LIGO's Hunt for Gravitational Waves

Yoichi Aso for the LIGO Scientific Collaboration
Columbia University, Experimental Gravity Group
Nov. 9th 2007 @ Columbia Graduate Student Seminar

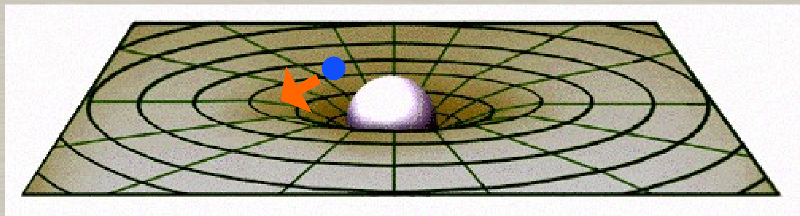
LIGO-G070785-00-Z

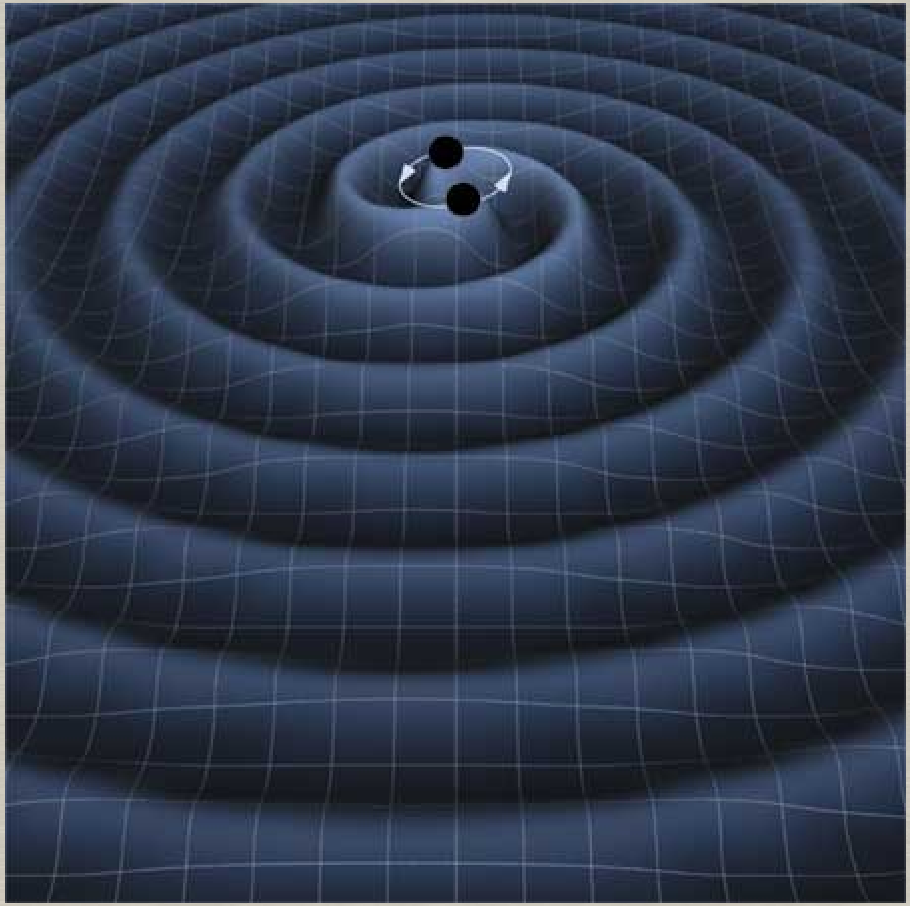
What is Gravitational Wave ?

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

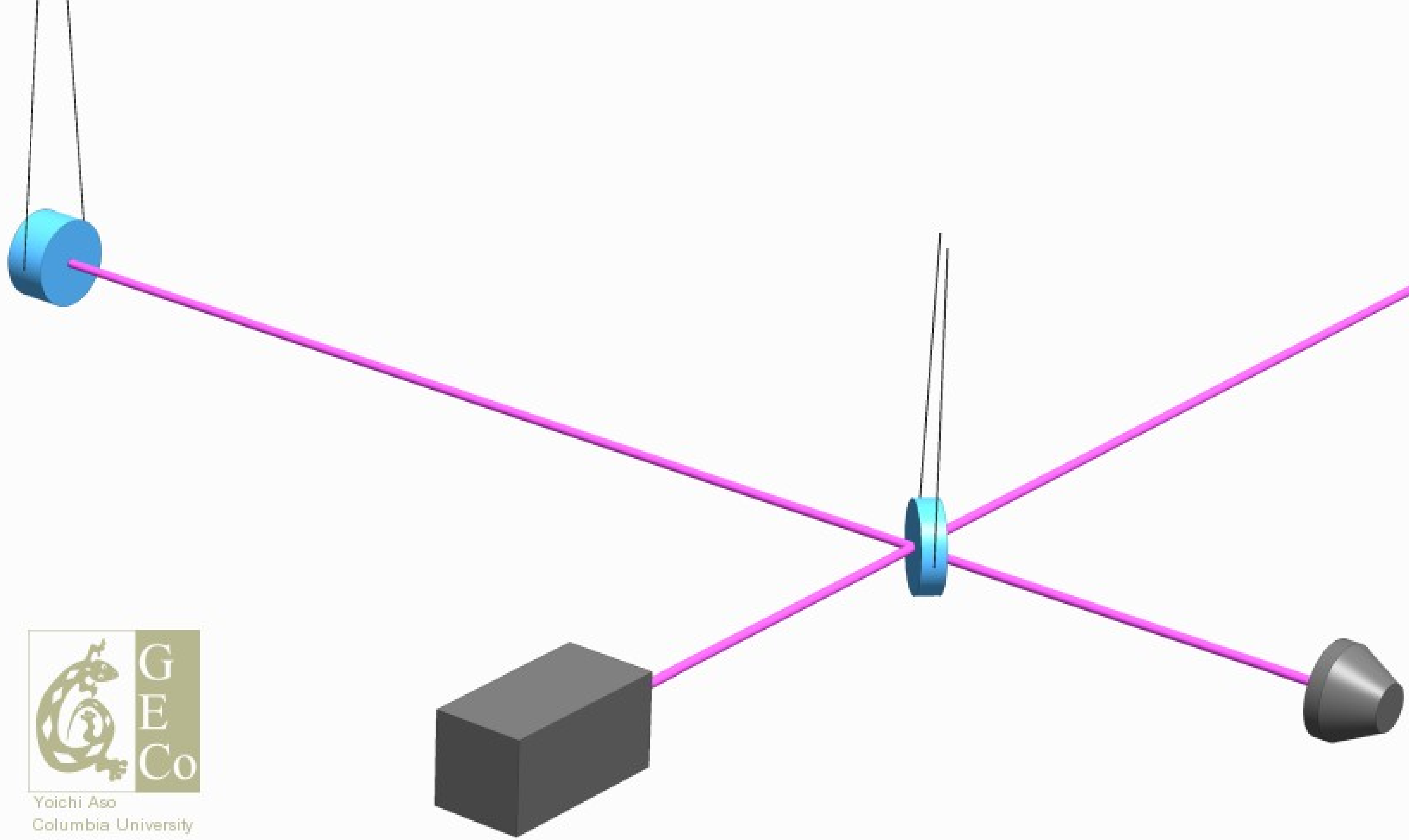




Theoretical prediction
1916 by A. Einstein

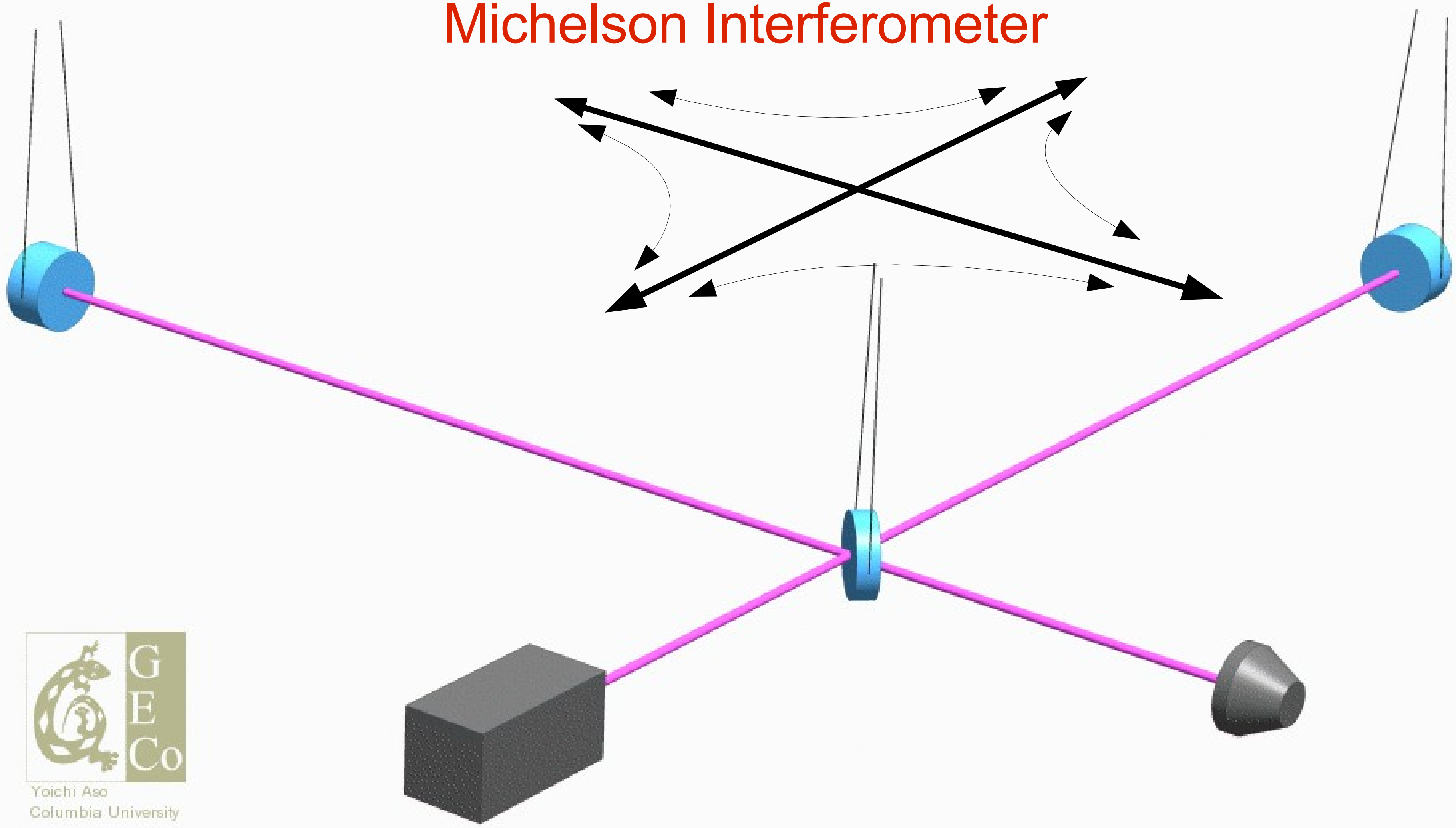
Interferometric Gravitational Wave Detector

