Gravitational Wave Astronomy

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Sakharov meeting, 22.5.2009

My last Sakharov meeting (1996)

- Title ***The Stochastic Gravity Wave Background: Sources and Detection***
- At that time, large-scale gravitational wave detectors were ‘under construction’
- A lot has happened in the past 13 years, but have not yet made a direct gravitational wave detection
- In 13 **MORE** years (2022) many things I discuss today will be complete
- My new home (since January 2007)

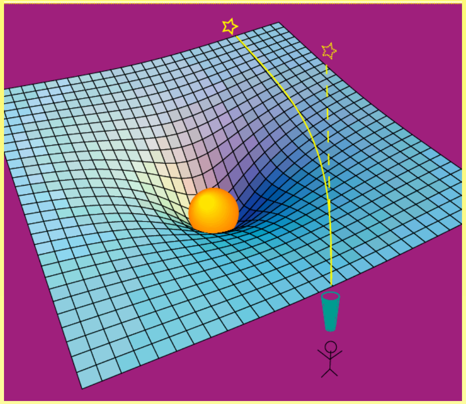
Albert Einstein Institute, Hannover

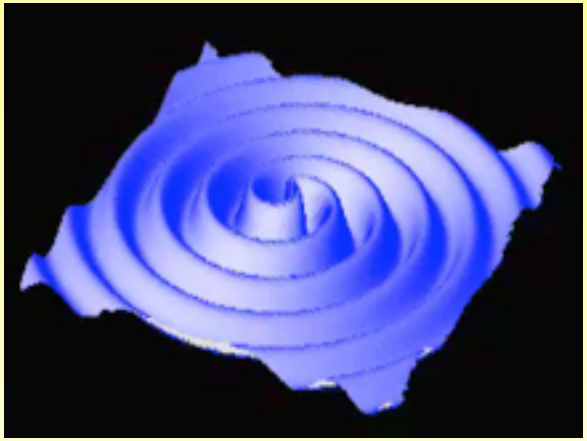
What are gravitational waves?

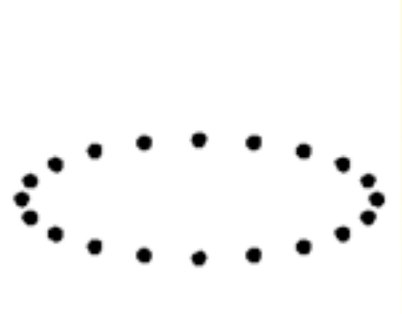
- Predicted by general relativity, Einstein, 1915-7
- Consequence of ‘nothing can go faster than light’
- Very weak, except for very compact massive objects undergoing large accelerations

$$L = \frac{G}{5c^5}\left(\frac{d^3}{dt^3}Q_{ab}\right)\left(\frac{d^3}{dt^3}Q_{ab}\right)$$

- Effect: differential acceleration in freely-falling test masses

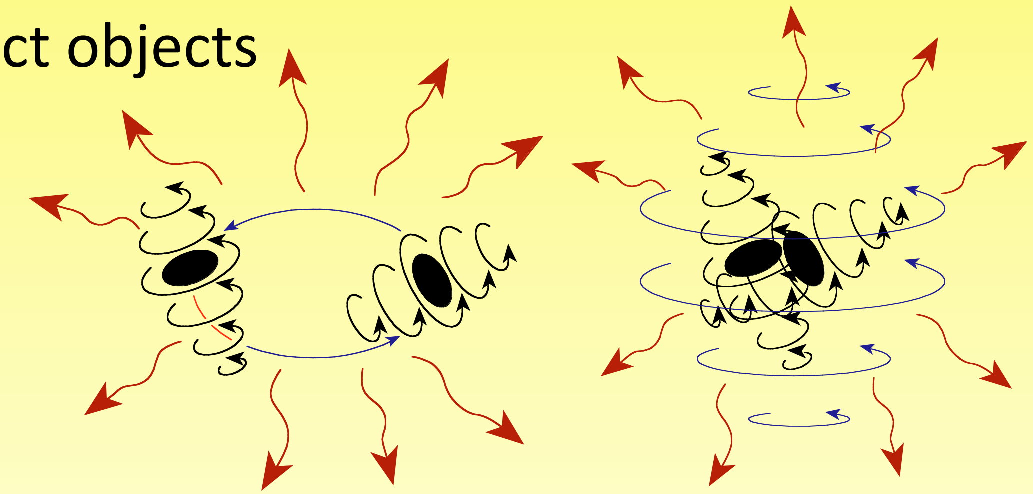






A "new window" on the universe

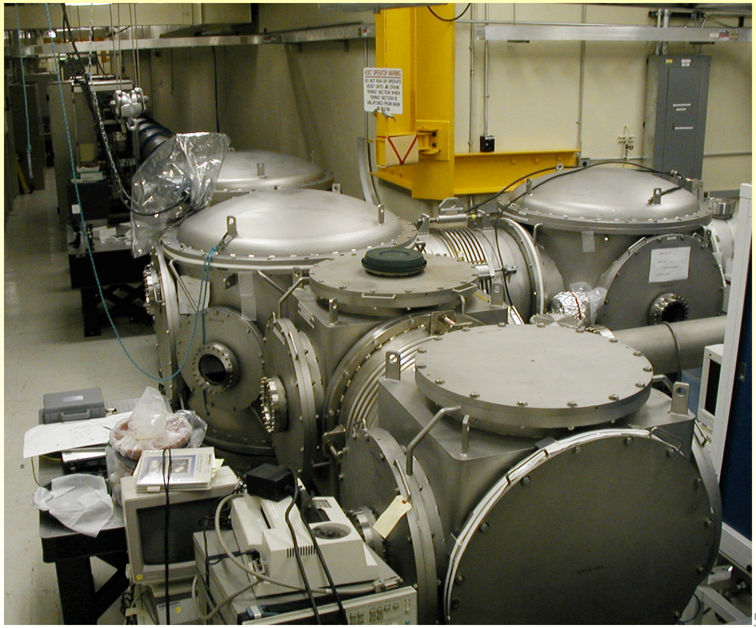
- Get information about the very early universe (10^{-22} to 10^{-14} s)
- Testing strong-field gravity and dynamic gravity near black holes and compact objects



- Population studies and stellar evolution
- Neutron star structure (eccentricity, glitches)
- Supernova mechanisms
- Origins of gamma-ray bursts
- The unexpected ...

