Astroparticleschool Obertrubach 2023

Interferometric Gravitational Wave Detection – how is that even possible..?

04. Oct. 2023

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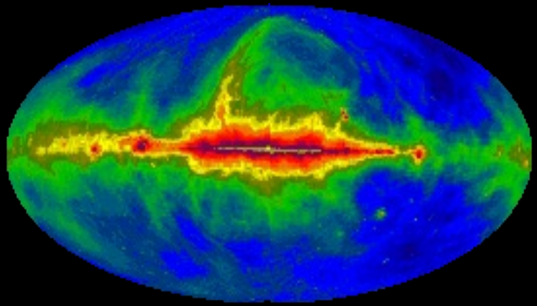
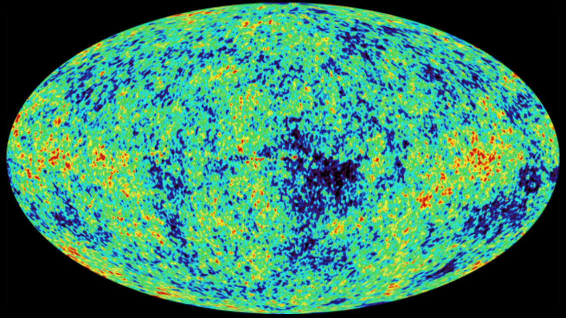
Leibniz Universität Hannover

PhoenixD
Photonics · Optics · Engineering
Innovation Across Disciplines

[Bilder: NASA, ESA, CSA, STScI; Joseph DePasquale (STScI), Anton M. Koekemoer (STScI), Alyssa Pagan (STScI)]

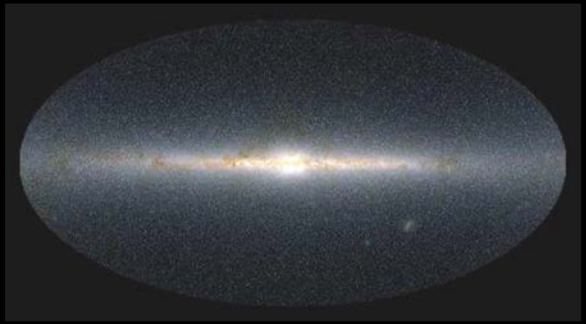
Radio waves





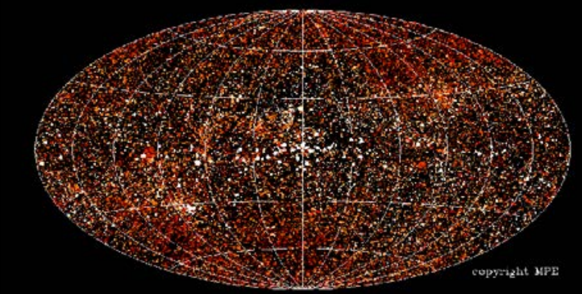
μ-wave background

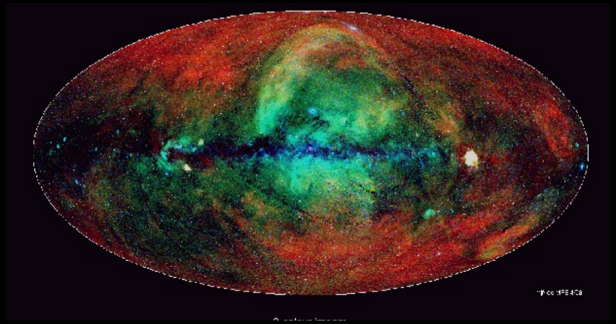
Infrared



Visible

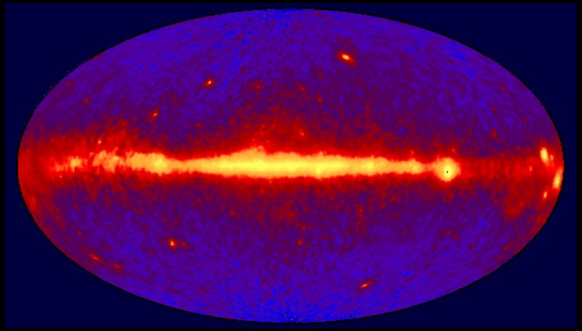
X-ray

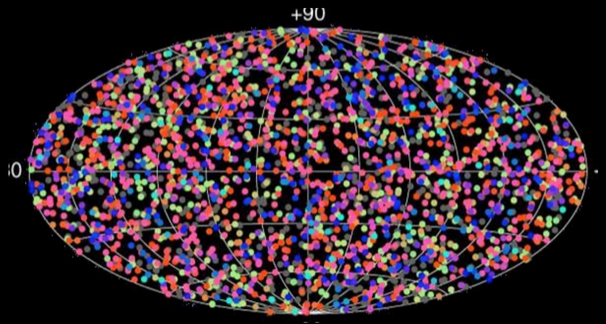




X-ray background

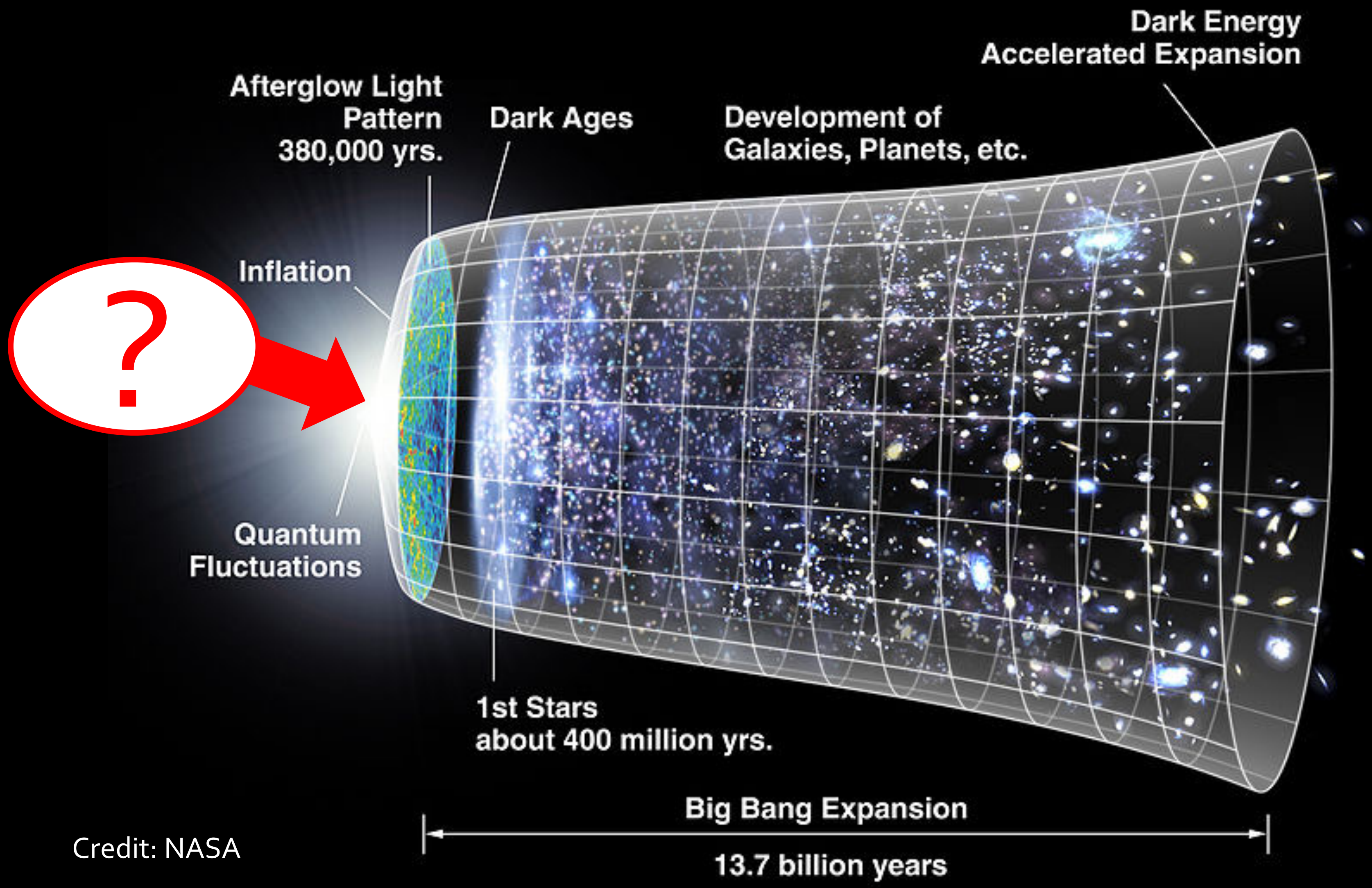
Gammaray





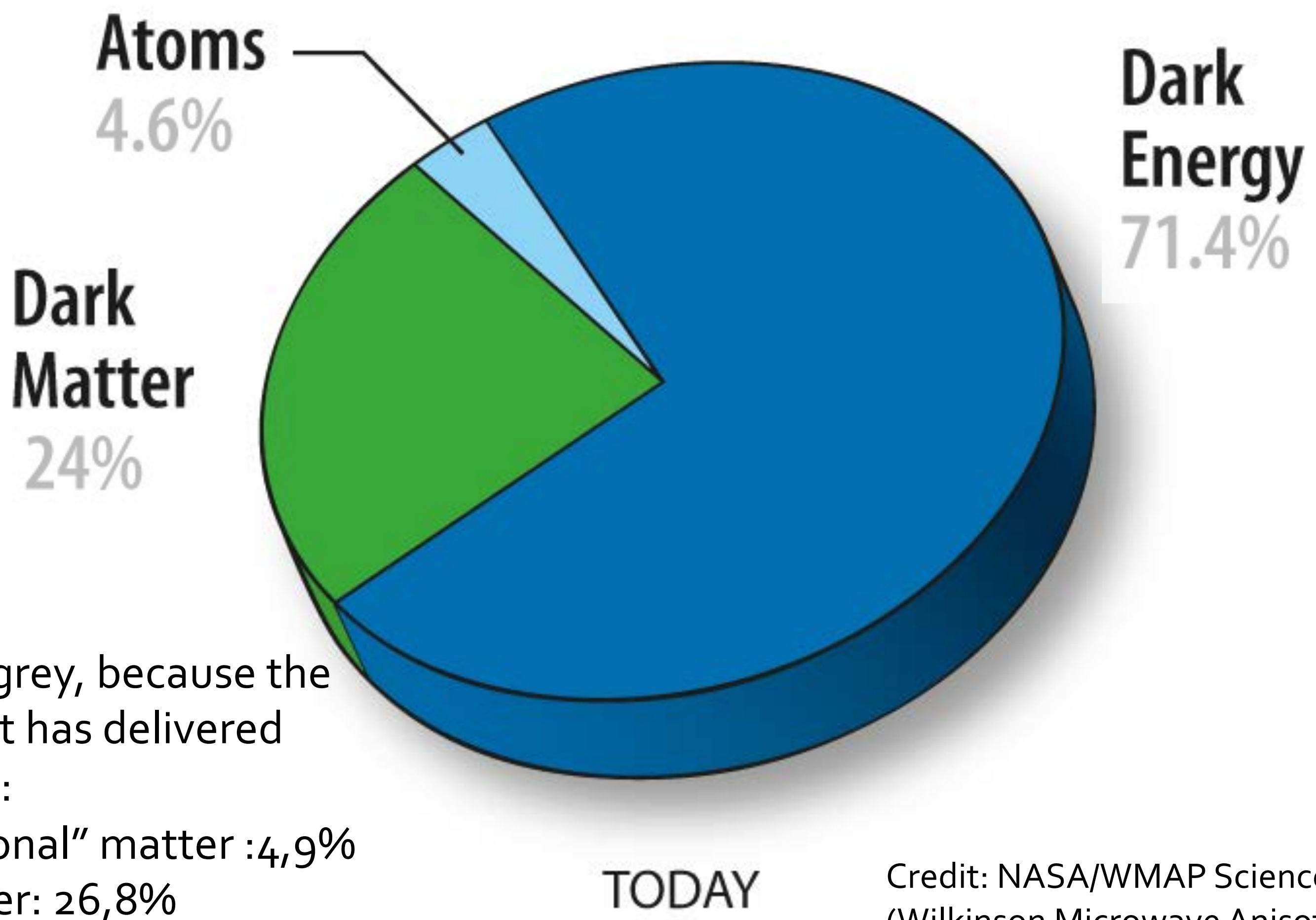
Gammaray bursts

Timeline of our Universe



Credit: NASA

Energy and matter in our Universe



(Numbers in grey, because the *Planck* project has delivered newer results:

- "conventional" matter :4,9%
- dark matter: 26,8%
- dark energy: 68,3%)

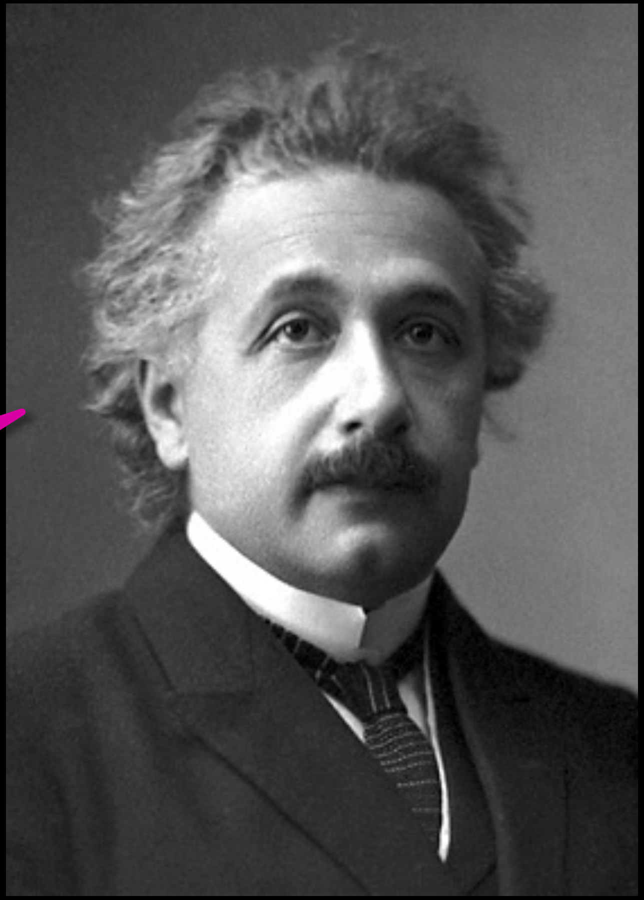
Credit: NASA/WMAP Science Team (Wilkinson Microwave Anisotropy Probe)

Newton vs. Einstein

Isaac Newton (1642-1726)

Gravitation:
Masses attract each other

Masses deform spacetime – and the curvature of spacetime determines the movement of the masses!



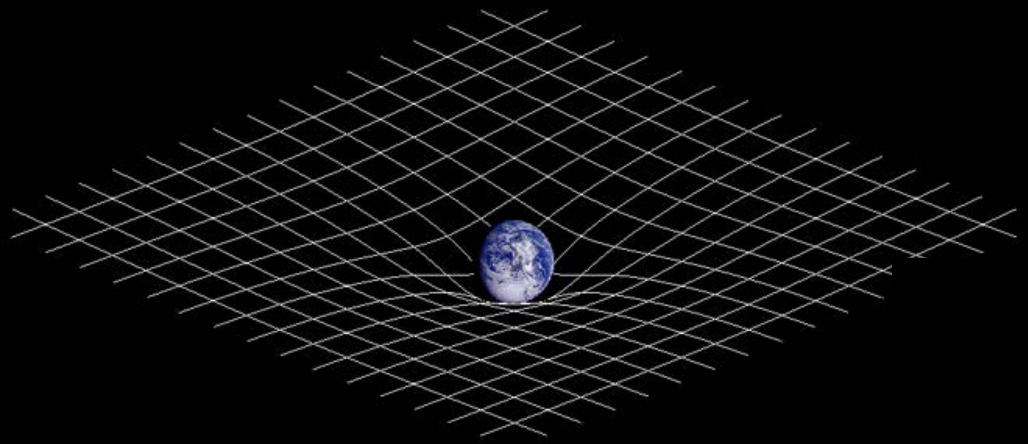
Albert Einstein (1879-1955)

Mass curves spacetime

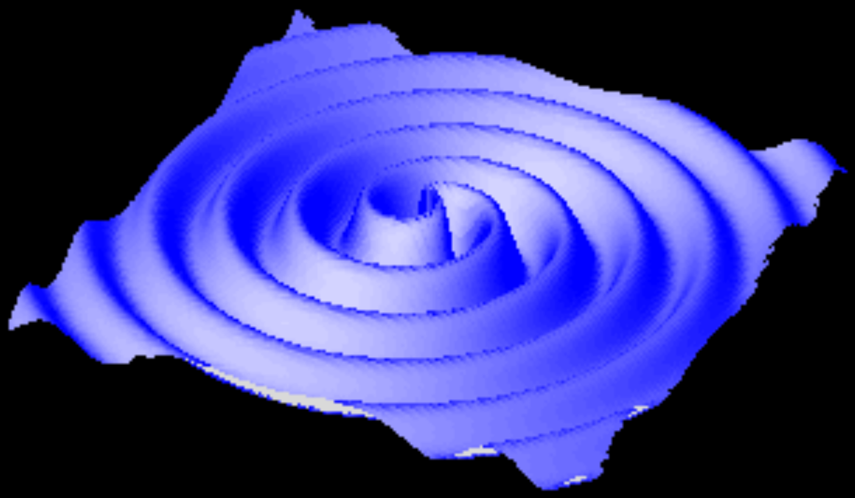
Masses deform spacetime (the larger the mass, the deeper the "dip") –

moving masses cause gravitational waves*

(that propagate at the speed of light)



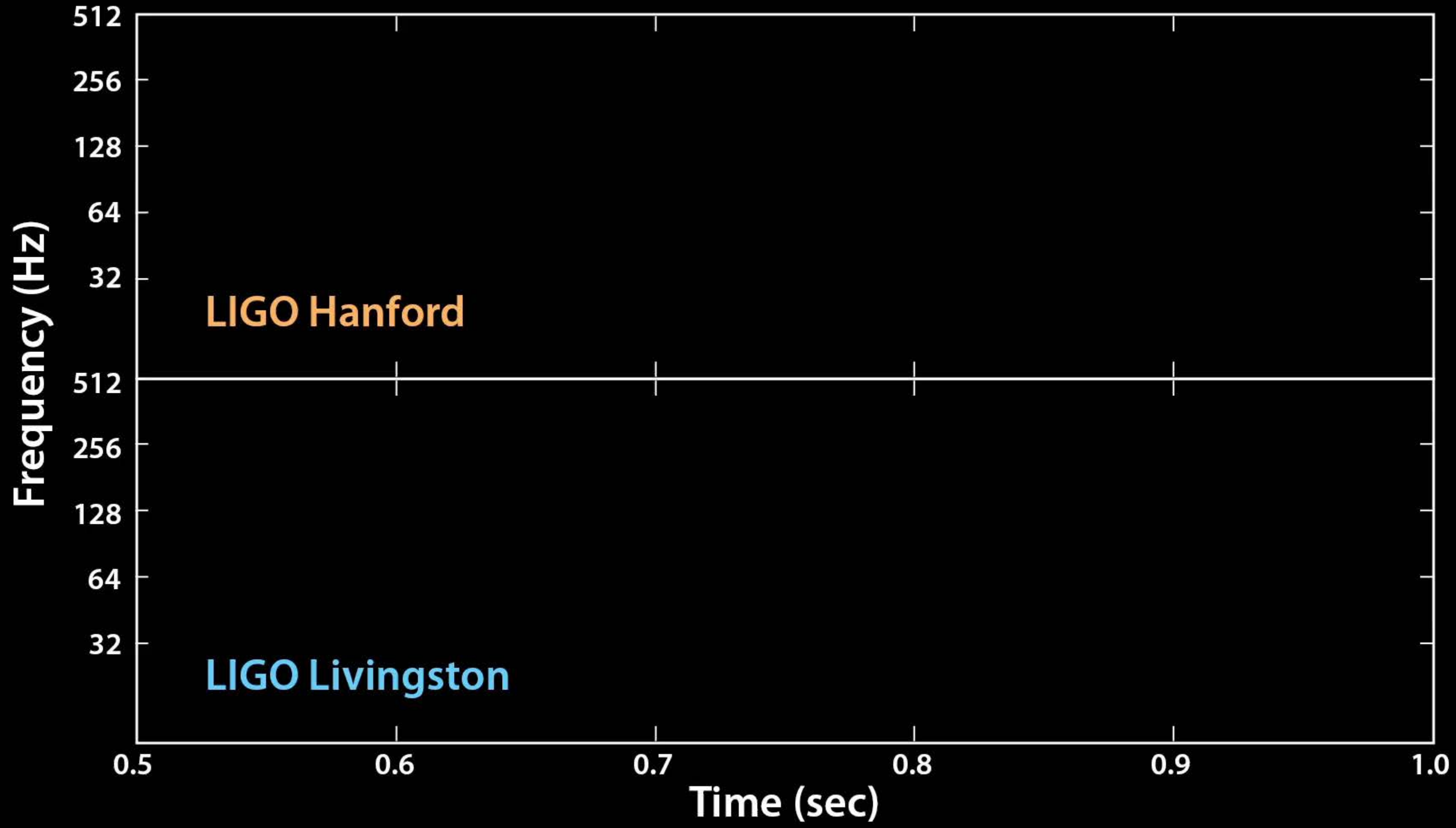
quadrupole waves!



* actually: non-spherically symmetric changes of mass distributions

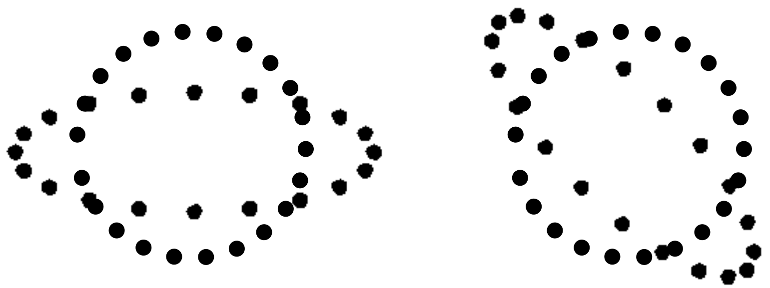
Gravitational waves are different!

GW150914: We can listen to merging black holes!



How do gravitational waves act on spacetime?

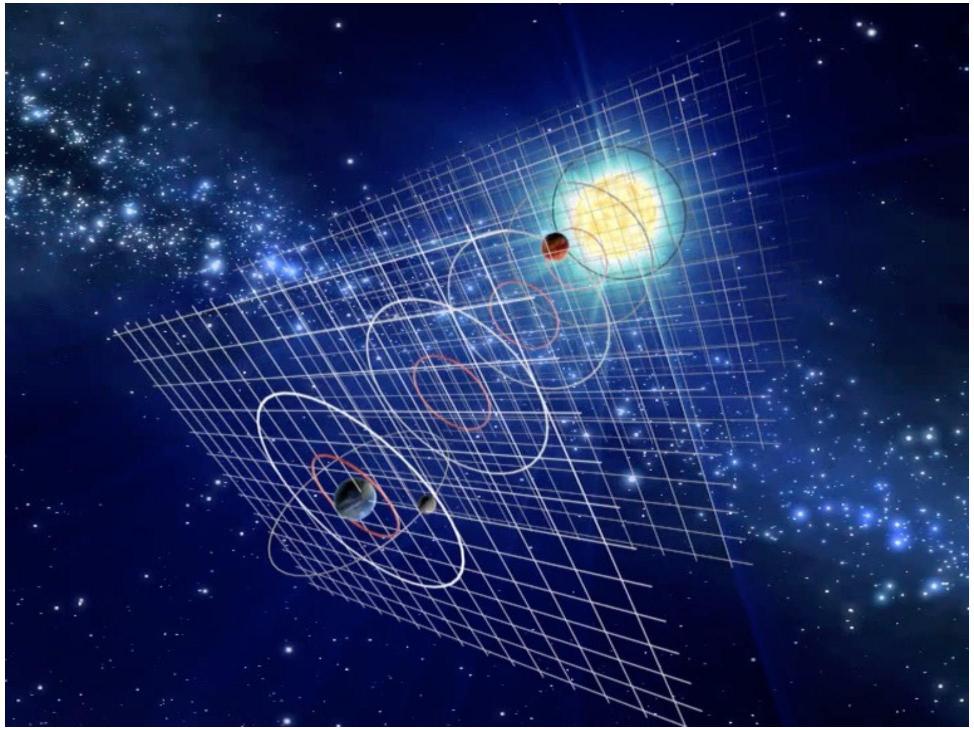
Effect on a ring of test masses:



How large would this effect be?

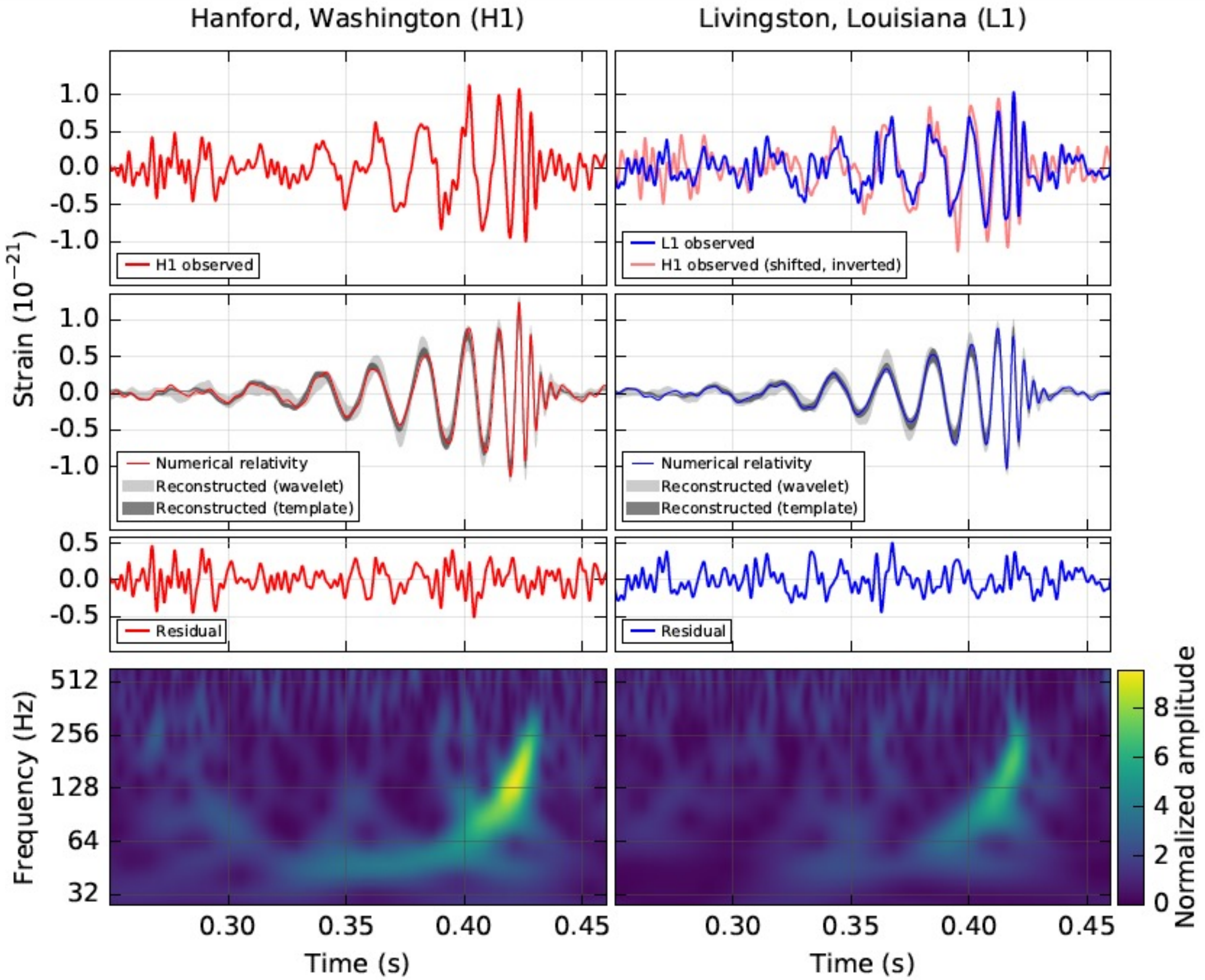
$$h = \frac{\Delta L}{L} = 10^{-21}$$

(strain h = relative length change)



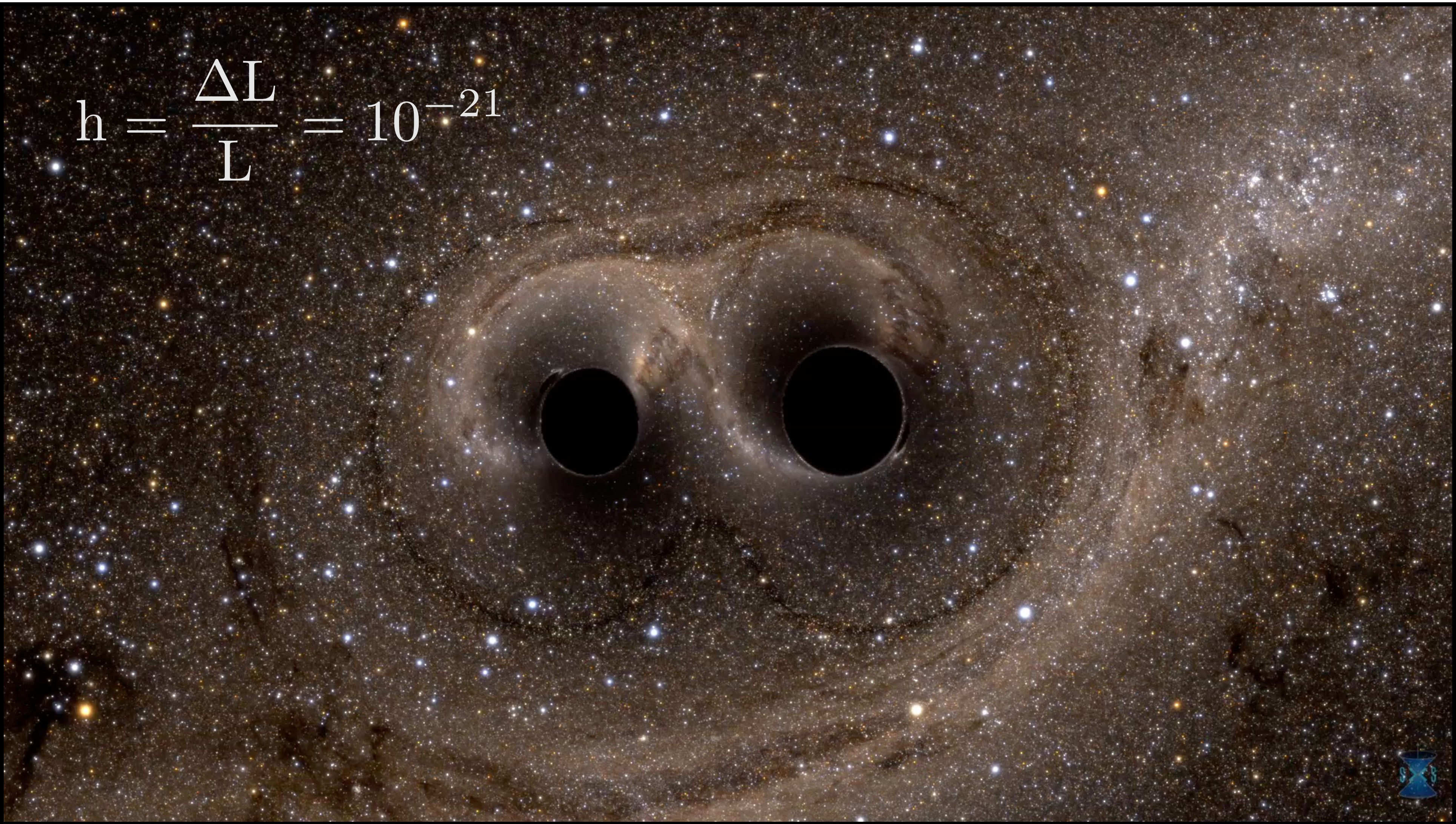
Gravitational waves are *everywhere*! ;)

The first direct detection: GW150914



B. P. Abbott, . . . , M. Heurs, . . . *(1004 authors!)*: *Observation of gravitational waves from a binary black hole merger*, Phys. Rev. Lett. **116** (6) 061102 (2016)

