LIGO

LSC

Status of LIGO and Advanced LIGO

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Swiss Institute of Particle Physics

CHIPP Workshop on Space Time and Gravitation

EPFL, Lausanne, April 07, 2006

LIGO DCC: LIGO-G060173-00-Z

Why look for Gravity Waves?

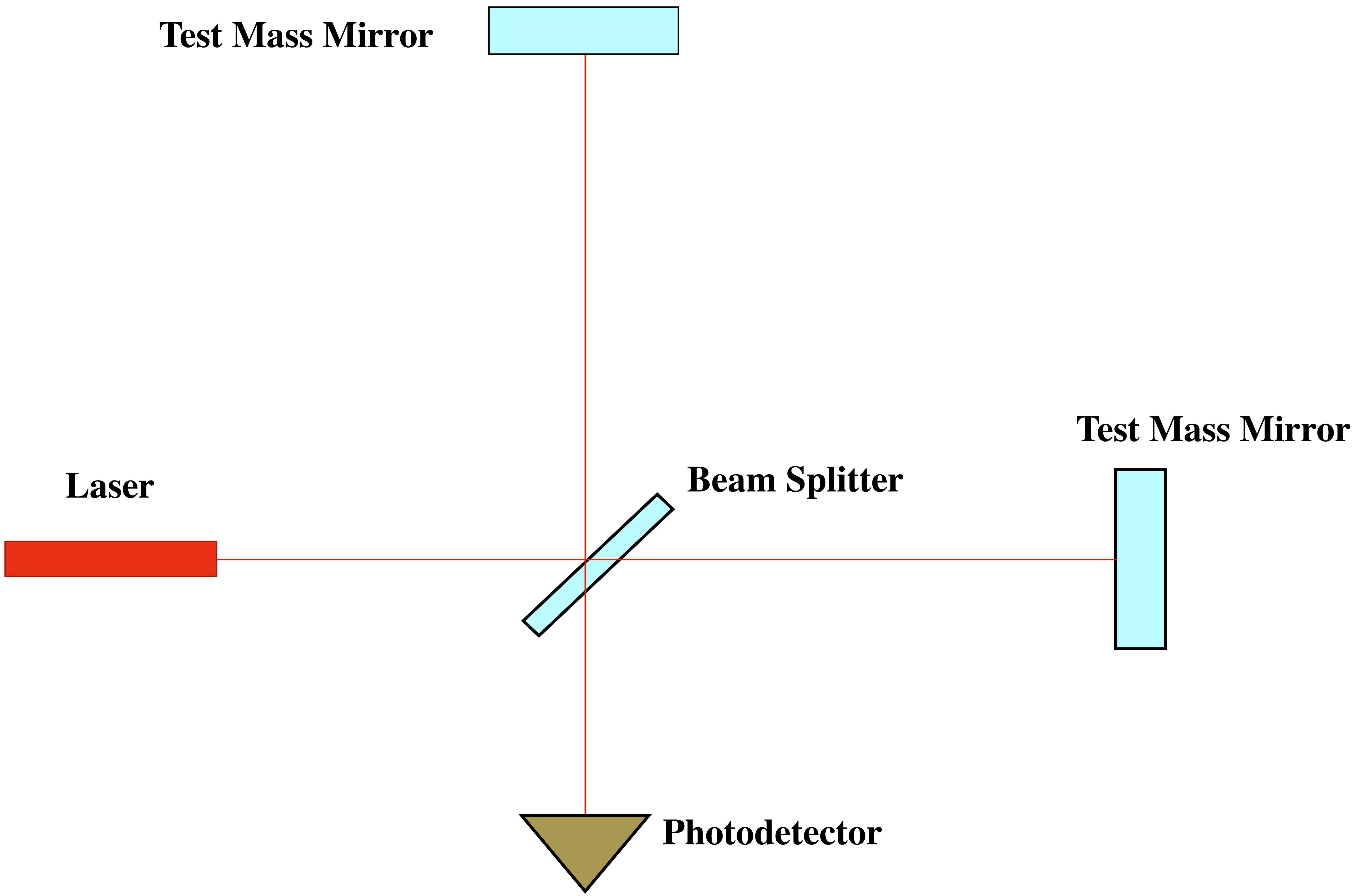
- Major test of the General Theory of Relativity
  - Test the Speed of Gravity Waves
  - Test GR in the Strong field limit

- Many GW sources not well understood with EM telescopes
  - Black Holes
  - Neutron Stars
  - Supernovae
  - Early Big Bang

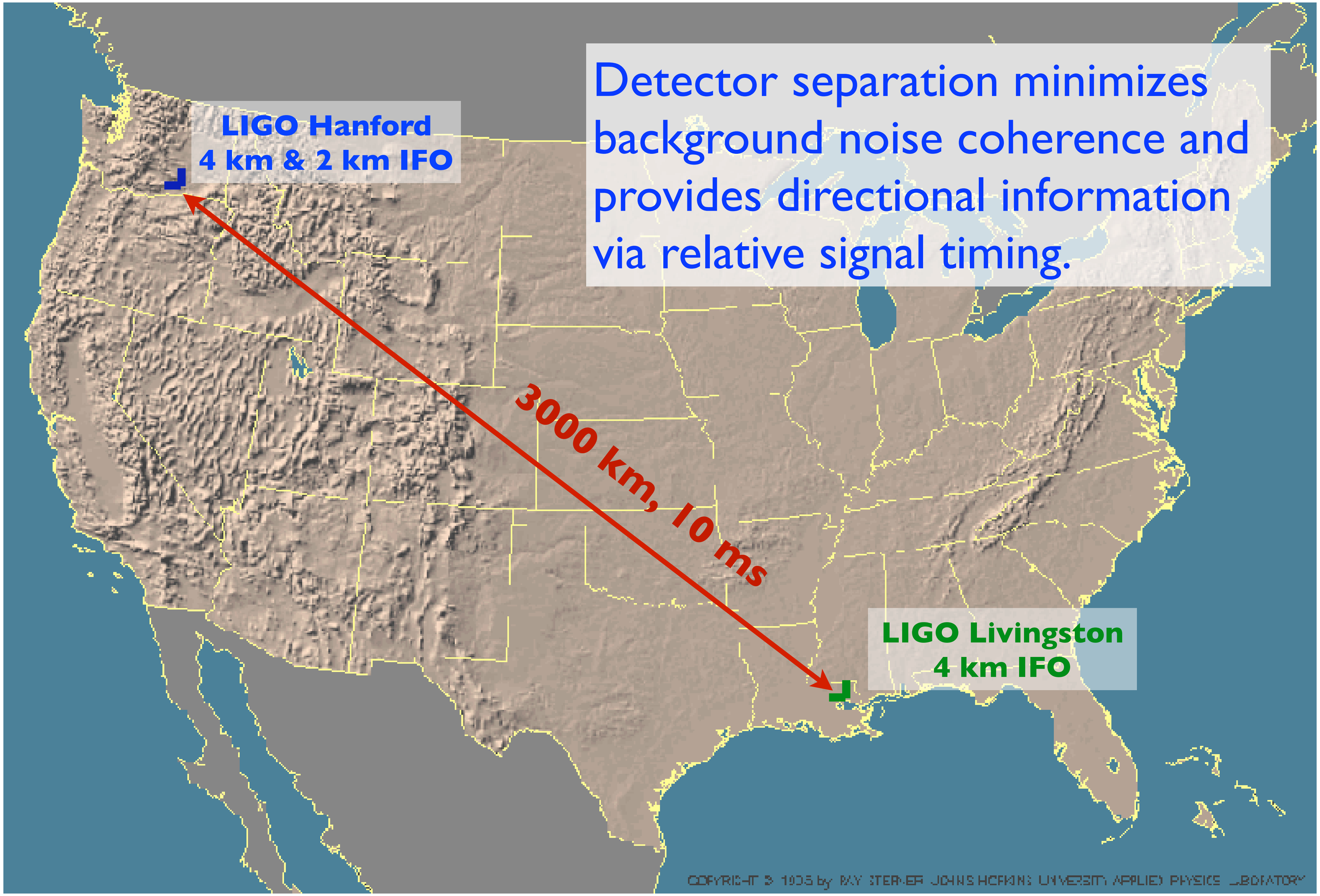
- New Window on Universe = Expect Surprises

- Difficult Challenge: BNS Inspiral in Virgo Cluster produces a strain on Earth of only 10^{-21}

Basic Interferometer



LIGO Observatory Sites



LIGO Livingston


LIGO Livingston
End Station

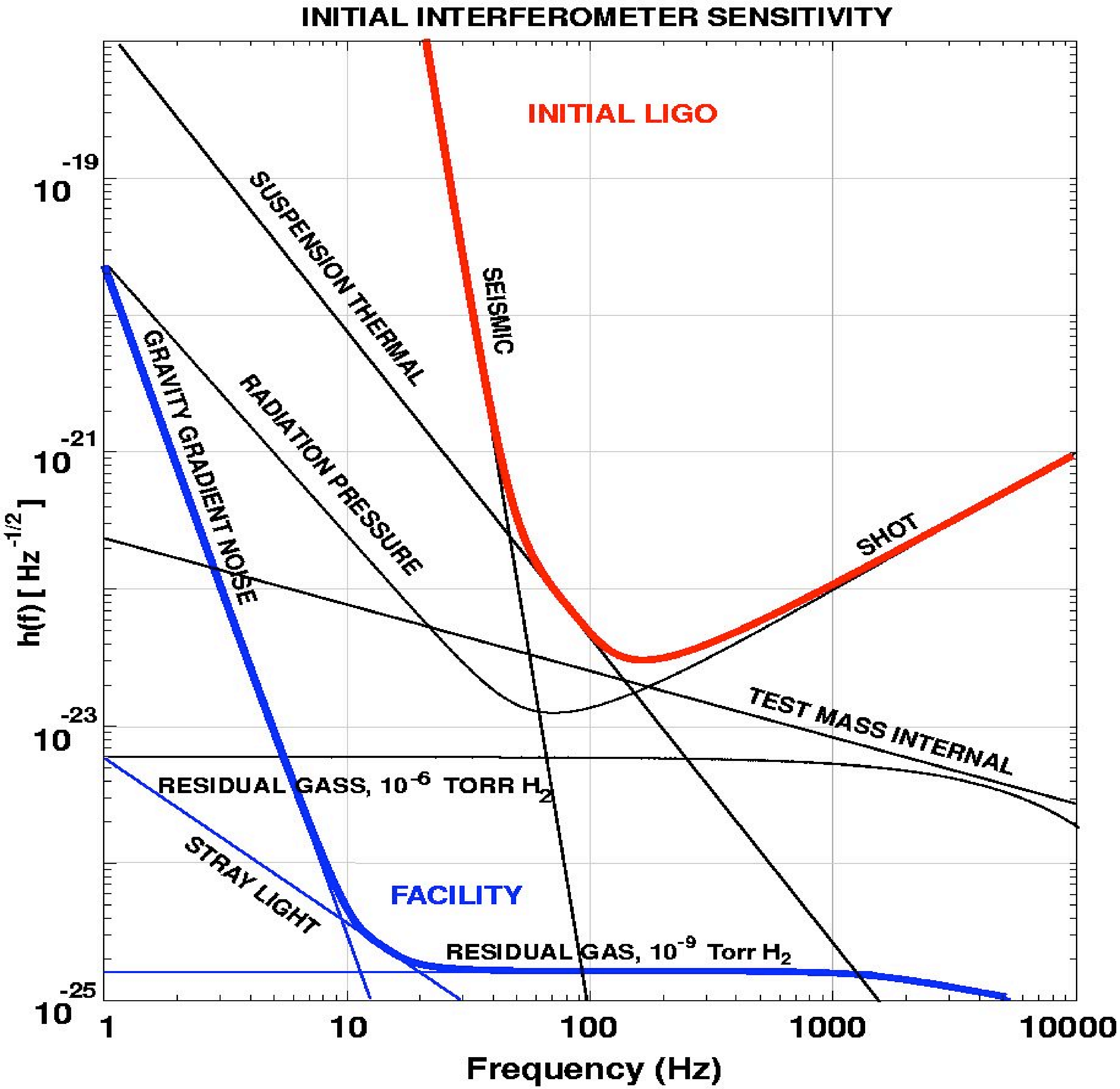

LIGO
Hanford

Design Layout of LIGO

- The Corner Station houses the laser, detector, and all of the optics except the End Test Masses.
- Each vacuum chamber has an independently supported, seismically isolated table on which the optics are mounted.
- The beam tubes are 1.2 m diameter, low oxygen stainless steel.

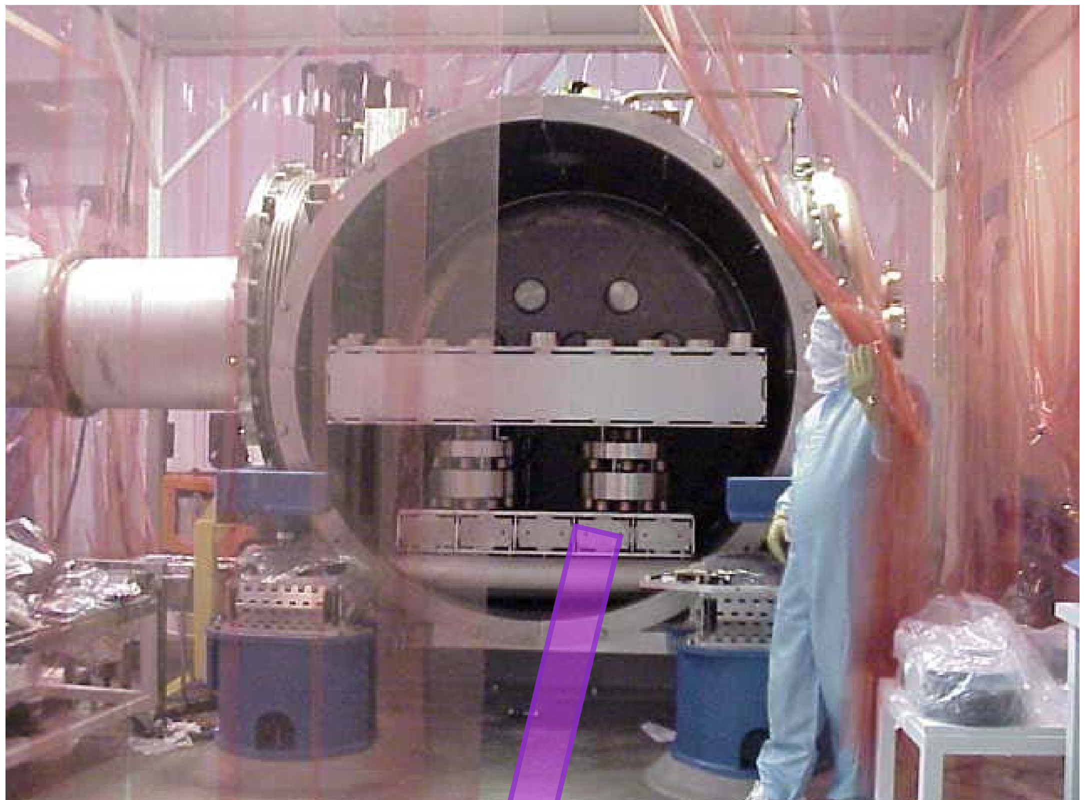
LIGO Livingston Observatory Corner Station Chambers