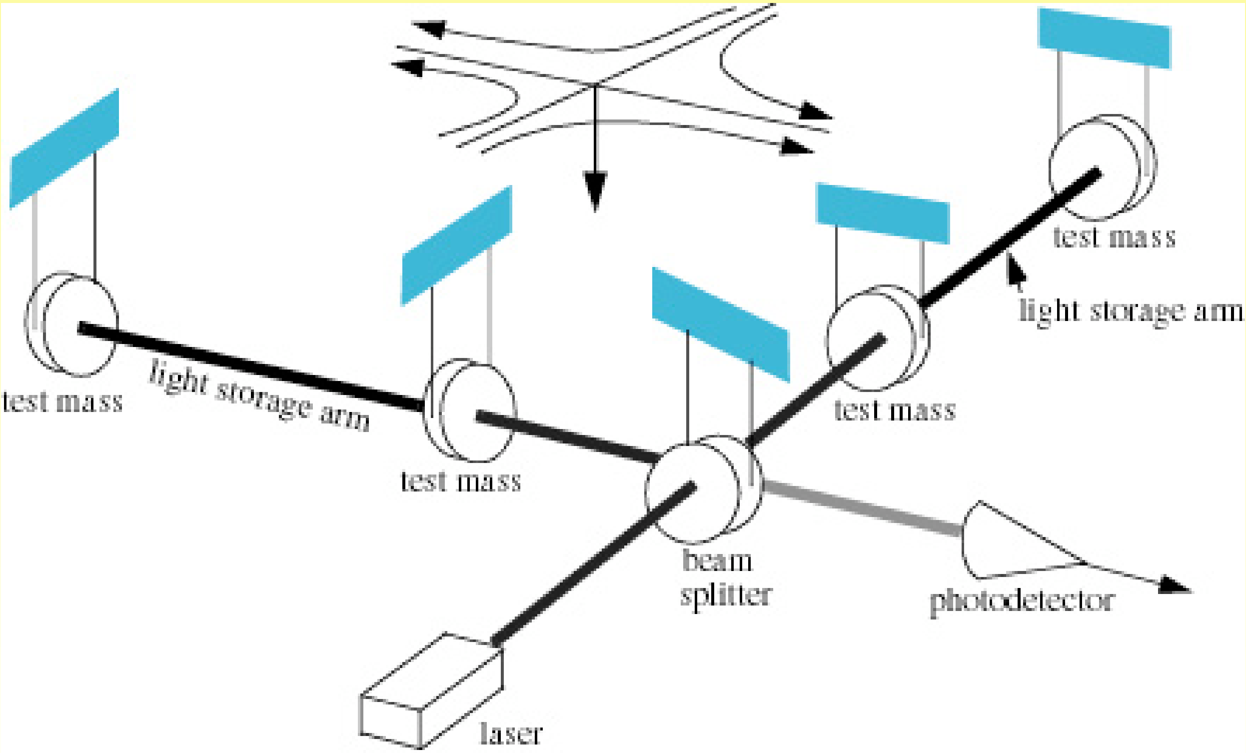
Detector Development History

- 1918: Einstein, too weak to detect
- late 1960s: Weber, bar detector, U. Maryland
- 1970s: Second generation (cryogenic) bars at LSU, Stanford, Rome, Maryland
- *1970s: first 'detection' in PSR B1913+16 (Hulse-Taylor binary pulsar)*
- 1980s: First generation of 'broadband' laser interferometer detectors at MIT, Caltech, Glasgow, Hughes
- 1990s: Development LIGO (USA), VIRGO (France/Italy), GEO-600 (UK/Germany), TAMA (Japan), Dulkyn (Russia)
- 2005-7: LIGO + VIRGO completed first joint science run



How do laser interferometers work?

- Lasers measure distance to test-mass mirrors
- Differential motion cases shift in fringe pattern
- Detected via error signal in locked loop



