LIGO-G070401-00-Z

Ground based Gravitational Wave Interferometers

Peter Fritschel, MIT

(on behalf of the

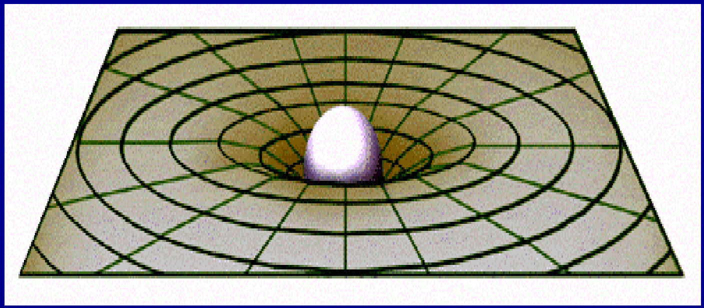
LIGO Scientific Collaboration)

DFG-NSF Astrophysics Research Conference

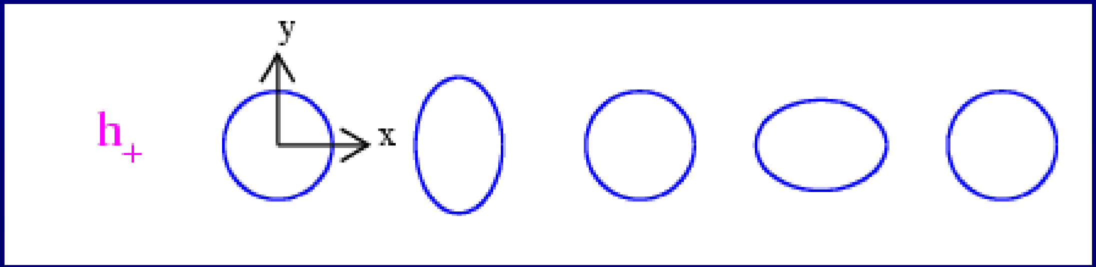
Advanced Photonics in Application to Astrophysical Problems

Basics of GW Detection

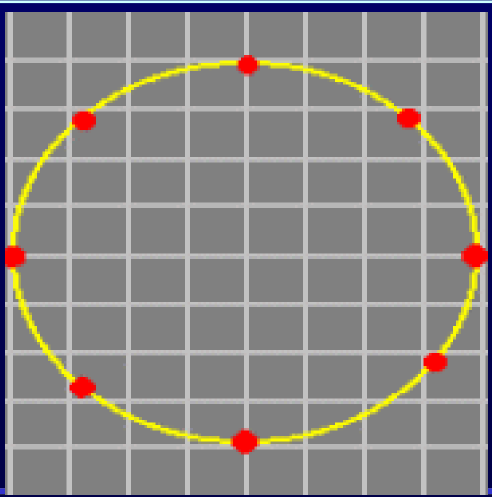
- Gravitational Waves "Ripples in space-time"
- Stretch and squeeze the space transverse to direction of propagation



Example:
Ring of test masses responding to wave propagating along z



$$\textit{GW strain} = \boxed{h = \frac{\Delta L}{L}}$$



Strength of GWs: Neutron Star Binary in the Virgo cluster

- Gravitational wave amplitude (strain)

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \Rightarrow h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

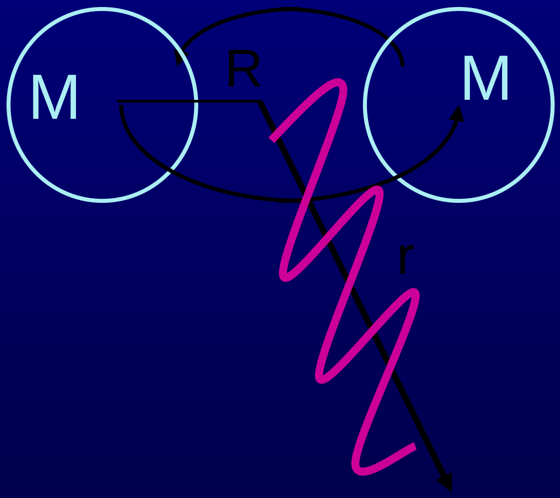
I = quadrupole mass distribution of source

- For a binary neutron star

~1.4 M_o pair in Virgo cluster

$$M \approx 10^{30}\ \mathrm{kg}$$
$$R \approx 20\ \mathrm{km}$$
$$f \approx 400\ \mathrm{Hz}$$
$$r \approx 10^{23}\ \mathrm{m}$$

➡ $h \sim 10^{-21}$



Inspiral Range*: distance at which an NS-NS inspiral would produce an SNR = 8 signal, averaged over source directions and geometry*

First generation interferometers

LIGO
VIRGO
TAMA
GEO

Global network of detectors

Hanford, WA
4 km interferometer
2 km interferometer

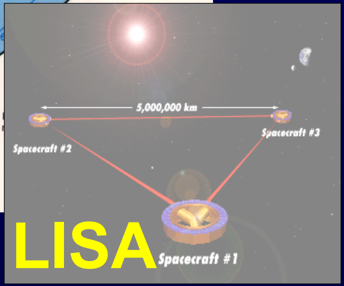
Hannover, Germany
600 m interferometer

Pisa, Italy
3 km interferometer

Tokyo, Japan
300 m interferometer

Livingston, LA
4 km interferometer

- Coincident detection to eliminate instrumental artifacts
- Source localization in the sky
- Wave polarization

