Tema 1

Astrofísica, astronomía y astrofísica nuclear

Asignatura de Estructura y Astrofísica Nuclear
Máster de Física

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Universidad de Santiago de Compostela

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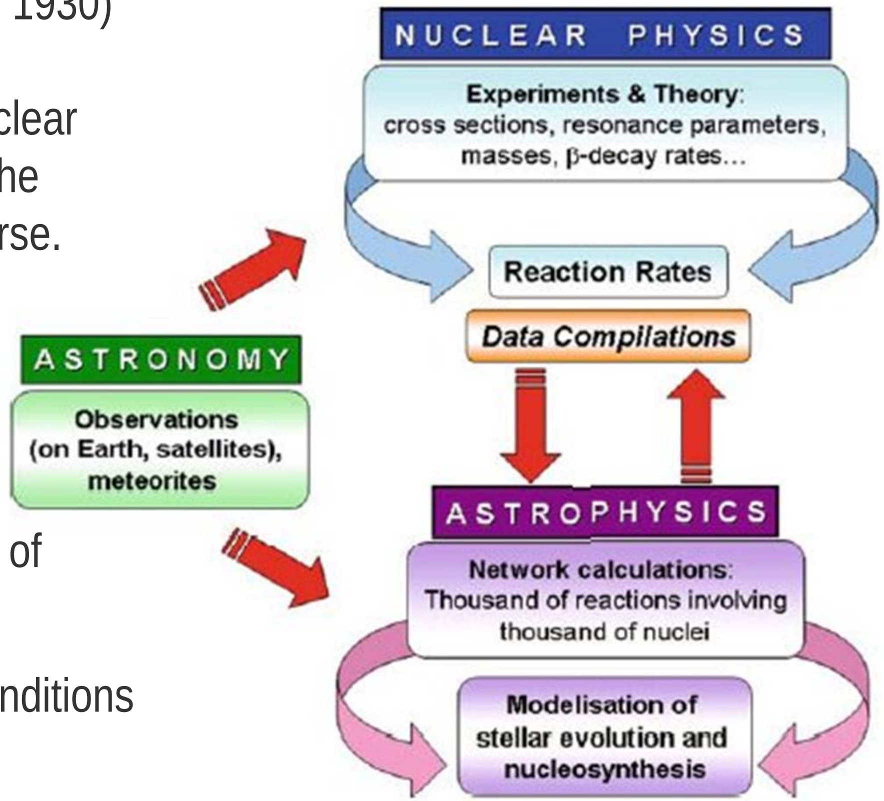
1. Nuclear Astrophysic's domain

Nuclear Astrophysics is a relatively recent discipline (~ 1930) explaining the processes in our Universe governed by nuclear reactions or nuclear properties. Therefore, Nuclear Astrophysics provides the direct connection between the microscopic and macroscopic description of our Universe.

Nuclar Astrophysics takes advantage of other scieintific disciplines:

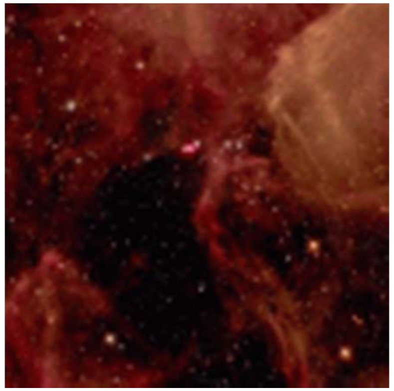
- Nuclear Physics provides the description of nuclear reactions and nuclear properties, e.g. bulk properties of nuclei or the equation of state of nuclear matter.
- Astrophysics describes the stellar or cosmological conditions for the fenomena ruled by nuclear properties.
- Astronomy provides observational data required for validating model calculations.

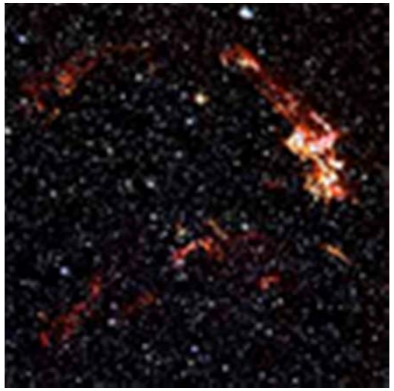


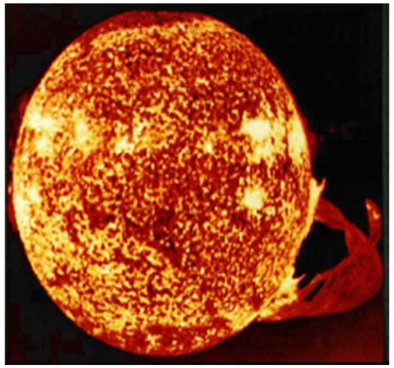
1. Nuclear Astrophysic's domain

Most important areas of interest for Nuclear Astrophysics are the following:

- ✓ Primordial nucleosynthesis
- ✓ Stellar nucleosynthesis
- ✓ Dense stellar objects (e.g. super-nova explosions)
  Equation of state of nuclear matter
- ✓ Cosmic radiation
- ✓ Cosmochronology







2. Historical evolution

- ✓ 1920, Eddington suggested that the difference in mas between helium and four hydrogen nuclei could explain the energy generation in the Sun via the conversion of hydrogen to helium.
- ✓ 1929, Atkinson and Houtermans used the quantum mechanical tunneling calculations by Gamow to explain how hydrogen fusion could take place at the Sun despite its relatively low temperature.
- ✓ 1932, Cockcroft and Walton performed the first nuclear reaction experiments using and accelerator for reproducing one of the reactions powering the Sun $p + {}^{7}Li \rightarrow {}^{4}He + {}^{4}He$.
- ✓ 1936, Atkinson proposed the fusion of two hydrogen nuclei to deuterium as a source for stellar energy generation.
- ✓ 1938, Weizsacker and Bethe proposed the CNO cycle an additional reaction chain for energy generation in stars.
- ✓ 1946, Hoyle presented the theory of nucleosynthesis within the framework of stellar evolution using the nuclear data available at that time. This seminal work is considered as the first real contribution to nuclear astrophysics.

