Search for Gravitational Waves from Cosmic Sources

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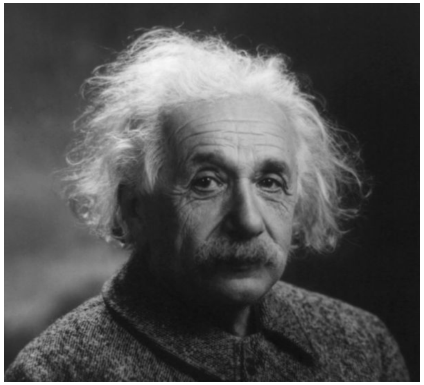
Vulcano Workshop 2012

https://www.cascina.virgo.infn.it/

Fundacja na rzecz
Nauki Polskiej

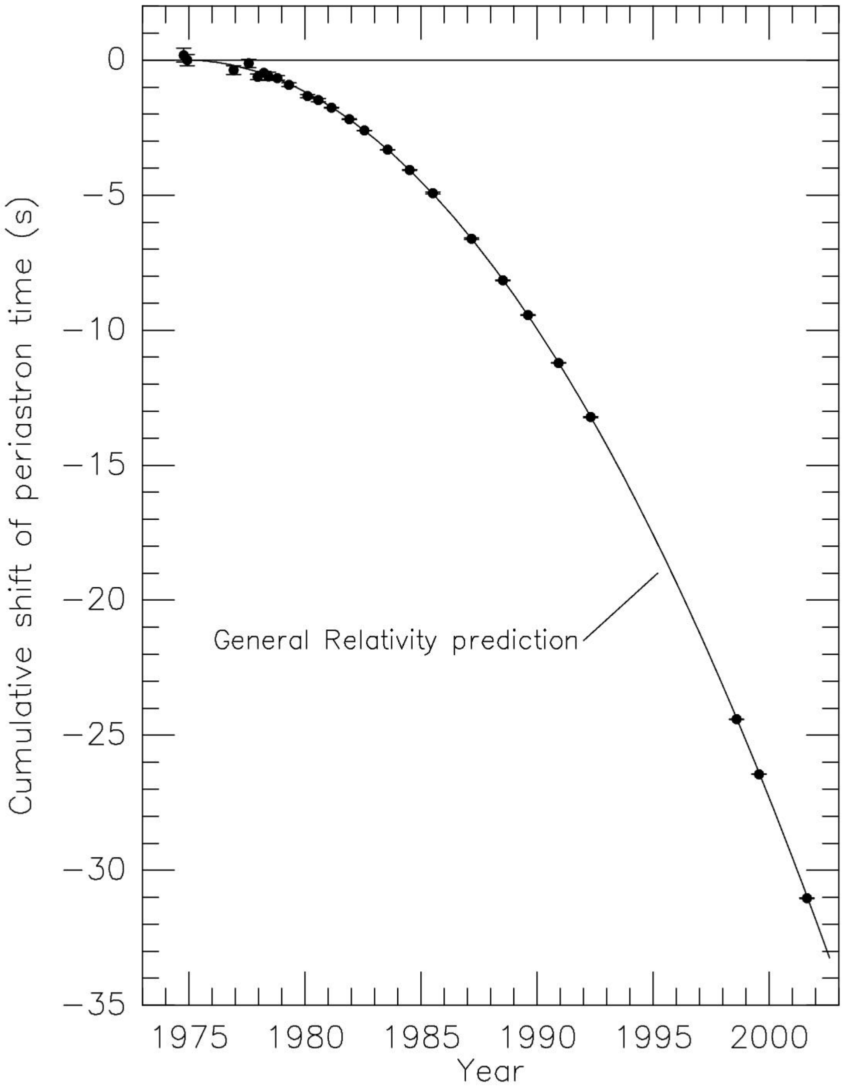
Gravitational waves – ripples of spacetime

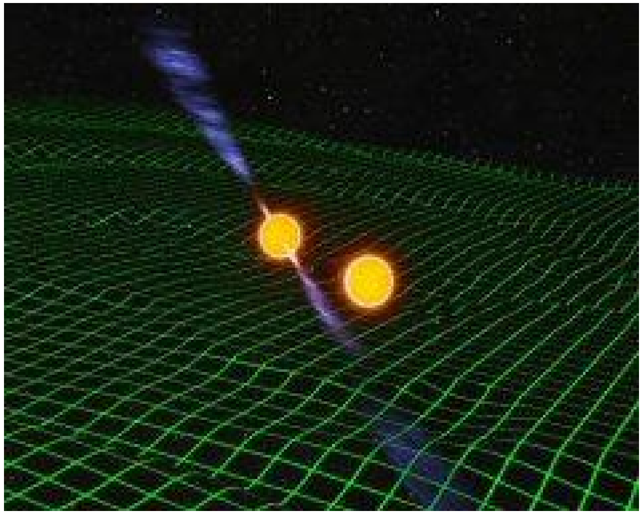


- predicted by GR, 1918
- spacetime oscillations that travel at velocity v = c
- If concentration of mass (energy) moves/changes shape, the warpage propagates (GW)
- Carry energy and momentum, interact weakly with matter
- Their existence has been indirectly proved by Hulse & Taylor (a Nobel Prize 1993) - observation of PSR 1913+16

- Using linearised Einstein equations, one finds that:
  - at first order amplitude $h \sim d^2Q/dt^2$, Q - quadrupole moment
  - the efect of a wave on 2 test particles $dL \sim h\ L$

Observational proof – PSR 1913+16

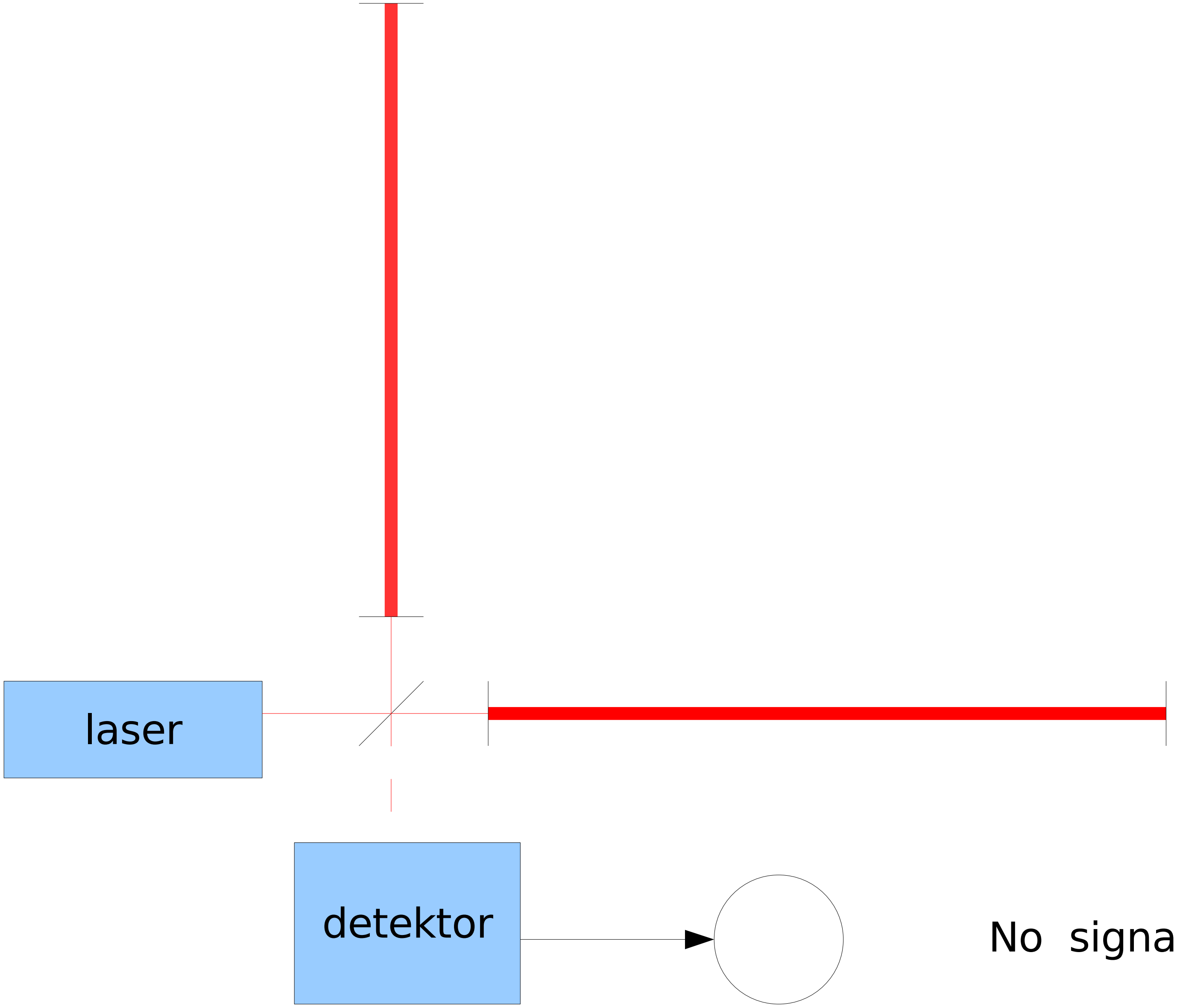




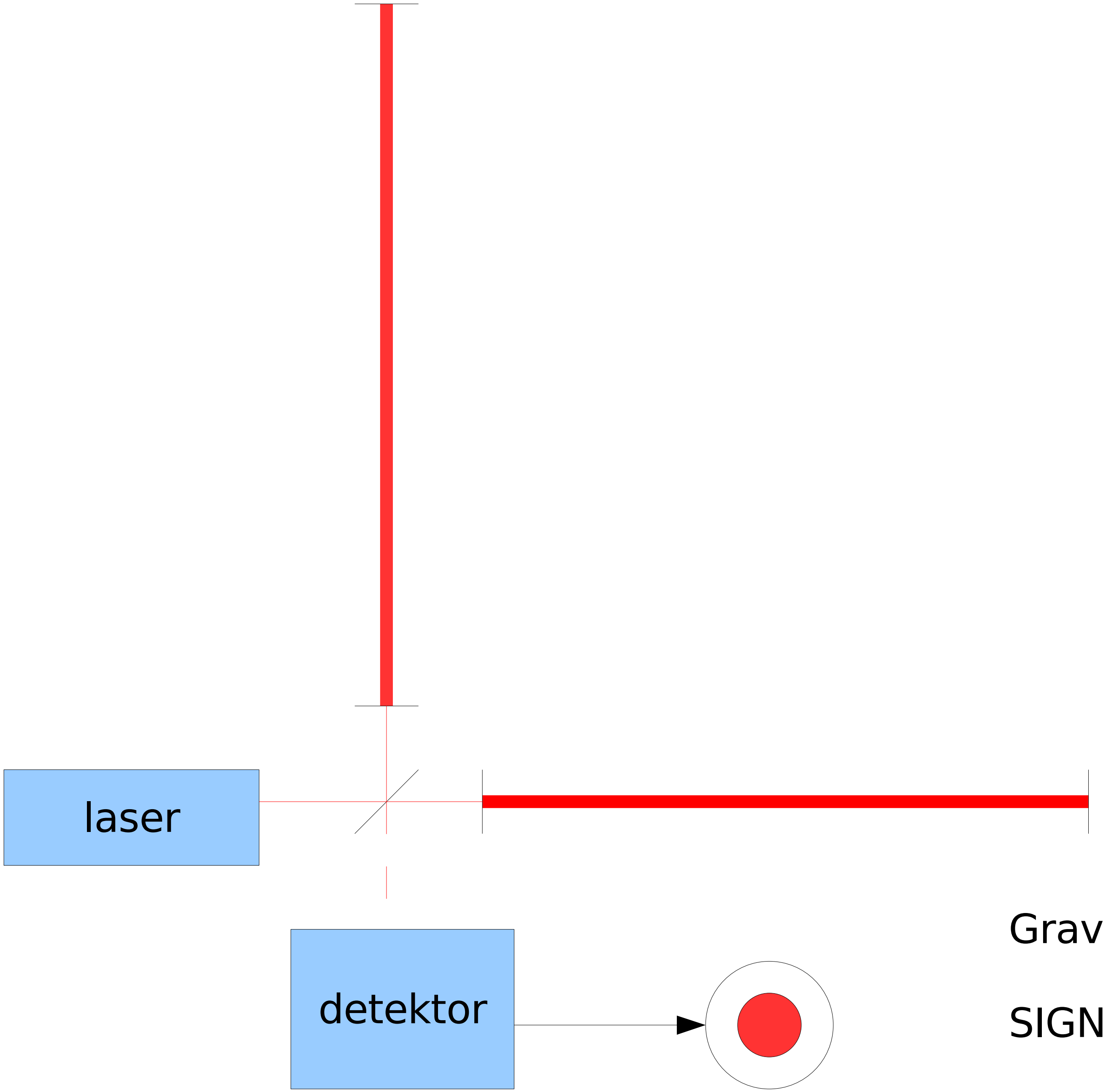
Nobel 1993 - Hulse & Taylor

<-- observed decay of P = 7 h 45 min (75 microsekund/yr) due to gravitational radiation ---> merger in 140 Myr

