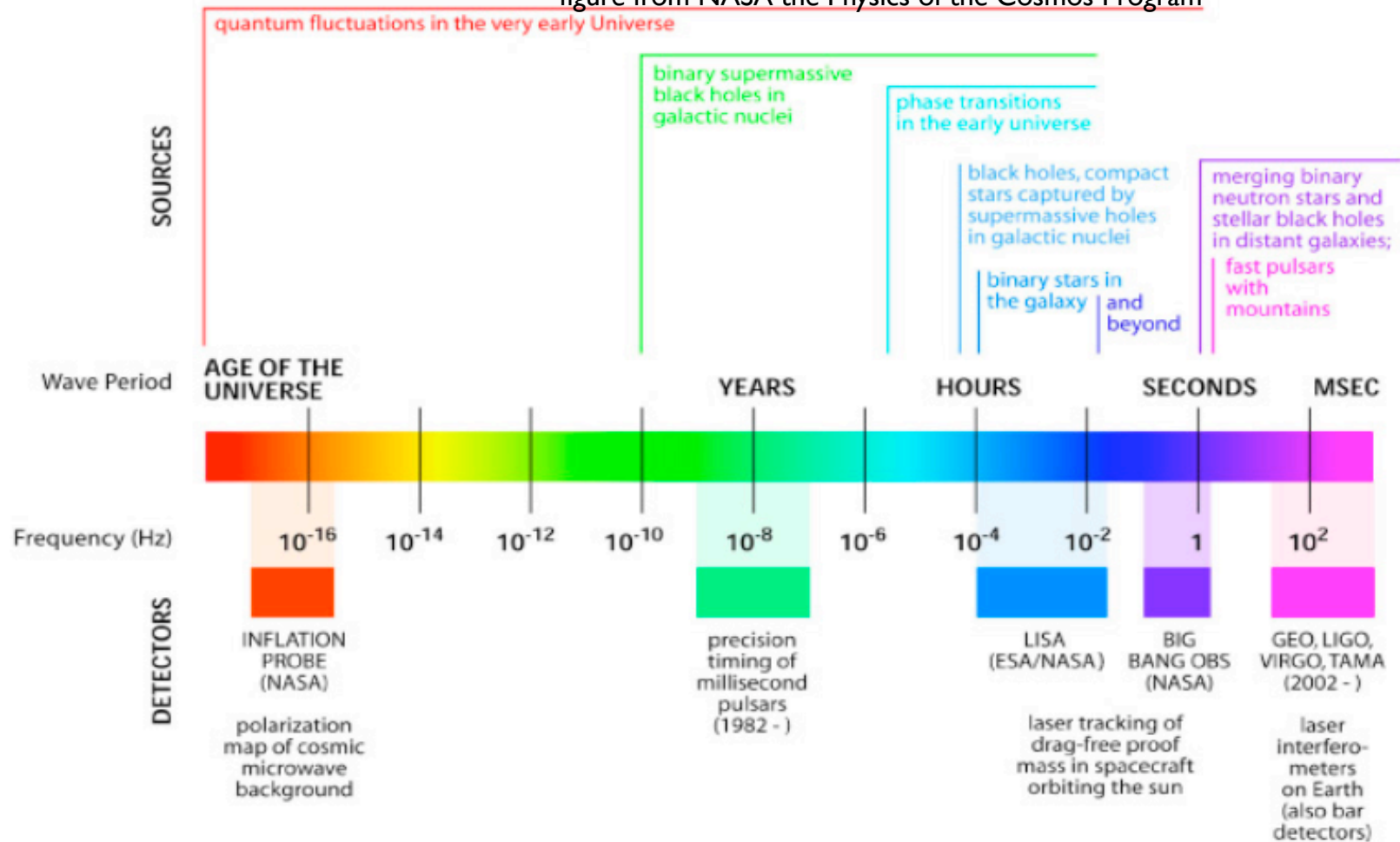


THE GRAVITATIONAL WAVE SPECTRUM

figure from NASA the Physics of the Cosmos Program



The Physics of Gravitational Wave Detection

AST 541 – 2009 Fall

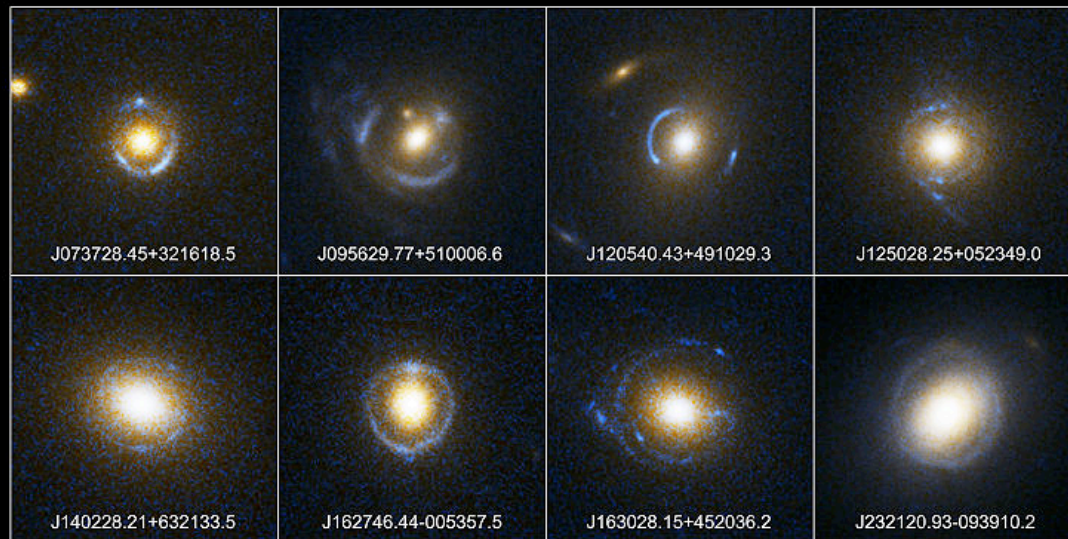
Xin Liu, 10-07-09

Outline

- ▶ **Overview**
 - ▶ why *direct* detection?
 - ▶ what to detect? – nature of GW
- ▶ **Bar detectors – resonant mass**
- ▶ **Laser interferometers**
 - ▶ LIGO – Laser Interferometer Gravitational-wave Observatory
 - ▶ Fabry-Perot cavity
 - ▶ noise limit
 - ▶ advanced LIGO
 - ▶ LISA – Laser Interferometer Space Antenna
 - ▶ mission – orbit
 - ▶ core technology
 - ▶ LISA pathfinder
- ▶ **Summary and References**

Why direct detection?

test of Einstein's theory of GR



