HIGH-ENERGY TRANSIENTS AND THE MULTIMESSENGER CONTEXT

A course for the Bachelor and Master Degree Programs

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DIDACTIC MATERIAL

1. M. Spurio
   "Probes of Multimessenger Astrophysics – Charged cosmic rays, neutrinos, γ-rays and gravitational waves"
   Springer International Publishing (2018) https://www.springer.com/gp/book/9783319968537
2. A. De Angelis & M. Pimenta
   "Introduction to Particle and Astroparticle Physics – Multimessenger Astronomy and its Particle Physics Foundations"
   Springer International Publishing (2018) – https://www.springer.com/gp/book/9783319781808
3. M. Longair
   "High Energy Astrophysics"
   Cambridge University Press (2011) – https://www.cambridge.org/core/books/high-energy-astrophysics/CF25E2E5FC0EDFC51FCD7846A262C0AE

- A. De Angelis & M. Pimenta
  "Introduction to Particle and Astroparticle Physics – Questions to the Universe"
  Springer International Publishing (2015)
- A. De Angelis & M. Mallamaci
  "Gamma-ray astrophysics"
  The European Physical Journal Plus volume 133, Article number: 324 (2018)
- R. Hill, K.W. Masui & D. Scott
  "The Spectrum of the Universe"
  Appl. Spectrosc. 72, 663 (2018)
  https://www.osapublishing.org/as/abstract.cfm?uri=as-72-5-663 https://arxiv.org/pdf/1802.03694.pdf

OUTLINE

1. Introduction and overview of High-energy and Multimessenger astrophysics
2. Cosmic rays in Our Galaxy
3. Galactic and Extragalactic Accelerators, Acceleration Mechanisms
4. The sky seen in Gamma-Rays
5. Gamma-Ray Bursts
6. Gravitational Wave observations
7. HE neutrino observations
8. The TeV sky and multiwavelength observations

1. INTRODUCTION AND OVERVIEW

High-energy and Multimessenger astrophysics

INTRODUCTION

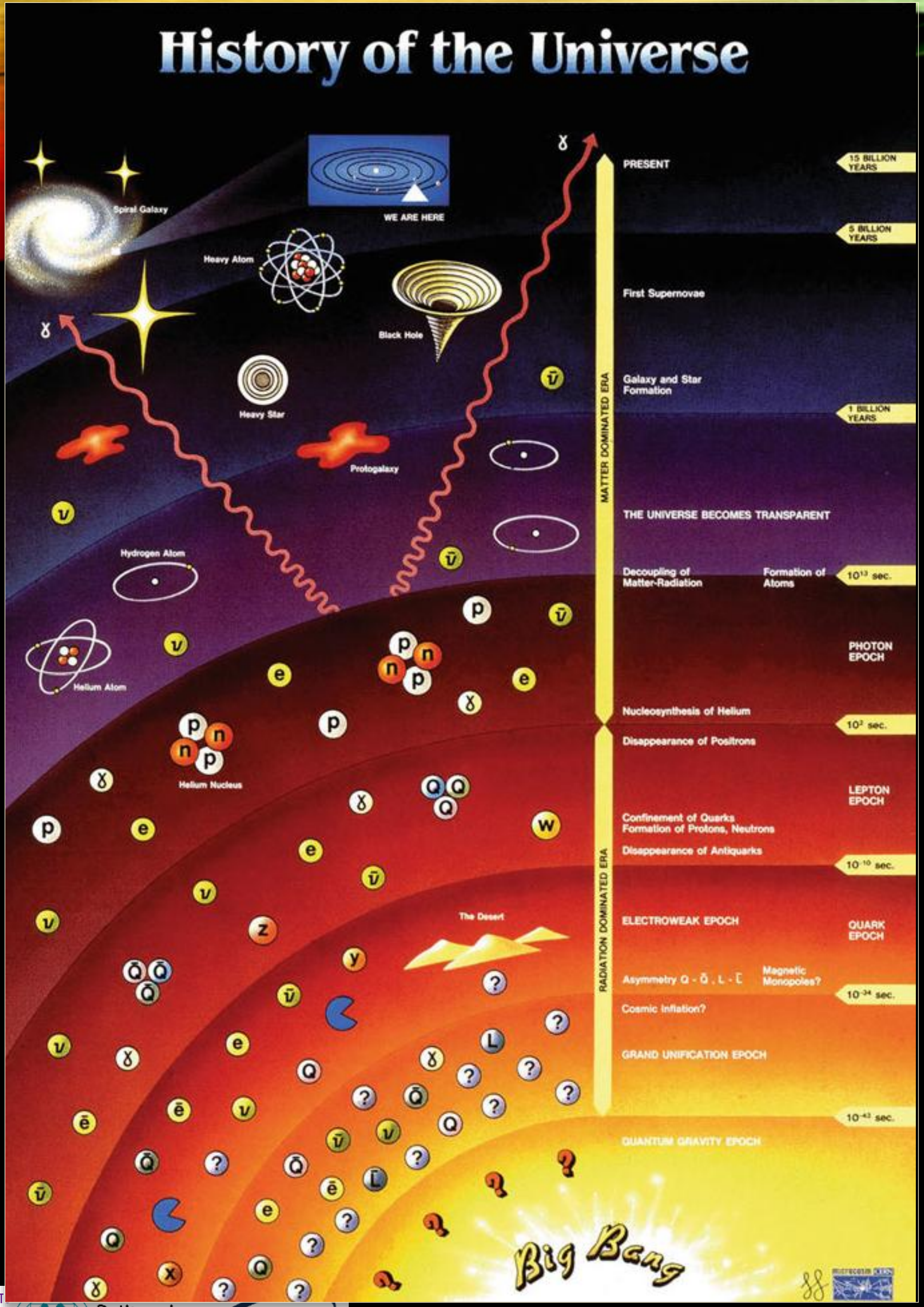
- Standard Model (SM) of particle physics
  - Includes theory of **electroweak interaction** and **quantum chromodynamics** for strong interaction
  - Explains all available **experimental results in particle physics** quite well
  - Confirmed from **measurements** performed with the LEP and SLAC electron-positron colliders, and with the discovery of the **top quark** at the Tevatron $p\bar{p}$ collider
  - Crowned with the detection by the CERN Large Hadron Collider (LHC) of the last missing piece of the theory: **the Higgs boson**

