LIGO

Laser Interferometer Gravitational Wave Observatory:

Status Quo and the Future

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For the LIGO Scientific Collaboration

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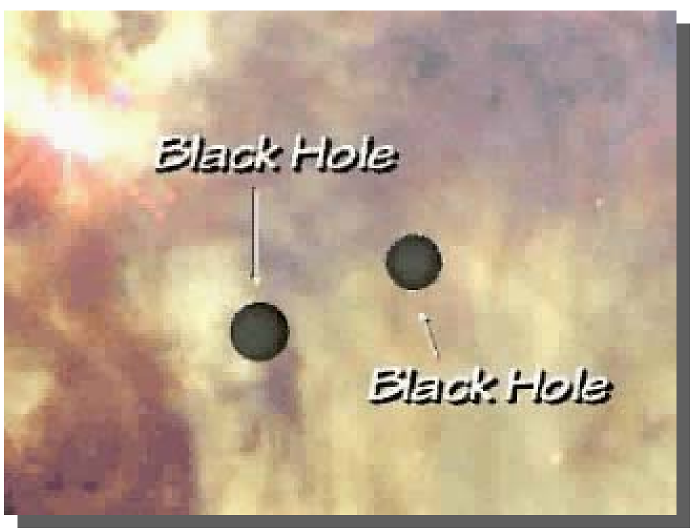
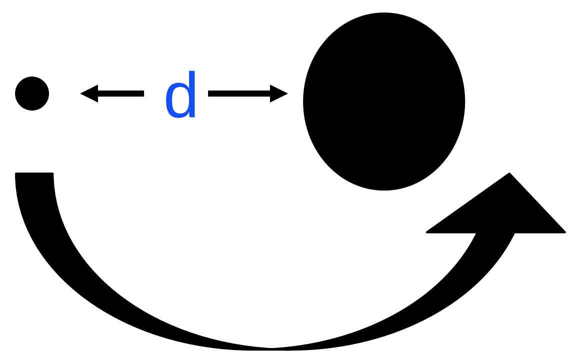
Table of Content

Gravitational Waves

- Predicted by Einstein, never detected
- Generated by accelerates masses
- Main difference to EM-waves: Matter has no charge
    - No dipole moment,
    - Lowest moment is a quadrupole moment
- Typical sources: NS/NS, BH/BH binaries





Gravitational Waves

NS/NS binary (M_{NS} ~ $3x10^{30}$kg ~ 1.4 M_{Sun})

1. Smallest Distance: d_{min} ~ 20km (2xDiameter of NS)
2. Potential Energy: E = - GM^2/d ~ $3x10^{46}$J
3. Newton: f (d=100km) ~ 100 Hz, f (d=20km) ~ 1 kHz
4. Takes about 1s to get from 100km to 20km
5. During that second nearly half of the Potential Energy is radiated away!
6. Assume binary is in the Virgo cluster (15 Mpc ~ $6x10^{24}$ m)

We receive about P=1..100mW/m^2 from each binary!
Like full moon during a clear night!

Gravitational Waves

We can see the moon, why haven't we seen Gravitational Waves yet?

GW-Amplitude: h=δL/L is

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}(I_{\mu\nu})$$

$G/c^4 = 10^{-45} s^2/kg\ m$

Our example (f=400Hz):

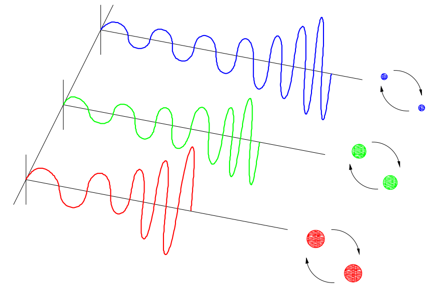
$$h \approx \frac{10^{-21}}{(r/15\mathrm{Mpc})}$$

Or 1am over 1km

Answer: Space is stiff

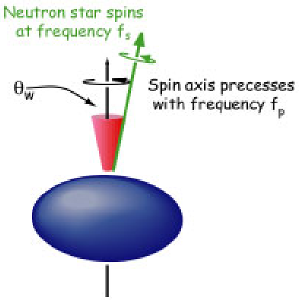
What makes Gravitational Waves?

- **Compact binary inspiral:** *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms

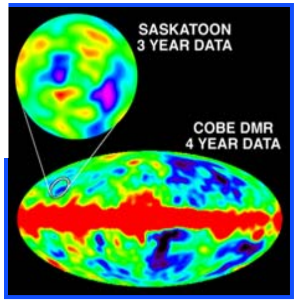


- **Supernovae / GRBs:** *"bursts"*
  - » Amplitude scales with asymmetry
  - » searches triggered by EM- or neutrino detectors
  - » all-sky untriggered searches too

- **Pulsars in our galaxy:** *"periodic"*
  - » Amplitude scales with ellipticity
  - » search for observed neutron stars
  - » all-sky search



- **Cosmological Signals** *"stochastic background"*



Gravitational Waves

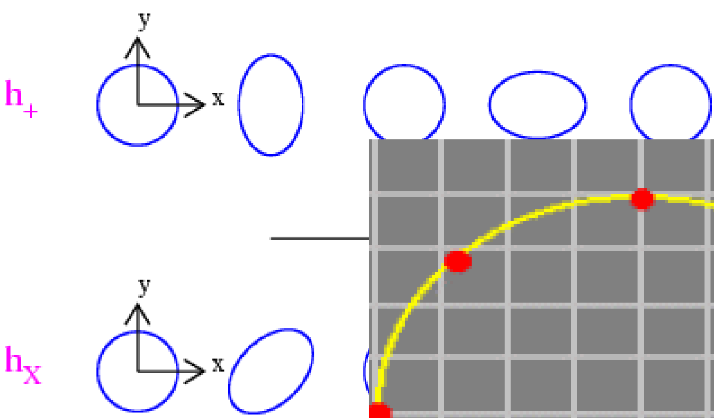
- **GW: Propagation similar to light (obeys same wave equation!)**
  - » **Propagation speed = c**
  - » **Two transverse polarizations – <u>quadrupole waves</u>: + and x**

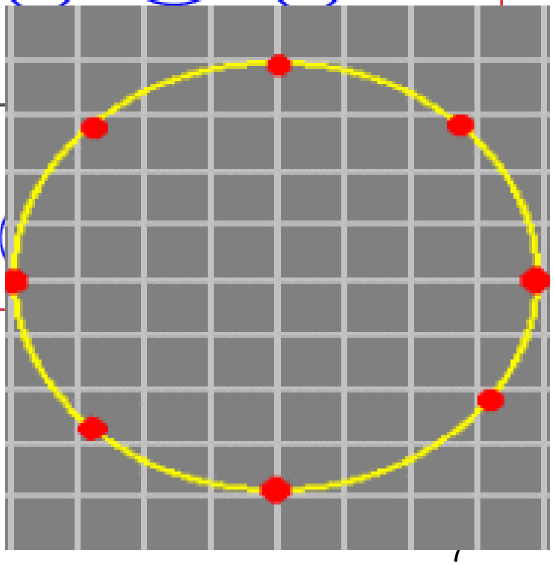
Example:

