Gravitational Radiation Experiments

Rana Adhikari
Caltech

They Exist !

On the Earth:

- TAMA 300 - Tokyo/TAMA, Japan
- GEO 600 - Hannover/Ruthe, Germany
- Virgo 3000 - Pisa/Cascina, Italy
- LIGO 4000 - Washington+Louisiana, USA
- BARS: ALLEGRO, AURIGA, NAUTILUS, EXPLORER

Space:

- LISA 5x10^6 - Orbiting the Sun (2015-2020)
- Pulsar Timing - Analyzing Radio data (NOW)
- BBO/DECIGO - Directly Observe Inflation

GWs and Bars

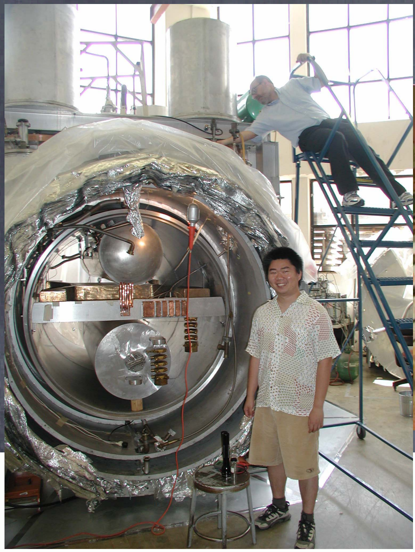
- First ground-based detectors—the beginning of GW detection: Weber
- Much improvement in Bars
  - Cryogenics
  - Quantum Limited Readout

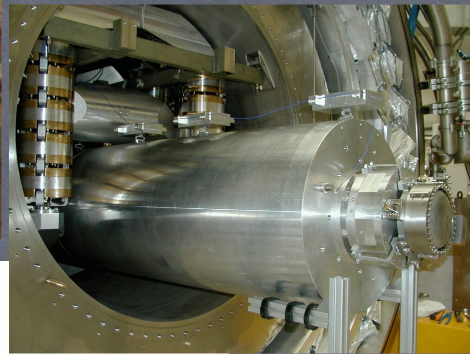
Bar display at LIGO Hanford

Joe Weber + Bar

First World-wide GW Network: IGEC

International Gravitational Event Collaboration
Established 1997 in Perth





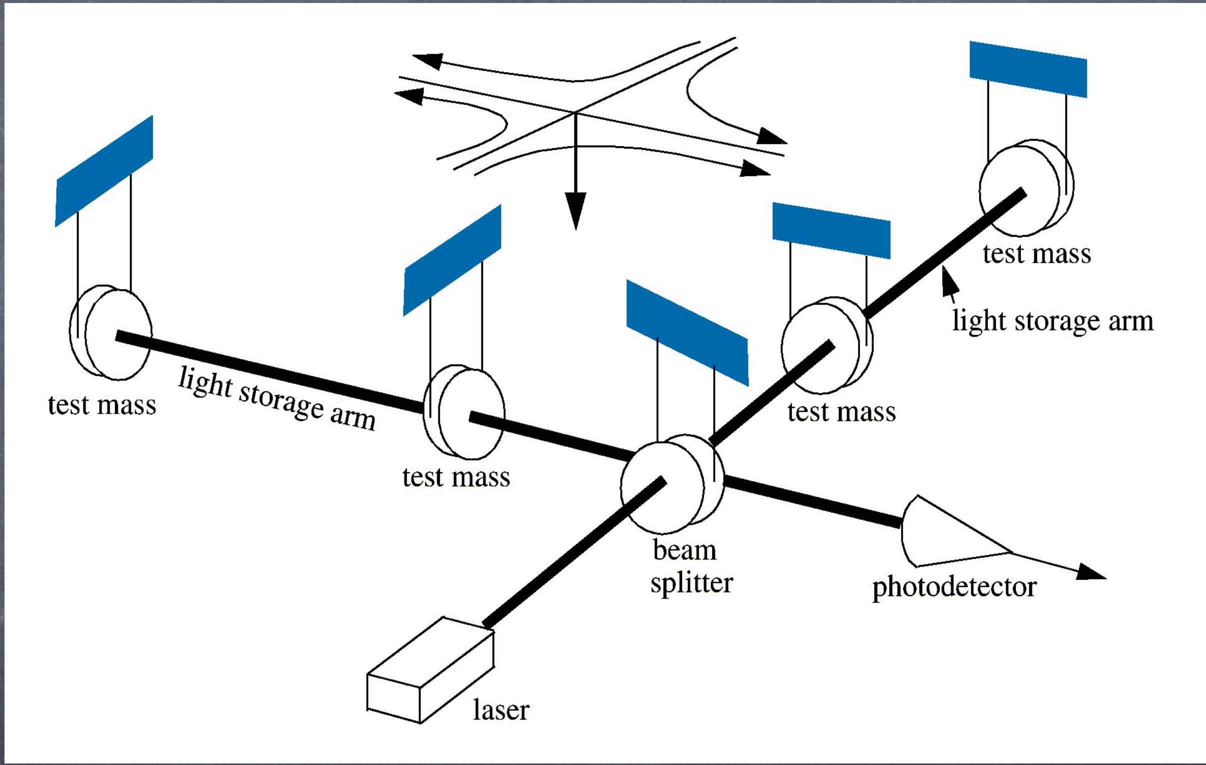
Included all operating bar detectors in the world

Figure courtesy of Massimo Cerdonio

Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses (in horizontal plane) for frequencies $f \gg f_{pend}$

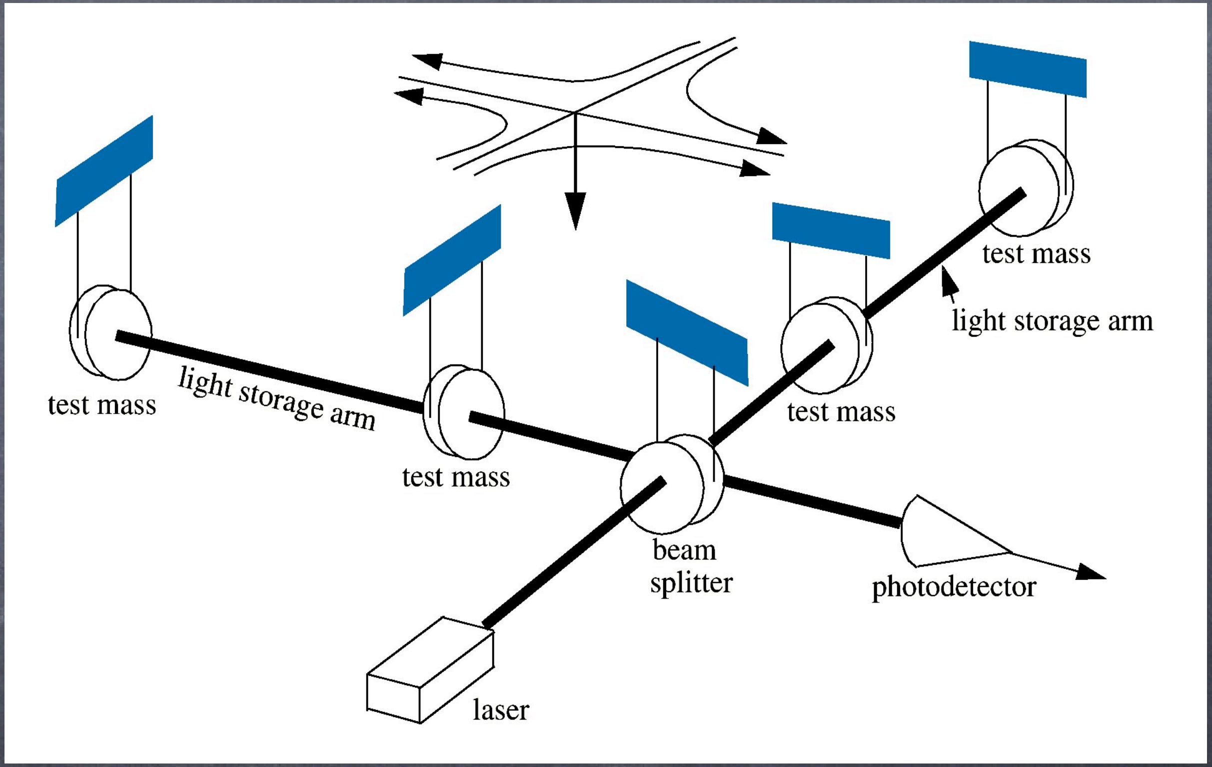
$$h = \Delta L / L$$



Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses (in horizontal plane) for frequencies $f \gg f_{pend}$

$$h = \Delta L / L$$



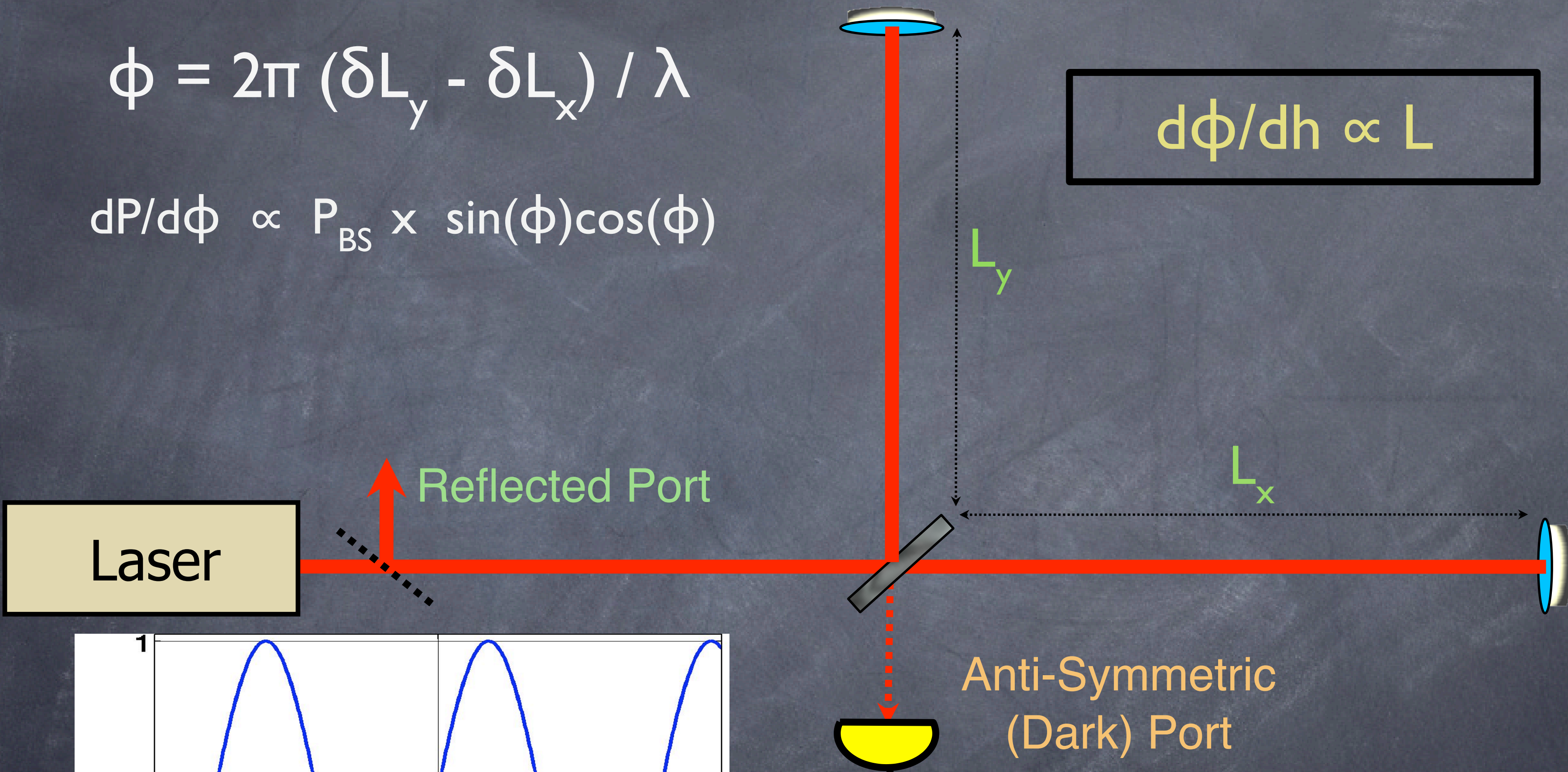
Terrestrial detector
For $h \sim 10^{-22} - 10^{-21}$
L ~ 4 km (LIGO)
$\Delta L \sim 10^{-18}$ m

