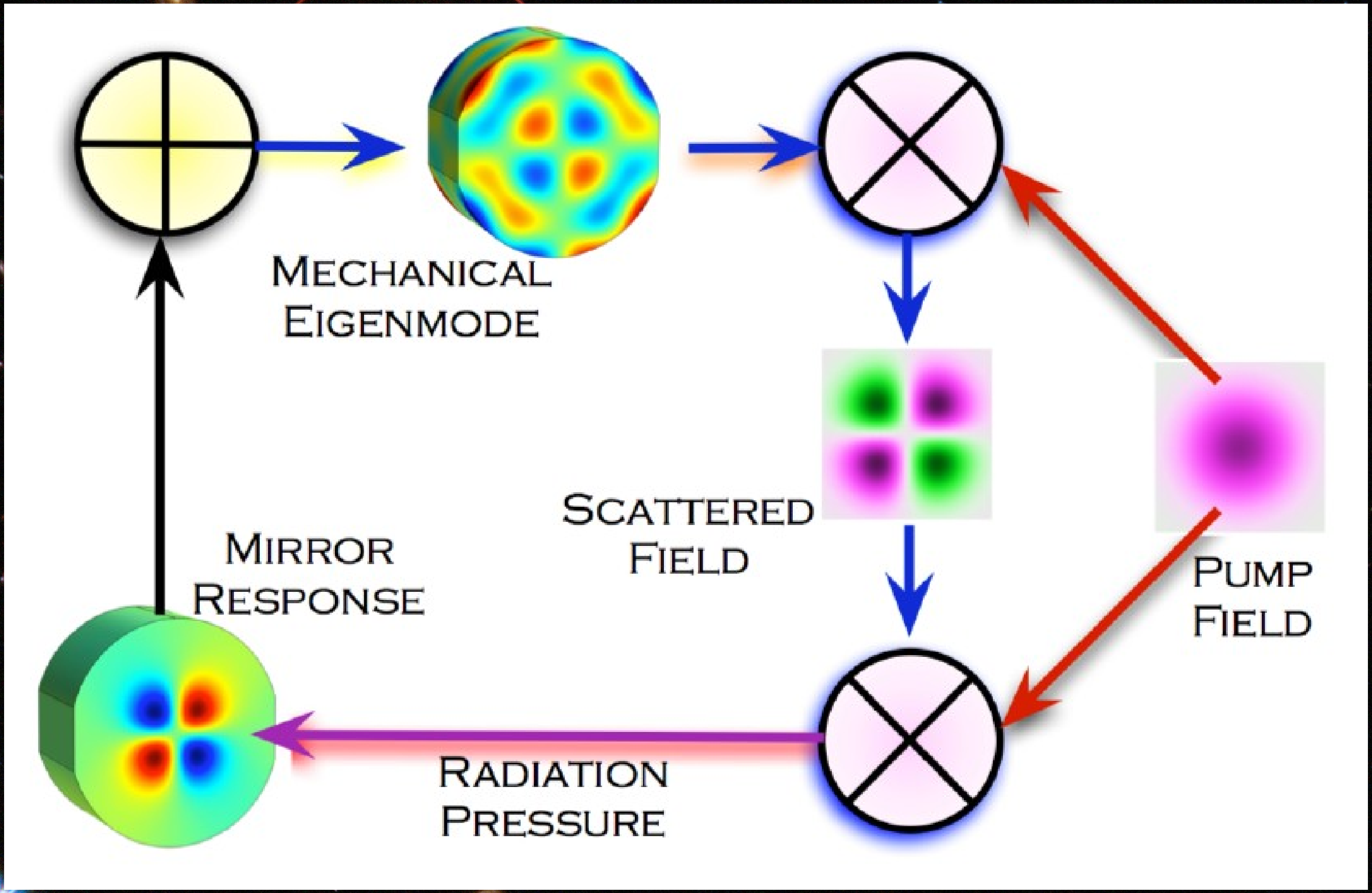

Nov 2011 - Oct 2012
Jan 2013 - Dec 2013
Jan 2014 - Dec 2014
Jan 2015 - Dec 2015
Jan 2016 - Aug 2016
last ~100 days
time (d)
squeezing level (dB)
0
5
10
15
20
25
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

h (Hz^-1/2)
without squeezing
with squeezing
4.3 dB
2
3
4
5
6
200
500
1000
2000
5000





Need lower losses
In optical path and materials

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



...a technical problem for high power operation
For now: feedback control. But perhaps not enough in the future...

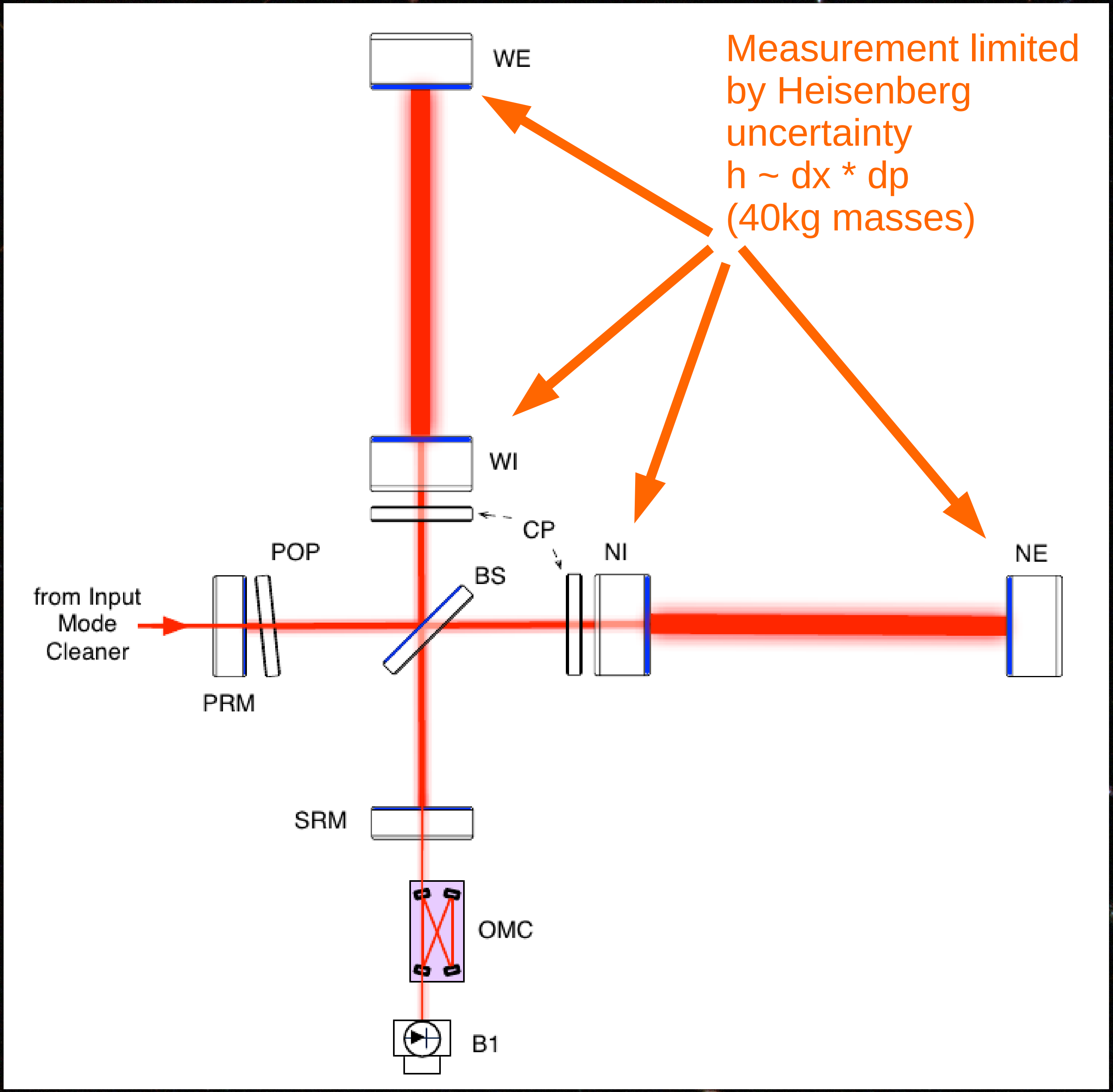
From 2G to 2G+

-Newtonia noise subtraction
-squeezing the EM vacuum (being installed in LIGO and Virgo now)
-filter cavities to squeeze rad. Pressure noise (amplitude quadrature)
-better coatings, heavier masses
-new materials and cryogenics: Silicon (120K, 10K), Sapphire (20K)

