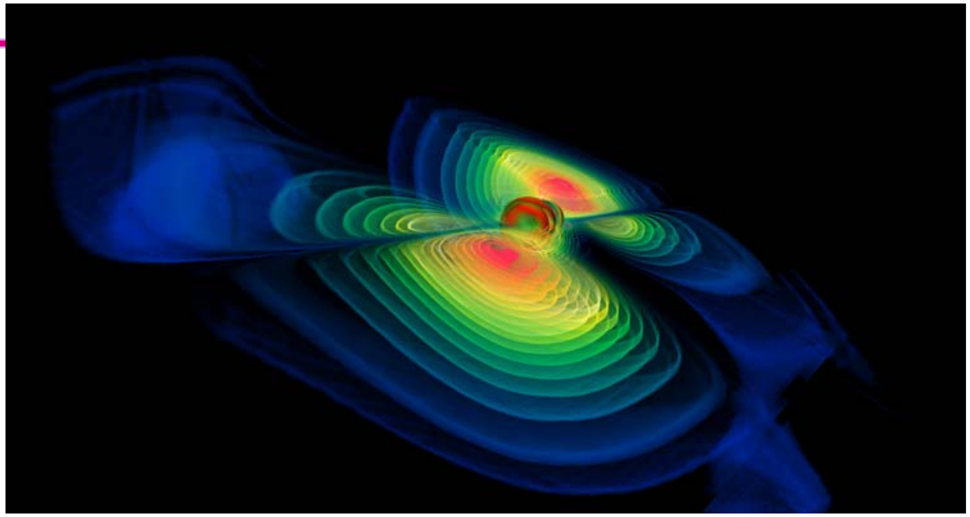
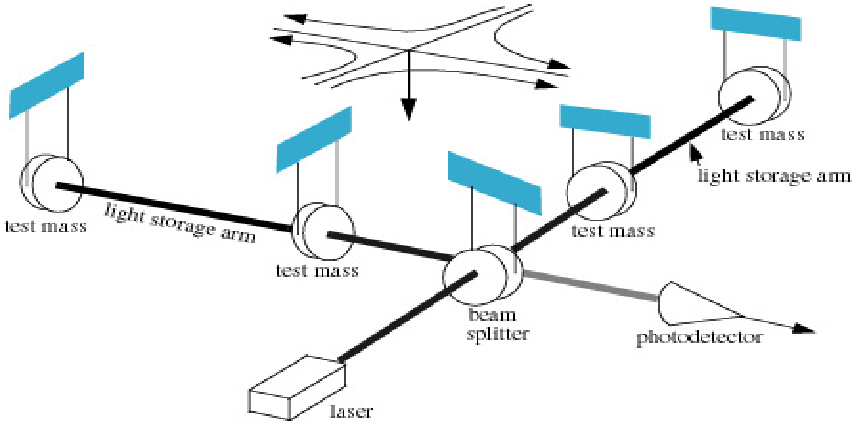
Status of the search for Gravitational Waves

- Gravitational waves
- Detection of GW's
- Astrophysical sources
- The LIGO project and its sister projects
- Recent results
- Conclusions



"Colliding Black Holes"
National Center for Supercomputing Applications (NCSA)

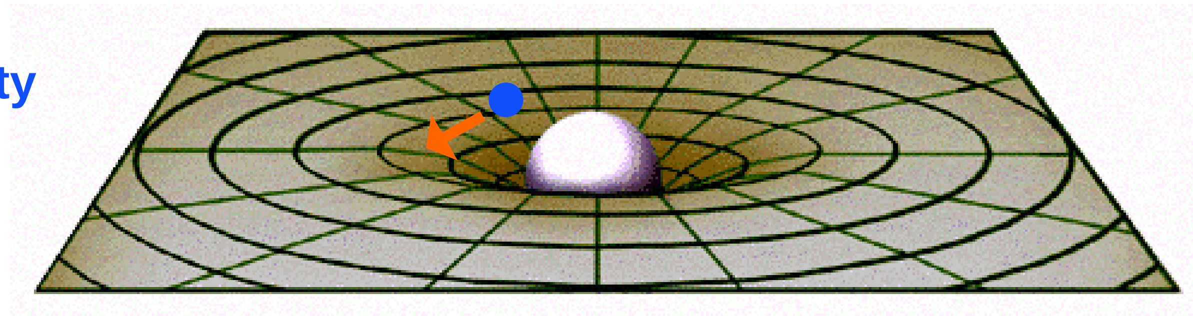


No discovery to report here!

Alan Weinstein, Caltech

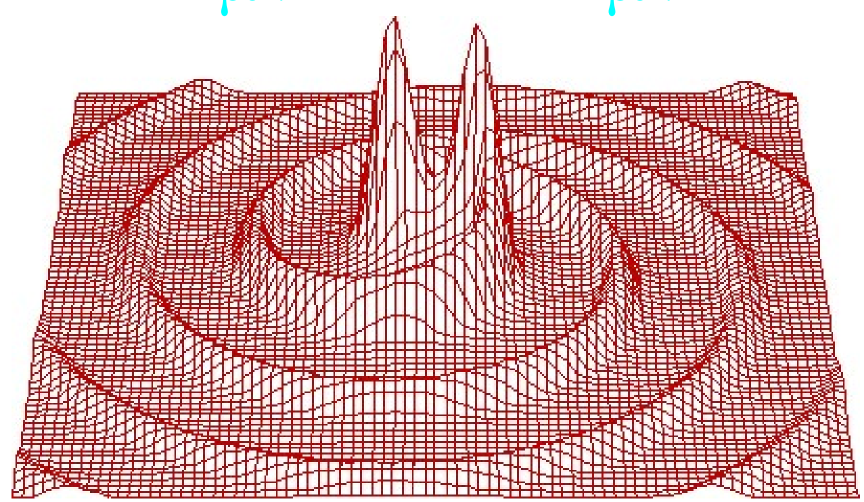
Gravitational Waves

Static gravitational fields are described in General Relativity as a curvature or warpage of space-time, changing the distance between space-time events.



Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.

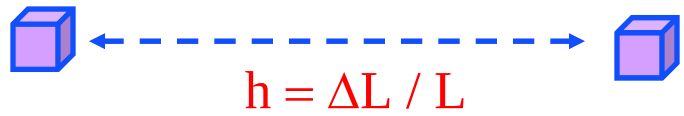
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



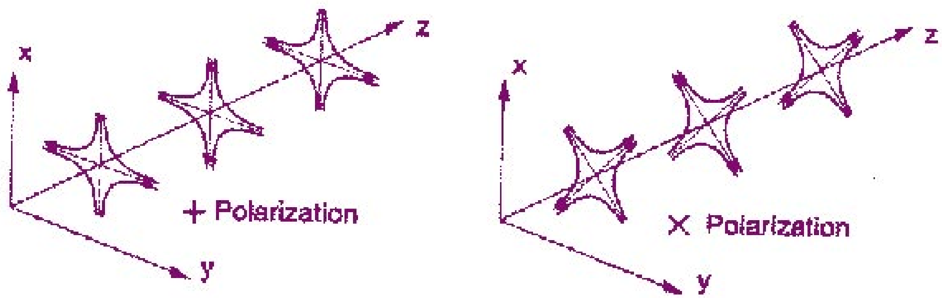
If the source is moving (at speeds close to c), *eg,* because it's orbiting a companion, the "news" of the changing gravitational field propagates outward as gravitational radiation – a wave of spacetime curvature

Nature of Gravitational Radiation

General Relativity predicts that rapidly changing gravitational fields produce ripples of curvature in fabric of spacetime



- propagating at speed of light
    - *mass of graviton = 0*
- Stretches and squeezes space between "test masses" – strain $h = \Delta L / L$
- space-time distortions are transverse to direction of propagation
- GW are tensor fields (EM: vector fields)
  two polarizations: plus (⊕) and cross (⊗)
  (EM: two polarizations, *x* and *y*)
  Spin of graviton = 2



Contrast with EM dipole radiation:

$\hat{x}$ ((⟷)) $\hat{y}$ ↕

LIGO

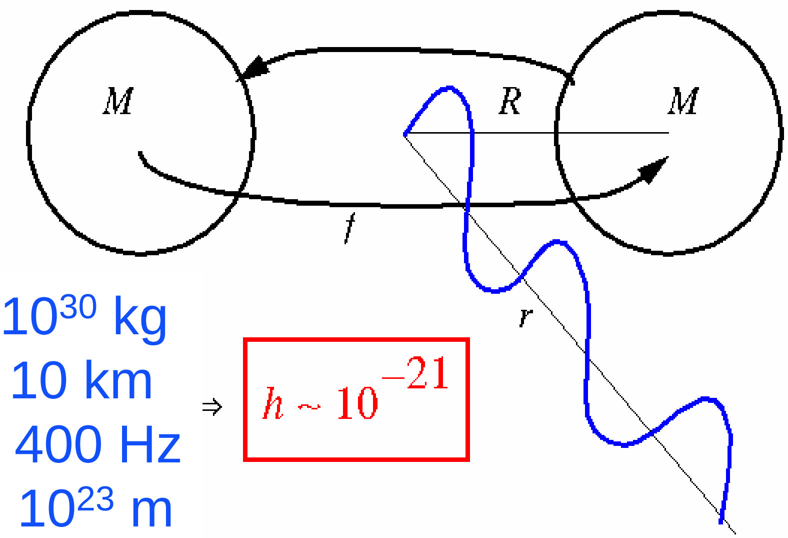
Sources of GWs

Energy-momentum conservation:
cons of energy $\Rightarrow$ no monopole radiation
cons of momentum $\Rightarrow$ no dipole radiation
lowest multipole is quadrupole wave

- Accelerating charge $\Rightarrow$ electromagnetic radiation (dipole)
- Accelerating mass $\Rightarrow$ gravitational radiation (quadrupole)
- Amplitude of the gravitational wave (dimensional analysis):

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \quad \Rightarrow \quad h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

- $\ddot{I}_{\mu\nu}$ = second derivative of mass quadrupole moment (non-spherical part of kinetic energy – tumbling dumb-bell)
- G is a small number!
- Need huge mass, relativistic velocities, nearby.
- For a binary neutron star pair, 10m light-years away, solar masses moving at 15% of speed of light:



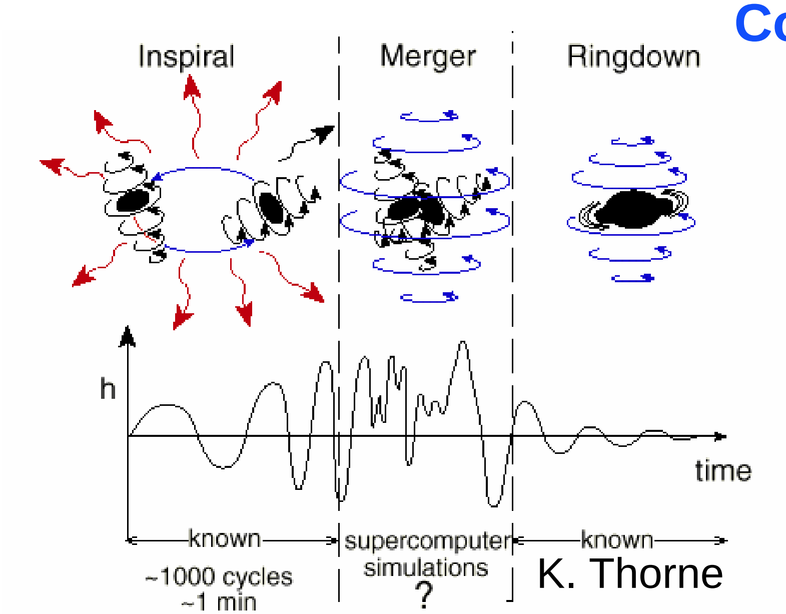
M ~ 10^{30} kg
R ~ 10 km
f ~ 400 Hz
r ~ 10^{23} m

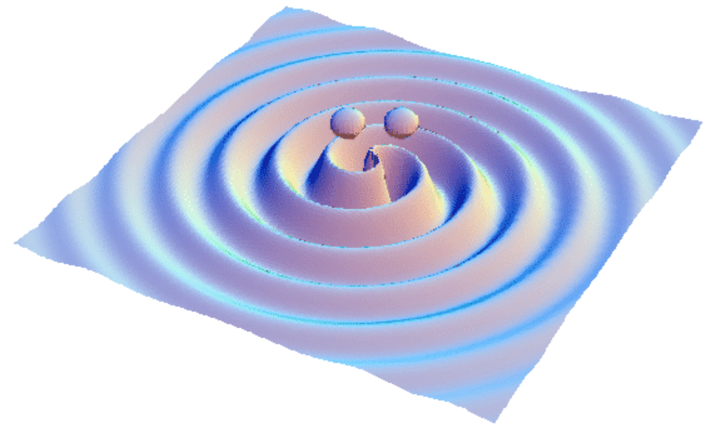
$\Rightarrow$ $\boxed{h \sim 10^{-21}}$

Terrestrial sources *TOO WEAK*!

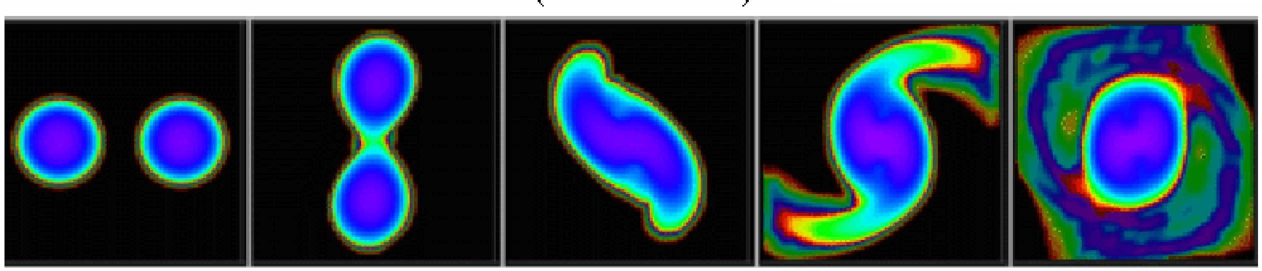
GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

Compact binary mergers





- Neutron star – neutron star (Centrella et al.)

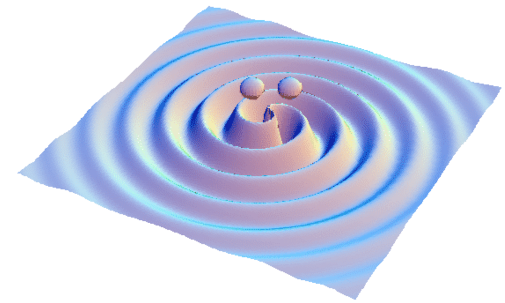


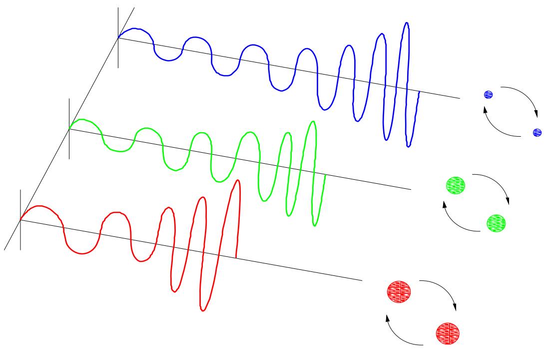
NASA / D. Berry

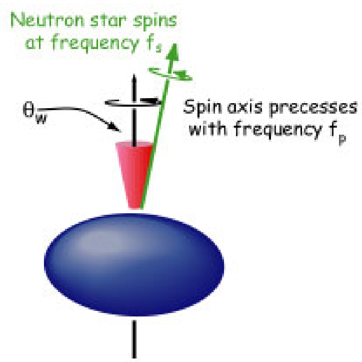
The physics of Coalescing Compact Binaries

- The best understood potential source of gravitational waves.
- Stellar mass systems (neutron stars) extend to high frequencies before merging (100's of Hz; v/c ~ 0.5).
- NS/NS mergers give information about the nuclear equation of state
- More massive black hole mergers provide unequivocal evidence that there really are black holes, and powerful tests of GR ("no hair theorem").
- Standard "sirens" – can be used to construct Hubble diagrams (luminosity distance vs redshift).
- Supermassive black hole mergers are believed to play a major role in the formation and evolution of galaxies from z~20 till present time.
- The largest source of energy conversion known in the universe.
- They can be detected out to cosmological distances.
- Unfortunately, the rate is very uncertain!

What will we see?

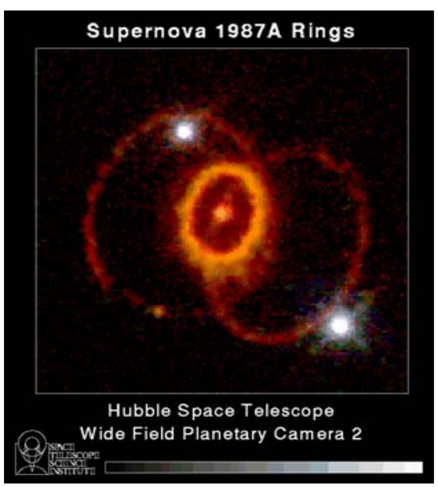


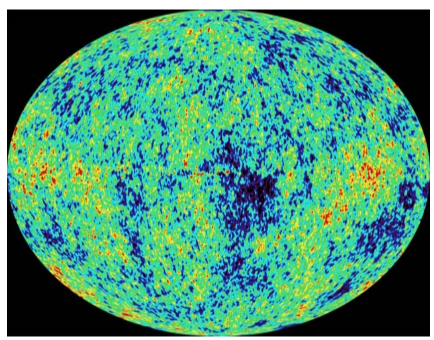




GWs from the most energetic processes in the universe!

- black holes orbiting each other and then merging together
- Supernovas, GRB engines
- rapidly spinning neutron stars
- Vibrations from the Big Bang



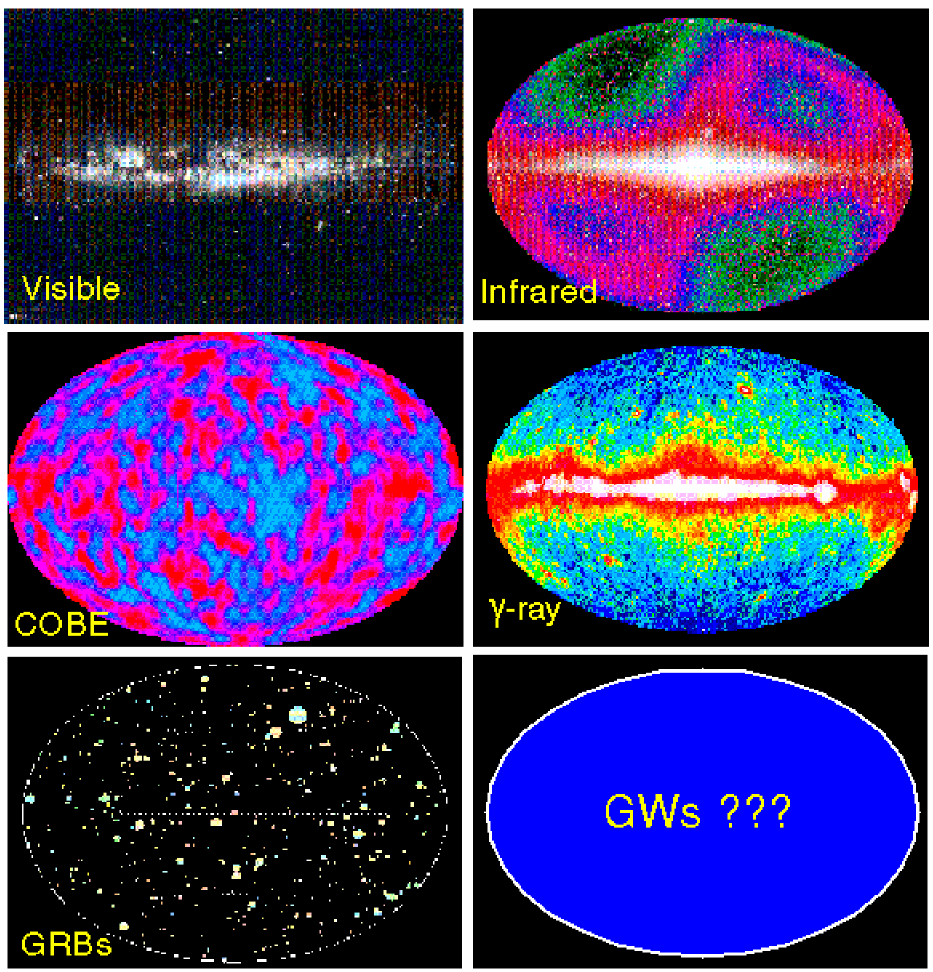


Analog from cosmic microwave background -- WMAP 2003

A NEW WINDOW ON THE UNIVERSE WILL OPEN UP FOR EXPLORATION.