Ring of test masses

responding to wave

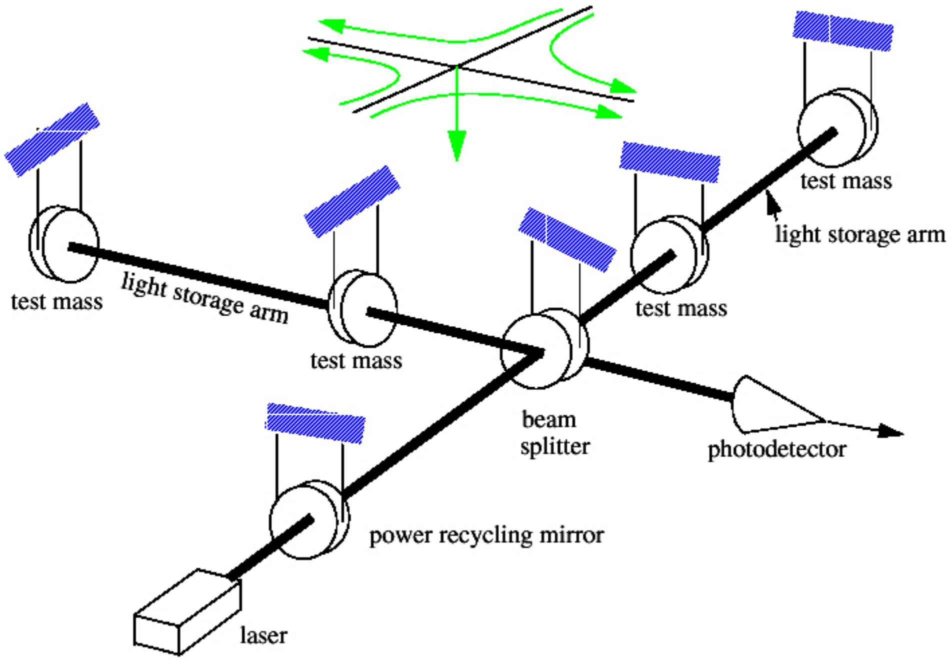
propagating along z





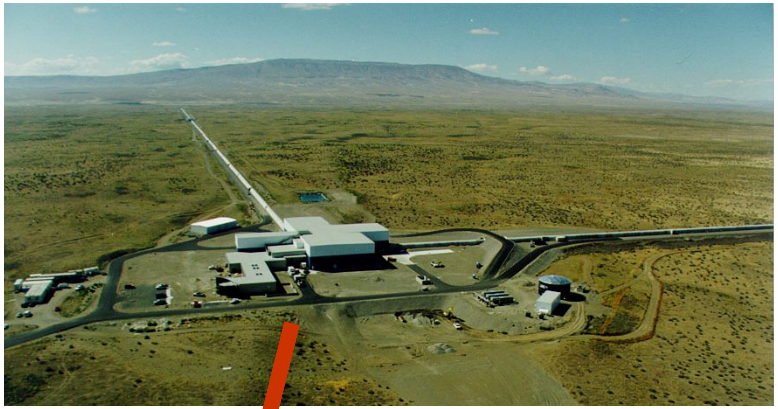
Gravitational Wave Detection

- **Suspended Interferometers**
  - » **Suspended mirrors in "free-fall"**
  - » **Michelson IFO is "natural" GW detector**
  - » **Broad-band response (~50 Hz to few kHz)**

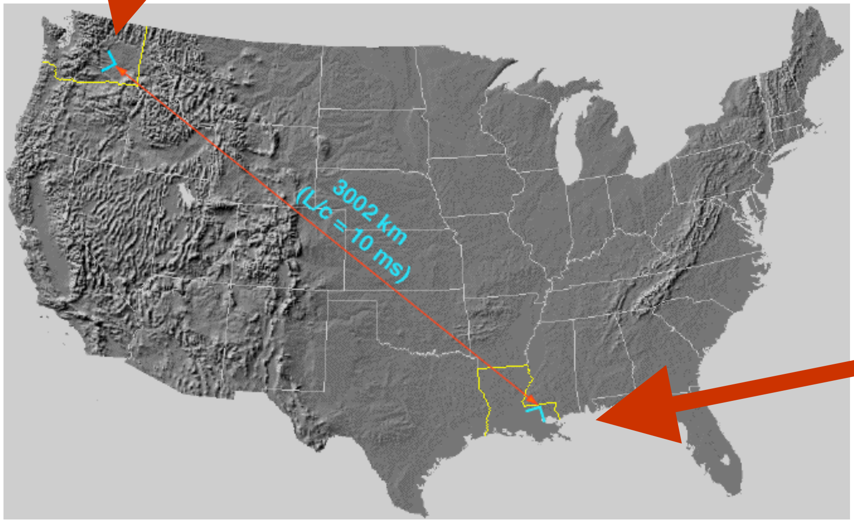


LIGO Observatories

Hanford (H1=4km, H2=2km)

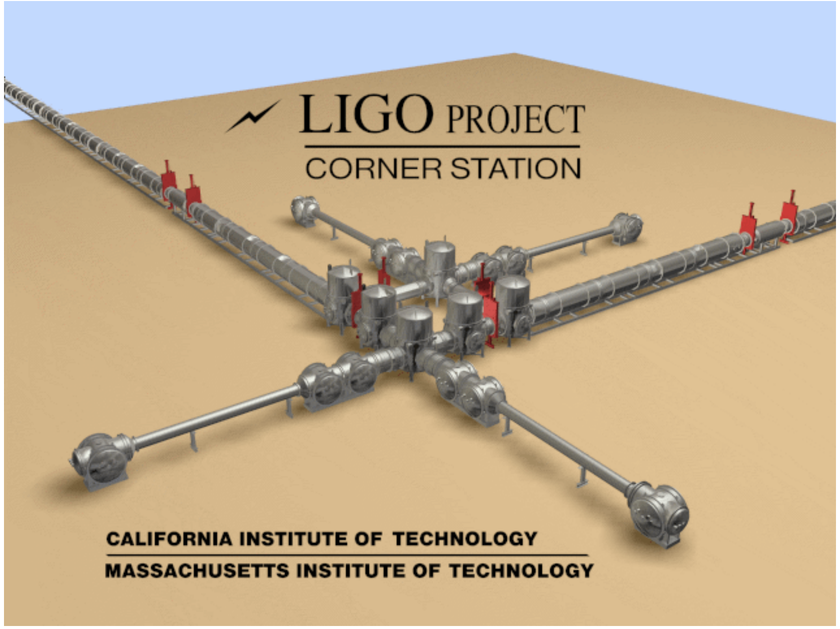


Observatories nearly 3000 km apart to rule out correlations due to terrestrial effects



Livingston (L1=4km)

LIGO Detector Facilities



- **Stainless-steel tubes**
  (1.24 m diameter, ~10^{-9} torr)
- **Worlds largest vacuum system**
- **Protected by concrete enclosure**

Vacuum System

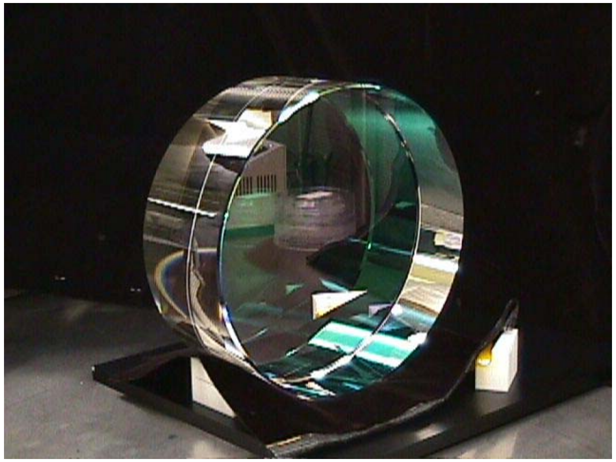
LIGO Detector Facilities

LASER

- Infrared (1064 nm, 10-W) diode pumped Nd-YAG laser
- Frequency stabilized to main interferometer

