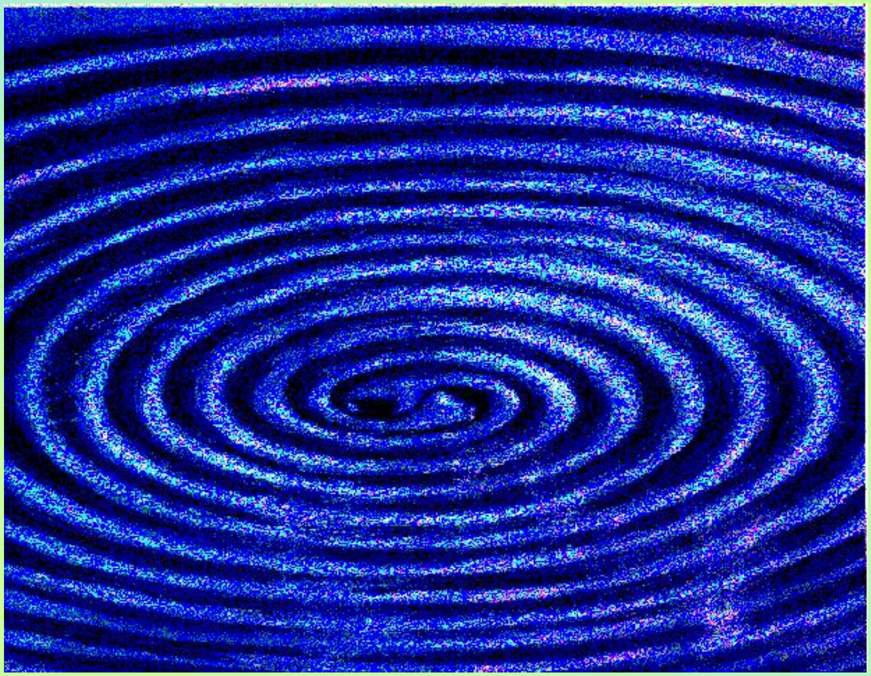
Ground-based Gravitational Wave Detection: Now and Future



Stan Whitcomb
Caltech

GR18 / Amaldi7
9 July 2007

Theme:
Celebration of a Transition

Looking back

- **Resonant bar detector network achieved mature operation**
- **First extended searches with interferometers at design sensitivity**

Looking Forward

- **Continued improvements to existing interferometers and construction of advanced interferometers**
- **R&D into new ideas for acoustic detectors (bars or spheres) for high frequencies**

General Relativity: "a theorist's Paradise, but an experimentalist's Hell"

C. Misner, K. S. Thorne and J.A Wheeler, ***Gravitation*** p. 1131 (1973)

AIP Emilio Segrè Visual Archives

- **Nothing exemplifies this statement like gravitational waves**
- **Convincing observational evidence for their existence not available until ~70 years after initial prediction (Binary Pulsar)**
- **After 90 years, direct detection still eludes us**
- **With luck, we may have a direct detection before the 100th anniversary of their prediction**

Resonant Bar Detectors

- **First ground-based detectors—the beginning of GW detection**
  - » **Joseph Weber 1960's**
- **At least 19 different bar detectors (8 countries) were built and used in searches**
  - » **Several hundred scientists, students, engineers, and technicians involved in the effort**
  - » **Many of the current leaders in the field got their start**

Resonant Bar Operation

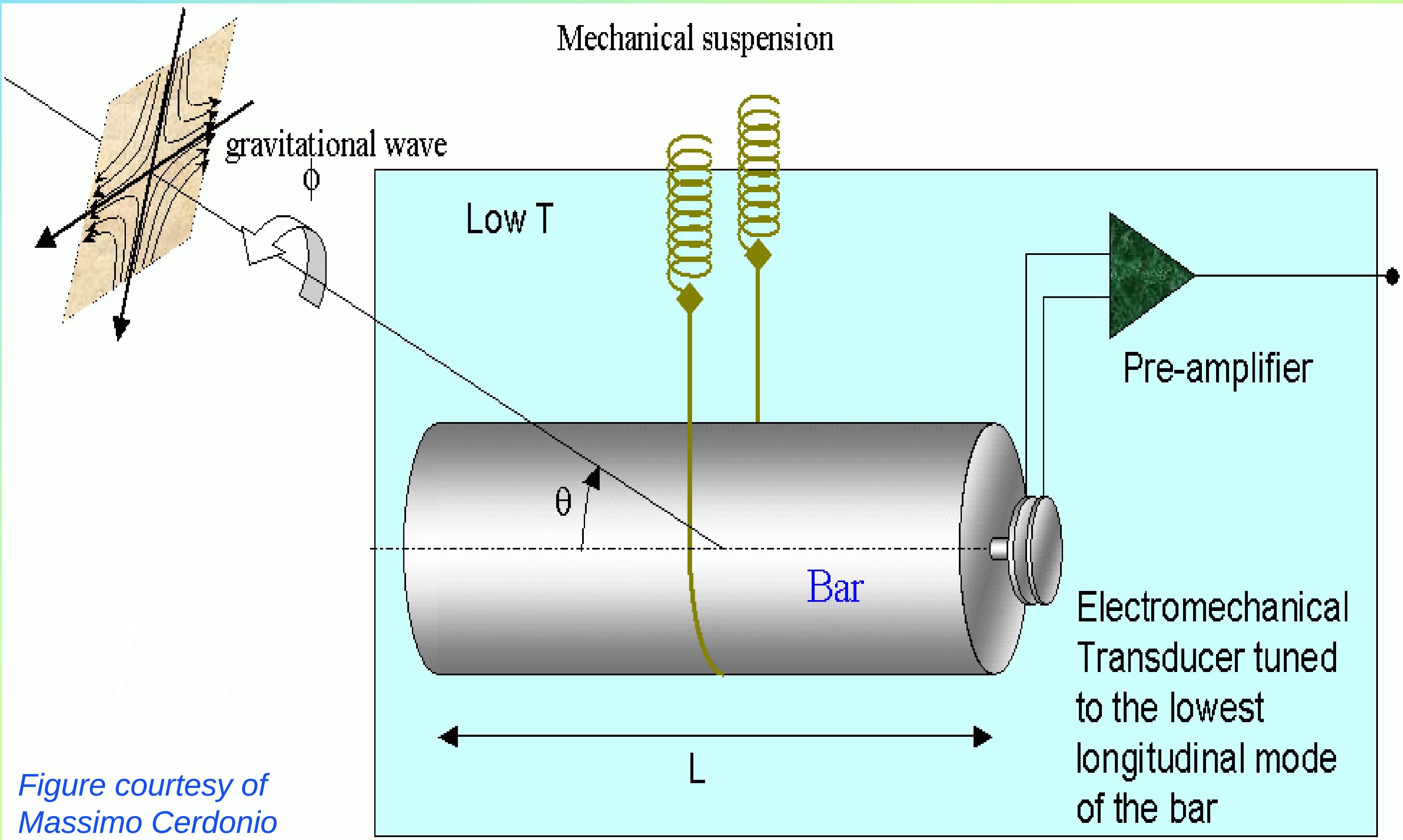


Figure courtesy of Massimo Cerdonio

Pioneering Achievements of Resonant Bars

- **Triggered interest in gravitational waves**
  - » **Theoretical studies of sources**
- **Recognition of important noise sources**
  - » **Thermal**
  - » **Back action/Quantum**
  - » **Seismic/acoustic**
- **Large cryogenic systems**
- **Need for multiple detectors**

First World-wide GW Network: IGEC

International Gravitational Event Collaboration
Established 1997 in Perth

Included all operating bar detectors in the world

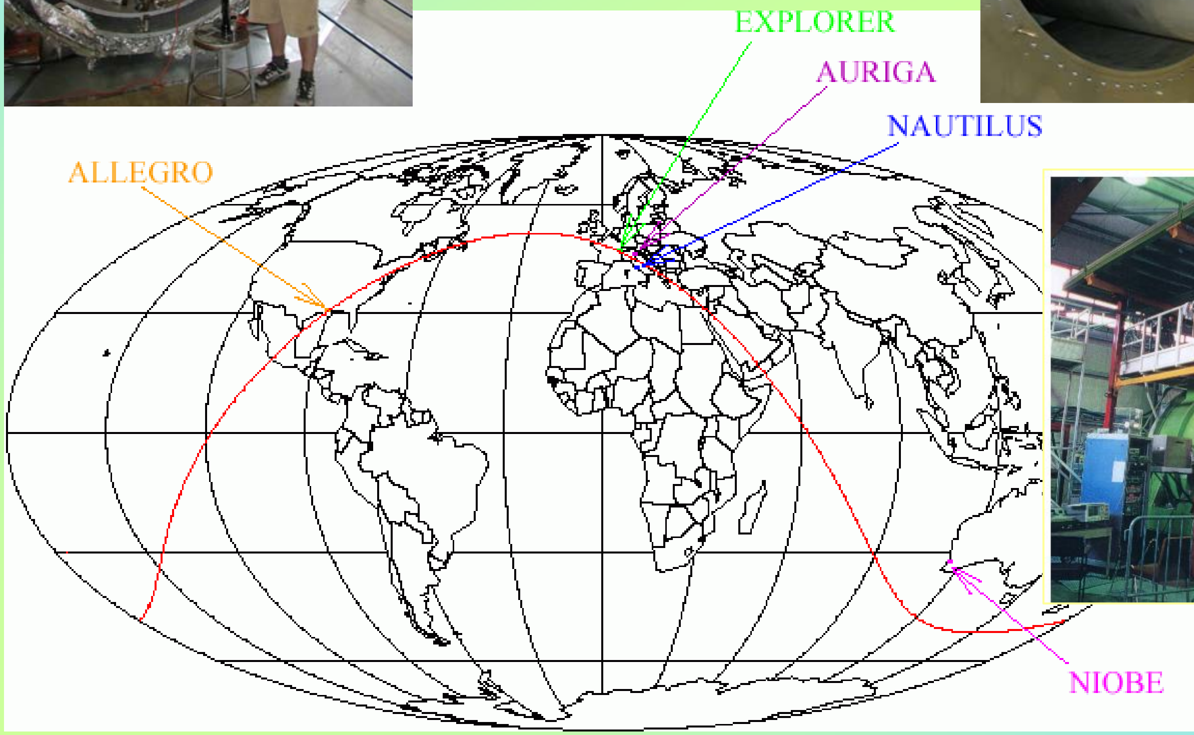


Figure courtesy of Massimo Cerdonio

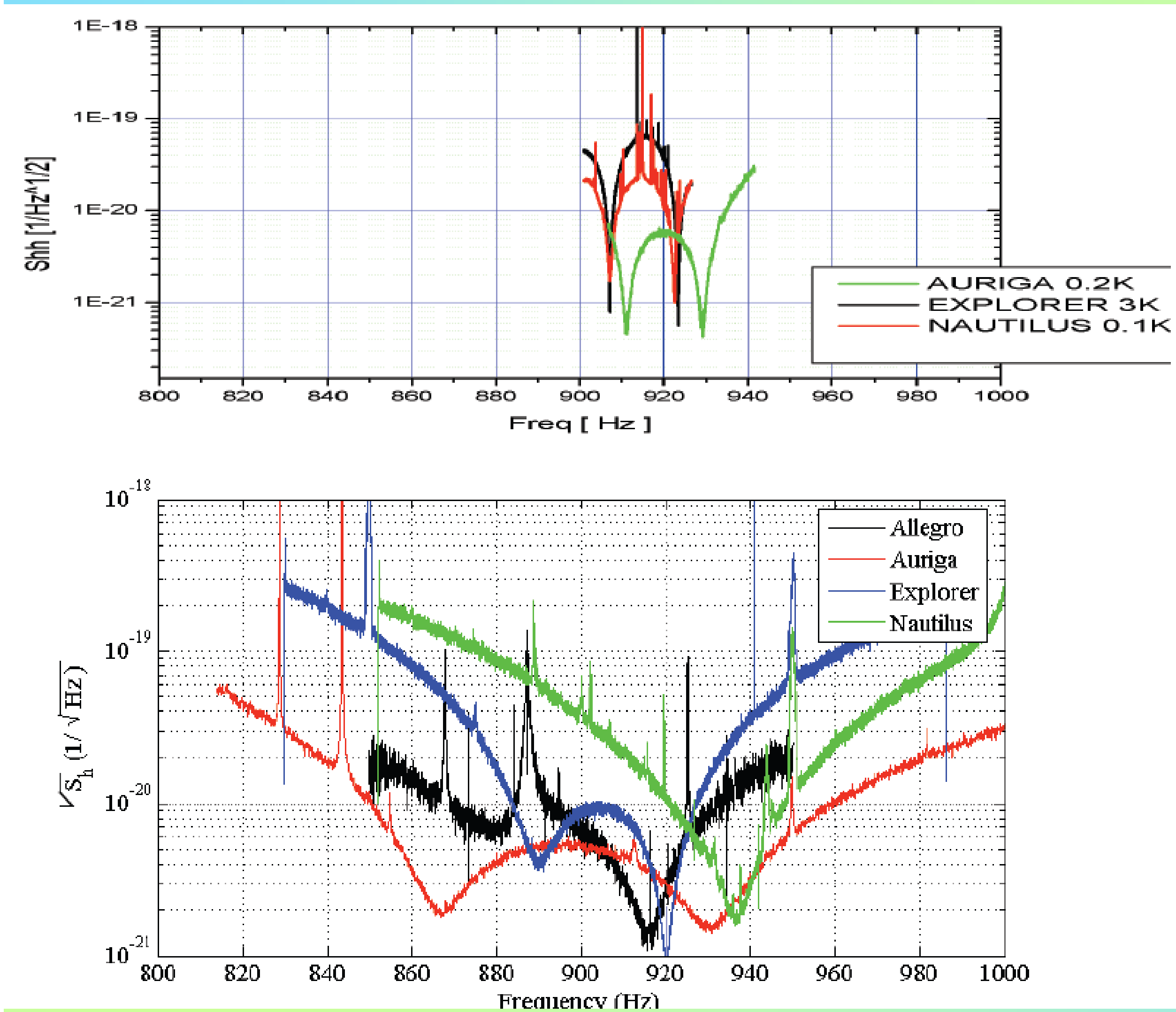
IGEC-2

- **IGEC-1 (1997-2000)**
  - » Four years produced 29 days of four-fold coincidences-178 days of three-fold coincidences - 713 days of two-fold coincidences
- **Followed by a series of upgrades**
  - » EXPLORER resumed operations in 2000
  - » AURIGA resumed operations in 2003
  - » NAUTILUS resumed operations in 2003
  - » ALLEGRO resumed operations in 2004
  - » NIOBE ceased operation
- **IGEC-2 (2005--)**
  - » First data analyzed covered May-November 2005 when no other observatory was operating

Massimo Visco
on behalf of the IGEC2 Collaboration

Rencontres de Moriond
Gravitational Waves and Experimental Gravity
March 11-18, 2007
La Thuile, Val d'Aosta, Italy

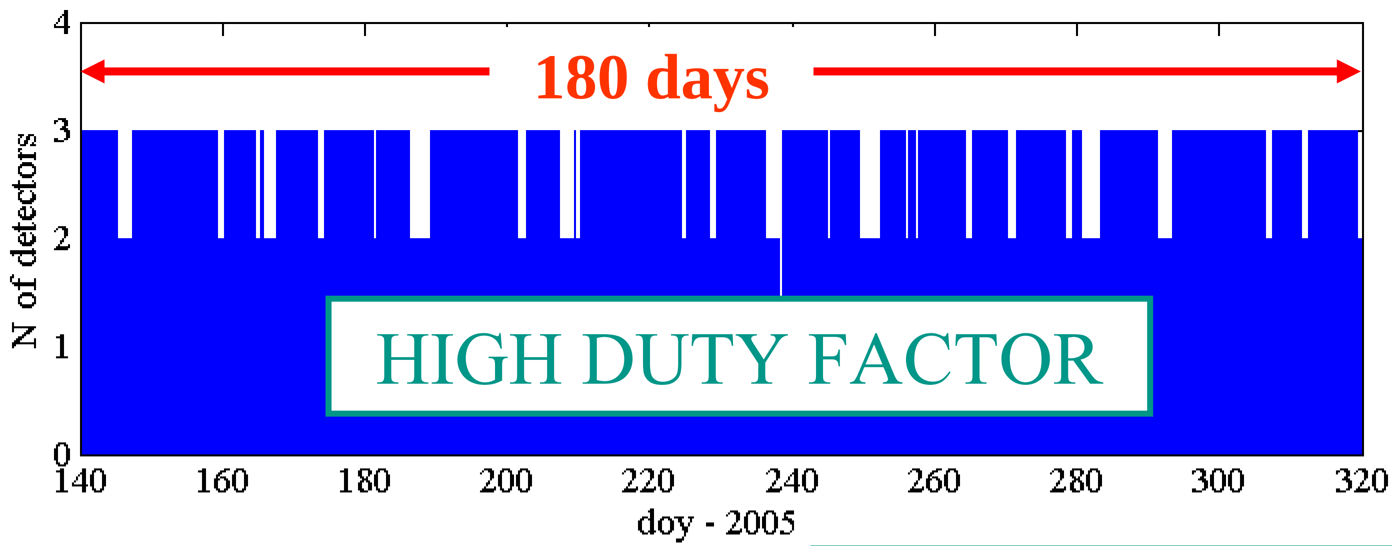
Sensitivity Improvements for IGEC-2



- Sensitivity to most signals scales as $\Delta f^{-1/2}$
- Approximately 3x more sensitive than IGEC-1

Massimo Visco
Rencontres de Moriond

First Analysis of IGEC-2 Data
May 20 –Nov 15, 2005



	AL	AU		NA
AL	**0**			
AU	**0**	172.9		
EX	**0**	**151.8**	158.0	
NA	**0**	**150.2**	**135.3**	155.0

days of operation

96 %

87 %

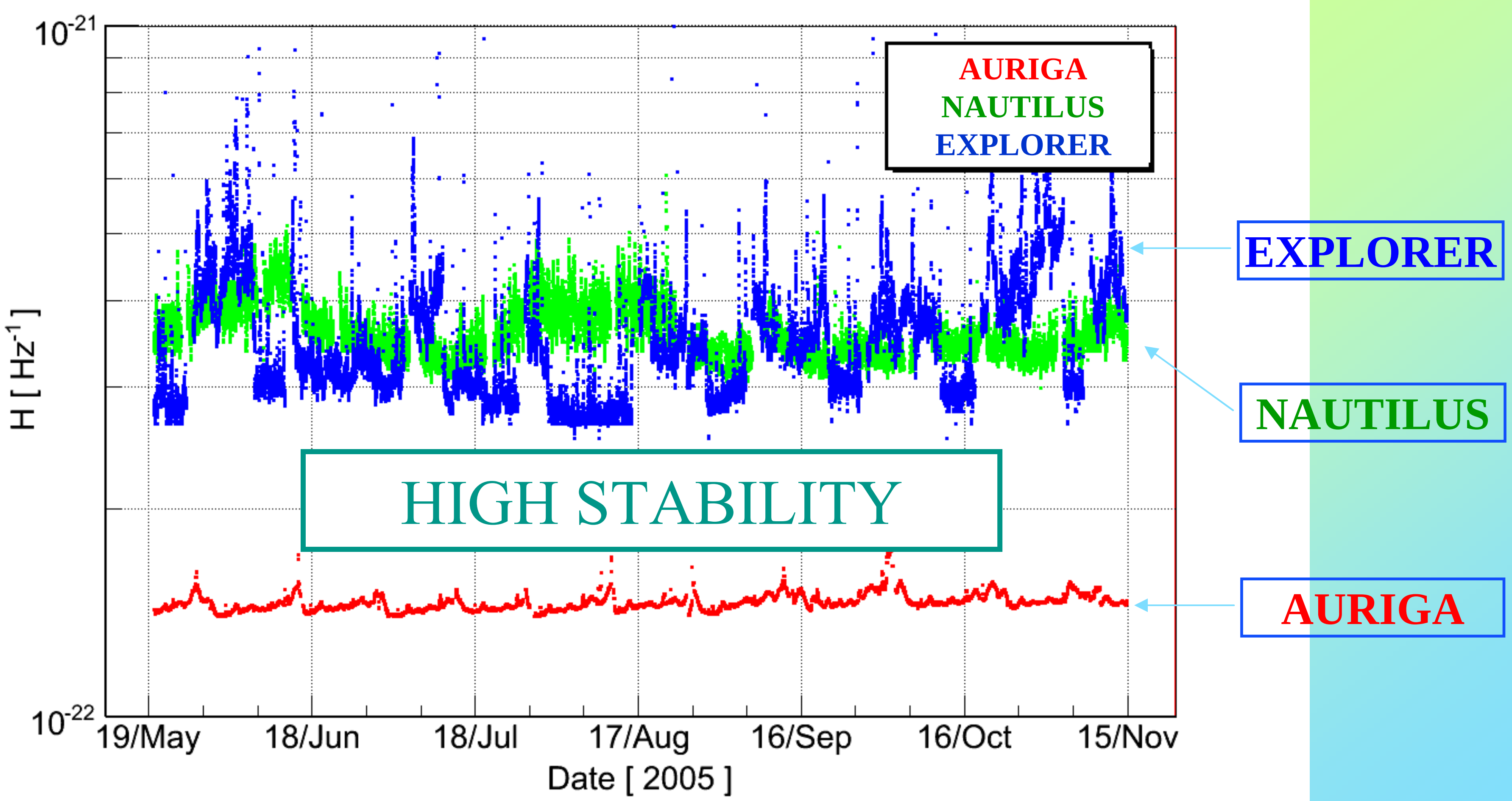
86 %

AURIGA- EXPLORER- NAUTILUS
ALLEGRO to be added

- no detector 0.6 days
- Single 3.6 days
- Double 45.0 days
- **Triple 130.8 days**