Michelson Interferometer



Yoichi Aso
Columbia University

Michelson Interferometer

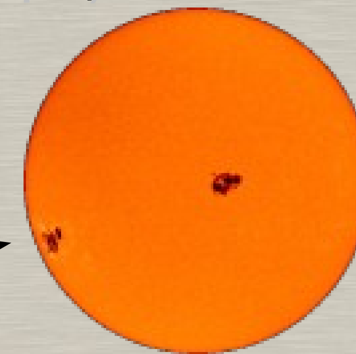


Effect of GW is extremely weak

Typical Event

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

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

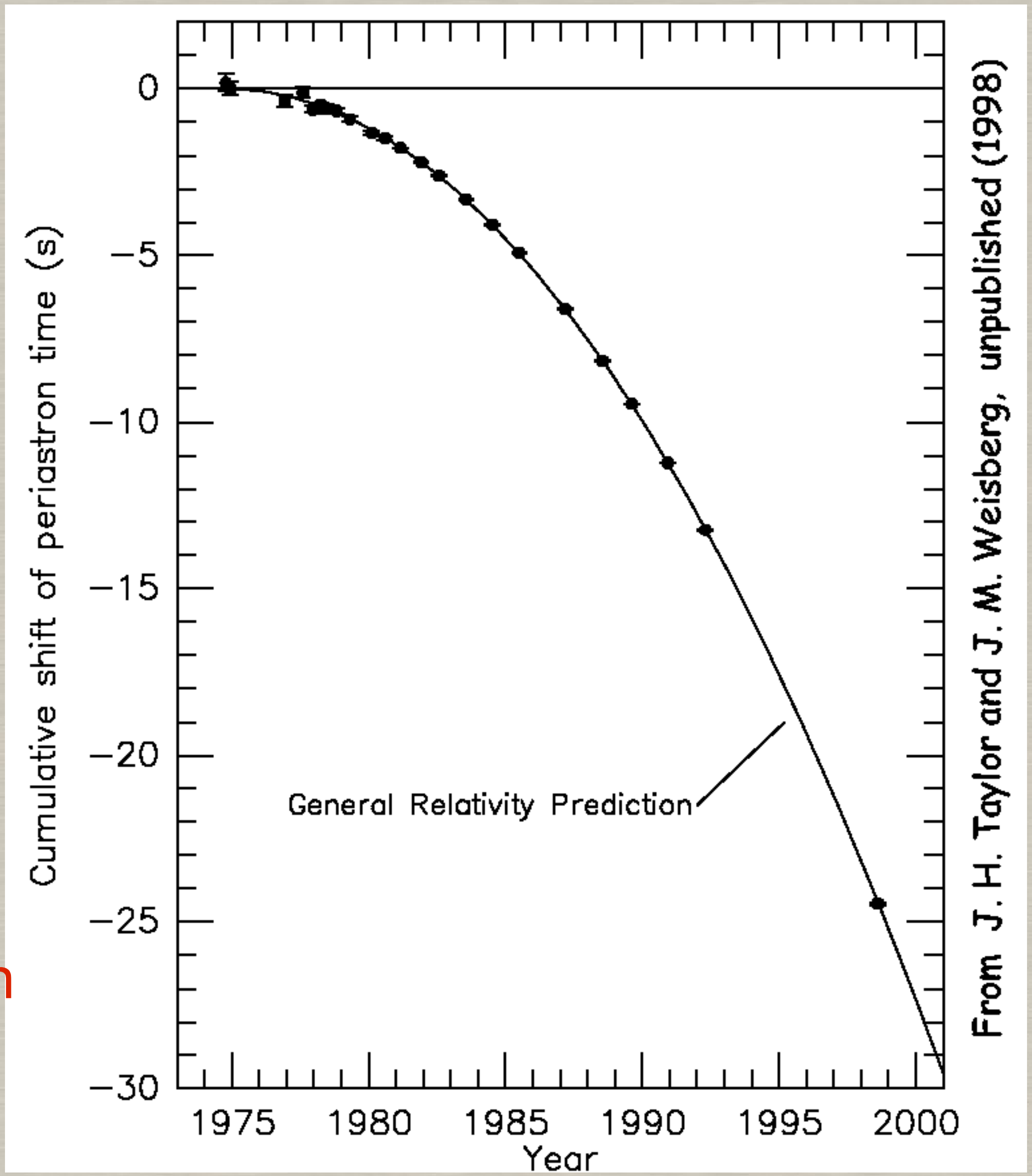


Change by the diameter of a hydrogen atom

Indirect evidence of gravitational radiation

Hulse

Taylor



Radio pulsar B1913+16

Periodic modulation

→ Binary neutron star

GW emission

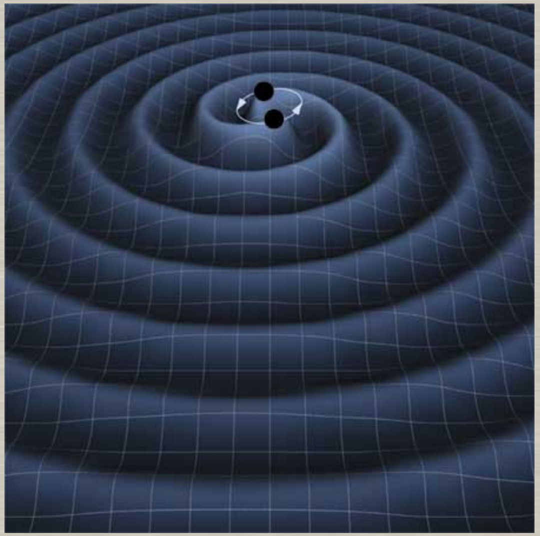
→ Orbital decay

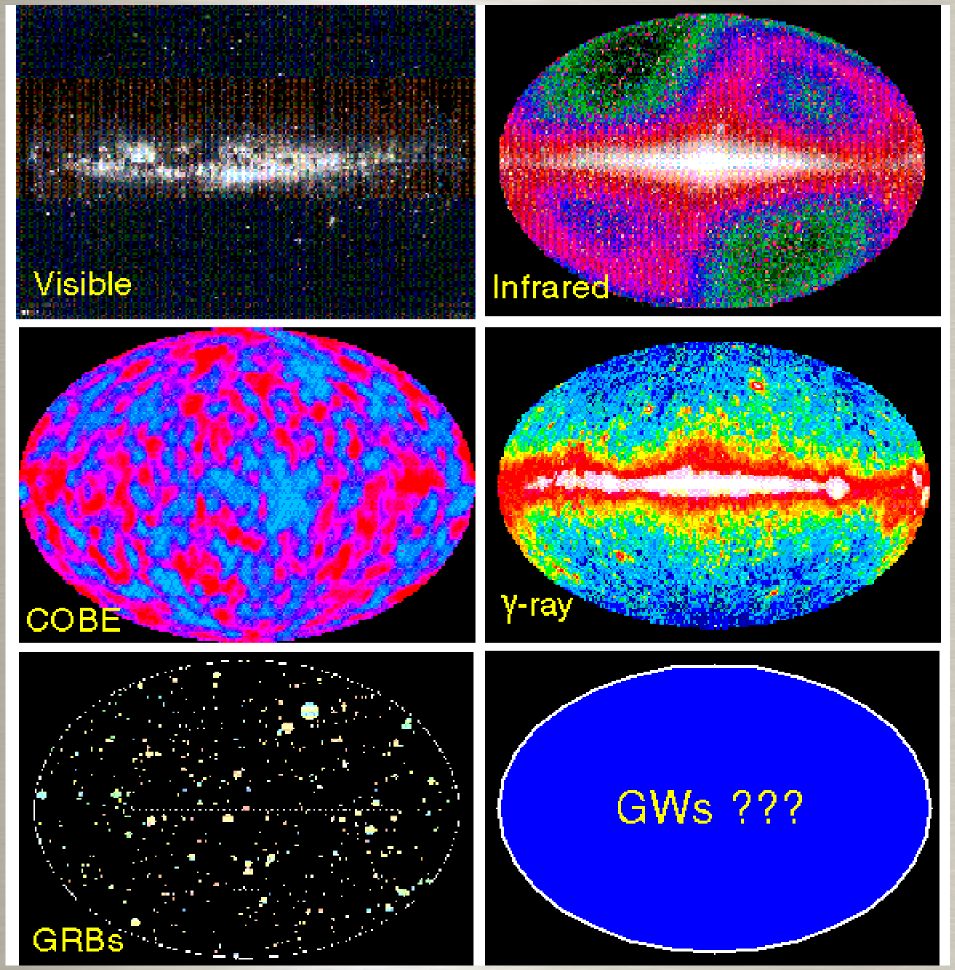
Perfect matching with the GR prediction

Nobel Prize in Physics, 1993

Sources of Gravitational Waves

- Coalescences of compact binary systems
- Black hole ring down
- Non-axisymmetric pulsars
- Supernovae
- Primordial background GW





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

Global network of detectors

(interferometers)

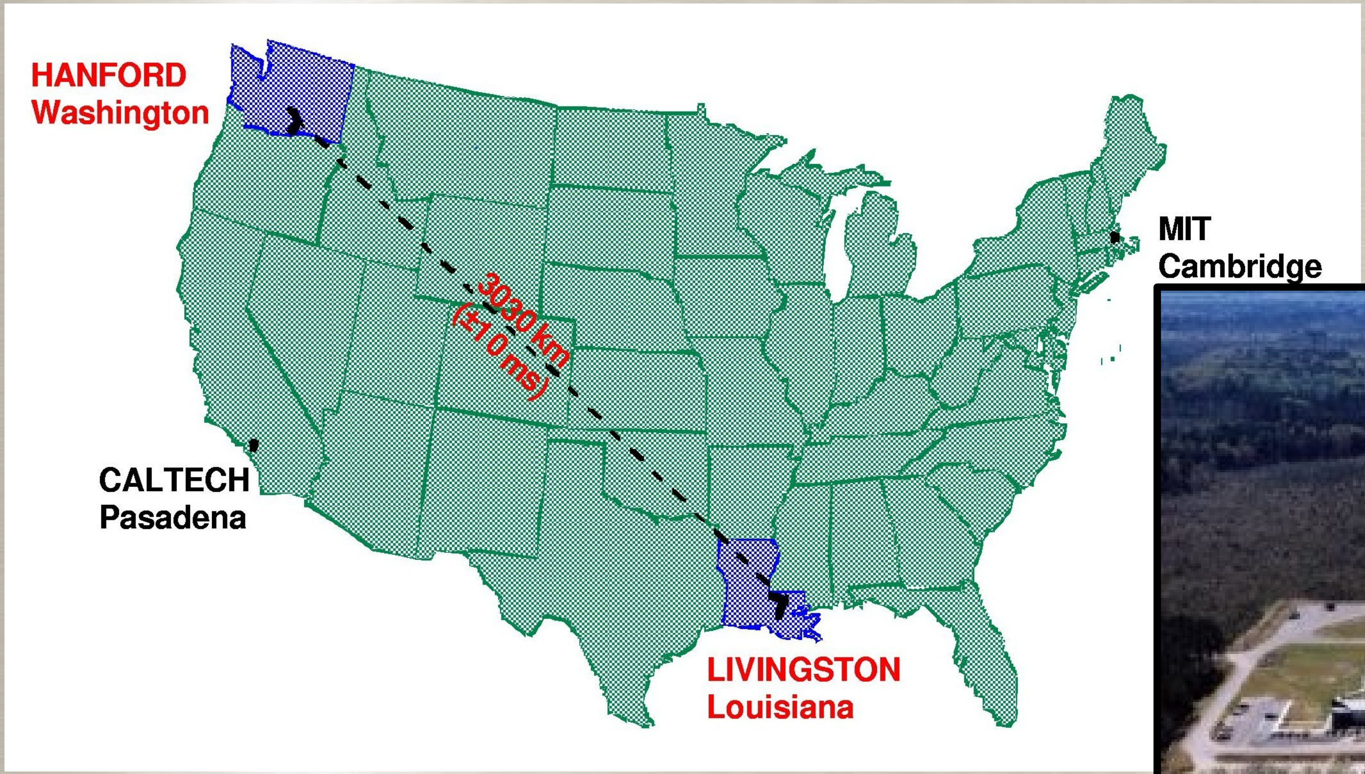
Operating detectors: Yellow, Planned detectors: Blue

LIGO

(Laser Interferometer Gravitational-wave Observatory)

Hanford, Washington

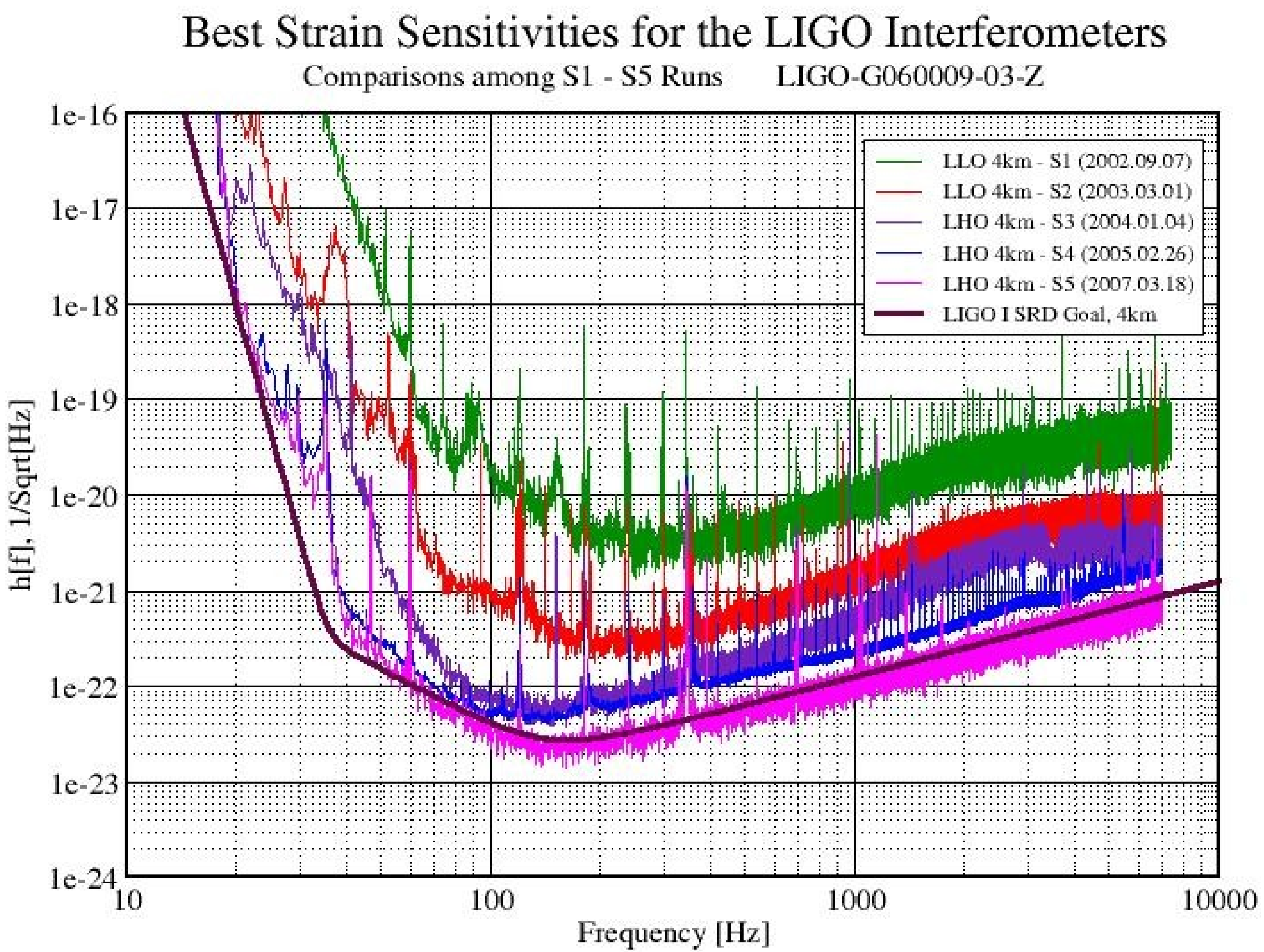
4km and 2km interferometer in the same vacuum system



