Ph237 - Gravitational Waves

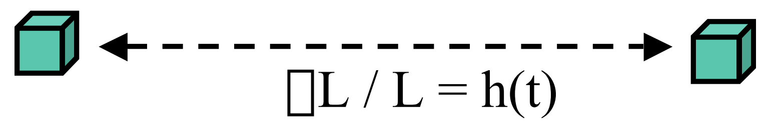
Week 1: Overview

Kip S. Thorne, Caltech, 7 & 9 January 2001

Via video feed from Cambridge England

Physical Nature of Gravitational Waves - 1

- Waves push freely floating objects apart and together

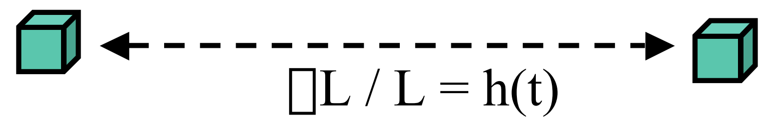


  - Local inertial frames do not mesh
- Like non-meshing of Cartesian coordinates on Earth's surface
  - Earth's curvature causes non-meshing
- Spacetime curvature causes inertial-frame non-meshing

- ***Gravitational waves are ripples of spacetime curvature***

Physical Nature of Gravitational Waves - 2

- Great richness to a wave's spacetime curvature:
  - Heuristically:
    - Stretch and squeeze of space
    - Slowing and speeding of rate of flow of time
    - …

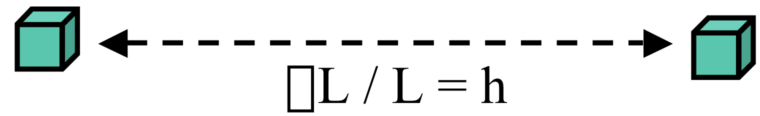


  - Measure stretch and squeeze with light beams

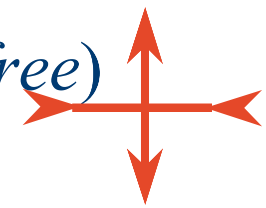
    - Does light wavelength get stretched and squeezed the same as mirror separation, so no effect is seen?
    - NO! Spacetime curvature influences light differently from mirror separations.
  - Mathematically:
    - Curvature described by rank-4 Riemann tensor, R□□□□

Physical Nature of Gravitational Waves - 3

- Stretch and squeeze are:

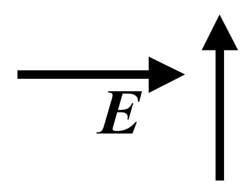


  - *transverse* to direction of propagation
  - Equal and opposite along orthogonal axes (*trace-free*)

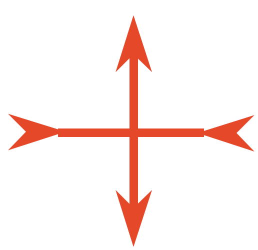


  - Force pattern invariant under 180^{o} rotation
  - Contrast with EM waves: invariant under 360^{o} rot'n

- (Spin of quantum) = (360 degrees) / (invariance angle) = 1 for photon, 2 for graviton
  - Irreducible representation of Little Subgroup of Lorentz grp
- Two polarizations: axes rotated 90^{o} EM



  - 45^{o} GW

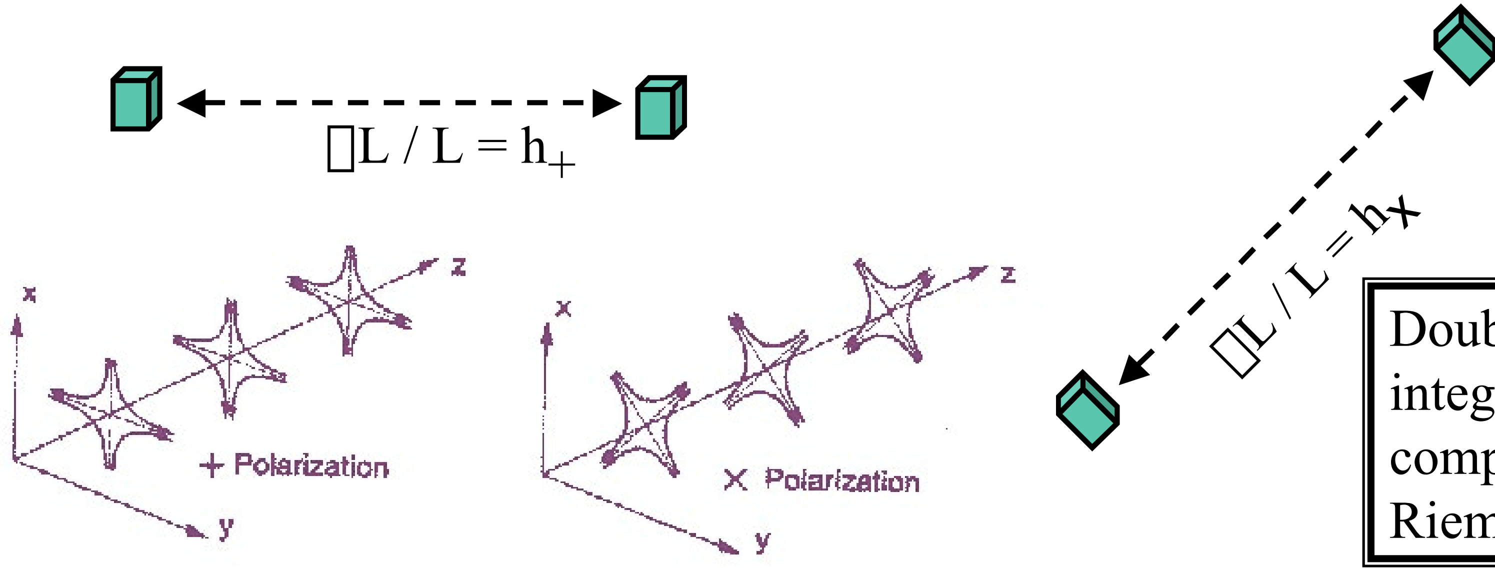


plus

cross

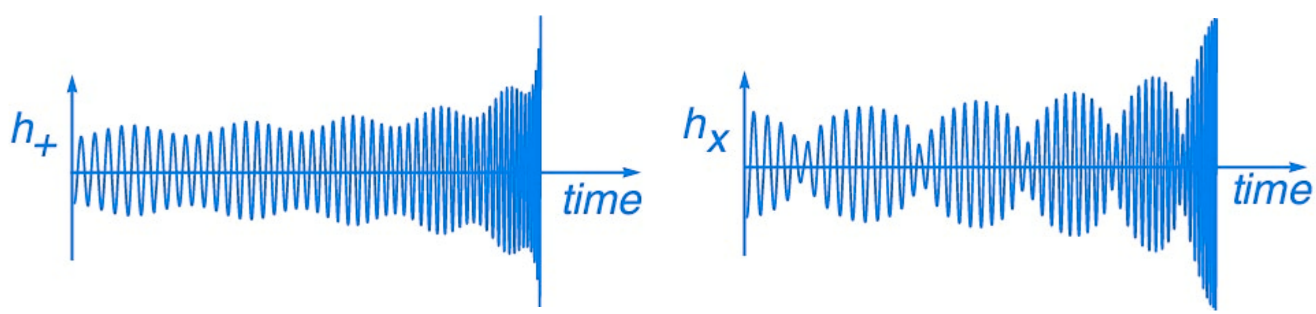
Physical Nature of Gravitational Waves - 4

- Each polarization has its own gravitational-wave field



Double time integral of certain components of Riemann tensor

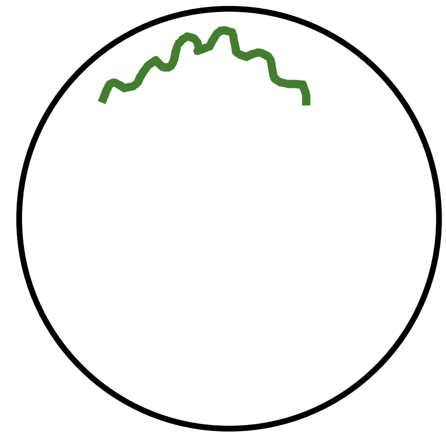
- These fields' evolutions $h_+(t)$ & $h_\times(t)$ are the ***waveforms***



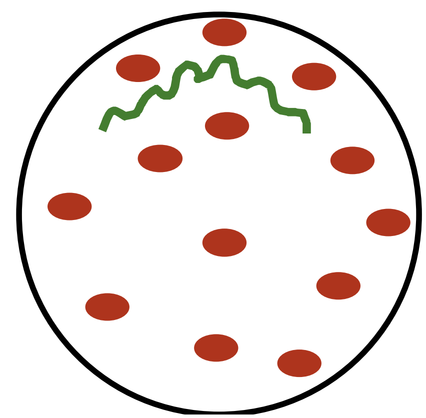
Waveforms carry detailed Information about source

Propagation of Gravitational Waves

- High-frequency waves (wavelength λ << radius of curvature *R* of background spacetime; geometric optics): propagate at light speed
  - => graviton has rest mass zero (like photon)
  - Redshifted and grav'ly lensed, like light

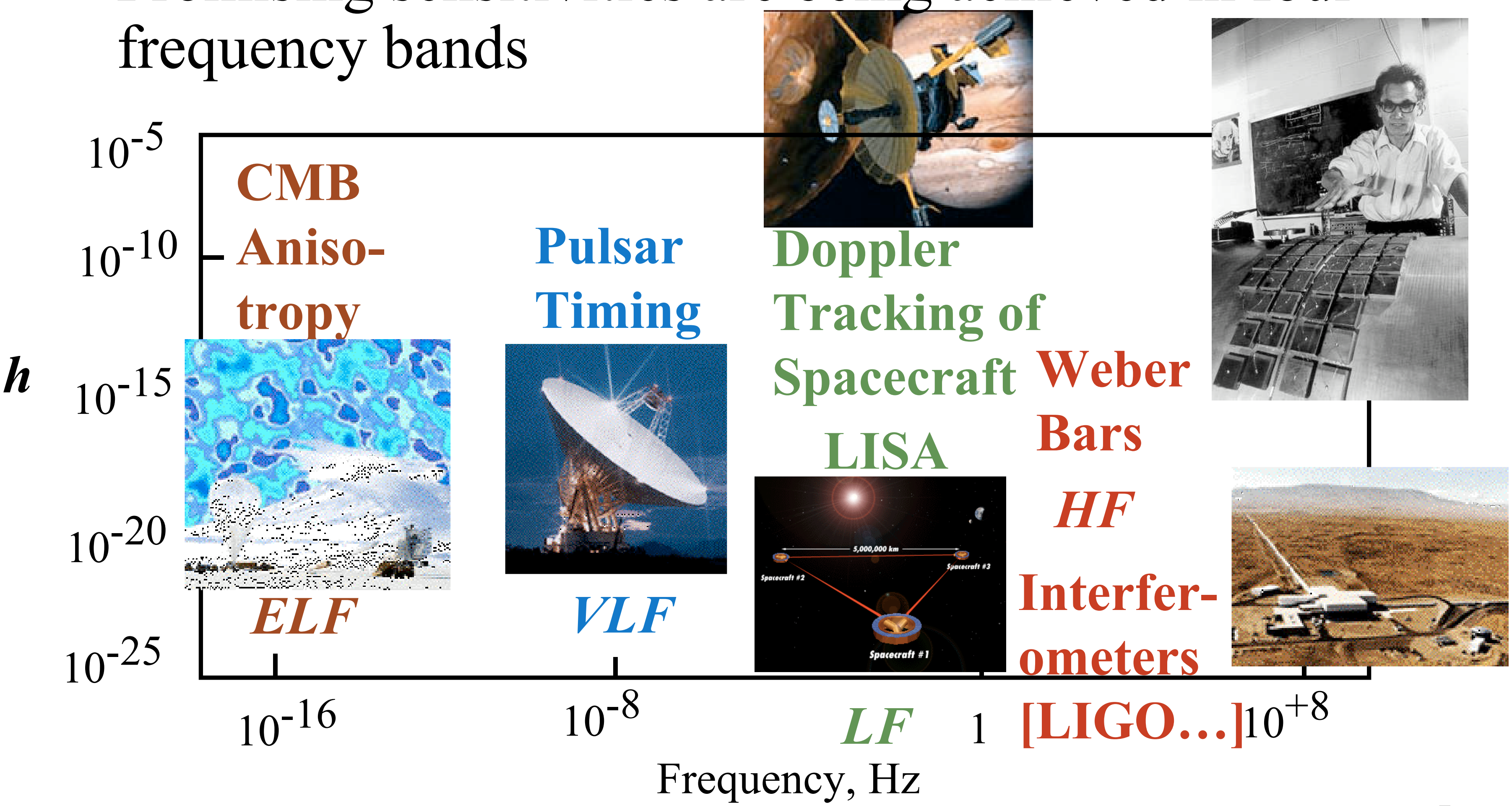


- If □ □ *R*, scattered by spacetime curvature
- Absorption by matter in our universe:
  - Negligible … even back to big bang
- Dispersion due to interaction with matter:
  - Negligible
  - Example: Universe filled with neutron stars or black holes:
    - In propagating around the universe once:
    - Dispersion delays the GW by about one wavelength λ



The Gravitational Wave Spectrum

- Spectrum of known and expected sources extends over 22 decades of frequency
- Promising sensitivities are being achieved in four frequency bands



Some Sources in our Four Bands:

ELF	VLF	LF	HF
CMB Anisotropy	**Pulsar Timing**	**Doppler LISA**	**LIGO**

The Big Bang Singularity in which the Universe was born, Inflation of Universe

Exotic Physics in Very Early Universe: Phase transitions, cosmic strings, domain walls, mesoscopic excitations, … ?