Optics

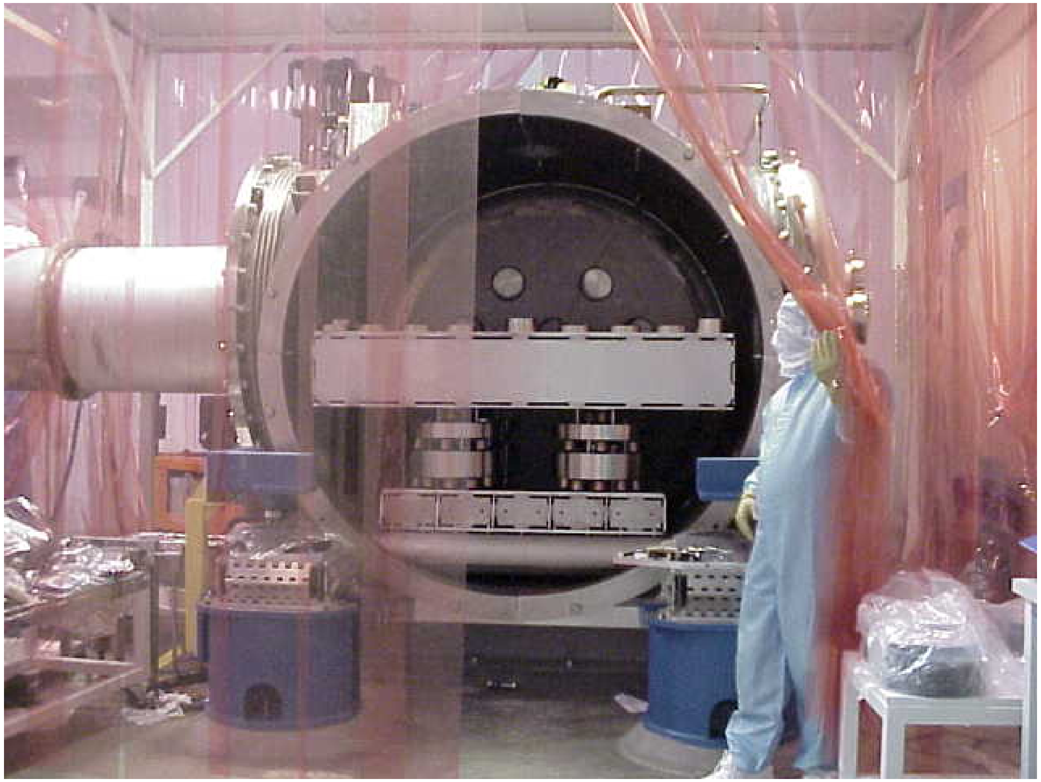
- Fused silica (25-cm diameter, super-polished)
- Suspended by single steel wire
- Actuated via magnets & coils



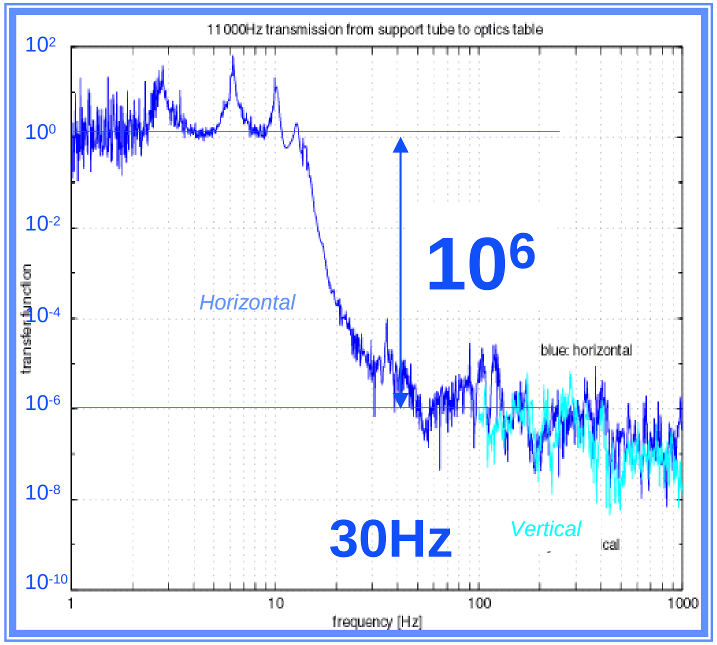
LIGO Detector Facilities

Seismic Isolation

- **Optical table supported by multi-stage (mass & springs) seismic isolation**
- **Pendulum suspension gives additional 1 / f ^{2} suppression above ~1 Hz**



Seismic isolation

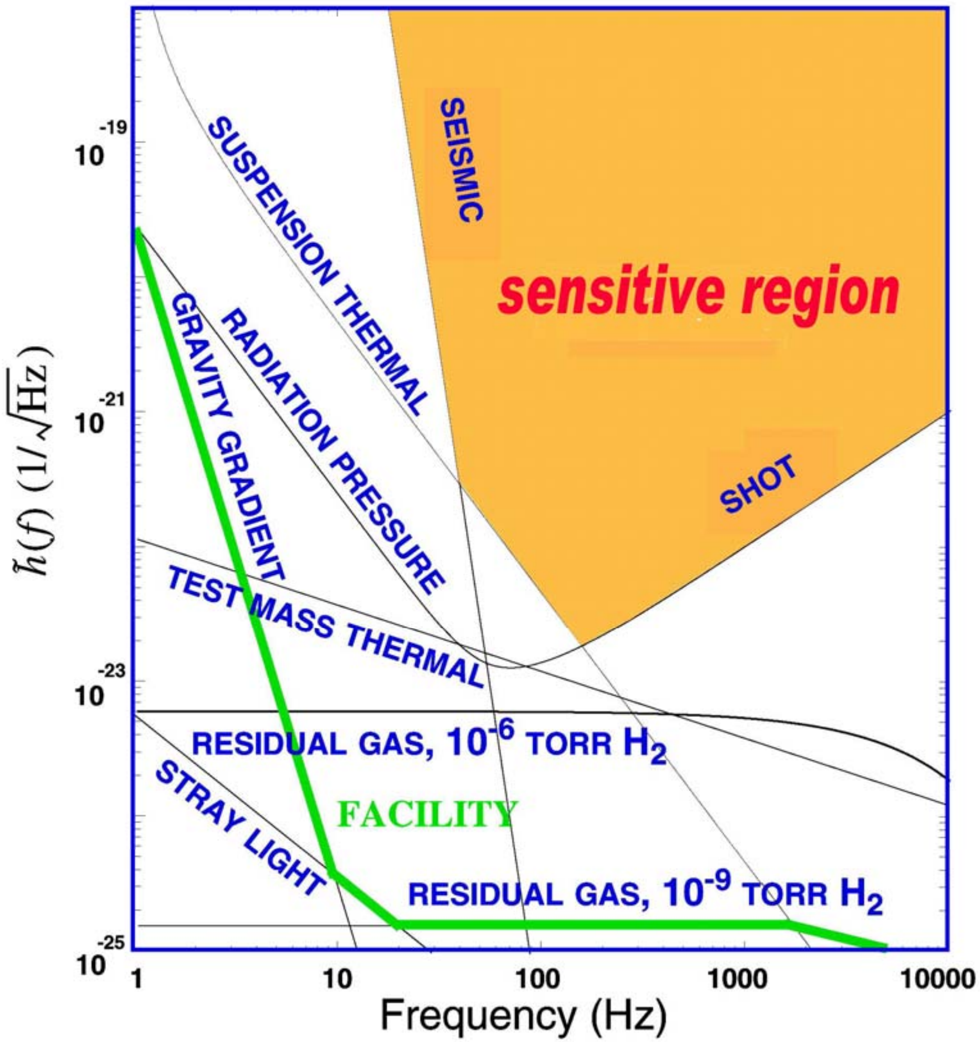


What Limits the Sensitivity of the Interferometers?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Shot noise limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