L = 4 km

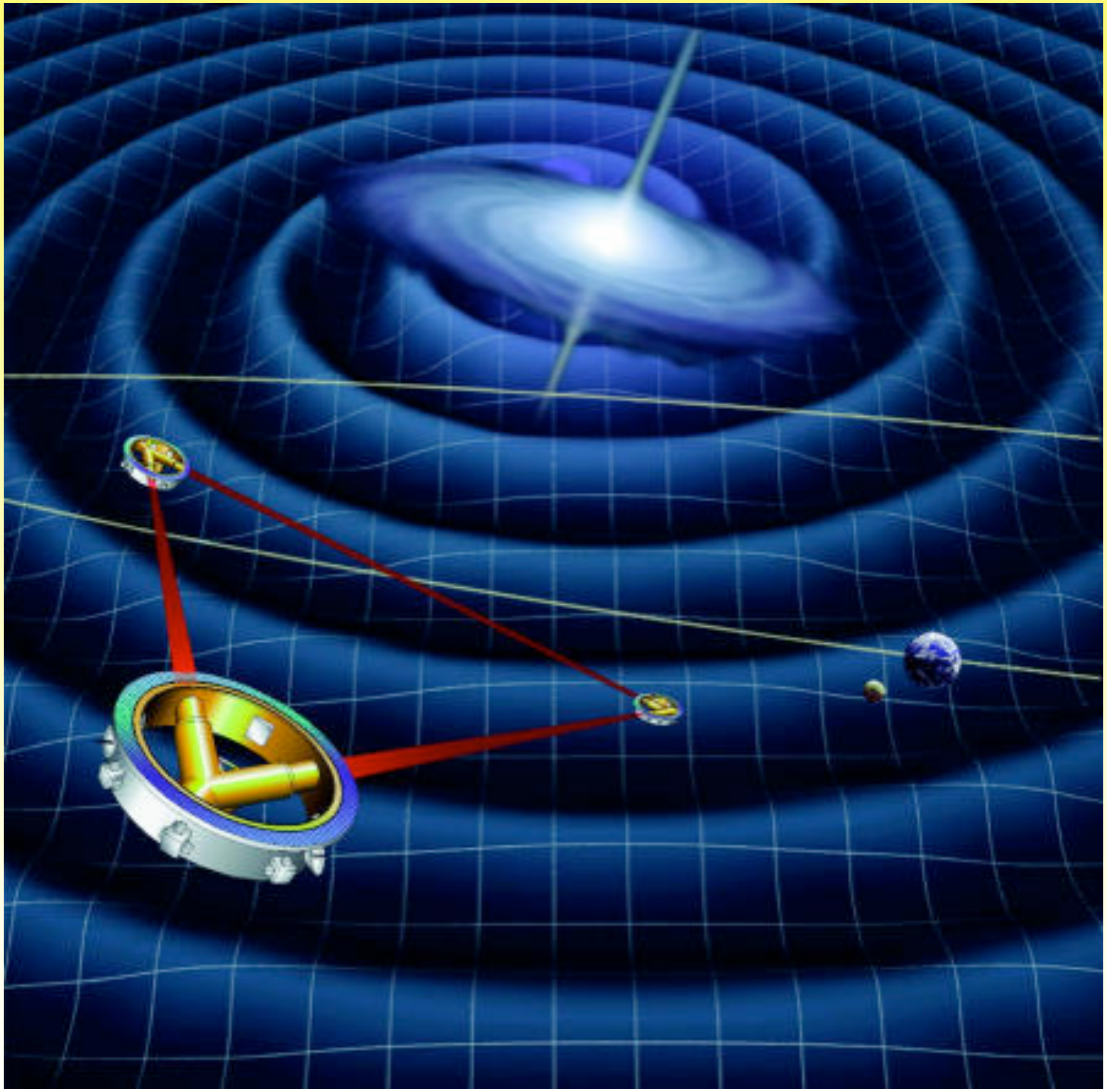
$\Delta L = 10^{-16}$ cm

$$h = \frac{\Delta L}{L} \approx 10^{-21}$$

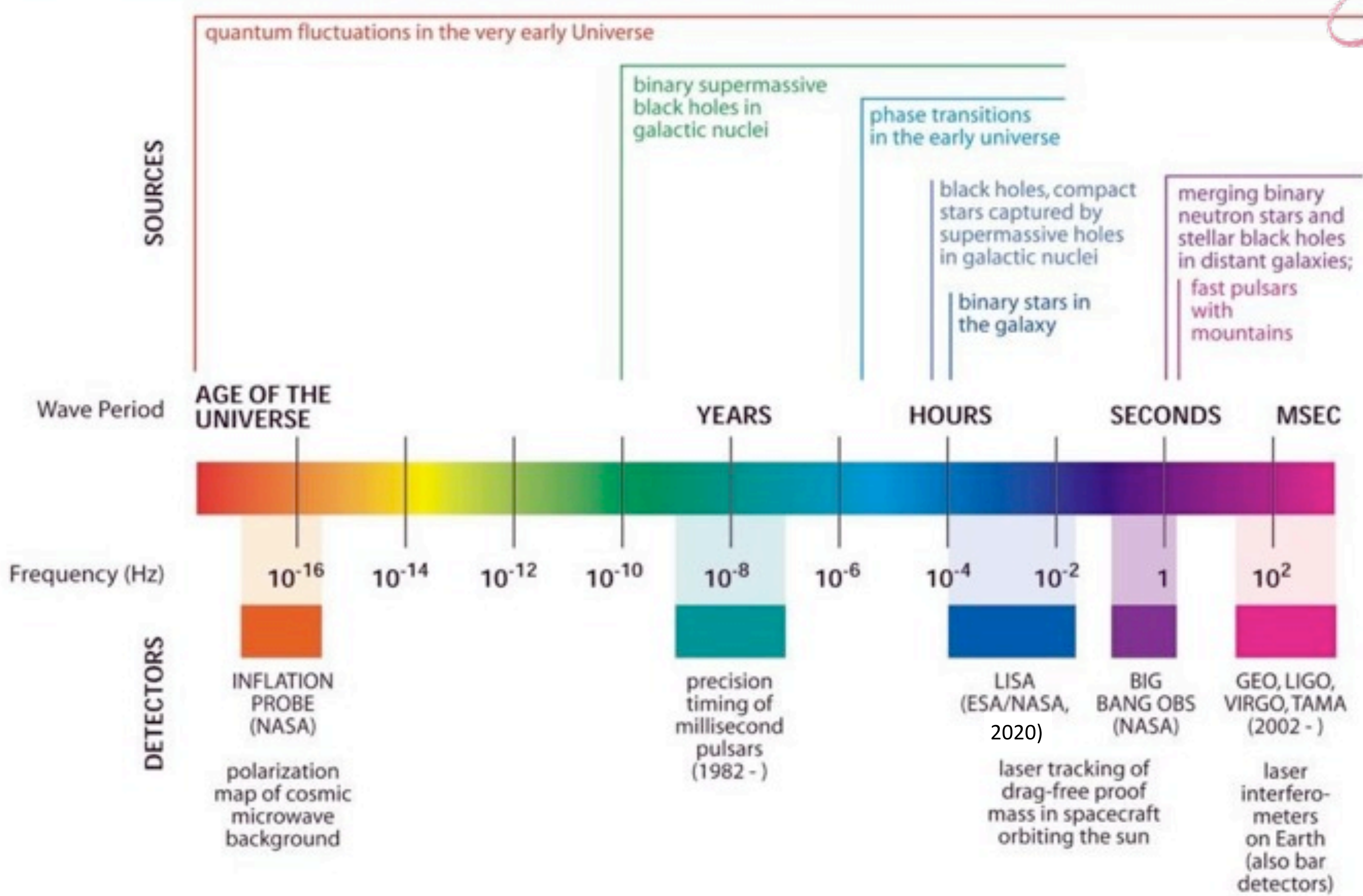
Most sensitive detectors

Laser Interferometer Space Antenna

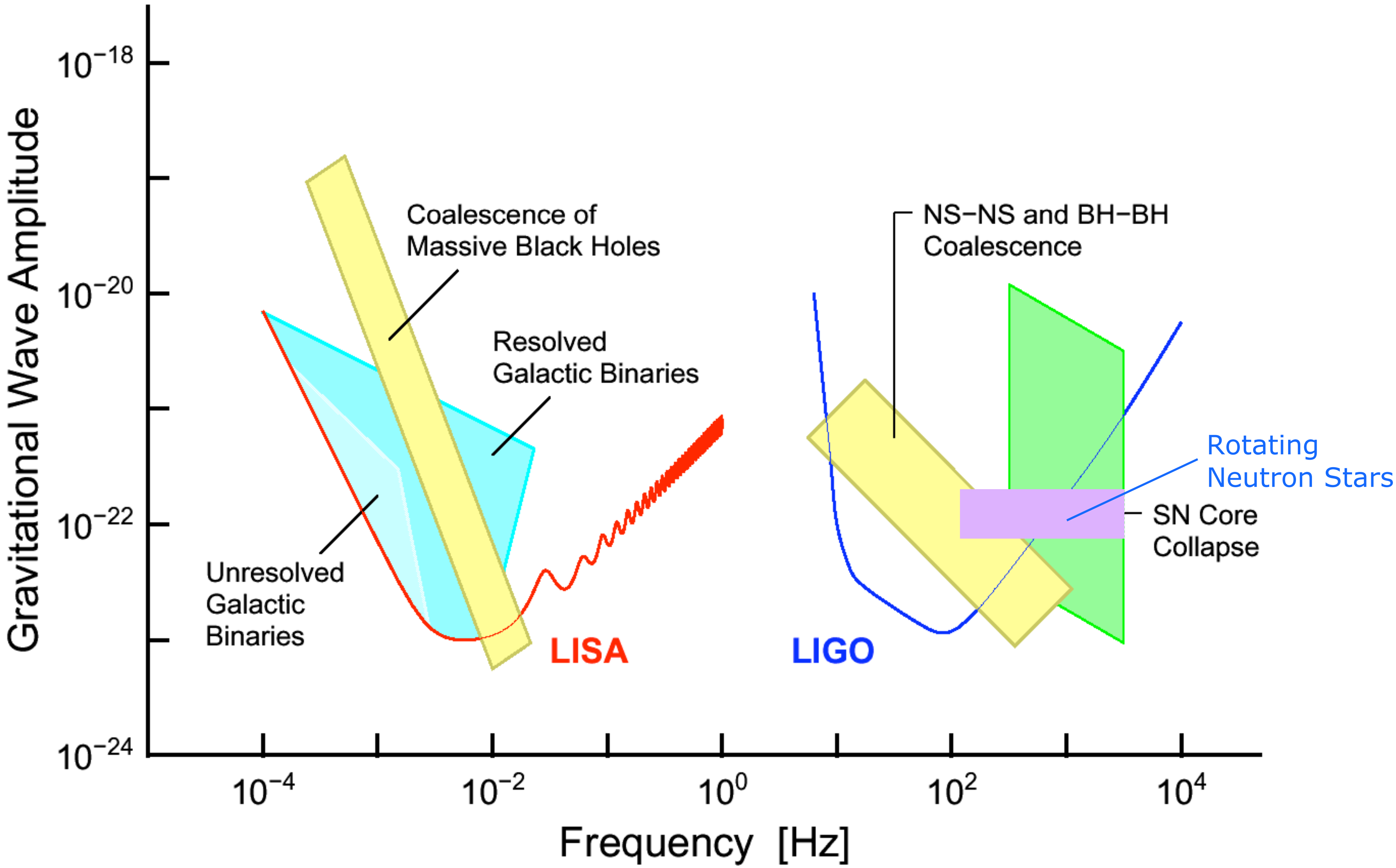
- LISA joint NASA/ESA mission
- Launch 2020
- 3 spacecraft, 5 Gm arms
- Sensitive band 10^{-4} to 10^{-1} Hz