Two black holes become one

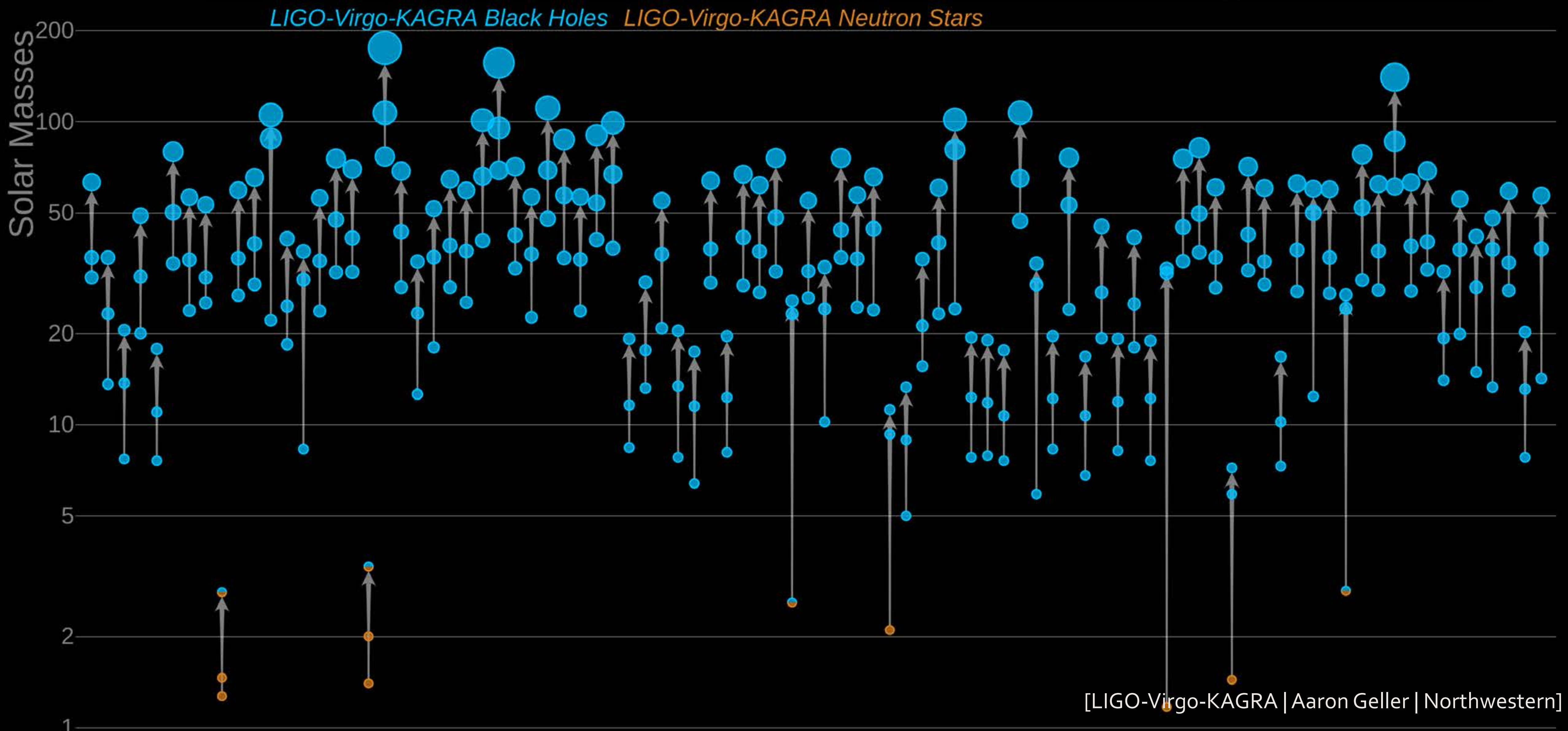


Two neutron stars merge

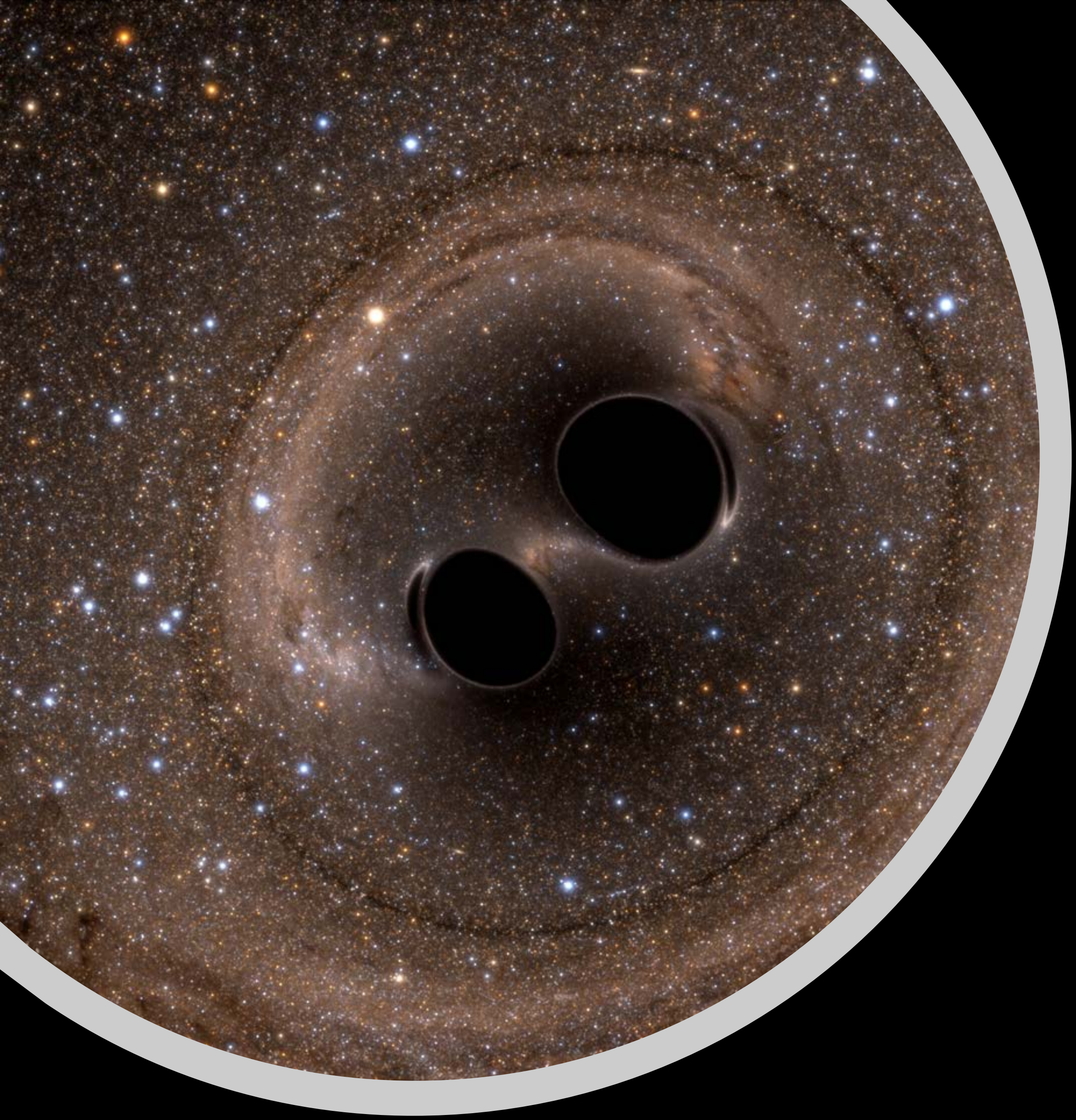
Credit: NASA's Goddard Space Flight Center/CI Lab

A black hole swallows a neutron star whole

Masses in the stellar graveyard (in solar masses)



[LIGO-Virgo-KAGRA | Aaron Geller | Northwestern]

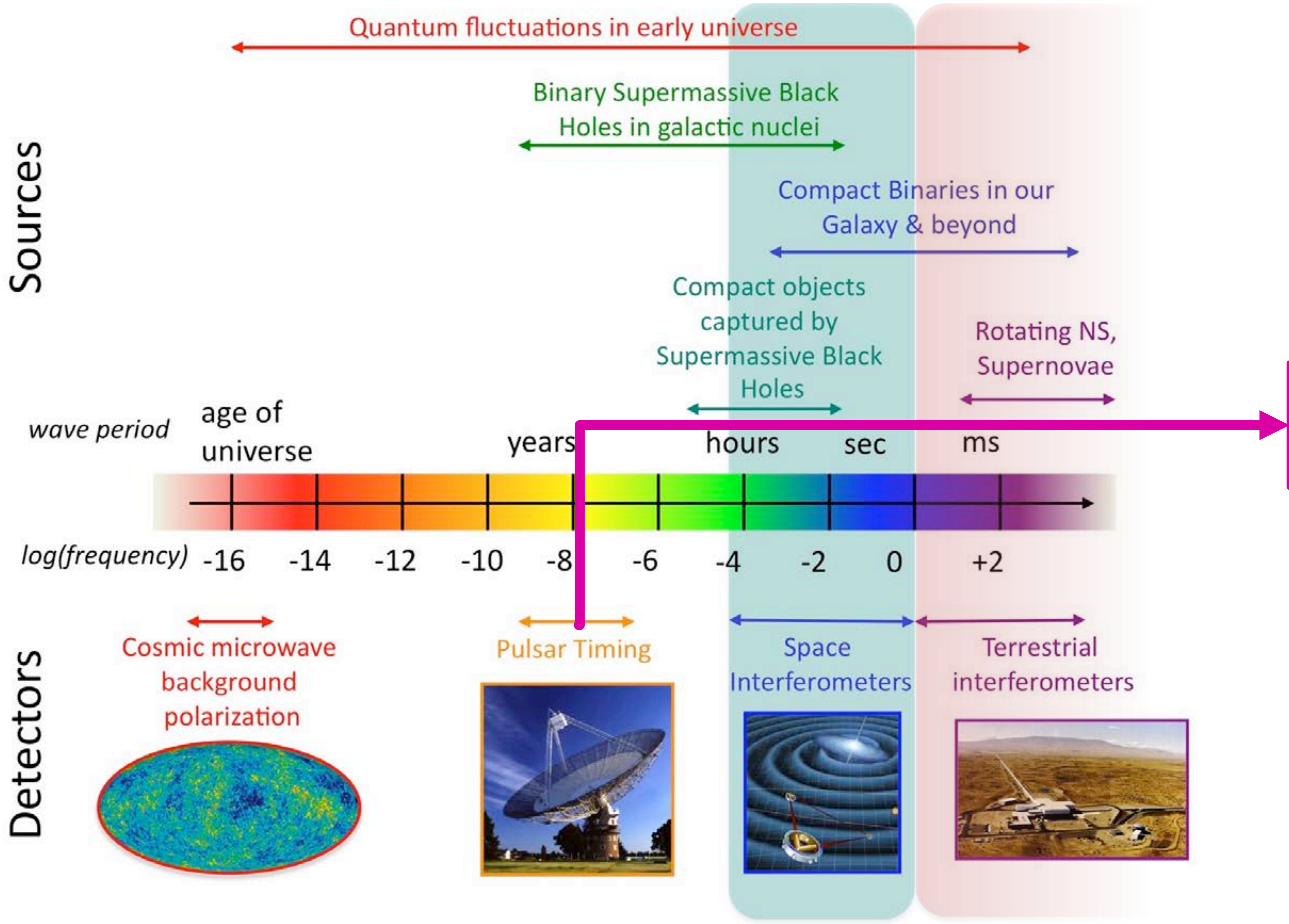


What have we already learned?

- **First detection of GWs** from a BBH system (GW150914)
  - Physics of BHs
- First detection of **GWs from a BNS** system (GW170817)
  - Birth of multimessenger astronomy with GWs
  - Constraining the equations of state of neutron stars
- **Localisation** capabilities of a GW source
- Measurement of the GW propagation speed
- **Test of General Relativity**
- Alternative measurement of the **Hubble constant**
- GW polarisations
- **Intermediate mass black hole** (GW190521)

[Slide modified from M. Punturo, APS Talk 2022 „GW Perspectives"]

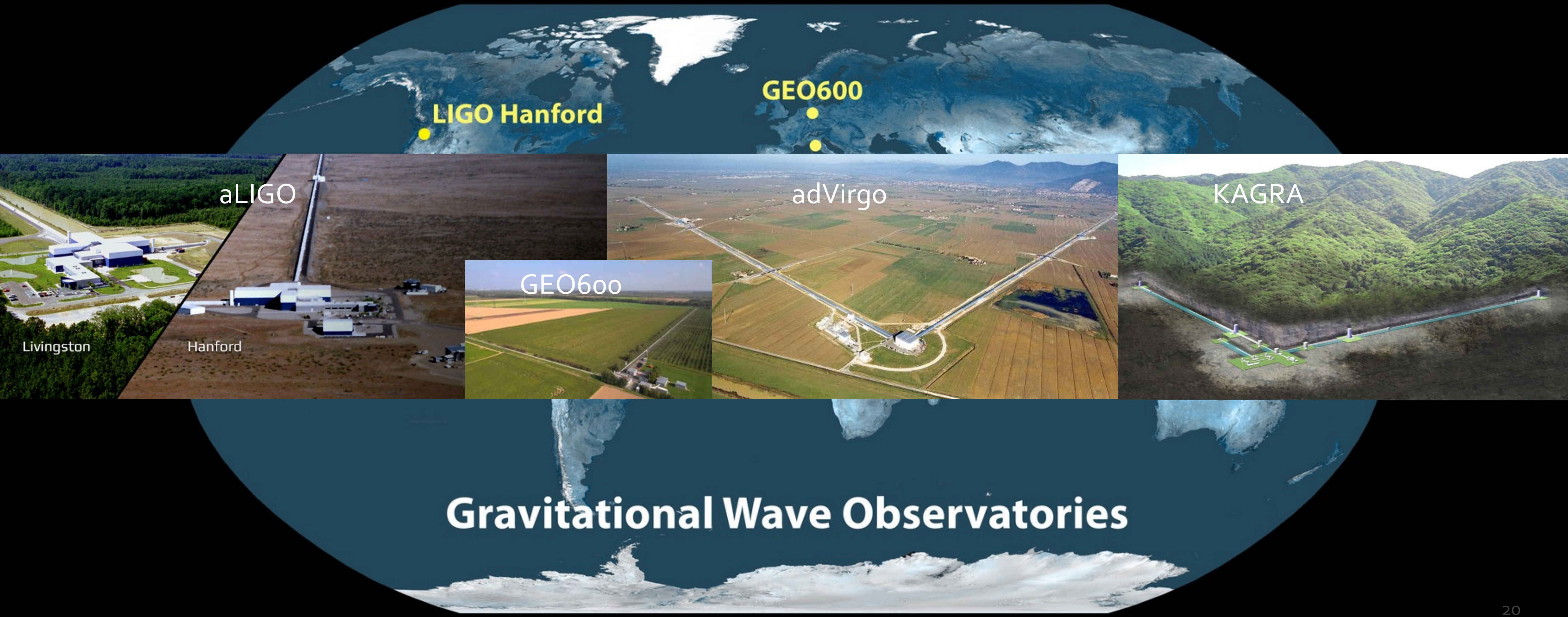
The gravitational wave spectrum



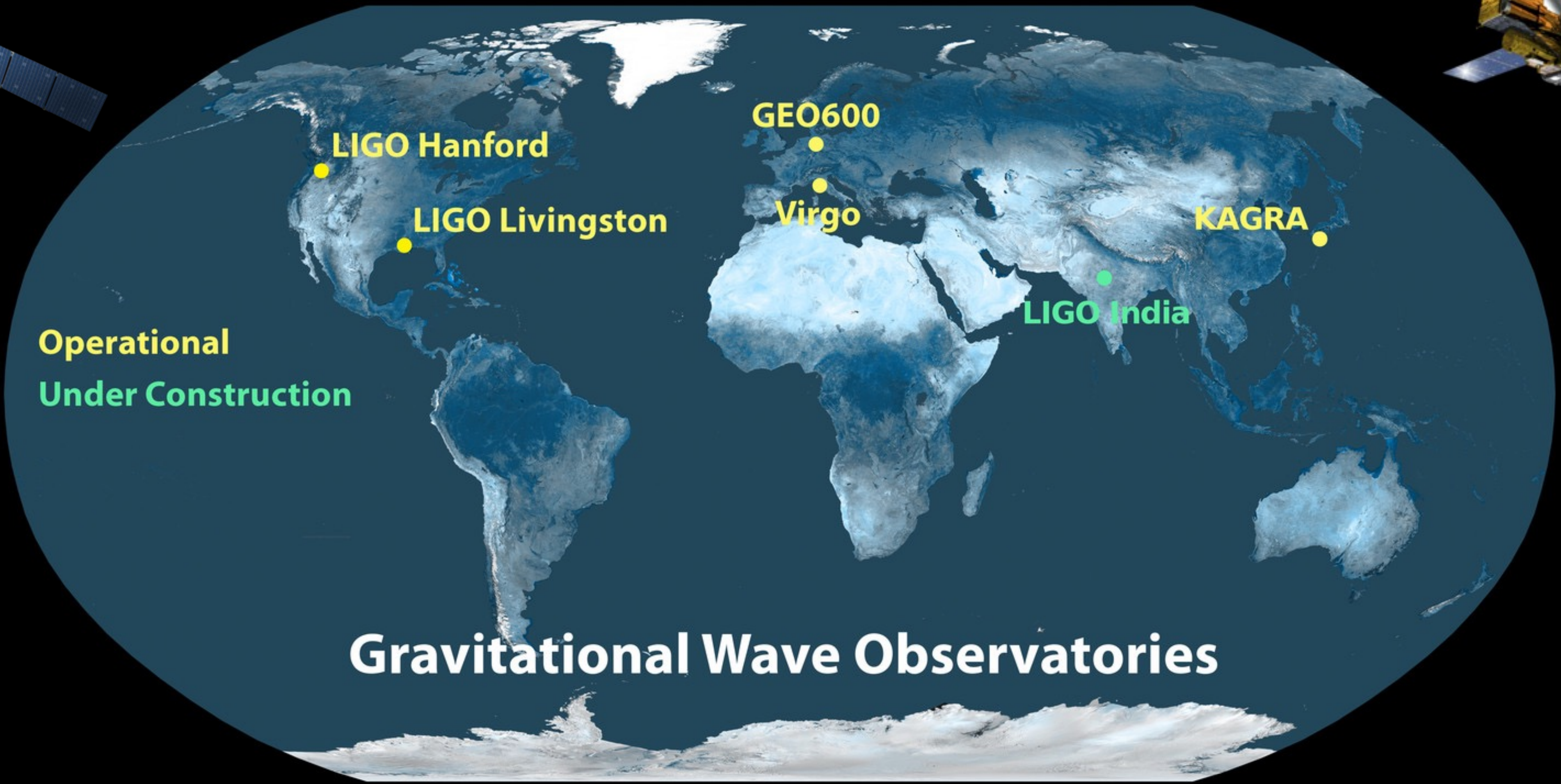
Lectures by Kai Schmitz!

[Modified from the original source (NASA)]

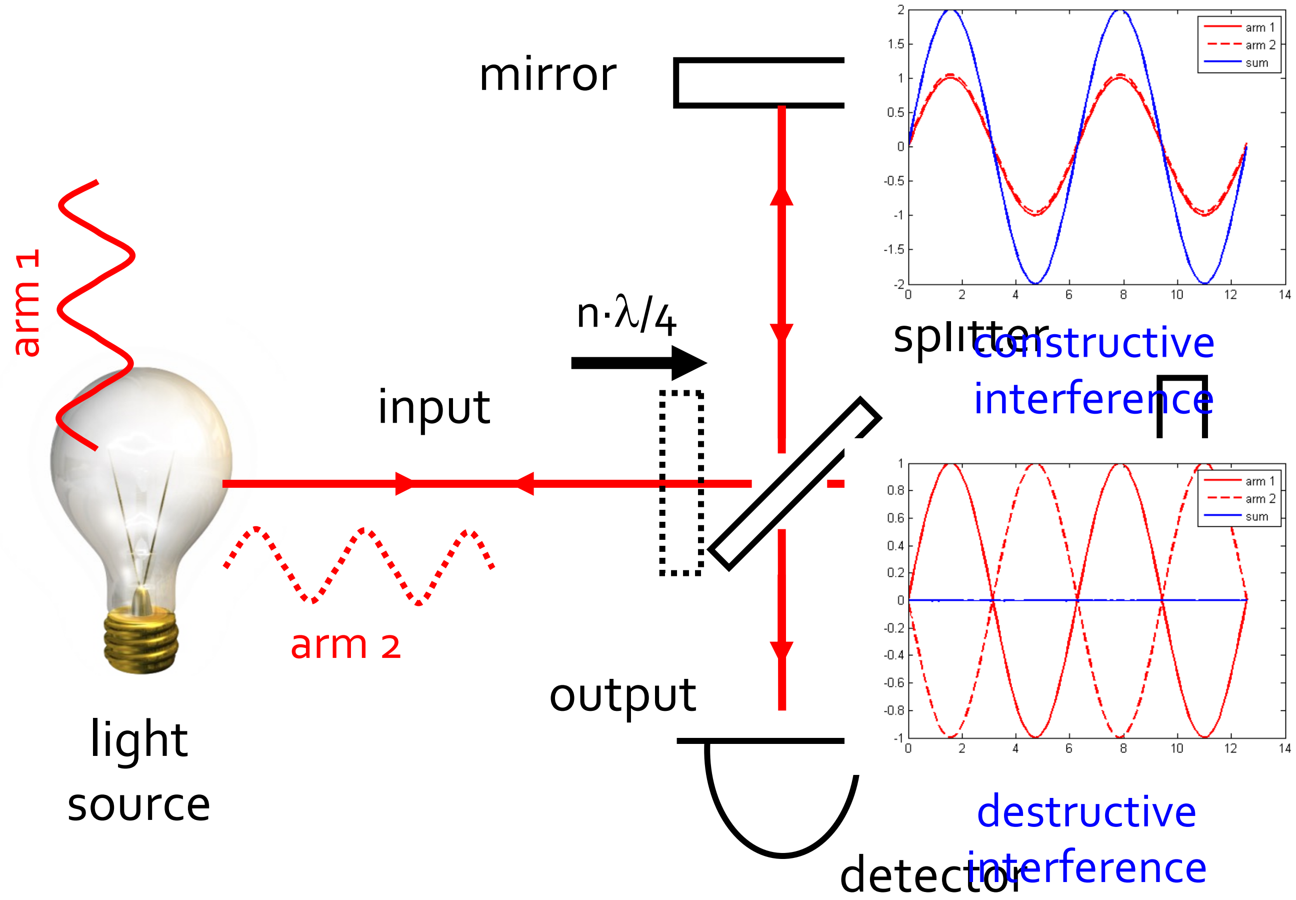
The global GWD network (current status, 2G)



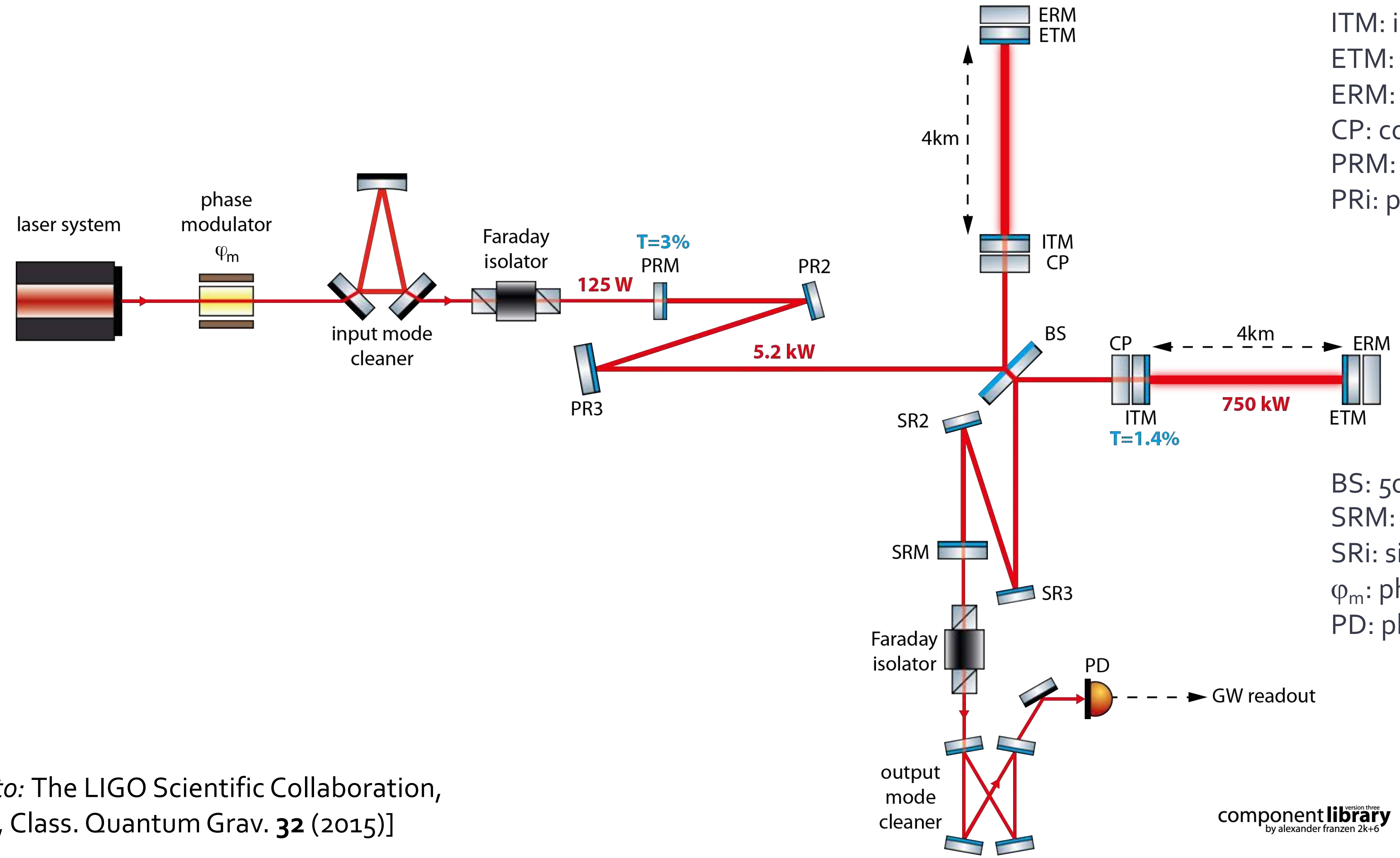
The current GWD network + E.M. followup



The Michelson interferometer



Simplified optical setup of Advanced LIGO

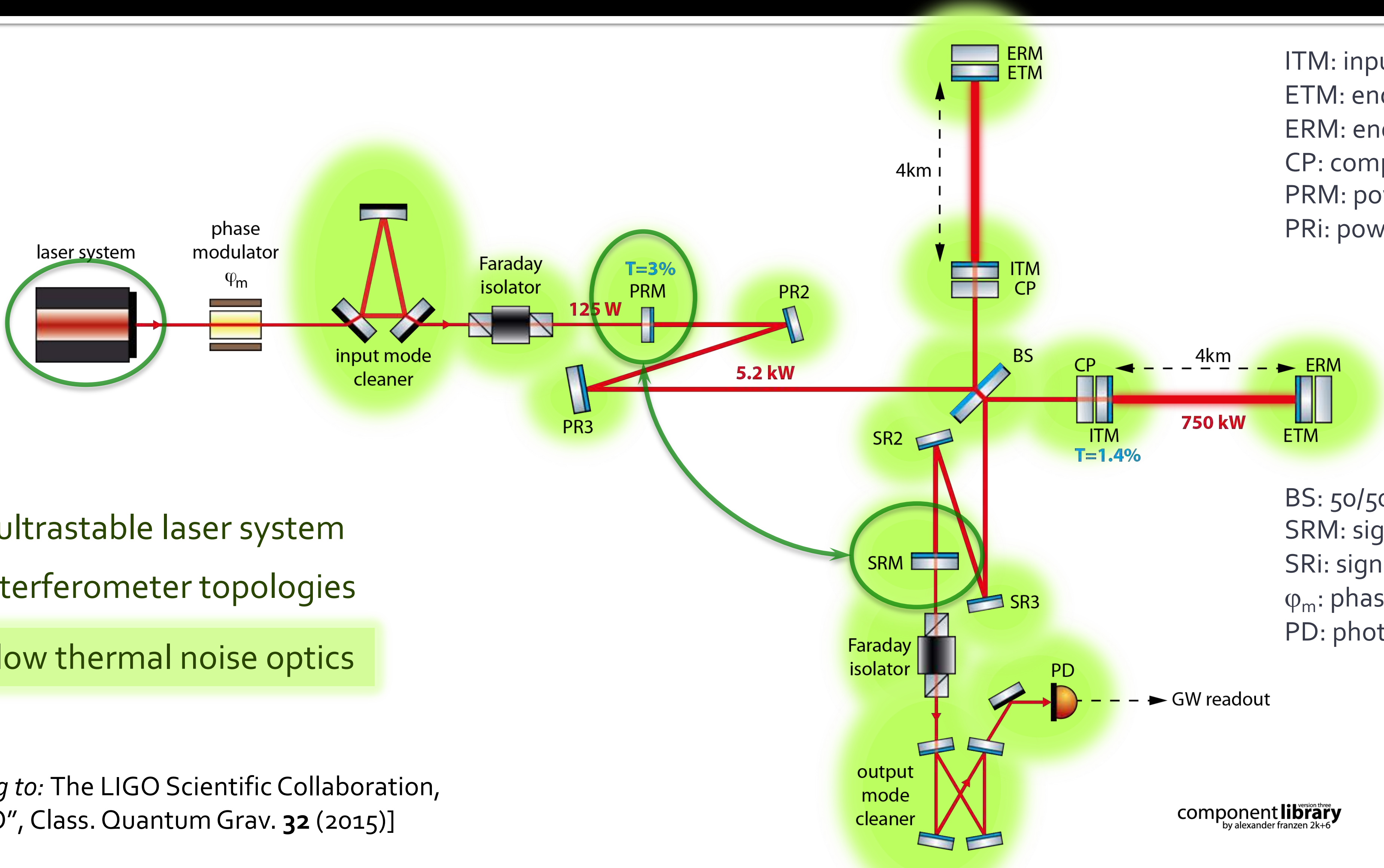


ITM: input test mass
ETM: end test mass
ERM: end reaction mass
CP: compensation plate
PRM: power recycling mirror
PRi: power recycling mirror I

BS: 50/50 beam splitter
SRM: signal recycling mirror
SRi: signal recycling mirror i
φ_m: phase modulator
PD: photodetector

[Image according to: The LIGO Scientific Collaboration, "Advanced LIGO", Class. Quantum Grav. **32** (2015)]

Advanced technology for aLIGO (examples)



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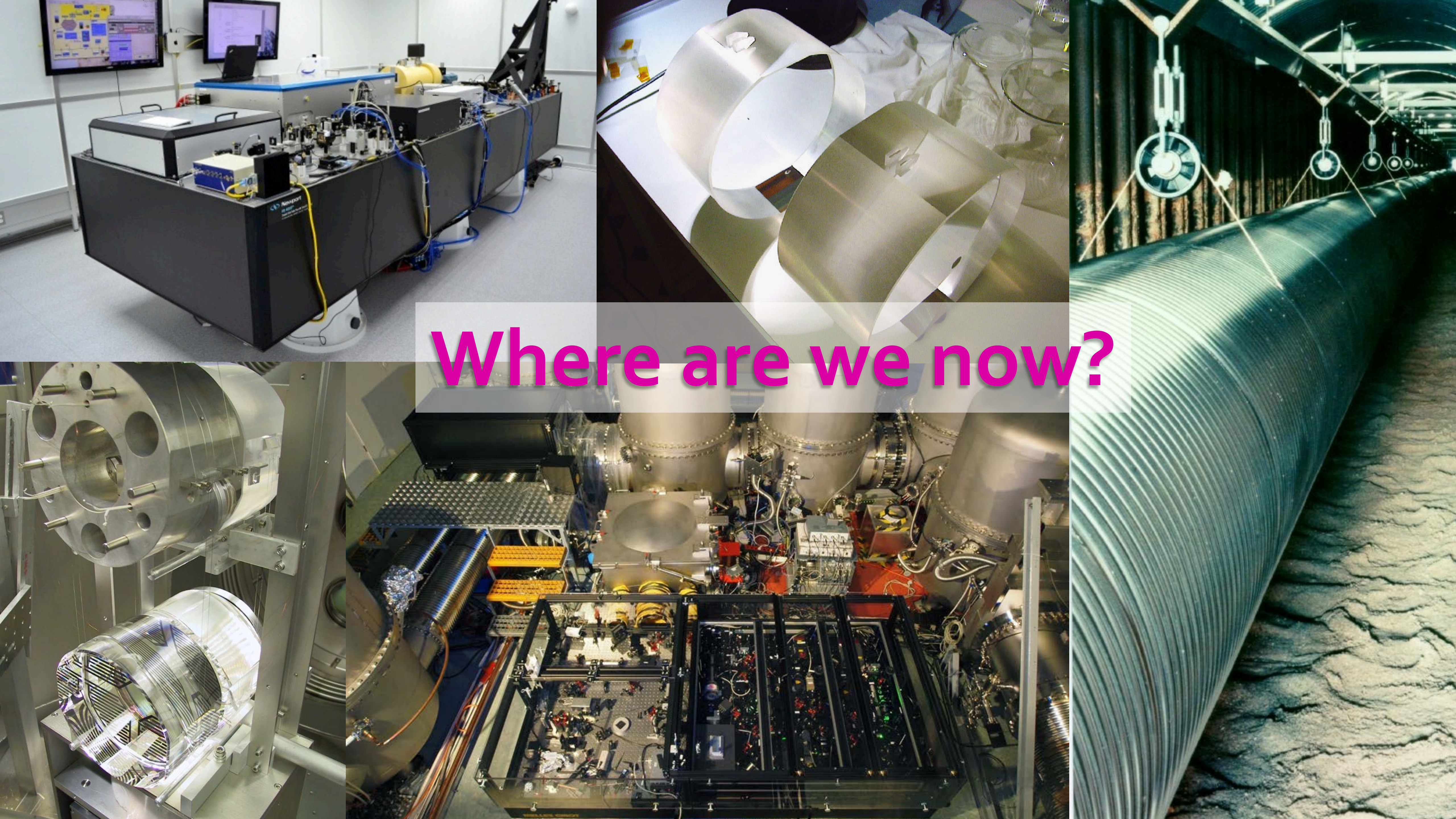
High power ultrastable laser system

Advanced interferometer topologies

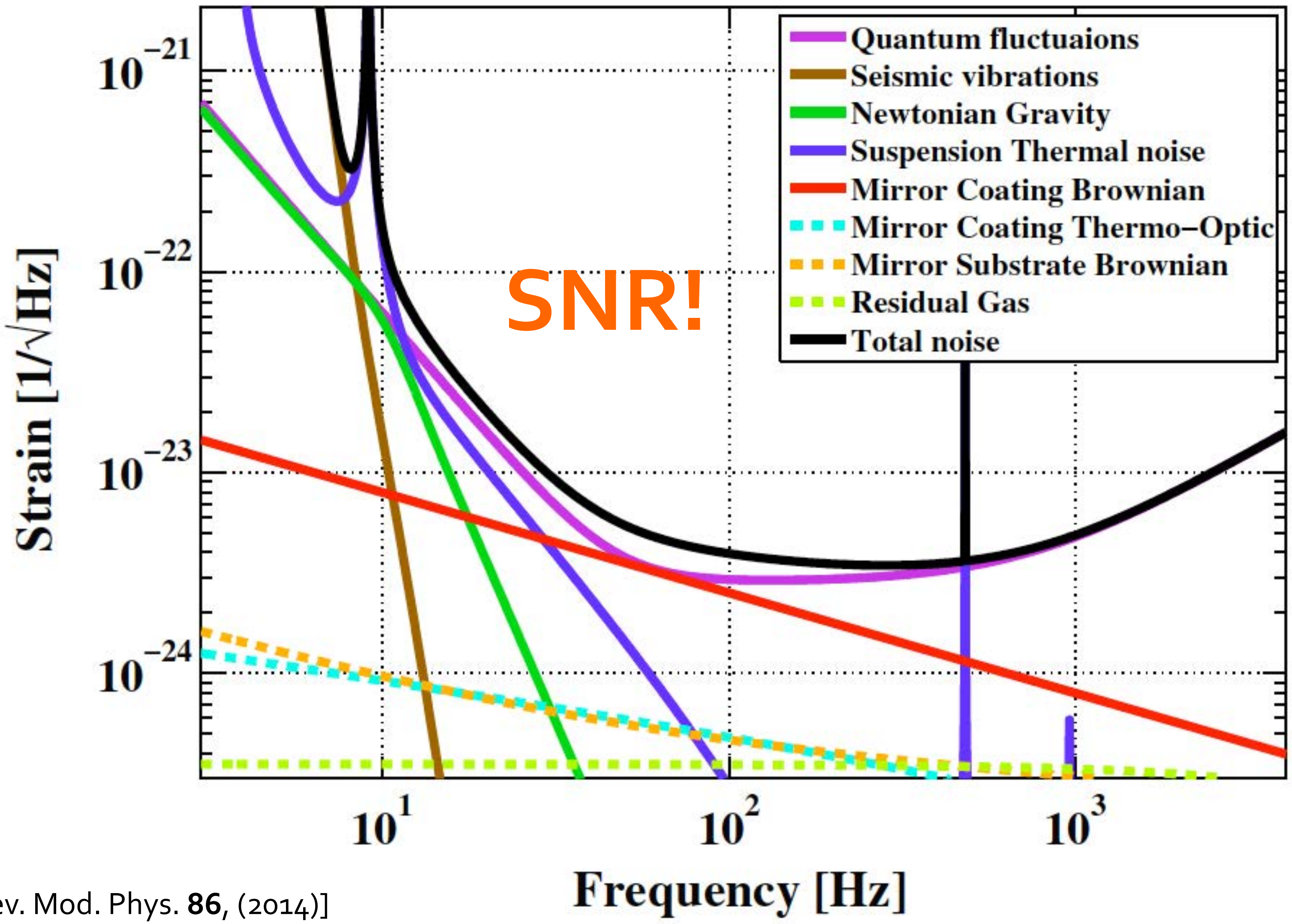
Suspended low thermal noise optics

[Image according to: The LIGO Scientific Collaboration, "Advanced LIGO", Class. Quantum Grav. **32** (2015)]

Where are we now?

