Gravitational Radiation Detectors

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Caltech

ICTS / RRCAT
GW School / Dec 2013

They Exist !

On the Earth:

- TAMA 300 / KAGRA - Tokyo / Toyama, Japan
- GEO 600 / HF - Hannover/Ruthe, Germany
- Virgo 3000 / AdVirgo - Pisa/Cascina, Italy
- LIGO 4000 / aLIGO - Washington+Louisiana, USA

- BARS: ALLEGRO, AURIGA, NAUTILUS, EXPLORER

Space:

- LISA 5x10^6 - Orbiting the Sun (2035-2040)
- Pulsar Timing (IPTA) - Analyzing Radio data (NOW)
- BBO/DECIGO - Directly Observe Inflation (???)

GWs and Bars

- First ground-based detectors—the beginning of GW detection: Weber
- Much improvement in Bars
  - Cryogenics
  - Quantum Limited Readout

Detector	Location	Freq. (Hz)	Peak Strain (h_c)	Strain Noise ($h(f)$)
ALLEGRO	LSU	900	7×10^{-19}	7×10^{-19}
EXPLORER	CERN	900	7×10^{-19}	7×10^{-19}
NIOBE	UWA	700	5×10^{-19}	7×10^{-19}
NAUTILUS	Frascati	900	6×10^{-19}	7×10^{-19}
AURIGA	Legnaro	900	3×10^{-19}	7×10^{-19}


Bar display at LIGO Hanford

Joe Weber + Bar

Ju, L., D. G. Blair, and C. Zhao, 2000, Reports on Progress in Physics 63(9), 1317

First World-wide GW Network: IGEC

International Gravitational Event Collaboration
Established 1997 in Perth

Included all operating bar detectors in the world

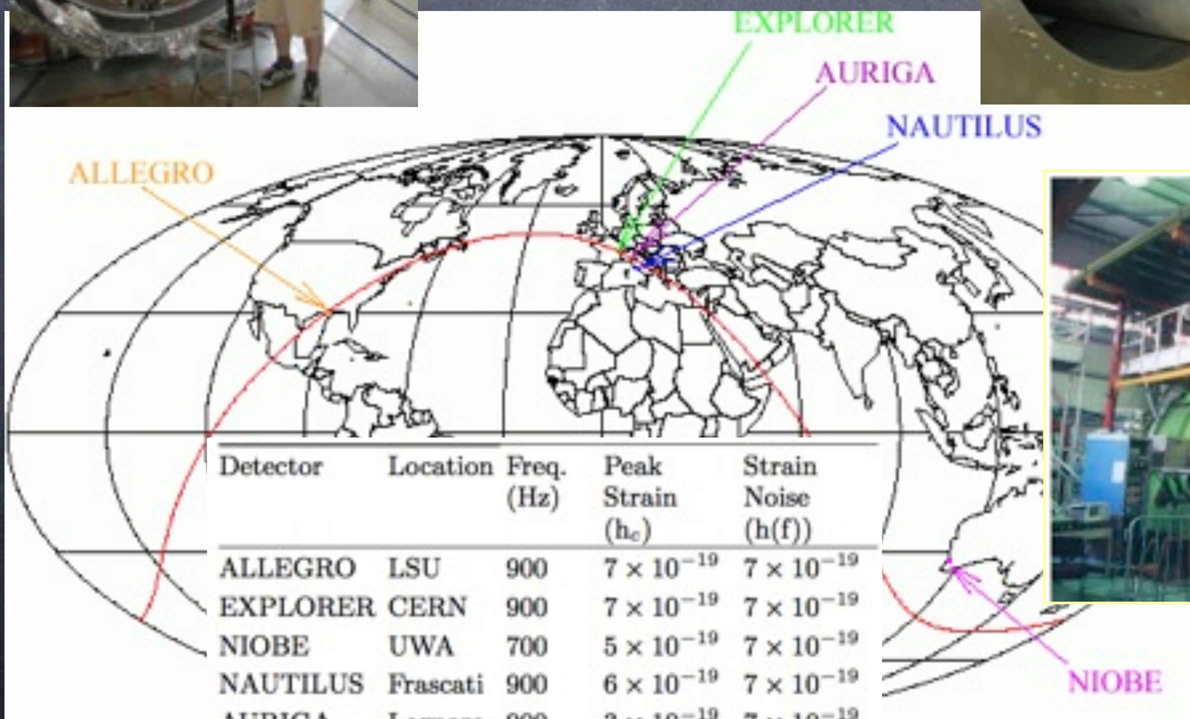

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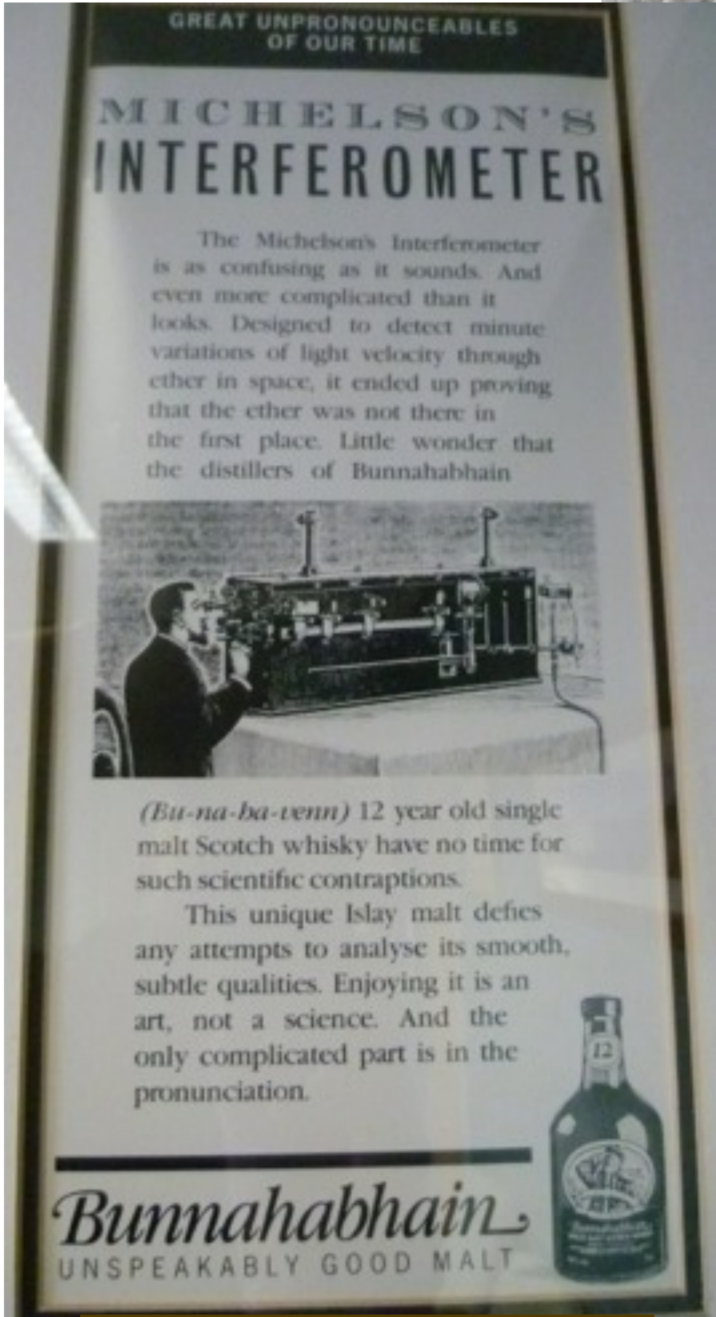
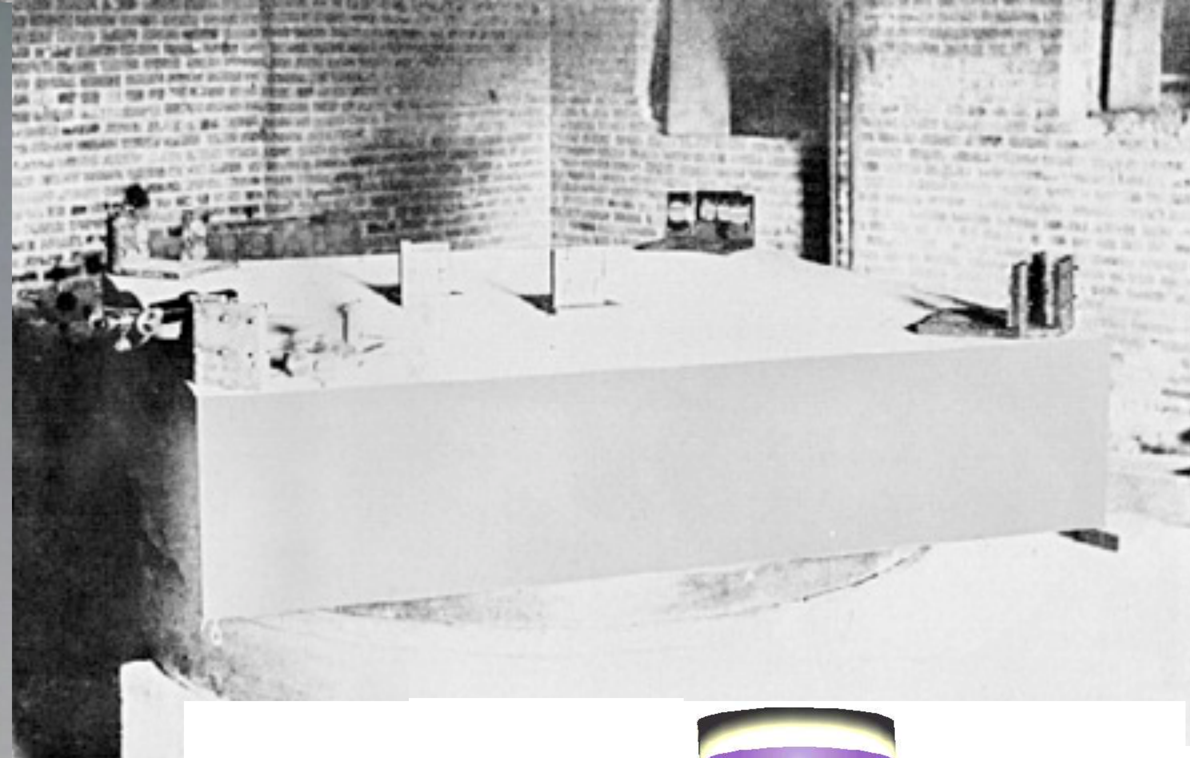
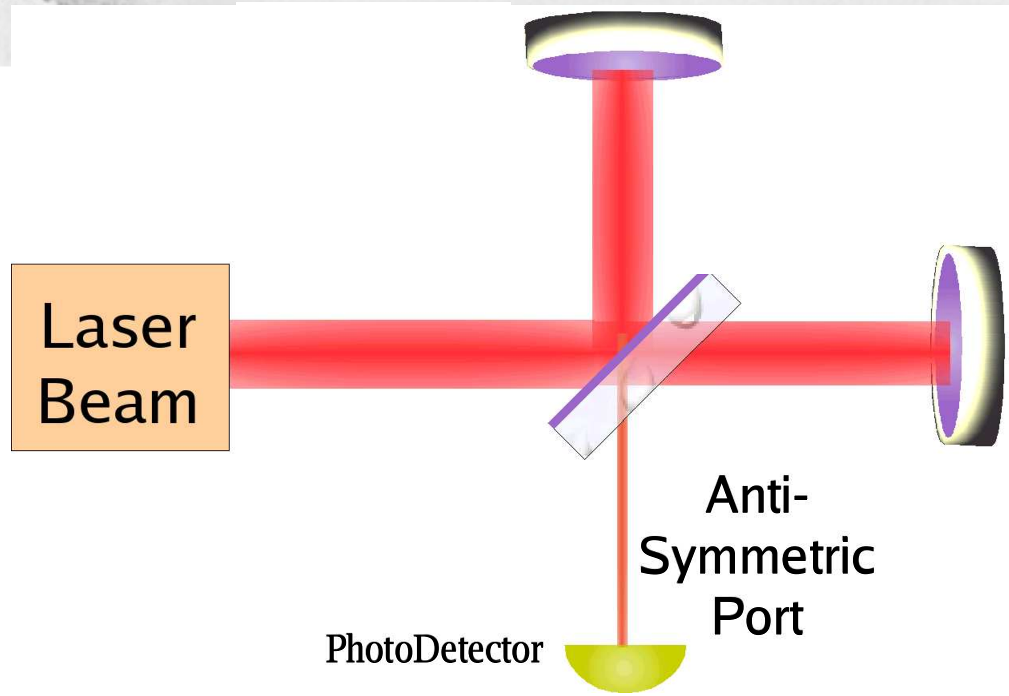
Figure courtesy of Massimo Cerdonio



