Prospects for joint transient searches with LOFAR and the LSC/Virgo gravitational wave interferometers

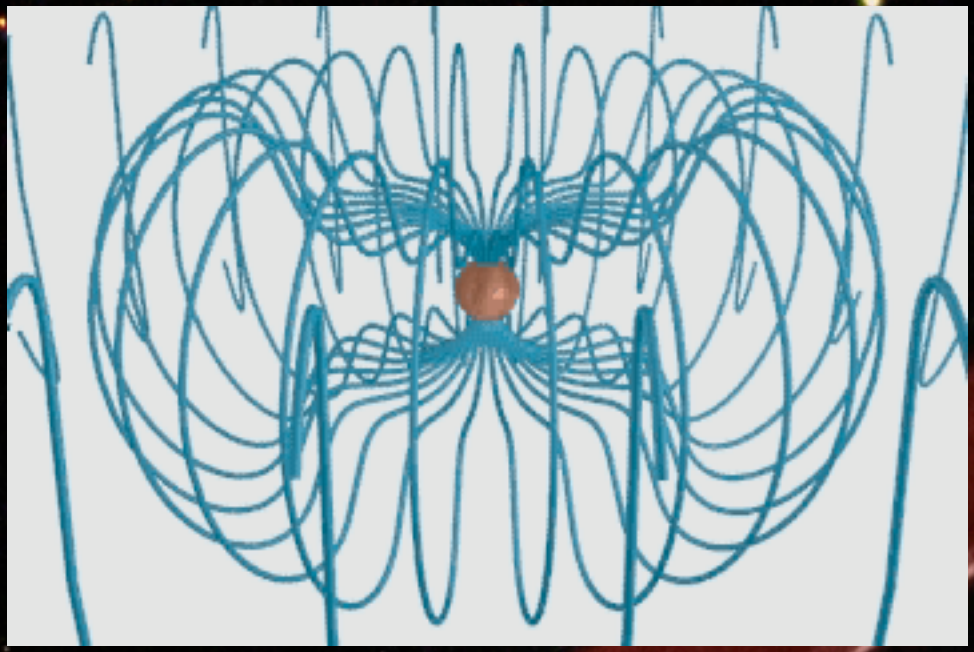
Ed Daw - University of Sheffield
On behalf of the LIGO Scientific Collaboration and the Virgo collaboration (LVC):

LIGO-G080641-00-K

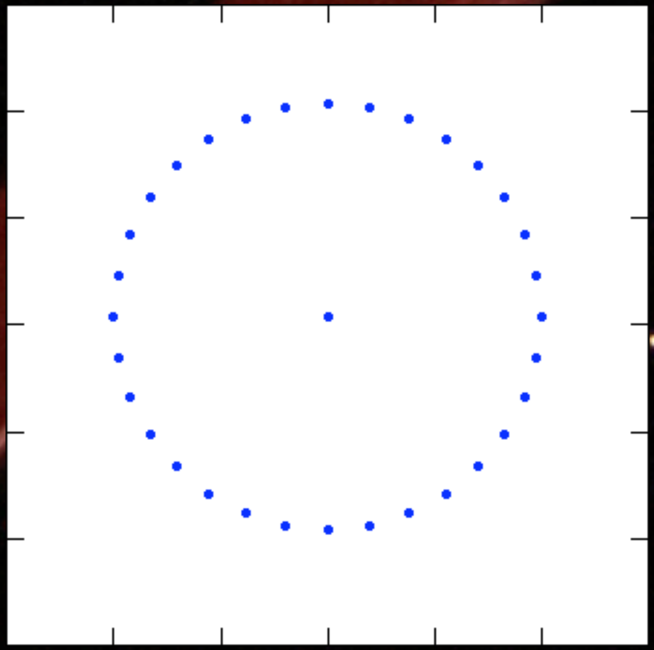
http://apod.nasa.gov/apod/image/0809/sn1006_hst_big.jpg

Electromagnetic Waves

Oscillations in electromagnetic field induced by accelerating charges



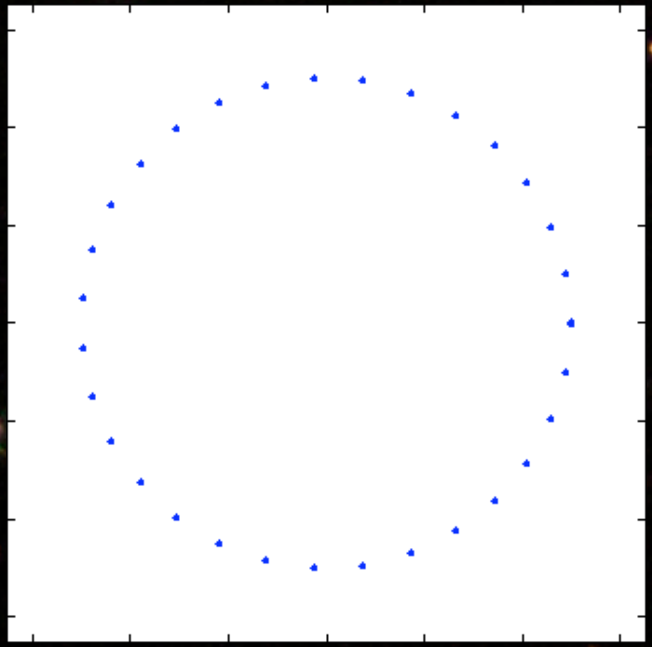
[1]



Gravitational Waves

Oscillations in spacetime geometry (time of flight of massless particles between test masses in free fall)

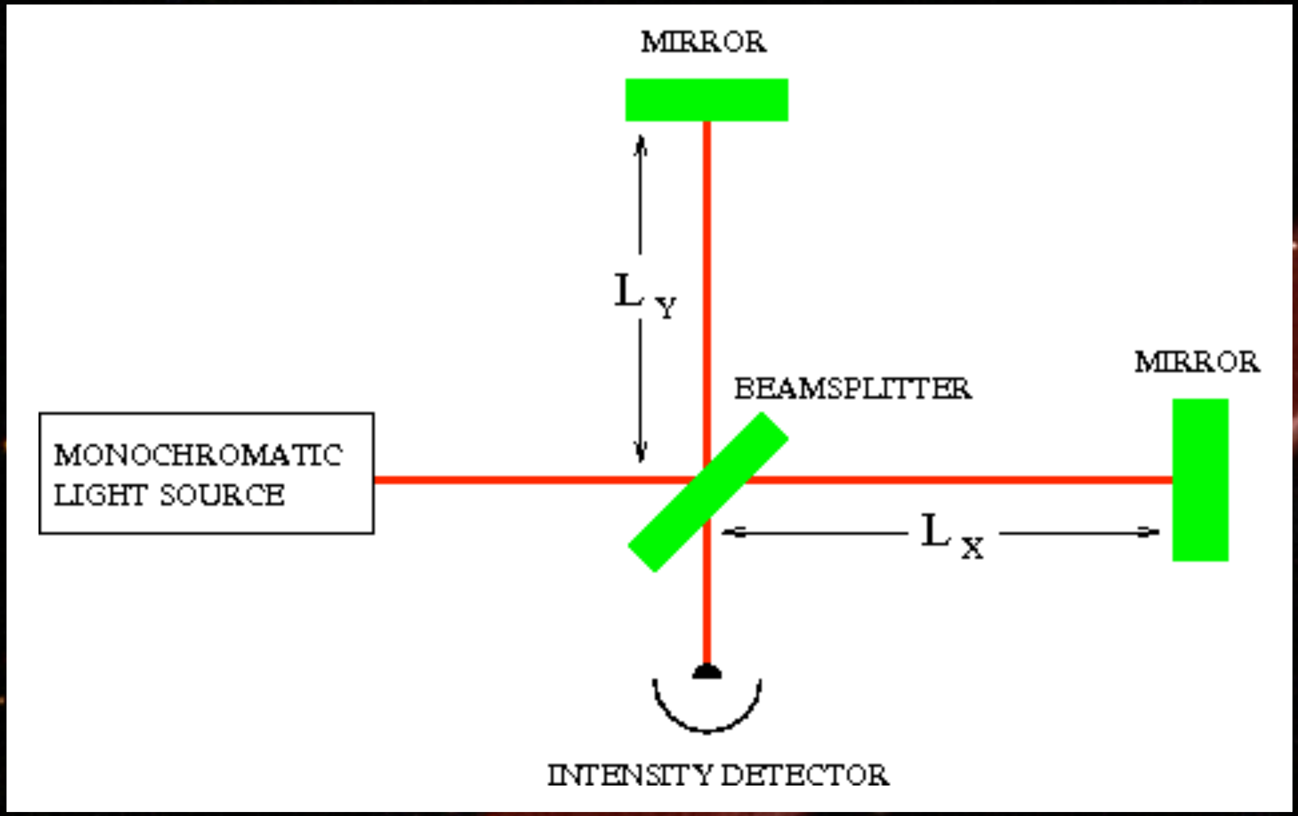
[2]

