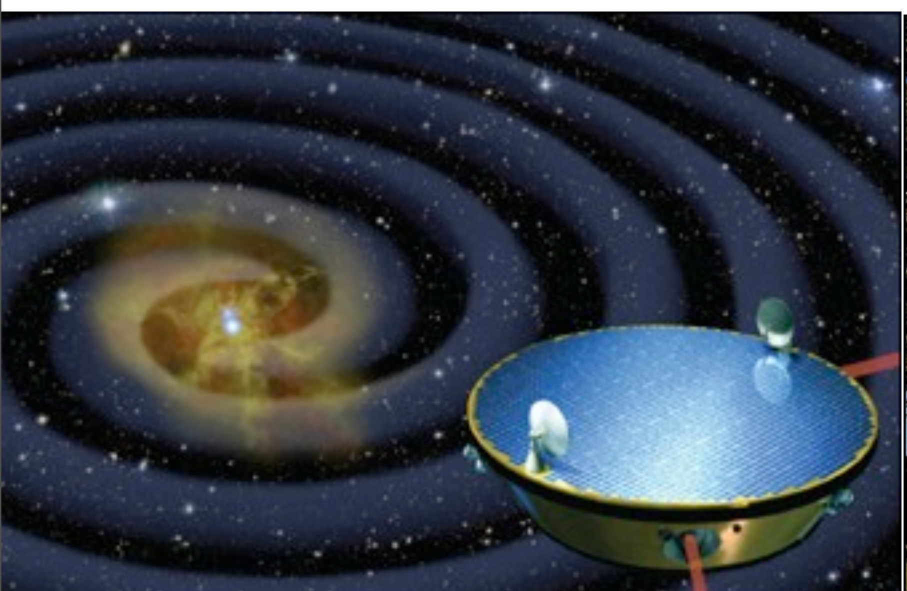
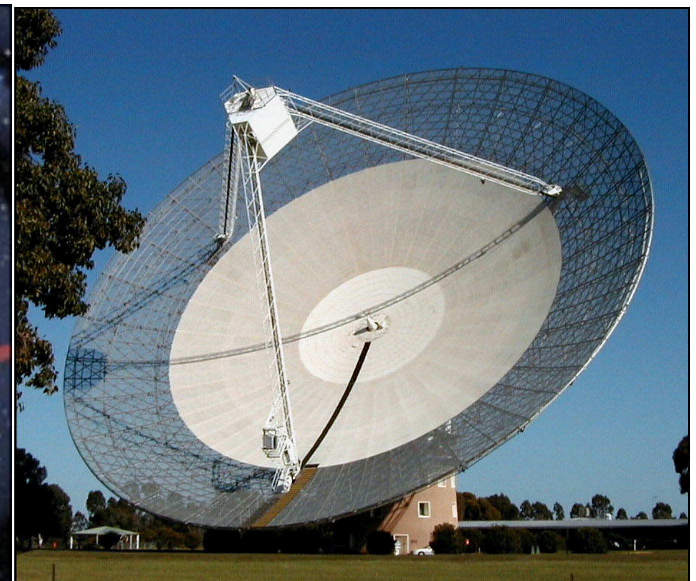
Gravitational wave detection

Sam Waldman
June 14, 2011
TIPP Chicago



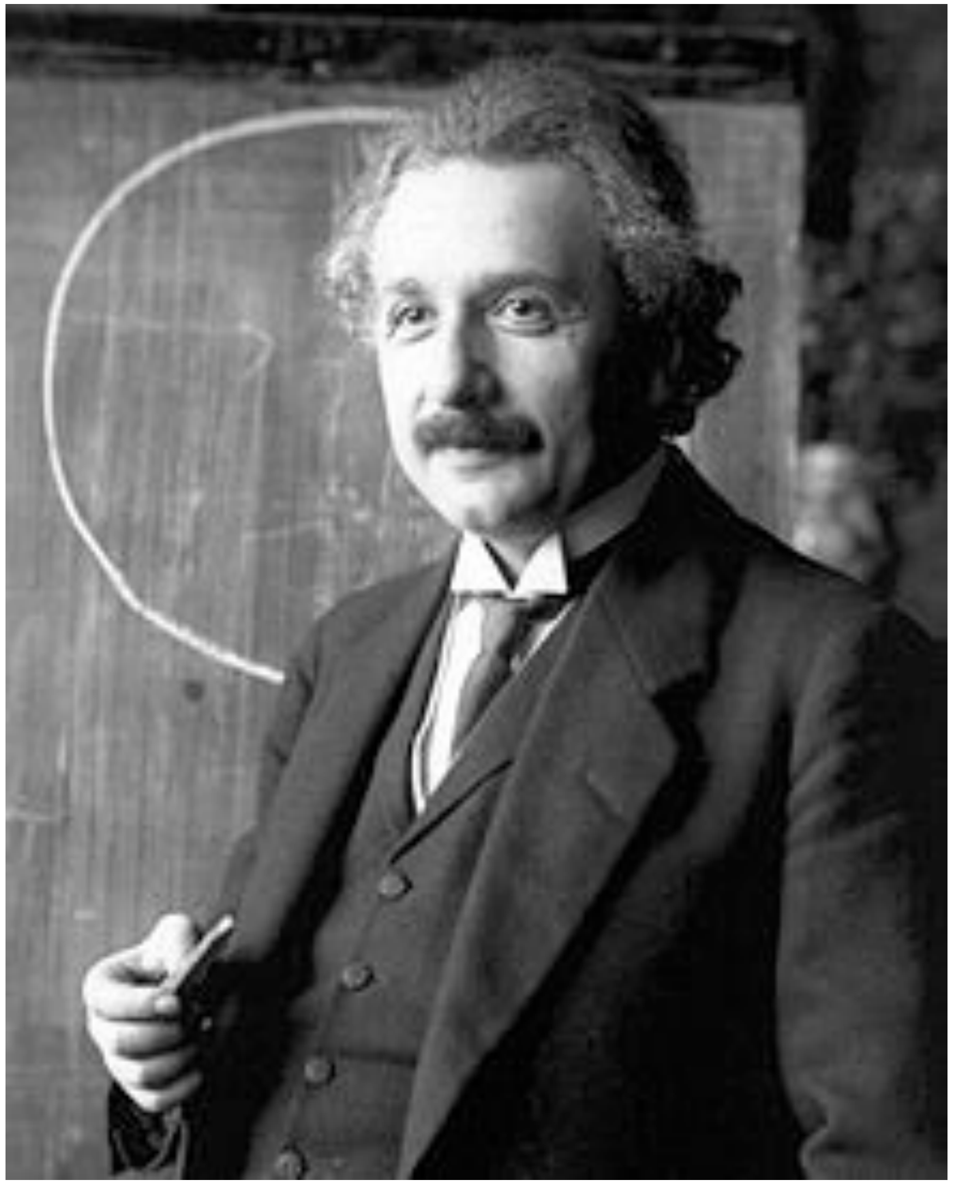
GW Astronomy

Pulsar timing

LISA/LPF/GRACE-C

LIGO/Virgo/GEO

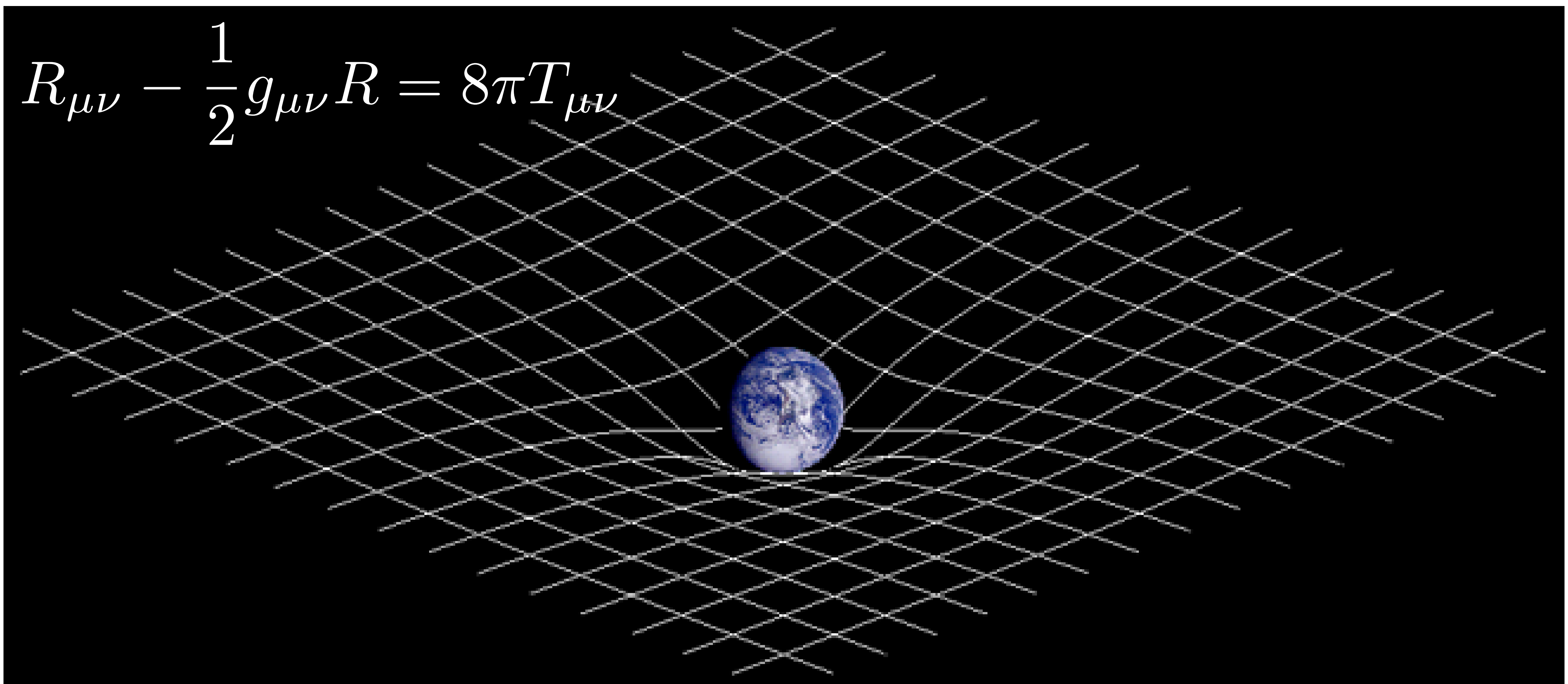
Future Detectors



Special thanks to: A. Lommen, M. Hewitson, G. Losurdo, H. Grote, O. Jennrich, and M. Ando

General Relativity

"Mass tells space-time how to curve, and space-time tells mass how to move." J.A. Wheeler



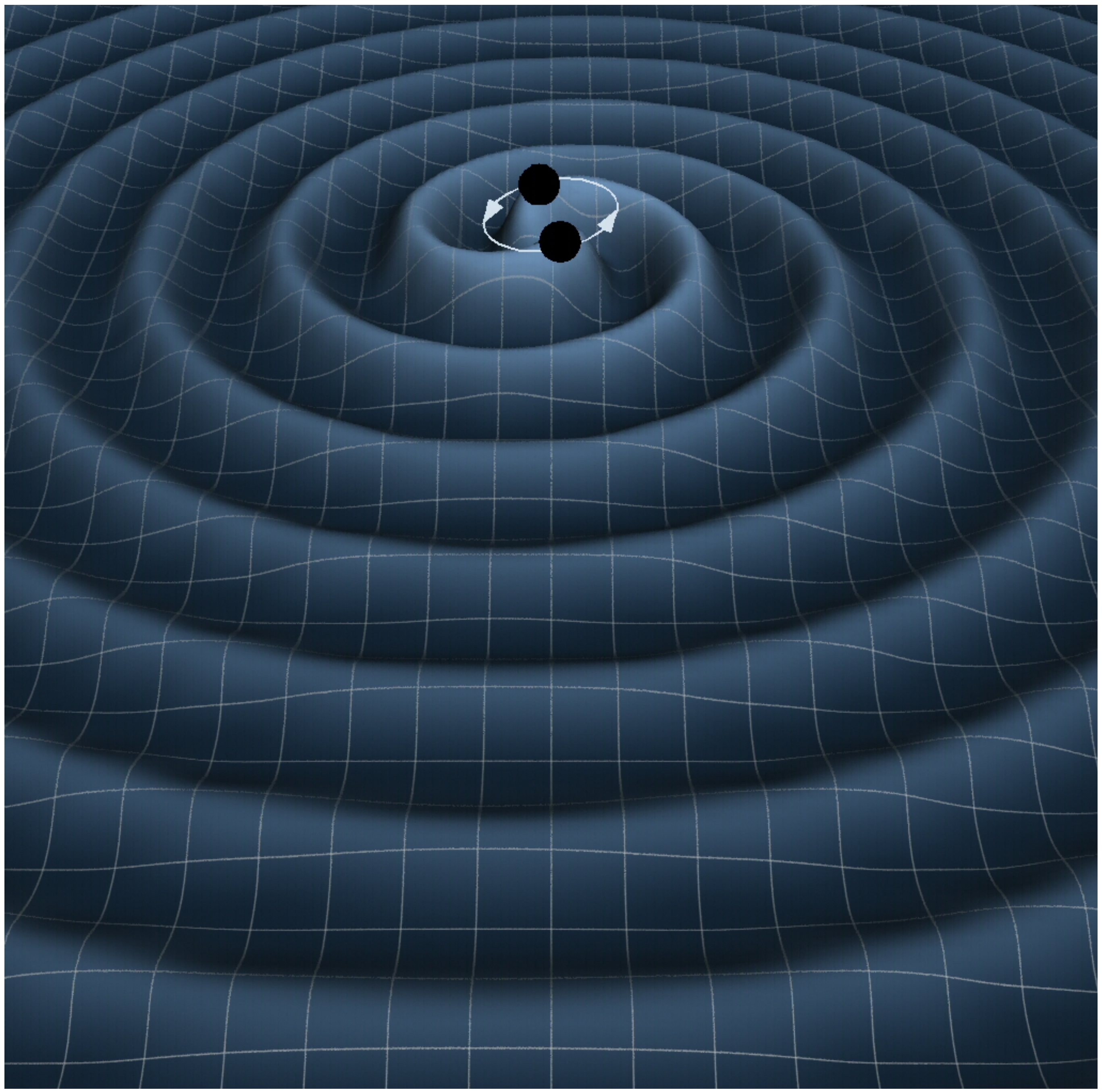
GR Predictions
from 1916-1918

SpaceTelescope.org/opo9020a

1. Mercury's perihelion advance
   43" / century, first noted by Urbain Le Verrier in 1859
2. Gravitational deflection of light
   Observed by Eddington during the 1919 eclipse, repeated in 1922 by Lick Observatory
3. Gravitational redshift
   Definitively measured by the Pound-Rebka experiment in 1959 using Mössbauer spectroscopy.
4. **Gravitational waves**
   Predicted in 1918, indirectly observed via the orbital dynamics of the Hulse-Taylor binary pulsar, 1974

Glen Rebka © Bettmann/CORBIS4

Gravitational waves



Flat space w/small perturbations:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Two plane wave solutions as a strain:

$$h_{\pm} = A_{\mu\nu} \exp\left(\kappa_{\alpha} x^{\alpha}\right)$$
$$= \delta L / L$$

for a binary system:

$$|h| \simeq \frac{G^2}{c^4} \frac{M_1 M_2}{r} \frac{1}{R}$$

(for a man-made system, h ~ 10^{-47})

(Einstein 1916 / 1918)

Compact objects

Neutron Stars (1930):

THE MAXIMUM MASS OF IDEAL WHITE DWARFS

By S. CHANDRASEKHAR

Trinity College
Cambridge
November 12, 1930

Black Holes (1939):

PHYSICAL REVIEW

On Continued Gravitational Contraction

J. R. Oppenheimer and H. Snyder
University of California, Berkeley, California
(Received July 10, 1939)

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University of California, Berkeley,
(Received July 10, 1939)

PHYSICAL REVIEW

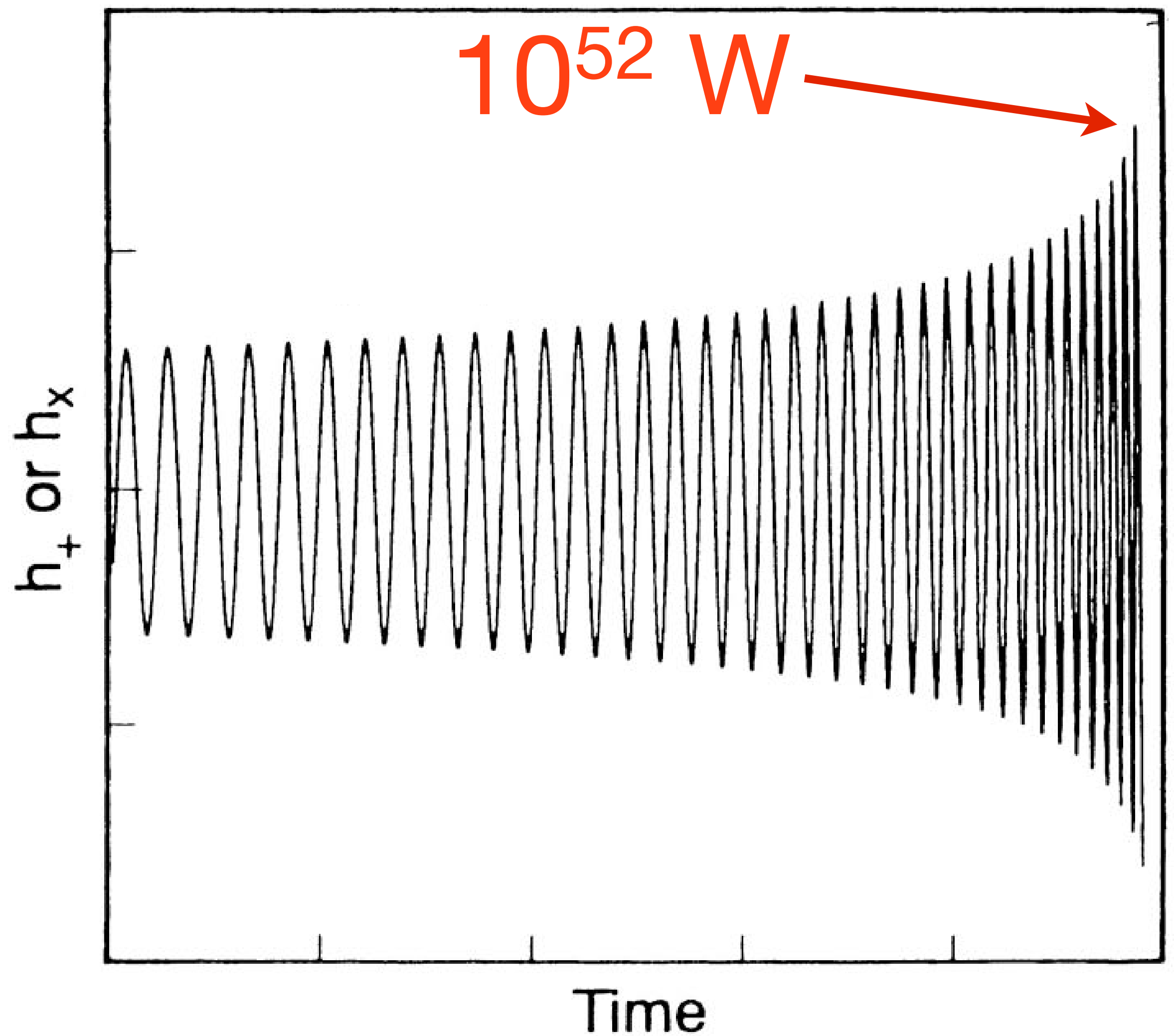
The Mechanism of Nuclear Fission

NIELS BOHR
Copenhagen, Denmark, and The Institute for Advanced St

AND

JOHN ARCHIBALD WHEELER
Princeton University, Princeton, New Jersey
(Received June 28, 1939)

GW generation



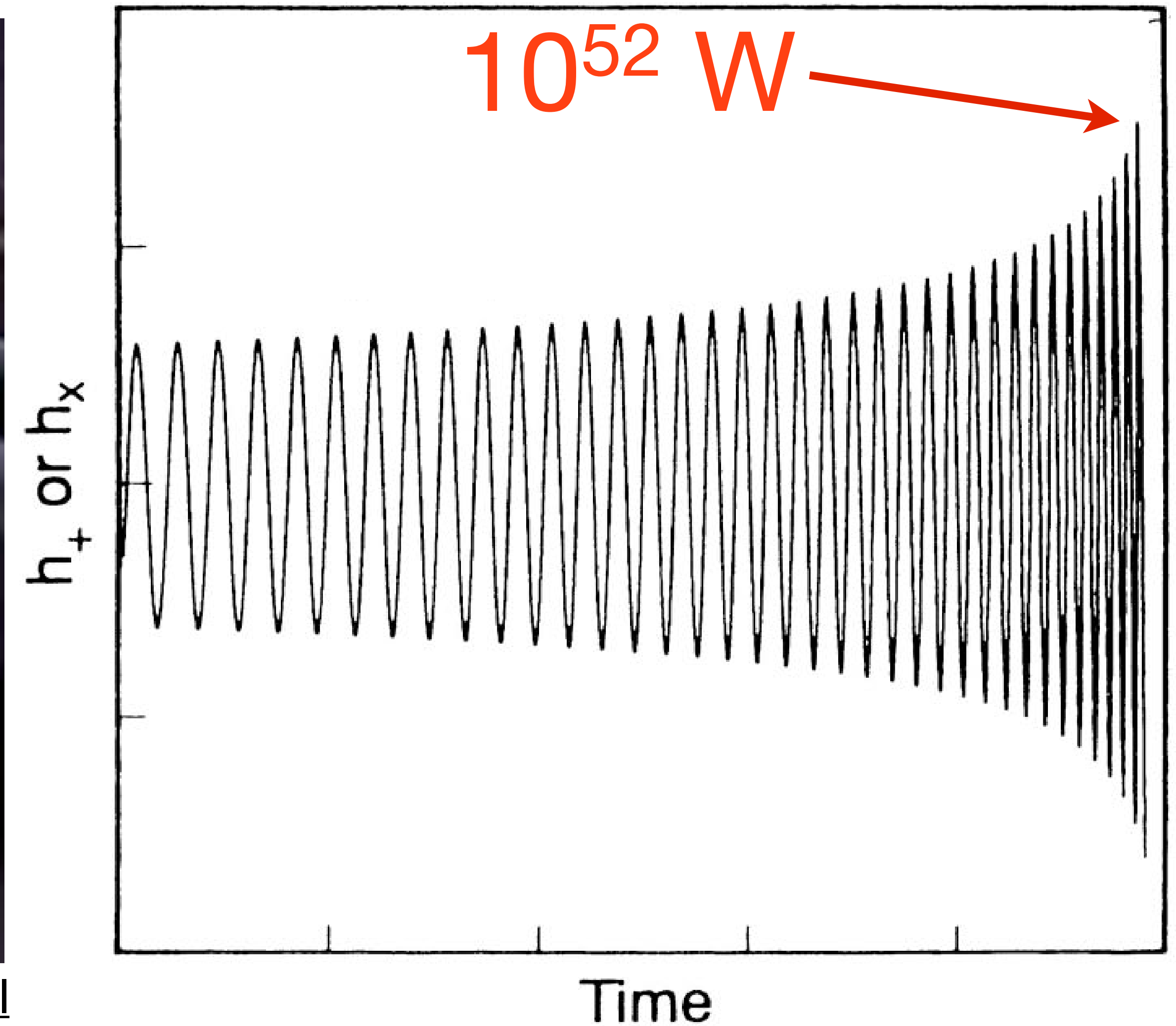
http://chandra.harvard.edu/resources/animations/neutronstars.html

$$h \approx 1.5 \times 10^{-21} \left[\frac{M}{1.4\ M_\odot}\right] \left[\frac{6\ r_S}{r}\right] \left[\frac{15\ Mpc}{R}\right]$$

(sound courtesy R. Lang, MIT)

GW generation

http://chandra.harvard.edu/resources/animations/neutronstars.html



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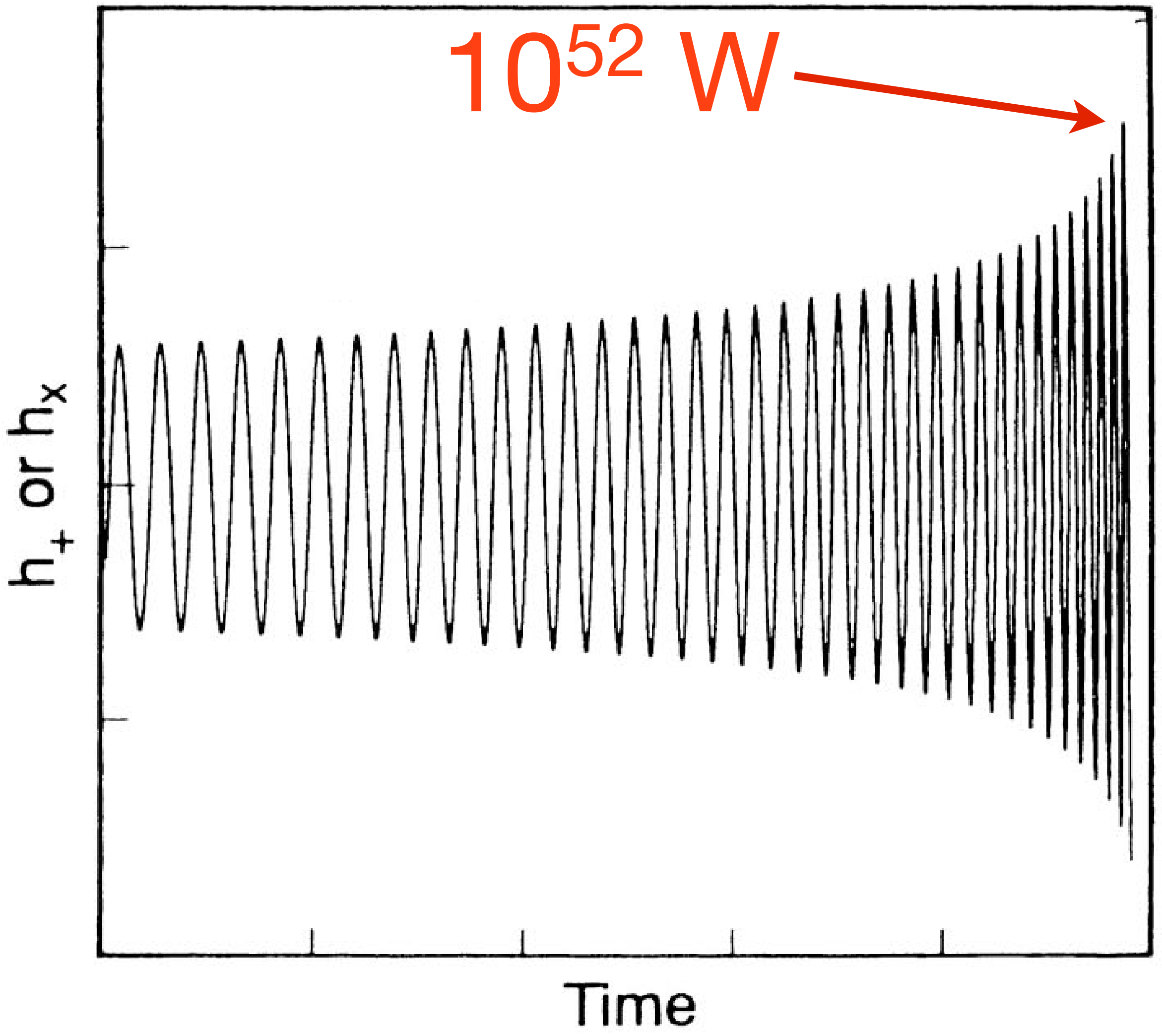

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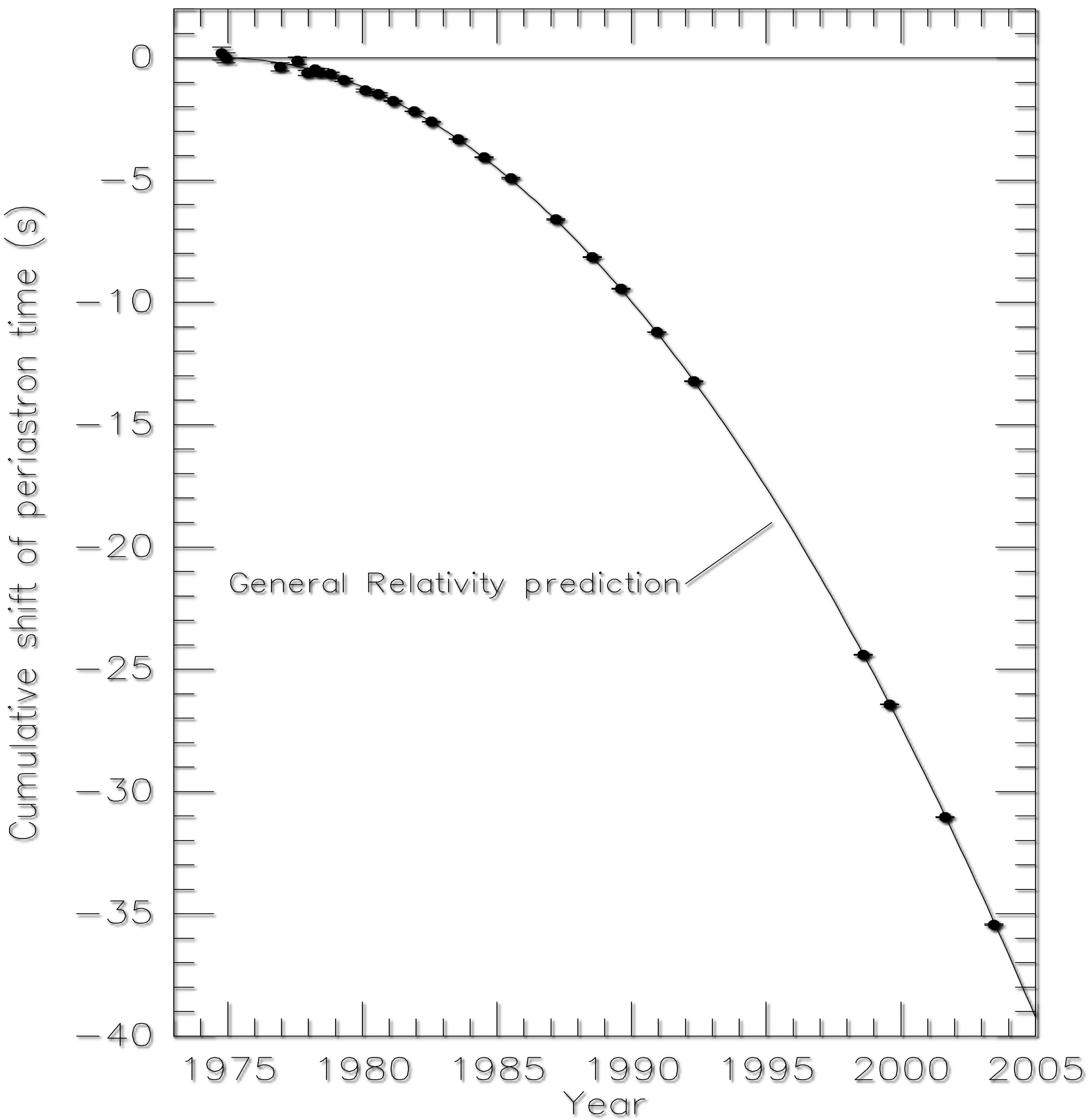
(sound courtesy R. Lang, MIT)

PSR 1913+16



Weisberg, Taylor - ASP Conf. Series 2004

Binary NS system

- $m_1 \sim m_2 \sim 1.4\ M_\odot$
- $r = 1.6 \times 10^6$ km
- $T_{orbit} = 8$ hr
- 7.5 kpc from Earth

GR prediction
3mm/orbit

$dx/x \sim 1.5 \times 10^{-23}$

Gravity c. 2011

Black holes
- Active Galactic Nuclei
- Xray Binaries
- Sagittarius A*

Neutron Stars:
- Millisecond pulsars
- Soft Gamma Repeaters

Gamma Ray Bursts
- Long GRBs, core collapse supernova?
- Short GRBs, compact binary inspirals?

