Detection of Gravitational Waves: A New Window to the Universe

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Jul. 25th 2007 @ Nevis REU talk

LIGO-G070547-00-Z

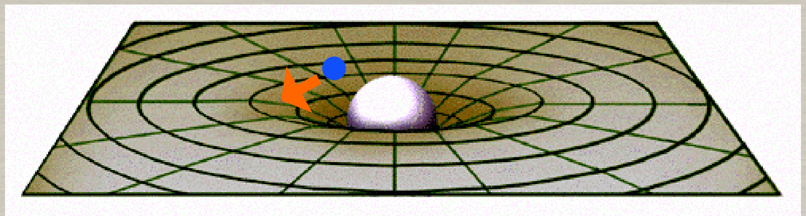
What is Gravitational Wave ?

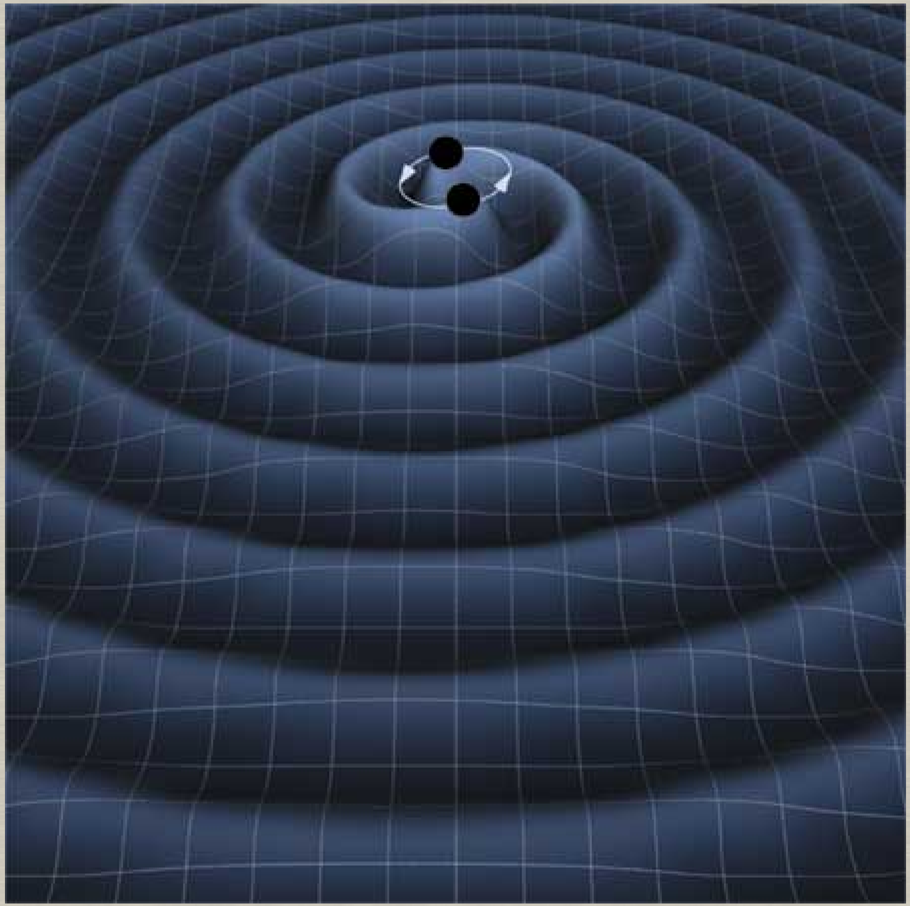
- Ripples of spacetime
- Propagate at the speed of light
- Generated by non-spherical motion of heavy masses

Perturbation of metric tensor $g_{\mu\nu}$

Einstein equation: $G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$

Theoretical prediction
1916 by A. Einstein

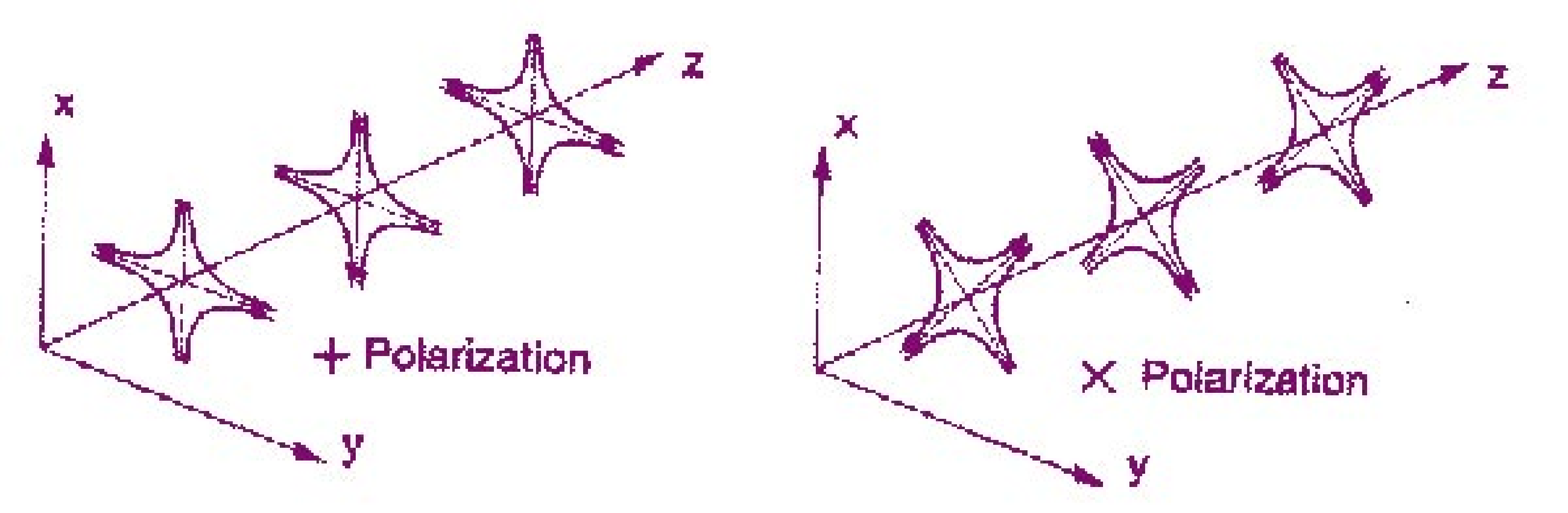




Properties of Gravitational Waves

Generation: Variation of quadruple moment of mass distribution

Two polarizations (spin=2)



Extremely weak interaction with matters

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Curvature

Mass/Energy (Source)

Coupling constant $\sim 10^{-43}$

No detection so far

Sources of Gravitational Waves

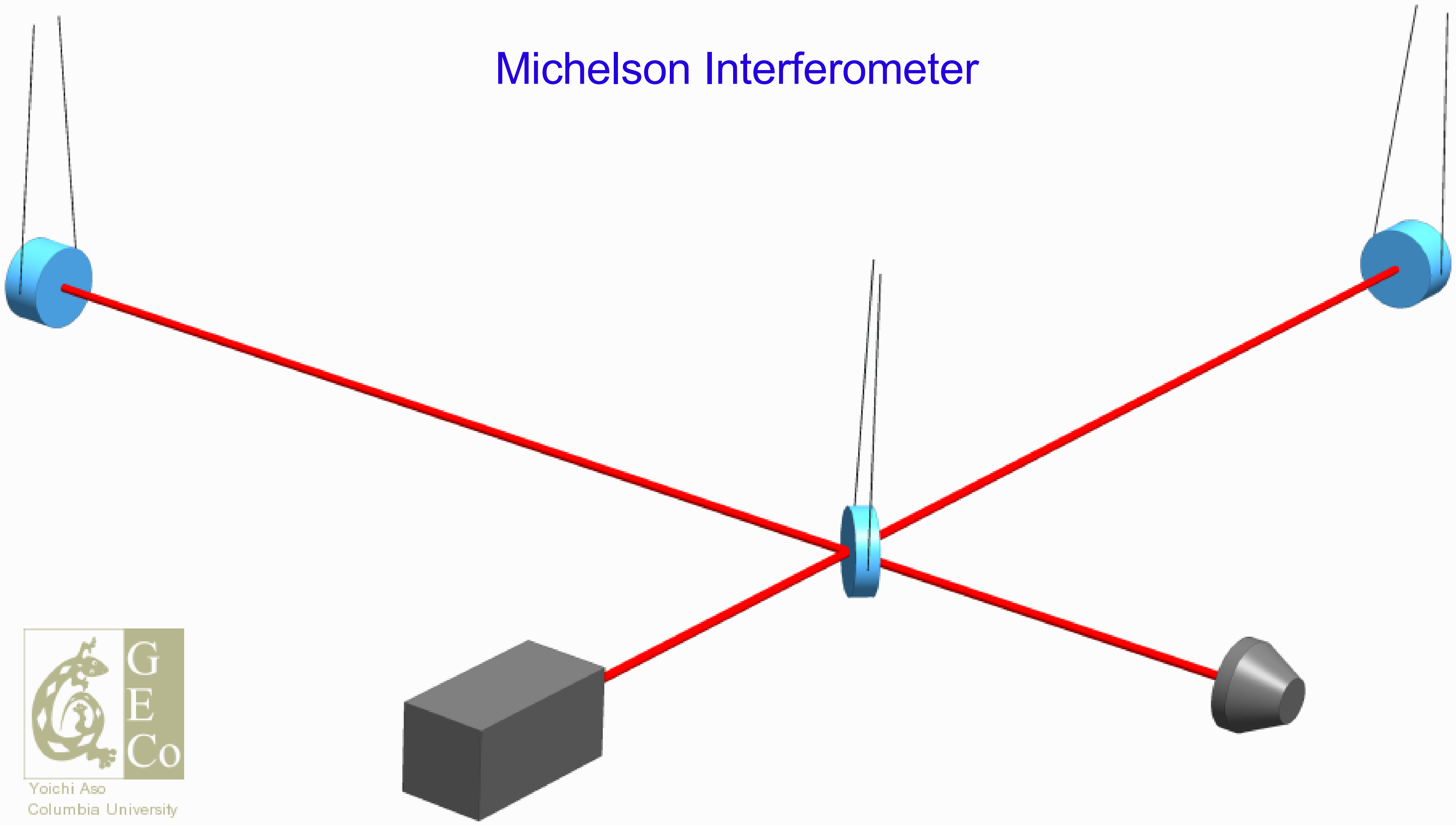
Detectable Gravitational Waves: Impossible to generate on the Earth

Violent Astronomical Events

- Coalescence of Binary Neutron stars / Black holes
- Black hole ringdown
- Super Novae
- Pulsars
- Stochastic Background GWs

How do we detect it ?

Michelson Interferometer



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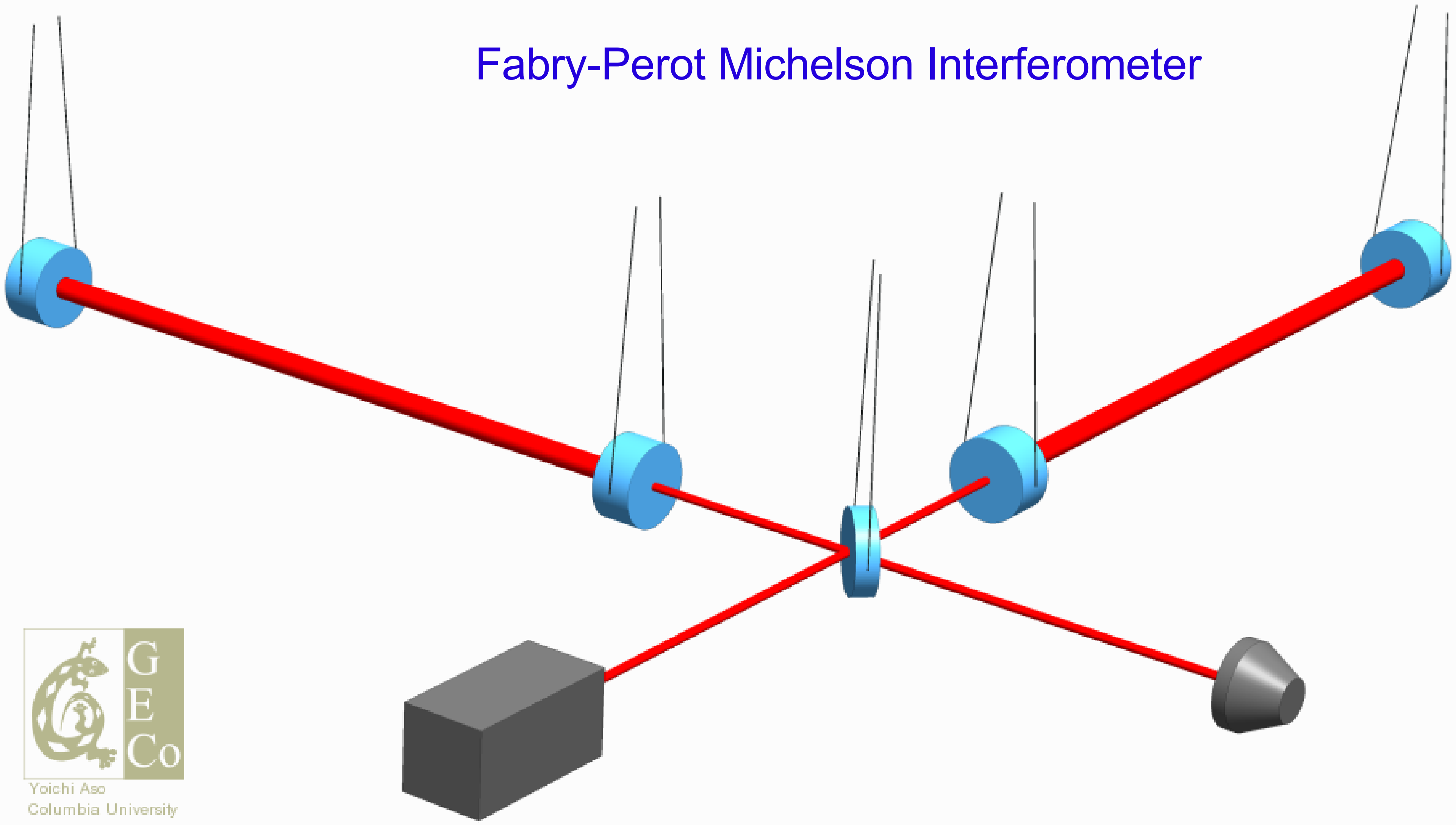
How do we detect it ?