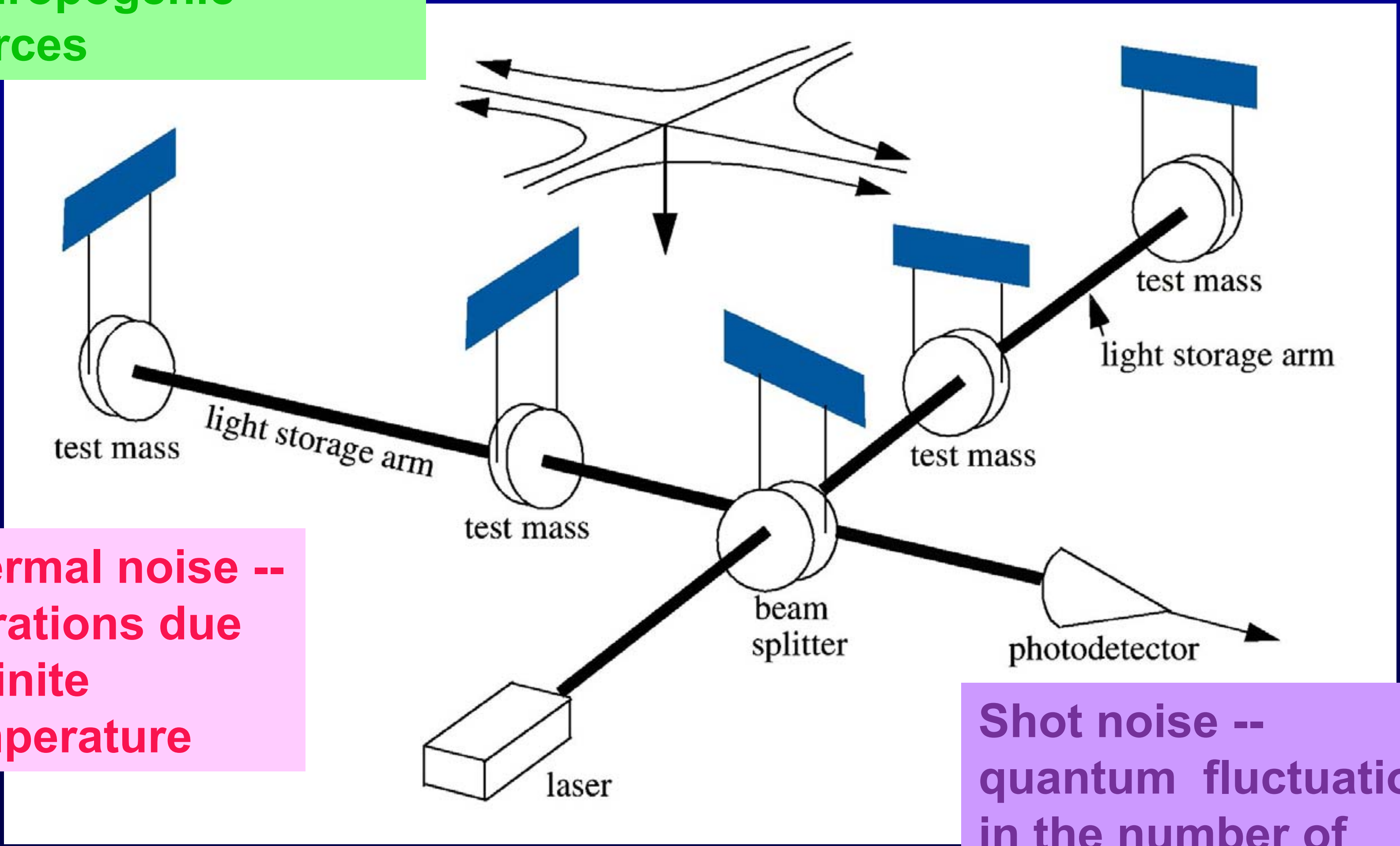


GW detector at a glance

Seismic motion -- ground motion due to natural and anthropogenic sources

$$h = \Delta L / L$$

L ~ 4 km
For *h* ~ 10^{-21}
ΔL ~ 10^{-18} m

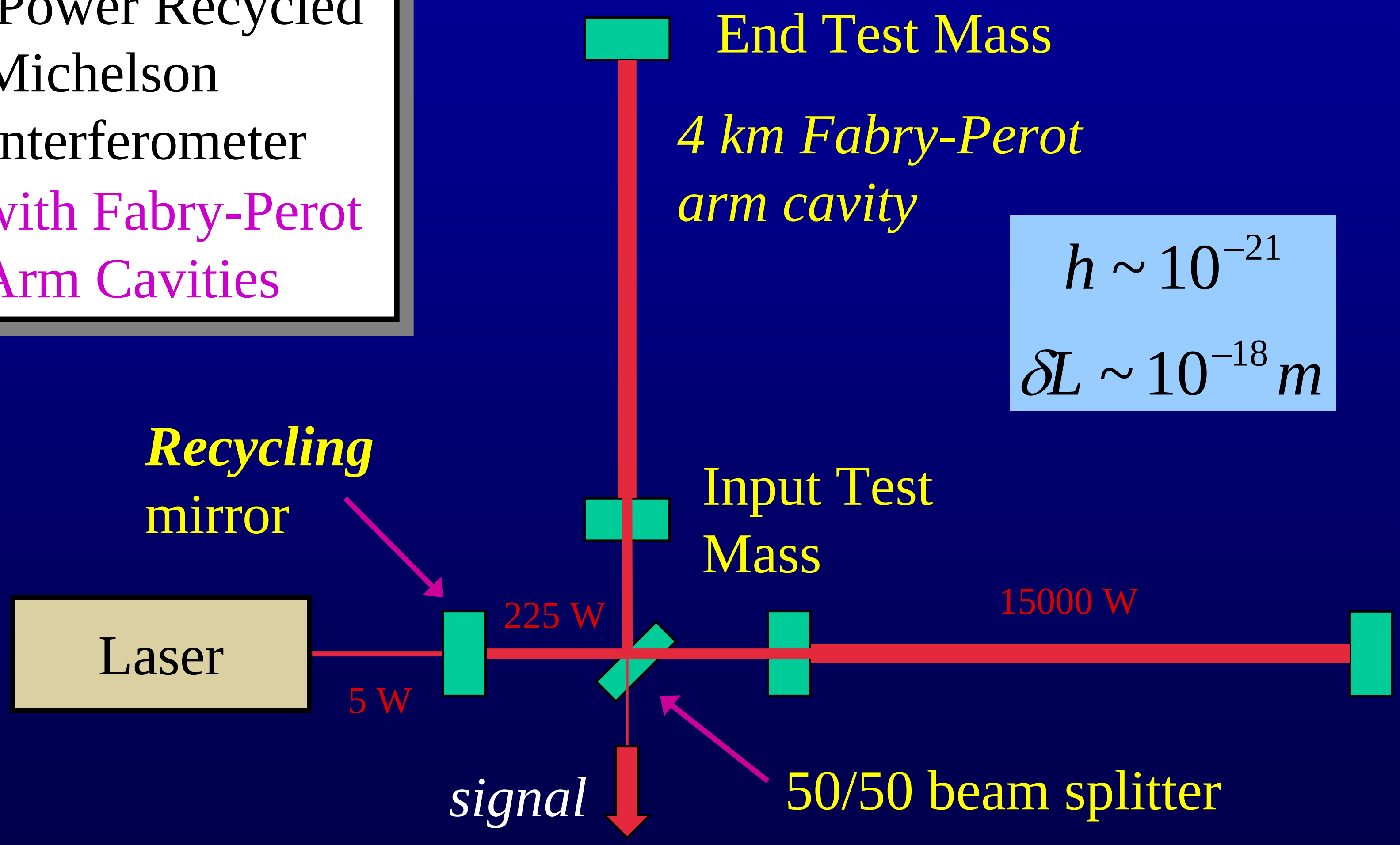


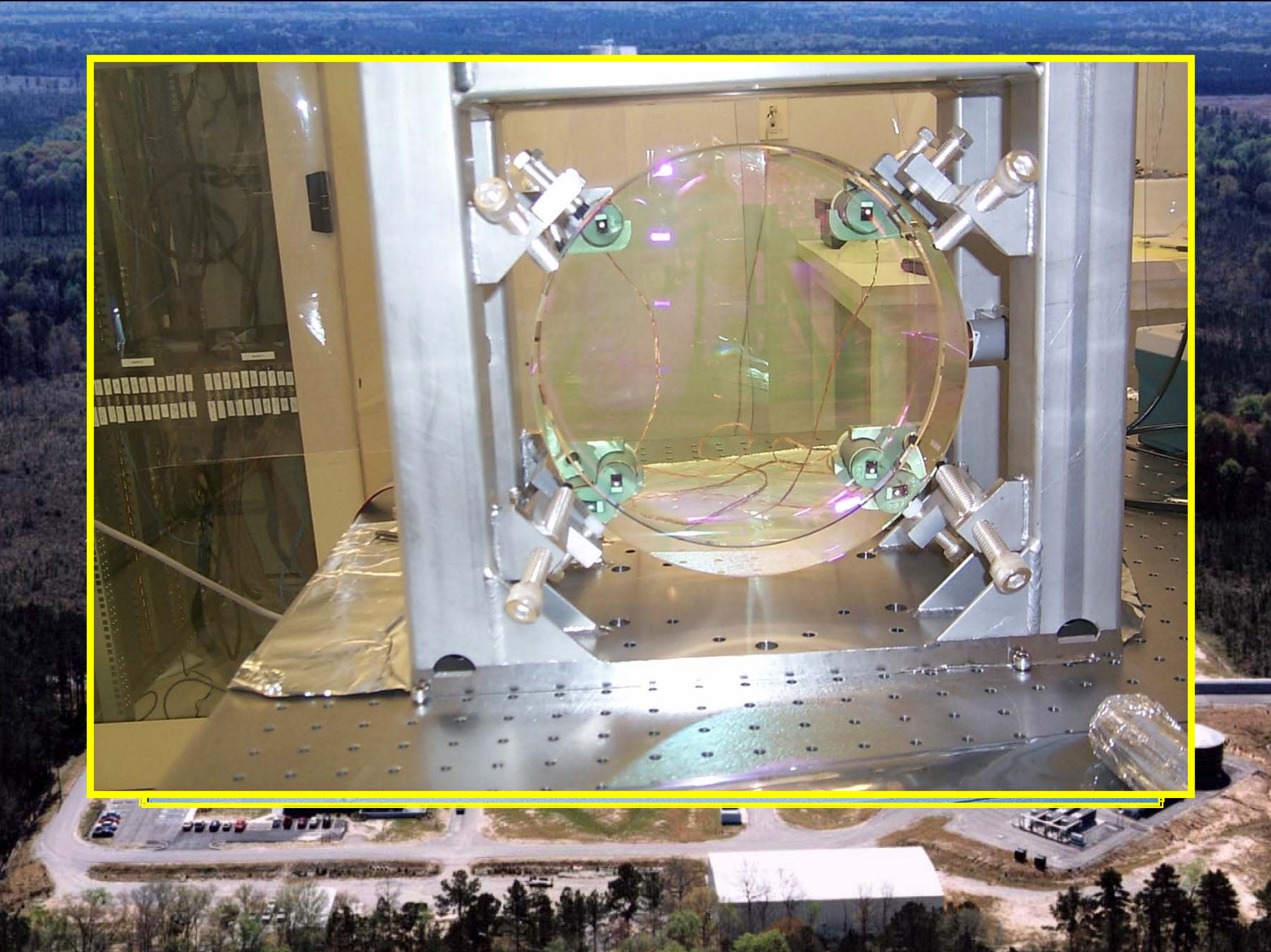
Thermal noise -- vibrations due to finite temperature

