LIGO-G1401365-v1

LIGO-India Detector Master Class Introduction

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Who is this guy!?

- Ph.D at Univ of Tokyo (1995-1999)
  - Design & build of TAMA300 double-pendulum suspensions
  - Interferometer length sensing for power recycled Fabry-Perot Michelson Interferometer
- Commissioning and science runs of TAMA300 interferometer (1999-2009)
- @LIGO Caltech (2009-)
  Output mode cleaner development
  eLIGO/aLIGO commissioning

LIGO-India Detector Master Class: Overview

- **Mission:**
  To convey technical knowledge necessary for building and operating the LIGO India detector, or similar interferometer, including prototypes

- by going through:
  - the common technologies in laser interferometer GW detectors
  - Detailed description / discussion about the interferometer sensing & control

LIGO-India Detector Master Class: Overview

Lecture plan

DAY1 General overview of laser interferometer GW detectors
Interferometer configurations

DAY2 Noises in GW detectors

DAY3 Control system & its modeling

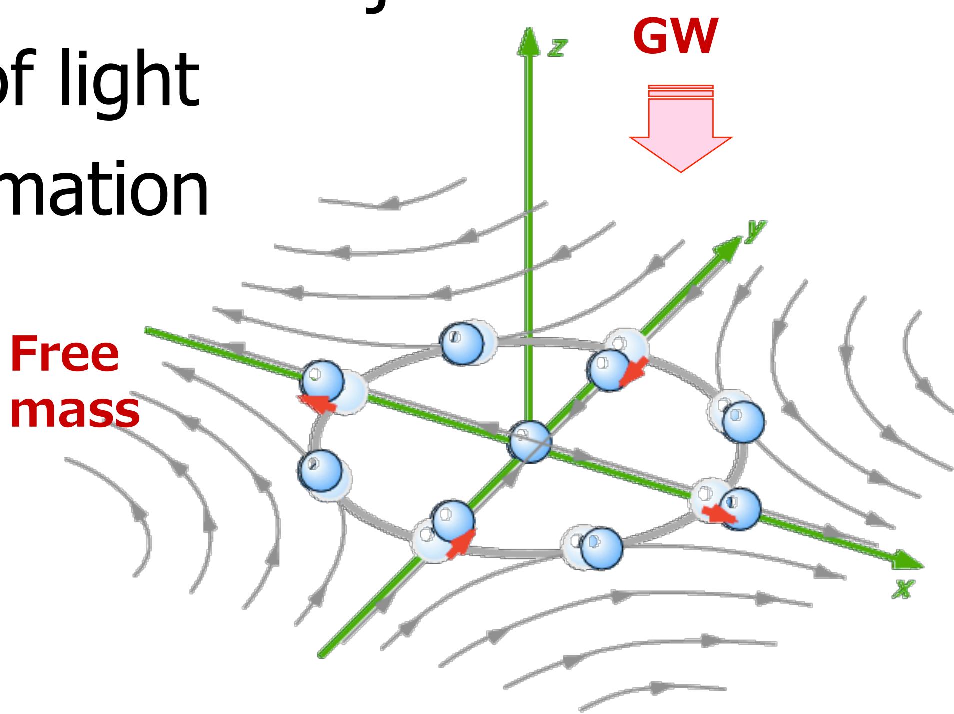
DAY4 Interferometer length sensing and control
Feedforward noise cancellation
Quantum noise

DAY5 Higher-order laser modes

Interferometer GW detection

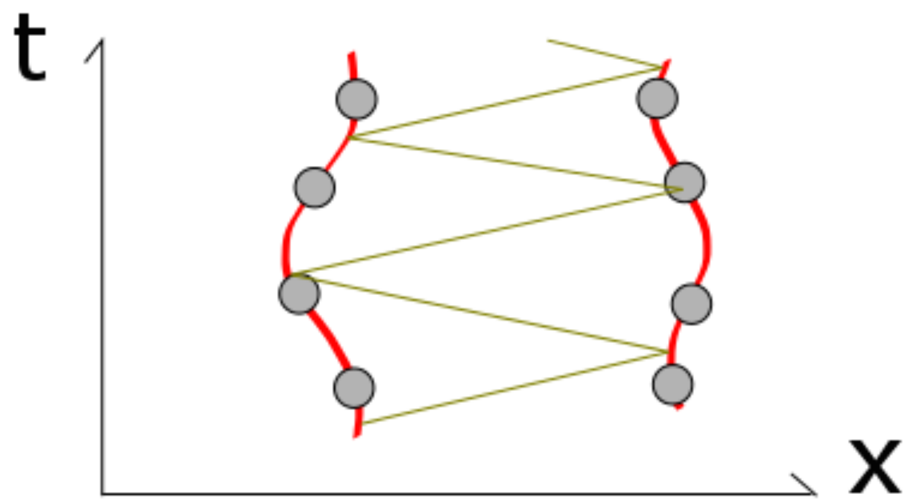
Gravitational wave

- General Relativity
  - Gravity = Spacetime curvature
  - Gravitational Wave = Wave of spacetime curvature
- GW
  - Generated by motion of massive objects
  - Propagates with speed of light
  - Cause quadrupole deformation of the spacetime

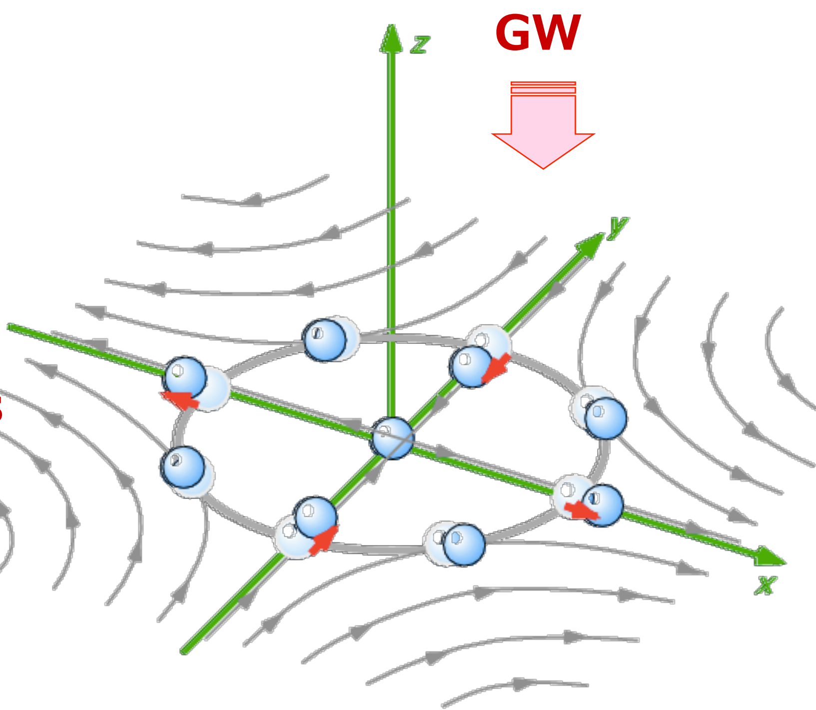


Gravitational wave

- What does the balls feel?
  - The balls are free mass (= free falling)
  - ...Geodesic lines