LF:

Massive BH's (300 to 30 million suns),

Binary stars

Soliton stars?

Naked singularities?

HF:

Small BH's (2 to 1000 suns),

Neutron stars

Supernovae

Boson stars?

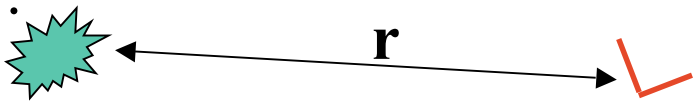
Naked singularities?

Caltech Faculty Involved in GW Research

- LIGO (high frequencies, ~10 Hz to ~1000 Hz):
  - Barish, Drever, Libbrecht, Weinstein, Kip
- LISA (low frequencies, ~ 10^{-4} Hz to ~ 0.1 Hz):
  - Prince, Phinney, Kip. + heavy JPL involvement
- Doppler tracking (very low frequencies)
  - Kulkarni
- Cosmic microwave polarization anisotropy
  - Kamionkowski, Lange, Readhead

- **CaJAGWR:** Caltech/JPL Association for Gravitational Wave Research
  - Seminars ~ every other Friday [alternate with LIGO seminars]
  - http://www.cco.caltech.edu/~cajagwr/
    - Links to LIGO, LISA, and other GW sites

Multipolar Decomposition of Waves



- Expand h in multipole moments of source's mass and mass-current (momentum) distributions: M_0, M_1, M_2, …; S_1, S_2, …
- h is dimensionless; must fall off as 1/r =>
  - $h \sim (G/c^2)(M_0/r)$ & $(G/c^3)(\dot{M}_1/r)$ & $(G/c^4)(\ddot{M}_2/r)$ & …

    Mass can't oscillate

    Momentum can't oscillate

    Mass quadrupole Moment dominates
  - & $(G/c^4)(\dot{S}_1/r)$ & $(G/c^5)(\ddot{S}_2/r)$ & …

    Angular Momentum can't oscillate

    Current quadrupole

- Theorem in canonical field theory:
  - (Waves' multipole order) ≥ (spin of quantum) = 2 for graviton

Strengths of Waves

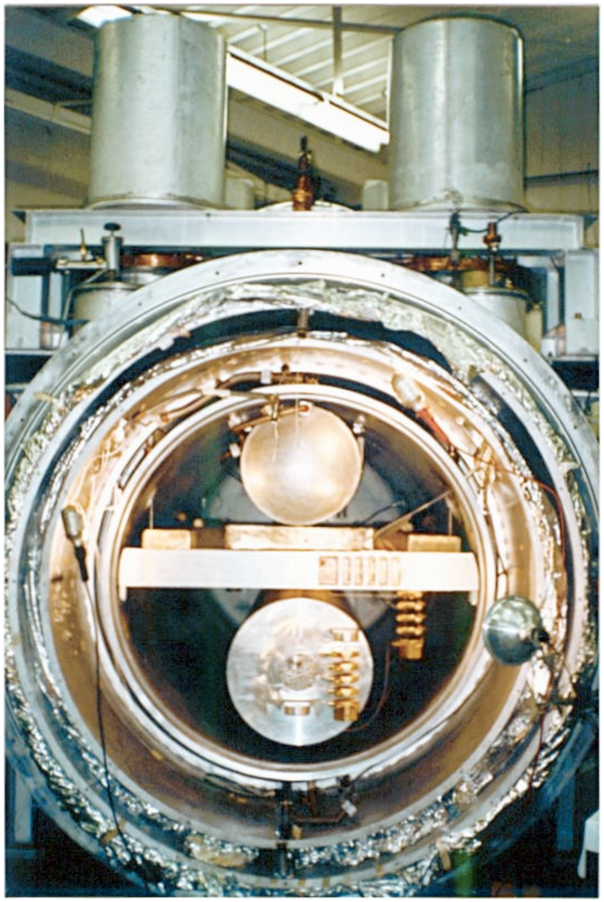
- Source: mass M, size L, oscillatory period P,
  - quadrupole moment $M_2 \sim M L^2$
- Quadrupole moment approximation:
  - $h \sim (G/c^4)(\ddot{M}_2/r) \sim (G/c^4)(M L^2/P^2)/r$

    $\sim (G/c^4)$(internal kinetic energy) / r

    $\sim (1/c^2)$ (Newton potential of [mass-equivalent] kinetic energy)

    $\sim (1/c^2)$ (Newton potential of [mass-equivalent] potential energy)
- Higher multipoles: down by (v/c) to some power
- Magnitude:
  - Colliding BH's or NS's @ $r \sim 100$ Mpc $\sim 3 \times 10^8$ ltyr $\sim 3 \times 10^{27}$ cm
  - [Mass-equivalent] Kinetic energy $\sim M_{sun}$
  - $h \sim$ few $\times 10^{-22}$

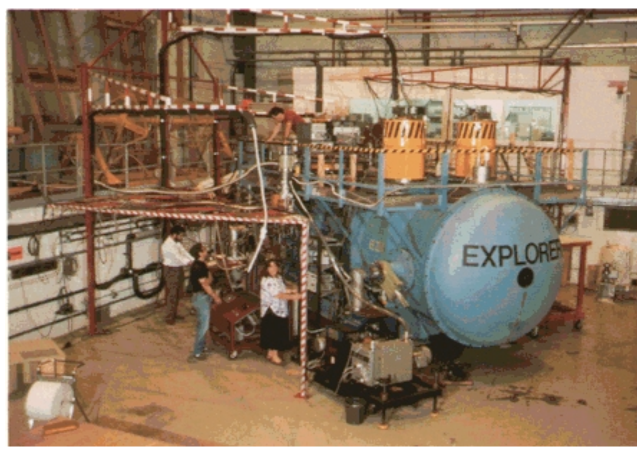
International Network of Bar Detectors
Now in Operation [~1000 Hz]



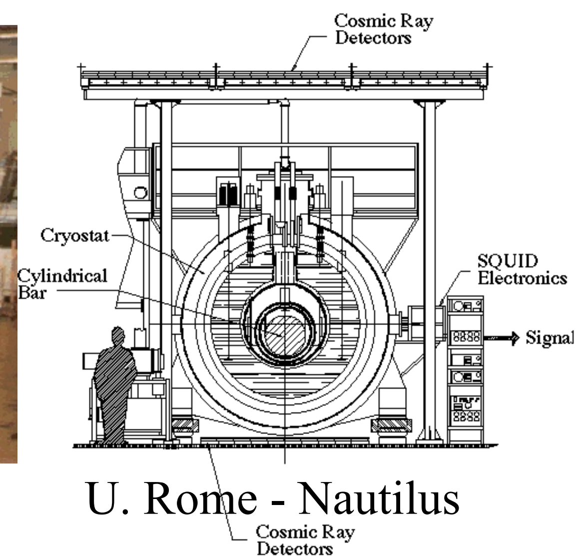
Louisiana State U. - Allegro

U. West Australia - Niobe

U. Padova - Auriga



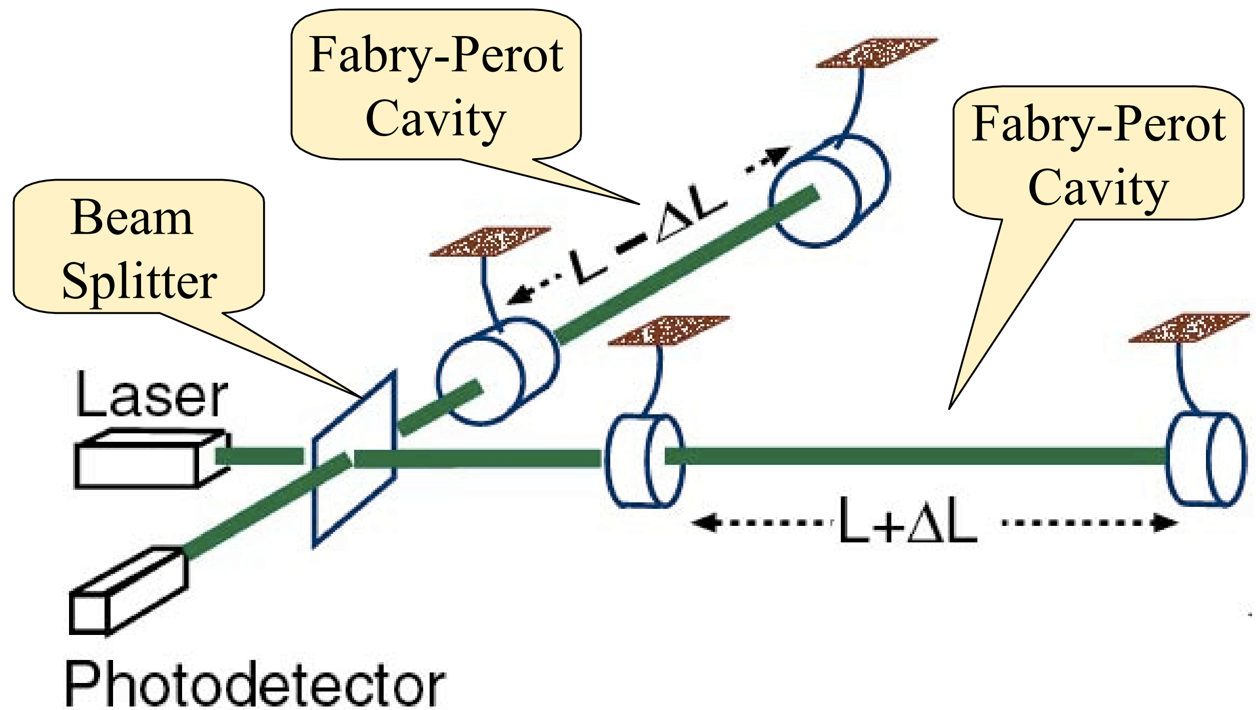
CERN - Explorer



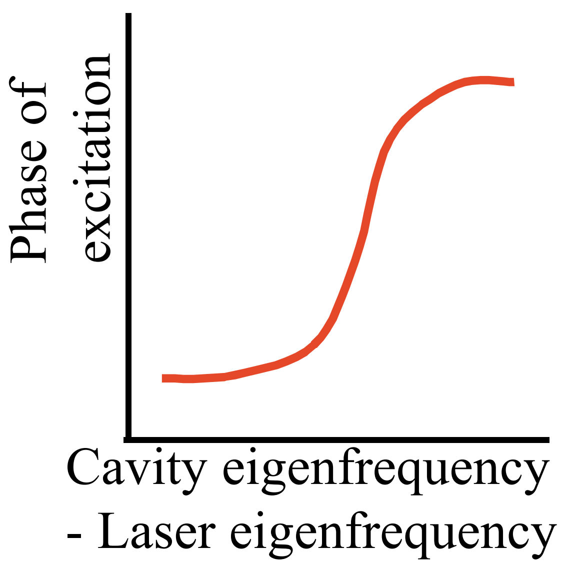
U. Rome - Nautilus

How a LIGO Interferometer Works

- **Schematic description of detector:**

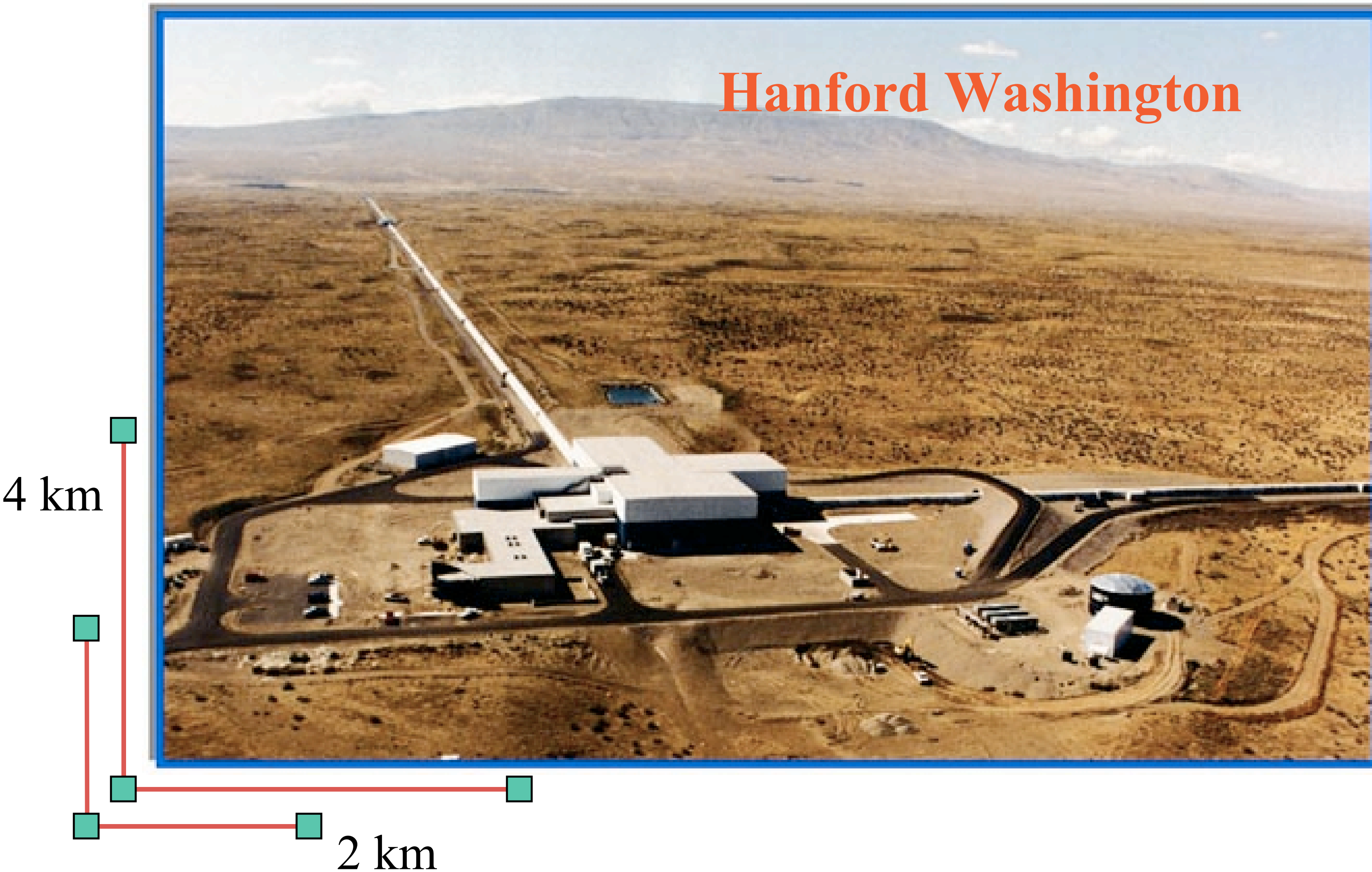


$\Delta L = h\,L \lesssim 4\times10^{-16}$ cm, with $h \lesssim 10^{-21}$ and L = 4 km