courtesy Lillian MacArthur
Bunnahabhain Distillery





Michelson Cheat Sheet

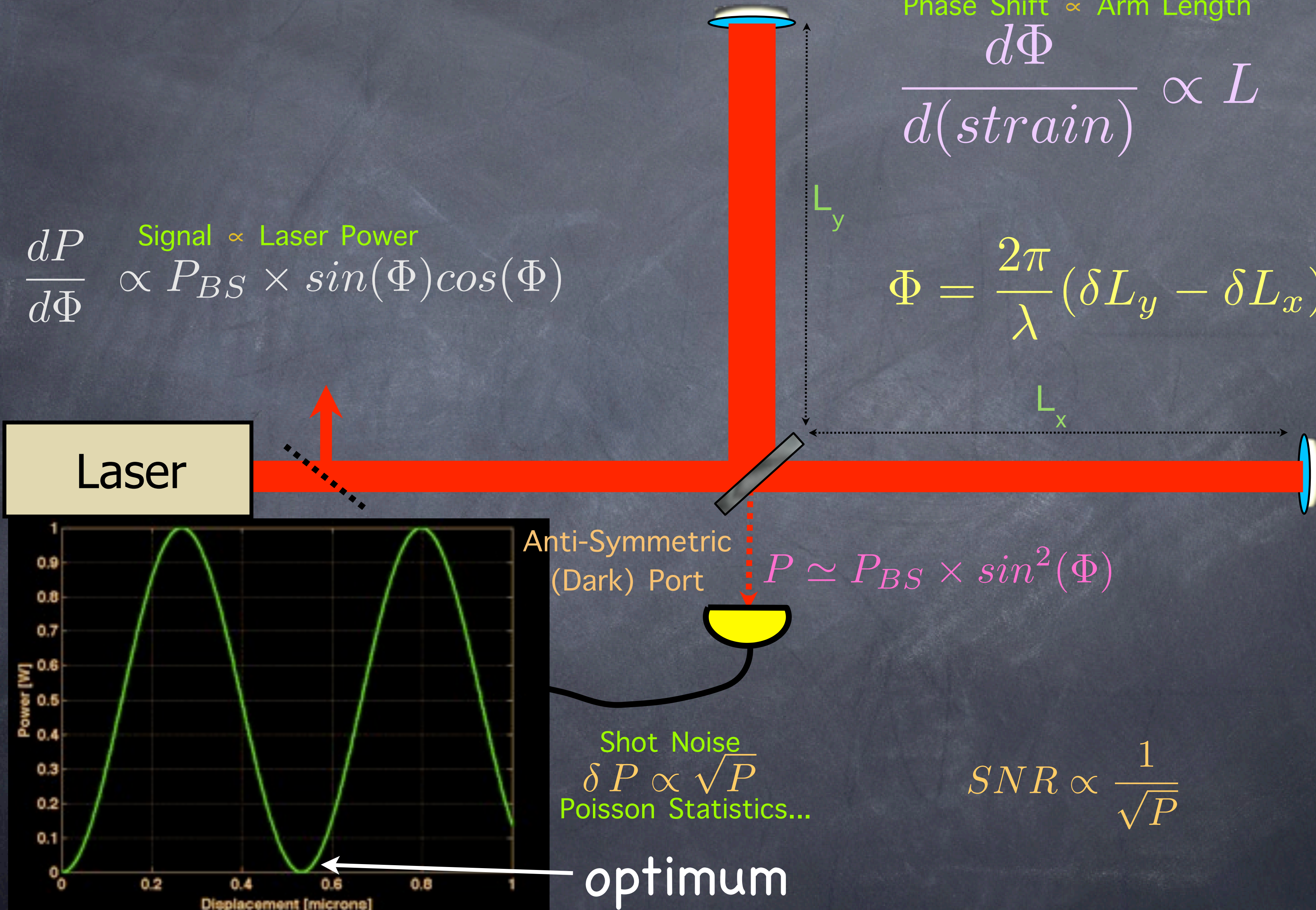
Phase Shift ∝ Arm Length

$$\frac{d\Phi}{d(strain)} \propto L$$

Signal ∝ Laser Power

$$\frac{dP}{d\Phi} \propto P_{BS} \times sin(\Phi)cos(\Phi)$$

$$\Phi = \frac{2\pi}{\lambda}(\delta L_y - \delta L_x)$$



$$P \simeq P_{BS} \times sin^2(\Phi)$$

Shot Noise

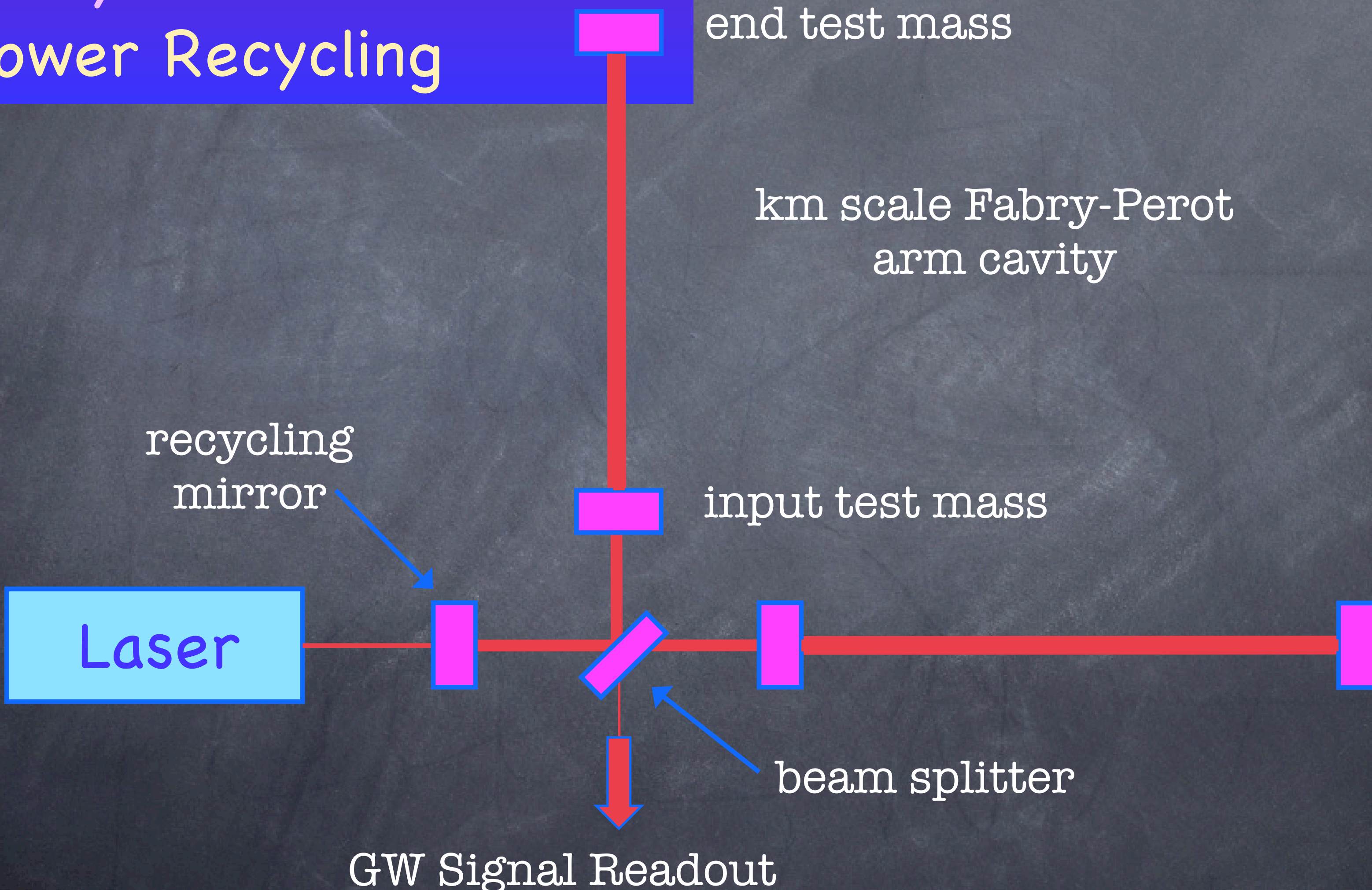
$$\delta P \propto \sqrt{P}$$

Poisson Statistics...

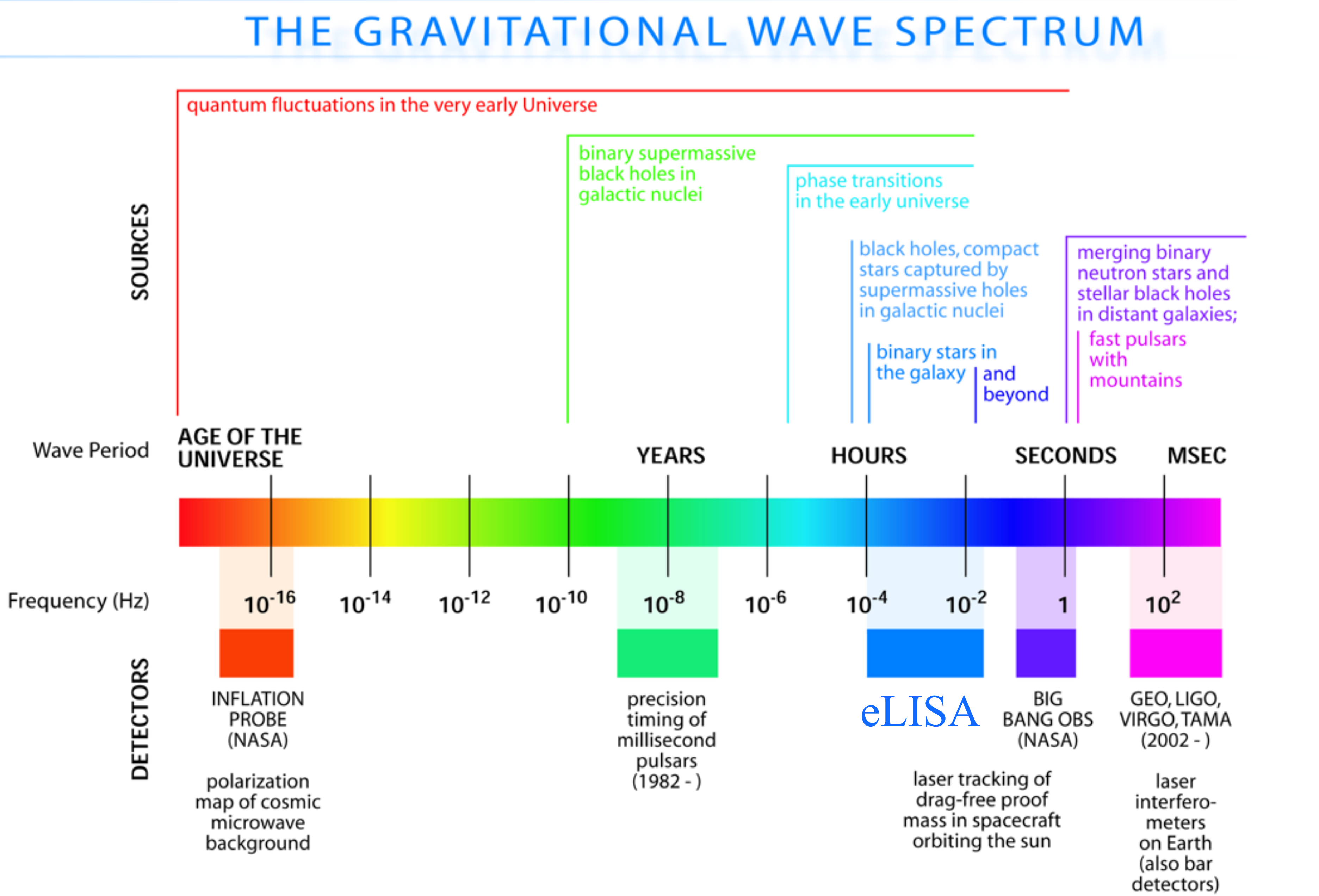
$$SNR \propto \frac{1}{\sqrt{P}}$$

Typical 20th century Optical Configuration

Michelson Interferometer
+ Fabry-Perot Arms
+ Power Recycling

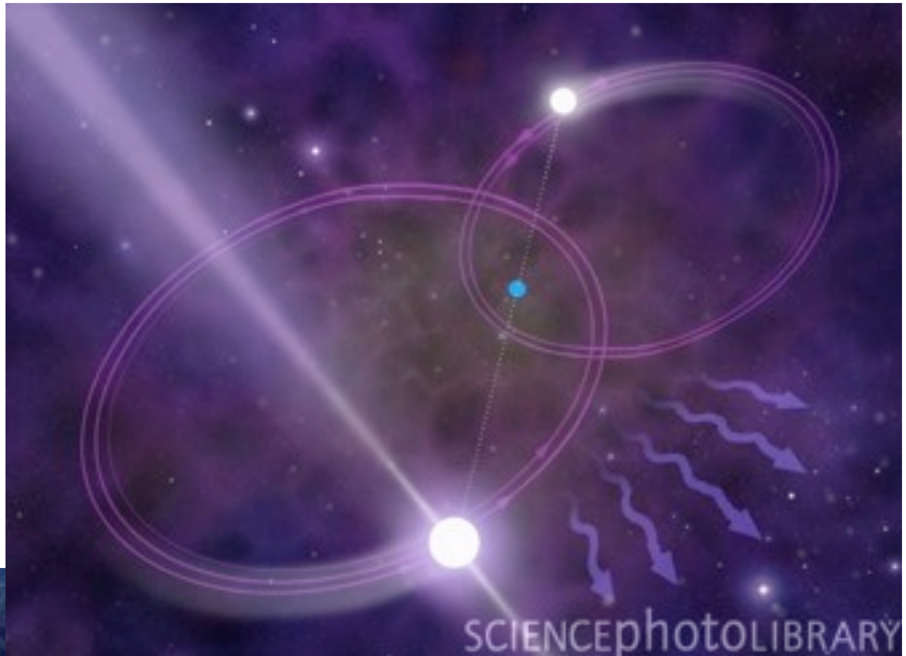


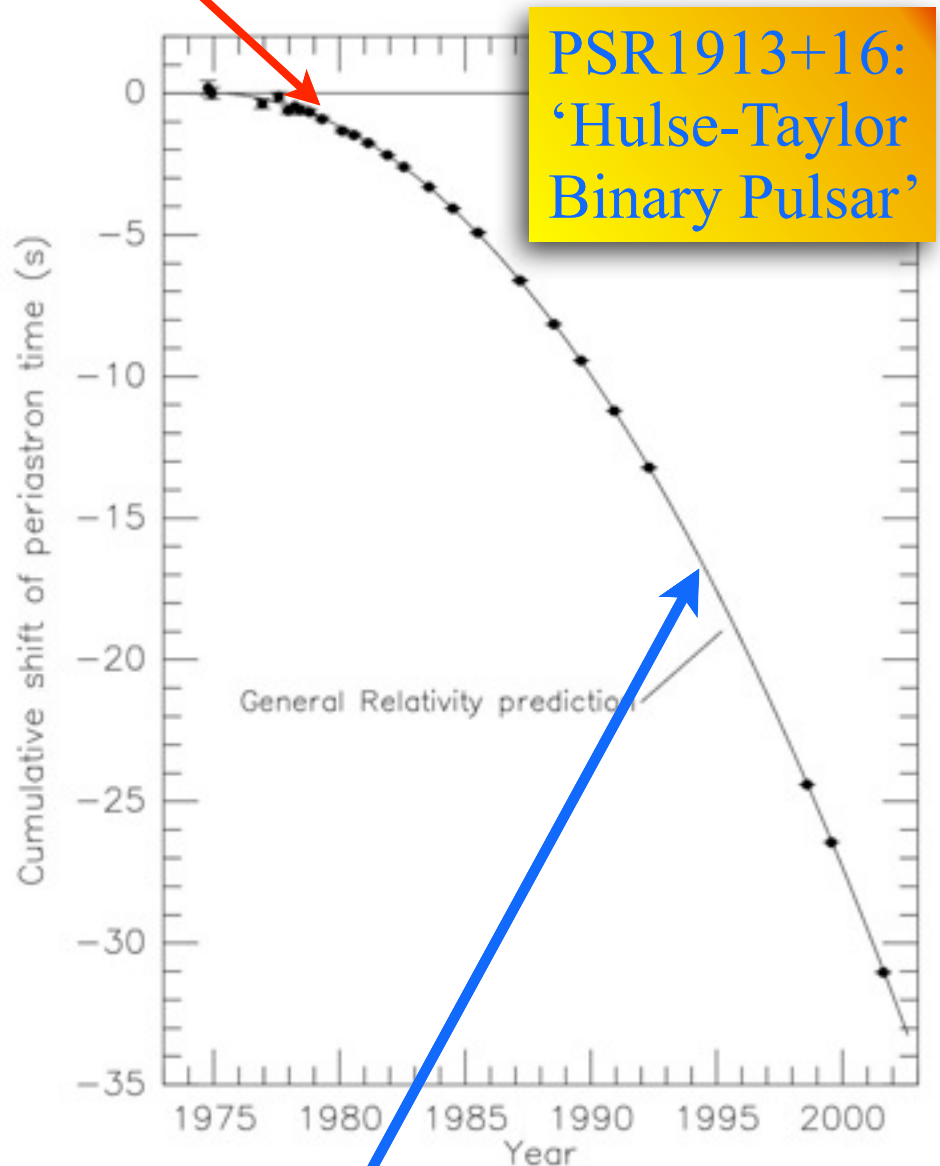
http://www.srl.caltech.edu/lisa/graphics/LISA_science.html



