

Forschung trifft Schule: CERN Summer School

Gravitationswellenastronomie

27. Juli 2022

Michèle Heurs, Leibniz Universität Hannover, Germany

11
102
1004

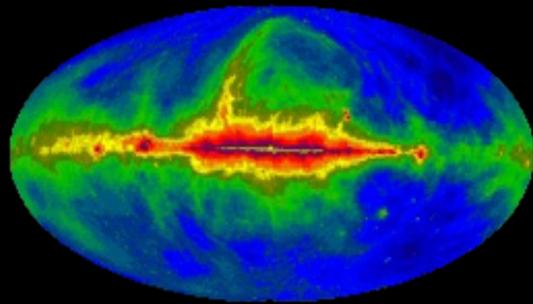
Leibniz
Universität
Hannover

PhoenixD
Photonics · Optics · Engineering
Innovation Across Disciplines

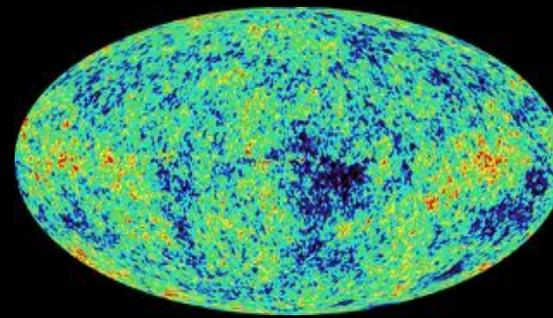




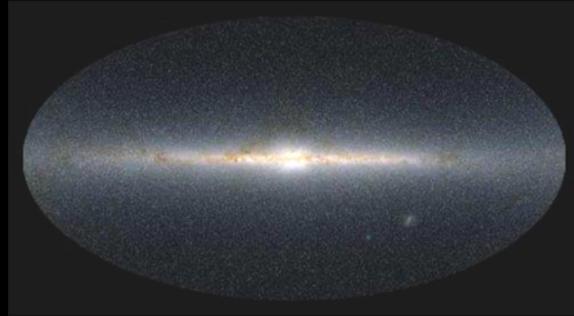
Radio waves



μ -wave background



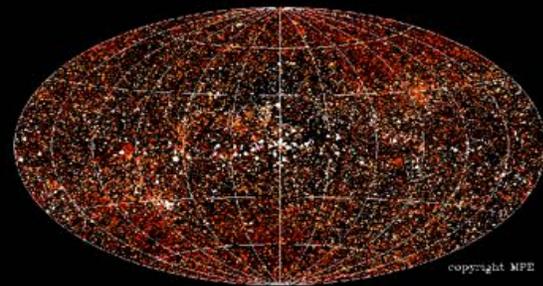
Infrared



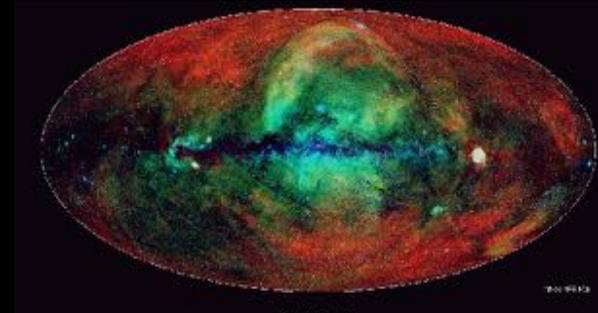
Visible



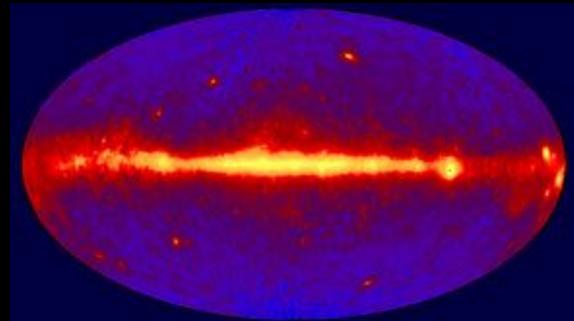
X-ray



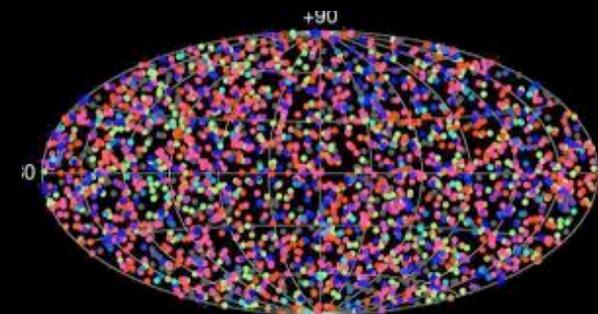
X-ray background



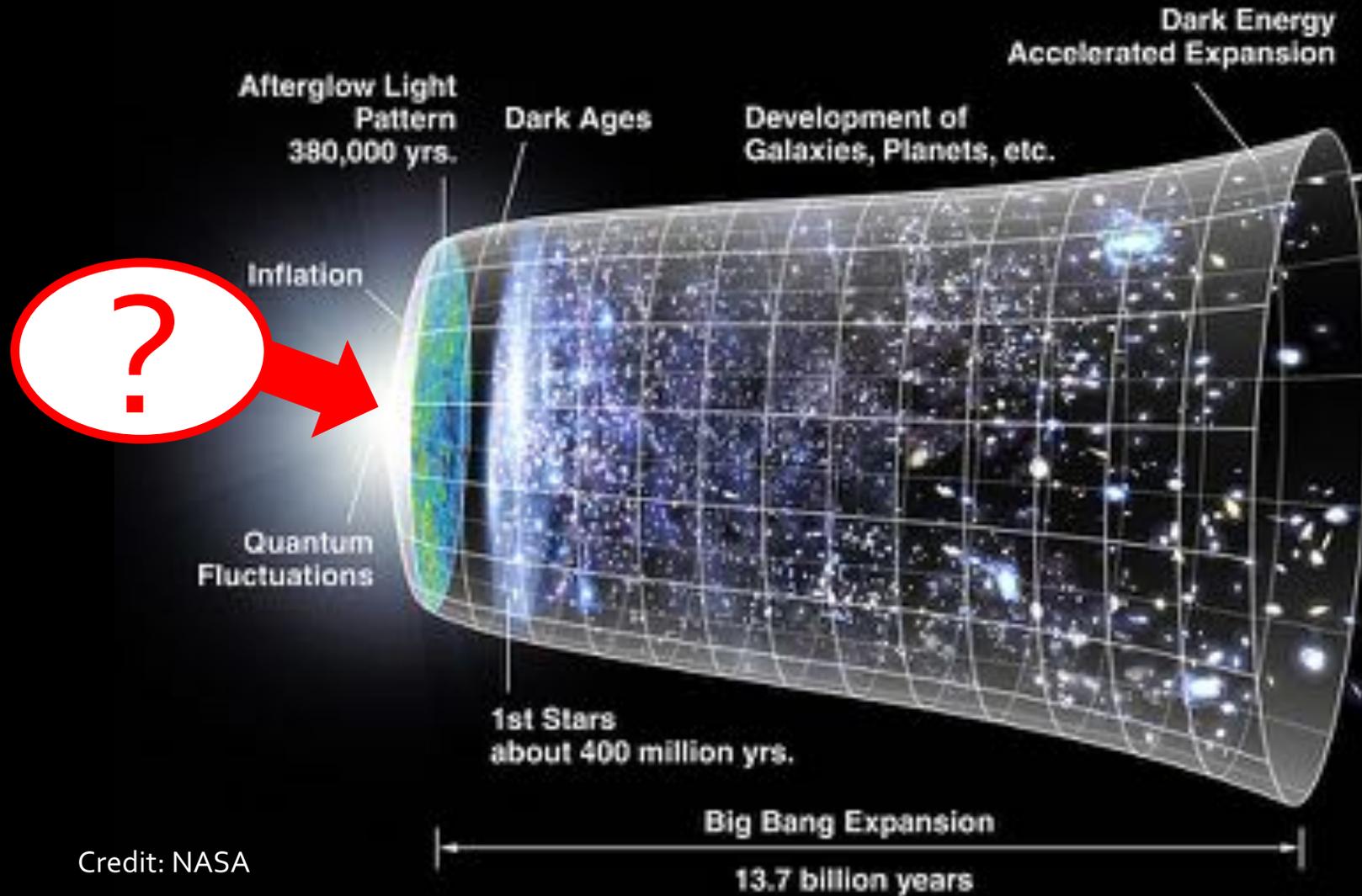
Gammaray



Gammaray bursts

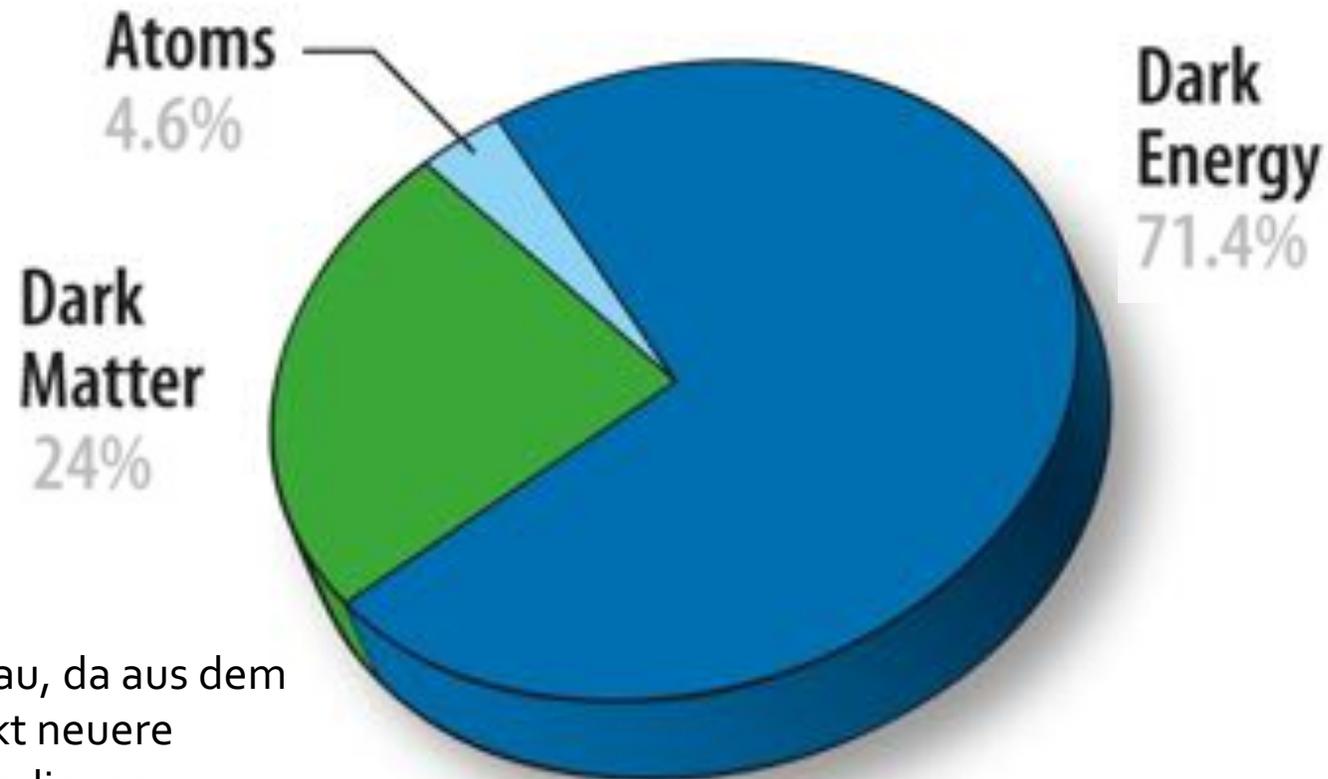


Zeitlinie unseres Universums



Credit: NASA

Energie und Masse im Universum



(Zahlen in grau, da aus dem *Planck* Projekt neuere Ergebnisse vorliegen:

- "gewöhnliche" Materie: 4,9%
- Dunkle Materie: 26,8%
- Dunkle Energie: 68,3%

TODAY

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

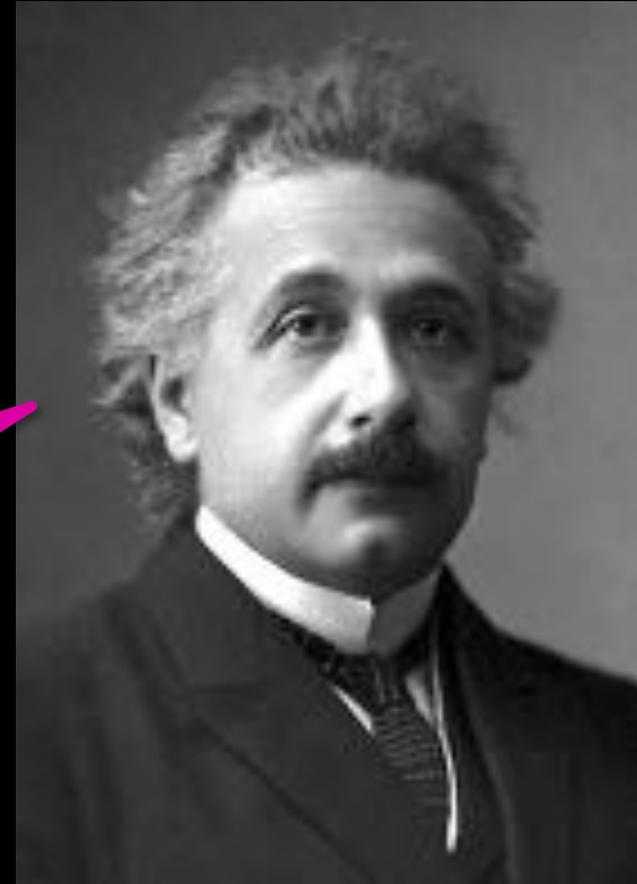
Newton vs. Einstein



Isaac Newton (1642-1726)

Gravitation:
Massen ziehen
einander an

Massen verformen die
Raumzeit – und die
Krümmung der
Raumzeit bestimmt
die Bewegung der
Massen!



Albert Einstein (1879-1955)

Masse krümmt die Raumzeit

Masse verformt die Raumzeit (je größer die Masse, desto tiefer die "Delle") –

bewegte Massen verursachen Gravitationswellen*

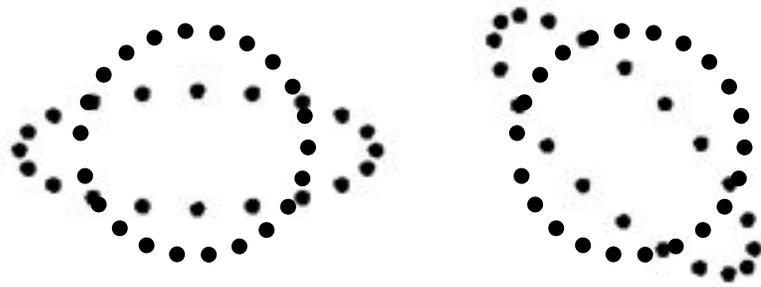
(die mit Lichtgeschwindigkeit propagieren)



* korrekter: nicht-sphärisch symmetrische
Änderungen der Massenverteilung

Wie wirken Gravitationswellen?

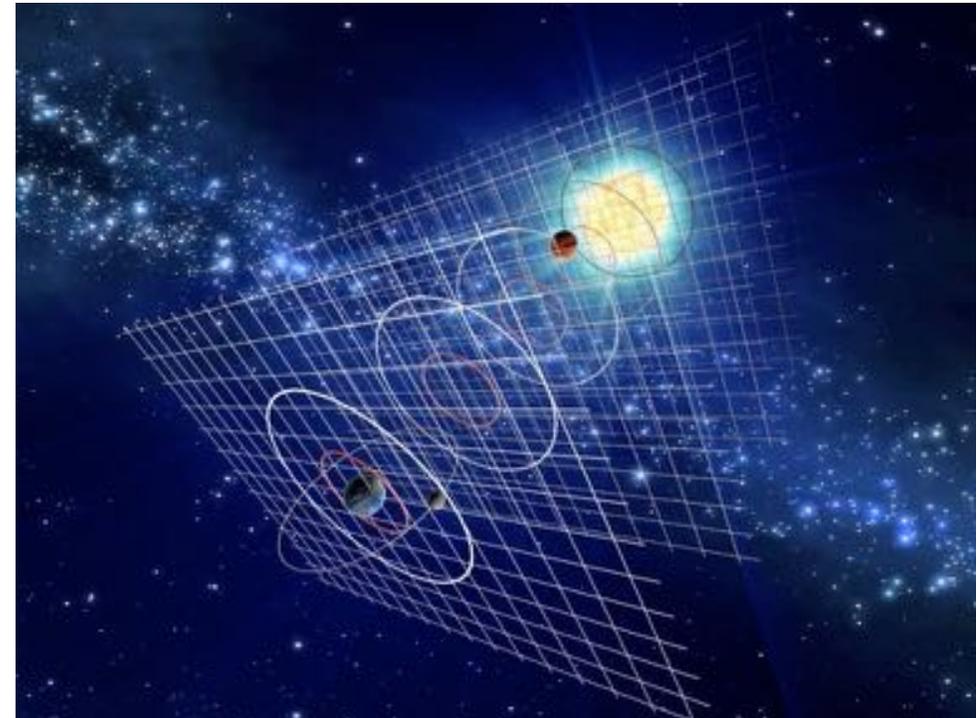
Effekt auf einen Ring von Testmassen:



Wie groß wäre dieser Effekt?

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

(strain h = relative Längenänderung)

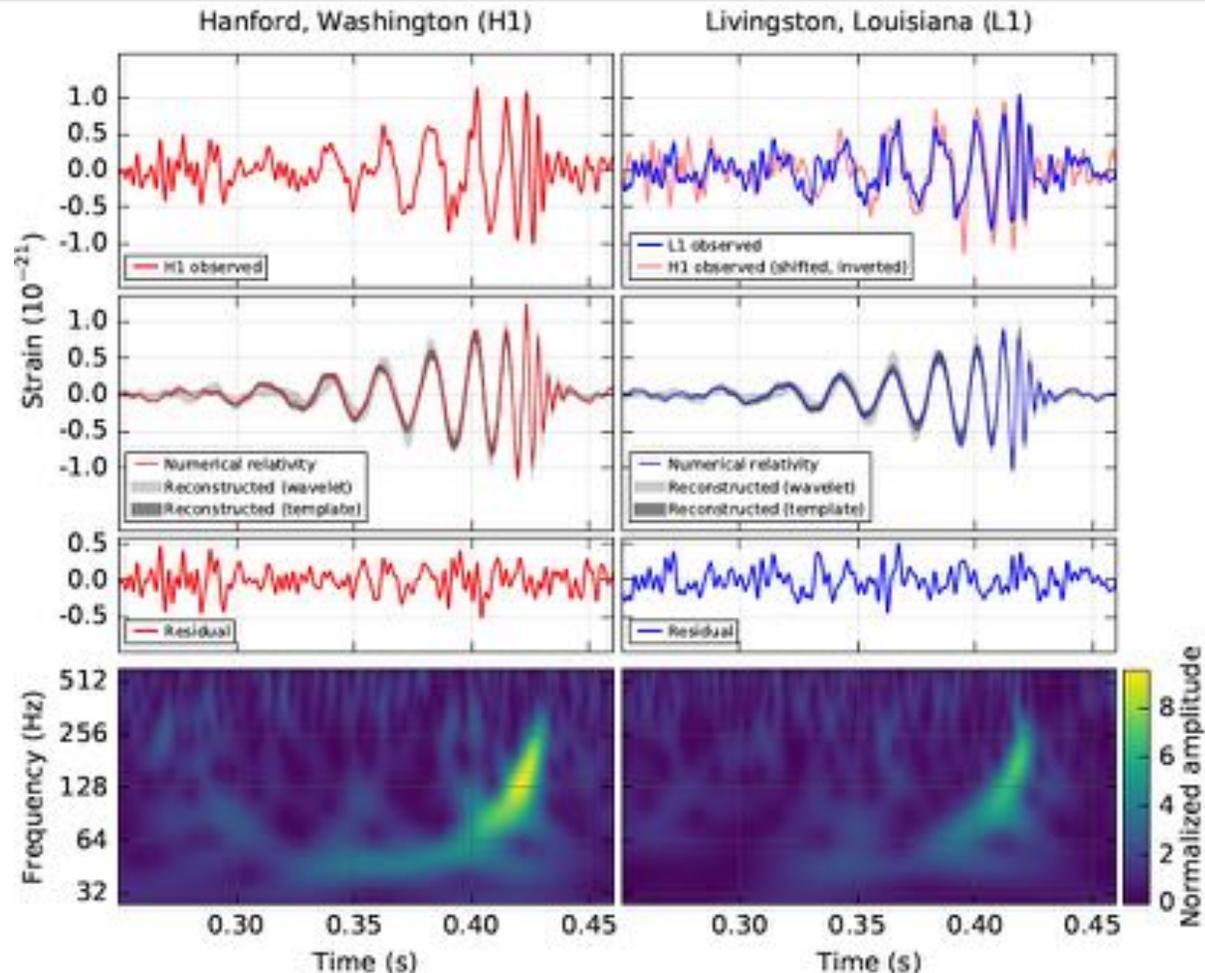


© AEI

Gravitationswellen sind *überall!*

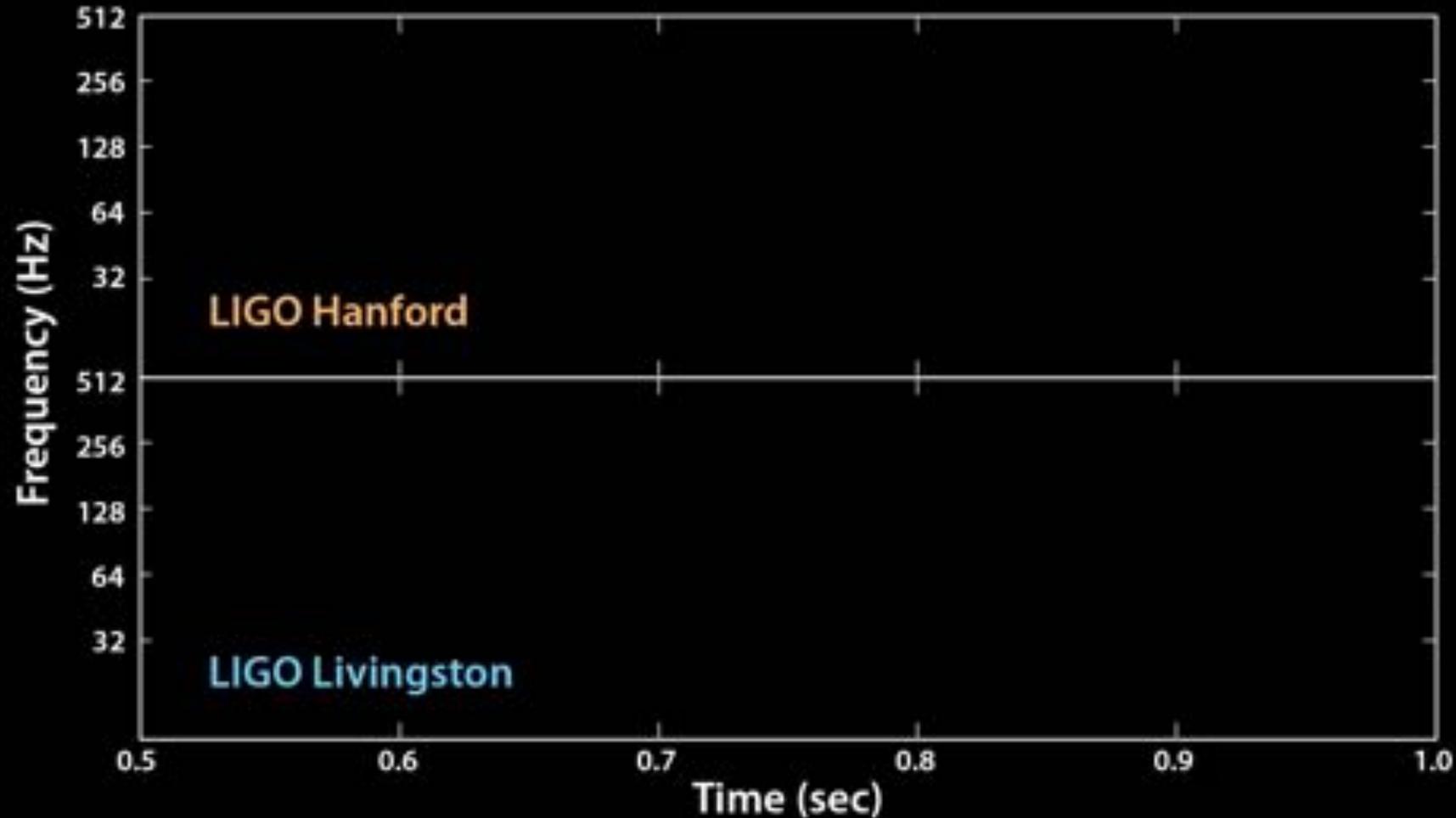


Die erste direkte Detektion: GW₁₅₀₉₁₄



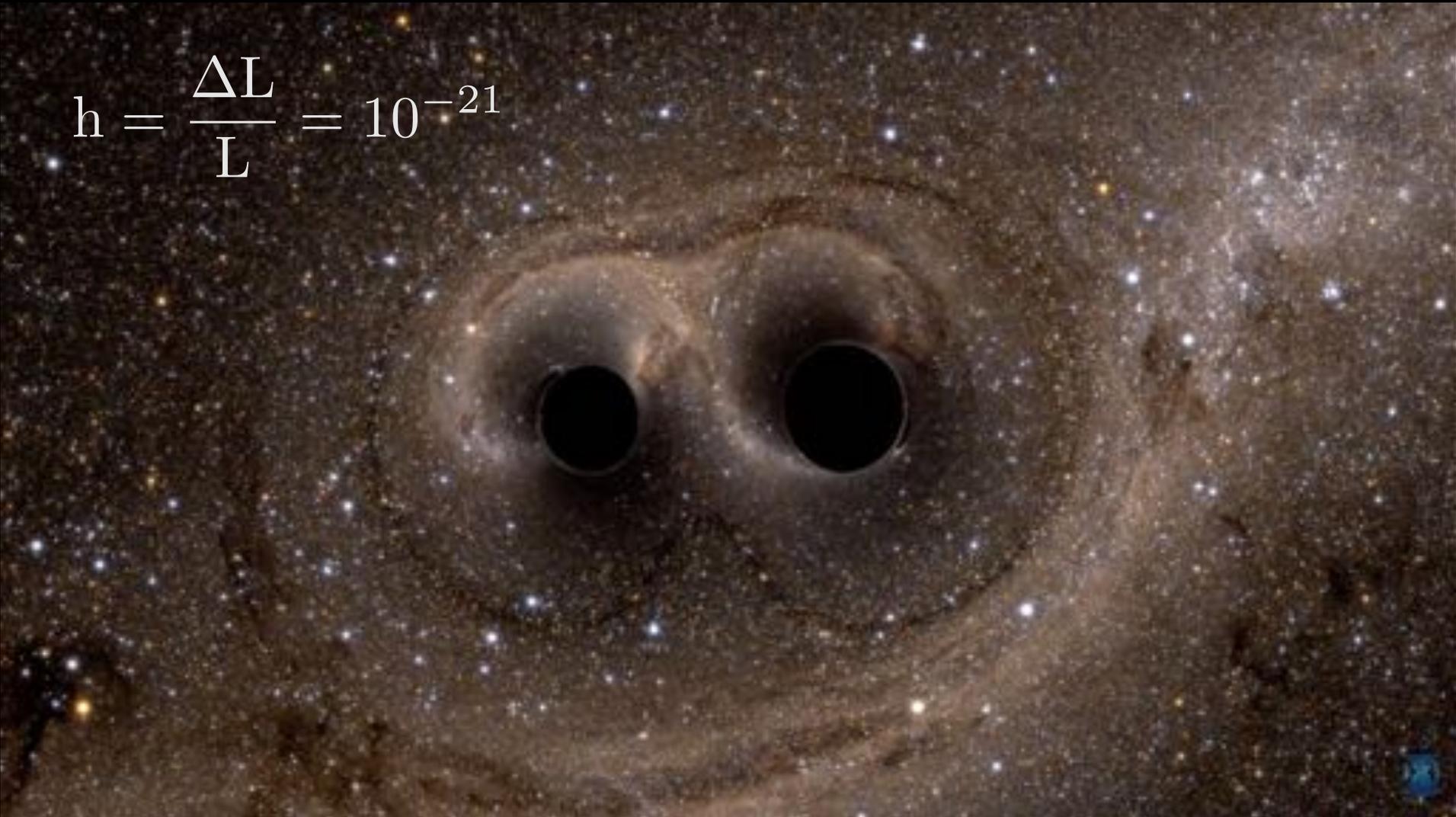
B. P. Abbott, . . . , M. Heurs, . . . (1004 authors!): *Observation of gravitational waves from a binary black hole merger*, Phys. Rev. Lett. **116** (6) o61102 (2016)

GW₁₅₀₉₁₄: Wir können die Verschmelzung von schwarzen Löchern nun *hören*!