Einstein Ring Gravitational Lenses
Hubble Space Telescope • Advanced Camera for Surveys

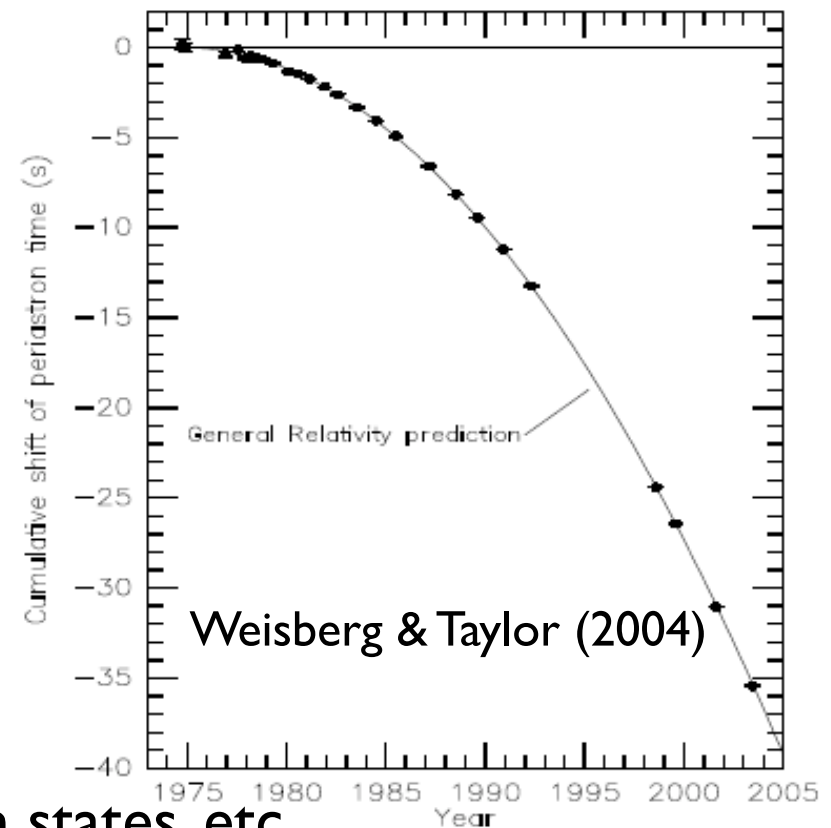
NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

STScI-PRC05-32

Eddington's
photograph of a solar
eclipse



- Hulse-Taylor binary pulsar
strong, indirect evidence for GW



- ▶ direct detection can offer ?

- ▶ tests - propagation speed, polarization states, etc.

- ▶ an otherwise unattainable view of the Universe

Nature of gravitational wave

- ▶ self-sustaining excitations of spacetime, carrying energy and traveling at the speed of light

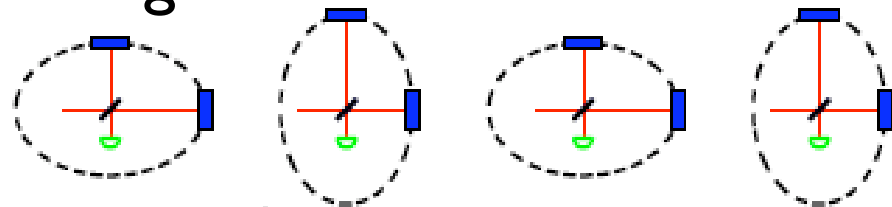


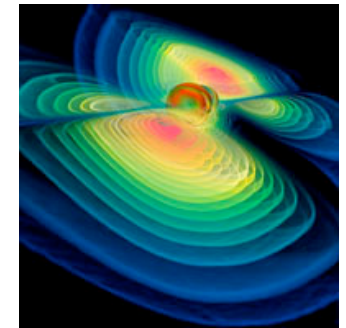
figure from the LIGO scientific collaboration