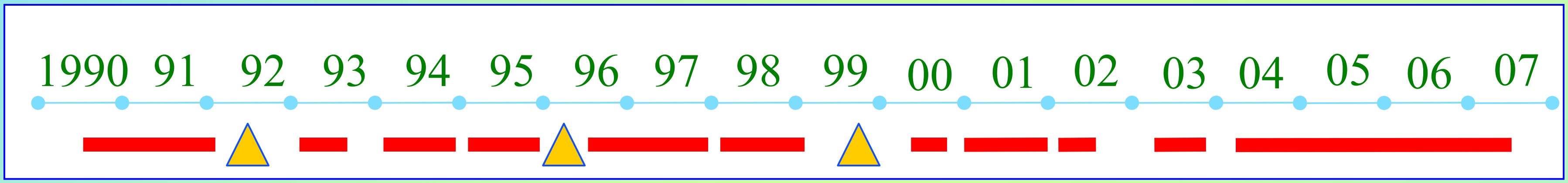
Giovanni Prodi

Noise of Detectors vs Time in Terms of Fourier Component h



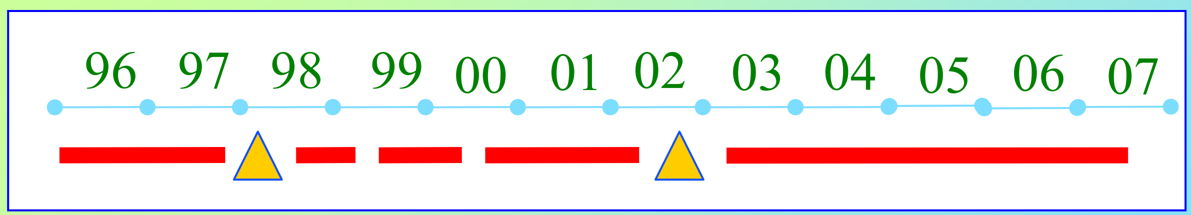
Data Taking
During the Last 17 Years

EXPLORER



NAUTILUS

△ Major upgrades



A Cloudy Future

- **Gradual shrinkage of the bar network due to loss of funding**
  - » **NIOBE (Perth) shut down, did not join IGEC-2**
  - » **ALLEGRO (LSU) ceased operation this year**
- **Continued operation of AURIGA, EXPLORER, NAUTILUS evaluated annually**

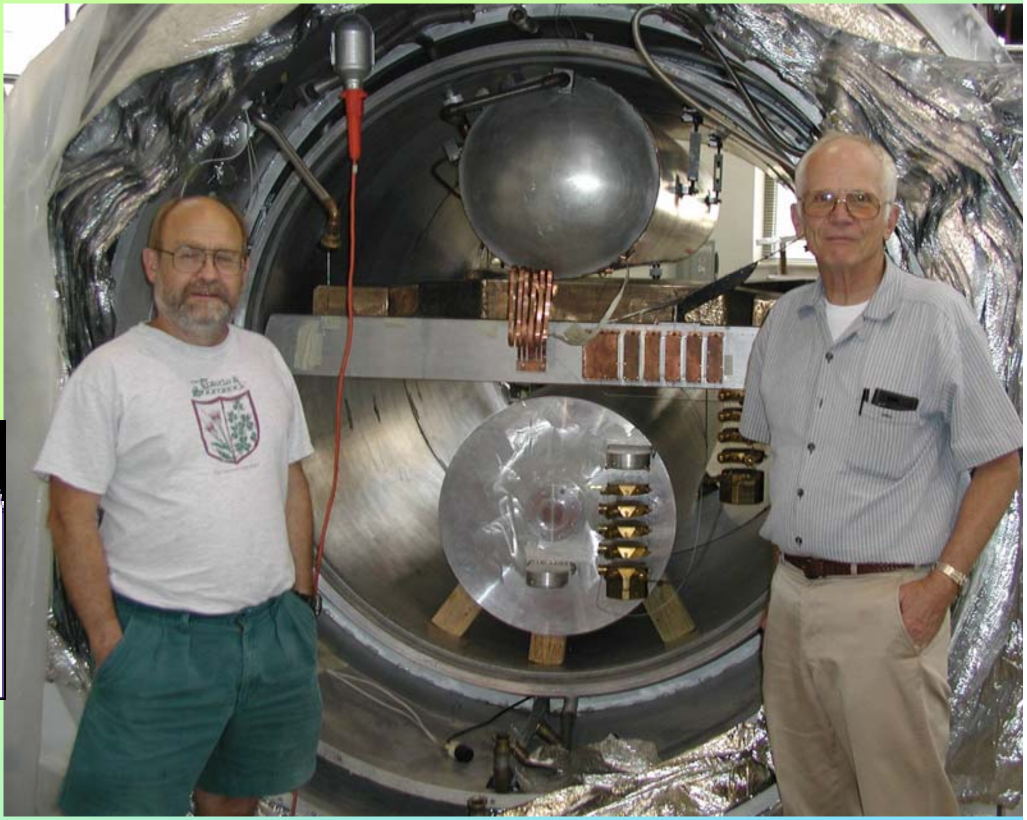
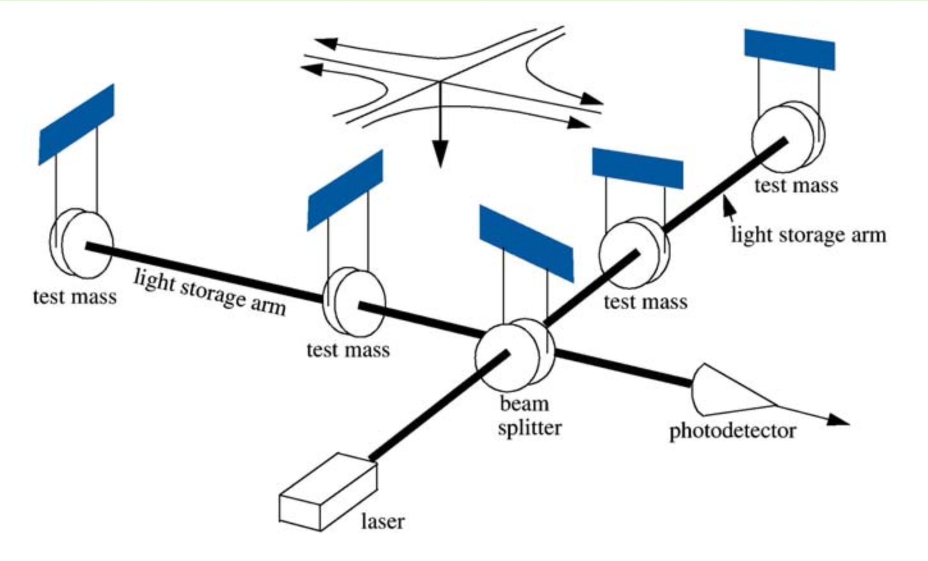


Figure courtesy of ALLEGRO Group, LSU

Detecting GWs with Interferometry

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

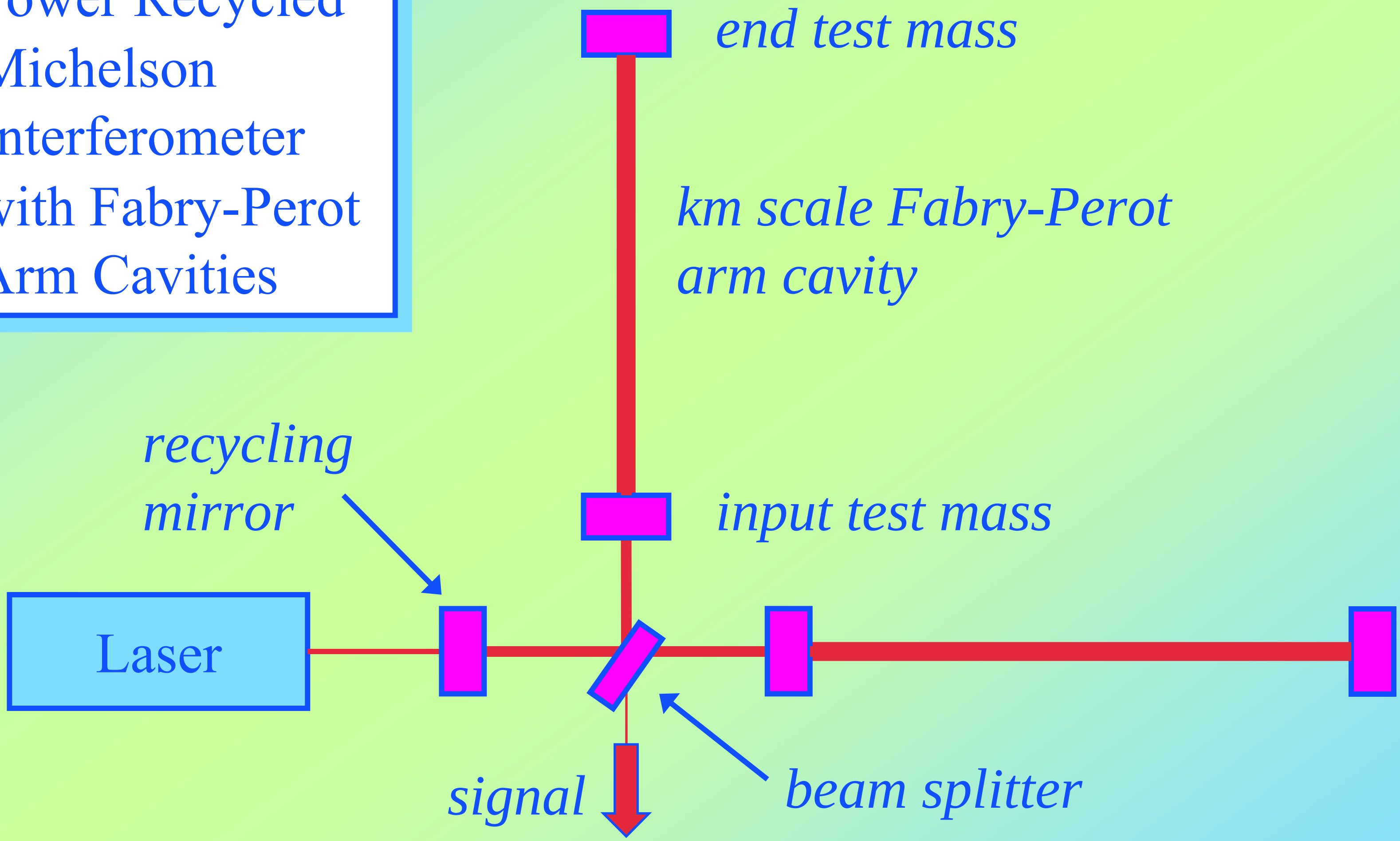
$$h = \Delta L / L$$



Terrestrial detector
For *h* ~ 10^{-22} – 10^{-21}
L ~ 4 km (LIGO)
ΔL ~ 10^{-18} m

Typical Optical Configuration

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



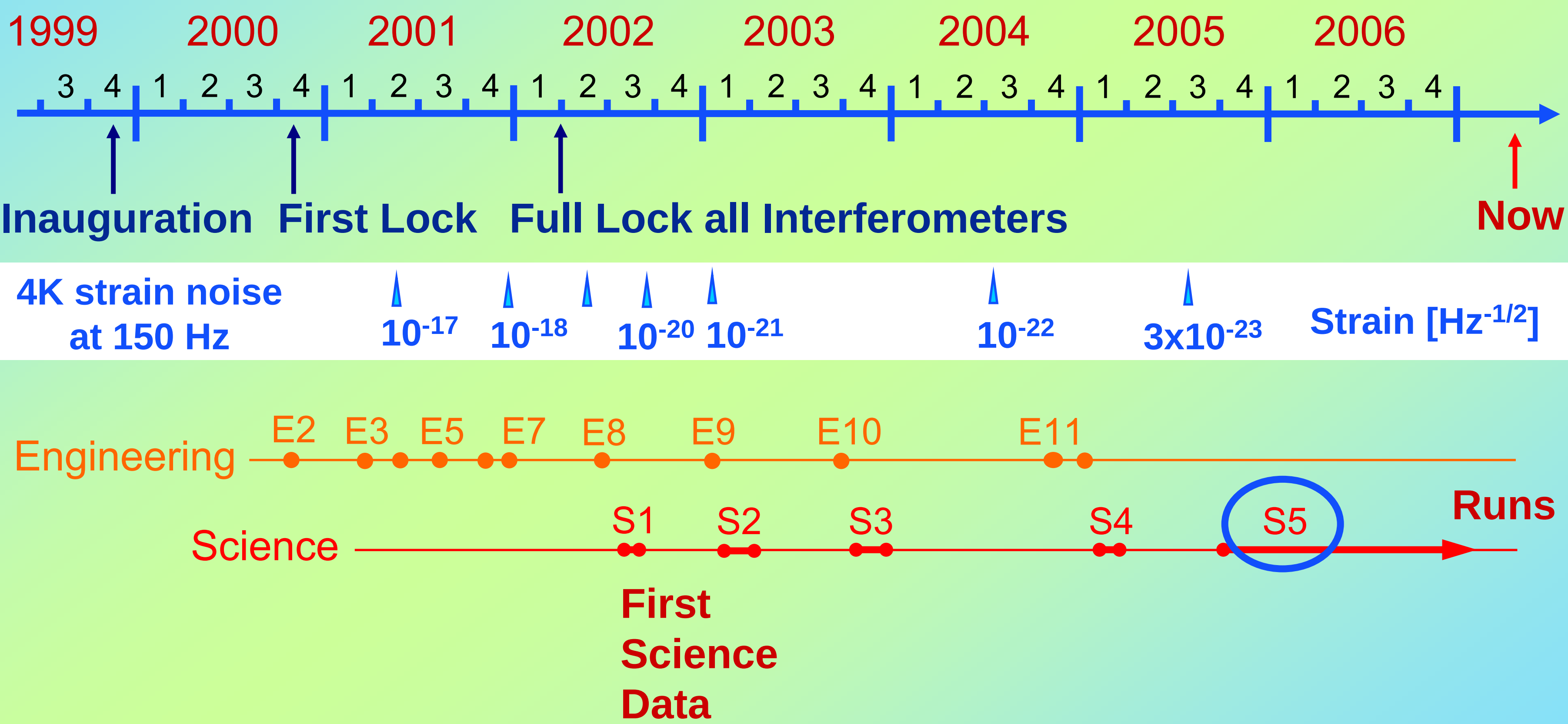
LIGO

(Laser Interferometer Gravitational-wave Observatory)

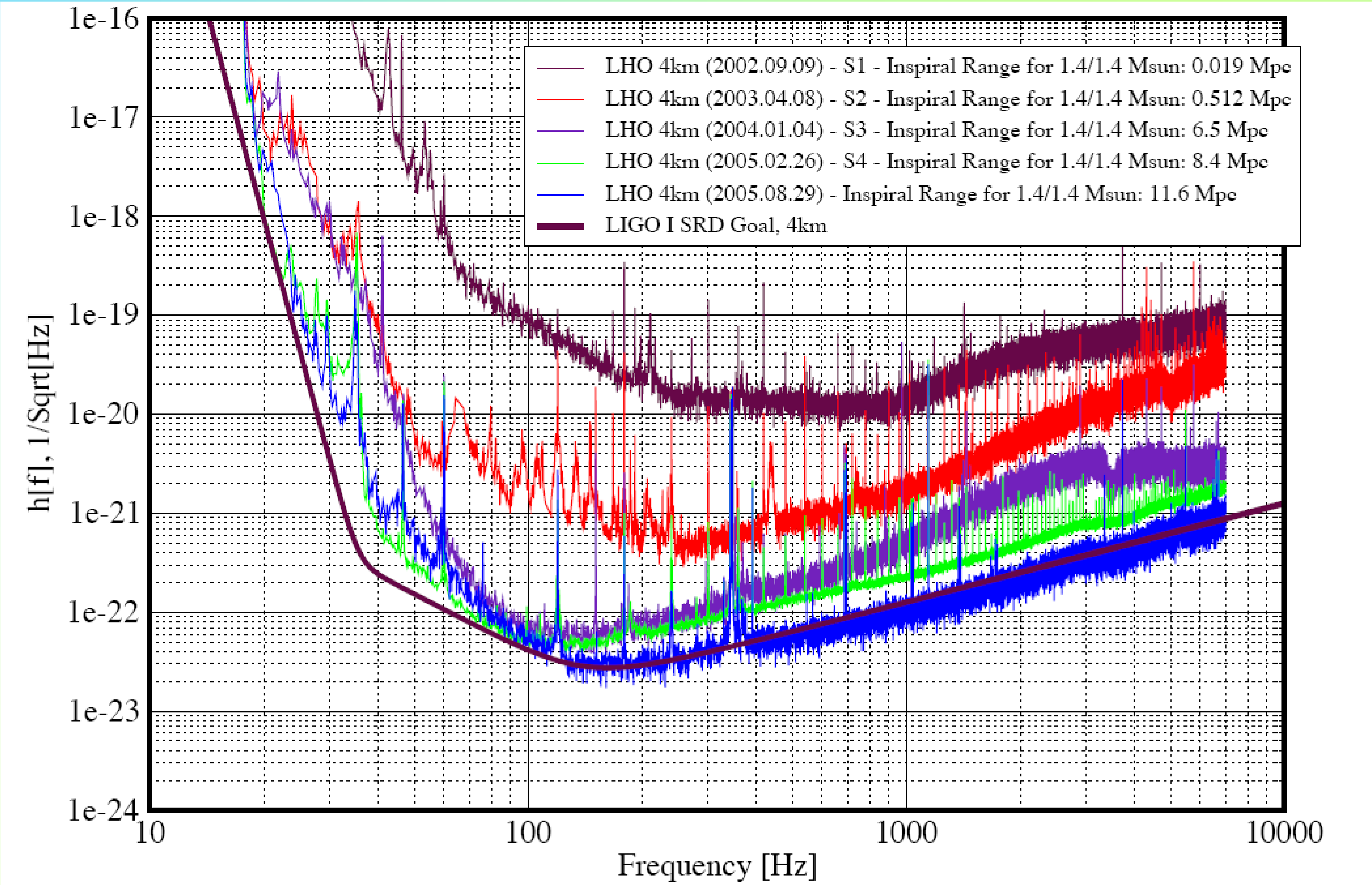
One interferometer with 4 km Arms, One with 2 km Arms

