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Massachusetts Institute of Technology
and California Institute of Technology

LIGO Vacuum Technology and the Discovery of Gravitational Waves

AVS 64th International Symposium and Exhibition
Tampa, Florida
31 October, 2017
LIGO-G1701259

Image Credit: Aurore Simmonet/SSU

Today's Topics

- About Gravitational Waves
- Precision Measurement
- Focus on Vacuum
- Discoveries
- Parting Thoughts

General Relativity and Gravitational Waves

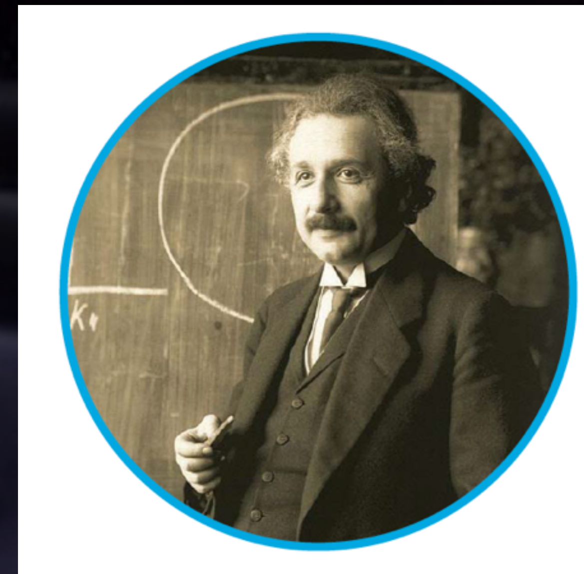
- 2016 was the centenary of Einstein's General Relativity
- A *geometric* theory:

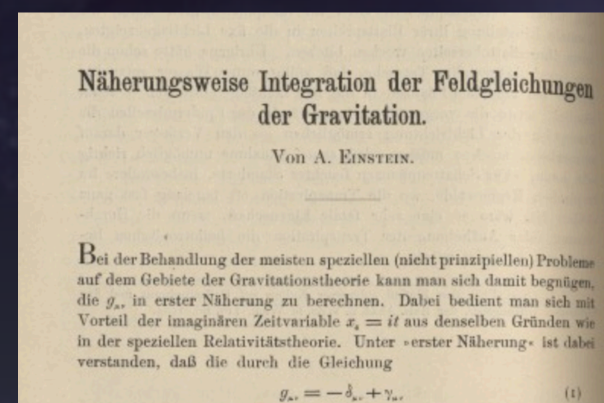
  Gravitation arises from *curvature of space-time*

  Curvature arises from matter, energy… and *curvature!*
- Bizarre, but so far *completely 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.

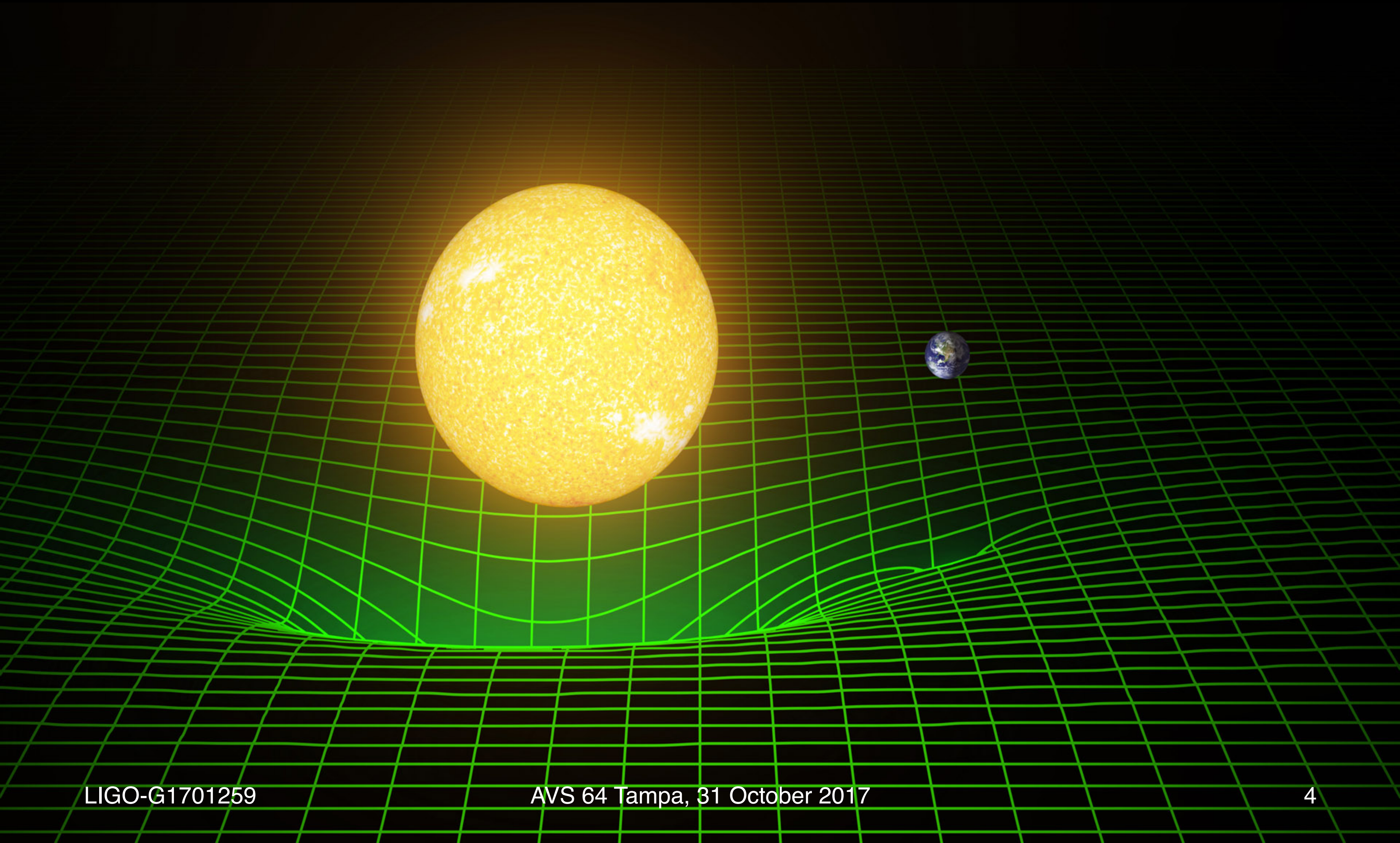
Von A. Einstein.

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

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

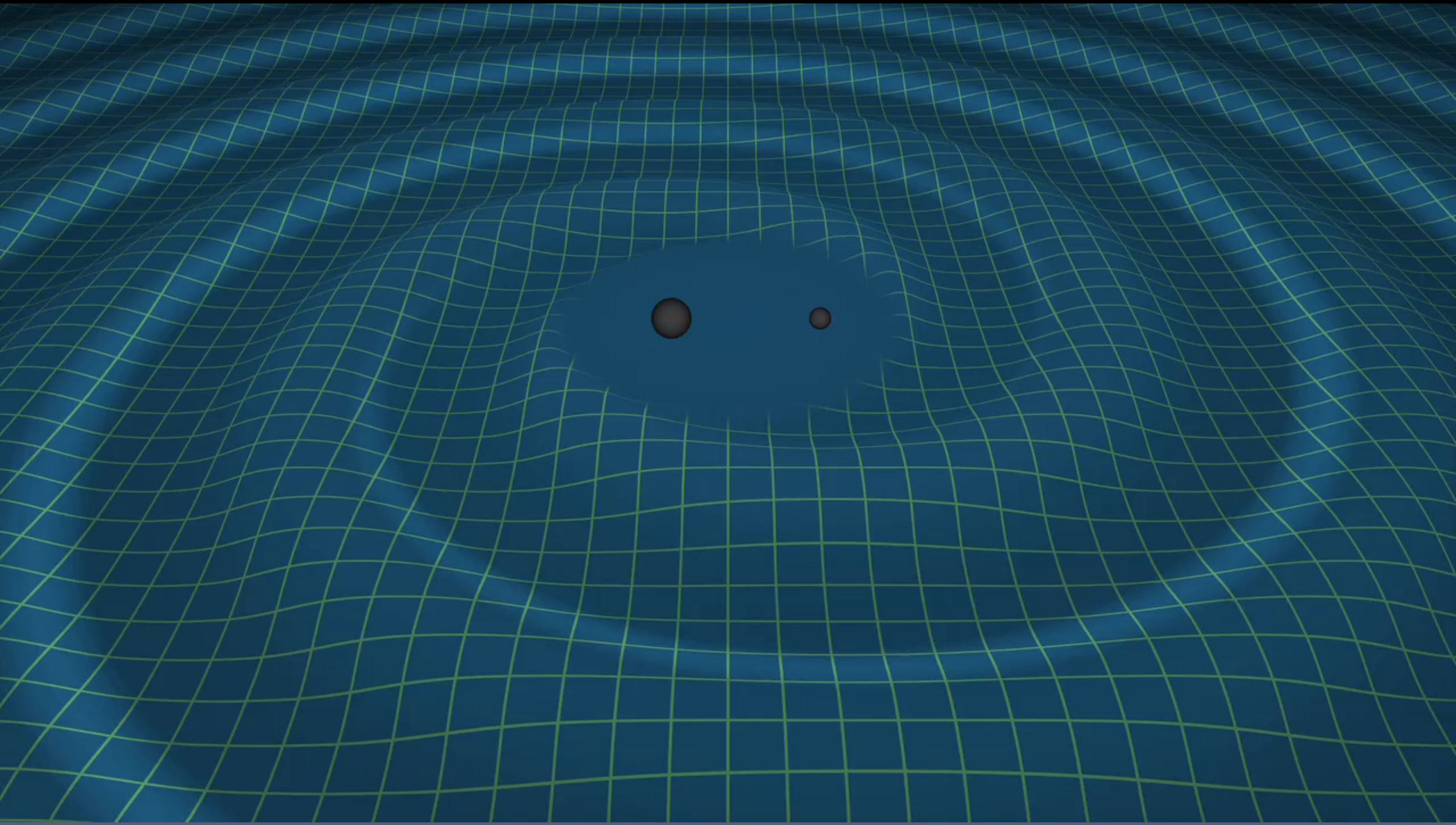
A. Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 1916

Gravity & Curved Space-time



Gravitational Waves

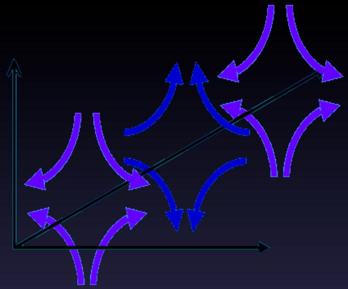
Credit: LIGO/Tim Pyle



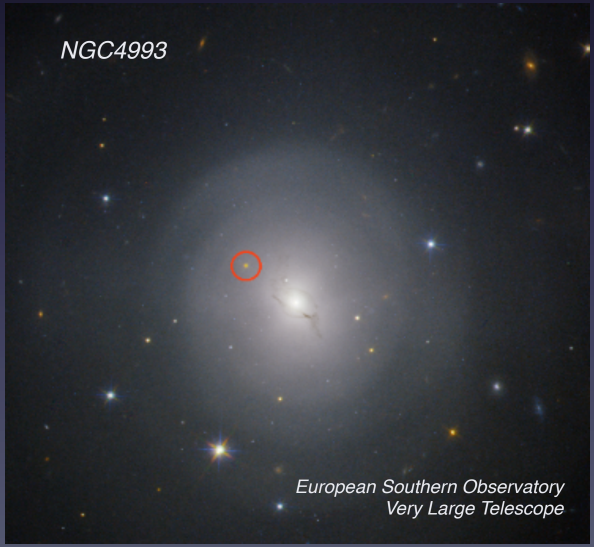
Detecting the effects

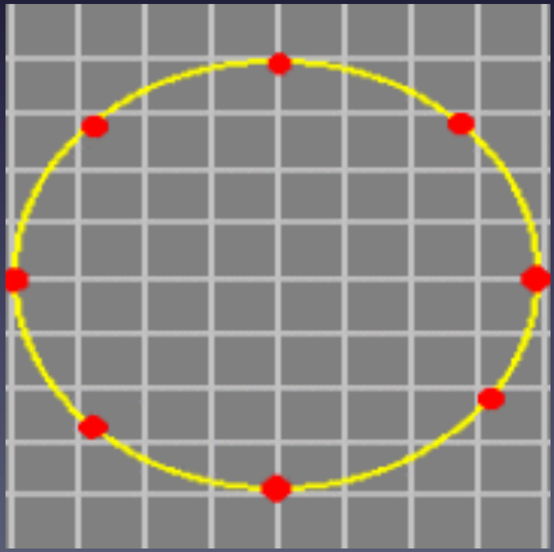
GW's produce time-varying *transverse strain* in space
→ Monitor separations of *free test particles*

(Earth)



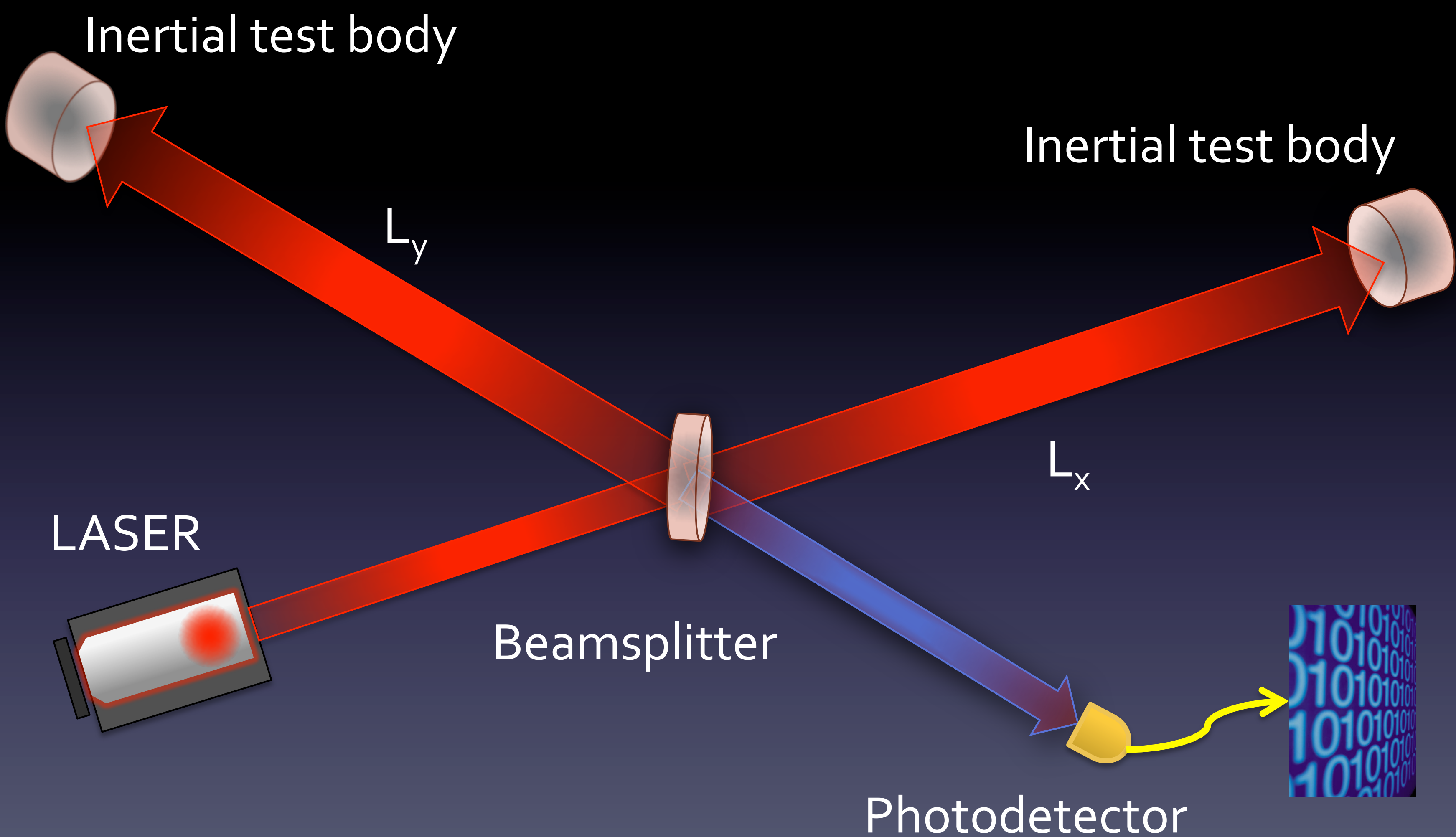
In a galaxy far far away…





Graphic: M. Evans, MIT

Michelson interferometer



A "small" problem...

A wave's strength is measured by the *strain* induced in the detector,

$$h = \Delta L / L$$

We can calculate expected strain at Earth;

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

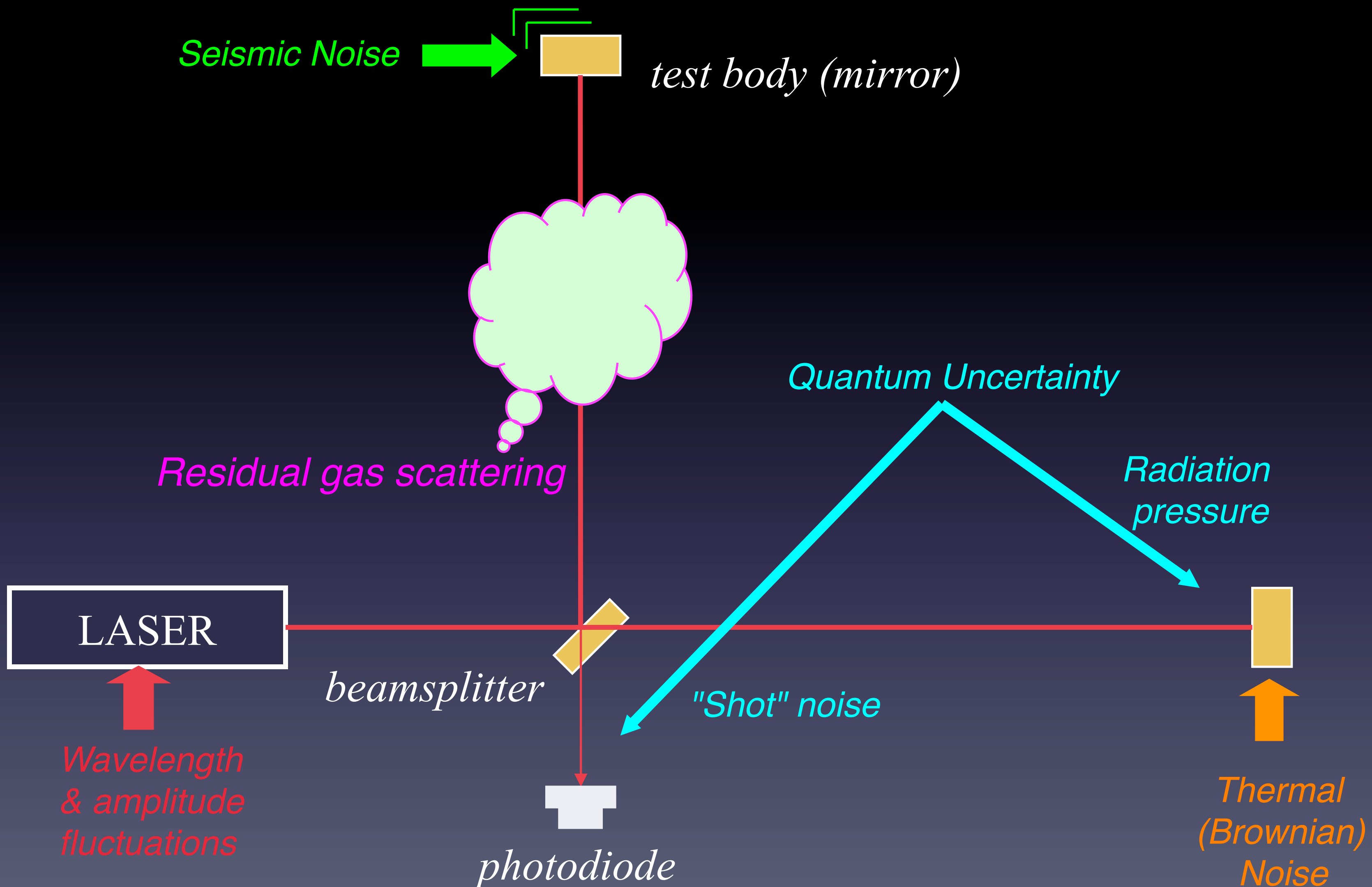
If we make our interferometer arms 4,000 meters long,

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

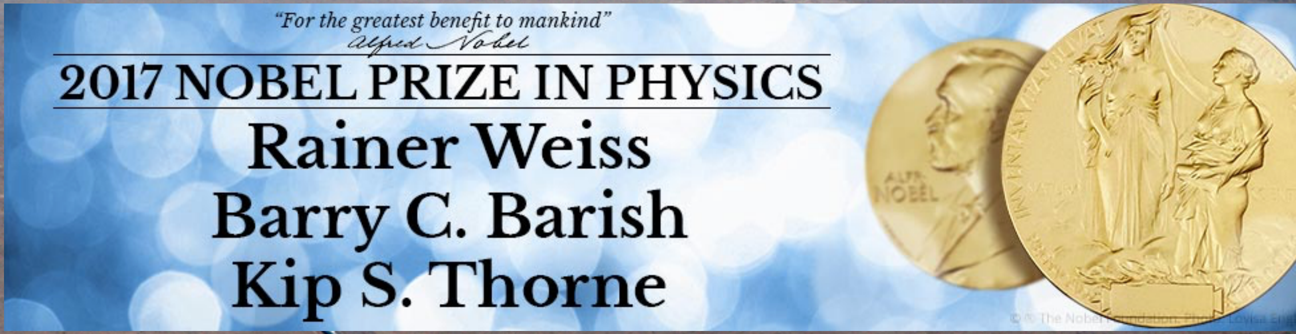
!!

