Fundamental theories and gravitational waves

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Outline

1. Introduction
    1. Physical principles and equations of motion
    2. What is a theory?
    3. Why a new theory? Dark matter, dark energy
2. Gravity and its issues
    1. The Planck scale
    2. Gravity as a wave
    3. Detection of gravitational waves

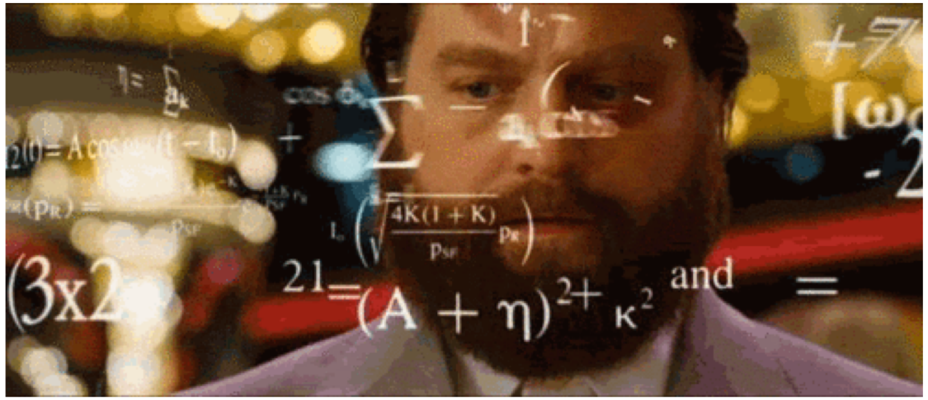
Why a theory?

The work of a physicists is to find laws that govern phenomena we observe.

- Look for principles that explain fundamental forces.

- Physicists describe these principle through the language of mathematics. It is easy to check the consistency of the mathematics language and follow its logic to make new predictions.

We need this mathematical setup to derive the equations that nature obeys.



What is a theory?

Equations of motion

$$\vec{F}_{\text{tot}} = m\,\vec{a}$$

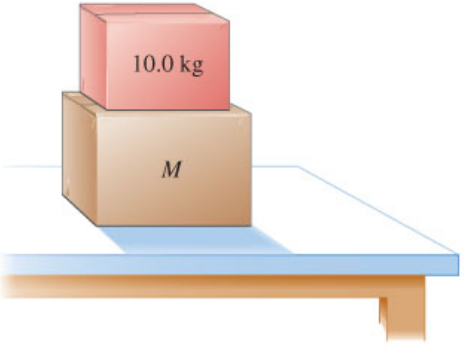
- Theory: classical mechanics
- A physical system is a *solution* of the *equations of motion* if its physical parameters obey the corresponding equation derived from a law, expressed through a mathematical principle.

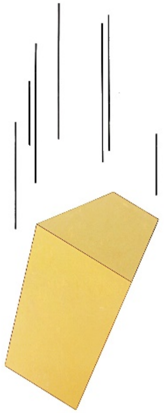
<u>Example</u>:

➢ A box on a table $\vec{a} = 0$

➢ A free falling box $\vec{a} = \vec{g}$

They are solutions of the equation. $\vec{F} = m\,\vec{a}$

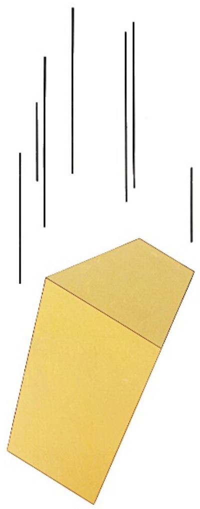




What is a theory?

A change of perspective:

Before: A box, an apple... of course they obey Newton's law (equation of motion), that's why the law was formulated, by *observing* these phenomena.

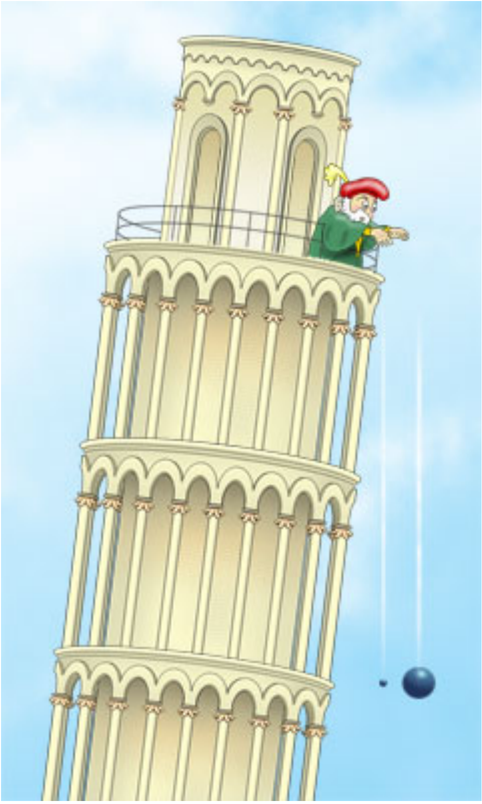


After: *With the knowledge* of Newton's law (eom), if we don't want the box to fall, we will not remove the table below it!!

What is a theory?

Physicists keep looking for new (less conventional) phenomena.

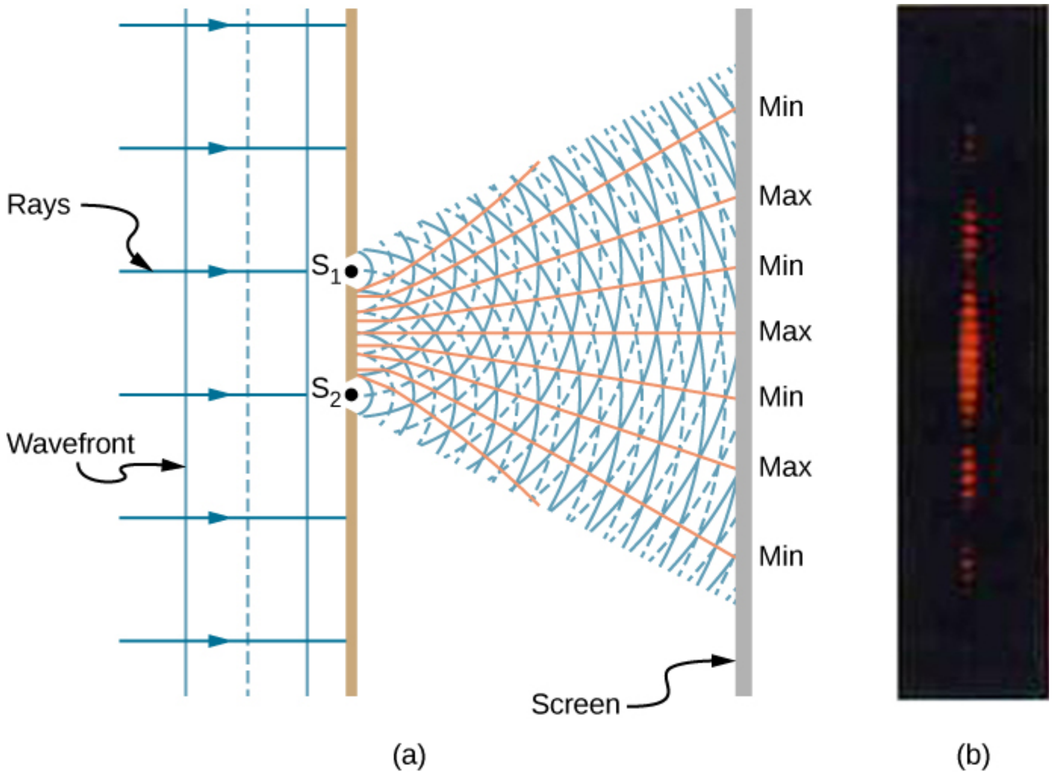
Theoretical physicists are continuously moving between the two perspective, to **understand the laws of fundamental forces** and apply them to **predict new phenomena** or physical systems that can then be *discovered.*



Why are we looking for a new theory?

Experimental physicists look for “discrepancies” in the experiments, by tuning a **scale** in their experiments. (Energy of the interactions... density of nucleons....)

We say that at that scale, the theory breaks down and one needs a more refined one, which usually involves understanding a new fundamental principle.



It works!