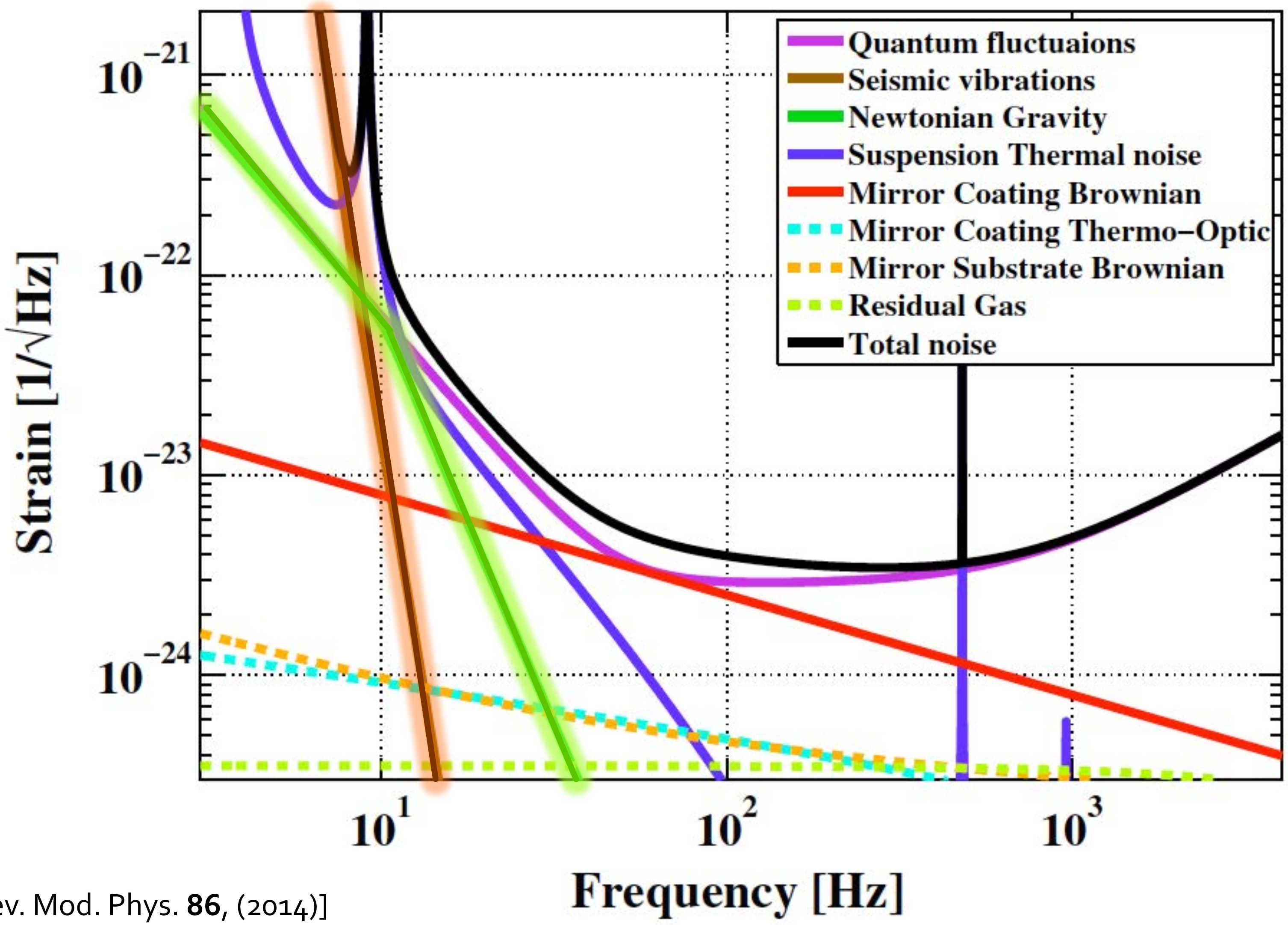


Design sensitivity of aLIGO



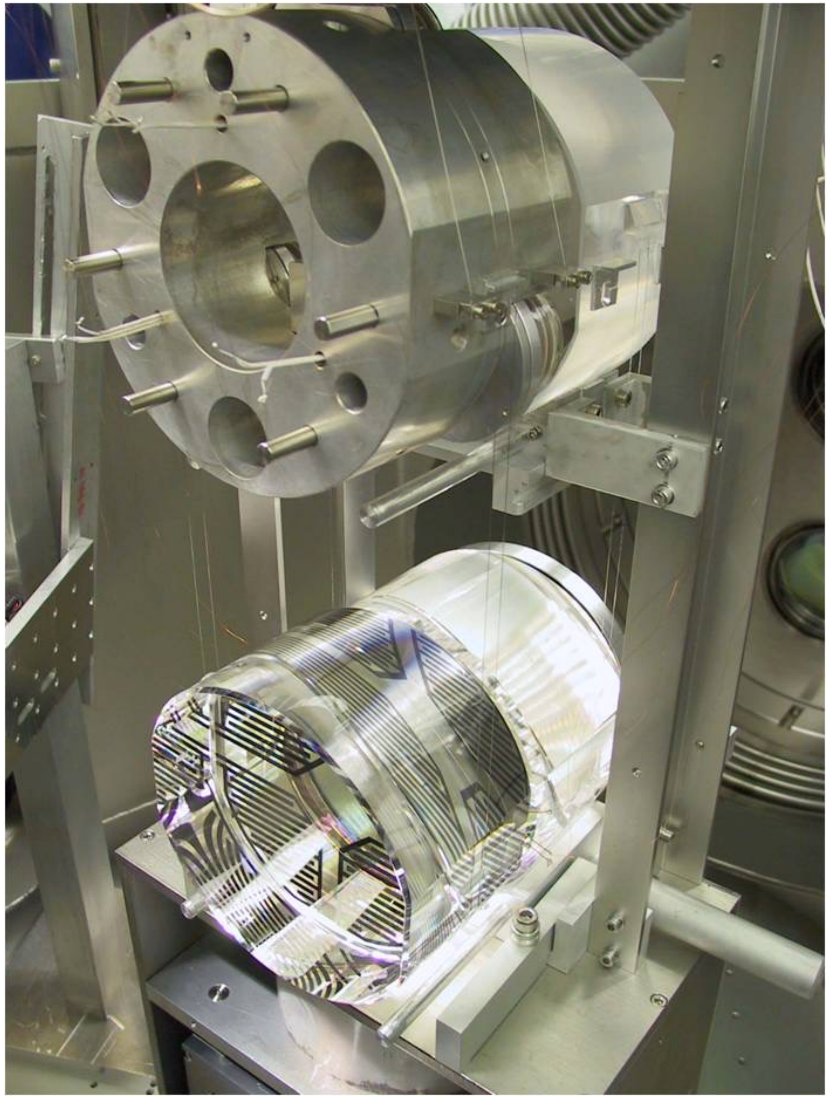
[*Image:* R. X. Adhikari, Rev. Mod. Phys. **86**, (2014)]

Design sensitivity of aLIGO



[*Image:* R. X. Adhikari, Rev. Mod. Phys. **86**, (2014)]

Monolithic mirror suspensions

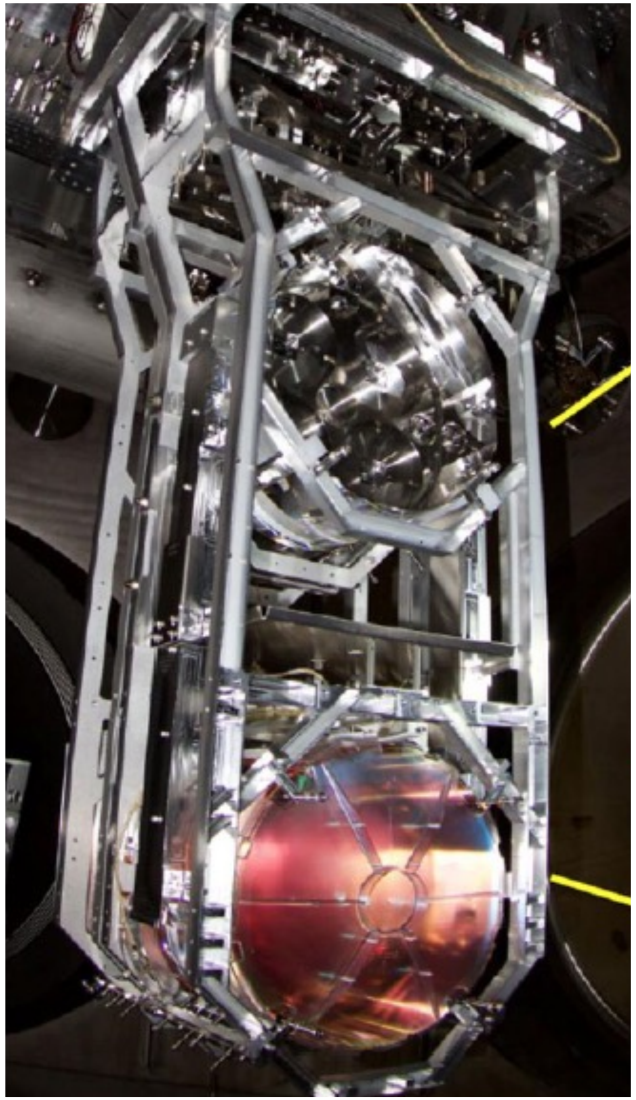


🡐
GEO600 triple suspension
fused silica mirror
180 mm diameter
m = 10 kg
suspended by FS fibres
reaction chain for electro-
static actuation

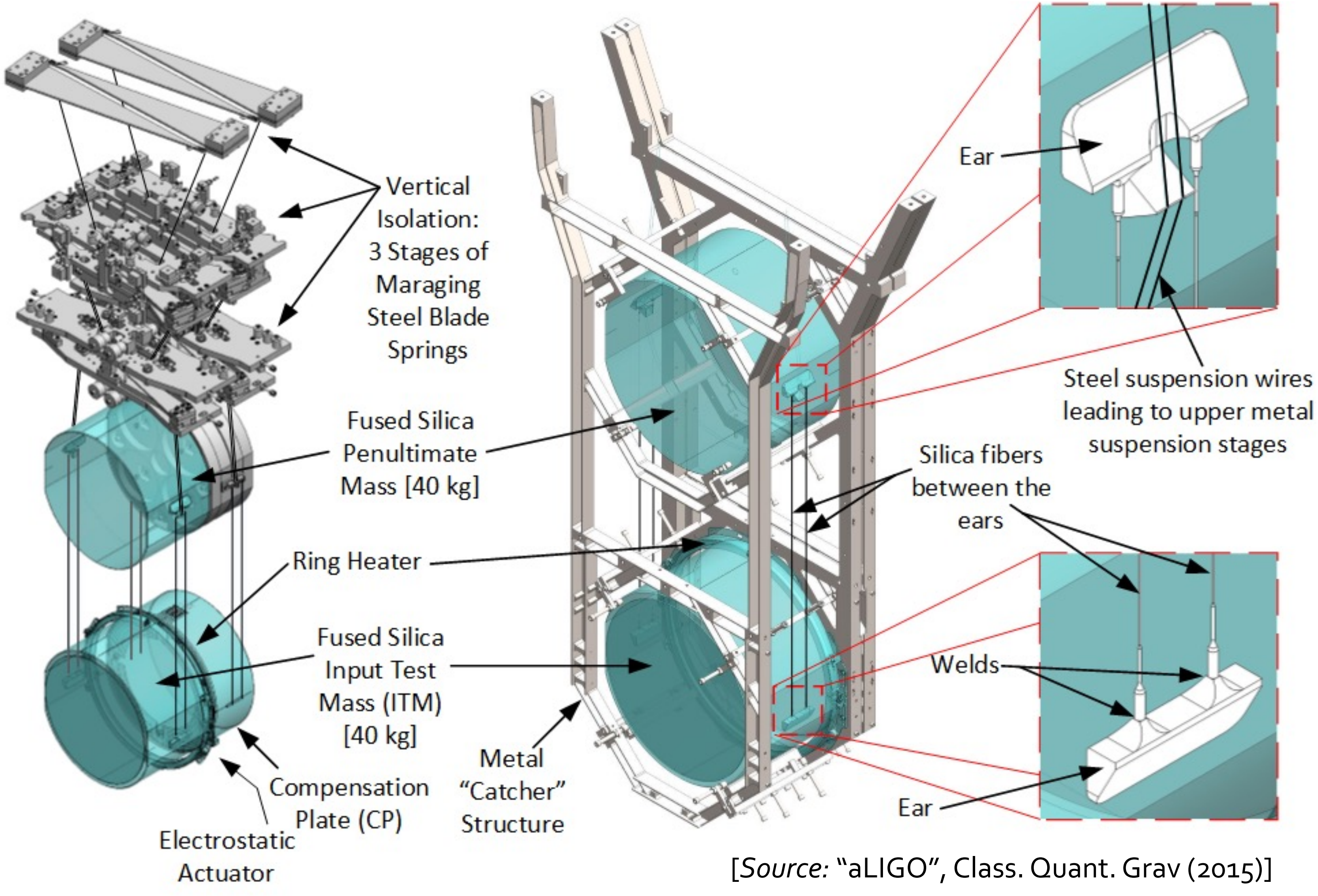
[*image*: H. Lück]

🡒
aLIGO quadruple suspension
fused silica mirror:
340 mm diameter
200 mm thickness
m = 40 kg
suspended by FS fibres:
400 um diameter
600 mm length

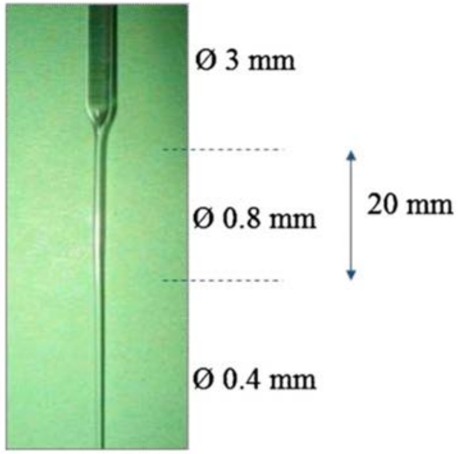
[*image*: M. van Veggel, RSTA 2018]



Monolithic mirror suspensions



[*Source:* "aLIGO", Class. Quant. Grav (2015)]



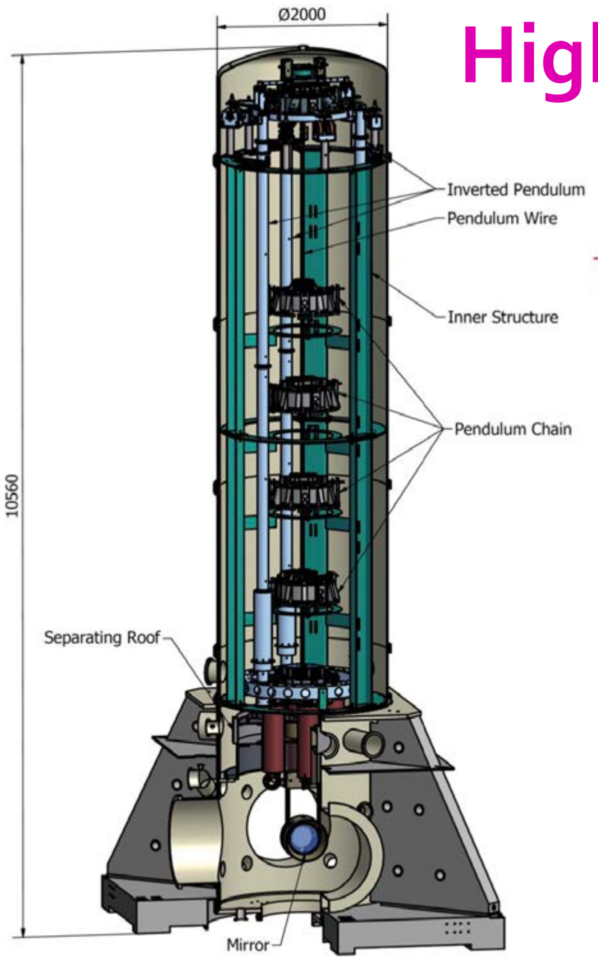
[*Source:* S. M. Aston "Update on quadruple suspension design for Advanced LIGO", Class. Quantum Grav. 29 (2012)]

Suspended test masses, quo vadis?

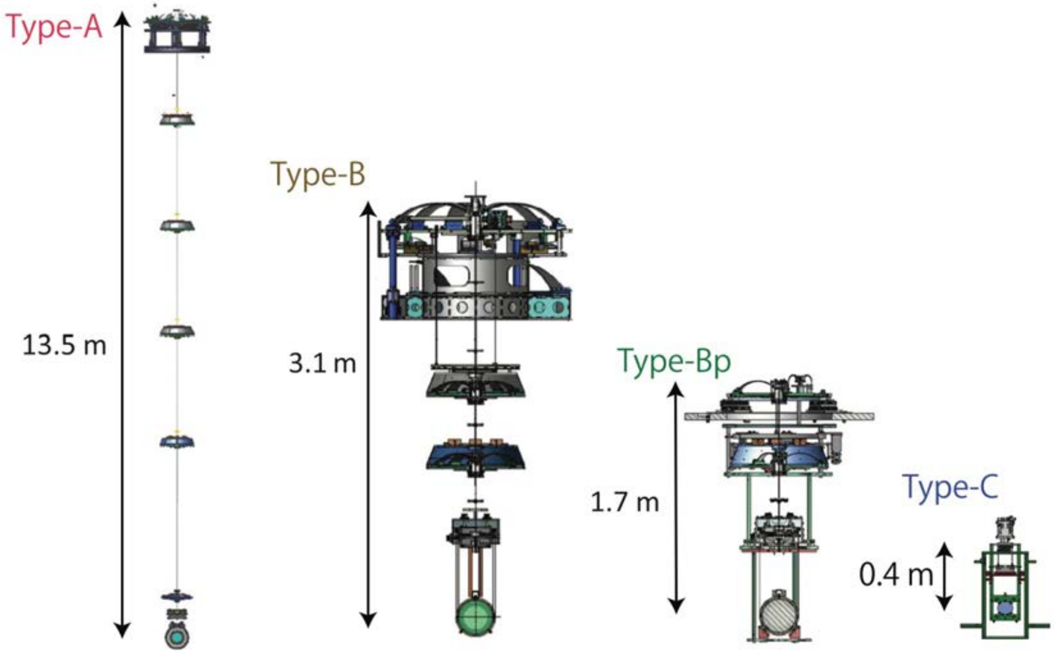
Higher?

…or nested?

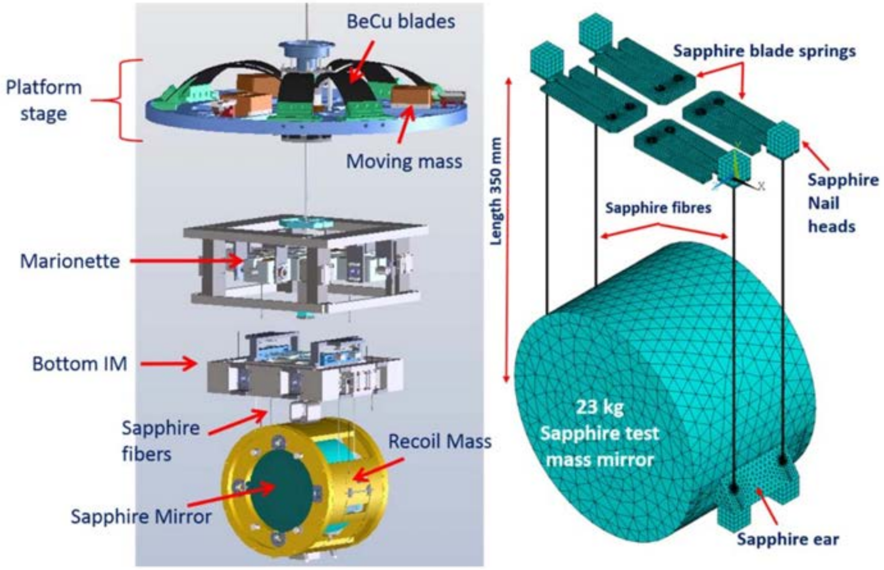
…and cryogenic?



[*Source:* T. Accadia et al. "Virgo: a laser interferometer to detect gravitational waves ", JINST 7 P03012 (2012)]

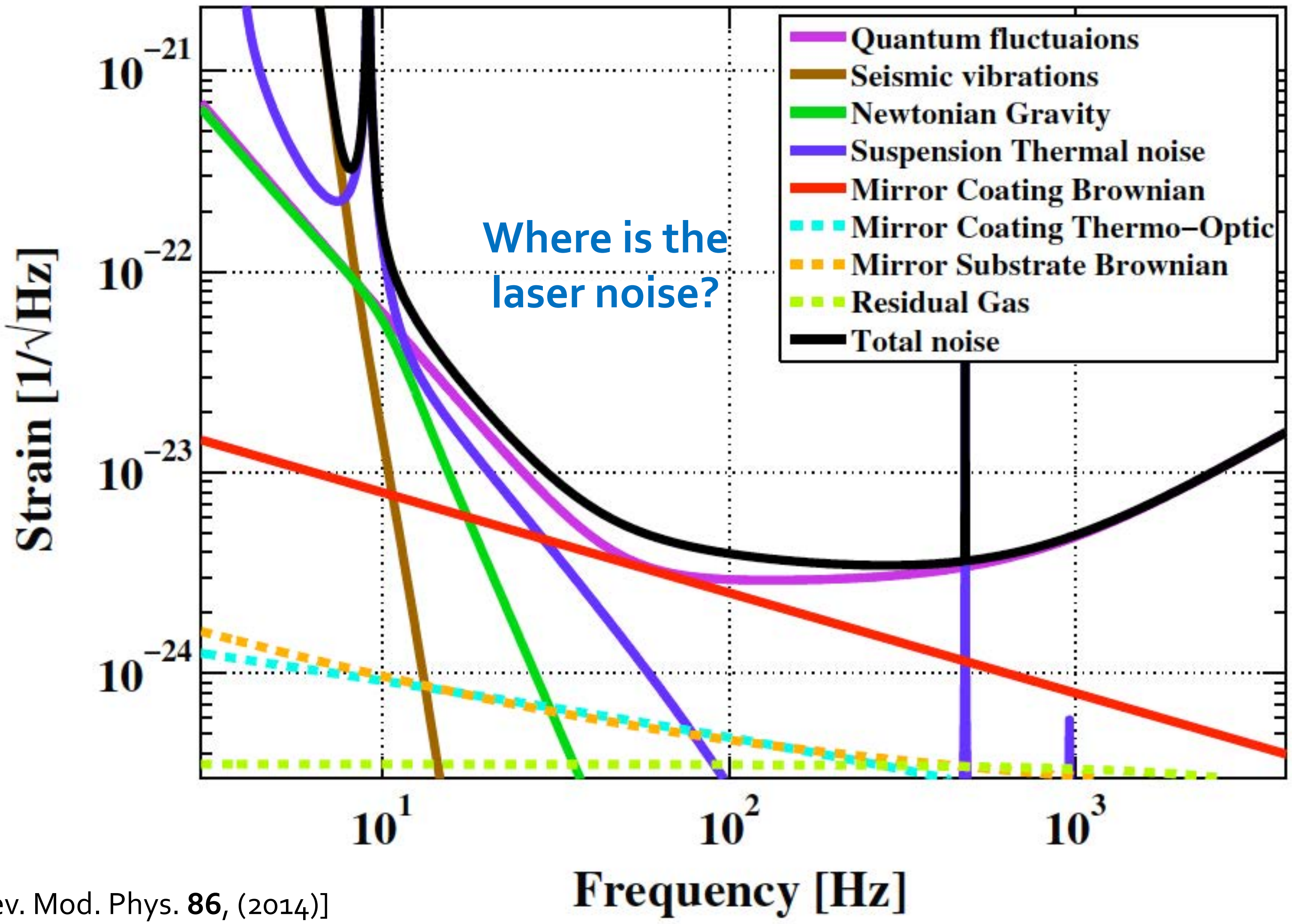


[*Source:* T. Aki et al., "Vibration isolation system with a compact damping system for power recycling mirrors of KAGRA", Class. Quantum Grav. **36** (2019) 095015]



[*Source:* R. Kumar et al., "Status of the cryogenic payload system for the KAGRA detector", Journal of Physics: Conference Series **716** (2016)]

Design sensitivity of aLIGO

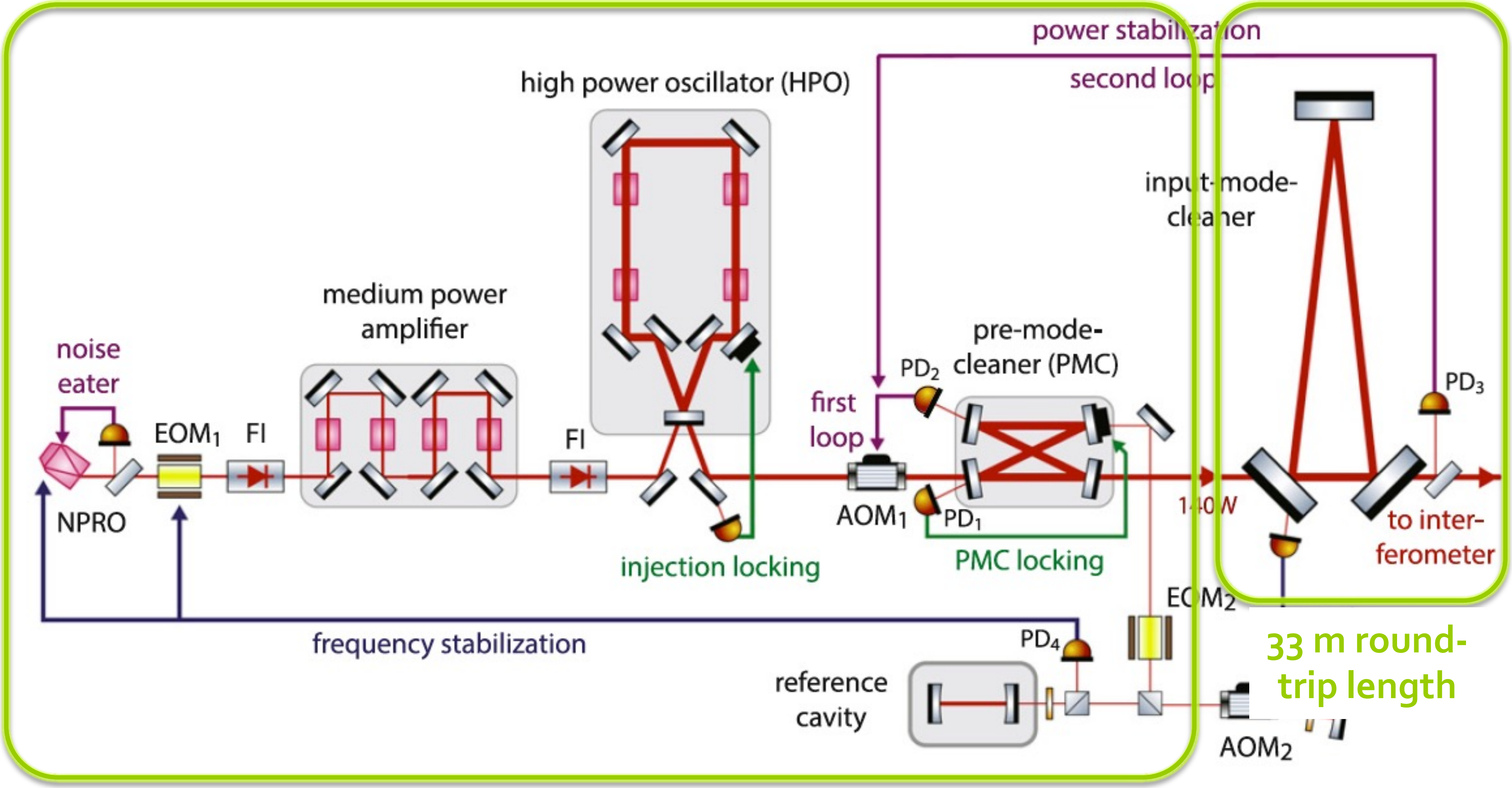


[*Image:* R. X. Adhikari, Rev. Mod. Phys. **86**, (2014)]

High power ultrastable laser systems (here: aLIGO)

[*Photo from:* www.advancedligo.mit.edu courtesy AEI-Max Planck / LZH]

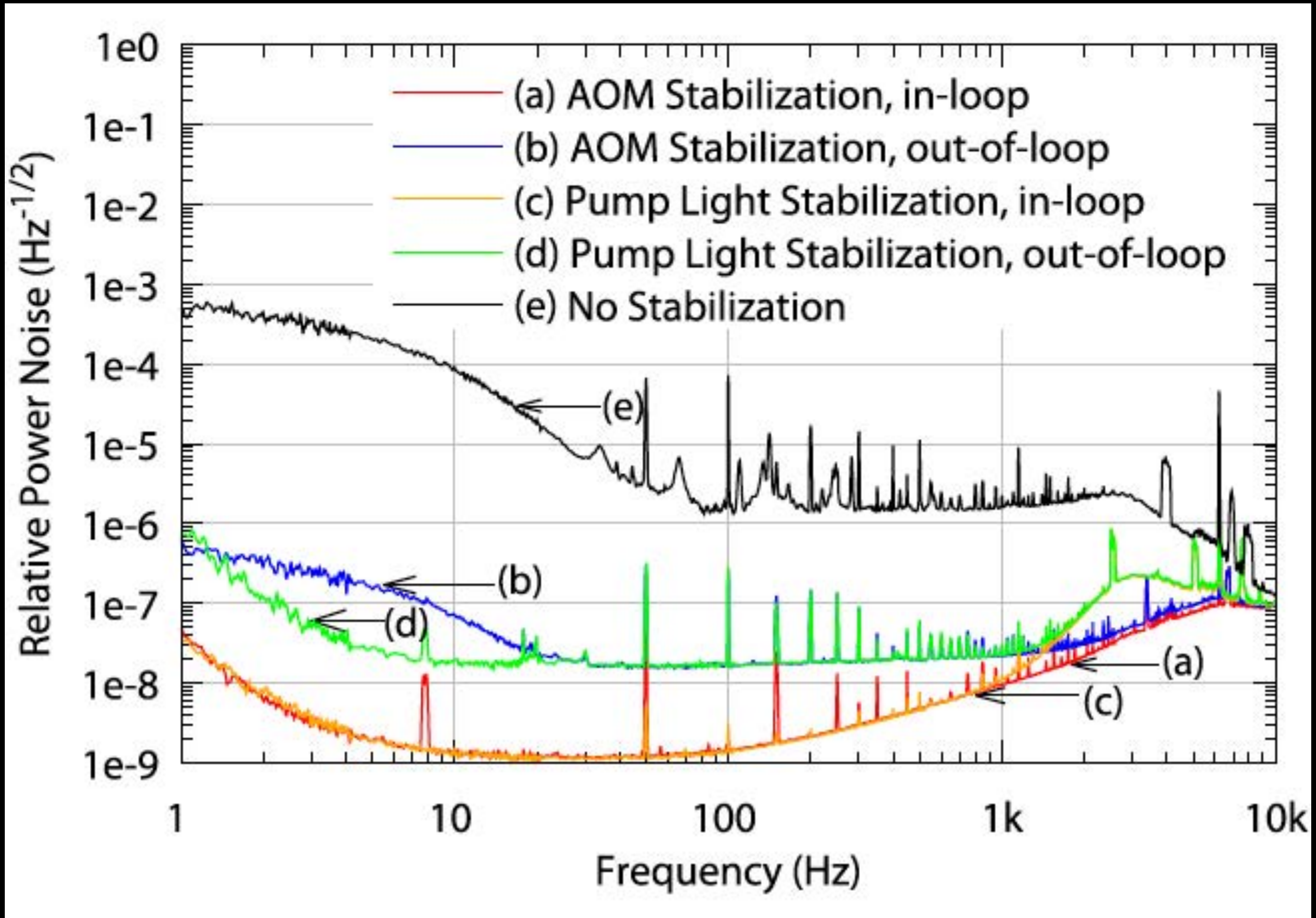
The aLIGO laser system (until ~2019)



[*Image:* LIGO Scientific Collaboration, Class. Quantum Grav. **32** (2015)]

approx. 1.5 x 3 m table

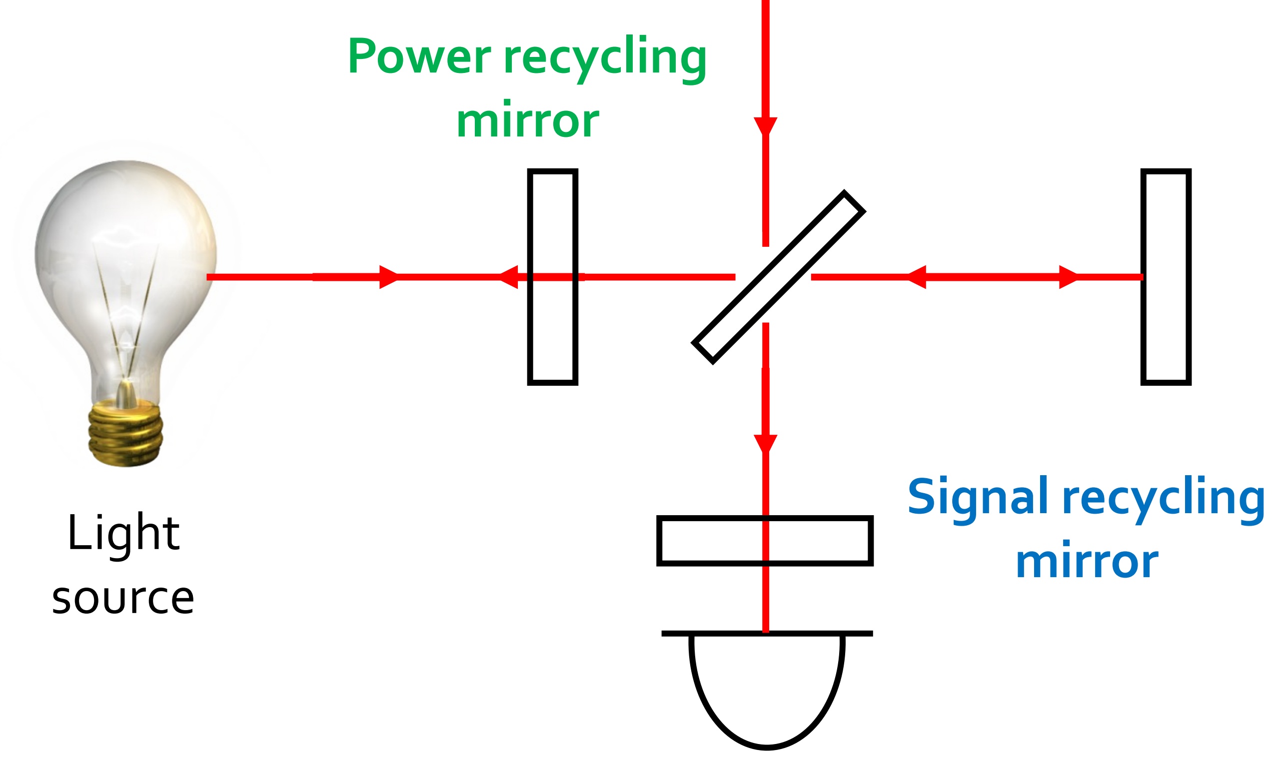
Power noise of the current aLIGO laser system



[F. Thies et al., Nd:YVO_4 high-power master oscillator power amplifier laser system for second-generation gravitational wave detectors, Opt. Lett. **44** (3) 2019]

Recycling techniques (power & signal recycling)

MI operation point near destructive interference: What happens?