$\dot{P}$obs/$\dot{P}$teo =1.0025 +/-0.0022



No signal

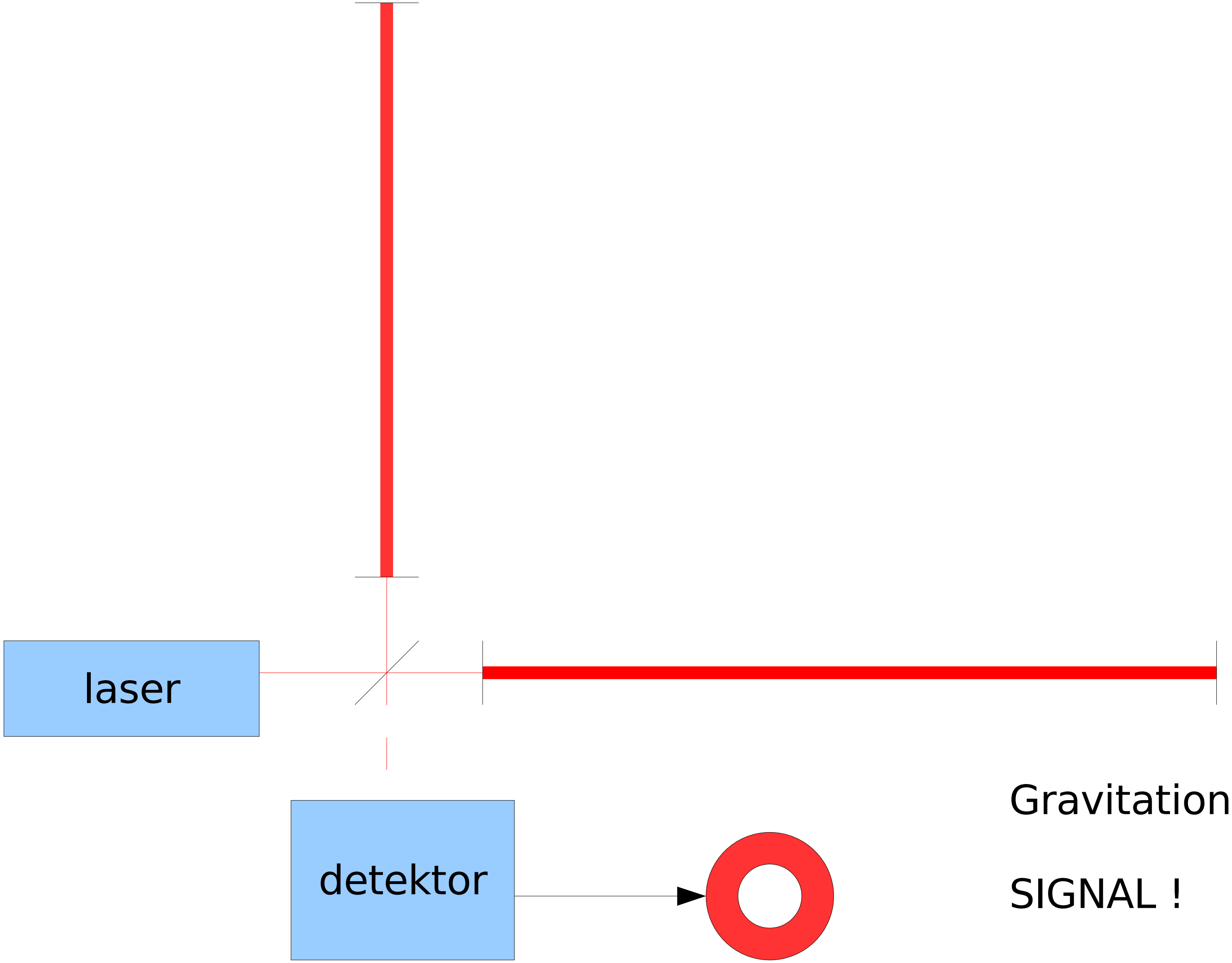


laser

detektor

Gravitational wave

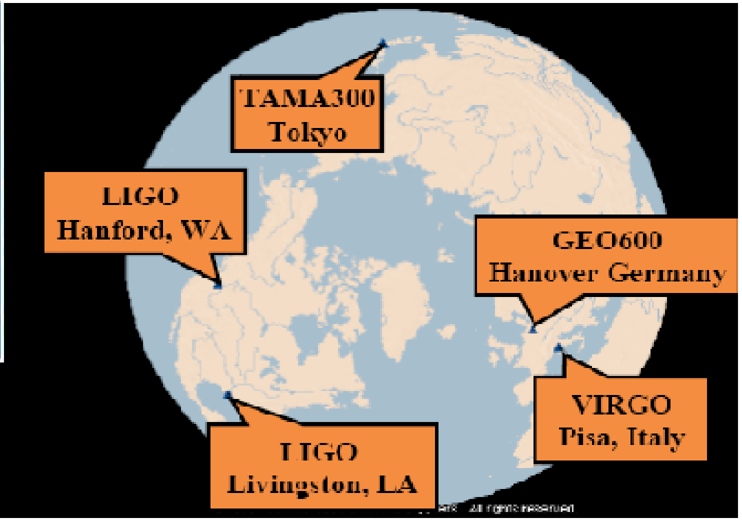
SIGNAL !



Gravitational wave

SIGNAL !

1^{st} detectors: LIGO,VIRGO, GEO600, TAMA
f_{GW} ~10Hz-1kHz



Gravitational wave sources

Requirements: compact M/R, relativistic and highly asymmetric

$-10 < \log f_{GW}$ [Hz] < 6

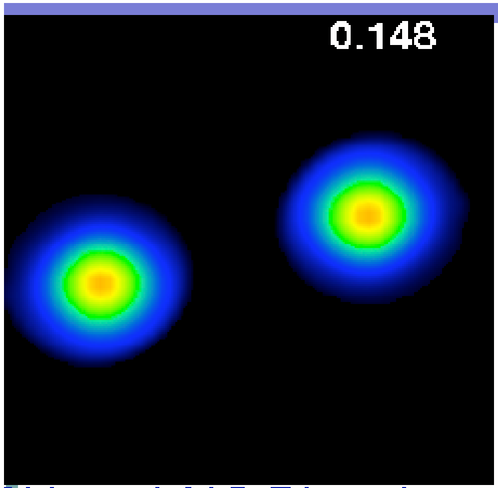
- unknown sources
- known sources:

- rotating and oscillating neutron stars
- **binaries** **S/N~Mchirp/Distance,**

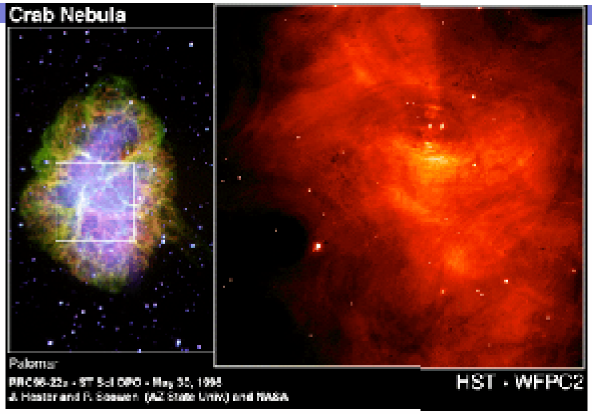
  $f_{GW}=2 f_{orb}$,

  $f_{merger} \sim 2$kHz/M_{tot}
- supernovae
- stochastic background (primordial and originating from cosmic sources

Astrophysical Sources of GW
10 Hz – 1 kHz



BH and NS Binaries

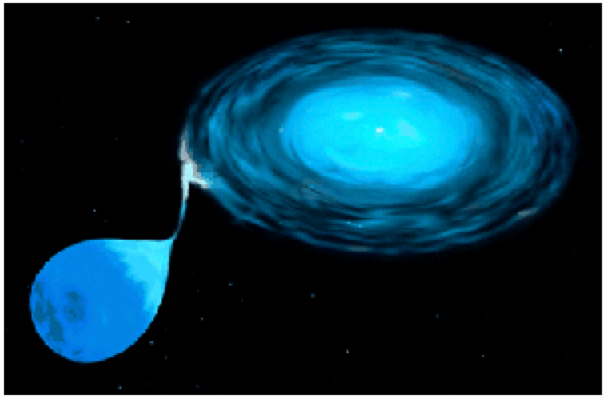


Supernovae, BH/ NS formation

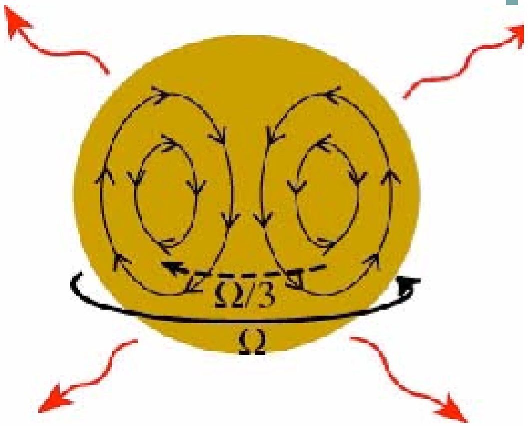
$$L_{GW} \sim \left(\frac{M}{R}\right)^5$$

$$h \sim \varepsilon \cdot \left(\frac{M}{r}\right) \cdot \left(\frac{M}{R}\right)$$

Black Holes : $M/R = 0.5$
Neutron Stars : $M/R \sim 0.2$
White Dwarfs : $M/R \sim 10^{-4}$

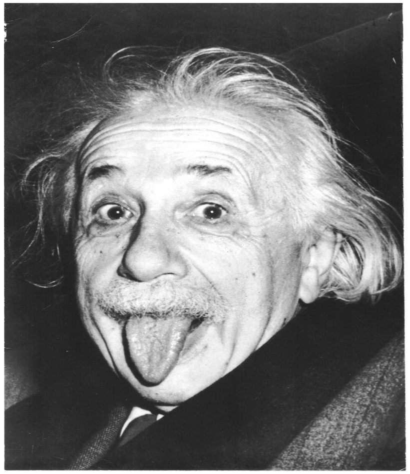


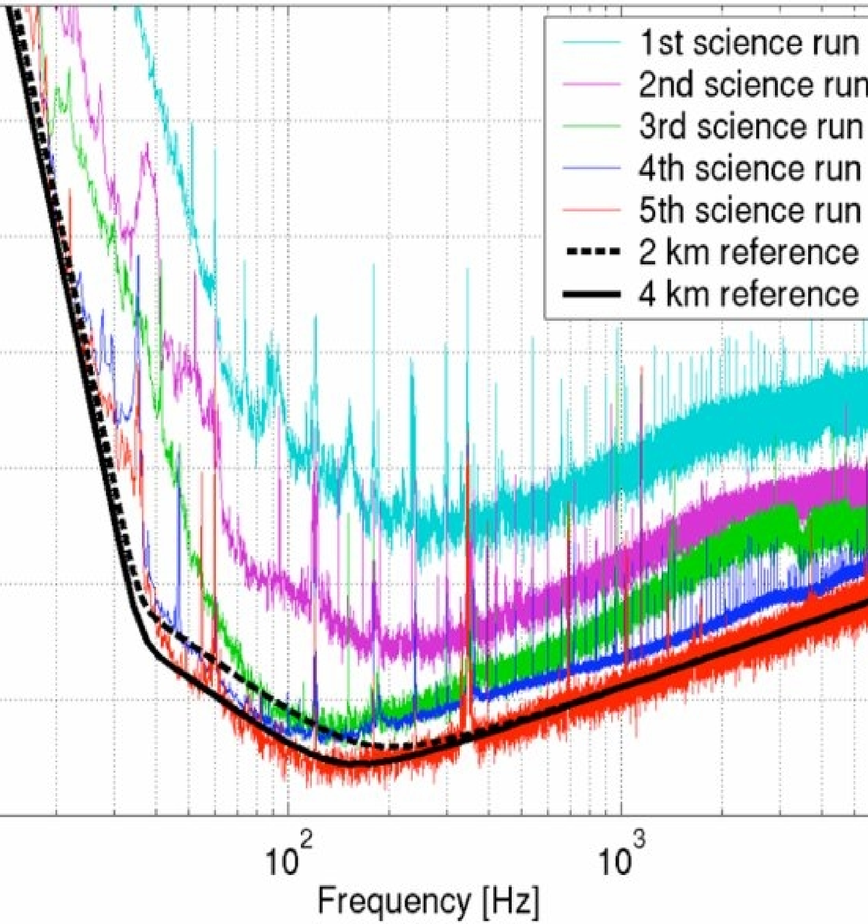
Spinning neutron stars in X-ray binaries