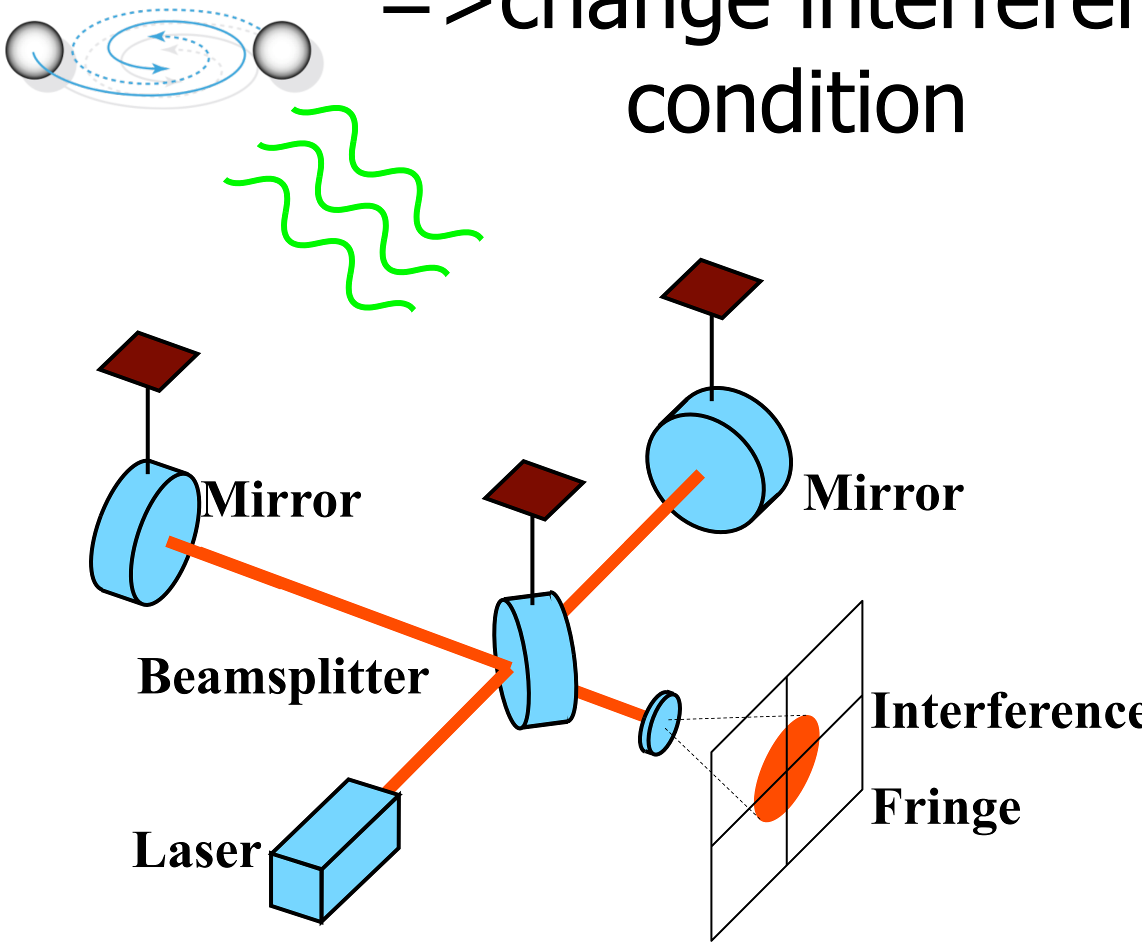
- Q. What happens
  if the balls are connected
  by bars



Interferometer GW detection

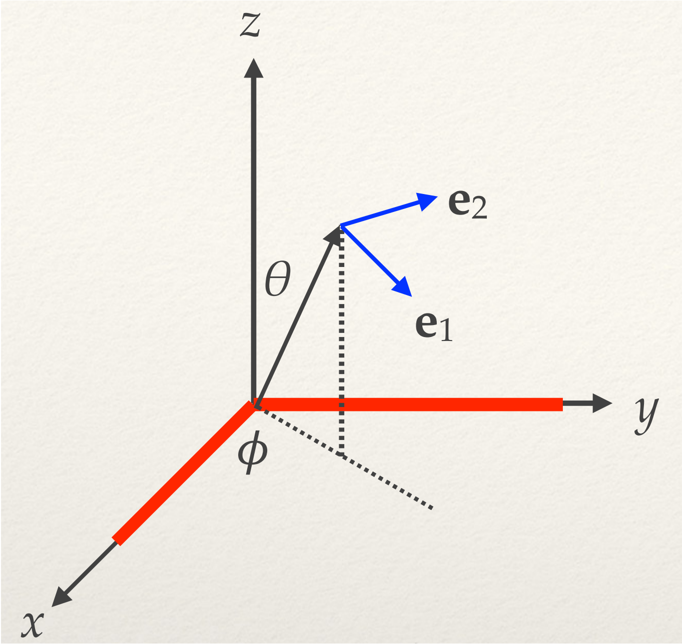
- Michelson-type interferometers are used
- Differential change of the arm path lengths

=>change interference condition



Antenna pattern

- Antenna pattern (at low frequencies)



