Future Laser Interferometer Gravitational Wave Antennae and their Vacuum Requirements

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NSF Workshop on Large UHV Systems for Frontier Scientific Research
LIGO Livingston Observatory
29-31 January, 2019

LIGO-G1900136

Image Credit: Aurore Simmonet/SSU

Topics

Primer: Gravitational Waves

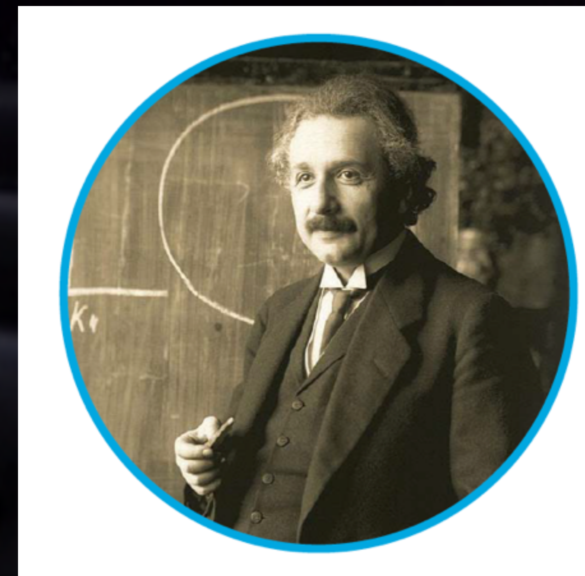
Orientation: Future GW Machines

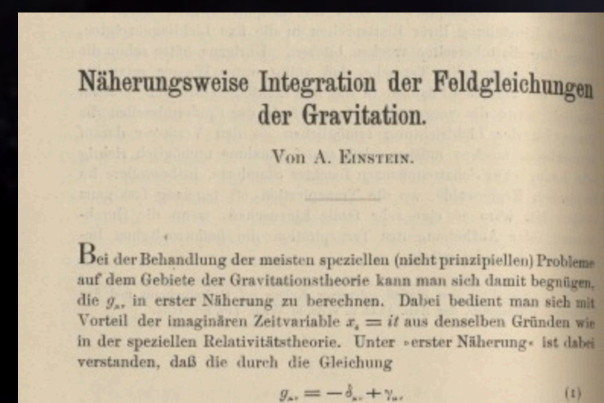
Focus: Vacuum Requirements

General Relativity and Gravitational Waves

- 2016 was the centenary of Einstein's General Relativity
- A *geometric* theory:
  Gravitation arises from *curvature of space-time*
  Curvature arises from matter, energy… and *curvature!*
- Bizarre, but (so far) *totally successful*, predictions:
  Perihelion shift, bending of light, frame dragging, gravitational redshift, gravitational lensing, black holes,…
- **One key prediction remained elusive until September 14th 2015:**

  Gravitational Waves





Näherungsweise Integration der Feldgleichungen der Gravitation.

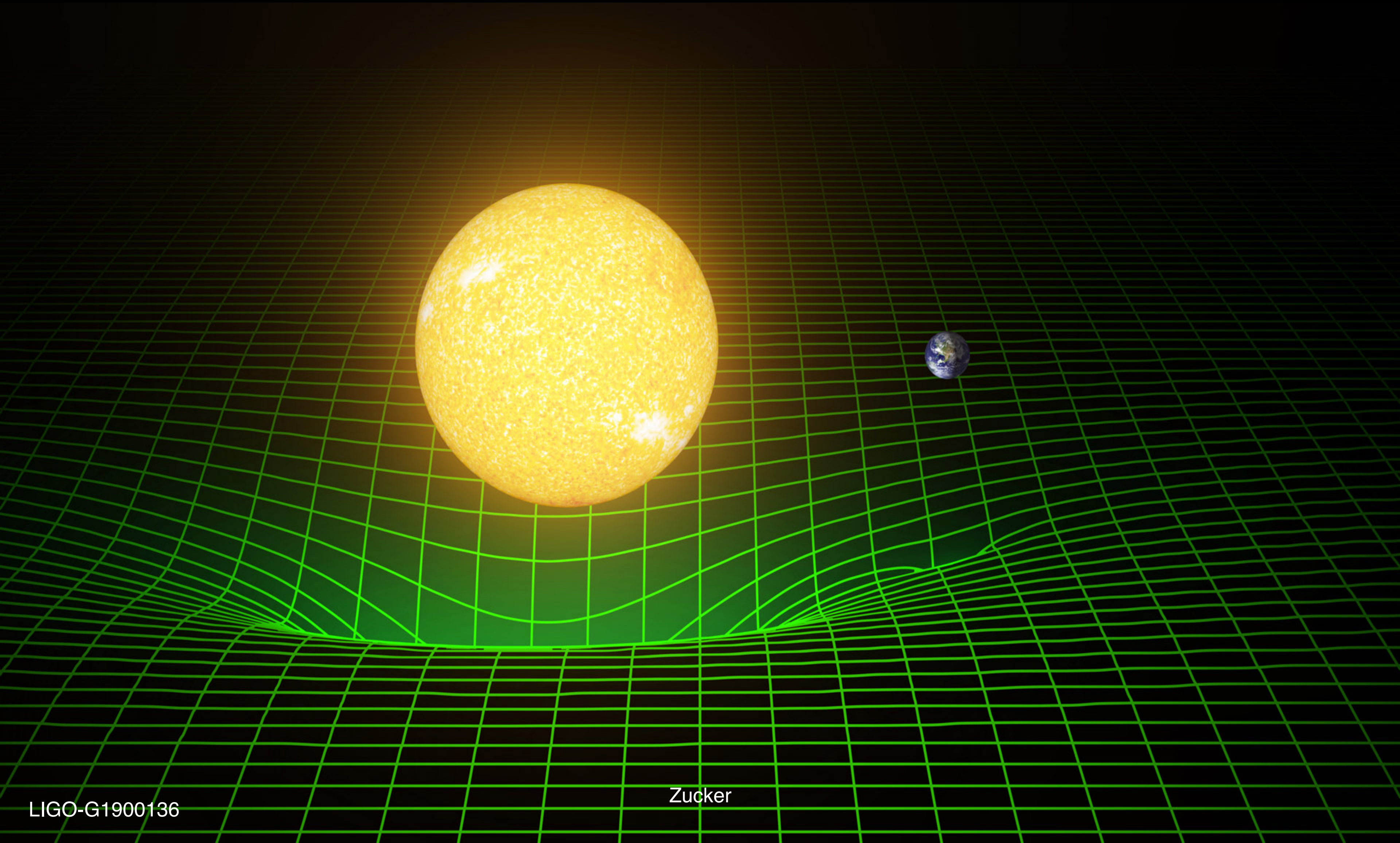
Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

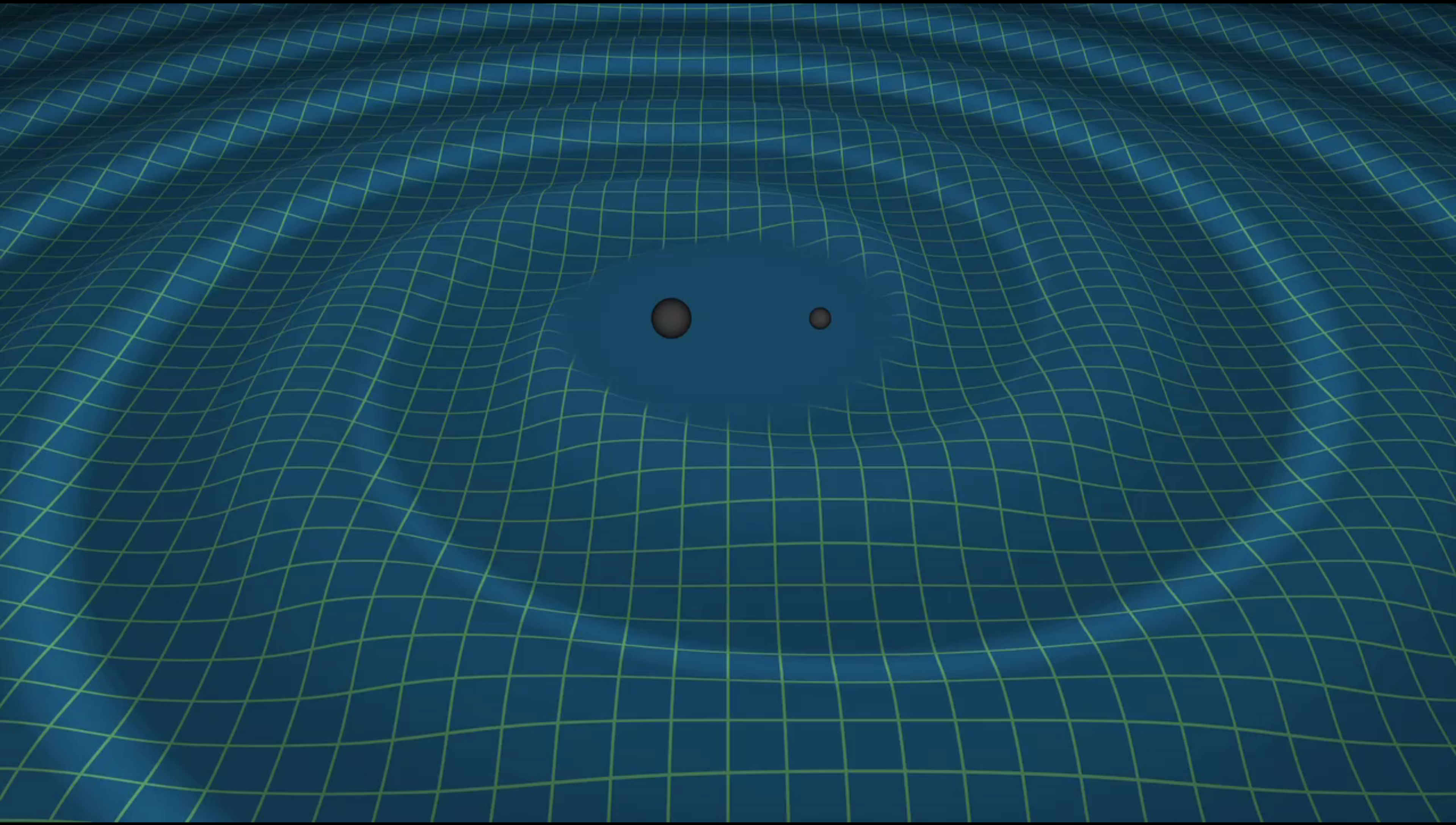
A. Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 1916

Gravity & Curved Space-time



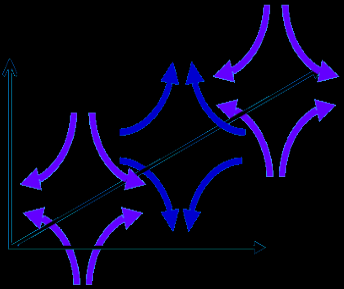
Gravitational Waves

Credit: LIGO/Tim Pyle



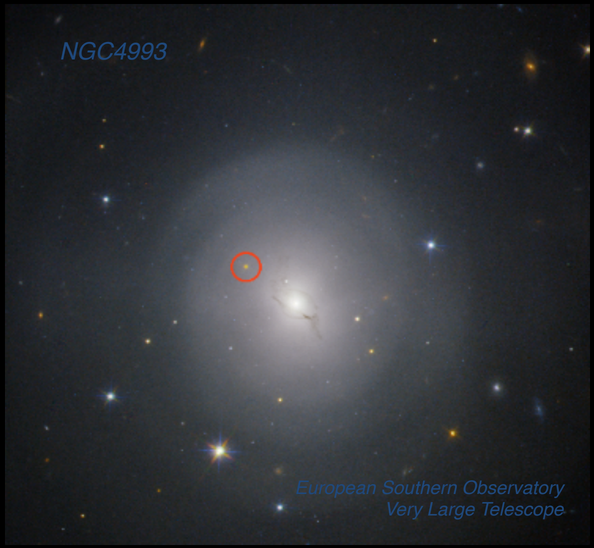
Detecting the effects

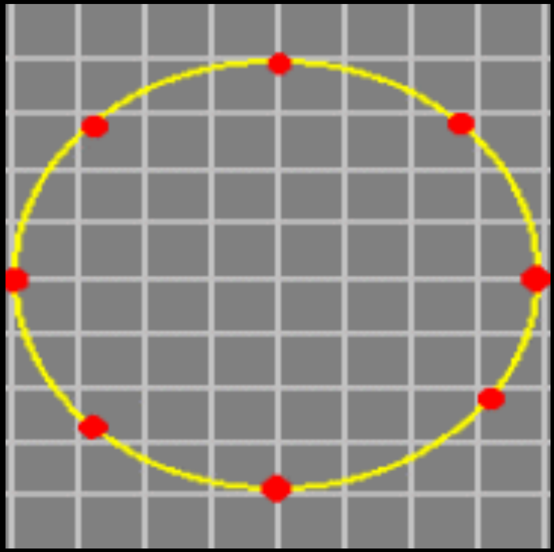
transverse strain
free test particles



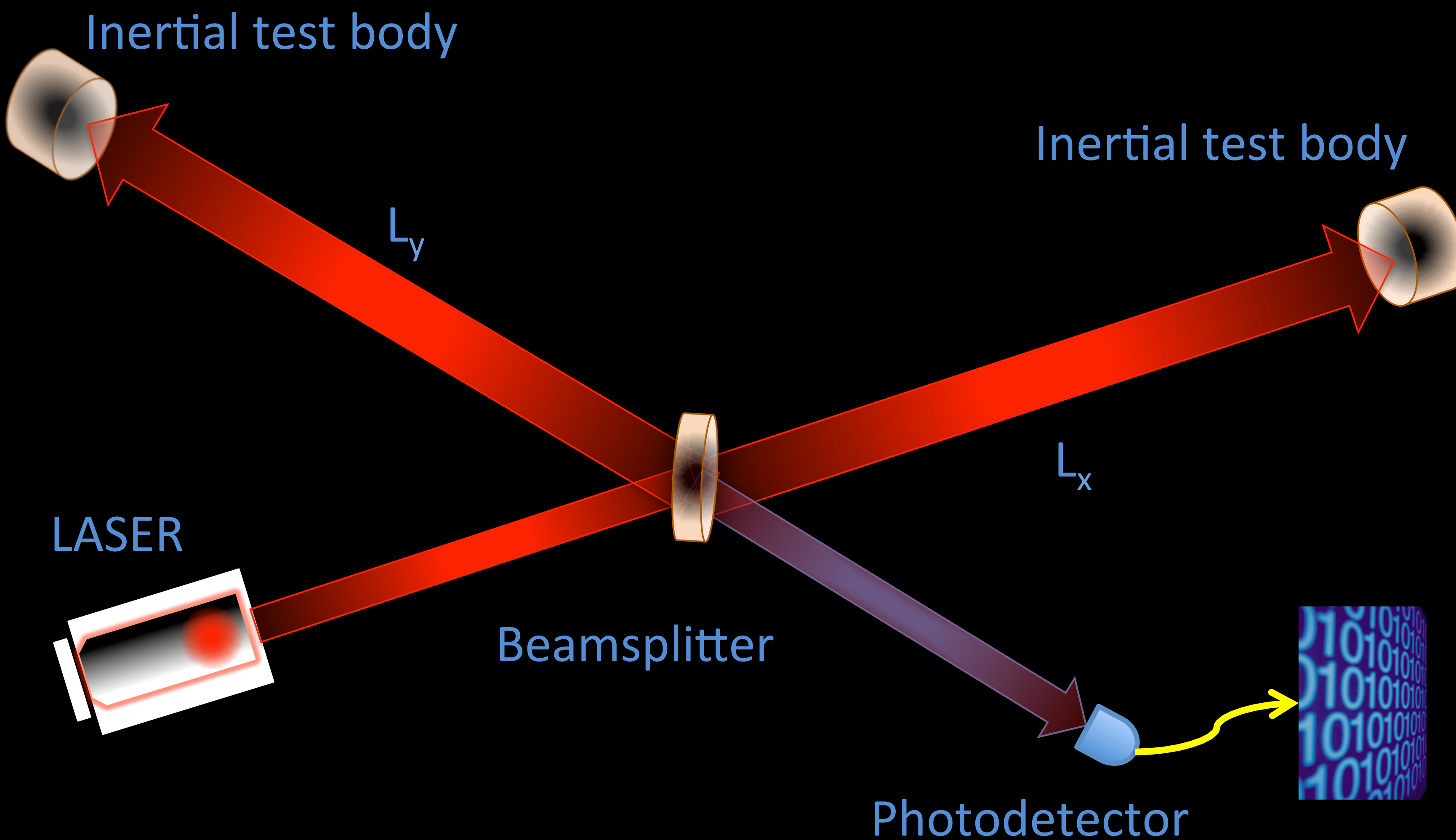
(Earth)