Young Neutron Stars

1^{st} generation – summary



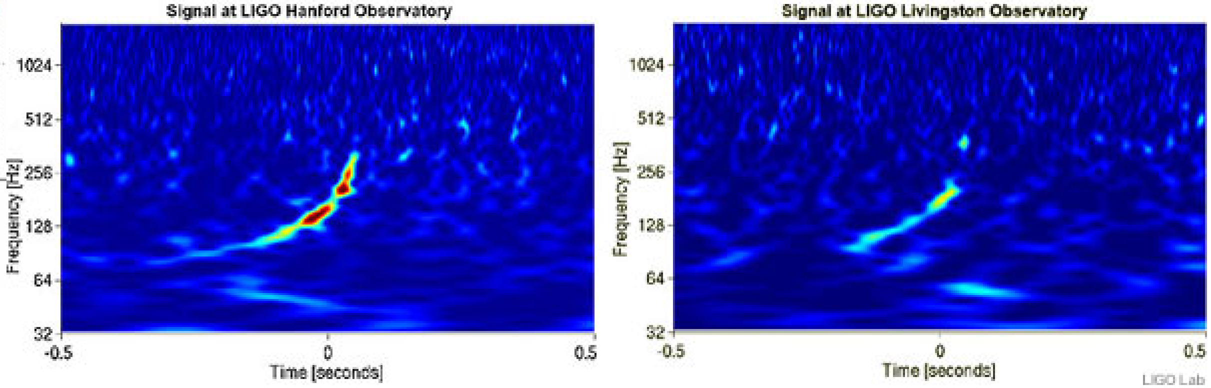


- no detection :(
- obtained required S/N :)
- common scientific runs :)

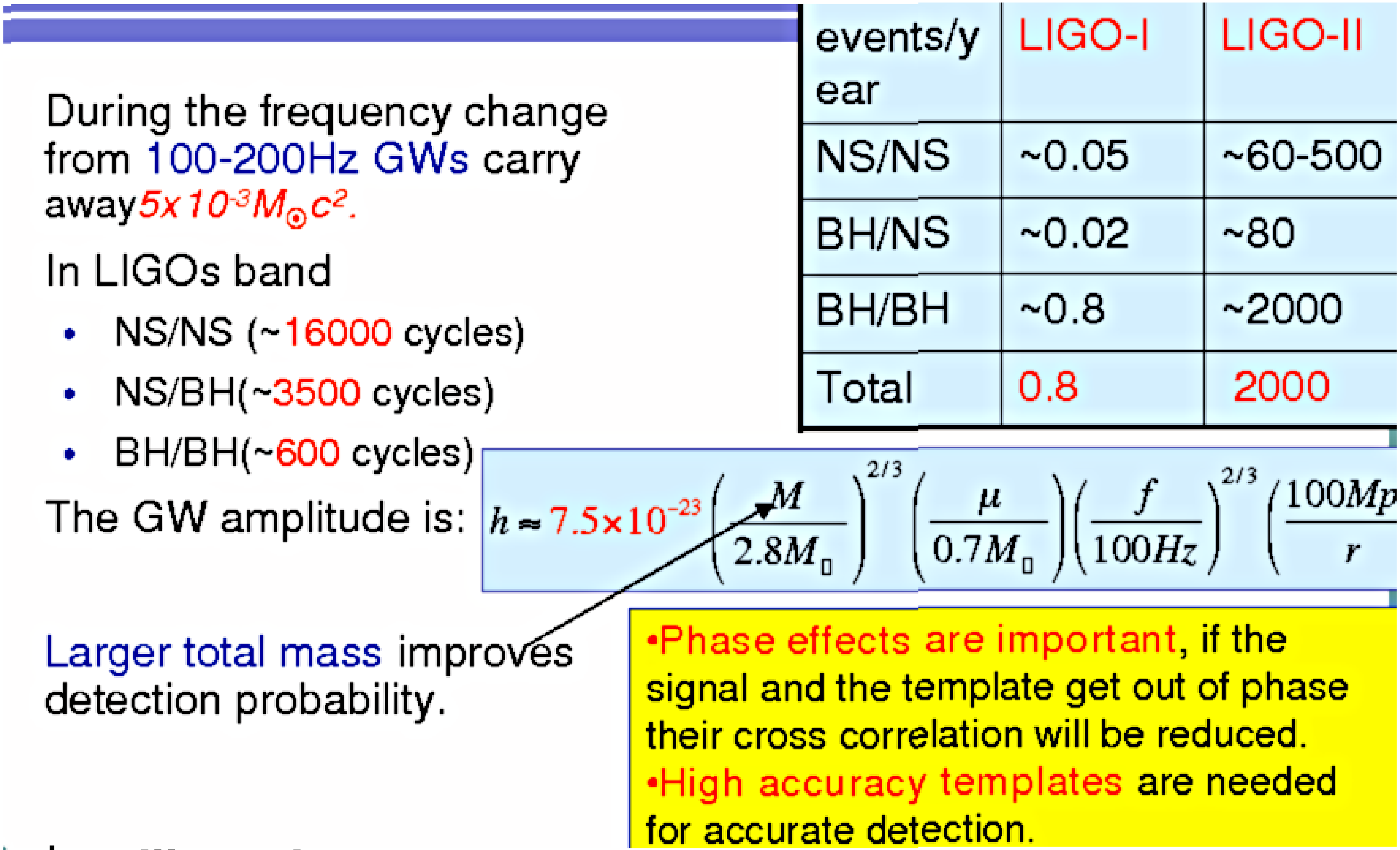
S5-VSR1 (4 months, 2007),

S6-VSR2/ VSR3 (6/2months, 2009/2010:)

- blind injection test – Big Dog event, NS-BH :)



Coalescing compact binaries



During the frequency change from 100-200Hz GWs carry away $5x10^{-3}M_\odot c^2$.

In LIGOs band

- NS/NS (~16000 cycles)
- NS/BH(~3500 cycles)
- BH/BH(~600 cycles)

The GW amplitude is:

$$h \approx 7.5\times10^{-23}\left(\frac{M}{2.8M_\odot}\right)^{2/3}\left(\frac{\mu}{0.7M_\odot}\right)\left(\frac{f}{100Hz}\right)^{2/3}\left(\frac{100Mp}{r}\right.$$

Larger total mass improves detection probability.

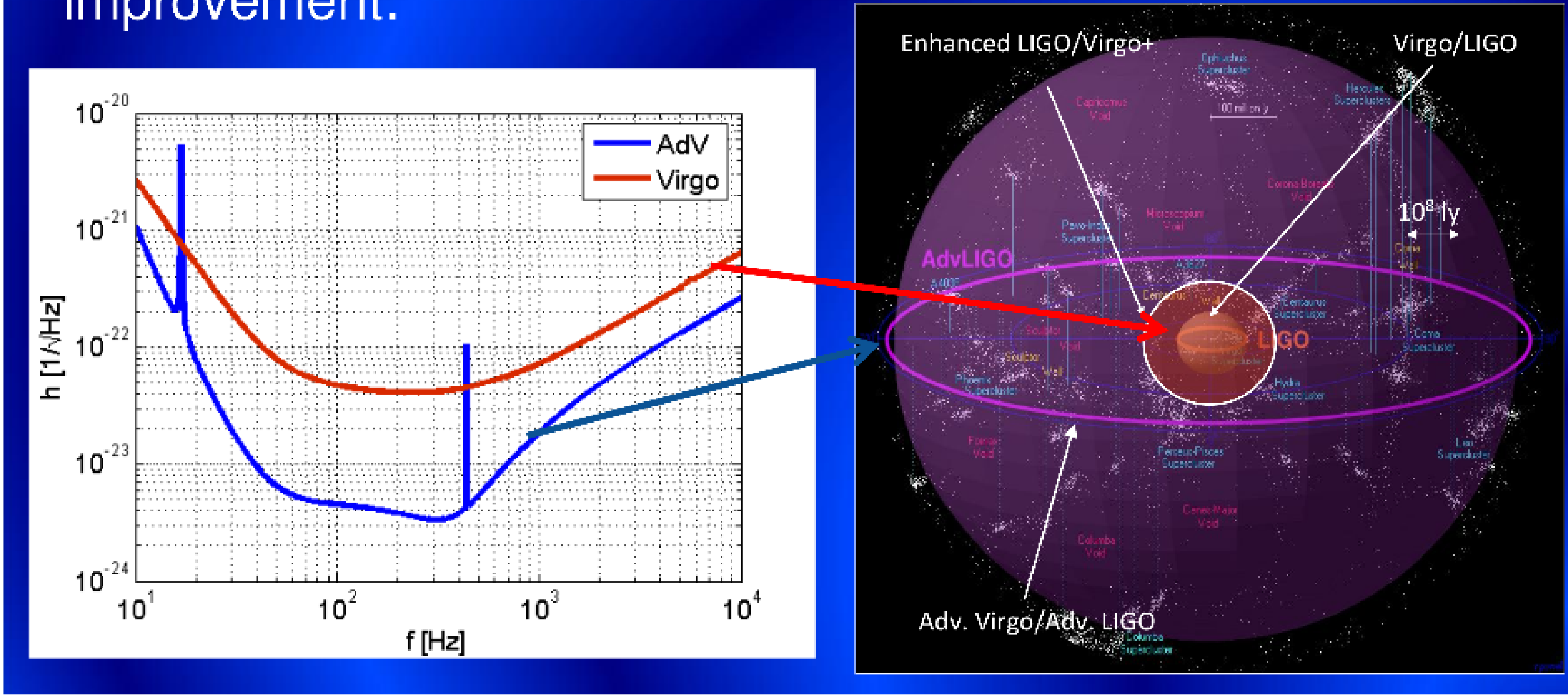
events/year	LIGO-I	LIGO-II
NS/NS	~0.05	~60-500
BH/NS	~0.02	~80
BH/BH	~0.8	~2000
Total	0.8	2000

•Phase effects are important, if the signal and the template get out of phase their cross correlation will be reduced.
•High accuracy templates are needed for accurate detection.

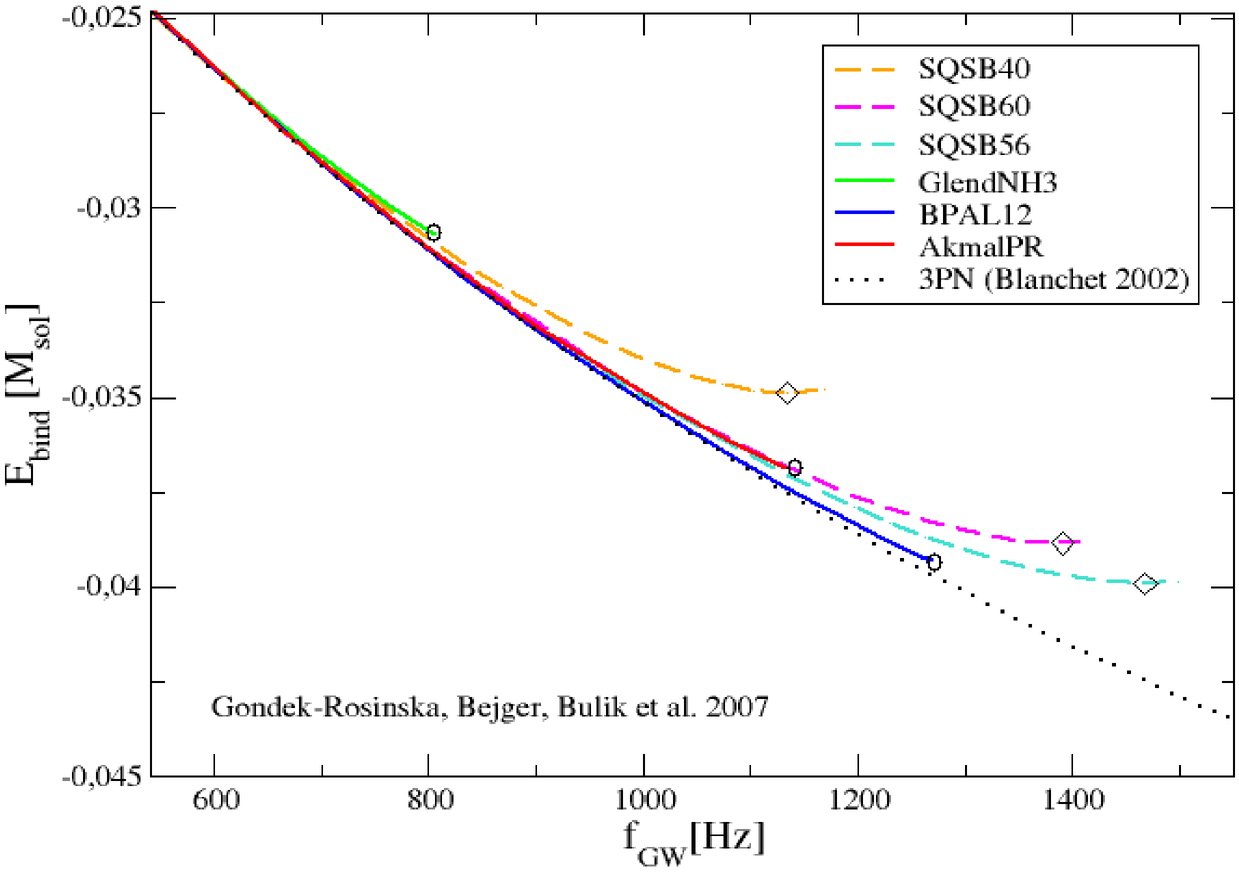
but **Bulik et al. 2011, IC10 X-1/NGC300 X-1: THE VERY IMMEDIATE PROGENITORS OF BH-BH BINARIES (BH-WR) will form BH-BH system with Mtot~40 Msol in < 0.3 Myr, d< 2 Mpc => 1-3 events/yr for Initial VIRGO/LIGO**

