Overview of Gravitational Wave Physics [PHYS879]

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Content:

- **What are gravitational waves made of? How are they generated?**
- **What are the main cosmological and astrophysical gravitational-wave sources?**
- **How do we search for gravitational waves?**
- **What will we learn about the Universe and fundamental physics by detecting gravitational waves?**

THE GRAVITATIONAL WAVE SPECTRUM

SOURCES

Quantum Fluctuations in th

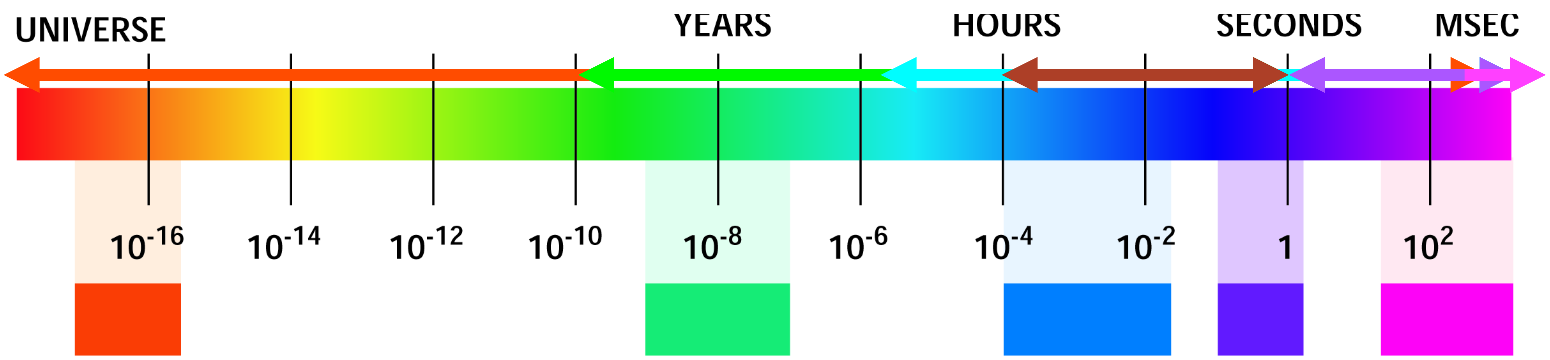
Merging super
black hole at g

Pha
tran
the
Uni

Capture of
black holes
and
compact
stars by
SMBH

Me
bin
neu
sta
bla
in distant
galaxies

Neutron star
quakes and
magnetars



Wave Period: **UNIVERSE** · **YEARS** · **HOURS** · **SECONDS** · **MSEC**

Frequency (Hz): 10^{-16} · 10^{-14} · 10^{-12} · 10^{-10} · 10^{-8} · 10^{-6} · 10^{-4} · 10^{-2} · 1 · 10^{2}

DETECTORS

INFLATION
PROBE
(NASA)

polarization
map of cosmic
microwave
background

precision
timing of
millisecond
pulsars
(1982 -)

LISA
(ESA/NASA,
2010)

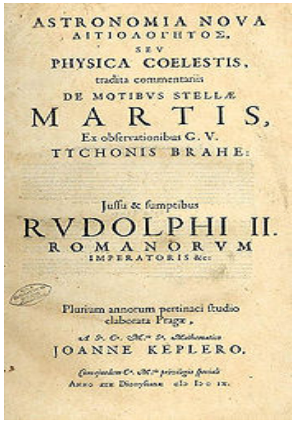
BIG
BANG OBS
(NASA)

laser tracking of
drag-free proof
mass in spacecraft
orbiting the sun

GEO, LIGO,
VIRGO, TAMA
(2002 -)

laser
interfero-
meters
on Earth
(also bar
detectors)

Milestones in understanding gravity:

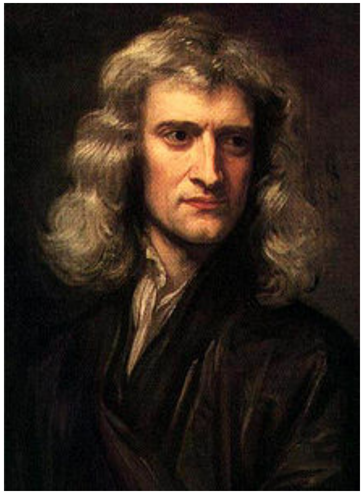


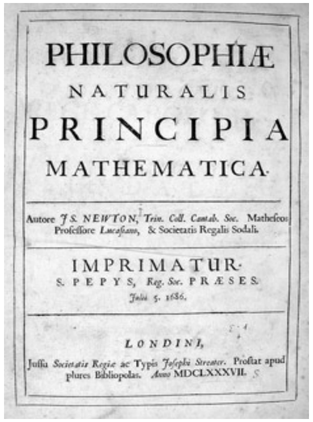
ASTRONOMIA NOVA
ΑΙΤΙΟΛΟΓΗΤΟΣ,
SEV
PHYSICA COELESTIS,
tradita commentariis
DE MOTIBVS STELLÆ
MARTIS,
Ex obſervationibus G. V.
TYCHONIS BRAHE:

Juſſu & ſumptibus
RVDOLPHI II.
ROMANORVM
IMPERATORIS &c:

Plurium annorum pertinaci ſtudio
elaborata Pragæ,
A S. C. M.tis S. Mathematico
JOANNE KEPLERO.

Cum ejusdem C. M.tis privilegio ſpeciali
ANNO ÆRÆ Dionyſianæ CIↃ IↃ C IX.





PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

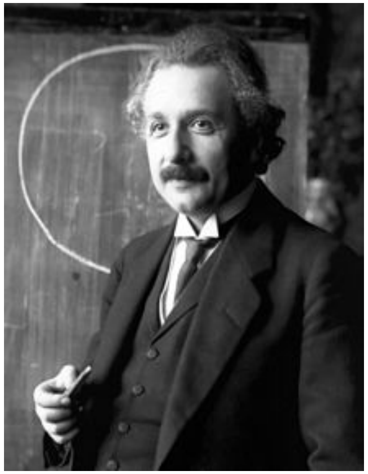
Autore *JS. NEWTON*, *Trin. Coll. Cantab. Soc.* Matheſeos
Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

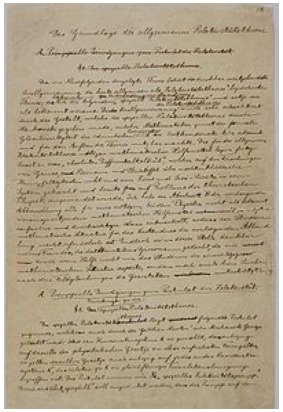
IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud
plures Bibliopolas. *Anno* MDCLXXXVII.

Laws of planetary motion

Theory of gravitation





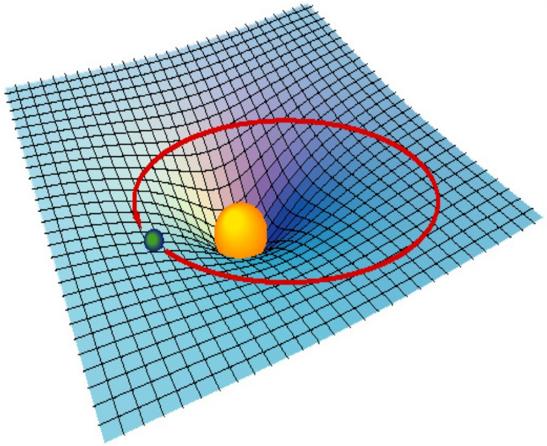
General Relativity

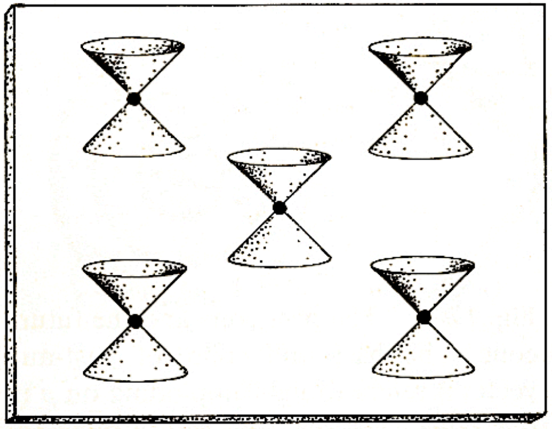
General relativity:

1907-1915: Einstein develops the theory of general relativity

- Space-time is no longer given a priori; it is no longer independent of all material content.

- Space-time is a dynamic and elastic entity both influencing and influenced by the distribution of mass-energy that it contains.



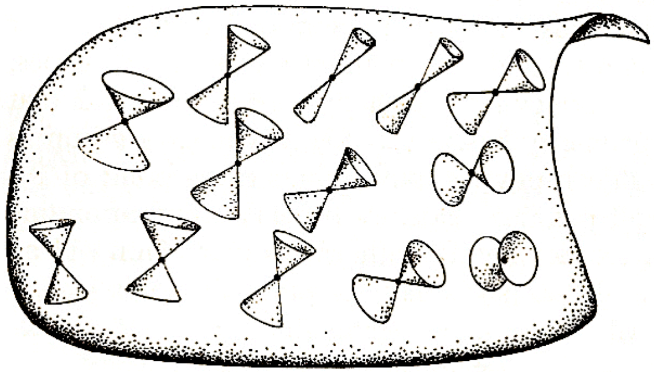


$$\Leftarrow ds^2 = \eta_{\mu\nu}\, dx^\mu\, dx^\nu$$

$$\eta_{\mu\nu} = (-1,+1,+1,+1)$$

$$\mu,\nu = 0,1,2,3$$

$$ds^2 = g_{\mu\nu}(x)\, dx^\mu\, dx^\nu \quad \Rightarrow$$



Rigid spacetime in special relativity

Elastic spacetime in general relativity

Gravitational waves: prediction of general relativity

- **1916: Einstein predicts the existence of gravitational waves, describing them as space-time elastic.**

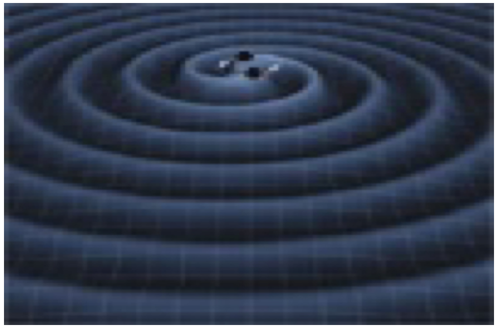
- **Linearized gravity**: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad \text{with} \quad |h_{\mu\nu}| \ll 1$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} \quad \Rightarrow \quad \Box \tilde{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

- **Analogy with Maxwell equations:** $\Box A_\mu = -4\pi \, J_\mu$

A distribution of mass deforms the space-time in its neighborhood. This deformation propagates at finite speed away from the source in the form of waves whose oscillations reflect the temporal variation of the matter distribution.

Ripples of water from a stone thrown in the water



Ripples of warping in the fabric of space-time from orbiting black holes

Post-Newtonian approximation:

First developed by Einstein, Droste and Infeld in 1917

Newtonian gravity is recovered assuming a weak deformation of flat spacetime, a slowly varying field, and a non-relativistic source.

