LIGO & LISA

Gravitational Waves
A new window to the universe

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Gravitational Waves

What are gravitational waves?

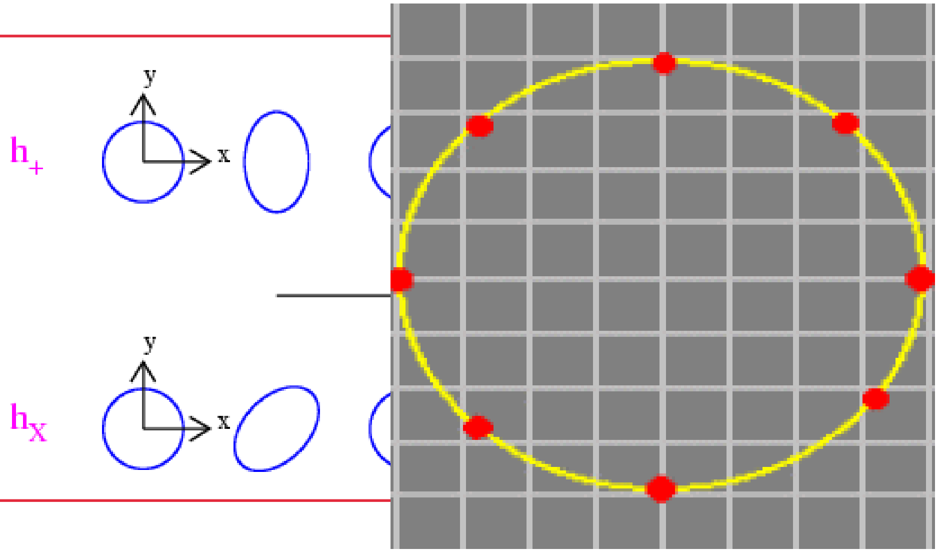
- **Amplitude is a relative length change: h = dL/L**
- **GW: Propagation similar to light (obeys same wave equation!)**
  - **Propagation speed = c (as far as we know)**
  - **Two transverse polarizations – <u>quadrupole waves</u>: + and x**

Example:

Ring of test masses

responding to wave

propagating along z



Gravitational Waves

How are gravitational waves generated?

- **Generated by huge accelerated masses such as accelerated black holes in a binary system**
- **Amplitude** $h = \delta L/L$

$$h = \frac{2G}{c^4}\frac{\ddot{I}}{r}$$

$$\sim \frac{r_S}{R}\frac{r_S}{r}$$

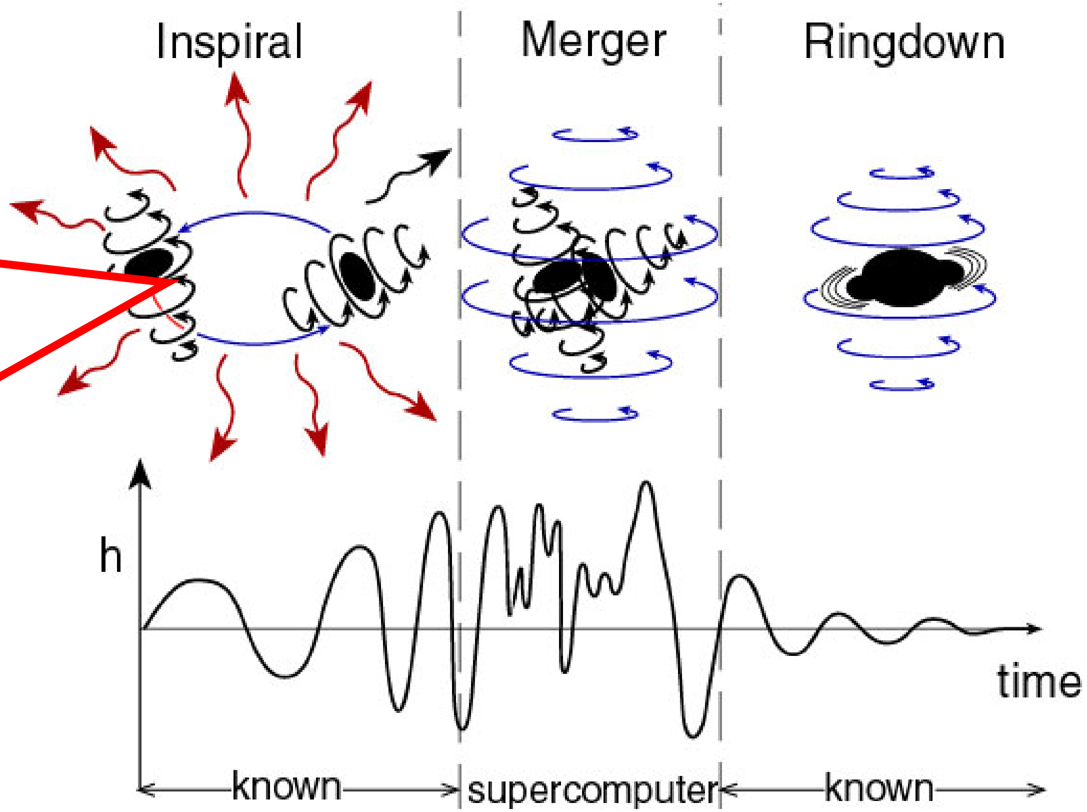
I: Quadrupole Tensor

R: Distance between Stars
r : Distance to binary system
r_S : Schwarzschild radius of stars

Binaries and Mergers

- **Mass Range:**
  NS/NS → SMBH/SMBH ($10^8/10^8$ Solar mass BH)

measure masses and spins of binary system. Loose energy due to GW emission.



Courtesy of Kip Thorne

Binaries and Mergers

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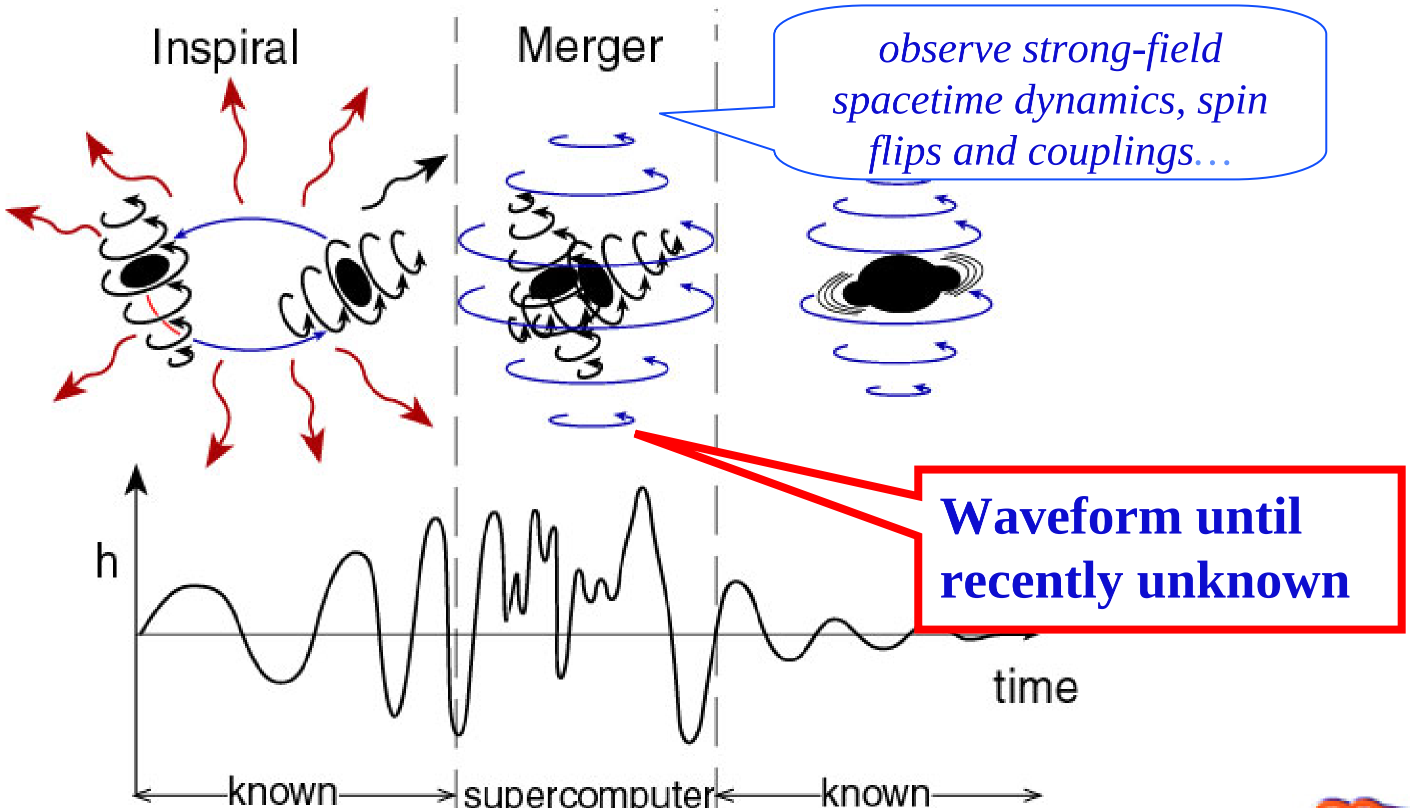

Courtesy of Kip Thorne

Binaries and Mergers

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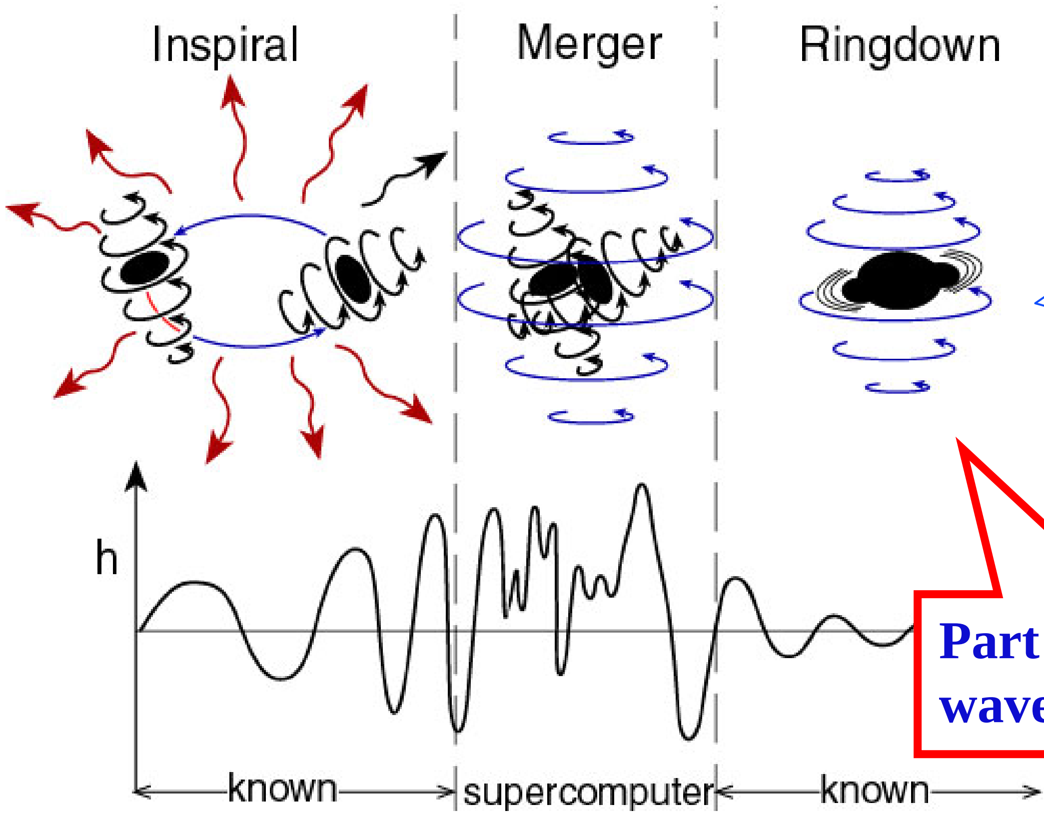


detect normal modes of ringdown to identify final NS or BH.

Part of the merger waveform

Courtesy of Kip Thorne

Binaries and Mergers

Example: NS/NS merger (M_{NS} ~ $3x10^{30}$kg ~ 1.4 M_{Sun})

1. Smallest Distance: d_{min} ~ 20km (2xDiameter of NS)
2. Potential Energy: $E = - GM^2/d$ ~ $3x10^{46}$J
3. Newton: f (d=100km) ~ 100 Hz, f (d=20km) ~ 1 kHz
4. Takes about 1s to get from 100km to 20km
5. During that second nearly half of the Potential Energy is radiated away!
6. Assume binary is in the Virgo cluster (15 Mpc ~ $6x10^{24}$ m)

We receive about P=1..100mW/m^2 from each binary!
Like full moon during a clear night!

Gravitational Waves

We can see the moon, why haven't we seen Gravitational Waves yet?

GW-Amplitude: h=δL/L is

$$h_{\mu\nu} = \ldots (I_{\mu\nu})$$

G/c^4

Answer: Space is stiff

Our exa

$$h \approx \frac{10^{-21}}{(r/15\mathrm{Mpc})}$$

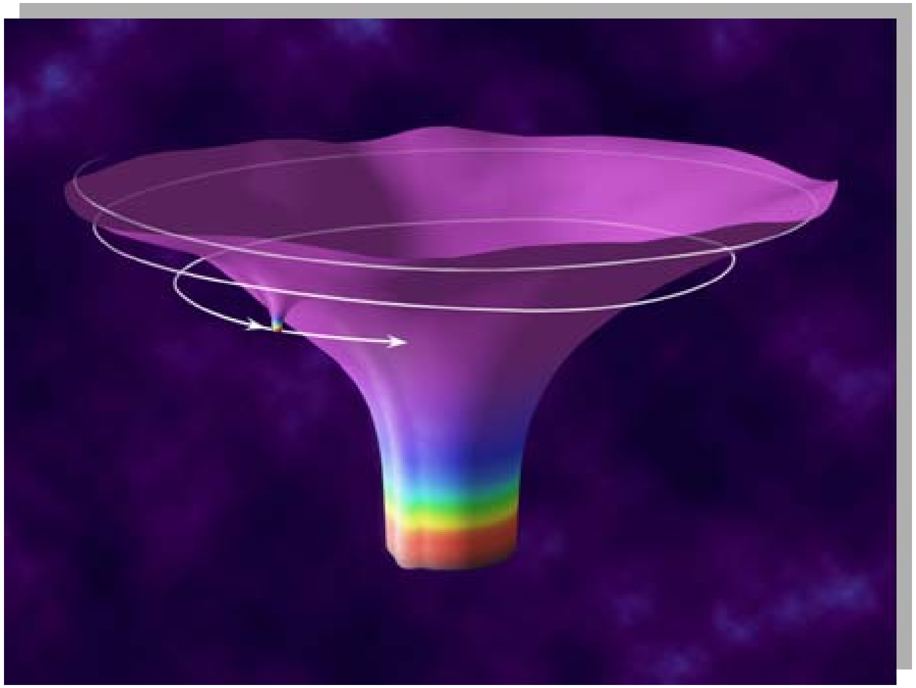
Or 1am over 1km

EMRI

EMRI: Extreme Mass Ratio Inspiral

$10^2 M_S$ falls into $10^8 M_S$

- **LISA Core Target**
- **Test particle case for gravitational waves**
- **Measures multipole moments of BH**