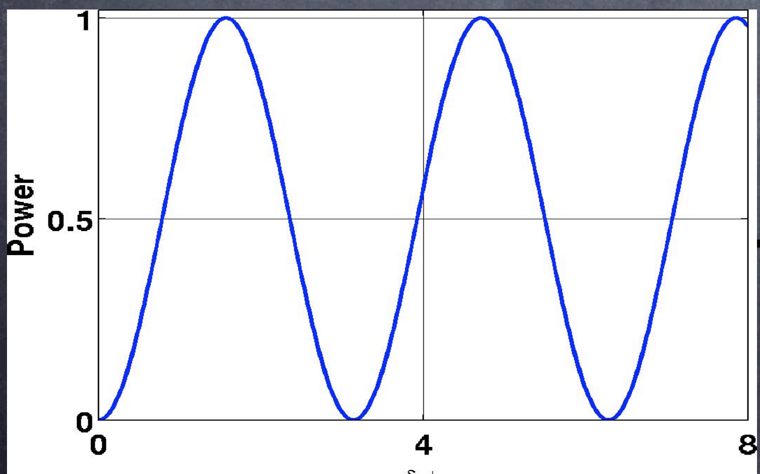
Michelson Interferometer

$$\phi = 2\pi\,(\delta L_y - \delta L_x) / \lambda$$

$$dP/d\phi \;\propto\; P_{BS} \times \sin(\phi)\cos(\phi)$$

$$d\phi/dh \propto L$$

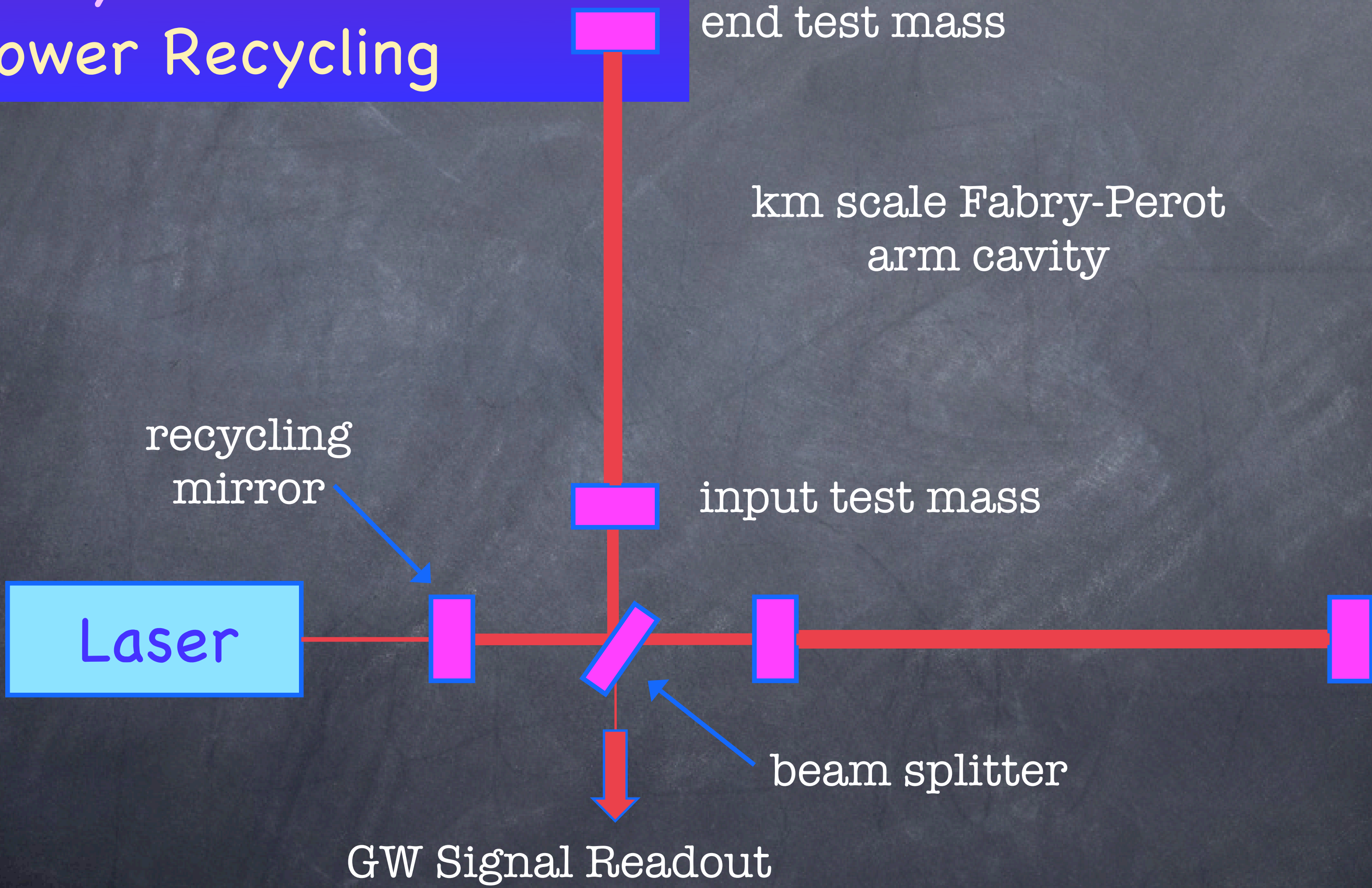


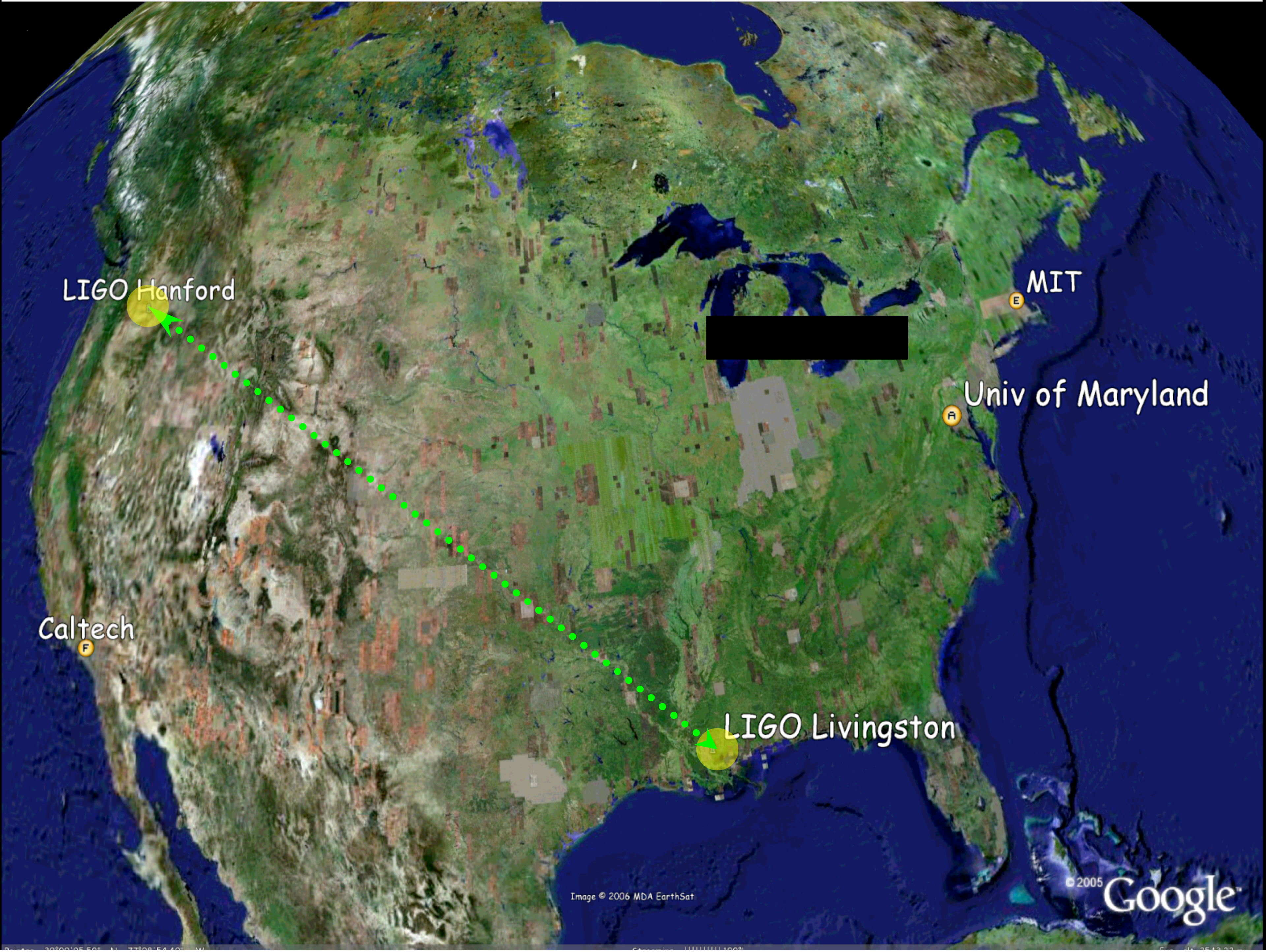


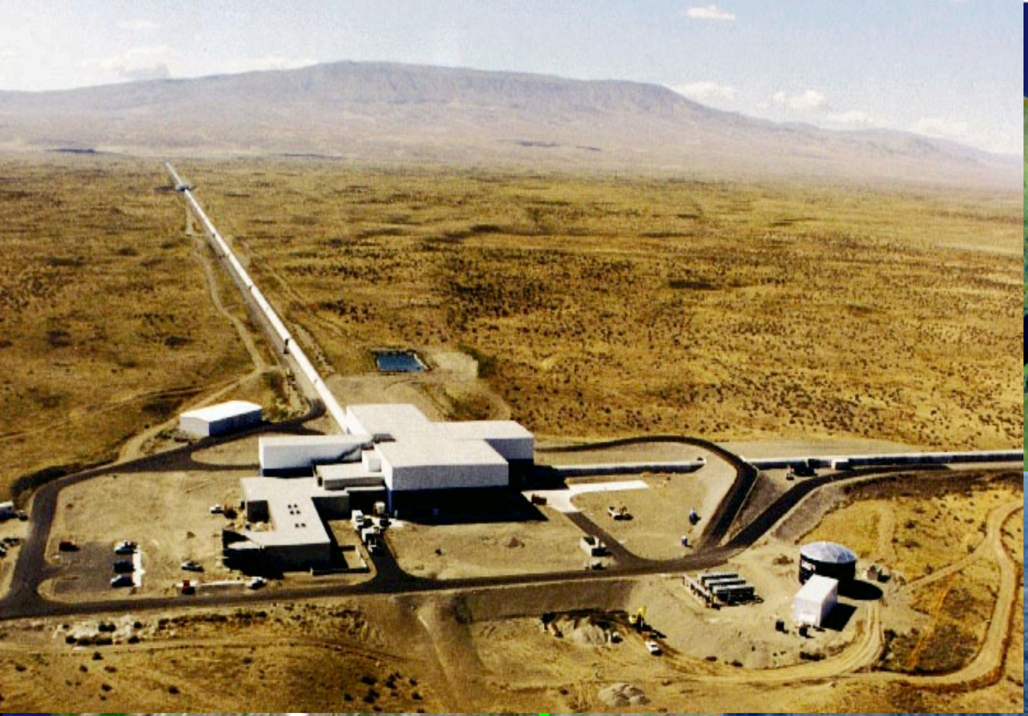
$$\mathbf{P \;\propto\; P_{BS} \times \sin^2(\phi)}$$

Typical Optical Configuration

Michelson Interferometer
+ Fabry-Perot Arms
+ Power Recycling



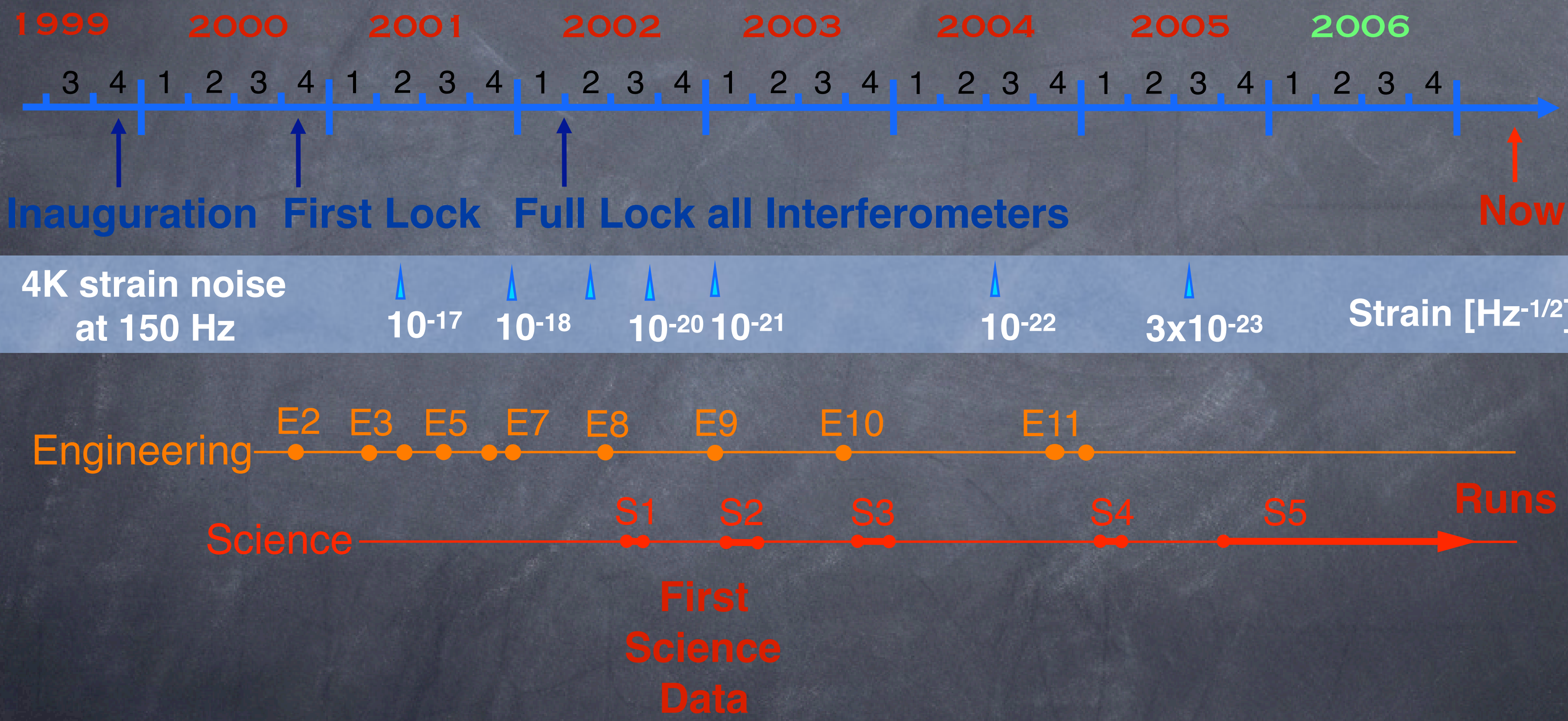

LIGO Hanford
MIT
[redacted]
Univ of Maryland
Caltech
LIGO Livingston
Image © 2006 MDA EarthSat
© 2005 Google