http://www.srl.caltech.edu/lisa/graphics/LISA_science.html

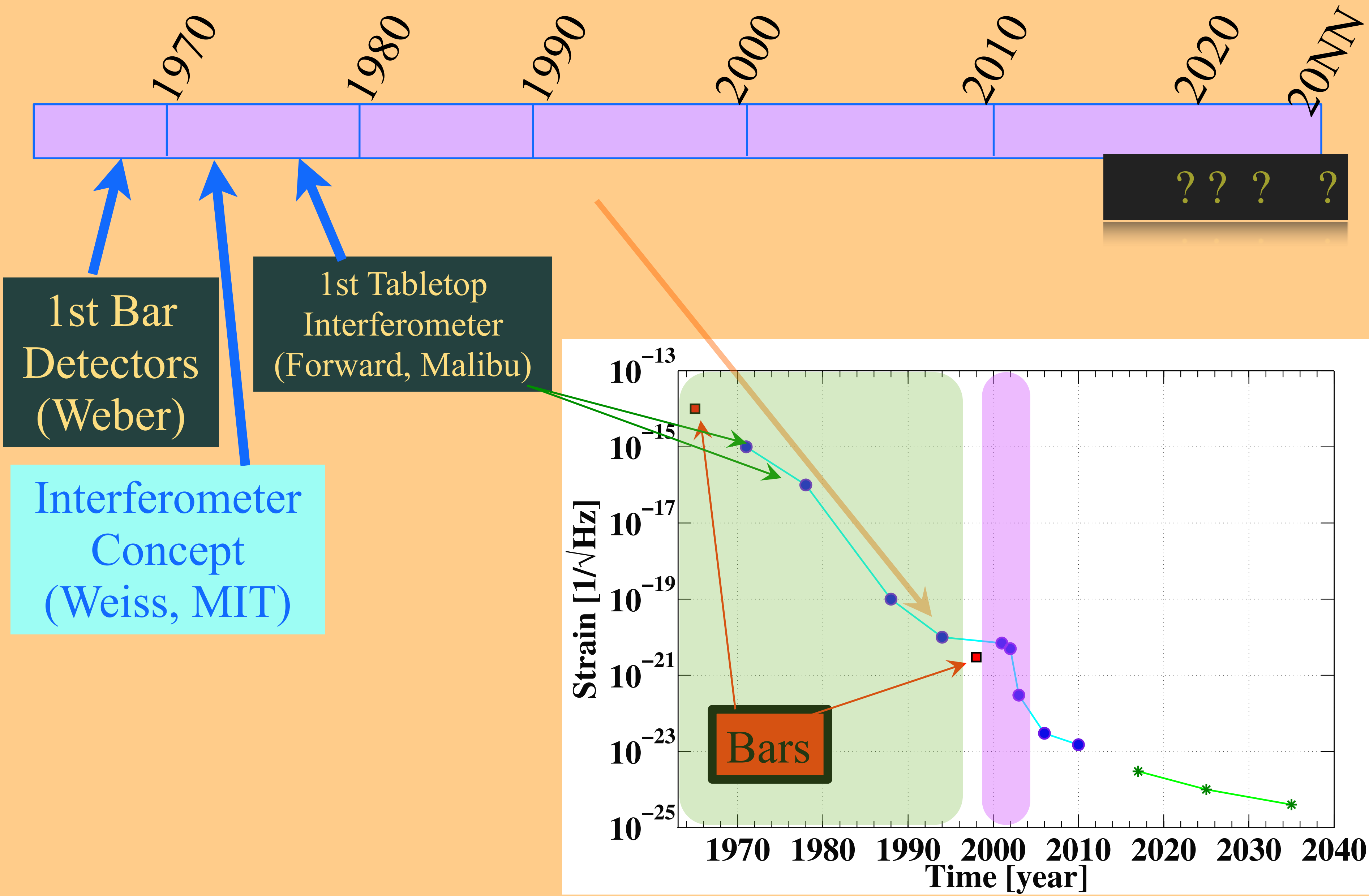
1979:
Gravitational Waves Observed





http://nobelprize.org/nobel_prizes/physics/laureates/1993/

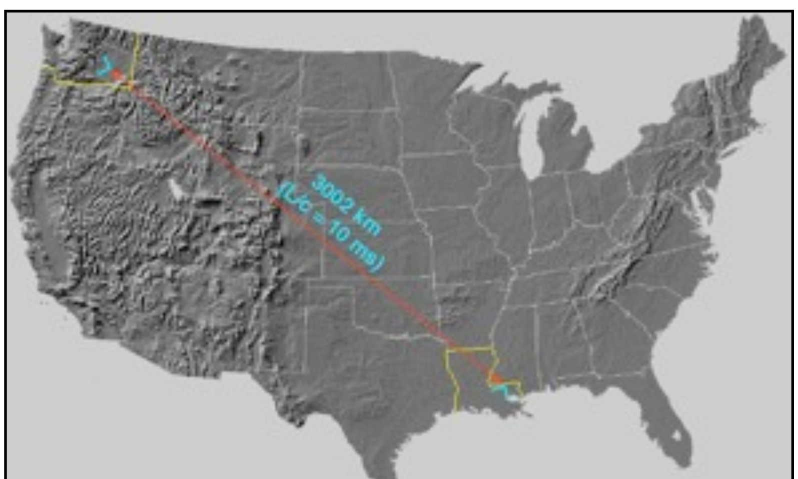
Timeline of GW Detectors



LIGO: Laser Interferometer Gravitational-wave Observatory

Hanford Nuclear Reservation, Eastern Washington

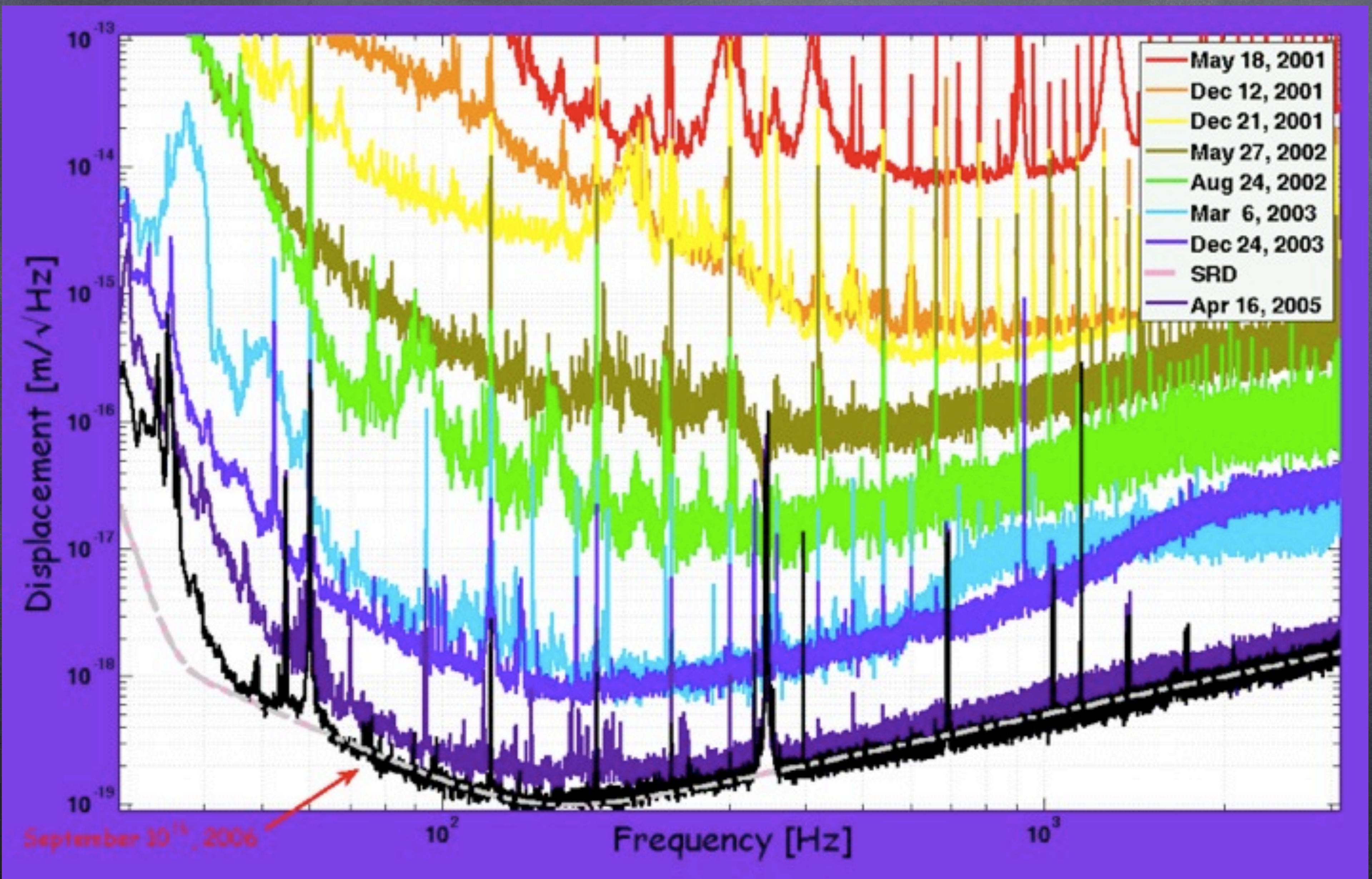
- *Two nearly identical sites (very different seismic, cultural environments)*
- *Arms aligned to observe same polarization*
- *Hanford used to have a 3rd interferometer of half length*



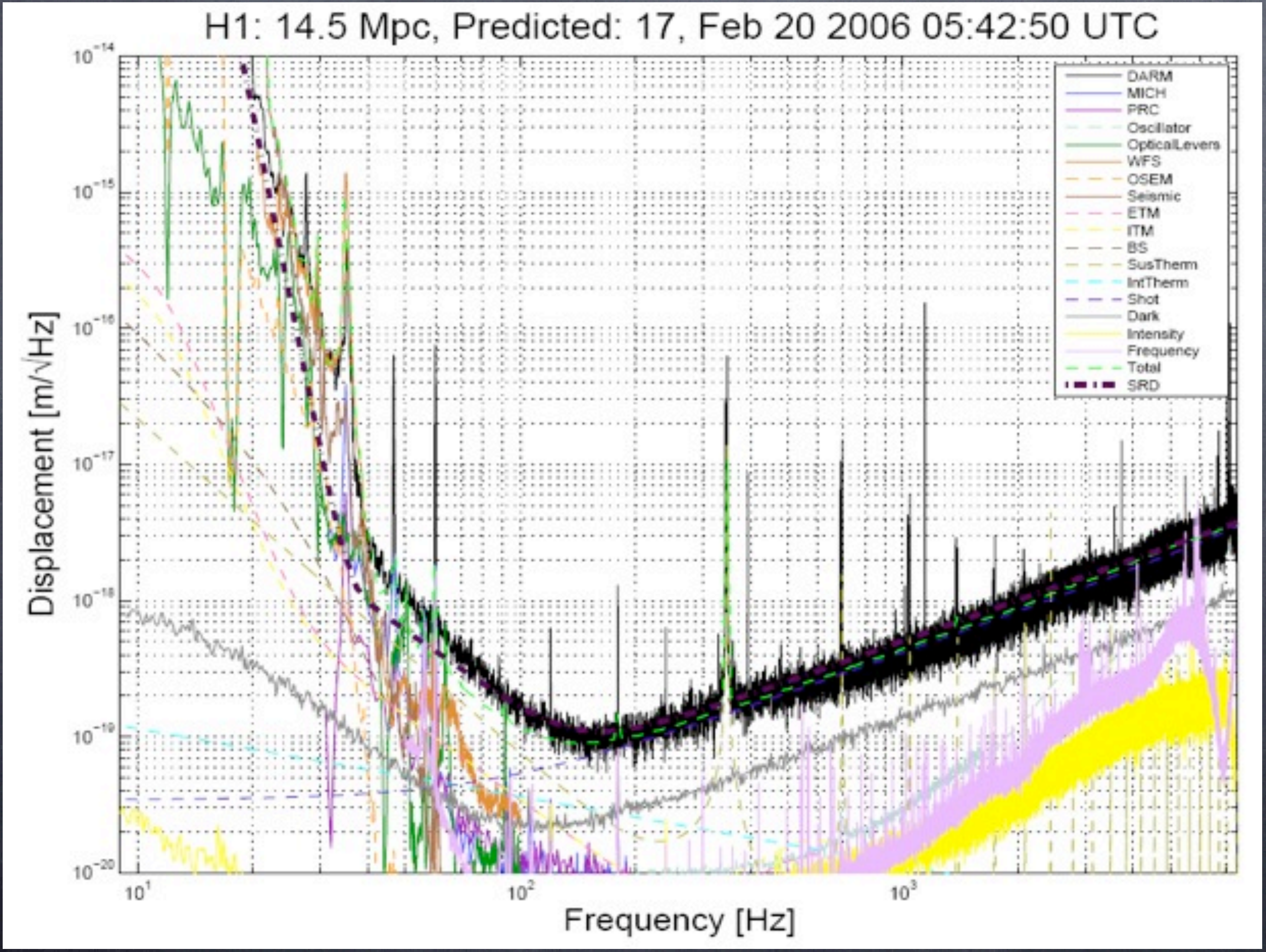
Livingston, LA (L1 4km)

