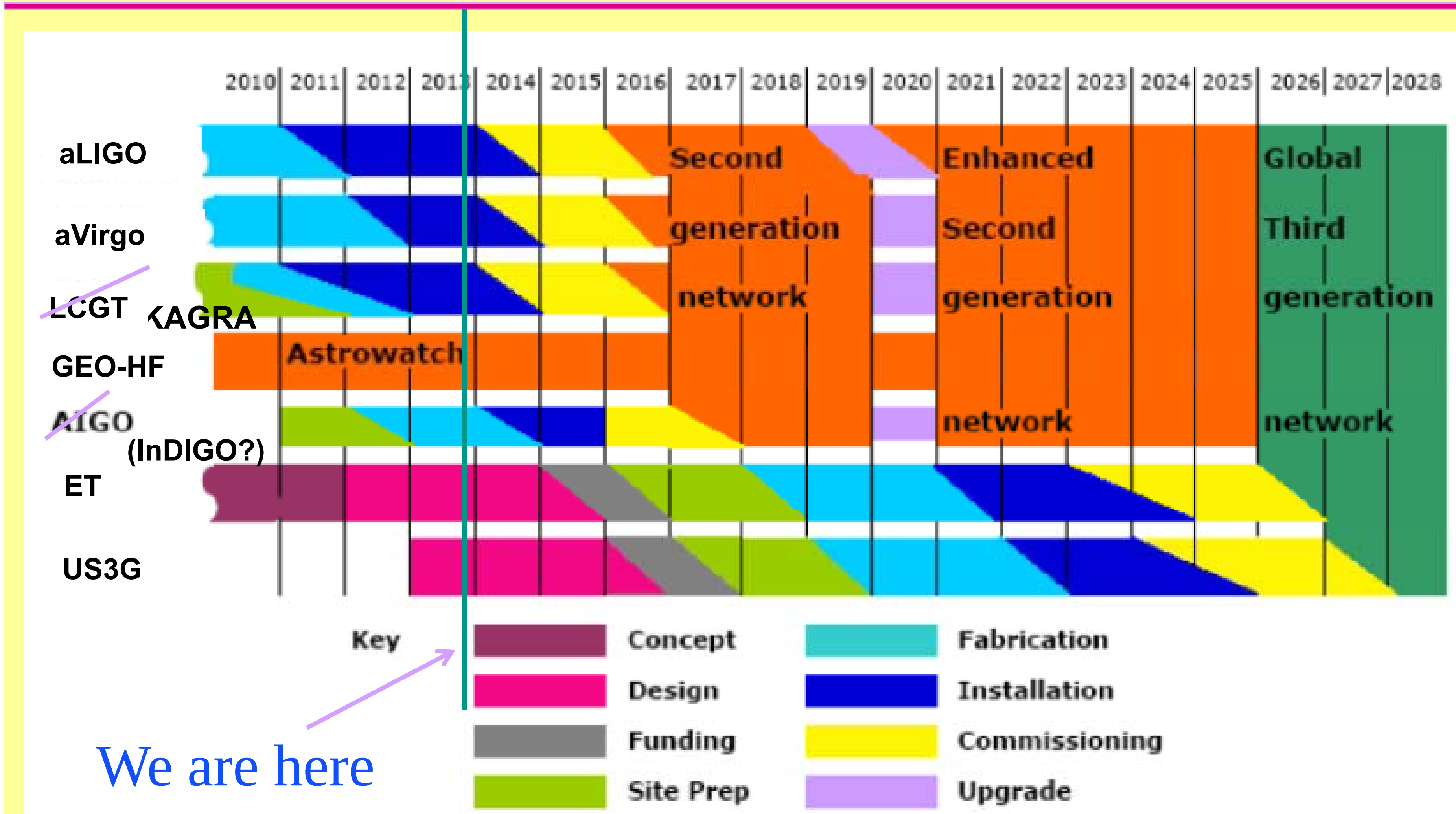
Status and plans for advanced gravitational wave detectors

Sheila Rowan
For the LIGO Scientific Collaboration and
Virgo collaborations

ASGRG 7
Hamilton Island
December 2013

GWIC
Gravitational Wave International Committee

The global GW roadmap

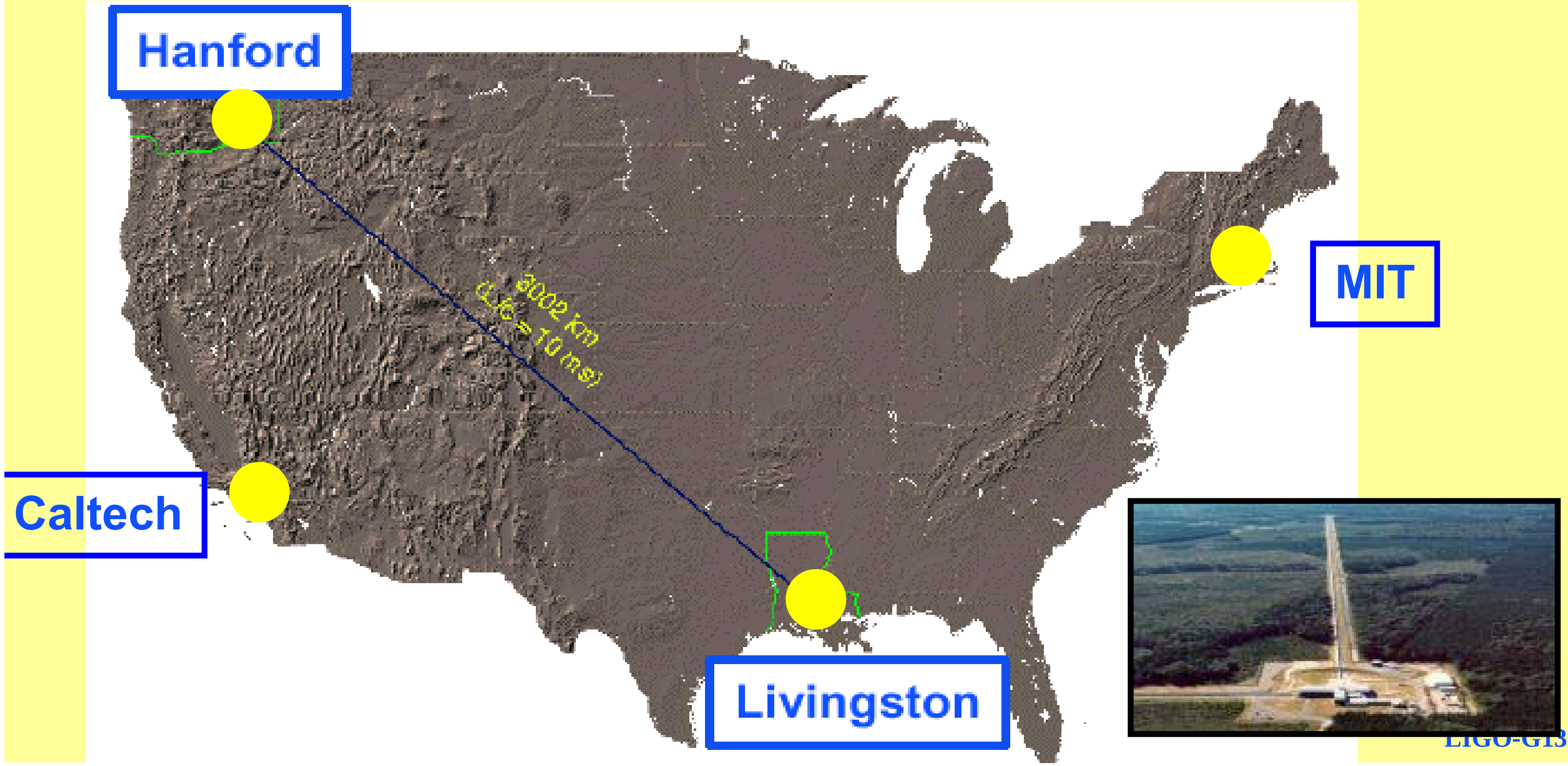


We are here

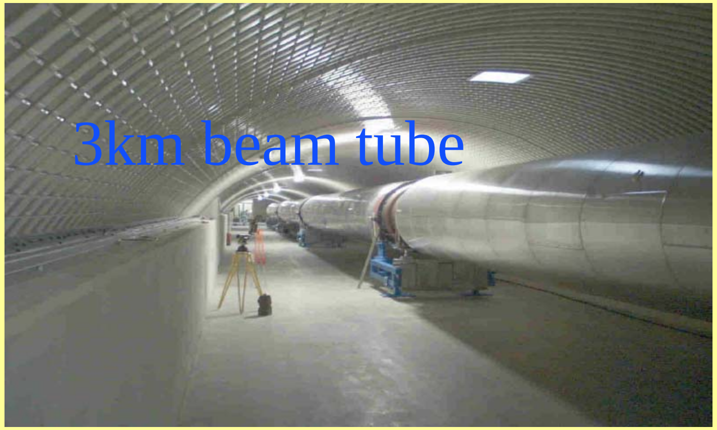
From the Gravitational Wave International Committee (GWIC roadmap – available at: http://gwic.ligo.org/roadmap/)

LIGO Laboratory: two Observatories and Caltech, MIT campuses

- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits

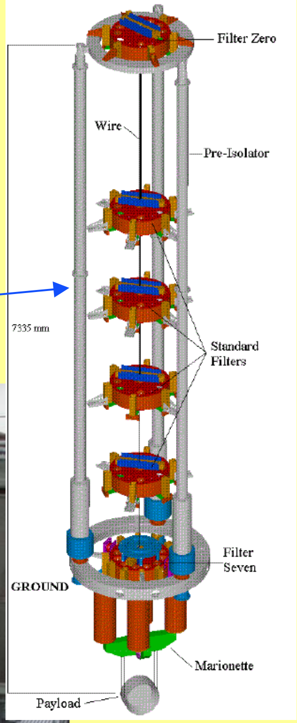


Virgo: The French-Italian Project
3 km armlength at Cascina near Pisa



3km beam tube

The ‘Super Attenuator’ filters the seismic noise above 4 Hz



GEO 600

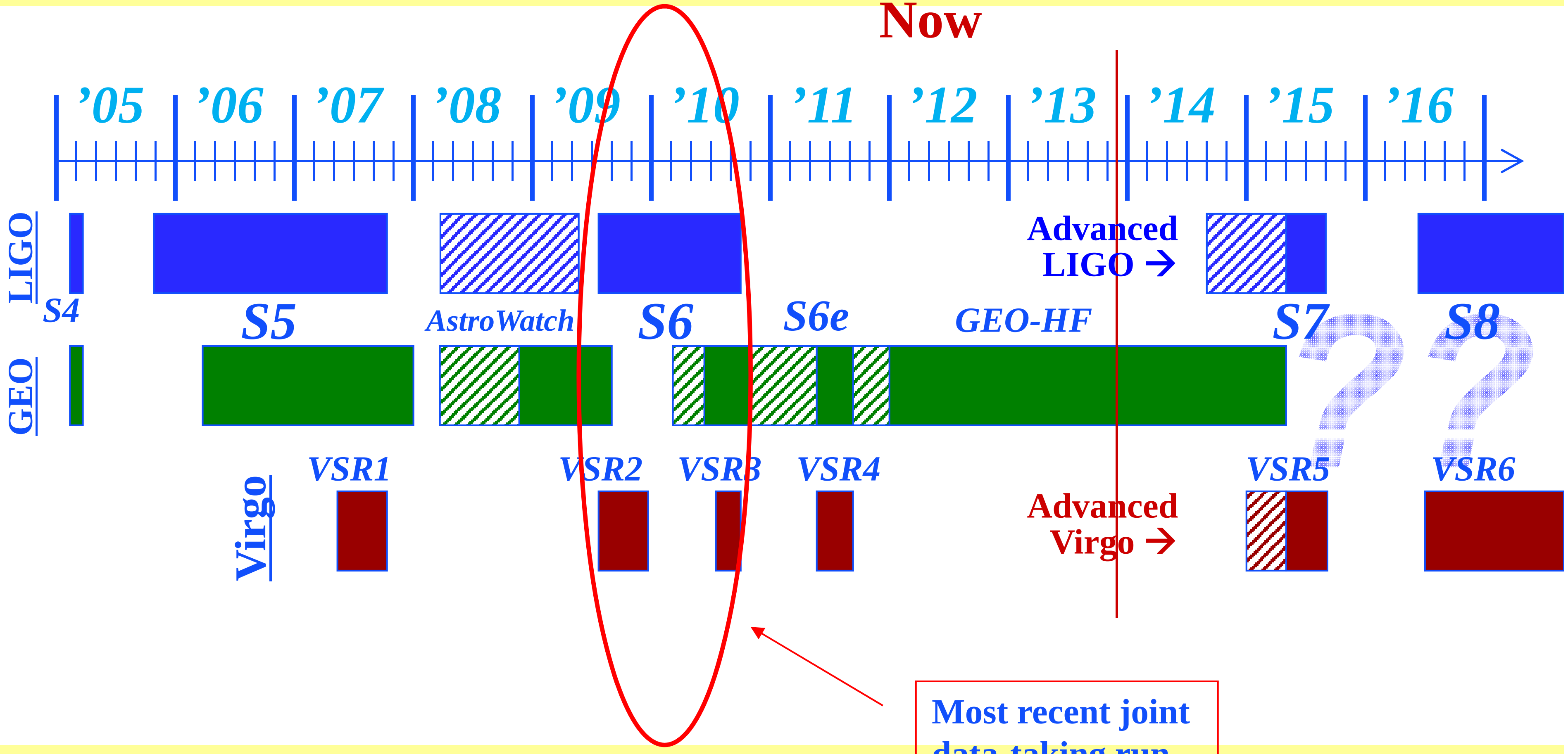
Initial GEO 600 strategy:

to build a low cost detector of comparable sensitivity to the initial LIGO and Virgo detectors to take part in gravitational wave searches in coincidence with these systems

Disadvantage:

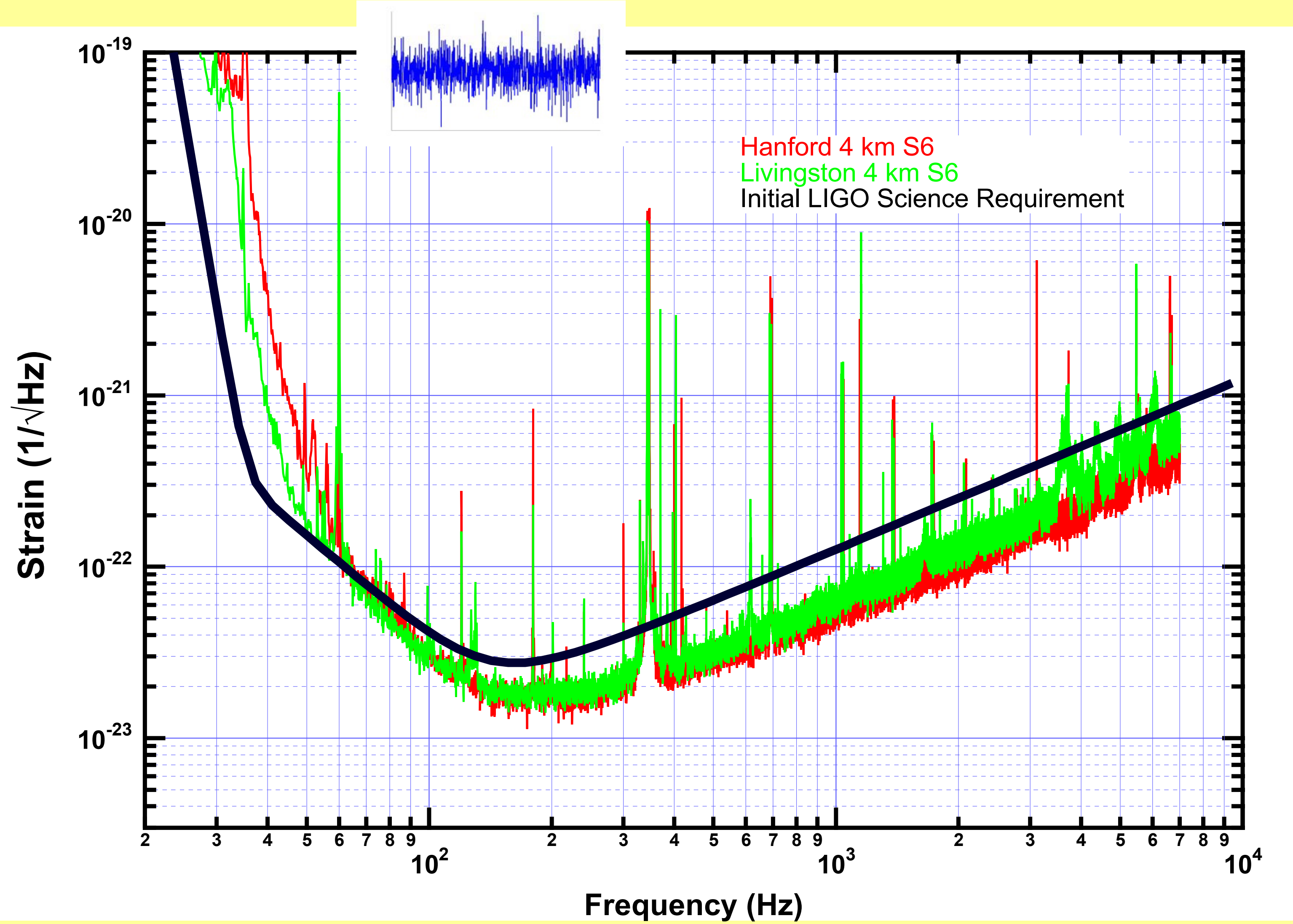
For geographical reasons the GEO armlength (600m) cannot be extended to the 3/4kms of Virgo/LIGO

Science Runs: Past, Present & Future



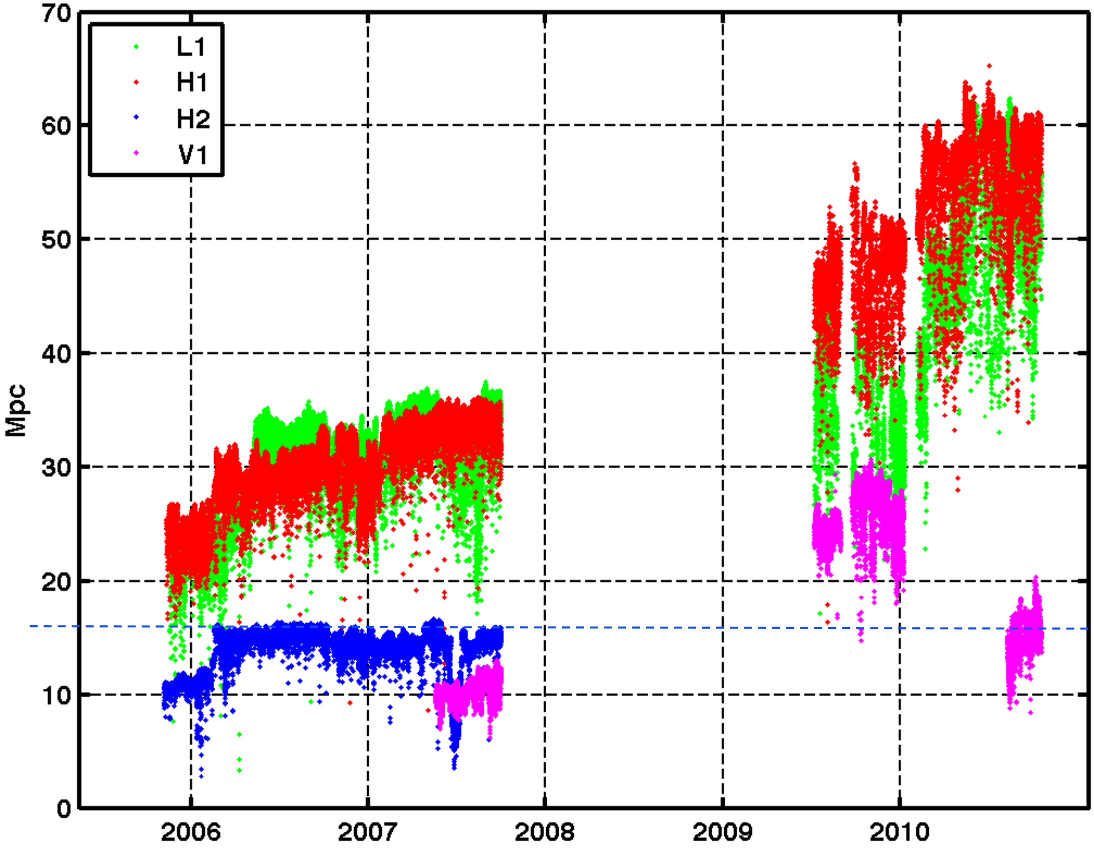
Most recent joint data-taking run

LIGO Detectors 2009-10 (S6)