2^{nd} generation: Adv Virgo/LIGO

- The upgrade to the advanced phase (2^{nd} generation) is just started (LIGO) or will start within this year (Virgo). The detectors should be back in commissioning in 2014
- Advanced are promising roughly a factor 10 in sensitivity improvement:



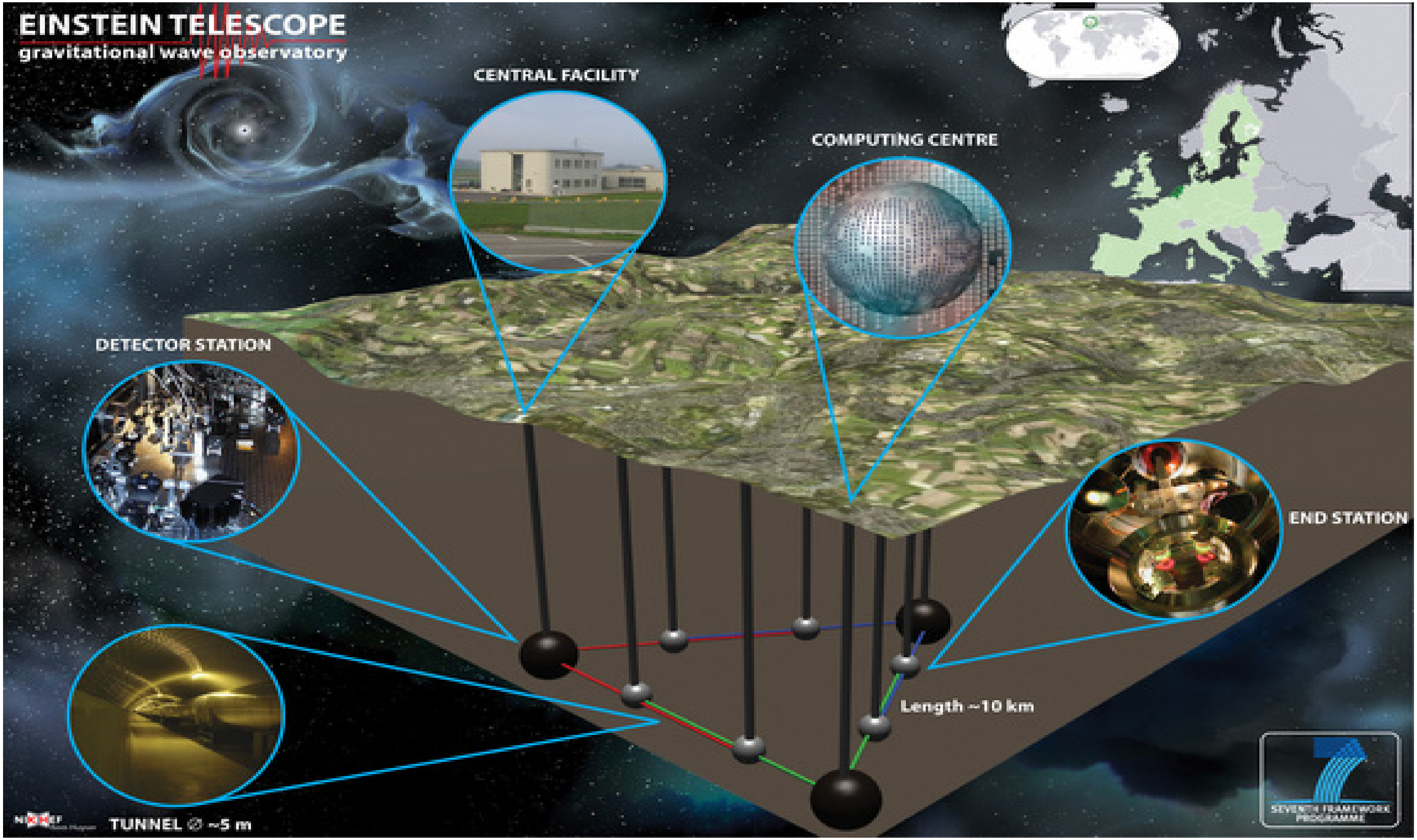
The last orbits of binary neutron stars with M1=M2=1.35 Msol



Goals of GW detectors

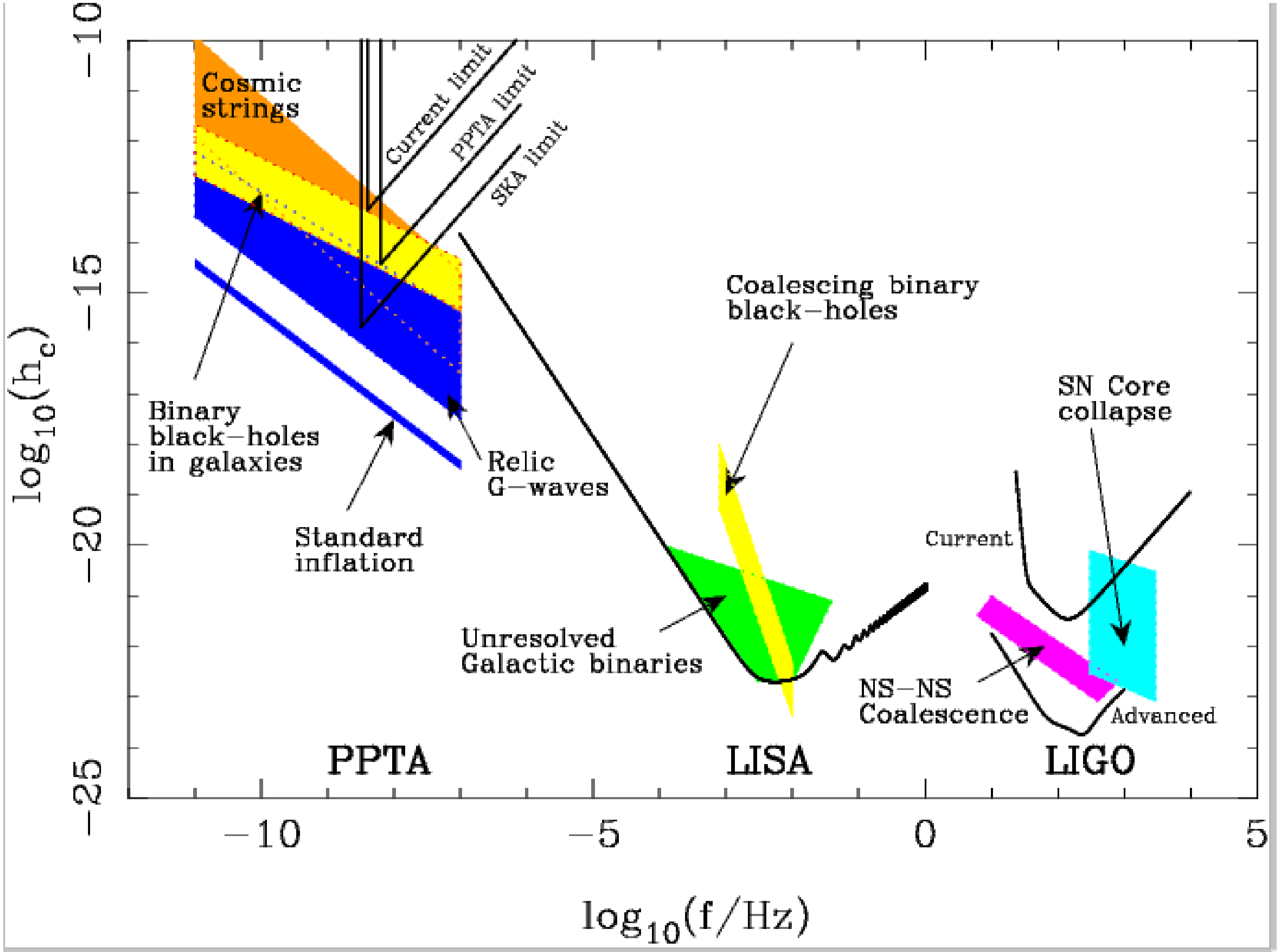
- open a new Window on the Universe
- test GR and GR instabilities
- Solving the enigma of GRBs and resolving their different classes
- Measuring the cosmological parameters with GW standard sirens.
- Understanding the mass-spectrum of compact stars and their populations – constraints on evolution
- Measuring masses, spins,..of compact objects in binaries (constraints on NS EOS)
- ....

3rd: Einstein Telescope (1 Hz-10kHz)



GW Astronomy

ELF log f = -16 to -10, VLF log f= -10 to -6, LF log f = -6 to 0, HF log f = 0 to 6



Gravitational wave astronomy

No detection yet, but lower limits on distances to GRBs, upper limits on GW from PSRs, on event rates (Abadie, J. Abbot,et al.2009, 2010)

Detector development:

2015: 2nd :Adv LIGO/VIRGO ~10 times more sensitive (10^3 times more events/yr), NS-NS (450 Mpc), NS-BH (1Gpc),BH-BH (2Gpc),

10Hz-10kHz

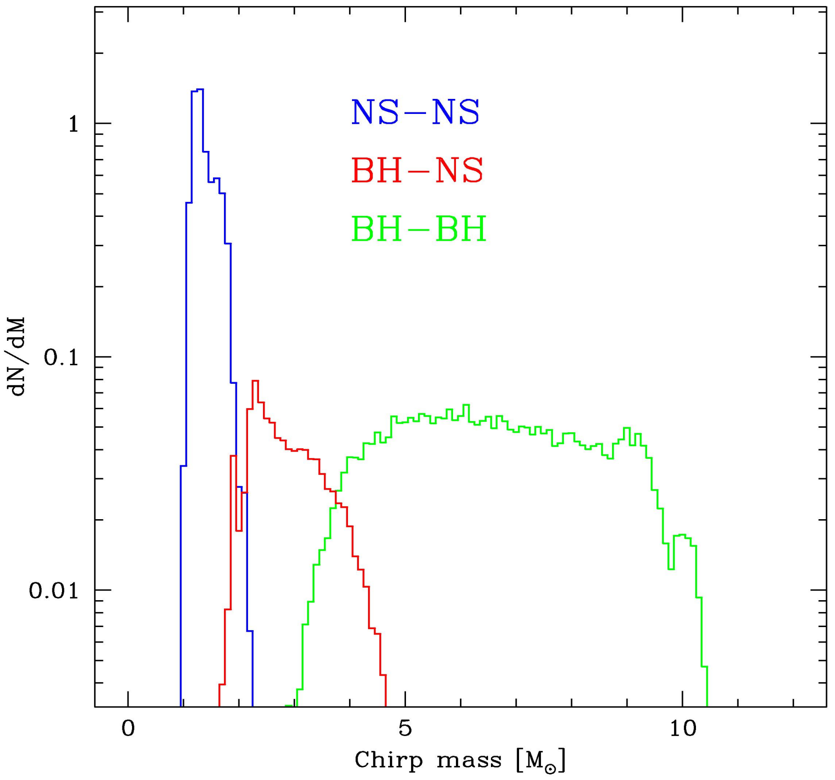
2025 ?: 3rd : ET ~ 100 (10^6 events/yr), 1 Hz-10 kHz

2030 ?: space detectors: LISA/NGO (0.003-0.01 Hz), DECIGO (0.1-1Hz)

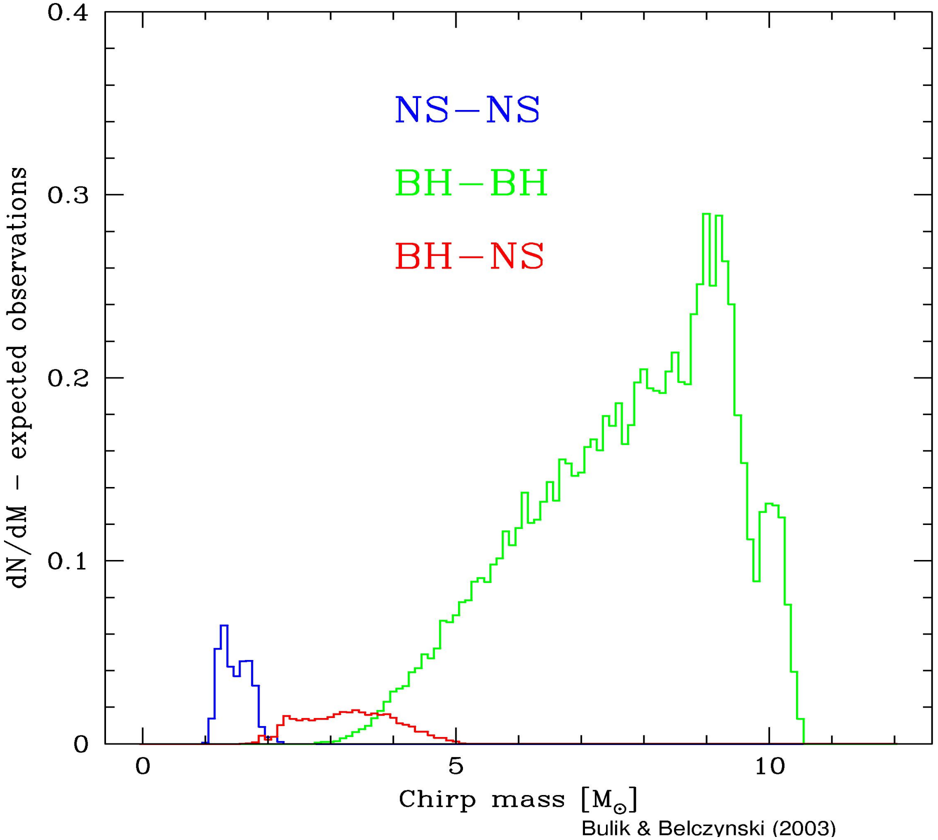
First detection is near!

