Gravitational wave detectors
- broadening their horizon -

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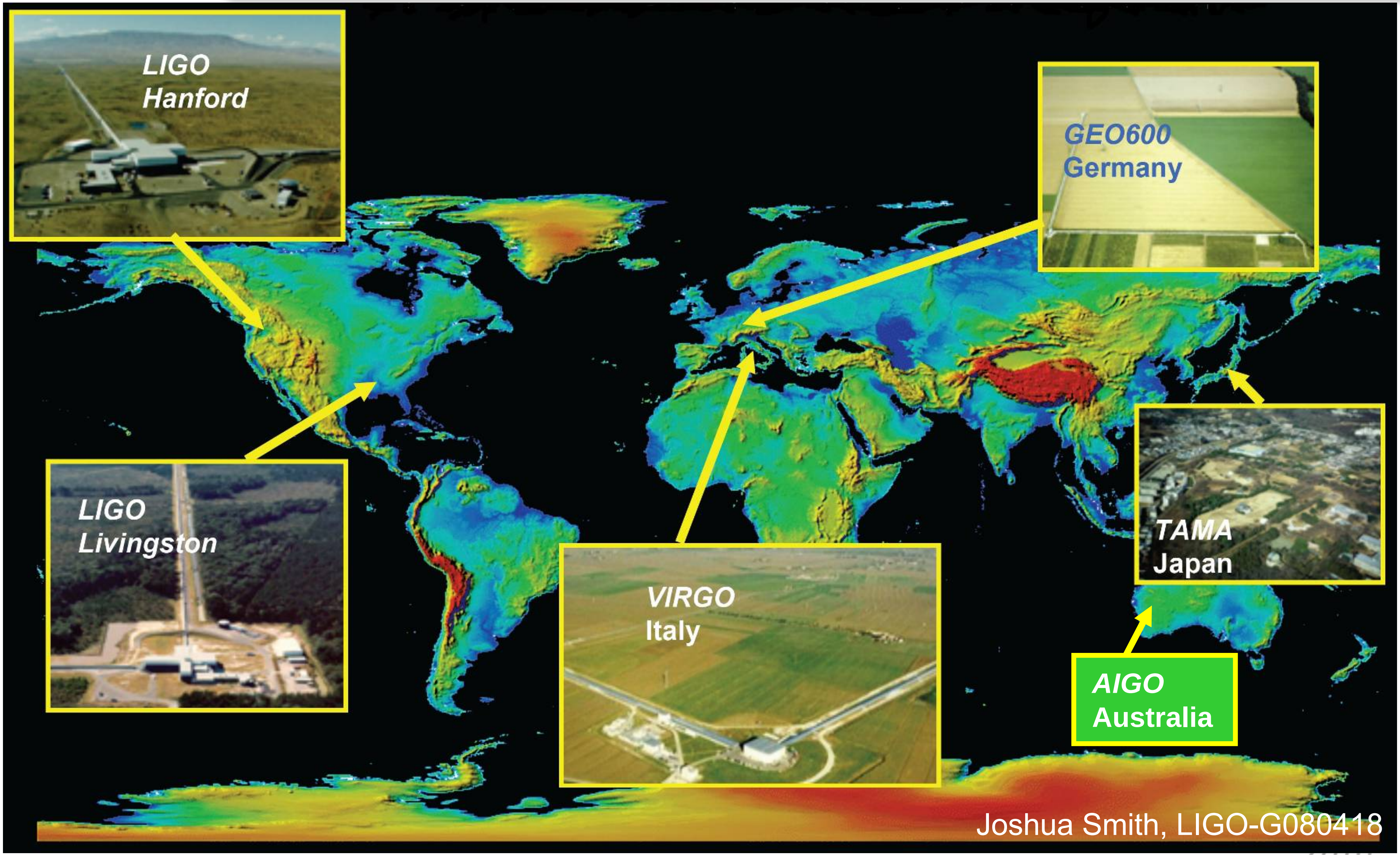
on behalf of the LIGO Scientific Collaboration

NRDA 2009, AEI, Golm, 6th – 9th July 2009
LIGO-G0900652-v2

Real progress in recent years

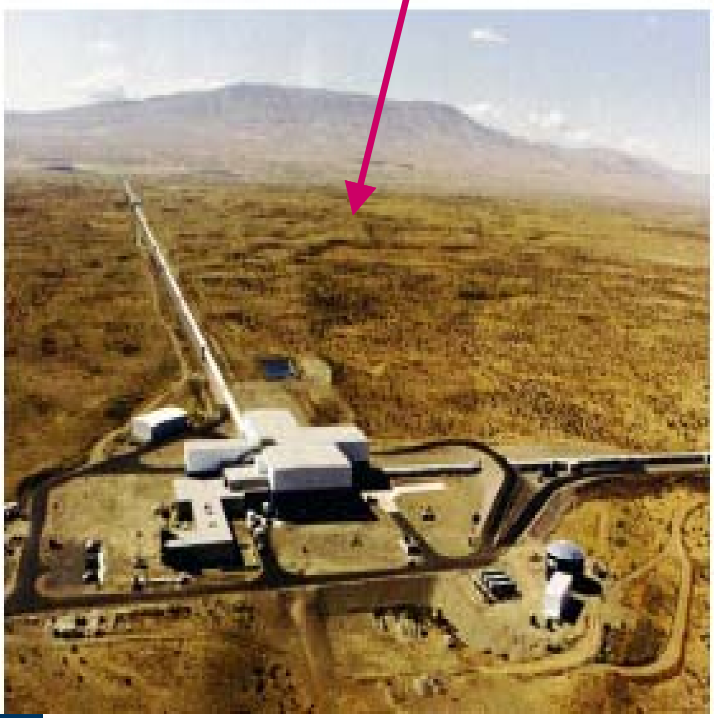
- Ground based detectors (this talk)
- Waveform Predictions from Numerical Relativity (this meeting)
- Space Borne Detectors – LISA and DECIGO
- Pulsar Timing
- Multi-messenger Astronomy

World wide network of interferometric ground-based detectors

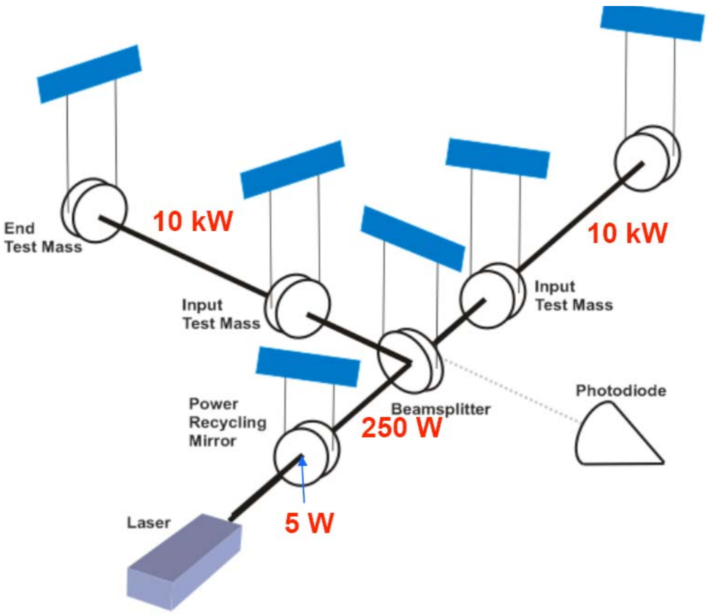


LIGO detectors

- 2 detectors of 4 km arm length + 1 detector of 2 km arm length Washington State and Louisiana

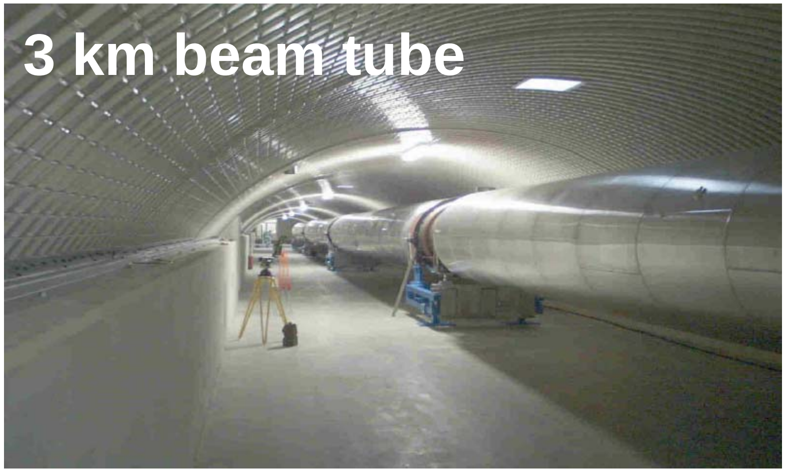


- Fabry-Perot Michelson configuration
- Laser power: 10 W Nd:YAG laser @ 1064 nm

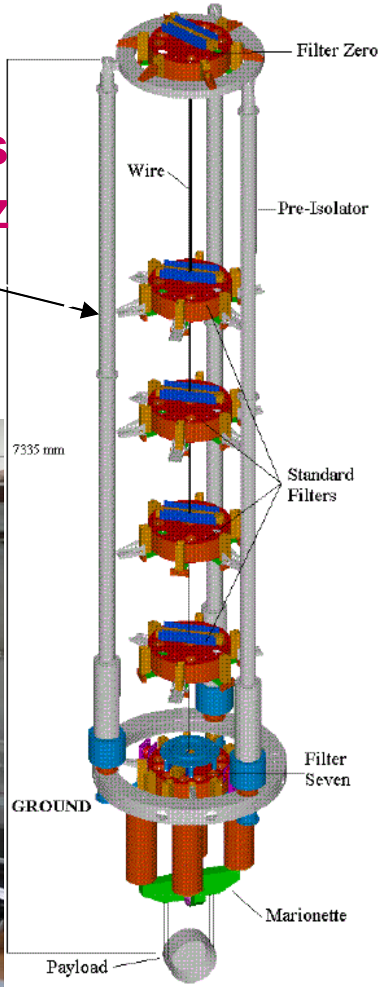


VIRGO: The French-Italian Project

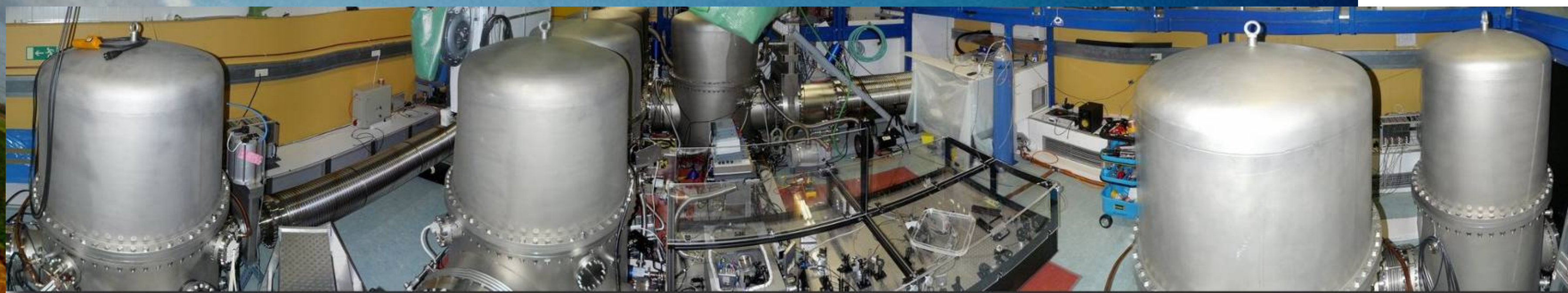
3 km armlength at Cascina near Pisa



The 'Super Attenuator' filters the seismic noise above 4 Hz



GEO600



Arm length is 600 m

Novel technologies make GEO unique and allow it to run in coincidence with the larger LIGO (and Virgo) instruments

Novel technologies are e.g.