LIGO-Virgo detectors 2005-2011

Horizon distance for a binary neutron star system (with m=1.4 solar masses)



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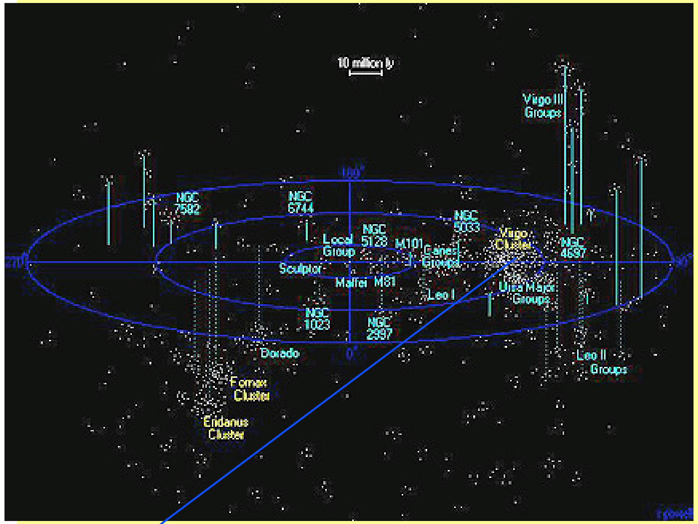
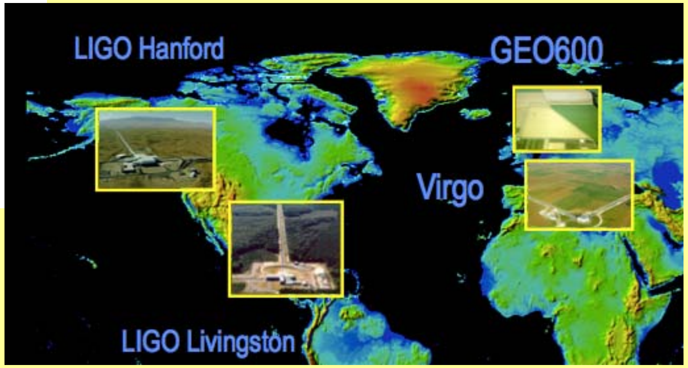


The Virgo Cluster
~16.5 Mpc from earth)



Astrophysical searches

- Six science runs to date involving LIGO, Virgo, GEO and (and TAMA) (>80 publications to date) see: https://www.lsc-group.phys.uwm.edu/ppcomm/Papers.html
- Continuous waves
  - Rapidly rotating deformed neutron stars
    - Known radio pulsars (using radio and X-ray observations to provide signal phase) and unknown sources
  - Targeted (supernova remnants, globular clusters, galactic centre, X-ray sources) and all-sky searches
- **Compact binary coalescences**
  - late stage neutron star or black hole binary inspirals, mergers and ring-downs
- **Transient ('burst') searches**
  - Coincident excess power from short duration transient sources
  - 'multi-messenger astronomy': Gamma Ray Bursts, X-ray transients, radio transients, supernova, neutrino observations
- Stochastic background
  - Cosmological i.e. from inflation
  - Combined background of astrophysical sources

All-Sky Generic GW Burst Search

- Analysed all LIGO and Virgo data since 2005 when at least 2 detectors were running (plus GEO for investigating event candidates)

- Sensitive to arbitrary GW signals between 64–5000 Hz
  - » Event selection thresholds set for low false alarm probability

- No event survived all selection cuts (not surprising given estimates of astrophysical event rates)

“Multi-Messenger Astronomy”

- If an event has already been detected (say using an optical or other electromagnetic signal), then GW searches:
  - know *when* to look at the data
  - know *where* in the sky to look
  - may know *what kind* of GW signal to search for
  - may know the distance to the source

- As a result,
  - Background is suppressed, so a weaker GW signal could be confidently detected
  - The extra information from the combined observations will reveal more about the astrophysics of the source
  - *Non*-detection of a GW signal can still provide useful information

Some interesting results 2005-2011

Astrophys. J. **681** (2008) 1419

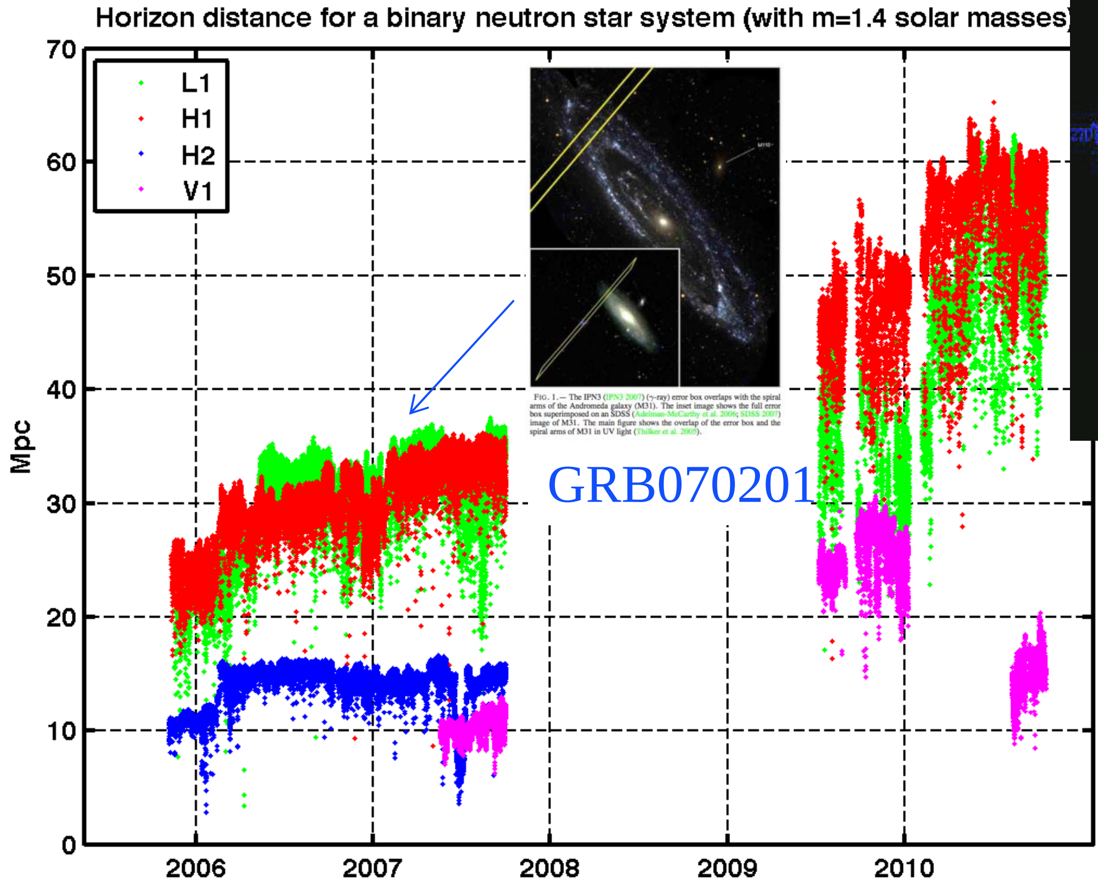
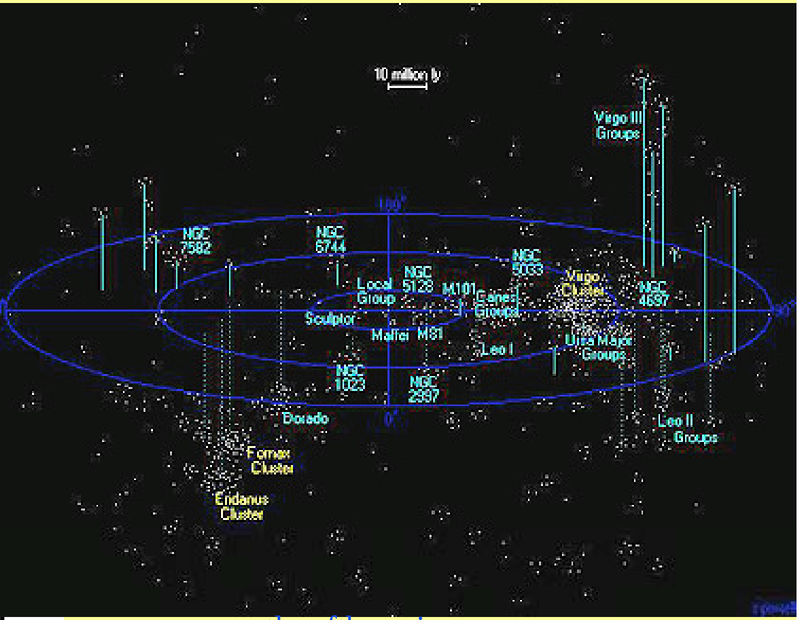


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (Adelman-McCarthy et al. 2006; SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).



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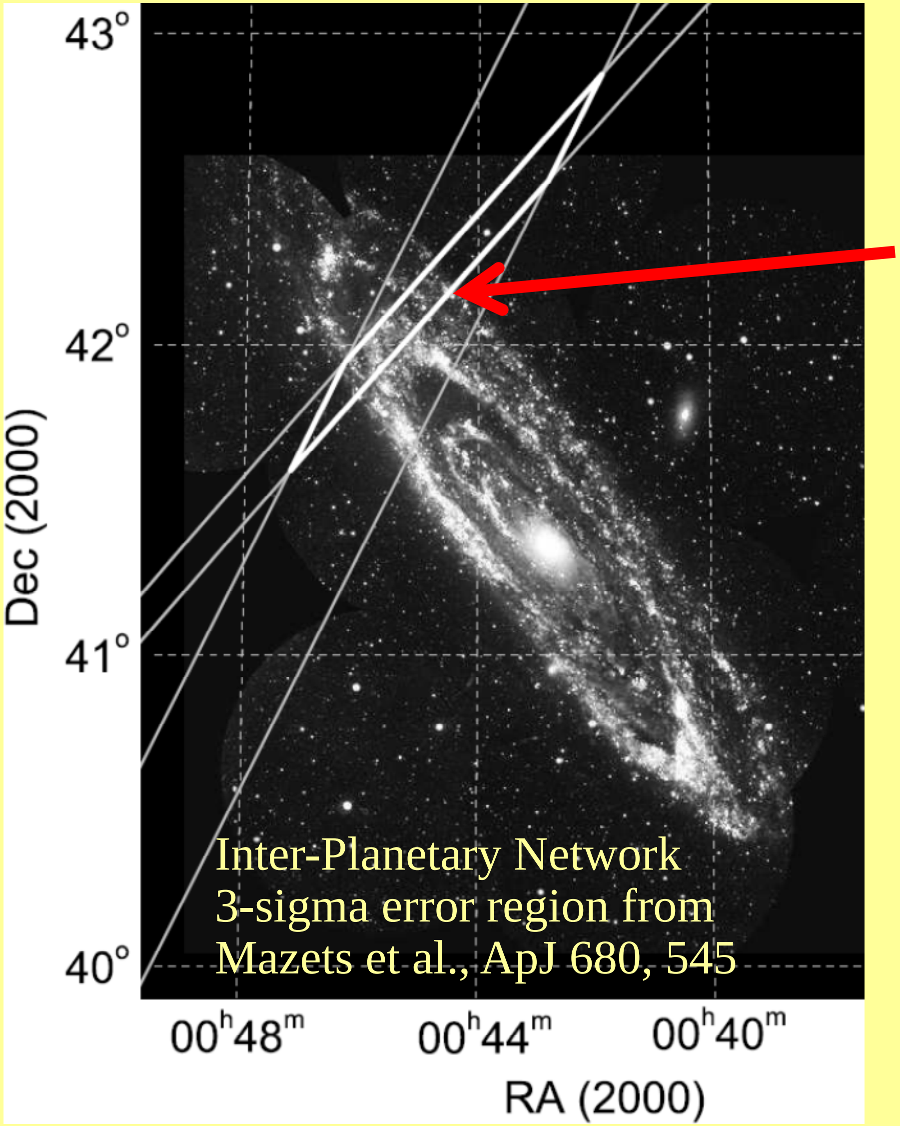
‘GRB 070201’



Inter-Planetary Network 3-sigma error region from Mazets et al., ApJ 680, 545

- Short, hard gamma-ray burst (GRB)
  - Leading model for short GRBs: merger involving a neutron star
- Position was consistent with being in M31 (Andromeda galaxy~ 0.78 Mpc from earth)

- Both LIGO Hanford detectors were operating
  - Searched for inspiral & burst signals
- No GW signal found ➔ very unlikely to be a merger in Andromeda

- **Abbott et al., ApJ 681, 1419 (2008)**

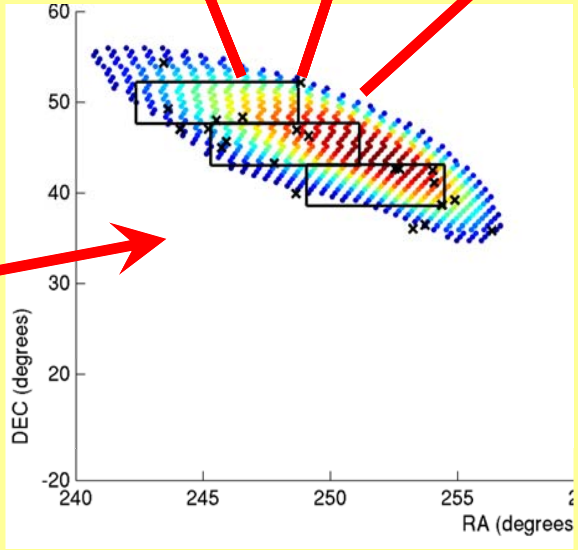
Similar analysis done for GRB 051103

- **Abadie et al., arXiv:1201.4413**

Electro-Magnetic Follow-ups

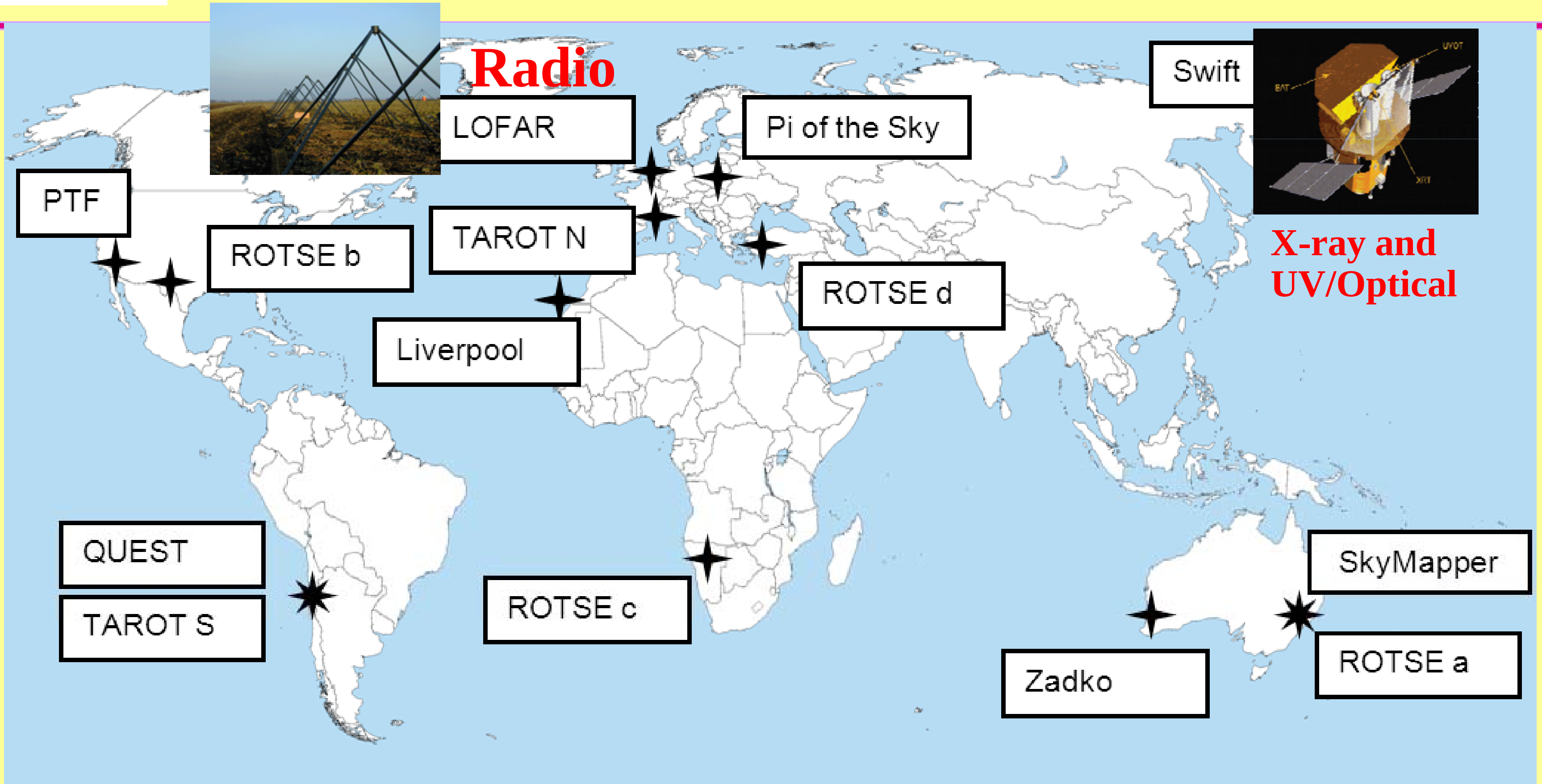
…

Analyze Gravitational Wave data, select candidates



[e.g. see Kanner et al., CQG 25, 184034]

Observing Partners During 2009–2010

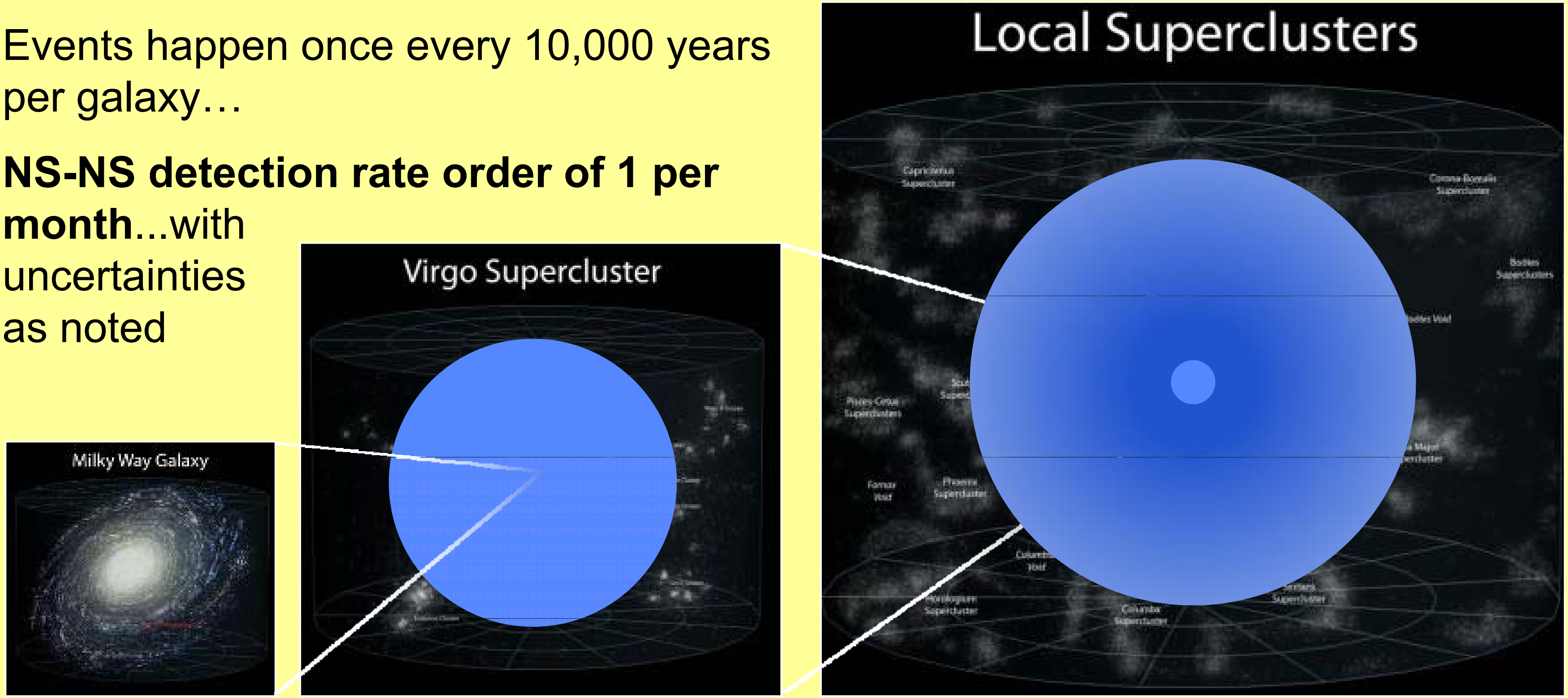


- Mostly (but not all) robotic wide-field optical telescopes
  - » Many of them used for following up Gamma Ray Bursts, surveying for supernovae and other optical transients