One interferometer with 4 km Arms

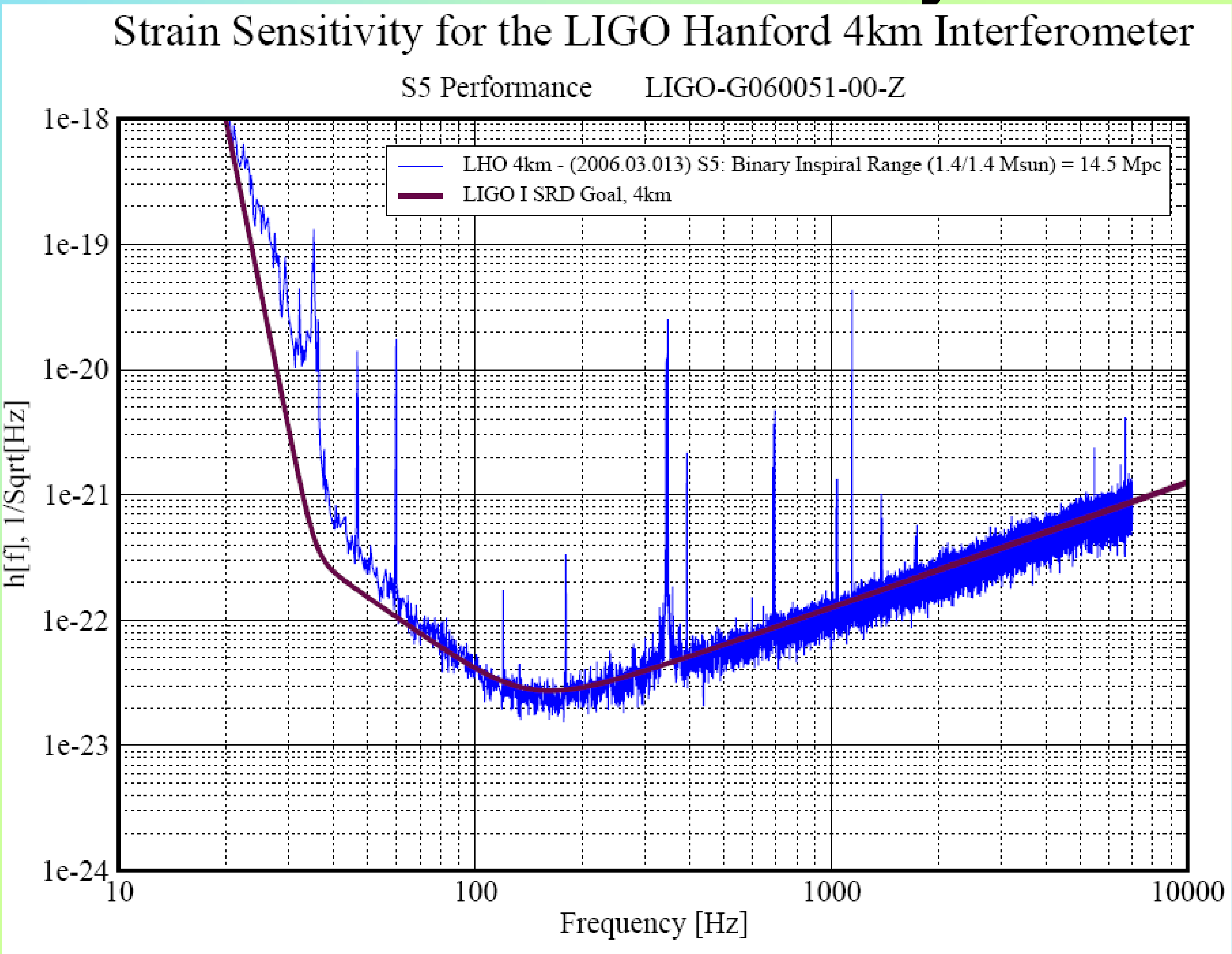
LIGO History



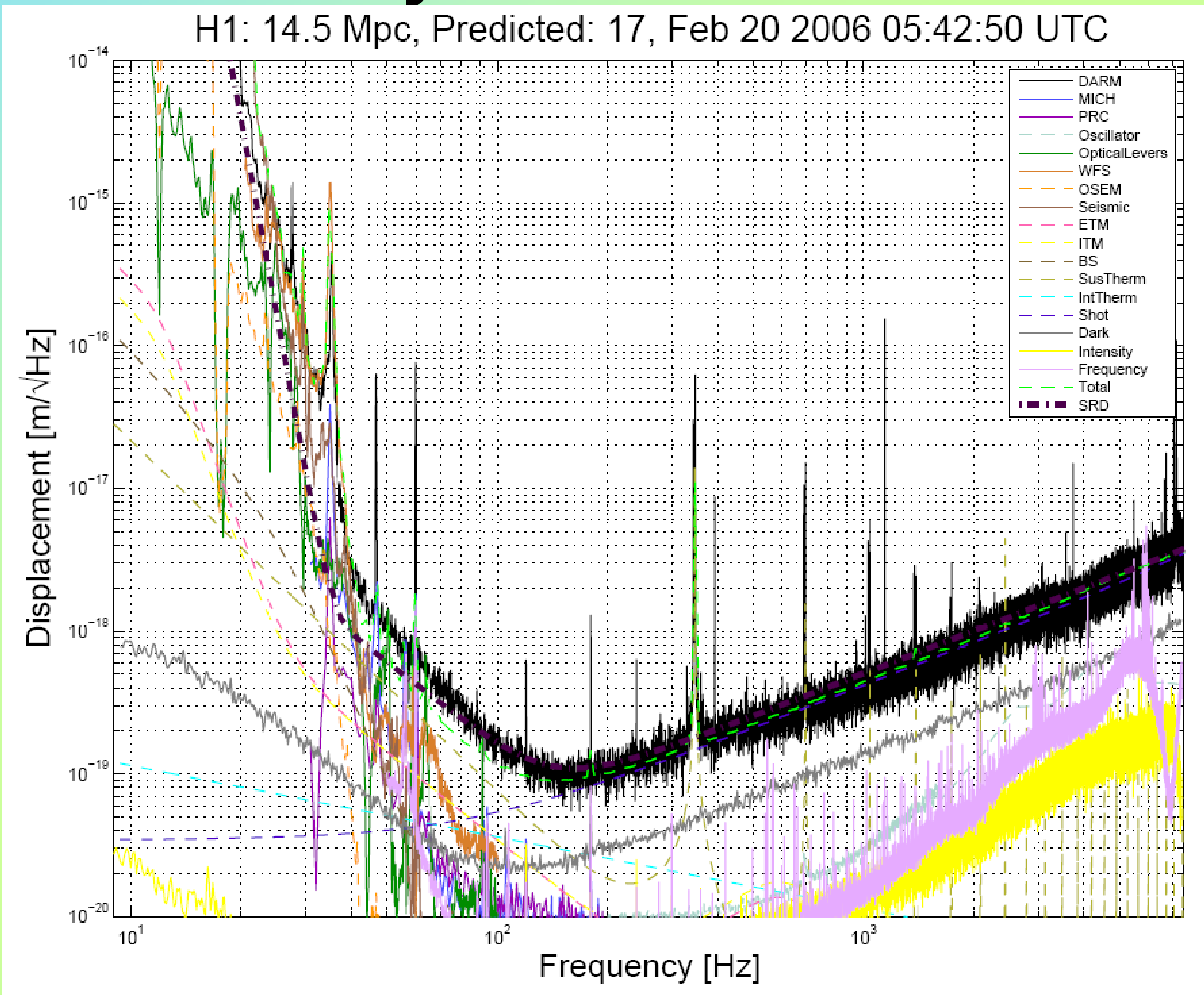
Progress of LIGO Sensitivity



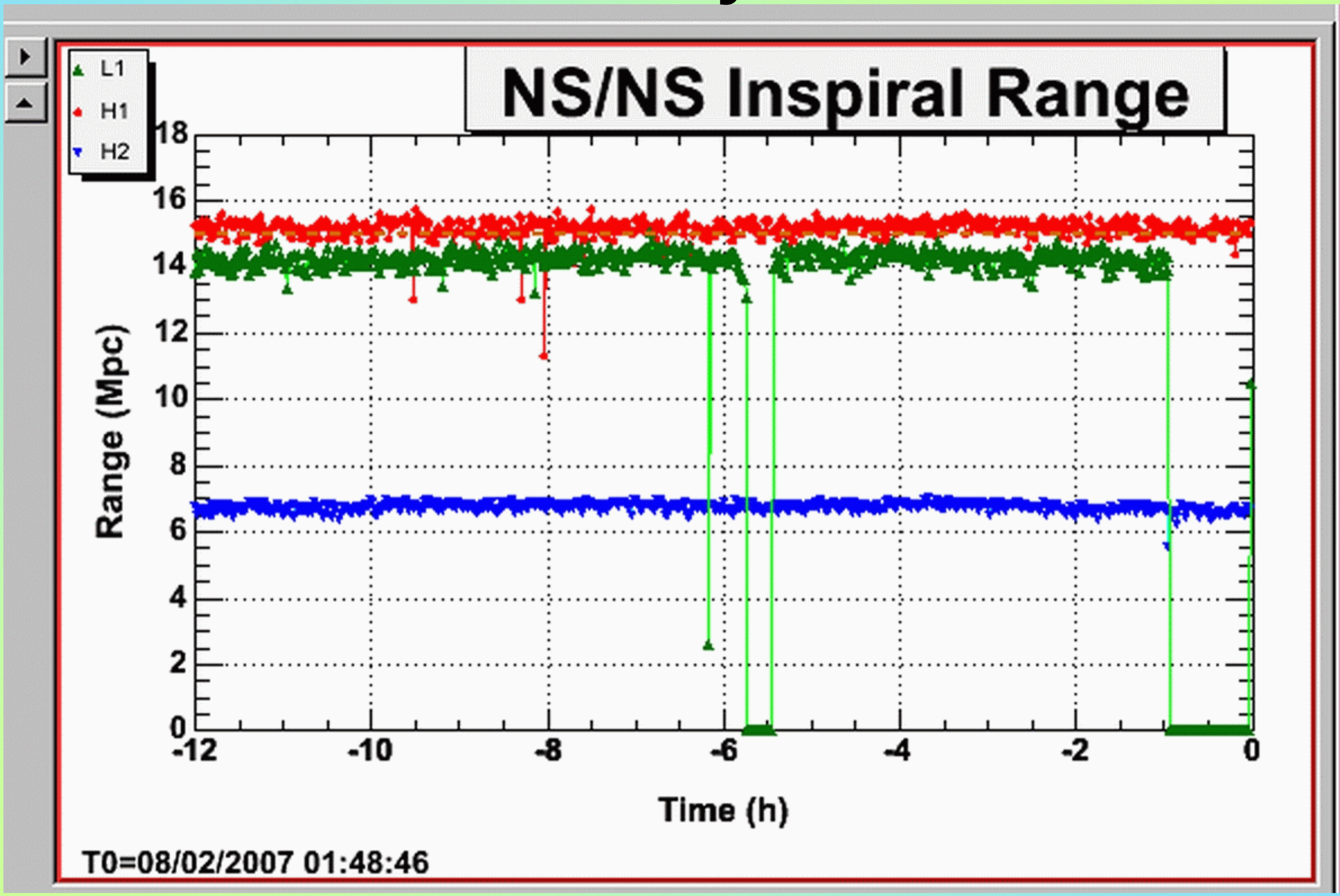
LIGO Sensitivity



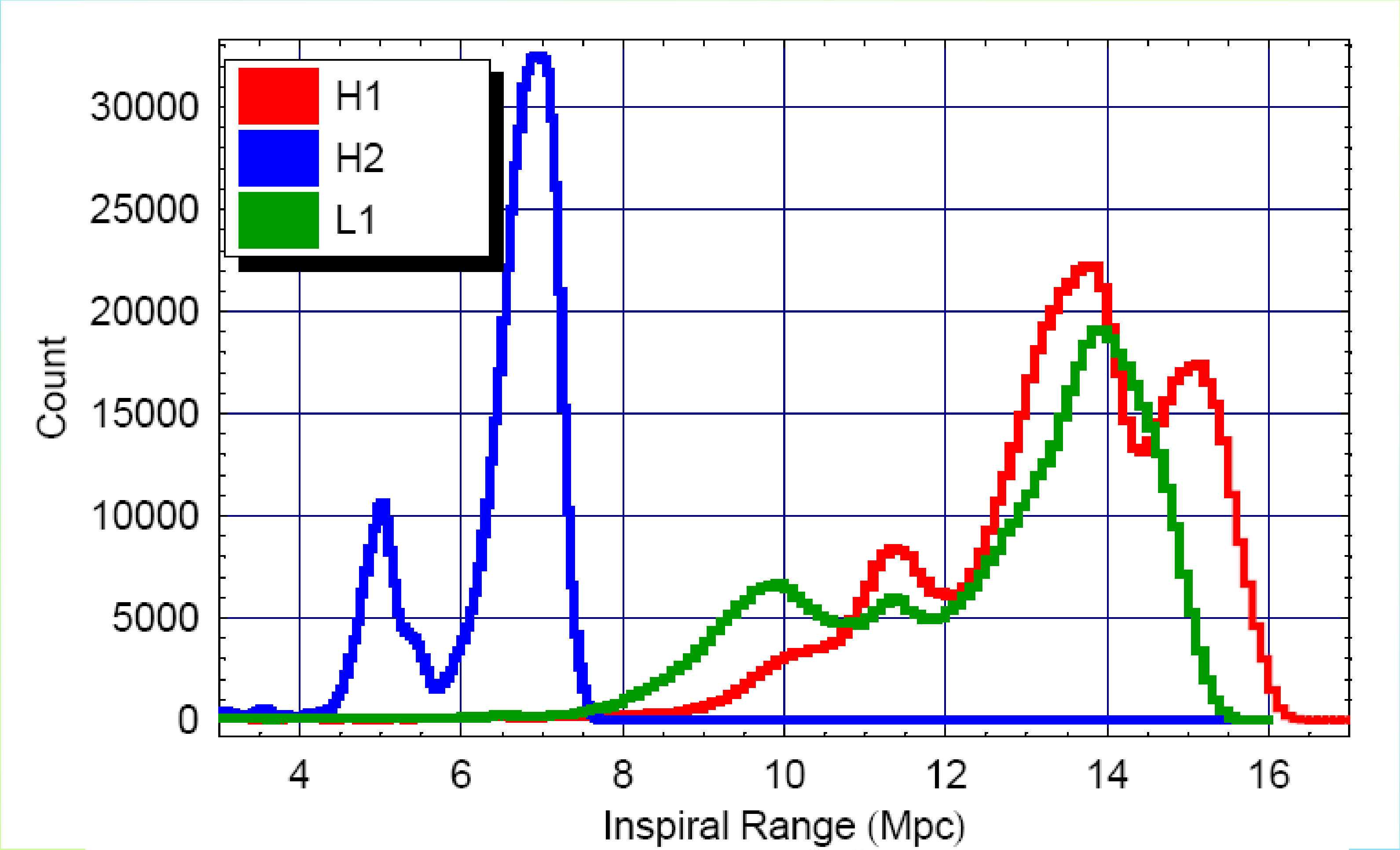
Anatomy of a Noise Curve



LIGO Duty Factor



Duty Factor for S5



GEO600

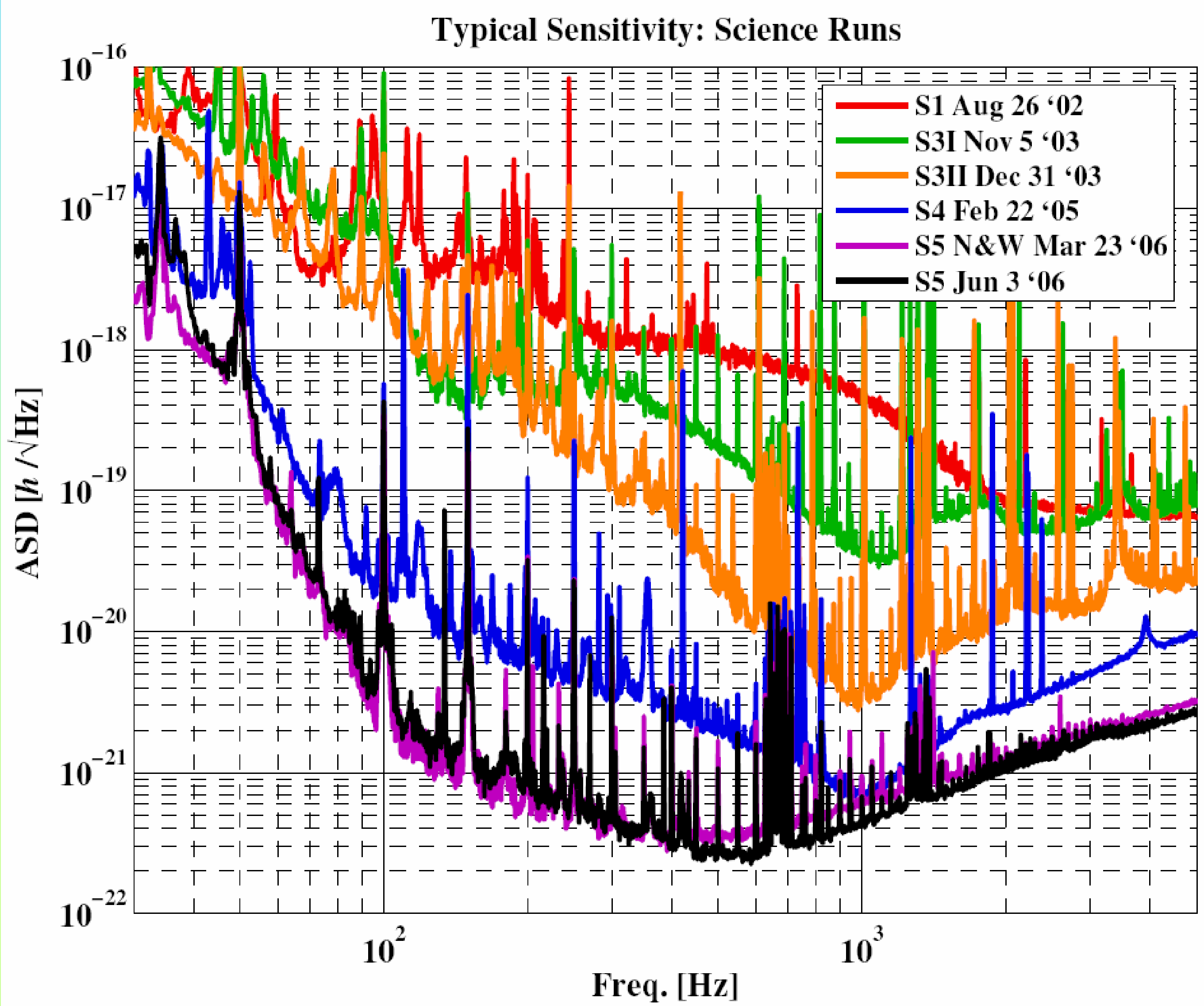
Interferometer with 600 m arms, located near Hannover

Harald Lück
for the Ruthe Team

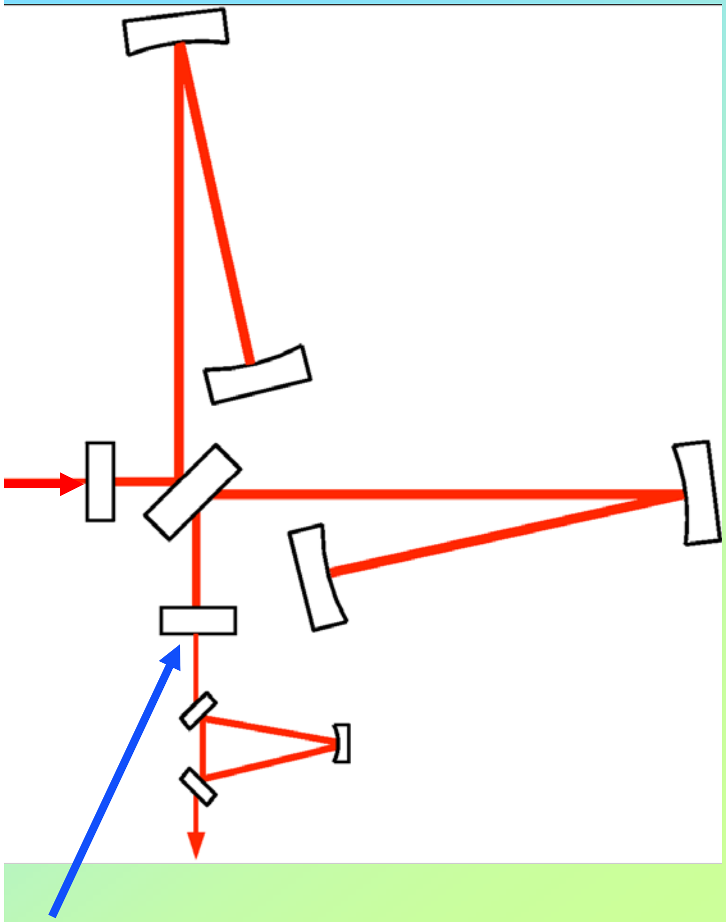
Rencontres de Moriond
Gravitational Waves and Experimental Gravity
March 11-18, 2007
La Thuile, Val d'Aosta, Italy