Cosmology
- *Inflation era GWs*
- *Dark Energy / Dark Matter*
- *Large scale structure formation*

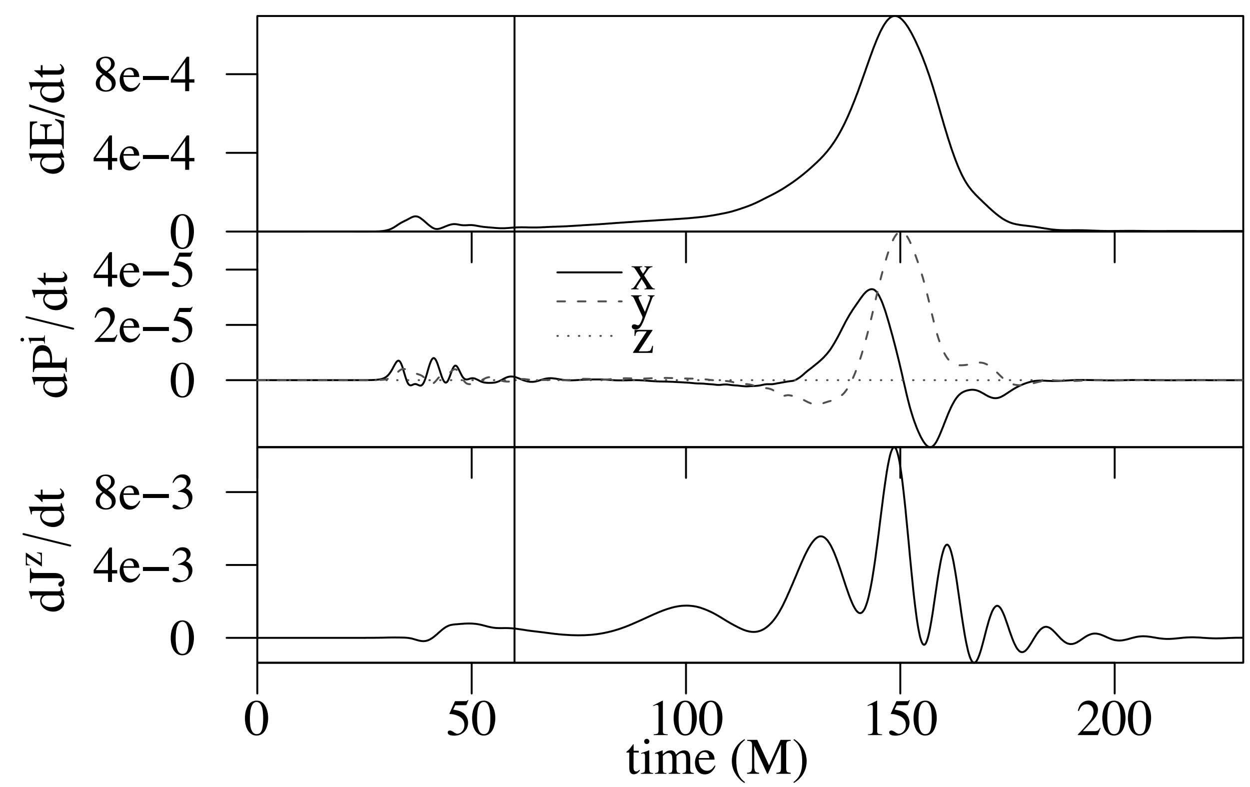
Directly observable with gravitational waves

Accessible with GW astronomy

NR::Merger_kicks

First numerically simulated black hole merger in 2005

Exploring spin, mass ratio, eccentricity, 3-body etc...



400 km/s

M Campanelli et al. CCRG@RIT

F. Hermann et al.; ApJ 661 2007

NR::Merger_kicks

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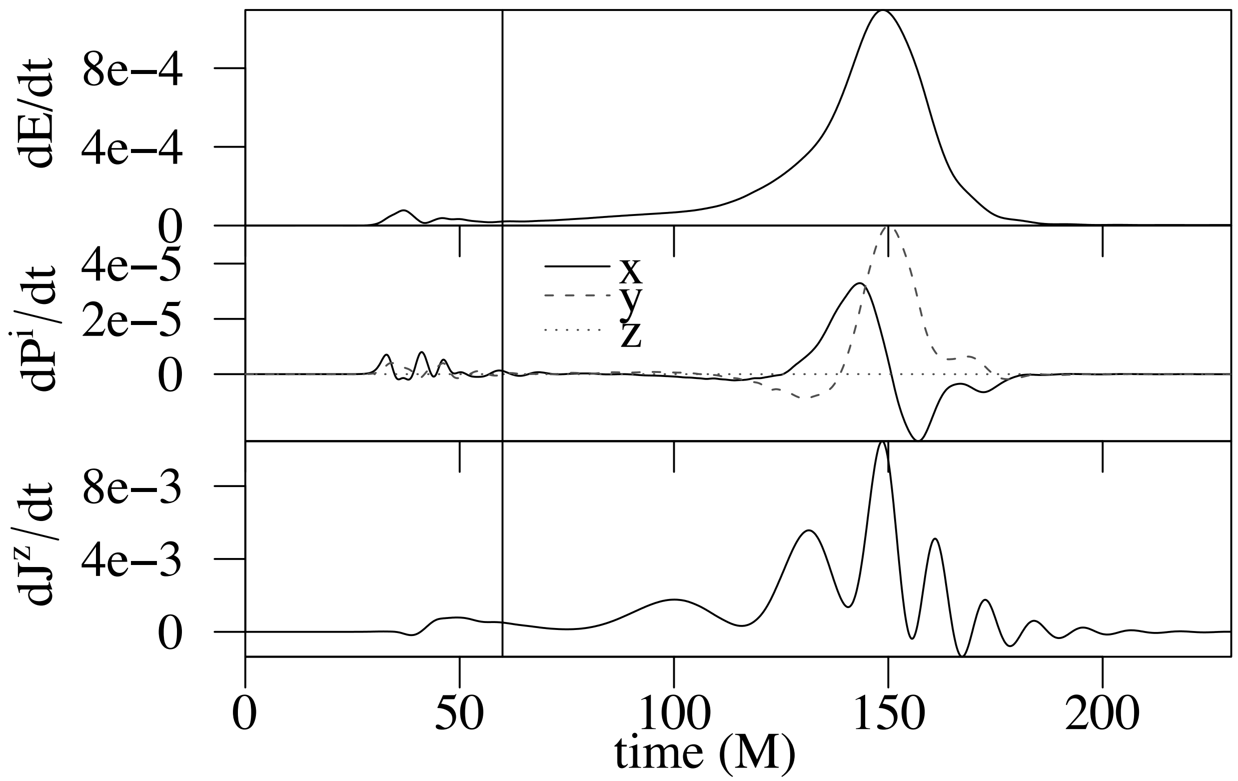
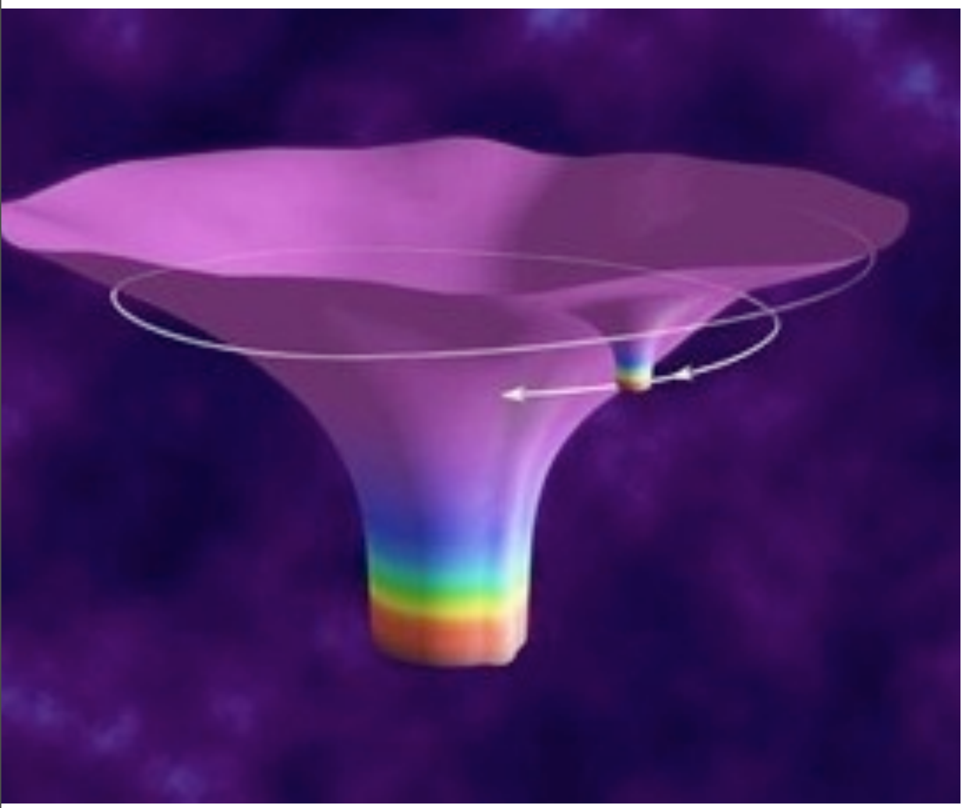
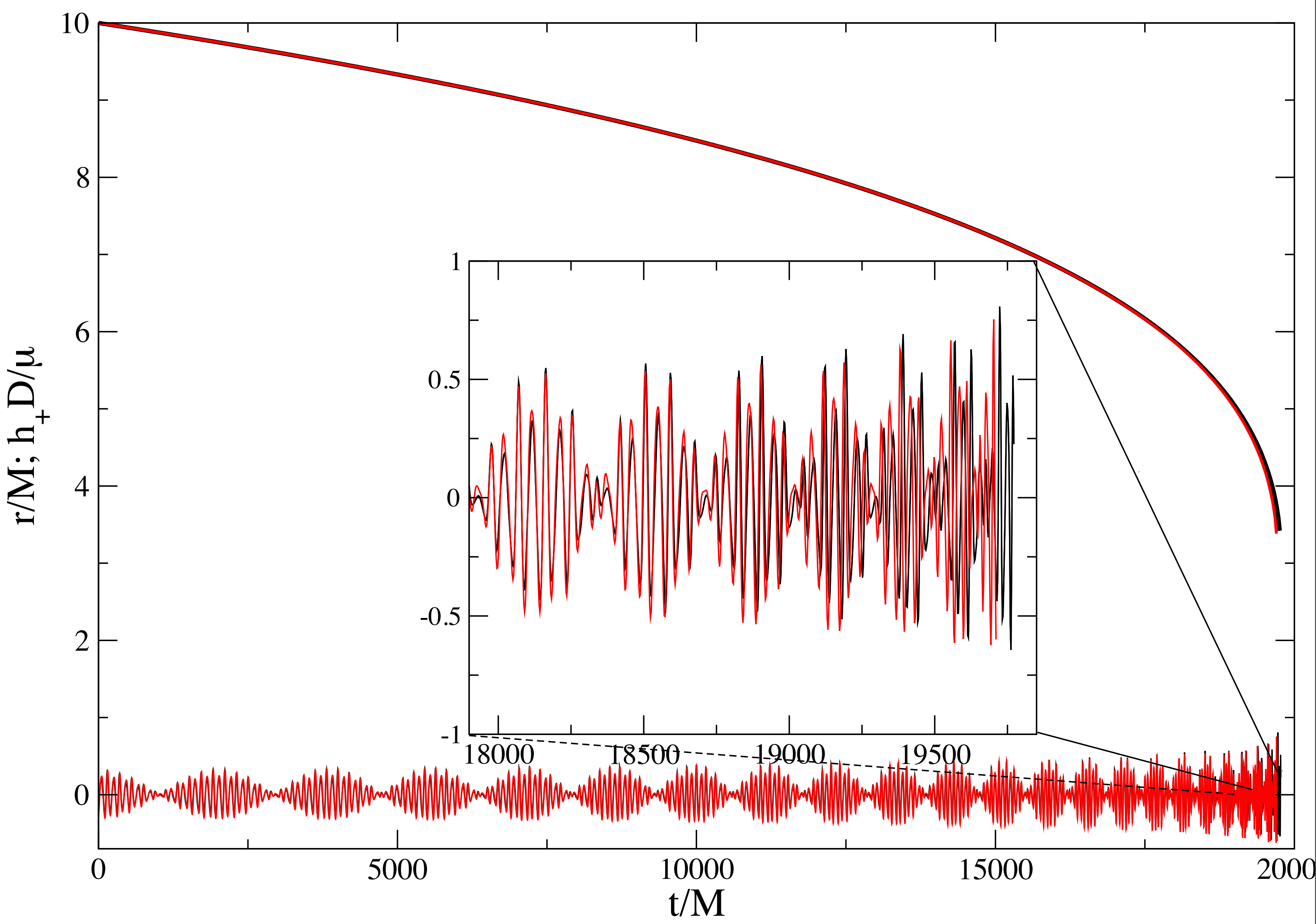


F. Hermann et al.; ApJ 661 2007

Black hole spectroscopy

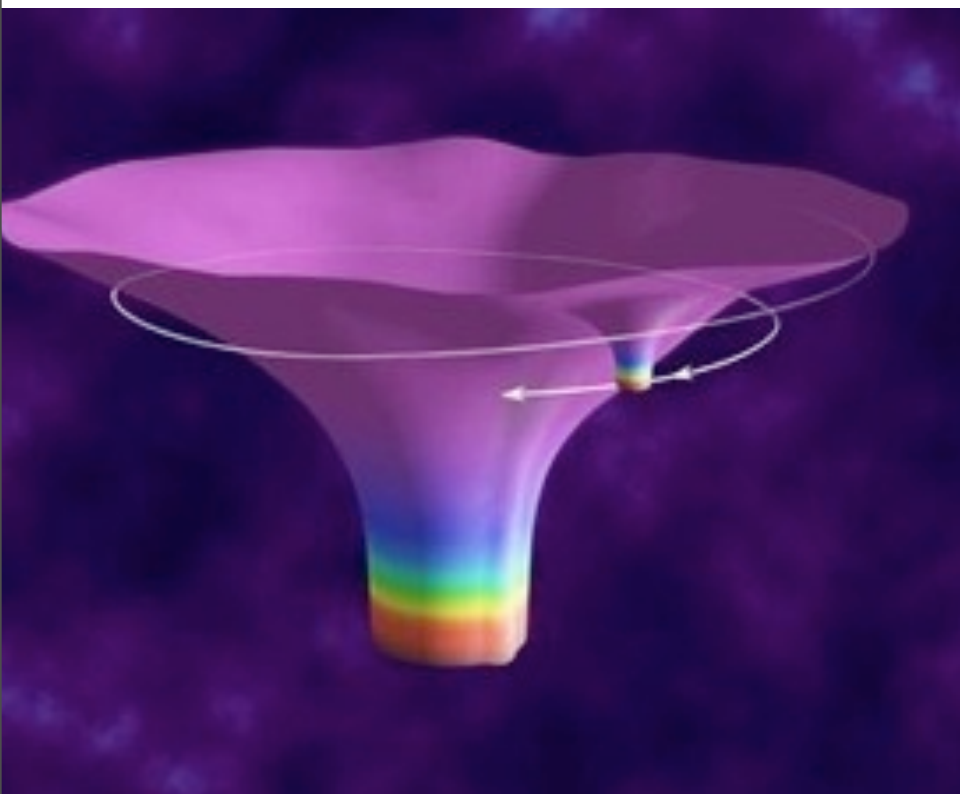


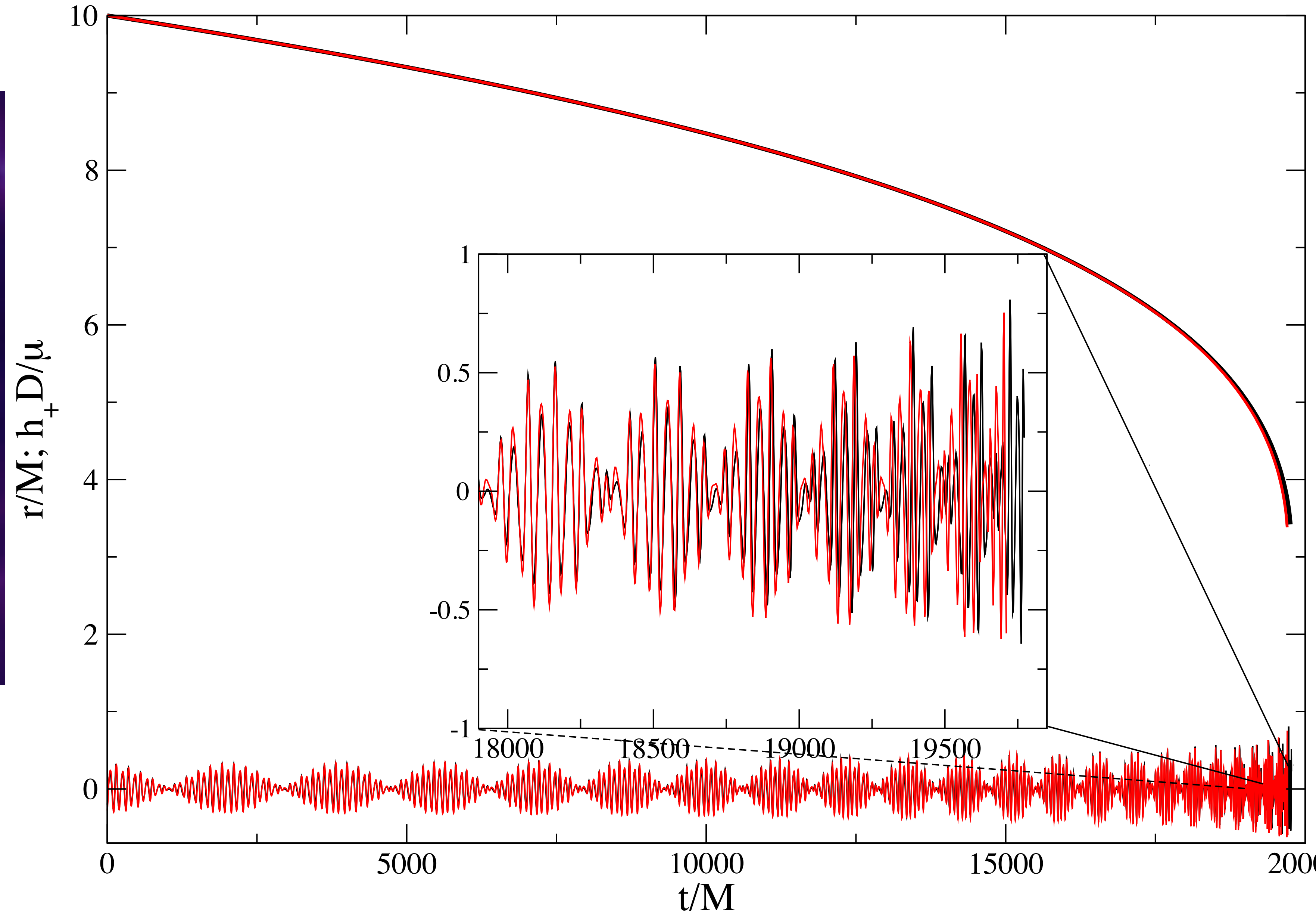


"test the *nature of massive compact bodies within general relativity*"

S. Hughes: arXiv:gr-qc/0608140

Black hole spectroscopy





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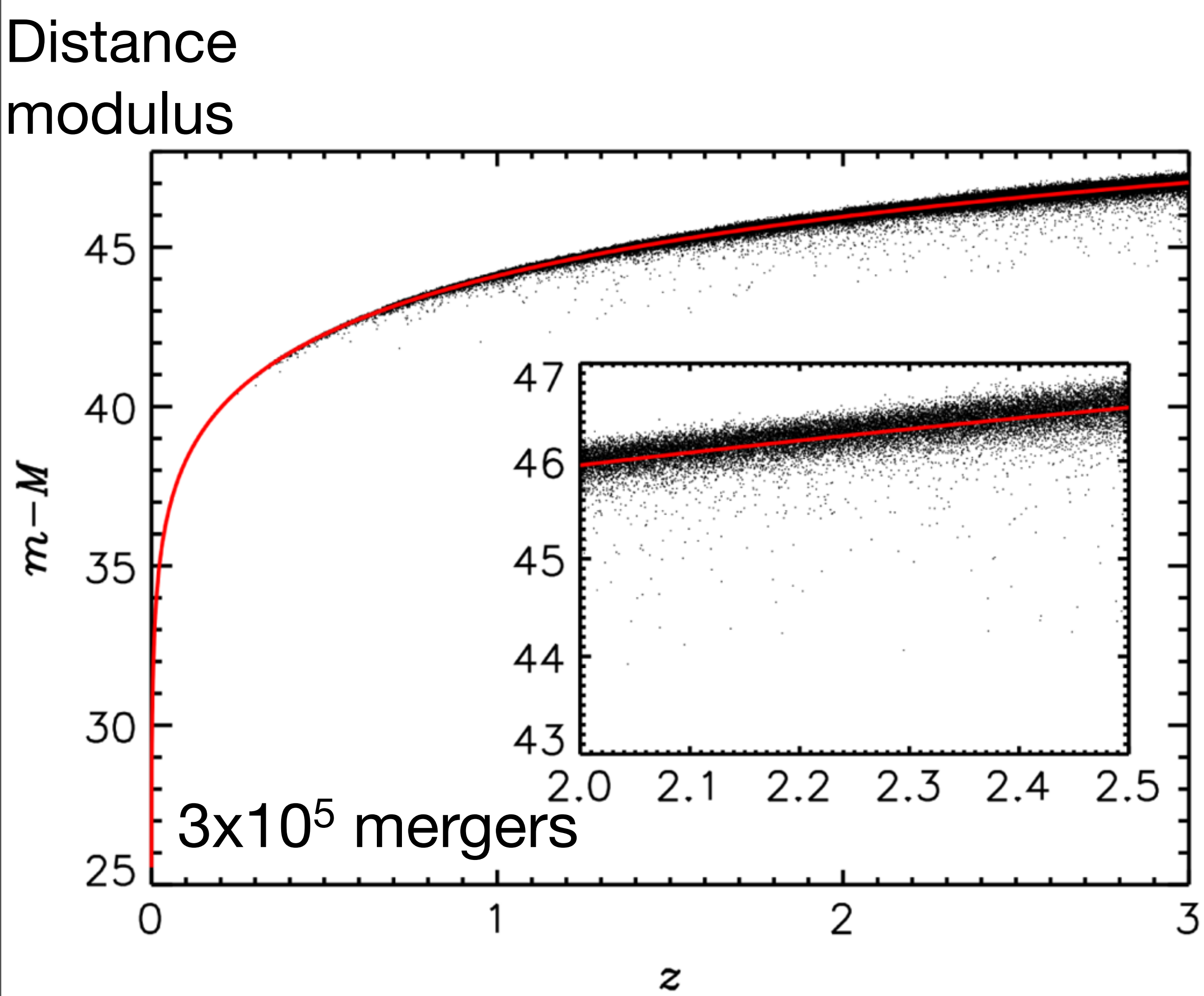
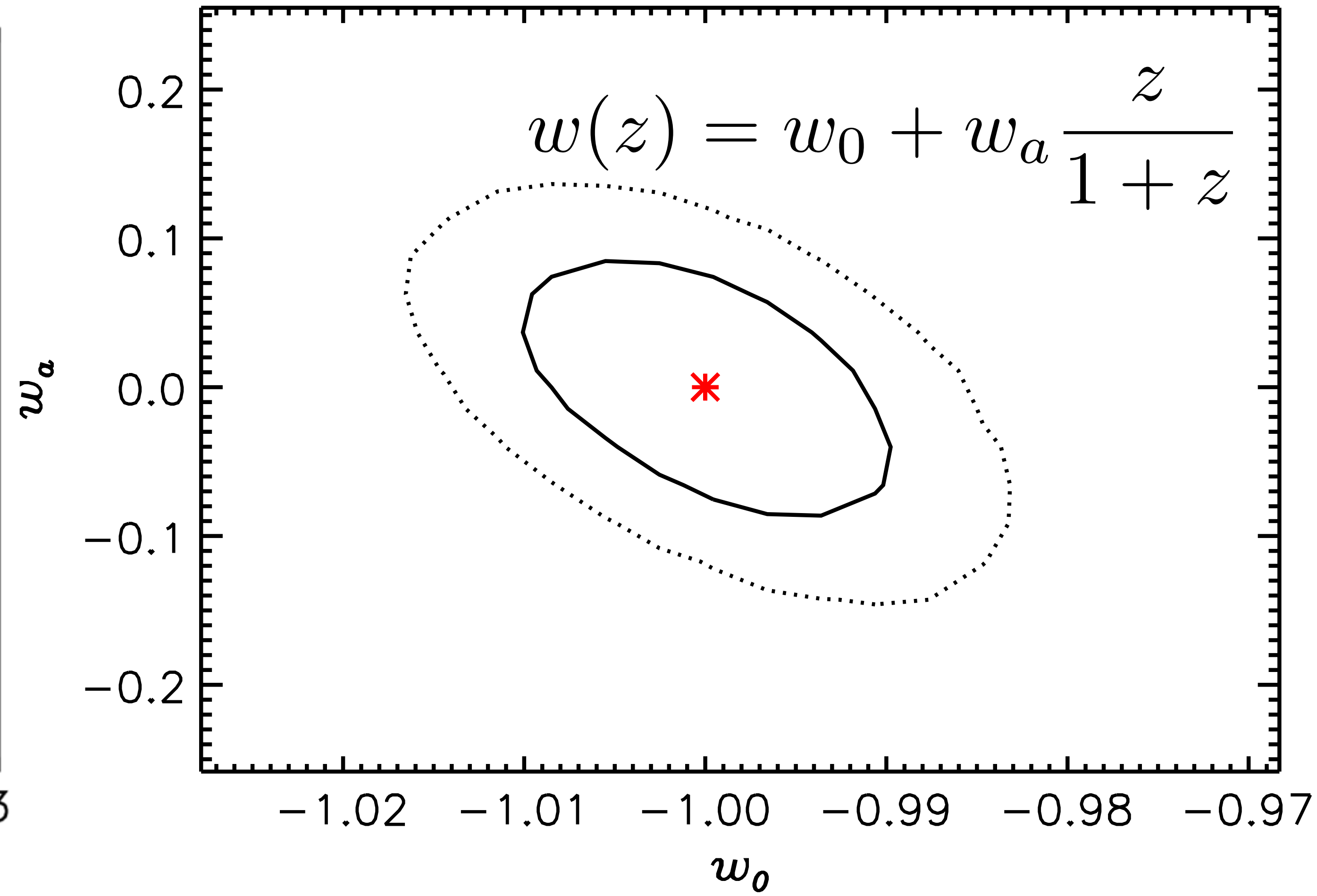
GW Cosmology