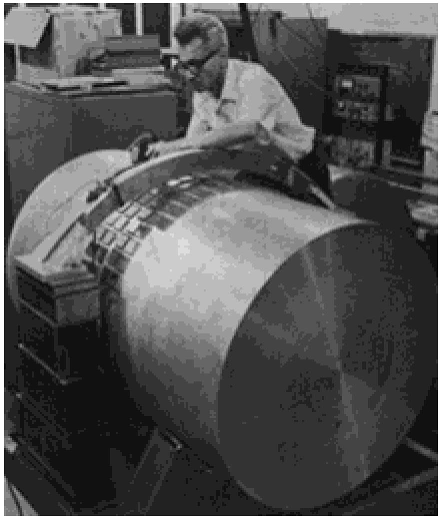


Little Sister Process:
- **NS spiraling into small BH**
  - **Short Gamma Ray Bursts**
  - **GW in LIGO band**

Detection Schemes I

Historic:

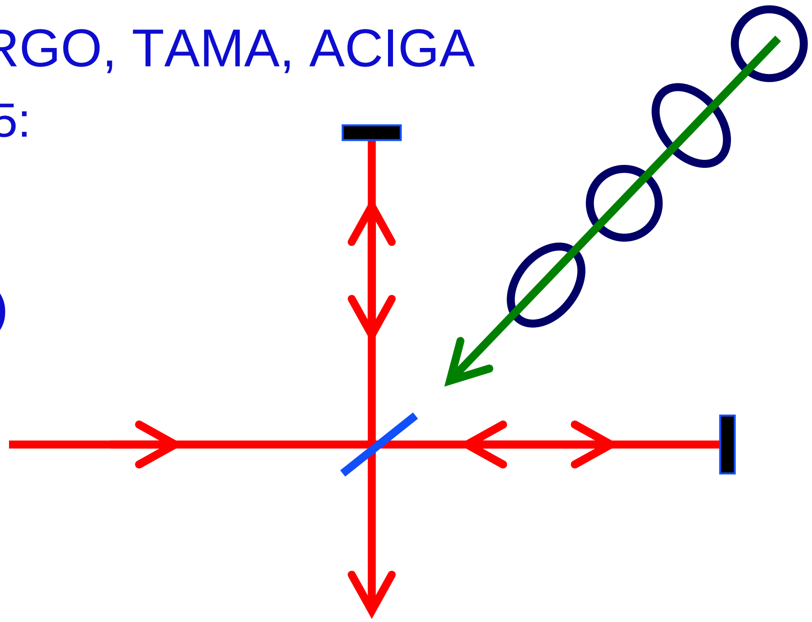
- Einstein predicted GW 1917
  - » It was assumed that they will never be detected
  - » So far, Einstein was right
- Joe Weber (U. of Md) built first Bar Detector
  - » Idea published 1959
  - » Experimental results published in 1969
    - – **J.W. claimed positive results**
    - – **Very unlikely**
  - » Other bar detectors: LSU, Rome, Perth, Legarno, Cern…
    - – **Orders of magnitude better sensitivity: No detection**
  - » Others reproduced results based on electronic noise
  - » But J.W. started the business
    - – **also involved also in laser/maser development among other areas**



Detection Schemes II

Laser Interferometer

- Ground based: LIGO, GEO 600, VIRGO, TAMA, ACIGA
  - » Experiments started between '72-'75:
    - – **Rai Weiss (MIT)**
    - – **Ron Drever (Glasgow/CIT)**
    - – **Karl Maischberger (MPQ, Munich)**
  - » Detector Theory:
    - – **Rai Weiss (MIT)**
    - – **Kip Thorne (CIT)**
    - – **Vladimir Braginsky (Moscow)**

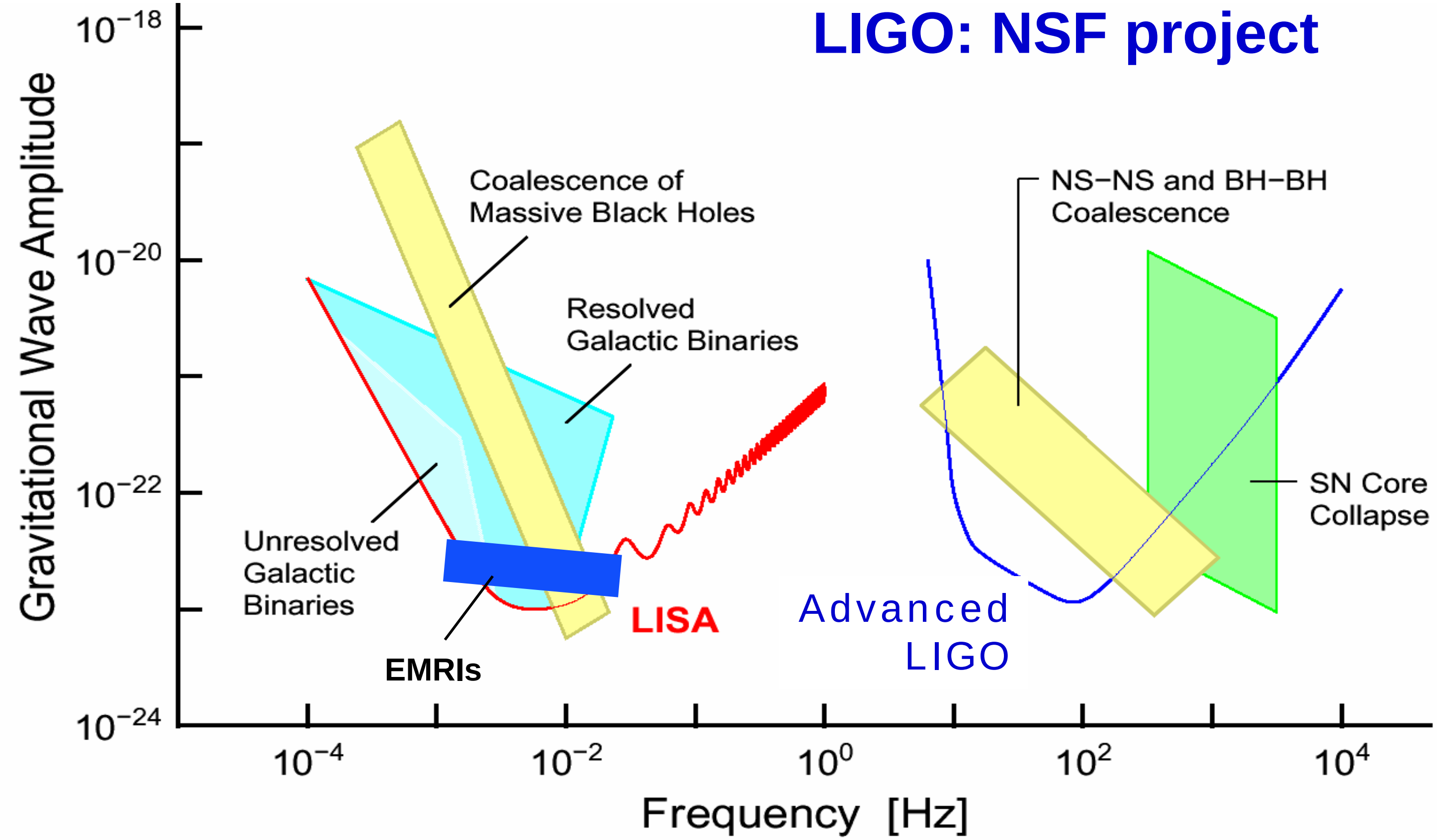


- Space based: LISA
  - » Idea: Pete Bender, Jim Faller (1975, JILA, Colorado)
  - » Was proposed to NASA, later as an M3-mission to ESA
  - » Now: NASA-ESA mission in Phase A
  - » Scheduled for launch in 2015[1]

[1] **Currently under review by the National Research Council**

LIGO & LISA

LISA: Joint NASA/ESA project

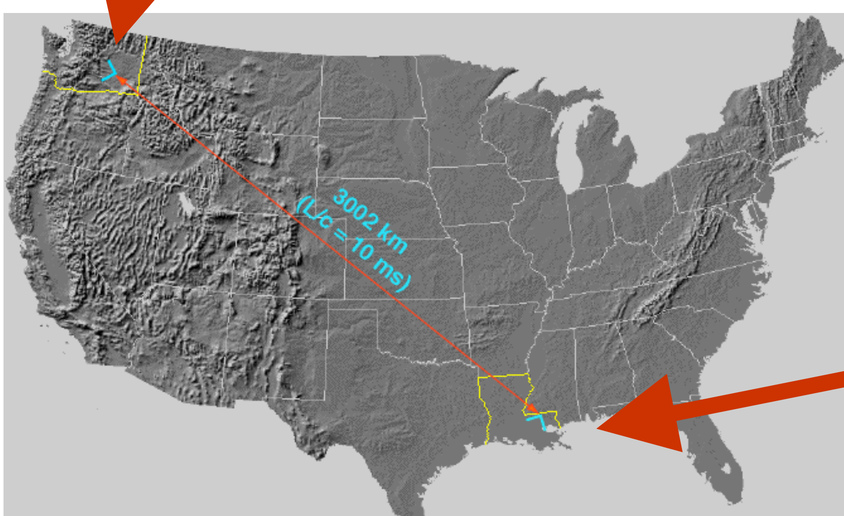


LIGO Facilities

Hanford (H1=4km, H2=2km)

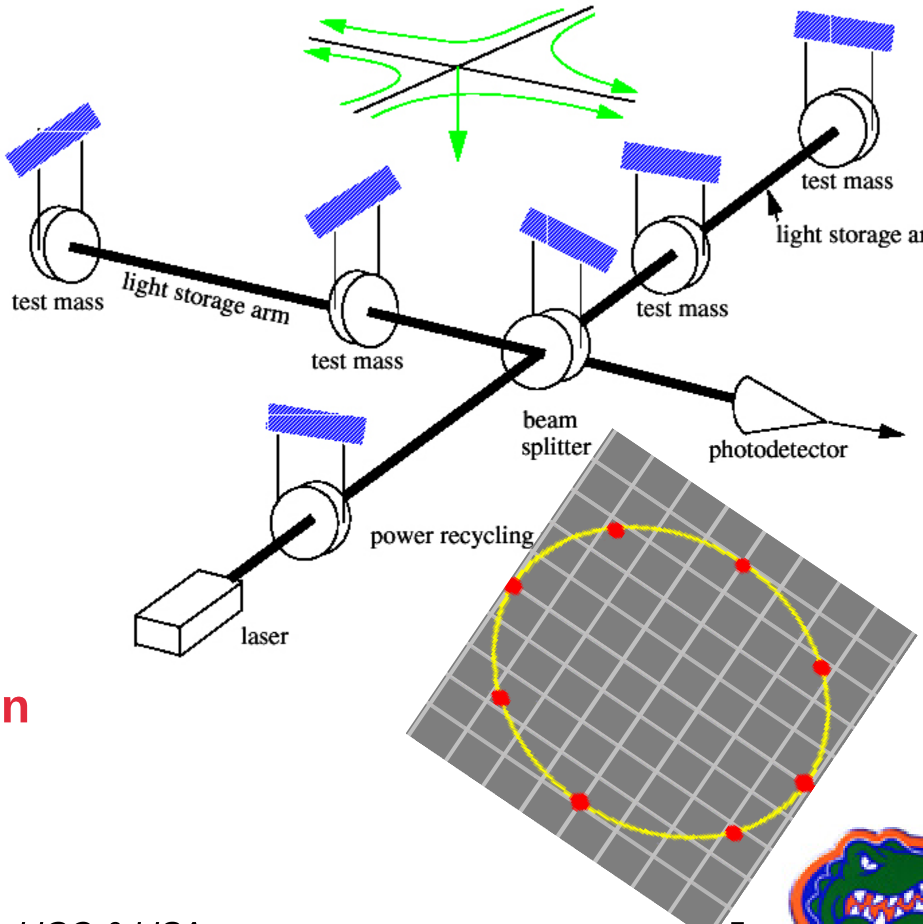
LIGO : Laser Interferometer Gravitational-wave Observatory

Livingston (L1=4km)

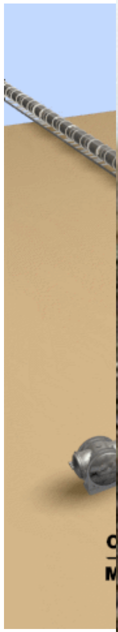


Interferometer

- Suspended Interferometers
  - » Suspended mirrors in "free-fall"
  - » Michelson IFO is "natural" GW detector
  - » Broad-band response (~50 Hz to few kHz)
  - » Feedback loops control position and alignment of all mirrors and of the laser frequency and beam direction
  - → Large Control Challenge



LIGO Detector Facilities



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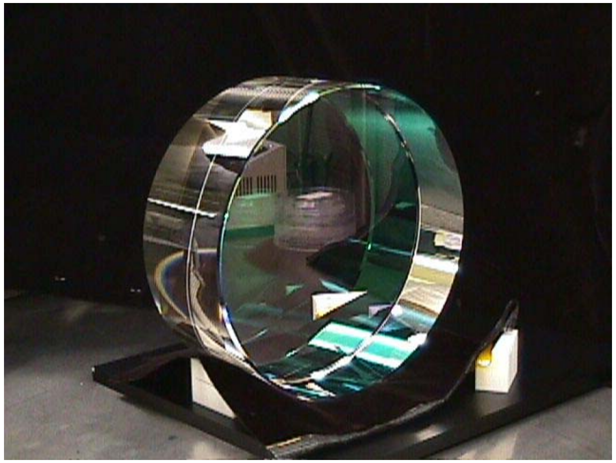
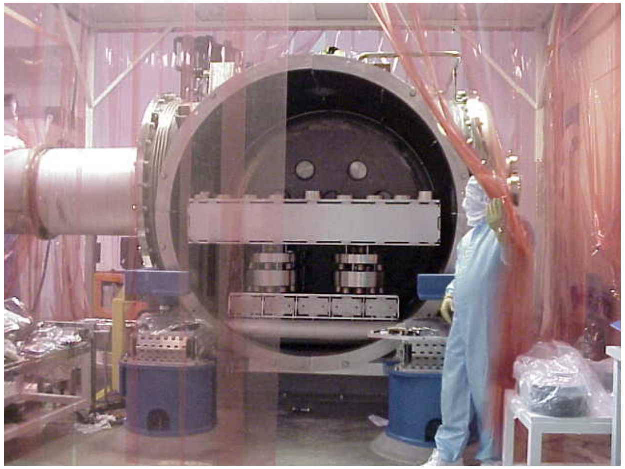
LIGO Suspension