- Signal recycling
- Monolithic suspensions

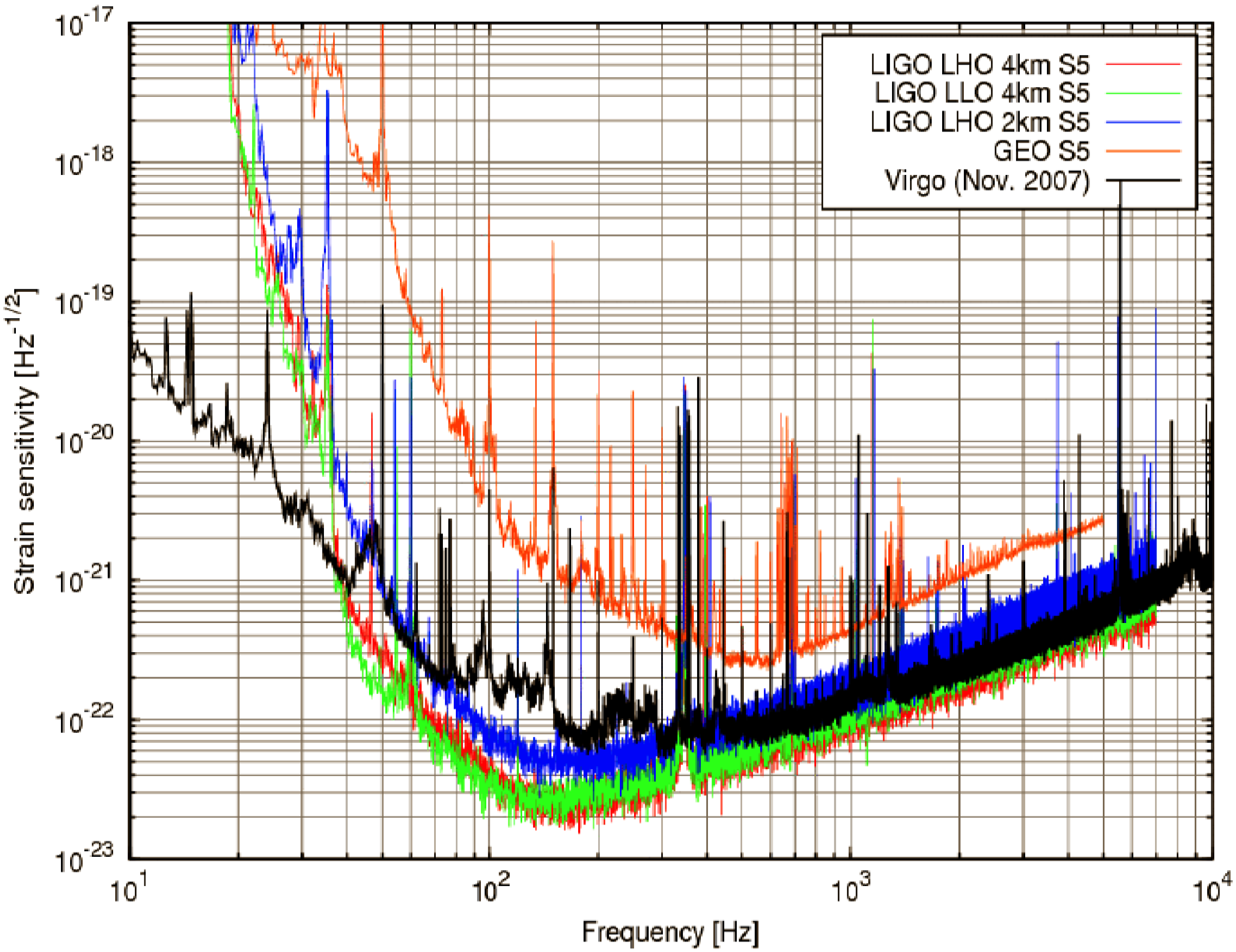
Other Detectors and Developments

300 and AIGO

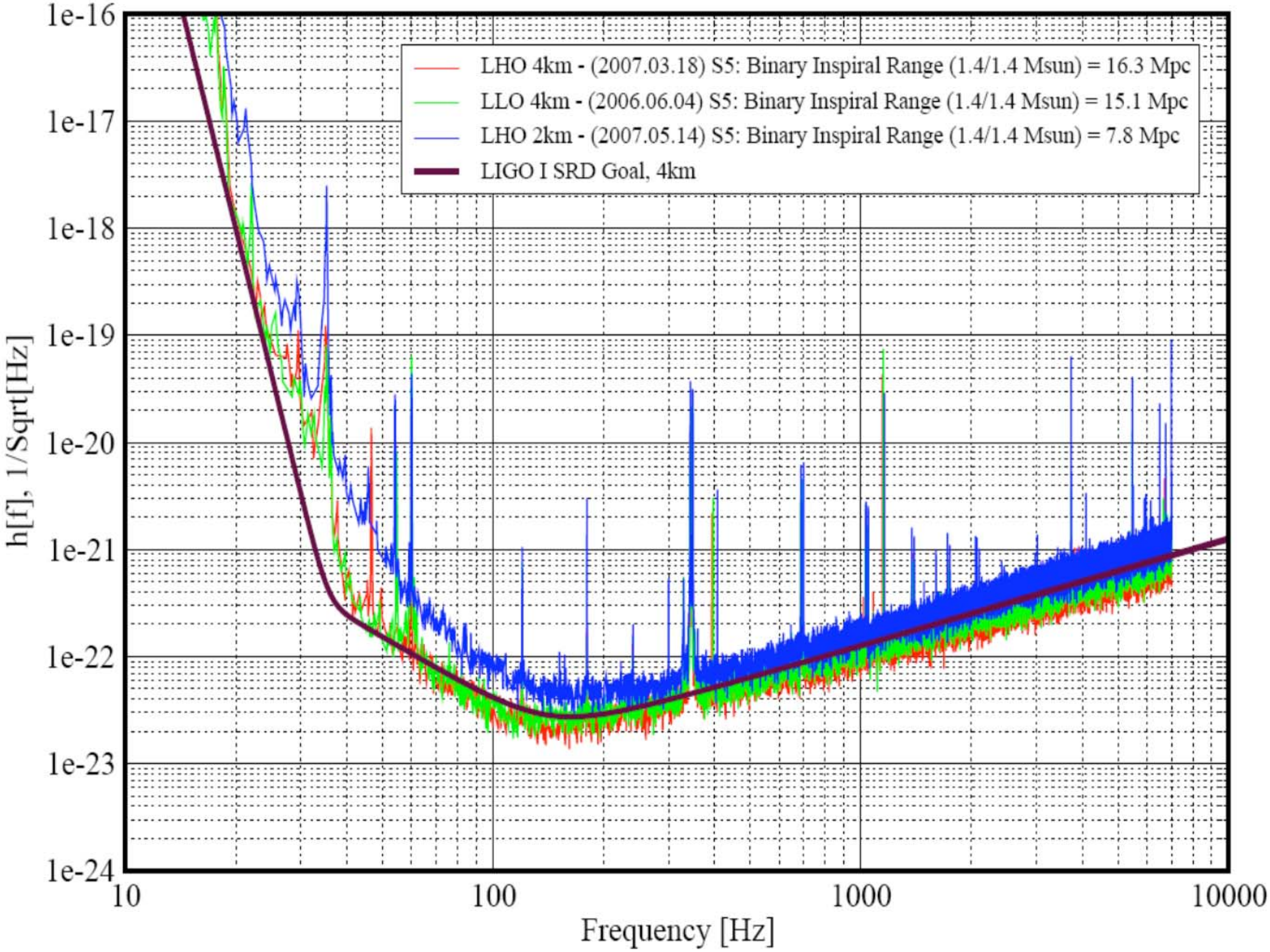
TAMA 300
Tokyo
300 m arms

AIGO
Gingin, West Australia
80 m arm test facility

Gravitational wave network sensitivity



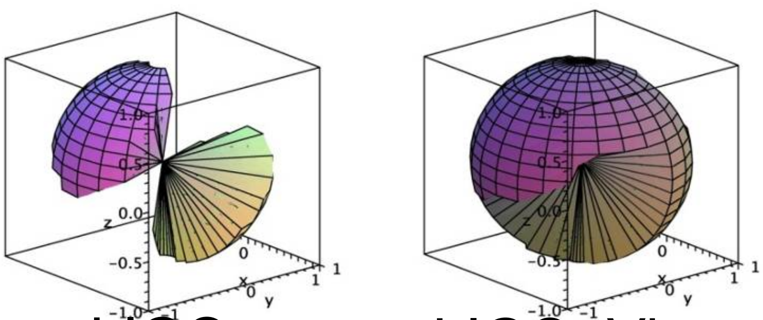
LIGO reached design sensitivity during S5



The LIGO Scientific Collaboration (LSC)

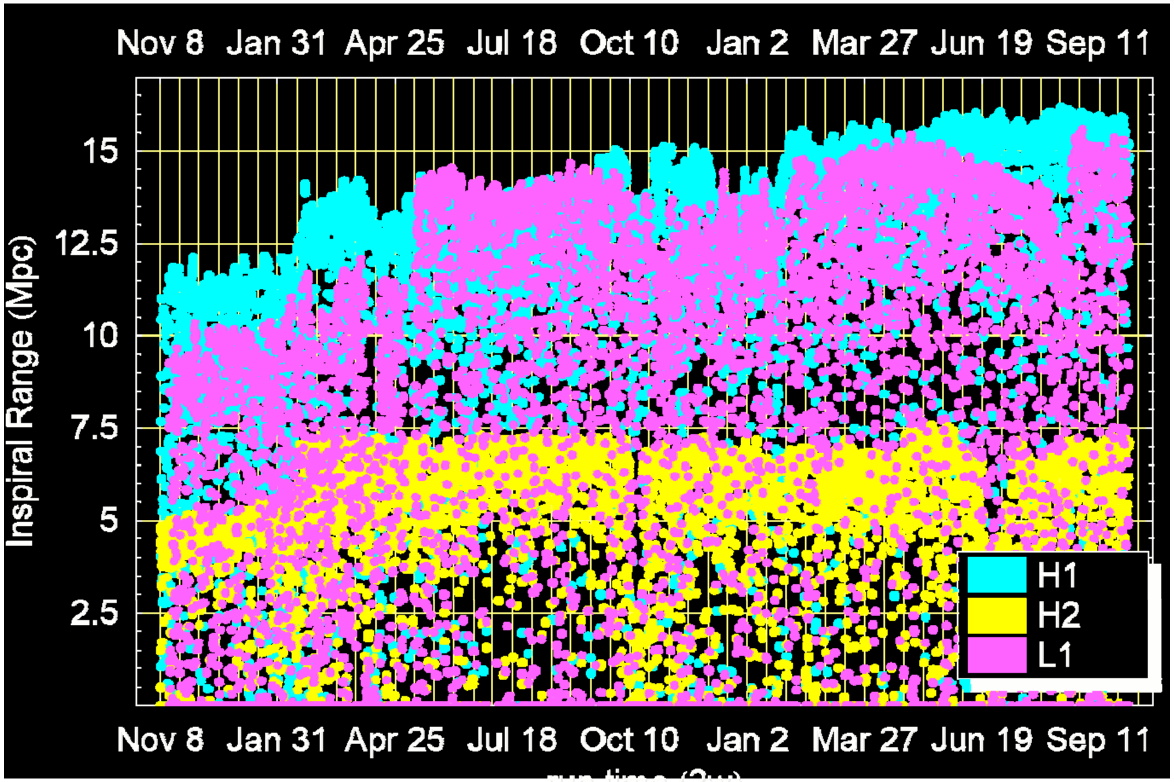
- 55 institutions and > 500 people
- The LSC carries out a scientific program of instrument science and data analysis
- The 3 **LIGO interferometers** and the **GEO600 instrument** are analysed as one data set

- **LSC & Virgo signed a ‘Memorandum of Understanding’**
  - Joint data analysis
  - Increased science potential
  - Joint run plan for the single, global GW network
    - Goal of observation of the gravitational sky over the next decade


LIGO LIGO+Virgo

Fifth science run (S5)

- **S5 started in Nov 2005 and ended Oct 2007**
  - LIGO collected 1 year of triple coincidence data at design sensitivity
  - Duty cycle: ~75% per interferometer, 53% triple coincidence
- **GEO joined**
  - in overnight & weekend mode January 20th 2006
  - in 24/7 mode May 1st 2006 (Duty cycle: ~91%)
  - back in overnight & weekend mode Oct. 2006 – Oct. 2007
- **VIRGO joint May 18th 2007 (VSR1)**
  - Duty cycle: 81%



A figure of merit is the range to which a NS/NS binary (1.4 $M_\odot$) is seen at SNR of 8

– LIGO:	4 km range 15 Mpc
	2 km range 7 Mpc
– VIRGO:	range 4 Mpc

Astrophysical searches

Five science runs to date involving LIGO, GEO and recently also VIRGO (approaching 40 publications)

- Continuous waves
  - e.g. Rapidly rotating deformed neutron stars etc
- Compact binary coalescences
- Transient searches
  - e.g. GRBs, etc
- Stochastic background

Interesting upper limits set of a variety of sources

What about the future?