PN expansion: working within the Newtonian limit and keeping terms of higher order in the parameter

$$\epsilon \sim \frac{v^2}{c^2} \sim \frac{GM}{c^2 r}$$

PN force of gravitational attraction between two bodies:

$$F_{\mathrm{PN}} = -\frac{G\,m_1\,m_2}{r^2}\left(1 + a_{1\mathrm{PN}}\,\frac{v^2}{c^2} + a_{2\mathrm{PN}}\,\frac{v^4}{c^4} + a_{2.5\mathrm{PN}}\,\frac{v^5}{c^5} + a_{3\mathrm{PN}}\,\frac{v^6}{c^6} + a_{3.5\mathrm{PN}}\,\frac{v^7}{c^7} + \cdots\right)$$

1PN prediction tested in solar system ($v/c = 10^{-5} - 10^{-4}$) and binary pulsars ($v/c = 10^{-3}$)

Multipolar decomposition of waves (linear order in G):

Multipole expansion in terms of mass moments (I_L) and mass-current moments (J_L) of the source:

$$h \sim \overbrace{\frac{G}{c^2}\frac{I_0}{r}}^{\text{can't oscillate}} + \overbrace{\frac{G}{c^3}\frac{\dot{I}_1}{r}}^{\text{can't oscillate}} + \overbrace{\frac{G}{c^4}\frac{\ddot{I}_2}{r}}^{\text{mass quadrupole}} + \underbrace{\frac{G}{c^4}\frac{\dot{J}_1}{r}}_{\text{can't oscillate}} + \underbrace{\frac{G}{c^5}\frac{\ddot{J}_2}{r}}_{\text{current quadrupole}} + \cdots$$

Typical strength: $$h \sim \frac{G}{c^4}\frac{M\,L^2}{P^2}\frac{1}{r} \sim \frac{G(E_{\rm kin}/c^2)}{c^2\,r}$$

If $E_{\rm kin}/c^2 \sim 1M_\odot$ depending on r $\Rightarrow$ $h \sim 10^{-23}$–10^{-17}

Comparison between GW and EM luminosities:

$$\mathcal{L}_{\rm GW} = \frac{G}{5c^5} (\dddot{I}_2)^2 \qquad I_2 \sim \epsilon\, M\, R^2$$

$$\dddot{I}_2 \sim \omega^3\, \epsilon\, M\, R^2 \text{ with } \omega \sim 1/P \quad \Rightarrow \quad \mathcal{L}_{\rm GW} \sim \frac{G}{c^5}\, \epsilon^2\, \omega^6\, M^2\, R^4$$

$$\mathcal{L}_{\rm GW} \sim \frac{c^5}{G}\, \epsilon^2 \left(\frac{G\, M\, \omega}{c^3}\right)^6 \left(\frac{R\, c^2}{G\, M}\right)^4 \Rightarrow \quad \frac{c^5}{G} = 3.6 \times 10^{59}\ \text{erg/sec (huge!)}$$

Steel rod of mass 500 tons, radius 20 meters at max rotation freq:

$$\text{(GW energy flux)} = 10^{-60} \times \text{(EM energy flux of our Sun)}$$

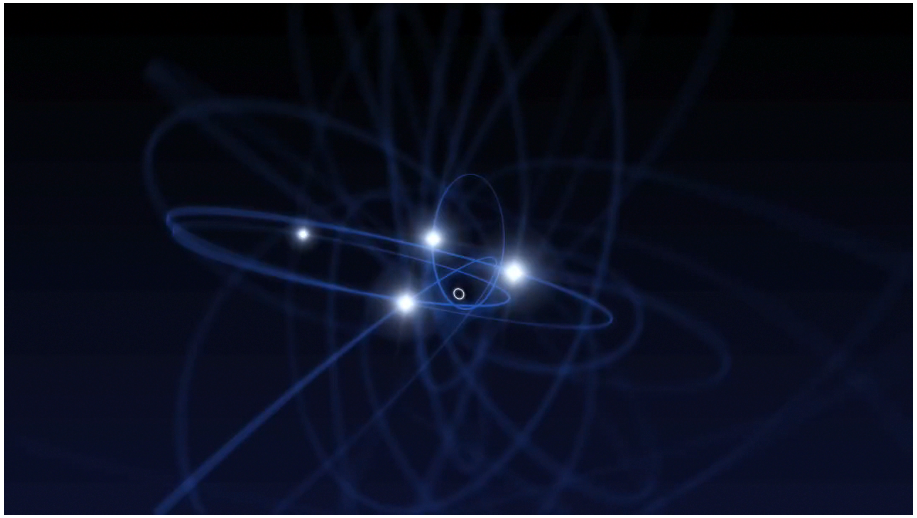
Two black holes spiraling each other close to the speed of light:

$$\text{(GW energy flux)} = 10^{26} \times \text{(EM energy flux of our Sun)}$$

Strong sources of gravitational radiation must have strong non-spherical dynamics, large velocities and large masses.

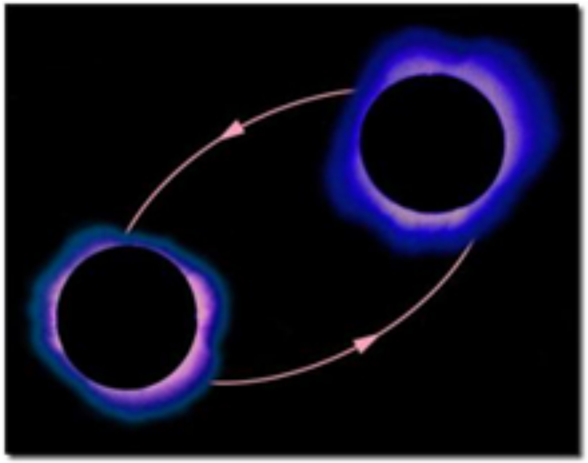
Black holes orbiting each other are an ideal source of gravitational waves:

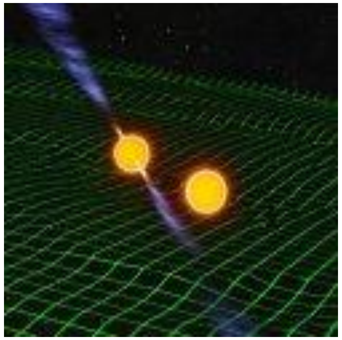
Supergiant star--Cygnus X-1 binary system



Black hole of 4 million solar masses in our galaxy’s center

Black-hole binary system





The Binary Pulsar PSR1913+16

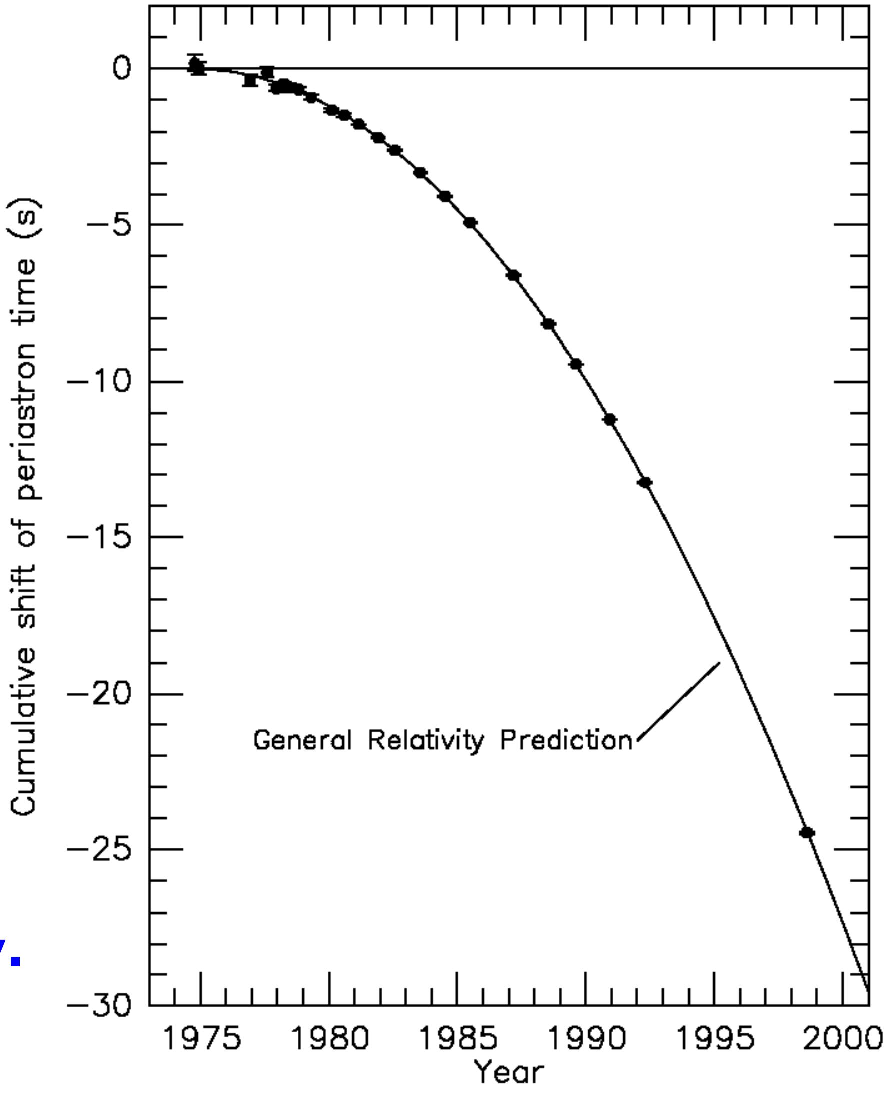
A radio pulsar in a close orbit with period 8 hours around an unseen companion

Discovered in 1974 by Hulse and Taylor

Long-term radio observations have yielded object masses and orbital parameters.

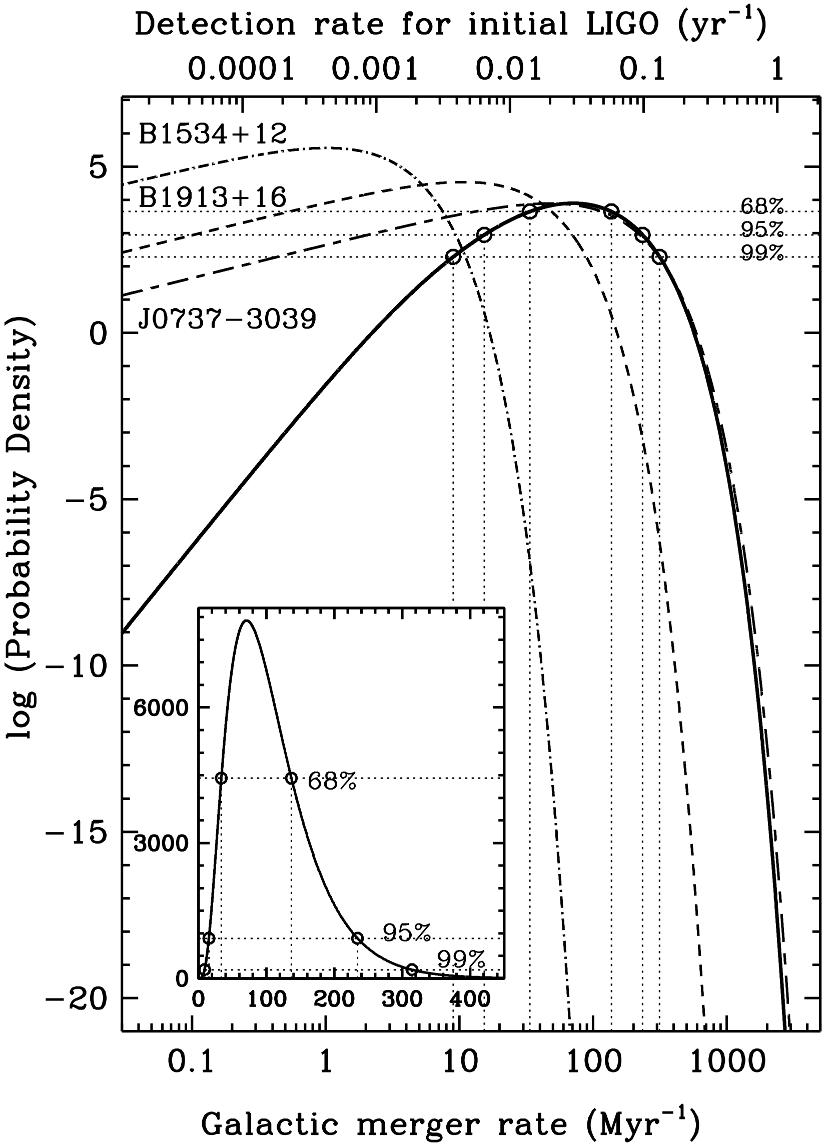
The orbital period is slowly decreasing at just the rate predicted by general relativity.