THE GRAVITATIONAL WAVE SPECTRUM

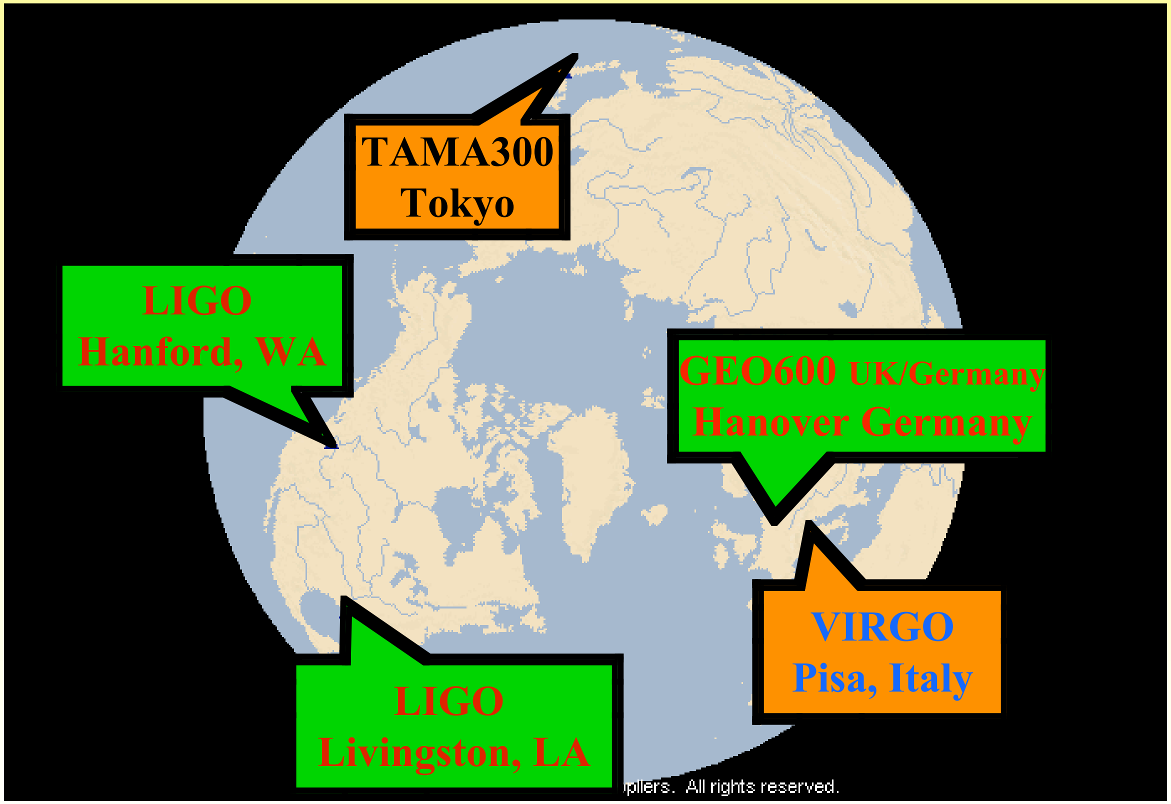


Toward Direct Detection



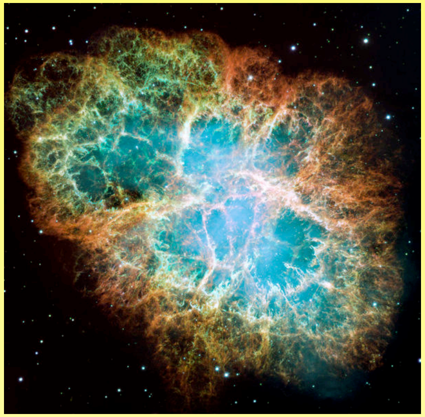
Data sharing

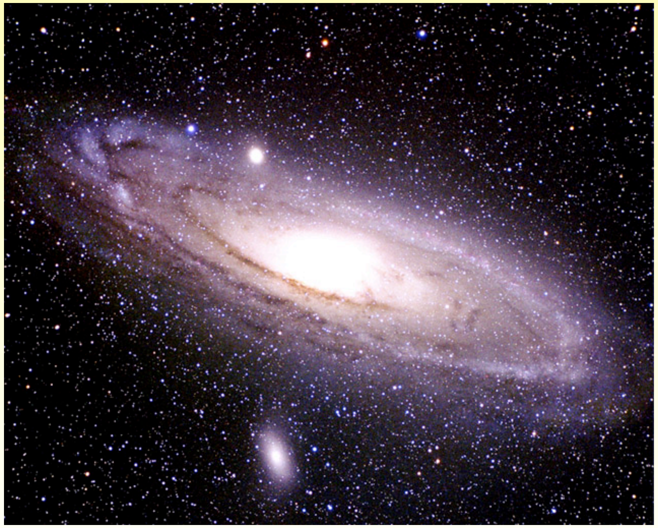
- LSC (LIGO Scientific Collaboration) has a data-sharing agreement with VIRGO and GEO600.
- improved sensitivity for weak signals
- detection confidence
- position reconstruction (triangulation)
- waveform reconstruction