Ultrahigh precision cosmology from gravitational waves

C. Cutler and D Holz PRD80, 104009





simulation of NS/NS binaries w/ WMAP5 cosmology as detected by the Big Bang Observer 2nd generation satellite mission

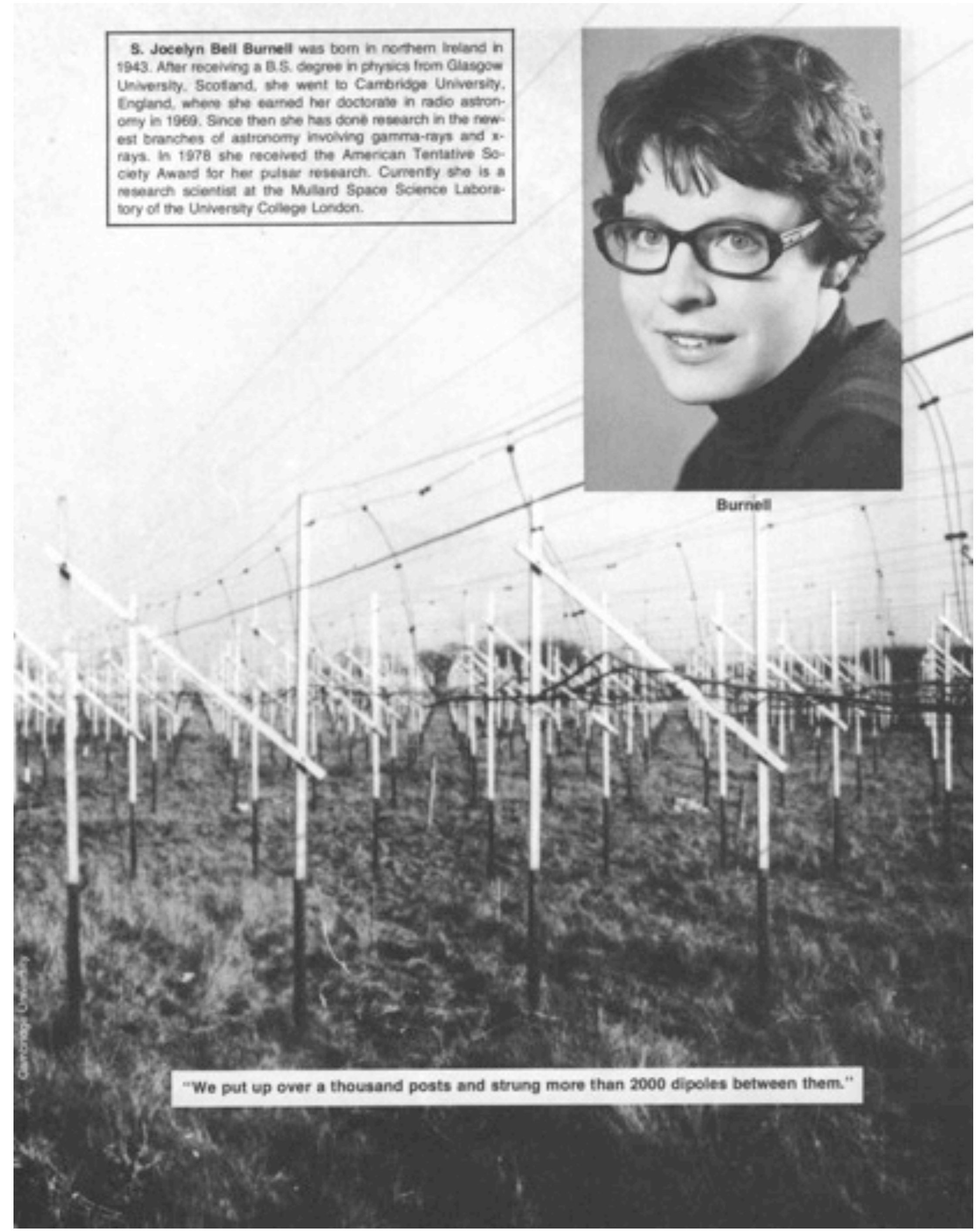
GW Astronomy

Pulsar timing

LISA/LPF/GRACE-C

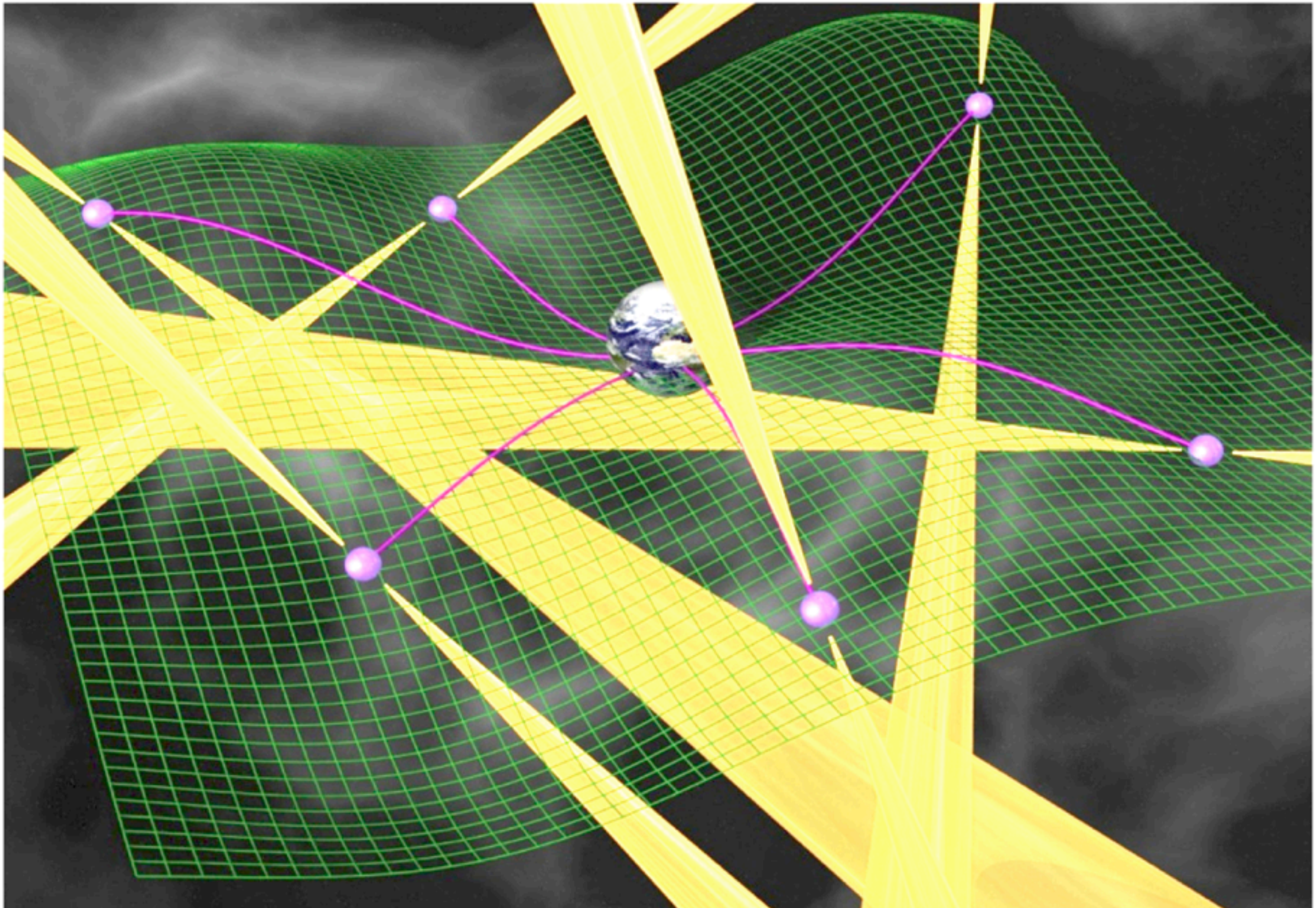
LIGO/Virgo/GEO

Future Detectors



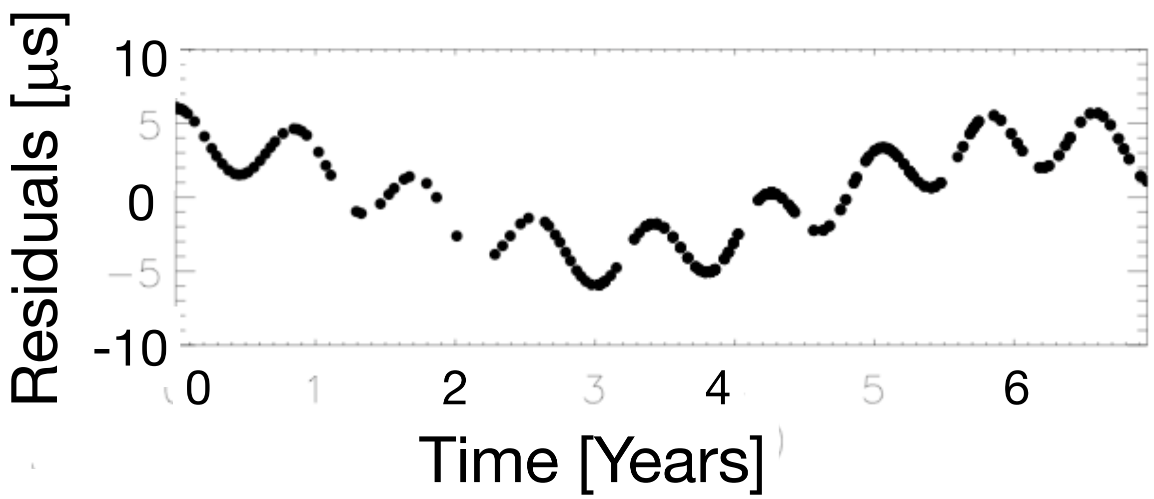
Dame Jocelyn Bell Burnell and the Mullard Radio Astronomy Observatory

Pulsar timing

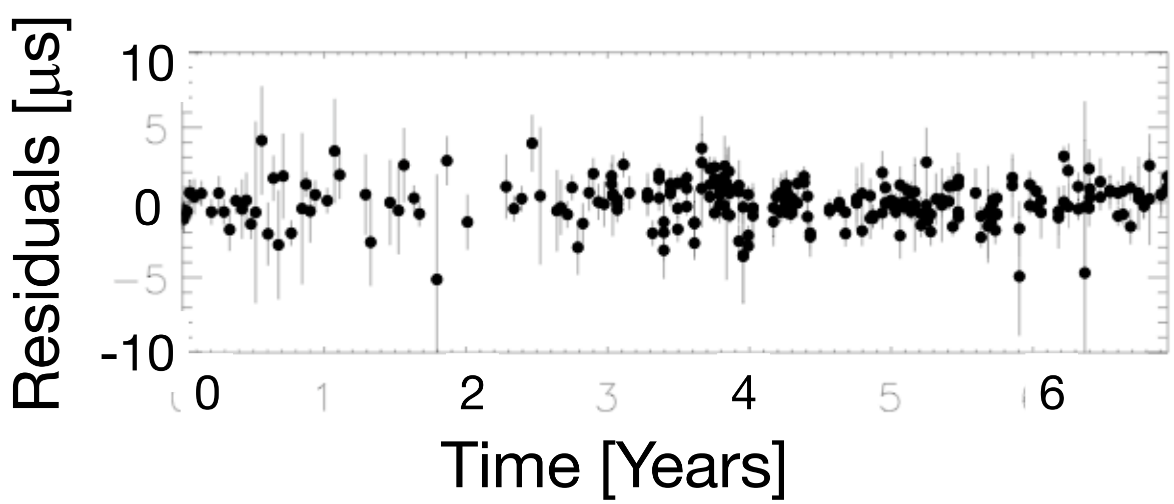


cf. Detweiler ApJ 1979

$$\left[\frac{D}{100\,Mpc}\right] = \left[\frac{M}{10^9\,M_\odot}\right]^{5/3}\left[\frac{P}{1\,yr}\right]^{1/3}\left[\frac{100\,ns}{\sigma_\tau}\right]$$

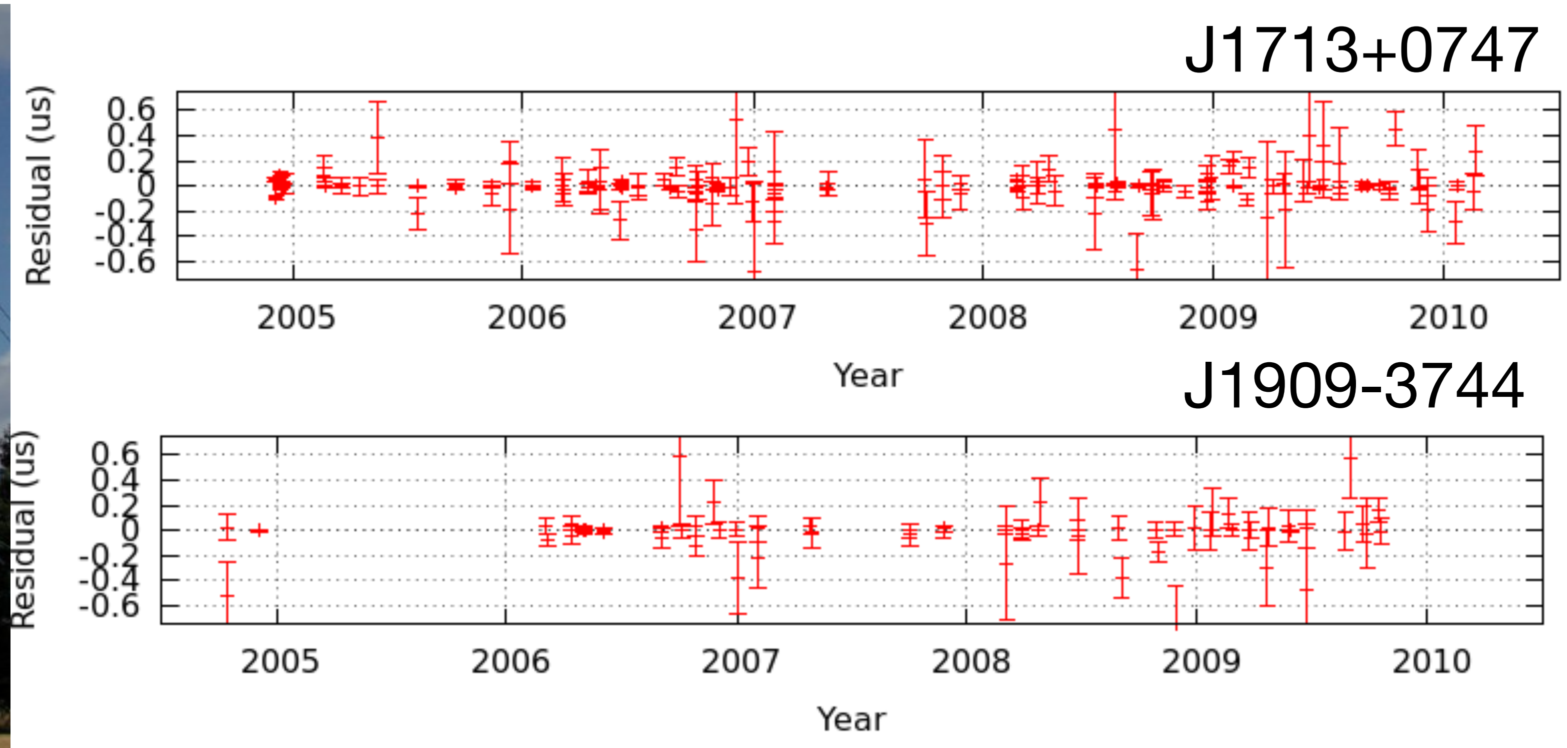


Simulated residuals due to 3c66b



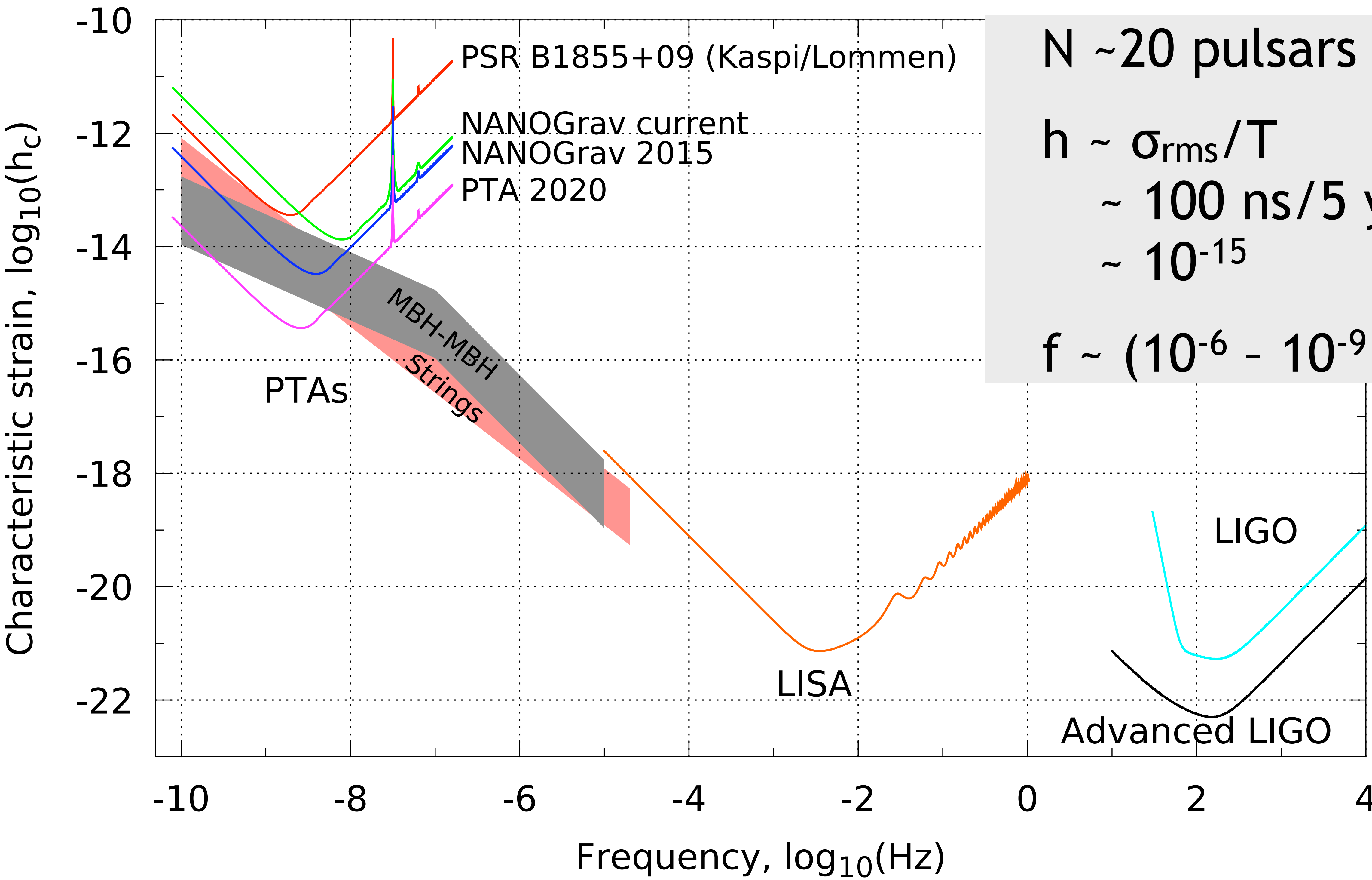
Data from Kaspi, Taylor, Ryba 1994

Constraining the Properties of Supermassive Black Hole Systems Using Pulsar Timing: Application to 3c 66b, Jenet et al. ApJ 2004



NanoGrav timing 23 pulsars w/ Green Bank and Arecibo

2 have 100 ns residuals



N ~20 pulsars

$h \sim \sigma_{rms}/T$

$\sim$ 100 ns/5 years

$\sim 10^{-15}$

$f \sim (10^{-6} - 10^{-9}$ Hz)

Figure by P. Demorest (see arXiv:0902.2968)

PIRE and IPTA

International Pulsar Timing Array

Image source, clockwse from upper left: http://www.gb.nrao.edu/; http://www.astron.nl/; http://www.mpifr-bonn.mpg.de/english/index.html; http://gmrt.ncra.tifr.res.in/; http://www.flickr.com/photos/shami_chatterjee/455275921/; http://www.srt.inaf.it/; http://www.obs-nancay.fr/; http://www.jb.man.ac.uk/; http://www.naic.edu/

Partnerships for
International
Research and
Education

$6.5M / 5yr NSF award for NanoGrav and the IPTA

Actively seeking collaborators:

www.ipta4gw.org

GW Astronomy

Pulsar timing

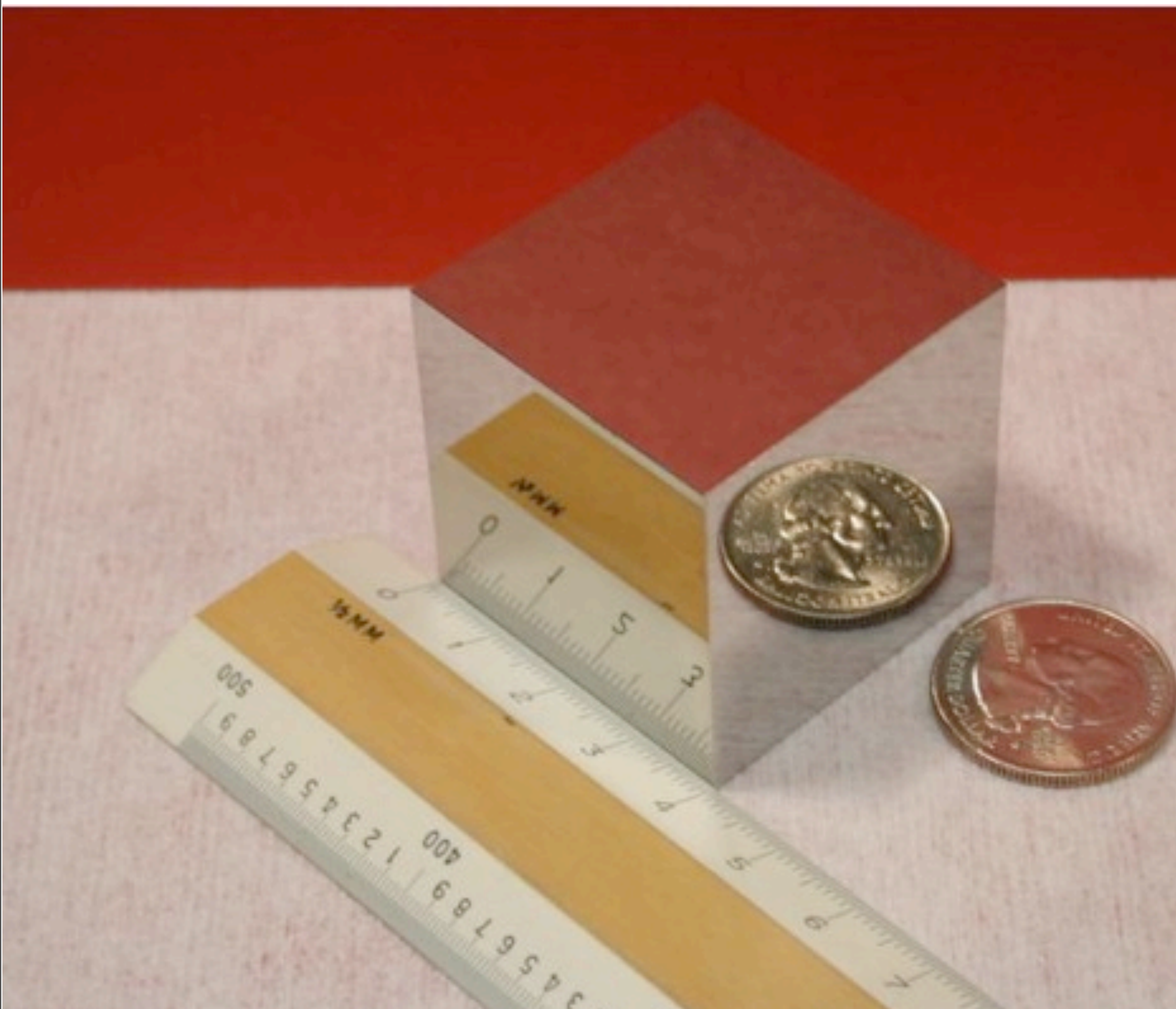
LISA/LPF/GRACE-C

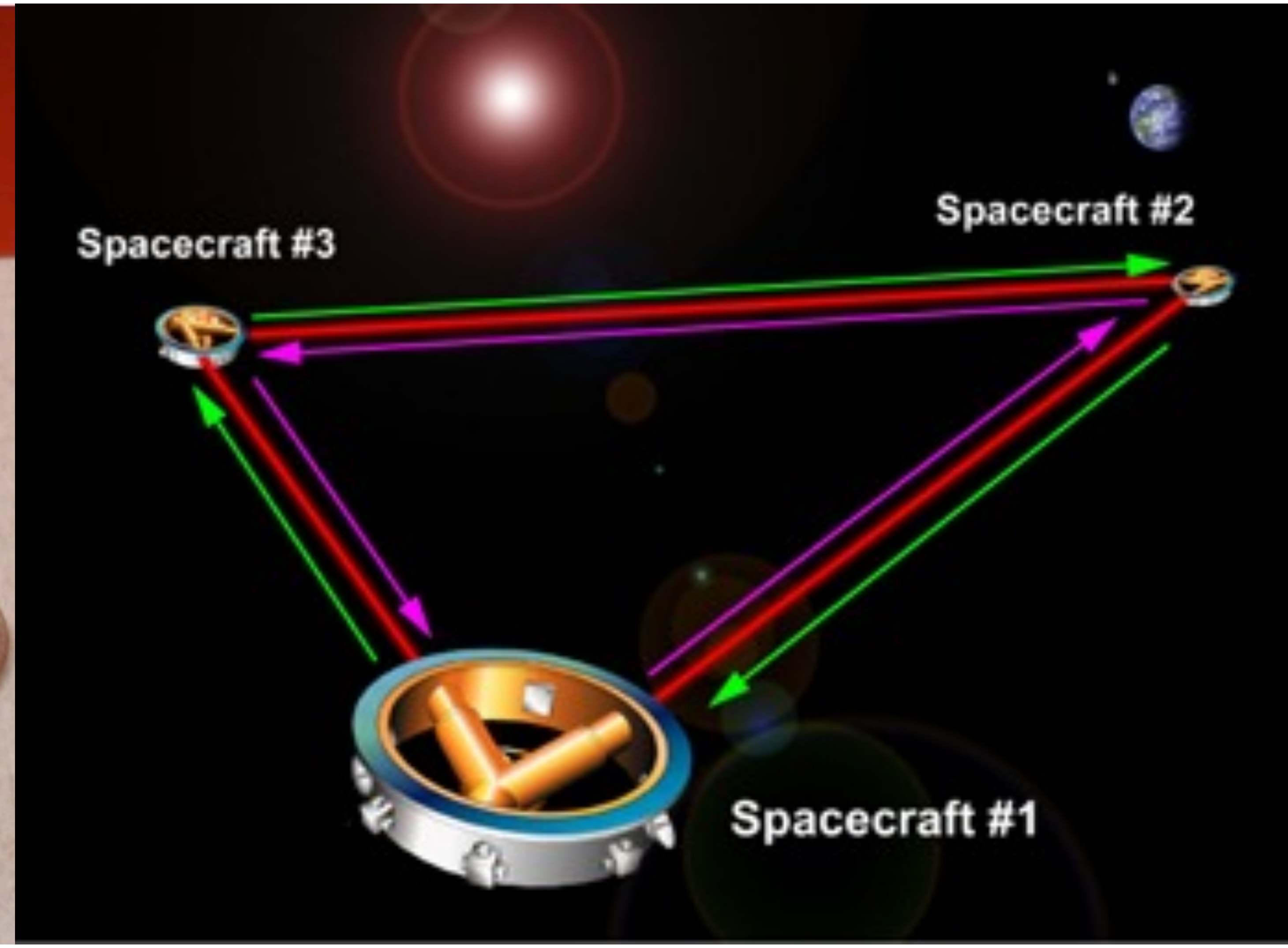
LIGO/Virgo/GEO

Future Detectors

Kip Thorne c. 1970
image from KipFest 2000

GW in Space

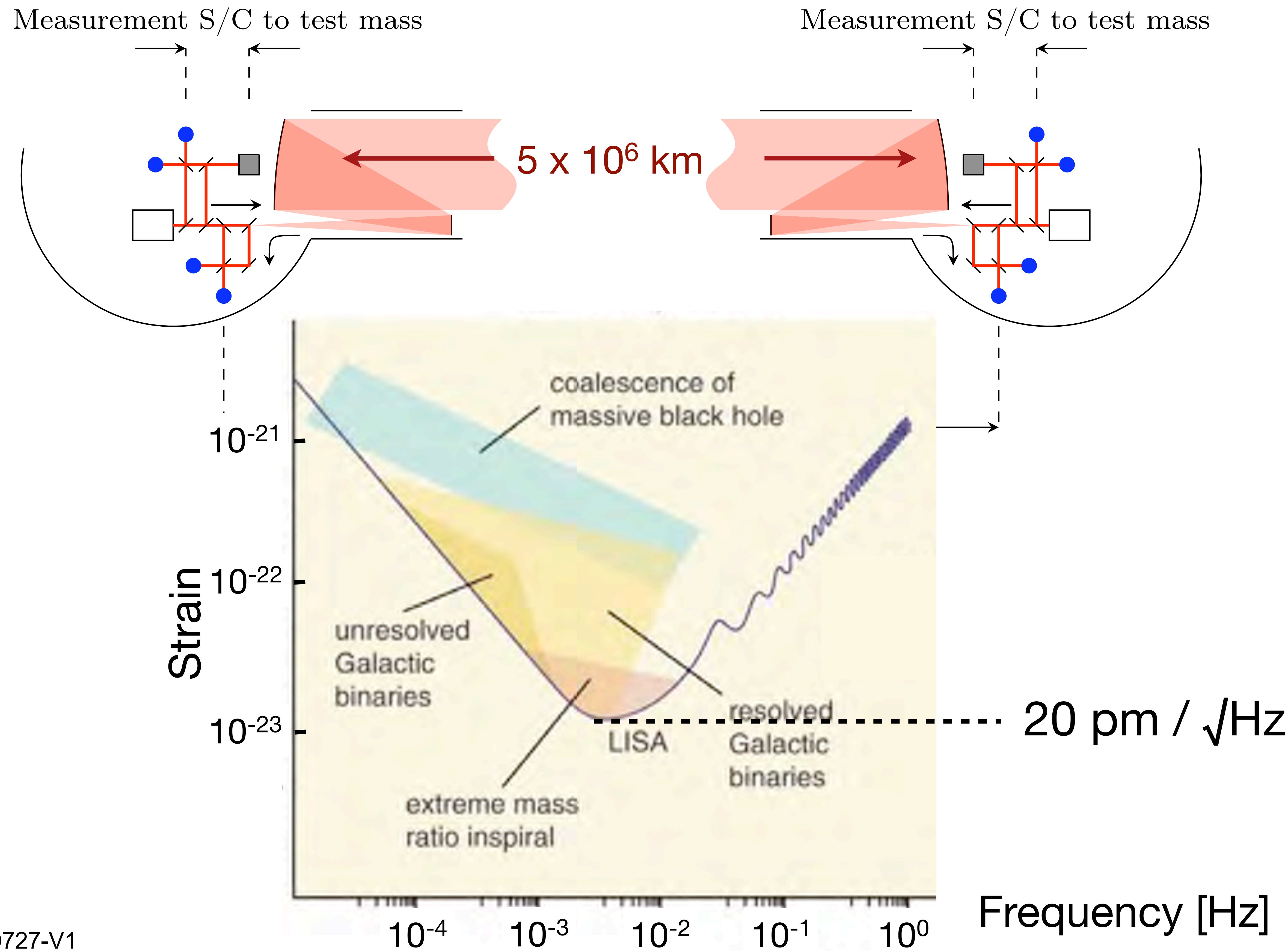




"LISA promises to open a completely new window into the heart of the most energetic processes in the universe, with consequences fundamental to both physics and astronomy." -National Academy

National Academy's 2008 "Beyond Einstein"

Laser Interferometer Space Antenna



LISA is dead...

April 8, 2011. Based on discussions with the European Space Agency (ESA) at the recent ESA-NASA bilateral meeting, we can provide the following information concerning LISA.

LISA was competing with X-ray and outer-planets missions for the L1 opportunity in ESA's Cosmic Vision Programme (2015-2025). *The U.S. decadal survey rankings and NASA's constrained out-year resources, as projected in the President's FY12 Budget Request, have led ESA to conclude that none of the three mission concepts were feasible* within the Cosmic Vision L1 schedule.

ESA has ended the study of LISA and the other concepts as partnerships at the scale proposed in the New Worlds New Horizons decadal survey (NWNH). ESA has [...] Revised mission concepts from the three science areas will be considered in a selection process commencing in February 2012.

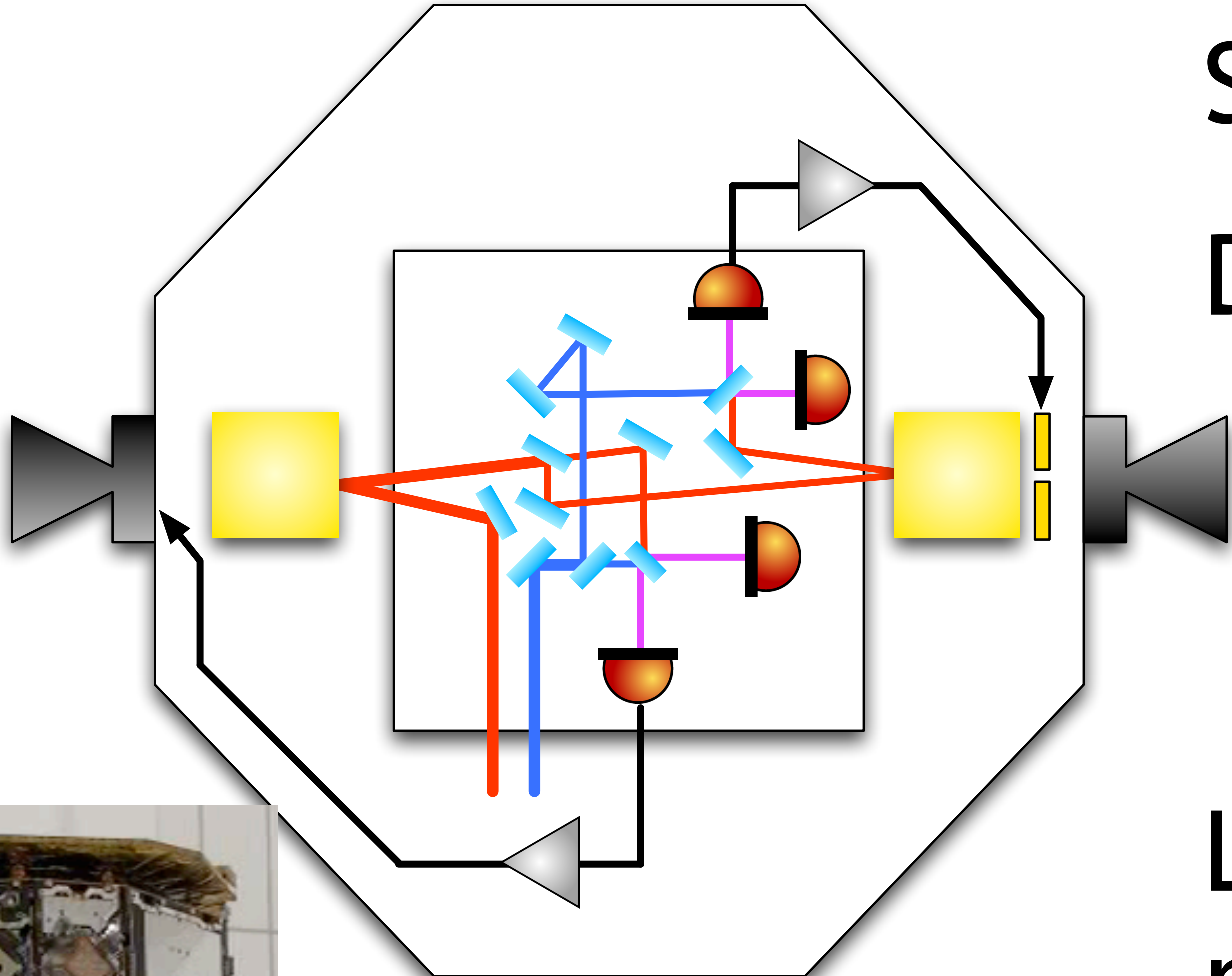
http://lisa.jpl.nasa.gov/

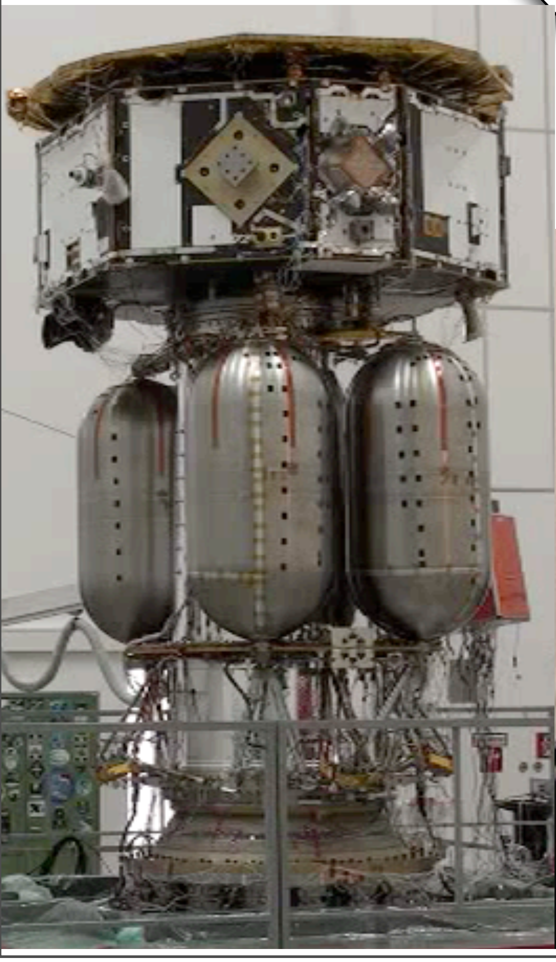
… Long live LISA

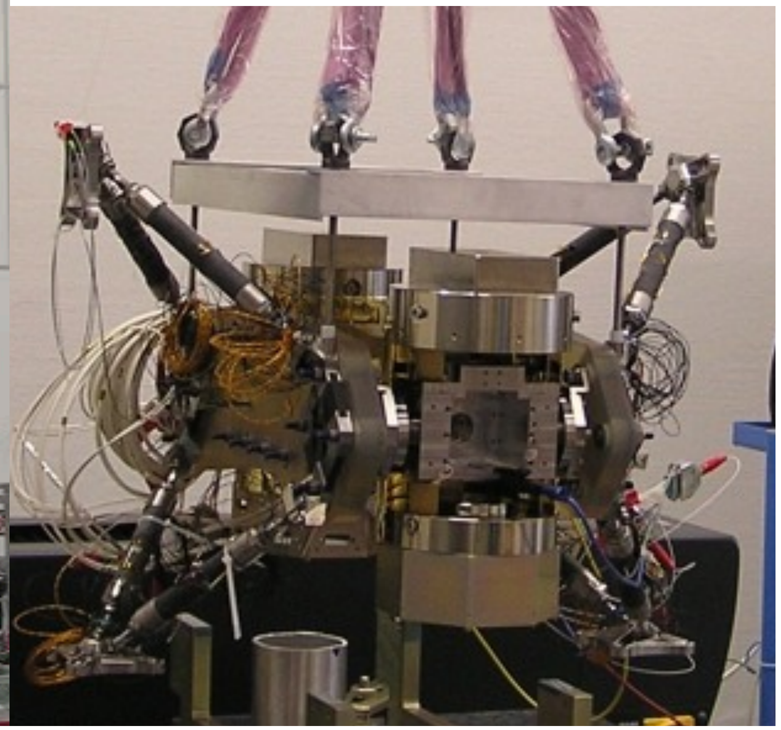
- ESA, with the LISA Science Working Team, will review potential changes to the mission:
  - mission requirements: sensitivity; orbits; arm length; duration; operations;
  - architecture: mothership/daughtership; 2 arm
  - payload: optical complexity; single/double TM;
  - propulsion module: based on selected orbit
  - launch vehicle: single/multiple launch scenario
- LISA Pathfinder will continue
- NASA space interferometry will continue

http://sci.esa.int/

LISA Pathfinder







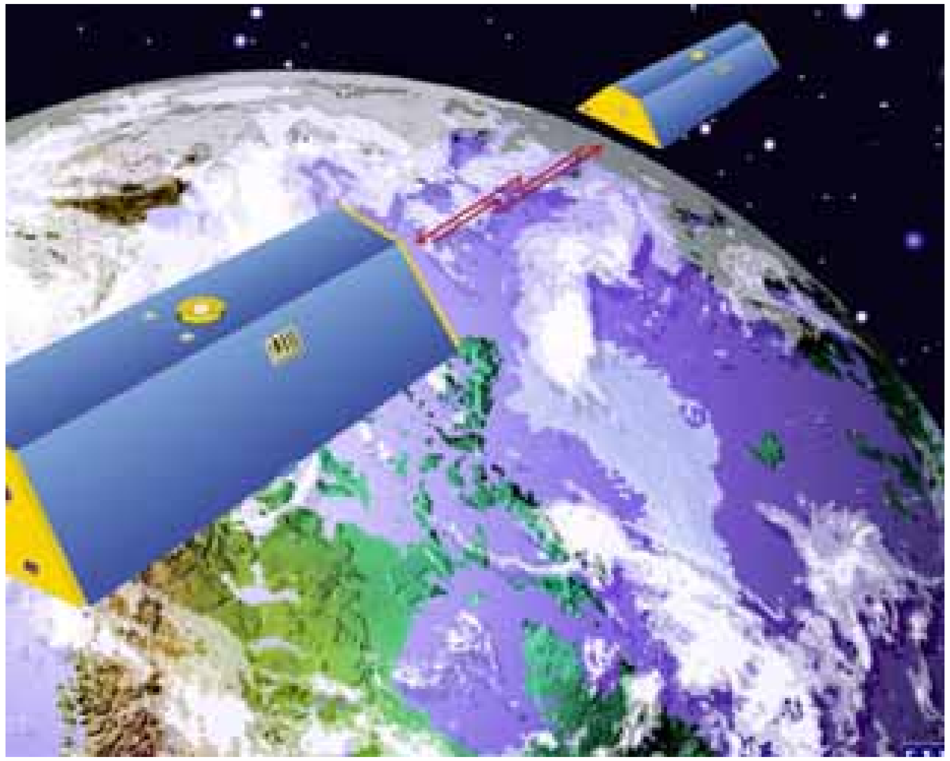
Single spacecraft

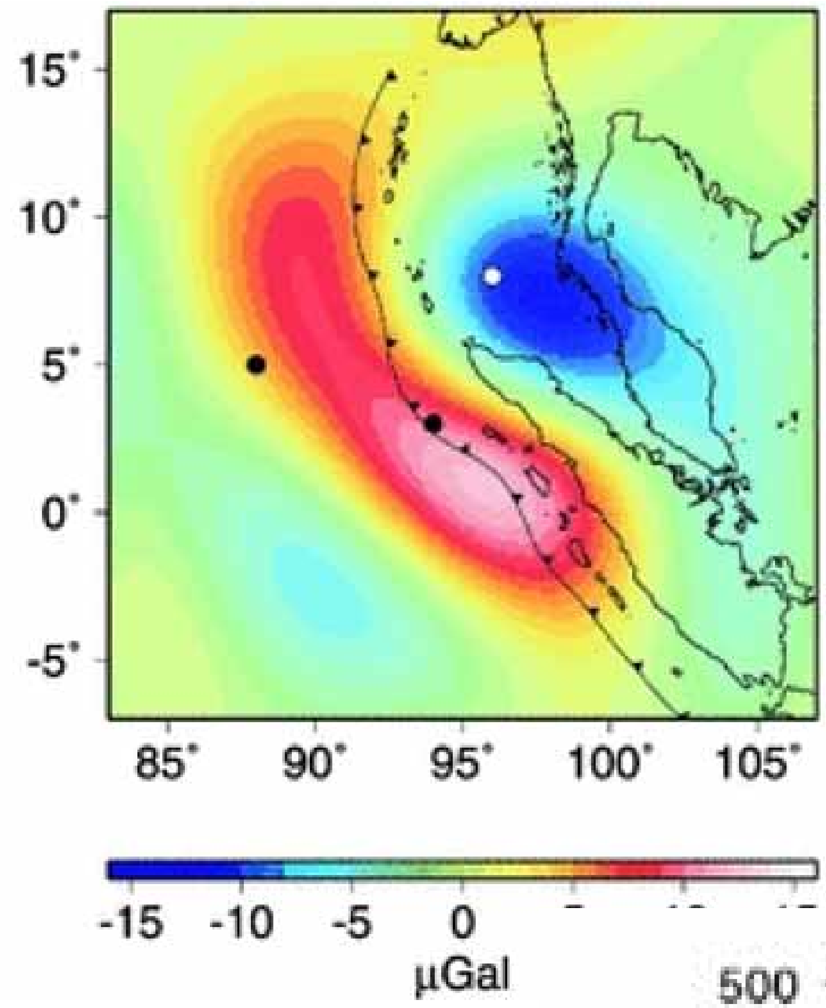
Demonstrate:
- LISA inertial reference
- Drag-free control
- micro-Newton thrust