Livingston, Louisiana

4km interferometer

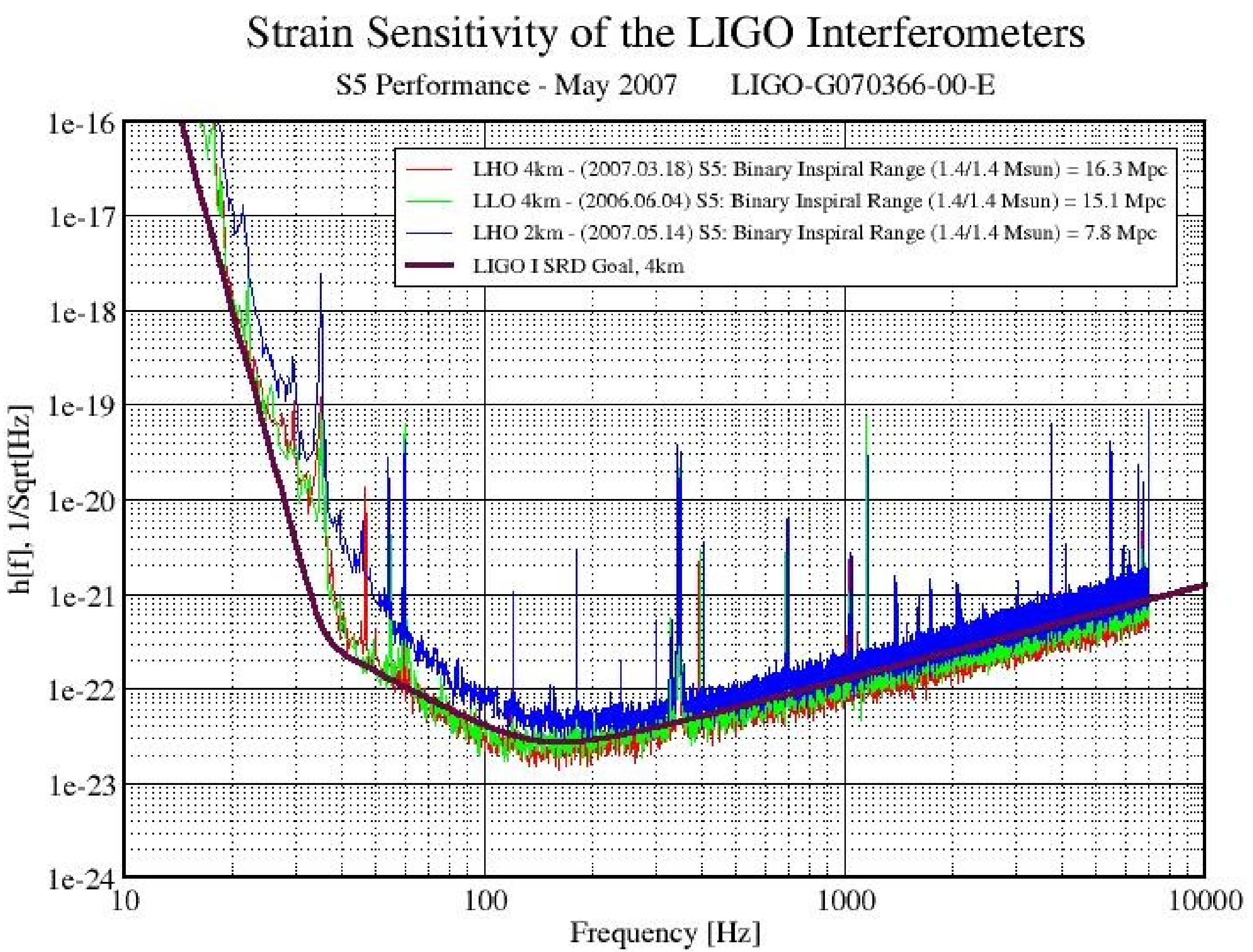
Noise History



http://www.ligo.caltech.edu/docs/G/G060009-03/

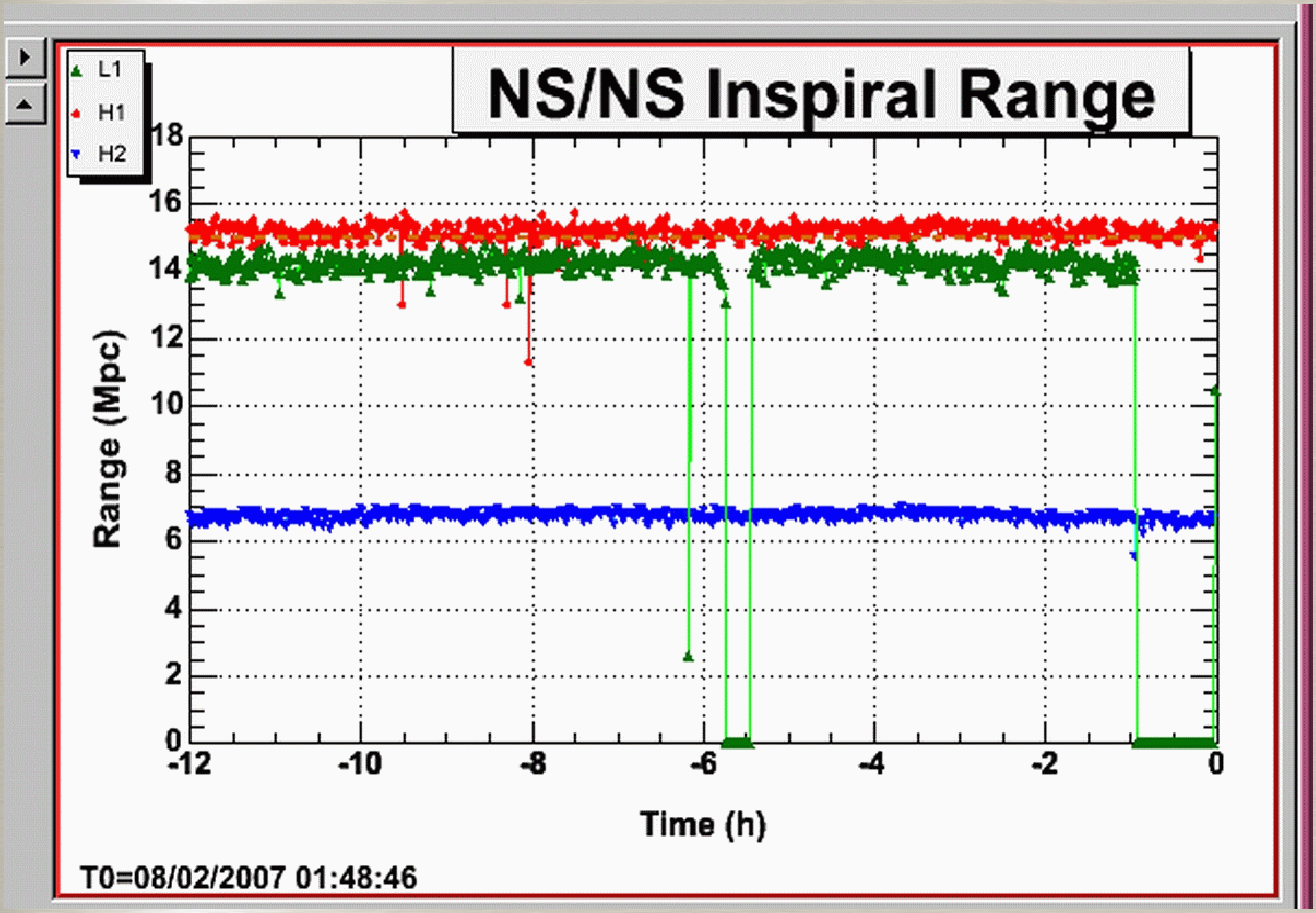
Fifth Science Run

- Nov. 4th 2005 - Oct. 1 2007
- Accumulated more than 1 year of triple coincidence data



http://www.ligo.caltech.edu/docs/G/G070366-00/

1.4M⊙ – 1.4M⊙ Neutron Star Binary
SNR=8



Some recent results from LIGO

Pulsar Search

I_{zz}:Principal moment of inertia

ϵ :Equatorial ellipticity

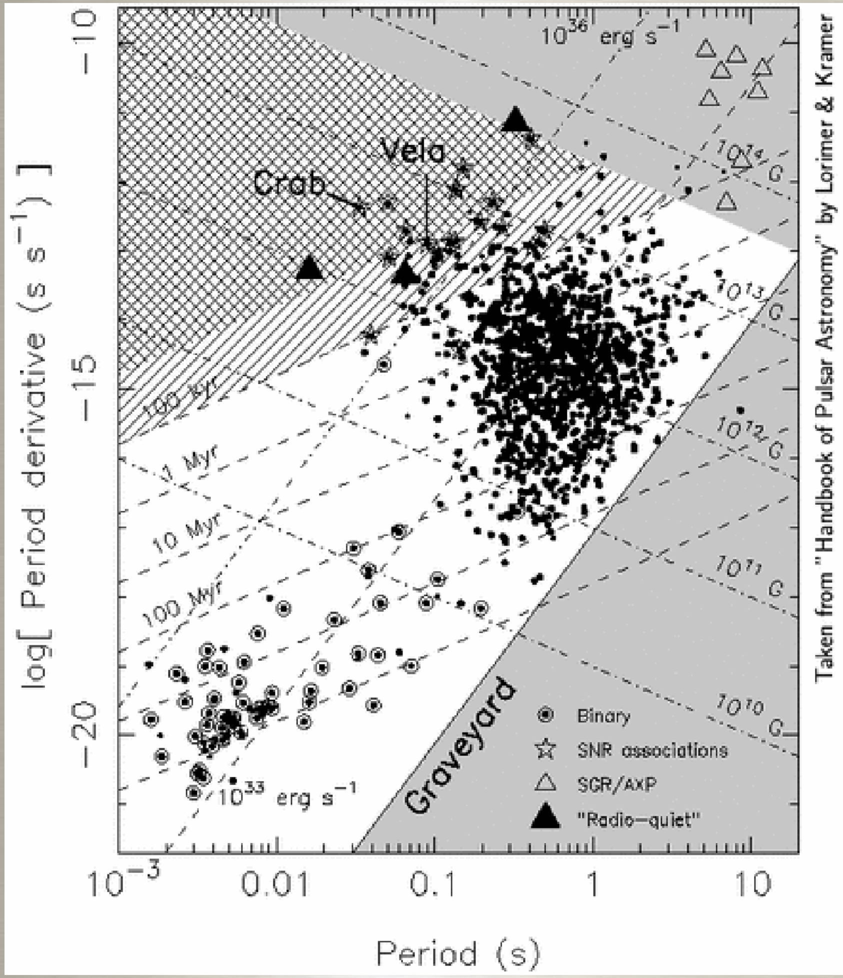
$$h_0 = \frac{16\pi^2 G}{c^4} \frac{\epsilon I_{zz} \nu^2}{r}$$

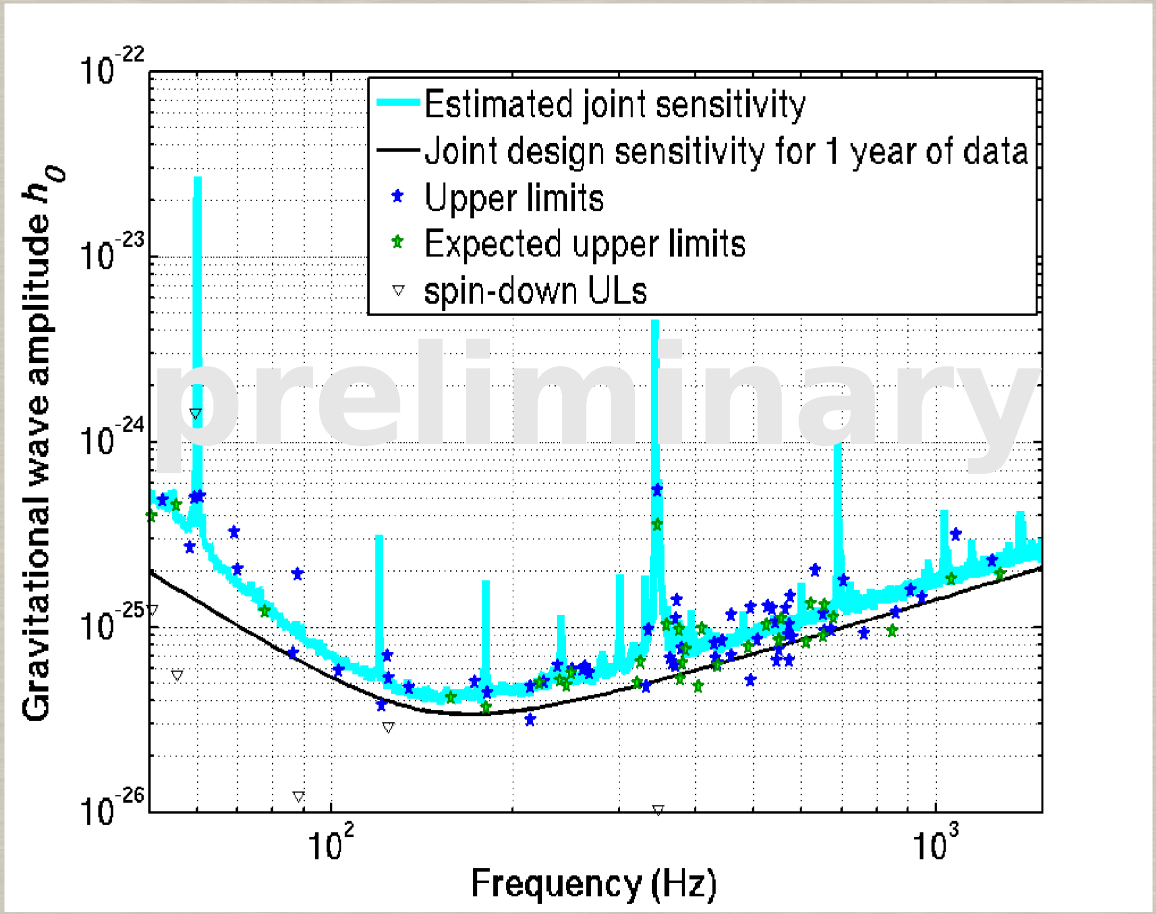
Rapidly rotating neutron stars

Non-axisymmetry ⟶ Continuous gravitational wave

Coherent integration for long time ⟶ a good SNR

Size of distortion can reveal information about NS Equation of State





Beating the Spin Down Upper Limit for the Crab Pulsar

Spin down UL: Assume energy dissipation is solely due to GW emission.