MIT
E

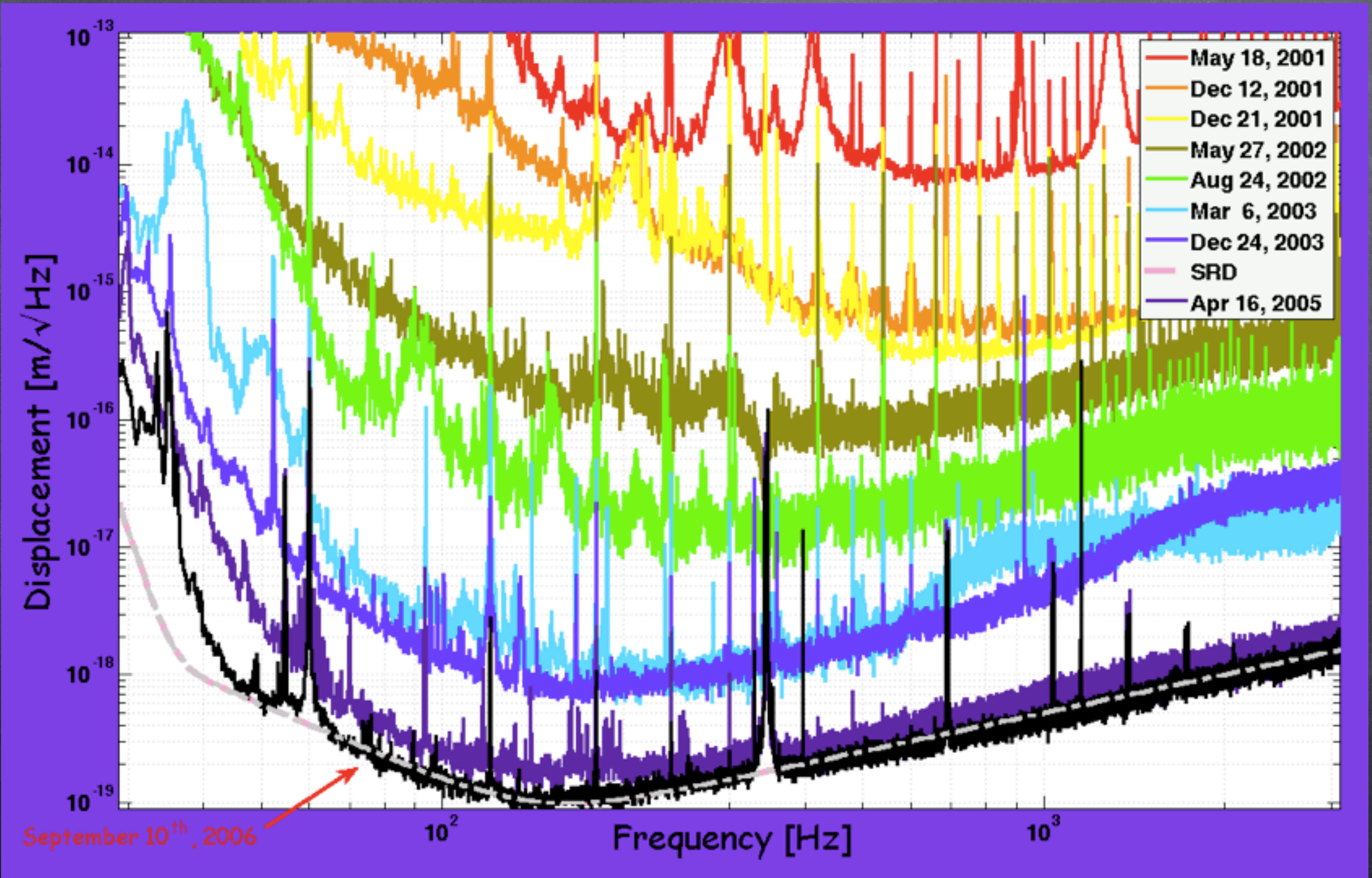

Caltech
F

LIGO History

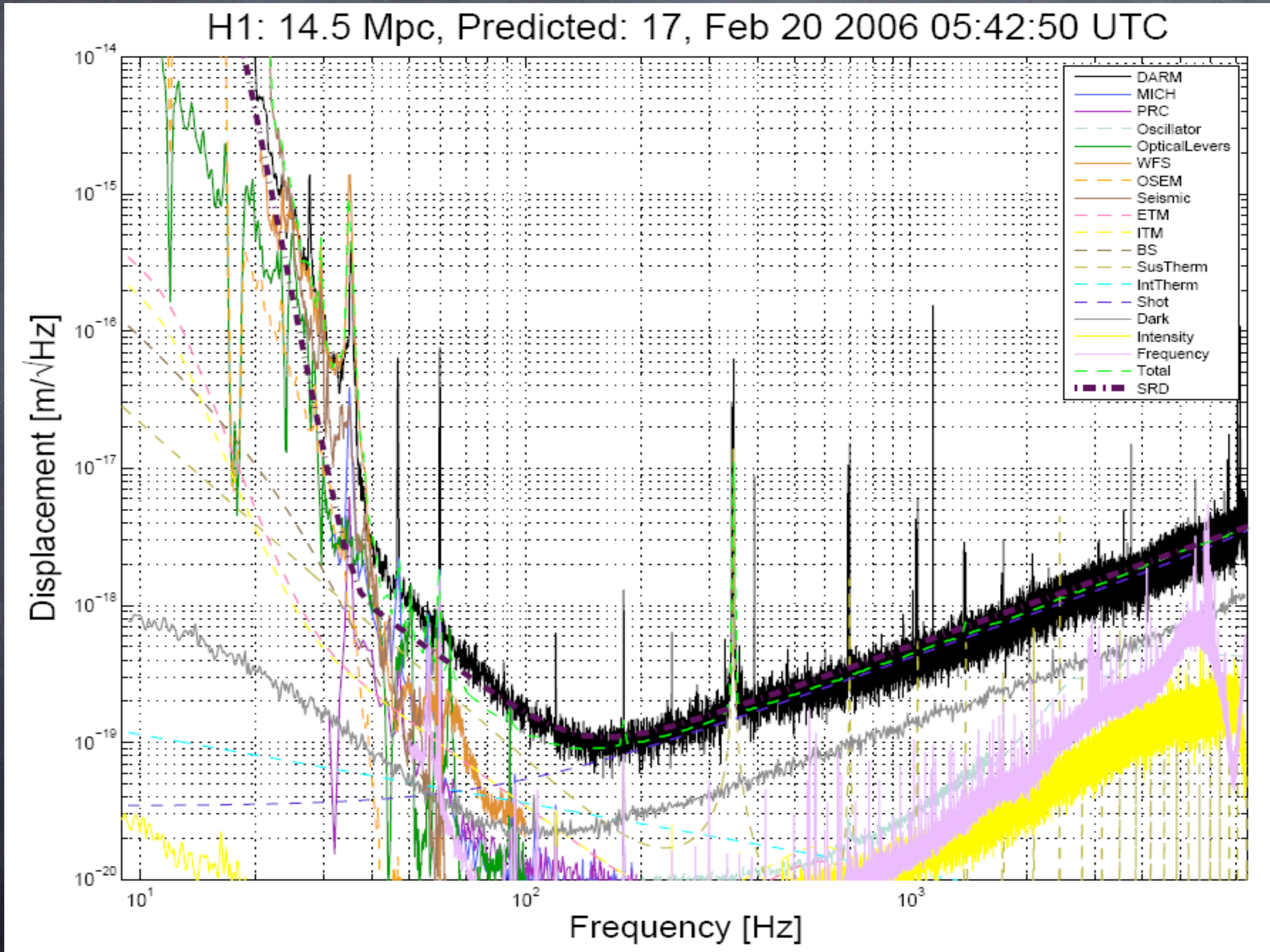


LIGO History

Progress of LIGO Sensitivity



Anatomy of the Noise

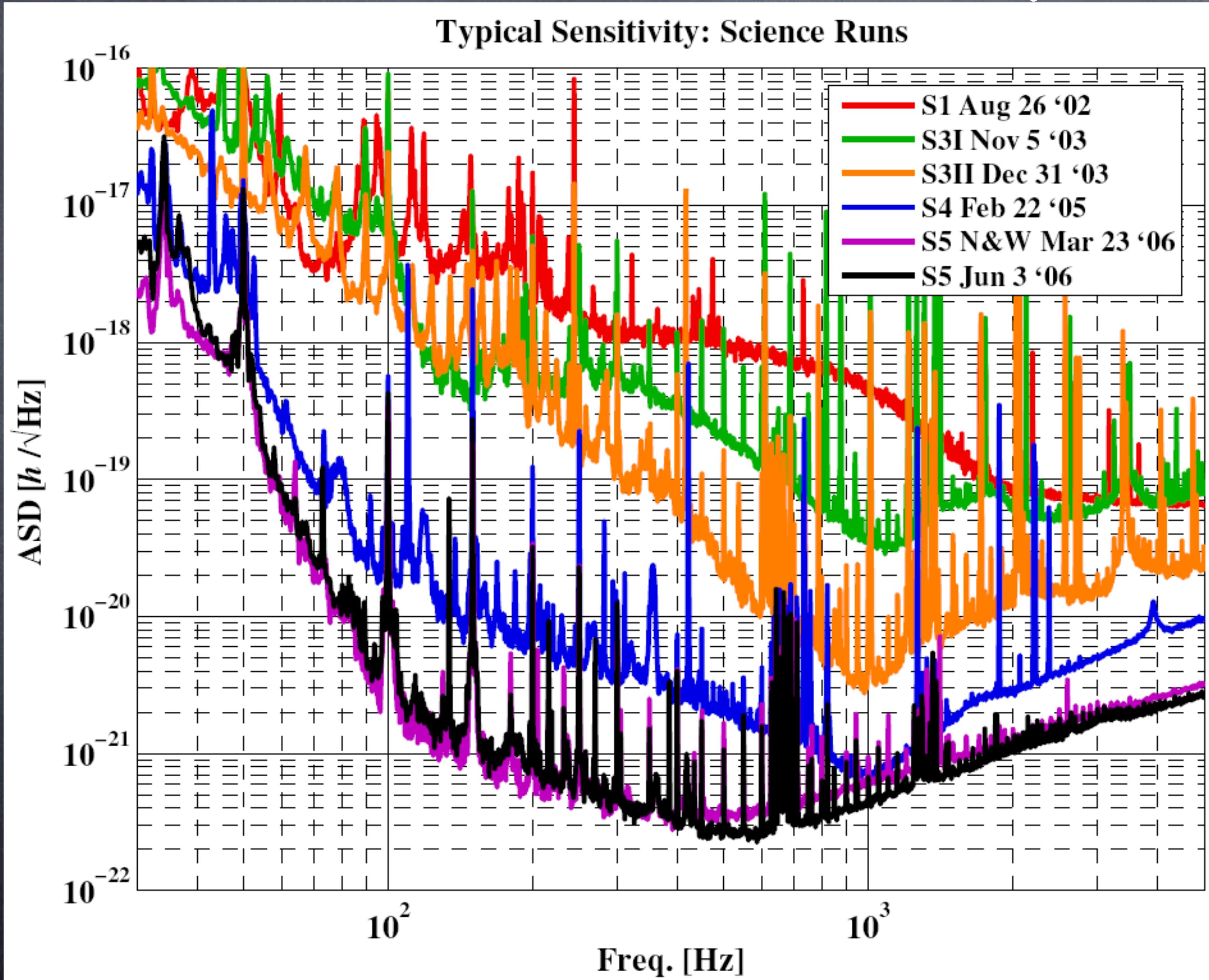


GEO600

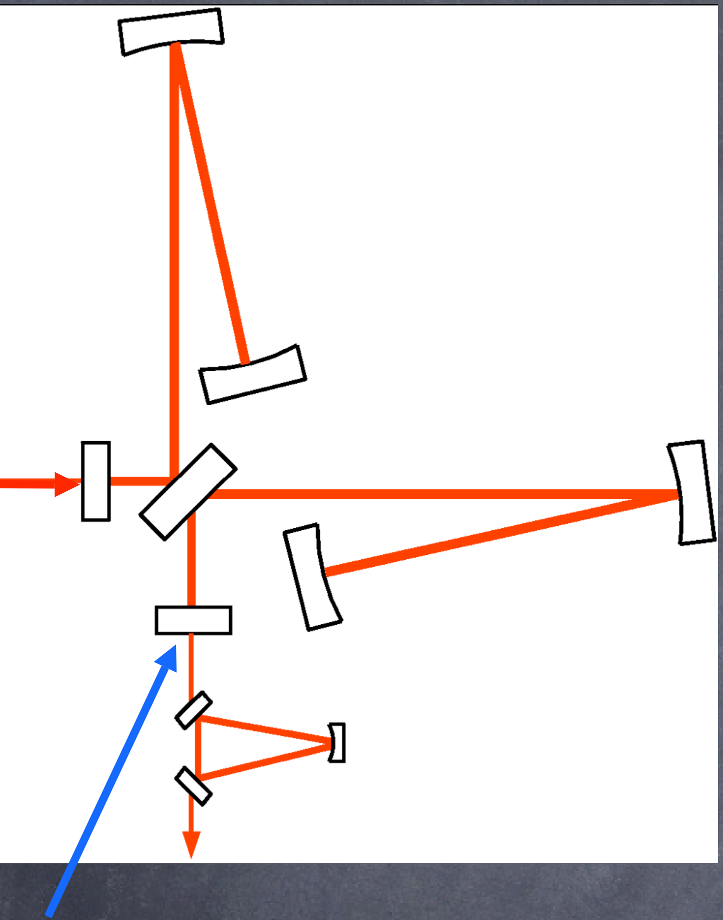
Interferometer with 600 m arms, located near Hannover

12

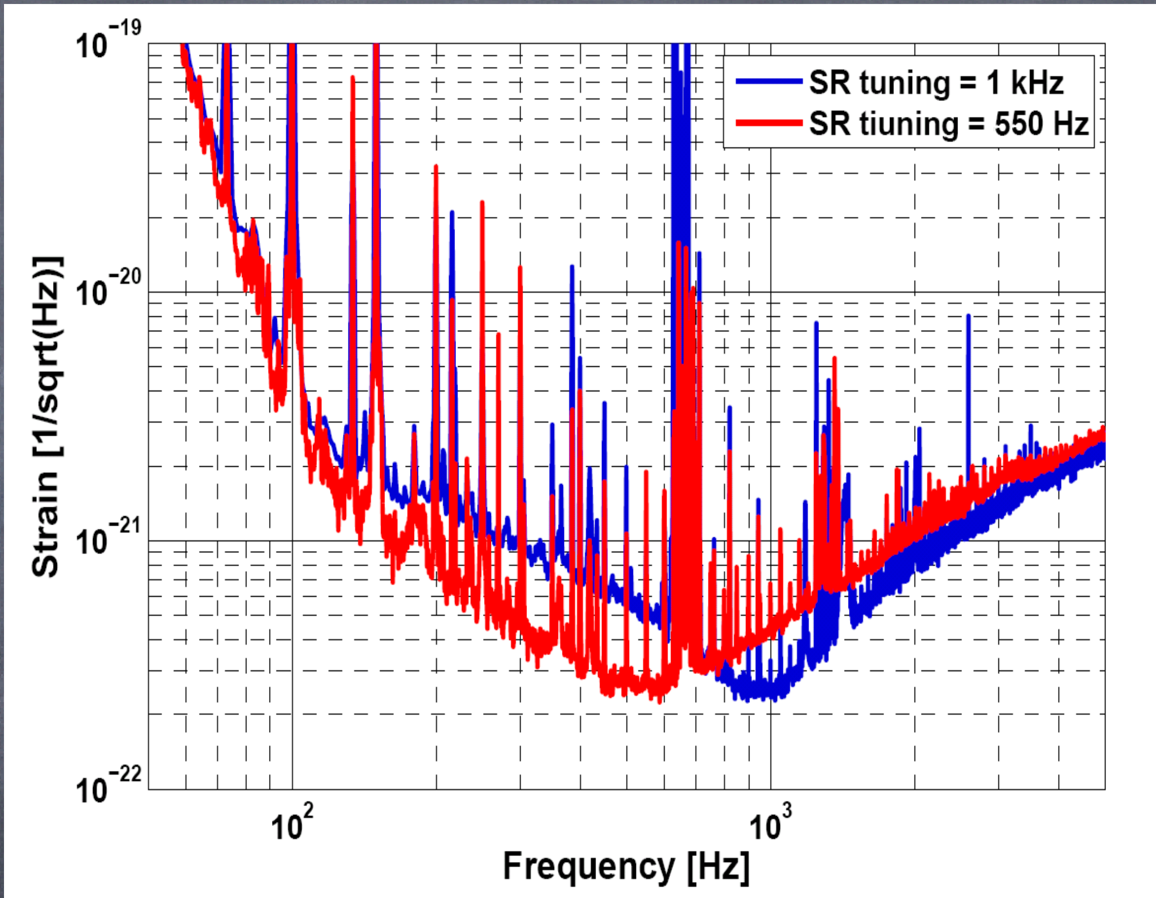
GEO600 Sensitivity



GEO600:



Signal Recycling Mirror



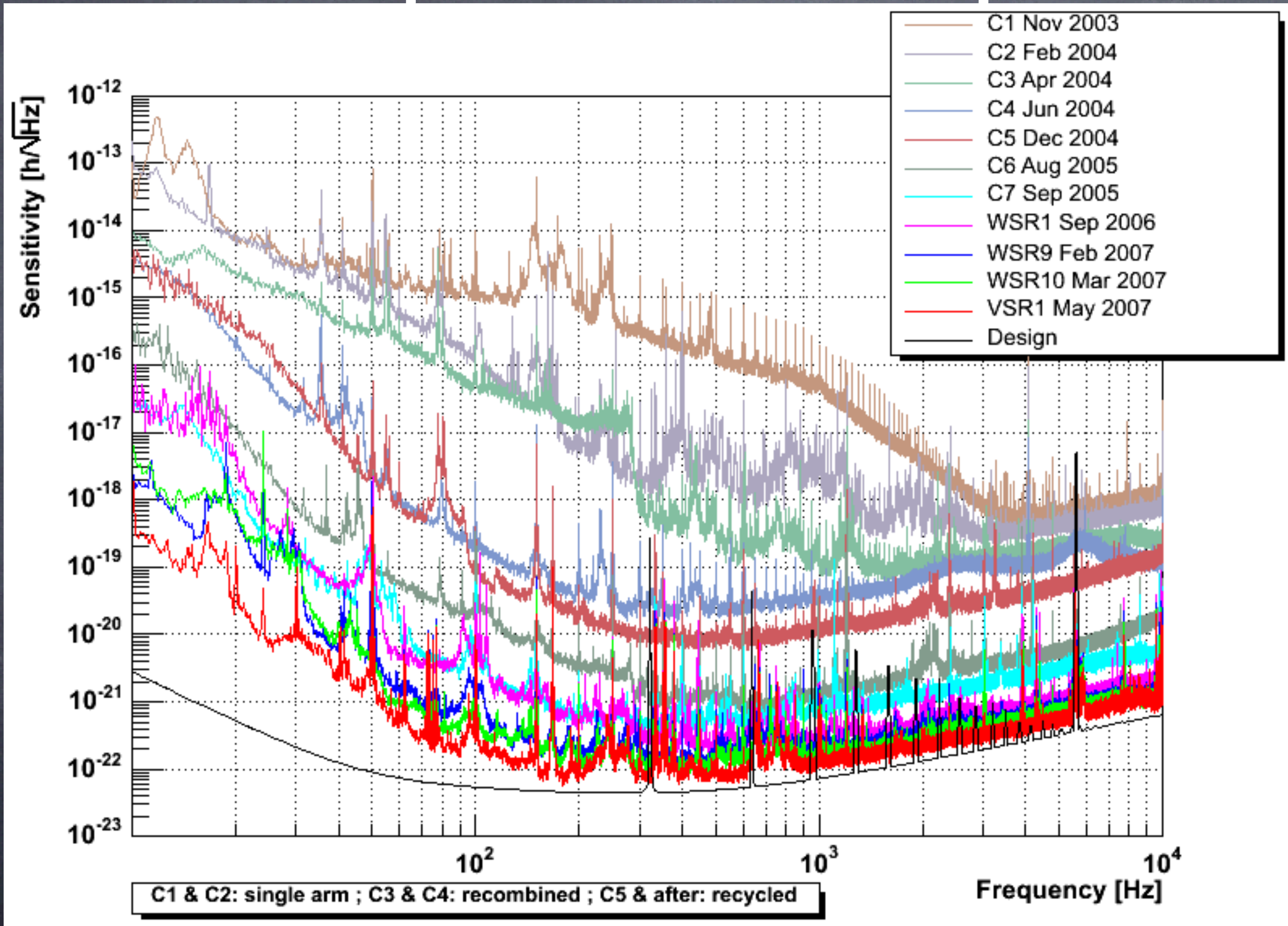
Location of Signal Recycling Mirror Changes Frequency Response (Frequency of Maximum Sensitivity)