Shot noise -- quantum fluctuations in the number of photons detected

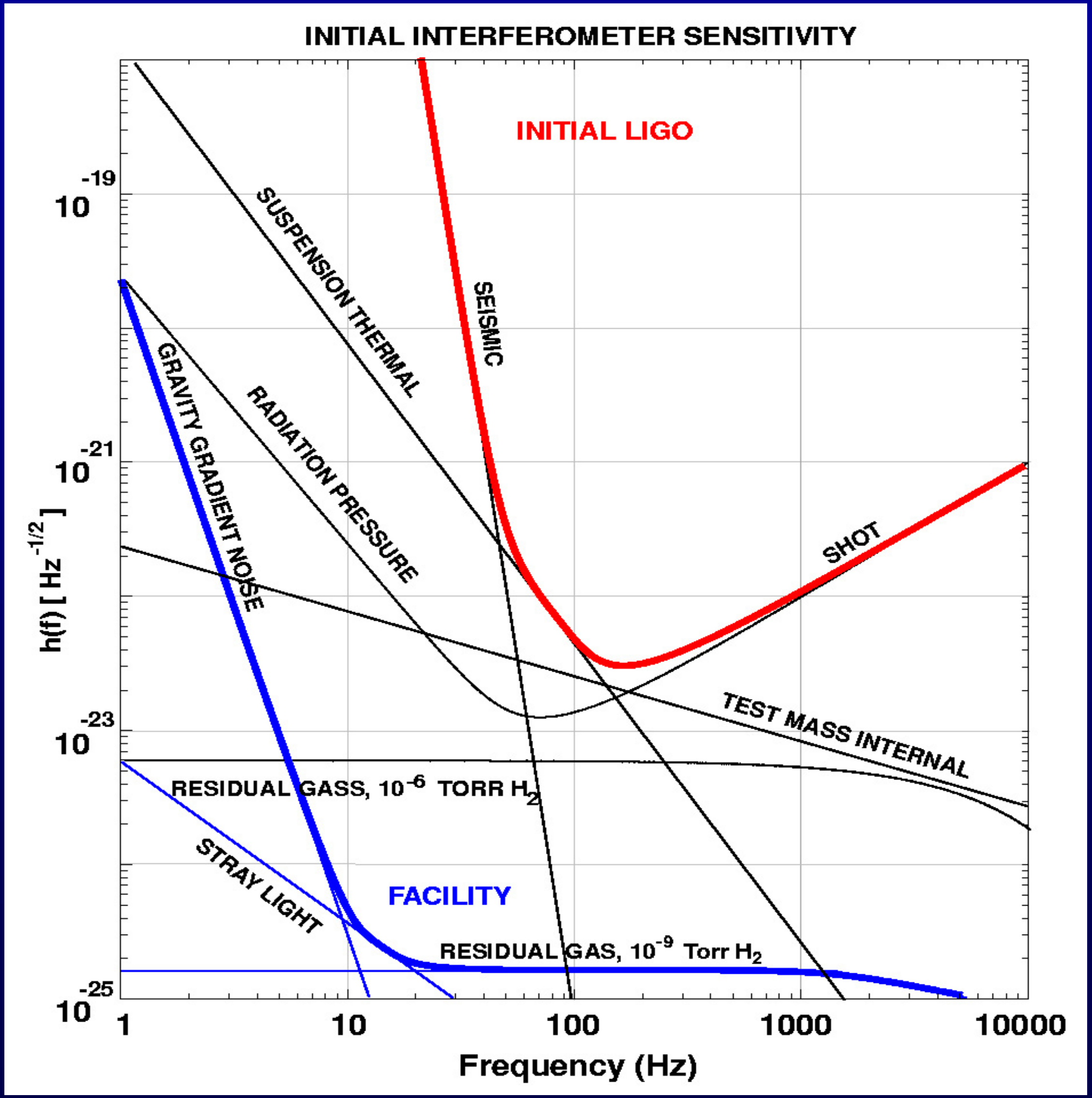
Optical Configuration

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities





Initial LIGO Sensitivity Goal



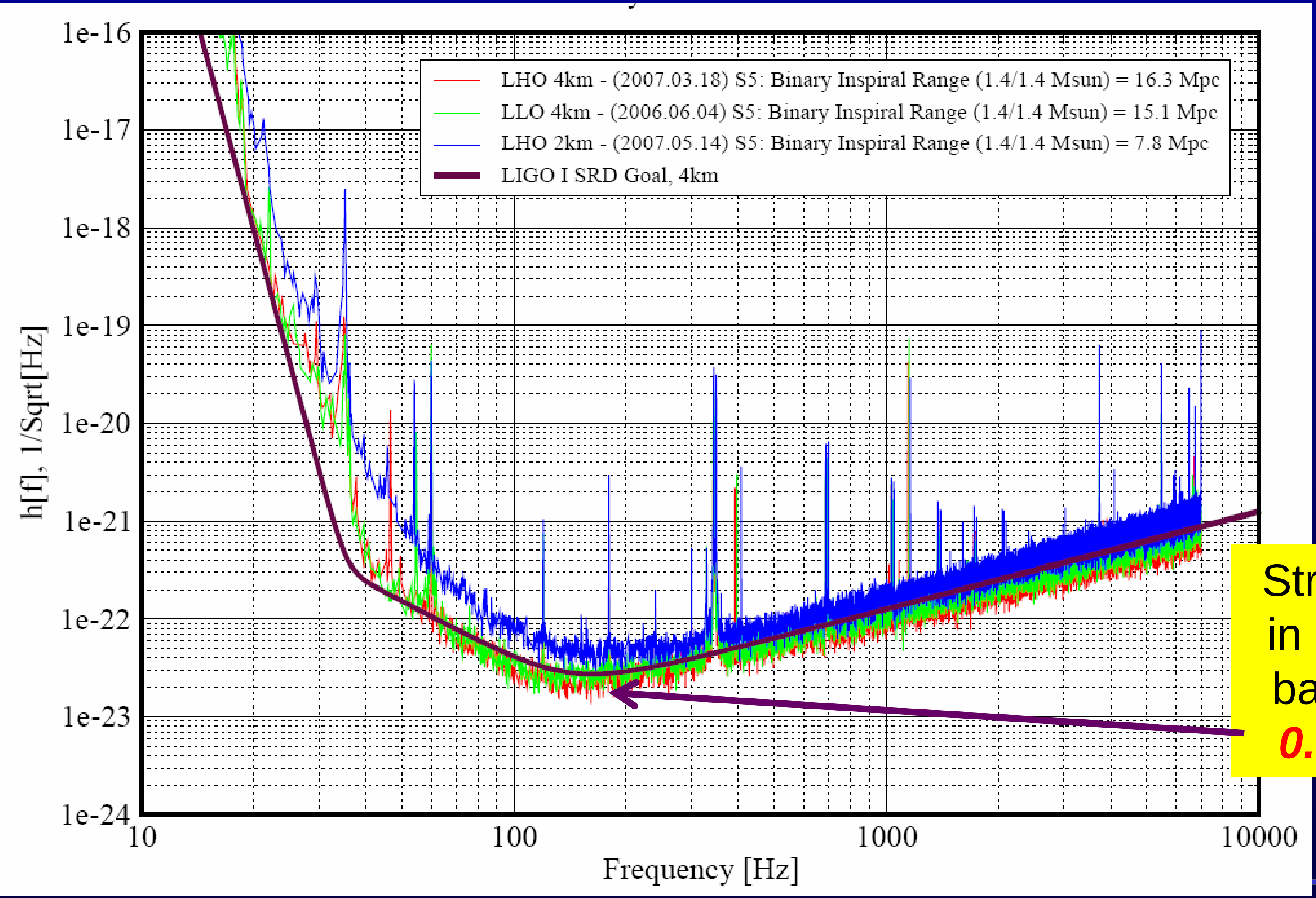
- Strain sensitivity: **10^{-21}-rms** in a 100 Hz bandwidth
- Instrument strain noise density: **3×10^{-23} /Hz$^{1/2}$** at 150 Hz
- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure
- Sensing Noise
  - Photon Shot Noise
  - Residual Gas
- Facilities limits much lower

Gravitational-wave searches

Instruments and data

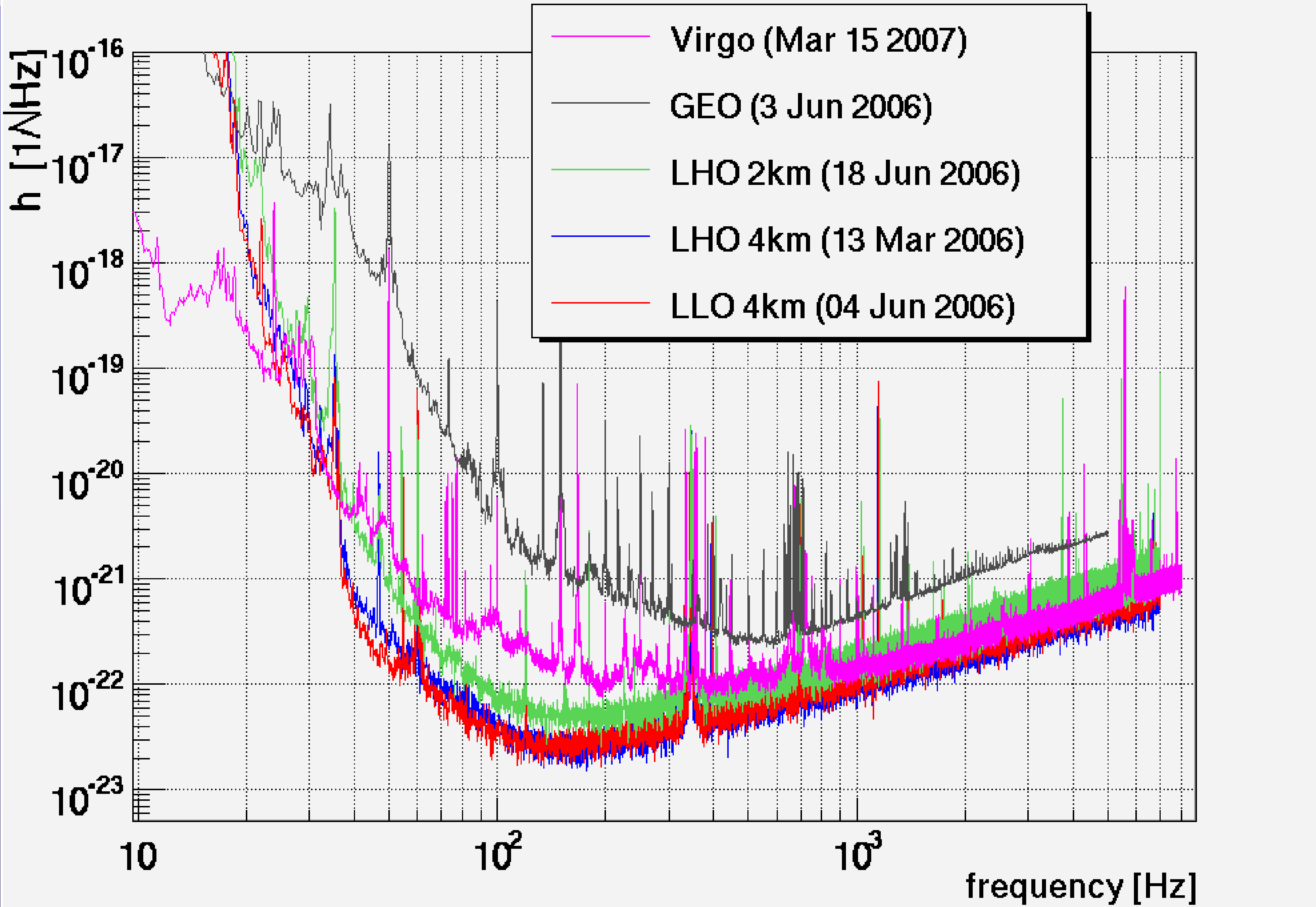
Meeting the experimental challenge

After 5 years of intense effort to reduce noise by orders of magnitude, the design sensitivity predicted in the 1995 LIGO Science Requirements Document was reached in 2005!



Strain noise in a 100 Hz bandwidth: ***0.3×10^{-21}***

LIGO, Virgo & GEO sensitivities



Astrophysical searches

Transient

- Coalescence of binary compact objects (neutron stars, black holes, primordial BH)
- Core collapse supernovae
- Black hole normal mode oscillations
- Neutron star rotational instabilities
- Gamma ray bursts
- Cosmic string cusps

High duty cycle

- Periodic emission from pulsars (esp. accretion driven)
- Stochastic background (incoherent sum of many sources or very early universe)
- Expect the unexpected!

