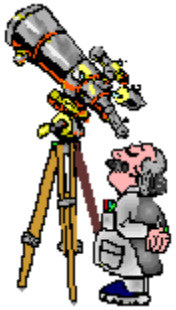
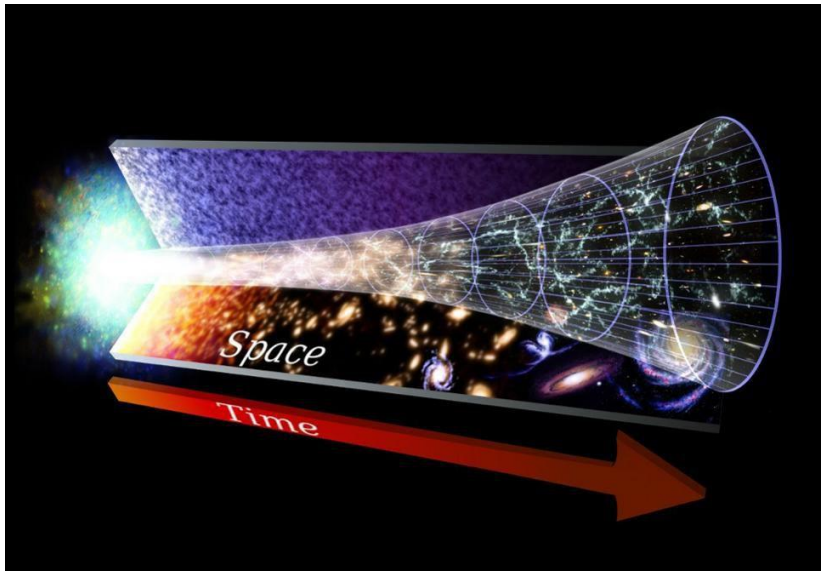
Unde gravitationale

GW

Mircea v. Rusu

Sibiu 2018







Now that gravitational waves have been discovered, it is time to put them to use.

23 March 2016

- The Universe is big and getting bigger all the time. A little-known fact about gravitational waves, the latest cosmological discovery to get physicists excited is that they could help to measure this expansion. And they could show why the expansion has been accelerating, rather than slowing down as expected, under the push of a mysterious force dubbed dark energy. The way in which astronomers conventionally measure distances has ancient roots.

- With ingenuity and a dash of basic trigonometry, the ancient Greek astronomer Aristarchus of Samos was able to measure the Moon's distance from Earth with surprising accuracy — in the third century bc.
- A similar method to Aristarchus', using a concept known as stellar parallax, was first applied to measure a star's distance from Earth in 1838, and is still used today.
- The European Space Agency's Gaia probe is currently using it to compile a state-of-the-art catalogue of one billion stars in the Milky Way, extending the reach of parallax to unprecedented distances and cutting errors down to less than 1%.

- Stellar parallax is good, but it can go only so far. It entails measuring a star's apparent position in the sky at different times of the year, as Earth (or a space probe such as Gaia) orbits the Sun. The distance between the two observing points, measured to high accuracy, provides the base of a triangle. The distant star is at the opposite vertex. The smaller the angle at that vertex, the farther away the star is.
- But because the size of Earth's orbit is fixed, as the vertex moves farther away the angle becomes smaller and smaller, and ultimately impossible to measure with any accuracy. (The basic unit of measurement of astronomical distance, the parsec, is short for 'parallax of one arcsecond', which refers to the size of that angle. One arcsecond is 1/3,600th of a degree, and in typical parallax measurements the angles are much smaller.)

- For objects in more distant galaxies, astronomers have devised steps that build on the parallax method. Each step is a ‘rung’ on what they call the cosmic distance ladder. For example, the distance from Earth of the Andromeda Galaxy, the closest large galaxy to the Milky Way, is estimated by measuring the brightnesses of various types of star in it and comparing them to the brightnesses of similar stars closer to Earth whose parallax is known. Such estimates exploit the fact that similar stars look fainter the farther away they are.
- Andromeda is roughly 780 kiloparsecs (2.54 million light years) away. Telescopes cannot resolve individual stars in galaxies that are hundreds of millions of parsecs away — except when those stars happen to blow up as supernovae. Astronomers use some supernovae as signposts of cosmic distances, or ‘standard candles’, meaning that their measured brightness is an indicator of their distance.

“Stellar parallax is good, but it can go only so far.”

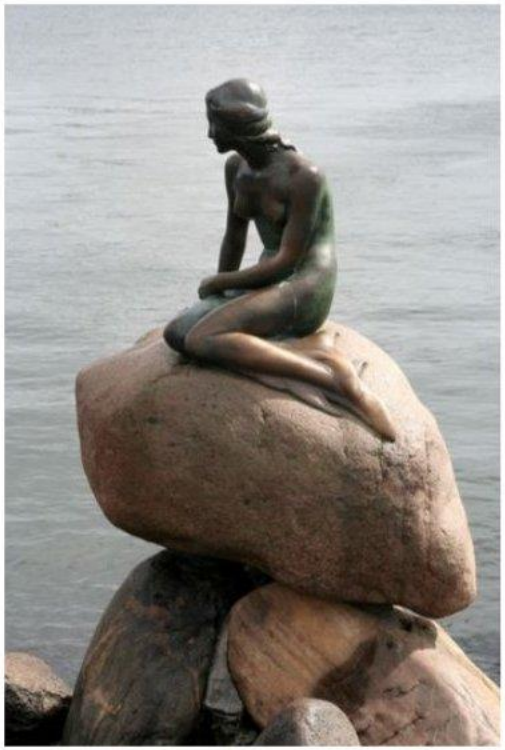
- A major complicating factor is that the observed brightness of distant objects can be affected by foreground matter such as dust. Wouldn’t it be wonderful to have a more direct and reliable way of measuring distances — one that were as precise as Gaia and worked at scales from the galactic to the cosmic?
- Beginning with a paper in this journal 30 years ago (B. F. Schutz *Nature* **323,** 310–311; 1986), physicists have suggested that gravitational waves could provide such a tool. The ripples, predicted by Albert Einstein in 1916 as a consequence of his general theory of relativity, travel across the Universe without being dimmed significantly by dust or gas.
- The gravitational waves that struck Earth in September and were recorded by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) carried information that revealed their strength at the source. In theory, this information can be used to work out the source’s distance

- In the next few years, other interferometers are scheduled to join LIGO to form a global network of gravitational-wave observatories. Together, these instruments could calculate the positions and distances of merger events.
- Neutron-star mergers are especially interesting to cosmologists because they should also produce bursts of short, high-energy γ-rays, which would help to pinpoint their galaxies of origin.
- Researchers hope that they will be able to use information from mergers as a way to calculate the distances of known galaxies. Because gravitational waves are more similar to sound than they are to light, physicists have dubbed these potential signposts ‘standard sirens’.

Standard sirens

GW emission by compact binaries can be used as
SuperNovae Ia (standard candles)
to test the content of the universe





One of the main uses of supernova standard candles has been to measure the current rate of cosmic expansion. Standard sirens could provide an independent way to do this. And, if space-based interferometers are added to the network, they could be used to track dark energy. Hear the call.

und die gesuchten allgemeinen [illegible]
Gravitation in gemischter Form. Anstelle von (47) ergibt
sich daraus rückwärts das System

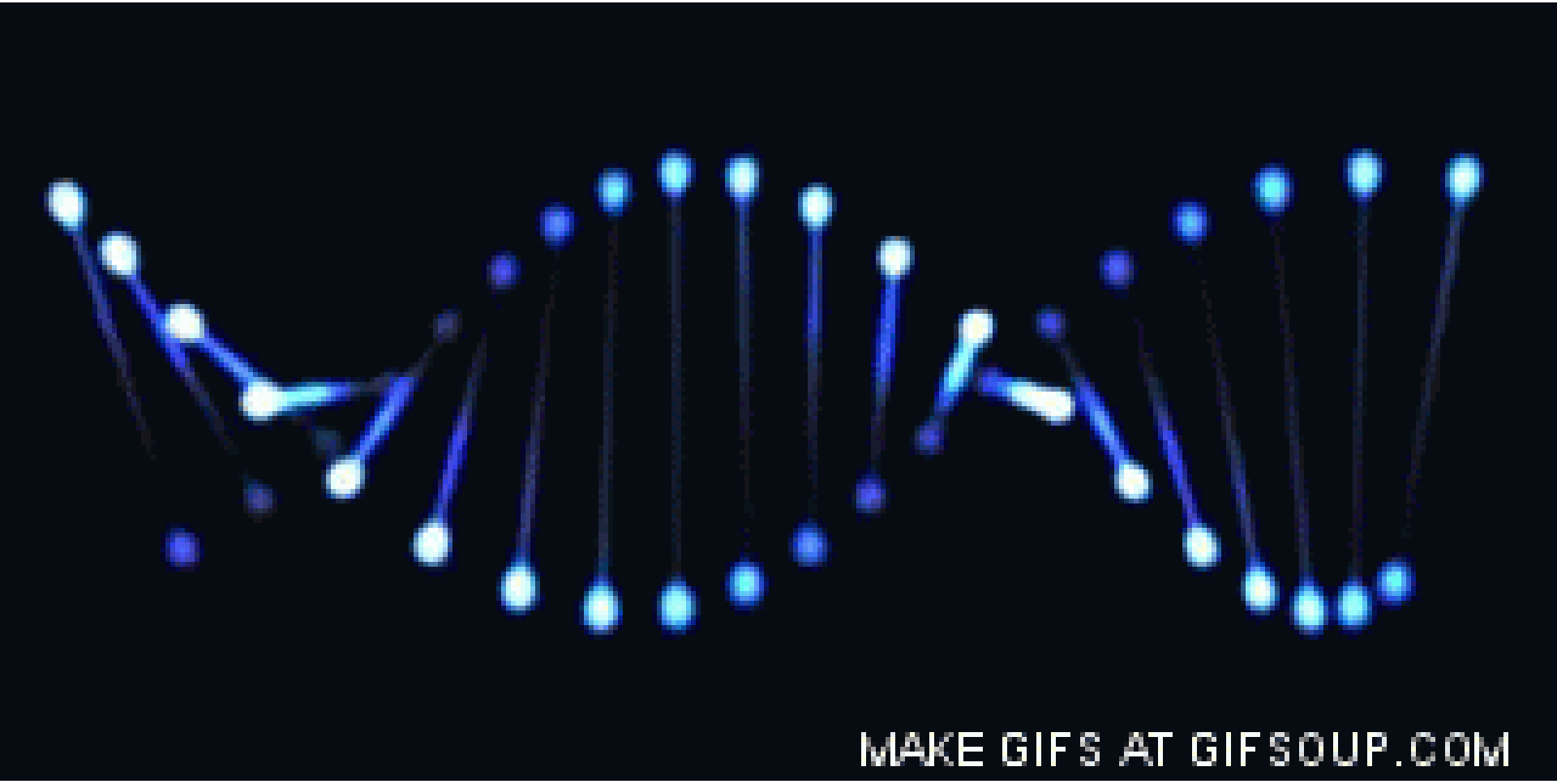
$$\left.\begin{aligned} \frac{\partial \Gamma^{\alpha}_{\mu\nu}}{\partial x_\alpha} + \Gamma^{\alpha}_{\mu\beta}\Gamma^{\beta}_{\nu\alpha} &= -\kappa\left(T_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} T\right) \\ \sqrt{-g} &= 1. \end{aligned}\right\} (53).$$

Es muss zugegeben werden, dass diese Einführung des
Energietensors der Materie durch das Relativitätsprinzip
allein nicht gerechtfertigt wird. Deshalb haben wir
im Vorigen ~~durch die~~ aus der Forderung ~~motiviert~~ abgeleitet, dass die Trägheit
des Gravitationsfeldes in gleicher Weise gravitierend wirke
soll, wie jegliche Energie anderer Art. Der stärkste Grund
für die Wahl der vorstehenden Gleichungen liegt aber darin

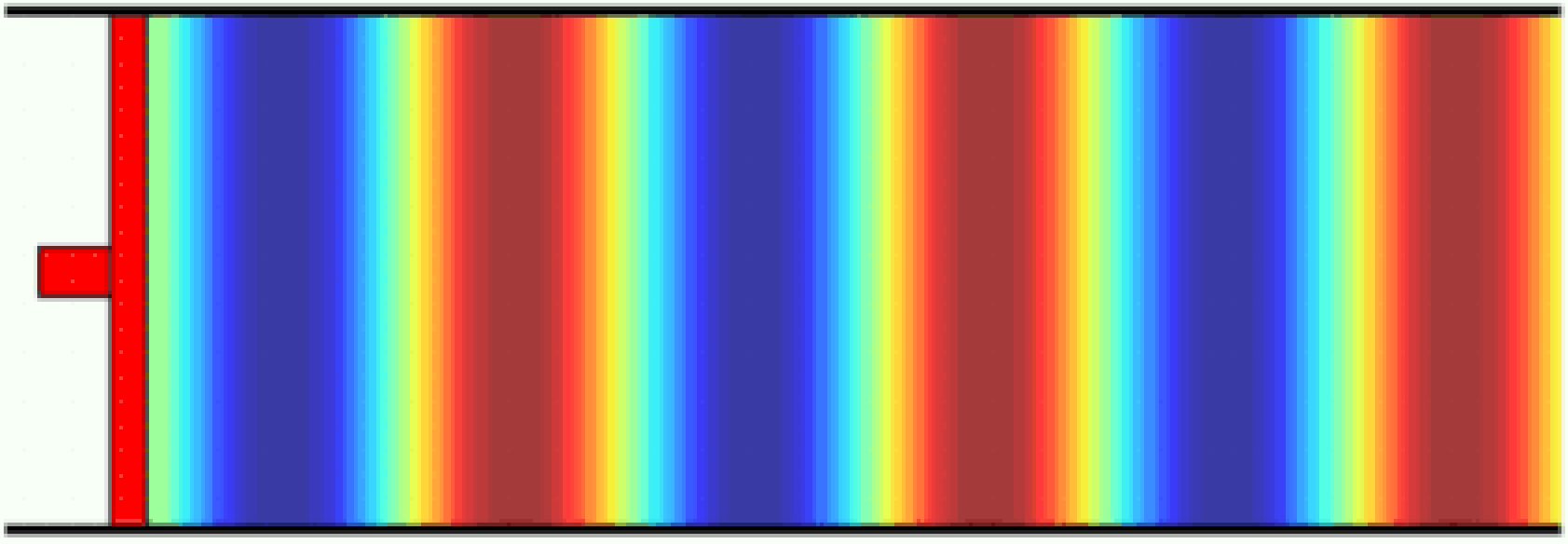
$\Gamma^{\alpha}_{\sigma\tau} = \Gamma^{\alpha}_{\tau\sigma}$ und $g^{\sigma\beta}\Gamma^{\alpha}_{\sigma\tau} = \Gamma^{\alpha\beta}$ sollen symmetrische Tensoren sein

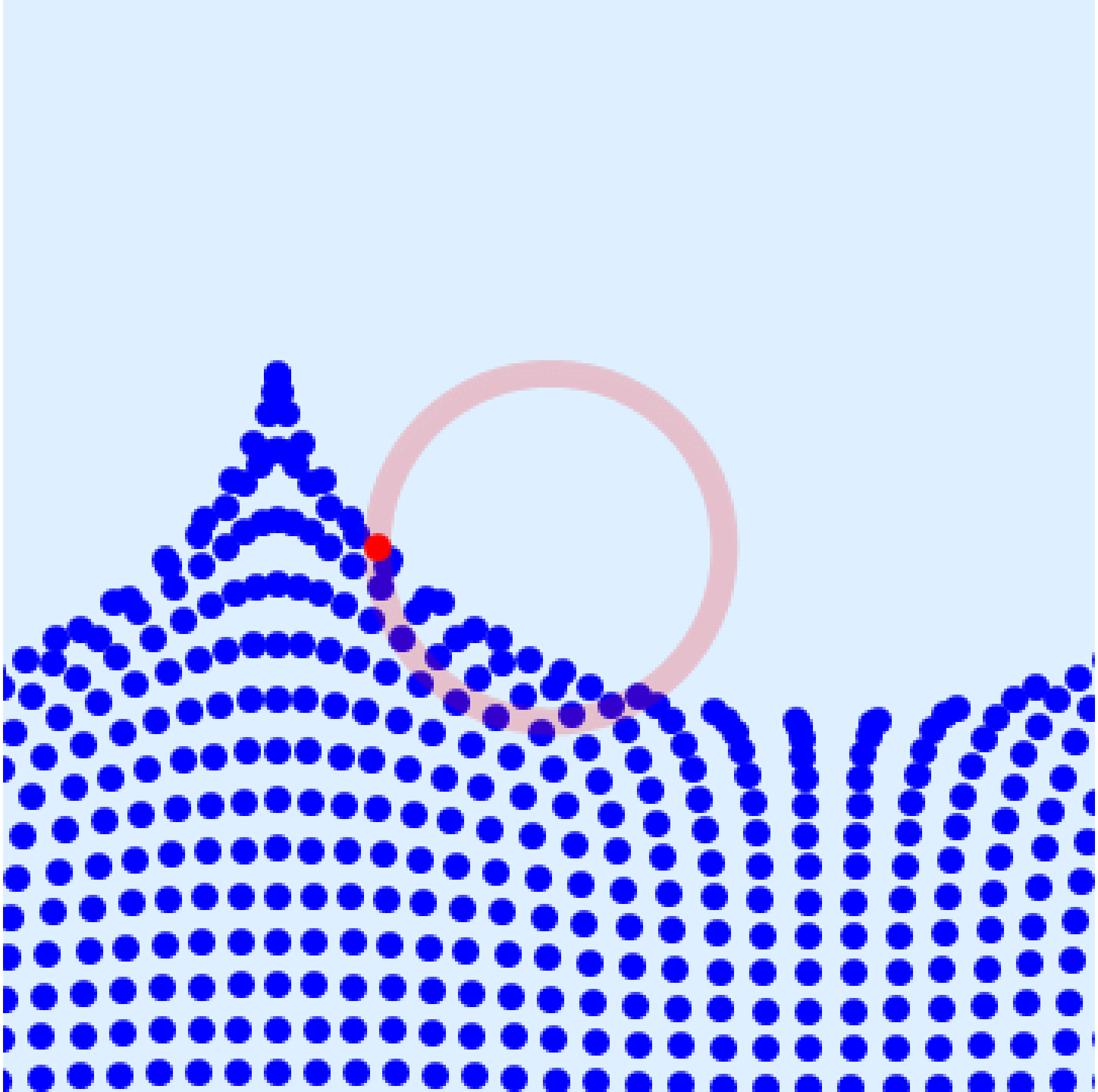
Albert Einstein Archives
120-788

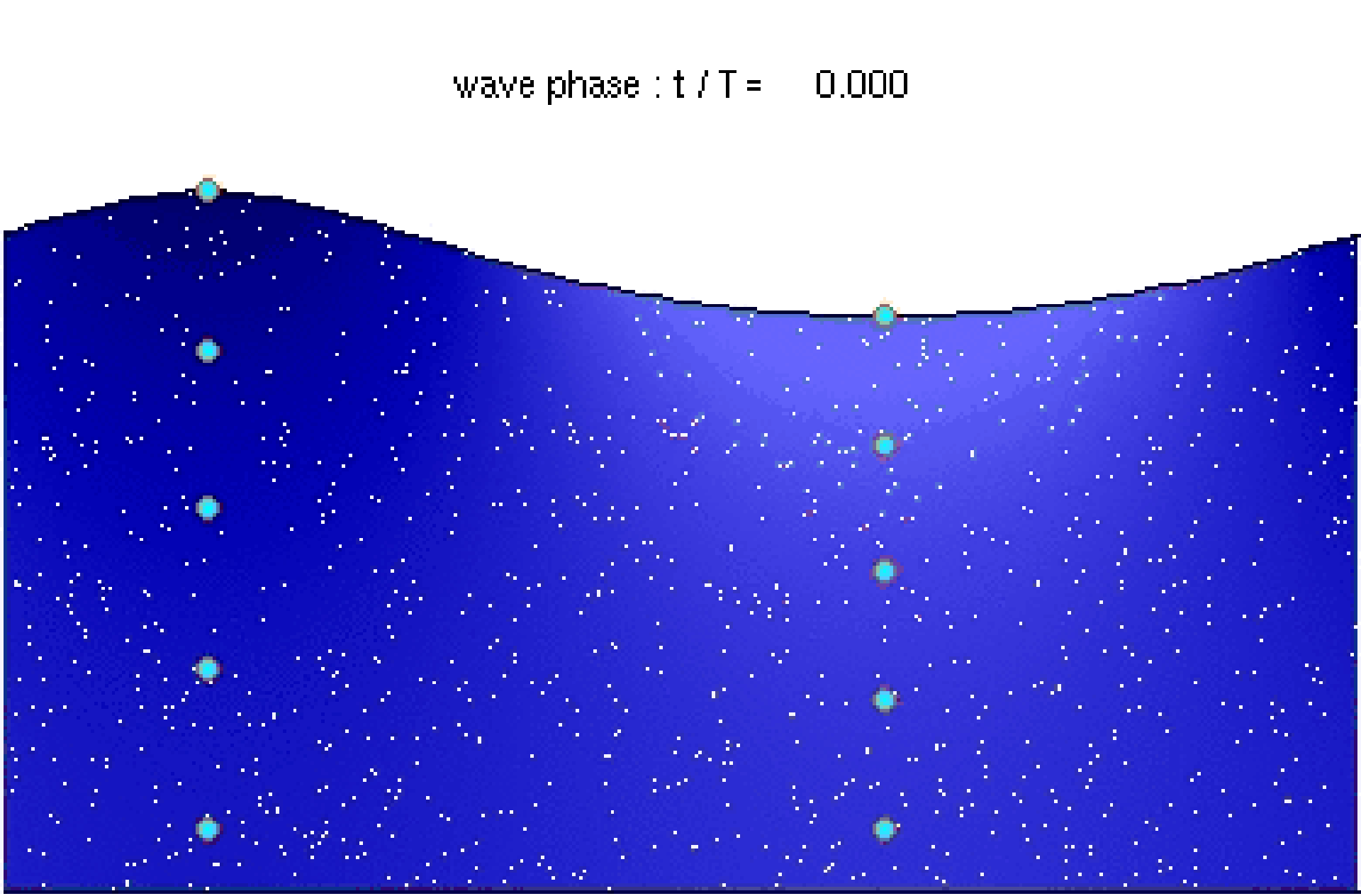
- Unde de toate felurile:
- - undele se propaga si nu se “misca”
- - au viteza finita de propagare (< c)
- - implica sisteme complexe (discontinui sau continui)
- -

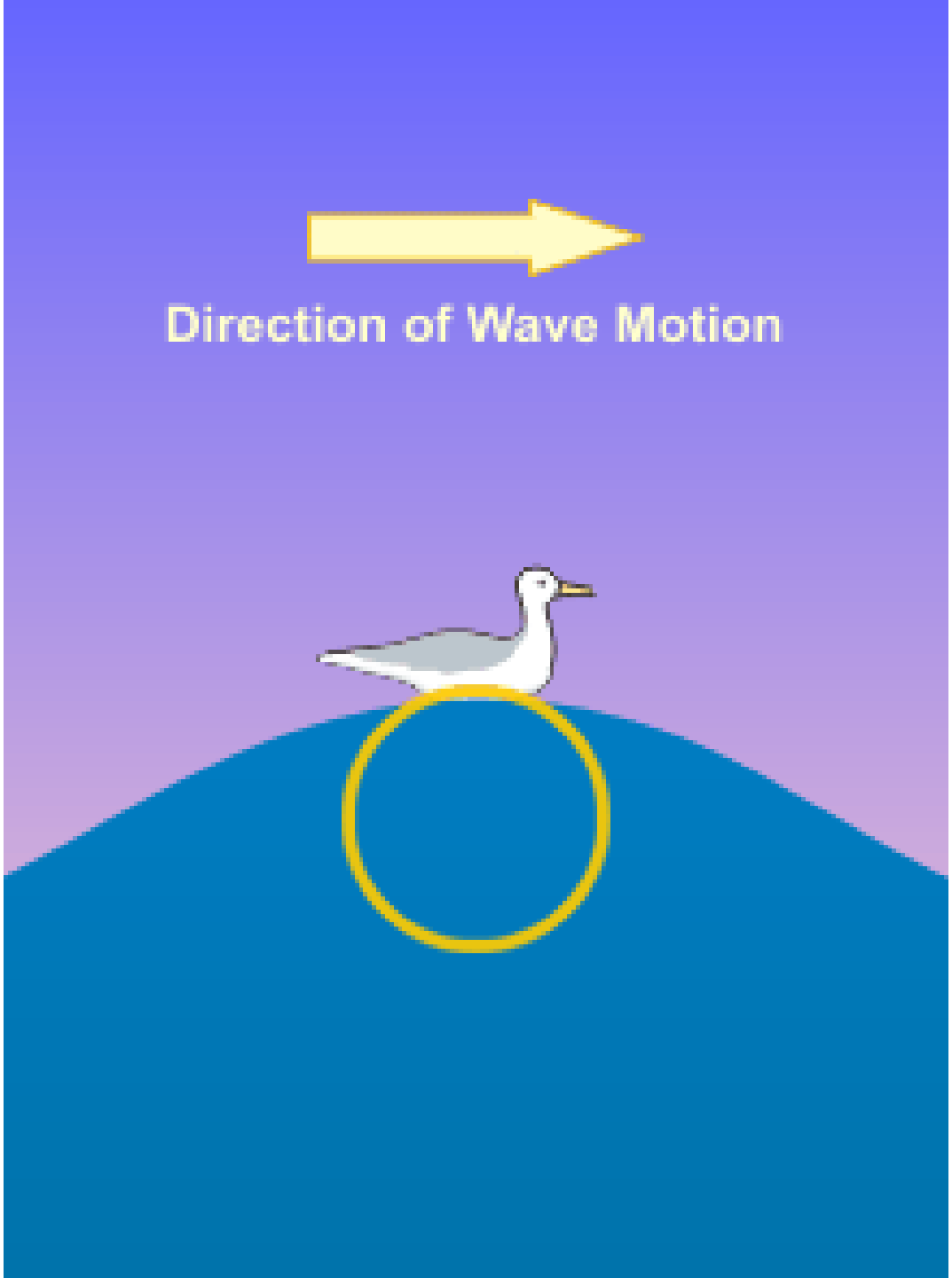

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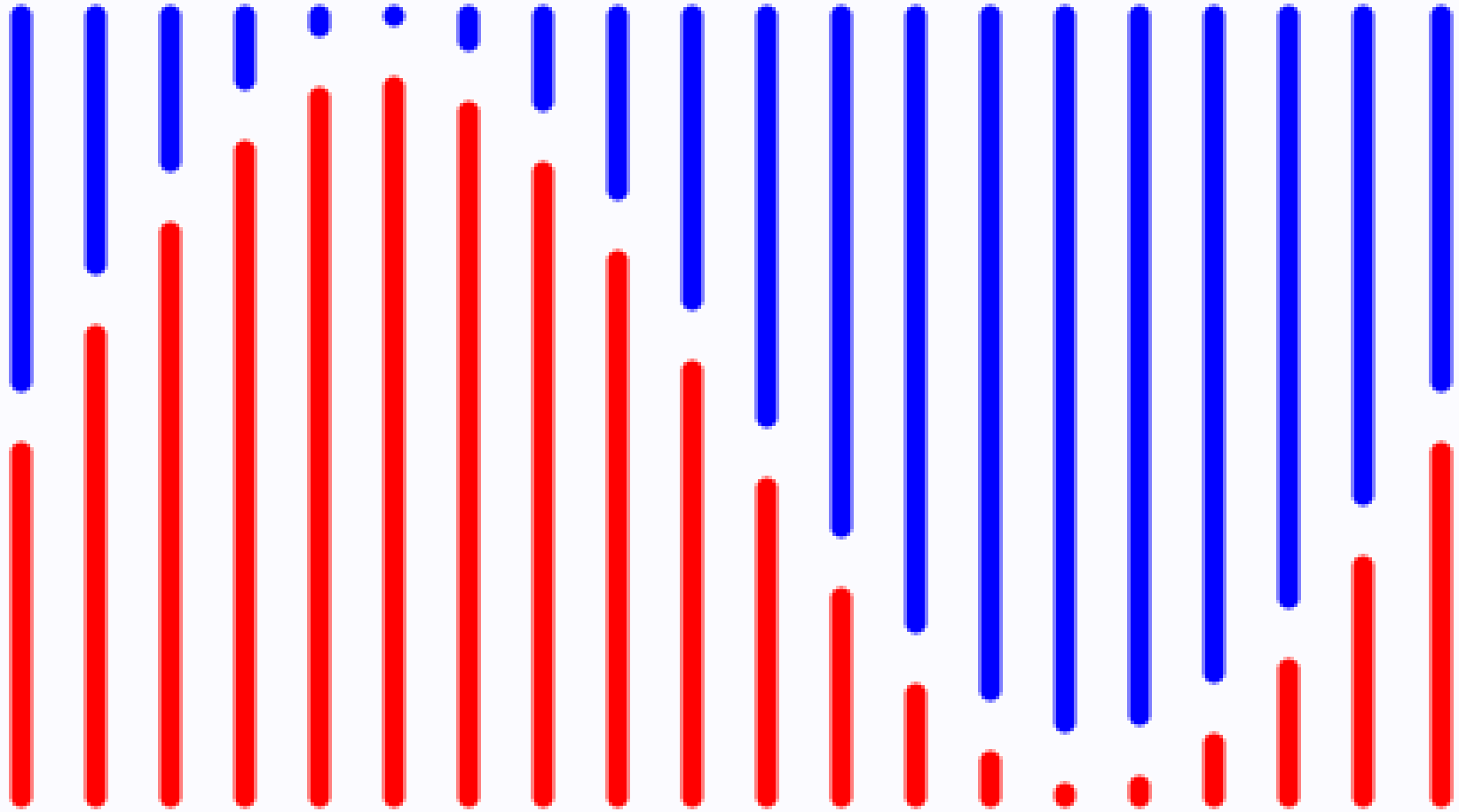
Longitudinal Wave