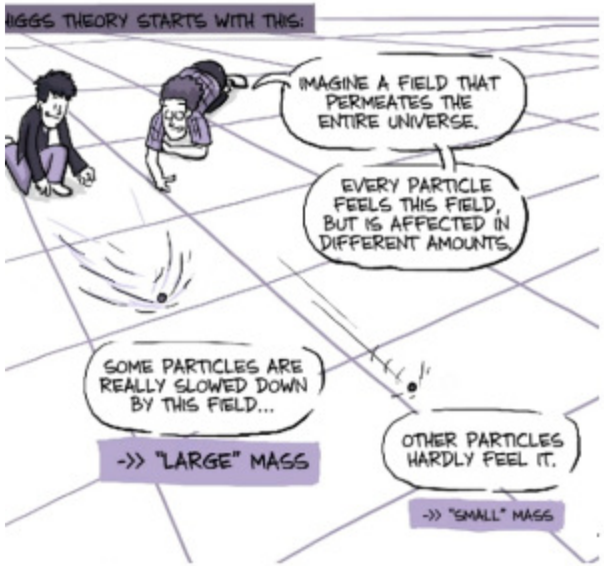
How do we explain the masses of the fundamental particles?

Based on the already confirmed Standard Model of fundamental interactions, a mechanism was proposed by theorists... to obtain particle masses. Particles simply interact with a new fundamental one, not related to any force.

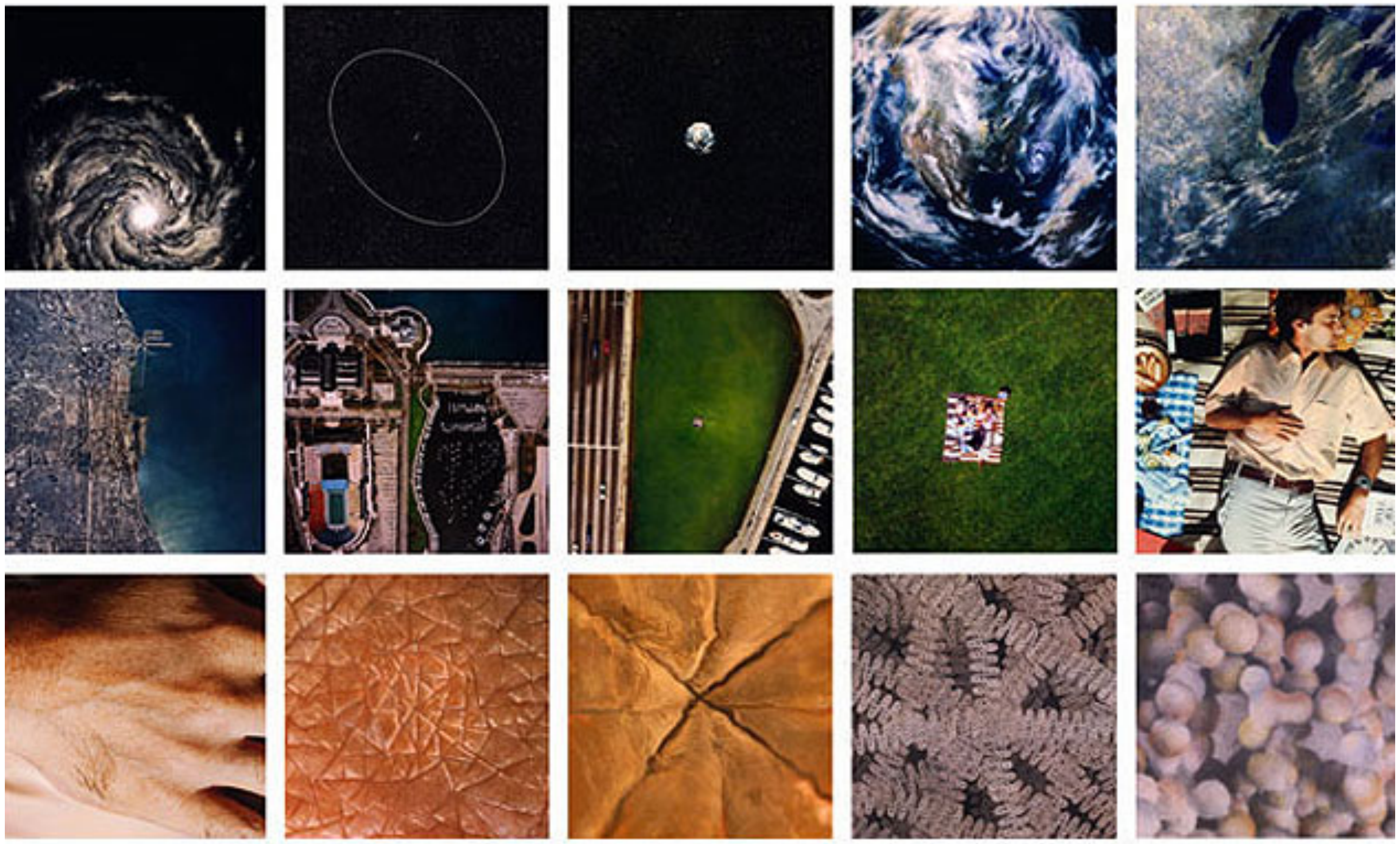
This particle is the Higgs boson.
Why didn't we see this particle before LHC?

At lower energies than its own mass (125GeV), this particle is inert. It is like a constant background that we perceive exactly by measuring the masses of the electron, the proton....

At high enough energies, this is no more just a background, but it behaves as a particle that, according to QFT, can decay in lighter particles. That's what is observed.

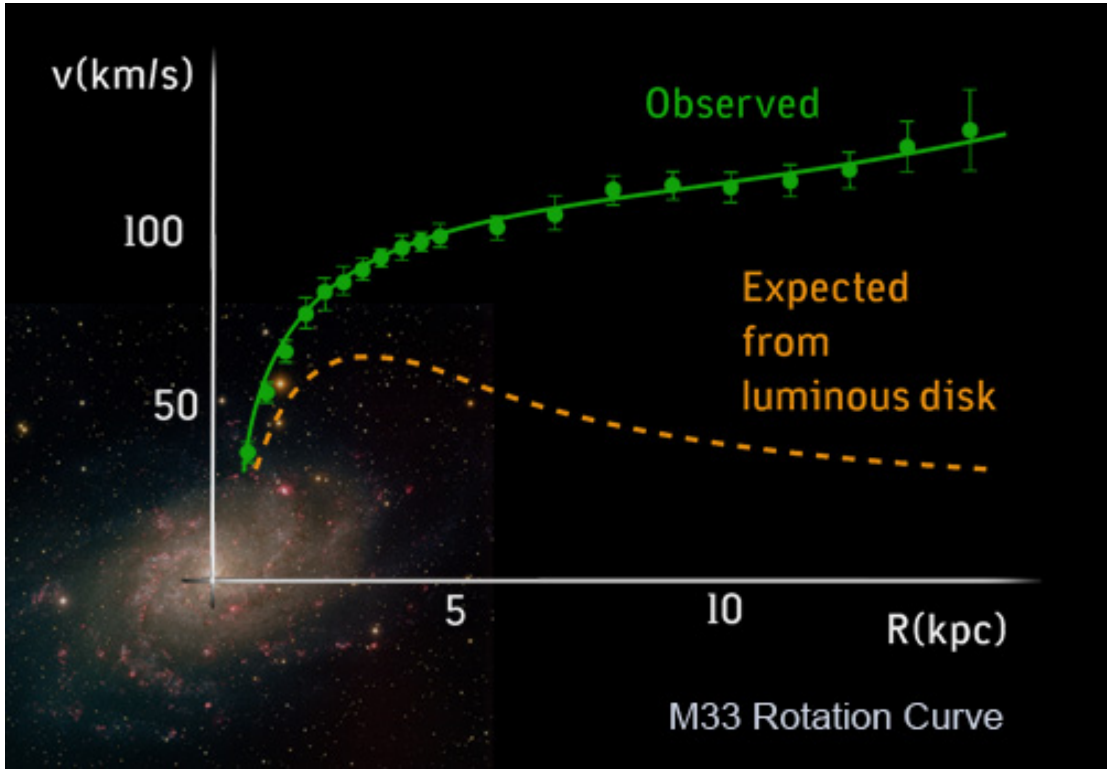


Scales: One theory to rule them all...