Zwei schwarze Löcher werden eins

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



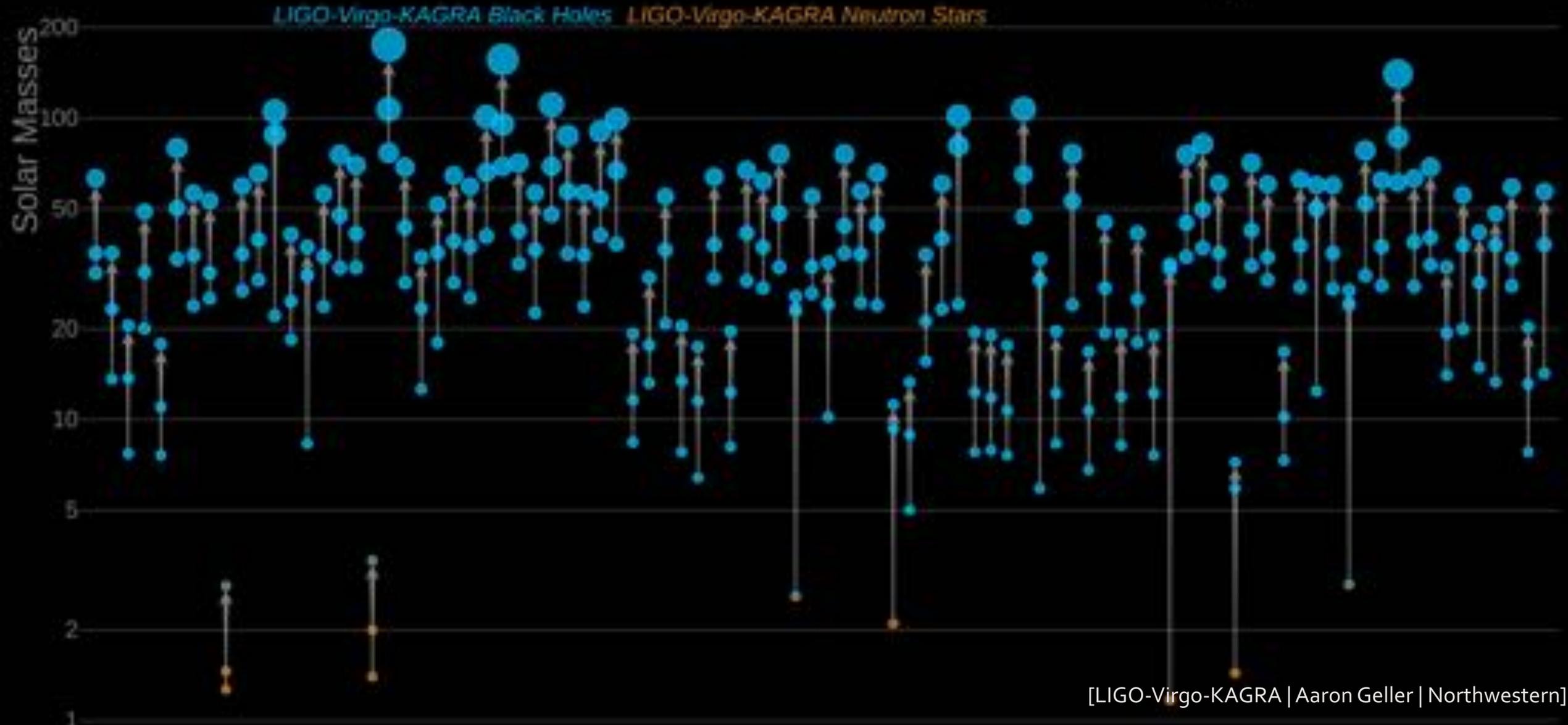
Zwei Neutronensterne verschmelzen



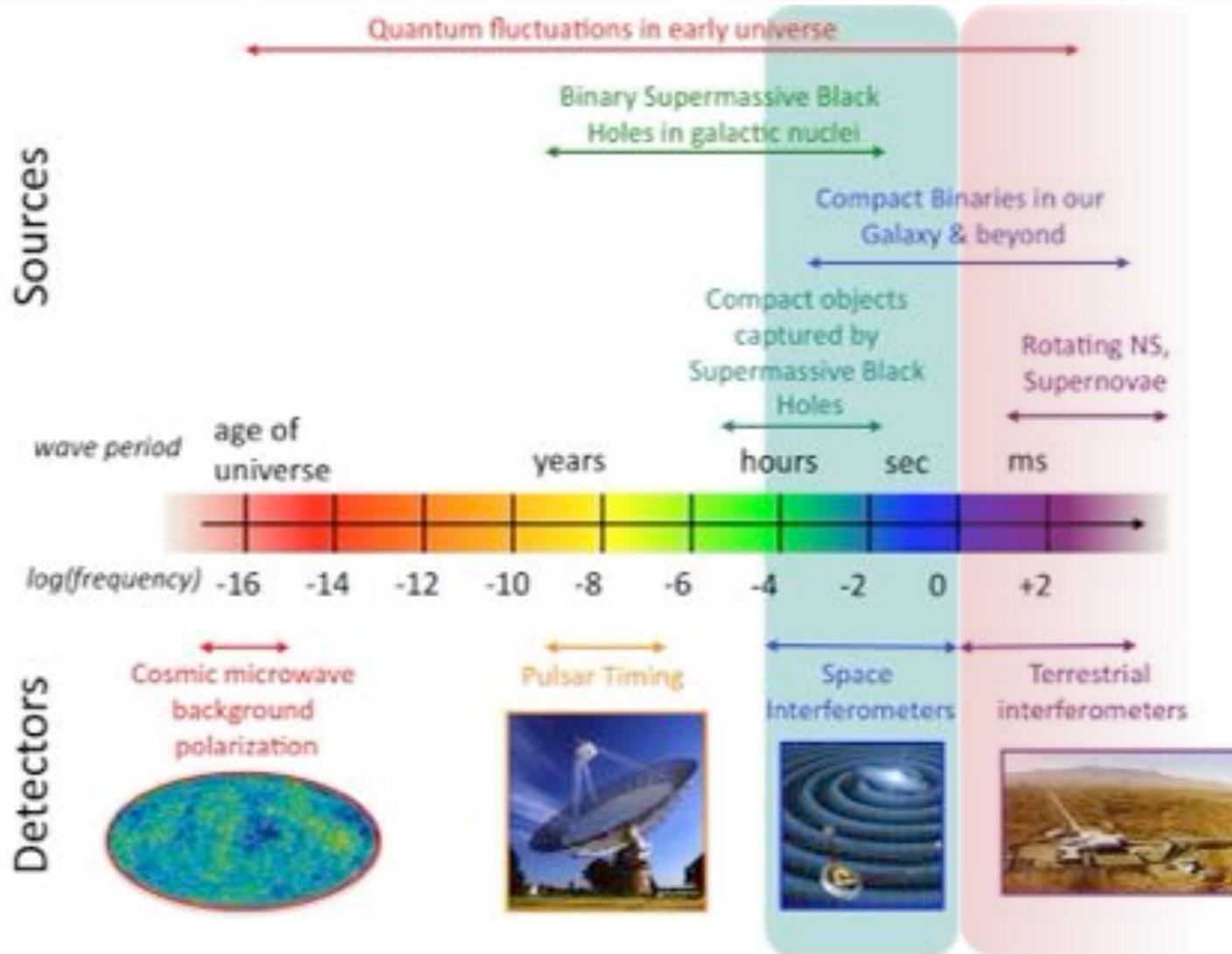
Ein schwarzes Loch verschluckt einen Neutronenstern



Massen im Sternenfriedhof (in Sonnenmassen)

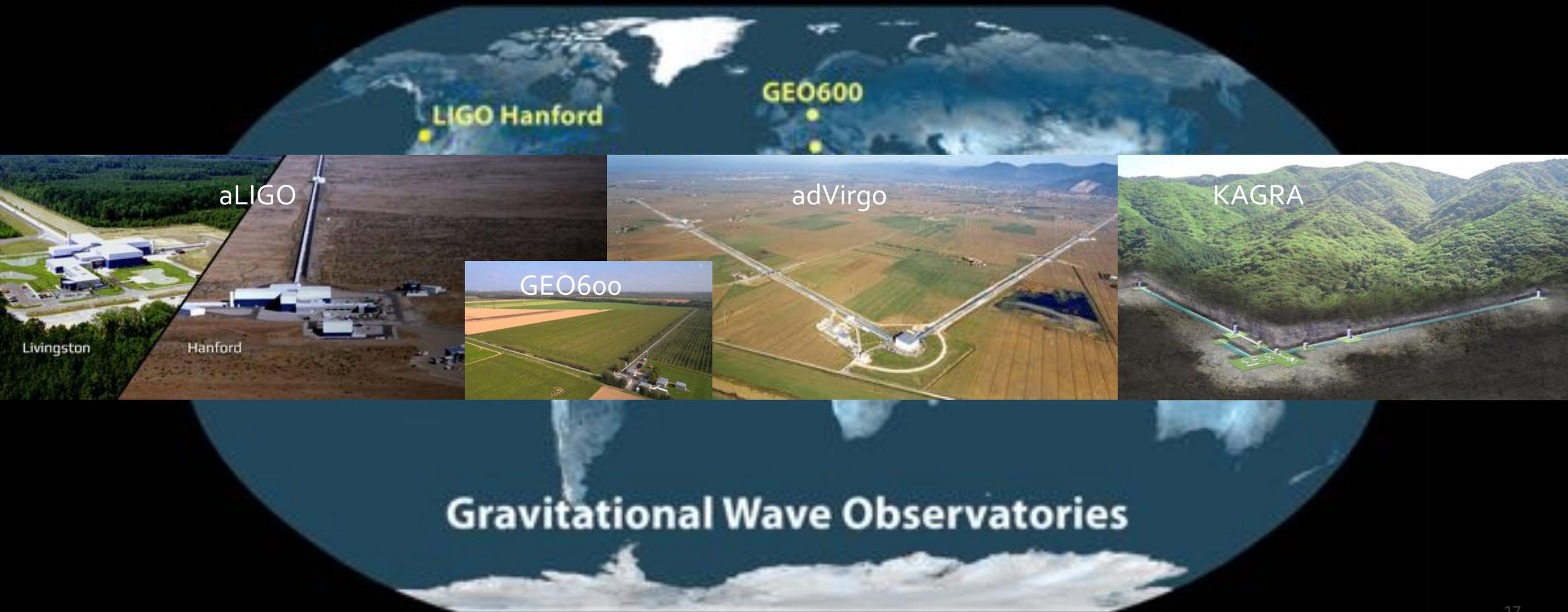


Das Gravitationswellenspektrum

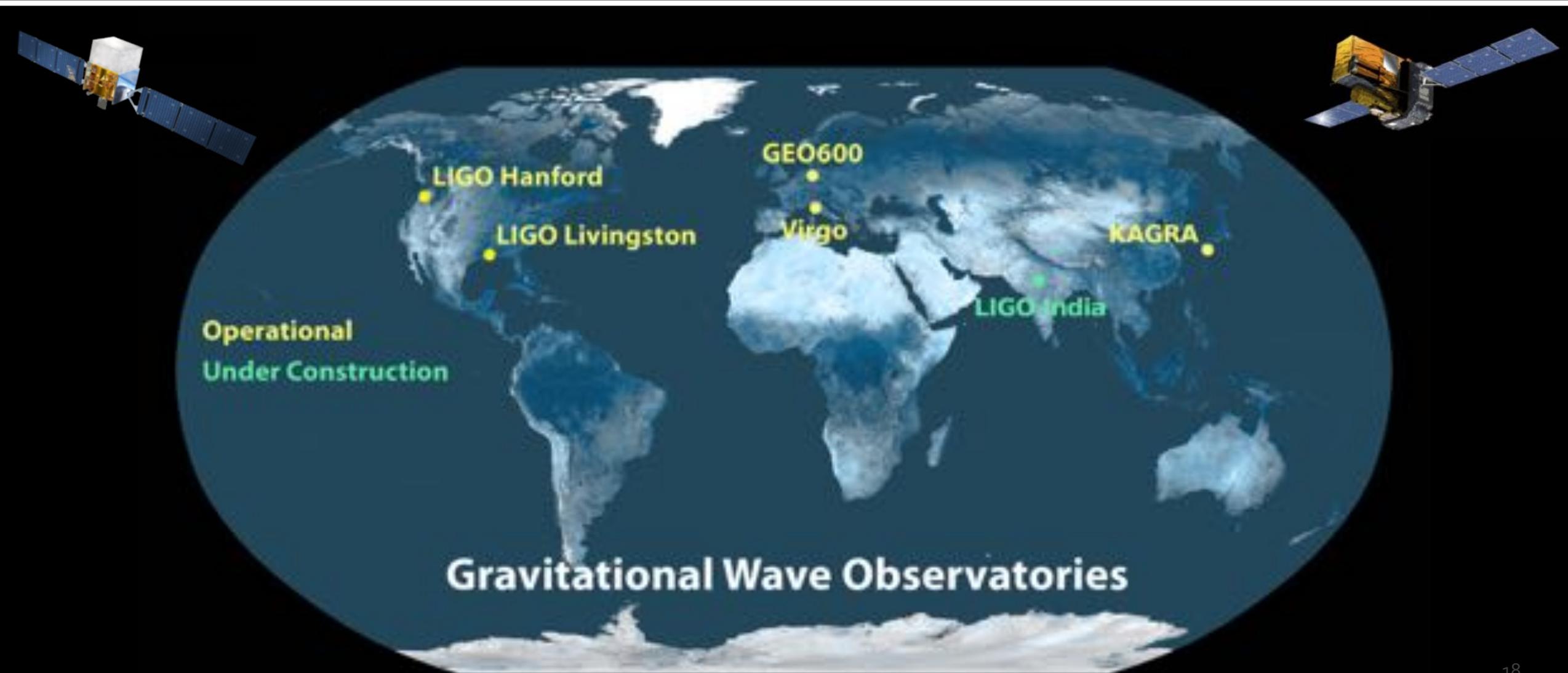


[Modified from the original source (NASA)]

Das weltweite GWD Netzwerk (aktueller Status, 2G)



Das aktuelle GWD Netzwerk + E.M. followup

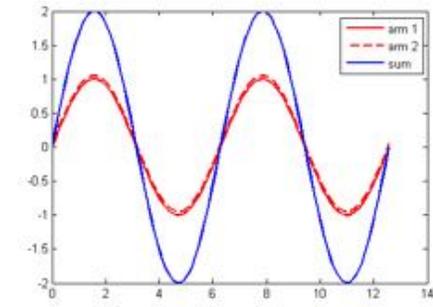
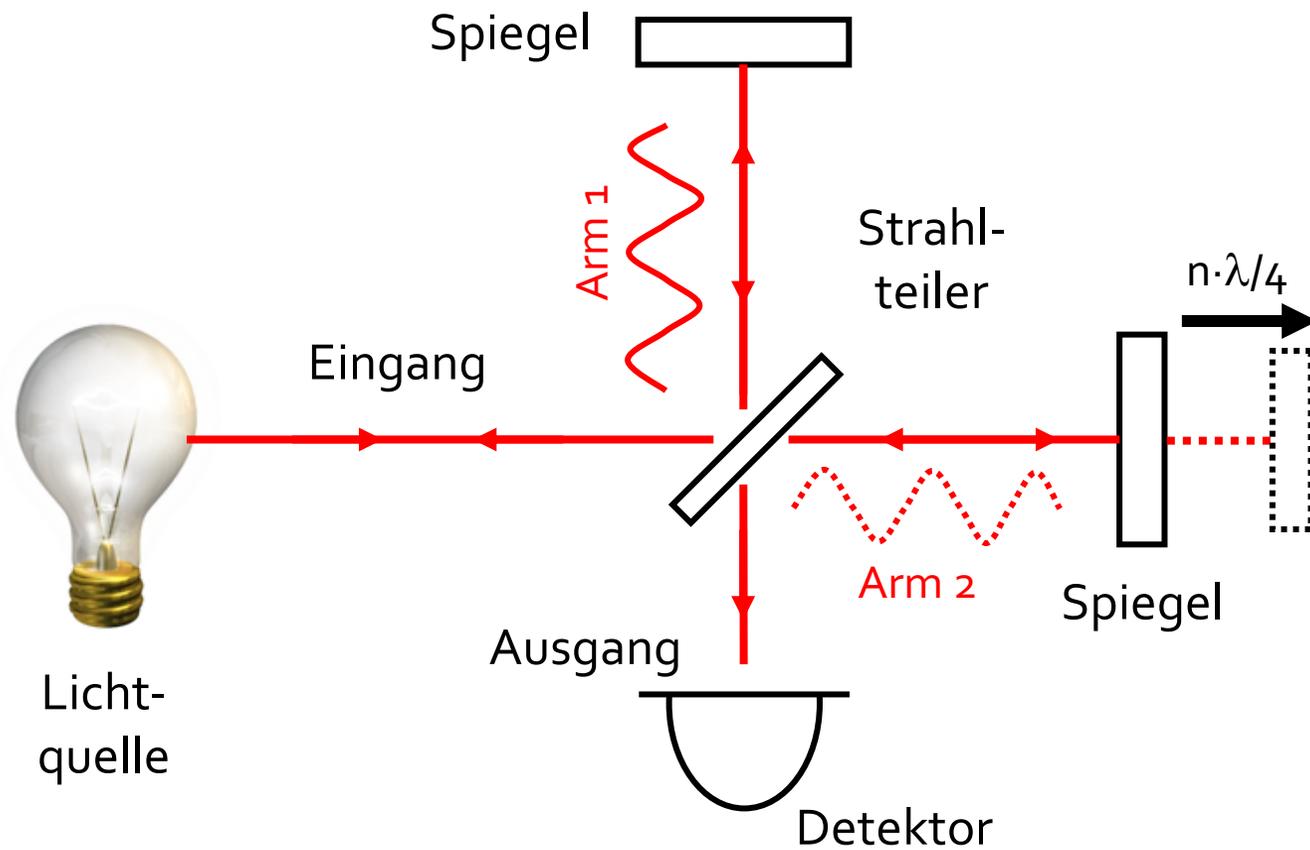




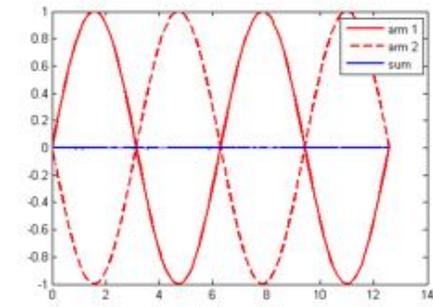
Was haben wir bereits gelernt?

- **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)

Das Michelson Interferometer



Konstruktive Interferenz



Destruktive Interferenz

Vereinfachter optischer Aufbau von aLIGO

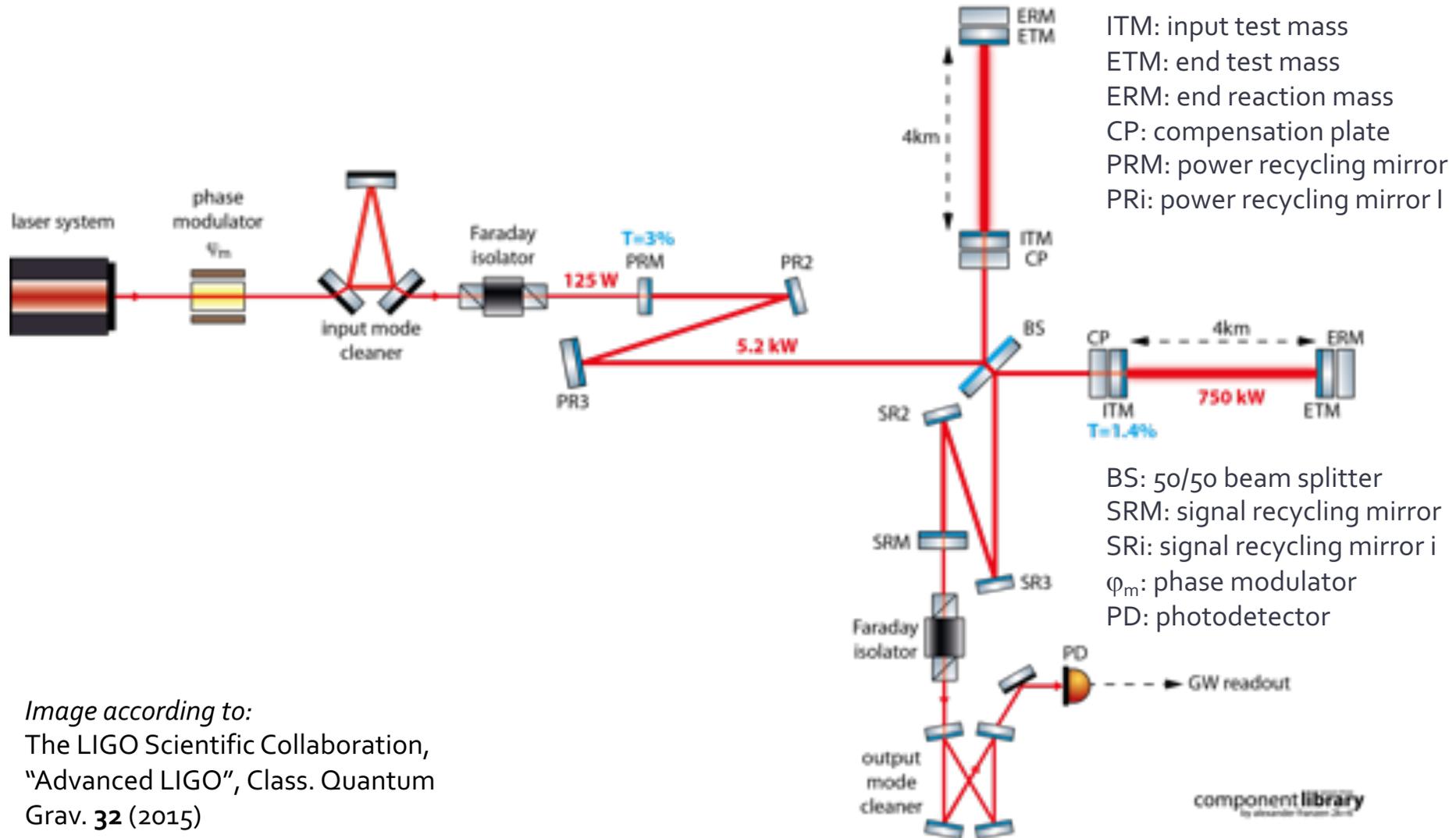
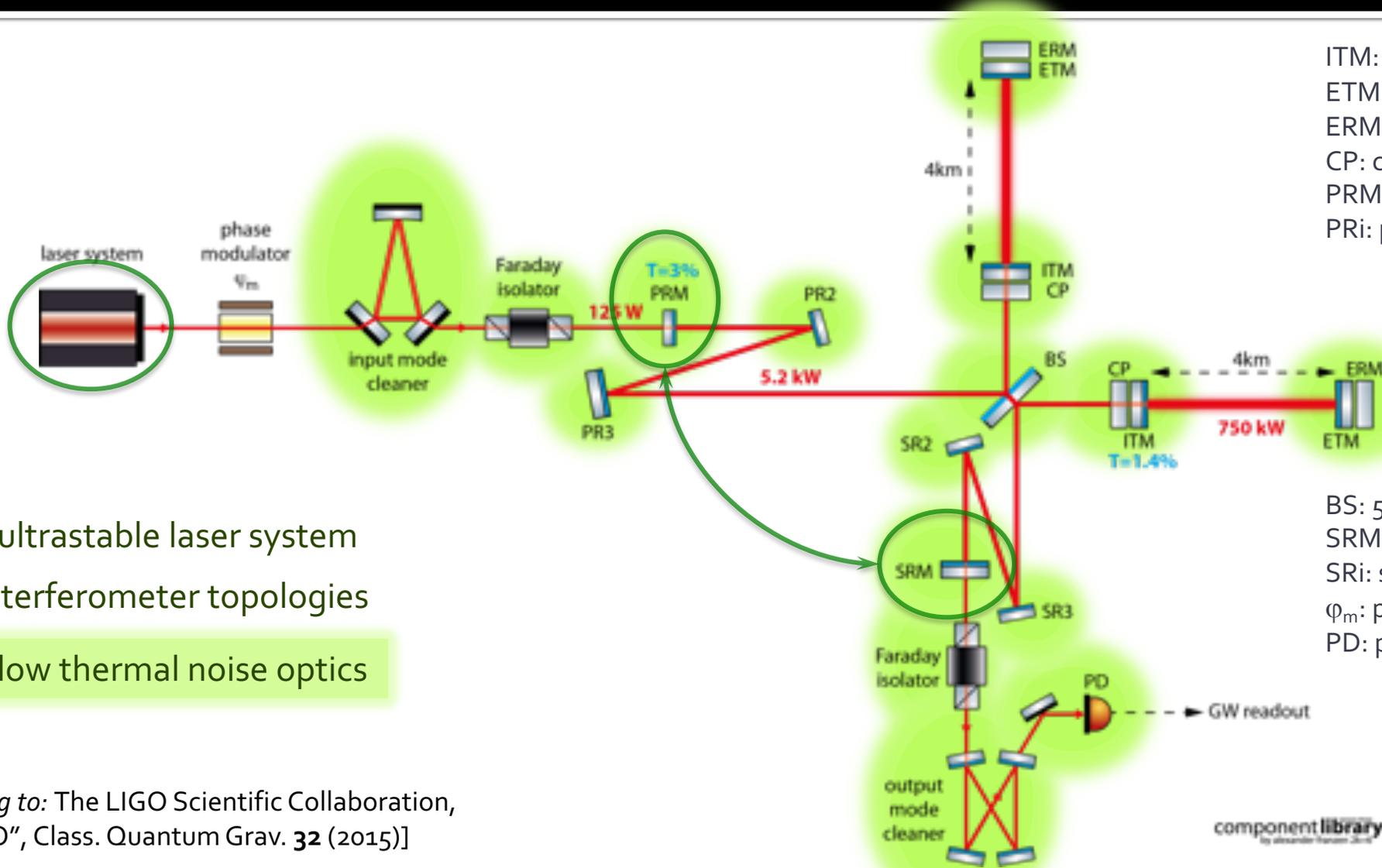


Image according to:
 The LIGO Scientific Collaboration,
 "Advanced LIGO", Class. Quantum
 Grav. **32** (2015)

Fortschrittliche Technologie für aLIGO (Beispiele)



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

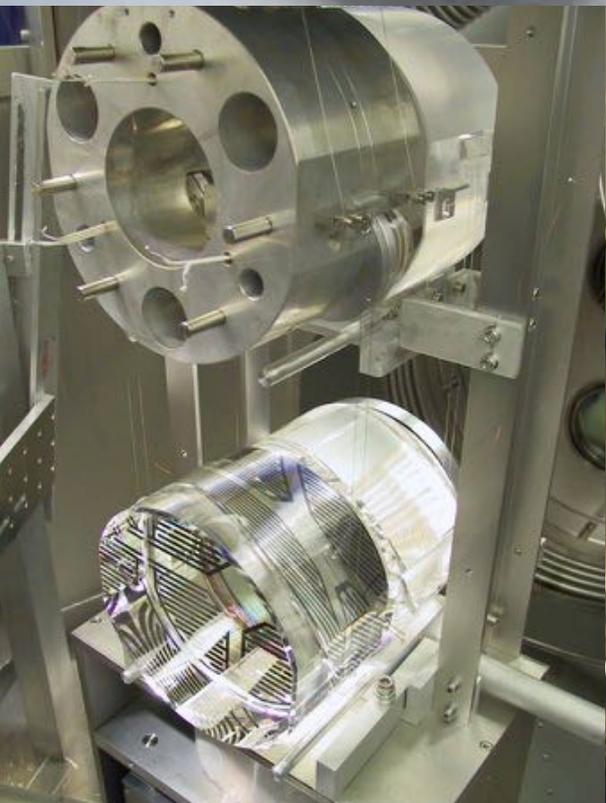
BS: 50/50 beam splitter
 SRM: signal recycling mirror
 SRI: signal recycling mirror i
 ϕ_m : phase modulator
 PD: photodetector