The strongest "indirect" evidence for gravitational radiation!



From J. H. Taylor and J. M. Weisberg, unpublished (1998)

Known binary pulsars merging in Hubble time



Kim et al. 2006

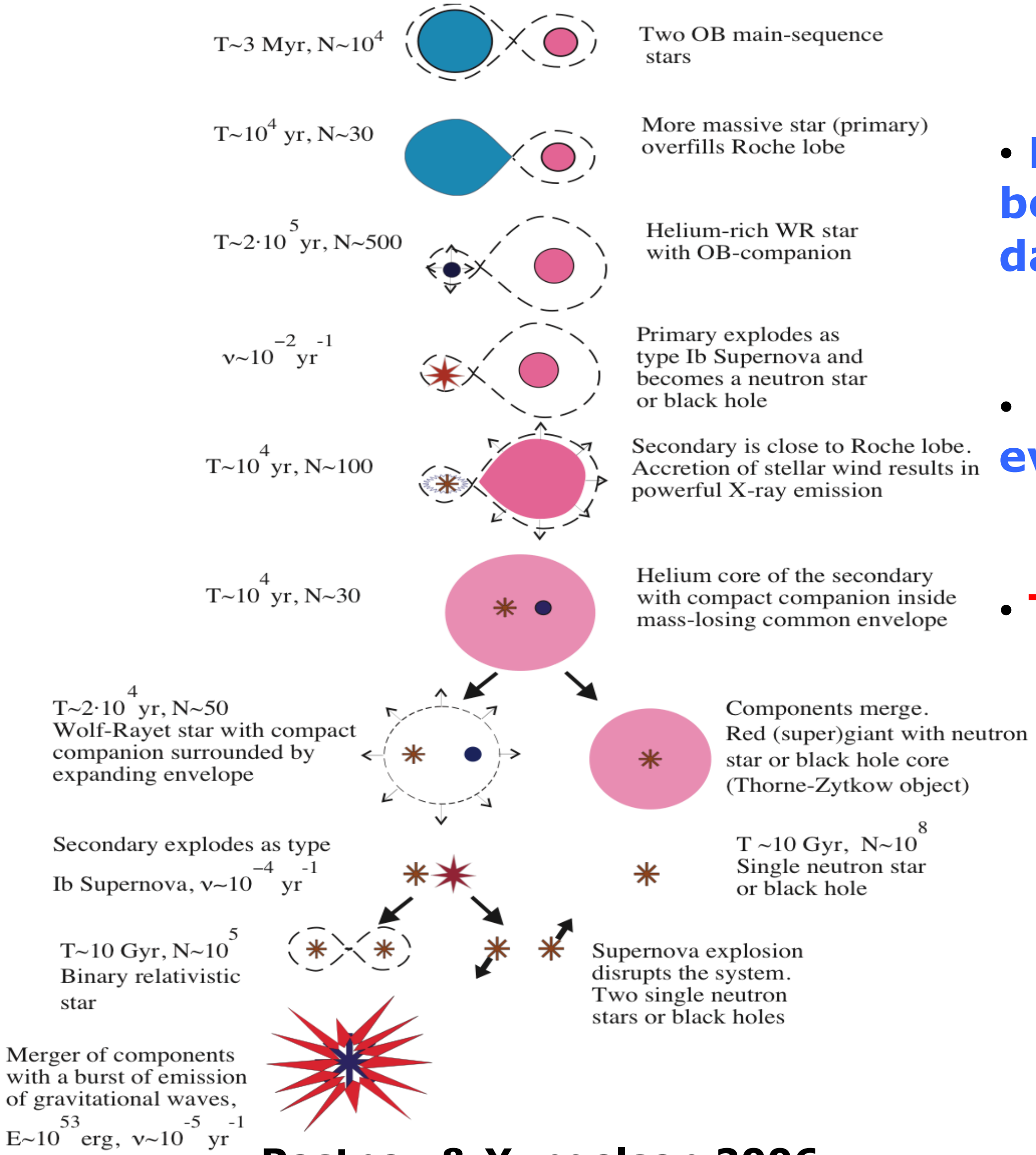
PSR name	P^a (ms)	P_b (hrs)	T_{life} (Gyr)
B1913+16	59.03	7.75	0.37
B1534+12	37.90	10.10	2.93
J0737-3039	22.70	2.45	0.23
J1756-2251	28.46	7.67	2.03
J1906+0746	114.14	3.98	0.082

- **Observations are used to estimate NS-NS merger rate in a Milky-way-like-galaxy; then, the rate is scaled to deduce rates for advanced LIGO.**

- **Observations are used to constrain population synthesis calculations, which predicts rates for NS-NS, and also NS-BH and BH-BH.**

- **So far, we have not observed binary pulsars with a BH companion.**

Population synthesis



$T \sim 3$ Myr, $N \sim 10^4$ — Two OB main-sequence stars

$T \sim 10^4$ yr, $N \sim 30$ — More massive star (primary) overfills Roche lobe

$T \sim 2 \cdot 10^5$ yr, $N \sim 500$ — Helium-rich WR star with OB-companion

$\nu \sim 10^{-2}$ yr^{-1} — Primary explodes as type Ib Supernova and becomes a neutron star or black hole

$T \sim 10^4$ yr, $N \sim 100$ — Secondary is close to Roche lobe. Accretion of stellar wind results in powerful X-ray emission

$T \sim 10^4$ yr, $N \sim 30$ — Helium core of the secondary with compact companion inside mass-losing common envelope

$T \sim 2 \cdot 10^4$ yr, $N \sim 50$
Wolf-Rayet star with compact companion surrounded by expanding envelope

Components merge. Red (super)giant with neutron star or black hole core (Thorne-Zytkow object)

Secondary explodes as type Ib Supernova, $\nu \sim 10^{-4}$ yr^{-1}

$T \sim 10$ Gyr, $N \sim 10^8$
Single neutron star or black hole

$T \sim 10$ Gyr, $N \sim 10^5$
Binary relativistic star

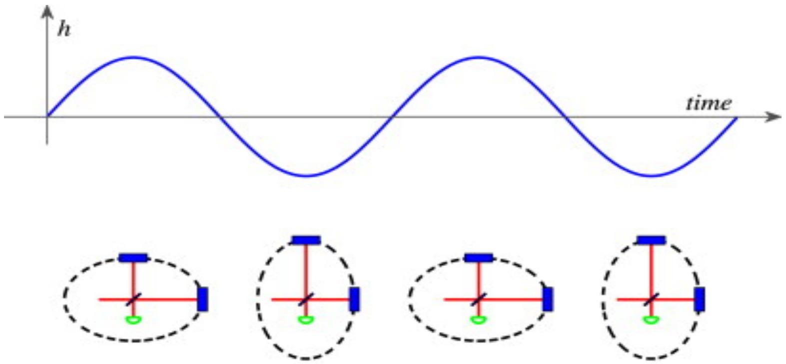
Supernova explosion disrupts the system. Two single neutron stars or black holes

Merger of components with a burst of emission of gravitational waves,
$E \sim 10^{53}$ erg, $\nu \sim 10^{-5}$ yr^{-1}

Postnov & Yungelson 2006

- **Method originally introduced because of lack of observational data.**
- **One simulates the entire evolution of the binary system.**
- **There are many uncertainties!**

The “direct” search for gravitational waves:



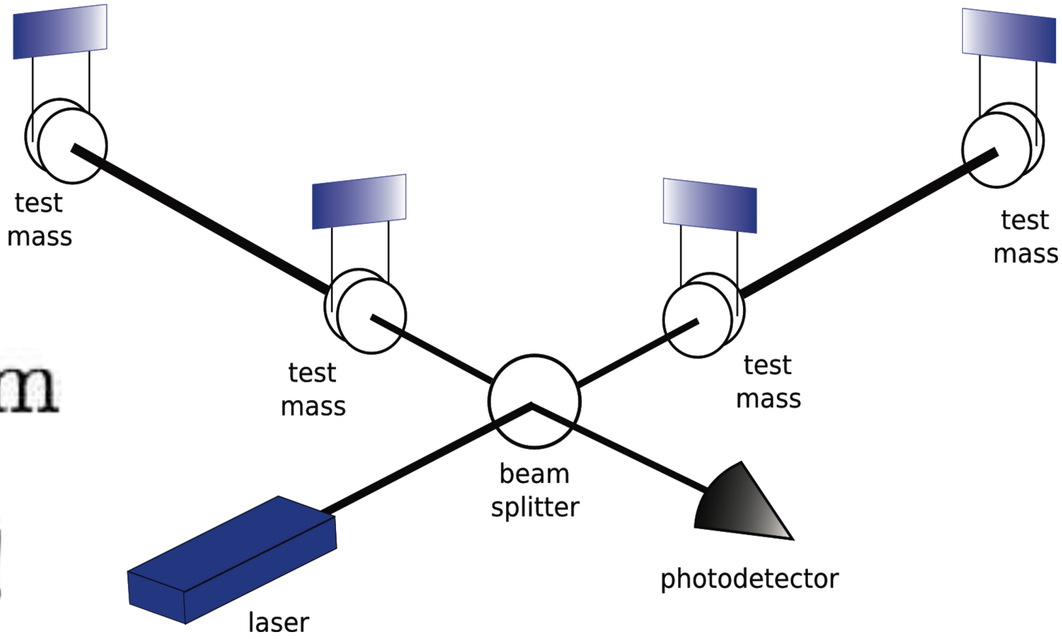
The effect of a gravitational wave on a ring of particles (like Moon-Earth tides!)