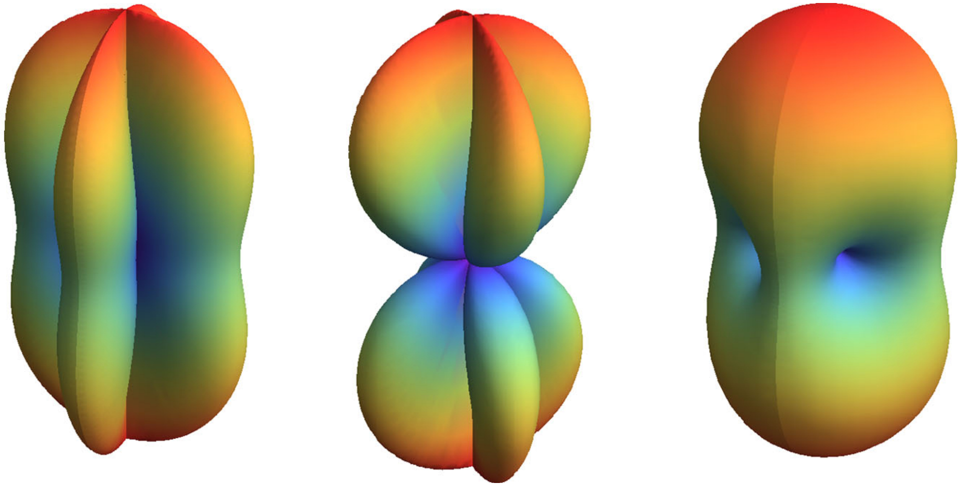


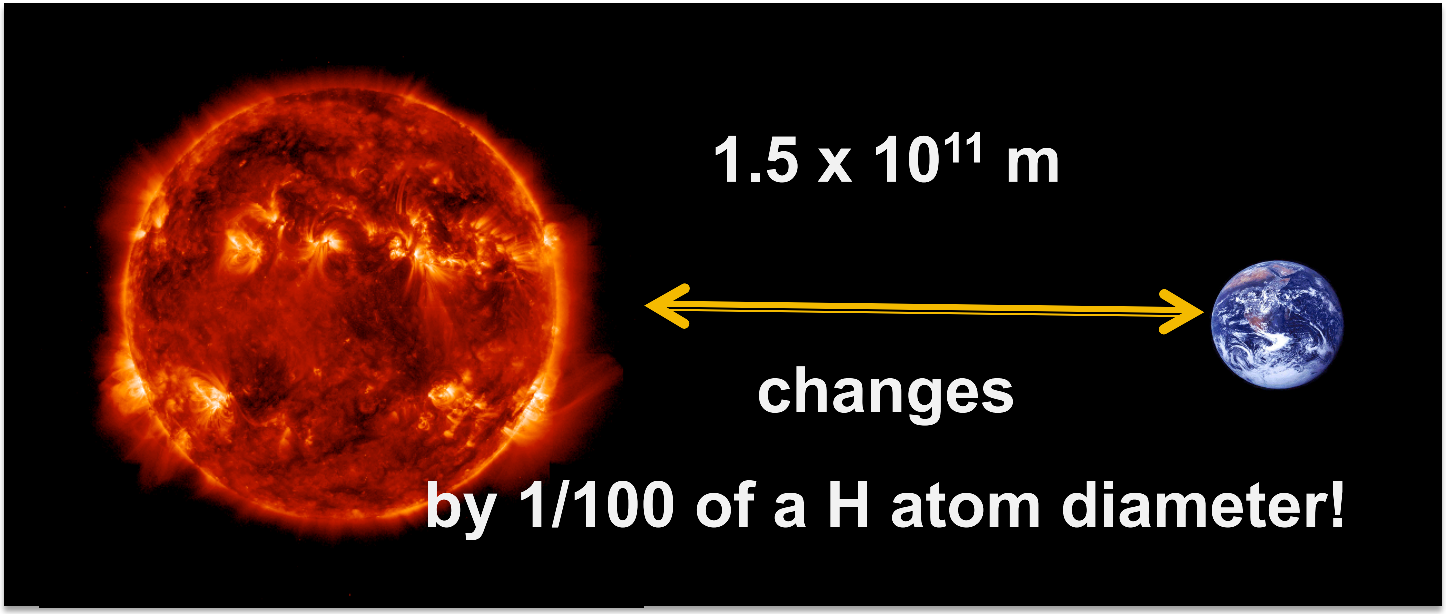
FIG. 2 (color online). Interferometer antenna response for (+) polarization (left), (×) polarization (middle), and unpolarized waves (right).

Rev. Mod. Phys. **86** (2014) 121-151
http://link.aps.org/doi/10.1103/RevModPhys.86.121
(http://arxiv.org/abs/1305.5188)

Amplitude of GWs

- The effect of GW is very small
- $h \sim 10^{-23}$ => distance of 1m changes 10^{-23}m

- Corresponds to:
  change by **~0.01 angstrom (or 1pm)**
  for distance between the sun and the earth