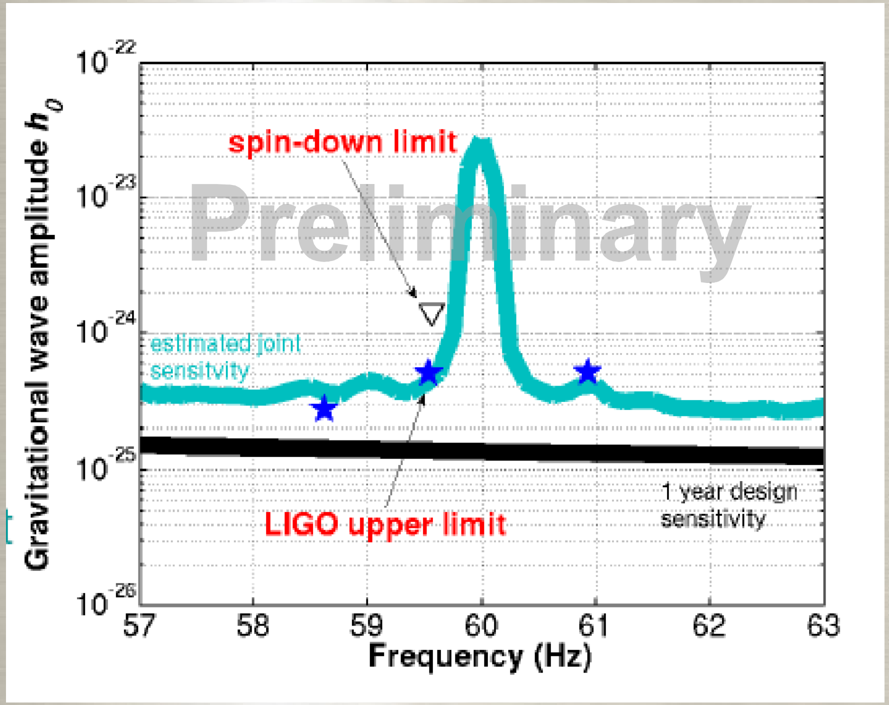
$$h_0^{\text{spin down}} = \left(\frac{5}{2} \frac{G I_{zz} \dot{\nu}}{c^3 r^2 \nu} \right)^{\frac{1}{2}}$$

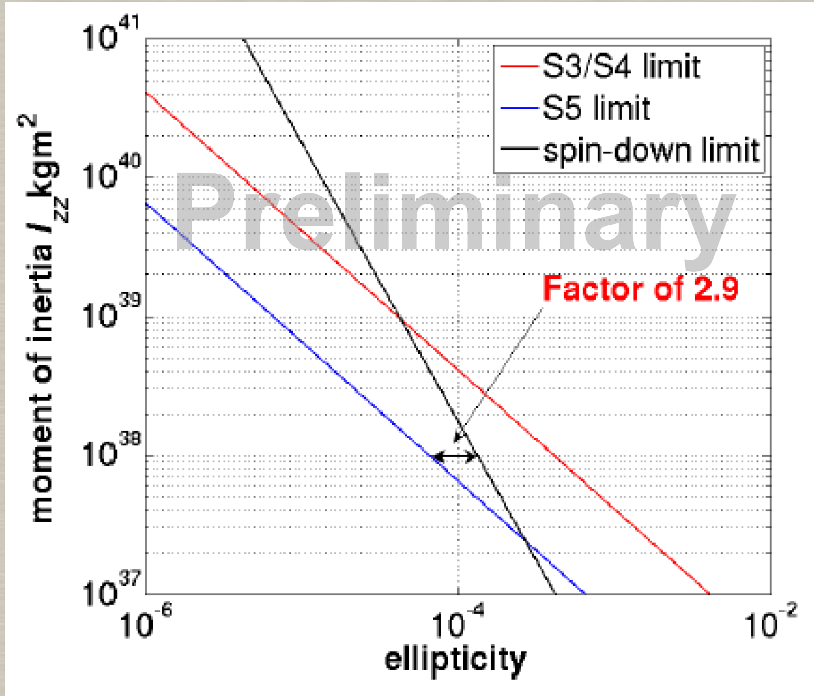
Current upper limit from LIGO S5 data (up to Aug. 23 2006)

$$\epsilon < 2.6 \times 10^{-4}, h_0 < 5.0 \times 10^{-25}$$

Beat the spin down limit $h_0 < 1.4 \times 10^{-24}$ by a factor of 2.9

The ellipticity: in the range of most speculative EQOS (Owen, 2005)





Stochastic Background GW

- Superposition of a large number of unresolved sources
- Cosmological sources
  - Vacuum fluctuations during inflation
  - Pre-big bang models
  - Phase transitions
  - Cosmic strings
- Astrophysical foregrounds
  - Binary neutron stars
  - Supernovae
  - Low-mas X-ray binaries

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c} \frac{d\rho_{\mathrm{GW}}}{df}$$

ρ_c : critical energy density for closing the universe

$d\rho_{\mathrm{GW}}$:energy density of GW in $[f, f+df]$

$$\Omega_{\mathrm{GW}}(f) = \Omega_\alpha \left| \frac{f}{100\,\mathrm{Hz}} \right|^\alpha$$

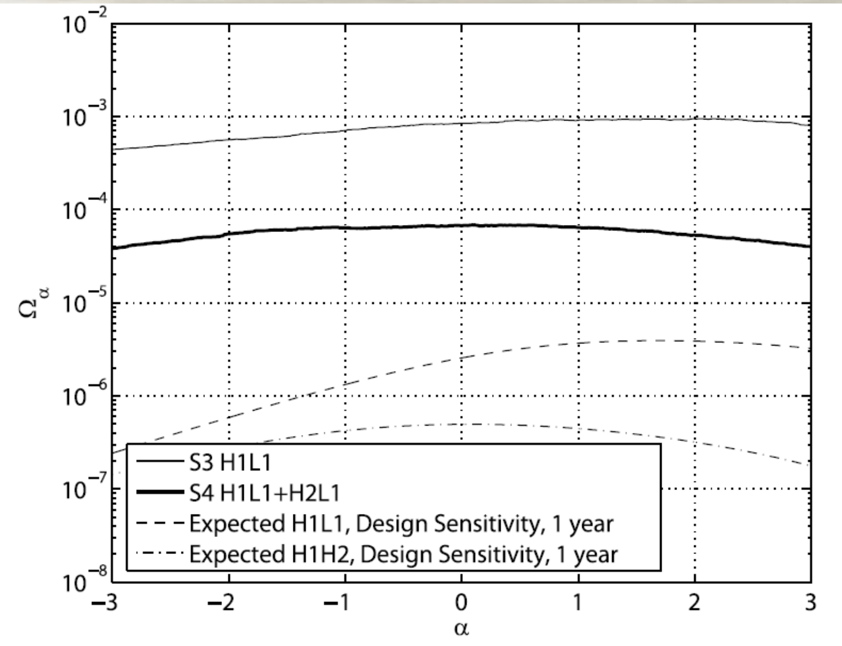
: power-low model of GW spectra

Search: Correlation between independent detectors

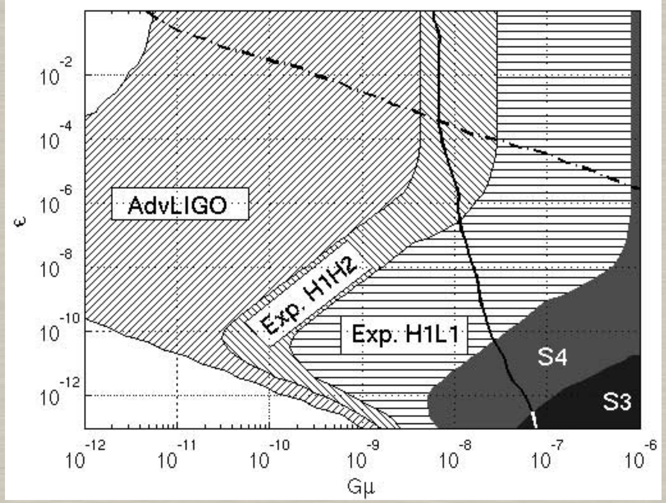
S3, S4 results

B. Abbott *et al.*, *Astrophys. J.* **659**:918-930, 2007

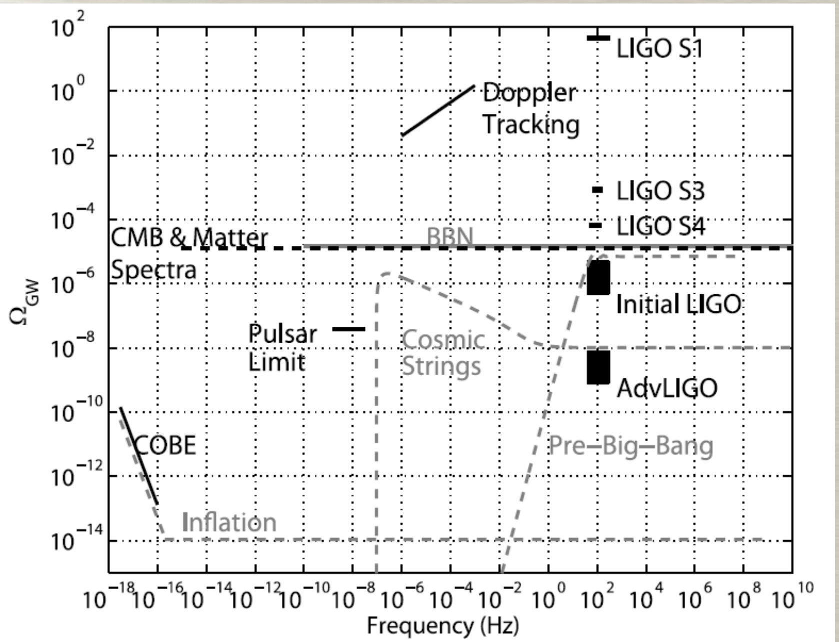
S3 (H1-L1)
S4(H1+H2-L1)
Combined UL
for Ω_α



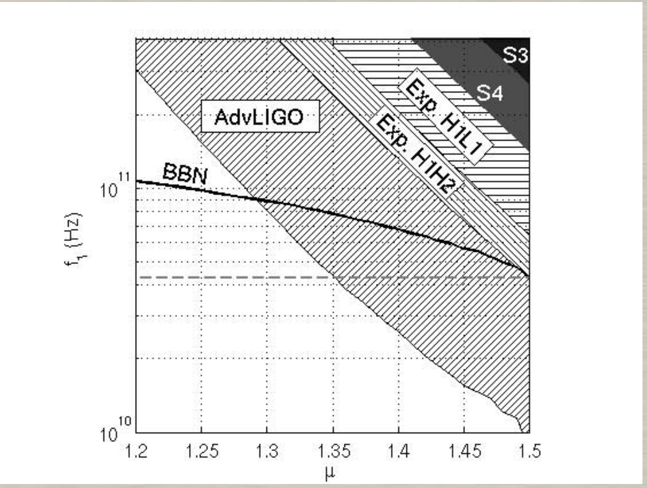
Cosmic string model excluded parameter space



Comparison with other experiments and theoretical models



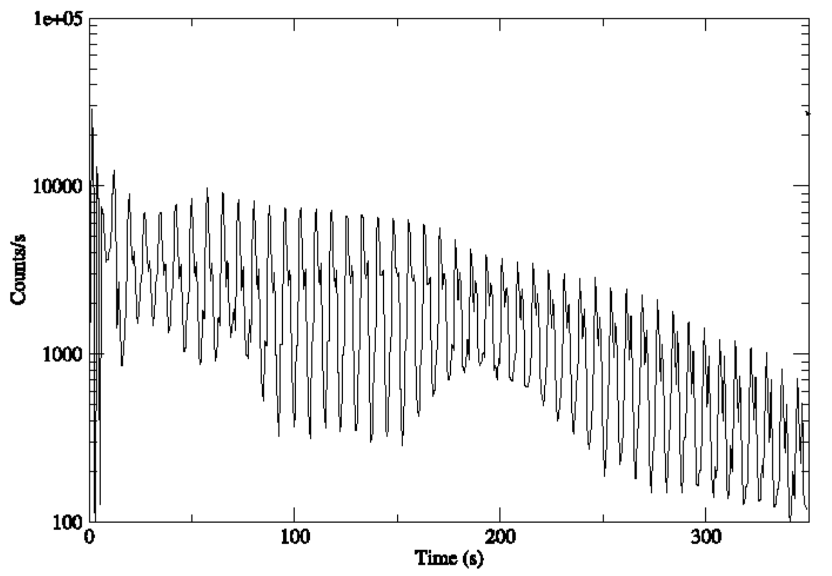
pre-big bang excluded parameter space



S5 data shall beat the big bang nucleosynthesis bound.

SGR1806-20 Hyper Flare

Soft Gamma-ray Repeater 1806-20: Hyper Flare on December 24 2004



T.Strohmayer and A.Watts, *ApJ* **653** L594 (2006)

- Quasi Periodic Oscillation(QPO) observed in X-ray tail
- Possible connection with excitations of neutron star's mechanical oscillation modes

LIGO status at the moment:
Post-S3, pre-S4
Only Hanford 4km was in operation

Search method:
Look for excess power at the event time in the QPO frequency range (several frequencies, time intervals)

No significant deviation from the background noise found.
The best upper limit: $4.5\times10^{-22}\,1/\sqrt{\mathrm{Hz}}$
(92.5Hz QPO observed from 150-260sec after the start of the flare)

Corresponding GW energy:
(assuming isotropic emission) $7.7\times10^{46}\,\mathrm{erg}=4.3\times10^{-8}M_{\odot}c^{2}$

Comparable to the electromagnetically radiated energy

The best GW upper limit on this type of source.
First multiple-frequency asteroseismology using a GW detector

Details published in B. Abbott et al., *Phys. Rev. D* **76**, 062003 (2007)

GRB070201

A short hard gamma-ray burst (Feb. 1st 2007)
Detected by Konus-Wind, INTEGRAL, Swift, MESSENGER

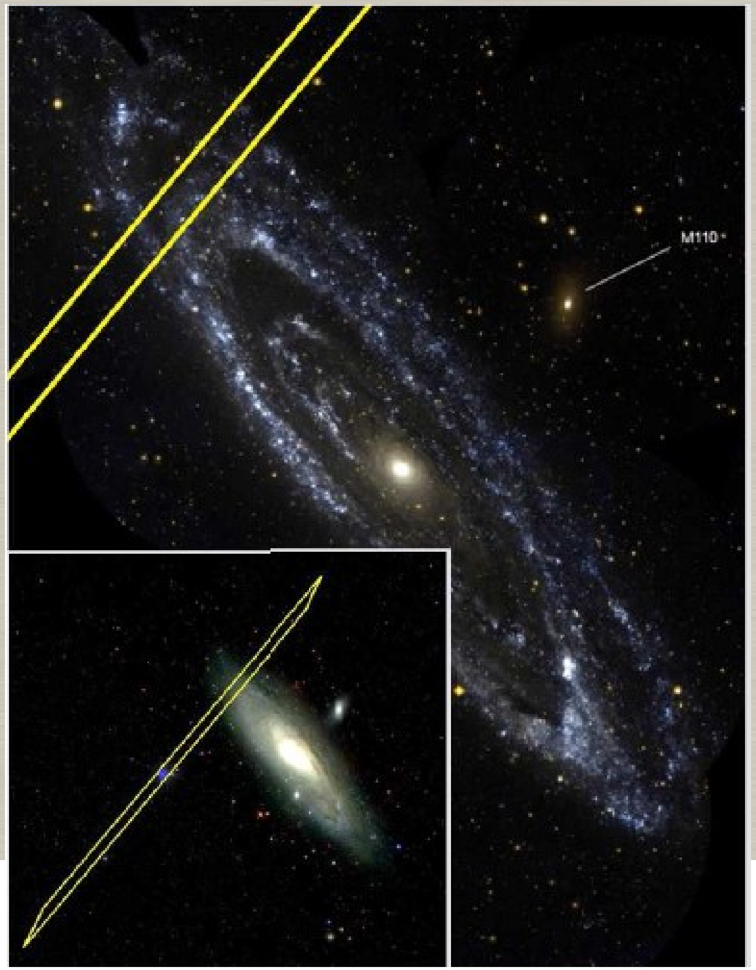
Short GRB progenitors: possibly NS/NS or NS/BH mergers

→ Emits strong gravitational waves

Other possibility: SGR (may emit GW but weaker)

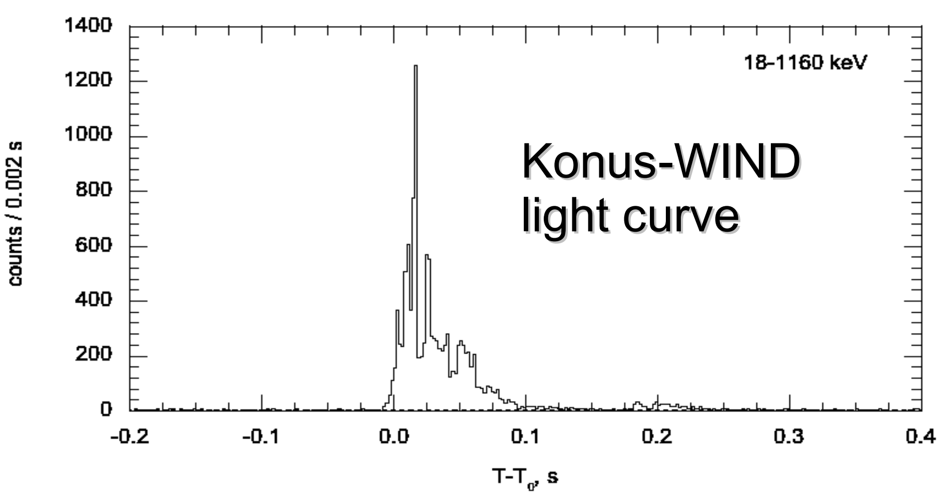
The error box for the source location overlaps with the spiral arms of M31

$E_{iso} \sim 10^{45}$ ergs
if at M31 distance
(more similar to SGR energy than GRB energy)



What can we do with this event ?