Advanced GW detector era – the coming years

Advanced GW detector sensitivity: a significant difference

- While observing with initial detectors, parallel R&D led to better concepts
- ‘Advanced detectors’ are ~10x more sensitive, will reach about 100,000 galaxies
- Events happen once every 10,000 years per galaxy…
- **NS-NS detection rate order of 1 per month**...with uncertainties as noted



M. Evans

Initial Reach

Advanced Reach

GW Detectors: 2015-2020

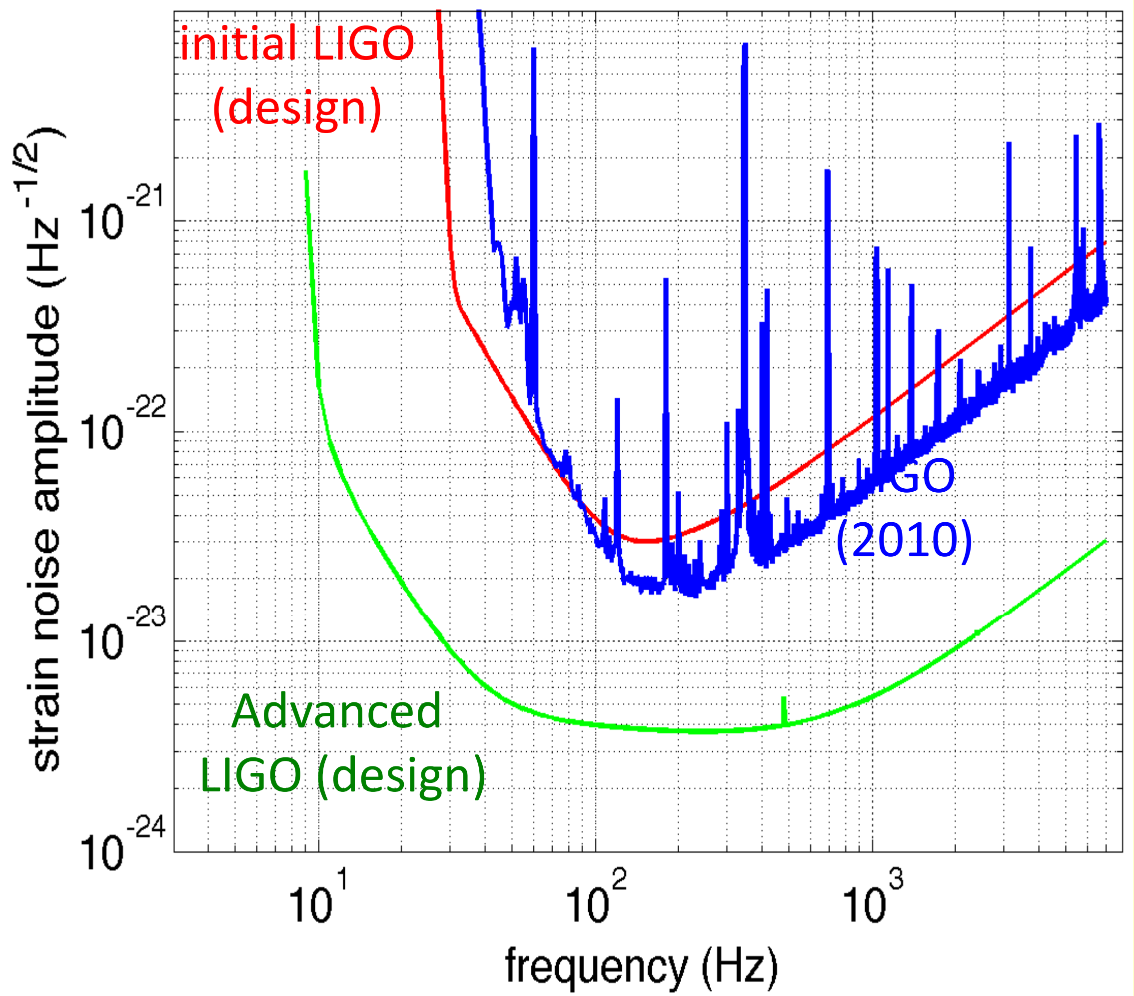
E.G

- LIGO’s maximum sensitive ranges:
  - NS-NS: 450 Mpc
  - NS-BH: 930 Mpc

- Expected detection rates:
  - NS-NS: 0.4 - 400 yr^{-1}
  - NS-BH: 0.2 – 300 yr^{-1}

Abadie et al., arXiv:1003.2480

Hardware upgrades to form aLIGO, aVirgo
(...with Geo-HF and KAGRA to form Advanced detector network)



Timescales Advanced LIGO

- Design began 1999 as a LIGO Scientific Collaboration concept paper
- Major Advanced LIGO R&D and designs during 1999-2006
- (Capital contributions via hardware by UK (2003), Germany, Australia)
- Final baseline review by NSF in November 2007
    - At this point, many aLIGO subsystem designs were far along
- **Advanced LIGO Project officially began on April 1, 2008**

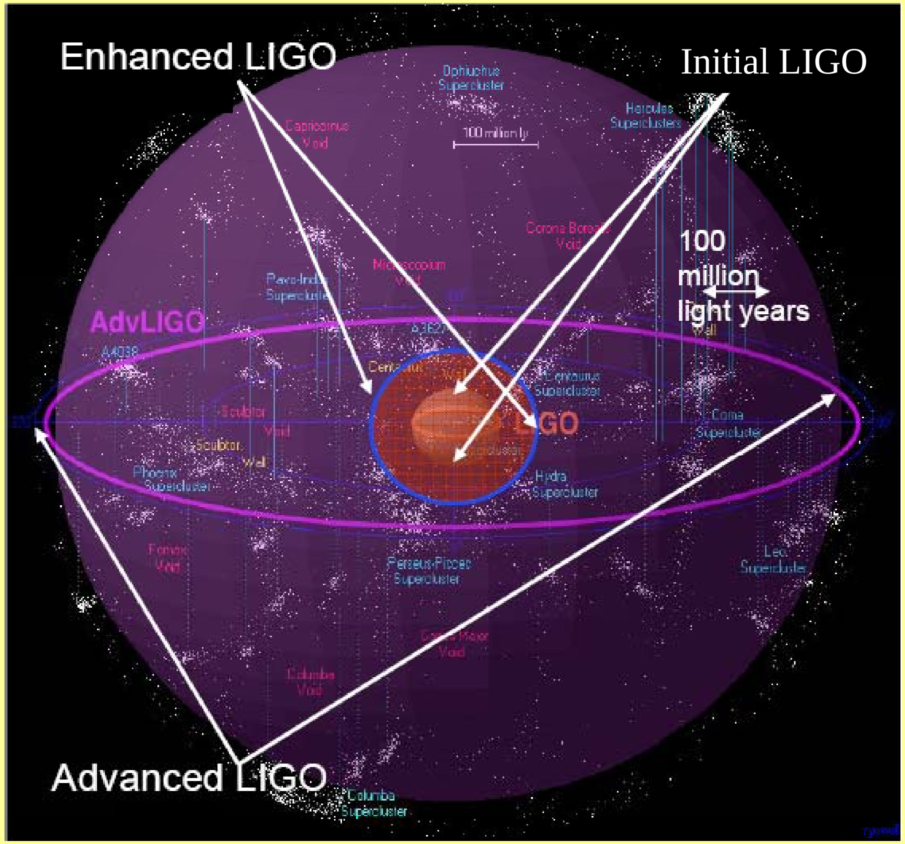
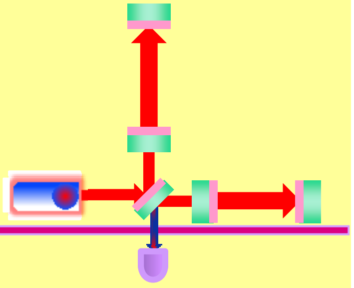
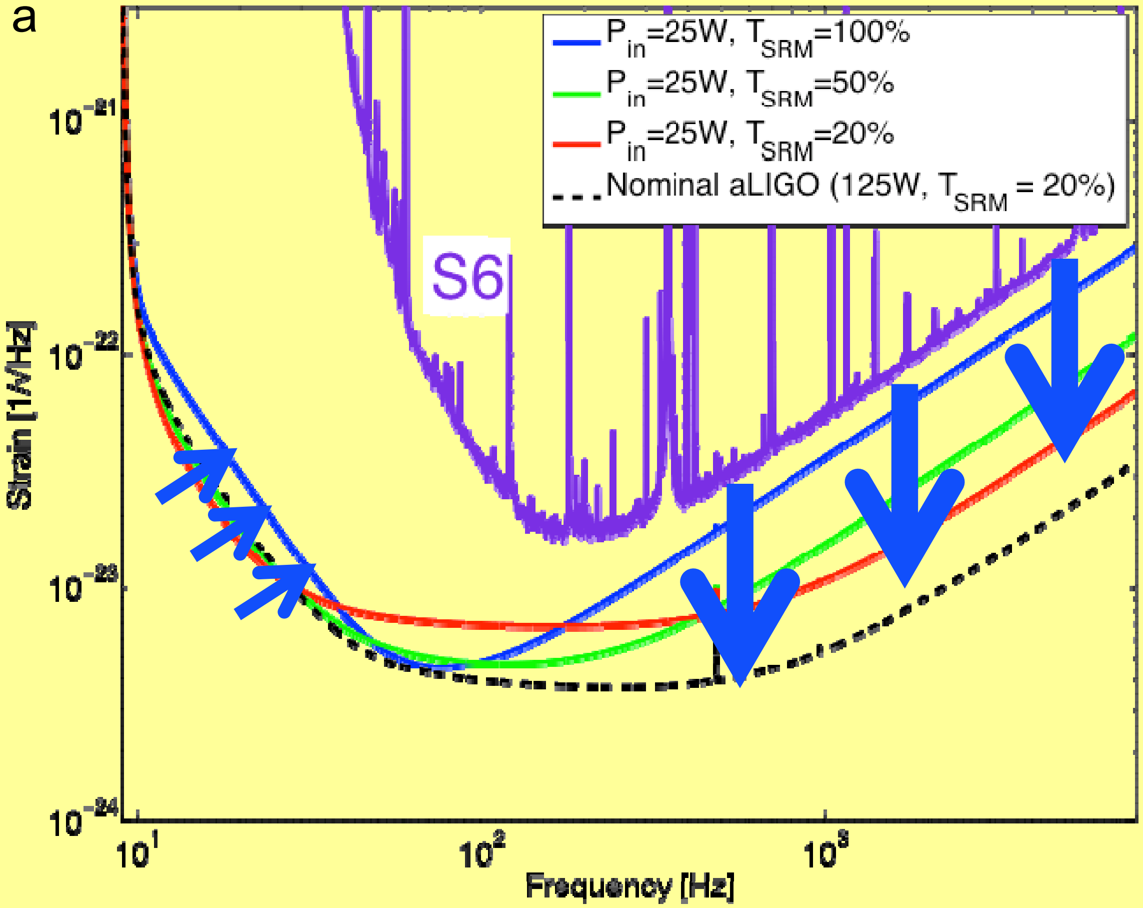


Image courtesy of Beverly Berger
Cluster map by Richard Powell

How to get there:
Addressing limits to performance

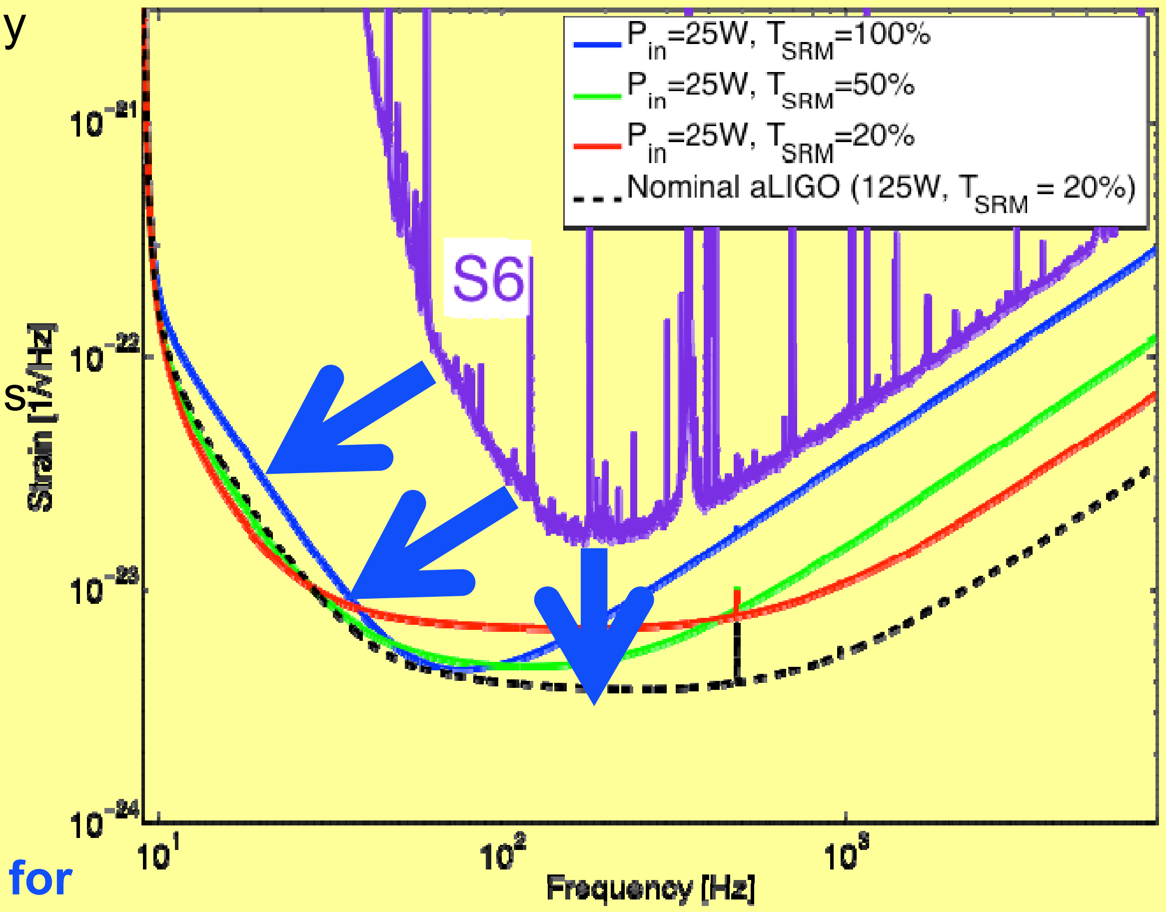


- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- Fringe Resolution at high frequencies improves as as (laser power)$^{1/2}$
- Point of diminishing returns when buffeting of test mass by photons increases low-frequency noise – use heavy test masses
- ‘Standard Quantum Limit’
- Advanced LIGO reaches this limit with its **200W laser, 40 kg test masses**