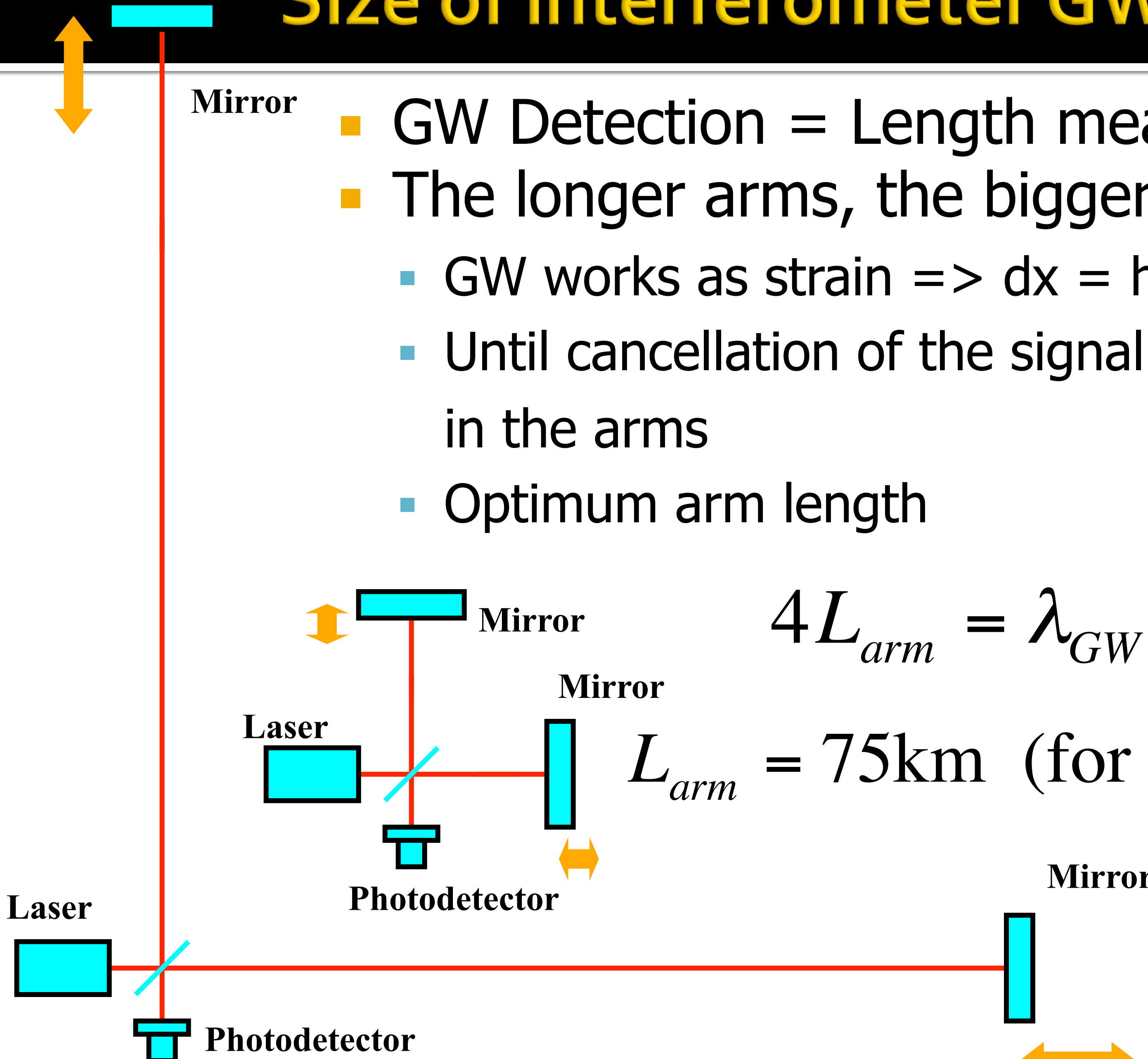


Size of interferometer GW detectors

- GW Detection = Length measurement
- The longer arms, the bigger the effect
  - GW works as strain => dx = h_{GW} x L_{arm}
  - Until cancellation of the signal happens in the arms
  - Optimum arm length

$$4L_{arm} = \lambda_{GW} (= c / f_{GW})$$

$$L_{arm} = 75\text{km} \ \ (\text{for } f_{GW} = 1\text{kHz})$$



Size of interferometer GW detectors

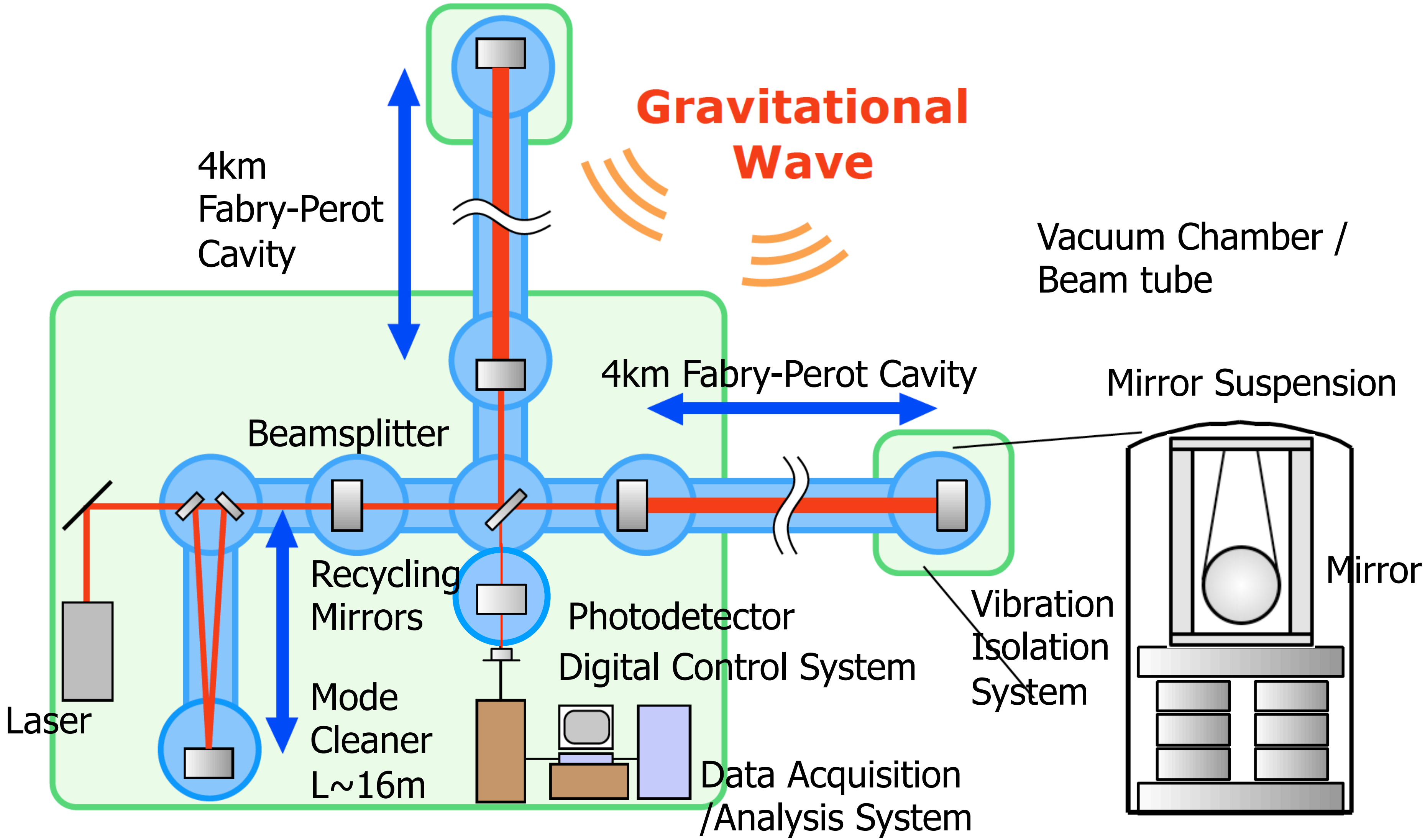
- **LIGO Observatories**
  Hanford / Livingston 4km