However…

  - Probably **NOT the ultimate theory**, looks **incomplete**!
    - SM **does not contain gravity**, several unresolved "fine-tuning" problems, three-family structure of leptons and quarks remains unexplained, etc.
  - Represents a sort of "**low energy limit**" of a more fundamental theory, which should reveal itself at **higher energies**
    - Threshold could be so high that no accelerator on Earth, even in the far future, will be able to reach it
      - Grand Unified Theories (**GUTs**) of electroweak and strong interactions **predict that new physics would appear at extremely high energies (>10^{14} GeV)**

→ In this context *astroparticle physics* plays a fundamental role!

INTRODUCTION



Credit: Giorgio Giacomelli

- Important connections between **astrophysics**, **particle physics**, and **cosmology**, in particular in the "early Universe" = gas of very energetic particles

- As time proceeded
  - The Universe **expanded**
  - The energy per particle **decreased**
  - **Phase transitions** took place
  - The nature of particles **changed**
  - There was a **symmetry breaking** from unified to nonunified interactions

INTRODUCTION

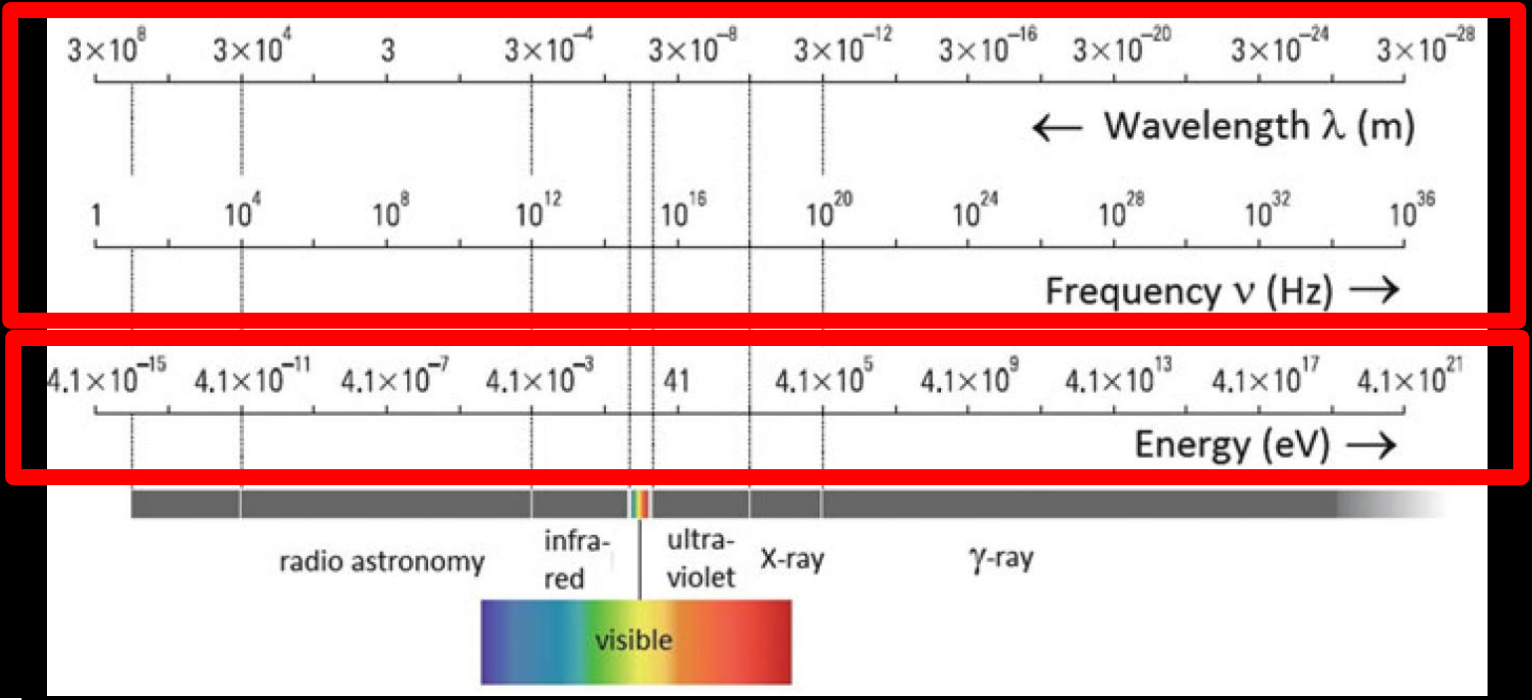
- In recent years, the **study of the early Universe** pointed out some features that are completely **outside the SM**

  - **~70%** of the mass-energy is made of an unknown form of **dark energy**
  - **~ 25%** of the mass-energy is made of an unknown form of **dark matter**
  - The matter–antimatter asymmetry observed in the Universe is not fully justified by the charge-parity violation allowed within the SM