Modeled & Unmodeled waveforms

Sampling of current GW searches

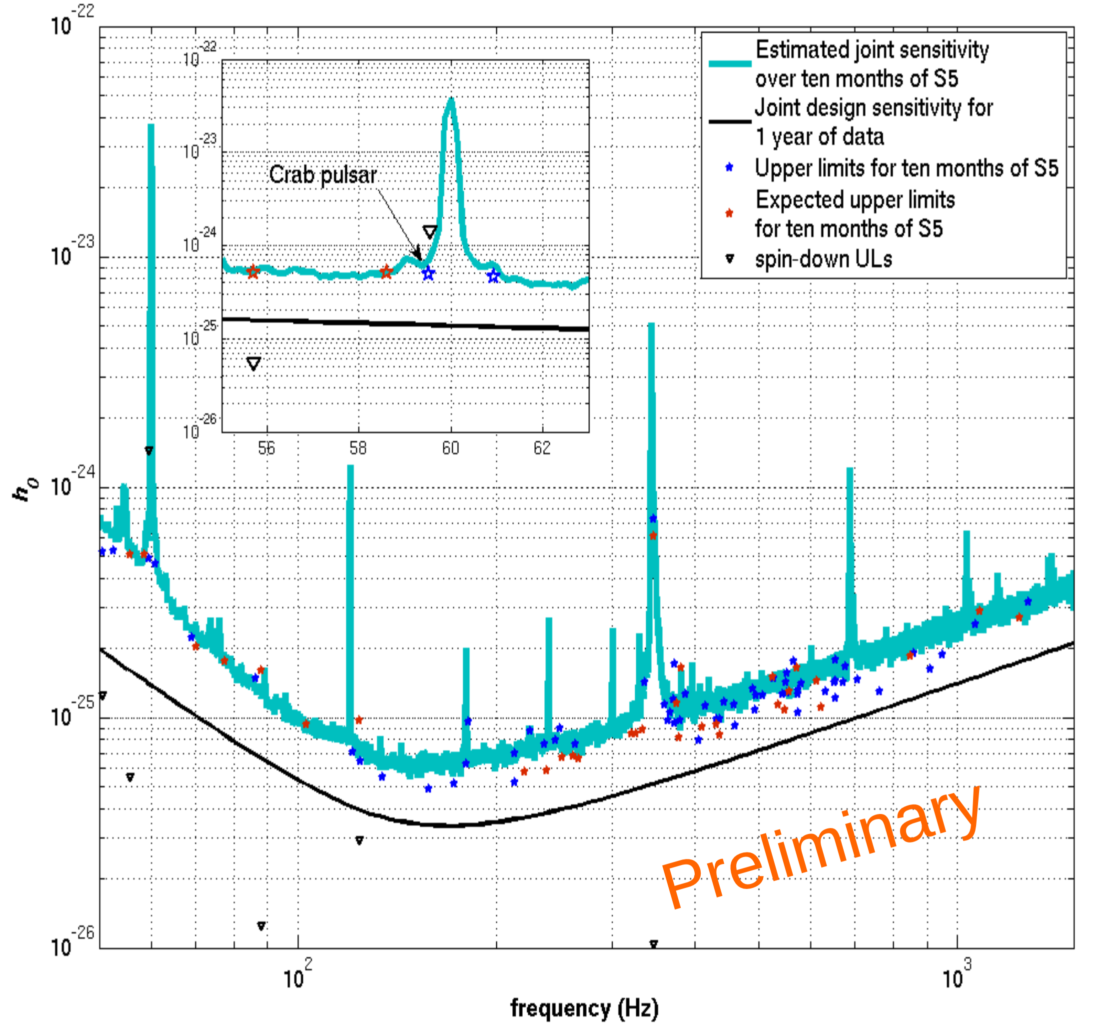
Pulsars

Search for GWs from known pulsars

In the absence of detection, we establish upper limits on the GW strain, or the ellipticity of the rotating star

Lowest GW strain upper limit:
PSR J1802-2124
(f_{gw} = 158.1 Hz, r = 3.3 kpc)
$h_0 < 4.9\times10^{-26}$

Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6 Hz, r = 0.25 kpc)
$\varepsilon < 1.1\times10^{-7}$



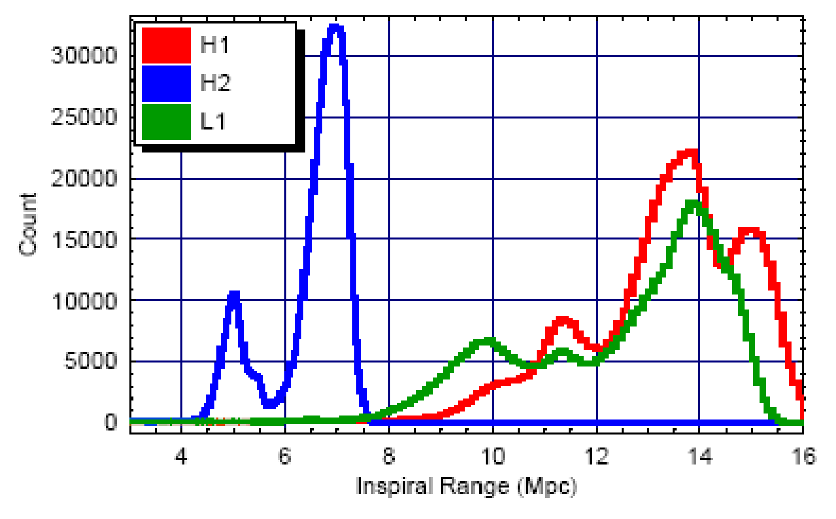
Pulsar timings provided by the Jodrell Bank pulsar group

Sampling of current GW searches

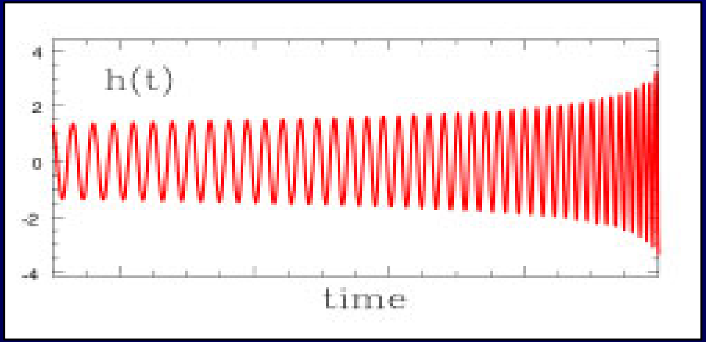
Binary Inspirals

Search for Binary Inspirals

- **Sources**
  - Binary *neutron stars* (~1 – 3 M_{sun})
  - Binary *black holes* (< 30 M_{sun})
  - *Neutron star-black hole* pair (potential source of short-hard gamma ray bursters)



- Search method
  - Look for "chirps"

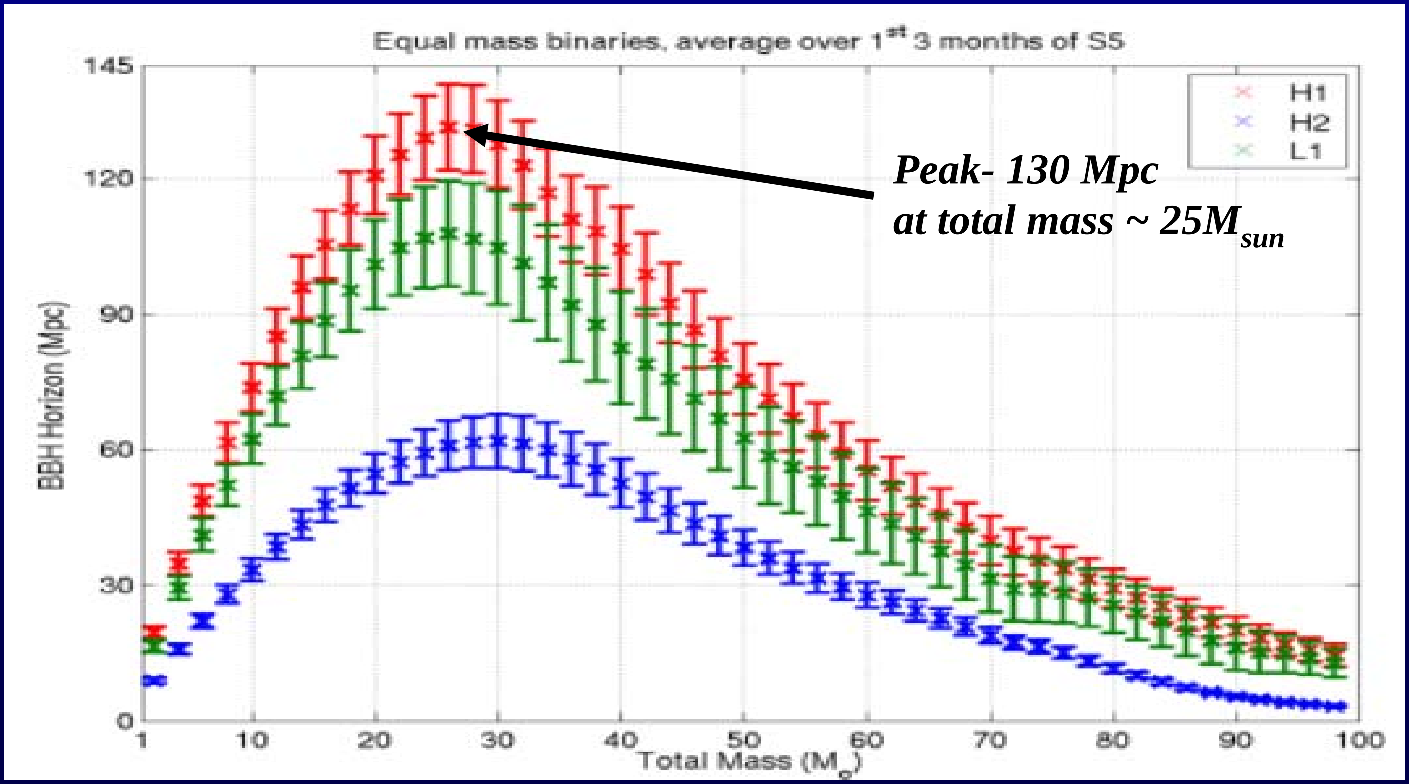


In the absence of detection, we establish a limit on the rate at which stars are coalescing in galaxies like our own

Binary inspirals: LIGO S5 data

- 3 months of data analyzed- no signals seen
- For 1.4-1.4 M_{sun} binaries, ~ 200 MWEGs in range
- For 5-5 M_{sun} binaries, ~ 1000 MWEGs in range
- Plot- Inspiral horizon for equal mass binaries vs. total mass