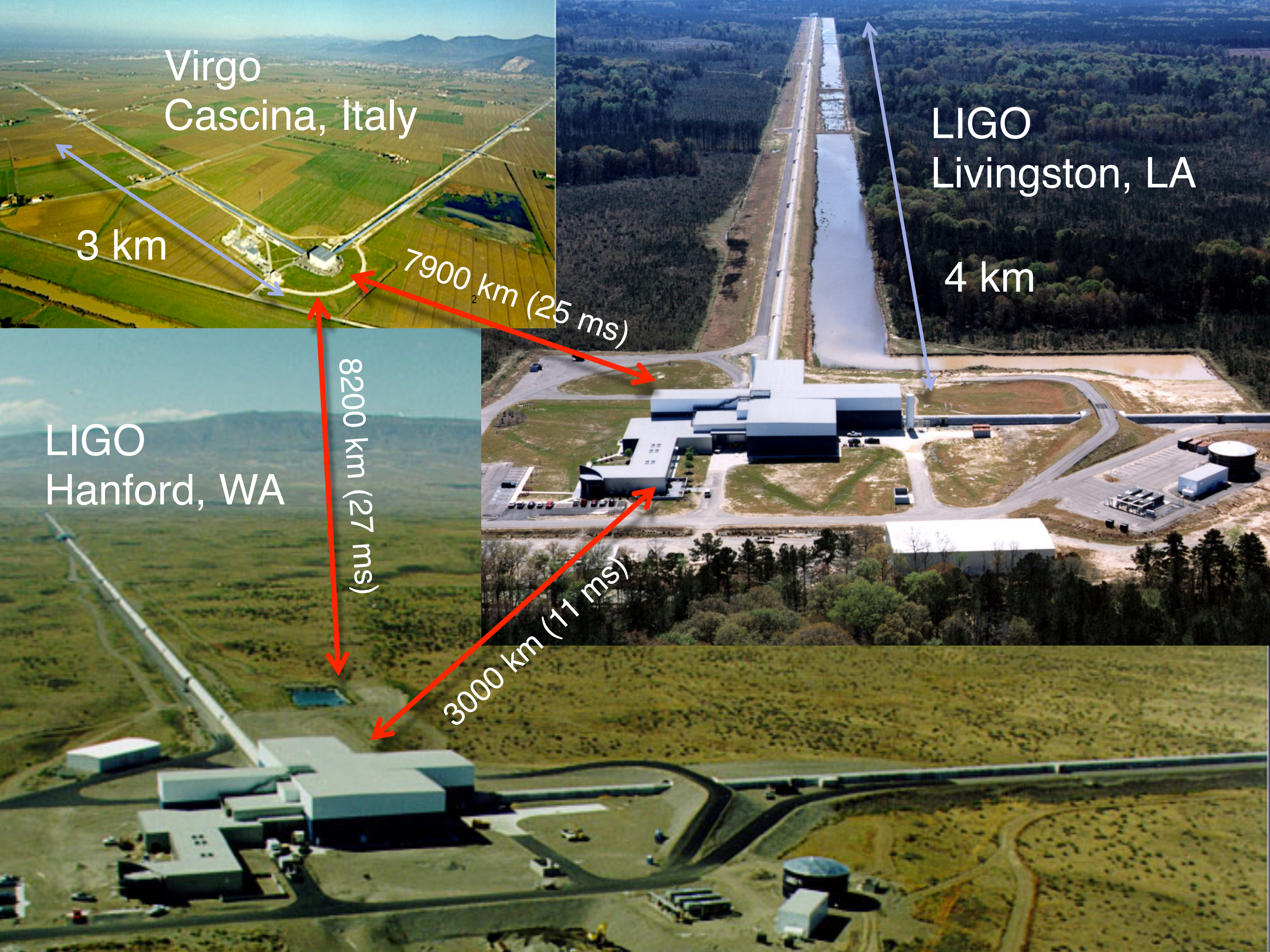
A ten-thousandth the size of an atomic nucleus

The Enemies: NOISE

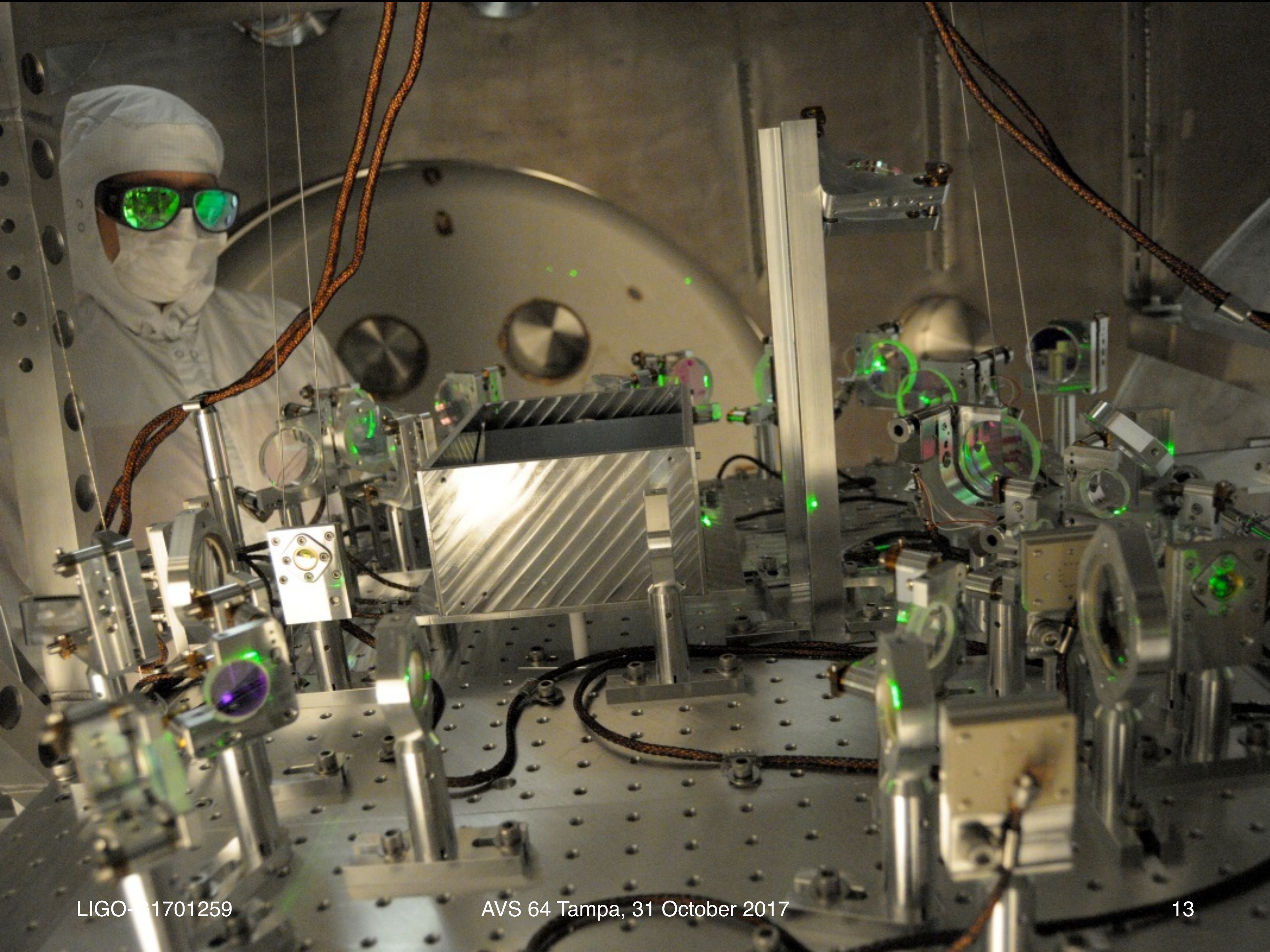


the LASER Interferometer Gravitational-wave Observatory




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)

LIGO Hanford Vertex Station

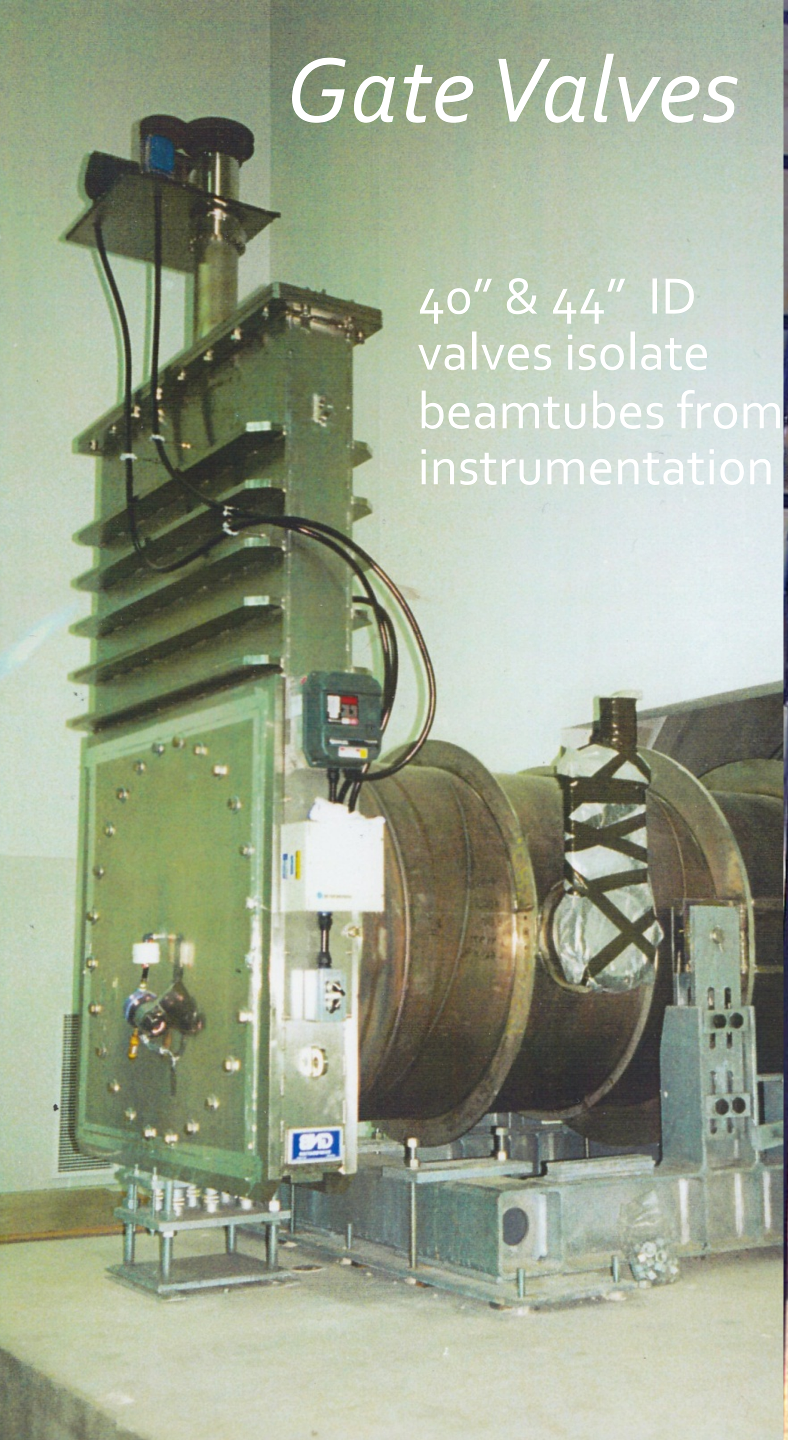


LIGO Beamtube

- 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

Gate Valves

40" & 44" ID valves isolate beamtubes from instrumentation

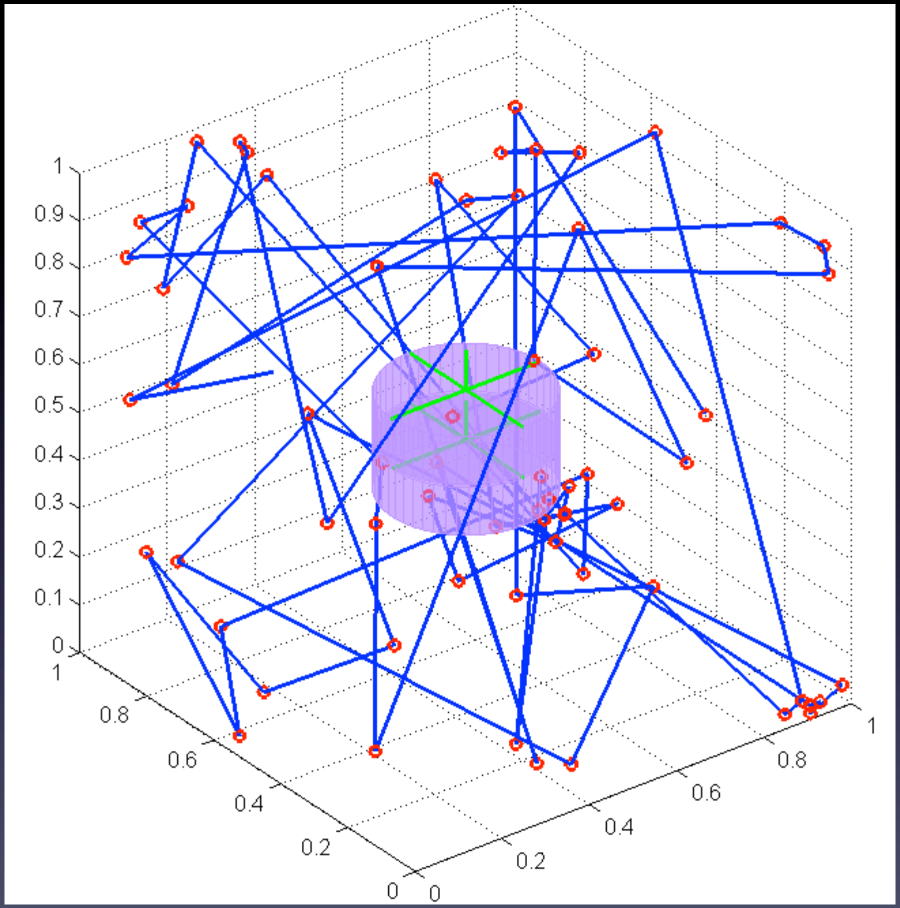


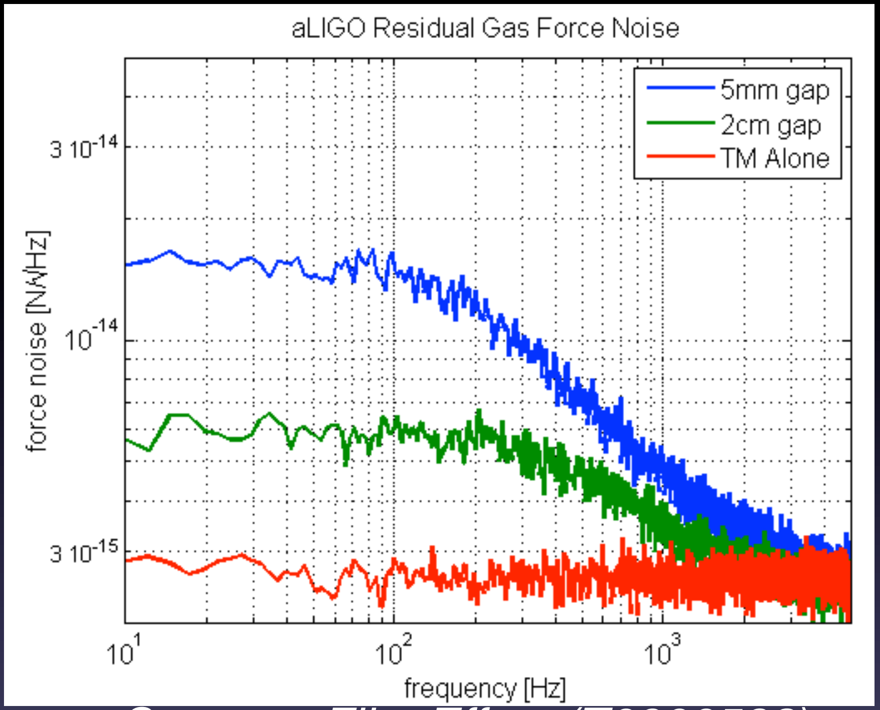
LIGO Vacuum Requirements

Vacuum Requirements

- Brownian noise due to gas impact
    - Exacerbated by small gaps
        - $P(H_2) < 10^{-8}$ Torr
- Contamination of optics
    - 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 phase noise from residual gas
    - A function of molecular polarizability and thermal speed
    - Primary goals for beam tubes:
        - ➔ $P(H_2) < 10^{-9}$ Torr
        - ➔ $P(H_2O) < 10^{-10}$ Torr

Vessel Vacuum: Gas damping (Brownian motion)





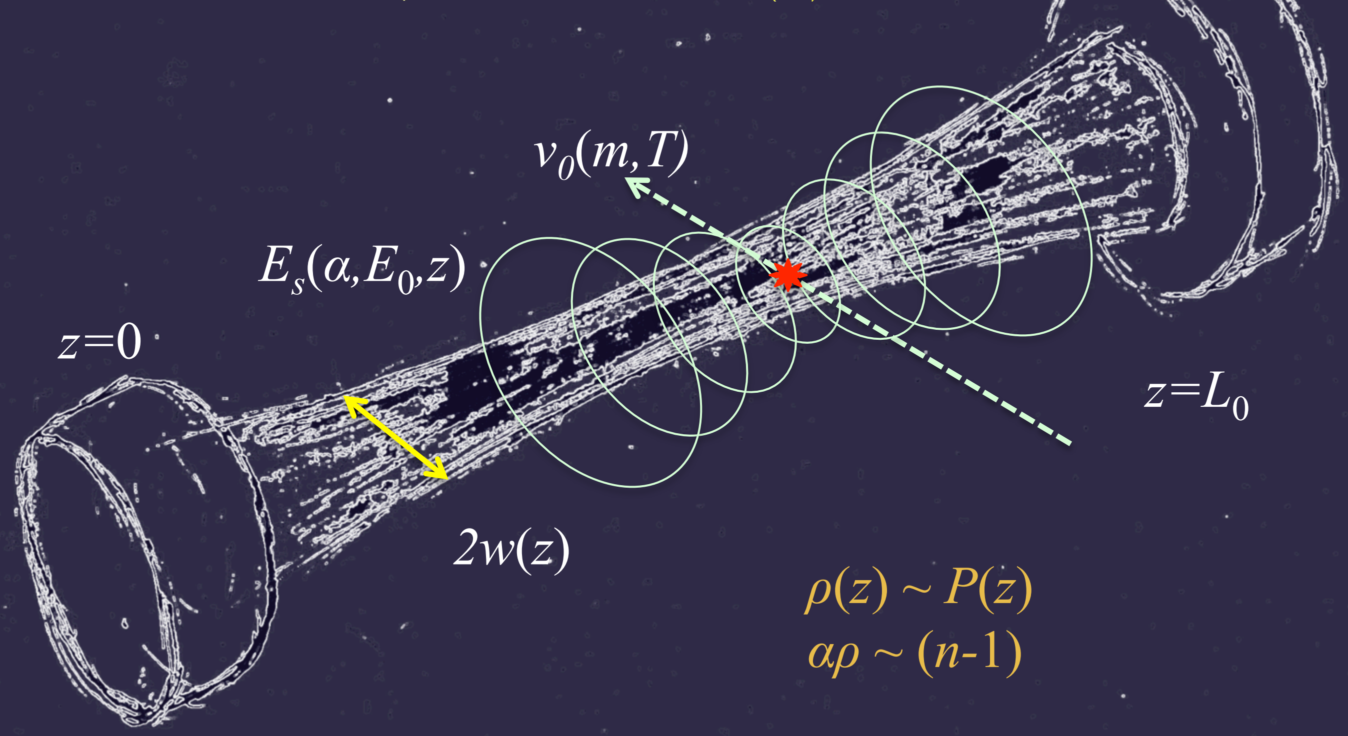
Squeeze Film Effect (T0900582)