- ▶ distortions transverse to propagation direction
- ▶ two polarizations
- ▶ unperturbed through space
- ▶ require detection of minute changes

a mere fraction of the size of an atomic nucleus

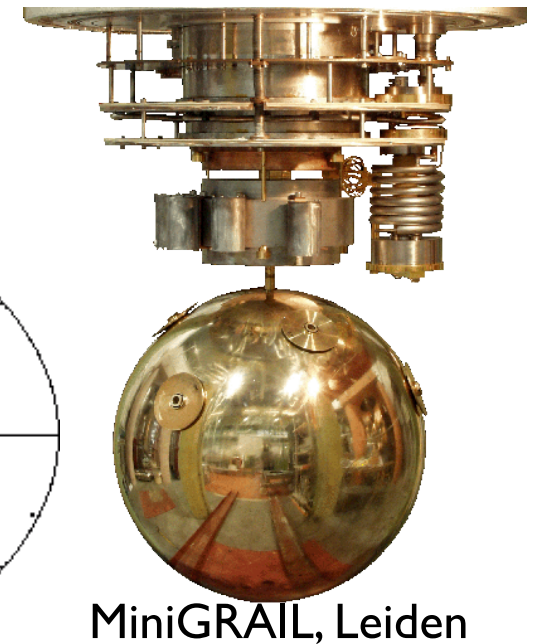
km-scale separations between free-floating masses

- ▶ detectors respond to amplitude -
 - volume increases as cube of strain sensitivity



Bar detectors – resonant mass

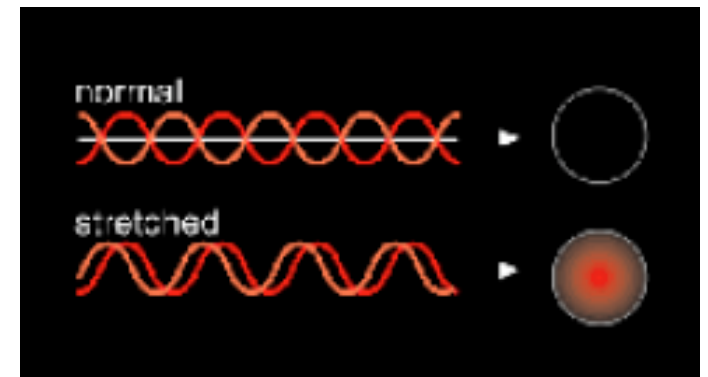
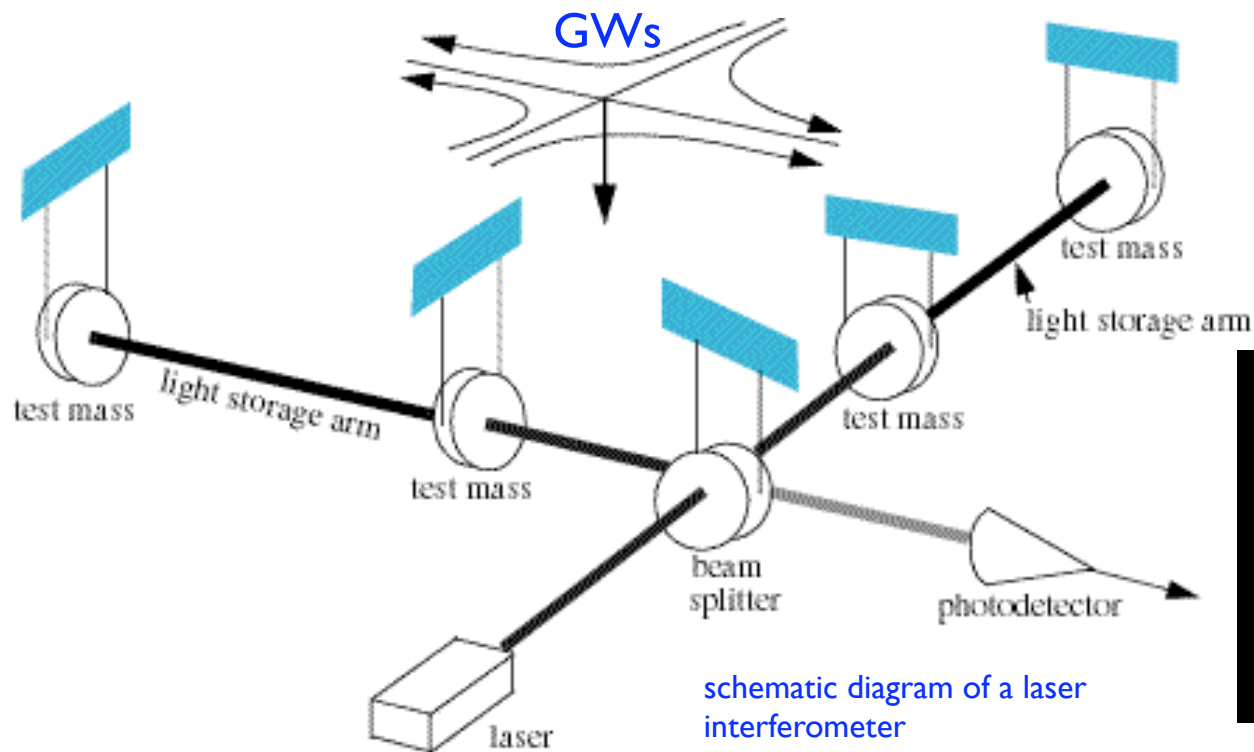
- ▶ pioneered by Joseph Weber, '60
- ▶ GW excites bar's resonant frequency - amplified



- ▶ narrow frequency range (\sim kHz)
- ▶ only sensitive to extremely powerful GWs

Laser interferometers

- ▶ Pirani `56, Gerstenshtein & Pustovoit, Weber & Forward, Weiss `72
- ▶ measure space-time distortions from light travel time difference