- In the case of a detection:
  - Confirmation of a progenitor (e.g. coalescing binary system)
  - GW observation could determine the distance to the GRB
- No-detection:
  - Exclude progenitor in mass-distance region
  - With EM measured distance to hypothetical GRB, could exclude binary progenitor of various masses
  - Possible statements on progenitor models
  - Bound the GW energy emitted by a source at M31

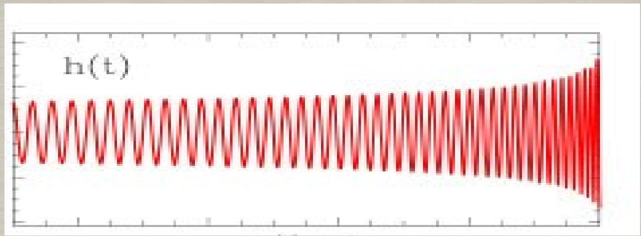


GRB070201

Search for compact binary inspiral signals

- Waveform: analytically given by Post Newtonian approximation
- Matched filtering: Good SNR signal extraction
- Mass parameters unknown: search in the parameter space

$$1\,M_\odot < m_1 < 3.0\,M_\odot \quad 1.0\,M_\odot < m_2\,40.0\,M_\odot$$



Chirp signal

No plausible gravitational waves identified

A compact binary progenitor at M31 is excluded at > 99% confidence level
A compact binary progenitor up to 3.5Mpc away is excluded at 90% confidence level

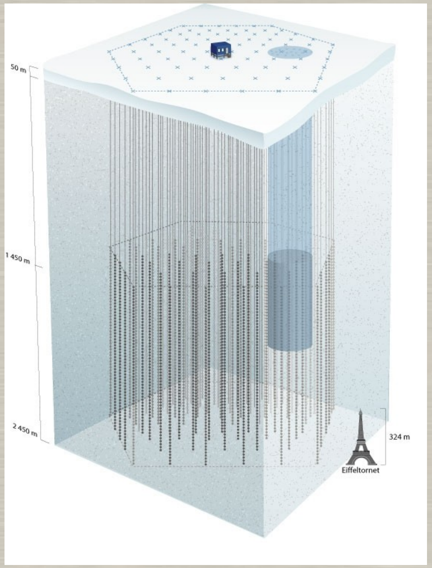
Burst signal search

- Wide bandwidth correlation based burst signal search (40 – 2000Hz)
- Upper limit: $h_{\mathrm{RSS}}^{90\%} = 1.25 \times 10^{-21}\, 1/\sqrt{\mathrm{Hz}}$ within a ~100ms period peaked at 150Hz
- Corresponding energy: $E_{\mathrm{ISO}} < 4.4 \times 10^{-4}\, M_\odot c^2 (7.9 \times 10^{50}\,\mathrm{ergs})$ assuming the distance of M31
- Does not exclude SGR at the M31 distance

For more quantitative discussion: refer to a paper to be appear soon in ApJ

Pre-print is available as arXiv:0711.1163

Opportunity for a Coincidence Analysis with IceCube



Burst GW search: Overwhelming number of noise events

IceCube: a neutrino detector at the south pole

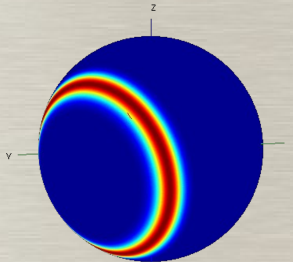
Search for astrophysical events emitting GW and high-energy neutrino bursts simultaneously.

Coincident analysis between independent detectors

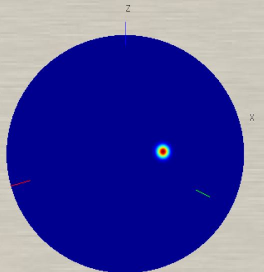
→ Reject most background events

Two-stage coincidence

- Event time coincidence
  (within a certain time window)
- Spatial coincidence
  (evaluated by an unbinned maximum likelihood method)

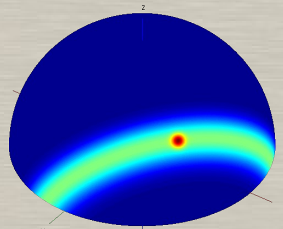


LIGO event



IceCube event

→



Overlap event

Monte Carlo simulations

Simulated LIGO S5 and IceCube 9-string events

$$\text{False Alarm Rate [events/year]} = \frac{1}{435}\left(\frac{p}{1\,\%}\right)\left(\frac{T_w}{1\,\text{sec}}\right)$$

T_w : Time Window

p : p-value

Better than the SNEWS standard

We can relax the event trigger threshold → better sensitivity

Note: Above are not real data analysis results. This is a proposal of a method.

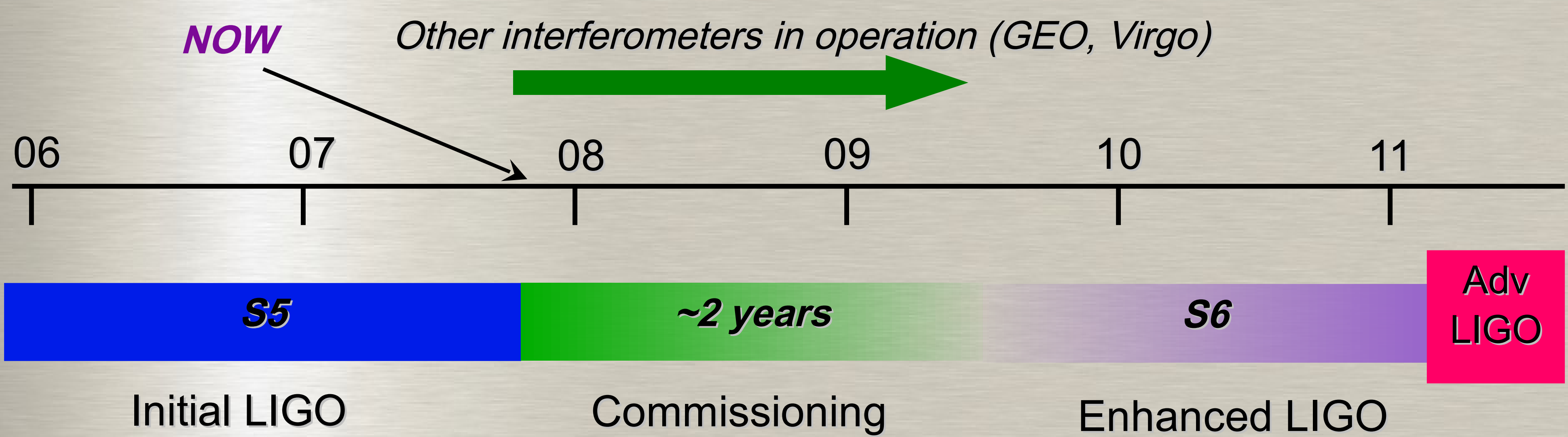
Advanced LIGO

- Major upgrade of LIGO interferometers
- A factor of 10 improvement in strain sensitivity ⟶ x1000 in detectable volume
- 1 day of AdvLIGO observation = 1 year of current LIGO observation
- Detect gravitational waves regularly
- Installation : planed to start in 2011, Observation: start in 2014

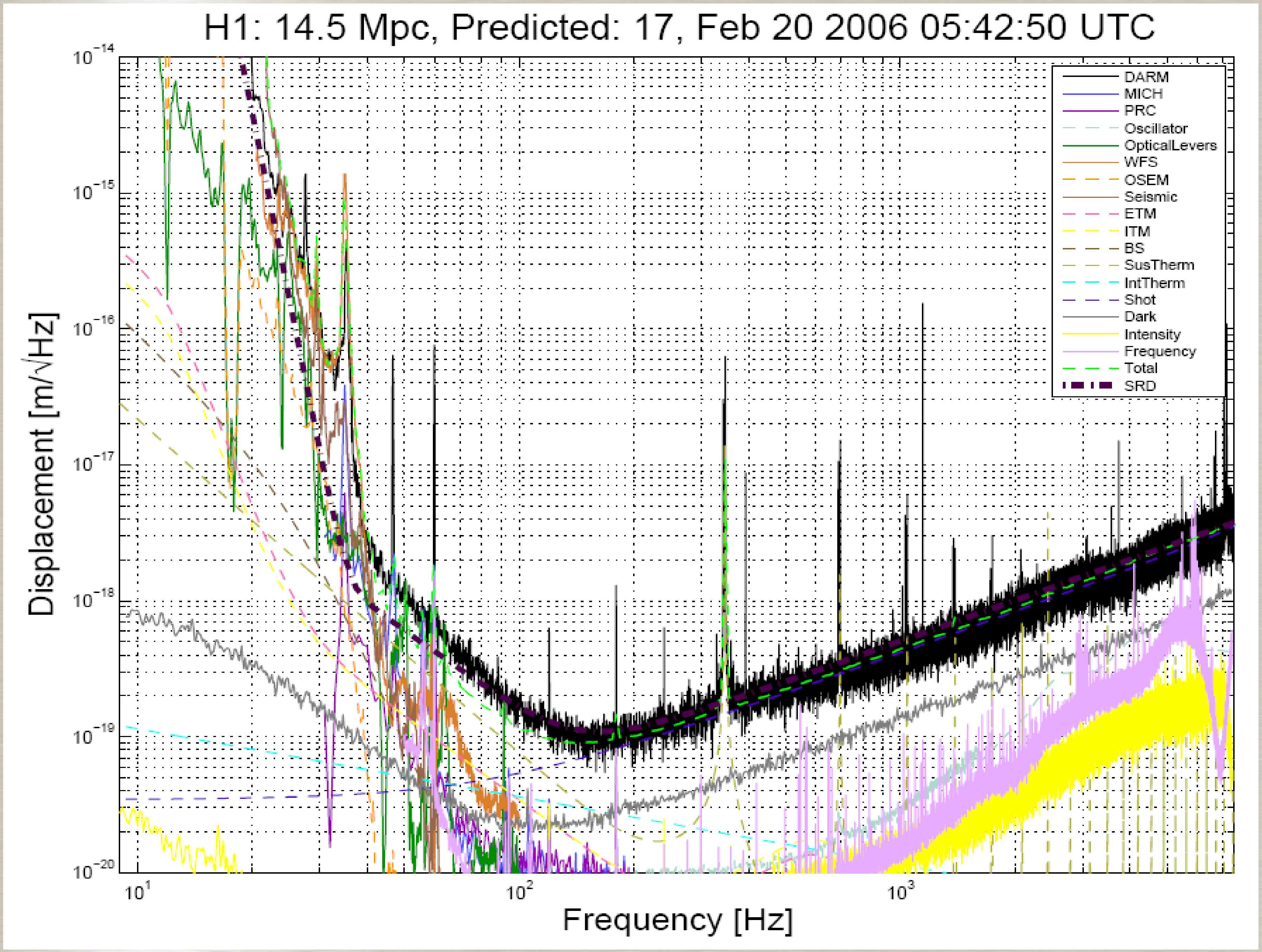
Before Advanced LIGO

- Enhanced LIGO: a factor of 2 improvement from the current LIGO
- Installation and commissioning has just started (2 years)
- S6: 1 year of triple coincidence data with improved sensitivities