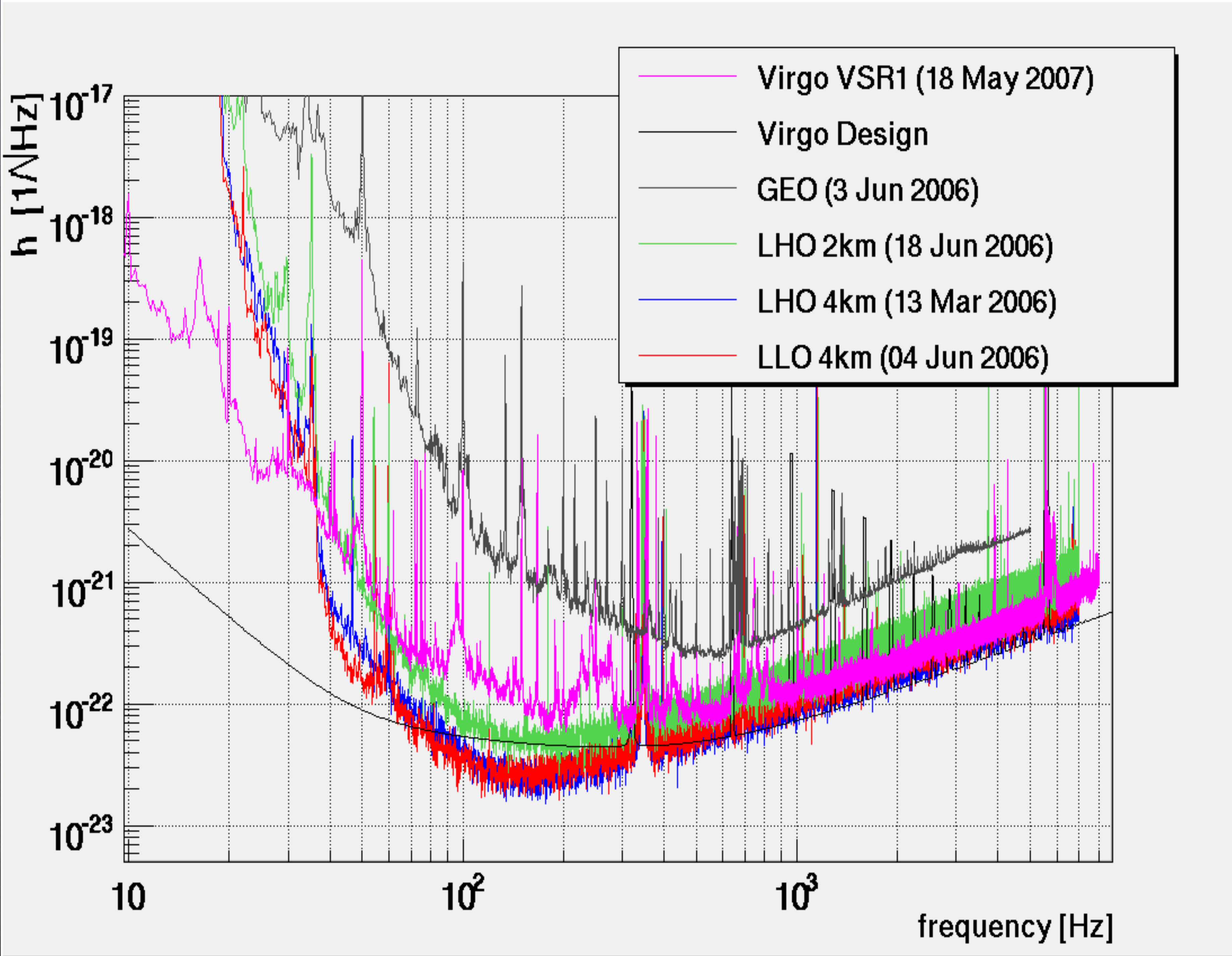
Harald Lück
Rencontres de Moriond

Virgo

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

Progress of Virgo





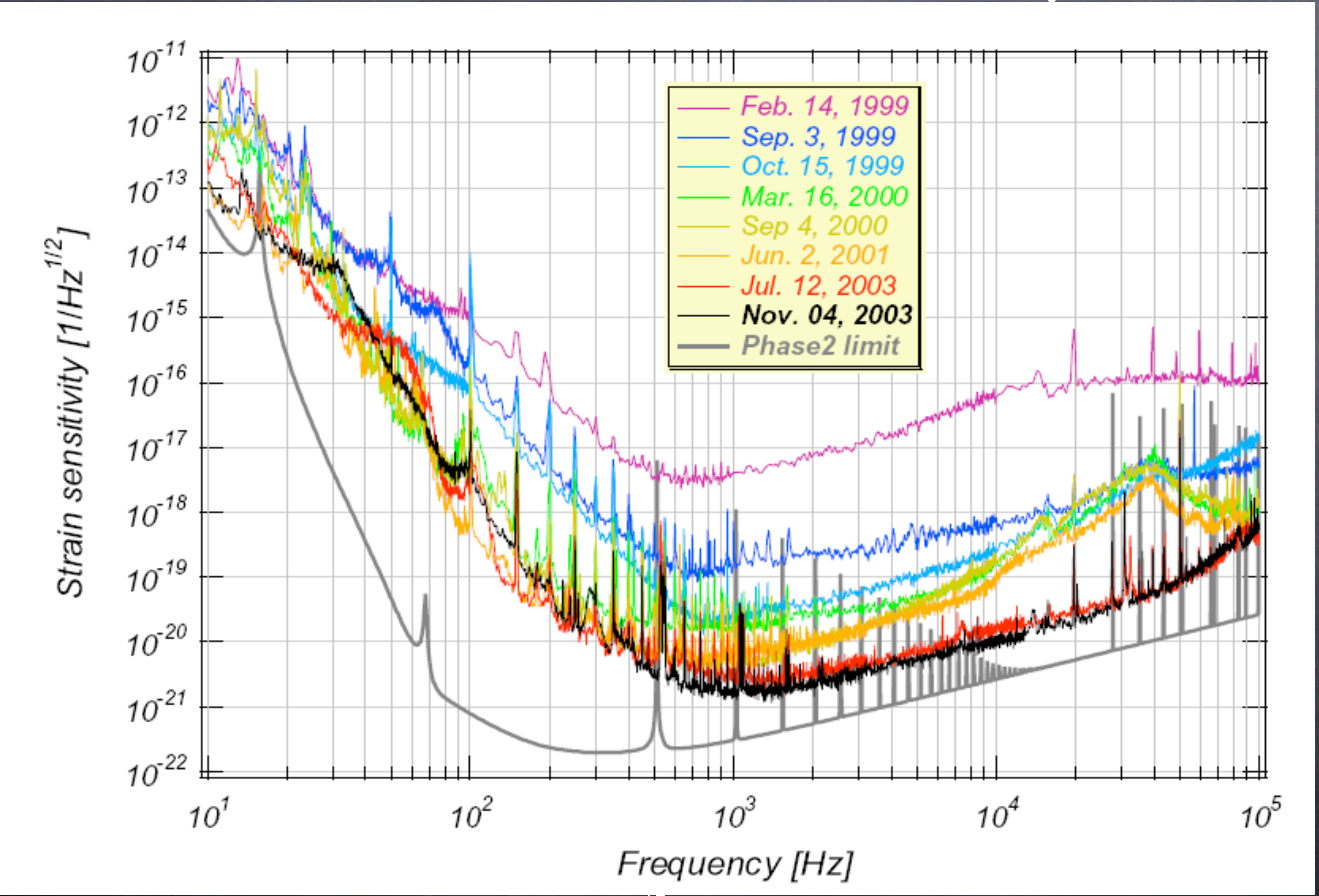
Virgo VSR1 (18 May 2007)
Virgo Design
GEO (3 Jun 2006)
LHO 2km (18 Jun 2006)
LHO 4km (13 Mar 2006)
LLO 4km (04 Jun 2006)
h [1/√Hz]
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10
10^2
10^3
frequency [Hz]

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

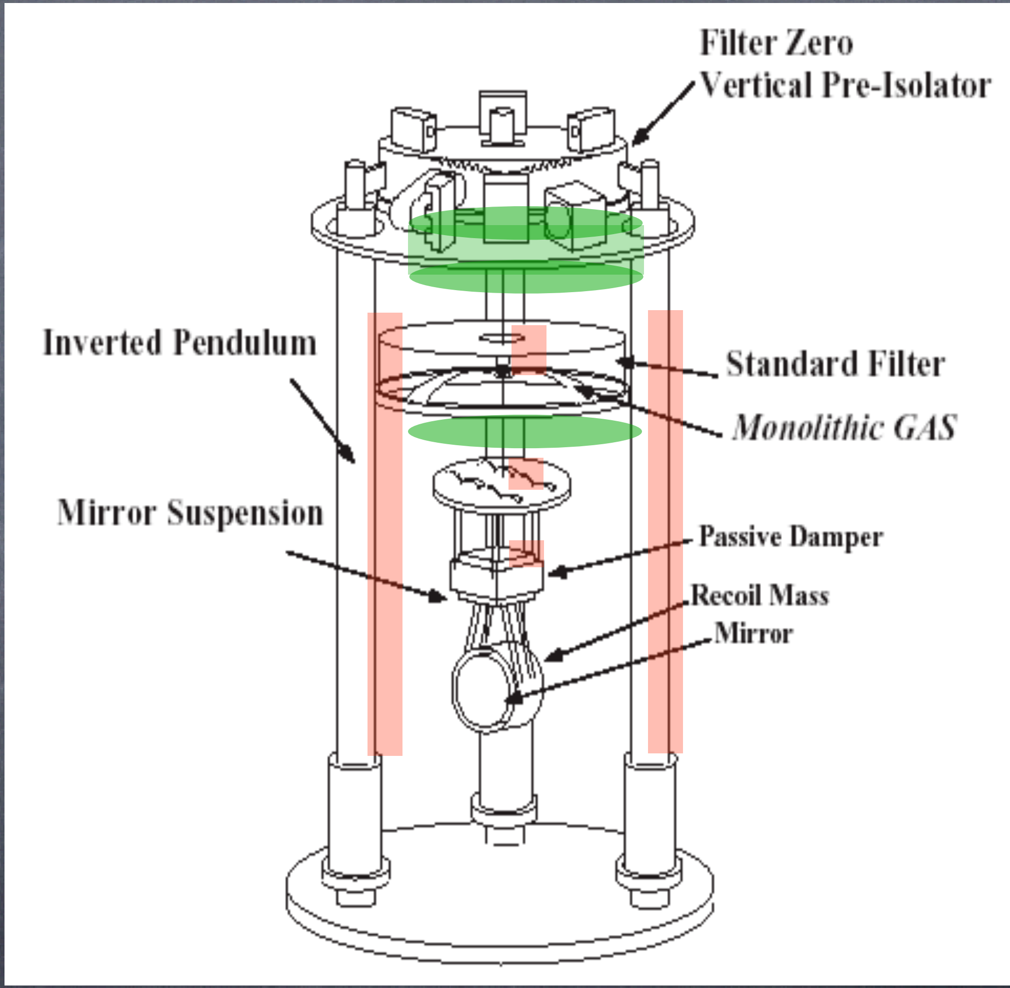
from Kazuaki Kuroda
for the TAMA/CLIO/LCGT Collaboration

TAMA300 Sensitivity



New Seismic Attenuation

- Recognized need for better seismic isolation
- Joint development with LIGO, based on earlier Virgo concept
- Now being installed

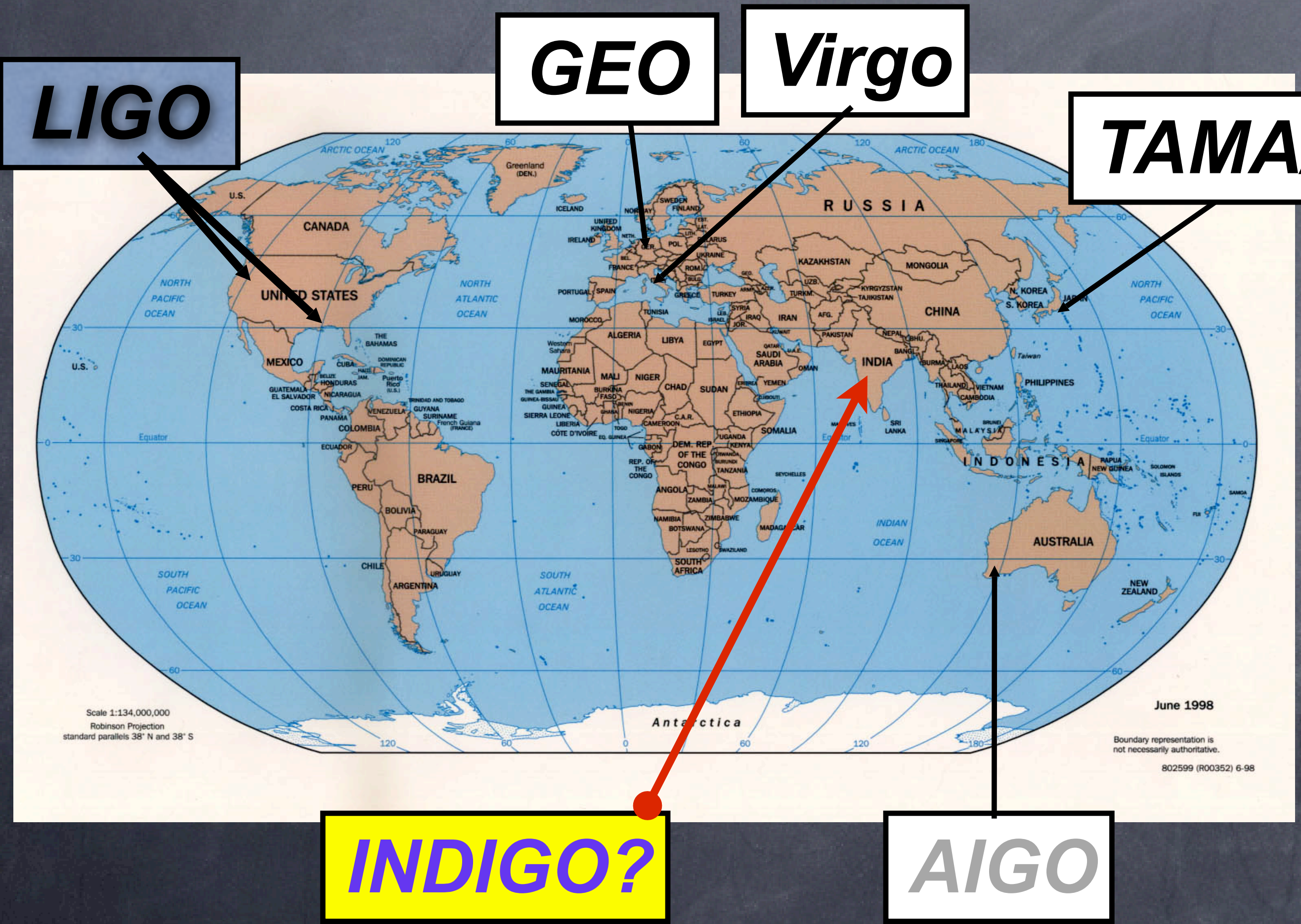


AIGO:

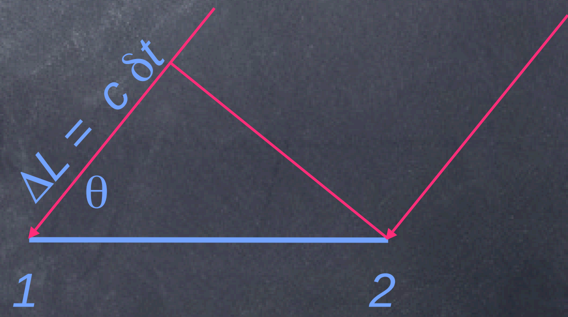
Australian International Gravitational-Wave Observatory

- 8km x 8km AIGO site 70km north of Perth granted 1998.
- Construction begun 1999
- Currently operating 80m High Optical Power interferometer test facility in collaboration with LIGO.