Fabry-Perot Michelson Interferometer



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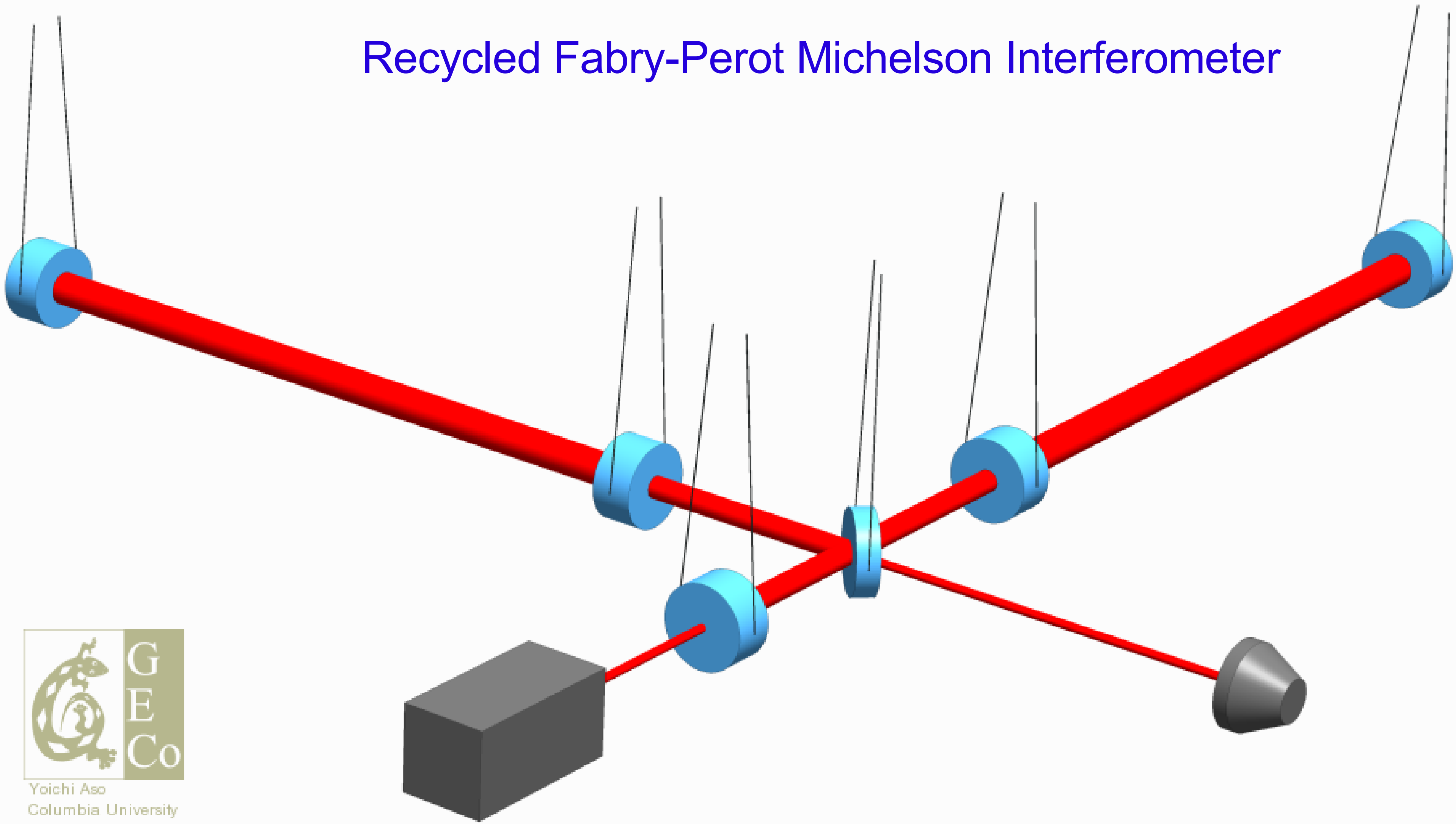
How do we detect it ?

Recycled Fabry-Perot Michelson Interferometer



GECo

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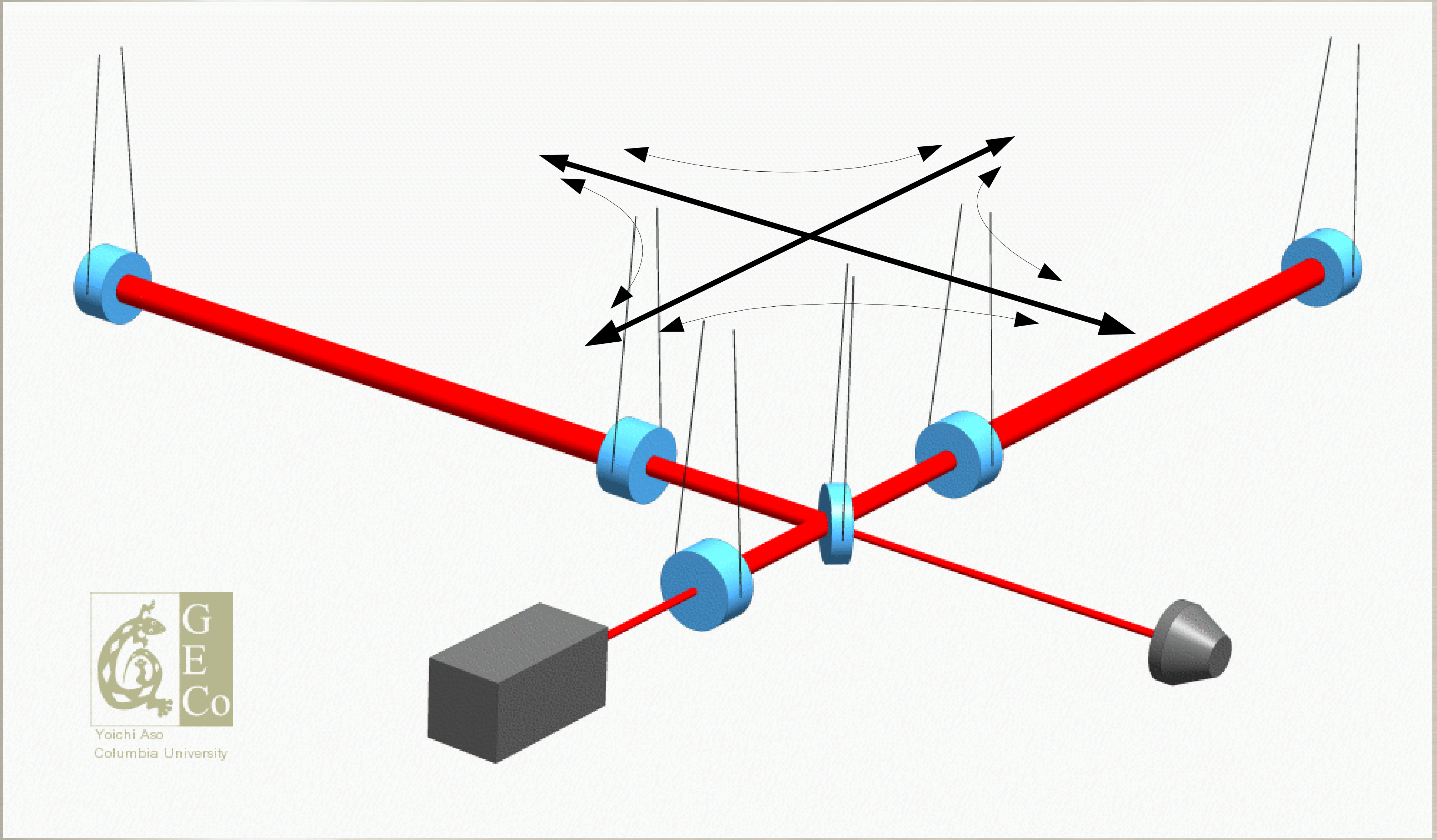
Columbia University

Differential change in the arm lengths

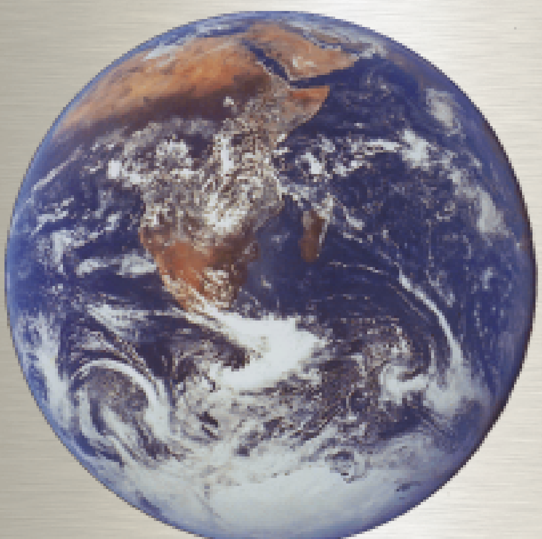


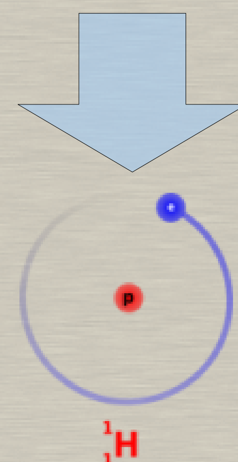
Effect of GW is extremely weak

Typical Event

1.4 $M_{\odot}$ NS- NS binary inspiral in Virgo cluster (15Mpc)

$$\longrightarrow h \sim 10^{-21}$$

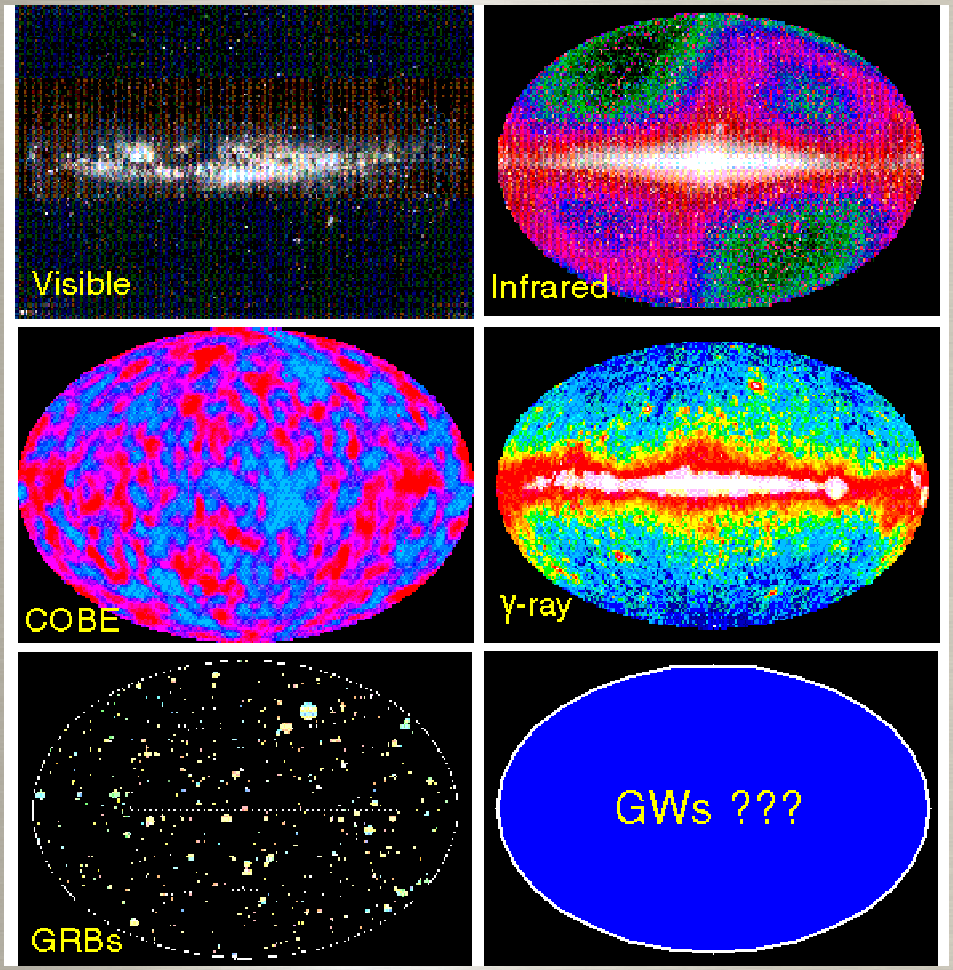




Change by the diameter of a hydrogen atom

Why do we bother to look for gravitational waves ?

A NEW WINDOW
ON THE UNIVERSE



Electro-Magnetic Wave Observations

New wavelength → Discoveries

Gravitational Waves: Totally New
(not even EMW)

EM	GW
Motion of charged particles	Coherent motion of huge masses
Wavelength < source size (imageable)	Wavelength > source size (no image)
Absorbed, scattered, by matter	Almost no absorption, scattering
10MHz and up	10kHz and down

Compact Binary Coalescences

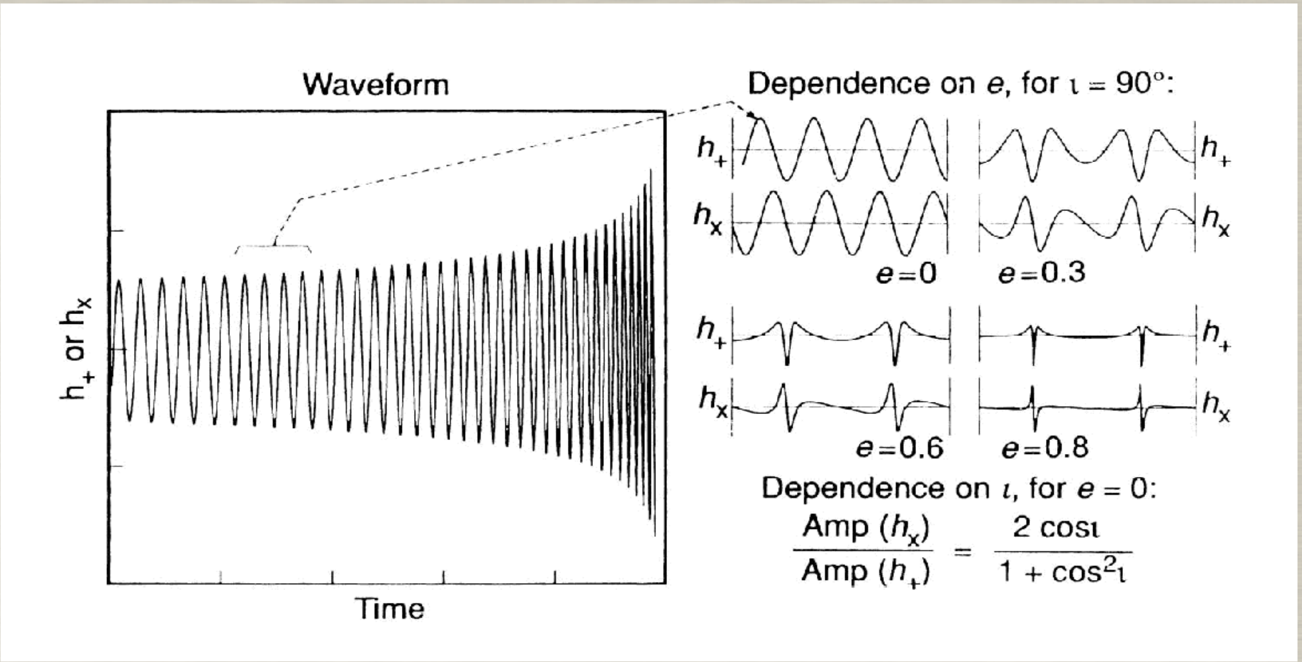
Neutron star – Neutron star, Black hole – Neutron star, Black hole – Black hole