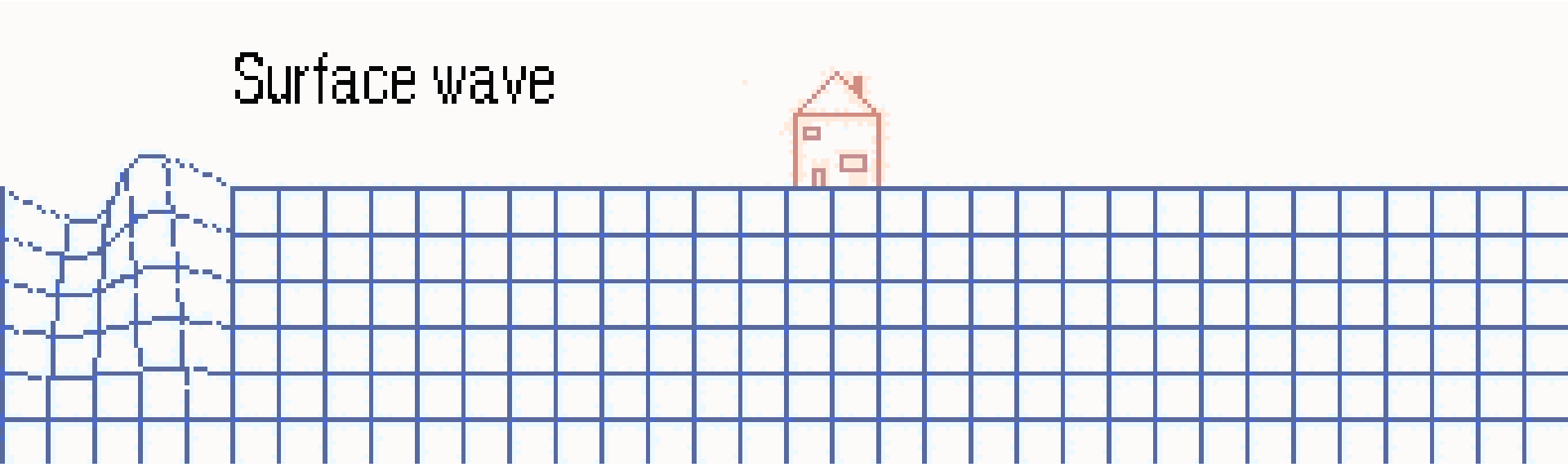


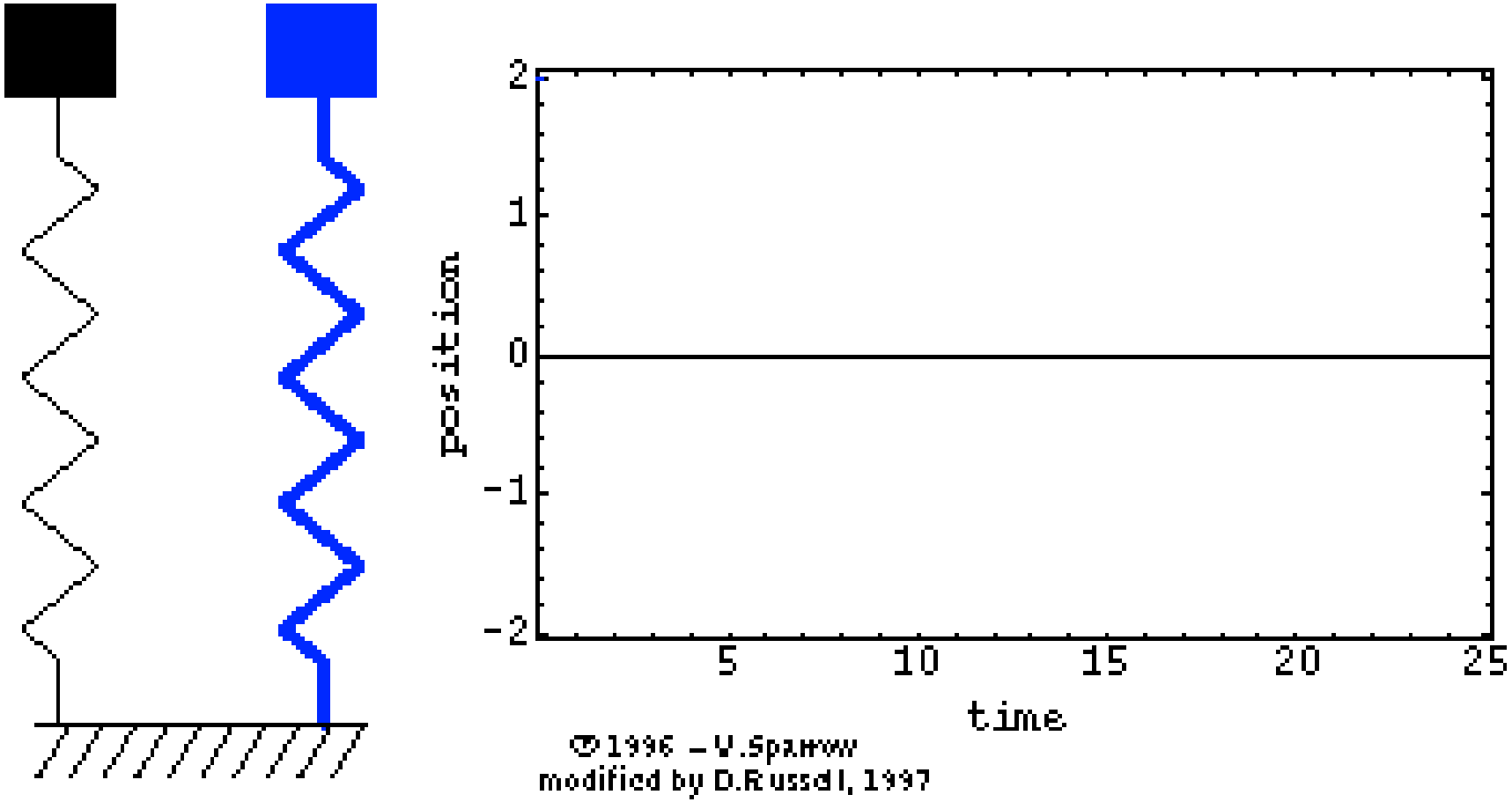


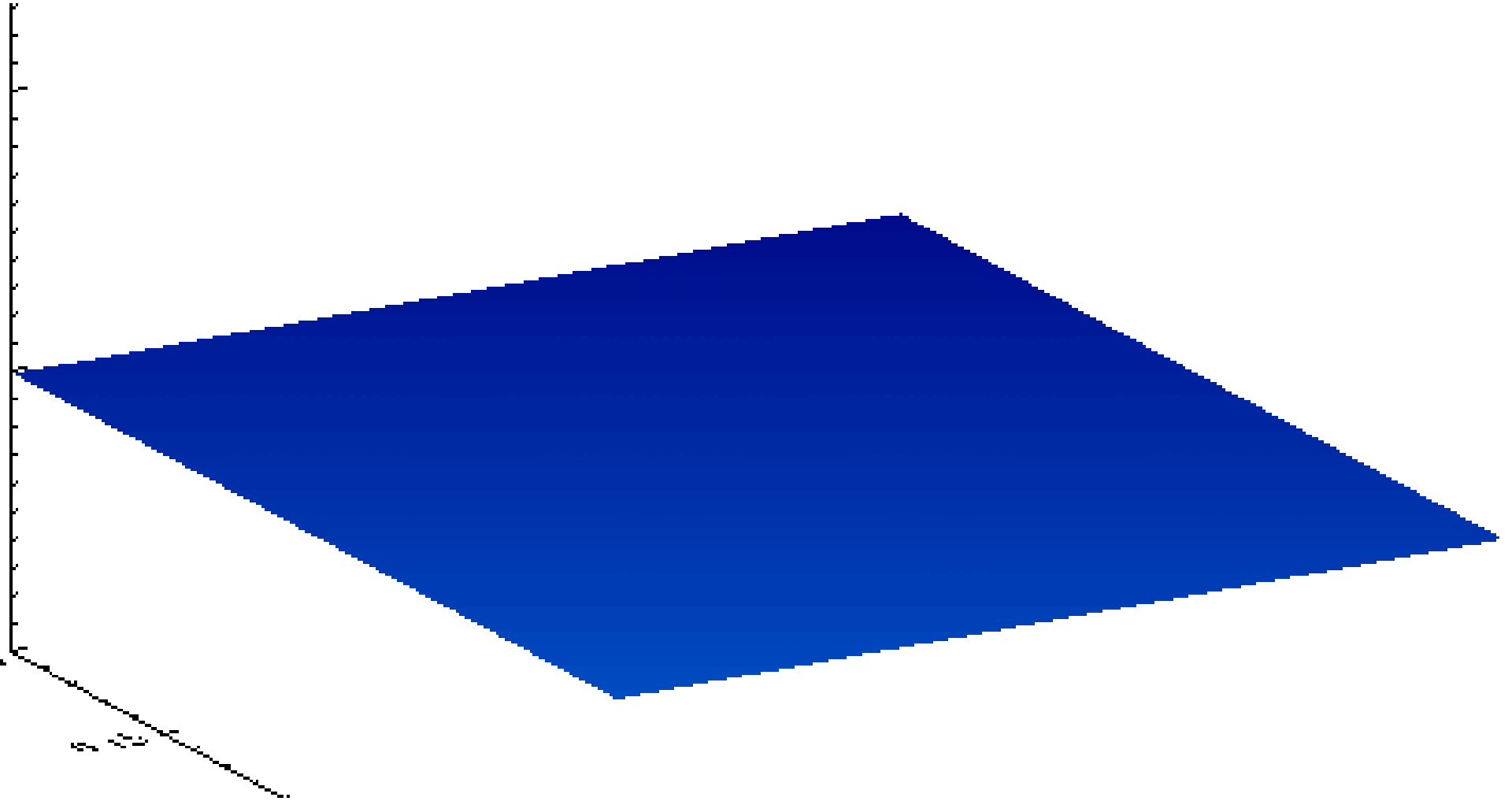

wave phase : t / T = 0.000

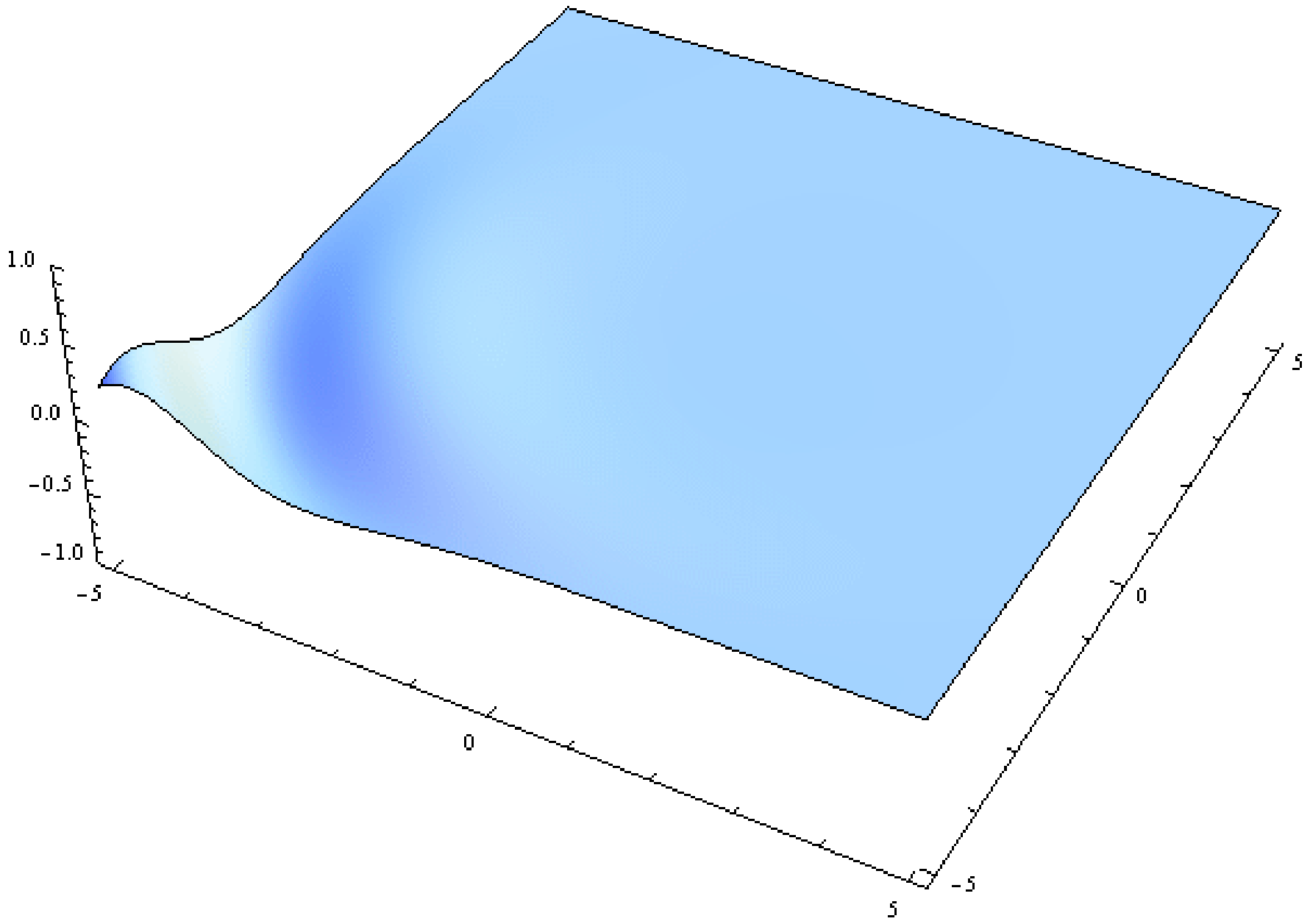

Direction of Wave Motion

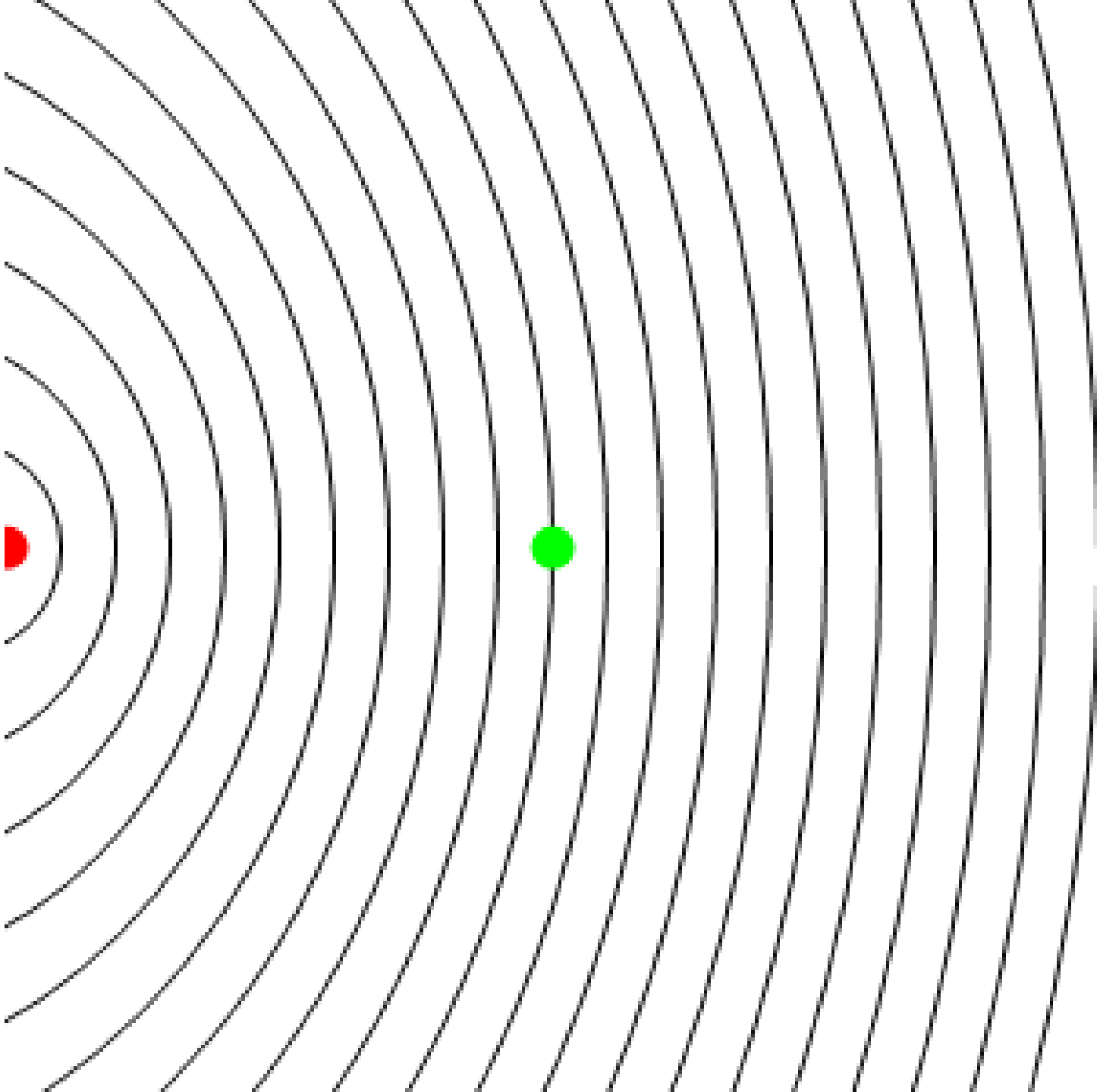



Surface wave


position
time
2
1
0
-1
-2
5
10
15
20
25
©1996 – V.Sparrow
modified by D.Russell, 1997




1.0
0.5
0.0
-0.5
-1.0
-5
0
5
-5
0
5

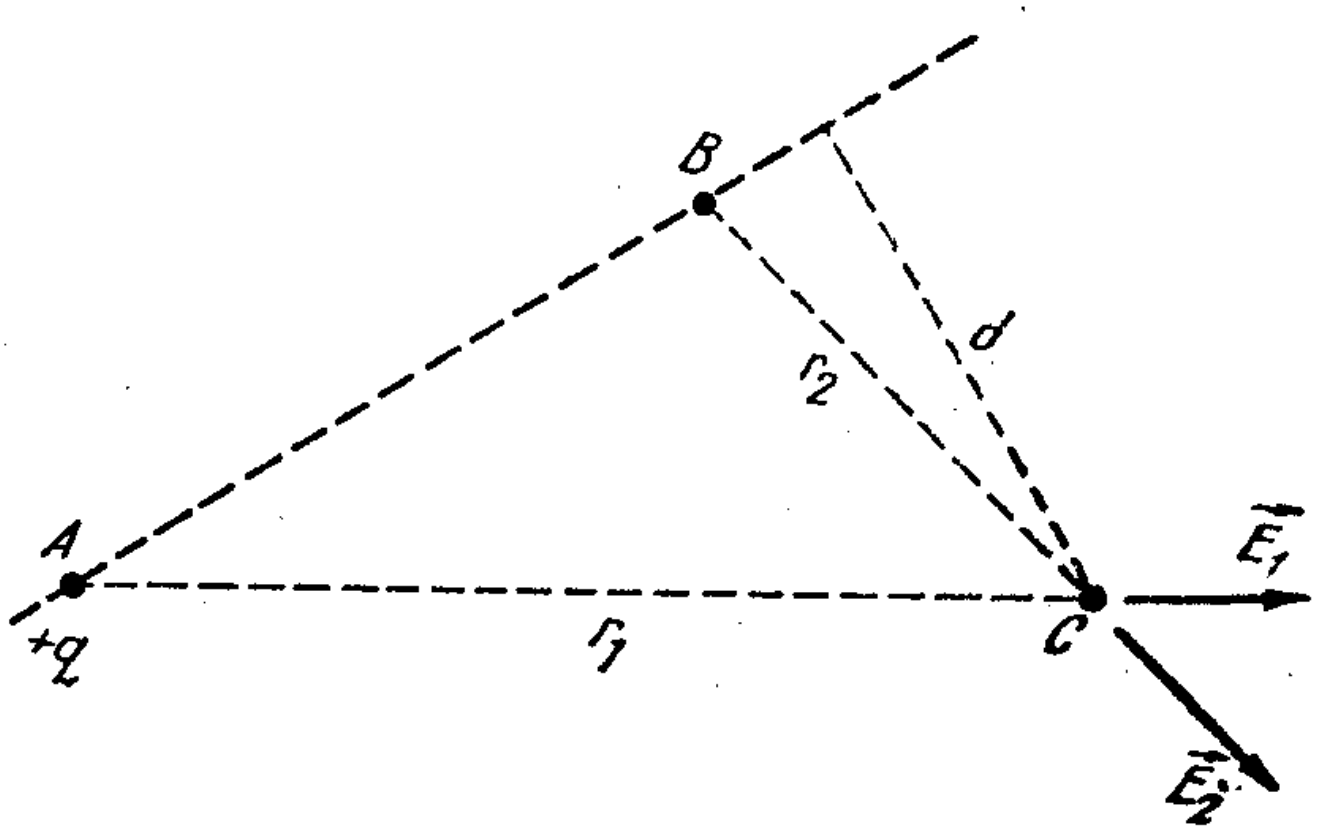


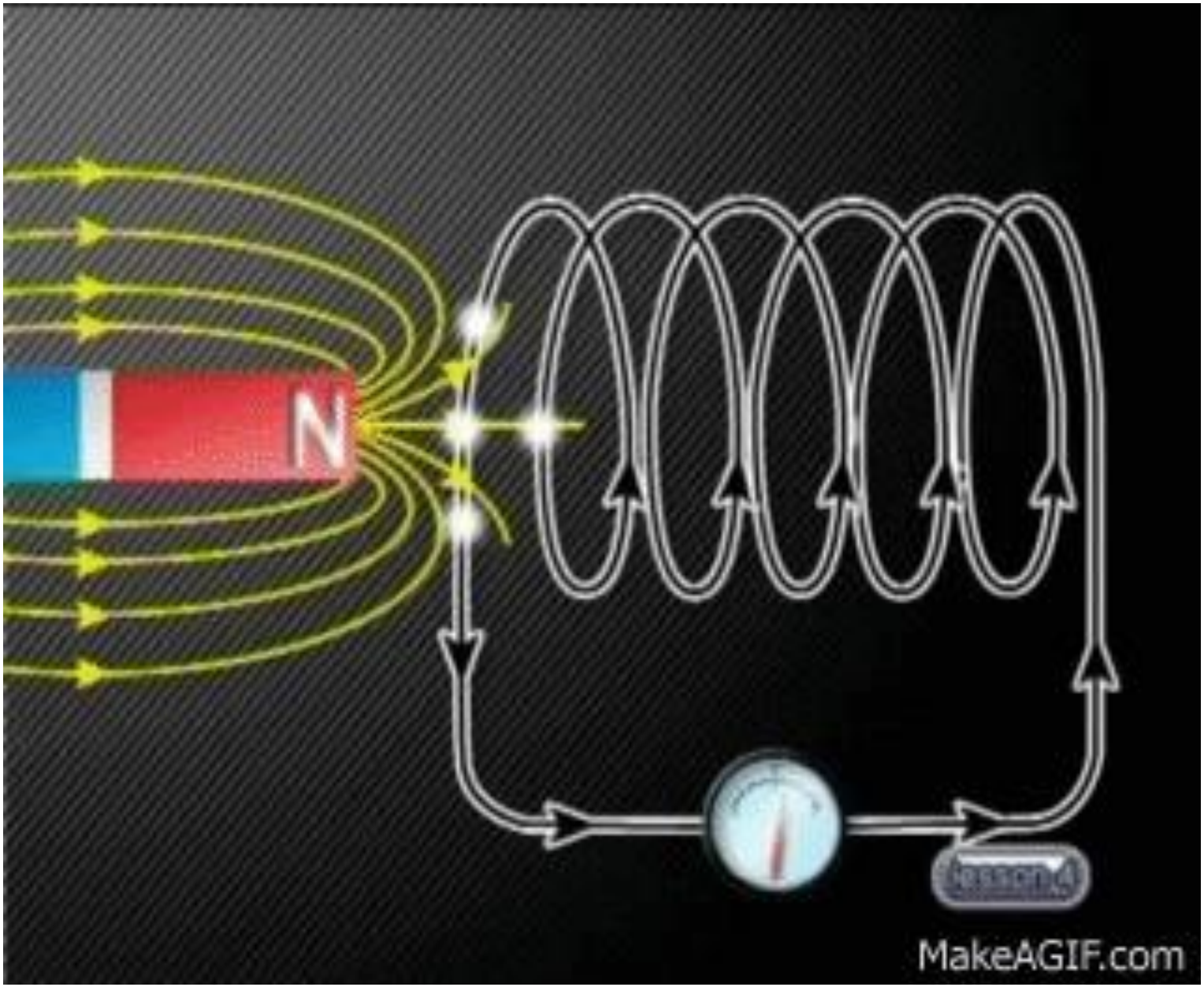
Dece undele electromagnetice sunt mai speciale?

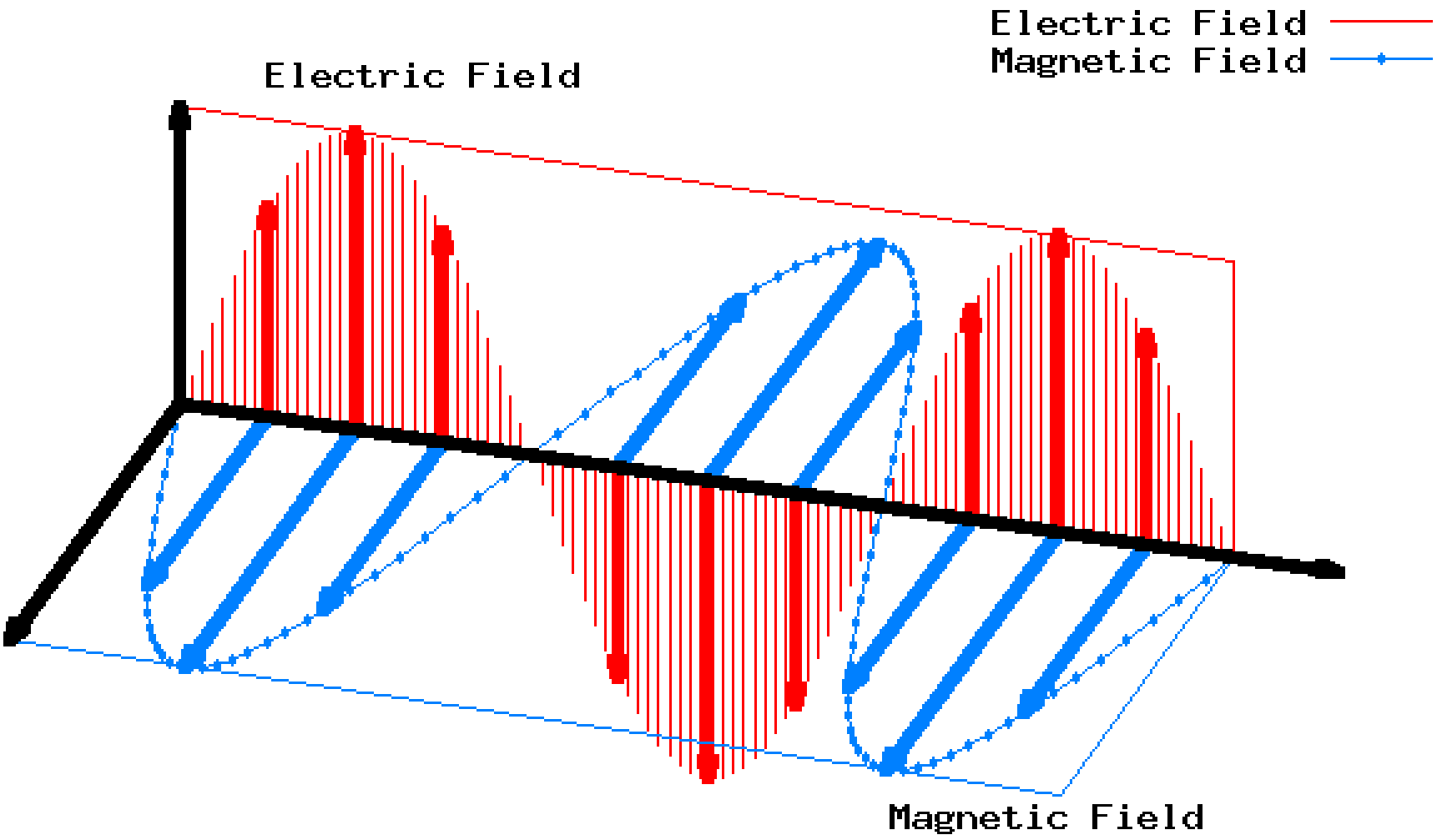
- Se propaga in vid

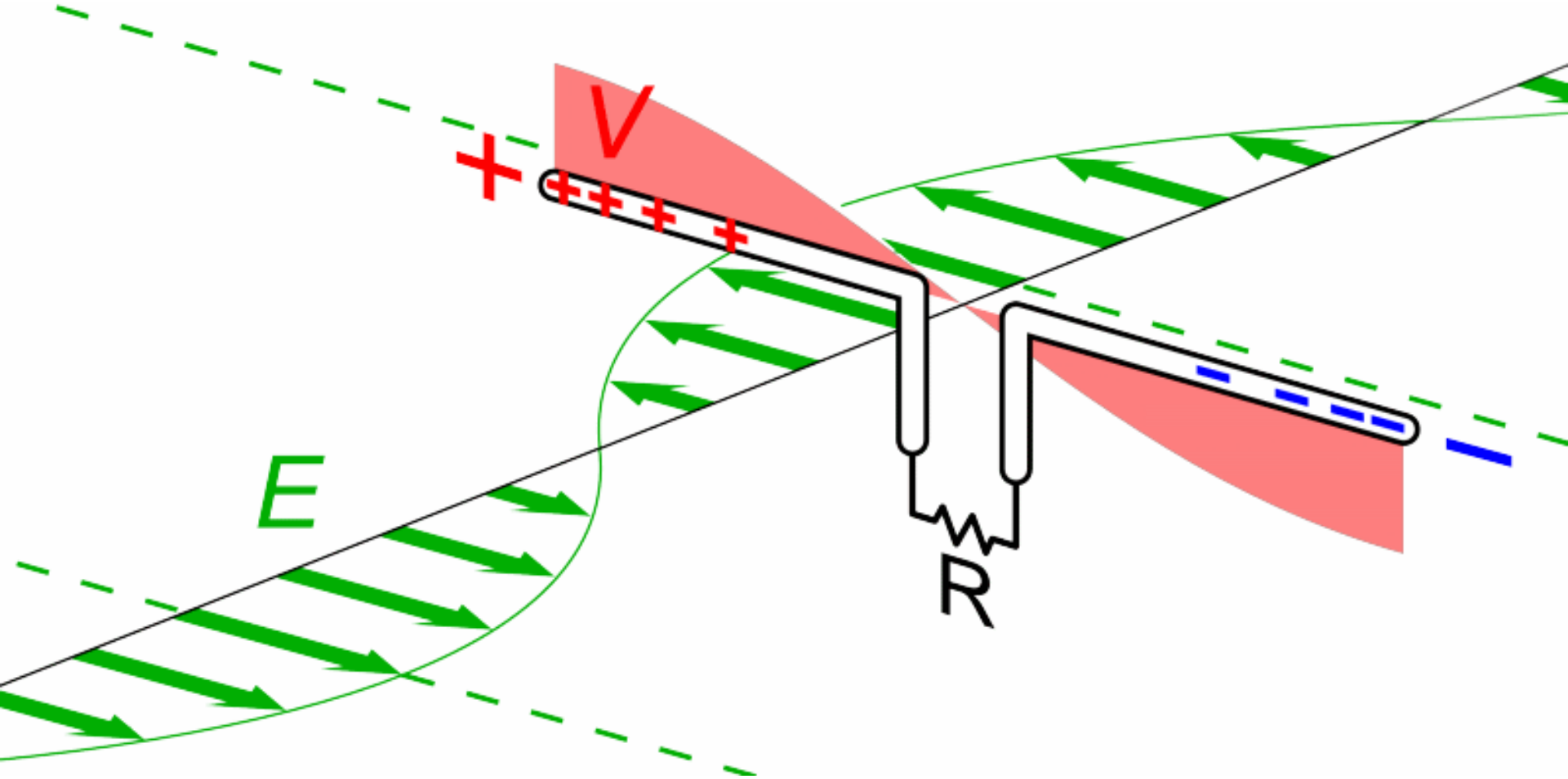
- Sunt transversale

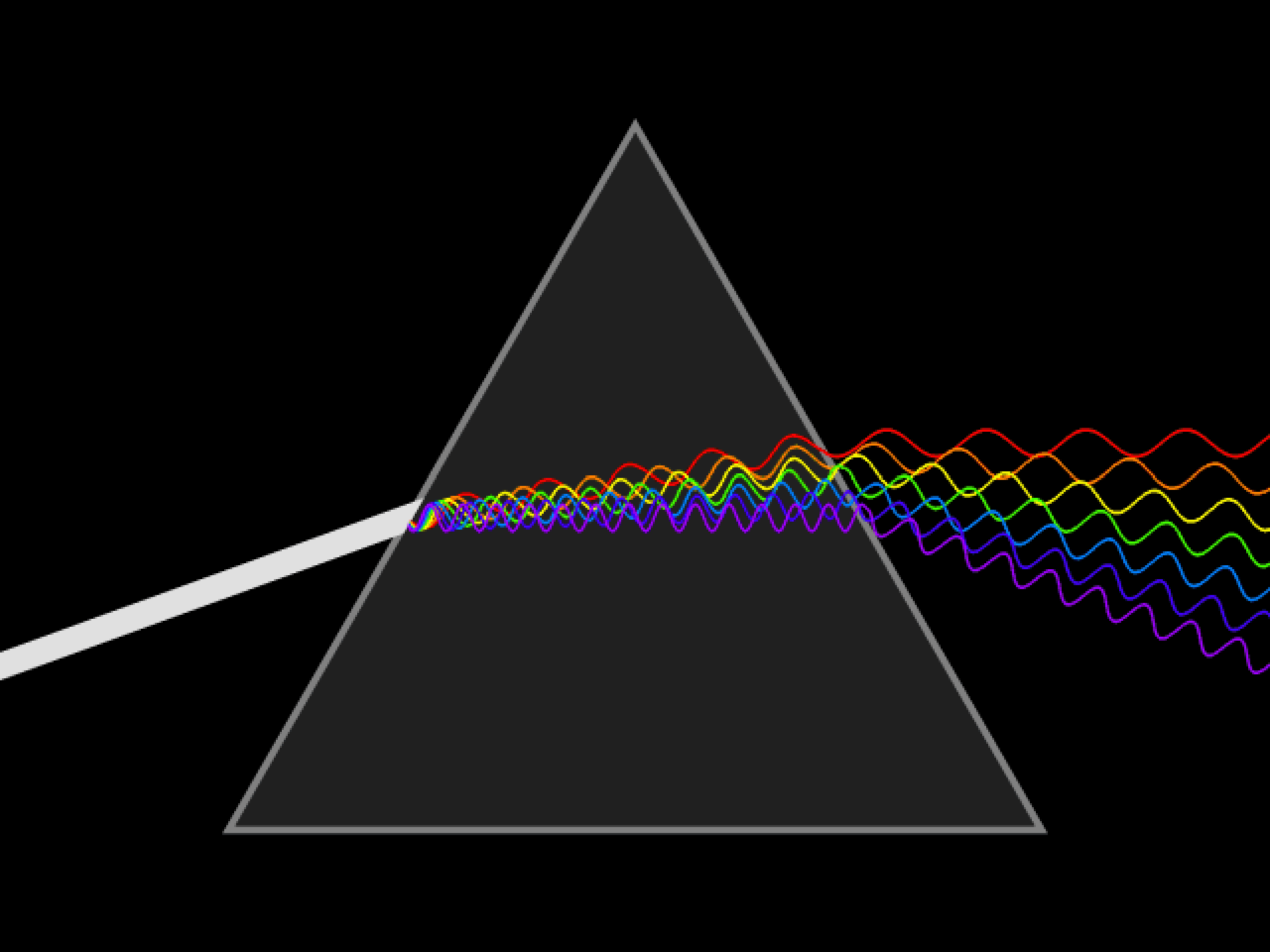
- contin doua componente E si B care se autointretin

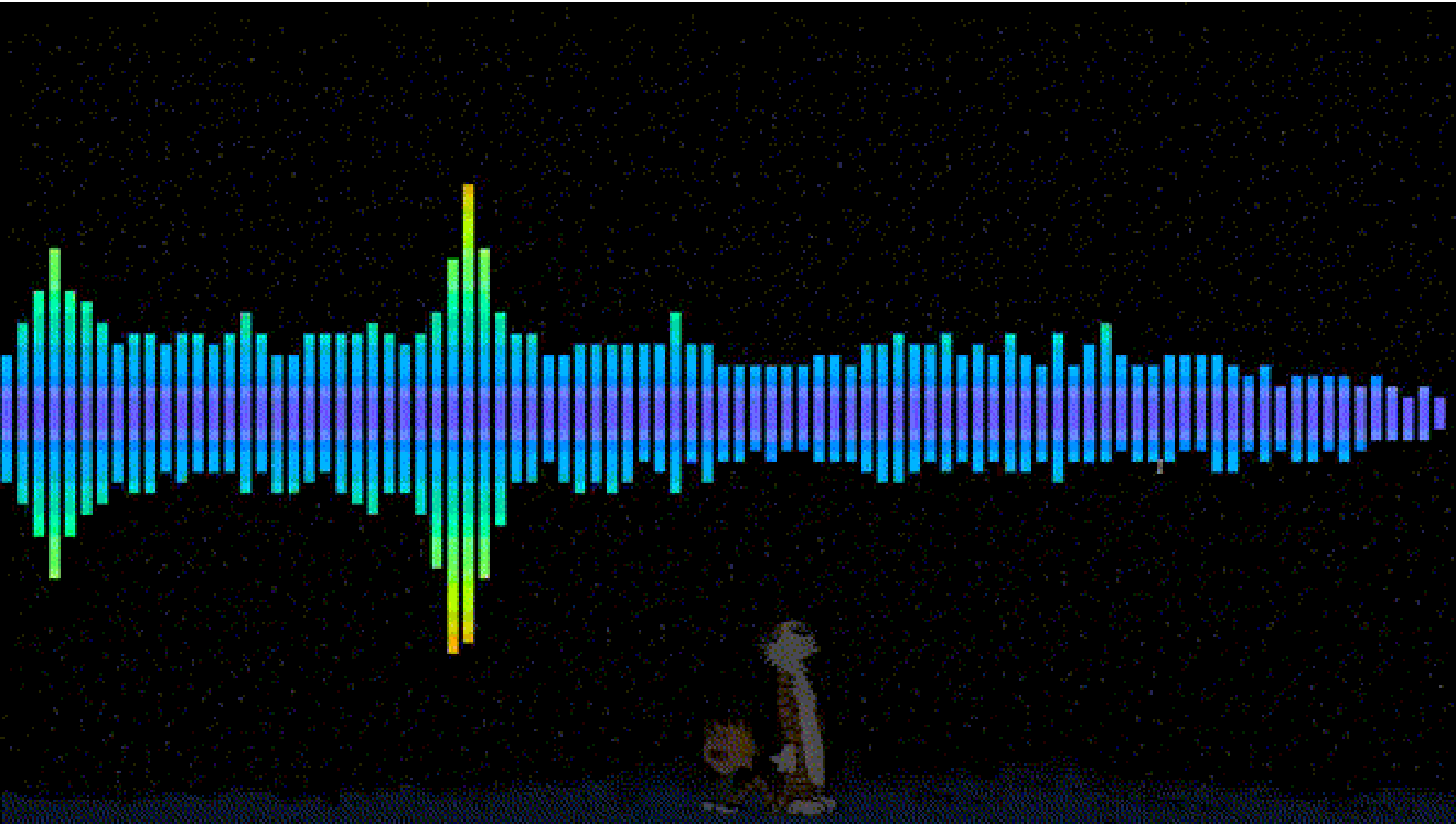


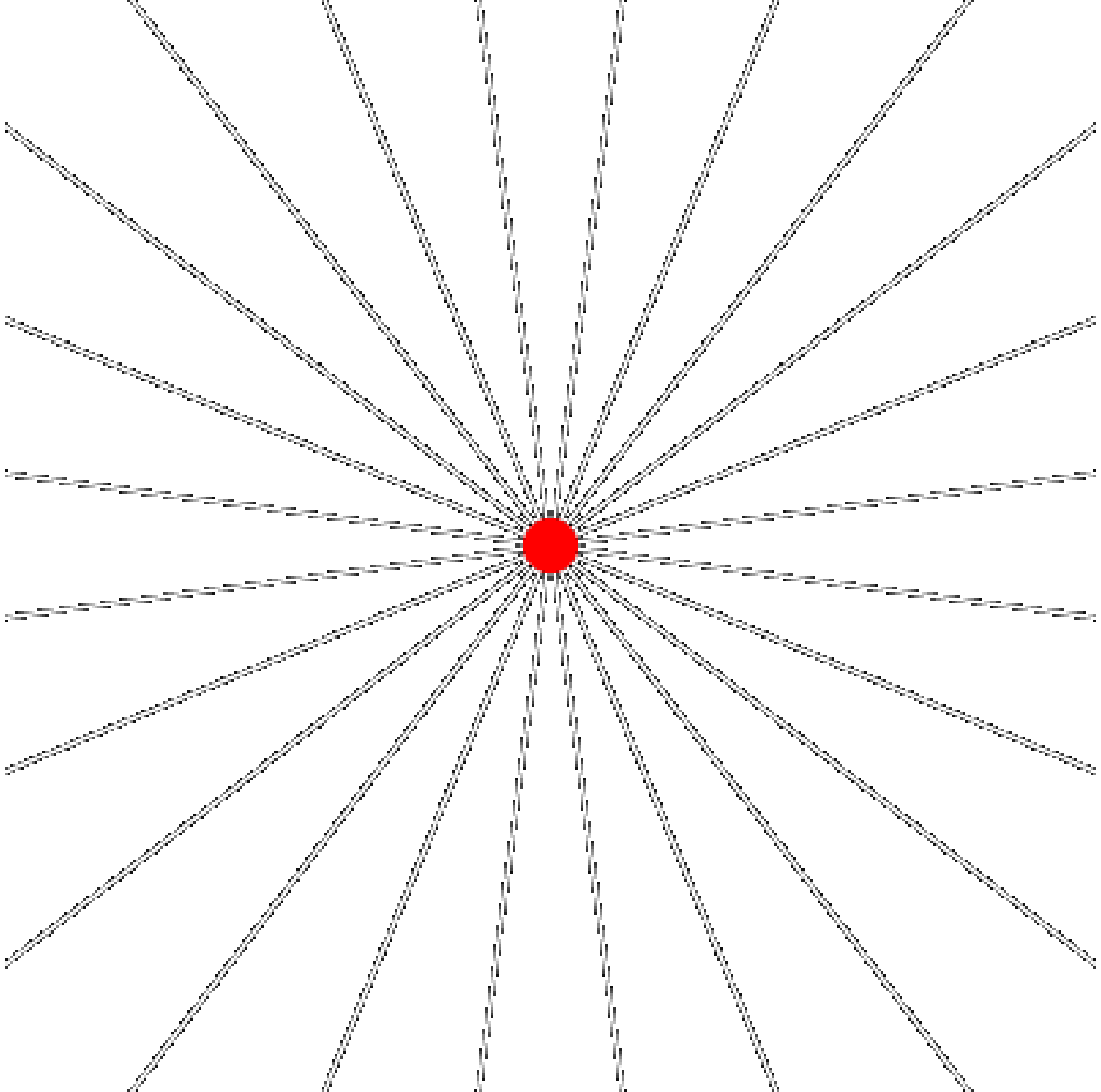

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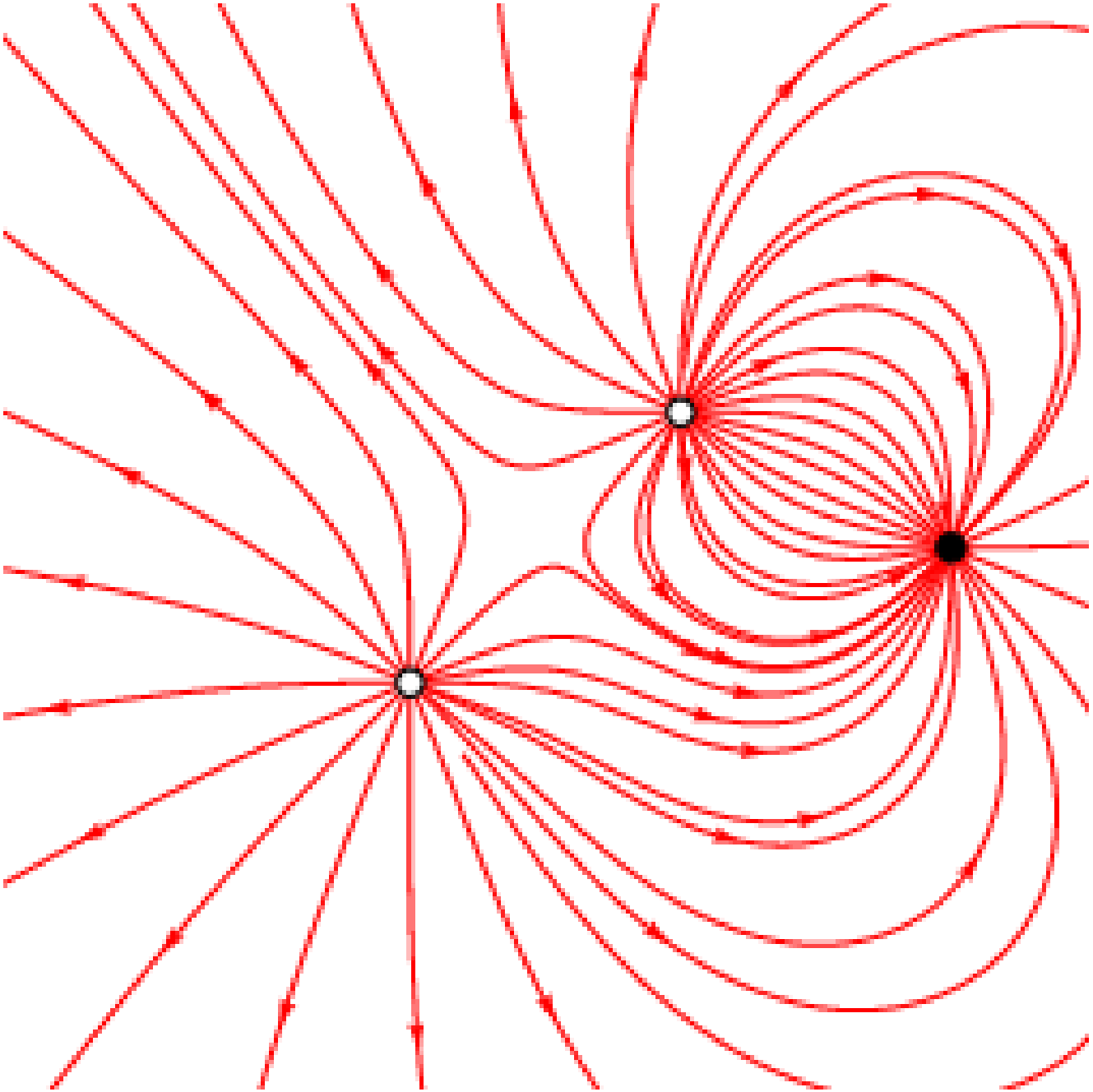