- High power ultrastable laser system
- Advanced interferometer topologies
- Suspended low thermal noise optics

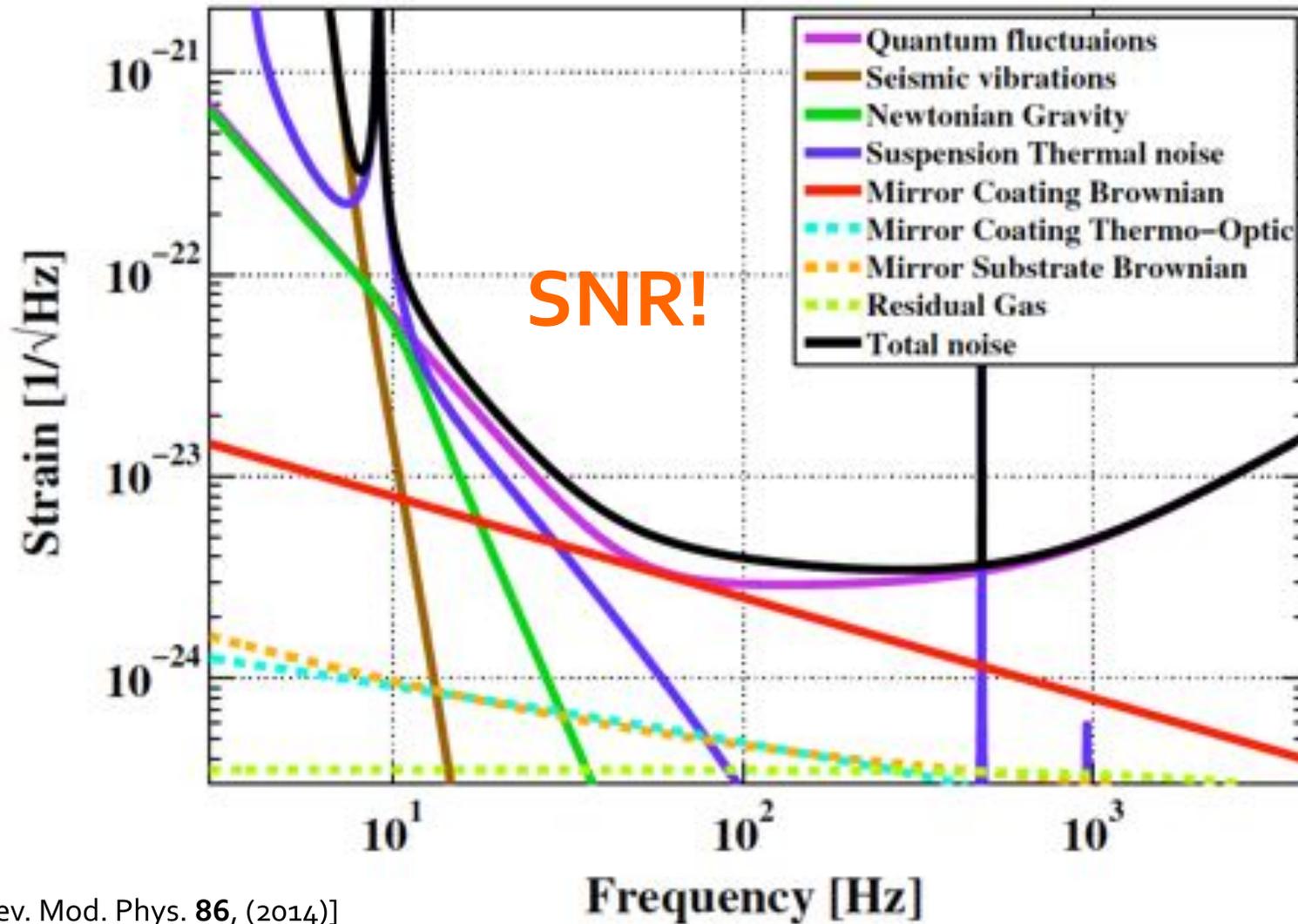
[Image according to: The LIGO Scientific Collaboration, "Advanced LIGO", Class. Quantum Grav. **32** (2015)]



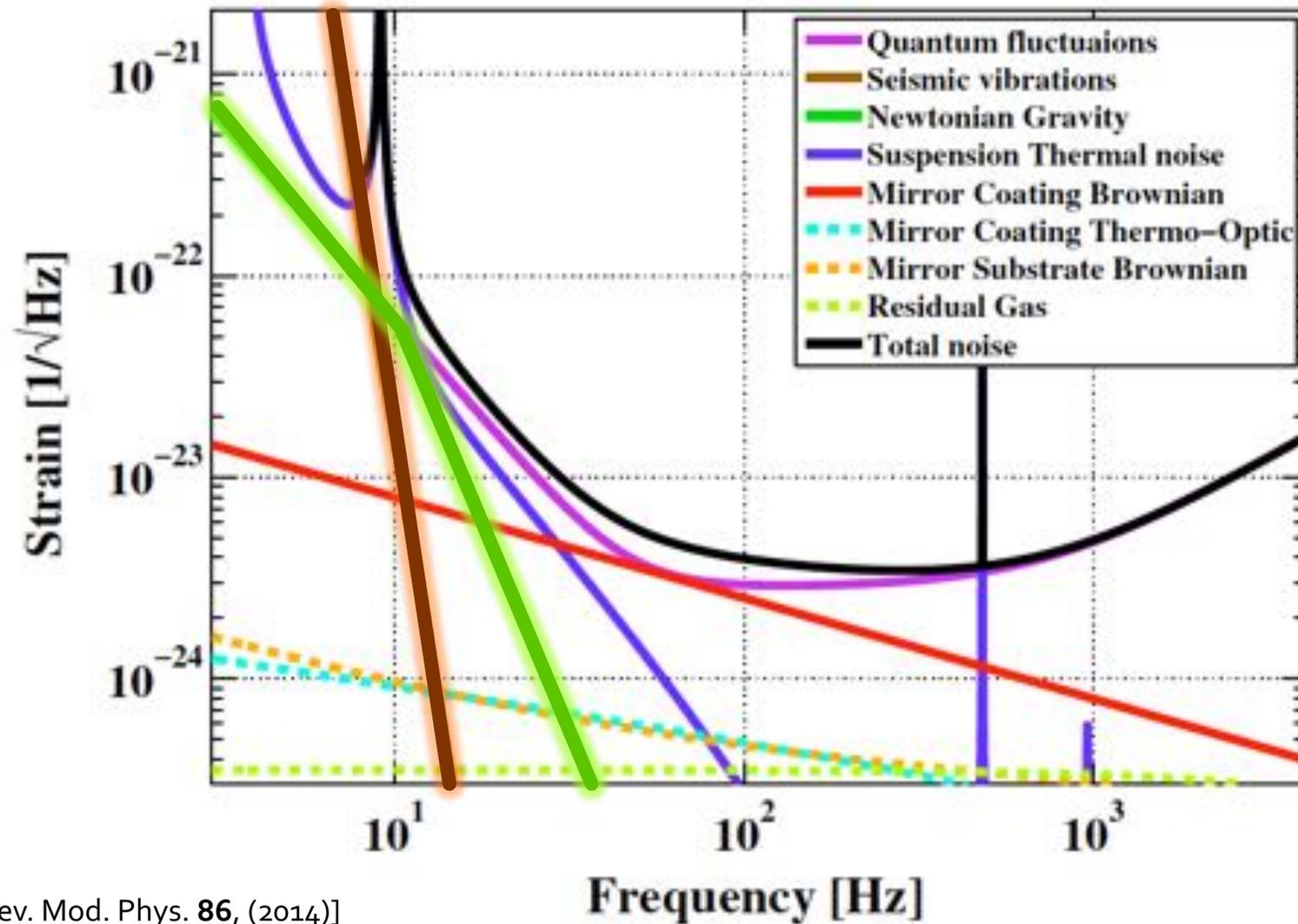
Wo sind wir jetzt?



Designempfindlichkeit von aLIGO



Designempfindlichkeit von aLIGO



Monolithische Spiegelaufhängungen



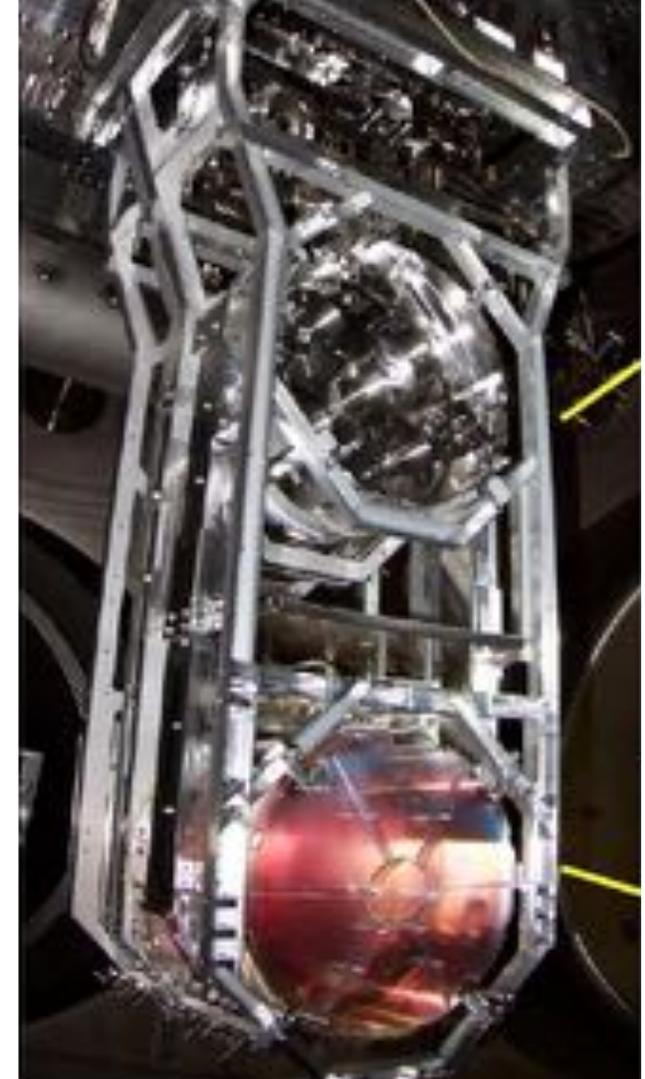
GEO600 triple suspension
fused silica mirror
180 mm diameter
 $m = 10 \text{ kg}$
suspended by FS fibres
reaction chain for electro-
static actuation

[image: H. Lück]

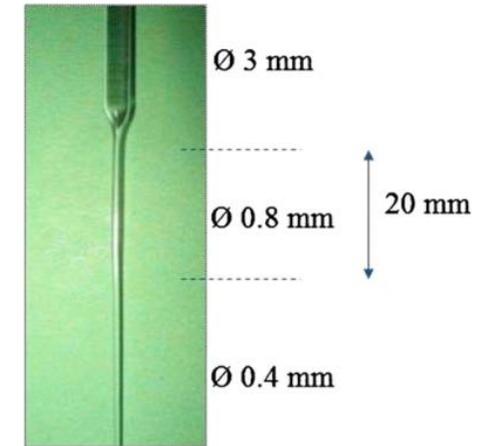
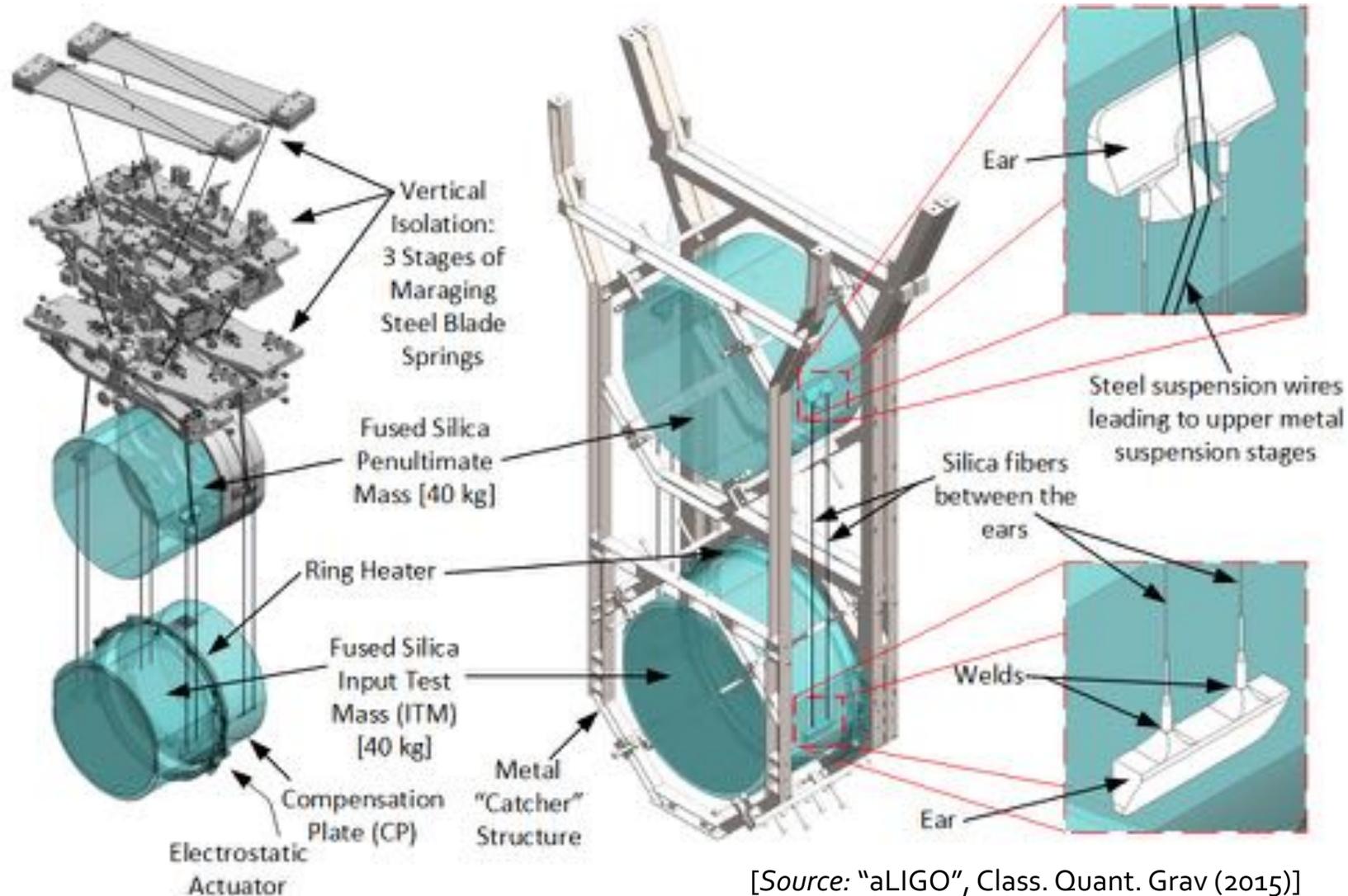


aLIGO quadruple suspension
fused silica mirror:
340 mm diameter
200 mm thickness
 $m = 40 \text{ kg}$
suspended by FS fibres:
400 μm diameter
600 mm length

[image: M. van Veggel, RSTA 2018]



Monolithische Spiegelaufhängungen



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

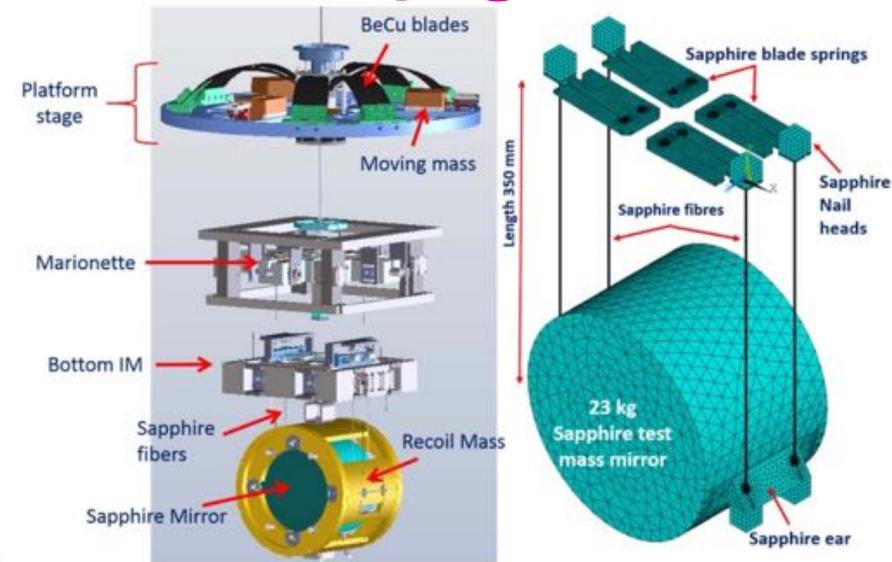
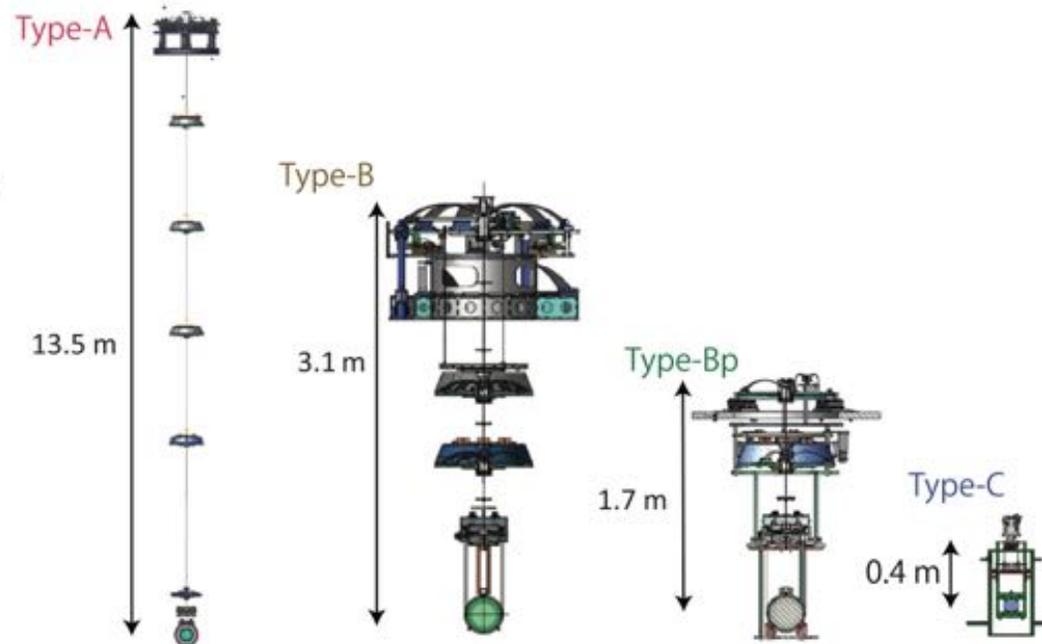
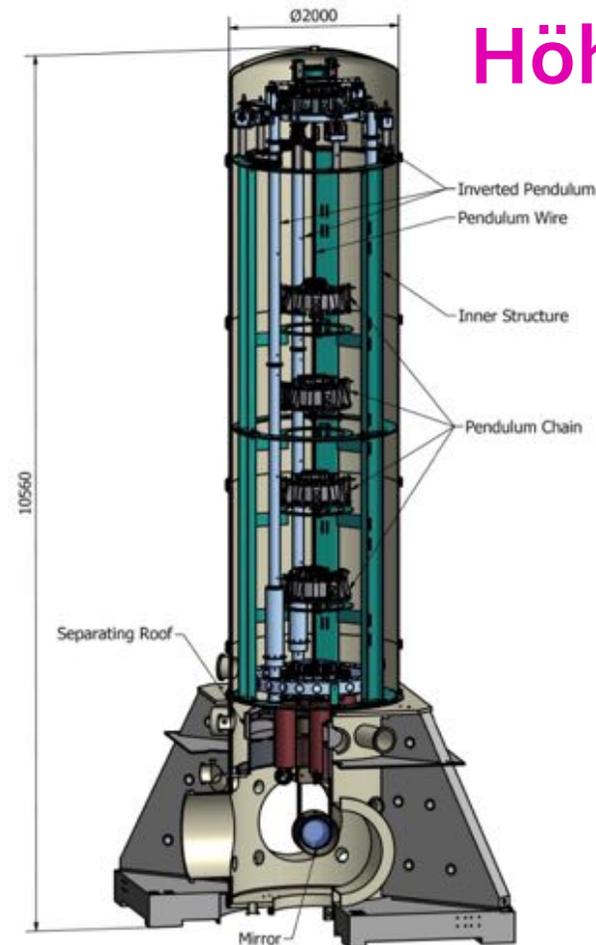
[Source: "aLIGO", Class. Quant. Grav (2015)]

Aufgehängte Testmassen, quo vadis?

Höher?

...oder verschachtelt?

...und kryogen?

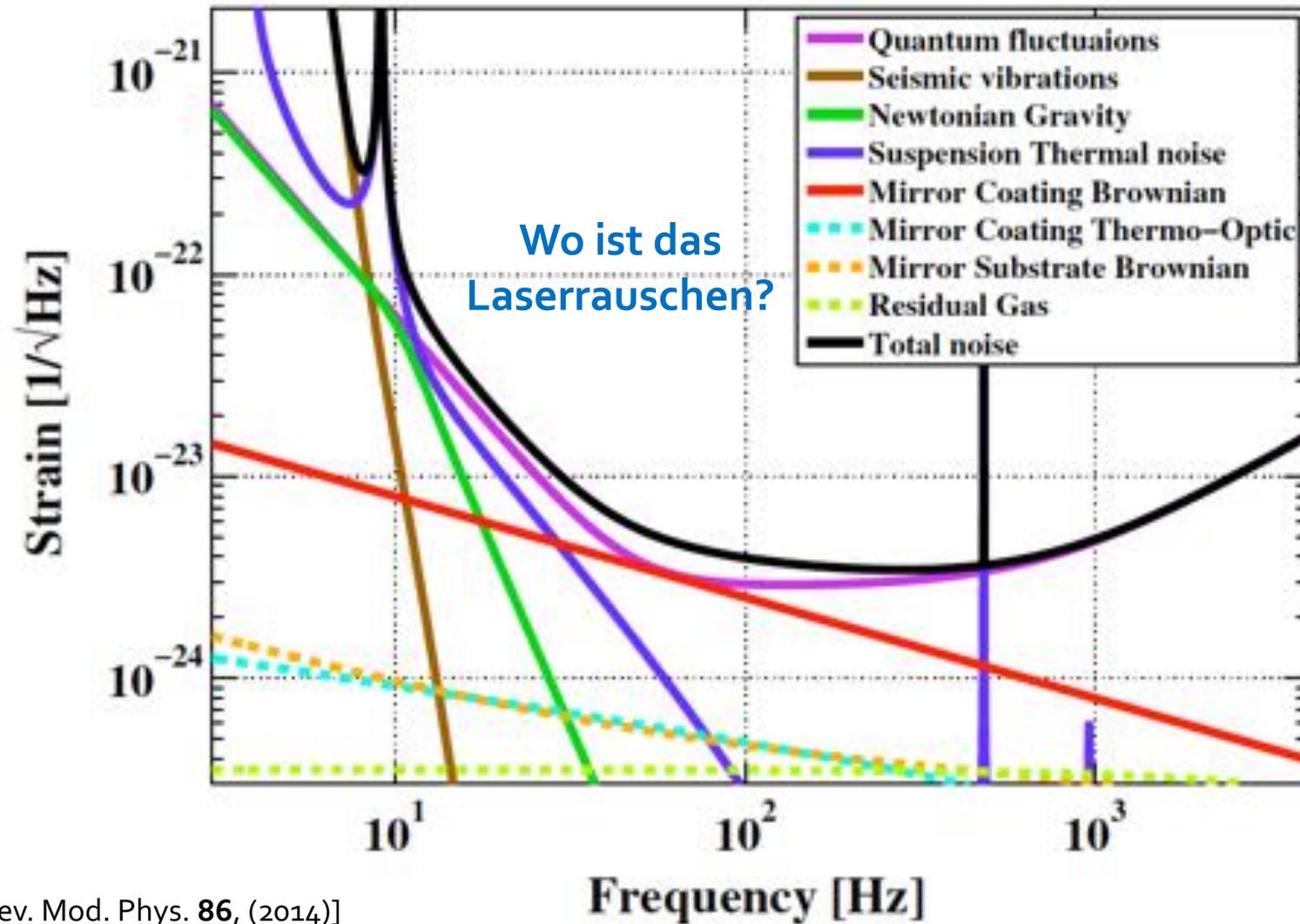


[Source: T. Accadia et al. "Virgo: a laser interferometer to detect gravitational waves", JINST 7 P03012 (2012)]

[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)]

Designempfindlichkeit von aLIGO

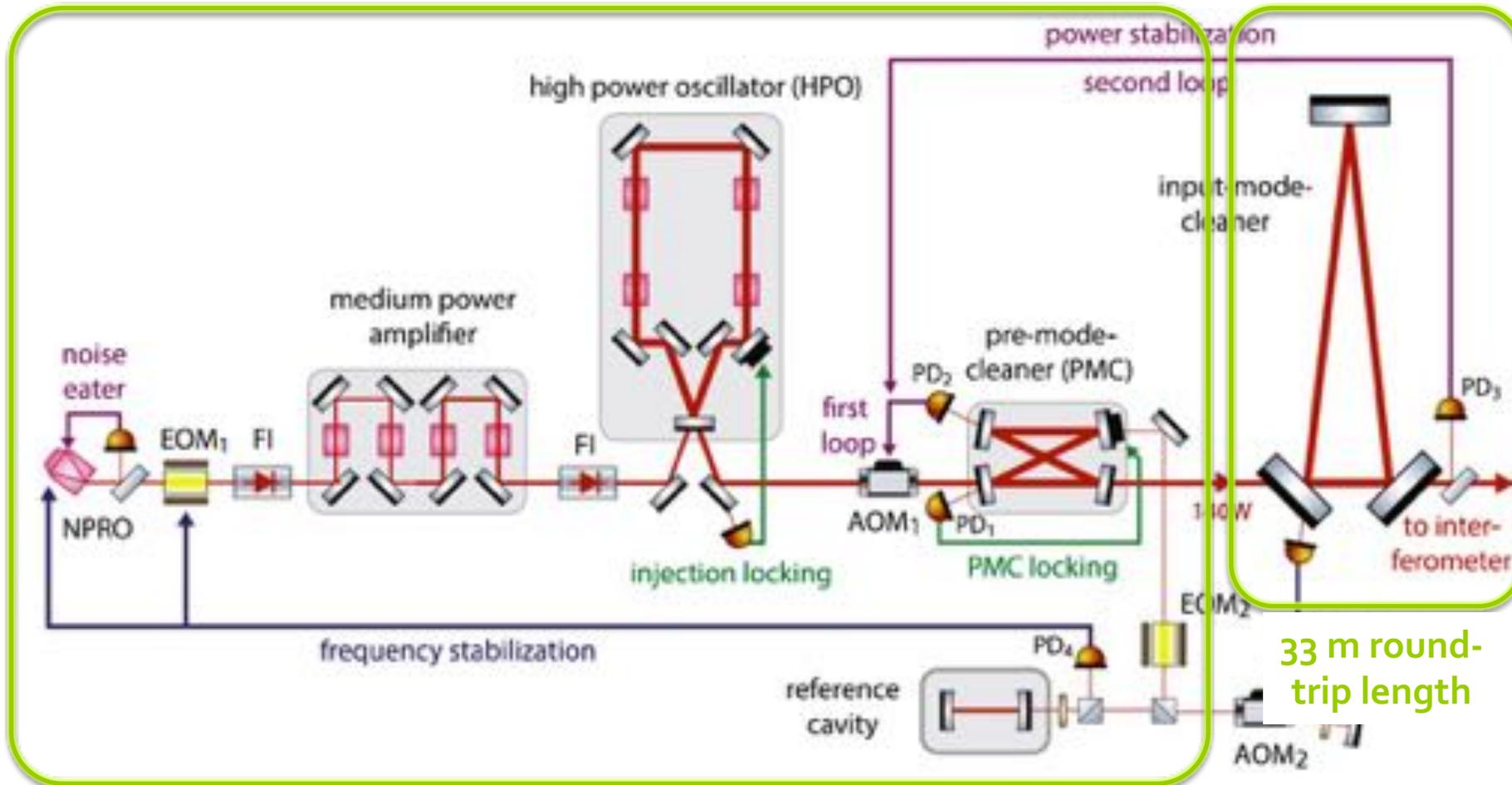


Ultrastabile Hochleistungs-Lasersysteme (hier: aLIGO)