Still shorter than the optimum length
=> Use optical cavity to increase life time of the photons in the arm

c.f. Virgo (FRA/ITA) 3km, KAGRA (JPN) 3km, GEO (GER/GBR) 600m

Components of the interferometer

- "Still simplified" LIGO Interferometer

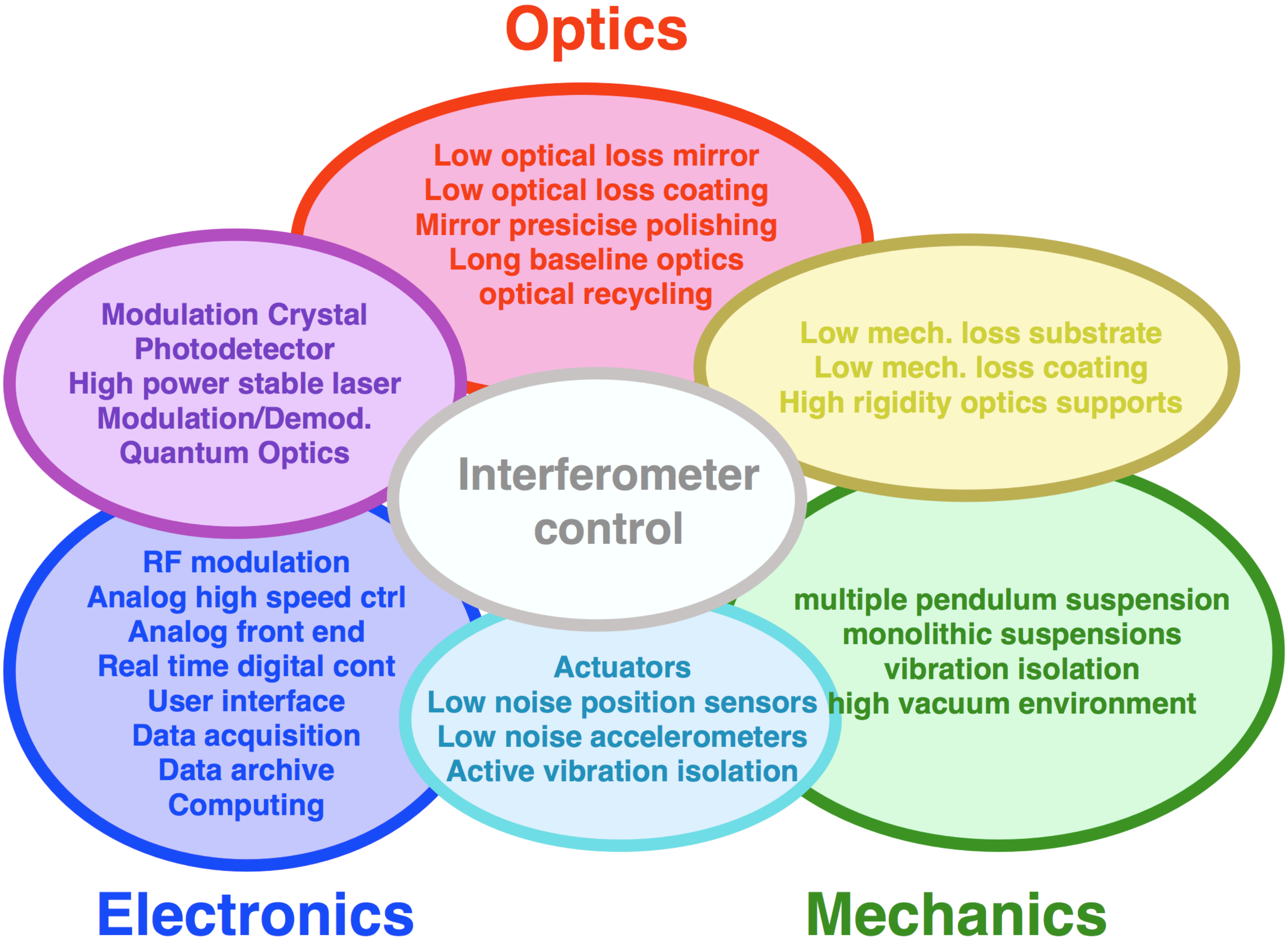


Components of the interferometer

- 3 fundamentals of the GW detector
- Mechanics
- Optics
- Electronics

Components of the interferometer

- 3 ˙
- M
- O
- El

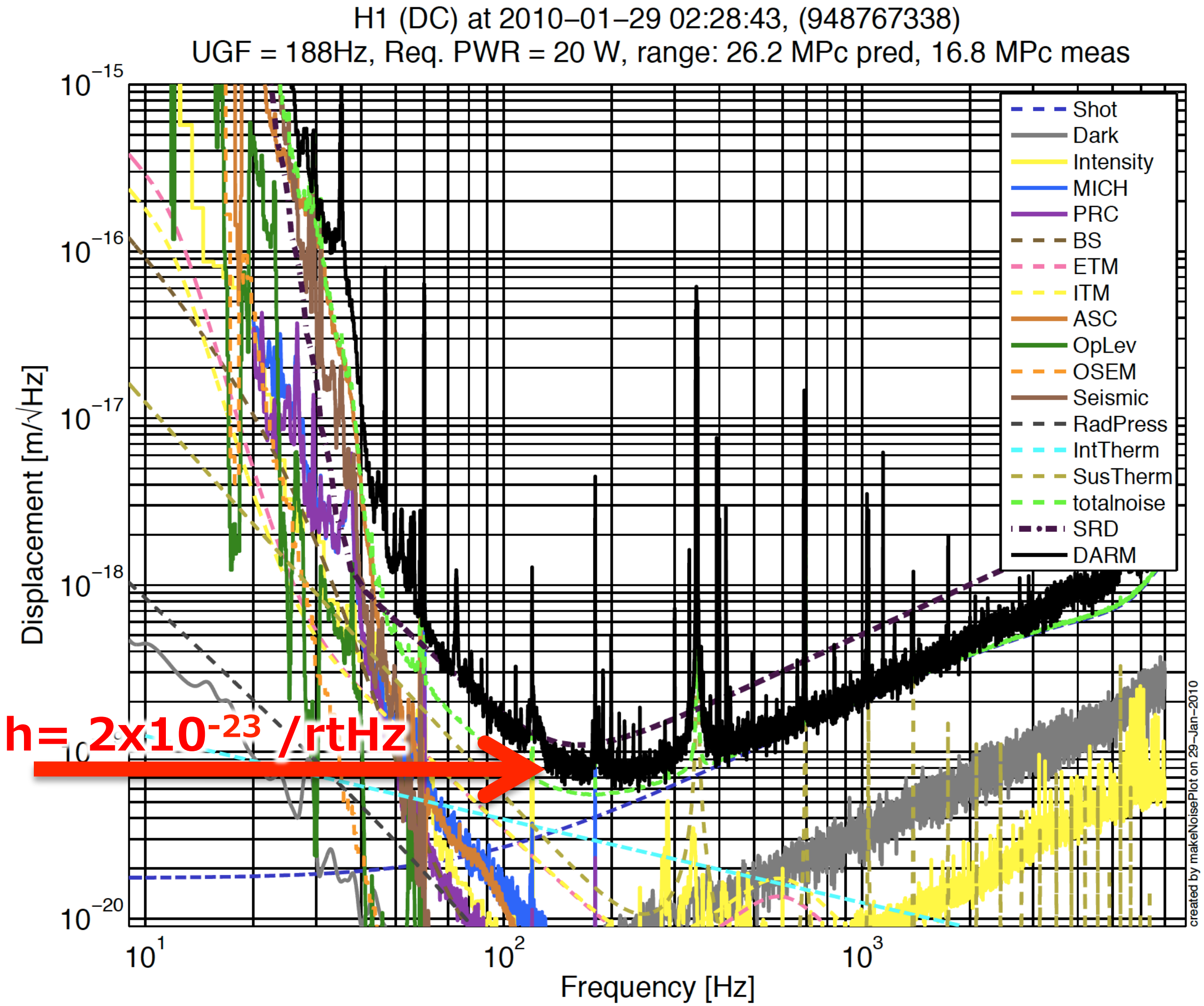


What can we do for the detection?