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

Cleaning a LIGO Mirror In-Chamber

Residual Gas Scattering

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



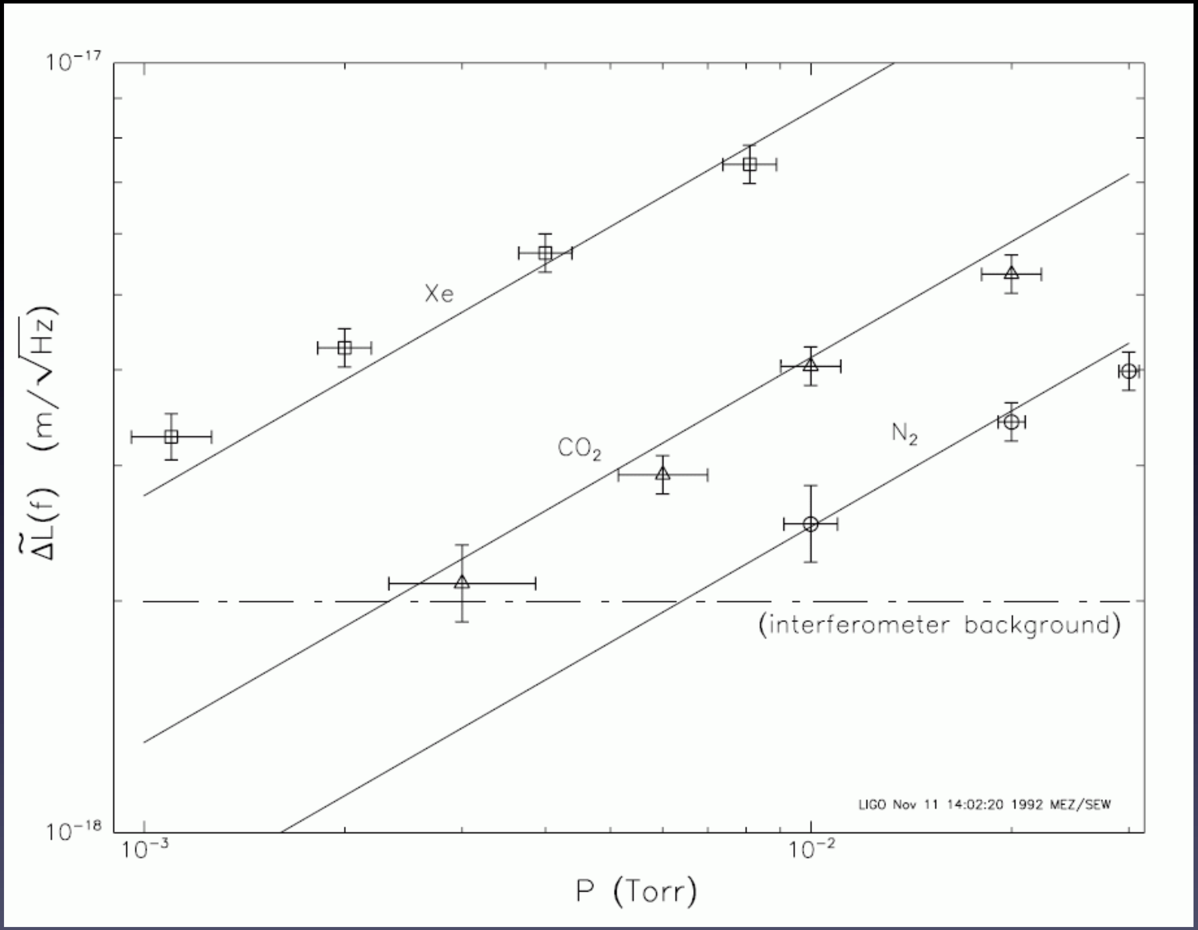
Residual Gas Scattering

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

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

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

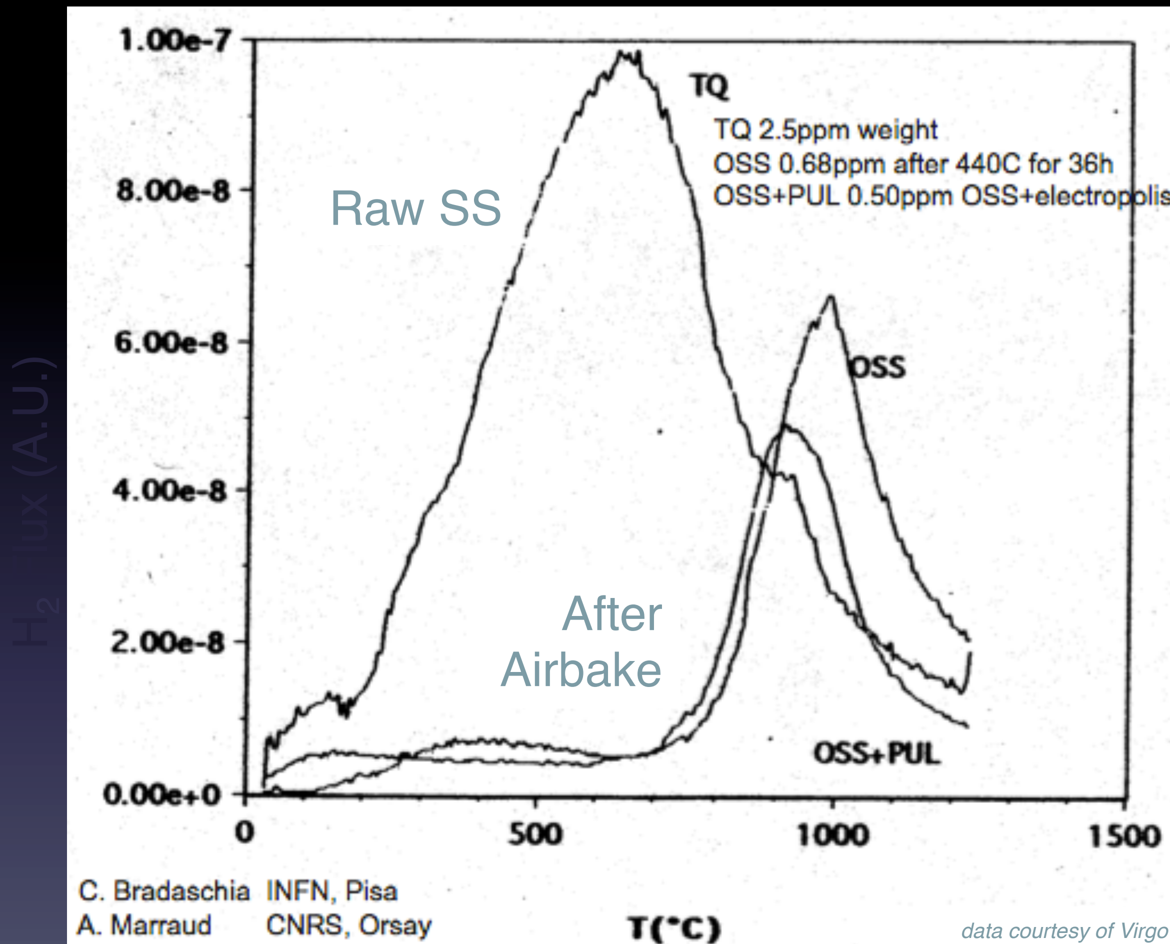
Statistical model verified by interferometer experiment



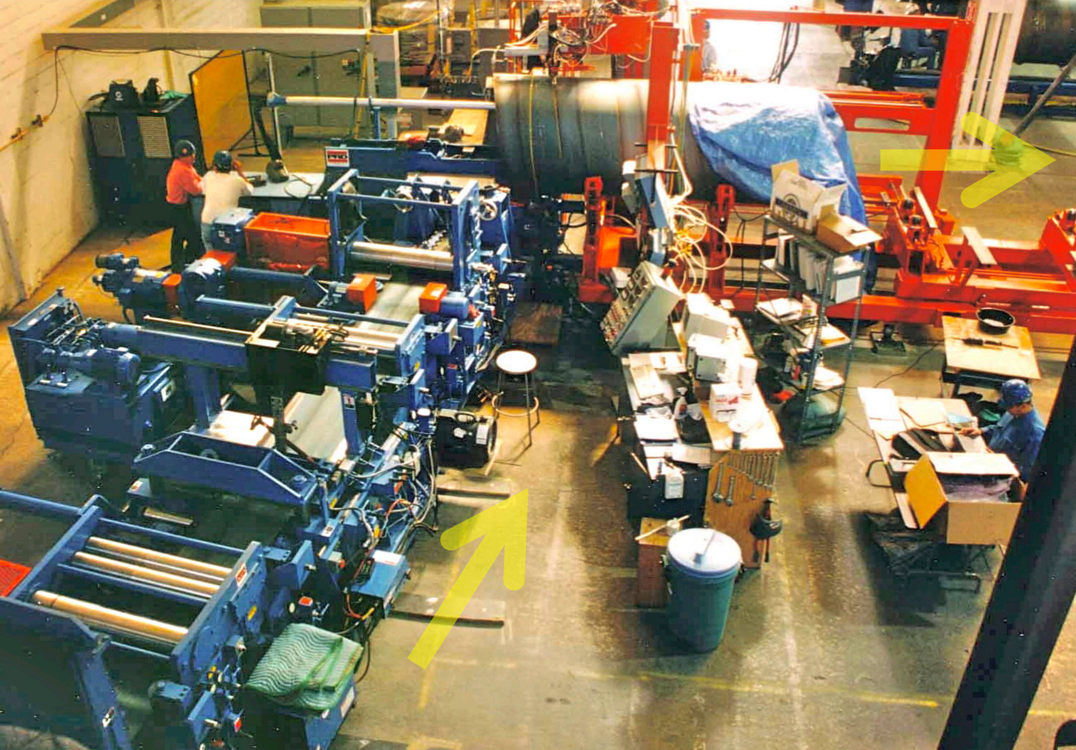
S. Whitcomb and MZ, Proc. 7th Marcel Grossmann Meeting on GR, R. Jantzen and G. Keiser, eds. World Scientific, Singapore (1996).

Depleting Hydrogen from raw SS before tube fabrication: An economical alternative to high T vacuum bakeout

- SS sheet from mill is baked in air 36 hours at 455 °C
- (Hotter treatment deemed inadvisable due to carbide formation)
- Total dissolved hydrogen is reduced ~ 3x
- Remaining H is tightly bound, high activation T
- Care is required in welding to avoid re-introduction of H

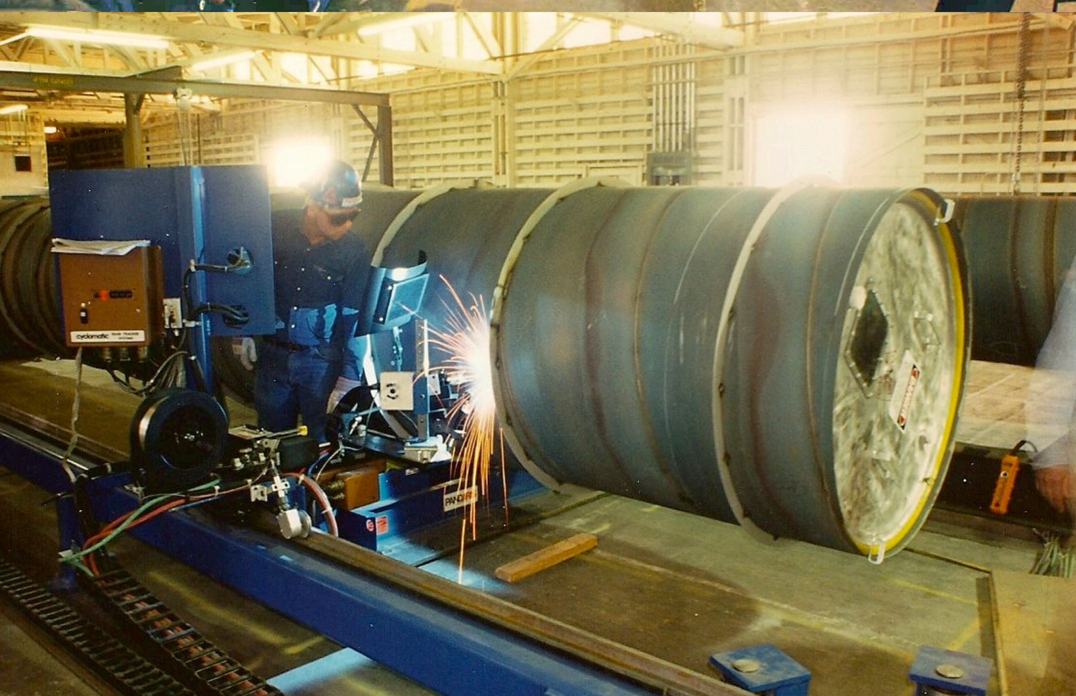


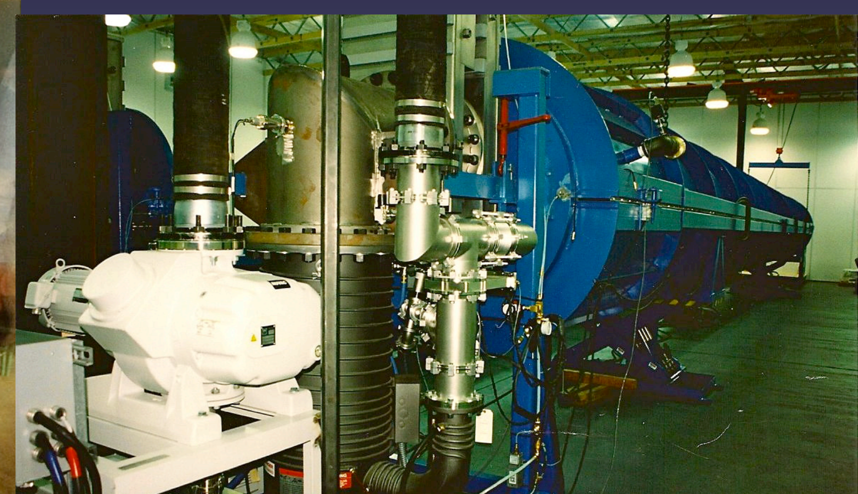
Sample Temperature (°C)



Beam Tubes

- 304L SS
- 3.2 mm thick with external stiffeners
- Raw stock air baked 36h @ 455C
  - Final J_{H_2} < 1e-13 Tl/s/cm^2
- coil spiral-welded into 1.2m tube 16m long
- method adapted from sewer pipe industry
- 16m sections cleaned, leak checked
- FTIR analysis to confirm HC-free
- sections field butt-welded together in travelling clean room
- Over 50 linear km of weld—