You can help - Einstein@home

First detection- BBH

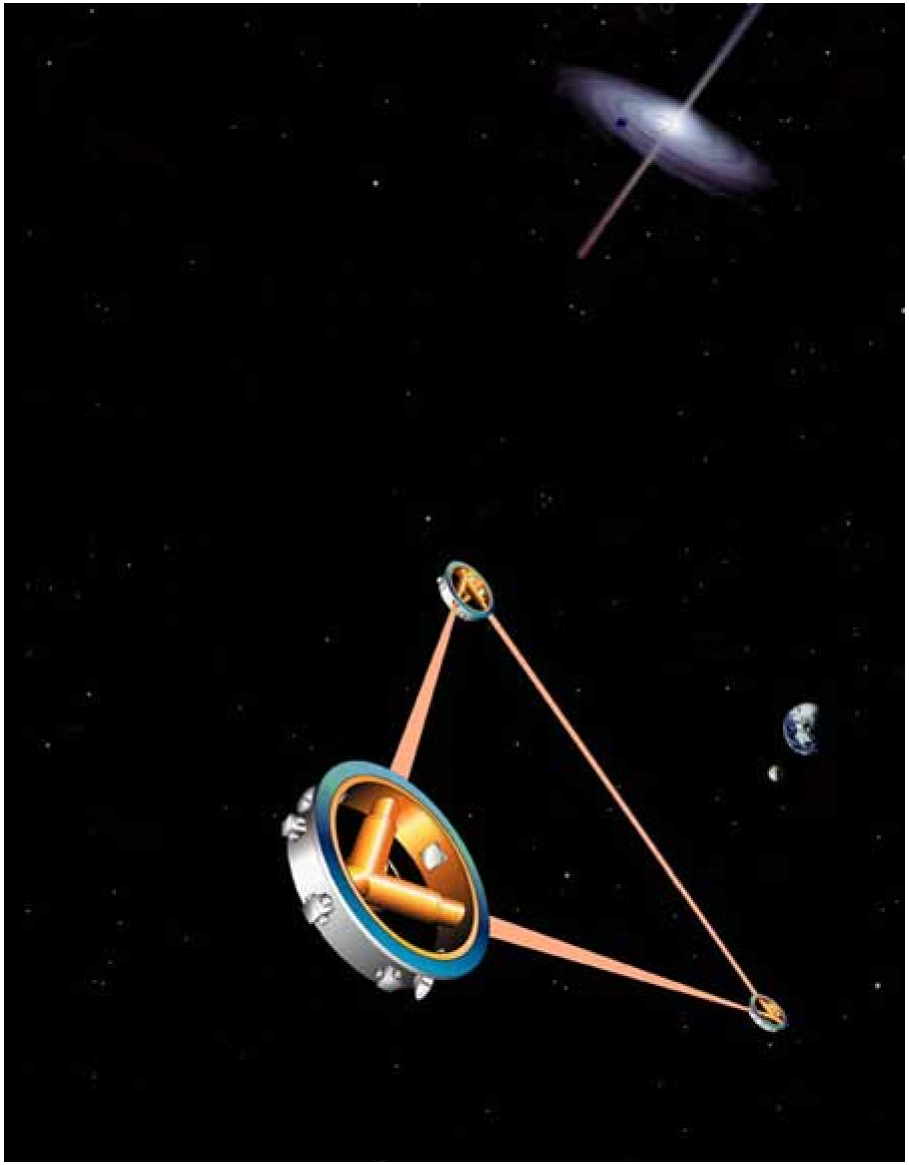


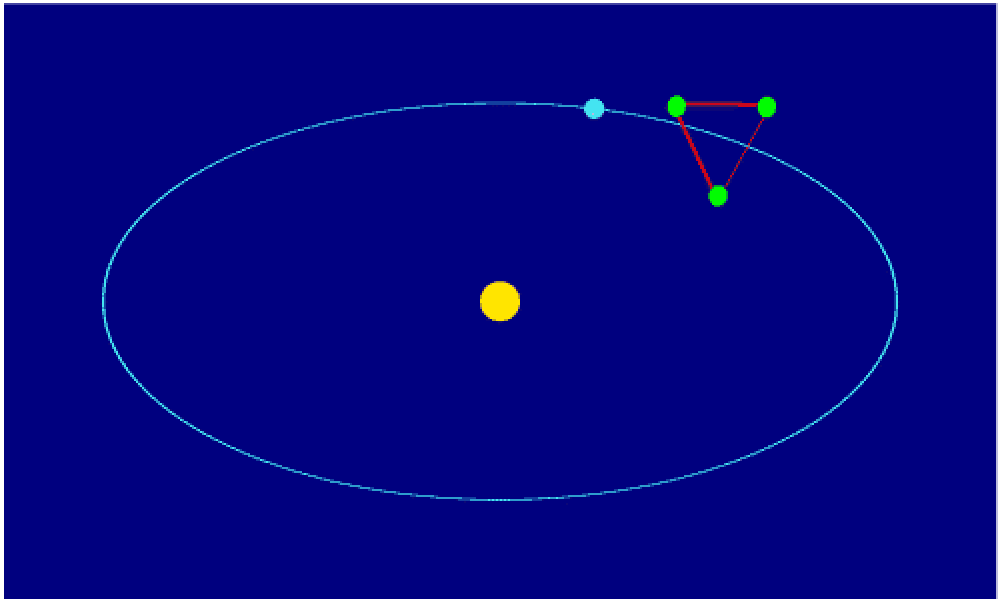
Belczynski et al 2010



Bulik & Belczynski (2003)