~1 hour from New Orleans

Progress of LIGO Sensitivity



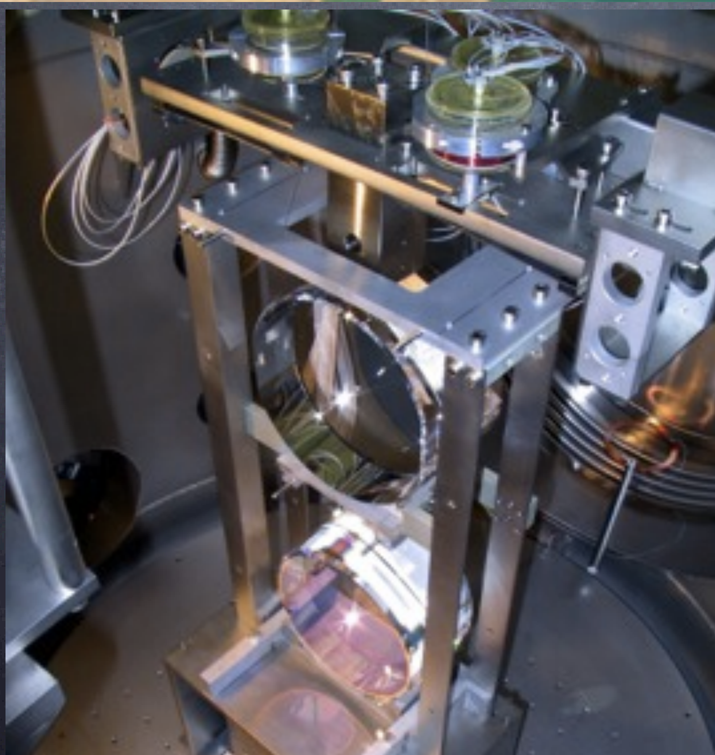
Anatomy of the Noise



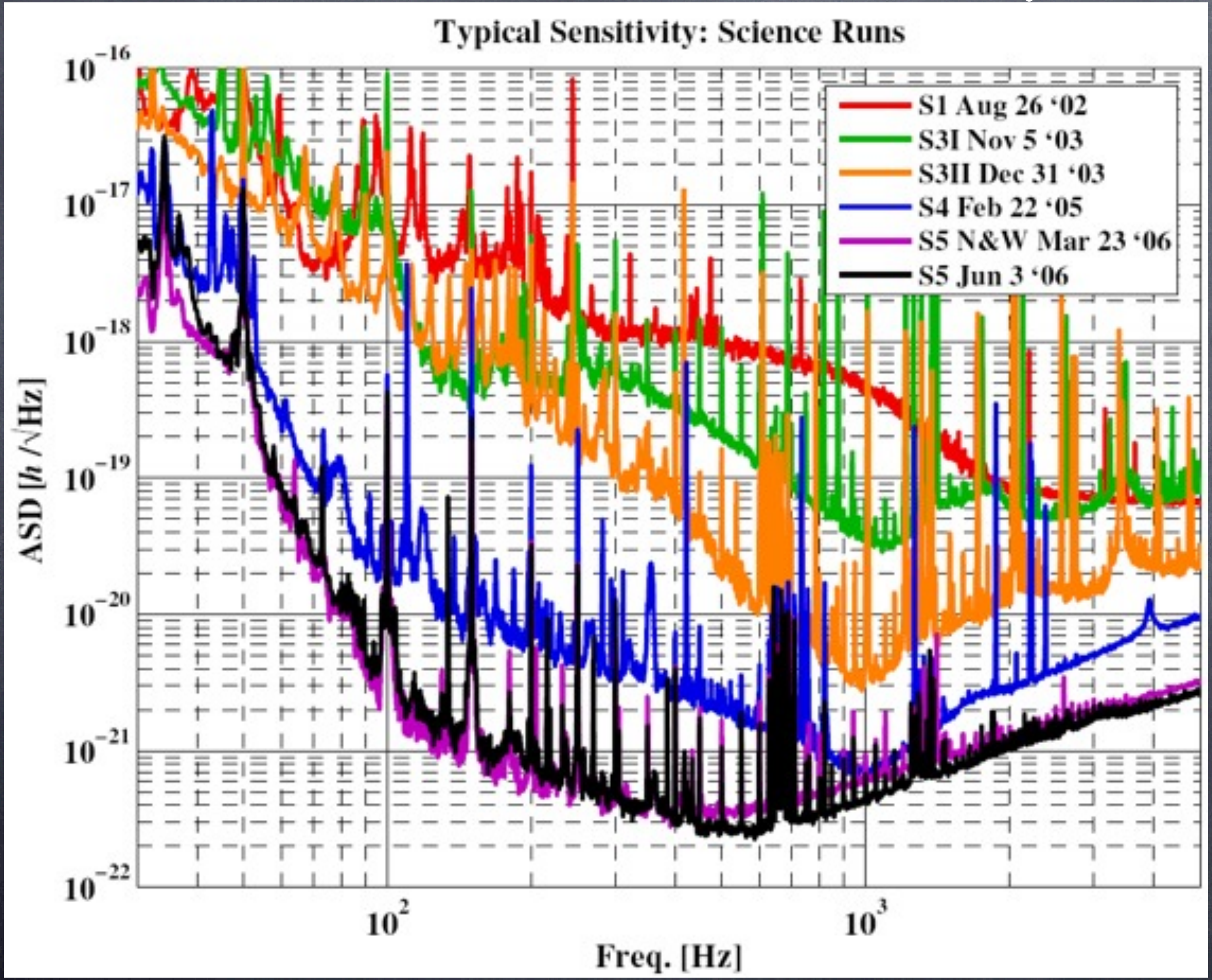
GEO600

Interferometer with 600 m arms, located near Hannover, Germany

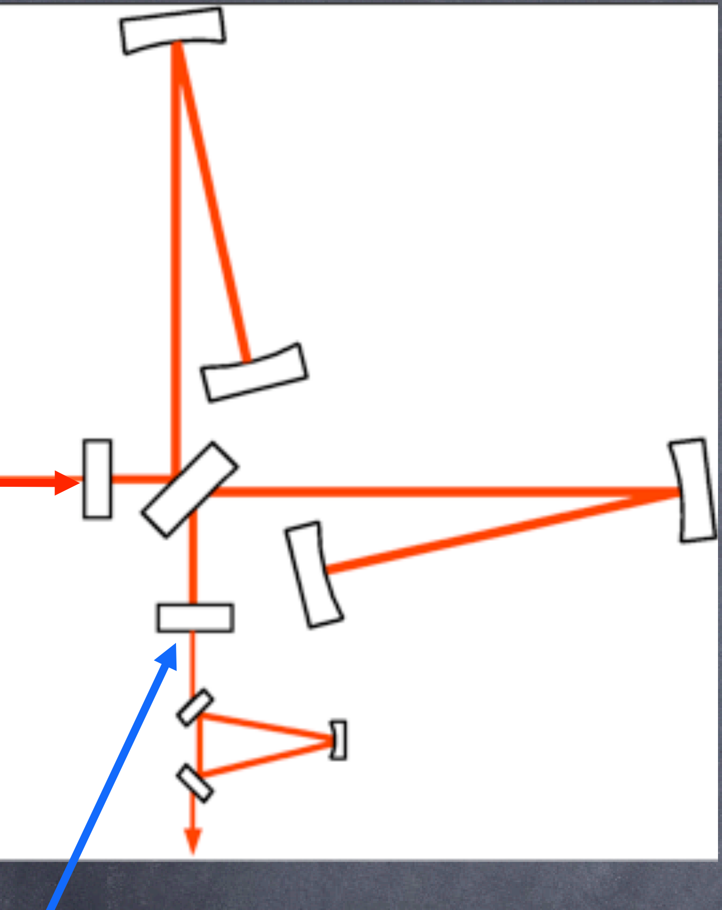
Developed many advanced techniques:
monolithic glass suspensions, signal recycling, electro-static drive, stray charge reduction,...



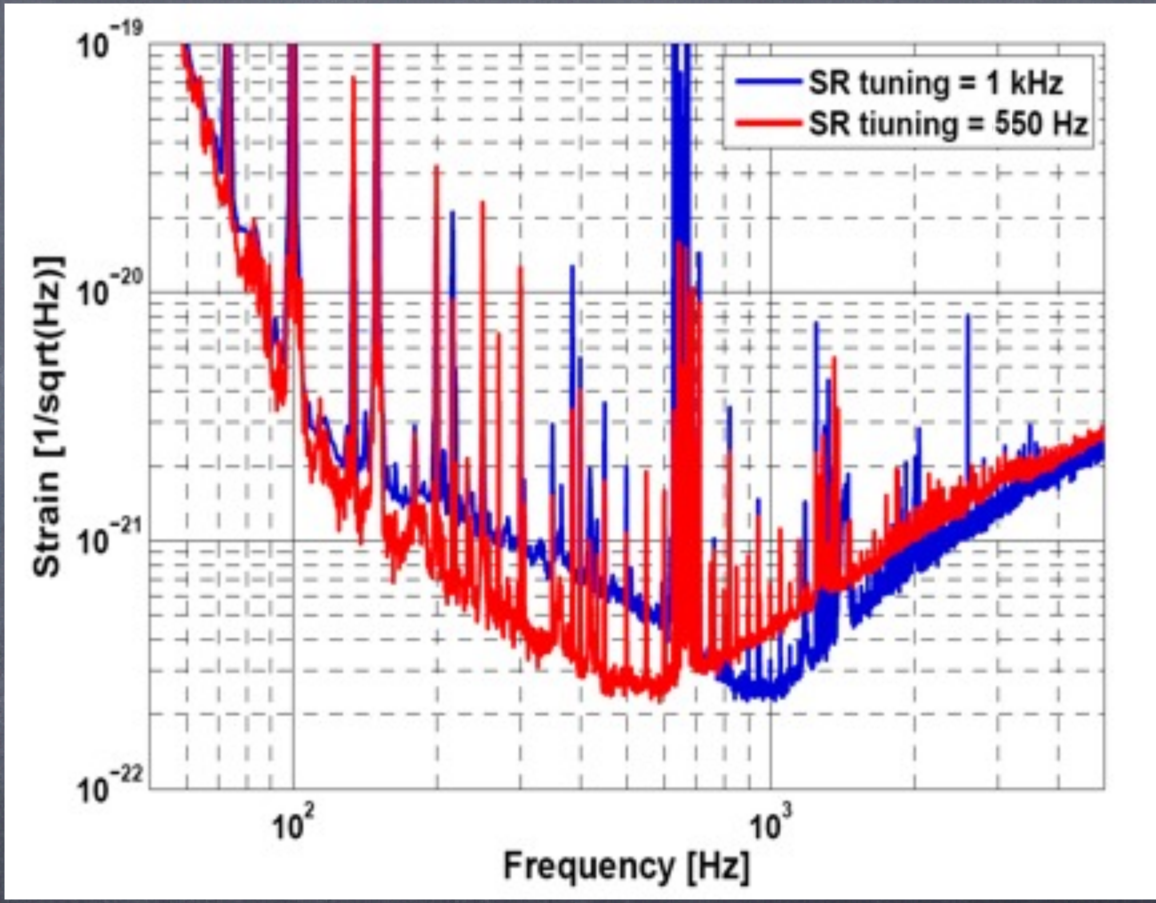
GEO600 Sensitivity



GEO600:



Signal Recycling Mirror



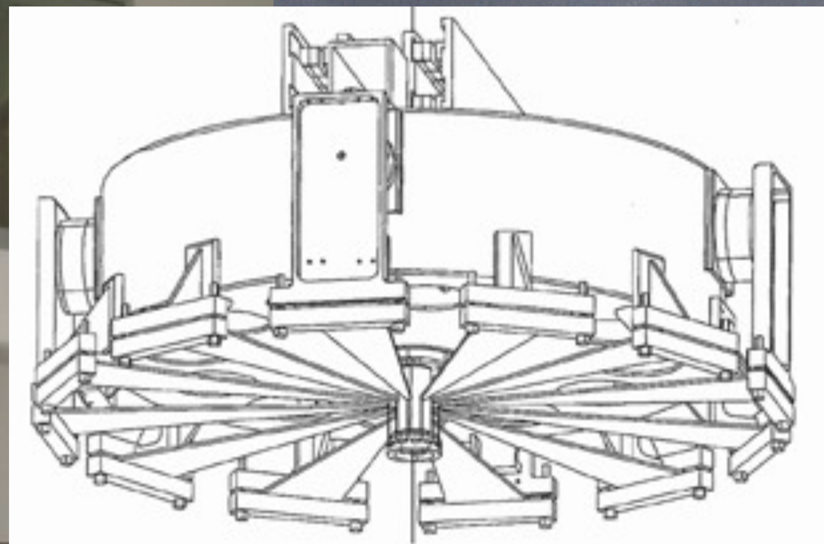
Location of Signal Recycling Mirror Changes Frequency Response (Frequency of Maximum Sensitivity)