Initial LIGO Noise Spectrum



Seismic Isolation

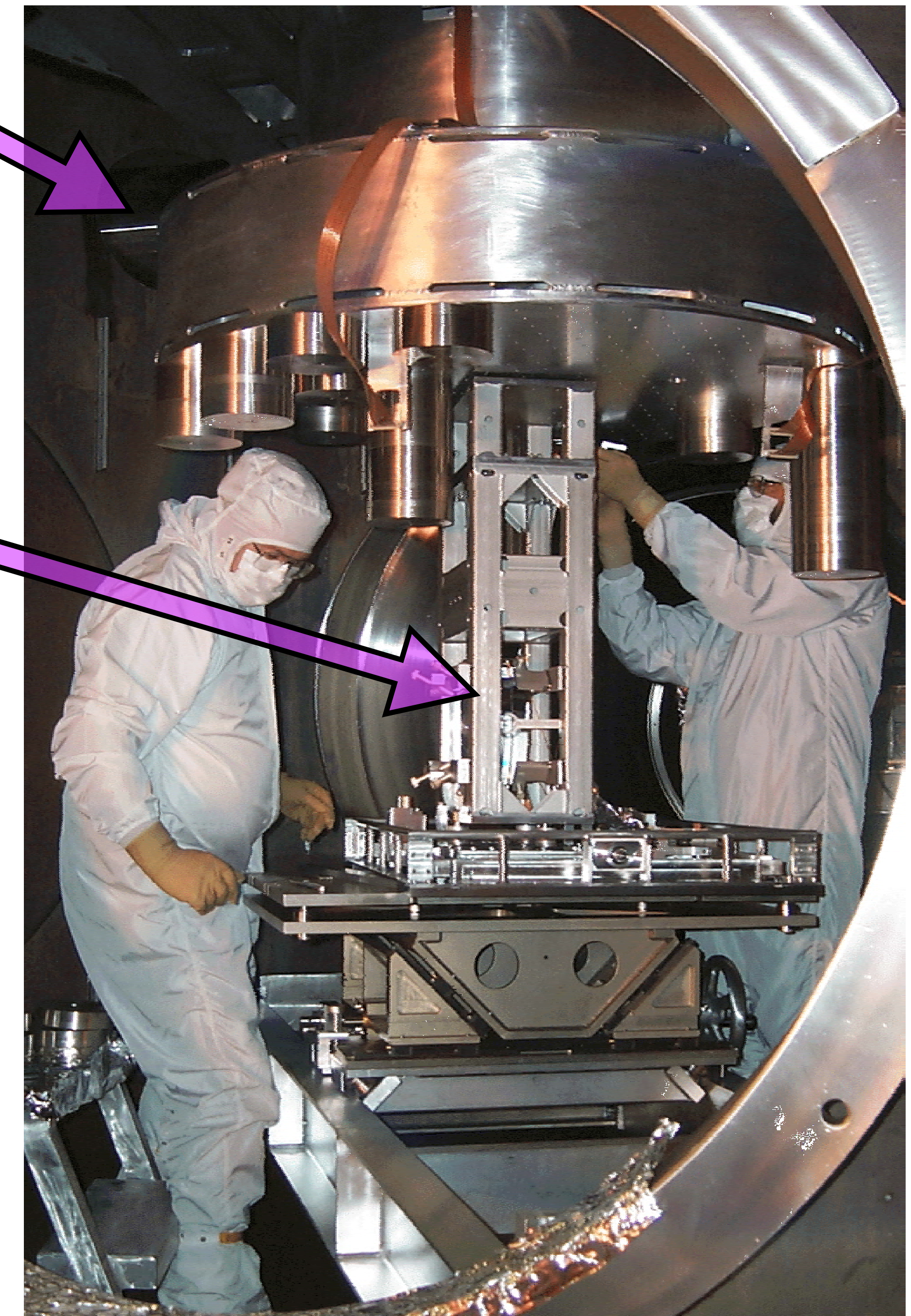
HAM Chamber

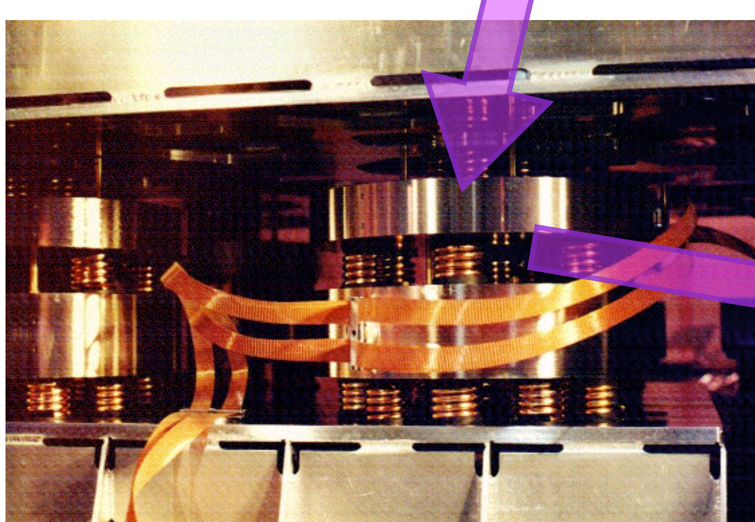


BSC Chamber

Support arms for upper optical table

Large Optic suspension cage



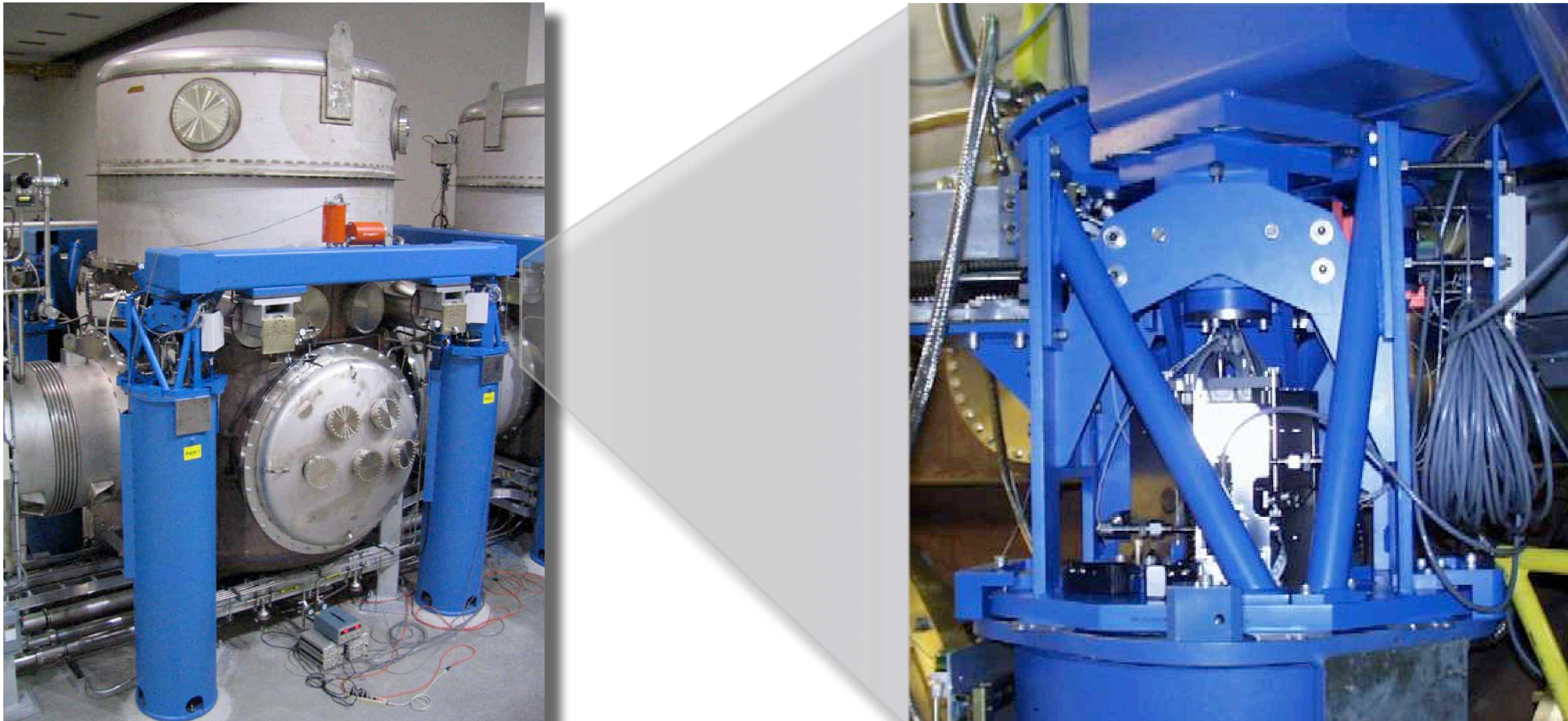


Coil Springs & Reaction Mass Stack

Tubular Coil Springs with internal damping

HEPI System

Hydraulic External Pre-Isolator

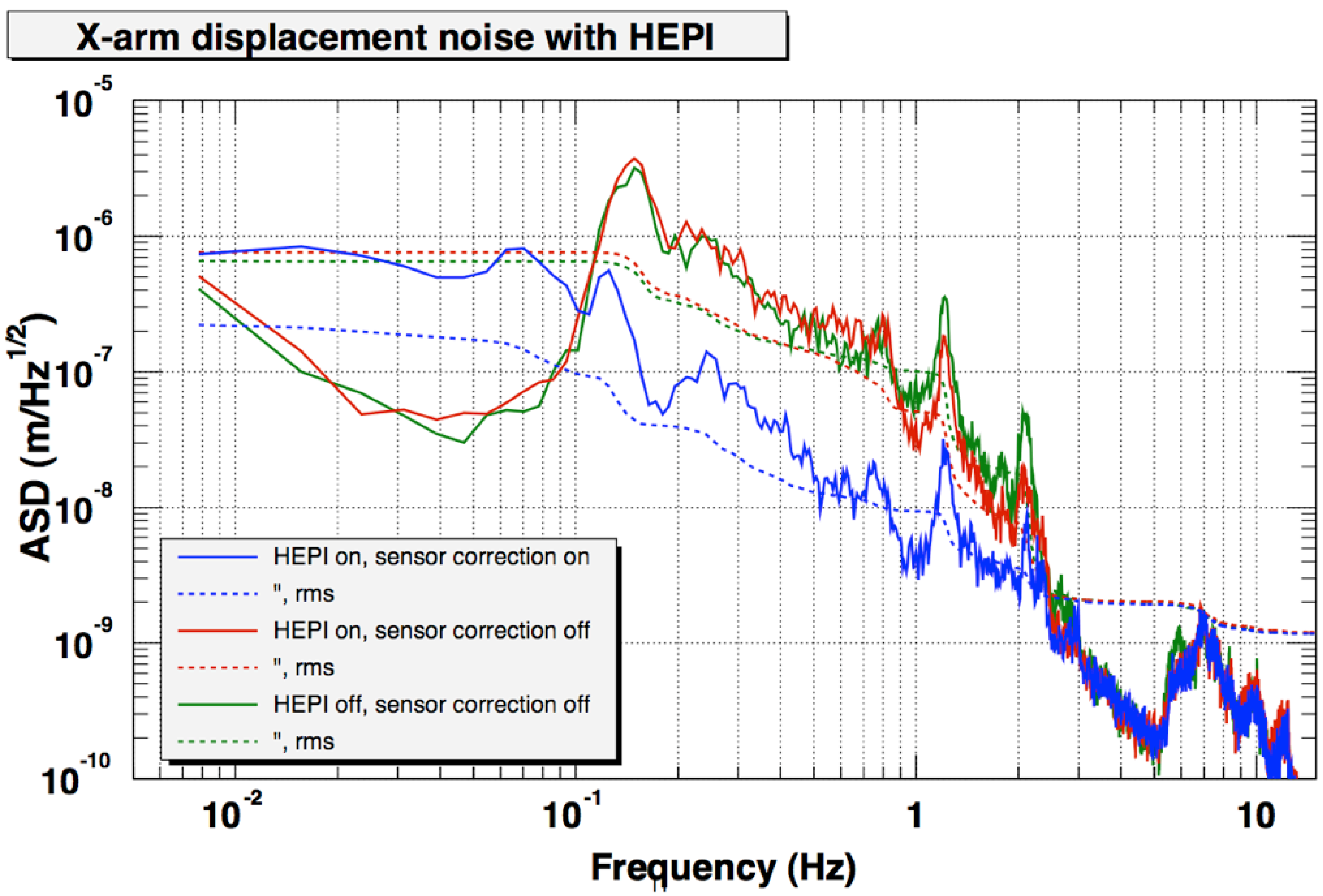


- Implemented early at LLO to mitigate excess seismic noise (trains, cars, logging, …)
- Active sensing and actuation reduces noise in 0.1–10 Hz range by nearly a factor 10.
  - Sensors overdetermine all 6 DOF
  - Actuator use laminar flow, quiet hydraulics to adjust space frame support
- LLO can now regularly lock the IFO during the day. Still knocked out during late night trains.