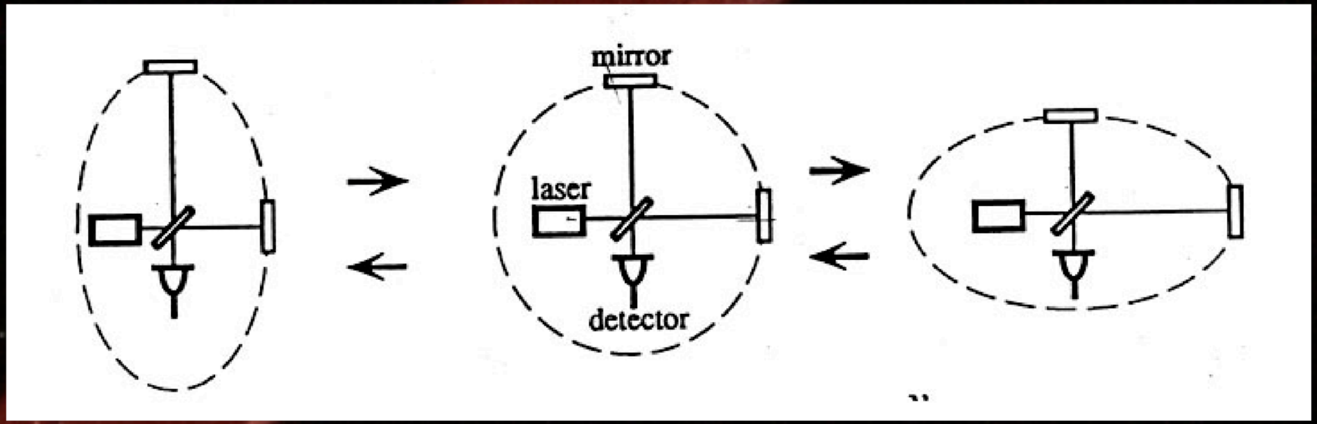


[1] http://web.mit.edu/course/urop/8.emfields/Public/animations/dipint3D.mov

[2] http://www.nasa.gov/mov/116648main_CollidingWdwarves.mov

A Gravitational wave strain transducer - the Michelson interferometer





Gravitational waves cause fluctuations in the difference between the arm lengths. Define differential length as:

$$L_- = \frac{L_x - L_y}{2}$$

Many noise sources cause fluctuations in the sum of the arm lengths. Define common arm length as:

$$L_+ = \frac{L_x + L_y}{2}$$

Gravitational waves excite differential strain, defined as

$$h = \frac{L_-}{L_+}$$

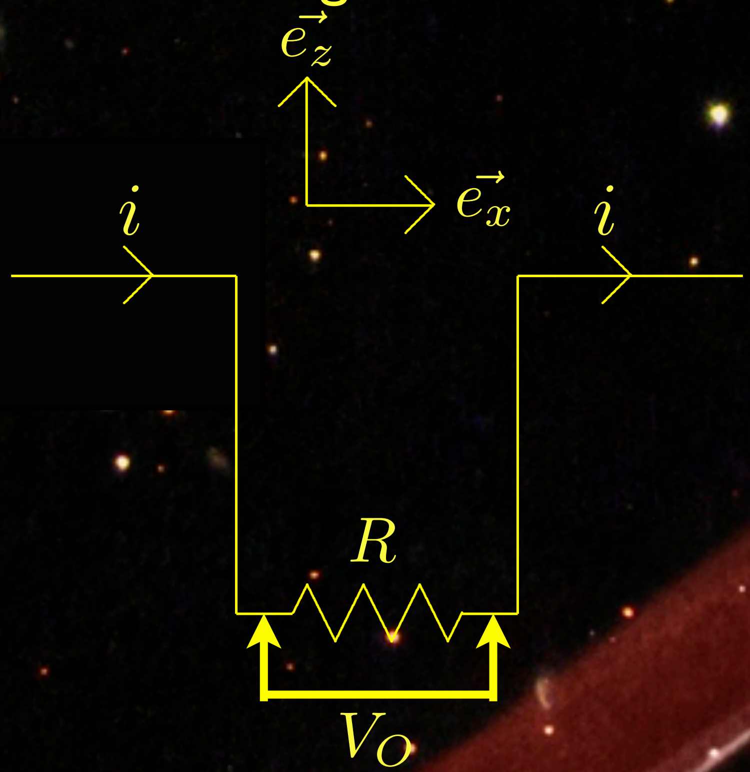
The problem is that for realistic signals

$$h \leq 10^{-21}$$

The detected quantity, the signal, is L_- , excited by gravitational waves in h .

Signal strength versus source distance

Electromagnetic antenna

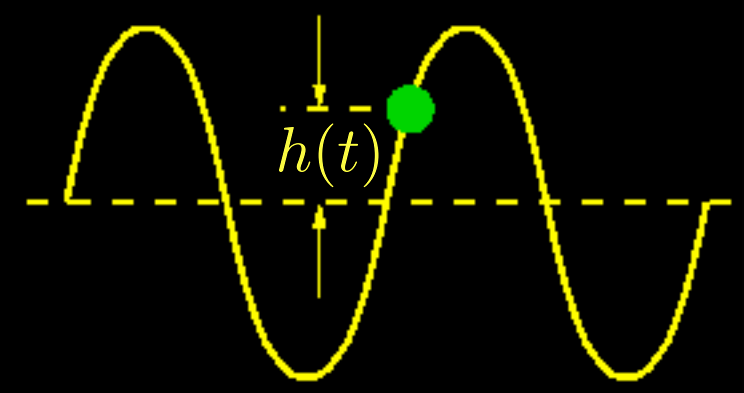


$$V_O = iR = R\frac{dq}{dt} \propto E_x$$

Detect current through load, proportional to electric field. But the sources are usually incoherent across the baseline, and therefore stochastic, averaging to zero. Therefore measure $\langle E_x^2 \rangle$

$$E_x \propto \frac{1}{r} \quad \text{so} \quad \langle E_x^2 \rangle \propto \frac{1}{r^2}$$

Gravitational wave antenna



Detect displacement of mass, proportional to gravitational potential. But most sources are coherent, not stochastic, therefore infer V from h, and

$$V \propto \frac{1}{r}$$

Small strains necessitate big interferometers


LIGO Livingston Observatory, Louisiana, U.S.A.