Fused Silica
25-cm diameter

Suspended by
steel wire



Sits on seismically
insulated platform

LIGO I

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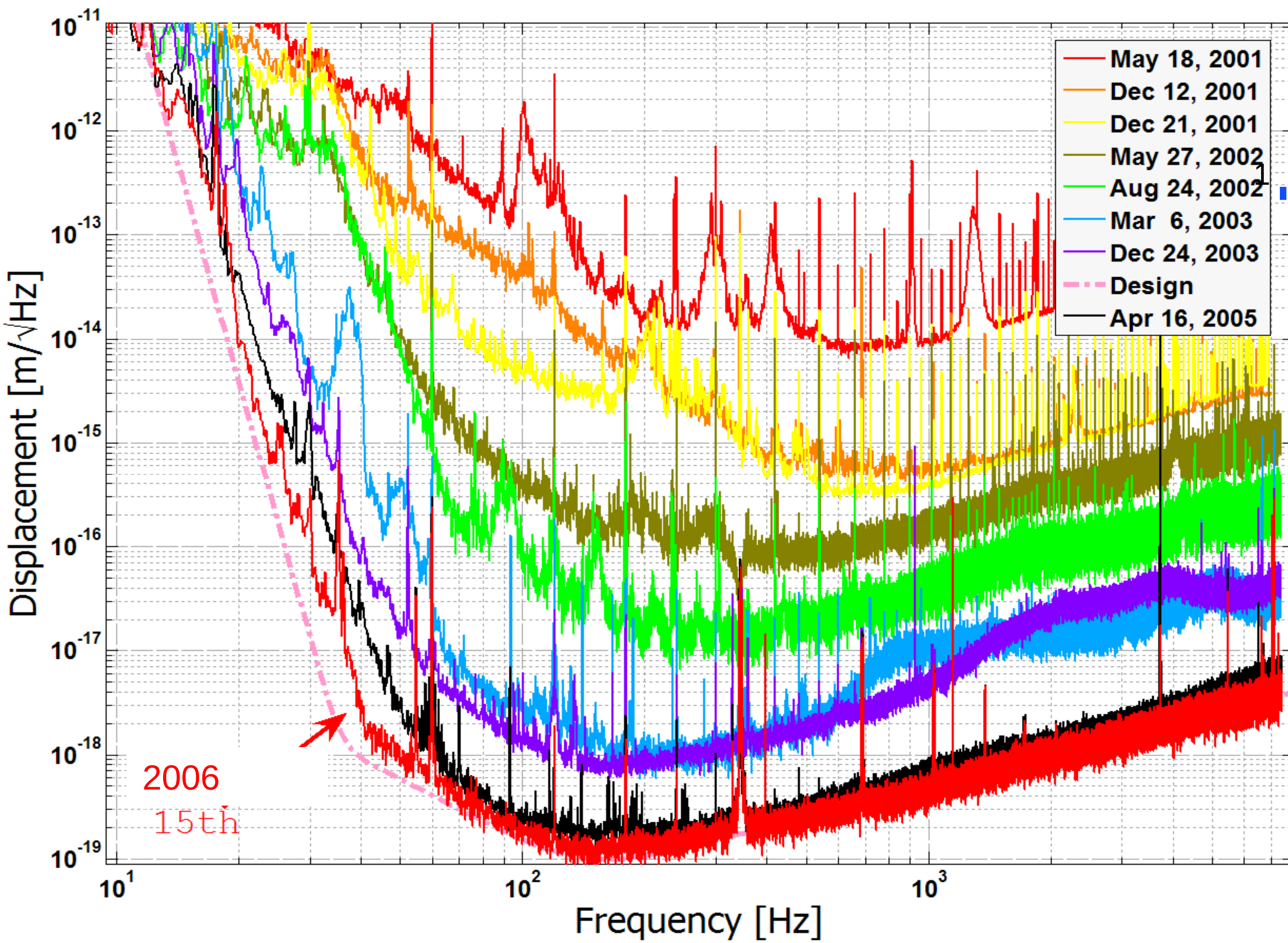


2006

15th

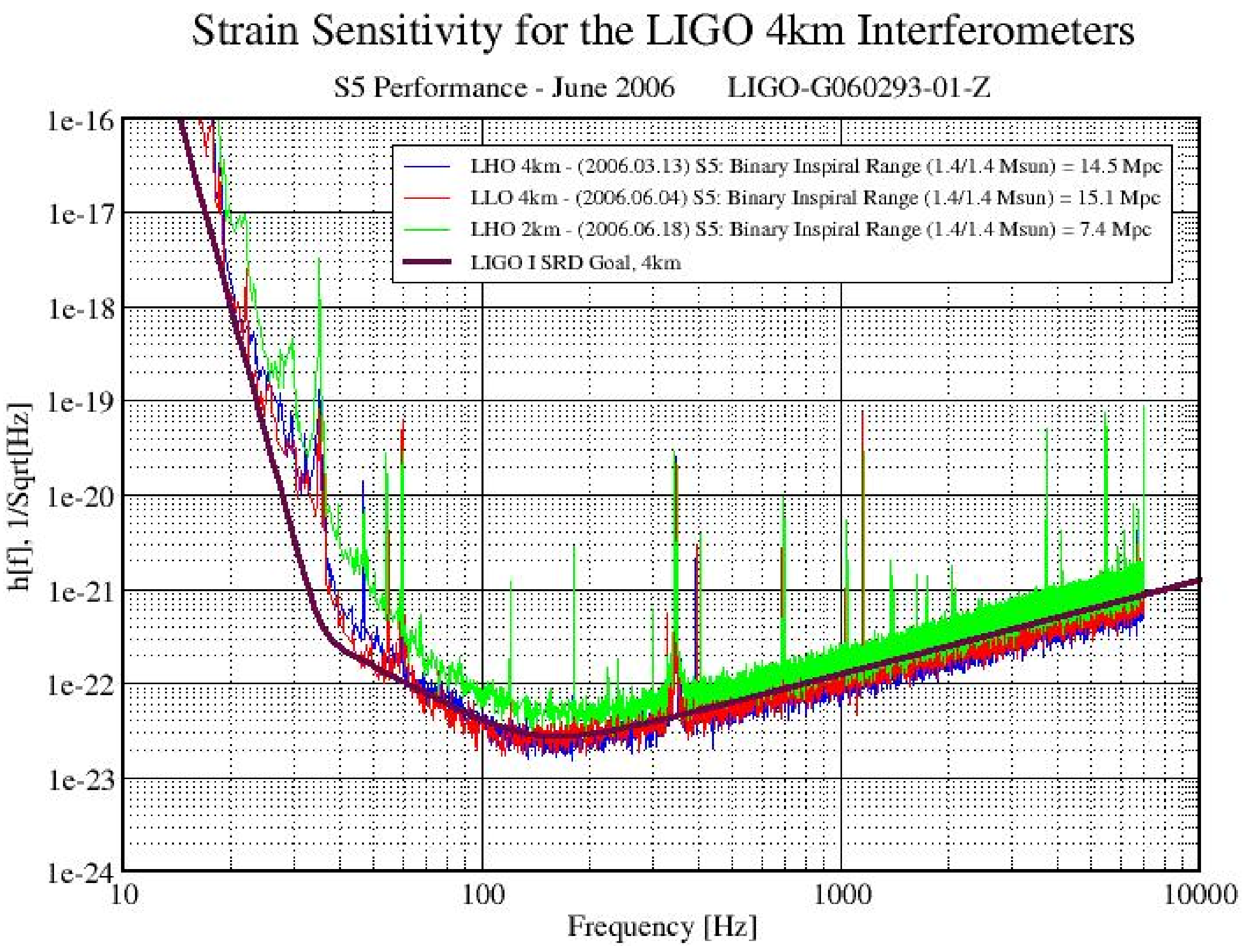
2007

1 2 3 4

ns

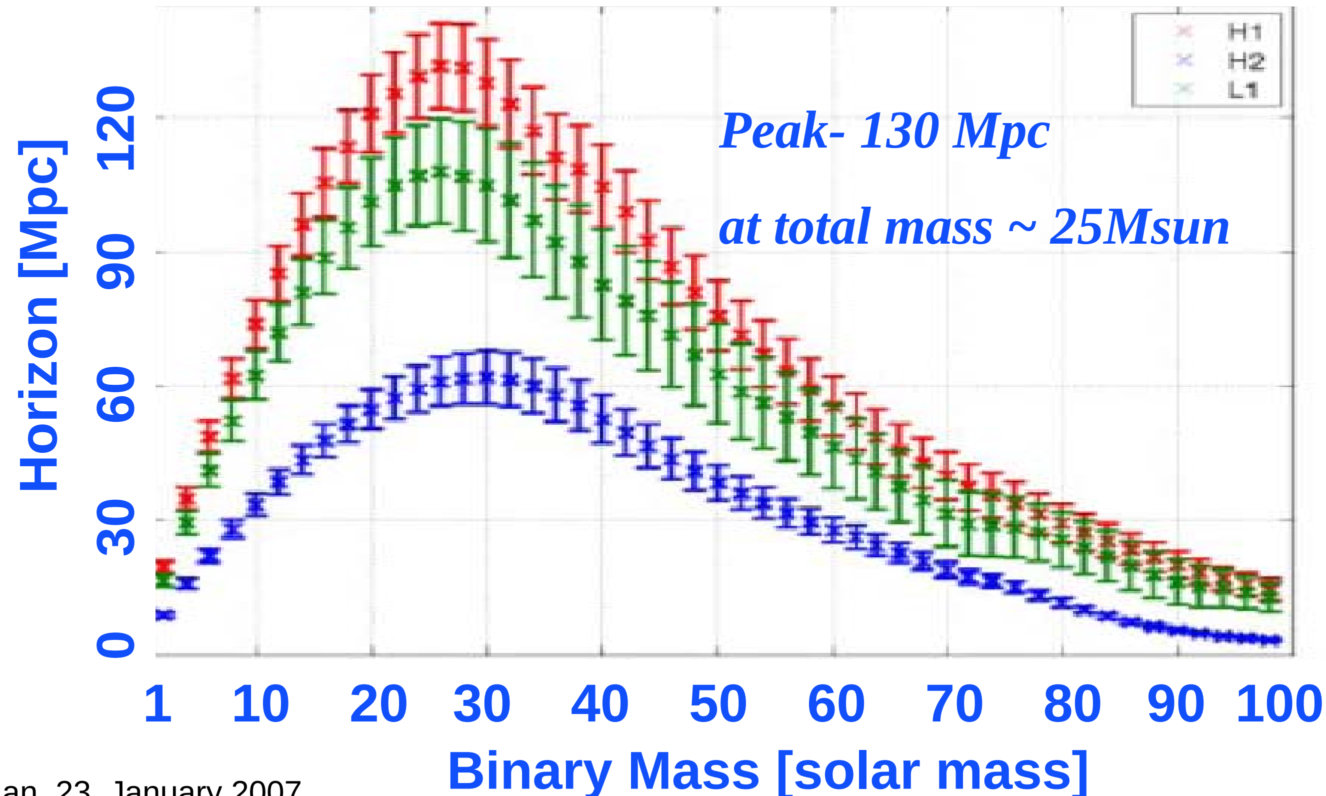
a

S5 Sensitivity



Results

- **Rates for neutron star mergers**
  - **S4: $R_{90\%}$ < 1 inspirals / year /** "milky-way-equivalent-galaxy"
  - **S5: 3 months data, no signals seen**
    - for 1.4-1.4 M mergers with ~200 MWEGs in range
    - for 5-5 M mergers with ~ 1000 MWEGs in range



LIGO

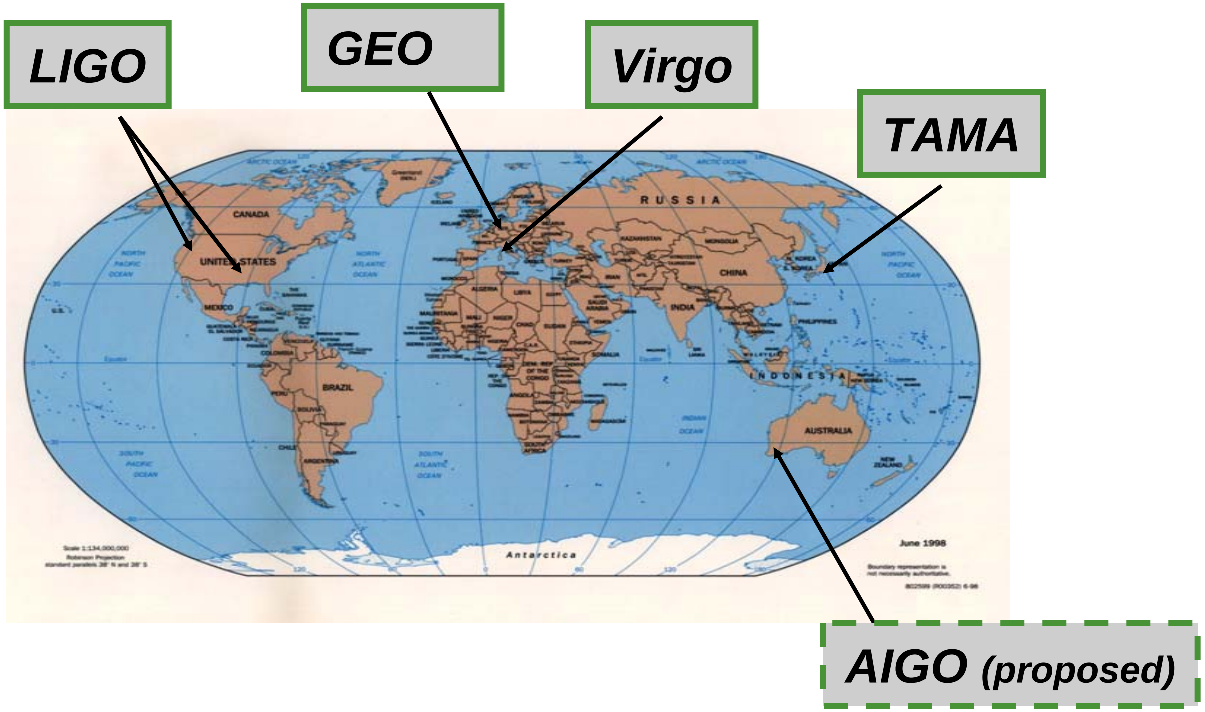
Results

- GW-Bursts
  - » Triggered Searches (Swift, HETE-2, IPN, Intergral, RXTE, RHESSI)
  - » Measured in GW-energy
    - – S2, S3, S4-runs: 39GRBs, no signal found
    - – S5-run: 53 GRB triggers in first 5 months
      - **Typical S5 sensitivity at 250 Hz: E_{GW} ~ 0.3 M at 20 Mpc**
- Periodic Signals
  - » Upper limits on 97 pulsars in 10 months LIGO S5 run
  - » Lowest ellipticity limit: PSR J2124-3358
    - – f_{GW}= 405.6 Hz, r = 0.25 kpc → **$\varepsilon < 1.1\times10^{-7}$**
- **Stochastic GW-background:**
  - » **$\Omega_{GW} < 6.5\times10^{-5}$ (S4)**
  - » **$\Omega_{GW} < \sim4\times10^{-6}$ (expected for S5) (starts to exclude some Big Bang models)**
- **No Signals, only upper limits (preliminary)**

Worldwide network

Forming Global Network:

- Increased detection confidence
- Improved source locations and wave polarizations



Beyond S5

Enhanced LIGO:

- Increase Laser Power (30 W)
- DC-Sensing (improves shot noise)