Chirp signal

Inspiral Phase

Analytic template (Post-Newtonian expansion)

Matched filtering search

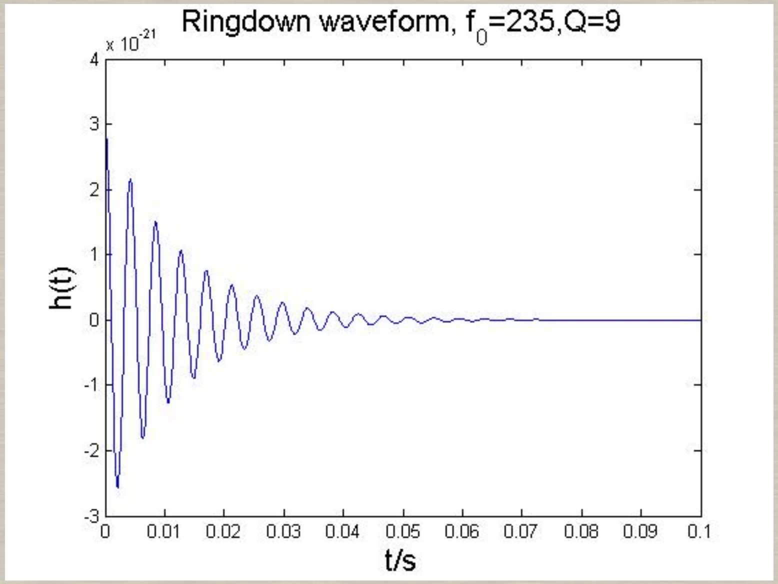


Merger Phase (Highly Relativistic): Numerical Simulations (Numerical Relativity)

Merger of 1.4-1.4 Solar Mass Binary Neutron Stars

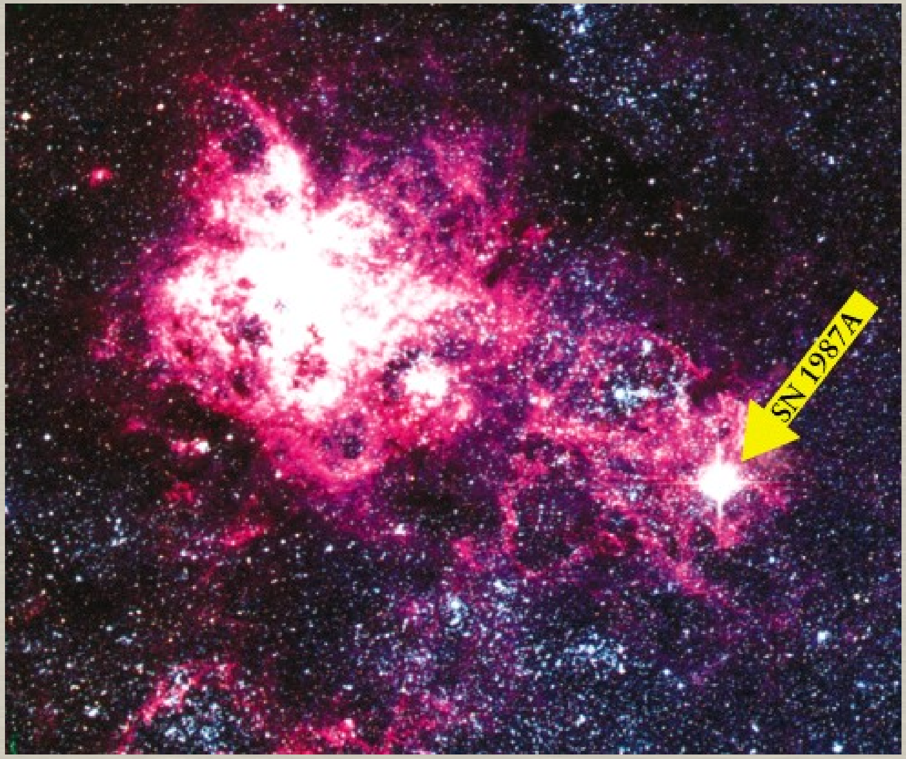
Simulation by M. Shibata (University of Tokyo)

Black hole ringdown



- Radiation from black hole perturbation
- Quasi-normal modes
- Determine: Spin, Mass

Supernova



- Non-axisymmetric core collapse
- Waveform not well modeled
- Optical/Neutrino coincidence

Pulsars

- Asymmetry in rapidly rotating neutron stars
- Continuous wave
- Improvement of SNR by integration
- Extract information of the equation of state

Crab pulsar

Stochastic background GW

Cosmological Sources

- Inflation
- Cosmic string
- Cosmic phase transition
- Reheating

GWs generated before CMB era
Information not available with photons

Detection strategy

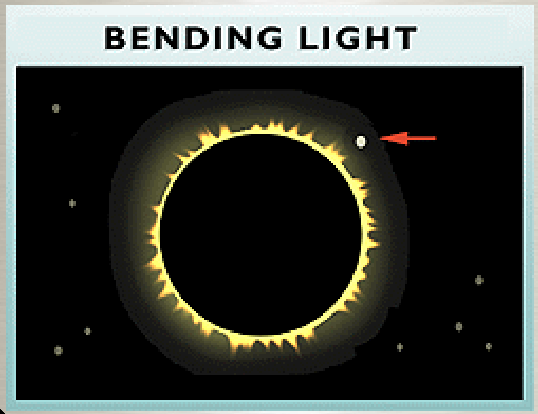
Correlation between multiple detectors

Einstein’s Theory of General Relativity

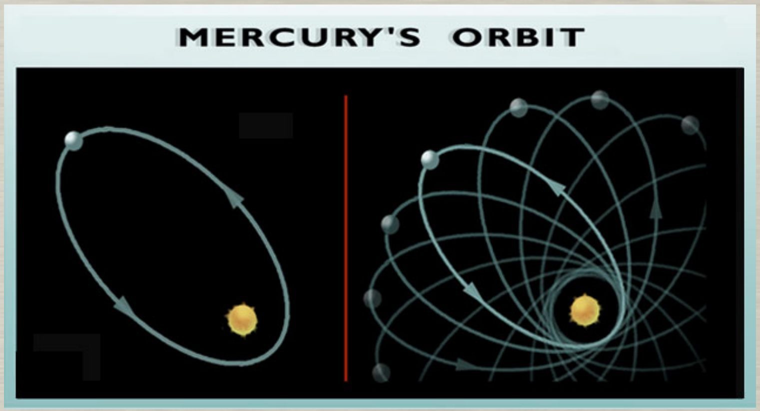
experimental tests

<u>All theories must be experimentally tested</u>

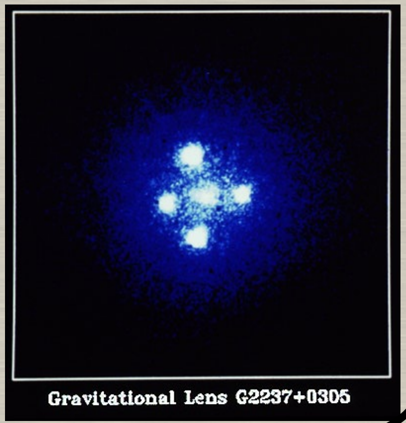
Sir Eddington's expedition



Perihelion precession



Gravitational lensing

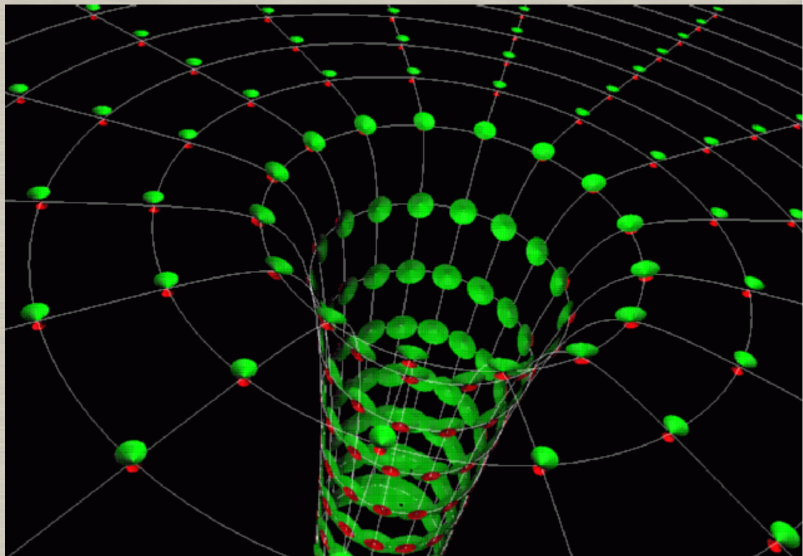


Test in the weak curvature

Gravitational Waves:
Generated in the strongly curved spacetime
e.g. in the vicinity of Black holes

Highly non-linear effect of GR becomes apparent

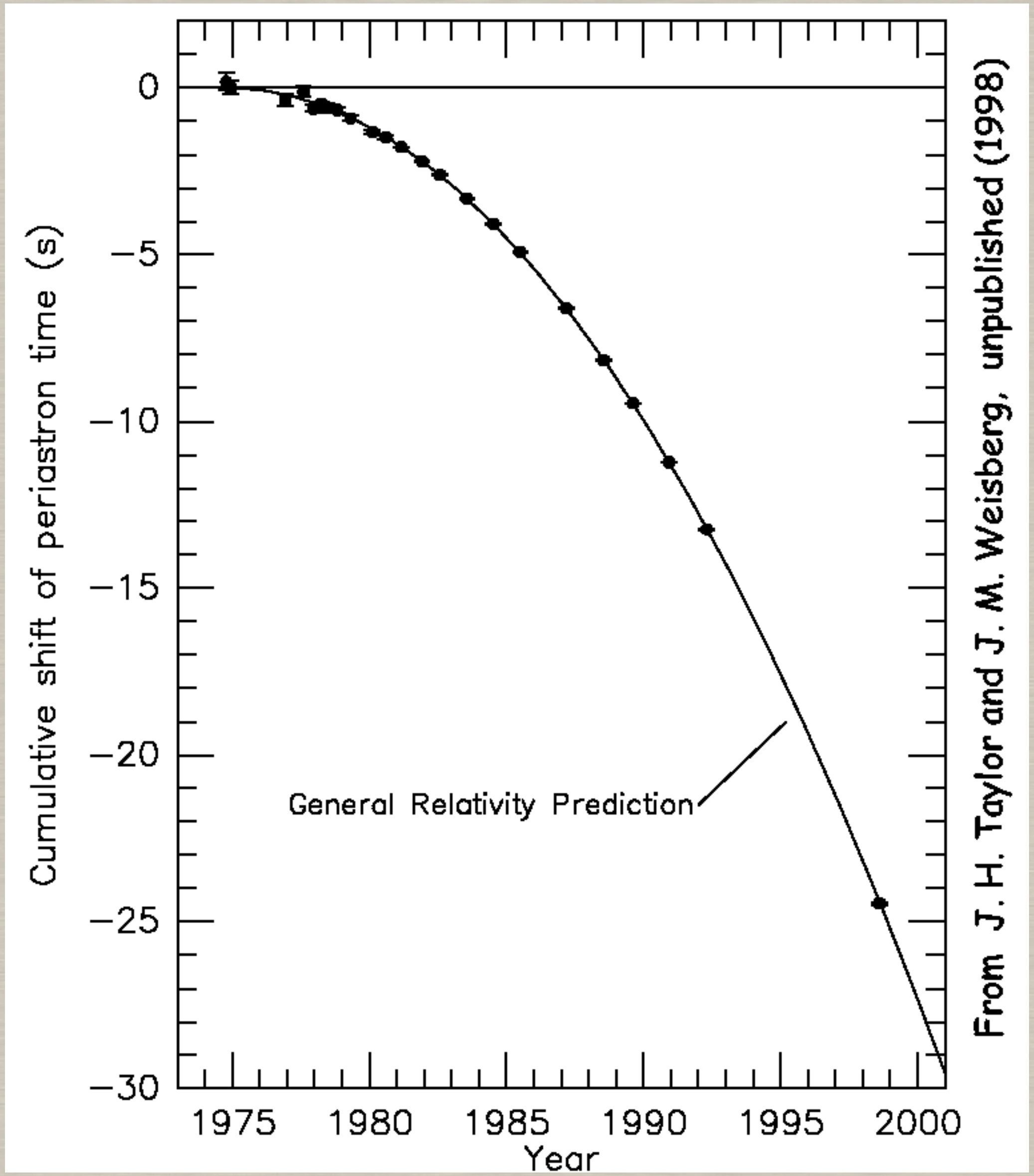
A good test of GR
Discrimination from alternative gravity theories



Indirect evidence of gravitational radiation

Hulse

Taylor



Radio pulsar B1913+16

Periodic modulation

→ Binary neutron star

GW emission

→ Orbital decay

Perfect matching with the GR prediction

Nobel Prize in Physics, 1993

Efforts for Gravitational Wave Detection

- First Attempt
  Joseph Weber in 1960's
  at University of Maryland

  Resonant Bar Detector
  Weber Event

Since then 19 bar detectors have been built in 8 countries

Transition

Resonant detectors ⟶ Interferometers

Robert L. Forward:
The first interferometric GW detector in 1970's

Several prototype interferometers around the world

Garching, Glasgow, Caltech, Tokyo ...