LIGO

Collaboration of ~350 scientists at ~30 institutions



LIGO

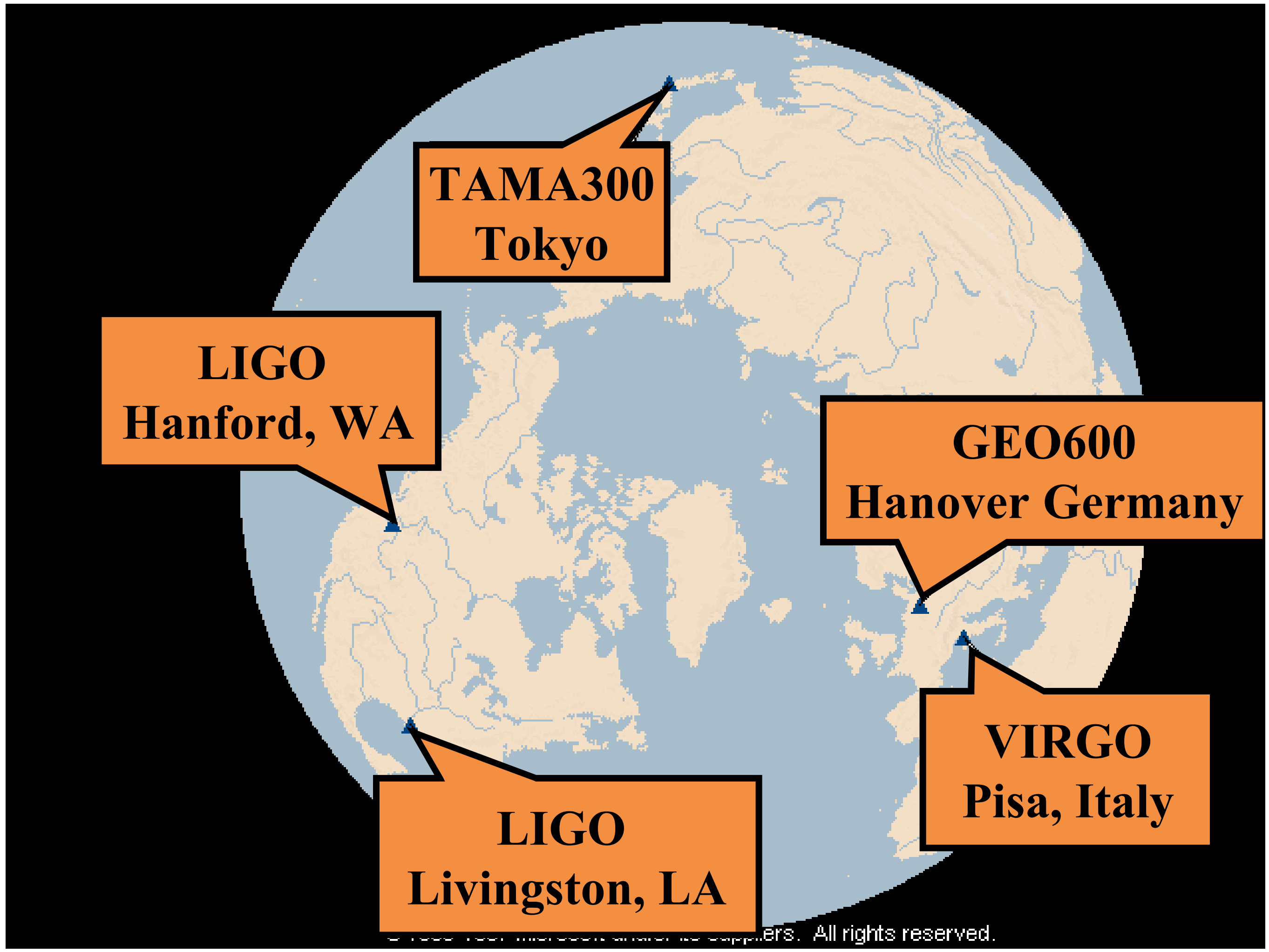
- ***First searches for GW's: 2002 to 2006 -- sensitivity where plausible to see waves***
- ***Upgrade to advanced interferometers: ~2007; 3000 higher event rate***
  - ***new search: 2008 ... -- sensitivity where should see rich waves from wide variety of sources***

LIGO Organization

- **LIGO Laboratory**
  - Responsible for Facilities; and for Design, Construction, & Operation of Interferometers
  - Caltech & MIT; Director: Barry Barish [Caltech]
- **LIGO Scientific Community (LSC)**
  - Formulates science goals
  - Carries out Interferometer R&D
  - ~350 scientists and engineers in ~25 institutions
    - Caltech, California State University, Carleton, Cornell, FermiLab, U. Florida, Harvard, Iowa State, JILA (U. Colorado), LSU, Louisiana Tech, MIT, U. Michigan, U. Oregon, Penn State, Southern U., Stanford, Syracuse, U. Texas-Brownsville, U. Wisconsin-Milwaukee, ACIGA (Australia), GEO600 (Britain & France), IUCAA (India), NAOJ-TAMA (Japan), Moscow State U. & IAP-Nizhny Novgorod (Russia)
  - Spokesman: Rai Weiss [MIT]

International Network of Interferometric Detectors

- **Network Required for:**
  - Detection Confidence
  - Waveform Extraction
  - Direction by Triangulation



LIGO’s International Partners

VIRGO: Pisa, Italy [Italy/France]

GEO600, Hanover Germany [UK, Germany]

TAMA300, Tokyo [Japan]

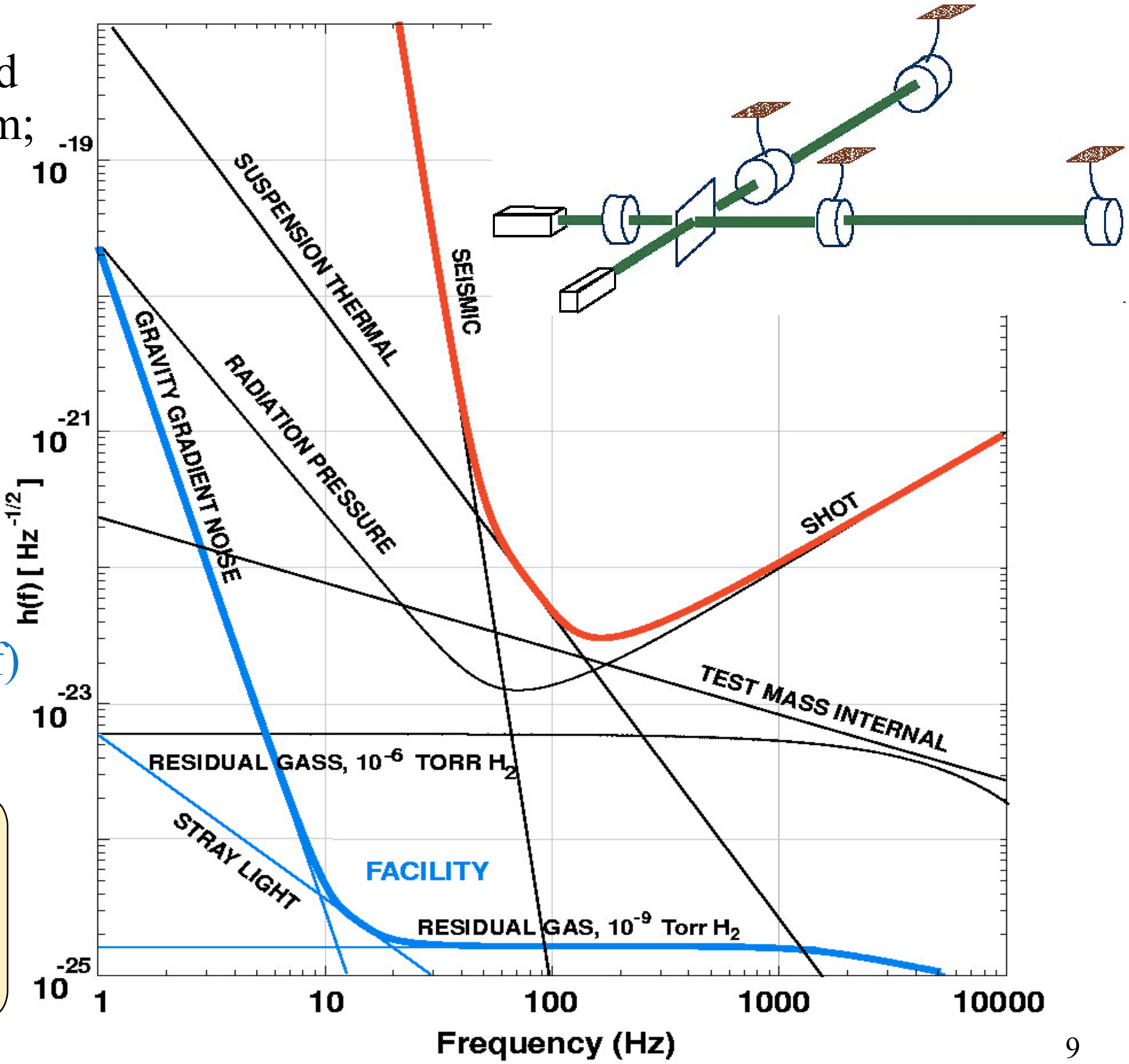
AIGO, Jin-Jin West Australia

LIGO: Initial Interferometers

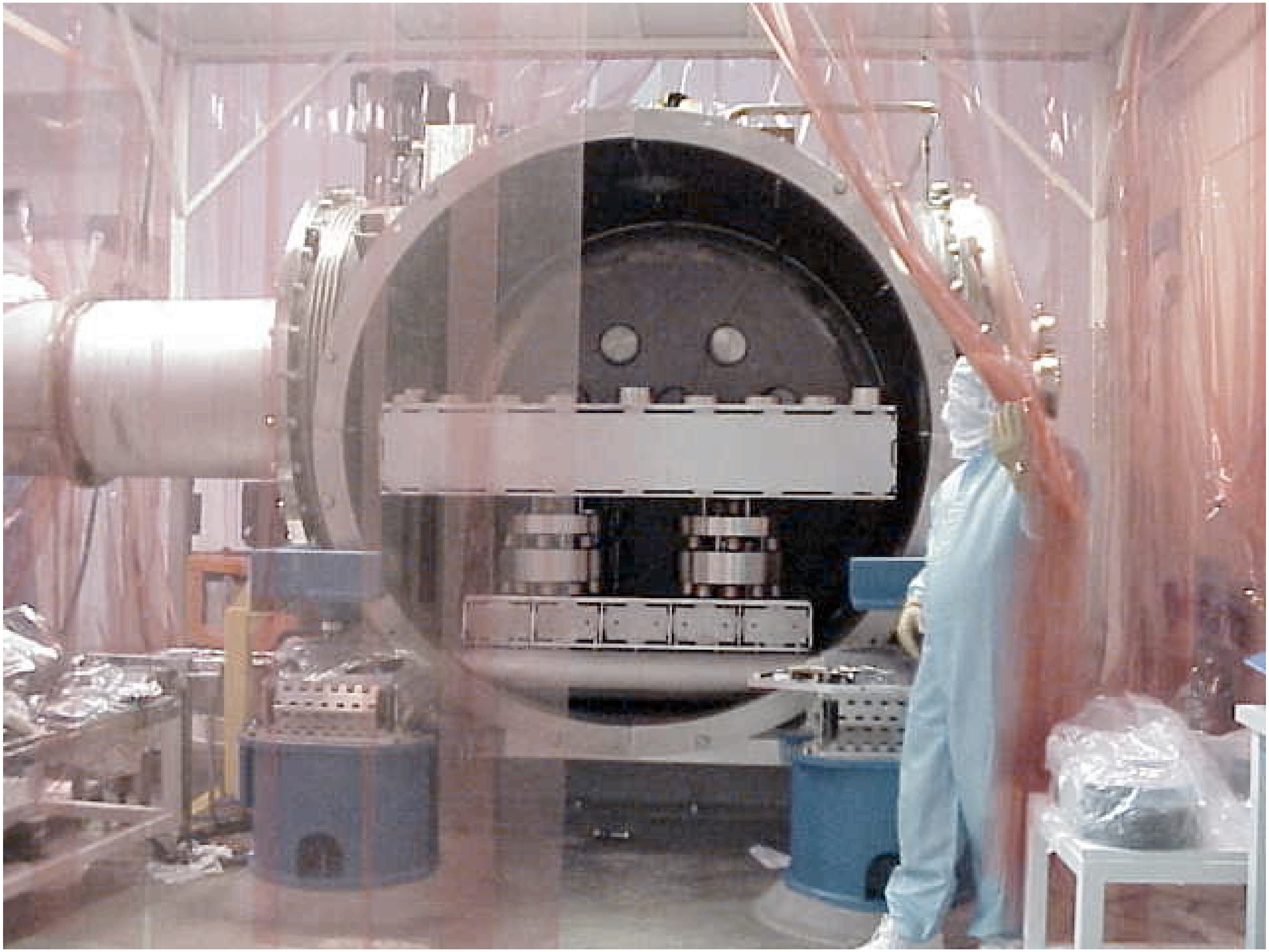
- Have been installed (Hanford 4km, 2km; Livingston 4 km)
- Are being debugged; first search underway (at poor sensitivity)