- An IFO produces a continuous signal stream in the GW channel
- The detector is fixed on the ground => can not be directed to a specific angle
- GWs and noises are, in principle, **indistinguishable** => Anything we detect is GW
- **Reduce noises!**
- Obs. distance is inv-proportional to noise level
- x10 better => x10 farther => x1000 more galaxies

Sensitivity and noise

- Sensitivity (=noise level) of Enhanced LIGO



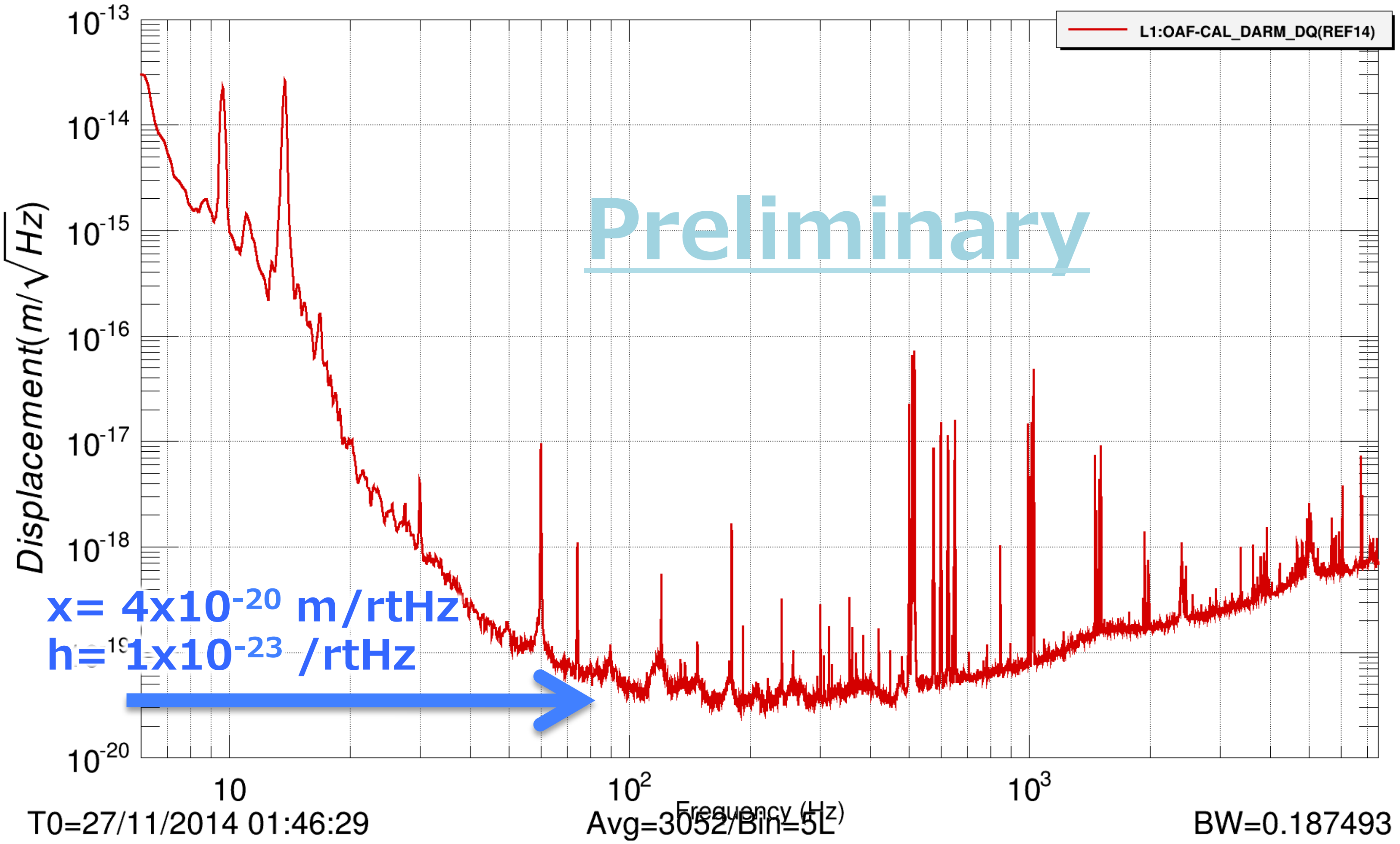
Laser shot noise
Laser radiation pressure noise
thermal noise
seismic noise
Laser intensity /frequency noise