HEPI System

Hydraulic External Pre-Isolator

X-arm length disturbance, quiet evening



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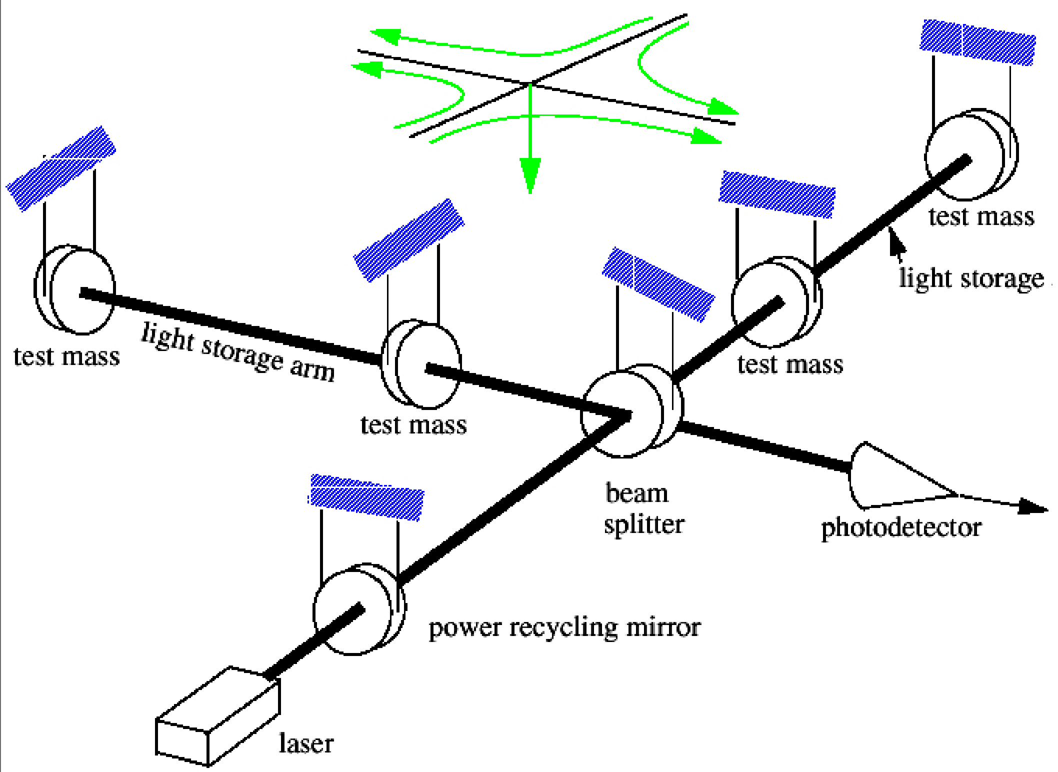
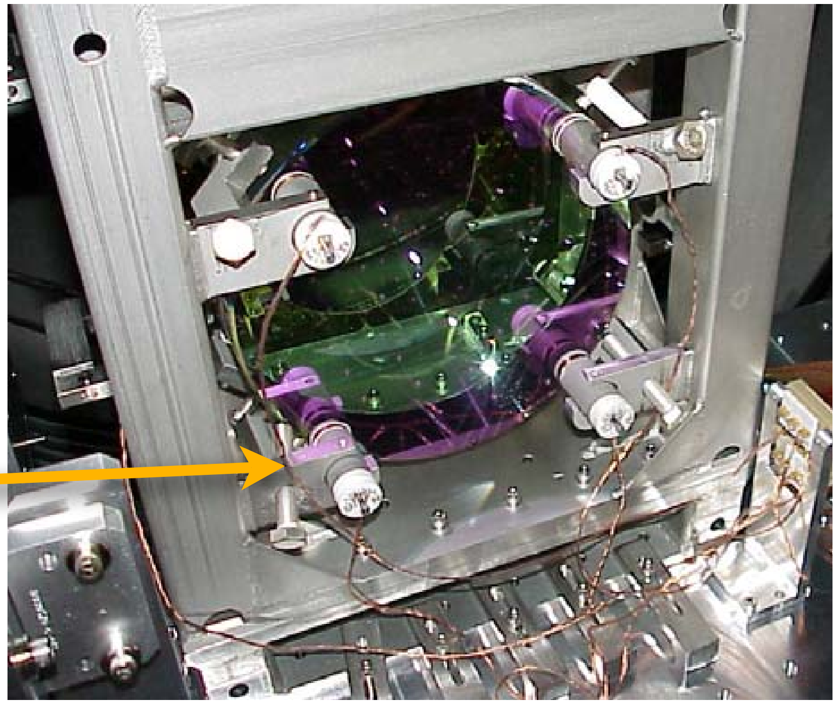
LIGO's Main Optics



- The large optics are suspended on a single wire loop and are free to move (in "free fall") in the plane of the interferometer. The fused silica optics are 25 cm in diameter, 10 cm thick and have a 10 kg mass.
- Fast servo controls adjust all the optics positions and the laser wavelength to keep the interferometer locked. Slower servos correct for land tide drifts and temperature dependent changes in mirror curvature.
- Each optic's position is controlled by 5 sensor/actuators which maintain the optics relative position to 10^{-13} m and angular orientation to 10^{-8} radians.