LIGO

A NEW WINDOW ON THE UNIVERSE



The history of Astronomy: new bands of the EM spectrum opened → major discoveries!

GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

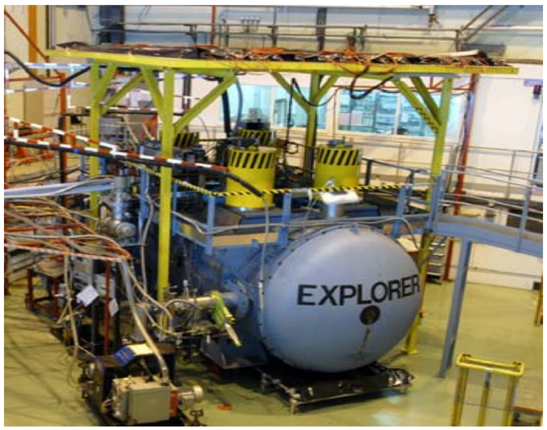
GW astronomy is a totally new, unique window on the universe

Gravitational wave detectors

- **Bar detectors**
  - Invented and pursued by Joe Weber in the 60's
  - Essentially, a large cryogenic "bell", set ringing (at ~ 900 Hz) by GW
  - Operated as a network: IGEC
- **Michelson interferometers**
  - At least 4 independent discovery of method:
  - Pirani `56, Gerstenshtein and Pustovoit, Weber, Weiss `72
  - Pioneering work by Weber and Robert Forward, in 60's
  - Now: large, earth-based detectors.
  - Soon: space-based (LISA).

Cryogenic Resonant detectors-
sensitivity ~ h_{rms}~ 10^{-19}; excellent duty cycle

Explorer (at CERN)
Univ. of ROME ROG group



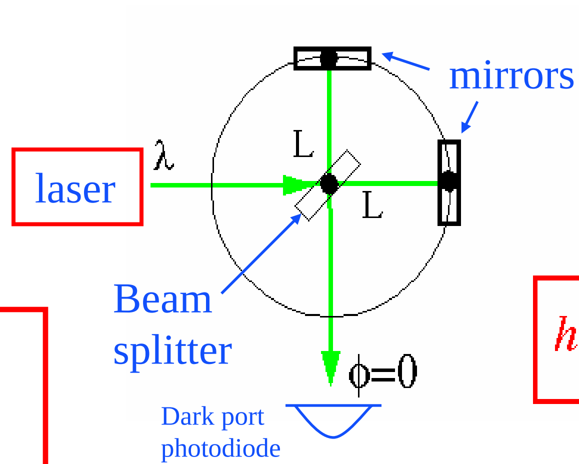
Nautilus (at Frascati)
Univ. of ROME ROG group

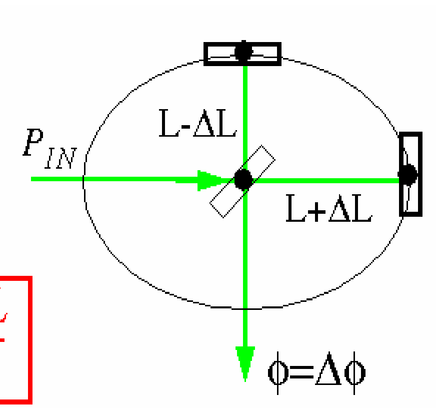
AURIGA LNL, Padova

ALLEGRO, LSU

Interferometric detection of GWs

GW acts on freely falling masses:



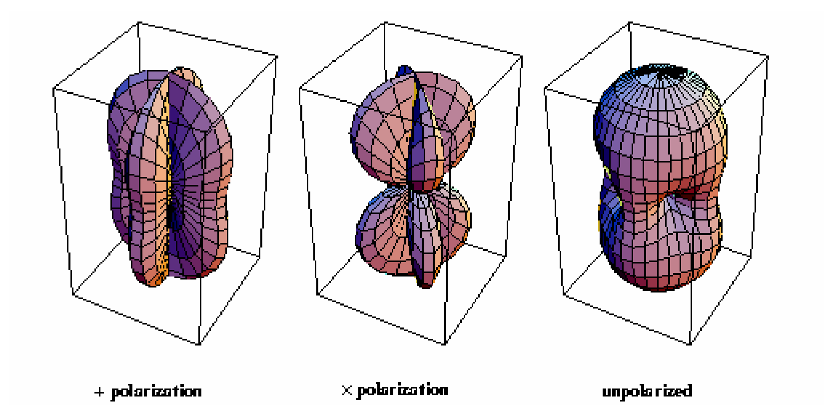


$$\boxed{h = \frac{\Delta L}{L}}$$

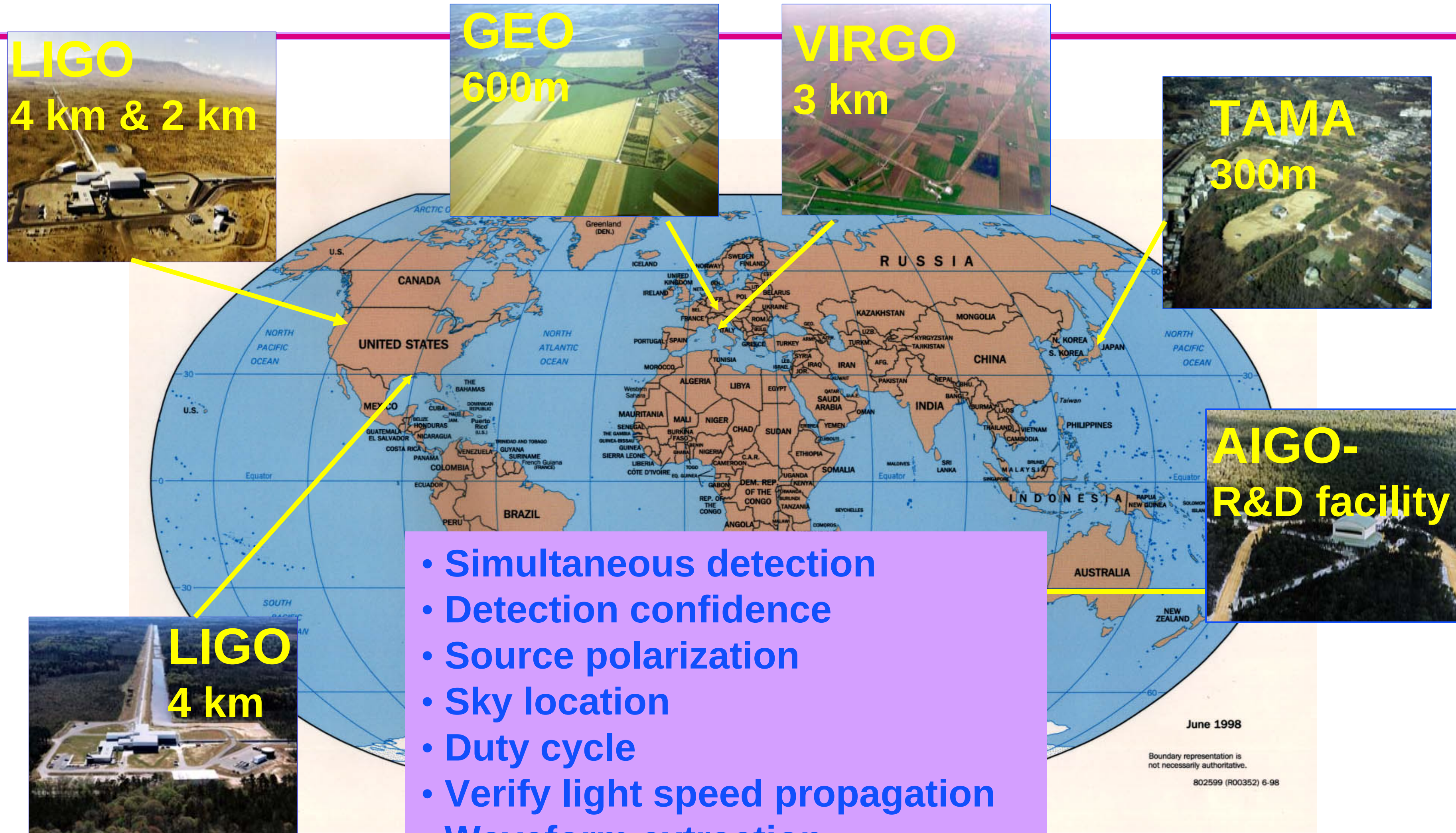
For fixed ability to measure *ΔL*, make *L* as big as possible!

$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

Antenna pattern:
(not very directional!)



Global network of interferometers

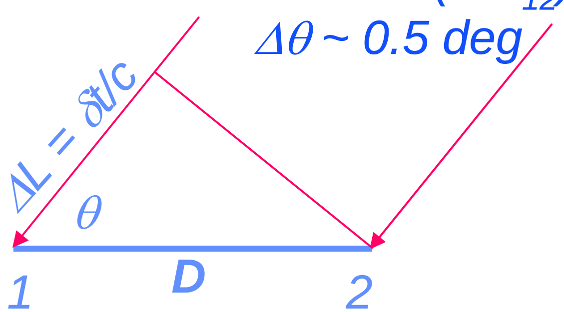


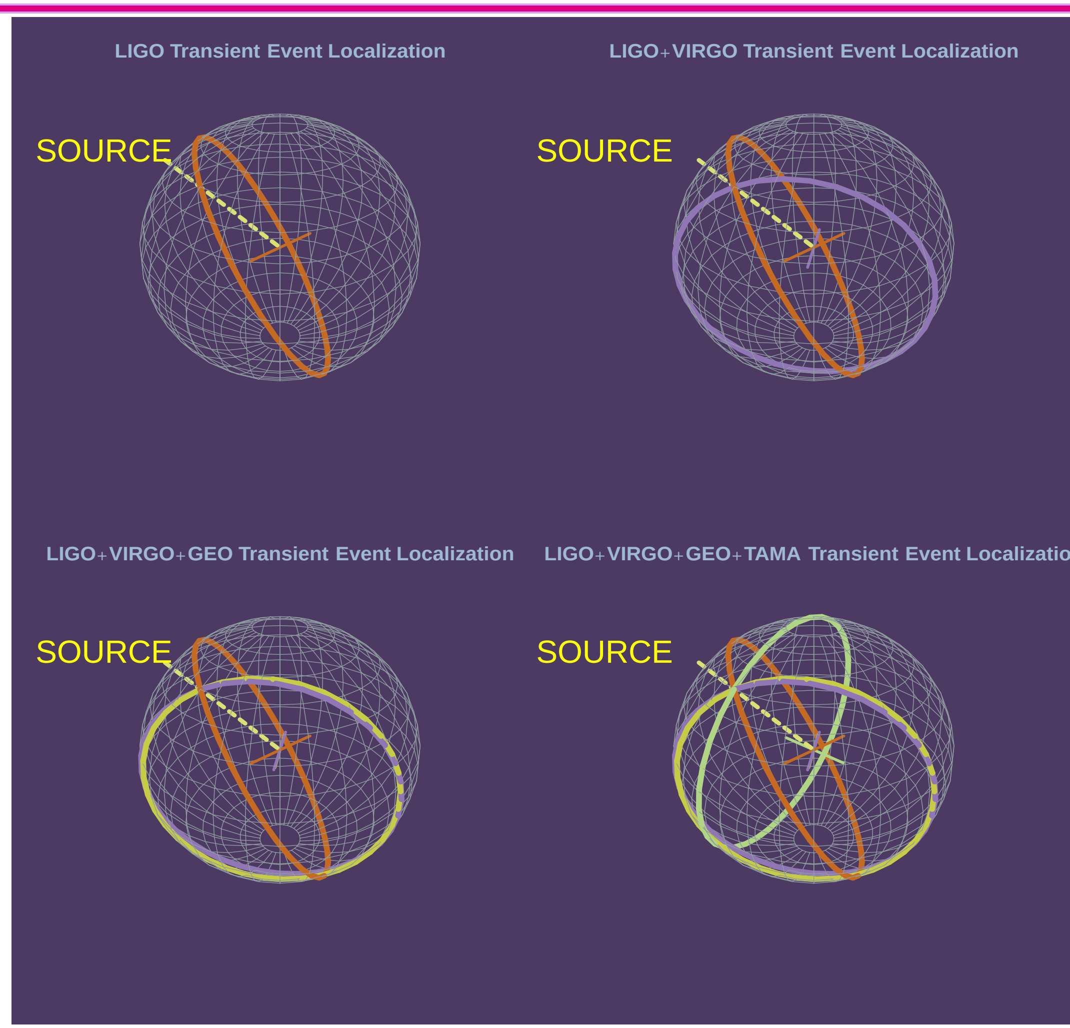
- Simultaneous detection
- Detection confidence
- Source polarization
- Sky location
- Duty cycle
- Verify light speed propagation
- Waveform extraction

Event Localization With An Array of GW Interferometers

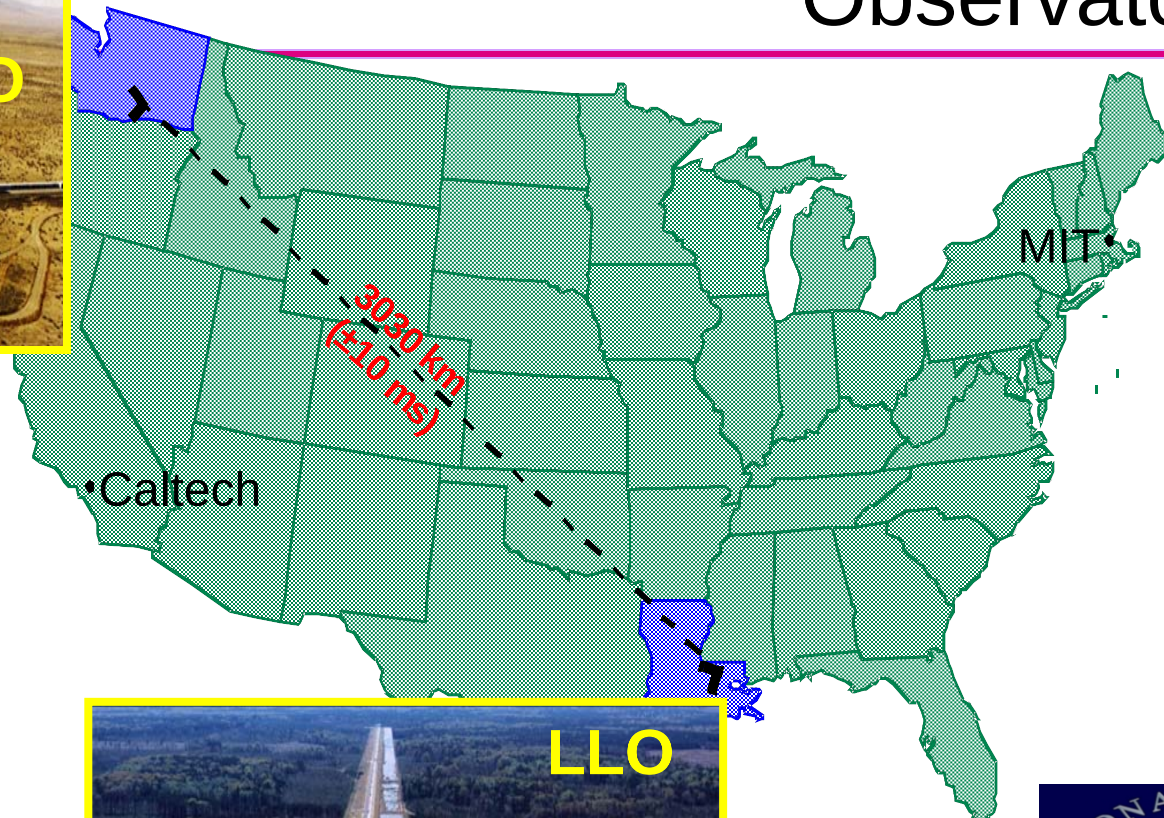
$\cos\theta = \delta t / (c\, D_{12})$

$\Delta\theta \sim 0.5$ deg

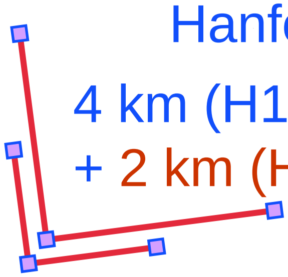




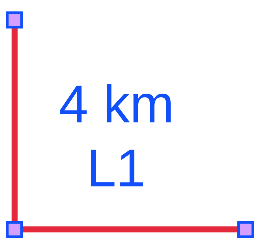
LIGO: Laser Interferometer Gravitational-wave Observatory



Hanford, WA



4 km (H1)
+ 2 km (H2)