2. Historical evolution

- ✓ 1952, Salpeter propopossed a triple-α reaction as a mechanism for producing heavy nuclei above A=5 and 8. Hoyle precited that this reaction could only be effective through an ^{12}C excited state around 7.7 MeV.

- ✓ 1952, Merrill discovered spectral lines in red giant stars corresponding to technetium. Since all technetium isotopes are unstable and the longest lived isotope has a half life of 4.2 10^6 y, this discovery supported the nucleosynthesis theory since this element had been produced recently in stars.

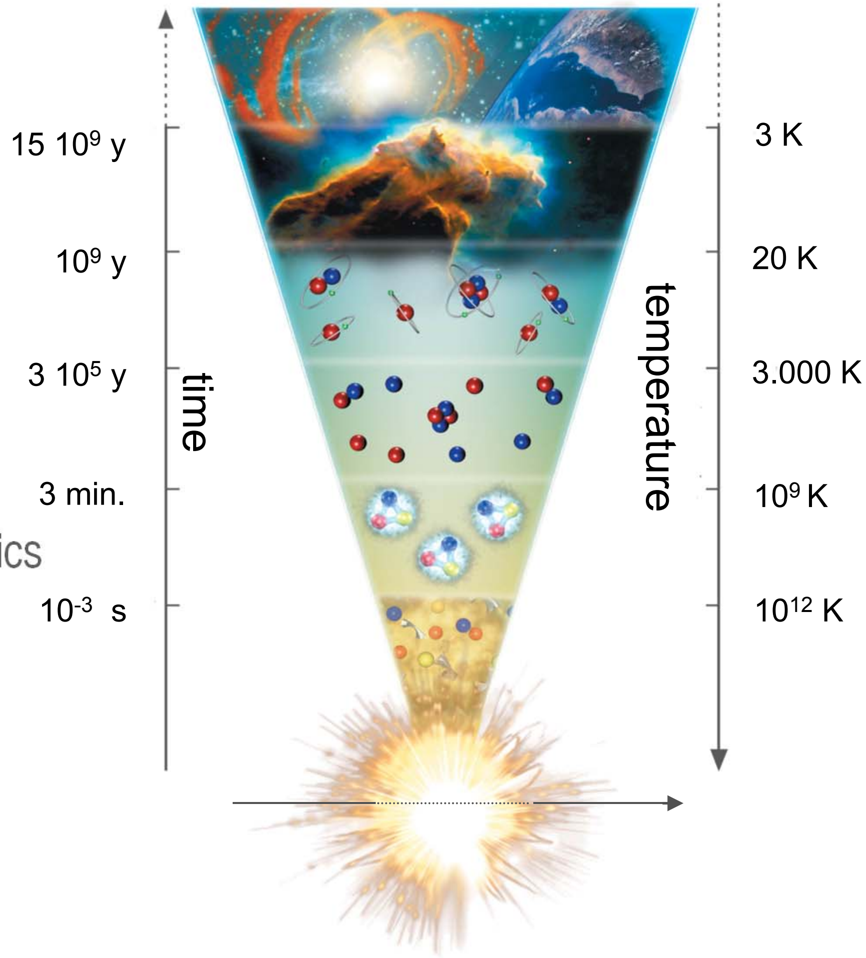
- ✓ 1956, Suess and Urey demonstrated that the double peaks observed in the Solar system abundance curve were associated to the neutron magic numbers of the nuclear shell model recently proposed by Jensen and Goeppert Mayer (1949).

- ✓ 1957, Burbidge and Cameron published independently two review articles stablishing the grounds for the modern theory of nuclear astrophysics.

3. Brief history of the Universe

The history of our Universe can be divided into four different periods:

- ✓ First moments and atomic formation (~ 10^6 y):
  - Nuclear and particle physics dominated
  - Primordial nucleosynthesis
- ✓ Galactic condensation (~1-2 10^9 y)
  - Gravitation driven
- ✓ Stellar evolution (~ 12 10^9 y)
  - Thermodynamics, gravitation and nuclear physics
  - Stellar nucleosynthesis
- ✓ Evolution of the Solar system



4. First moments of the Universe

4.1 Big Bang Cosmology

The present state of the Universe is characterized by few large-scale observables and some basic physical laws.

Large-scale observables:
- expansion of .the Universe (red shift)
- background radiation at 2.76 K
- 10^{-9} asymmetry between density of baryons and photons
- universal abundance of about 75% H and 25% He

Physical laws:
- General Theory of Relativity provides a relation between the elapsed time and temperature of the Universe

$$T = \frac{1.5 \cdot 10^{10}}{\sqrt{t}}$$

- Statistical Mechanics (Stefan-Boltzman law) provides a relation for the energy density of radiation (photon gas)

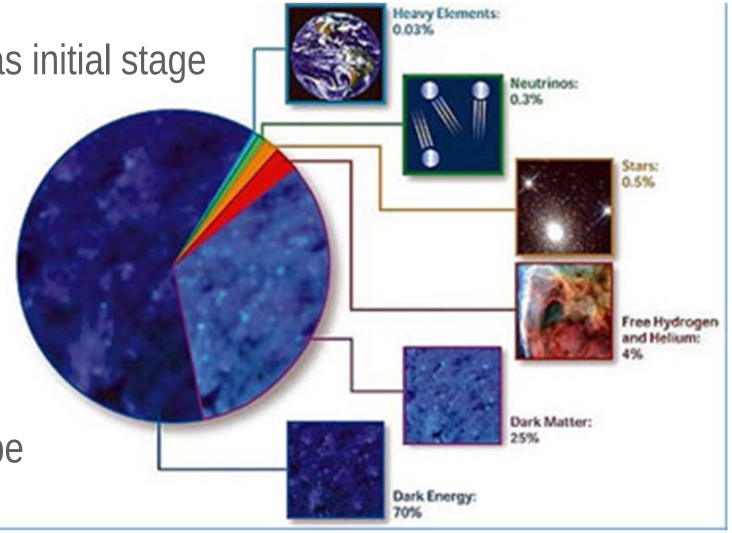
$$u_\gamma(E)\,dE = \frac{8\pi E^3}{(hc)^3}\frac{1}{e^{E/kT}-1}\,dE$$