$h_{rms} = h(f) \quad f \approx 10\, h(f)$

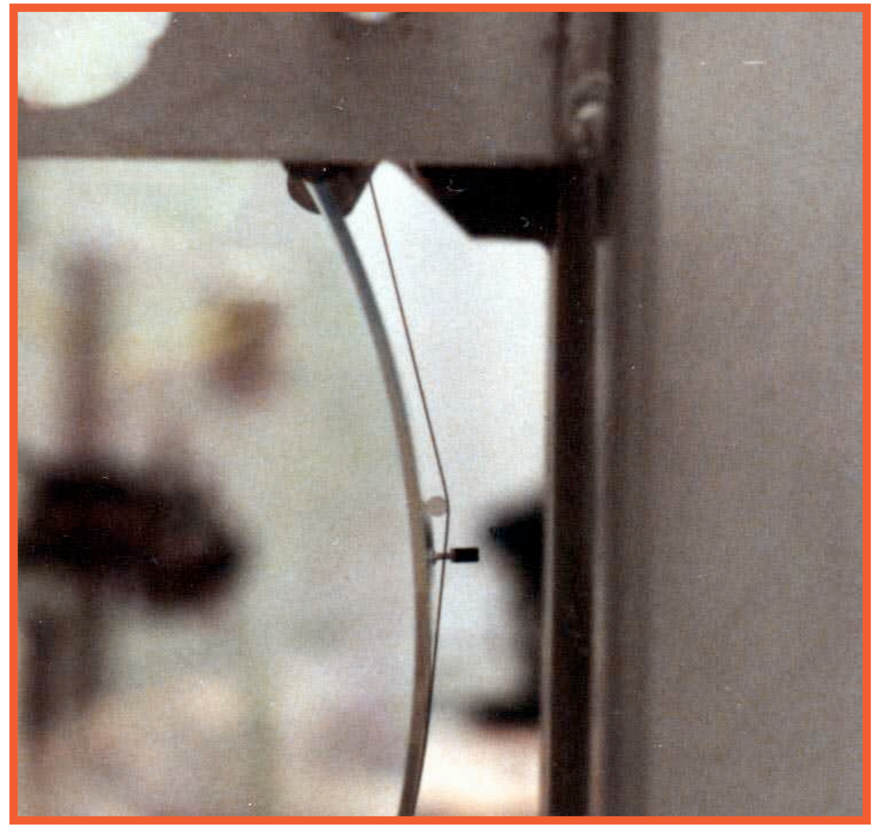
Square root of Spectral density of h(t) ["theory of random processes"]



Seismic Isolation



Test-Mass Mirror and its Suspension



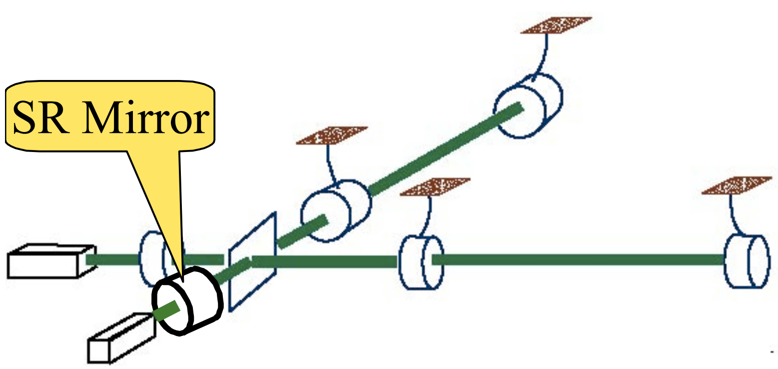
Mirror Installation and Alignment

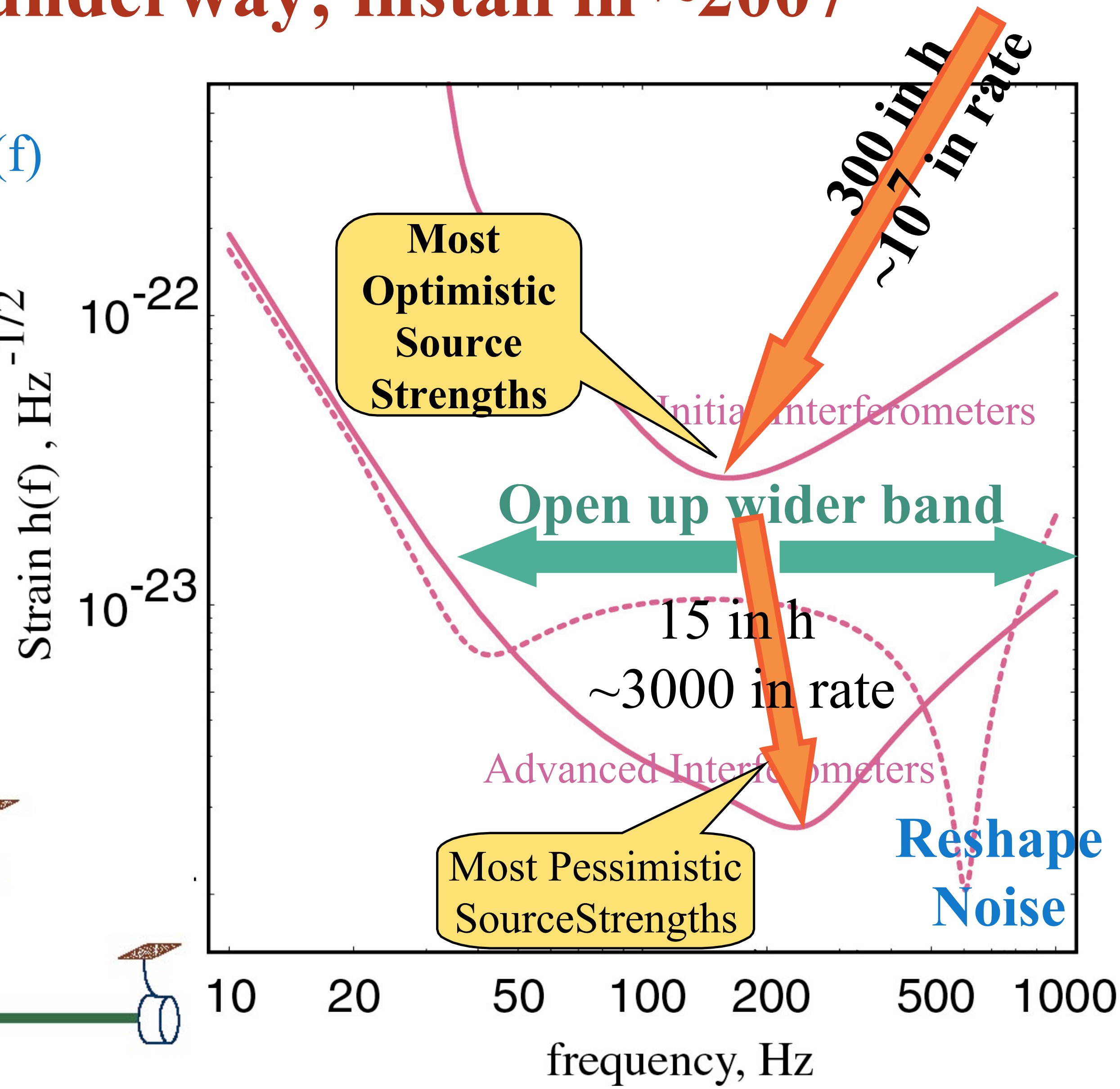
Protection from Elements

LIGO: From Initial Interferometers to Advanced

R&D underway; install in ~2007

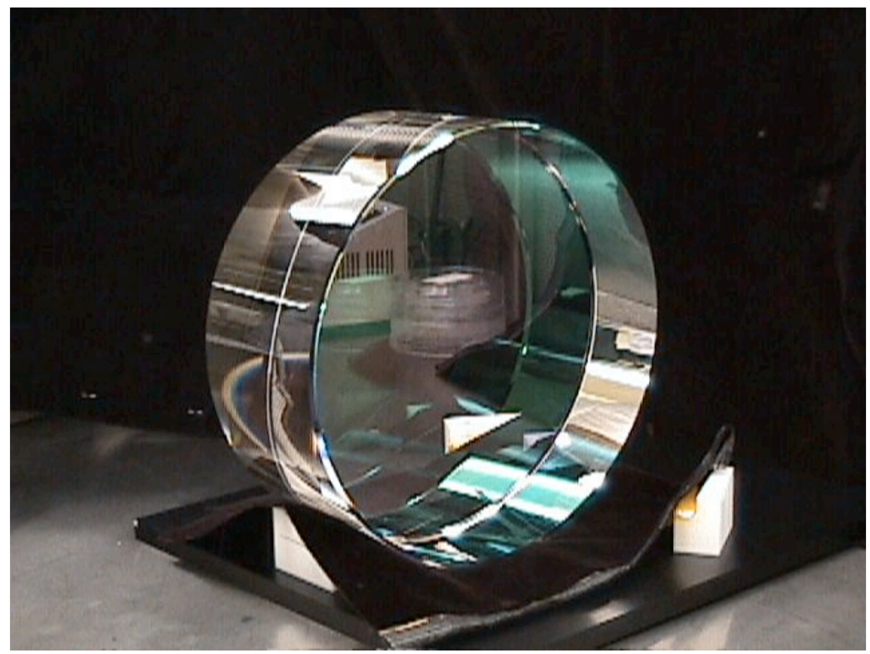
$h_{rms} = h(f) \quad f \approx 10\, h(f)$