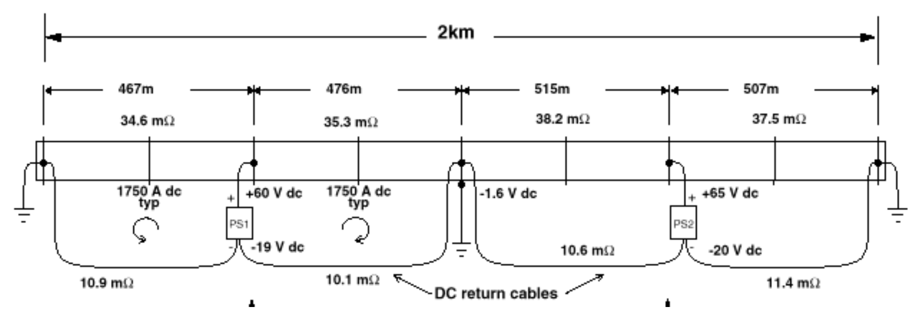


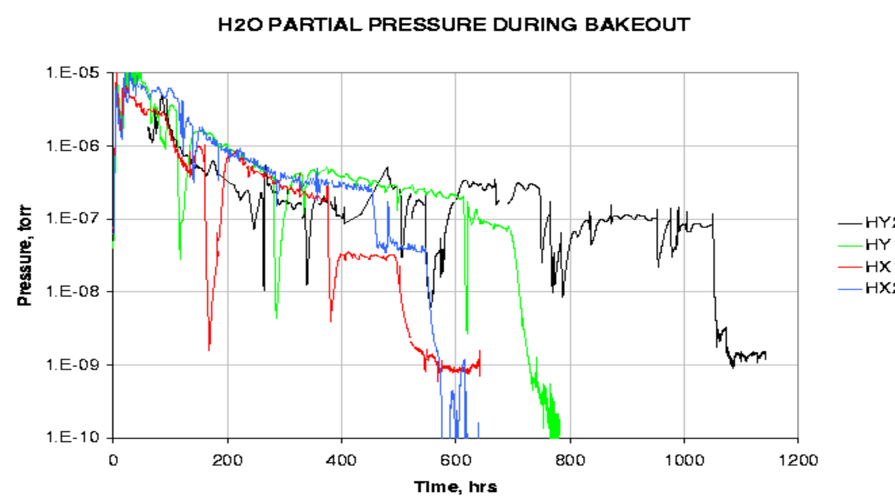


Beamtube Field Assembly

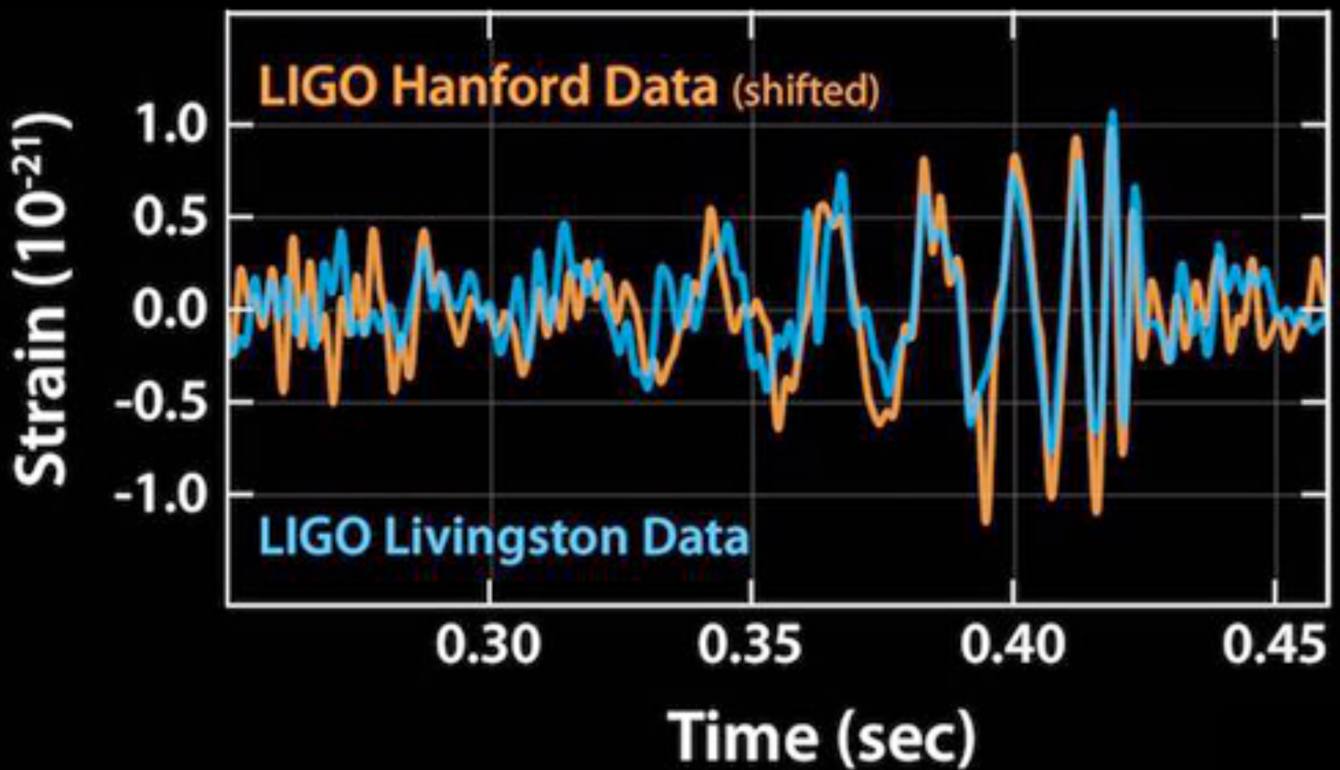
I^2R Bakeout to Desorb Water

- I_{DC} = 2,000 A
- 3 weeks @ 160ºC
- Final $J_{H_2O} < 2e\text{-}17$ Tl/s/cm²



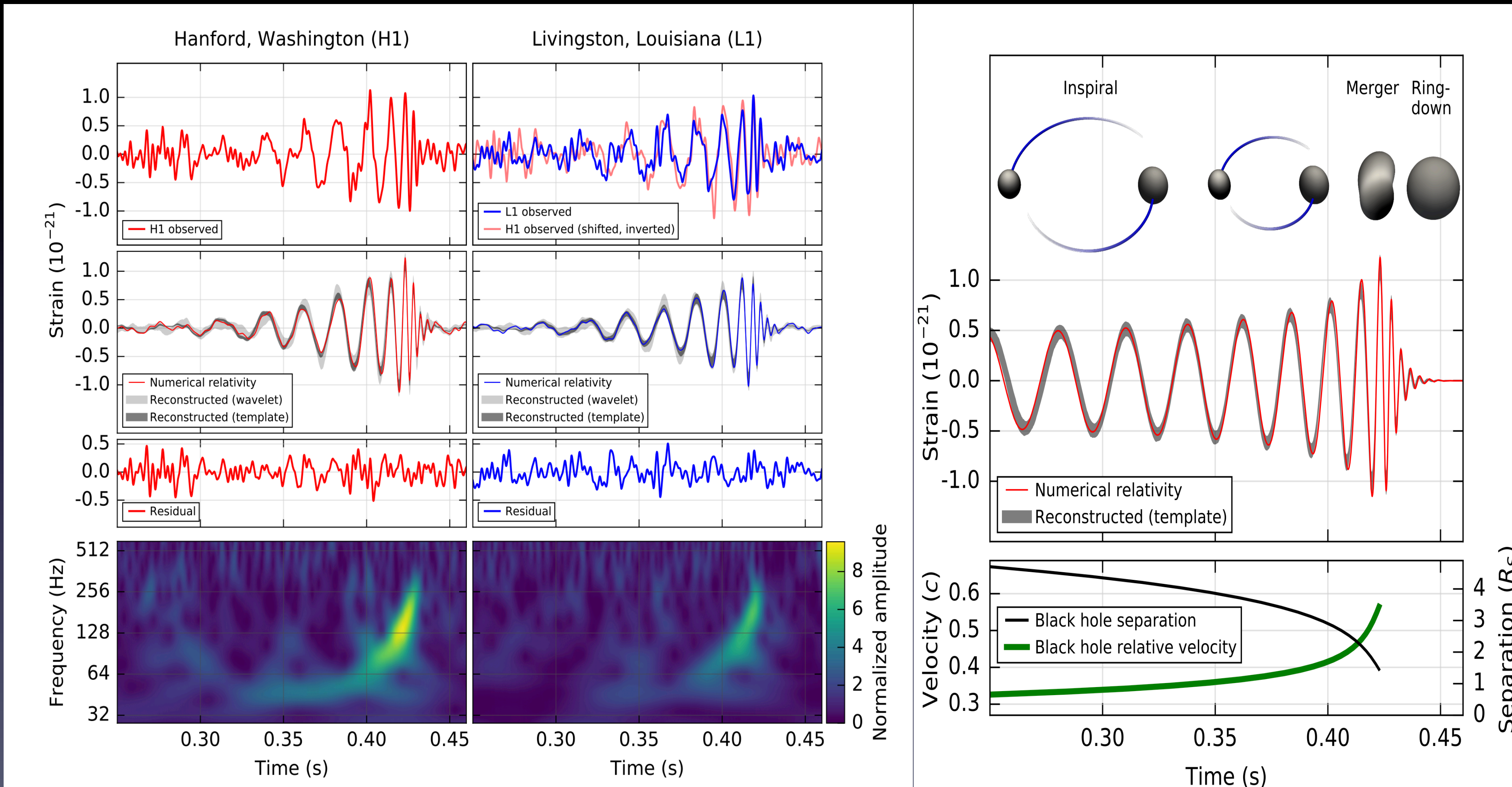


14 September, 2015



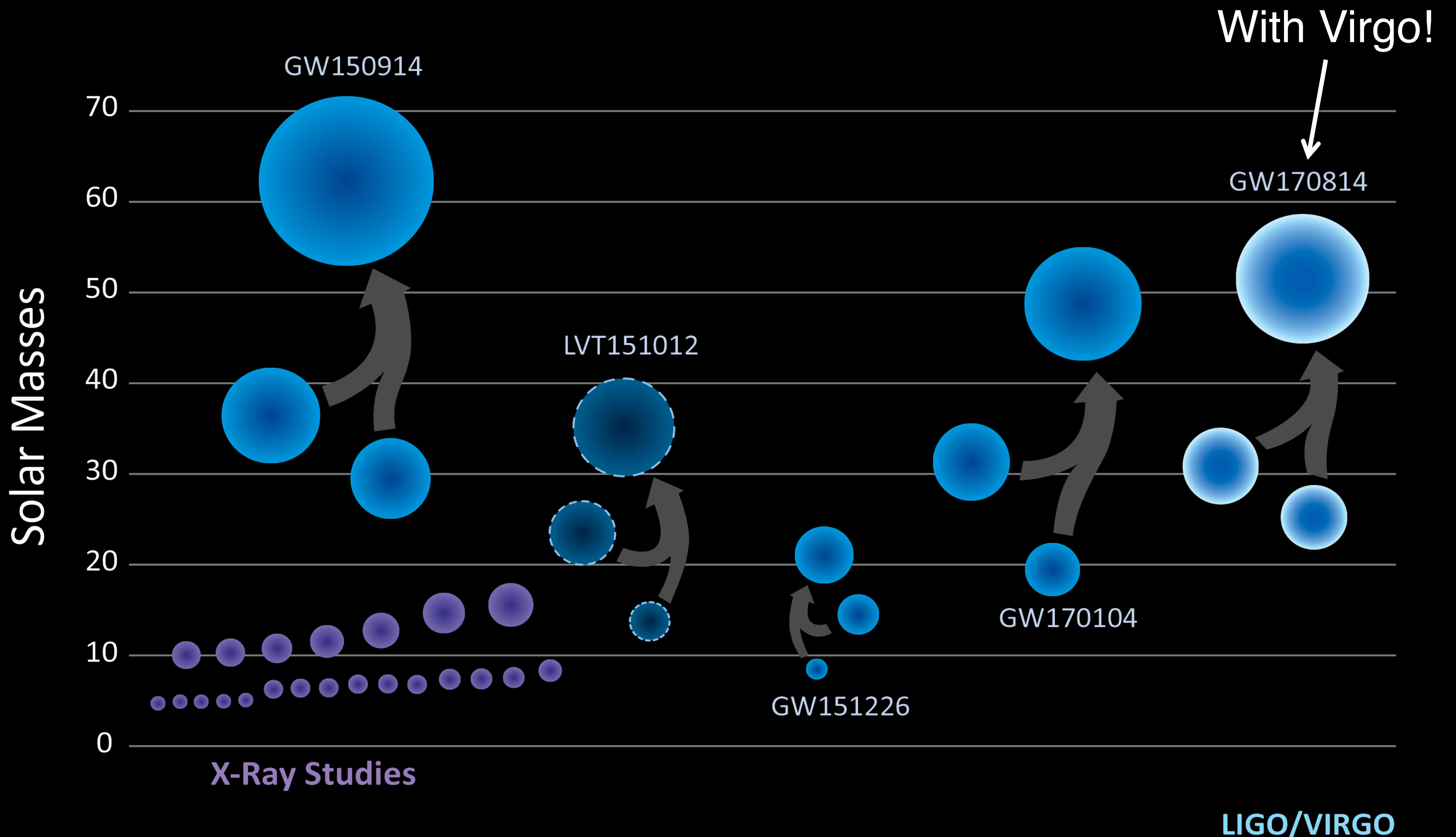
GW150914

29$M_\odot$ and 36$M_\odot$ black holes 1.3 billion light years away inspiral and merge, emitting 3$M_\odot$ of gravitational wave energy and briefly "outshining" the entire universe



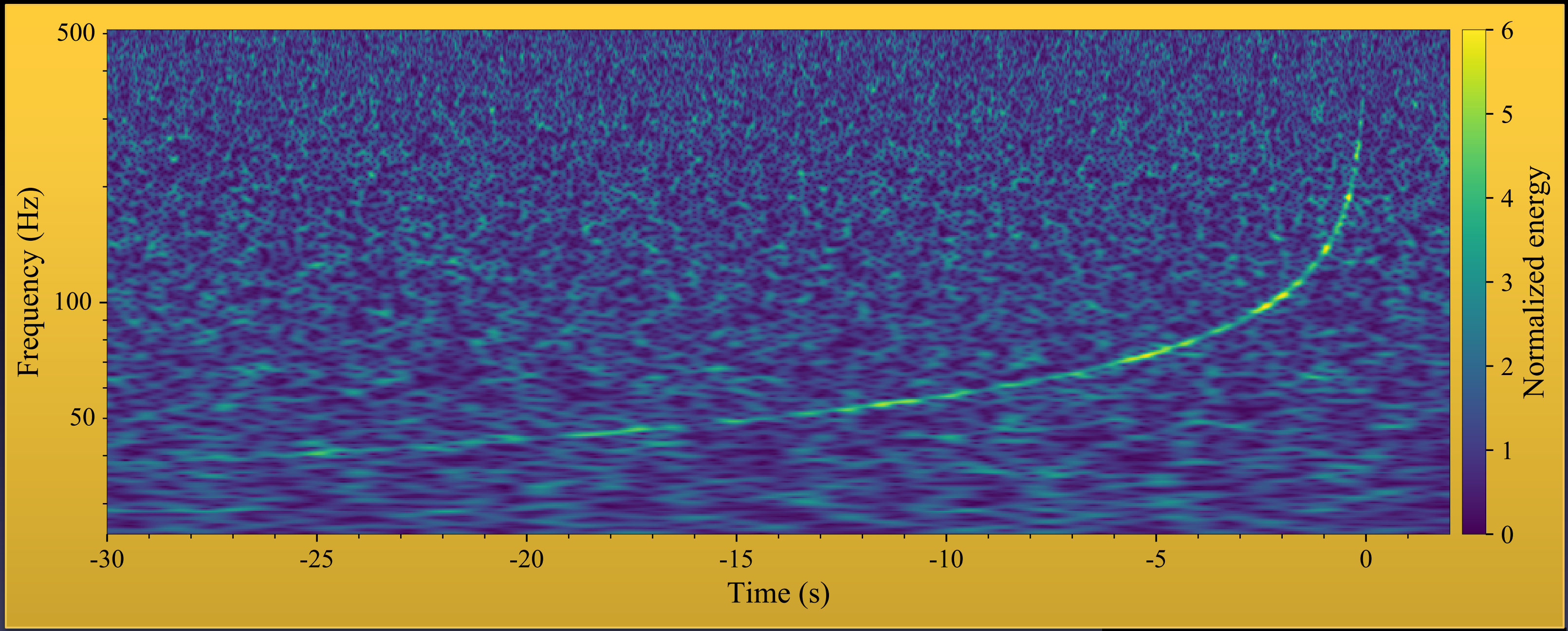
Abbott et al Phys. Rev. Lett. 116 (2016) 061102

Black Holes of Known Mass



LIGO / L. Singer

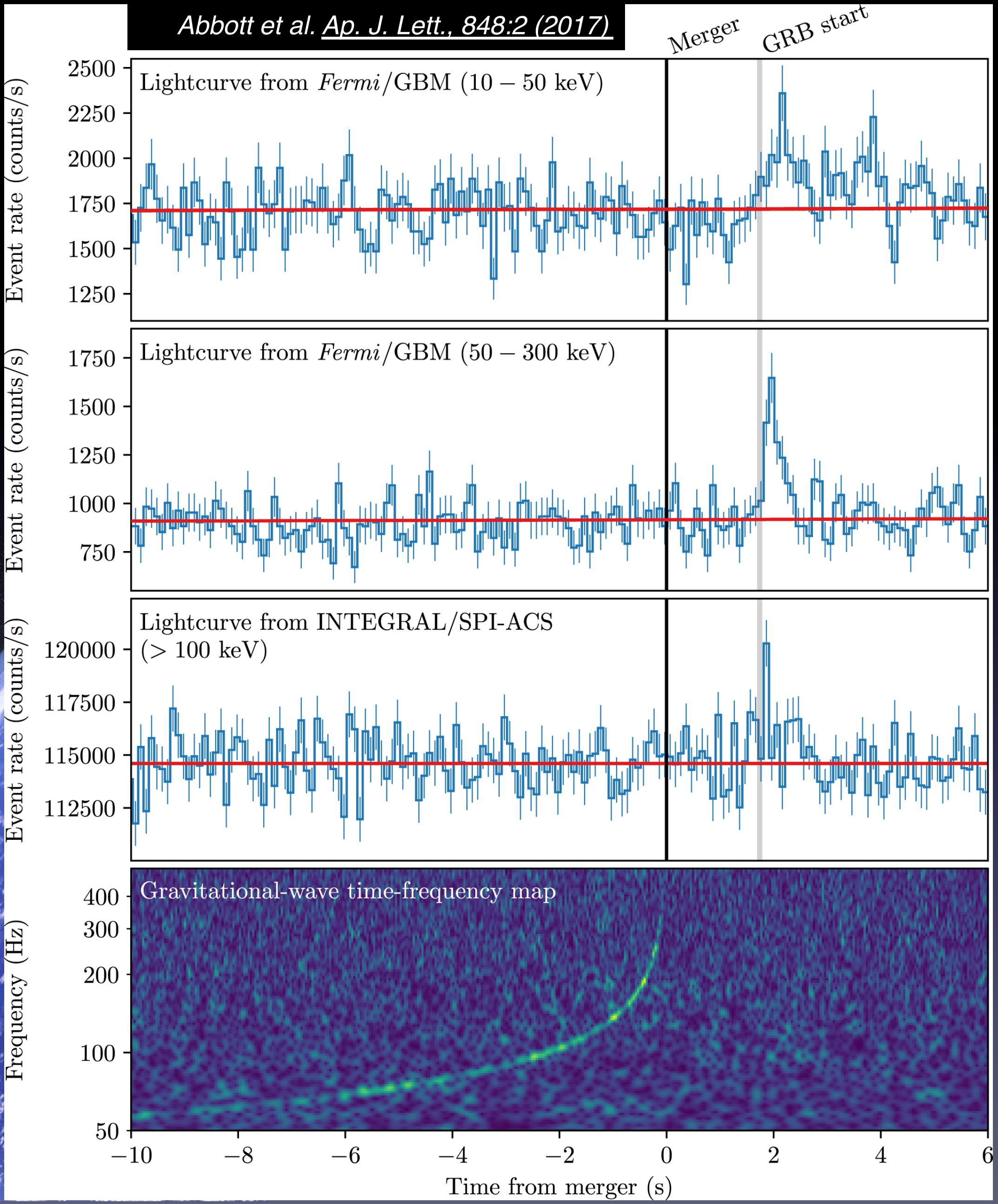
August 17th 2017



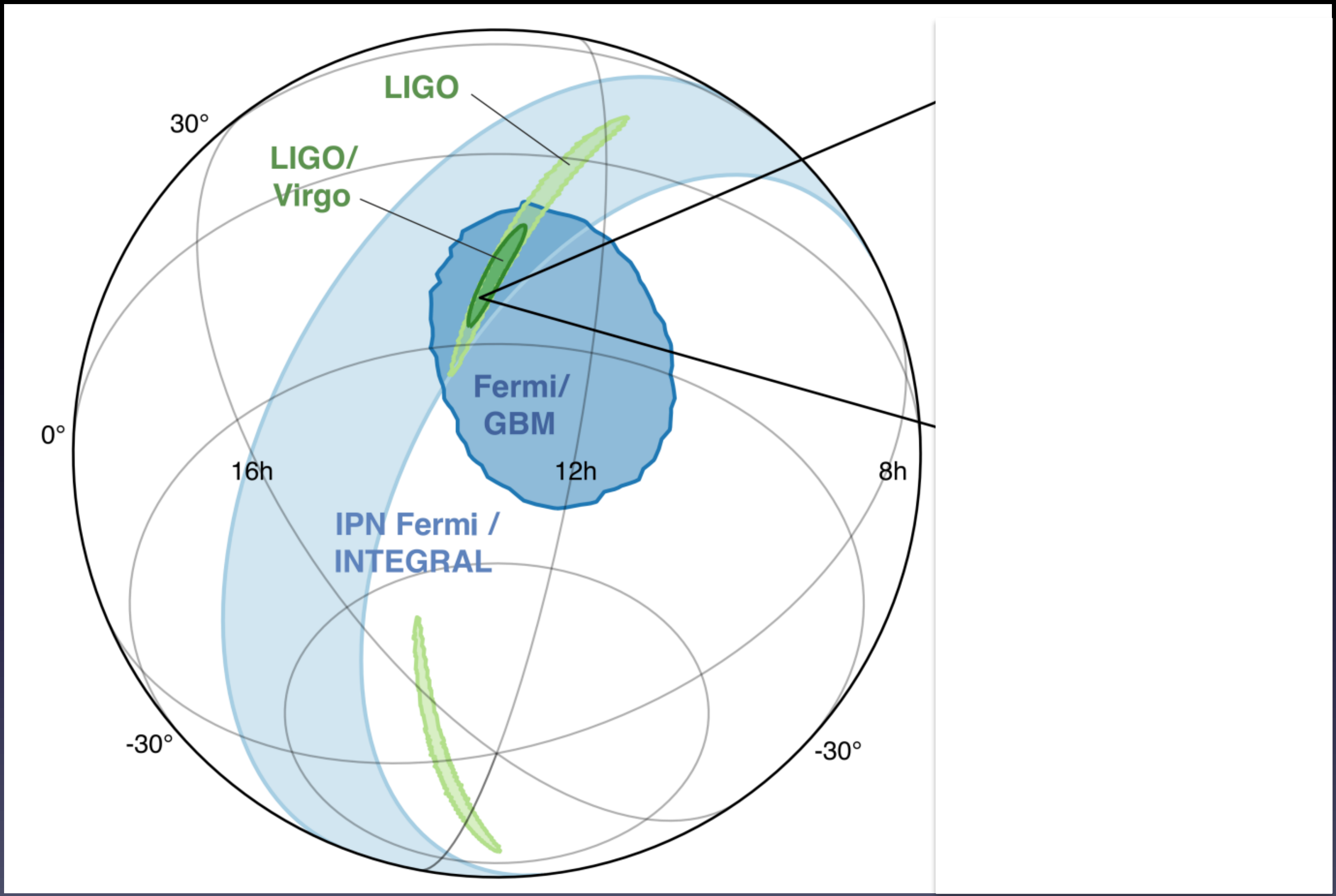
Abbott et al., Phys. Rev. Lett. 161101 (2017)