LTP ground tests exceed requirements

Launch 2014

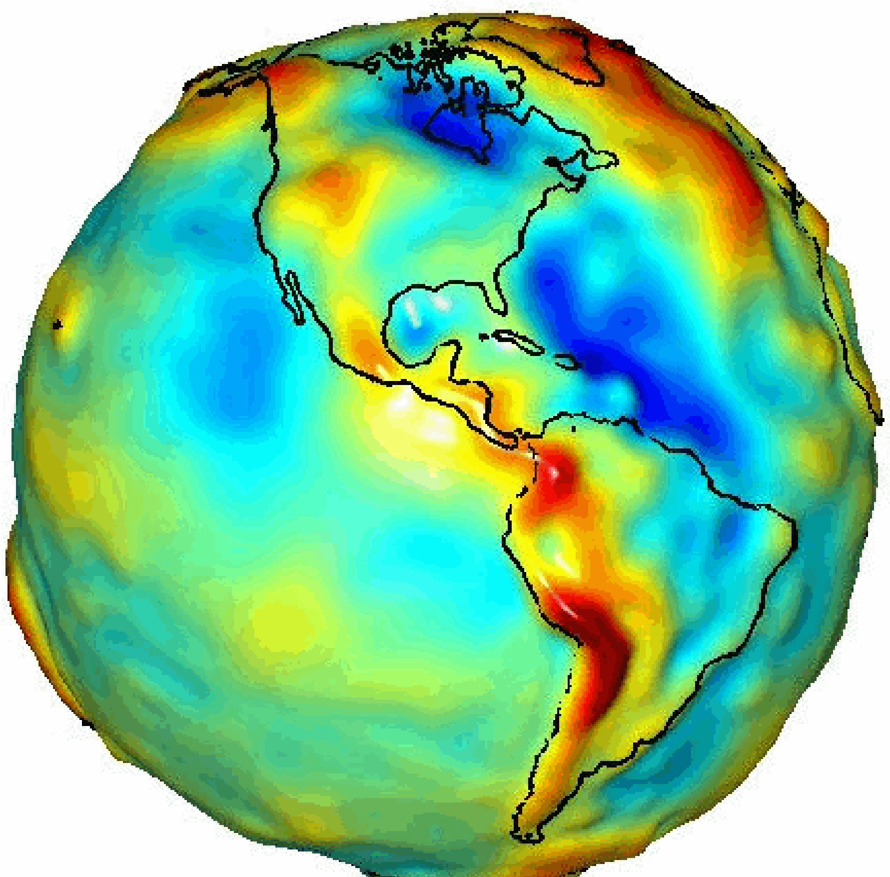
GRACE-C

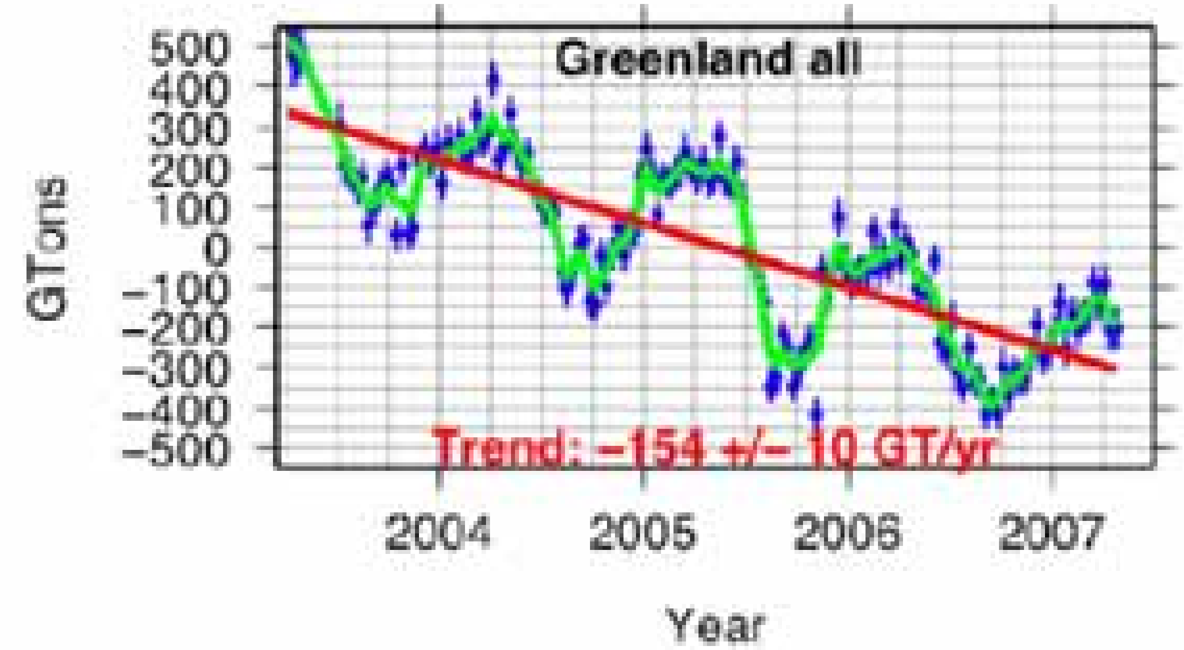




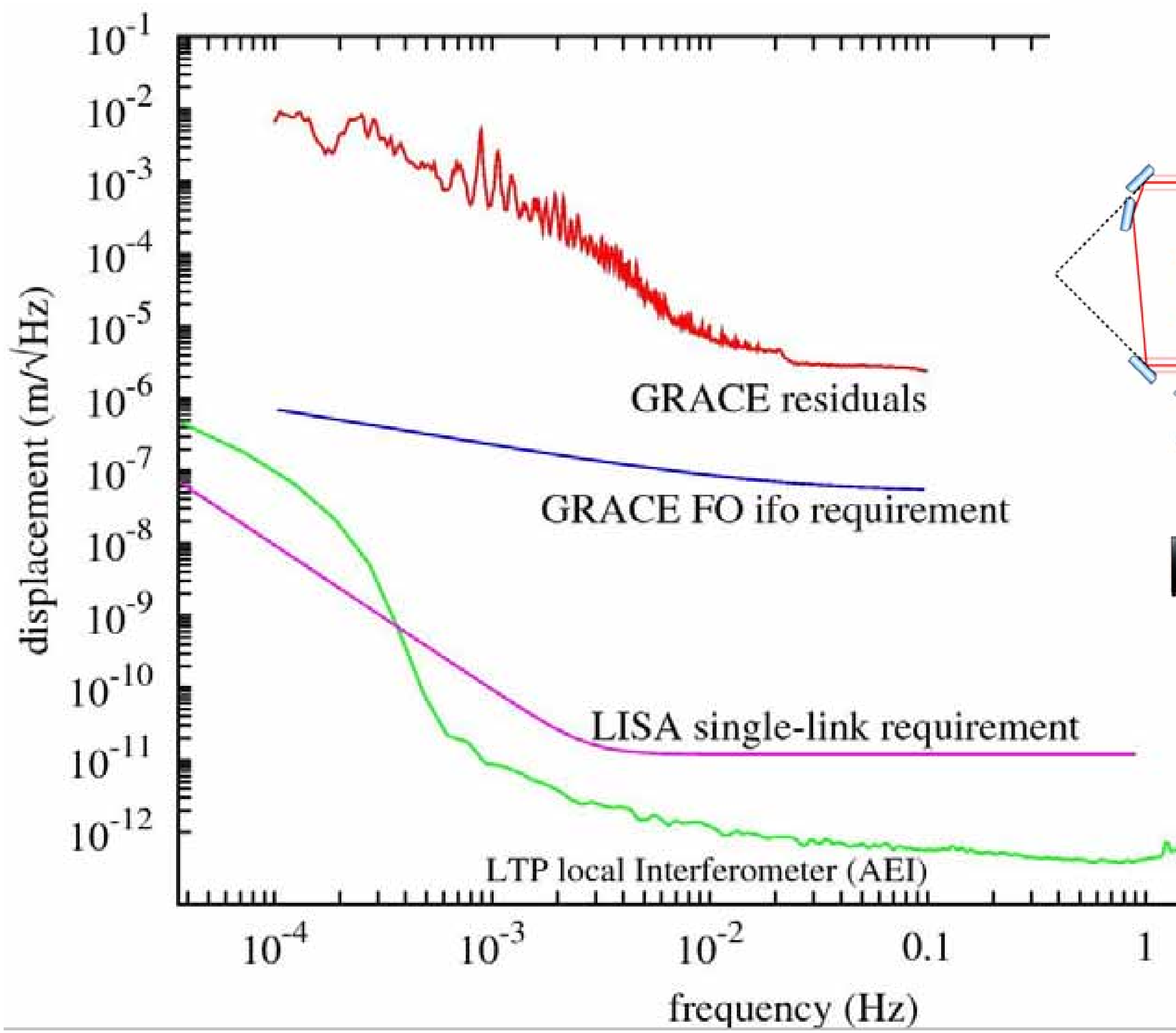
Sumatra earthquake

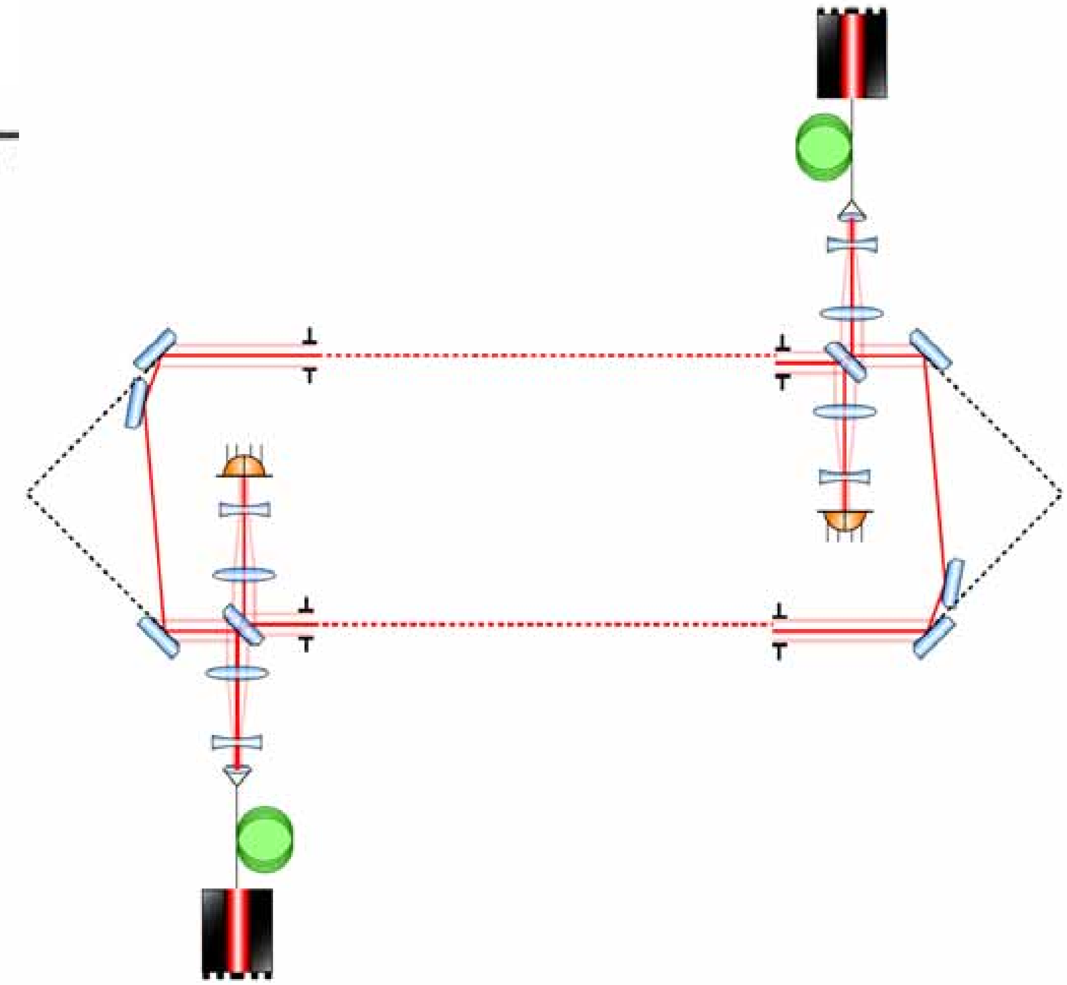
Gravity
Recovery
And
Climate
Explorer





Luthcke et al 2007





NASA+
40x sensing gain
Launch in 2015

GW Astronomy

Pulsar timing

LISA/LPF/GRACE-C

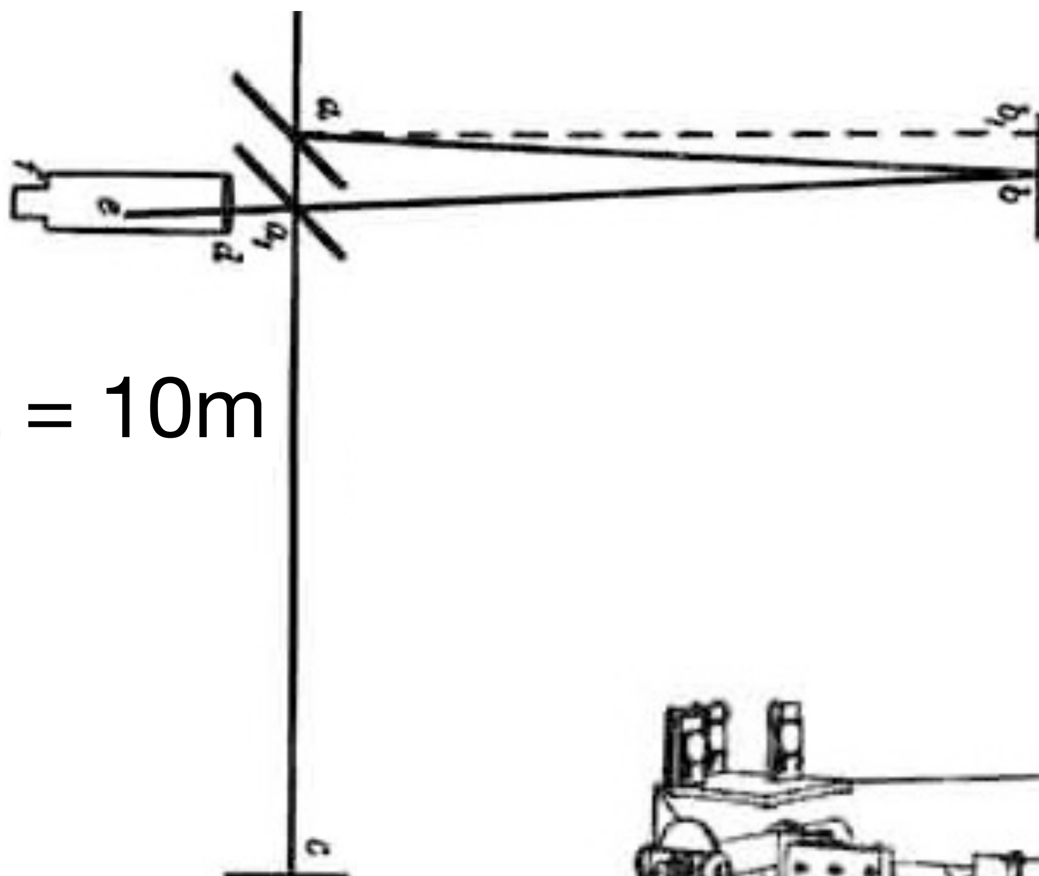
LIGO/Virgo/GEO

Future Detectors

Rainer Weiss (top) and Ronald Drever with a Weber bar at the LIGO Hanford Observatory, 2002