LIGO S5 (completed October 2007)

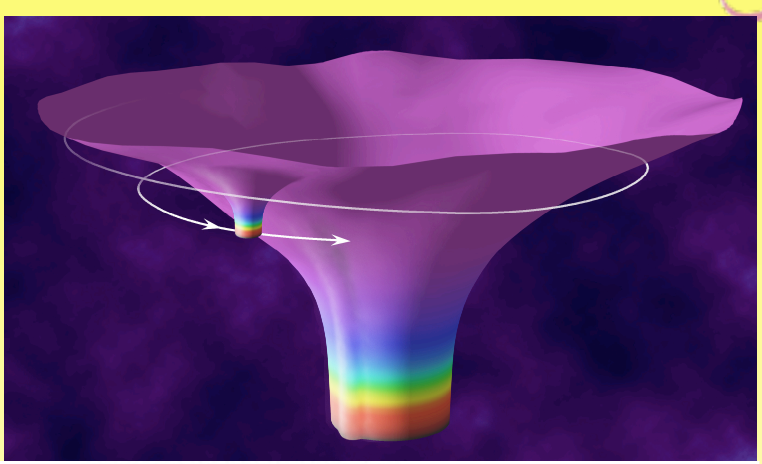
- Gravitational-wave stochastic background $\Omega(100\ \text{Hz}) < 5 \times 10^{-5}$
- Gravitational wave energy-loss from Crab pulsar < 10% electromagnetic energy-loss
- Gravitational waves from gamma-ray burst 070201: if in Andromeda, not due to coalescing NS/NS or NS/BH
- Upper limits on rates of binary inspiral

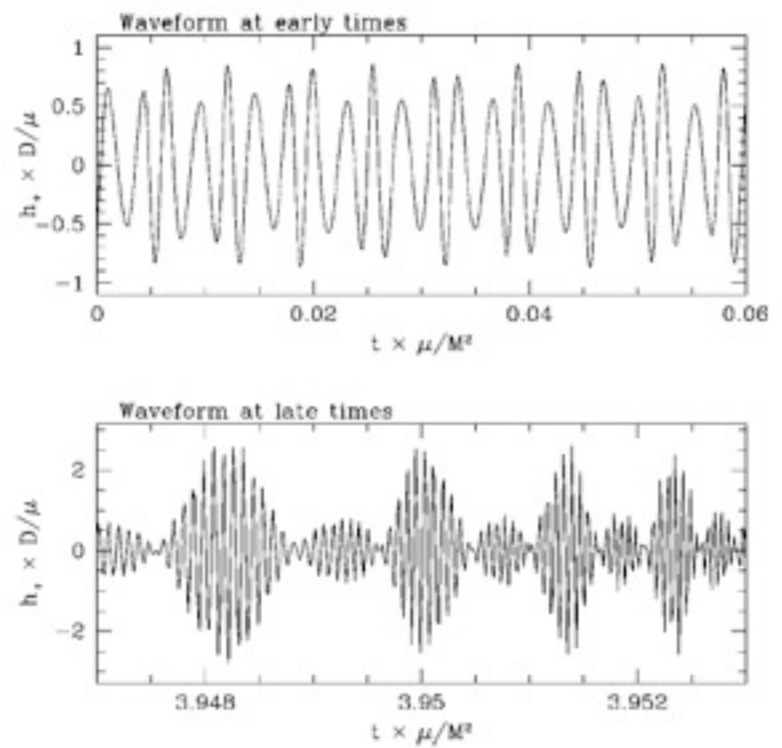




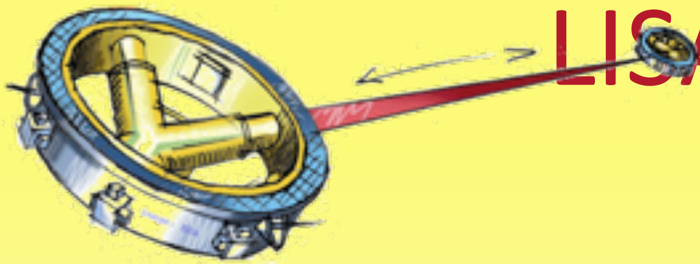
Current status (LISA)

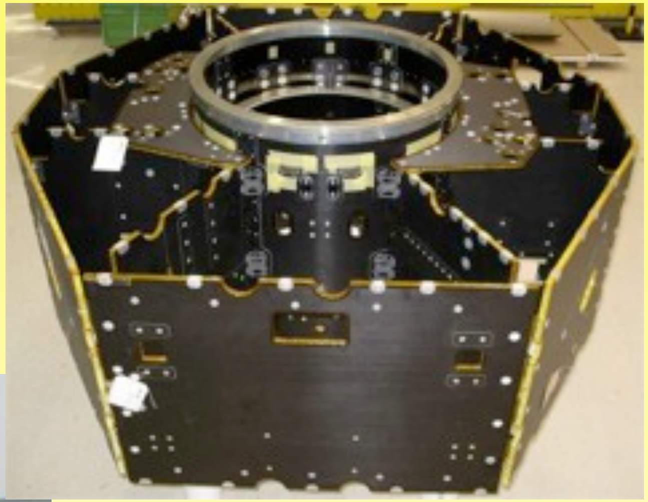
- History/Evolution of super massive black hole binaries (to z=20!)
- Normal stars falling into massive black holes
- Completely characterize compact binary population of our Galaxy
- Measure cosmological parameters
- Test GR in strong field limit
- $10^5 + 10^6$ binary merger at z=1 has amplitude SNR=3000