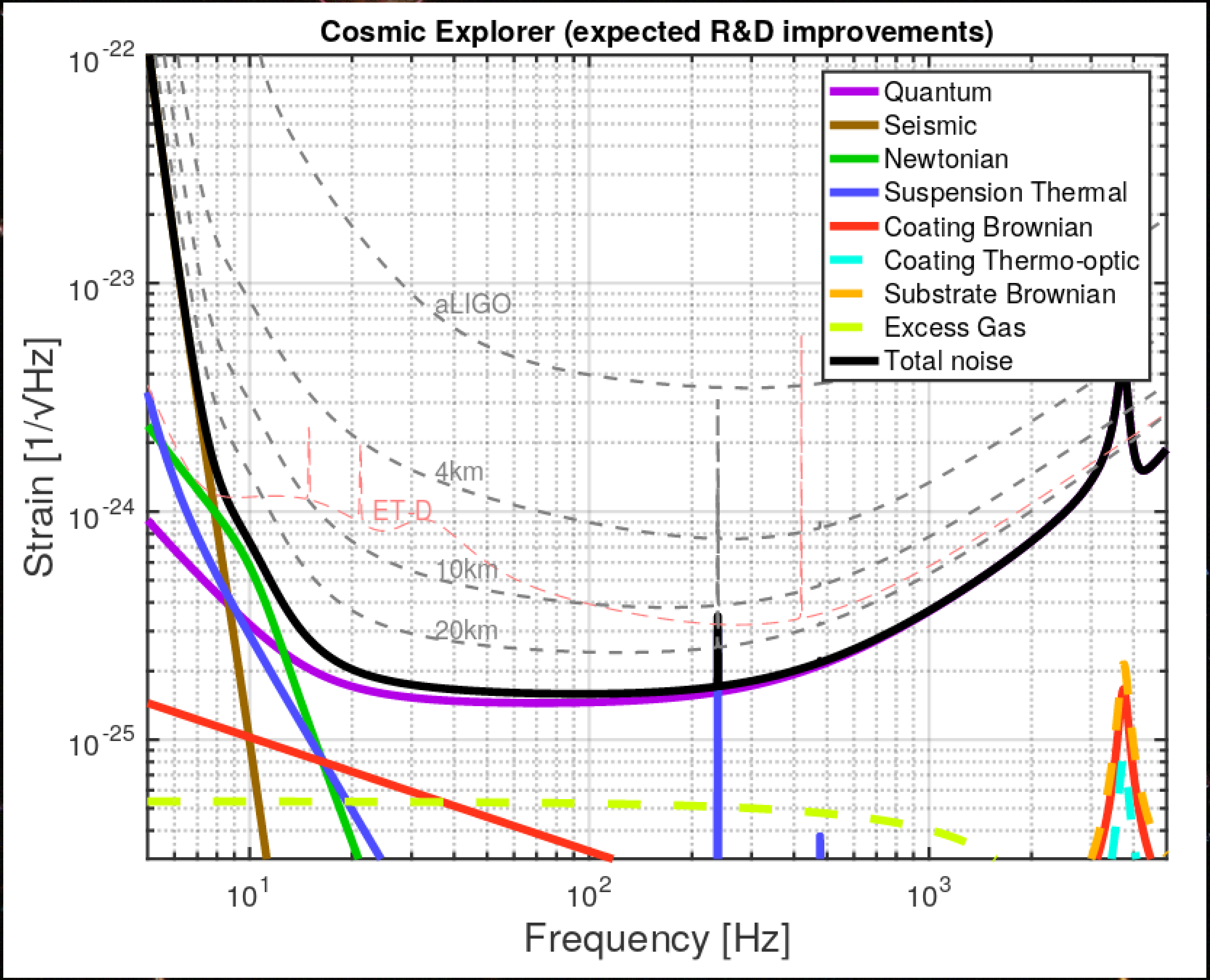
From 2G+ to 3G

-new facilities: longer arms
-heavier test masses, larger beams, longer suspensions
-new materials and cryogenics: Silicon (120K, 10K), Sapphire (20K)
-higher power lasers (500W ? → 3MW in IFO arms?)
-new topologies: speed meters

Measure speed
Not position !

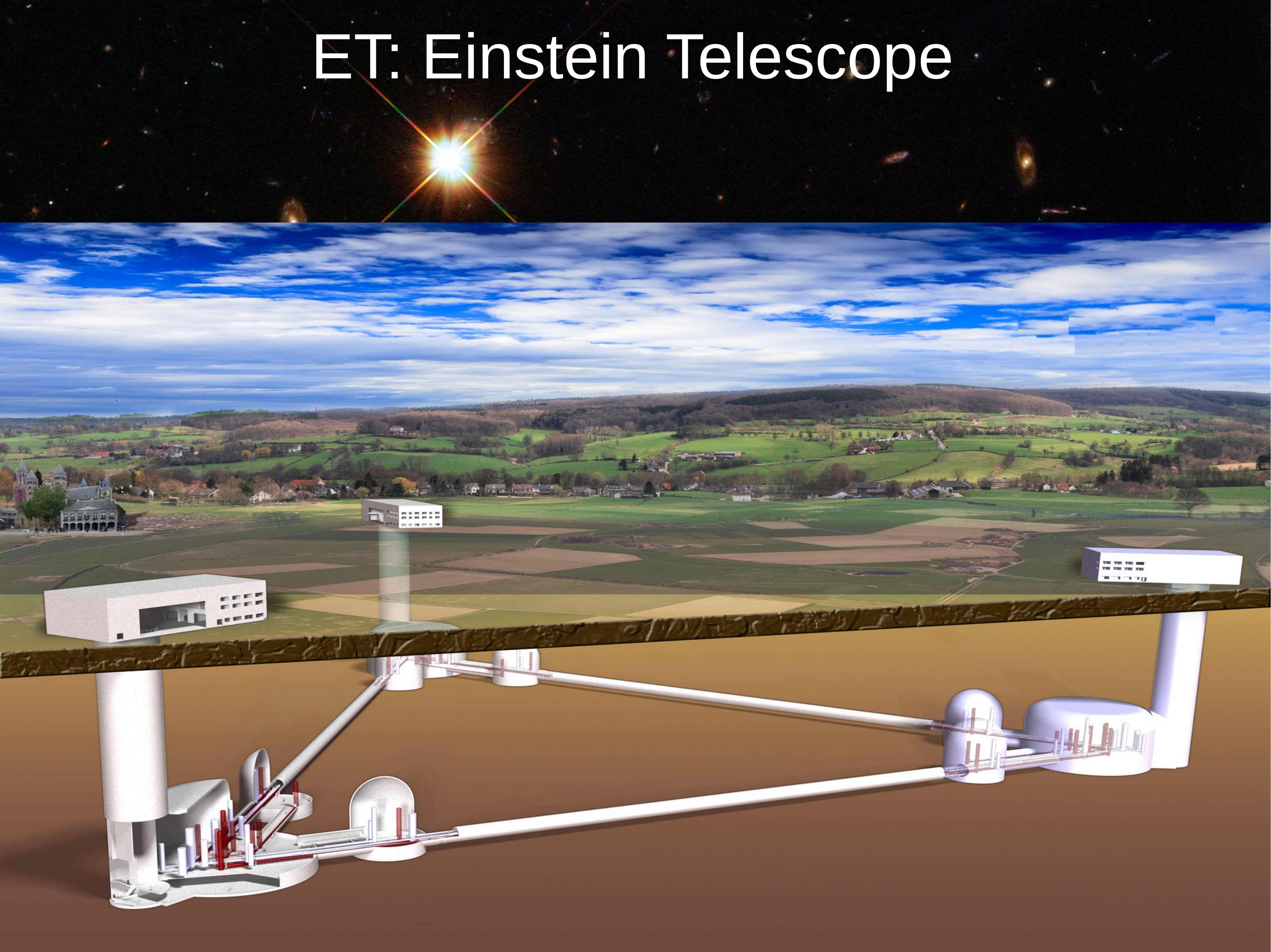


Longer arms



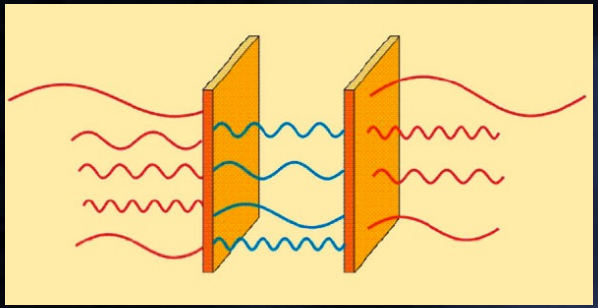
Cosmic Explorer (expected R&D improvements)
Quantum
Seismic
Newtonian
Suspension Thermal
Coating Brownian
Coating Thermo-optic
Substrate Brownian
Excess Gas
Total noise
aLIGO
4km
ET-D
10km
20km
Strain [1/√Hz]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{1}
10^{2}
10^{3}
Frequency [Hz]