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

Das aLIGO Lasersystem

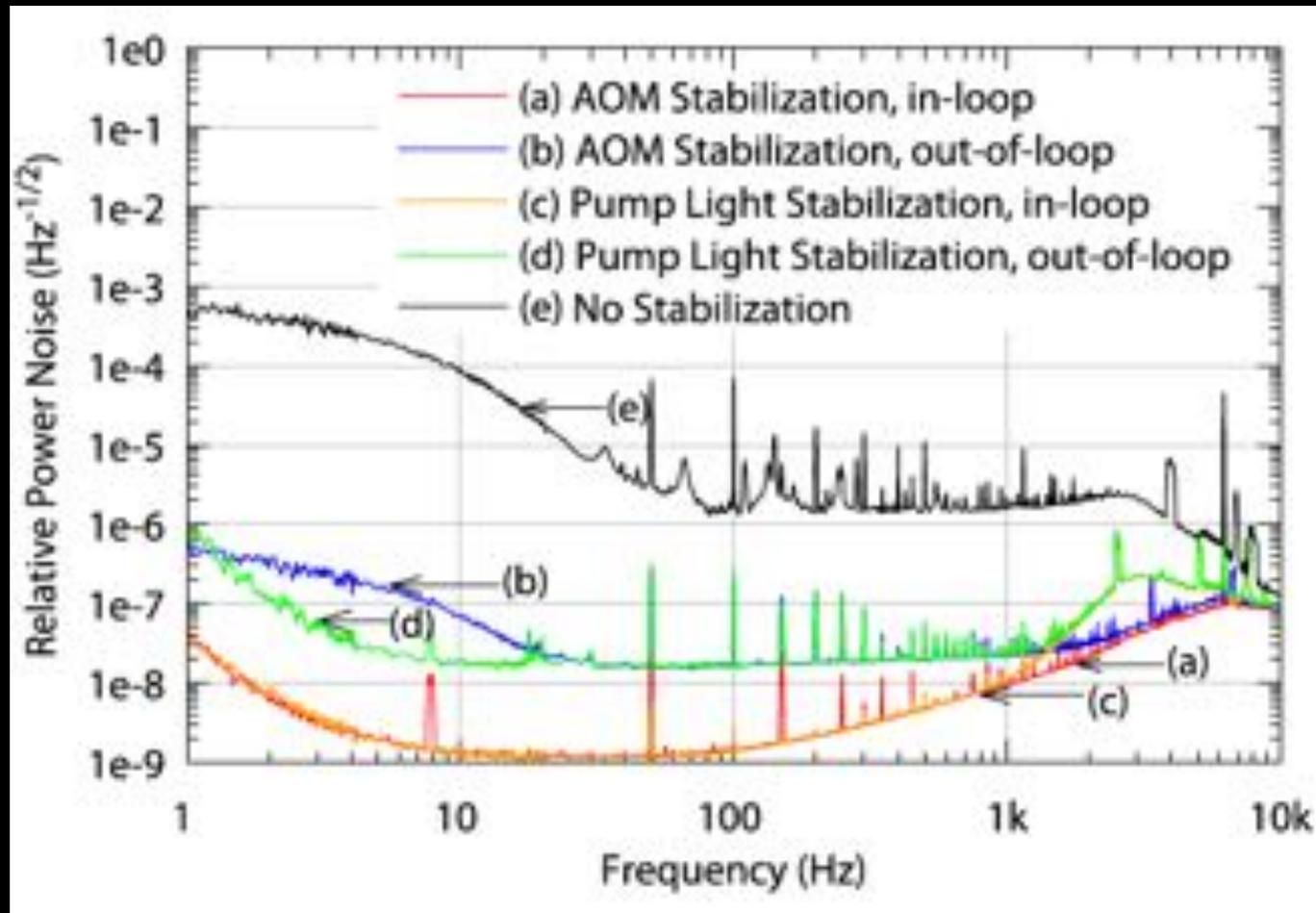


[Image: LIGO Scientific Collaboration, Class. Quantum Grav. **32** (2015)]

approx. 1.5 x 3 m table

33 m round-trip length

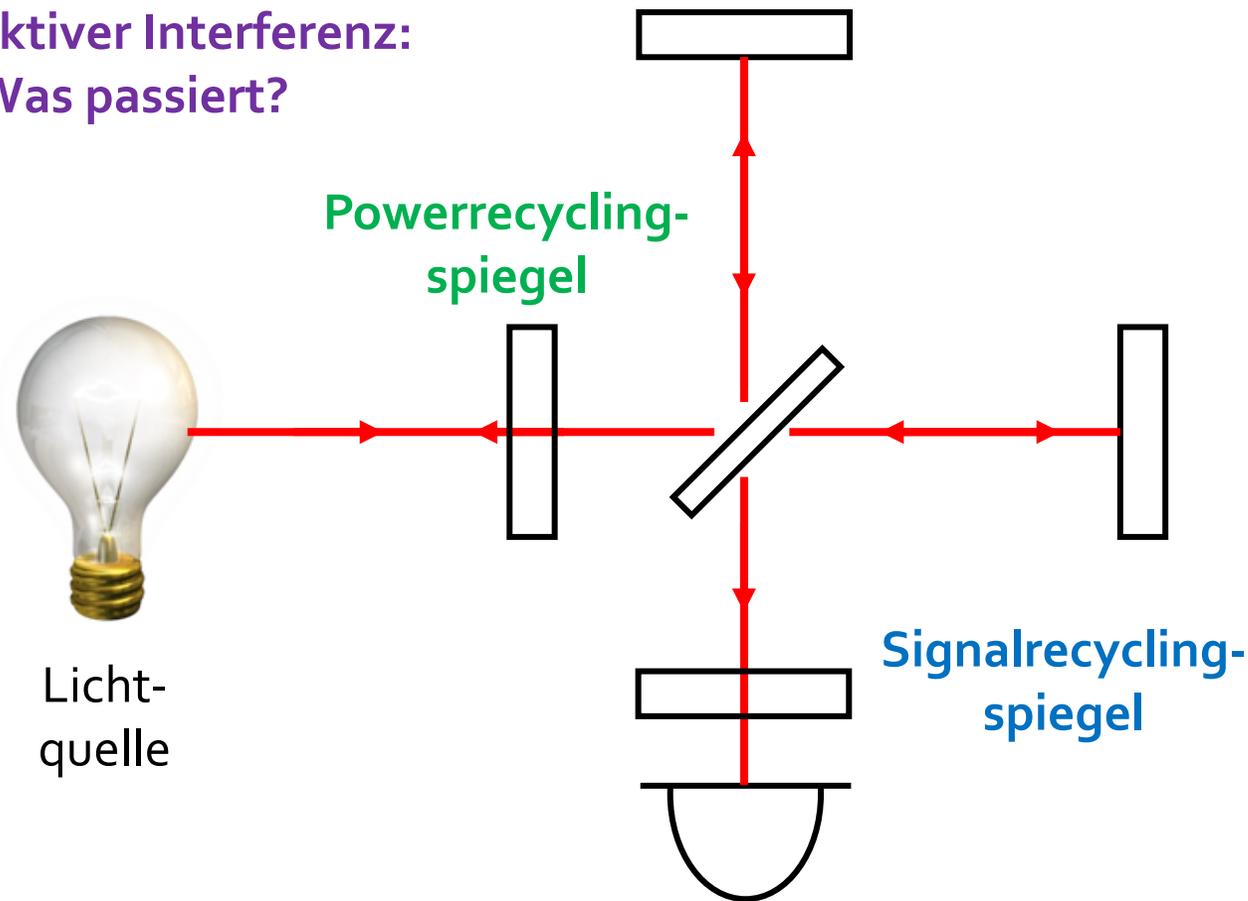
Leistungsrauschen des aLIGO Lasersystems



[F. Thies et al., Nd:YVO₄ high-power master oscillator power amplifier laser system for second-generation gravitational wave detectors, Opt. Lett. 44 (3) 2019]

Recyclingtechniken (Power und Signal Recycling)

Betrieb des MI nahe an
destruktiver Interferenz:
Was passiert?



Was macht die GW
mit dem Interferometer?

- ⇒ Sie staucht und streckt die Raumzeit!
- ⇒ Wirkt wie eine Phasenmodulation (erzeugt Signal-Seitenbänder)
- ⇒ Interaktion mit der GW maximieren!

Vereinfachter optischer Aufbau von aLIGO

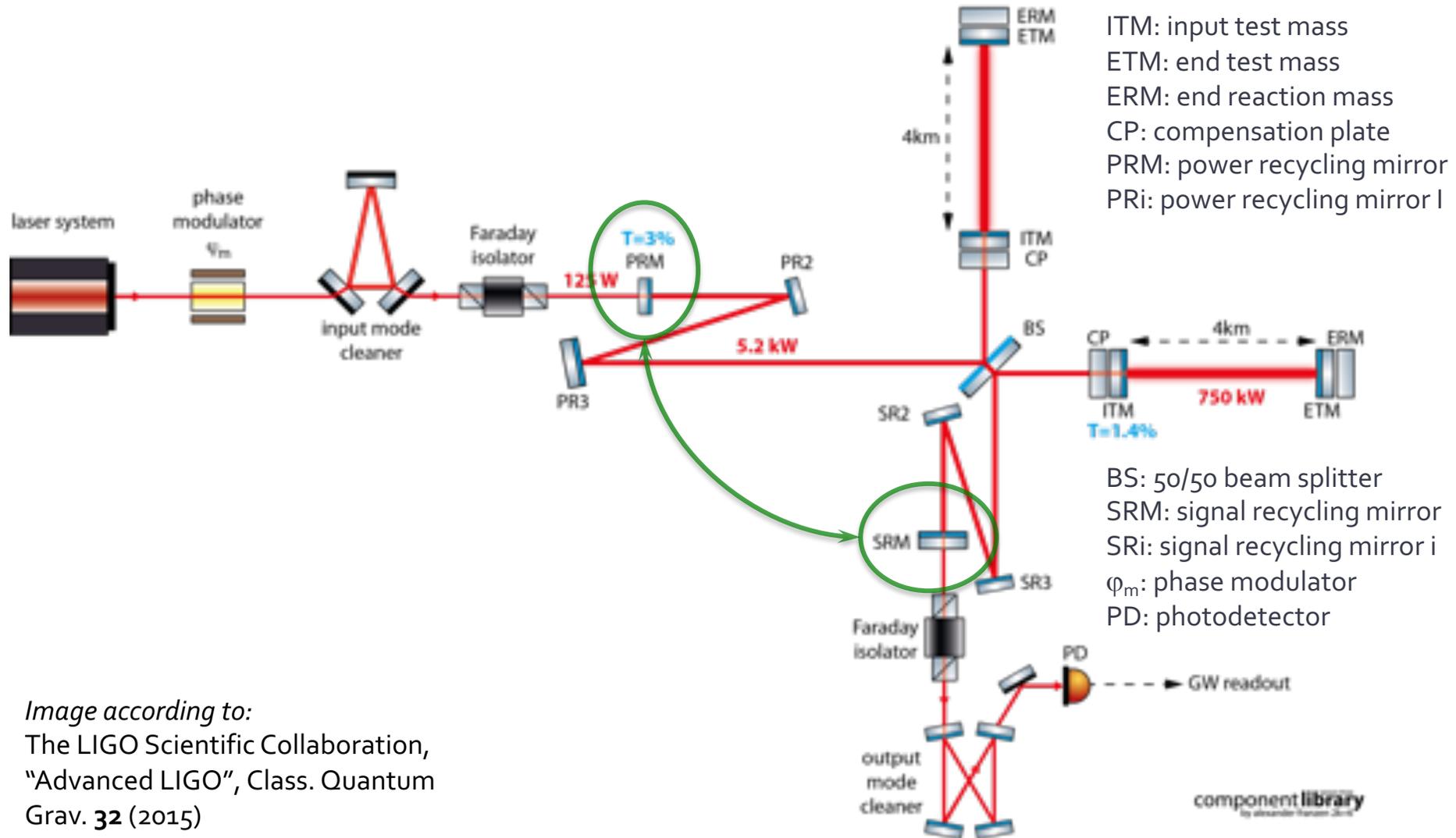
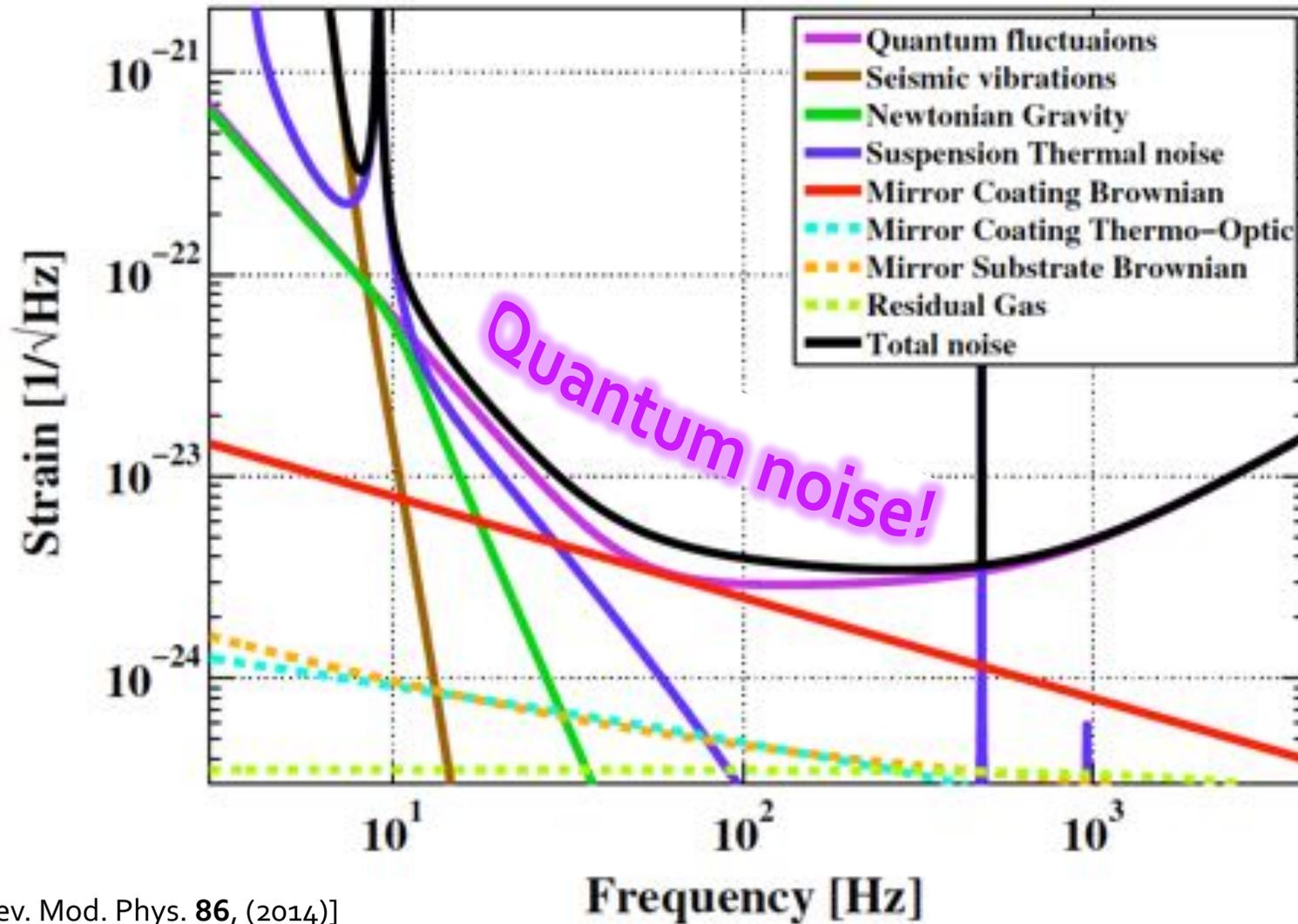
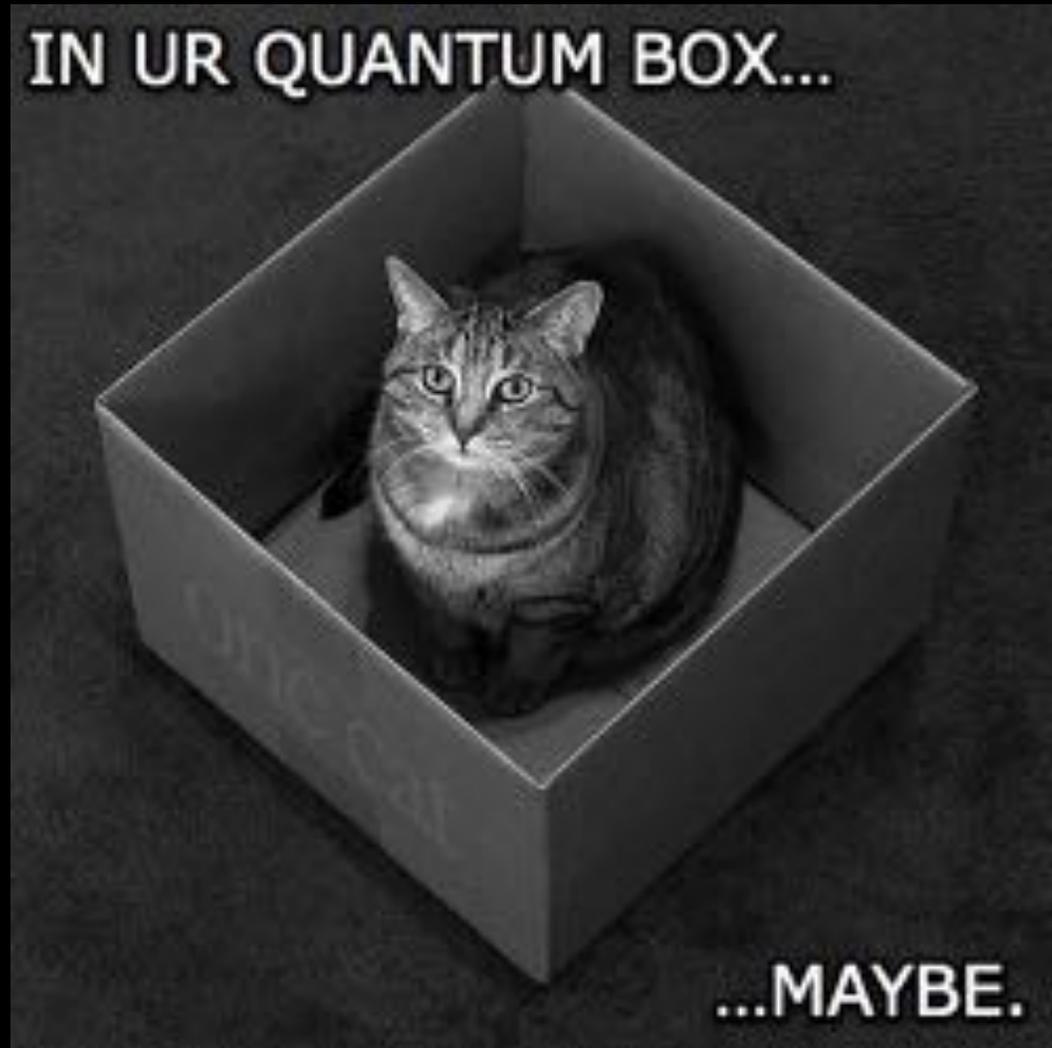


Image according to:
 The LIGO Scientific Collaboration,
 "Advanced LIGO", Class. Quantum
 Grav. **32** (2015)

Designempfindlichkeit von aLIGO



Quantenrauschen: Heisenberg & Co.



Ist Quantenrauschen relevant?

PHYSICAL REVIEW LETTERS

VOLUME 45

14 JULY 1980

NUMBER 2

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

Carlton M. Caves

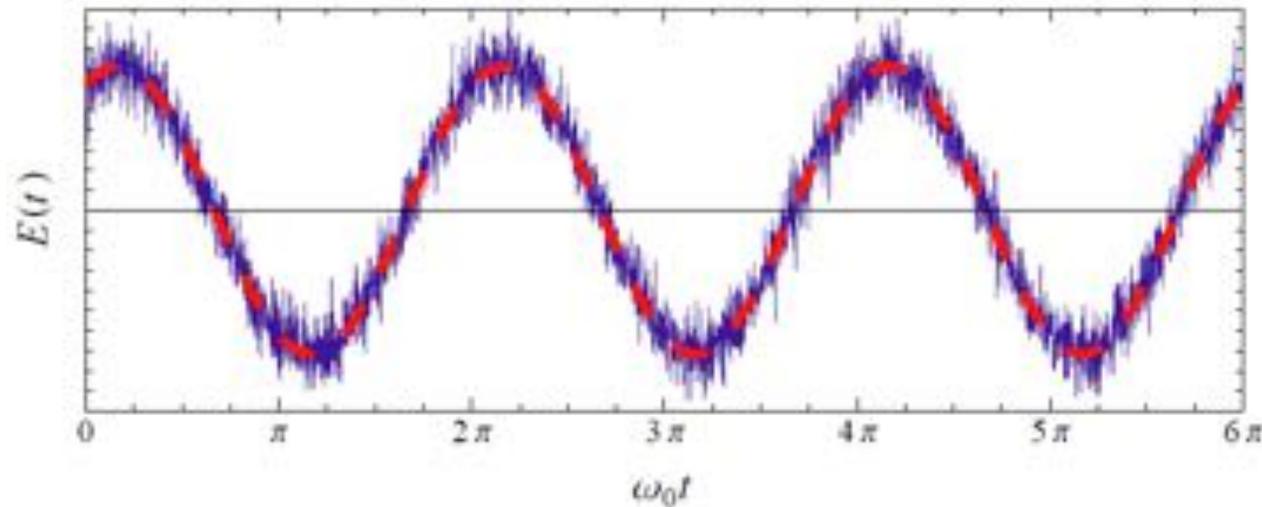
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

(Received 29 January 1980)

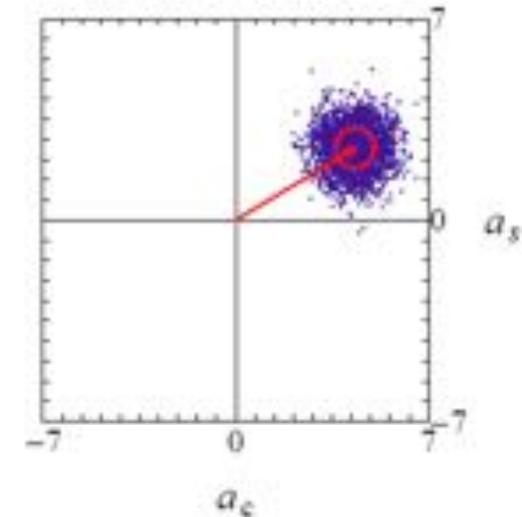
The interferometers now being developed to detect gravitational waves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy. They do.

Zwei Visualisierungen für Licht

Zeitreihe:



Phasenzustandsdiagramm:



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

⇒ Die Spitze des Phasors ist irgendwo innerhalb der „blaugepunkteten Fläche“ (Gauss'sche Verteilung im Phasenraum)

Quadraturoperatoren und Heisenberg

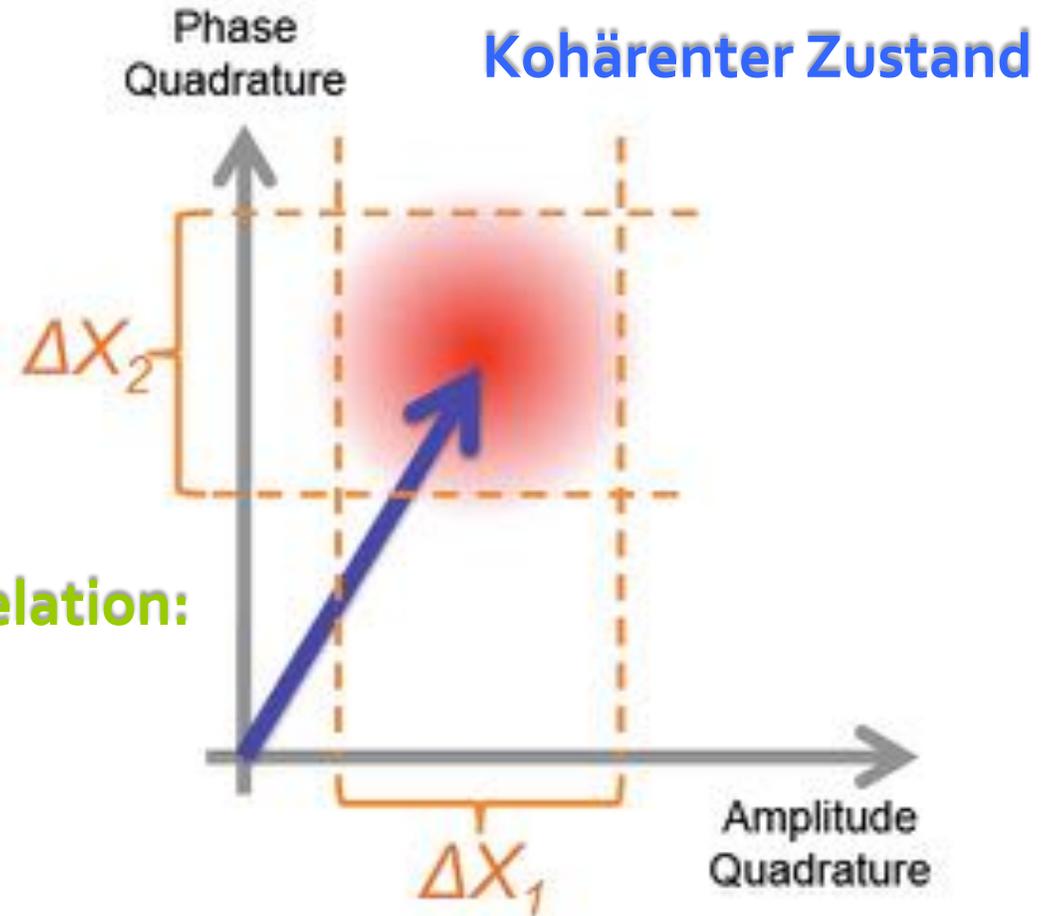
Quadraturoperatoren:

$$\hat{X}_1 = \hat{a}^\dagger + \hat{a}$$

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

Heisenbergsche Unschärferelation:

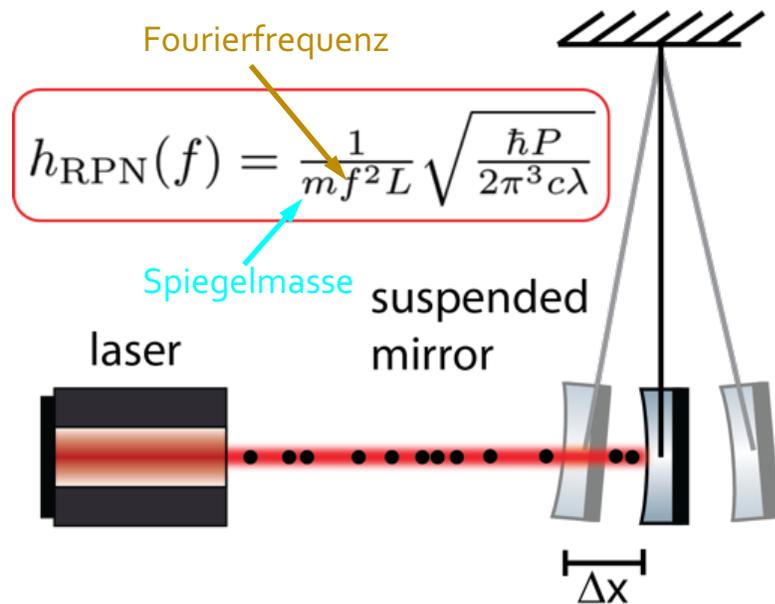
$$\Delta \hat{X}_1 \cdot \Delta \hat{X}_2 \geq 1$$