Leibniz Universität Hannover
University of Birmingham
IGR
Universitat de les Illes Balears
Cardiff University

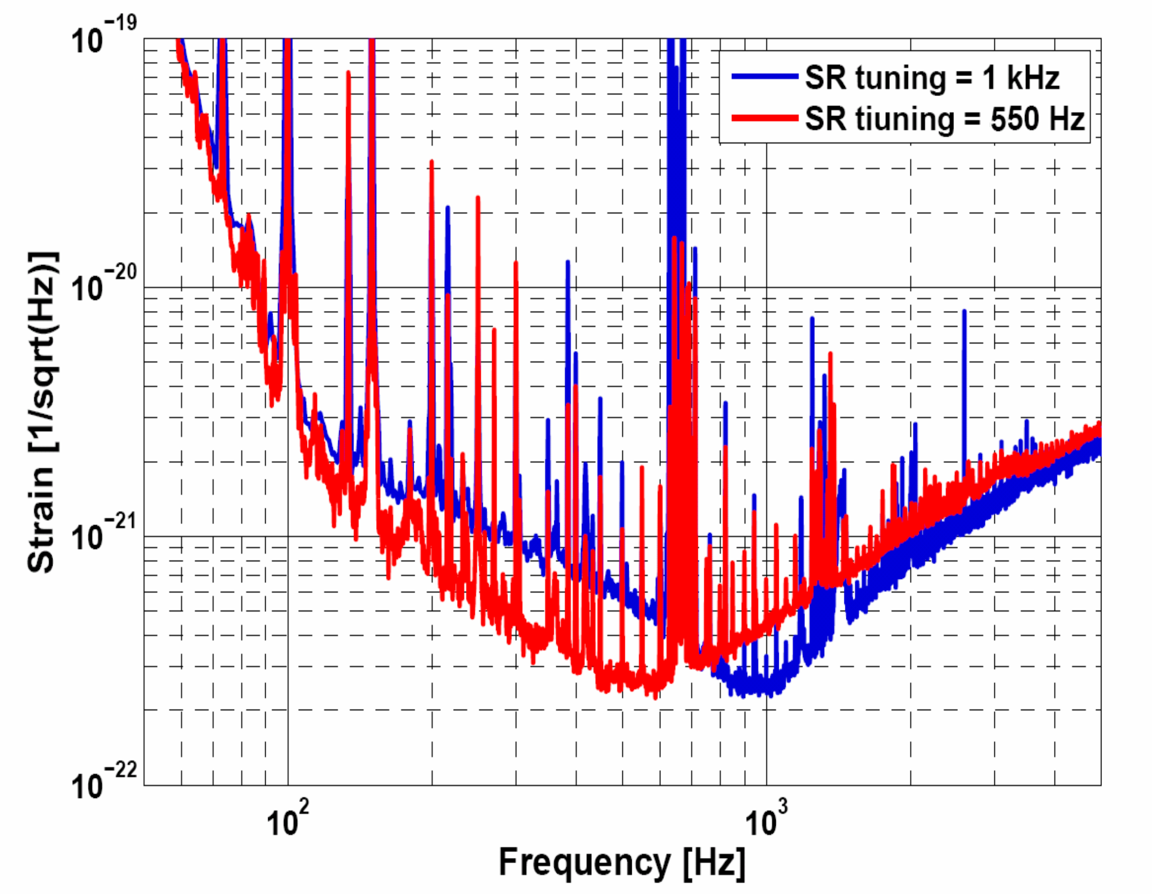
Progress of GEO600 Sensitivity



GEO600: Signal Recycling



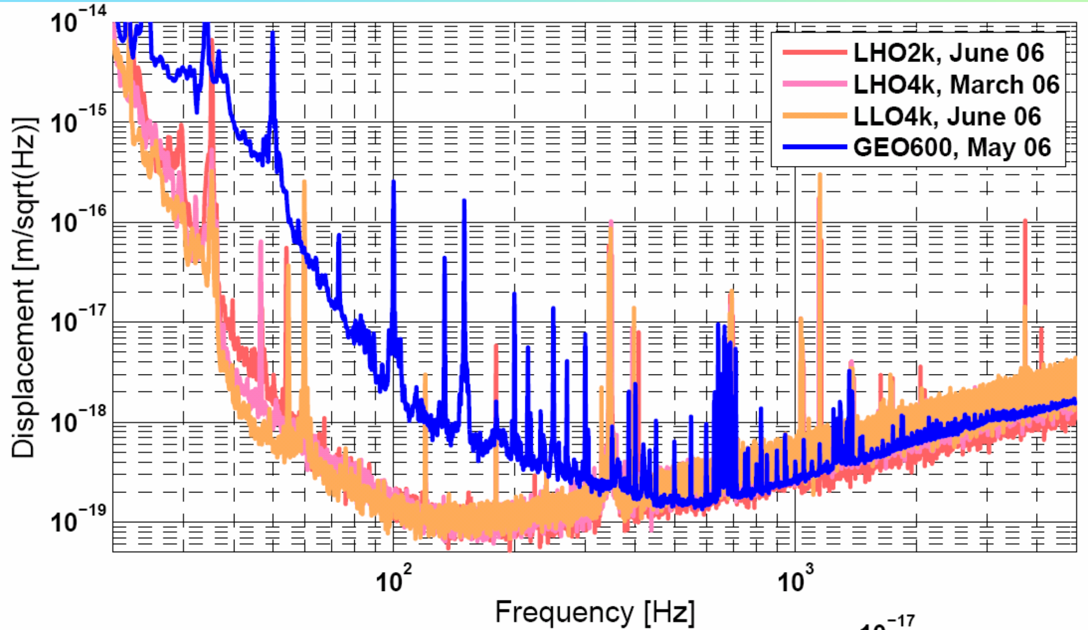
Signal Recycling Mirror



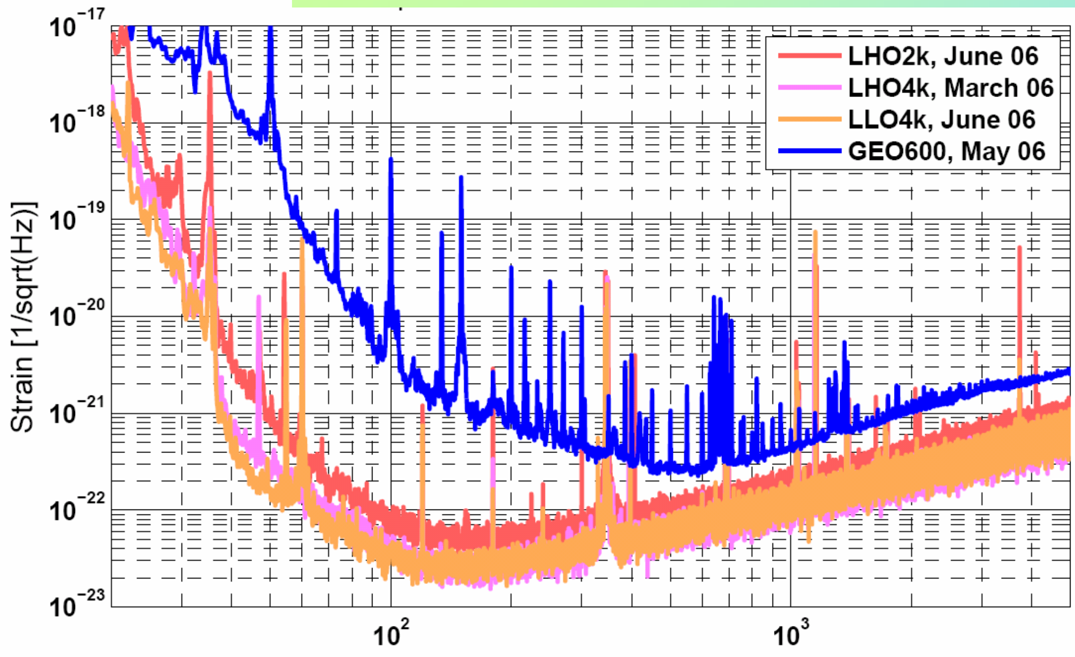
Location of Signal Recycling Mirror Changes Frequency Response (Frequency of Maximum Sensitivity)