In a galaxy far far away…





Michelson interferometer



Graphic: M. Evans, MIT

A “small” problem…

wave’s strength corresponds to *strain* induced in the detector,

$$h = \Delta L / L$$

We can calculate expected strain at Earth;

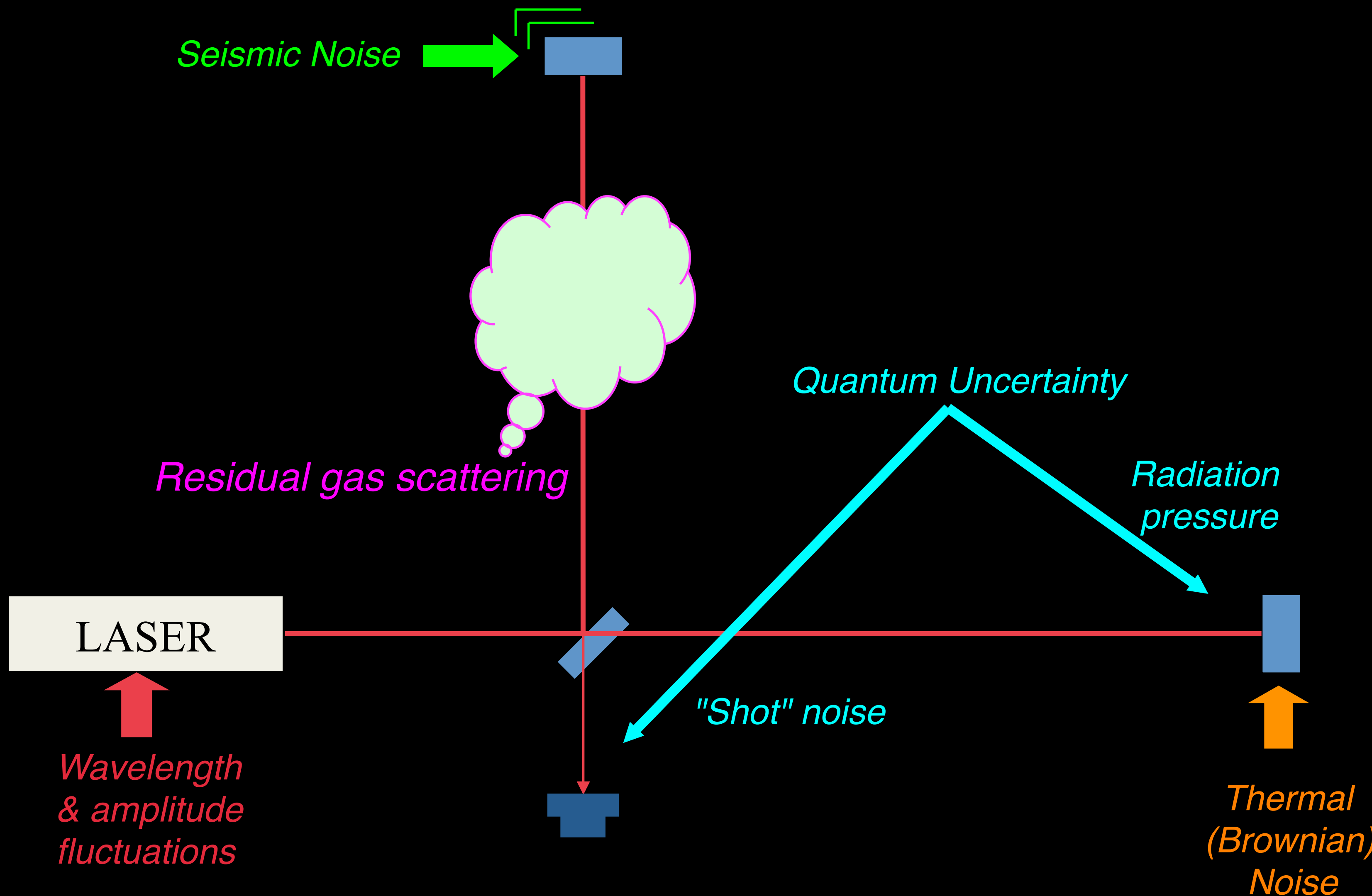
$$|h| \approx 4\pi^2 GMR^2 f_{orbit}^2 / c^4 r \approx 10^{-22} \left(\frac{R}{20\text{km}}\right)^2 \left(\frac{M}{M_\Theta}\right) \left(\frac{f_{orbit}}{400\text{Hz}}\right)^2 \left(\frac{100\text{Mpc}}{r}\right)$$

If we make our interferometer arms 4,000 meters long,

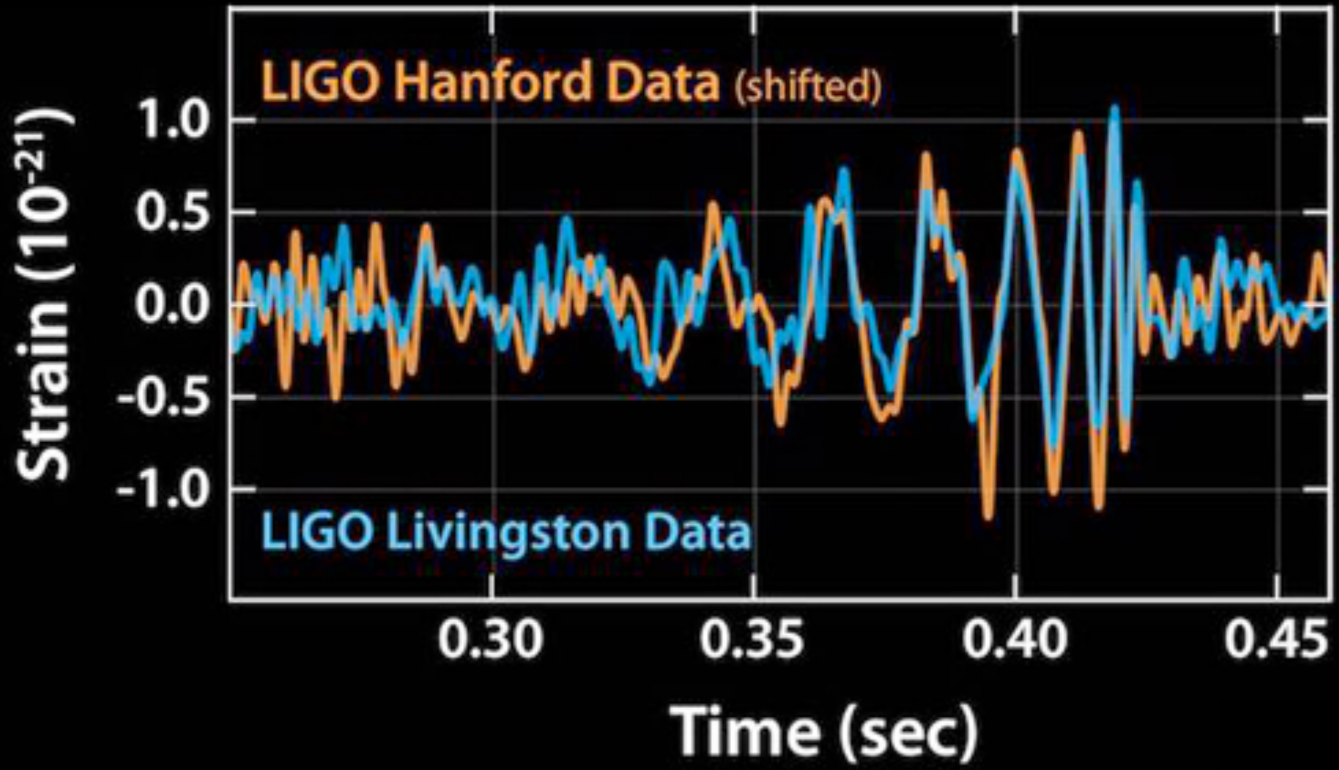
$$\Delta L = h \times L \approx 10^{-22} \times 4{,}000\, m \approx 4 \cdot 10^{-19}\, m$$

A ten-thousandth the size of an atomic nucleus

The Enemies: NOISE

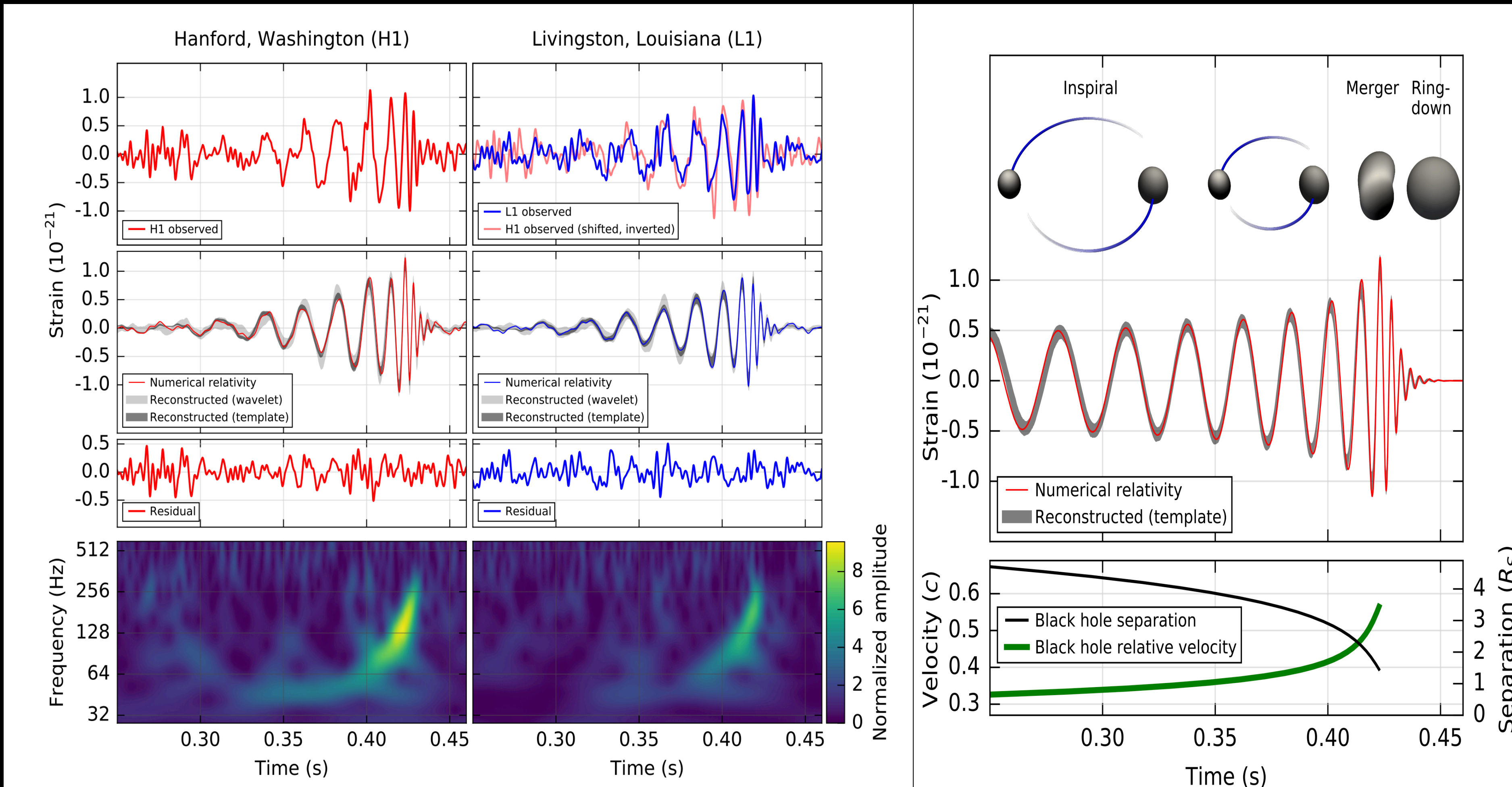


14 September, 2015



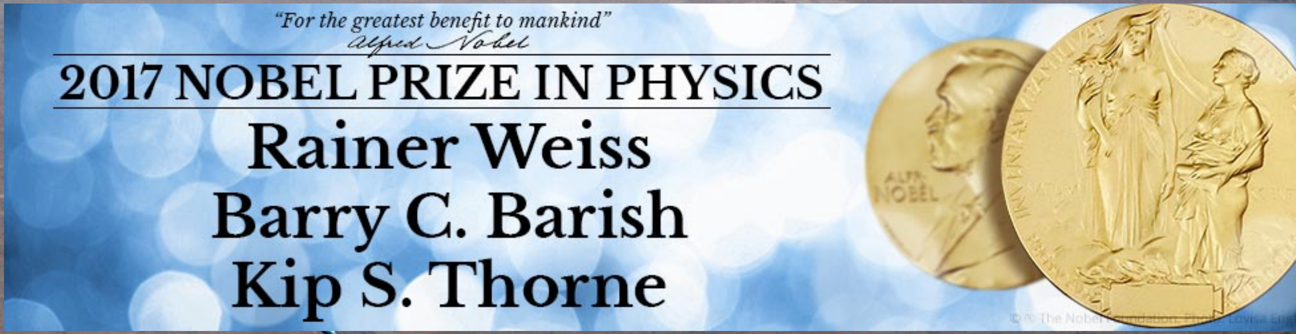
GW150914

29$M_\odot$ and 36$M_\odot$ black holes 1.3 GLY away inspiral and merge, emitting 3$M_\odot$ of GW energy, briefly “outshining” the entire universe



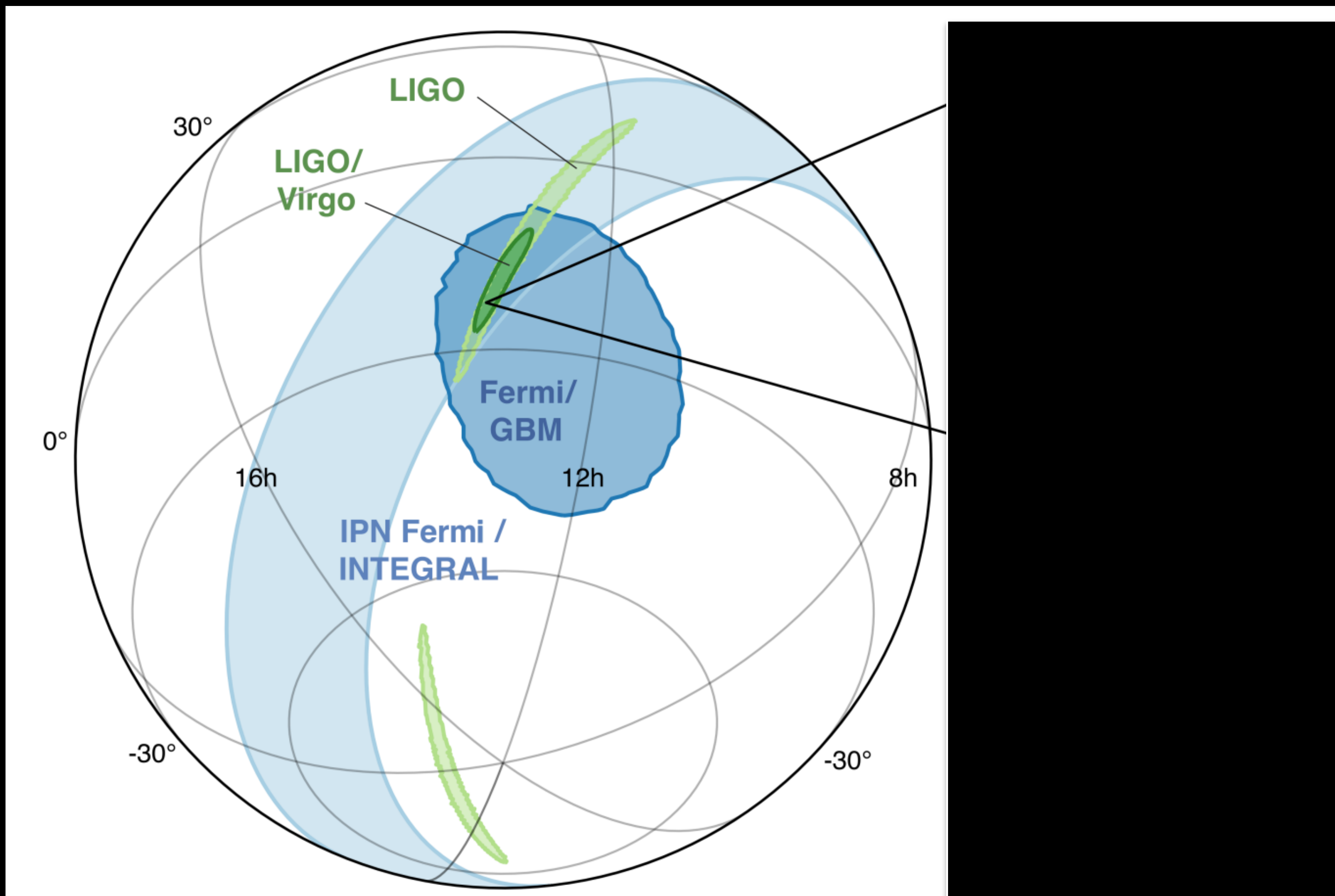
Abbott et al Phys. Rev. Lett. 116 (2016) 061102