Global network of detectors

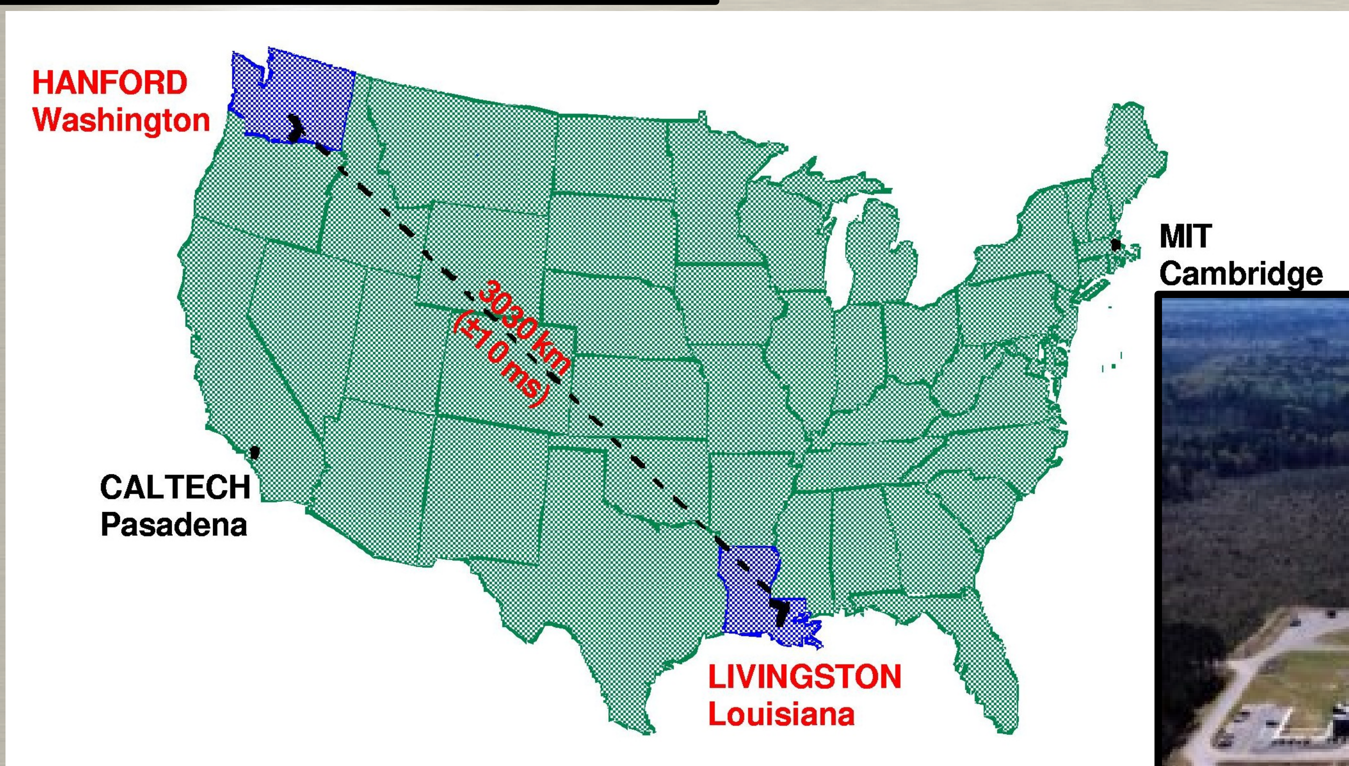
(interferometers)

Operating detectors: Yellow, Planned detectors: Blue

LIGO

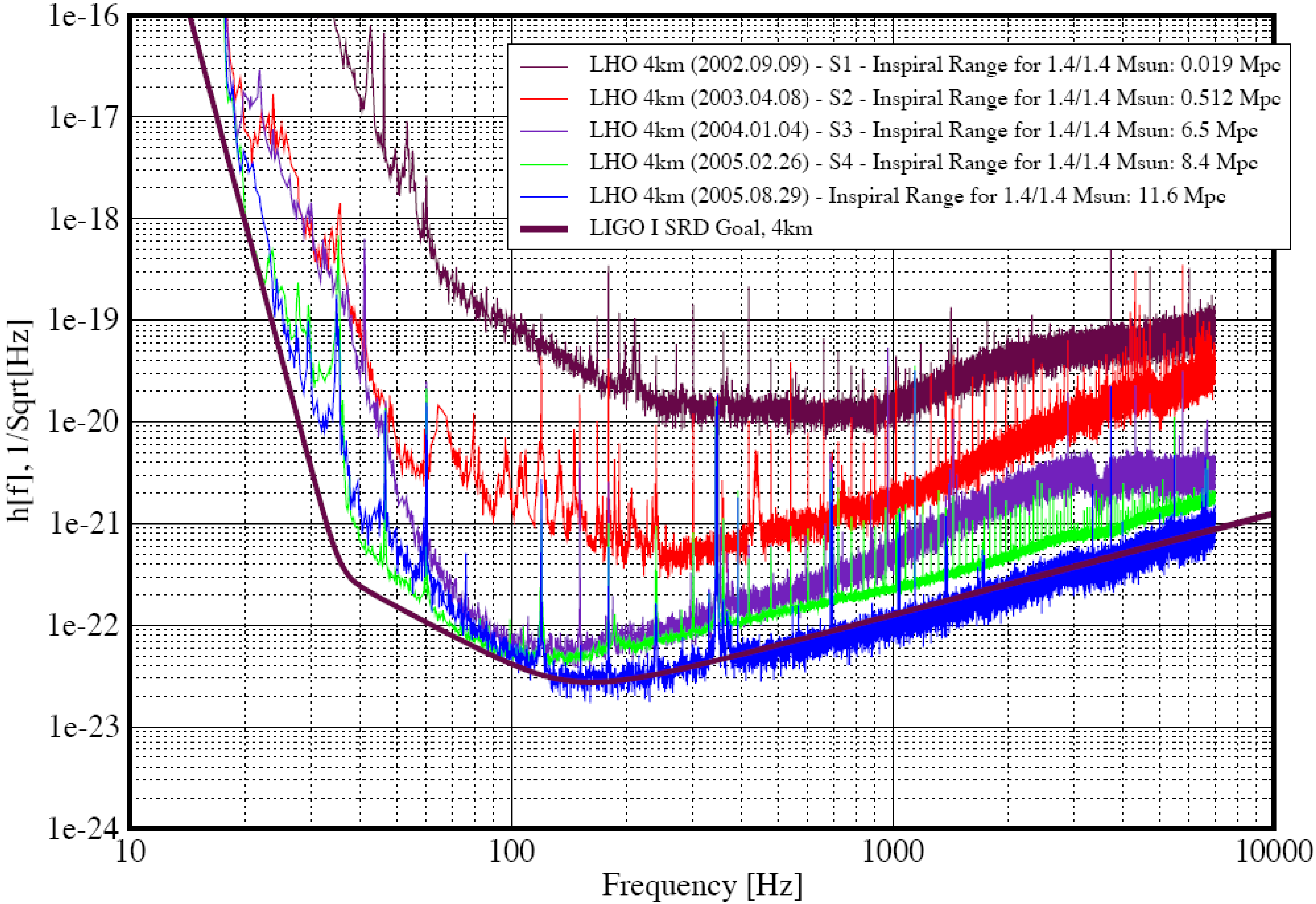
(Laser Interferometer Gravitational-wave Observatory)

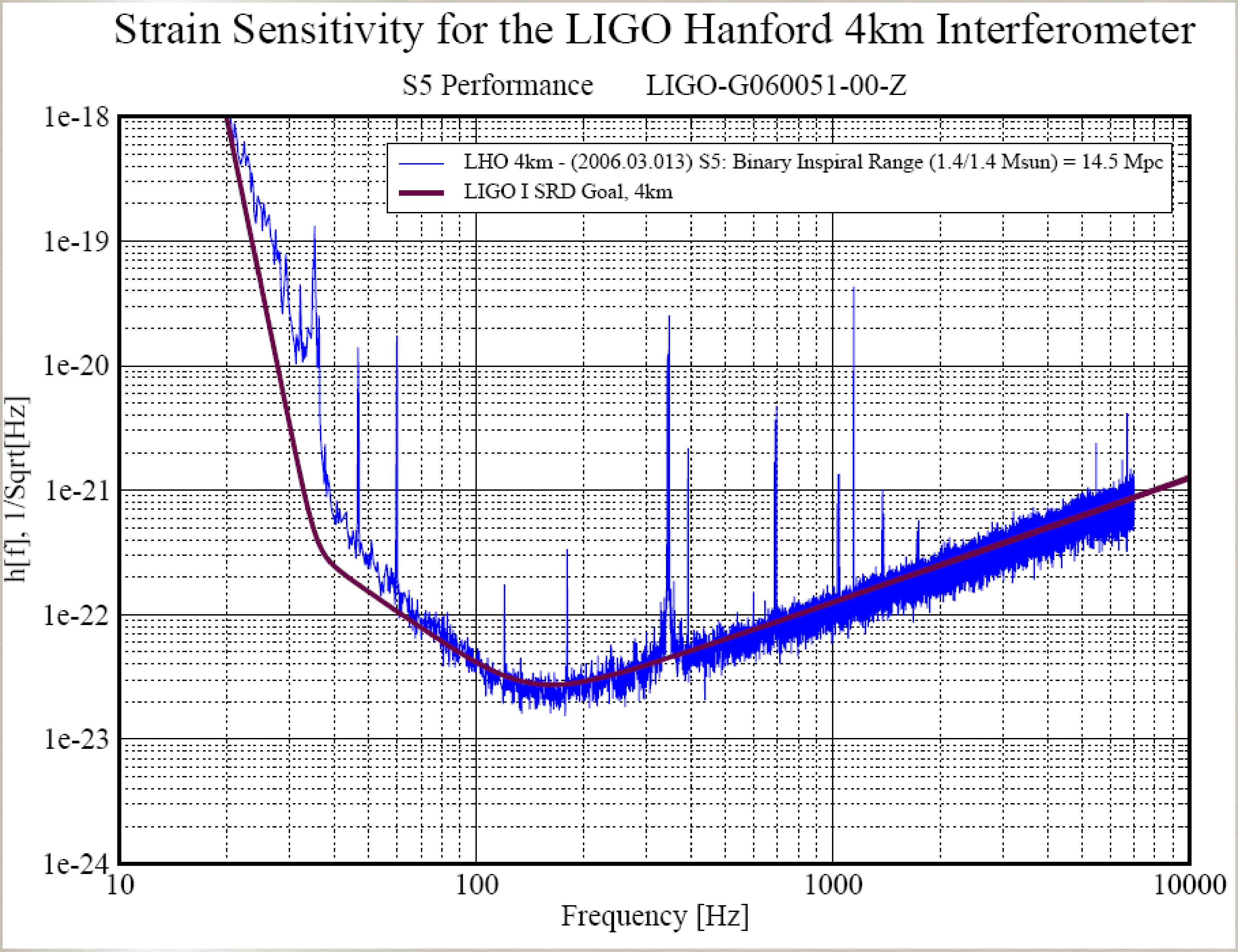
Hanford, Washington
4km and 2km interferometer
in the same vacuum system

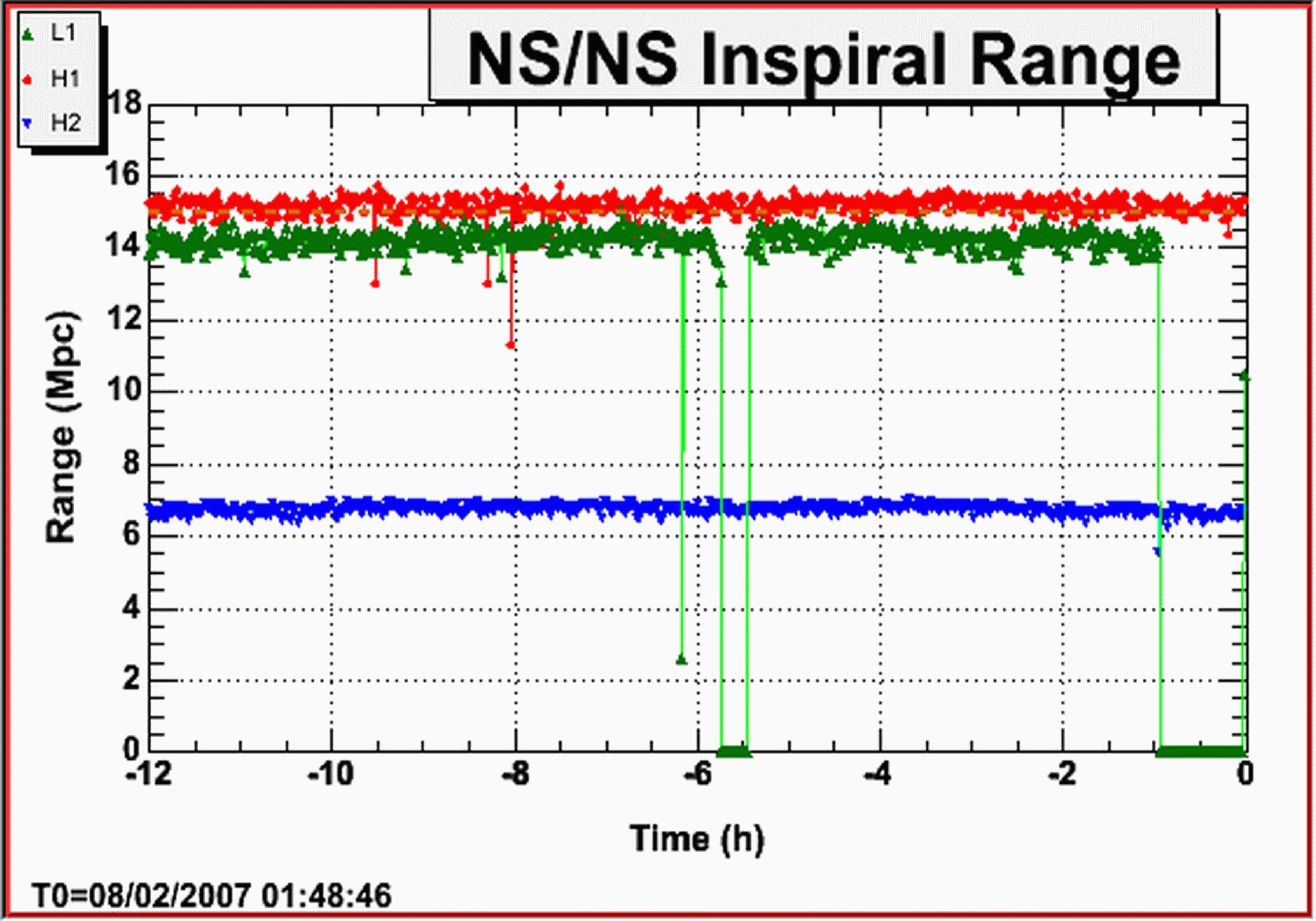


Livingston, Louisiana
4km interferometer

Noise History




Strain Sensitivity for the LIGO Hanford 4km Interferometer
S5 Performance LIGO-G060051-00-Z
LHO 4km - (2006.03.013) S5: Binary Inspiral Range (1.4/1.4 Msun) = 14.5 Mpc
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]