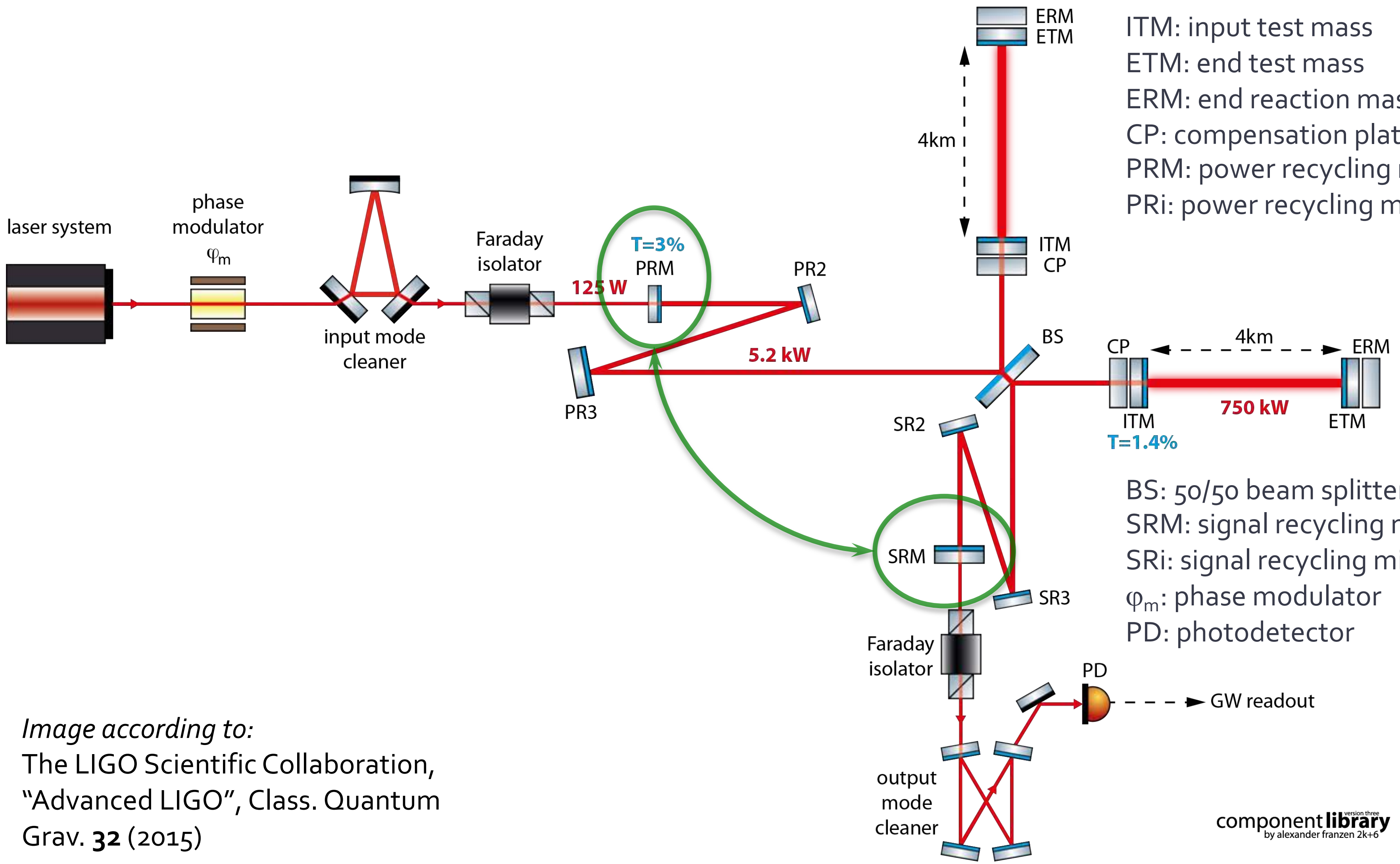
What does the GW do with the interferometer?

⇒ It stretches and compresses spacetime!

⇒ Acts like a phase modulation (generates signal sidebands)

⇒ Maximise interaction of the GW with the interferometer!

Simplified optical setup of aLIGO



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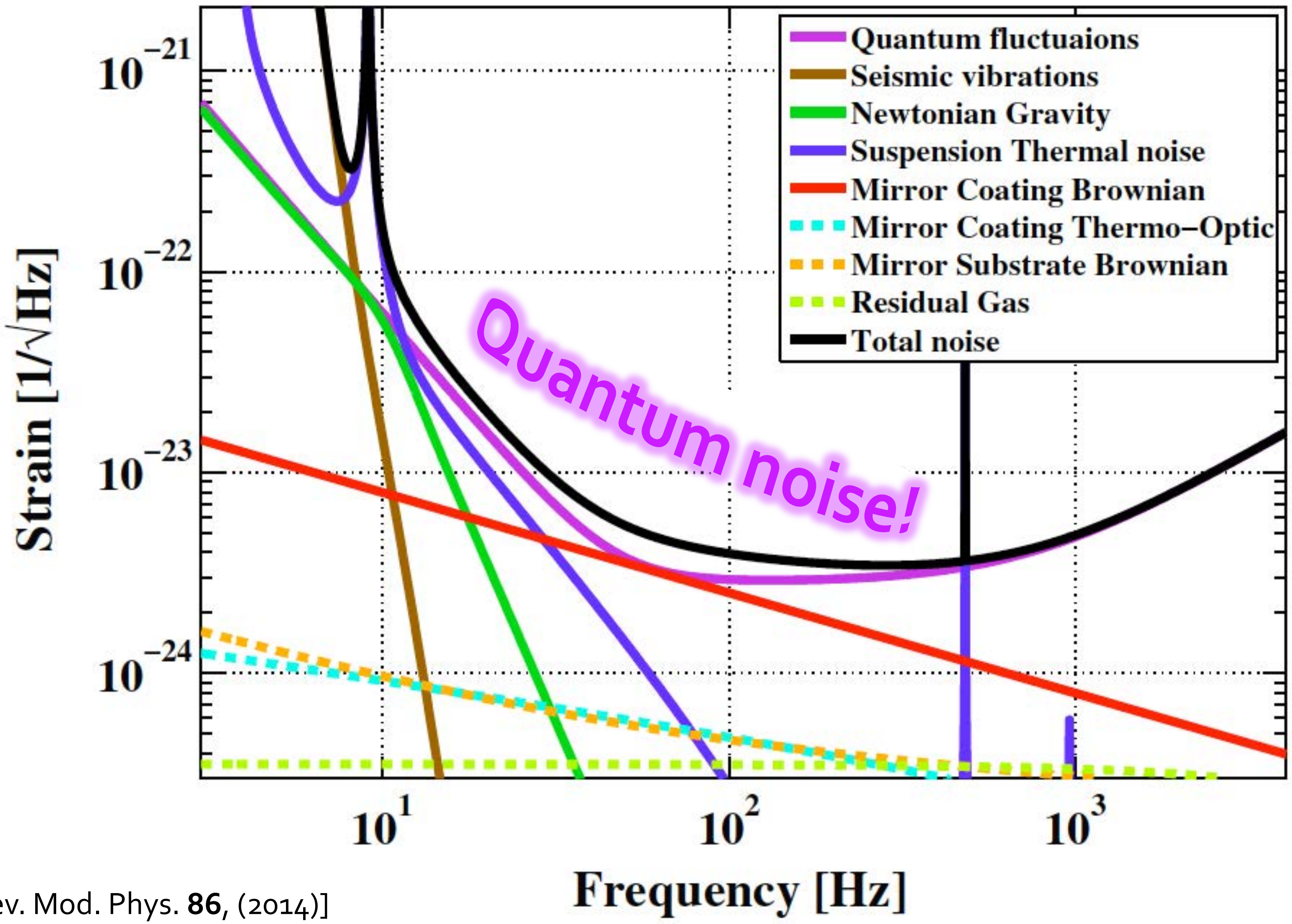
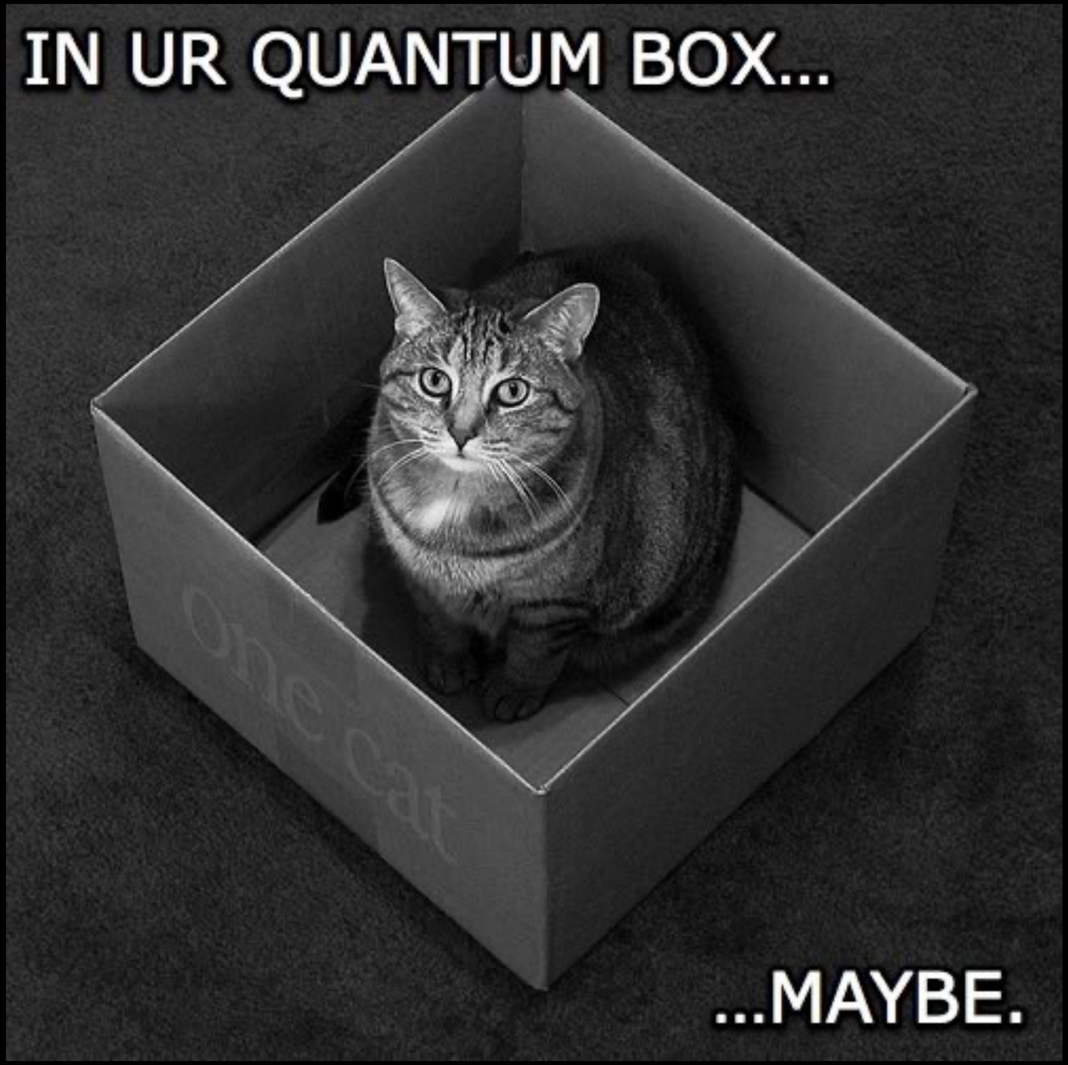


[*Image:* R. X. Adhikari, Rev. Mod. Phys. **86**, (2014)]

Quantum noise: Heisenberg & Co.



Is quantum noise relevant?

PHYSICAL REVIEW LETTERS

VOLUME 45 | 14 JULY 1980 | NUMBER 2

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

Carlton M. Caves

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

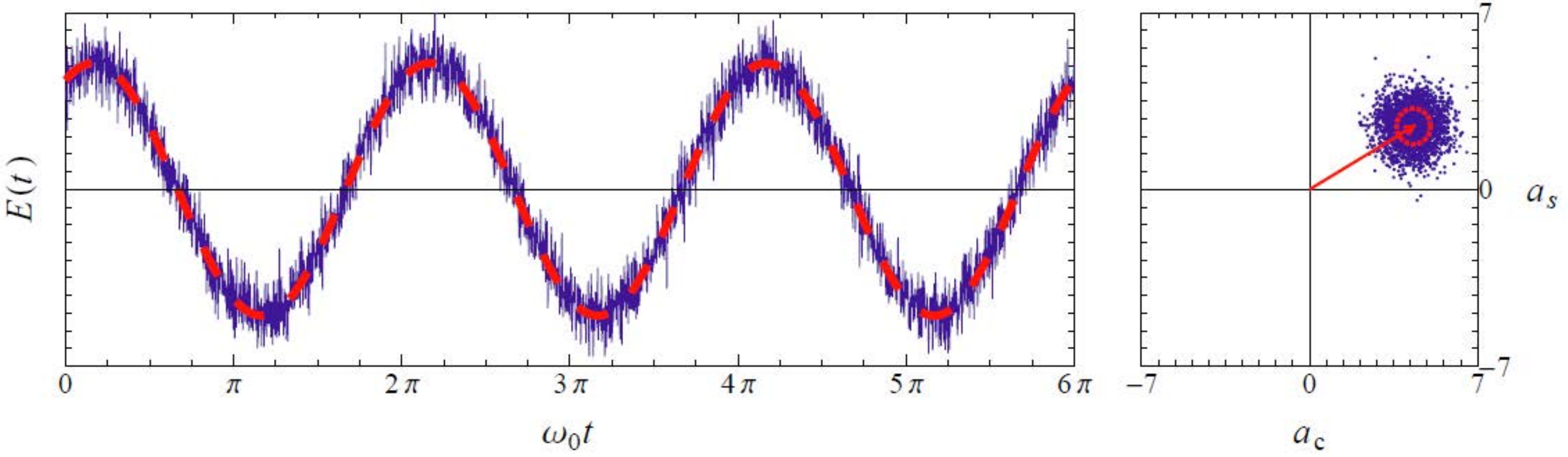
(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

Two visualisations of light

Time series:

Phase state diagramme:



[Bilder: S. Danilishin et al, Living Rev. Relativity, 15, (2012), 5, http://www.livingreviews.org/lrr-2012-5]

$\Rightarrow$ **The tip of the phasor is somewhere within the „blue-dotted area" (Gaussian distribution in phase space)**

Quadrature operators

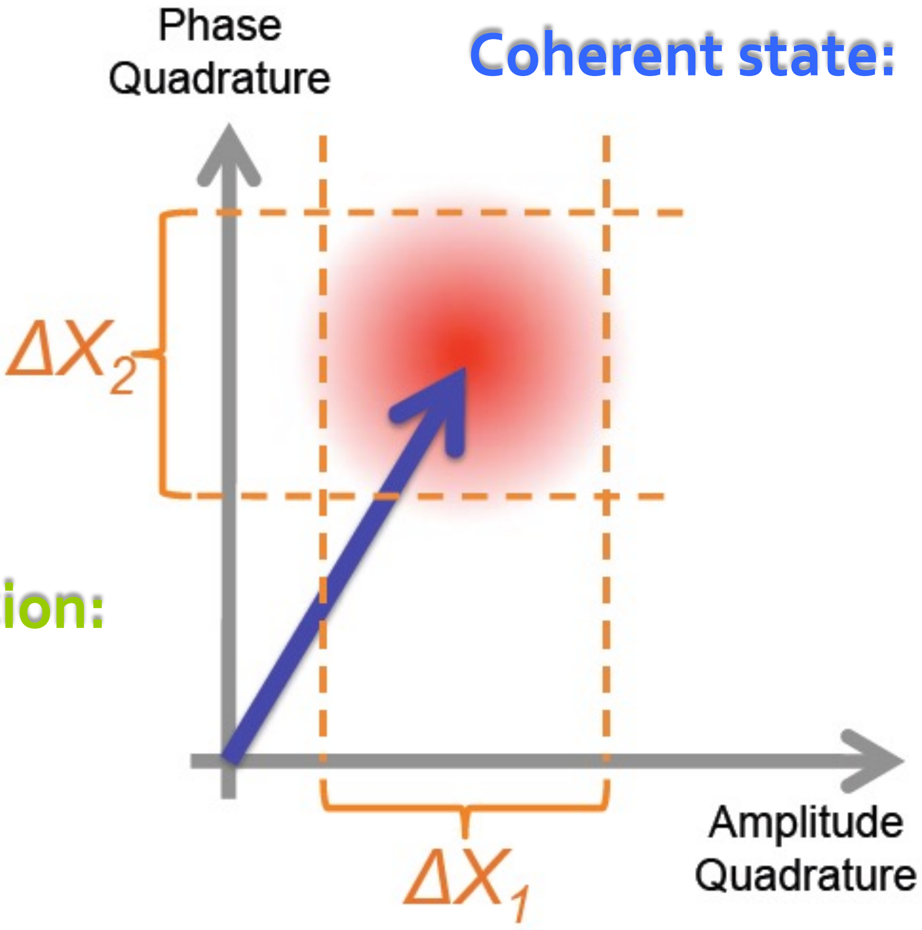
Quadrature operators:

$$\hat{X}_1 = \hat{a}^\dagger + \hat{a}$$
$$\hat{X}_2 = i(\hat{a}^\dagger - \hat{a})$$

Heisenberg uncertainty relation:

$$\Delta\hat{X}_1 \cdot \Delta\hat{X}_2 \geq 1$$

Coherent state:

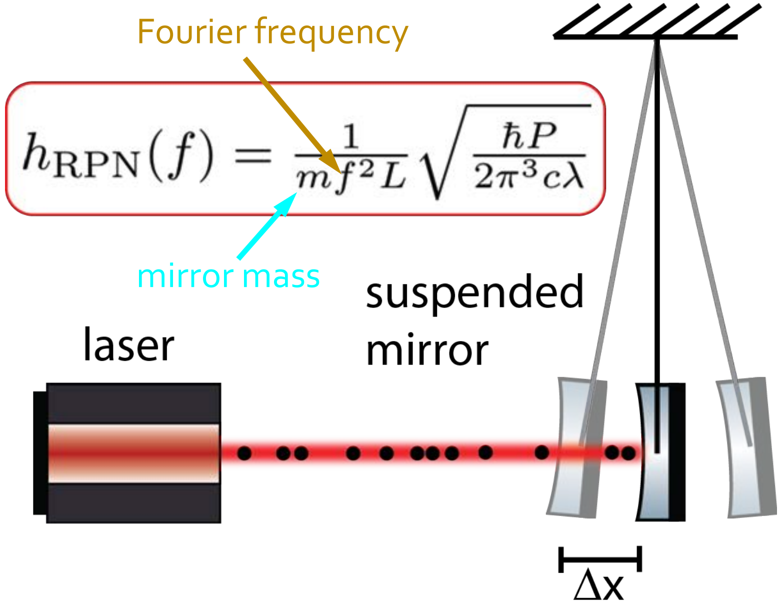


[*Image*: S. Hild]

Quantum noise in an interferometer

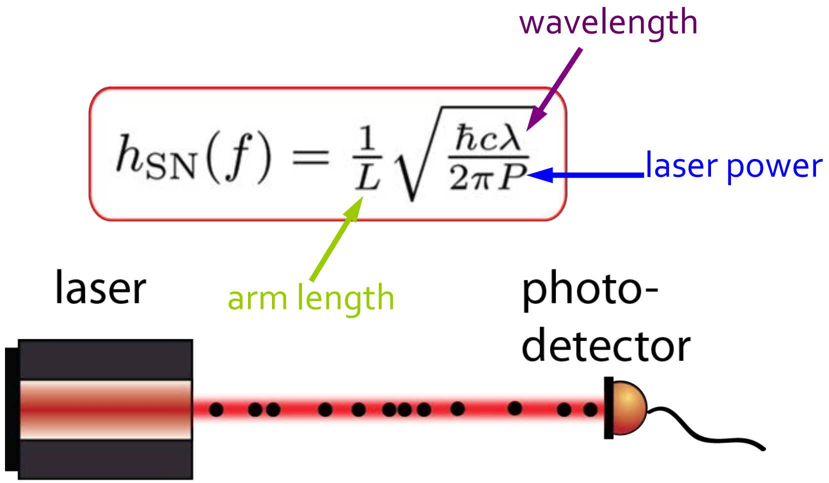
radiation pressure noise (RPN)

$$h_{\mathrm{RPN}}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$



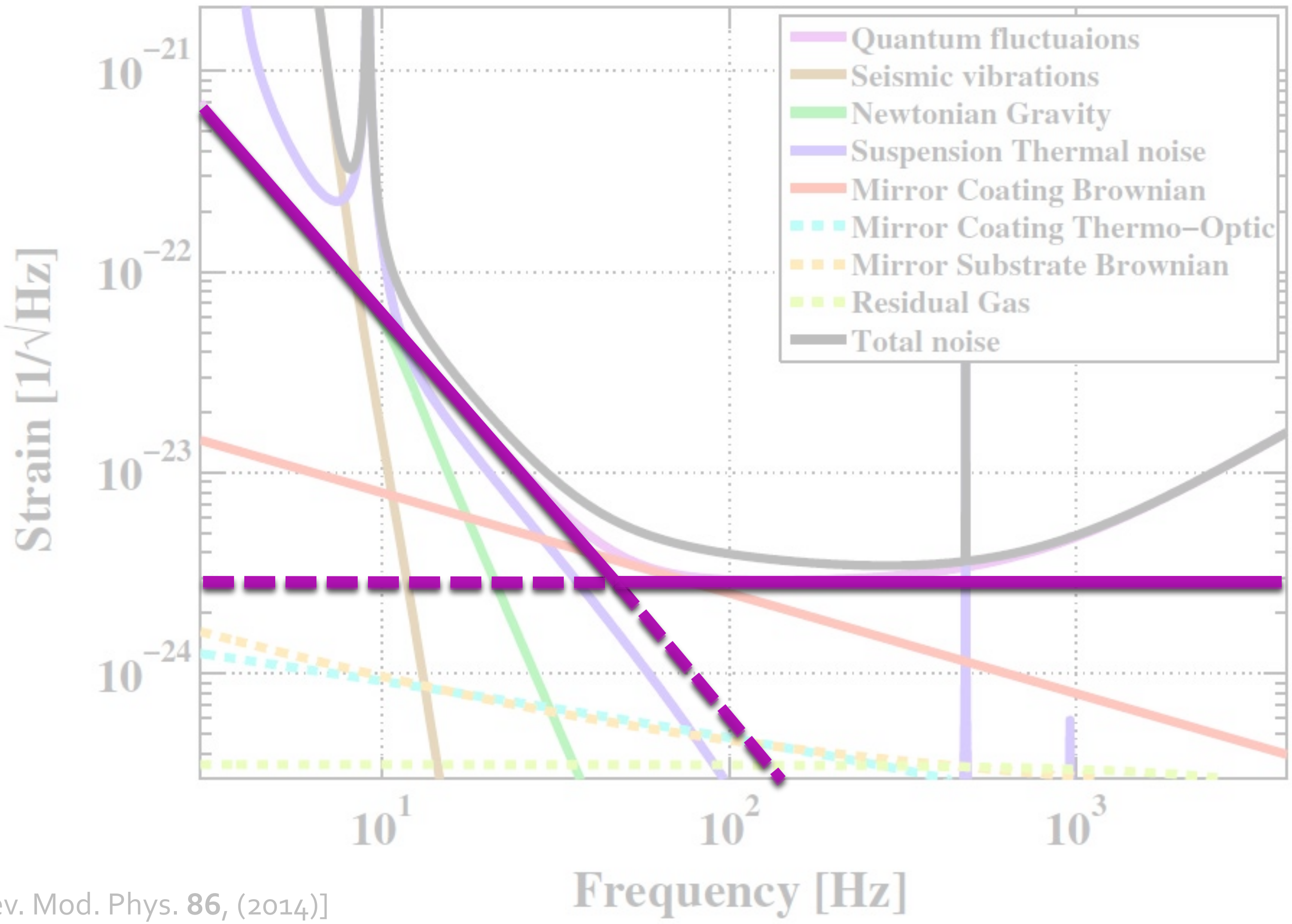
relative shot noise (SN)

$$h_{\mathrm{SN}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$



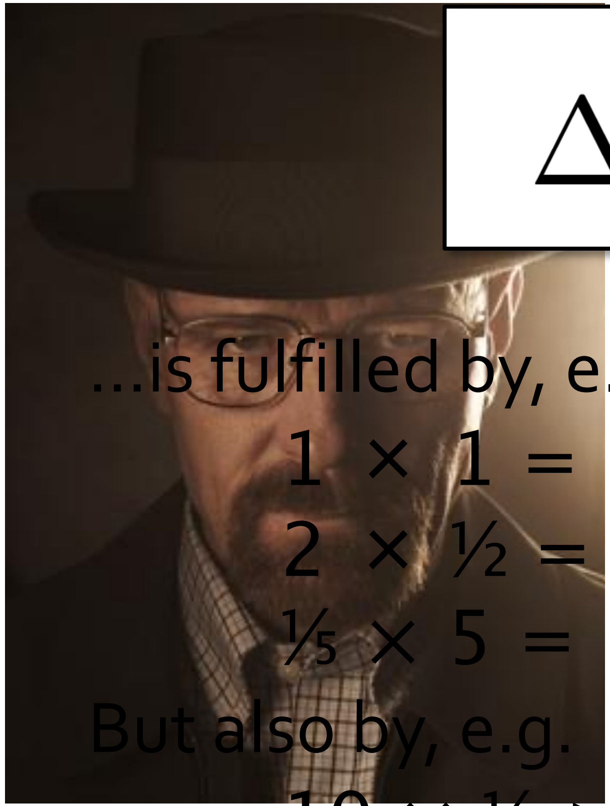
Backaction noise ⟷ **Detection noise**

The Standard Quantum Limit (SQL) of interferometry



[*Image:* R. X. Adhikari, Rev. Mod. Phys. **86**, (2014)]

Heisenberg Uncertainty Relation



"Heisenberg"

$$\Delta\hat{X}_1 \cdot \Delta\hat{X}_2 \geq 1$$

…is fulfilled by, e.g.

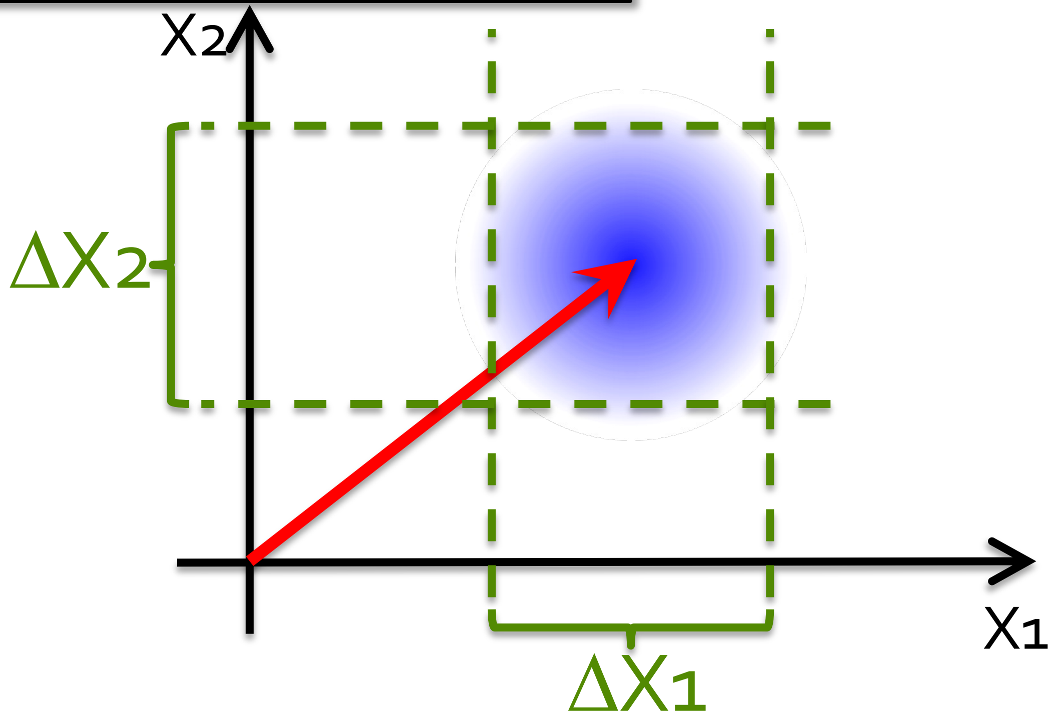
$1 \times 1 = 1$

$2 \times ½ = 1$

$⅕ \times 5 = 1$

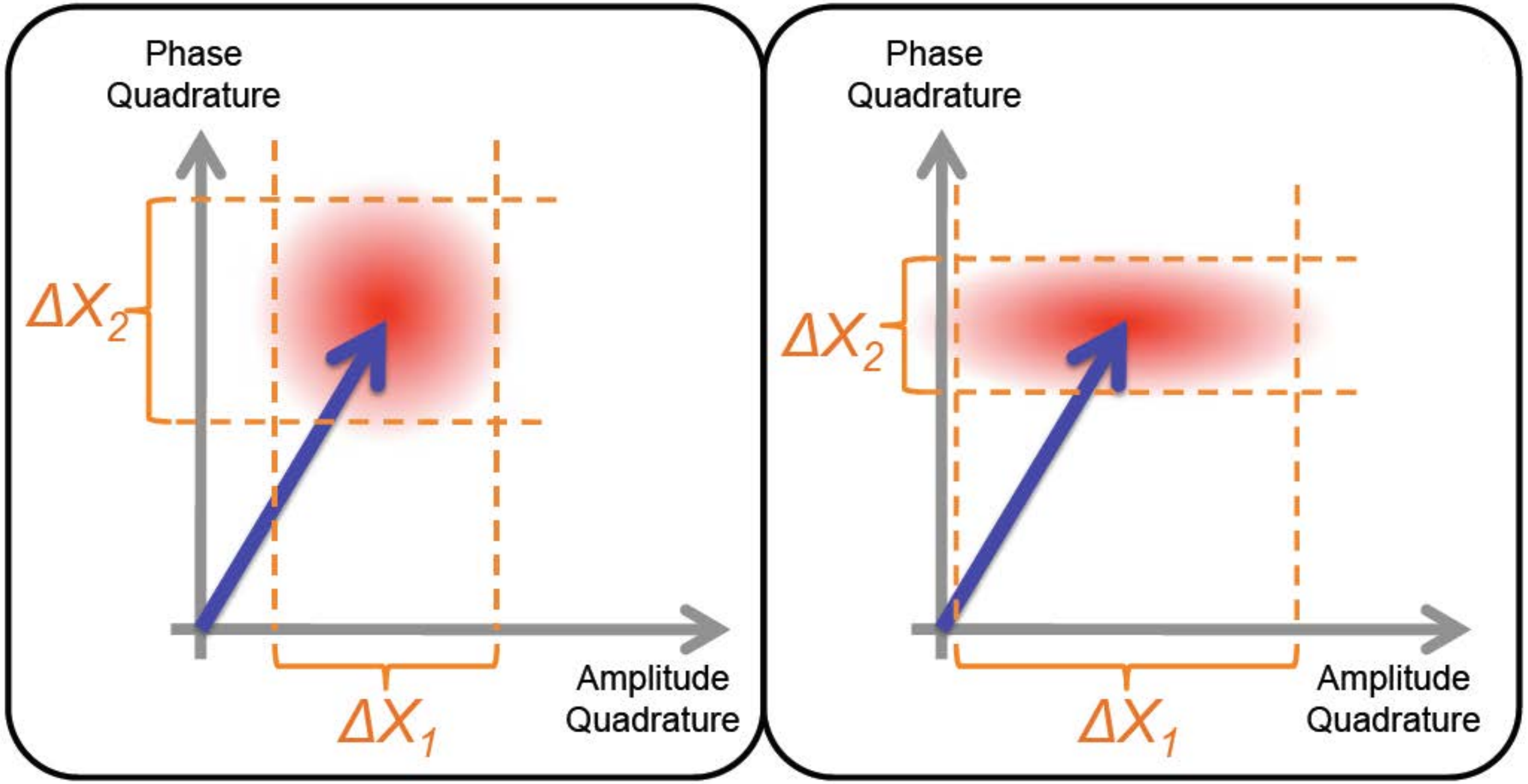
But also by, e.g.

$10 \times ⅓ > 1$



=> we can *reduce* the uncertainty in one measurement quantity, but at the cost of *increasing* the uncertainty in the other measurement quantity!