4 km
L1

Livingston, LA

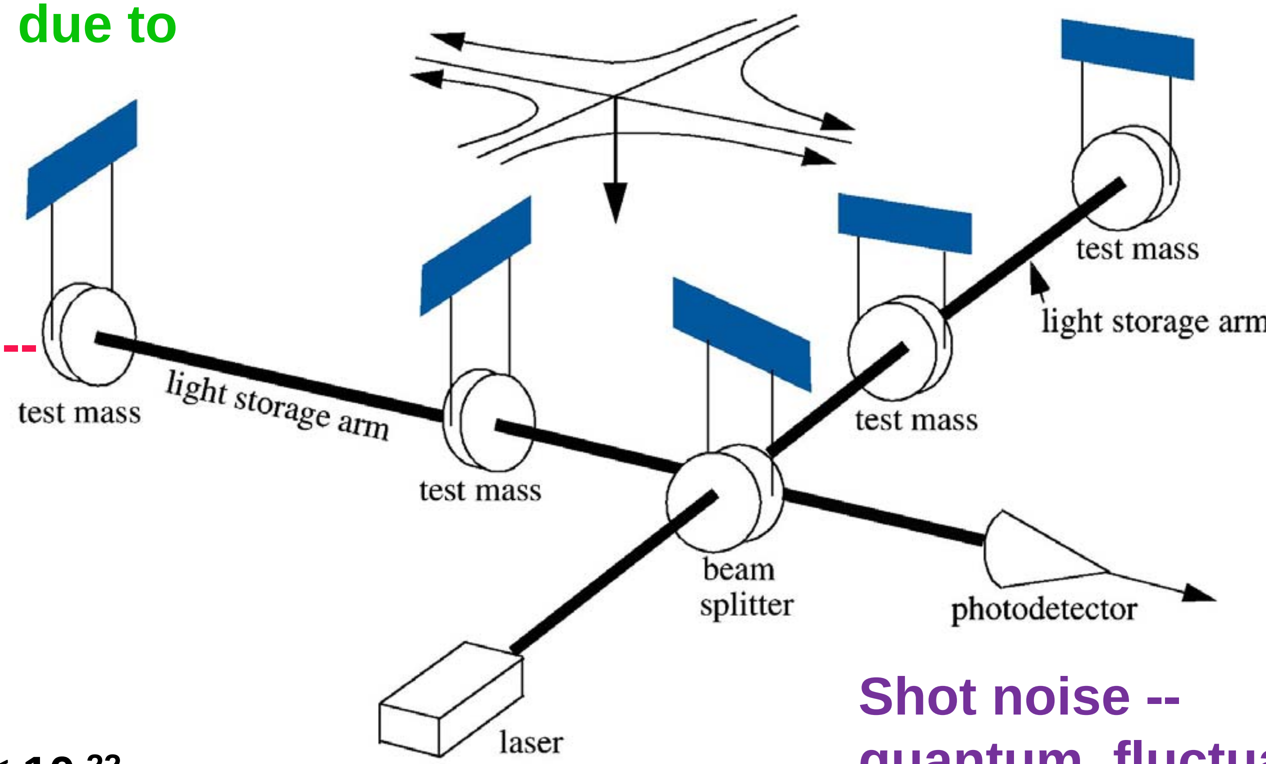
GW detector at a glance

Seismic motion -- ground motion due to natural and anthropogenic sources

Thermal noise -- vibrations due to finite temperature

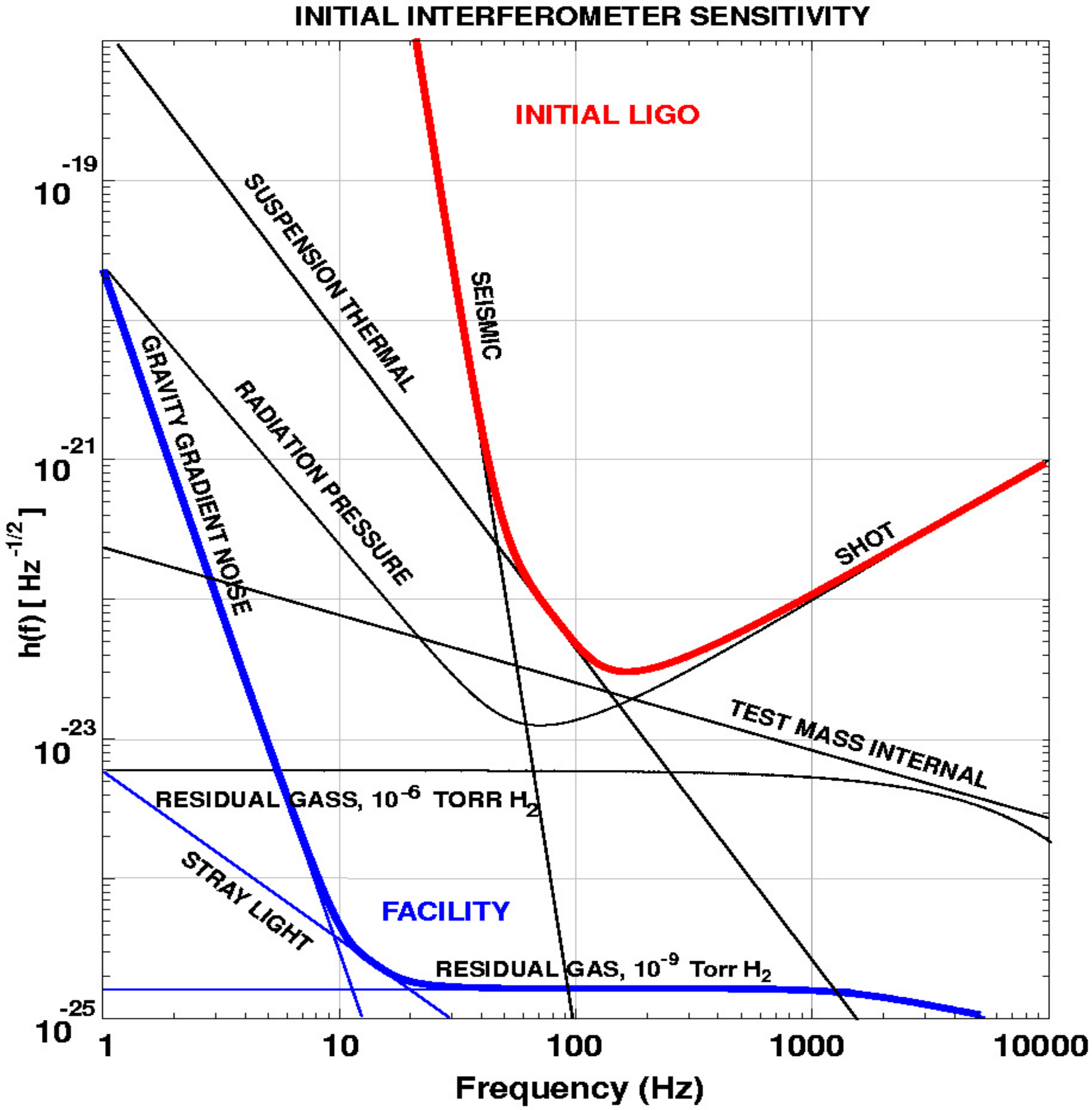
$$h = \Delta L / L$$

want to get h $\leq 10^{-22}$; can build L = 4 km; must measure ΔL = h L $\leq 4\times10^{-19}$ m



Shot noise -- quantum fluctuations in the number of photons detected

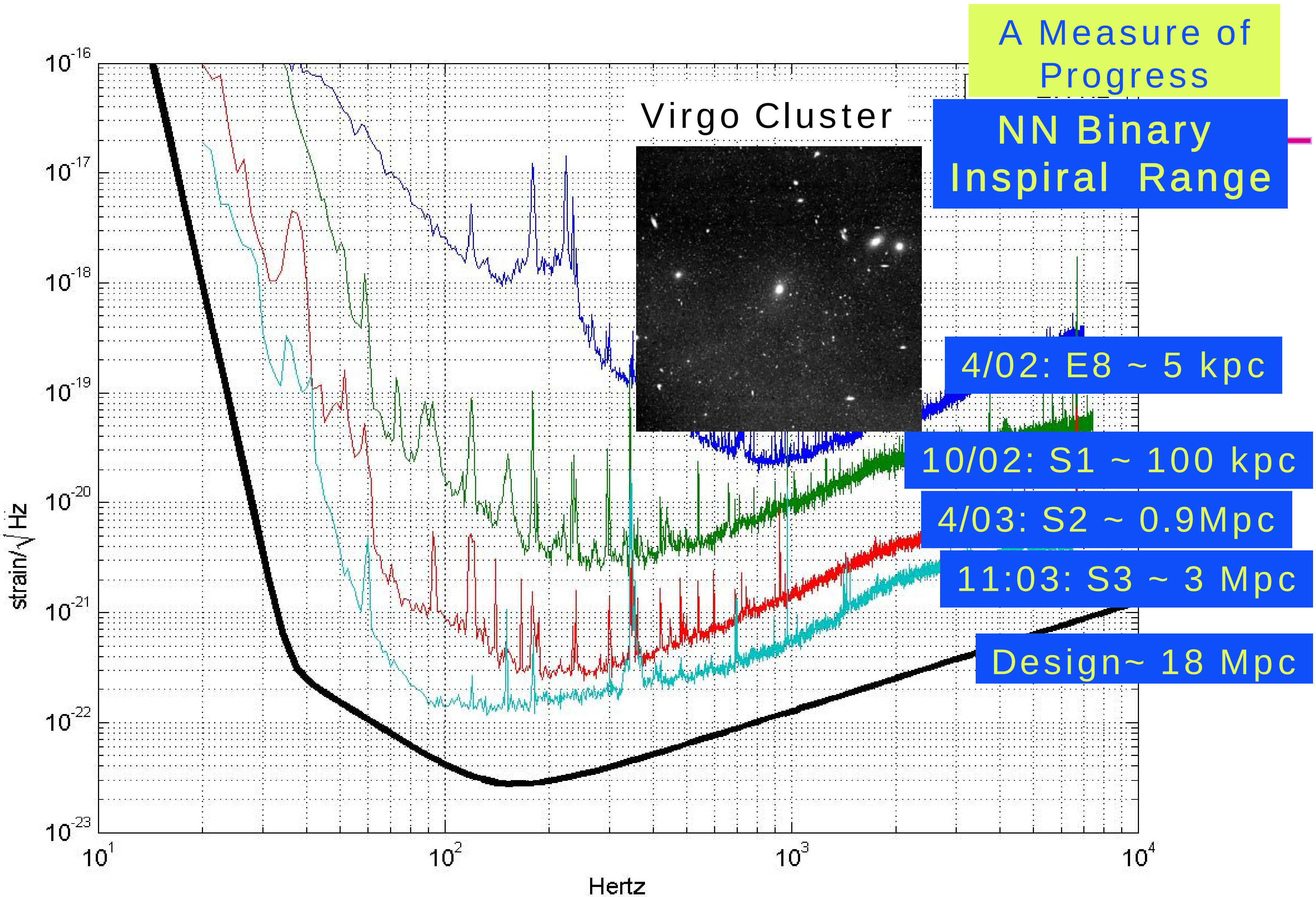
Initial LIGO Sensitivity Goal

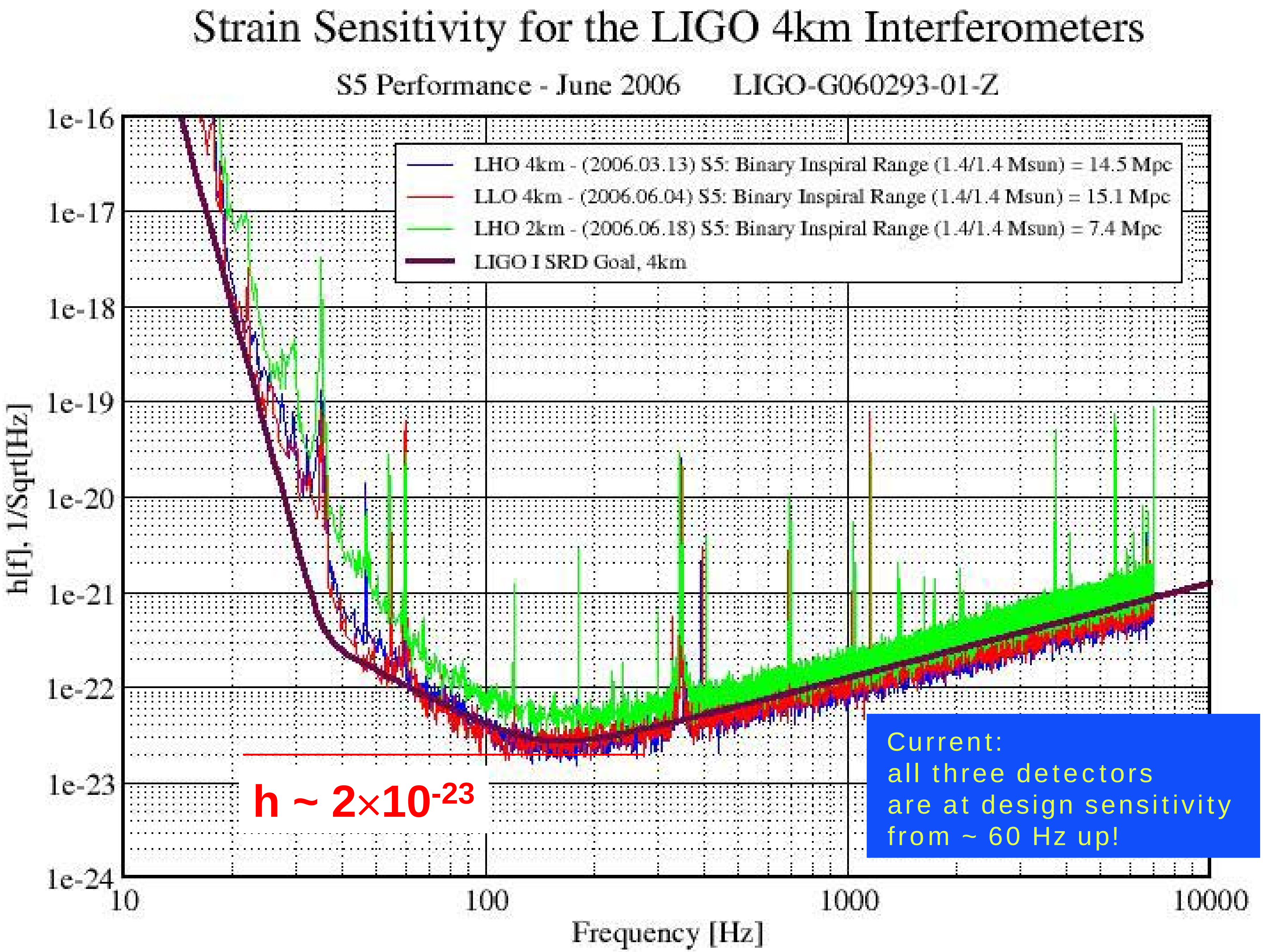


- Strain sensitivity
  < 3×10^{-23} $1/Hz^{1/2}$
  at 200 Hz
- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure
- Sensing Noise
  - Photon Shot Noise
  - Residual Gas
- Facilities limits much lower

- BIG CHALLENGE:
  reduce all other (non-fundamental, or technical) noise sources to insignificance

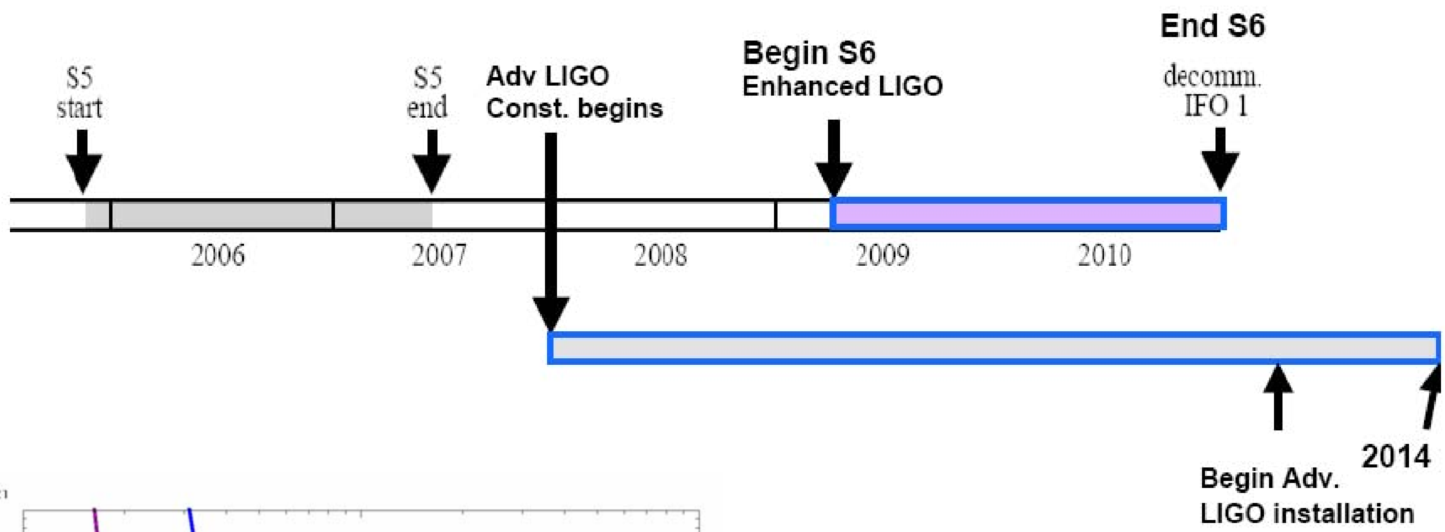
Science Runs

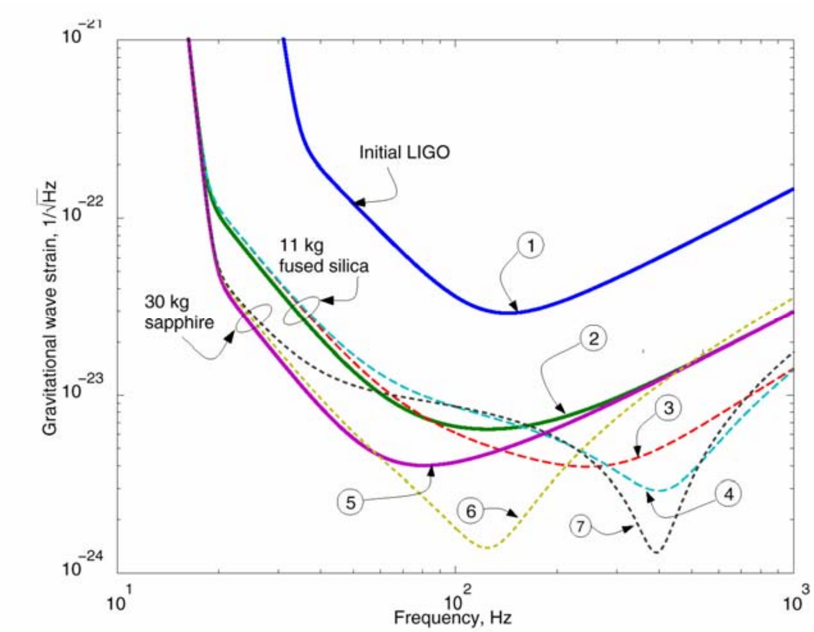




Strain Sensitivity for the LIGO 4km Interferometers
S5 Performance - June 2006
LIGO-G060293-01-Z
LHO 4km - (2006.03.13) S5: Binary Inspiral Range (1.4/1.4 Msun) = 14.5 Mpc
LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
LHO 2km - (2006.06.18) S5: Binary Inspiral Range (1.4/1.4 Msun) = 7.4 Mpc
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]
h ~ 2×10-23
Current:
all three detectors
are at design sensitivity
from ~ 60 Hz up!

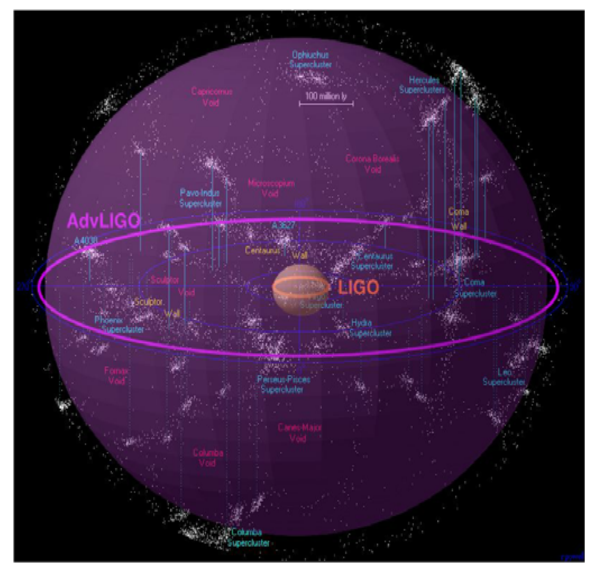
LIGO → eLIGO → AdvLIGO





Improve amplitude sensitivity by a factor of 10x, and…

⇒ Number of sources goes up 1000x!