Electric Field
Magnetic Field
Electric Field
Magnetic Field

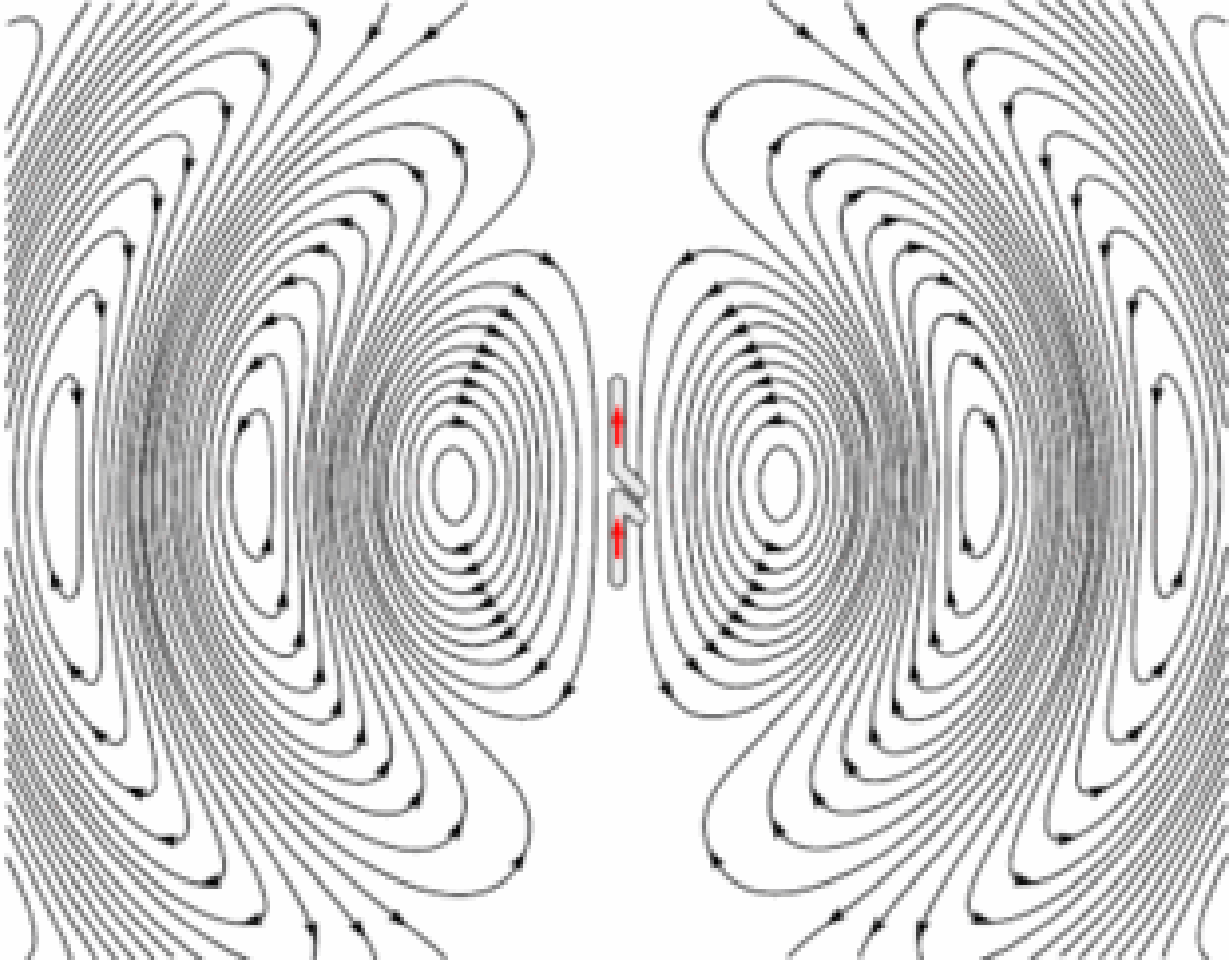

V
+
E
R

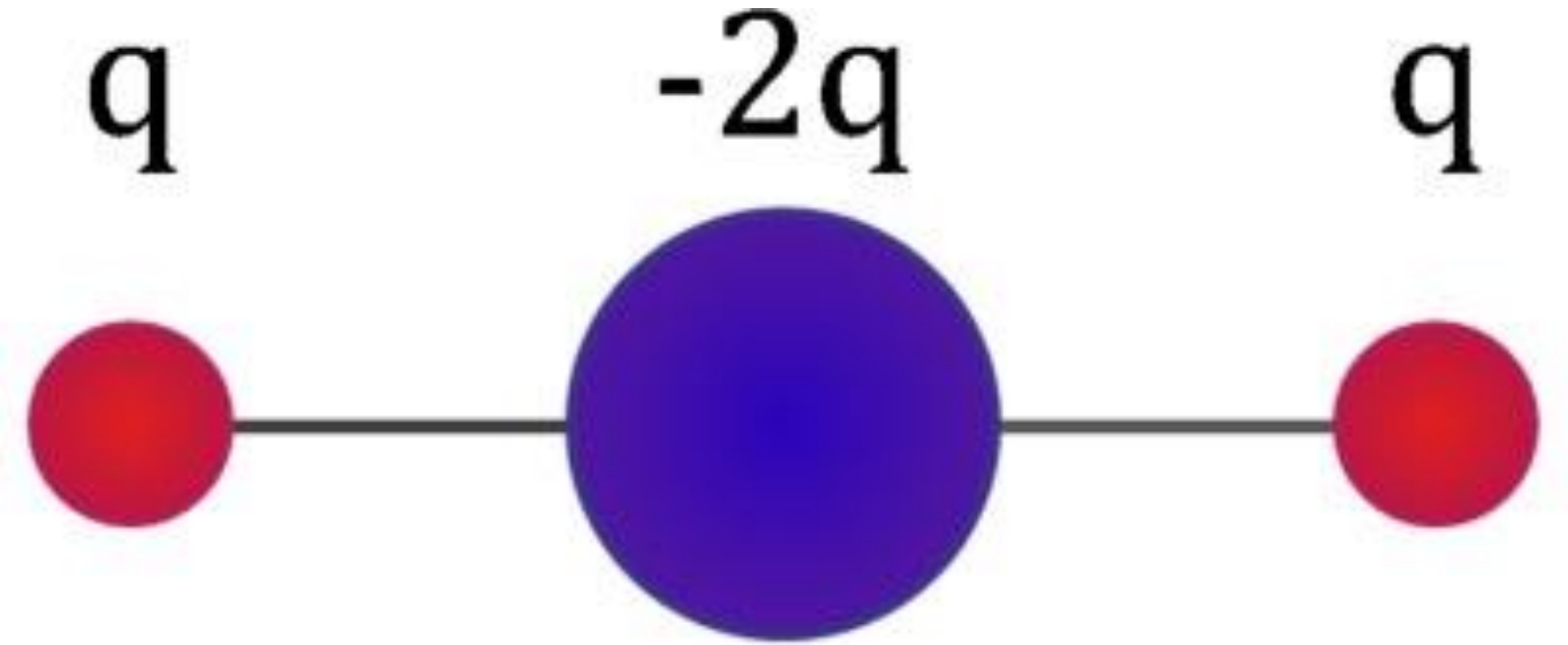




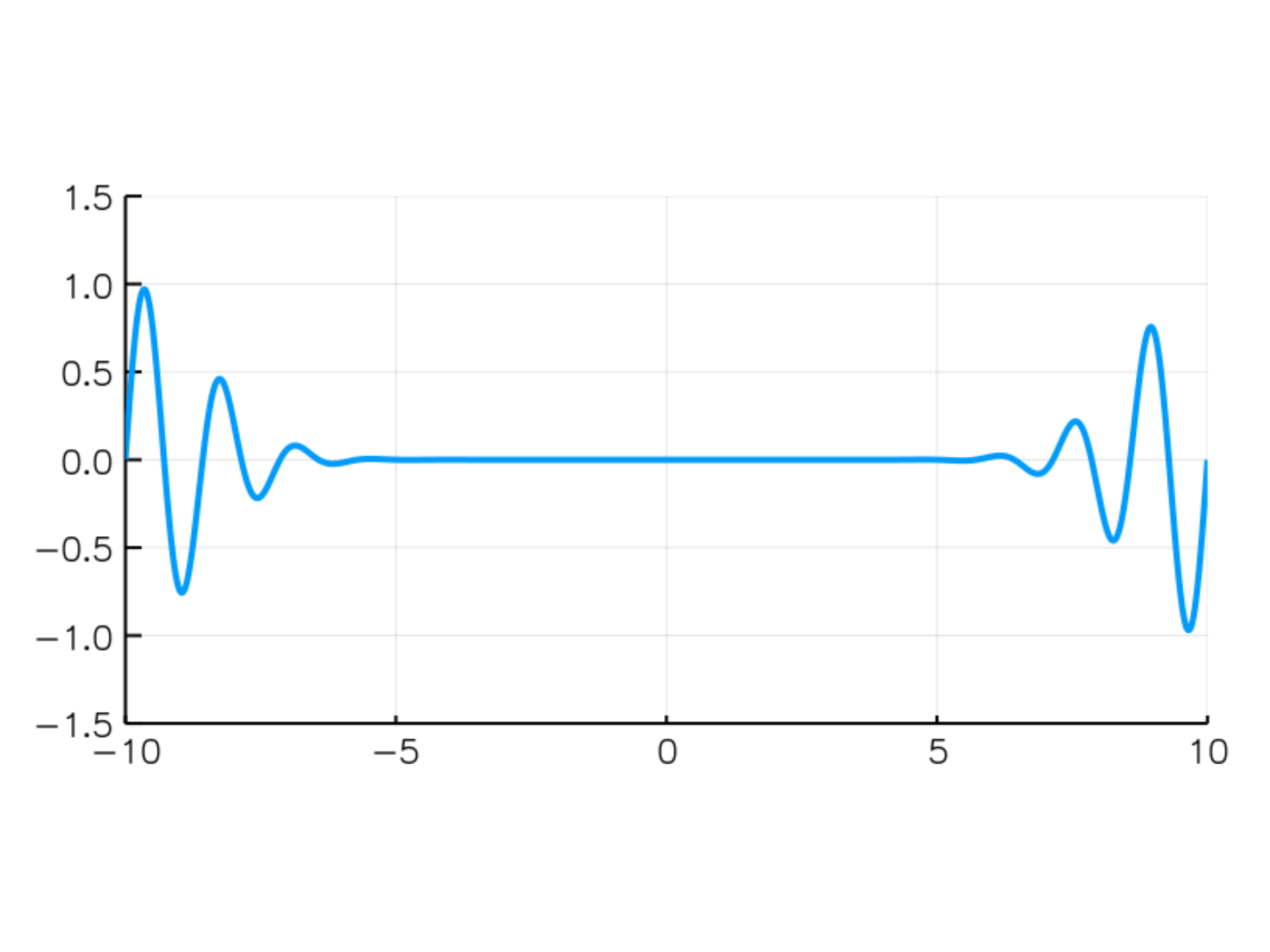


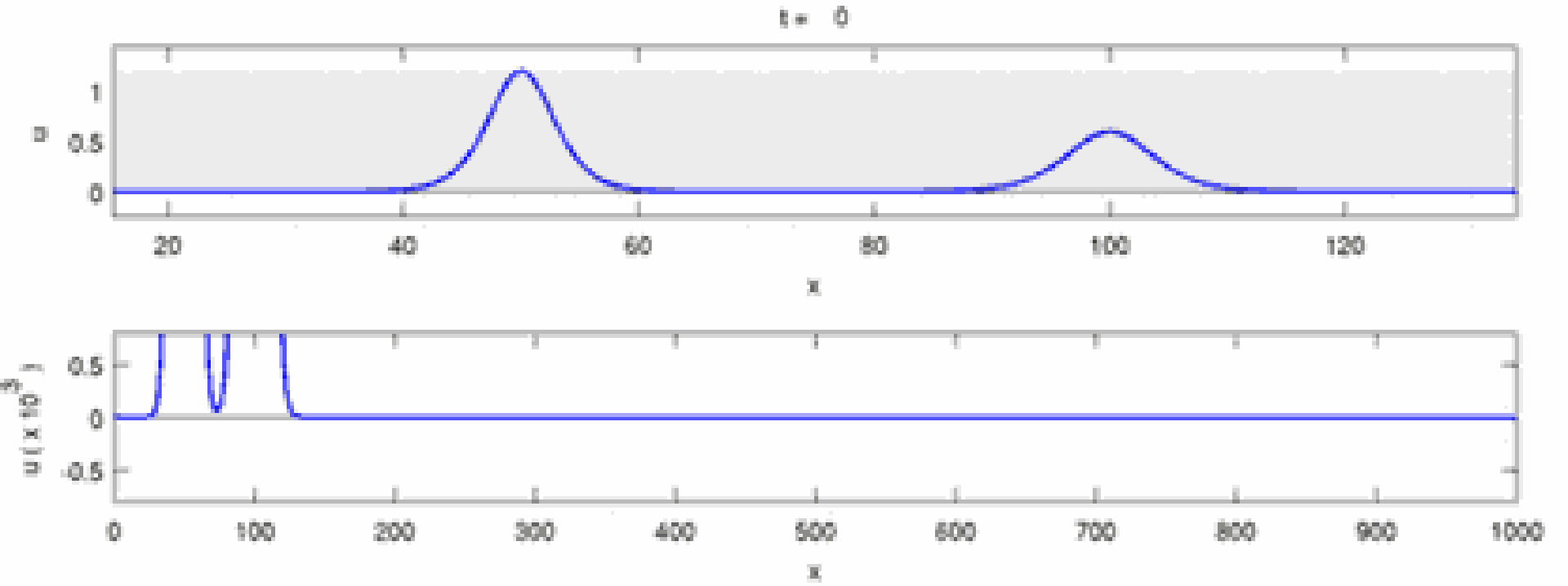






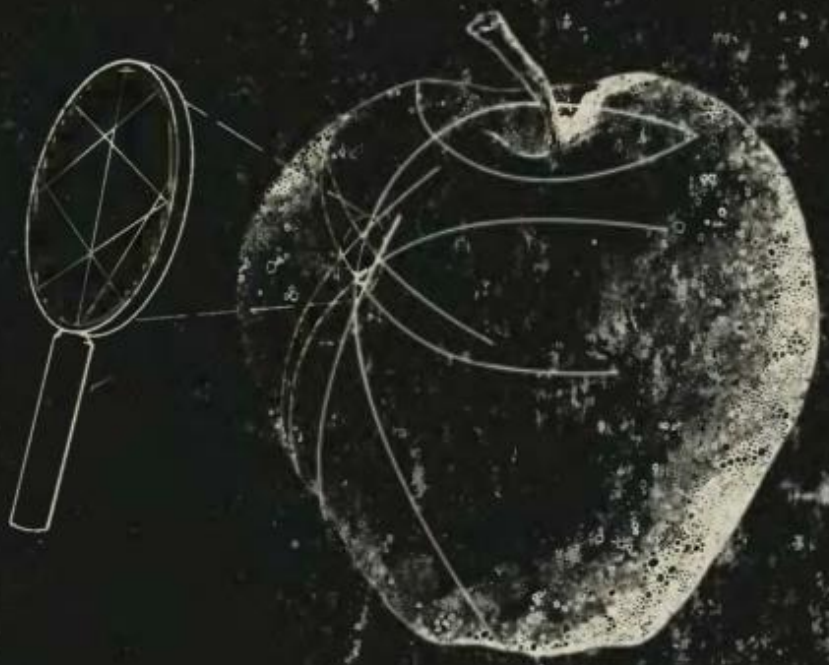
Linear electric quadrupole moment


1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−10
−5
0
5
10


t = 0
u
1
0.5
0
20
40
60
80
100
120
x
u (x 10^-3)
0.5
0
-0.5
0
100
200
300
400
500
600
700
800
900
1000
x

GRAVITATION

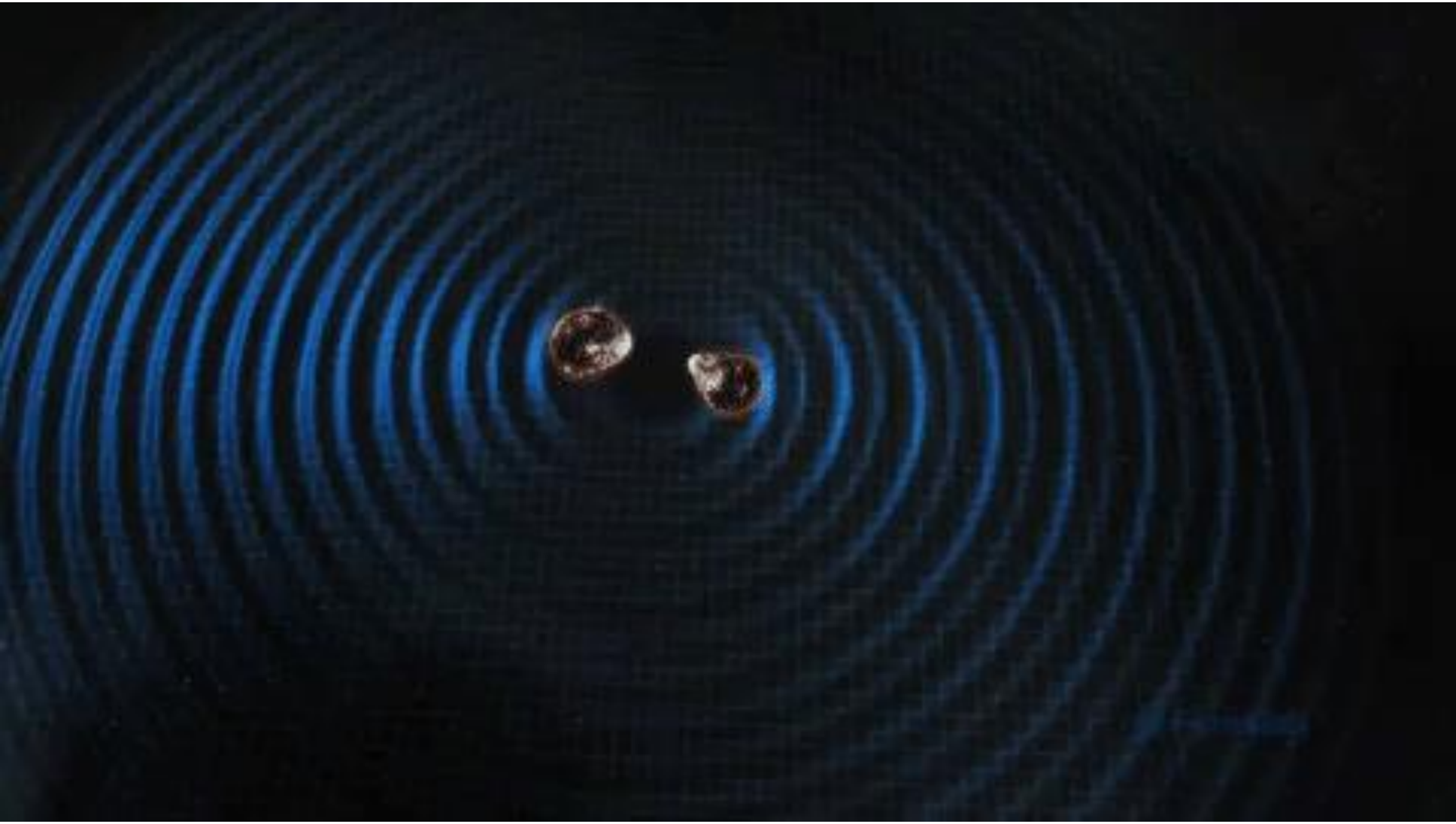
Charles W. MISNER Kip S. THORNE John Archibald WHEELER

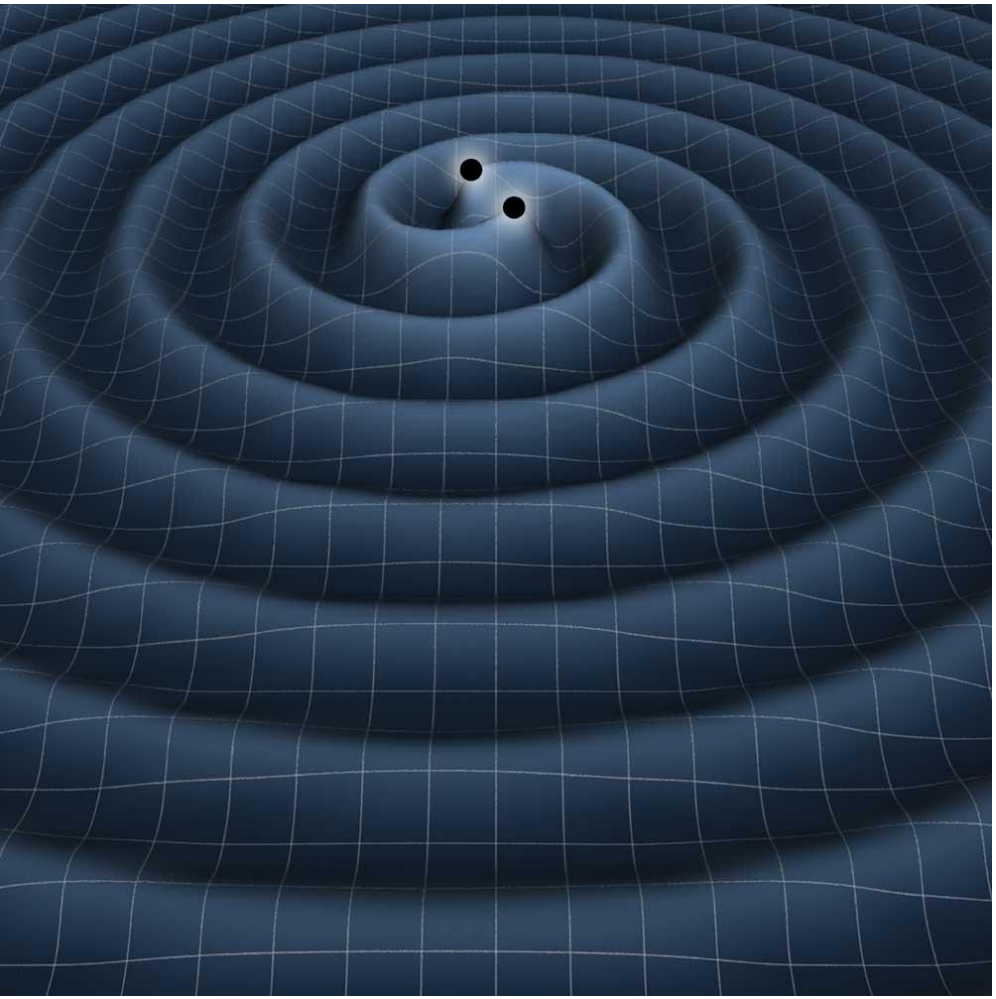


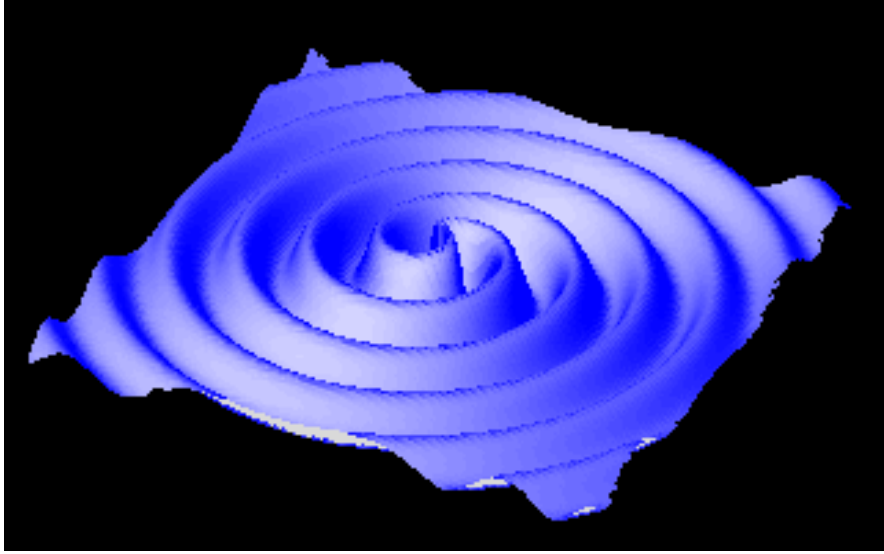
Unde gravitationale

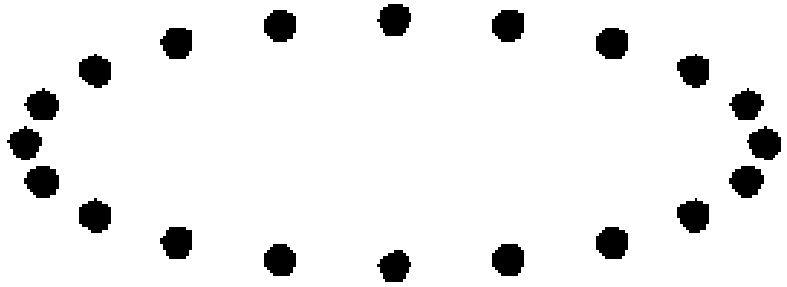


J. Weber - 1962

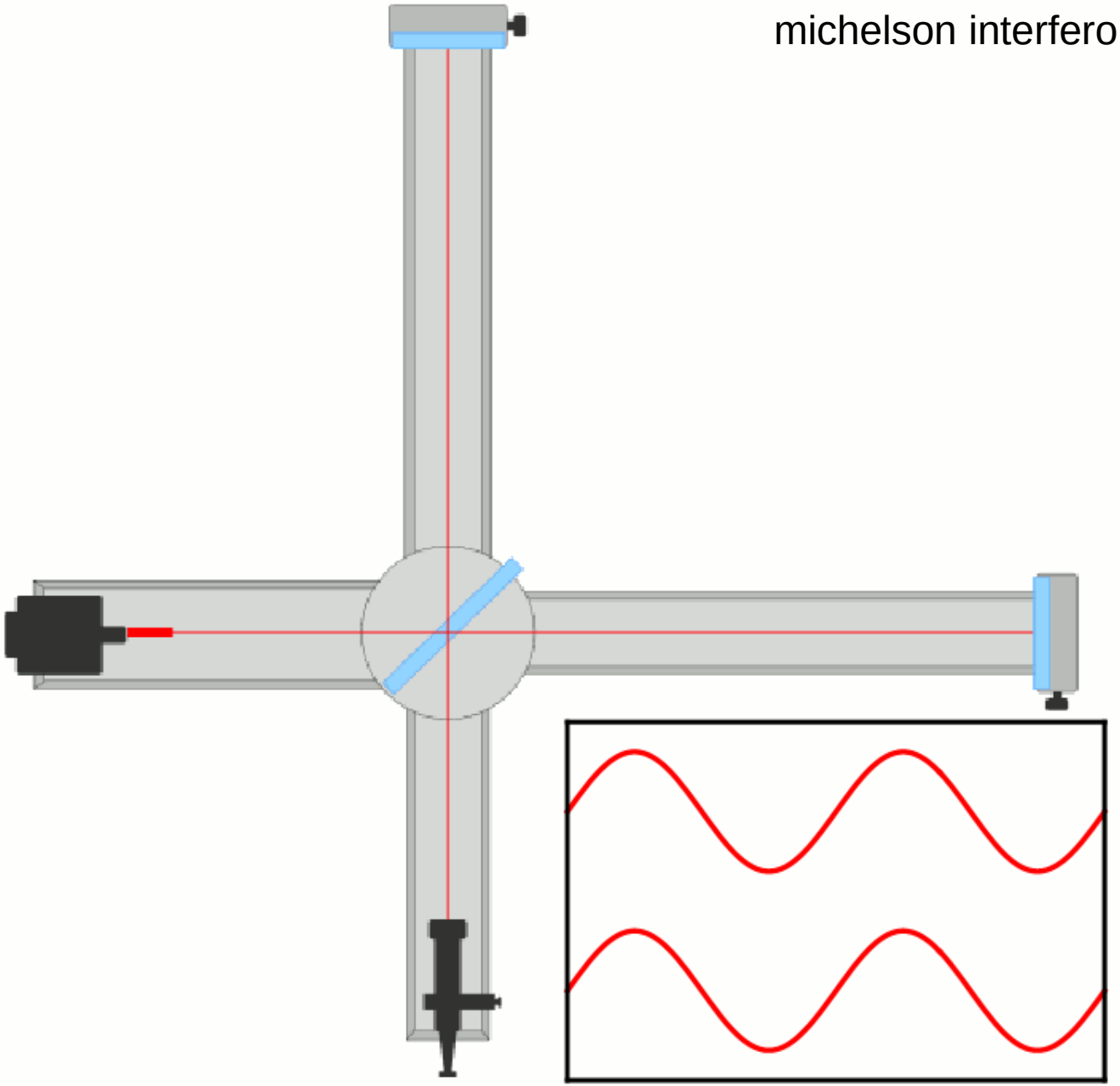




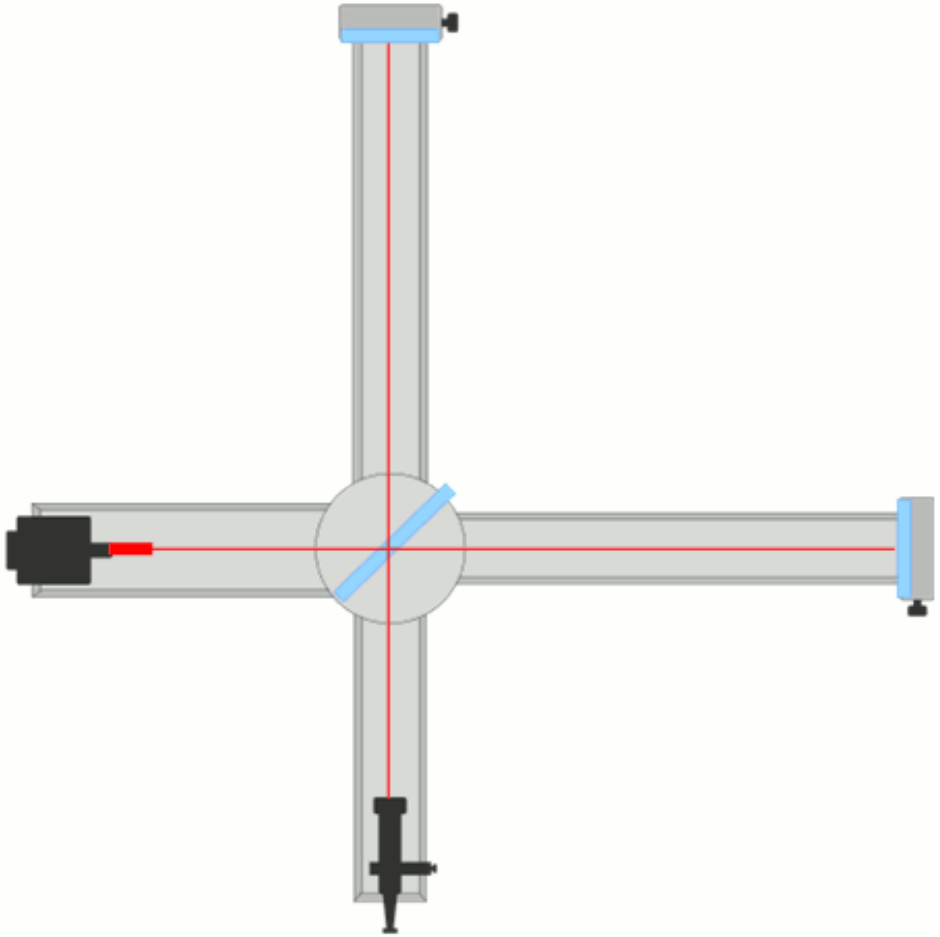


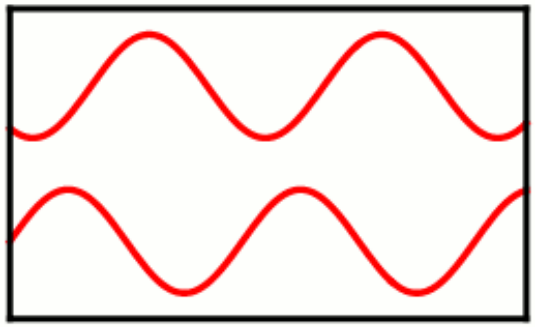


michelson interferometer

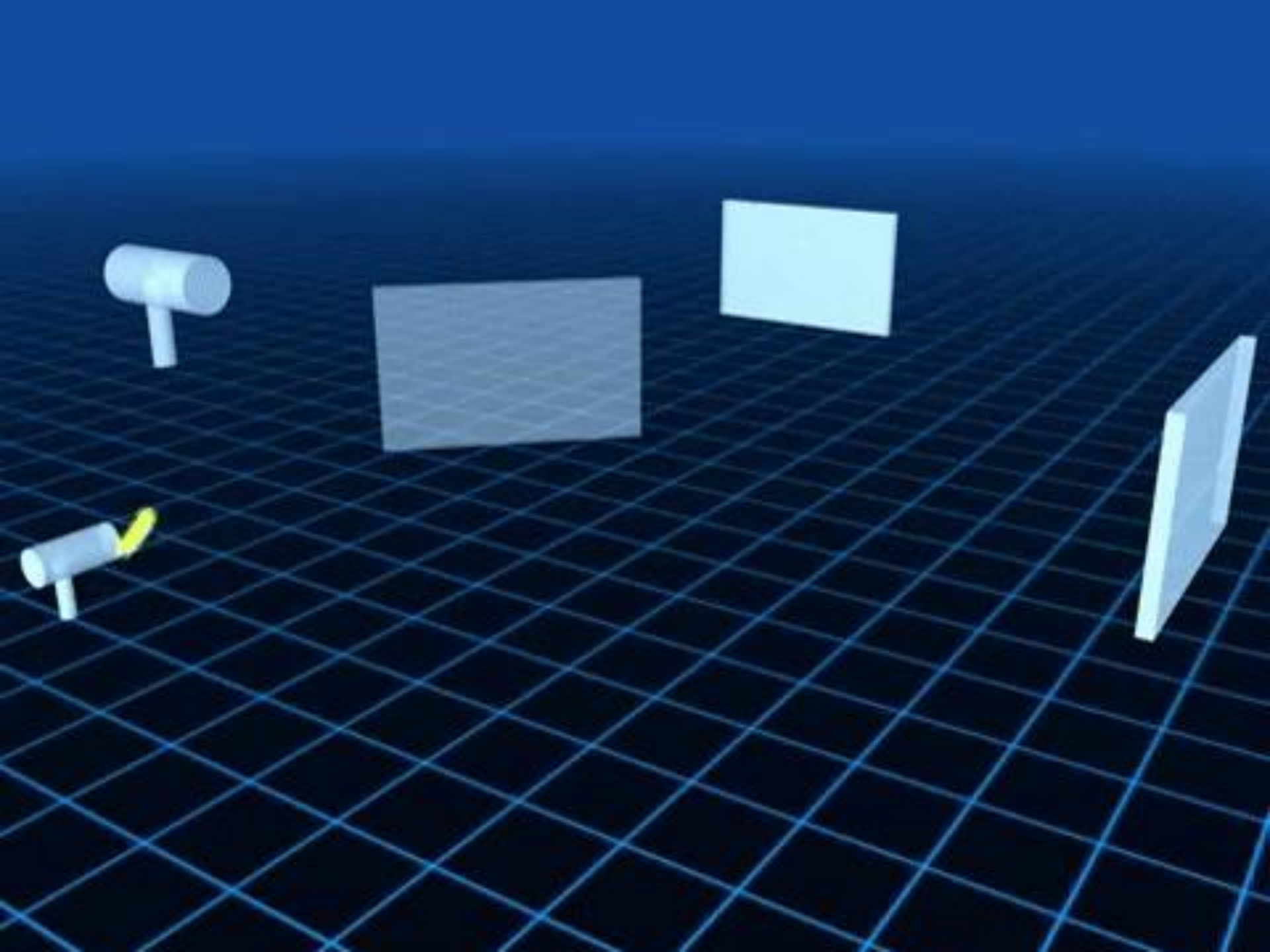


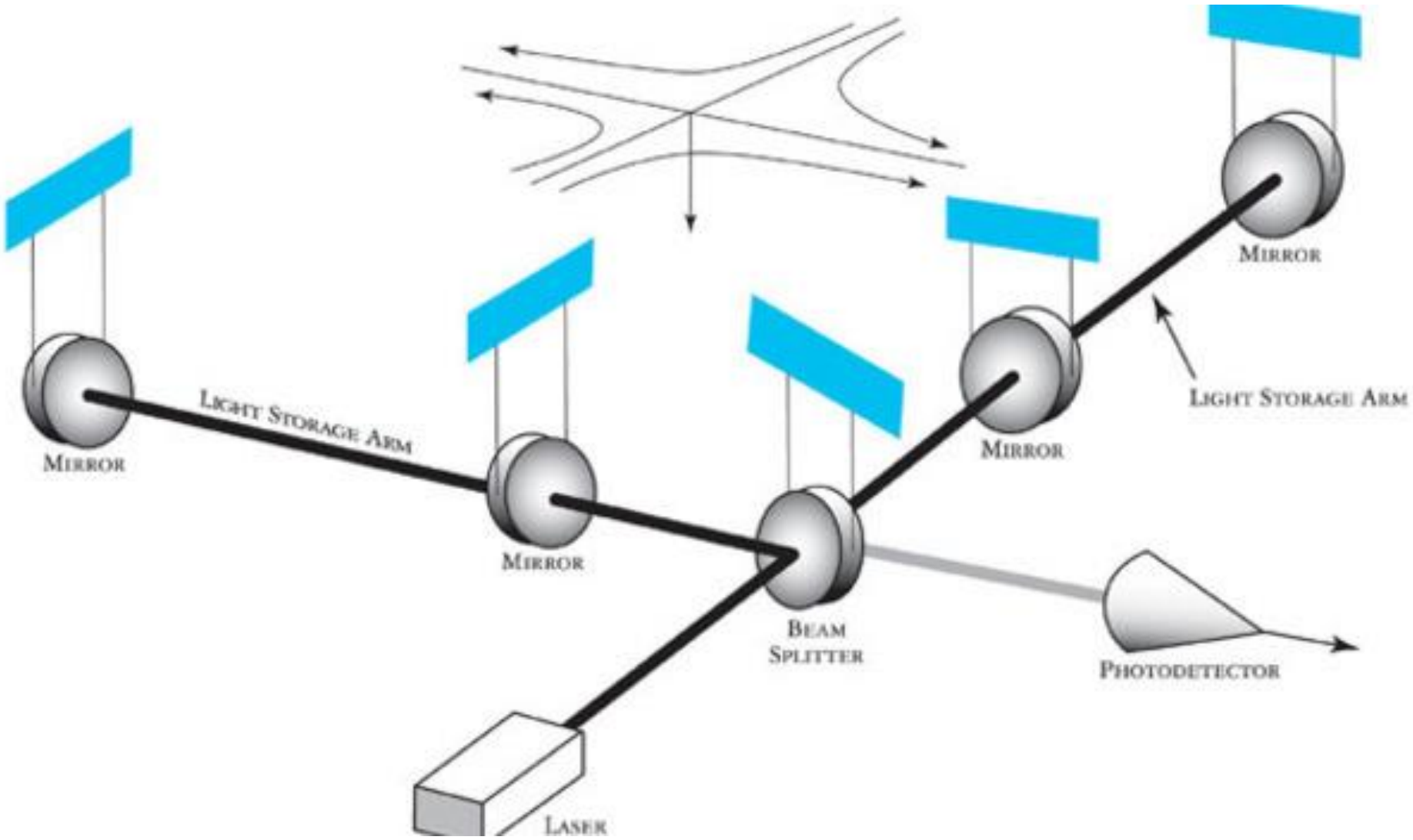
michelson interferometer



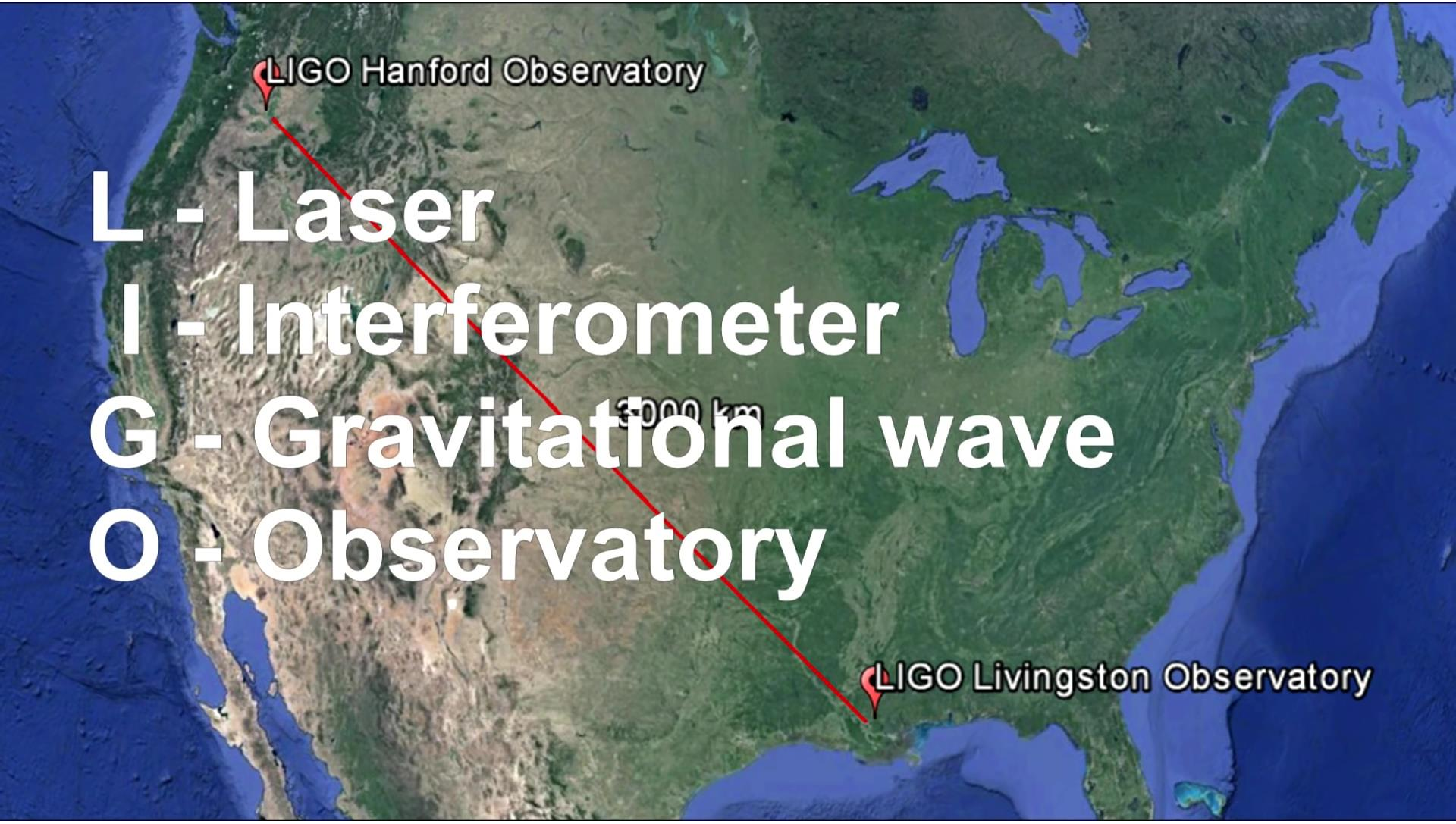


?