- Most probable rate of binary black hole coalescences detectable by the LIGO system ~ 1/100 years
  (I Mandel, NRDA 2009)
- Thus detection at the sensitivity level of the initial detectors is not guaranteed

- Need another **10 to 15 x improvement** in strain sensitivity
- Then the most probable expected rate of detectable BH-BH binaries: **~ 20 per year**
  (I Mandel, NRDA 2009)

Principal limitations to sensitivity

- **Photon shot noise** – improves with increasing laser power and
- **Radiation pressure** – becomes worse with increasing laser power

  There is an optimum light power which gives the same limitation expected by application of the Heisenberg Uncertainty Principle – the 'Standard Quantum limit'

- **Seismic noise** relatively easy to isolate against – use suspended test masses
- **Gravitational gradient noise**, – particularly important at frequencies below ~10 Hz
- **Thermal noise** – Brownian motion of test masses and suspensions

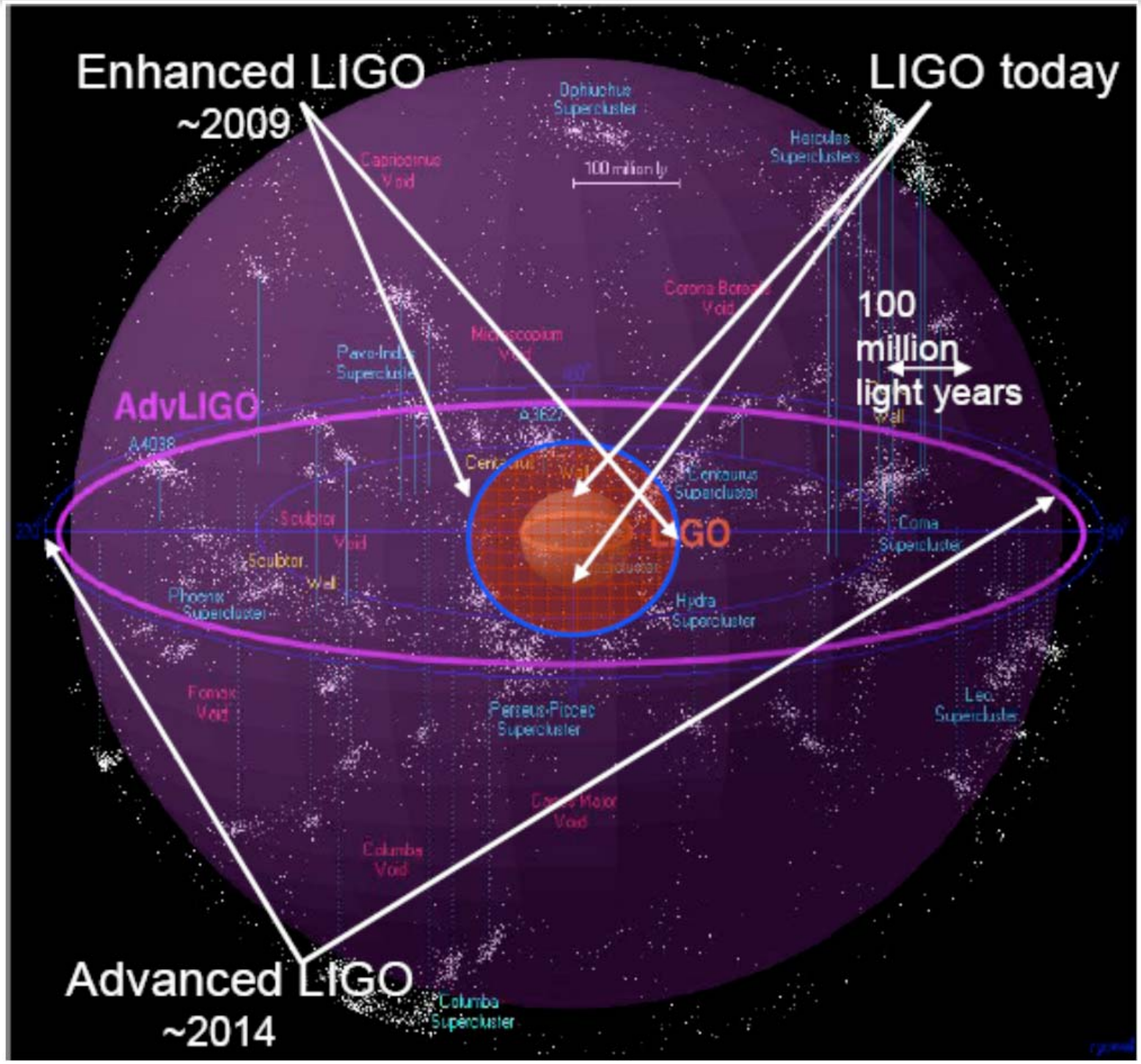
Astronomical reach
for 1.4 M_o binary neutron star inspirals

- Aimed improvement in range over the coming years in **two stages**:
  - Enhanced detectors

    Enhanced LIGO x 2

    VIRGO+ x 1.5 - 4
  - Advanced detectors

    x 10



In the past 1.5 years (broadening our horizon stage 1)

- LIGO and Virgo have been working on incremental detector enhancements
  - **Enhanced LIGO**

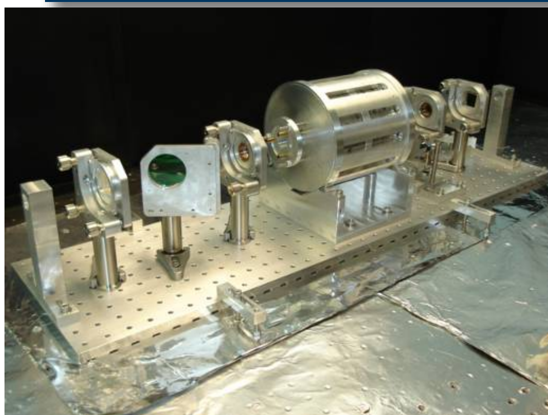
    higher laser power, improved faraday isolator, enhanced internal seismic isolation, better optical readout, higher power optics ⇒ goal x 2 improvement of sensitivity
  - **VIRGO+**

    higher laser power, improved faraday isolator, better optical readout, some infrastructural upgrades ⇒ goal x 1.5 – 4 improvement of sensitivity

Meanwhile **GEO + LIGO H2 + bar detectors** have maintained **'Astrowatch'** until two days ago (6th July 2009)

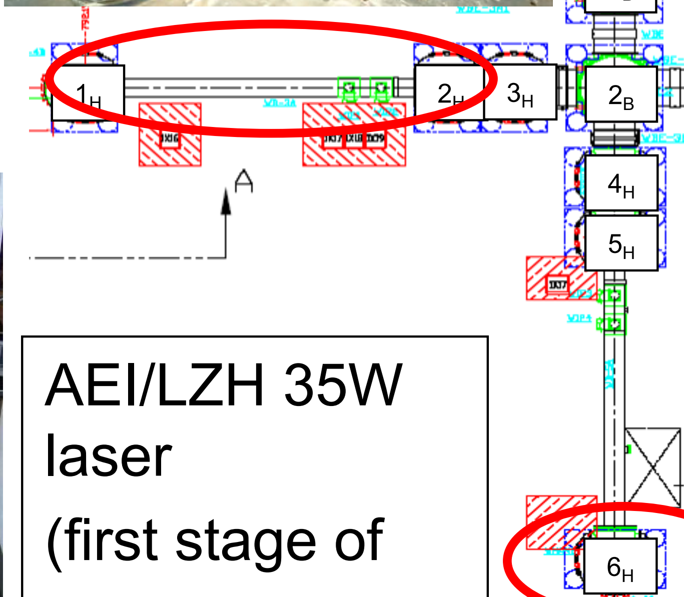
Some images of the upgrades in enhanced LIGO

UFL Faraday Isolater, input optics



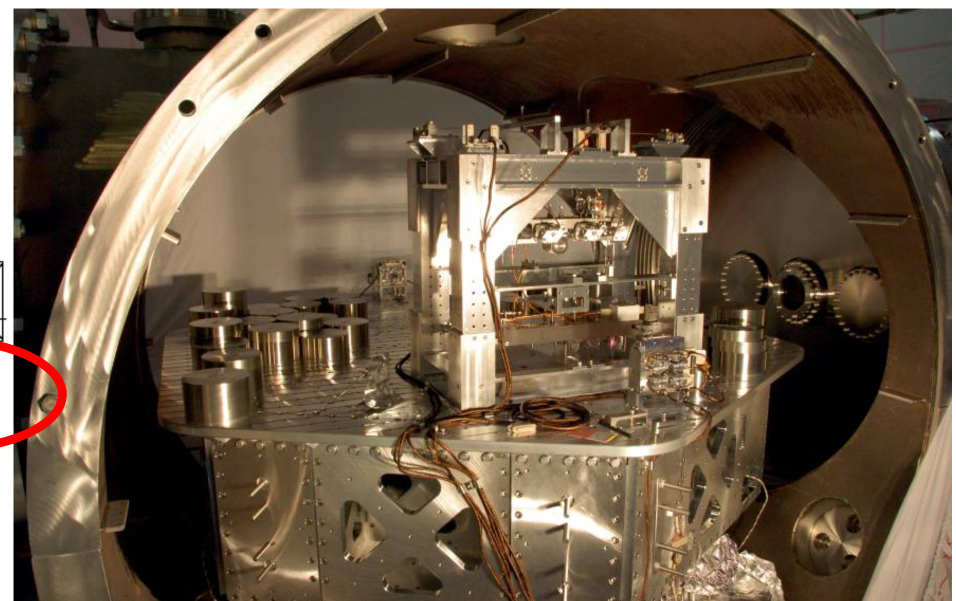
Active seismic system (ISI), multi-stage output mode cleaner suspension (OMC SUS), in-vacuum OMC and modified readout electronics

PSL



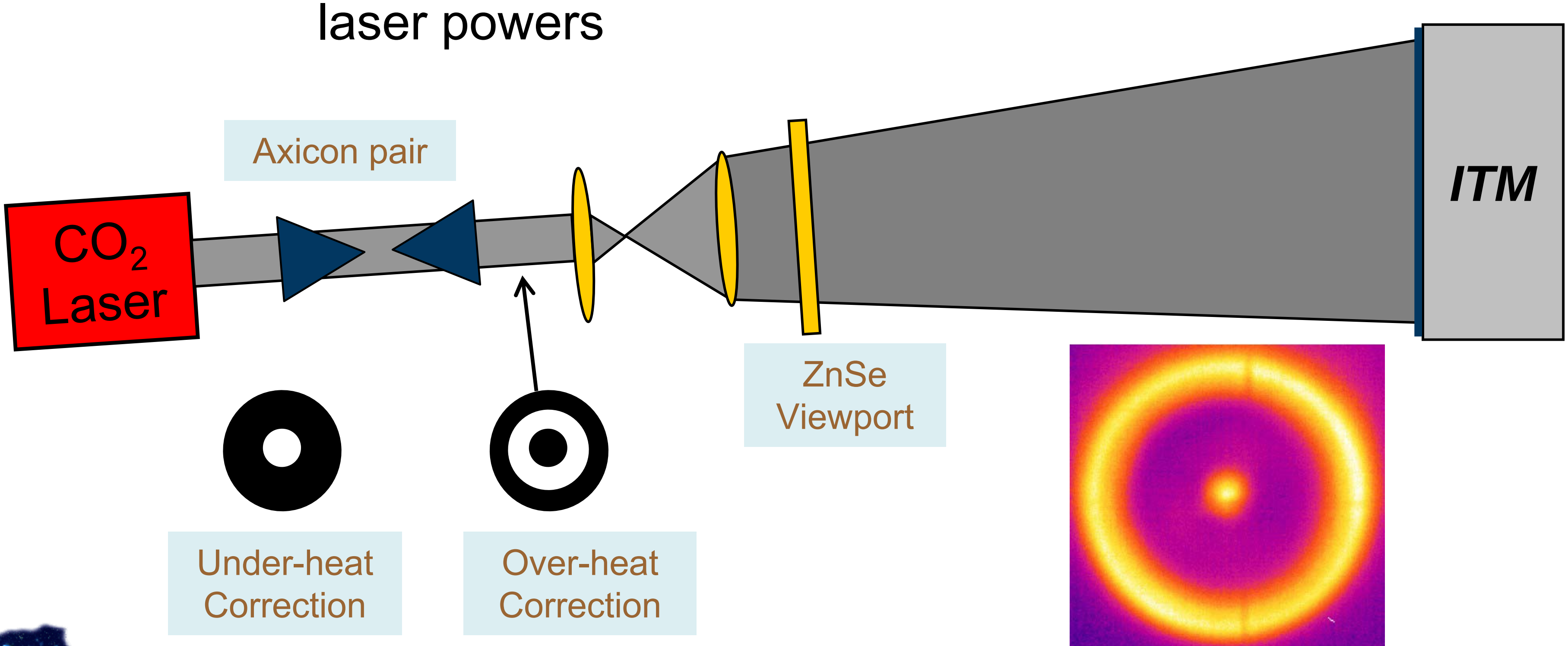
AEI/LZH 35W laser

(first stage of Advanced LIGO laser)