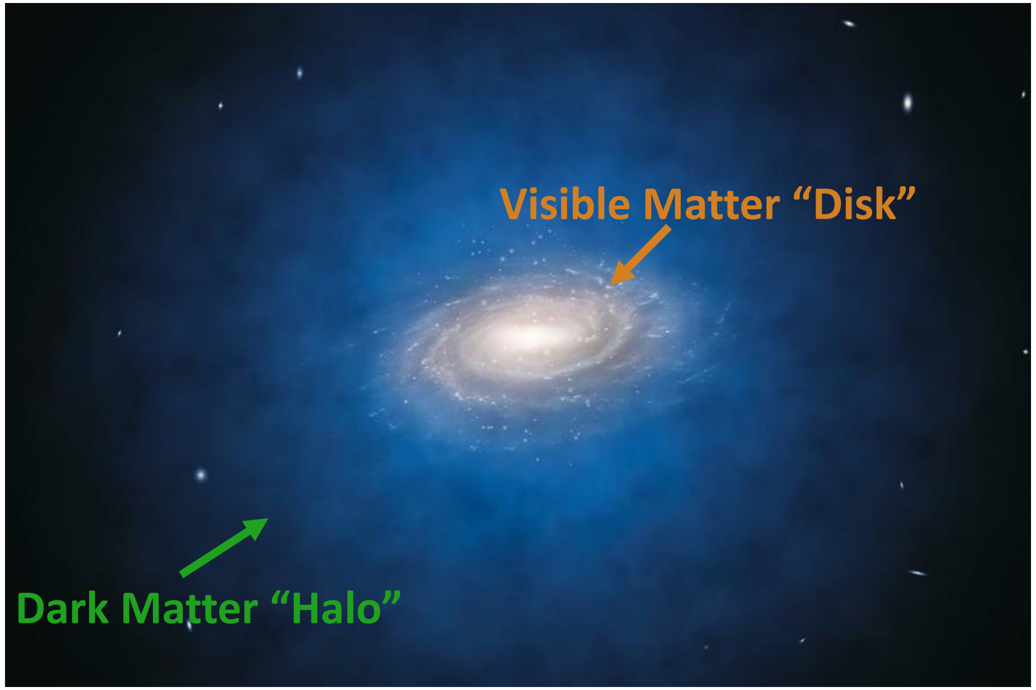
Unexplained observations
aka
Why are we looking for new theories?

Dark Matter



learner.org/courses/physics/visual/img_lrg/andromeda.jpg

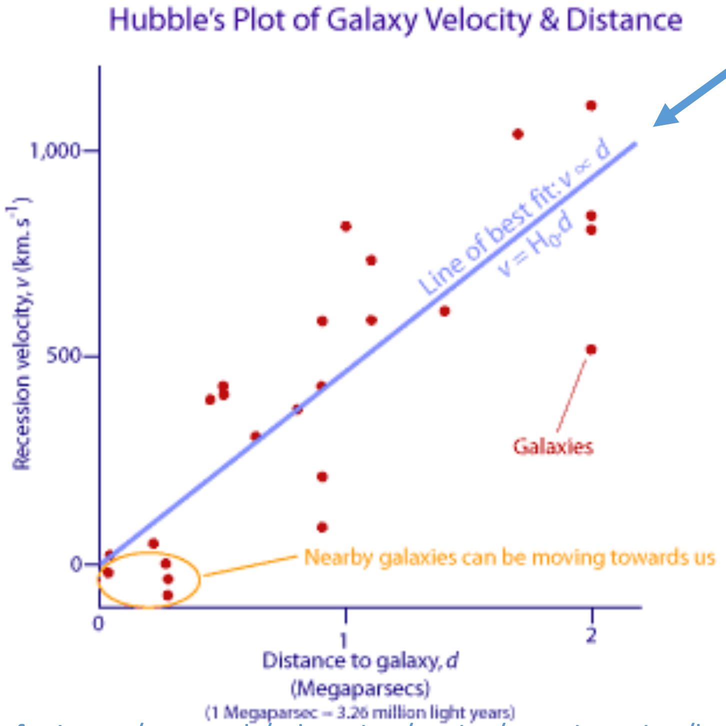
$$v = \sqrt{\frac{GM(R)}{R}}$$



phys.org/news/2017-12-dark-energy-survey-view-halos.html

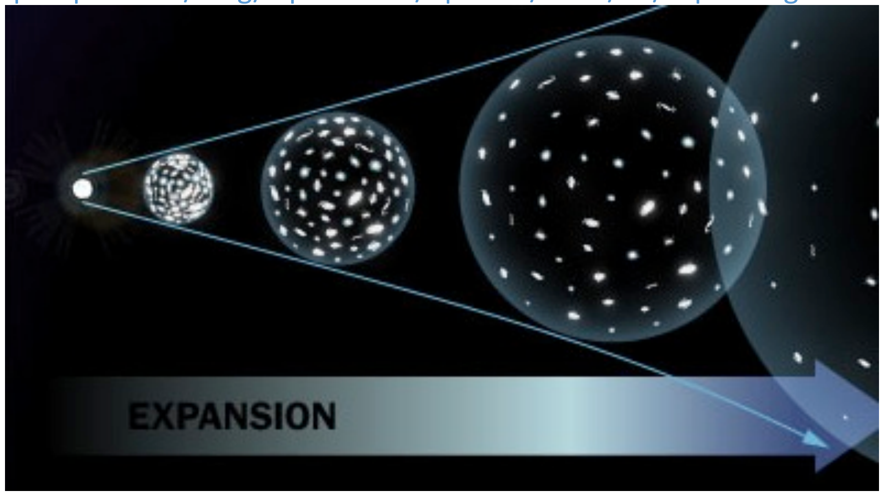
Dark Energy

Universe is expanding



atnf.csiro.au/outreach/education/senior/cosmicengine/hubble.html

p1repair.com/blog/wp-content/uploads/2017/07/expanding-universe.jpg



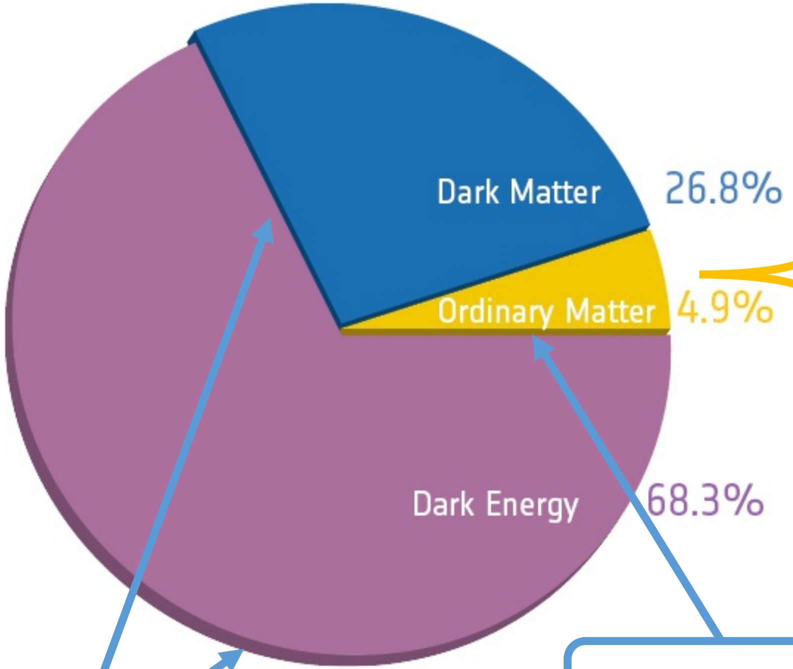
Gravity should cause expansion to **slow down**…

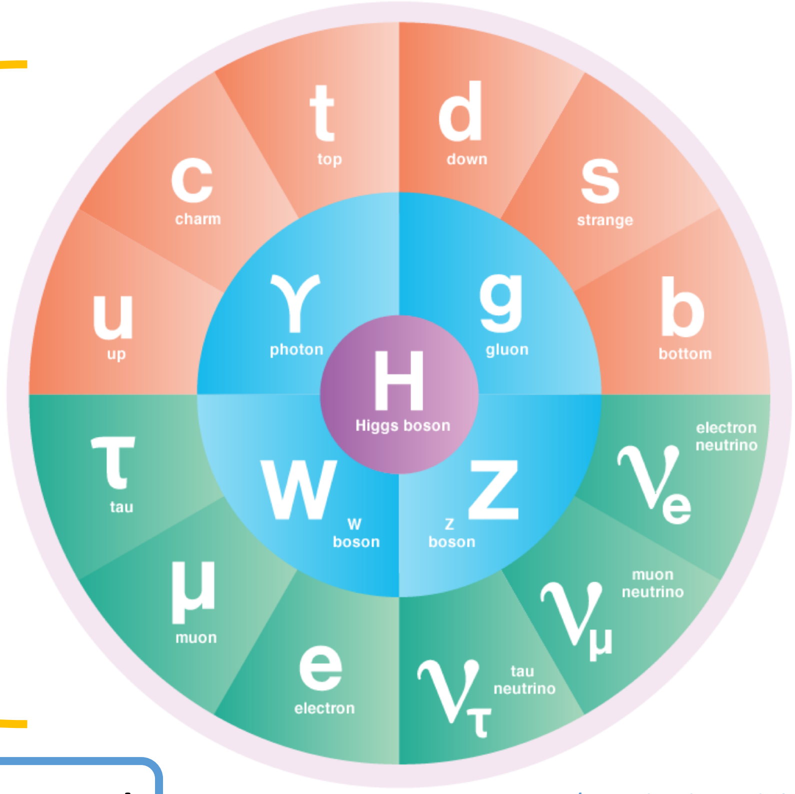
…but it's actually **speeding up!**

There must be some **source** of energy **causing** this acceleration

The Unknown Universe

physics.ox.ac.uk/research/dark-matter-dark-energy





symmetrymagazine.org/standard-model/

Well-understood

What are **these**?!