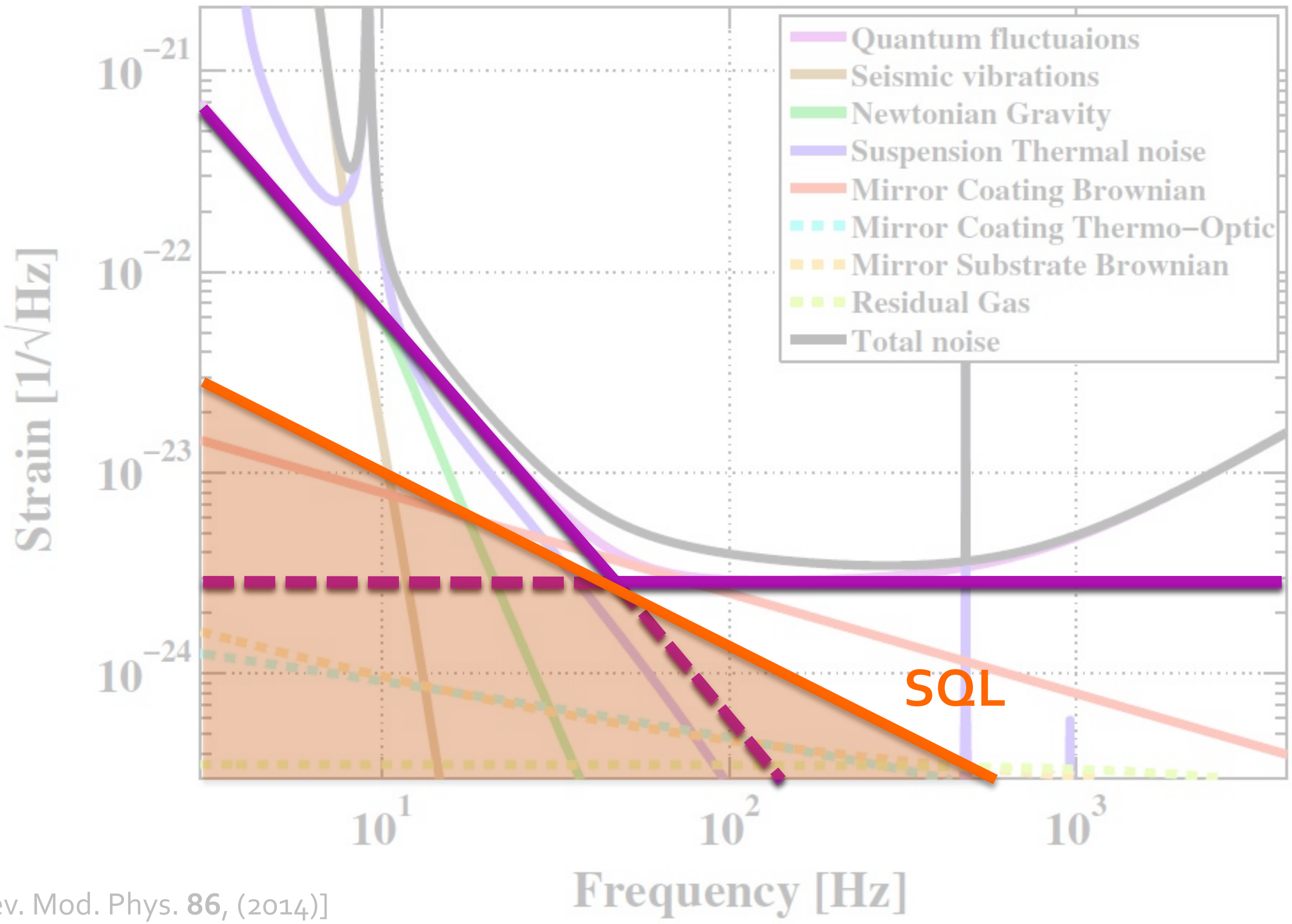
Coherent vs. squeezed state



Heisenberg merely says

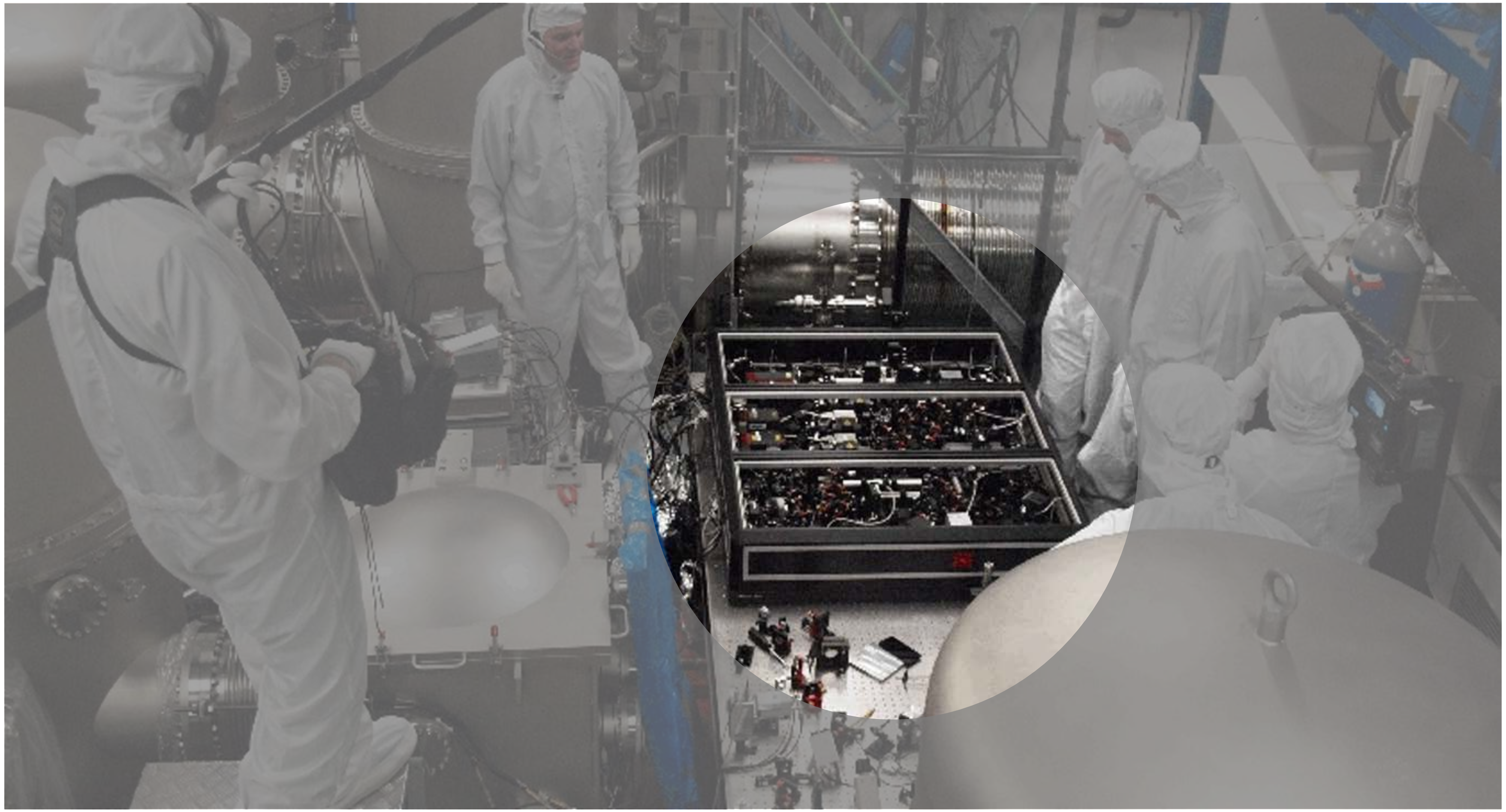
$$\Delta \hat{X}_1 \cdot \Delta \hat{X}_2 \geq 1$$

The Standard Quantum Limit (SQL) of interferometry



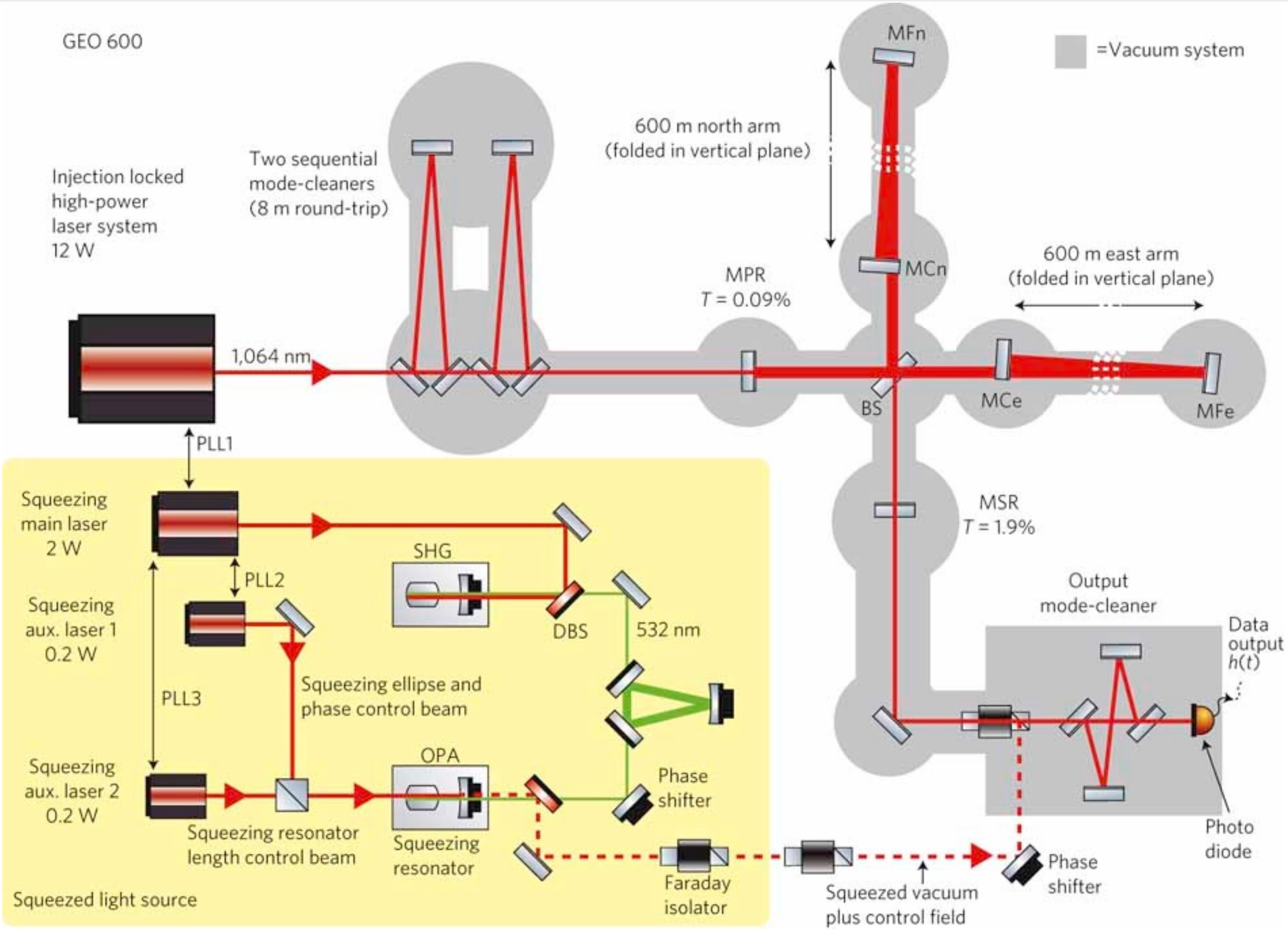
[*Image:* R. X. Adhikari, Rev. Mod. Phys. **86**, (2014)]

GEO600: The first GWD to use squeezed light (since 2010!)!



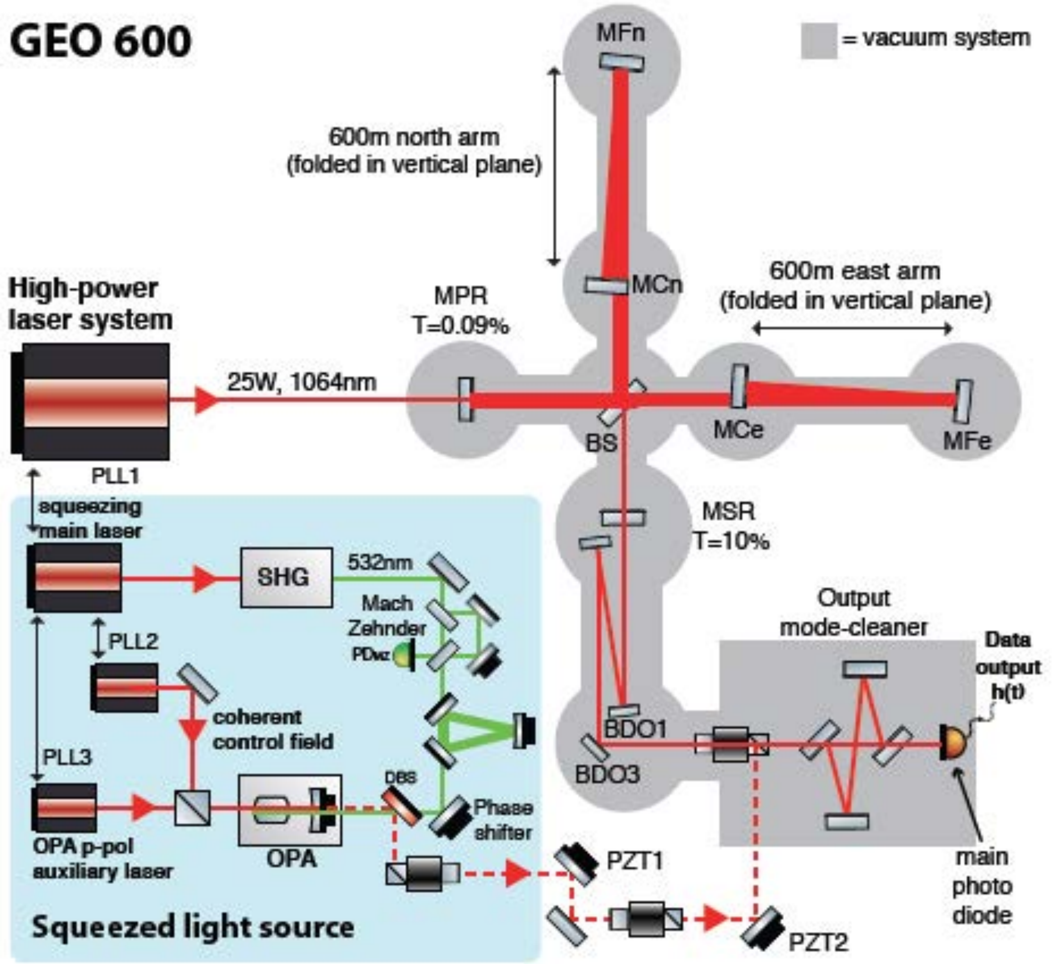
[Nat. Phys. **7**, 962–965 (2011)]

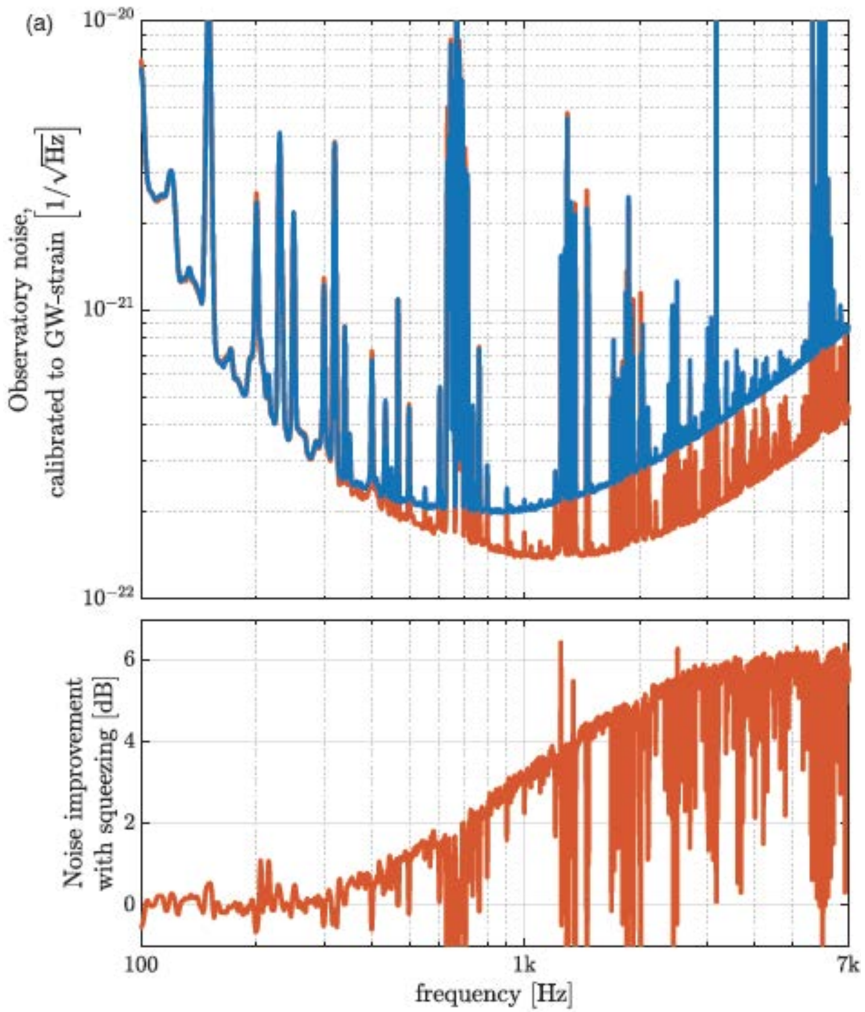
The GEO600 squeezed light source



Source: LIGO Scientific Collaboration „A gravitational wave observatory operating beyond the quantum shot-noise limit“, Nature Physics (2011), DOI: 10.1038/NPHYS2083

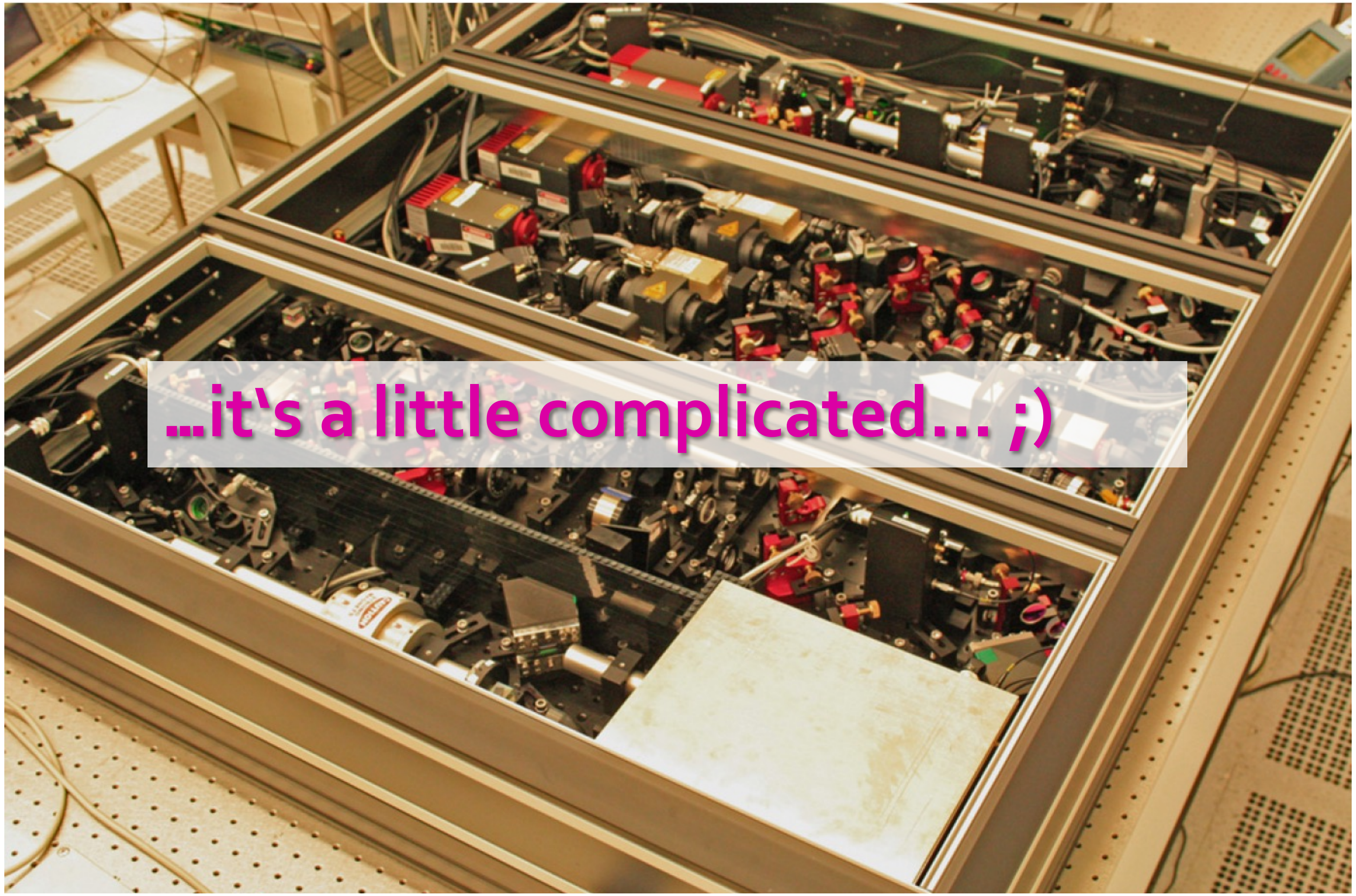
6 dB (fixed-quadrature) squeezed light at GEO600





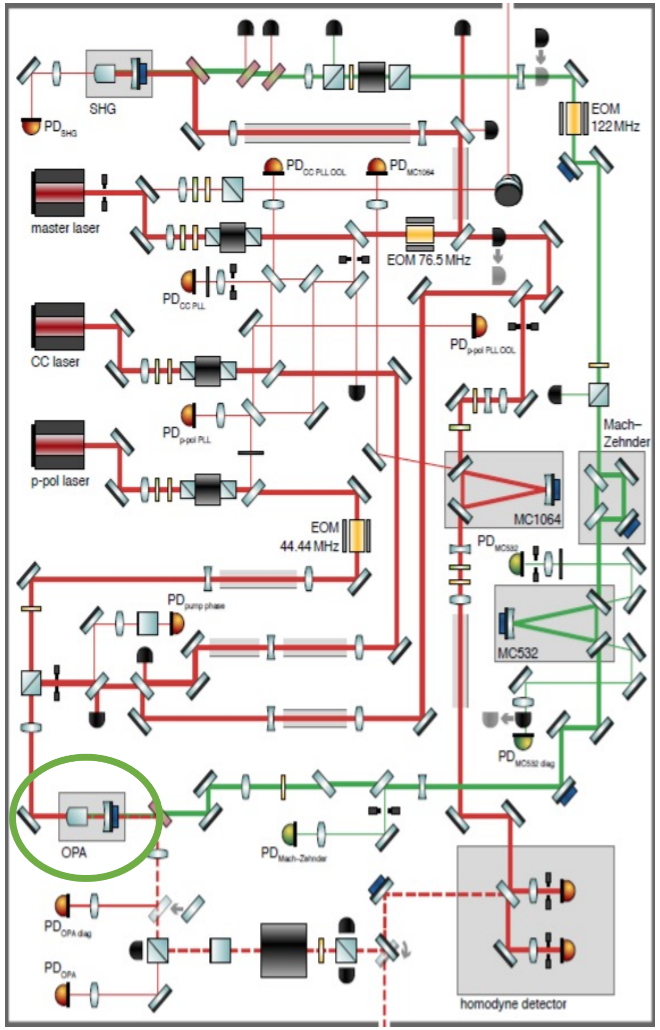
[J. Lough et al., "First demonstration of 6 dB quantum noise reduction in a kilometer scale gravitational wave observatory", Phys. Rev. Lett. **126**, 041102 (2021)]

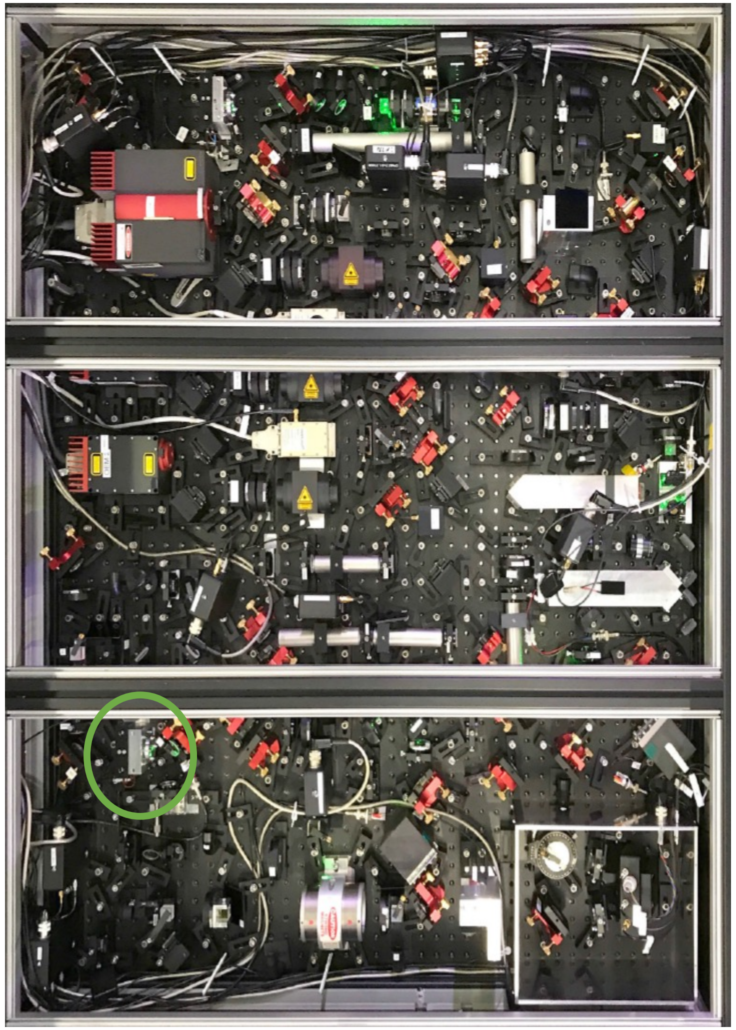
How do you produce squeezed light?



[Image: Vahlbruch et al., "The GEO600 squeezed light source", Class. Quantum Grav. **27** (2010)]

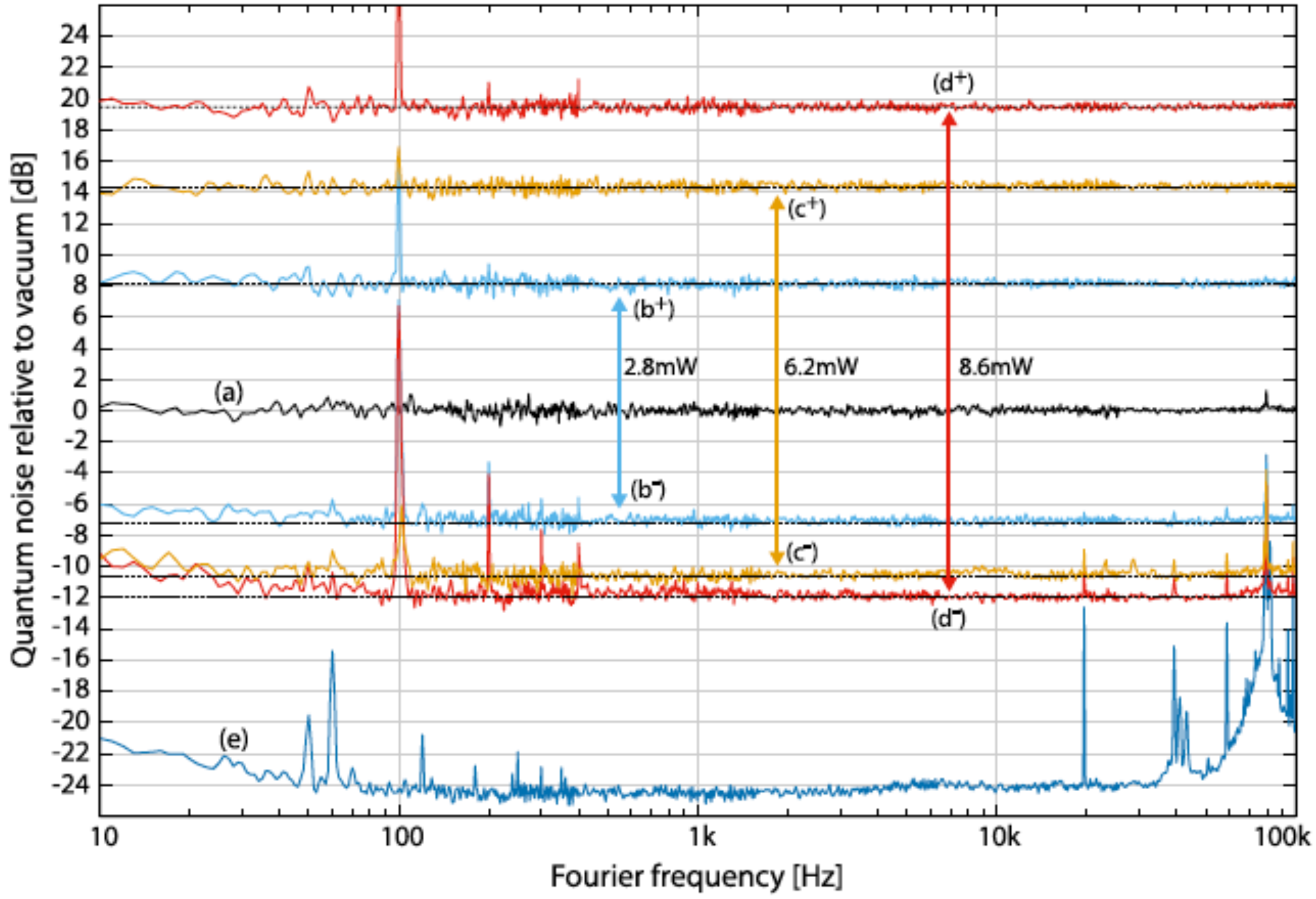
Squeezing at GEO600





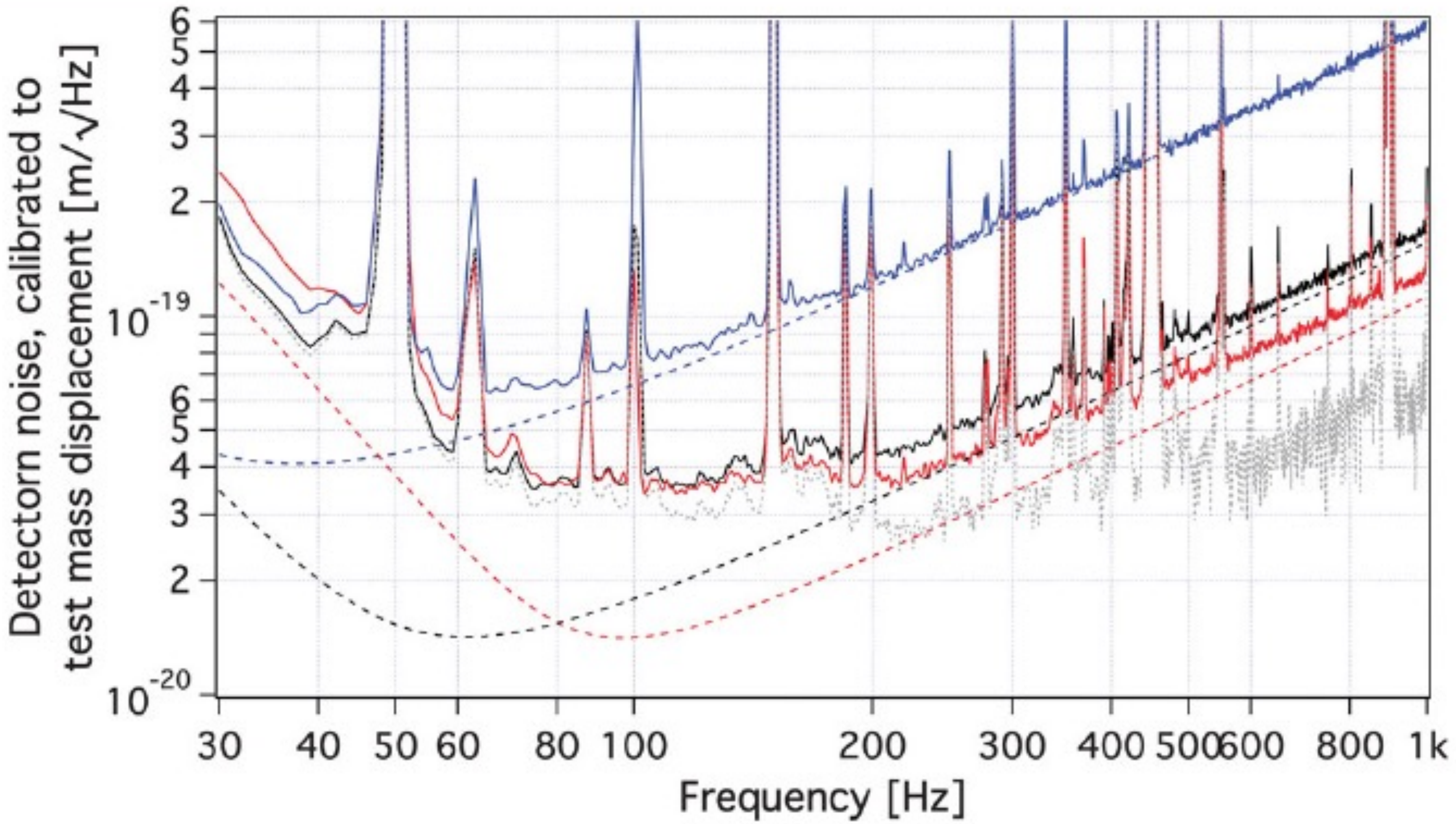
[*Source*: Dissertation E. Schreiber (2018)]

(Low frequency) squeezing for GWDs



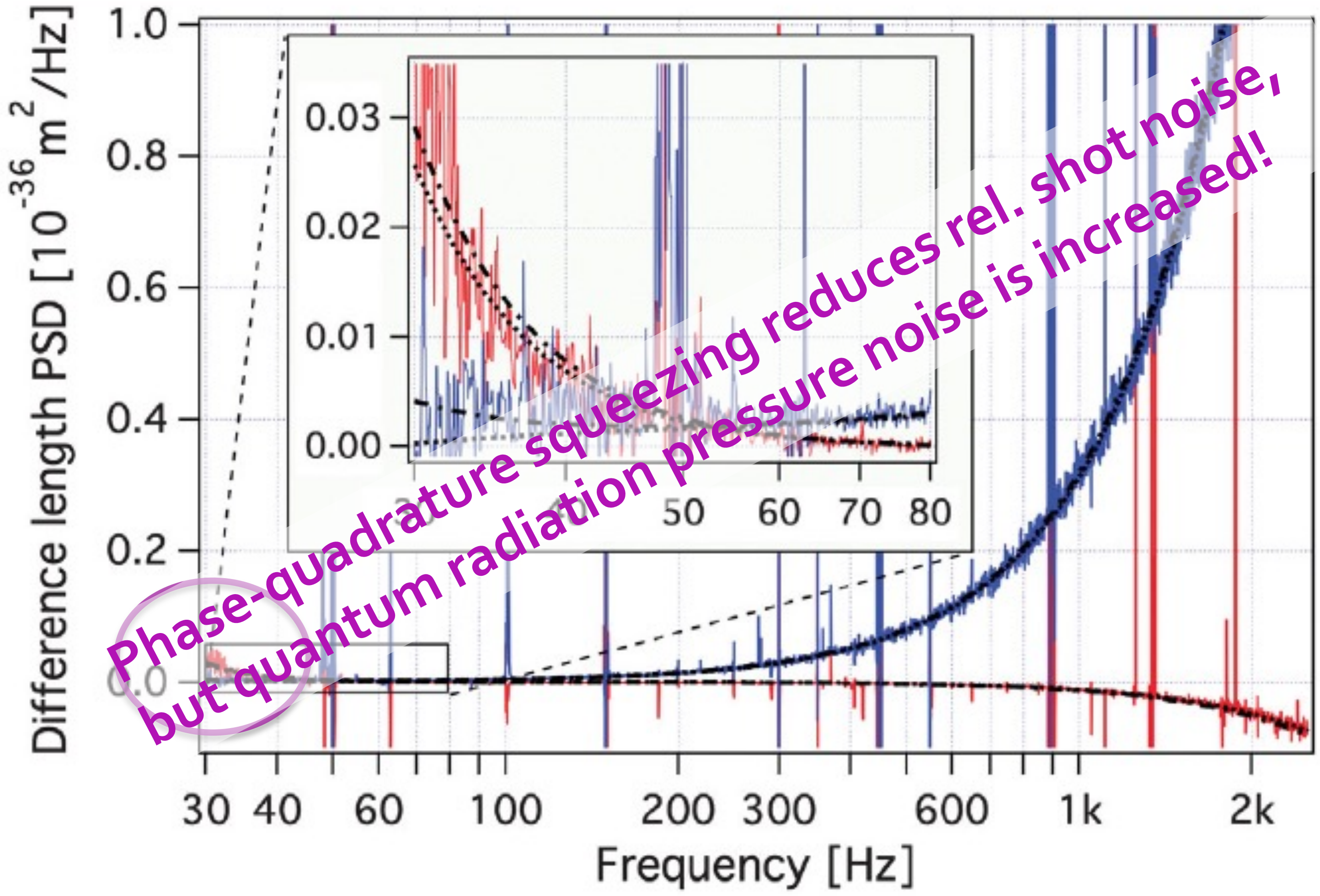
[M. Mehmet and H. Vahlbruch, "High-efficiency squeezed light generation for gravitational wave detectors" *Class. Quantum Grav.* **36** 015014 (2019)]