- ▶ compare time in two ortho directions transverse to GW
- ▶ measure interference phase difference
- ▶ more sensitive, wider frequency range

LIGO

- ▶ Michelson interferometer with **Fabry-Perot cavity** arms
- ▶ cofounded in 1992 by Thorne, Drever, & Weiss
- ▶ two ground observatories, separated by ~ 3000 km – use triangulation to locate source
- ▶ L-shaped ultra-high vacuum, 4 km on each side

Hanford, Washington



Livingston, Louisiana



- quote from Alan Weinstein (LIGO, Caltech) --



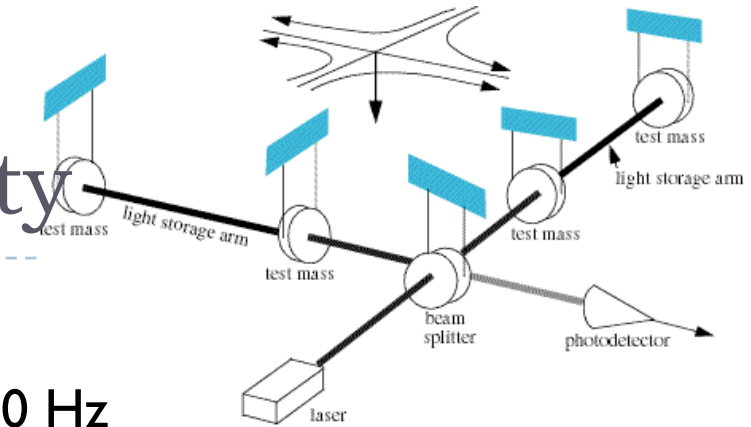
Despite a few difficulties, science runs started in 2002.



AJW, LIGO SURF, 6/16/06

- as of Nov 2005, sensitivity $h \sim 10^{-21}$ in a 100 Hz band around 100 Hz

Fabry-Perot Resonator Cavity



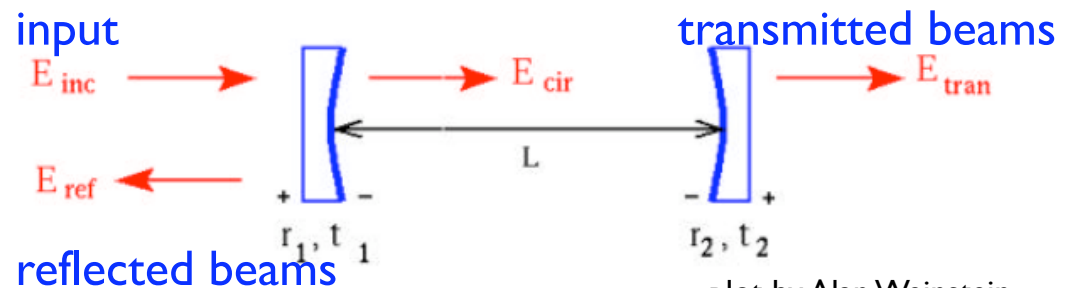
- ▶ suspended test mass on pendulum
 - ▶ $l \sim 50$ cm, so $f \sim 1$ Hz, mass 'free' above ~ 100 Hz
- ▶ arm length
 - ▶ measure $\delta \phi = 4\pi \delta L / \lambda_{\text{laser}} = 4\pi(Lh) / \lambda_{\text{laser}}$; **need large L** for small h
 - ▶ not too large (GW switches sign while laser in arms, canceling $\delta \phi$)
 - ▶ optimal $L \sim \lambda_g / 4 \sim c/f/4 \sim 750$ km (!)
 - ▶ to get longer paths – fold – **light storage** – NL ($L \sim 4$ km, $N \sim 200$)

▶ resonance: $L_0 = n \lambda_{\text{laser}} / 2$

- ▶ $E_{\text{cir}}, E_{\text{tran}}$ maximized
- ▶ $E_{\text{ref}} = 0$ when resonance

▶ near resonance:

- ▶ $L = L_0 + \delta L$
- ▶ detect phase shift in E_{ref} to measure δL



plot by Alan Weinstein

Noise budget

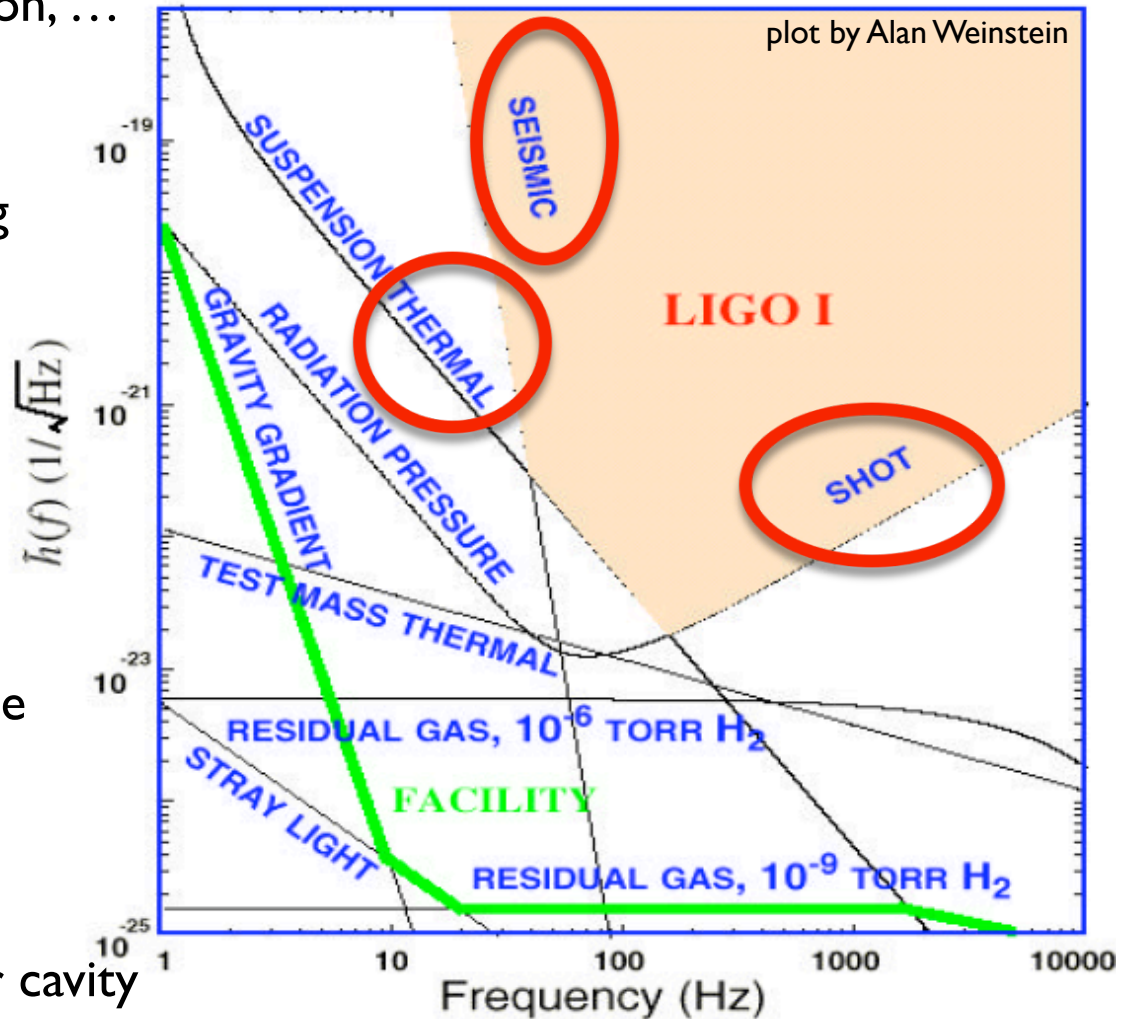


▶ displacement noise

- ▶ seismic noise, brownian motion, ...
- ▶ picked up in each bounce
- ▶ **solution** -
 - ▶ make the interferometer long
 - ▶ low dissipation, low temp
 - ▶ seismic isolation systems
 - ▶ multiple pendulums