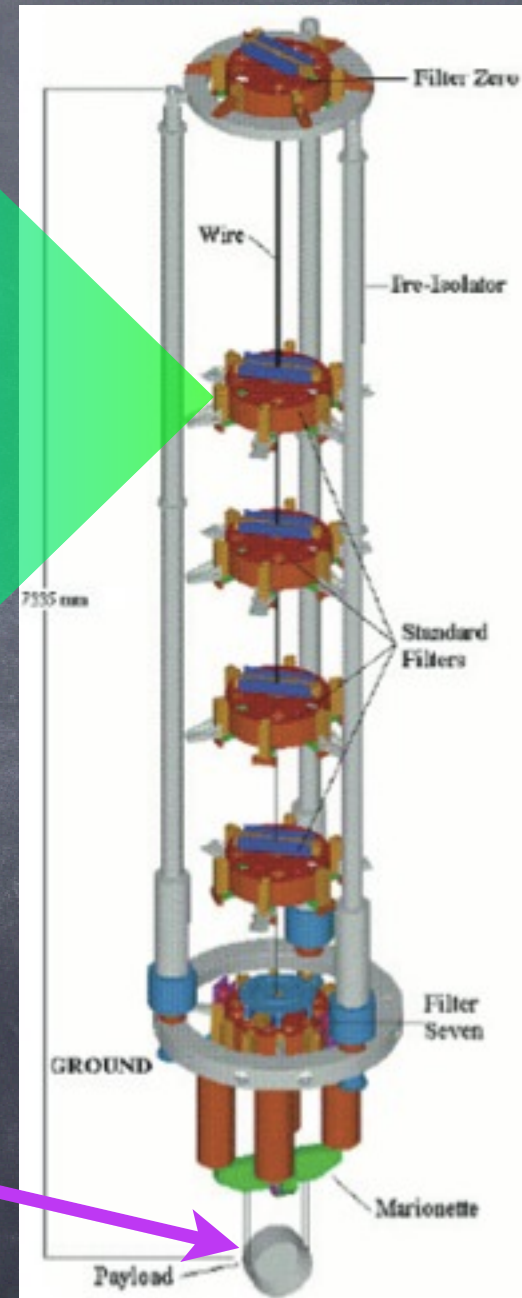
Harald Lück
Rencontres de Moriond

Virgo

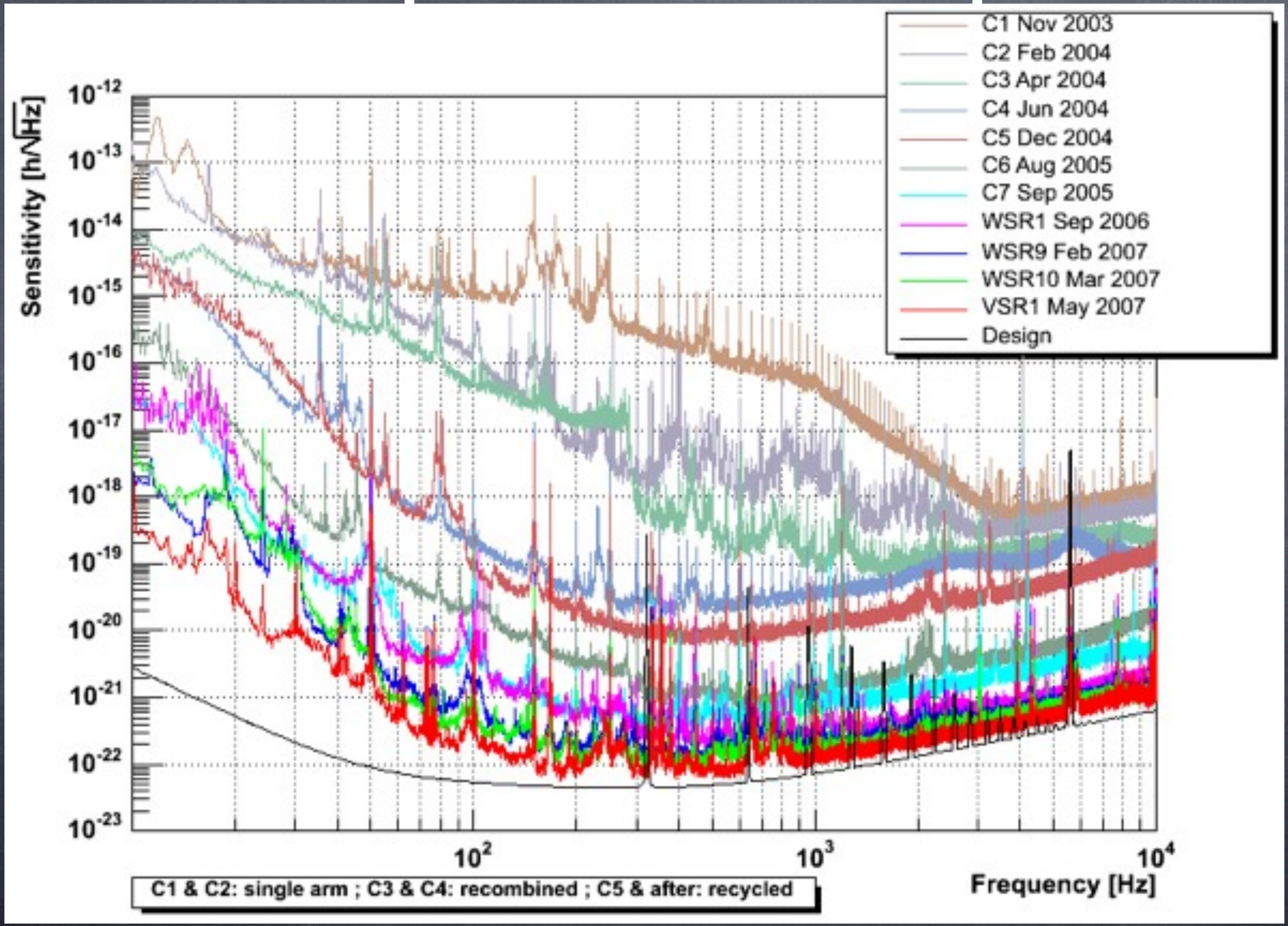
One interferometer with 3 km arms, located near Pisa, Italy


Virgo Office
Building




Filter Zero
Wire
Pre-Isolator
Standard
Filters
Filter
Seven
GROUND
Marionette
Payload

Progress of Virgo

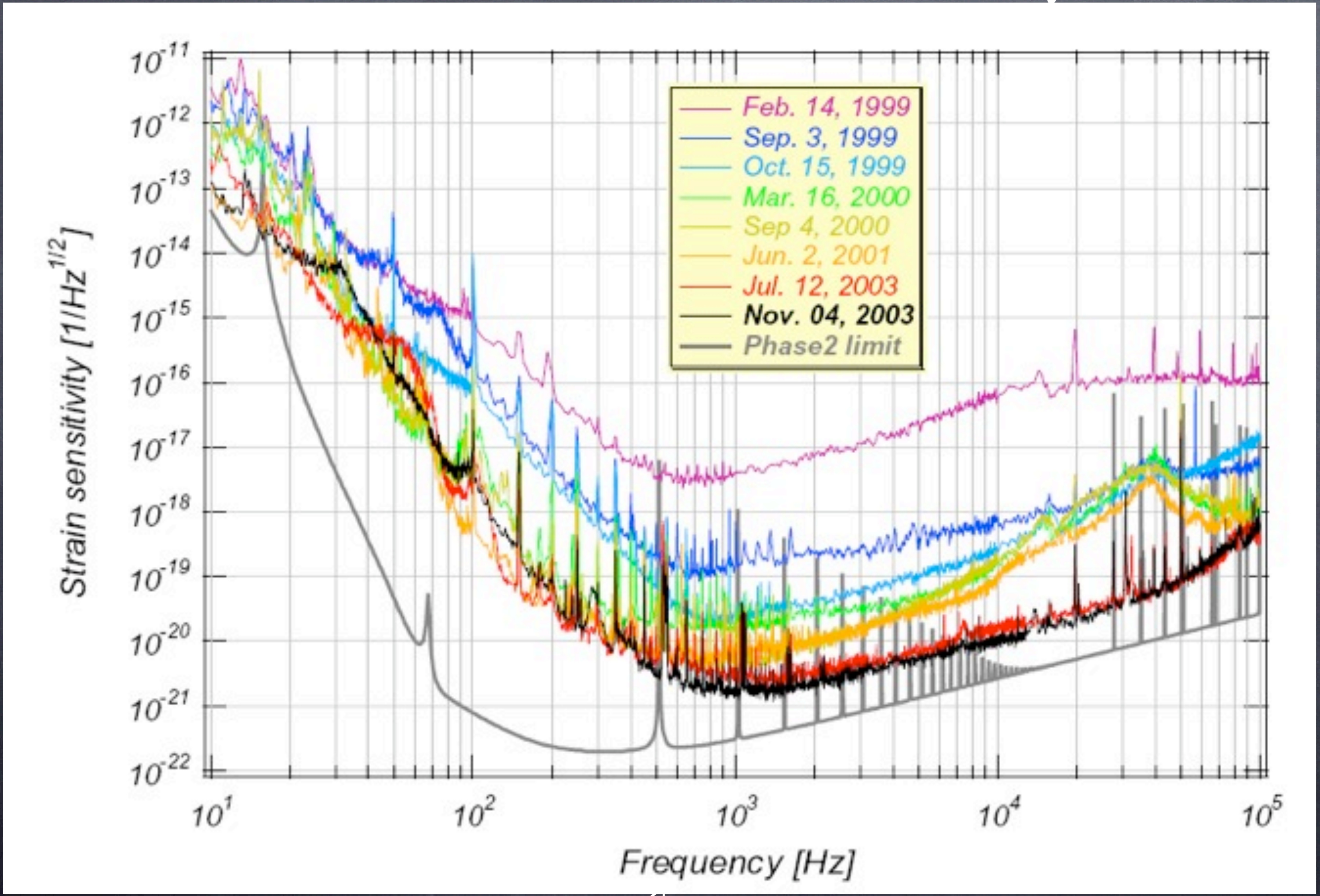


TAMA300

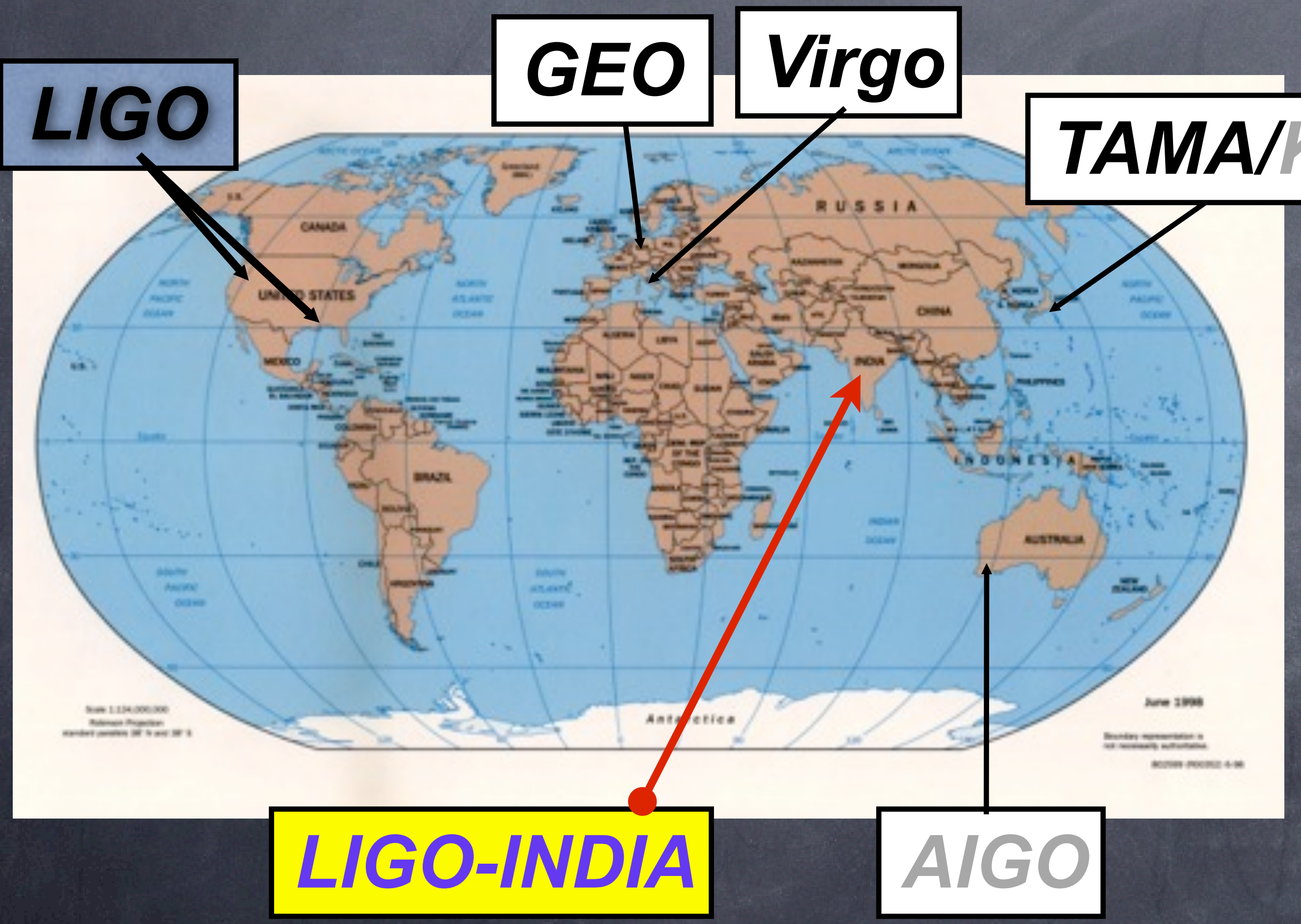
- 300 m interferometer, located at National Astronomical Observatory of Japan (Tokyo)
- Project started 1995
- First large interferometer to begin observations
- Best sensitivity in world 2000-2002

from Kazuaki Kuroda for the TAMA/CLIO/LCGT Collaboration

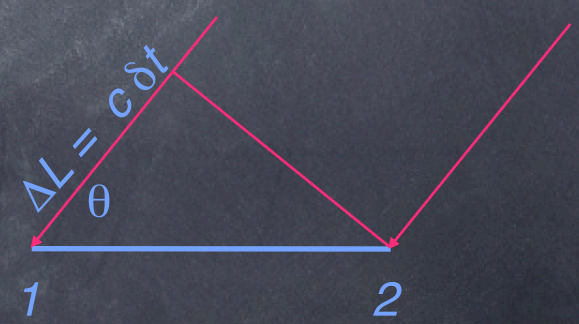
TAMA300 Sensitivity



A Global Network



- Detection confidence
- Locate sources
- Decompose the polarization of gravitational waves