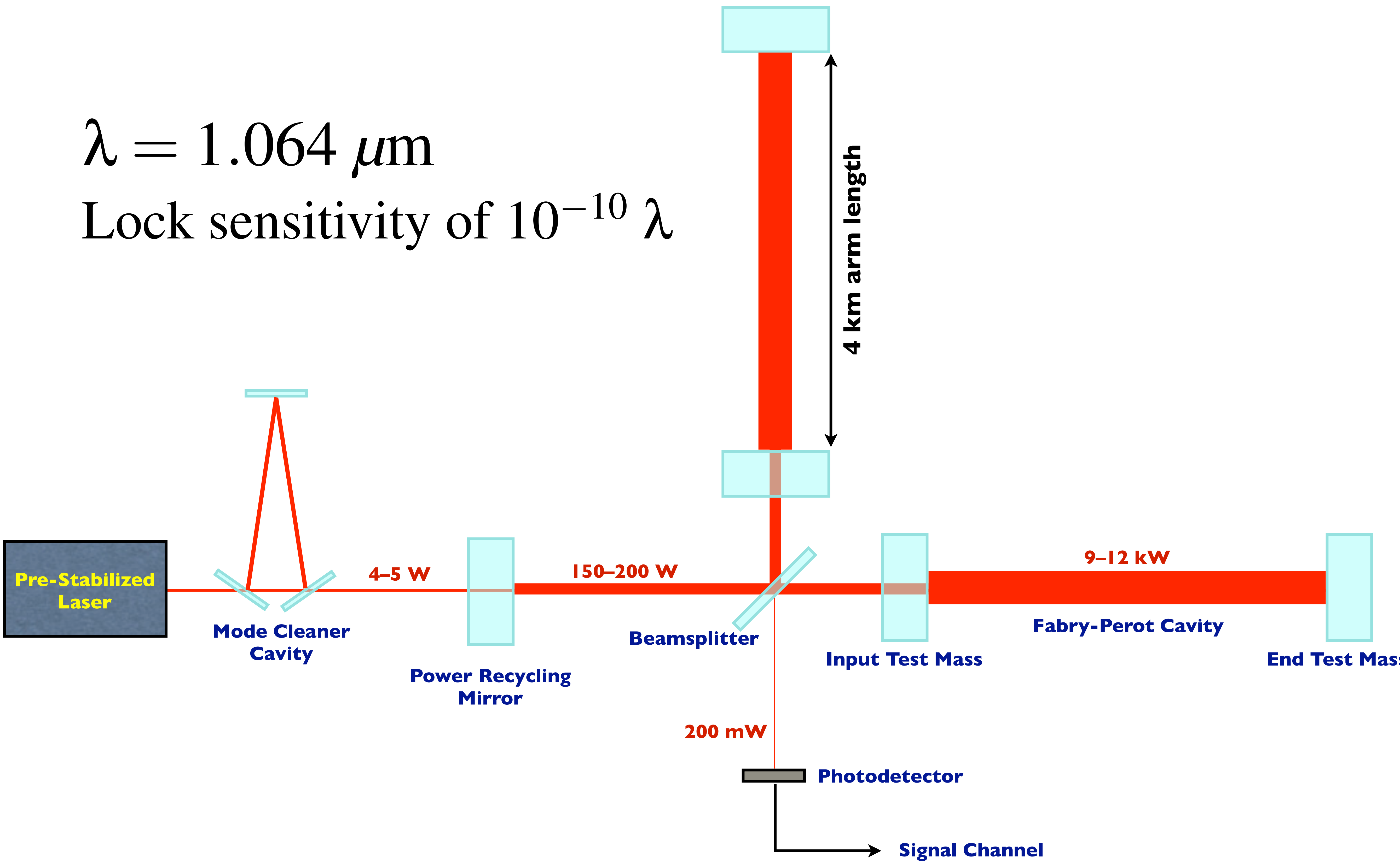
OSEM sensor-actuators



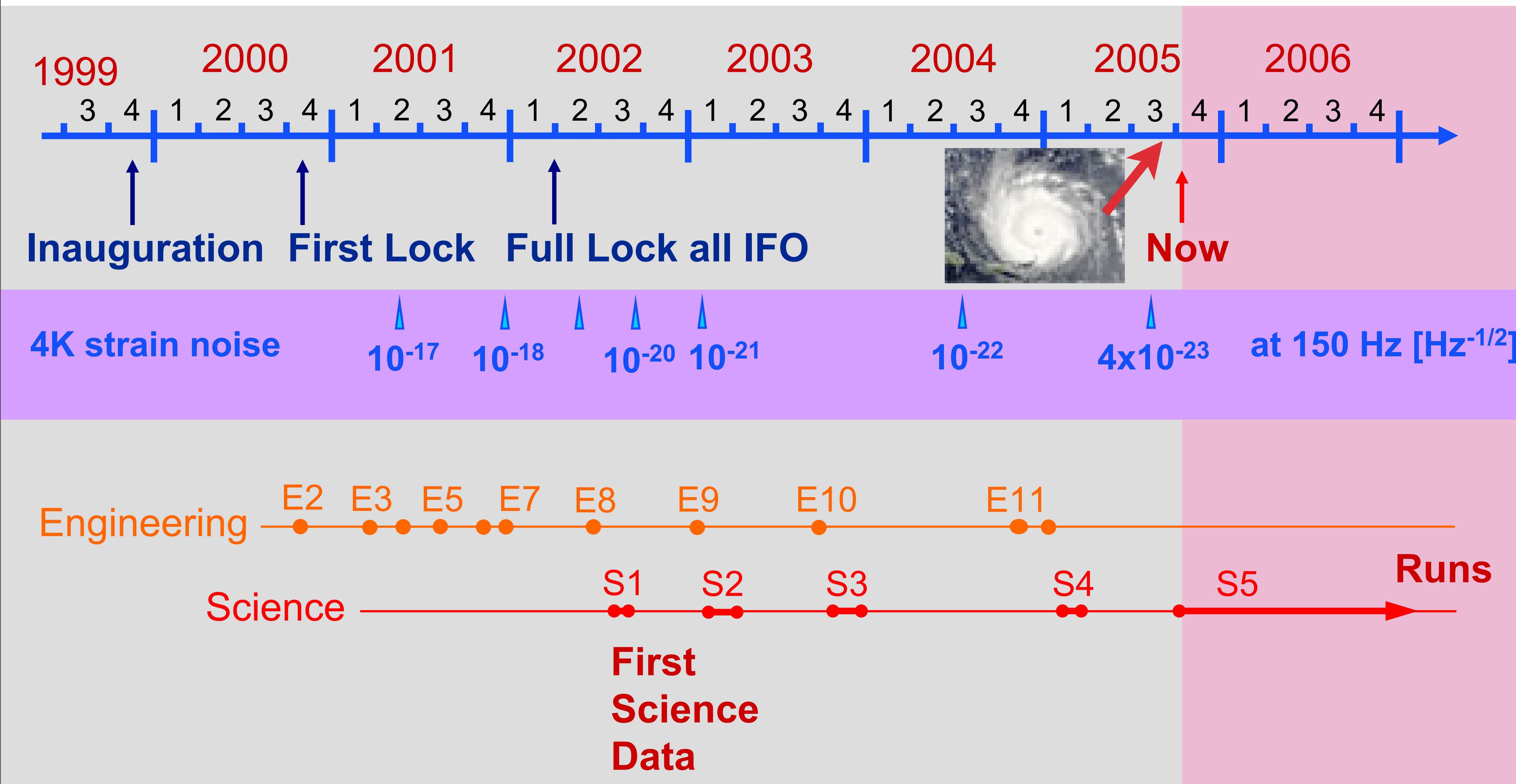
LIGO Laser System

$$\lambda = 1.064\ \mu m$$

Lock sensitivity of $10^{-10}\ \lambda$

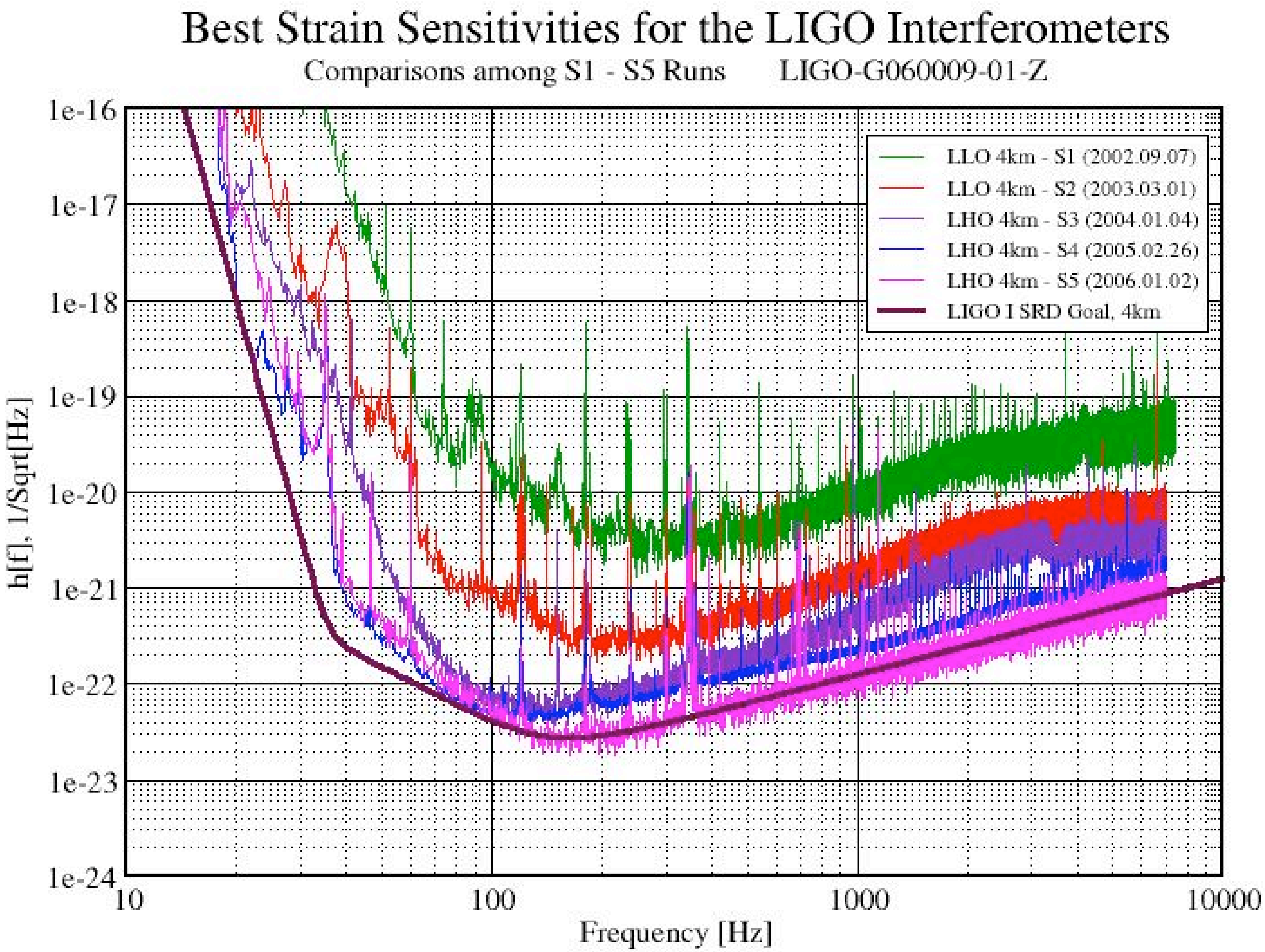


LIGO History



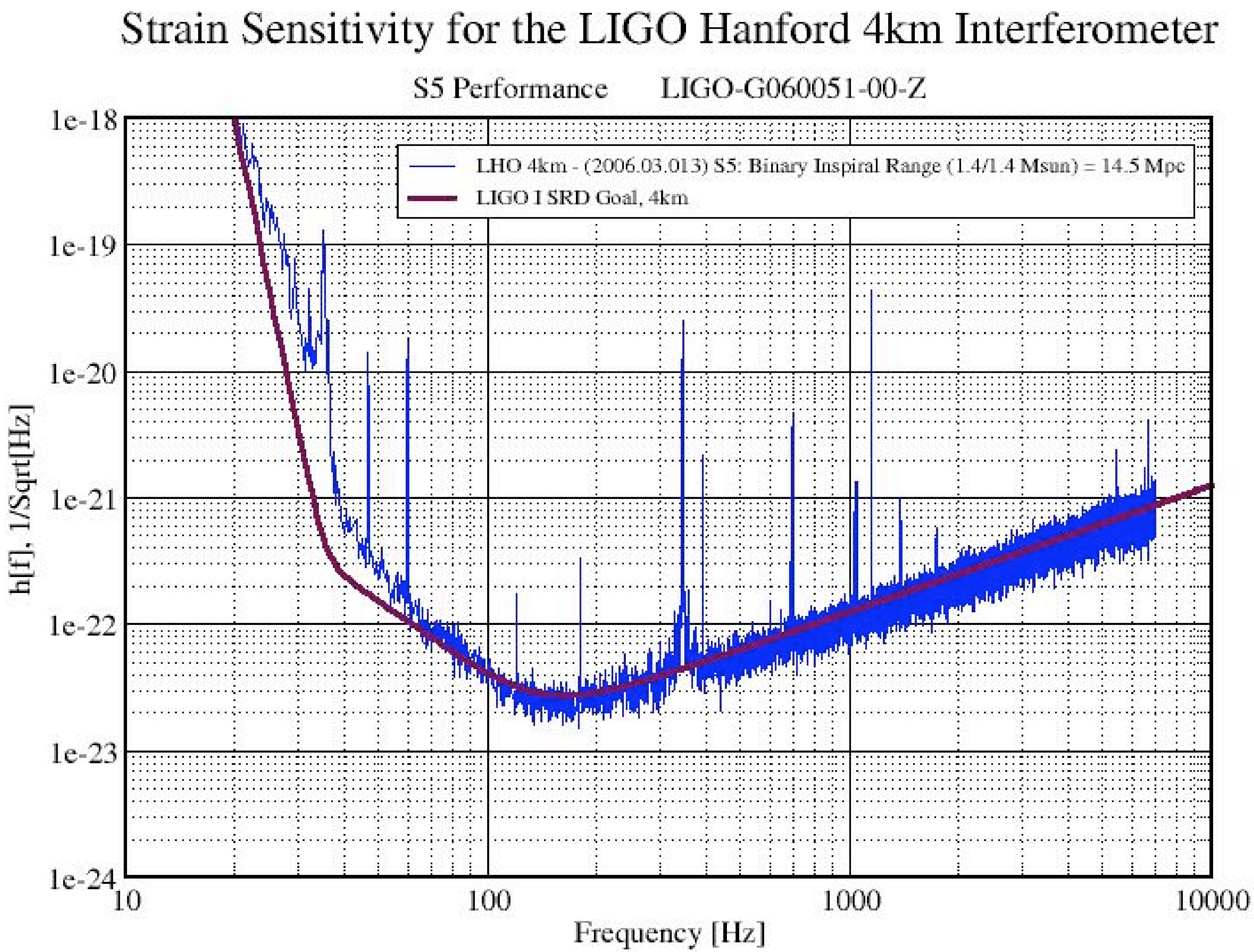
(Graphic borrowed from Sam Waldman)

The March to the SRD...

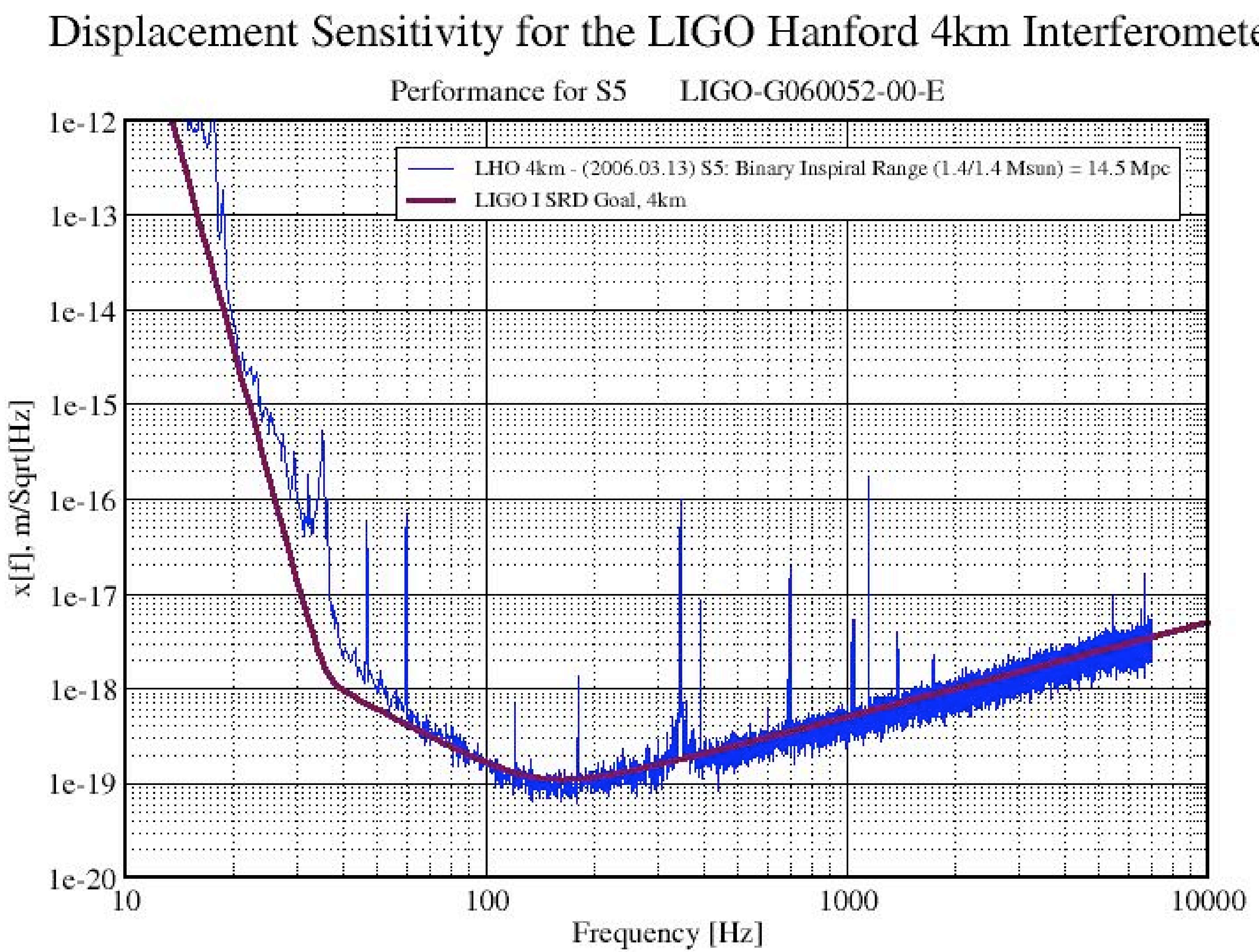


LIGO

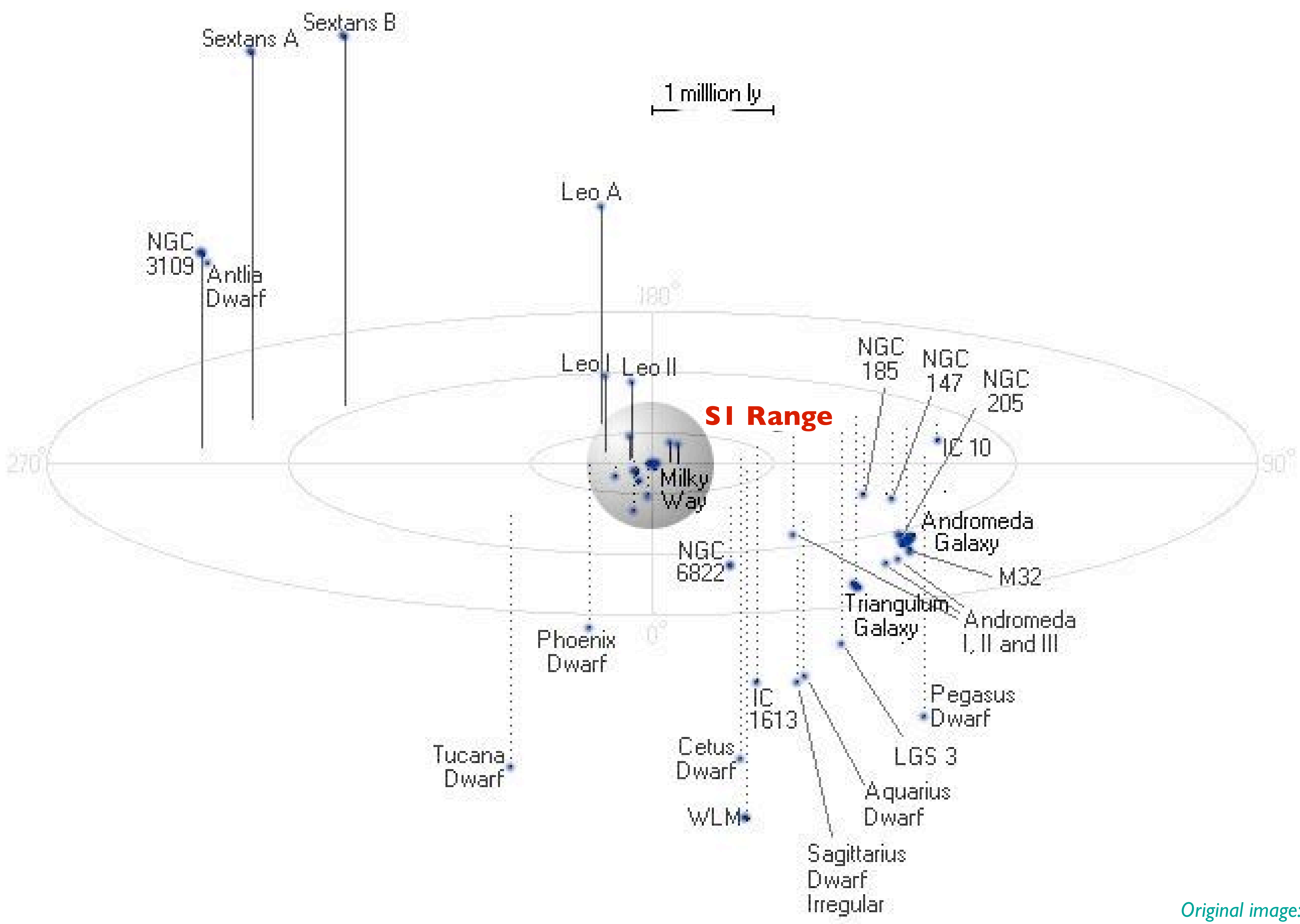
Current Strain Sensitivity



Current Displacement Sensitivity

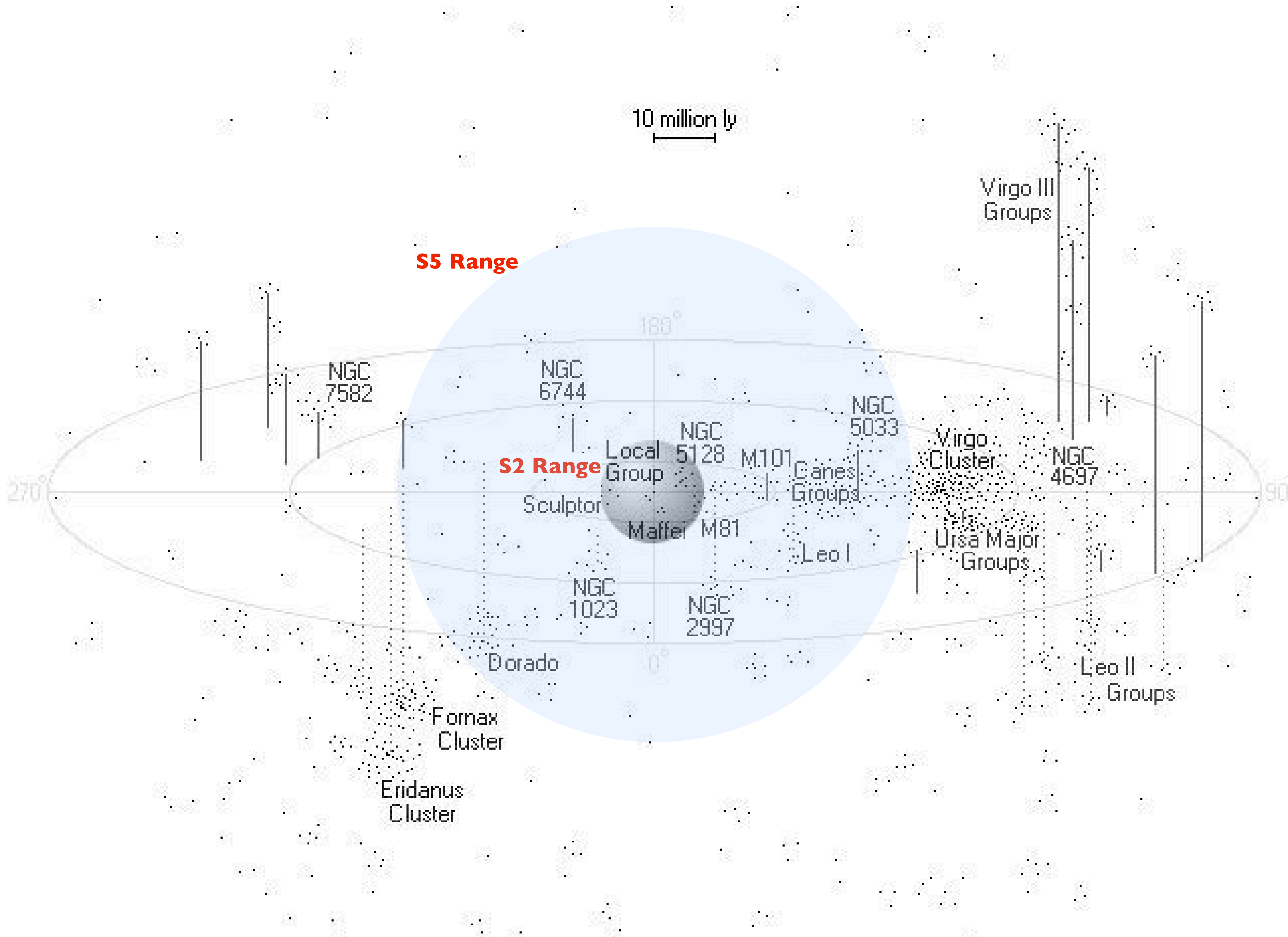


Initial LIGO Range for BNSI: S1



Original image: R. Powell

Initial LIGO Range for BNSI: S2



Original image: R. Powell

LIGO

GW Data Sources

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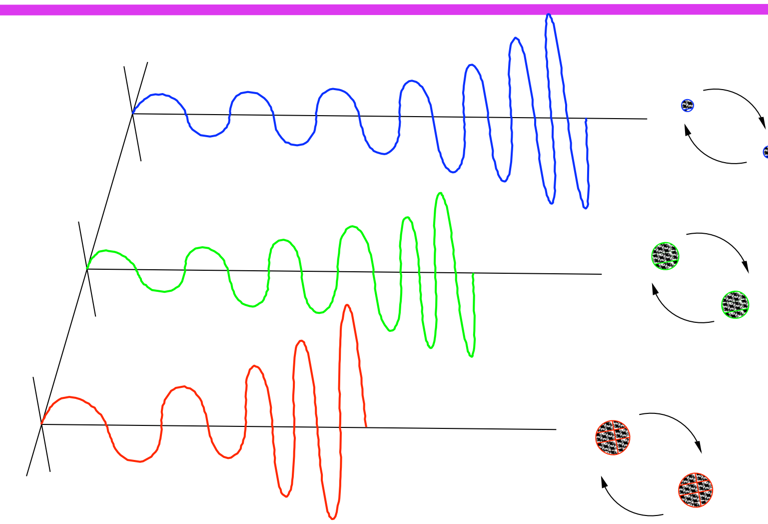
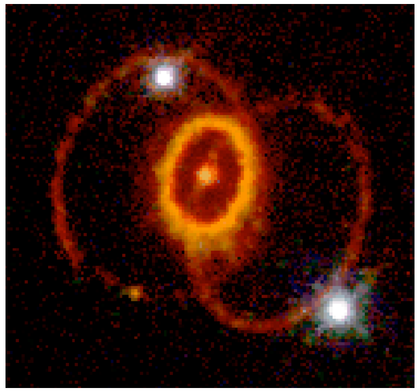
Classes of Astrophysical Sources