GEO 600 - Hopfenberg, near Hannover, DE


LIGO Hanford Observatory, Washington State, U.S.A.


Virgo - EGO laboratory, Cascina, near Pisa, Italy.

Some LIGO Technology

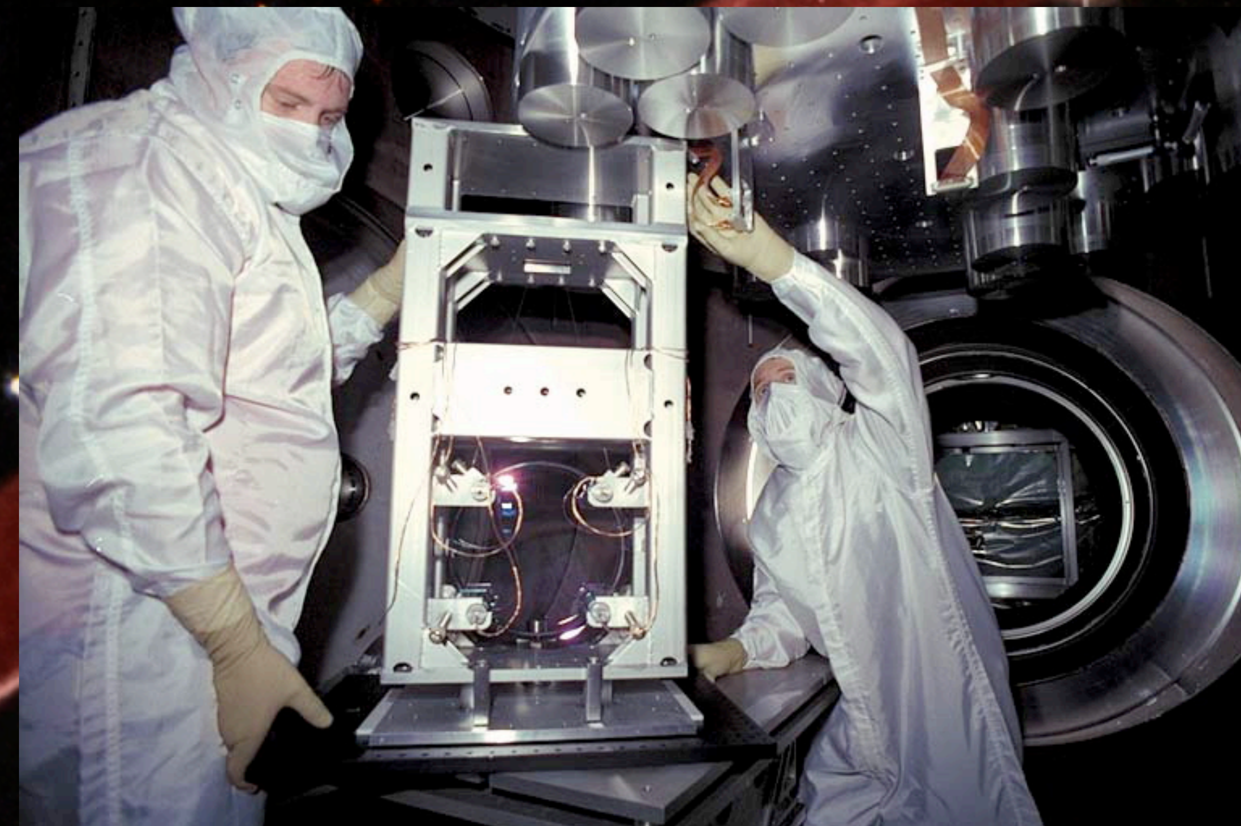
The University Of Sheffield.