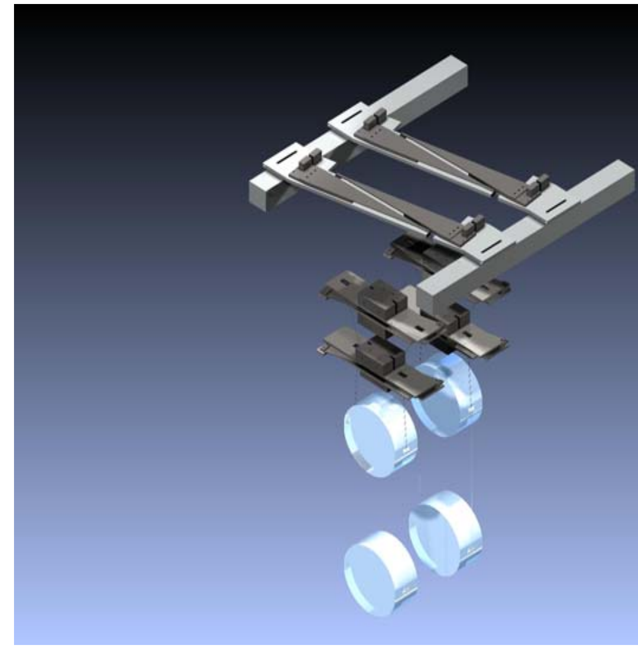
→ Start next Science Run: ~2009

- Duration: ~ 1 year integrated data
- Expected End: ~ 2010/11

→ Start Advanced LIGO Installation

Advanced LIGO

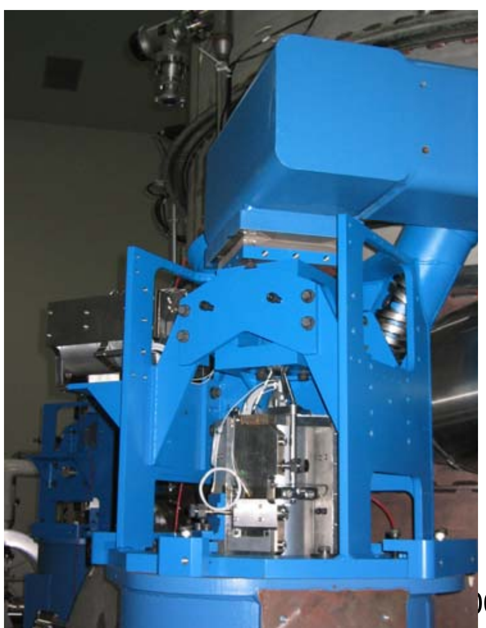
Detector Improvements installation and commissioning starting in 2010/11:



New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal noise in detection band



Improved seismic isolation:

Passive → Active

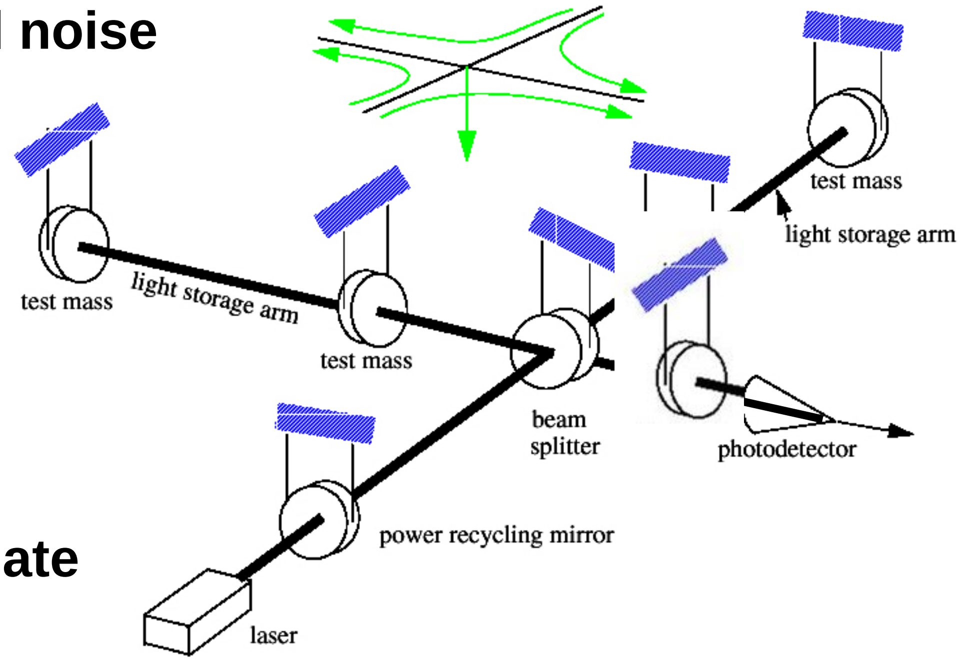
Lowers seismic "wall" to ~10 Hz

Advanced LIGO

Increased and better test mass:

10 kg → 40 kg ⟶ decrease radiation pressure noise

Higher Q ⟶ lower thermal noise



Increased laser power:

10 W → 180 W

Improved shot noise (high freq)

The mirrors will float on light:

~800 kW laser power will propagate between the mirrors

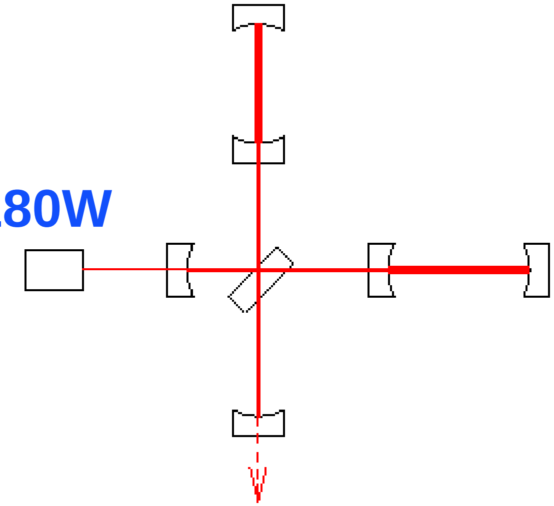
→ Photon pressure will lift the mirrors by several μm

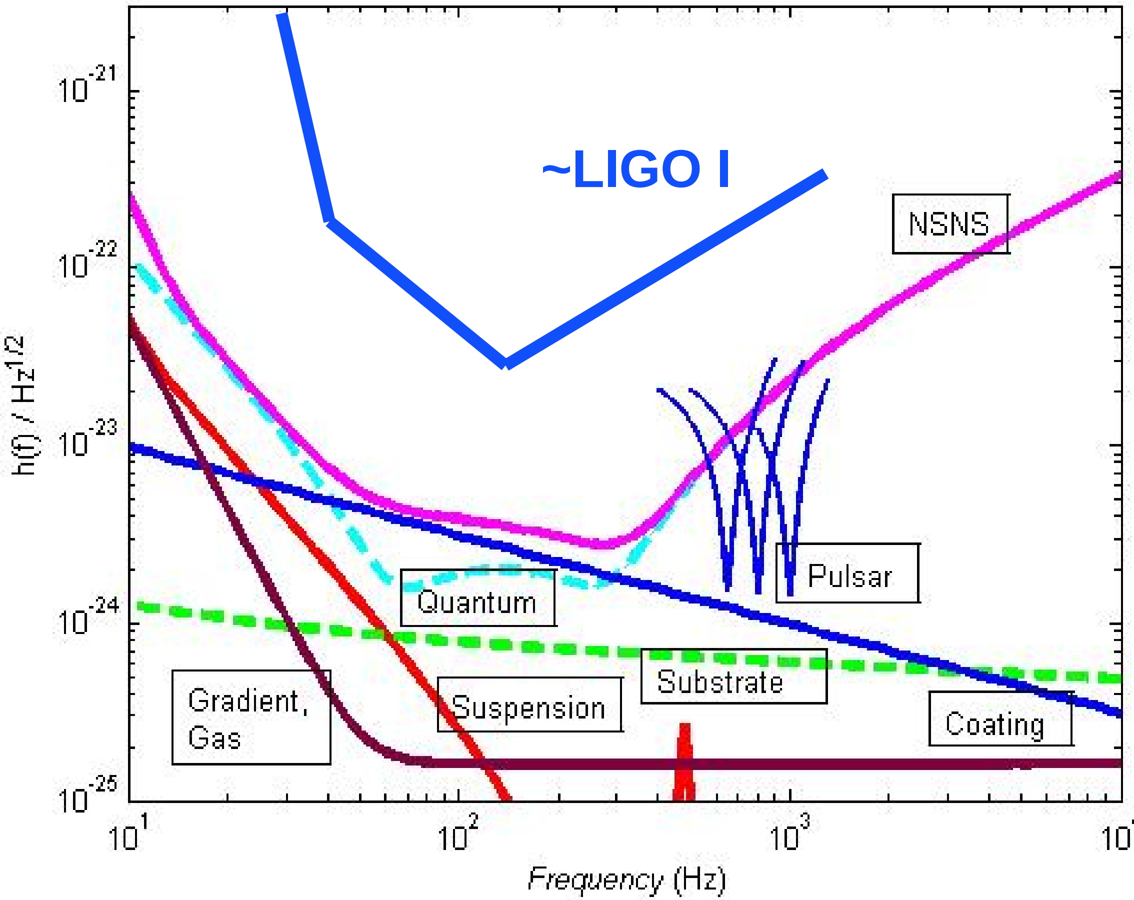
Advanced LIGO:

New Configuration:
→ Dual Recycled

Adv. LIGO:

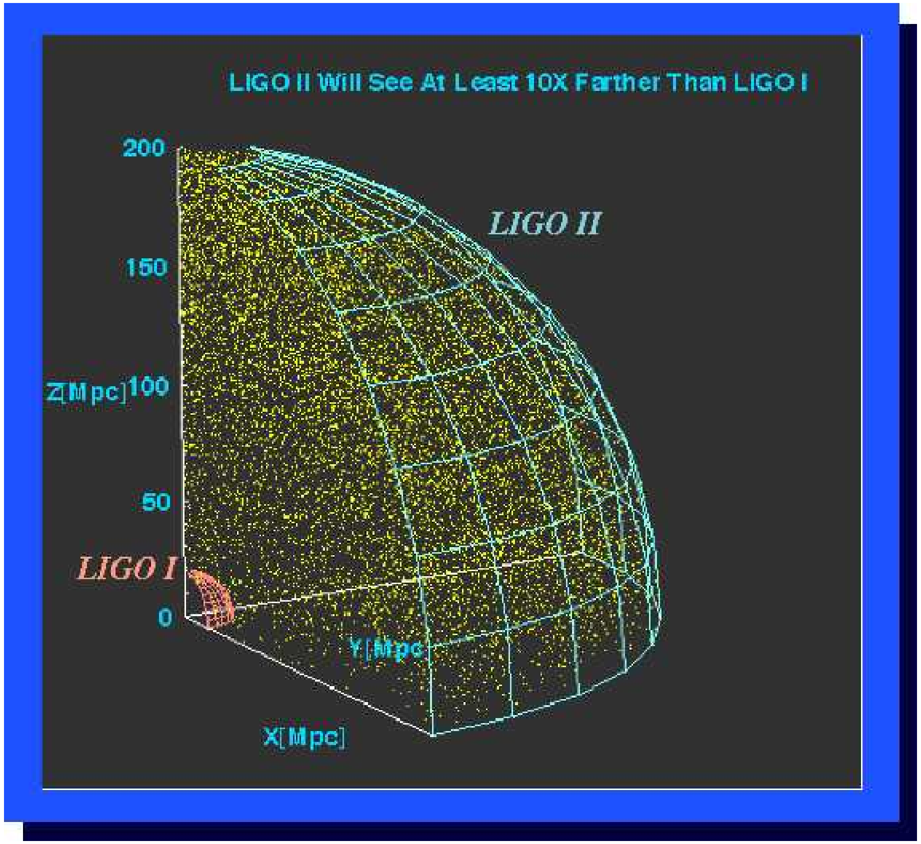
180W





Advanced LIGO

Advanced LIGO will have ~ factor 10 better sensitivity and higher bandwidth:



Searched Volume and number of expected signals increase by factor 1000-10000!

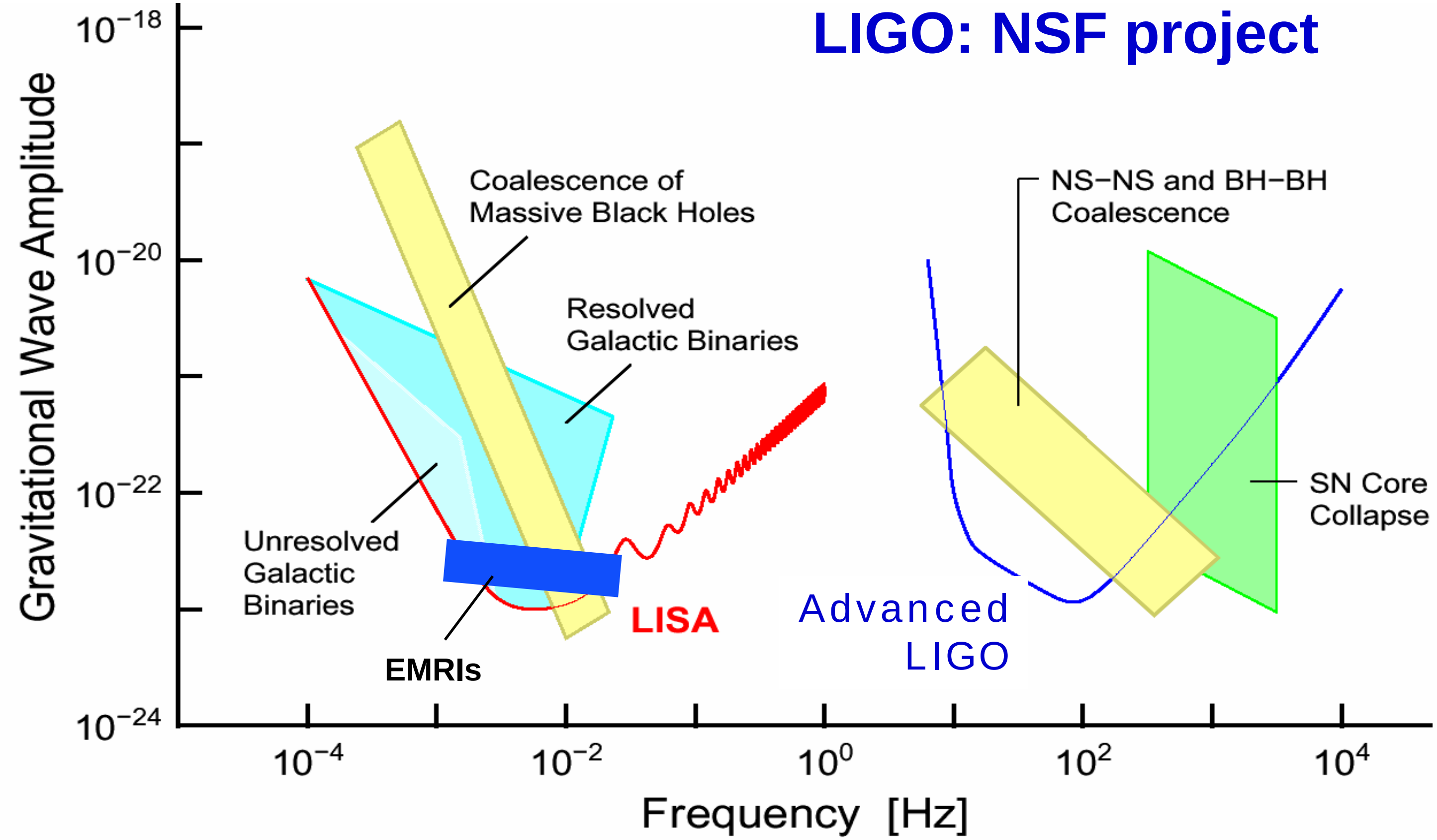
We should be detecting gravitational waves regularly within the next 10 years!