electronics noise
digitization noise
angular control noise

……

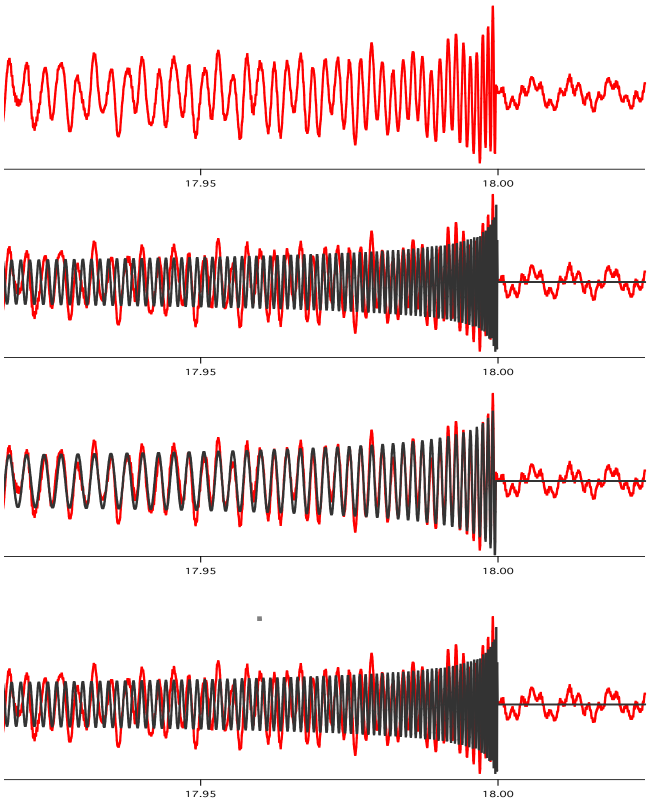
aLIGO sensitivity

- aLIGO sensitivity



Data Analysis

- Compact Binary Coalescence
  => Chirp signal
  - **NS-NS binaries**
    Accurate waveforms predictable (Post Newtonian approximation)
    => Template banks & Matched Filter analysis (amplitude & phase information)
  - **BH-BH binaries**
    Similar waveforms,
    but more difficult to predict because of earlier merging

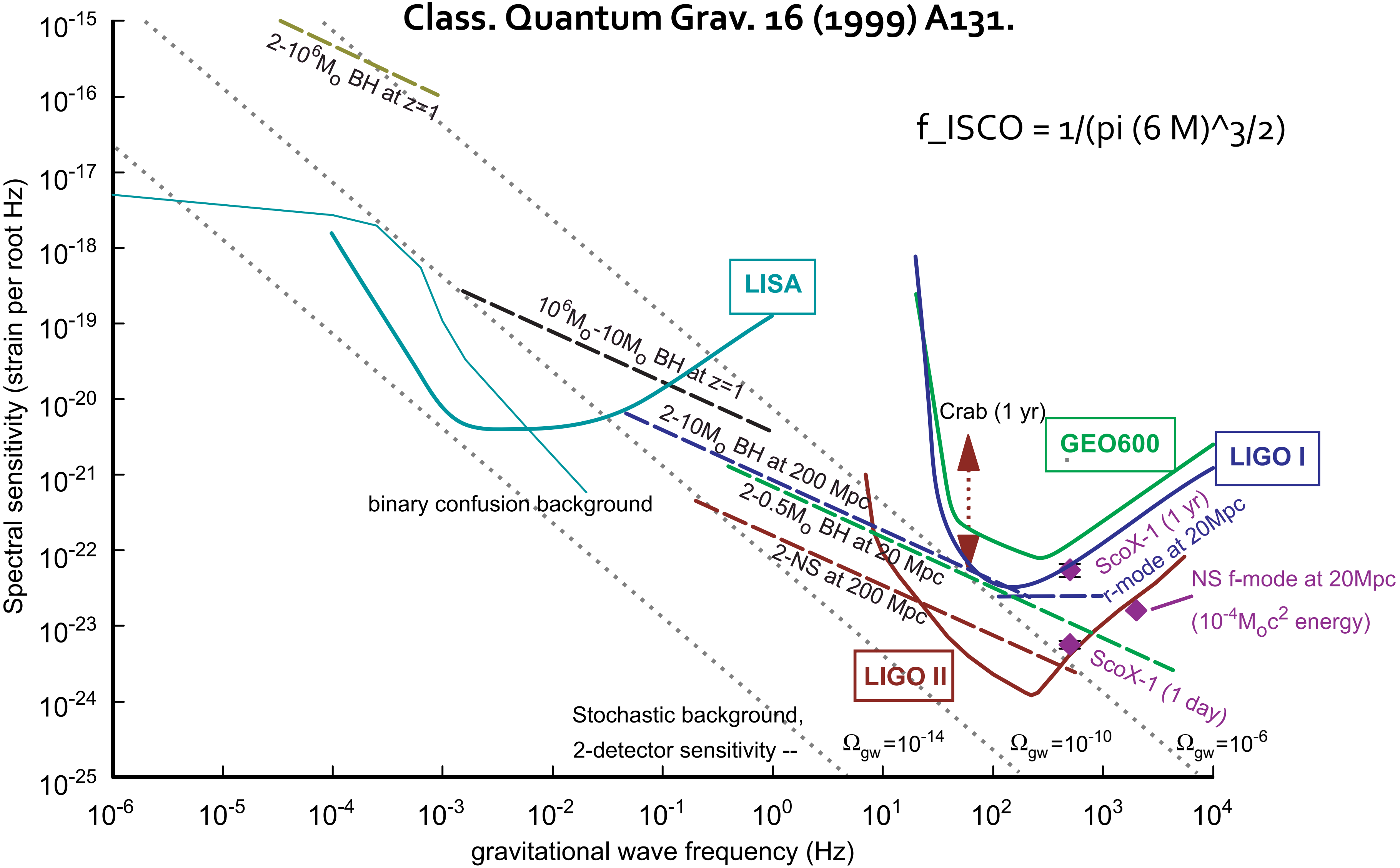


Mat]ched filtering analysis

Data Analysis

B. F. Schutz, "Gravitational wave astronomy", Class. Quantum Grav. 16 (1999) A131.

f_ISCO = 1/(pi (6 M)^3/2)



Binary range

- Binary inspiral range
  - Chirp waveform PSD

$$\tilde{h}(f) = \frac{1}{D}\left(\frac{5\pi}{24c^3}\right)^{1/2}(G\mathcal{M})^{5/6}(\pi f)^{-7/6}e^{i\Psi(f;M)},$$

  - ISCO freq (HF cut off freq)

$$f_{isco} = \frac{c^3}{6\sqrt{6}\pi GM},$$

  - Horizon range (Integrated SNR of 8)

$$D = \frac{1}{8}\left(\frac{5\pi}{24c^3}\right)^{1/2}(G\mathcal{M})^{5/6}\pi^{-7/6}\sqrt{4\int_{f_{low}}^{f_{high}}\frac{f^{-7/3}}{S_n(f)}df},$$