Harald Lück
Rencontres de Moriond

The Importance of Length



Displacement Sensitivity
Measure of Experimenter's skill



Strain Sensitivity
Measure of Experiment's funding

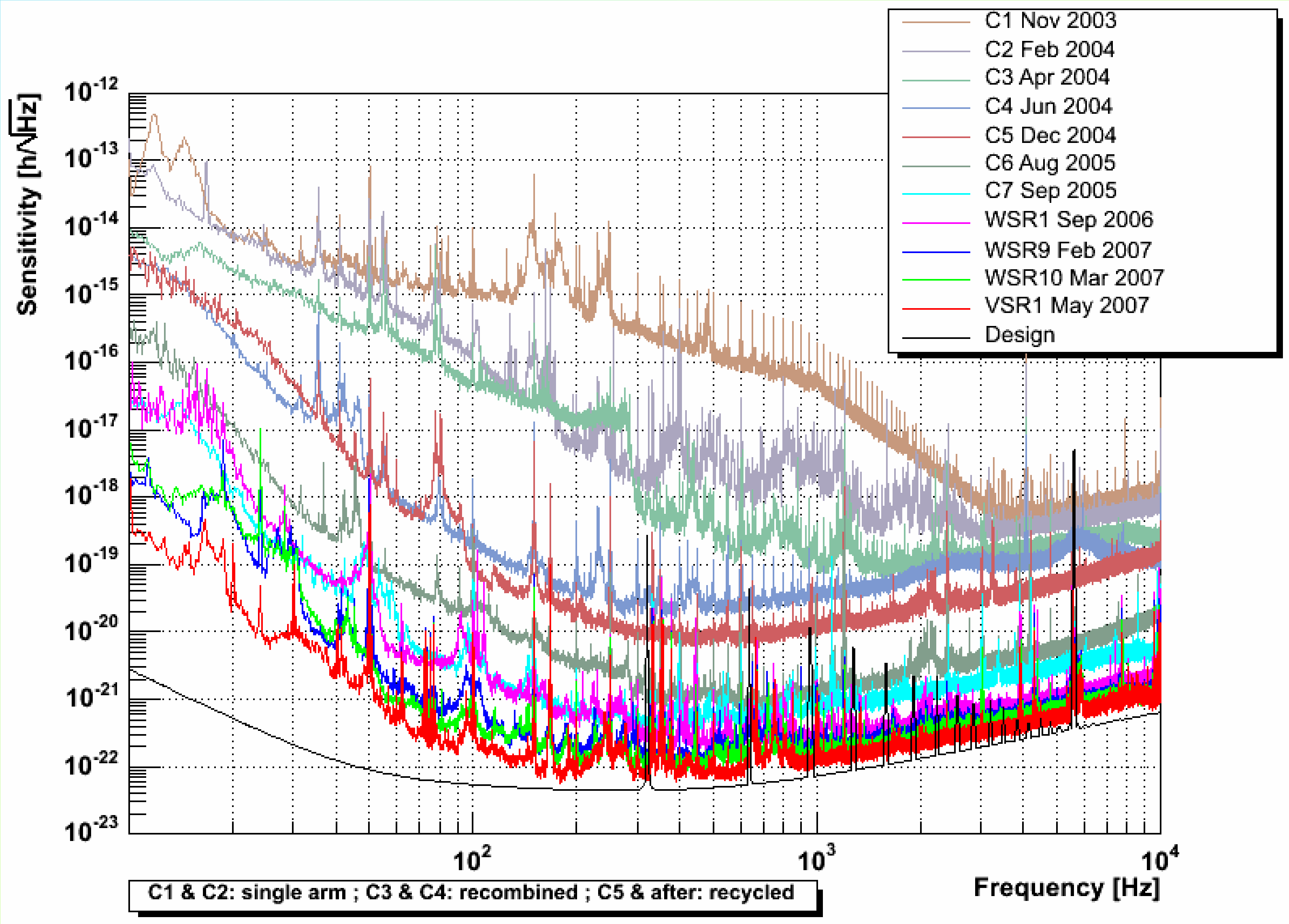
Harald Lück
Rencontres de Moriond

LIGO-G070419-00-R

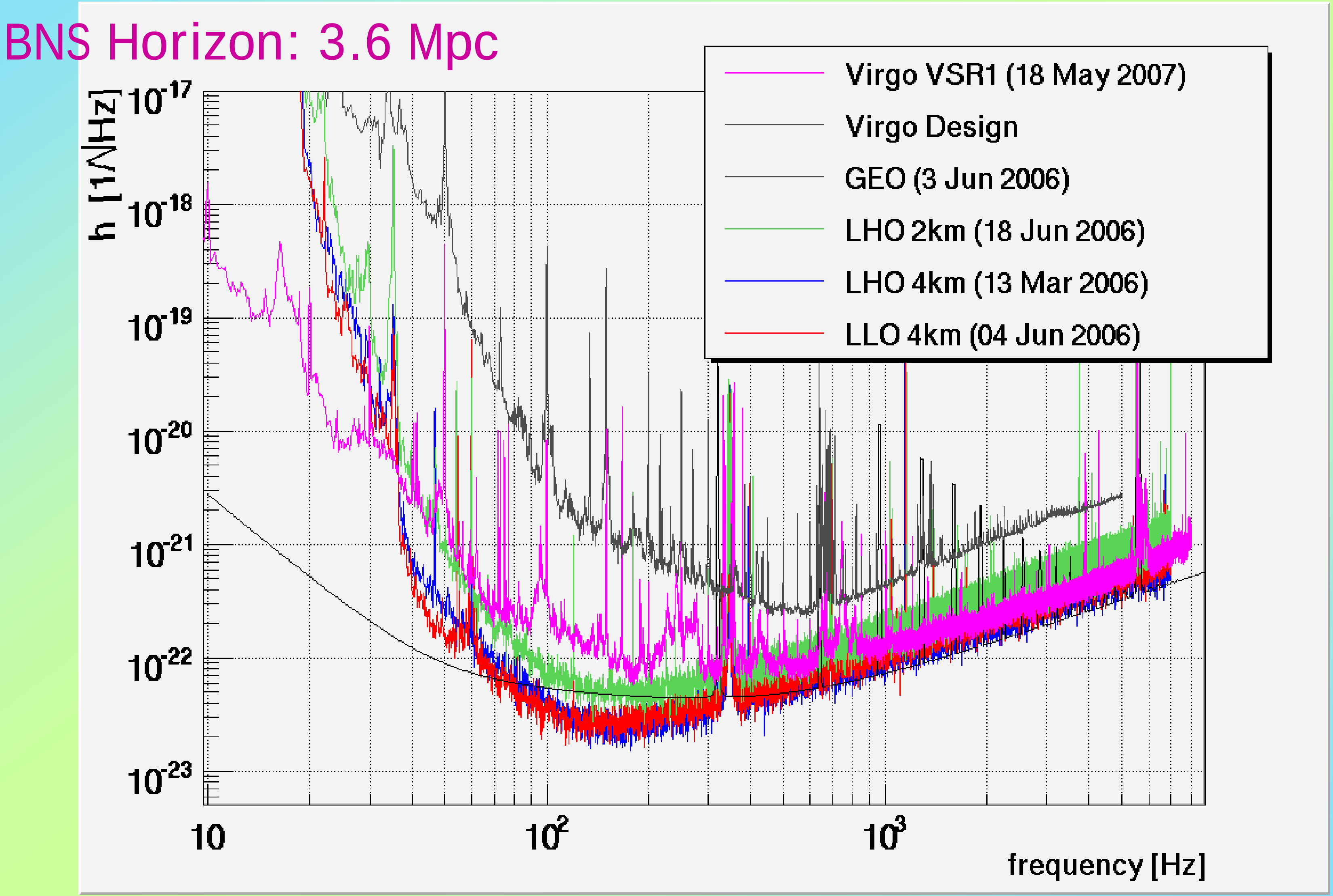
Virgo

One interferometer with 3 km arms, located near Pisa

Progress of Virgo Sensitivity

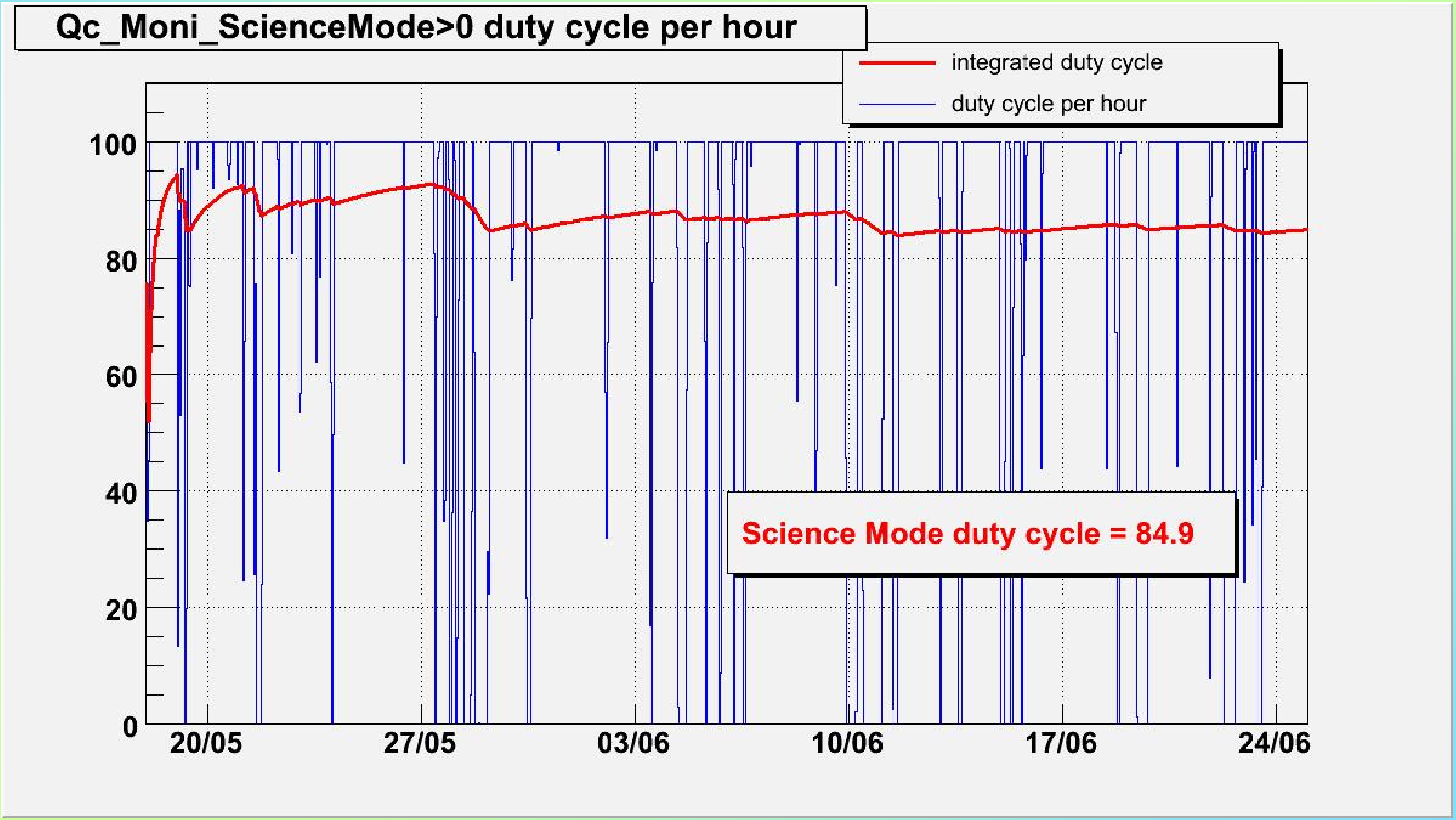


Virgo Sensitivity

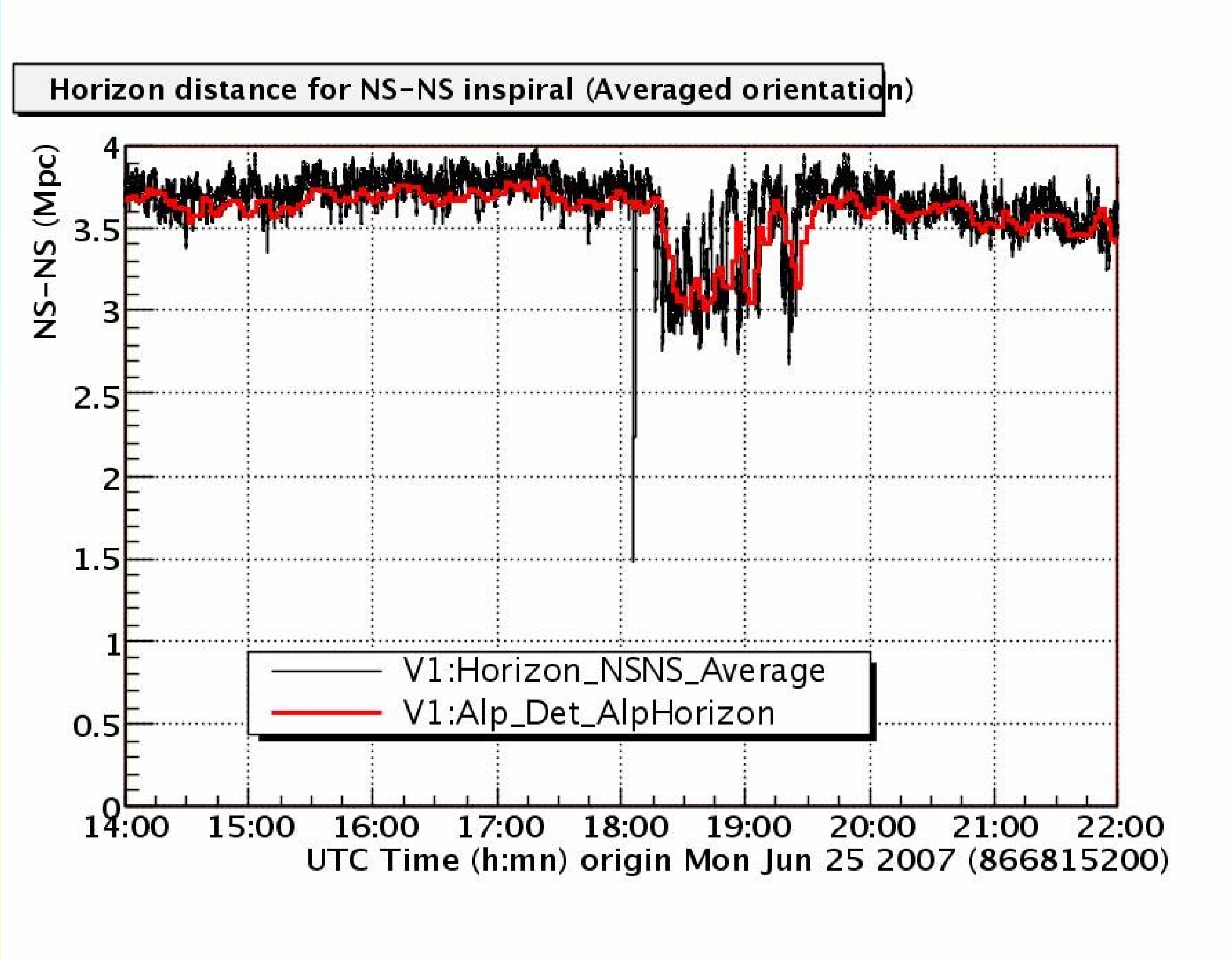


Virgo Science Run 1 (VSR1)

- **Started on May 18—data will be analyzed with LIGO/GEO**
- **First five weeks**

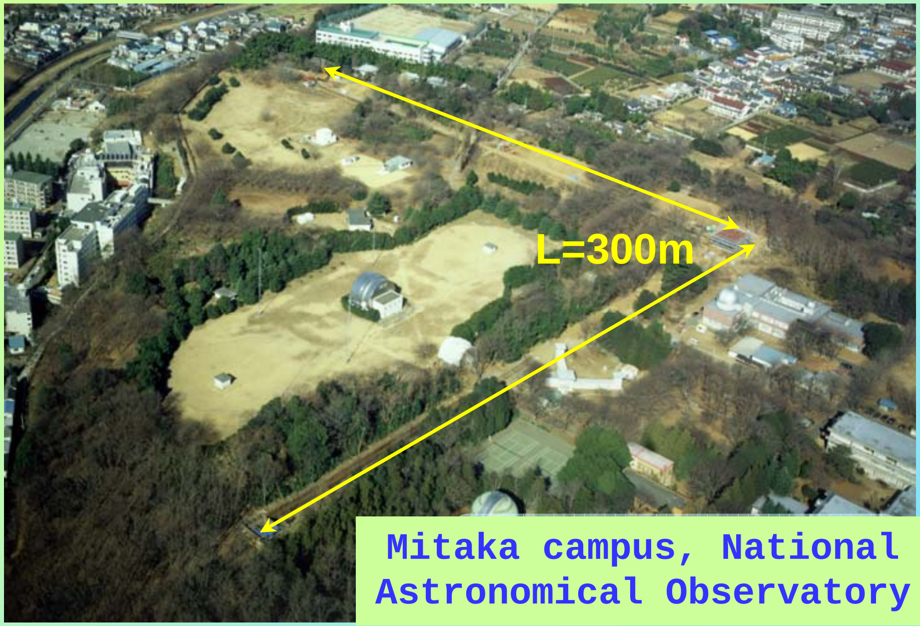


Stability of Sensitivity



TAMA300

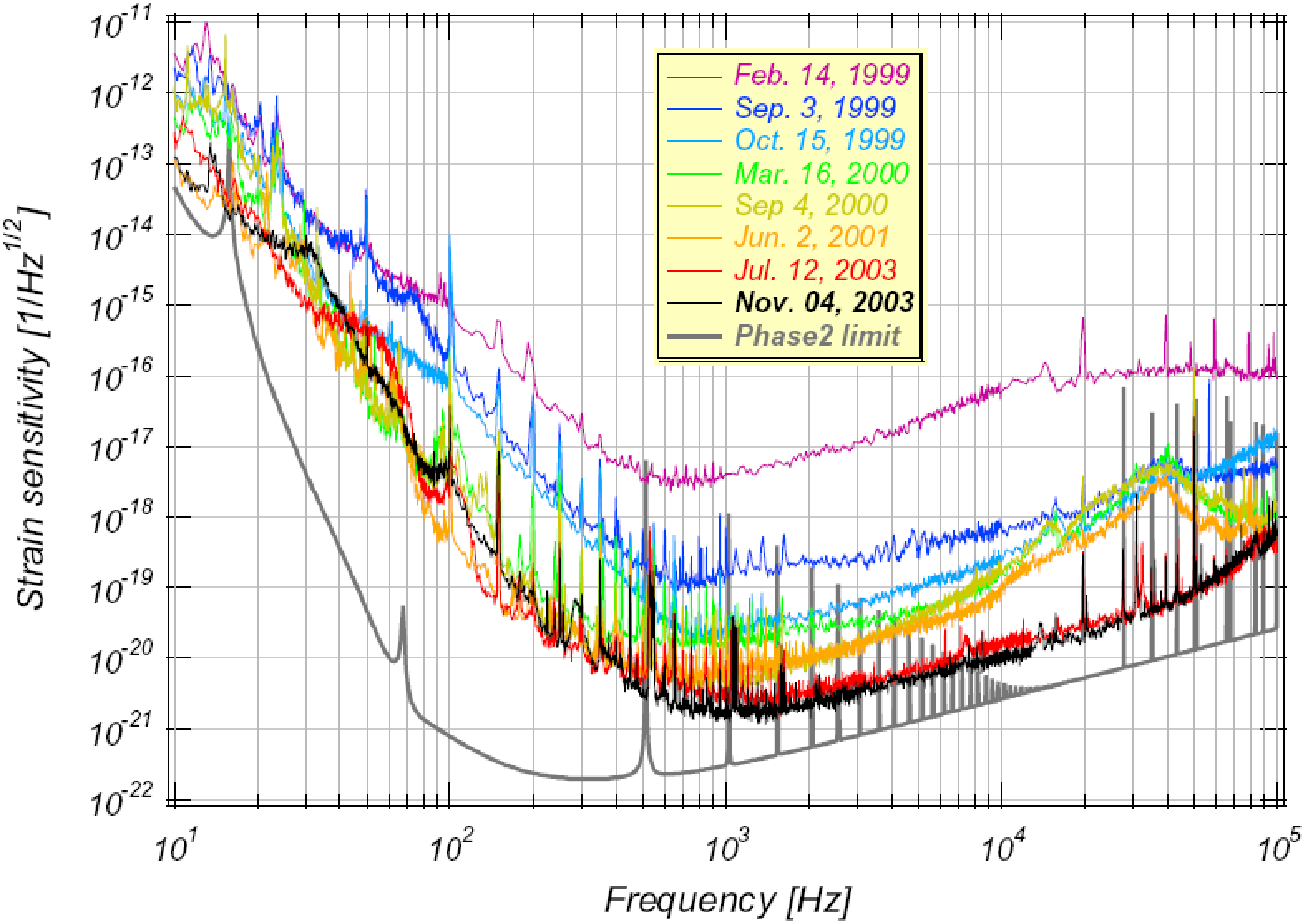
- **300 m interferometer, located at National Astronomical Observatory of Japan (Tokyo)**
- **Project started 1995**
- **First large interferometer to begin observations**
- **Best sensitivity in world 2000-2002**



Mitaka campus, National Astronomical Observatory

Kazuaki Kuroda
for the TAMA/CLIO/LCGT Collaboration

Progress of TAMA300 Sensitivity



Kazuaki Kuroda
for the TAMA/CLIO/LCGT Collaboration

TAMA 300 Observation Summary

TAMA data-taking runs including long-term observations

Run	Term	Year	Live Time (Hour)
DT1	6-Aug → 7-Aug	1999	7
DT2	17-Sept → 20-Sept	1999	31
DT3	20-Apr → 23-Apr	2000	13
DT4	21-Aug → 4-Sept	2000	161
DT5	2-Mar → 8-Mar	2001	111
DT6	15-Aug → 20-Sept	2001	1038
DT7	31-Aug → 2-Sept	2002	25
DT8	14-Feb → 14-Apr	2003	1158
DT9	28-Nov → 10-Jan	2004	558

In 1999, TAMA started to make observations (DT1)

The world best sensitivity (DT4)

Continuous observation more than 1000 hr with the highest sensitivity. (DT6)

Power recycling (DT7)

LIGO S1 (DT8)

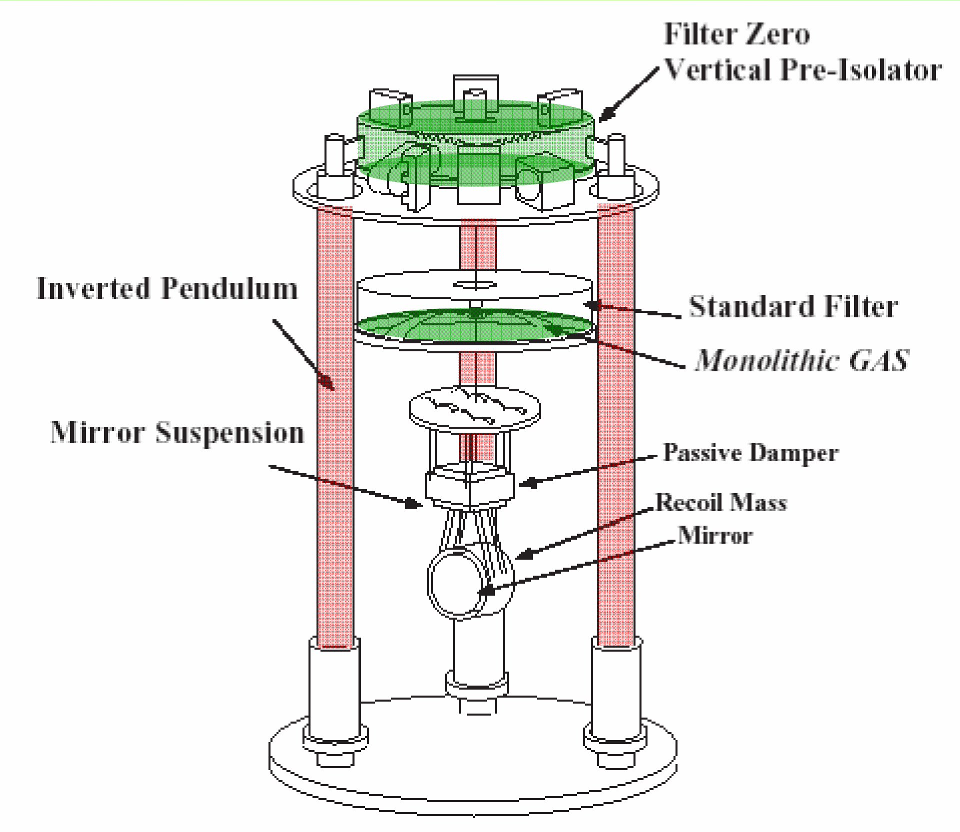
Total 3102 hours data was accumulated

Joint observations with LIGO/GEO during DT7-DT9

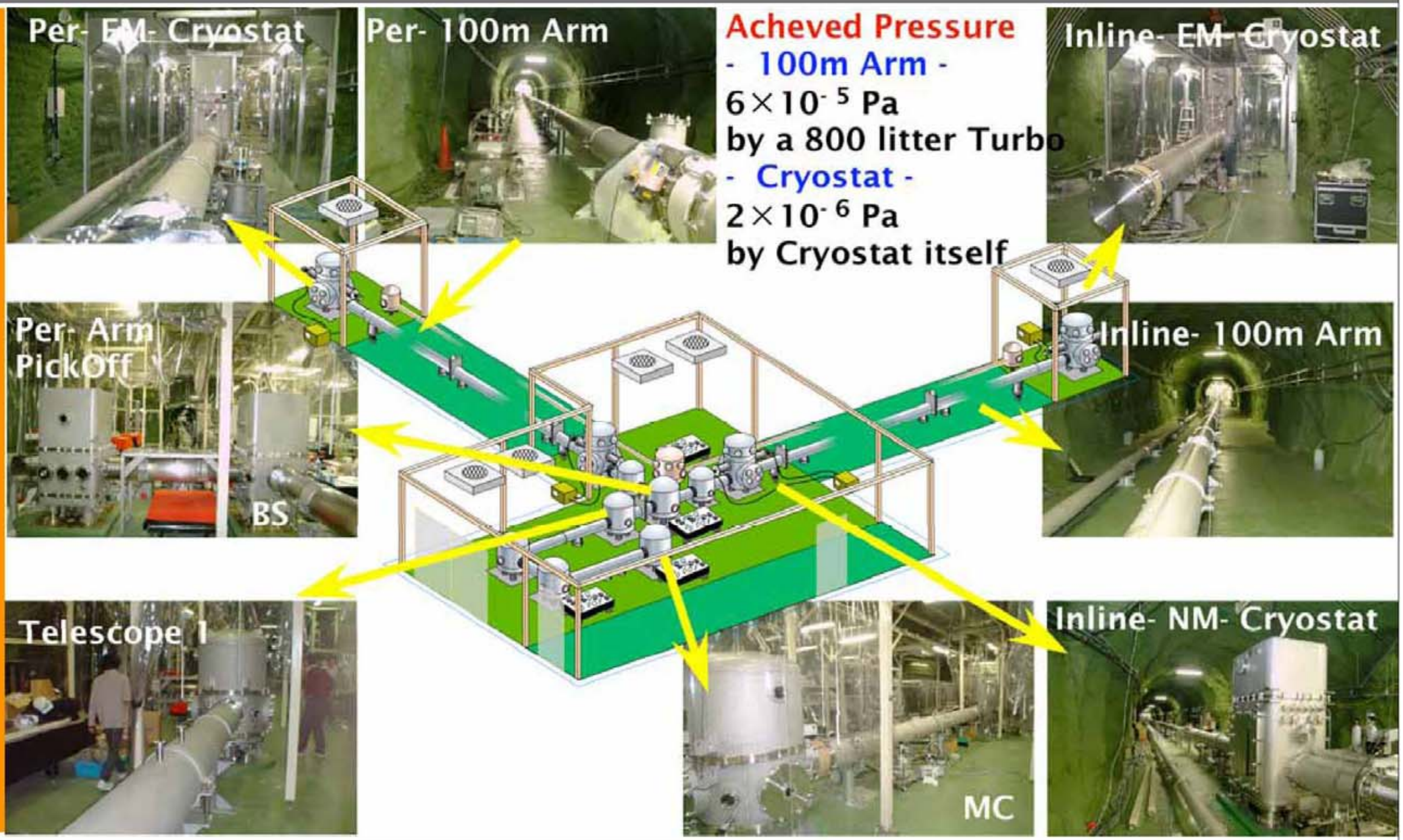
Kazuaki Kuroda
for the TAMA/CLIO/LCGT Collaboration

New Seismic Attenuation System for TAMA300

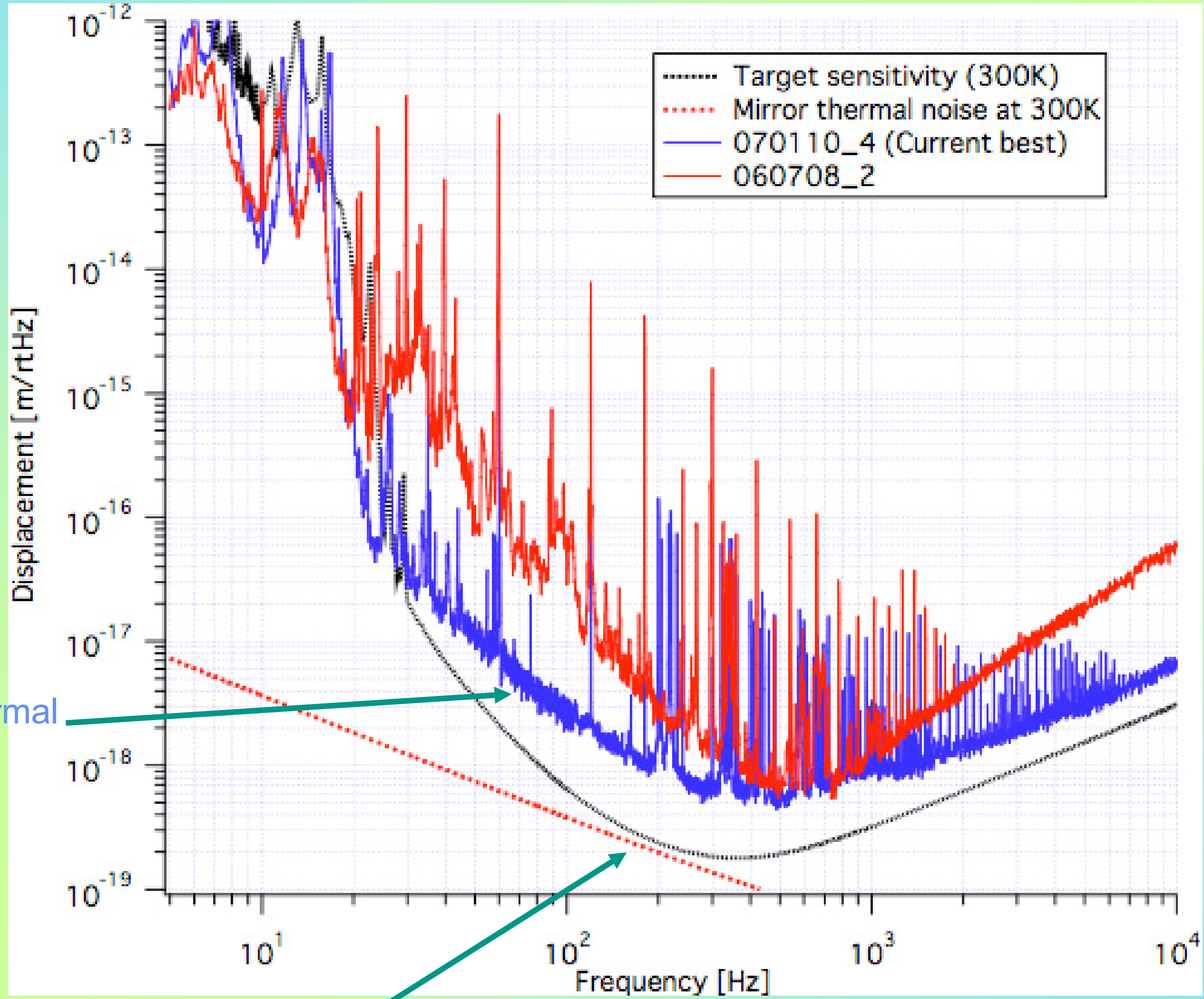
- Recognized need for better seismic isolation
- Joint development with LIGO, based on earlier Virgo concept
- Now being installed



Construction of CLIO



Current sensitivity of CLIO



After reaching thermal limit, start cooling

Mirror thermal noise(300K)

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.