Gravity

Maxwell & Einstein: energy scales

- Electromagnetism
  - Interaction between two charged particles

$$F_{em} = \frac{1}{4\pi\epsilon_0}\frac{Q_1Q_2}{r^2}$$

- (Newtonian) gravity
  - Interaction between two massive particles

$$F_g = G_N\frac{m_1m_2}{r^2}$$

Comparing the two forces

$$\frac{F_{em}}{F_G} \approx 10^{42}\ (e)$$
$$\approx 10^{36}\ (p)$$

$$\overline{m} \sim \underbrace{\sqrt{\frac{e}{\hbar c\, 4\pi\epsilon_0}}}_{\alpha}\ \underbrace{\sqrt{\frac{\hbar c}{G_N}}}_{\boldsymbol{M_{Pl}}}$$

Gravity: Planck scale

<u>A fundamental scale</u>

$$\boldsymbol{M_{Pl}} = \sqrt{\frac{\hbar c}{G_N}} \approx 1.22\ 10^{19}\ \frac{GeV}{c^2} \sim 2.176\ *\ 10^{-8}\ \mathrm{Kg}$$

$$\boldsymbol{l_{Pl}} = \boldsymbol{M_{Pl}}\ \frac{G_N}{c^2} \sim 1.616 * 10^{-35}\ \mathrm{m}$$

- At this scale gravity cannot be neglected in quantum particle interactions
- There is no consistent picture to describe particle interactions at a distance equal to the Planck length

The theory of general relativity is not compatible with the description of fundamental particles as quantum fields
→ *What is quantum gravity?*
What happens to space time at the Planck scale?

Particle experiments

- Tests of standard model of particle physics

- Experiments can be made
  1. In laboratories (particle accelerators)
  2. Through Earth-based telescopes
  3. Through satellites

- Accelerator physics: LHC

  Energy $\sim$ 1-10 TeV = 1-10 $* 10^{12}$ eV = $10^3 - 10^4$ GeV

  Looking for interaction and possible production of intermediate states (particles) at scales much lower than the Planck scale

The Universe as a laboratory

Electromagnetic radiation

- Sources:
  Stellar explosions (high energy radiation)
  Cosmic microwave background (CMB, 240 μeV) (inflation)
  Galaxies (dark matter)

- Distances ~ 15 Mpc

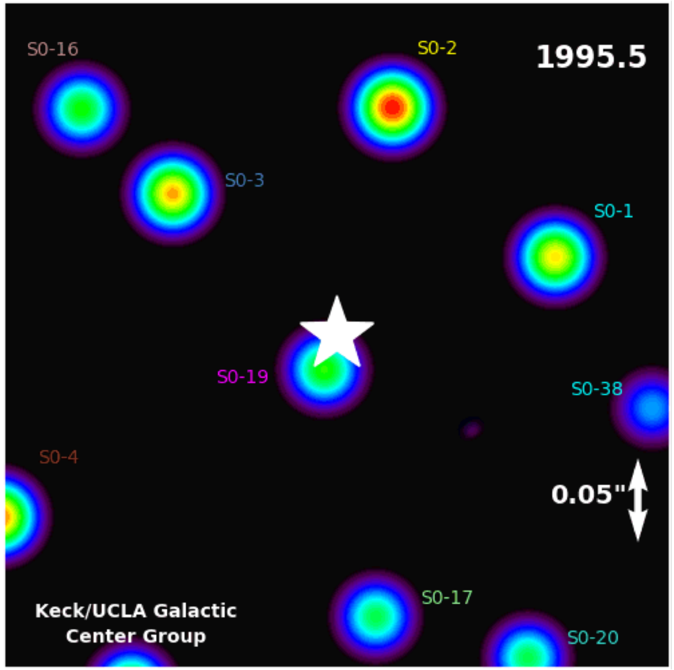
- Energies
  - solar radiation ~ 100 MeV – 1.6,3.4eV (visible light)
  - Gamma ray bursts ~ TeV

- Beyond Newtonian gravity
  - GR tests, nonlinear regimes

$$1\ eV = 1.06 \times 10^{-19}\ J$$

Black holes

- Final point of gravitational collapse
- Classically do not emit radiation but can be nonetheless studied
  - *Their gravitational attraction influences the orbit of nearby stars*
  - **<u>We can now detect gravitational waves!!</u>**



Animation created by Prof. Andrea Ghez and her research team at UCLA and are from data sets obtained with the W. M. Keck Telescopes.

From the Movie «Interstellar»

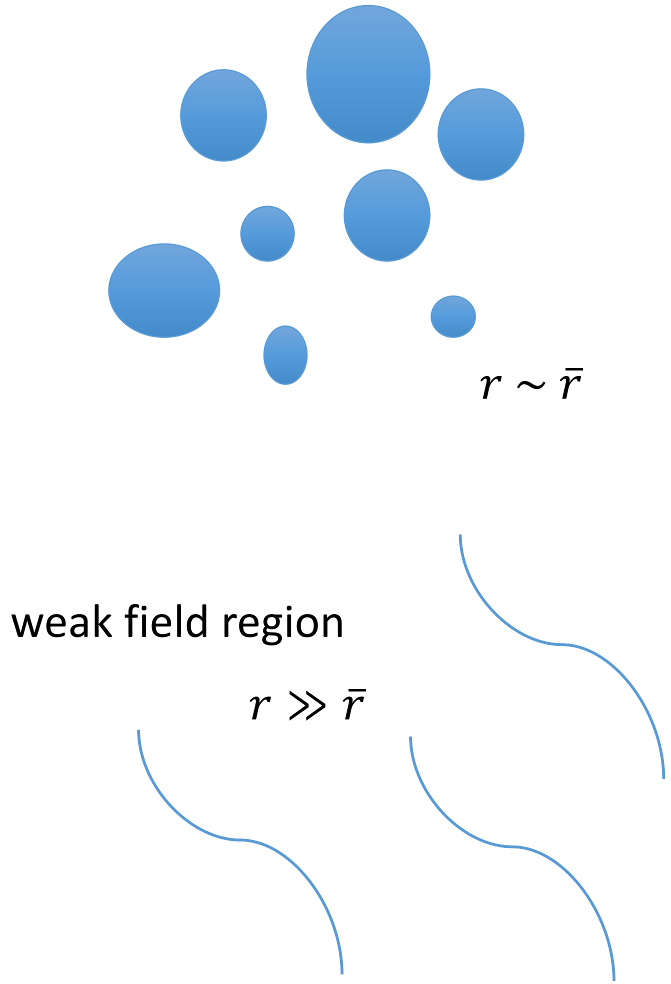
- Black holes are the harmonic oscillator of quantum gravity

(A. Strominger)

Wave phenomena for gravity

- *Source:* matter distribution determines the *shape* of space-time
- Far from the source, where the mass density of the region is much smaller than the source, we are in a region of *weak field*
- There, changes in the distribution of matter are perceived as perturbation over a fixed background
- Gravitational systems can be studied by an approximation called *linearized gravity* (around a fixed background)