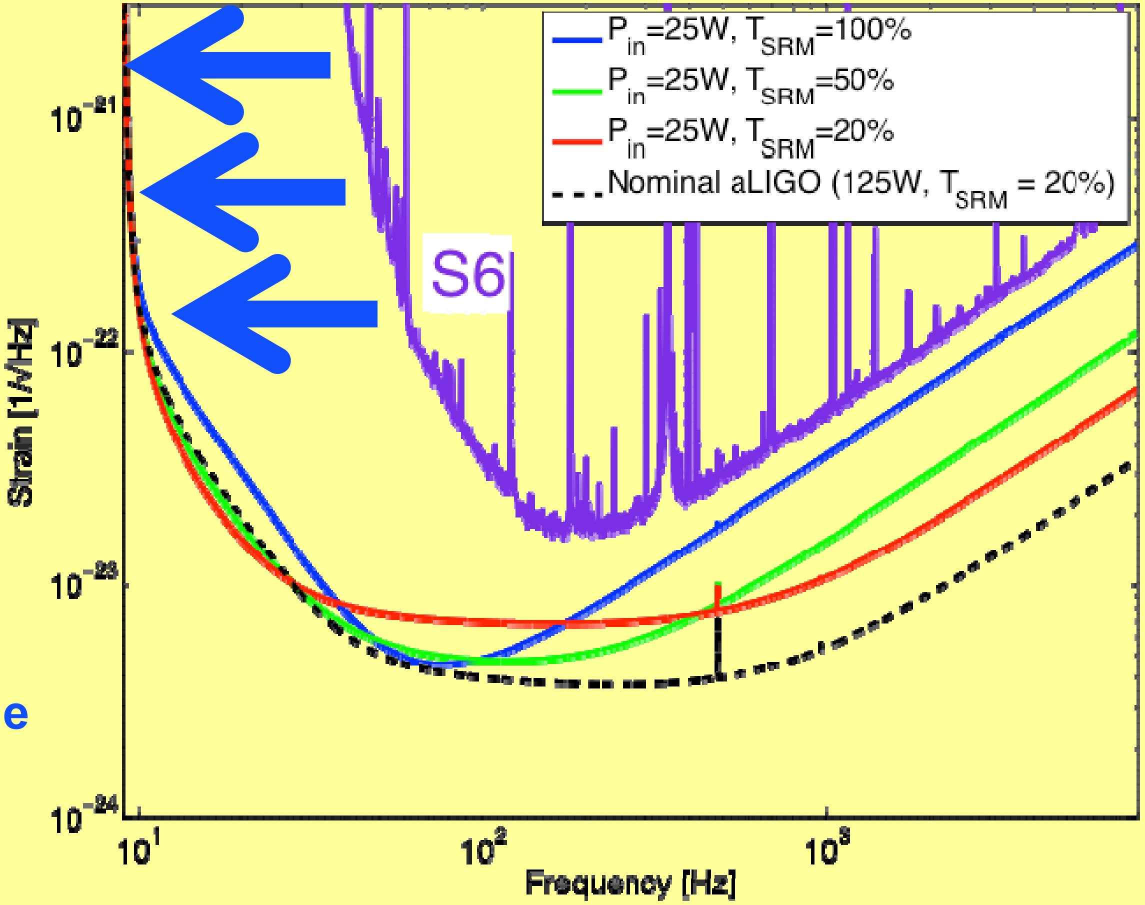
Addressing limits to performance

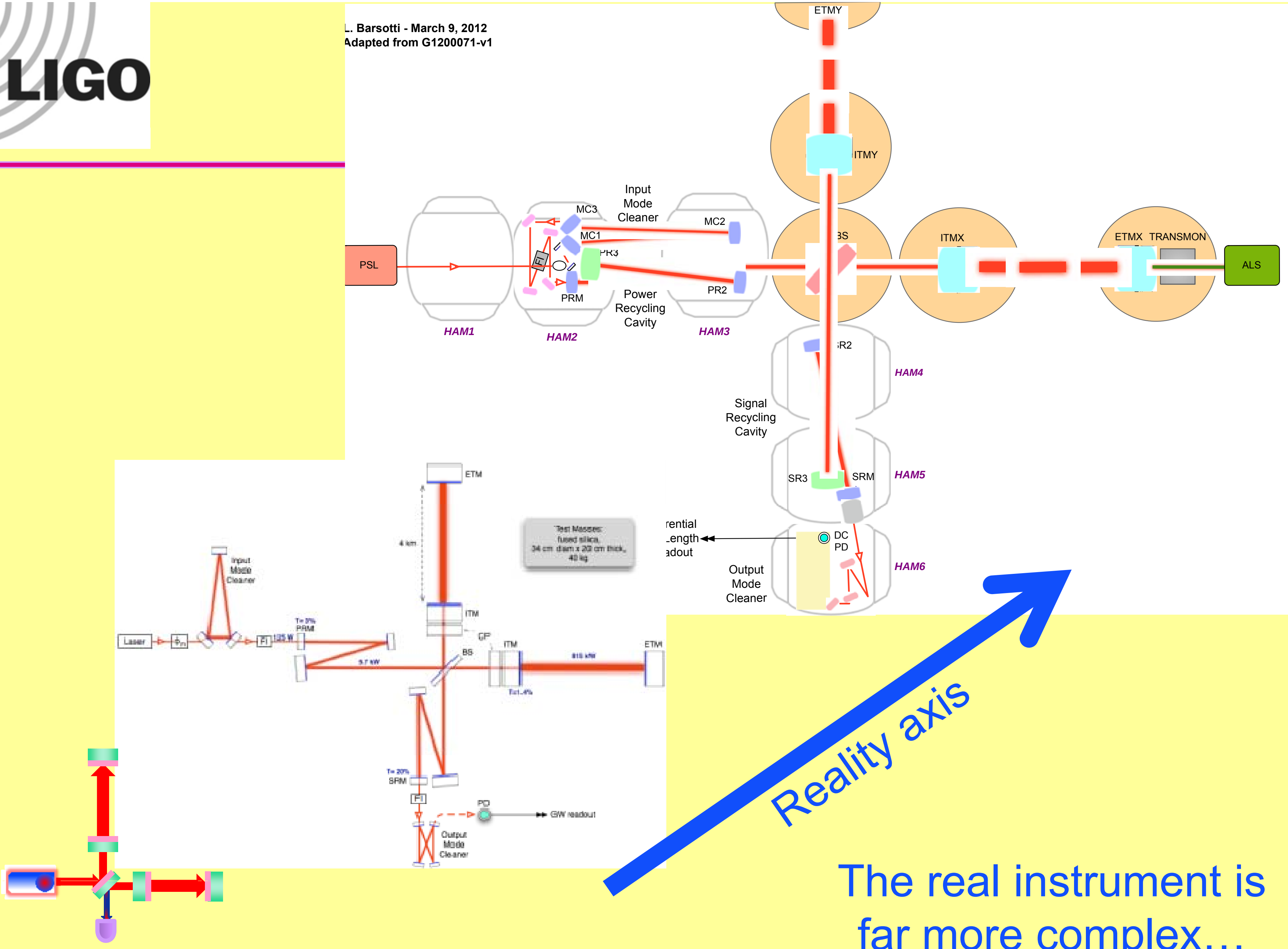
- **Thermal noise** – kT of energy per mechanical mode
- Wish to keep the motion of components due to thermal energy below the level which masks GW
- Low mechanical loss materials gather this motion into a narrow peak at resonant frequencies of system
- Realized in aLIGO with an all **fused-silica test mass suspension** – *Q* of order 10^9
- **Test mass internal modes, Mirror coatings engineered for low mechanical loss**



Addressing limits to performance

- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- Motion from waves on coasts…and people moving around
- GW band: 10 Hz and above – direct effect of masking
- Control Band: below 10 Hz – forces needed to hold optics on resonance and aligned
- aLIGO uses **active servo-controlled platforms, multiple pendulums**
- Ultimate limit on the ground: Newtownian background – wandering net gravity vector; a limit in the 10-20 Hz band



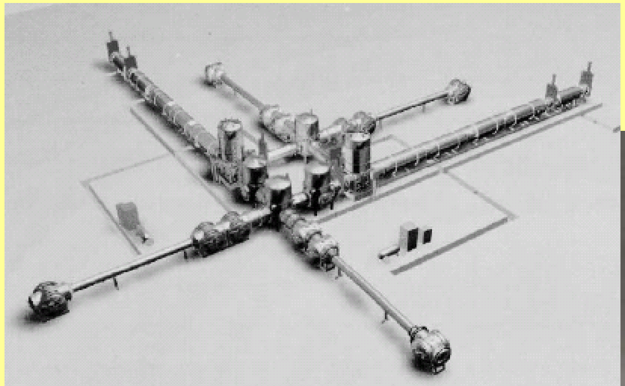


The real instrument is far more complex…

Existing infrastructure : 4km Beam Tubes

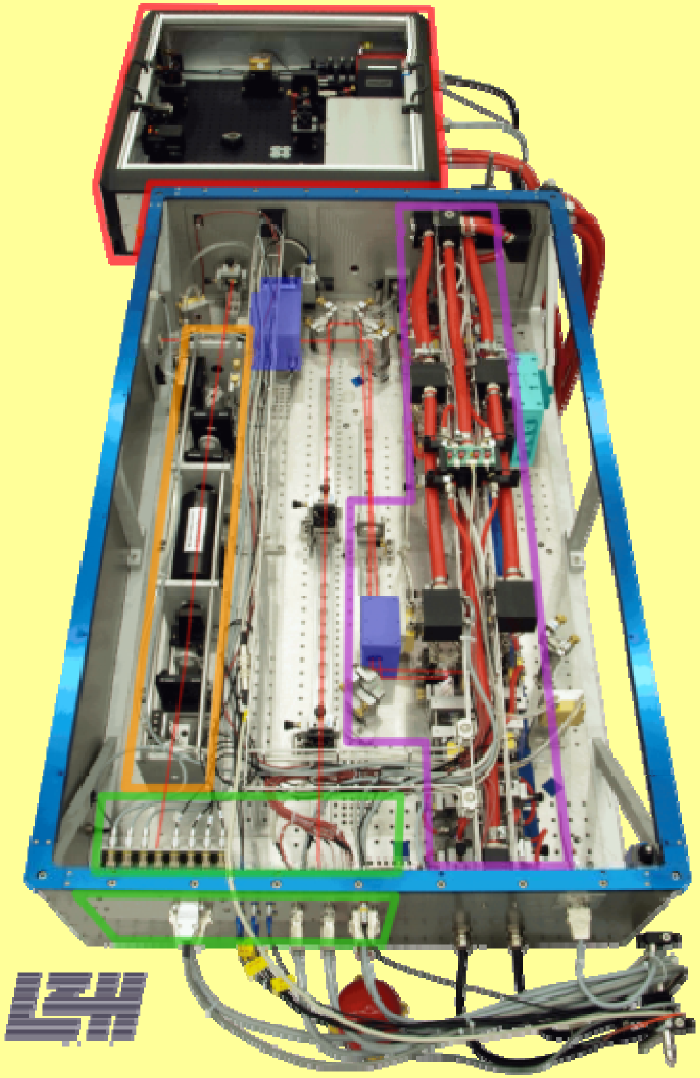
- Light must travel in an excellent vacuum
  - Just a few molecules traversing the optical path makes a detectable change in path length, masking GWs
  - 1.2 m diameter – avoid scattering against walls
- Cover over the tube – stops hunters' bullets and the stray car
- Tube is straight to a fraction of a cm…not like the earth's curved surface

LIGO Vacuum Equipment – designed for several generations of instruments



200W Nd:YAG laser

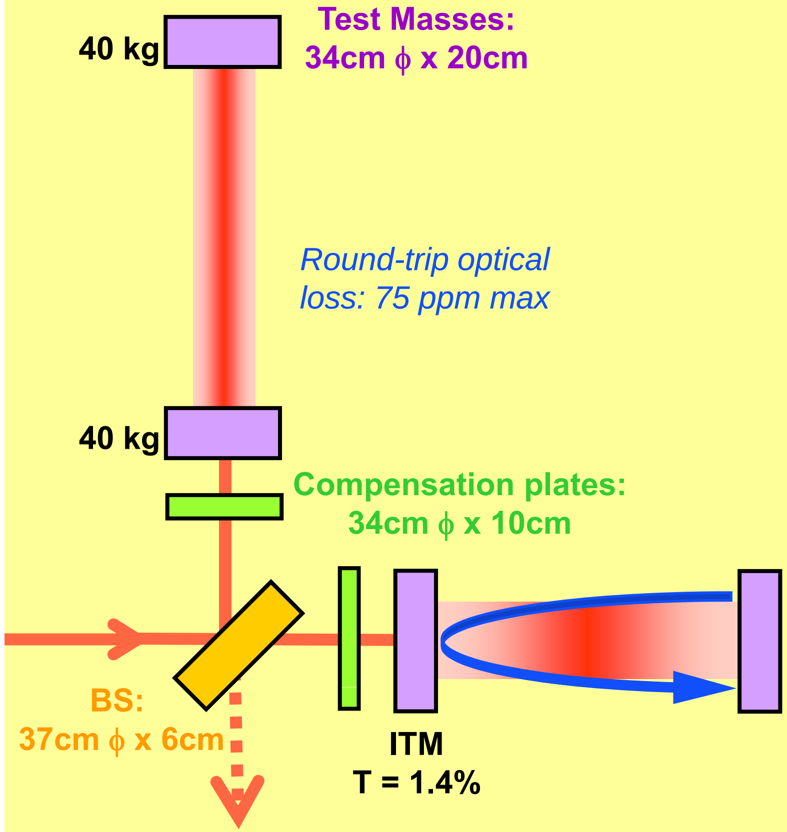
Designed and contributed by
Max Planck Albert Einstein Institute

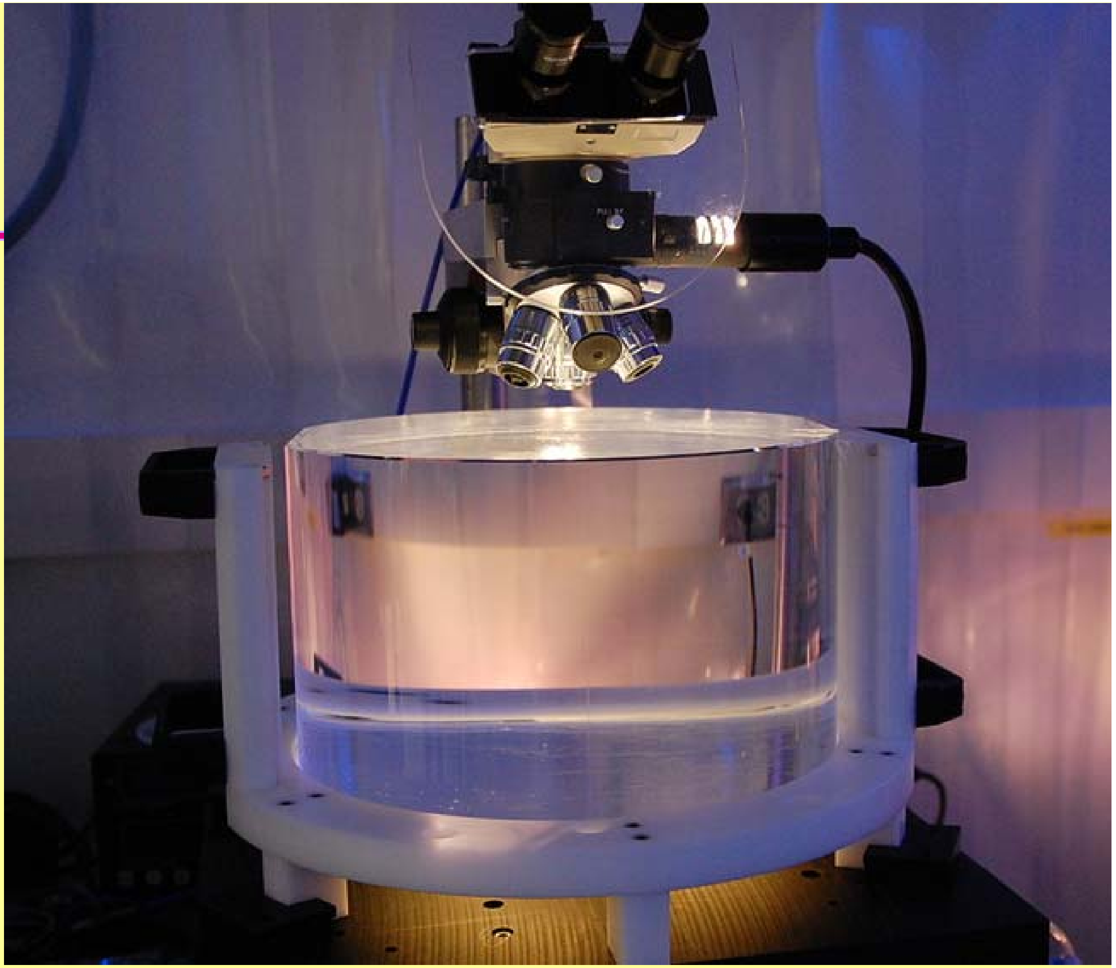


- Stabilized in power and frequency
- Uses a monolithic master oscillator followed by injection-locked rod amplifier

Test Masses

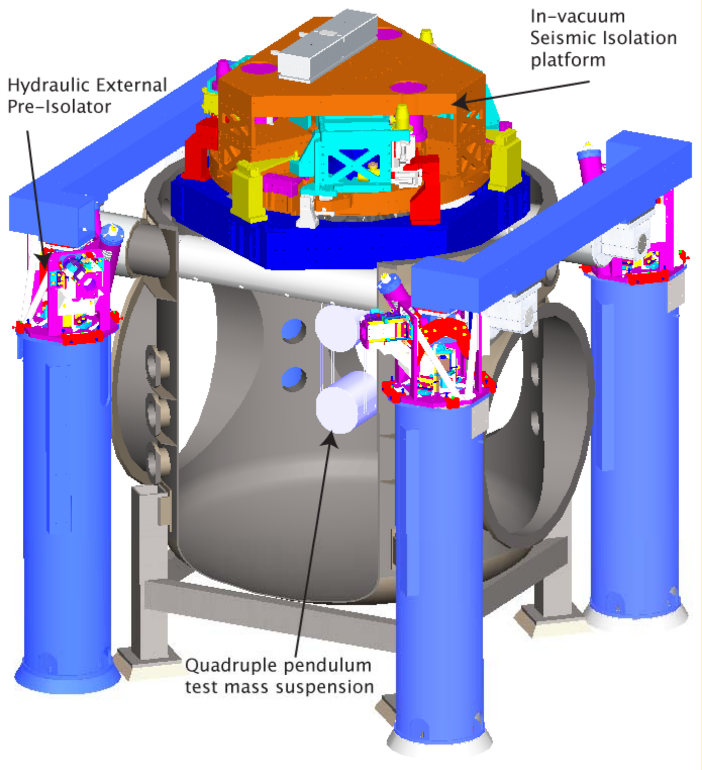
- Requires the state of the art in substrates and polishing
- Pushes the art for coating
- Sum-nm flatness over 300mm



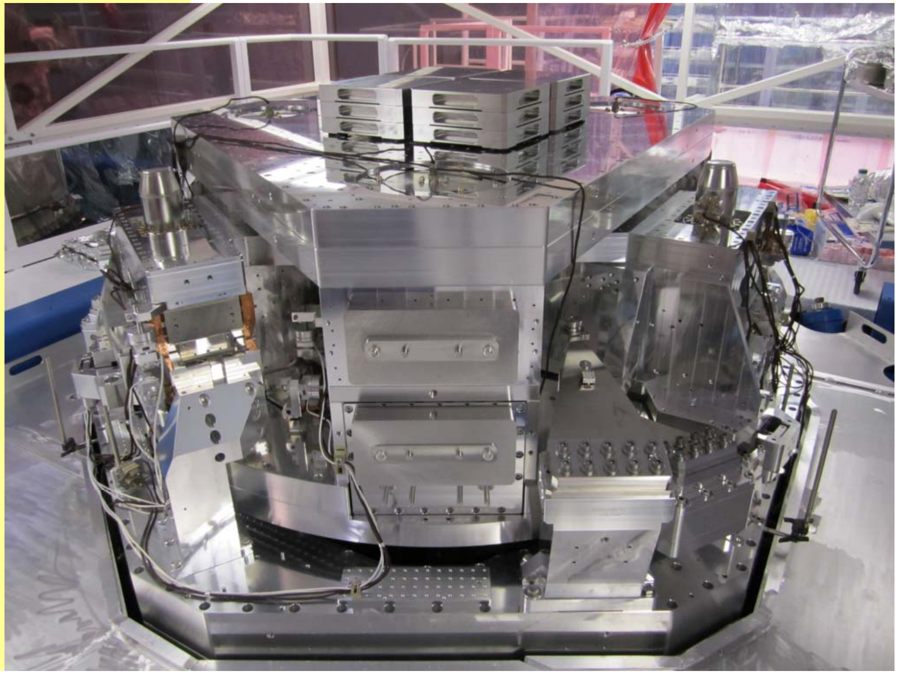


- ☐ Both the physical test mass – a free point in space-time – and a crucial optical element
- ☐ Mechanical requirements: bulk and coating thermal noise, high resonant frequency
- ☐ Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

Seismic Isolation: Multi-Stage Solution



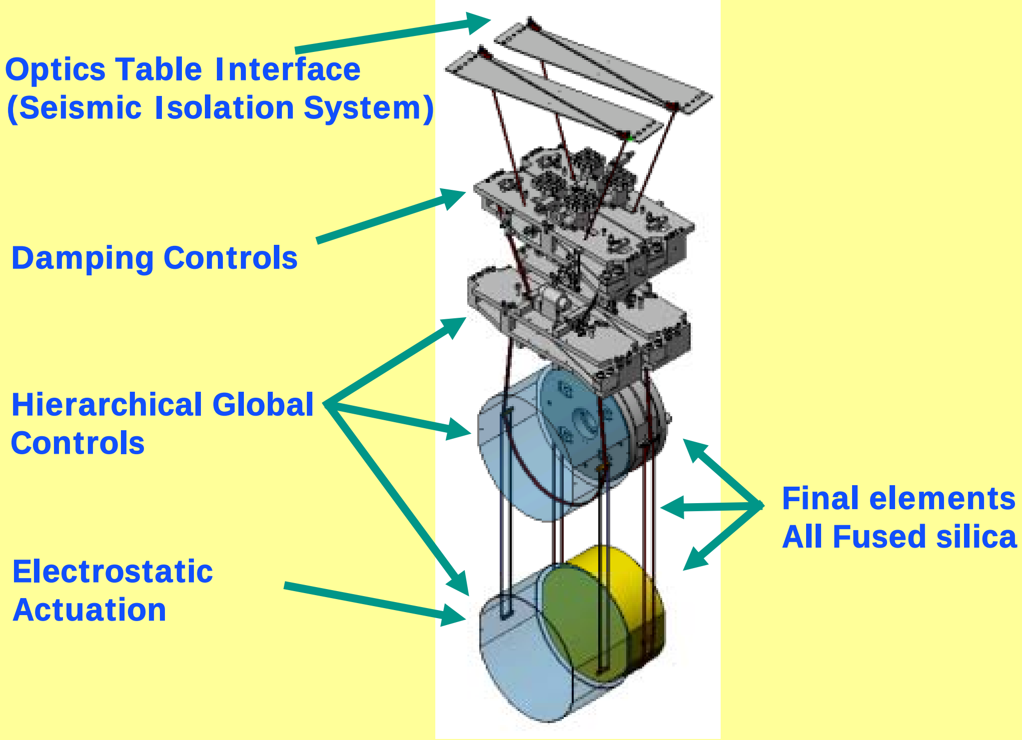
- Objectives:
  - Render seismic noise a negligible limitation to GW searches
  - Reduce actuation forces on test masses
- Both suspension and seismic isolation systems contribute to attenuation
- Choose an active isolation approach, 3 stages of 6 degrees-of-freedom :
  - 1) Hydraulic External Pre-Isolation
  - 2) Two Active Stages of Internal Seismic Isolation
- Low noise sensors (position, velocity, acceleration) are combined, passed through a servo amplifier, and delivered to the optimal actuator as a function of frequency to hold platform still in inertial space



Test Mass Quadruple Pendulum suspension

designed jointly by the UK and LIGO lab,
with capital contribution funded by PPARC/STFC

- Quadruple pendulum suspensions for the main optics; second ‘reaction’ mass to give quiet point from which to push
- Create quasi-monolithic pendulums using fused silica fibers to suspend 40 kg test mass
  - VERY Low thermal noise