ET: Einstein Telescope

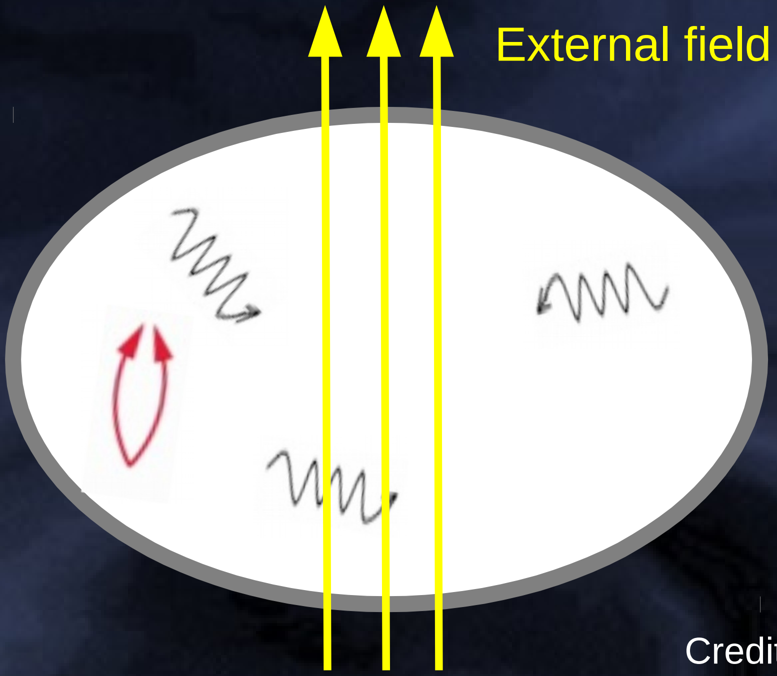


The quantum vacuum

Examples that can be associated:
-Lamb shift
-Anomalous magnetic moment of e and μ
-Casimir force (though other interpretations exist)



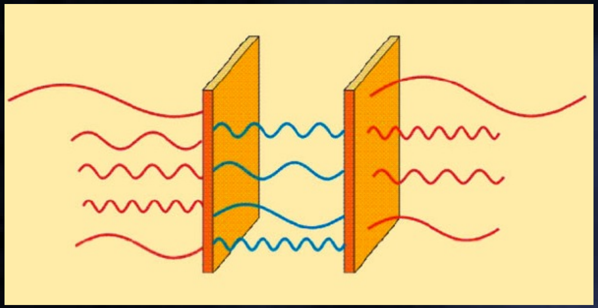
Here:
-Properties of the quantum vacuum in the presence of an external field



Credit:
G. Ruoso

The quantum vacuum

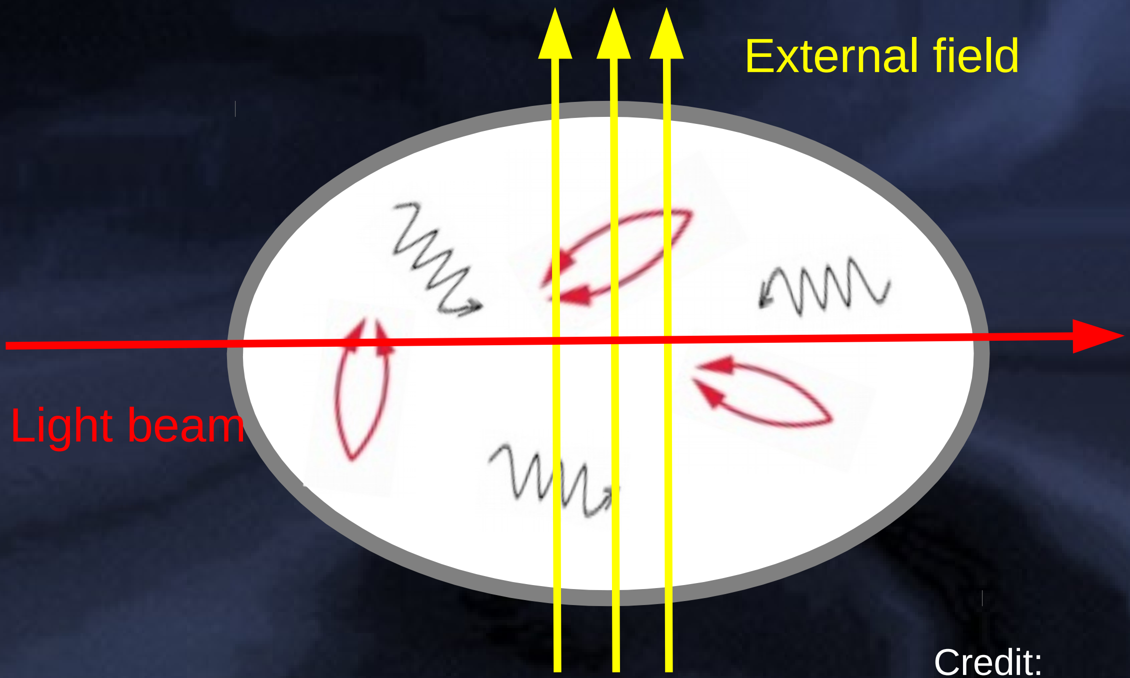
Examples:
-Lamb shift
-Anomalous magnetic moment of e and μ
-Casimir force



Here:
-Properties of the quantum vacuum in the presence of an external field

-Study with light

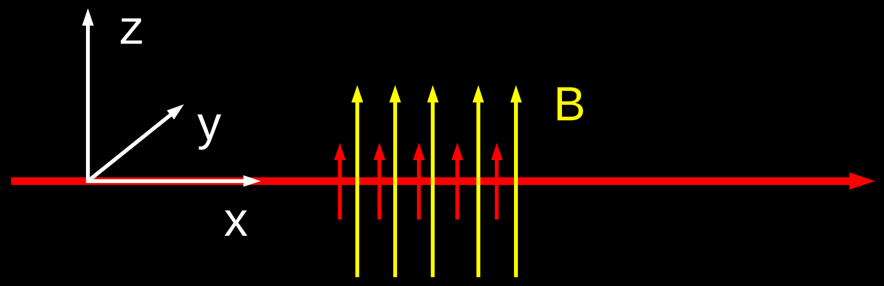
$\Delta n > 0$?



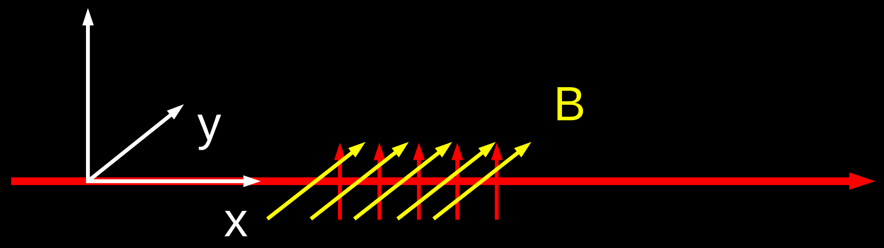
Credit:
G. Ruoso

QED Prediction

- Light slows down in vacuum in the presence of a magnetic field (perpendicular to the direction of light propagation) .



$$\Delta n_{\|} = 9.3 * 10^{-24} * B^2 [1/T^2]$$

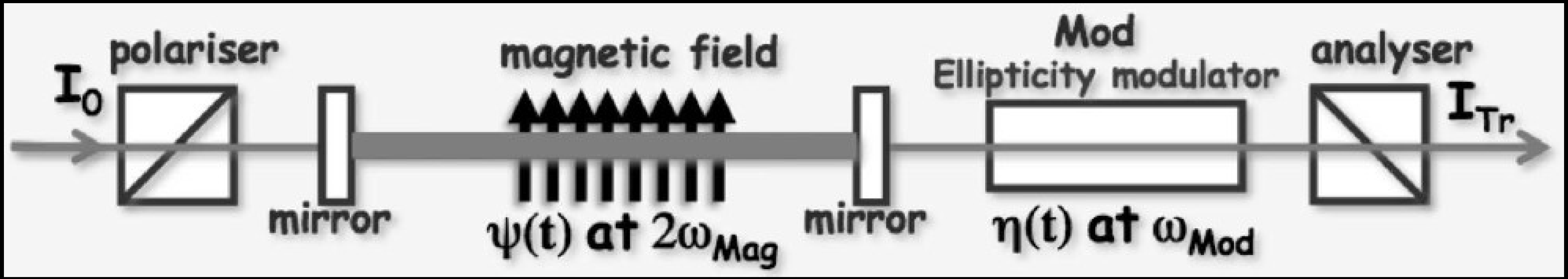


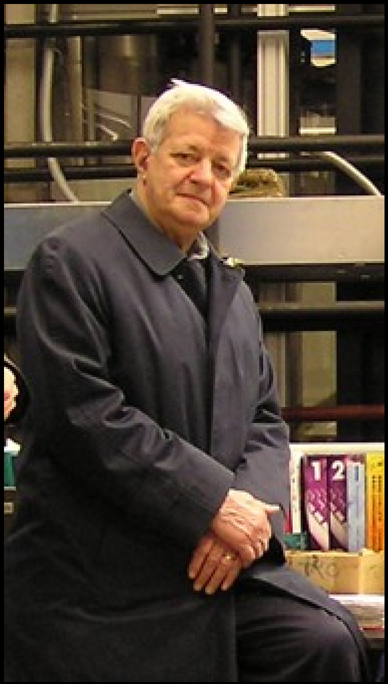
$$\Delta n_{\perp} = 5.3 * 10^{-24} * B^2 [1/T^2]$$

Vacuum is birefringent:

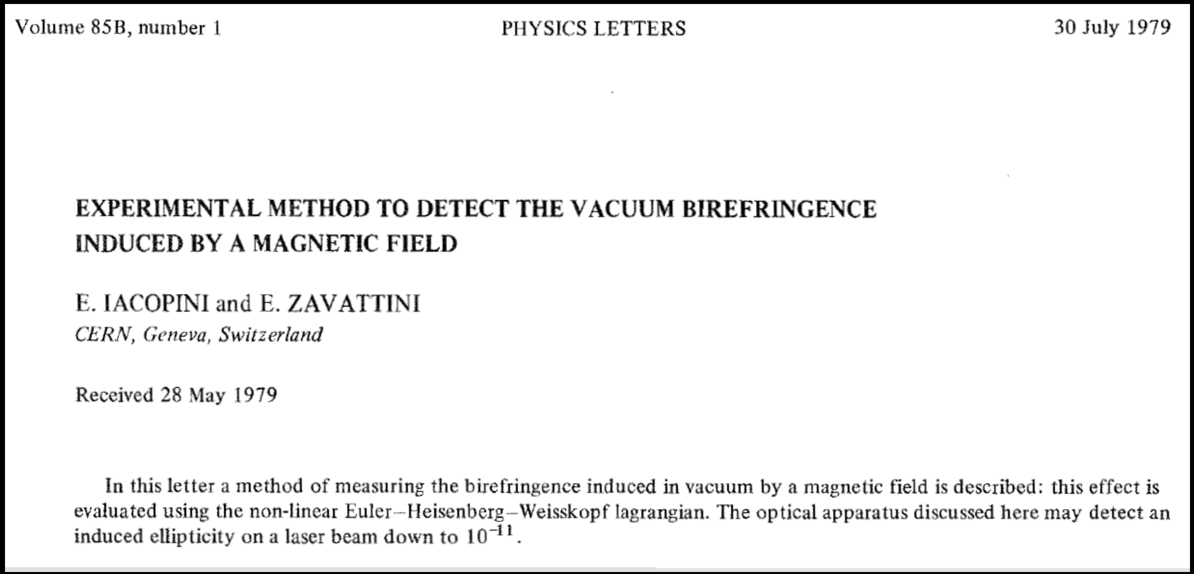
$$\Delta n_{\|-\perp} = 4 * 10^{-24} * B^2 [1/T^2]$$

Ellipsometer Method





Emilio Zavattini
(1927 -2007)



Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

EXPERIMENTAL METHOD TO DETECT THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD

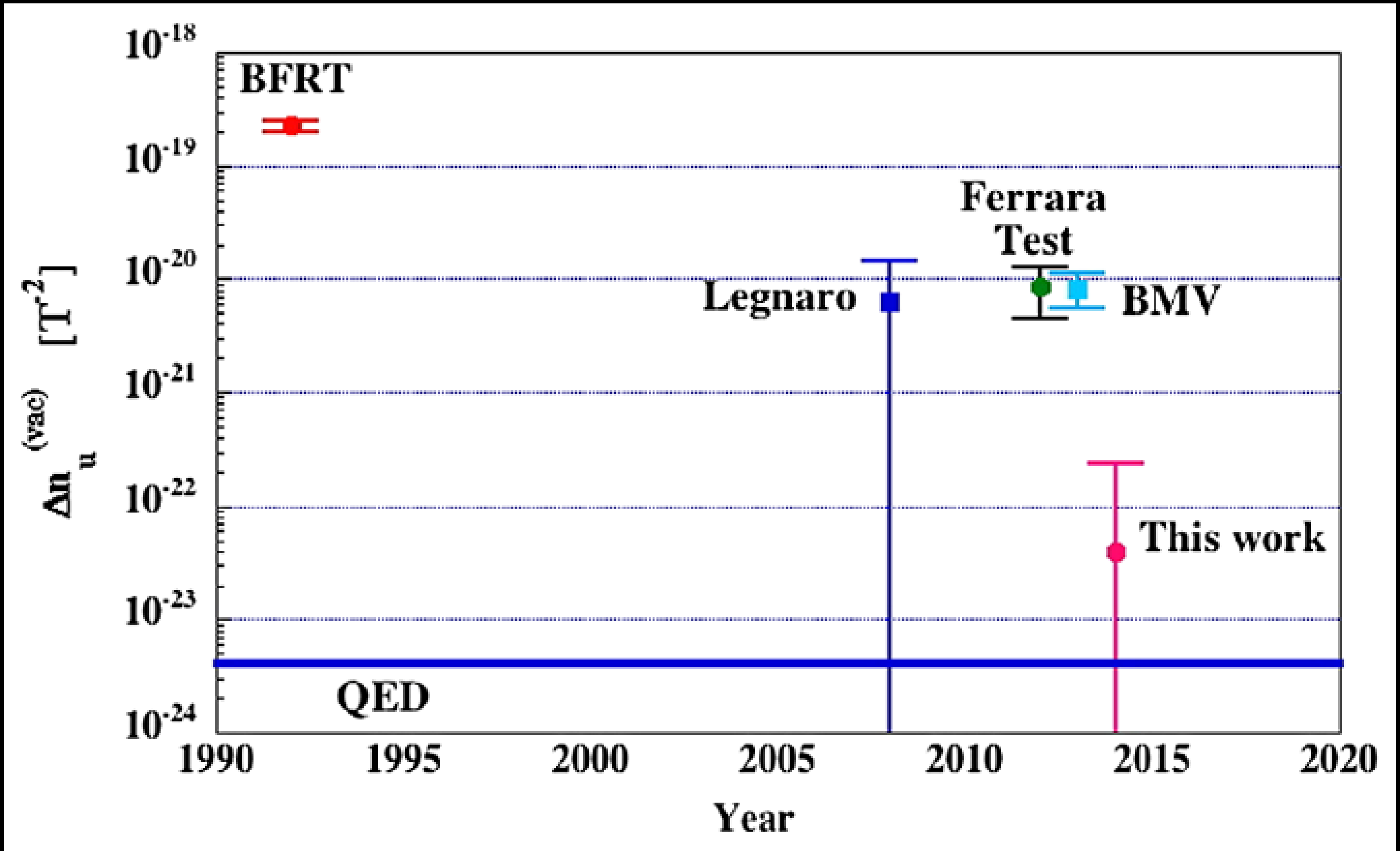
E. IACOPINI and E. ZAVATTINI
CERN, Geneva, Switzerland

Received 28 May 1979

In this letter a method of measuring the birefringence induced in vacuum by a magnetic field is described: this effect is evaluated using the non-linear Euler–Heisenberg–Weisskopf lagrangian. The optical apparatus discussed here may detect an induced ellipticity on a laser beam down to 10^{-11}.

Absolute phase shift is hard to measure, study anisotropic
Changes of refractive index instead. (birefringence, dichroism)

PVLAS: recent progress



New PVLAS
(Ferrara, It.)

Limited by currently unexplained noise:
One suspect: birefringence of mirror coatings

Field modulation vs. measurement technique

	Rotate B-field	Modulate strength of B-field
Measure polarization	PVLAS, others	BMV
Measure phase	GW detectors?	GW detectors? (Get refractive indices for par. and perp. direction independently! → More implications for particle physics)

Connection to particle physics

- Milli charged particles:
  Hypothetical particles with mass < m(e),
  ->virtual pairs at lower energy, would show up as ellipticity in addition to QED prediction
- Axions: Effective absorption of photons (due to coupling to axions) would show up as dichroism (linear polarization rotation)

1979: Proposal to use Laser Interferometers

PHYSICAL REVIEW D VOLUME 19, NUMBER 8 15 APRIL 1979

Testability of nonlinear electrodynamics

A. M. Grassi Strini, G. Strini, and G. Tagliaferri
Institute of Physical Sciences of the University and Sezione dell'I.N.F.N.,20133 Milano, Italy

(Received 21 April 1978; revised manuscript received 9 November 1978)

Laser interferometry combined with present-day electronic techniques now make it possible to test nonlinear-electrodynamics predictions in the weak-field limit, up to a sensitivity of 10^{-23} in the relative variation of the velocity of light. The significance of such tests in regard to QED predictions is noted.

I. INTRODUCTION

In the past, nonlinear equations for electromagnetism have often been proposed, on the basis of theoretical motivations of a widely varying nature. Such proposed nonlinearities are either intrinsic or represent the interaction with other fields such as, for instance, the effects of vacuum polarization deriving from the interaction of the electromagnetic field with the electronic field. However, as far as experimental confirmation is concerned, there is a nearly total lack of direct information because the theoretically anticipated nonlinearities are exceedingly small.

The purpose of the present paper is to suggest that the progress in instrumentation and experimental techniques in recent years now makes it

equations predicted by QED should be o some testable case. For clarity, we pr report the procedure followed rather th stating the resulting figures.