Credit: NASA/GSFC
https://svs.gsfc.nasa.gov/12307

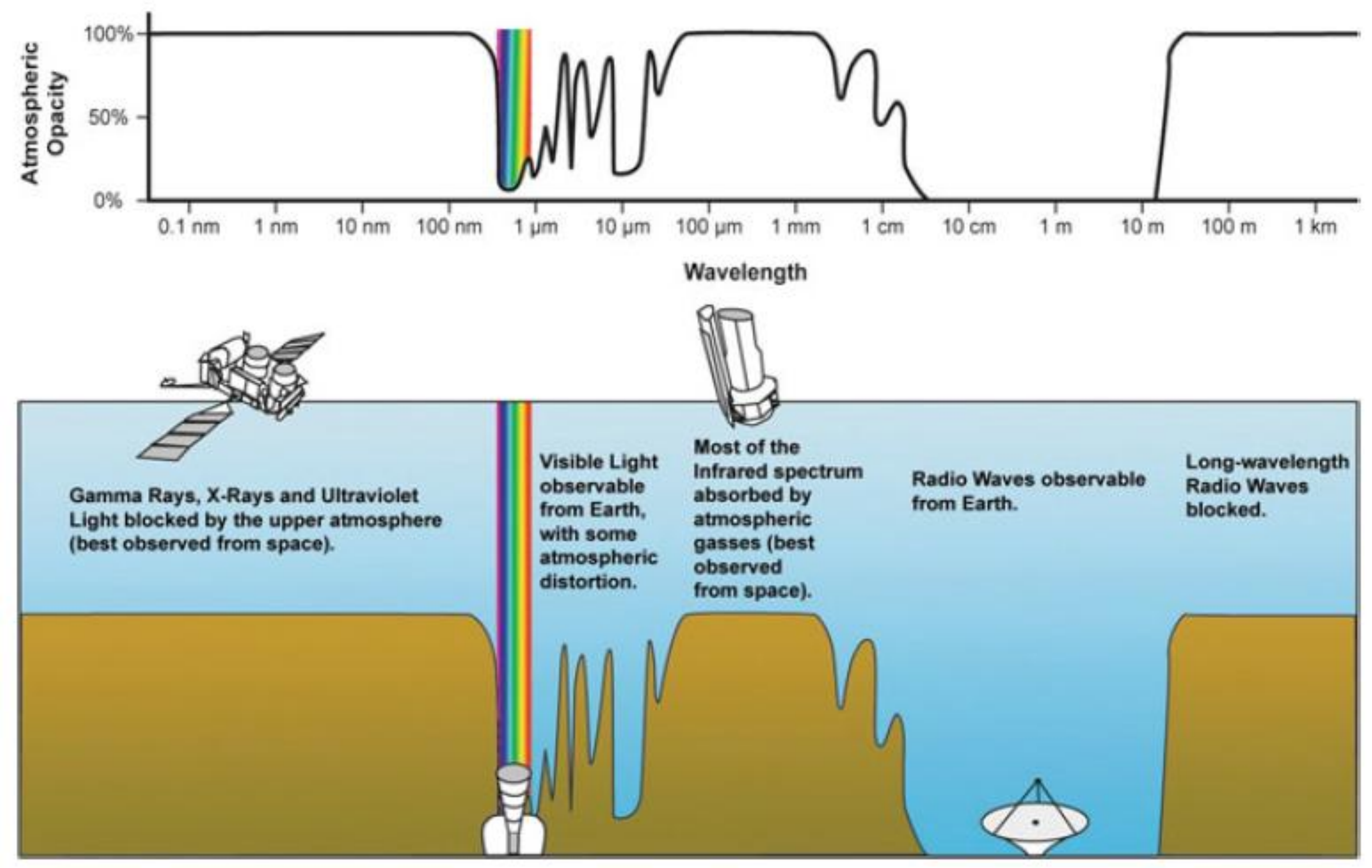
Atrophysics vs Astroparticle Physics

- Study the nature of cosmic objects using different experimental techniques
  - **Astrophysics**: the astronomical messenger is electromagnetic (EM) radiation
  - **Astroparticle Physics**: the astronomical messengers are charged cosmic rays, neutrinos and high-energy gamma-rays (plus dark matter, etc)



INTRODUCTION

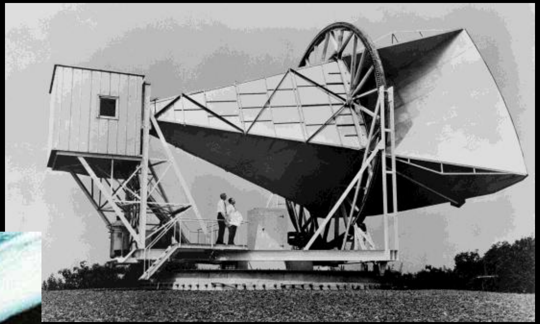
Opacity: percentage of electromagnetic radiation which does not reach the Ground



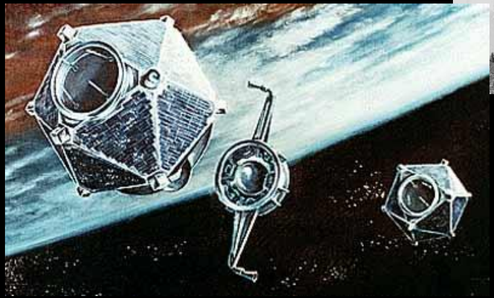
The energy scale decreases from left to right