NS/NS Inspiral Range
L1
H1
H2
Range (Mpc)
18
16
14
12
10
8
6
4
2
0
-12
-10
-8
-6
-4
-2
0
Time (h)
T0=08/02/2007 01:48:46

GEO600

British-German Collaboration

600m Folded Michelson Interferometer with a Signal Recycling Mirror

Located near Hannover, Germany

Leibniz Universität Hannover

University of Birmingham

IGR

Universitat de les Illes Balears

Cardiff University

Virgo

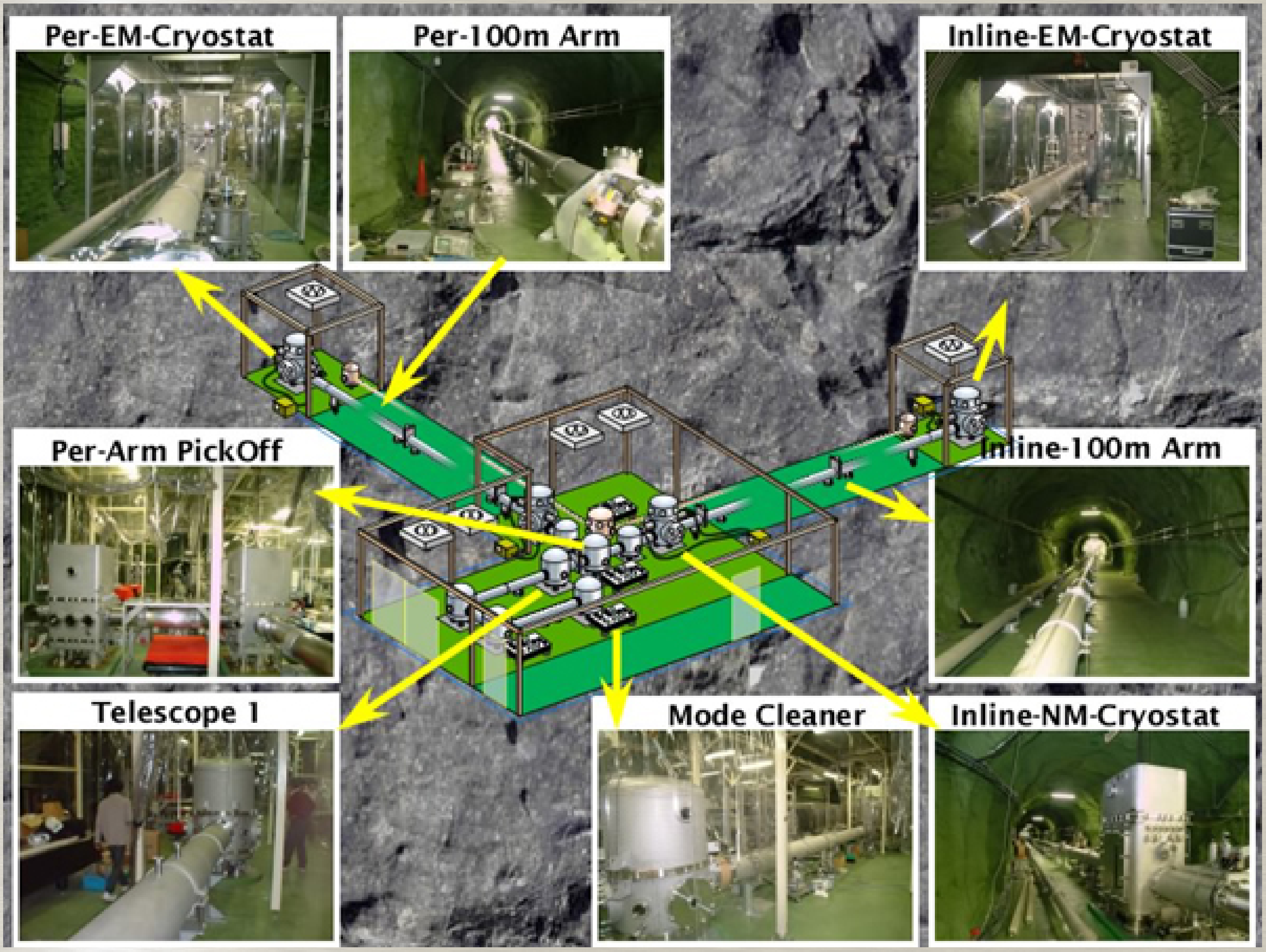
French-Italian Collaboration
3km Recycled Fabry-Perot Michelson interferometer
Located near Pisa, Italy

TAMA300

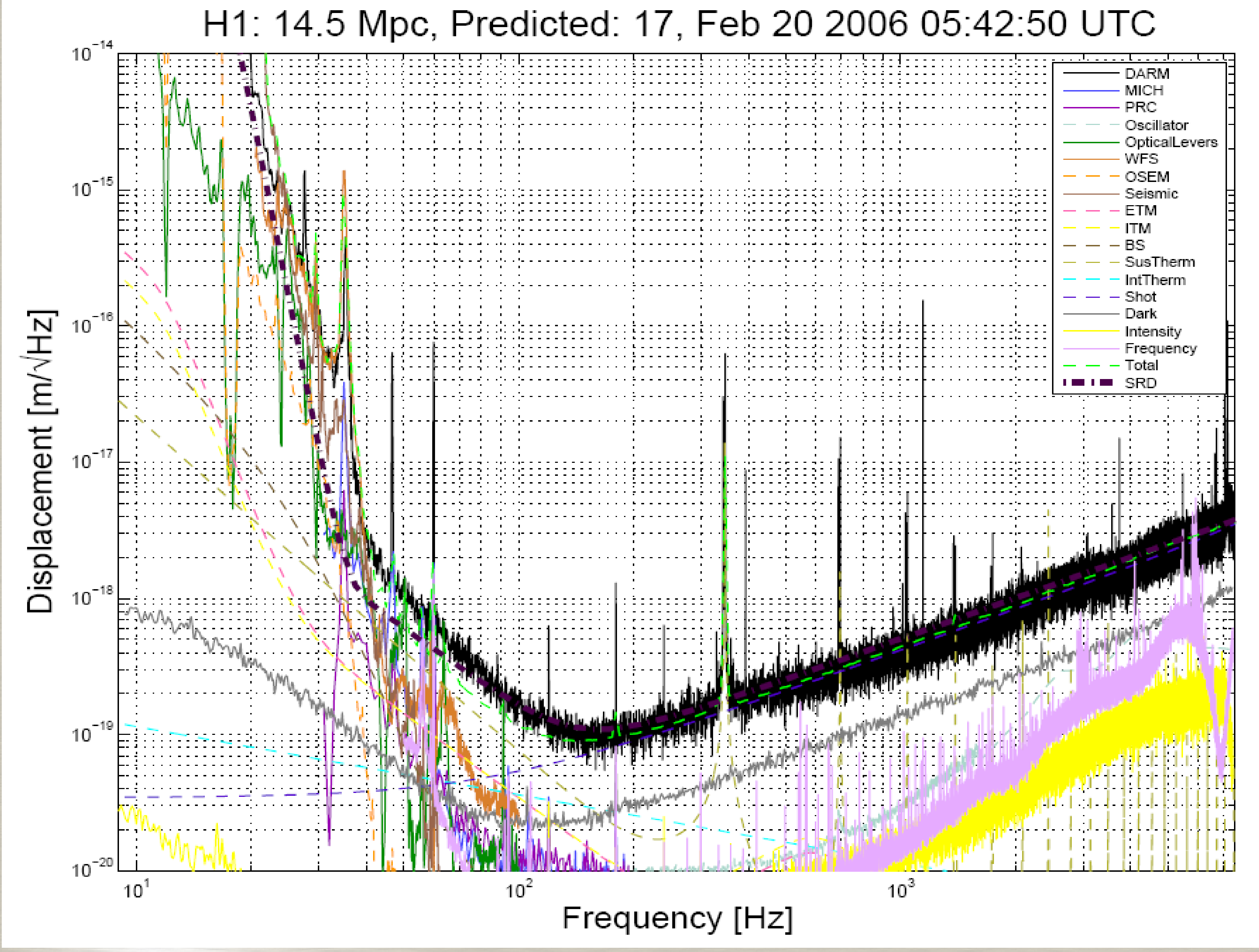
- Japanese project
- 300m Recycled Fabry-Perot Michelson interferometer
- The first large scale interferometer started operation
- Located at National Astronomical Observatory in Tokyo

CLIO

- Cryogenic prototype interferometer (100m)
- Located underground in Kamioka mine (near SK)
- Comparable sensitivity with LIGO around 20Hz



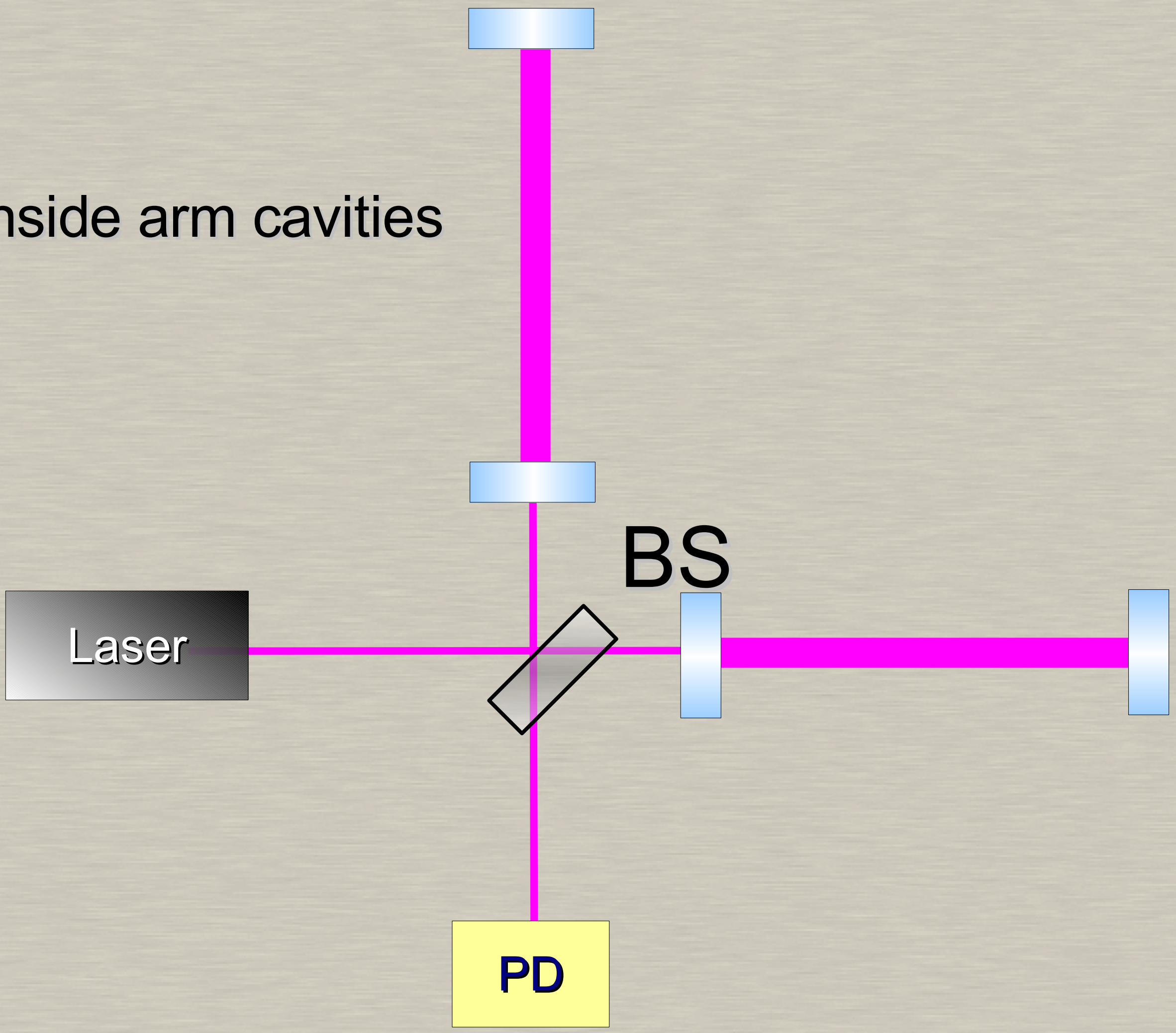
Technical Challenges of Interferometers



Interferometer Scheme

Fabry-Perot Michelson Interferometer

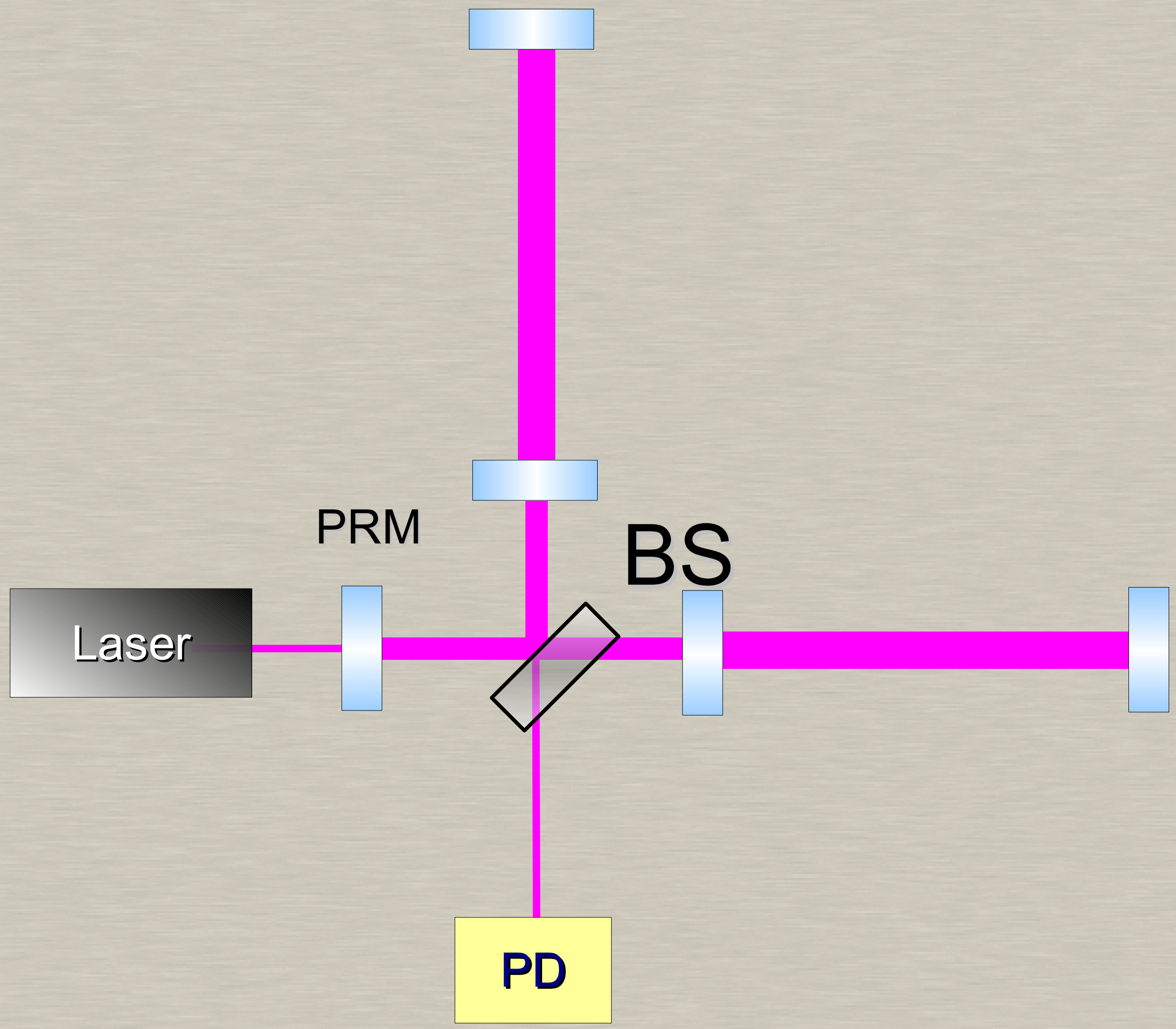
- Multiple bounce of photons inside arm cavities
- Signal enhancement