the LASER Interferometer Gravitational-wave Observatory

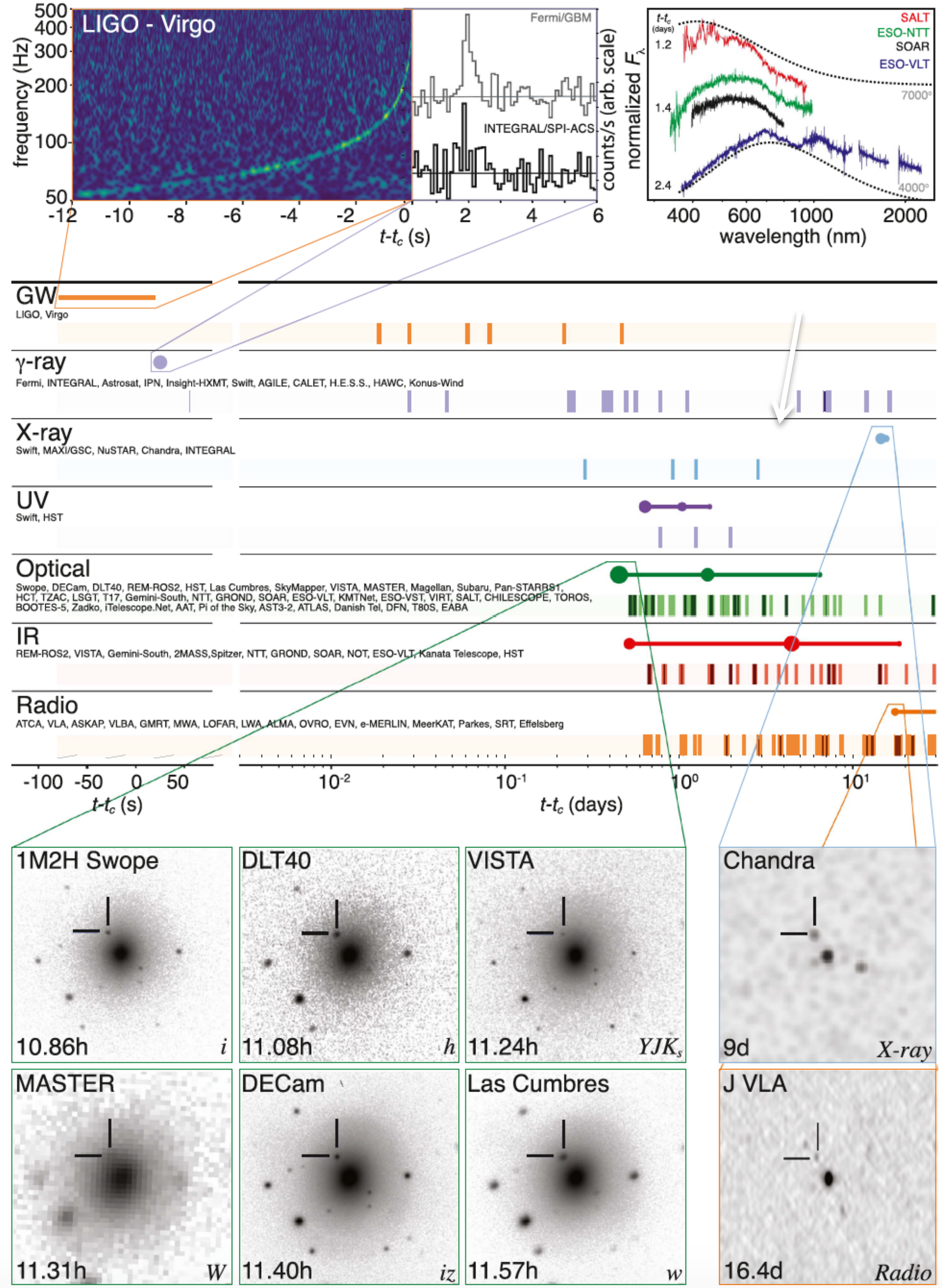



Virgo
Cascina, Italy
3 km
7900 km (25 ms)
LIGO
Livingston, LA
4 km
8200 km (27 ms)
LIGO
Hanford, WA
3000 km (11 ms)

August 17th 2017

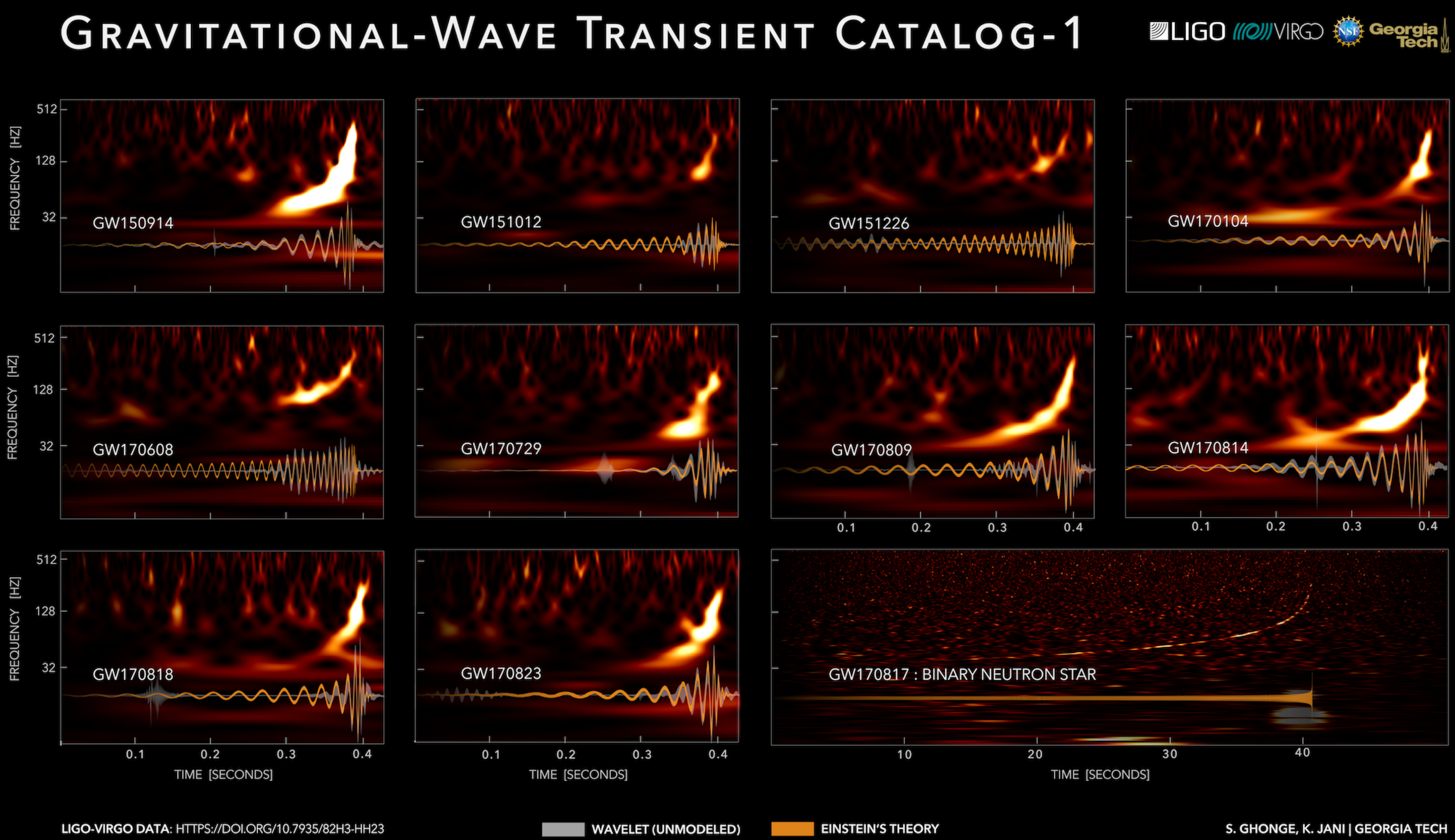


Abbott et al. Ap. J. Lett., 848:2 (2017)

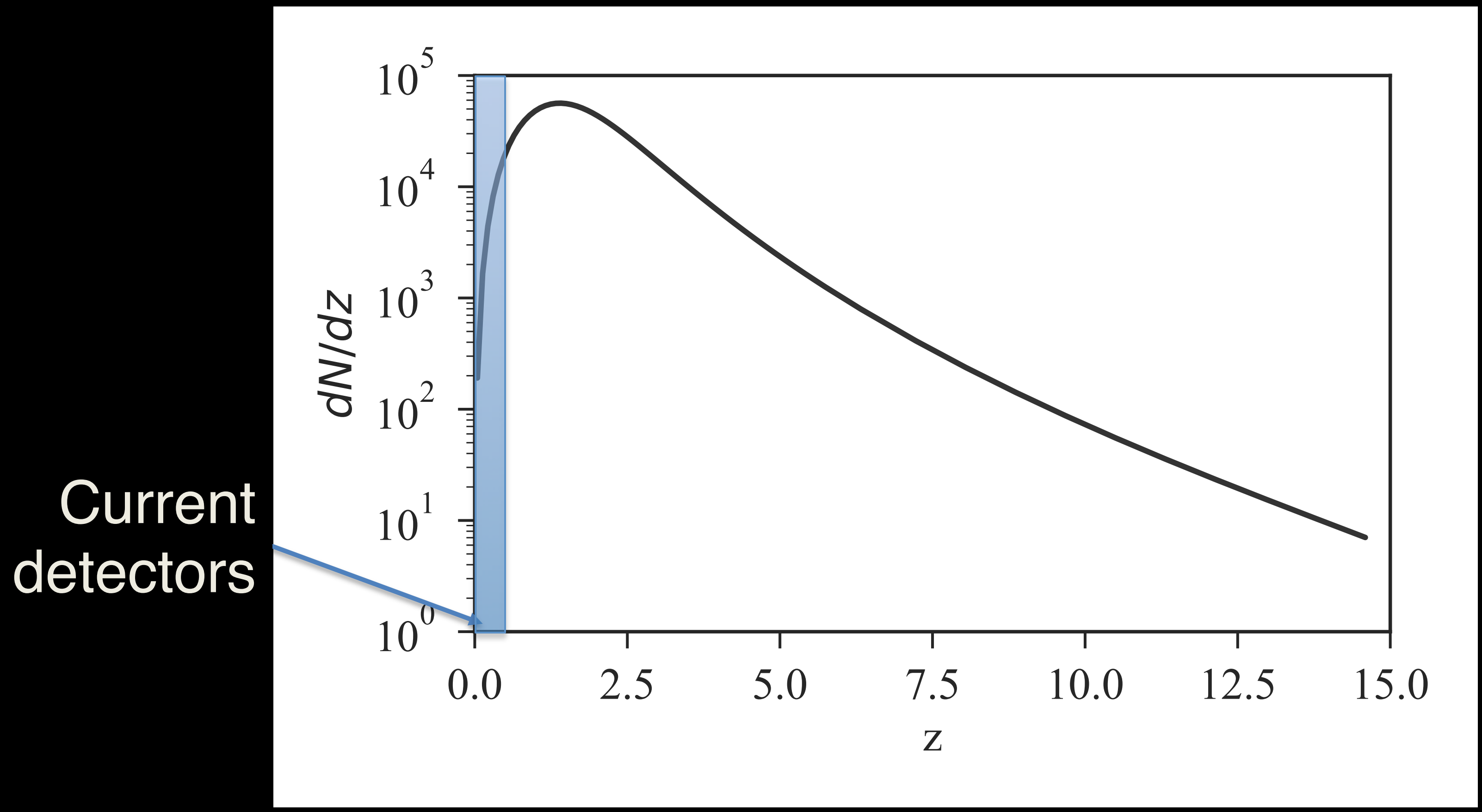


Abbott et al. *Astrophys. J. Lett., 848:L12, (2017)*

O1 and O2 Observing Run Catalog



Where do we stand?
Number of coalescing binaries vs. redshift

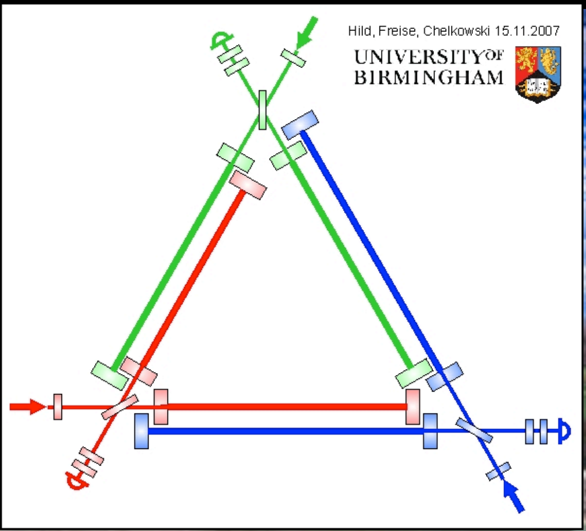


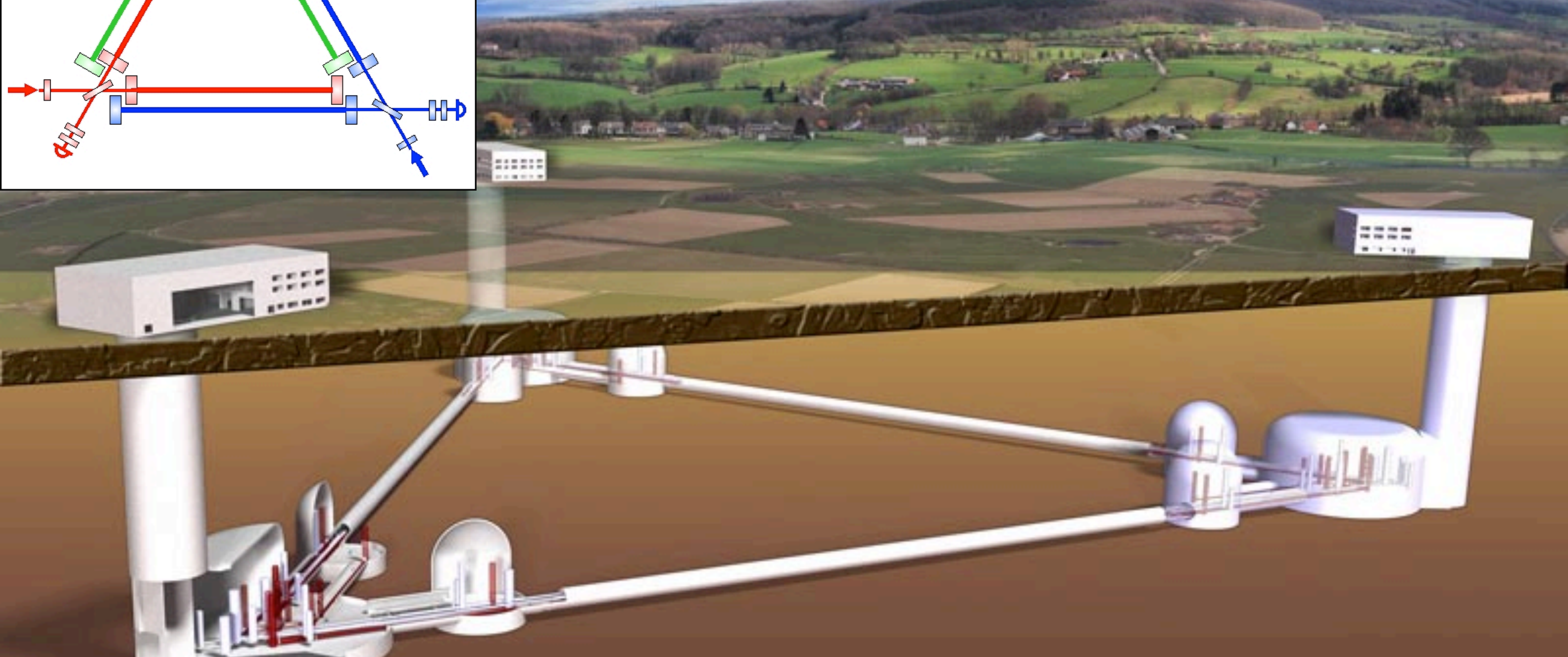
To detect more distant objects, make the interferometers larger