Optics Table Interface (Seismic Isolation System)

Damping Controls

Hierarchical Global Controls

Electrostatic Actuation

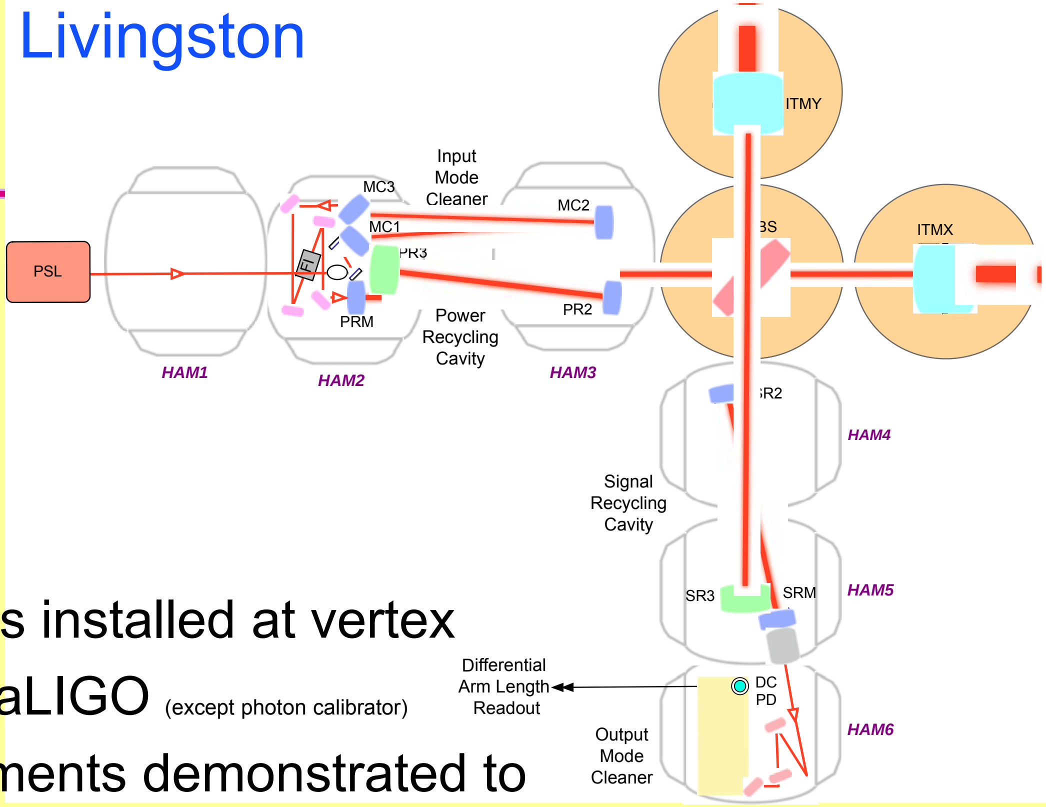
Final elements All Fused silica

Suspension testing

Big Picture as of now

- The detector subsystems are 99.1% complete : procurement, fabrication, cleaning, assembly, and stand-alone testing
- Most of the hardware is now installed; almost every vacuum chamber has almost every component in it
- At both observatories, installation is now interleaved with integrated test – multiple subsystems working together
- Believe we can deliver instruments ready for commissioning on time
  - Have used several months of schedule over last 6 months due to installation hitches, surprises, etc; getting close to the end date…
  - Have some cost contingency remaining to handle problems
  - so far integrated test schedule matches planning, (*really* good news)

Accomplishments: Livingston observatory

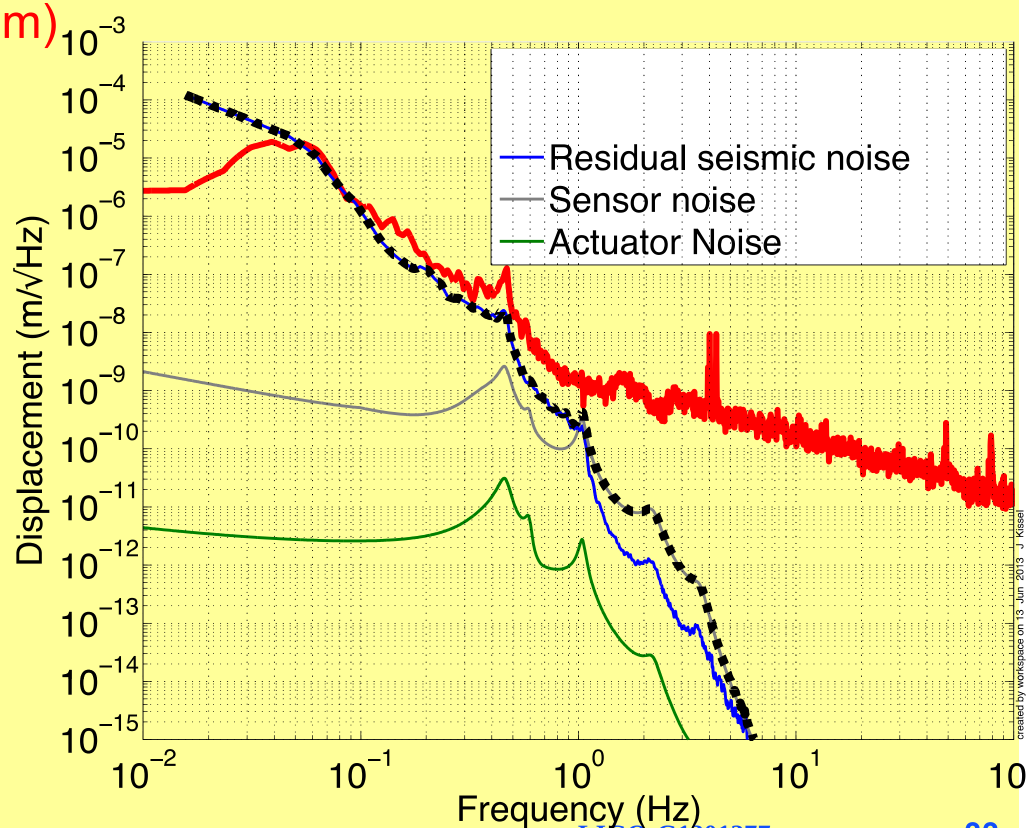


- **Dual-recycled Michelson Interferometer**
  - All interferometer components installed at vertex
  - Uses every ifo subsystem in aLIGO (except photon calibrator)
  - System easily locked; all elements demonstrated to work together,
  - End test masses now being installed;
- **Plans: All installed March 2014 → LSC access to subsystems**
  - **2-hour lock November ’14 → LSC access to commissioning**

Accomplishments: Hanford observatory

- **Half-Interferometer i**ncluding 4km arm
  - Demonstrated ability with Arm Length Stabilization system (green light through end mirror) to lock, and position 4km cavity at any point
  - (Pre-Lock Arm Length Stabilization Contributed by Australian consortium)
  - Cavity motion in good agreement with seismic and suspension models (laser noise dominates at high frequencies as expected)

- **Plans: All installed July ’14**
  → LSC access to subsystems
- **2-hour lock December ’14**
  → LSC commissioning

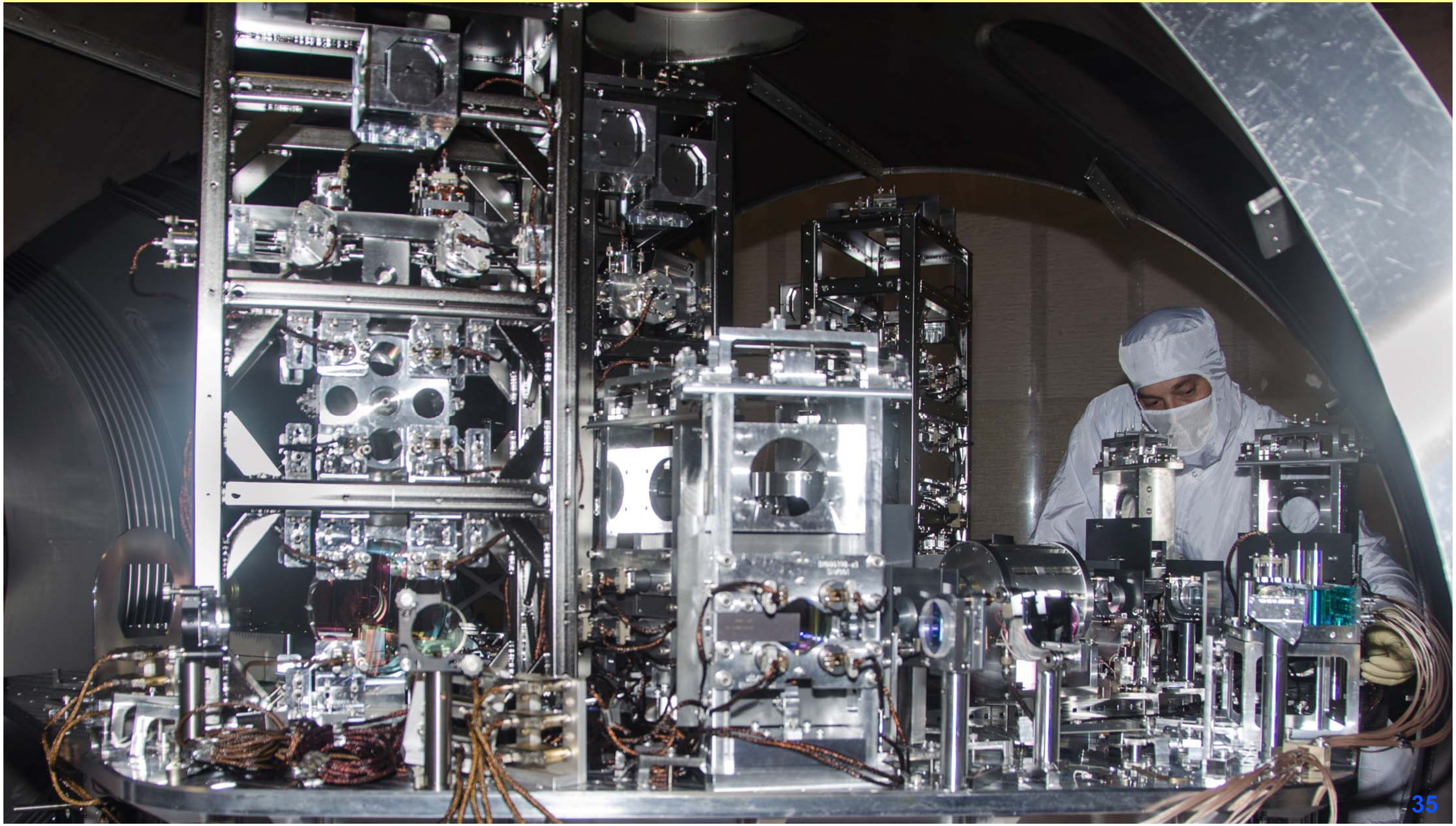


What else to Complete?

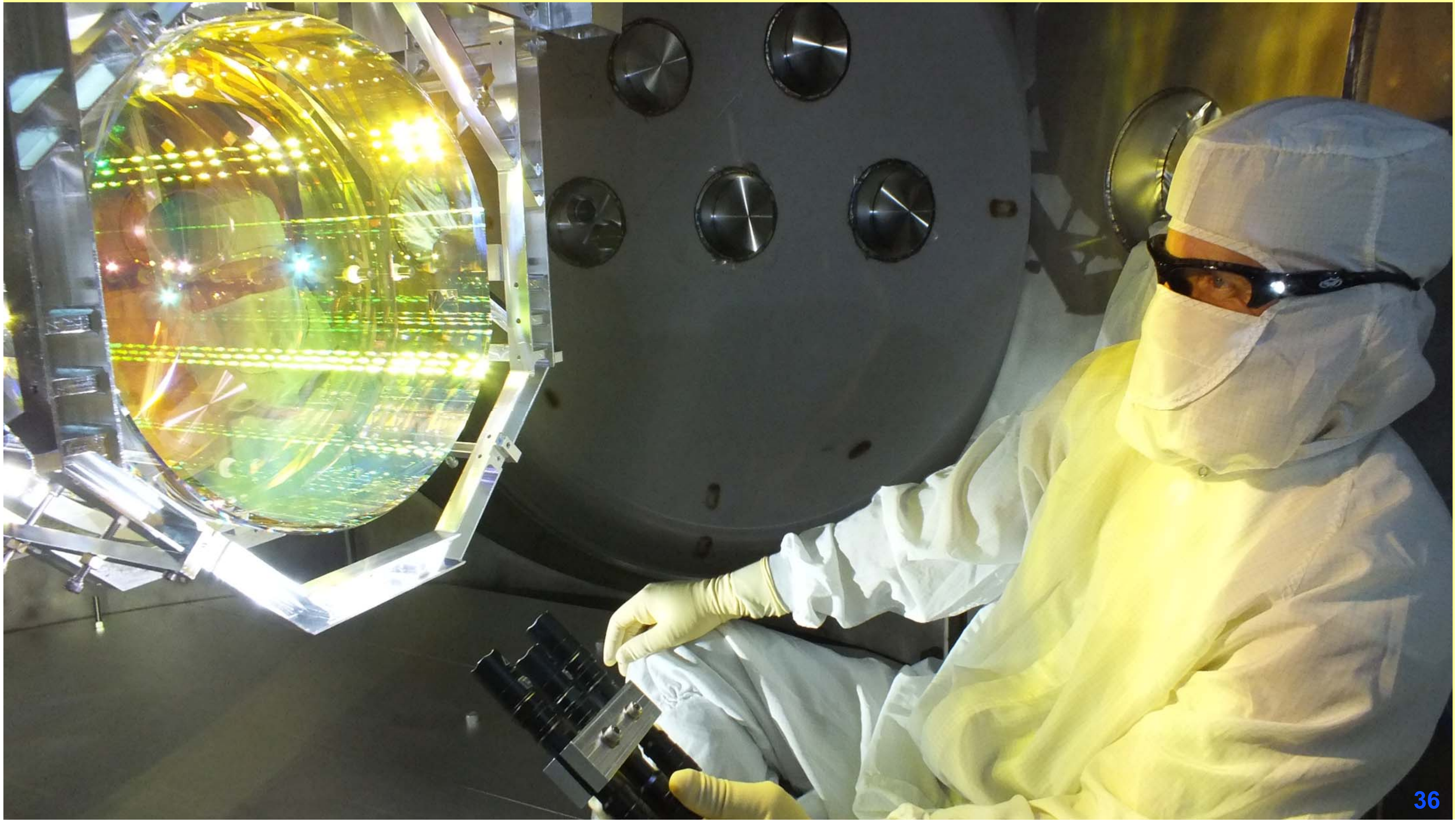
- Continued interleaved installation and integrated test
- Data and Computing Storage procurement, installation, test
  - NSF wishes to review plans

- aLIGO into the 'end game'
  - Only $26M out of $205M remain, and ~$13M of that in computers
  - Staffing now at ~115 full-time-equivalent persons – peak of ~200
- The Transition to Operations
  - Positioning the project AND operations organization for the commissioning

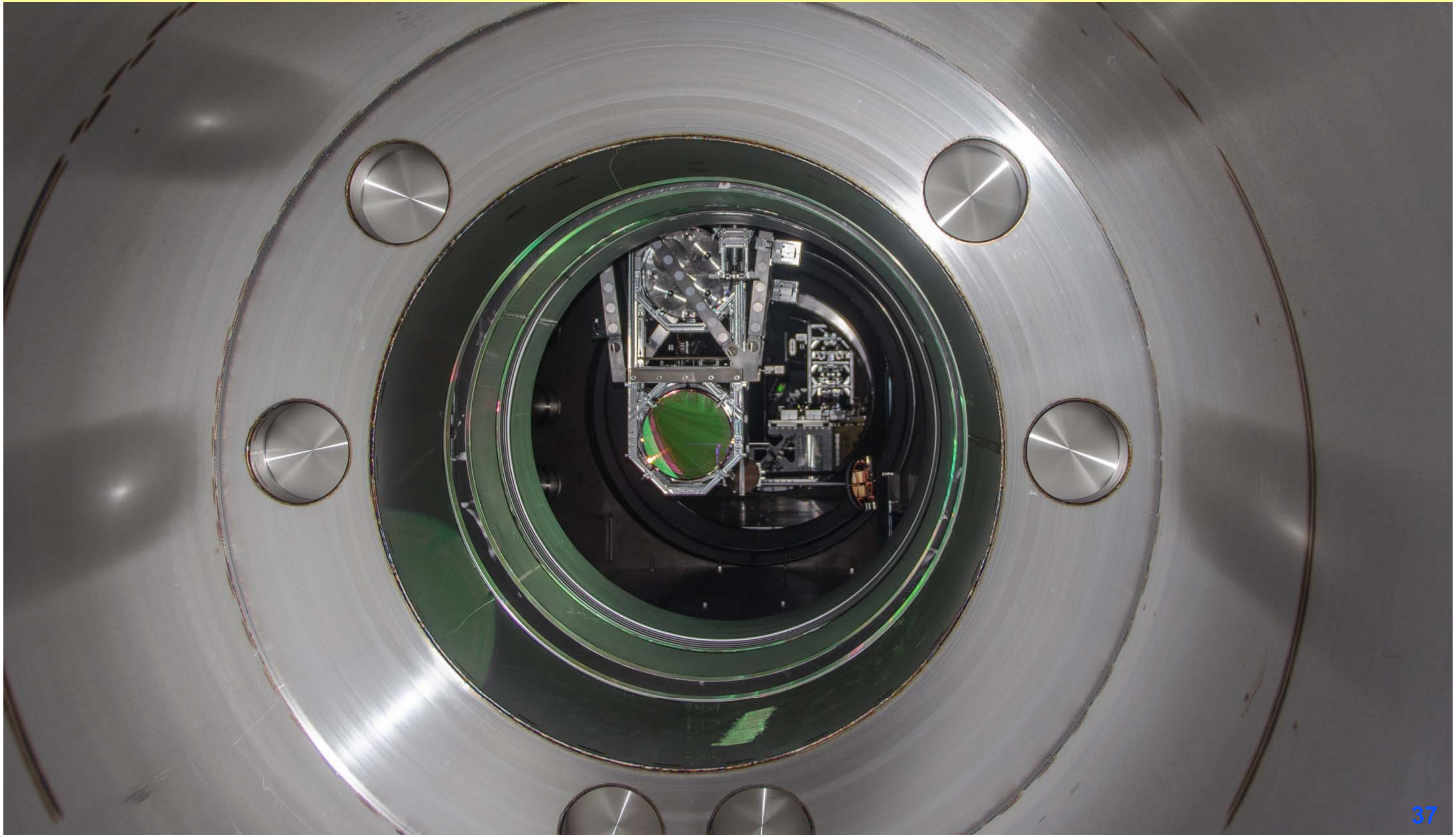
A few family photos: Livingston site (mode cleaner, recycling optics)