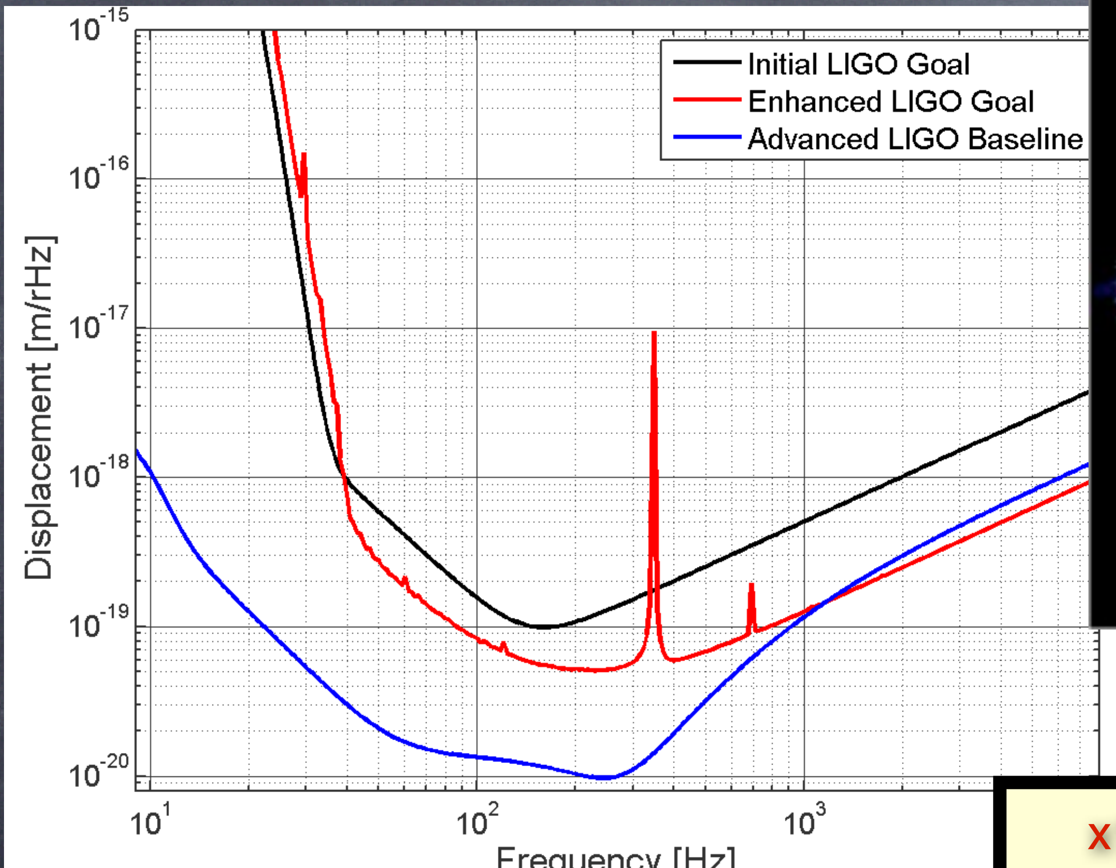
Looking to the Future

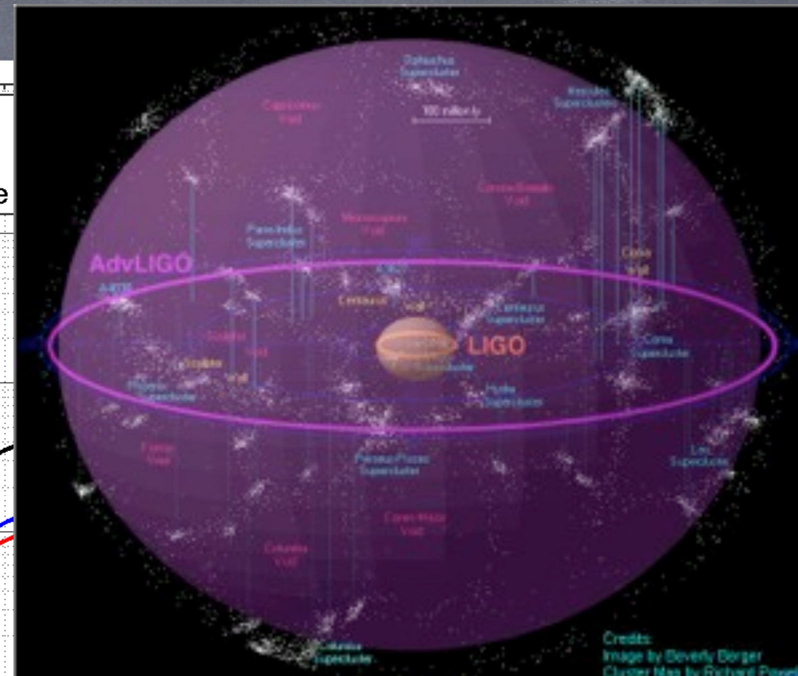
LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Stuart Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravita[illegible]

- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

Advanced LIGO



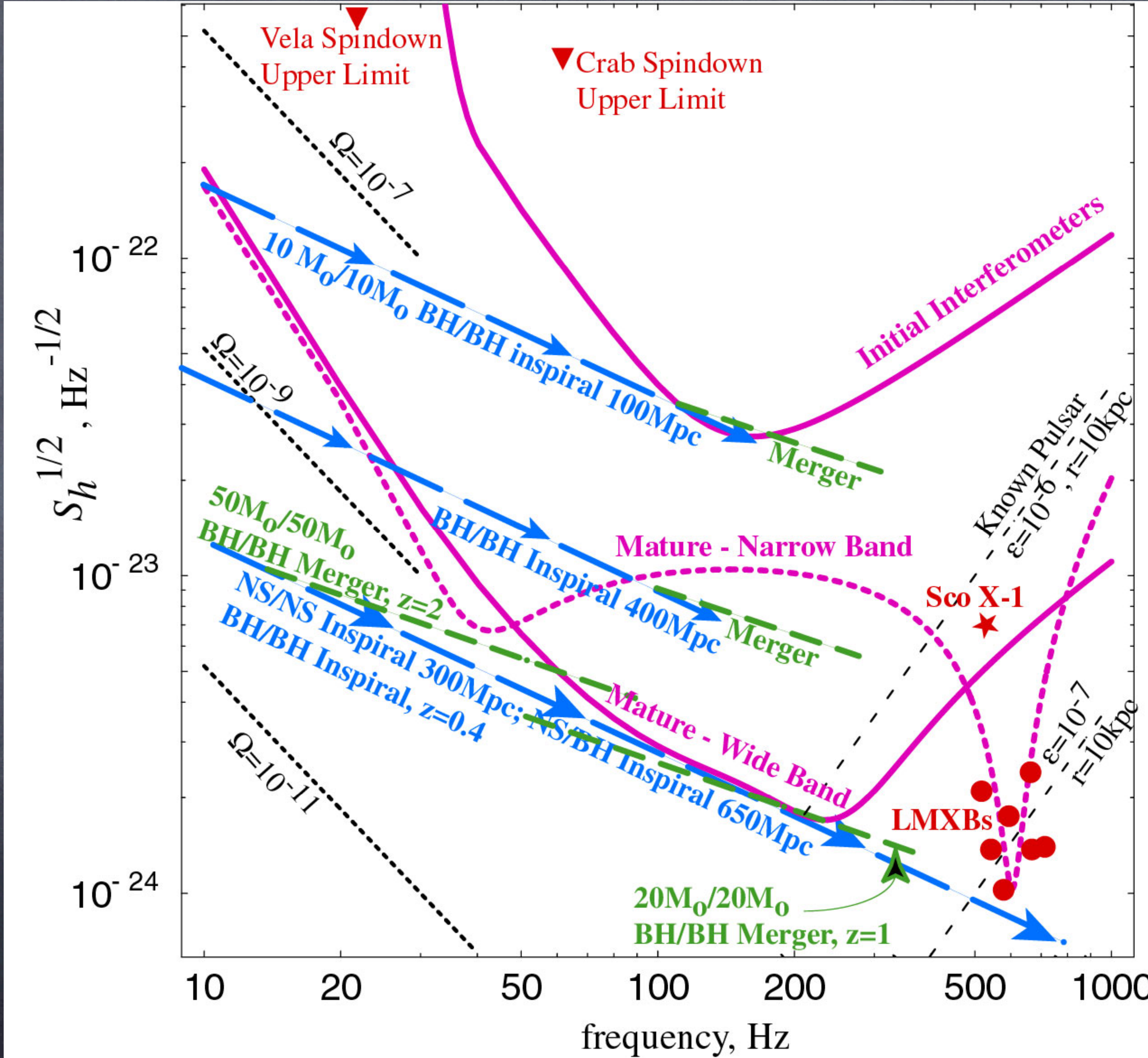


x10 better amplitude sensitivity

⇒ x1000 rate=(reach)³

⇒ 1 day of Advanced LIGO

» 1 year of Initial LIGO !



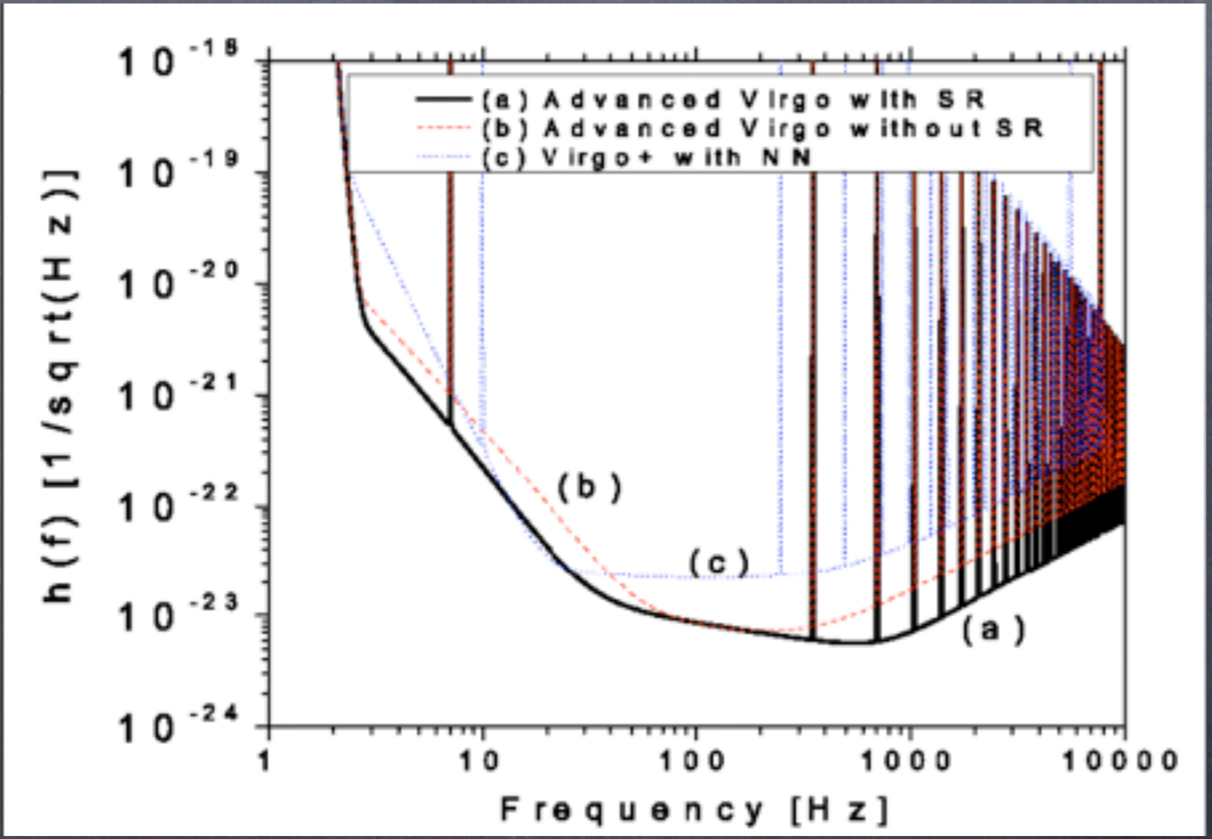
LIGO
Vela Spindown Upper Limit
Crab Spindown Upper Limit
Ω=10-7
Ω=10-9
Ω=10-11
10 Mo/10Mo BH/BH inspiral 100Mpc
Merger
Initial Interferometers
BH/BH Inspiral 400Mpc
Merger
50Mo/50Mo BH/BH Merger, z=2
NS/NS Inspiral 300Mpc; NS/BH Inspiral 650Mpc
BH/BH Inspiral, z=0.4
Mature - Narrow Band
Mature - Wide Band
Sco X-1
Known Pulsar ε=10-6, r=10kpc
ε=10-7 r=10kpc
LMXBs
20Mo/20Mo BH/BH Merger, z=1
10- 22
10- 23
10- 24
$S_h^{1/2}$, $Hz^{-1/2}$
10
20
50
100
200
500
1000
frequency, Hz

What is so Advanced?

Parameter	*LIGO*	*Advanced LIGO*
Stored Laser Power	20 kW	800 kW
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in broadband
Seismic Isolation Performance	f_{low} ~ 50 Hz	f_{low} ~ 10 Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum

Advanced Virgo

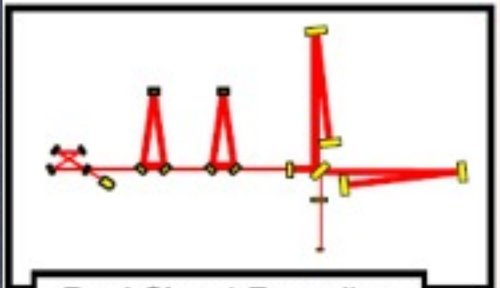
- Similar scope to AdLIGO
  - Larger mirrors
  - Improved coatings
  - Higher laser power
  - DC read-out

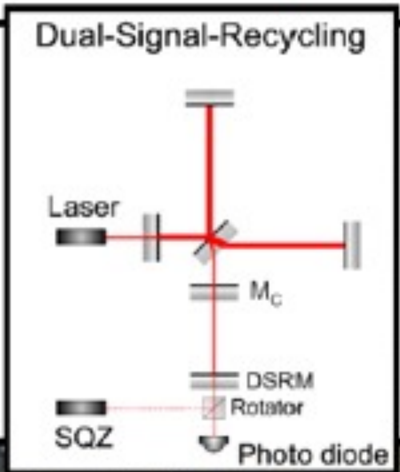


Julien Marque
Rencontres de Moriond

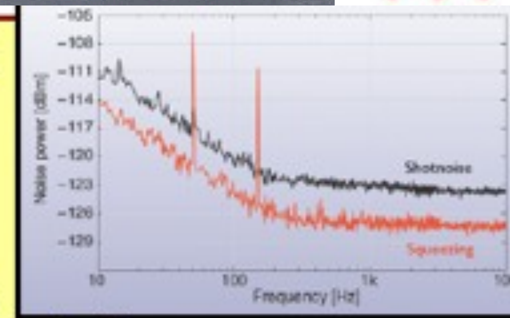
Plans of GEO

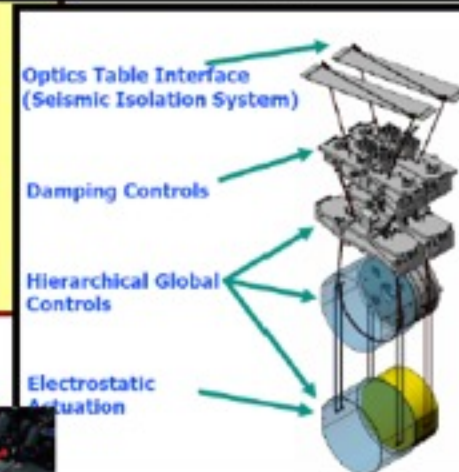
Stefan Hild

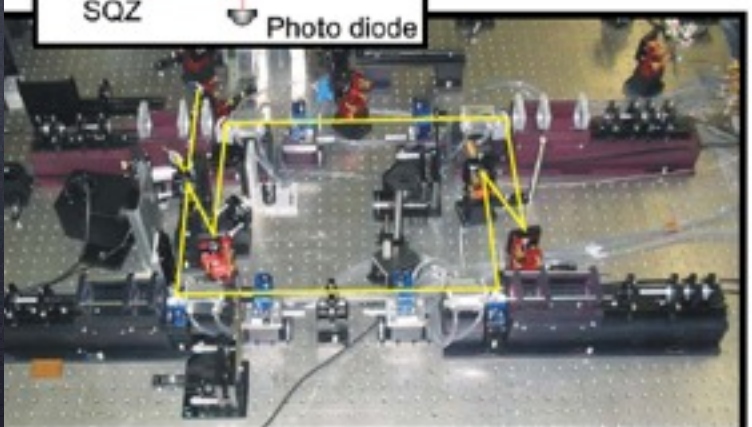


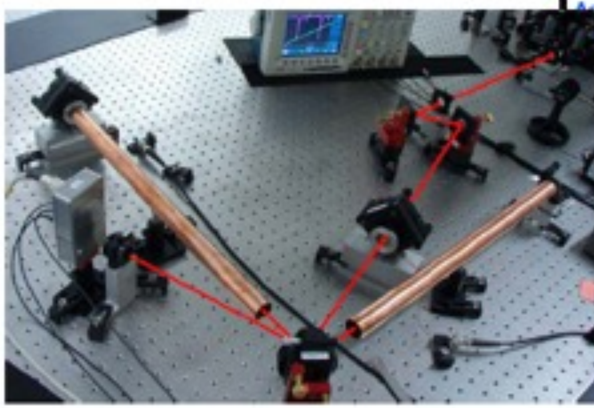


- operate GEO600 / GEO-HF as LSC detector
- LSC data analysis
- laser and suspensions for AdvLIGO (laser for Enh. LIGO)
- contribute to AdvVIRGO design
- R&D and design towards third generation detectors