Schematic layout of a LIGO interferometer


LIGO Hanford Observatory
L - Laser
I - Interferometer
G - Gravitational wave
O - Observatory
LIGO Livingston Observatory



LIGO -

§36.1. THE QUADRUPOLE NATURE OF GRAVITATIONAL WAVES

Masses in an isolated, nearly Newtonian system move about each other. How much gravitational radiation do they emit?

For an order-of-magnitude estimate, one can apply the familiar radiation formulas of electromagnetic theory, with the replacement $e^2 \longrightarrow -m^2$, which converts the static coulomb law into Newton's law of attraction. This procedure treats gravity as though it were a spin-one (vector) field, rather than a spin-two (tensor) field; consequently, it introduces moderate errors in numerical factors and changes angular distributions. But it gives an adequate estimate of the total power radiated.

In electromagnetic theory, electric-dipole radiation dominates, with a power output or "luminosity," L, given (see §4.4 and Figure 4.6) by

$$L_{\text{electric dipole}} = (2/3)e^2\boldsymbol{a}^2$$

for a single particle with acceleration $\boldsymbol{a}$ and dipole moment changing as $\ddot{\boldsymbol{d}} = e\ddot{\boldsymbol{x}} = e\boldsymbol{a}$;

$$L_{\text{electric dipole}} = (2/3)\,\ddot{\boldsymbol{d}}^2$$

for a general system with dipole moment $\boldsymbol{d}$. [Geometric units: luminosity in cm of mass-energy per cm of light travel time; charge in cm, $e = (G^{1/2}/c^2)e_{\text{conv}} = (2.87 \times 10^{-25}\,\text{cm/esu}) \times (4.8 \times 10^{-10}\,\text{esu}) = 1.38 \times 10^{-34}\,\text{cm}$, acceleration in cm of distance per cm of time per cm of time. For conventional units, with e in esu or $(\text{g cm}^3/\text{sec}^2)^{1/2}$,

insert a factor c^{-3} on the right and get L in erg/sec]. The gravitational analog of the electric dipole moment is the mass dipole moment

Why gravitational waves cannot be dipolar

$$\boldsymbol{d} = \sum_{\text{particles } A} m_A \boldsymbol{x}_A.$$

Its first time-rate of change is the total momentum of the system,

$$\dot{\boldsymbol{d}} = \sum_{\text{particles } A} m_A \dot{\boldsymbol{x}}_A = \boldsymbol{p}.$$

The second time-rate of change of the mass dipole moment has to vanish because of the law of conservation of momentum, $\ddot{\boldsymbol{d}} = \dot{\boldsymbol{p}} = 0$. Therefore *there can be no mass dipole radiation in gravitation physics.*

The next strongest types of electromagnetic radiation are magnetic-dipole and electric-quadrupole. Magnetic-dipole radiation is generated by the second time-derivative of the magnetic moment, $\ddot{\boldsymbol{\mu}}$. Here again the gravitational analog is a constant of the motion, the angular momentum,

$$\boldsymbol{\mu} = \sum_A (\text{position of } A) \times (\text{current due to } A) = \sum_A \boldsymbol{r}_A \times (m\boldsymbol{v}_A) = \boldsymbol{J};$$

$$\boldsymbol{\mu} = \sum_A (\text{position of } A) \times (\text{current due to } A) = \sum_A \boldsymbol{r}_A \times (m\boldsymbol{v}_A) = \boldsymbol{J};$$

so it cannot radiate. *Thus, there can be no gravitational dipole radiation of any sort.*

When one turns to quadrupole radiation, one finally gets a nonzero result (see Figure 36.1). The power output predicted by electromagnetic theory,

$$L_{\text{electric quadrupole}} = \frac{1}{20}\,\ddot{\mathcal{Q}}^2 \equiv \frac{1}{20}\,\ddot{Q}_{jk}\ddot{Q}_{jk},$$

$$Q_{jk} \equiv \sum_A e_A \left(x_{Aj}x_{Ak} - \frac{1}{3}\delta_{jk}{r_A}^2 \right)$$

($Q_{jk\,\text{here}} = Q_{jk\,\text{in much other literature}}$), has as its gravitational counterpart

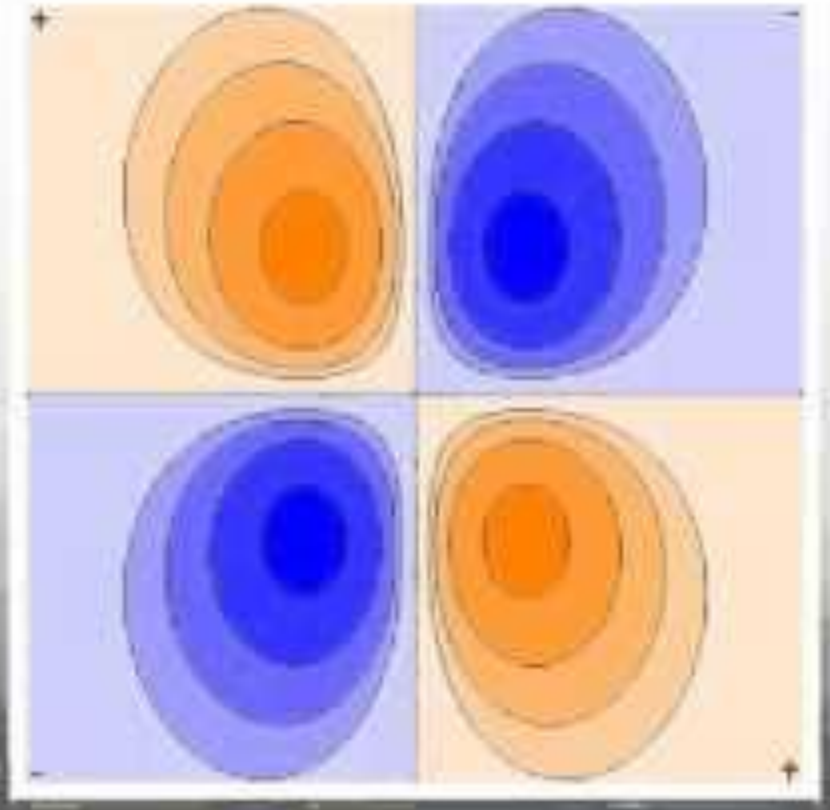
$$L_{\text{mass quadrupole}} = \frac{1}{5}\langle \dddot{I}^2 \rangle \equiv \frac{1}{5}\langle \dddot{I}_{jk}\dddot{I}_{jk} \rangle, \tag{36.1}$$

Gravitational-wave power output expressed in terms of "reduced quadrupole moment" of source

$$I_{jk} \equiv \sum_A m_A \left(x_{Aj}x_{Ak} - \frac{1}{3}\delta_{jk}{r_A}^2 \right) = \int \rho \left(x_j x_k - \frac{1}{3}\delta_{jk}r^2 \right) d^3x. \tag{36.2}$$

Formula (36.1) contains the correct factor of 1/5, which comes from tensor calculations (see §36.10), instead of the incorrect factor 1/20 suggested by the electromagnetic analog; and the righthand side of (36.1) has been averaged ("⟨ ⟩") over several characteristic periods of the source to accord with one's inability to localize the energy of gravitational radiation inside a wavelength.

Quadrupole

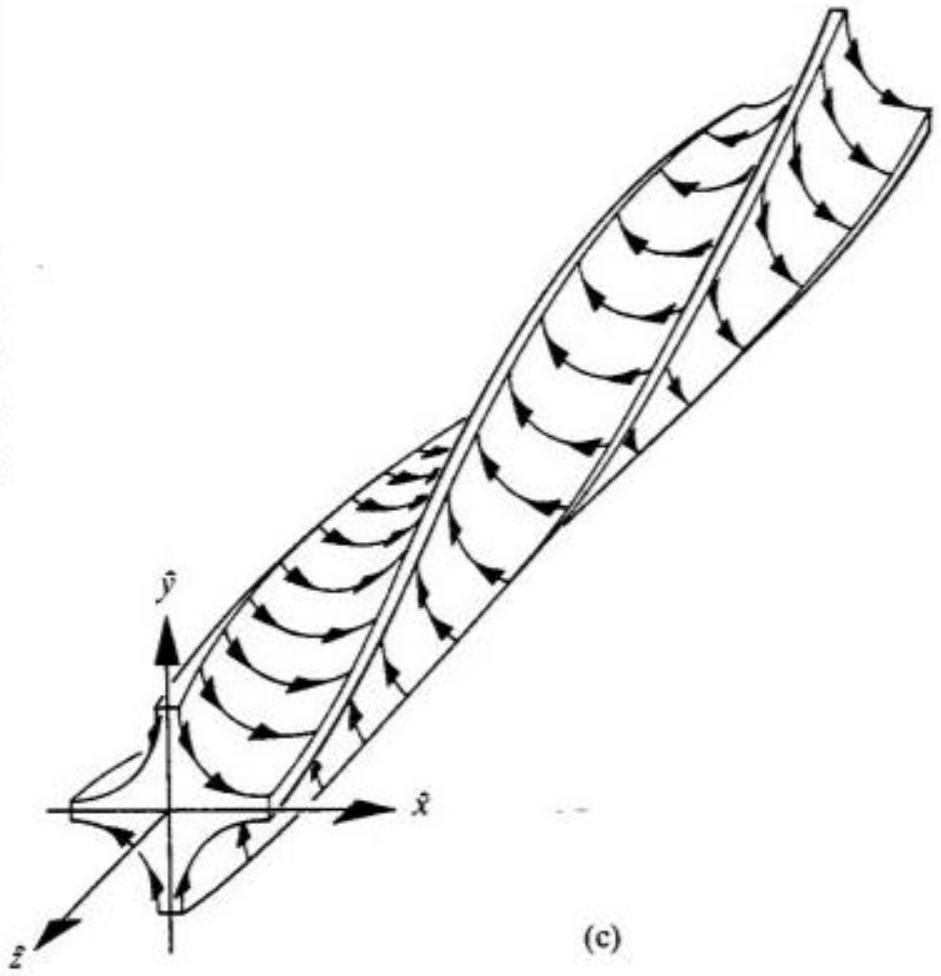


A quadrupole is one of a sequence of configurations of—for example—electric charge or current, or gravitational mass that can exist in ideal system

B. Three-Dimensional Diagram

At each value of $\hat{t} - \hat{z}$, the wave-produced accelerations have a specific polarization [orientation angle ϕ_0 of sketch (b)] and a specific amplitude (density of lines of force). Draw the lines of force in a three-dimensional $(\hat{x}, \hat{y}, \hat{z})$ diagram for fixed $\hat{t}$. Then as time passes the over-all diagram will remain unchanged in form, but will propagate with the speed of light in the $\hat{z}$ direction.

Sketch (c) shows such a diagram for righthand circularly polarized waves of unchanging amplitude. *Note:* The authors are not aware of diagrams such as these [(a), (b), (c) above] and their use in analyzing detector response prior to William H. Press (1970).



(c)

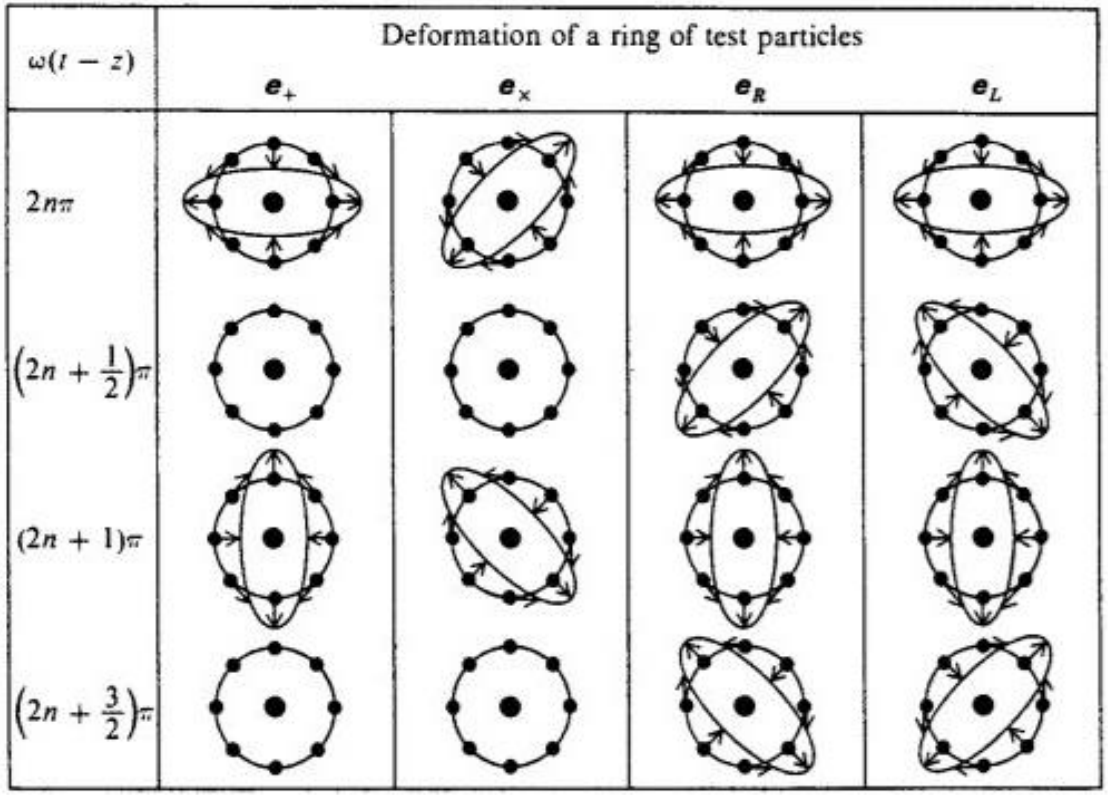


Figure 35.2.
Plane Gravitational Waves. Polarization tensor: e_P

Metric perturbation:

$$h_{jk} = \Re\,[A_0 e^{-i\omega(t-z)} e_{Pjk}]$$

Tidal acceleration between two test particles:

$$\frac{D^2 n_j}{D\tau^2} = -R_{j0k0} n_k = \frac{1}{2}\frac{\partial^2 h_{jk}}{\partial t^2} n_k$$

$$= \Re\left[-\frac{1}{2}\omega^2 A_0 e^{-i\omega(t-z)} e_{Pjk} n_k\right]$$

Separation between two test particles:

$$n_j = n_j^{(0)} + \Re\left[\frac{1}{2} A_0 e^{-i\omega(t-z)} e_{Pjk} n_k^{(0)}\right]$$

Position of test particle B in proper reference frame of test particle A. (In drawing, A is the central particle and B is any peripheral particle):

$$x_B{}^j = x_{B(0)}{}^j + \Re\left[\frac{1}{2} A_0 e^{-i\omega(t-z)} e_{Pjk} x_{B(0)}{}^k\right]$$

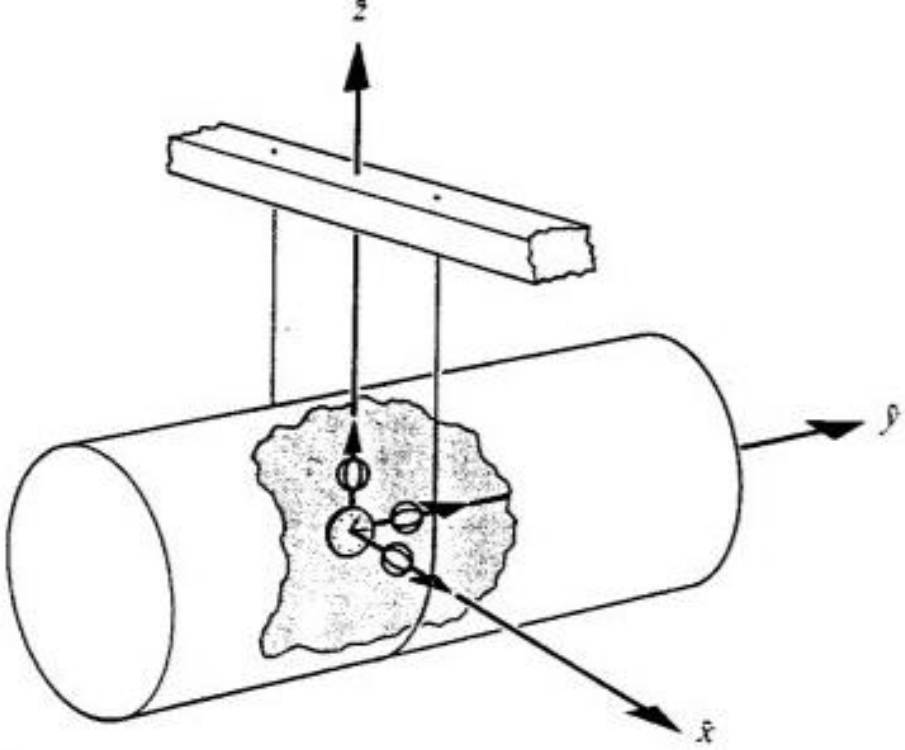
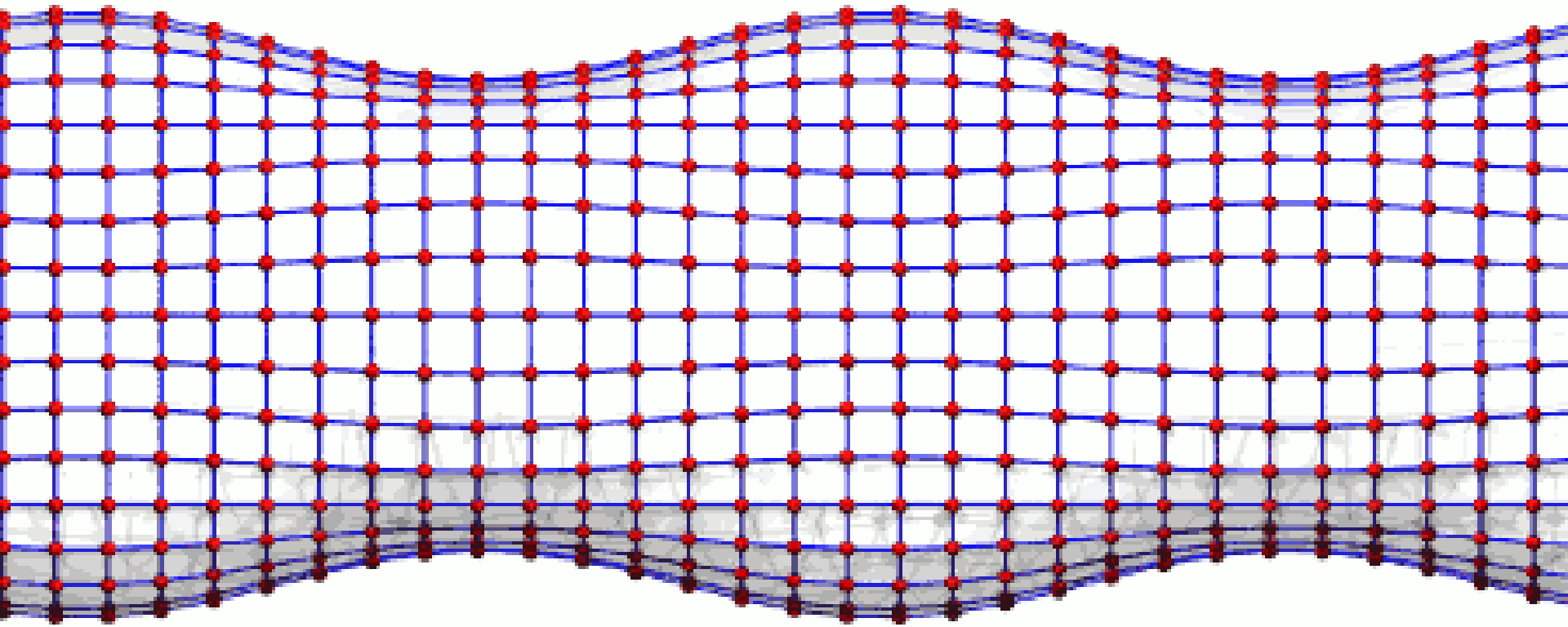
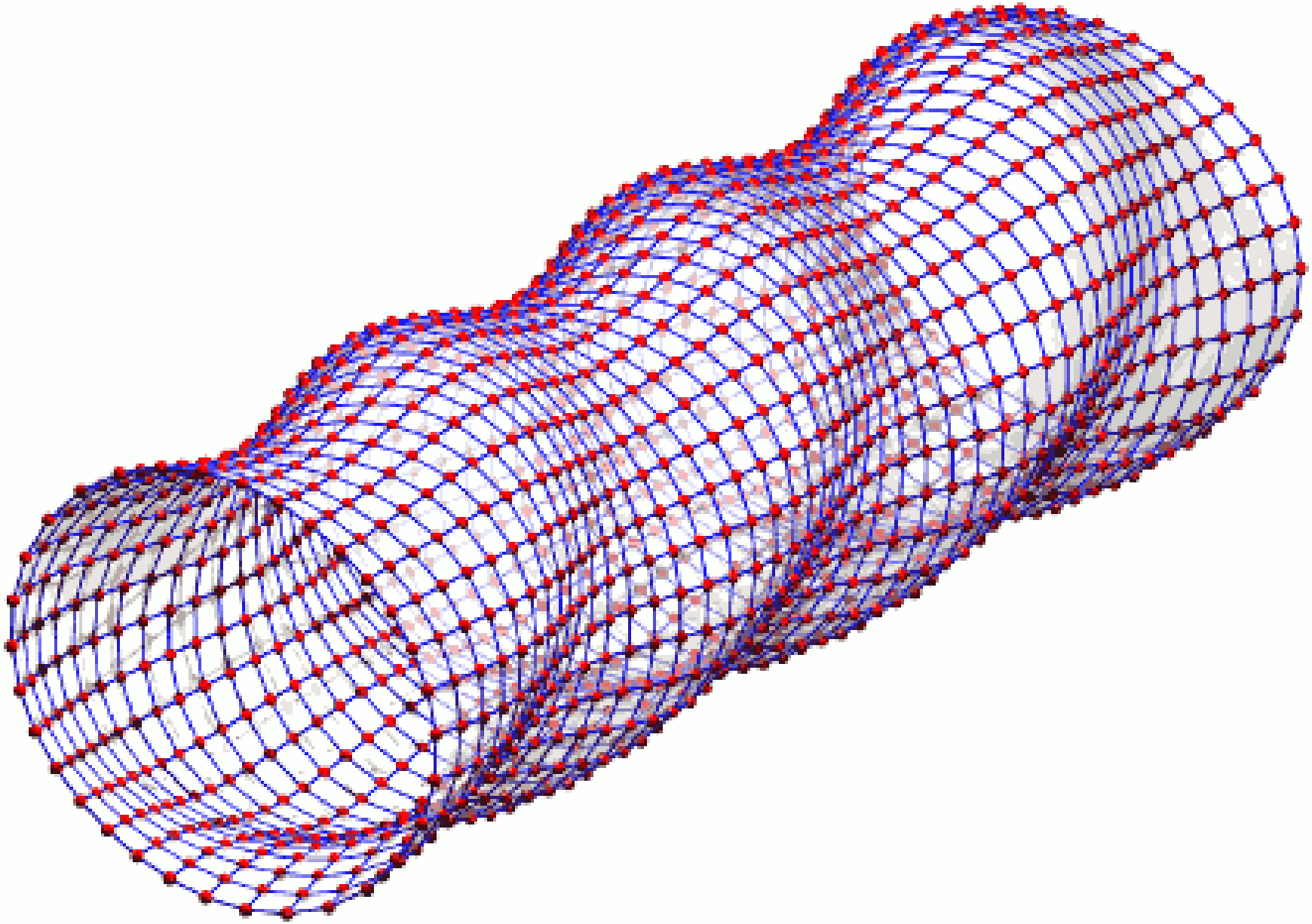


Figure 37.1.
The proper reference frame of a vibrating-bar detector. The bar hangs by a wire from a cross beam, which is supported by vertical posts (not shown) that are embedded in the Earth. Consequently, the bar experiences a 4-acceleration given, at the moment when this diagram is drawn, by $\boldsymbol{a} = g(\partial/\partial\hat{z})$, where g is the "local acceleration of gravity" ($g \sim 980$ cm/sec^2). Later, the spatial axes will have rotated relative to the bar ("Foucoult-pendulum effect" produced by Earth's rotation), so the components of $\boldsymbol{a}$ but not its magnitude will have changed.

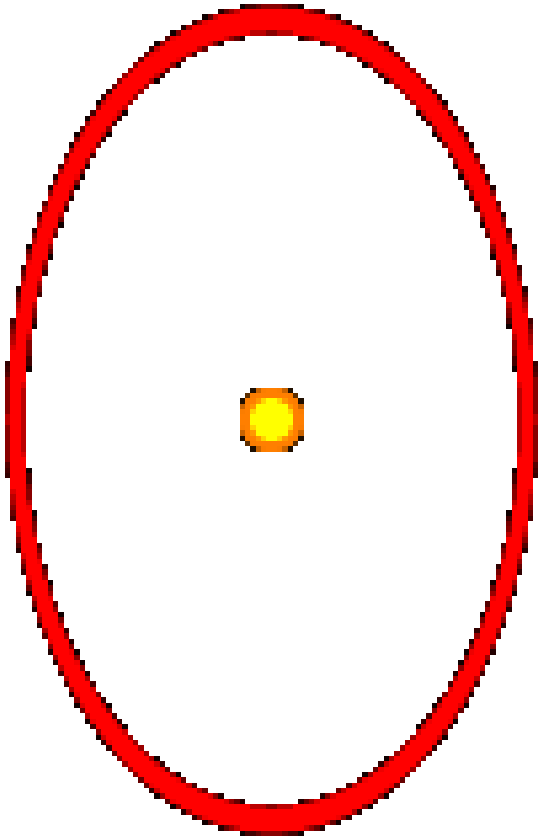
The proper reference frame relies on an imaginary clock and three imaginary gyroscopes located at the bar's center of mass (and shown above in a cut-away view). Coordinate time is equal to proper time as measured by the clock, and the directions of the spatial axes $\partial/\partial x^j$ are attached to the gyroscopes. The forces that prevent the gyroscopes from falling in the Earth's field must be applied at the centers of mass of the individual gyroscopes (no torque!).

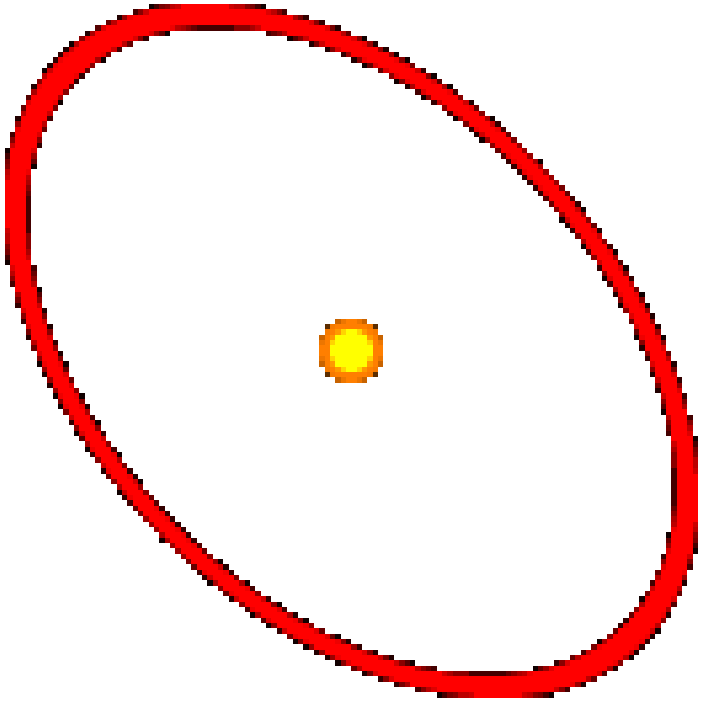



www.einstein-online.info

Sounds

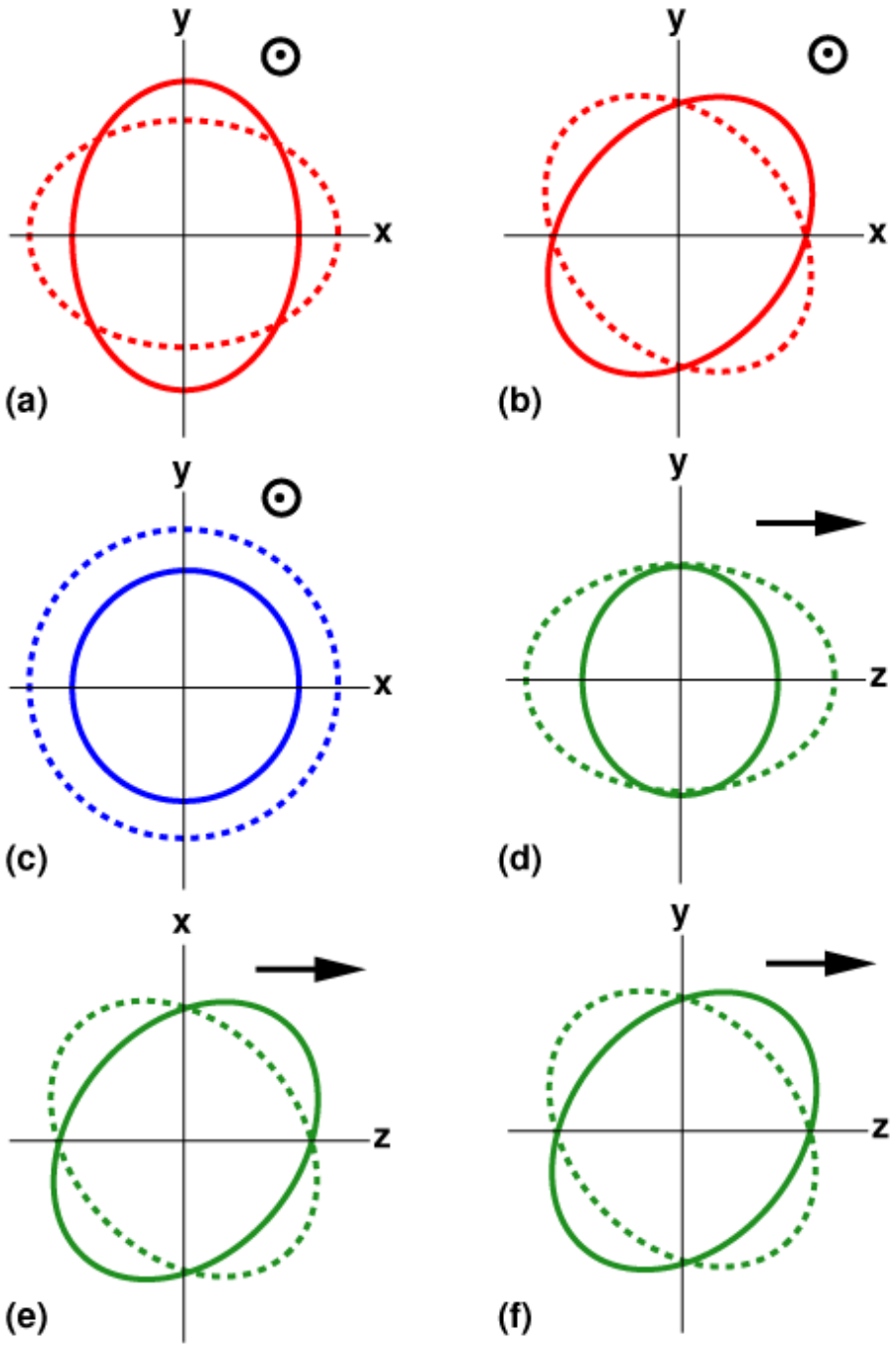
- https://www.soundsofspacetime.org/detection.html
- https://www.soundsofspacetime.org/detection.html#
- https://losc.ligo.org/events/GW150914/

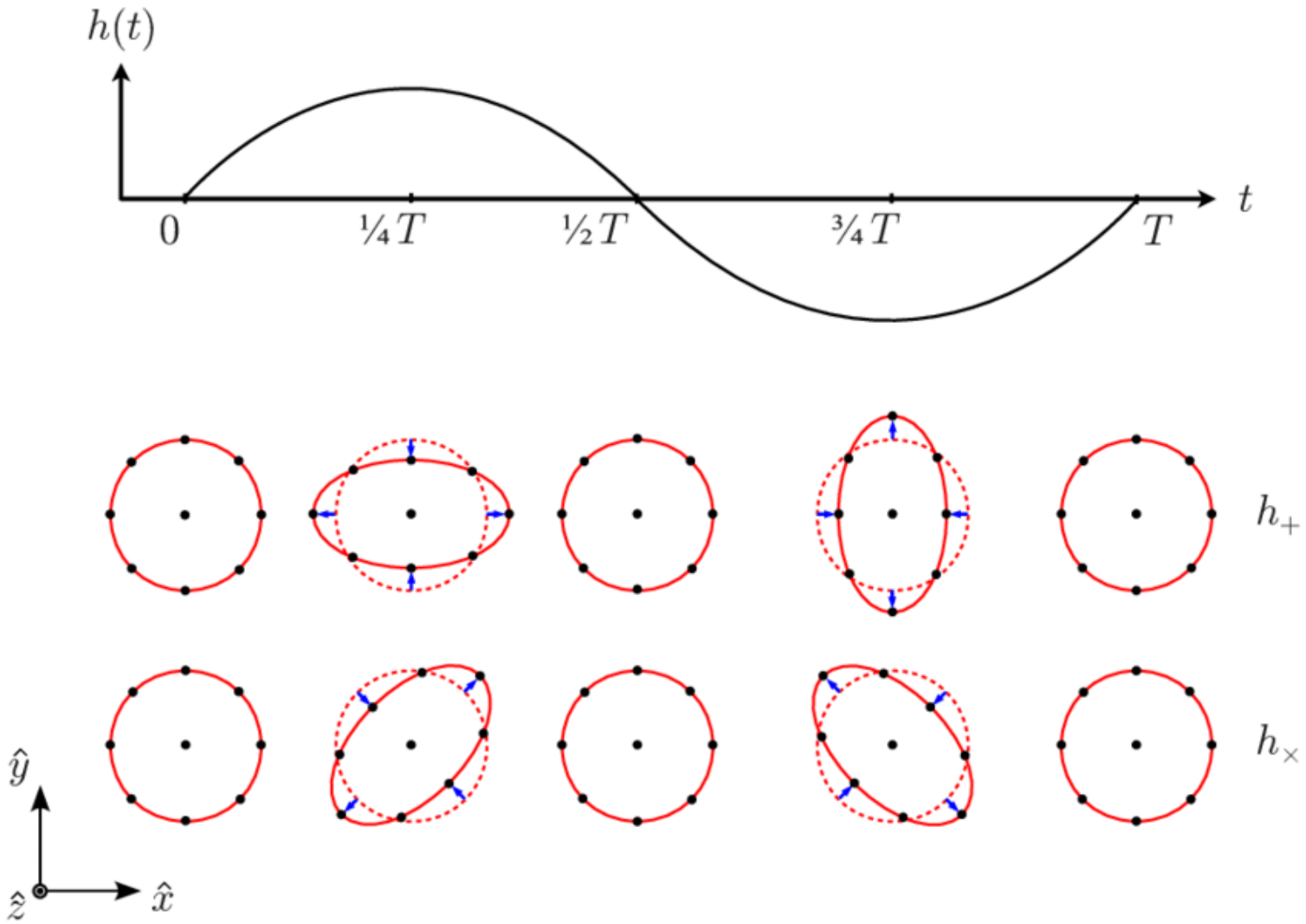




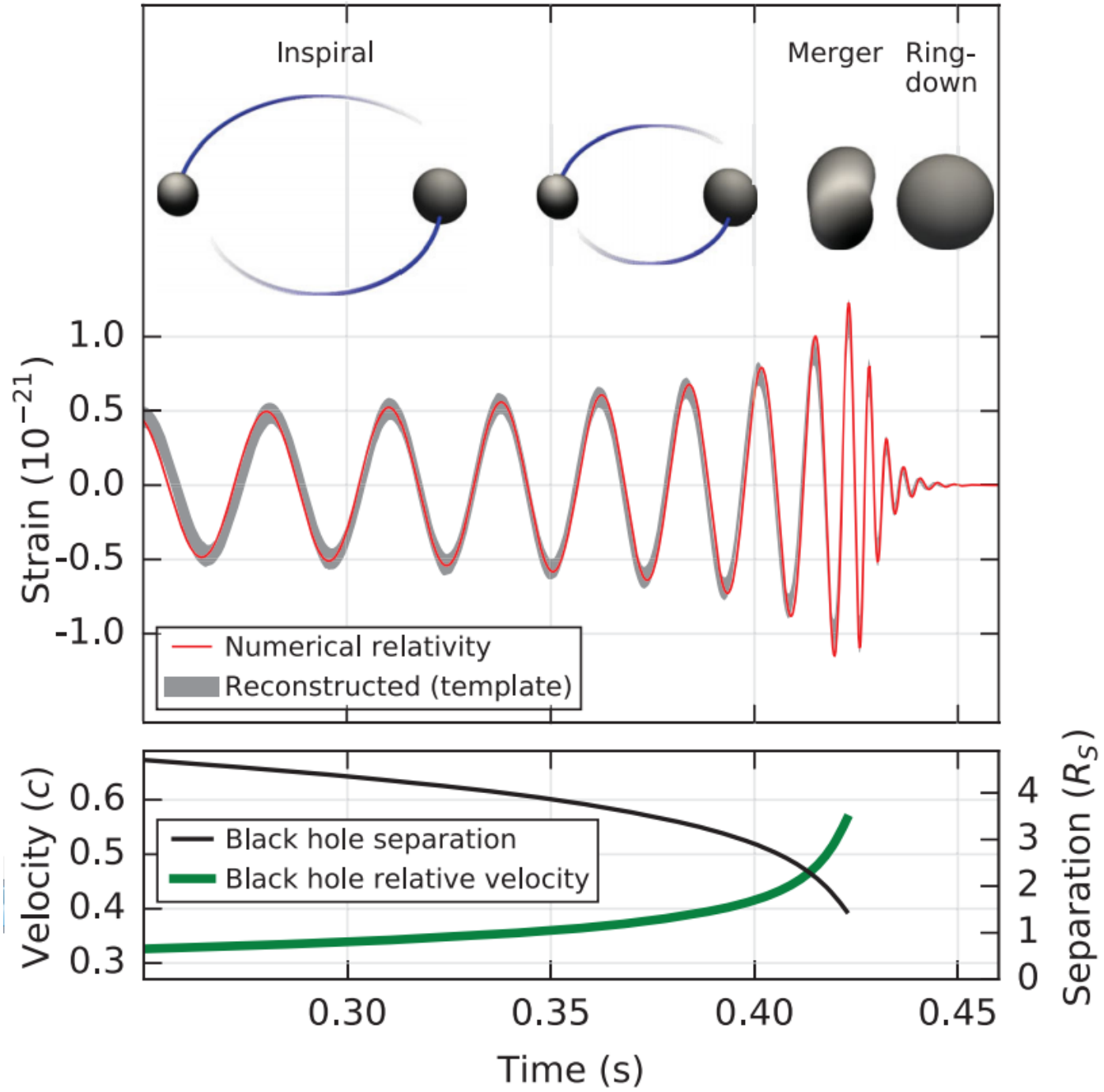
Gravitational radiation at a specified frequency can be decomposed into left- and right-handed circular polarizations

Gravitational–Wave Polarization





A monochromatic gravitational wave of pulsation ω = 2π/T propagates along the z direction. The lower panel shows the effects of the + and × polarizations.