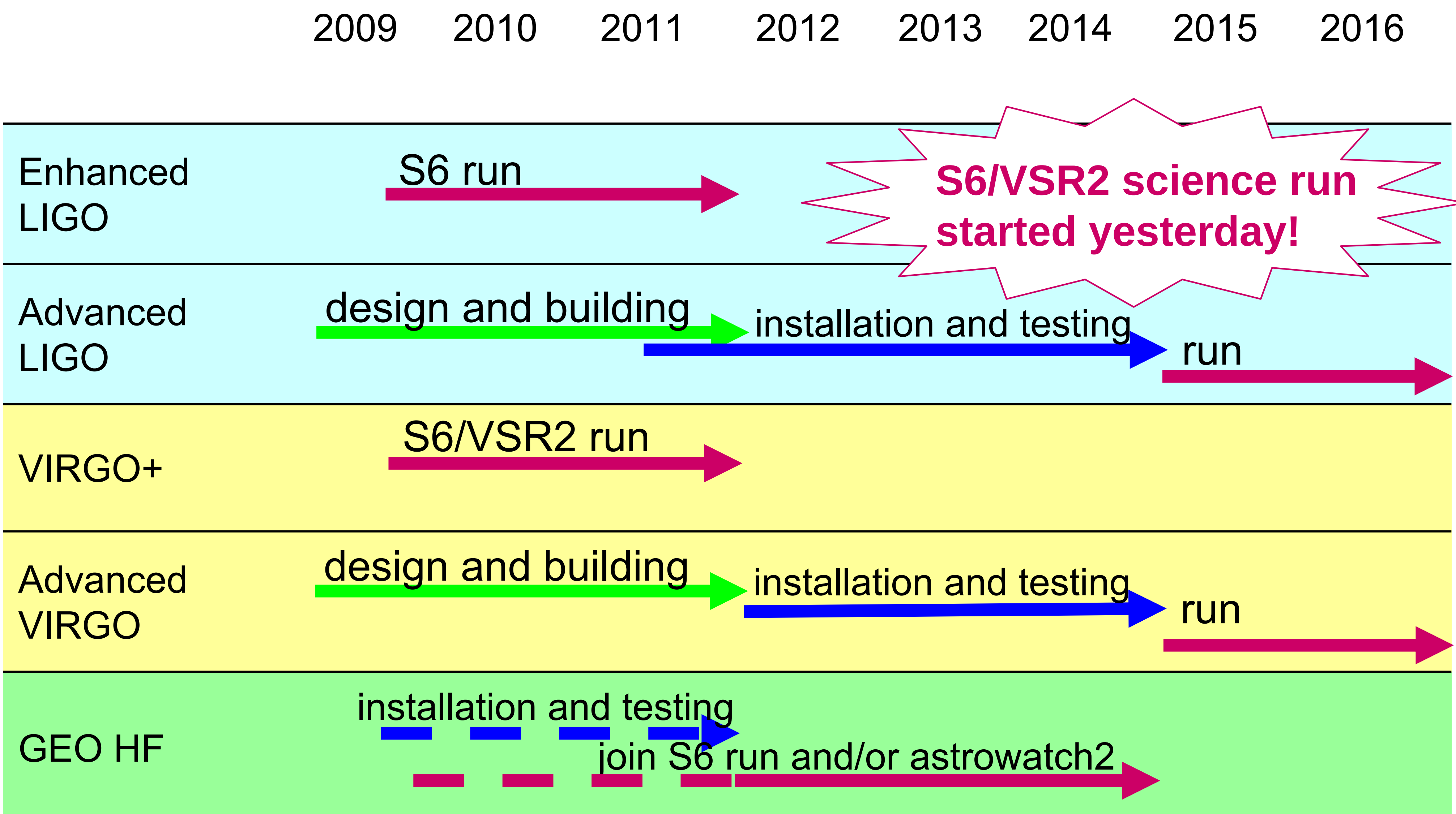


Also …

- Enhanced LIGO, VIRGO+ and GEO HF are working towards adding in a thermal compensation system (TCS) which was pioneered during S5 in iLIGO
- To minimise thermal lensing of the input mirrors at high laser powers



And from now into the future



Plans for Advanced detectors (broadening the horizon stage 2)

To move from detection to astronomy the current detector network will upgrade, starting 2011, to a series of 'Advanced' instruments with sensitivity improvements of 10 to 15

$\Rightarrow$ **1 year of Initial LIGO = < 1 day of Advanced LIGO**

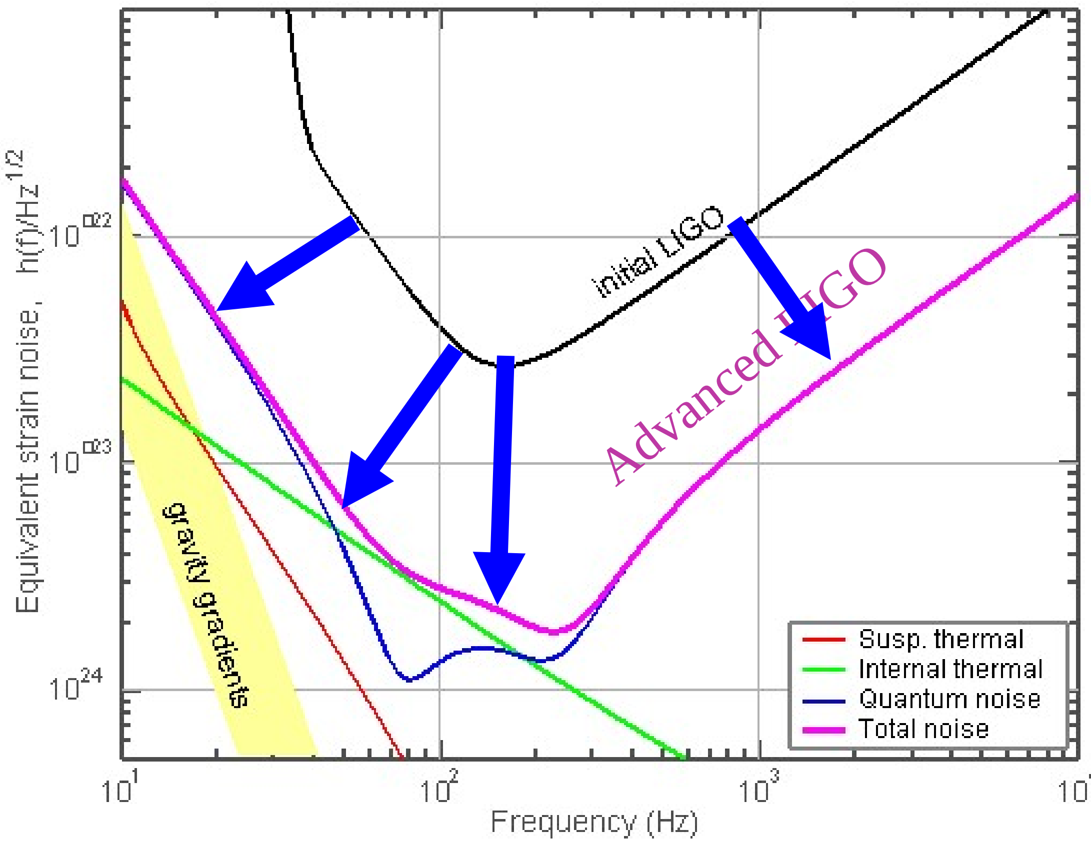
- **Advanced LIGO** (major upgrades, in advanced design stage, currently under construction)
- **Advanced Virgo** (major upgrades, in advanced design stage, currently under construction)
- **GEO-HF** (incremental upgrades, some elements nearing installation)
- **Large Cryogenic Gravitational Telescope (LCGT)** (a lot of experience from TAMA300 and CLIO, in proposal phase)

Upgrades Advanced LIGO

- Aim to improve overall strain sensitivity with a factor 10 w.r.t. initial LIGO

- Aim to improve lower frequency limit with a factor 4

  ~10 Hz instead of ~40 Hz

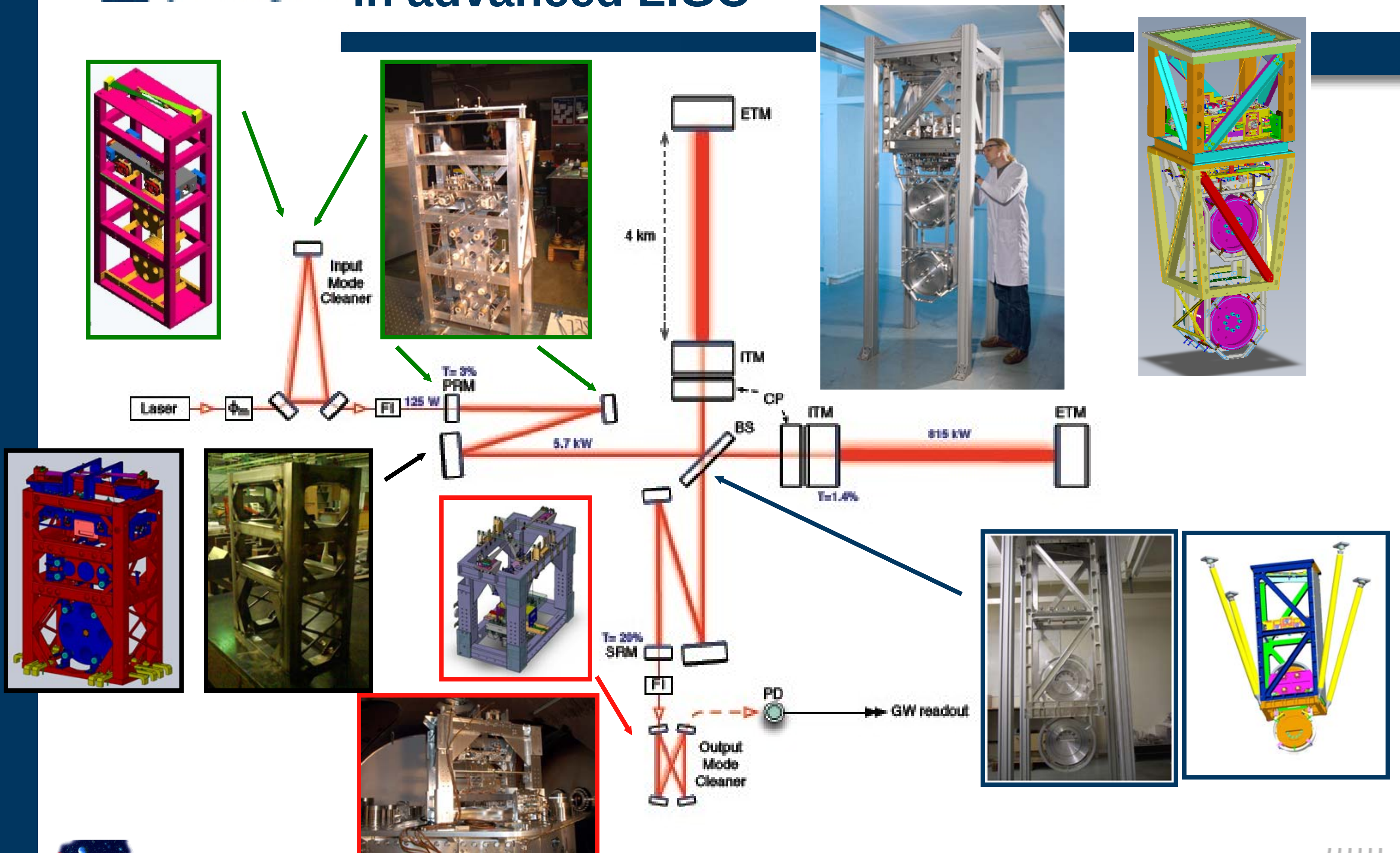


Upgrades Advanced LIGO

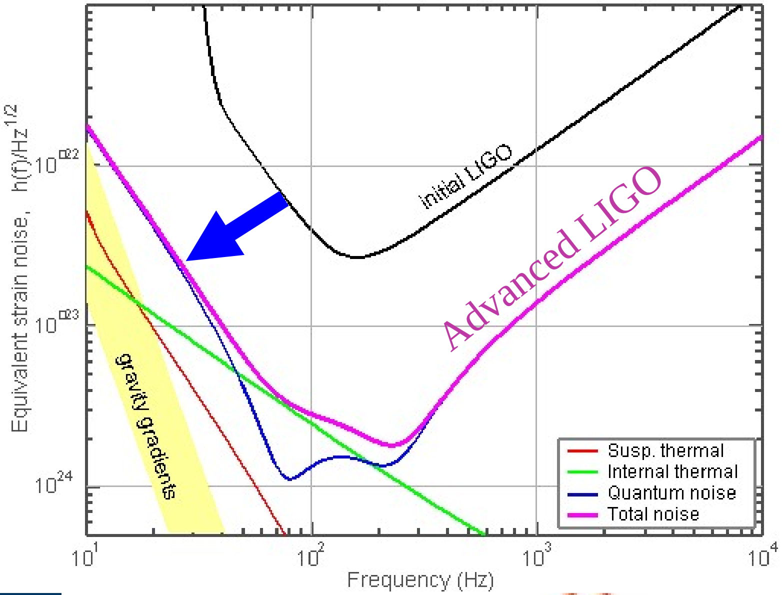
Some main upgrades for advanced LIGO are:

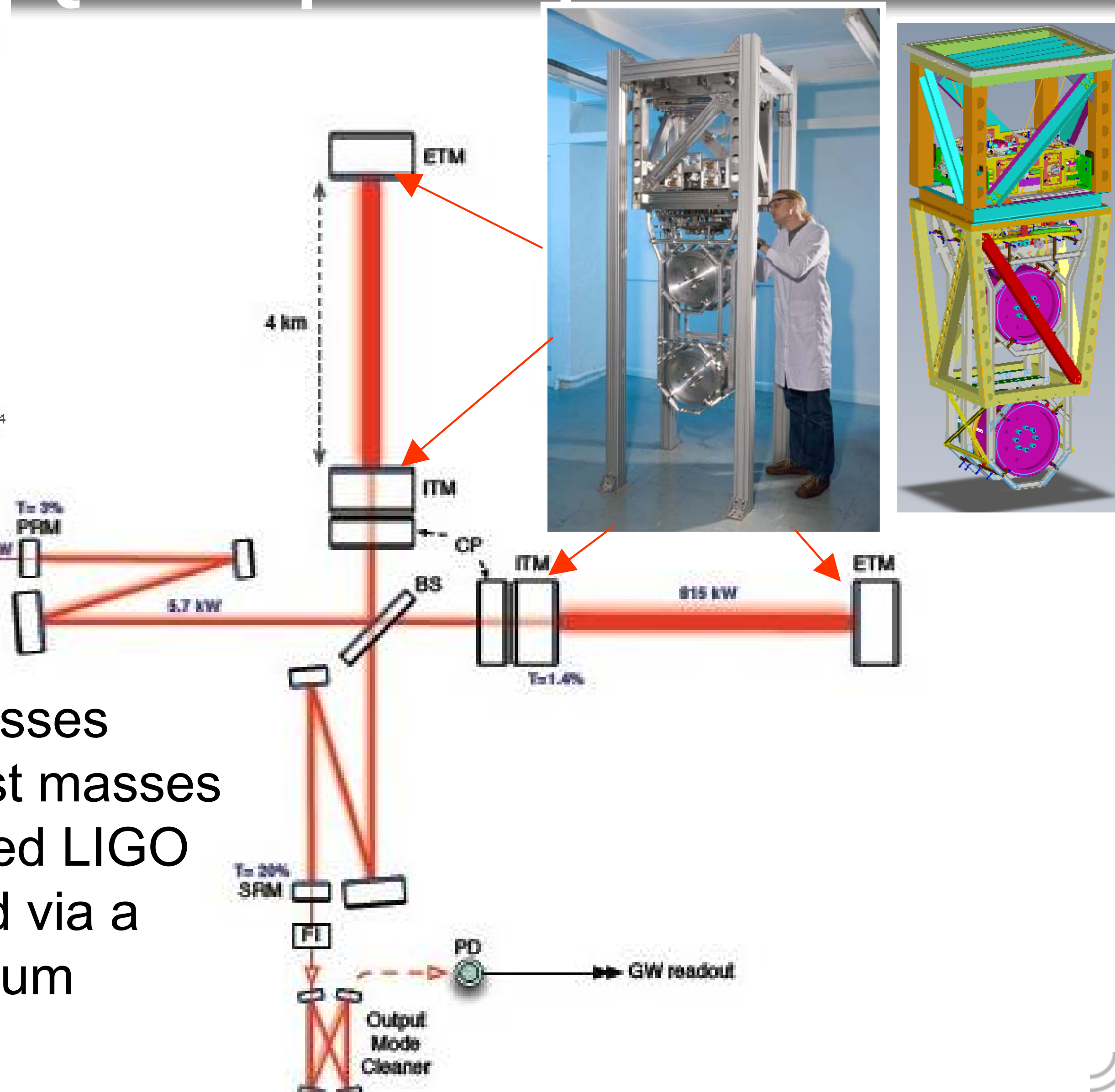
- Replace seismic isolation systems and suspensions
- Replace cavity optics
- Second stage of AEI/LZH Laser increasing power from 35 W to 180 W power
- Add signal recycling

Some suspensions that will be replaced in advanced LIGO



Quadruple suspension



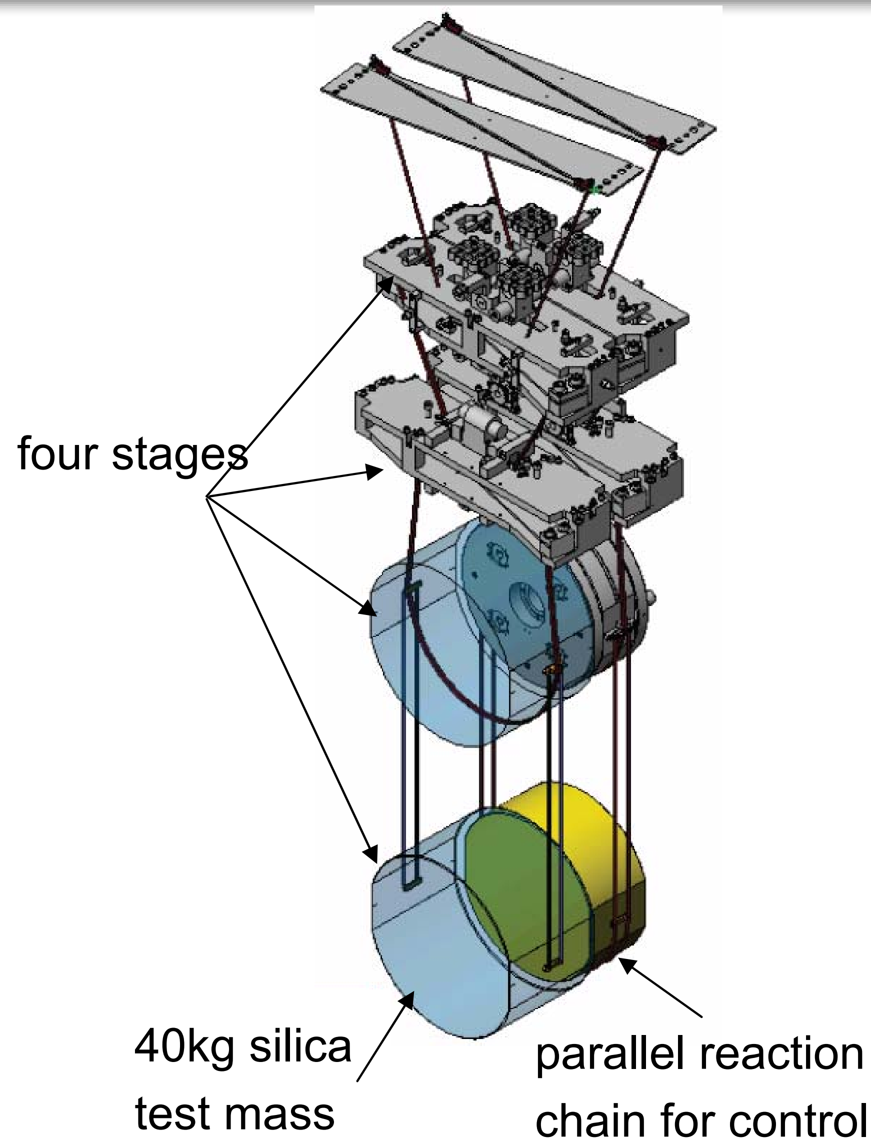


- The input test masses (ITM) and end test masses (ETM) of Advanced LIGO will be suspended via a quadruple pendulum system

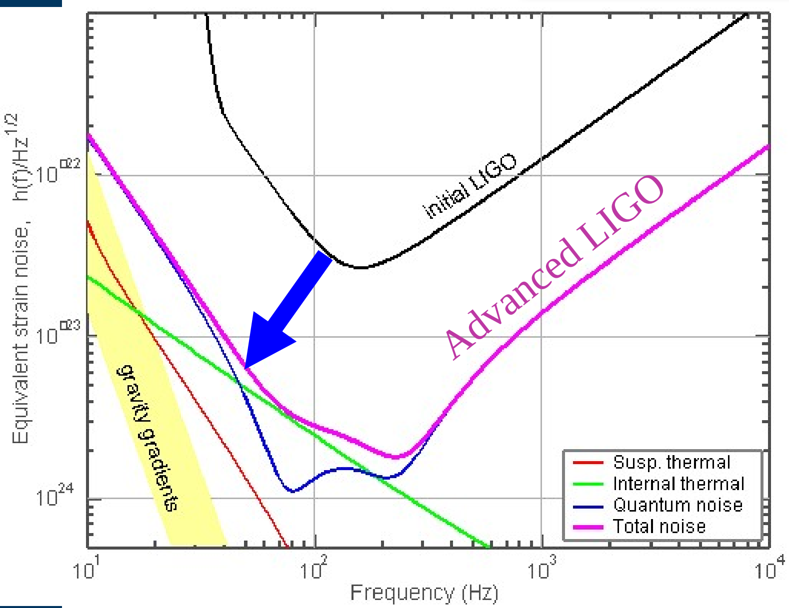
Quadruple suspension

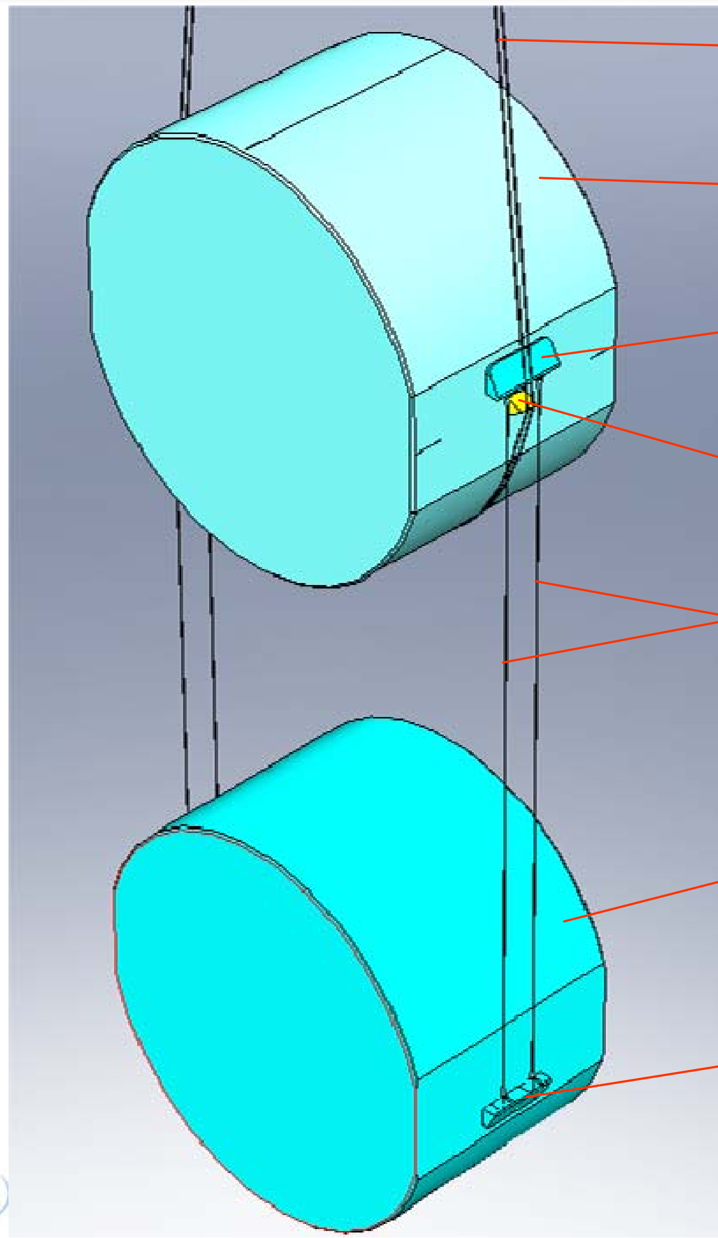
- Thermal noise reduction: monolithic fused silica suspension as final stage - low pendulum thermal noise and preservation of high mirror quality factor
  – *silica fibre loss angle ~ 3·10^{-7},*
  – *c.f. steel ~2·10^{-4}*

- Seismic isolation: use quadruple pendulum with 3 stages of maraging steel blades for enhanced vertical isolation