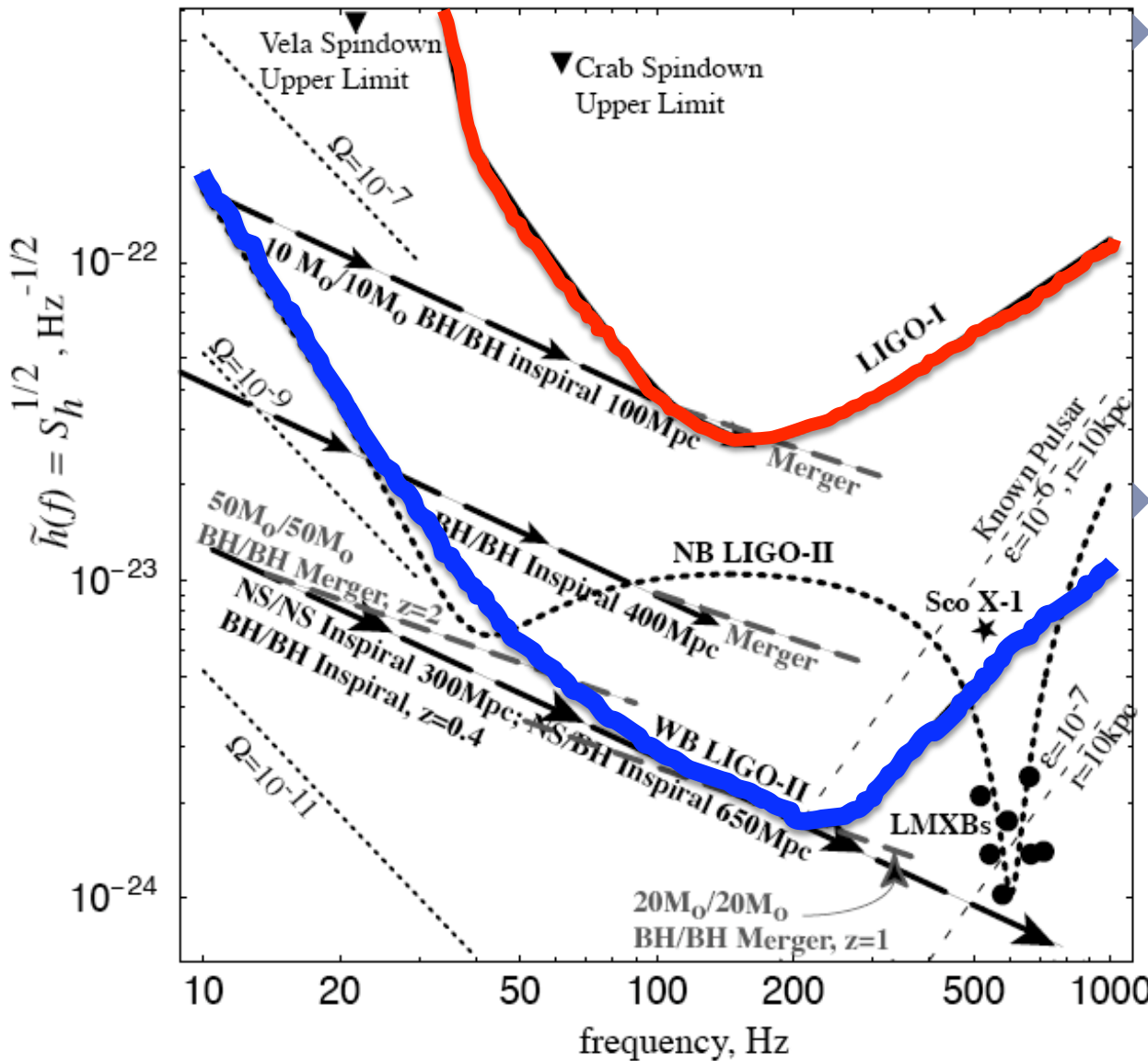
▶ readout noise

- ▶ shot noise ($\sim 1/\sqrt{N}$)
- ▶ radiation pressure
- ▶ amplitude and frequency noise
- ▶ **solution** -
 - ▶ powerful, quiet laser
 - ▶ recycle laser
 - ▶ recycle GW signal w. another cavity



Advanced LIGO

▶ expected ~2014

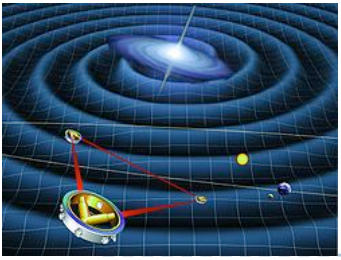


▶ reduced noise

- ▶ higher power laser
- ▶ signal recycling
- ▶ low loss optics
- ▶ active seismic isolation
- ▶ multiple suspensions

▶ sensitivity: > an order of magnitude improvements

e.g., NS/NS	
$\mathcal{R}_{gal}, yr^{-1}$	$10^{-6} - 5 \times 10^{-4}$
D_I	20 Mpc
\mathcal{R}_I, yr^{-1}	<u>$3 \times 10^{-4} - 0.3$</u>
D_{WB}	300 Mpc
$\mathcal{R}_{WB}, yr^{-1}$	1 - 800



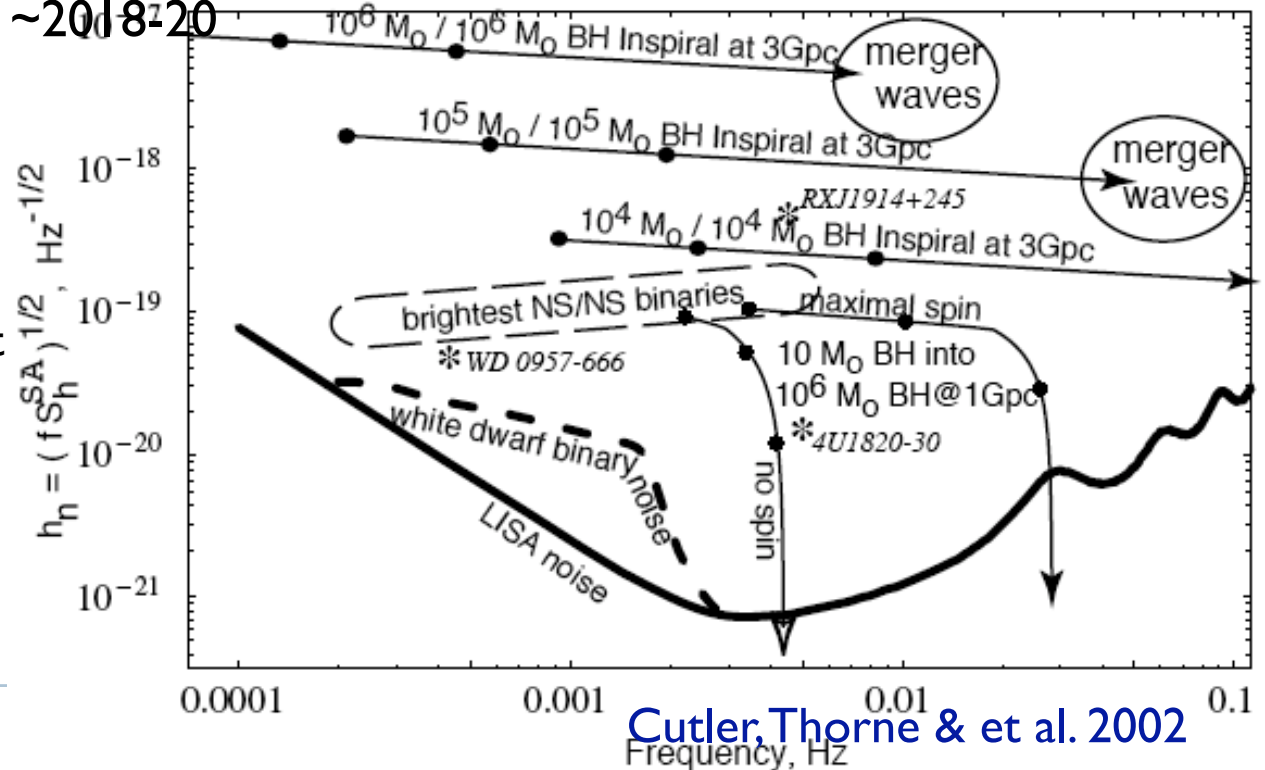
LISA - overview

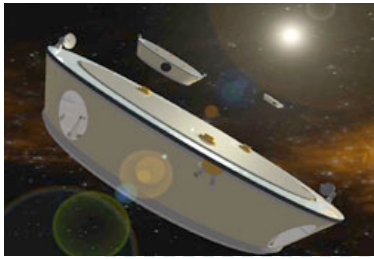
- ▶ laser interferometry over astronomical distances
- ▶ sensitive to lower frequencies, complementary with LIGO
- ▶ timeline
 - ▶ technology development begun in 1999
 - ▶ major updates in 2003, 05
 - ▶ earliest possible launch ~2018-2020