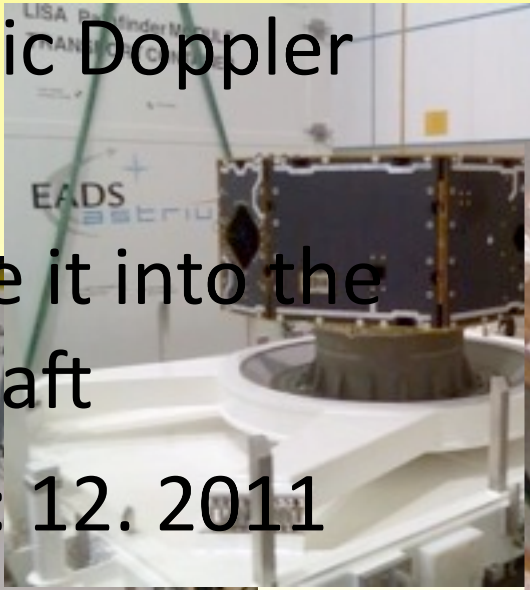


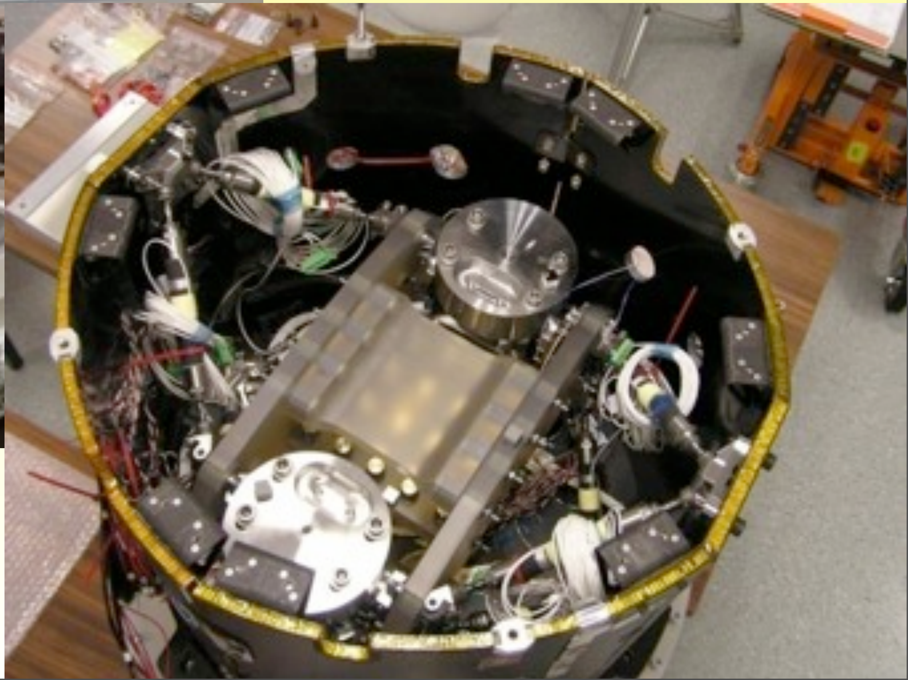
LISA Pathfinder





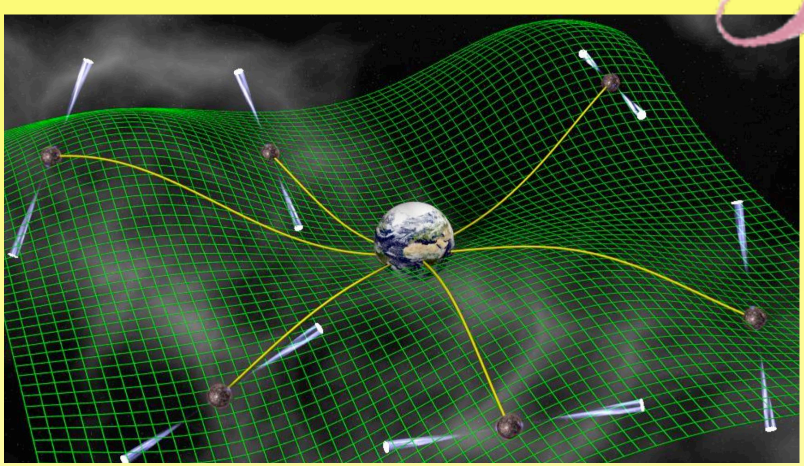
- Take one spacecraft
- Take one LISA Geodesic Doppler Link
- Squeeze it into the spacecraft
- Launch: 12. 2011

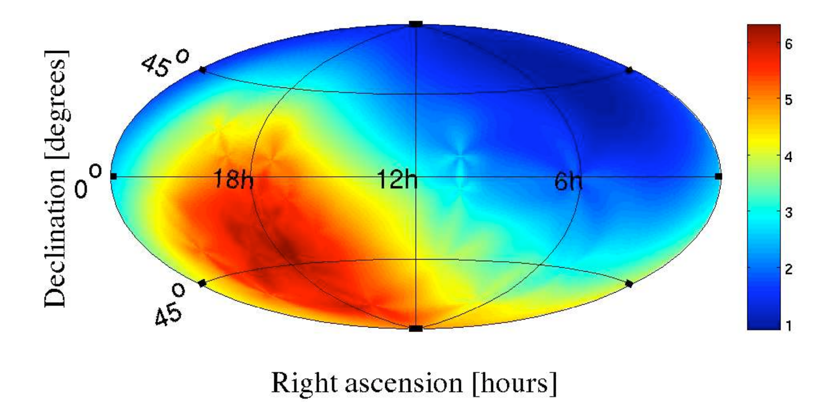




Pulsar timing

- Network of very stable pulsars: nHz gravitational wave detector
- NANOgrav, Parkes Pulsar Timing Array (PPTA), European Pulsar Timing Array (EPTA).In future: IPTA
- Typical goal: 20 pulsars, Δt < 100 ns over 10 years
- "Given sufficient telescope time ... expect to make a GW detection within the next five years." (NANOgrav decadal survey white paper)
- Broad-band observations to model/remove ISM dispersion





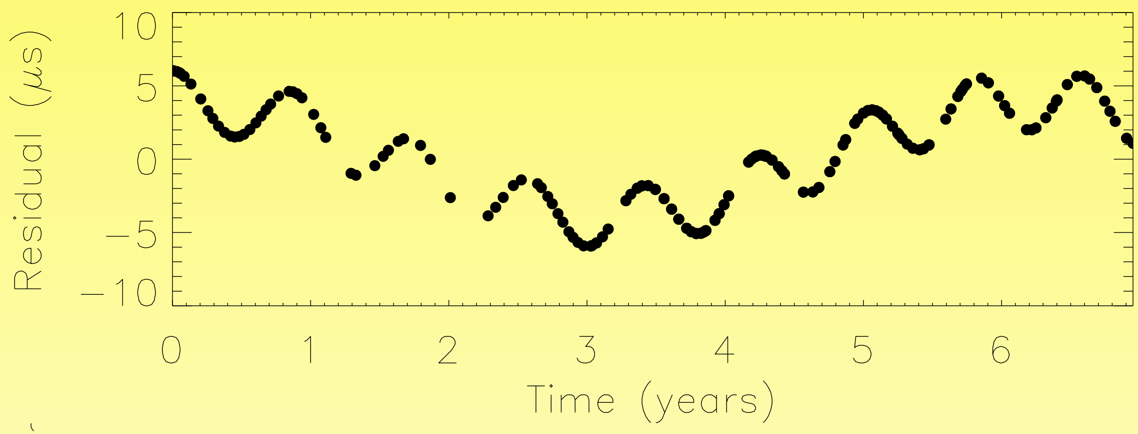
Anholm, Ballmer, Creighton, Price, Siemens, arXiv:0809.0701v2 [gr-qc]