LISA – cosmic mission

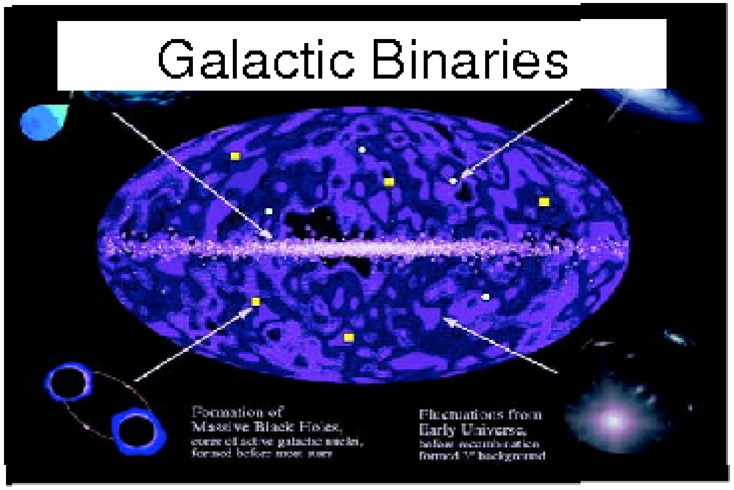


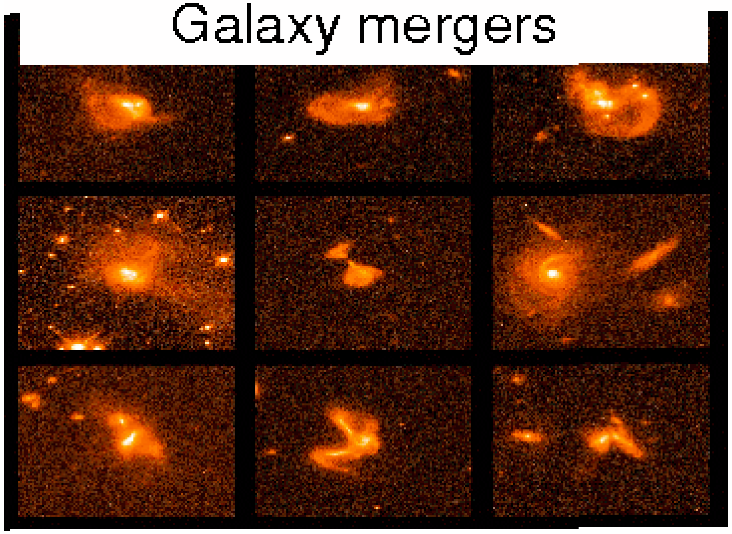


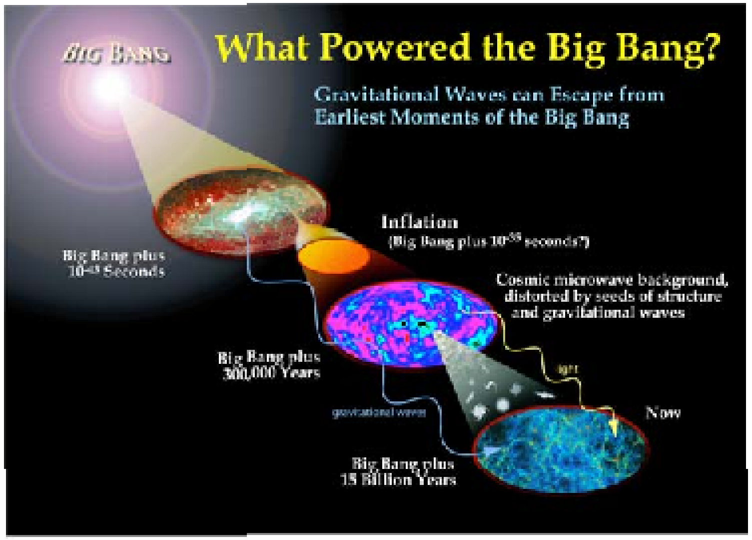
3 detectors - 5 mln km

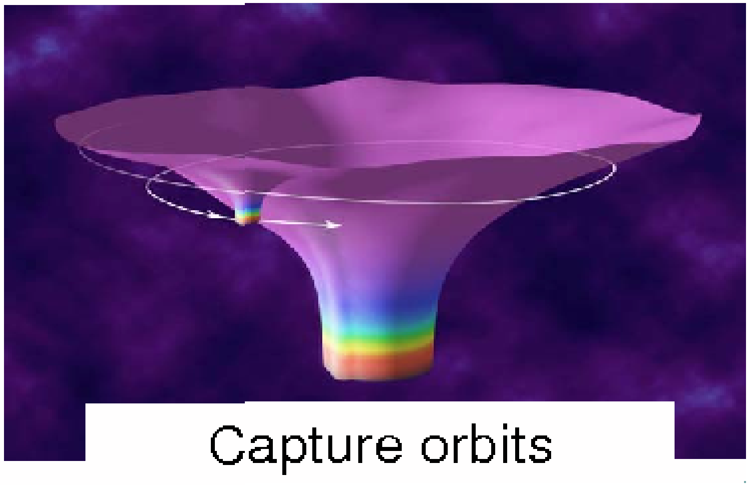
f_{GW}~ 0.001 - 0. 01 Hz

Astrophysical sources for LISA


Galactic Binaries


Galaxy mergers




Capture orbits

Pulsar timing

PTA, EPTA, NanoGrav

Sensitivity: wave amplitude – 10^{-13}, 10^{-14}

Frequency range: below 10^{-7} Hz

Directional sensitivity – important to monitor many pulsars

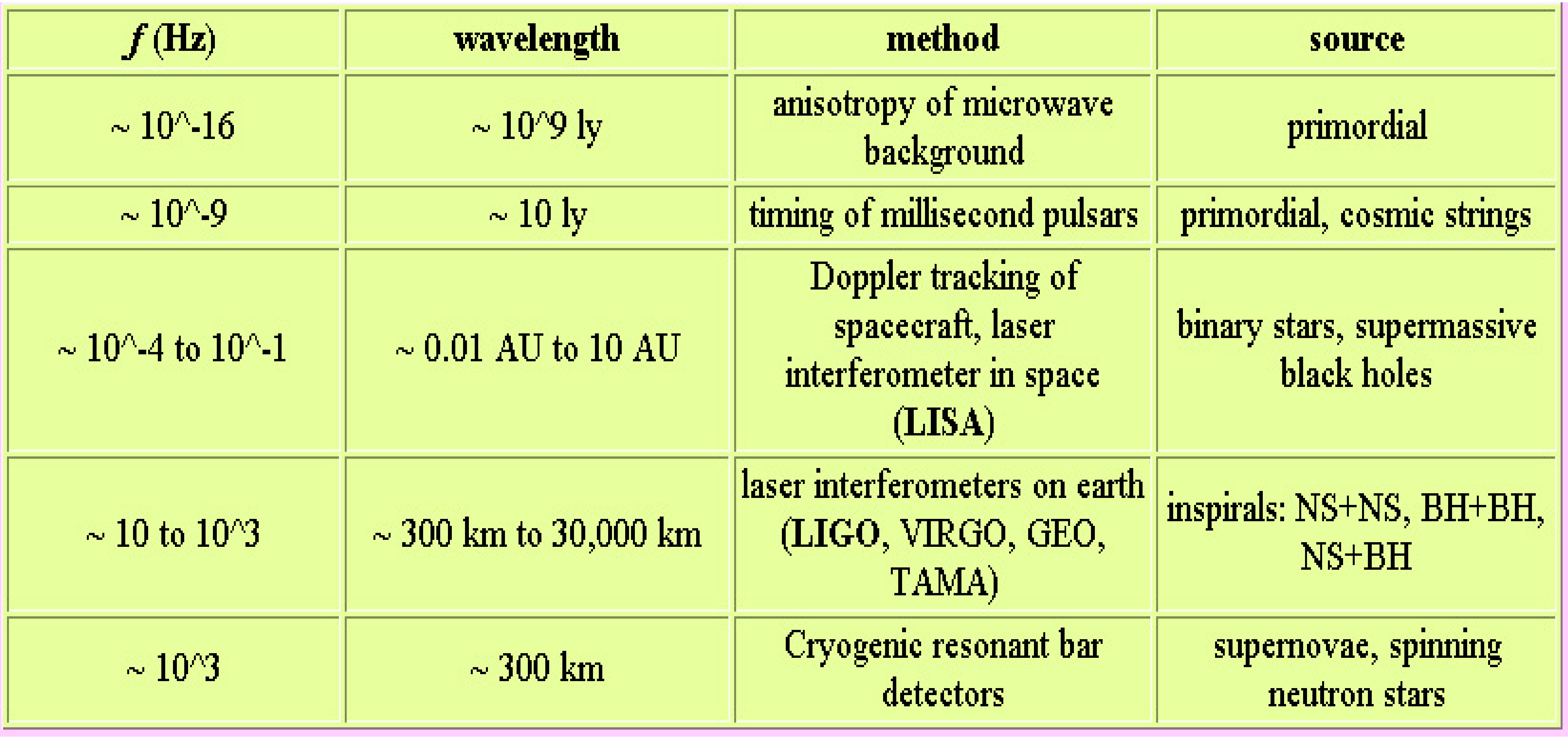
Timescale for detection

vs. frequency range

Animacja

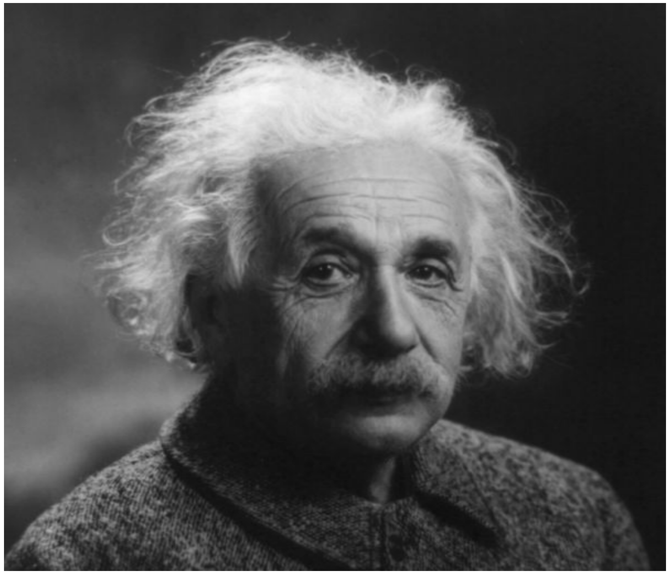
Astrophysical sources of GW

ELF log f = -16 to -10, VLF log f= -10 to -6, LF log f = -6 to 0, HF log f = 0 to 6



f (Hz)	wavelength	method	source
~ 10^-16	~ 10^9 ly	anisotropy of microwave background	primordial
~ 10^-9	~ 10 ly	timing of millisecond pulsars	primordial, cosmic strings
~ 10^-4 to 10^-1	~ 0.01 AU to 10 AU	Doppler tracking of spacecraft, laser interferometer in space **(LISA)**	binary stars, supermassive black holes
~ 10 to 10^3	~ 300 km to 30,000 km	laser interferometers on earth **(LIGO**, VIRGO, GEO, TAMA)	inspirals: NS+NS, BH+BH, NS+BH
~ 10^3	~ 300 km	Cryogenic resonant bar detectors	supernovae, spinning neutron stars

Gravitational Waves



- predicted by GR, 1918
- spacetime oscilations
- new sort of radiation
  --> new discoveries
- we can see objects that cannot be seen in any other way
- a new test of GR

POLGRAW

- 2008 – Polgraw a member of VIRGO/LIGO
- 10 members (VIRGO~150, LIGO~500) from UW, IMPAN, UZ, CAMK, IPJ, UWB,UMK
- data analysis: coalescing binaries, continious waves, bursts

LSC-VIRGO Conference, Crakow, September 2010

Projects in UZ on astrophysical sources of gravitational waves

- Expected event rates for BH-BH, NS-BH, NS-NS, expected masses, eccentricities..
- Last orbits of inspiral for NS-NS in GR, realistic EOS
- Rotational instabilities of NS, differentially and rigidly rotating NS
- Properties of LMXBs

Detection rate

Future evolution: stable mass transfer
Formation of BBH

$$R = 0.63\left(\frac{4\pi}{\Omega_s}\right)\left(\frac{M_{chirp}}{18M_\odot}\right)^{5/2}\left(\frac{r_{BNS}}{18\mathrm{Mpc}}\right)^3\left(\frac{2\mathrm{Mpc}}{r_s}\right)^3\left(\frac{10^6\,\mathrm{yr}}{t_{obs}}\right)\mathrm{yr}^{-1}$$

May already be detected in current LIGO/VIRGO data!

Estimate of the amplitude

Source: mass M, size L, variability P

Quadrupole moment ML^2

$$h = (G/c^4)(ML^2/P^2)/r$$

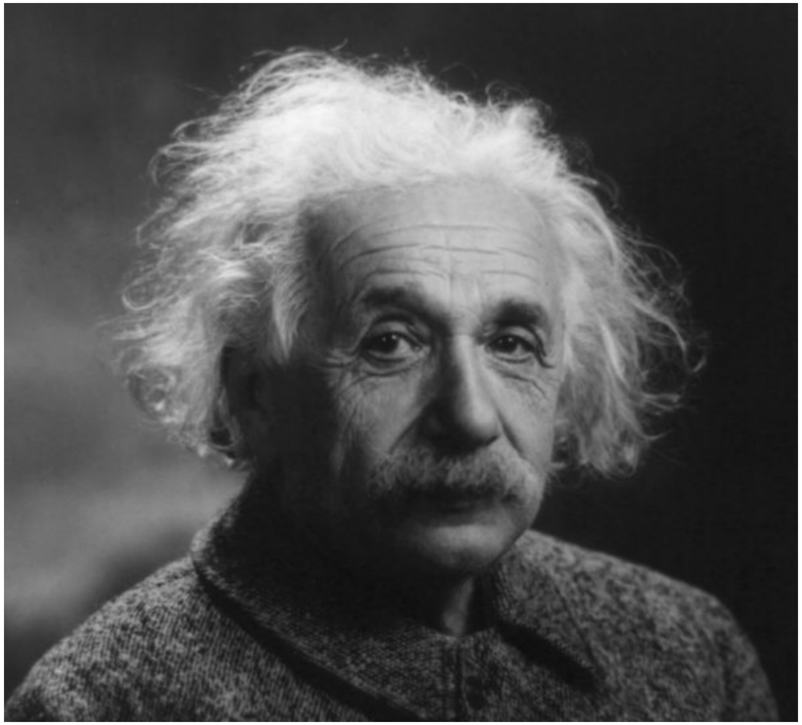
h ~ second derivative of quadrupole moment

Higher moments – factors (v/c)

Maximally:

$$h \approx \frac{r_g}{r}\left(\frac{v}{c}\right)^2$$

Gravitational Waves

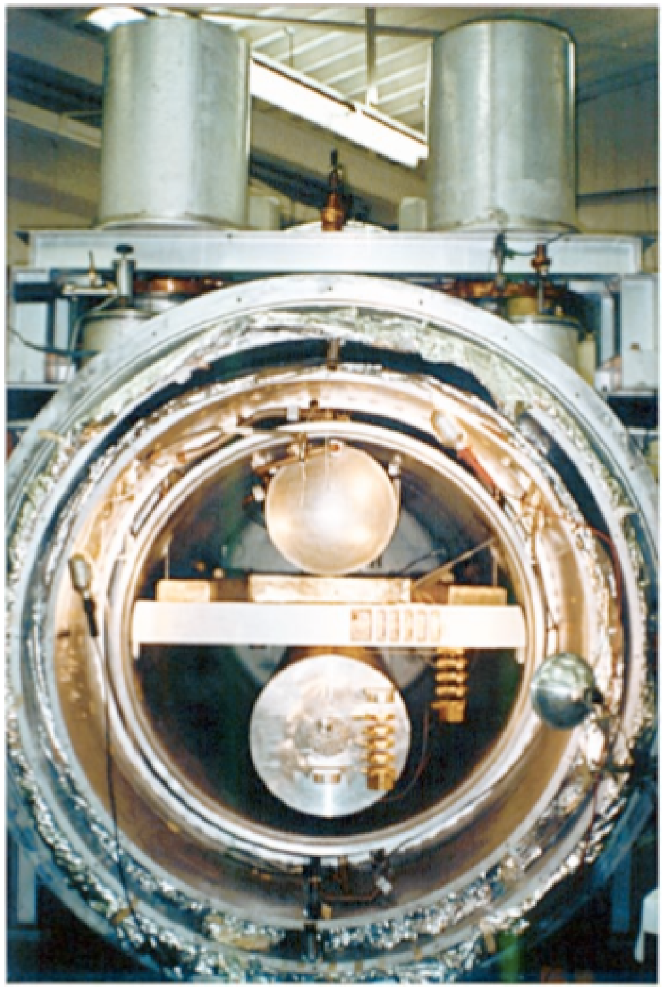


What are they?

How can they be detected?

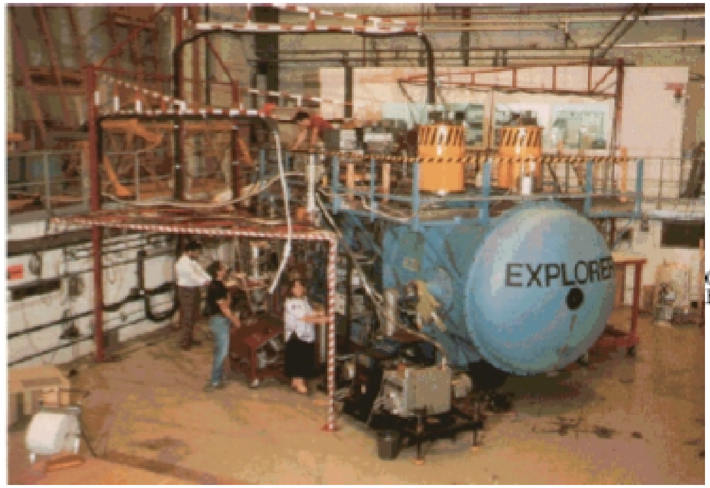
What are the sources?