LSC

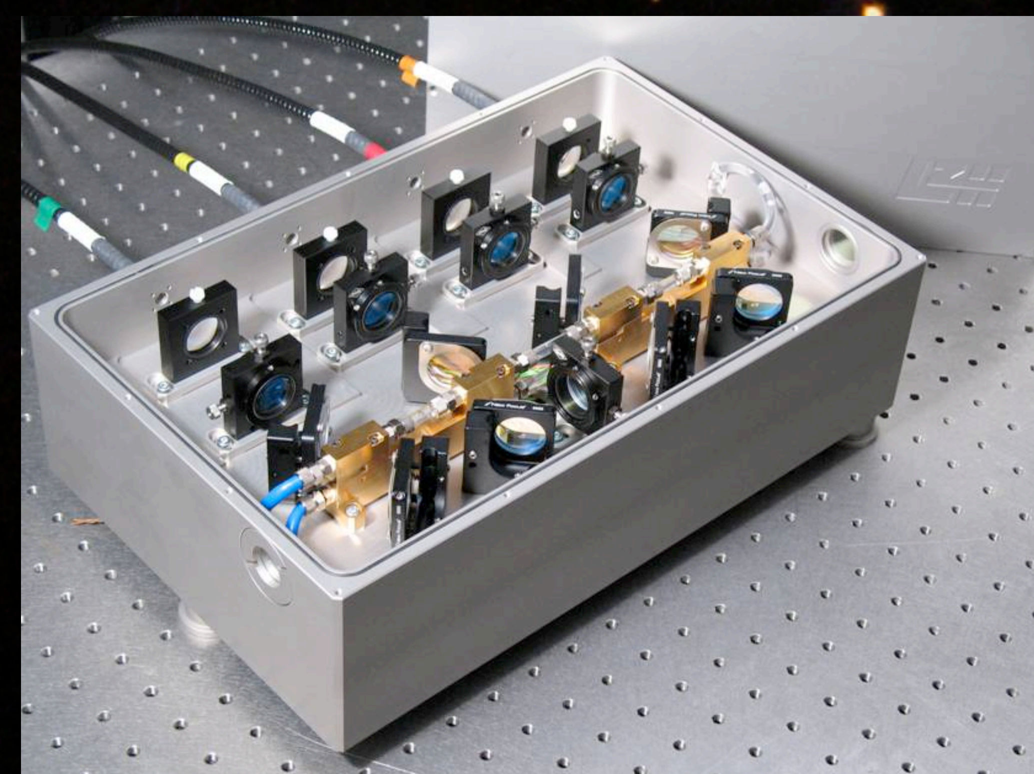
VIRGO

Vacuum system inside the corner station at Livingston

Livingston beam splitter installation

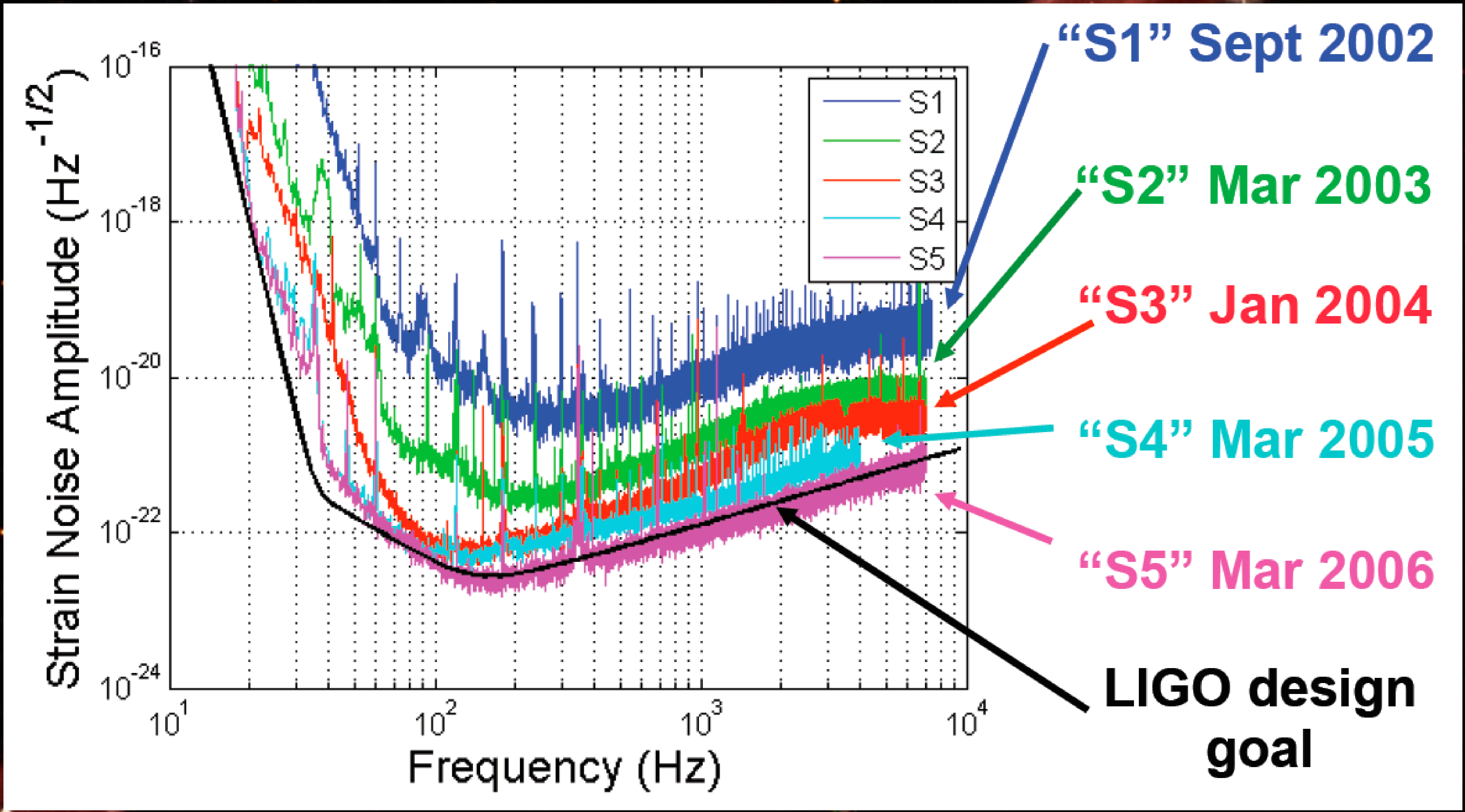


Initial LIGO fused silica optics



35W CW output 1.06um laser amplifier (Enhanced LIGO)

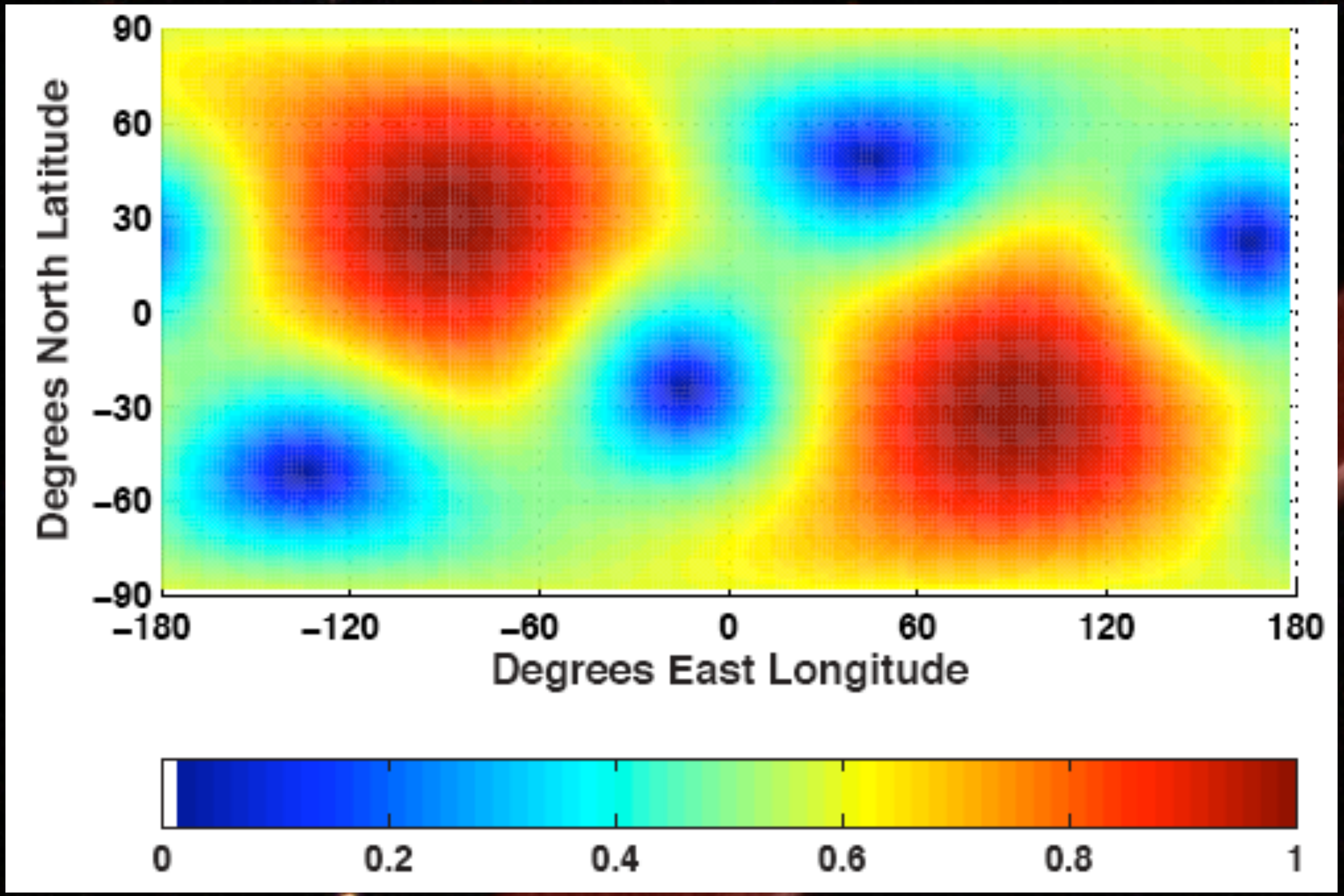
Initial LIGO Hanford strain sensitivity



Narrow line features removed by characterization and subtraction

Some excess noise above initial LIGO design remains below 100Hz.

Antenna pattern of a single interferometer



[3]

Assumes wave is + polarized with respect to the arms - pattern for other x polarization is different

Sensitive lobes are very broad, with most of the sky having better than 40% pickup. Exceptions are waves incident down lines parallel to either of the two arms.