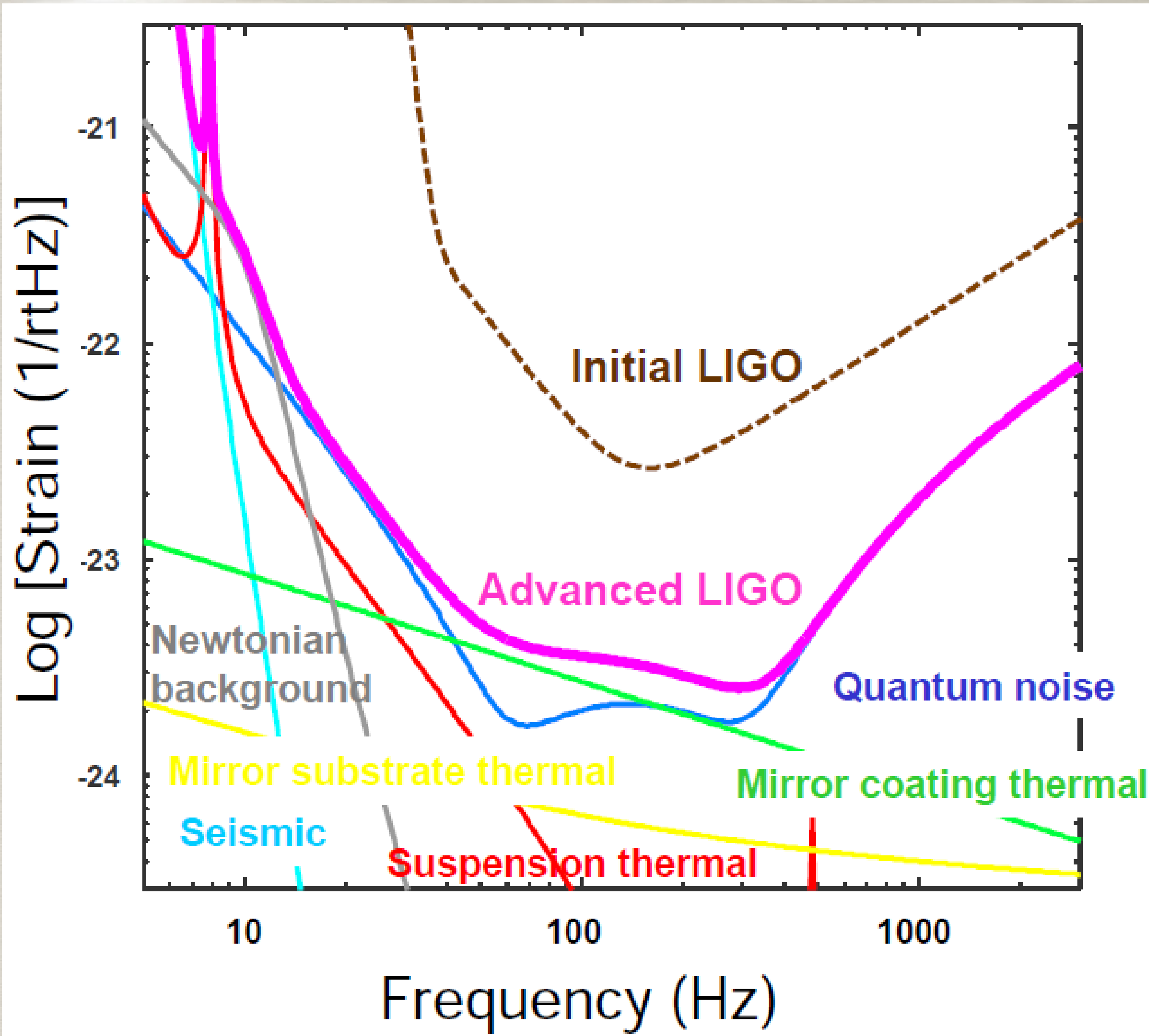
Time-line



Technical Challenges for Advanced LIGO detector



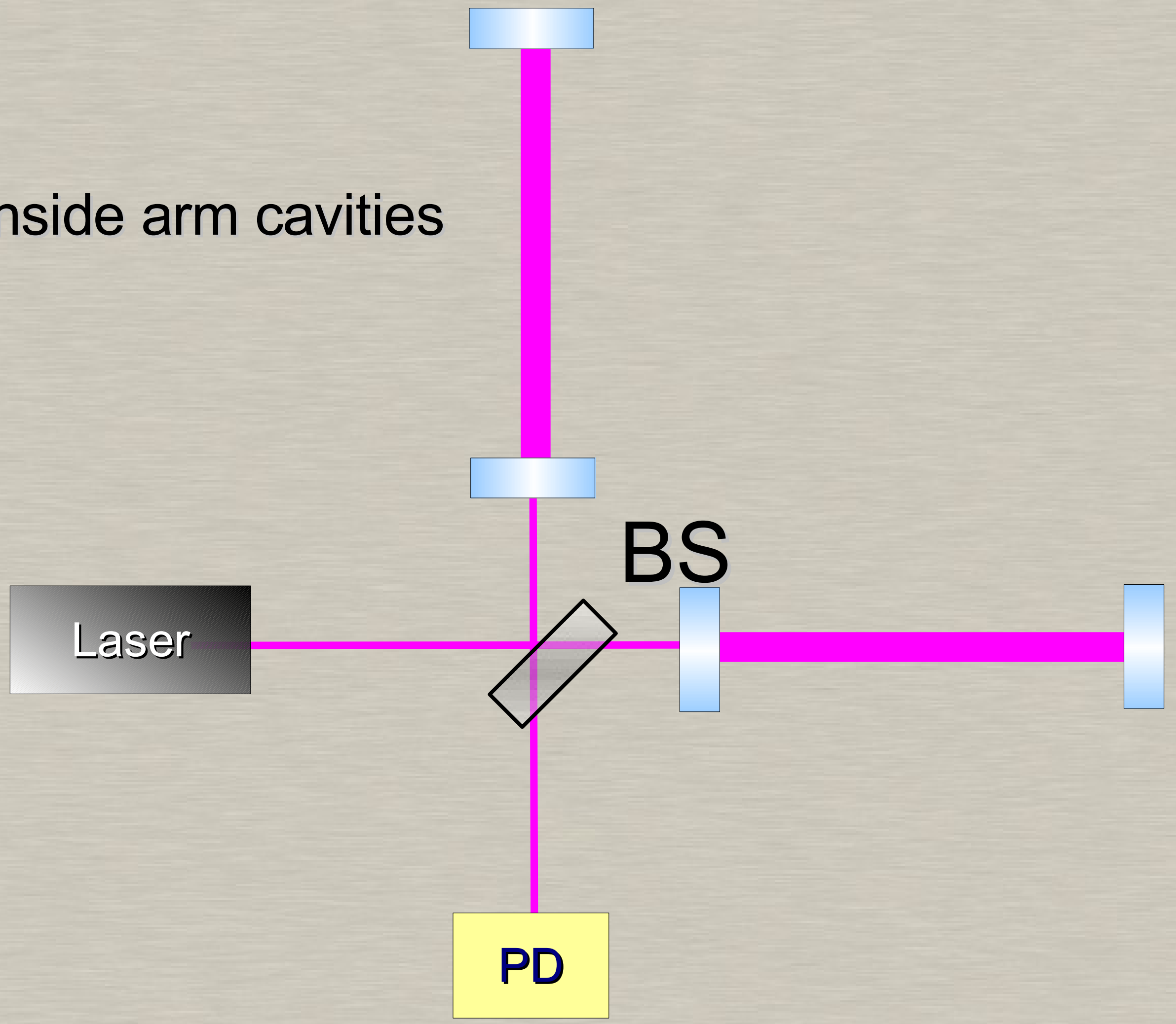
Sensitivity estimate of Advanced LIGO



Evolution of Interferometer Scheme

Fabry-Perot Michelson Interferometer

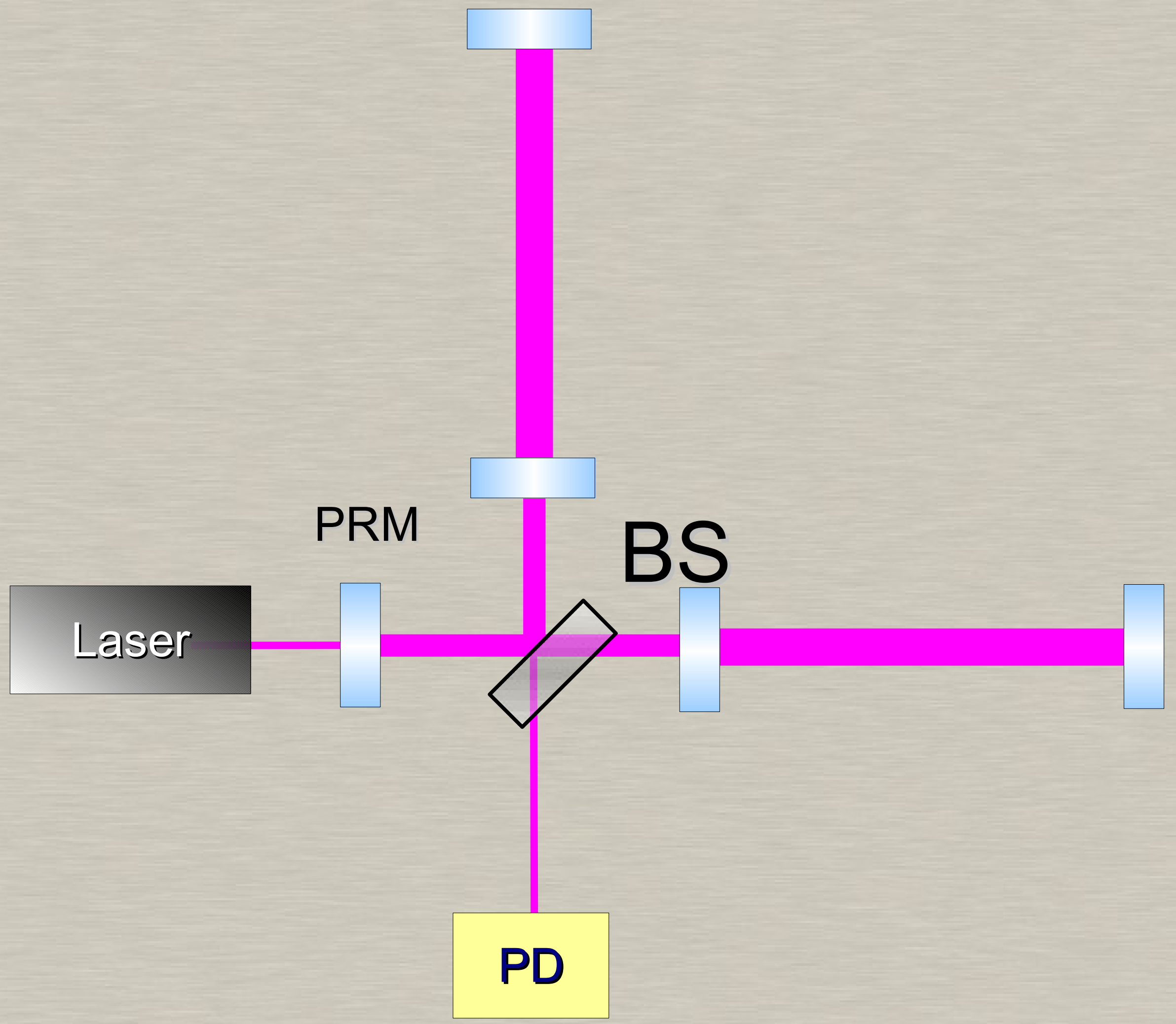
- Multiple bounce of photons inside arm cavities
- Signal enhancement