[Image: S. Hild]

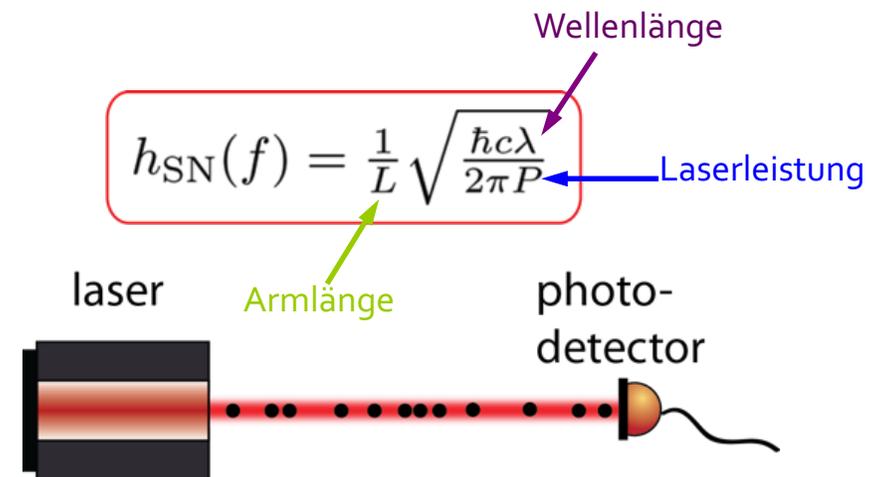
Quantenrauschen in einem Interferometer

Strahlungsdruckrauschen (RPN)



Rückwirkungsrauschen

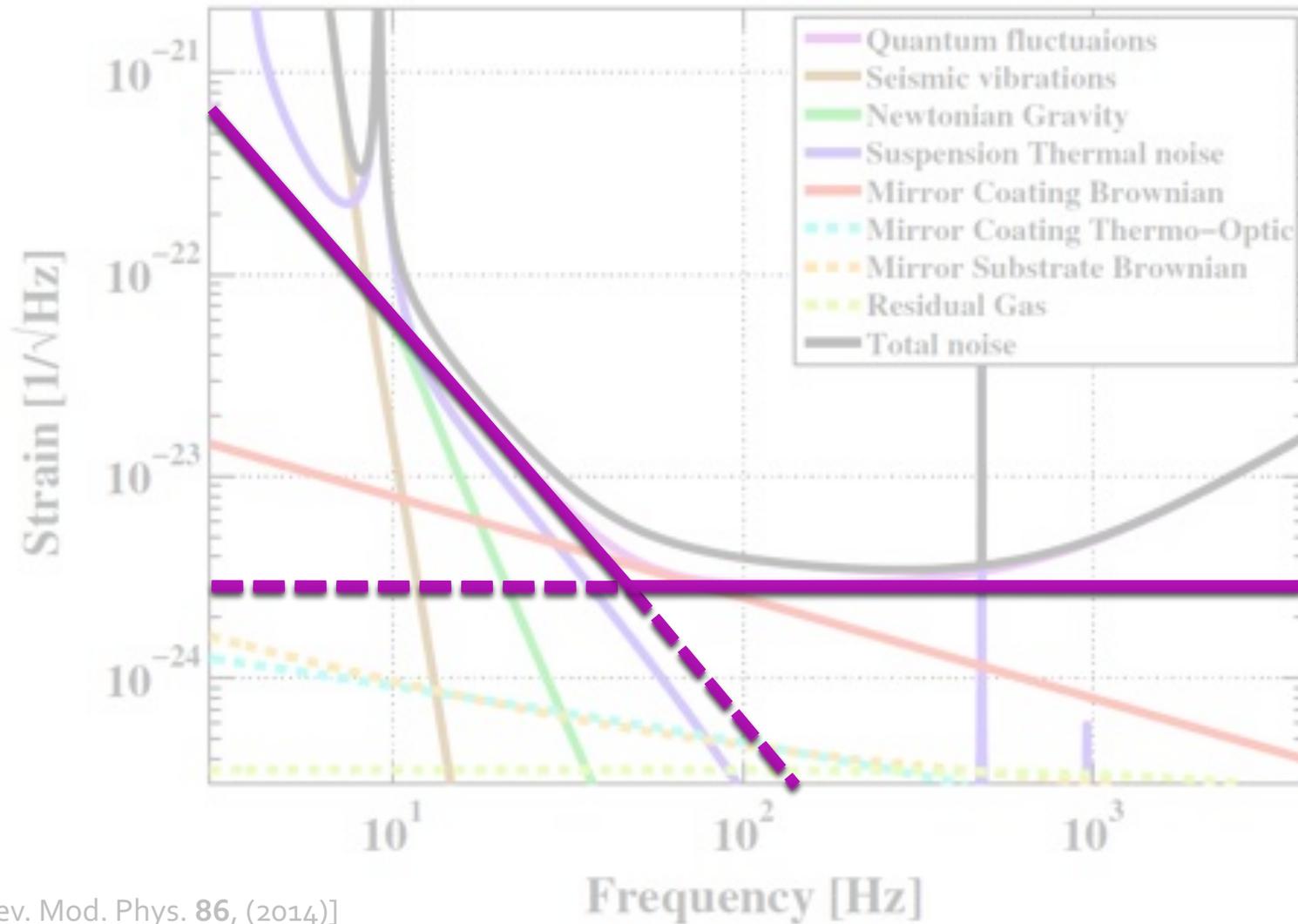
Relatives Schrotrauschen (SN)



Detektionsrauschen



Das Standard-Quantenlimit (SQL)



Heisenbergsche Unschärferelation



“Heisenberg”



Werner Heisenberg

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

.wird erfüllt durch z.B.

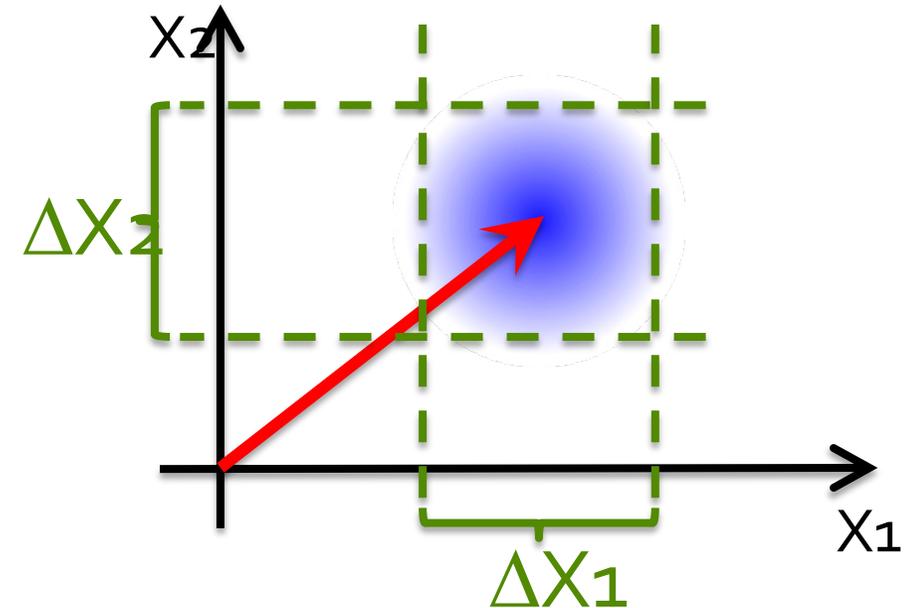
$$1 \times 1 = 1$$

$$2 \times \frac{1}{2} = 1$$

$$\frac{1}{5} \times 5 = 1$$

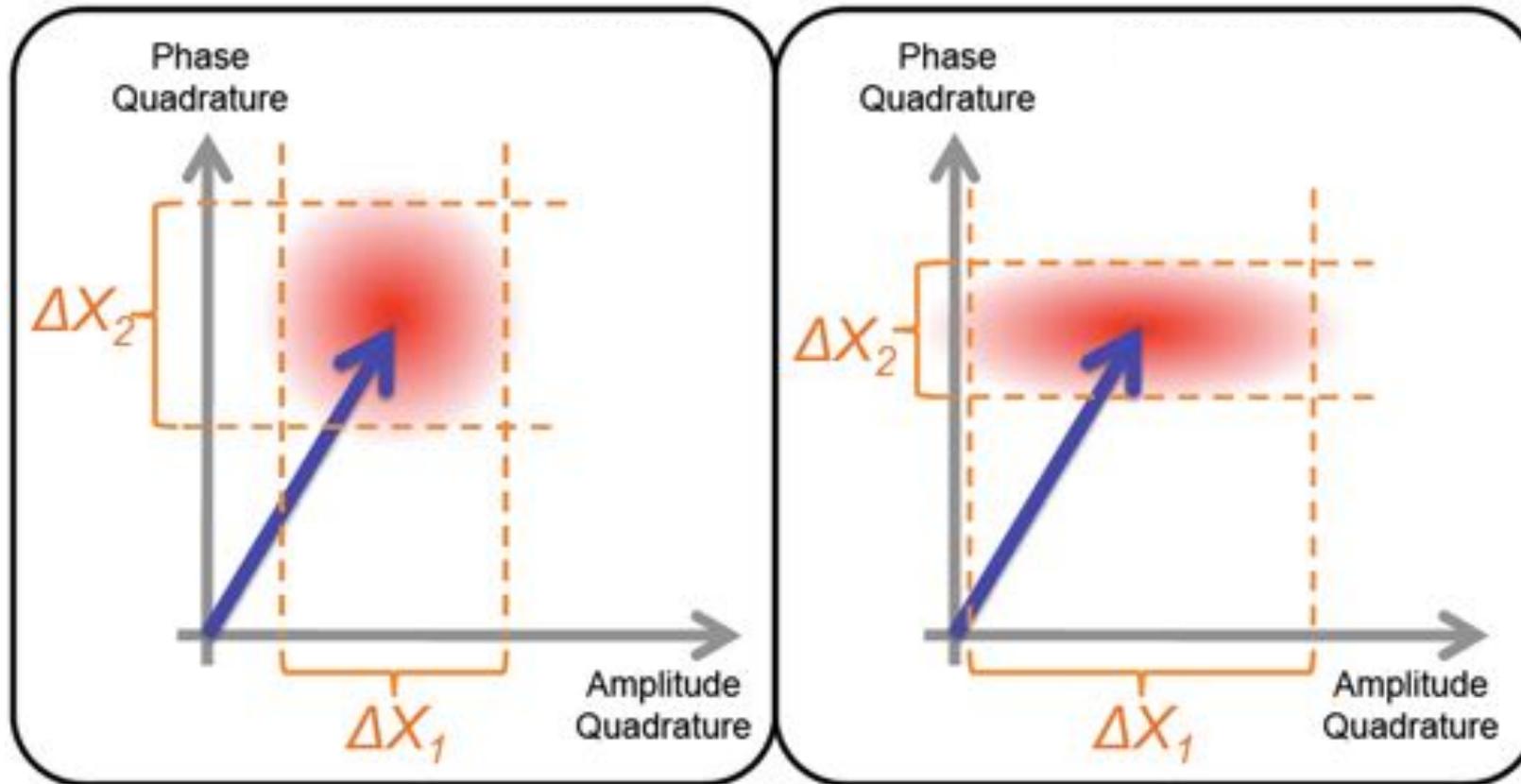
ber auch durch z.B.

$$10 \times \frac{1}{3} > 1$$



=> Wir können die Unschärfe in der Messung der einen Größe *reduzieren*, aber auf Kosten einer *Erhöhung* der Unschärfe in der anderen Messgröße!

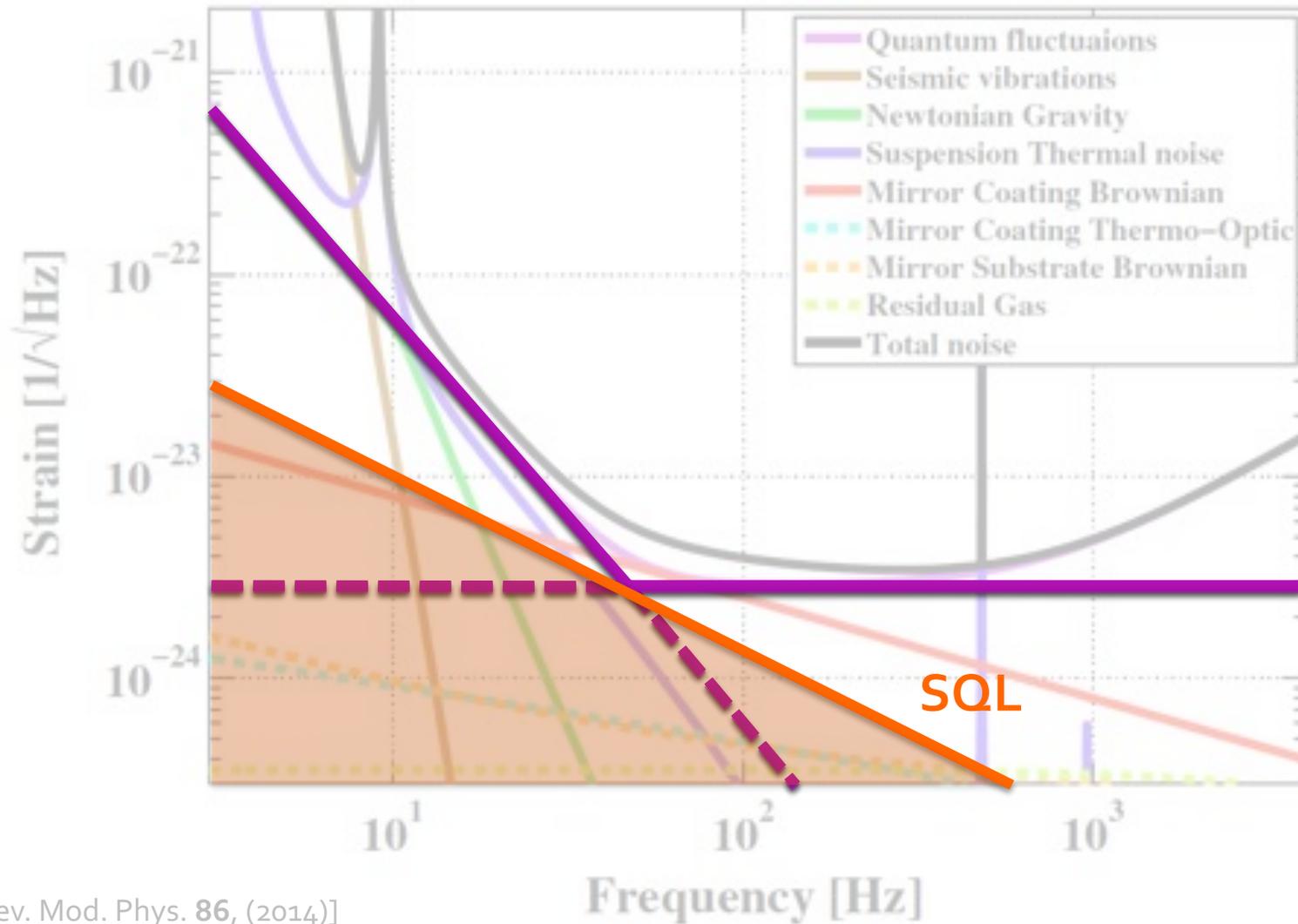
Kohärenter vs. gequetschter Zustand



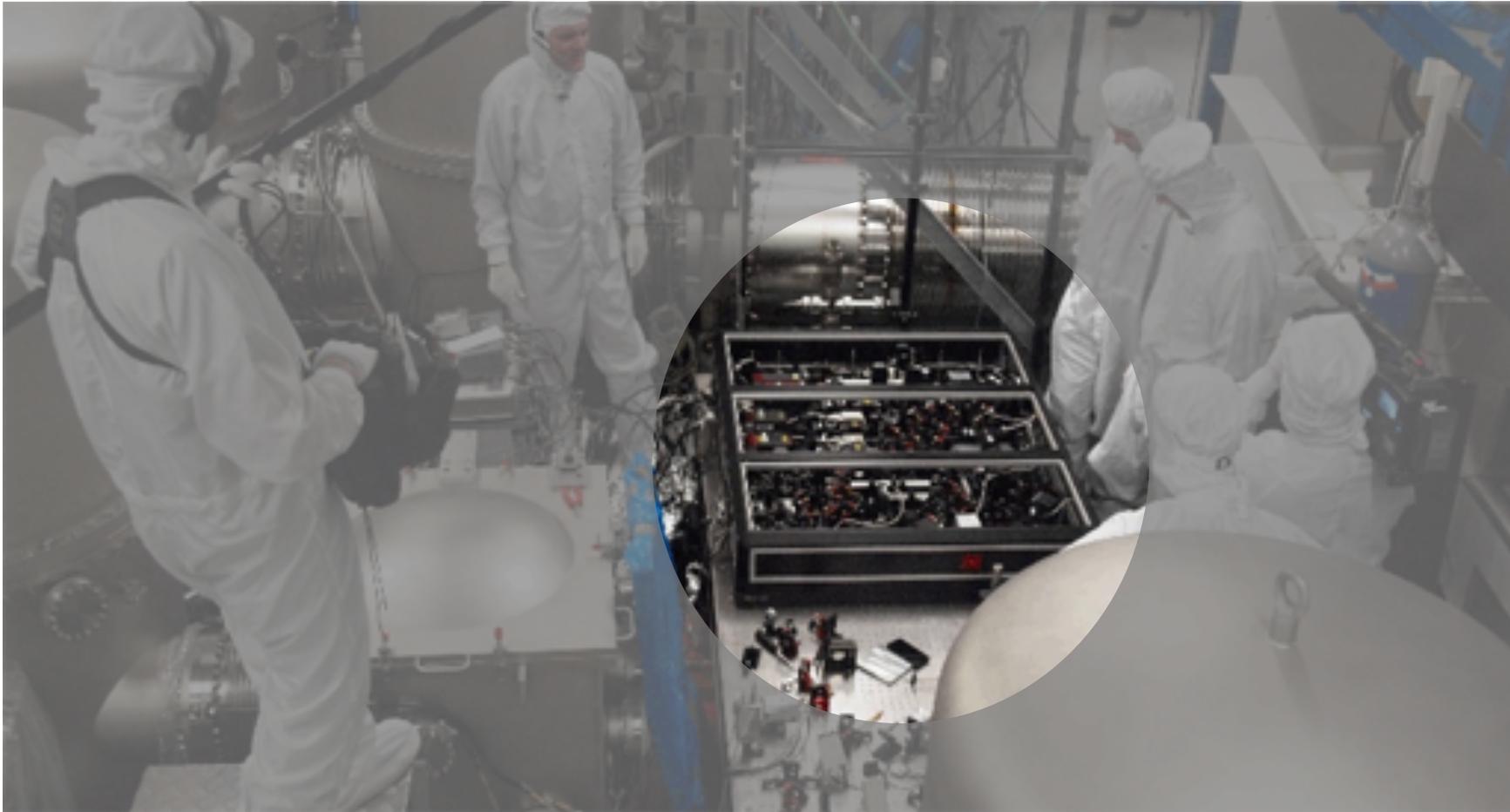
Heisenberg sagt lediglich

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

Das Standard-Quantenlimit (SQL)

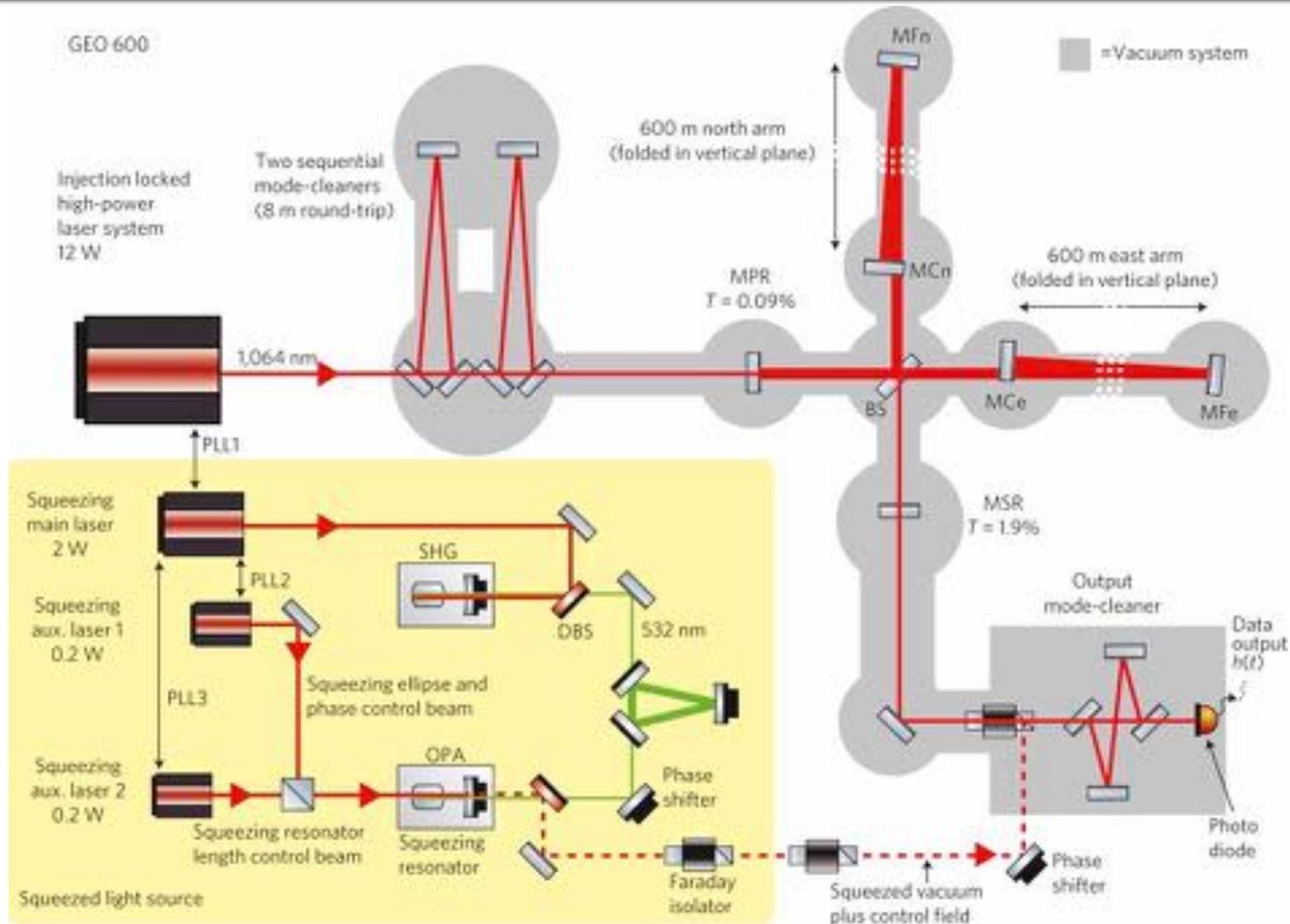


GEO600: Der erste GWD mit gequetschtem Licht (seit 2010!!)



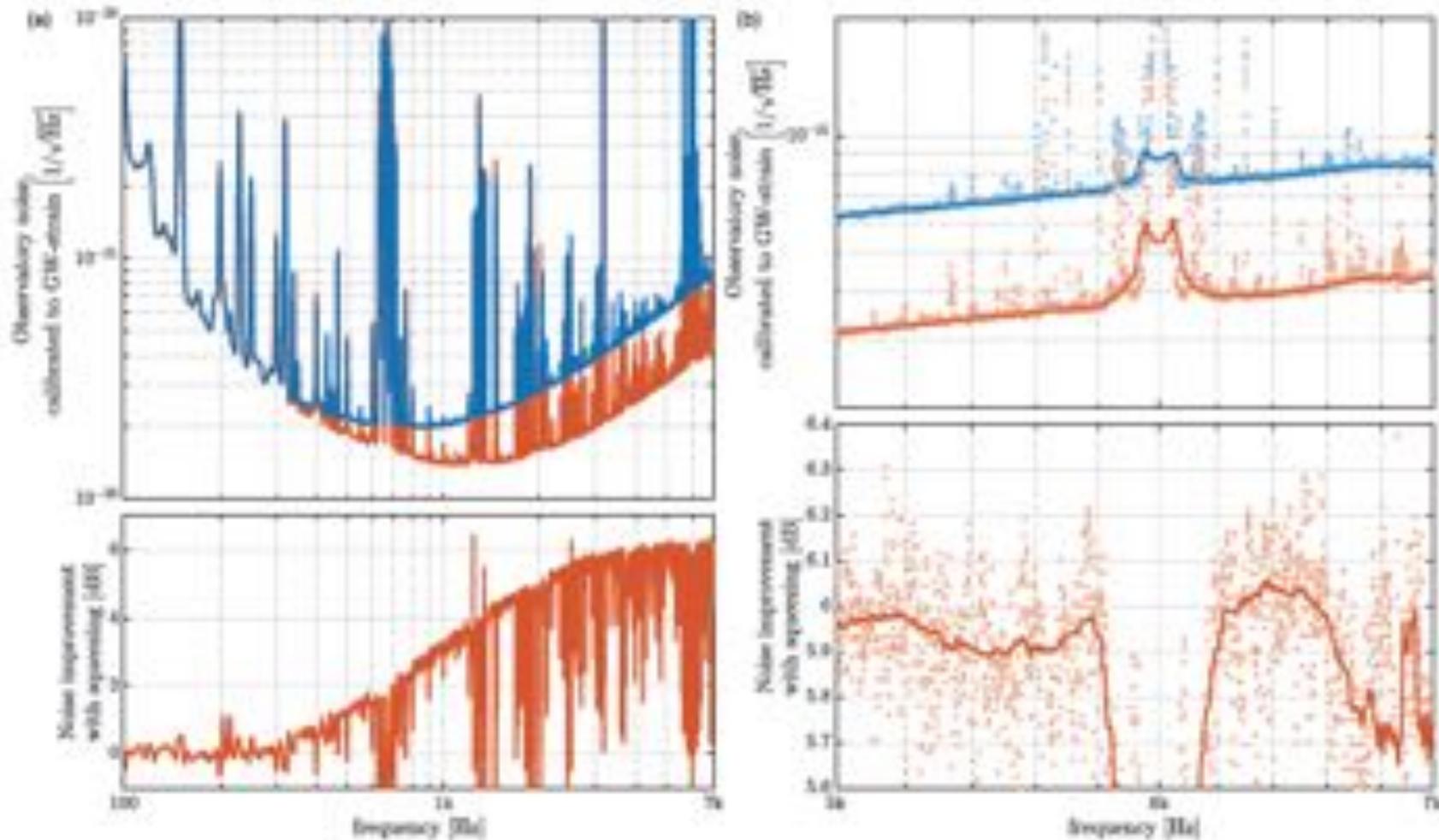
[Nat. Phys. **7**, 962–965 (2011)]

Die GEO600 Quetschlichtquelle



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

6 dB Squeezing bei GEO600



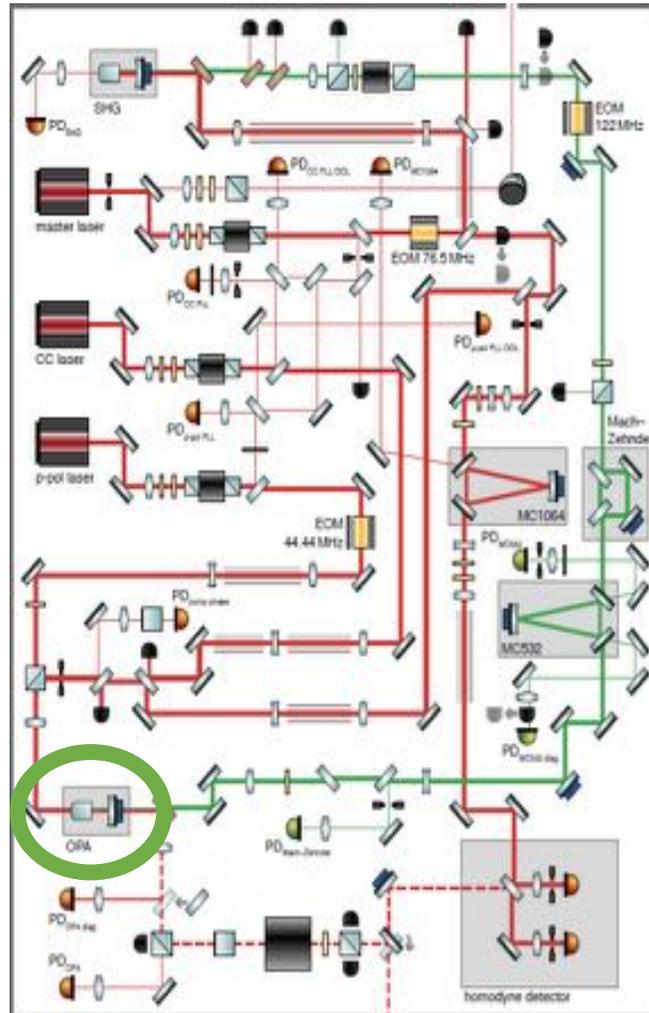
[J. Lough et al., "First demonstration of 6 dB quantum noise reduction in a kilometer scale gravitational wave observatory", arXiv:2005.10292v1 (accepted for publication in PRL)]

Wie stellt man gequetschtes Licht her?