Inspecting an Input Tess Mass surface

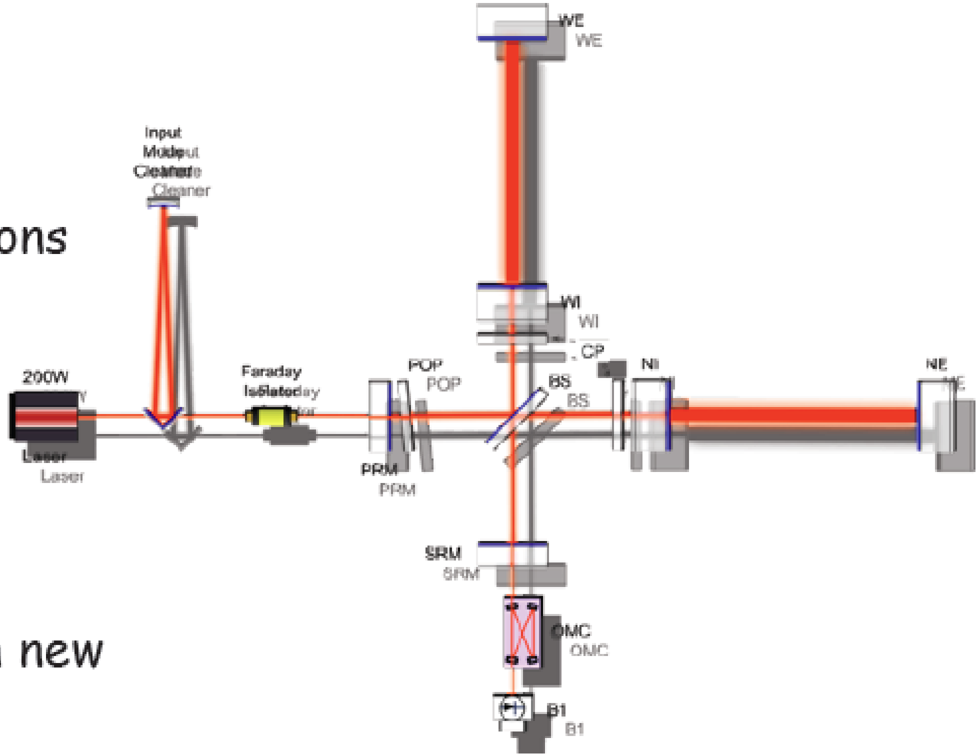


Input Test Mass viewed from the Beam Tube side



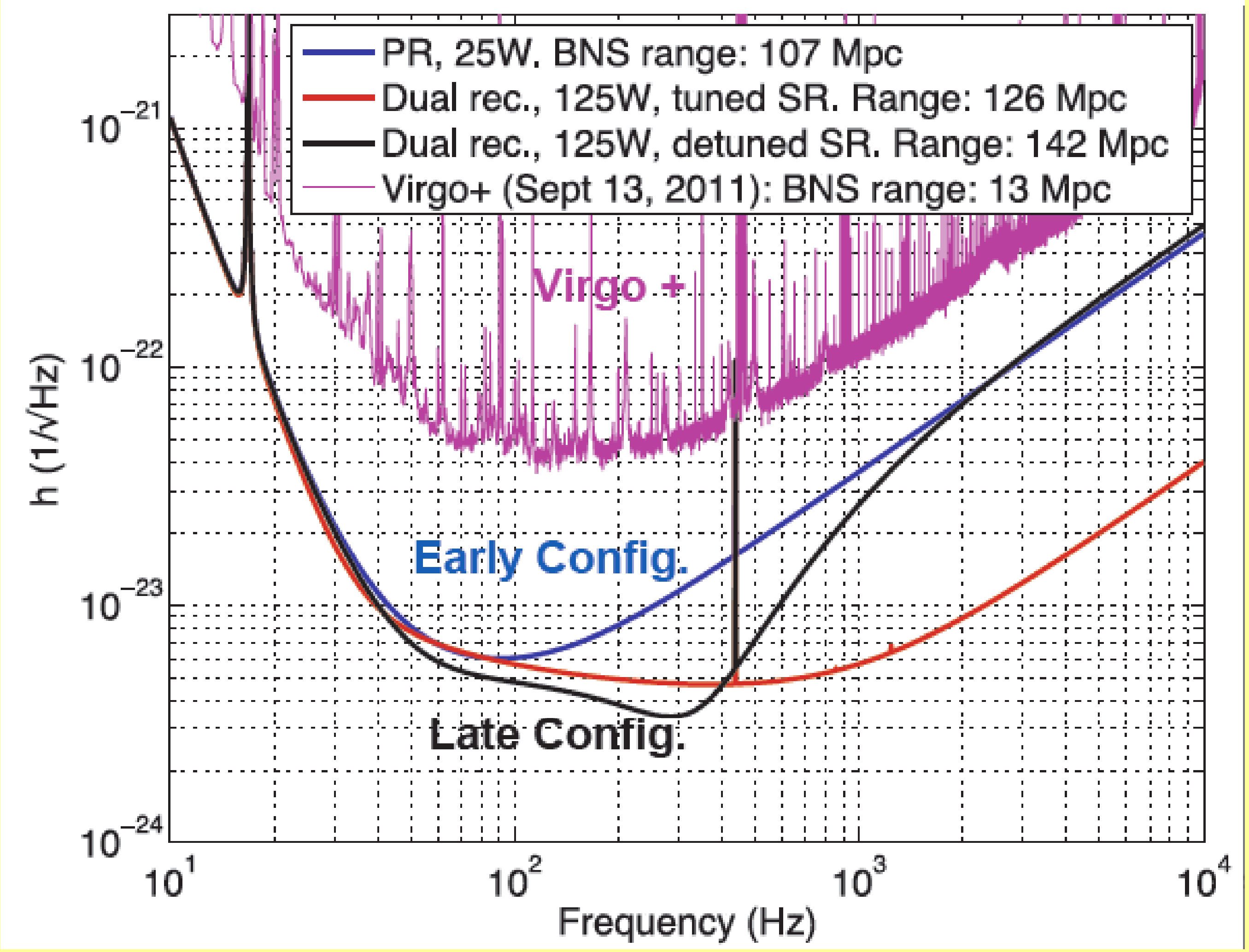
In parallel – Advanced Virgo

- Main changes with respect to VIRGO:
  - larger beam
  - heavier mirrors
  - higher quality optics
  - thermal control of aberrations
  - 200W fiber laser
  - Signal Recycling



- Vibration isolation by VIRGO Superattenuators:
  - performance compliant with new requirements
  - wide experience with commissioning at low frequency

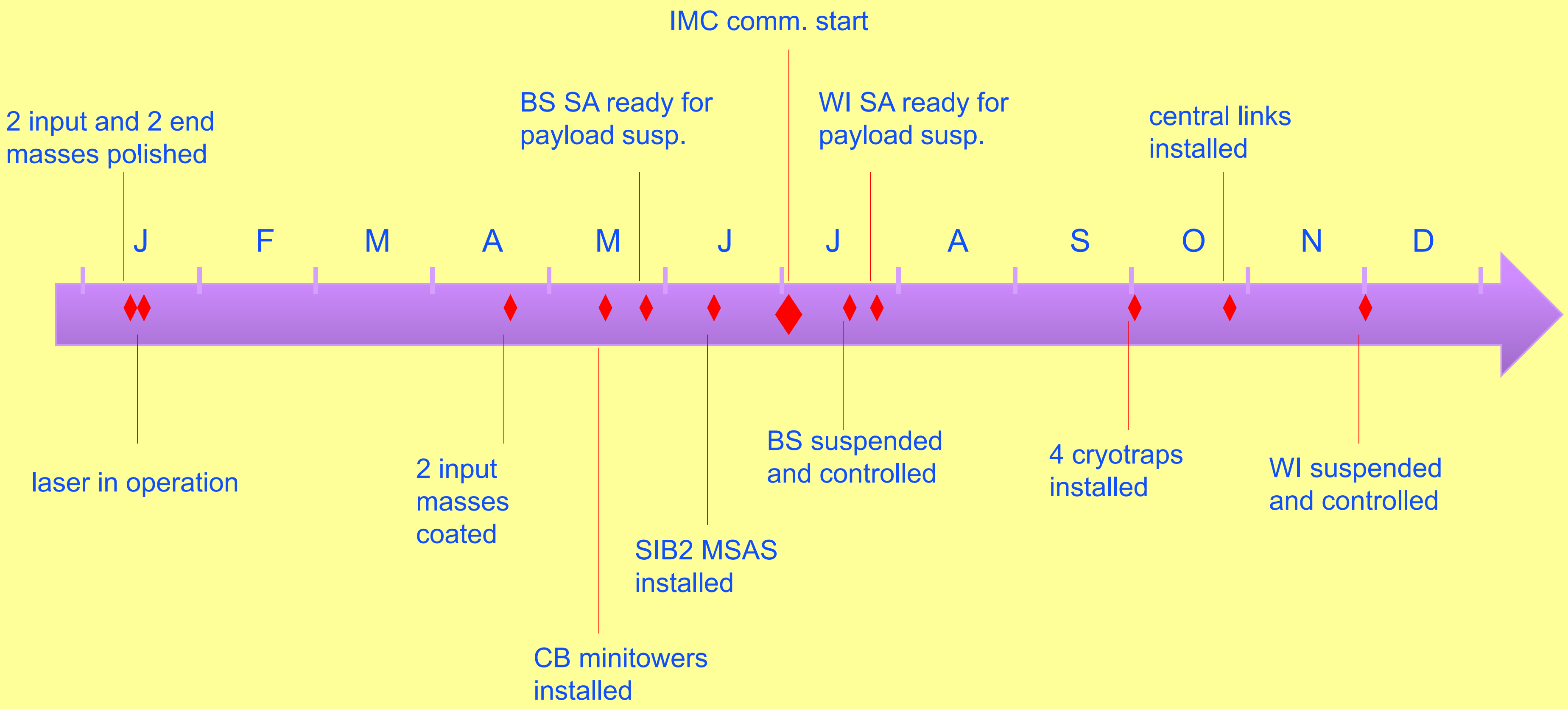
Staged implementation



- Top level milestones
  commissioning of input mode cleaner to start mid 2014
  construction ends 7/15

- Strategy pursued so far:
  Start with a simplified configuration likely to speed up commissioning (no SR, low power)

MILESTONES FOR THE NEXT YEAR



IMC comm. start

2 input and 2 end masses polished

BS SA ready for payload susp.

WI SA ready for payload susp.

central links installed

J F M A M J J A S O N D

laser in operation

2 input masses coated

CB minitowers installed

SIB2 MSAS installed

BS suspended and controlled

4 cryotraps installed

WI suspended and controlled

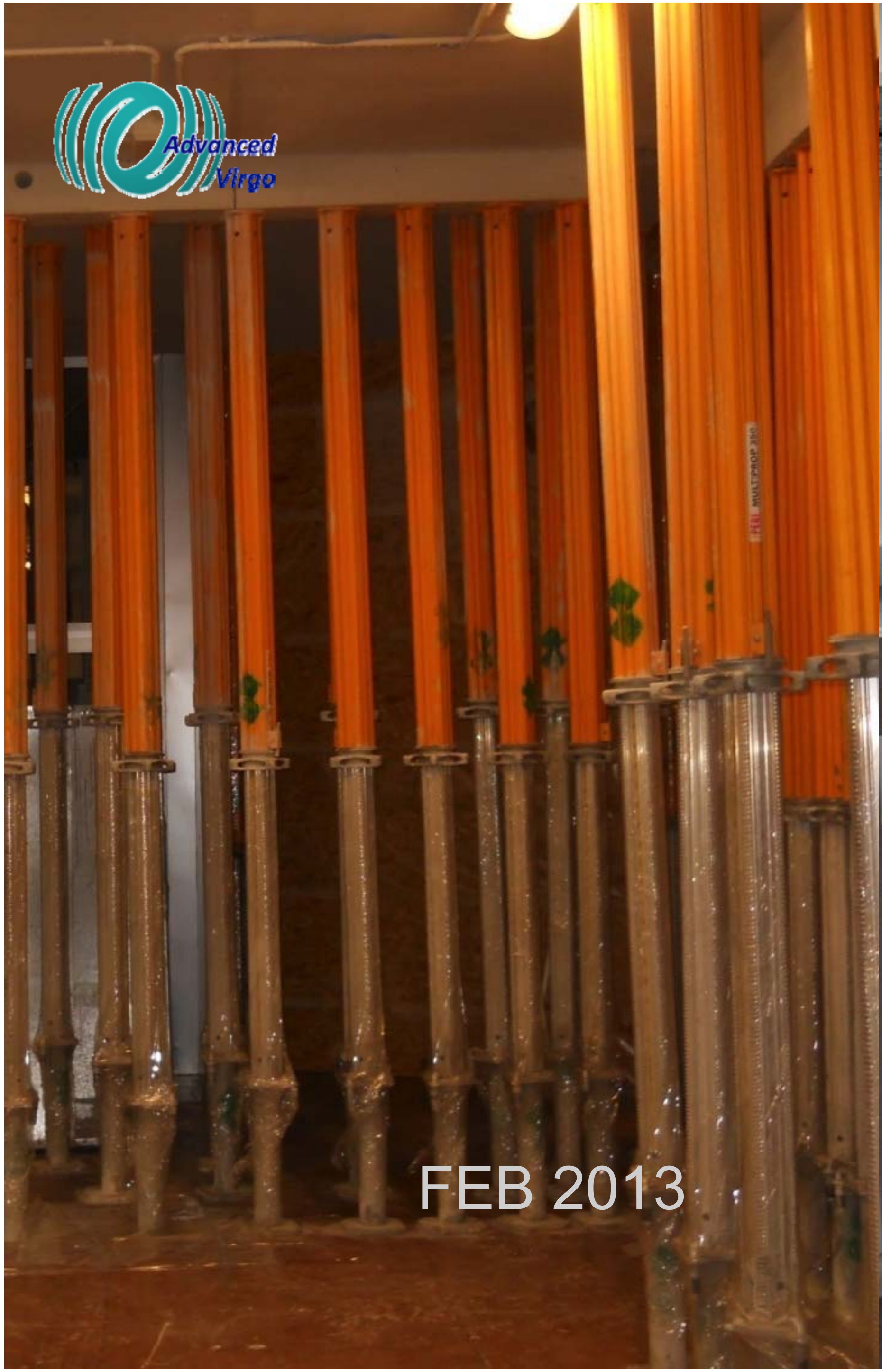
Infrastructure upgrades

- Civil engineering : Injection/Detection clean laboratories
  - civil works completed
  - final details being worked out
  - start-up/tests in 1-2 weeks

DET lab

INJ lab

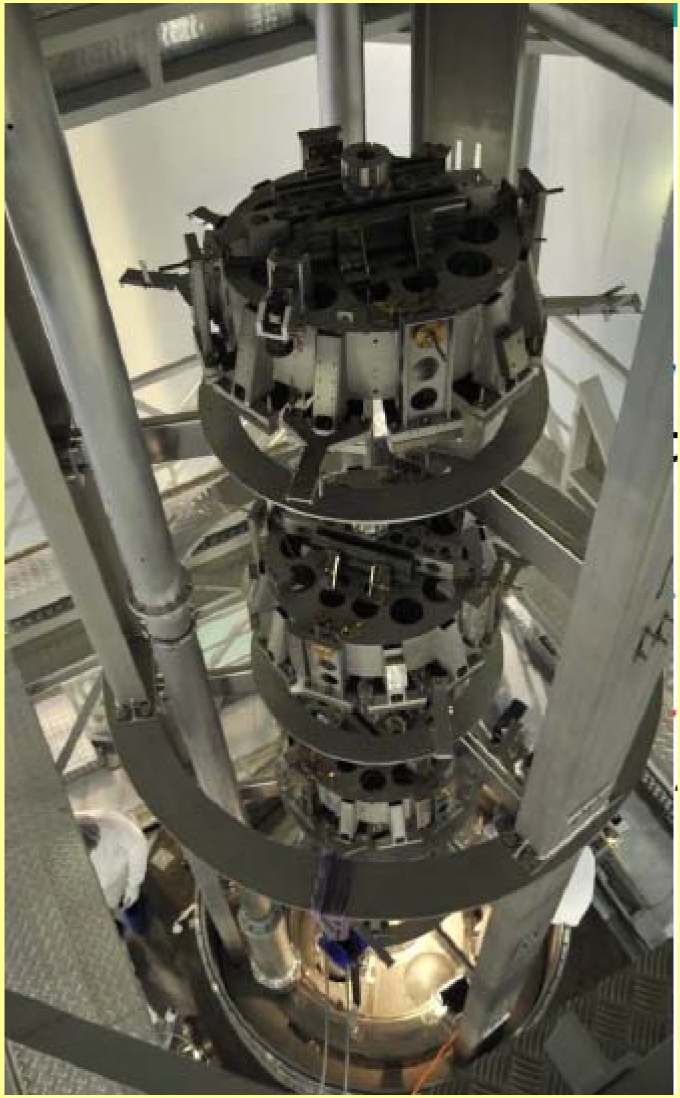
Advanced Virgo



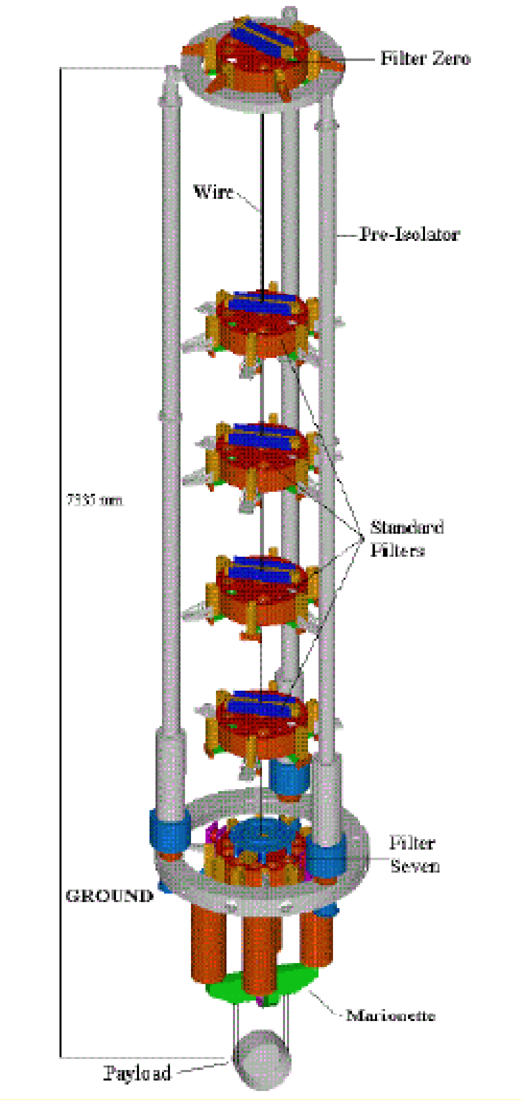
FEB 2013

OCT 2013

Suspension upgrade of the main optical elements

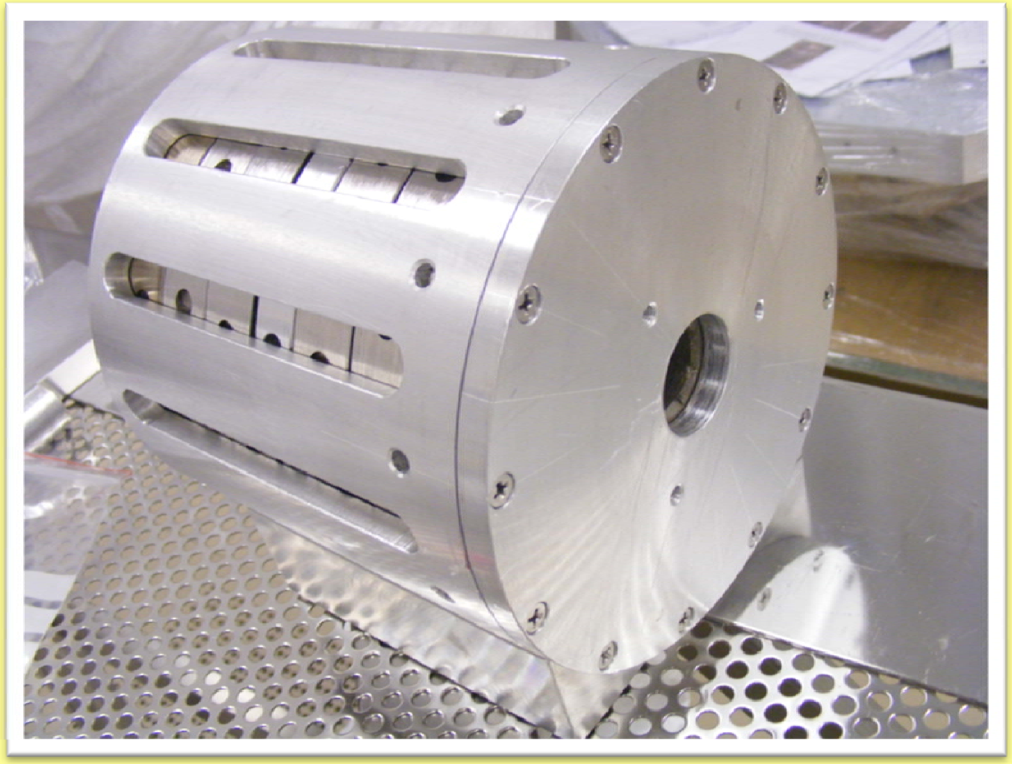


- The superattenuators suspending the input mode cleaner cavity have been upgraded:
  - one more filter for extra isolation
  - possibility to control the tilt (actuators in place)