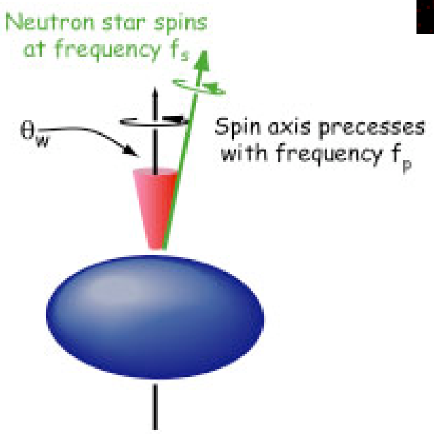
- **Compact binary inspiral:** ***Chirp Signal***
  - Search technique: Matched templates
  - NS-NS waveforms -- good predictions
  - BH-BH (<10 M_s) – would like better models



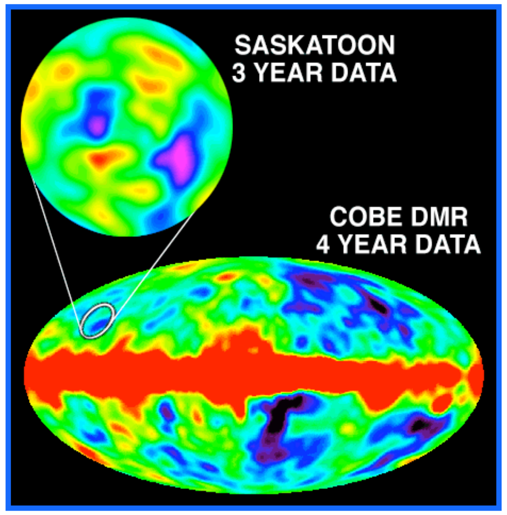
- **Supernovae/GRBs/Strings:** ***Burst Signal***
  - Time-Frequency concentration of excess power
  - Possible coincidence with neutrinos, EM bursts
  - Alarms received from neutrino & GRB detectors



- **Pulsars in our galaxy:** ***Periodic Signal***
  - Search for known pulsars: Continuous wave with Doppler shifting
  - Einstein@Home provides significant computing power: 70 Tflops, 10^5 users



- **Cosmological Signals:** ***Stochastic Background***
  - Search for coherent background across detectors

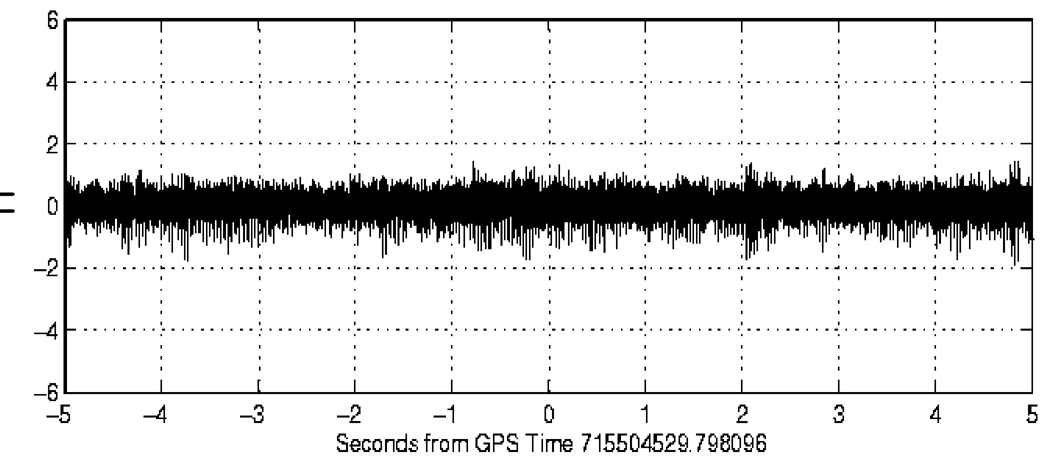


Inspiral Sources

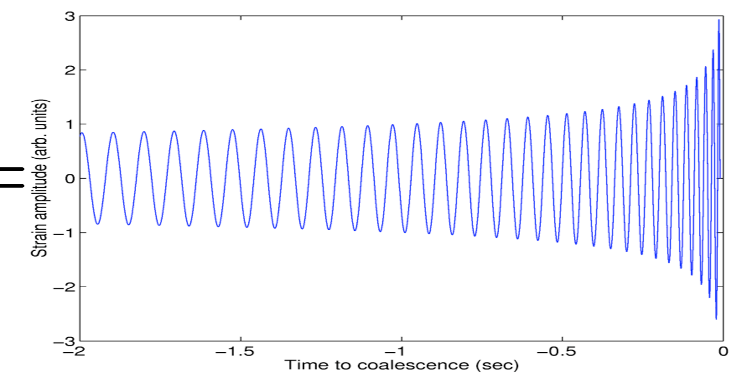
- Sources include NS-NS, BH-BH, & BH-NS
  - Waveforms of inspiral phase well known
  - Waveform of merger phase less well known, especially BH mergers
- Parameter space is very large:
  - Masses, separation, distance, location, orientation, spins
- **S2 Results**
  - **NS-NS** (1–3 solar masses)
    - No detections
    - Range: 1.5 Mpc
    - Rate < 47/year/MWEG
  - **BH-BH** (> 3 solar masses)
    - No detections
    - Range: few Mpc
  - **Primordial BH-BH** (0.2–1 solar mass)
    - No detections
    - Rate < 63/year/MW halo

Using matched filtering

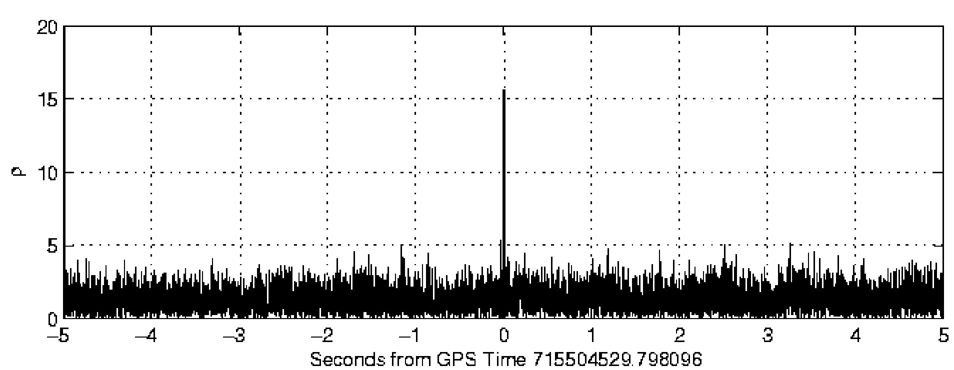
$x(t) =$



$h(t) =$



$g(\tau) =$



$$g(\tau) = \int x(t)h(t+\tau)\,dt$$

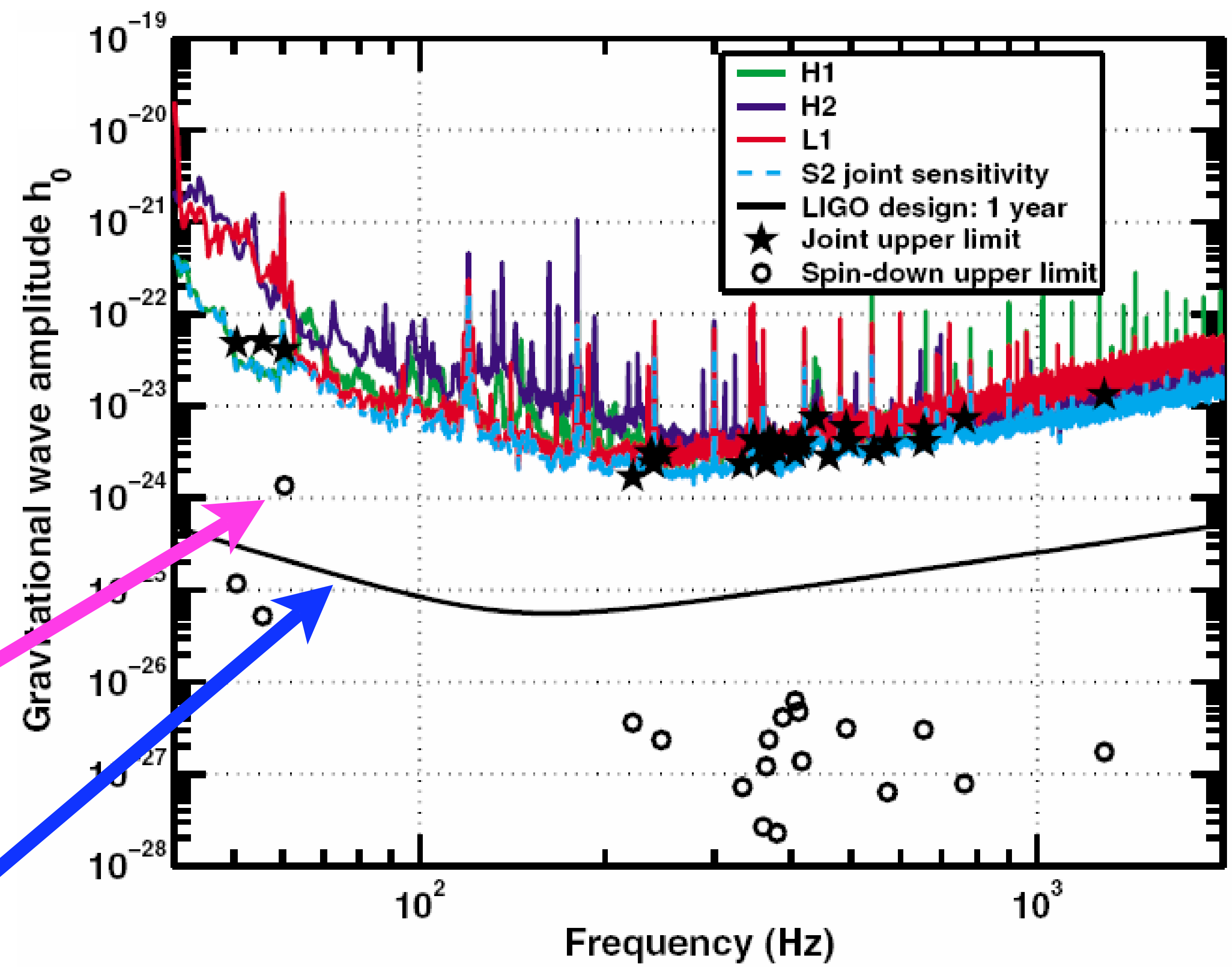
Periodic Sources

- Sources are rotating neutron stars in our galaxy. Target 28 well studied pulsars.

- Search using matched filtering on periodic signal adjusted for Earth's rotation.
  - Frequency adjusted for diurnal Doppler shifting.
  - Amplitude adjusted because rotating antenna pattern changes detection efficiency.

- **S2 Result:**
  - Strain Limit: $h_0 < 1.7 \times 10^{-24}$
  - Ellipticity Limit: $\varepsilon < 4.5 \times 10^{-6}$

- Additional Searches (publishing soon)
  - Unknown periodic sources
    - All sky. Wide frequency band
  - Sco X-1 companion
  - Search using Hough transform



Crab Pulsar

S5 Sensitivity Limit

Burst Sources

- Sources include anything that might produce a short (< 100 ms) ***Burst*** of Gravity Waves.
  - Supernovae (asymmetric)
  - GRB sources
  - Collapse of Super-massive Star
  - BH-BH, pulse during merger phase
  - Cosmic strings: kinks and cusps

- Search for correlated, excess power in the detectors.
  - **WaveBurst:** Locates coincident excess power
    - Performs wavelet time-frequency spectrum
    - Time-Frequency Clusters assigned significance based on excess power
    - Significant clusters – coincident in all detectors – passed to *r*-statistic test
  - ***r*-statistic Test:**
    - Calculates normalized cross-correlations of detector signals
    - Scans through time delay from signal travel time.

- Injected simulated sources used to set search method thresholds
- Strain threshold for 50% detection rate: $h_{\rm rss} \approx 10^{-20}\ \mathrm{Hz}^{-1/2}$

- **S3 results: 8 days. No detections.**

Stochastic Sources

- Search for Coherent GW Background
  - Echo of Inflationary period, like CMBR
  - Superposition of numerous unresolved events
- GW energy density has power law form: $\Omega_{GW}(f) = \Omega_\alpha (f/100\ \mathrm{Hz})^\alpha$
  - Critical density of Universe: $\Omega = 1$
  - Inflation or Cosmic strings: $\alpha = 0$
  - Rotating Neutron Stars: $\alpha = 1$
  - Pre-Big Bang cosmology: $\alpha = 2$
- Calculated correlation between h_1 and h_2, the strains of two detectors, and $\Omega_{GW}(f)$
- Only most recent measurements from S3 (218 hours, 69–156 Hz) limit $\Omega_0 < 1$

α	Ω_α **S3 Result**	Ω_α **Theoretical Limit**
0	8.4×10^{-4}	$< 1.1 \times 10^{-5}$
1	9.4×10^{-4}	$< 10^{-7}$
2	8.1×10^{-4}	????

Bound set by Big Bang nucleosynthesis theory. Results from S5 should be several times below this limit.