Fixed-quadrature squeezing at adVirgo



[The Virgo Collaboration & Mehmet et al. „Quantum Backaction on Kg-Scale Mirrors: Observation of Radiation Pressure Noise in the Advanced Virgo Detector " Phys. Rev. Lett. **125**, 131101 (2020)]

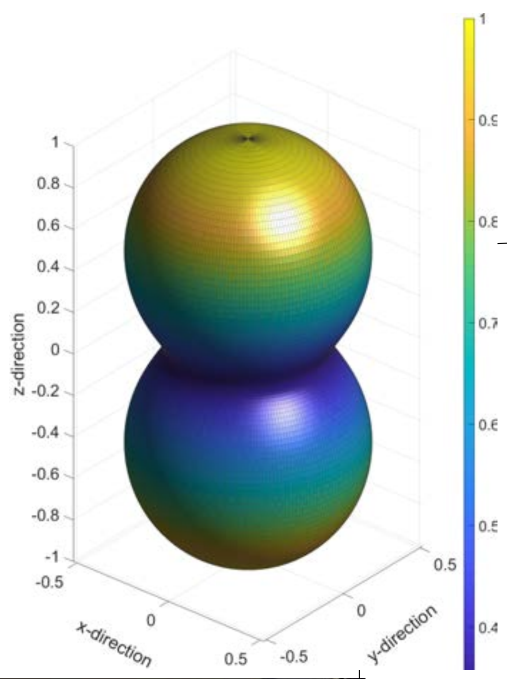
Fixed-quadrature squeezing at adVirgo

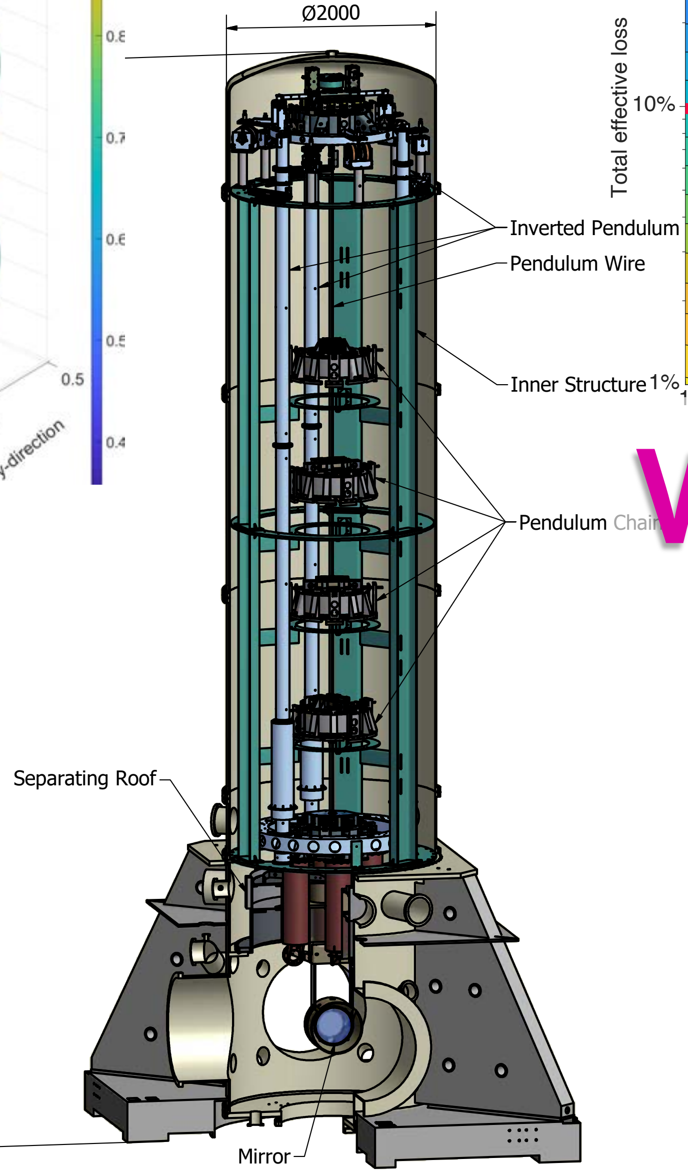


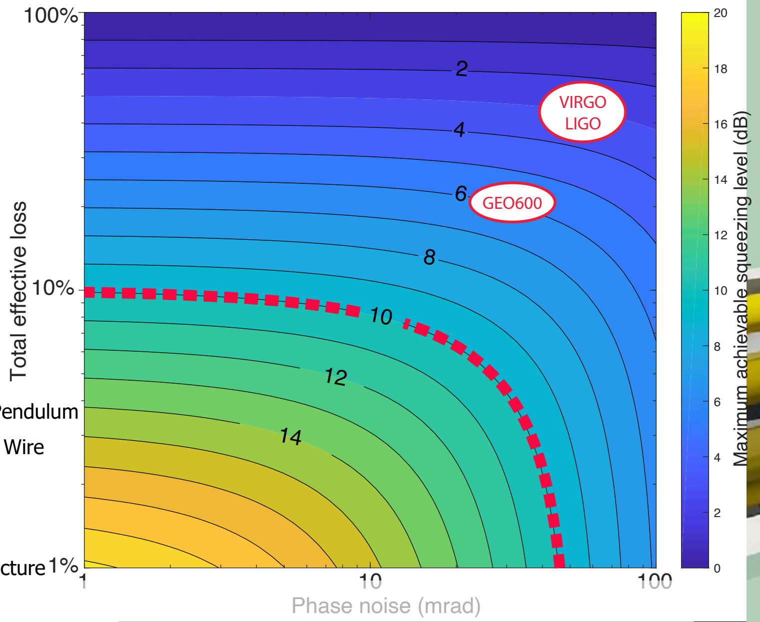
Fixed ampl. quadr. SQZ (normalised)

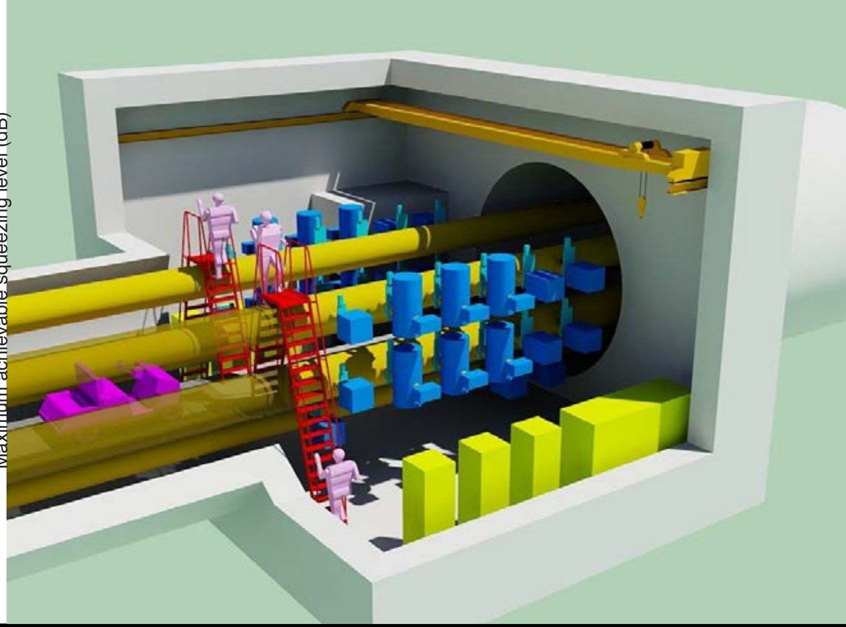
Fixed phase-quadr. SQZ (normalised)

[The Virgo Collaboration & Mehmet et al. „Quantum Backaction on Kg-Scale Mirrors: Observation of Radiation Pressure Noise in the Advanced Virgo Detector " Phys. Rev. Lett. **125**, 131101 (2020)]

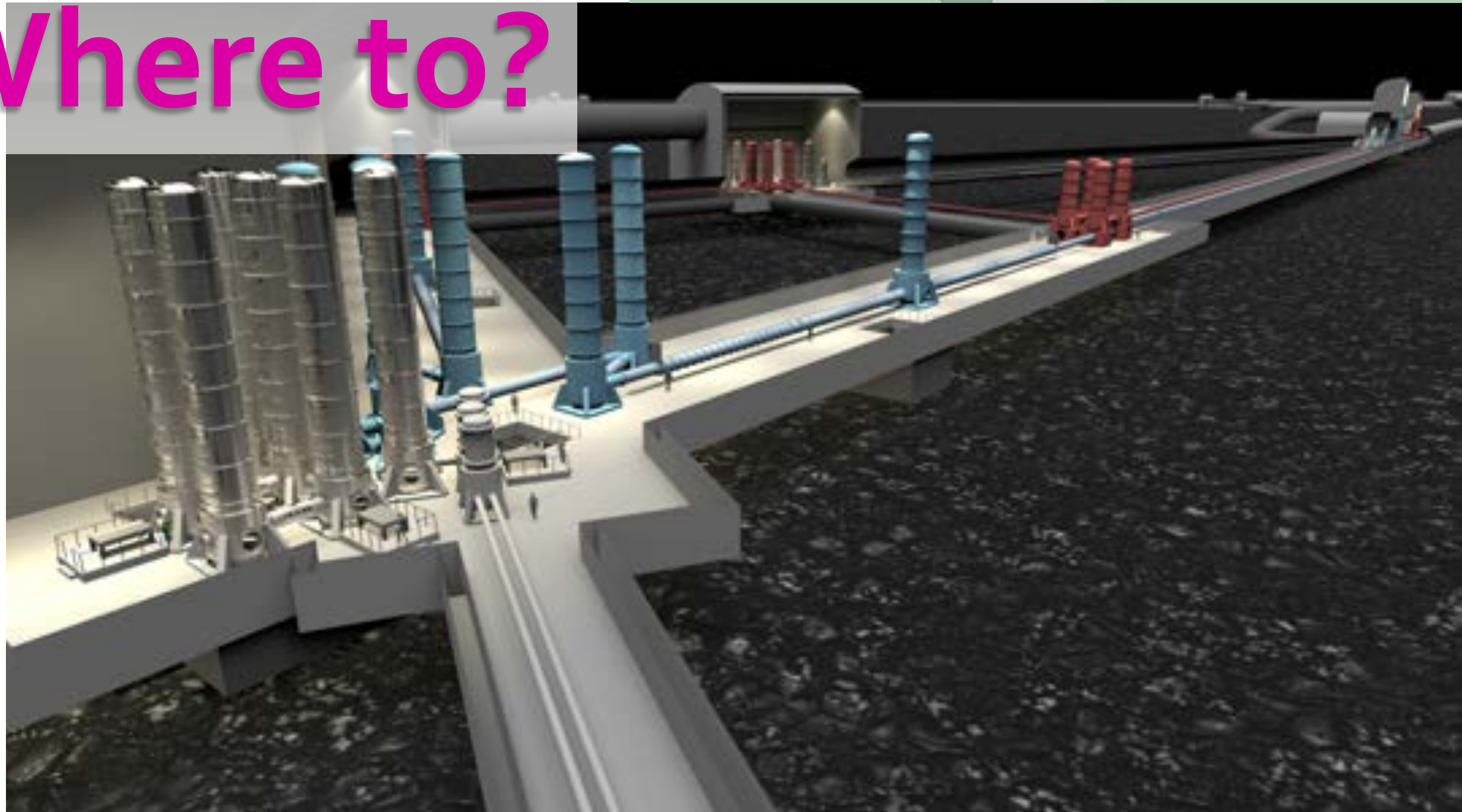

z-direction
x-direction
y-direction


Ø2000
Inverted Pendulum
Pendulum Wire
Inner Structure
Pendulum Chain
Separating Roof
Mirror
10560


Total effective loss
Phase noise (mrad)
Maximum achievable squeezing level (dB)
VIRGO
LIGO
GEO600



Where to?



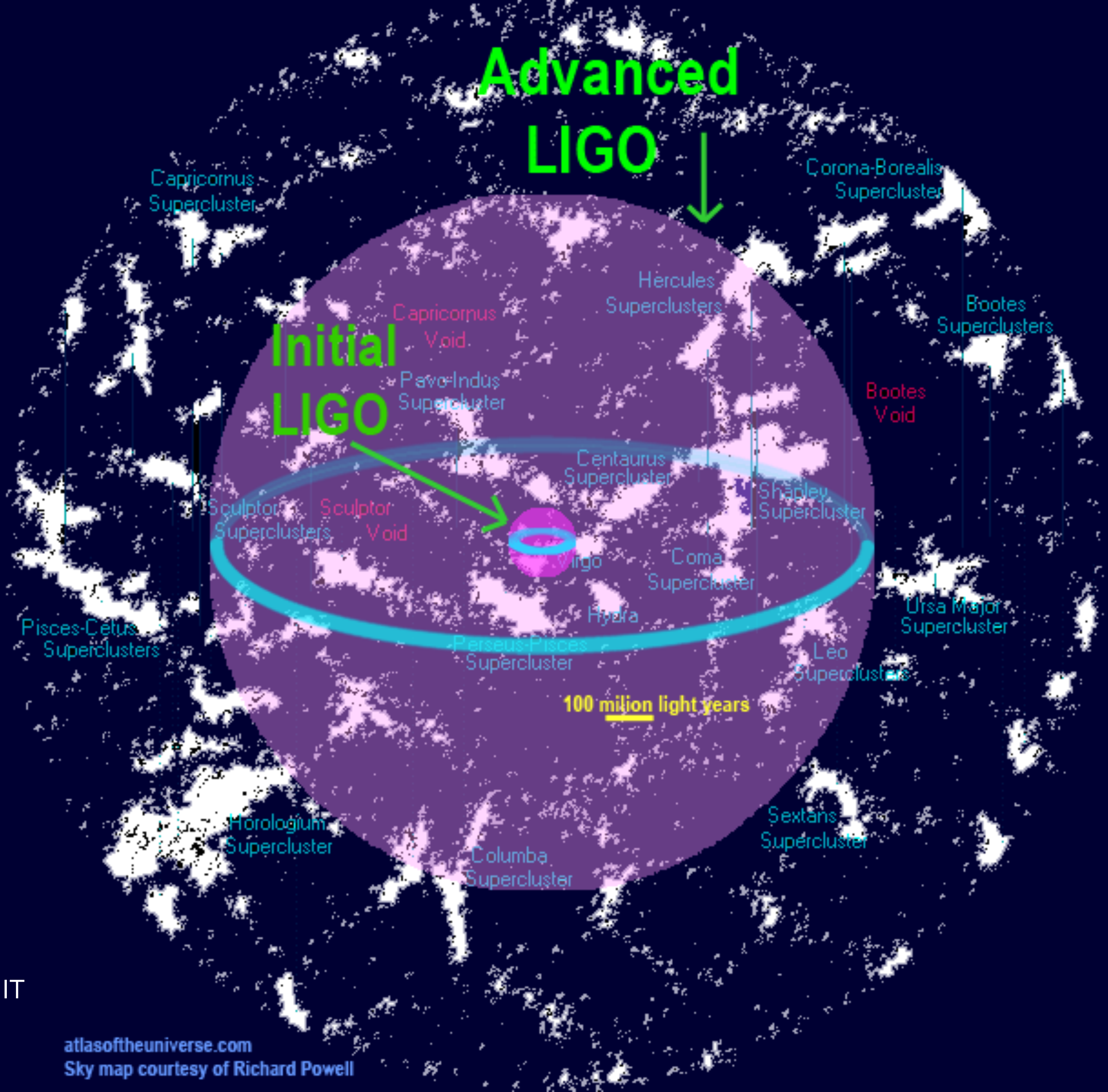
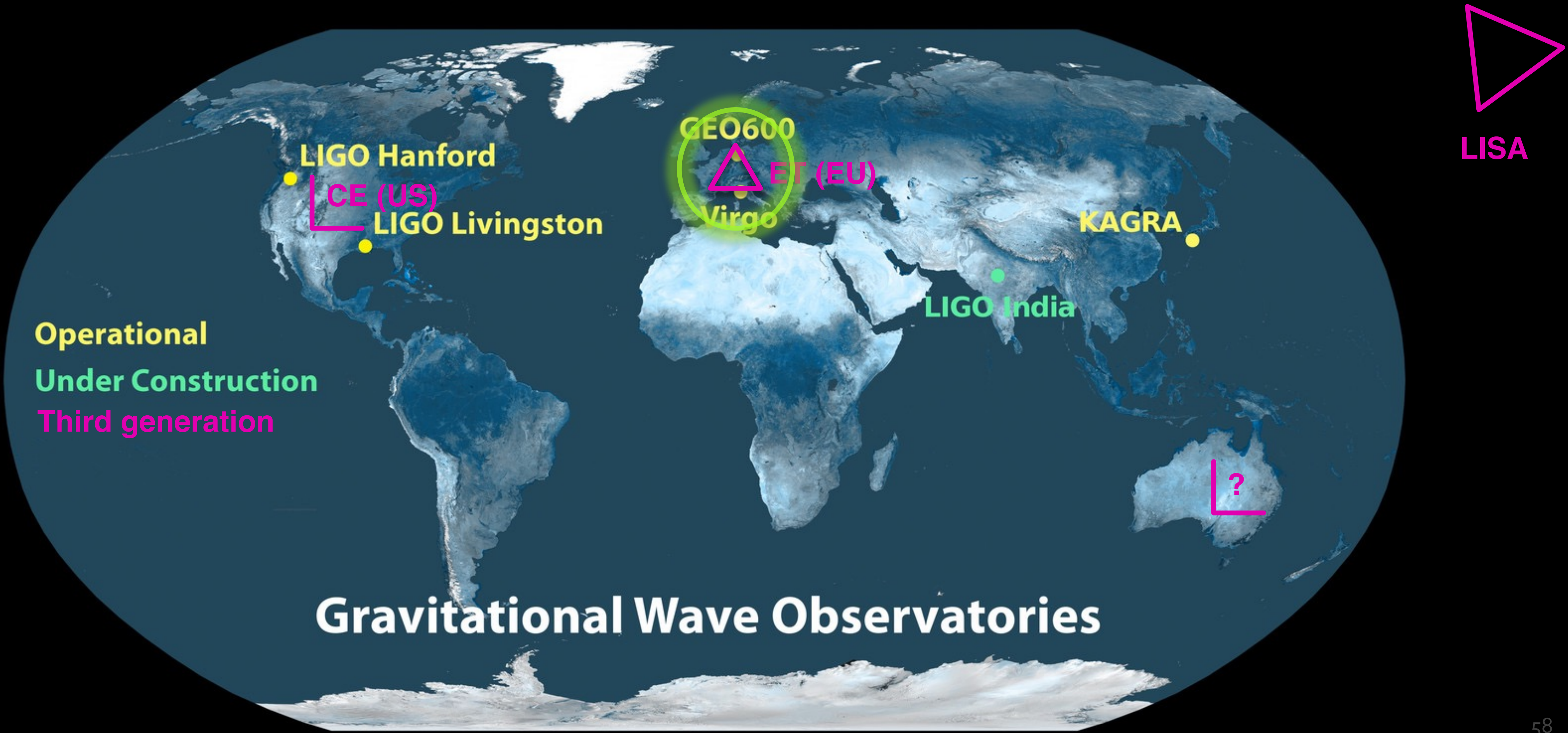


Image:
aLIGO@MIT

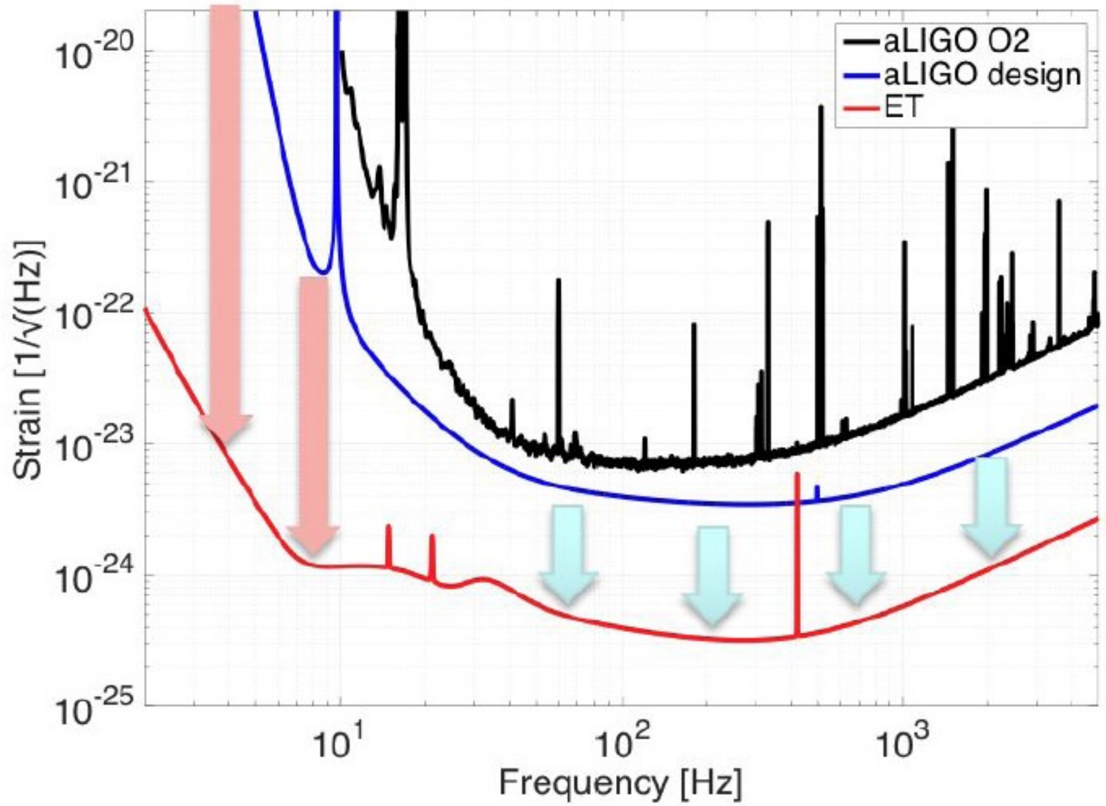
The next generation

The worldwide detector network of the future



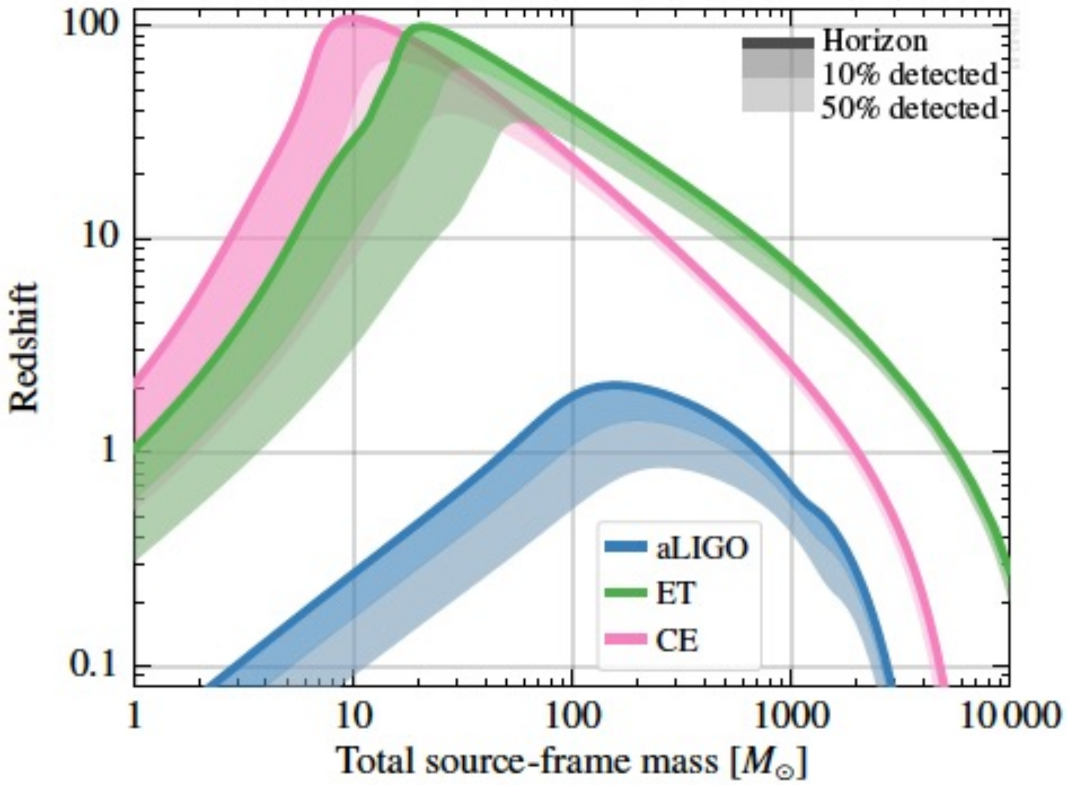
Sensitivities of 3G GWDs

Sensitivity comparison of Advanced LIGO and Einstein Telescope (design)



[source: Einstein Telescope Design Report Update 2020]

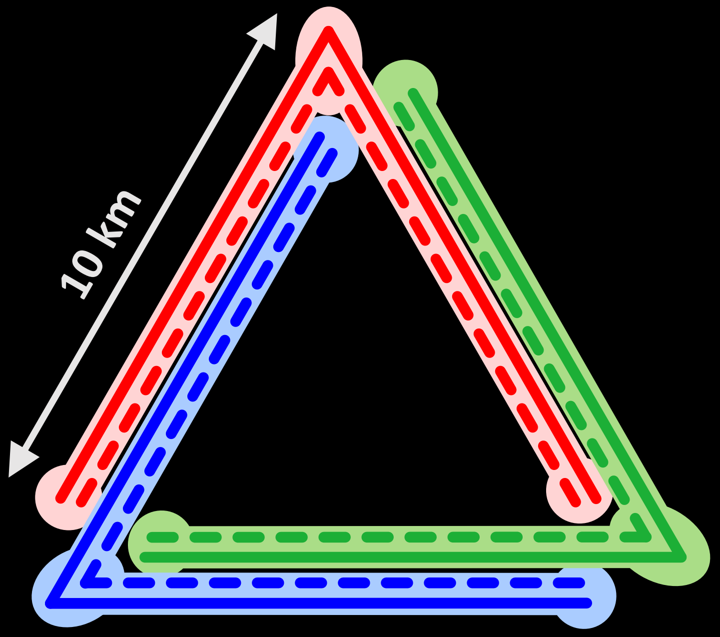
Astrophysical reach for equal-mass, nonspinning binaries for Advanced LIGO, Einstein Telescope and Cosmic Explorer

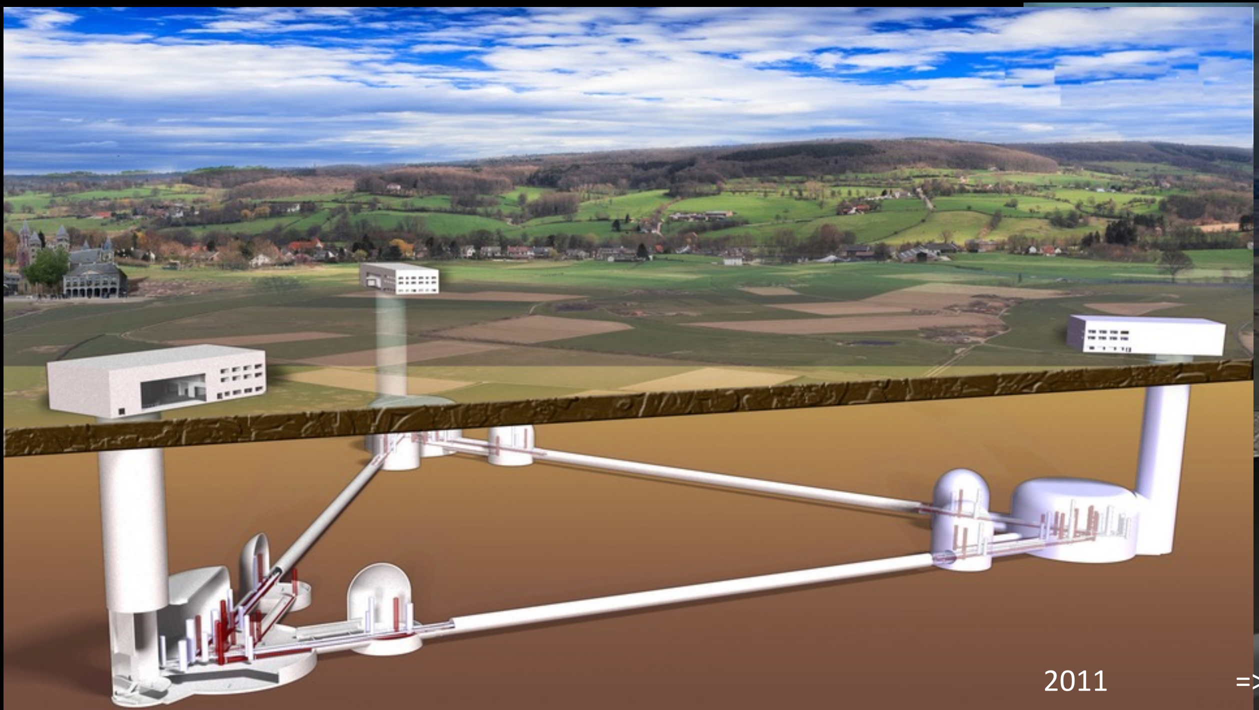


[source: ET Design Report Update 2020, and references therein].