The equations of electromagnetism m the inclusion of nonlinear terms read[1]

$$\nabla \times \vec{E} + \frac{1}{c}\dot{\vec{B}} = 0, \quad \nabla \times \vec{H} - \frac{1}{c}\dot{\vec{D}} = 0,$$

$$\nabla \cdot \vec{B} = 0, \quad \nabla \cdot \vec{D} = 0,$$

$$\vec{D} = \vec{E} + \gamma[\alpha(E^2 - B^2)\vec{E} + \beta(\vec{B}\cdot\vec{E})\vec{B}],$$

$$\vec{H} = \vec{B} + \gamma[\alpha(E^2 - B^2)\vec{B} - \beta(\vec{B}\cdot\vec{E})\vec{E}],$$

where all symbols conform to common the coefficients α, β, γ have the followin QED:

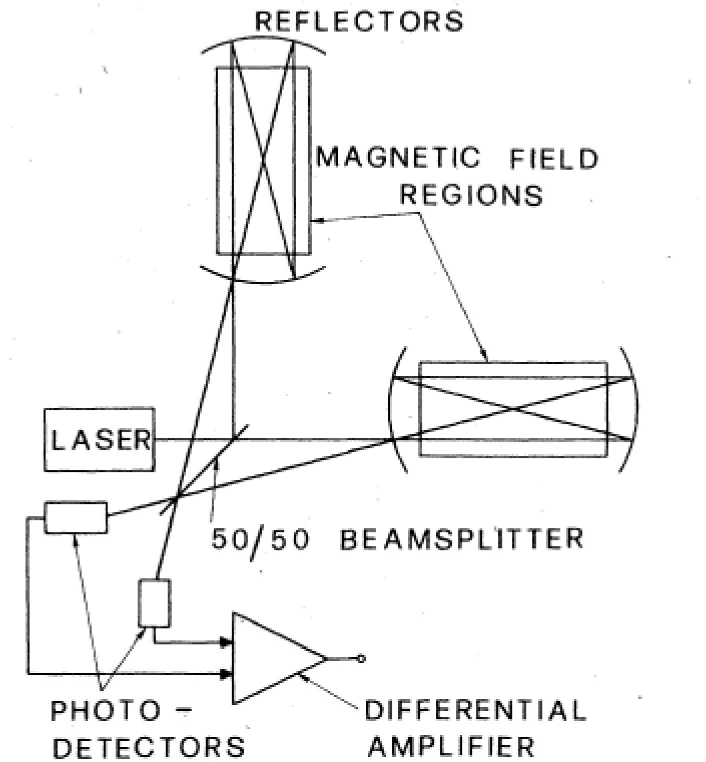


FIG. 1. Sketch of laser interferometer with magnetic field perturbation.

2002: Proposal to use GW detectors.

hep-ph/0204207
NIKHEF/2002-001

Exploring the QED vacuum with laser interferometers

Daniël Boer[1] and Jan-Willem van Holten[1,2]

[1] *Division of Physics and Astronomy, Vrije Universiteit, De Boelelaan 1081 NL-1081 HV Amsterdam, The Netherlands*

[2] *NIKHEF, P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands*

February 1, 2008

It is demonstrated that the nonlinear, and as yet unobserved, QED effect of slowing down light by application of a strong magnetic field may be observable with large laser interferometers like for instance LIGO or GEO600.

12.20.Fv, 07.60.Ly, 41.20.Jb, 42.25.Lc, 41.25.Bs, 95.75.Kk

-too optimistic in assuming possible increase in sensitivity with increasing cavity Finesse
-neglecting possible integration of signal over time

2009: Virgo / Electro-Magnets

Eur. Phys. J. C (2009) 62: 459–466
DOI 10.1140/epjc/s10052-009-1079-y

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Probing for new physics and detecting non-linear vacuum QED effects using gravitational wave interferometer antennas

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-pointing out new physics potential

2009: LIGO/GEO Pulsed Magnets

A Letters Journal Exploring the Frontiers of Physics

July 2009

EPL, **87** (2009) 21002
www.epljournal.org
doi: 10.1209/0295-5075/87/21002

Interferometry of light propagation in pulsed fields

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PACS 12.20.Fv – Quantum electrodynamics: Experimental tests
PACS 14.80.-j – Other particles (including hypothetical)

Abstract – We investigate the use of ground-based gravitational-wave interferometers for studies of the strong-field domain of QED. Interferometric measurements of phase velocity shifts induced by quantum fluctuations in magnetic fields can become a sensitive probe for nonlinear self-interactions among macroscopic electromagnetic fields. We identify pulsed magnets as a suitable strong-field source, since their pulse frequency can be matched perfectly with the domain of highest sensitivity of gravitational-wave interferometers. If these interferometers reach their future sensitivity goals, not only strong-field QED phenomena can be discovered but also further parameter space of hypothetical hidden-sector particles will be accessible.

-assumes aperture of O~cm

2015: Feasibility / Magnet design

PHYSICAL REVIEW D **91,** 022002 (2015)

On the possibility of vacuum QED measurements with gravitational wave detectors

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(Received 17 September 2014; published 7 January 2015)

Quantum electrodynamics (QED) comprises virtual particle production and thus gives rise to a refractive index of the vacuum larger than unity in the presence of a magnetic field. This predicted effect has not been measured to date, even after considerable effort of a number of experiments. It has been proposed by other authors to possibly use gravitational wave detectors for such vacuum QED measurements, and we give this proposal some new consideration in this paper. In particular, we look at possible source field magnet designs and further constraints on the implementation at a gravitational wave detector. We conclude that such an experiment seems to be feasible with permanent magnets, yet still challenging in its implementation.

DOI: 10.1103/PhysRevD.91.022002 PACS numbers: 04.80.Nn, 42.50.Xa, 95.55.Ym, 95.75.Kk

I. INTRODUCTION

Corrections to the Maxwell equations that emerge from the quantum properties of the vacuum have been proposed many decades ago; see, e.g., [1]. Quantum electrodynamics

All of the ongoing experiments make use of the difference $\Delta n_{\parallel - \perp}$ of the predicted refractive index changes for different angles of the magnetic field with respect to the polarization direction of the light; i.e., they attempt to

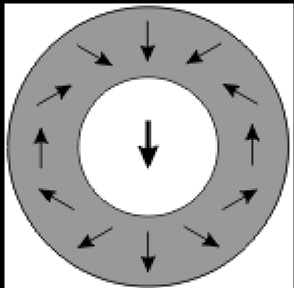
Integration time for sinusoidal signal

$$t_{SNR=1} = \left(\frac{\tilde{n}(f)}{S_{RMS,\|}} \right)^2$$

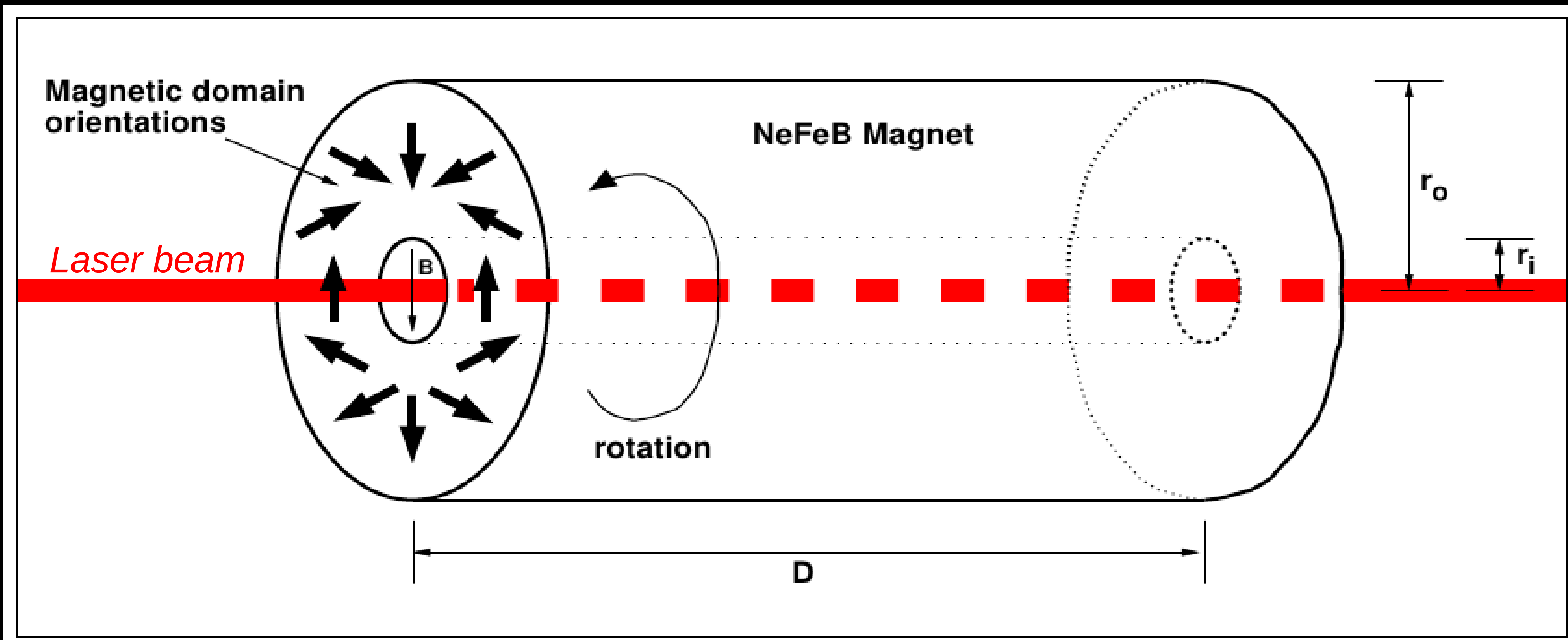
Displacement noise
Ampl. spectral density