LIGO

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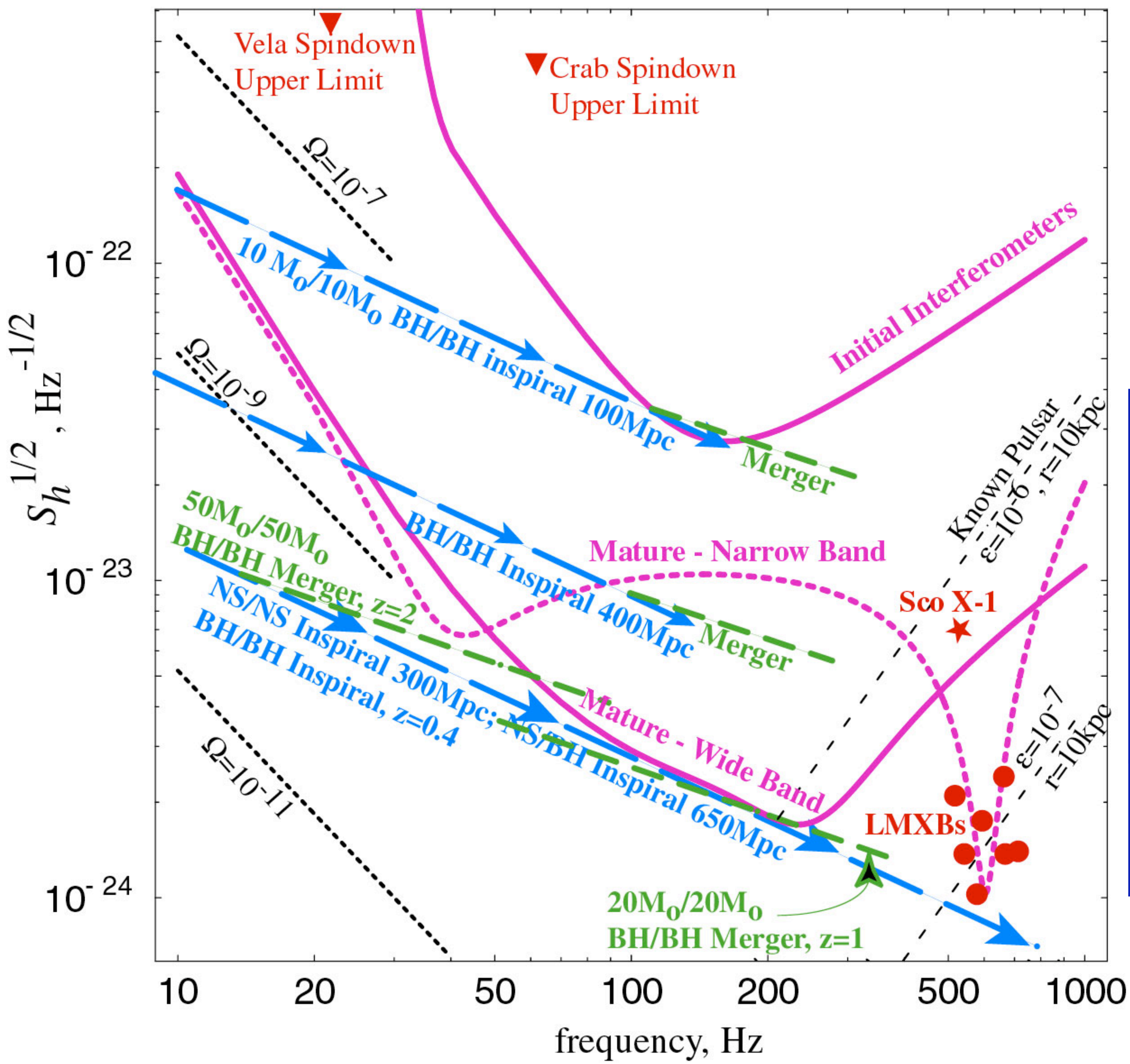
Advanced LIGO Sources



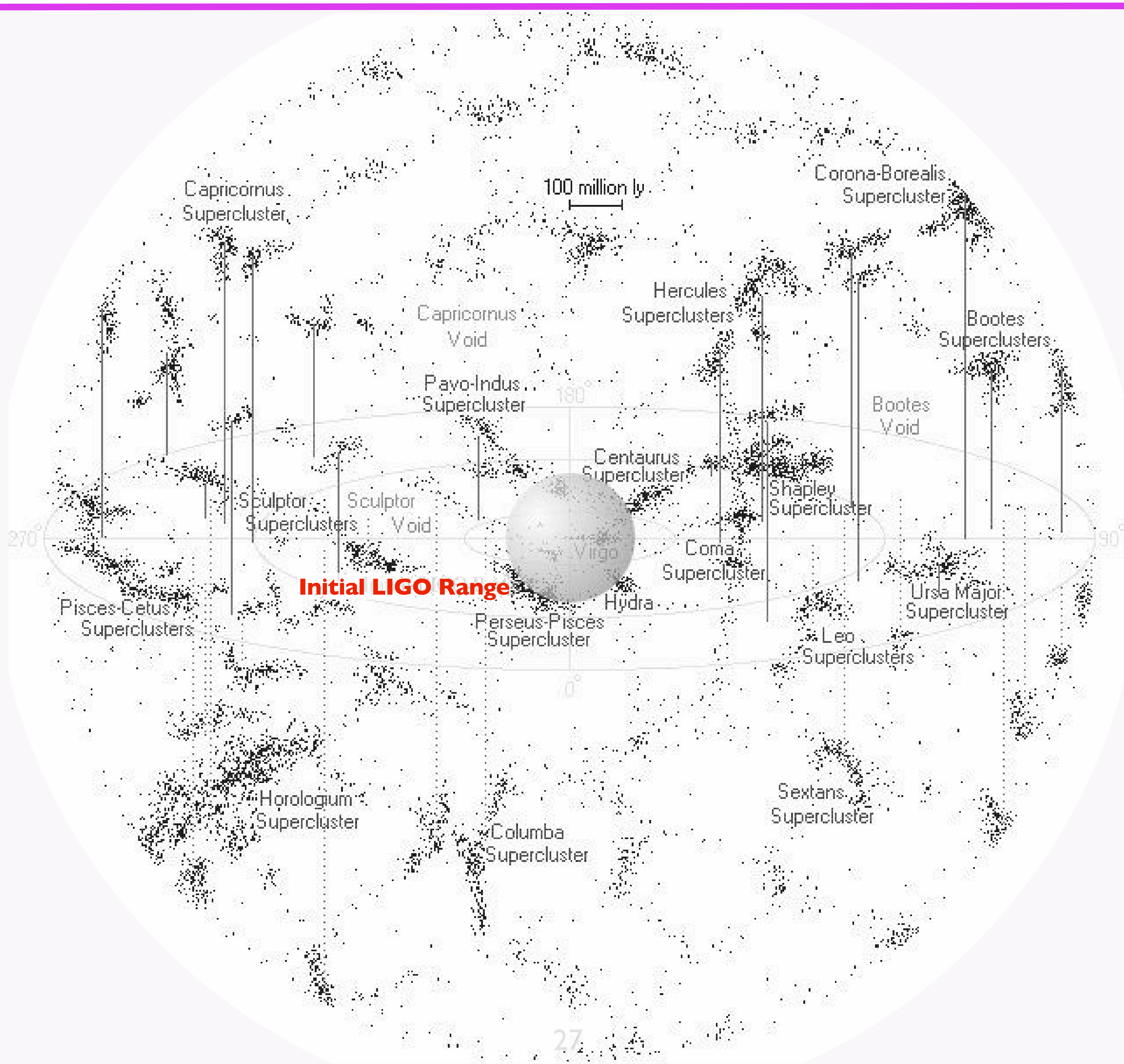
Strain sensitivity increase ≈ 20x

Range increases ≈ 20x

Rate increases as (Range)^3

SOURCE	RANGE	RATE
NS/NS	200–350 Mpc	2–1000 /yr
BH/BH	1.7 Gpc	10–10^4 /yr
BH/NS	750 Mpc	1–300 /yr