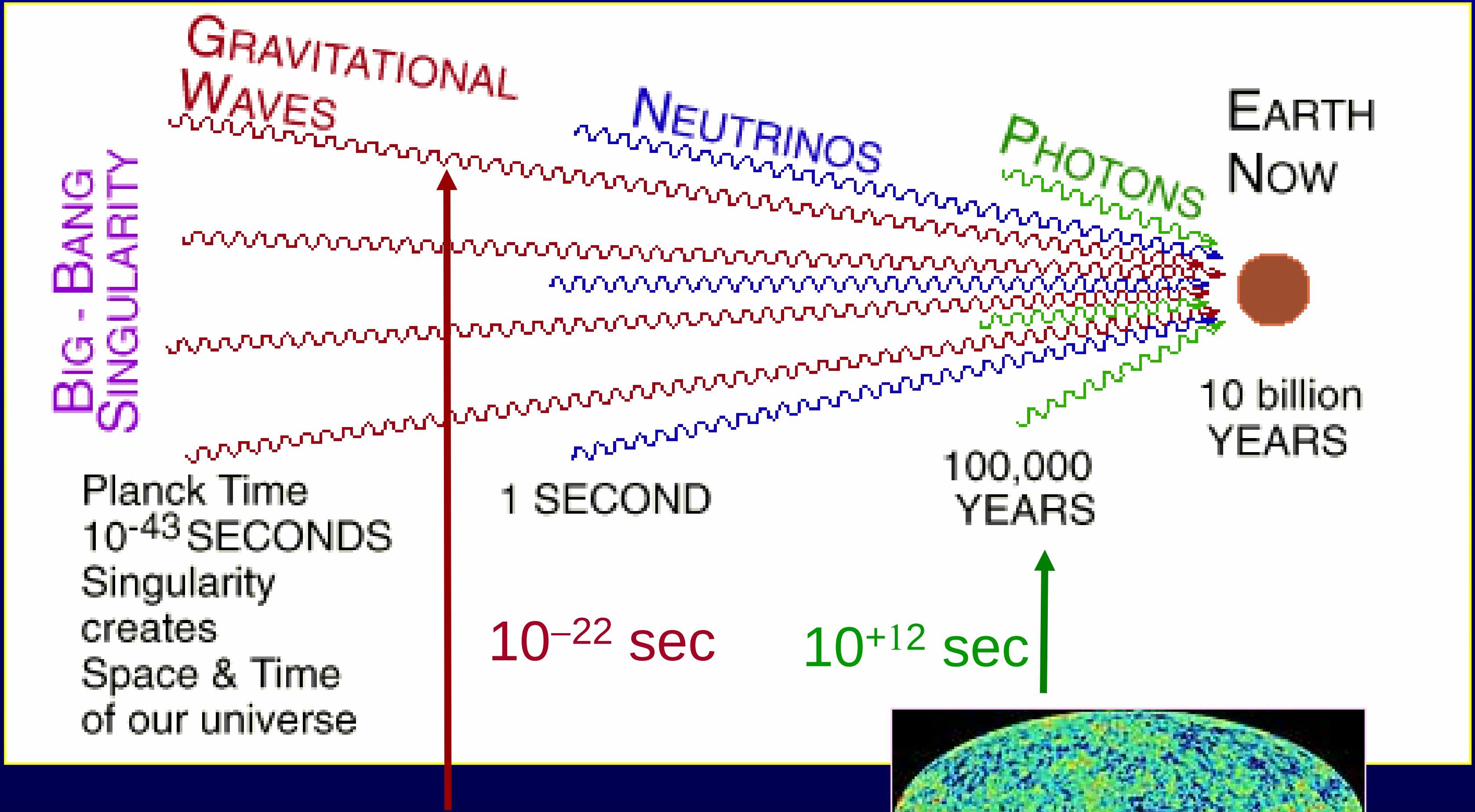
(horizon=range at peak of antenna pattern=2.3 x antenna pattern average)

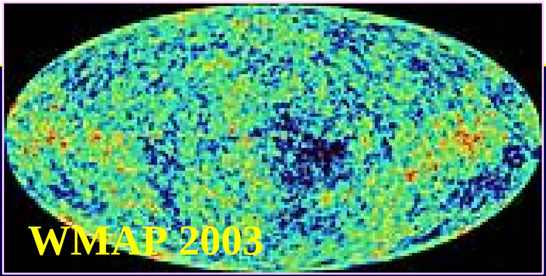


Sampling of current GW searches

Stochastic Background

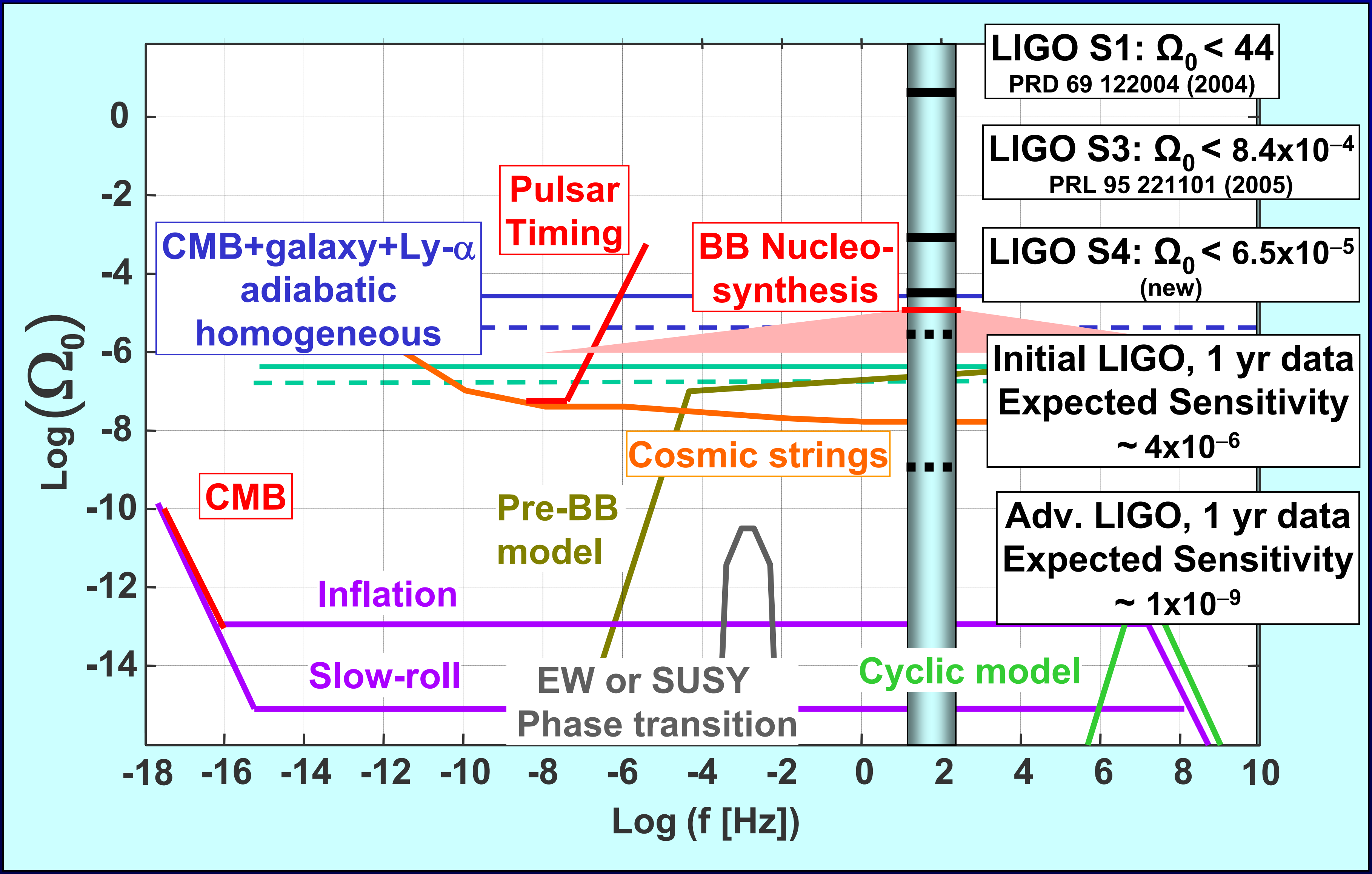
Cosmological GW Background





Waves now in the LIGO band were produced 10^{-22} sec after the Big Bang

Predictions and Limits

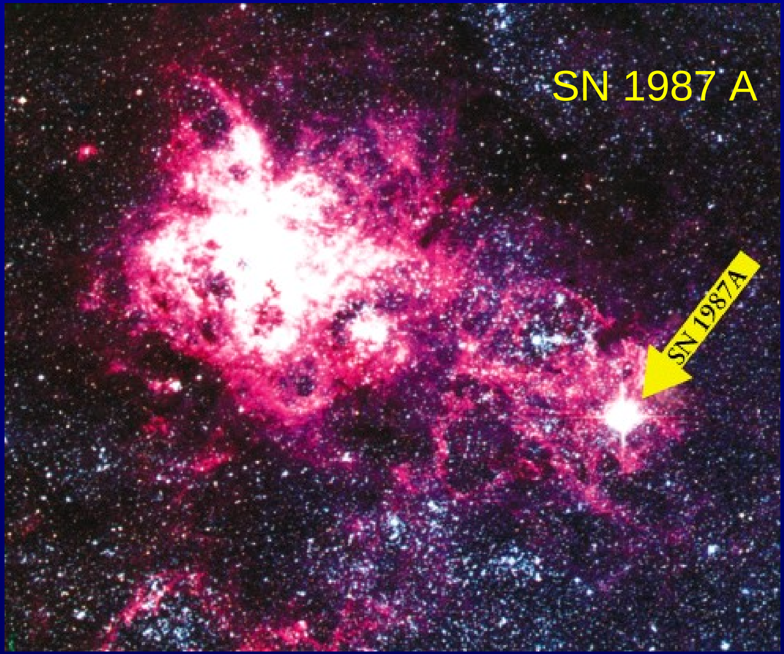


Other GW searches

Transient or “burst’ events

Gravitational-Wave Bursts

- Expected from very energetic catastrophic cosmic events involving solar-mass (1-100 M_o) compact objects
  - Core-collapse supernovae
  - Accreting and merging black holes
  - Gamma-ray burst engines
  - Other … ???



GW Burst Sensitivity

- What's the minimum total energy emission in GWs from a given distance that we could detect?