A Global Network



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



22

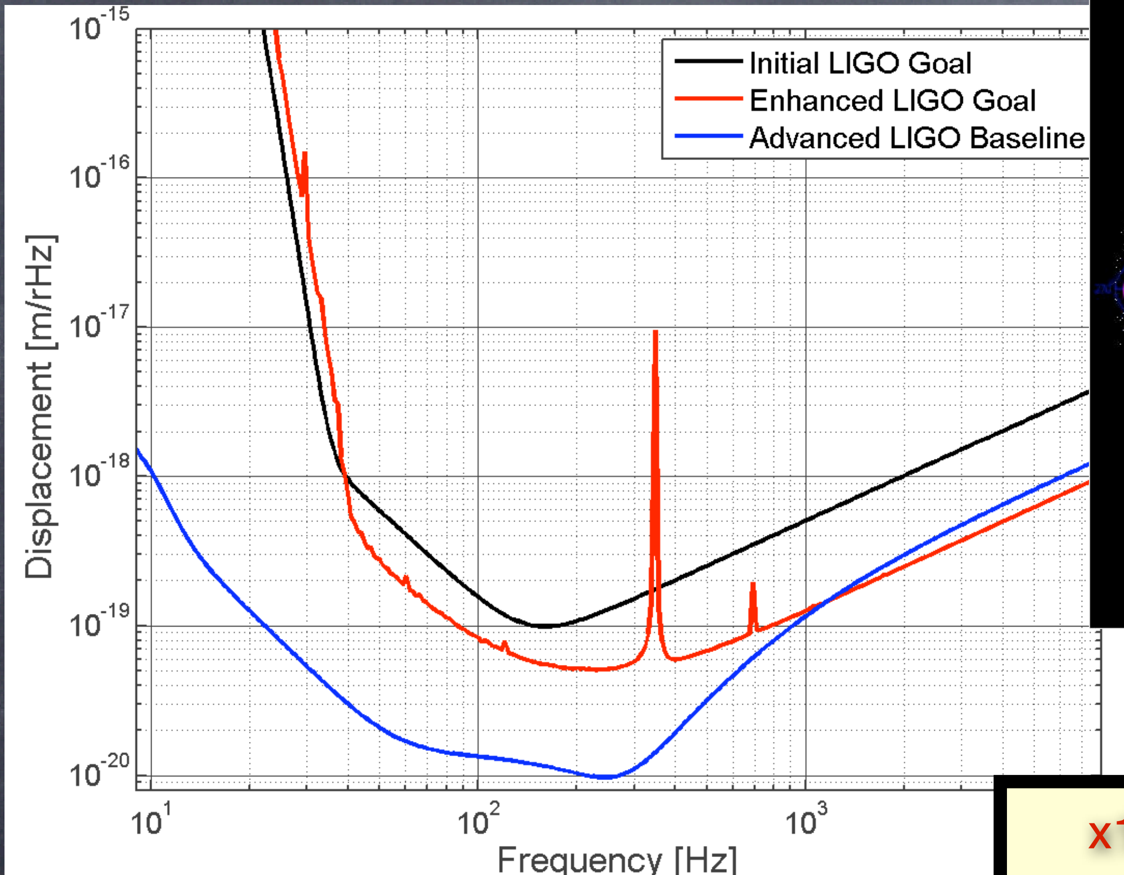
Looking to the Future

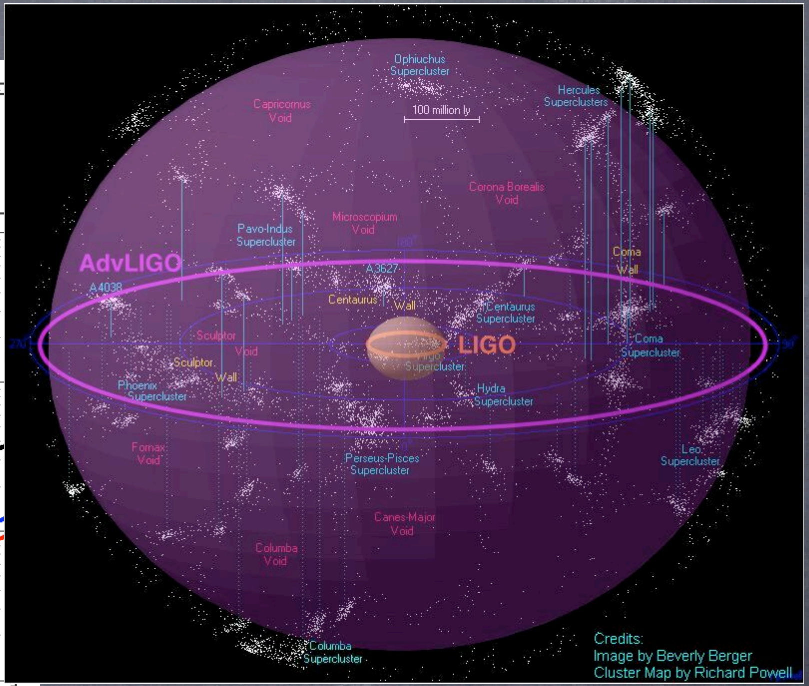
LIGO Scientific Collaboration

- 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 Gravit

- 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





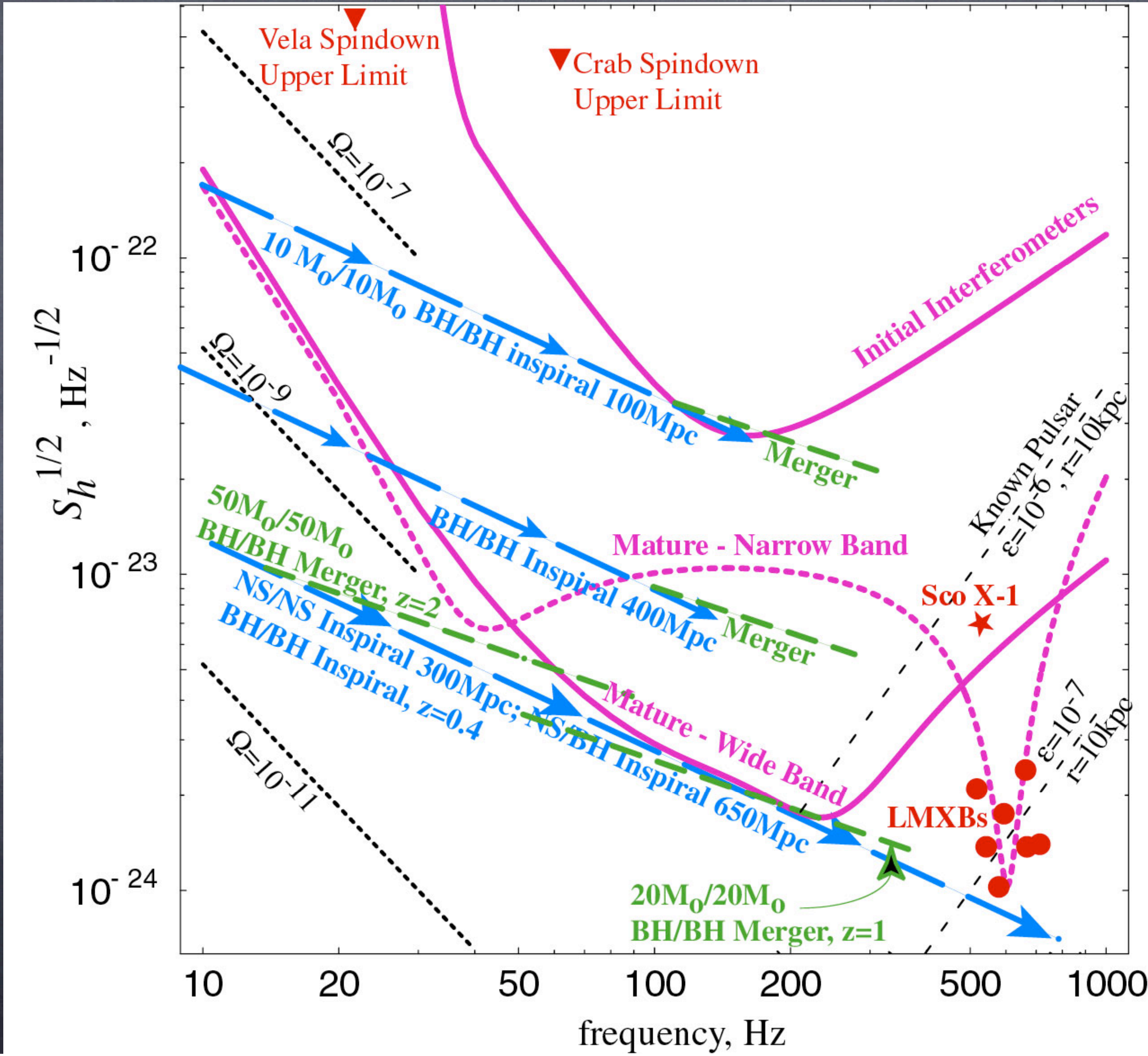
x10 better amplitude sensitivity

⇒ 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
Mature - Narrow Band
50Mo/50Mo
BH/BH Merger, z=2
NS/NS Inspiral 300Mpc; NS/BH Inspiral 650Mpc
BH/BH Inspiral, z=0.4
Mature - Wide Band
Known Pulsar
ε=10-6, r=10kpc
ε=10-7
r=10kpc
Sco X-1
LMXBs
20Mo/20Mo
BH/BH Merger, z=1
$S_h^{1/2}$, $Hz^{-1/2}$
10^{-22}
10^{-23}
10^{-24}
10
20
50
100
200
500
1000
frequency, Hz

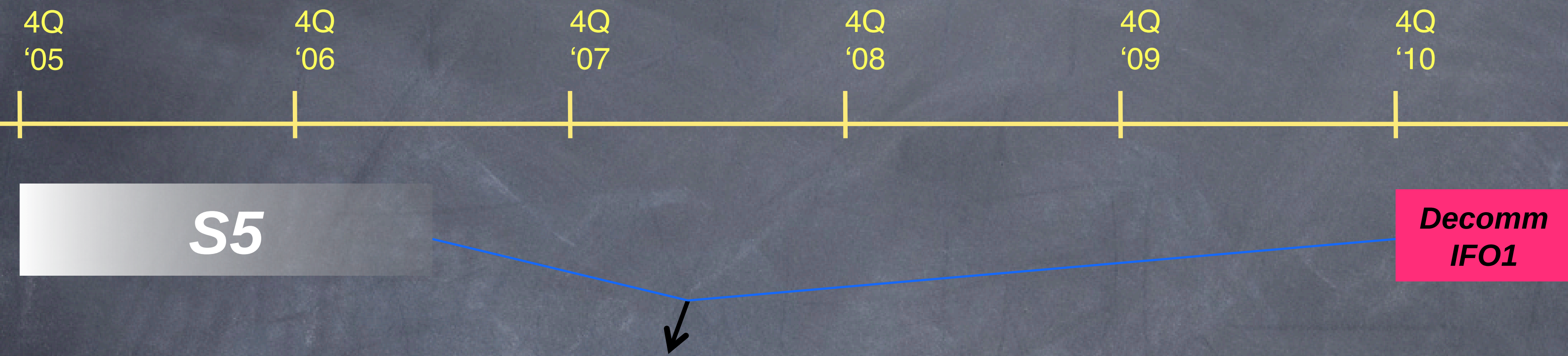
LIGO

What is so Advanced?

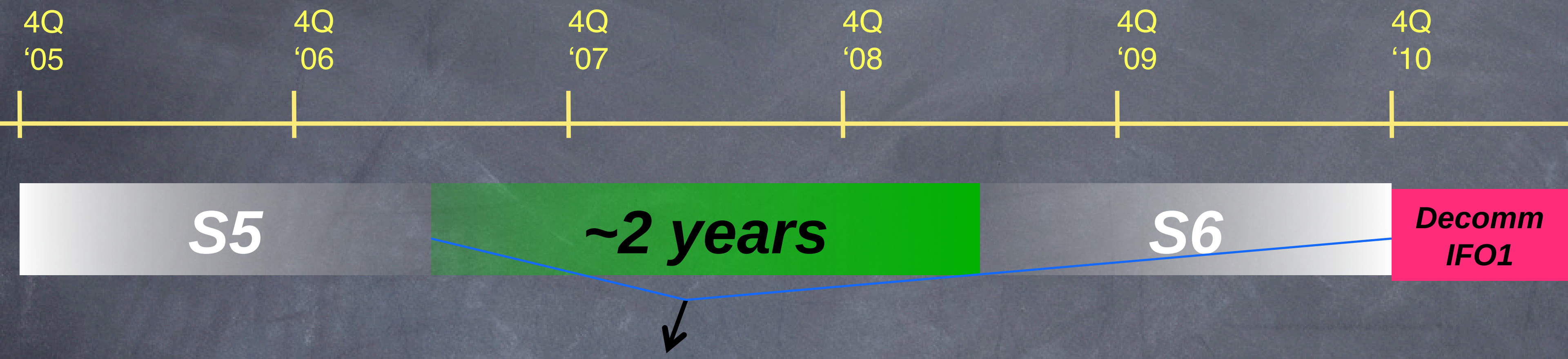
Parameter	*LIGO*	*Advanced LIGO*
Stored Laser Power	20 kW	800 kW
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, 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

27

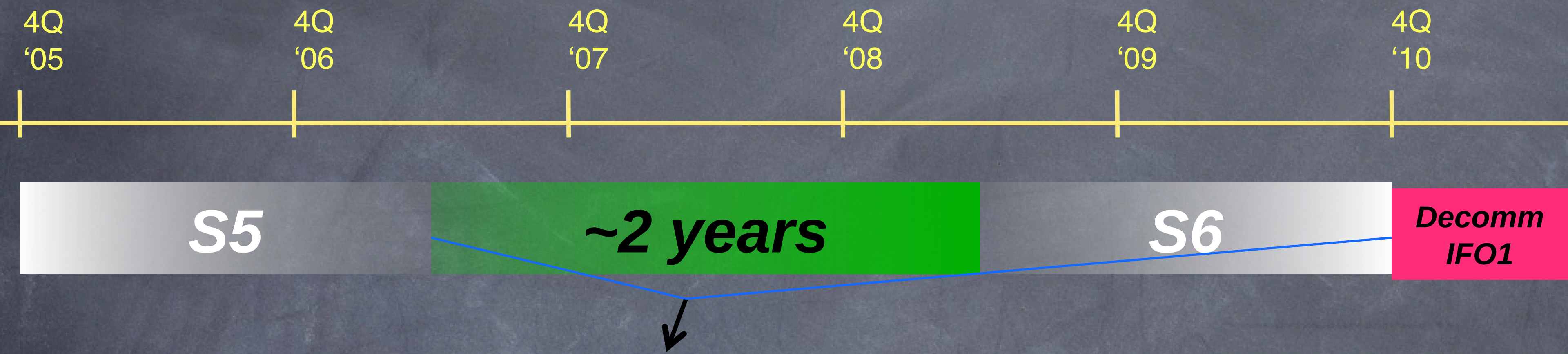
Enhanced LIGO



Enhanced LIGO



Enhanced LIGO



- Enough time for one significant set of enhancements
  - Higher laser power
  - DC readout
  - Output modecleaner
- Aim for a factor of 2 improvement in sensitivity (factor of 8 in event rate)
- Early tests of Advanced LIGO hardware and techniques

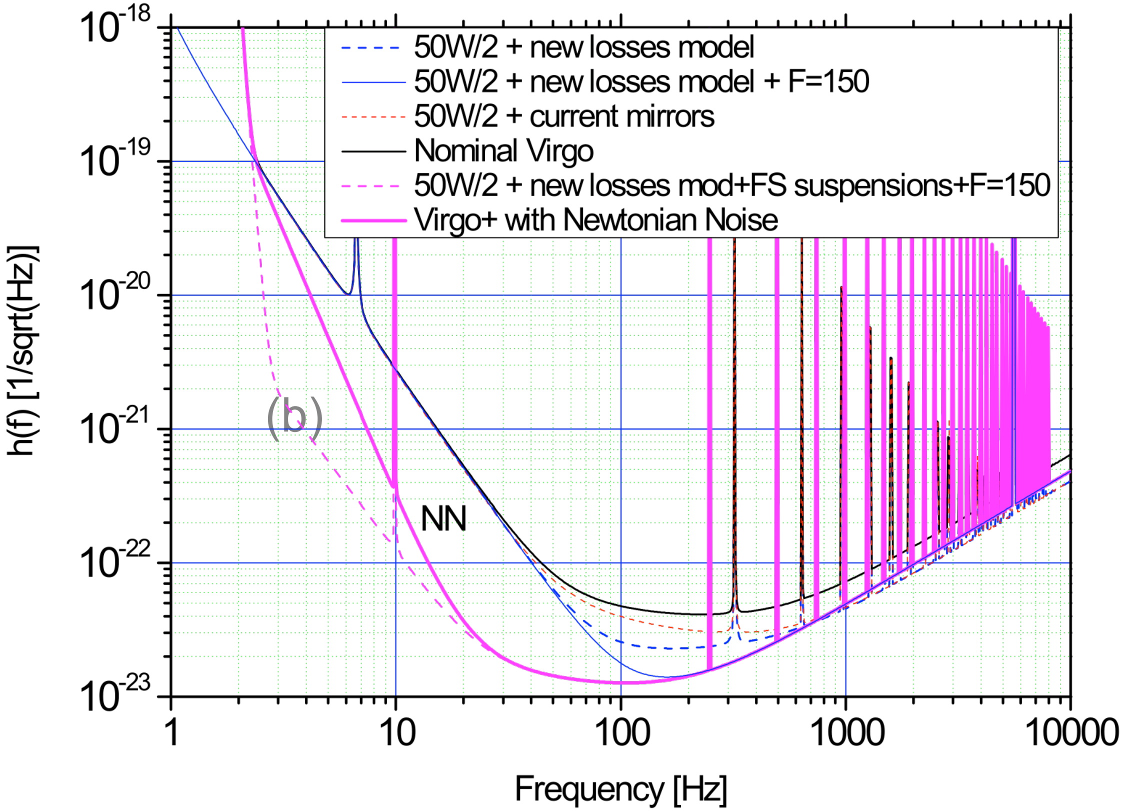
28

Virgo Plans

- Virgo+:
  - Intermediate upgrade toward Advanced Virgo
  - At least2 times sensitivity increase over nominal Virgo
  - Build and commission from 2008 to mid 2009
  - Science run in 2010
- Advanced Virgo:
  - Major upgrade for all subsystems
  - 10 times sensitivity increase over nominal Virgo
  - Installation beginning in 2011