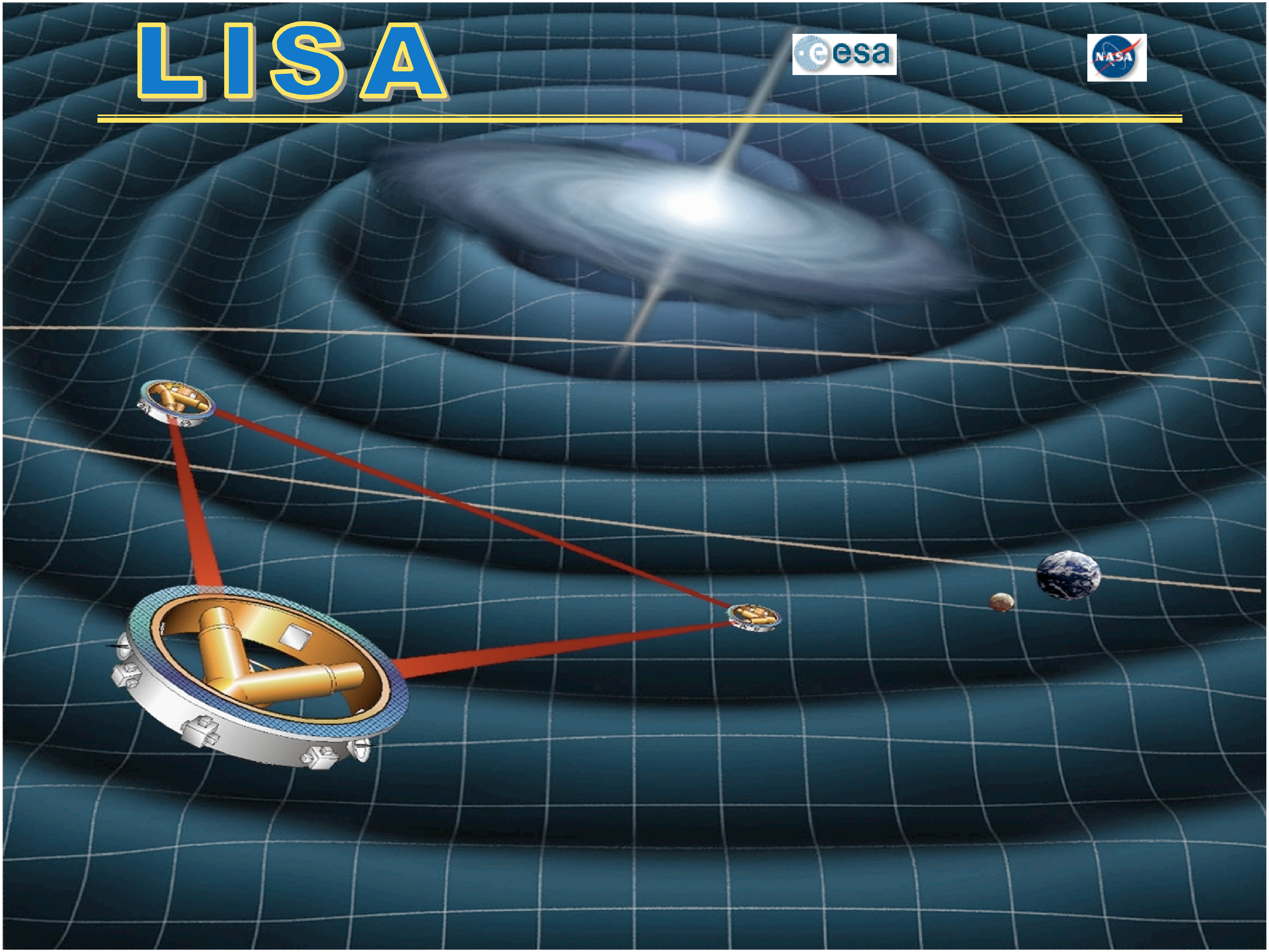




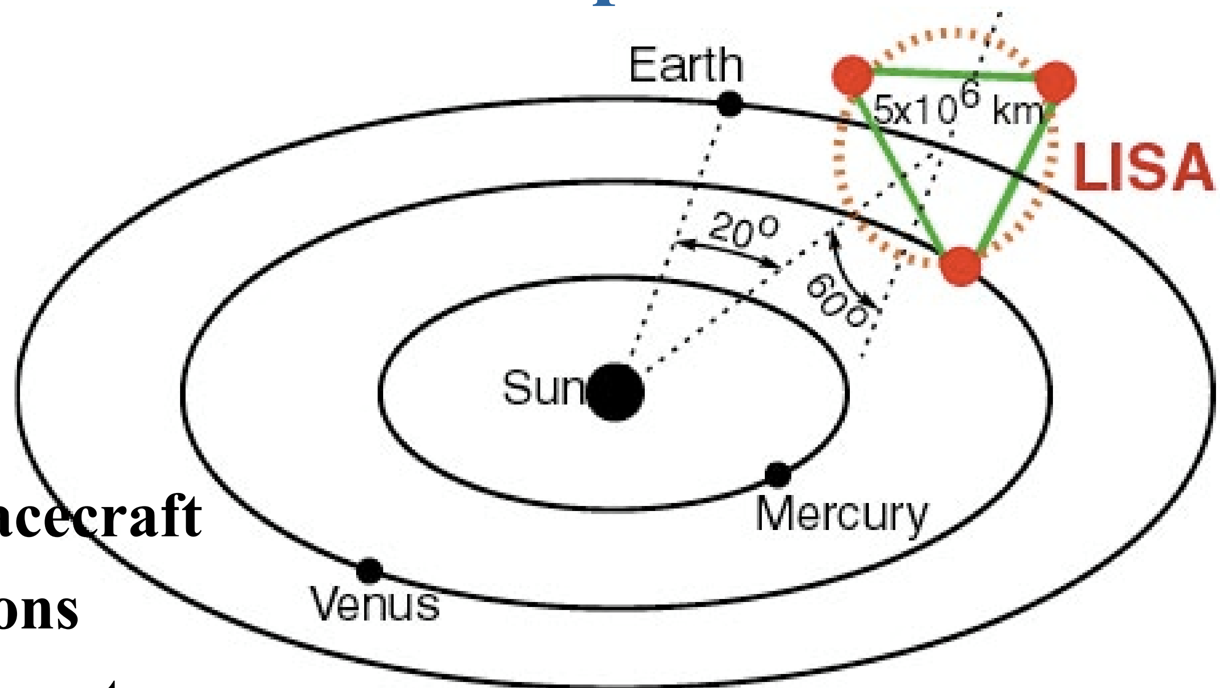
Advanced IFOs: The Technical Challenge

- **In advanced interferometers:**
  Monitor motions of 40 kg saphire mirrors to:
  - $\sim 10^{-17}$ cm ~ 1/10,000 diameter of atomic nucleus
  - $\sim 10^{-13}$ of the wavelength of light
  - ~ the half width of the mirror's quantum wave function
- **Quantum Nondemolition (QND) Technology**
  - Branch of quantum information science




LISA
esa
NASA

LISA: Laser Interferometer Space Antenna



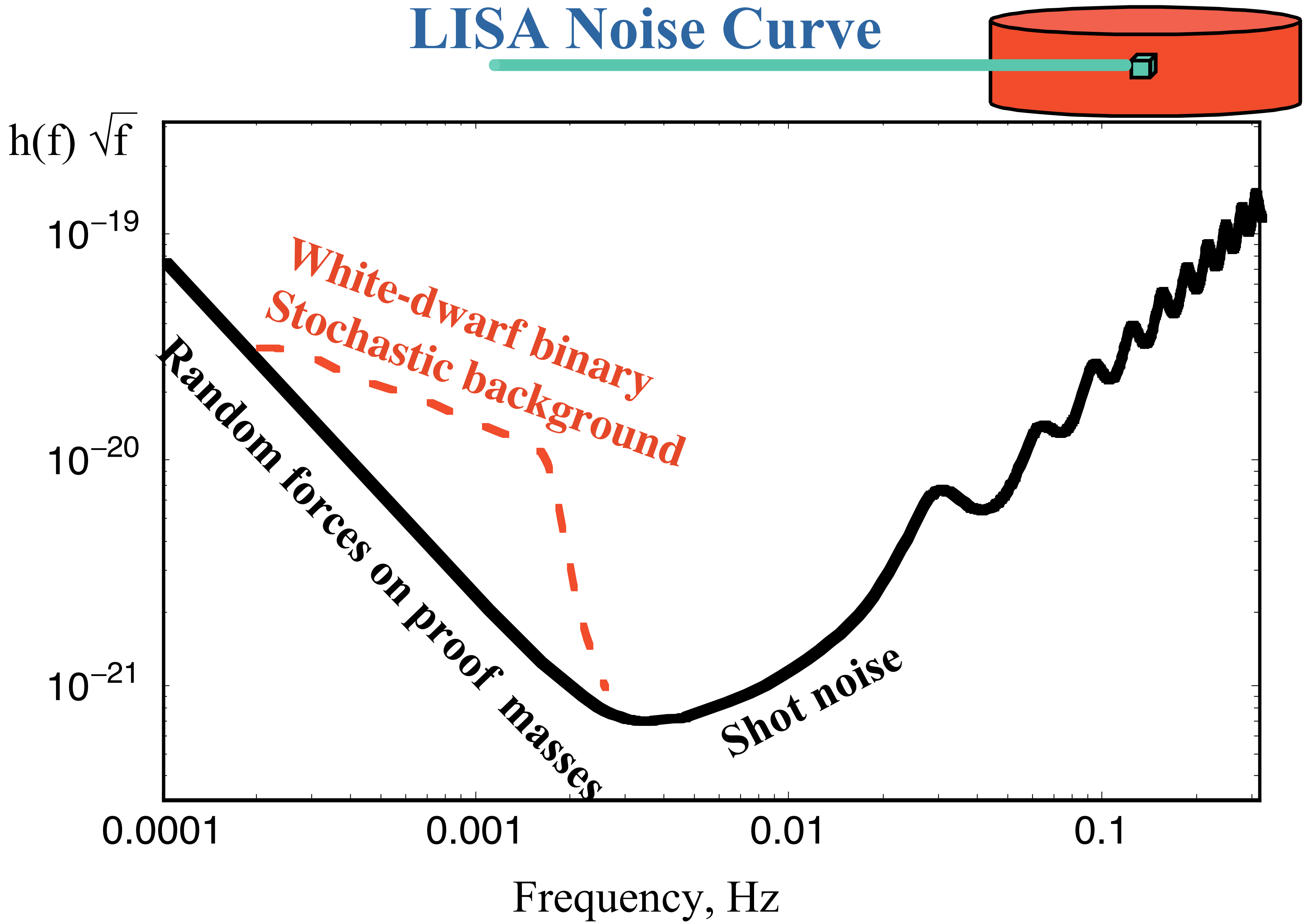
- Three "drag-free" spacecraft
- 5 million km separations
- 1 Watt laser, 30cm diameter telescopes
- Relative motions of spacecraft: ~ 1 million wavelengths / sec
- Light beams beat against each other (heterodyne detection); beat signal fourier analyzed

- Joint American/European
- US: Managed at GSFC (Md)
  - Payload & Science: JPL/Caltech
  - Tom Prince: Mission Scientist
- Launch: 2011

LISA: The Technical Challenge

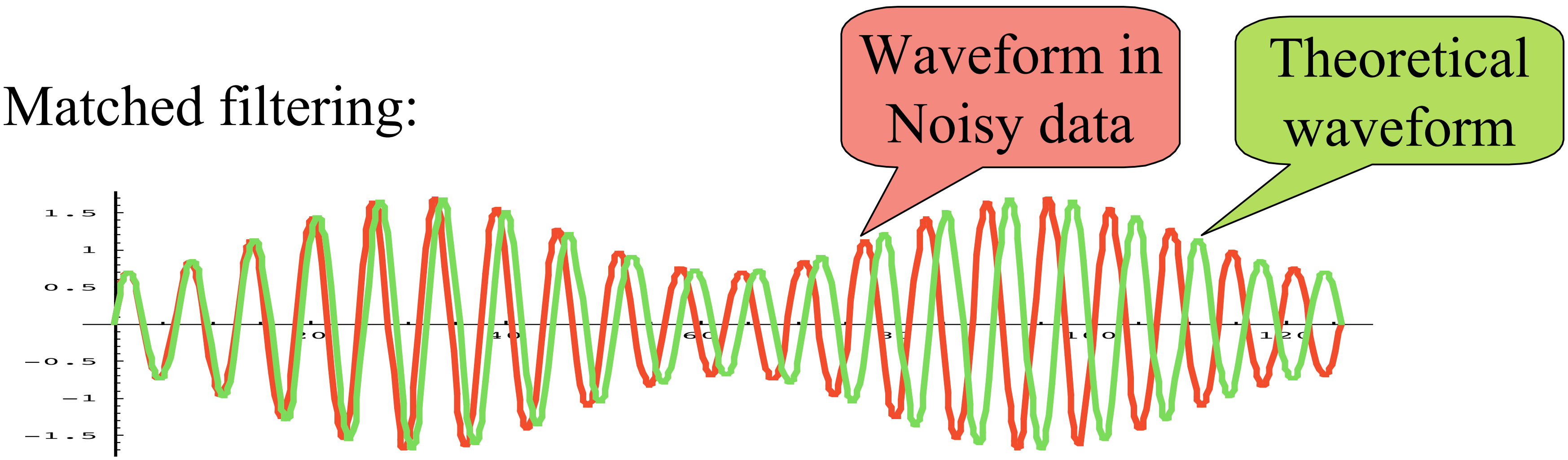
- **Monitor the relative motion of the satellites' "proof masses", 5 million kilometers apart, to a precision**
  - $\sim 10^{-9}$ cm [in frequency band f $\sim$ 0.1 - 10^{-4} Hz]
  - $\sim 10^{-5}$ of the wavelength of light
  - accelerations $\sim 10^{-16}$ g
- **Guarantee that the only forces acting on the proof masses at this level are gravitational, from outside the spacecraft**

LISA Noise Curve



Gravitational-Wave Data Analysis

- Matched filtering:



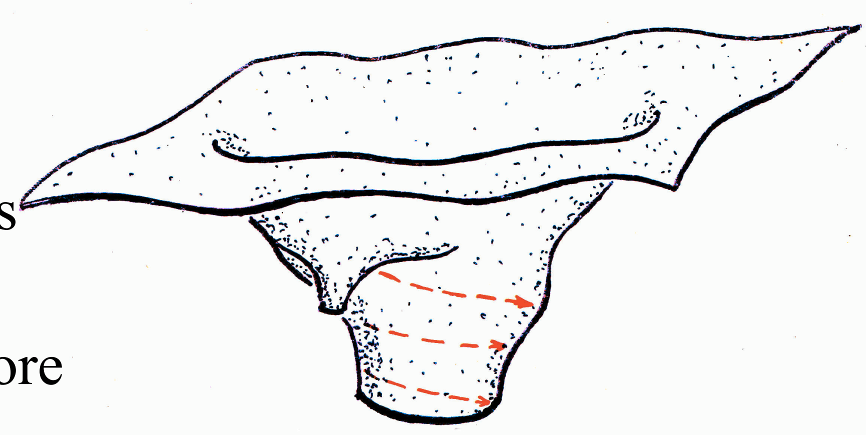
  - If waveforms slip by ~ 1 radian, it is obvious in cross correlation
  - LIGO: up to ~20,000 cycles (~100,000 radians)
  - LISA: up to ~200,000 cycles (~1 million radians)
- Theoretical challenge: compute waveforms to this accuracy
- If waveforms poorly known:
  - Must use other analysis methods: significant loss of signal strength!
    - e.g. Flanagan's excess power method: filter h(t) then square & integrate.