We use light beams to measure stretching and squeezing of mirrors induced by GWs.

$$\Delta L = L\,h$$

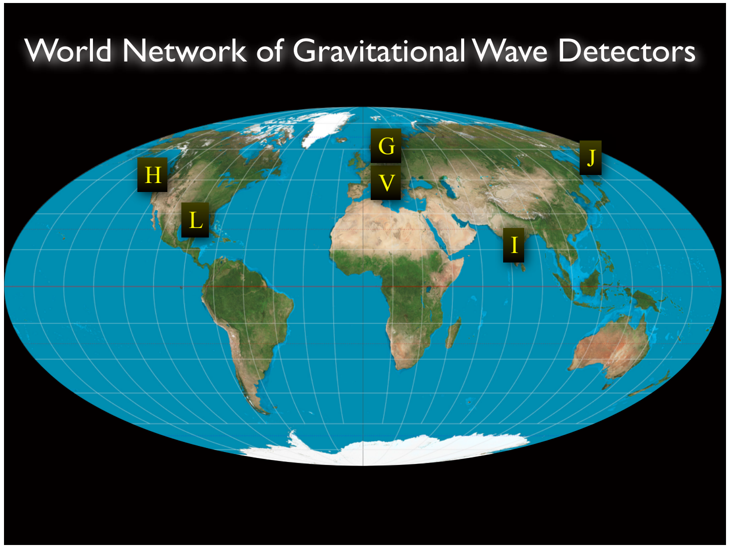
$$h \sim 10^{-21}, L = 4\text{km}$$

$$\Rightarrow \Delta L \sim 10^{-16}\text{cm!}$$



International network of detectors: 10-10^3 Hz

Hanford, WA

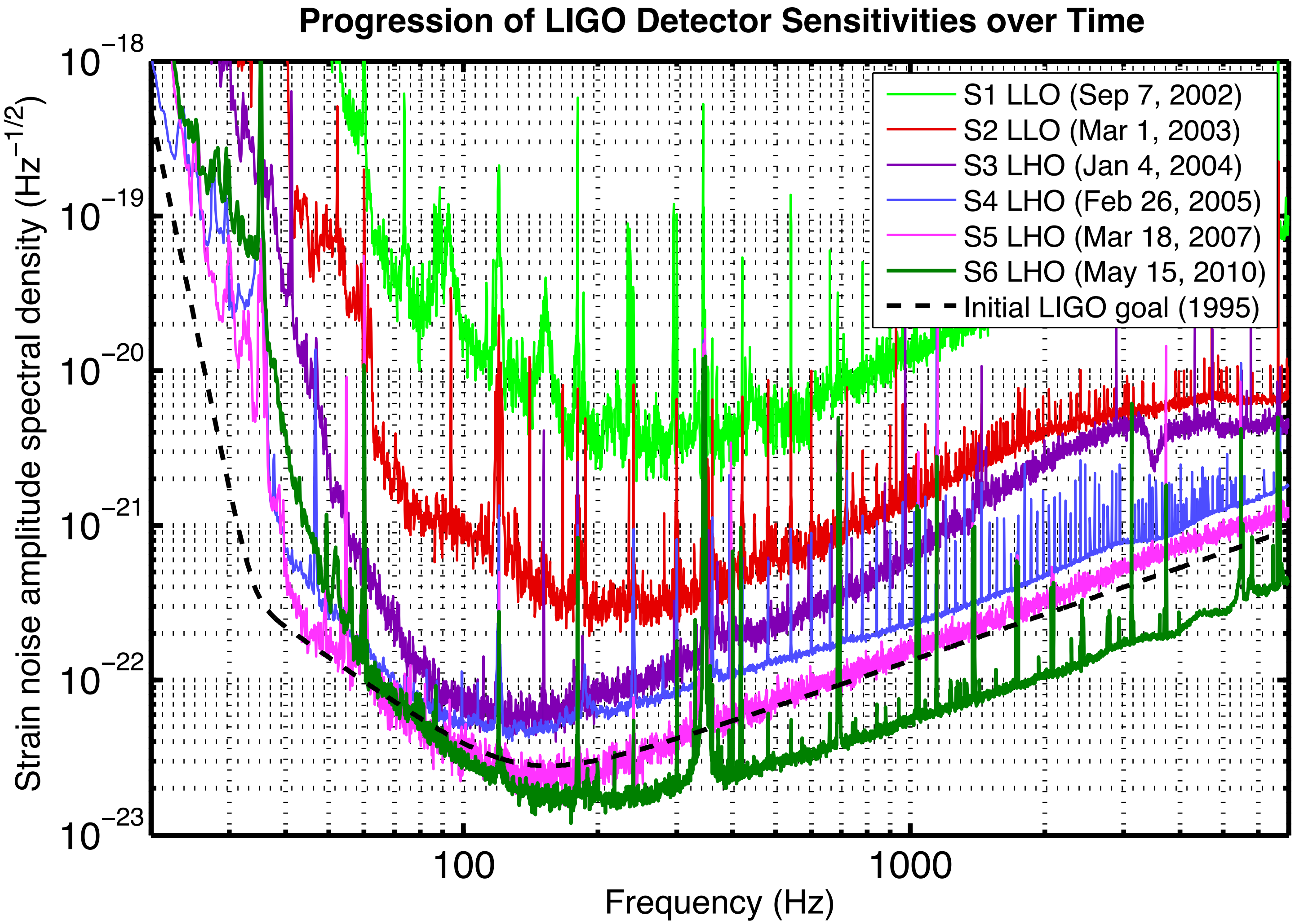


LIGO (2004-2010):
could **observe** NS-NS binary systems
up to **30 Mpc.**
Event rates: 2x10^{-4}/year - 0.2/year
No detection, but it has proved the technology.

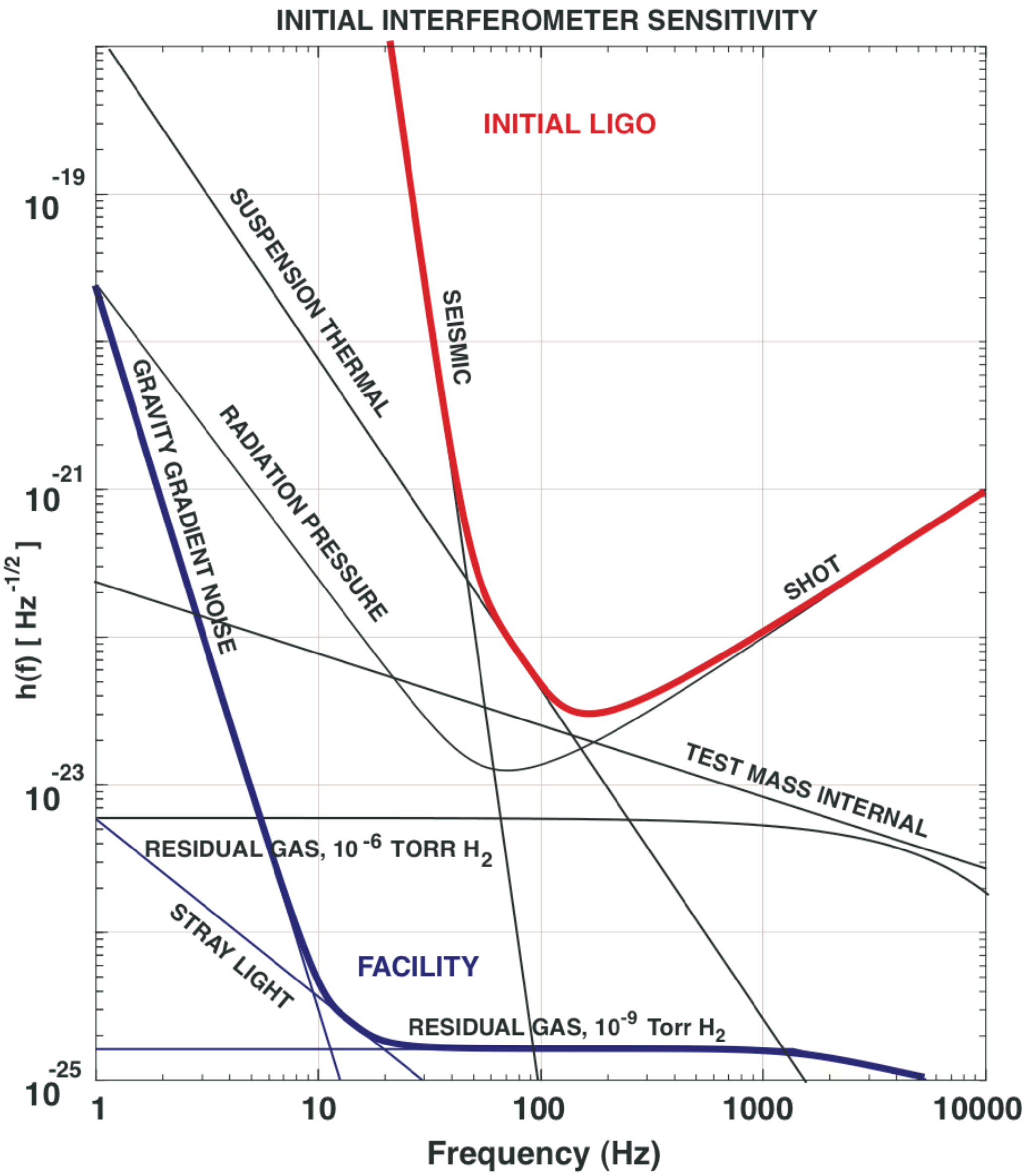
40 kg silica mirror

advanced LIGO (2015 - …):
could **observe** NS-NS binary systems up to
200 Mpc.
Event rates: 0.4/year – 400/year (40/year)

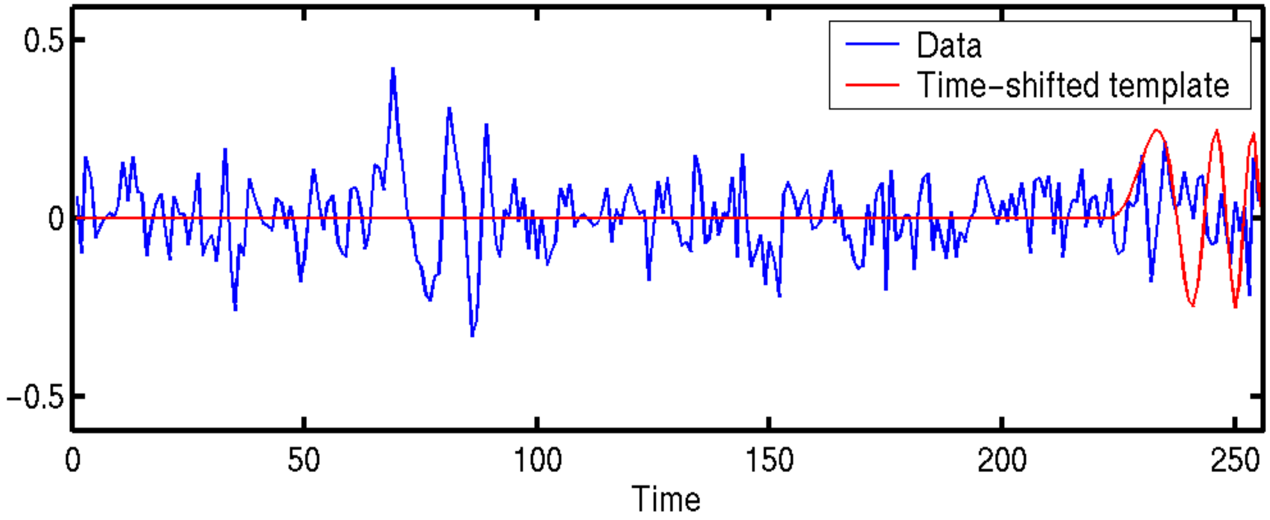
LIGO progression over time:

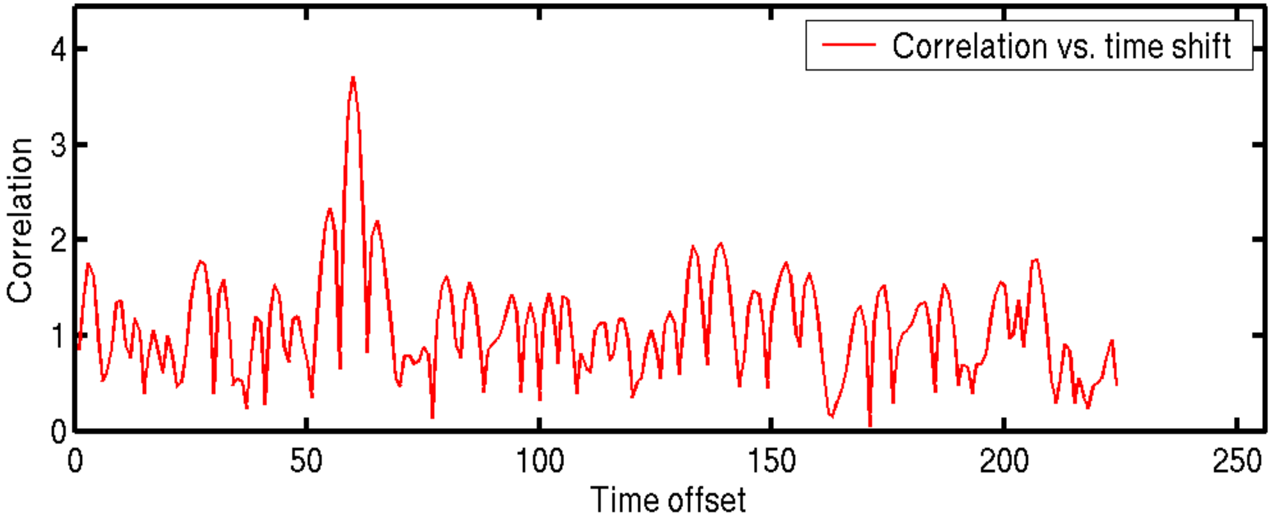


Typical noise in ground-based gravitational-wave detectors:



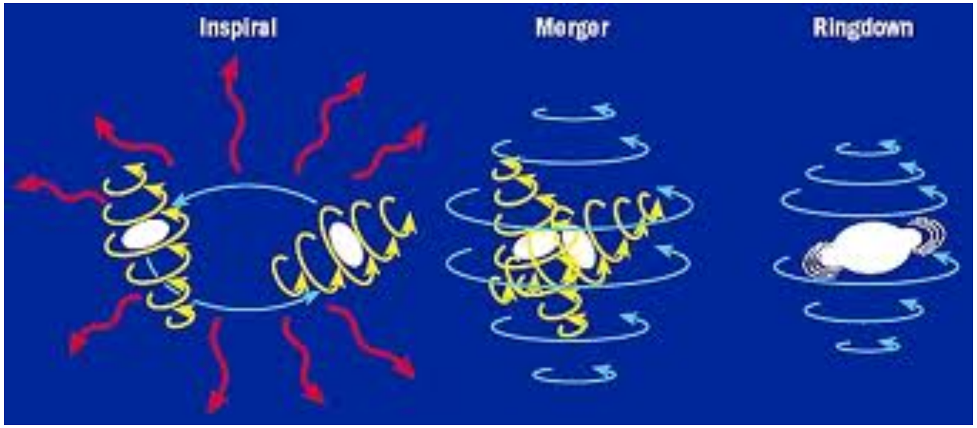
How we detect gravitational waves from binary systems:



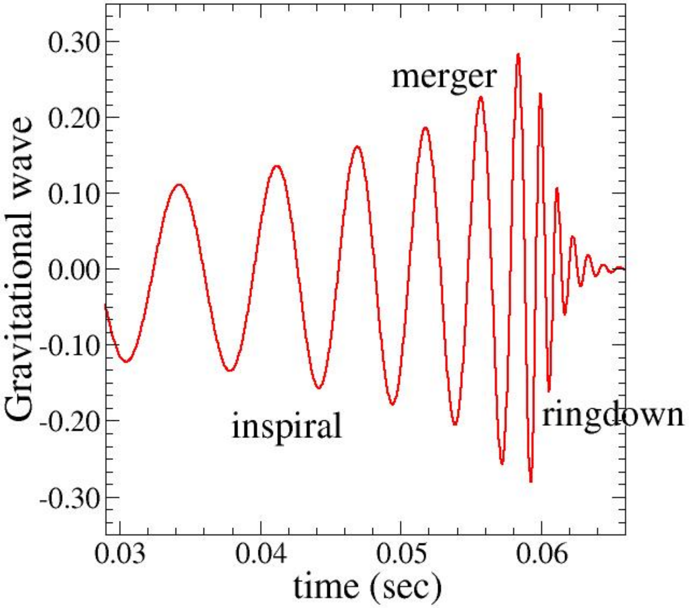


(courtesy from Peter Shawhan)

Modeling the dynamics and gravitational-wave emission of coalescing black holes:



When perturbed, black holes ring at their proper frequencies!



Inspiraling signal can be well modeled by analytical techniques that go beyond Newtonian dynamics.

Merger signal computed with numerical relativity simulations on very powerful computers.

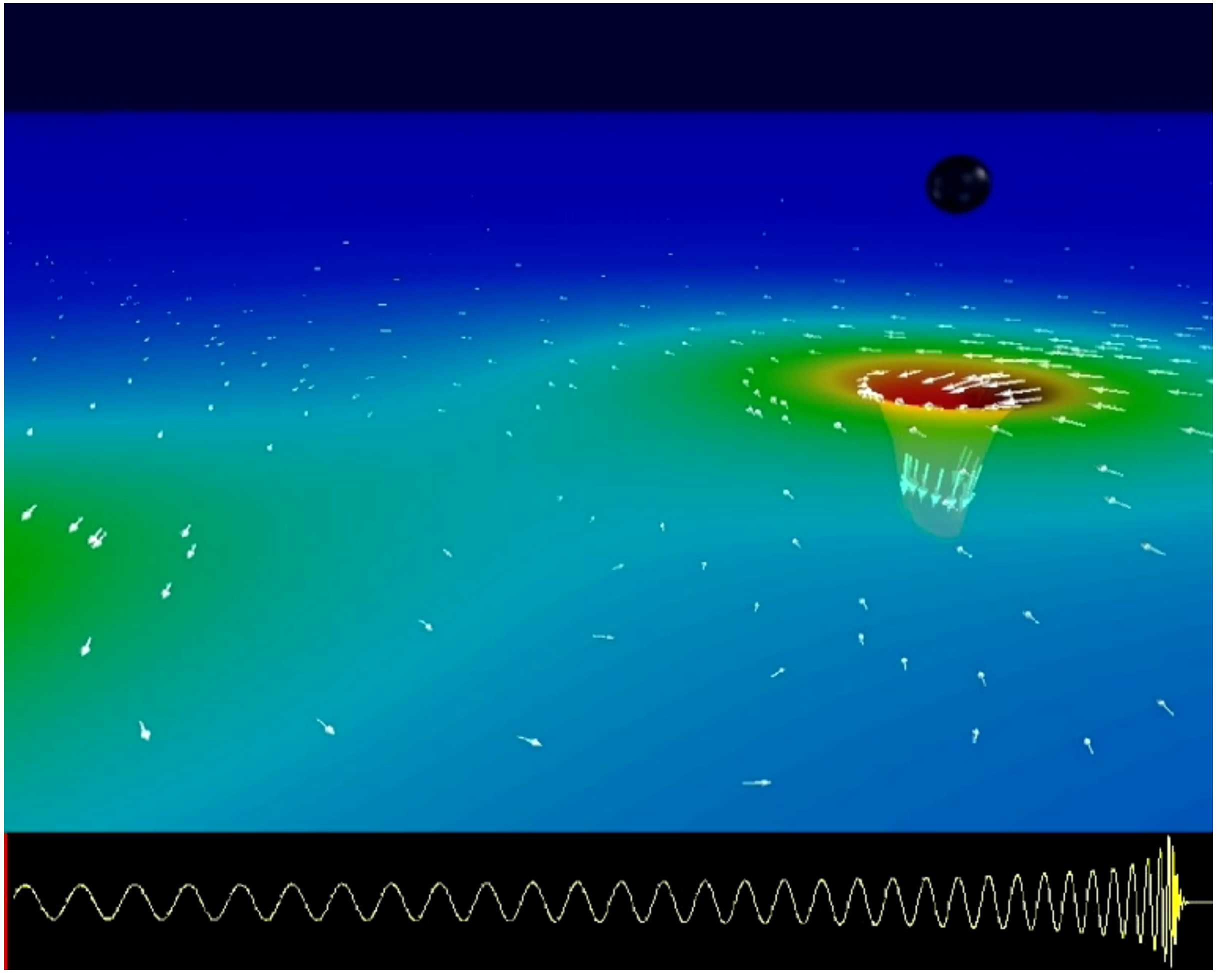
Templates are obtained by combining analytical and numerical relativity techniques.

Analytical and numerical relativists at work:

"DATA, DATA EVERYWHERE!"

Merging black holes in numerical relativity:

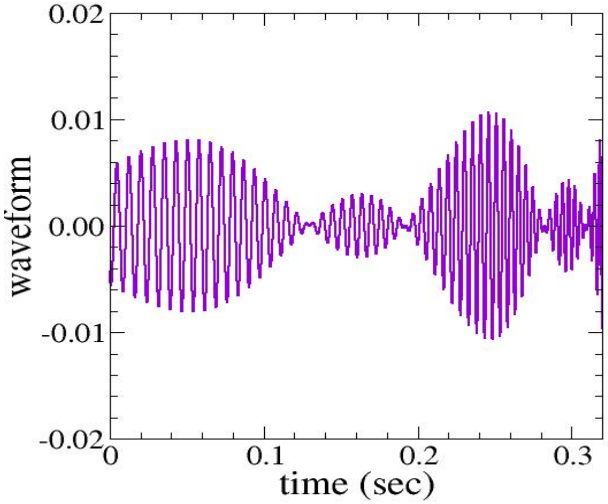
If black-hole mass is 10 solar masses, the initial separation in the simulation is 900 km, and wave sweeps in detector band in half a second!