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

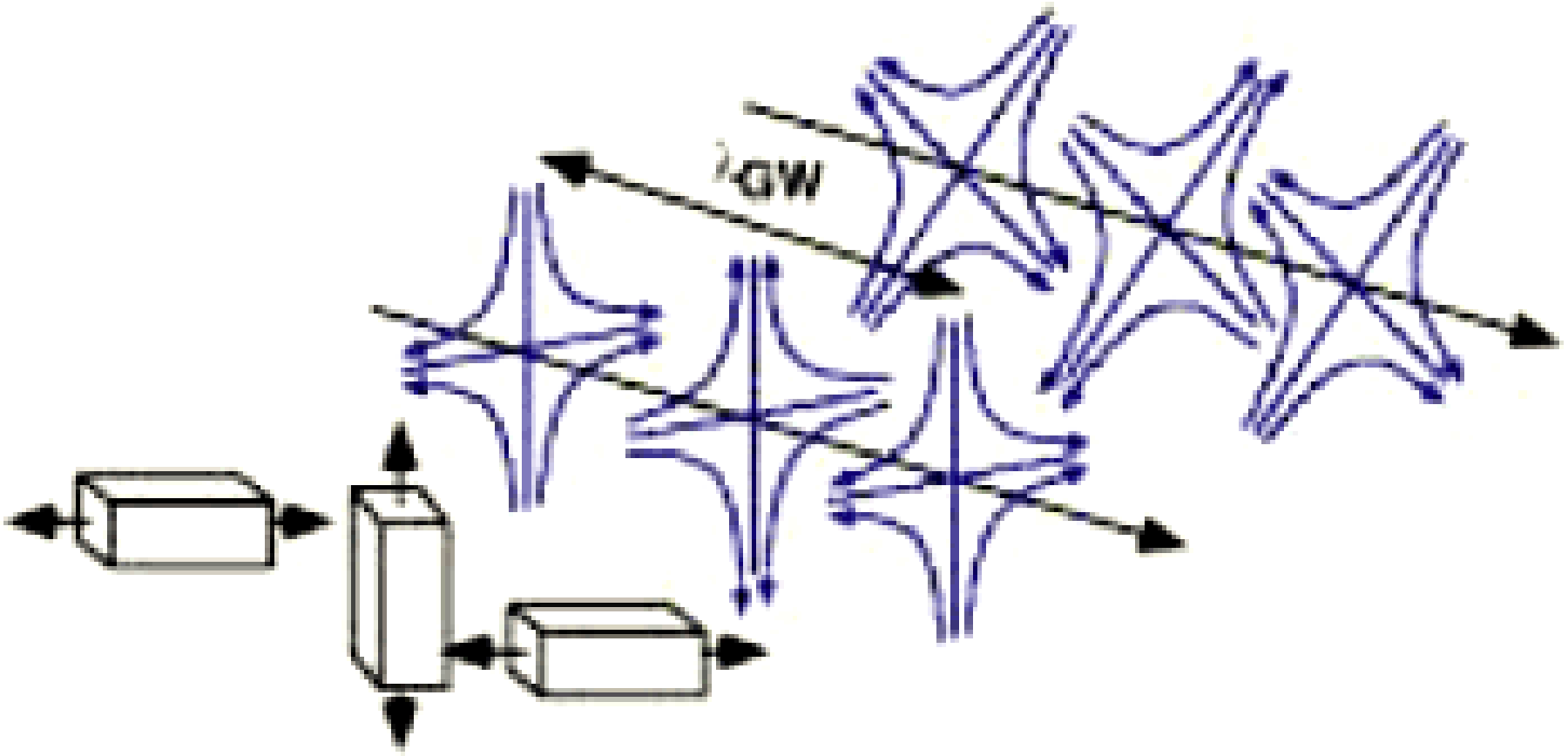


Figure 1. The propagation of gravitational waves having two polarizations.

LISA Science Ground Segment

D. Texier
LISA Consortium, 21st November 2017

esa

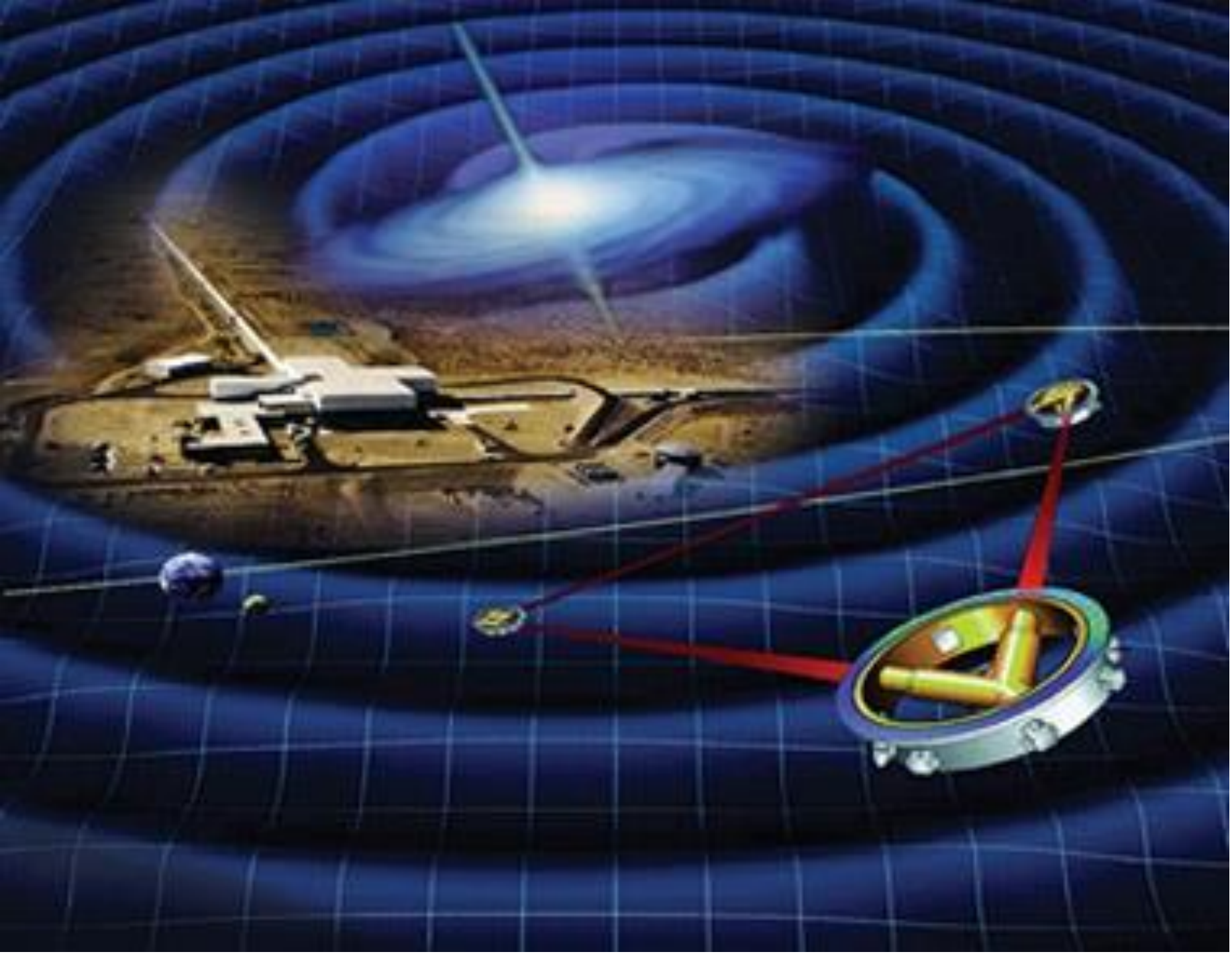
European Space Agency

Contents



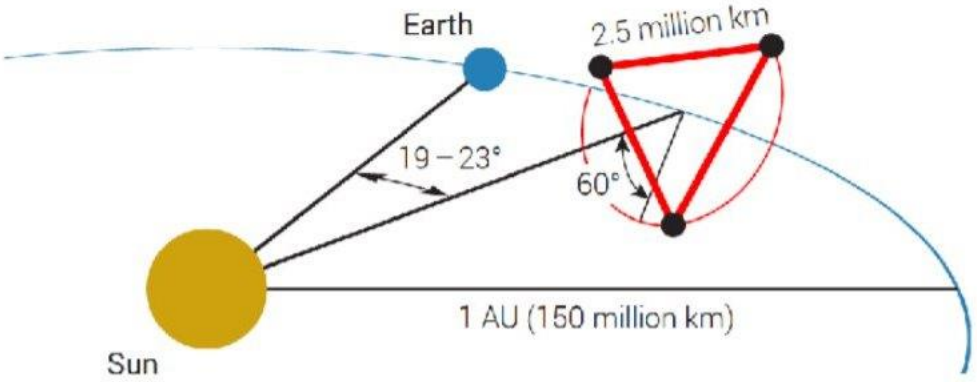
esa

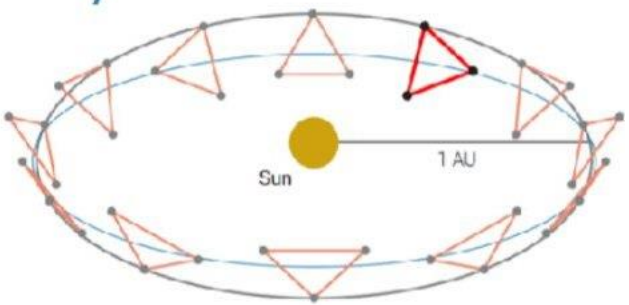
- Overview of Science Ground Segment (SGS)



LISA configuration

frequency range of detection: $10^{-4}\,\mathrm{Hz} < f < 1\,\mathrm{Hz}$

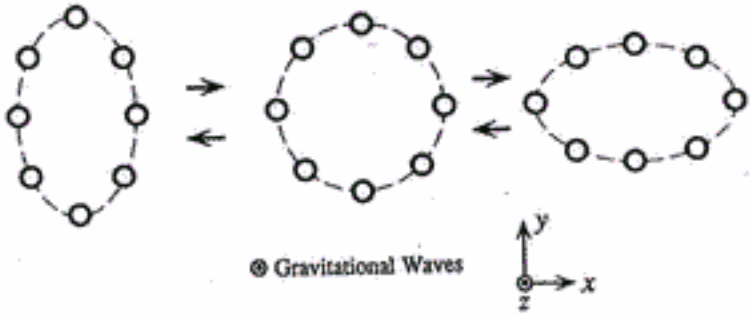




it is a survey instrument:

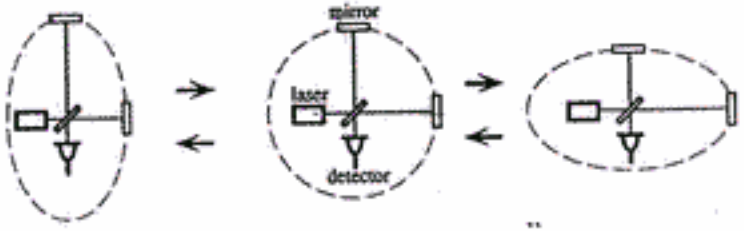
no pointing
continuous sky observation
very best angular resolution for high SNR sources: $1\mathrm{deg}^2$

Gravitational waves

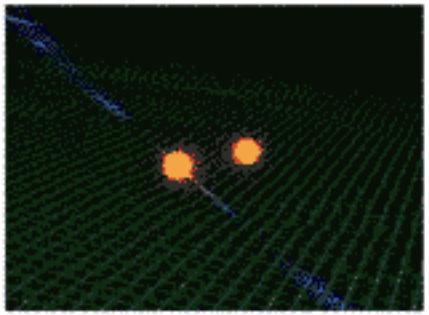


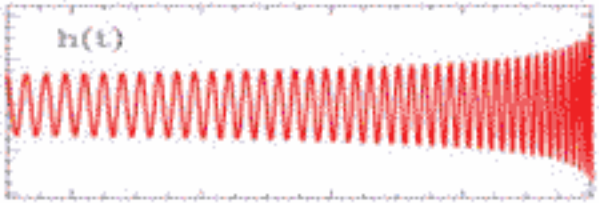
Gravitational waves are quadrupolar distortions of distances between freely falling masses: "ripples in space-time"

Michelson-type interferometers can detect space-time distortions, measured in "strain" $h=\Delta L/L$.



Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have $h=\Delta L/L \sim 10^{-21}$





LIGO

Effect of Gravitational Waves

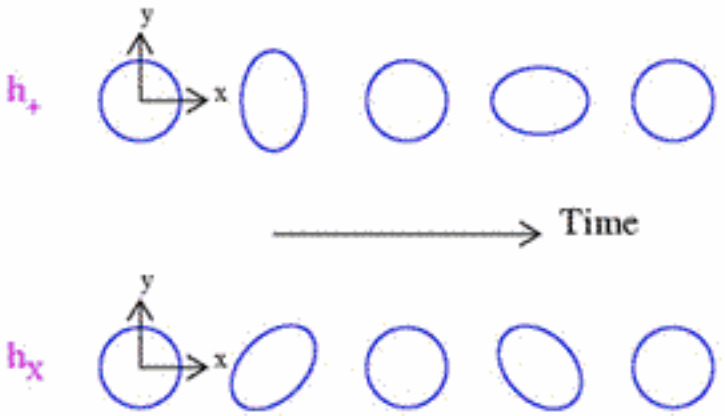
- Two transverse polarizations - quadrupolar: + and x

Example:

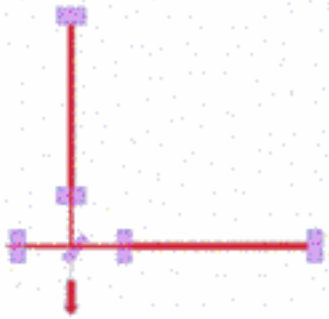
Ring of test masses

responding to wave

propagating along z



Amplitude parameterized by dimensionless strain h: $DL = h(t) / 2 \times L$



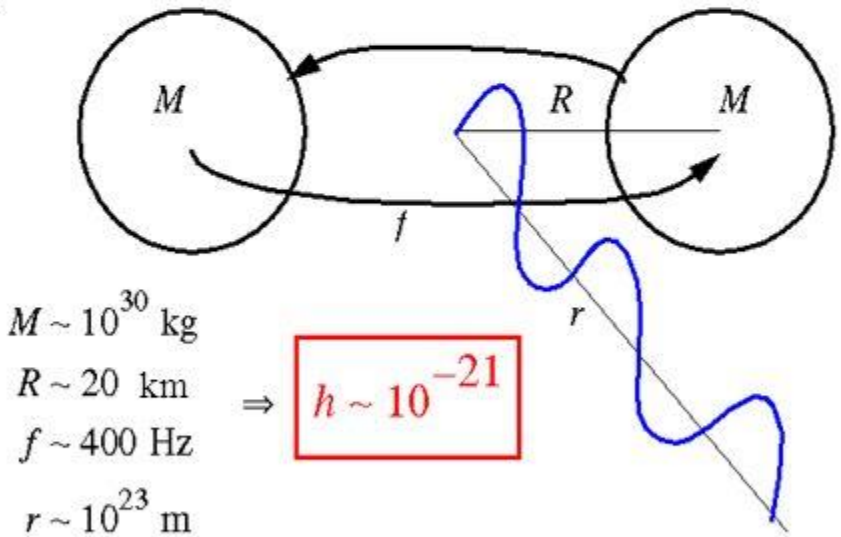
LIGO

Sources of GWs

- Accelerating charge ⟹ electromagnetic radiation (dipole)
- Accelerating mass ⟹ gravitational radiation (quadrupole)
- Amplitude of the gravitational wave (dimensional analysis):

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \quad \Rightarrow \quad h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r}$$

- $\ddot{I}_{\mu\nu}$ = second derivative of mass quadrupole moment (non-spherical part of kinetic energy – tumbling dumb-bell)
- G is a small number!
- Need huge mass, relativistic velocities, nearby.
- For a binary neutron star pair, 10m light-years away, solar masses moving at 15% of speed of light:



$M \sim 10^{30}$ kg
$R \sim 20$ km
$f \sim 400$ Hz
$r \sim 10^{23}$ m

$\Rightarrow \quad h \sim 10^{-21}$

Terrestrial sources *TOO WEAK*!

LIGO

Binary Orbit Evolution



- A binary system in a close orbit

has a time-varying quadrupole moment
➔ emits gravitational waves

$$f_{GW} = 2 f_{orbit}$$

Gravitational waves carry away energy and angular momentum

$$dE/dt \propto -f^{10/3}$$

➔Frequency increases, orbit shrinks

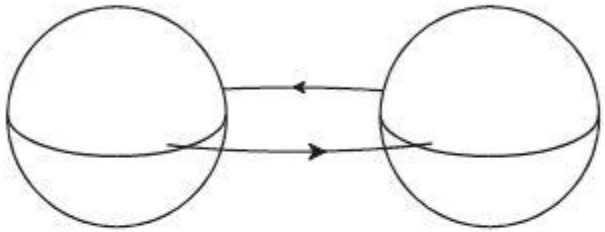
$$df/dt \propto f^{11/3} \qquad dr/dt \propto -f^{2}$$

Objects spiral in until they finally coalesce

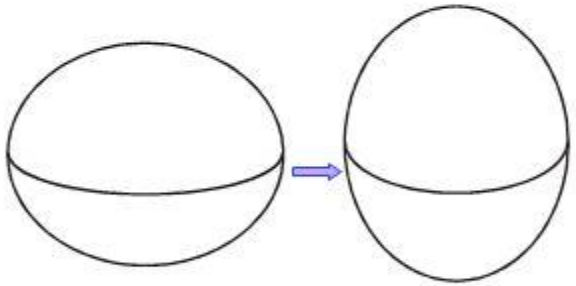
Additional relativistic effects kick in as (Gm/rc^2) grows away from zero

Gravitational wave sources: time-varying quadrupole moments

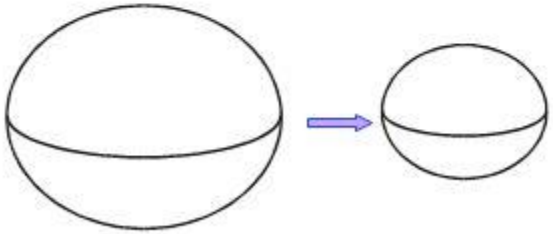
Binary stars (especially compact objects, e.g. neutron stars or black holes.)

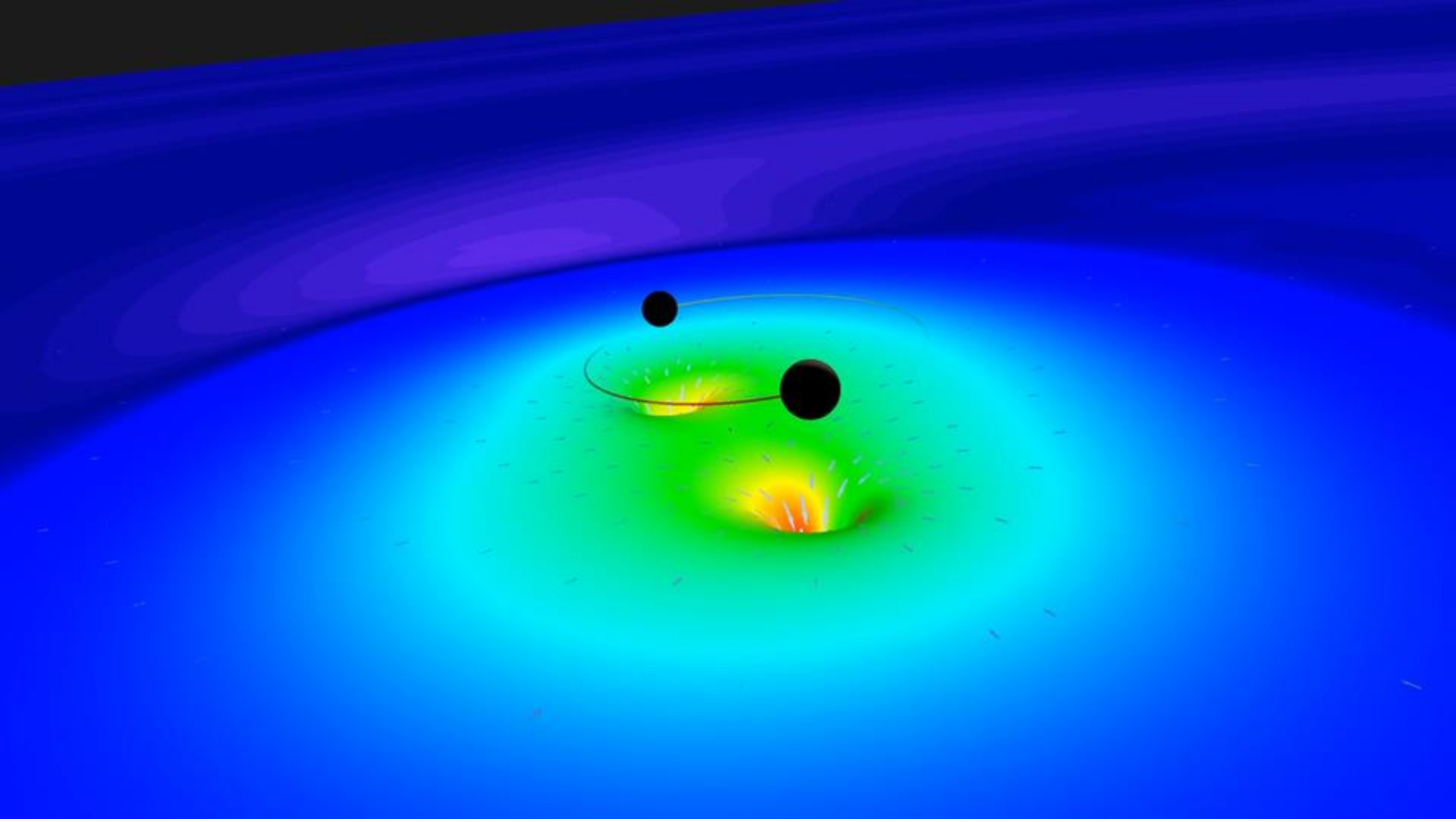


Compact objects just after formation from core collapse.



Or anything else with a dramatic and rapid variation in its mass quadrupole moment.





This computer simulation shows the warping of space and time around two colliding black holes observed by LIGO on September 14, 2015

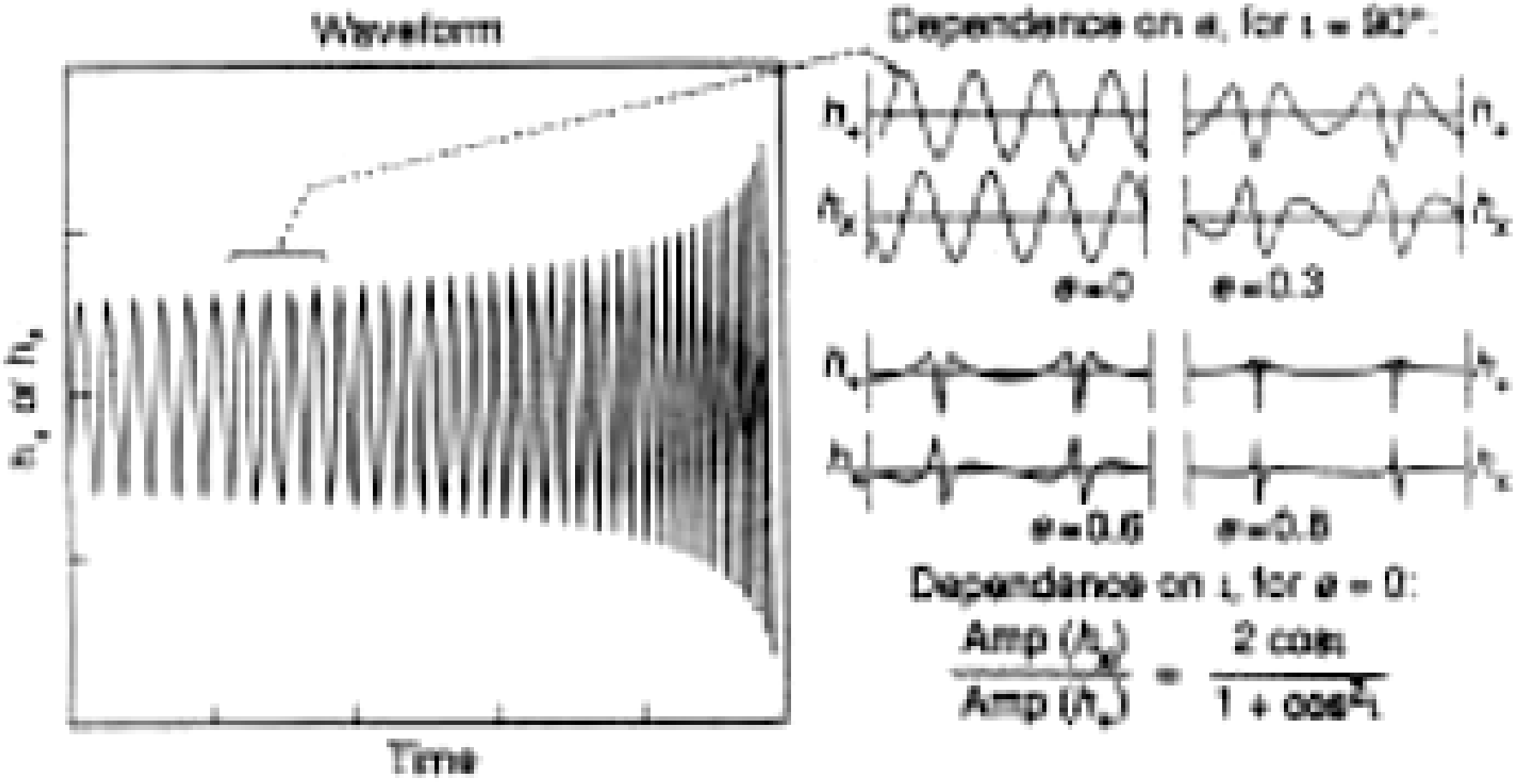


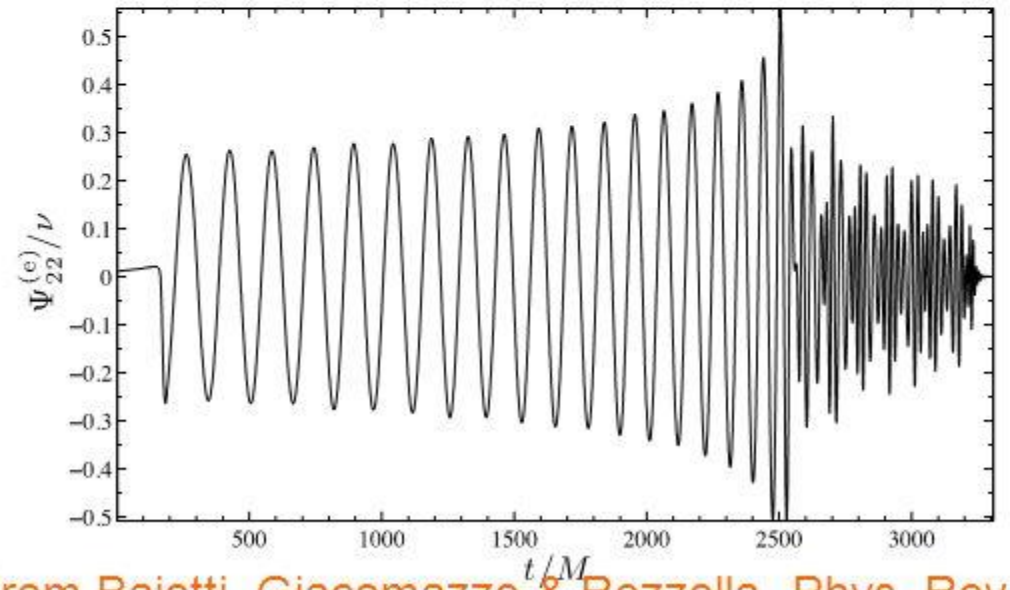
Figure 5. An example is shown of the final chirp waveforms. The amplitude and frequency increase as the system approaches coalescence. The detailed waveforms can be quite complicated as shown at the right, but enable determination of the parameters (eg. ellipticity) of the system.

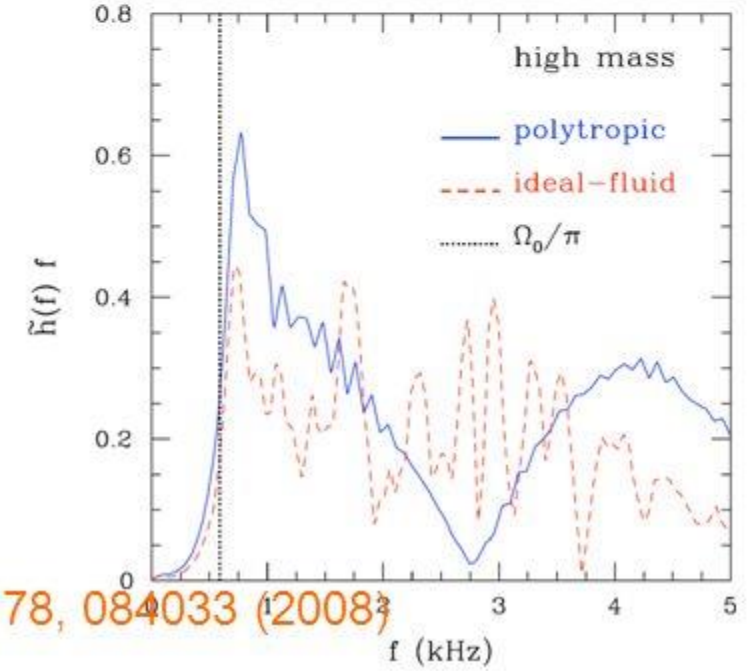
Late-inspiral and coalescence of binary neutron stars (BNS)

Inspiralling (and merging) Binary Neutron Star (BNS) systems: important and "secure" targets for GW detectors

Recent progress in BNS and BHNS numerical relativity simulations of merger by several groups [Shibata et al., Baiotti et al., Etienne et al., Duez et al., Bernuzzi et al. 12, Hotokezaka et al. 13] See review of J. Faber, Class. Q. Grav. 26 (2009) 114004
Most sensitive band of GW detectors

Need analytical (NR-completed) modelling of the late-inspiral part of the signal before merger [Flanagan&Hinderer 08, Hinderer et al 09, Damour&Nagar 09,10, Binnington&Poisson 09]
Extract EOS information using late-inspiral (& plunge) waveforms, which are sensitive to tidal interaction. Signal within the



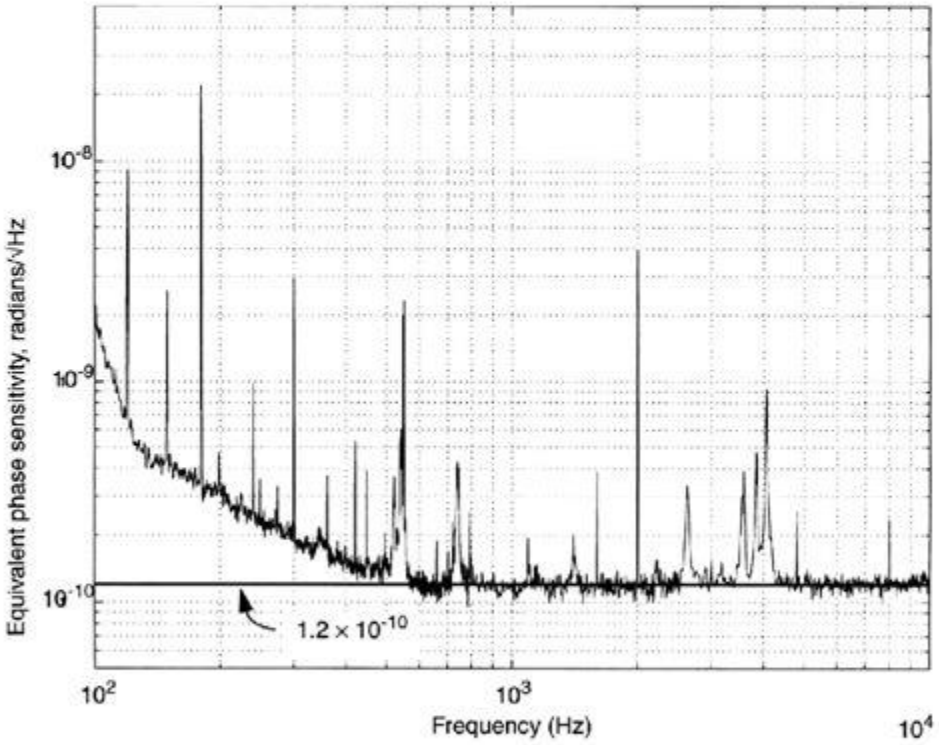


From Baiotti, Giacomazzo & Rezzolla, Phys. Rev. D 78, 084033 (2008)

LIGO

Phase Noise

splitting the fringe



- spectral sensitivity of MIT phase noise interferometer
- above 500 Hz shot noise limited near LIGO I goal
- additional features are from 60 Hz powerline harmonics, wire resonances (600 Hz), mount resonances, etc