▶ sensitivity

- ▶ 0.03 mHz -- 0.1 Hz
- ▶ noise limits
 - ▶ low ν - displacement
 - ▶ mid ν - readout
 - ▶ high ν - arm length

▶ sources





LISA – mission - orbit



figure from <http://lisa.nasa.gov>

▶ equilateral triangle in earth trailing orbit

- ▶ three identical spacecraft
 - ▶ arm length: 5 million km
- ▶ center - earth trailing orbit, 20° behind
- ▶ plane - inclined 60° to ecliptic

▶ advantages

- ▶ easier to design, test, deploy
- ▶ two independent interferometers
 - ▶ help validate data
- ▶ away from Earth - minimize disturbance
- ▶ natural free-fall orbits maintaining configuration

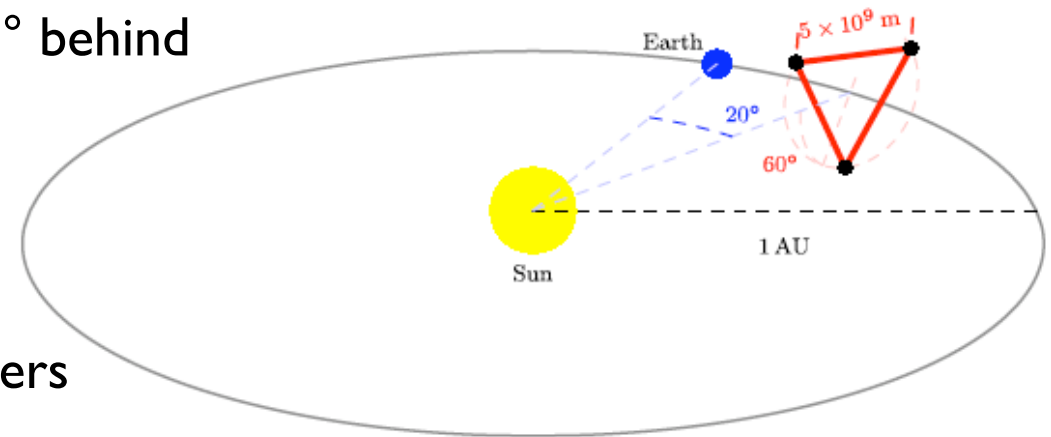
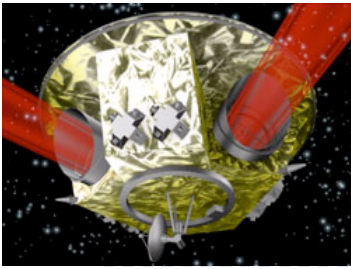


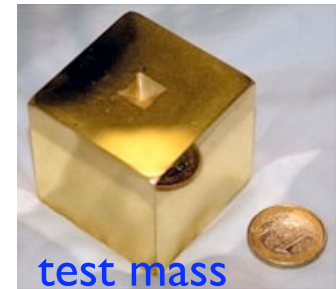
figure from Jennrich 2009

▶ mission duration goal - ten years



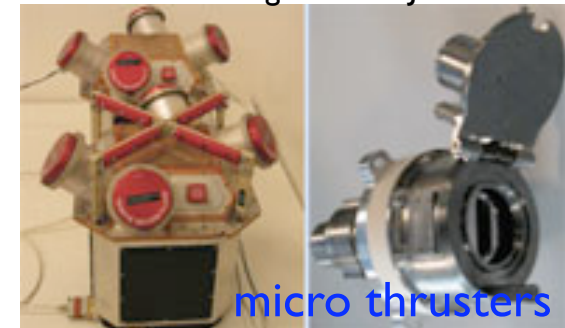
LISA - core technology

- ▶ to eliminate disturbance from:
 - ▶ **external**
 - ▶ light pressure, solar wind, B field, gravity from Earth and Moon, etc.
 - ▶ **internal**
 - ▶ electric field, residual gas pressure, thermal radiation, etc.
- ▶ **drag free operation**
 - ▶ spacecraft controlled to follow test masses
 - precision of ~ 10 nm
 - ▶ microNewton thrusters
 - tiny bursts of thrust with low noise
- ▶ **laser interferometry**
 - ▶ correct for diffraction losses - transponding
 - ▶ residual laser frequency noise - post-processing
 - using Time Delay Interferometry