INTRODUCTION

1. Astrophysics was born when **spectroscopy techniques** were applied to **optical observations of light from stars**
2. **1960s:** After the Second World War, the opening of the **radio window** made the 60s a **golden decade for astronomy**
   ➔ Discovery of cosmic microwave background, pulsars, quasars
3. **1960 – 1970:** advent of **rocket technology** carrying X-ray and gamma-ray detectors above the atmosphere
   ➔ Discovery of Gamma-Ray Bursts



Holmdel horn antenna at Bell Telephone Laboratories (New Jersey, USA)
Credit: NASA



Vela satellites (artistic view)
Credit: Los Alamos National Laboratory

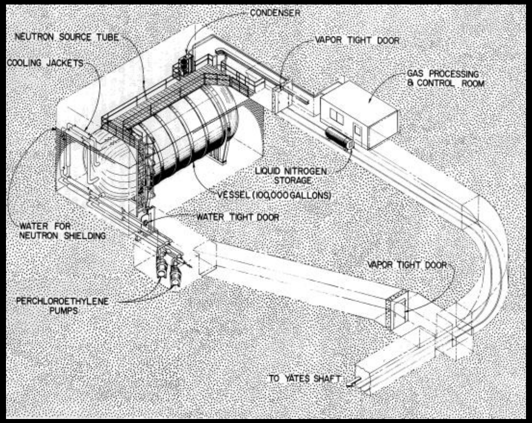
Multiwavelength Astronomy

Combined information from different instruments (usually, from radio to X-rays or soft gamma-rays) covering a wide part of the electromagnetic spectrum

INTRODUCTION

- 1980s: new kinds of detectors or “telescopes” developed in order to capture:
  - **Individual photons with energy above the GeV**
  - **Charged cosmic rays**
  - **Neutrinos**
  - **Gravitational waves**

SN1987a debris evolution seen by HST
Collision of expanding remnant with a ring of material ejected by the progenitor 20k years before the supernova

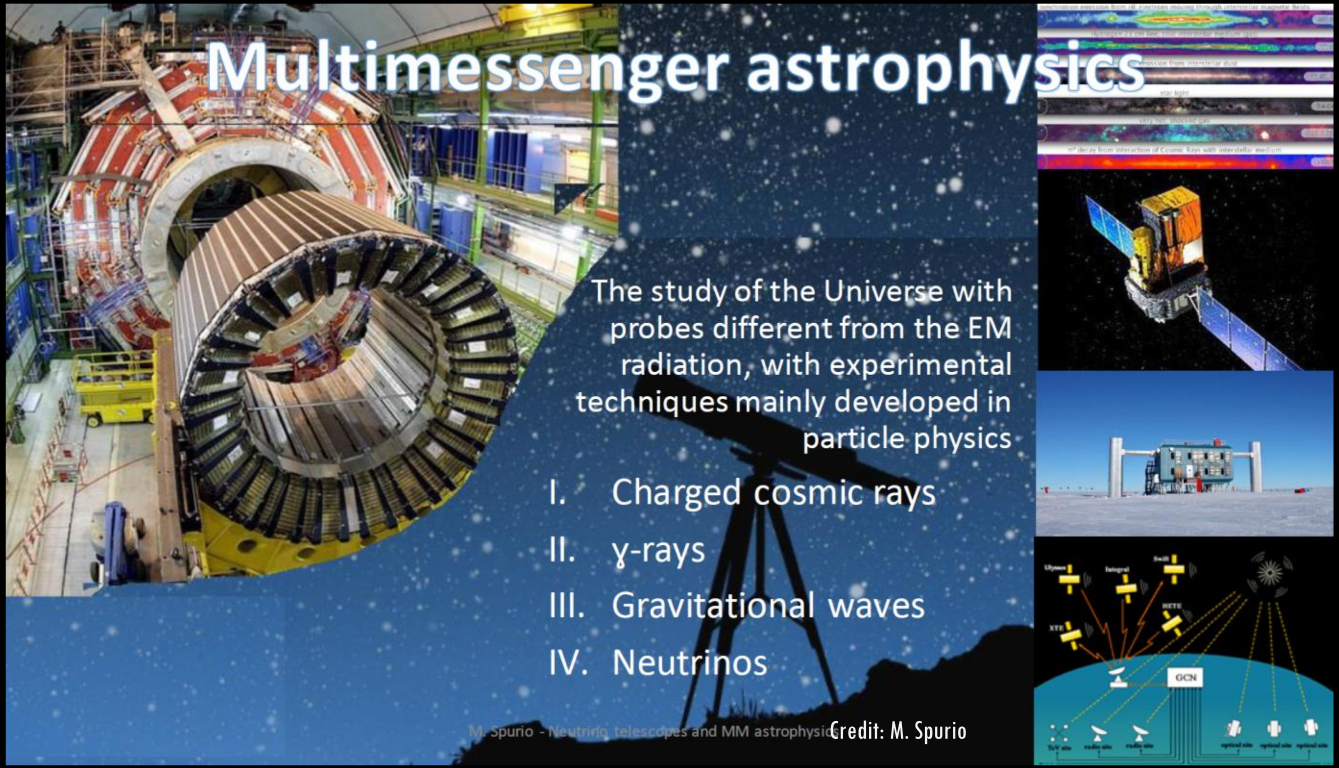


Atomic Energy Commission's Brookhaven National Laboratory solar neutrino detector. c. 1972