Interferometer Scheme

Power Recycling

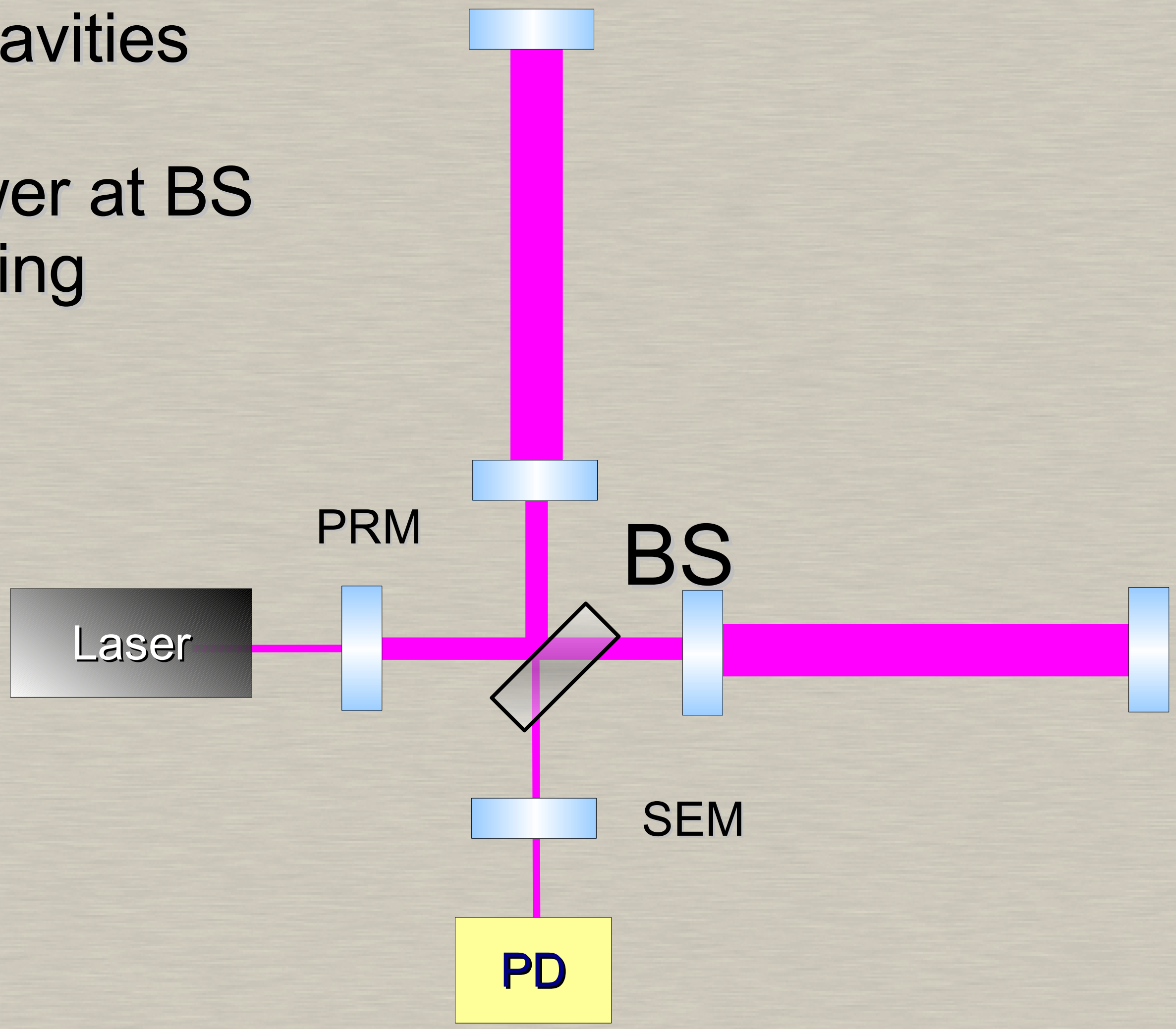
Higher laser power
Smaller shot noise



Interferometer Scheme

Resonant Sideband Extraction

Higher finesse arm cavities
Retain bandwidth
Reduce the light power at BS
Smaller thermal lensing



Control System

5 degrees of freedom to control
with extremely high precision

$L+=(Lx+Ly)/2$

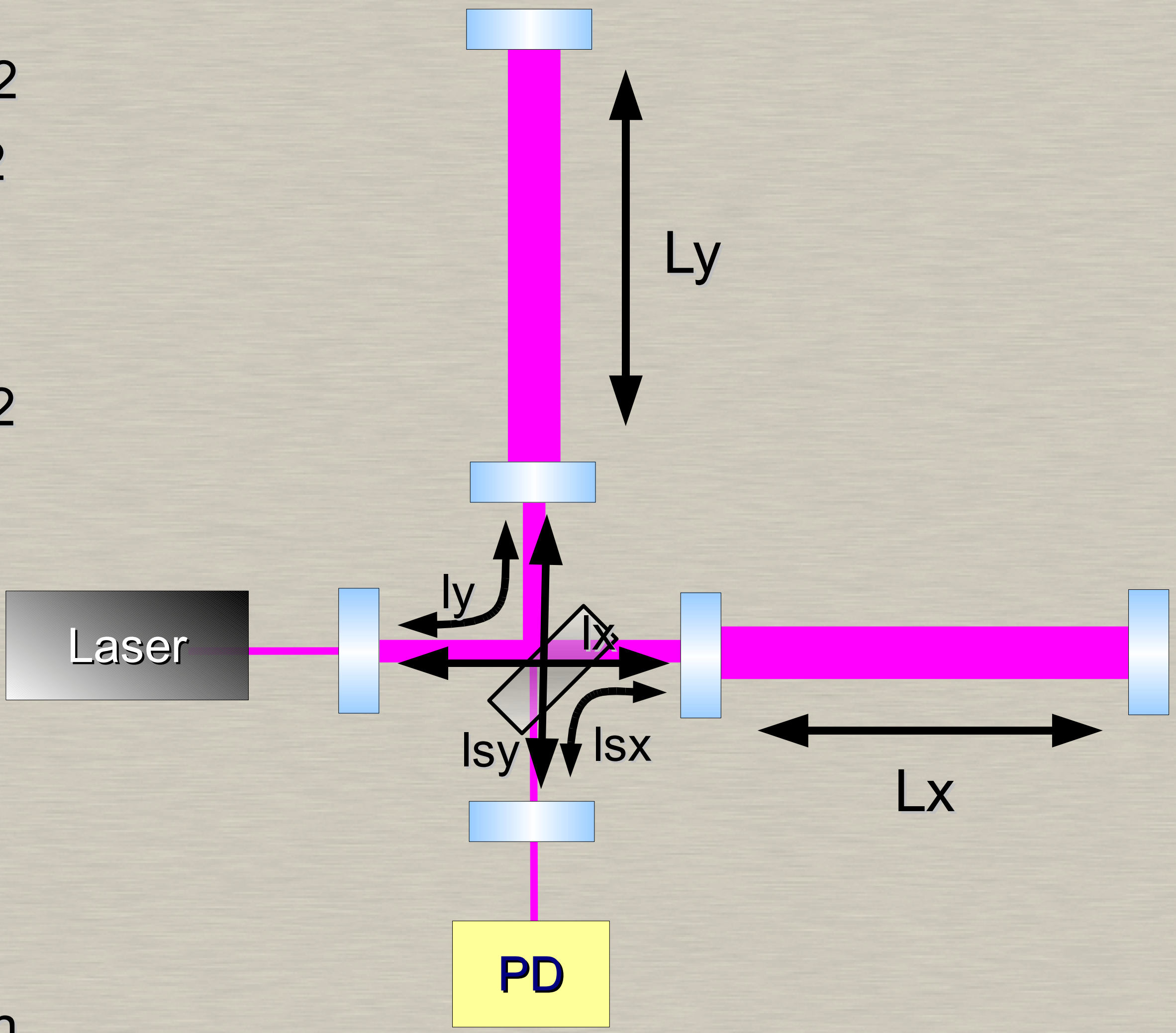
$L- =(Lx-Ly)/2$

$l+=(lx+ly)/2$

$l-=(lx-ly)/2$

$ls=(lsx+lsy)/2$

Complicated MIMO system



Signal Extraction schemes

RF phase/amplitude modulation

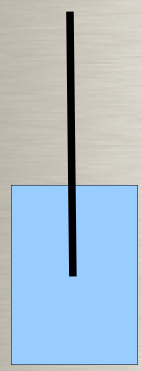
Demodulation at various ports/harmonics/quadratures

Suspension System

•Seismic vibration ~ 1 micro meter

•Isolate mirrors from ground

•Above pendulum resonant frequency
Mirrors ⟶ Free Mass



Simple pendulum
Vibration isolator above its
resonant frequency

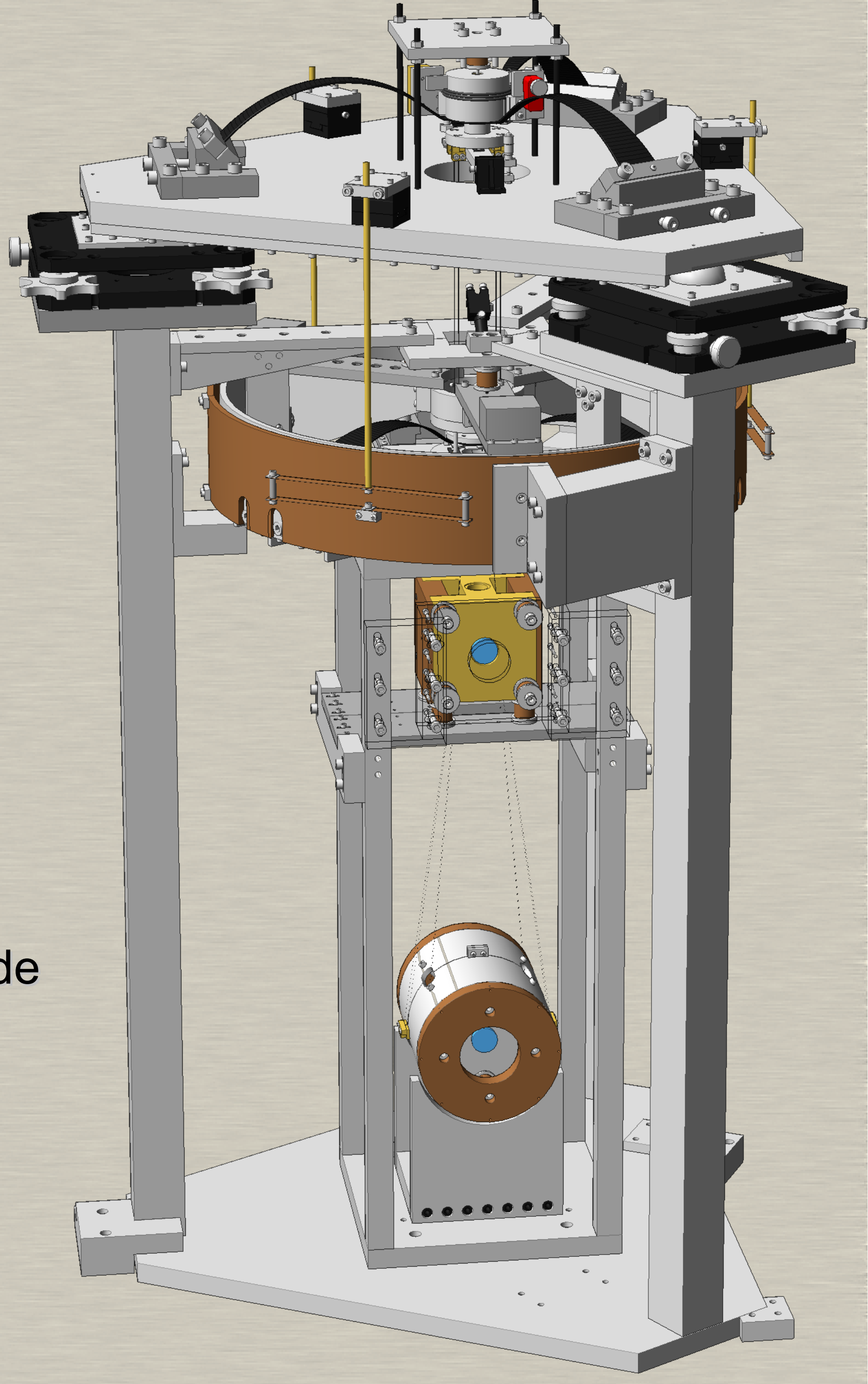
Required attenuation ~ 10 orders of magnitude