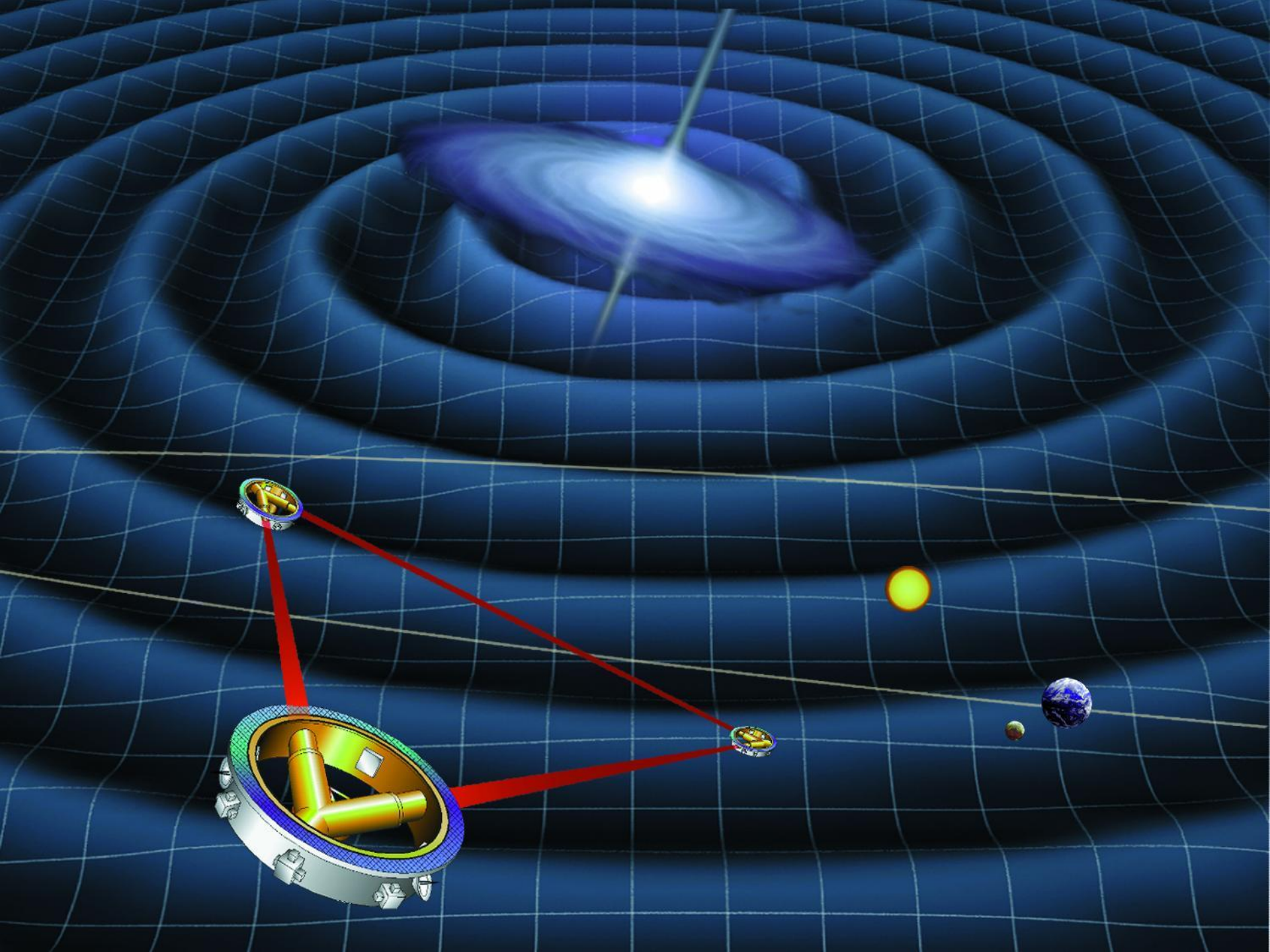
LIGO -

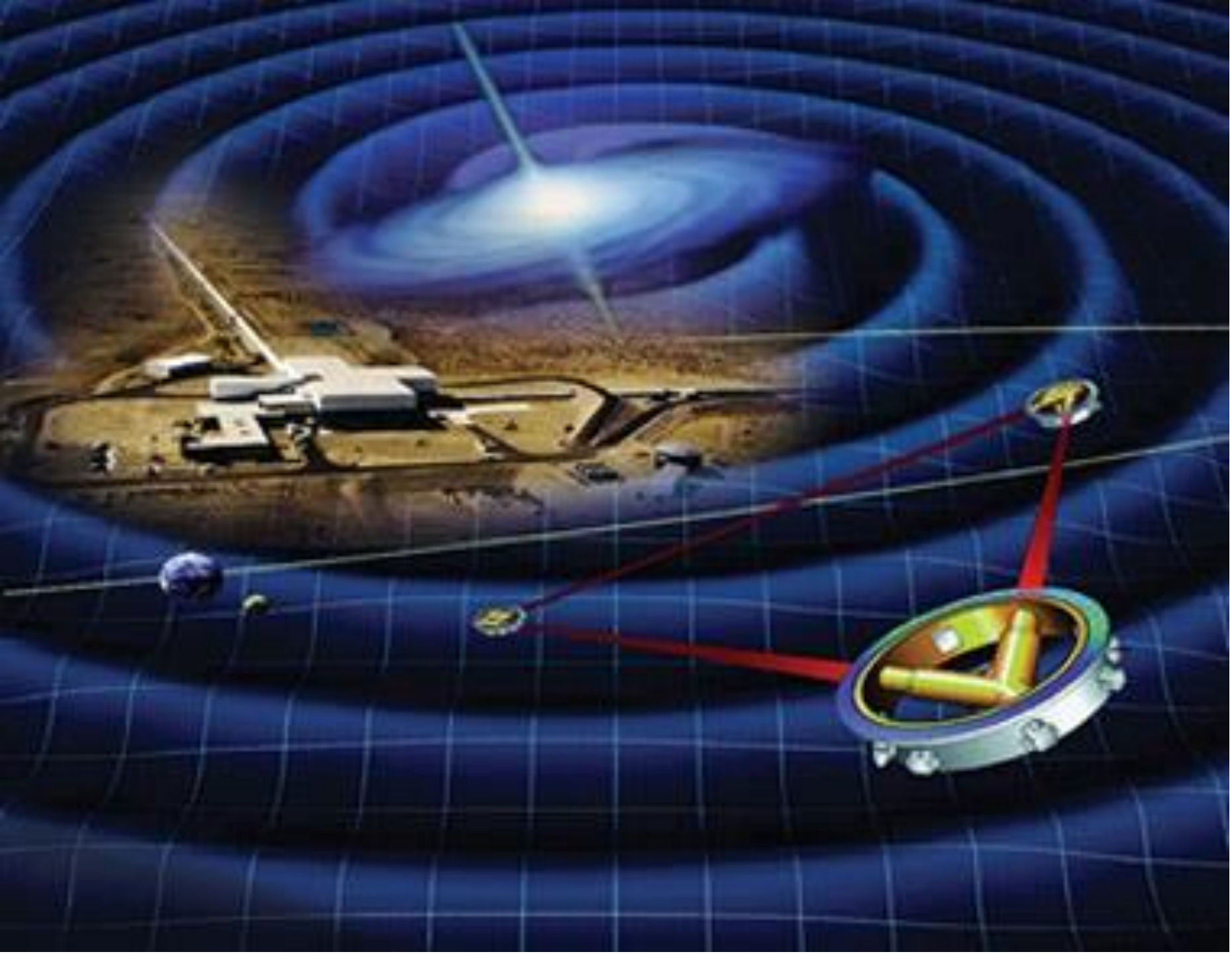
Conclusions

- GW can be a powerful mean to probe late-time background cosmology
- the measurement of the luminosity distance is clean
- in the case of LISA, using MBHB one needs an independent em counterpart to get the redshift, but one can have sources up to redshift 7
- LISA using MBHB + Planck can provide a below 1% measurement of H_0
- LISA using MBHB can also offer constraints on models where the DE starts to play a role at high redshift
- using lower redshift sources, it is possible to improve constraints on DE and get a probe of the universe acceleration fully independent on em emission

LISA chronology

- 1980s - 2011: joint NASA/ESA proposal
- 2011: NASA withdraws, ESA continues with descoped mission NGO (two arms)
- 2012: ESA selects JUICE for L1
- 2013: ESA selects LISA scientific theme for L3: "the gravitational universe"
- 2013 - 2016: studies of different configurations and refinement of the scientific case
- 25/10/2016: ESA call for mission
- 13/01/2017: LISA Consortium submits the LISA proposal (3 arms), APPROVED BY ESA
- 3/2017 - fall 2017: ESA Phase 0 study
- beginning 2018 - 2019: ESA Phase A study (with industries)
- 2019 - 2020: preparation of industrial implementation
- 2021: ESA mission adoption
- 8.5 years: mission construction
- around 2030 - 2034: launch (Ariane 6)
- nominal mission duration 4 years, tested extension up to 10 years
- cost: 1050 M€

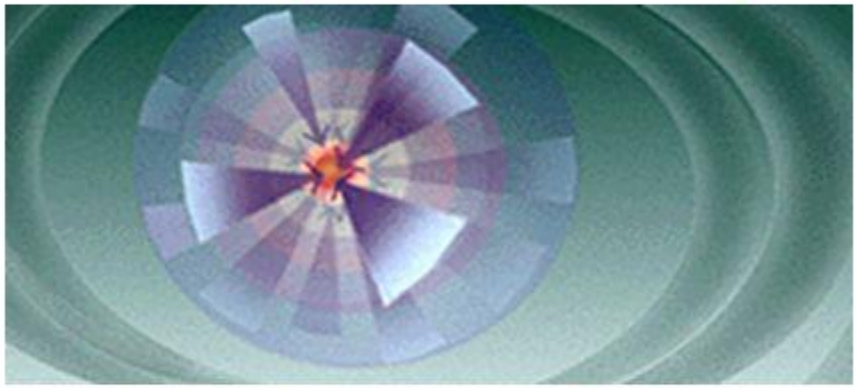




LIGO

Gravitational Waves from Supernova collapse

Non axisymmetric collapse

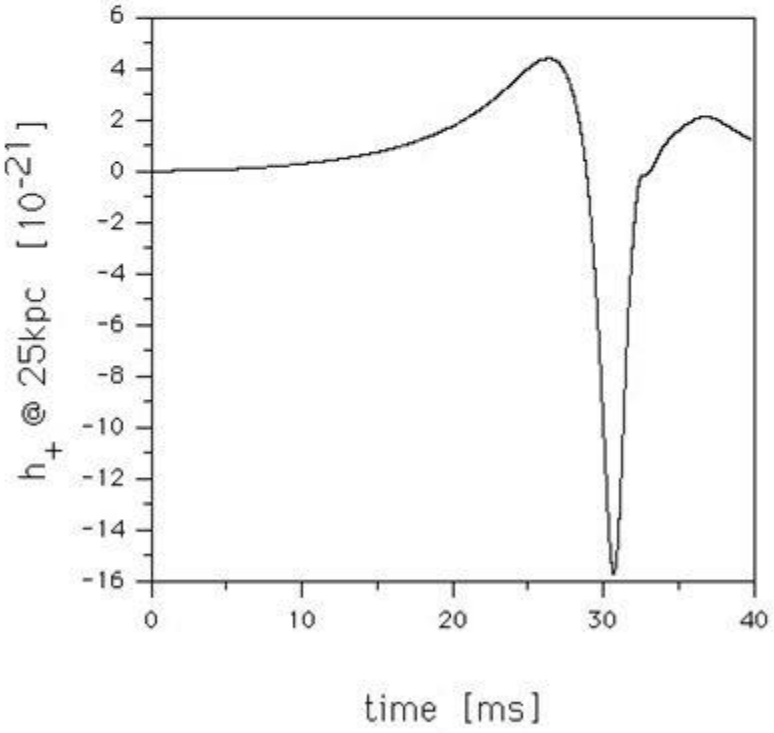


Rate

1/50 yr - our galaxy

3/yr - Virgo cluster

'burst' signal



AJW, Caltech, LIGO Laboratory

LIGO

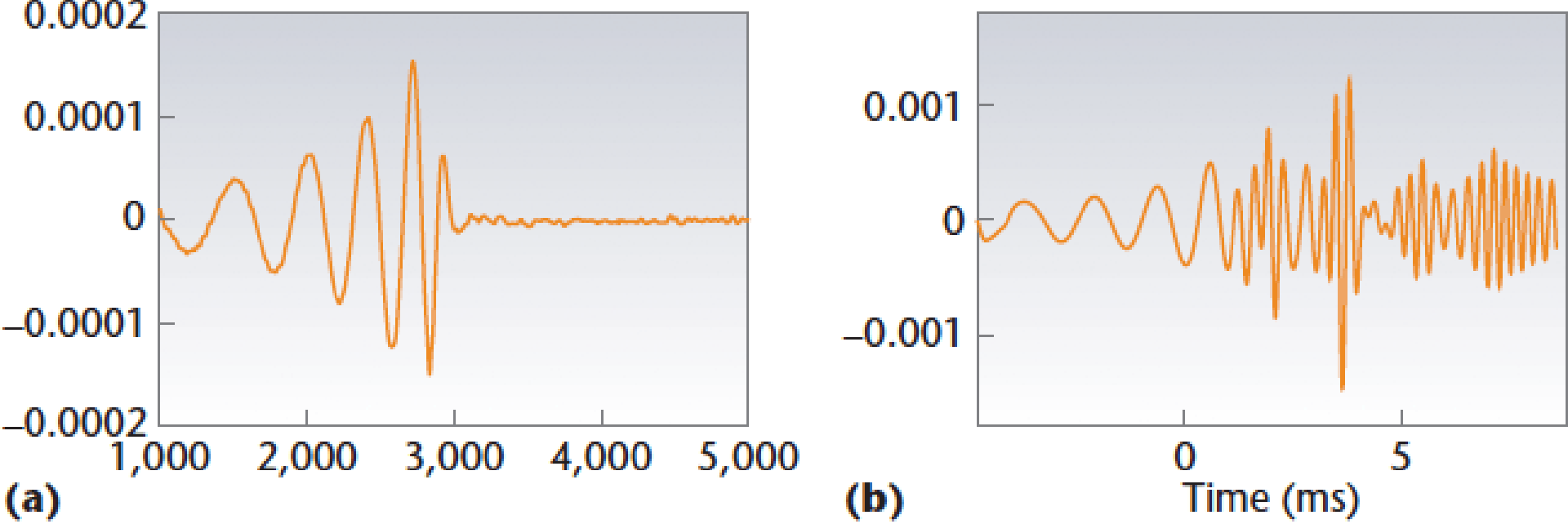
Gravitational wave detectors

- **Bar detectors**
  - Invented and pursued by Joe Weber in the 60's
  - Essentially, a large "bell", set ringing (at ~ 900 Hz) by GW
  - Won't discuss any further, here
- **Michelson interferometers**
  - At least 4 independent discovery of method:
  - Pirani `56, Gerstenshtein and Pustovoit, Weber, Weiss `72
  - Pioneering work by Weber and Robert Forward, in 60's

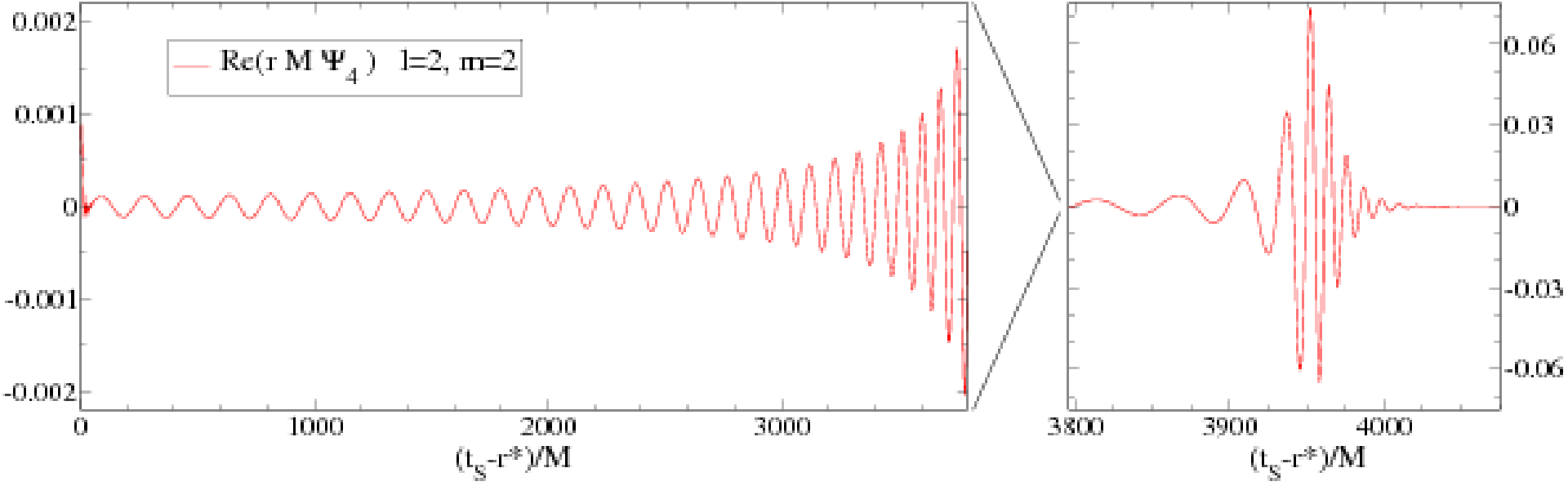
LIGO

Waveforms of Gravitational Waves

- "Chirps" (reasonably known waveforms)
  - » Neutron star (NS/NS) binary pairs
  - » Black hole (BH/BH) binaries; NS/BH binaries
- Periodic (well defined waveforms)
  - » Pulsars with ellipticity
  - » "Wagoner" stars (neutron stars spinning up, with instabilities)
- Impulsive (unknown waveforms)
  - » Supernova bursts
- Stochastic (random, indistinguishable from noise)
  - » Background from primordial cosmological event (Big Bang)
- Unknown???
  - » Rates, signal sizes, waveforms for all the above are *very* uncertain
  - » Surprises are *certain*!

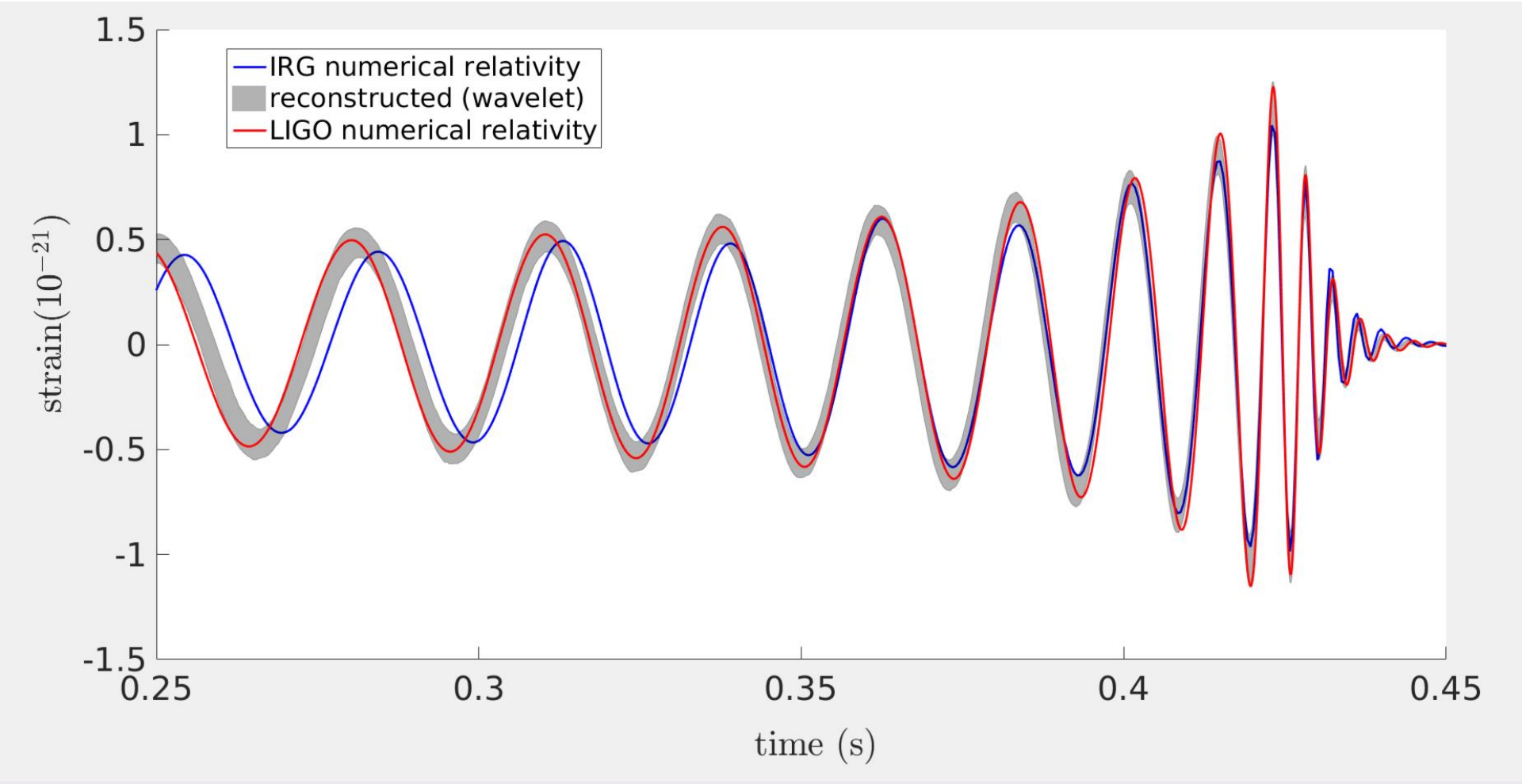


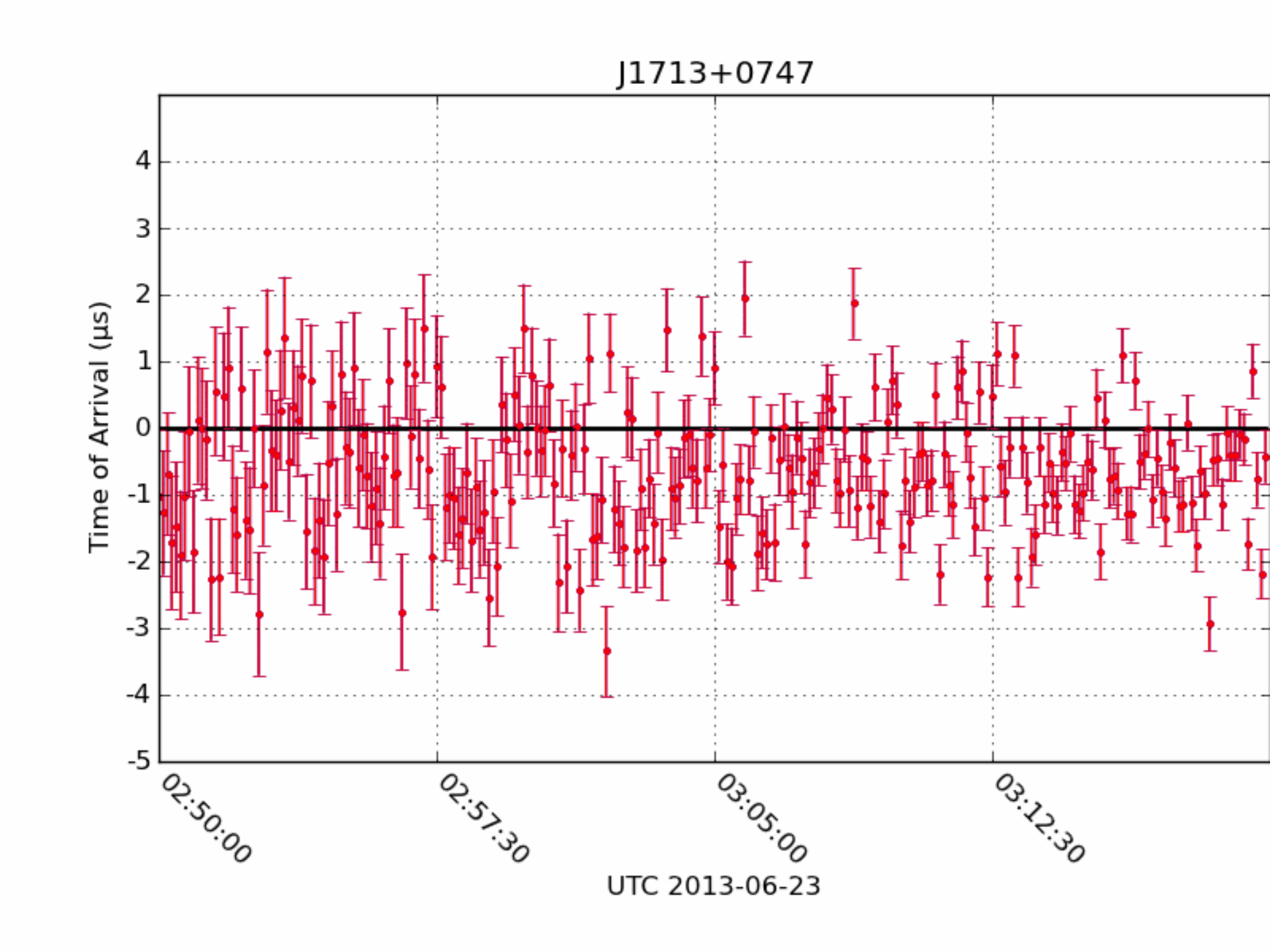
Gravitational wave signature from (a) a black hole-neutron star (BHNS) and (b) a binary neutron star (BNS) system. The BHNS signal shuts off rather abruptly



High-accuracy waveforms for binary

Gravitational waveform extracted at finite radius r=225Mr=225M, for the case 30c1/N6 in Table~???????. The left panel zooms in on the inspiral waveform,and the right panel zooms in on the merger and ringdown


IRG numerical relativity
reconstructed (wavelet)
LIGO numerical relativity
1.5
1
0.5
0
-0.5
-1
-1.5
strain(10^{-21})
0.25
0.3
0.35
0.4
0.45
time (s)

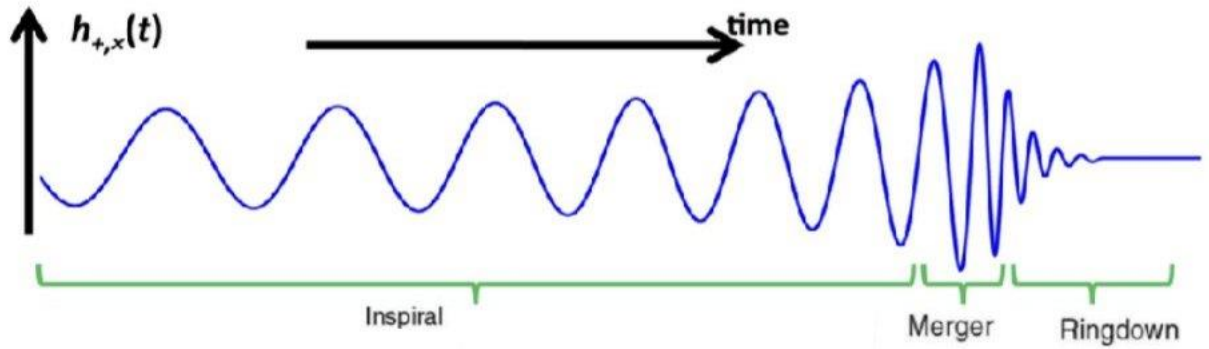

J1713+0747
Time of Arrival (μs)
4
3
2
1
0
-1
-2
-3
-4
-5
02:50:00
02:57:30
03:05:00
03:12:30
UTC 2013-06-23

What LISA measures

1. The gravitational wave strain from the inspiral and merger of compact binaries : it encodes information on the binary parameters

$$h(t) \sim 2\,\frac{\Delta L}{L} \qquad\qquad \mathcal{M}_c,\ d_L,\ t_c,\ \eta,\ \Phi_c,\ \phi$$

LISA target :
- BH binaries, massive (high SNR) and LIGO-like
- galactic binaries
- Extreme Mass Ratio Inspirals

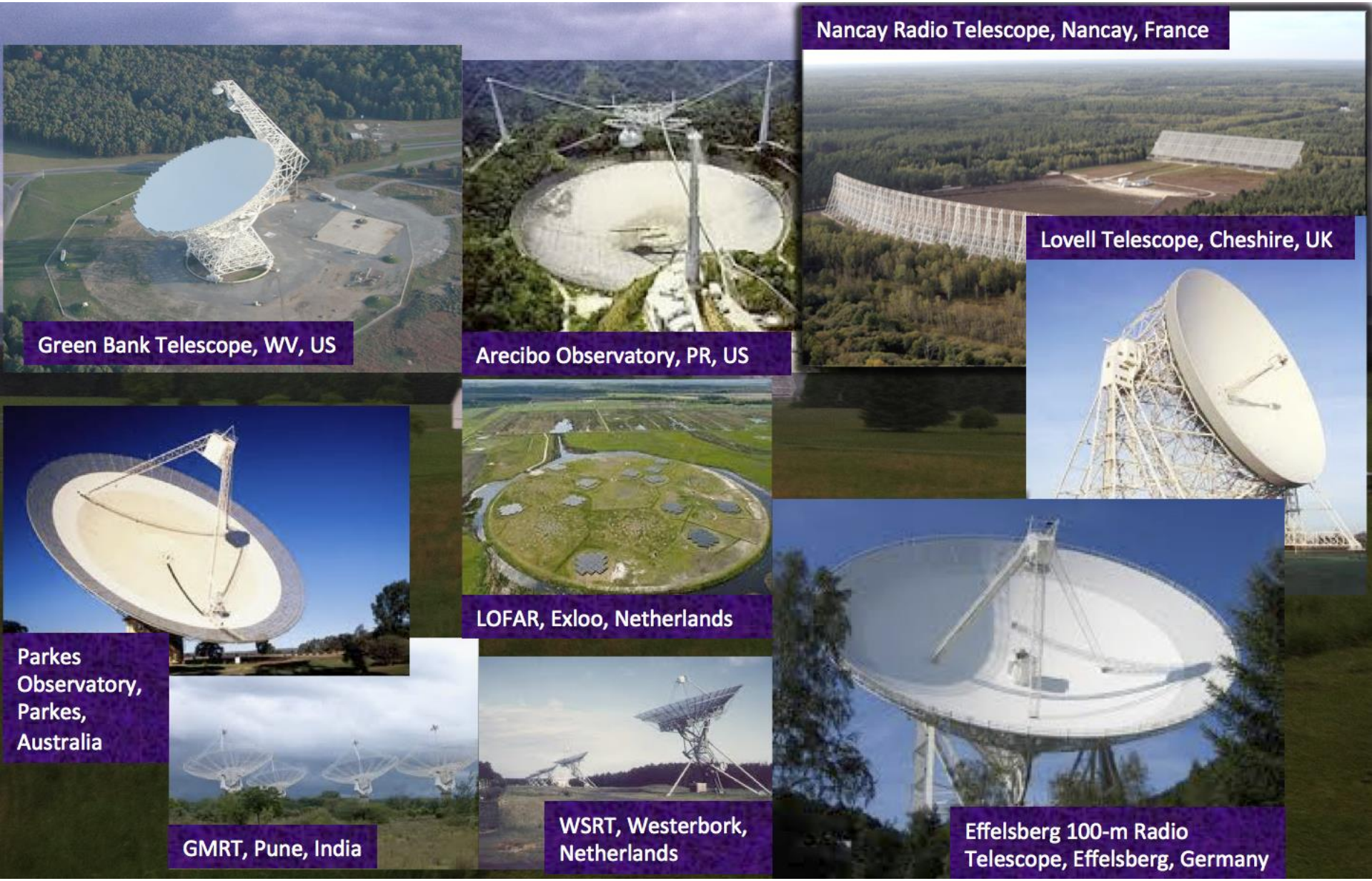


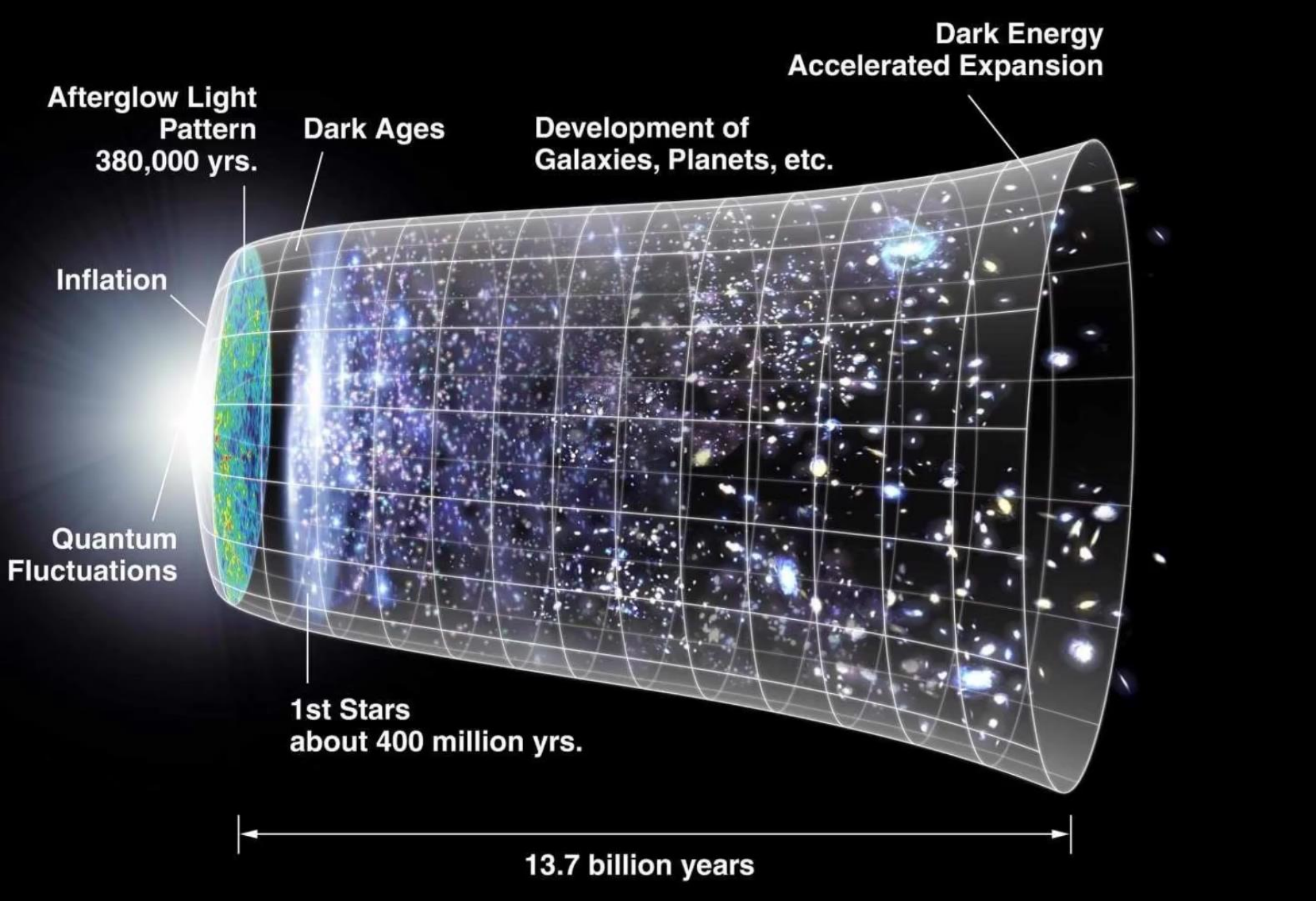
LISA AND COSMOLOGY:

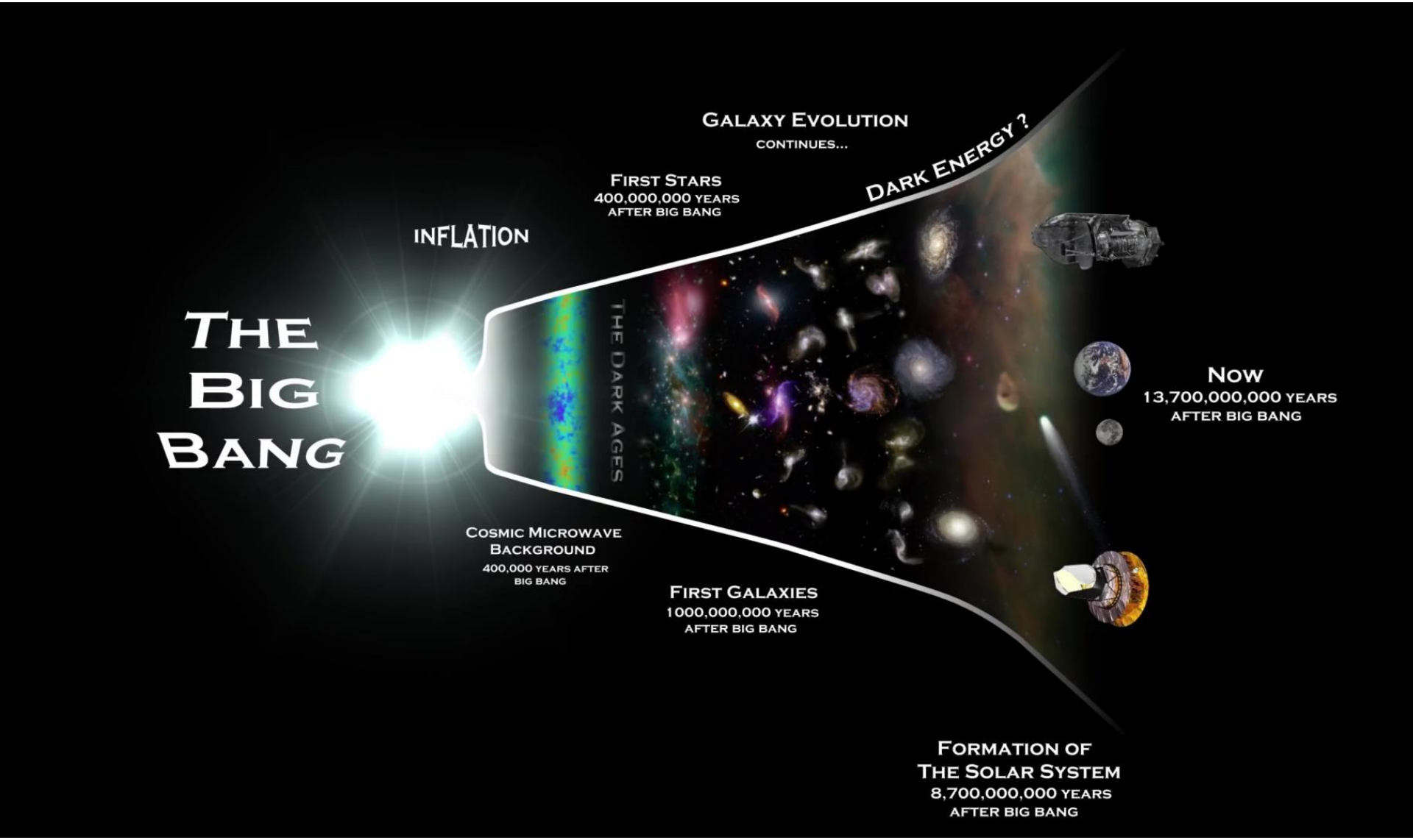
some results from the *LISA cosmology working group*
(Germano Nardini, CC)

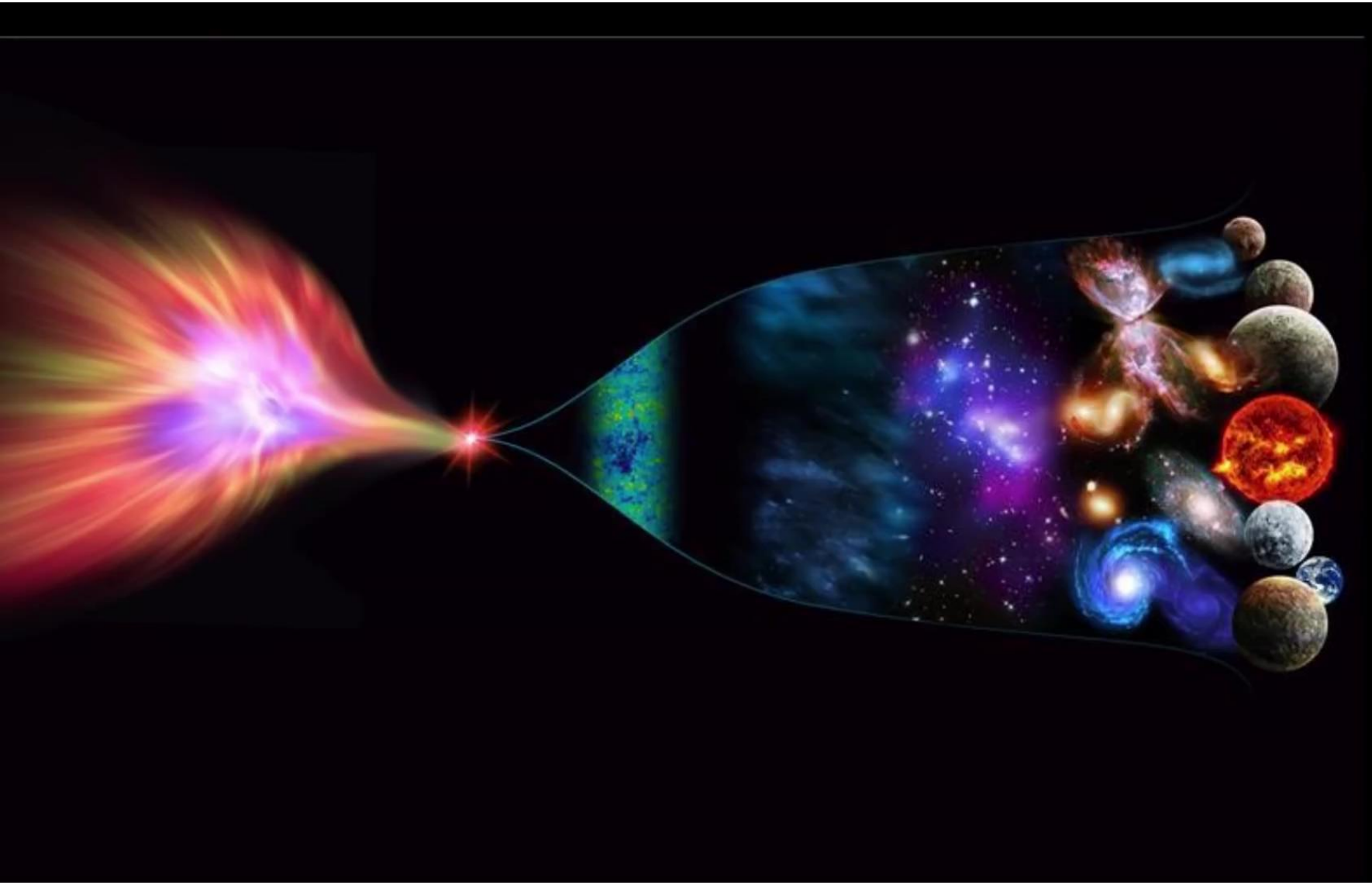
the stochastic GW background from primordial sources: test of early universe and high energy phenomena

use of GW emission from binaries to probe the background expansion of the universe : test of acceleration