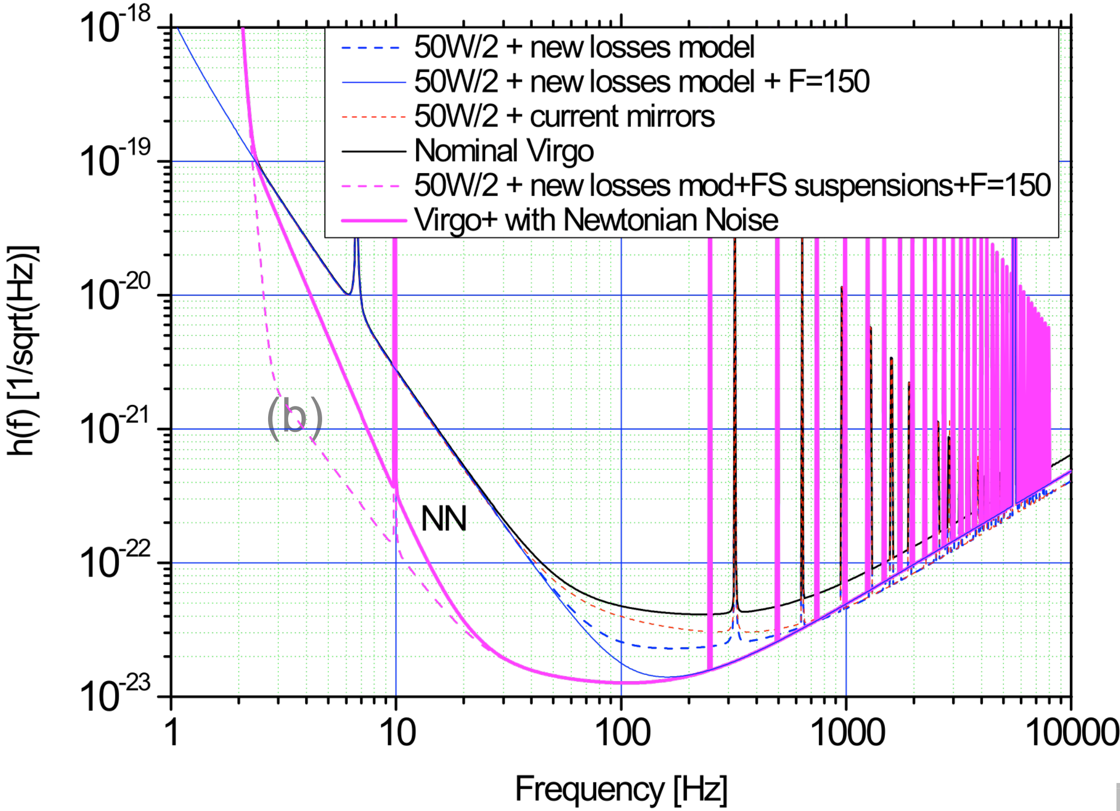
29

Expected sensitivity of Virgo+



- **Virgo+ configuration not yet set**
  - » **Higher power laser**
  - » **Fused silica suspensions**
  - » **Increase arm finesse**
- **Final Decision to be made late 2007**

Expected sensitivity of Virgo+



- **Virgo+ configuration not yet set**
  - » **Higher power laser**
  - » **Fused silica suspensions**
  - » **Increase arm finesse**
- **Final Decision to be made late 2007**

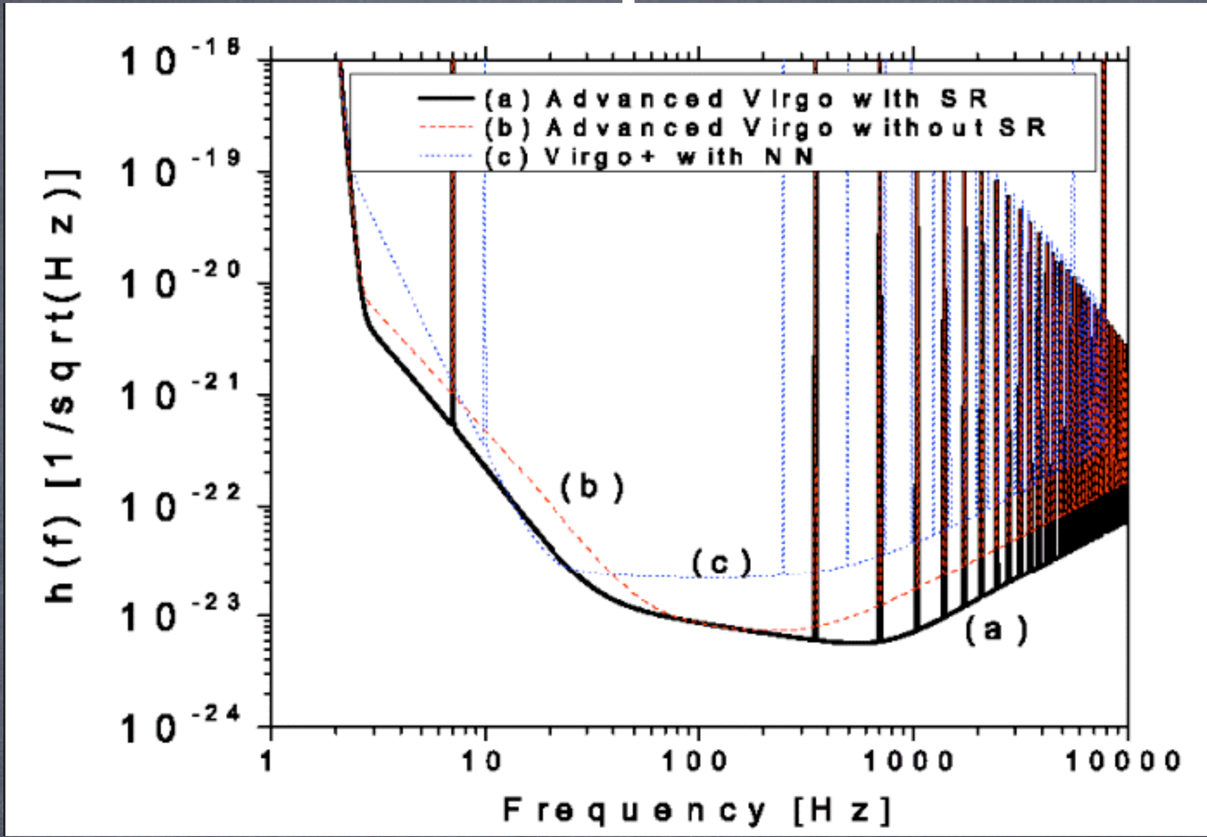
	Virgo+ (NN) (Mpc)
NSNS	28-61

Julien Marque
Rencontres de Moriond

30

Advanced Virgo

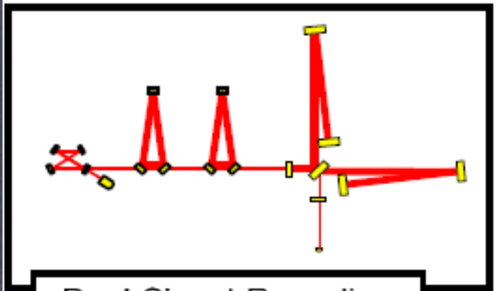
- Similar scope to AdLIGO
  - Larger mirrors
  - Improved coatings
  - Higher laser power
  - DC read-out
- R&D underway

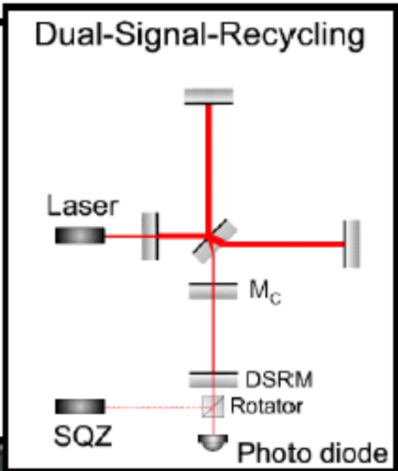


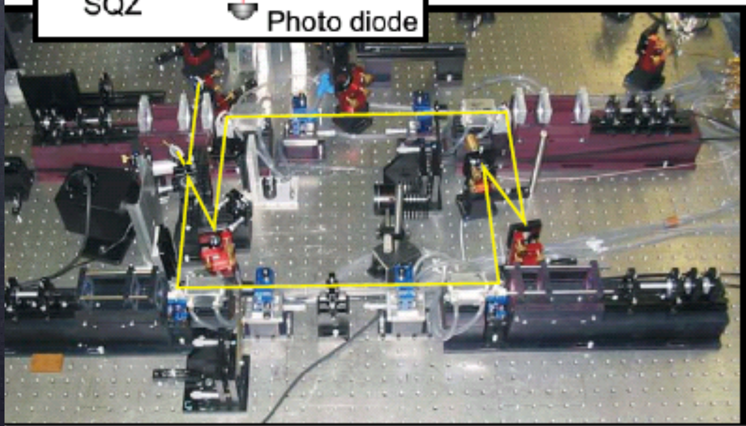
Julien Marque
Rencontres de Moriond

Stefan Hild

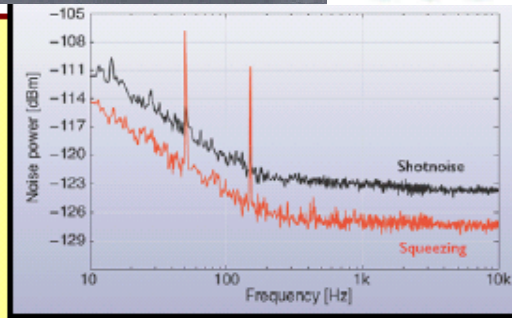
Plans of GEO

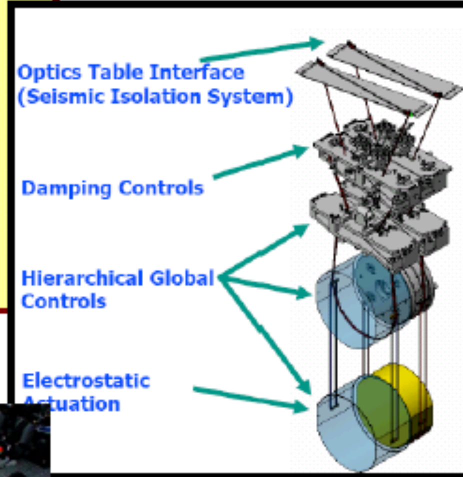


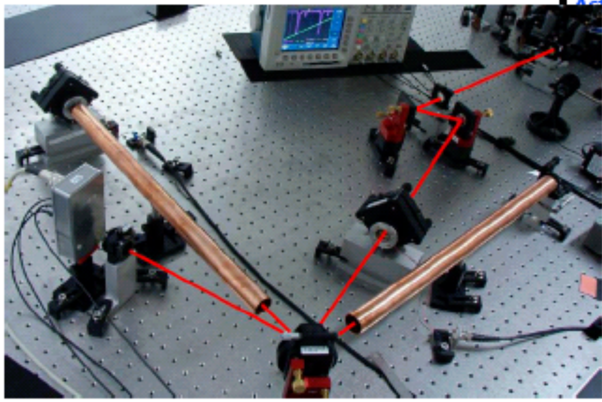


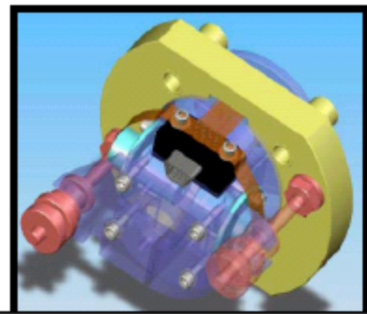


- operate GEO600 / GEO-HF as LSC detector
- LSC data analysis
- laser and suspensions for AdvLIGO (laser for Enh. LIGO)
- contribute to AdvVIRGO design
- R&D and design towards third generation detectors





