Astrofisica Nucleare e Subnucleare

Nuclear Astrophysics - 1

Nuclear Astrophysics: Supernova Evolution and Explosive Nucleosynthesis

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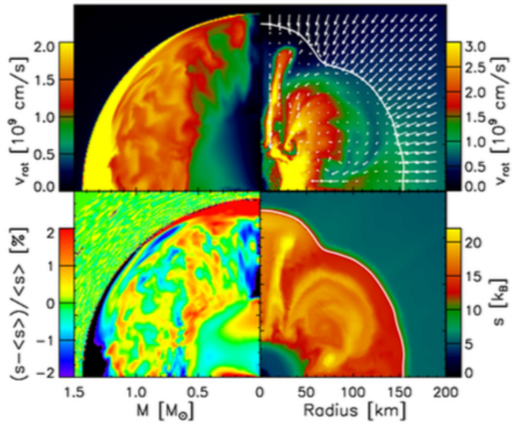
TECHNISCHE UNIVERSITÄT DARMSTADT

HIC for FAIR
Helmholtz International Center

A new Era for Nuclear Astrophysics

Improved observational capabilities

Improved supernovae models

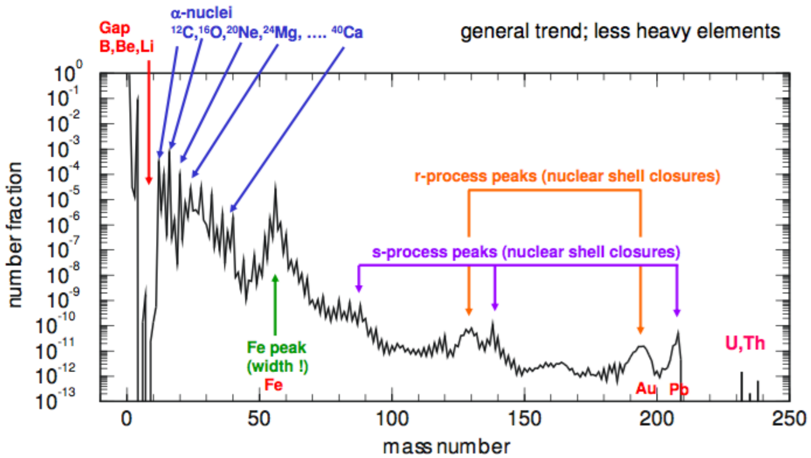


- New radioactive ion beam facilities (RIBF, SPIRAL 2, FAIR, FRIB) are being built or developed that will study many of the nuclei produced in explosive events. Hydrostatic burning phases studied in underground labs (LUNA)
- We need improved theoretical models to fully exploit the potential offered by these facilities.

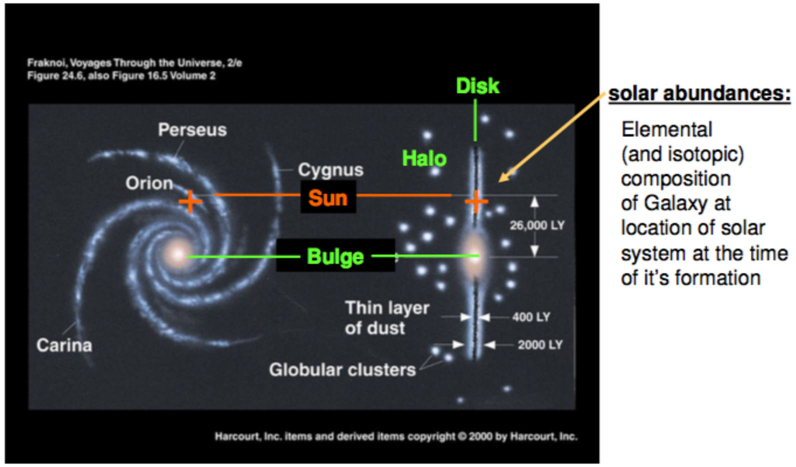
What is Nuclear Astrophysics?

- Nuclear astrophysics aims at understanding the nuclear processes that take place in the universe.
- These nuclear processes generate energy in stars and contribute to the nucleosynthesis of the elements and the evolution of the galaxy.