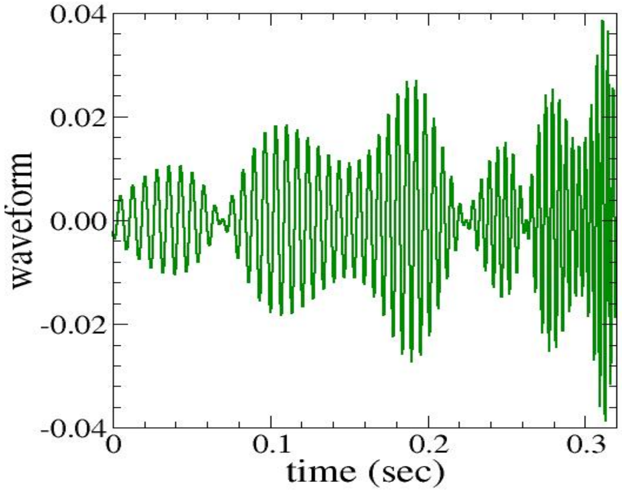
(From Caltech-Cornell-CITA Collab.)

Energy emitted during merger is larger than energy in all stars in observable Universe

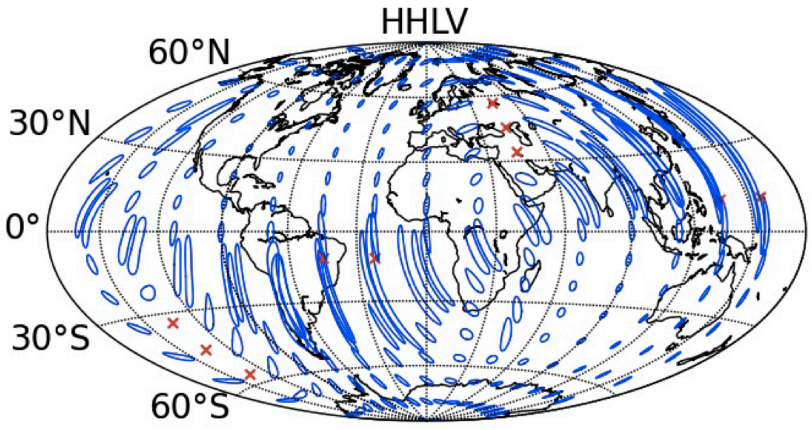
Unique information to extract upon detection:



**different shapes
different binary
parameters**



GWs can tell us how heavy each of the black holes was, how fast they were spinning, the shape of their orbits (circular? elongated?), where the holes are in the sky, and how far they are from Earth.



GW detection will tell us whether Einstein was right!

Can we extract information on NS's equation of state?

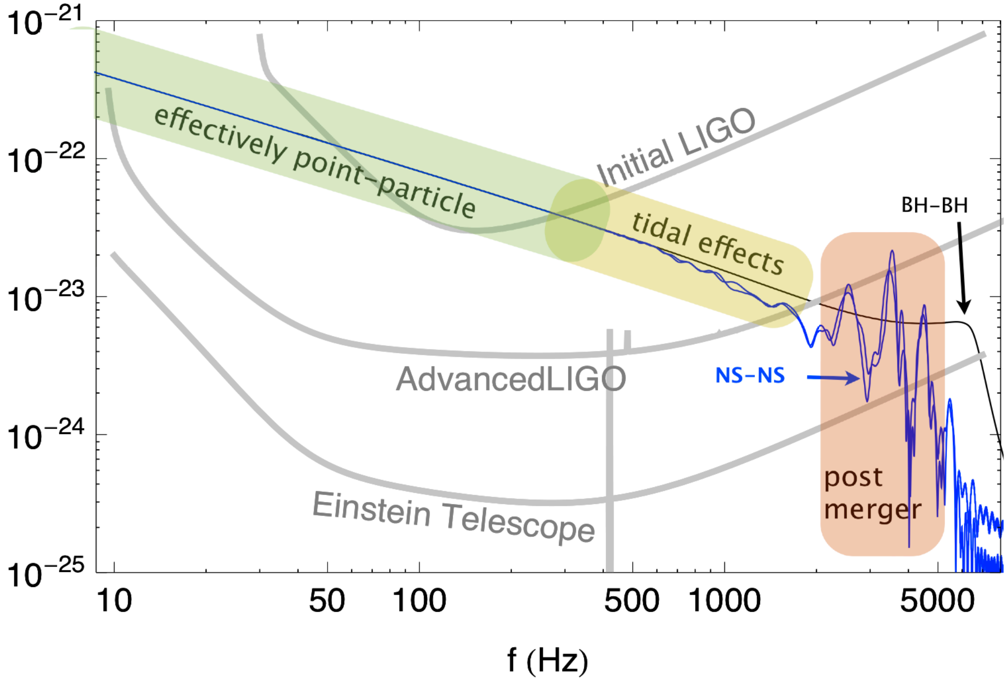
- **NS are composed of the densest form of matter known to exist in our Universe.**

- **NSs provide a unique laboratory for exploring the properties of baryonic matter at super-nuclear density.**

$$M_{\rm NS} \sim 1\text{–}3 M_\odot$$

$$R_{\rm NS} \sim 11\text{–}13\,{\rm km}$$

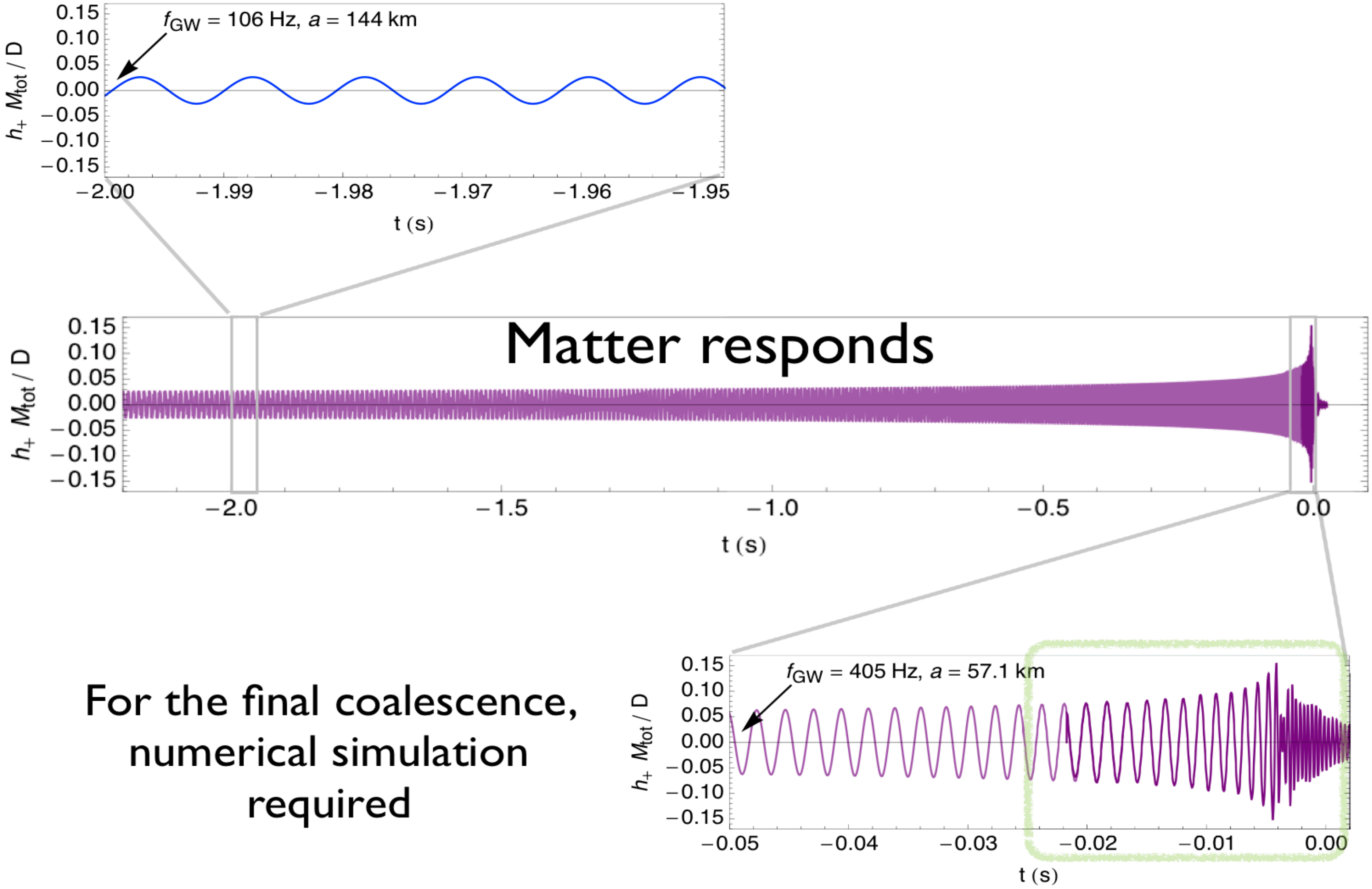
$$\rho_{\rm NS-core} > 10^{14}\,{\rm g/cm^3}$$



(courtesy from Jocelyn Read)

- **Measurements of the NS's masses or radii can strongly constraint the NS's equation of state and its interior composition.**

Imprint of NS's equation of state in the gravitational waveform:

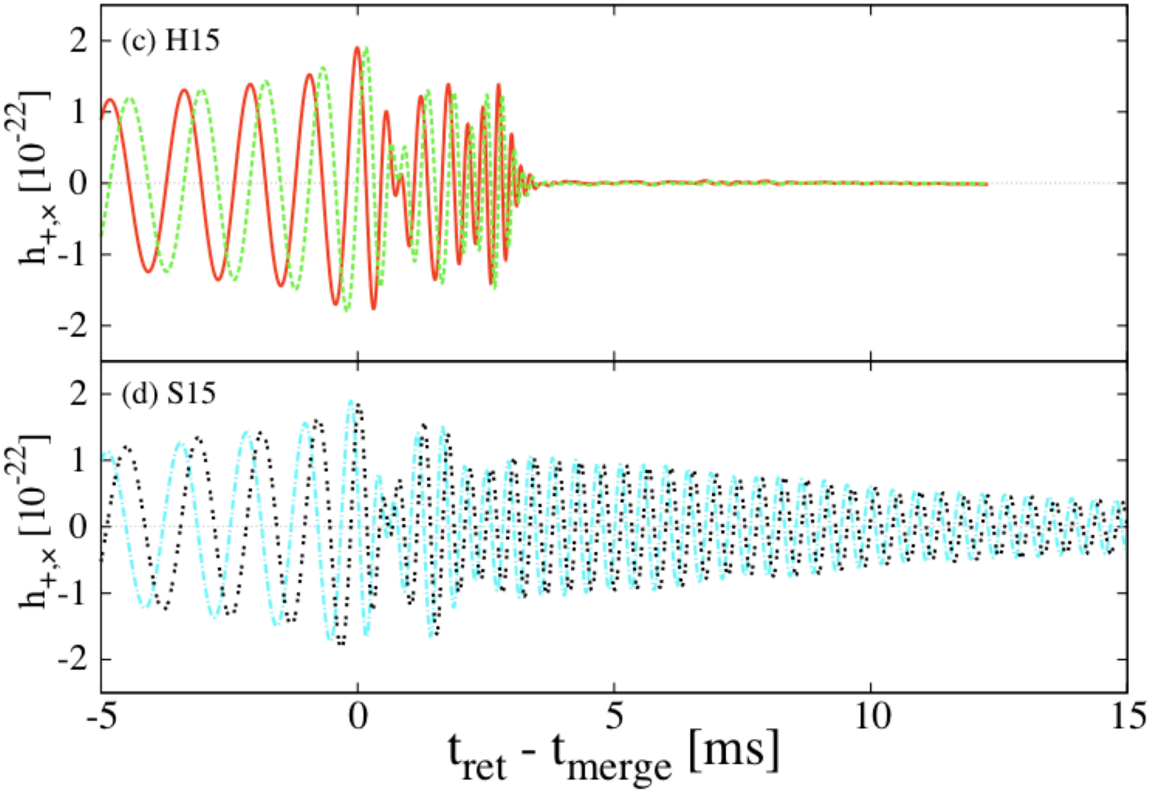


Matter responds

For the final coalescence,
numerical simulation
required

(courtesy from Jocelyn Read)