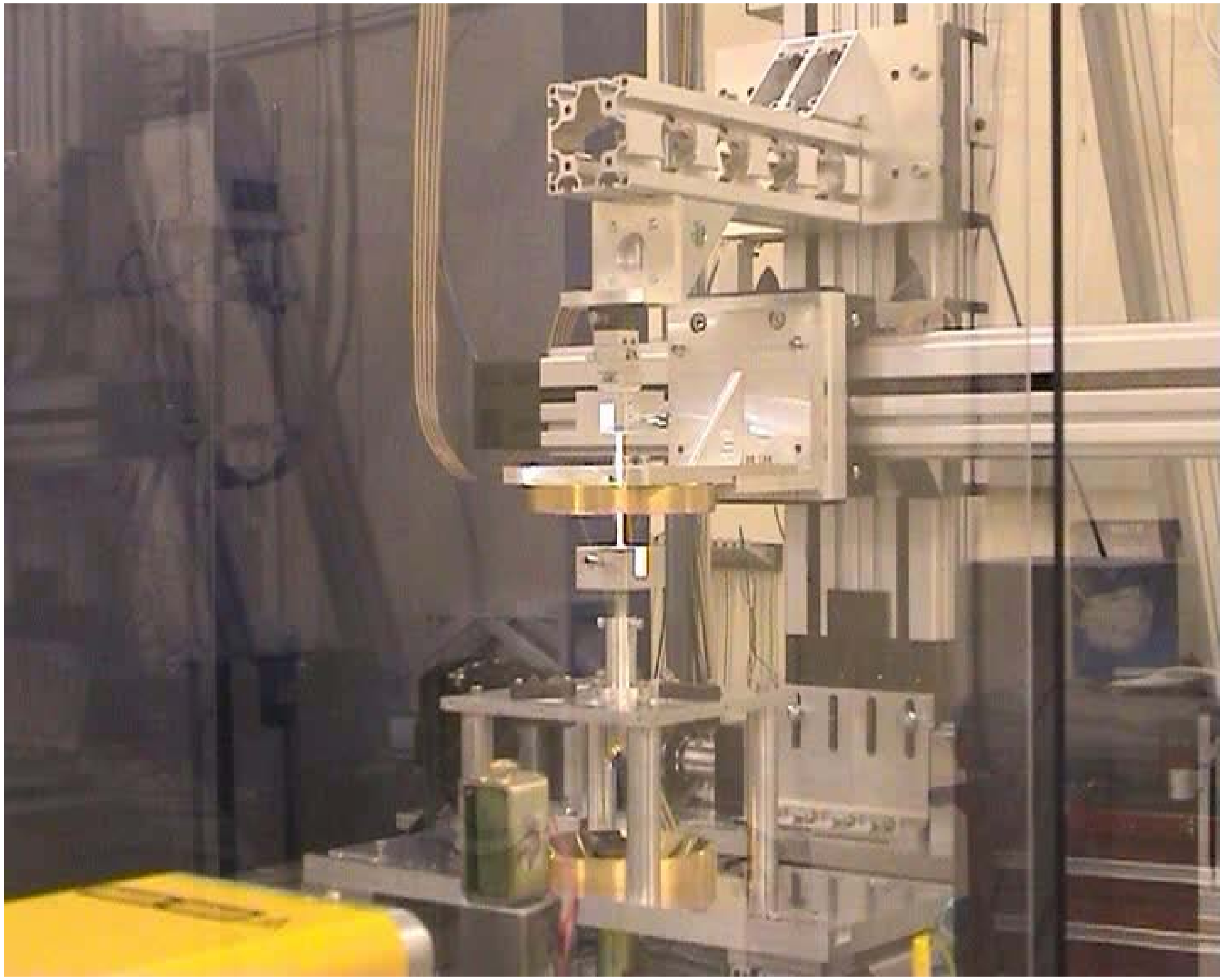


Monolithic final stage of the quadruple suspension





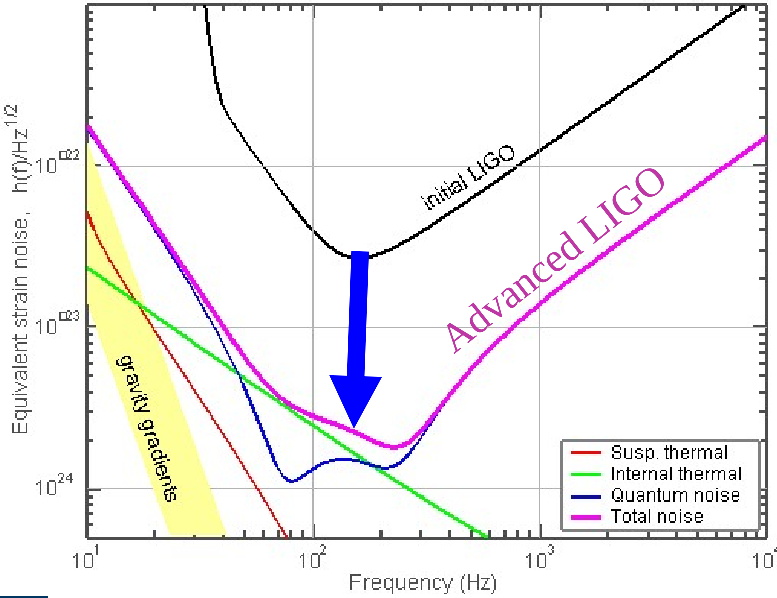
Manufacturing fibres for the monolithic suspension



Current status of monolithic suspension development

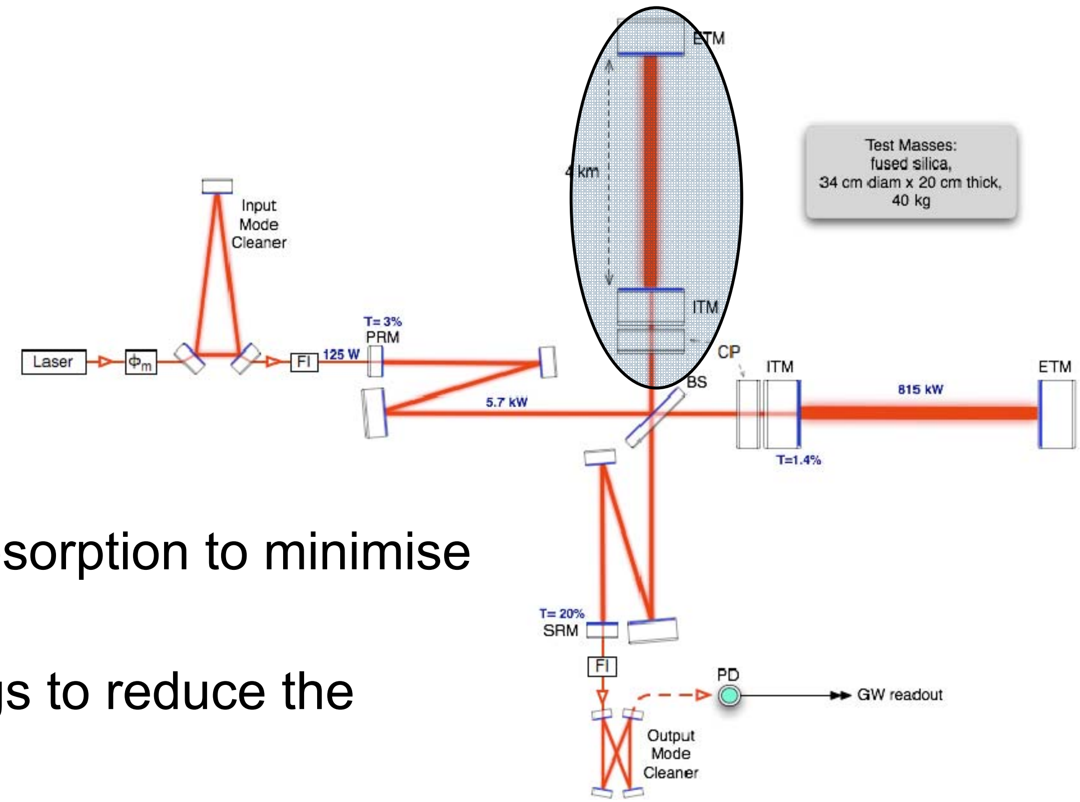
(40 kg test hang in Glasgow)

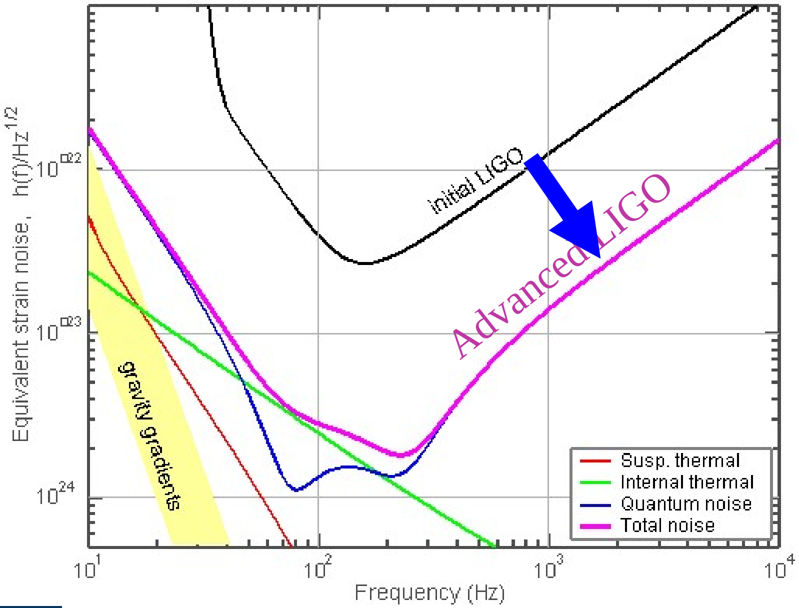
Replace optics in the arm cavity



- **Finesse**
  - 2x higher than iLIGO
  - Minimize light scatter and absorption to minimise optical loss
  - Low mechanical loss coatings to reduce the thermal noise
- **Beam sizes**

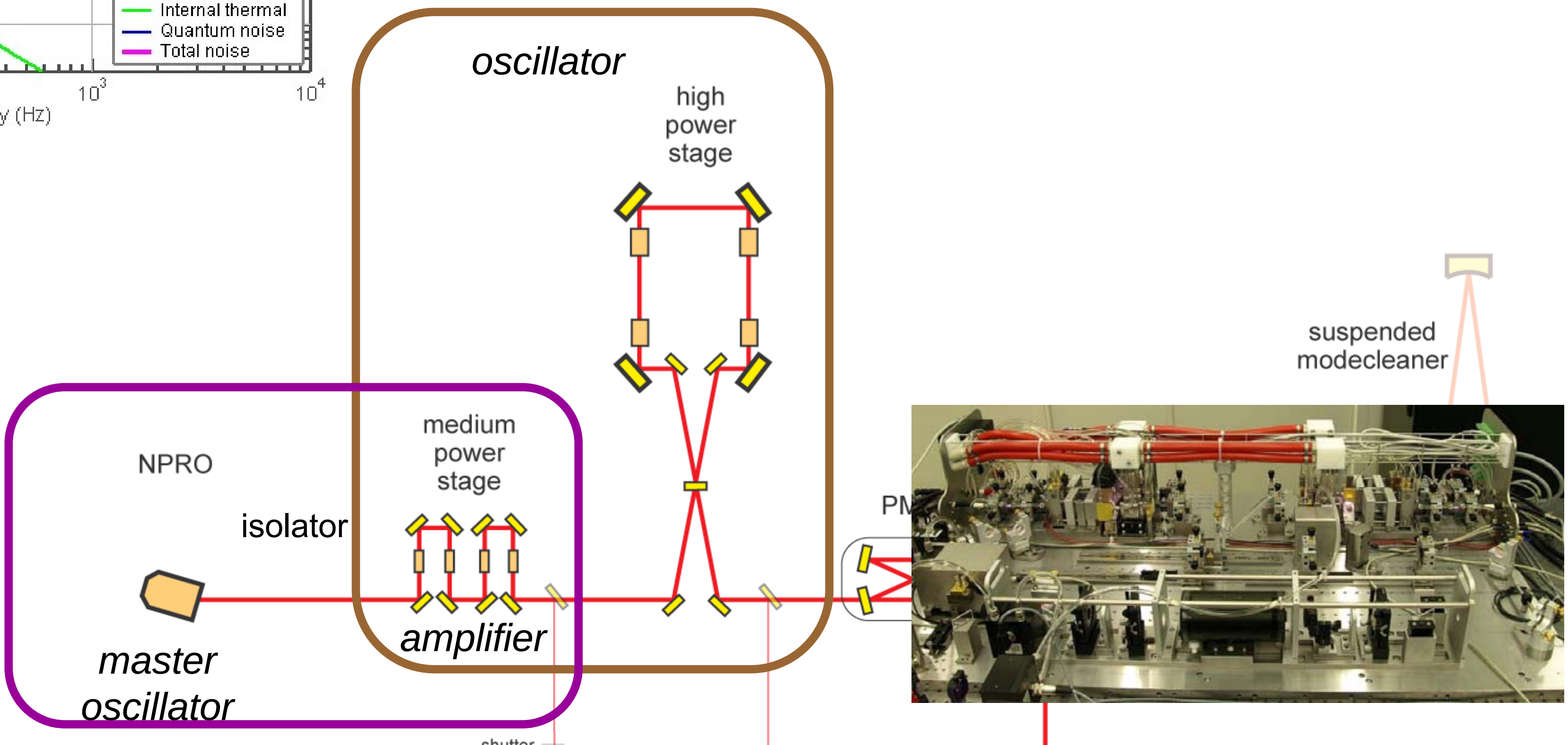
~ 50% larger than iLIGO, to reduce thermal noise