4. First moments of the Universe

4.1 Big Bang Cosmology

Universe expansion and background radiation:

- these are considered as evidences for the Big Bang theory
- moving back in time one would reach infinity density and energy as initial stage



Universe composition:

- assuming that at t=to the Universe was in thermal equilibrium, its properties are determined by the values of the conserved quantities: energy (temperature), charge, baryon number and lepton number

- at present (T=2.7 K), energy density and density of photons can be obtained integrating the following equations:

$$u(E)dE = \frac{8\pi\pi^3}{(hc)^3}\frac{1}{e^{E/kT}-1}dE \quad \Rightarrow \quad \rho_\gamma = 4.7\cdot 10^3 T^4 \ \ eV/m^3 \quad T=2.7K \rightarrow 250keV/m^3$$

$$n(E)dE = \frac{u(E)}{E}dE = \frac{8\pi\pi^2}{(hc)^3}\frac{1}{e^{E/kT}-1}dE \quad \Rightarrow \quad N_\gamma = 2.0\cdot 10^7 T^3 \ \ \gamma/m^3 \quad T=2.7K \rightarrow 4\cdot 10^8 \gamma/m^3$$

- the density of visible matter is estimated to be ~3 10^{31} g/cm^3 and the density of dark matter could be up to a factor of 4 larger (ρ_{matter} ~ 0.4 nucleons/m^3) → $\rho_{matter} / \rho_\gamma \sim 10^{-9}$

- the present Universe is made almost of matter rather than antimatter (no evidences for annihilation)

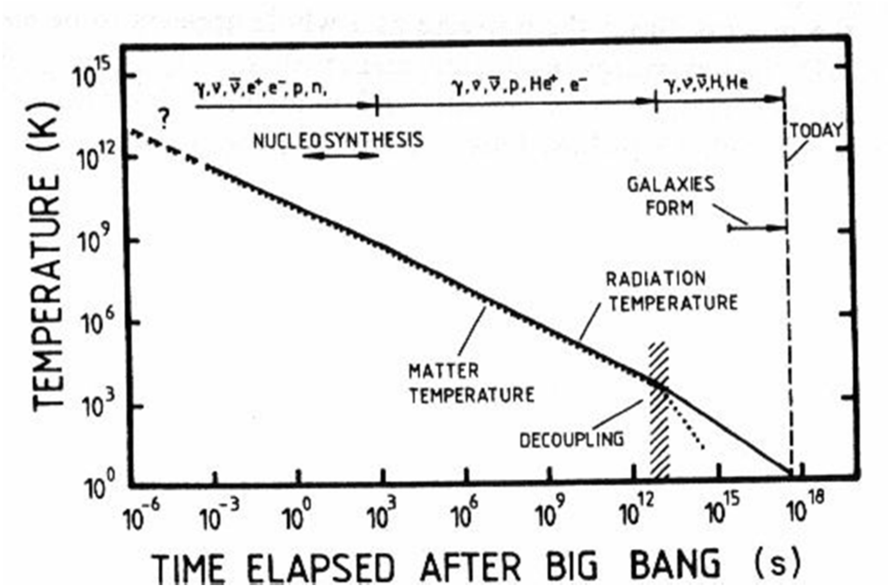
4. First moments of the Universe

4.2 Nuclear and particle physics at the early Universe

- At the early Universe ($t=10^{-12}$ s, $T=10^{16}$ K, E~1000 GeV) matter and radiation were in equilibrium, all species of particles and anti-particles were created but also annihilated.

- From that moment on the expansion and cooling of the Universe prevented radiation the creation of particle pairs starting with the more massive particles until the lighter ones (e^+,e^-) at t=190 s ($T=10^9$ K, E<0.5 MeV).

- In parallel, a mechanism should account for the present imbalance between matter and radiation (~10^{-9}) and between matter and anti-matter → CP violating decays.



- Then, protons and neutrons underwent a series of nuclear reactions leading to the transformation of protons and neutrons in ^{4}He with no free neutrons surviving. After this process the Universe was composed of protons, helium, electrons, photons and neutrinos.

5. Stellar evolution and nucleosynthesis

✓ Stars are objects composed mainly by hydrogen and helium at relatively low density (gas).

✓ The stellar gas is confined by the competition between the gravitational force and thermal pressure due to the temperature of the star (hydrostatic equilibrium).

✓ The energy flow emitted by the star is compensated by nuclear energy generation (thermal equilibrium).