Scientific Goals of LIGO and LISA

- **Astronomy: Open up a Radically New Window Onto the Universe**
- **Physics: Convert the study of highly curved spacetime**
  - **From a purely theoretical enterprise (exploring general relativity theory)**
  - **To a joint observational/theoretical enterprise**

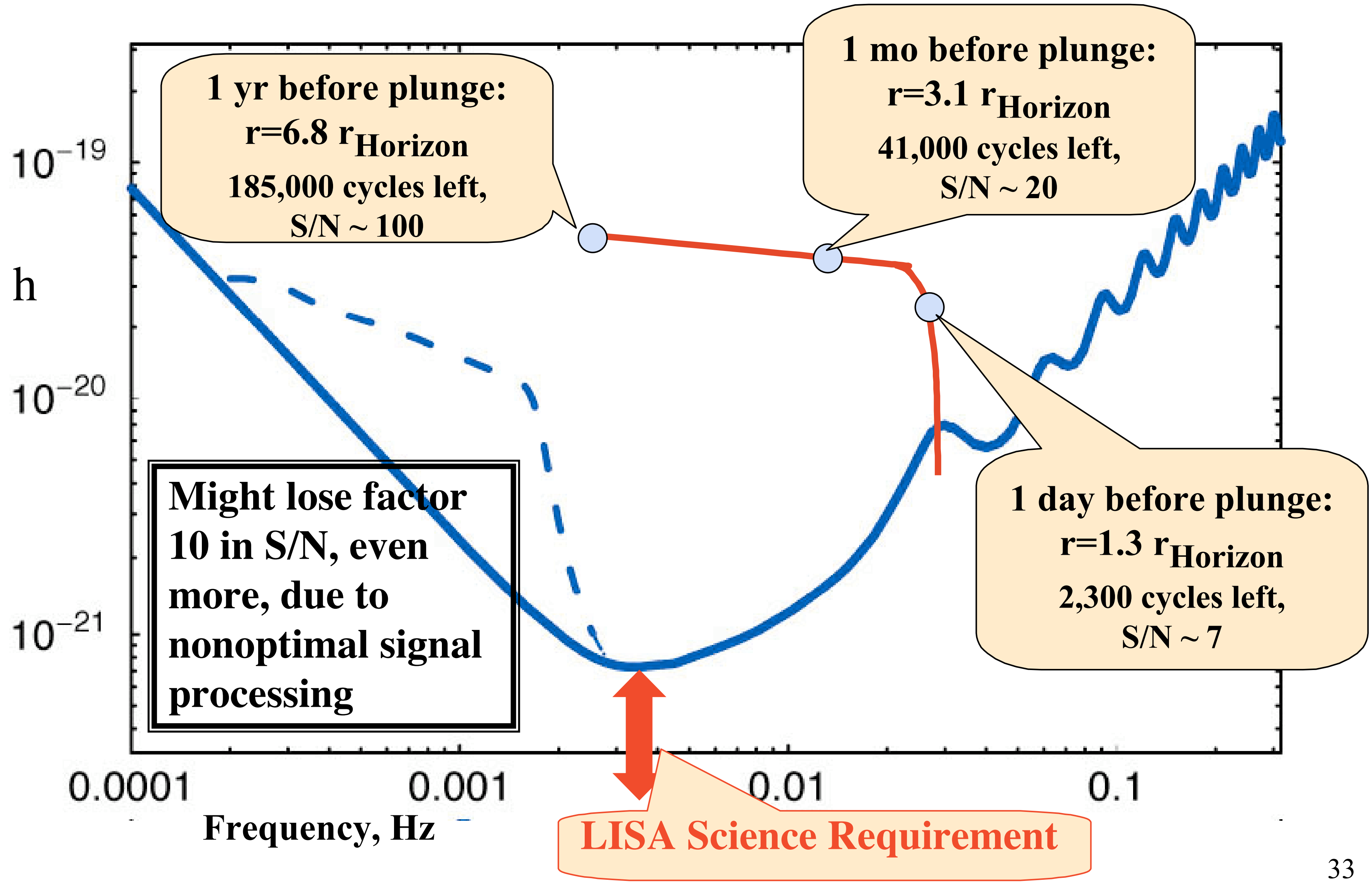
- **Examples: Sources organized by science we expect to extract, not by when they might be detected --**

The Inspiral of a White Dwarf (WD), Neutron Star (NS), or Small Black Hole (BH) into a Supermassive BH



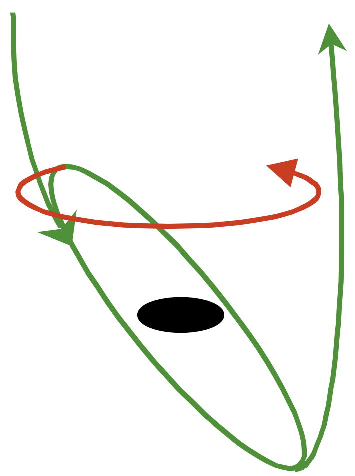
- **Astrophysical phenomenology:**
  - Occurs in nuclei of galaxies
  - Provides a probe of the environments of supermassive holes
  - Rates: a few per year; perhaps far more
- **Frequency band and detectors:**
  - Low frequencies; LISA
- **Information carried by the waves:**
  - High-precision map of the spacetime curvature of the supermassive BH
- **Science to be done:**
  - Map black holes, test "no hair theorem", test theory of evolution of black-hole horizons when gravitationally perturbed, observe extraction of spin energy from black holes.
- **Method of computing waveforms:**
  - Black-hole pertubation theory; radiation-reaction theory

LISA Inspiral Example: Circular, Equatorial orbit; 10 Msun / 10^6 Msun; fast spin -- @1 Gpc [optimistic] (pessimistic: signal 10 times weaker)



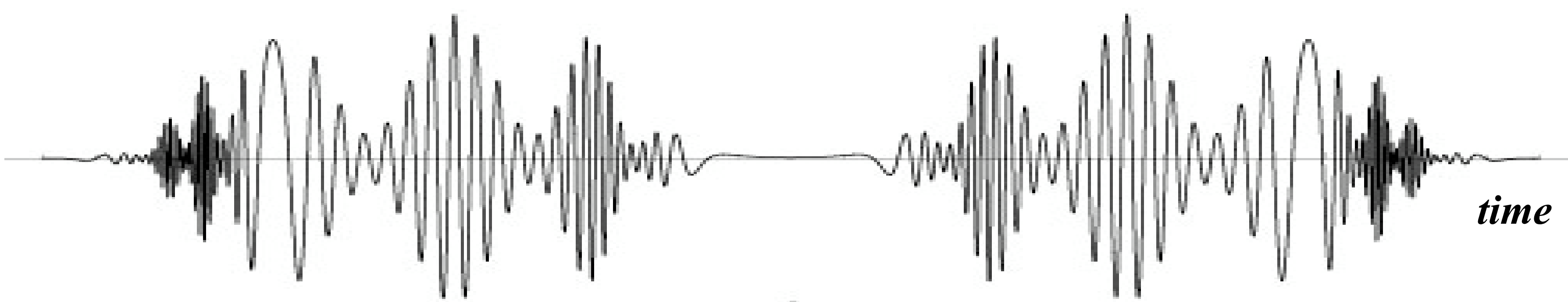
Inspiral Waves:
Why might signal processing be non-optimal?

- Typical Orbit in last year:

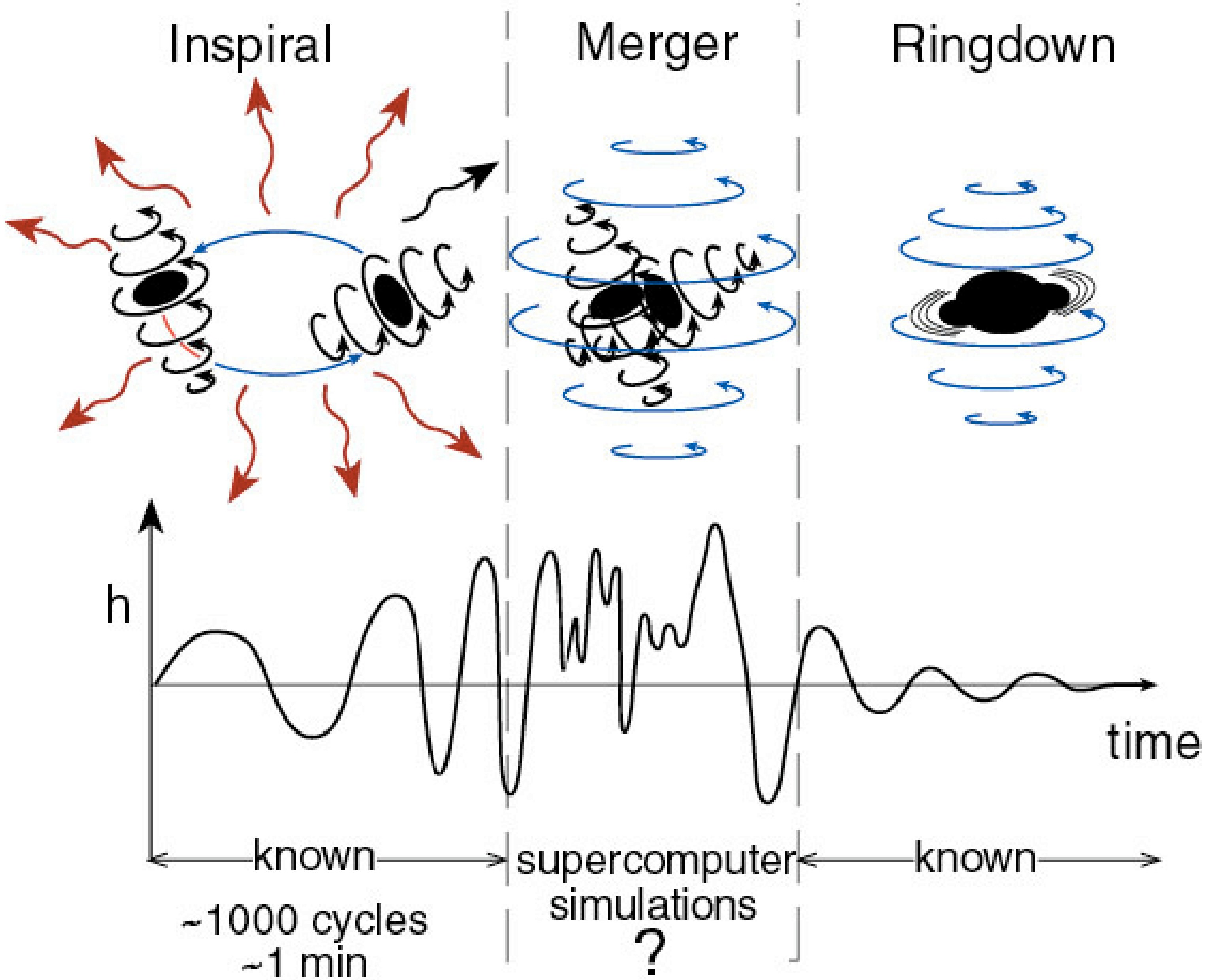


- Extreme sensitivity of orbit to initial conditions => ?? Coherent matched filtering no longer than a few days ?? Less?
- Many distant inspirals may give troublesome stochastic background; hard to separate strongest inspirals
- *To explore & quantify this: need waveforms. Will take ~2 years of concerted effort to produce them & quantify loss of S/N*

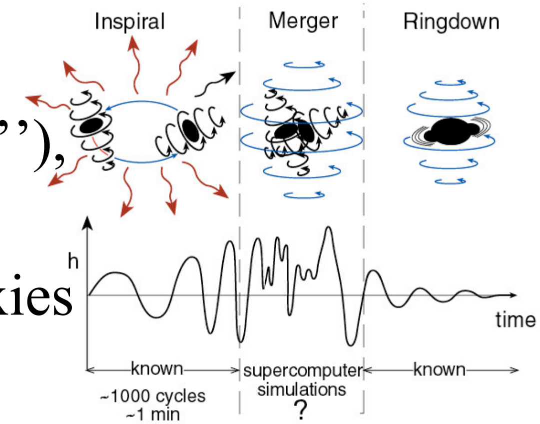
- Corresponding Waveform [schematic]:



Binary Black Hole Mergers



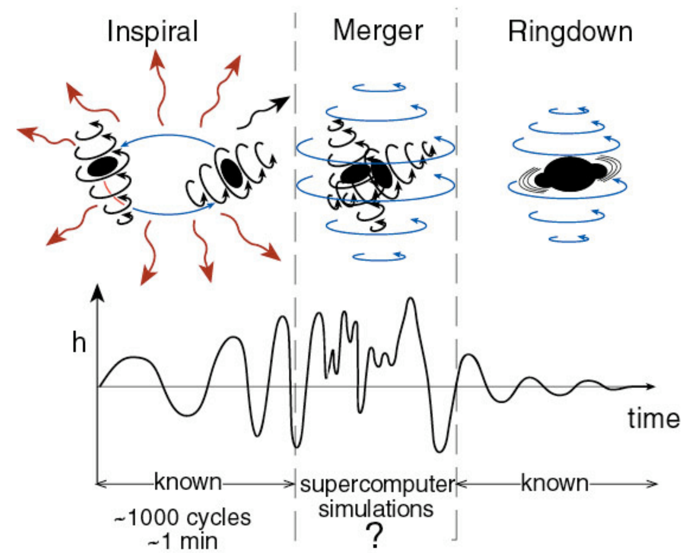
Binary Black Hole Mergers [cont.]