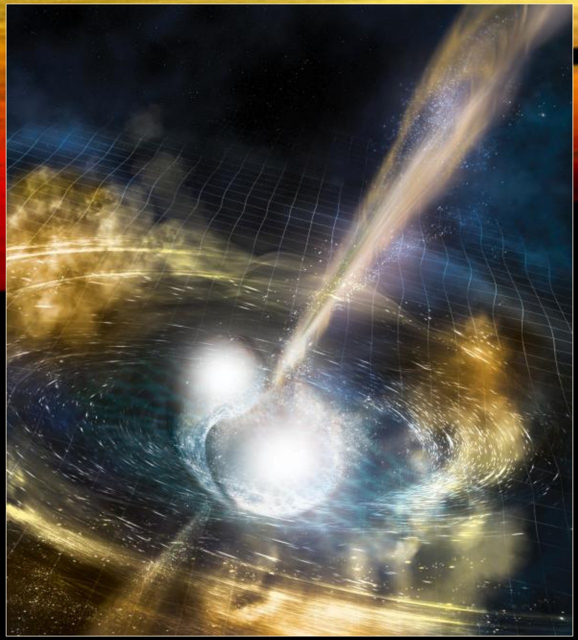
- These led to **unexpected breakthroughs**
  - Measurements of **neutrinos from the Sun**
  - Detection in 1987 of a **neutrino burst** from a stellar gravitational collapse occurring in the Large Magellanic Cloud
    - Opening the field of neutrino astrophysics
    - Providing first examples of multimessenger observations of astrophysical phenomena

Multimessenger astronomy connects different kinds of observations of the same astrophysical event or system

- Joint efforts of merging information from:
  1. Traditional electromagnetic measurements **from radio to X-rays**;
  2. Observations of **charged particles**, **gamma-rays** and **neutrinos** with **instruments of high-energy physics**;
  3. Detection of gravitational waves with **laser interferometers**



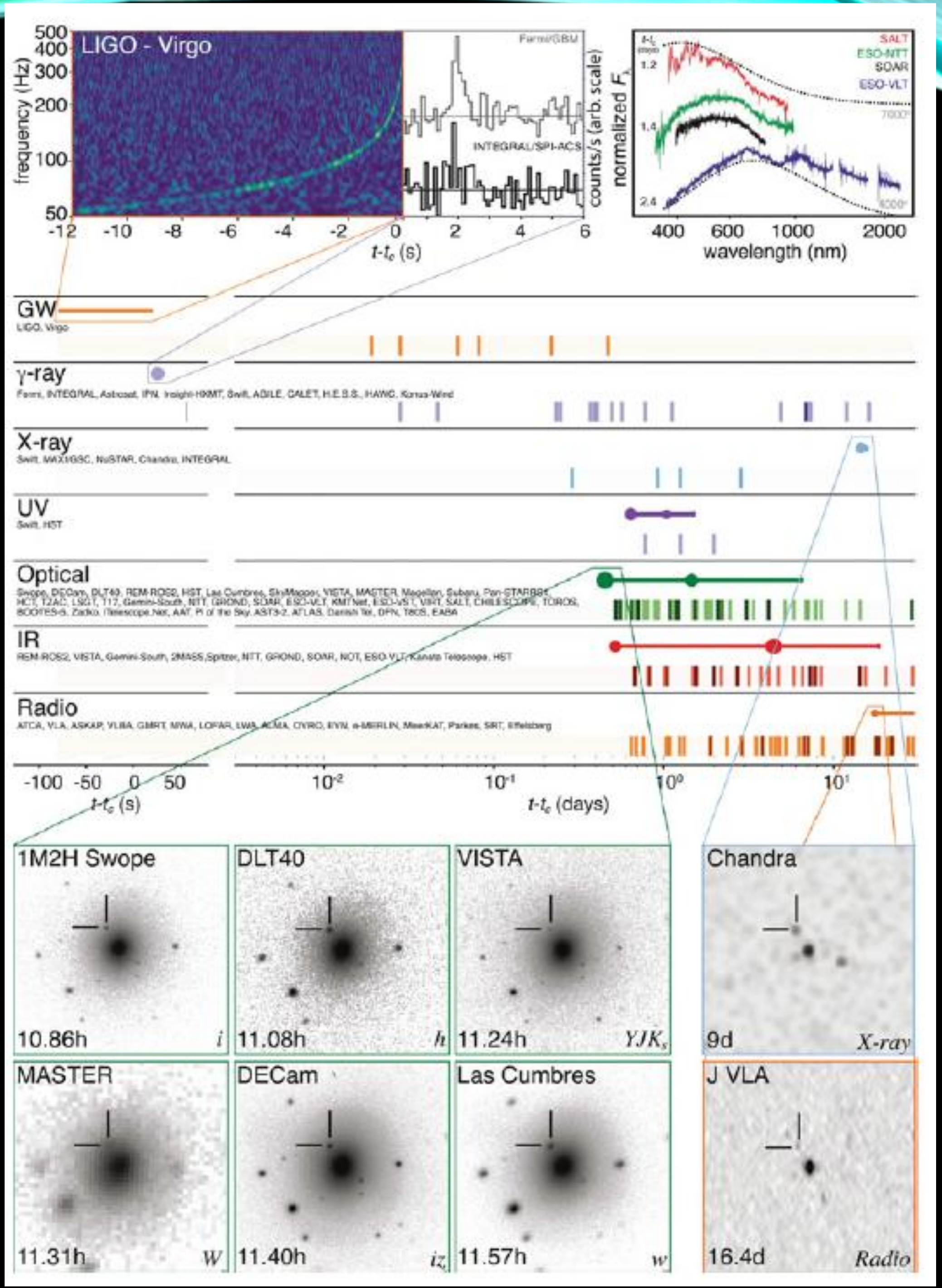
➔ New field of multimessenger astrophysics!!