Displacement signal

$$S_{\|} = \Delta n_{\|} \times D = 9.3 \times 10^{-24} \times B^2 [\frac{1}{T^2}] \times D$$



Magnet as Halbach Cylinder



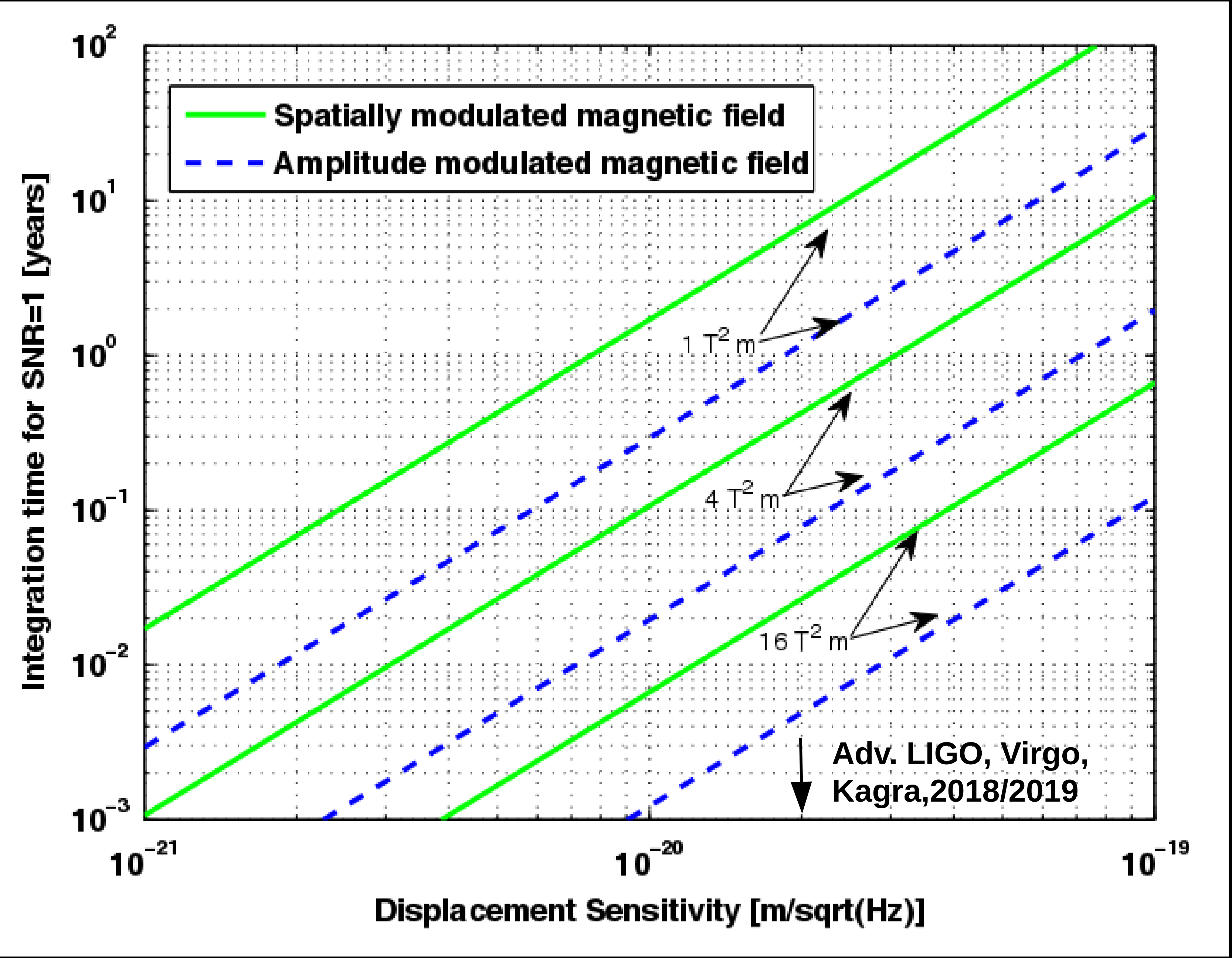
$B = Br * \ln(ro/ri)$

$Br \sim 1.3T$ for NeFeB

Example: B = 1.0T for ro=121mm, ri=55mm → m=328kg for D=1.2m

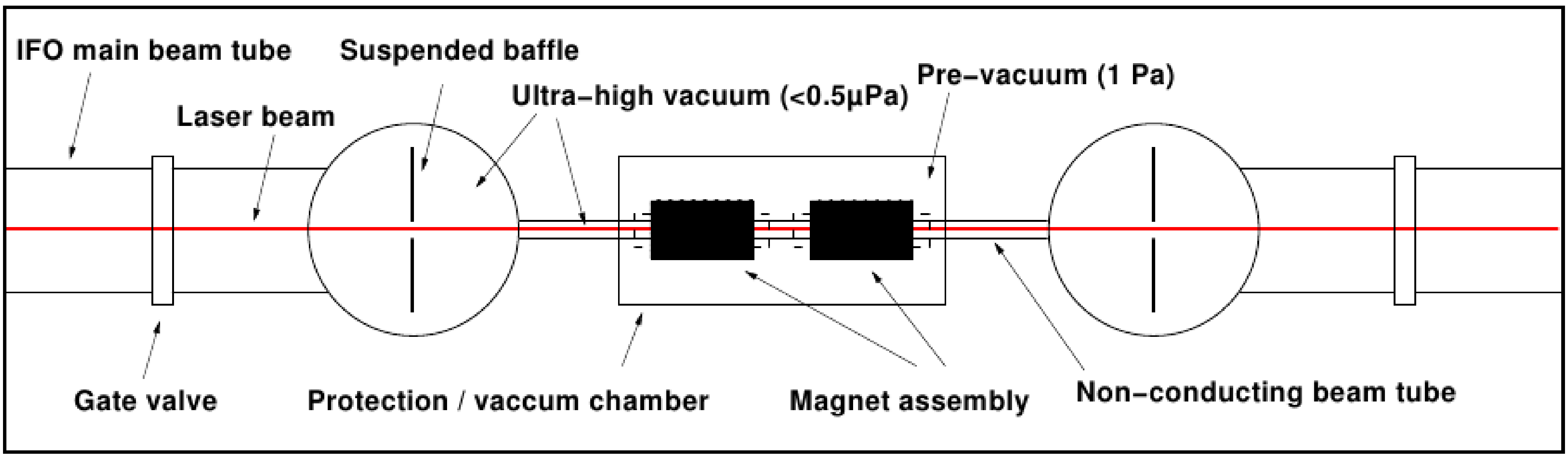
NeFeB: 150$ / kg → 50k$ / Magnet

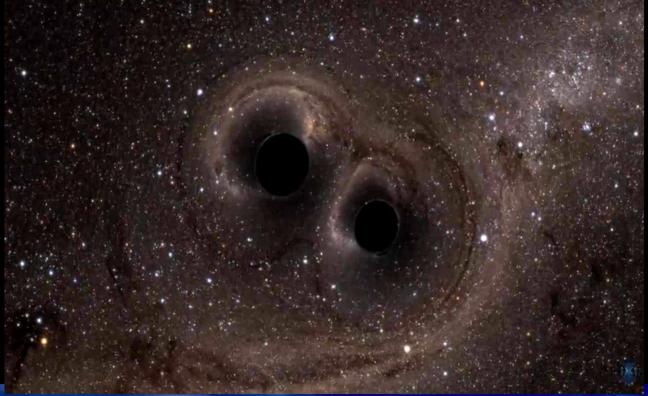
Measurement time as function of displacement sensitivity