- **Astrophysical phenomenology:**
  - Stellar-mass holes: in bodies of galaxies (``field''), in globular & other clusters.
  - Supermassive holes: as result of merger of galaxies
- **Frequency band and detectors:**
  - Stellar-mass: High frequencies; LIGO & partners
  - Supermassive: Low frequencies; LISA
- **Rates, Signal to noise ratios:**
  - LIGO, initial interferometers: seen to 100Mpc, ~1/200yr to ~1/yr; S/N ~ 10 or less
  - LIGO, advanced interferometers: seen to z~0.4, ~2/mo to ~15/day; S/N ~ 10 to 100
  - LISA: seen to z~10s (earliest objects in universe), ~few/yr; S/N ~ 100 to 100,000

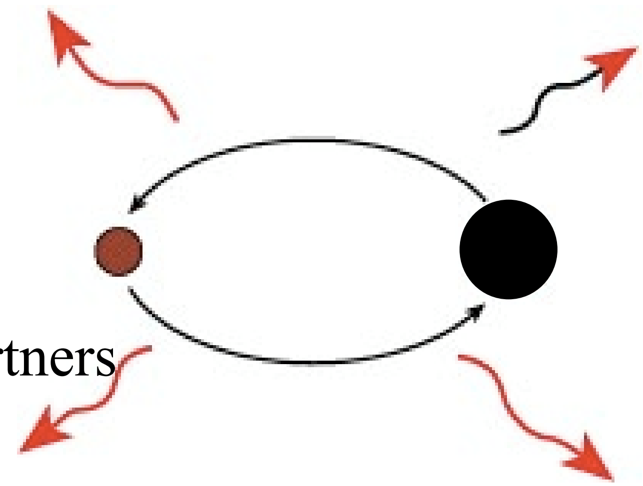
Binary Black Hole Mergers [cont.]

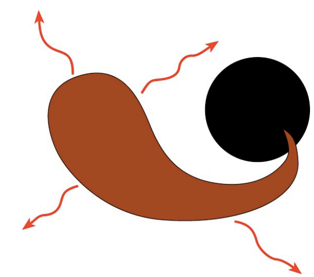
- **Information carried by the waves:**
  - Inspiral: Masses, spins, surface areas, and orbits of initial holes
  - Merger: The highly nonlinear dynamics of curved spacetime
  - Ringdown: Mass, spin, surface area, … of final hole



- **Science to be done:**
  - Test Penrose's cosmic censorship conjecture
  - Test Hawking's second law of black hole mechanics (horizon area increase)
  - Watch a newborn black hole pulsate, radiating away its excess "hair"
  - Probe the nonlinear dynamics of spacetime curvature under the most extreme of circumstances that occurs in the modern universe
  - Probe demography of black hole binaries
- **Methods of computing waveforms:**
  - Inspiral: post-Newtonian expansion; merger: numerical relativity; ringdown: black-hole perturbation theory

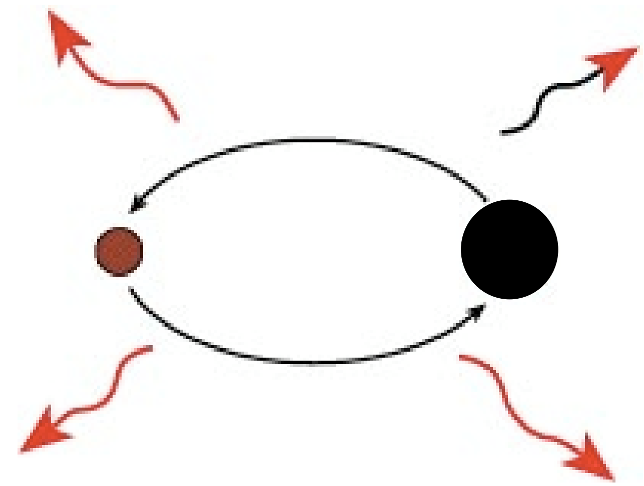
Neutron-Star / Black-Hole Mergers





- **Astrophysical phenomenology:**
  - Stellar-mass objects: in field, in globular & other clusters.
- **Frequency band and detectors:**
  - High frequencies: LIGO and partners
- **Rates:**
  - Initial IFOs: 43Mpc, 1/2500yrs to 1/2yrs
  - Advanced IFOs: 650Mpc, 1/yr to 4/day
- **Information carried by waves:**
  - Inspiral: masses, spins, orbit
  - Tidal disruption of NS: neutron-star structure (e.g. radius)
- **Science to be done:**
  - Probe neutron-star structure, equation of state of matter
- **Methods of analysis:**
  - Inspiral: post-Newtonian; disruption of NS: numerical relativity

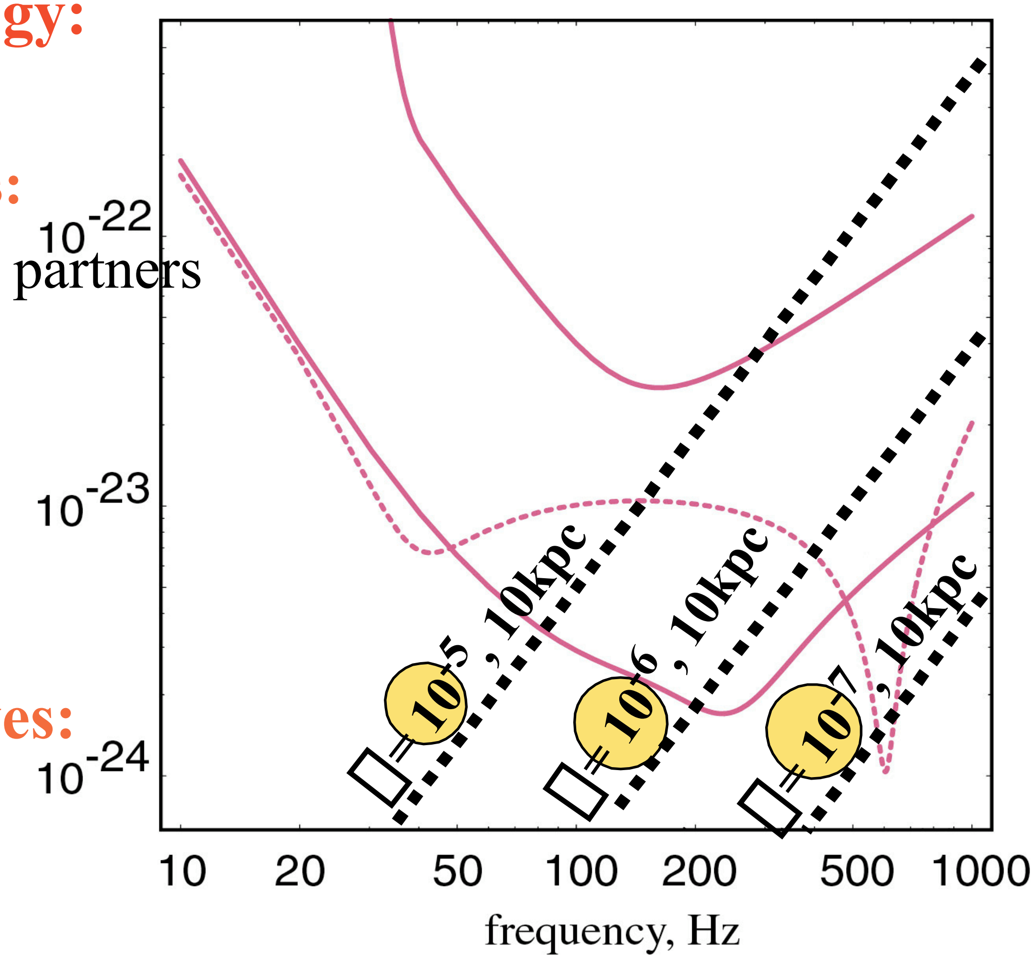
Neutron-Star / Neutron-Star Inspiral



- **Astrophysical phenomenology:**
  - Main-sequence progenitors in field, capture binaries in globular clusters
- **Frequency band and detectors:**
  - High frequencies: LIGO and partners
- **Rates:**
  - Initial IFOs: 20Mpc, 1/3000yrs to 1/3yrs
  - Advanced IFOs: 300Mpc, 1/yr to 3/day
- **Information carried by waves:**
  - Inspiral: masses, spins, orbit
  - Merger: probably lost in LIGO's high-frequency noise
- **Science to be done:**
  - Test relativistic effects in inspiral [also for NS/BH and BH/BH]
- **Methods of analysis:**
  - Post-Newtonian expansions

Spinning Neutron Stars: Pulsars

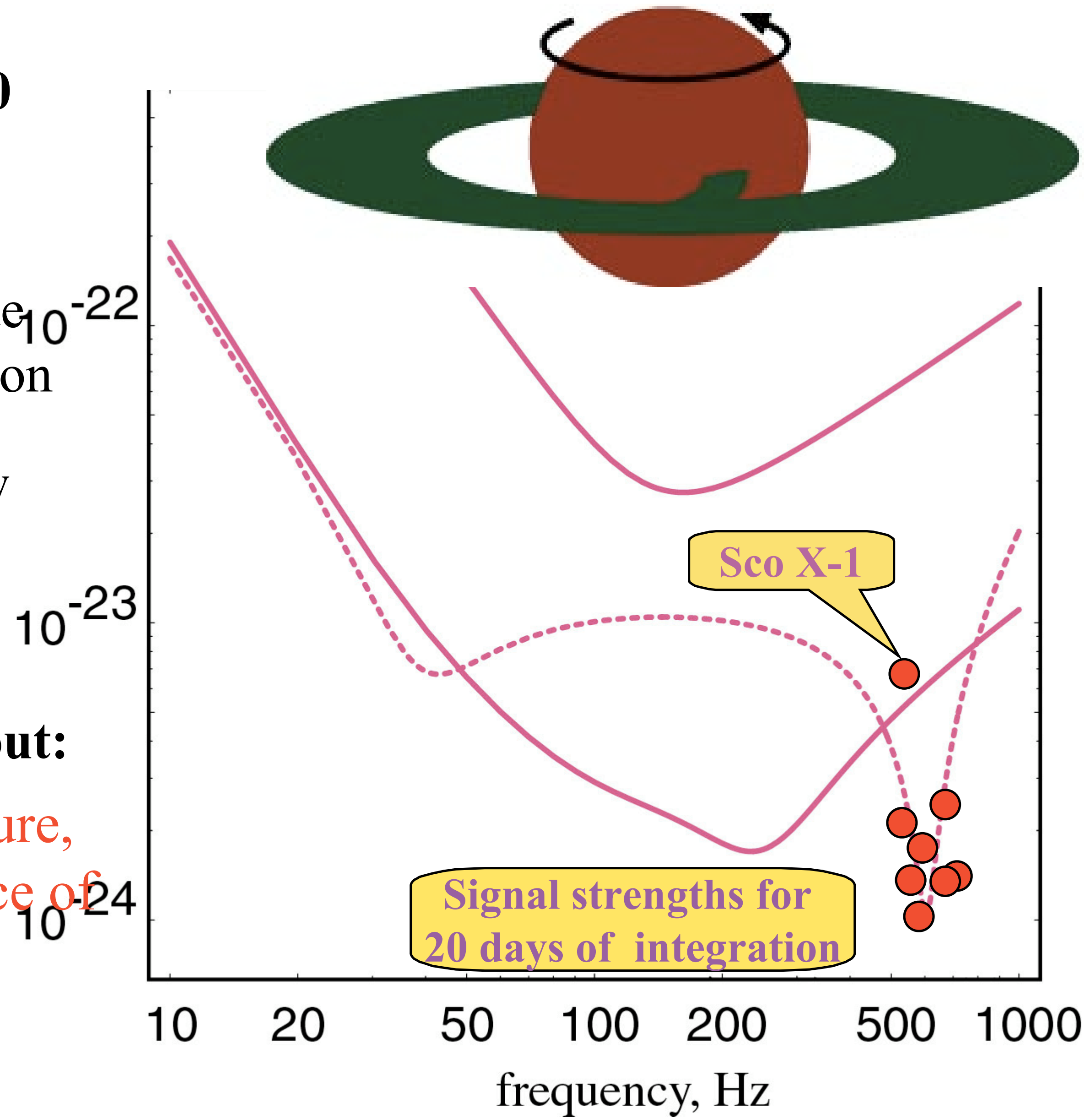
- **Astrophysical phenomenology:**
  - Pulsars in our galaxy
- **Frequency band and detectors:**
  - High frequencies: LIGO and partners
- **Detectability:**
  - Governed by ellipticity, spin
  - Ellipticities thought to be $\epsilon \lesssim 10^{-6}$; possibly 10^{-5}
- **Information carried by waves:**
  - NS structure
  - Behavior in quakes
- **Methods of analysis:**
  - Slow-motion, strong-gravity



Spinning Neutron Stars:
Low-Mass X-Ray Binaries in Our Galaxy [LIGO]

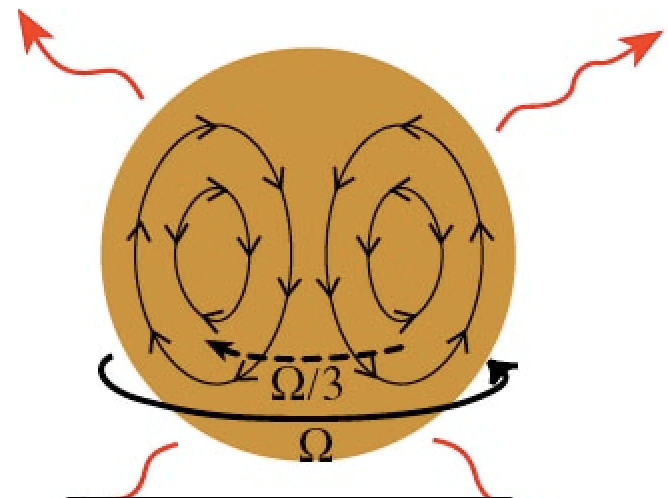
- **Rotation rates ~250 to 700 revolutions / sec**
  - Why not faster?
  - **Bildsten**: Spin-up torque balanced by GW emission torque
- **If so, and steady state: X-ray luminosity ~ GW strength**

- **Combined GW & EM obs's => information about:**
  - crust strength & structure, temperature dependence of viscosity, ...