LIGO

Late breaking news

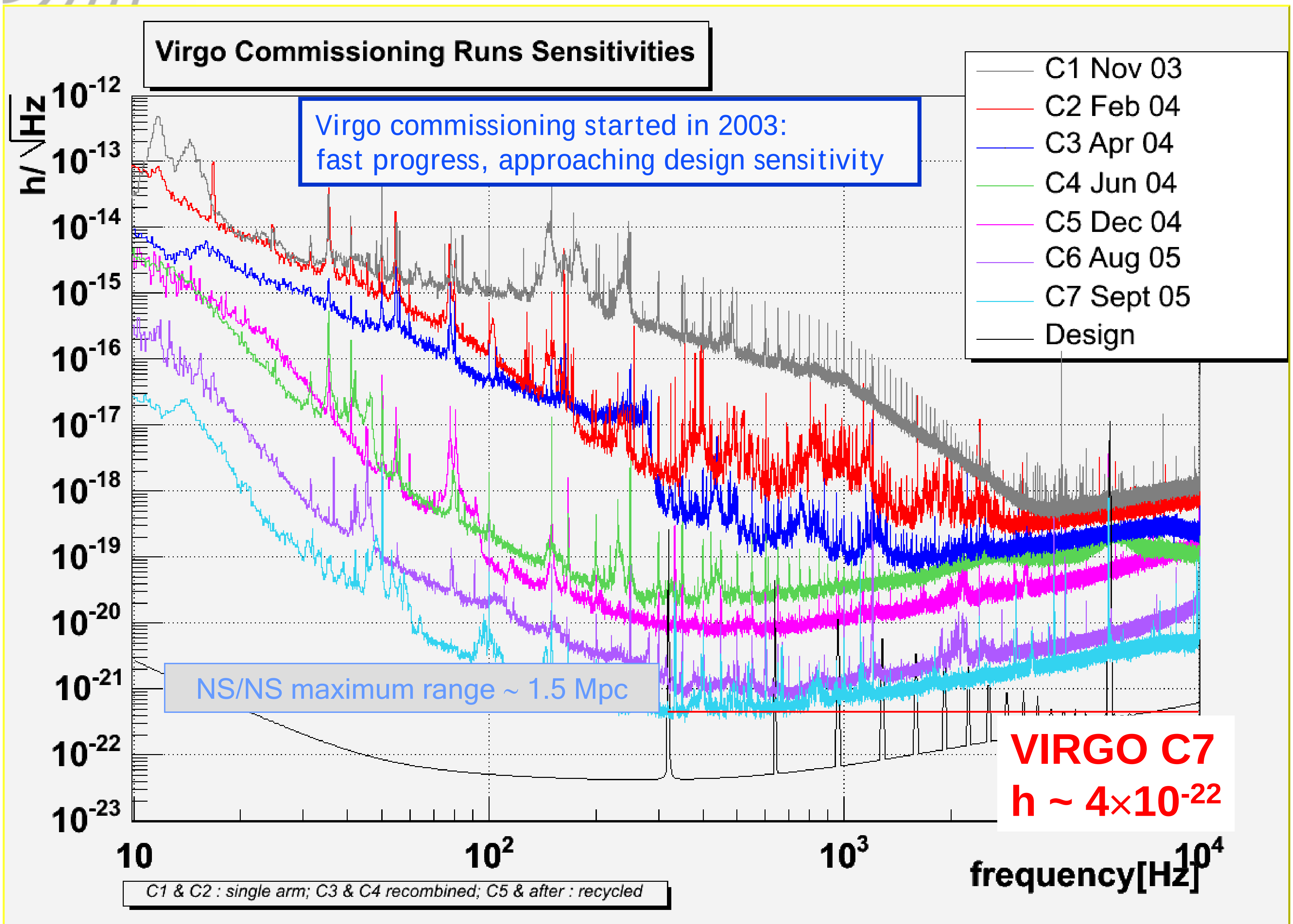
Under the new FY 2008 request, the President asked Congress to increase overall FY 2008 funding for the National Science Foundation, Department of Energy Office of Science, and the National Institute of Standards and Technology core research program by 7.2 percent over his request of a year ago.

- AdvLIGO was approved by the US-NSB in 2004.
- It is in the President's budget for start in 2008!

MREFC Account Funding
(Dollars in Millions)

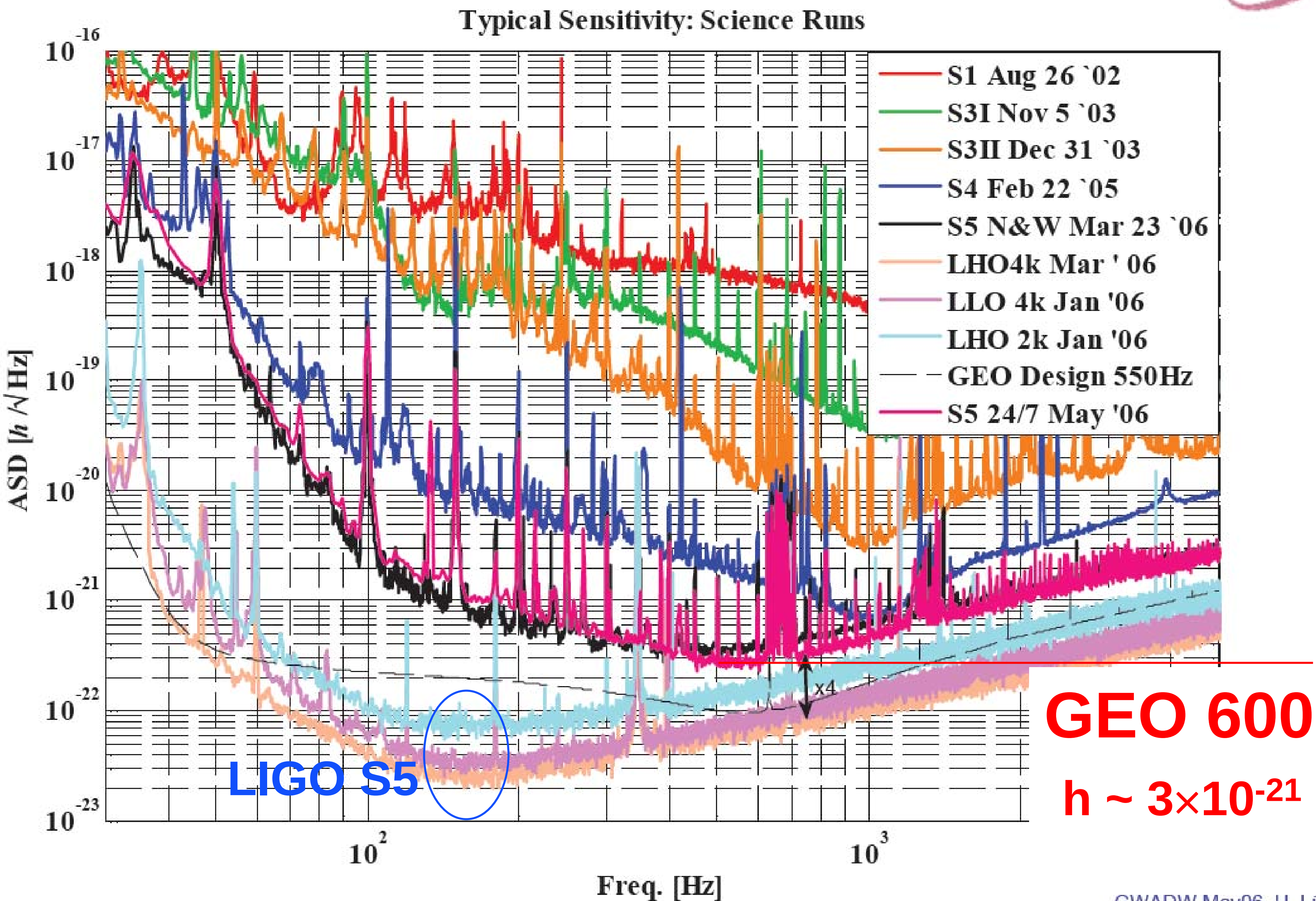
	FY 2006 Actual	FY 2007 Request	FY 2008 Request	FY 2009 Estimate	FY 2010 Estimate	FY 2011 Estimate	FY 2012 Estimate	FY 2013 Estimate
Ongoing Projects								
ARRV[1]		56.00	42.00	25.00	-			
ALMA[2]	48.66	64.27	102.07	74.75	42.76			
DOJ Judgment		3.00	-					
EarthScope	49.62	27.40	-					
IceCube	56.44	28.65	22.38	11.33	0.95			
NEON[3]		4.00	8.00	20.00	30.00			
OOI[4]		5.12	30.99	80.00	90.00			
SODV	66.03	42.88	-					
SPSM[5]	13.07	9.13	6.55	-				
New Starts								
AdvLIGO[6]		-	32.75	51.43	46.30	15.21	23.73	15.50
MREFC Account Total	$233.81	$240.45	$244.74	$262.51	$210.01	$157.65	$68.73	$15.50

- the Alaska Region Research Vessel
- the Atacama Large Millimeter Array
- the IceCube Neutrino Observatory
- the National Ecological Observatory Network
- the Ocean Observatories Initiative, and
- the South Pole Station Modernization project.



Virgo Commissioning Runs Sensitivities
Virgo commissioning started in 2003:
fast progress, approaching design sensitivity
C1 Nov 03
C2 Feb 04
C3 Apr 04
C4 Jun 04
C5 Dec 04
C6 Aug 05
C7 Sept 05
Design
h/√Hz
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
NS/NS maximum range ~ 1.5 Mpc
VIRGO C7
h ~ 4×10^-22
10
10^2
10^3
10^4
frequency[Hz]
C1 & C2 : single arm; C3 & C4 recombined; C5 & after : recycled

Sensitivity in Science Runs



TAMA 300

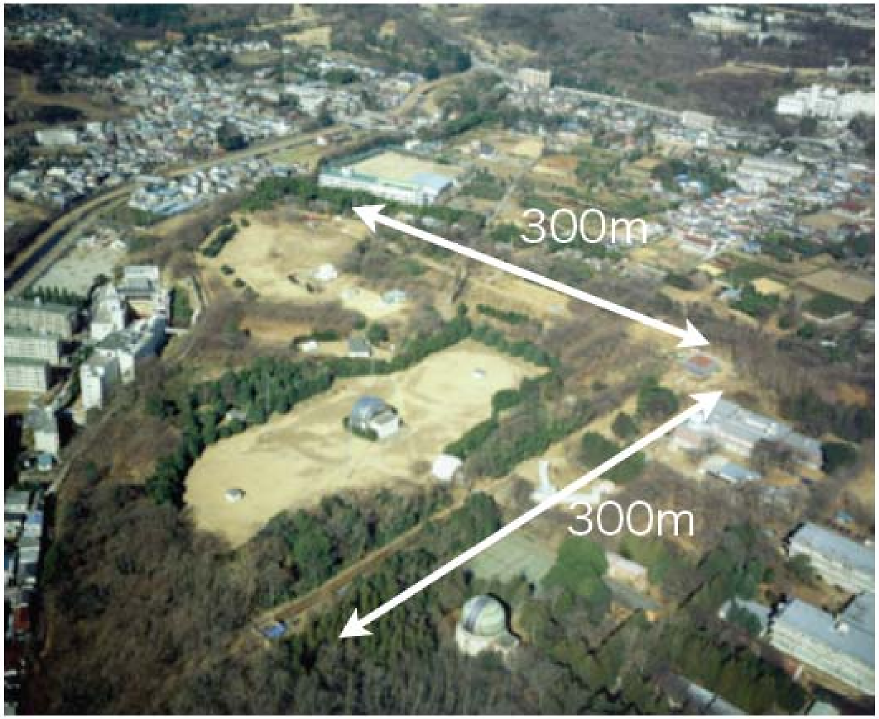
Construction Start : 1995

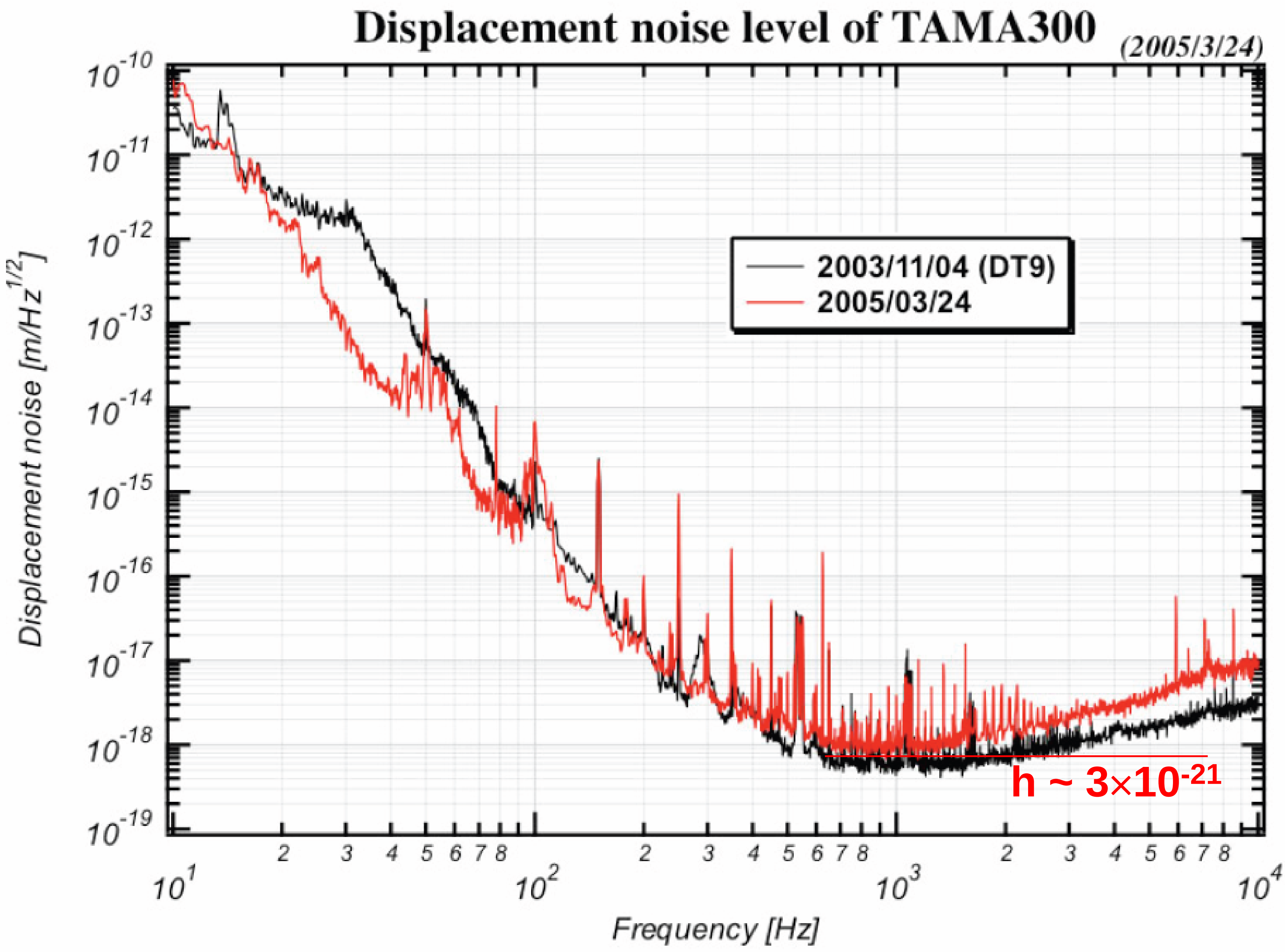
Configuration

- Fabry=Perot=Michelson, with Power Recycling
- baseline: 300m
- laser: Injection-lock Nd:YAG, 10W, 1064nm

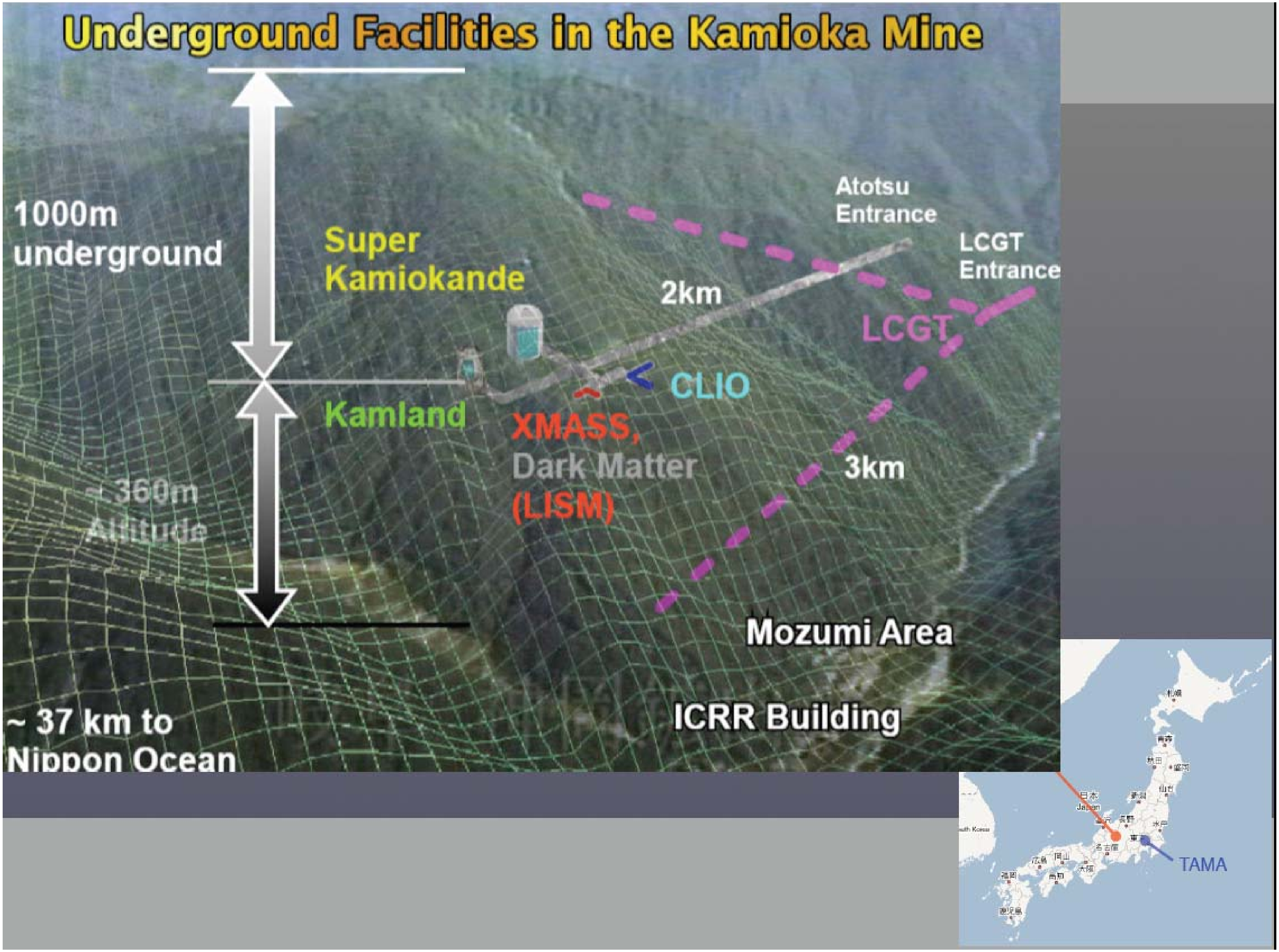
Site

- National Astronomical Observatory, Mitaka, Tokyo





Displacement noise level of TAMA300
(2005/3/24)
2003/11/04 (DT9)
2005/03/24
h ~ 3×10-21
Displacement noise [m/Hz1/2]
Frequency [Hz]


Underground Facilities in the Kamioka Mine
1000m underground
Super Kamiokande
Kamland
~ 360m Altitude
~ 37 km to Nippon Ocean
Atotsu Entrance
LCGT Entrance
2km
LCGT
CLIO
XMASS,
Dark Matter
(LISM)
3km
Mozumi Area
ICRR Building
TAMA