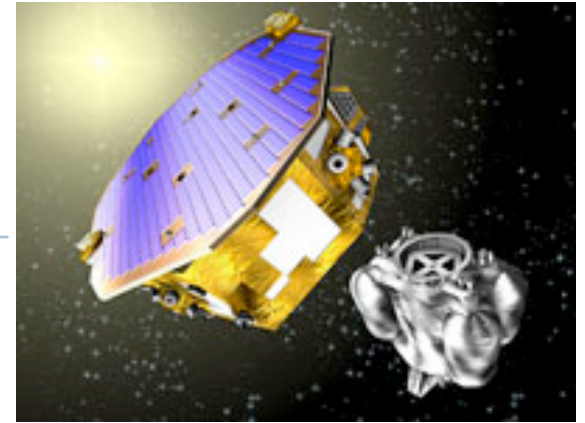
test mass

figure from Jennrich 2009



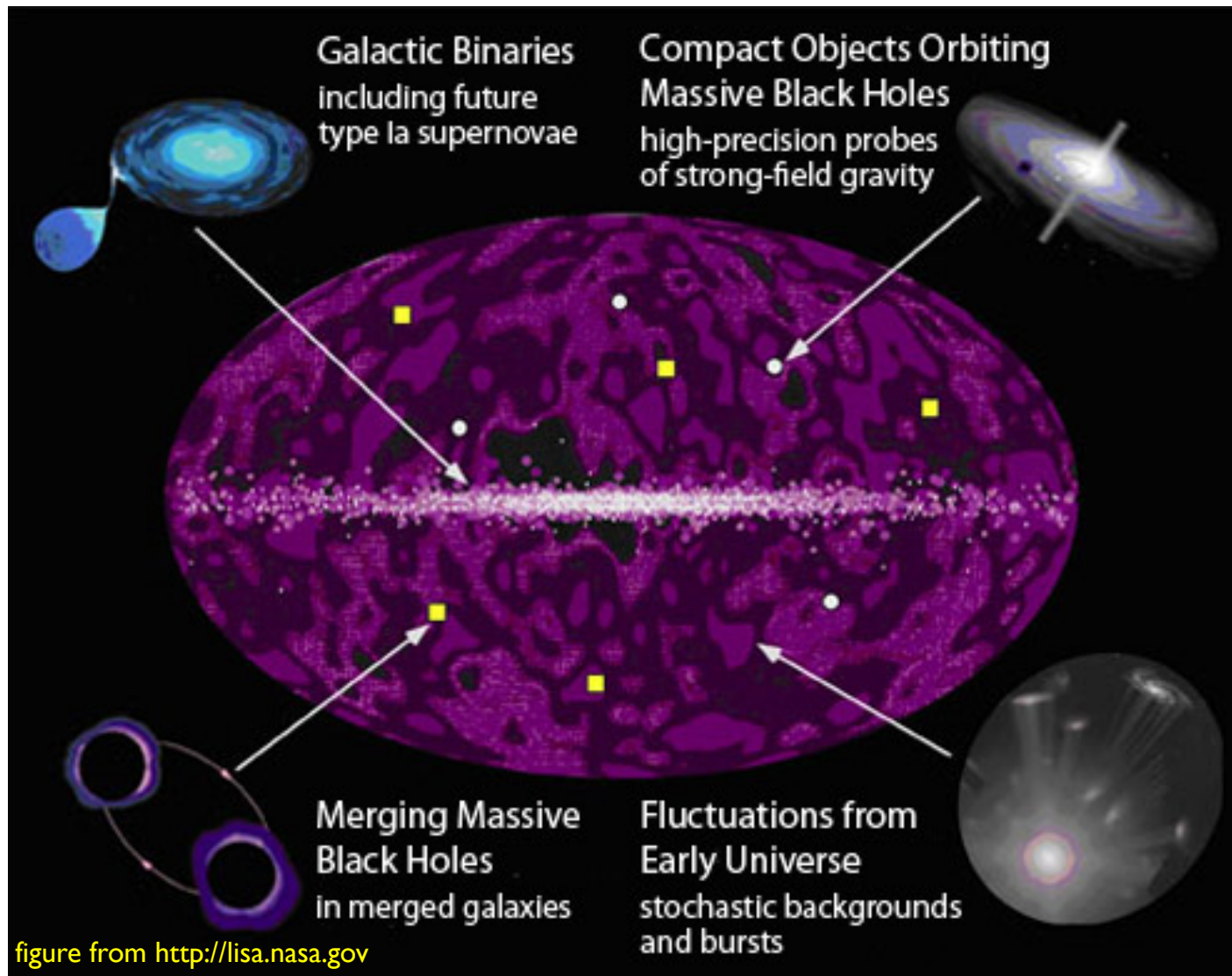
micro thrusters

LISA pathfinder



- ▶ launch due 2010
- ▶ to validate design and configuration of LISA
 - ▶ techs that cannot be properly verified on ground
 - ▶ drag-free and attitude control in spacecraft with two test masses
 - ▶ feasibility of laser interferometry at the level of accuracy envisaged for LISA
 - ▶ endurance of different instruments and hardware in the space environment
- ▶ pave the way for LISA, and for any other future space-based test of GR

“New eyes” for physics and astronomy



Summary

- ▶ direct detecting GW: important for testing GR; a brand new window for physics and astronomy
- ▶ Bar detectors
 - ▶ resonant mass, narrow frequency range, moderate sensitivity
- ▶ Laser interferometers
 - ▶ LIGO
 - ▶ Michelson interferometer with Fabry-Perot cavities
 - ▶ noise limits: seismic, thermal, shot noise
 - ▶ advanced LIGO: > ten times better sensitivity
 - ▶ LISA
 - ▶ mission - equilateral triangle in earth trailing orbit
 - ▶ core technology: drag free operation, laser interferometry in space
 - ▶ LISA pathfinder - test LISA techs

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