August 17th 2017

Fermi Gamma Ray Observatory



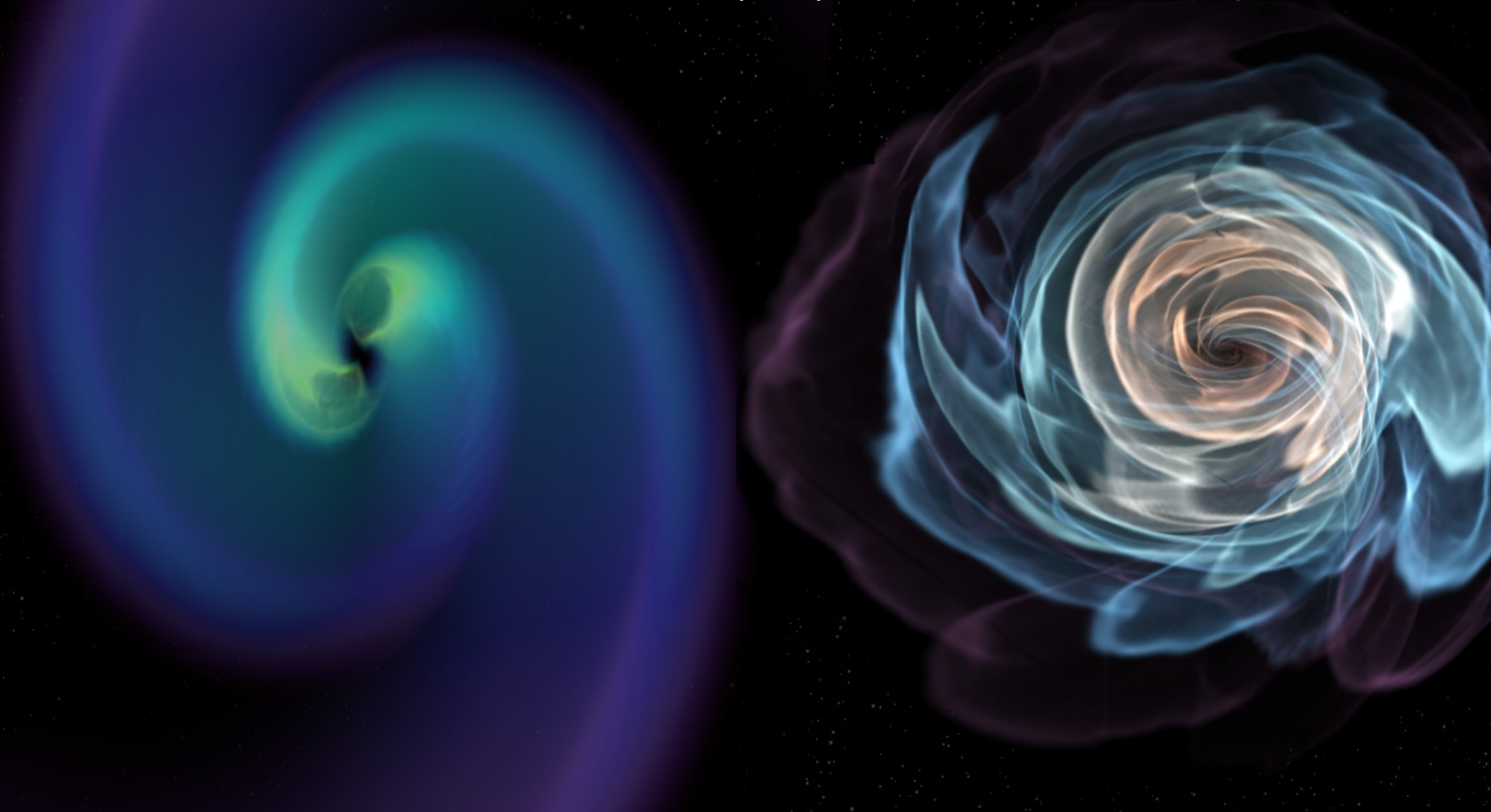
August 17th 2017



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

First Cosmic Event Observed in Gravitational Waves and Light

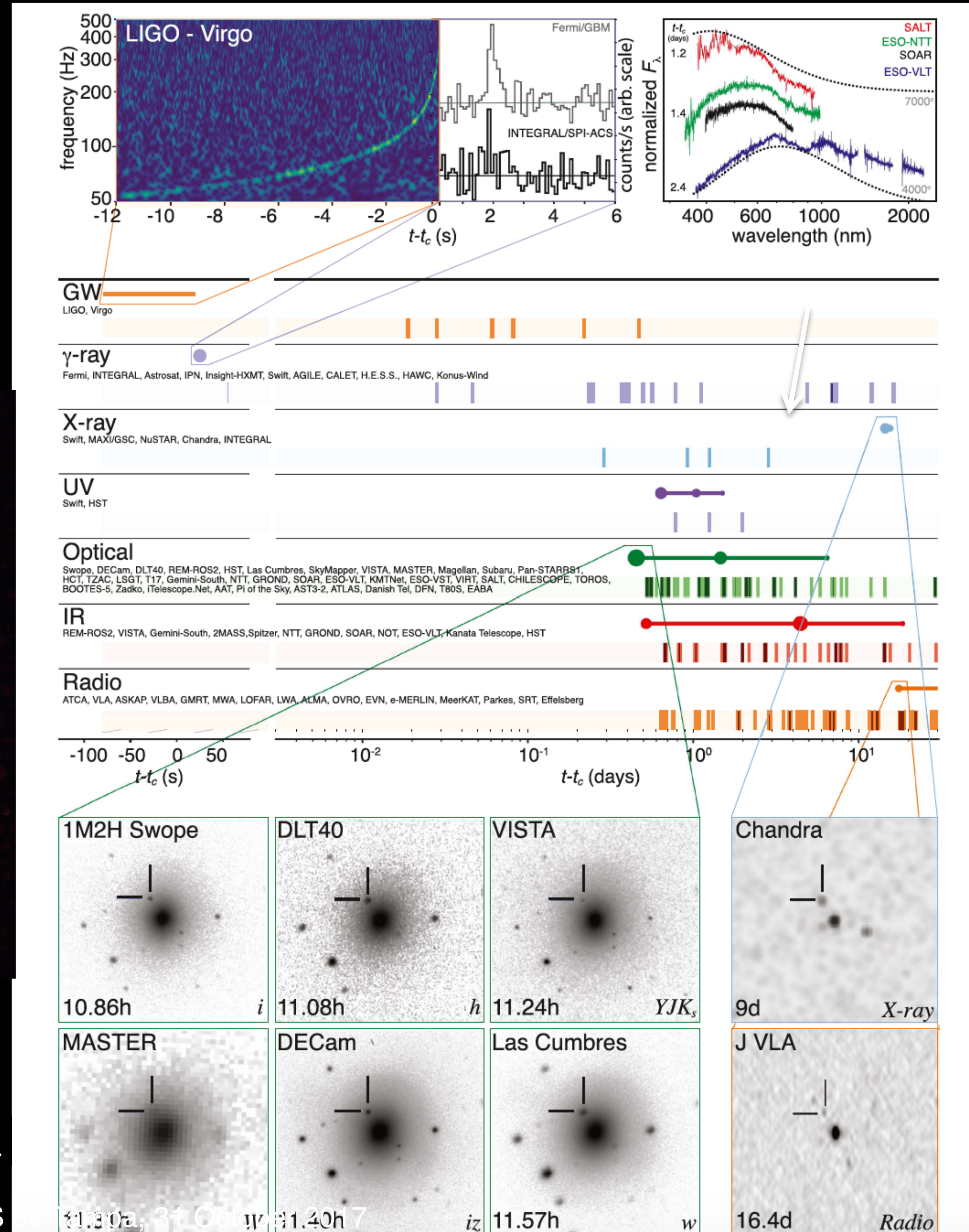
GW170817



LIGO

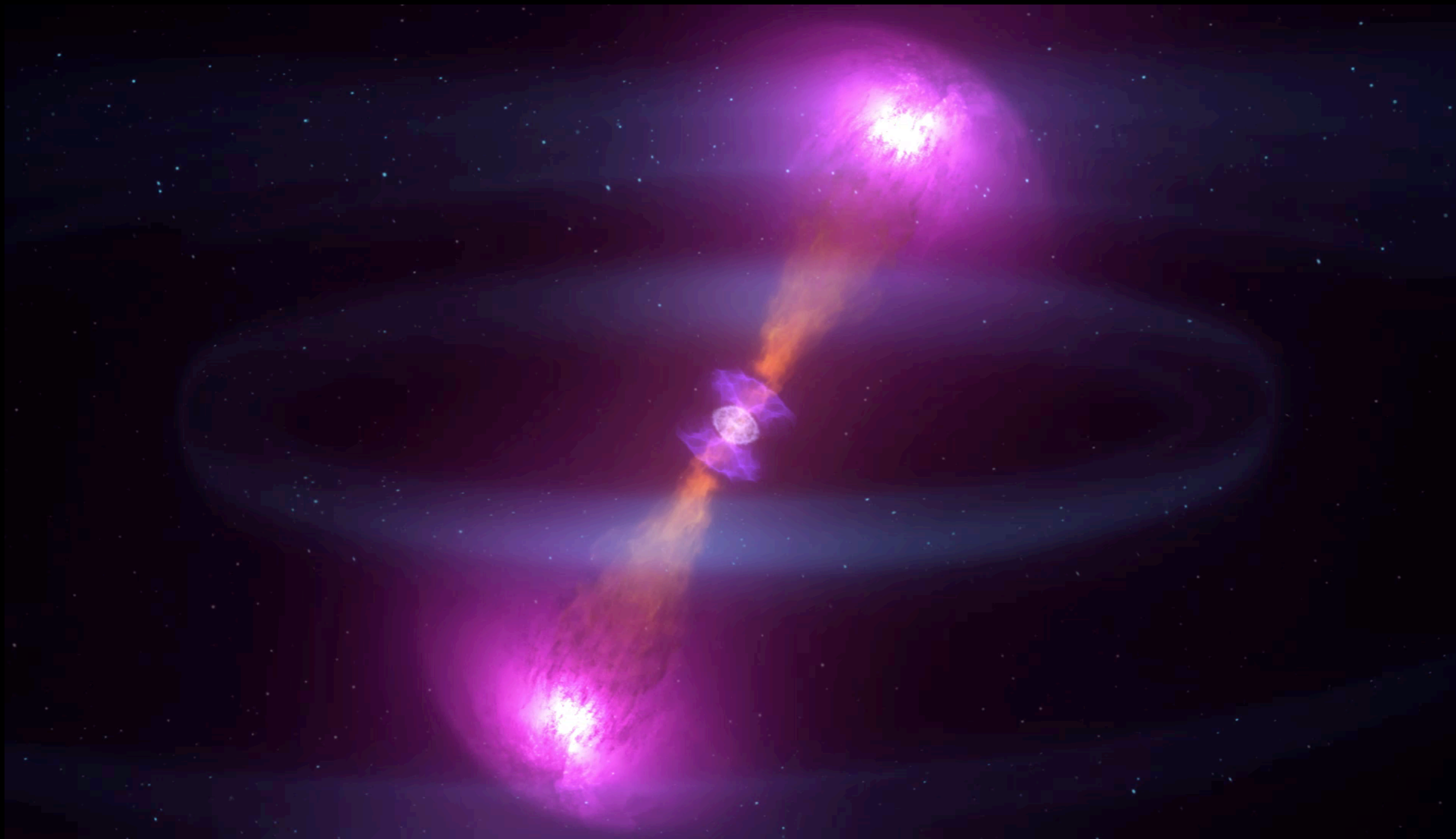
Georgia Tech Center for Relativistic Astrophysics College of Sciences

Observations Across the Electromagnetic Spectrum



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

A ‘Kilonova’- Foundry for the Universe’s Heavy Elements



What next?

Vacuum technology played a central role in opening a revolutionary new window on the Universe

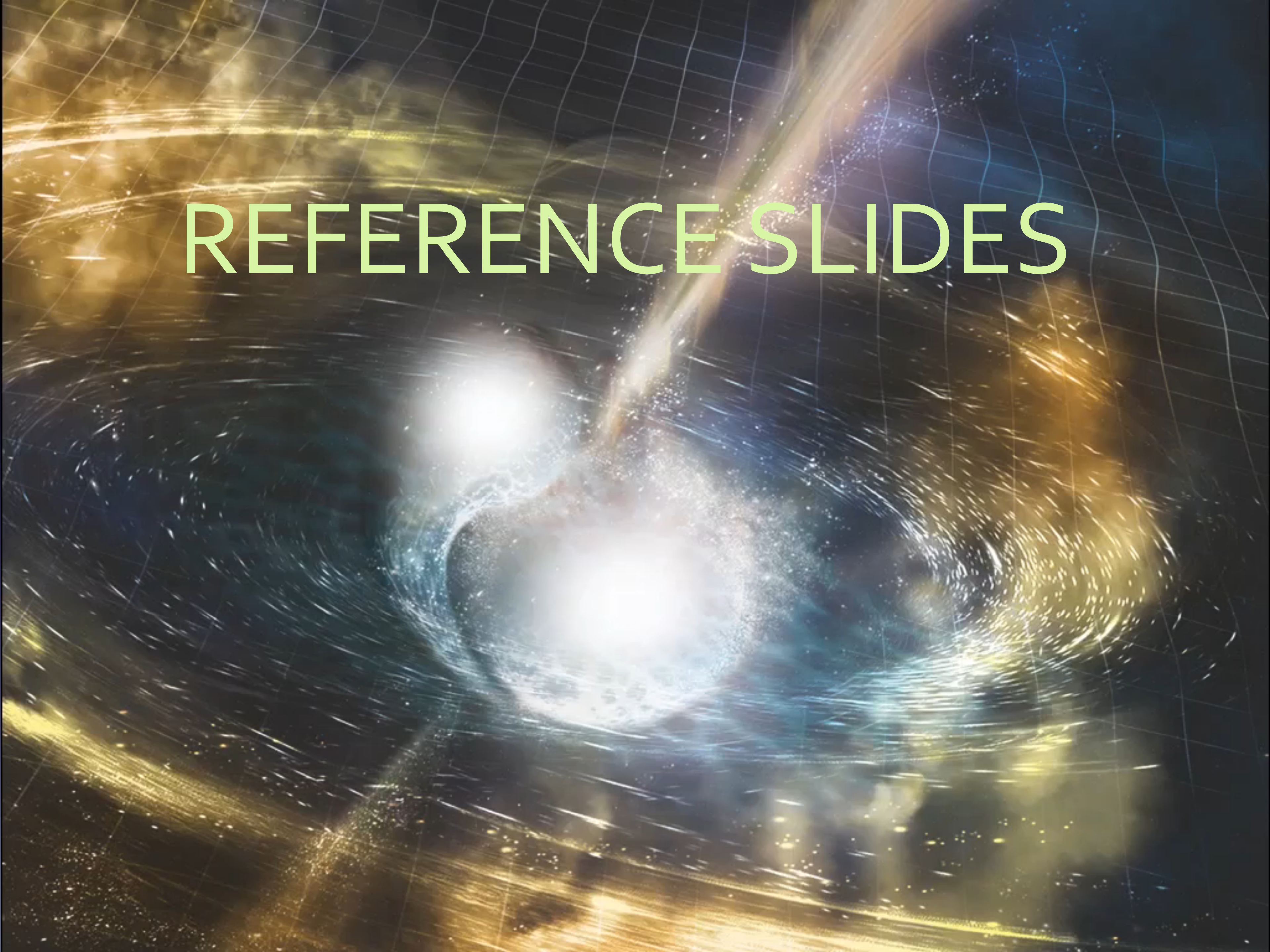
This is a new field- we've just scratched the surface. We have plans for increasing sensitivity to sample 100x greater volume of space.

Beyond that, we are developing concepts for bigger instruments, up to 40km in size, that can map the *entire universe* in gravitational waves

40 km arms?
Now THAT's a LARGE vacuum system !

Thank You

REFERENCE SLIDES



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 Science Foundation
- 1993- Funded for construction
  - Initial phase to use existing (1990's) technology; "Advanced" detector R&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…

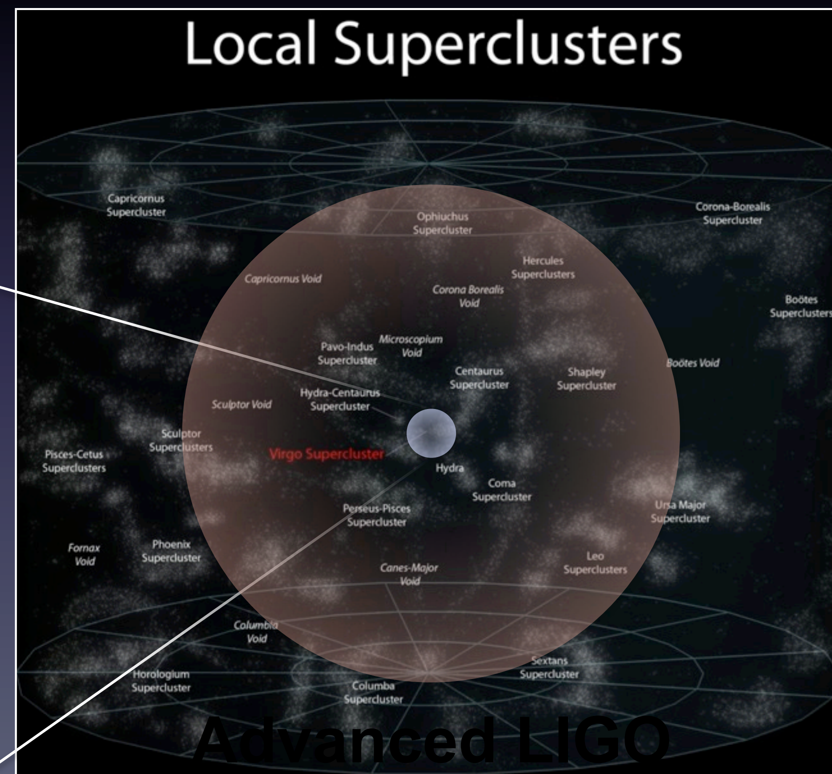
BANG! GW150914!!!

Advanced LIGO

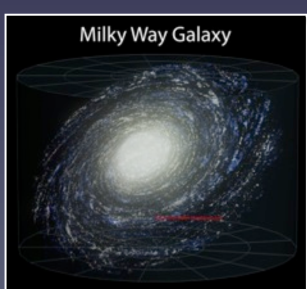
- Complete redesign and rebuild of the LIGO interferometers
- A discovery machine – expect 10's of BNS detections per year at design sensitivity (BBH? Supernovae? Other?)
- An astrophysical observatory – high SNR gravitational waveforms encode information about the dynamics of cataclysmic events

- **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

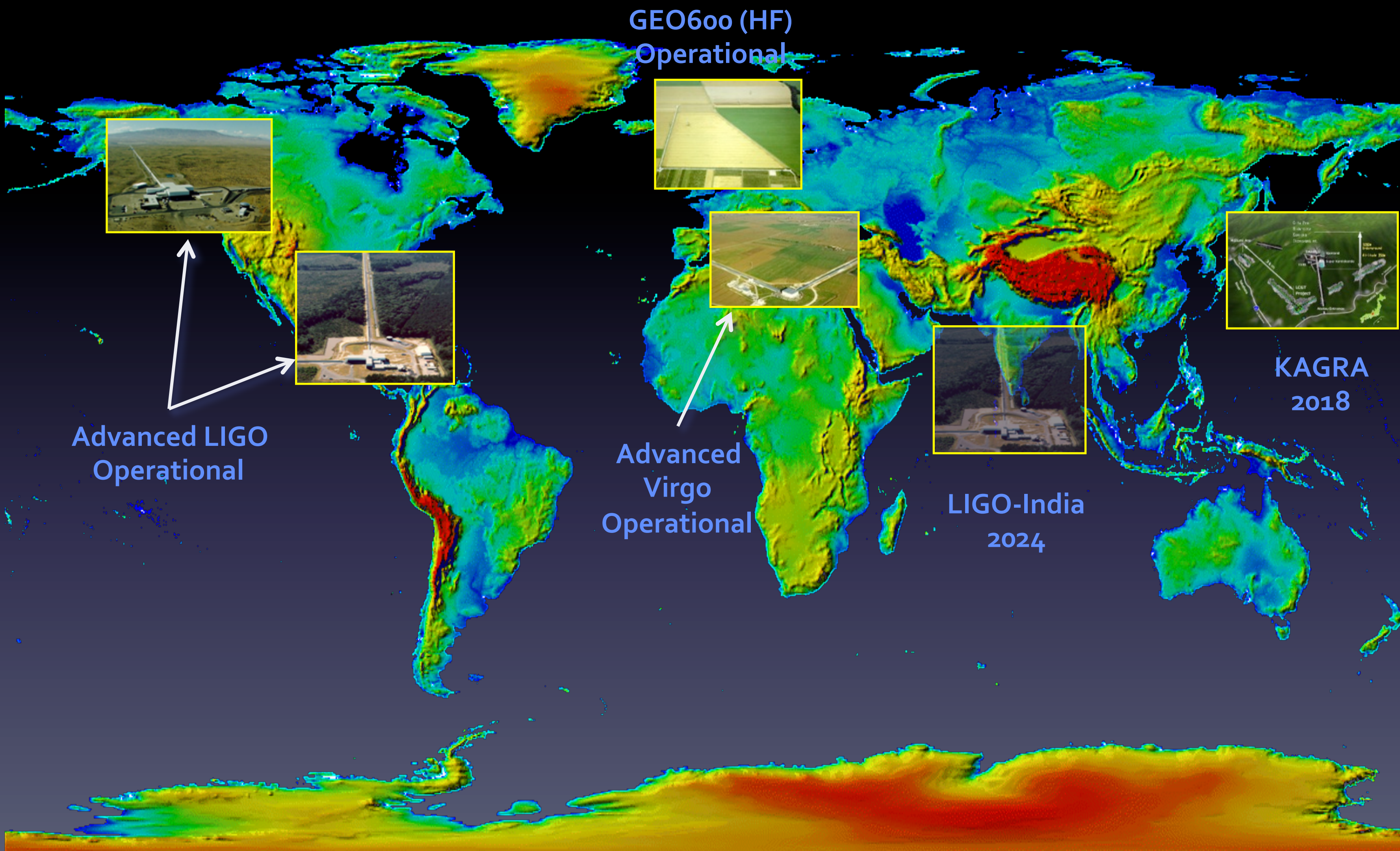


The LIGO Scientific Collaboration

LIGO
LSC

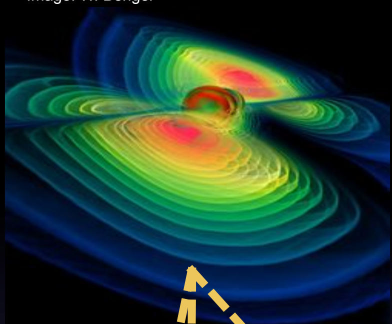
Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
American University Washington, DC
University of the West of Scotland UWS
Texas Tech University
Tsinghua University
University of Strathclyde
Michigan
RIT
Max Planck Institute for Gravitational Physics Albert Einstein Institute
Università degli Studi del Sannio
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique théorique
NASA Goddard Space Flight Center
ICTP SAIFR
The University of Western Australia
ACU
Monash University
University of Cambridge
The University of Chicago
Montana State University
Southern University Agricultural & Mechanical College
Columbia University in the City of New York
Caltech
University of Minnesota
The University of Mississippi
The University of Adelaide Australia
University of Birmingham
The University of Melbourne
UIB Universitat de les Illes Balears
University of Washington
University of Wisconsin Milwaukee
Cardiff University Prifysgol Caerdydd
UTRGV
Northwestern
Syracuse University
Universität Hamburg
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