Best design sensitivity:

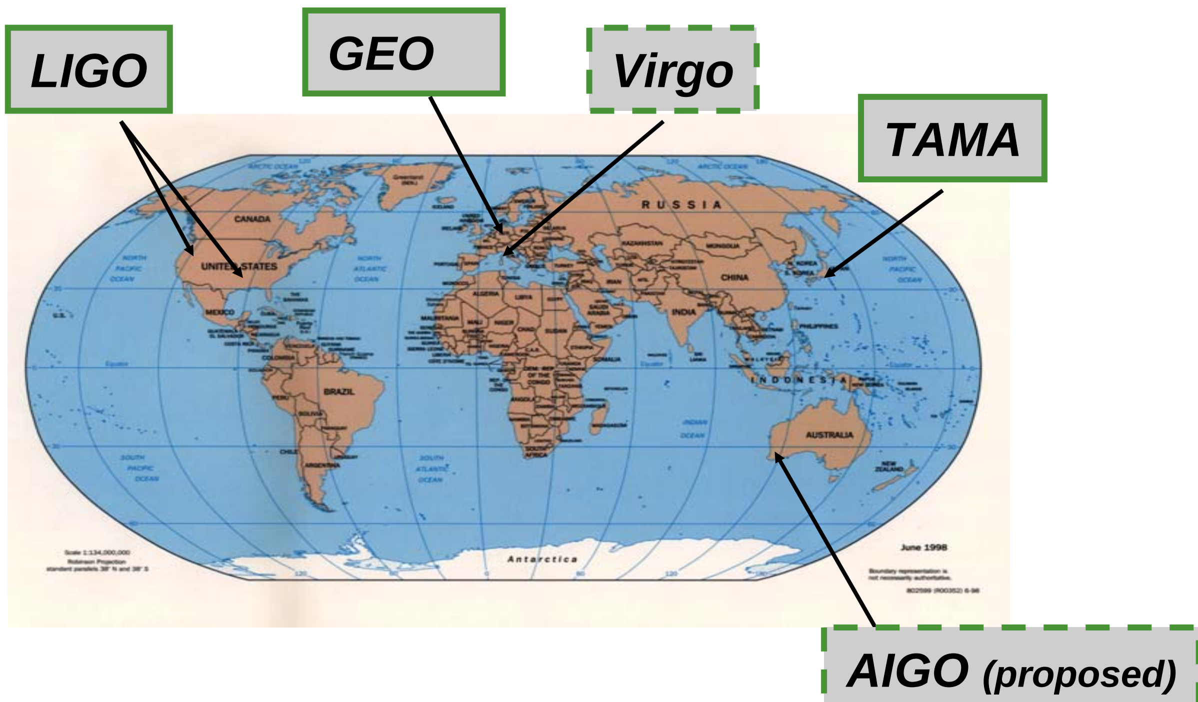
~ 3 x 10^{-23} $Hz^{-1/2}$ @ 150 Hz



Worldwide network

Forming Global Network:

- Increased detection confidence
- Improved source locations and wave polarizations



Data Runs

Had series of Engineering Runs (E1--E10) and three Science Runs (S1--S3) interspersed with commissioning.

S1 run:

17 days (August / September 2002)
Four detectors operating: LIGO (L1, H1, H2) and GEO600
H1 (235 hours/58%) H2(298 hours/73%) L1(170 hours/42%)
GEO600(400h/98%)

Four S1 astrophysical searches published (*Phys. Rev. D 69*, 2004):

- » **Inspiraling neutron stars 122001**
- » **Bursts 102001**
- » **Known pulsar (J1939+2134) with GEO 082004**
- » **Stochastic background 122004**

Data Runs

S2 run:

59 days (February—April 2003)

Four interferometers operating: LIGO (L1, H1, H2) and TAMA300 plus Allegro bar detector at LSU

H1 (1044 hours/74%) H2 (822 hours/58%) L1 (536 hours/38%)

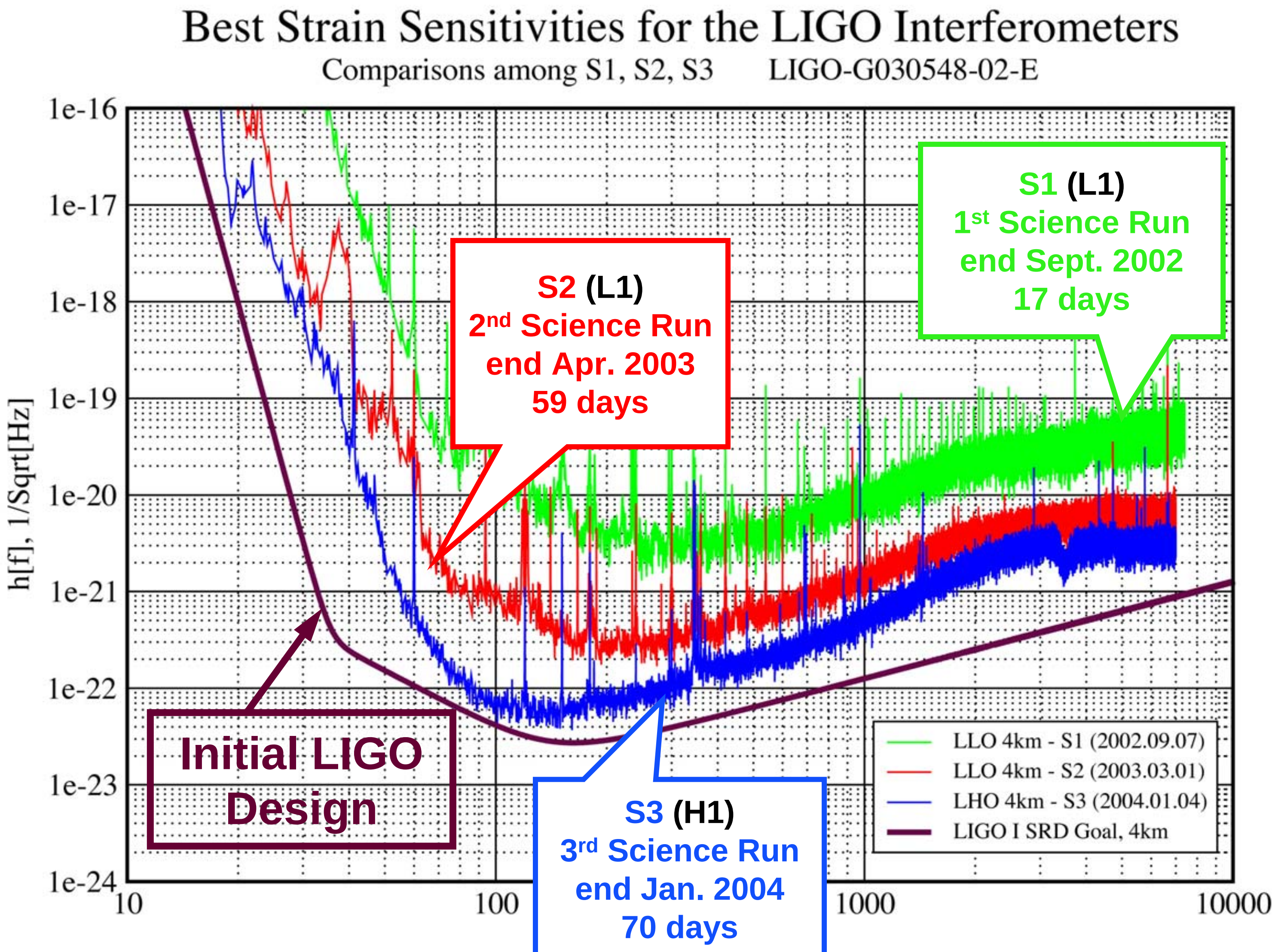
S3 run:

70 days (October 2003 – January 2004) – Analysis ramping up…

Future Science runs:

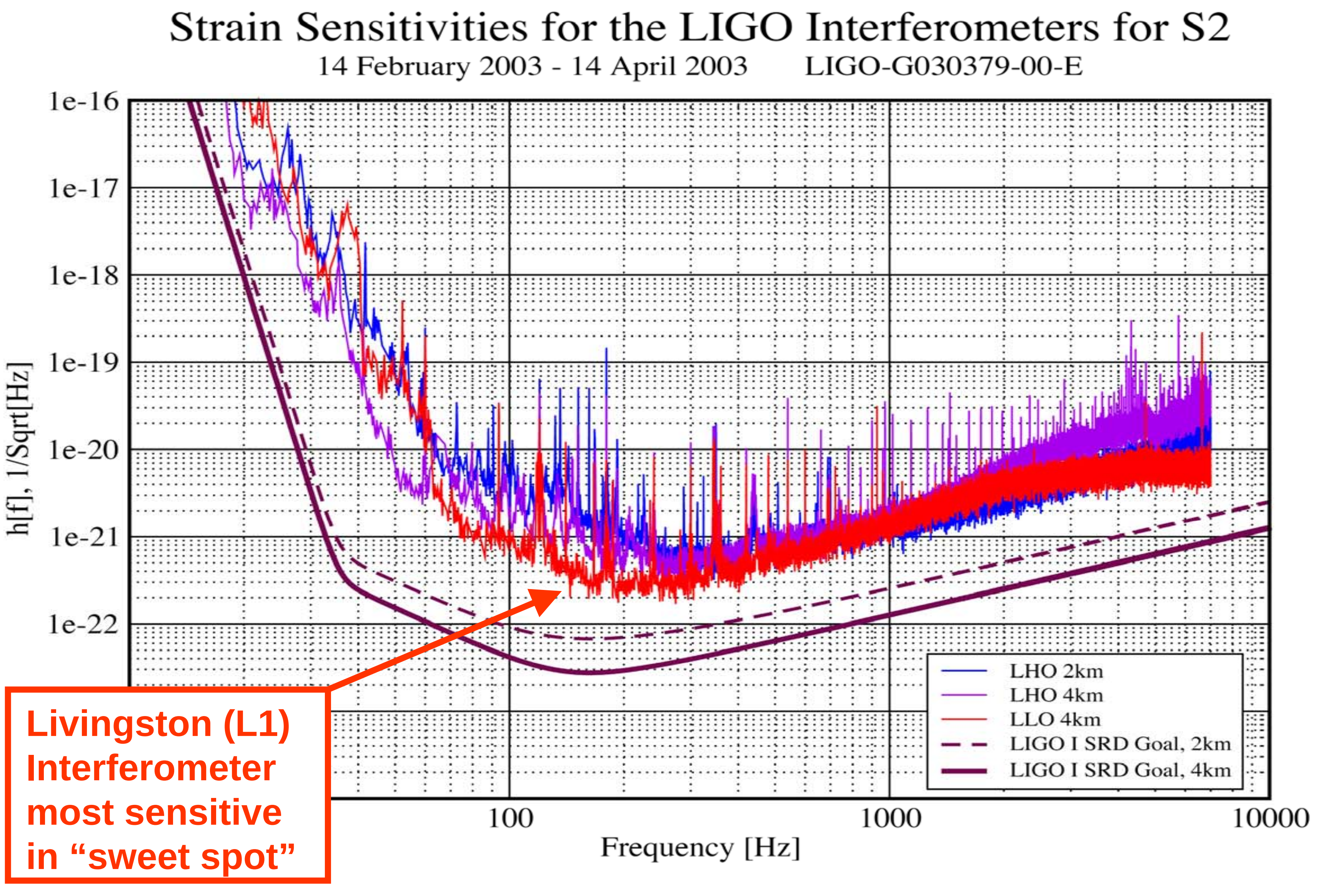
Expect a 6 months run in 2005

Improvements



LIGO

S2 Sensitivities



PRELIMINARY S2-Results

- **Compact binary inspiral:** ***"chirps"*** **(Preliminary results!)**
  - » **Range: up to 1Mpc (incl. Andromeda)**
    - – $R_{90\%}$ < 50 inspirals per year per **"milky-way-equivalent-galaxy"**

- **Supernovae / GRBs:** ***"bursts"*** **(Preliminary results!)**
  1. **Detailed searches triggered by observations with EM/neutrino-detectors**
     - **Example: GRB030329 during S2-run (800Mpc away) No excess cross correlation discovered**
  2. **all-sky untriggered searches**
     - **Sensitivity h > $10^{-20}/Hz^{1/2}$ (Upper limits pending further analysis)**

PRELIMINARY S2-Results

- **Pulsars in our galaxy:** *"periodic"* **(Preliminary results!)**
  - » **search for 28 known isolated pulsars**
  - » **precise timing was provided by radio astronomers**
    - – **No signals detected, preliminary upper limits for each pulsar ranges between 10^{-22} to 10^{-24}**
    - – **Upper limit on ellipticity < 10^{-5} for 4 pulsars**
- **Cosmological Signals** *"stochastic background"* **(Preliminary results!)**
  - » ***Random radiation assumed to be isotropic, unpolarized, stationary, and Gaussian***
  - » ***Parametrized as fractional contribution to critical energy density of the Universe***
    - – ***Upper limit:*** $\Omega_{GW} (h_{100})^2 < 0.018 \ (+0.007/-0.003)$

      (preliminary systematic error estimates)

Looking further ahead

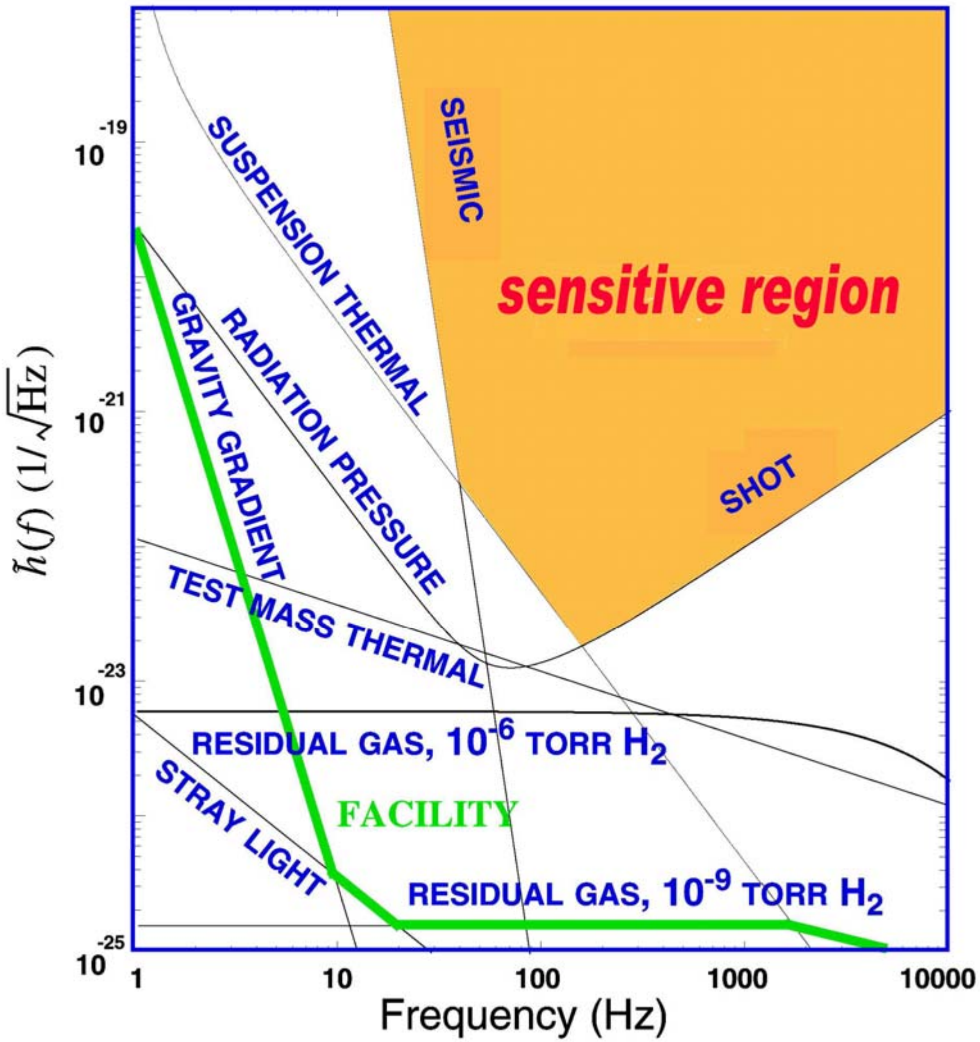
How can we further improve LIGO?