$$h = \Delta L / L$$

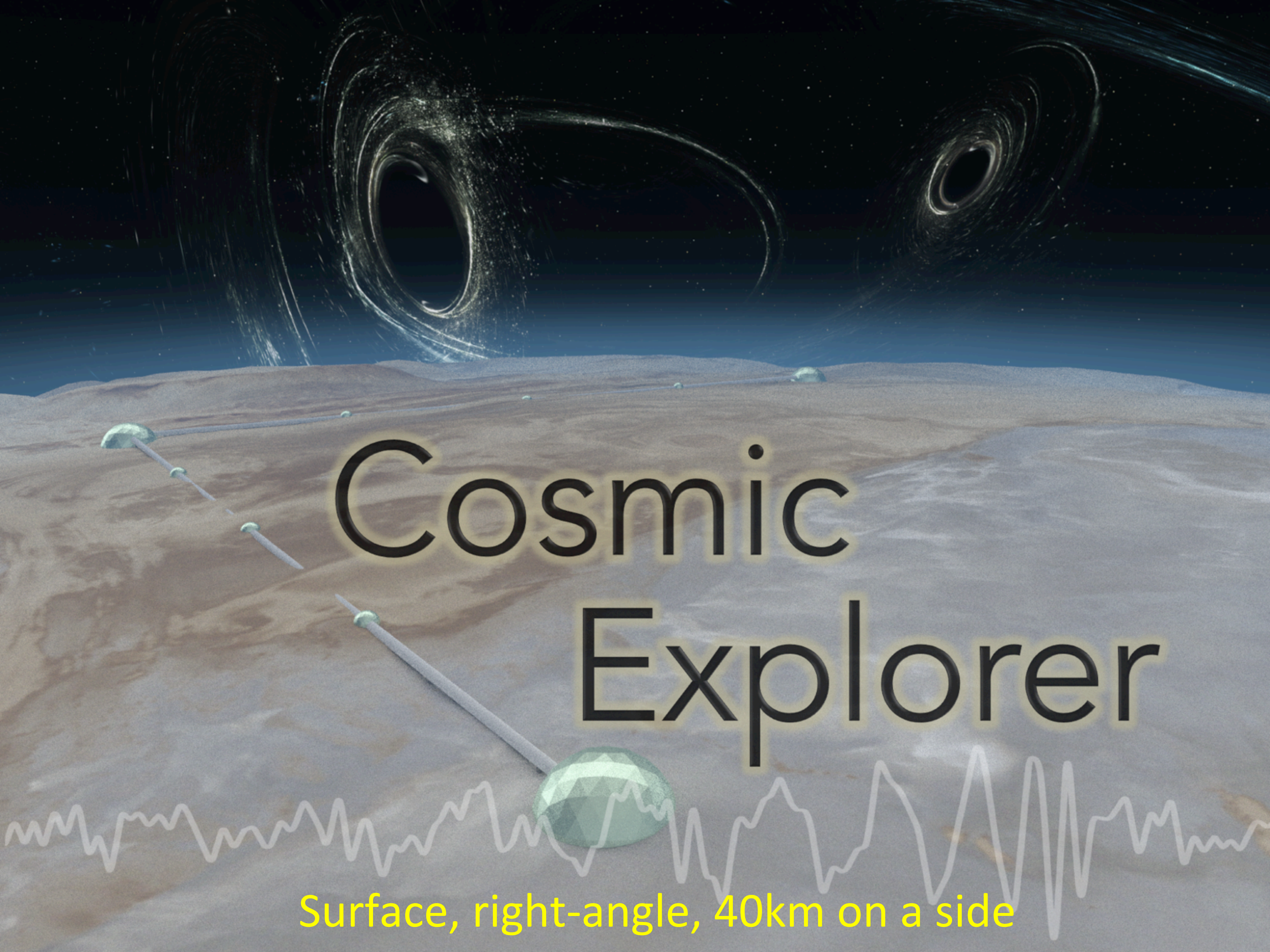
$$\Delta L = h \times L \approx 10^{-22} \times 4{,}000\, m \approx 4 \cdot 10^{-19}\, m$$

Einstein Telescope

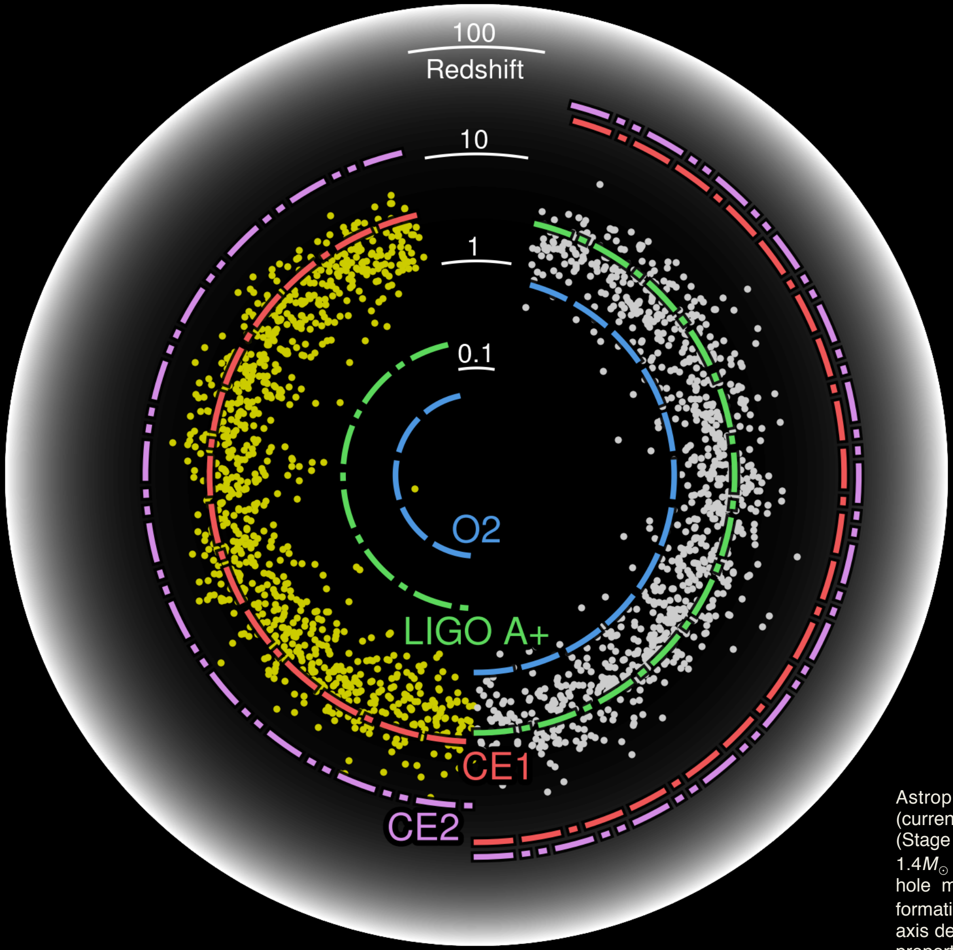




Underground, triangular, 10km on a side


Cosmic
Explorer
Surface, right-angle, 40km on a side

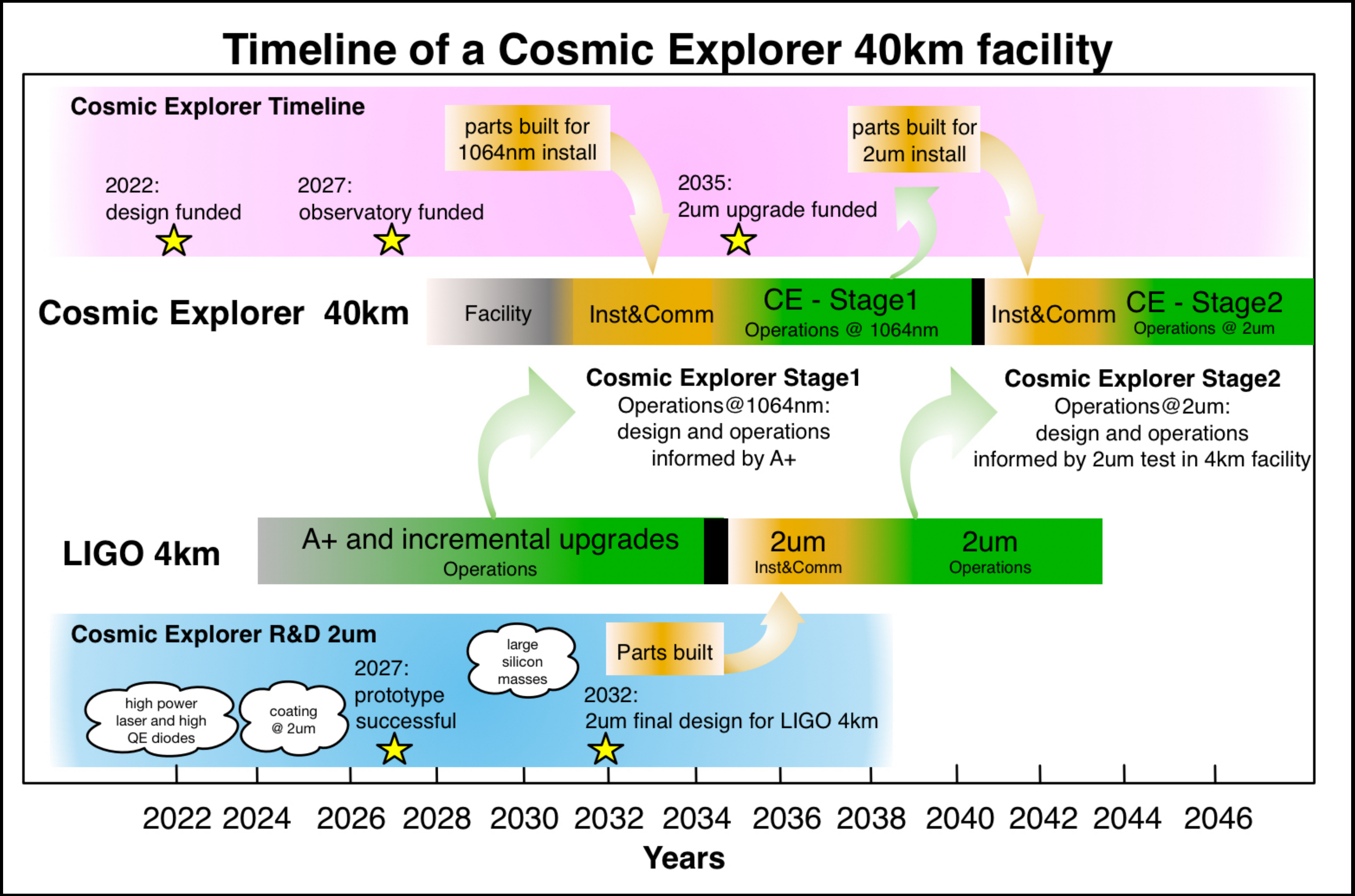
Cosmic Explorer will detect compact binaries throughout the observable universe



Astrophysical response distance of Advanced LIGO (current best sensitivity), LIGO A+, and Cosmic Explorer (Stage 1 and 2), plotted on top of a population of 1.4–1.4$M_\odot$ neutron star mergers (yellow) and 30–30$M_\odot$ black hole mergers (gray), assuming a Madau–Dickinson star formation profile and a 100 Myr merger time. The radial axis denotes redshift, and the radial distribution of points is proportional to dR/dz, the detector-frame merger rate per unit redshift.

Courtesy S. Vitale and E. Hall, MIT

Conceptual timeline



40 km interferometers will need very large vacuum systems.

Vacuum Requirement Drivers

Brownian recoil of mirrors due to gas molecule impact

(exacerbated by small gaps)

$P(H_2) < 10^{-8}$ Torr

Contamination of optics leading to scattering, heating or damage

Mirror absorption budget: < 0.1 ppm change over operating life

Hydrocarbons: < 1 monolayer/10 years

Particles: < one 10 μm particle on any mirror

Light scattering from residual gas

A function of molecular polarizability and thermal speed

Primary goals:

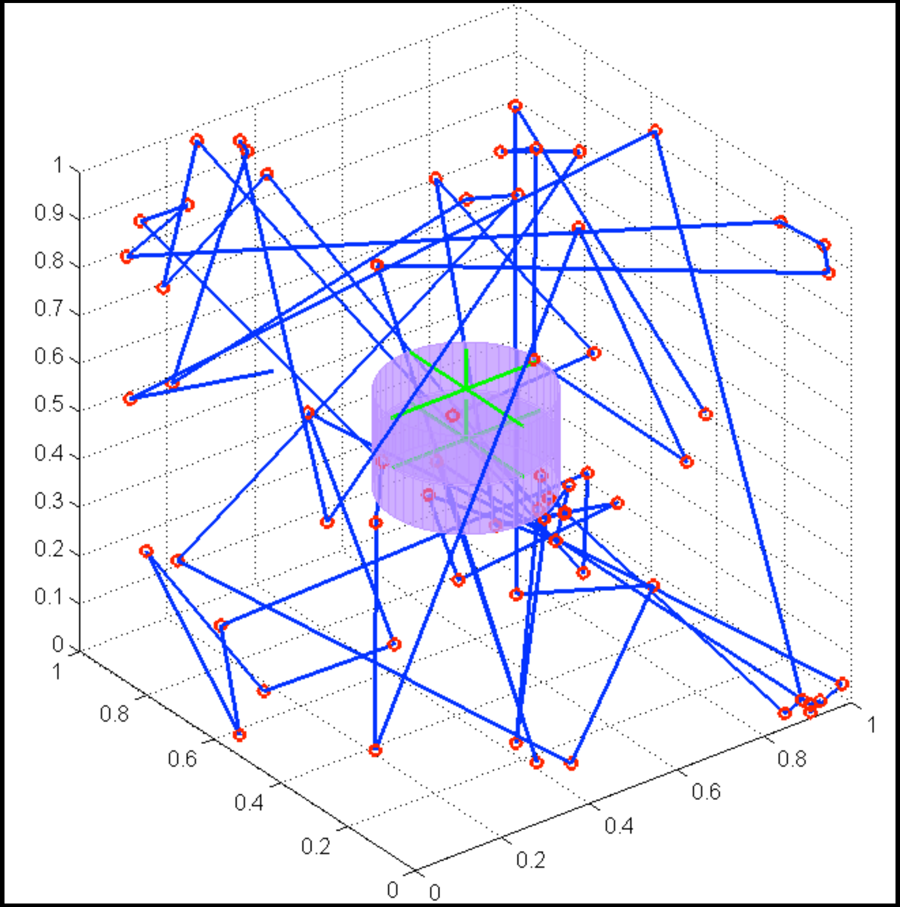
➔ $P(H_2) < 10^{-9}$ Torr

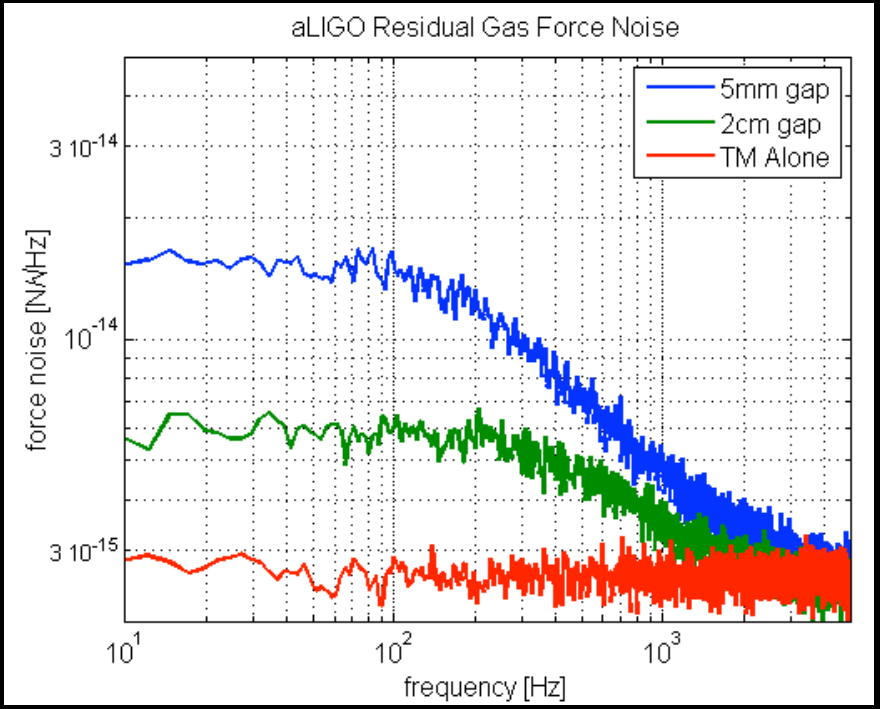
➔ $P(H_2O) < 10^{-10}$ Torr

Light scattering from tube walls

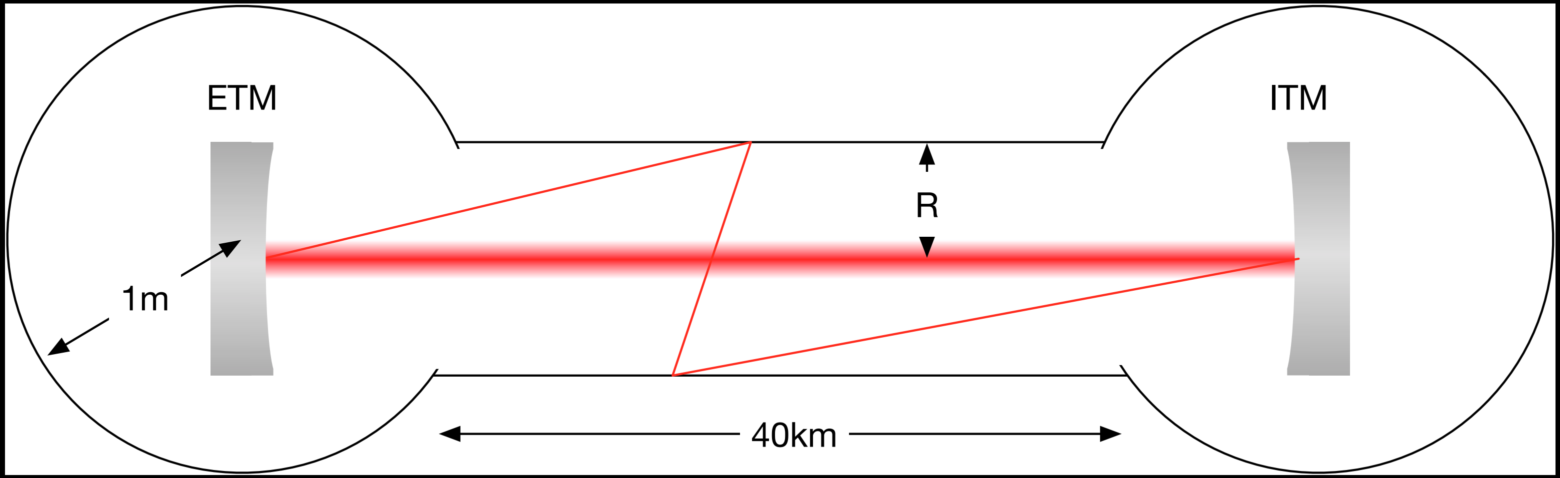
Not a "vacuum requirement" per se, but drives tube diameter, surface finish and construction (e.g., vibration)

Vessel Vacuum: Gas damping (Brownian motion)



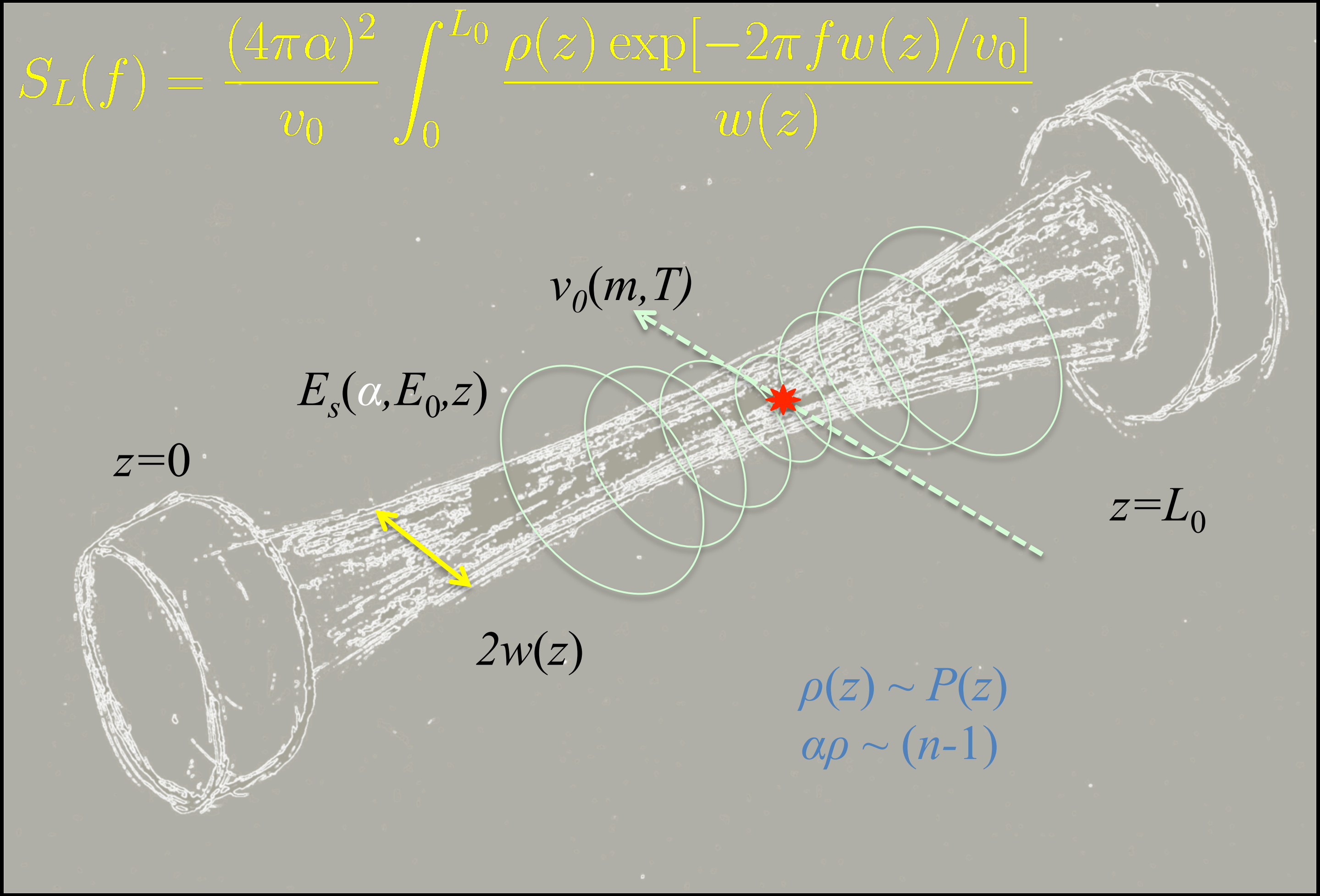


Beamtube Wall Scattering




Cleaning a LIGO Mirror In-Chamber

Light Scattering from Residual Gas



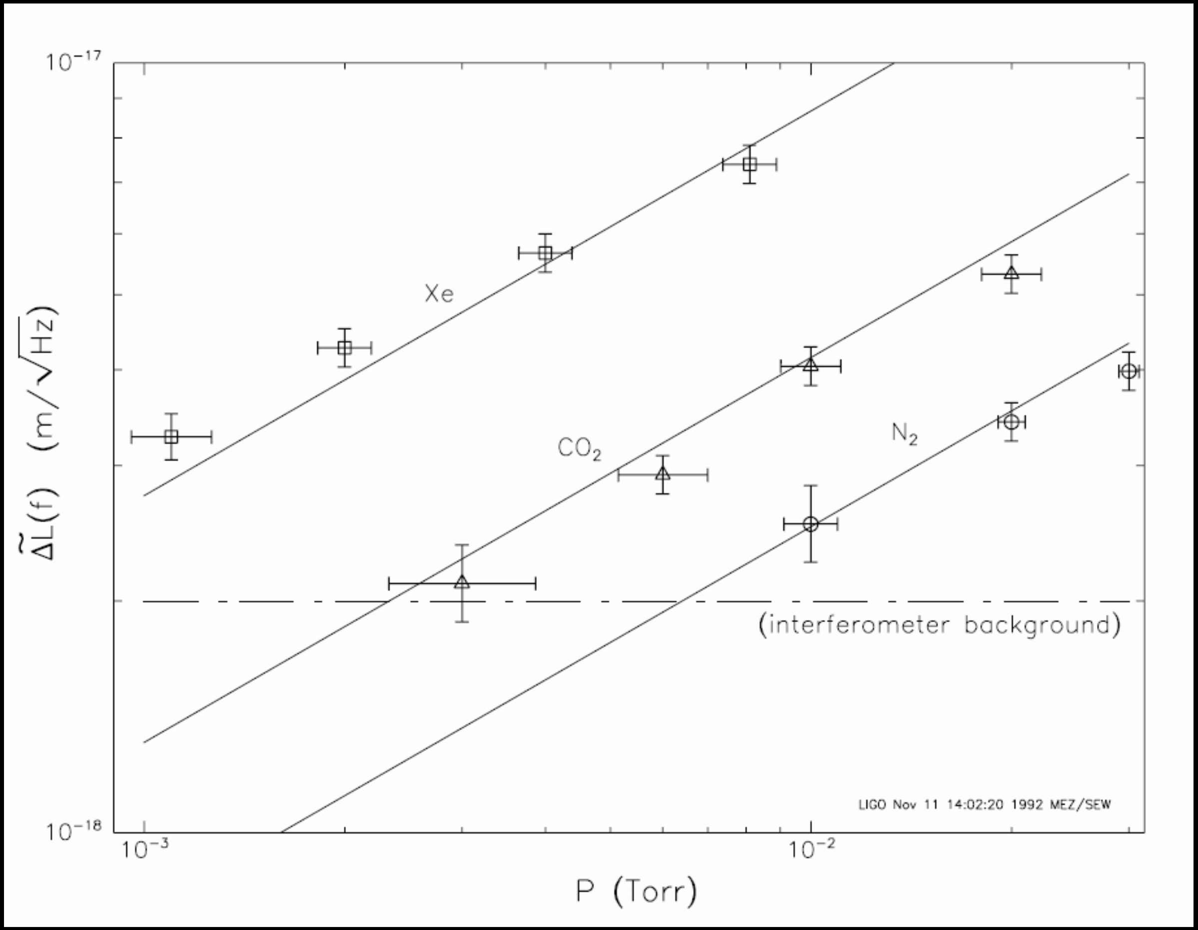
Residual Gas Scattering

$$S_L(f) = \frac{4\rho(2\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{\exp\left[-2\pi f\, w(z)/v_0\right]}{w(z)}\, dz$$

$$\Delta\tilde{L}(f) \equiv \sqrt{S_{\Delta L}(f)} = \sqrt{2S_L(f)}$$

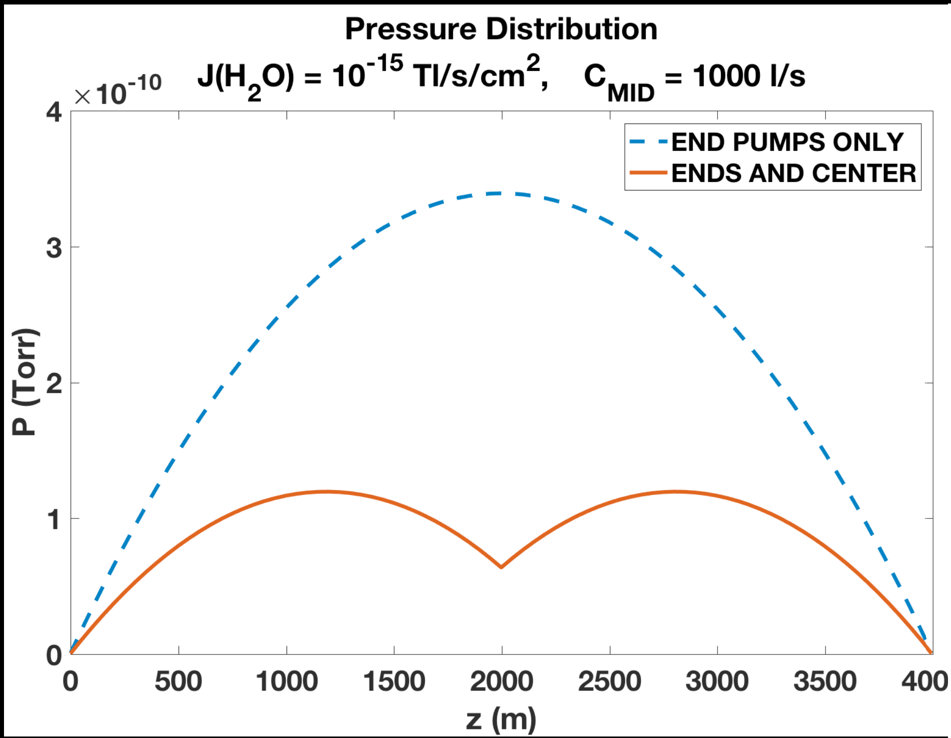
ϱ = gas number density (~ pressure)
α = optical polarizability (~ index)
w = beam radius
v_0 = most probable thermal speed
L_0 = arm length
ΔL = arm optical path difference

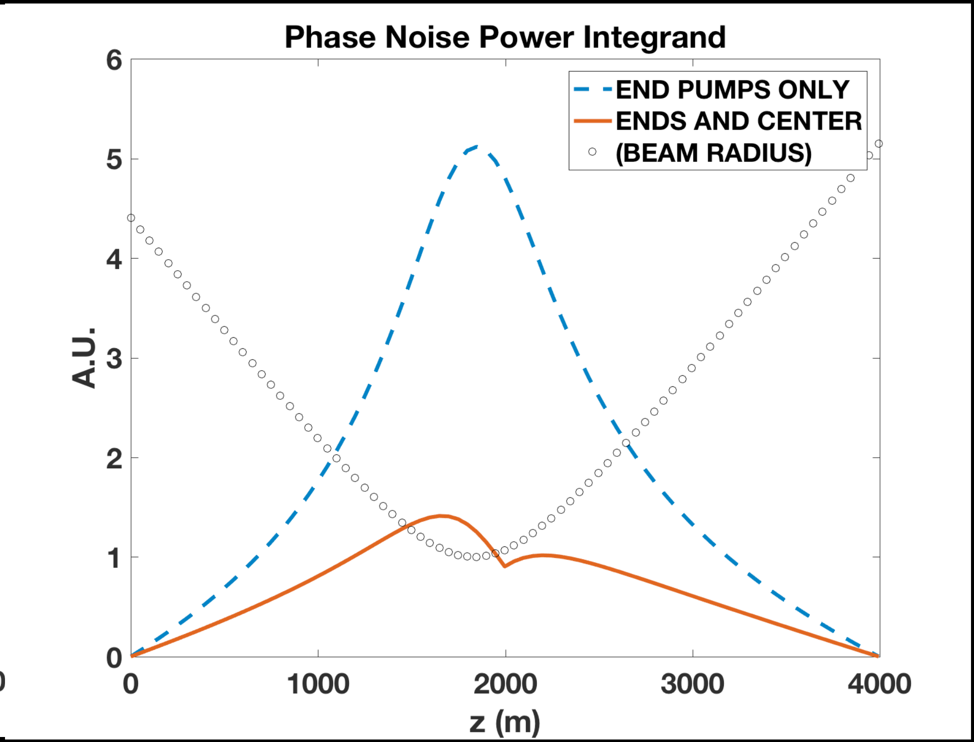
Statistical model verified by interferometer experiment



S. Whitcomb and MZ, Proc. 7th Marcel Grossmann Meeting on GR, R. Jantzen and G. Keiser, eds. World Scientific, Singapore (1996).