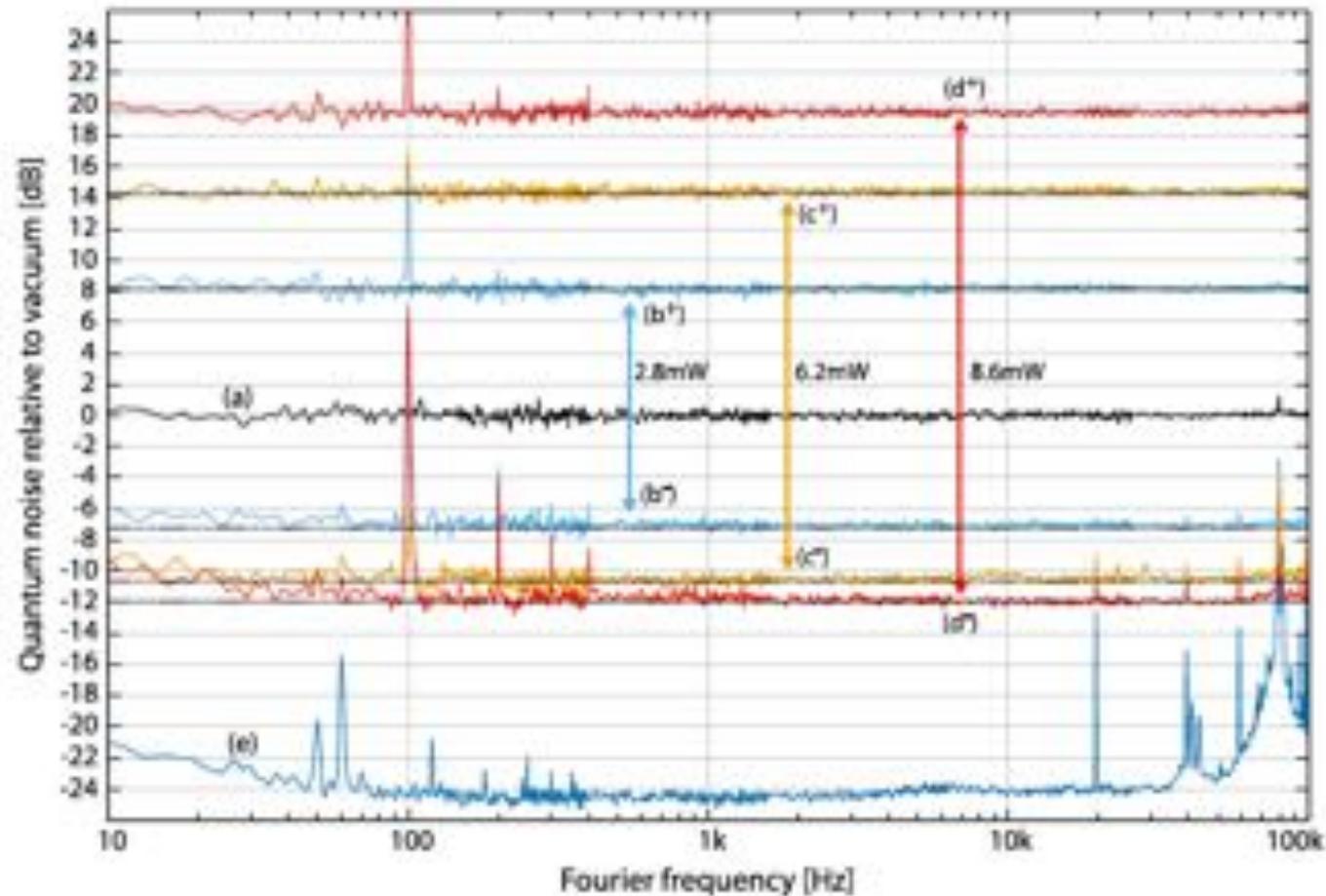
[Image: Vahlbruch et al., "The GEO600 squeezed light source", Class. Quantum Grav. **27** (2010)]

Squeezing bei GEO600



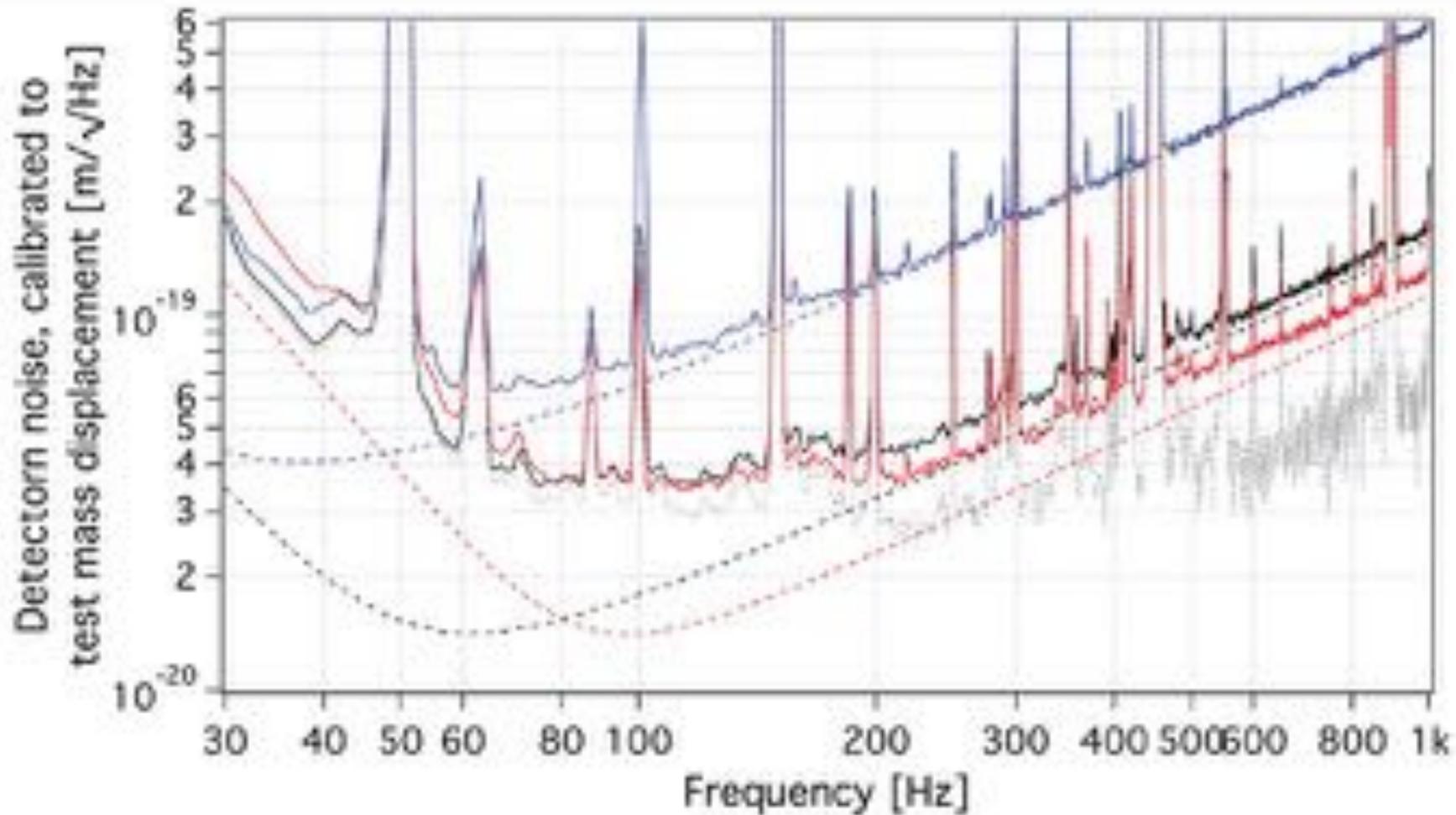
[Source: Dissertation E. Schreiber (2018)]

(Niederfrequentes) Squeezing für GWDs



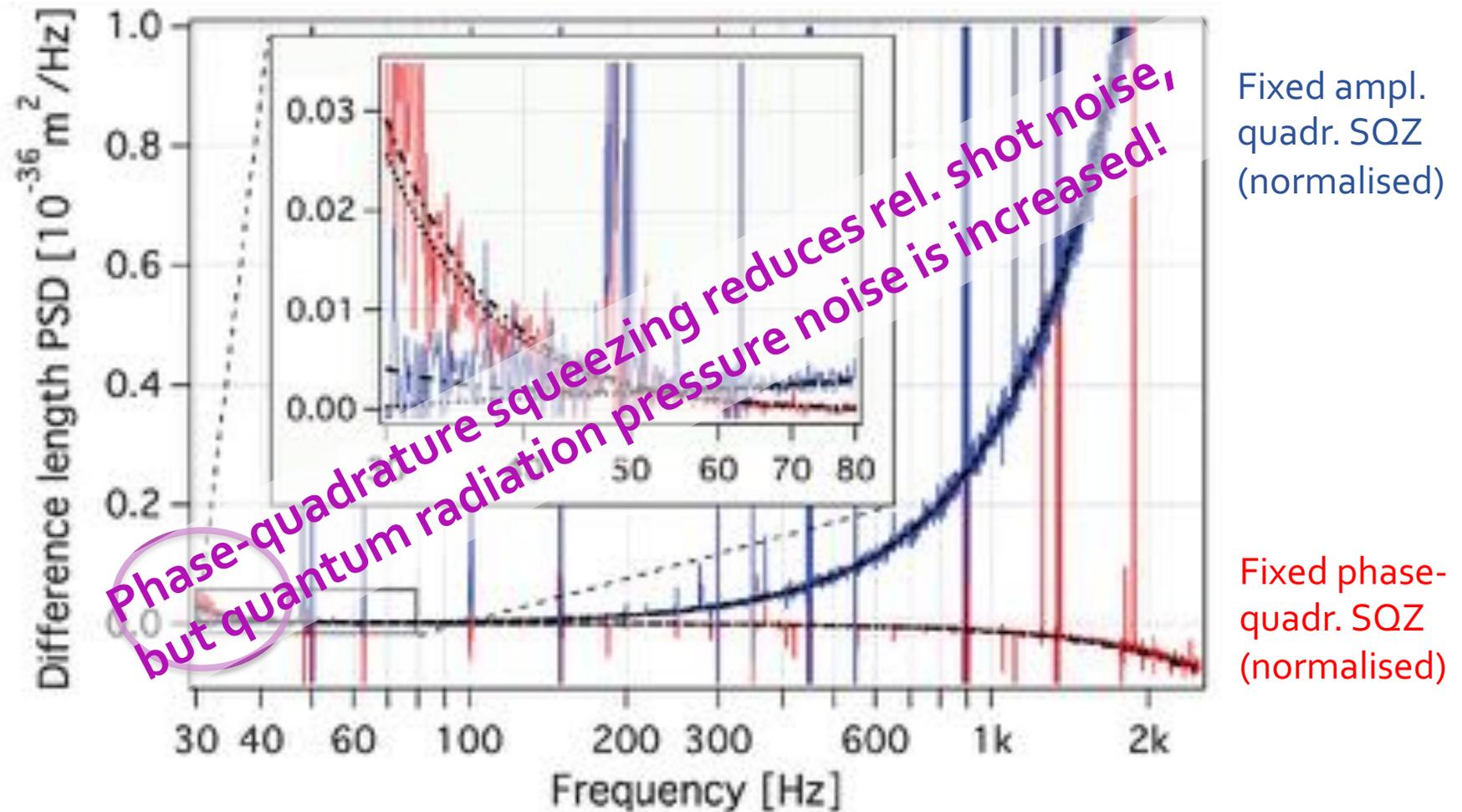
[M. Mehmet and H. Vahlbruch, "High-efficiency squeezed light generation for gravitational wave detectors" *Class. Quantum Grav.* **36** 015014 (2019)]

Squeezing in adVirgo

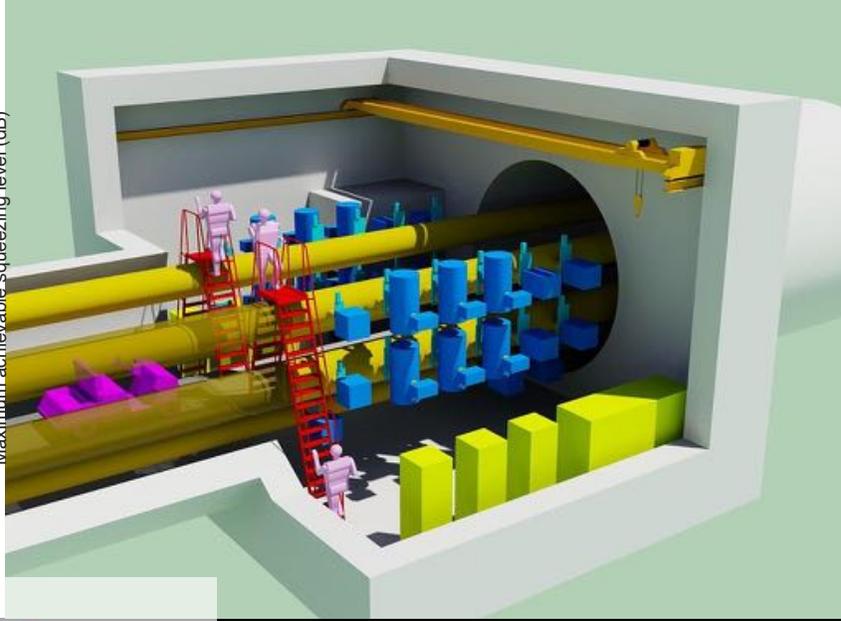
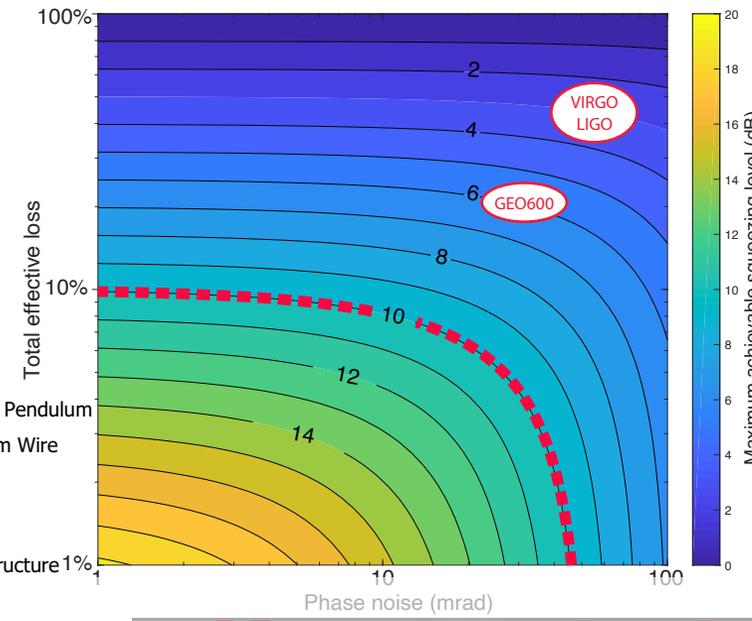
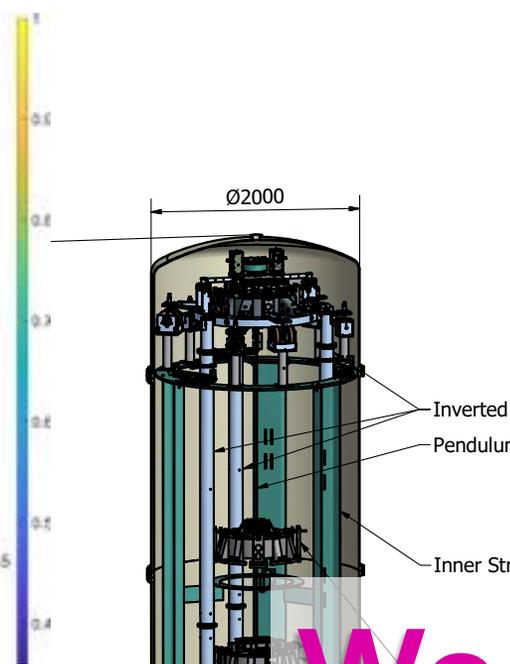
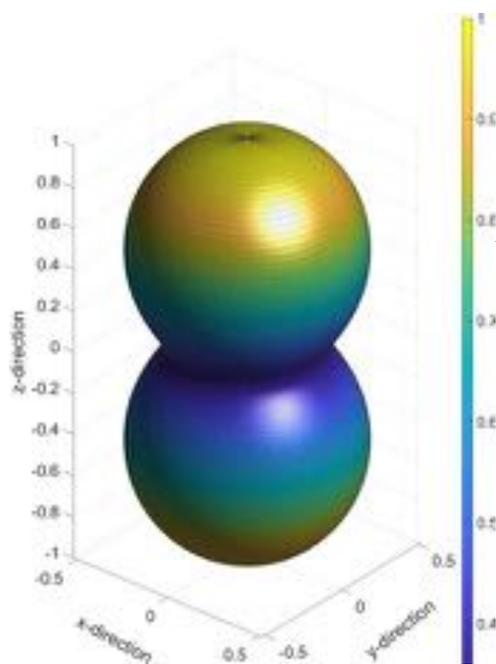


[The Virgo Collaboration & Mehmet et al. „Quantum Backaction on Kg-Scale Mirrors: Observation of Radiation Pressure Noise in the Advanced Virgo Detector “ Phys. Rev. Lett. **125**, 131101 (2020)]

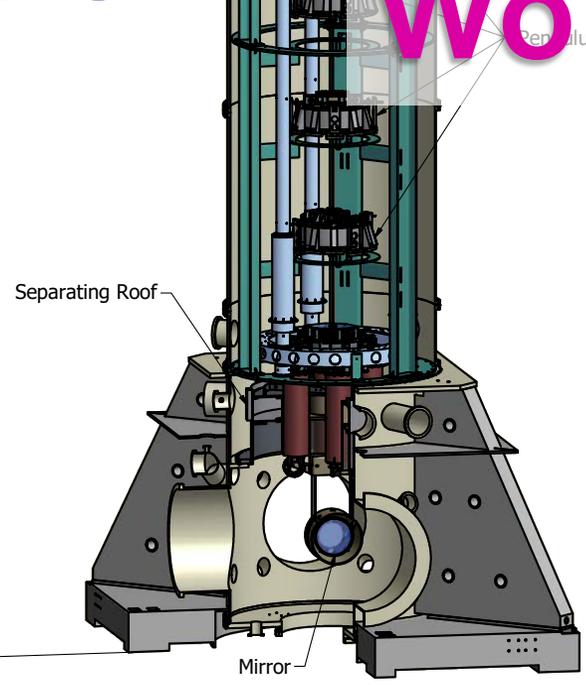
Squeezing in adVirgo



[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)]



Wo wollen wir hin?



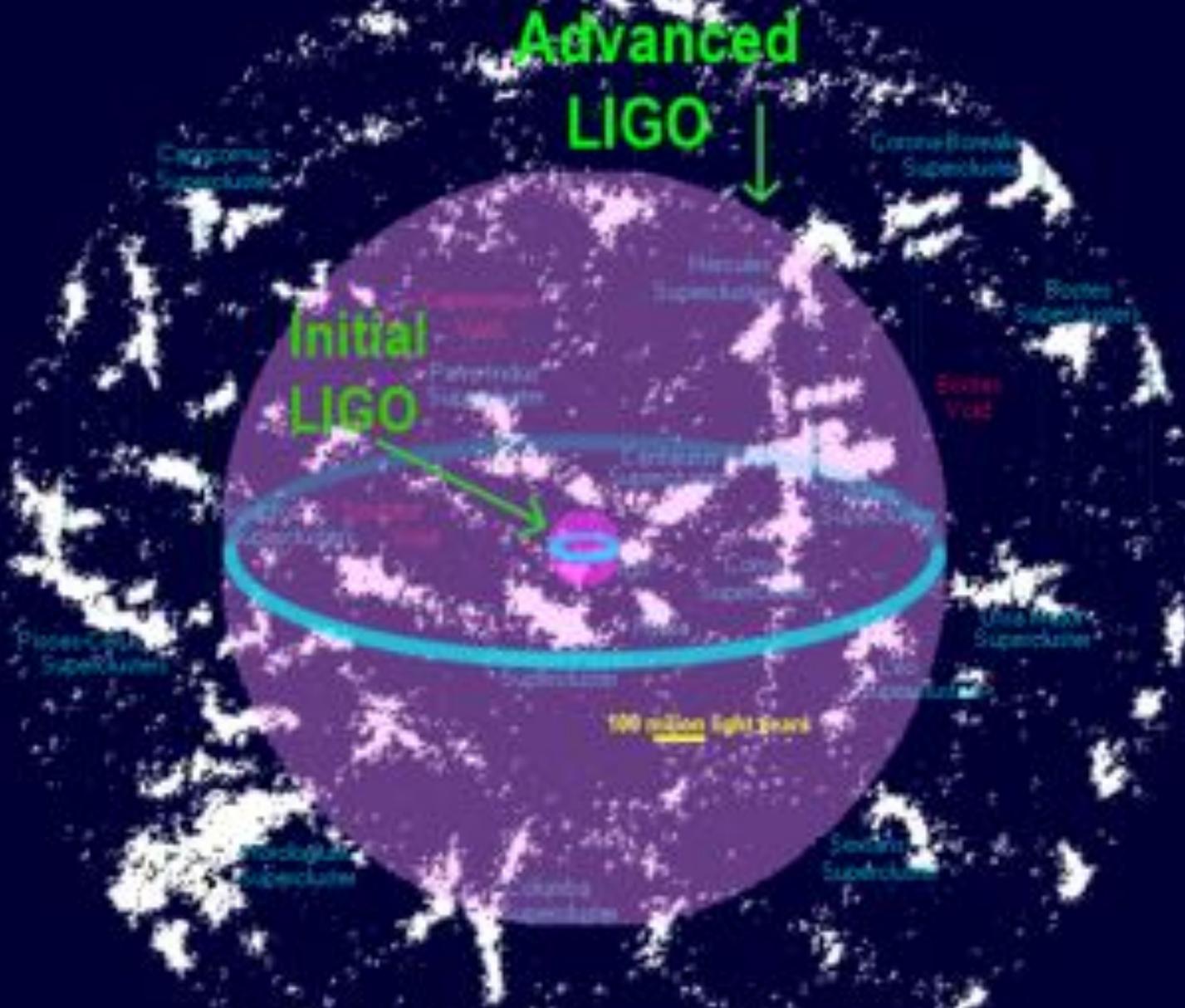
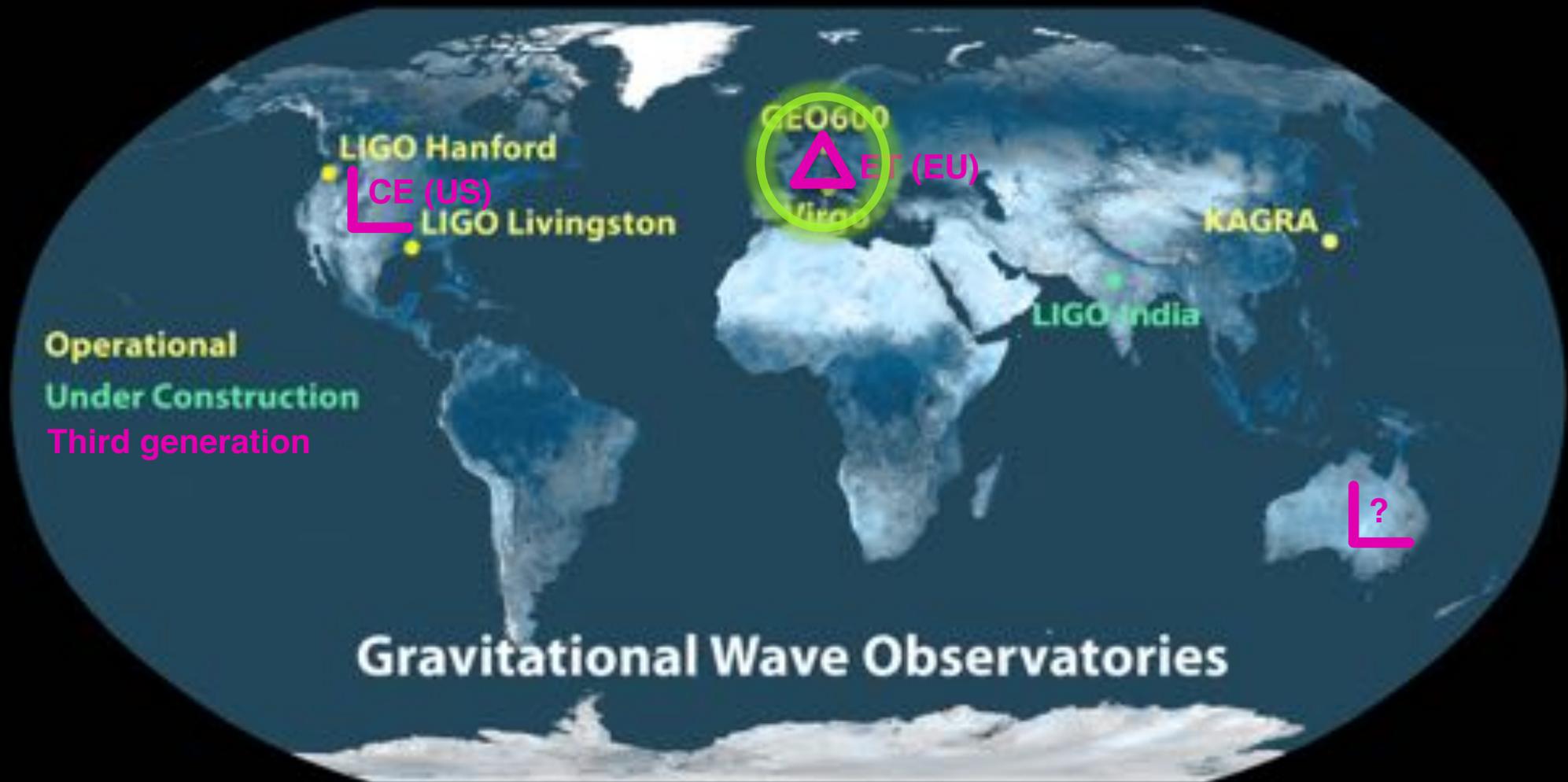