Hydrogen mass fraction	X = 0.71
Helium mass fraction	Y = 0.28
Metallicity (mass fraction of everything else)	Z = 0.019
Heavy Elements (beyond Nickel) mass fraction	4E-6

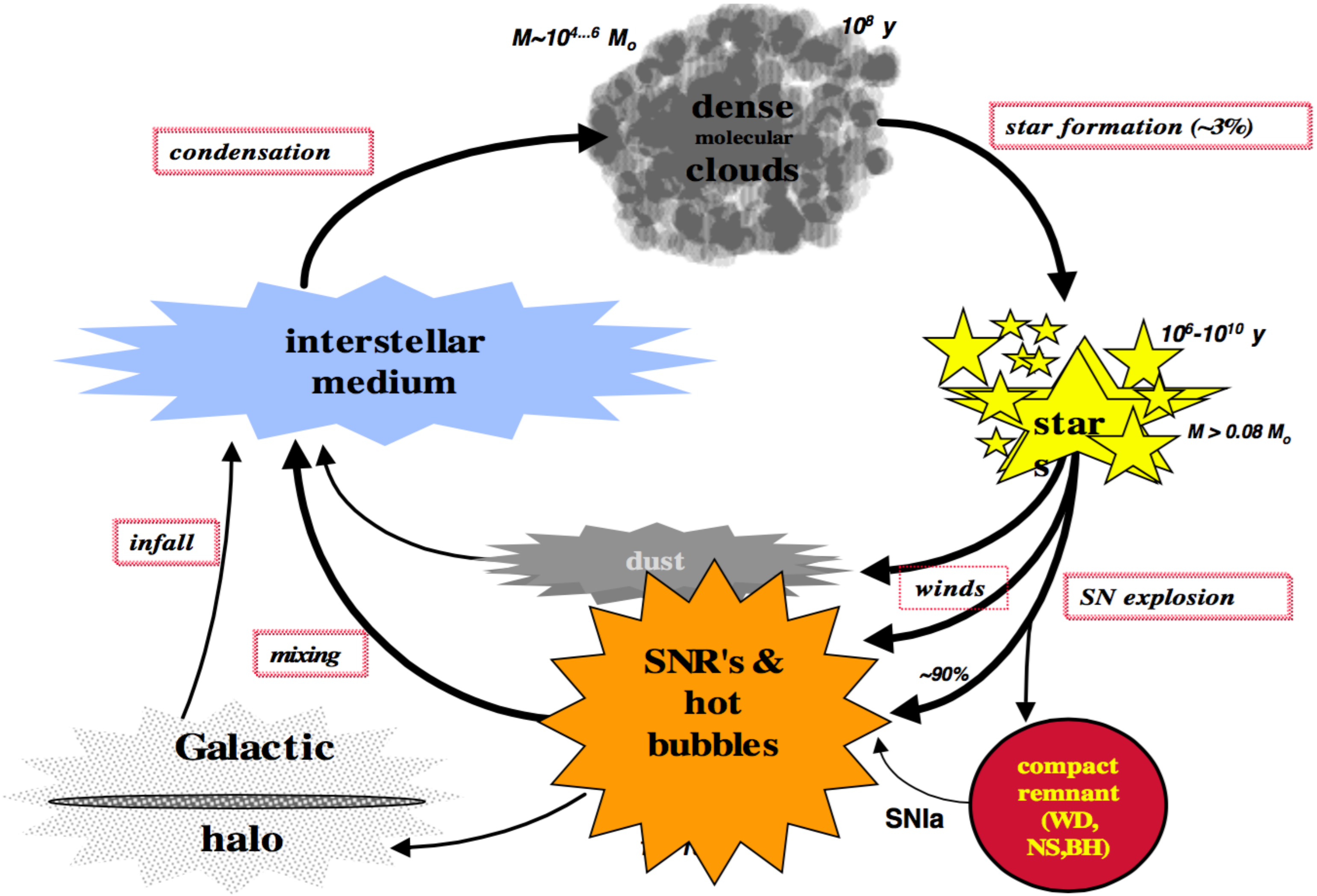


3. The solar abundance distribution



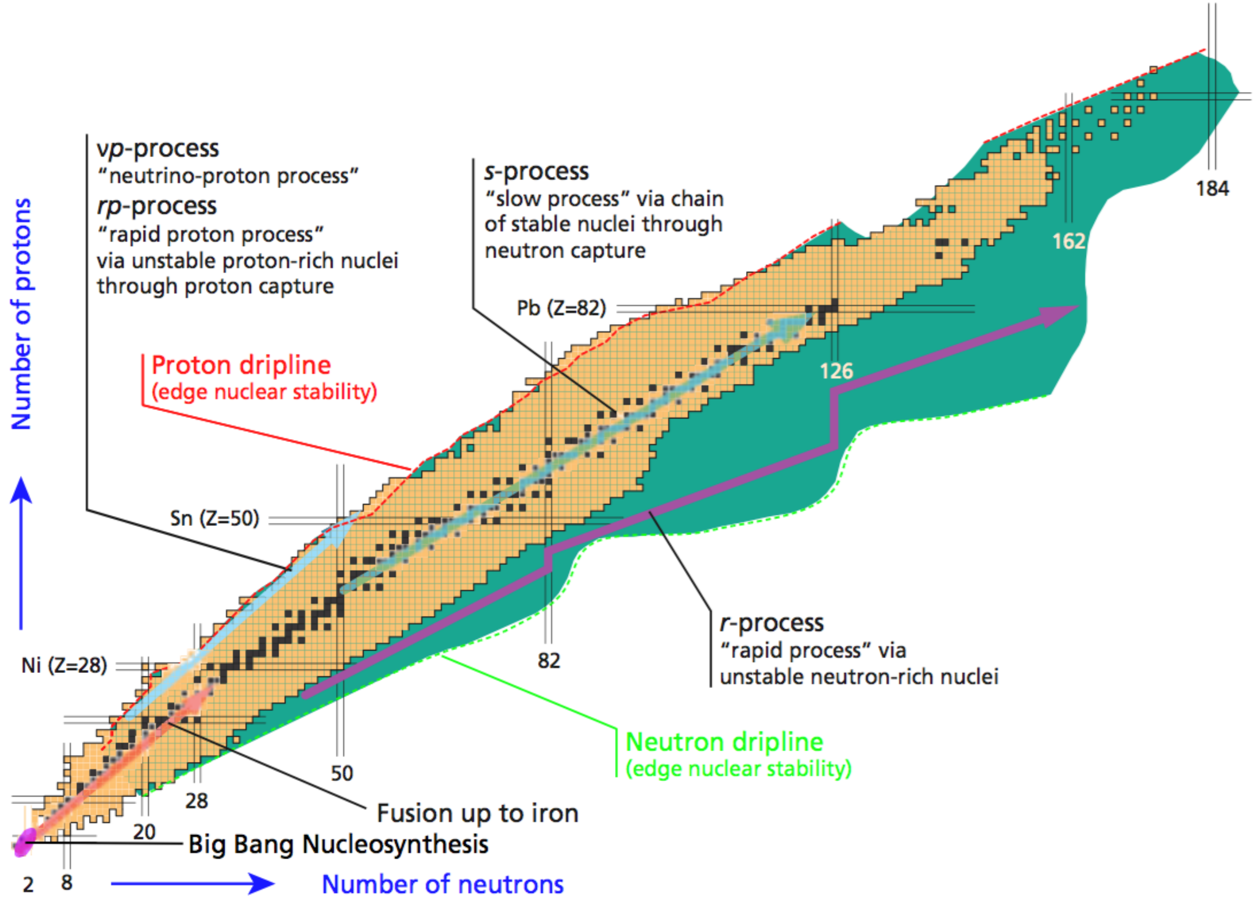
K. Lodders, Astrophys. J. **591**, 1220-1247 (2003)