LIGO today is the Lab plus The LIGO Scientific Collaboration

- **The LSC carries out the scientific program of LIGO – instrument science, data analysis.**
- **The 3 LIGO interferometers and the GEO600 instrument are analyzed as one data set**
- **Approximately 540 members**
- **~ 35 institutions plus the LIGO Laboratory.**
- **Participation from Australia, Germany, India, Italy, Japan, Russia, Spain, the U.K. and the U.S.A.**

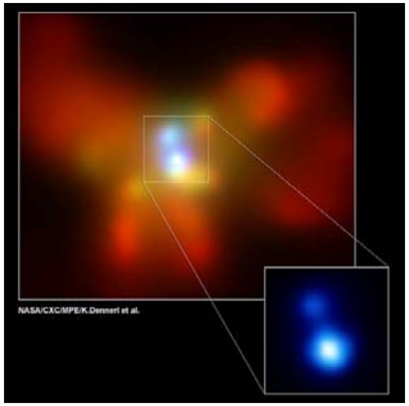
LIGO & LISA

LISA: Joint NASA/ESA project

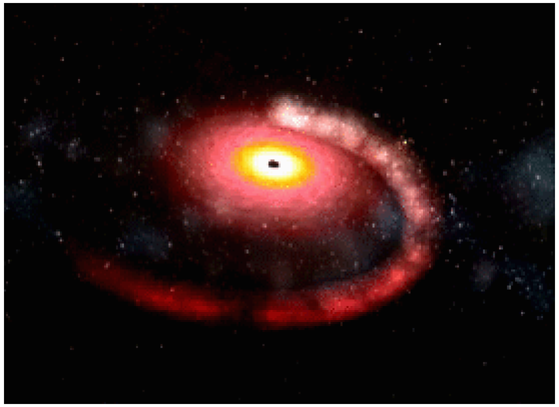


LISA Sources

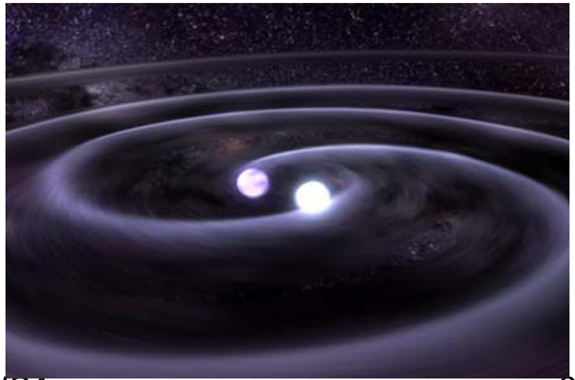
1. **Super-massive Black Hole mergers**



Chandra: NGC6240



2. **Extreme mass ratio Inpirals (EMRIs)**



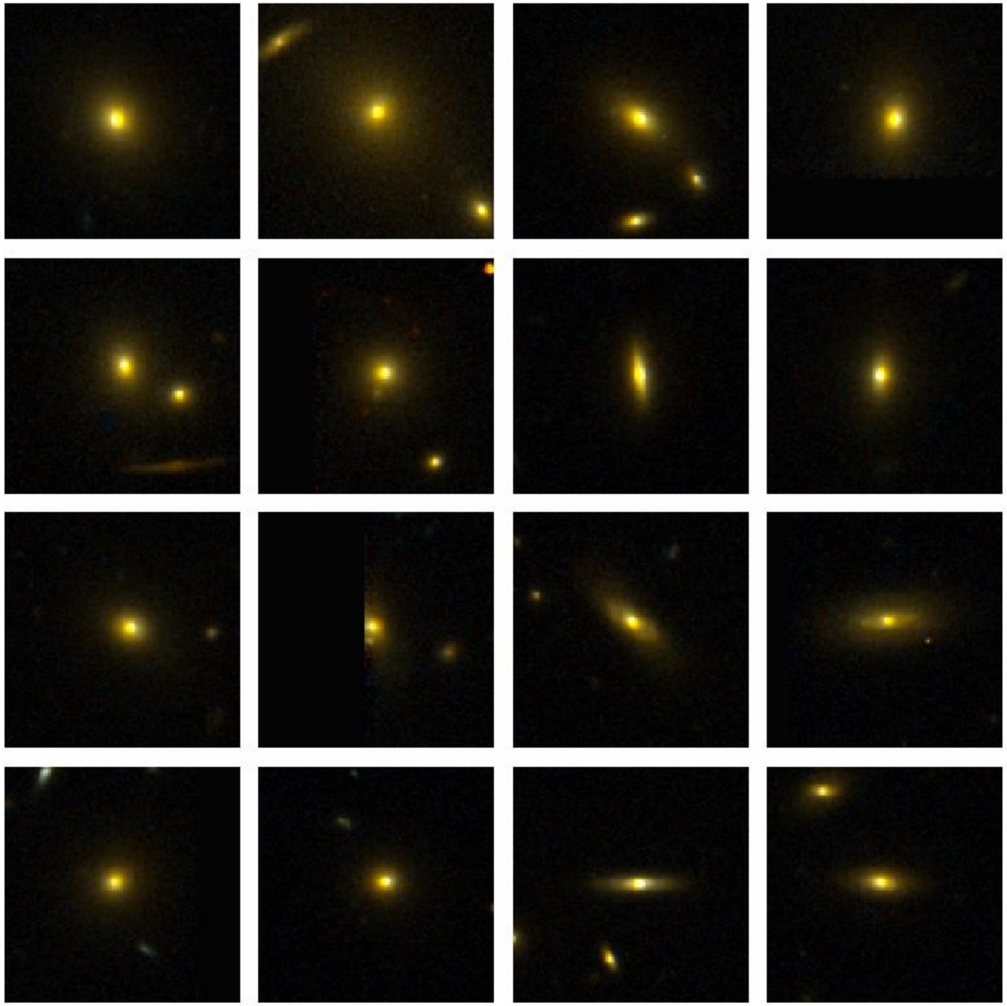
Credit: Tod Strohmayer (GSFC)

3. **Galactic Binaries**

SMBH merger rates

What do we know?

- **Almost all galaxies host a massive black hole. But do they merge?**
- **Essentially no mergers seen in cluster MS 1358-62 (z = 0.32)**
- **Shown: 16 brightest galaxies. No apparent mergers!**

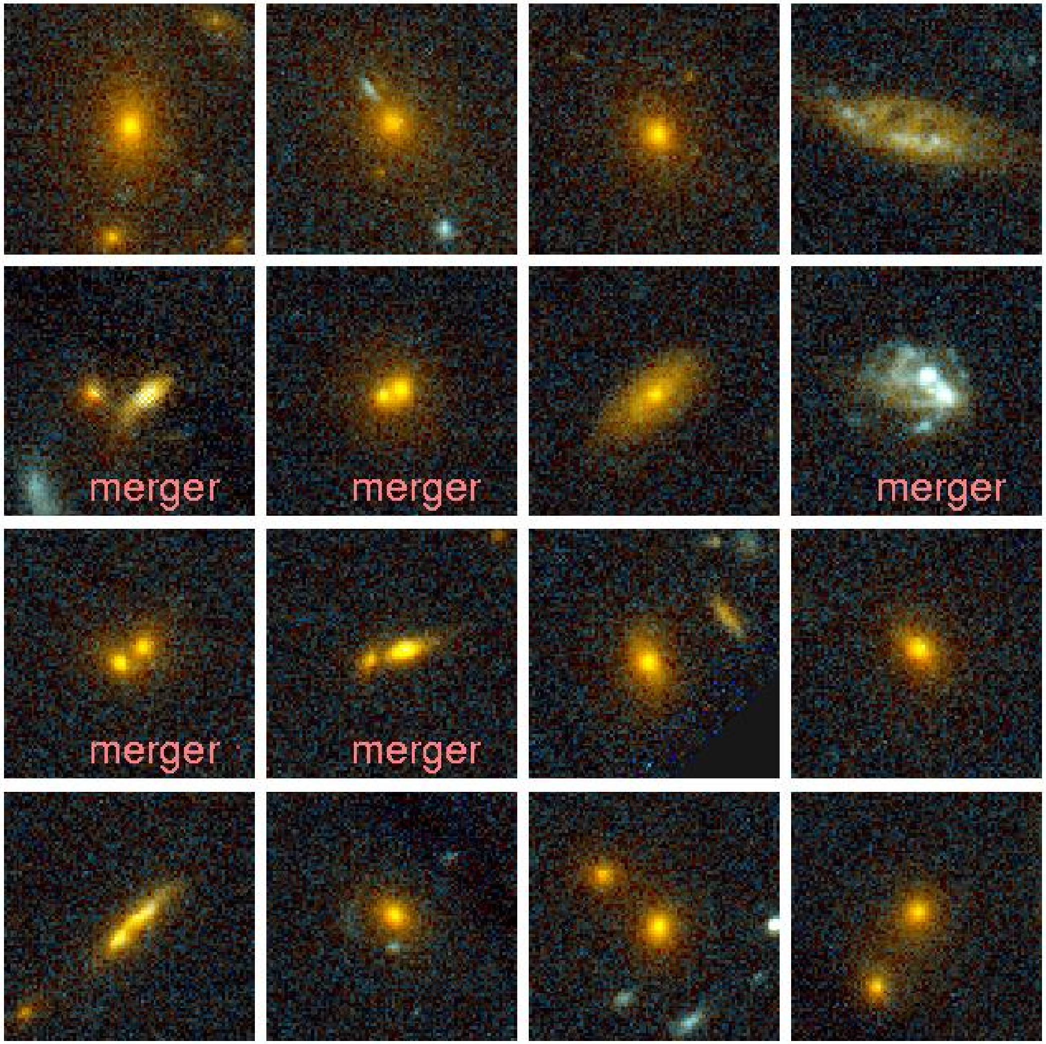


SMBH merger rates

What do we know?

- **Almost all galaxies host a massive black hole. But do they merge?**
  - **Mergers in rich cluster MS 1054-03 (z = 0.83)**
  - **Shown: 16 brightest galaxies. About 20% are merging!**

van Dokkum et al 1999, ApJ 520,L95.



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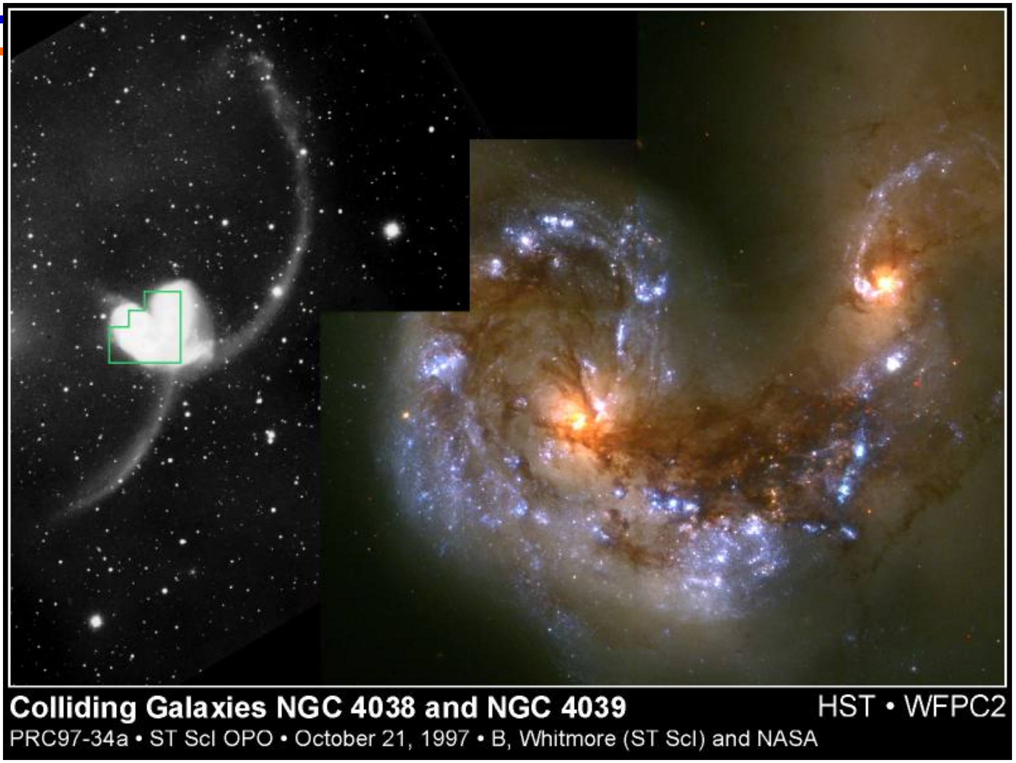
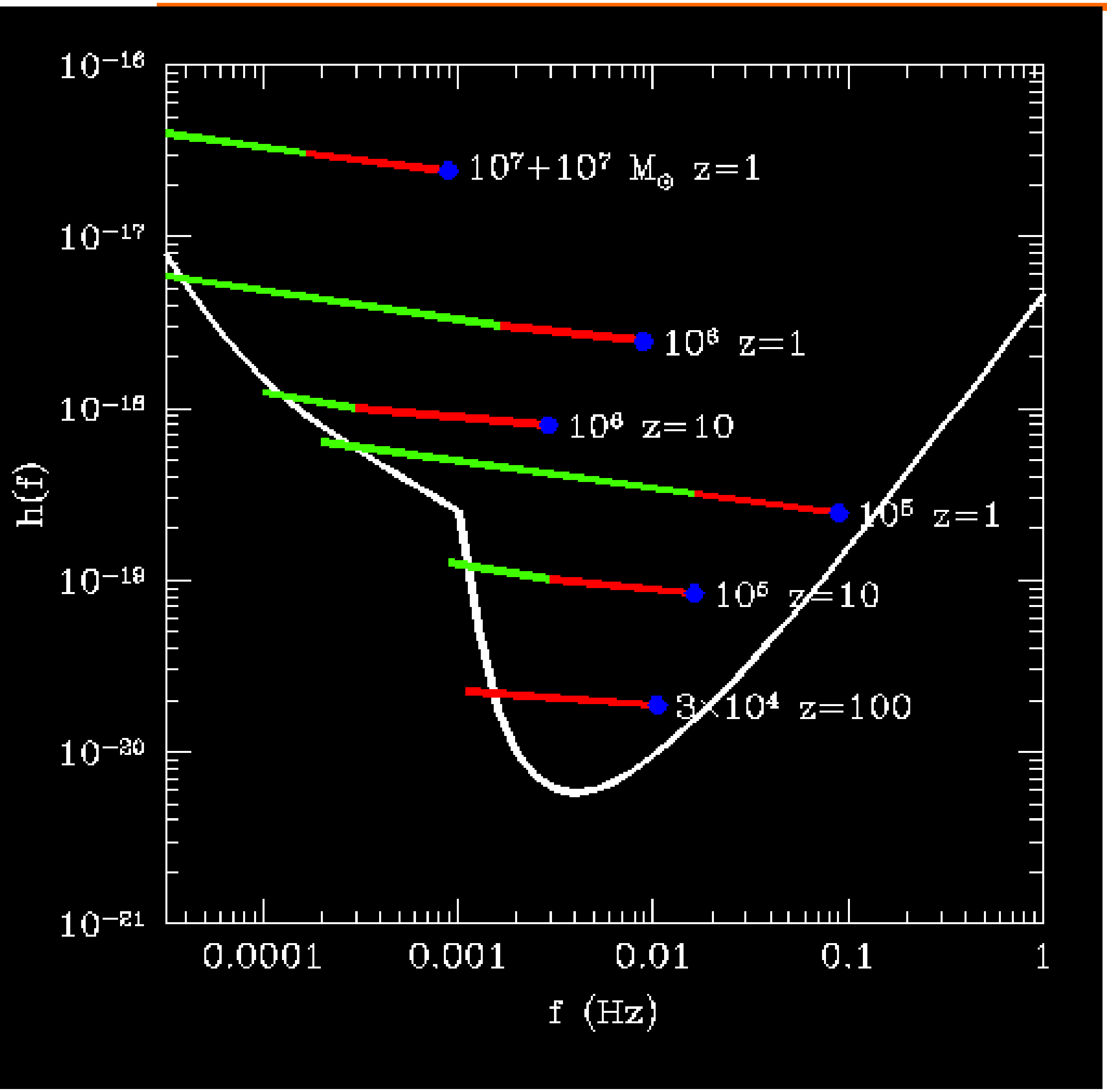


Event rate: At least a few events per year!