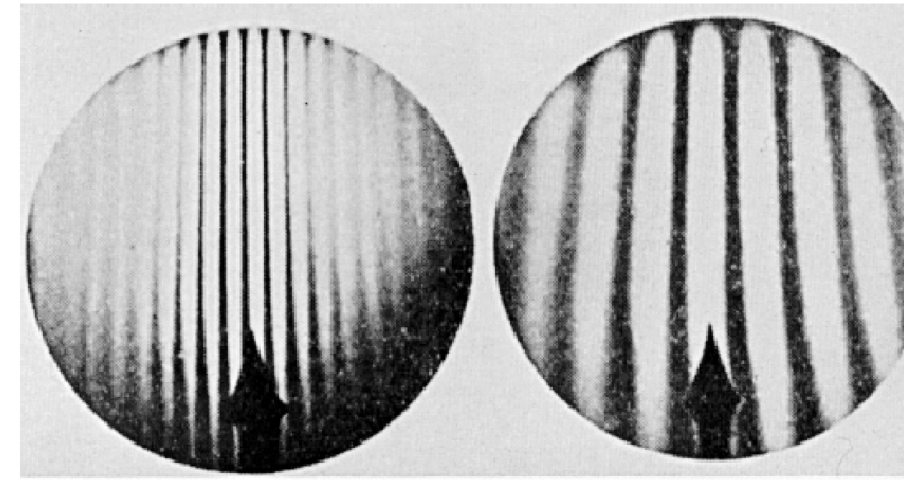
GW 0.01

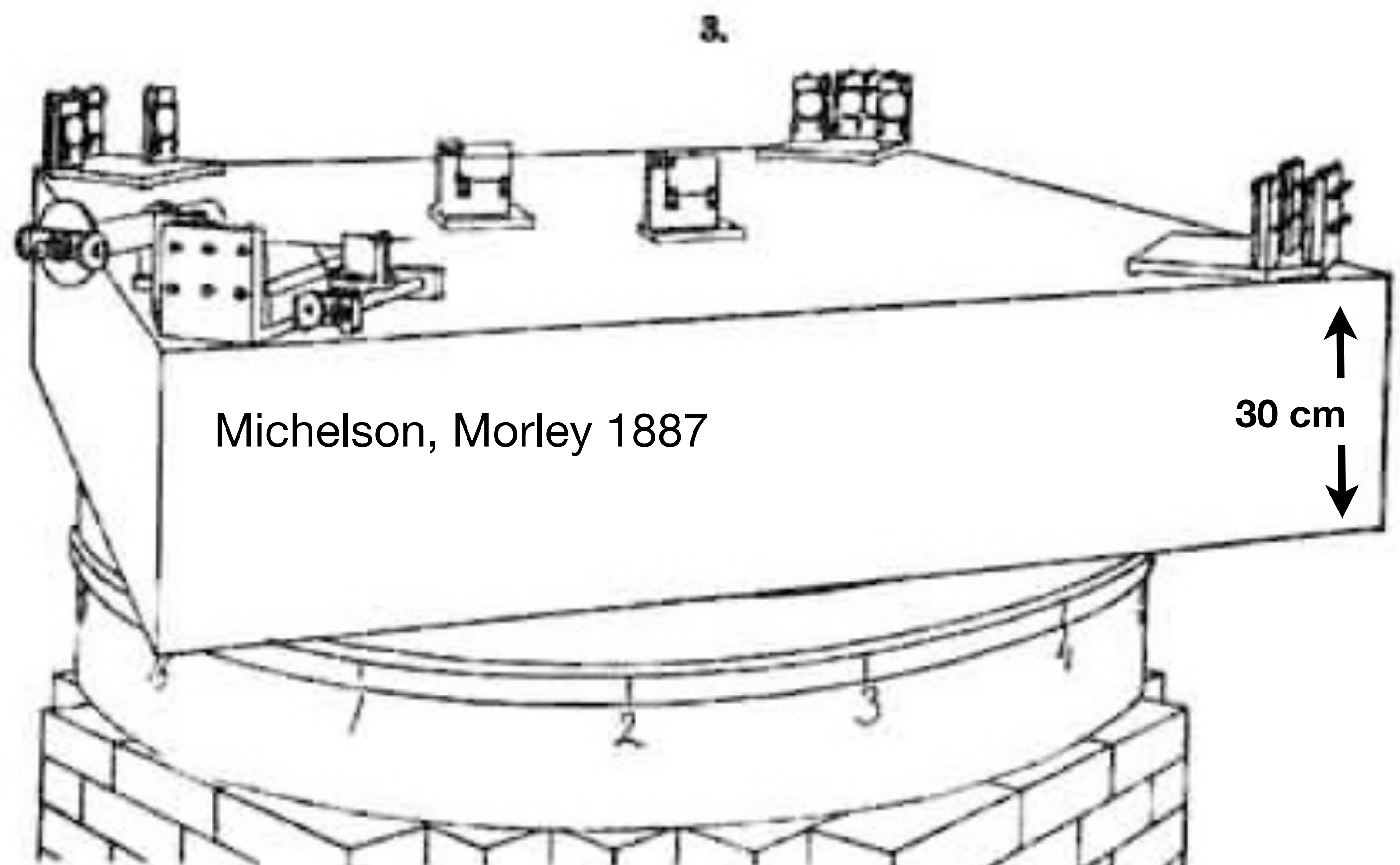
~ 1 mW



L = 10m

Albert A. Michelson





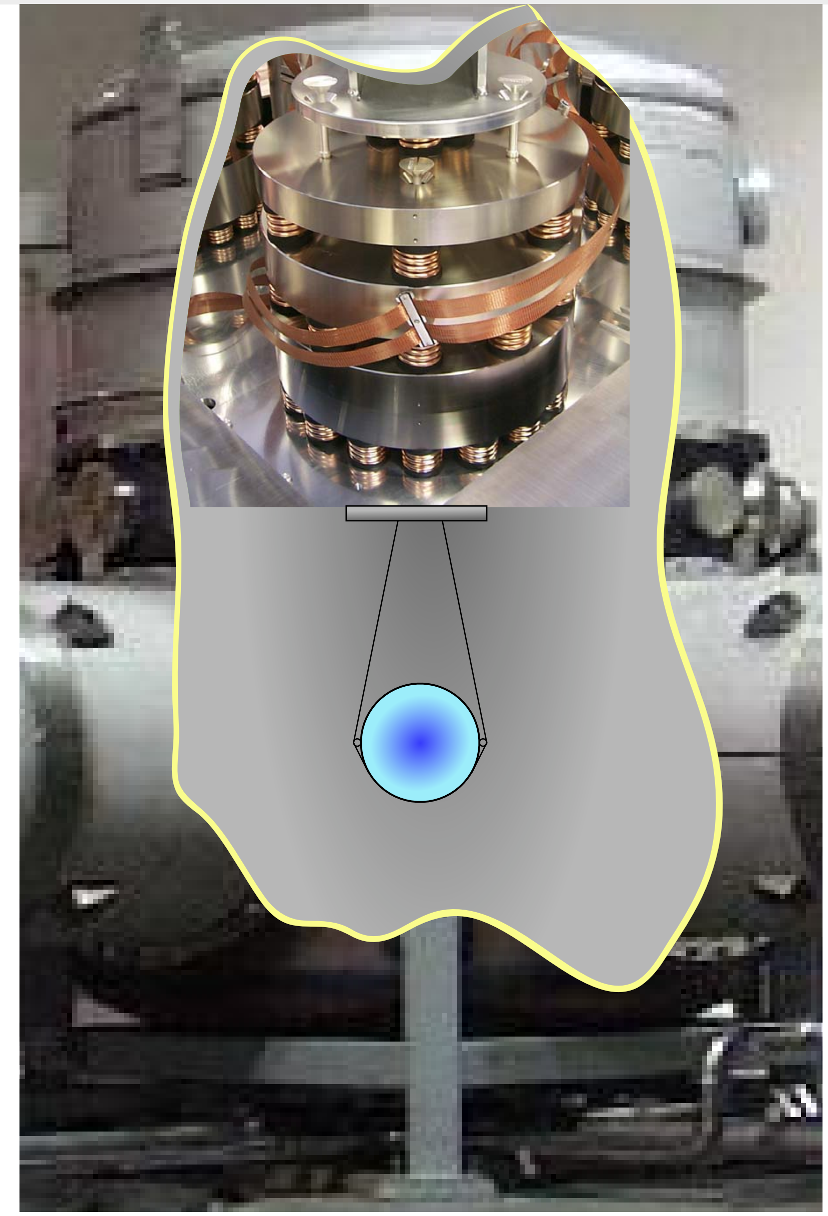
Michelson, Morley 1887

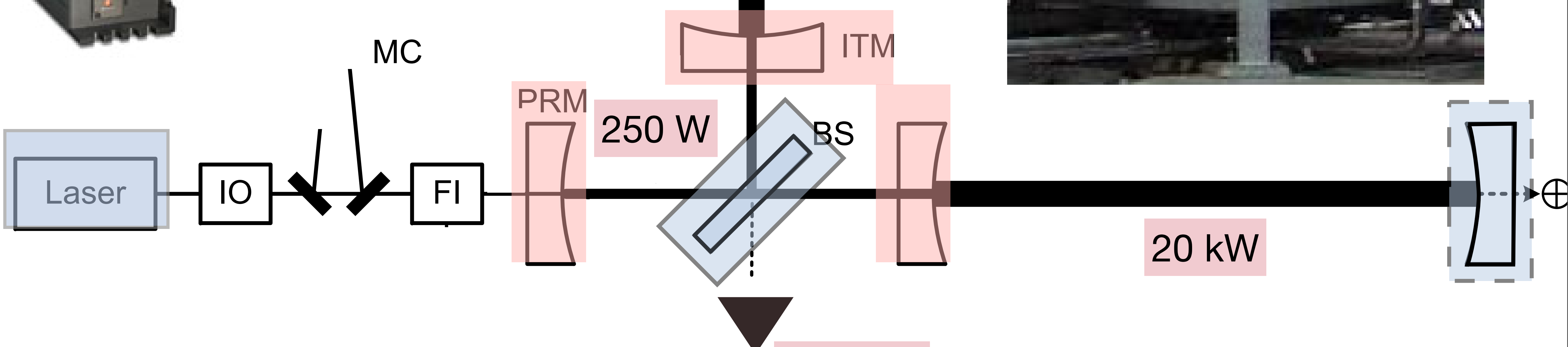
$0.02\ \lambda = 20$ nm

$h \sim 2 \times 10^{-9}$

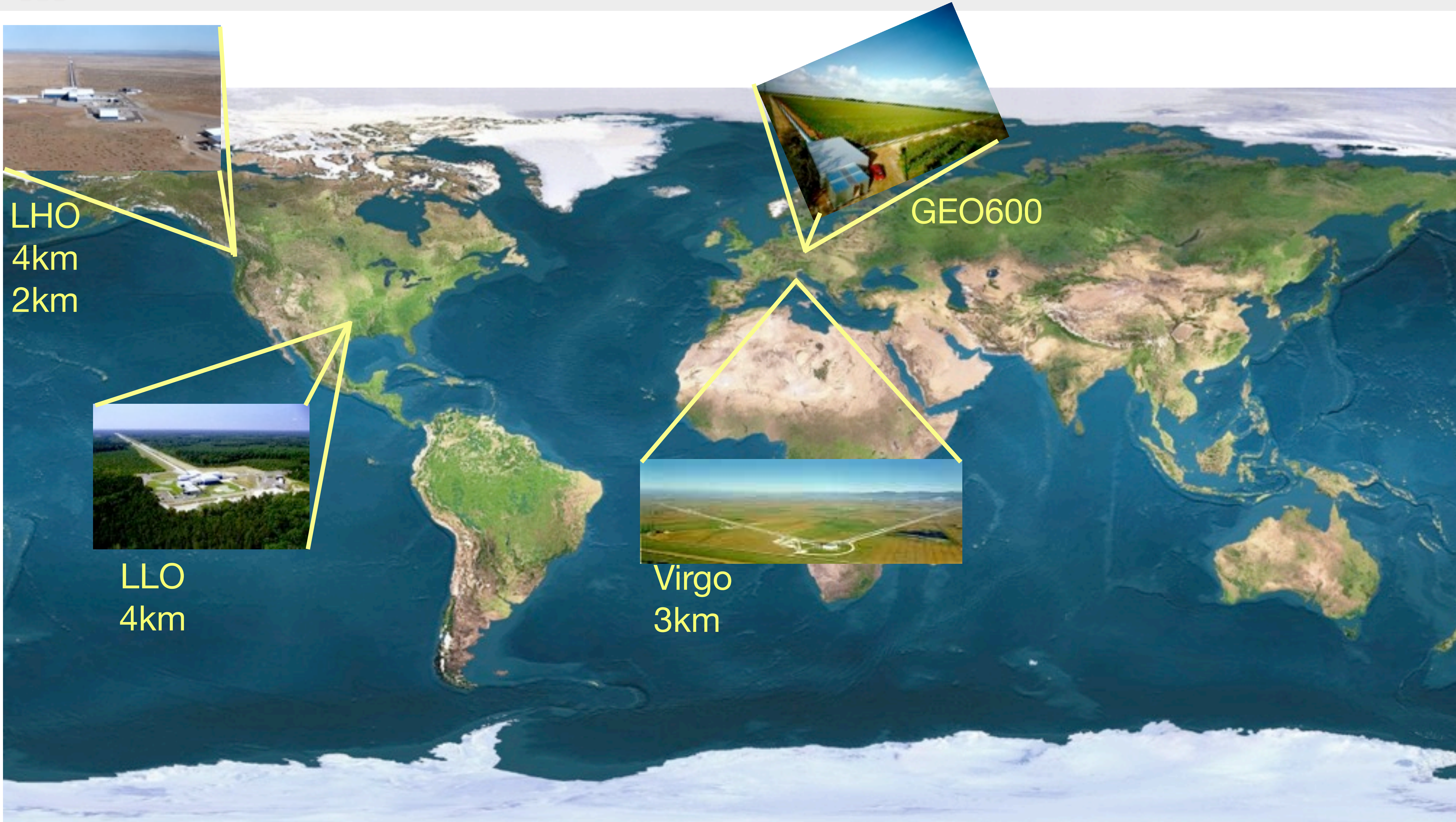
Initial LIGO

10 W Nd:YAG
MOPA @ 1064nm

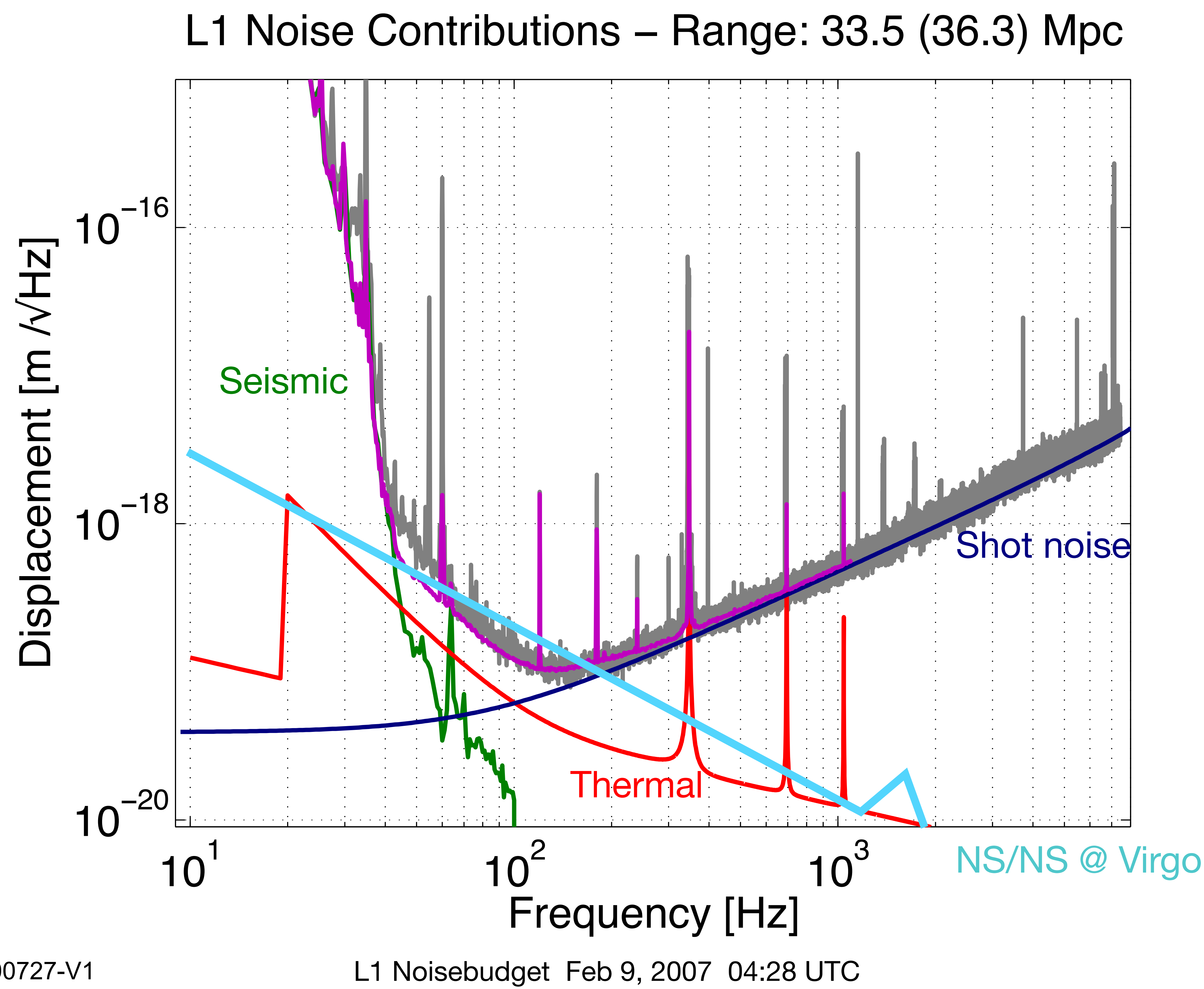




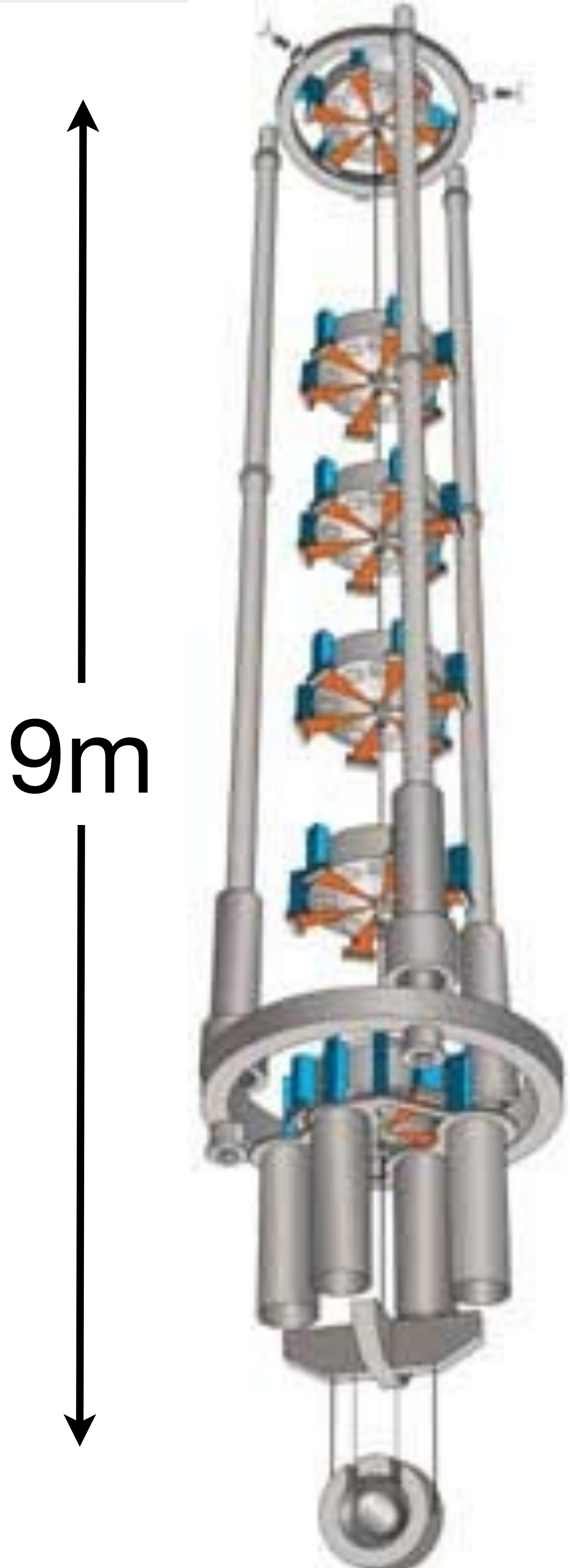
Worldwide Network

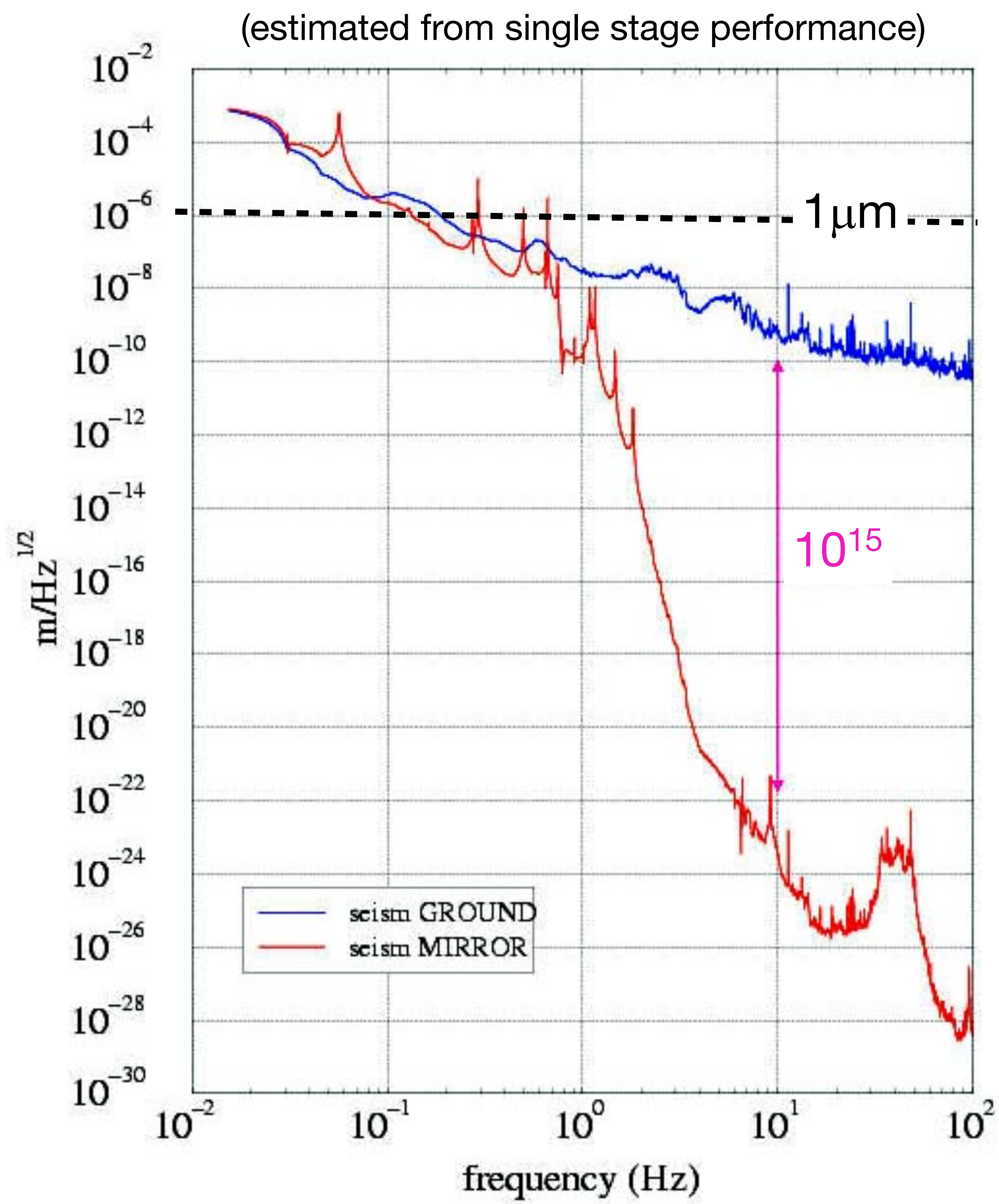


Noise Budget



Seismic isolation



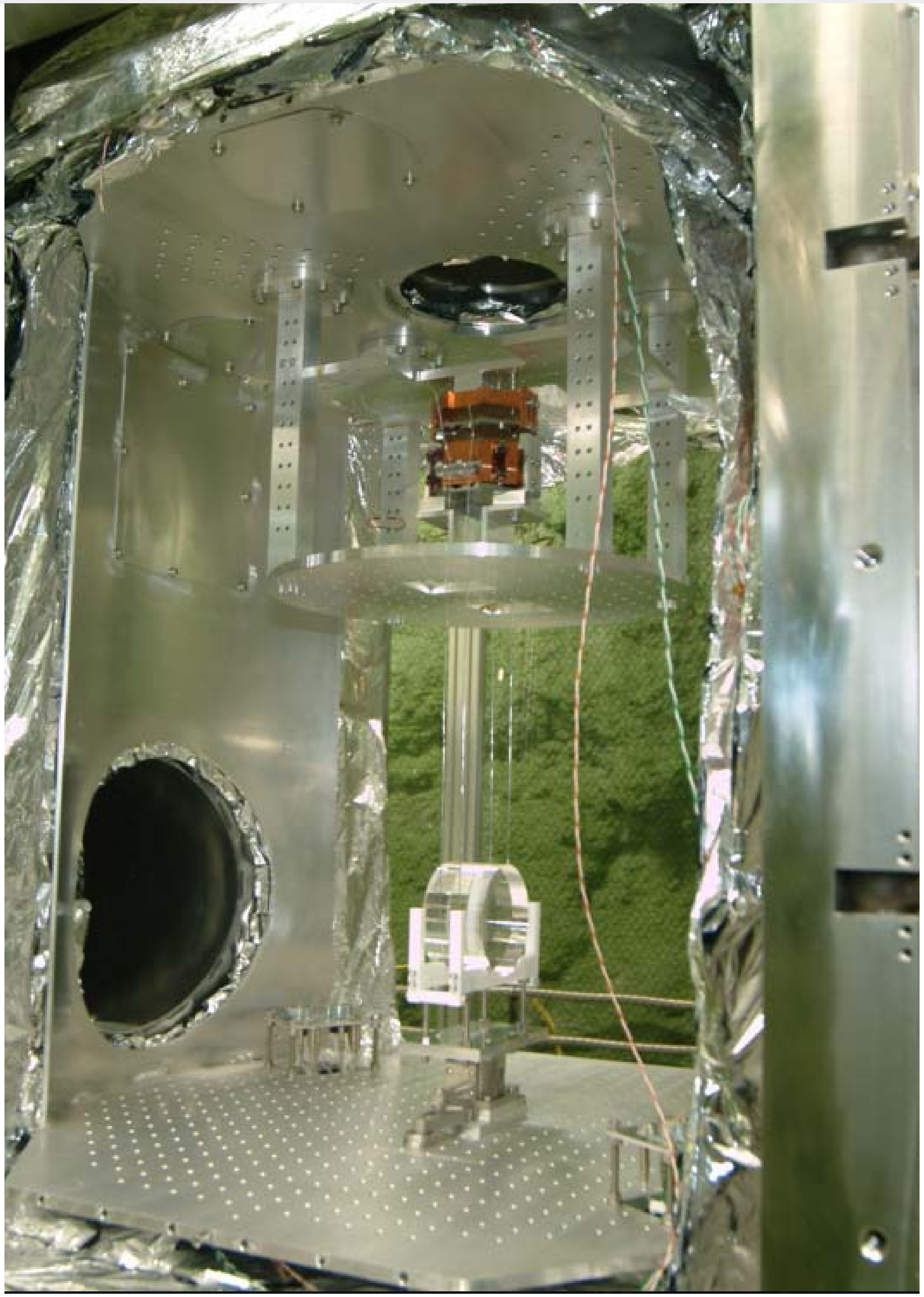


Virgo's super-attenuator

c.f. M. Beker TIPP 2011

F. Ricci, GWADW 2011

Thermal noise



Mechanical equivalent of

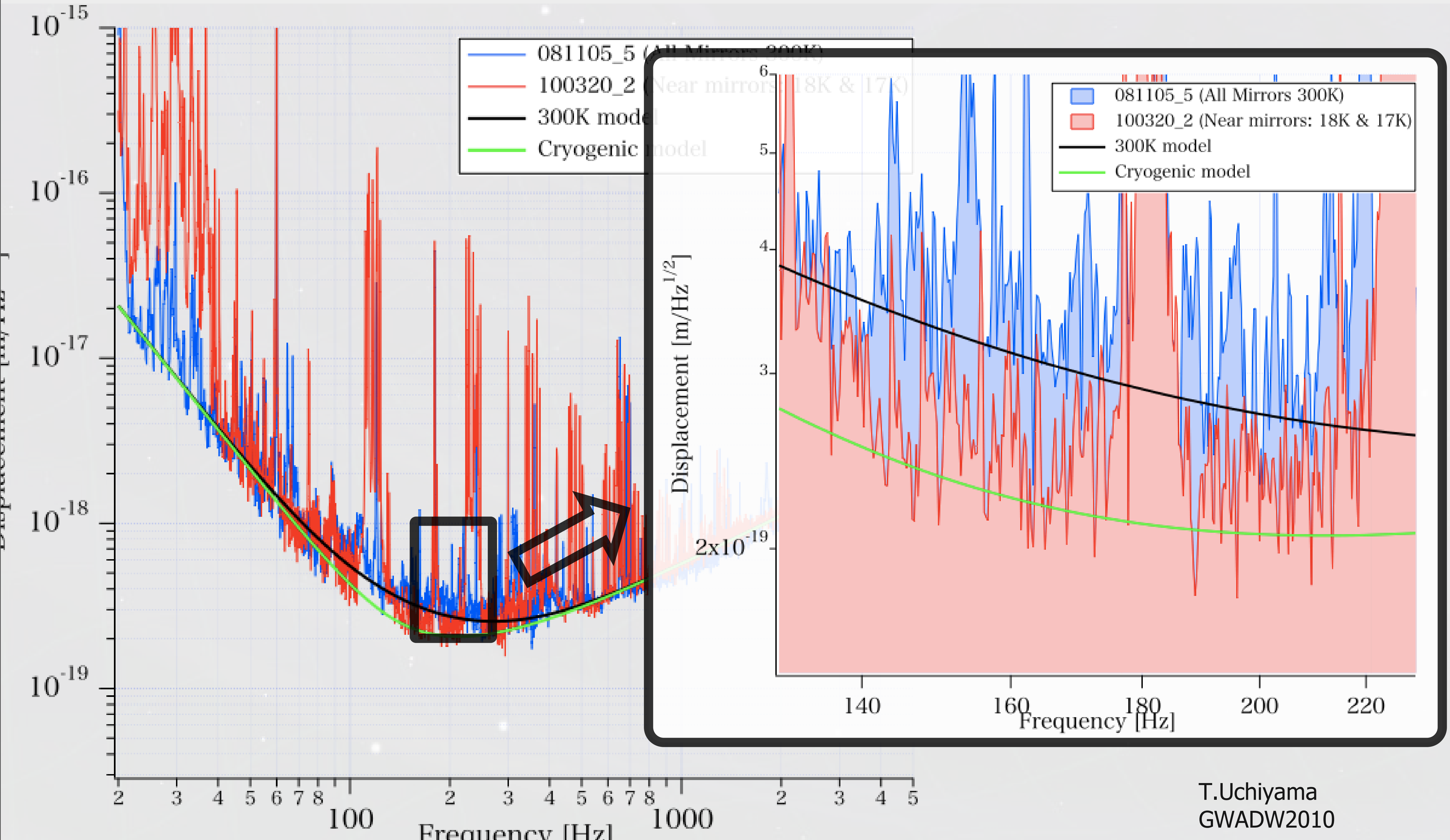
$$v_n^2 = 4k_bTR$$

Cryogenic **L**aser **I**nterferometer **O**bservatory

- Located in Kamioka
- 100 m arm lengths
- Sapphire masses
- Operate at 20K

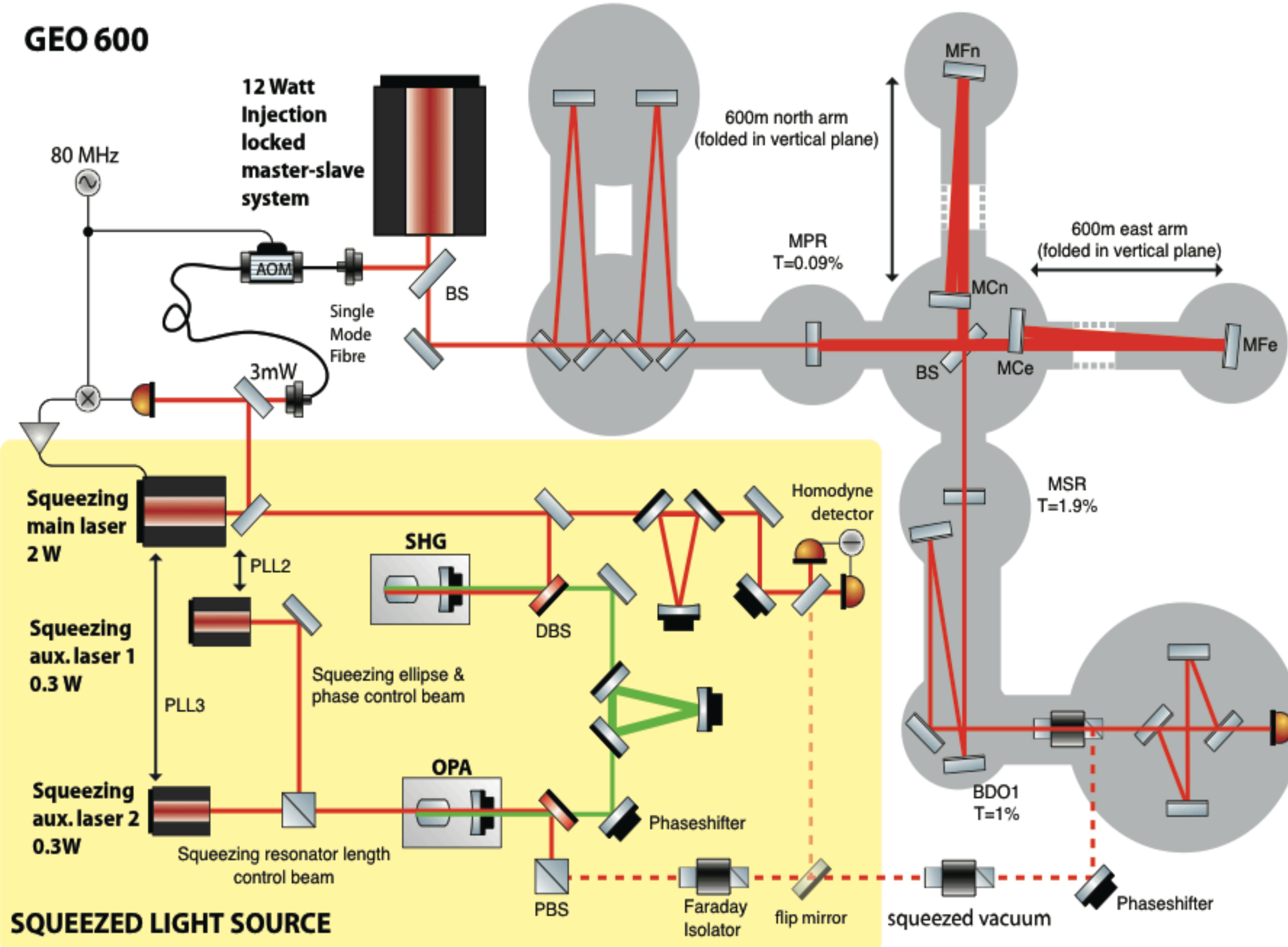
Reduce thermal noise from

- Mirror coatings
- Suspension wires

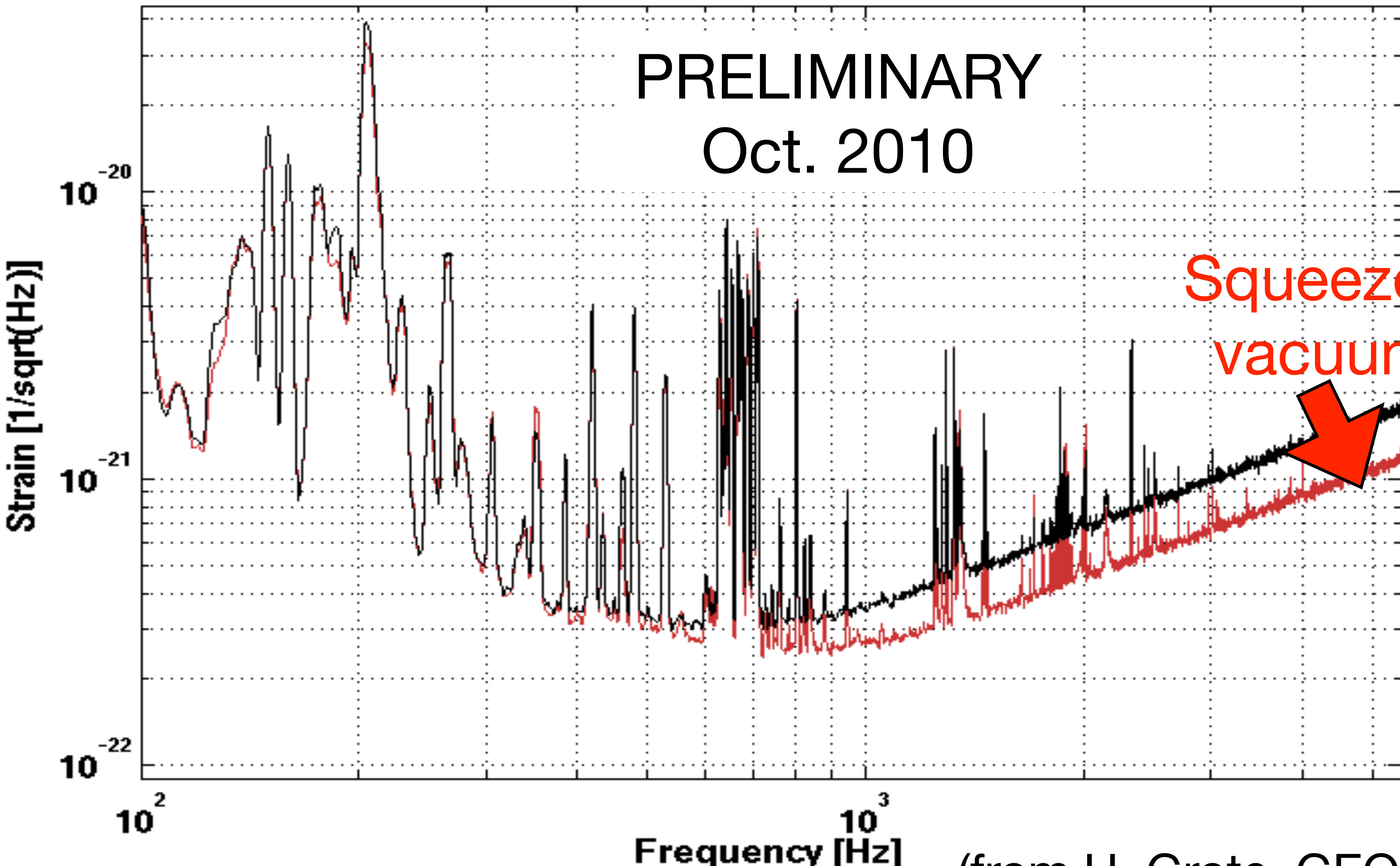


NB: Low vibration Pulse tube refrigerators and cryostats developed at KEK

Squeezing at GEO

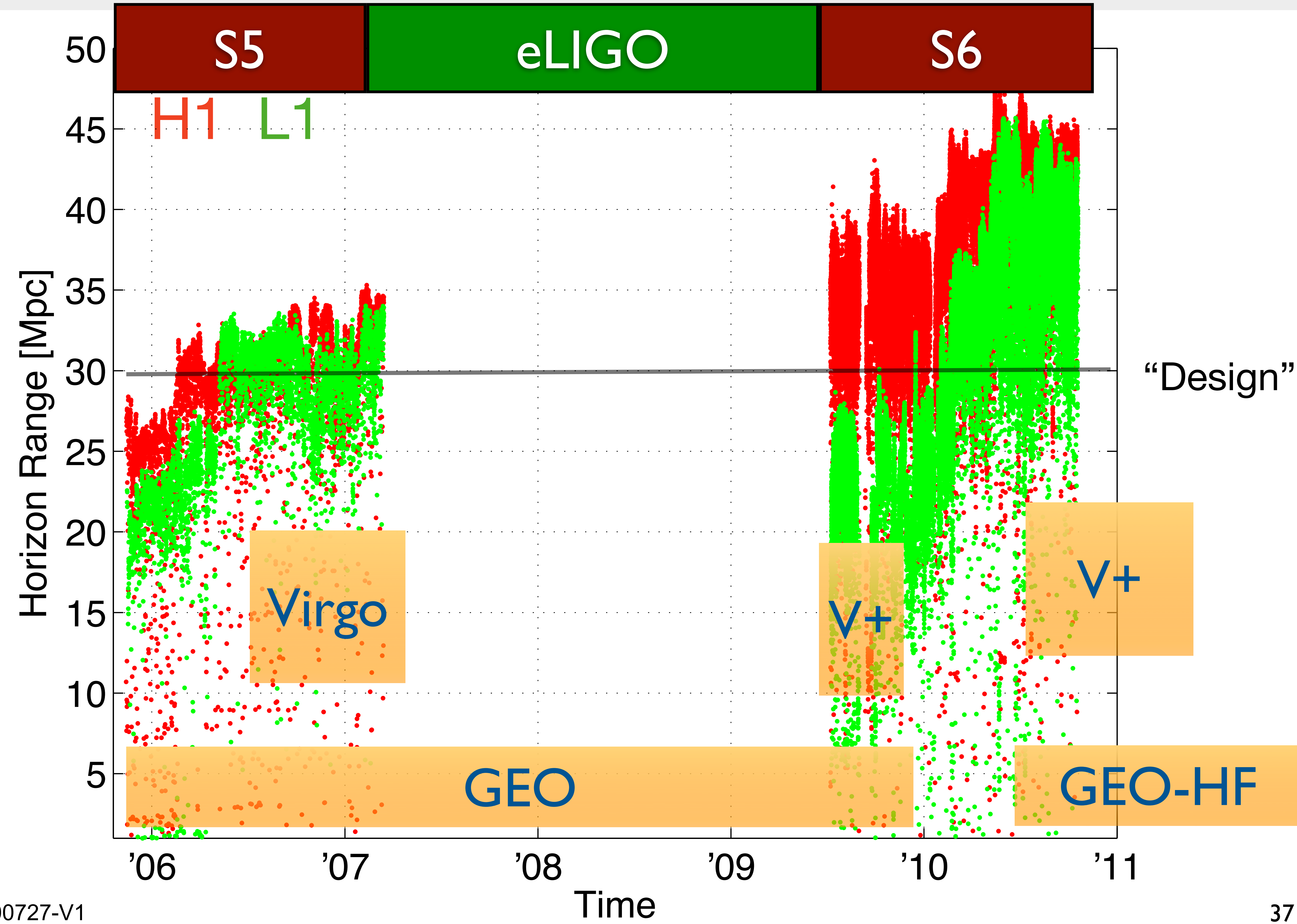


3.5 dB squeezing



(from H. Grote, GEO600 submitted to Nature)

Observing Campaigns



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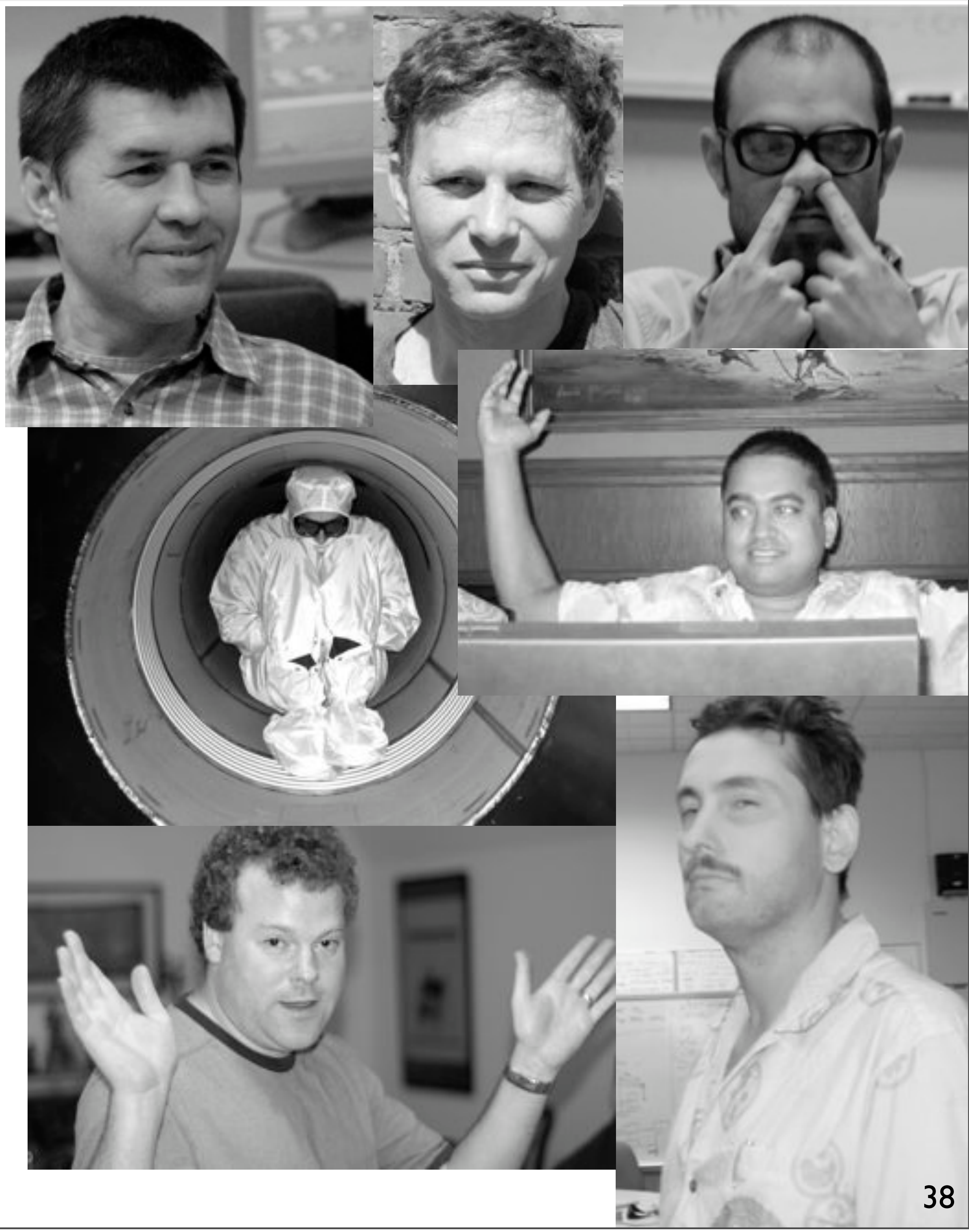
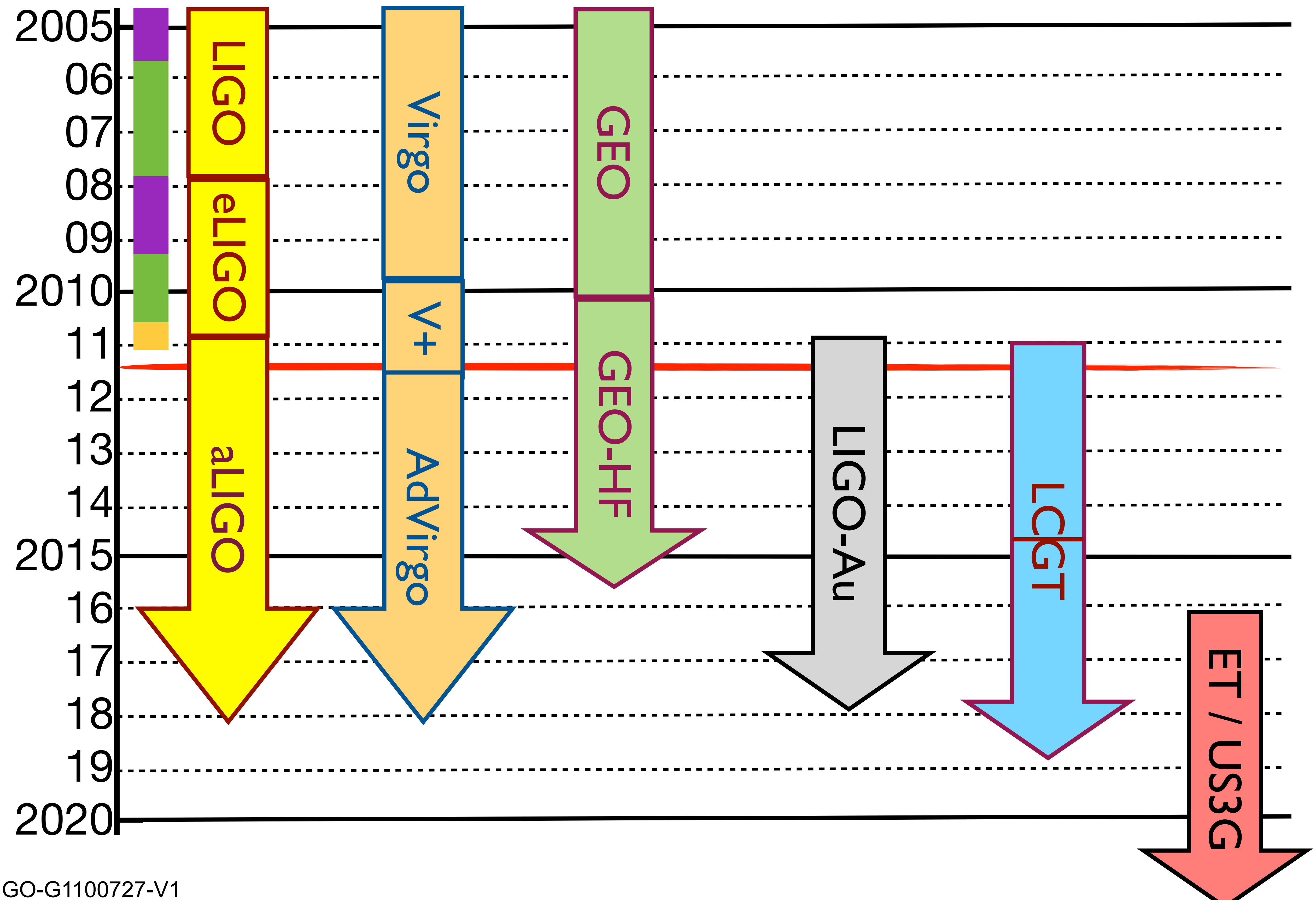
LIGO/Virgo/GEO