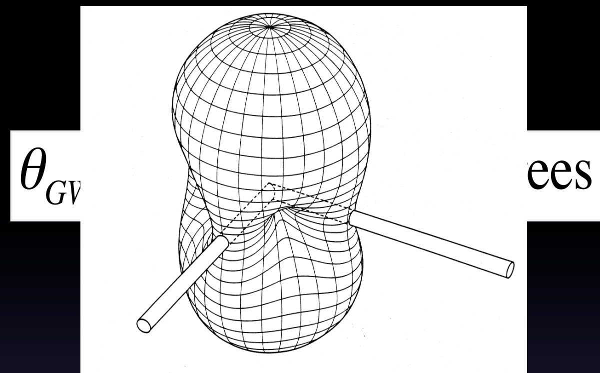
The World Advanced GW Detector Network



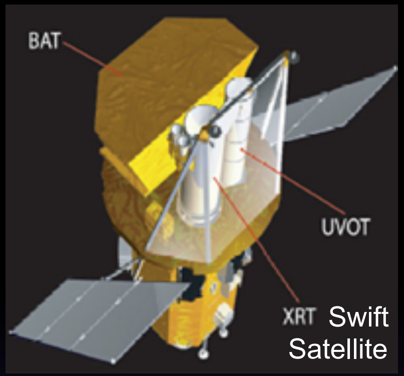
Network Aperture Synthesis and EM Source Follow-up

Image: W. Benger



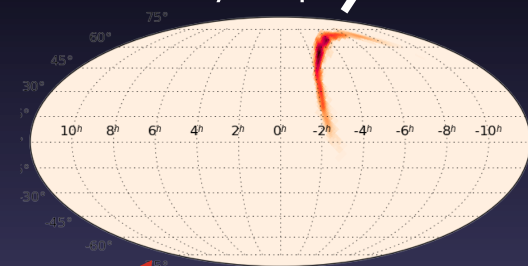


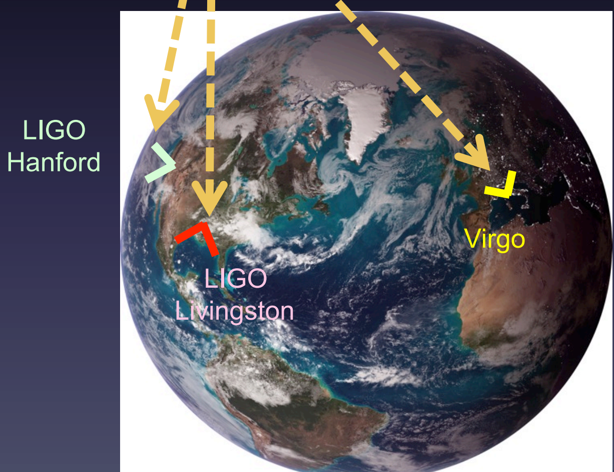
Each detector is omnidirectional



X-ray, γ-ray follow-up

Sky map

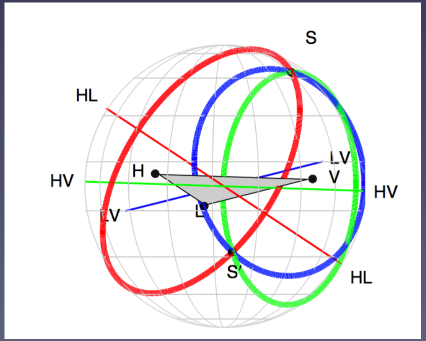




http://earthobservatory.nasa.gov/

(t_L, t_H, t_V)

Arrival time triangulation



Optical follow-up

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

5 European countries
19 labs, ~200 scientists and engineers

2

KAGRA

KAGRA（かぐら）

Large-scale Cryogenic Gravitational-wave Telescope

2nd generation GW detector in Japan

Large-scale Detector

Baseline length: 3km

High-power Interferometer

Cryogenic interferometer

Mirror temperature: 20K

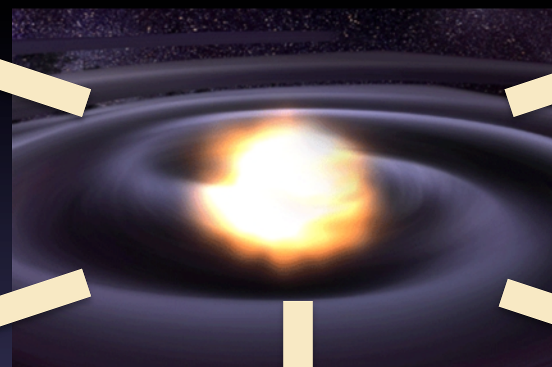
Underground site

Kamioka mine,

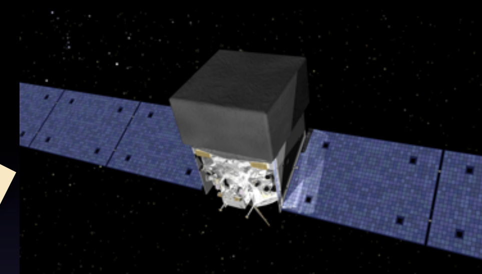
1000m underground

Multi-messenger Astronomy with Gravitational Waves

Binary Neutron Star Merger



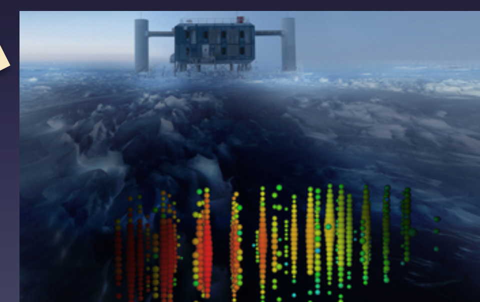
Gravitational Waves



X-rays/Gamma-rays

Visible/Infrared Light

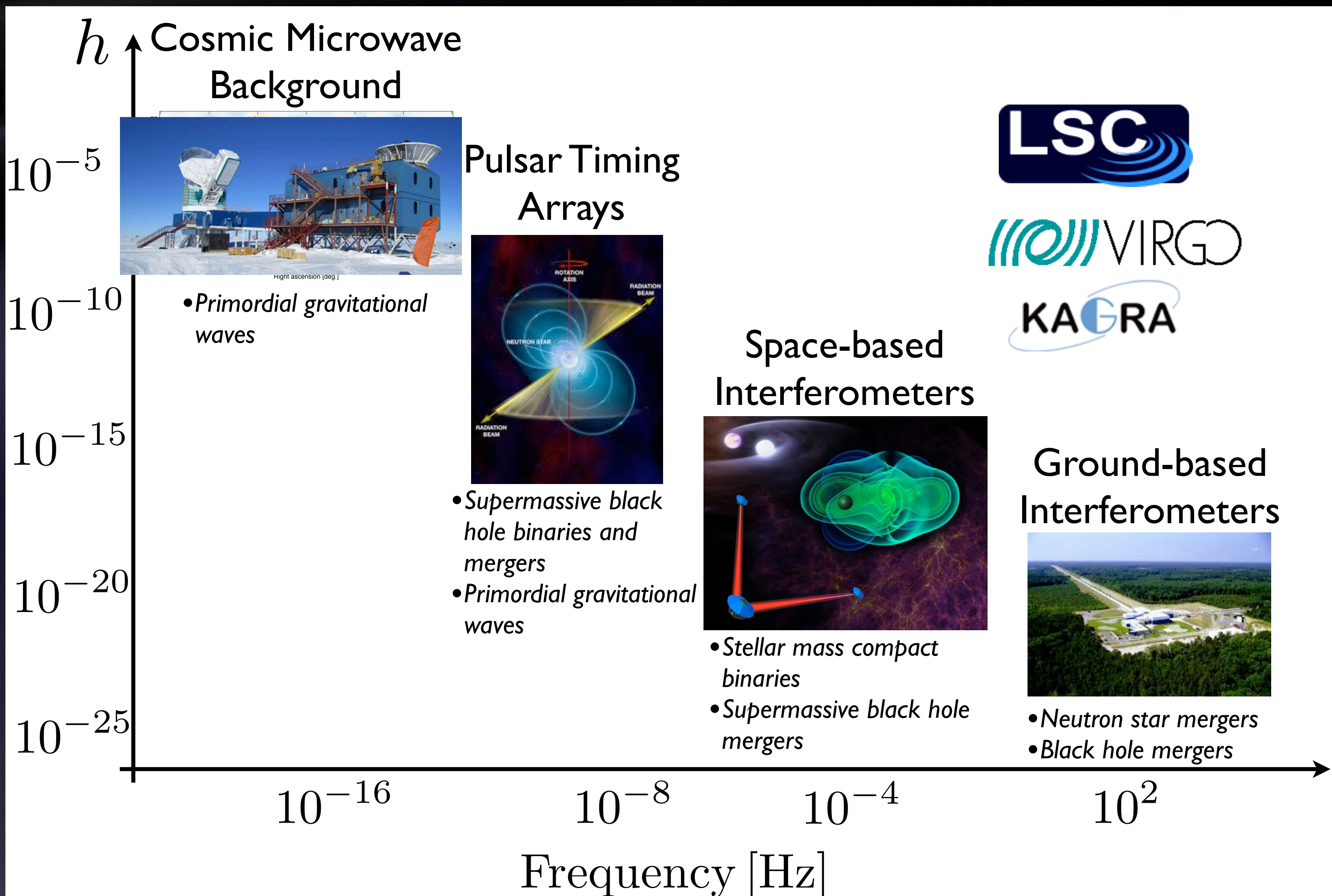
Radio Waves



Neutrinos

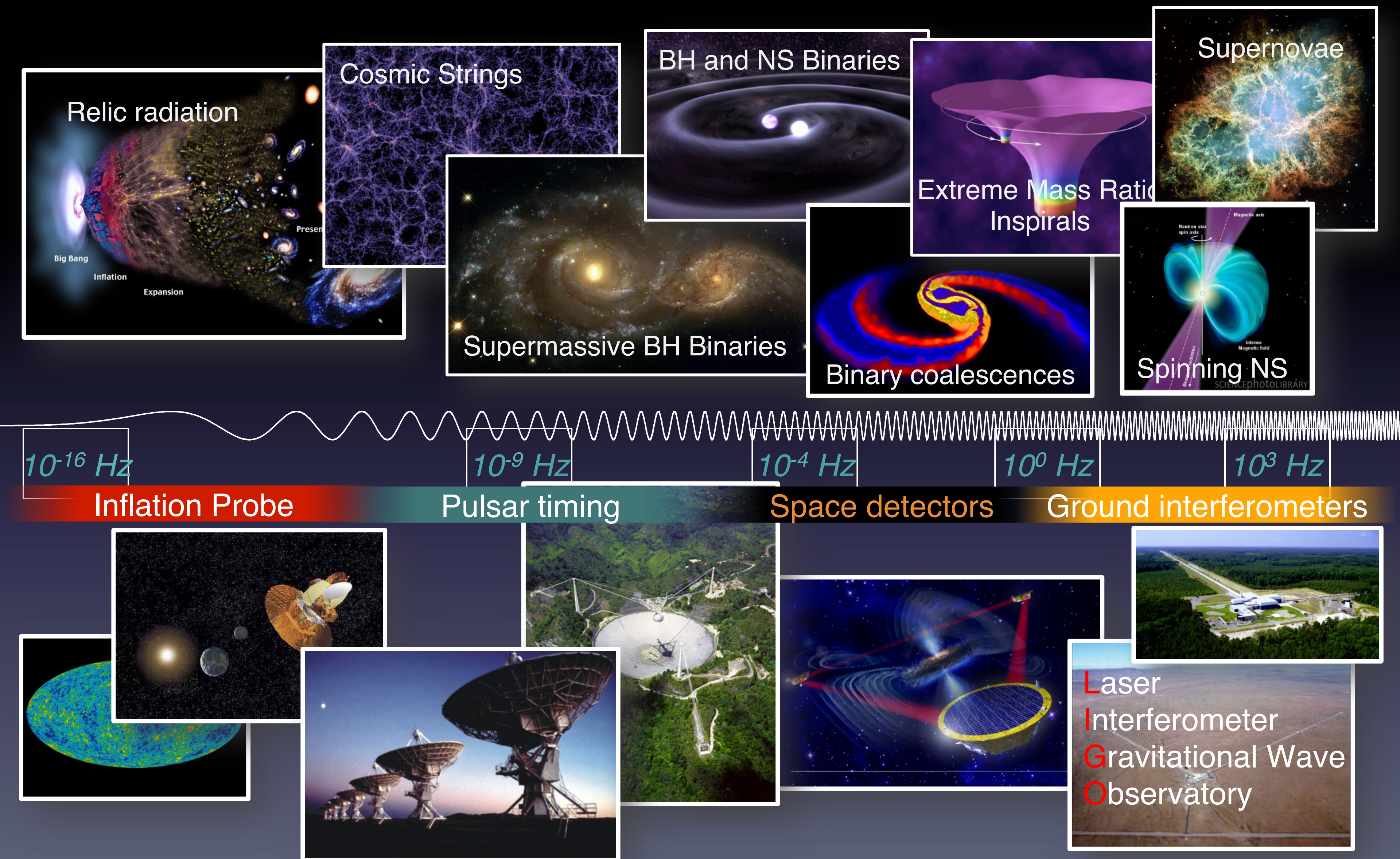
GW landscape

Many sources, many frequencies, many detectors, many collaborations



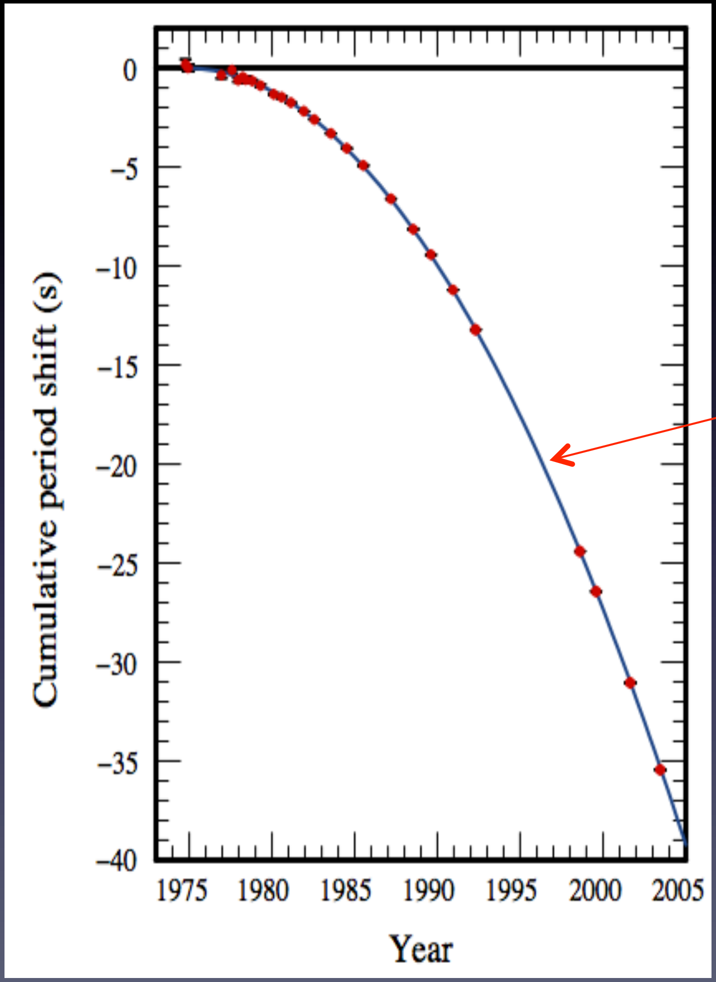
Credit: Nanograv/Bicep2

The GW Spectrum



GW energy loss from binary pulsar system PSR1913+16

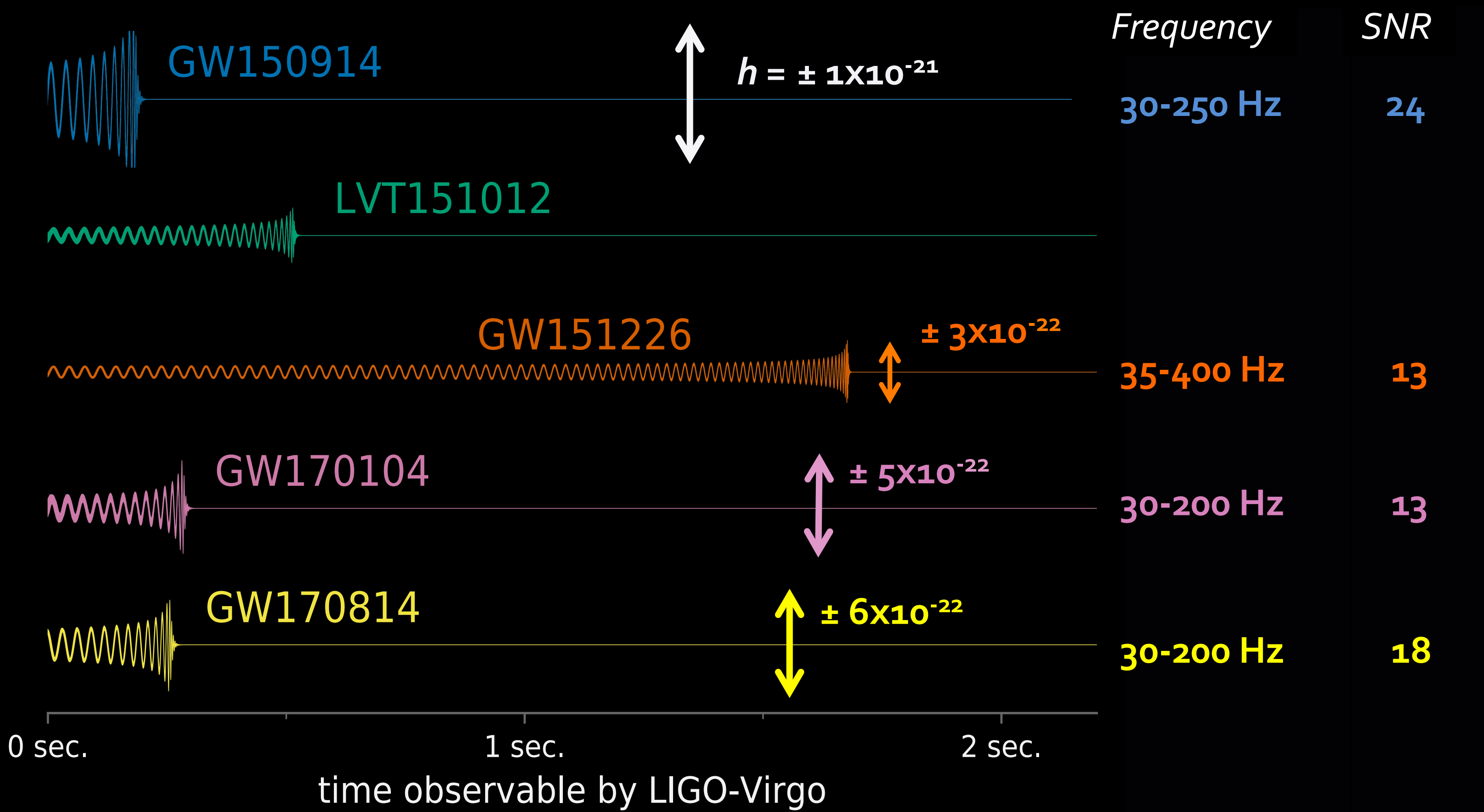
Hulse, Taylor
Nobel Prize 1993



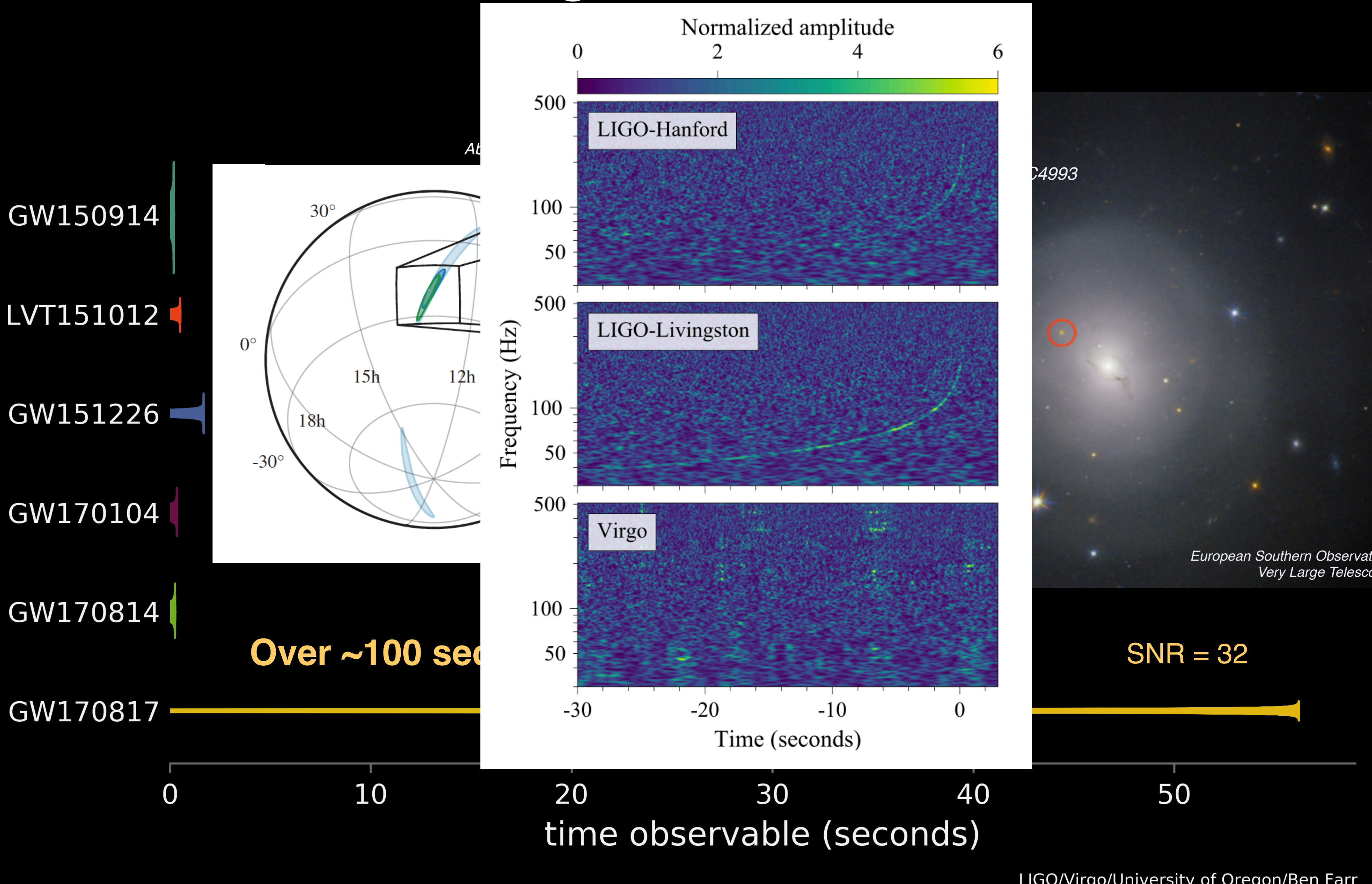
Weisberg, Nice & Taylor, 2010
(Courtesy Joel Weisberg)