  Assuming isotropic energy emission, concentrated in frequency around 150 Hz:

  - ***From the Galactic center:*** ***$3 \times 10^{-8}\ M_{sun}c^2$***
  - ***From the Virgo galaxy cluster:*** ***$0.1\ M_{sun}c^2$***

Better detectors are on the way …

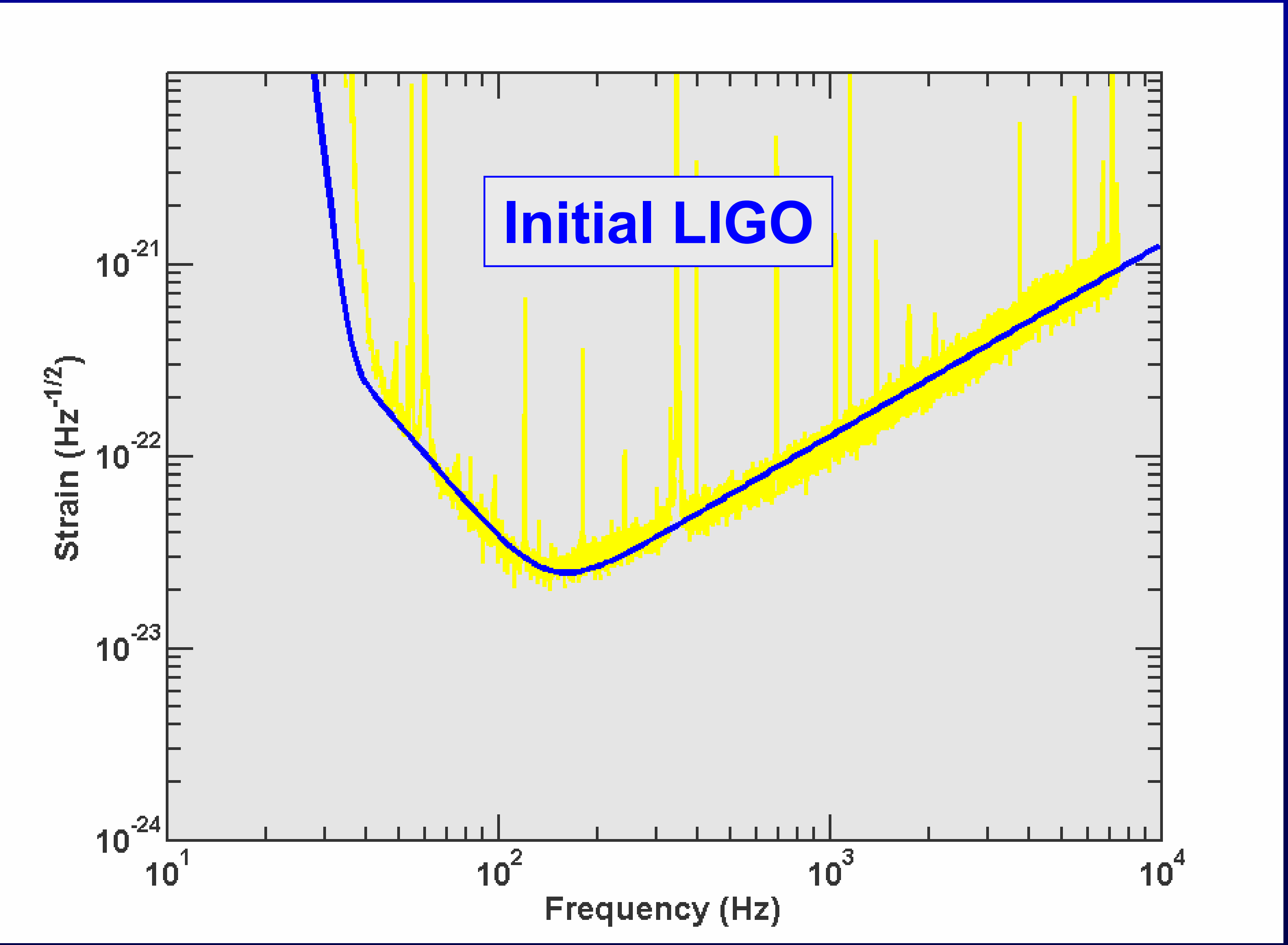
Enhanced LIGO
Advanced LIGO

Initial LIGO - Sept 15 2006

Input laser power
~ 6 W

Circulating power
~ 20 kW

Mirror mass
10 kg

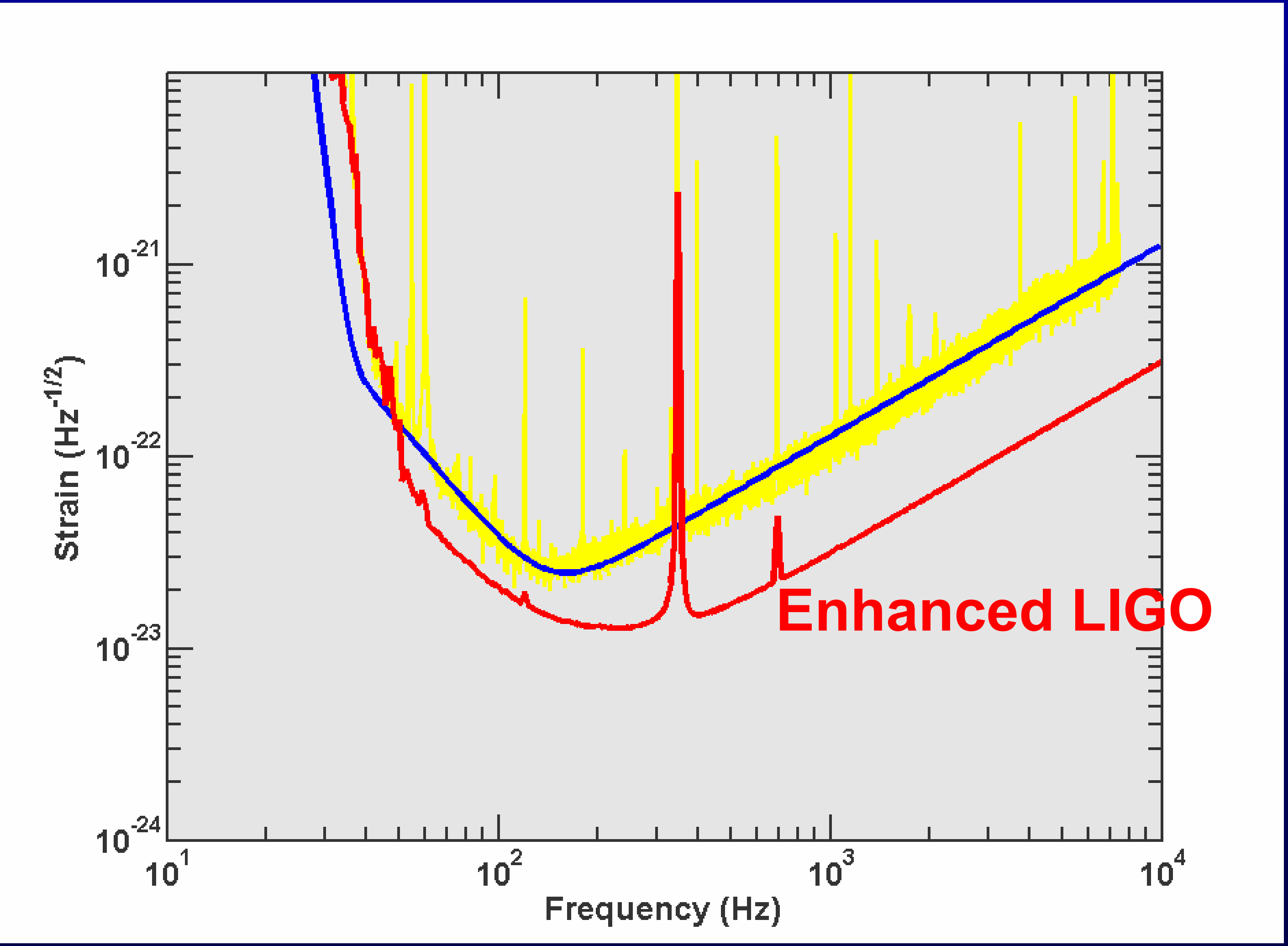


Enhanced LIGO

Input laser power
~ 30 W

Circulating power
~ 100 kW

Mirror mass
10 kg

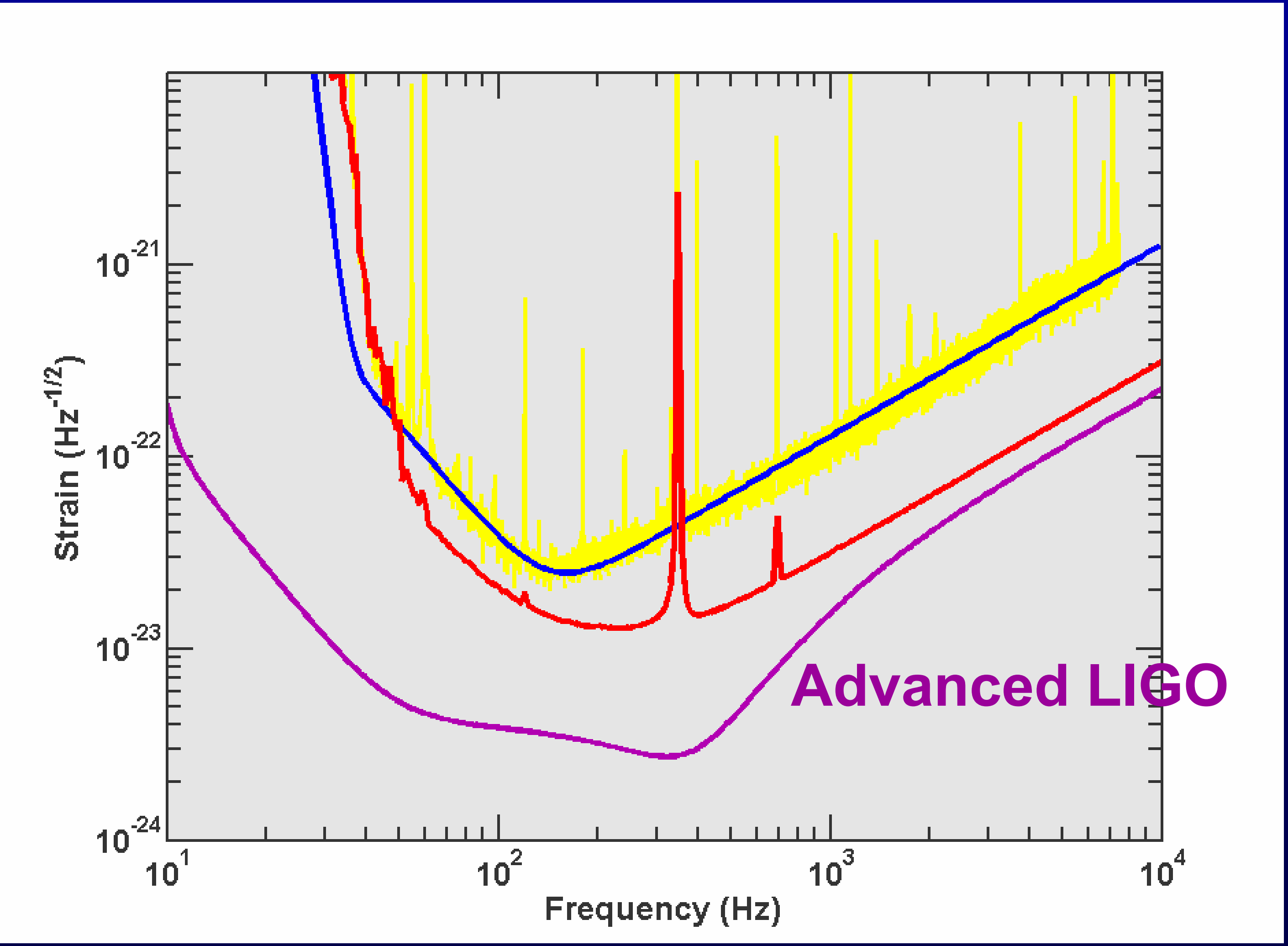


Advanced LIGO

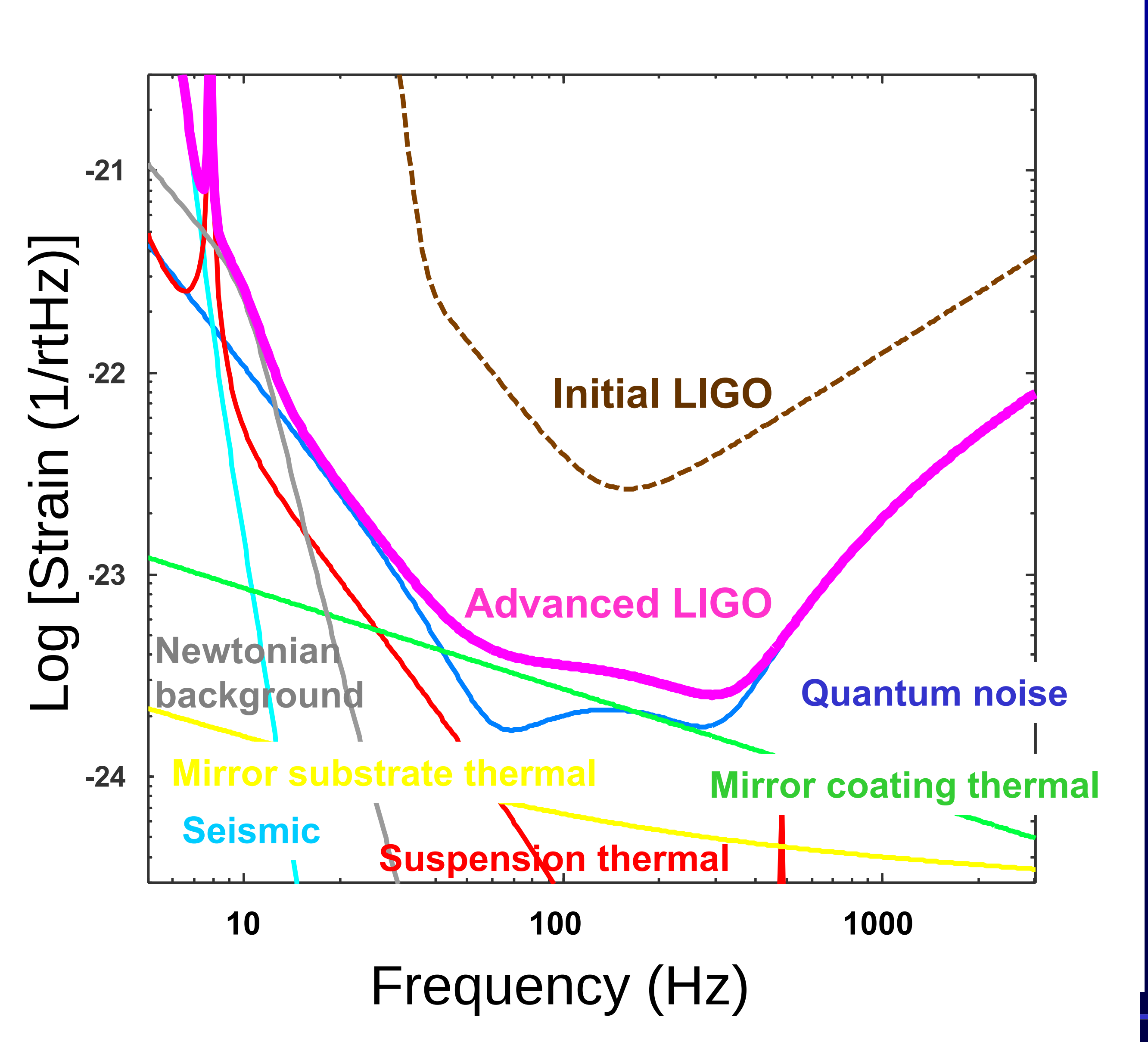
Input laser power
> 100 W