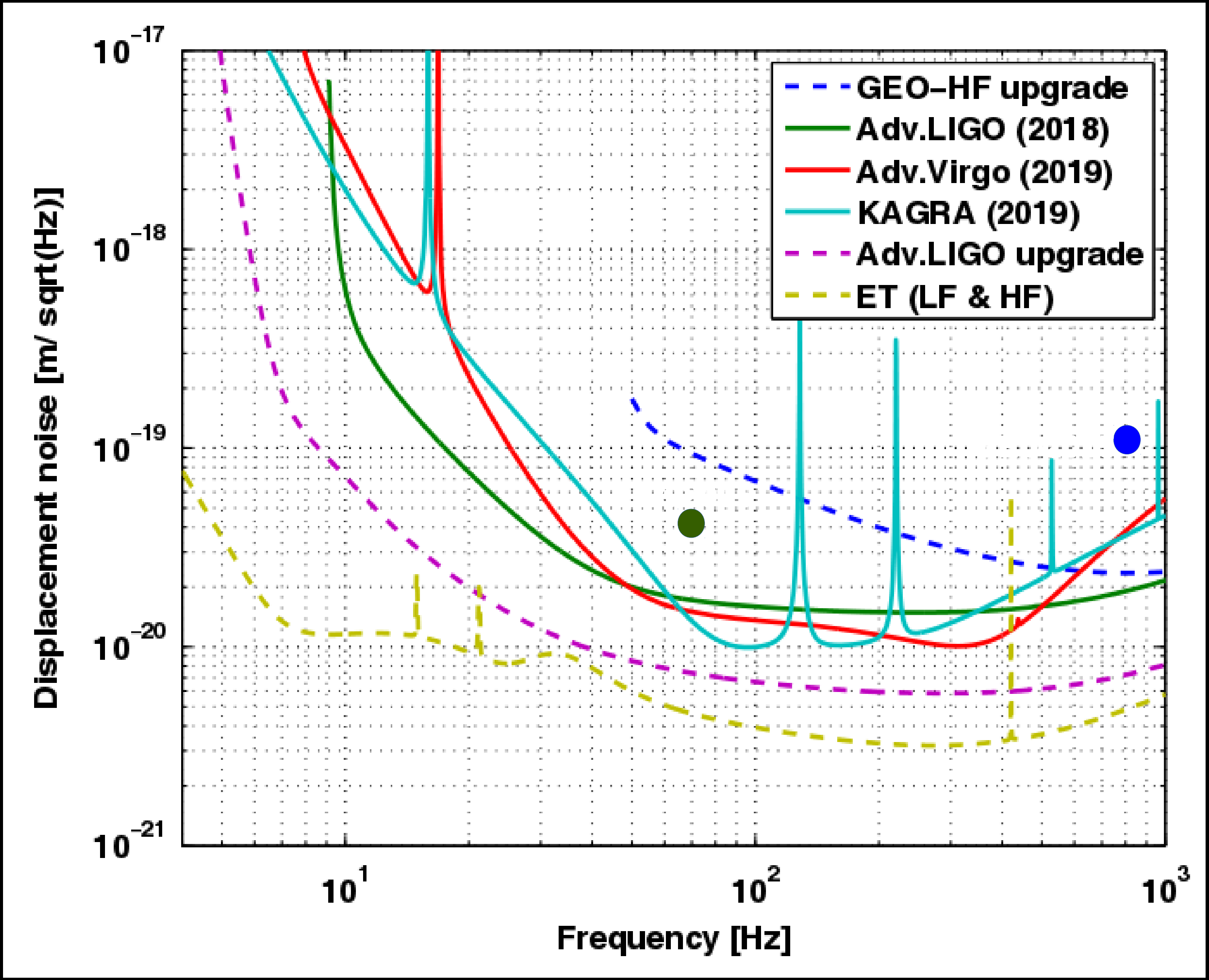
For Gravitational-wave IFO: Assembly with valves and baffles

- Chamber for baffle suspension at entry to small-aperture tube



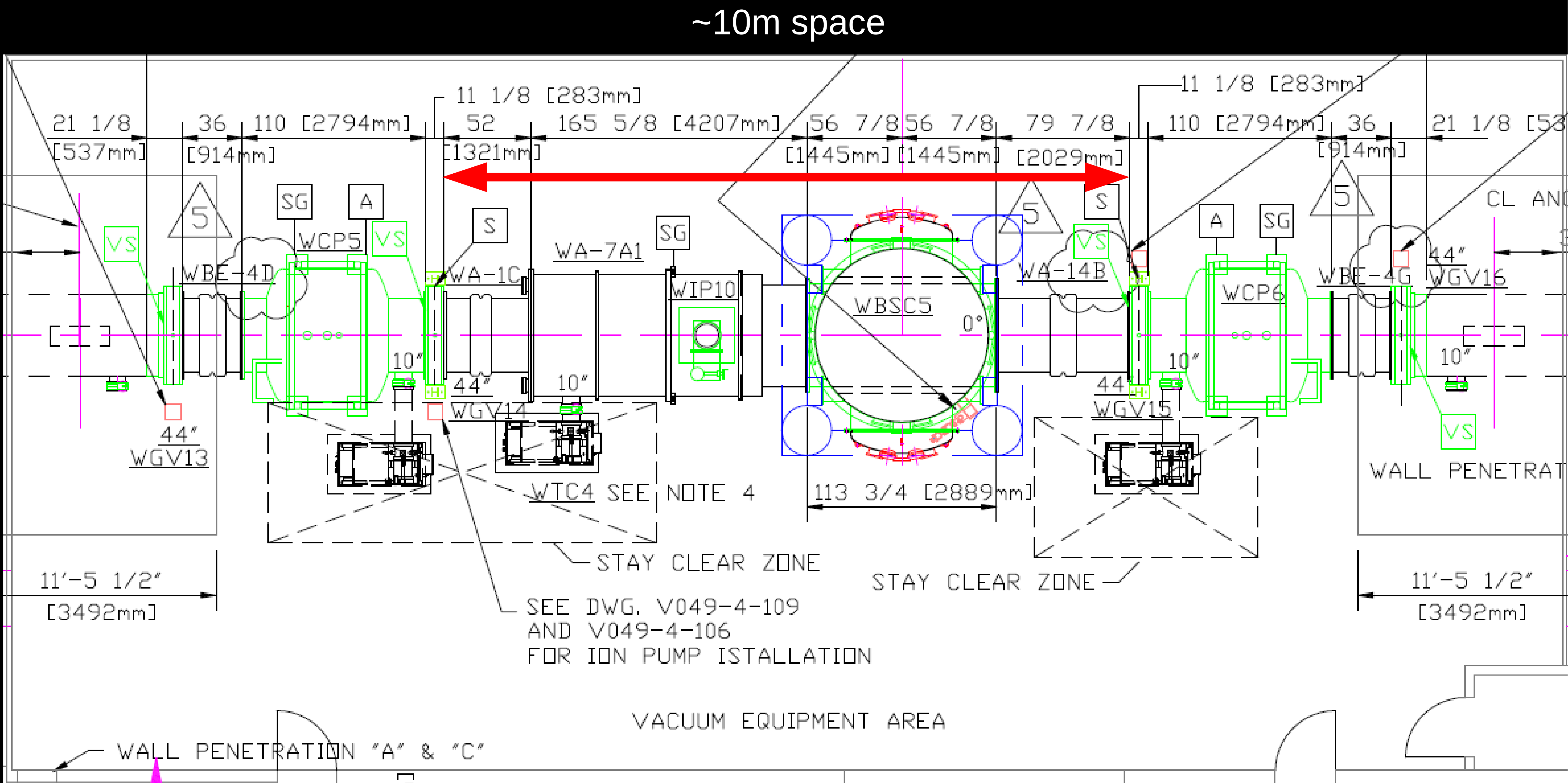


Where?



Low displacement noise hard to reach with small beams

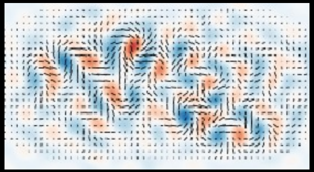
LIGO Hanford:
Only facility with mid-tube gate valves



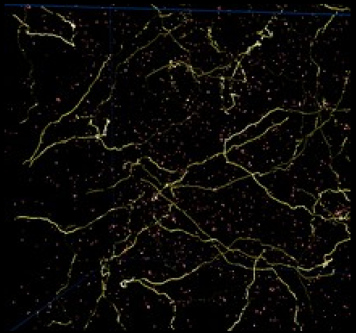
e.g: install during A+ 2. upgrade phase, or Voyager upgrade...