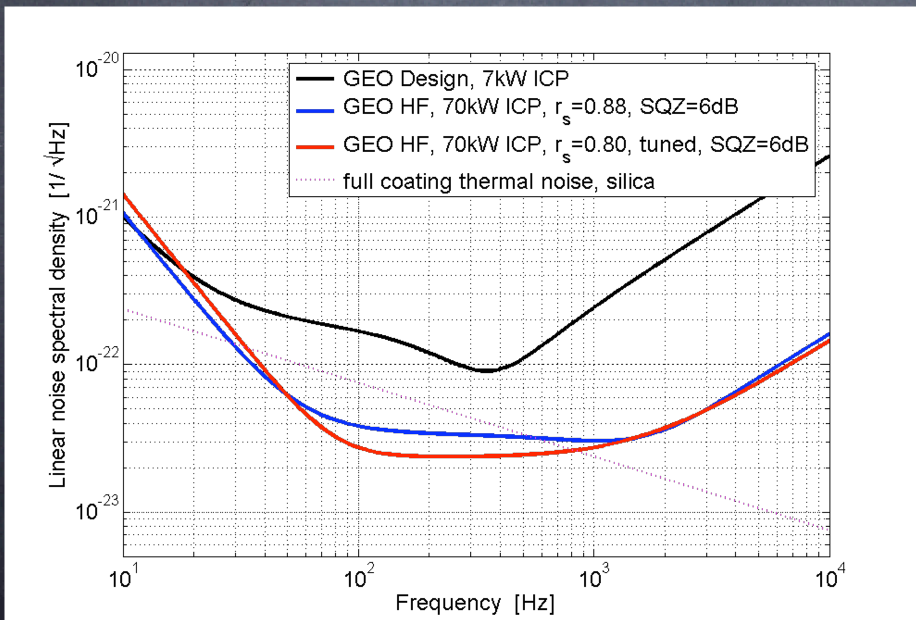


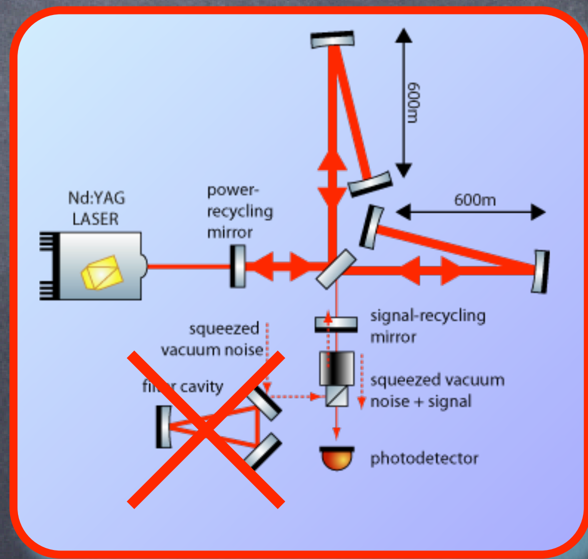


Stefan Hild

GEO HF

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

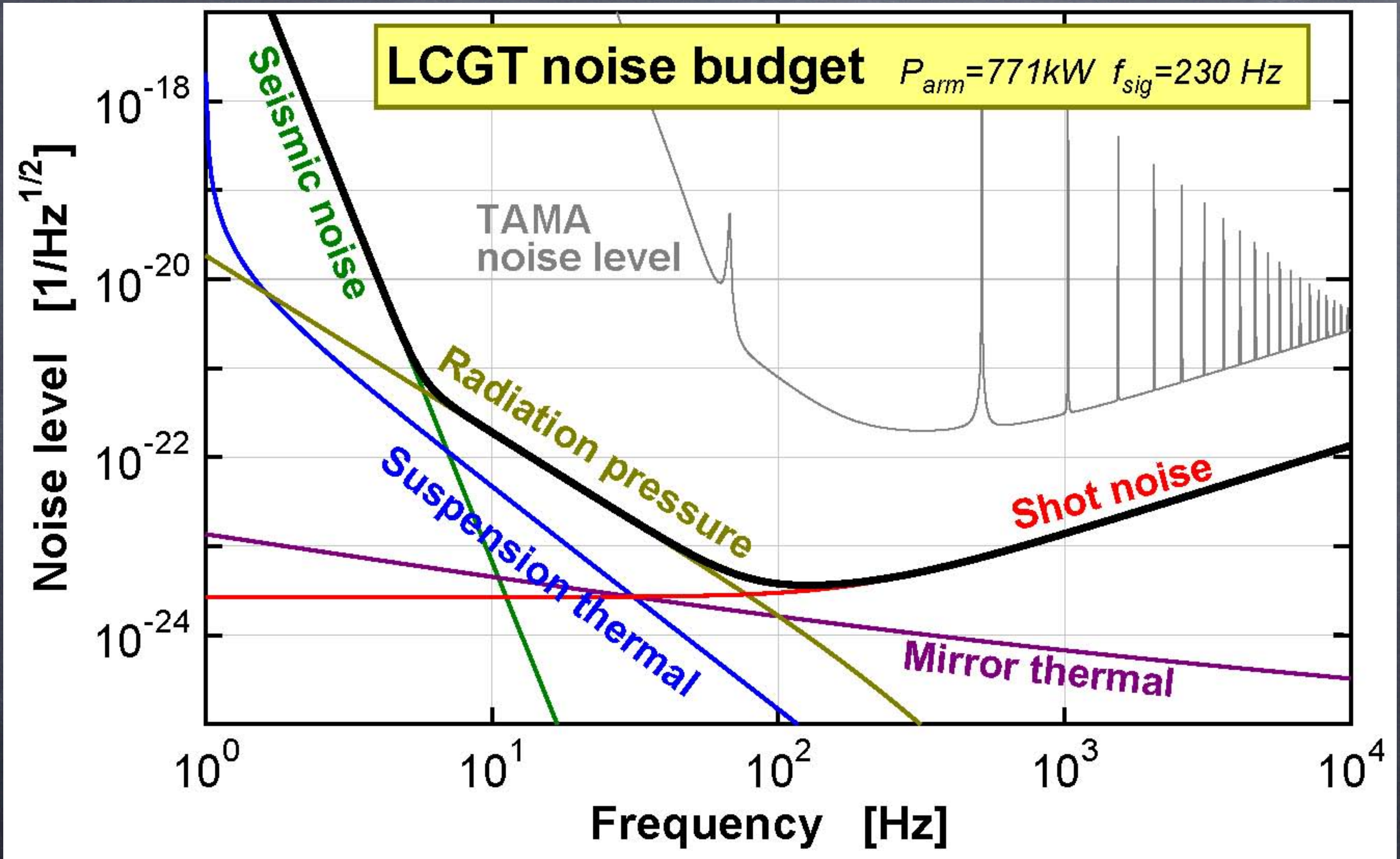




Large-scale Cryogenic

- 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

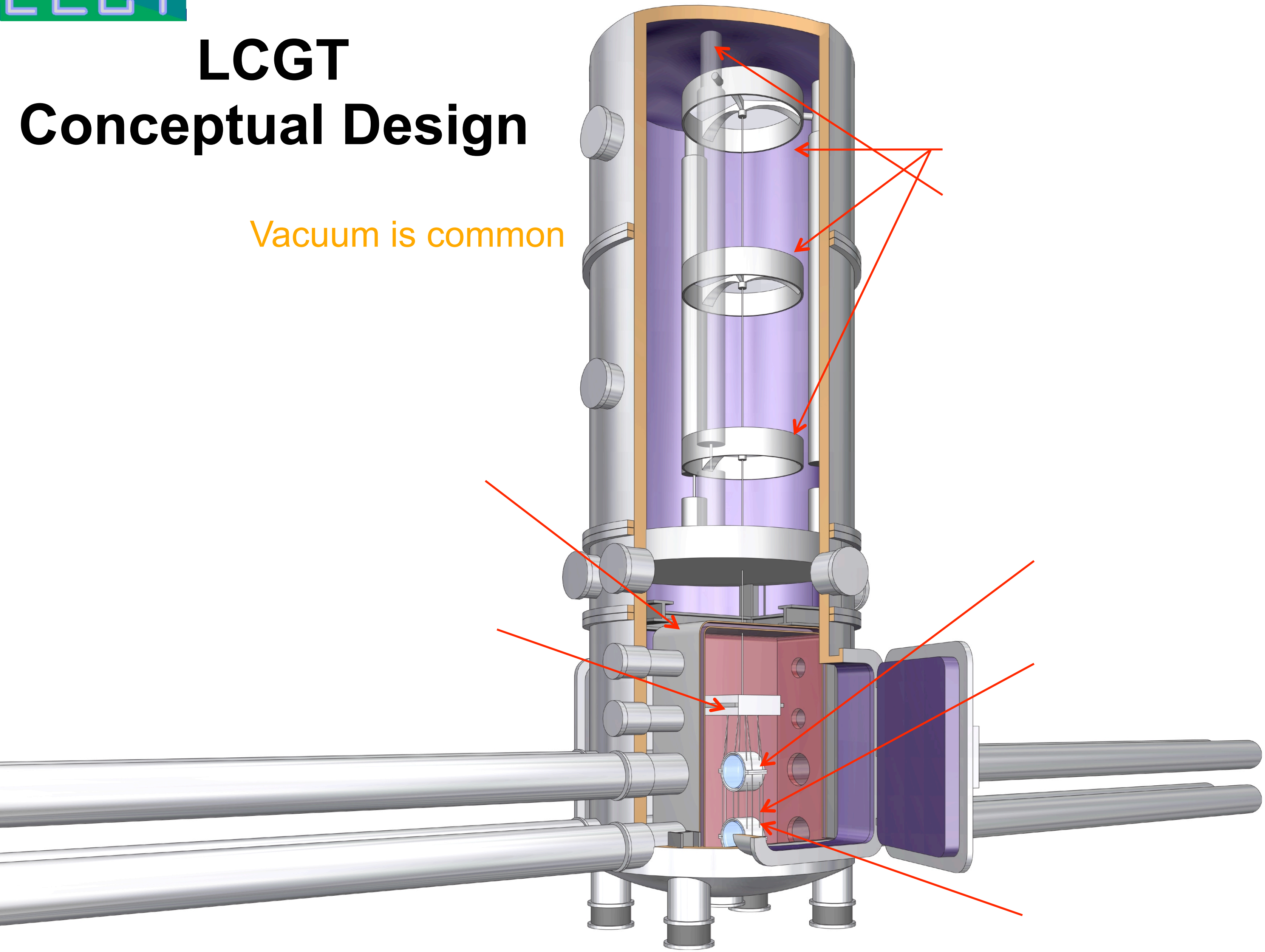
LCGT Design Sensitivity



Kazuaki Kuroda
for the TAMA/CLIO/LCGT Collaboration

LCGT
Conceptual Design

Vacuum is common

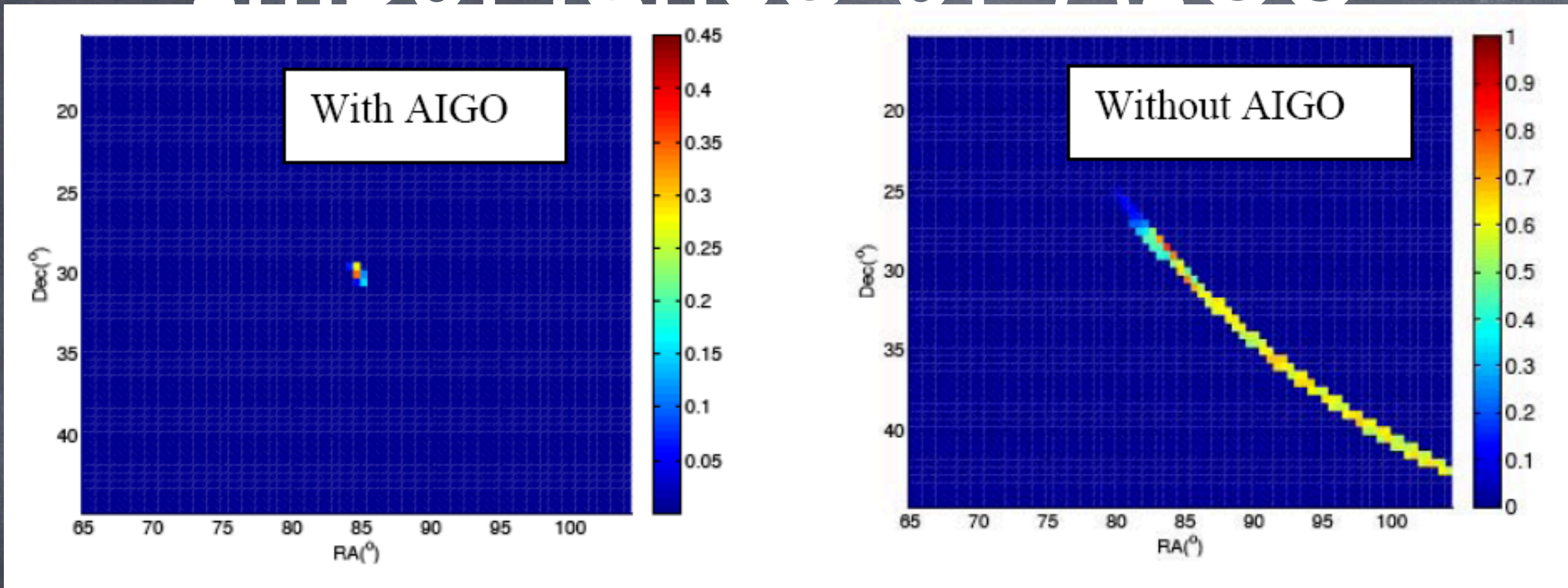


AIGO Planning

- Western Australian Centre of Excellence for Gravitational Astronomy 2005
- WA Government Steering Committee
- Project prospectus completed 2006
- AIGO concept plan submitted to Minister for Science Oct 2006
- AIGO International Advisory Committee appointed

David Coward
Rencontres de Moriond

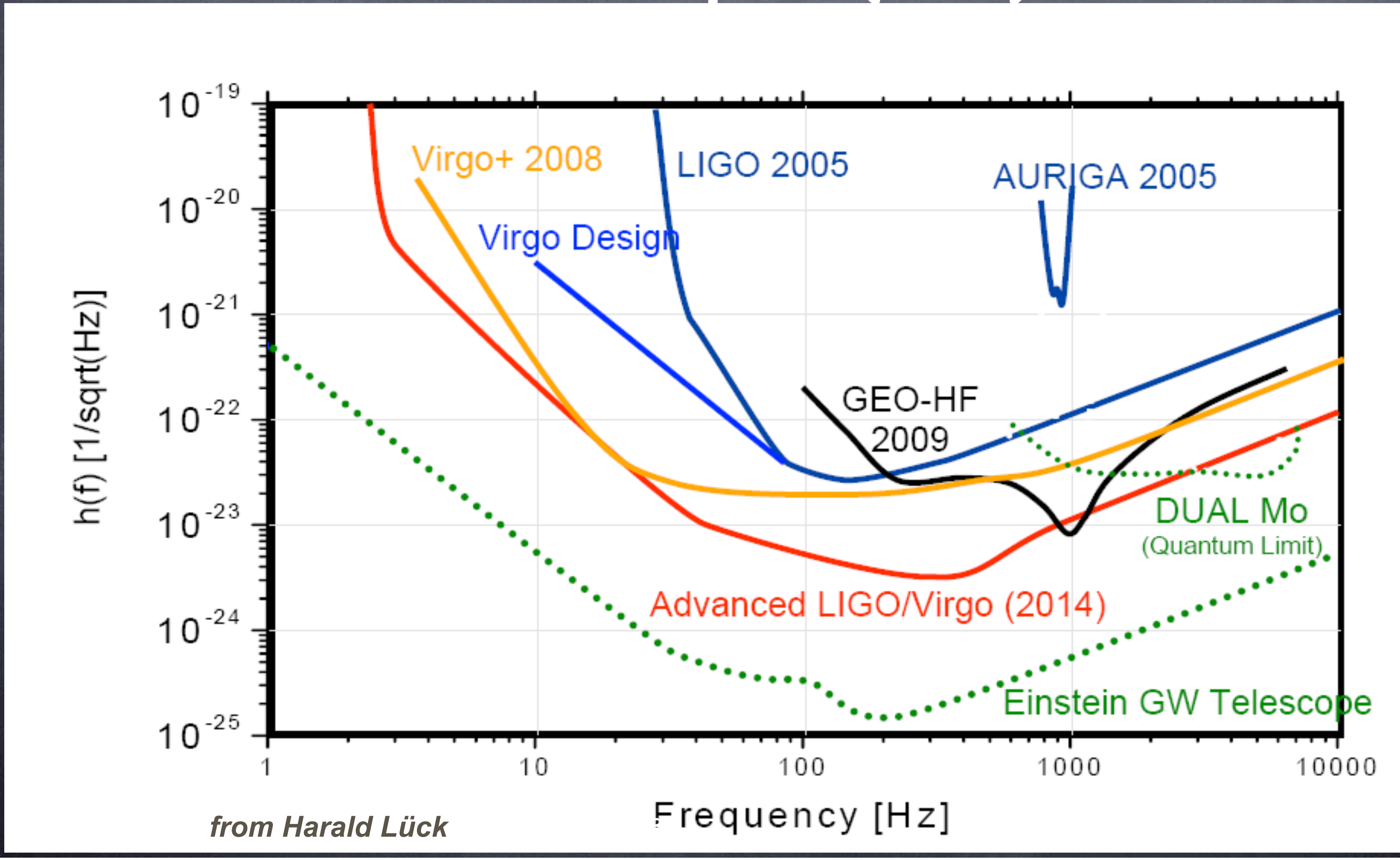
Importance of AIGO



- AIGO provides strong science benefits e.g. host galaxy localization
- 5km baseline sensitive to inspirals in the range ~ 250Mpc
- Australian Consortium welcomes new partners in this project

David Coward and David Blair

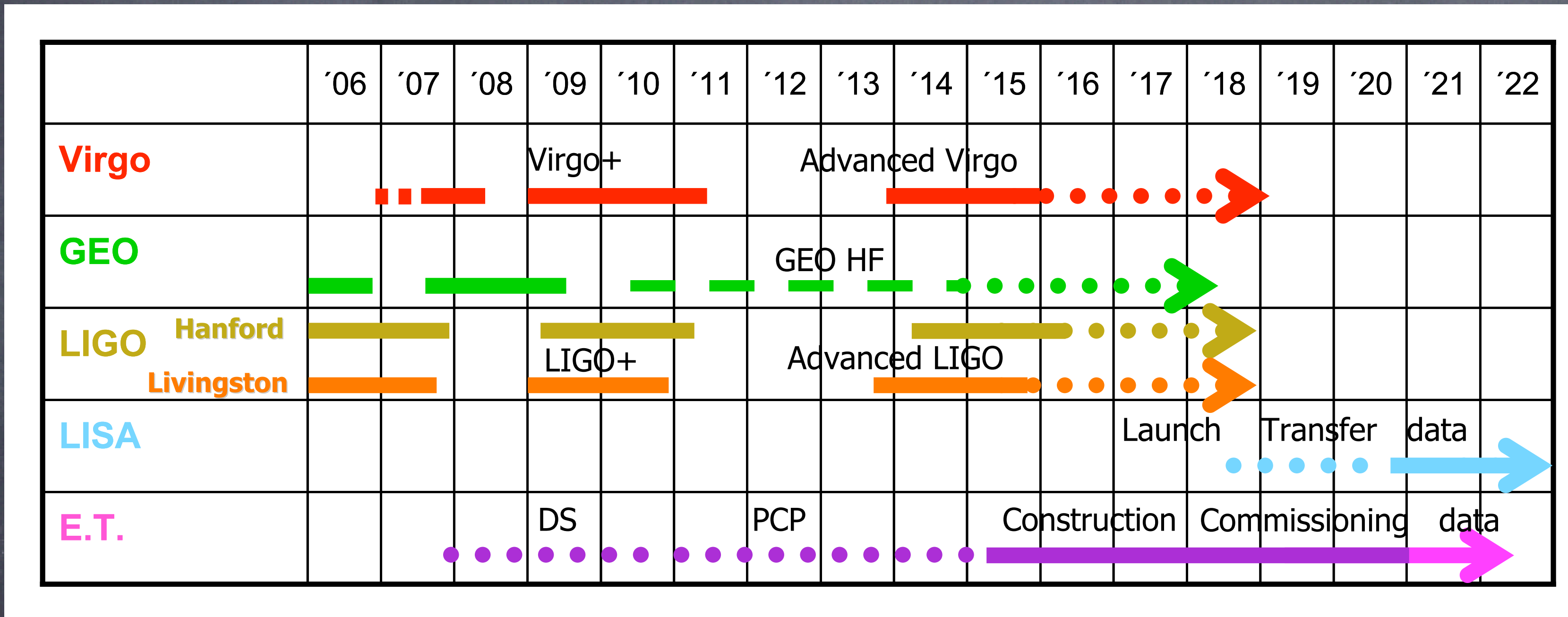
Einstein Gravitational-Wave Telescope (ET)