LCGT :

Cryogenic interferometer

- Mirror temperature: 20K

  Reduce thermal noise

Underground site

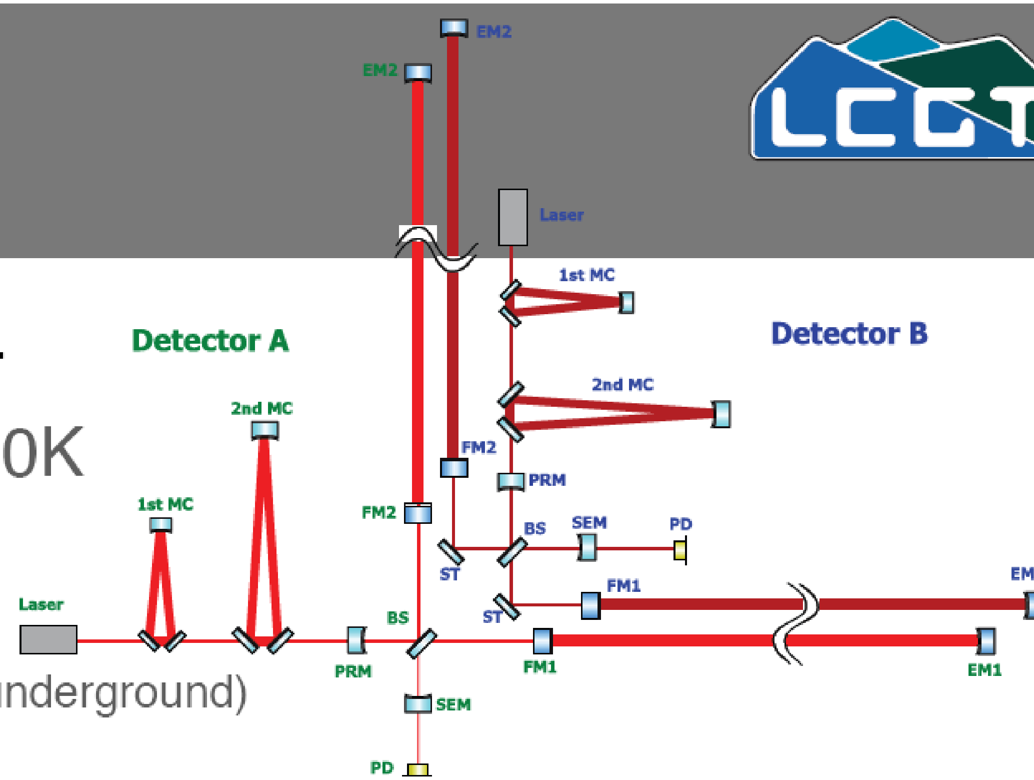
- Kamioka mine (1000m underground)

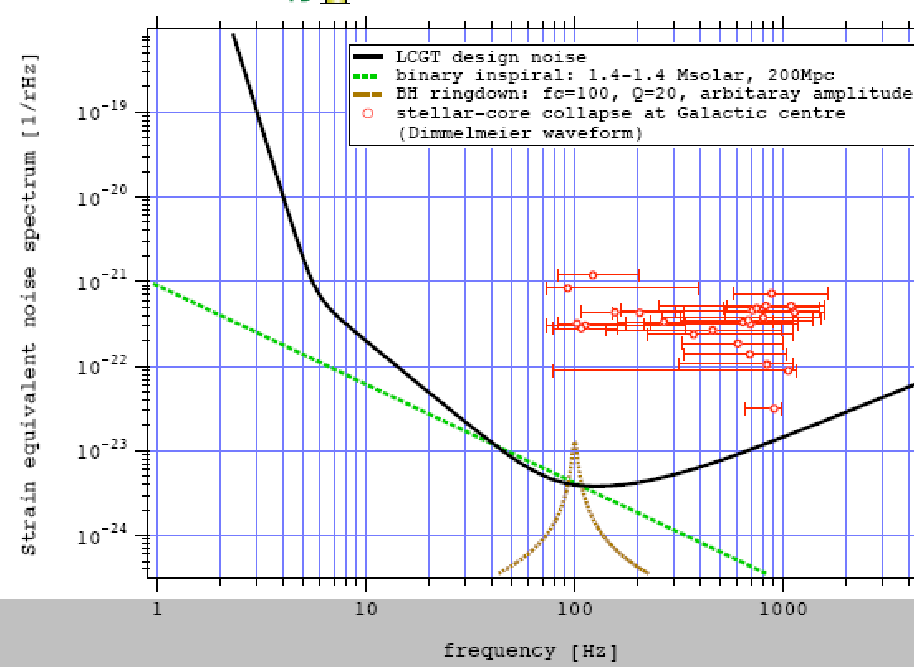
  Reduce seismic noise

  stable operation

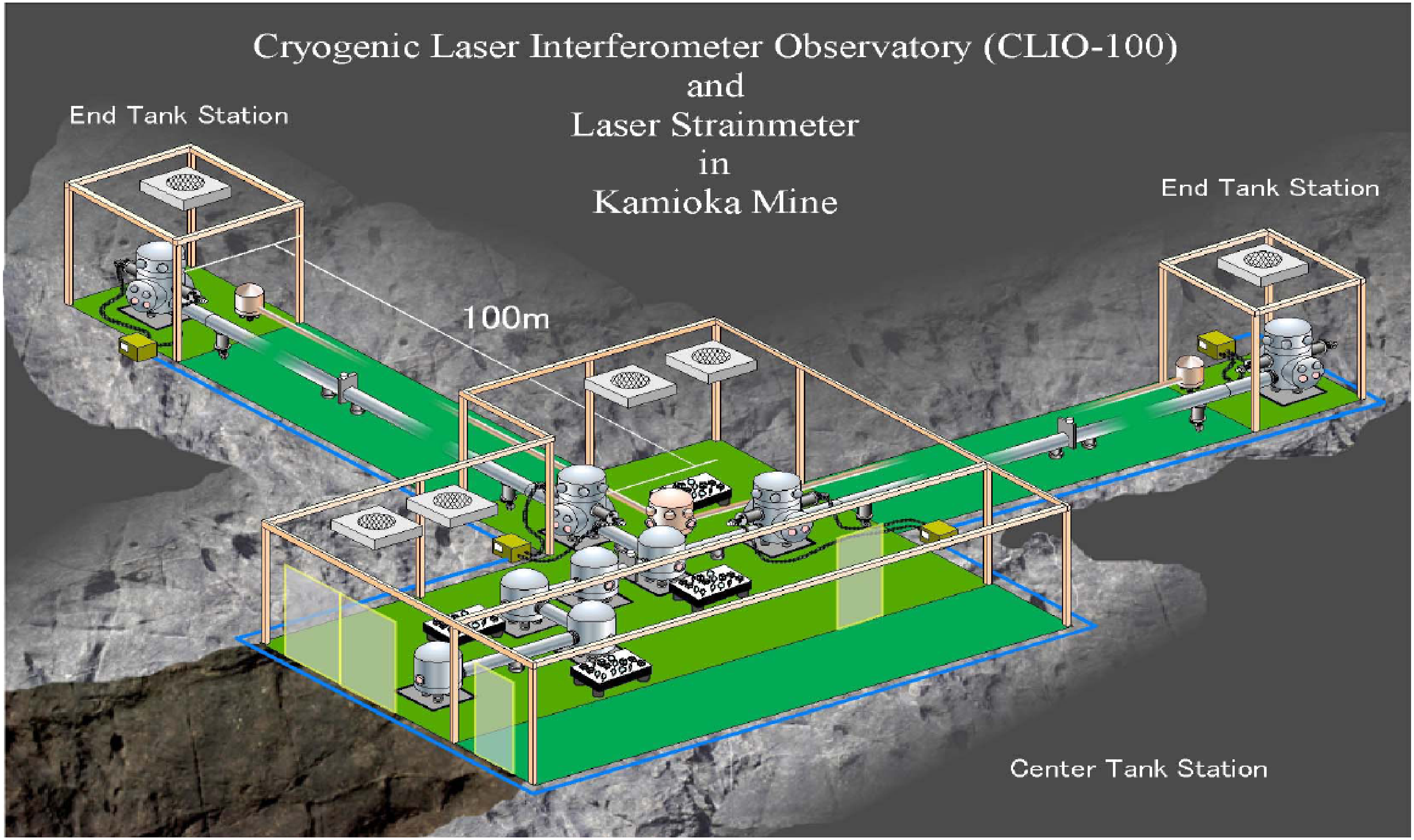
Large-scale interferometer

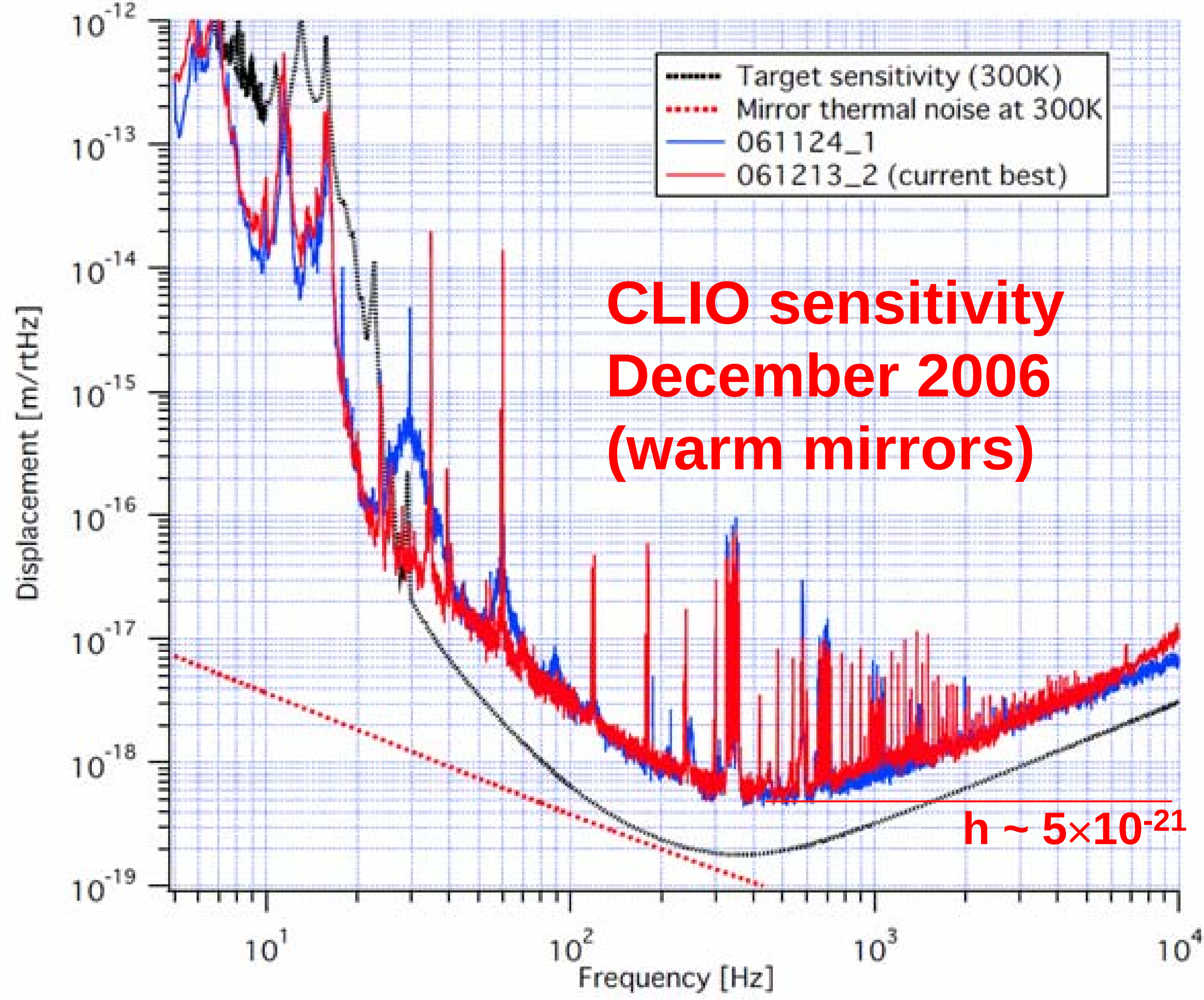
- Two interferometers
- Baseline length: 3km
- High-power laser





CLIO - 100


Cryogenic Laser Interferometer Observatory (CLIO-100)
and
Laser Strainmeter
in
Kamioka Mine
End Tank Station
End Tank Station
100m
Center Tank Station

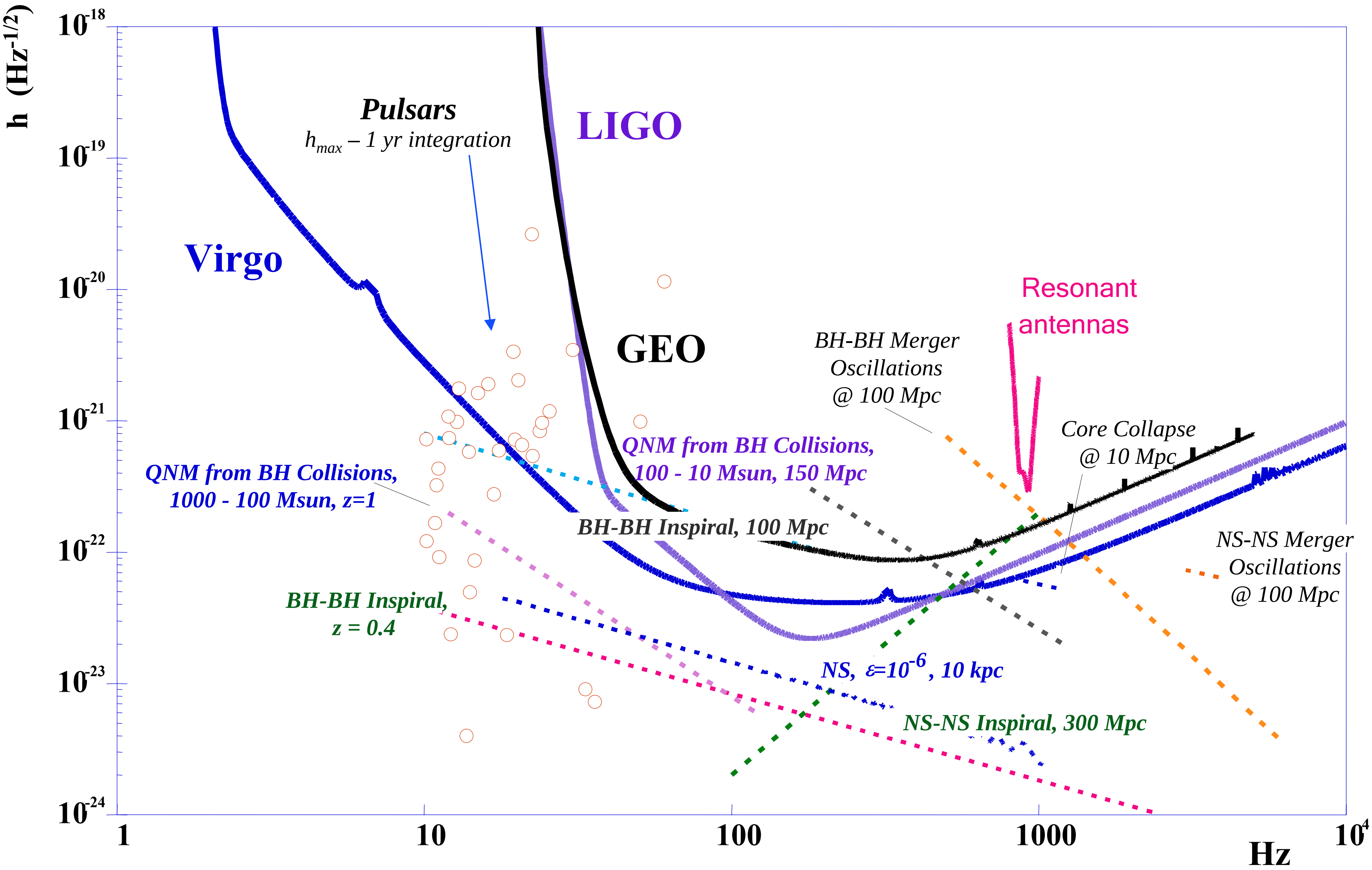


Target sensitivity (300K)
Mirror thermal noise at 300K
061124_1
061213_2 (current best)
CLIO sensitivity
December 2006
(warm mirrors)
h ~ 5×10-21
Displacement [m/rtHz]
Frequency [Hz]

Status of the global network

- **GEO and LIGO carry out all observing and data analysis as one team, the LIGO Scientific Collaboration (LSC).**
- **LSC and Virgo have almost concluded negotiations on joint operations and data analysis.**
  - » **This collaboration will be open to other interferometers at the appropriate sensitivity levels.**
- **LIGO has carried out joint searches with TAMA and with the network of resonant detectors.**
- **LIGO fully supports efforts for full-scale detectors in Japan and Australia**

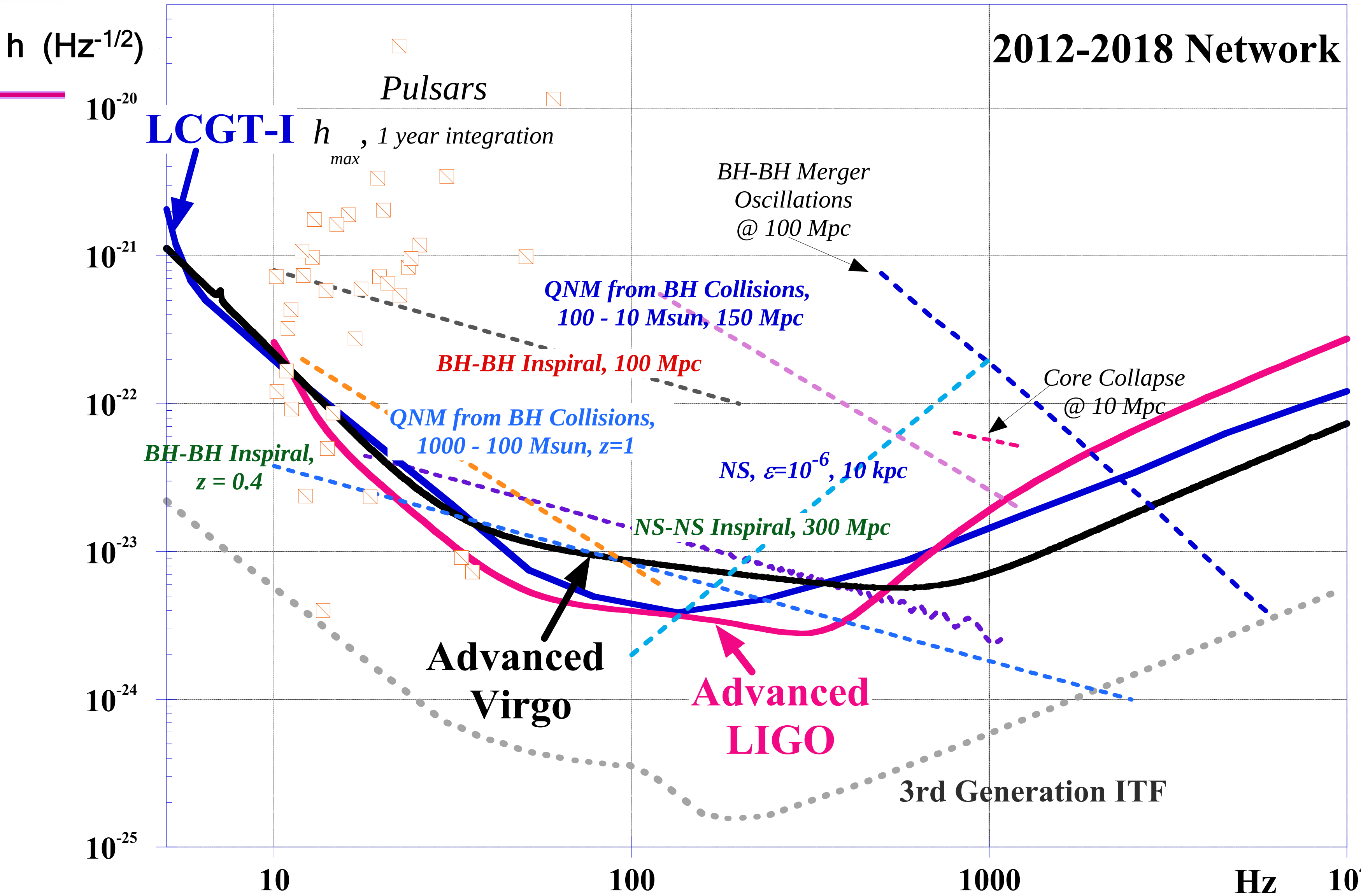
First Generation Detectors



The future for ground based GW interferometers

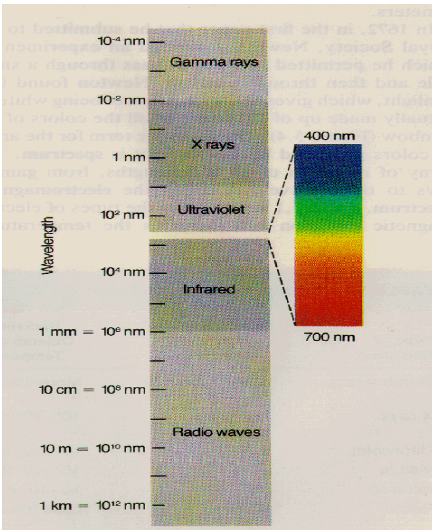
- Advanced LIGO will be operating in ~2014
- Advanced Virgo will be built on the same time scale as Advanced LIGO, and will achieve comparable sensitivity.
- GEO HF will improve the sensitivity beyond GEO600, mainly at high frequencies
- The Japanese GW community is proposing LCGT, a 3 km cryogenic interferometer in the Kamioka mine.
- The Australian GW community is working towards AIGO, a 5 km interferometer at the Gingin site near Perth
- Ongoing technology development towards the third generation-- even better sensitivity and lower frequency