Evolution of Interferometer Scheme

Power Recycling

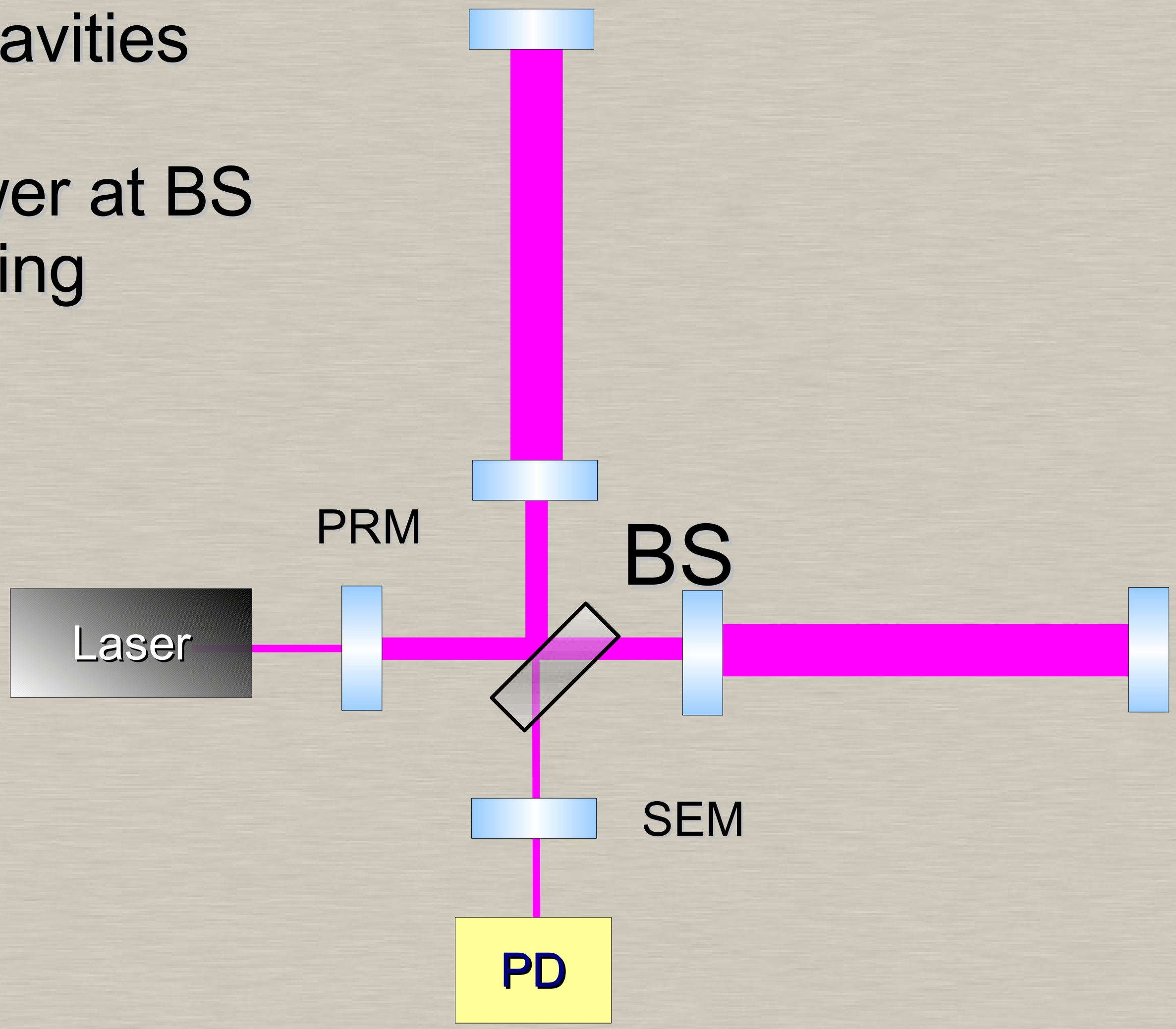
Higher laser power
Smaller shot noise



Evolution of 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

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

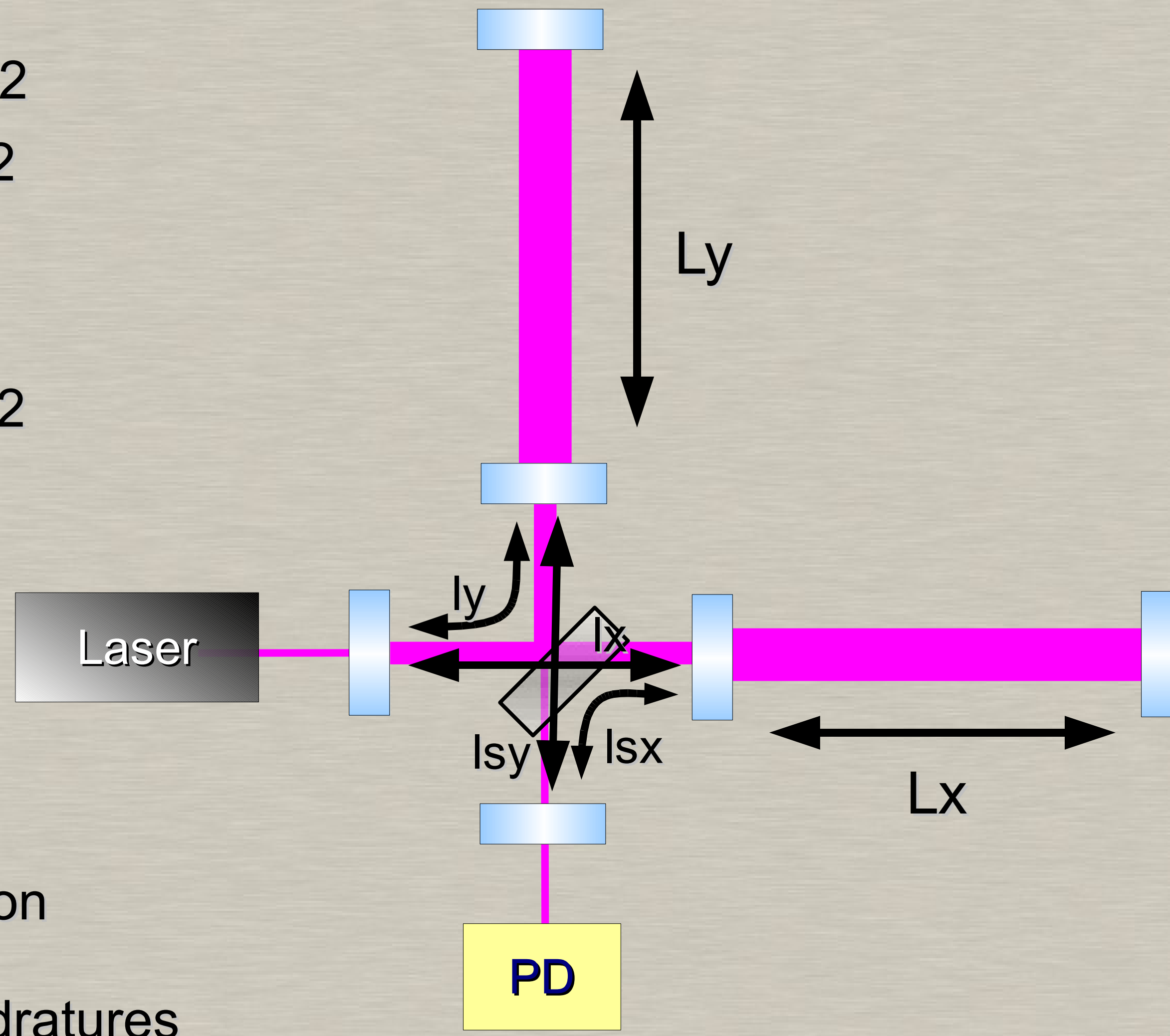
$L- =(Lx-Ly)/2$

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

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

$ls=(lsx+lsy)/2$

Complicated MIMO system



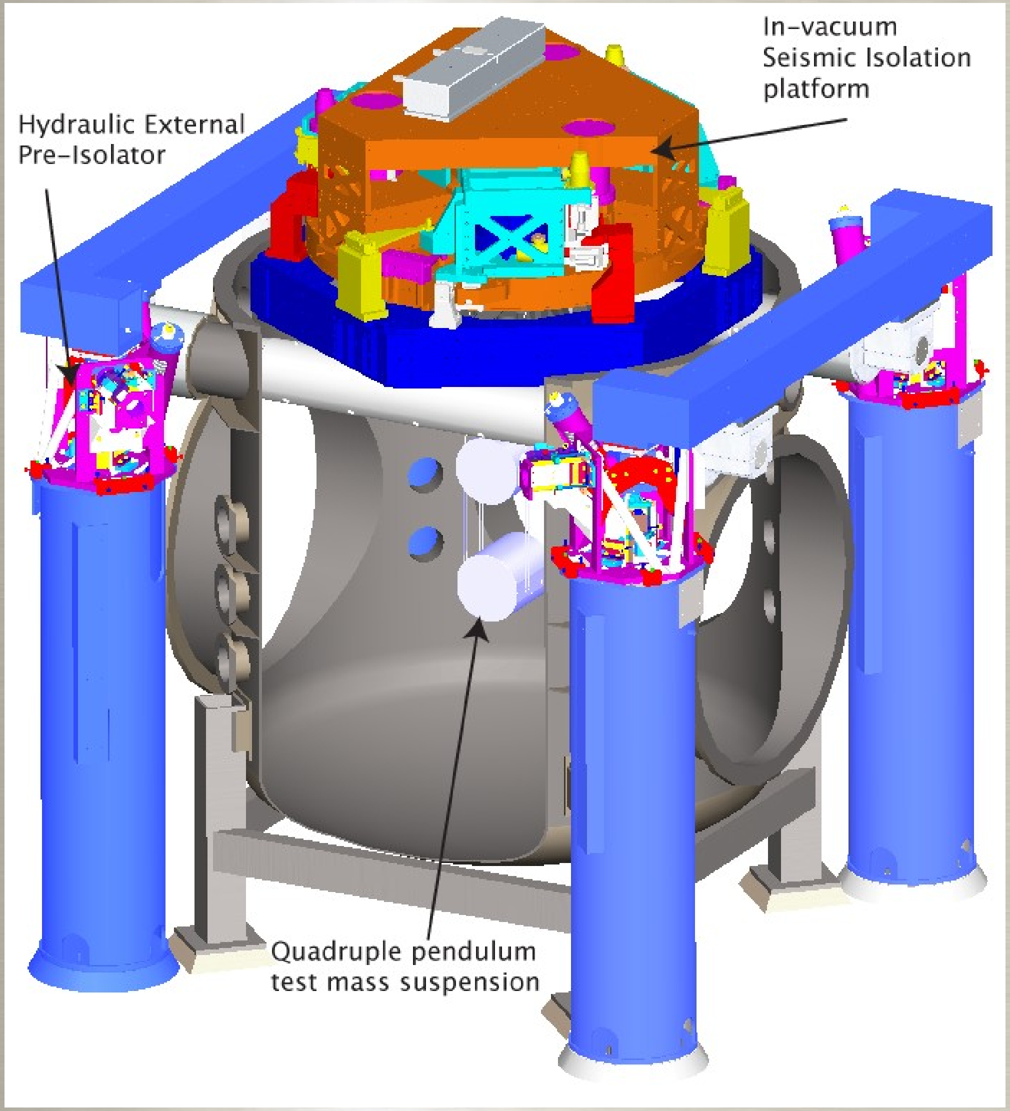
Signal Extraction schemes

- RF phase/amplitude modulation
- Demodulation at various ports/harmonics/quadratures
- Homodyne detection for GW channel

Seismic Isolation

Required for: Seismic noise reduction, Stable operation

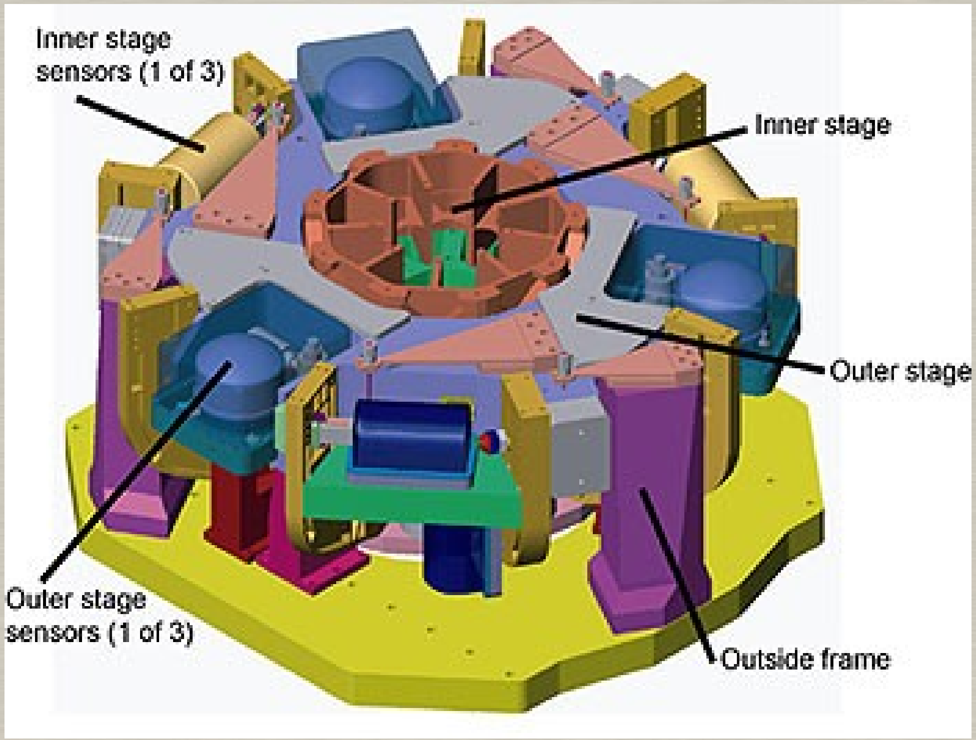
Combination of active and passive isolation stages.



Active system requirement

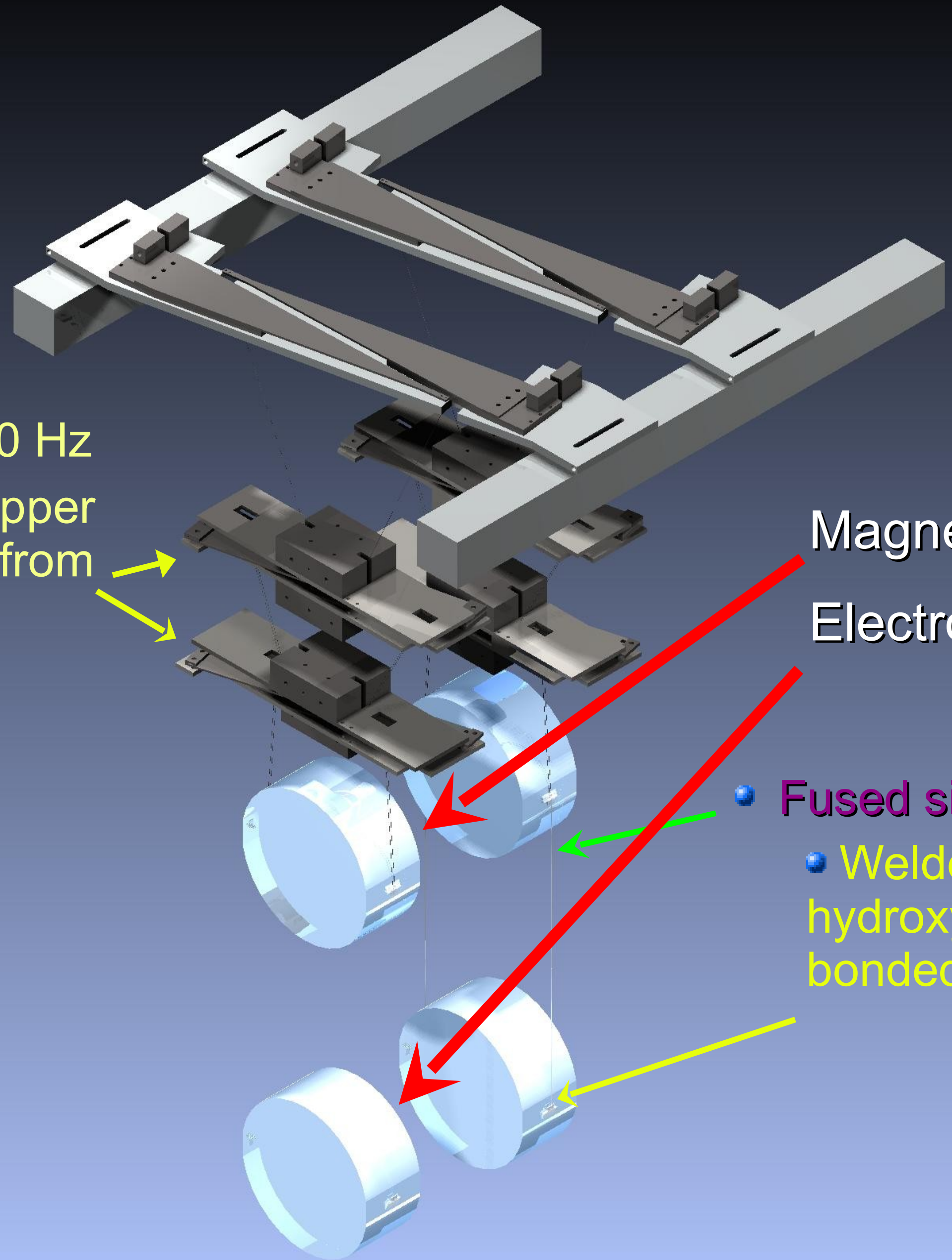
x3000 attenuation @ 10Hz

Internal Active Isolation Platform



Passive Vibration Isolation Chain

- Quadruple pendulum:
  - ~10^7 attenuation @10 Hz
  - Controls applied to upper layers; noise filtered from test masses
- Seismic isolation and suspension together:
  - 10^{-19} m/rtHz at 10 Hz



Magnets

Electrostatic

- Fused silica fiber
  - Welded to 'ears', hydroxy-catalysis bonded to optic

Thermal Noise

Thermal vibration of the molecules of mirror / suspension material

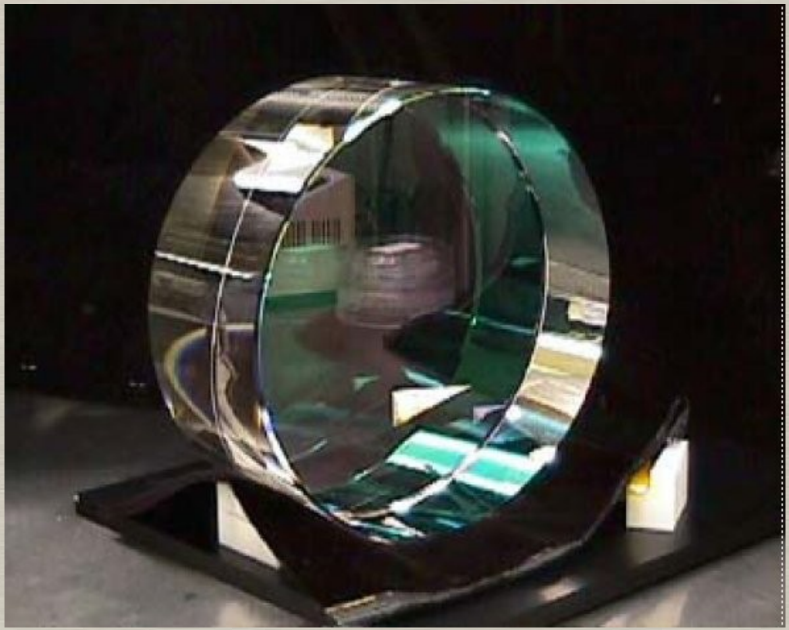
Fluctuation Dissipation Theorem

Mechanical loss ⟷ Connection to the heat bath ⟶ Thermal fluctuation

High mechanical quality mirror substrate / coating materials

Low mechanical loss suspension fibers
Fused silica fibers with silica bonding

Fused silica mirror



Other challenges for mirrors

Large mirror (40kg):