Pulsar timing: no SBBH in 3C66B

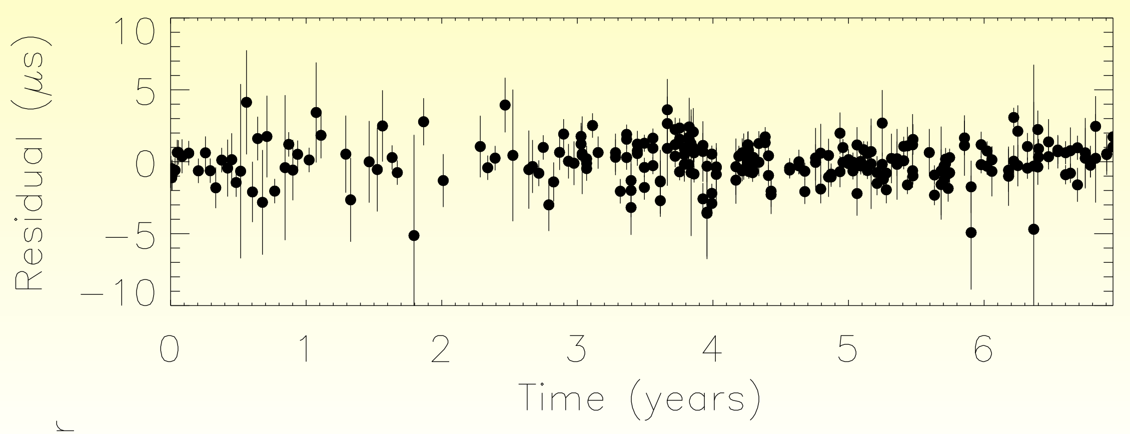
- Proposed SBBH had period ~ 1 year and total mass

$$5.4 \times 10^{10} M_\odot$$

- Ruled out based on 7 years of pulsar timing data

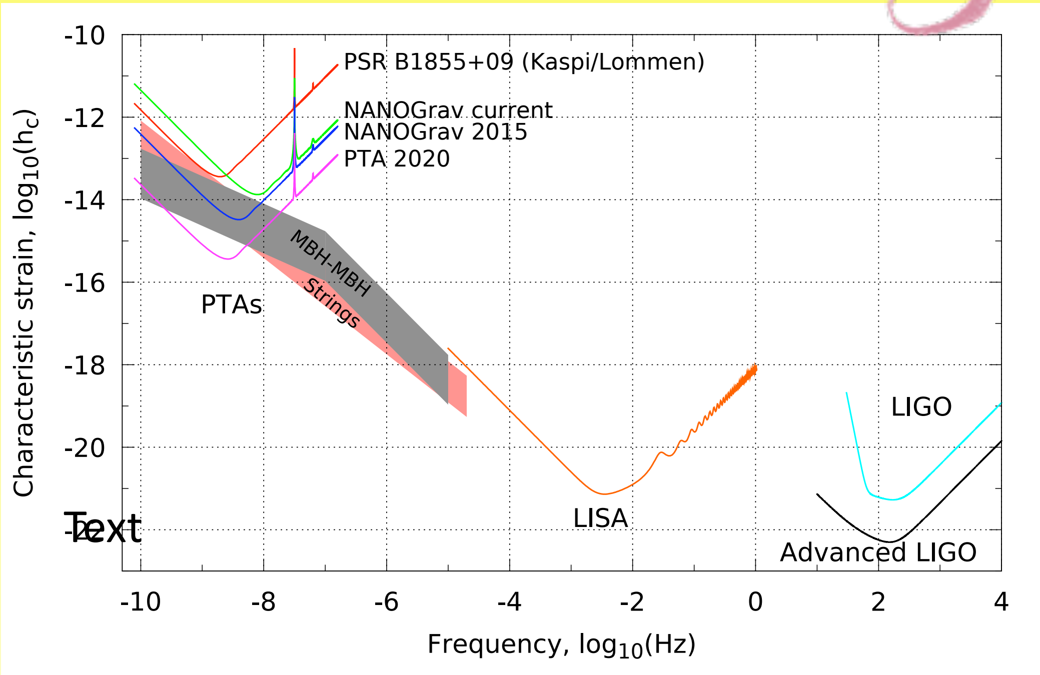


B1855+09 (Jenet, Lommen, Larson, & Wen (2004), ApJ 606:799)

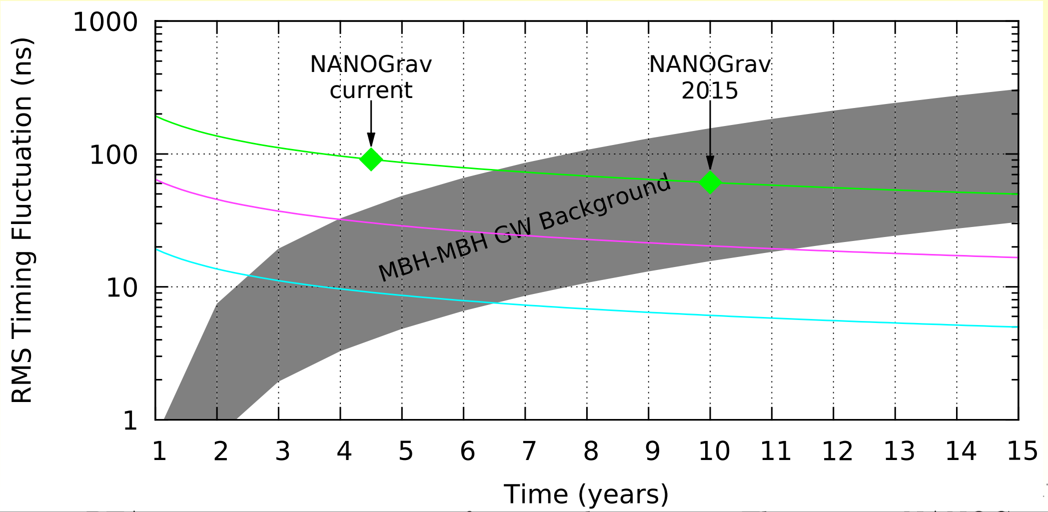


Pulsar timing sources

- Massive black hole mergers (B0402+769, 7pc)
- Resulting stochastic background
- Other possible sources include cosmic string networks, other sources of stochastic background
- ~ 500 hours/month of time required on 100m equivalent telescope