(almost certain)

(Haehnelt 1994; Menou, Haiman, & Narayanan 2001; Wyithe & Loeb 2003; Islam, Taylor, & Silk 2004; Sesana et al 2004)

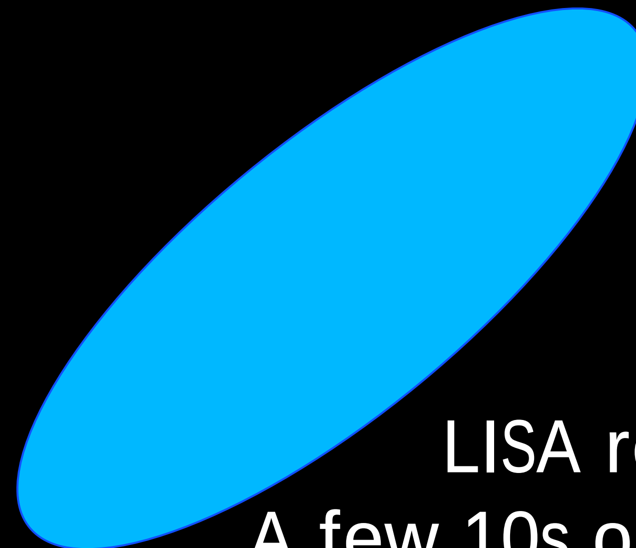
SMBH Mergers



- Mass/Redshift range: $10^5 M_{sun} < (1+z)M < 10^7 M_{sun}$ out to z~10
- Start to show up at low frequencies **months** before merging.
- Predict merger weeks in advance.
- The "dream comes true" event: Parallel Observations with Hubble, Chandra, and other EM-telescopes.

Angular Resolution

Full moon:
~30 arcminutes.



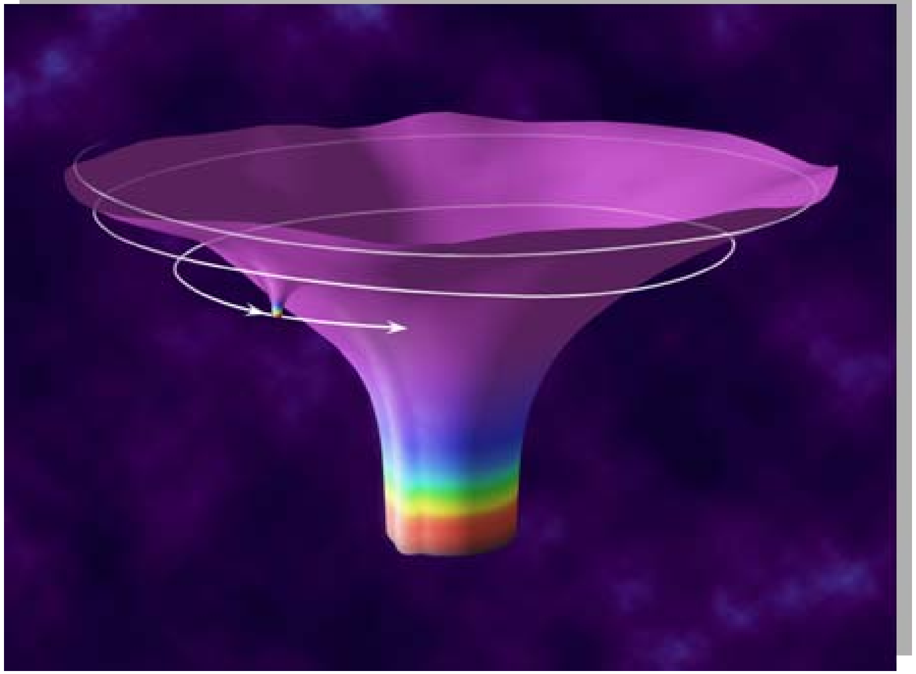
LISA resolution:
A few 10s of arcmin along major axis,
~10 along minor axis
for z~1 type signals.

The Hubble Deep Field:
144 arcseconds.

EMRI

EMRI: Extreme Mass Ratio Inspiral

$10^2 M_S$ falls into $10^8 M_S$



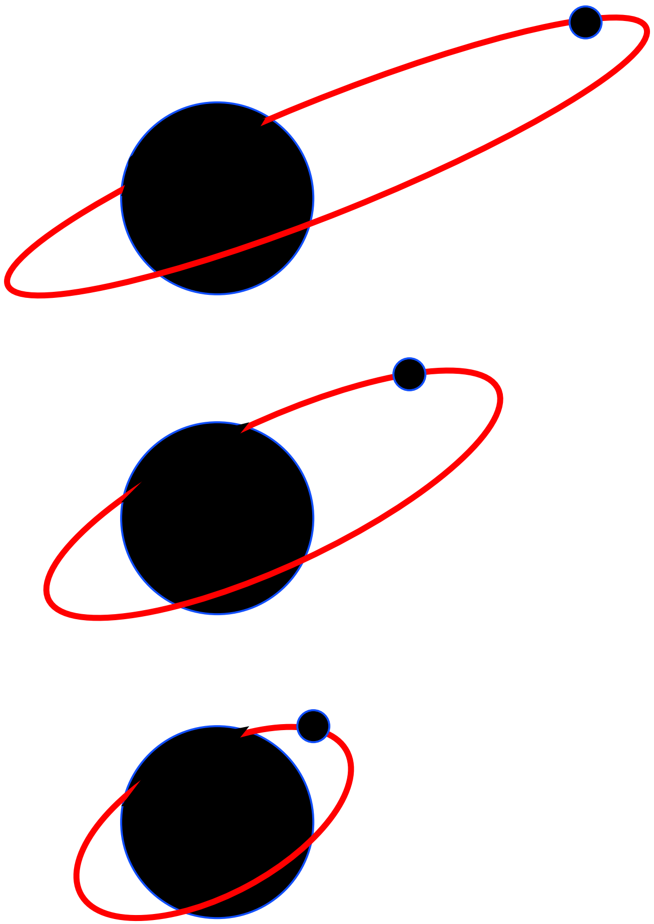
- LISA Core Target
- Test particle case for gravitational waves
- Measures multipole moments of BH

Little Sister Process:

- NS spiraling into small BH
  - Short Gamma Ray Bursts
  - GW in LIGO band

EMRI

- Predominantly Stellar mass black hole capture
- Reach: z~1
- Track phase over ~ 10^5orbits
  - » Determine mass and spin of SMBH
  - » Determine spacetime with high precision
  - » Measure multipole moments of SMBH
- Relativists test particle experiment

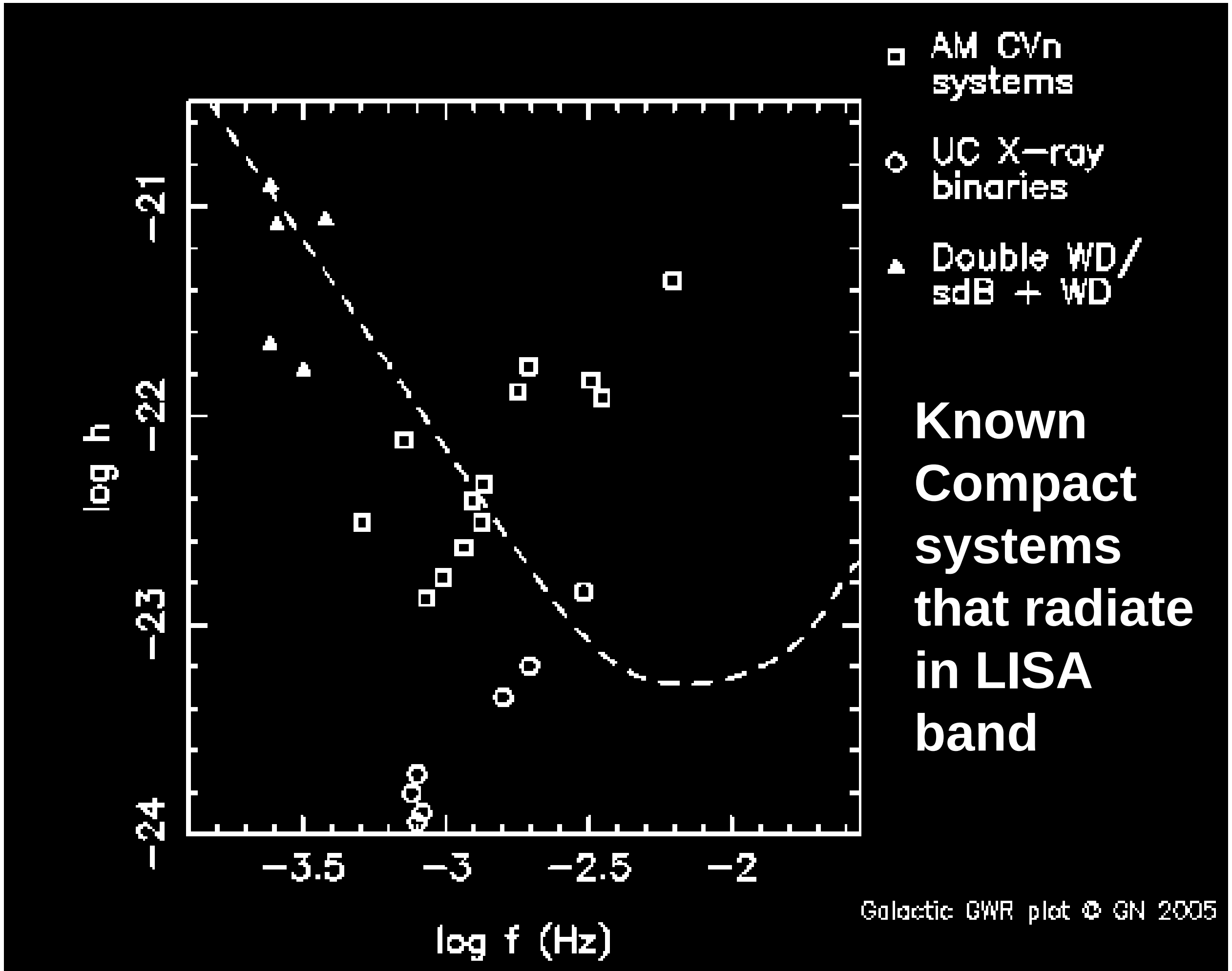


<u>Main Problem:</u>

- Other GW signals might mask these signals.

See: Barack and Cutler, PRD **69**, 082005 (2004).

Galactic Binaries



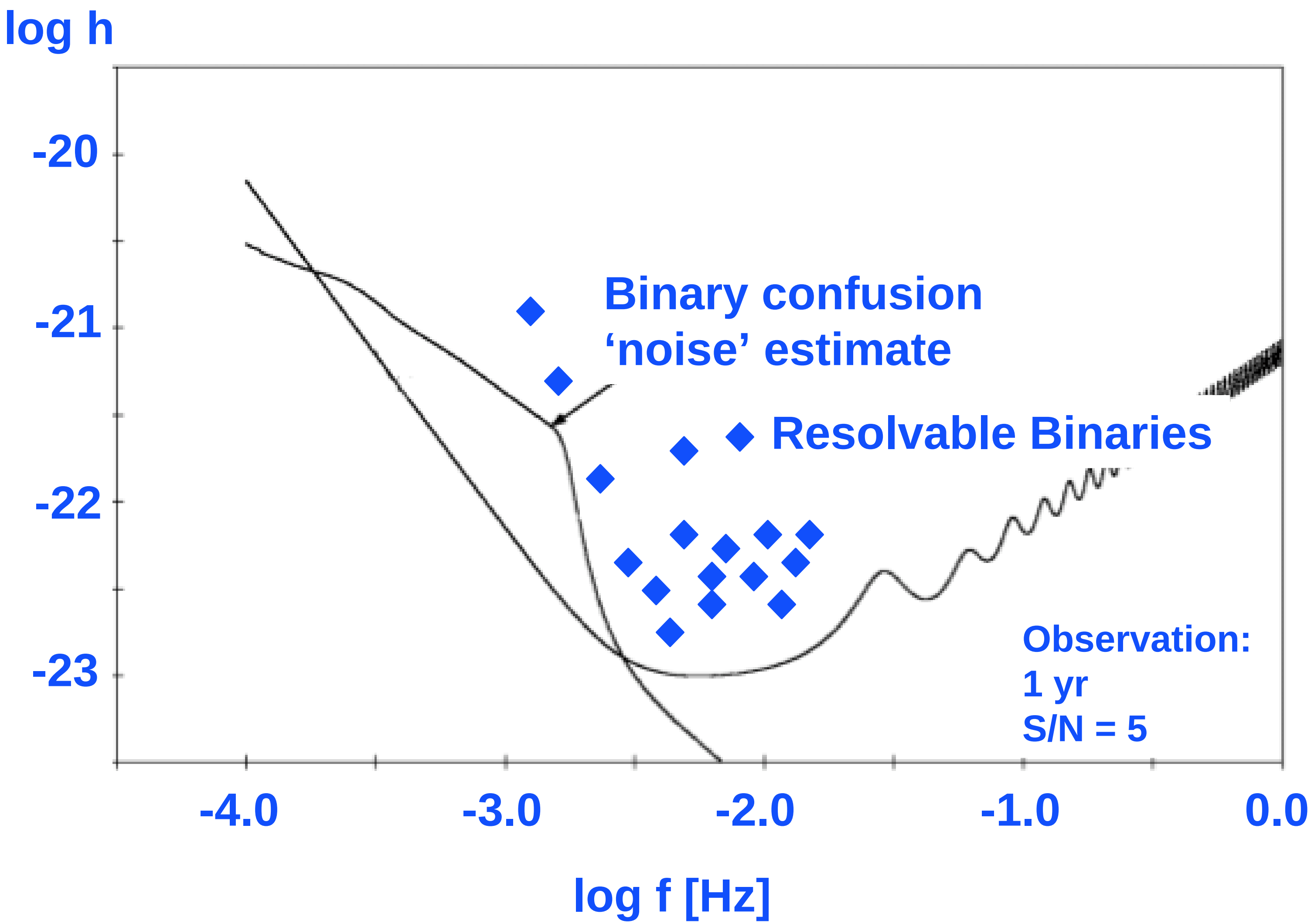
Source: Gijs Nelemans

Galactic Binaries
or
The other noise source:

- **~100000 NS/NS and WD/WD mergers in milkyway will generate GW at LISA frequencies. Guaranteed!**
- **Main Problem: Separation of the signals**

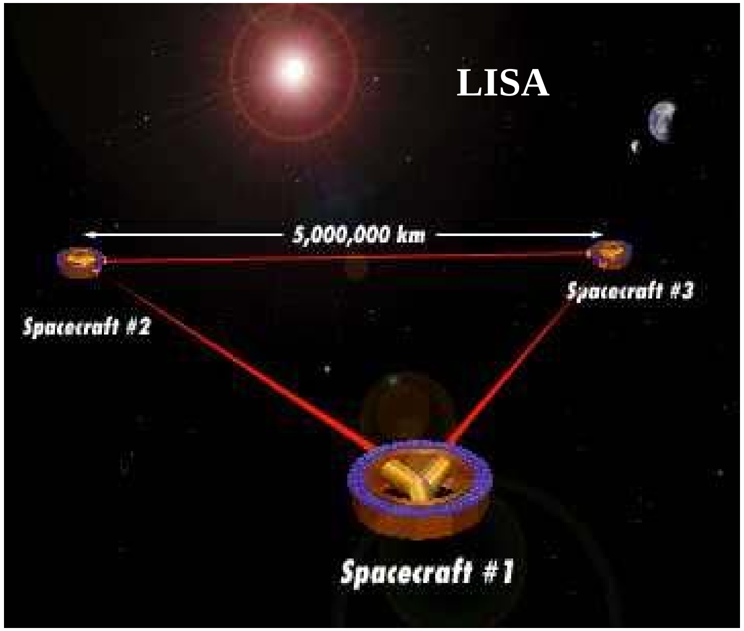
Galactic Binaries

Binary Confusion ‘Signal’ or ‘Noise’



- Noise, if you are interested in SMBH or EMRIs
- Signal, if you are interested in Galactic Binary populations
- Signal rich in contrast to LIGO

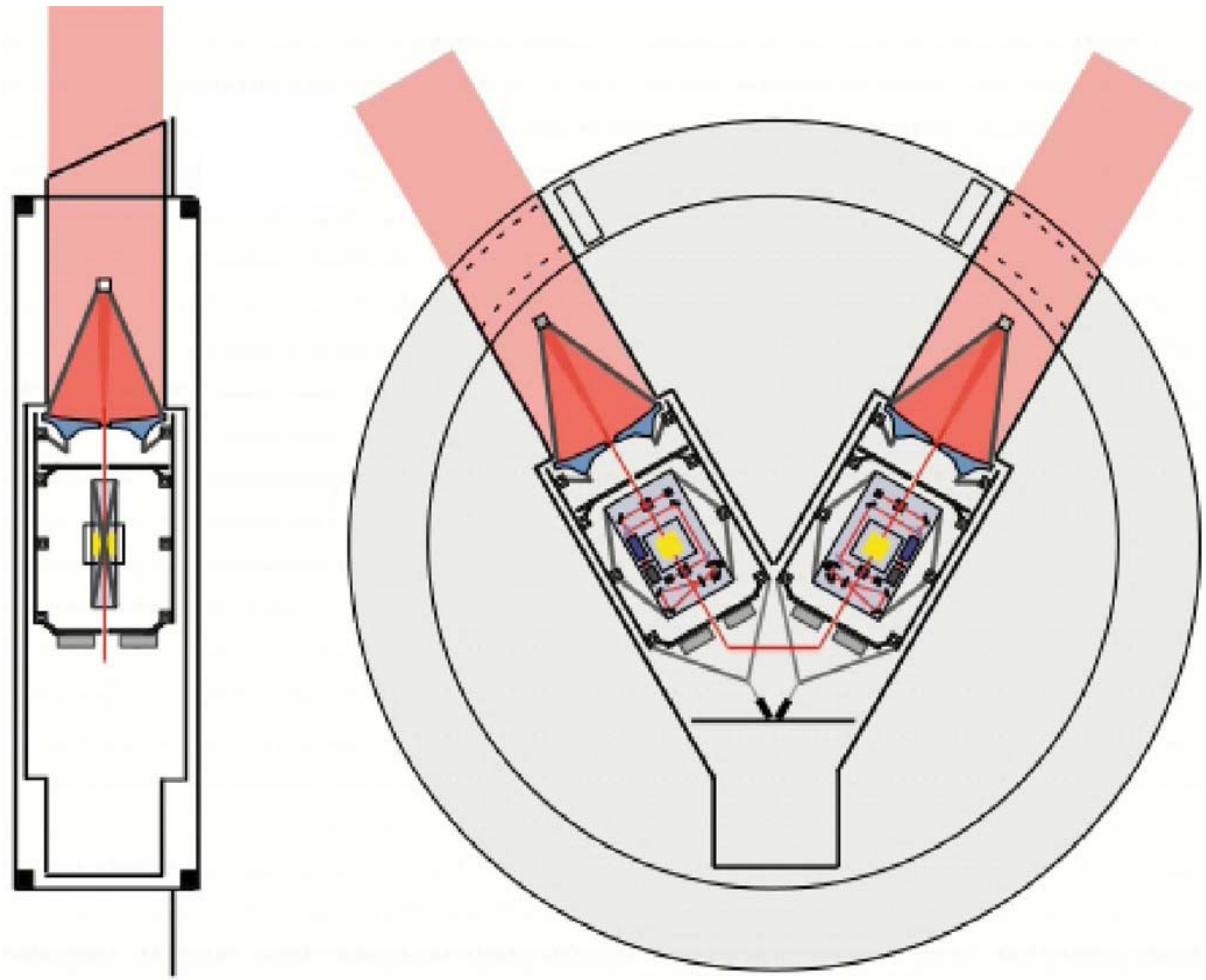
The Mission



Movie

- 3 spacecraft constellation
- S/C separated by $5x10^6$km
- Drag-free proof masses inside each S/C
- Earth-trailing solar orbit
- 5 year mission life
- pm-Sensitivity

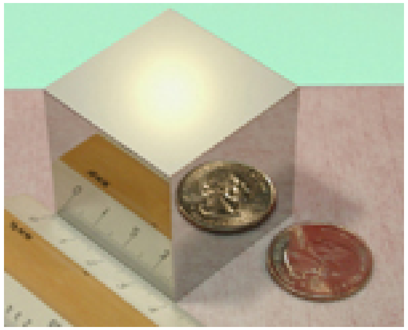
Instrument Architecture



Instrument Concept

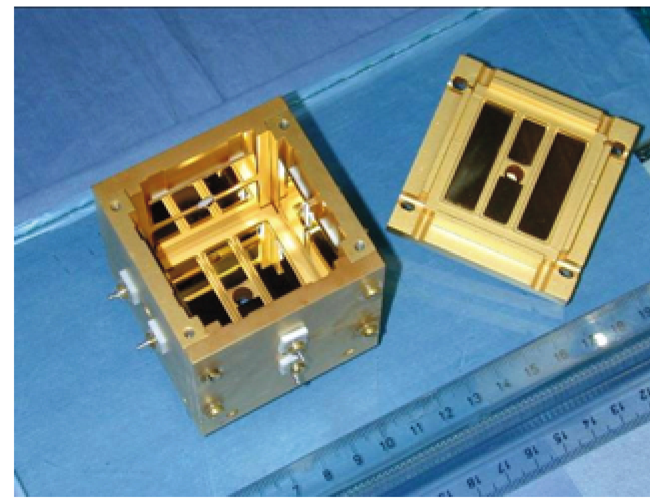
- **Free falling masses inside the spacecraft which define the distances**
  - » **Gravitational Reference Sensor (GRS)**
    - – isolate the free falling proof masses from all forces
    - – Acceleration < $3x10^{-15}$ m/s^2/rtHz
  - » **Interferometry Measurement System (IMS)**
    - – Measures the changes in the 5 Gm distances between the proof masses with an accuracy of 10 pm/rtHz!

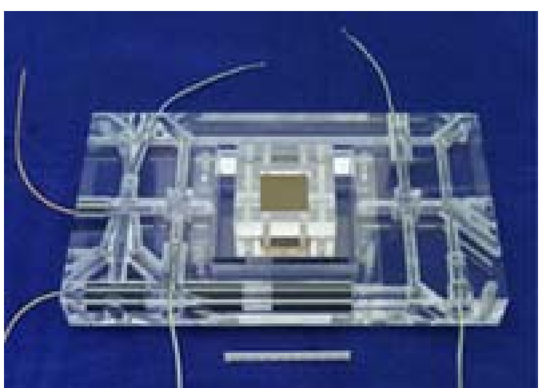
GRS



The Proof Mass:
- Gold Platinum alloy
- Cube (4cm)

Housing:
- Thermally Stable
- Electrodes for
  - Position Read out
  - Position Control





Proof Mass inside optical bench

GRS

A few (obvious) forces pushing the PM:

- Lorentz Force:

  Charged PM moving in variable solar magnetic field

  » **Charge Control (UV-light, continuous or every ~10h)**

- Magnetic Force:

  Magnetic Susceptibility couples to magnetic fields

  » **Gold Platinum Alloy: $\chi_m \sim 0$ (Problem: Grains in PM have variable χ_m)**

- Gravity from S/C:

  1kg mass 10cm from PM gives a gradient of 10^{-7}m/s^2/m

  » **S/C motion < 10nm/rHz (Design of S/C, μN-Thrusters)**

GRS

A few (not so obvious) forces pushing the PM:

- Patch Fields:

  Crystal Boundaries create voltage potentials
- Gas pressure noise:

  Gas hitting the PM from both sides
  - » **$m\Delta a \sim P\Delta T$ requires $\Delta T < 10^{-4}$K/rHz and $P < 10^{-8}$torr**
- Thermal photon pressure:

  Black Body Radiation from walls
  - » **$m\Delta a \sim \Delta T$ requires $\Delta T < 10^{-4}$K/rHz**
- …

Smart 2: LISA Pathfinder

Dedicated technology demonstrator mission of ESA

- Interferometry (not LISA like)
  - » Laser
  - » Optical Bench
  - » Phase Meter
- Inertial Sensor
  - » Proof mass
  - » Electrode housing
  - » Front end electronics
  - » Caging mechanism
  - » UV discharge system
  - » Vacuum System
- Micro-Newton Thrusters

Courtesy of Paul McNamara

Launch Sites

- **Baseline launch vehicle: Rockot**
  - » **Proven vehicle with heritage**
    - – SS19 ICBM!
  - » **Launch from Plesetsk, Russia**
  - » **Winter temperature: -30°C**

- **Target launch vehicle is VEGA**
  - » **New launcher**
    - – ESA directive to target European launchers
    - – LPF could be first flight!
  - » **Launch from Kourou,**
  - » **Winter temperature : +28°C!**

Instrument Concept

- **Free falling masses inside the spacecraft which define the distances**
  - » **Disturbance Reduction System (DRS)**
    - – isolates the free falling proof masses from all forces
  - » **Interferometry Measurement System (IMS)**
    - – Measures the changes in the 3 million miles distances between the proof masses with an accuracy of a billionth of an inch!

Interferometry

LIGO vs. LISA

Cavity-enhanced, equal arm Michelson Interferometer:

- ➢ **Static Interferometer**
  - **Operates on optimum working point.**
- ➢ **Sensing scheme: Modulation/Demodulation**
  - **Signal is quadrature amplitude of RF signal**
  - **Zero at lock point**
  - **DC-Sensing: Intensity measurement**

Synthesized equal arm Interferometer:

- ➢ **Dynamic Interferometer**
  - **Arm lengths are changing: ~1m/s**
- ➢ **Sensing scheme: Heterodyne Interferometer**
  - **Signal is Phase of a laser beat signal**
  - **Change in a constantly changing signal**
- ➢ **Laser frequency noise is removed in post processing**

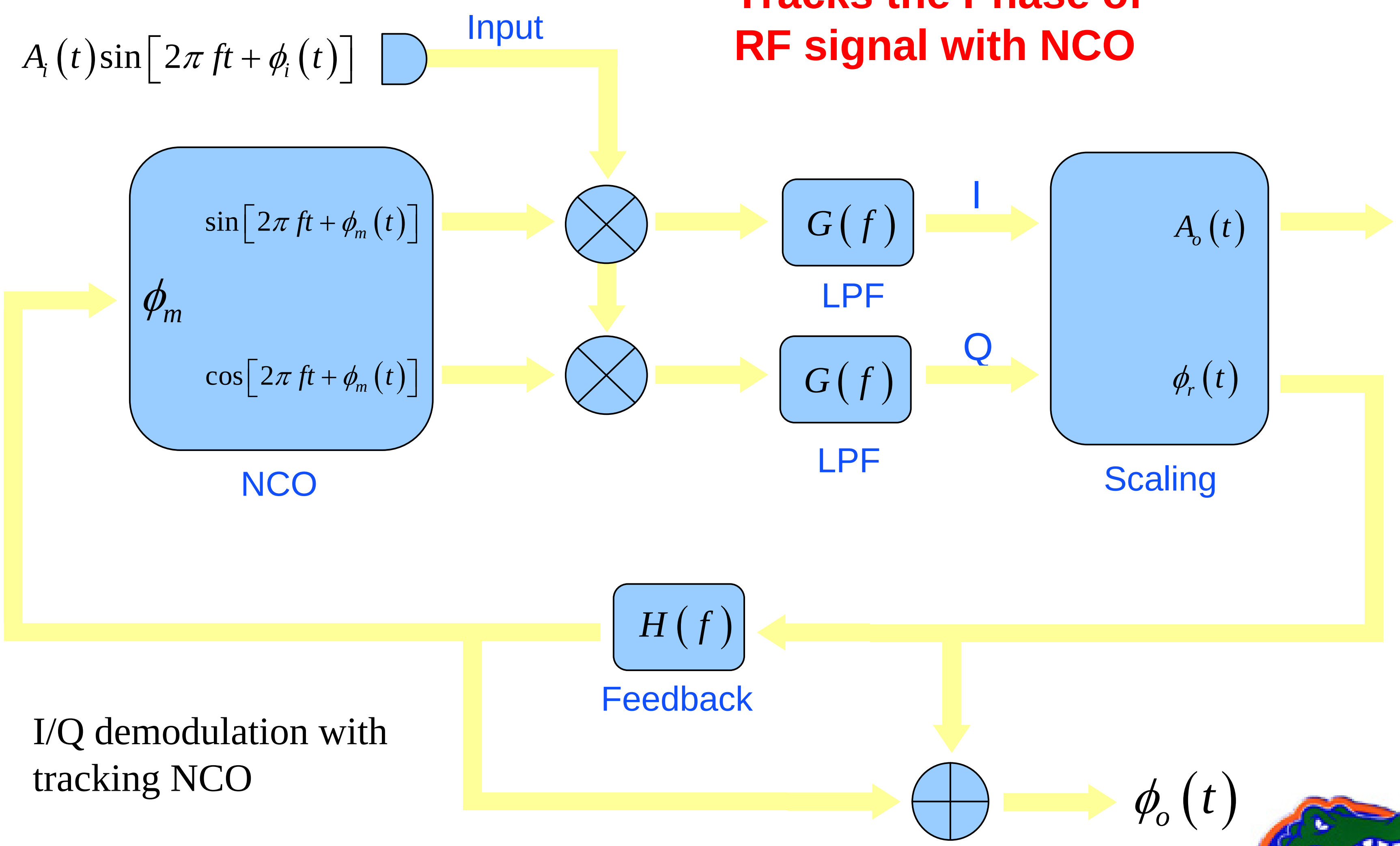
Phase meter

Signal: Phase in laser beat signal

- Measure phase of RF signal
  - Required accuracy: 10^{-5}cycl/rtHz in LISA band
  - Carrier frequency will change from 2-20 MHz due to Spacecraft motion (Doppler effect)
  - Laser frequency noise of ~1000 cycl/rtHz in LISA band in each phase meter signal!
- Different Designs
  - Colorado Phase meter: Counting and Timing Phase meter
  - JPL: Tracking Filter (likely candidate)