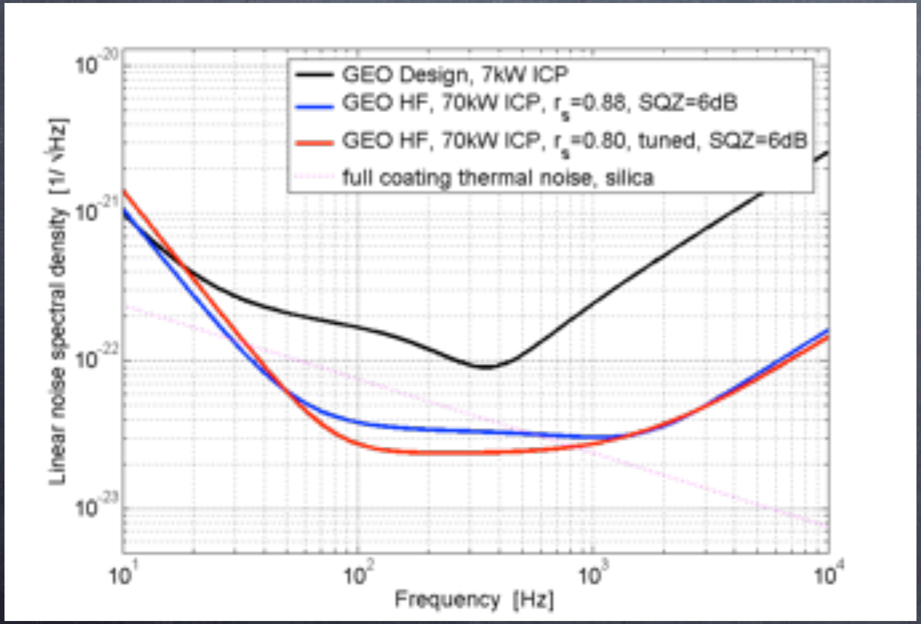


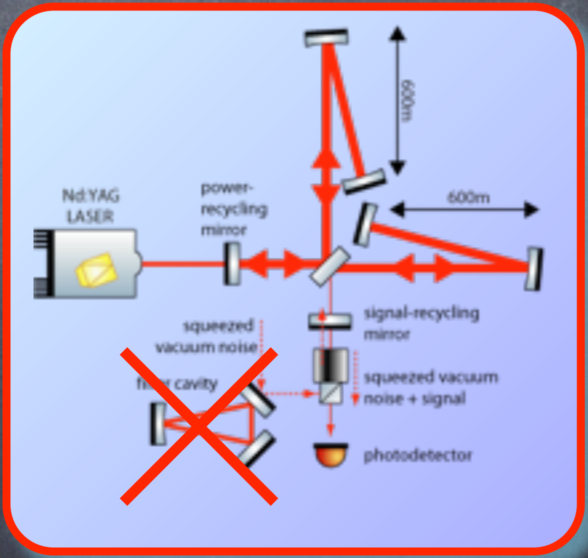


Stefan Hild

GEO HF

- Emphasize high frequencies--length less important
- Pioneer advanced techniques for other large interferometers
- Tuned signal recycling and squeezing



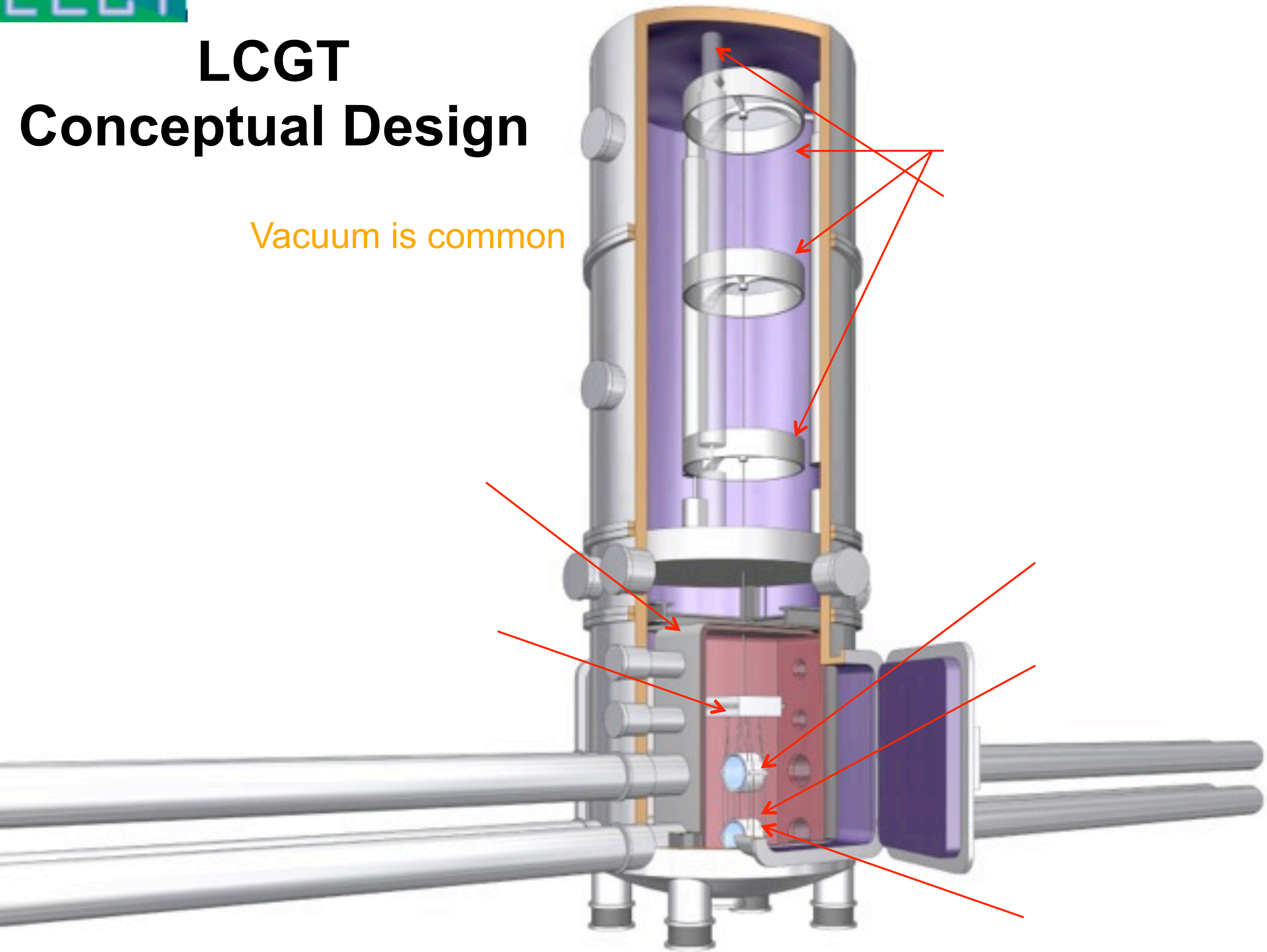


KAGRA

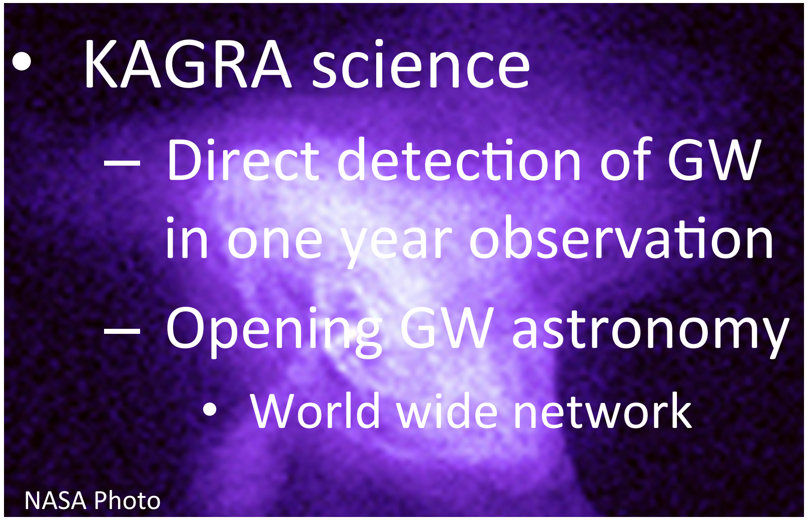
- 3 km baseline
- Utilizes cryogenic mirrors (sapphire)
- Construction at an underground site (Kamioka mine)
- Two parallel interferometers installed in a common vacuum envelope
- Suspension point interferometer

LCGT
Conceptual Design

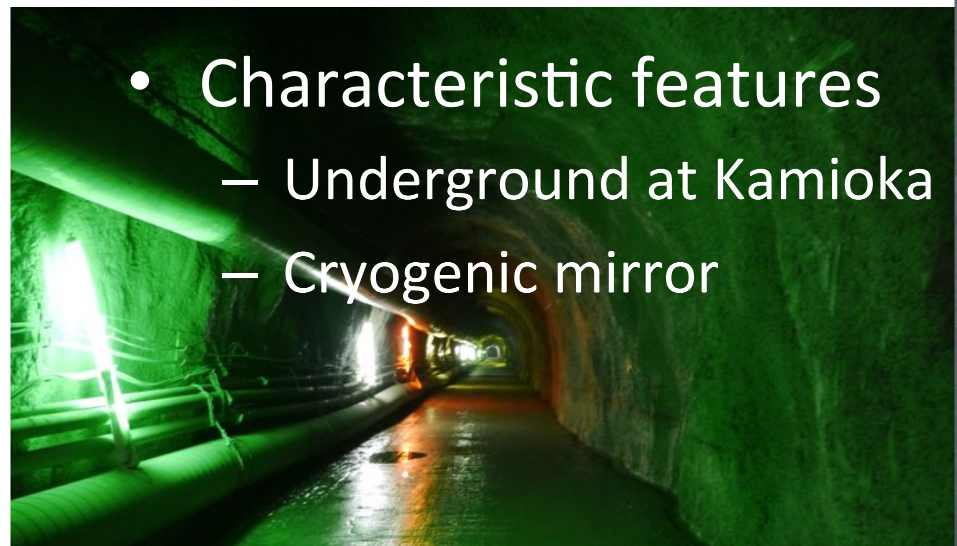
Vacuum is common



Overview of KAGRA

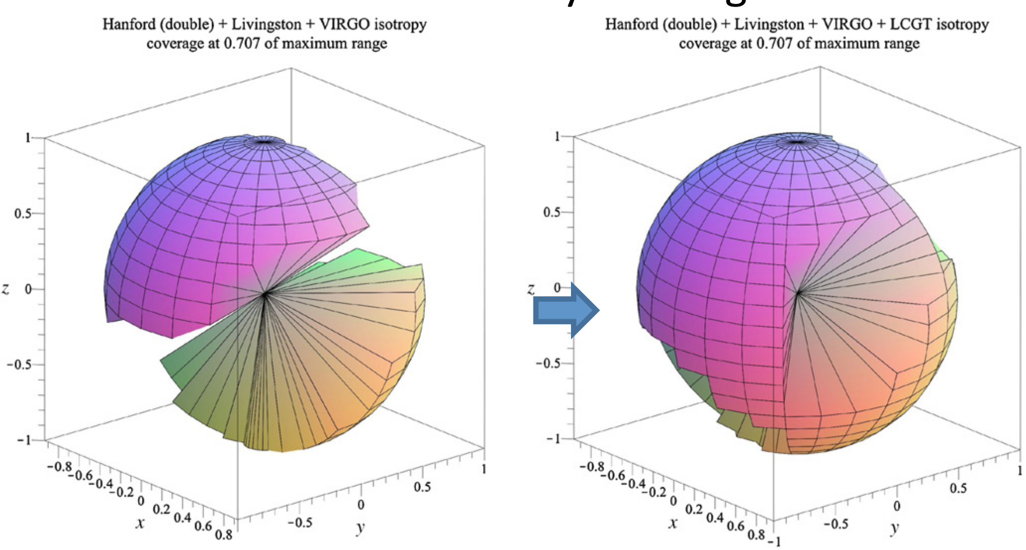


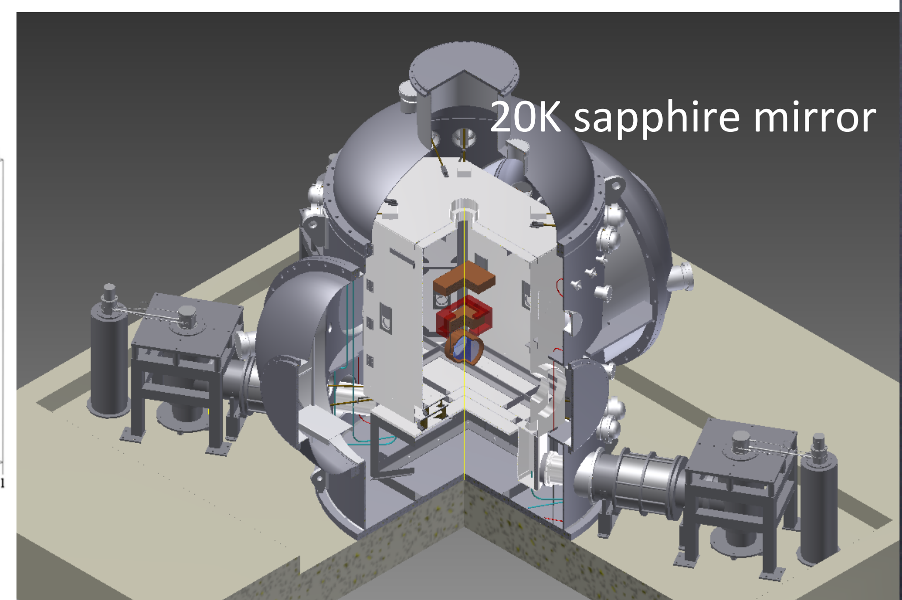
- KAGRA science
  - Direct detection of GW in one year observation
  - Opening GW astronomy
    - World wide network



- Characteristic features
  - Underground at Kamioka
  - Cryogenic mirror

KAGRA enhances sky coverage !