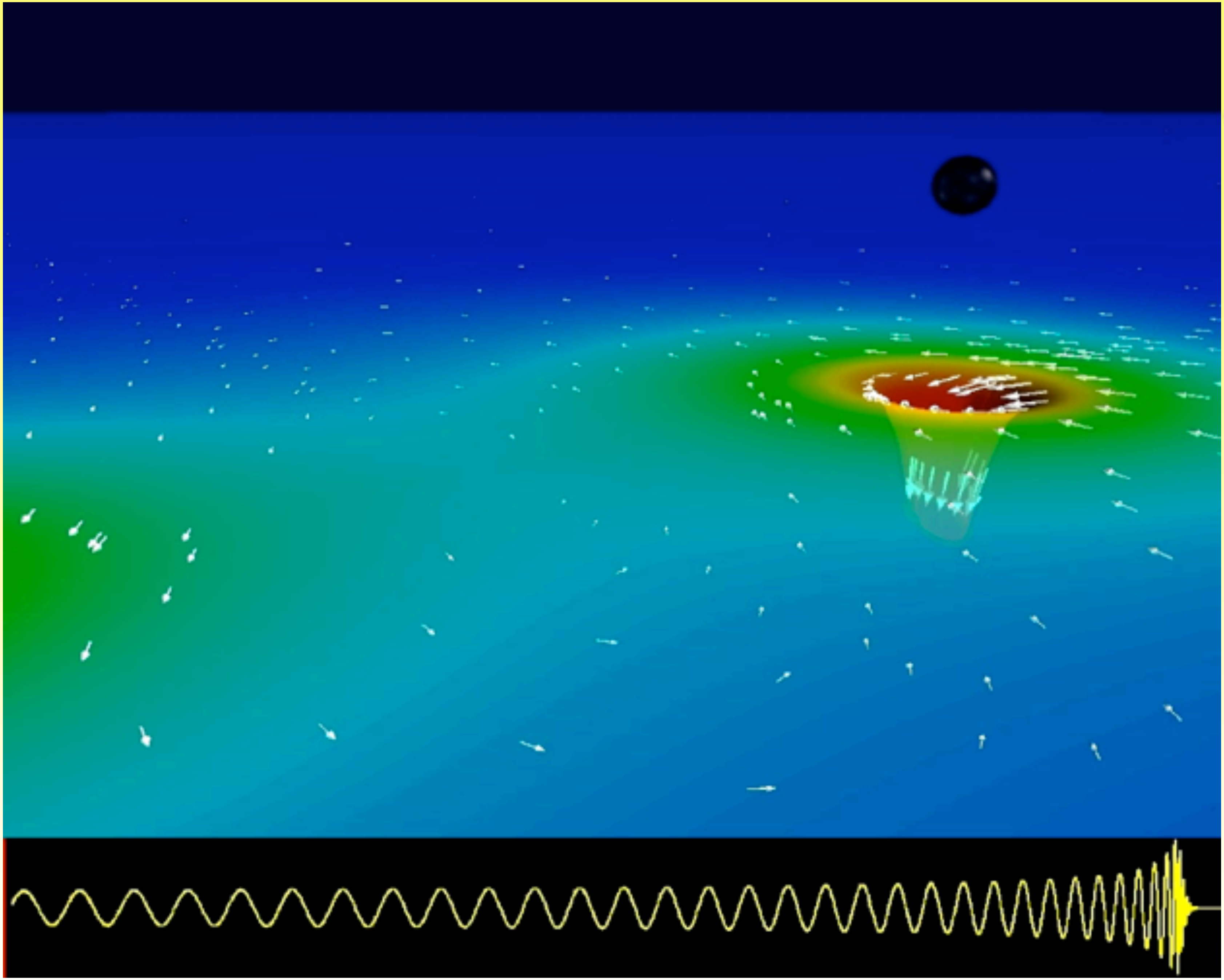


NANOgrav Decadal Survey White Paper

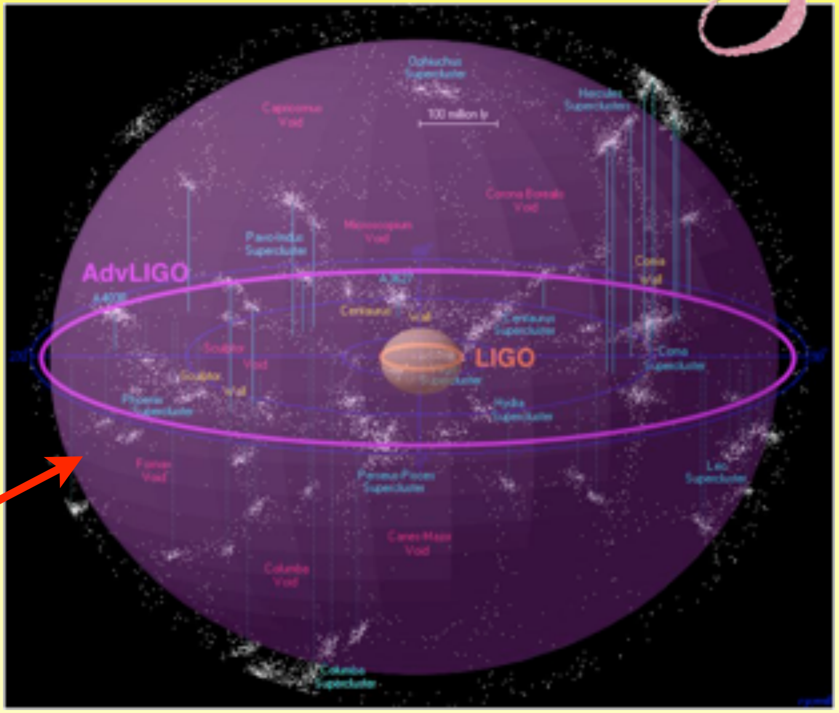


Detection needs waveforms

- Recent advances in numerical relativity now allow strong-field gravity regime to be accurately modeled
- Many new results: **UK**: Cambridge, Southampton. **Ireland**: Cork. **Germany**: AEI, Jena. **Japan**: Osaka. **Canada**: UBC, Guelph/ Perimeter, CITA. **USA**: Caltech/Cornell, Princeton, Chicago, Maryland, Oakland, RIT, UT Austin, LSU, Goddard, Penn State, Georgia Tech, U. Illinois - Urbana, FAU,...
- Active research group 'NINJA' working on incorporation of the latest numerical results and catalogs into the data analysis for gravitational wave searches.
- Following simulation shows 16 orbits of two non-spinning black holes, followed by coalescence and merger. Caltech/Cornell collaboration [Kidder, Lindblom, Pfeiffer, Scheel, Teukolsky, ...]



Future prospects and plans



- 2009: LIGO/VIRGO will start S6/VSR2. Sensitivity increase ~ 2 (30 Mpc for NS/NS inspiral), event rate increase ~ 10
- 2011: Planck CMB polarization data (**no time in this talk for this topic**!)
- 2014: Advanced LIGO, Advanced VIRGO. Sensitivity increase ~5 (150 Mpc), rate increase ~100
- 2015: Large Cryogenic Gravitational Telescope (Japan)
- 2015: Pulsar timing arrays

First detection

- 2020: LISA
- 2025: Einstein Telescope. Sensitivity increase ~40 (6000 Mpc, z=1), see all NS/BH inspirals in Hubble radius