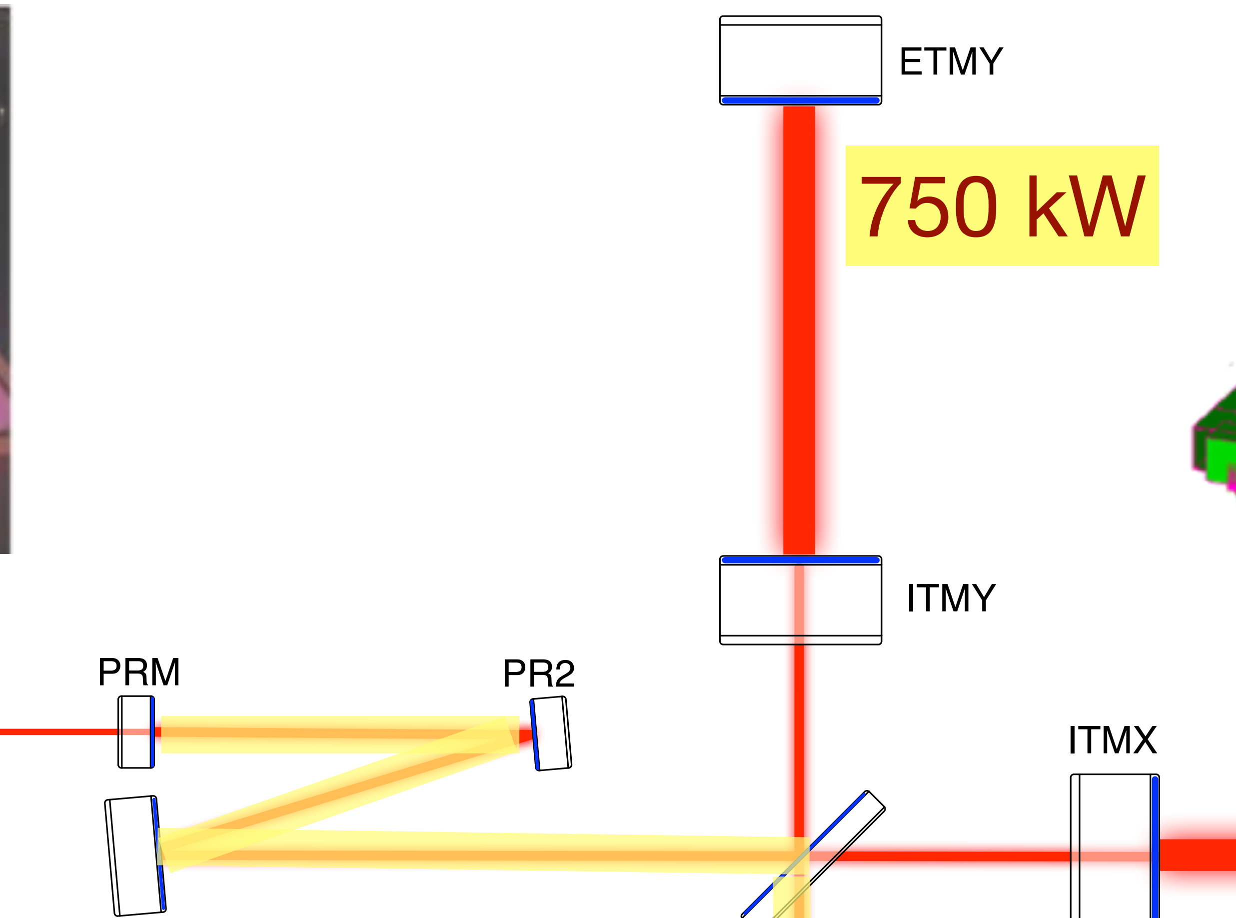
Future Detectors

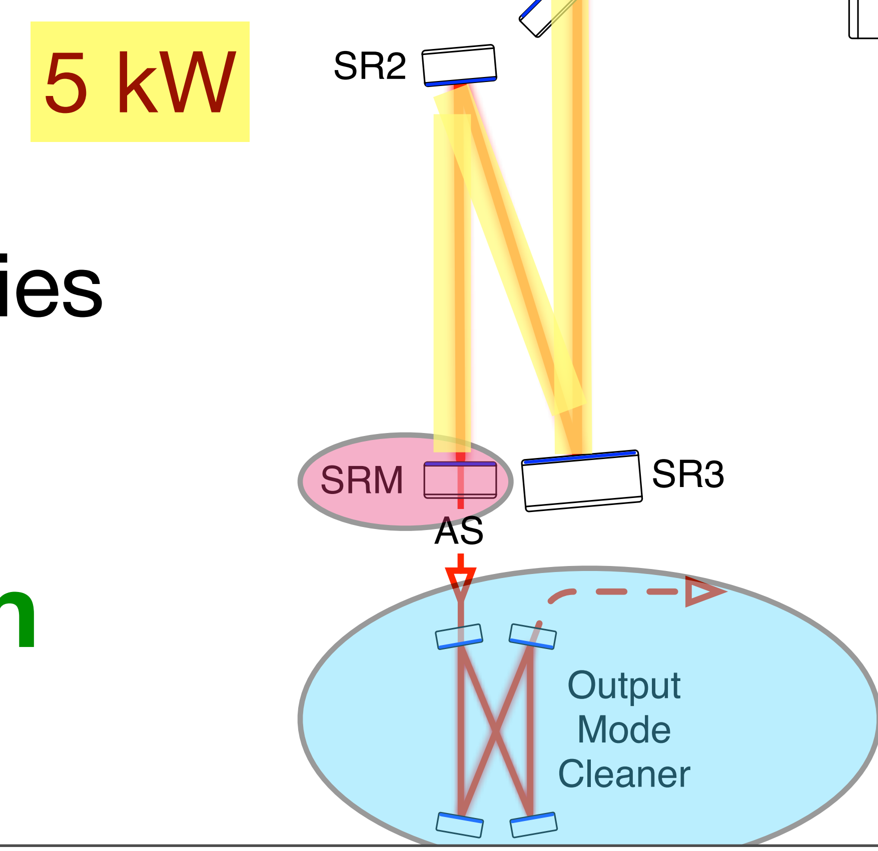


The GW decade

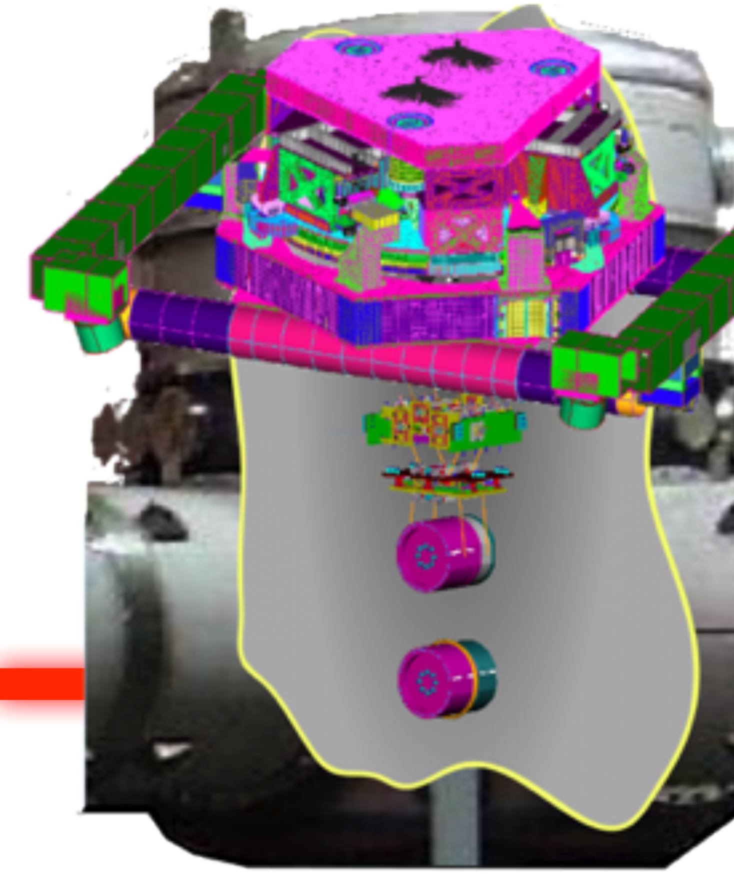


Advanced LIGO



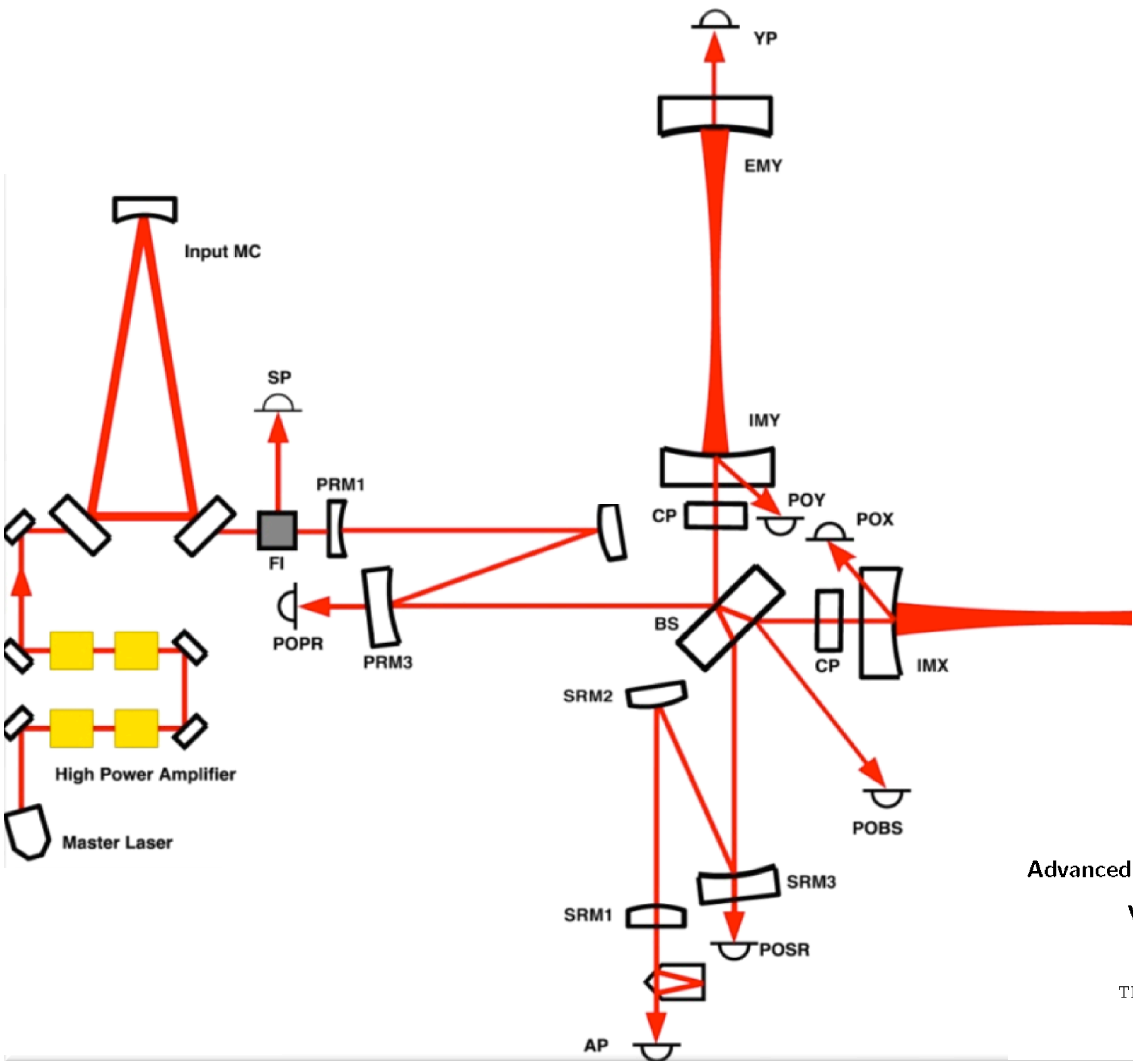


Active isolation & quad pendulum



- Increased power
- Improved isolation
- Stable recycling cavities
- Signal recycling
- DC readout
- **Installation began October 20, 2010**

Advanced Virgo



Upgraded
- Optics
- Suspension
- Laser

Sensitivity consistent w/ aLIGO

Installation scheduled w/ aLIGO

Advanced Virgo Baseline Design

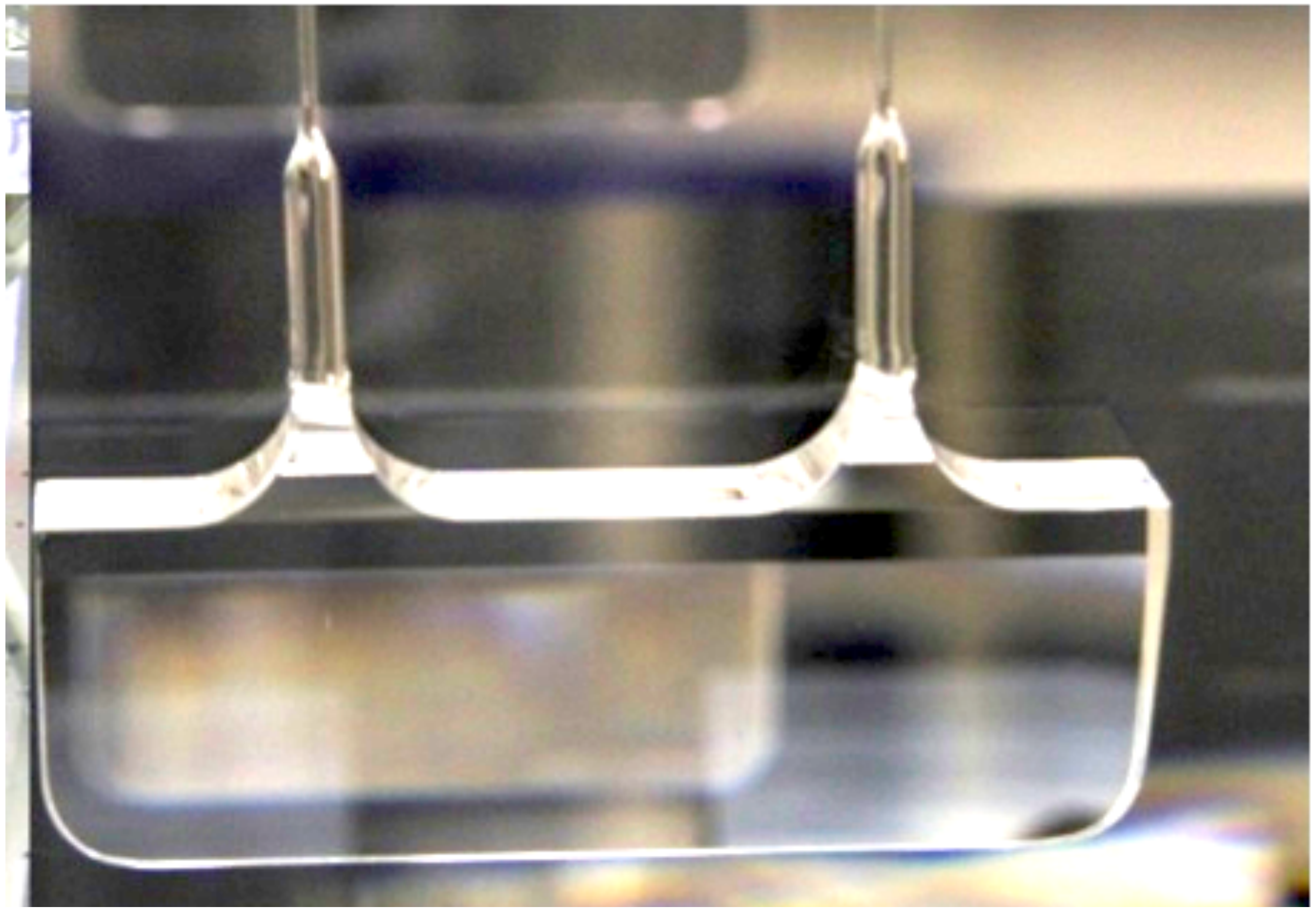
VIR–027A–09

Issue 1

The Virgo Collaboration

May 16, 2009

Lower thermal noise

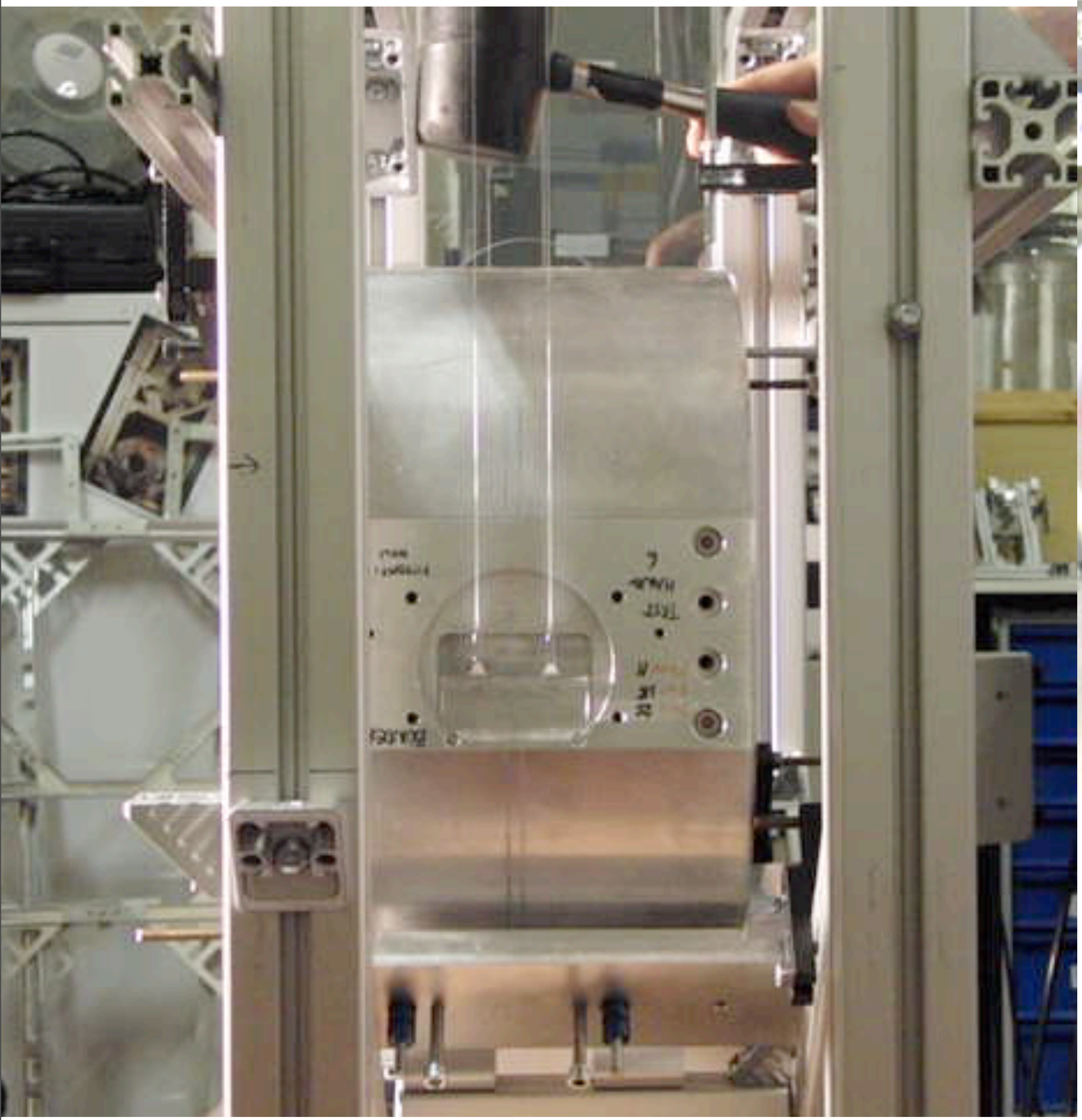


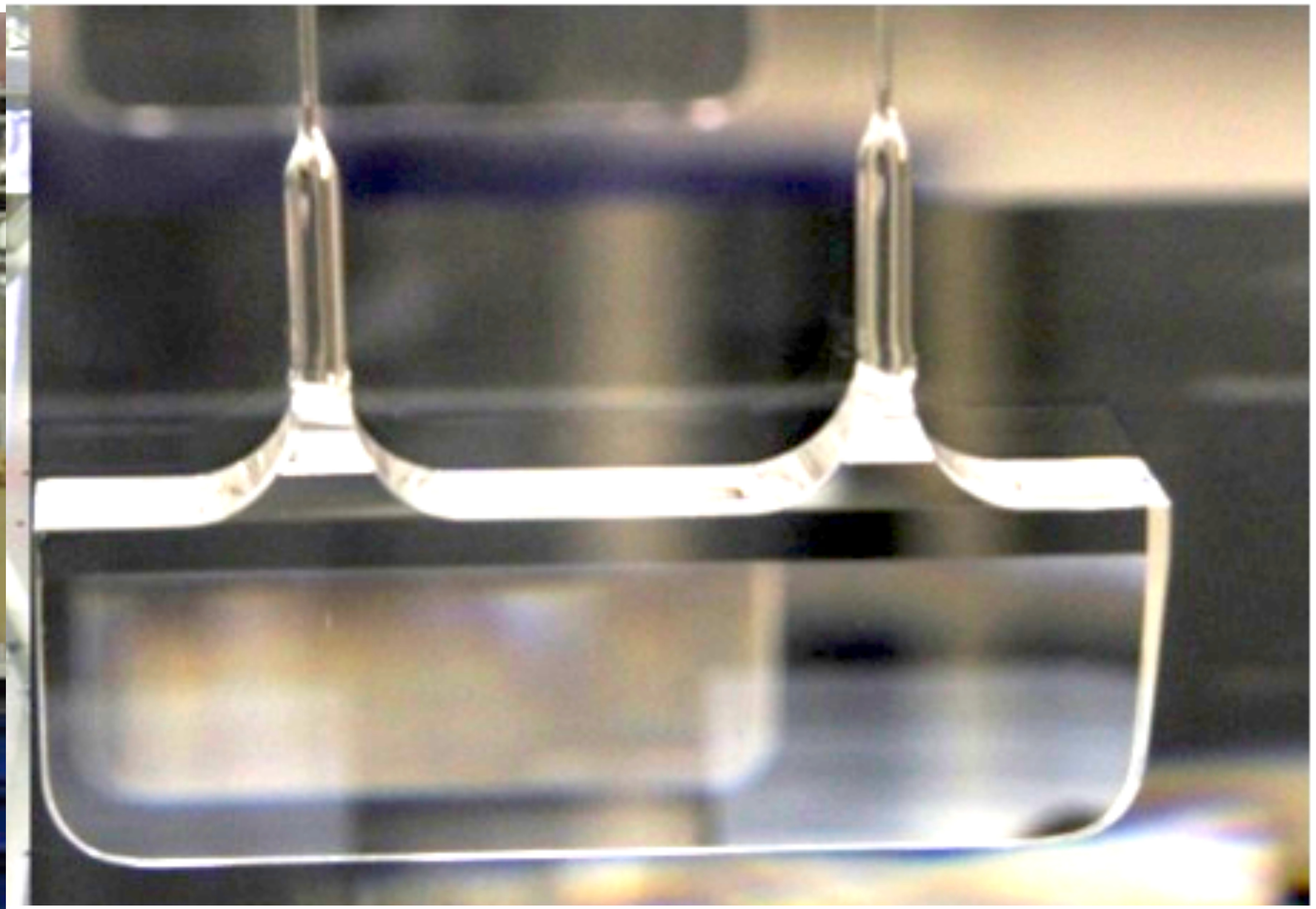
MIrror suspended from monolithic fused-silica suspension