Cosmic Cycle

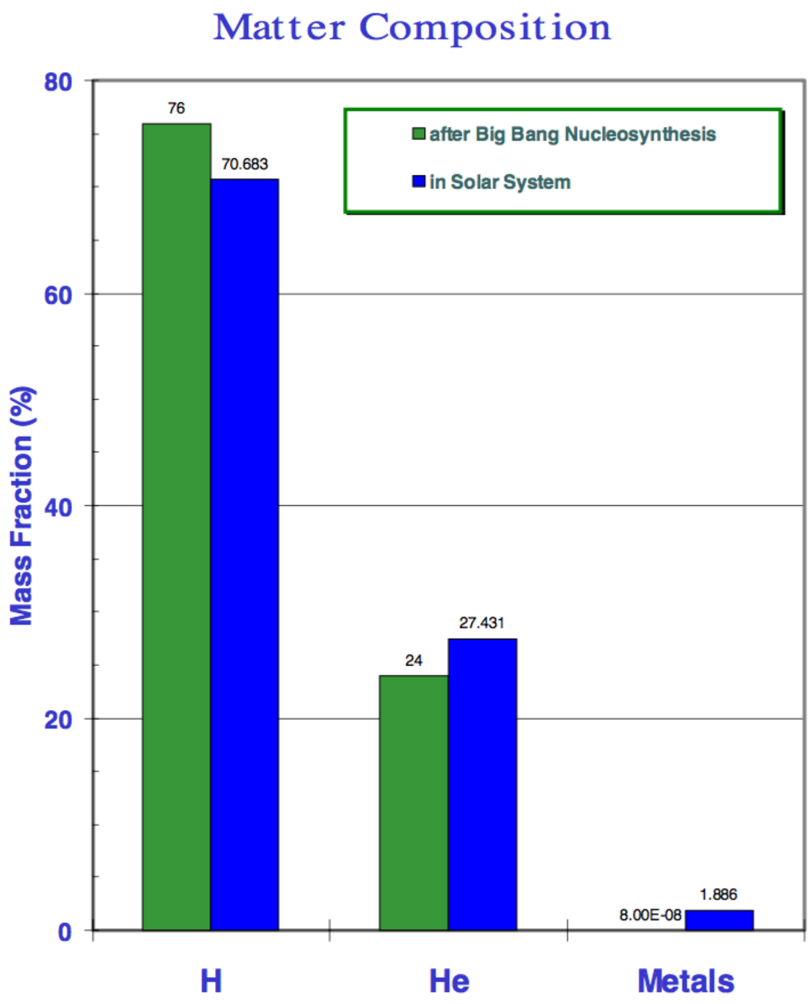


Nucleosynthesis processes

In 1957 Burbidge, Burbidge, Fowler and Hoyle and independently Cameron, suggested several nucleosynthesis processes to explain the origin of the elements.

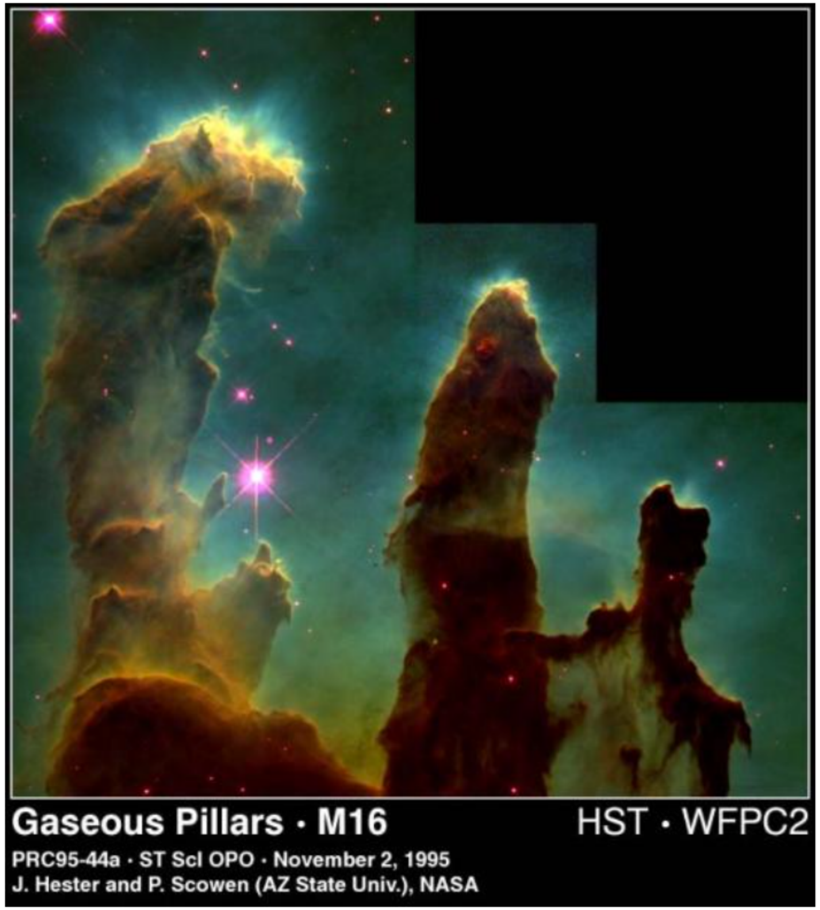


Composition of the Universe after Big Bang



Stars are responsible of destroing Hydrogen and producing “metals”.