Das Gravitationswellen-Spektrum

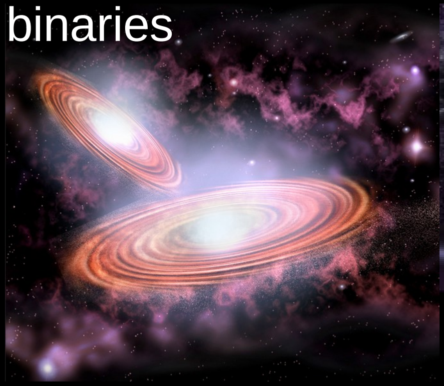
Primordial GWs



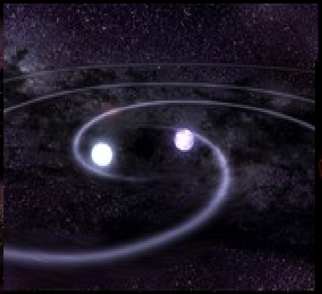
Cosmic strings



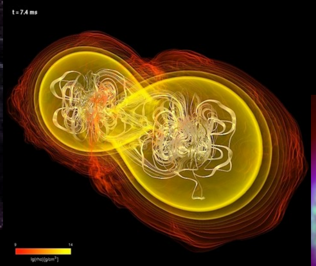
Supermassive BH binaries



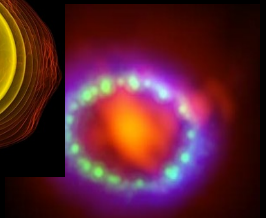
BH and NS binaries



Binary coalescence



Spinning NS

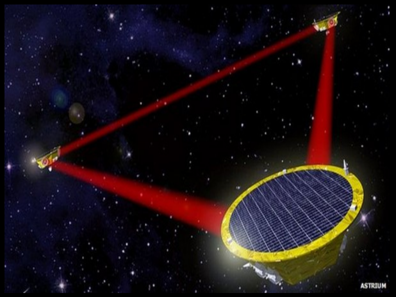


Supernovae

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

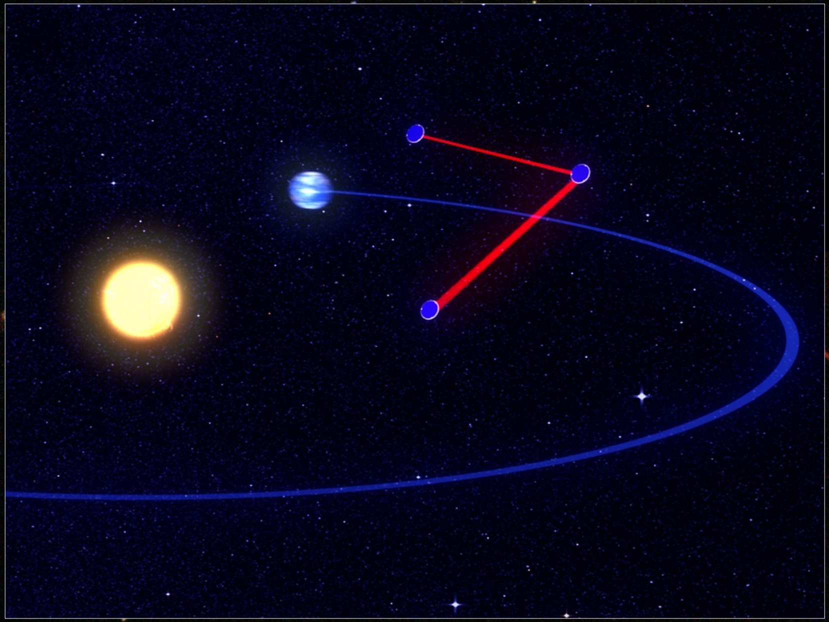
Inflation probe

Pulsar timing

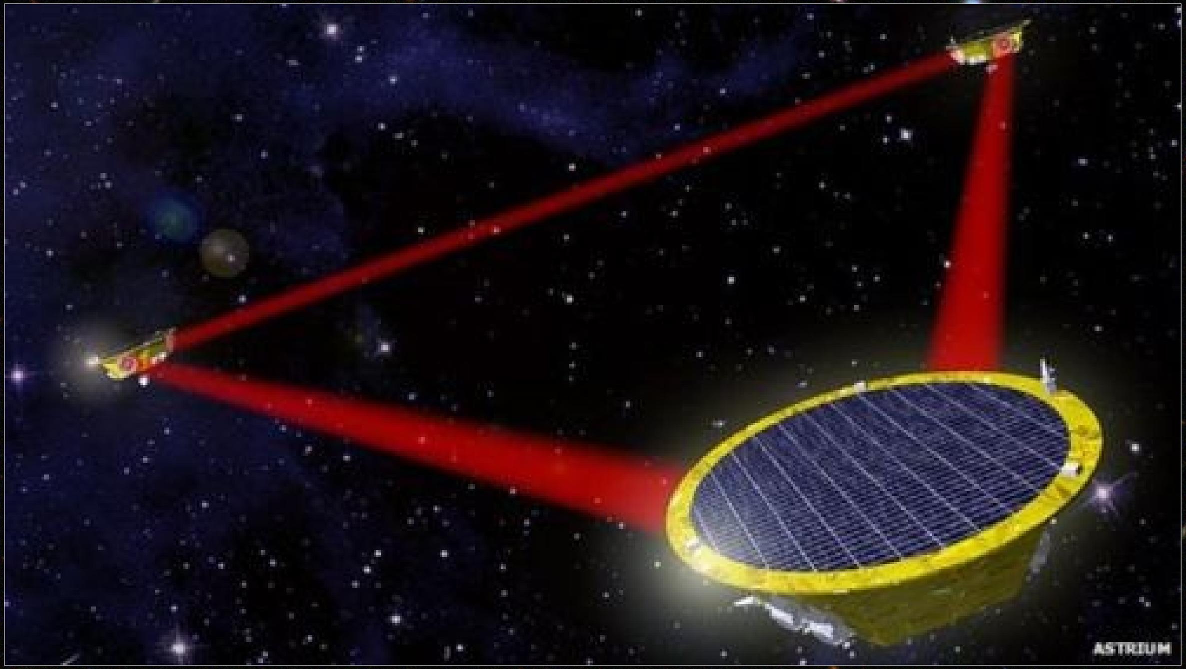


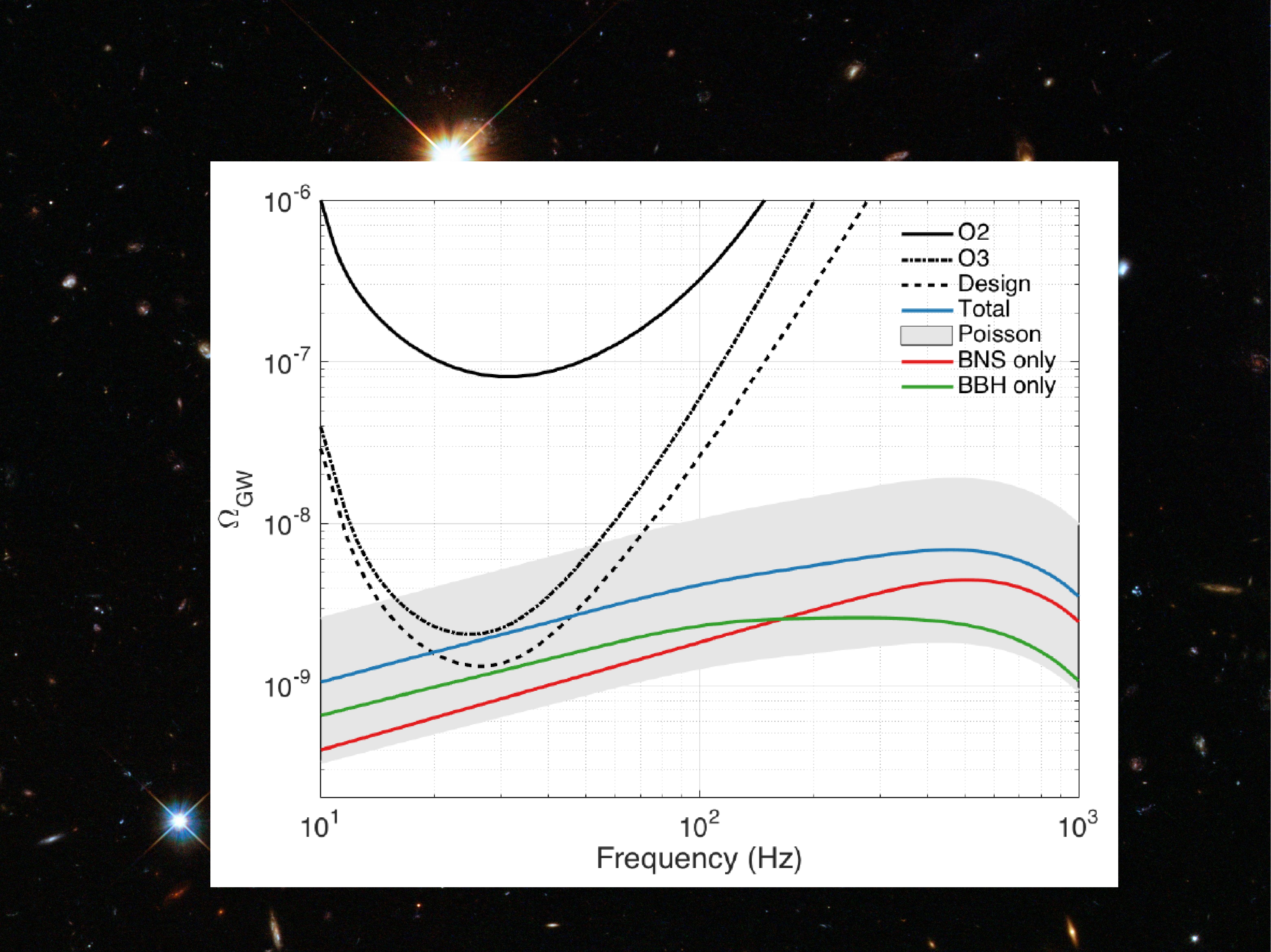
Interferometers In space

Ground-based interferometers



LISA





10^{-6}
10^{-7}
10^{-8}
10^{-9}
Ω_{GW}
10^{1}
10^{2}
10^{3}
Frequency (Hz)
O2
O3
Design
Total
Poisson
BNS only
BBH only