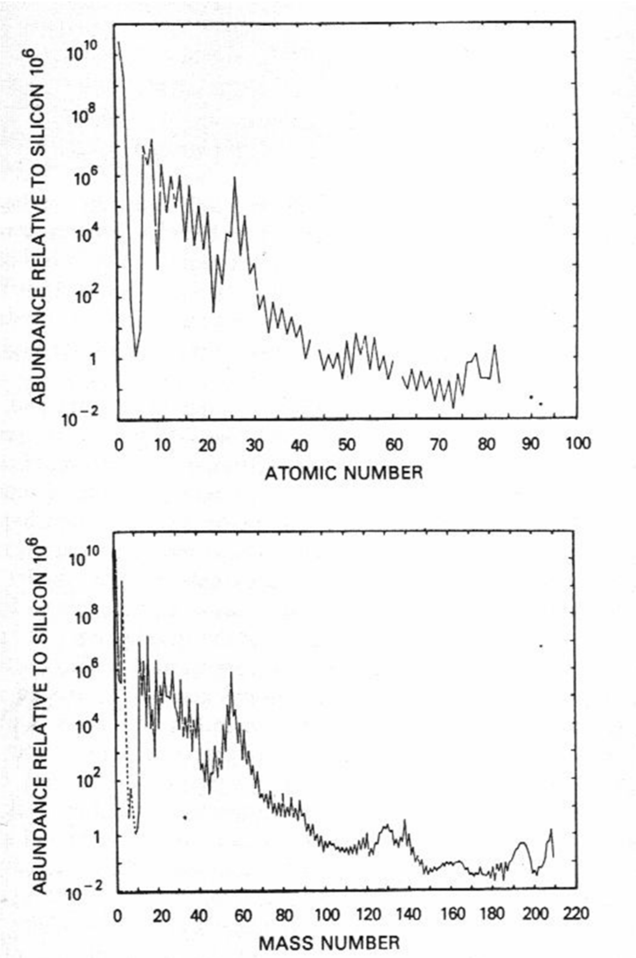
✓ Thermonuclear reactions are also responsible for the transformation of hydrogen and helium into heavier elements (nucleosynthesis).

✓ Nucleosynthesis proceeds through different phases and thermonuclear reactions (cycles) depending on the mass and temperature (age) of the star.

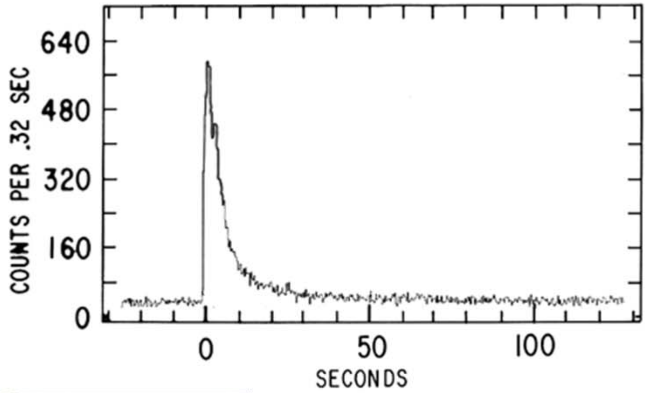
- The lowest energy reactions transform hydrogen into helium.
- When hydrogen becomes exhausted, preassure and temperature increases, because of the heavier mass of the interior star, then helium burning becomes possible.
- Subsequent phases produces heavier and heavier elements up to iron, then the mass of the interior of the star becomes so important that a gravitational collapse can produce the explosion of the star (supernova)

6. Astronomic observables

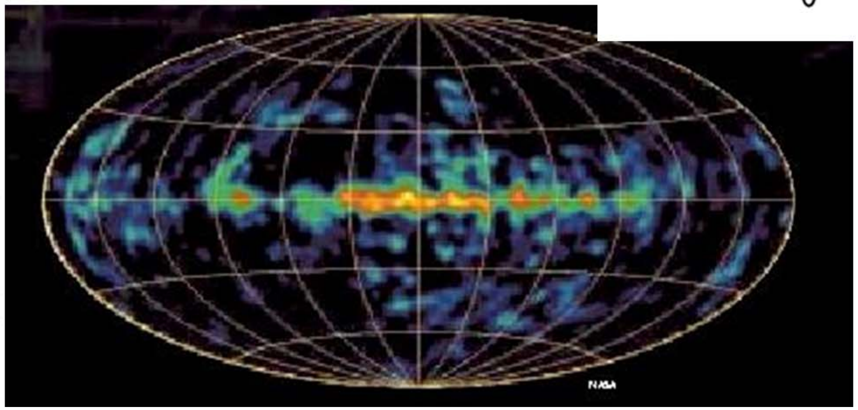
Abundance curves



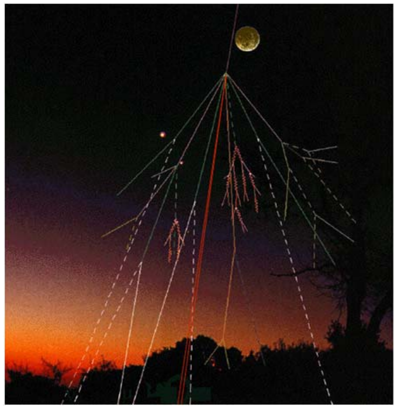
X-ray burst



γ rays (^{26}Al)



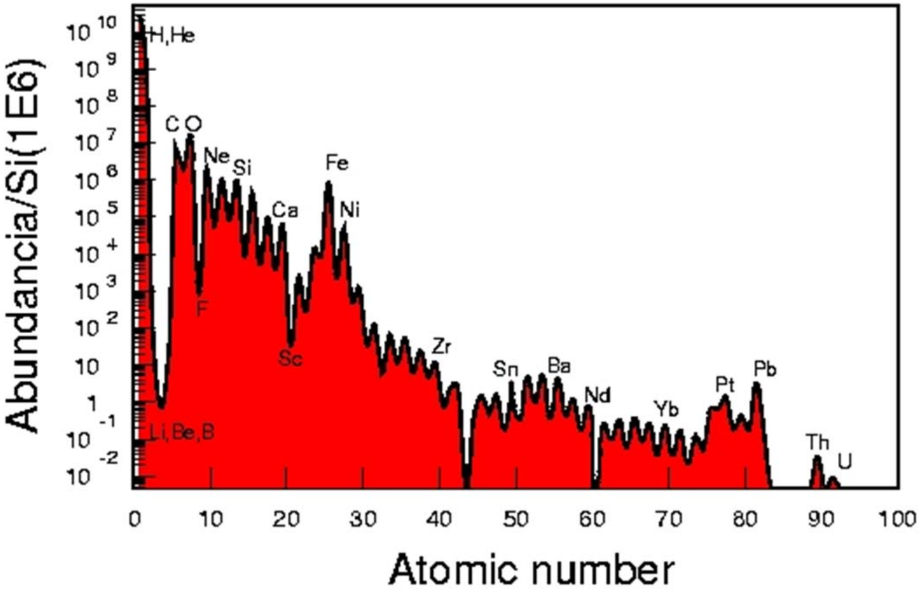
Cosmic rays



Neutrinos

6. Astronomic observables

6.1 Abundance curves



✓ The abundance curve reflects the chemical composition of our Universe. The sources defining this curve are:

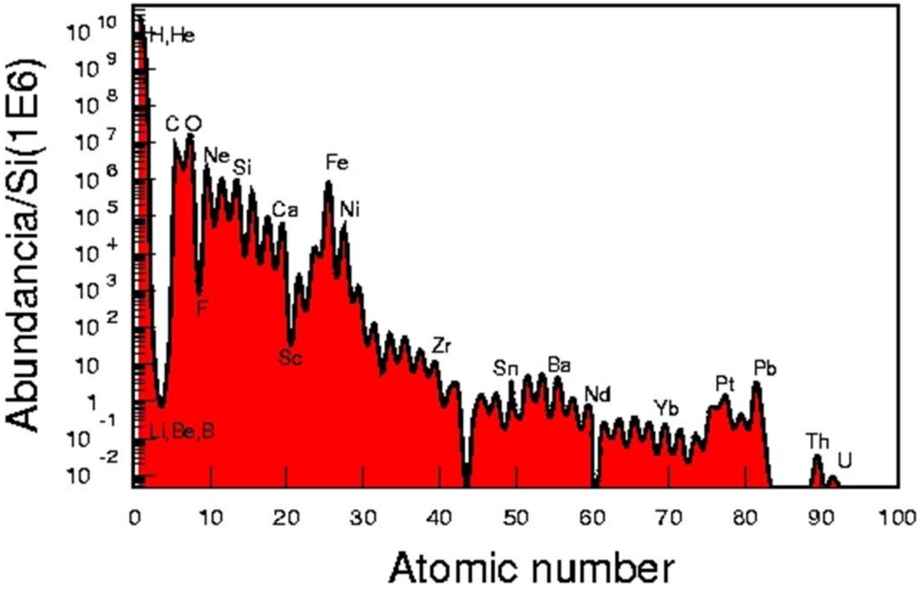
- Earth's chemical composition
- Analysis of metheorits
- Cosmic-ray analysis
- Spectral analysis of stars

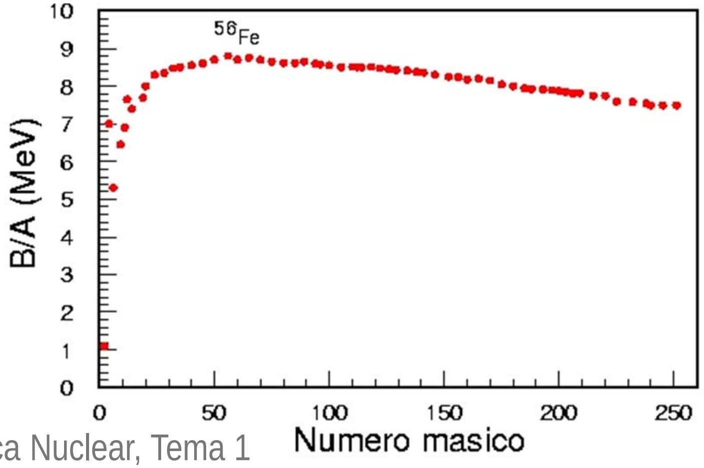
✓ One can distinguish different abundance curves:

- Universal abundance curve
- Solar system abundances
- Cosmic-ray abundance curve

6. Astronomic observables

6.1 Abundance curves





✓ The abundance curve also reveals the role of Nuclear Physics in the nucleosynthesis processes.

✓ Nuclear bulk properties shape the abundance curve:

- the fast decreases in abundances above the Fe/Ni region is explained by the dependence of nuclear binding energies with the mass number.

- the even-odd pattern reflects pairing effects in nuclei.

- the non existence of stable nuclei with mass numbers 5 and 8 is clearly observed.