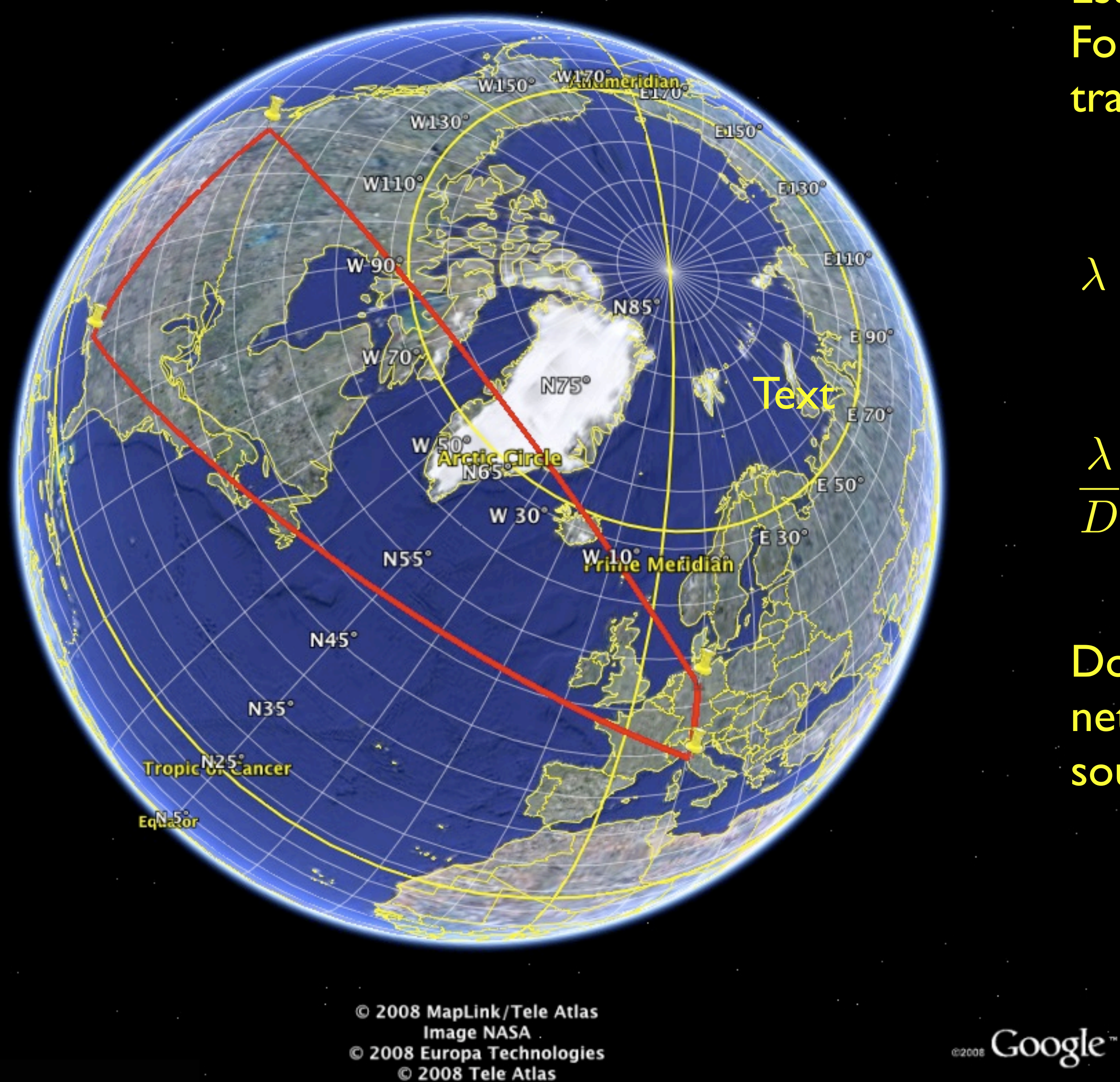
Rather as for early gamma-ray detectors, a single interferometer will fire in response to most of the sky, but it will not tell you where the source is. So...

[3] - LIGO T-040202 http://antares.ligo.caltech.edu/dcc/default.htf

The University Of Sheffield.

LSC/Virgo as a detector array

Longest baseline is approximately 10^7 m



Estimate the resolving power.
For a gravitational wave transient centered at 100 Hz:

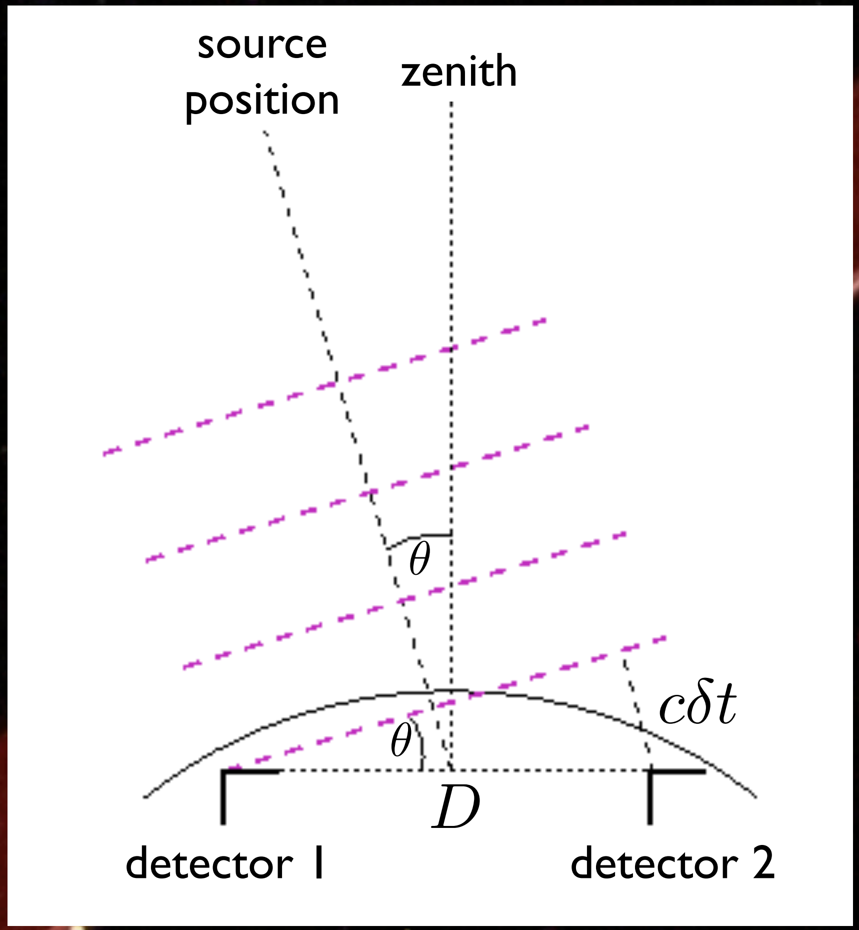
$$\lambda = \frac{c}{100} = 3 \times 10^6 \text{ m}$$

$$\frac{\lambda}{D} \sim \frac{3 \times 10^6 \text{ m}}{10^7 \text{ m}} \sim \frac{1}{3} \text{ radians}$$

Does this mean that the network can't tell you where a source is ? No, it doesn't.

Position reconstruction accuracy

Poor resolving power seems like a problem, but it is not. The interpretation is that the LVC network can't resolve the source image on the sky. But this is not what we are trying to do here. We require an accurate estimate of the central position of the source, not an image.