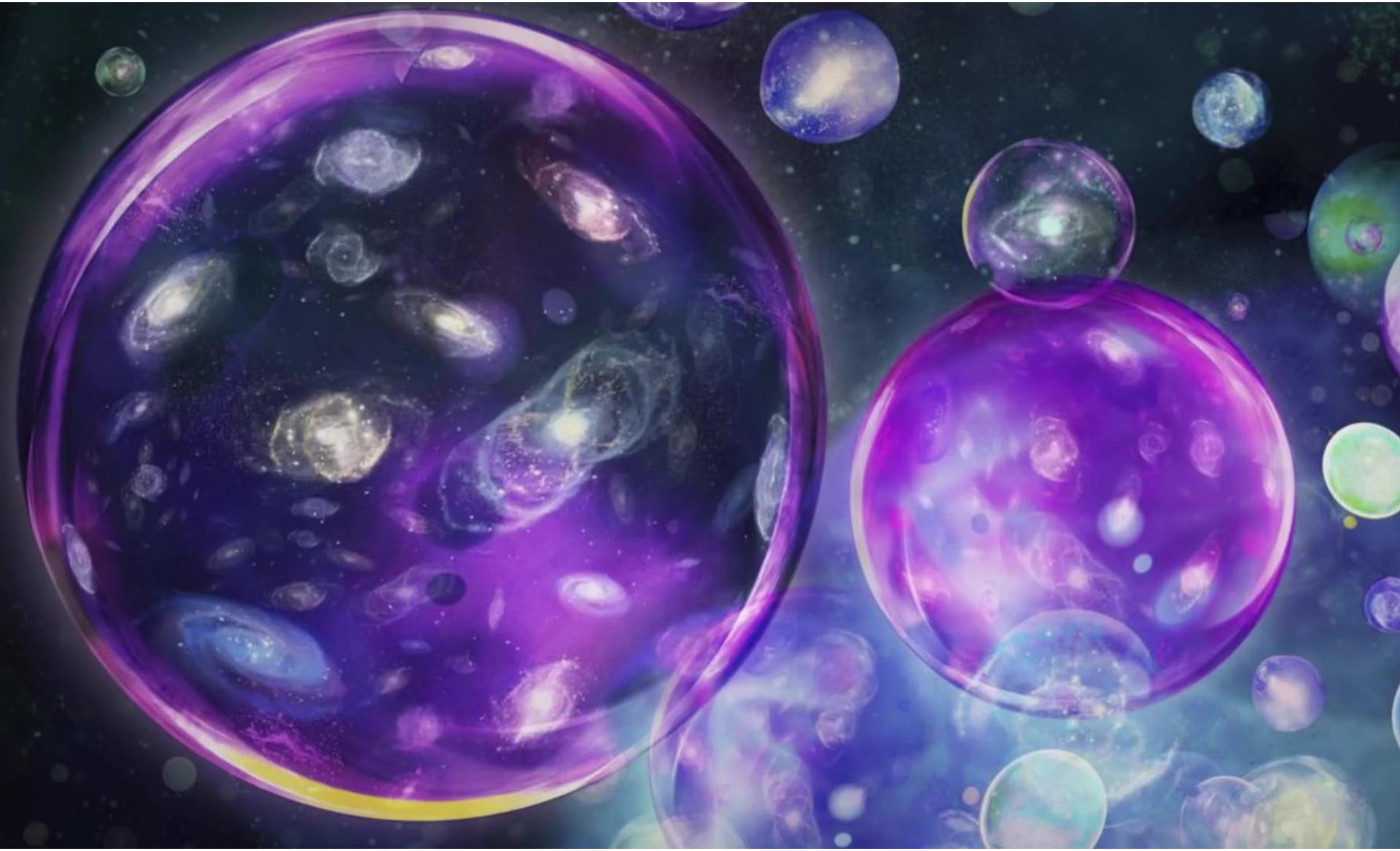

Green Bank Telescope, WV, US
Arecibo Observatory, PR, US
Nancay Radio Telescope, Nancay, France
Lovell Telescope, Cheshire, UK
LOFAR, Exloo, Netherlands
Parkes Observatory, Parkes, Australia
GMRT, Pune, India
WSRT, Westerbork, Netherlands
Effelsberg 100-m Radio Telescope, Effelsberg, Germany


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
13.7 billion years

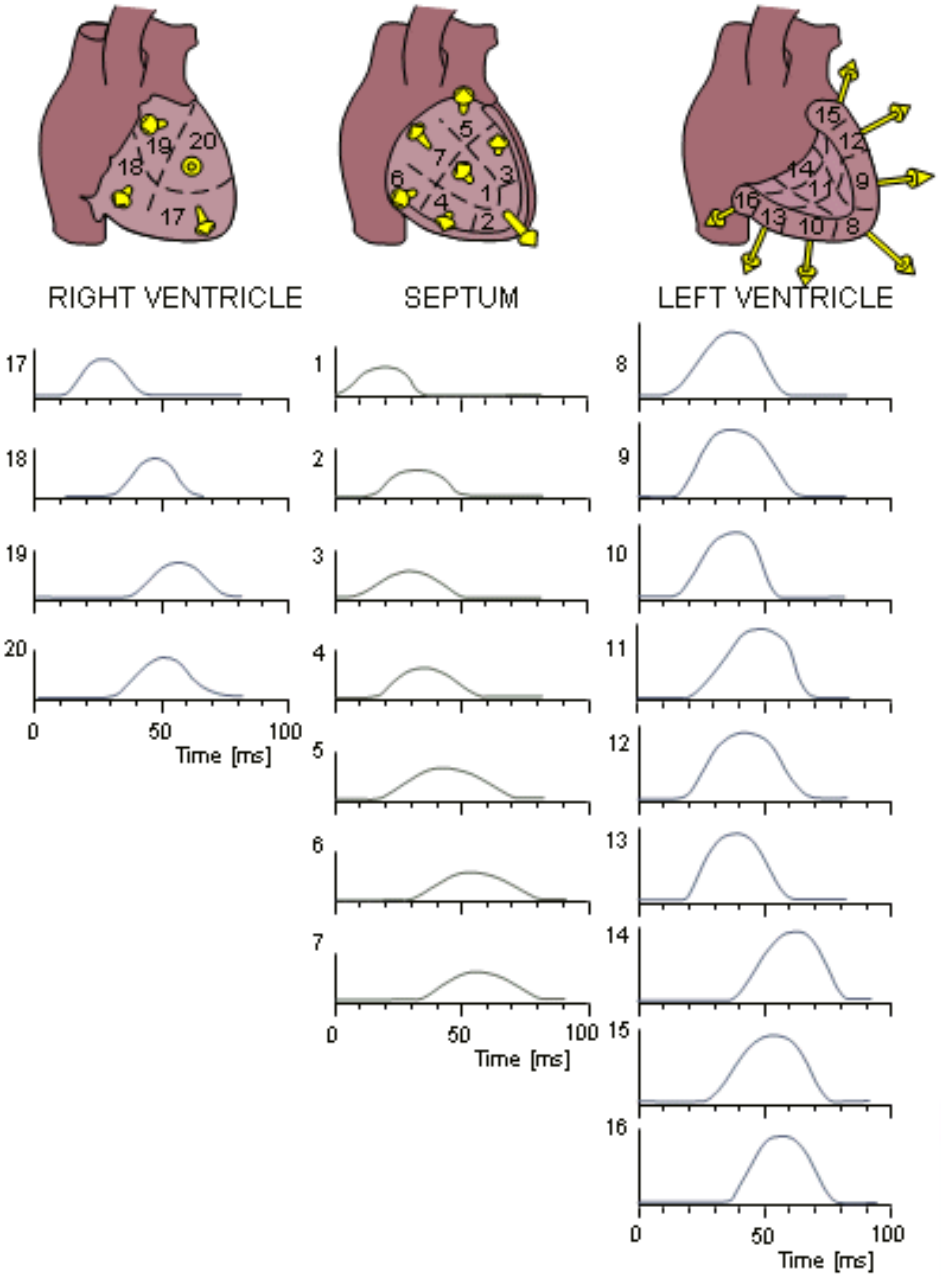

THE BIG BANG
INFLATION
FIRST STARS
400,000,000 YEARS
AFTER BIG BANG
GALAXY EVOLUTION
CONTINUES...
DARK ENERGY ?
THE DARK AGES
COSMIC MICROWAVE
BACKGROUND
400,000 YEARS AFTER
BIG BANG
FIRST GALAXIES
1000,000,000 YEARS
AFTER BIG BANG
NOW
13,700,000,000 YEARS
AFTER BIG BANG
FORMATION OF
THE SOLAR SYSTEM
8,700,000,000 YEARS
AFTER BIG BANG



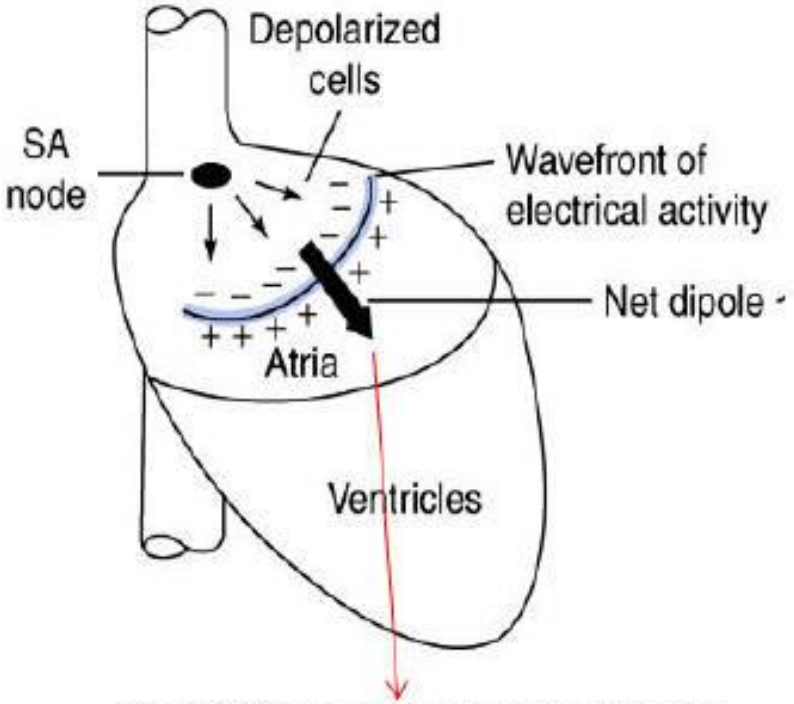

Gravitational Pull

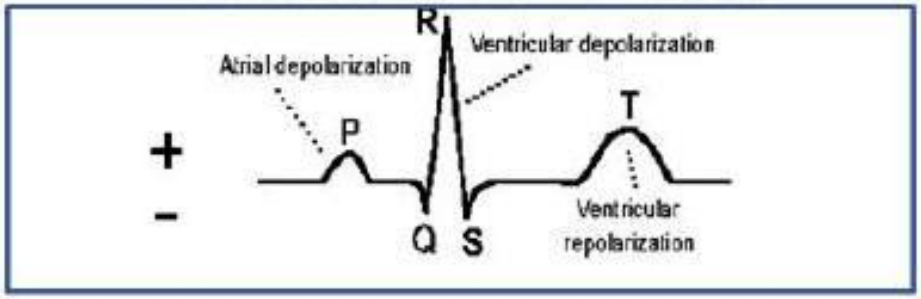


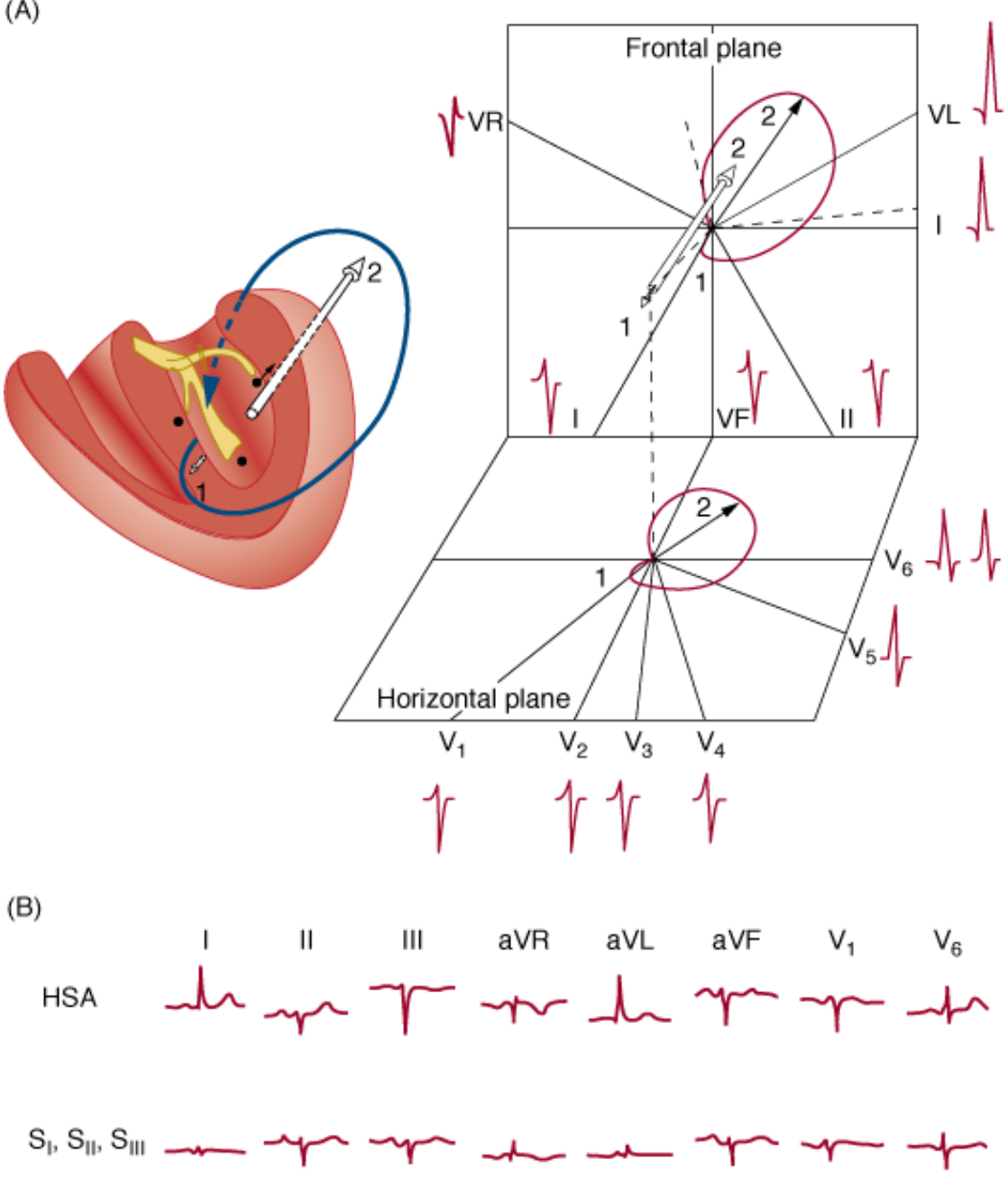
Surpinzatoarele prezente ale fenomenlor cuadrupolare in viata de toate zilele



representation on ECG of the electrical activity of the heart

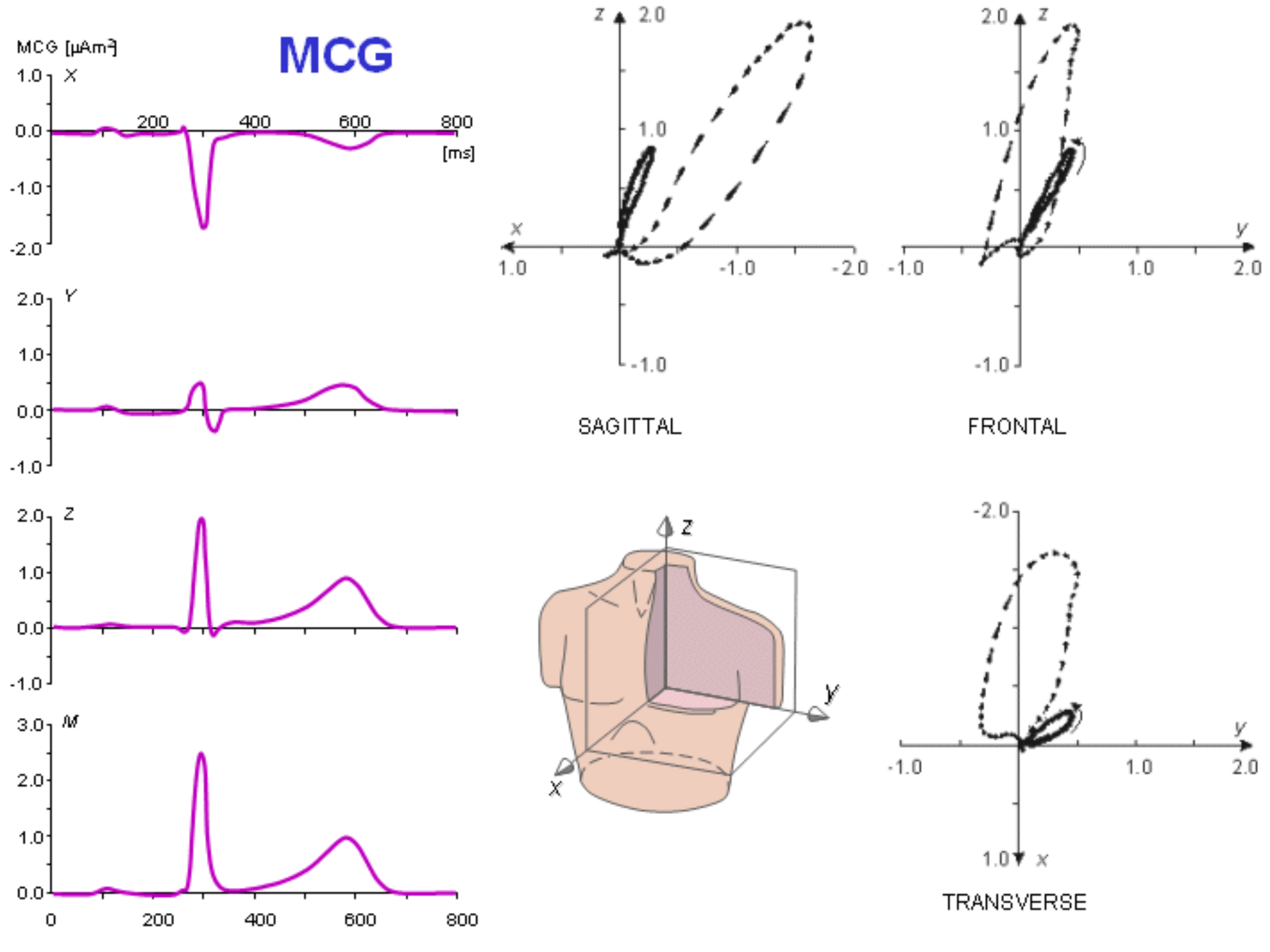




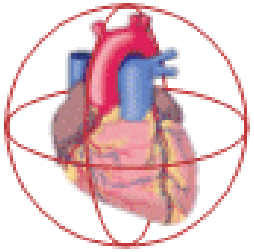


Source: Fuster V, Walsh RA, Harrington RA: *Hurst's The Heart, 13th Edition:* www.accessmedicine.com

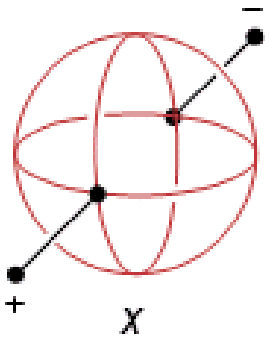
Copyright © The McGraw-Hill Companies, Inc. All rights reserved.

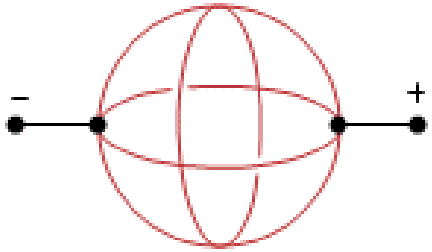

MCG
MCG [μAm]
X
Y
Z
M
200
400
600
800
[ms]
1.0
0.0
-1.0
-2.0
2.0
3.0
0
z
x
y
SAGITTAL
FRONTAL
TRANSVERSE

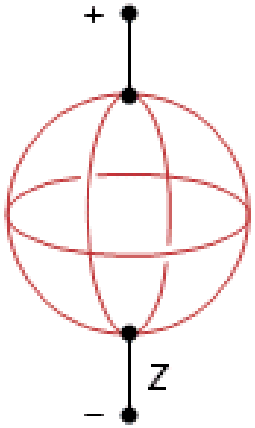
Measurement of the dipolar components



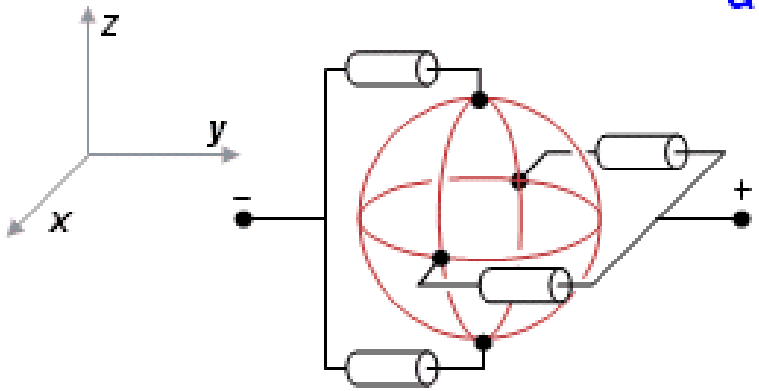
Spherical homogeneous volume conductor



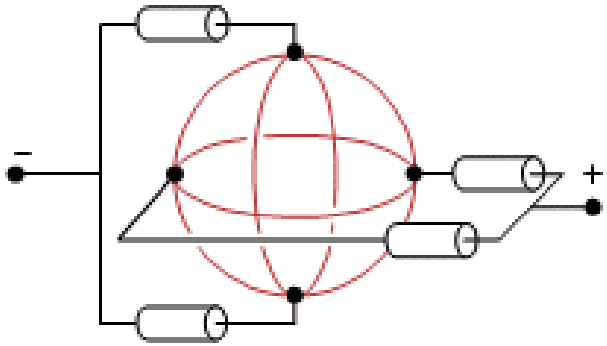




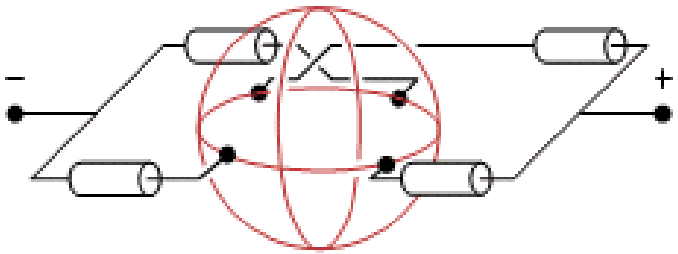
and the quadrupolar components



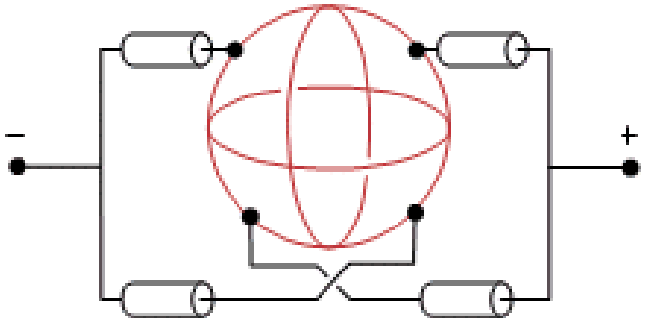
XX-ZZ



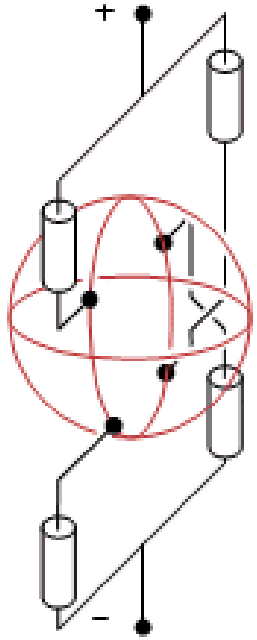
YY-ZZ



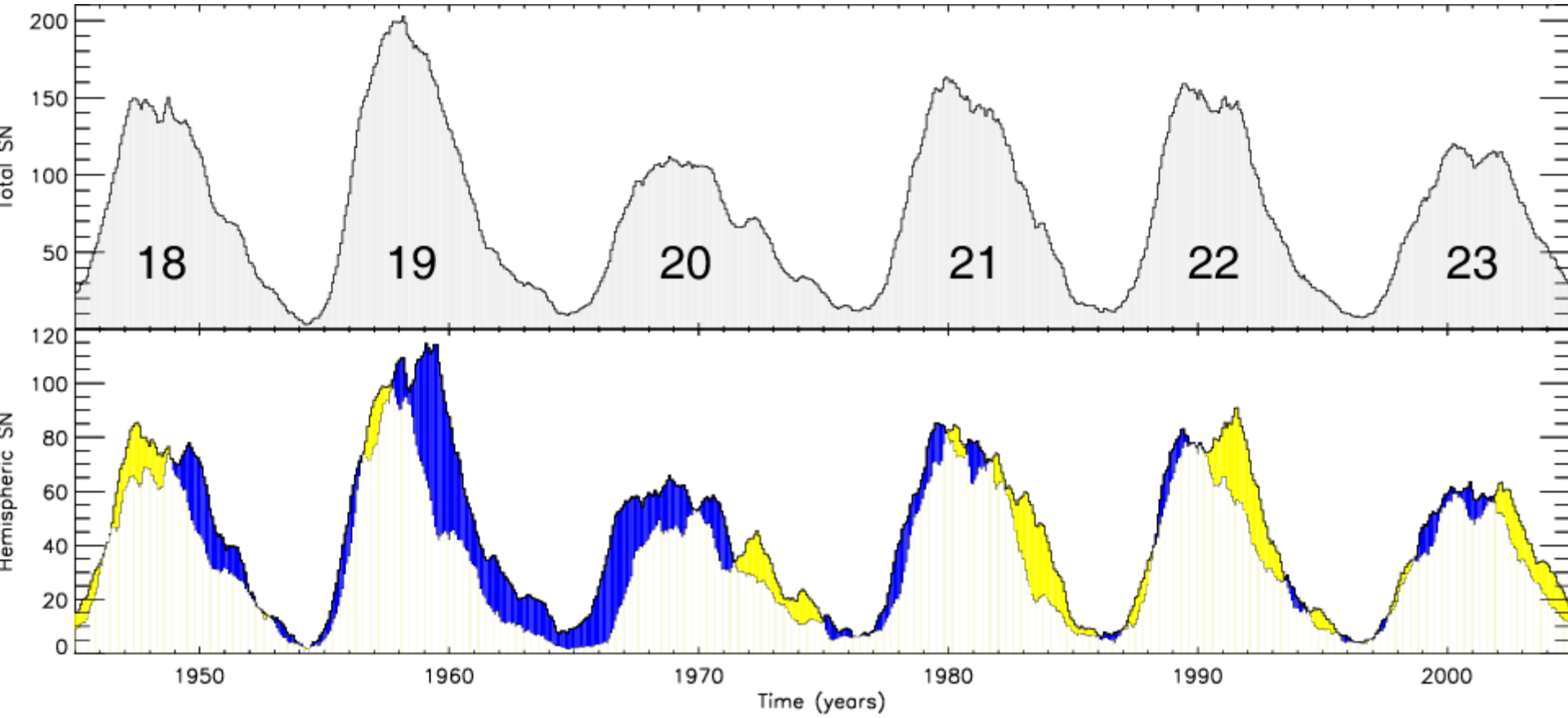
XY

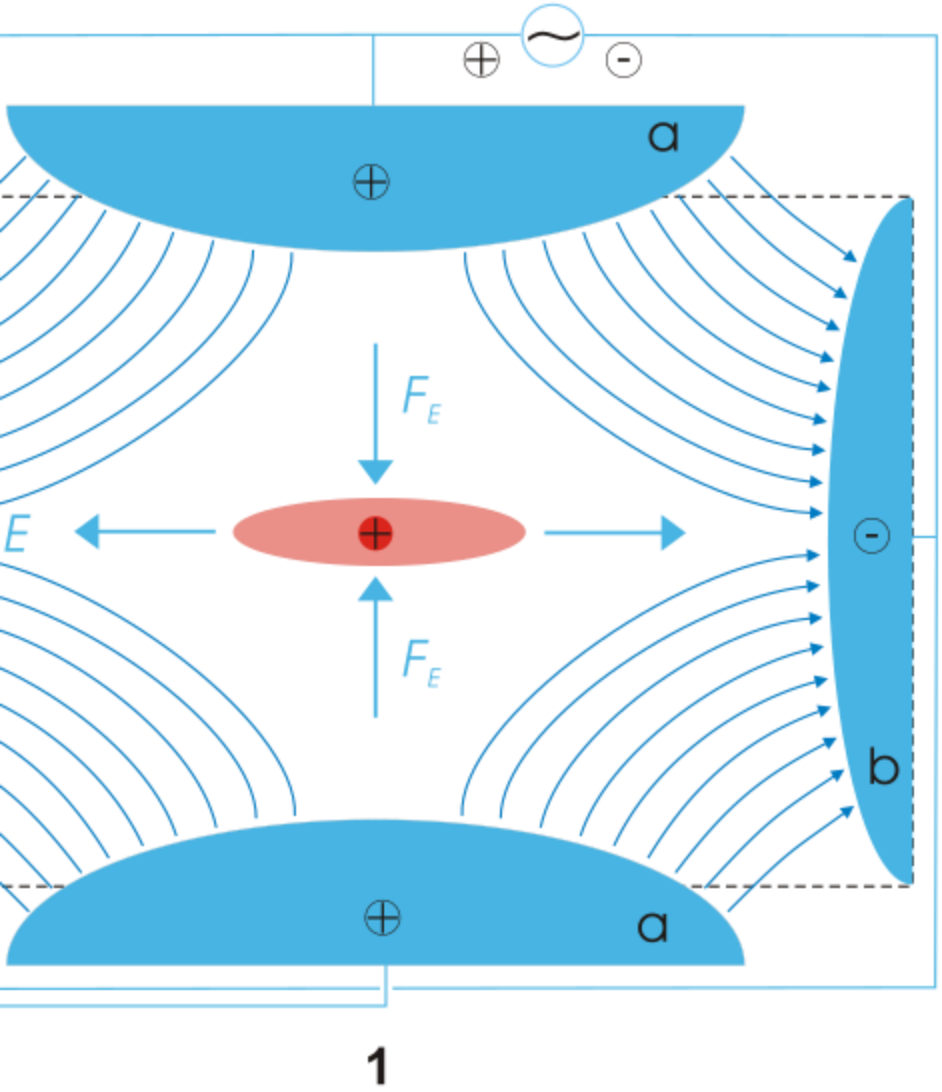


YZ

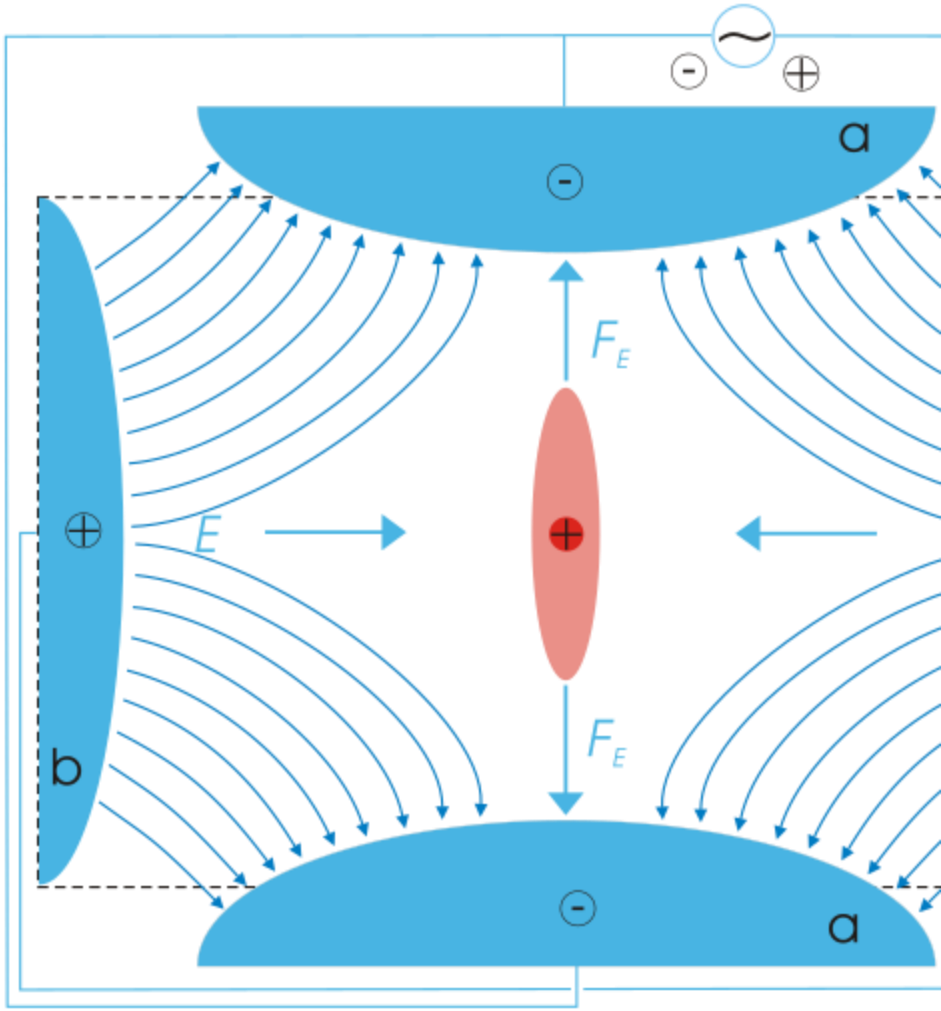


ZX


Total SN
200
150
100
50
18
19
20
21
22
23
Hemispheric SN
120
100
80
60
40
20
0
1950
1960
1970
1980
1990
2000
Time (years)



1



2

Quadrupole ion trap

The electric quadrupole moment of the deuteron

The bare neutron and proton have no electric quadrupole moment, and so any measured nonzero value for the quadrupole moment must be due to the orbital motion.

— The pure $l = 0$ wave function would have a vanishing quadrupole moment.

The observed quadrupole moment for the deuteron is

$$Q = 0.00288 \pm 0.00002 \text{ b} \qquad (27)$$

When the mixed wave function [equation (24)] is used to calculate the quadrupole moment of the deuteron (Q) the calculation gives two contribution terms. One is proportional to $(a_d)^2$ and another proportional to the cross-term $(a_s a_d)$.

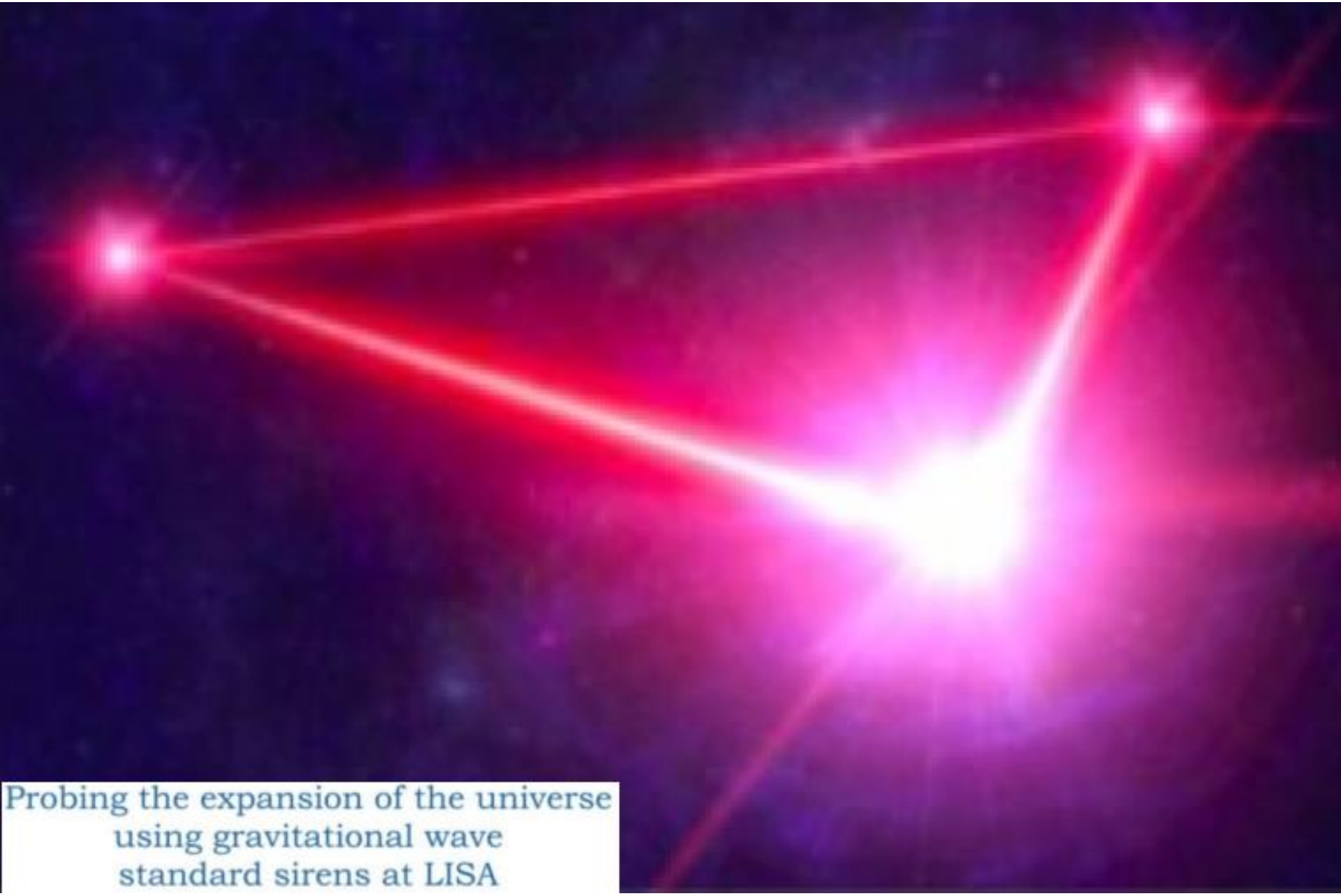
$$Q = \frac{\sqrt{2}}{10} a_s a_d \left\langle r^2 \right\rangle_{sd} - \frac{1}{20} a_d^2 \left\langle r^2 \right\rangle_{dd} \qquad (28)$$

where $\left\langle r^2 \right\rangle_{sd} = \int r^2 R_s(r) R_d(r) r^2 dr$ $\qquad$ $\left\langle r^2 \right\rangle_{dd} = \int r^2 R_d(r) R_d(r) r^2 dr$

To calculate Q we must know the deuteron d-state wave function and it is obtainable from the realistic phenomenological potentials. The d-state admixture is of several percent in this calculation and is consistent with the 4% value deduced from the magnetic moment.