Gaussian laser beam diameter varies
➔ Pressure gradients matter





Sample parameters for CE design operating at 1 micron laser wavelength

parameter	aLIGO	CE (1 μm)
L (m)	4,000	40,000
w_0 (mm)	62	83
h_{gas} ($Hz^{-1/2}$)*	$< 2 \times 10^{-25}$	$< 5 \times 10^{-26}$
P[H_2] (Torr)	$< 10^{-9}$	$< 10^{-9}$
P[H_2O] (Torr)	$< 10^{-10}$	$< 10^{-10}$
P[CO_2] (Torr)	$< 2 \times 10^{-11}$	$< 2 \times 10^{-11}$

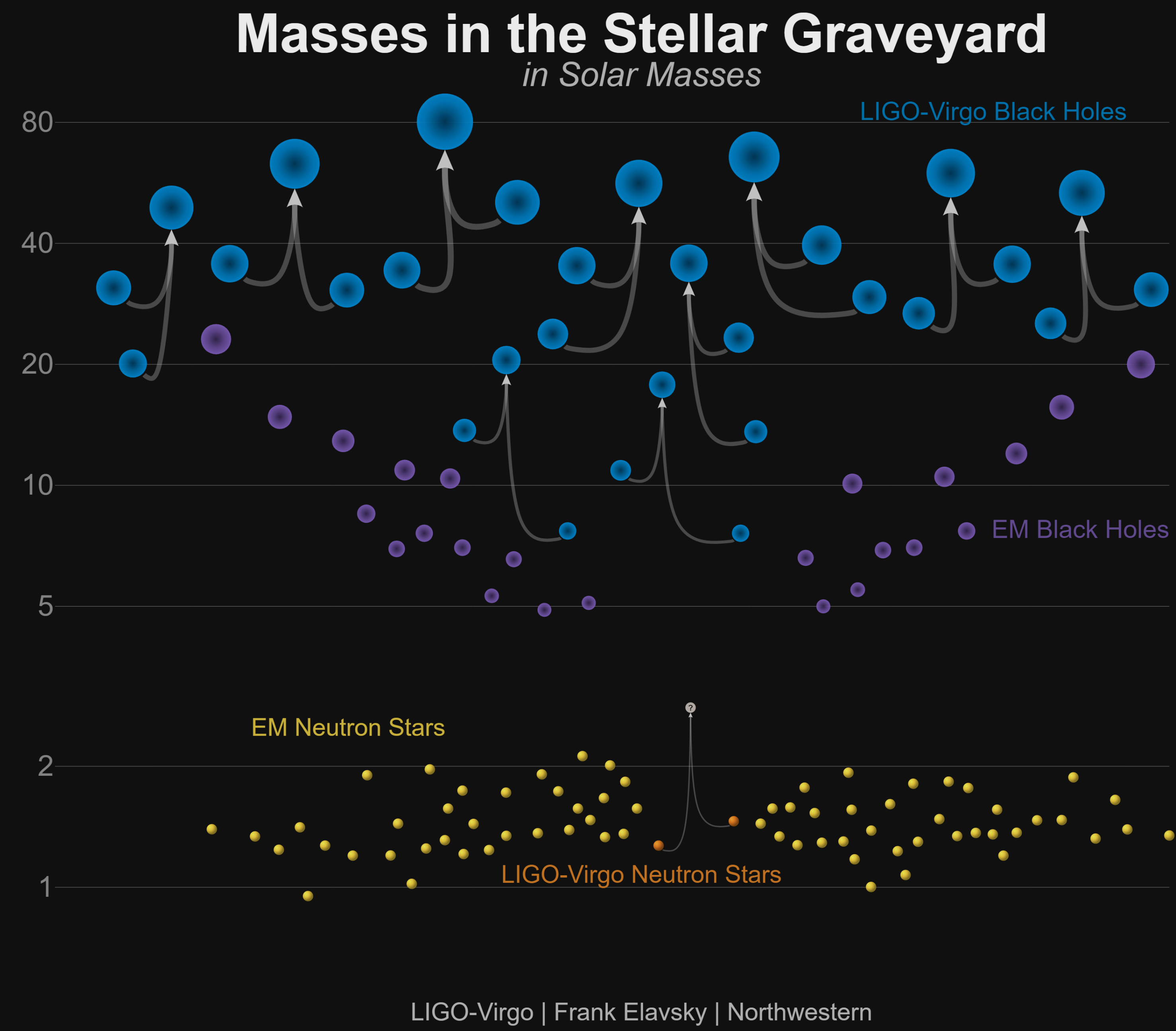
*3x safety margin

Assuming 40km x 1.2m ϕ tubes with 'LIGO-typical' outgassing, e.g.,
J(H_2O) ~10^{-15} T l s^{-1} cm^{-2} and
J(H_2) ~ 5×10^{-14} T l s^{-1} cm^{-2} ,
this could be achieved with one 1,000 l/s ion pump deployed each kilometer.

LIGO Beamtube

- 9000 m^3 volume/site
- 30000 m^2 area/site
- 50 km of spiral welds
- ~10^{-9} torr
- budget ~ $40M (1997)
  $2500/m
  $50/lb

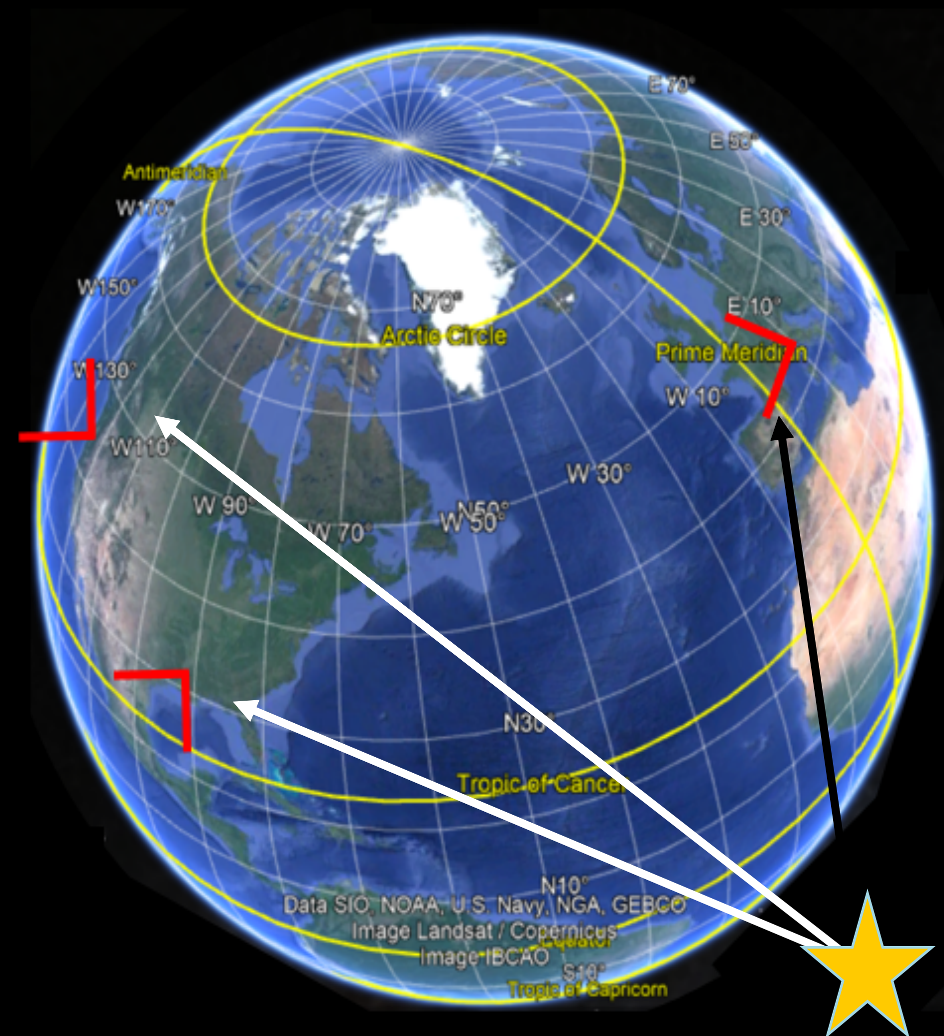
REFERENCE SLIDES


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern


Virgo, Cascina, Italy


LIGO, Livingston, LA


LIGO, Hanford, WA


Antimeridian
W 170°
W 150°
W 130°
W 110°
W 90°
W 70°
W 50°
W 30°
W 10°
E 70°
E 50°
E 30°
E 10°
N 70°
Arctic Circle
Prime Meridian
N 50°
N 30°
Tropic of Cancer
N 10°
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Image IBCAO
S 10°
Tropic of Capricorn

LIGO: a quick history

- 1980's- Lab-scale R&D prototypes (MIT, Caltech, UK, Germany; up to 40m long) explored interferometer technology
- 1989- Proposed twin 4km instruments to U.S. National Sc[illegible]oundation
- 1993- Funded for construction
  - Initial phase to use existing (1990's) technology; "Advanced" de[illegible]D to proceed concurrently with construction and first observations
  - Chances for detection at initial design sensitivity "plausible," but not assured
- 1997- *LIGO Scientific Collaboration* formed to share LIGO science and develop community of gravitational wave researchers (now over 900 members, 88 institutions, 14 nations)
- 2000- Finished construction; at design sensitivity 2005; collected data through 2010
  - NO confirmed astrophysical detections; only upper limits so far
  - Data are open, publicly available to other researchers
- 2008- "Advanced LIGO" upgrade approved, installation 2010, completed 2015
  - Total redesign; everything but the buildings & the vacuum system is new
  - Installation begun in 2010
- 2015- Hanford and Livingston advanced instruments reached initial target performance
  - Just started shaking down for the first observing run and…

BANG! GW150914!!!

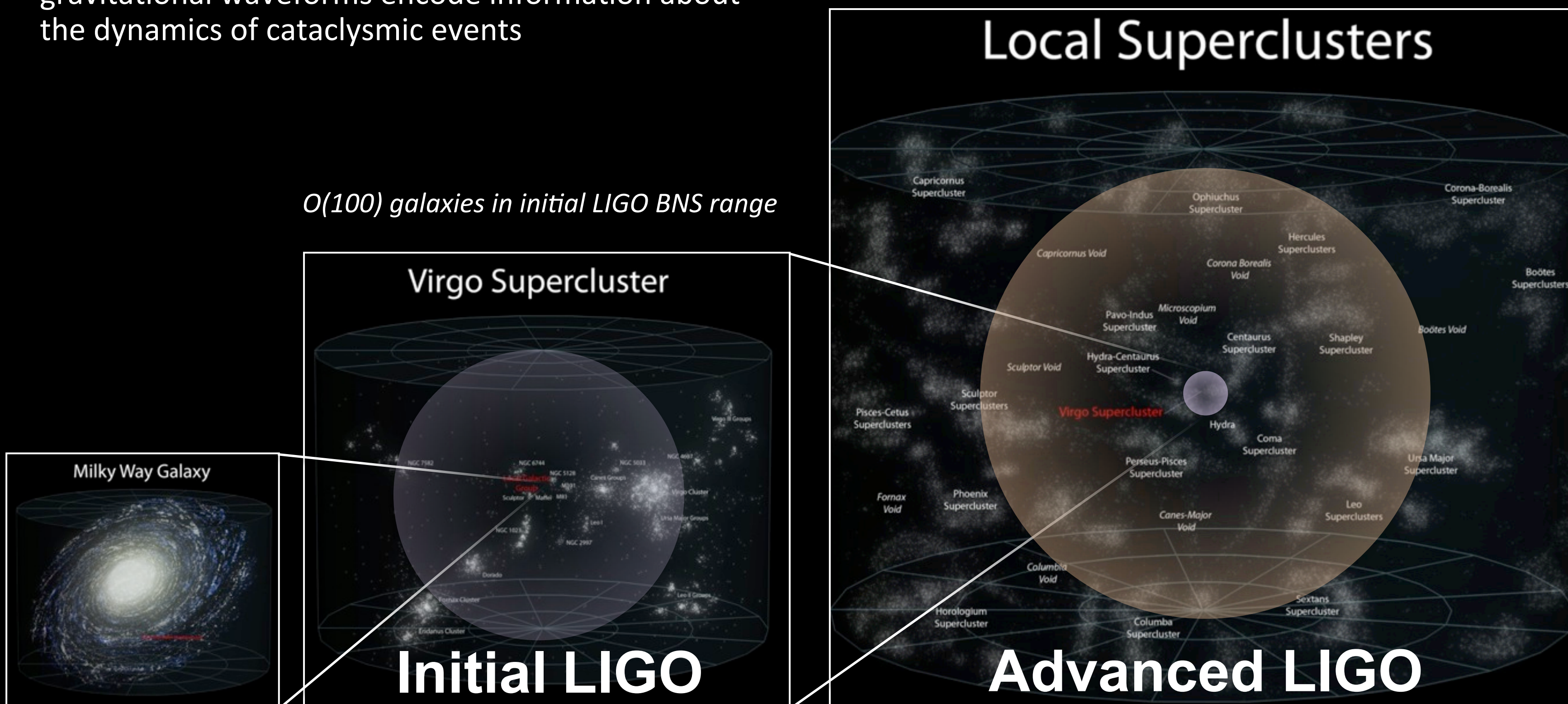
Advanced LIGO

- Complete redesign and rebuild of the LIGO interferometers
- A discovery machine – expect 10's of BNS detections per year at design sensitivity (BBH? Supernovae? Other?)
- An astrophysical observatory – high SNR gravitational waveforms encode information about the dynamics of cataclysmic events

- **10x more sensitive than initial instruments in *h* → 1,000x greater volume at design sensitivity**

O(100,000) galaxies in Advanced LIGO BNSrange

O(100) galaxies in initial LIGO BNS range



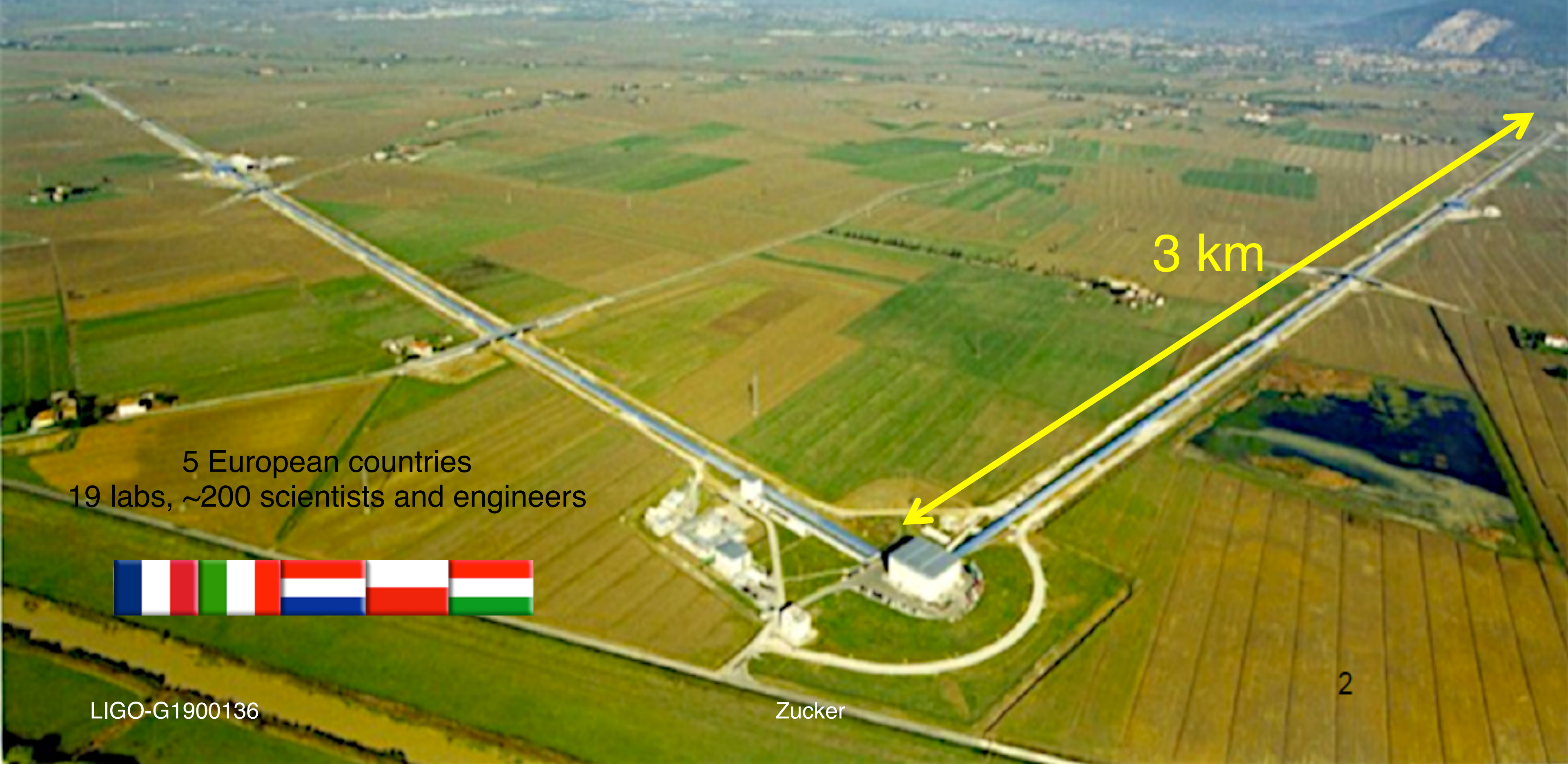
LIGO

LSC

Trinity University
University of Maryland 1856
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
American University Washington, DC
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
University of the West of Scotland UWS
University of Strathclyde
Tsinghua University
R·I·T
Max Planck Institute for Gravitational Physics Albert Einstein Institute
Michigan
Università degli Studi del Sannio
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique theorique
Massachusetts Institute of Technology
NASA Goddard Space Flight Center
ICTP SAIFR
The University of Western Australia
РАН
University of Cambridge
The University of Chicago
Montana State University
University of Minnesota
The University of Mississippi
The University of Adelaide Australia
Southern University Agricultural & Mechanical College
Columbia University in the City of New York
Caltech
Universitat de les Illes Balears UIB
University of Birmingham
The University of Melbourne
GEO 600
UTRGV
University of Washington
University of Wisconsin Milwaukee UWM
Universität Hamburg
Syracuse University
Cardiff University Prifysgol Caerdydd
Northwestern
Monash University
INPE
UF University of Florida
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState
Hobart and William Smith Colleges
Science & Technology Facilities Council Rutherford Appleton Laboratory