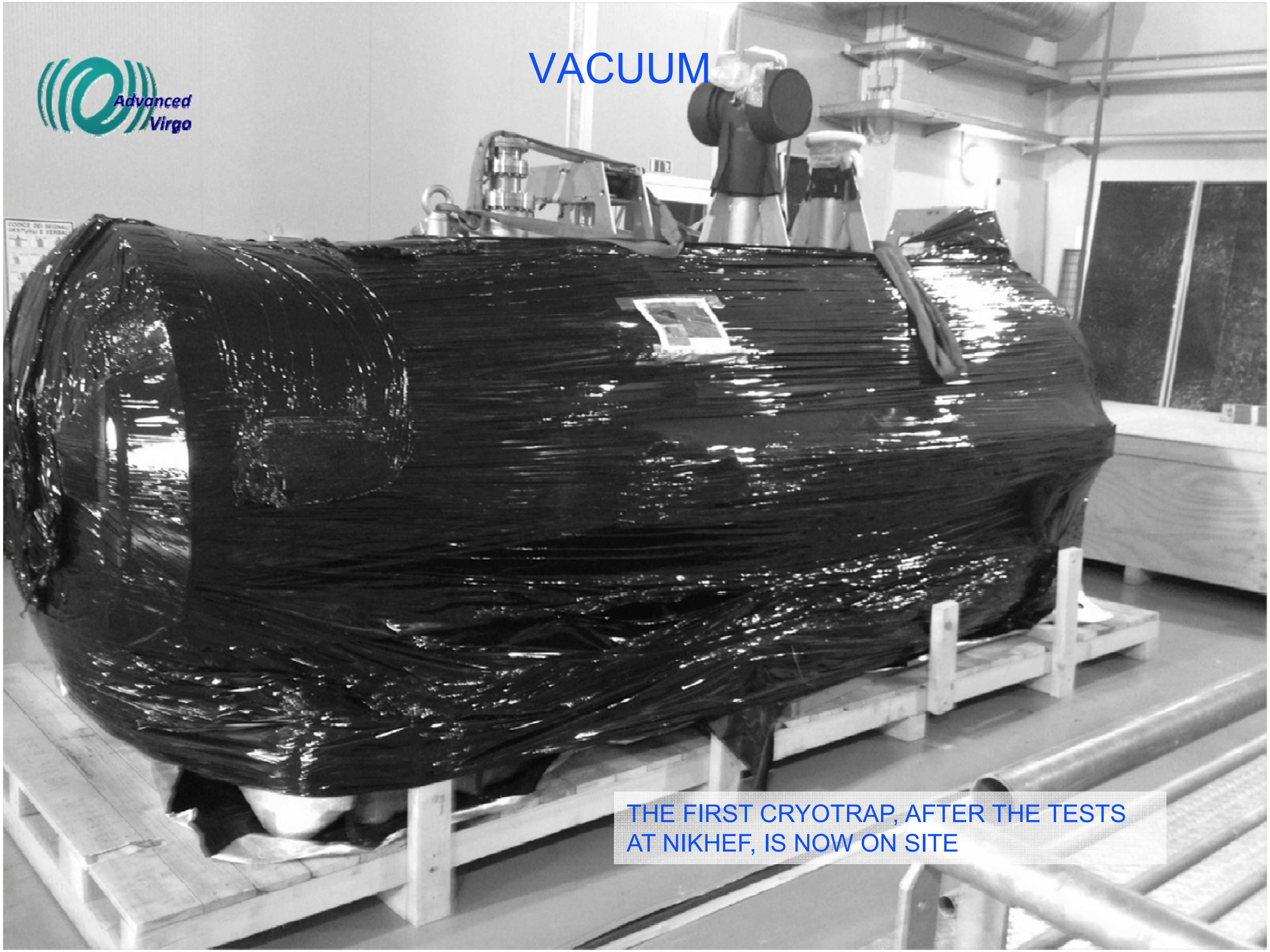


FARADAY ISOLATOR

- AdV Faraday isolator assembled on site (with the help of the staff of the Institute of Applied Physics, Russia)

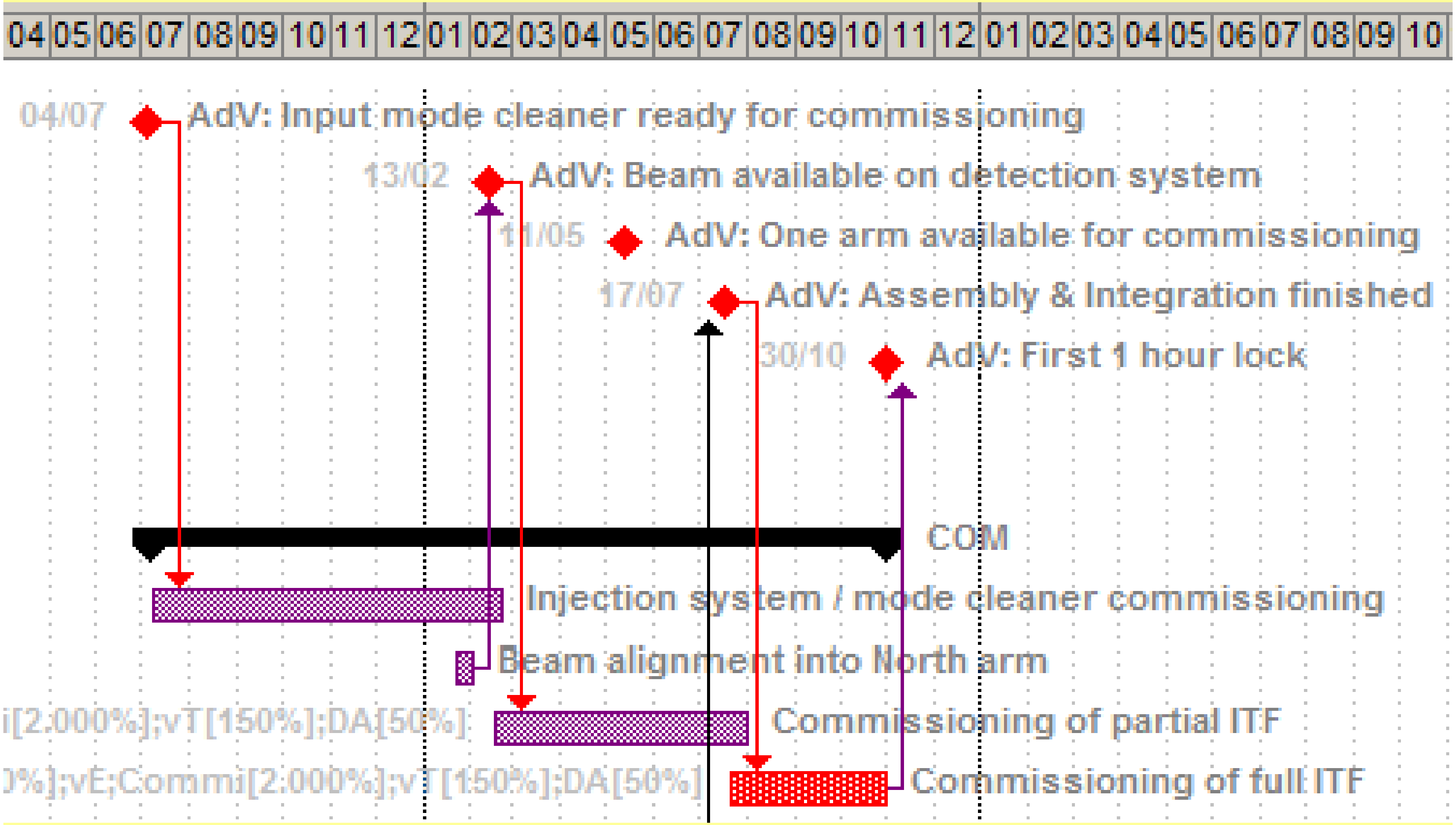


VACUUM



THE FIRST CRYOTRAP, AFTER THE TESTS AT NIKHEF, IS NOW ON SITE

CRUCIAL DATES

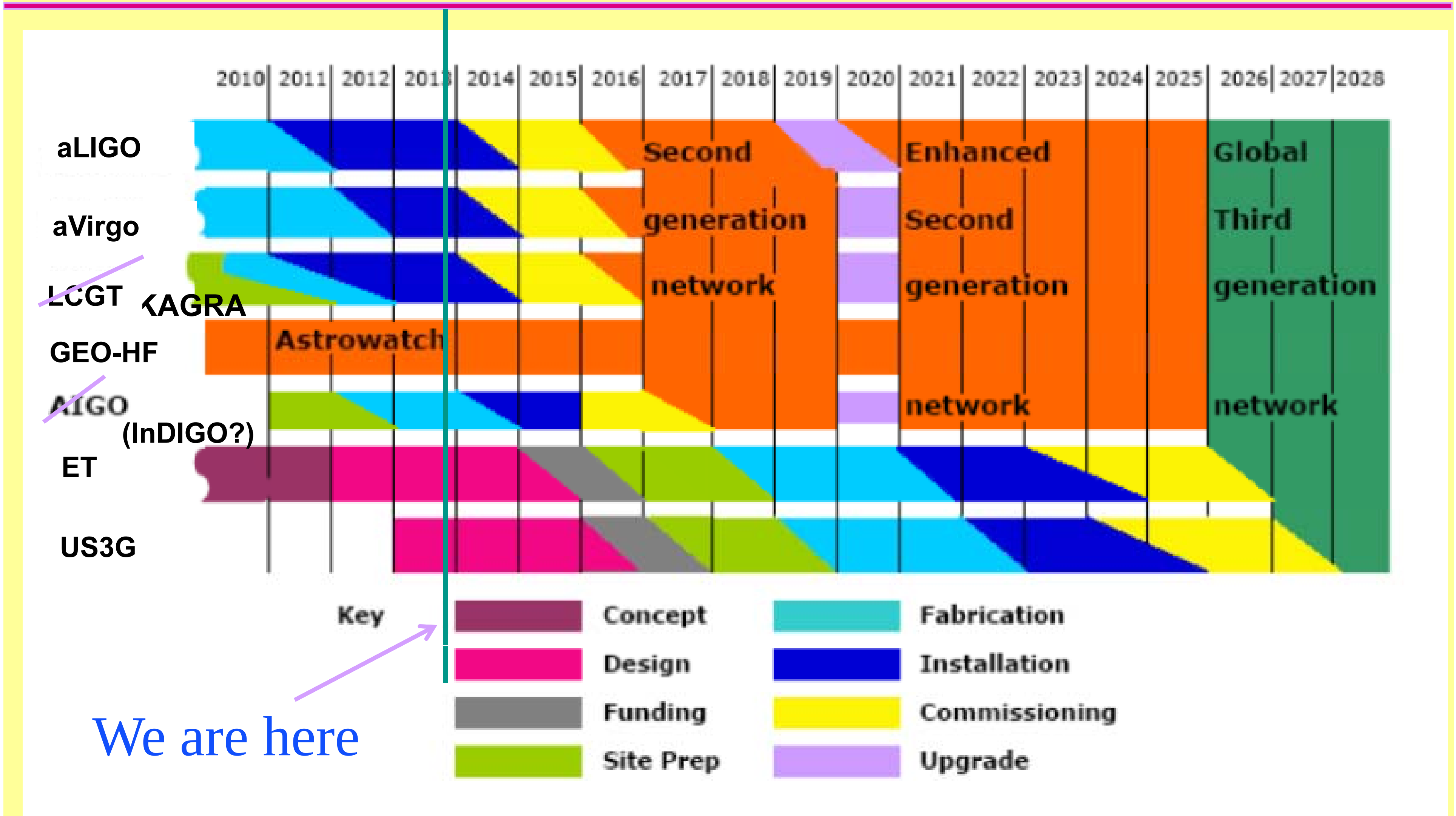


Status

- Completion (on schedule) of infrastructure works in the central area is a very important achievement
  - Now full speed on installation with main focus on injection system
  - Top level milestone (start of input modeclenaer commissioning): early July 2014
- Now at halfway towards extracting Science from Advanced Virgo
- up to now,…. *……on schedule*

GWIC
Gravitational Wave International Committee

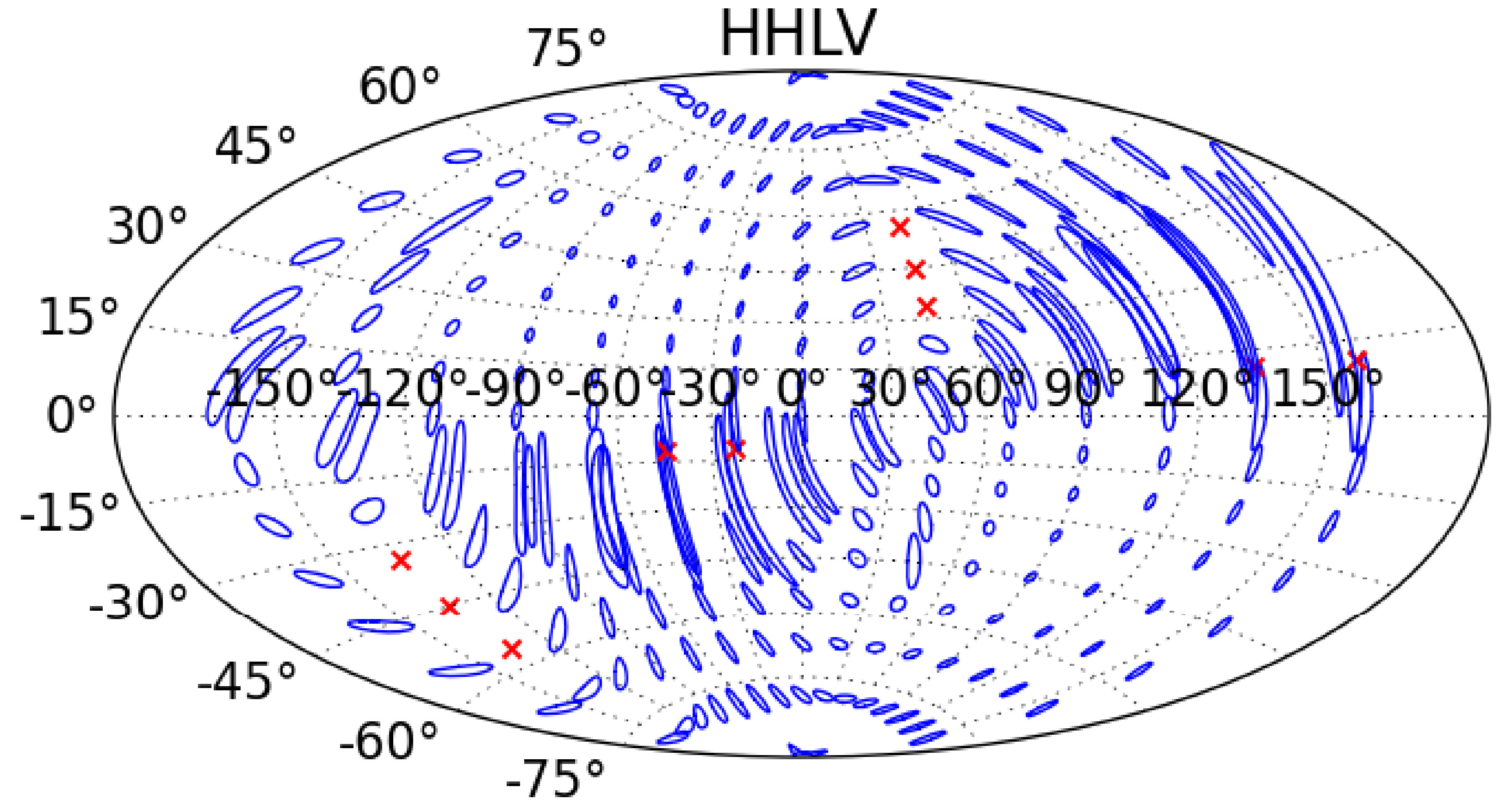
The global GW roadmap



We are here

From the Gravitational Wave International Committee (GWIC roadmap – available at: http://gwic.ligo.org/roadmap/)