Next Decade Network



AJW, KEKTC6, Feb 7, 2007

Frequency range of GW Astronomy

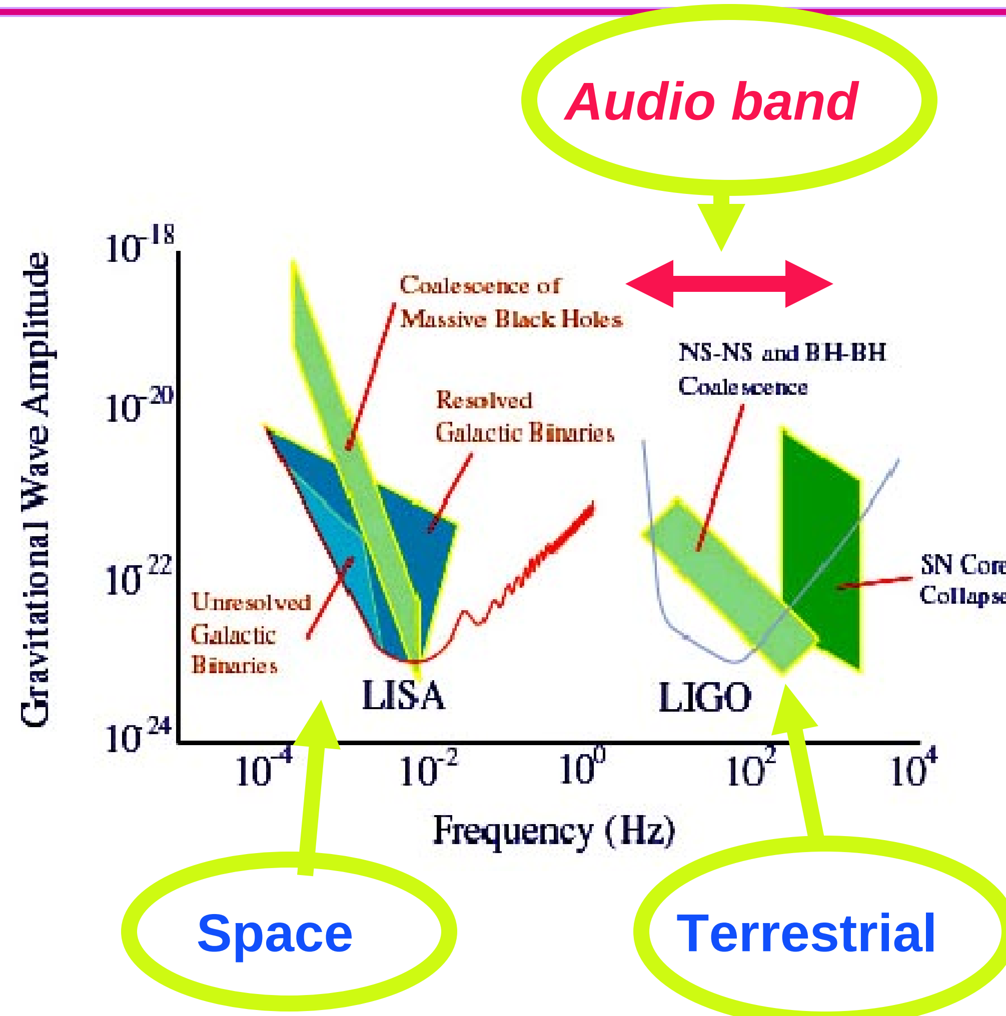


Electromagnetic waves

- over ~16 orders of magnitude
- Ultra Low Frequency radio waves to high energy gamma rays

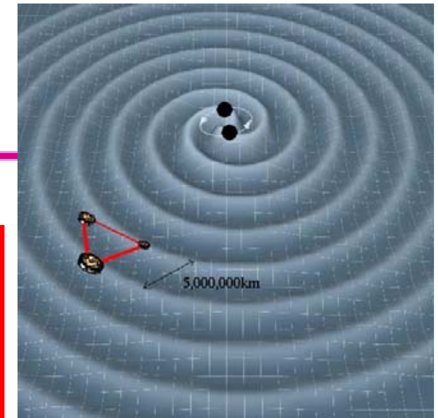
Gravitational waves

- over ~8 orders of magnitude
- Terrestrial + space detectors



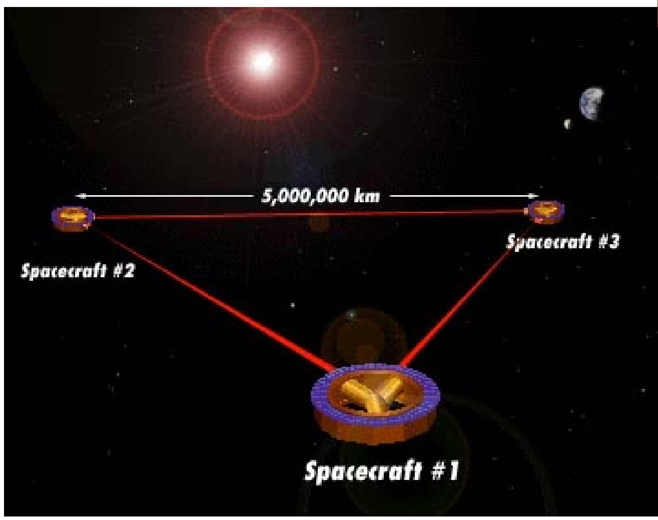
The Laser Interferometer Space Antenna

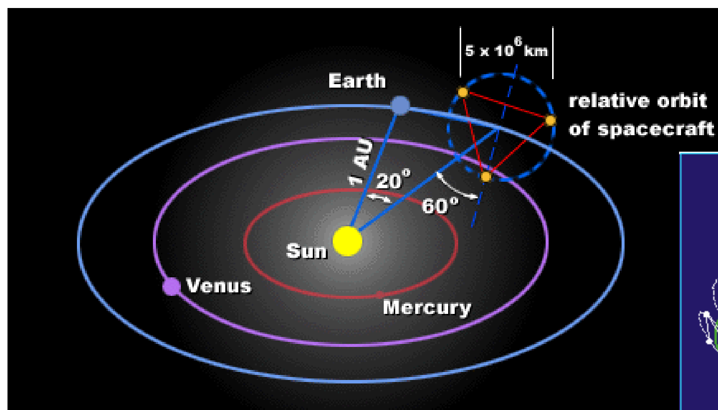
LISA

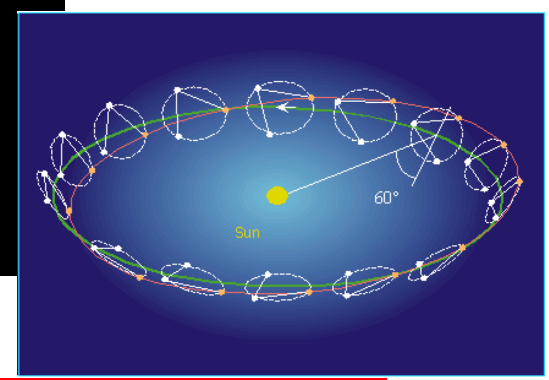


Three spacecraft in orbit about the sun,
with 5 million km baseline

The center of the triangle formation will be in the ecliptic plane
1 AU from the Sun and 20 degrees behind the Earth.



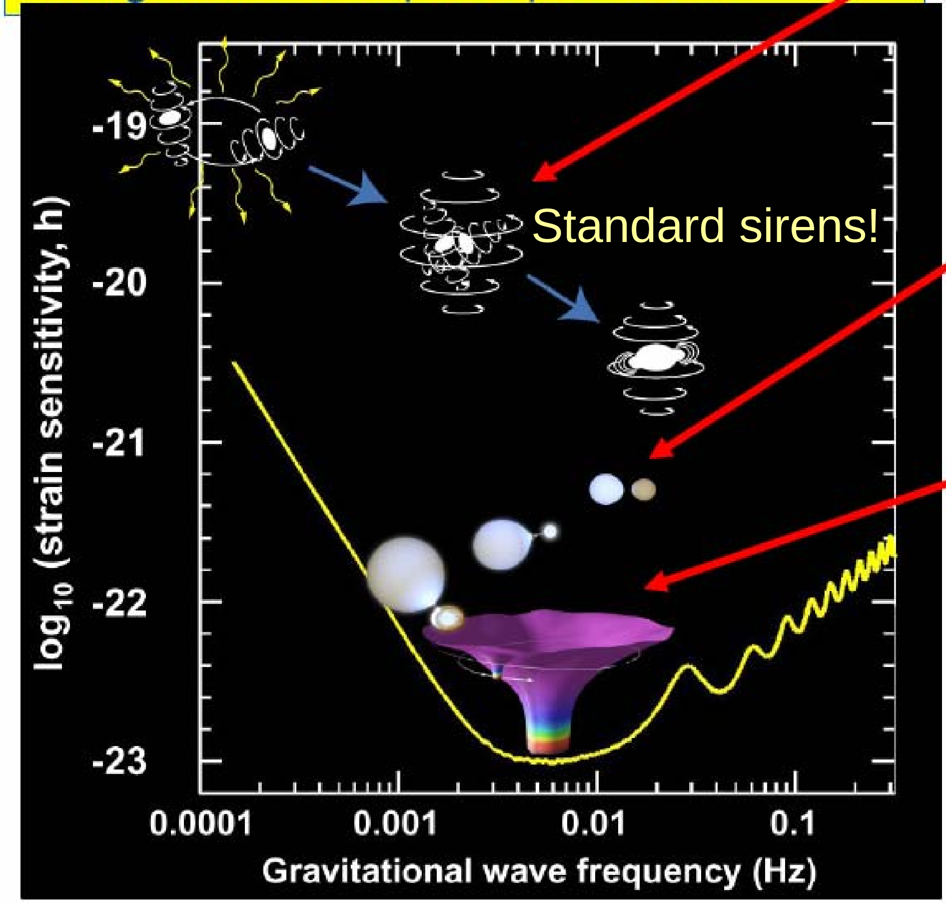




LISA (NASA/JPL, ESA) may fly in the next 10 years!

LISA Sources

LISA will record a rich symphony of thousands of long-lived (>year) individually identifiable sources, plus backgrounds and perhaps bursts.



Massive Black Hole Binary (BHB) inspiral and merger
Sample: last 40 days of 10^6Msun at z=1, S/N=2500.

Ultra-compact Galactic binaries
Samples: 1kpc, S/N=6-210

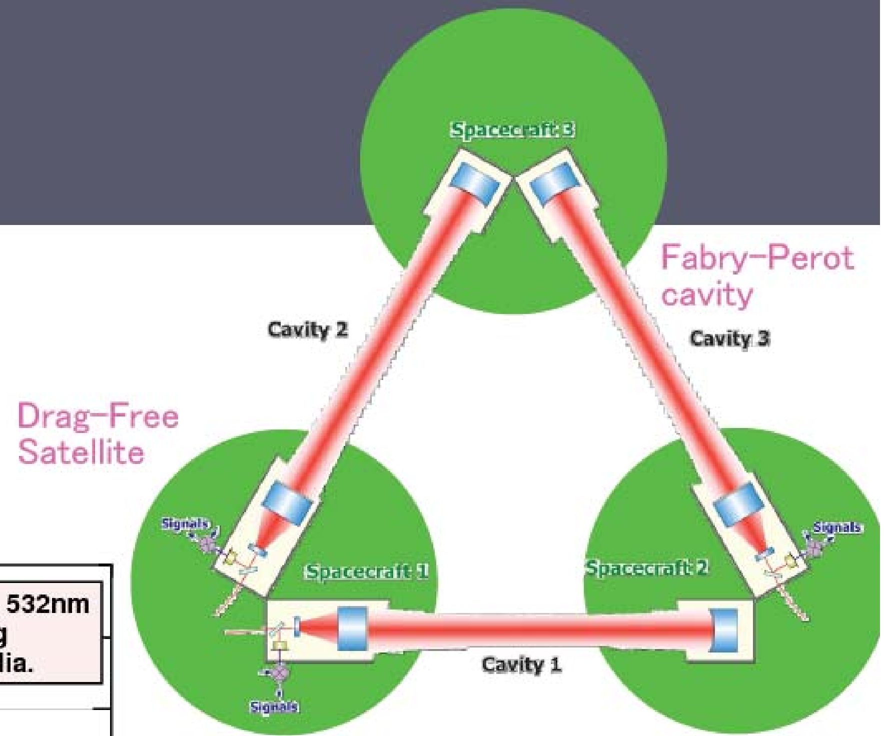
Extreme Mass Ratio Inspiral (EMRI):
Samples: last 5 years of 1Msun into 10^6Msun, z=0.2, S/N=30

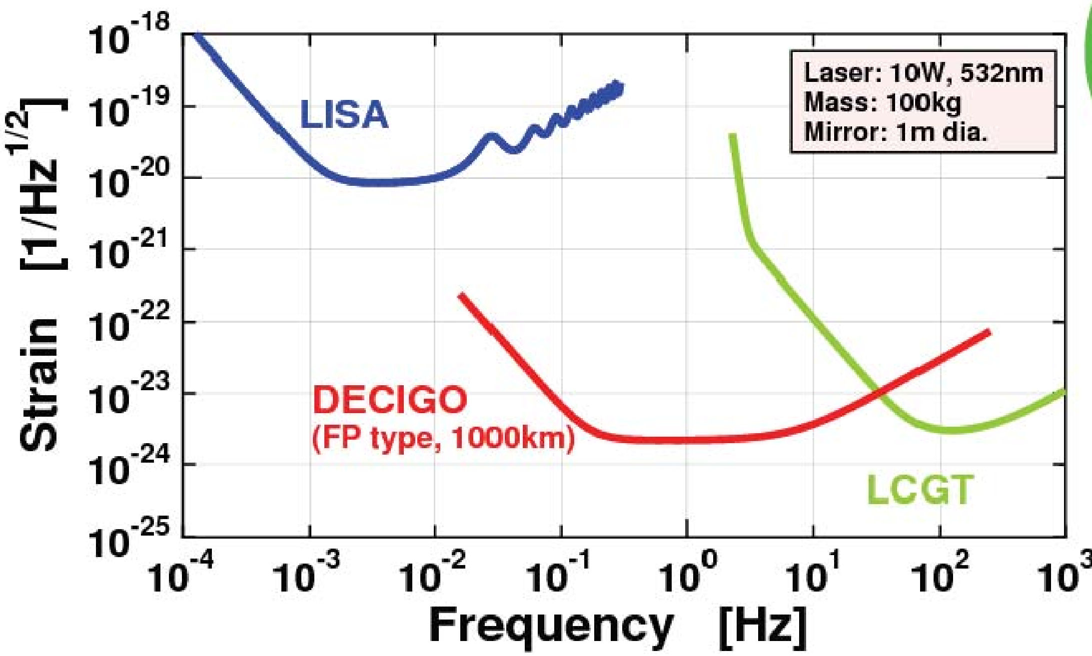
Cosmological backgrounds, superstring bursts?