The Virgo GW Detector

- Located in Cascina, near Pisa
- Advanced Virgo (AdV): upgrade of the Virgo Detector
- Joint collaboration among Italy, France, The Netherlands, Poland and Hungary
- Funding approved in Dec 2009 (€23.8M)
- Construction in progress. End of installation expected in fall 2015



KAGRA

KAGRA（かぐら）

Large-scale Cryogenic Gravitational-wave Telescope

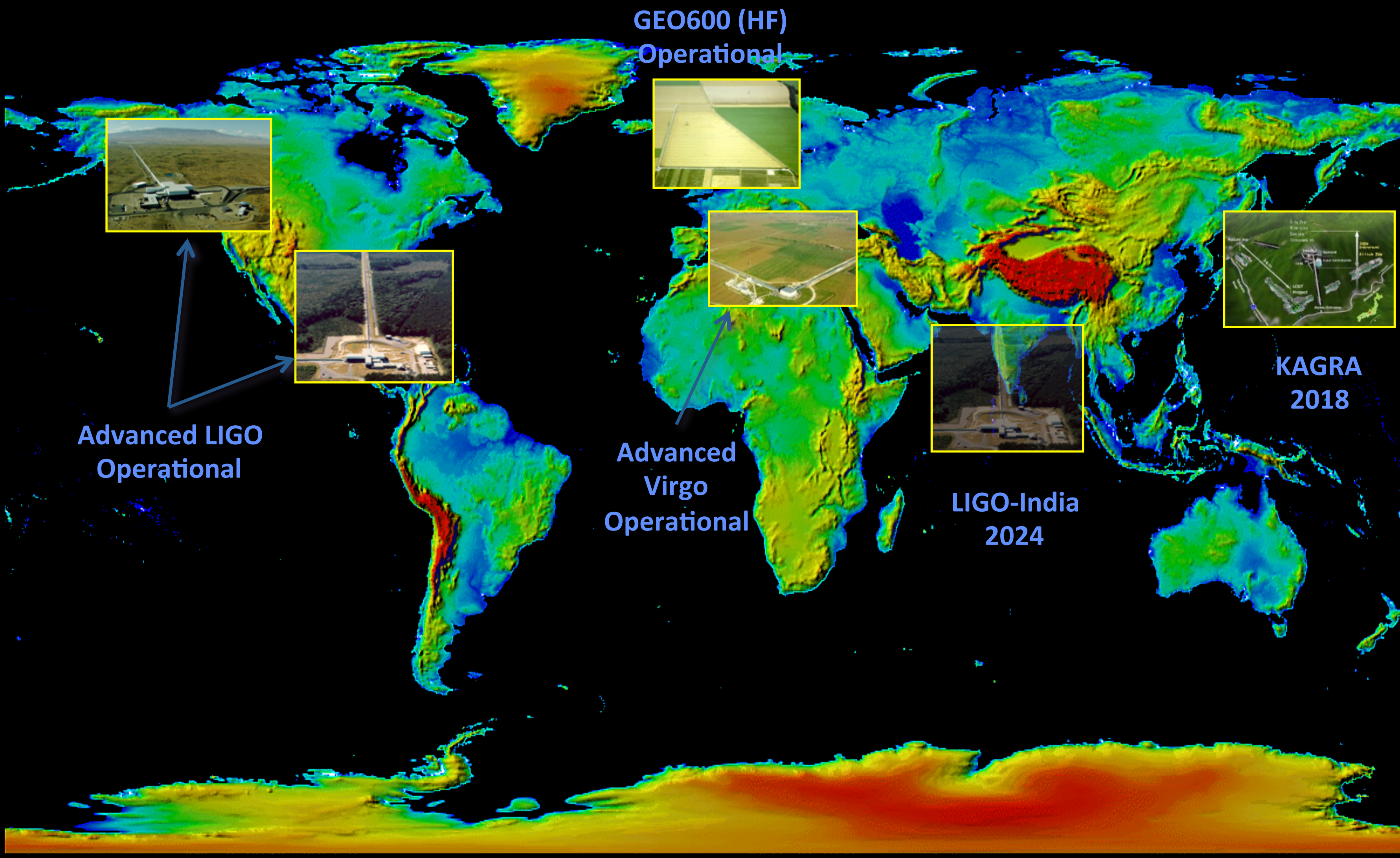
2^{nd} generation GW detector in Japan

Large-scale Detector
- Baseline length: 3km
- High-power Interferometer

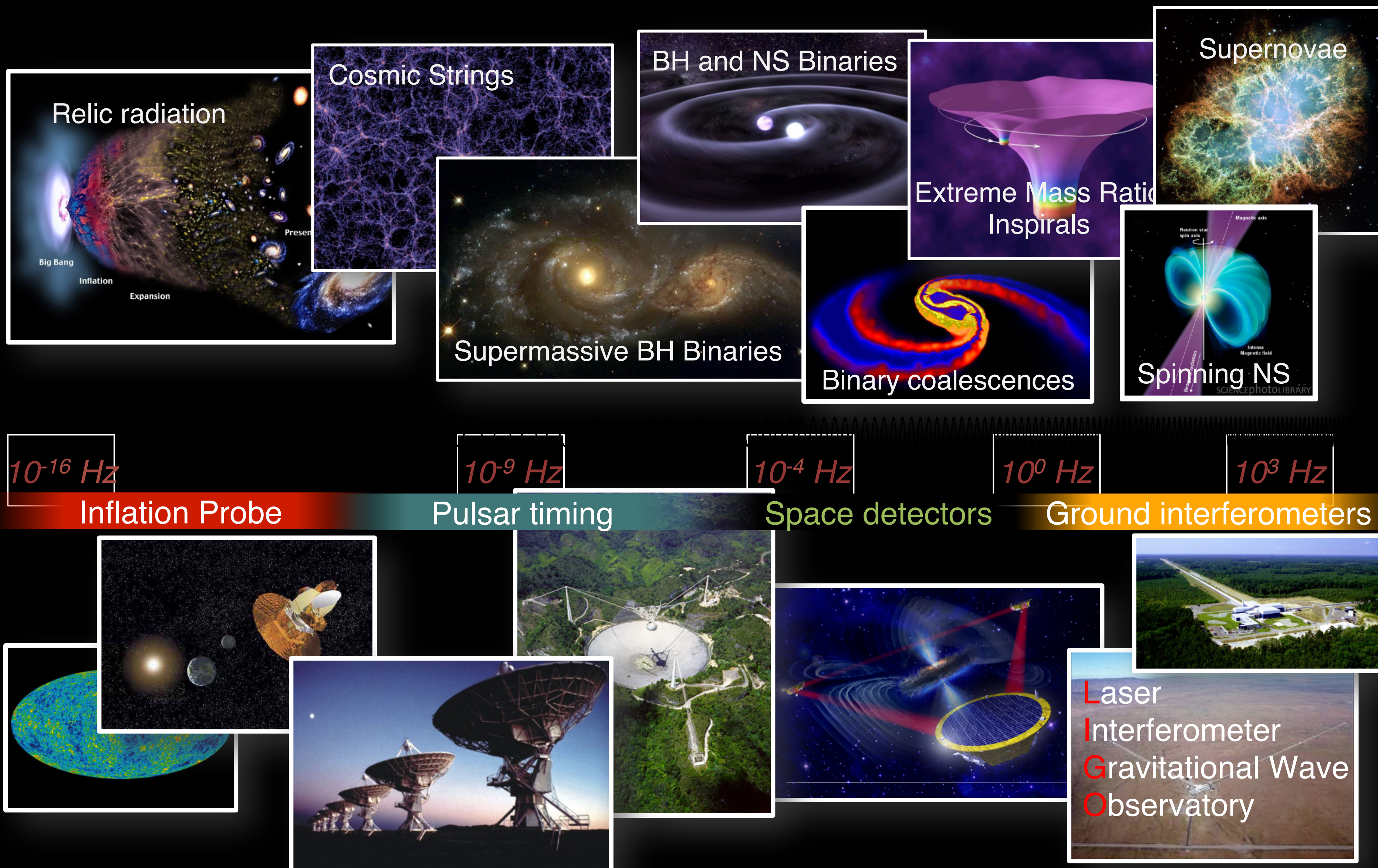
Cryogenic interferometer
- Mirror temperature: 20K