Multiple pendulums

Low-frequency vertical springs

Active / Passive damping

Actuators for controlling mirrors



Thermal Noise

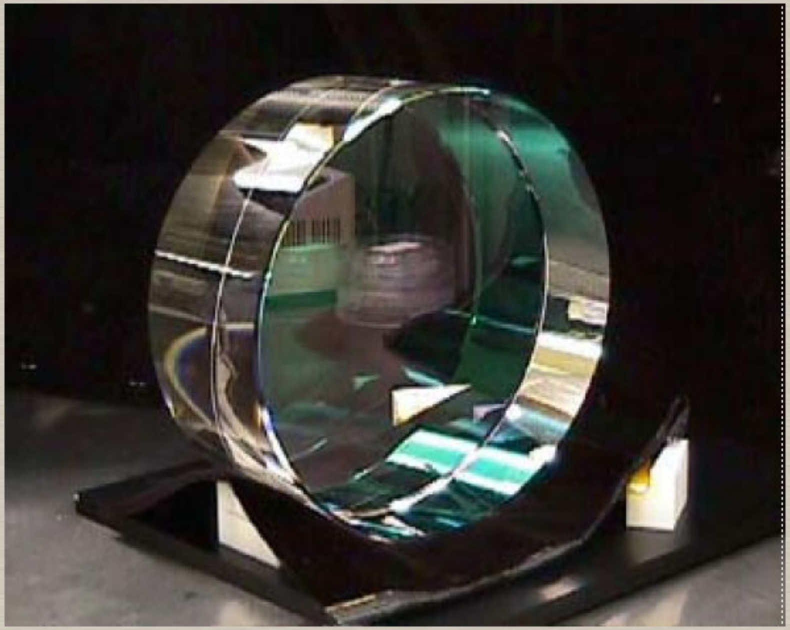
Thermal vibration of the molecules of mirror / suspension material

Fluctuation Dissipation Theorem

Mechanical loss ⟷ Connection to the heat bath ⟶ Thermal fluctuation

High quality mirror substrate / coating materials
(not only optically)

Fused silica mirror



Low mechanical loss suspension fibers
Fused silica fibers with silica bonding

Go to Cryogenic

- LCGT cooled down to 20K
- Sapphire mirrors / fibers
- Ultra low mechanical loss at low temperature

Laser

Shot Noise: Photon number fluctuation

Larger laser power → Less significant

Requirements

- High power (over 100W)
- Ultra stable in amplitude and frequency
- Good mode shape (TEM00 Gaussian beam)

- MOPA
- Injection Locked laser
- Coherent addition
- Fiber amplifier
- etc...

LIGO Pre-Stabilized Laser

Beating the Standard Quantum Limit

Heisenberg's uncertainty principle

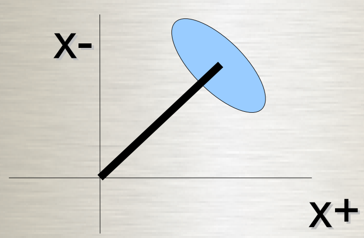
$$\Delta x \Delta p \geq \hbar/2$$

Measurement uncertainty = Shot Noise
Measurement back action = Radiation Pressure

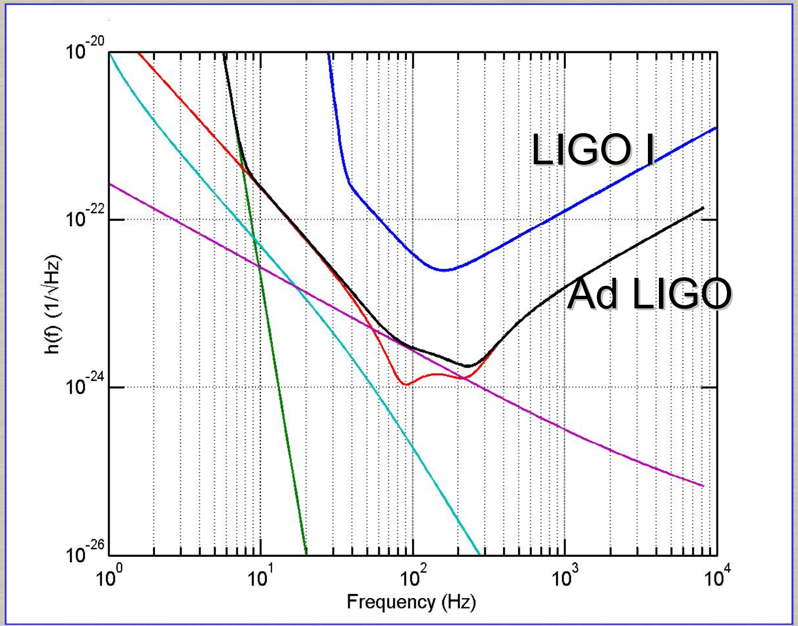
Free mass SQL $$h_{\mathrm{SQL}} = \frac{1}{L\omega}\sqrt{\frac{8\hbar}{m}}$$

Quantum Non-Demolition Measurement

Squeezed light: non-classical state of light



One quadrature is less fluctuating than the other



- Squeezed vacuum injection
- Ponderomotive squeezing

Future Detectors

Enhanced & Advanced LIGO

Enhanced LIGO

- Some upgrades to Initial LIGO before going to Advanced LIGO
- Upgrade work start from this fall for 2 years
- factor of 2 improvement in sensitivity

Advanced LIGO

- Take advantage of new technologies and on-going R&D
  - Active anti-seismic system operating to lower frequencies
  - Lower thermal noise suspensions and optics
  - Higher laser power
  - More sensitive and more flexible optical configuration

x10 better amplitude sensitivity

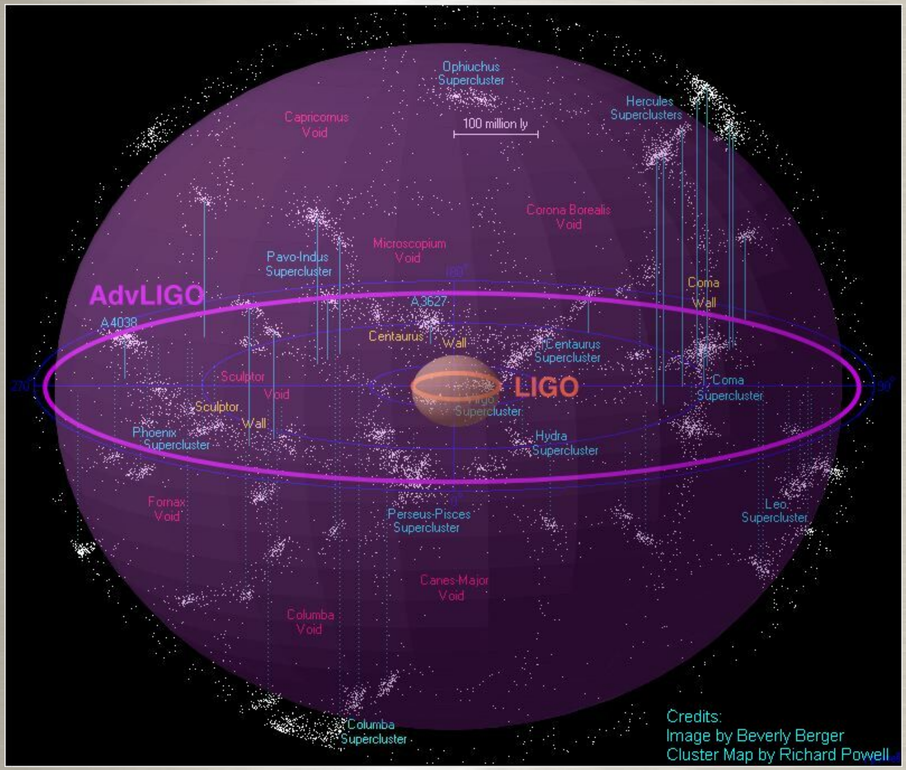
x1000 rate=(reach)^3

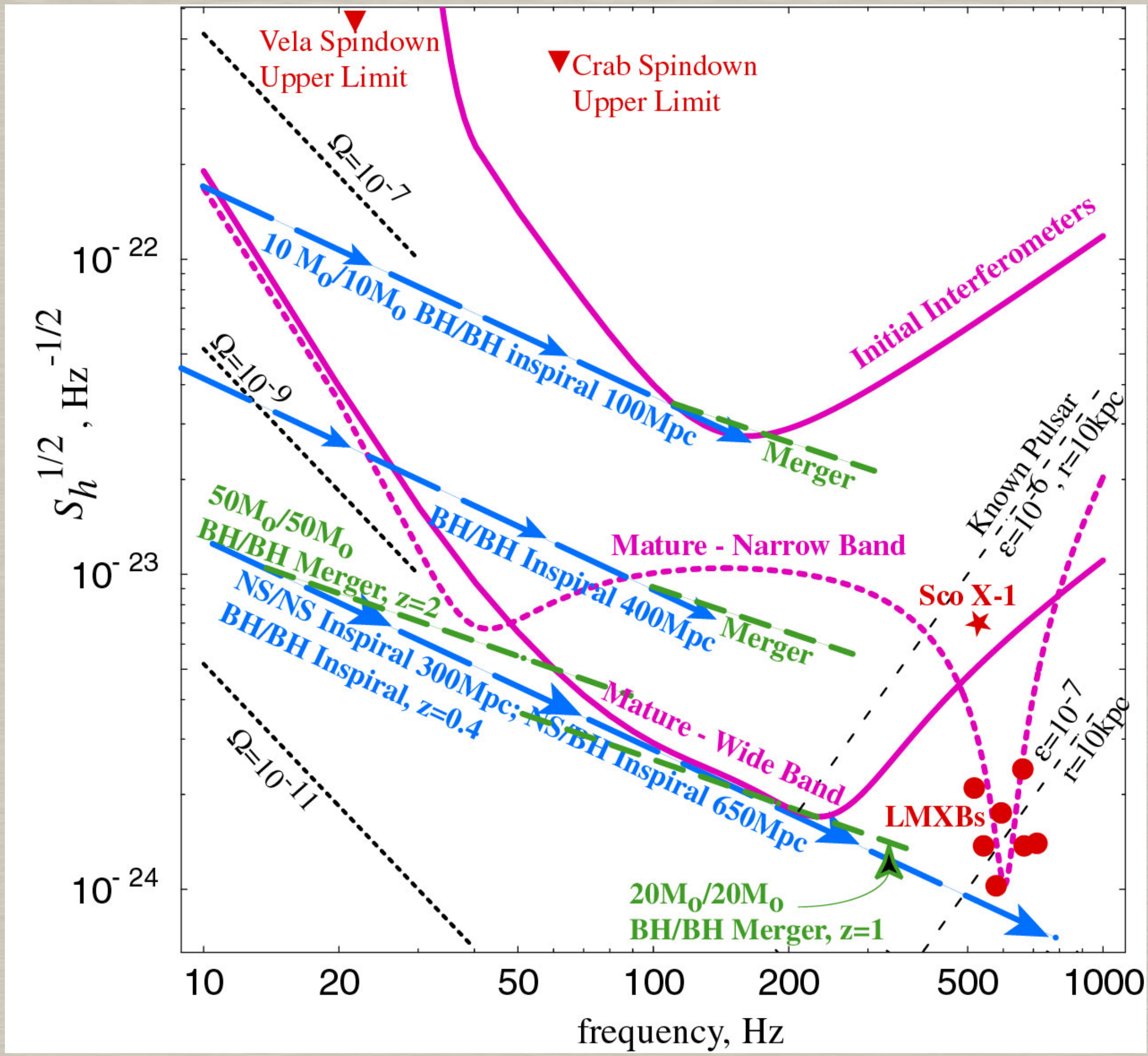
1 day of Advanced LIGO

» 1 year of Initial LIGO !