Phase meter a la JPL

Tracks the Phase of RF signal with NCO

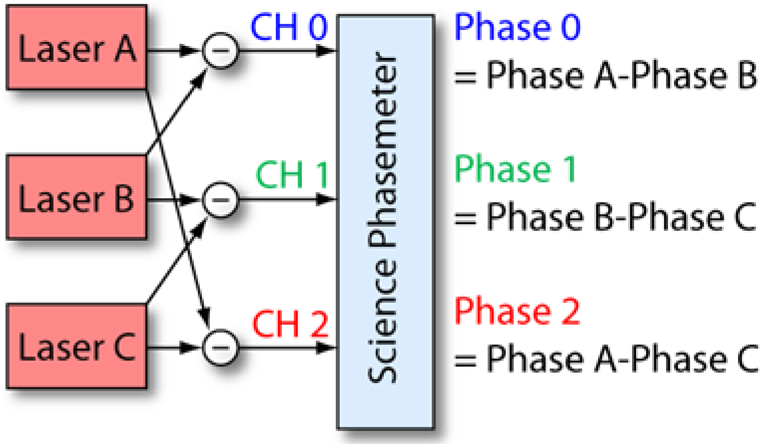


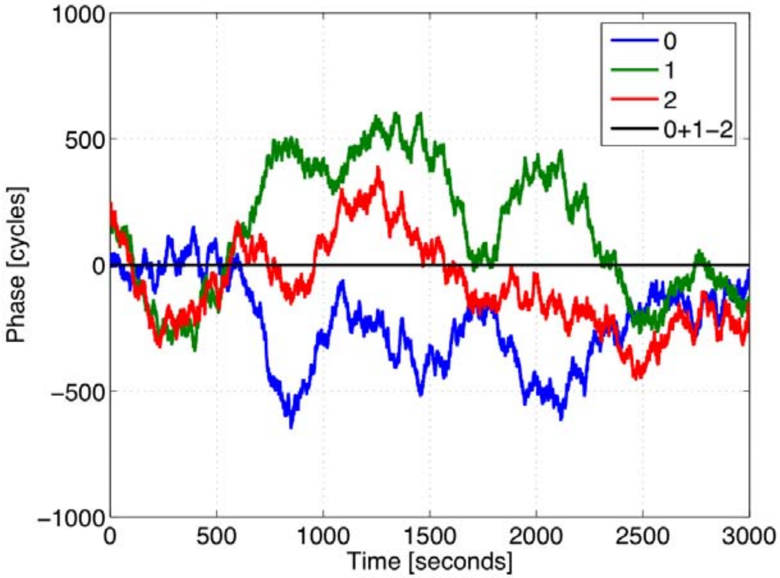
I/Q demodulation with tracking NCO

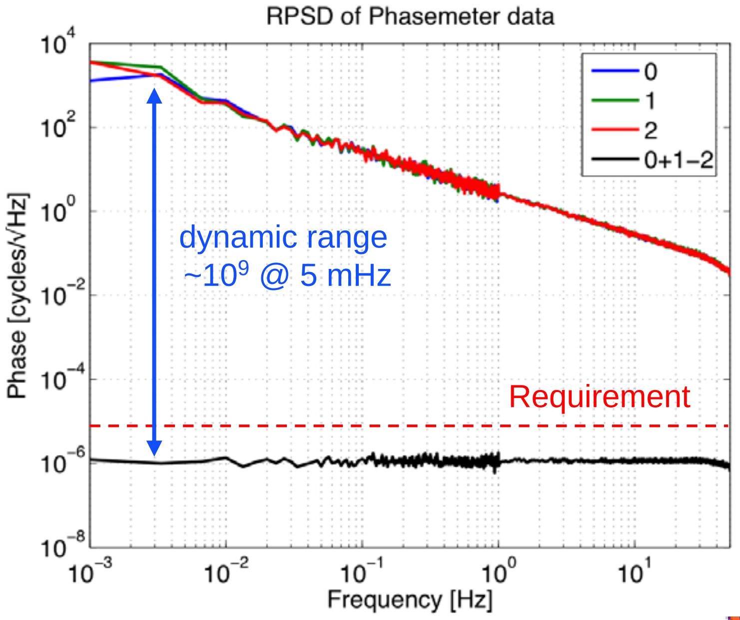
Science phasemeter testing

- **Digitally tested dynamic range requirement.**
  - **Digitally generated 3 independent, laser-like noise sources such that,**

Phase 0 + Phase 1 - Phase 2 = 0

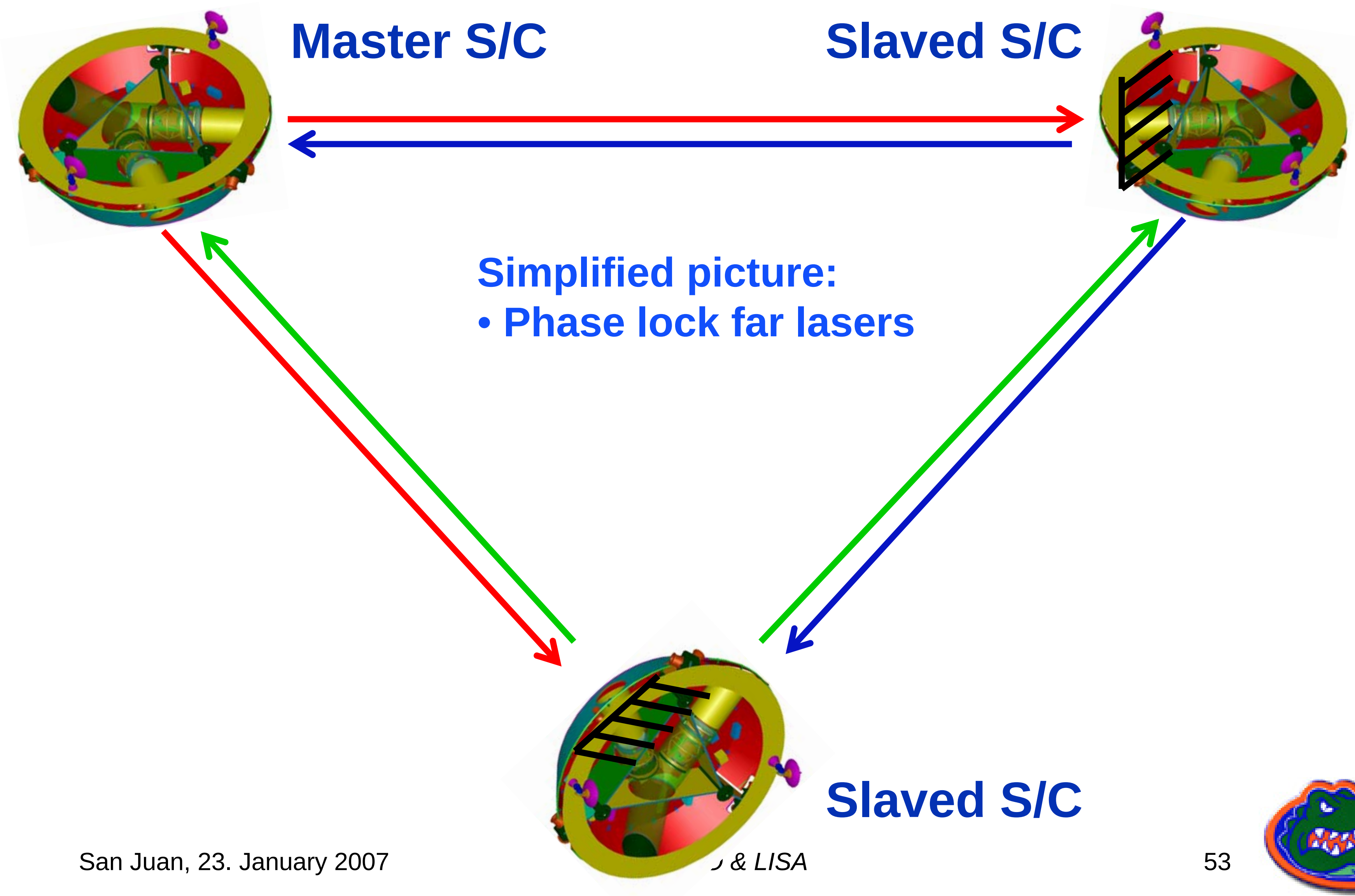






(Results from Daniel Shaddock, Brent Ware, Bob Spero, JPL)

LISA Interferometry



Simplified picture:
- Phase lock far lasers

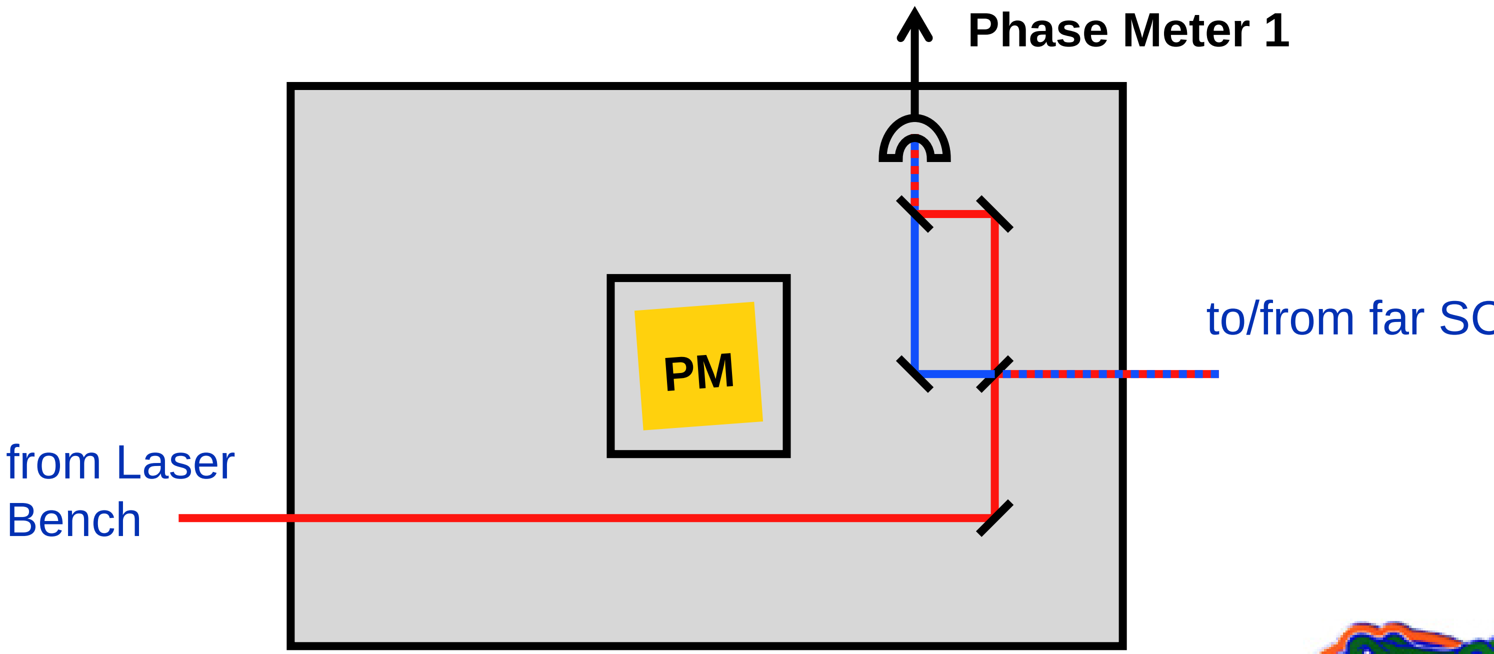
Optical Bench

Phase Meter Signal on Master S/C:

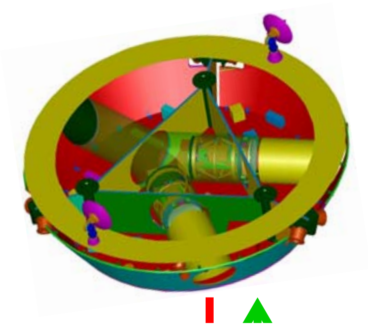
$\phi_1(t)-\phi_1(t-2\tau)$ + GW (Signal: ~ Unequal Arm MI-Signal)

- **Dominated by Laser frequency noise δf :**

$\phi_1(t)-\phi_1(t-2\tau) \sim 5\,\mathrm{Gm} \times \delta f / c$



Time Delay Interferometry



$S_1(t) = \phi_1(t) - \phi_1(t-2\tau_1) + GW_1$

$S_2(t) = \phi_1(t) - \phi_1(t-2\tau_2) + GW_2$

$S_1(t) - S_2(t) - S_1(t-2\tau'_2) + S_2(t-2\tau'_1) =$

Gravitational Wave Signals

+ Terms ~ $[(\tau_1-\tau'_1) + (\tau_2-\tau'_2)]$

TDI: Synthesizes equal arm Michelson Interferometer

Laser frequency Noise

$\phi_1(t)-\phi_1(t-2\tau) \sim 5\ \mathrm{Gm} \times \delta f / c$

<u>Two Step Approach:</u>

1. **Stabilize Laser frequency**
   - **Reduce δf**
     - **Optical Reference Cavity**
     - **Arm locking**
2. **Time Delay Interferometry**
   - **“Reduce Arm length Difference”**

Time Delay Interferometry

Can TDI cancel 8 orders of magnitude of laser frequency noise?

What is necessary to make TDI work and test it on the ground?

<u>**Make it work:**</u>

- **Need ranging between SC of better than ~30m**
- **Need a phase meter with**
  - **pm/rtHz accuracy**
  - **large dynamic range to handle**
    - **real laser noise**
    - **~20-MHz Doppler shifts**

<u>**Test it on Ground:**</u>

- **A way to simulate the 16s light travel time**
- **LISA-like laser frequency noise**

→ The UF Simulator

LISA Project

ESA:

- **ESA/Estec**
- **Astrium, Germany**
- **AEI Hanover**
- **University Trento**
- **University of Birmingham**
- **University of Glasgow**
- **…**

NASA:

- **GSFC**
- **JPL**
- **University of Florida**
- **JILA**
- **Stanford**
- **University of Washington**
- **…**