Underground site
- Kamioka mine,
  1000m underground

The World Advanced GW Detector Network

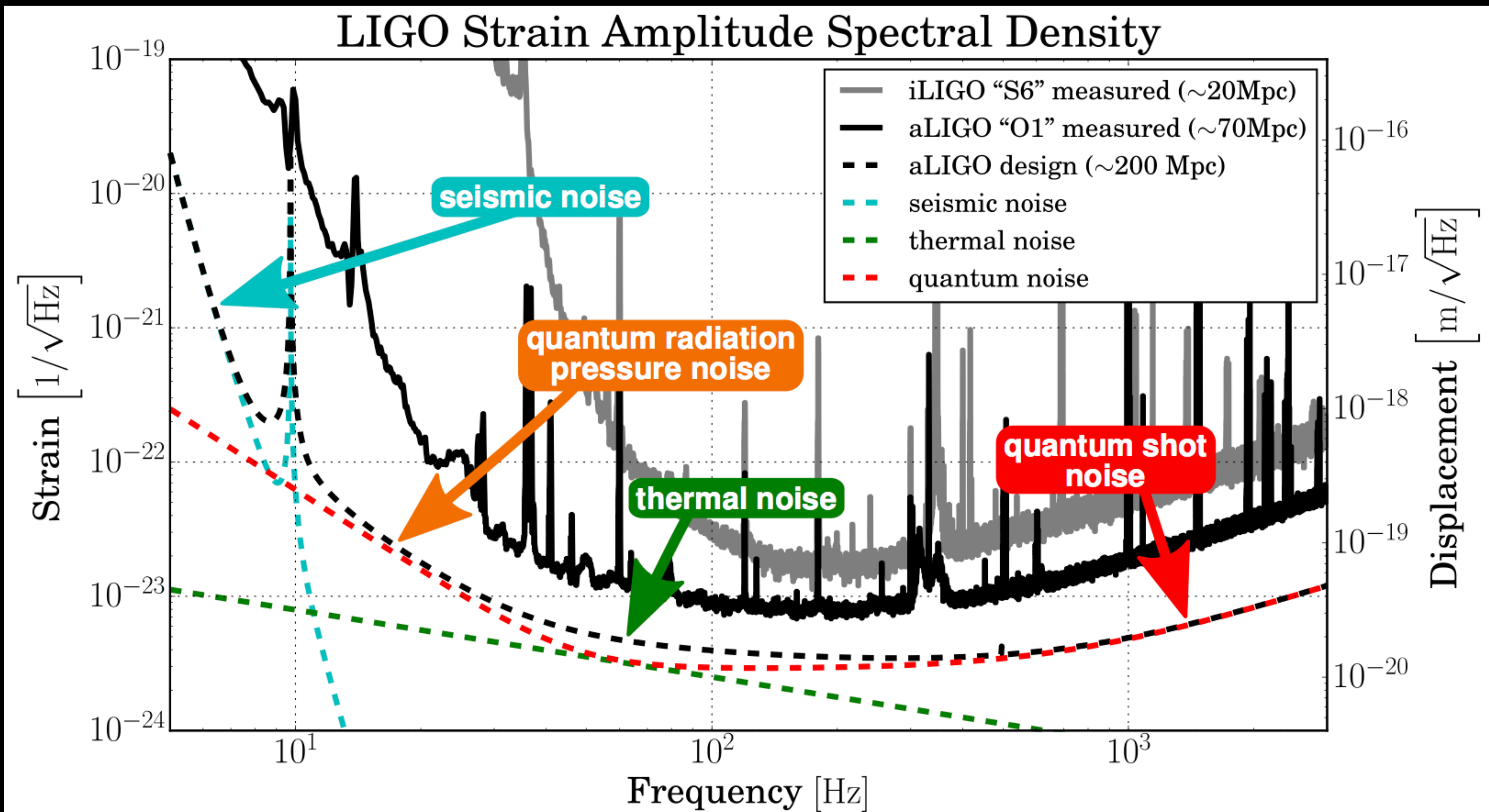


The GW Spectrum

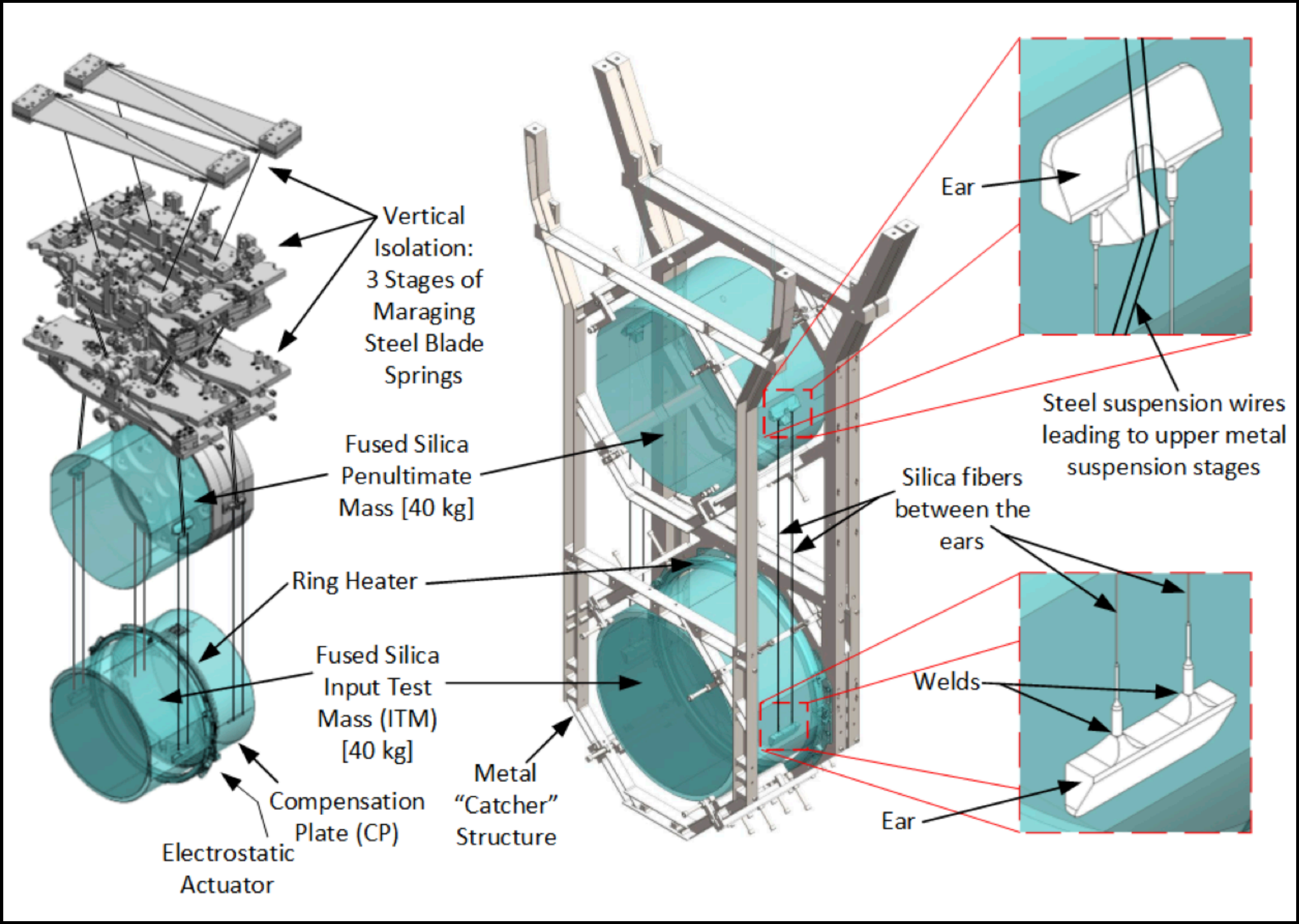


Battle Front: Fundamental Noise Sources

Graphics: J.G. Rollins, Caltech

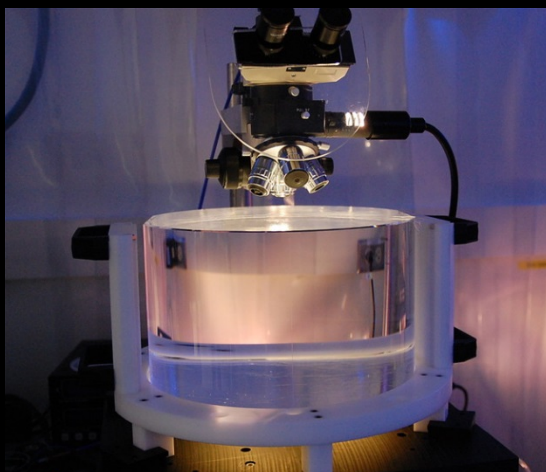


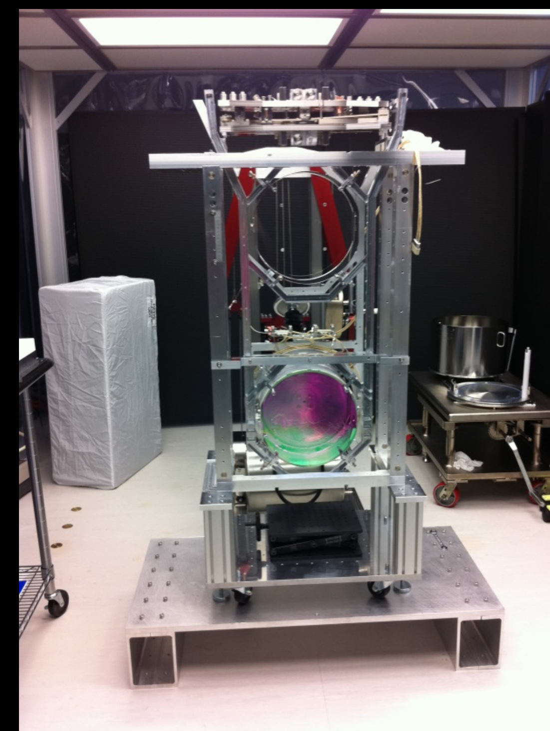
Monolithic silica suspensions

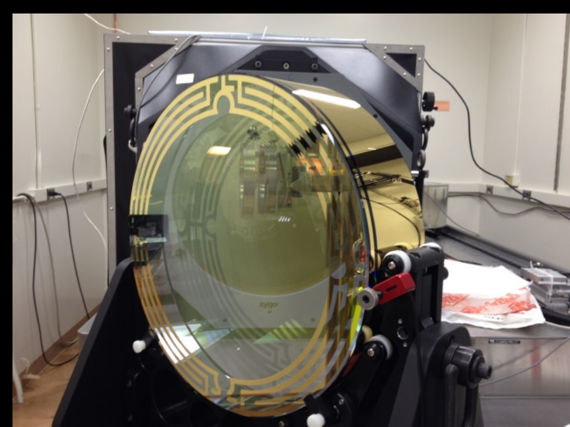


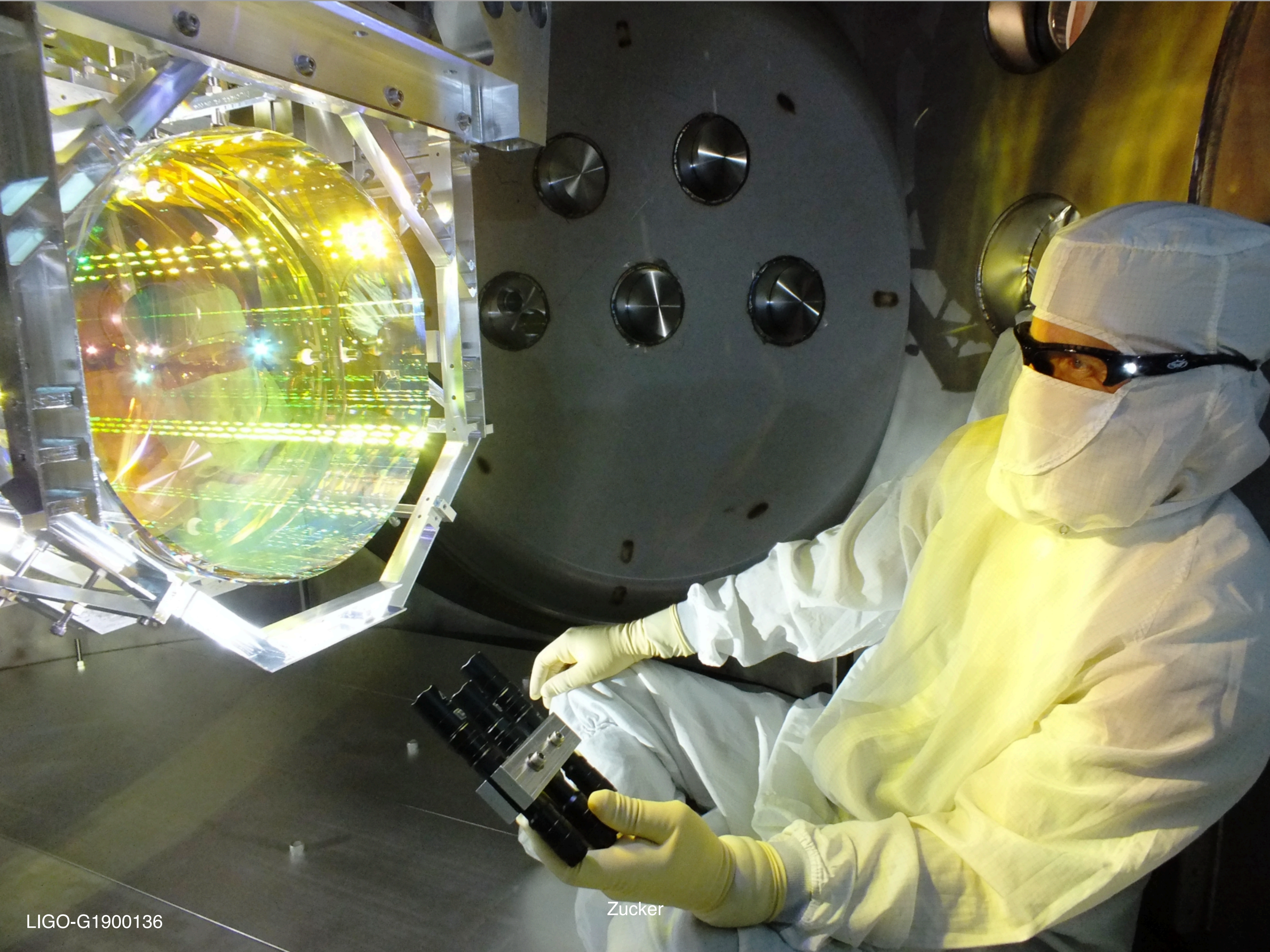
Core Optics and Low-Loss Coatings

- Main mirrors: 40 kg high quality silica, mechanical dissipation ~ 10^{-8}
- Polished to < 1.5 nm figure error with < Å microroughness
- Coated with alternating silica and titania-doped tantala by IBS; optical absorption < 0.5 ppm







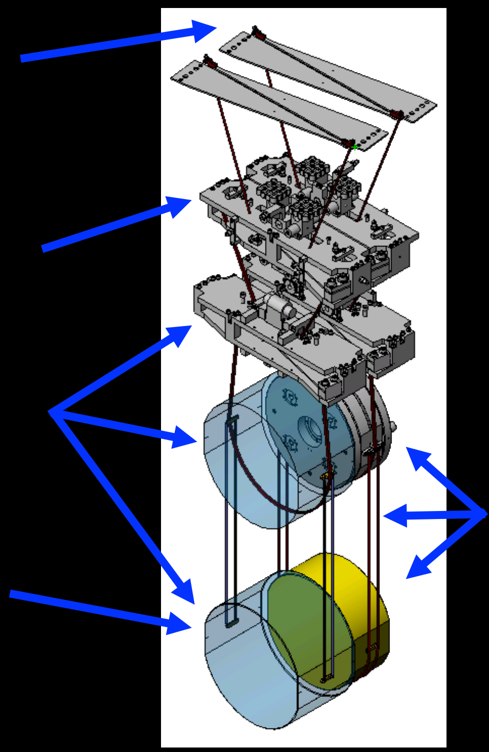


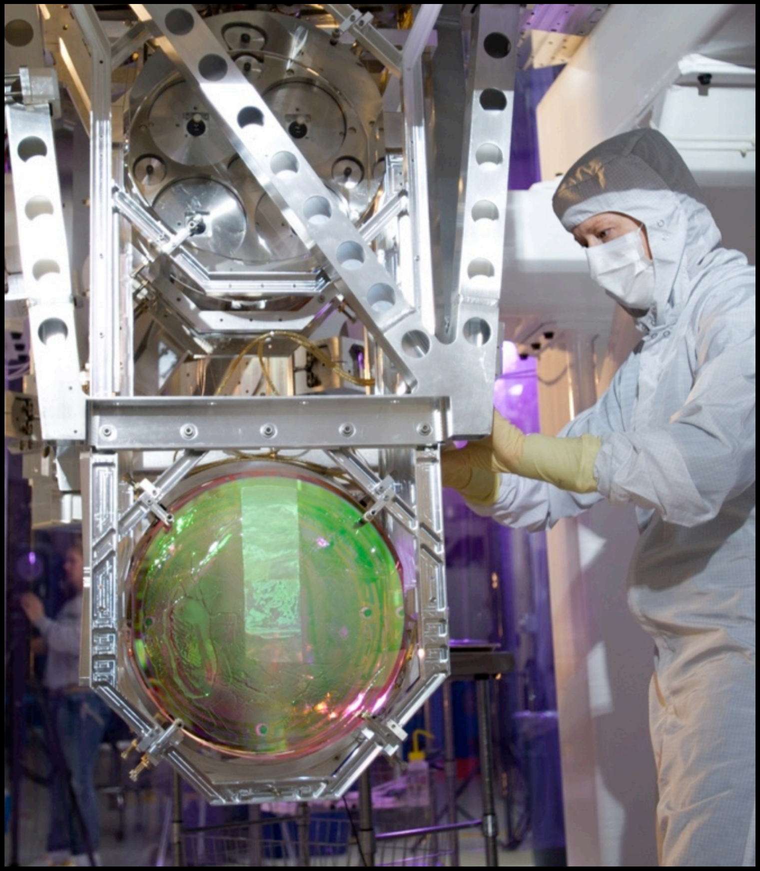
Zucker

LIGO-G1900136

Controlling Brownian Noise

- Quadruple pendulum suspensions for the 40 kg main test masses; parallel 'reaction' masses for electrostatic control forces
- Quasi-monolithic pendulums using welded fused silica fibers to suspend 40 kg test mass





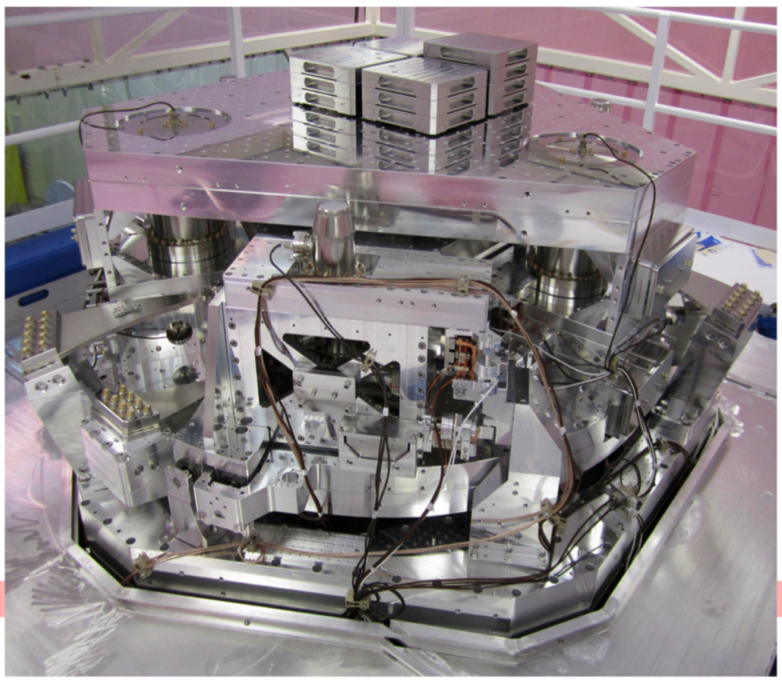
Blocking Earth’s Vibrations

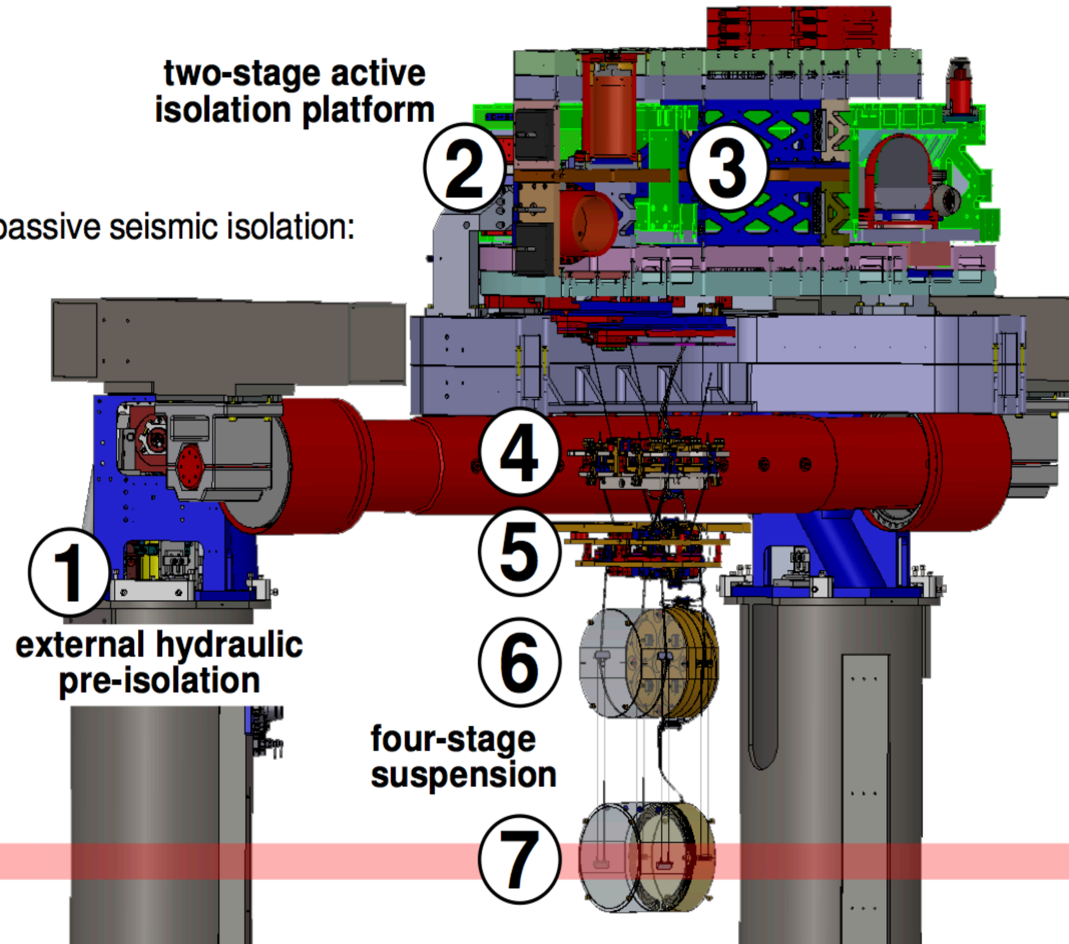
seismic noise

Ground motion at 10 Hz: 1e-9 m/Hz$^{1/2}$

>10 orders of magnitude supression required

Test masses suspended from 7 stages of active and passive seismic isolation:





LIGO Hanford Vertex Station


Maggie (MIT grad)
New Squeezed Light Source!