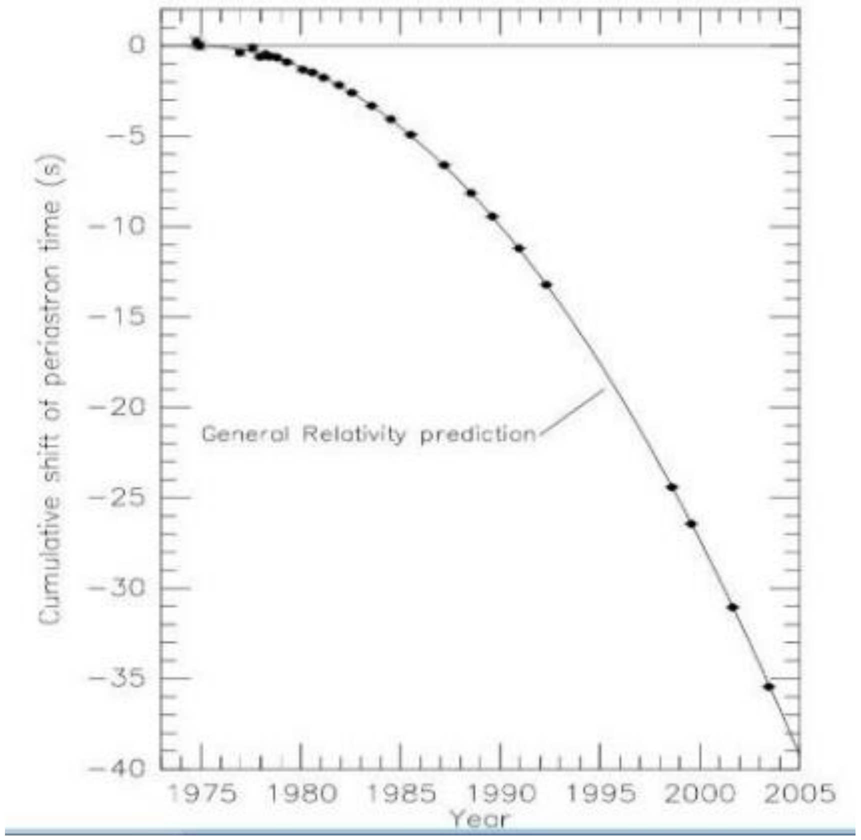
$$g_{\mu\nu} \approx \overline{g_{\mu\nu}} + h_{\mu\nu}$$



Wave phenomena for gravity

- In general, gravitational systems emit gravitational energy by **radiation**
- Gravitational **energy loss** affects e.g. the orbit period of a system of binary stars
- The effect of emitting gravitational waves has been observed in the past in **binary systems**

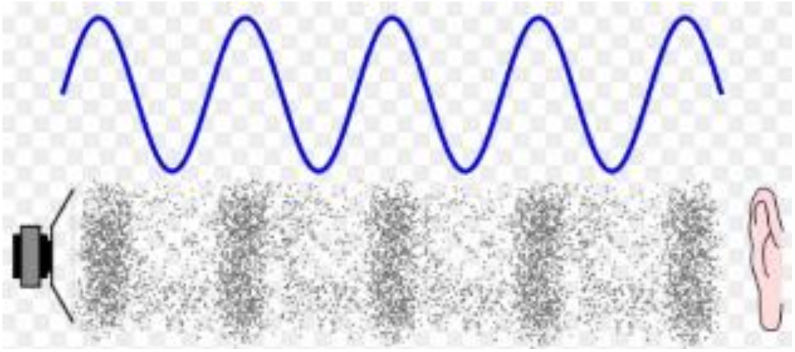
  - PSR B1913+16 - Hulse&Taylor, 1974
  - Pulsar + NS with period ~8h
  - 1993 Physics Nobel Prize



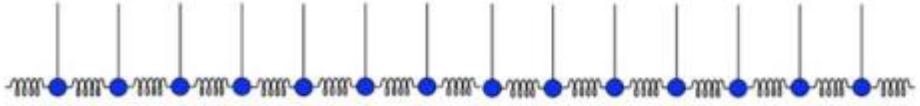
[ArXiv:astro/ph/0407149 Weisberg-Taylor]

Mechanical waves

- Acoustic waves



- System of springs



- Tension is an elastic force among the components of a rope

Maxwell & Einstein: waves in vacuum

- E&M
  - Electromagnetic potentials:

$$A_\mu \equiv (\varphi, \vec{A})$$

$$\nabla^2 \mathbf{A} - \frac{1}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} = -\mu_0 \mathbf{J}$$

$$\nabla^2 \varphi - \frac{1}{c^2}\frac{\partial^2 \varphi}{\partial t^2} = -\frac{\rho}{\varepsilon_0}$$

- Gravity (GR)
  - Space-time geometry, *metric tensor*

$$g_{\mu\nu} \approx \overline{g_{\mu\nu}} + h_{\mu\nu}$$

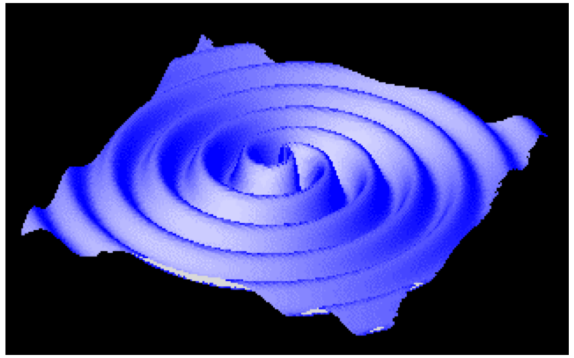
$$\Box h_{\mu\nu} = -\frac{16\pi G_N}{c^4} T_{\mu\nu}$$

Wave equation

- All previous examples are described by the same equation. In vacuum it is expressed as

$$\frac{\partial^2 \psi(x,t)}{\partial x^2} - \frac{1}{v_s^2}\frac{\partial^2 \psi(x,t)}{\partial t^2} = 0$$

$$\nabla^2 \psi(\vec{x},t) - \frac{1}{c^2}\frac{\partial^2 \psi(\vec{x},t)}{\partial t^2} = 0$$



- Waves are solutions of these equations, e.g.

$$\psi(\vec{x},t) \sim A\ e^{\pm i(\vec{k}\cdot\vec{x} - \omega t)} \ , \qquad |\vec{k}| = \frac{\omega}{c}$$

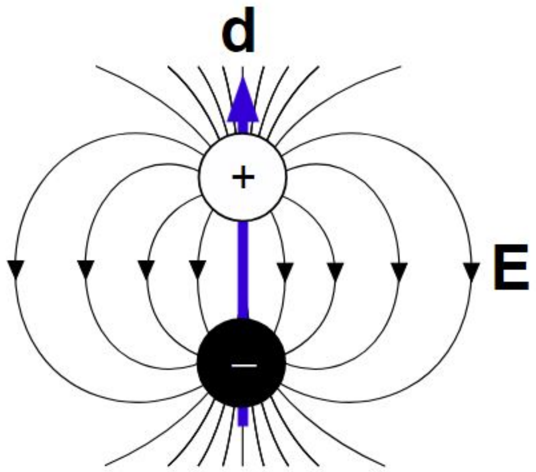
(dispersion relation for light waves in vacuum)

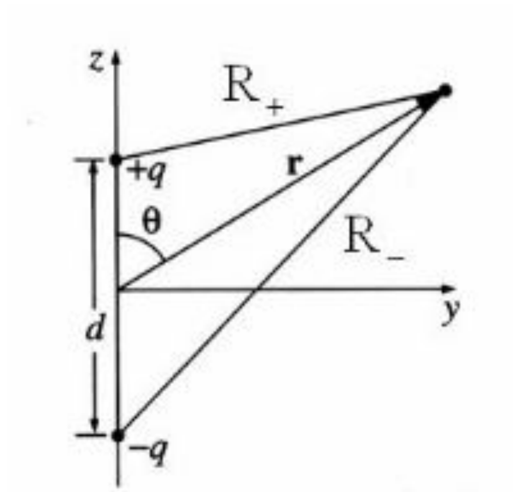
Wave phenomena - light

- Irradiation $\sim \frac{1}{r}$

- The electric field depends on the details of the *sources*
- Far from the source, *multiple expansion*
- Charge conservation prevents radiation from a *monopole* distribution

$$\int d^3\mathbf{x}' \rho(\mathbf{x}')$$



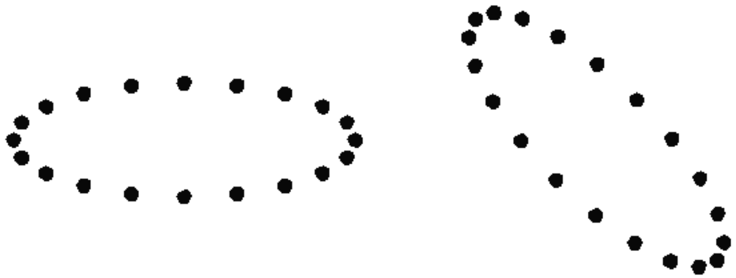


Wave phenomena - gravity

- ❑ Radiation $\sim \frac{1}{r}$

- ❑ Not only energy, but also momentum is conserved: no radiation from dipole distribution