Resonance detectors

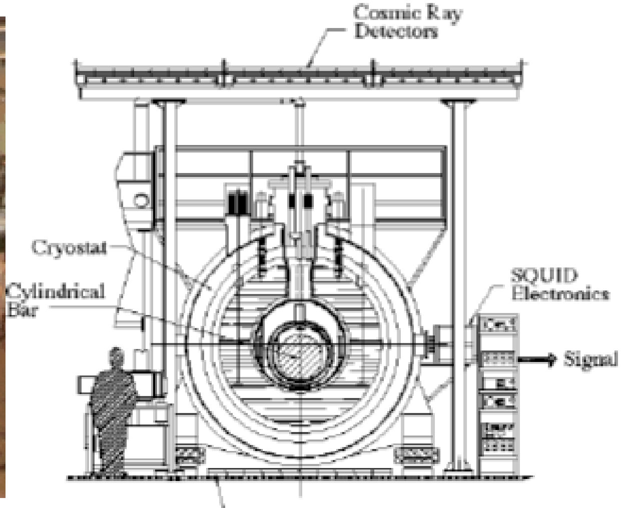

Louisiana State U. - Allegro


U. West Australia - Niobe


U. Padova - Auriga



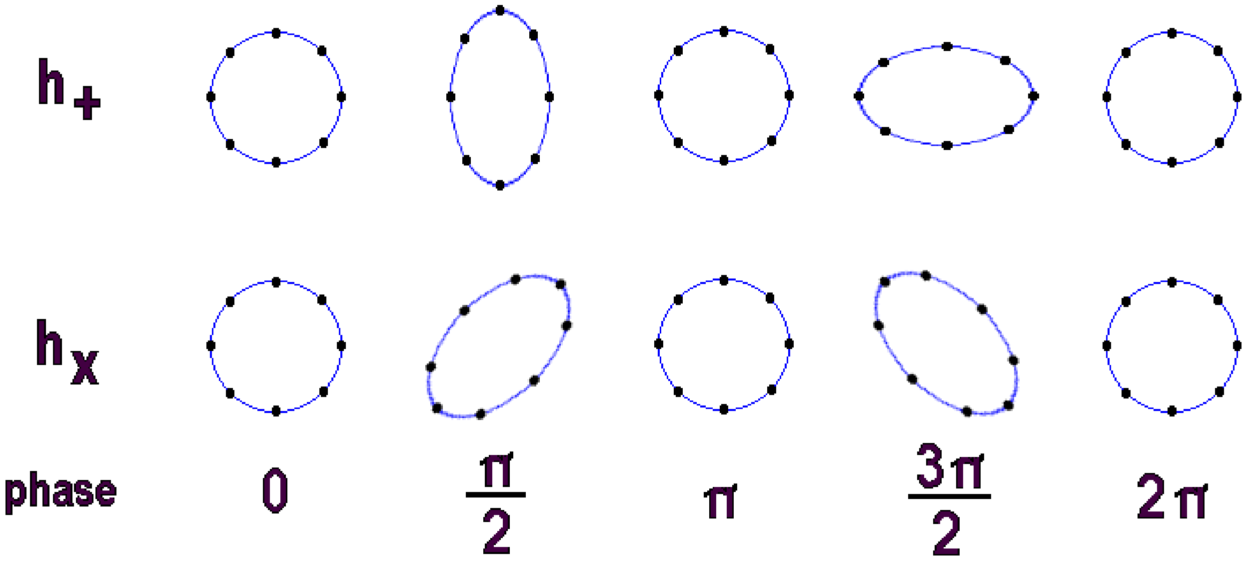
CERN - Explorer



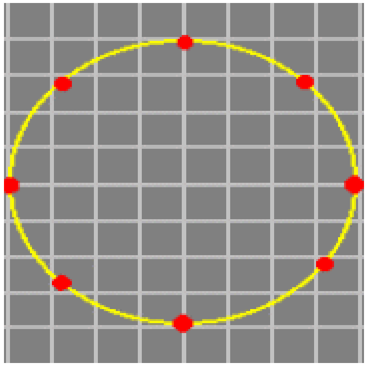
U. Rome - Nautilus

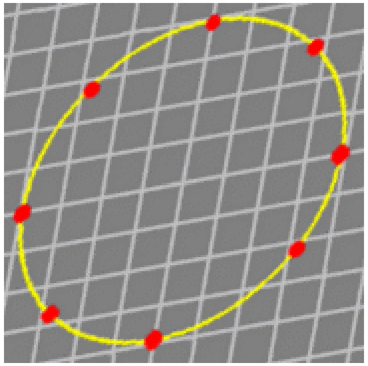
Gravitational wave polarisations

Gravitational waves are transverse
Two polarisations: EM 90 deg; GW 45 deg

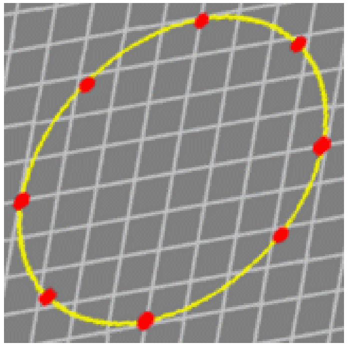


linear





Curcular



Physical background

Spacetime oscillations

Gravitational waves are transverse

Two polarisations: EM 90 deg; GW 45 deg

Rotating Neutron Stars

GW if NS non-axisymmetric

f_{GW} frequency depeds on a mechanism:

r-modes ~ 4/3*f_{rot}

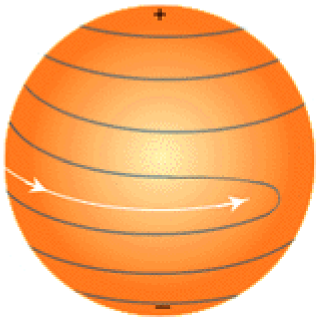
spin precession~ f_{rot}

bar shape ~2 f_{rot}

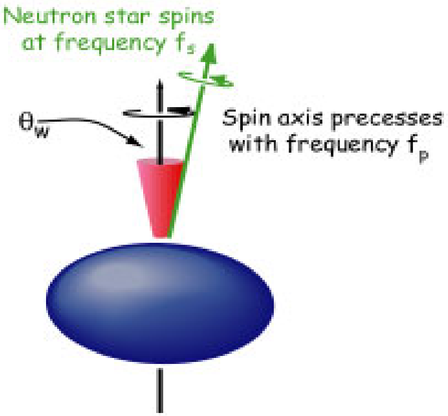
~10^9 NS in the Galaxy

~10^3 identyfied

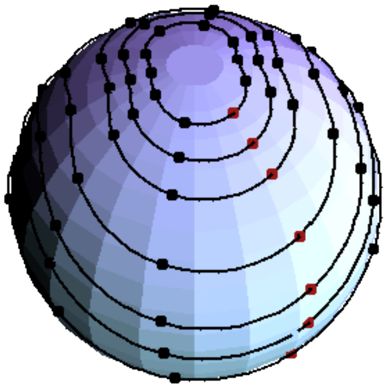
Upper limits: spin down luminosity



Magnetic mountains



Wobbling Neutron Star



R-modes in accreting stars

Supernovae

Asymmetry

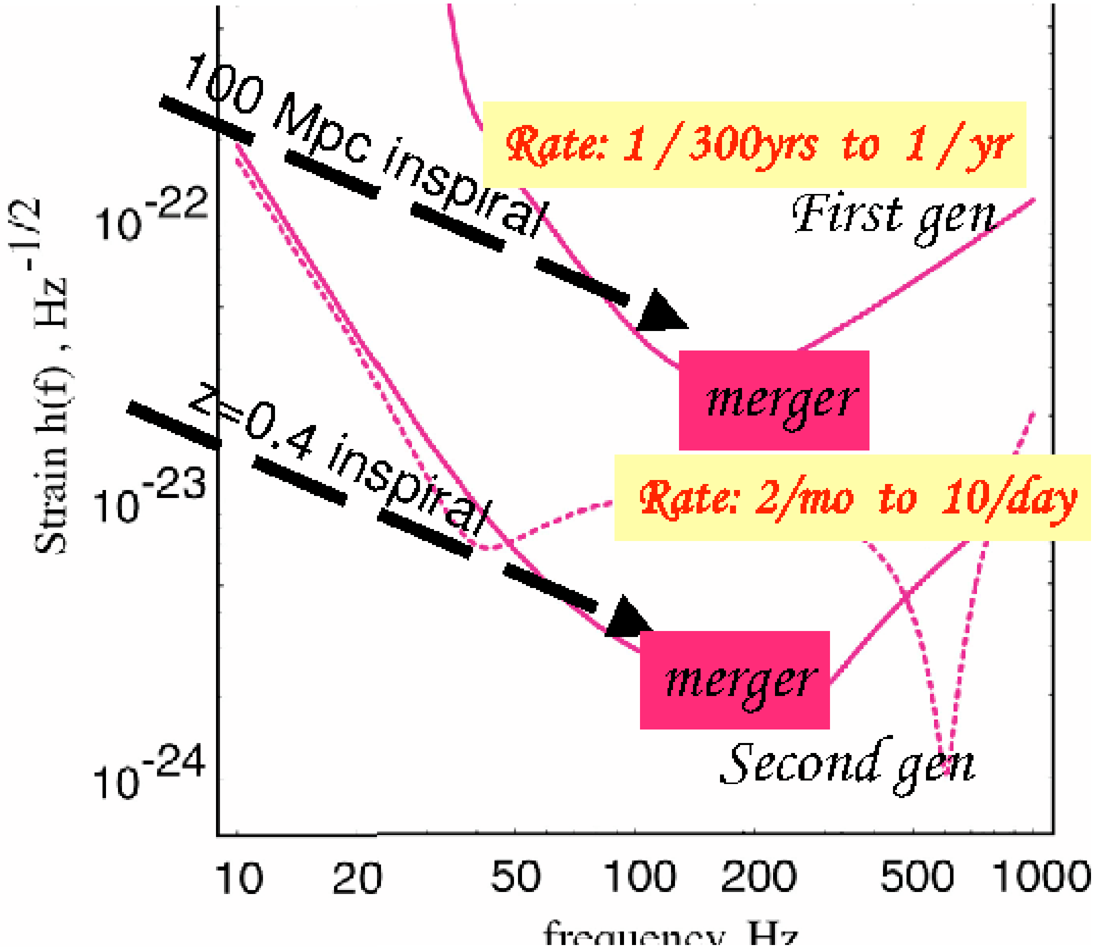
Graviational wave amplitude

Detectability

Galactic rate

Coalescing BBH

- $10M_\odot + 10\ M_\odot$ BH/BH binary
- Event rates based on population synthesis,
- mostly globular cluster binaries.
- Totally quiet!!