Adv. LIGO Range for BNSI

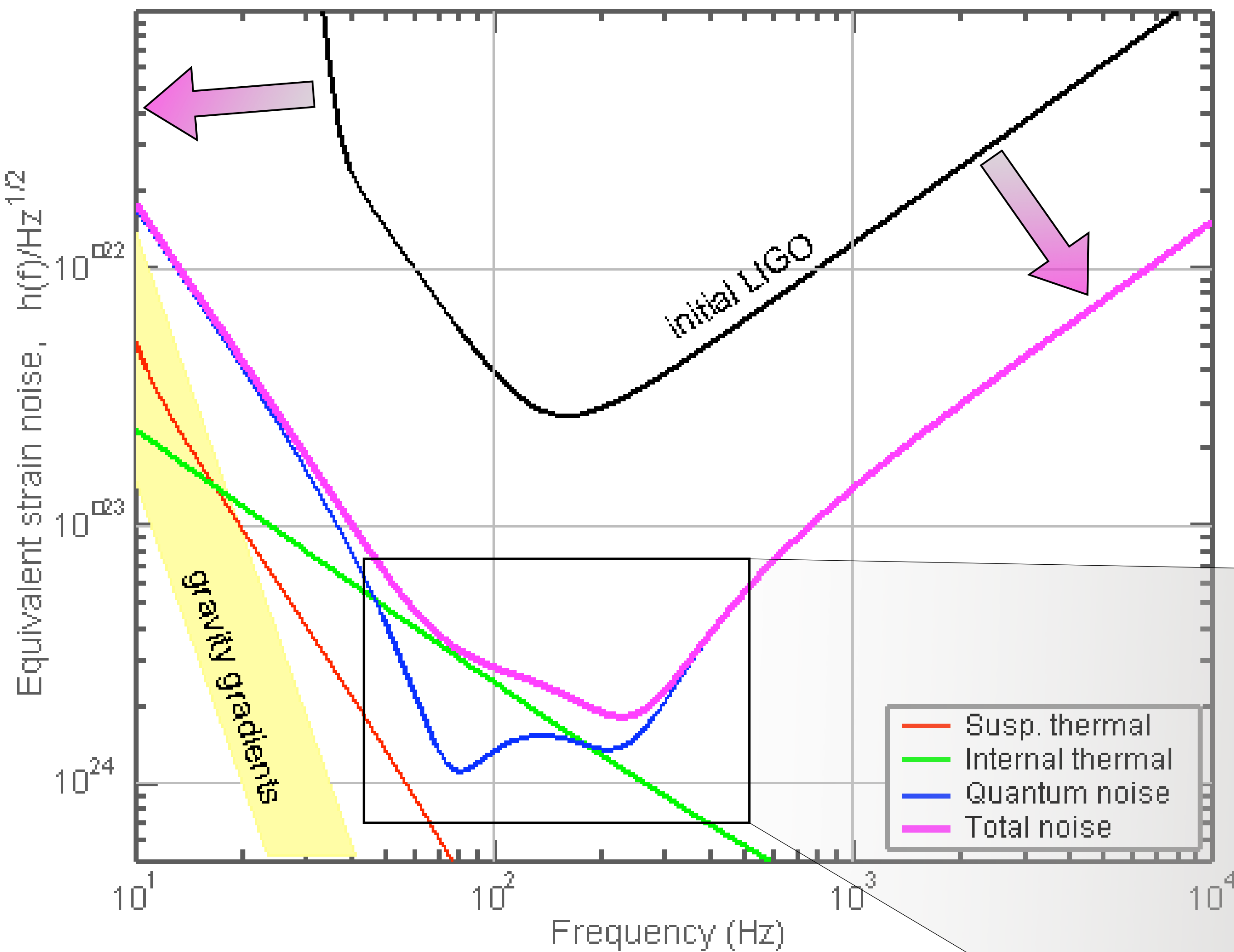


Original image: R. Powell

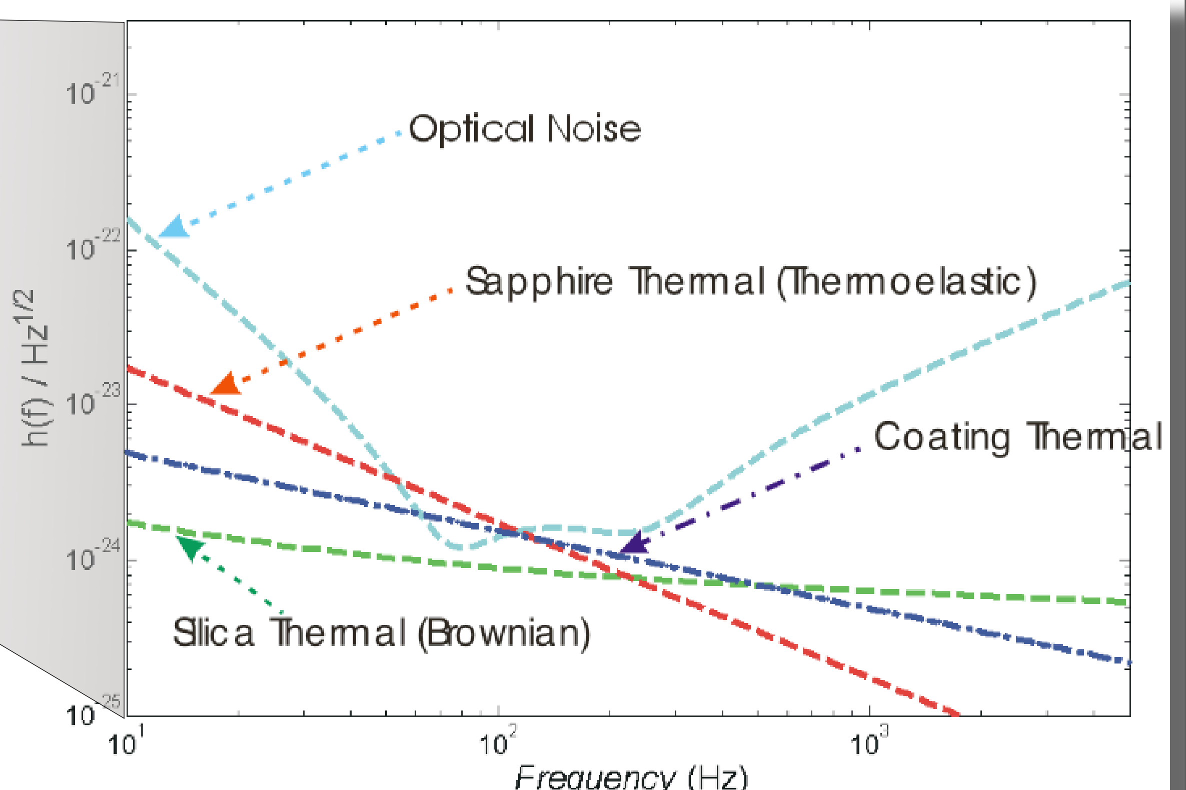
Advanced LIGO Improvements

Seismic Noise Wall:
h < 10^{-22} for f > 10 Hz

Shot Noise:
Stored laser power
to increase 25x



Quantum Noise Limited across most of band

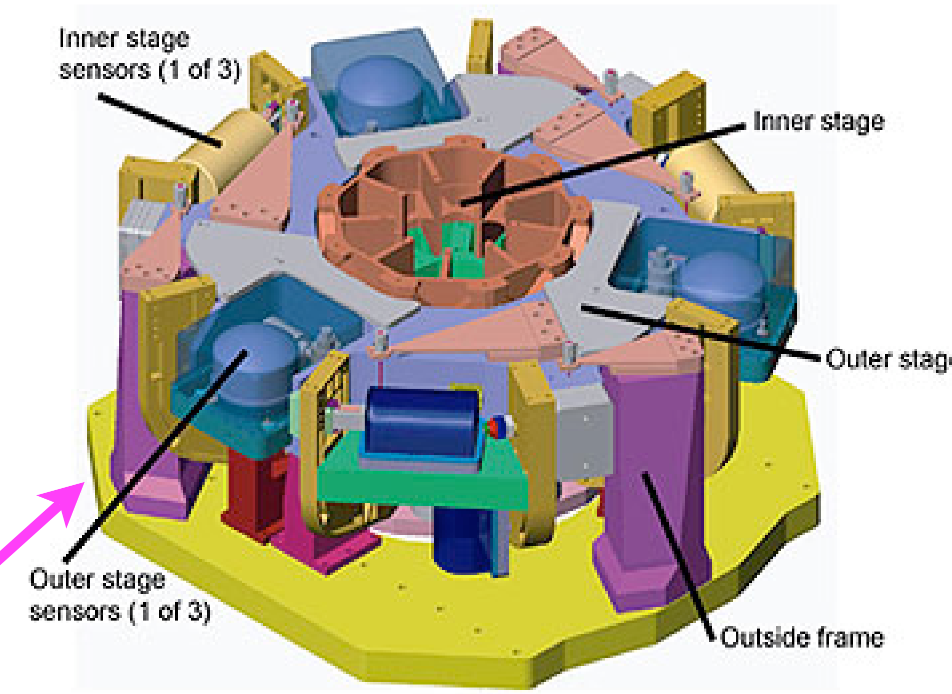


Limited by Thermal Noise in Test Mass Mirrors
≈ 4 – 40 Hz band

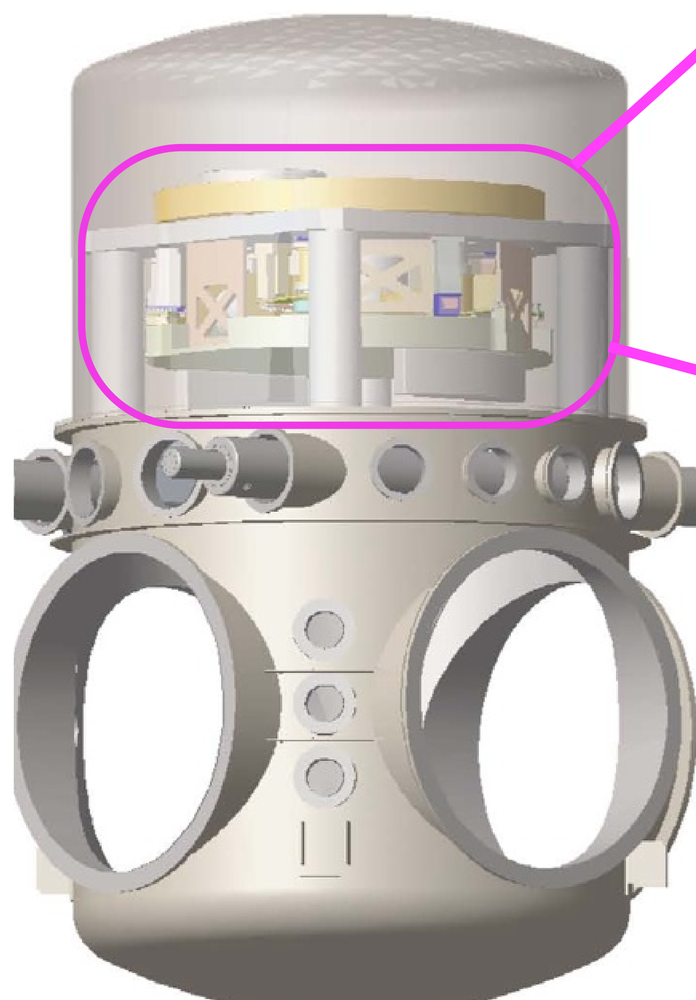
LIGO

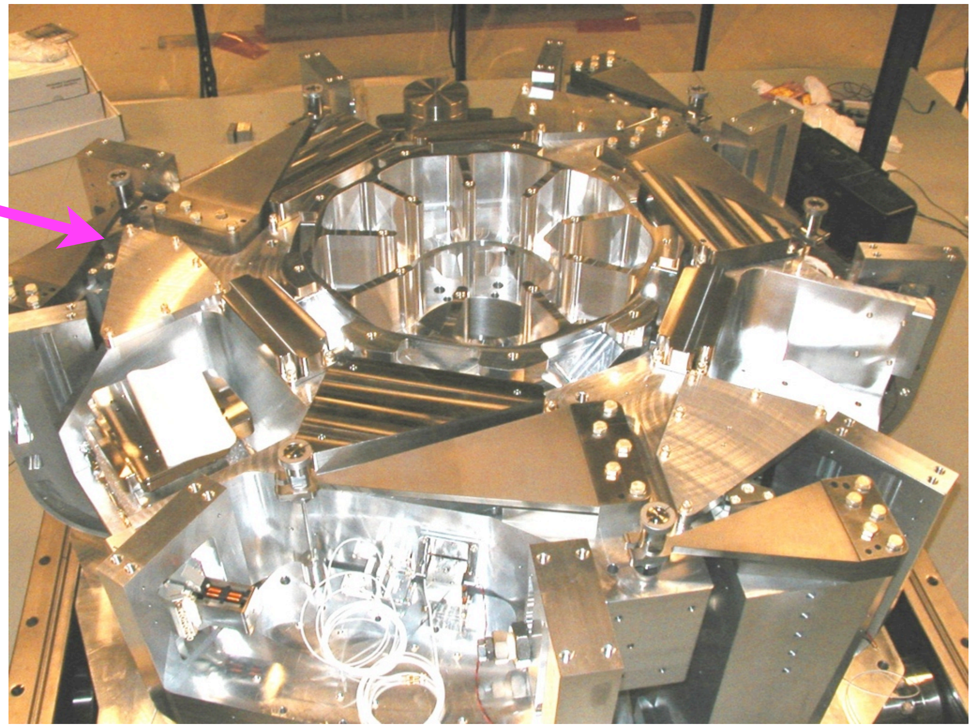
Adv. LIGO Seismic Isolation

- HEPI isolation of chamber supports
  - Overdetermined 6 DOF compensation in 0.1 – 10 Hz range
  - About 0.1 – 0.001 micron/s velocity over range
- Internal Chamber Isolation Stacks
  - Two isolation stages per stack
  - Passive isolation above 3 Hz. Active isolation below 30 Hz.
  - Supports Quad pendulum in BSC chambers
  - Supports Optical tables in HAM chambers



BSC Chamber

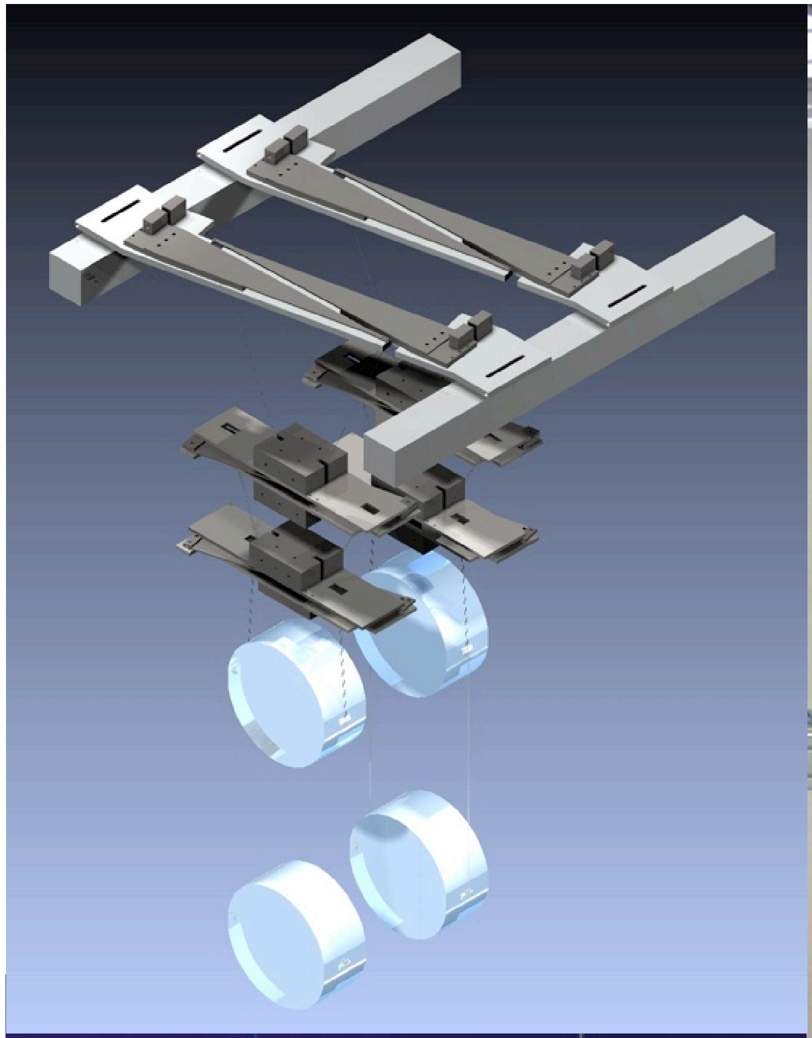


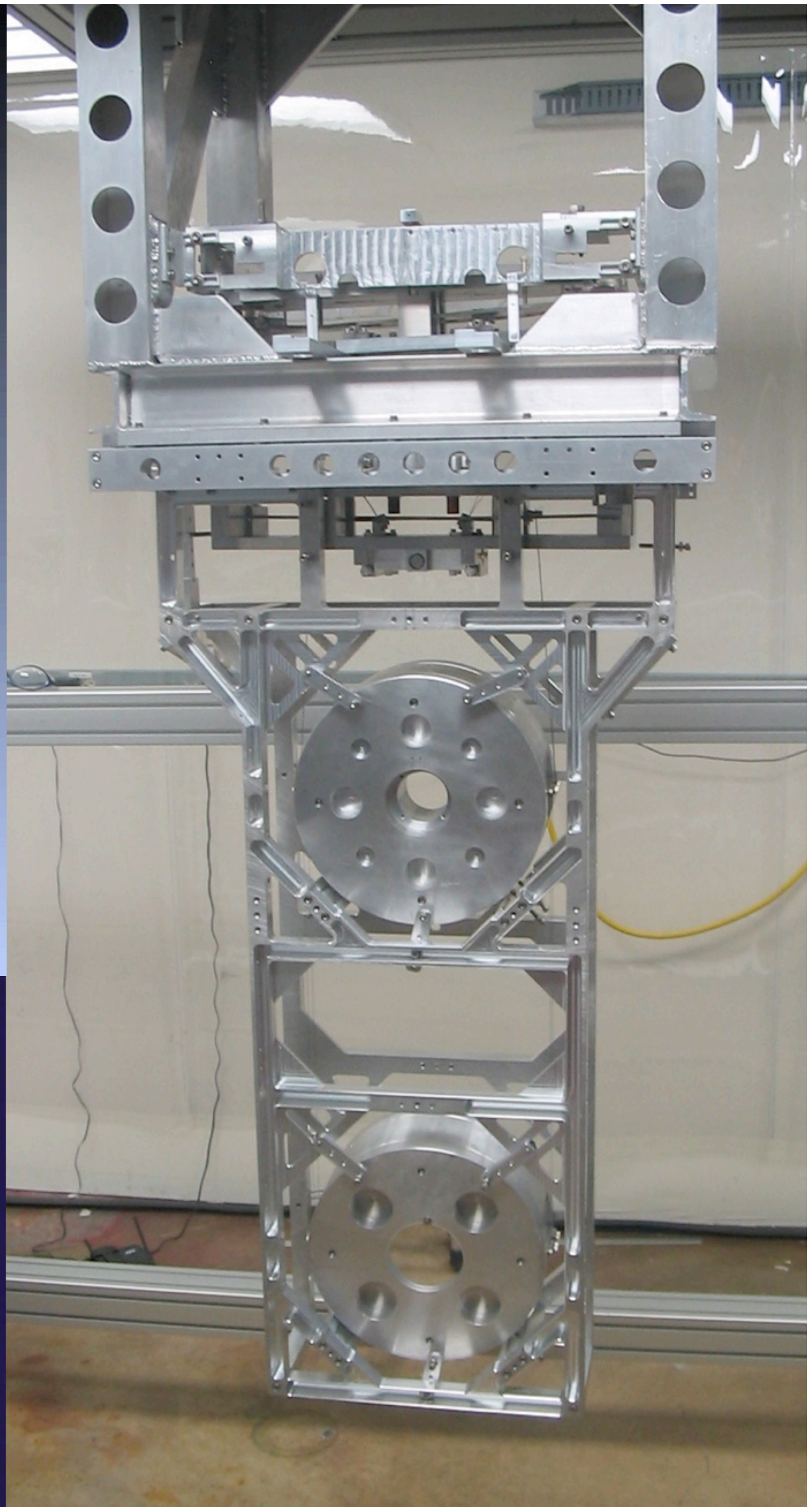


Advanced LIGO Suspensions

Quad Pendulum Design

- Fused silica test masses will be supported by Fused Silica fibers/ribbons.
  - Fibers welded to silica "ears" which are silicate bonded to the test mass.
  - Glasgow has developed a laser fiber drawing and welding apparatus.
- No Actuation on bottom test mass.
  - Actuation on upper test mass. Actuate against the reaction mass.
  - Marionette control of lower test mass
- Upper two pendula masses are Maragen Steel anti-springs and reaction masses.
- Design and construction was performed by UK collaborators, Stanford, and Caltech. Prototype is now being assembled in LASTI for testing of control systems.