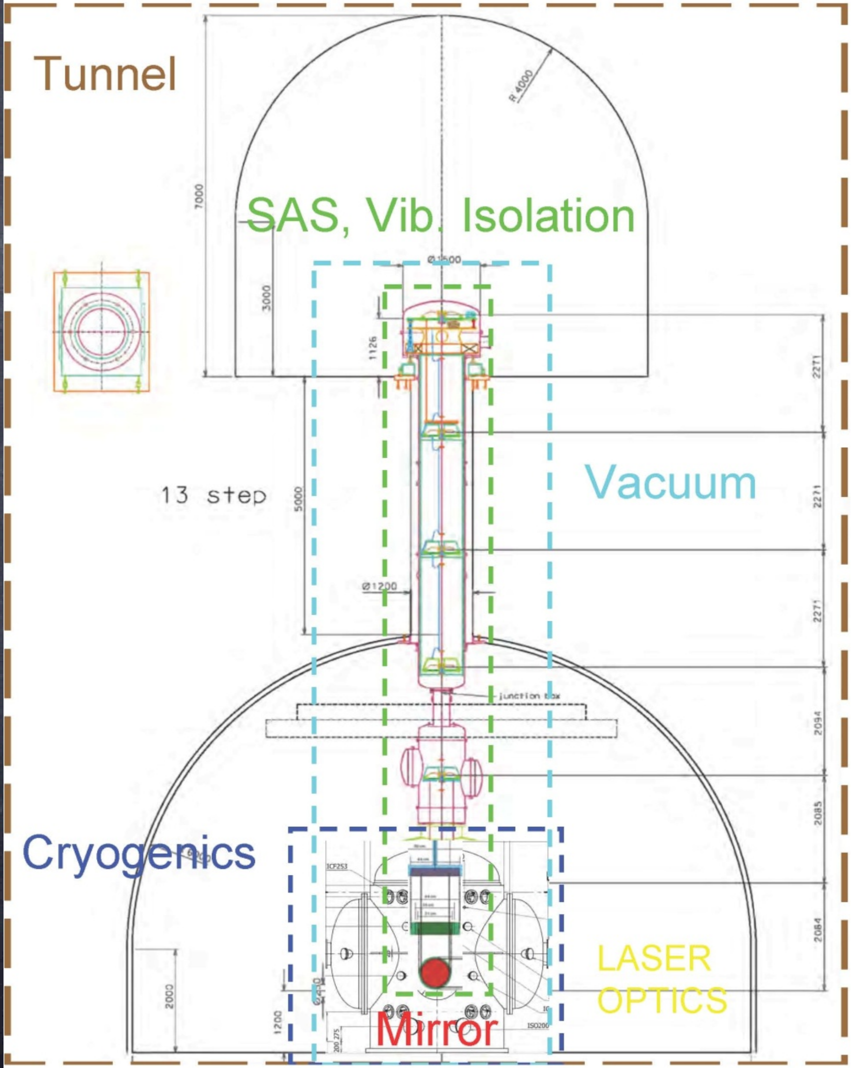


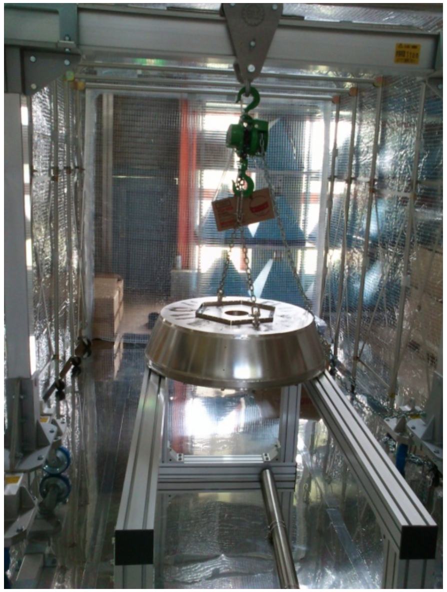


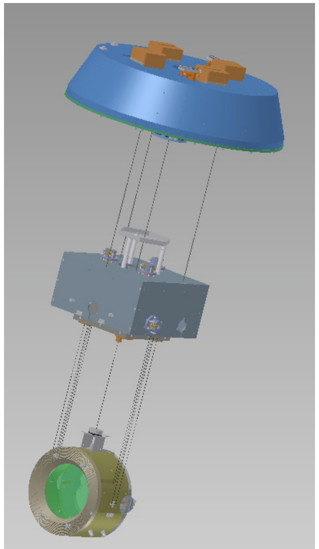
CQG 28 (2011) 125023 B.F. Schutz

Vibration Isolation

Main SAS: 13m tall
2 stages of floor







- 19 standard filters have been built and delivered: final assembly of the GAS filters is ongoing
- Six out of 11 pre-isolator top filters have been finished
- Prototypes of a complete chain pre–isolator, standard filter, bottom filter and optical payload have been completed and are under tests in Japan

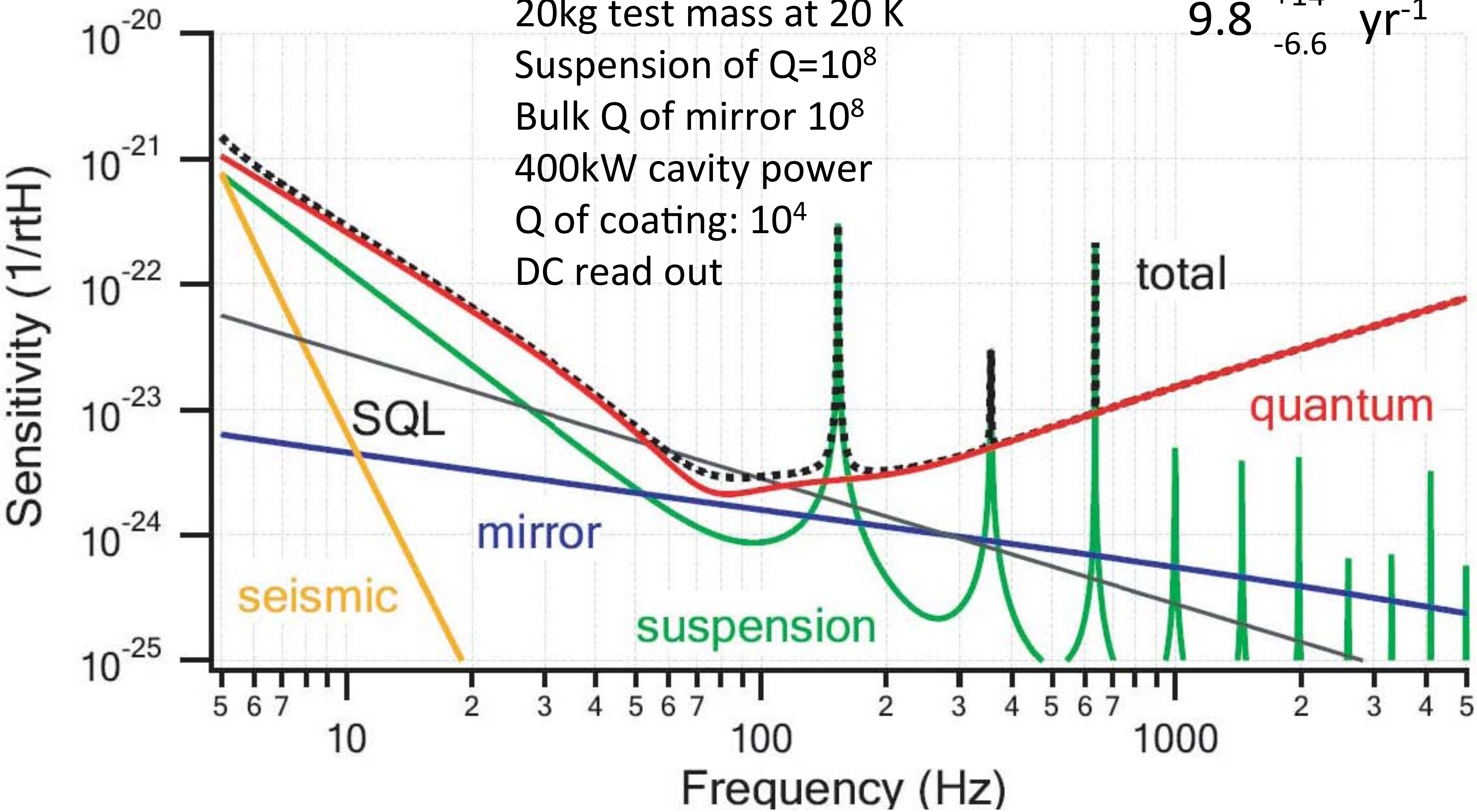
Ultimate design sensitivity of KAGRA

This sensitivity achieves 167 Mpc for coalescence GW of 1.4 Ms NSB.

Duty factor: > 80%
Expected event rate

$9.8^{+14}_{-6.6}$ yr^{-1}

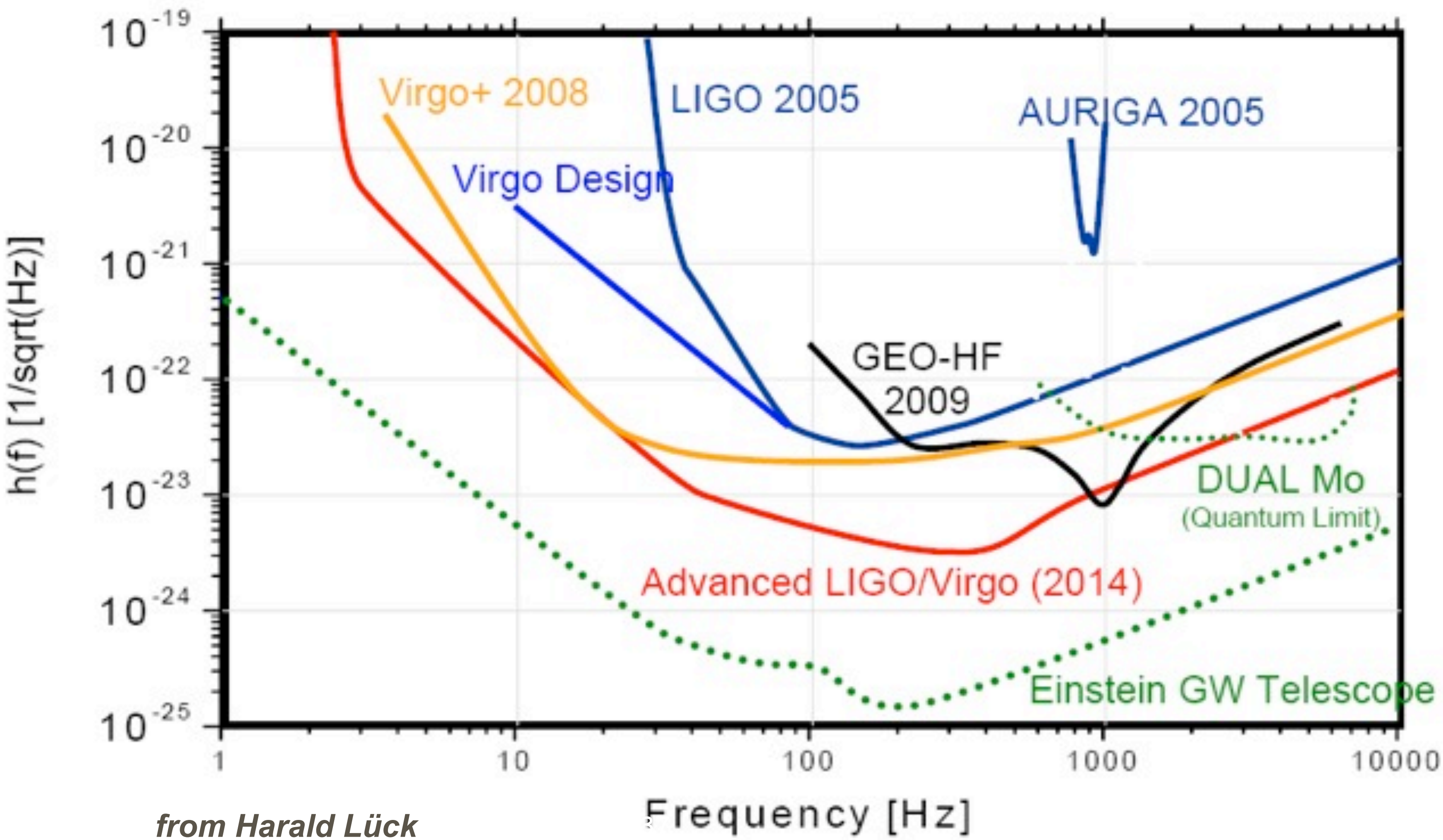
20kg test mass at 20 K
Suspension of Q=10^8
Bulk Q of mirror 10^8
400kW cavity power
Q of coating: 10^4
DC read out



ET Baseline Concept

- Underground location
  - Reduce seismic noise
  - Reduce gravity gradient noise
  - Low frequency suspensions
- Cryogenic
- Overall beam tube length ~ 30km
- Possibly different geometry

Einstein Gravitational-Wave Telescope (ET)



from Harald Lück