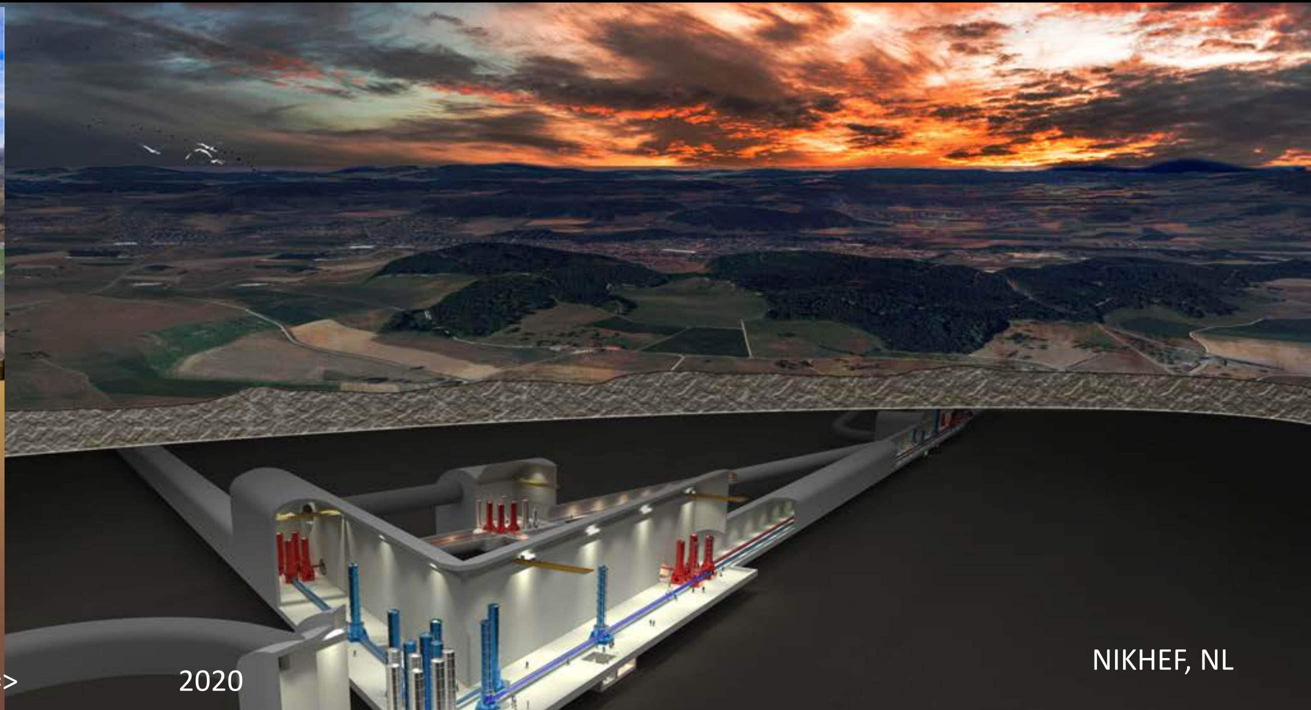
The Einstein Telesope (ET)

- A **European** project!
- triangular underground GW observatory (at 200 – 300 m depth) with 10 km arm length

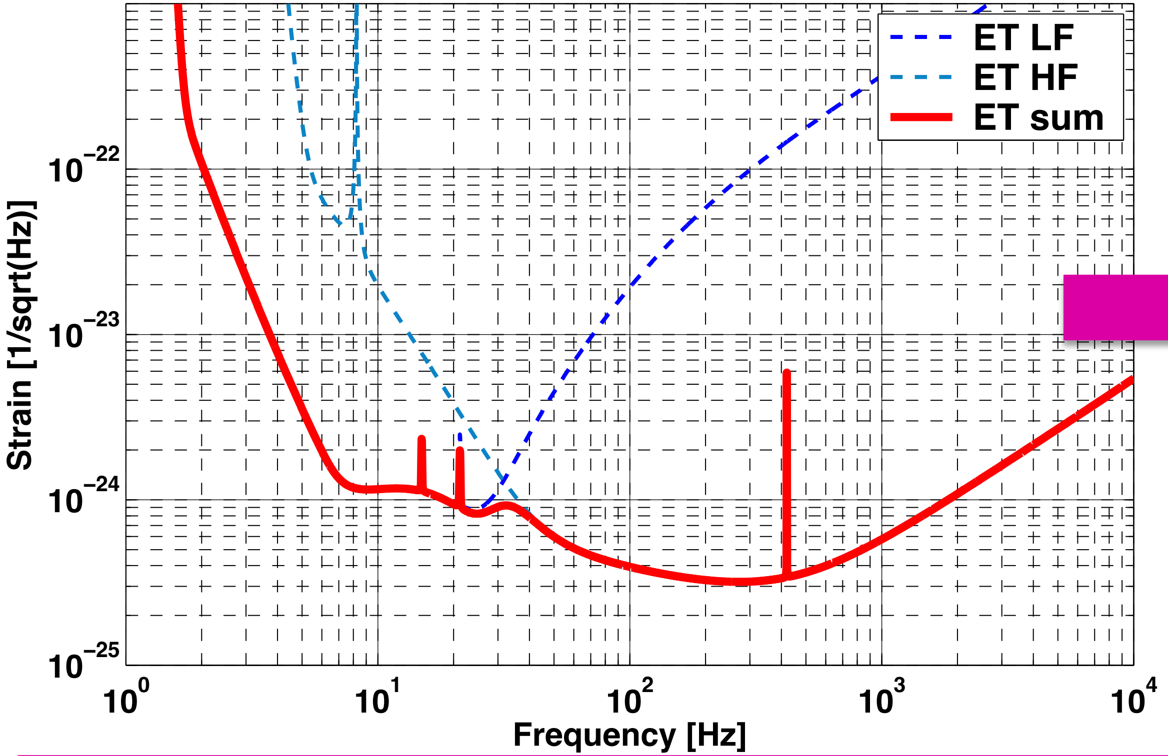


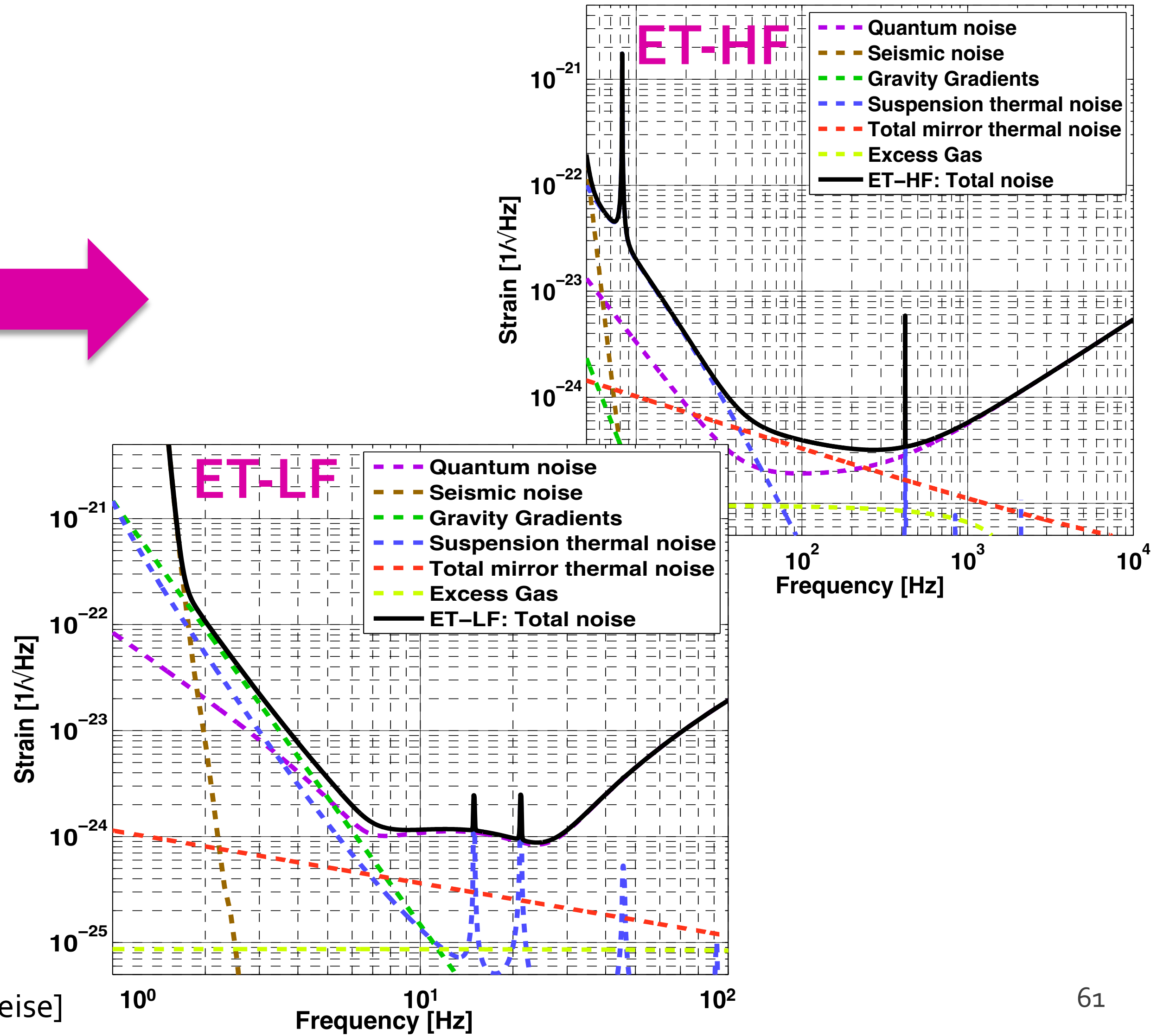


=>



ET xylophon design





Each detector (red, blue and green) is split into two interferometers:

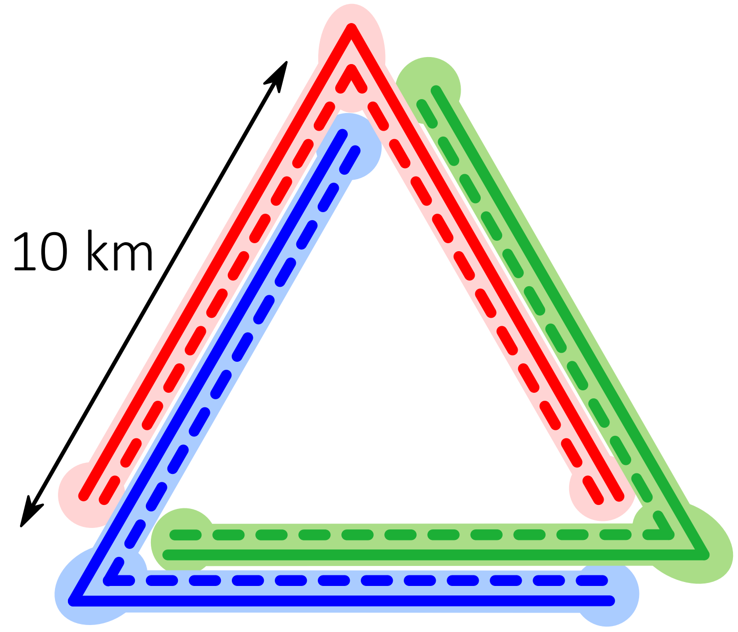
ET HF: high power operation, extend current technology

ET LF: optimise for low frequency and **new technology**

[Images: ET Design Report Update (2020), content presentation adapted from A. Freise]

ET design specifications

The Einstein Telescope:
***three detectors** in a single triangular site.*
*A near-optimal configuration for a **single-site GW observatory** in a cost-efficient and prominent infrastructure!*



[Source: ET Design Report Update (2020), text adapted from A. Freise]

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor of a few

ESFRI

Q1: Enabling Technologies

ET EINSTEIN TELESCOPE

- The multi-interferometer approach asks for two parallel technology developments:

- **ET-LF:**
  - Underground
  - Cryogenics
  - Silicon (Sapphire) test masses
  - Large test masses
  - New coatings
  - New laser wavelength
  - Seismic suspensions
  - Frequency dependent squeezing

- **ET-HF:**
  - High power laser
  - Large test masses
  - New coatings
  - Thermal compensation
  - Frequency dependent squeezing

Challenging engineering

New technology in cryo-cooling

New technology in optics

New laser technology

High precision mechanics and low noise controls

High quality opto-electronics and new controls

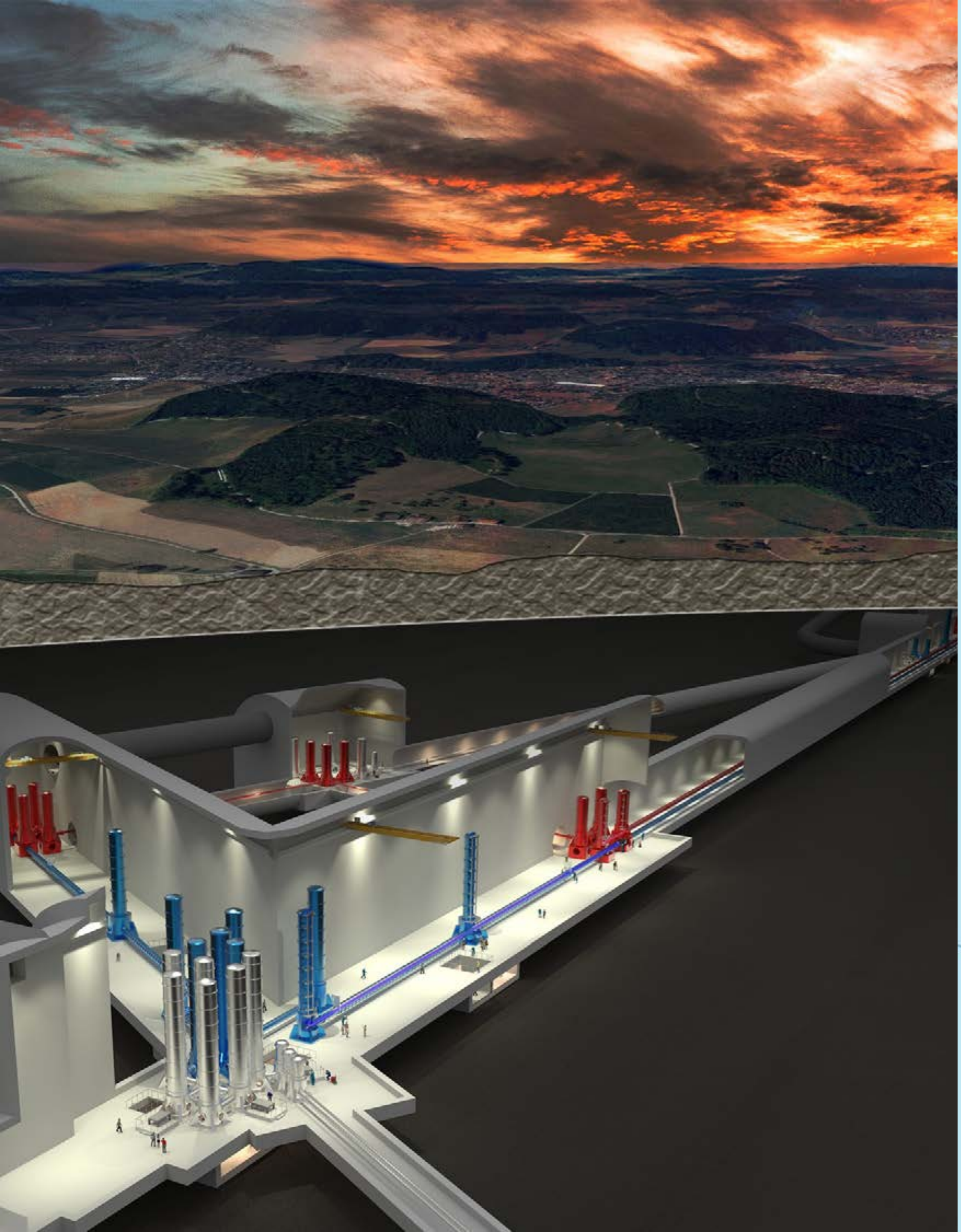
Evolved laser technology

Evolved technology in optics

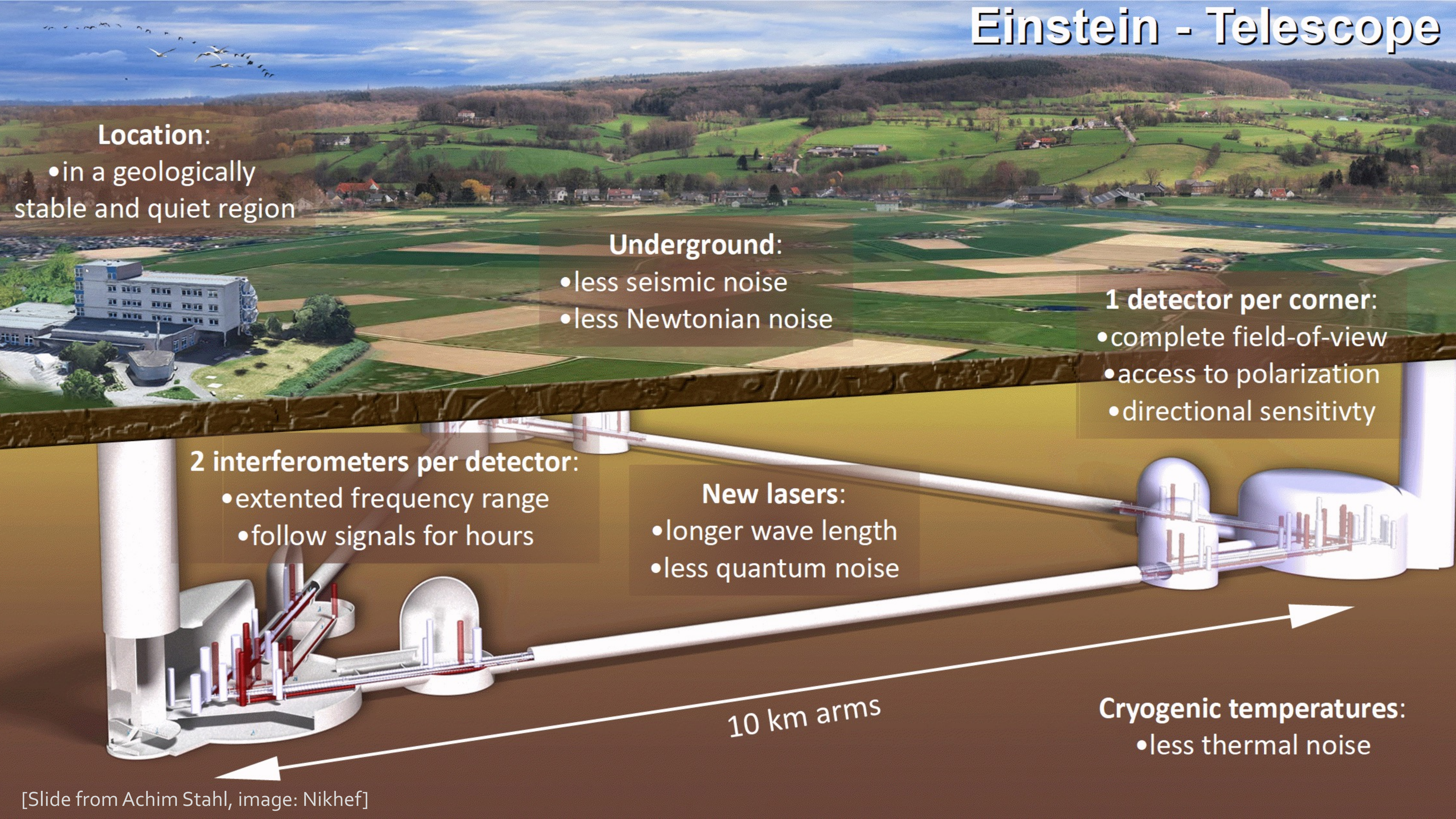
Highly innovative adaptive optics

High quality opto-electronics and new controls

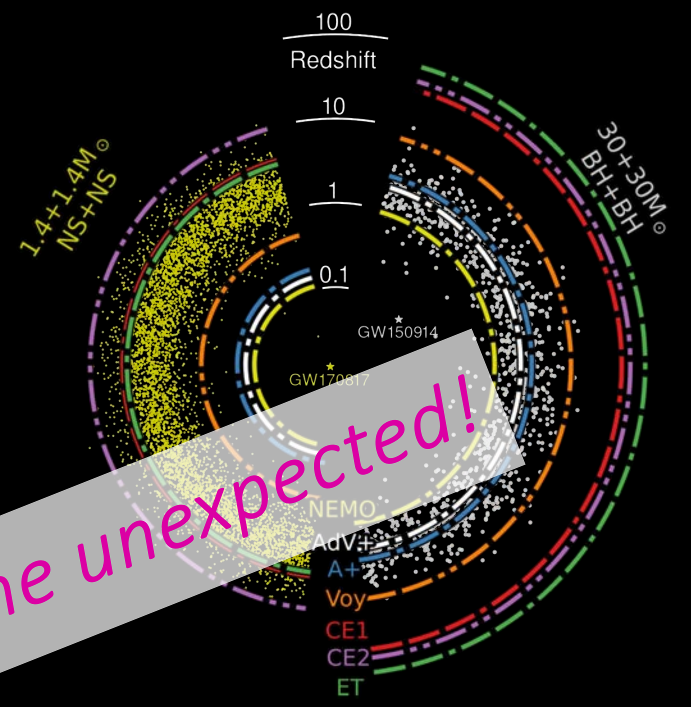
[*Source*: ESFRI Defense Presentation (2021)]



EU Regio
Rhein-Maas
Lausitz?
Sardinien
Atlantic Ocean
North Sea
Celtic Sea
Bay of Biscay
Ligurian Sea
Balearic Sea
Tyrrhenian Sea
Adriatic Sea
Mediterranean Sea
UNITED KINGDOM
IRELAND
DENMARK
NETH.
GERMANY
CZECH REPU
FRANCE
LUX.
SWITZ.
LIECH.
AUSTRIA
SLOVENIA
CROATIA
ITALY
SAN MARINO
VATICAN CITY
MONACO
ANDORRA
SPAIN
PORTUGAL
BALEARIC ISLANDS
Aberdeen
Glasgow
Edinburgh
Belfast
Isle of Man (U.K.)
Dublin
Leeds
Liverpool
Manchester
Birmingham
Cardiff
London
Göteborg
Copenhagen
Malmö
Bornholm
Hamburg
Bremen
Berlin
Poznań
Amsterdam
Rotterdam
Essen
Leipzig
Brussels
Bonn
Prague
Frankfurt
Luxembourg
Brno
Guernsey (U.K.)
Jersey
Paris
Strasbourg
Stuttgart
Munich
Vienna
Nantes
Zürich
Bern
Vaduz
Ljubljana
Lyon
Milan
Venice
Turin
Bordeaux
Genoa
A Coruña
Toulouse
Bilbao
Florence
Andorra la Vella
Marseille
Porto
Zaragoza
Corsica
Rome
Madrid
Barcelona
Naples
Lisbon
Sardinia
Valencia
Càgliari
Sevilla
Palermo
Gibraltar
Málaga
Sicily
40


Einstein - Telescope
Location:
•in a geologically stable and quiet region
Underground:
•less seismic noise
•less Newtonian noise
1 detector per corner:
•complete field-of-view
•access to polarization
•directional sensitivty
2 interferometers per detector:
•extented frequency range
•follow signals for hours
New lasers:
•longer wave length
•less quantum noise
10 km arms
Cryogenic temperatures:
•less thermal noise
[Slide from Achim Stahl, image: Nikhef]

What science can we do with ET?



Astrophysics

- Black hole properties
  - origin (stellar vs. primordial)
  - evolution, demography
- Neutron star properties
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- Multi-messenger astronomy
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- Detection of new astrophysical sources
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

Fundamental physics and cosmology

- The nature of compact objects
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- Tests of General Relativity
  - post-Newtonian expansion
  - strong-field regime
- Dark Matter
  - primordial Black Holes
  - Axion clouds, DM accreting on compact objects
- Dark Energy and modifications of gravity on cosmological scales
  - DE equation of state
  - modified GW propagation
- Stochastic backgrounds of cosmological origin and connections with high-energy physics
  - inflation
  - phase transitions
  - cosmic strings
  - …

Also: ET will be a "discovery machine", so expect the unexpected!

Einstein Telescope

„All" BBH back to Big Bang

Nearly all BNS back to Big Bang

Many supernovae

View to the Dark Ages

[This list was taken verbatim from the talk by M. Maggiore at the 11th ET Symposium (2020)]

Underground laboratory for next generation GWDs

- Lab of approx. (30 x 30 x 30) m^3 size
  at 200 m depth in Lusatia granite
- kilometer-scale *3D seismometer sensor array*

⇒ *Metrological validation* of advanced full-scale seismic isolation concepts

- + nuclear astrophysics

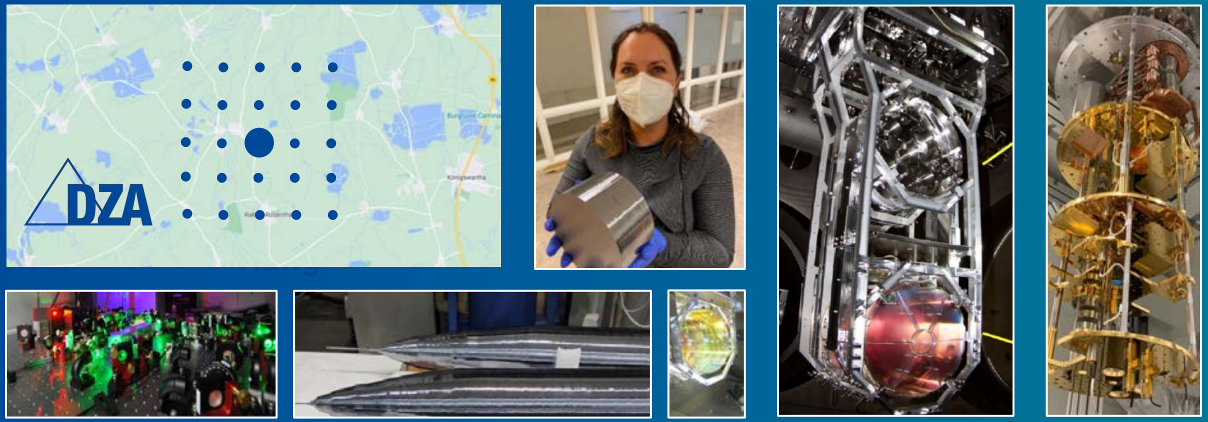
Photos: Tunnel / cavern in Sos Enattos (Sardinia) during ET site workshop (Oct. 2021)

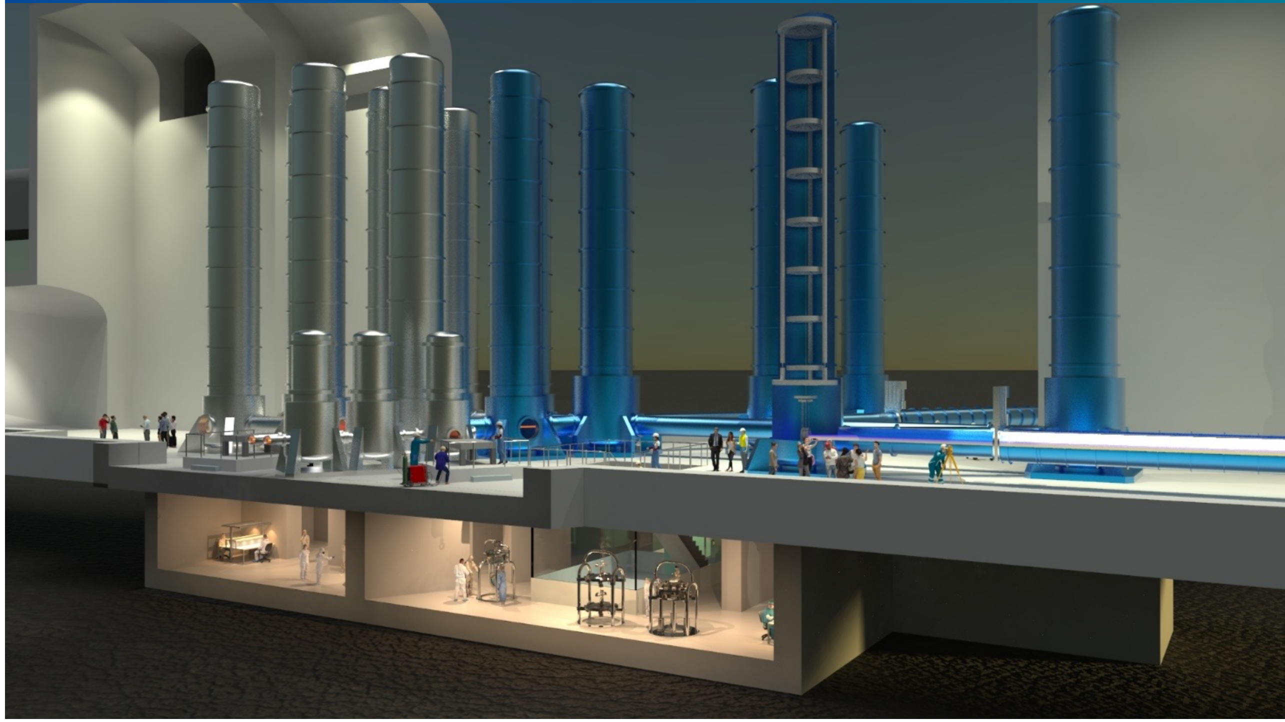
The Low Seismic Lab

Innovation platform with a size roughly (40 x 30 x 30) m^3 at a depth of 200m in the Lusatia Granite

With a square-kilometer size 3D seismometer cage

→ Real-life validation of new seismic isolation concepts





SITE FOR FUTURE «DEEP TECH»:

- Technology development for gravitational wave astrophysics
- Adaptive seismic noise suppression
- Subnanometer microscopy and photolithography
- Experiments for quantum computing
- Accelerator astrophysics

Auf gutem Grund

Das Deutsche Zentrum für Astrophysik,
ein Zentrum für Forschung, Technologie
und Digitalisierung.

DZA Deutsches Zentrum für Astrophysik

DZA: Joint initiative of German astronomy and astroparticle physics

- Germany makes outstanding contributions to astronomical research (Nobel Prize)
- European Southern Observatory (ESO) and European Space Agency (ESA) state treaties allow German astrophysics to play leading roles.
- In order to play a similar role also in new international large research projects, like the radio observatory Square Kilometre Array (SKA), the Einstein Telescope, or the Vera Rubin Observatory, requires new national structures that are not existing in Germany today.
- SKA is calling for regional data centres. The Einstein Telescope is looking for partners in Europe to set up large test and development centres for gravitational wave interferometers.
- The possibilities for German industry to participate in such tenders require institutional commitment.

DZA concept : 3 pillars

Astronomy

Square Kilometre Array Observatory (SKAO)

Einstein Telescope (Low Seismic Lab)

Instruments

Developments for future astronomical experiments

Strong participation of Saxon industry

Data Intensive Computing

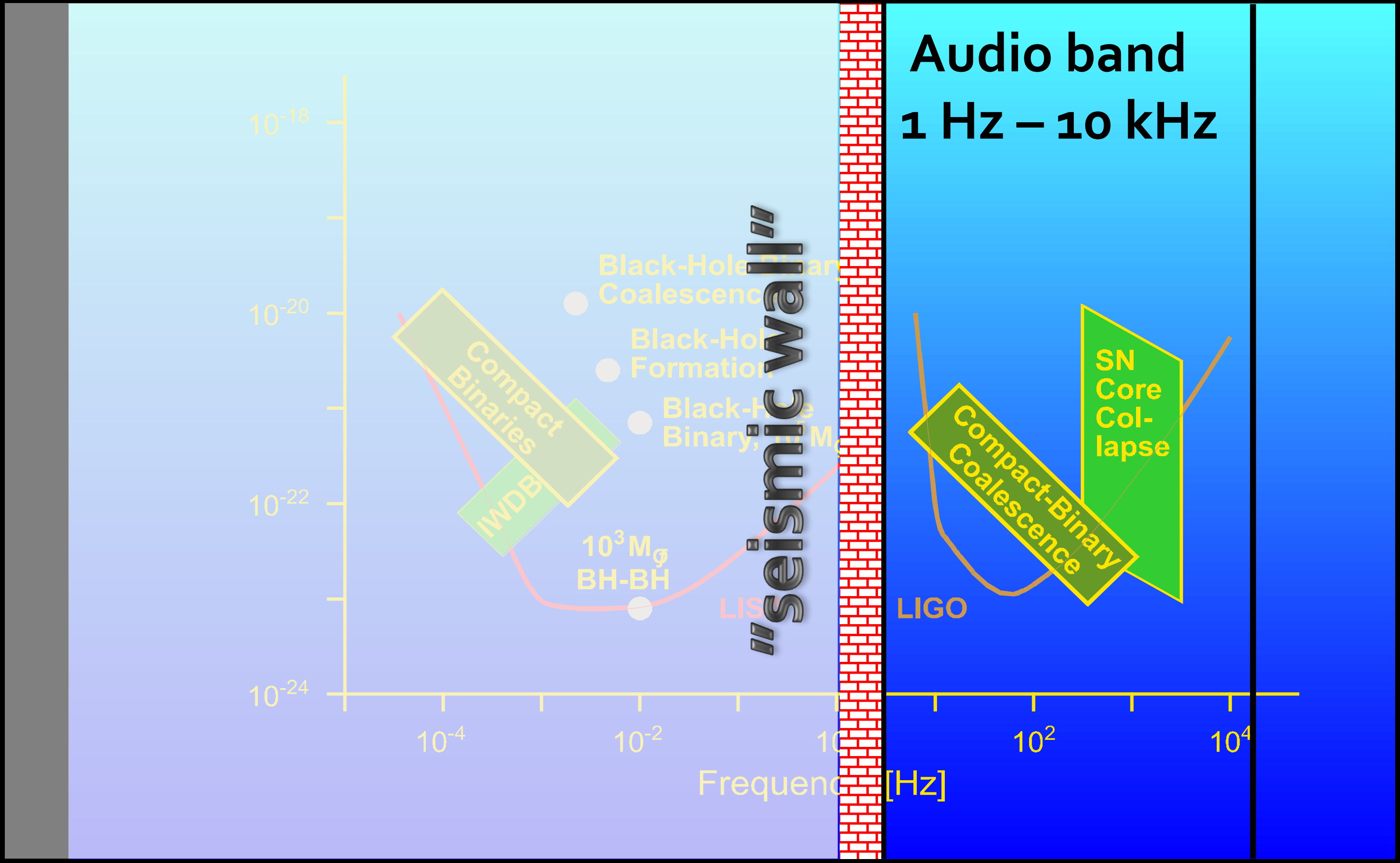
Processing huge amounts of astrophysics data from all over the world

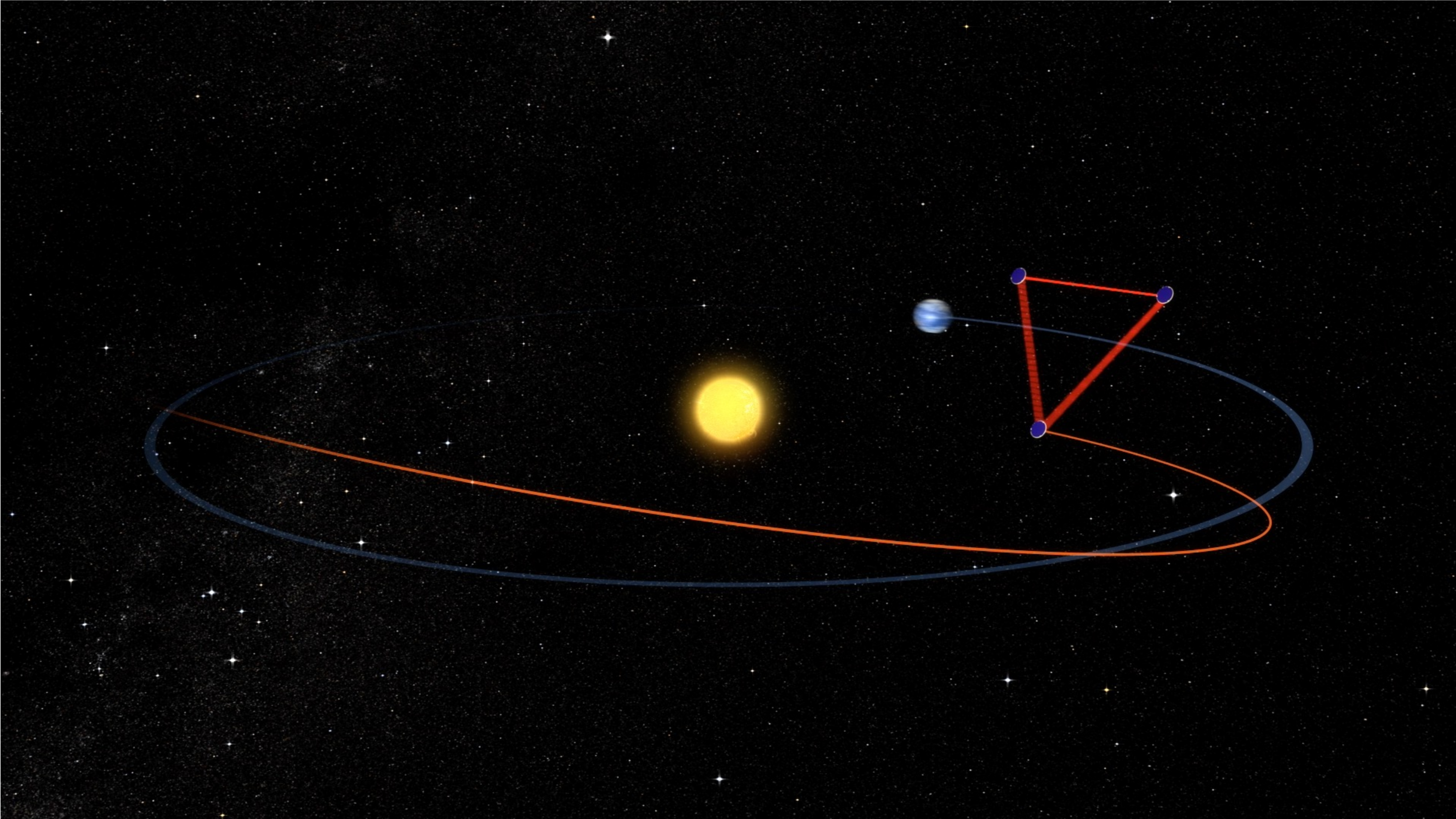
Innovative AI based and Smart Green Computing