NS-NS merger waveforms:

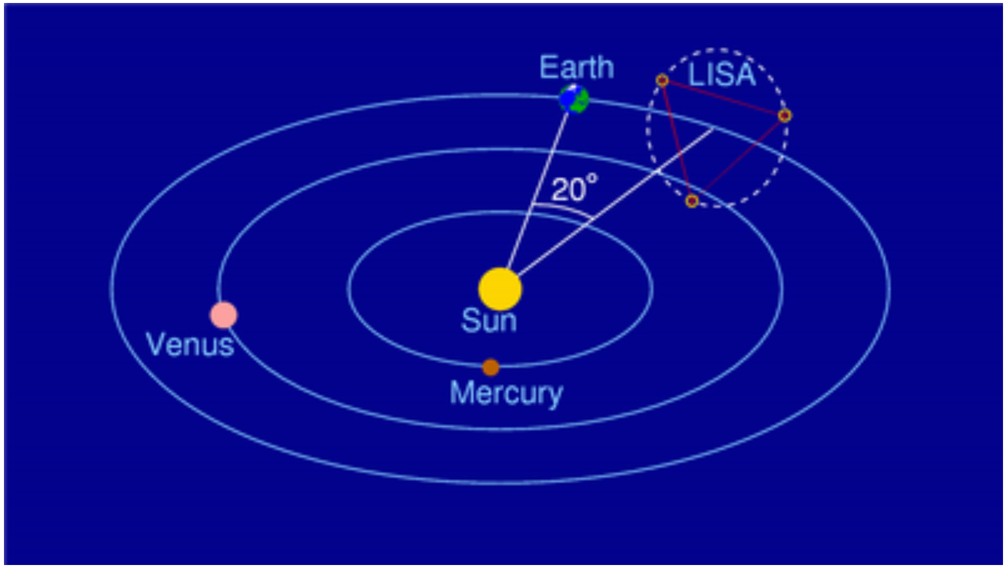


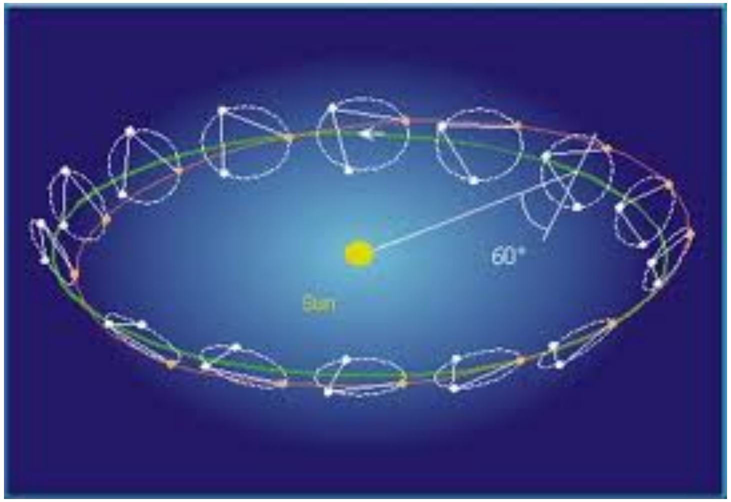
(Shibata’s group)

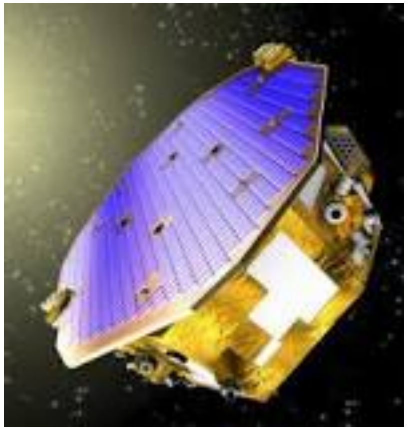
Merger and post-merger signals depend on binary’s mass and NS equation of state (nucleonic and hyperonic).

They can be associated to short duration Gamma Ray Bursts (GRB), and their optical and radio emissions.

Space-based gravitational-wave interferometer (10^{-4}-10^{-1} Hz):



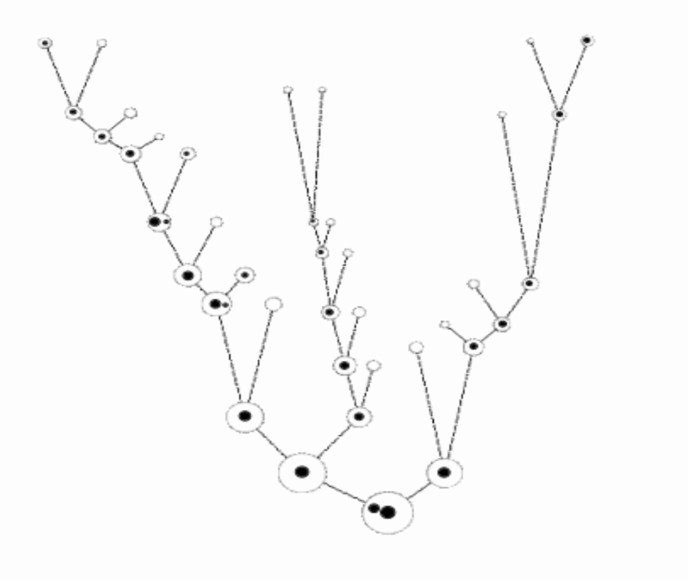




LISA Pathfinder mission in 2015 to prove technology

Binary of super-massive black holes:

Merging galaxies NGC4038 and NGC4039

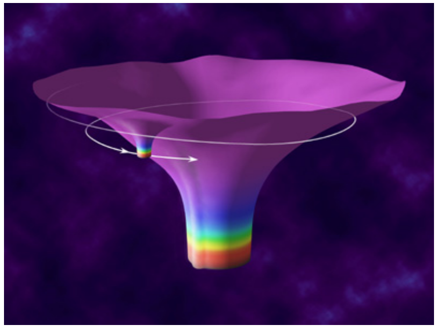


When galaxies collide, the super-massive black holes at their centers can interact and merge ⇒ strongest signals for space-based detectors

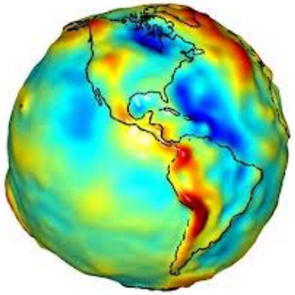
The GW signal can be observed for months/years as it sweeps in the detector bandwidth

We can learn how black holes have grown their masses, and how galaxies formed

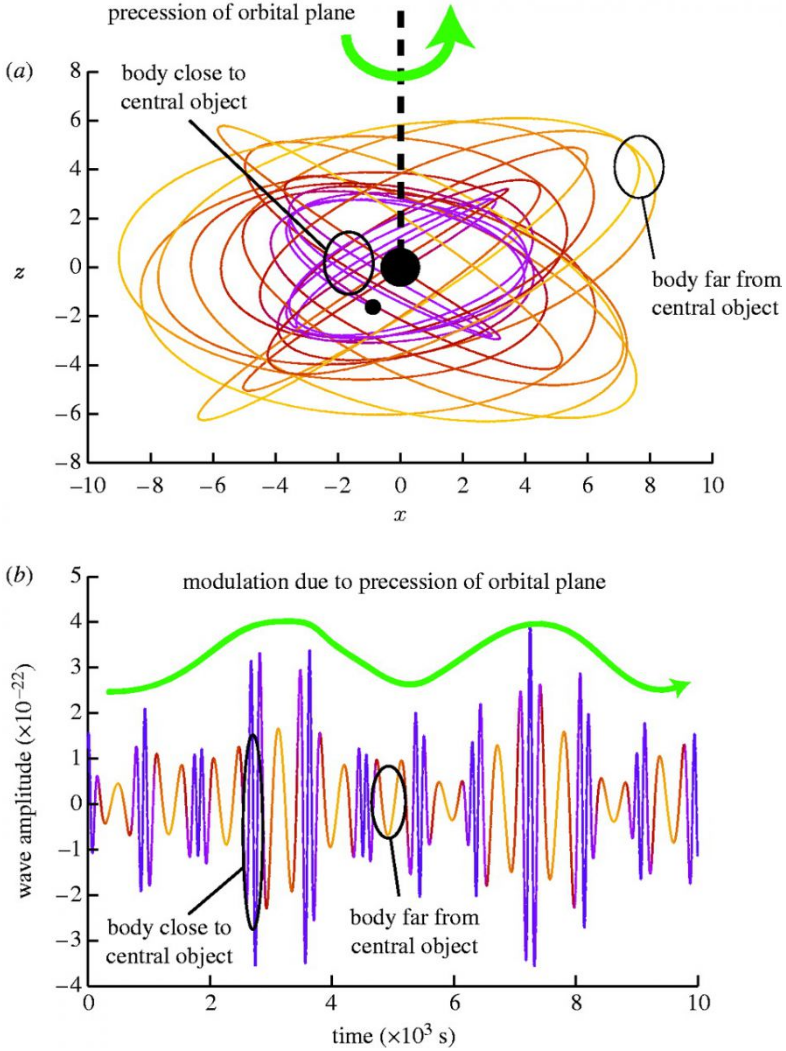
Mapping the black hole space-time:



Satellite orbits probe and map the matter distribution of the Earth.

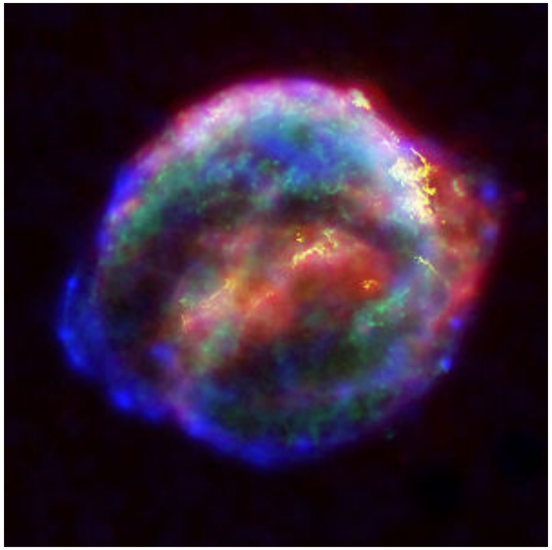


Black holes have very special multipole moment structure.