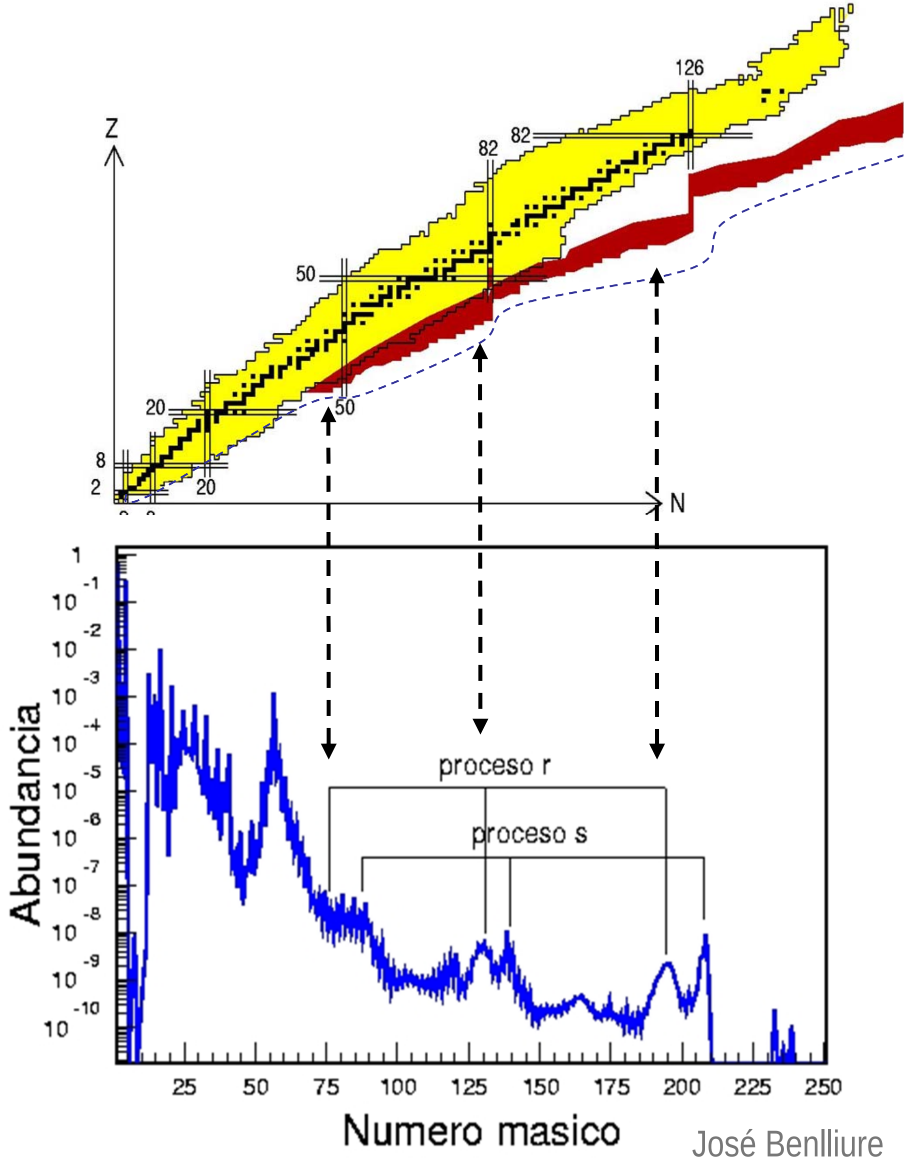
6. Astronomic observables

6.1 Abundance curves

✓ Nuclear shell effects are also present in the abundance curve:

- abundance peaks around A~80, 130 and 200 are known to be produced by the neutron shell closure at N=50, 82 and 126.

- the double nature of these peaks reflects the existence of two different nucleosynthesis processes leading to the production of the heaviest nuclei in the Universe.



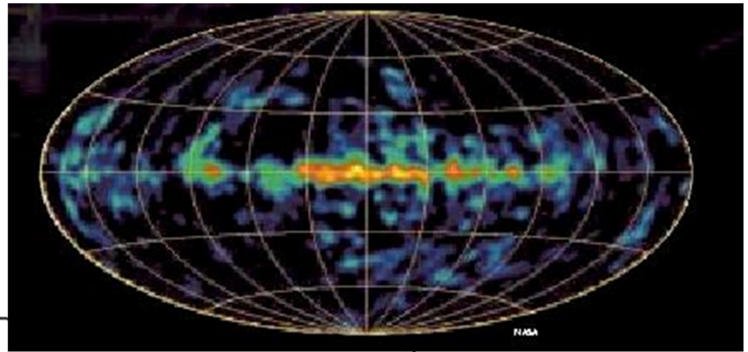
6. Astronomic observables

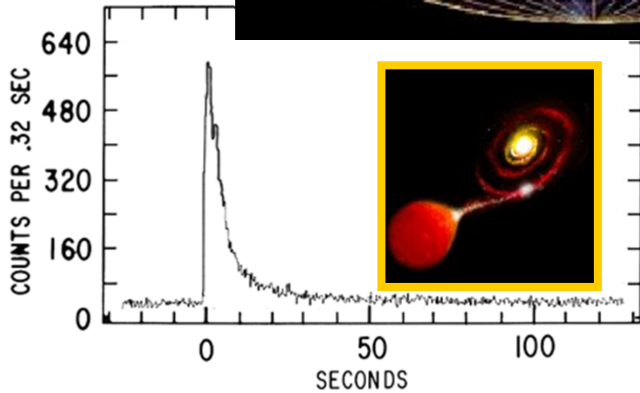
6.2 Gamma-ray astronomy

- ✓ gamma-ray bursts
- ✓ active galactic nuclei (AGN)
- ✓ supernova remmants (SNR)
- ✓ dark matter

- ✓ satélites: INTEGRAL (γ), Comptel, Glast
- ✓ telescopes: Hegra, HESS, Magic

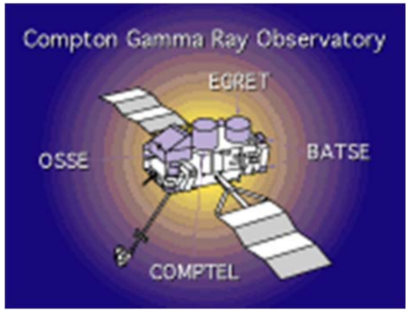
γ rays (^{26}Al)