THE BEST EXAMPLE

Timeline of discovery of
GW 170817
aka GRB 170817A
aka AT 2017gfo

- **Large number of papers** on different observations published in the same issue of **The Astrophysical Journal Letters** (Vol. 848, n. 2) on October 20, 2017
  - This includes **one paper** describing the multimessenger observations co-authored by almost **4000 physicists** from more than **900 institutions**, using **70 observatories** on all continents and in space



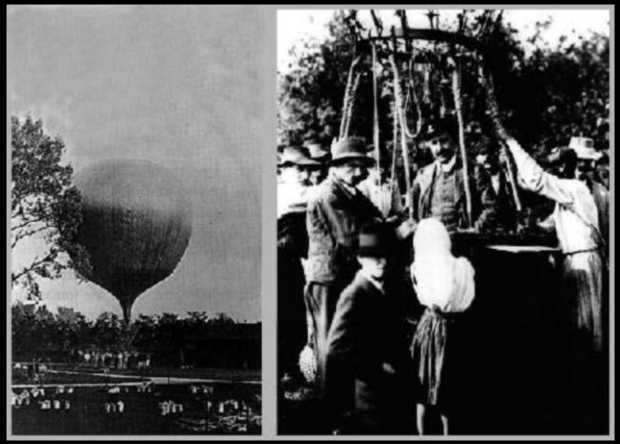
INTRODUCTION

- Open questions in particle physics and astrophysics

  - Is **galactic CR acceleration mechanism** provided by supernovae shock waves?
  - Can galactic objects **accelerate CRs up to 10^{18-19} eV**?
  - Can extragalactic objects (AGN, GRBs) **accelerate CRs up to $\sim 10^{20}$ eV**?
  - What mechanism(s) can **trigger GRBs**?
  - Is **antimatter** produced by secondary processes only?
  - Are there **fossil or primordial particles** in cosmic radiation?
  - Can we **directly or indirectly detect dark matter** and understand its nature?
  - Is the **proton really stable**?
  - What can we possibly learn from **neutrino astronomy**?
  - Which is the astrophysical use of new information on the Universe provided by the observation of **gravitational waves**?

INTRODUCTION

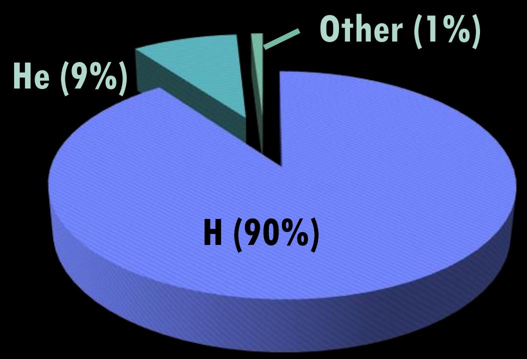
- **High-energy astrophysics**, as we know it today, is based on **2 fundamental discoveries** made around the **early twentieth century**



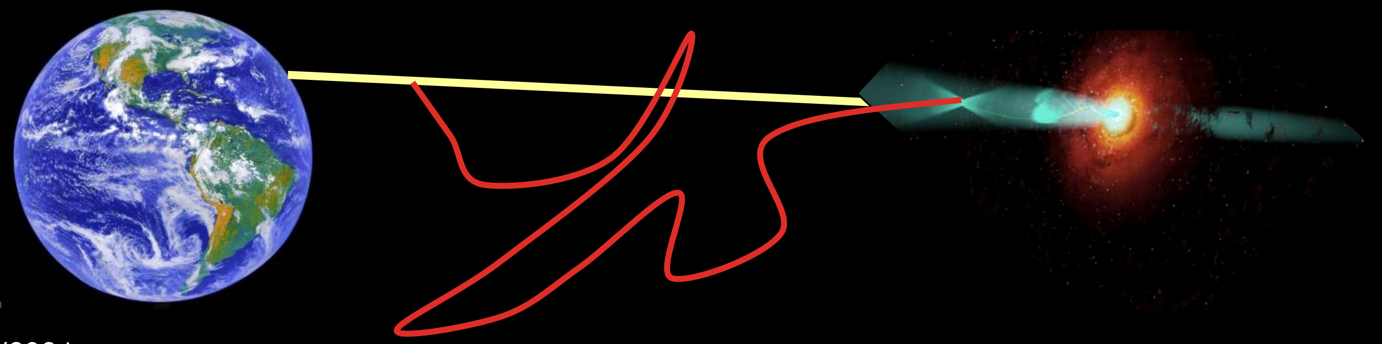
1. **RADIOACTIVITY** and the first **classification of subatomic particles** as α, β, and γ radiation
   (Becquerel 1896; Rutherford 1899; Villard 1900)

2. **COSMIC RAYS** measured as '*radiation of great penetrating power entering our atmosphere from above...*' (Hess 1912)
   - The '**cosmic radiation**' observed at **balloon altitudes** was mostly **secondary** to a very high-energy flux of <u>primary cosmic rays</u>
     - Before the advent of powerful particle accelerators, the beam of cosmic rays and their secondaries were the **major tool for the discoveries of the sub-nuclear zoo of particles**
     - The **<u>composition and origin</u>** of **primary cosmic rays** became a **major topic of high-energy astrophysics** until the present time

- Early measurements performed on balloons and sounding rockets made clear that **cosmic rays consisted of ~99% of protons and nuclei**
  - Electrons and gamma rays are just a **tiny fraction**
    - **BUT: interesting properties of high-energy photons**!
      1. Most penetrating form of radiation
      2. Not affected by cosmic magnetic fields