Image:
aLIGO@MIT

The next generation



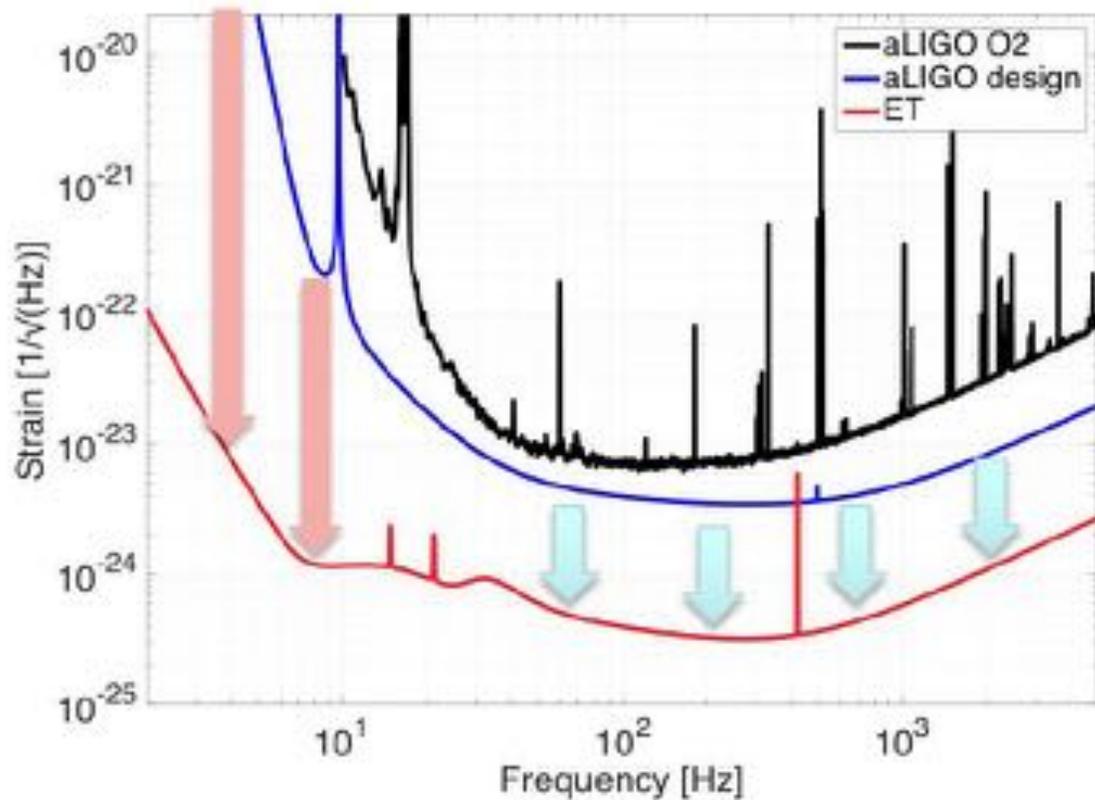
Das weltweite Detektornetzwerk der Zukunft



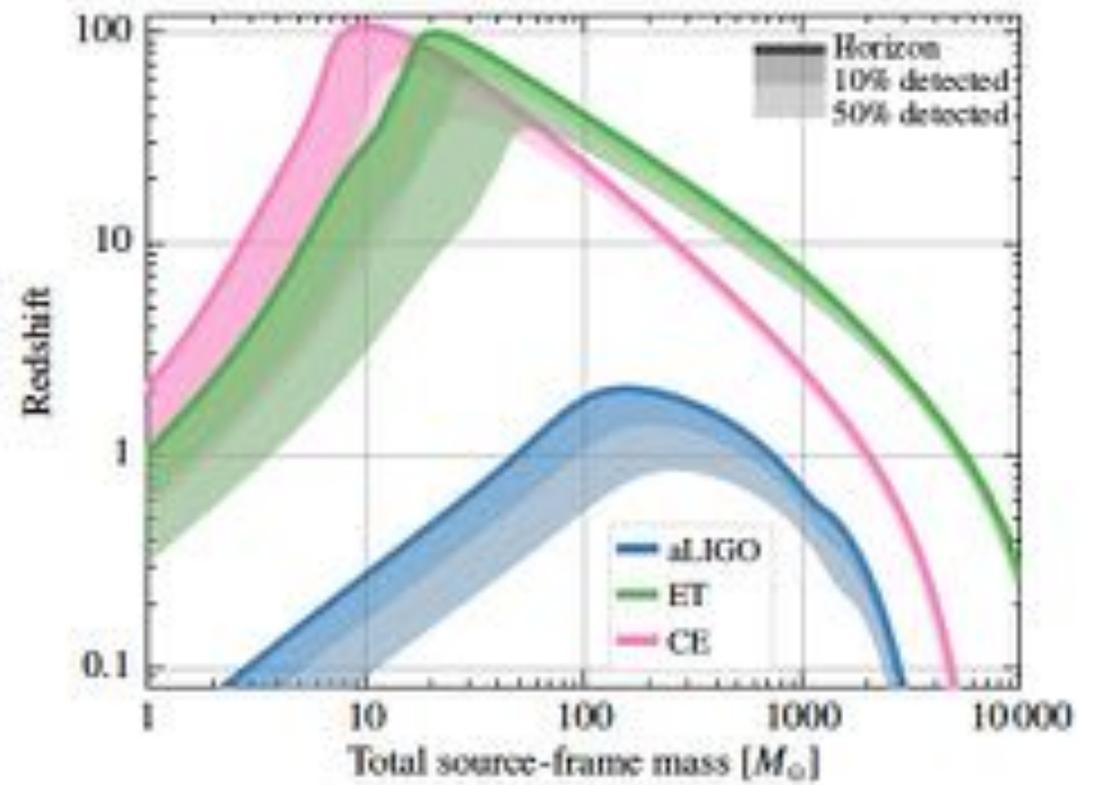
LISA

Empfindlichkeiten von 3G GWDs

Sensitivity comparison of Advanced LIGO and Einstein Telescope (design)



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

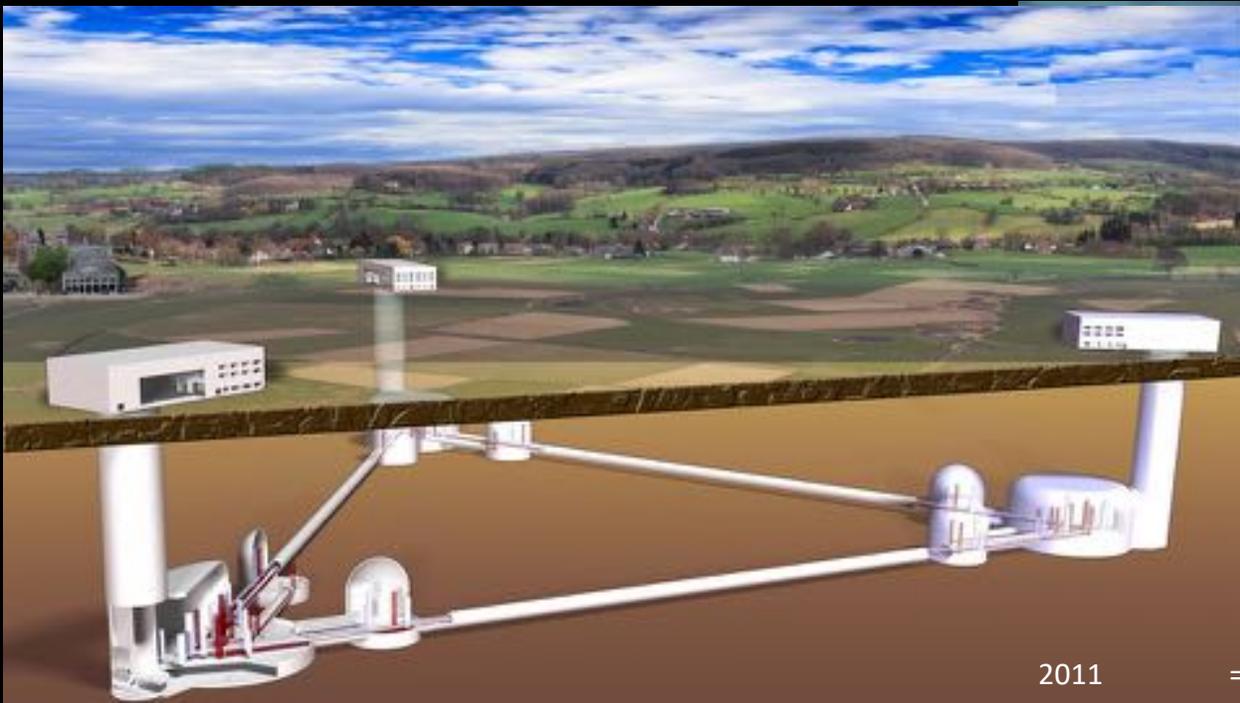
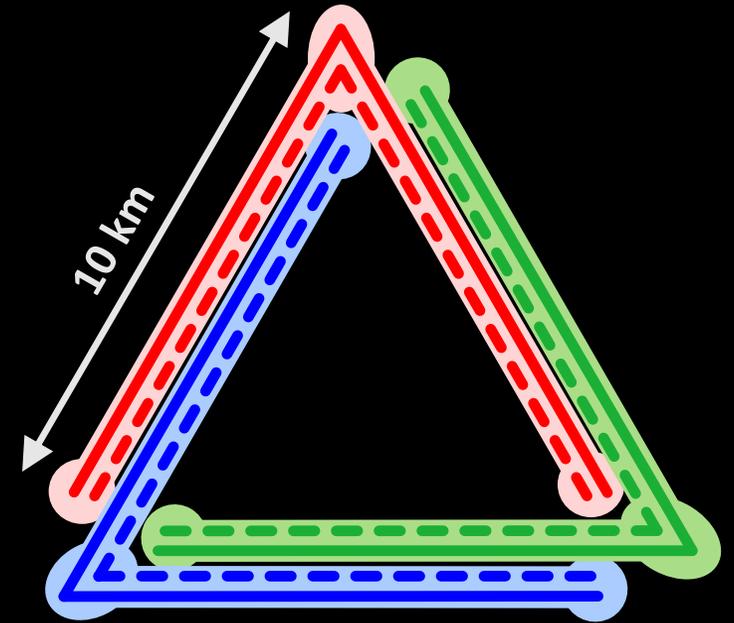


[source: Einstein Telescope Design Report Update 2020]

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

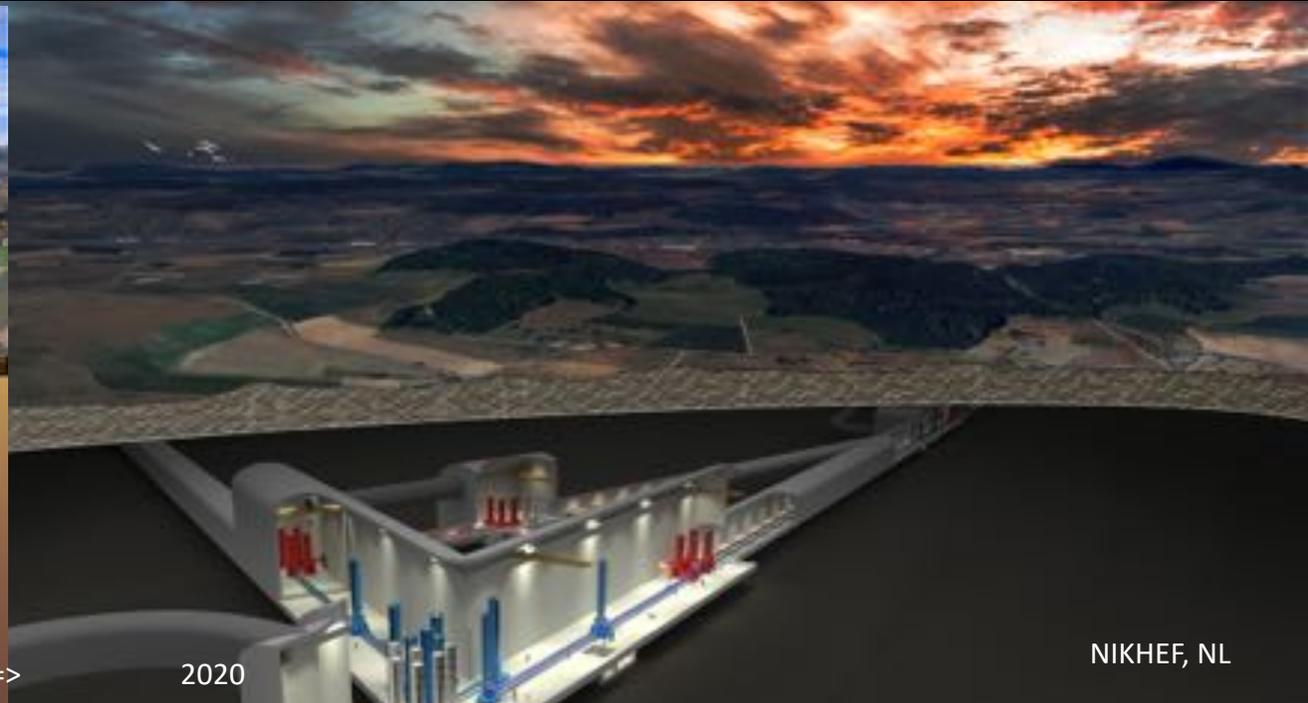
Das Einstein Telesope (ET)

- Ein **Europäisches** Projekt!
- Dreieckiges unterirdisches GW Observatorium (bei 200 – 300 m Tiefe) mit 10 km Armlänge



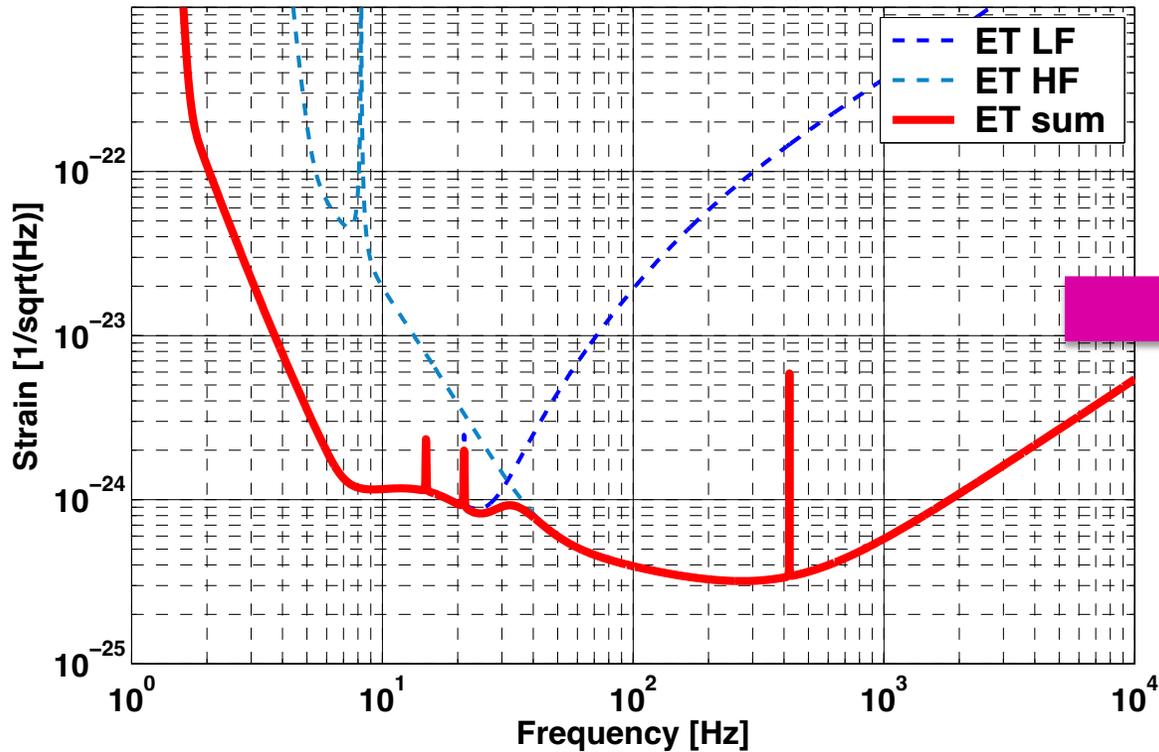
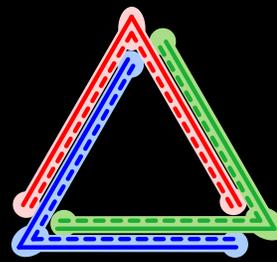
2011

=>

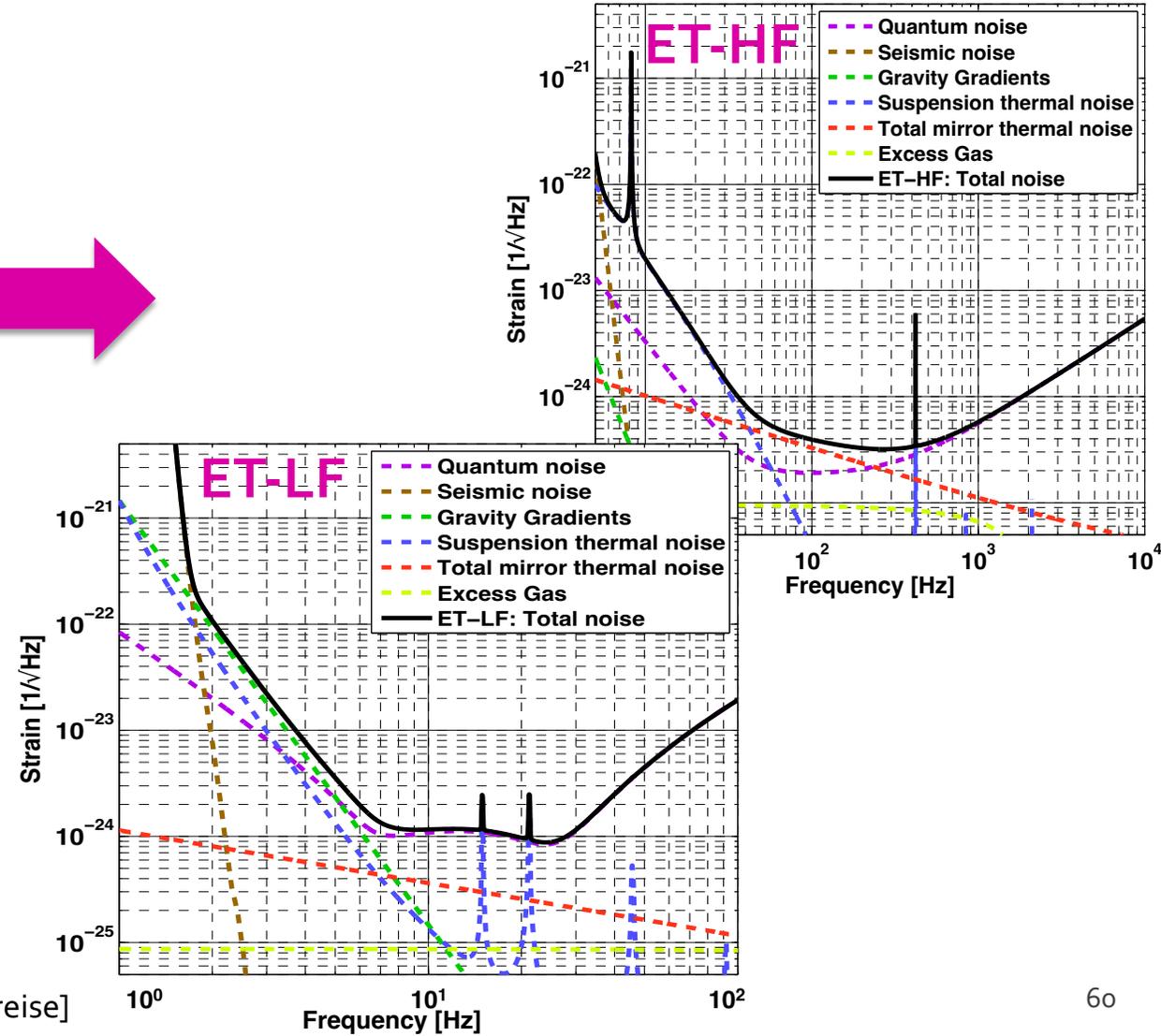


2020

ET Xylophon Design

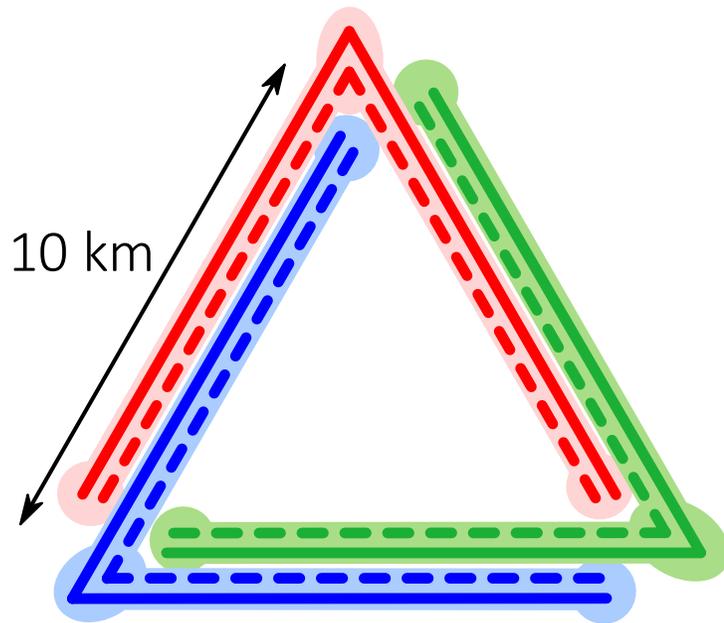


Each detector (red, blue and green) is split into two interferometers:
 ET HF: high power operation, extend current technology
 ET LF: optimise for low frequency and **new technology**



ET Designspezifikationen

*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)	$5 \cdot 10^{-10} \text{ m}/f^2$	$5 \cdot 10^{-10} \text{ m}/f^2$
Gravity gradient subtraction	none	factor of a few

- 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

Evolved laser technology

Evolved technology in optics

Highly innovative adaptive optics

High quality opto-electronics and new controls

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 sensitivity

2 interferometers per detector:

- extended frequency range
- follow signals for hours

New lasers:

- longer wave length
- less quantum noise

10 km arms

Cryogenic temperatures:

- less thermal noise

Untergrundlabor für next generation GWDs

- Lab of approx. (30 x 30 x 30) m³ 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)





Moderne Instrumentierung für die Astrophysik der Zukunft – Chancen für Innovation und Industrie!



seismic attenuation and controls



"one-stop" shop for mirror technology



computing facility

underground lab facility



www.deutscheszentrumastrophysik.de

Physik mit dem Einstein Teleskop

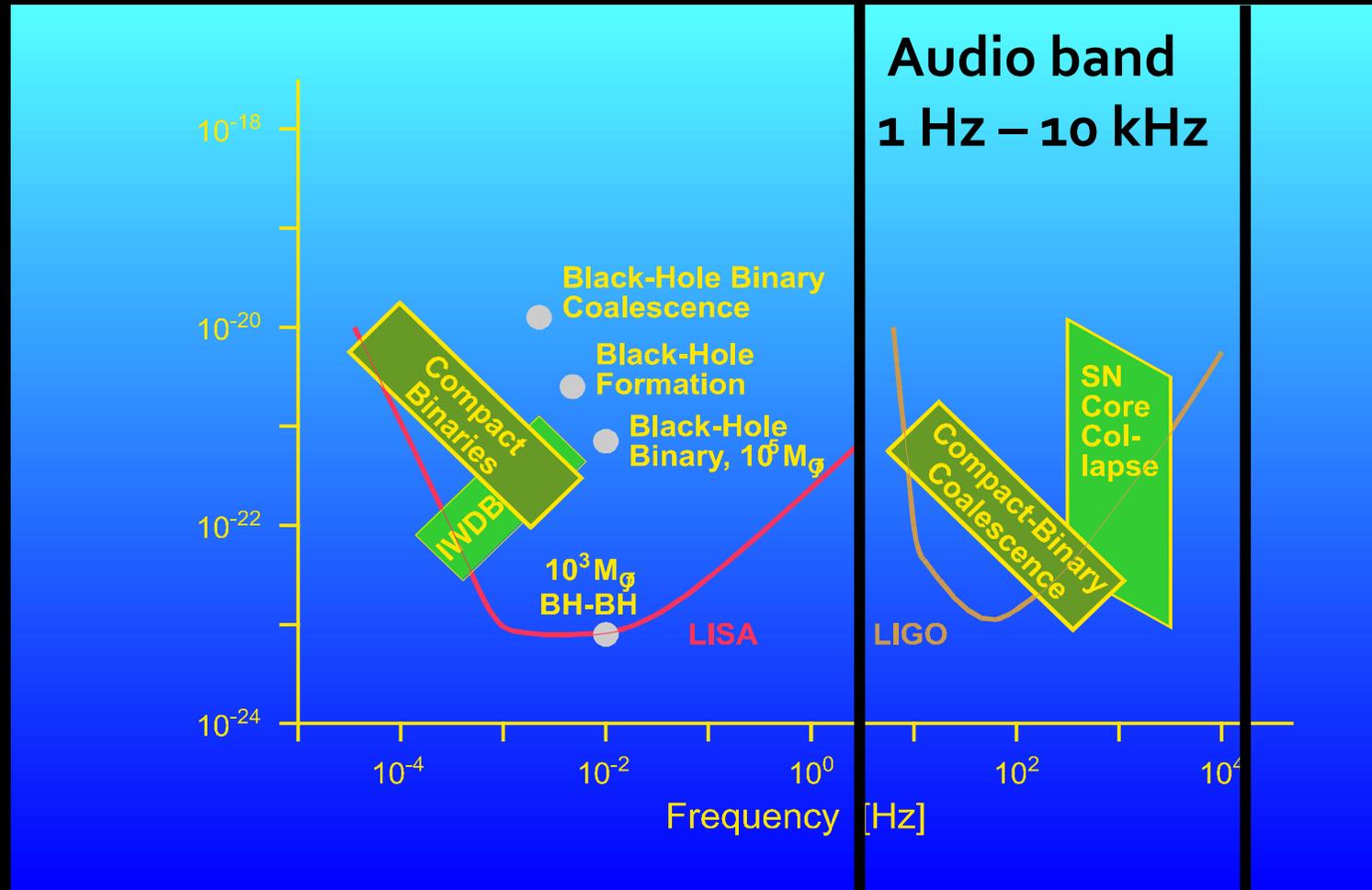
ASTROPHYSIK

- Eigenschaften schwarzer Löcher: Ursprung (stellar vs. primordial), Entwicklung, Demographie
- Eigenschaften von Neutronensternen: innere Struktur, exotische Materiezustände, Demographie
- Multi-messenger Astronomie: Nukleosynthese, Jets, Neutrinos (welche Rolle spielen sie?)
- Detektion neuer Quellen von GWn: core collapse Supernovae, isolierte (rotierende) Neutronensterne, stochastischer Hintergrund astrophysikalischen Ursprungs

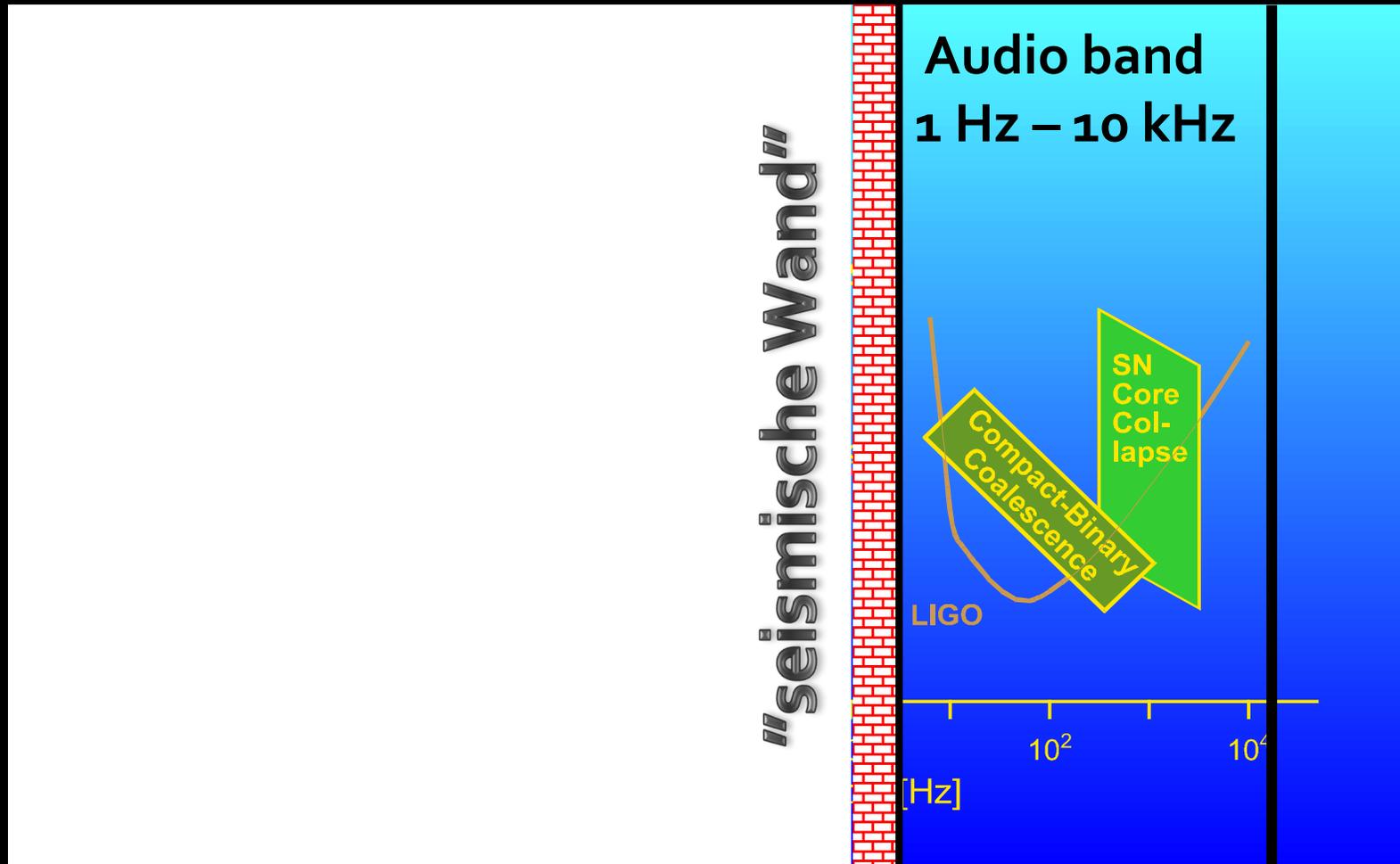
FUNDAMENTALPHYSIK UND KOSMOLOGIE

- Die Natur kompakter Objekte: Physik nahe dem Ereignishorizont, Tests des No-Hair Theorems, exotische kompakte Objekte
- Dunkle Materie: Primordiale Schwarze Löcher, Axionenwolken, Ansammlungen Dunkler Materie um kompakte Objekte
- Dunkle Energie und Modifizierte Gravitation auf kosmologischen Skalen
- Stochastischer Hintergrund kosmologischen Ursprungs und Verbindung zur Hochenergiephysik (Inflation, Phasenübergänge, kosmische Strings,...)