Sky localization with 3 sites …

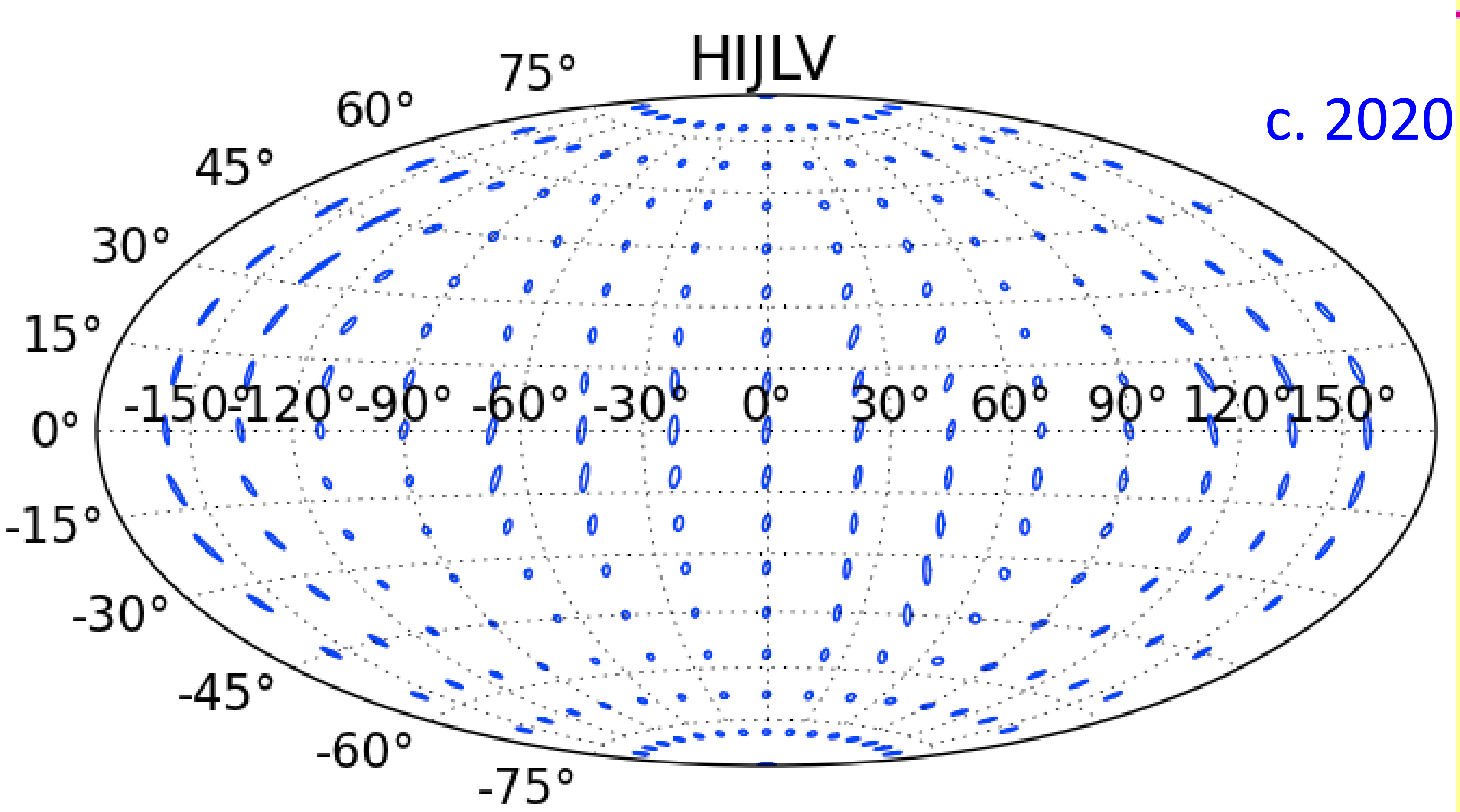


Typical 90% error box areas for NS-NS binaries

- median > 20 sq deg

Fairhurst, CQG 28 105021 (201

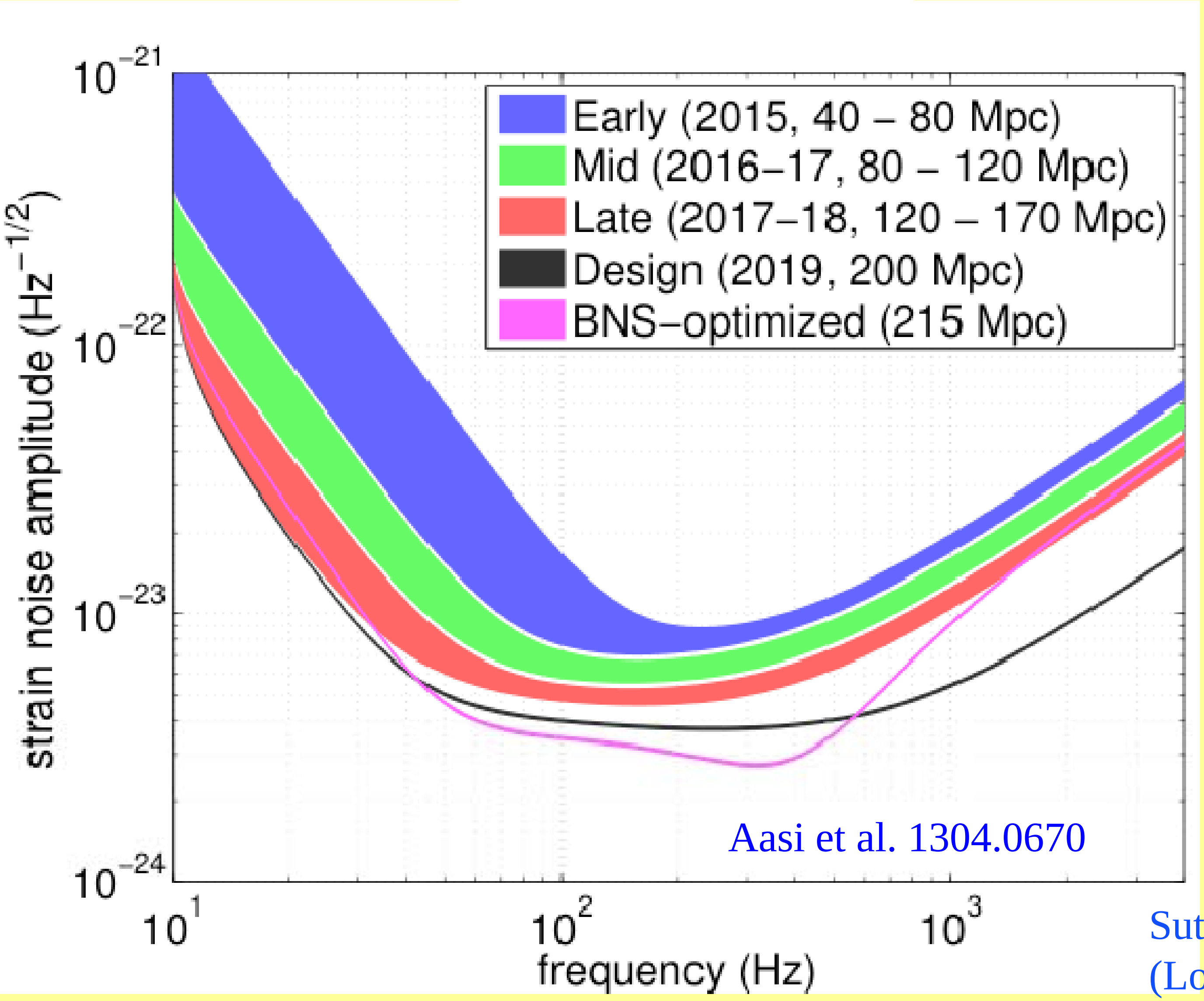
… and with 5 sites



c. 2020

Fairhurst (2011)

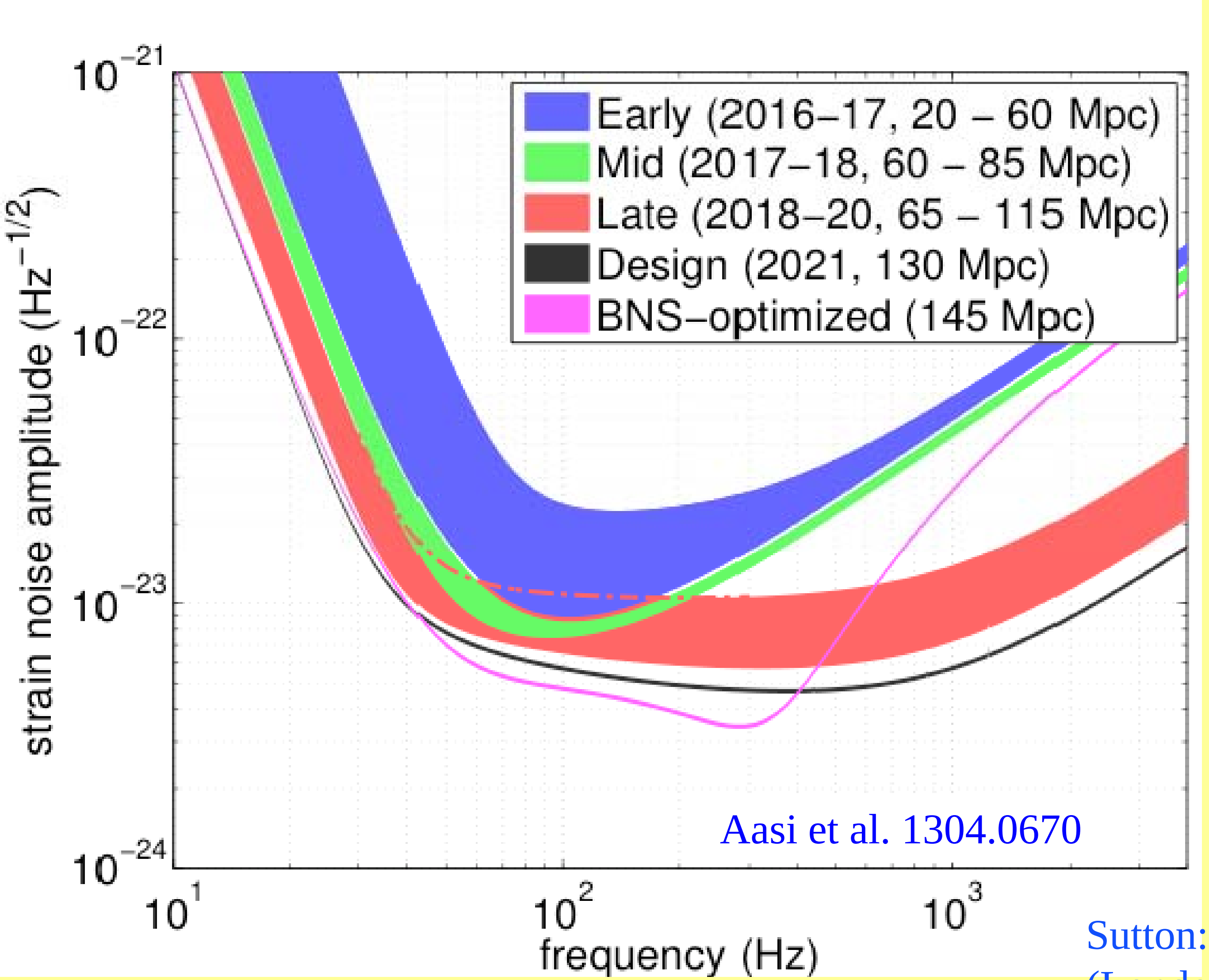
Advanced LIGO Evolution



Aasi et al. 1304.0670

Sutton: IOP 2013 (London)

Advanced Virgo Evolution



Aasi et al. 1304.0670

Sutton: IOP 2013 (London)

We are entering a very exciting time

- The baseline Advanced gravitational wave detectors are expected to accomplish the first direct detection of gravitational waves.

Projected ranges and detection rates for binary neutron star inspirals

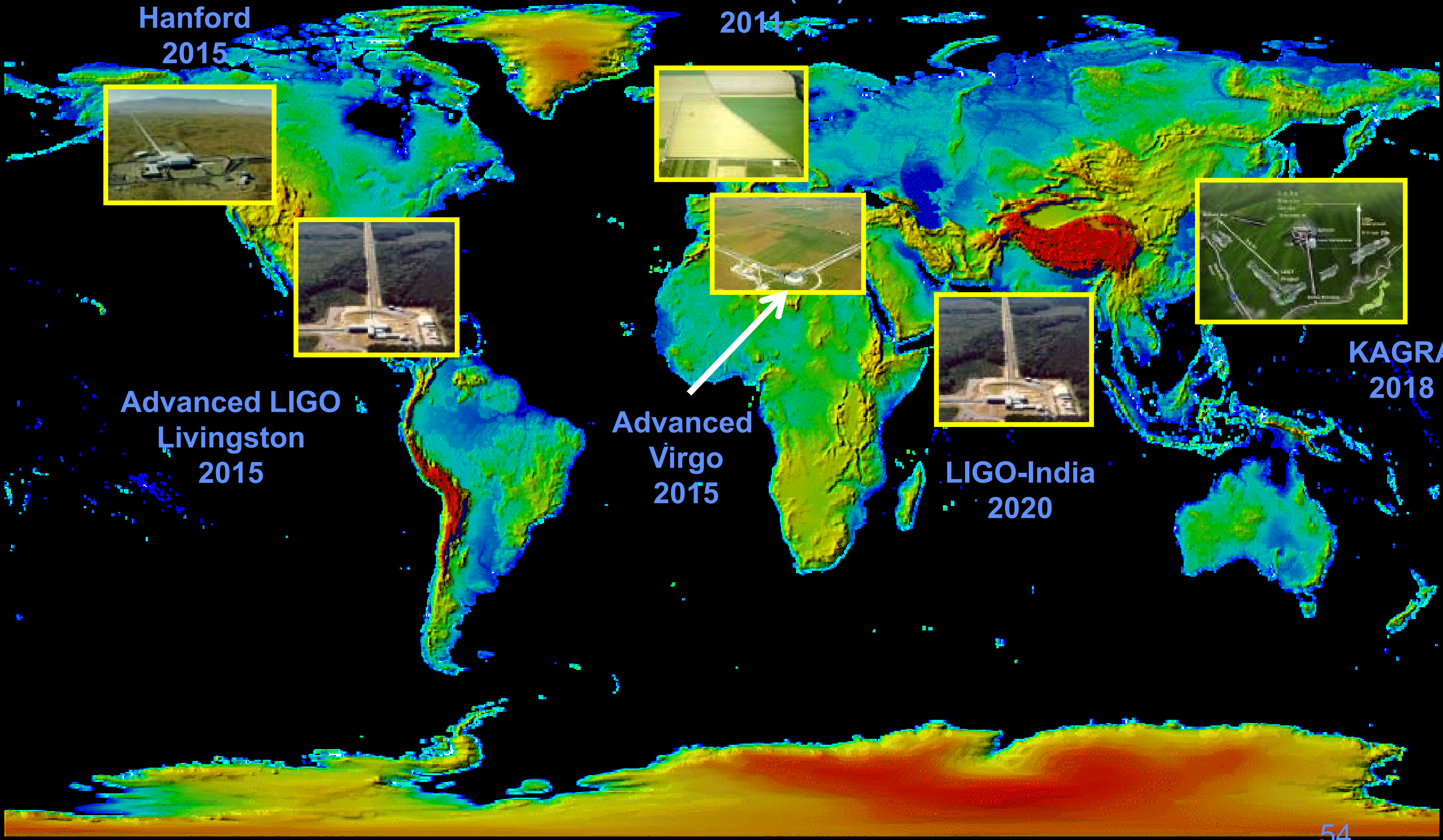
Epoch	Estimated Run Duration	BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo		$5\,\mathrm{deg}^2$	$20\,\mathrm{deg}^2$
2015	3 months	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	200	130	0.4 – 400	17	48

using “low” rate,
worst noise curve

using “high” rate,
best noise curve

At design sensitivity, advanced detectors have most probable detection rates of order tens per year

The advanced GW detector network



Advanced LIGO
Hanford
2015

GEO600 (HF)
2011

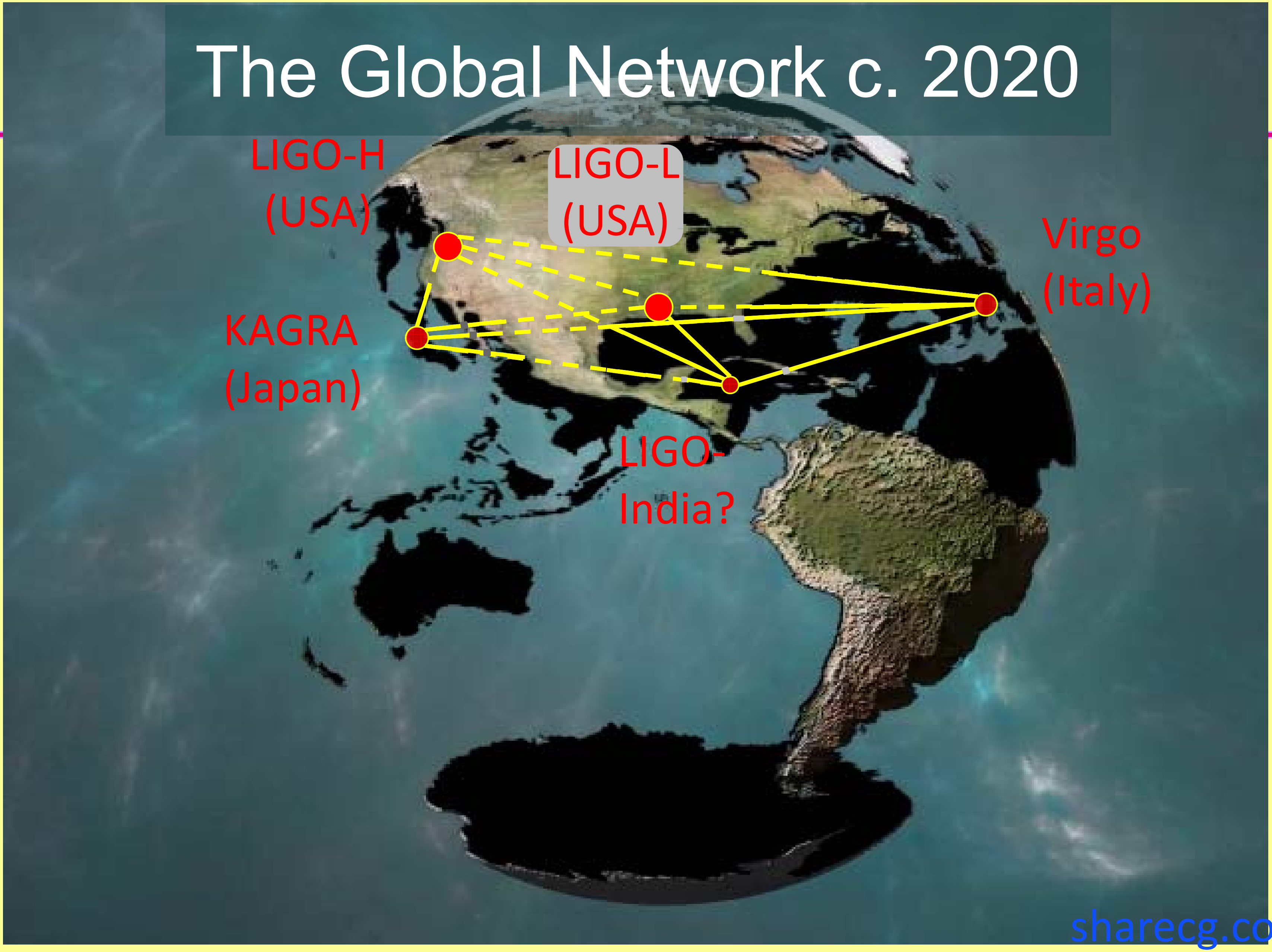
Advanced LIGO
Livingston
2015

Advanced
Virgo
2015

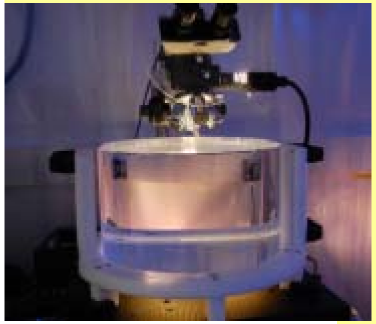
LIGO-India
2020

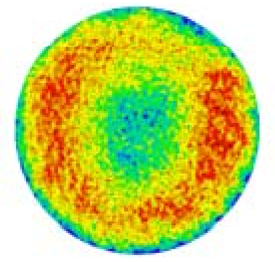
KAGRA
2018

The Global Network c. 2020



In Summary

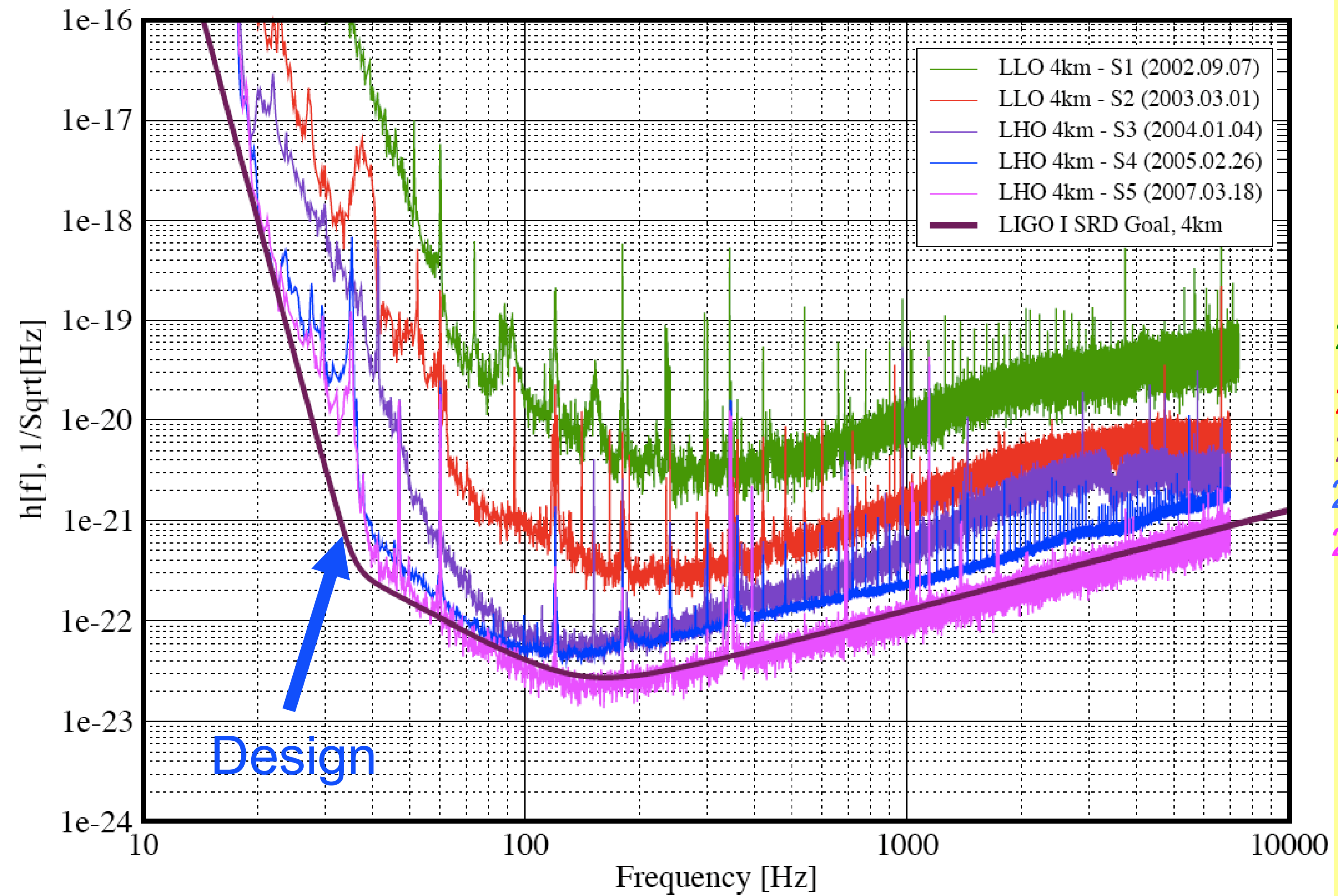




- The next generation of gravitational-wave detectors will have the sensitivity to make frequent detections
- The Advanced detectors are coming along well, planned to complete in 2015
- The world-wide community is growing, and is working together toward the goal of gravitational-wave astronomy

Goal: Direct Detection 100 years after Einstein's 1916 paper on GWs ?

Initial LIGO: first lock in 2000 – 7 years to reach goal



Design

2002
2003
2004
2005
2007