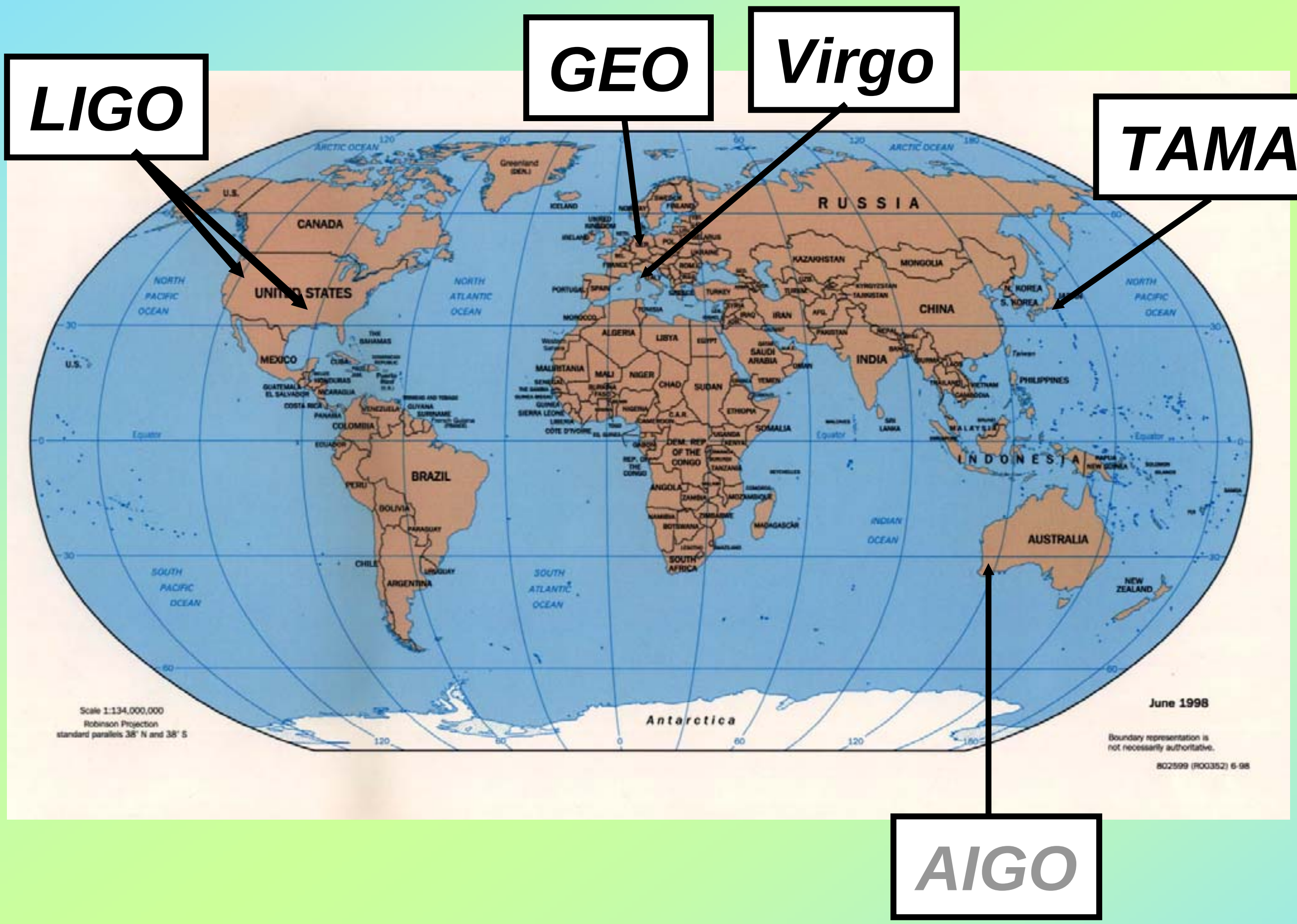
David Coward
for ACIGA
Rencontres de Moriond
Gravitational Waves and Experimental Gravity
March 11-18, 2007
La Thuile, Val d'Aosta, Italy

AIGO Site

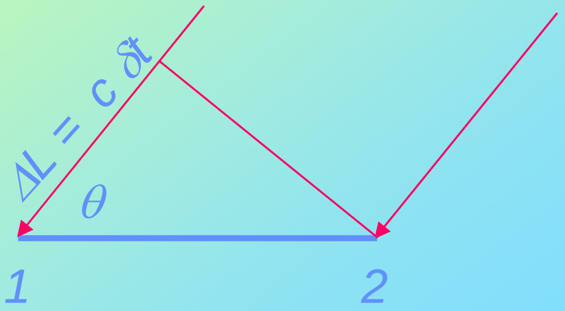
- Substantial AIGO facility now in place.
- Education and astronomy centre opened 2003.
- Roads, clean room laboratories, workshops, visitor accommodation completed.
- Facility designed for extension to long baseline Advanced LIGO type detector.

David Coward
Rencontres de Moriond

A Global Network of Gravitational Wave Interferometers



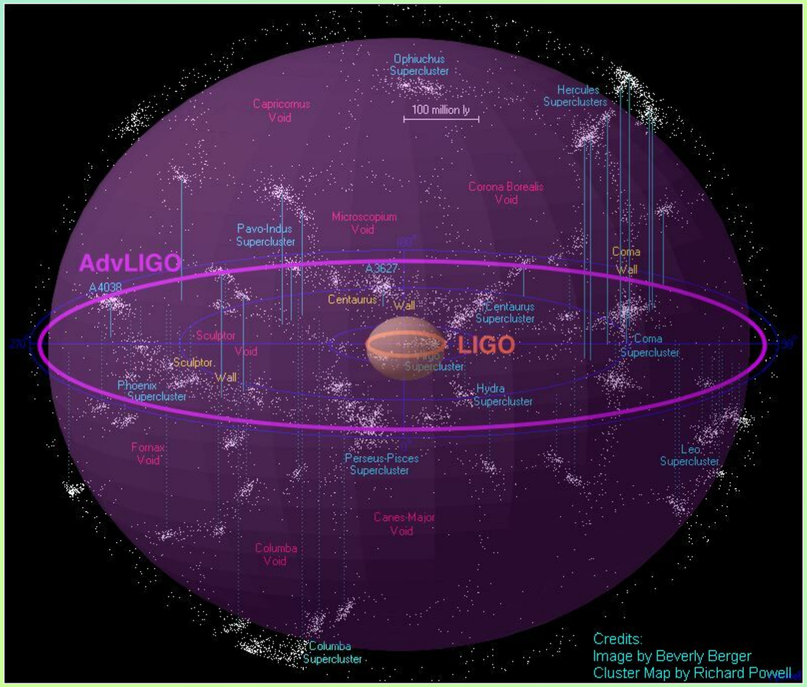
- Detection confidence
- Locate sources
- Decompose the polarization of gravitational waves



Looking to the Future

Advanced LIGO!

- **Take advantage of new technologies and on-going R&D**
  - » **Active anti-seismic system operating to lower frequencies**
  - » **Lower thermal noise suspensions and optics**
  - » **Higher laser power**
  - » **More sensitive and more flexible optical configuration**



x10 better amplitude sensitivity

⇒ x1000 rate=(reach)^3

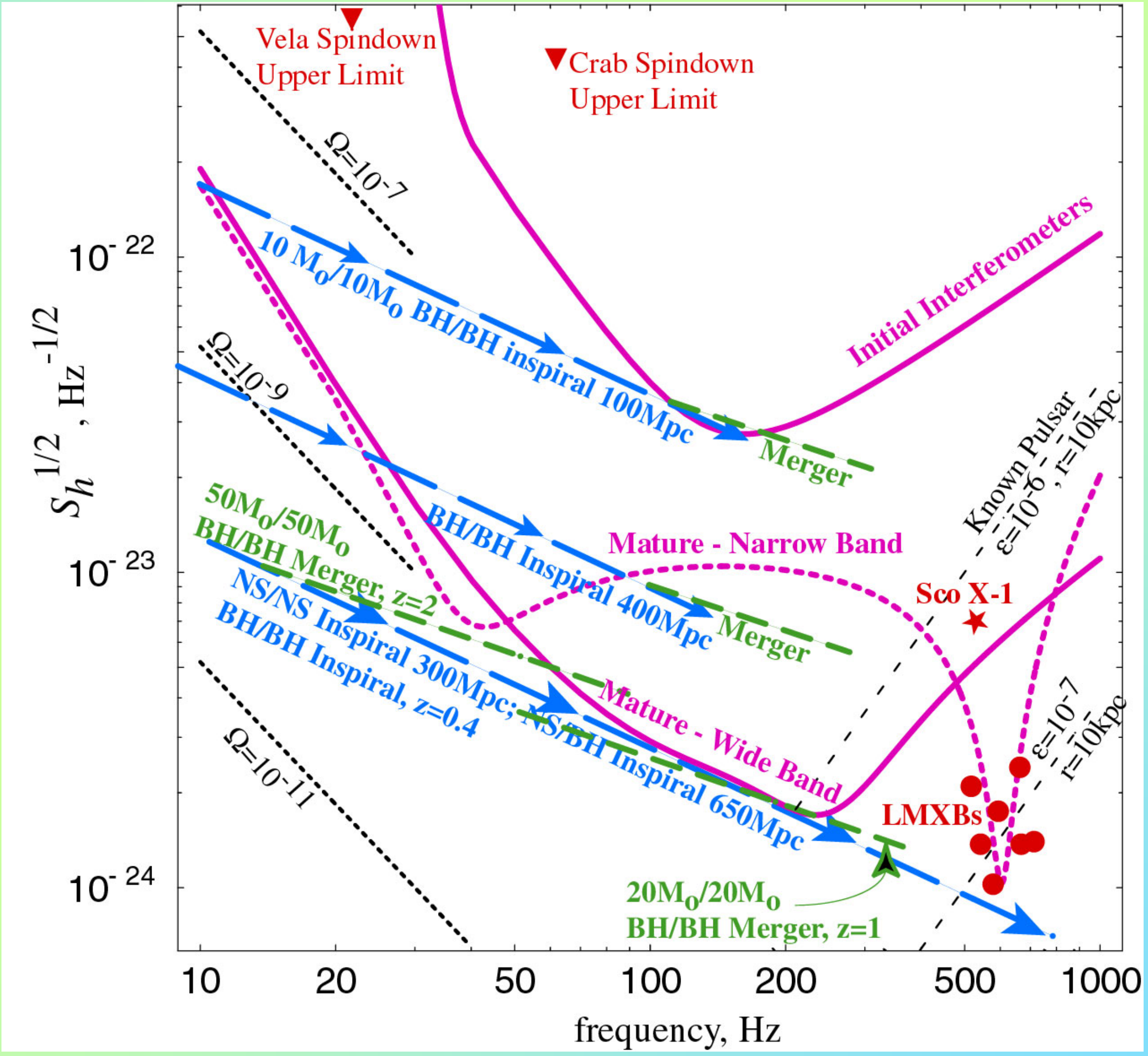
⇒ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

Planned for FY2008 start, installation beginning 2011

Astrophysical Targets for Advanced LIGO

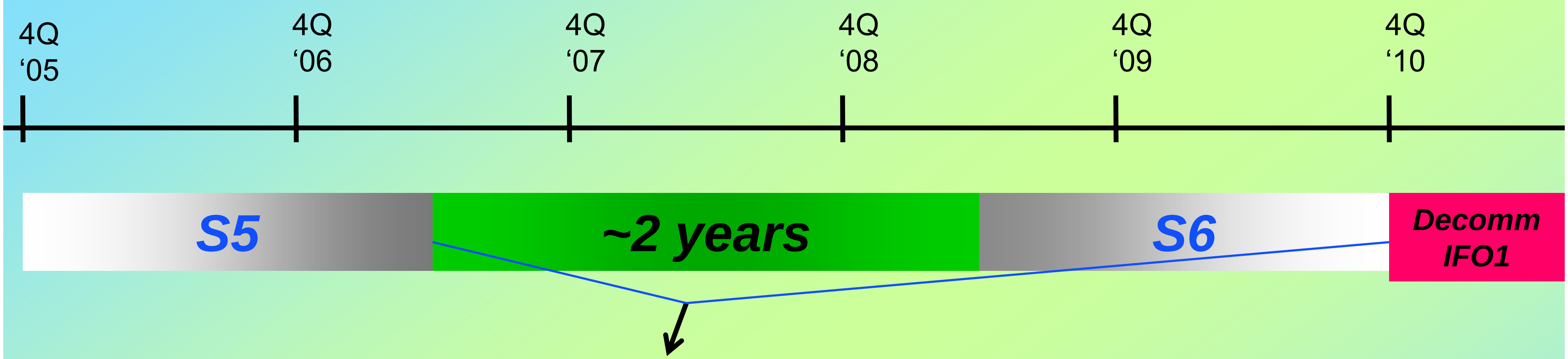
- Neutron star & black hole binaries
  - » inspiral
  - » merger
- Spinning neutron stars
  - » LMXBs
  - » known pulsars
  - » previously unknown
- Supernovae
- Stochastic background
  - » Cosmological
  - » Early universe



What is so Advanced about Advanced LIGO?

Parameter	*LIGO*	*Advanced LIGO*
Input Laser Power	**10 W**	**180 W**
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**

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**

Virgo Plans for Future Upgrades

- **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**

Julien Marque
for the Virgo Collaboration
Rencontres de Moriond
Gravitational Waves and Experimental Gravity
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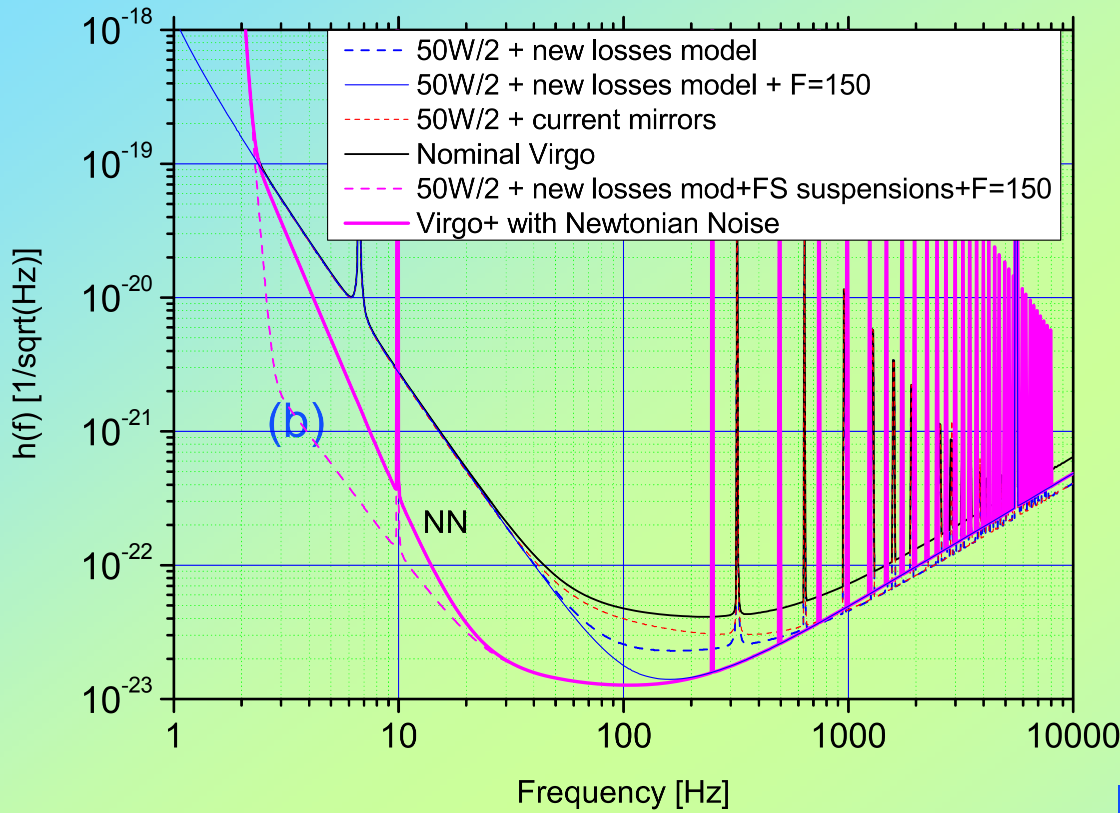
La Thuile, Val d'Aosta, Italy

Expected sensitivity of Virgo+

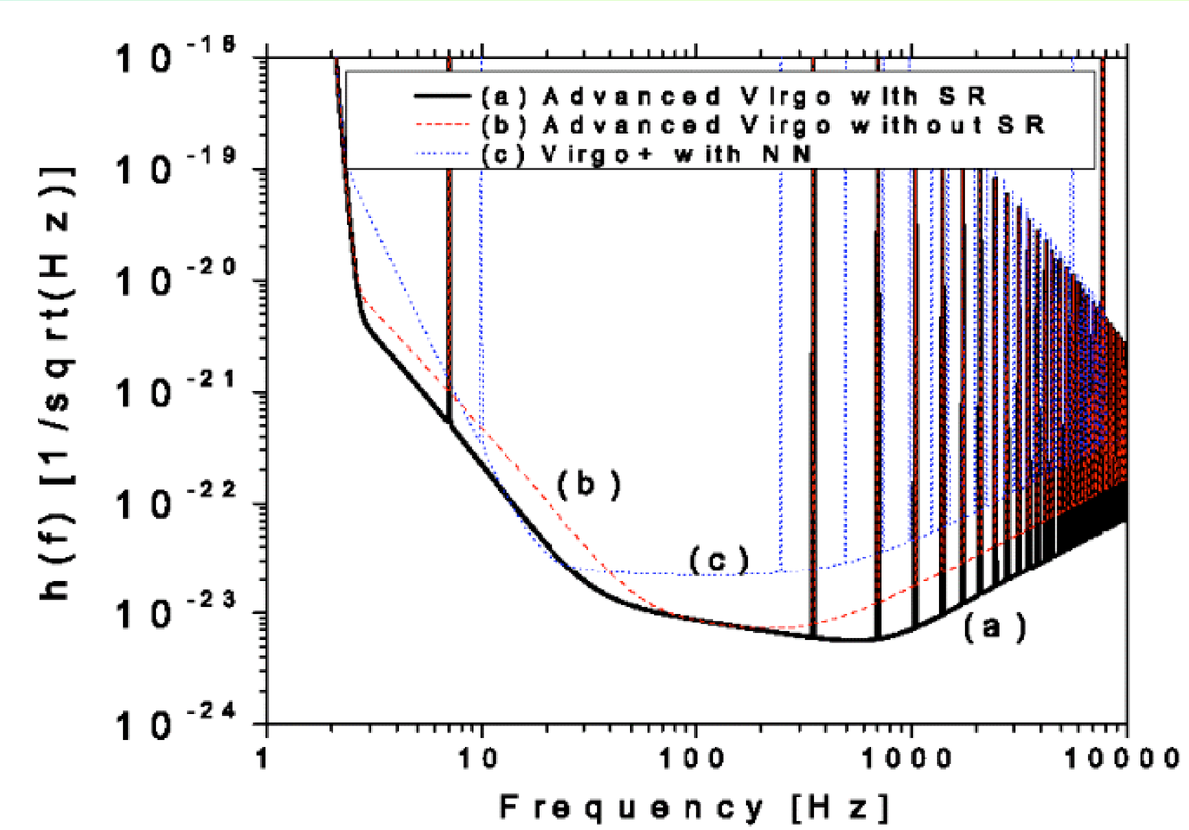


- **Virgo+ configuration not yet set**
  - » **Higher power laser**
  - » **Fused silica suspensions**
  - » **Increase arm finesse**
- **Final Decision to be made late 2007**