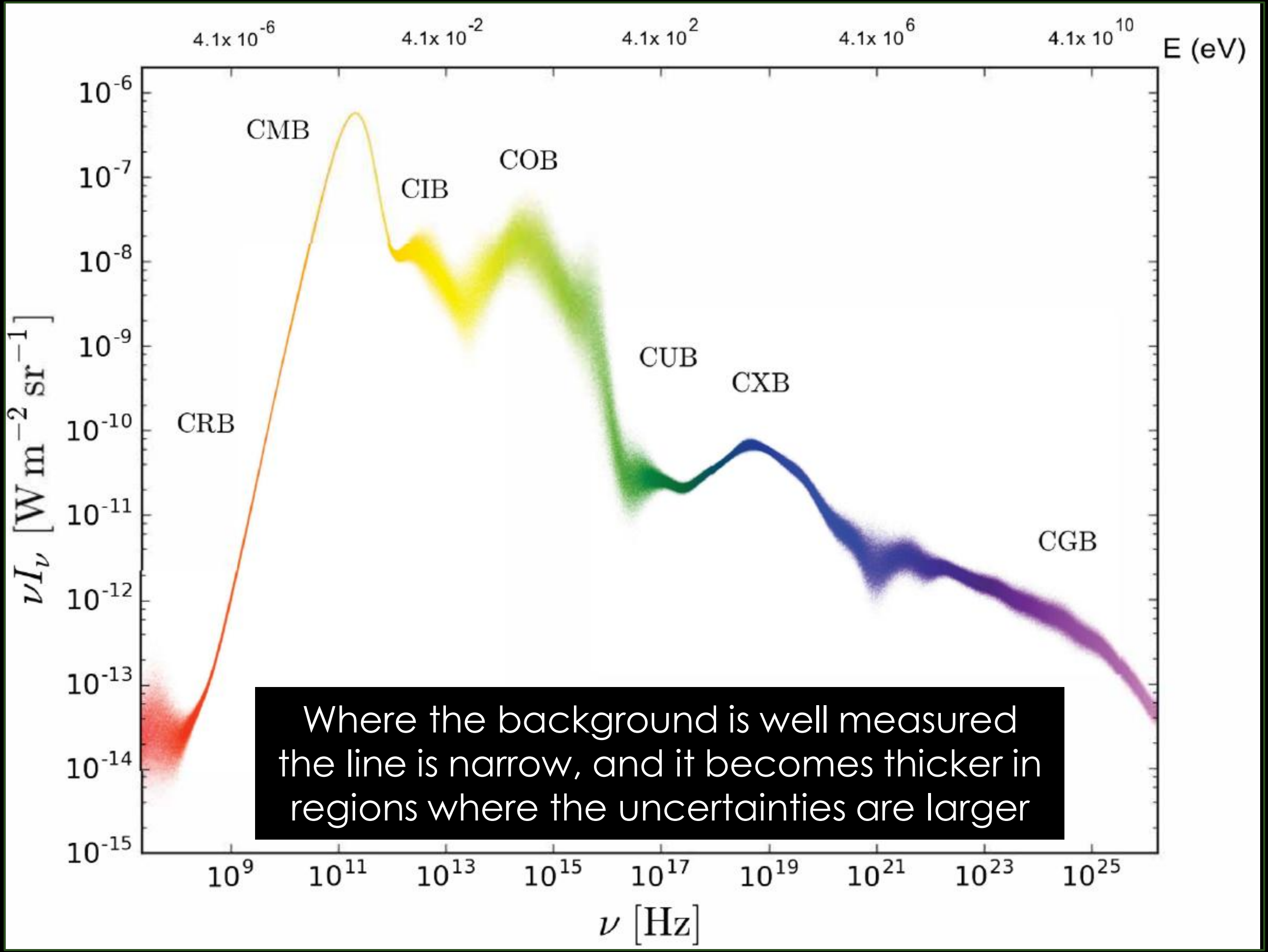
- **Gamma rays as fundamental tool for:**
  - Searches for **sources of cosmic rays in the Universe**
  - Investigation of the **energetic processes in their interior**



INTRODUCTION

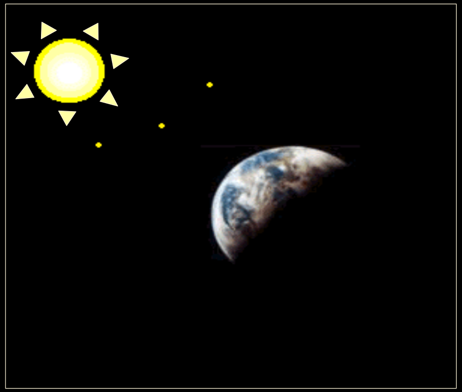
Cosmic photon energy spectrum

- Experimental data on **cosmic photon radiation** span ~30 energy decades
  - 1st bump corresponding to the **Cosmic Microwave Background (CMB)**
  - General behavior of the yield of **gamma rays at high energies** can be approximated by an **energy dependence as a power law $E^{-2.4}$**



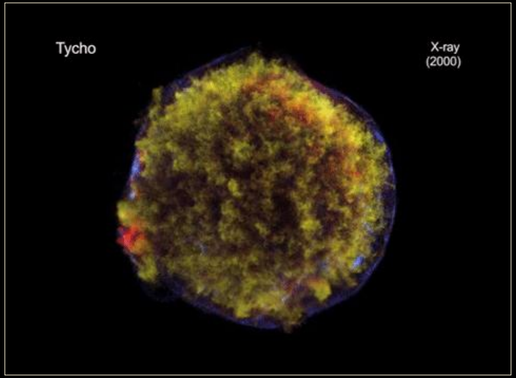
Hill, Masui, Scott, Applied Spectroscopy, 2018, Vol. 72(5) 663–688