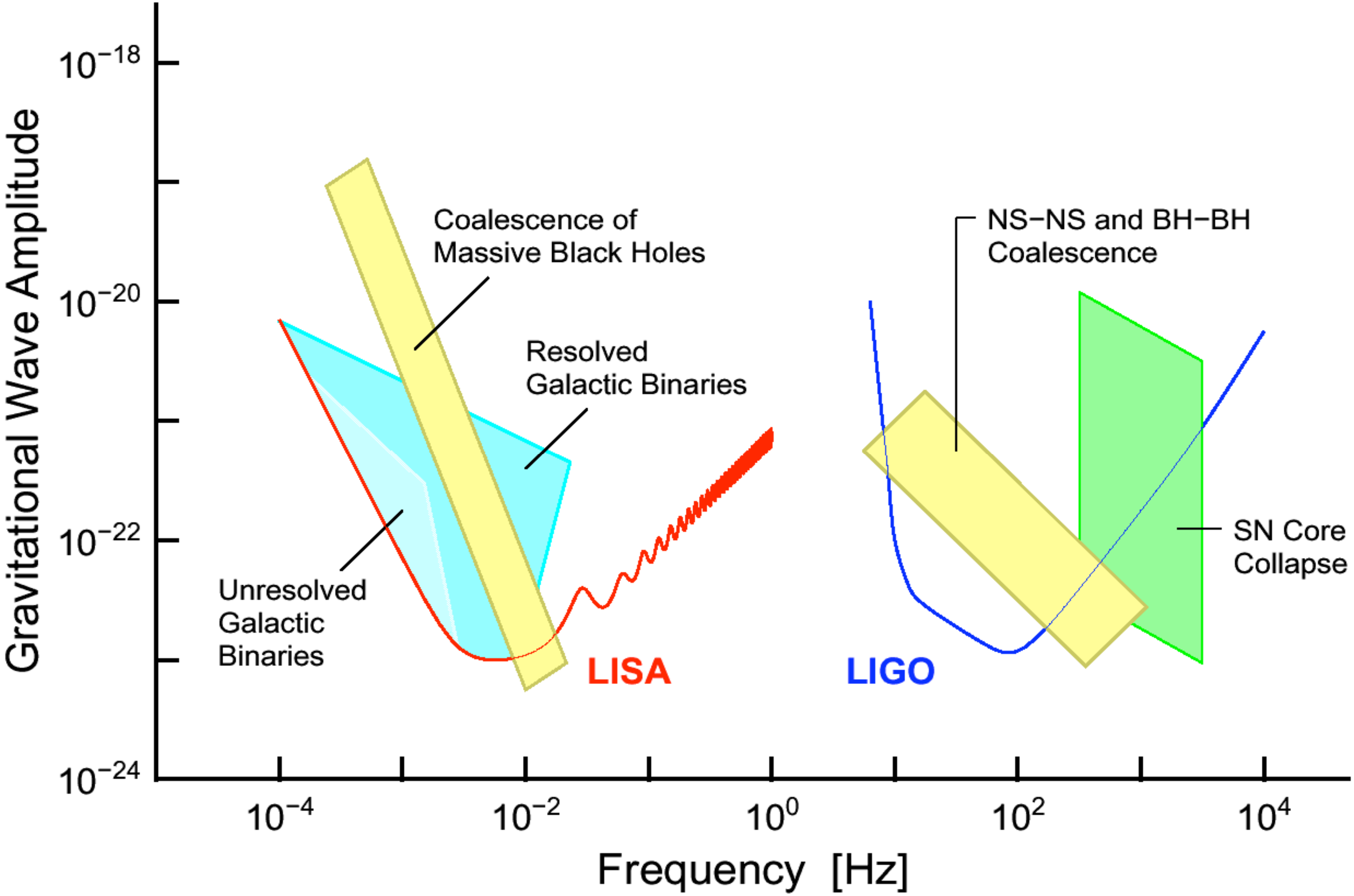
ET Baseline Concept

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

Some Timelines

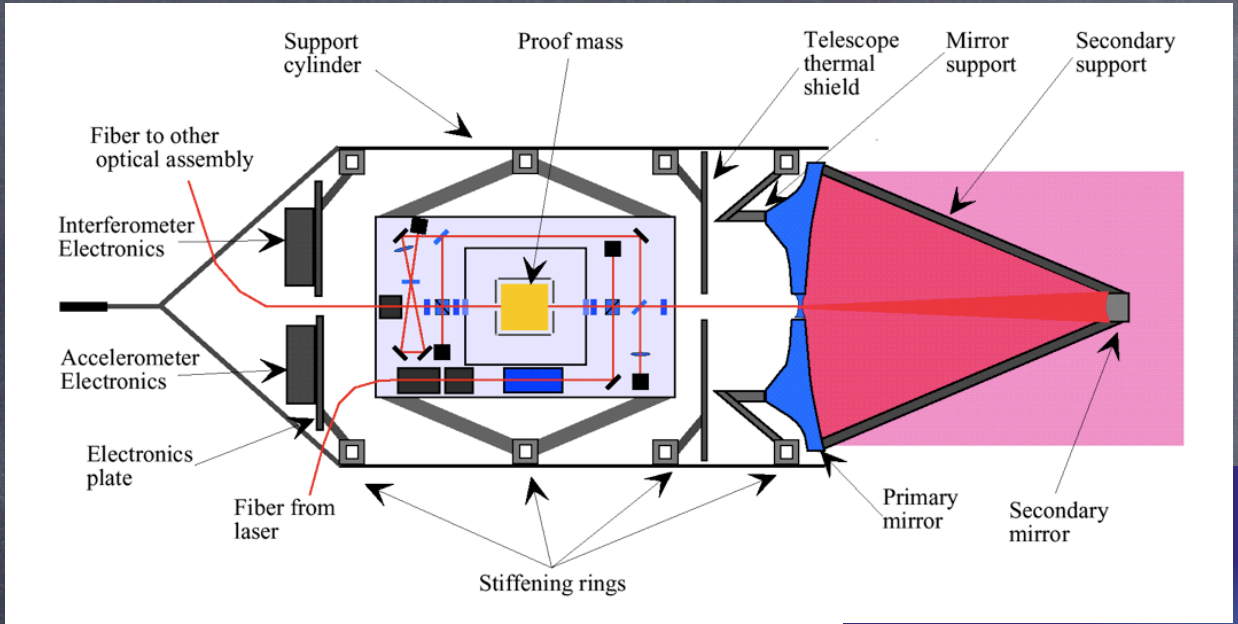


LISA

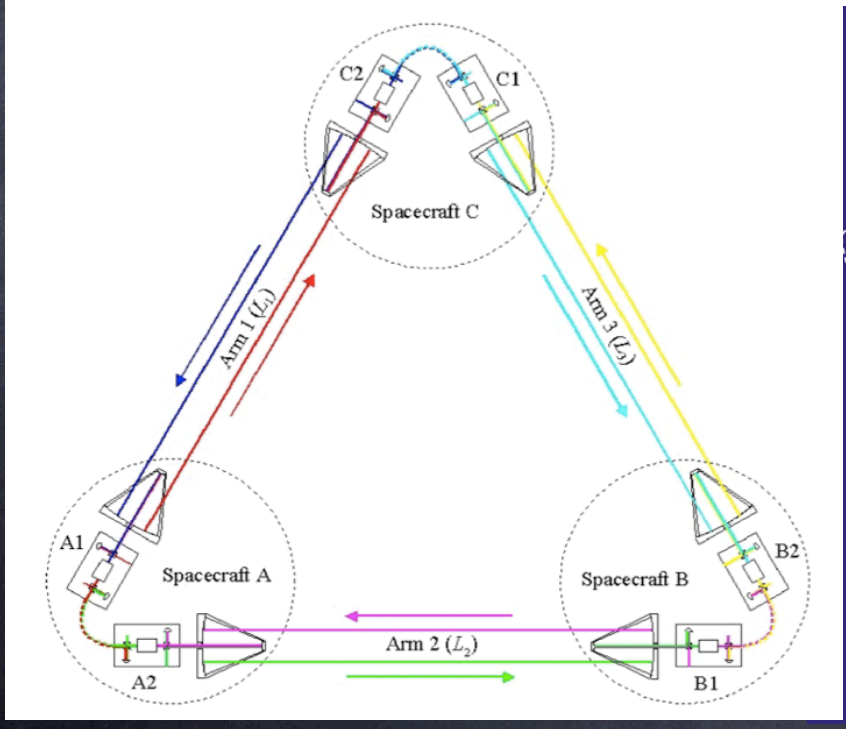


Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coalescence of
Massive Black Holes
Resolved
Galactic Binaries
Unresolved
Galactic
Binaries
LISA
NS−NS and BH−BH
Coalescence
SN Core
Collapse
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency [Hz]

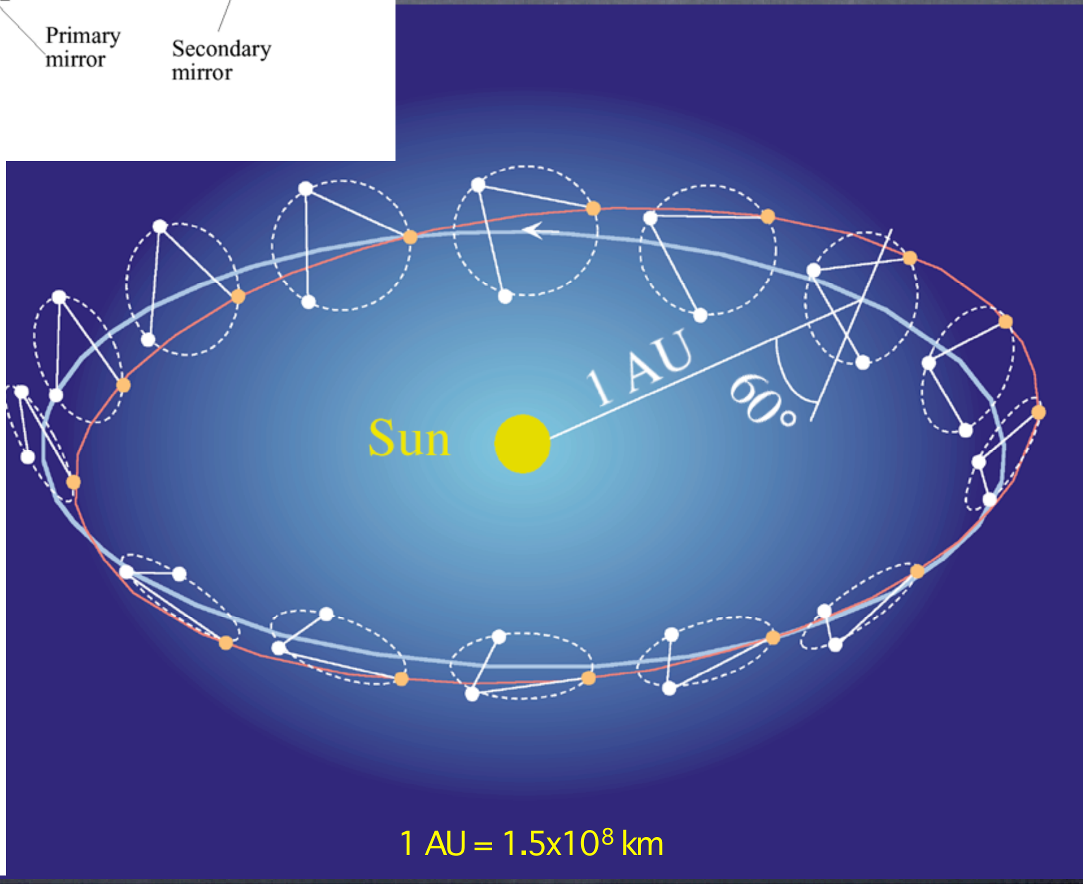
LISA



Support cylinder
Proof mass
Telescope thermal shield
Mirror support
Secondary support
Fiber to other optical assembly
Interferometer Electronics
Accelerometer Electronics
Electronics plate
Fiber from laser
Stiffening rings
Primary mirror
Secondary mirror



C2
C1
Spacecraft C
Arm 1 (L_1)
Arm 3 (L_3)
A1
Spacecraft A
B2
Spacecraft B
Arm 2 (L_2)
A2
B1

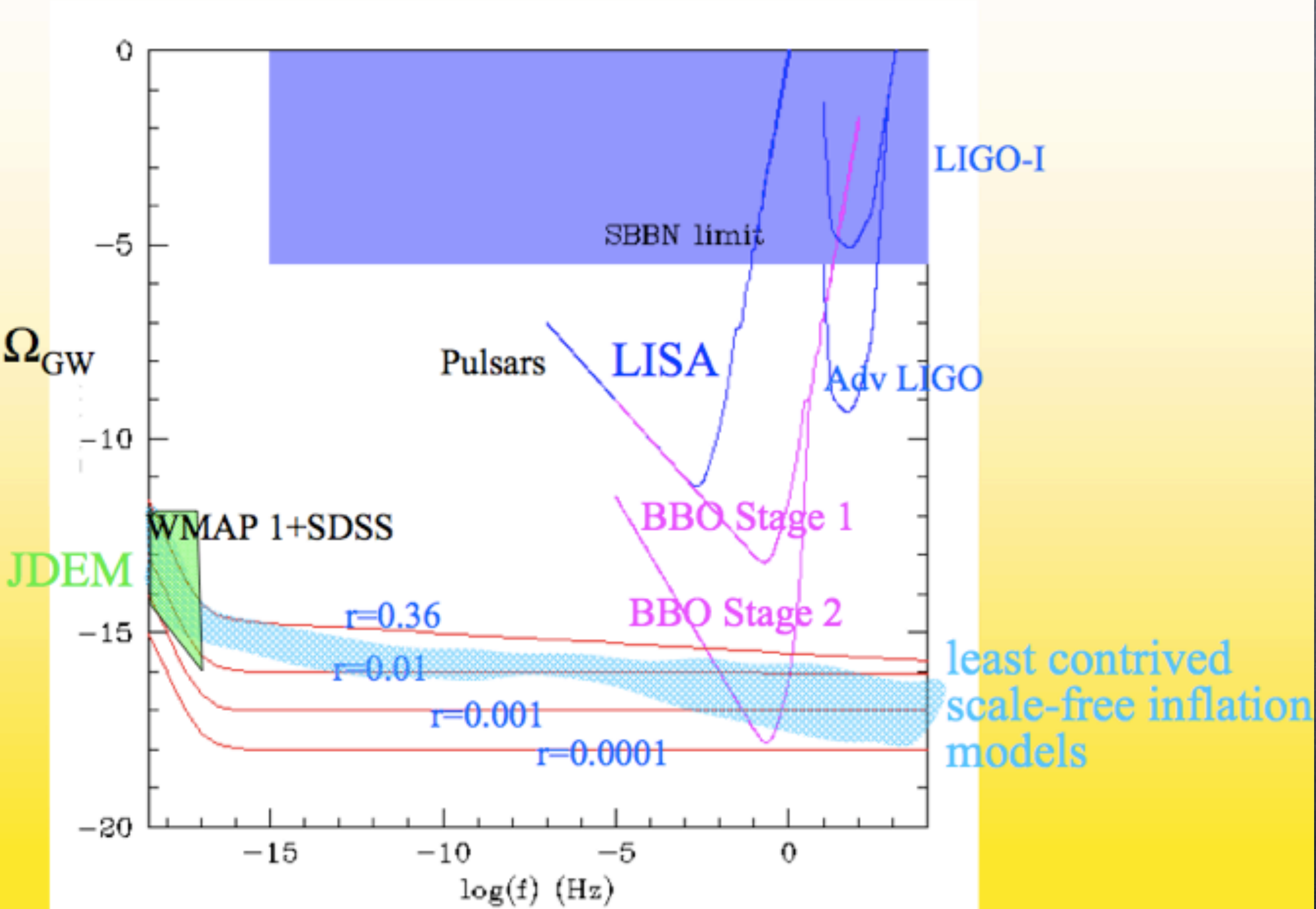


Sun
1 AU
60°
1 AU = 1.5x10^8 km

BBO

- Last year of every merging NS-NS, NS-BH, BH-BH of stellar mass at $z<8$. ~1 arcmin positions.
- Luminosity distances for (1): $\sim 10^4$-10^5 sources, accurate to < 1%
- Measure dz/dt in galactic sources from stretching of chirp, gives H(z). Dark energy probe.
- All mergers of intermediate mass BH at any z.
- Cosmic/Superstrings over entire range $G\mu/c^2 > 10^{-14}$

BBO & Stochastic Background



BBO v. LISA

	BBO	LISA
Arm length L (km)	5×10^4	5×10^6
Laser Power L (W)	300	1
Laser λ (nm)	355	1065
Mirror diam D (m)	2.5	0.3
Accel. noise (m $\mathrm{s}^{-2}\mathrm{Hz}^{-1/2}$)	3×10^{-17} at 0.1 Hz	3×10^{-15} at 1mHz
Proof Mass M (kg)	10 Al_2O_3	1.6 Au/Pt
Interferometer op	dark fringe	fringe counting
Proof mass accel	$3 \times 10^{-10}\mathrm{m\ s}^{-2}$	0
$c/(2\pi L)$ (Hz)	1	0.01
Position shot noise (m $\mathrm{Hz}^{-1/2}$)	1.5×10^{-17}	1.1×10^{-11}
Pointing stability req	$10^{-12}\mathrm{rad\ Hz}^{-1/2}$	$10^{-8}\mathrm{rad\ Hz}^{-1/2}$

Summary

- Existing Ground Based Interferometers at/near design
- Next Generation of IFOs promise daily/weekly detections
- Spaced Based Interferometers are 10-20 years in the future
- .