Developed at Glasgow University, tested at MIT

Video filmed March 2010, inspired by Virgo

Lower thermal noise





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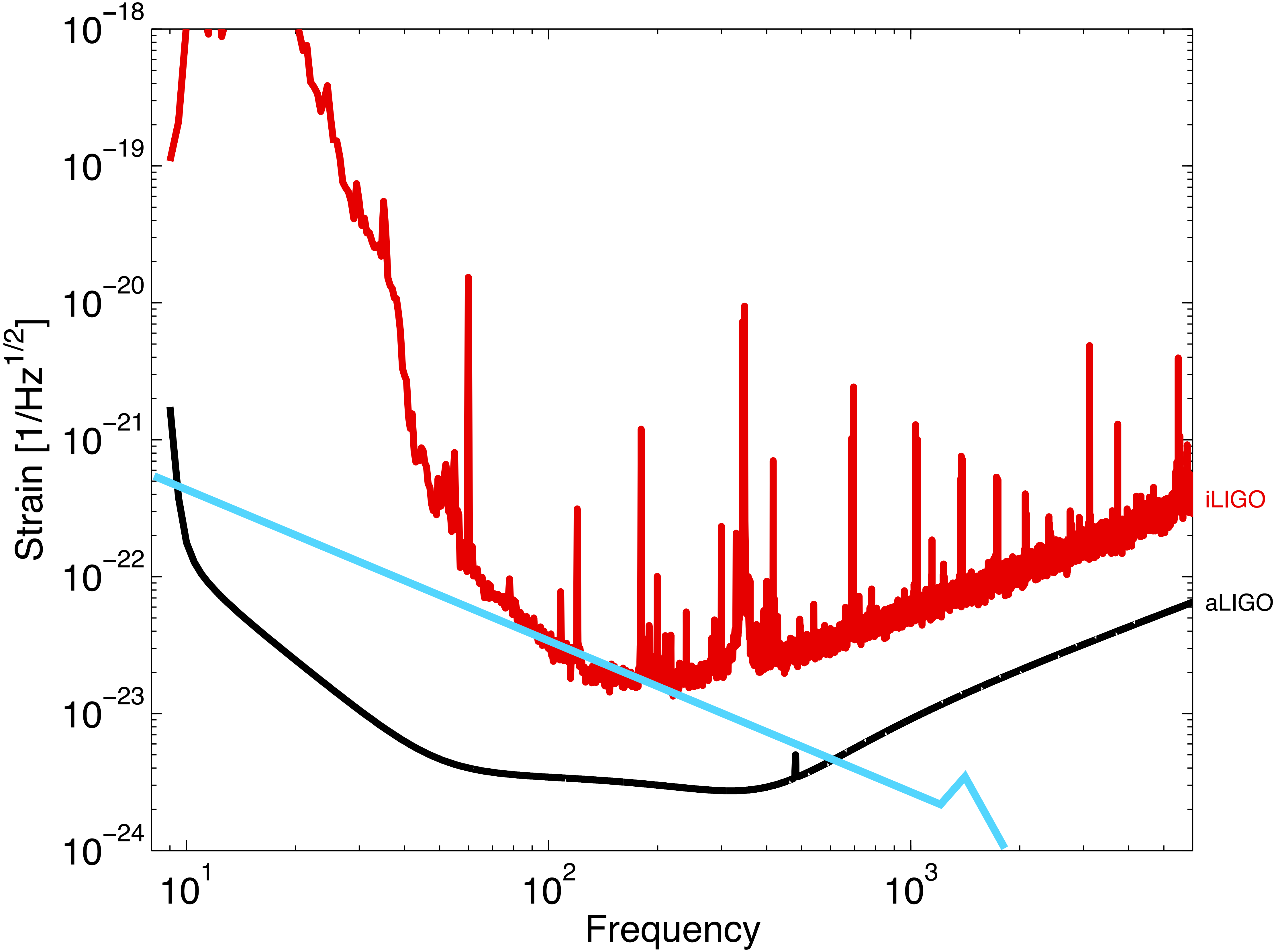
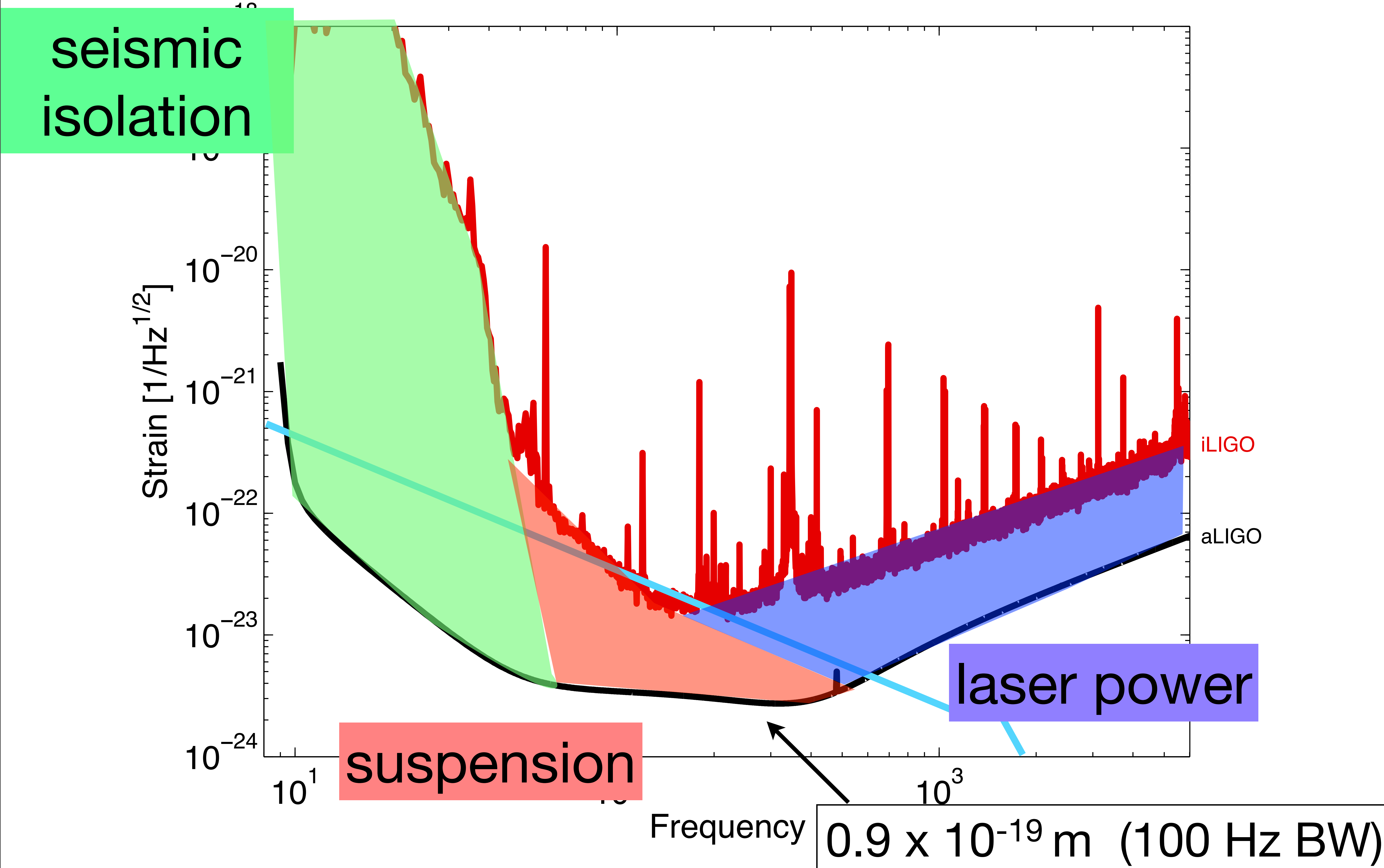
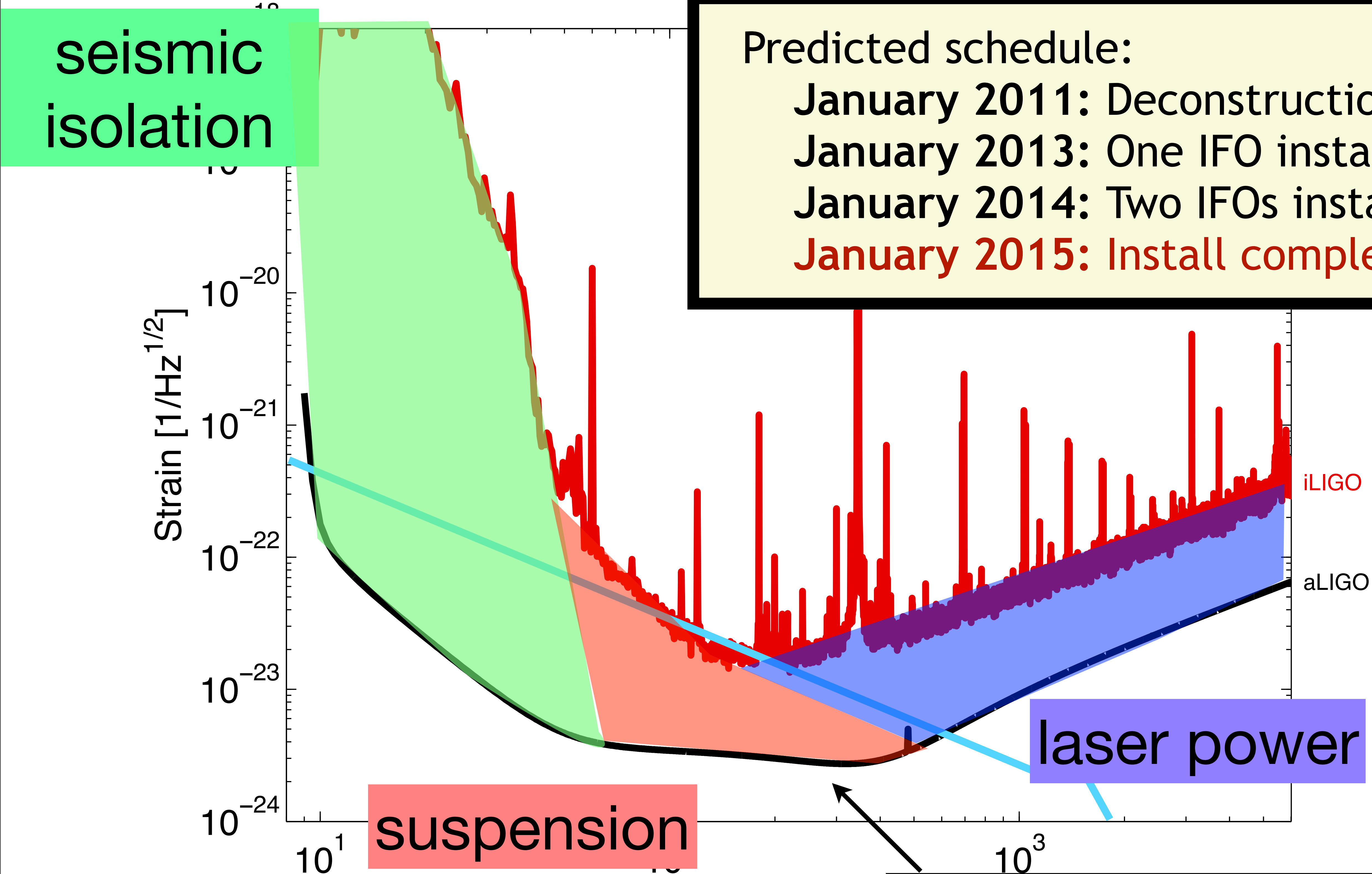

Strain [1/Hz$^{1/2}$]
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
Frequency
iLIGO
aLIGO


seismic isolation
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain [1/Hz$^{1/2}$]
iLIGO
aLIGO
laser power
suspension
10^{1}
10^{3}
Frequency
0.9 x 10^{-19} m (100 Hz BW)

Predicted schedule:

January 2011: Deconstruction
January 2013: One IFO installed
January 2014: Two IFOs installed
January 2015: Install complete



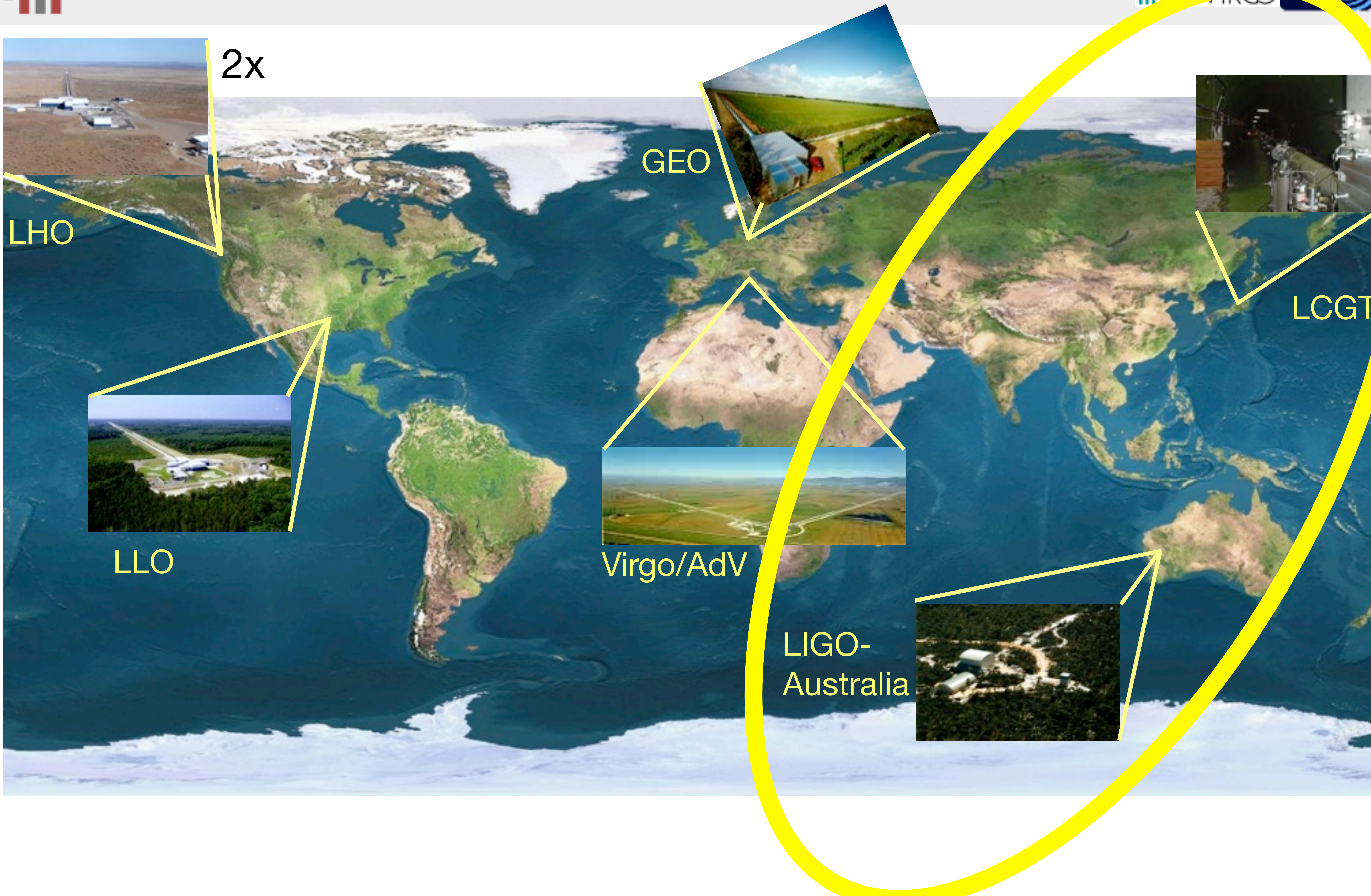
0.9 x 10^{-19} m (100 Hz BW)

Observation Rates

Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors
Classical and Quantum Gravity 27 (2010) 173001

	NS-NS	NS-BH	BH-BH
Rate ($MWEG^{-1}$ yr^{-1})	$100\,^{1000}_{1}$	$3\,^{100}_{0.05}$	$0.4\,^{30}_{0.01}$
iLIGO (yr^{-1})	$0.02\,^{0.2}_{2\times10^{-4}}$	$0.004\,^{0.1}_{7\times10^{-5}}$	$0.007\,^{0.5}_{2\times10^{-4}}$
aLIGO (yr^{-1})	$40\,^{400}_{0.4}$	$10\,^{300}_{0.2}$	$20\,^{1000}_{0.4}$

Worldwide Network



LIGO Australia

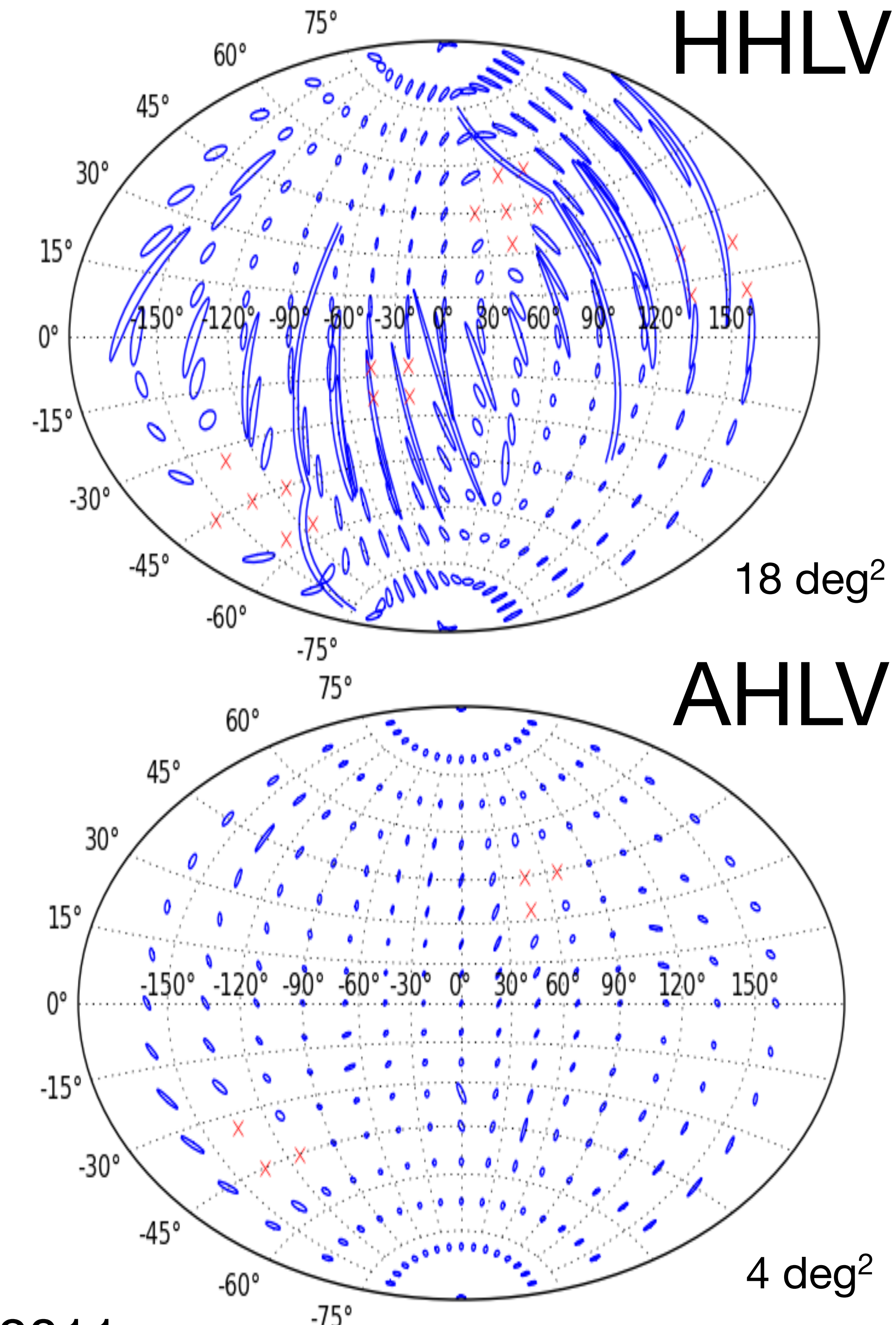
3rd aLIGO detector in Western Australia at Gingin (near Perth)

Australia (ACIGA) provides all the infrastructure - buildings, vacuum, clean rooms and staff

No new cost or delay to NSF/LIGO

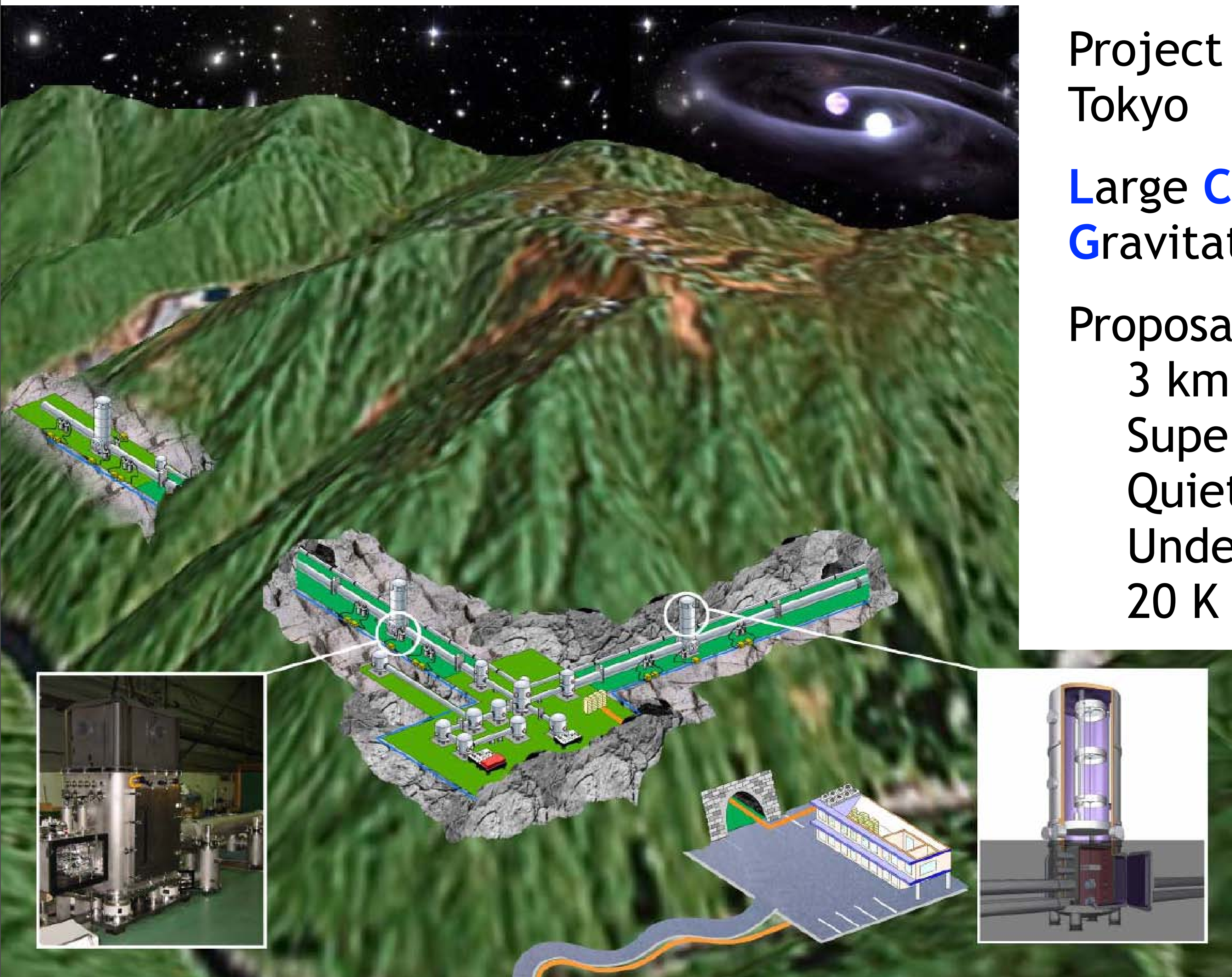
Approved by NSF, under consideration by Australian funding agencies

LIGO Australia could be online 2017



Fairhurst CQG 2011

LCGT Funded



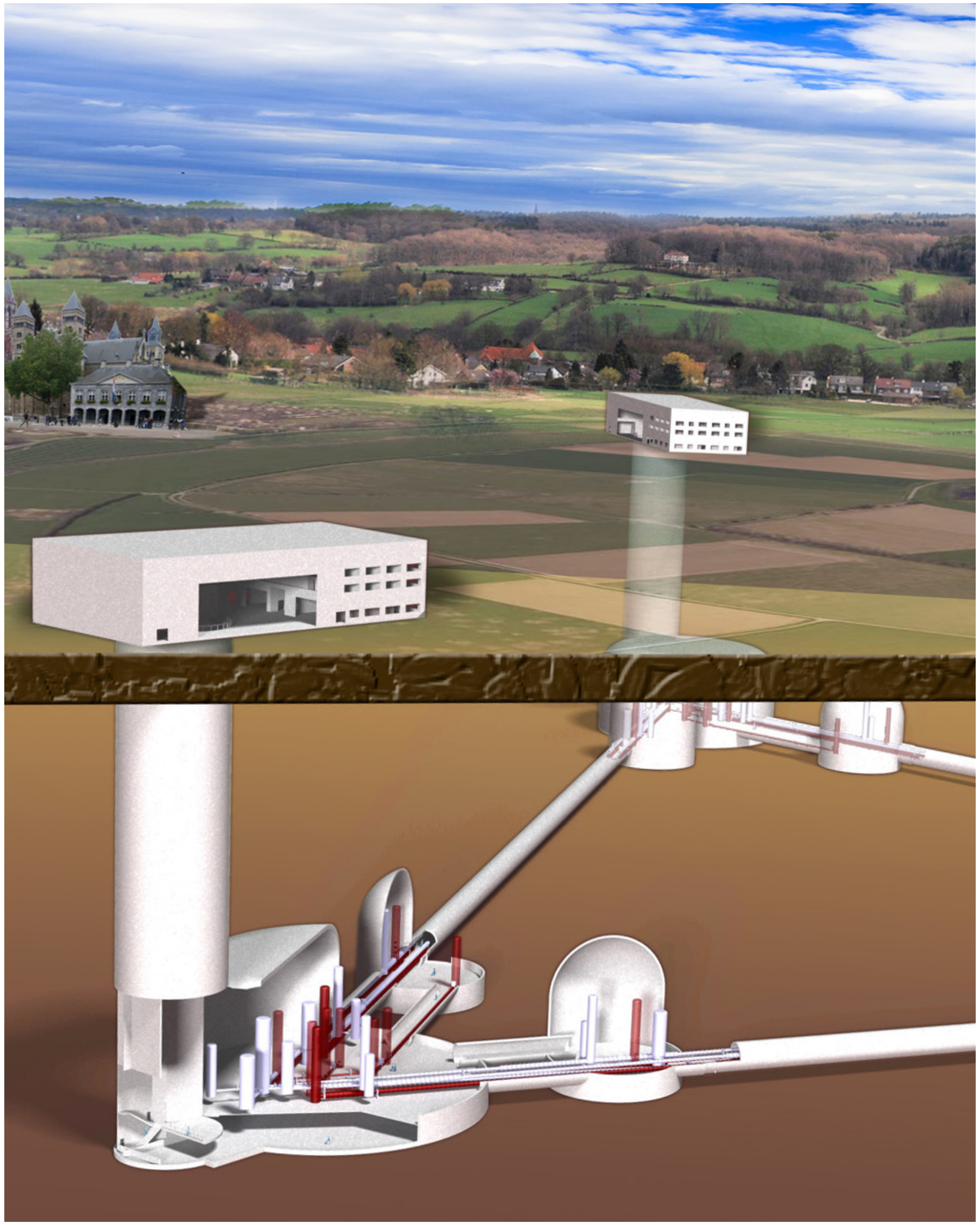
Project led by ICRR @ U Tokyo

Large **C**ryogenic **G**ravitational wave **T**elescope

Proposal includes:
- 3 km arms
- Super attenuators
- Quiet seismic environment
- Underground
- 20 K mirror & suspension

http://gw.icrr.u-tokyo.ac.jp/lcgt/

Einstein Telescope



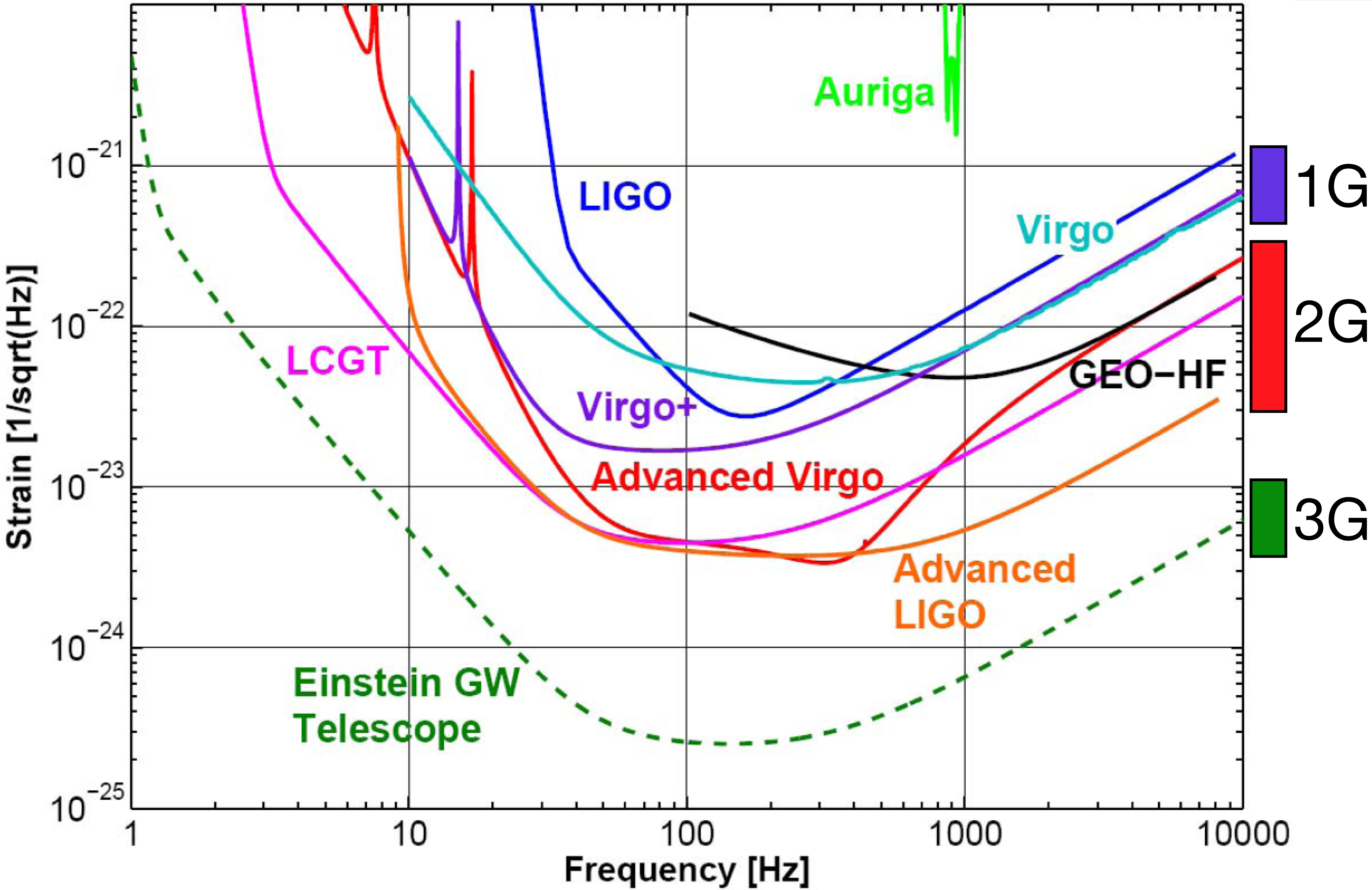
Design study supported under Programme Framework 7

Concept presented May 20, 2011:

- 10km, triangular geometry
- Subterranean, ultra-low seismic environment
- Dual HF, high power/ LF, cryogenic design

Construction ~2018 - 2025

http://www.et-gw.eu/


Strain [1/sqrt(Hz)]
Frequency [Hz]
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
1
10
100
1000
10000
Auriga
LIGO
Virgo
LCGT
Virgo+
GEO−HF
Advanced Virgo
Advanced LIGO
Einstein GW Telescope
1G
2G
3G

Future is bright

IPTA could see stochastic GW and SMBH in 5-10 years

LISA technology on orbit in 2014, spacecraft interferometry in 2015

1st generation detectors operated at design sensitivity through 2010

Virgo+ and GEO-HF upgrades now taking data

2nd gen. aLIGO 50% complete and on schedule, adVirgo under design. Earliest Science 2015

Chance for 6 (!!) 2nd generation detectors online 2018