E.S. Phinney Texas06, 11 Dec 2006

Pre-conceptual Design

DECIGO





Item	Value
Distance between satellites	1000 km
Effective laser power	10 W
Wavelength of light	532 nm
Mass of mirror	100 kg
Diameter of mirror	1 m
Finesse of cavity	10

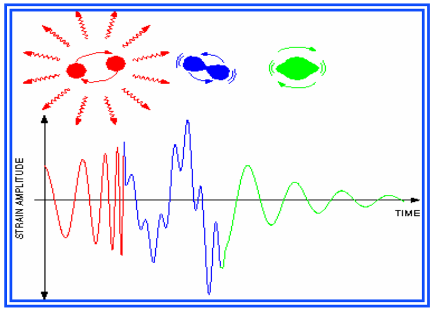
Orbit and constellation: TBD

by S.Kawamura

Recent results from LIGO

- Searches for coalescing compact binaries
- Searches for GW bursts from supernovas, GRB engines, newly-formed compact objects, etc
- Searches for continuous waves from known pulsars
- Searches for continuous waves from unknown spinning neutron stars
- Searches for a stochastic background of GWs from the Big Bang
- Searches for a stochastic signal of GWs from "foreground" astrophysical sources

Searches for coalescing compact binaries- S3 & S4



- Use modeled waveforms to filter data
- Sensitive to binaries with masses:

  $0.35\ M_{sun} < m_1, m_2 < 1\ M_{sun}$

  $1\ M_{sun} < m_1, m_2 < 3\ M_{sun}$

  $3\ M_{sun} < m_1, m_2 < 80\ M_{sun}$

- No plausible detections
- Sensitivity:
  - S3: 0.09 yr of data;

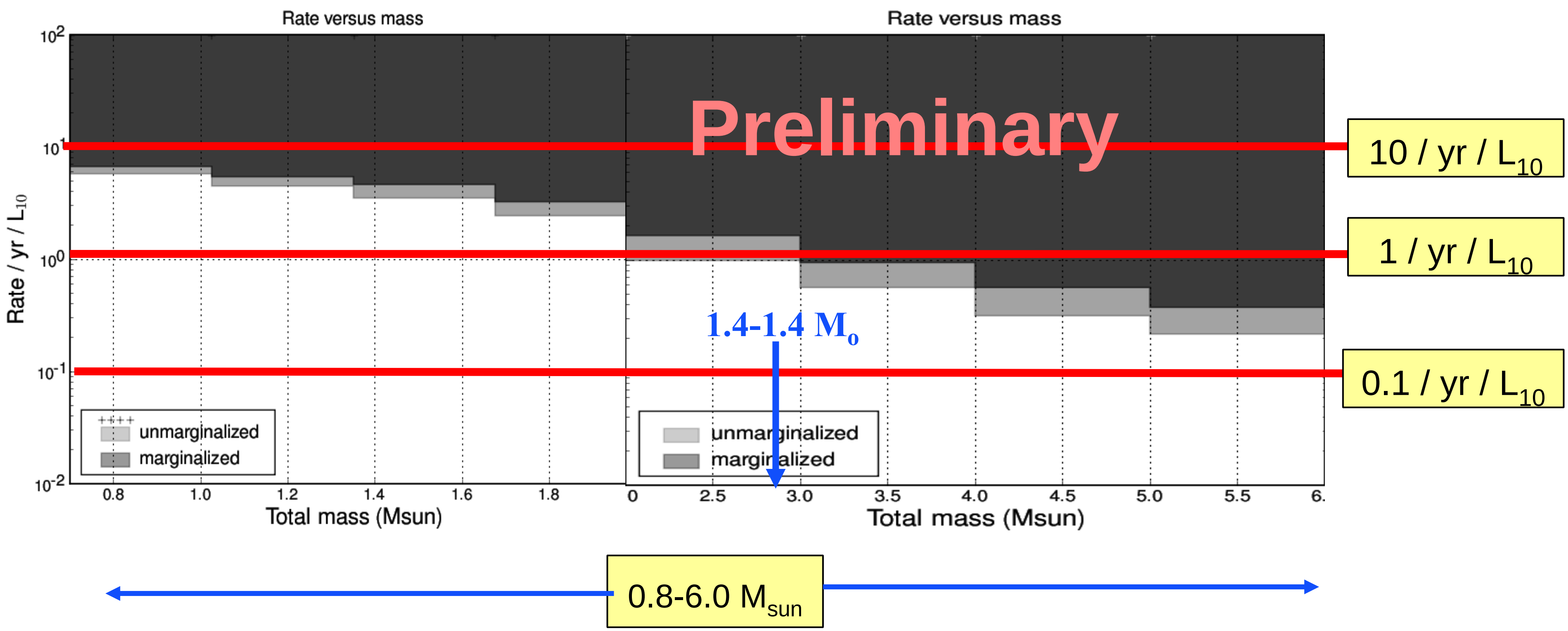
    ~3 Milky Way equivalent galaxies for 1.4 – 1.4 M_{sun} (NS-NS)
  - S4: 0.05 yr of data;

    ~24 Milky Way equivalent galaxies for 1.4 – 1.4 M_{sun} (NS-NS)

    ~150 Milky Way equivalent galaxies for 5.0 – 5.0 M_{sun} (BH-BH)

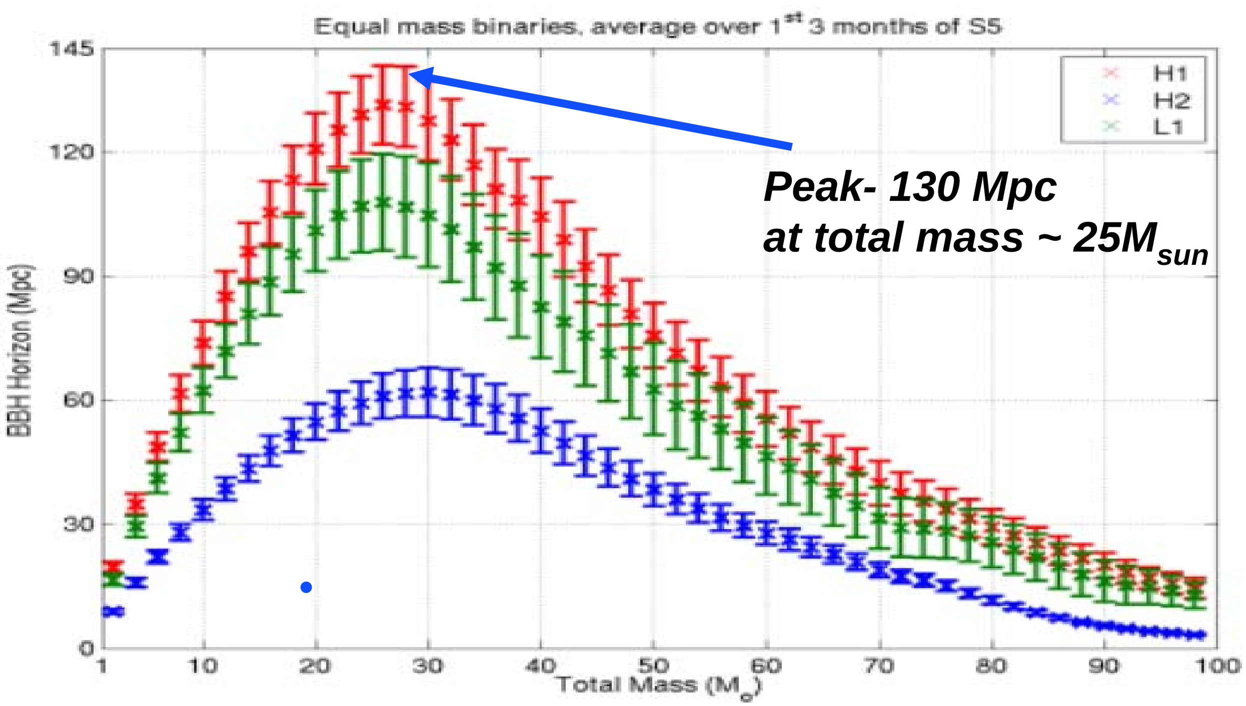
S4 upper limits-compact binary coalescence

- Rate/year/L_{10} vs. binary total mass
  $L_{10} = 10^{10} L_{sun,B}$ (1 Milky Way = 1.7 L_{10})
- Dark region excluded at 90% confidence.

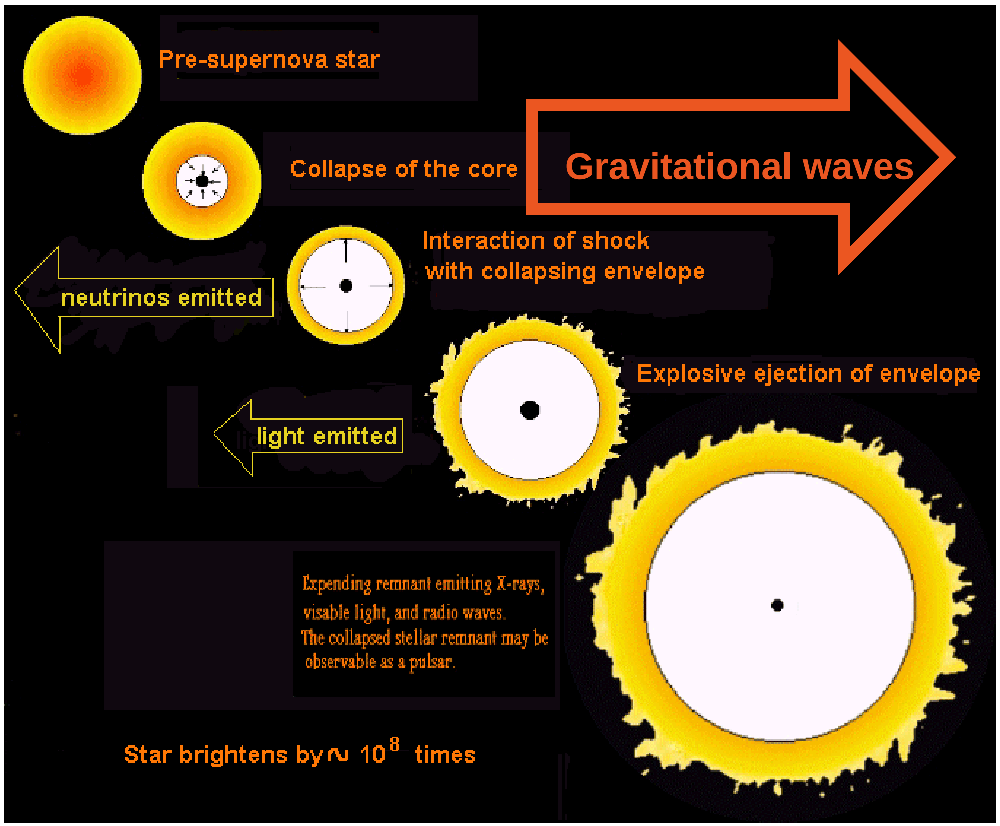


S5 search for compact binary signals

- 3 months of data analyzed- no signals seen
- For 1.4-1.4 M_o binaries, ~ 200 MWEGs in range
- For 5-5 M_o binaries, ~ 1000 MWEGs in range
- Plot- Inspiral horizon for equal mass binaries vs. total mass
  (horizon=range at peak of antenna pattern; ~2.3 x antenna pattern average)



Supernova collapse sequence



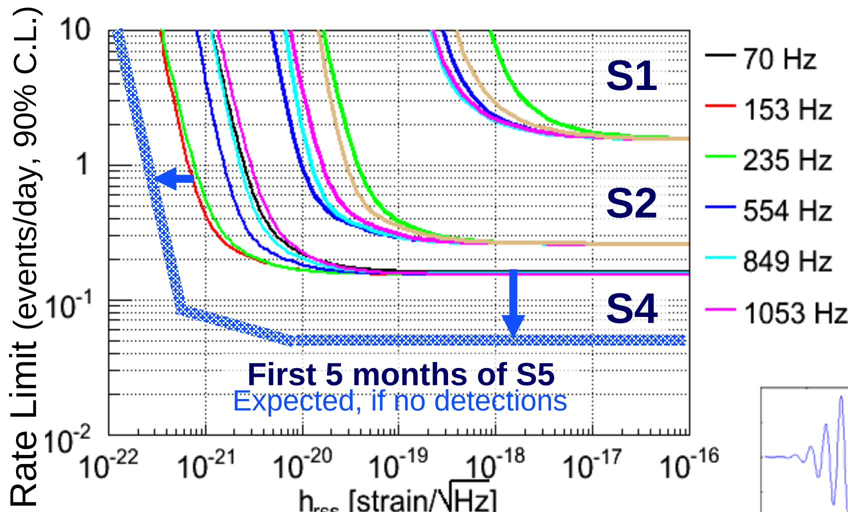
- Within about 0.1 second, the core collapses and gravitational waves are emitted.
- After about 0.5 second, the collapsing envelope interacts with the outward shock. Neutrinos are emitted.
- Within 2 hours, the envelope of the star is explosively ejected. When the photons reach the surface of the star, it brightens by a factor of 100 million.
- Over a period of months, the expanding remnant emits X-rays, visible light and radio waves in a decreasing fashion.

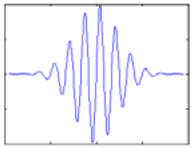
Untriggered GW burst search

- Look for short, unmodeled GW signals in LIGO's frequency band
  - –From stellar core collapse, compact binary merger, etc. — or unexpected source
- Look for excess signal power and/or cross-correlation among data streams from different detectors
- No GW bursts detected in S1/S2/S3/S4; preliminary results from 1st 5 months of S5

Limit on GWB rate vs. GW signal strength sensitivity

- Detection algorithms tuned for 64–1600 Hz, duration << 1 sec
- Veto thresholds pre-established before looking at data
- Corresponding energy emission sensitivity **$E_{GW} \sim 10^{-1}\ M_{sun}$ at 20 Mpc** (153 Hz case)





h_{rss} (root-sum-squared strain amplitude) preliminary

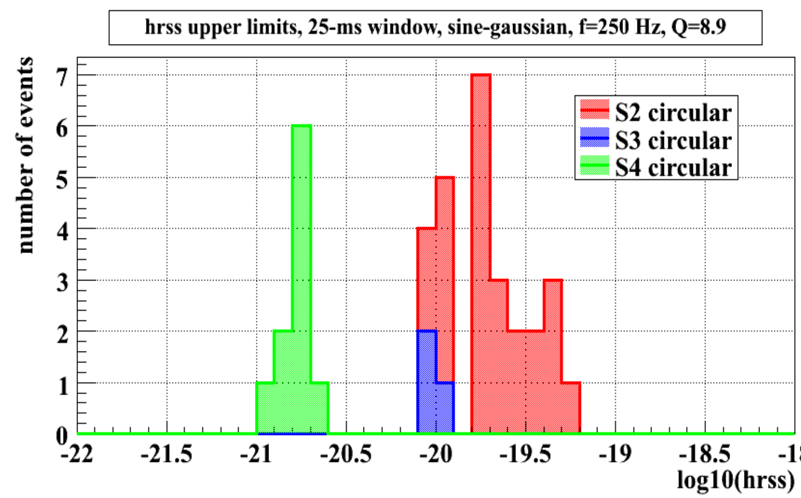
Triggered Searches for GW Bursts

Soft Gamma Repeater 1806-20

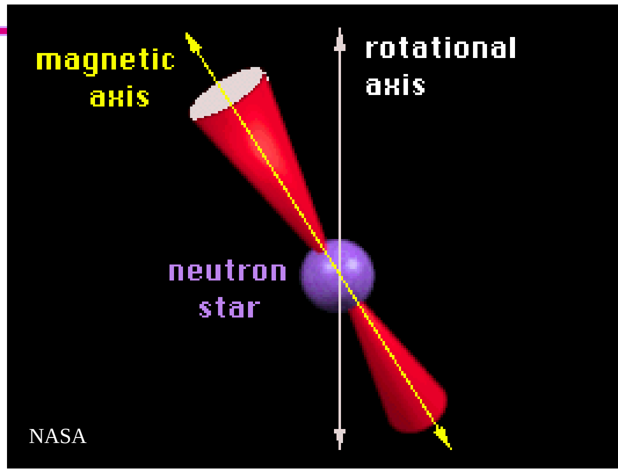
- galactic neutron star (10-15 kpc) with intense magnetic field (~1015 G)
- source of record gamma-ray flare on December 27, 2004
- quasi-periodic oscillations found in RHESSI and RXTE x-ray data
- search LIGO data for GW signal associated with quasi-periodic oscillations-- no GW signal found
- sensitivity: E_{GW} ~ 10–7 to 10–8 Msun for the 92.5 Hz QPO
- this is the same order of magnitude as the EM energy emitted in the flare

Gamma-Ray Bursts

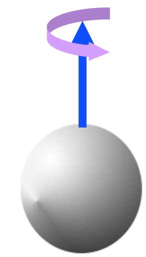
- search LIGO data surrounding GRB trigger using cross-correlation method
- no GW signal found associated with 39 GRBs in S2, S3, S4 runs
- set limits on GW signal amplitude
- 53 GRB triggers for the first five months of LIGO S5 run
- typical S5 sensitivity at 250 Hz: **E_{GW} ~ 0.3 M_{sun}** at 20 Mpc



Pulsars and continuous wave sources

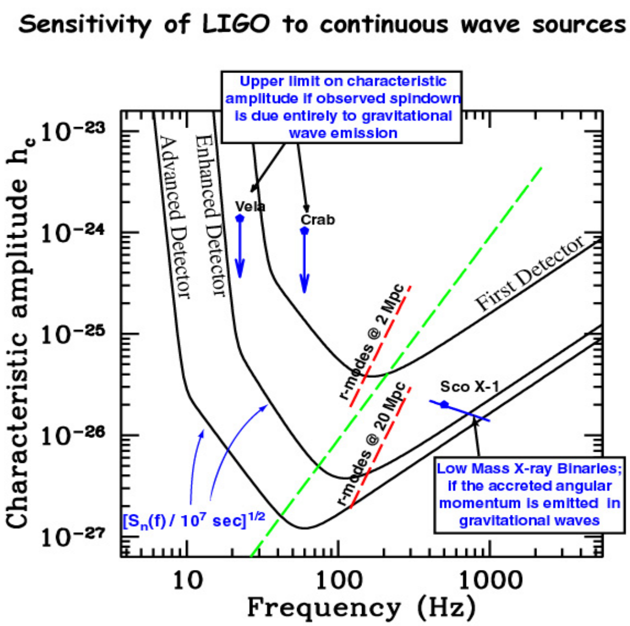


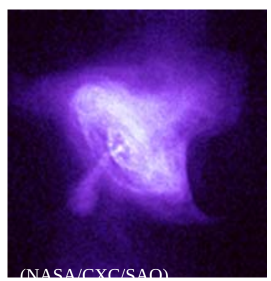
- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: EOS; precession; interiors
  - »"R-mode" instabilities
  - »narrow band searches best

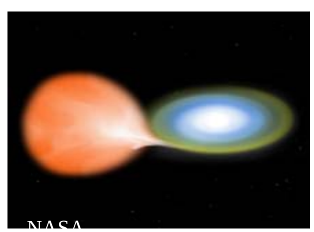


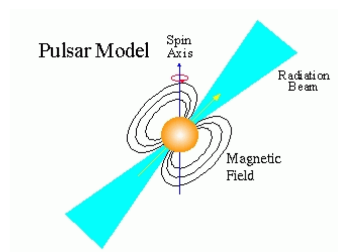
$$h = \frac{4\pi^2 G}{c^4} \frac{I f_{GW}^2}{d} \varepsilon$$

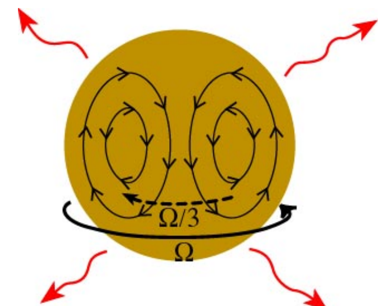
$$f_{GW} = 2\, f_{ROT}$$











R-modes

Search for known pulsars- preliminary

Joint 95% upper limits for 97 pulsars using ~10 months of the LIGO S5 run. Results are overlaid on the estimated median sensitivity of this search.

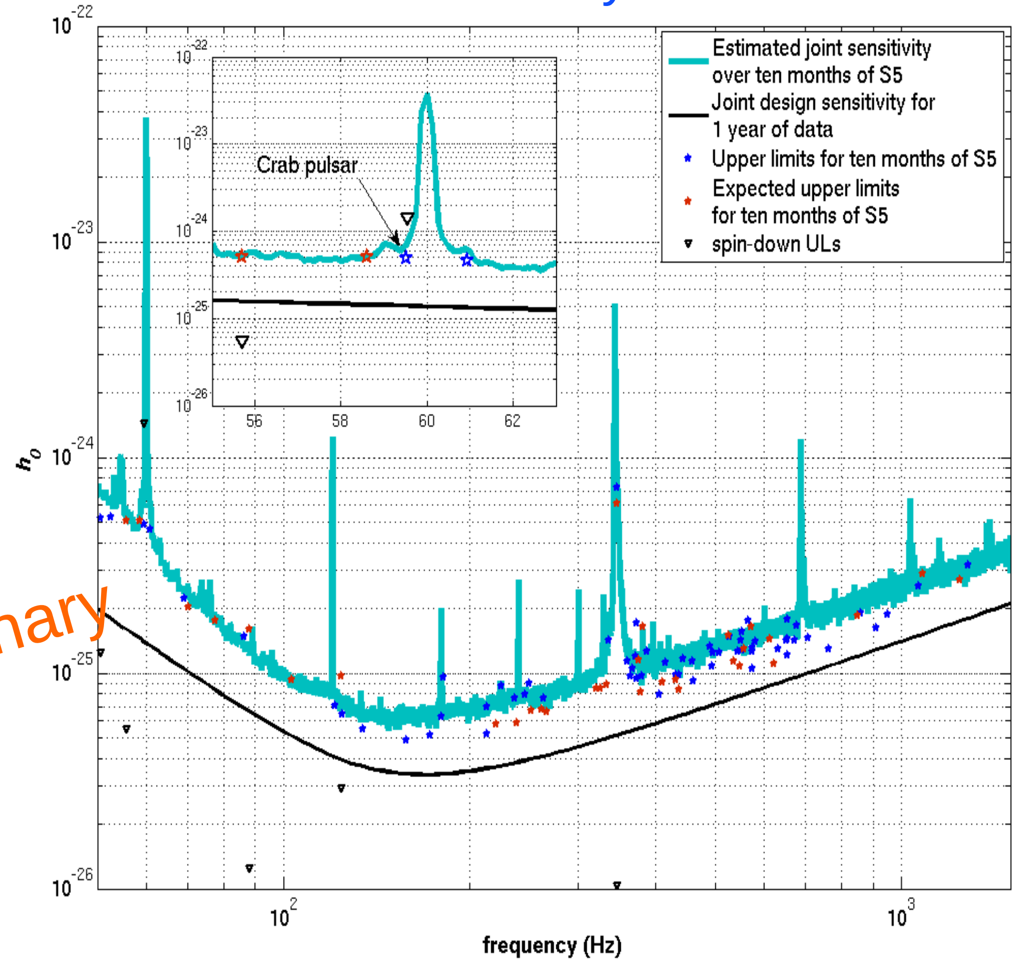
For 32 of the pulsars we give the *expected* sensitivity upper limit (red stars) due to uncertainties in the pulsar parameters .