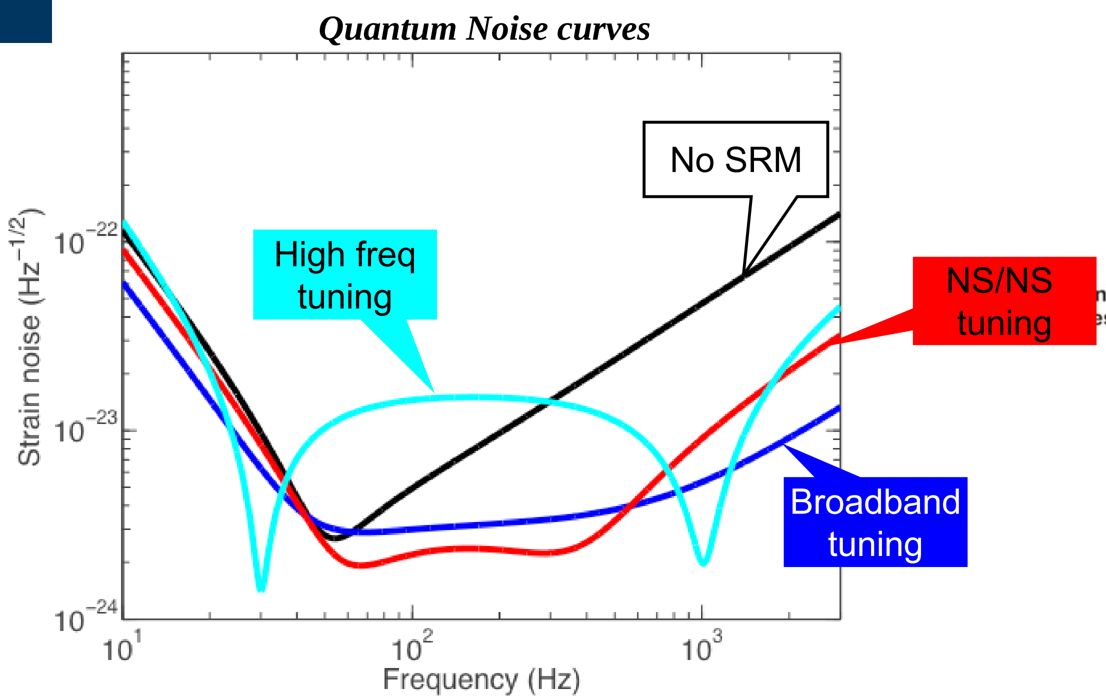
Pre-stabilized laser

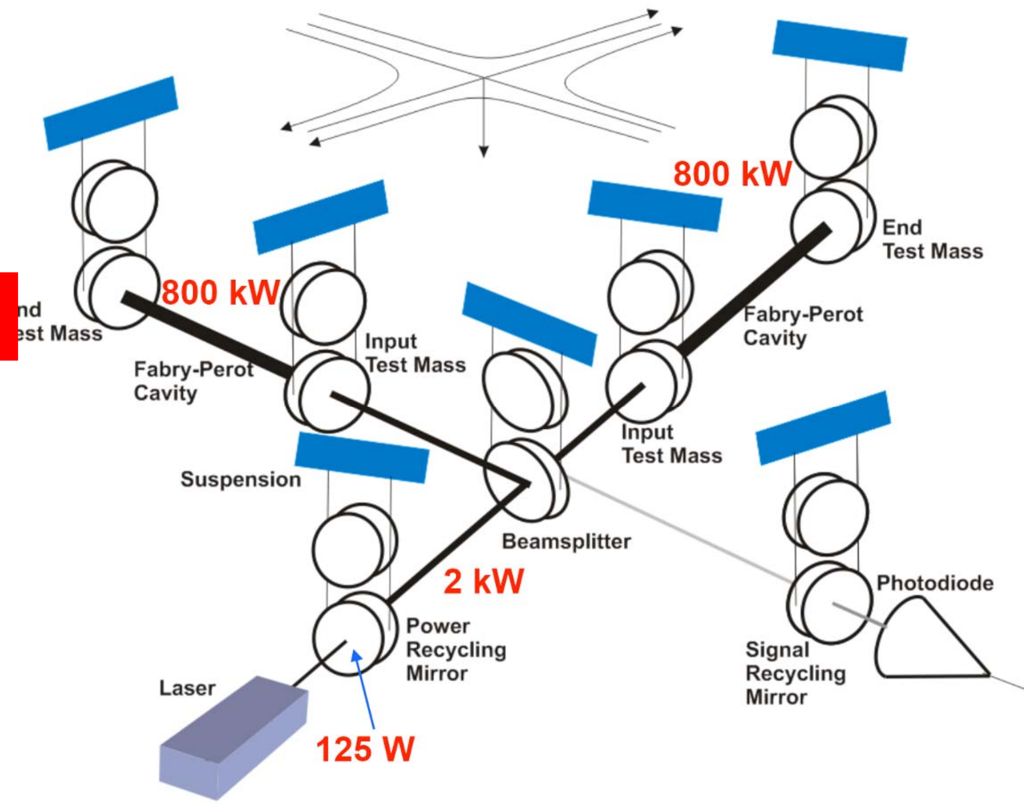
- Front end of AEI/LZH 35 W laser installed in eLIGO
- Second stage: pump up power to 180 W (in preliminary design review stage)



Signal recycling

- Pioneered in GEO
- Add a partially transmitting mirror to the output port
- Provides the ability to alter the interferometer frequency response





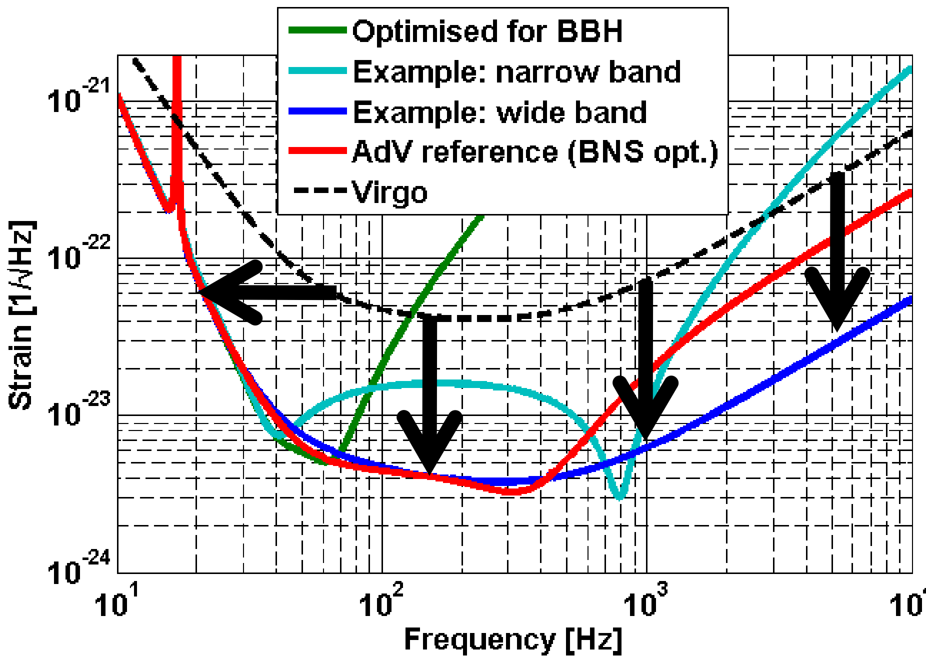
Upgrades Advanced LIGO

Parameter	LIGO	Advanced LIGO
Input Laser Power	10 W	180 W
Cavity laser power	10 kW	800 kW
Mirror Mass	10kg	40kg
Topology	Power recycled Fabry-Perot arm cavity Michelson	Power/Signal recycled Fabry-Perot arm cavity Michelson
Low frequency performance	f> 40Hz	f>10Hz
Mirror suspension	Single metal pendulum	Quadruple monolithic pendulum

Advanced VIRGO

- Aim to improve overall strain sensitivity with a factor 10 w.r.t. initial LIGO

- Hardware upgrades
  - Laser power increase
  - Include signal recycling
  - New optics and coatings
  - Monolithic suspensions
  - Etc.

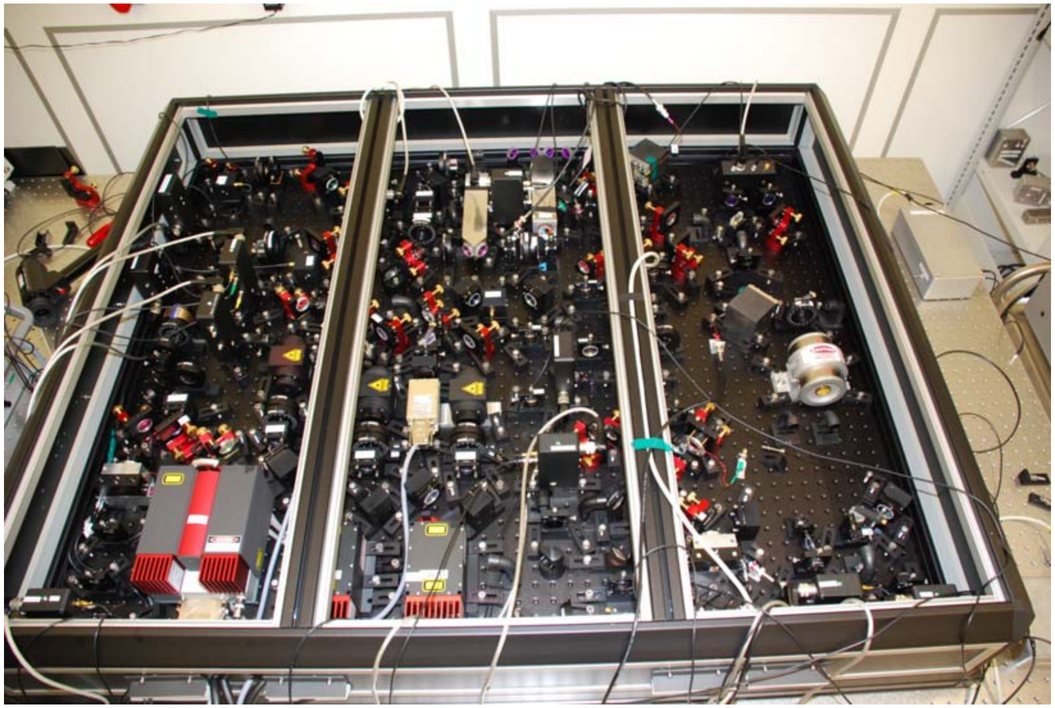


GEO HF

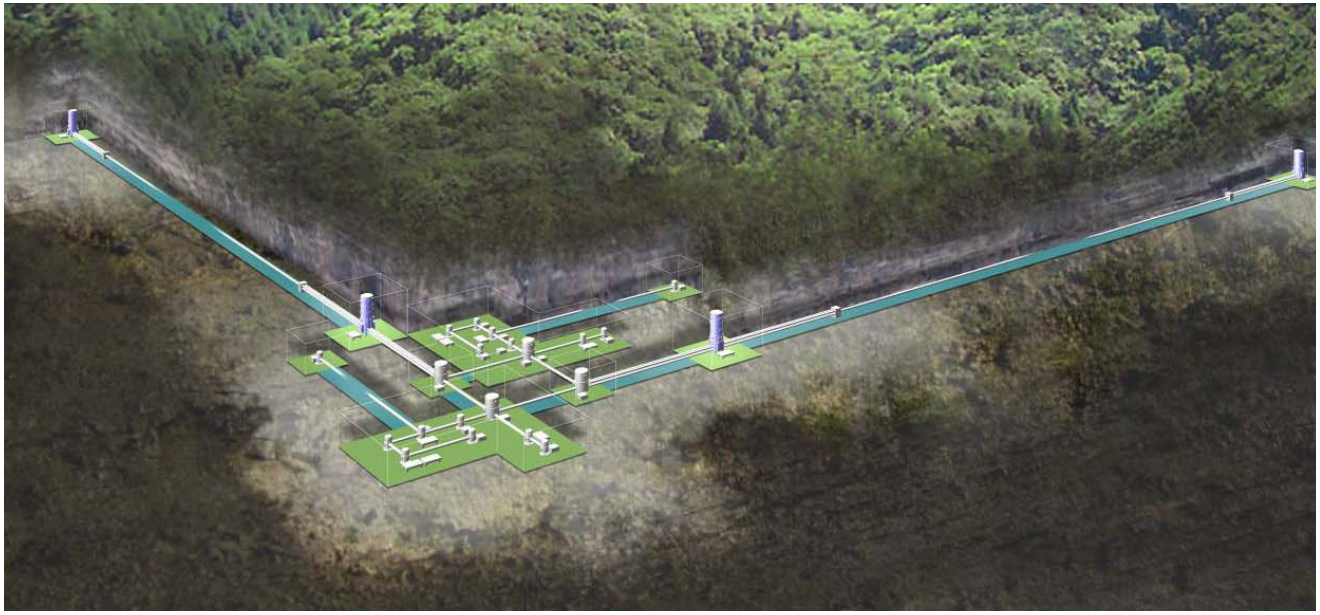
Some of the upgrades in GEO HF are:

- Optical readout change
- Squeezing
- Monolithic OMC (output mode cleaner)
- Increase laser power
- Thermal compensation system

Look in the squeezing box



Large Cryogenic Gravitational Telescope (LCGT)

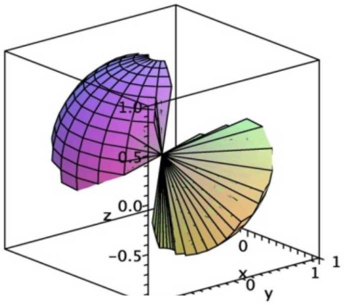


Planned for construction in the Kamioka mine in Japan

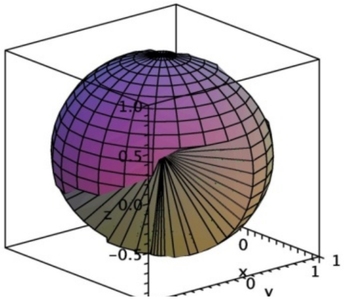
Will use sapphire mirrors cooled to 40K

Not yet funded – proposal still being developed

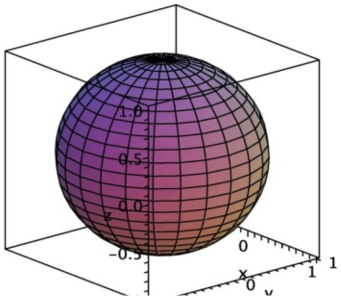
Sensitivity goals very similar to Advanced LIGO and Advanced VIRGO



LIGO



LIGO+Virgo



LIGO+Virgo+LCGT

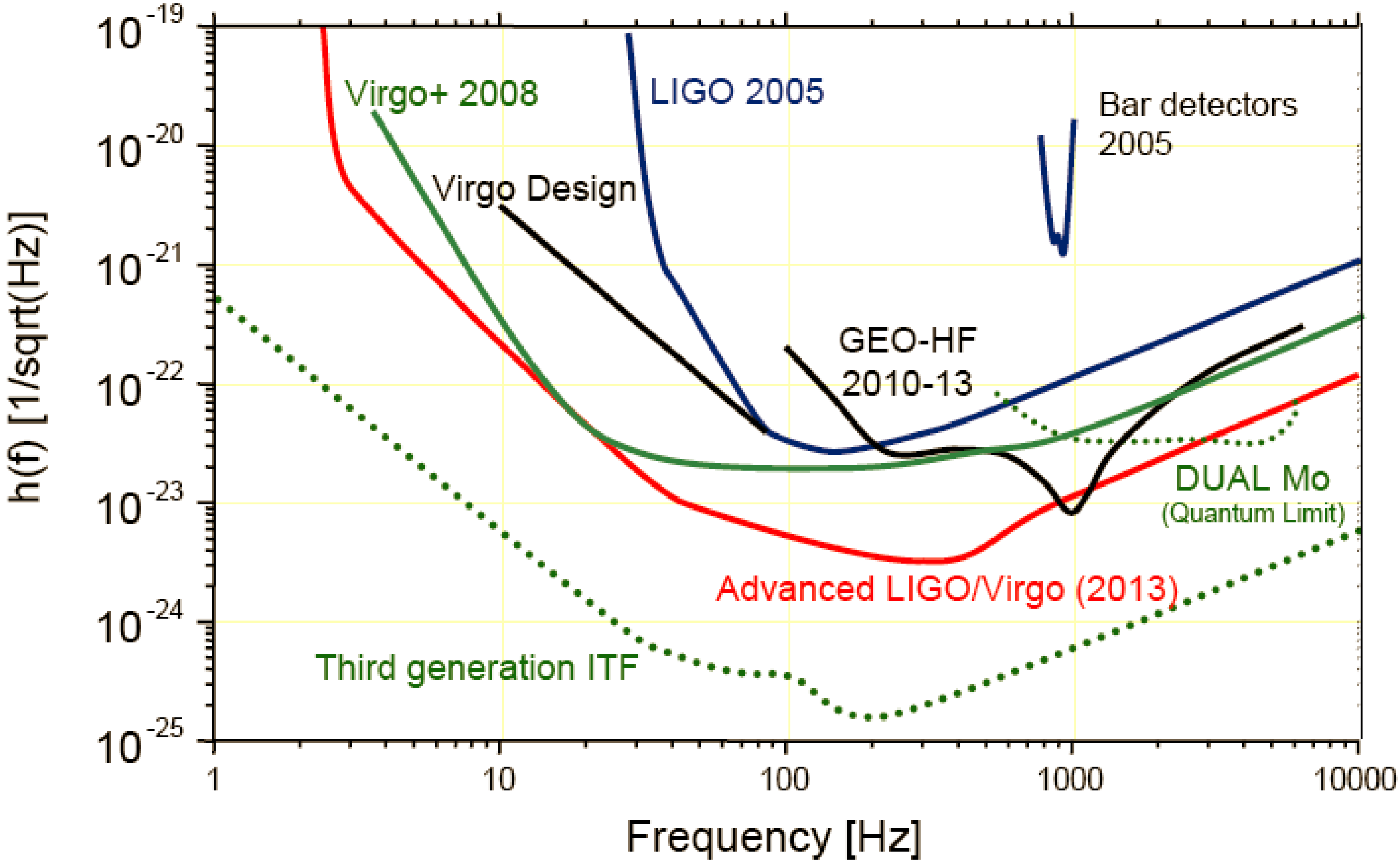
How about broadening the horizon stage 3?

3rd Generation detectors

- For a further factor of ten sensitivity improvement we need to
  - fully understand and further reduce seismic and thermal noise from mirrors and suspensions
  - improve interferometric techniques to reduce the significance of quantum noise in the optical system
  - refine data analysis techniques

- A design study for such a detector in Europe [the Einstein gravitational-wave Telescope – 'ET'] has now been funded by the EC under FP 7

Advanced detector network



The Network of Gravitational Wave Facilities

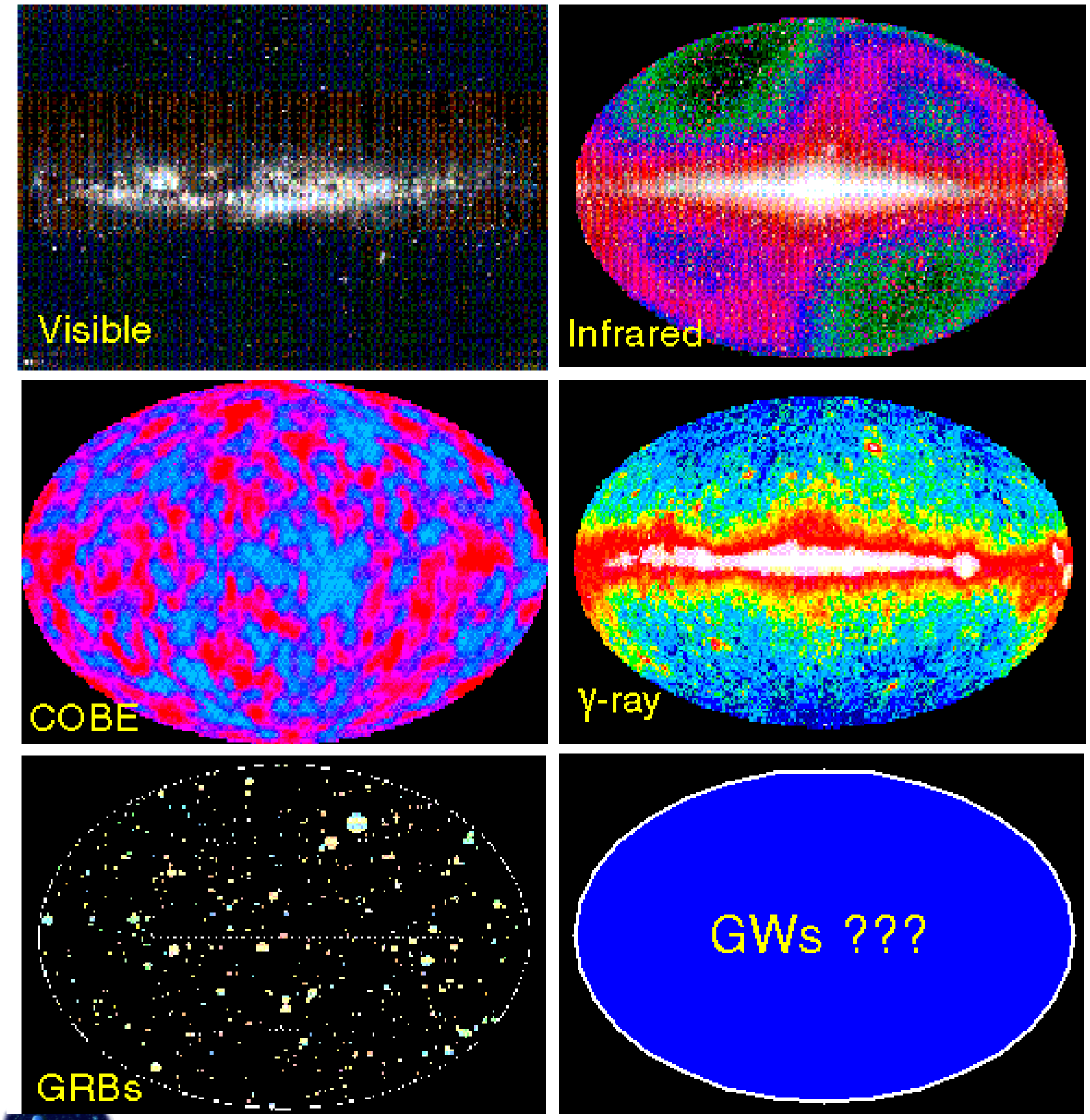
- During upgrades for enhanced detectors (enhanced LIGO and VIRGO+)
  - Astrowatch has been running at LIGO H2, GEO and bar detectors

- Enhanced detectors started Science run S6/VSR2 yesterday

- 2nd generation follows 2010-14, designs mature,
  - Advanced LIGO (USA/GEO Group/LSC)
  - Advanced VIRGO (Italy/France + GEO Group?)
  - Large Cryogenic Gravitational Telescope (LCGT) (Japan)
  - GEO-HF (GEO/LSC)

- 3rd generation
  - Lab research underway around the globe
  - Plans for a design proposal under FP7 framework for a 3rd generation detector in Europe

Gravitational Wave Astronomy



A new way to observe the Universe

LIGO Scientific Collaboration

LIGO

LSC

University of Maryland

Michigan

University of Strathclyde

ACIGA

Loyola University New Orleans

Stanford

Montana State University

University of Washington

Syracuse University

University of Glasgow

Università degli Studi del Sannio

Trinity University

San José State University

University of Wisconsin UW Milwaukee

ANU The Australian National University

NASA Goddard Space Flight Center

LSU

UTB TSC

The University of Western Australia

Caltech

Northwestern University

RIT

Andrews University

The University of Adelaide Australia

MIT

Southeastern Louisiana University

Moscow State University

University of Massachusetts Amherst

PAN

Carleton College

GEO 600

The University of Texas at Austin

Embry-Riddle Aeronautical University

University of Southampton

Penn State

Science & Technology Facilities Council Rutherford Appleton Laboratory

Cardiff University

Universitat de les Illes Balears

Washington State University

UF University of Florida

The University of Mississippi

Charles Sturt University

University of Rochester

NAOJ

University of Minnesota

Universität Hannover

Southern University and Agricultural & Mechanical College

Hobart and William Smith Colleges

IGR