1. Displacement Noise

- ⇨ Improve seismic isolation
- ⇨ Reduce Thermal Noise
- ⇨ Decrease Radiation Pressure Noise

2. Readout Noise

- ⇨ Increase Laser Power
- ⇨ Improve Optical Layout (increases signal)



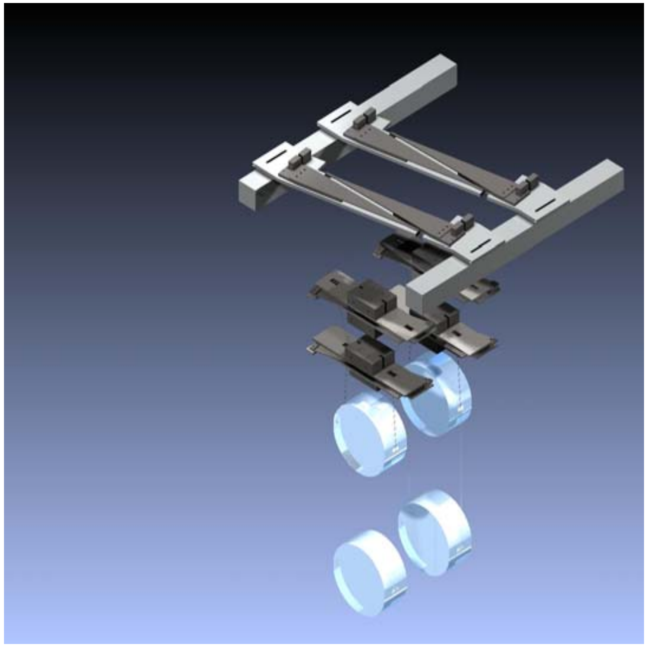
Advanced LIGO

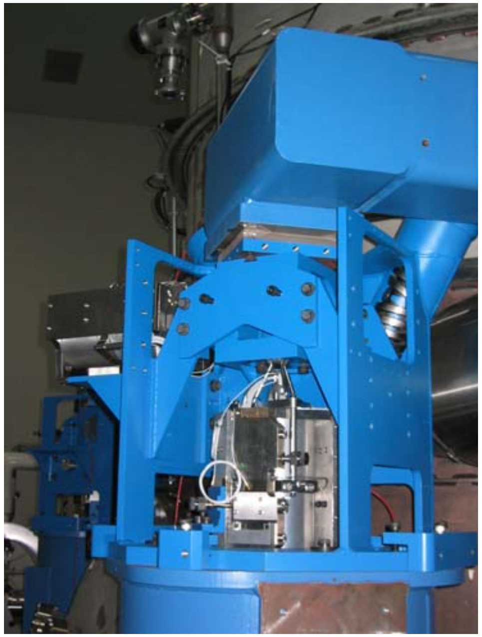
Detector Improvements:

New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal noise in detection band





Improved seismic isolation:

Passive → Active

Lowers seismic “wall” to ~10 Hz

Advanced LIGO

Increased and better test mass:

10 kg → 40 kg ⟶ decrease radiation pressure noise

Higher Q ⟶ lower thermal noise

New optical configuration:

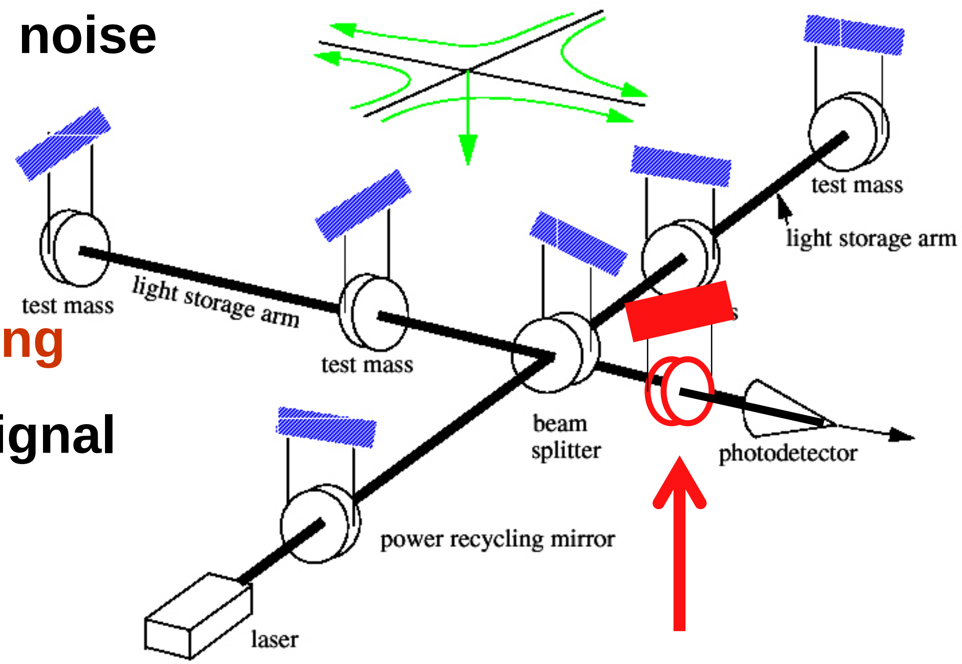
Power recycling → Dual recycling

"Optical amplification" of the signal

Increased laser power:

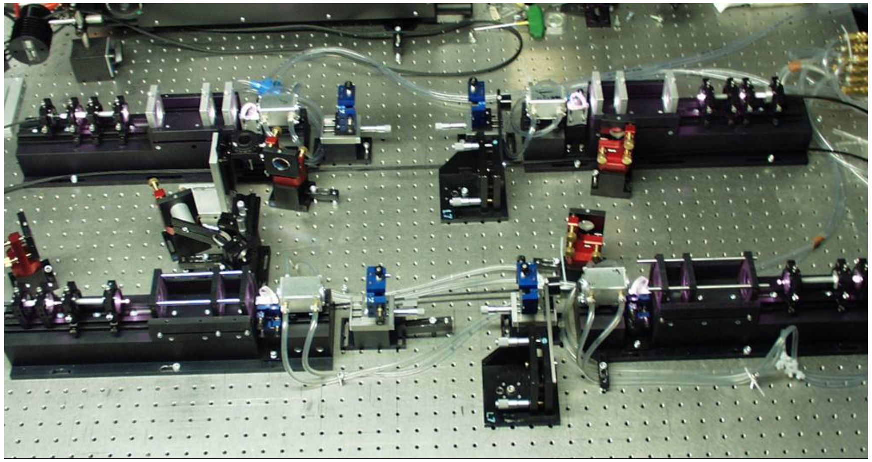
10 W → 180 W

Improved shot noise (high freq)