- ❑ The effect of quadrupole moment radiation can be measured by two test masses



Gravitational waves

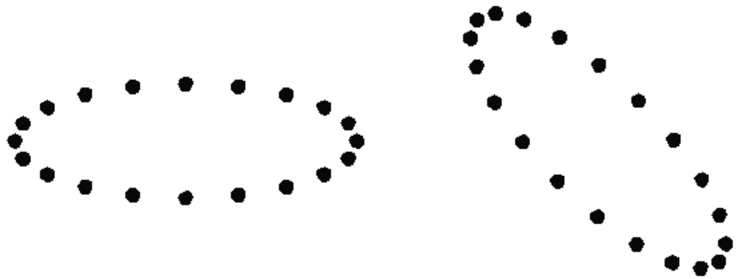
➢ The metric tensor satisfies a wave equation

$$\Box\, h_{\alpha\beta} = -\frac{16\,\pi\, G_N}{c^4}\, T_{\mu\nu}$$

a generic solution is a wave

$$h_{\alpha\beta} = a_{\alpha\beta} e^{i\,(k\cdot x - \omega\, t)}$$

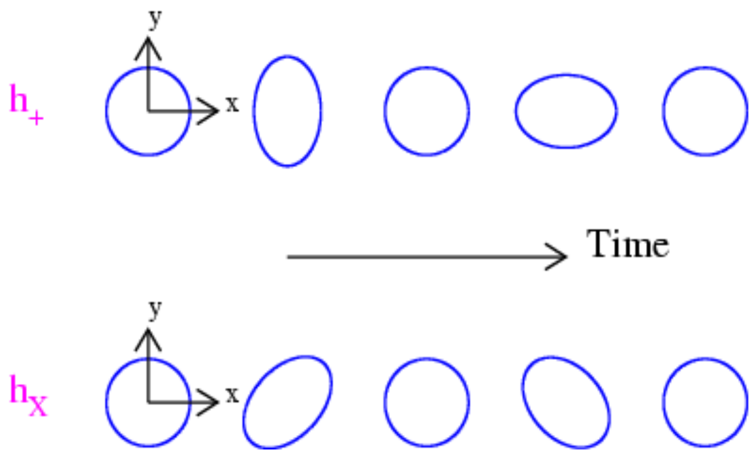
- GW propagate at the speed of light
- $a_{\alpha\beta}$ is a tensorial amplitude
- Two are the possible polarizations transverse to the direction of propagation



Gravitational waves

- Plane wave with frequency ω propagating along z-direction has a wave vector $k^{\alpha} = (\omega, 0, 0, \omega)$
- The metric fluctuation above the reference background are described by a traceless matrix with only two degrees of freedom

$$h_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_{+} & h_{\times} & 0 \\ 0 & h_{\times} & -h_{+} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



- *The metric tensor determines the distance between two* points in space-time

$$ds^2 = -dt^2 + (1 + h_{+})dx^2 + (1 - h_{+})dy^2 + 2h_{\times}\,dx\,dy + dz^2$$

- A GW passing through the laboratory modifies (temporarily) the distance between the two masses

arXiv:1209.0667

Sources of Gravitational waves

Binary system

- Metric fluctuations are given by derivatives of the quadrupole moment of mass distribution

$$h_{ij}^{TT}(t,\vec{x}) = \frac{1}{r}\frac{2G}{c^4}\ddot{M}_{ij}(t,\vec{x})$$

- For two masses rotating with frequency ω_s: $M_{ij} \approx m\, R^2\, e^{i\,\omega_s t}$

- An observer at distance ***r*** perceives a wave with amplitude

$$h_{\times +} \sim \frac{1}{r}\,\frac{2G_N m\, R^2 \omega_s^2}{c^4}$$

- Kepler's III law

$$\omega_s^2 \sim \frac{m}{R^3} \quad \longrightarrow \quad h \sim \frac{1}{r}\frac{2G}{c^4}\frac{m^2}{R}$$

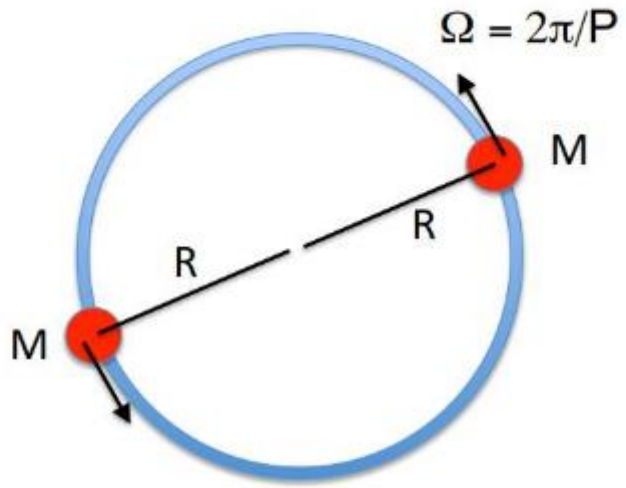


Image by P.Sutton

Sources of Gravitational waves

- Neutron stars binary system

$$M \approx 1.4\, M_{\odot}\,, \qquad \mathrm{r} = 5\ \mathrm{kpc}, \qquad \omega_s = 1\ hour^{-1}$$

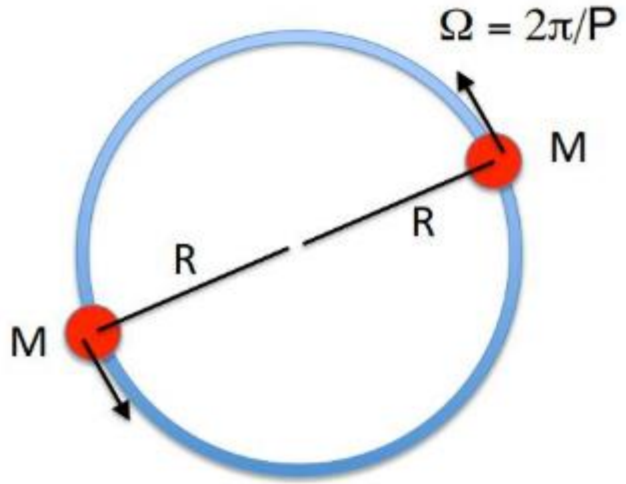
- Detectable amplitude:

$$h \sim 10^{-22}$$

- Interferometers can detect a signal at low noise around a frequency $f \sim 100\ Hz$, which, for the same amplitude $h \sim 10^{-22}$ gives a distance of $r = 15\ Mpc$ (~ Virgo galaxy cluster)
- The corresponding period being $T \sim 0.02\ s$, the resulting orbital separation is:

$$R \sim 100\ \mathrm{km}$$

Very compact objects!!! (NS-NS, NS-BH, BH-BH) (e.g. $R_{\odot} \sim 7 \times 10^5 \mathrm{km}$)