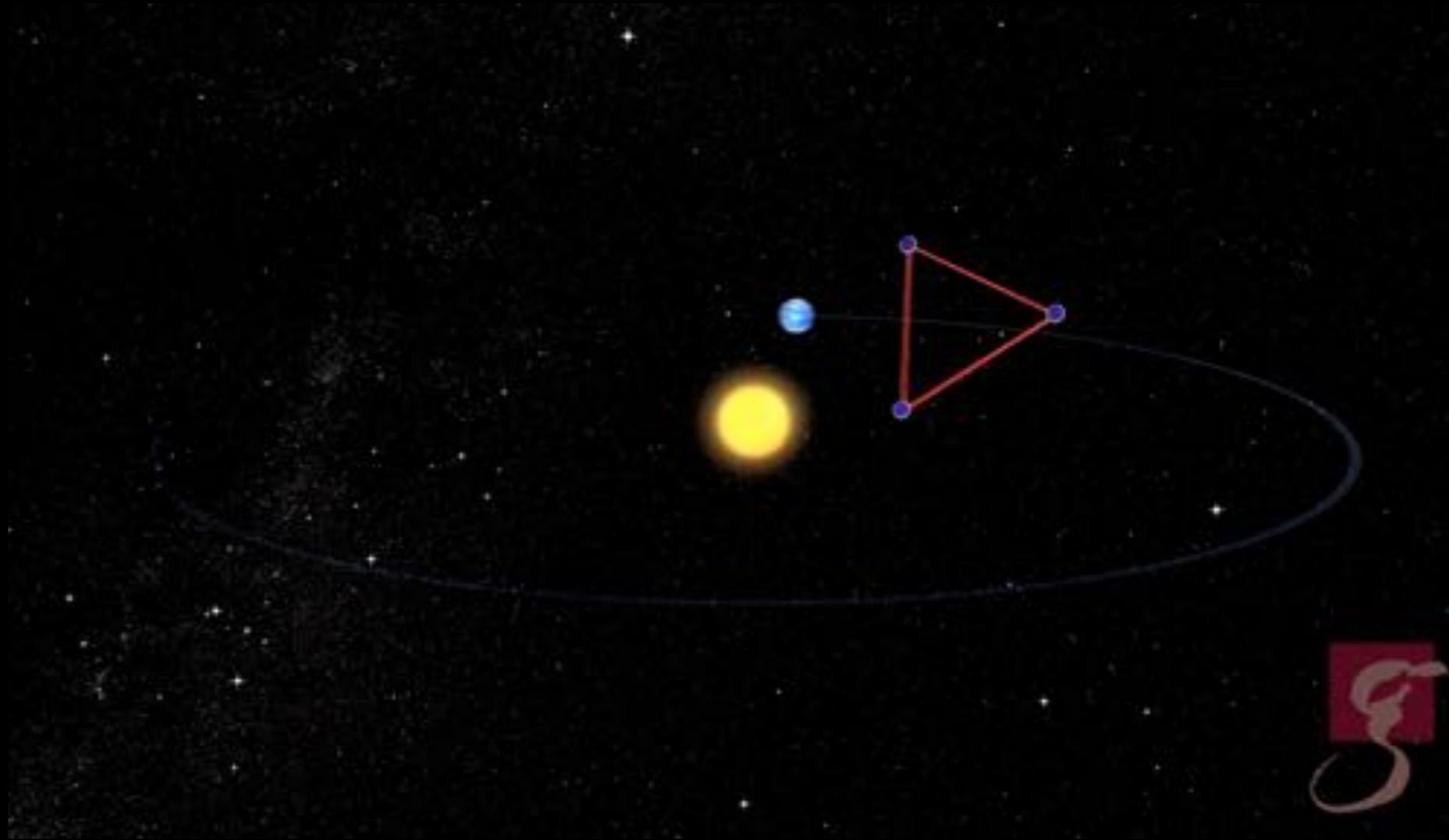
Das mikroseismische Problem



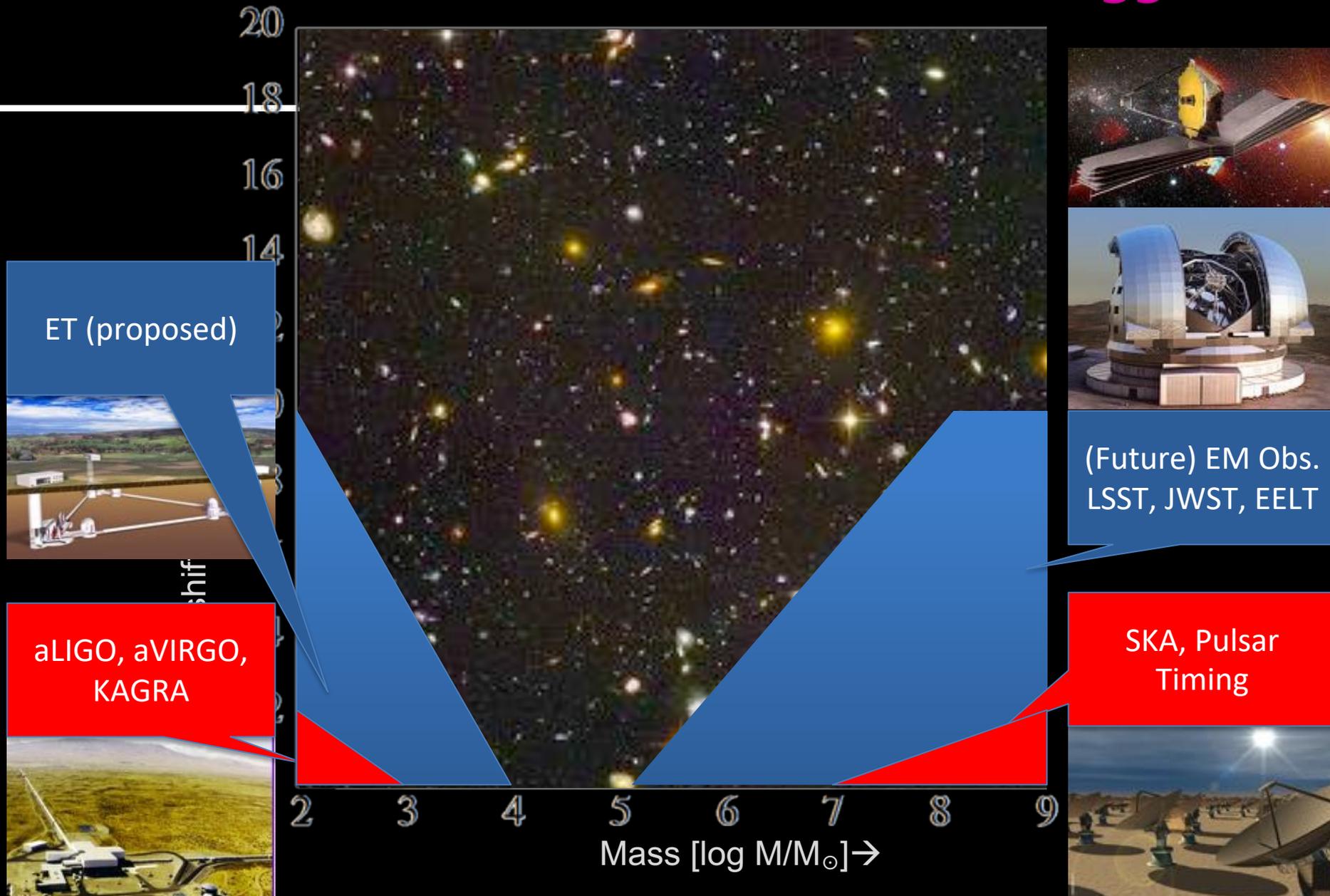
Das mikroseismische Problem



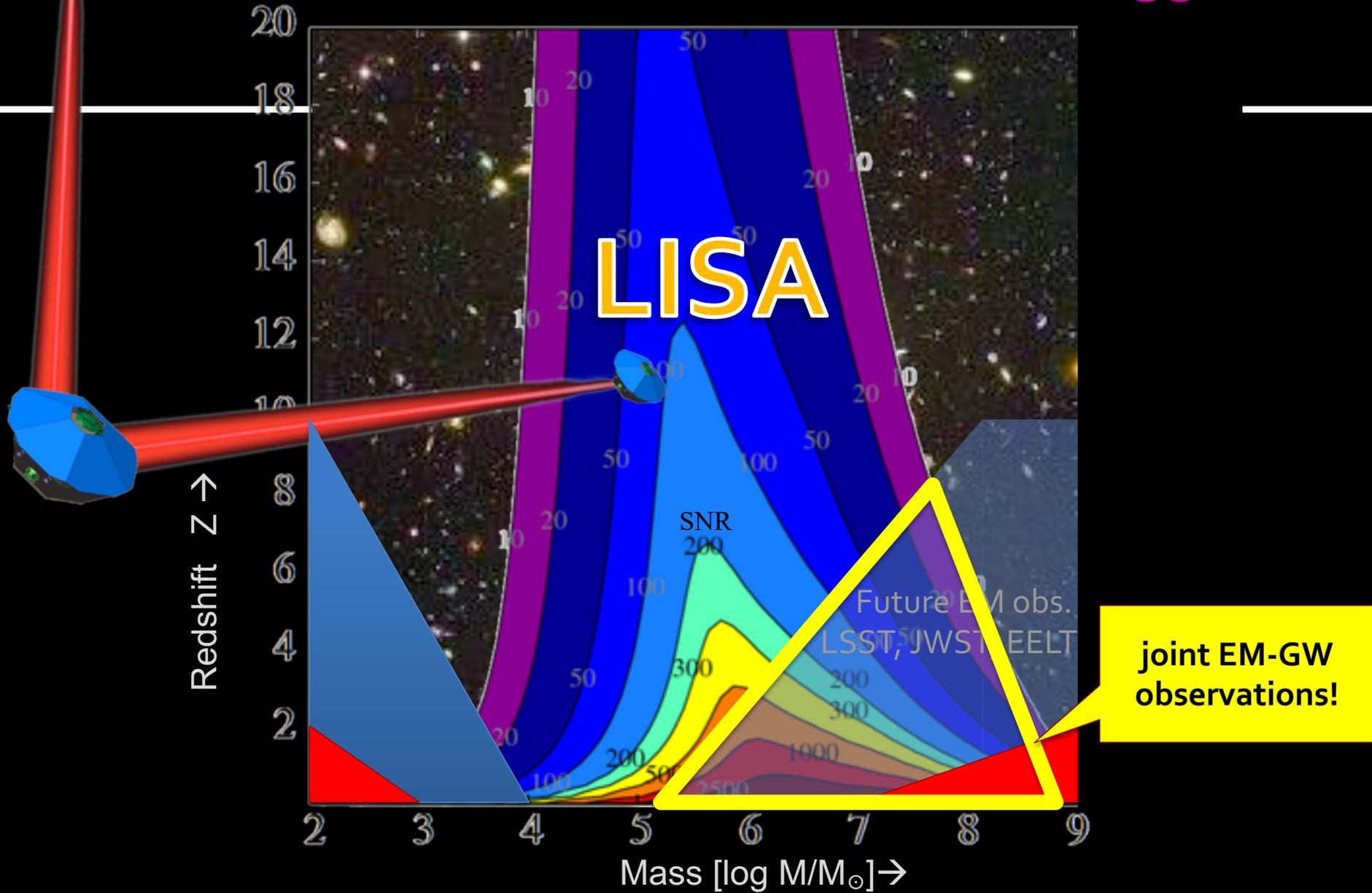
LISA: Ein GW-Observatorium im All



“Black Hole” Astronomie nach 2035



"Black Hole" Astronomie nach 2035



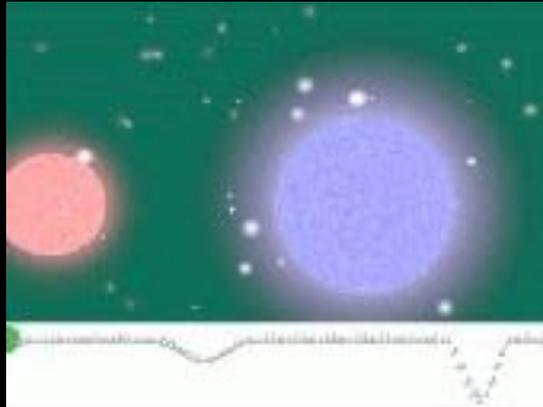


Und warum all die Mühe?



...um viele weitere Quellen hören zu können!

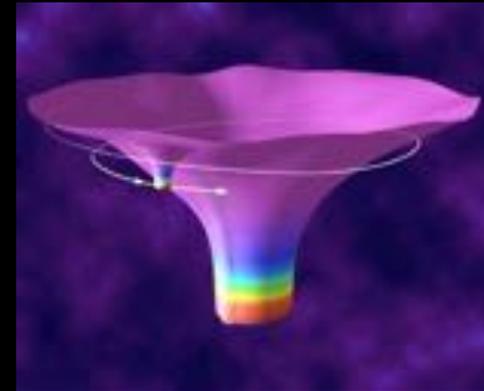
Luminosity of a NSNS system
(schematic), (Creative Commons)



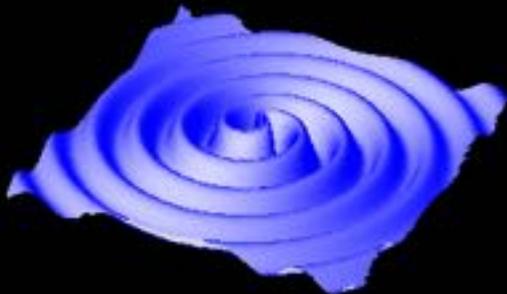
Supernovae
(here: SN 1987A, © NASA)



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

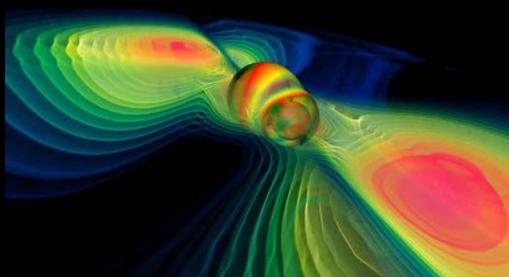


„Chirp“ of two merging neutron stars
(© B. Owen, Penn State University)



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

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



Merger of two black holes
(Simulation © AEI)

„Chirping inspiral“ of two
black holes

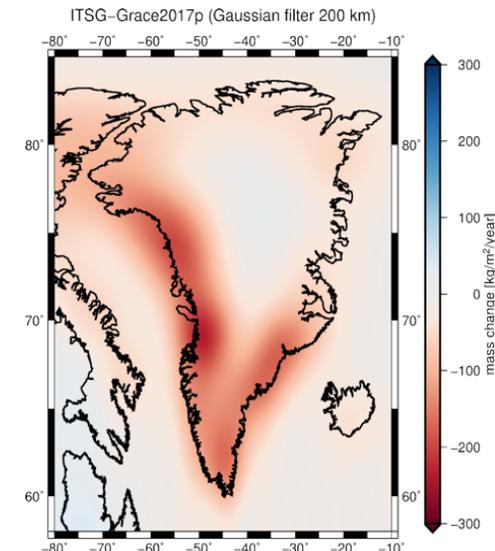
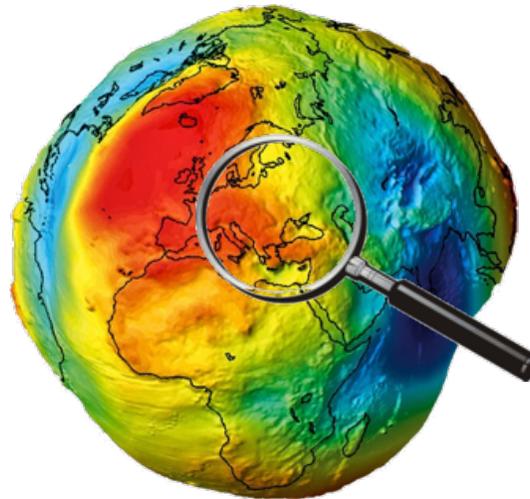
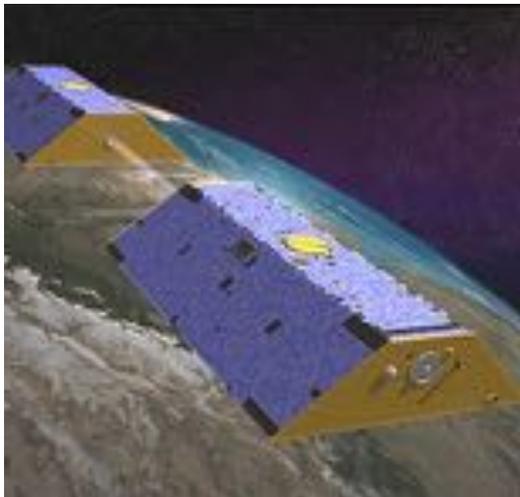


Crab nebula (NGC 1952, © NASA)

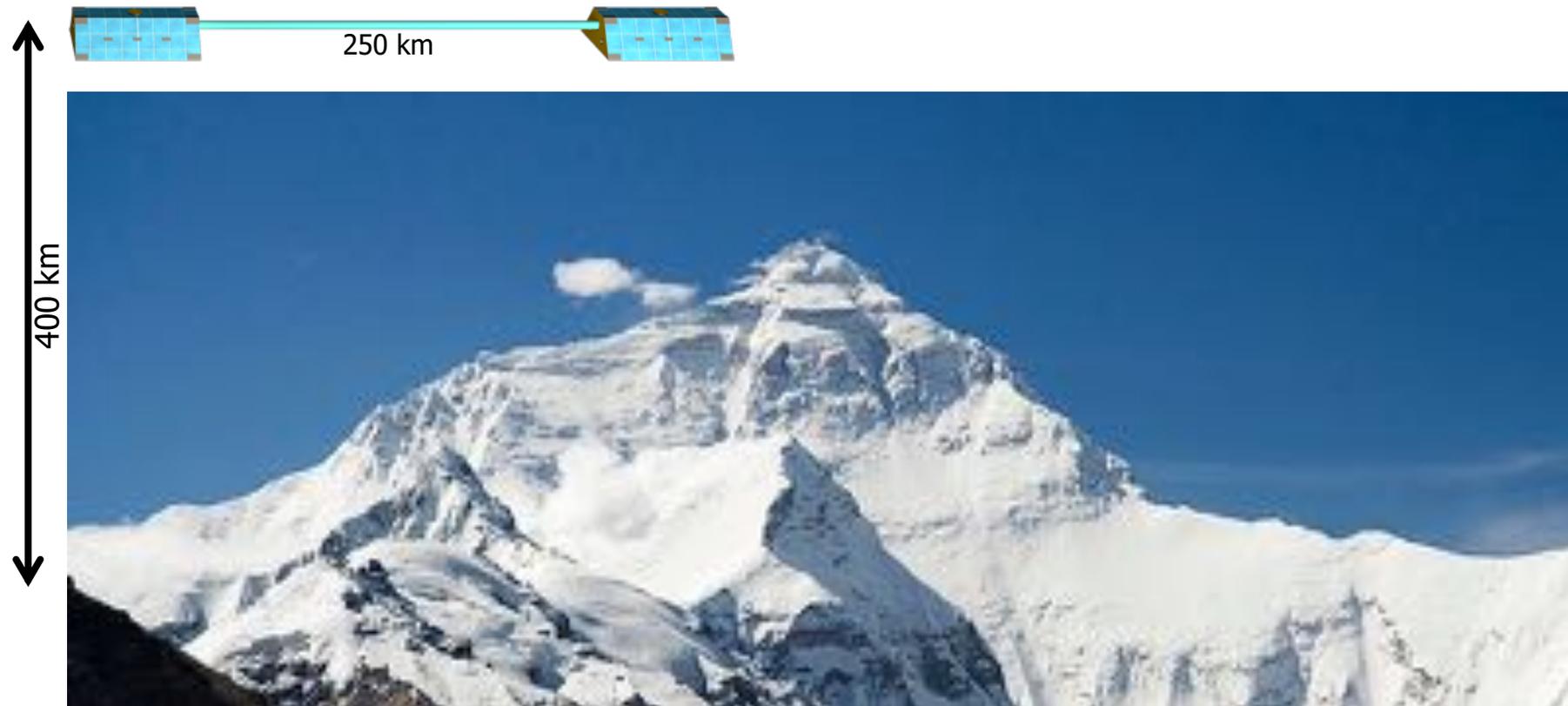
...aber auch: Anwendungen!

z.B. in Geodäsie und Gravimetrie

Intersatelliten-Laserinterferometrie erlaubt Aussagen über Änderungen im Grundwasserspiegel („Earth water cycle“) oder über Verluste der Eismassen auf Grönland



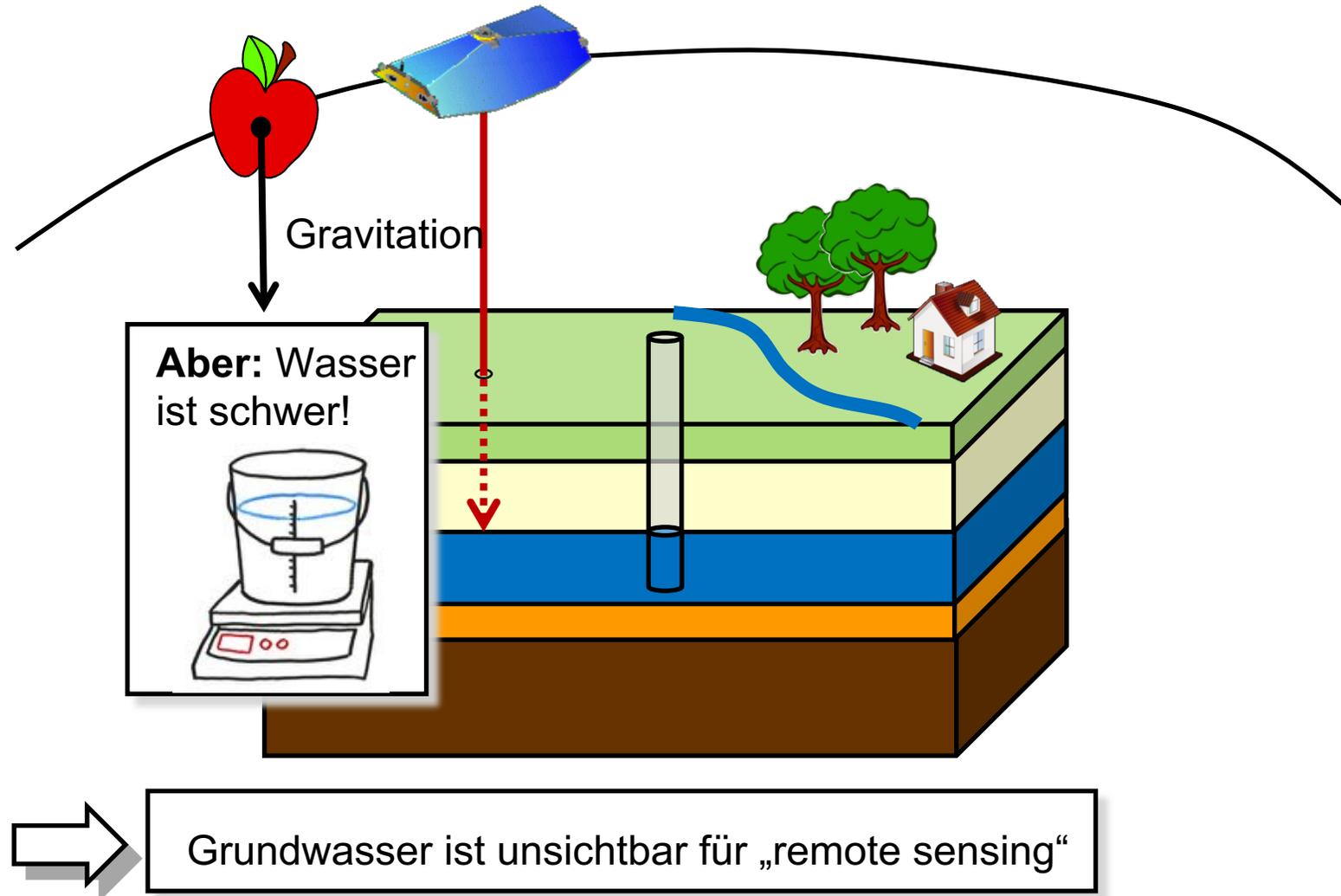
GRACE Follow-On: Laserinterferometrie im Orbit



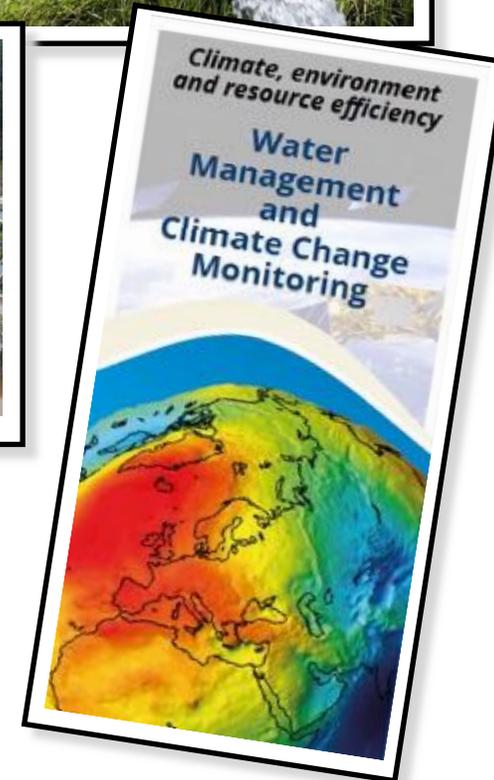
Beobachtung des Erdschwerefeldes durch Satellitentracking
(deutsch-amerikanische Kooperation)

GRACE: mit Mikrowellen => GRACE-FO: mit Lasern!

Vermessung des Grundwassers



Wasser ist Leben



Wasser ist eine der kritischsten geopolitischen Ressourcen!