For a source close to the zenith:

$$\sigma_\theta \simeq \frac{c\delta t}{D}$$

δt is the reciprocal of the Nyquist frequency.

For detectors separated by the Earth's radius, and where the sampling rate is 16384Hz, the precision with which you can measure arrival time leads to

$$\sigma_\theta \geq 0.35^\circ$$

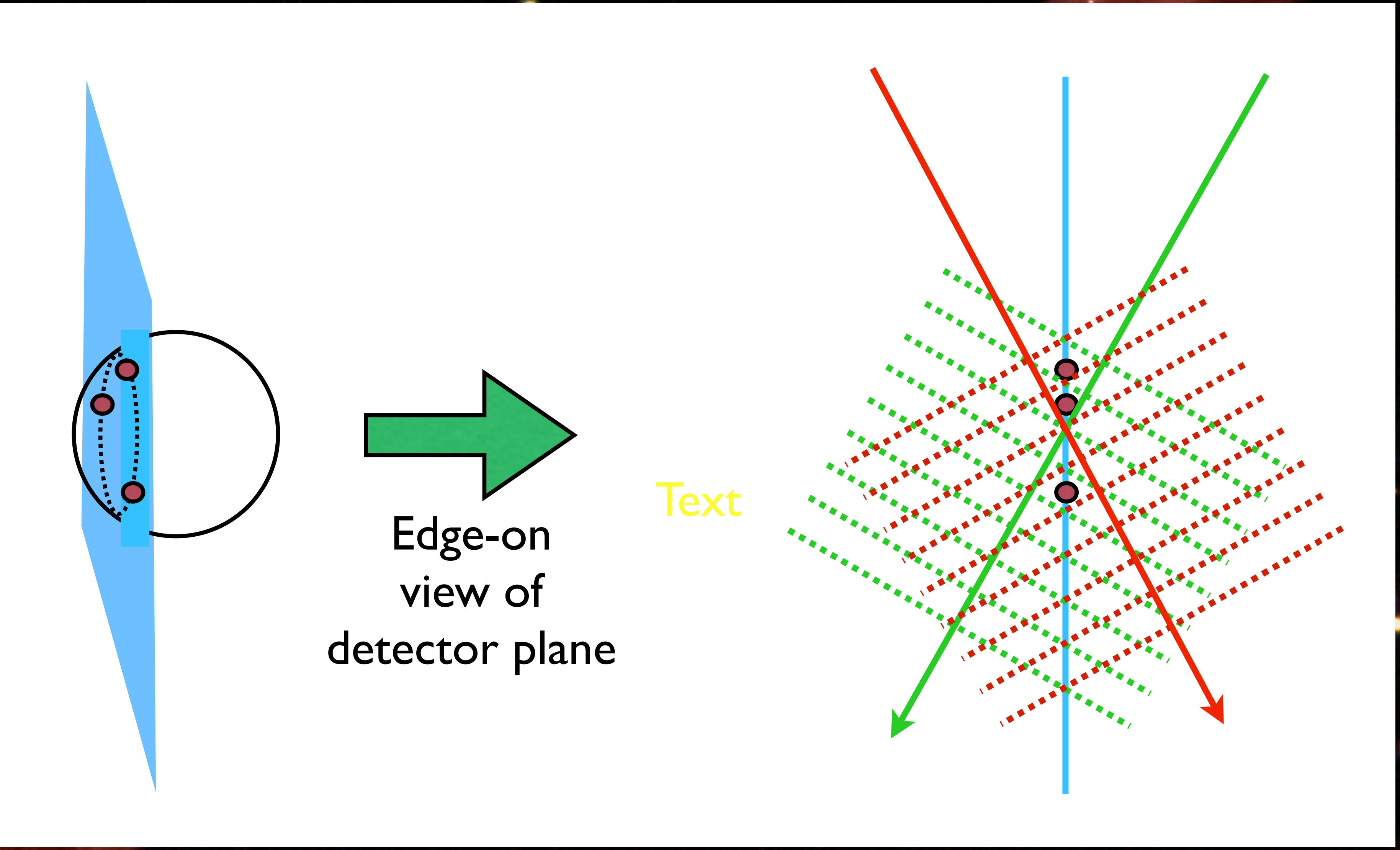
Actual pointing accuracy worse than this; source rarely close to zenith, detectors not aligned, polarization of source is uncertain. In reality, the current best case is:

$$\sigma_\theta \sim 1 - 2^\circ$$

LSC/Virgo network pointing is at the degree accuracy level.

Triangulation from three interferometers

- Consider the detector plane viewed edge-on



- In this simplified model, three interferometers gives you two possible sky positions. A fourth out-of-plane interferometer removes the degeneracy.
- In fact, in theory, three non-aligned interferometers are sufficient to break the two position degeneracy. This is also a subject of much work.

Target sources in the LSC/Virgo frequency band

Neutron stars

Soft gamma repeaters

Anomalous X-ray pulsars

Pulsars

Supernovae

Neutrino pulses

? gravitational wave bursts ?

? Orphan afterglows ?

'Long period (>2s)' gamma ray bursts

Coalescing compact binaries

? Gravitational wave 'chirps' ?

? Gravitational wave bursts ?

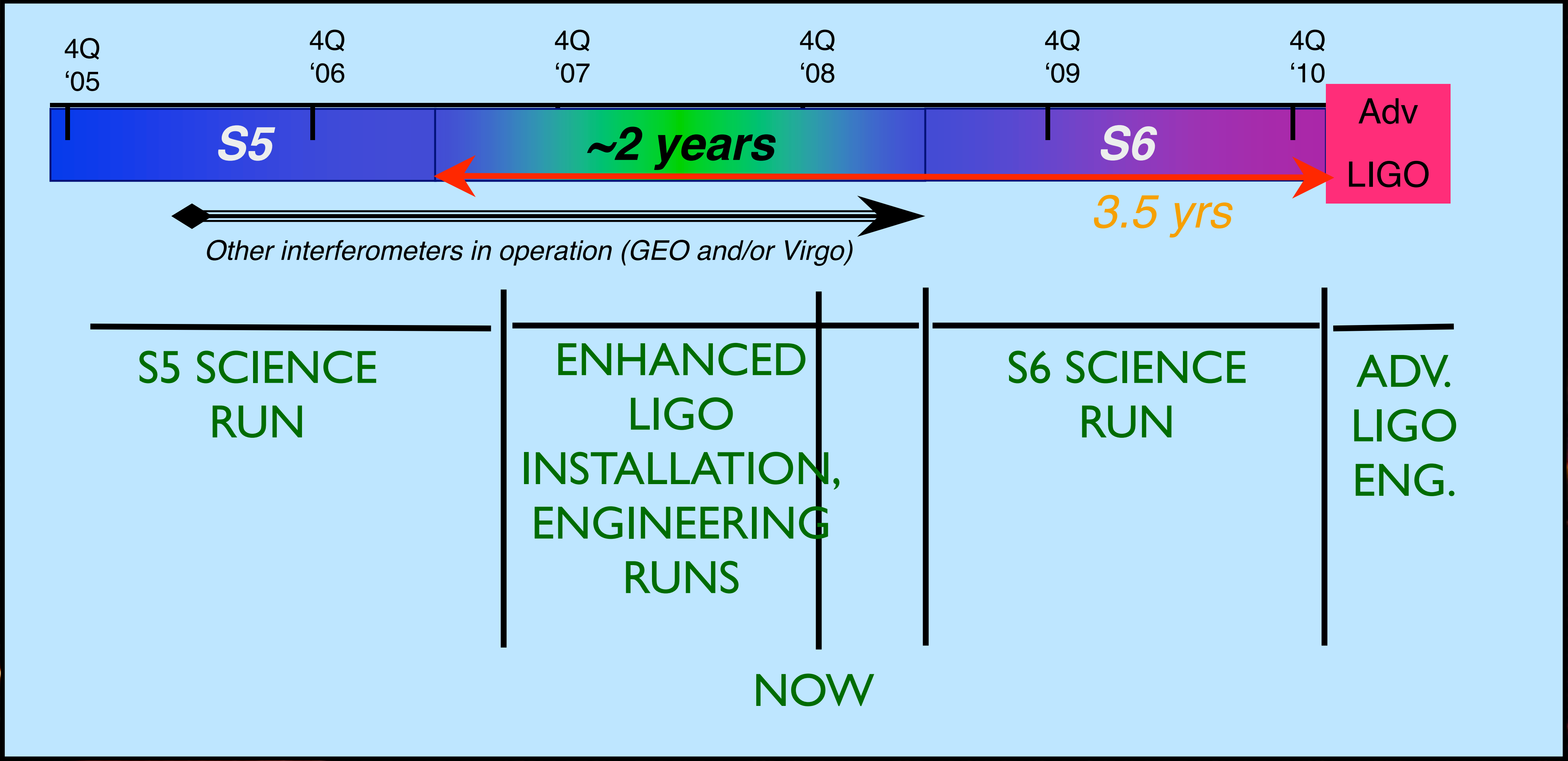
? 'Short period (<2s)' gamma ray bursts ?