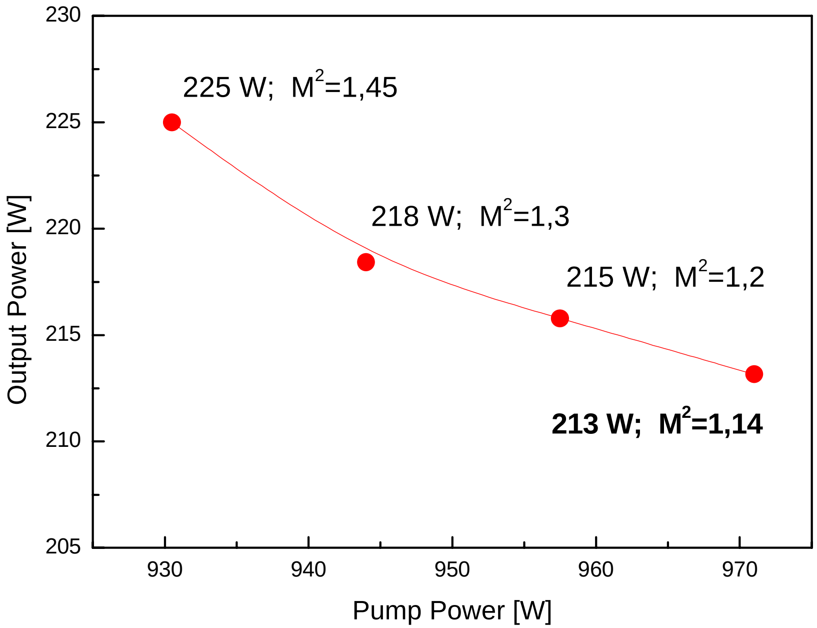


signal recycling mirror

Advanced LIGO Laser



4 head diode pumped Nd:YAG ring Laser



Courtesy of the
Laser Zentrum Hannover

Maik Frede, Ralf Wilhelm, Carsten Fallnich, Benno Willke, Karsten Danzmann

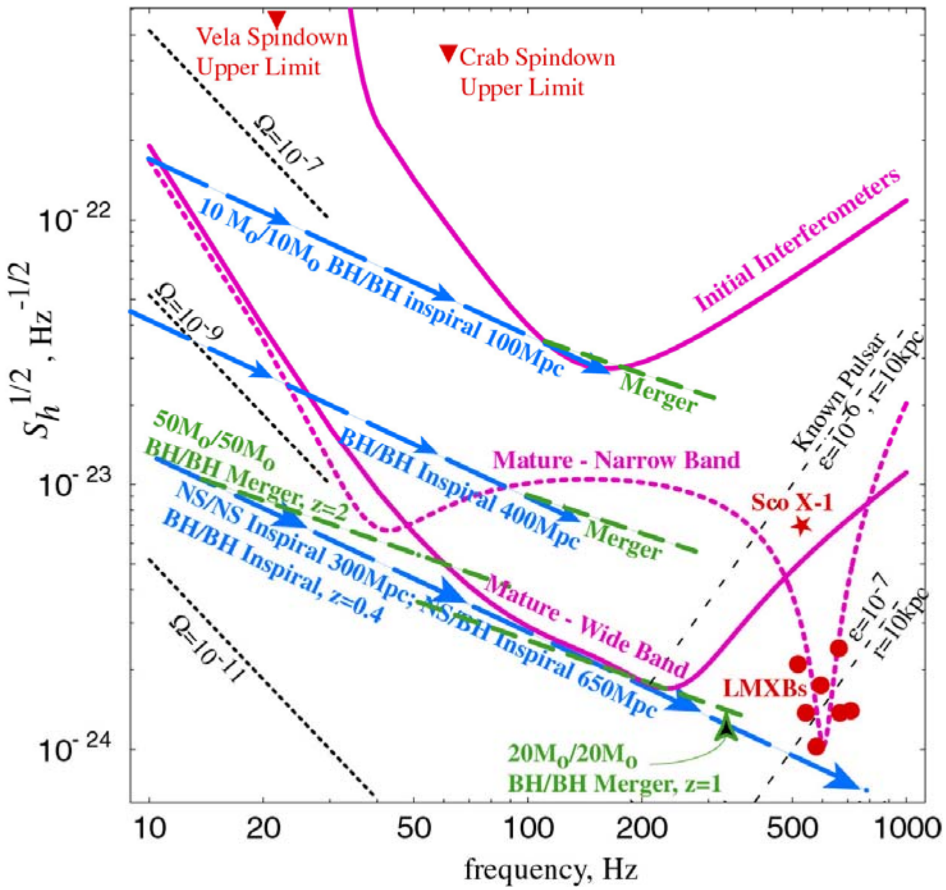
⇨ 213 W output power with $M^2 < 1.15$

Advanced LIGO

Signal Recycling allows us to tune the detector response:

1. Broadband Operation

2. Narrow Band Operation

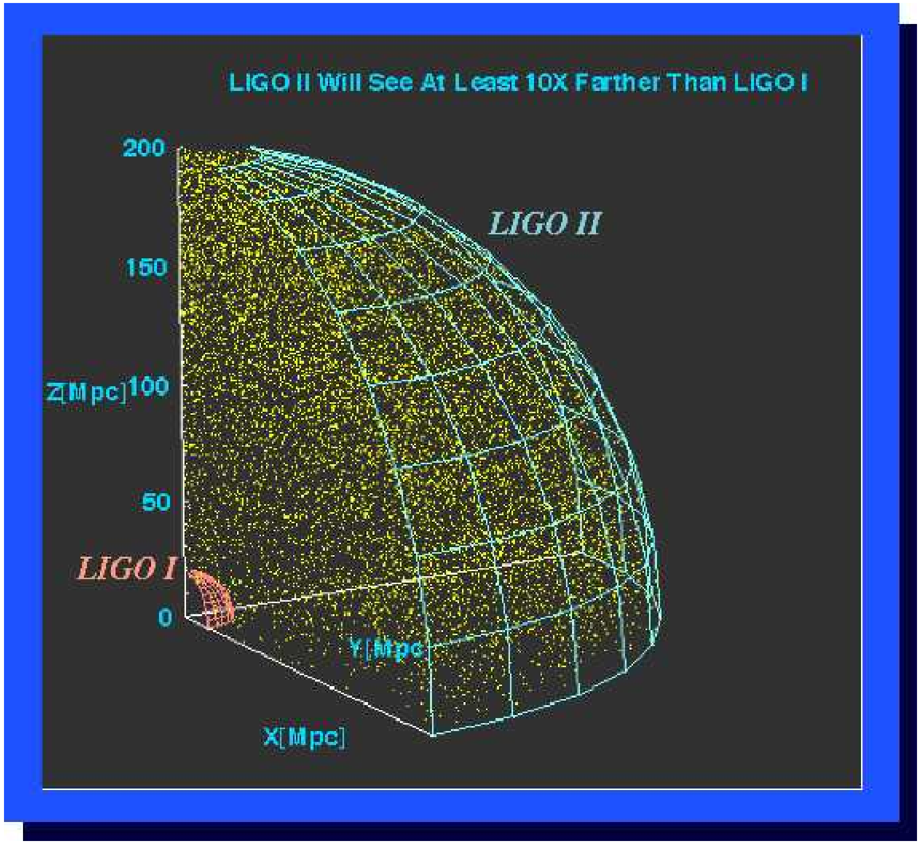


Advanced LIGO

Signal Recycling allows us to tune the detector response:

1. Broadband Operation:
   ~ Factor 10 better sensitivity
   at all frequencies

Searched Volume and number of expected signals increase by factor 1000!