COMPTEL experiment

GLAST experiment

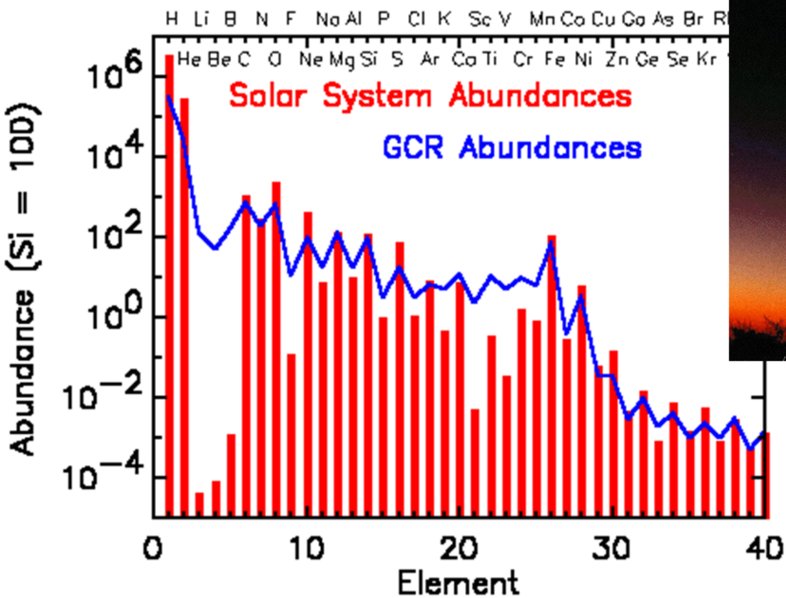


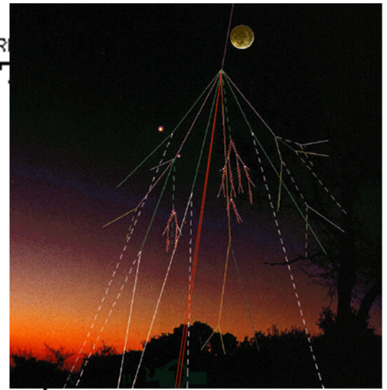
HESS experiment in Namibia

6. Astronomic observables

6.3 Cosmic rays

- ✓ composition
  - spallation reactions
  - propagation distances
- ✓ energy spectra

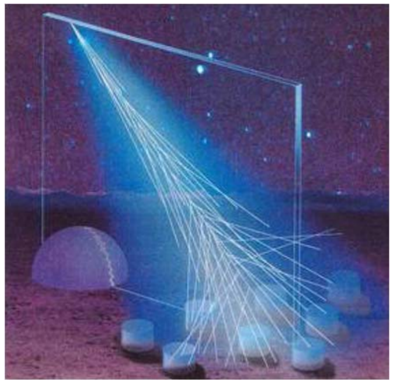


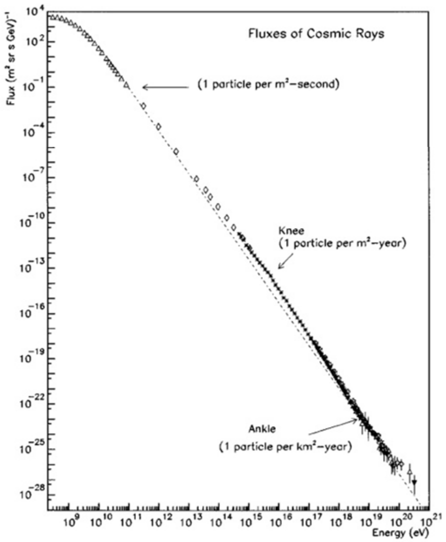


CREAM experiment

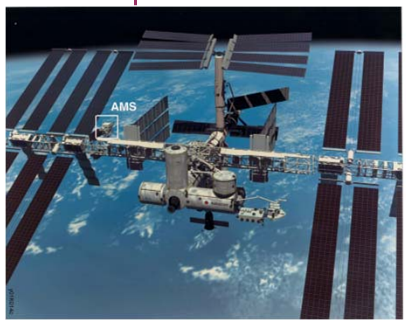
- ✓ ground experiments:
  Auger, KASCADE, GRAPES-3,…
- ✓ satellite experiments:
  - Voyager 1 and 2, Cassini-Huygens, AMS,..
- ✓ balloon-borne experiments
  - TRACER, CREAM, …

Pierre Auger obsevatory



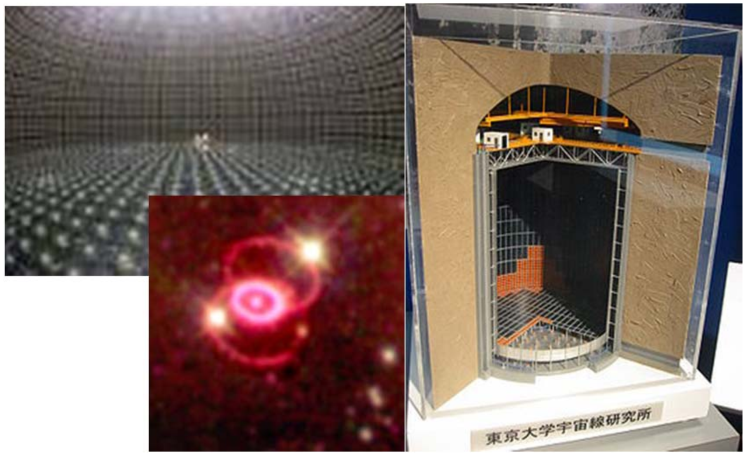


AMS experiment at the ISS

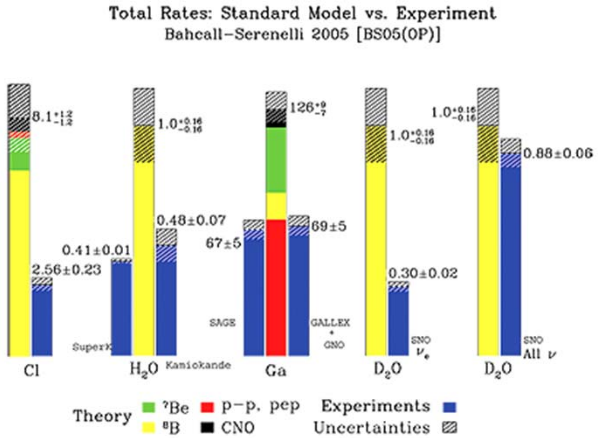


6.4 Neutrinos

Super Kamiokande experiment

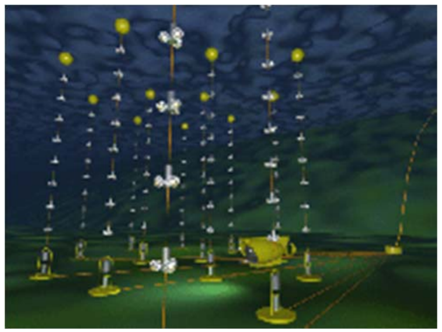


- ✓ the solar neutrino problem: discrepancies between solar neutrino fluxes observed in different experiments on Earth
- ✓ supernova neutrinos: sn 1987 observation
- ✓ neutrino oscillation
- ✓ experiments:
  - past: Home Stake, GALLEX
  - present: Super-Kamiokande, SNO
  - future: antares, KM3net, icecube