Interlocking of pillars ➔ unique synergies

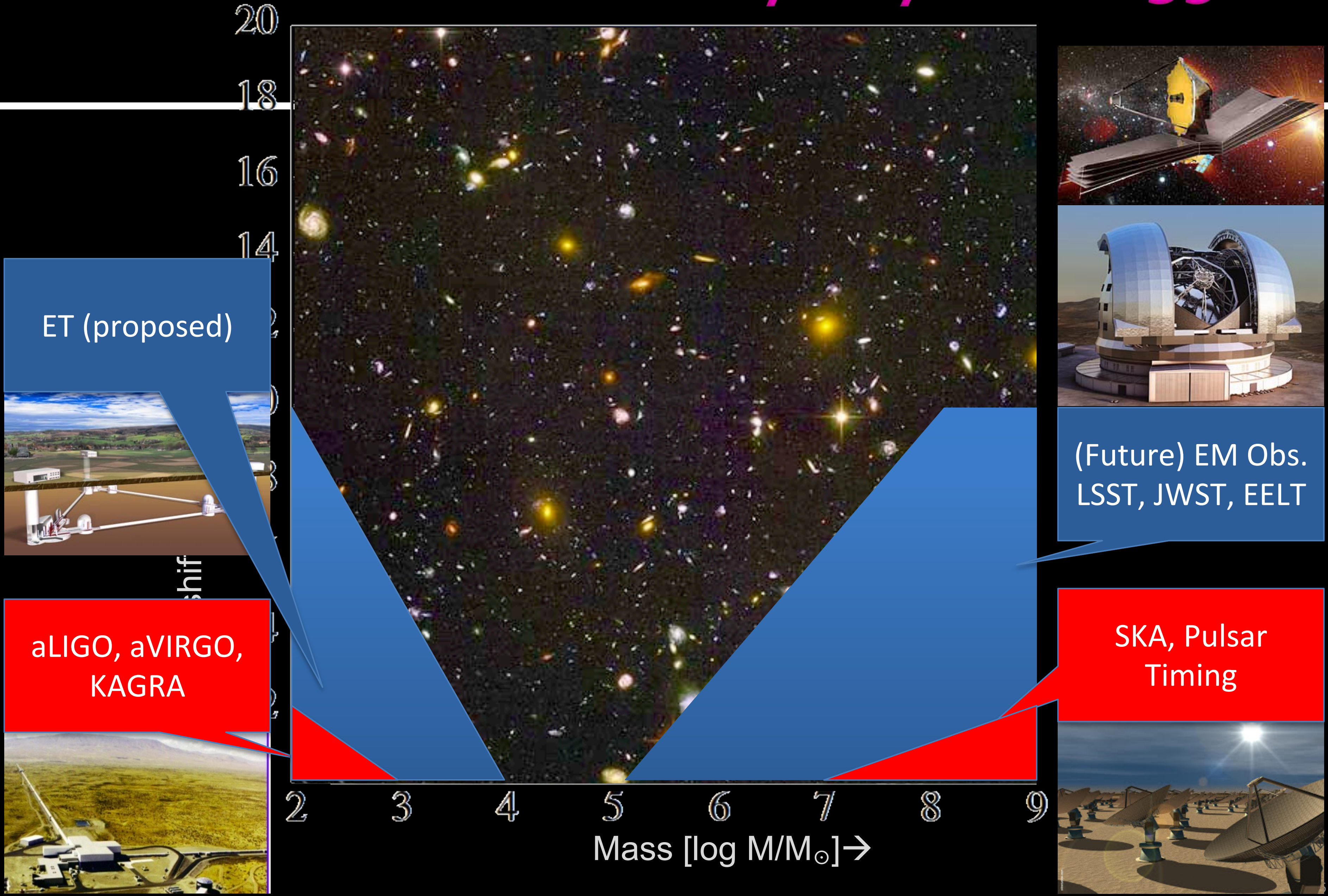
DZA Team and network

The microseismic problem

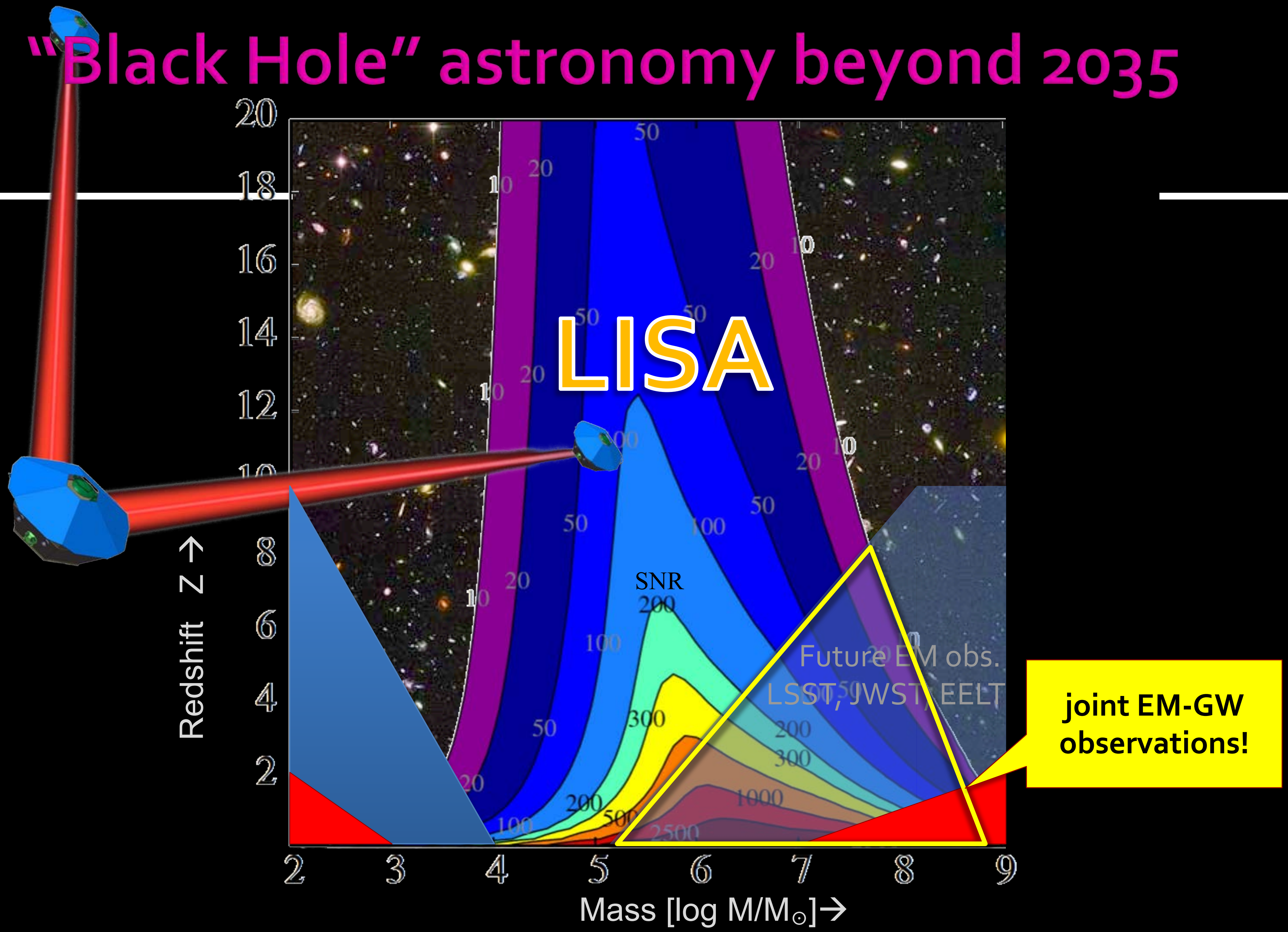




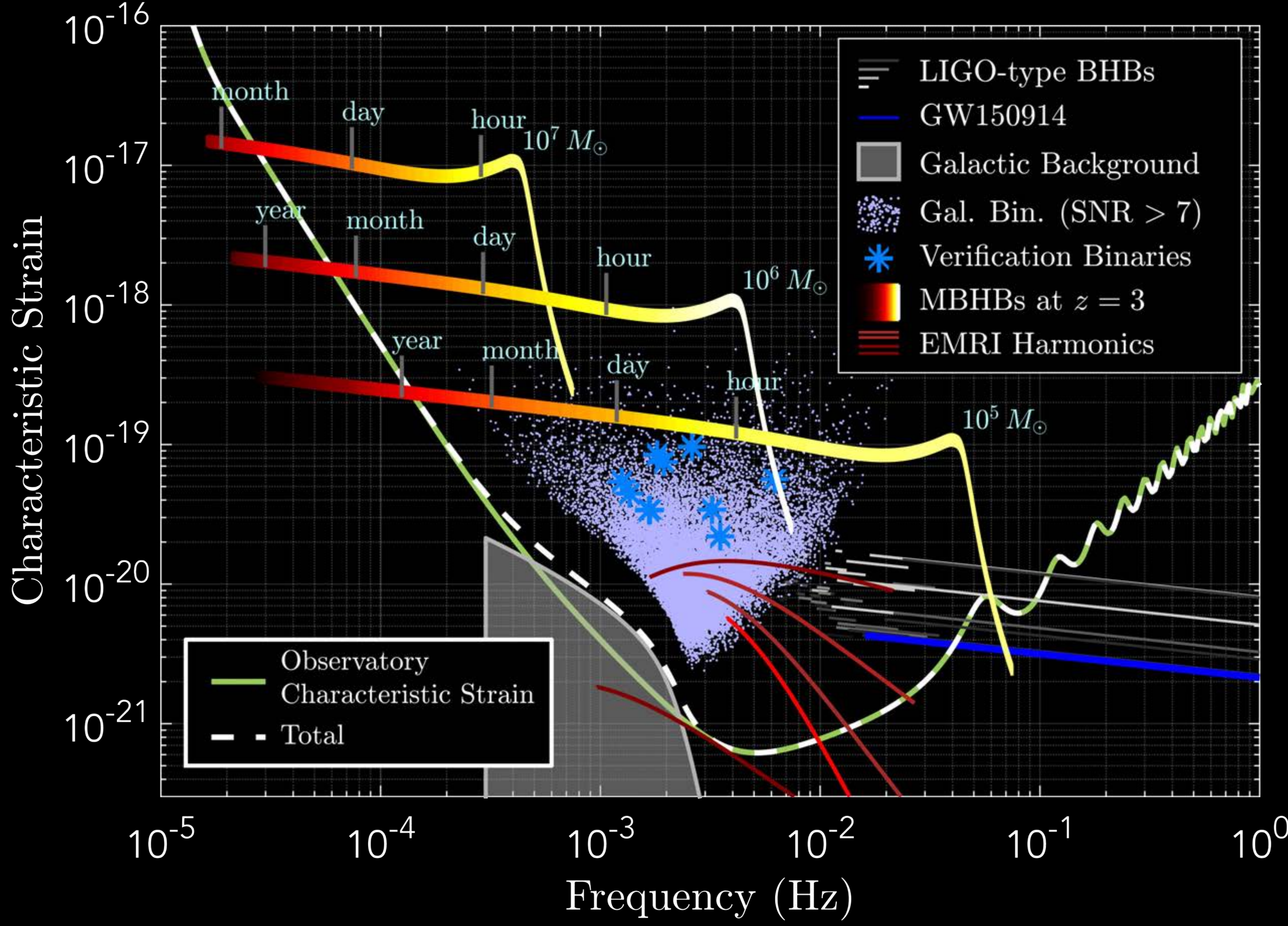
"Black Hole" astronomy beyond 2035



“Black Hole” astronomy beyond 2035

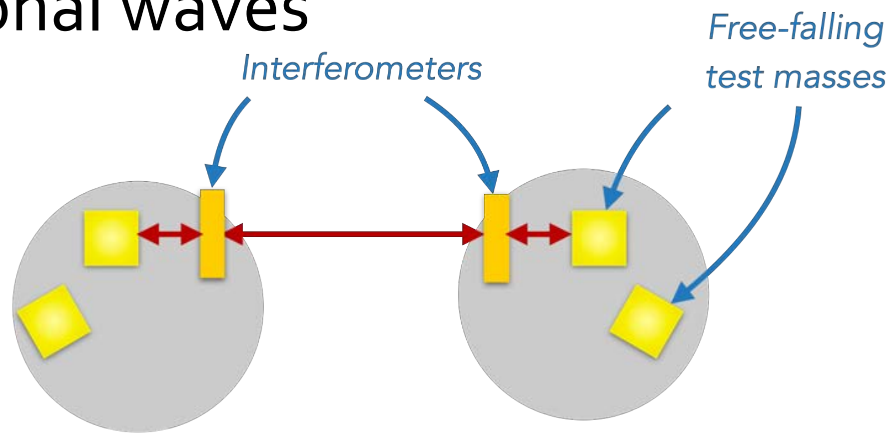


LISA science



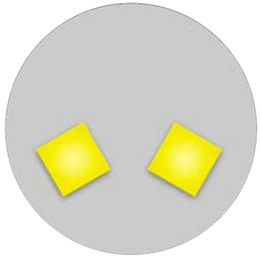
Challenges of observing at low(er) frequencies (~mHz)

We want to measure the relative proper motion of **free-falling** test masses and infer from that the effect of gravitational waves



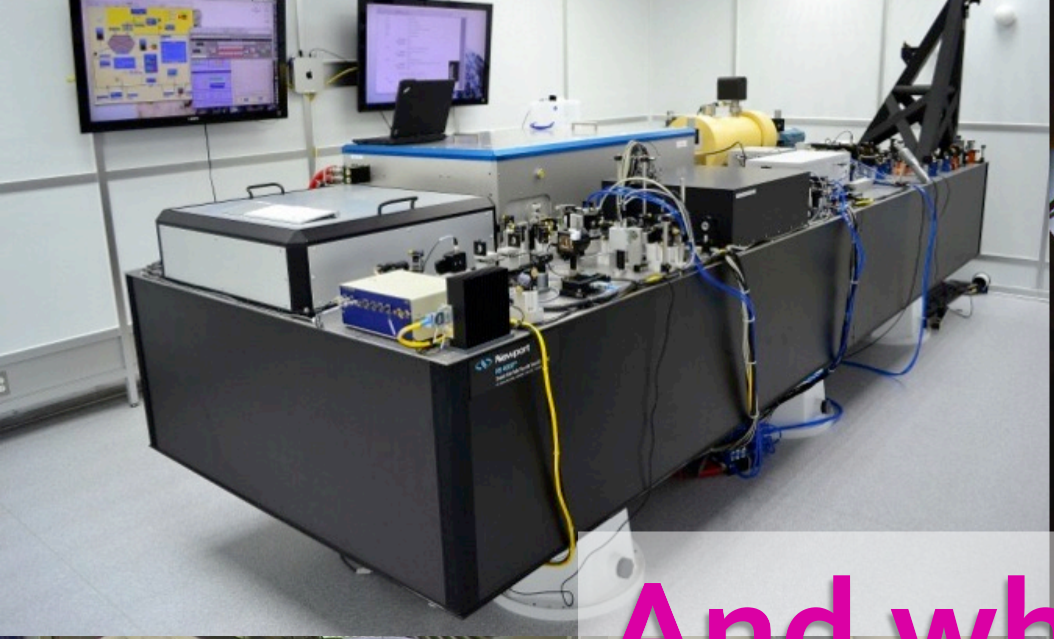
- Disturbances at low frequencies
  - on ground: external displacements, external forces
  - in space: small forces on test masses

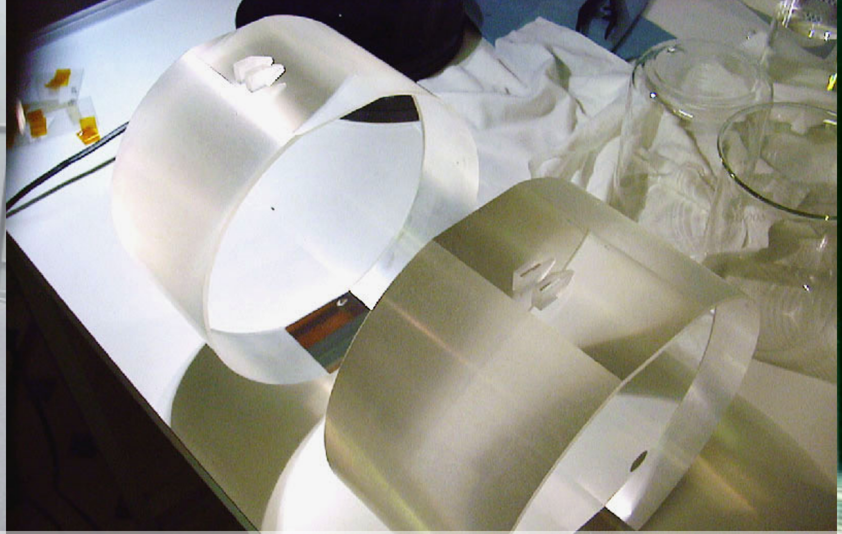
- Interferometry challenges
  - temperature, thermo-mechanical stability, dynamic range
  - readout noise

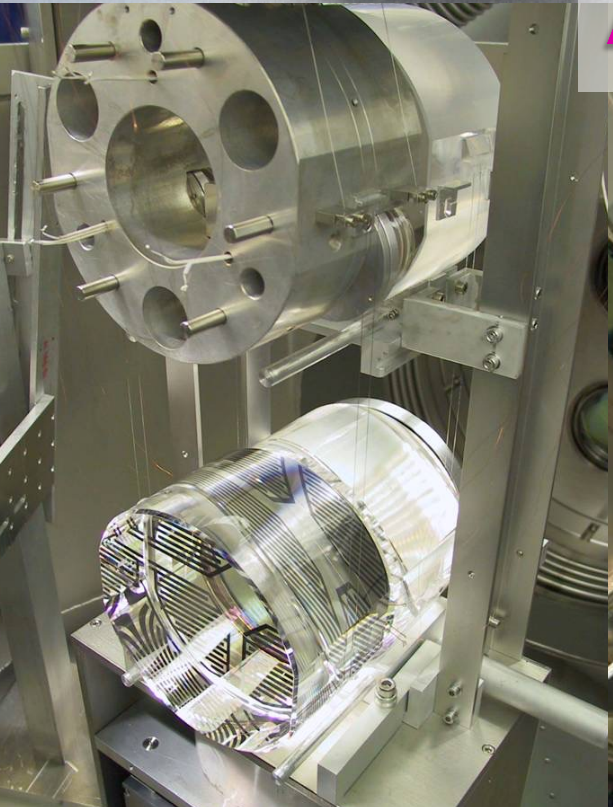


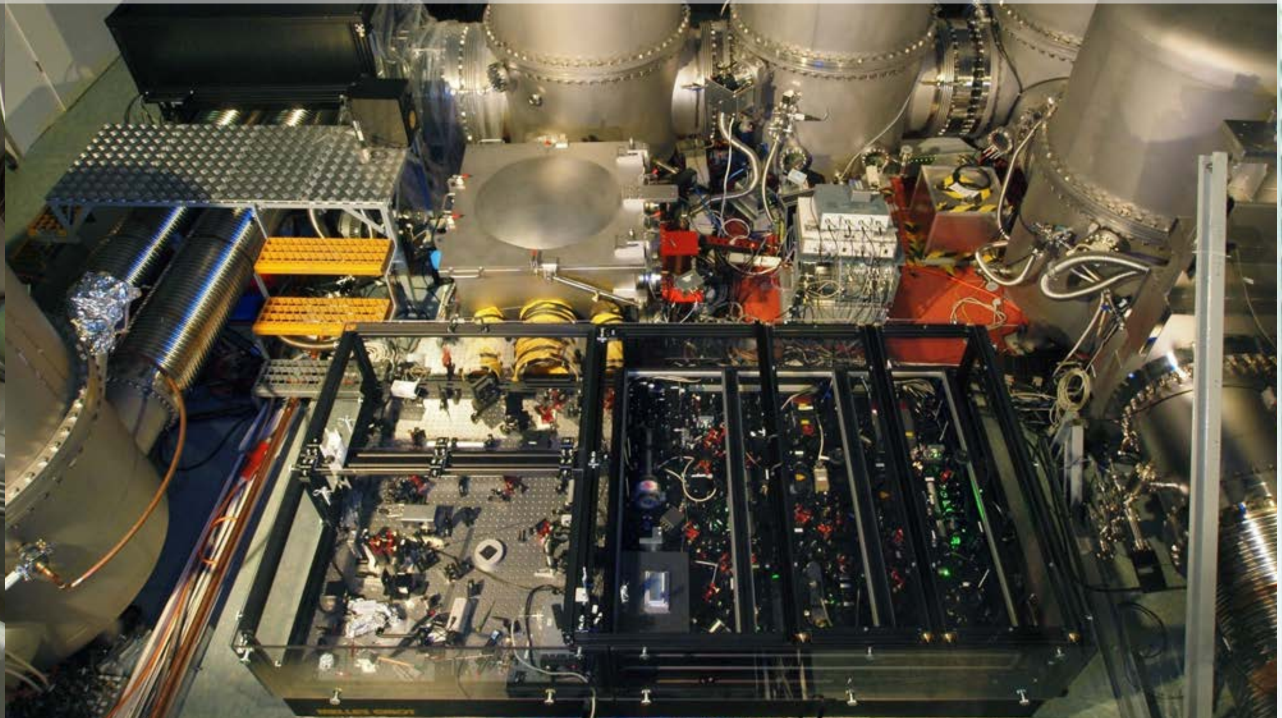
[Content courtesy of Martin Hewitson]

And why all the trouble?



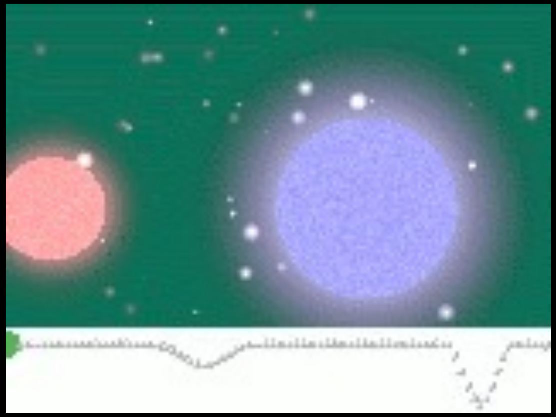






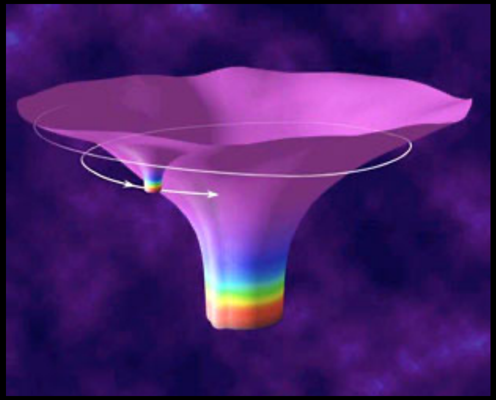
…to listen to many more sources!

Luminosity of a NSNS system (schematic), (Creative Commons)



Supernovae (here: SN 1987A,© NASA)

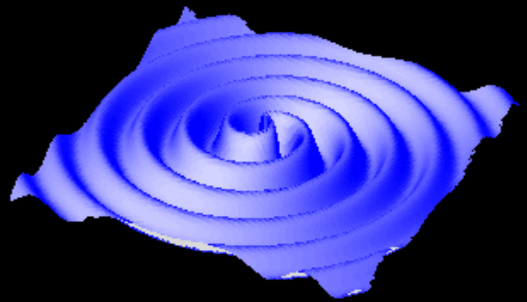
Extreme Mass Ratio Inspiral, (EMRI) (© NASA)



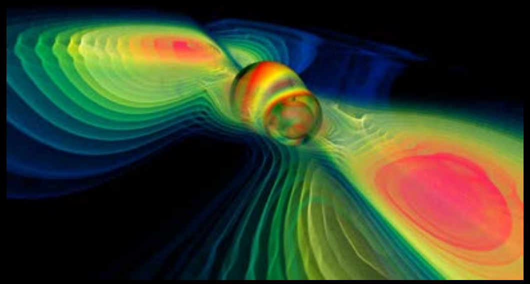
„Chirp“ of two merging neutron stars (© B. Owen, Penn State University)

NS merger buried in detector noise (© https://ligo.caltech.edu/)

„Chirping inspiral“ of two black holes



Emission of GWs in a double NS system (schematic), © NASA



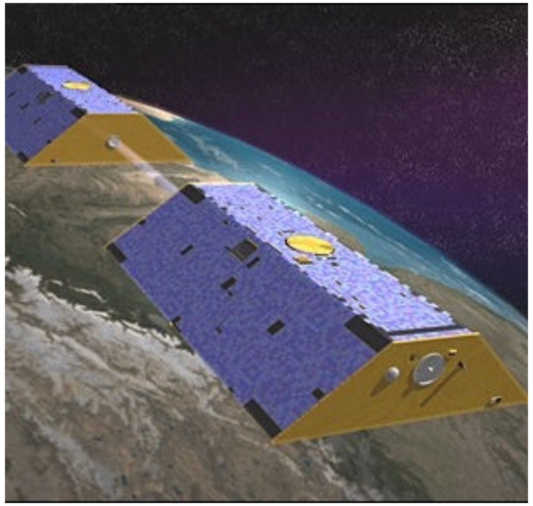
Merger of two black holes (Simulation © AEI)

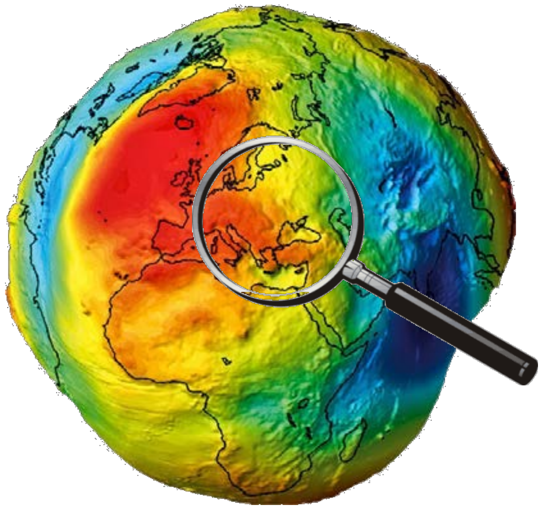
Crab nebula (NGC 1952, © NASA)

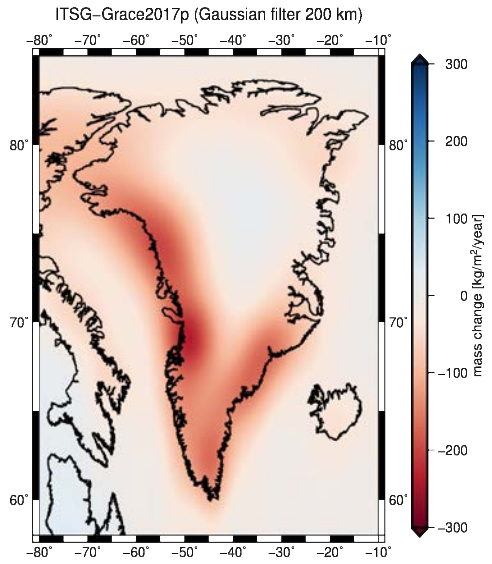
...but also: applications for society!

e.g. in geodesy and gravimetry

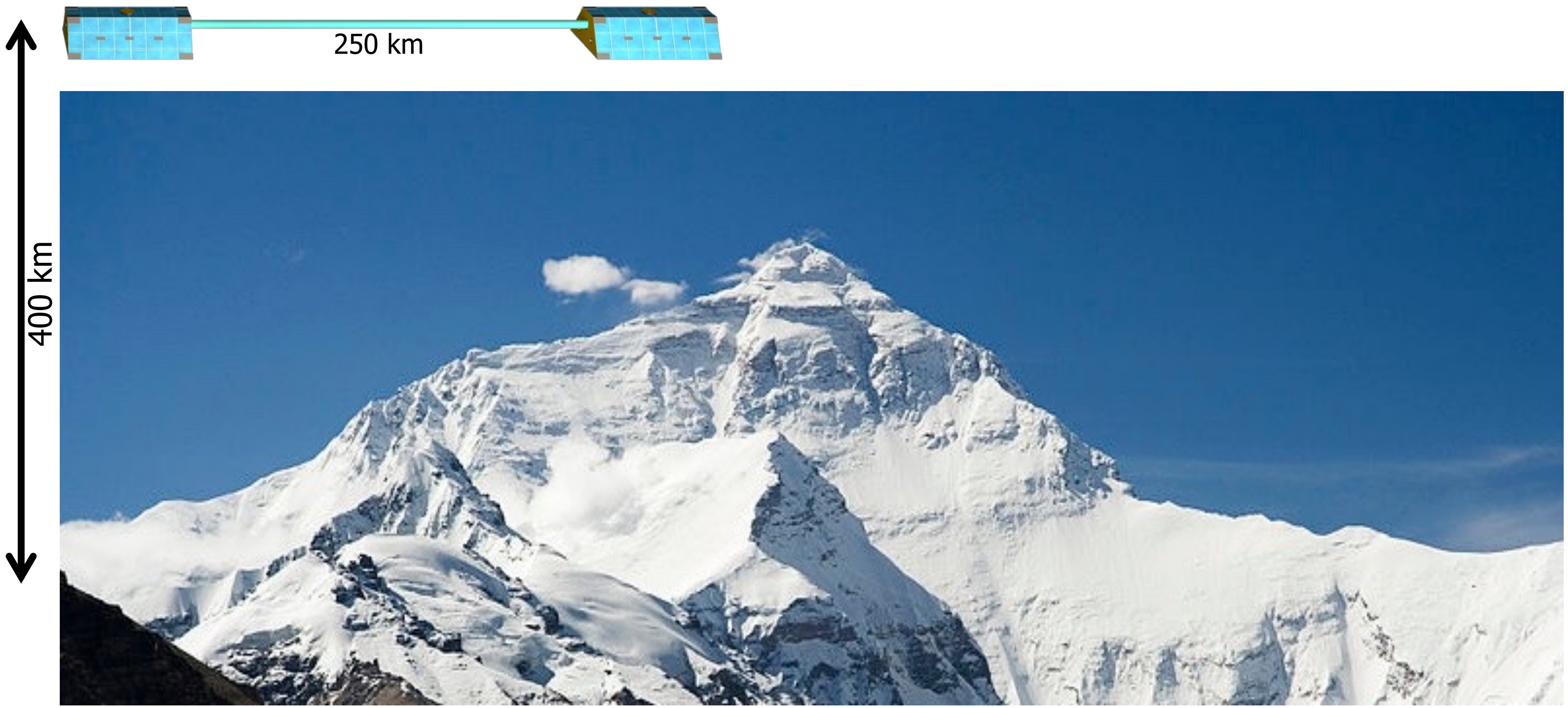
Intersatellite laser interferometry gives information about changes in ground water level („Earth water cycle") or about losses of ice masses on Greenland





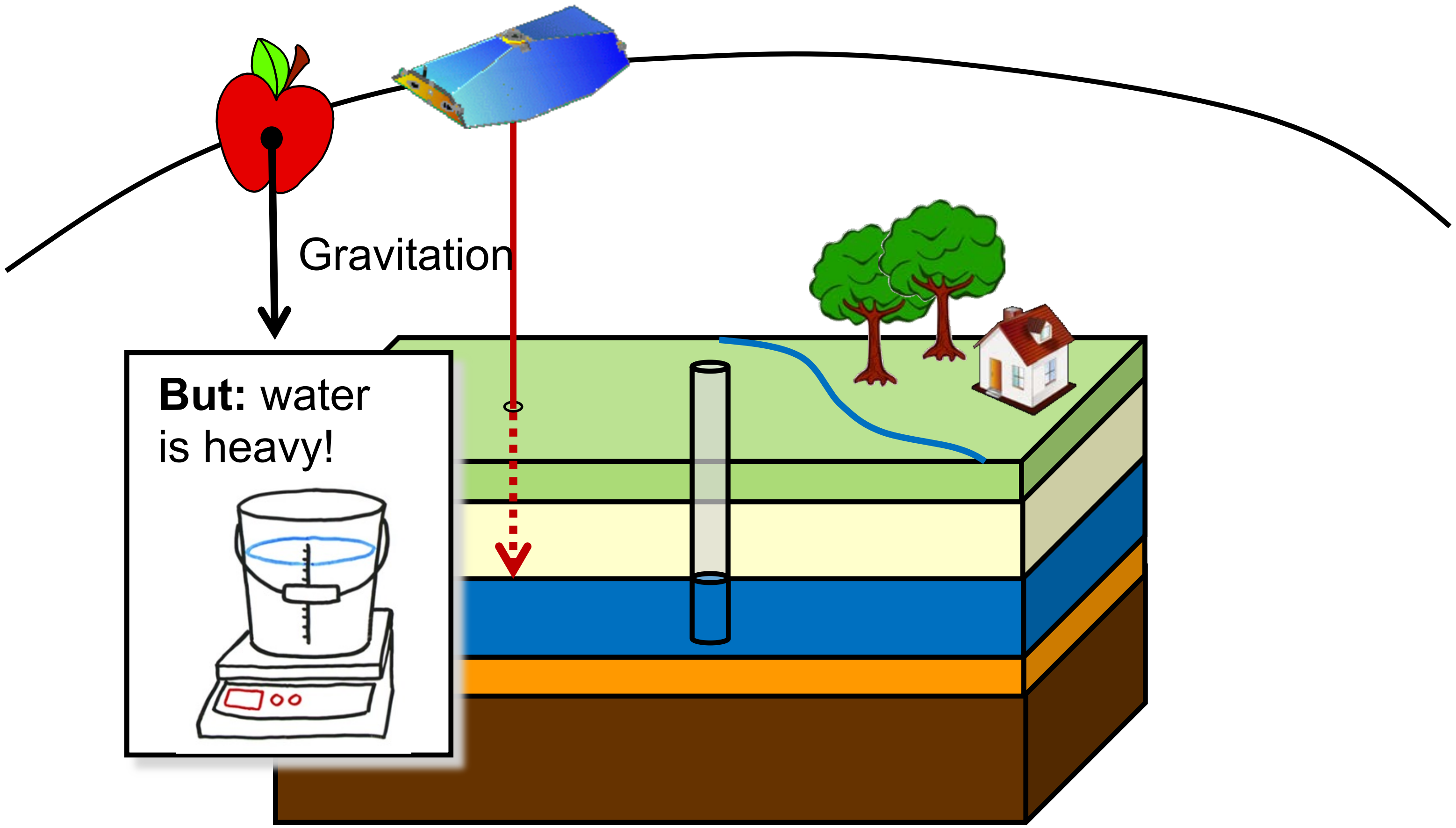


GRACE Follow-On: laser interferometry in orbit



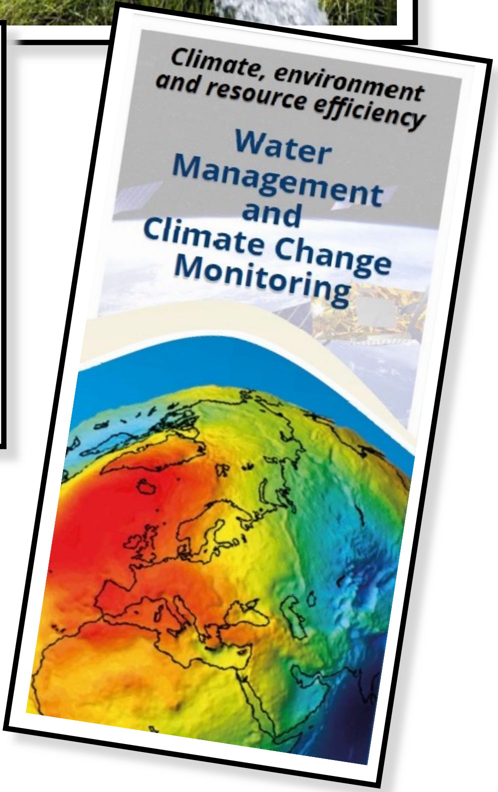
Observation of Earth's gravity field through satellite tracking
(german-US cooperation)
GRACE: with microwaves => GRACE-FO: with lasers!

Measurement of ground water



Ground water is for „remote sensing“

Water is life



Water is one of the most critical geopolitical resources!

(Part of) The Quantum Control group

(missing here: three PhD students, Masters, Bachelors, and our collaboration partners)