Pulsar timings provided by the Jodrell Bank pulsar group

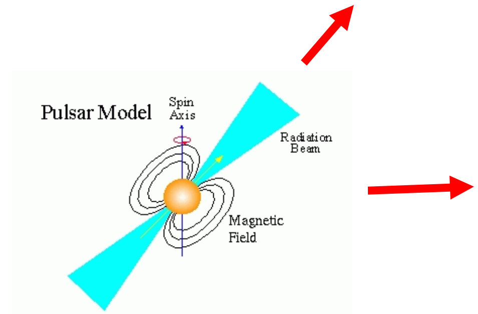
Lowest GW strain upper limit:
PSR J1802-2124
(f_{gw} = 158.1 Hz, r = 3.3 kpc)
$\mathbf{h_0 < 4.9\times10^{-26}}$

Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6 Hz, r = 0.25 kpc)
$\boldsymbol{\varepsilon < 1.1\times10^{-7}}$

Preliminary



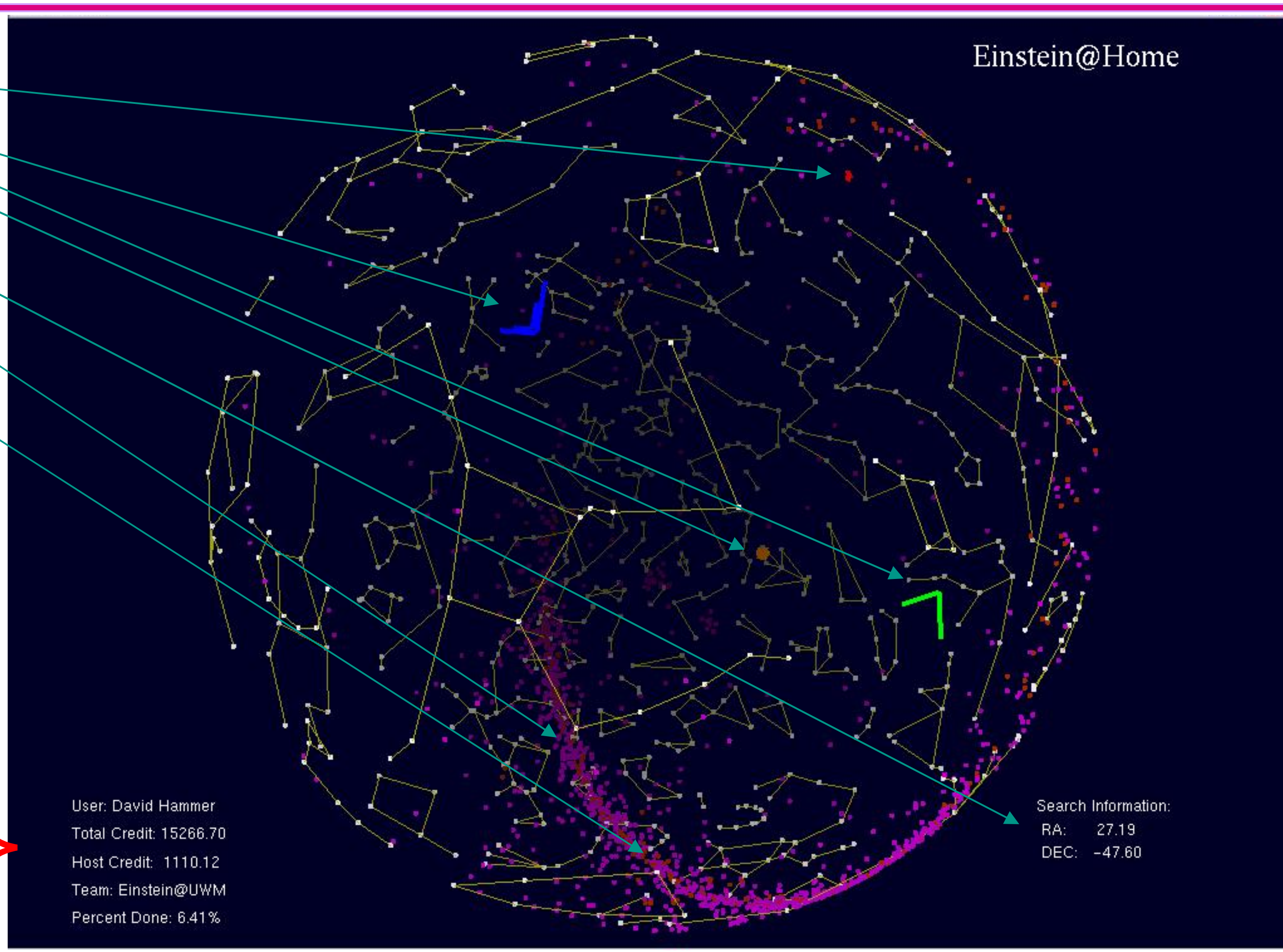
All sky searches



- Most spinning neutron stars are not observed pulsars; EM dim and hard to find.
- But they all emit GWs in all directions (at some level)
- Some might be very close and GW-loud!
- Must search over huge parameter space:
  - » sky position: 150,000 points @ 300 Hz, more at higher frequency or longer integration times
  - » frequency bins: 0.5 mHz over hundreds of Hertz band, more for longer integration times
  - » df/dt: tens(s) of bins
- Computationally limited! Full coherent approach requires ~100,000 computers (Einstein@Home)

Einstein@Home: the Screensaver

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants



- User name
- User's total credits
- Machine's total credits
- Team name
- Current work % complete

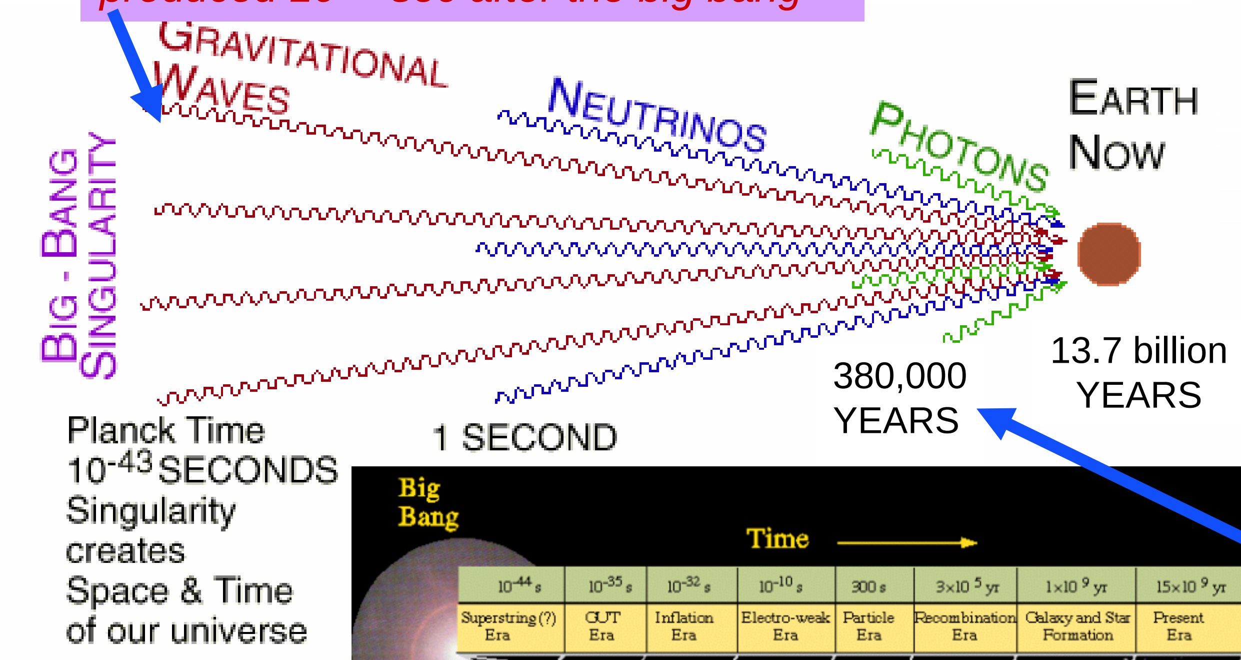
Gravitational waves from Big Bang

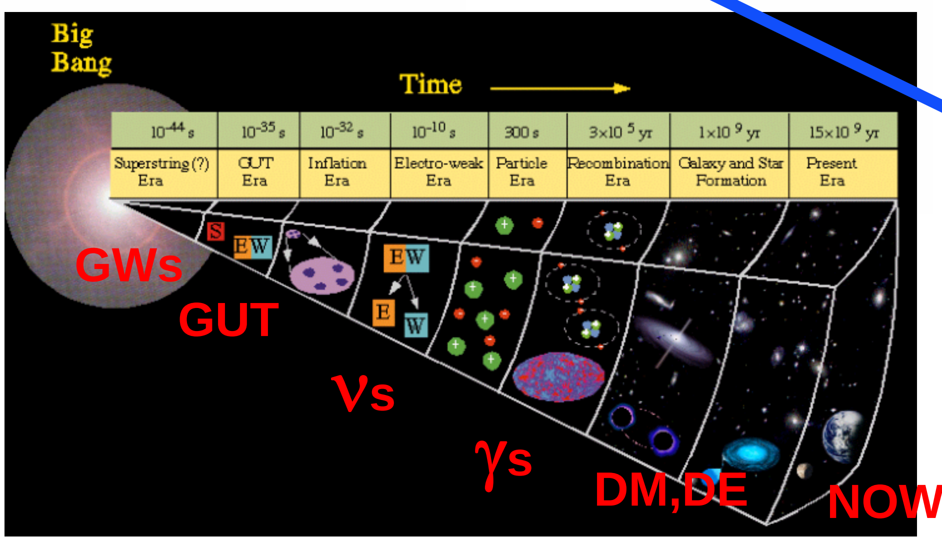
Waves now in the LIGO band were produced 10^{-22} sec after the big bang

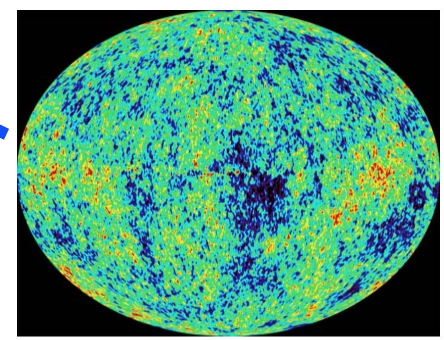
$$\Omega_{GW}(f) = \frac{1}{\rho_c}\,\frac{d\rho_{GW}(f)}{d\ln f}$$

$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab}\,\dot{h}^{ab} >$$

$$h(f) = 6.3\times10^{-22}\sqrt{\Omega_{GW}(f)}\left(\frac{100\text{ Hz}}{f}\right)^{3/2}\text{Hz}^{-1/2}$$

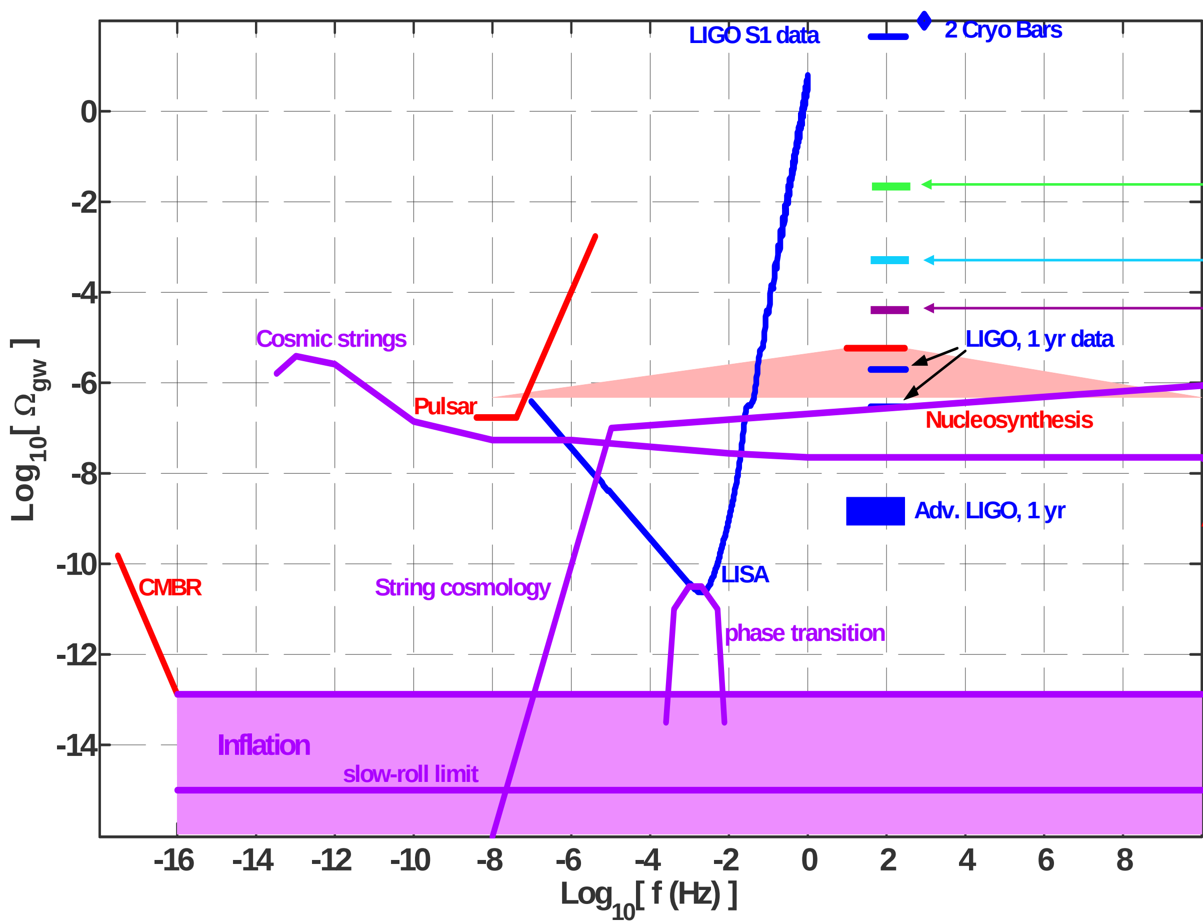






cosmic microwave background -- WMAP 2003

LIGO limits and expectations on Ω_{GW}



S1 result: $\Omega_{GW} < 23$

S2 result: $\Omega_{GW} < 0.02$

S3 result: $\Omega_{GW} < 8\times10^{-4}$

S4 result: $\Omega_{GW} < 6.5\times10^{-5}$

LIGO design, 1 year:
Ω_{GW} <~ 10^{-5} - 10^{-6}

Advanced LIGO, 1 year:
Ω_{GW} <~ 10^{-9}

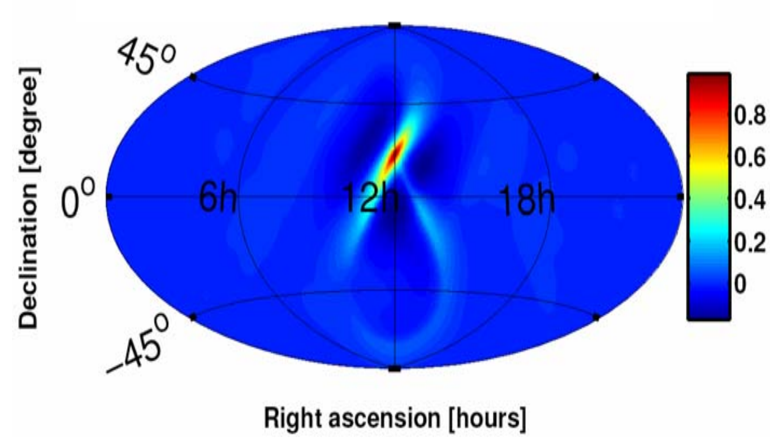
Challenge is to identify and eliminate noise correlations between H1 and H2!

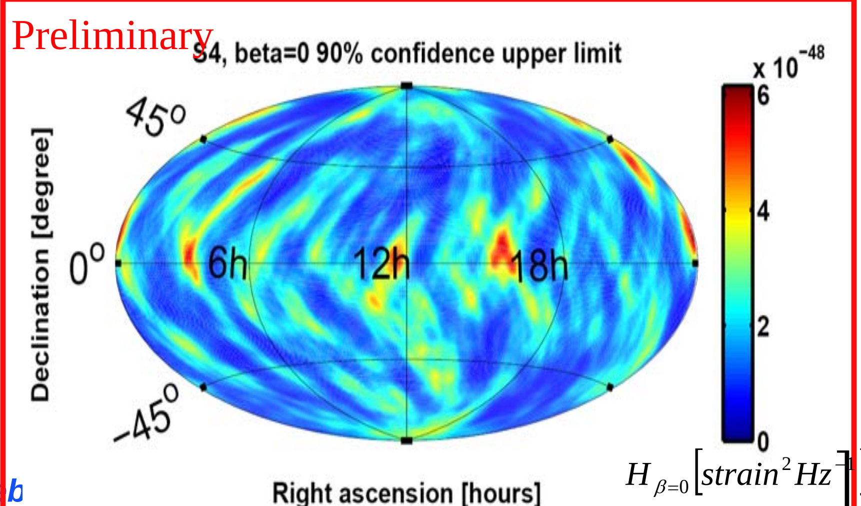
Upper limit map of a stochastic GW background

- S4 data- 16 days of 2 site coincidence data
- Get positional information from sidereal modulation in antenna pattern and time shift between signals at 2 separated sites
- **No signal was seen**.
- Upper limits on broadband radiation source strain power originating from any direction.

  (0.85-6.1 x 10^{-48} (Hz^{-1}) for min-max on sky map; flat source power spectrum)

Point Spread Function (calculated)





Summary

- LIGO is operating in a science mode at design sensitivity
  - » 1st long science run is ~67% complete
  - » No detection yet
- VIRGO, GEO, TAMA and CLIO approaching design sensitivity
- LIGO Sensitivity/range will be increased by ~ 2 in 2009 and another factor of 10 in ~2014 with Advanced LIGO
  - » Expect to be doing GW astrophysics with Advanced LIGO
- LIGO searches producing some interesting upper limits
- An international network of ground-based GW detectors is taking shape.
- Detections, and the exploration of the universe with GWs, will begin over the next decade!

The Beginning of a New Astronomy…