Exact calculation of orbital decay due to GW emission

More discoveries

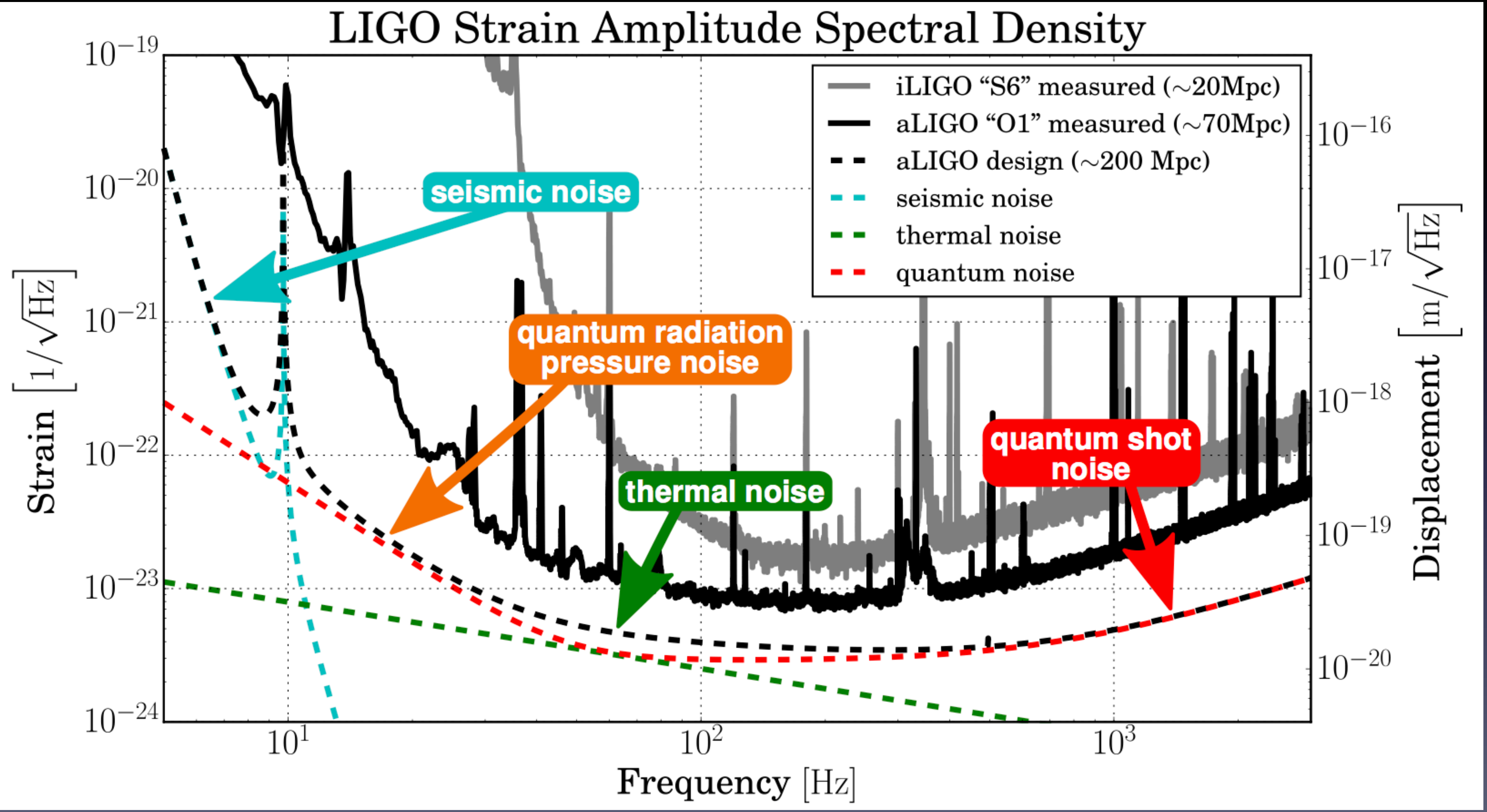


August 17th 2017



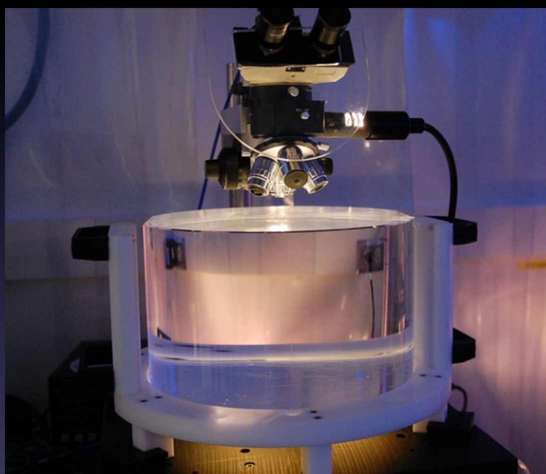
Battle Front:
Fundamental Noise Sources

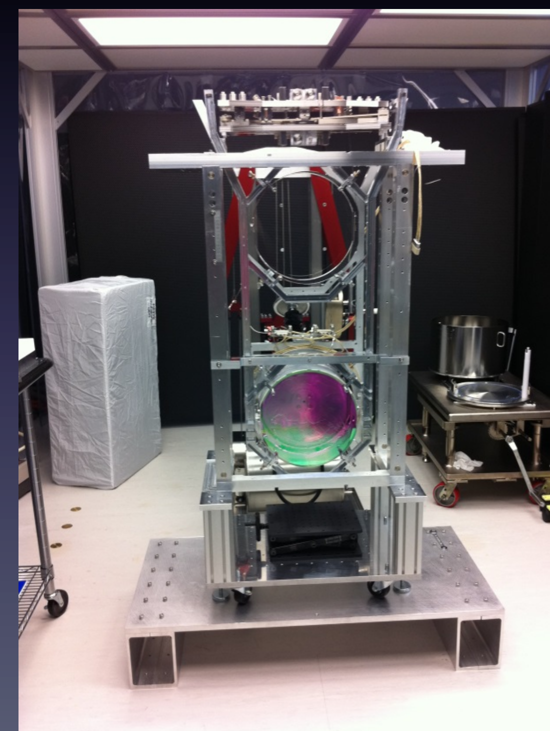
Graphics: J.G. Rollins, Caltech

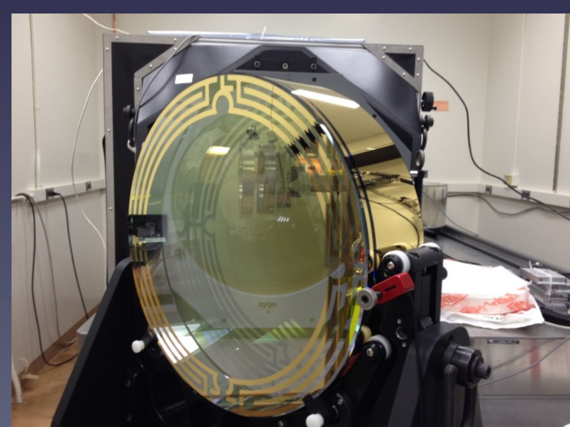


Core Optics and Low-Loss Coatings

- 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



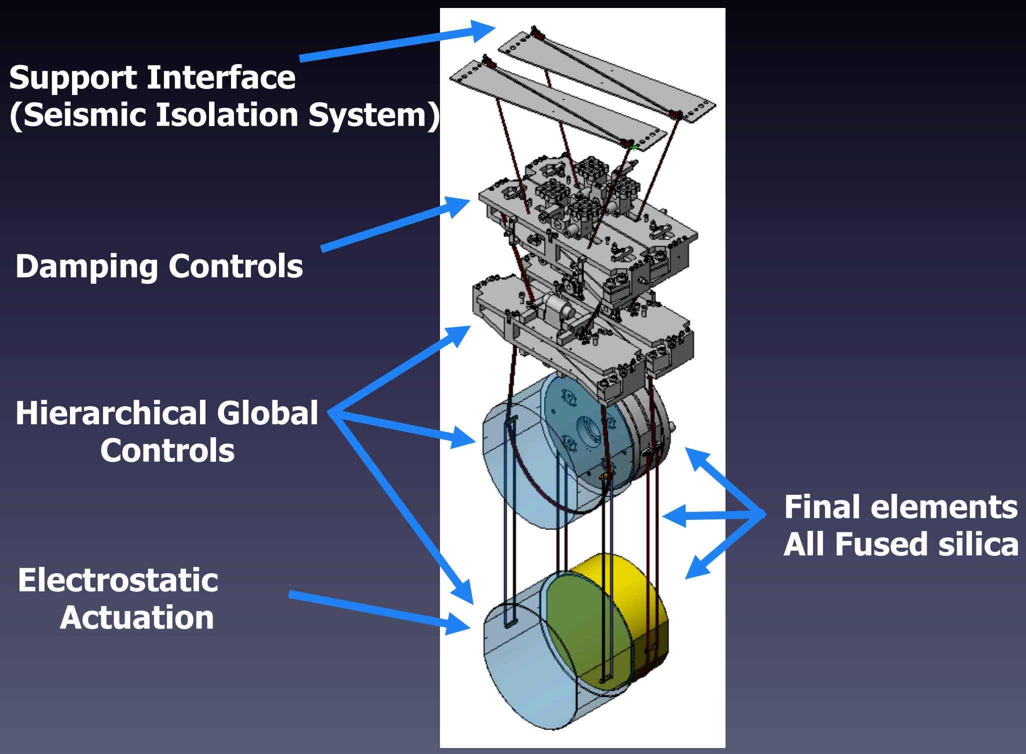


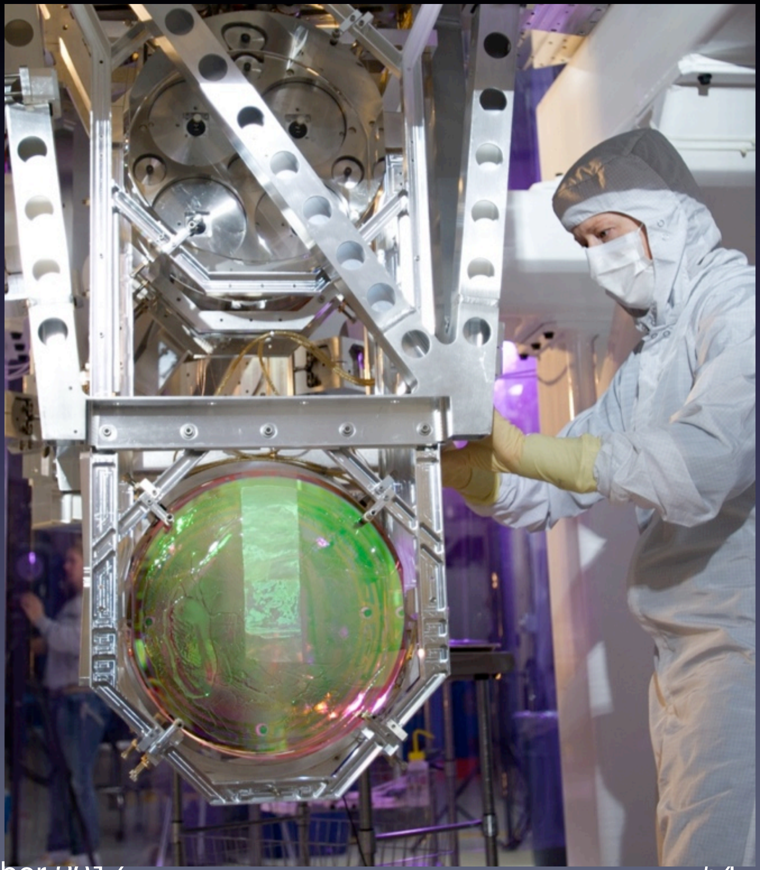


Controlling Brownian Noise

- 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

  VERY Low thermal noise!





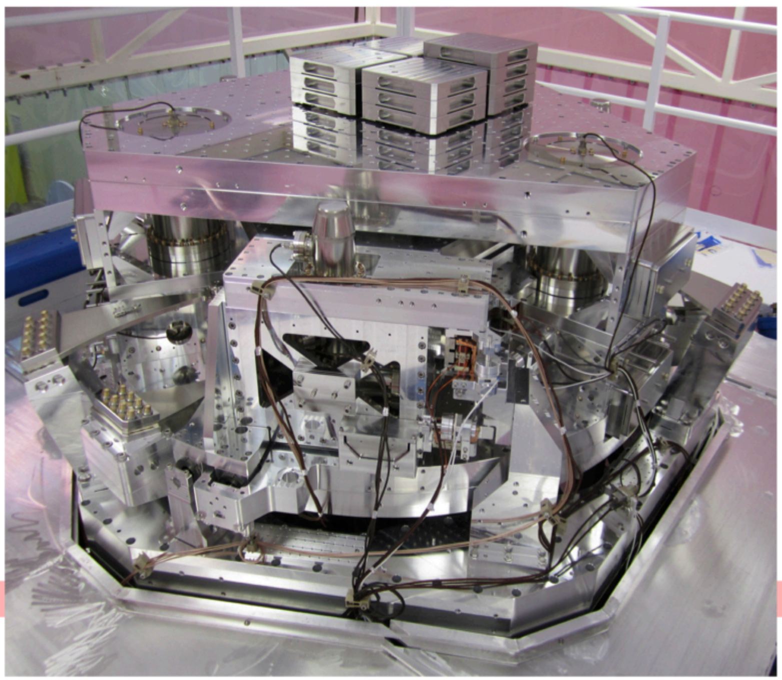
Blocking Earth's Vibrations

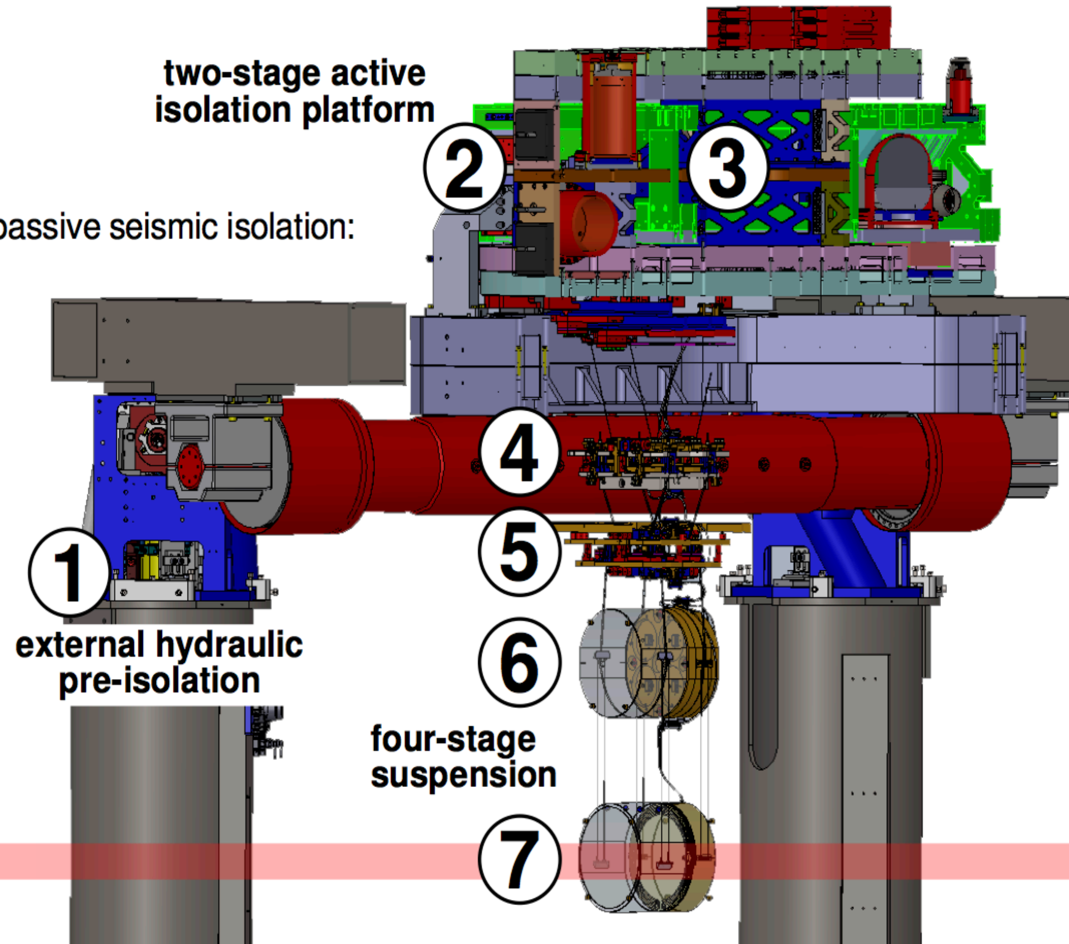
seismic noise

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

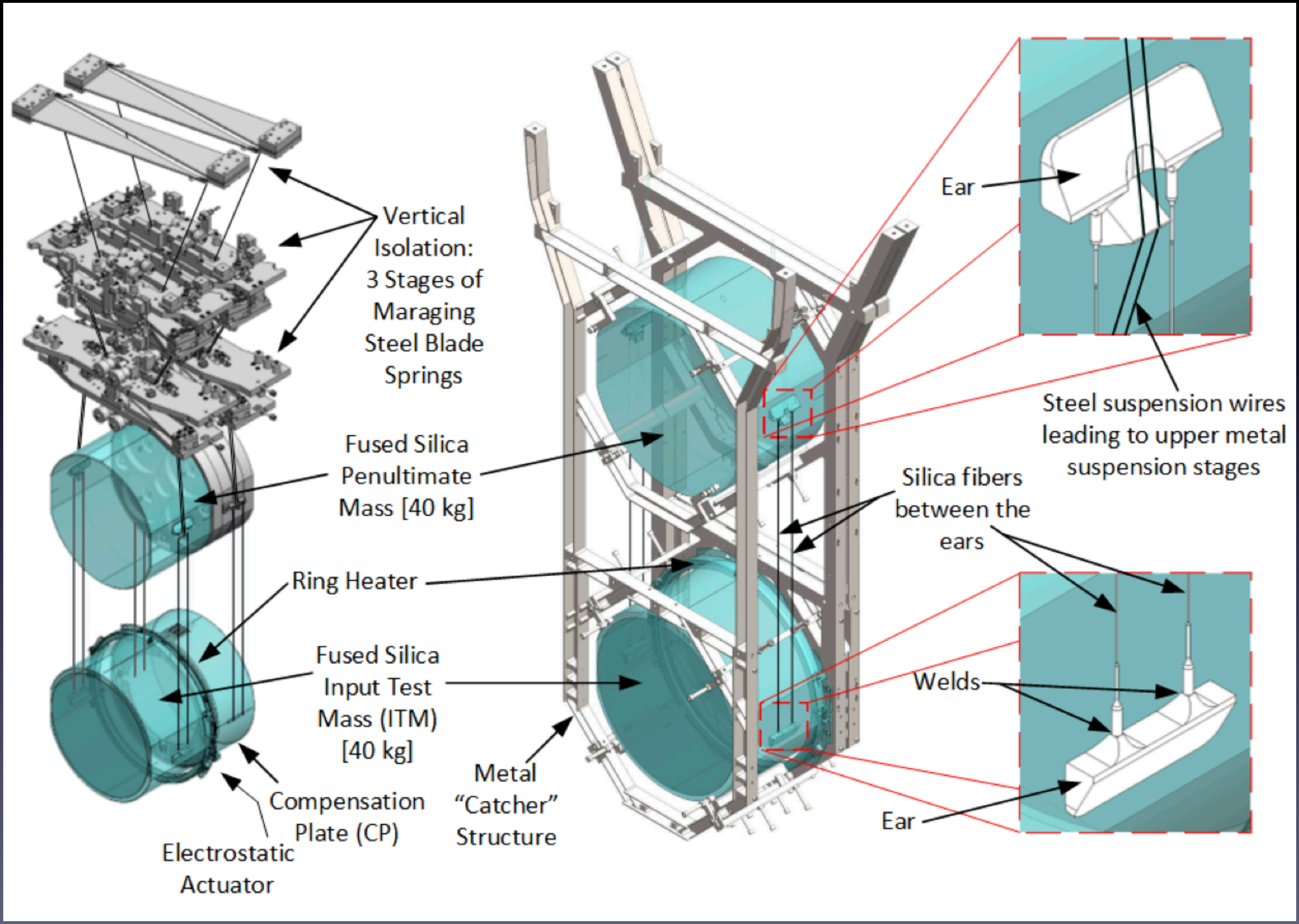
>10 orders of magnitude supression required