? Radio afterglow ?

? Optical afterglow ?

? Neutrino pulses ?

Interferometer Upgrades

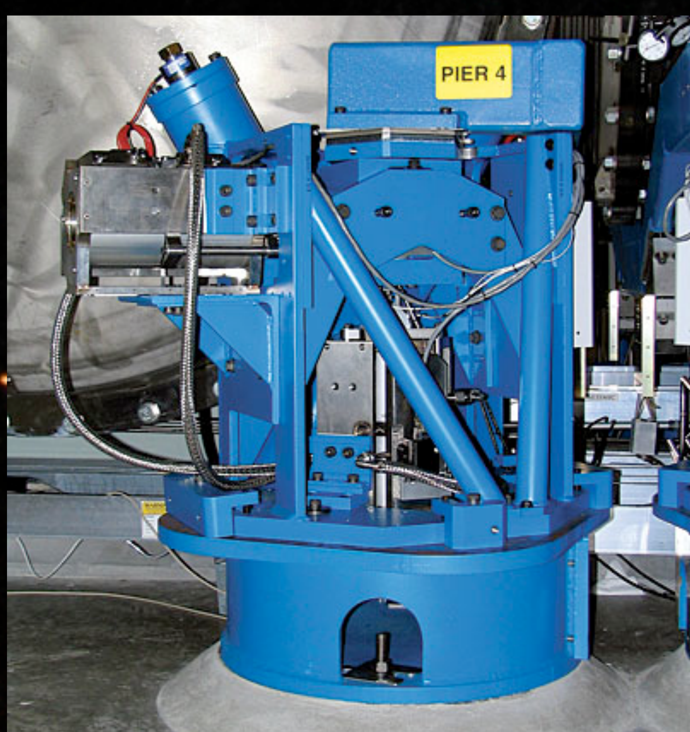


- S6/VSR2 run will be 1.5 years long.
- A key goal is to run analysis algorithms for transients in the detector network in real time.
- Group delay from signal arrival to reconstruction <30 mins.

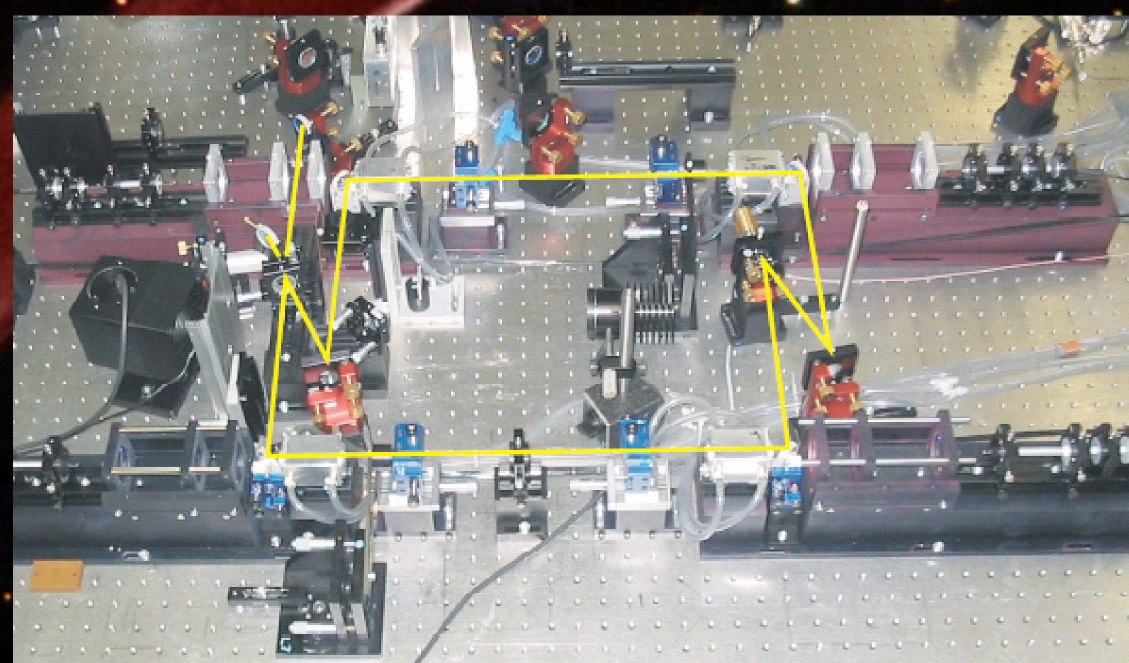
Advanced LIGO Upgrade

Approved by N.S.F. in U.S.