Circulating power
> 0.5 MW

Mirror mass
40 kg



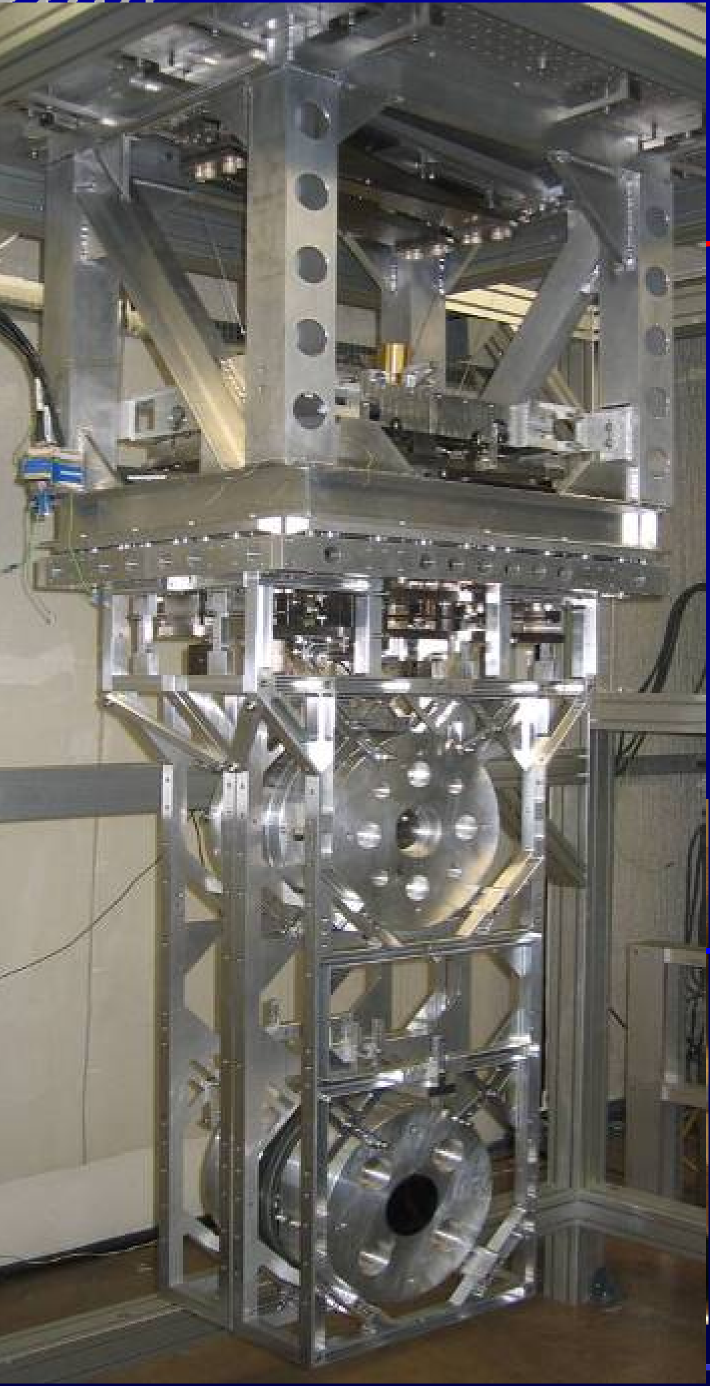
Advanced LIGO Target Sensitivity

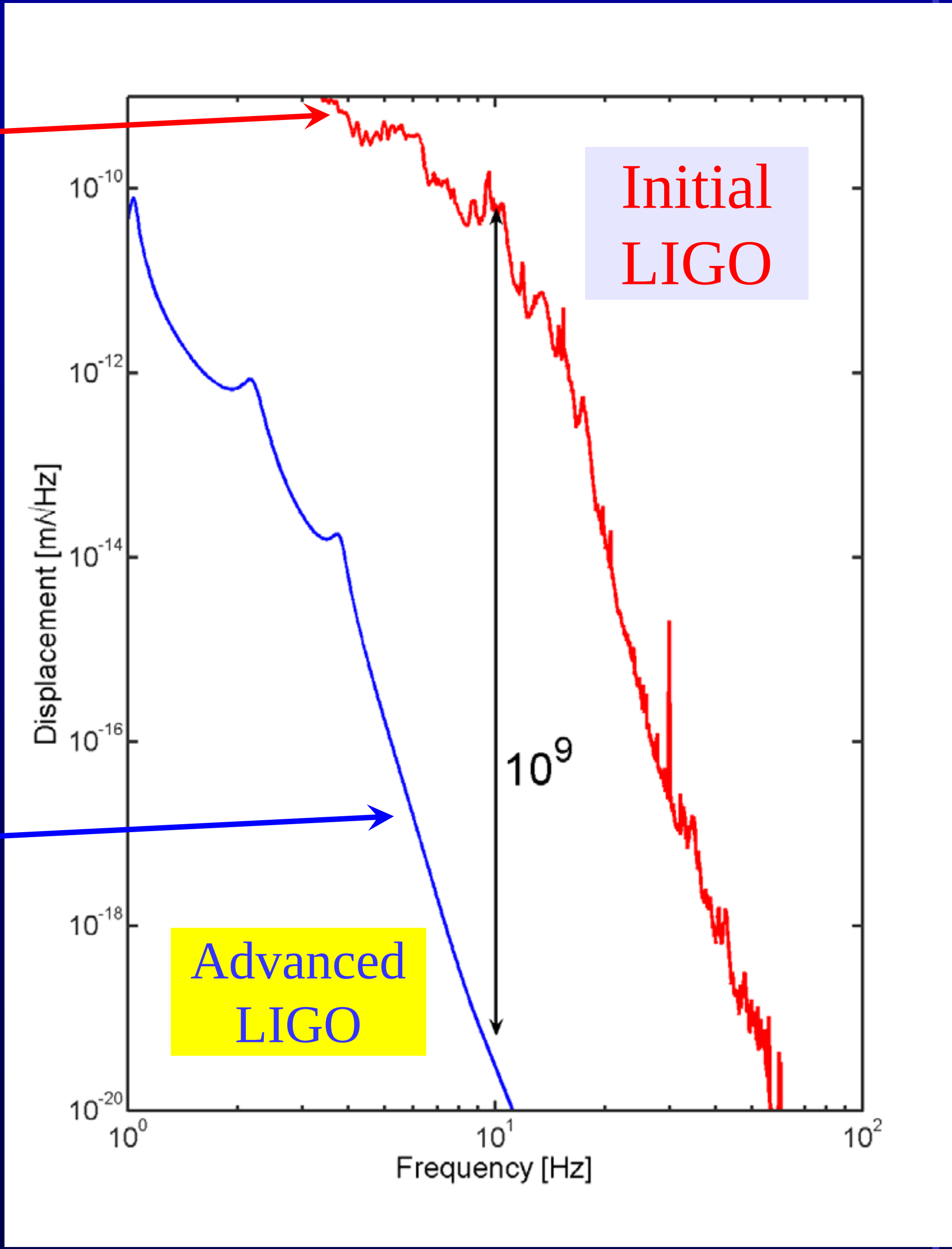


How will we get there?

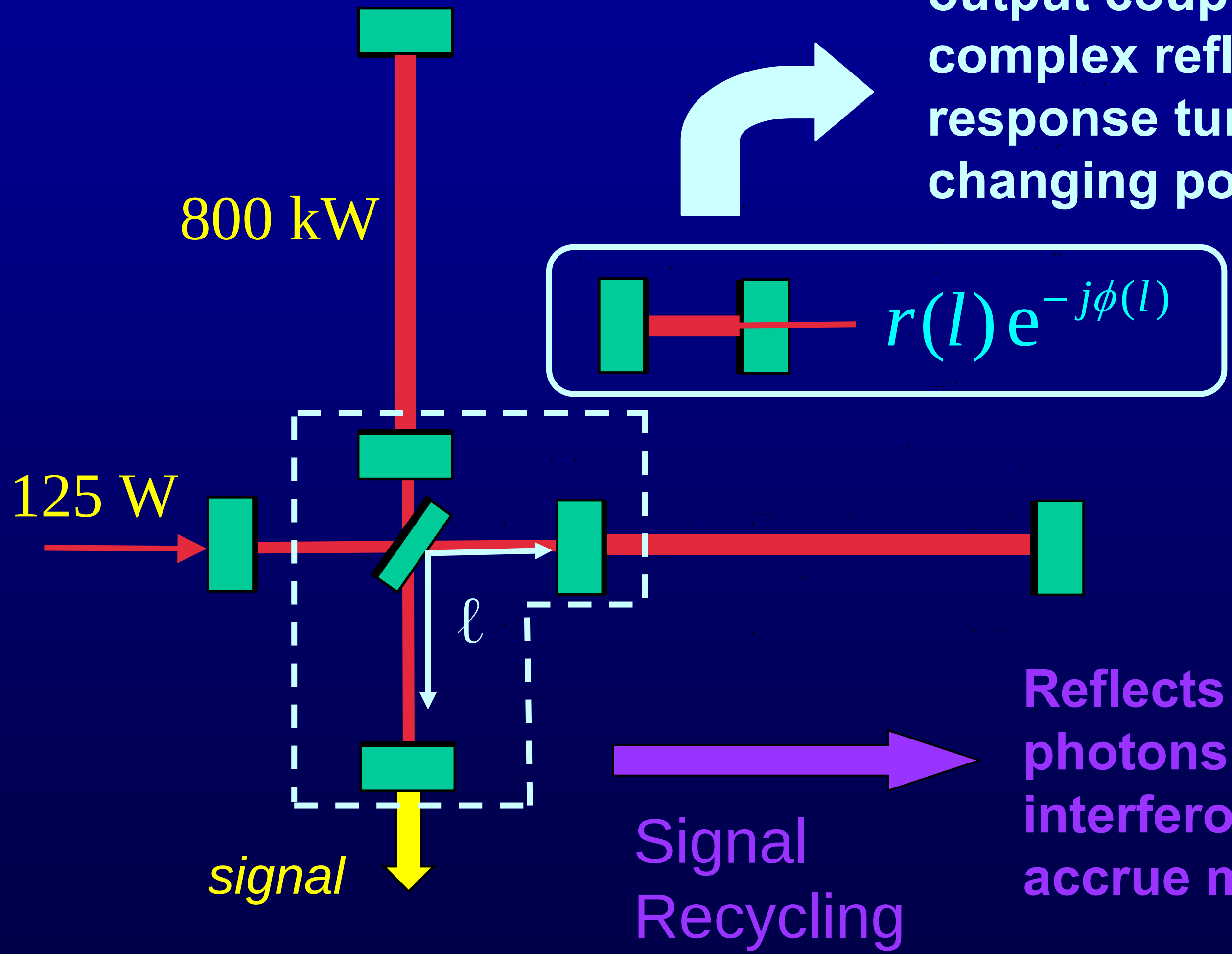
- Seismic noise
  - Active isolation system
  - Mirrors suspended as fourth (!!) stage of quadruple pendulums
- Thermal noise
  - Suspension ➔ fused silica fibers
  - Test mass ➔ more massive; better coatings
- Optical noise
  - Laser power ➔ increase to ~200 W
  - Optimize interferometer response
    ➔ signal recycling

Seismic Noise





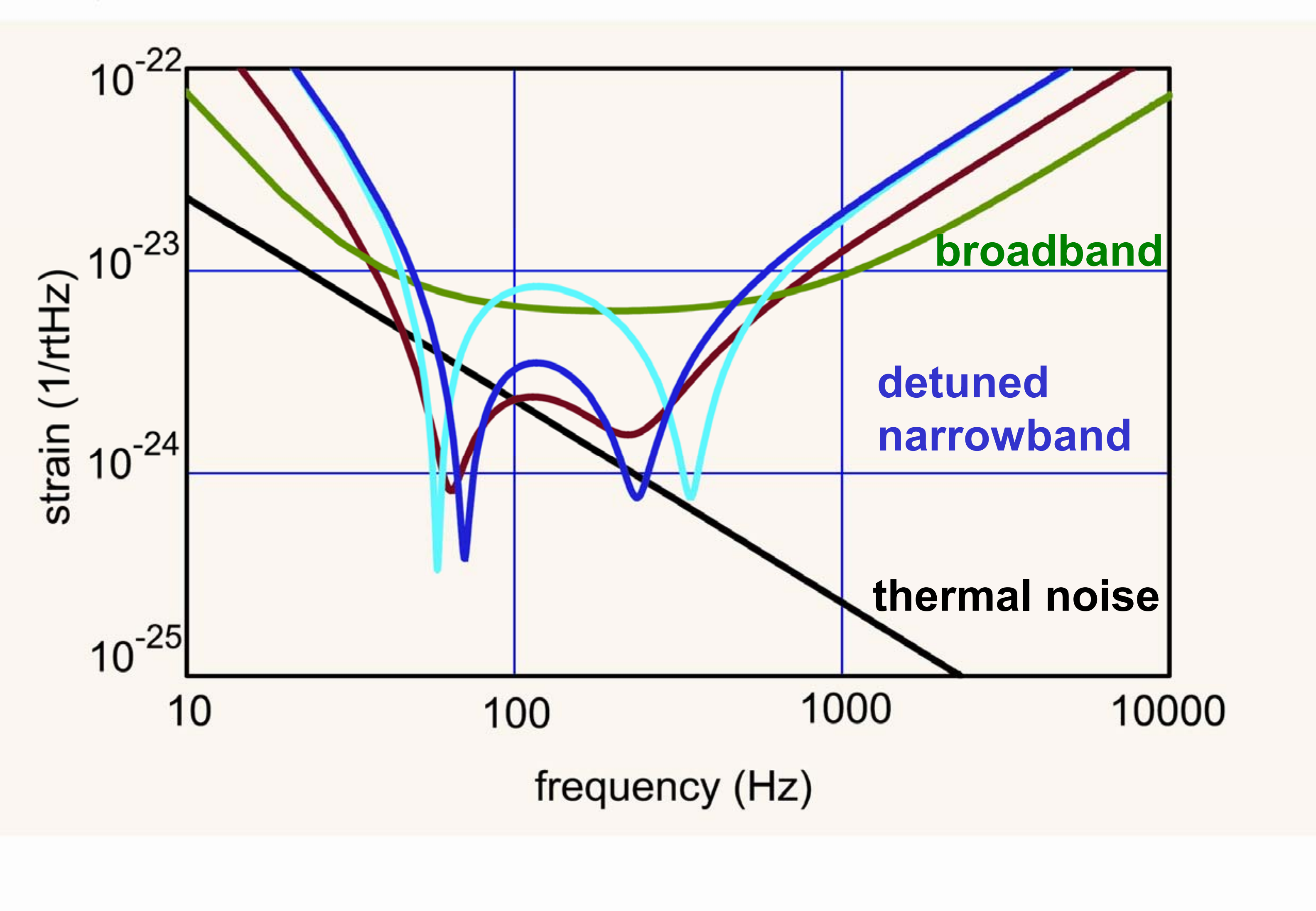
Signal-recycled Interferometer



Cavity forms compound output coupler with complex reflectivity. Peak response tuned by changing position of SRM

Reflects GW photons back into interferometer to accrue more phase

Advance LIGO Sensitivity: Improved and Tunable



In closing...

- LIGO interferometers are operating at design sensitivity & collecting 1 year of data
- Joint running & searches with partner observatories in Europe and Japan
- Planned enhancements that give 2x improvement in strain sensitivity underway
- Advanced LIGO approved by the NSB
  - US Construction funding expected to begin in FY2008
  - European partners are contributing significant components
  - Germany: Pre-stabilized, high power laser
  - UK: Test Mass suspensions