Neutron-Star Births: R-Mode Sloshing in First ~1yr of Life [LIGO]

- NS formed in supernova or accretion-induced collapse of a white dwarf.
  - *If* NS born with $P_{\mathbf{spin}}$ < 10 msec: ***R-Mode instability:***
  - Gravitational radiation reaction drives sloshing



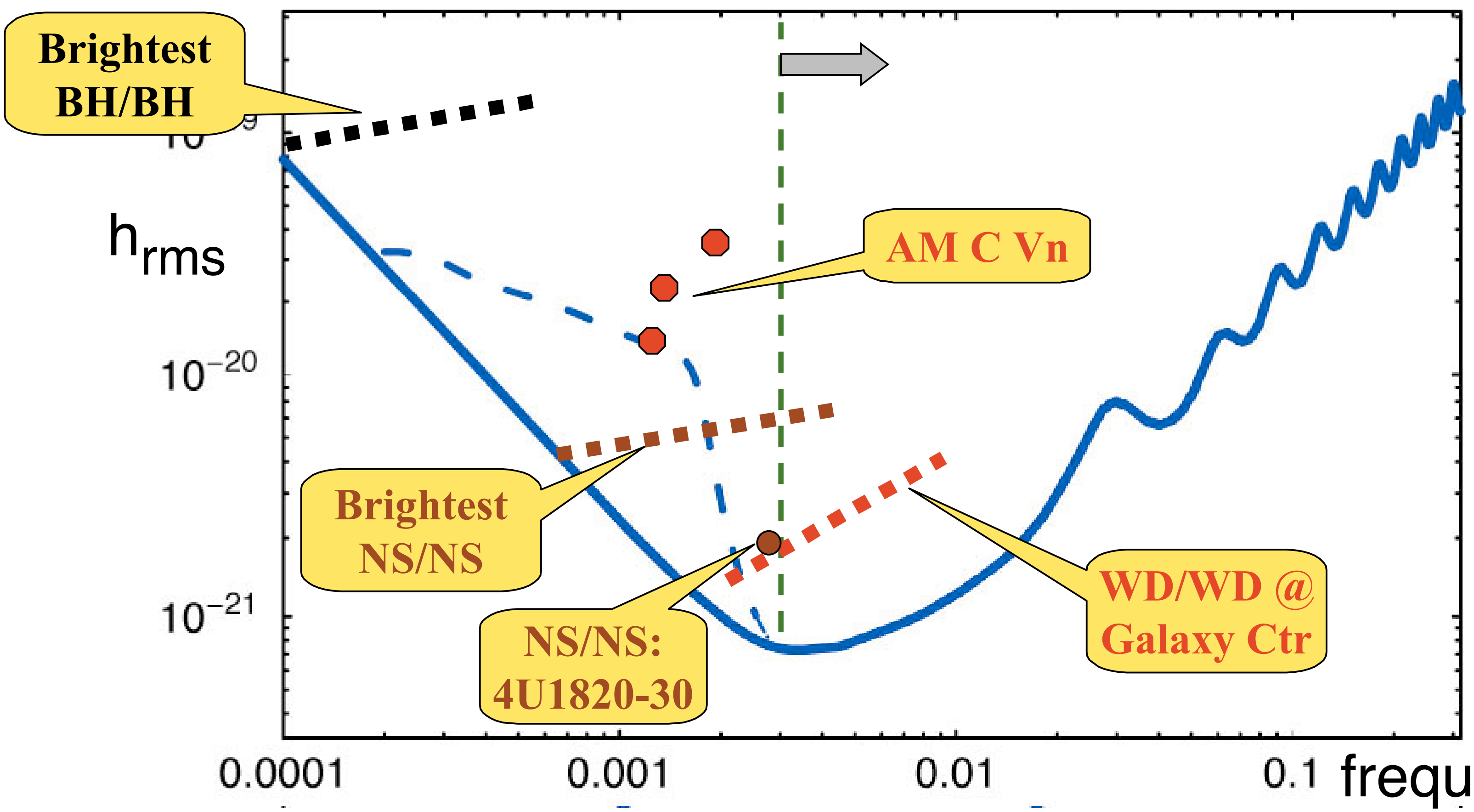
- Physics complexities:
  What stops the growth of sloshing & at what amplitude?
  - Crust formation in presence of sloshing?
  - Coupling of R-modes to other modes?
  - Wave breaking & shock formation?
  - Magnetic-field torques?

Depending on this,GW's may be detectable out to Virgo (supernova rate several per year). BUT recent research pessimistic

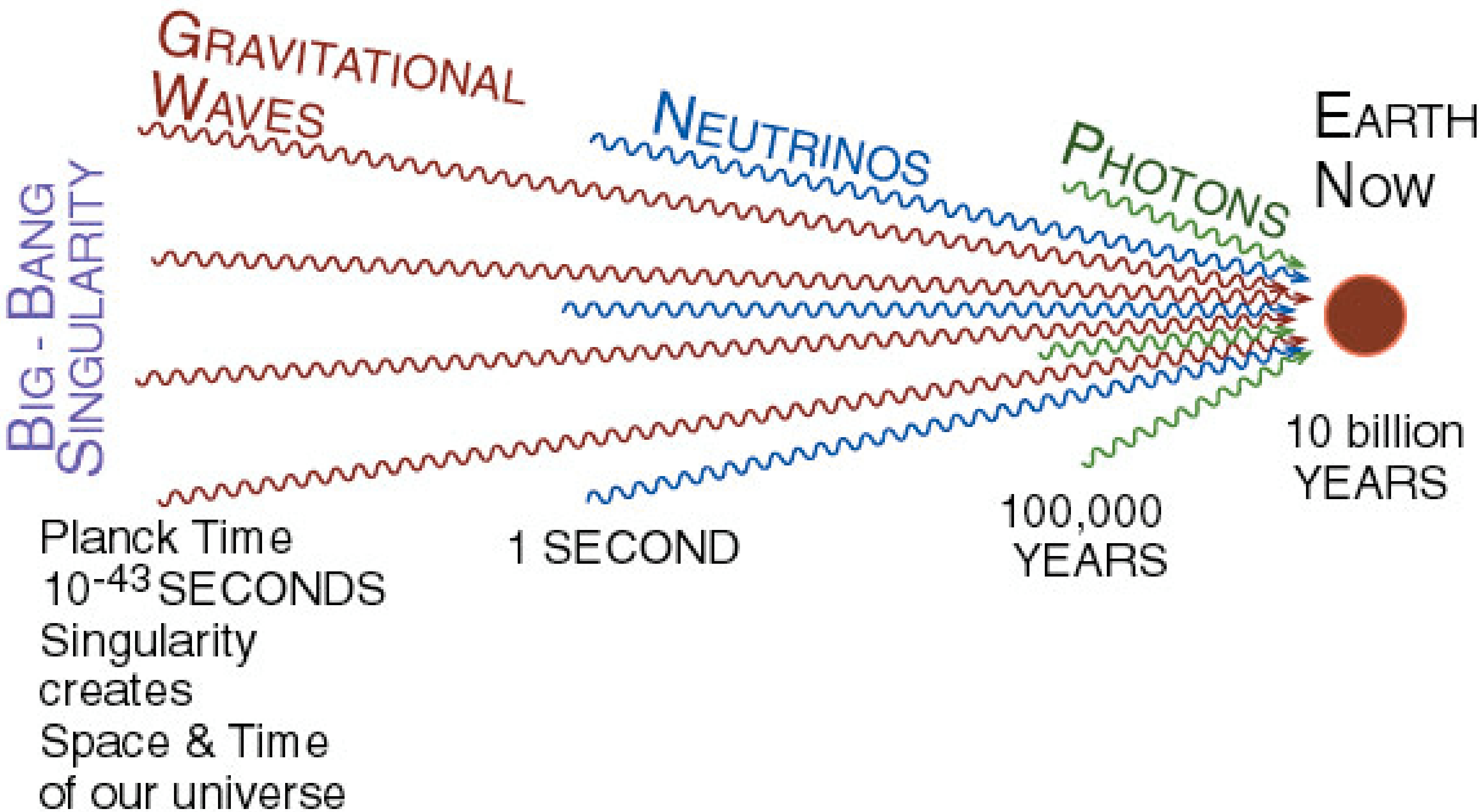
GW's carry information about these

COMPACT BINARIES IN OUR GALAXY: LISA

- Census of short-period compact binaries in our Galaxy; rich astro
- BH/BH studies: e.g. merger rate; compare with LIGO
- NS/NS studies -- e.g. merger rate; compare with LIGO et al
- 3000 WD/WD binaries will stick up above the WD/WD noise
- Inspiral (& M_{chirp}) will be measured if f > 0.003 Hz

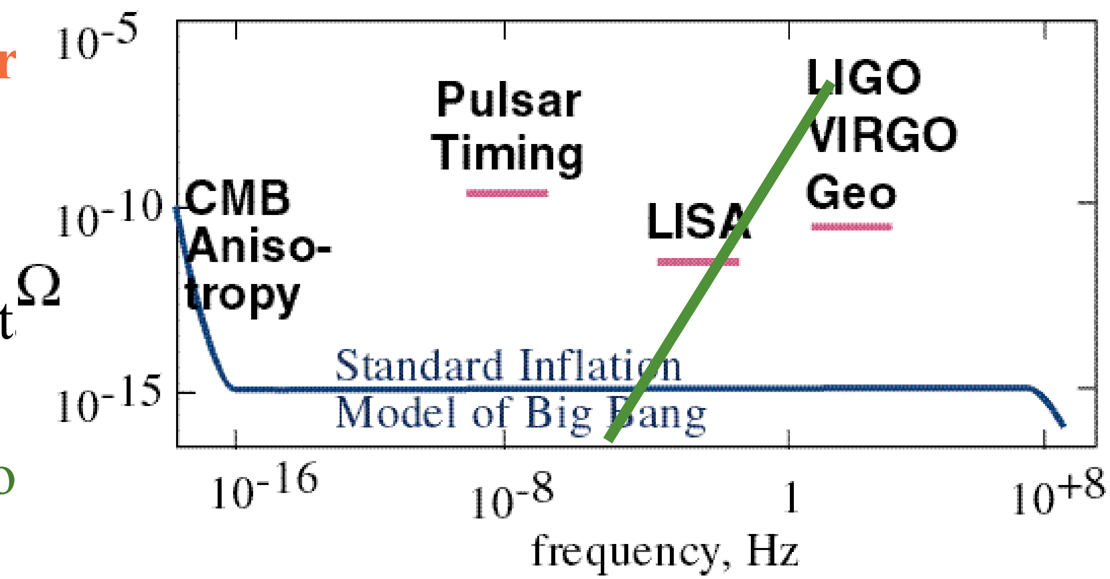


The First One Second of Universe's Life



Waves from Planck Era, Amplified by Inflation

- **Cosmological phenomenology:**
  - Vacuum fluctuations (at least) created in Planck era
  - Amplified by interaction with background spacetime curvature of universe during inflation
- **Frequency band and detector**
  - All bands, all detectors
- **Strength predictions:**
  - "Standard Inflation": detect only in ELF band (CMB)
  - "Pre-big-bang", etc: more o



- **Information carried:**
  - Physics of big bang, inflation; equation of state of very early universe
- **Methods of analysis:**
  - Cosmological perturbation theory; quantum gravity

Phase Transitions in Very Early Universe

- **Cosmological Phenomenology:**
  - As universe expanded, fundamental forces decoupled from each other; phase transition at each decoupling produced gravitational waves; GW's redshifted with expansion
- **Frequency bands and detectors:**
  - LISA probes Electroweak Phase Transition (~100 GeV) at universe age $\sim 10^{-15}$ sec
  - LIGO probes any phase transition that might have occurred at $\sim 10^{9}$ GeV and age $\sim 10^{-25}$ sec
- **Science:**
  - Probe high-energy physics, e.g. strength of electroweak phase transition; probe topological defects & evolution of inhomogeneities produced by phase transition

Mesoscopic Oscillations in Very Early Universe

- **Recent *speculations* about our observed universe as a 3-dimensional defect (*brane*) in a higher dimensional universe:**

- **All fundamental forces except gravity are confined to the brane.**
  - **Gravity is confined to some distance *b* < 1 mm from the brane, in the higher dimensions, and feels the shape of the brane.**

- **Excitations of our brane: [Craig Hogan]**
  - **Brane forms wrinkled on all scales up to *b*. Wrinkles evolve dynamically, producing GW's, with energy densities ~ those in other forms of radiation.**
  - **GW's from excitation scales ~ 10 A to 1 mm get redshifted to LISA band with GW strengths easily detected by LISA.**
  - **GW's from scales ~ 10^{-10} to 10^{-13} mm redshifted to LIGO band.**