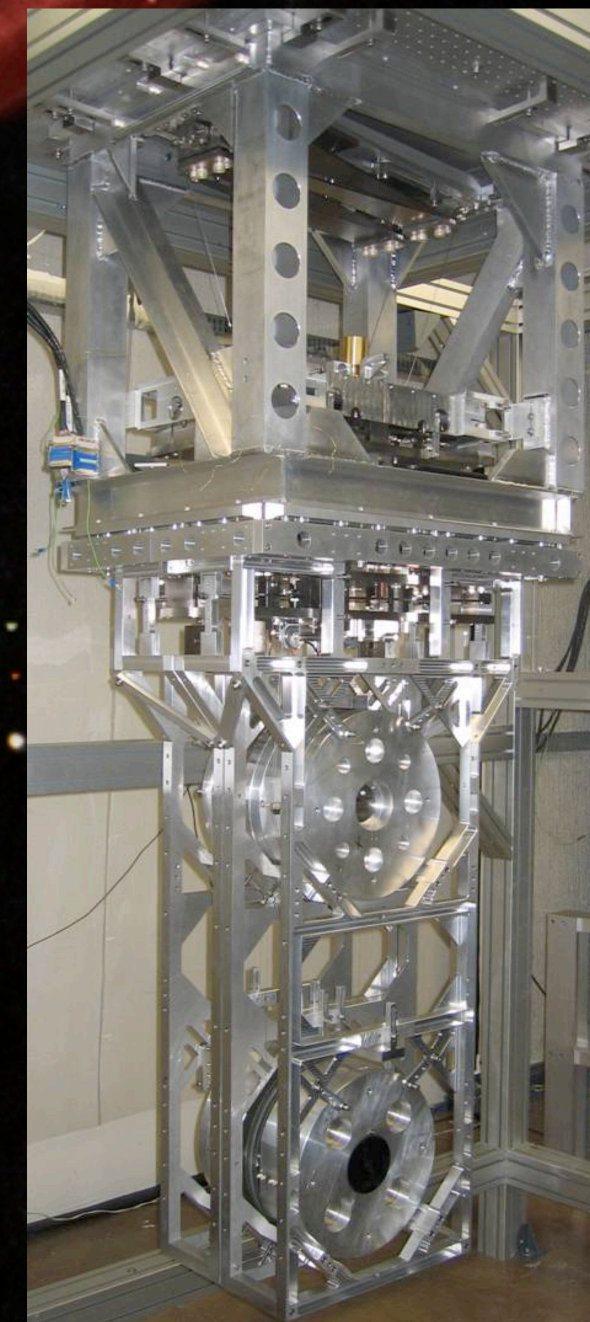
- 180W laser power
- HEPI active vibration isolation at both sites
- High Q compound pendulum suspensions
- 40kg optics to reduce radiation pressure noise
- Signal recycling mirror for narrowbanding
- Parallel comparable upgrades to Virgo



HEPI hydraulic actuator

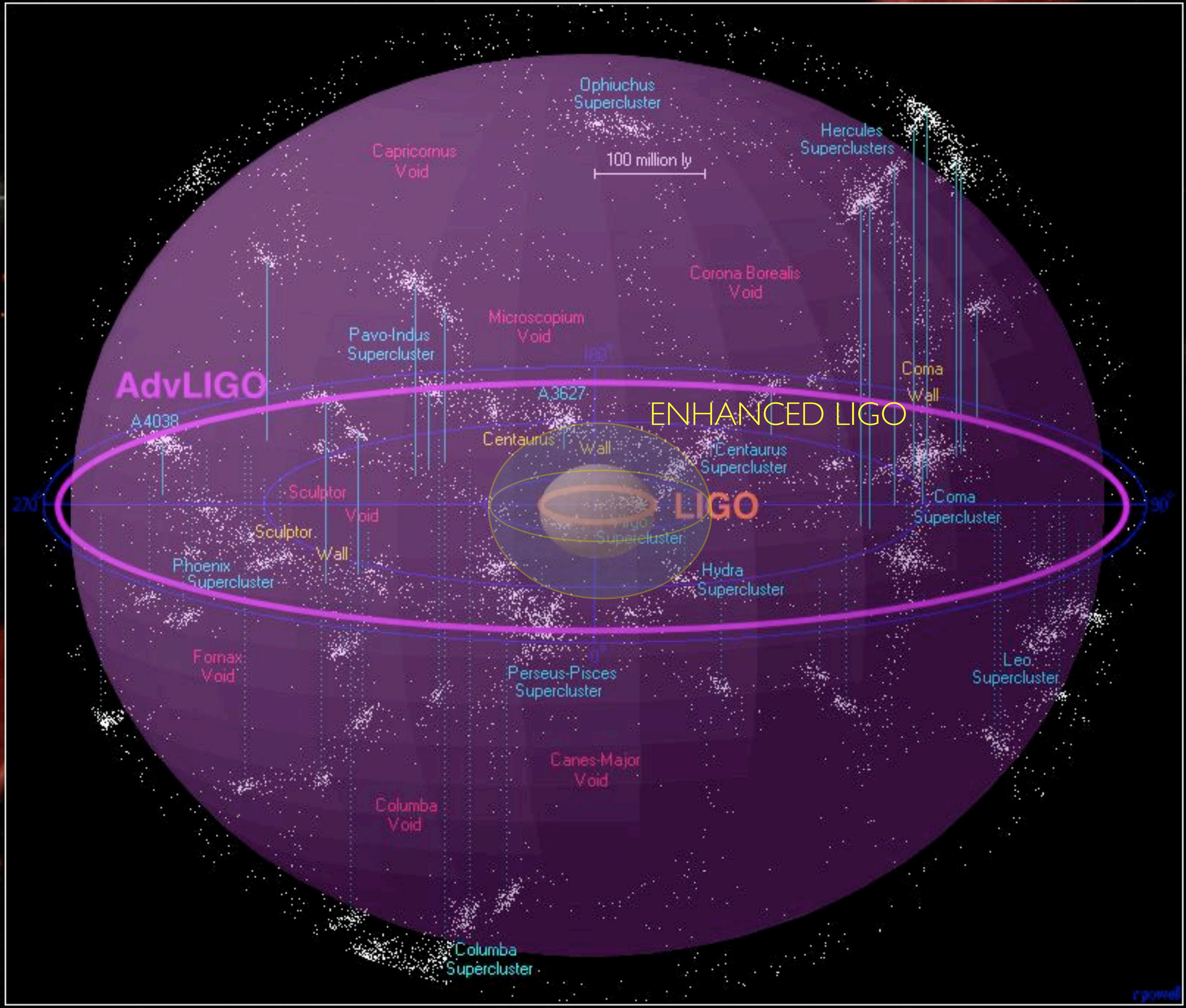


180W laser amplifier prototype (Germany)



Quad suspension prototype (U.K.)

Reach of Initial, Enhanced and Advanced LIGO



External collaboration with the LIGO scientific collaboration.

....and others. This is big science.

Virgo is a separate collaboration, with whom LSC has a data sharing agreement

Collaboration with other projects

LSC and Virgo scientists are very keen to collaborate with other entities. External entity could be an individual (astronomer with target of opportunity observing time, for example), a working group, or a facility - decided on a case-by-case basis.

External collaborations are one of the best paths to exciting science with LSC / Virgo interferometers.

Some guidelines for setting up collaborations.

- There must exist a memorandum of understanding (MOU) between LSC/Virgo and any external collaborator before cooperative efforts can commence.
- Collaboration is between the whole LSC/Virgo collaboration and the external entity, not just individual members of LSC/Virgo.
- Collaboration must be for an identified purpose.
- No collaborations guaranteeing exclusivity are permitted.
- MOU must include agreeement of the model for data sharing between the collaborating entitites.
- MOU must include statements of policies on joint publication of results / limits / technical work.

Conclusions

- Ground based gravitational-wave interferomtery has delivered the sensitivity it advertised on-schedule.
- World-wide efforts are now coordinated through the LSC/Virgo collaborations.
- The resulting network of interferometers is capable of wide-field coverage for detection of sources, but also of determination of the point of origin at the degree level.
- Though no sources have yet been detected, the funded advanced LIGO upgrade will push the search volume up by a factor of 10^3 compared to its current value.
- Transient sources observed both in gravitational waves and in photons would be one of the most convincing smoking guns for first detection of gravitational waves.
- Multi-messenger information on astrophysical sources would open up new windows on strong gravitational fields, compact objects, and beyond.
- Therefore LSC/Virgo is interested in pursuing collaborations with astronomers, in the hope that the LSC/Virgo instruments are about to become observing tools!

One of several alligators resident at the Livingston site. Don't annoy the operators !