Planned for FY2008 start,
Installation beginning 2011

Advanced LIGO Sensitivity and Sources



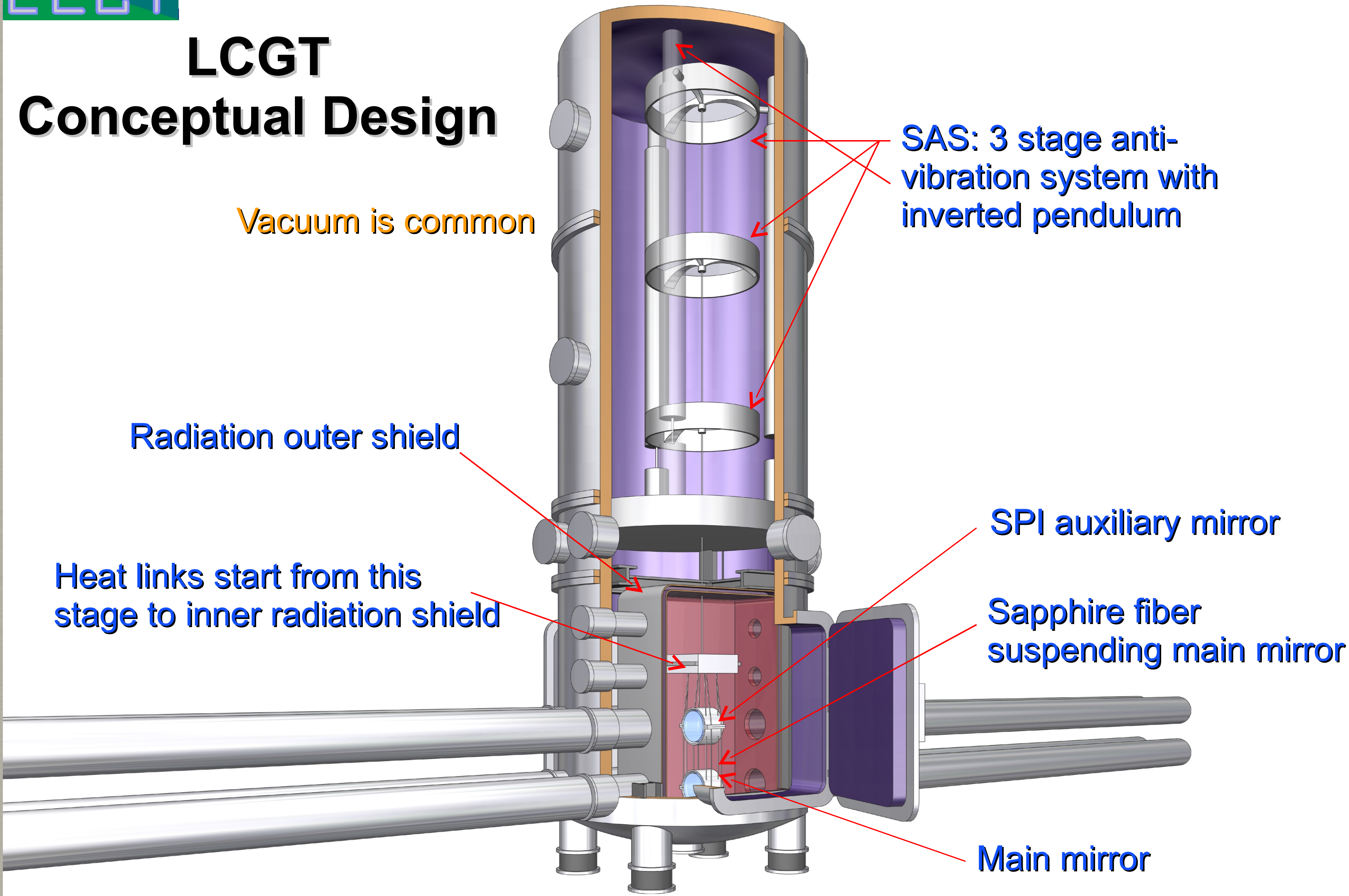


LCGT

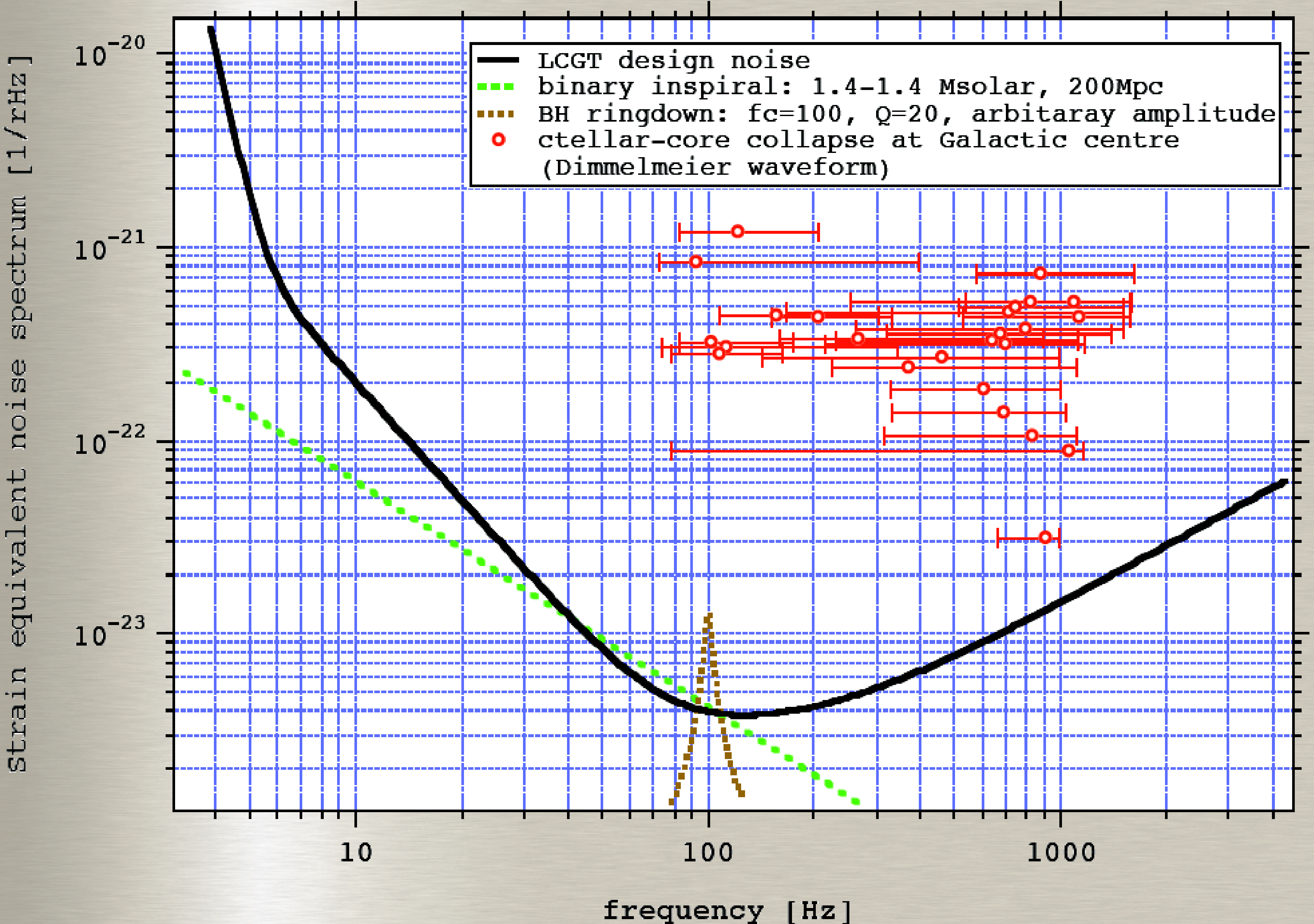
(Large-scale Cryogenic Gravitational wave Telescope)

- Japanese next-generation interferometer project
- Cryogenic mirrors for thermal noise reduction
- 3km arm length
- Underground location (smaller seismic activity)

LCGT
Conceptual Design

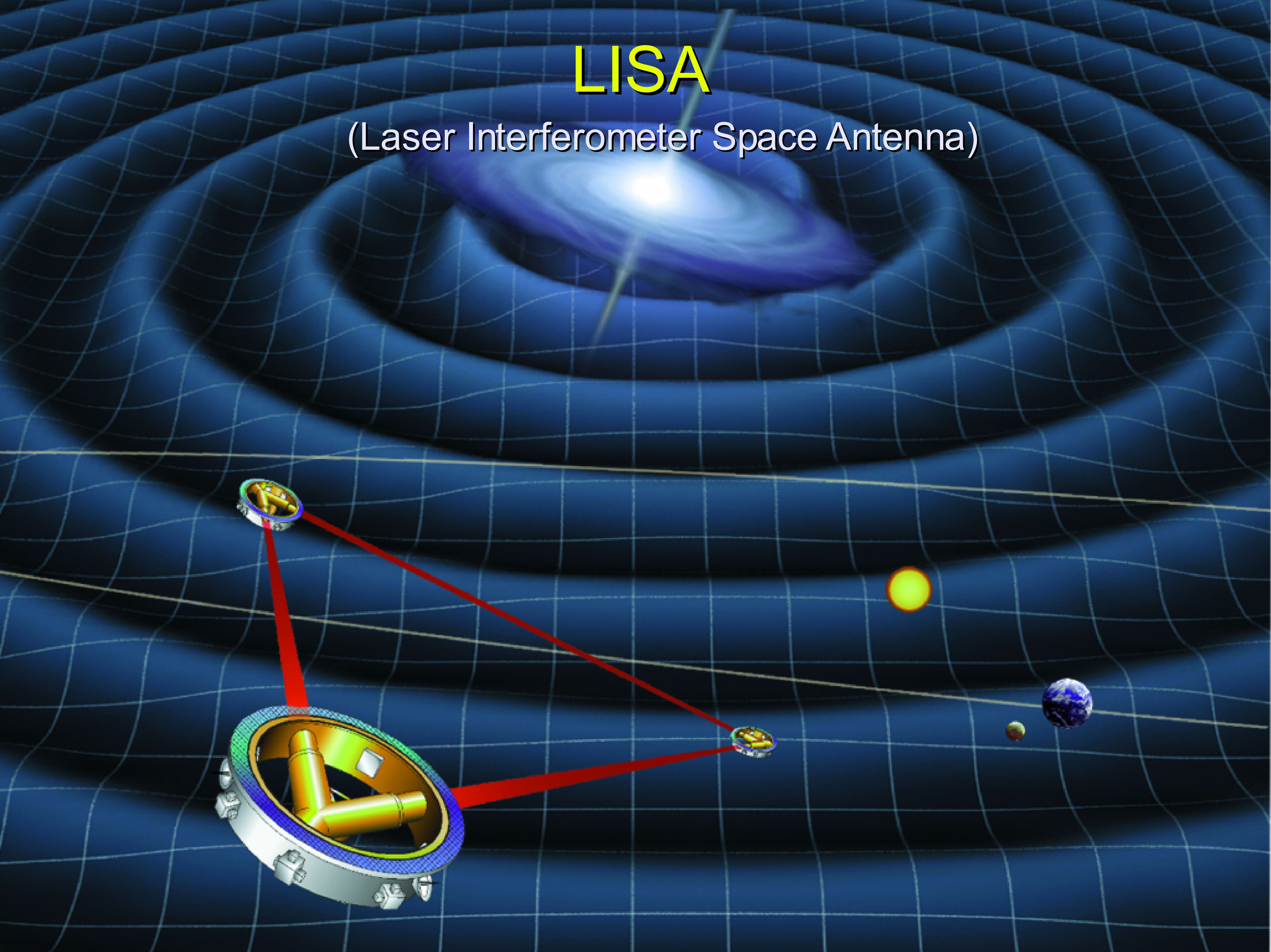


LCGT design sensitivity



AIGO

• Australian Project
• First interferometer in the southern hemisphere
• The site located in Gingin near Perth
• Currently used as a high power optics test facility


LISA
(Laser Interferometer Space Antenna)

•Space Interferometer

•Three space crafts

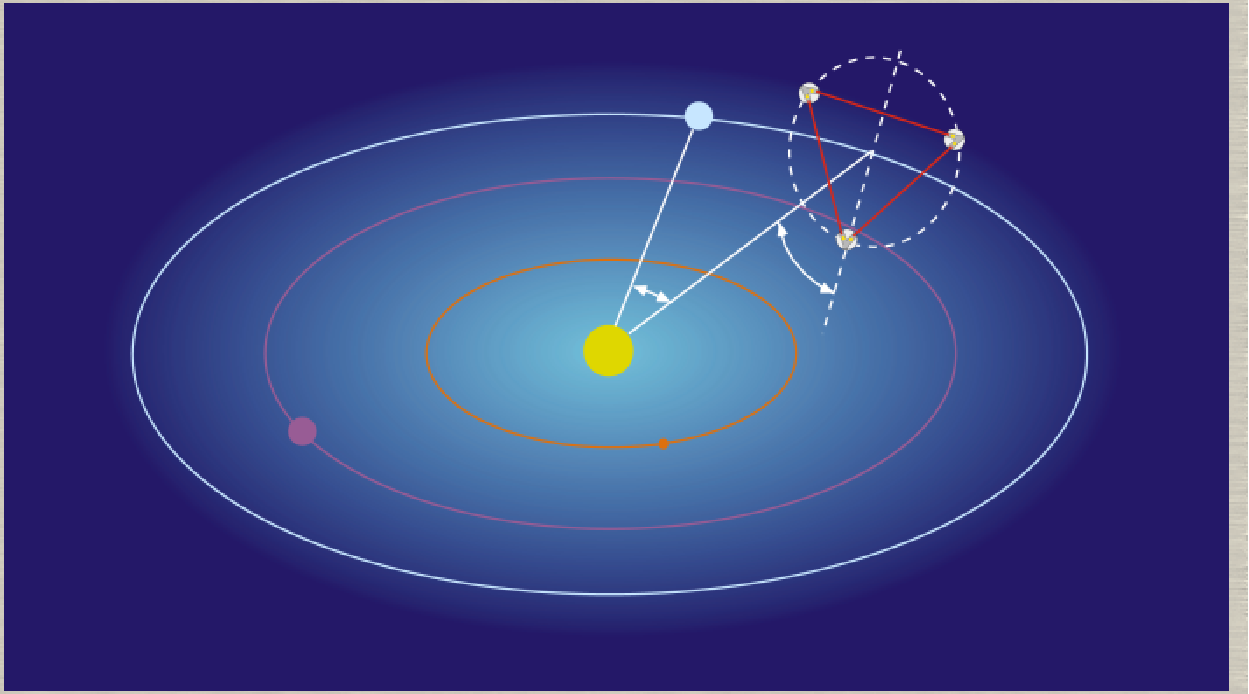
•5 million km arm length

•Ultra-low frequency GWs
(1mHz – 10mHz)

• ESA & NASA

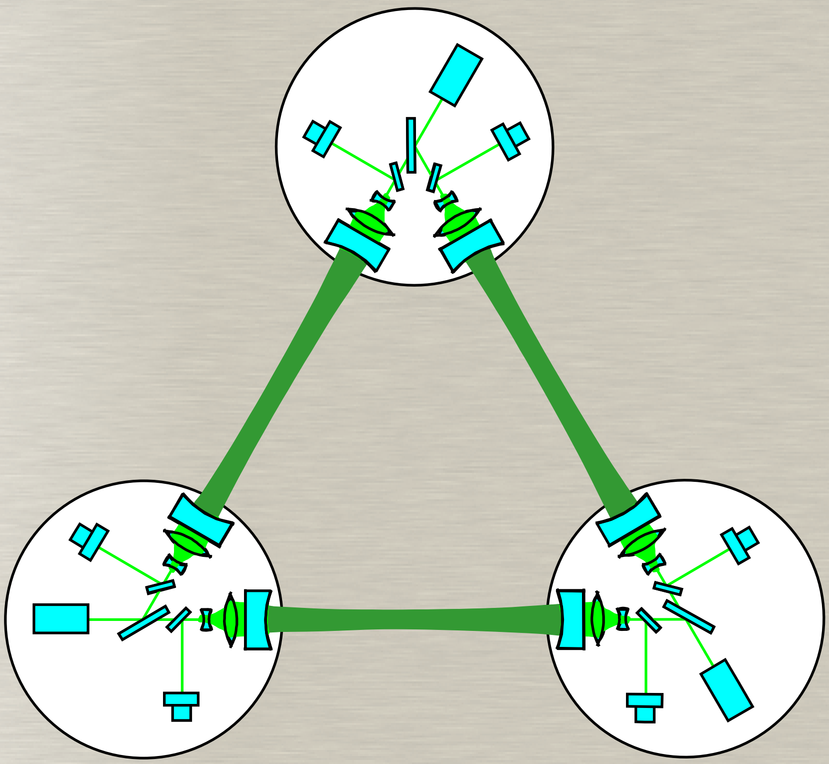
Targets

Galactic Binaries
Collision of massive black holes
Compact objects falling into black holes
Stochastic background GWs



DECIGO

- Japanese space interferometer project
- 10000 km Fabry-Perot arms
- Fill the gap between LISA and the ground interferometers
- (100mHz region)



Conclusion

Gravitational Waves: Open a unique new window to the universe

Information unavailable with electro-magnetic waves
Neutron star EOS, Black hole spin, metric etc ...

→ New Astrophysics !!

Gravitational Wave Detectors

Several detectors in operation around the world

LIGO will soon finish a long science run

Maybe detection ?

Next Generation Detectors

Enhanced LIGO,   Advanced LIGO
LCGT
Space interferometer   LISA

Stay tuned !!