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





Monolithic silica suspensions



Beam Tube Properties

module length	2 km
25 cm diameter pump ports/module	9
radius of beam tube	62 cm
volume of module	4.831×10^6 liters
area of module	1.55×10^8 cm^2
initial pumping speed/surface area	1.94×10^{-5} liters/sec/cm^2
length/short section	1.90×10^3 cm
wall thickness	3.23×10^{-1} cm
stiffener ring spacing	76 cm
stiffening ring width	4.76×10^{-1} cm
stiffening ring height	4.45 cm
expansion joint wall thickness	2.67×10^{-1} cm
expansion joint convolutions	9
expansion joint longitudinal spring rate	1.5×10^9 dynes/cm

Residual Gas Pressure Limits in Beam Tubes

$$h(f) = 4.8\times10^{-21} R\left(\frac{x}{H_2}\right)\sqrt{\langle P(torr)\rangle_L}$$

Table 1: Residual gas phase noise factor and average pressure

Gas Species	$R(x/H_2)$	Requirement (torr)	Goal (torr)
H_2	1.0	1×10^{-6}	1×10^{-9}
H_2O	3.3	1×10^{-7}	1×10^{-10}
N_2	4.2	6×10^{-8}	6×10^{-11}
CO	4.6	5×10^{-8}	5×10^{-11}
CO_2	7.1	2×10^{-8}	2×10^{-11}
CH_4	5.4	3×10^{-8}	3×10^{-11}
AMU 100 hydrocarbon	38.4	7.3×10^{-10}	7×10^{-13}
AMU 200 hydrocarbon	88.8	1.4×10^{-10}	1.4×10^{-13}
AMU 300 hydrocarbon	146	5×10^{-11}	5×10^{-14}
AMU 400 hydrocarbon	208	2.5×10^{-11}	2.5×10^{-14}
AMU 500 hydrocarbon	277	1.4×10^{-11}	1.4×10^{-14}
AMU 600 hydrocarbon	345	9.0×10^{-12}	9.0×10^{-15}

Leak Test "Coffin"

Postbake measurements of module X1 at Hanford

March 11-12, 1999

Table 1: Results from gas model solution of 16.9 hour postbake accumulation ending March 12, 1999 at 10:00AM .

molecule	Outgassing rate @ 10C	pressure@ 10C	outgassing rate @ 23C	pressure@ 23C
	torr liters/sec/cm^2	torr	torr liters/sec/cm^2	torr
H_2	1.6×10^{-14}	1.0×10^{-9}	5.2×10^{-14}	3.4×10^{-9}
CH_4	$< 2 \times 10^{-20}$	$< 3.4 \times 10^{-13}$	$< 8.8 \times 10^{-20}$	$< 1.5 \times 10^{-12}$
H_2O	$< 3 \times 10^{-19}$	$< 5.2 \times 10^{-13}$	$< 1.3 \times 10^{-18}$	$< 2.3 \times 10^{-12}$
N_2	$< 9 \times 10^{-19}$ **	$< 1.5 \times 10^{-13}$		
CO	$< 1.3 \times 10^{-18}$	$< 1.7 \times 10^{-13}$	$< 5.7 \times 10^{-18}$	$< 7 \times 10^{-13}$
O_2	$< 1.2 \times 10^{-20}$	$< 2.3 \times 10^{-14}$		
A	$< 2.5 \times 10^{-20}$	$< 3.6 \times 10^{-14}$		
CO_2	$< 6.5 \times 10^{-20}$	$< 1.2 \times 10^{-13}$	$< 2.9 \times 10^{-19}$	$< 5.2 \times 10^{-13}$
$NO+C_2H_6$	$< 1.5 \times 10^{-19}$	$< 1.6 \times 10^{-13}$	$< 6.6 \times 10^{-19}$	$< 7.2 \times 10^{-13}$
$H_nC_pO_q$	$\sum$ amu41,43,55,57 $< 1.2 \times 10^{-19}$	$< 2.2 \times 10^{-13}$	$\sum$ amu41,43,55,57 $< 5.3 \times 10^{-19}$	$< 9.7 \times 10^{-13}$

Volume = 2.4×10^6 liters and Area = 7.8×10^7 cm^2

** The equivalent air leak into the module Q < 3.5×10^{-11} torr liters/sec from amu 28.

Correction from 10C to 23C uses a binding temperature of 8000K for hydrogen and 10000K for all other molecules

The data shows the outgassing rates of the tube are acceptable. The higher temperature bake at 168C for a shorter time has accomplished a better result than the longer bakes at 150C.

LIGO is Really Two Vacuum Systems (at each site)

"Vacuum Equipment:"
Chambers, pumps, instruments

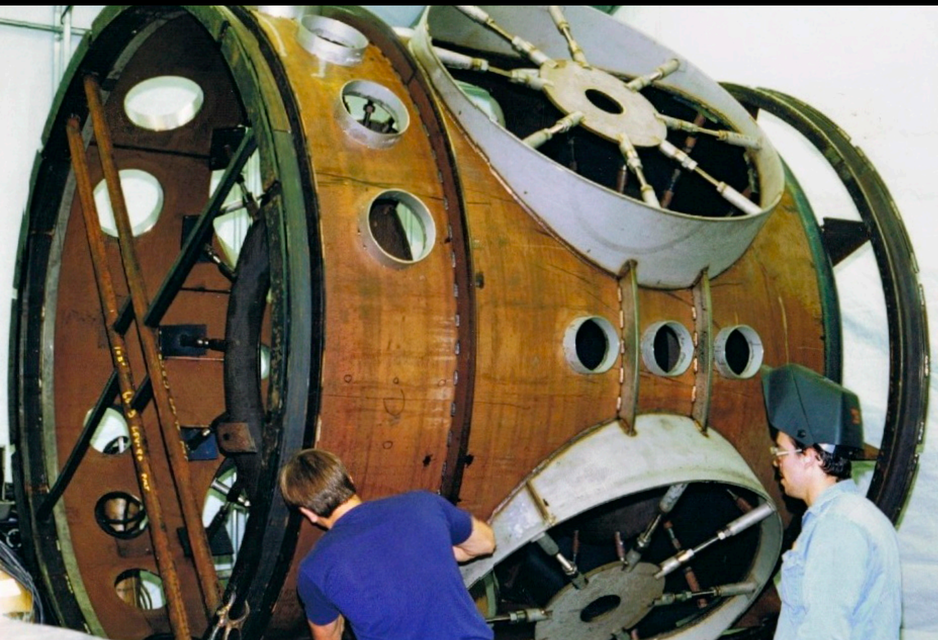
- Houses detector apparatus
- Isolation (valves), access (doors)
- Electrical, mechanical, optical penetrations/interfaces
- Pumping & instrumentation
- Somewhat "conventional"
- *F:A* ~ 10^{-2} $ls^{-1}cm^{-2}$

Beam tubes

- Just a long hole in the air;
  Never to be vented
- Highly "unconventional"
  - 10 million liters (per site)
  - 300 million cm^2 (per site)
  - 200 l/s char. conductance
  - *F:A* ~ 10^{-5} $ls^{-1}cm^{-2}$

BSC chamber

(Basic Symmetric Chamber)



- 2.8m Ø x 5.5m h
- Upper third removable dome
- Thin (10-15mm) 304L SS shell with welded stiffeners, F&D heads
- Combination of GTAW and plasma welding

- Ports < 35cm Ø: ConFlat™
- Ports > 35cm Ø: Dual O-ring
    - Treated Viton elastomer
    - Isolated pumped annulus between inner and outer seal
    - Permeation and damage tolerant

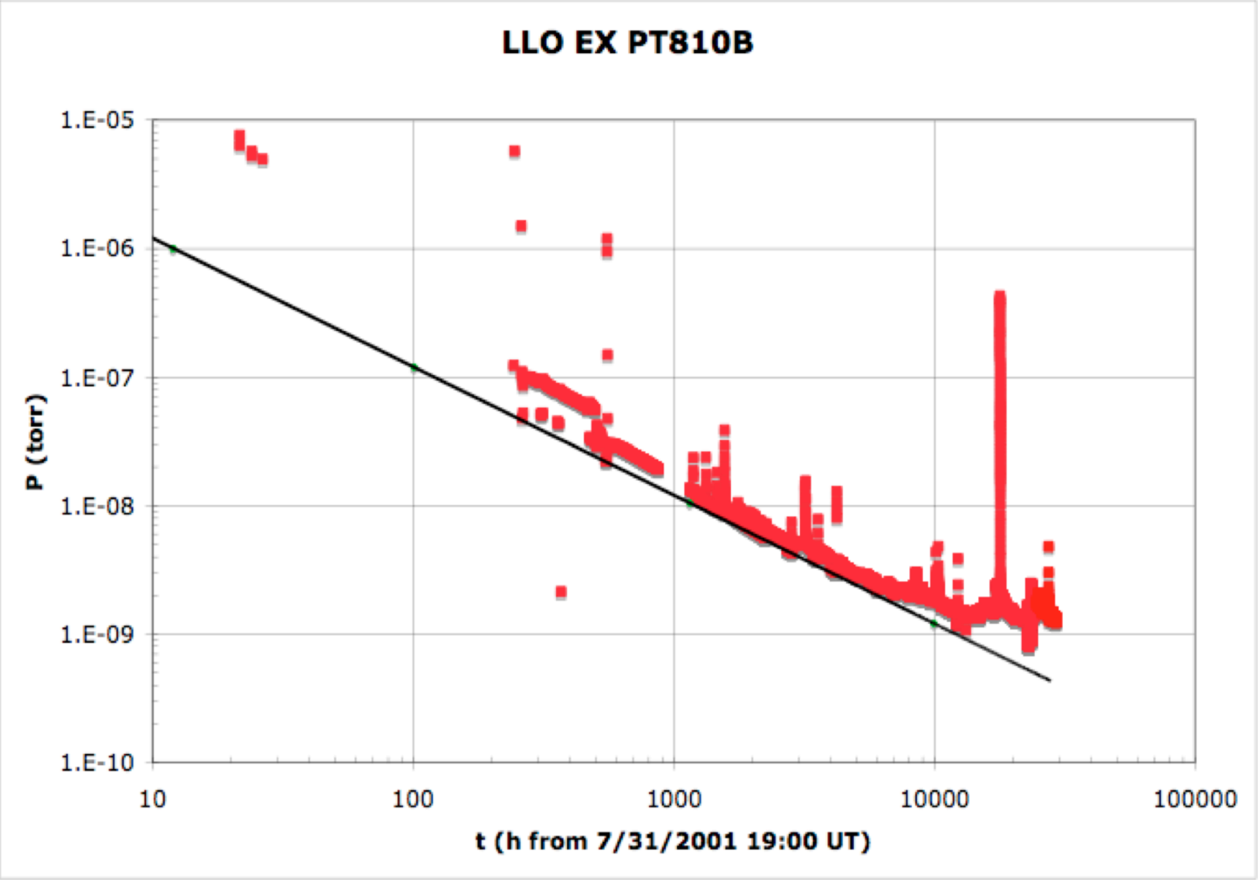
HAM chamber

(Horizontal Access Module)

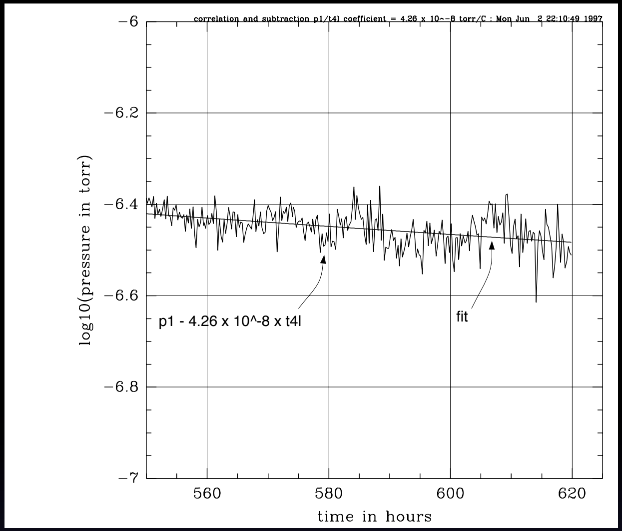
- House complex input/output optics
- 2.1m Ø x 2m w
- More than 70% of area is removable access doors


B2B-36
B5A-36

End Station Pressure



Unbaked Water Outgassing (norm. to 1000 hours)



Weiss et al, T970111

LHO beamtube

$J(H_2O) \sim 8 \times 10^{-12}$ T l s^{-1} cm^{-2} x (1000 h)/t

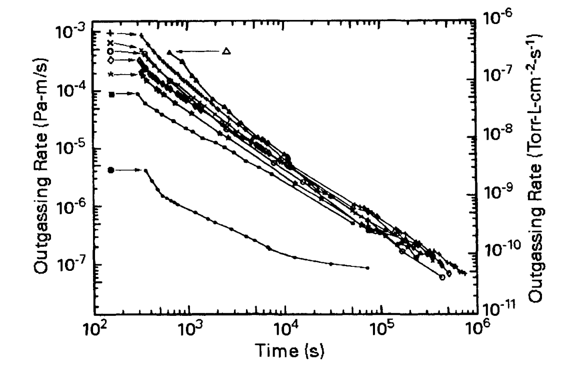


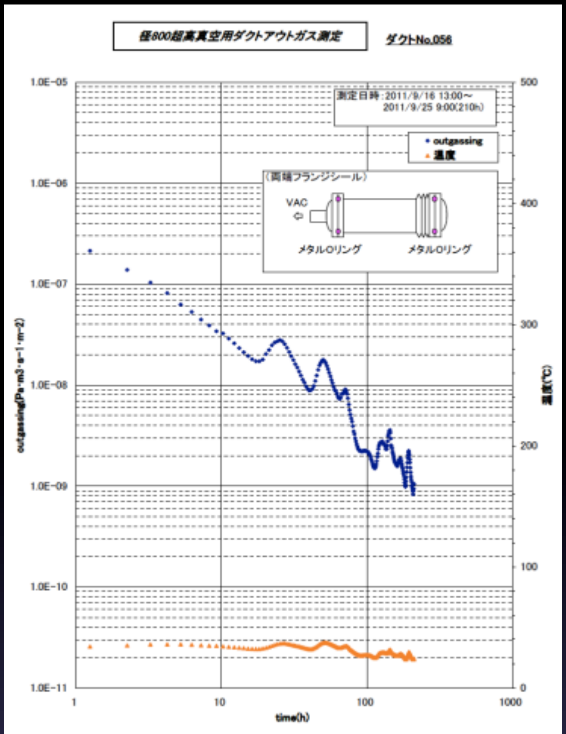
Fig. 4.5 Outgassing measurements for different H_2O exposures during venting of a 304 stainless steel chamber of inner surface area 0.4747 m^2. ○ Ambient air exposed, 7.8 ml absorbed; △ 600 ml exposed, 16.8 ml absorbed; + 400 ml exposed, 9.2 ml absorbed; × 200 ml exposed, 7.2 ml absorbed; ◊ 100 ml exposed, 3.6 ml absorbed; ★ 10 ml exposed, 2.3 ml absorbed; ■ N_2 gas with <10 ppm H_2O exposed, 0.7 ml absorbed; ● dry N_2 gas exposed, 0.017 ml absorbed; Reprinted with permission from *J. Vac. Sci. Technol. A*, **11**, p. 1702, M. Li and H. F. Dylla. Copyright 1993, AVS–The Science and Technology Society.

Li and Dylla (1993)

Electropolished 304L

10 ppm water content air re-exposure

$J(H_2O) \sim 4 \times 10^{-12}$ T l s^{-1} cm^{-2} x (1000 h)/t

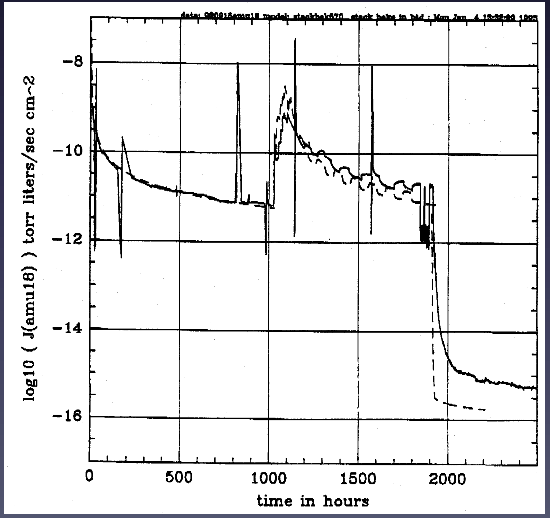


Saito et al (KAGRA, 2011)

ECB 304L, 200C conditioning bake

-40C dewpoint (127 ppm) re-exposure

$J(H_2O) \sim 2 \times 10^{-13}$ T l s^{-1} cm^{-2} x (1000 h)/t



Weiss et al, T940090

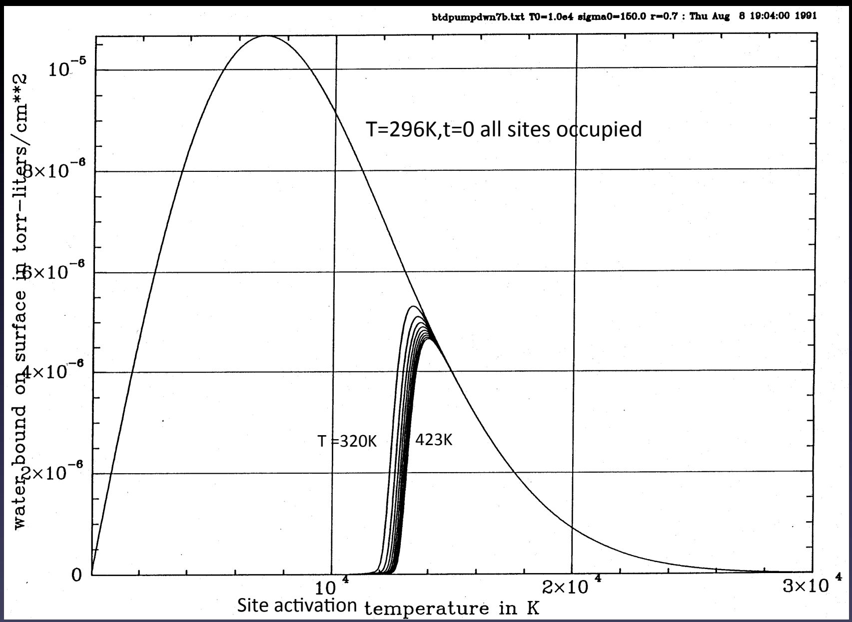
BTD at CB&I

$J(H_2O) \sim 3 \times 10^{-12}$ T l s^{-1} cm^{-2} x (1000 h)/t

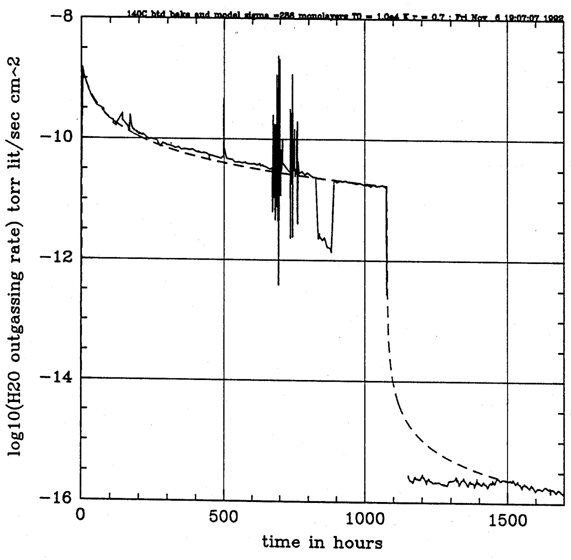
(~ 10^{-16} T l s^{-1} cm^{-2} post-bake)

- Tolerable pressure for H_2O ~ 1/10 that for H_2
- Passive 1/t desorption with time too weak
- Low-temperature bakeout was required
  - LIGO used 1-shot bakeout to save cost
  - Tubes cannot be re-exposed to atmosphere

“Dubinin-Radeschevich Isotherm” desorption model



T0 = 10000K
R = 0.7
α = 0.5
σ0 = 250 monolayers
amu = 18
τ0 = 10^{-13} sec



Weiss et al, LIGO-T970111