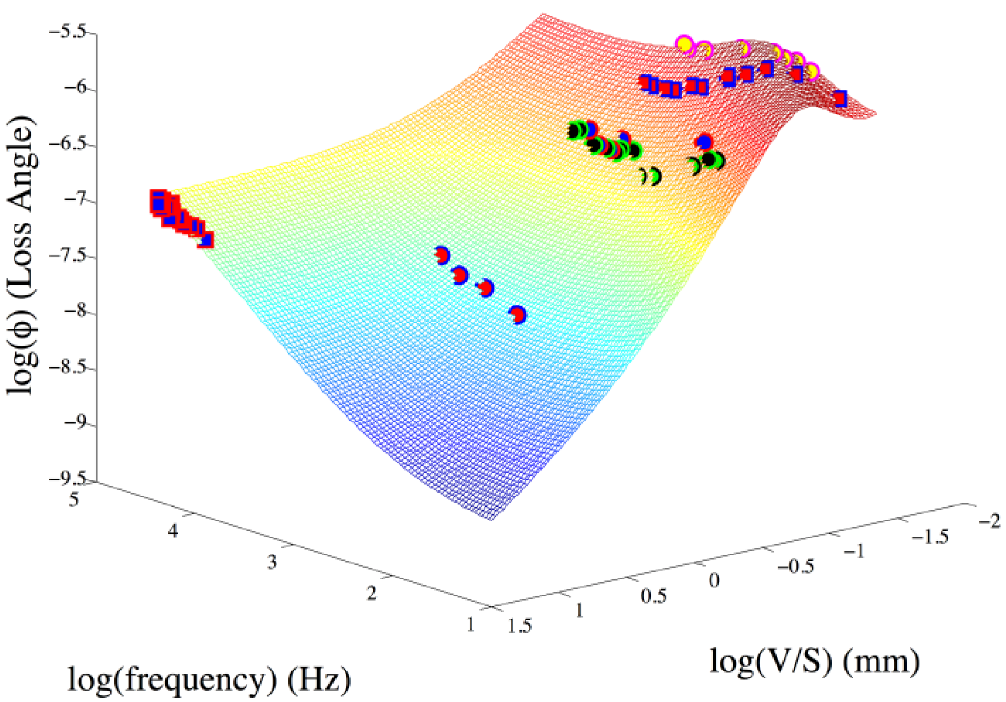


Adv. LIGO Thermal Noise

Test Mass: Fused Silica or Sapphire

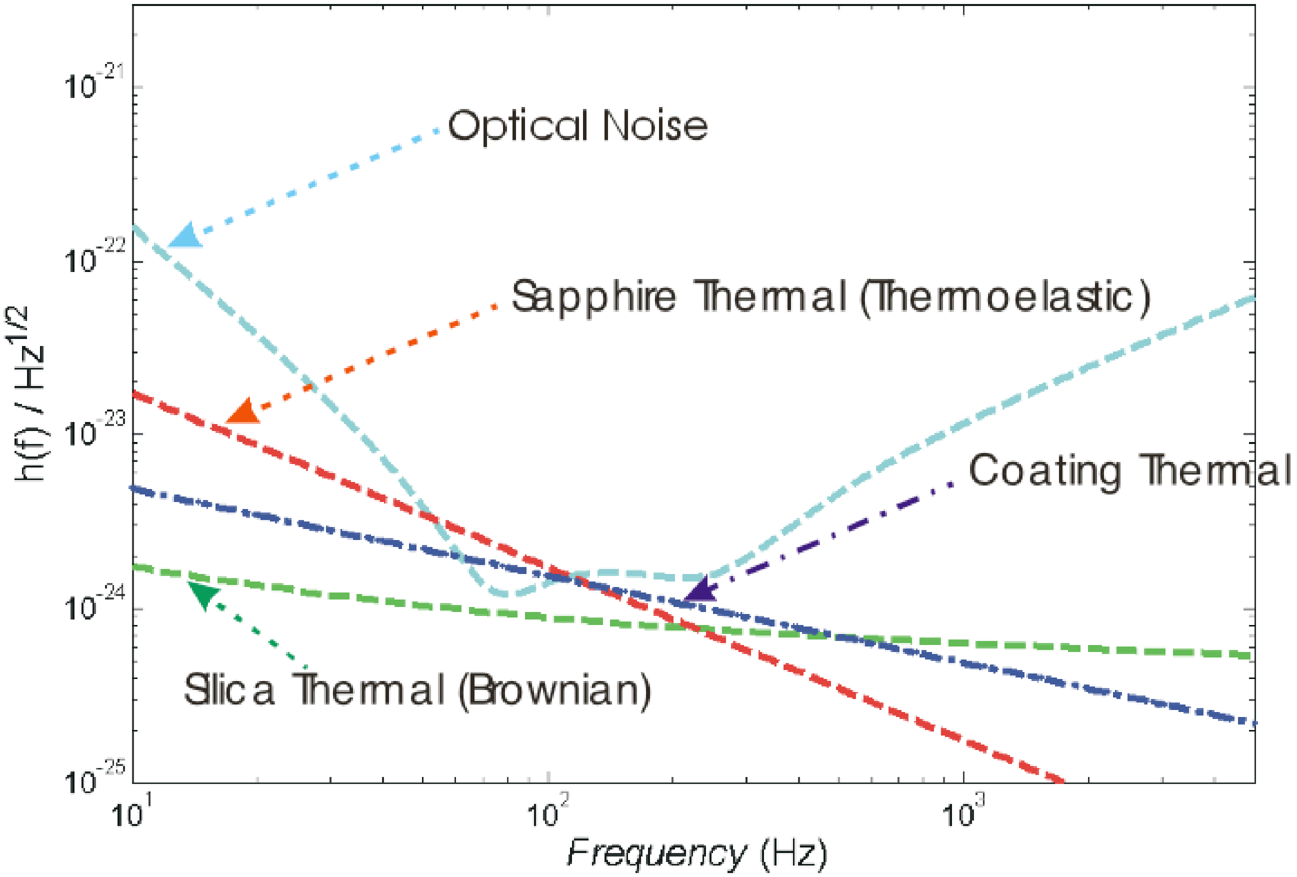
Property	Best Material
Young's Modulus	Sapphire
Thermal Conductivity	Sapphire
Density	Sapphire
Optical Absorption	Fused Silica
Thermoelastic loss	Fused Silica
History as Optical Material	Fused Silica
Ability to Polish & Coat	Fused Silica
Mechanical Loss	???

$$\phi = (8.55e{-}09\ S/V + 7.15e{-}12\ f^{0.822} + 1.02\ \phi_{th})$$



Fused Silica Chosen for Adv LIGO

- **Mechanical Loss is comparable with Sapphire.**
- **Extensive experience with producing, polishing, coating, and using high quality fused silica.**
- **Lower thermal conductivity requires uniform thermal compensation.**
- **Size for 40 kg fused silica optic will fit in suspension system.**

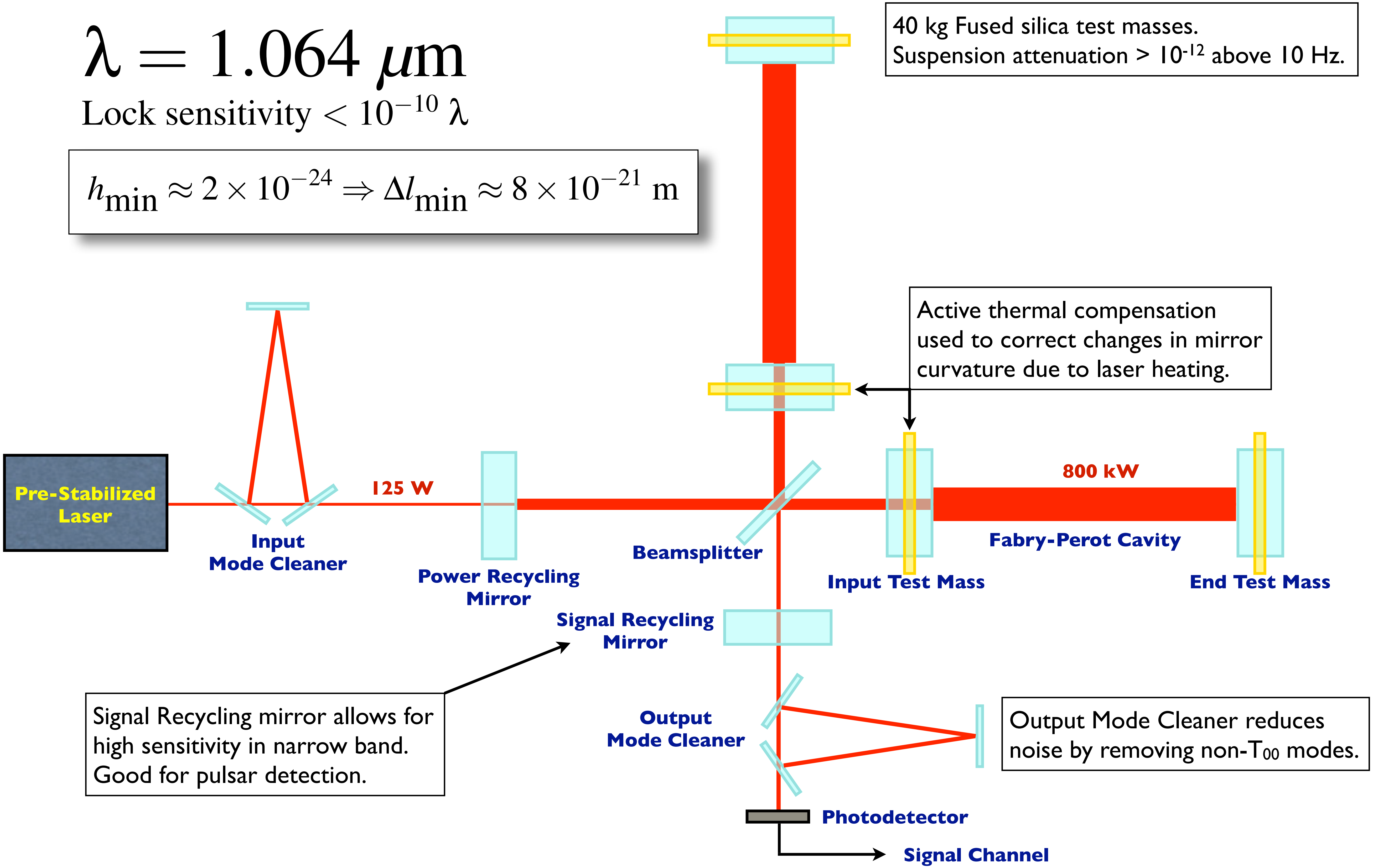


Adv. LIGO Laser System

$$\lambda = 1.064\ \mu m$$

Lock sensitivity $< 10^{-10}\ \lambda$

$$h_{\min} \approx 2 \times 10^{-24} \Rightarrow \Delta l_{\min} \approx 8 \times 10^{-21}\ \mathrm{m}$$

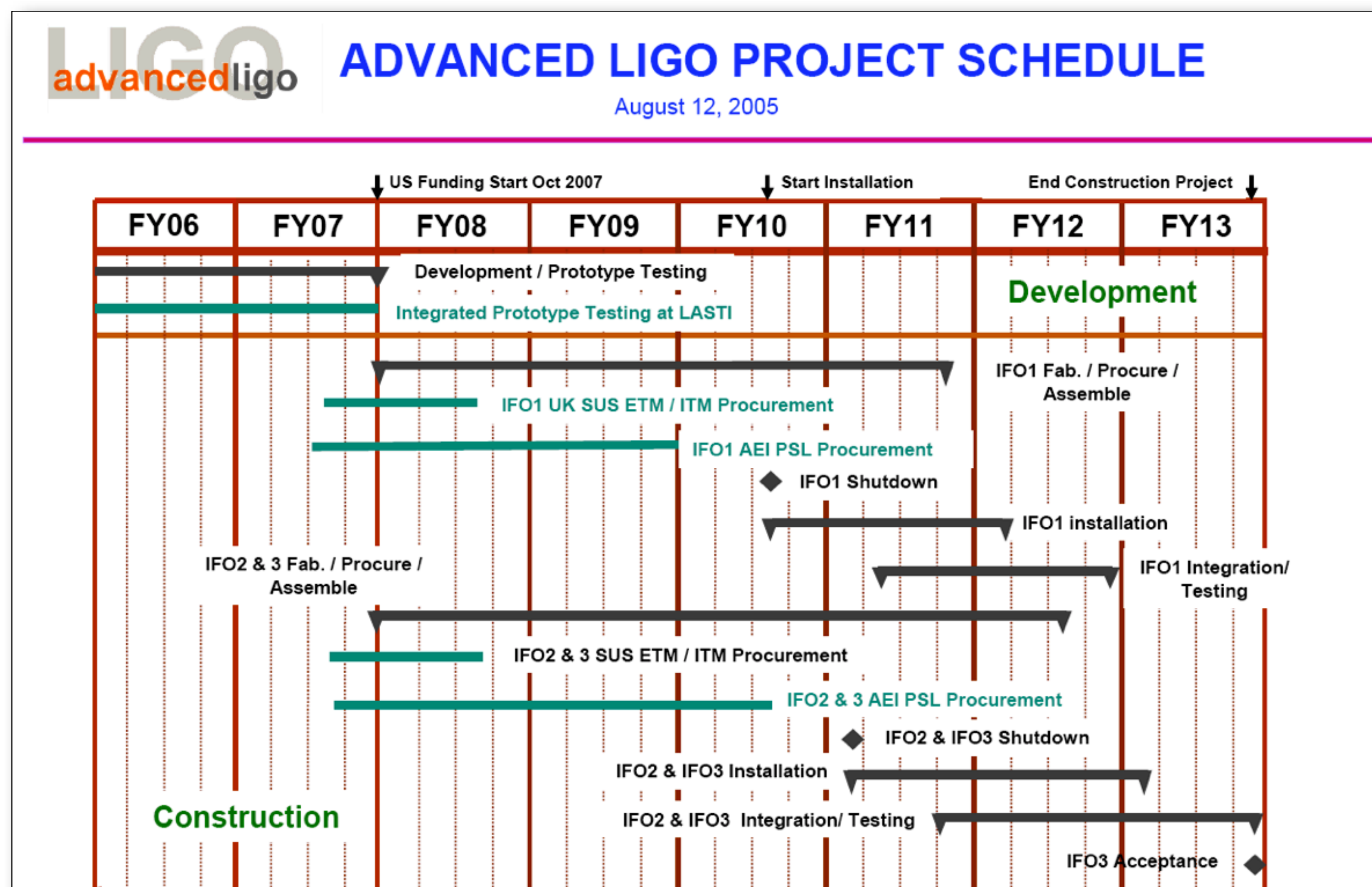


Advanced LIGO Specs

Subsystem	Advanced LIGO	Initial LIGO
Strain sensitivity [rms, 100Hz band]	8×10^{-23}	10×10^{-21}
Displacement sensitivity [rms, 100Hz band]	8×10^{-20}	4×10^{-18}
Optical power at laser output	180 W	10 W
Optical power at IFO input	125 W	6 W
Optical power at test masses	800 kW	30 kW
Input mirror transmission	0.5%	3%
End mirror transmission	15 ppm	15 ppm
Arm cavity power beam size	6 cm	4 cm
Light storage time in arms	5.0 ms	0.84 ms
Test masses	Fused Silica, 40 kg	Fused Silica, 11 kg
Mirror diameter	35 cm	25 cm
Test mass pendulum period	1s	1s
Seismic isolation system	3 stage active, 4 stage passive	passive 5 stage
Seismic system horizontal attenuation	$>=10^{-12}$ (10 Hz)	$>=10^{-9}$ (100Hz)
Suspensions	Quad Pendulum, FS fibers	Single steel wire loop

Advanced LIGO Schedule

- Advanced LIGO has been approved by the NSF and included in the President's budget. Congressional funding approval pending.
- Funding expected to begin in FY2008 (Oct 2007). Construction of instrumentation would begin immediately.
- First IFO shutdown would occur in mid-2010.
- System upgrades staggered by 6 months between IFOs.
- Last IFO back online by the end of 2013.



Conclusions

- Initial LIGO has reached design sensitivity and is engaged in a year long data run that will provide much improvement in event rates, and maybe make a detection.
- Advanced LIGO will increase our sensitivity more than 20x and make GW detection a frequent occurrence. Should be online by 2013.
- Collaboration in the worldwide GW community is growing. Very positive effects for us all.
- Exciting and unexpected physics awaits us!