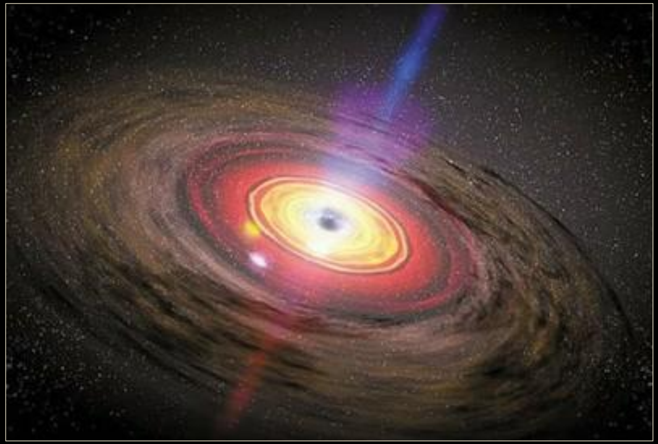
- We will mainly focus on the **most energetic photons: the gamma rays**
  - Electromagnetic radiation **above some 100 keV**
    - Highlight gamma rays in the high-energy (between a **few MeV and ~30 GeV**) and very high-energy (**>30 GeV**) ranges
- In recent years, a **large number of sources** has been detected, revealing the existence of a **very heterogeneous population** that lights up the gamma-ray sky, in our Galaxy and beyond.
- Gamma rays are related to all **cosmic messengers**:
  - **Cosmic rays**
  - **Neutrinos**
  - **Gravitational waves**
- Gamma-rays are an indirect probe for questions related to **fundamental physics**



INTRODUCTION

- The **study of gamma rays** unveals:
  - An exceptional view on the «non-thermal» Universe
  - The most violent phenomena happening on very different astronomical scales
    1. Gamma-ray sources in our Galaxy
       - Pulsars, pulsar wind nebulae (PWNe), supernova remnants (SNRs), micro-quasars, …
    2. Gamma-ray sources outside our Galaxy
       - Galaxies with an exceptional rate of star formation
       - Ultra-relativistic jets of particles escaping super-massive black holes (SMBHs)
       - Extremely energetic transient events (GRBs)
    3. Gamma-ray emission from diffuse regions in our Galaxy and beyond





GAUSSIAN UNITS

Table 2.1 Units of distance, mass and time in SI and c.g.s. and some derived quantities

Quantity	SI units	c.g.s. units	Conversion
Distance	Meter (m)	Centimeter (cm)	1 cm = 10^{-2} m
Mass	Kilogram (kg)	Gram (g)	1 g = 10^{-3} kg
Time	Second (s)	Second (s)	1 s = 1 s
Velocity	m s^{-1}	cm s^{-1}	1 cm/s = 10^{-2} m/s
Force	kg m s^{-2} = Newton	g cm s^{-2} = dyne	1 dyne = 10^{-5} Newton
Energy	kg m^2 s^{-2} = Joule	g cm^2 s^{-2} = erg	1 erg = 10^{-7} Joule

Table 2.2 Some electromagnetic formulas in Gauss and SI units

Name	Gauss units	SI units	Eq. #
Coulomb's law	$\mathbf{F} = \frac{q_1 q_2}{r^2}\hat{\mathbf{r}}$	$\mathbf{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}\hat{\mathbf{r}}$	I
Lorentz force	$\mathbf{F} = q\left(\mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{B}\right)$	$\mathbf{F} = q\,(\mathbf{E} + \mathbf{v}\times\mathbf{B})$	II
Gauss's law	$\nabla\cdot\mathbf{E} = 4\pi\rho$	$\nabla\cdot\mathbf{E} = \rho/\epsilon_0$	III
Gauss's law for magnetism	$\nabla\cdot\mathbf{B} = 0$	$\nabla\cdot\mathbf{B} = 0$	IV
Maxwell-Faraday equation	$\nabla\times\mathbf{E} = -\frac{1}{c}\frac{\partial\mathbf{B}}{\partial t}$	$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$	V
Ampère-Maxwell equation	$\nabla\times\mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial\mathbf{E}}{\partial t}$	$\nabla\times\mathbf{B} = \mu_0\mathbf{J} + \frac{1}{c^2}\frac{\partial\mathbf{E}}{\partial t}$	VI
Poynting's vector	$\mathbf{S} = \frac{c}{4\pi}\mathbf{E}\times\mathbf{B}$	$\mathbf{S} = \frac{1}{\mu_0}\mathbf{E}\times\mathbf{B}$	VII
Vacuum energy density	$u = \frac{1}{8\pi}(E^2 + B^2)$	$u = \frac{\epsilon_0 E^2}{2} + \frac{B^2}{2\mu_0}$	VIII
Electric field	$\mathbf{E} = -\nabla\phi - \frac{1}{c}\frac{\partial\mathbf{A}}{\partial t}$	$\mathbf{E} = -\nabla\phi - \frac{\partial\mathbf{A}}{\partial t}$	IX
Magnetic B field	$\mathbf{B} = \nabla\times\mathbf{A}$	$\mathbf{B} = \nabla\times\mathbf{A}$	X

Refer to the appendix of Jackson (1999) for a more exhaustive discussion