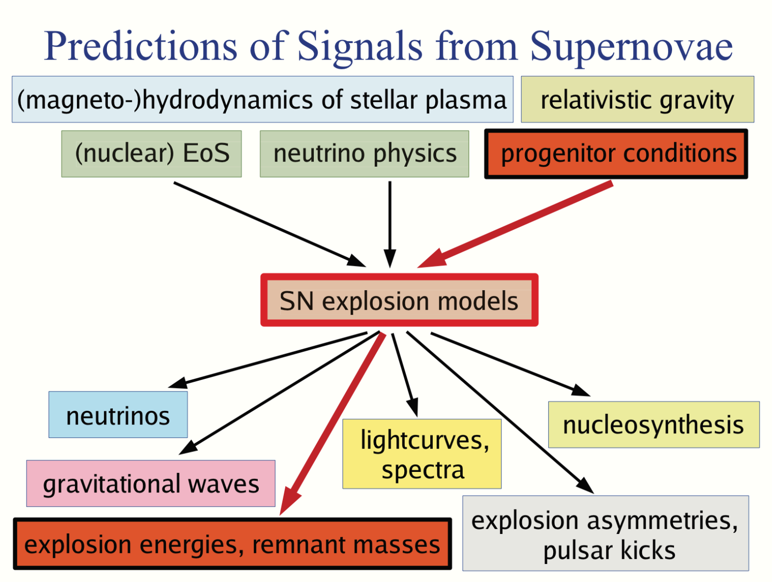


GWs will contain a map of the black-hole space-time curvature ⇒ test of general relativity.

Gravitational waves from supernovae:



Kepler's supernova SN 1604



Predictions of Signals from Supernovae

(magneto-)hydrodynamics of stellar plasma

relativistic gravity

(nuclear) EoS

neutrino physics

progenitor conditions

SN explosion models

neutrinos

gravitational waves

explosion energies, remnant masses

lightcurves, spectra

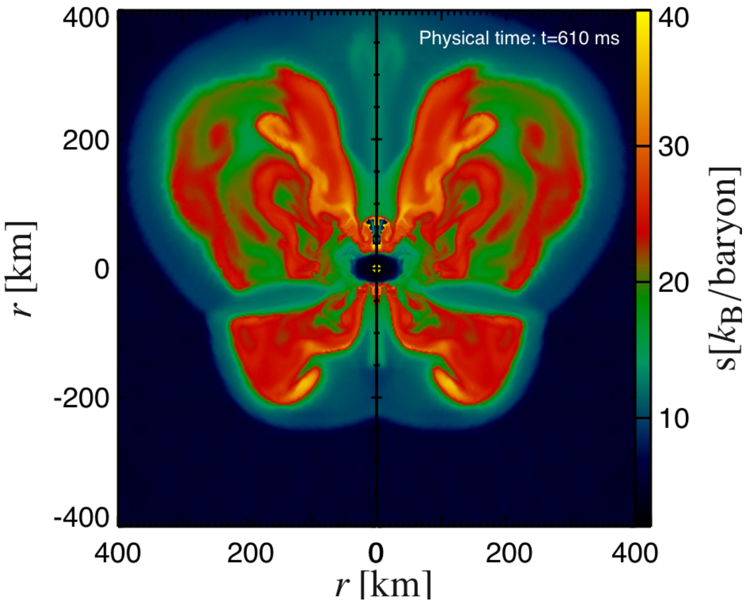
nucleosynthesis

explosion asymmetries, pulsar kicks

The core of a massive star ceases to generate energy from nuclear fusion and undergoes sudden gravitational collapse.

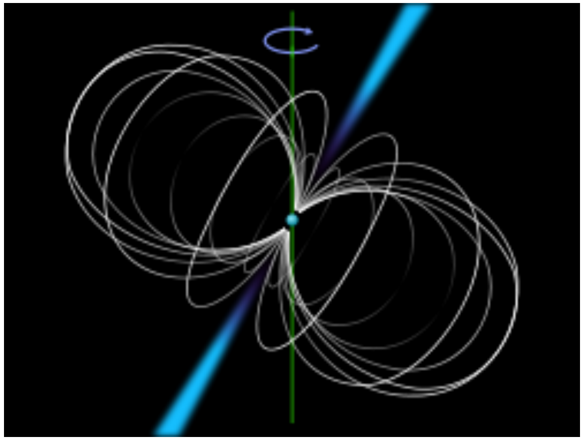
Strength of GW depends on the asymmetry of the core collapse

GW signal is an unshaped burst lasting for 10 msec



(from Thomas Janka)

Gravitational waves from radio pulsars:



Lighthouse model

Optical/X-ray image of the Crab Nebula

First discovered in 1967, a few thousand known today

Spin-down mostly due to accelerating energetic particles

Possible gravitational wave-emission due to ellipticity or wobbling

Ellipticity created by "mountains" on a pulsar of 1cm height!

Gravitational-wave signal is continuous and periodic

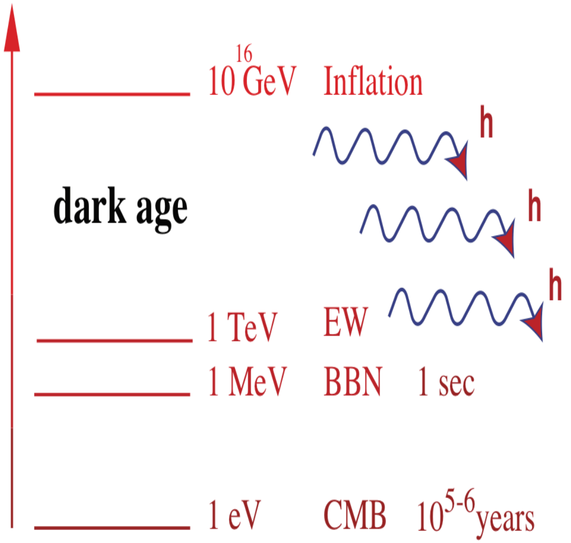
Gravitational waves from the early Universe:

Cosmological probes:

$$\gamma \to \text{free-streaming at} \sim 1\text{eV}$$

$$\nu \to \text{streaming at} \sim 1\text{MeV}$$

$$h \to \text{streaming since end of inflation} \sim 10^{?}\text{TeV}$$



Snapshot of the Universe around the Big Bang!

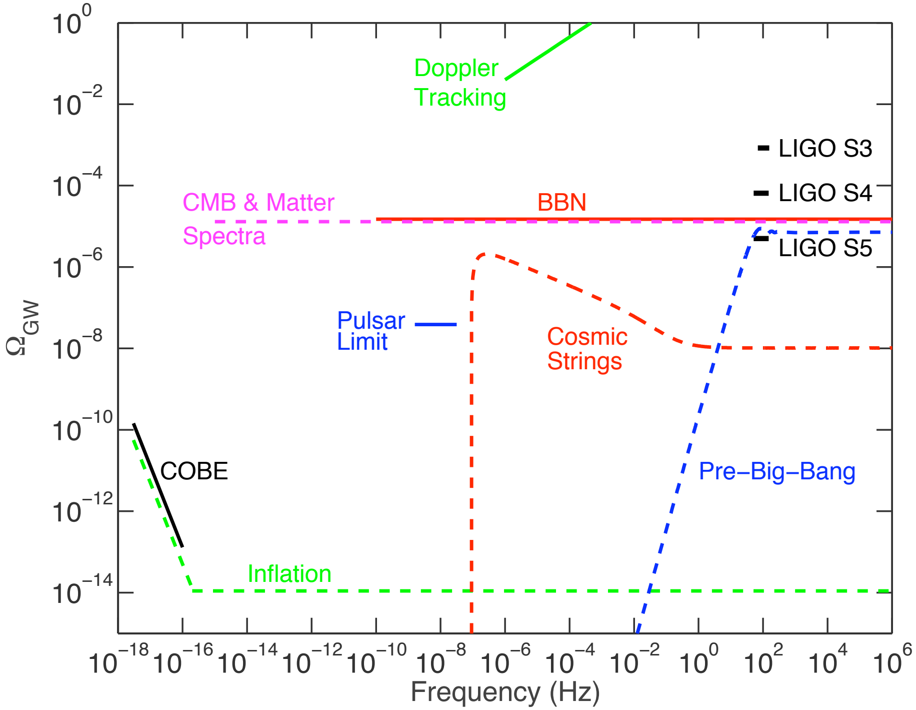
$$ds^2 = a^2\left[-d\tau^2 + (\delta_{ij} + h_{ij})\,dx^i\,dx^j\right]$$

Very clean cosmological probes

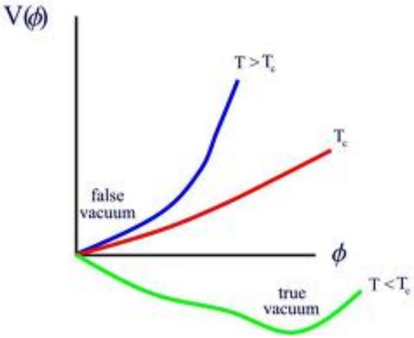
What is the right model of the Universe, soon after the Big Bang?

Unique information from the dark age of the Universe

Possible gravitational-wave signals from early Universe:

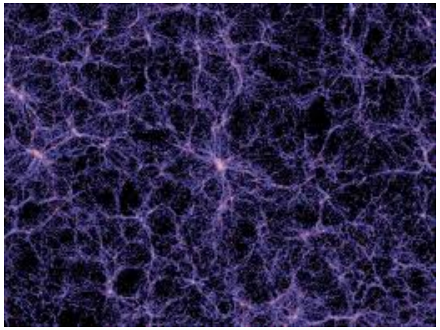


Amplification of quantum-vacuum fluctuations during inflation and subsequent eras.



First-order phase transition between "false" and "true" vacuum. Collision of bubbles of "true" vacuum produce GWs.

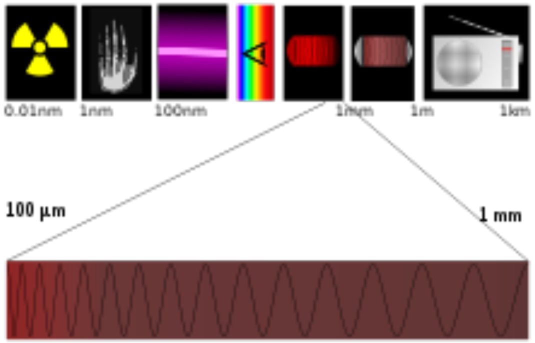
Cosmic (super) strings. Loop oscillations produce GWs.



Stochastic background and powerful bursts from kinks/ cusps.

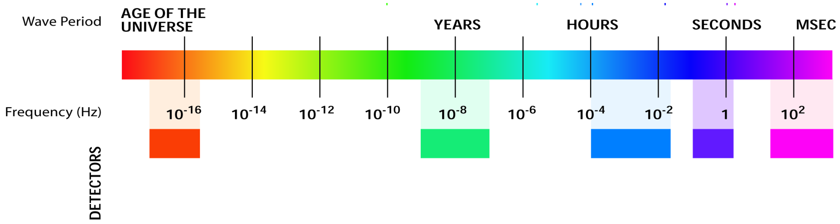
Radical new windows, always big surprises

Electromagnetic radiation



- Radio and X-ray windows have allowed us to discover new objects in the Universe:

  radio galaxies and black holes at their centers, quasars, pulsars, black holes in binary systems, etc.



- Frequencies to be opened spanned 19 orders of magnitude!

- Gravitational waves are far more radical than electro-magnetic radiation. There will be surprises!

Gravitational radiation