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

Advanced Virgo

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

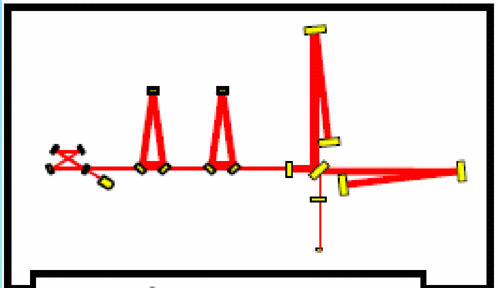


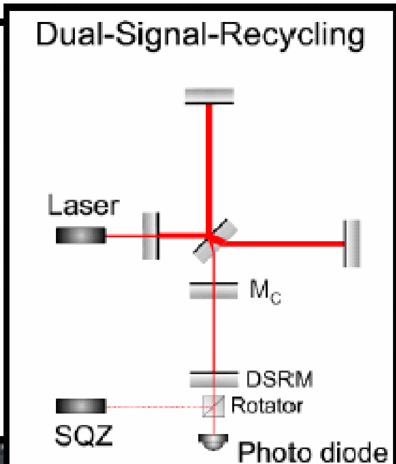
- R&D underway
- Design decisions late in 2007

Julien Marque
Rencontres de Moriond

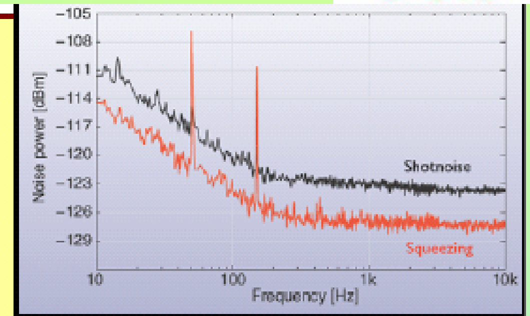
Plans of the GEO collaboration

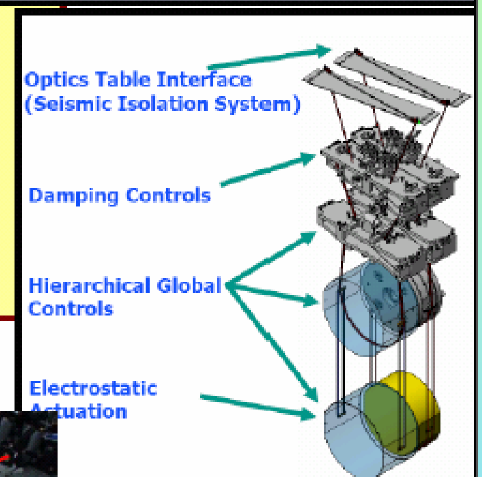
Stefan Hild

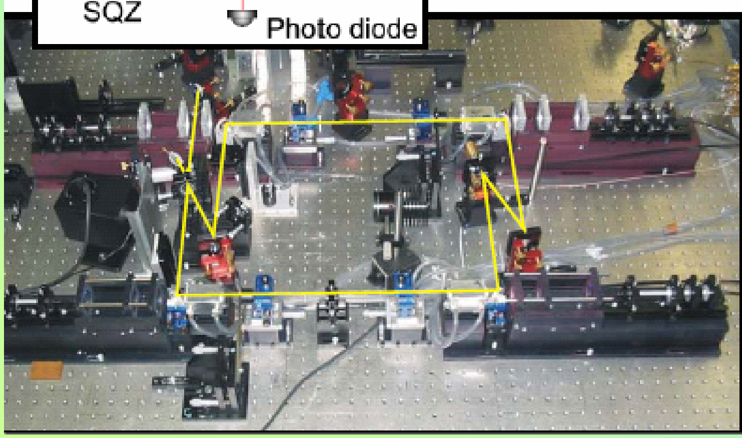


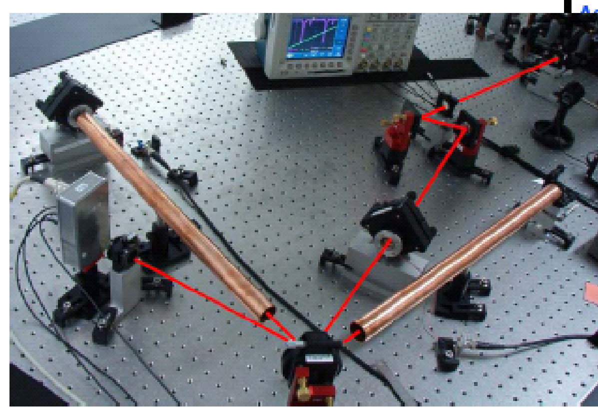


- operate GEO600 / GEO-HF as LSC detector
- LSC data analysis
- laser and suspensions for AdvLIGO (laser for Enh. LIGO)
- contribute to AdvVIRGO design
- R&D and design towards third generation detectors





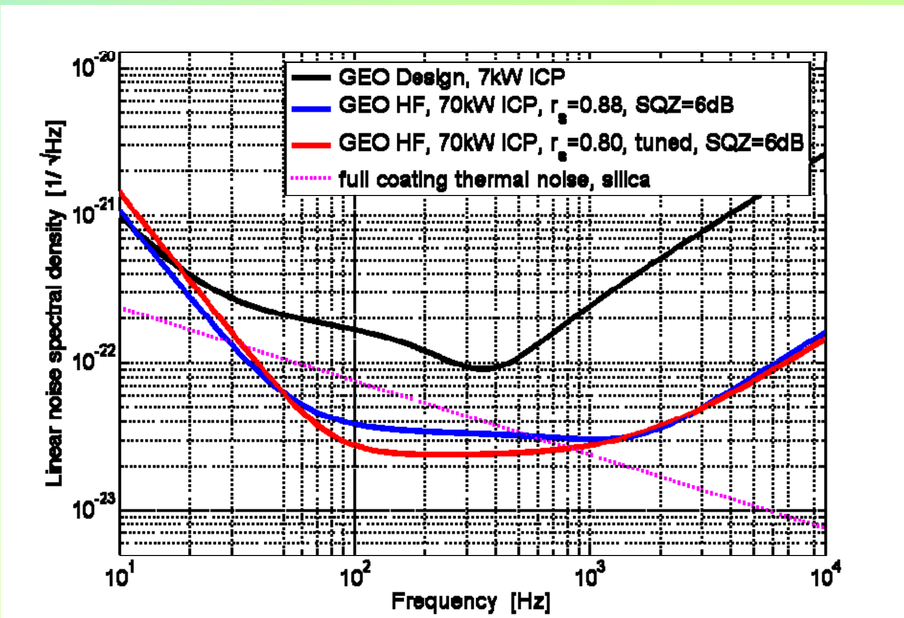


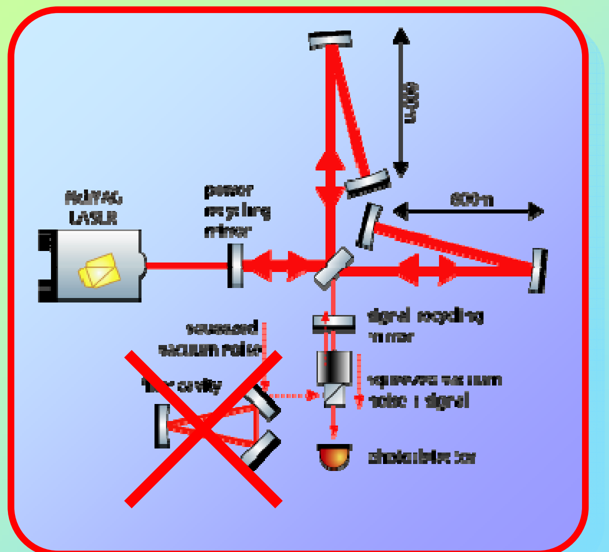


GEO HF

Stefan Hild

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

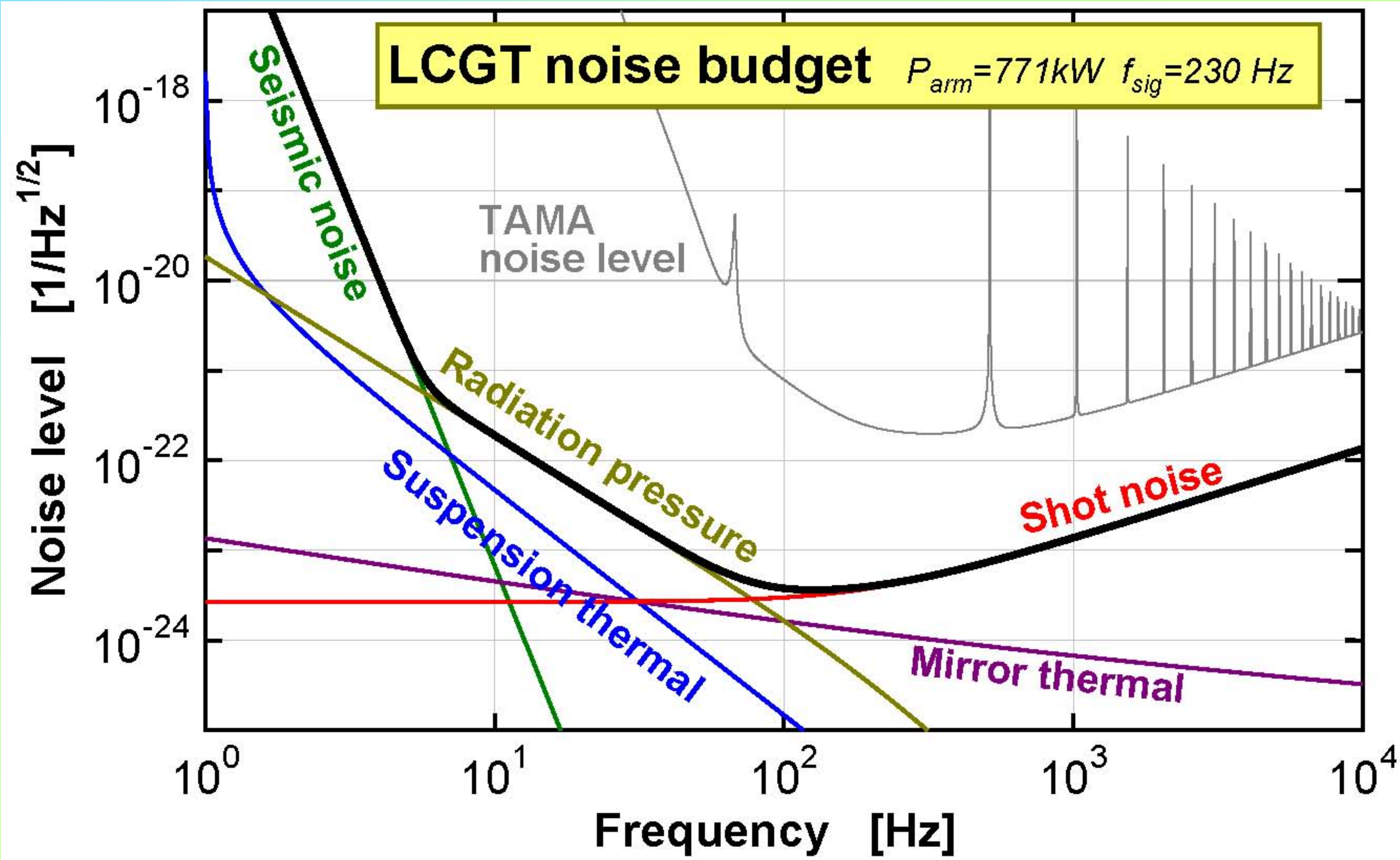




Large-scale Cryogenic Gravitational wave Telescope (LCGT)

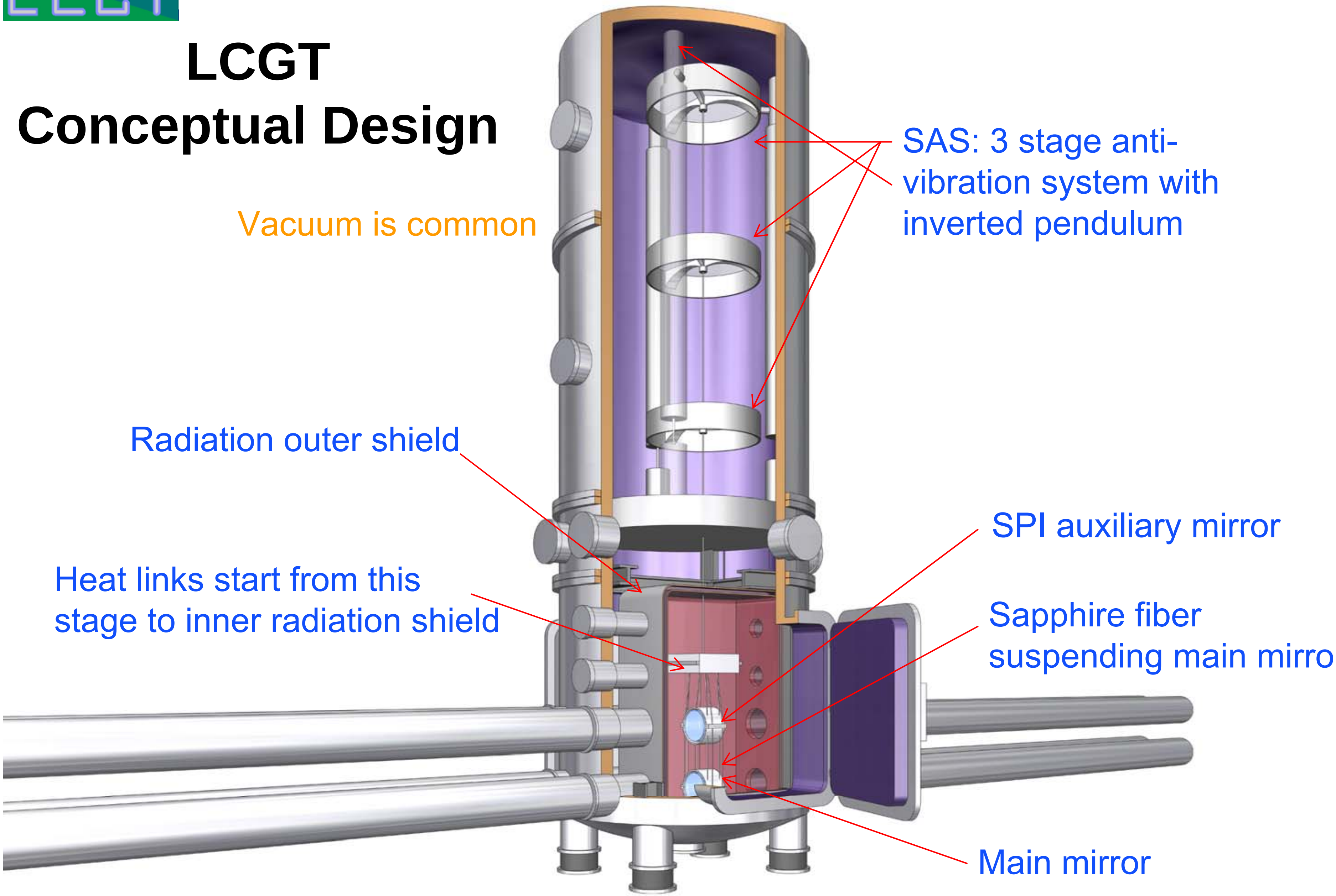
- **3 km baseline**
- **Utilizes cryogenic mirrors (sapphire)**
- **Construction at an underground site (Kamioka mine)**
- **Two parallel interferometers installed in a common vacuum envelope**
- **Suspension point interferometer**
- **Proposal currently under consideration for 2008 funding**