Coalescing BH-NS

NS-BH Event rates

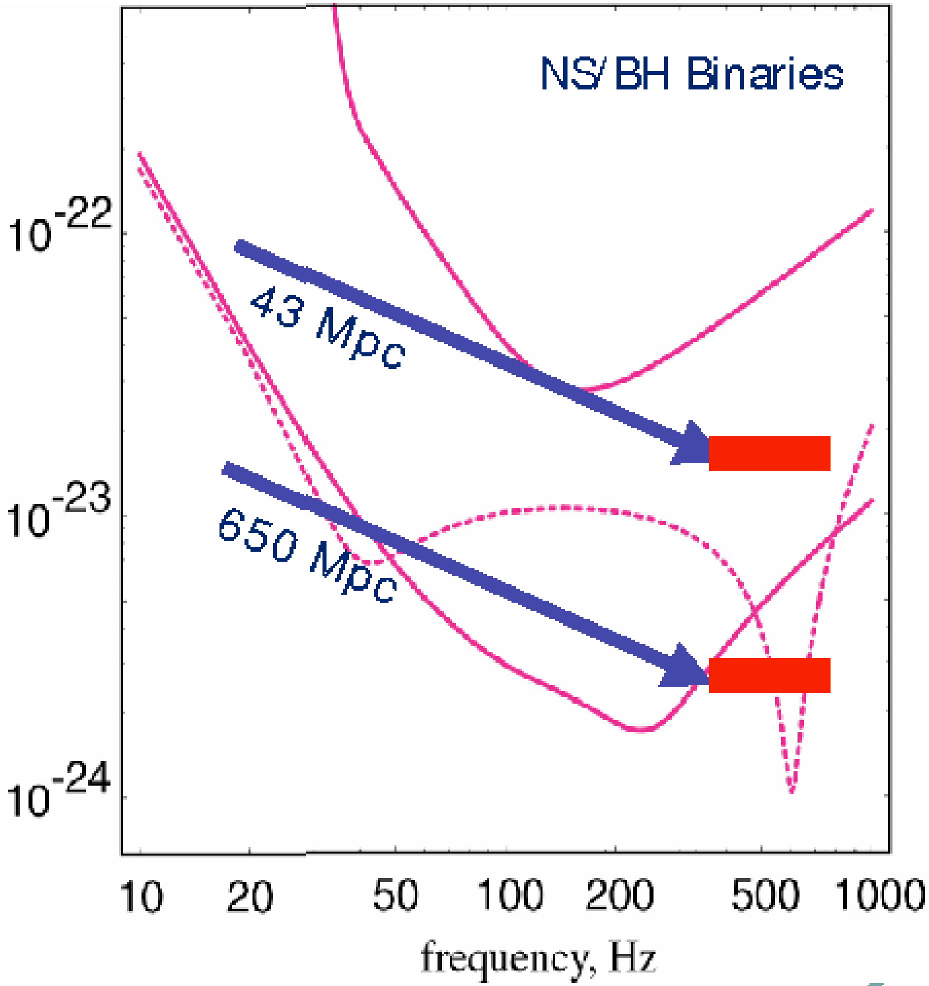
Based on *Population Synthesis*

Initial interferometers

- Range: 43 Mpc
- 1/1000 yrs to 1per yr

Advanced interferometers

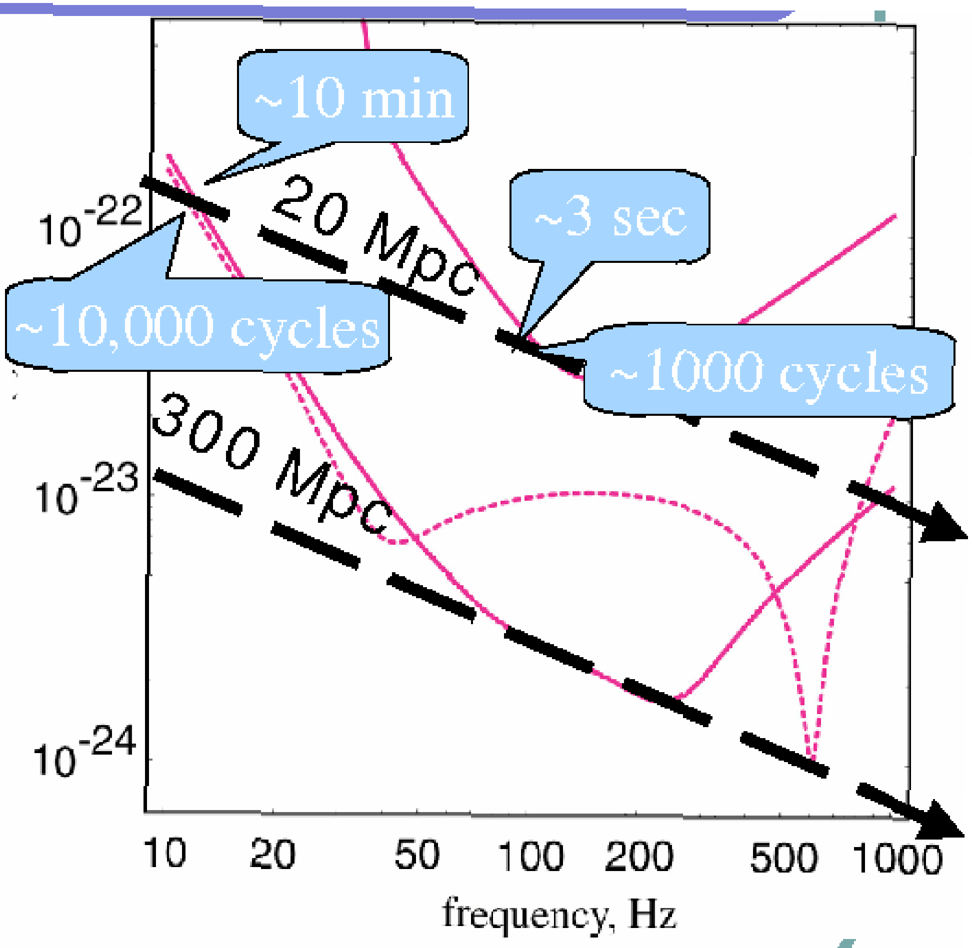
- Range: 650 Mpc
- 2 per yr to several per day



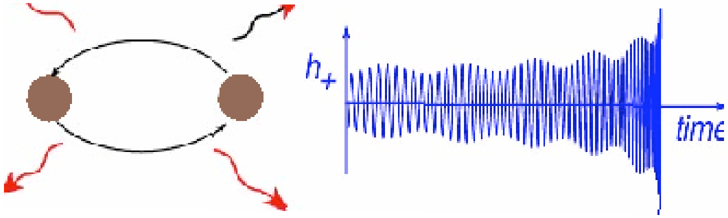
Coalescing BNS

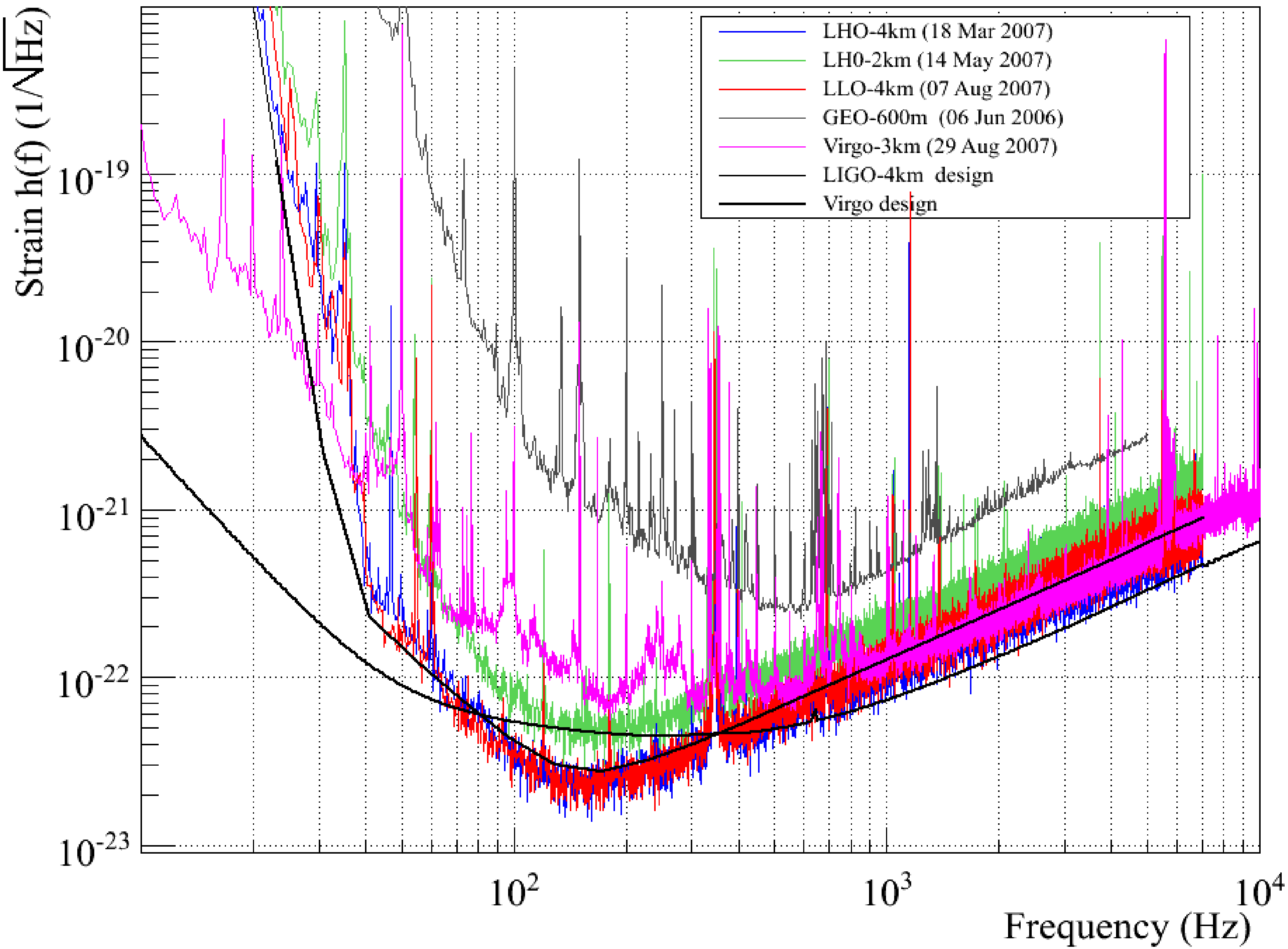
NS-NS coalescence event rates

- Initial interferometers
  - Range: 20 Mpc
  - 1 per 40 yrs to 1 per 2 yrs
- Advanced interferometers
  - Range: 300Mpc
  - few per yr to several per day
- The discovery of a new binary pulsar have increased the rate upwards by an order of magnitude

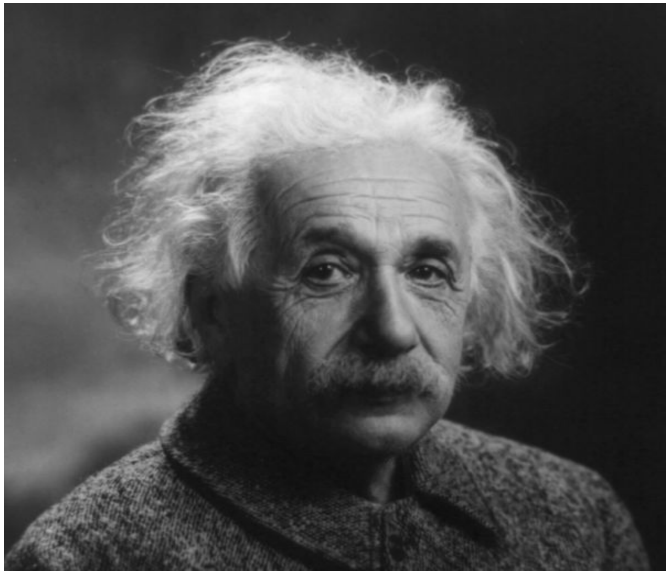


Signal shape very well known




Strain h(f) (1/√Hz)
10-19
10-20
10-21
10-22
10-23
10^2
10^3
10^4
Frequency (Hz)
LHO-4km (18 Mar 2007)
LH0-2km (14 May 2007)
LLO-4km (07 Aug 2007)
GEO-600m (06 Jun 2006)
Virgo-3km (29 Aug 2007)
LIGO-4km design
Virgo design

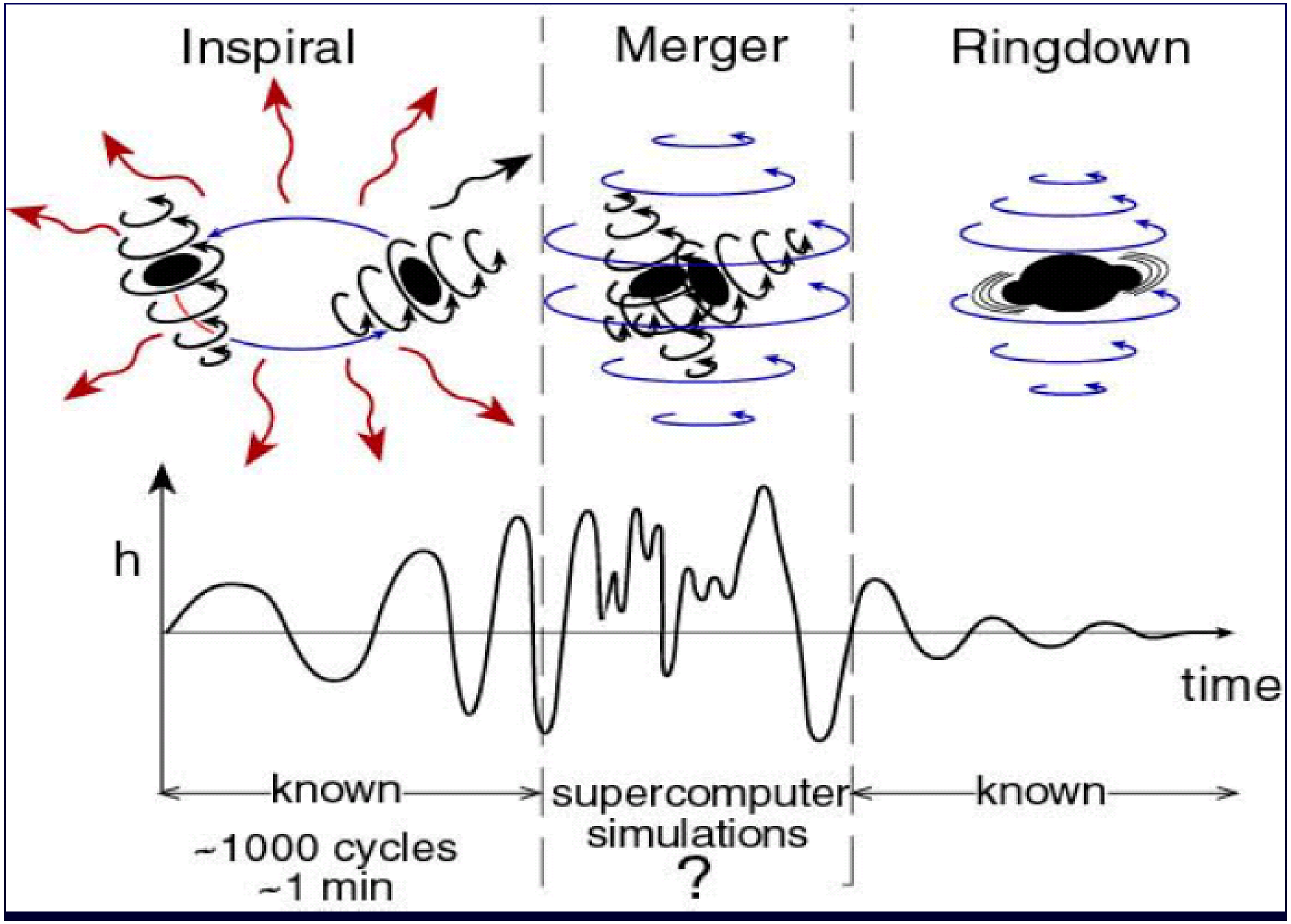
Gravitational Waves



- predicted by GR, 1915
- spacetime oscilations
- new sort of radiation
  --> new discoveries
- we can see objects that cannot be seen in any other way
- a new test of GR

Compact binaries- three phases of coalescence

"inspiral" - until marginally stable orbit
"merger" - until the common horizon
"ringdown" - black hole oscillations



Detection of gravitational waves

Test masses

A network of detectors needed: to confirm detections independently and open a new window on the Universe

narrow bandwidth: resonance detectors (~1 kHz)

large bandwidth: laser interferometers (~10Hz-1kHz)

Measurement of distances between them using light beams

$$dL \sim h\,L$$