- large beam size (average out thermal fluctuations)
- Small radiation pressure noise

Precision manufacturing/metrology:

- Large radius of curvature
- Smooth polishing (<0.1nm RMS micro roughness)

Optical Absorption:

- Optical loss < 0.5 ppm/cm
- Thermal lensing compensation system

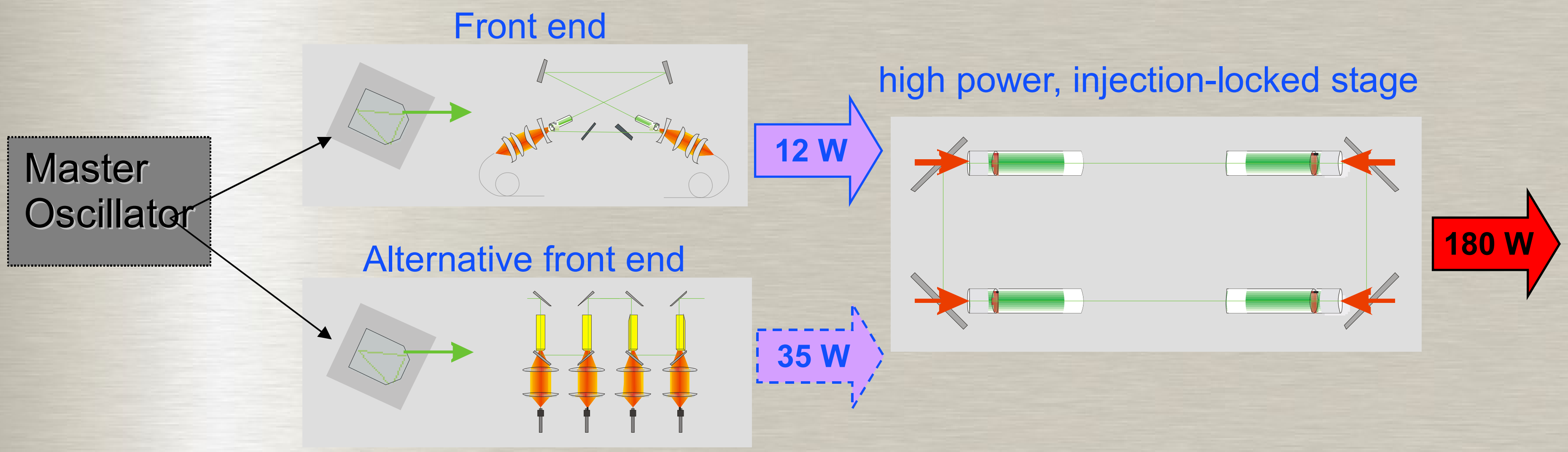
High Power Laser

Shot Noise: Photon number fluctuation
Larger laser power → Less significant

Requirements

- High power 180W
- Intensity stability: $\sim 2\times10^{-9}$
- Frequency stability: $\sim 10^{-7}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$
- Good mode shape (TEM00 Gaussian beam)

Advanced LIGO Laser System



Beating the Standard Quantum Limit

Heisenberg's uncertainty principle

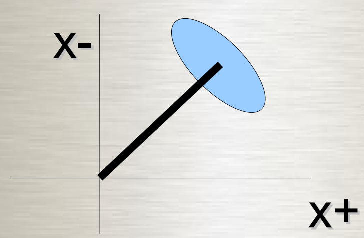
$$\Delta x \Delta p \geq \hbar/2$$

Measurement uncertainty = Shot Noise
Measurement back action = Radiation Pressure

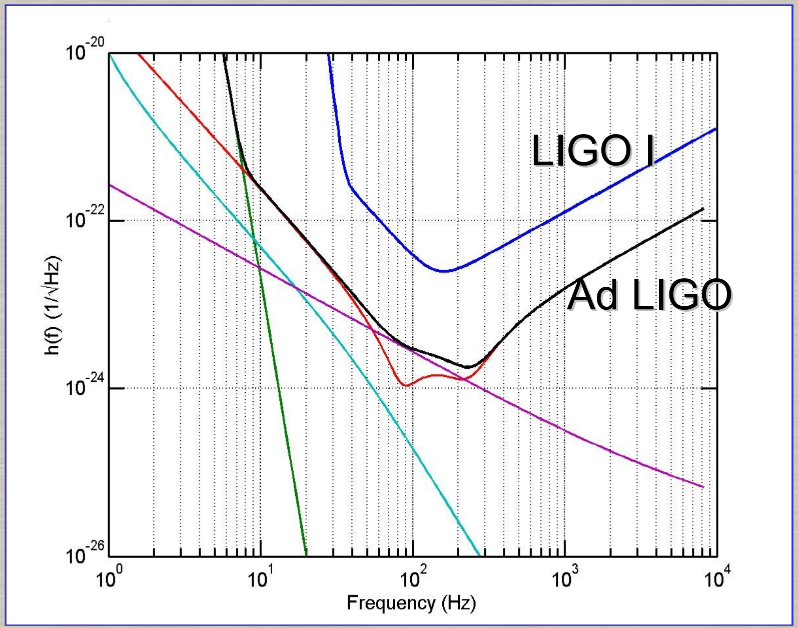
Free mass SQL $$h_{\mathrm{SQL}} = \frac{1}{L\omega}\sqrt{\frac{8\hbar}{m}}$$

Quantum Non-Demolition Measurement

Squeezed light: non-classical state of light

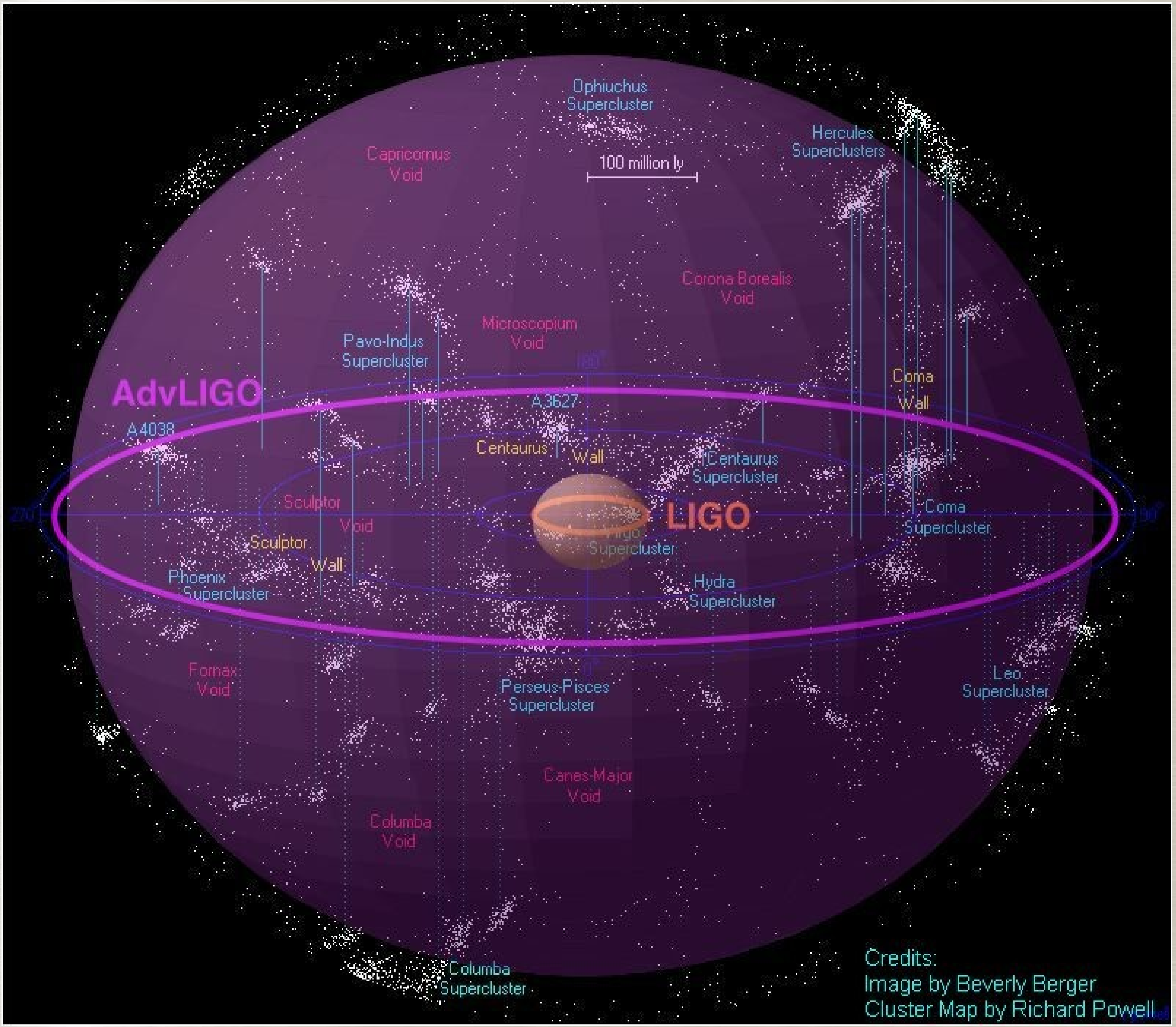


One quadrature is less fluctuating than the other



- Squeezed vacuum injection
- Ponderomotive squeezing

Astrophysical Reach of Advanced LIGO

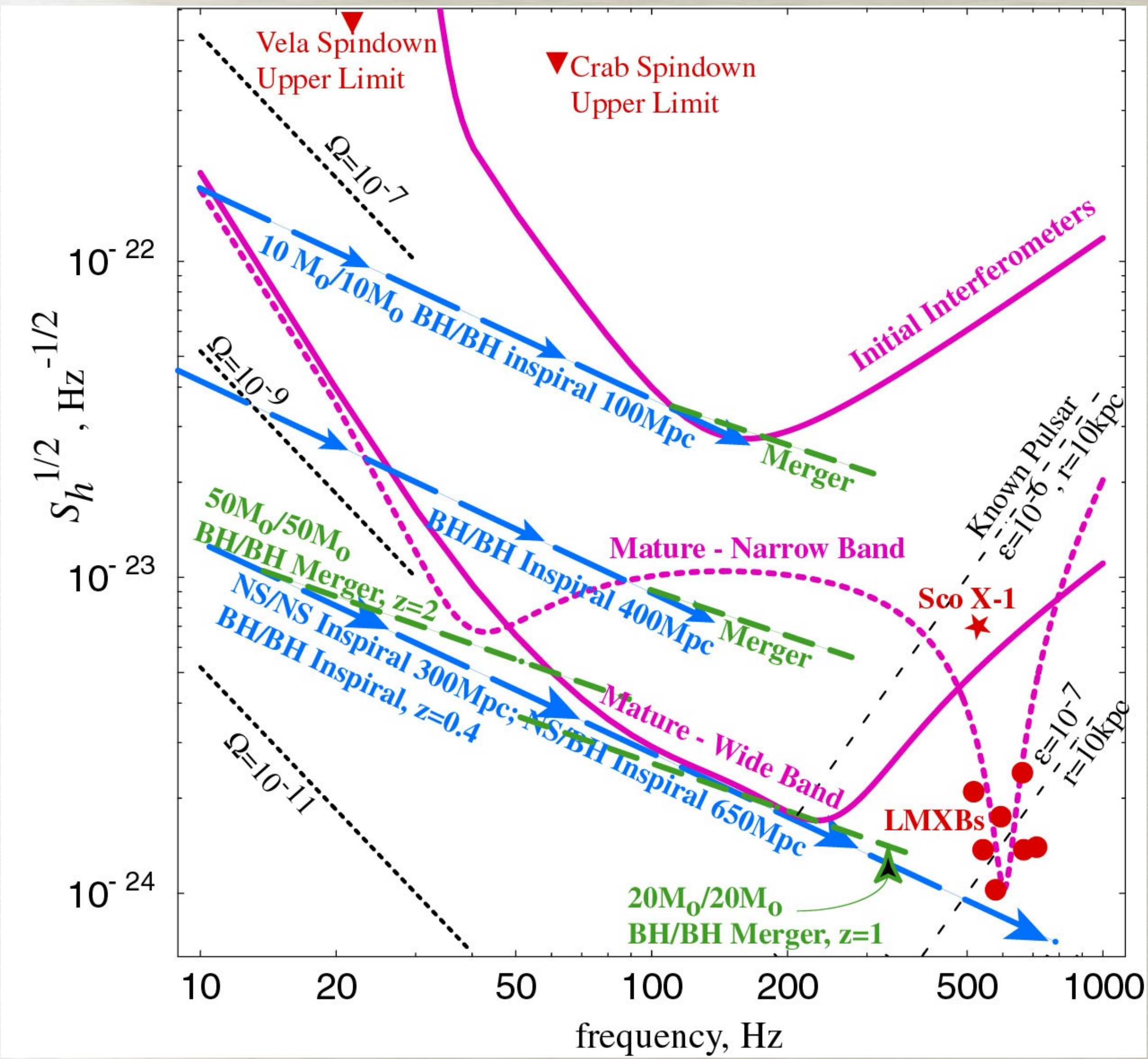


Event rate estimate for NS/NS inspirals

Current LIGO: 0.01 event/year

→ Advanced LIGO: 40 events/year

Many other astrophysical sources reachable



Conclusion

- Initial LIGO has reached its design sensitivity
- S5 accomplished : more than 1 year of data collected
- Several astrophysically interesting results are coming out
  - Crab pulsar upper limit
  - Stochastic background
  - SGR1806-20
  - GRB070201
  - and many others to come

Advanced LIGO

- Factor of 10 improvement in strain sensitivities
- Factor of 1000 increase in the detectable volume
- Many advanced technologies have developed and R&Ds are going on for Advanced LIGO
- Installation will start in 2011, Observation expected to start in 2014

Advanced LIGO is expected to start an era of gravitational wave astronomy

Acknowledgments

- Members of the LIGO Laboratory, members of the LIGO Science Collaboration, National Science Foundation