LCGT Design Sensitivity



Kazuaki Kuroda
for the TAMA/CLIO/LCGT Collaboration

LCGT
Conceptual Design

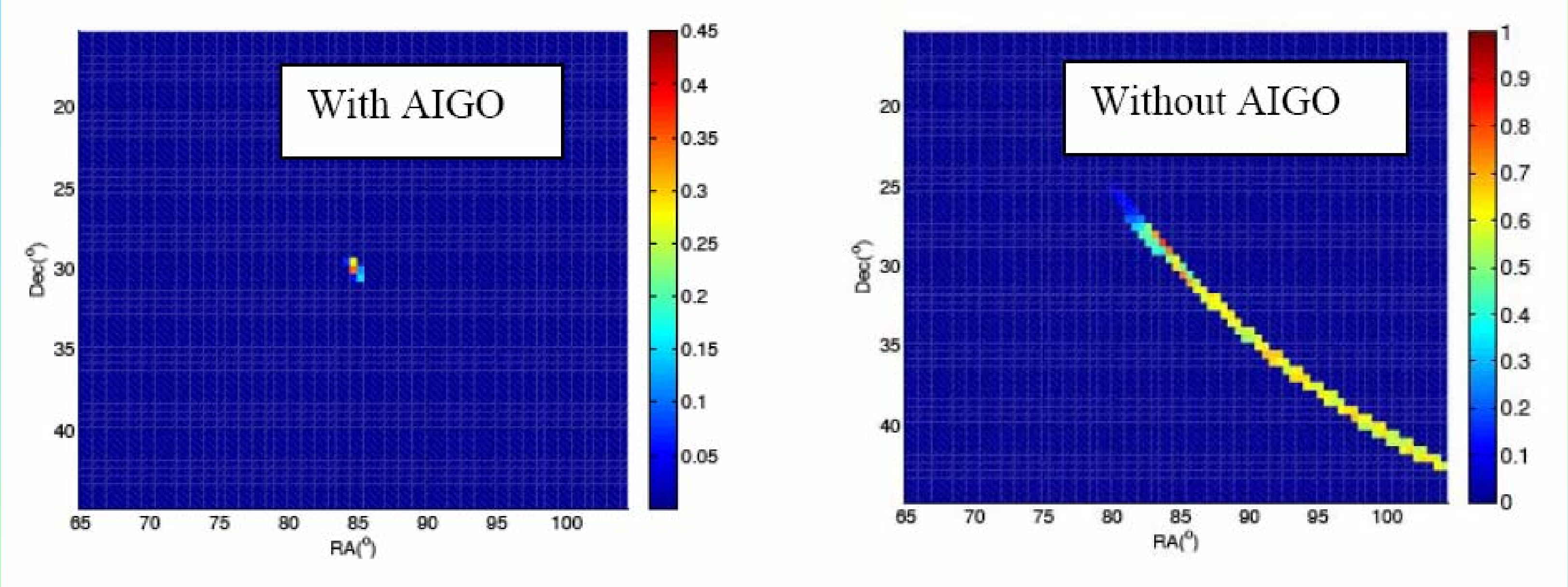


AIGO Planning

- 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

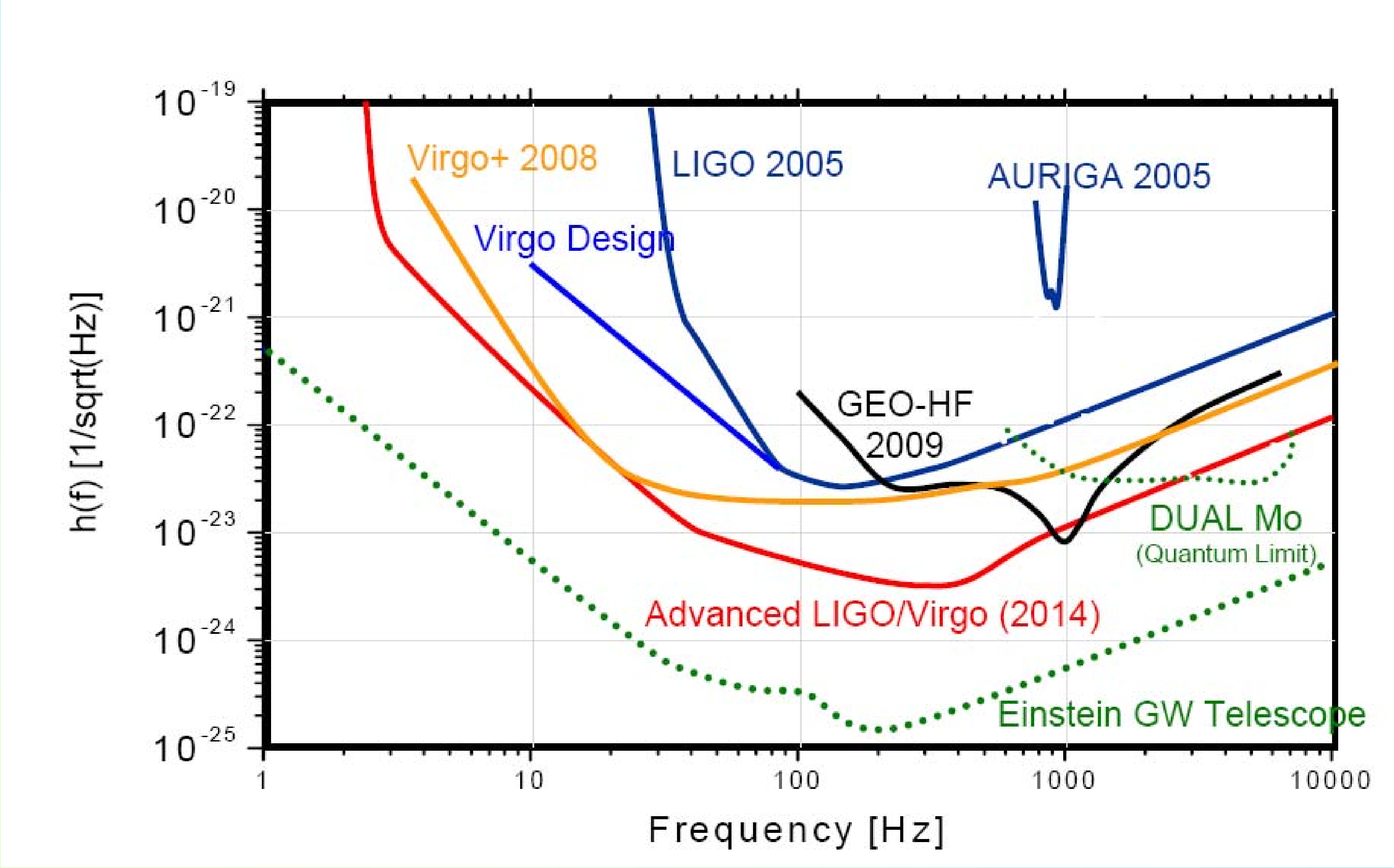
Importance of AIGO



- 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

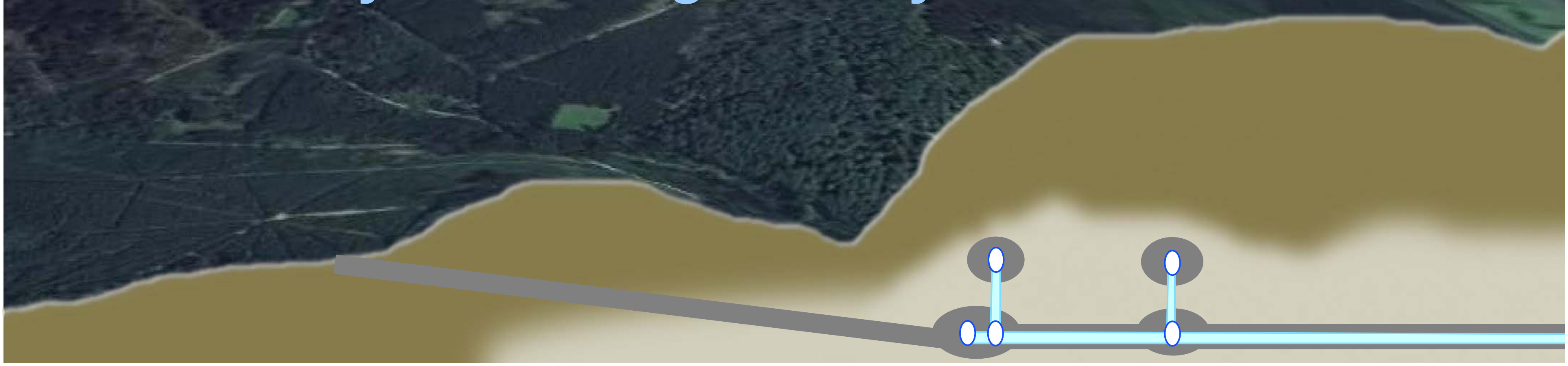
Einstein Gravitational-Wave Telescope (ET)



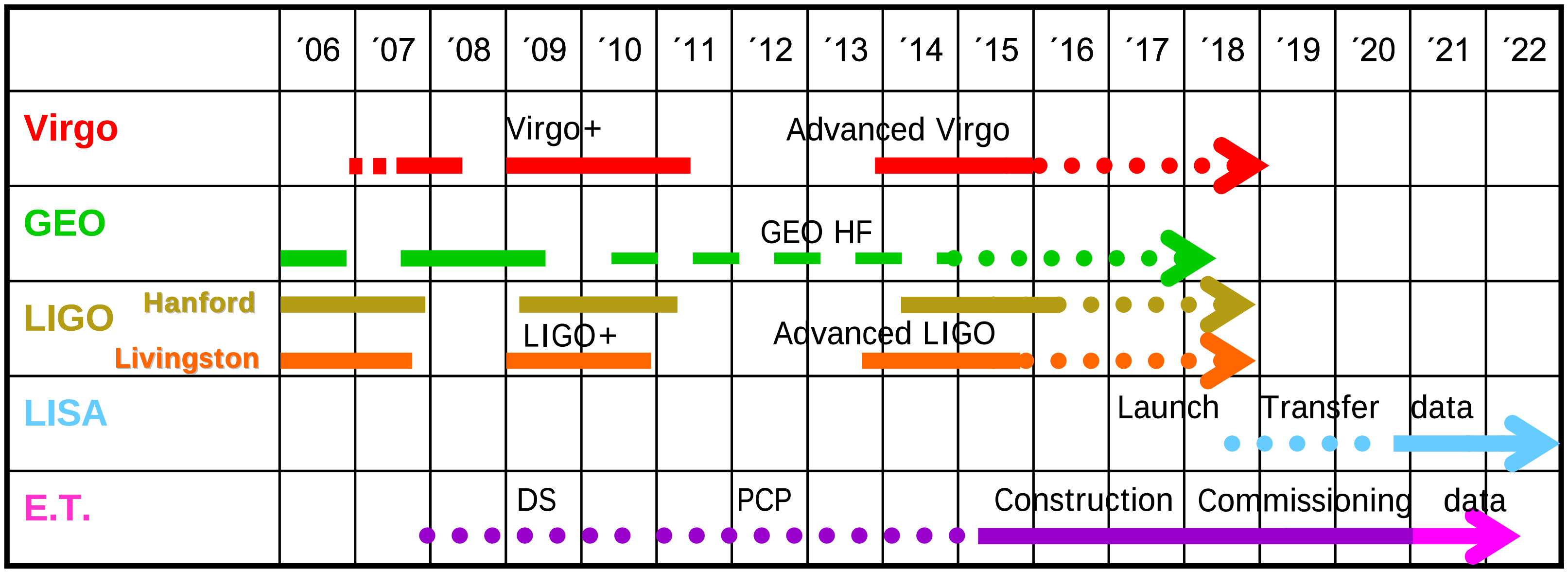
Harald Lück
for the European Gravitational-Wave Community

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



- **Timelines subject to R&D progress, funding, …**

Harald Lück
for the European Gravitational-Wave Community

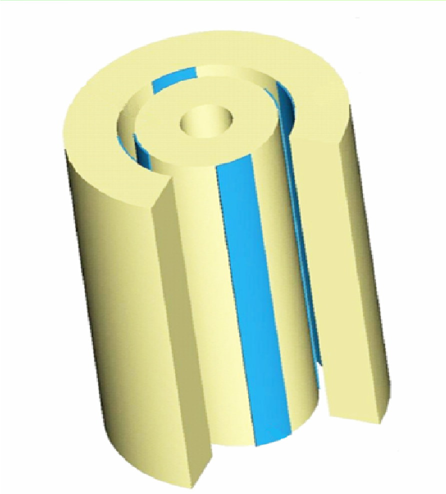
DUAL: R&D for a New Concept of Acoustic Gravitational Wave Detector

1 –the "dual" concept : read displacement between two massive resonators with a non-resonant read-out
M. Cerdonio et al. Phys. Rev. Lett. 87 031101 (2001)

avoid resonant bandwidh limit and thermal noise contribution by the resonant transducer

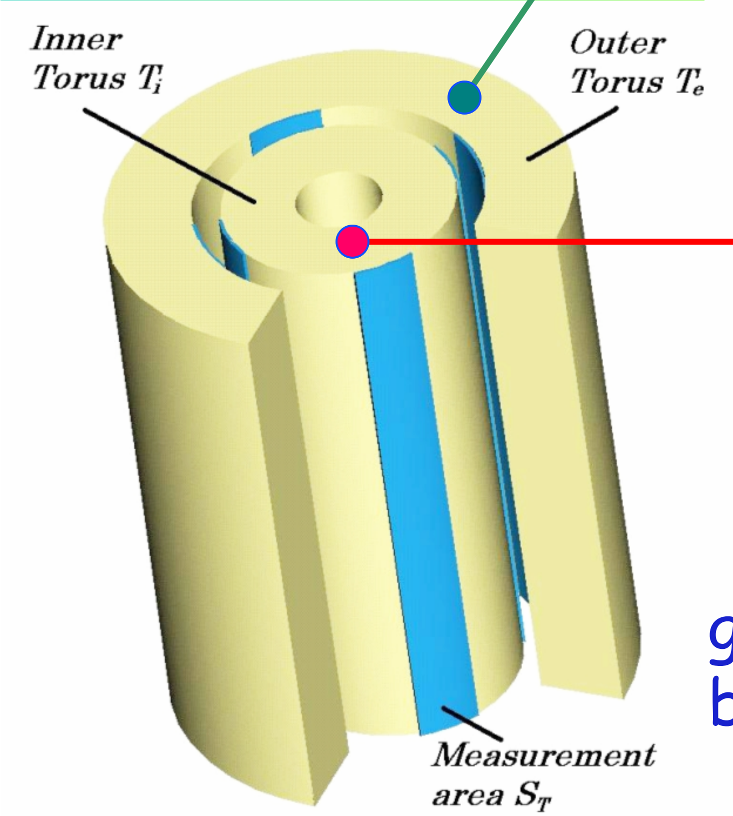
2 - selective readout: only the motion corresponding to GW sensitive normal modes is sensed
M. Bonaldi et al. Phys. Rev. D 68 102004 (2003)

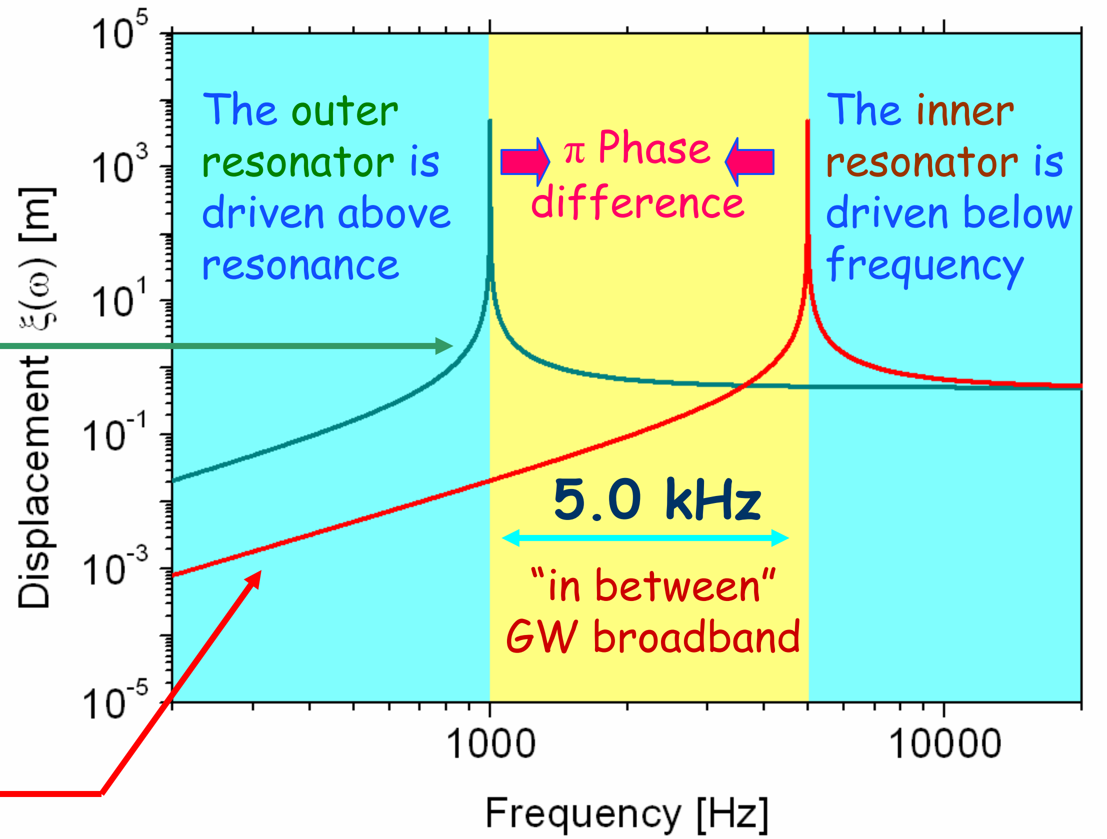
reduce overall thermal noise by rejecting the contribution of non-gw sensitive modes

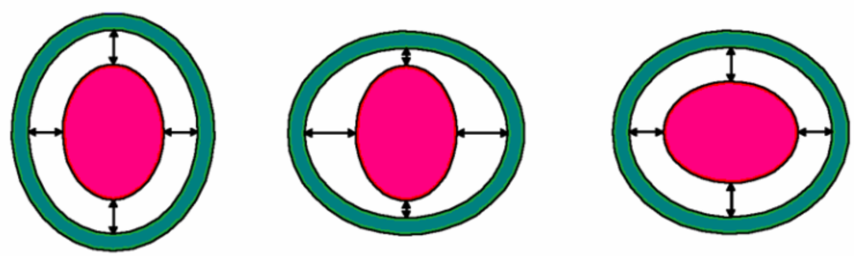


DUAL
the concept

read the differential deformations of two nested resonators

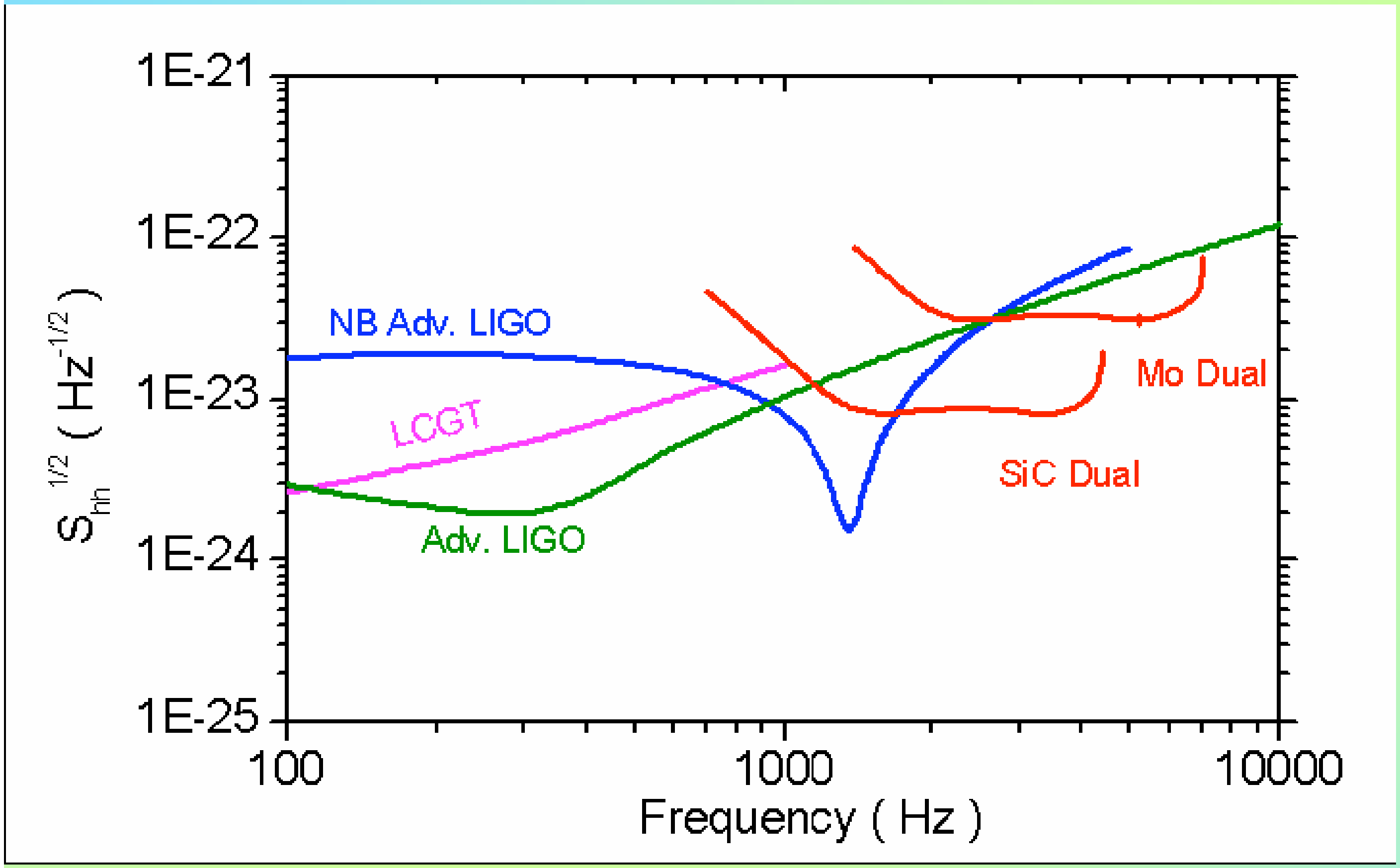


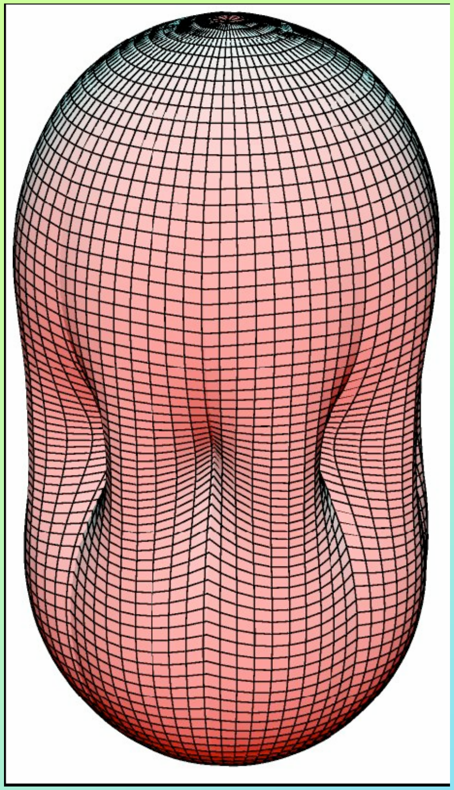




gw signal adds up
back-action subtracts out

Projected Sensitivities (Dual & Advanced ifos)





Mo Dual 16.4 ton height 3.0m Ø 0.94m

SiC Dual 62.2 ton height 3.0m Ø 2.9m

Antenna pattern

R&D in Progress to Define Achievable Sensitivity

- Configurations
- Materials
- Suspensions
- Readout:
  - » Optical
  - » Capacitive + SQUID
- Cosmic rays effect (→ underground?)
- Demonstrator of
  - » Large area readout
  - » Back-action reduction
  - » Mode selectivity

Final Thoughts

- In the past few years we have seen the individual bar detectors around the world mature into a coherent network, but we have also seen them passed in sensitivity by interferometers
- Interferometers are now showing the sensitivities and bandwidths that they promised and we are beginning to see the interferometer projects begin to organize themselves into similar networks
- Next generation detectors will soon be under construction giving up to a factor of 1000 more ‘science‘