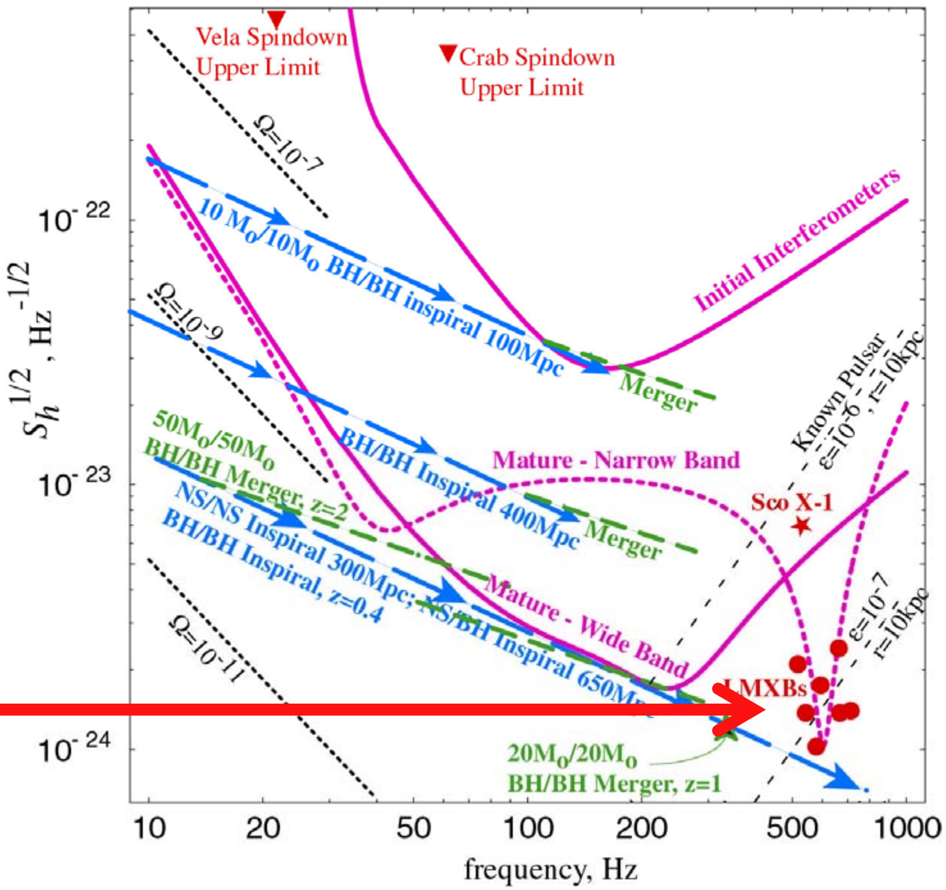


Advanced LIGO

Signal Recycling allows us to tune the detector response:

2. Narrow Band Operation:
   ~ Factor 100 better sensitivity at target frequencies

Can target for example specific known pulsar clusters.



Conclusions

LIGO commissioning is well underway

- **Good progress toward design sensitivity**
- **GEO, other instruments worldwide advancing as well**

Science Running is beginning

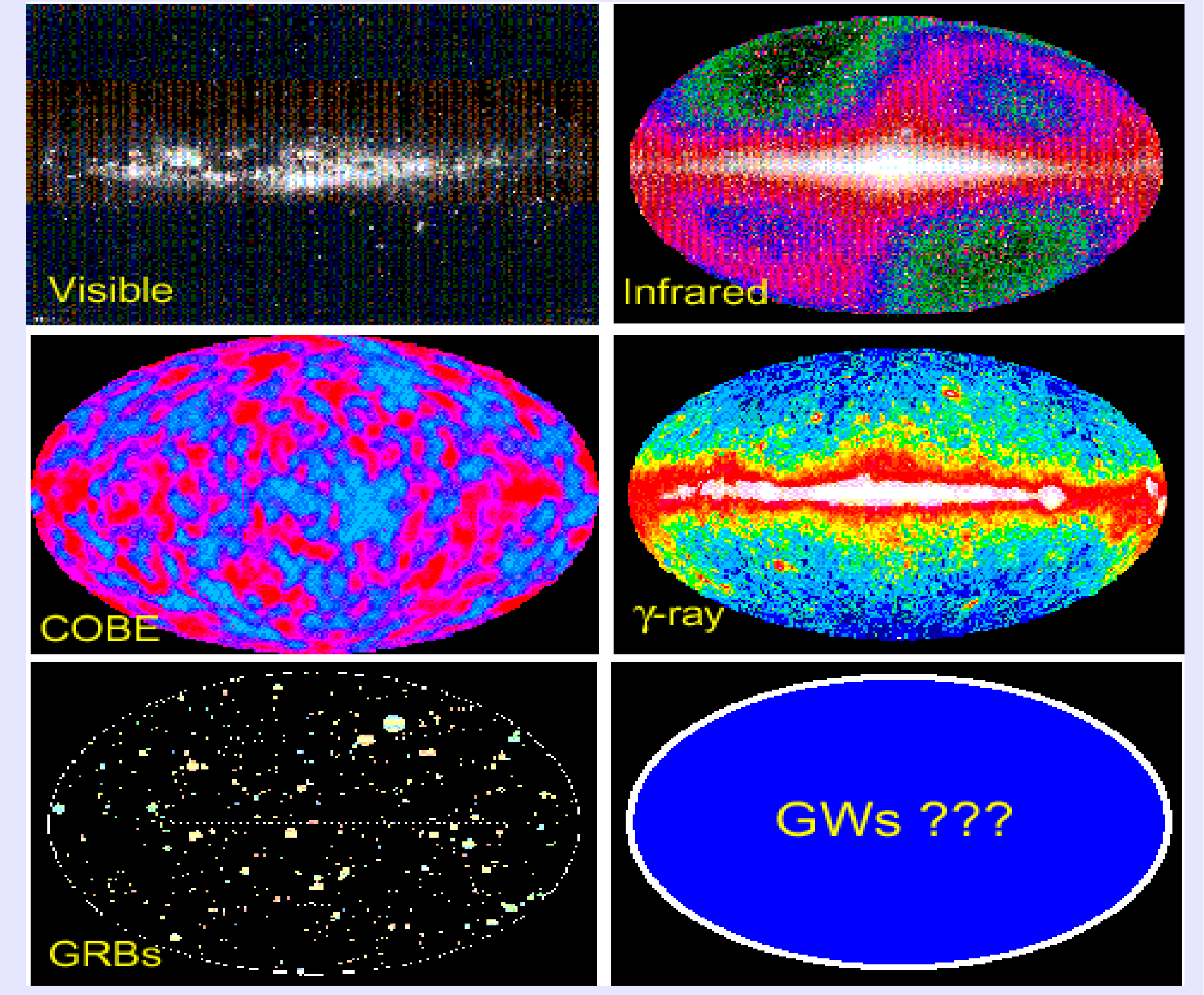
- **S1-Data is analyzed and results are published**
- **S2-Data analysis is approaching publication**
- **S3-Data analysis is beginning**

Our Plan:

- **Continue commissioning and data runs with GEO & others**
- **Collect ≥ one year of data at design sensitivity before starting upgrade**
- **Advanced interferometer with dramatically improved sensitivity – 2008+**
  (MRE proposal under review at NSF)

We should be detecting gravitational waves regularly within the next 10 years!

What might the sky look like?



LIGO Scientific Collaboration
A family photo

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A family photo

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