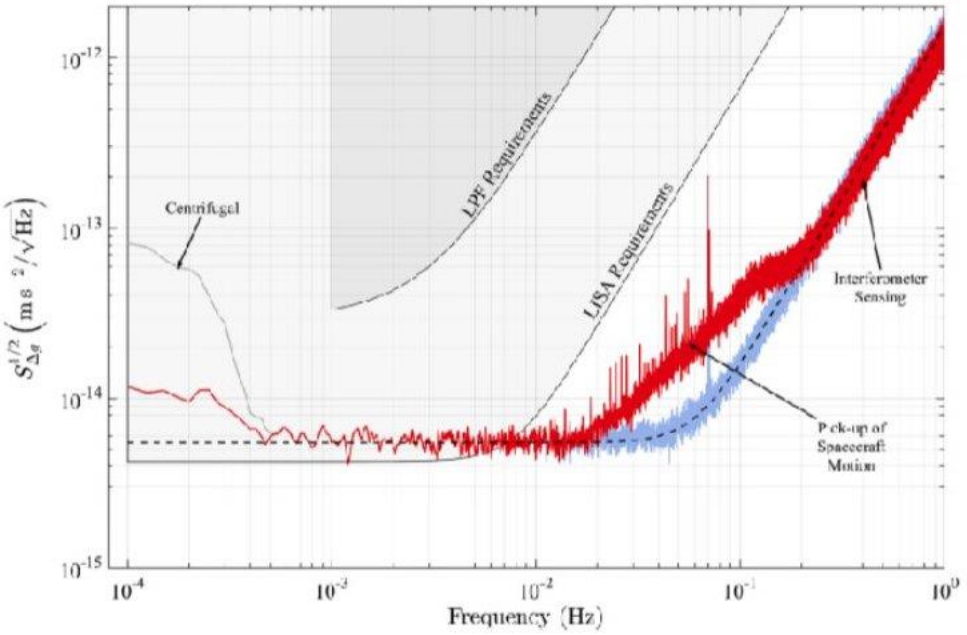


Asta nu-i o undă gravitaţională, este o familie. . . . . *Vă mulţumesc pentru atenţie* !


Probing the expansion of the universe
using gravitational wave
standard sirens at LISA

LISA
space-based interferometer performing direct GW detection

LISA Pathfinder launch Dec 2015, operations 2016-2017



one LISA arm reduced in one spaceship

test the ability to put two masses in free fall: measure the differential acceleration among them

Armano et al, PRL 116, 231101 (2016)

What LISA measures

2. the stochastic background of gravitational waves

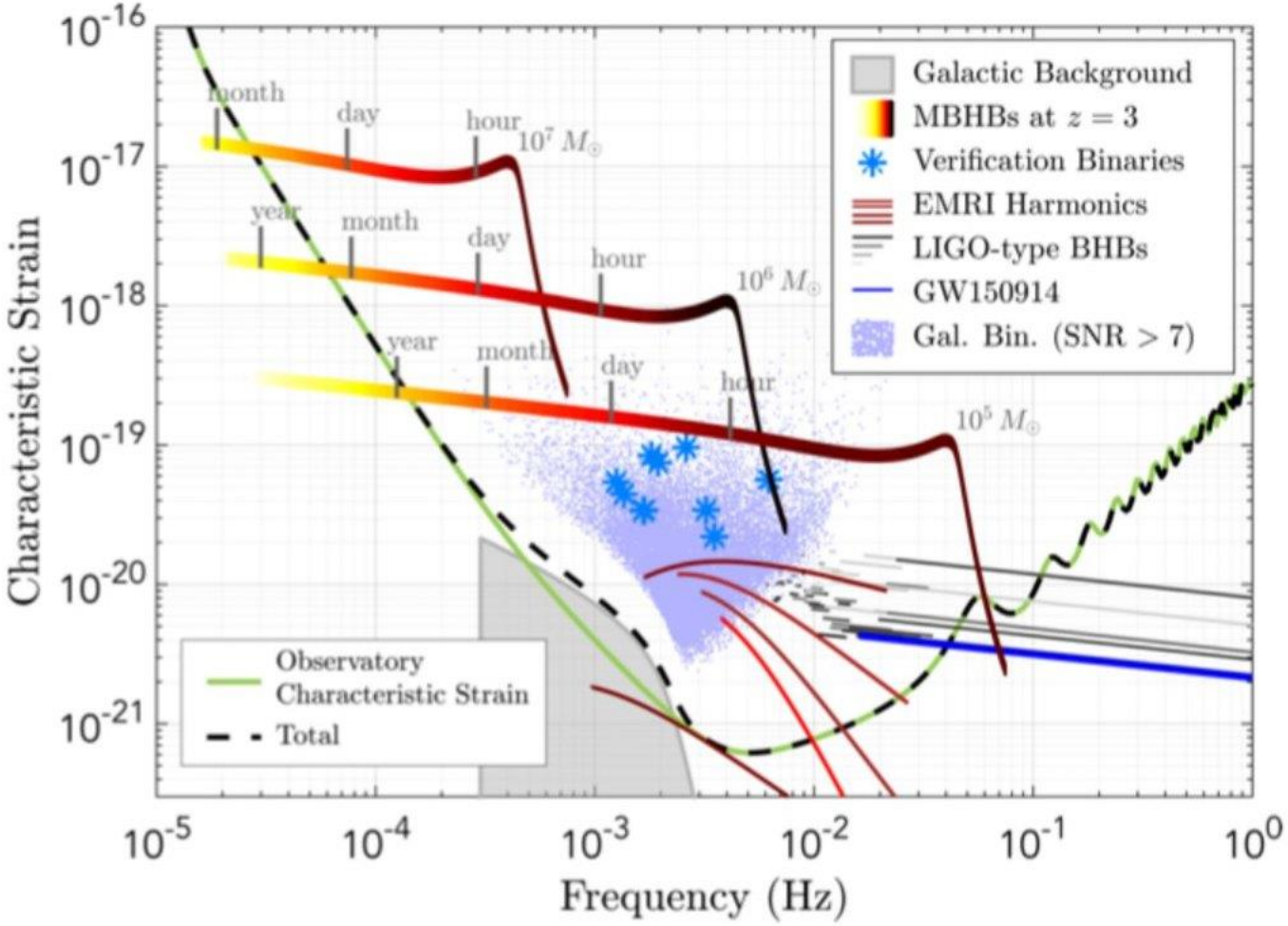
the superposition of sources that cannot be resolved individually

- binaries too numerous and with too low SNR to be identified
- signals from the early universe with too small correlation scale (typically horizon at the time of production) with respect to the detector resolution

$$\Omega_{\rm GW} = \frac{\rho_{\rm GW}}{\rho_c} = \frac{\langle \dot{h}_{ij} \dot{h}_{ij} \rangle}{32\pi G\, \rho_c} = \int \frac{{\rm d}f}{f} \frac{{\rm d}\Omega_{\rm GW}}{{\rm d}\ln f}$$

energy density power spectrum

What LISA measures



Standard sirens

GW emission by compact binaries + redshift by an EM counterpart can be used to probe the distance-redshift relation

$$h_+(t) = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}} \left(\frac{\pi f}{c}\right)^{\frac{2}{3}} \frac{1+\cos^2 \imath}{2} \cos[\Phi(t)]$$

$$h_\times(t) = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}} \left(\frac{\pi f}{c}\right)^{\frac{2}{3}} \cos\imath \sin[\Phi(t)]$$

$$\mathcal{M}_c = (1+z)M_c$$

redshifted chirp mass

$$d_L(H_0, \Omega_\Lambda, \Omega_M, w_0, w_a)$$

Standard sirens

GW emission by compact binaries + redshift by an EM counterpart
can be used to probe the distance-redshift relation

no distance ladder

Standard sirens

GW emission by compact binaries + redshift by an EM counterpart can be used to probe the distance-redshift relation

no distance ladder

but no redshift either!

Standard sirens

GW emission by compact binaries + redshift by an EM counterpart can be used to probe the distance-redshift relation

$$h_+(t) = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}} \left(\frac{\pi f}{c}\right)^{\frac{2}{3}} \frac{1+\cos^2 \imath}{2} \cos[\Phi(t)]$$

$$h_\times(t) = \frac{4}{d_L(z)} \left(\frac{G\mathcal{M}_c}{c^2}\right)^{\frac{5}{3}} \left(\frac{\pi f}{c}\right)^{\frac{2}{3}} \cos \imath \sin[\Phi(t)]$$

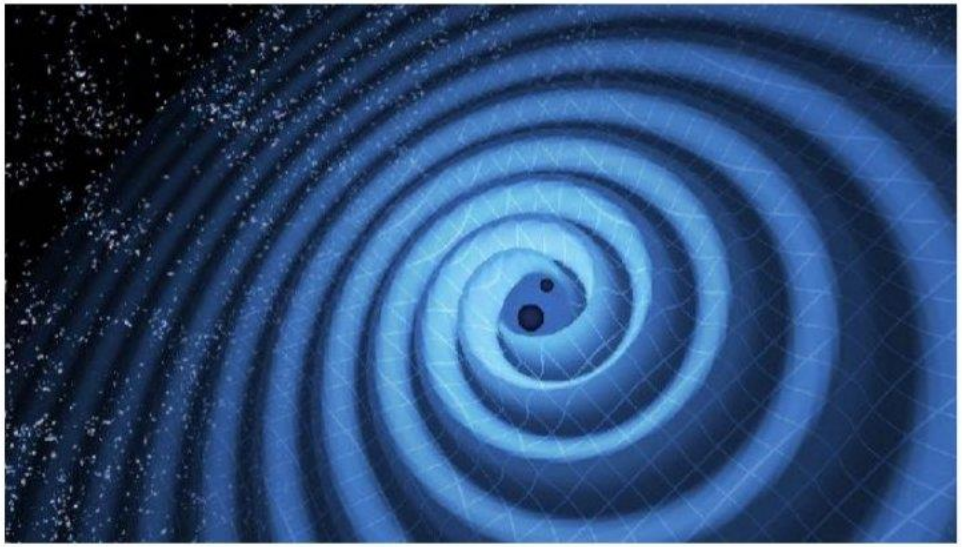
$$\mathcal{M}_c = (1+z) M_c$$

redshifted chirp mass

$$d_L(H_0, \Omega_\Lambda, \Omega_M, w_0, w_a)$$

Standard sirens: analogous to SNIa, but

GW emission by BH binaries provides a direct measurement of luminosity distance up to high redshift: 😃

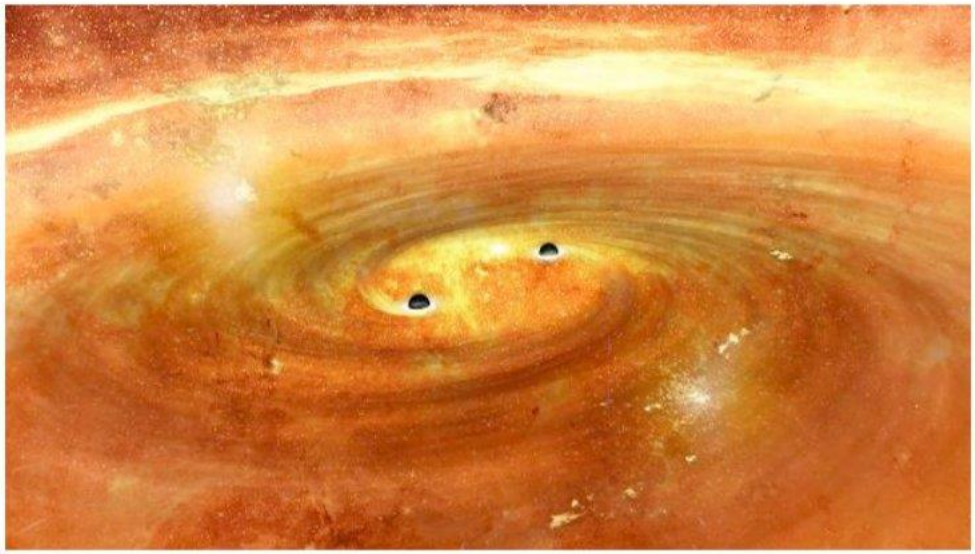


Standard sirens: analogous to SNIa, but

GW emission by BH binaries provides a direct measurement of luminosity distance up to high redshift: 😃

but

it needs to be combined with an independent measurement on the redshift : 😞



standard sirens with LISA: MBHB coalescence

- the rate and redshift distribution of MBH binary events are obtained from numerical simulations
  (three different models - PopIII, heavy seeds with delay, heavy seeds without delay)

- Fisher matrix code to calculate SNR, the error on d_L and on sky localisation from inspiral (conservative) or inspiral+merger and ringdown (optimistic)

- Select events with SNR>8 and sky localisation < 10 deg^2

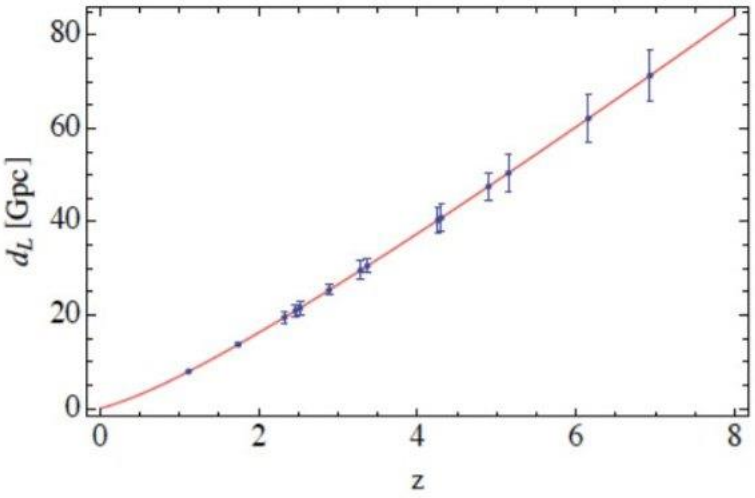
- Add weak lensing and peculiar velocities errors to d_L

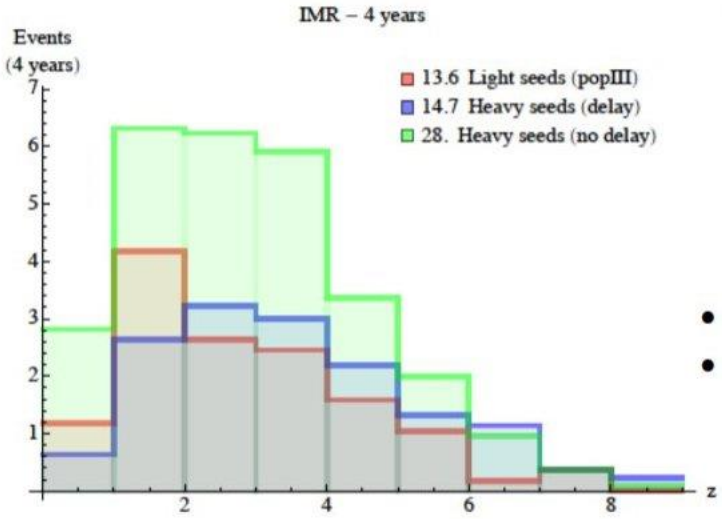
- model of the counterparts :
  - detected directly in the optical by LSST
  - detected first in the radio by SKA and then in the optical by E-ELT
  - add extra redshift error if photometric

standard sirens with LISA: MBHB coalescence

N. Tamanini et al arXiv:1601.07112

example of simulated data
with counterparts
(SKA+EELT)
and weak lensing errors





VERY FEW EVENTS AT
LOW REDSHIFT !

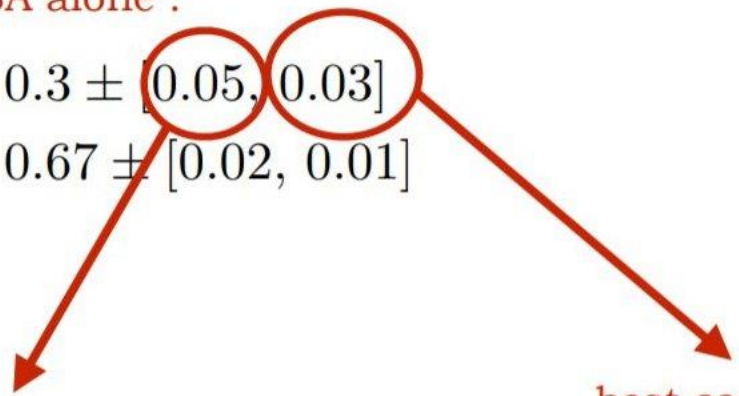
- where needed to probe DE (bad)
- can test expansion at high redshift (good)

standard sirens with LISA: MBHB coalescence

ΛCDM

LISA alone :

$$\Omega_M = 0.3 \pm [0.05, 0.03]$$
$$h = 0.67 \pm [0.02, 0.01]$$



worst case scenario regarding MBHB formation model and sky localisation

best case scenario regarding MBHB formation model and sky localisation

standard sirens with LISA: MBHB coalescence

ΛCDM

LISA alone :

$$\Omega_M = 0.3 \pm [0.05,\ 0.03]$$
$$h = 0.67 \pm [0.02,\ 0.01]$$

Planck alone :

$$\Omega_M = 0.308 \pm 0.0012$$
$$h = 0.678 \pm 0.009$$

most optimistic scenario for MBHB formation gives an independent measurement of the Hubble parameter to 1%

LISA FIXING Ω_M :

$$h = 0.67 \pm [0.006,\ 0.004]$$

- independent constraint
- 0.6% in best case

standard sirens with LISA: MBHB coalescence

Dynamical Dark Energy

too few events at low redshift to get a good measurement

$$w_0 = -1 \pm [0.3,\, 0.1]$$
$$w_a = 0 \pm [1.5,\, 0.8]$$

SNIa + Planck + BAO :
(Betoule et al 2014)

$$w_0 = -0.957 \pm 0.124$$
$$w_a = -0.336 \pm 0.552$$

Euclid forecast :

$$\Delta w_0 = 0.02$$
$$\Delta w_a = 0.1$$

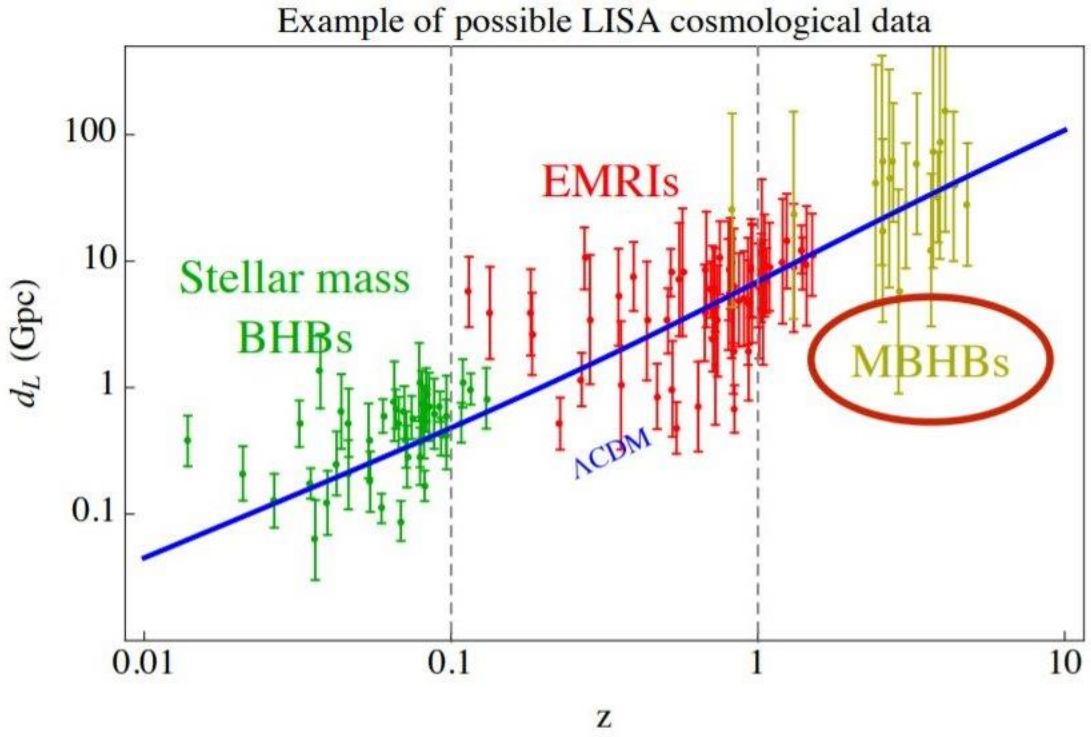
standard sirens with LISA: MBHB coalescence

Dynamical Dark Energy

too few events at low redshift to get a good measurement

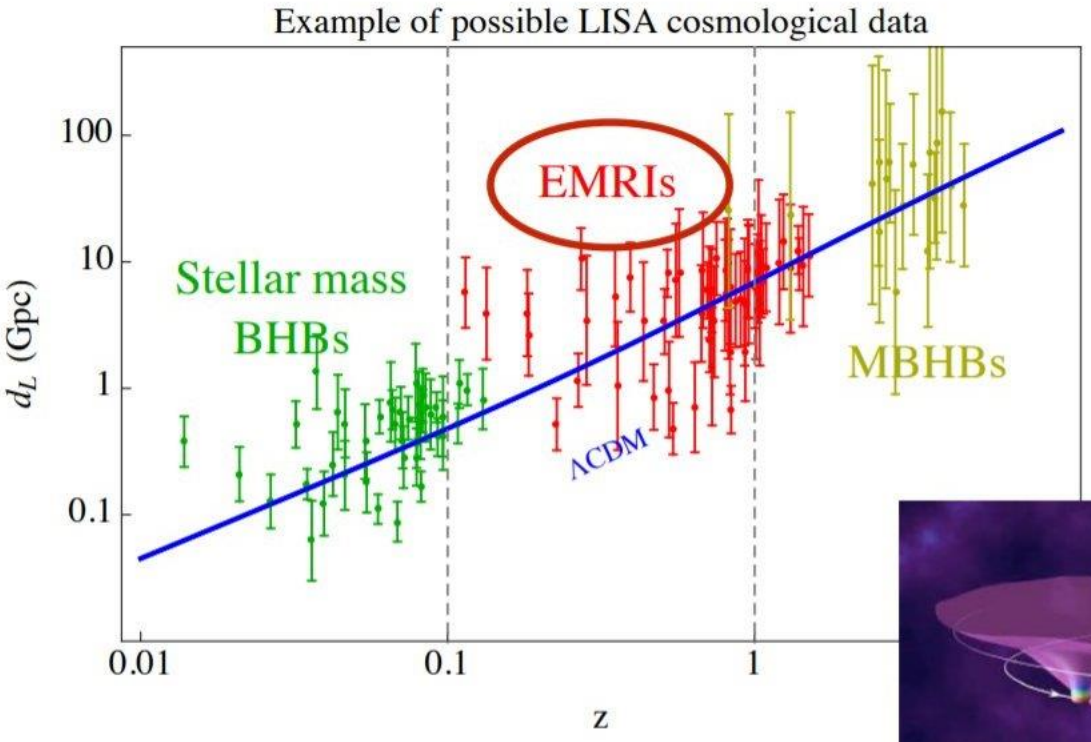
these constraints can get better using also other LISA sources

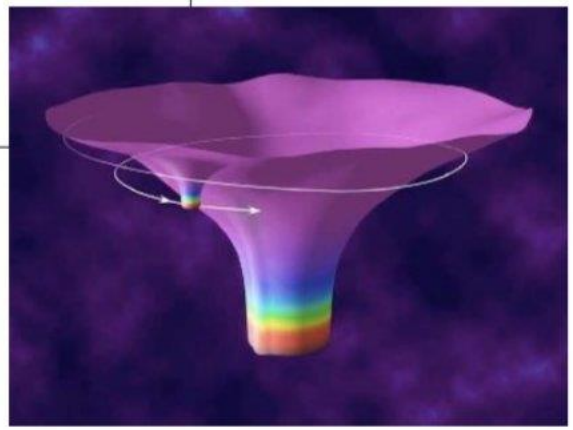
future work: use all LISA sources



credits: N. Tamanini

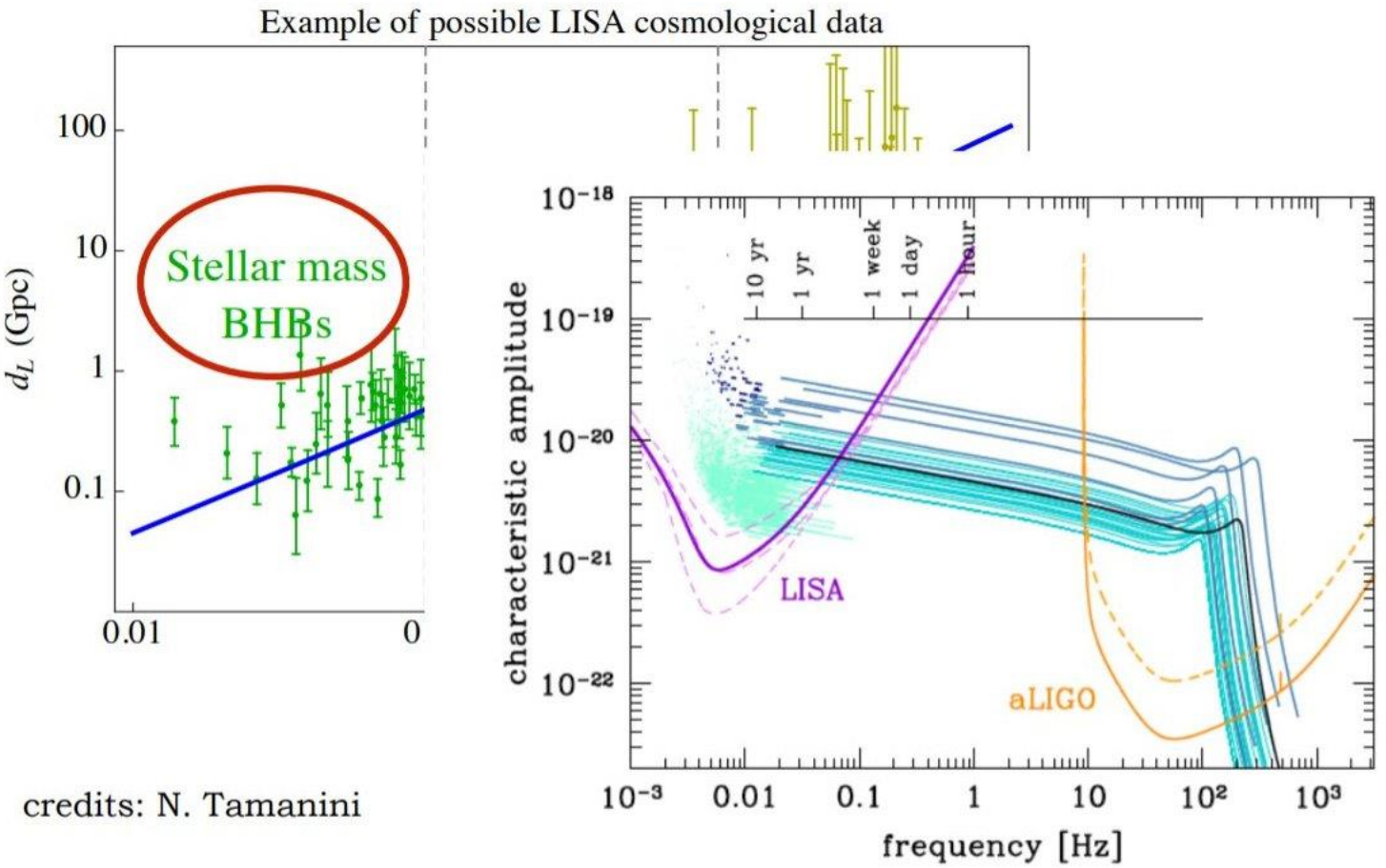
future work: use all LISA sources





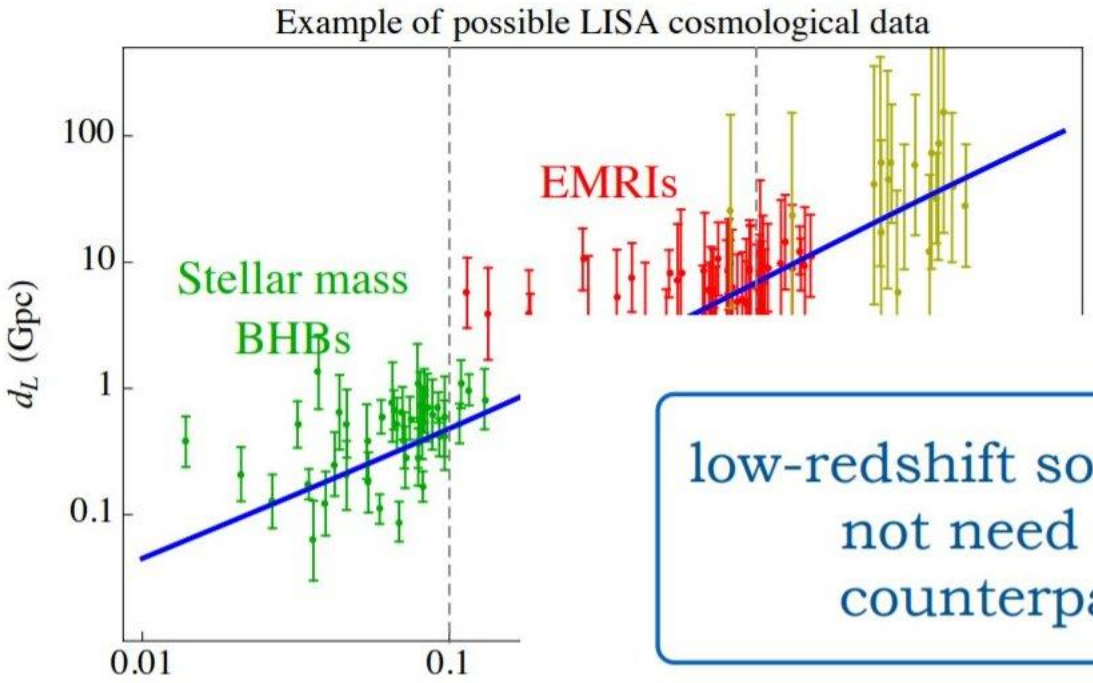
credits: N. Tamanini

future work: use all LISA sources



credits: N. Tamanini

future work: use all LISA sources

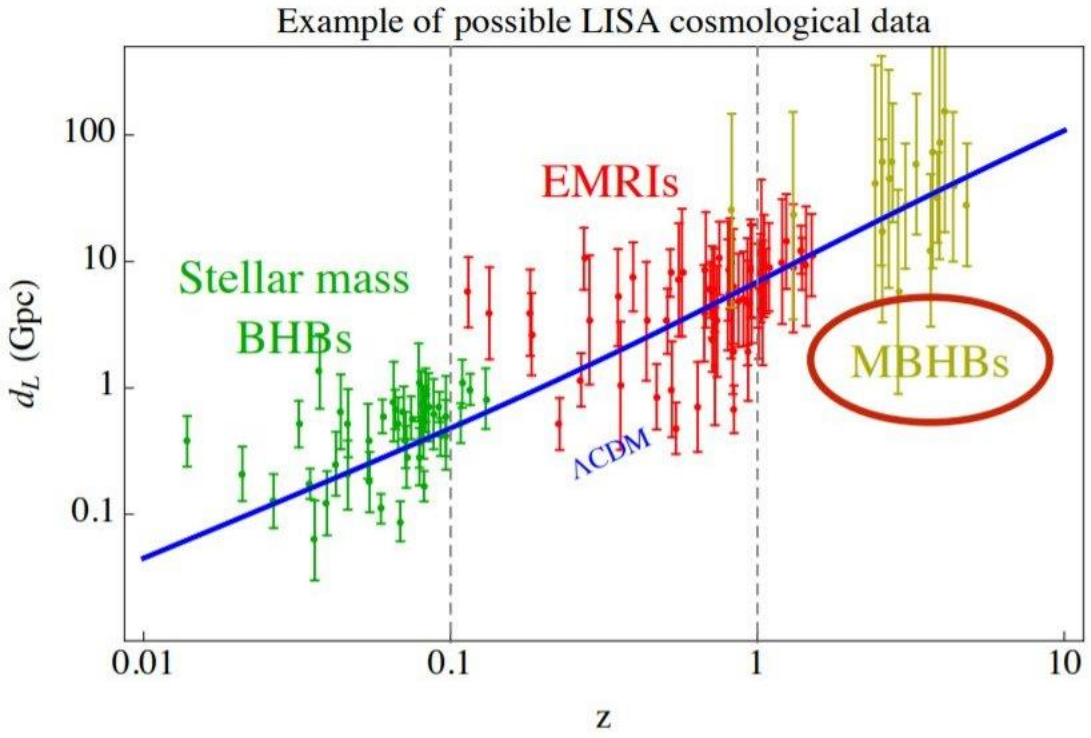


low-redshift sources do not need em counterpart!

credits: N. Tamanini

the identification of the redshift can be done with statistical methods

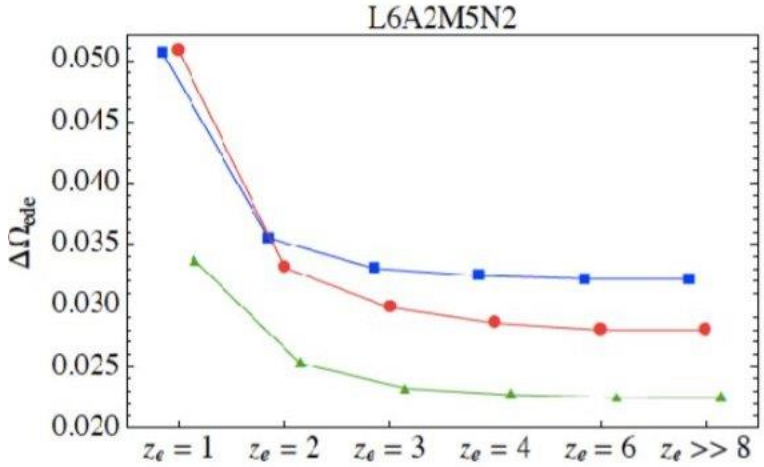
future work: use all LISA sources



credits: N. Tamanini

LISA can provide competitive constrains on models where dark energy starts to contribute at early times

Early Dark Energy



Ω_{de} fraction of dark energy at early times

z_e redshift up to which dark energy contributes

Planck alone : $\Delta\Omega_{de} = 0.0036$

but only if it contributes up to decoupling, otherwise the measurement quickly degrades

CC and N. Tamanini arXiv:1607.08755

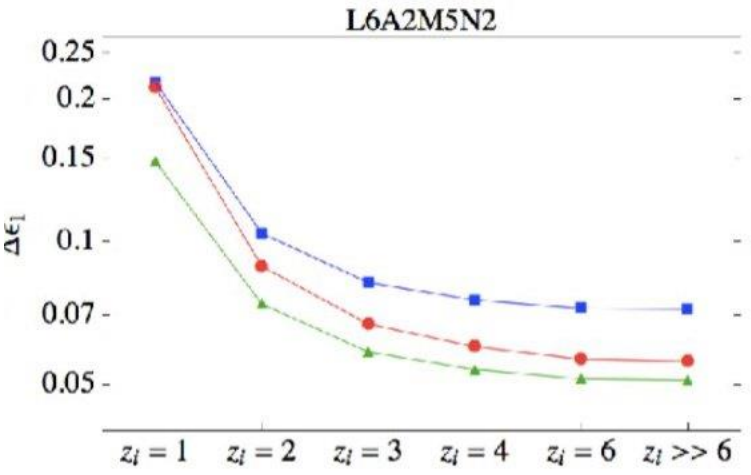
Interacting Dark Energy

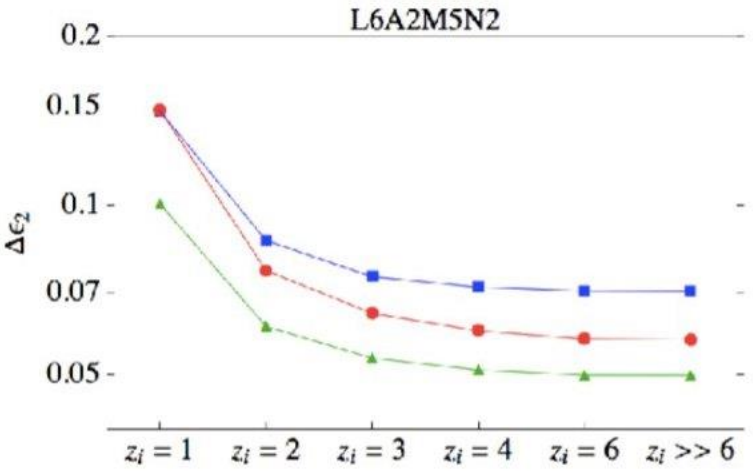
$$\dot{\rho}_{dm} + 3H\rho_{dm} = Q$$
$$\dot{\rho}_{de} + 3H(1+w_0)\rho_{de} = -Q$$

two models for the interaction

$$Q = \epsilon_1 H \rho_{dm} \text{ and } Q = \epsilon_2 H \rho_{de}$$

redshift when the interaction turns on : z_i





$$\epsilon_1 = 0.00199^{+0.00024}_{-0.00177}$$

Costa et al 2016

$$\epsilon_2 = 0.159^{+0.146}_{-0.154}$$

Radio Swiss Classic
Nikolai Rimsky-Korsakov - "Der junge Prinz und