$$h \sim \frac{1}{r}\frac{2G}{c^4}\frac{m^2}{R}$$

$$\omega_s^2 = \frac{G_N m}{R^3}$$

$$f_{GW} \sim 2 f_s = \omega_s/\pi$$

Detection of Gravitational Waves

Gravitational waves interferometers

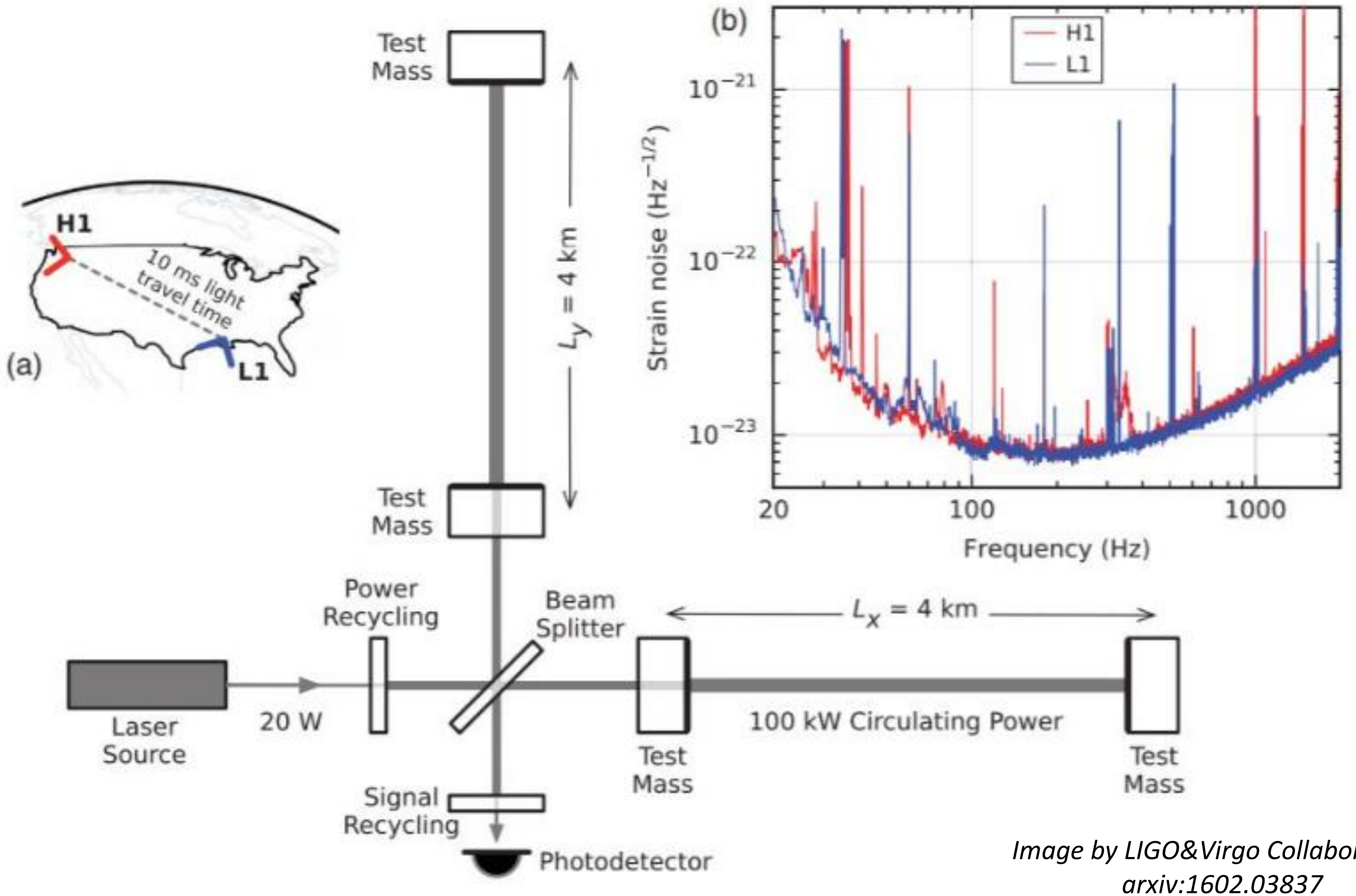
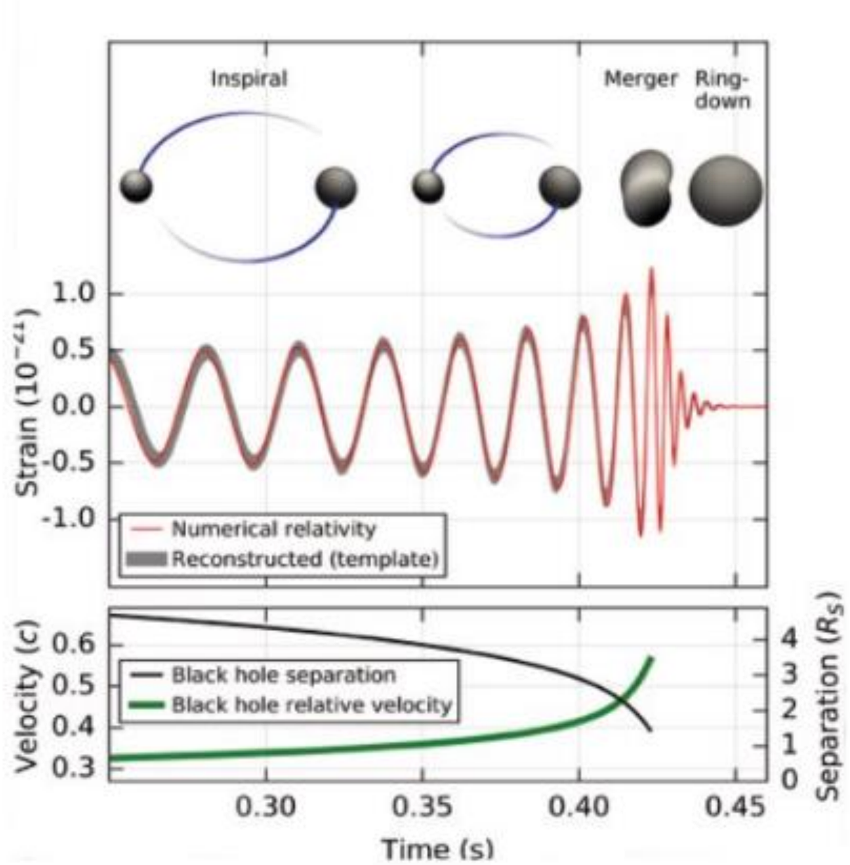
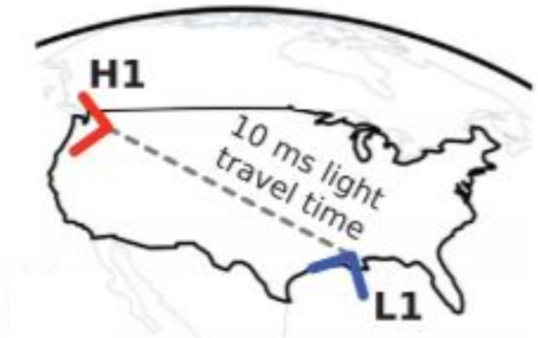


Image by LIGO&Virgo Collaborations
arxiv:1602.03837

Gravitational waves interferometers



LIGO & Virgo
Scientific Collaborations



ArXiv:1602.03837
PRL 116, 061102 (2016)

"On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal."

Gravitational waves interferometers

- Laser Interferometer Gravitational-Wave Observatory (**LIGO**)
  - LIGO Hanford, Washington
  - LIGO Livingston, Louisiana

  http://www.ligo.org/

Hanford Interferometer
Image by LIGO collaboration

- **Virgo** interferometer
  - Cascina (Pisa)

  http://www.virgo-gw.eu/

Image by Virgo collaboration

GW detection

Image credit: LIGO/Virgo/Caltech/MIT/Leo Singer (Milky Way image: Axel Mellinger)

Black hole mergers

- GW150914:
  36 + 29 Solar masses
- GW151226:
  14 + 7.5 Solar masses
- GW170104
  31 + 19 Solar masses
- GW170814
  30 + 25 Solar masses

Rivelatori sensibili
alle frequenze intorno a
~100Hz : *chirp*

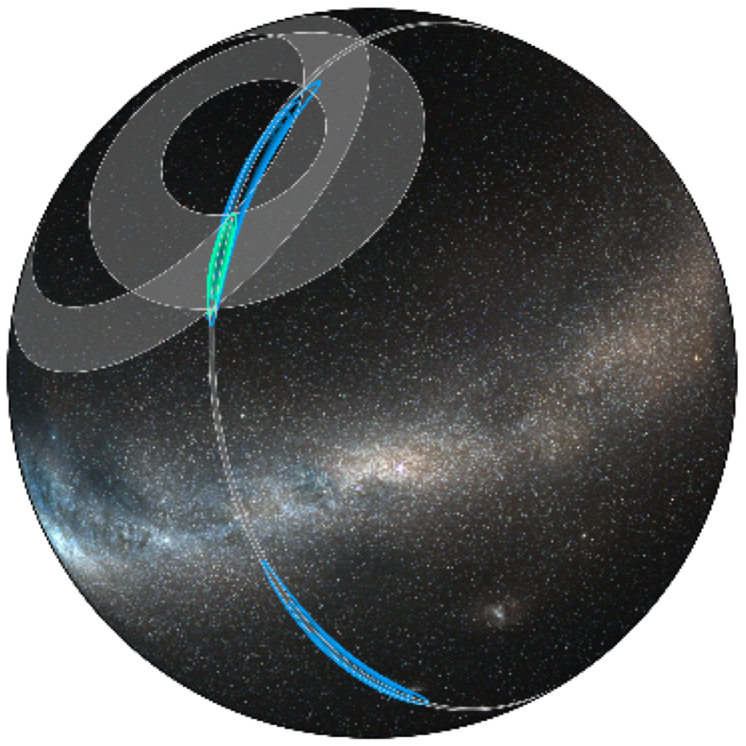
GW detection: Neutron stars

16 October 2016:
announcement of event GW170817 –
neutron stars mergere

Emitted energy is not only gravitational radiation but also light (photons) and matter (elementary massive particles).