SNO experiment

Antares experiment



7. Experimental techniques in nuclear astrophysics

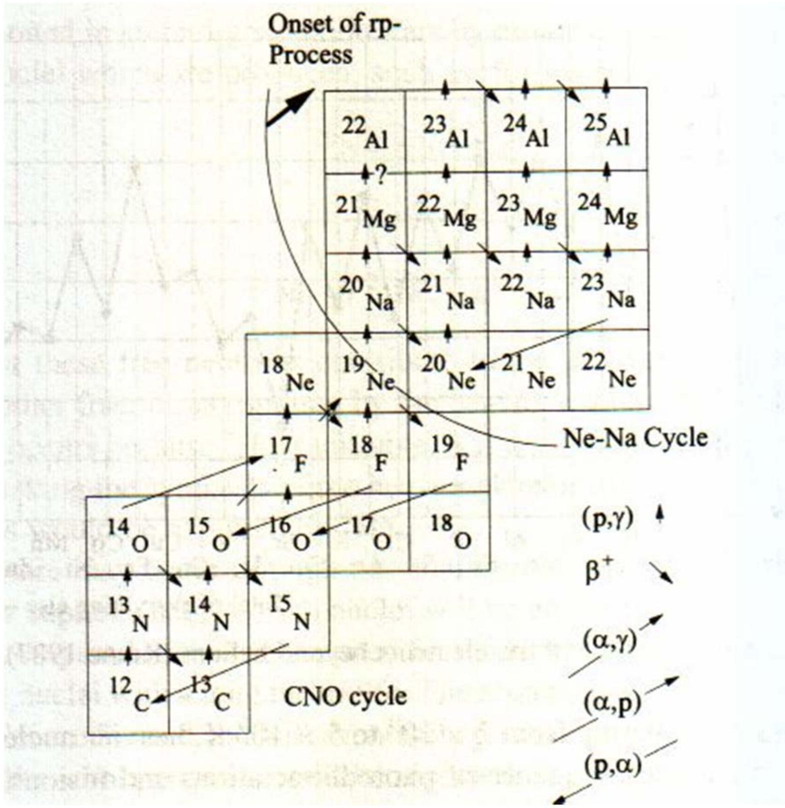
Models describing nucleosynthesis processes require Nuclear Physics inputs:

✓ Properties of nuclei:

- nuclear masses
- β-decay half lives
- exited states

✓ nuclear reactions rates:

- fusion reactions induced by light nuclei at energies well below the Coulomb barrier
- proton/neutron capture by nuclei far from stability
- neutrino-induced reactions
- spallation reactions



7. Experimental techniques in nuclear astrophysics

Techniques for investigating nuclear properties:

✓ mass measurements:

- storage rings
- ion traps

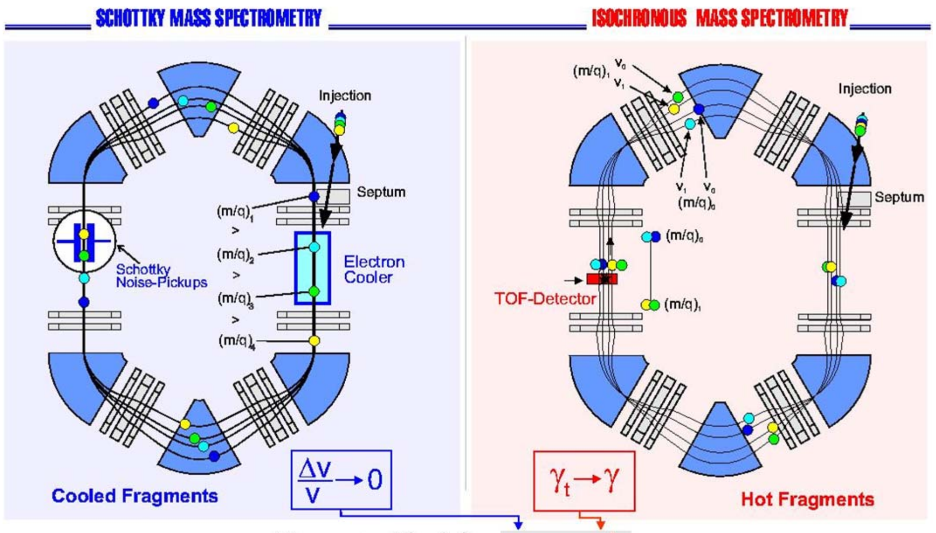
✓ β-half lives:

- time correlations.

✓ excited states:

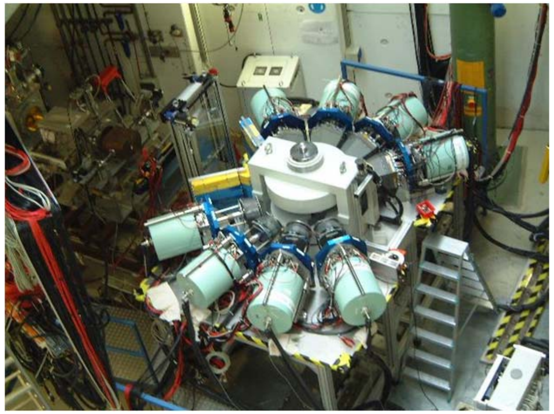
- γ-ray spectroscopy

Precise mass measurements using storage rings at GSI



$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

Gamma spectroscopy experiments using the RISING detector at GSI



Silicon detector array for nucleus-beta time correlations