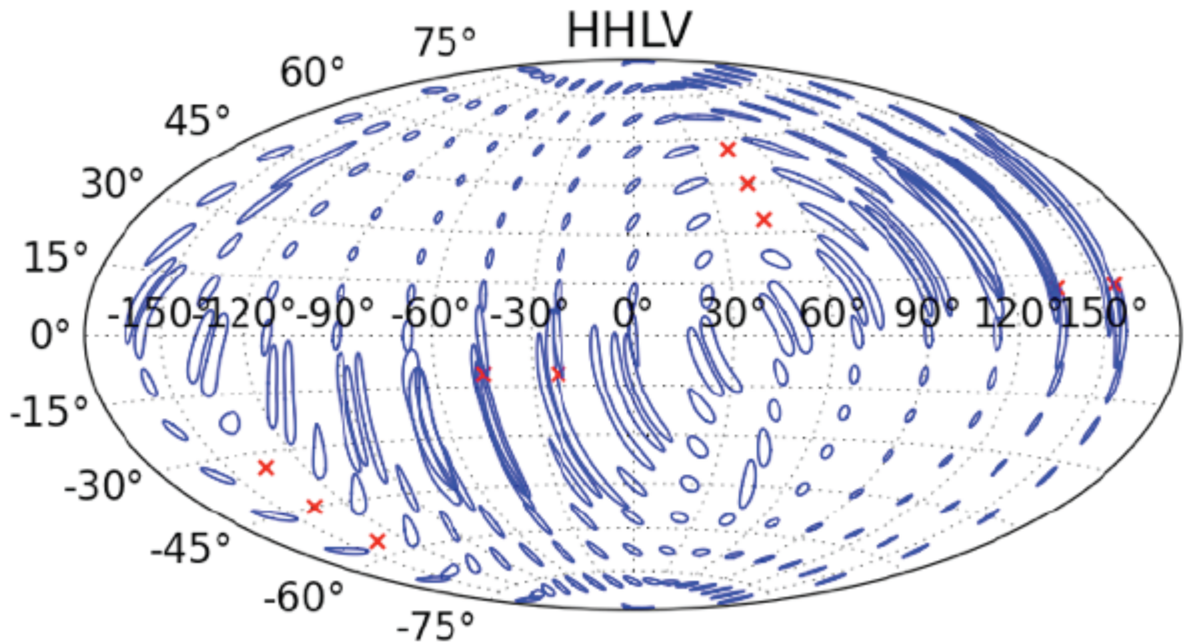
  - In the control room we use D/(2.26) taking all sky average

iLIGO 15Mpc
eLIGO 20Mpc
aLIGO 50Mpc

https://dcc.ligo.org/LIGO-T0900499/public

Localization capability:

- LIGO-Virgo only

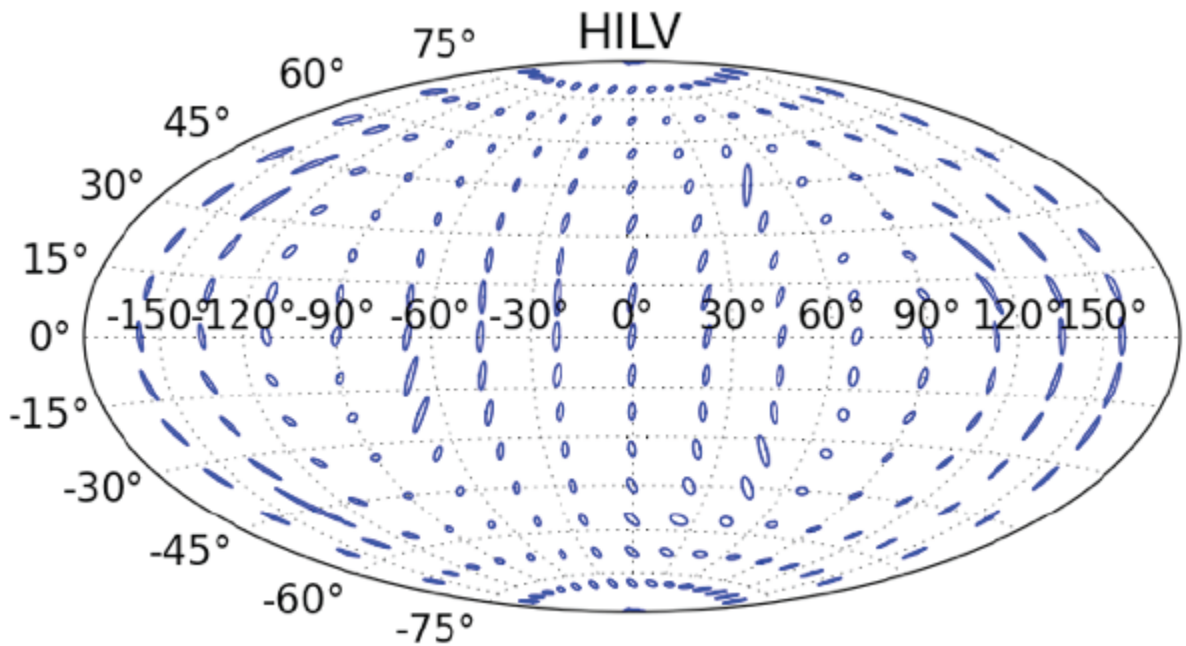


Fairhurst 2011

Red crosses denote regions where the network has blind spots

Localization capability:

- LIGO-Virgo plus LIGO-India



Fairhurst 2011

From LIGO-G1201135-v4

Data Analysis

- Burst gravitational waves
  - **Supernovae, binary merger phase, etc**
    Accurate waveforms unpredictable
    => Find signals with an "unusual" amplitude
    => Important to distinguish from **non-stationary noises**

- Continuous waves
  - **Pulsars**
    Sinusoidal signal with some modulations
    => Longterm integration
    => Important to distinguish from **line noises**
    (Remark: power line freq. US 60Hz, India 50Hz)

Data Analysis

- Stochastic gravitational wave background
  - **From early universe**
    The waveforms are random
    => Correlation analysis of the detector network
    => The total GW flux can be estimated
    => Or, skymap of the flux is obtained from radiometric analysis

- **In all cases, it is highly desirable to have the detectors to have comparable sensitivities**

Summary

- GWs ~ ripples of the spacetime
- **Not yet** directly detected
  ~ the effect is so small ($h<10^{-21}$)
- **Michelson**-type interferometers are used
- GW detection is a **precise** length (=displacement) measurement!
- GW effect is very small

Summary

- Basically, **the larger, the better.**
  LIGO has two largest interferometers
  in the world, and the **third one** will have
  very important role in GW astronomy

- **IFO consists of many components**
  Optics / Mechanics / Electronics
  and their combinations (e.g. Opto-Electronics)

- Noises and signals are, in principle,
  indistinguishable.
  Noise reduction is essential