Detection of the emitted radiation by studying decays into lighter particles through spectral lines

GW detection: Neutron stars



Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

LIGO-Virgo triangulation

The event was in the *black spot* of the Virgo detector, still an important information to determine the position of the event with enough accuracy.

With the precise location available, astronomical telescopes could be directed towards the event to receive the radiation throughout the following days

Multimessenger astronomy

New signals received, a new way to look at the Universe!

Electromagnetic waves	Gravitational waves
Accelerated charges	Acceleration of matter distribution
Continued emission in the days (and months following the merger)	Instantaneous emission
Highly interacted with interstellar medium	Transparent to matter
Frequency > 10 MHz	Frequency < 10 kHz (we can hear it!)

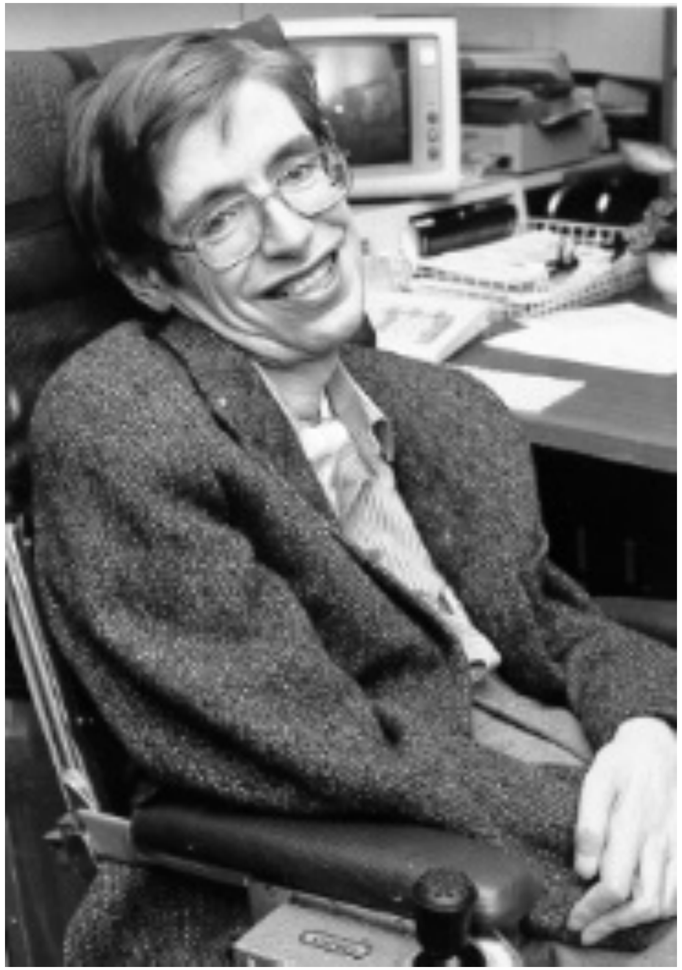
Multimessenger astronomy

New discoveries!

EM waves following the merger
• Origin of a class of Gamma ray bursts (< 2’’)
• Observation of a new state of a neutron star, where heavy nuclei are expelled: *kilonova*
• Confirmation of theoretical hypothesis on the origin of heavier than iron elements (gold, silver..)
• Successive more precise position detection

...is this all?
where are the puzzles coming from?

Stephen Hawking, 1942 -2018



Black hole thermodynamics

Study light quantum fields on a fixed black hole background

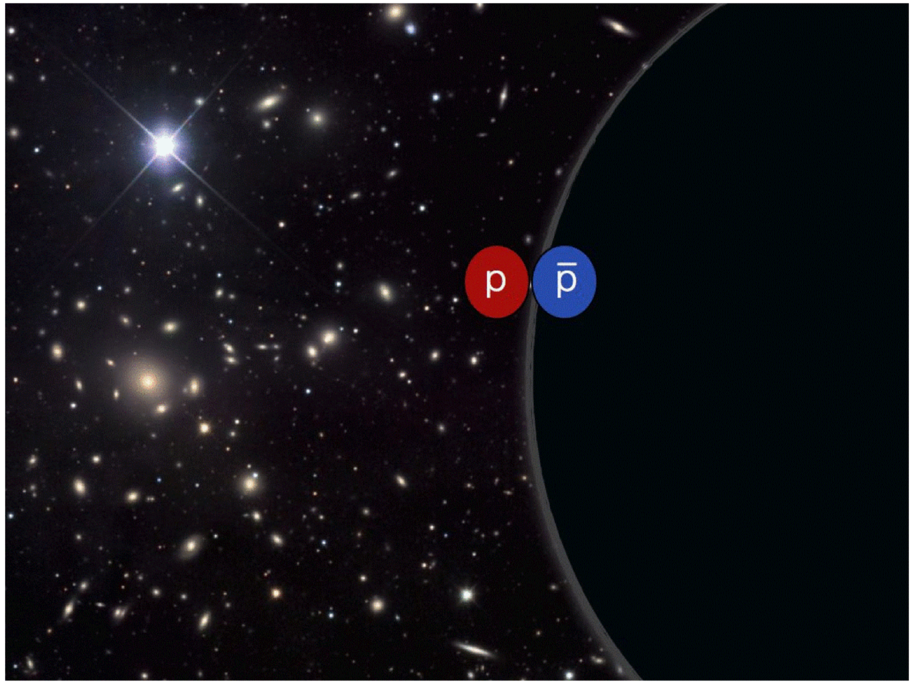
<u>Black holes first law</u>

$$dM = T\,dS + \Phi\,dQ$$

<u>Hawking radiation</u>

$$T = \frac{\kappa}{2\pi} \sim \frac{1}{2\,r_h}$$

Hints of a thermodynamics/statistical nature of black holes



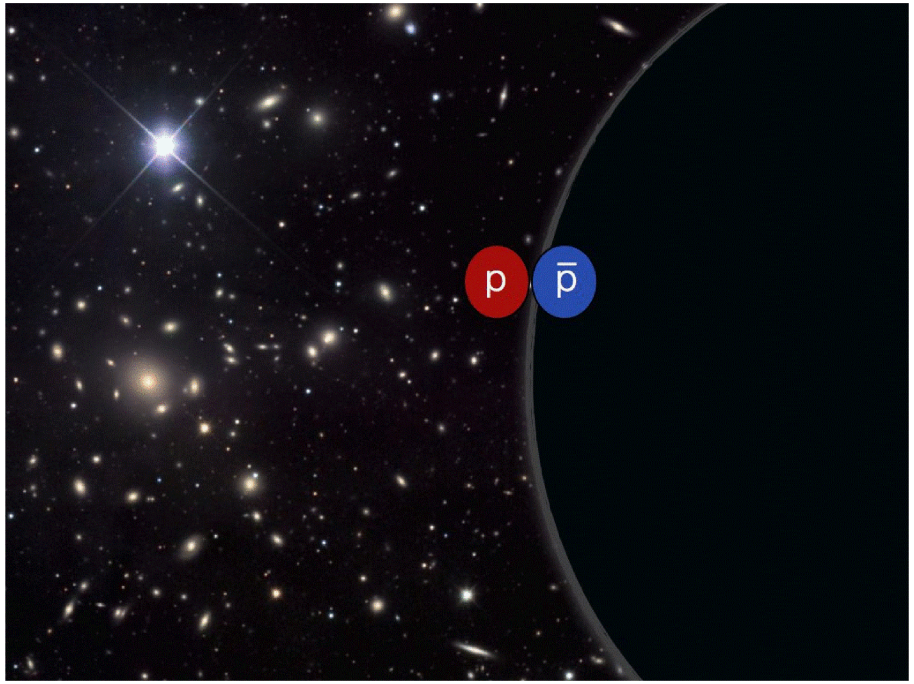
Particle-antiparticle production from the quantum vacuum in the near horizon region

Black hole thermodynamics

<u>Bekenstein - Hawking entropy</u>

$$S = \frac{c^3 k_B}{\hbar G_N} \frac{A}{4}$$

$$\# \, dof \sim e^S$$



- What's the **microscopic** origin of entropy for black holes?
- GR NO-Hair theorem:
  uniqueness of black hole solution (given Q,M,J)

Microstates might be described by a theory that extends GR and possibly allows a quantum description of gravity

Conclusions

- The interplay between observations, unexplained phenomena, and mathematical consistency of the physical laws is what keeps the theorists busy (...excited).
- The visible Universe offers a rich window to unexplained phenomena
- Recent detection of gravitational waves has opened a new era of investigations that may give precious hints on the unification of interactions and the quantum nature of gravity
- The future generation of physicists will face interesting challenges... We’re waiting for you!!!! ☺

Thank you!