Star formation



- Stars are formed from the contraction of molecular clouds due to their own gravity.
- Contraction increases temperature and eventually nuclear fusion reactions begin. A star is born.
- Contraction time depends on mass: 10 millions years for a star with the mass of the Sun; 100,000 years for a star 11 times the mass of the Sun.

The evolution of a Star is governed by gravity

The HR diagram

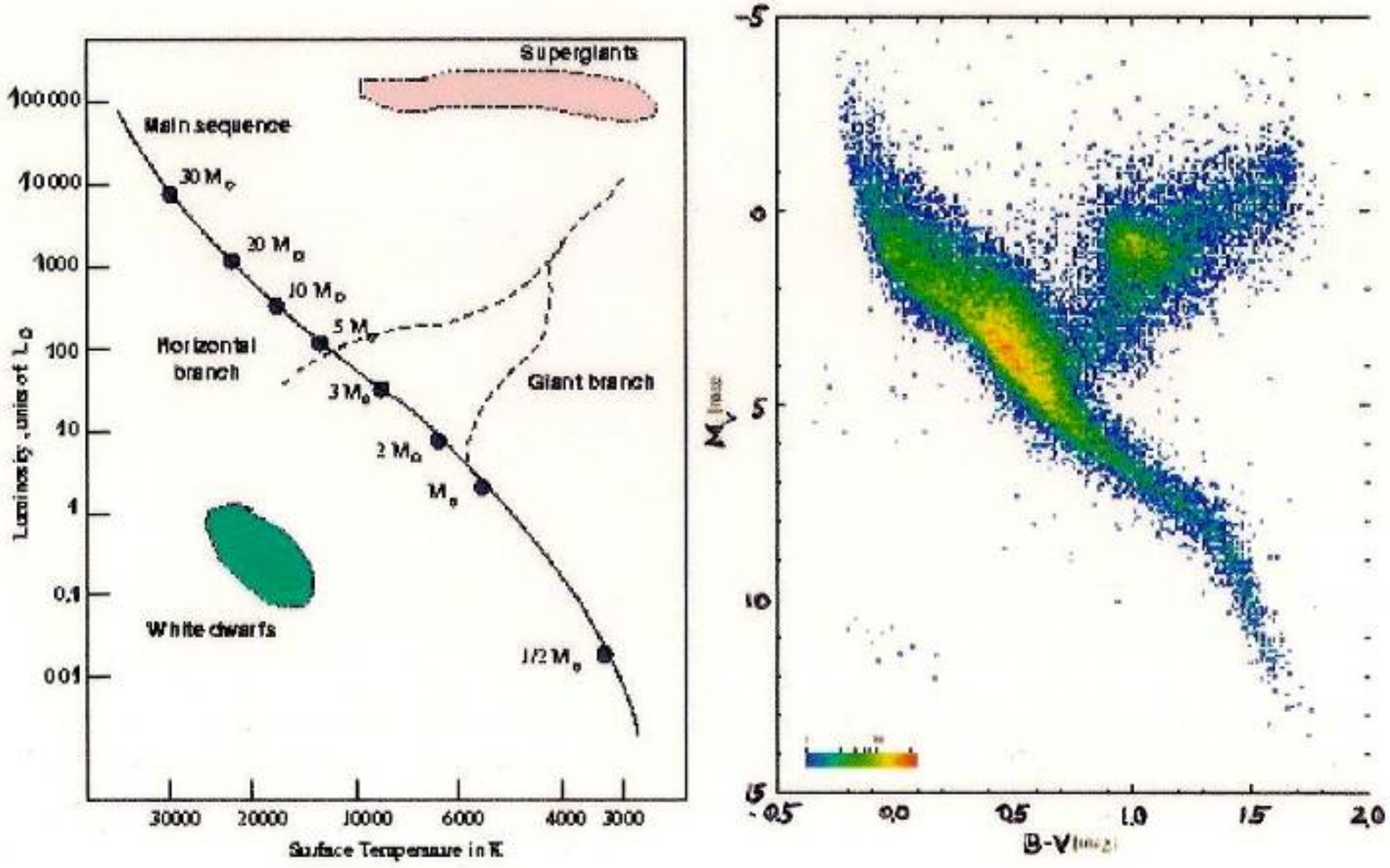
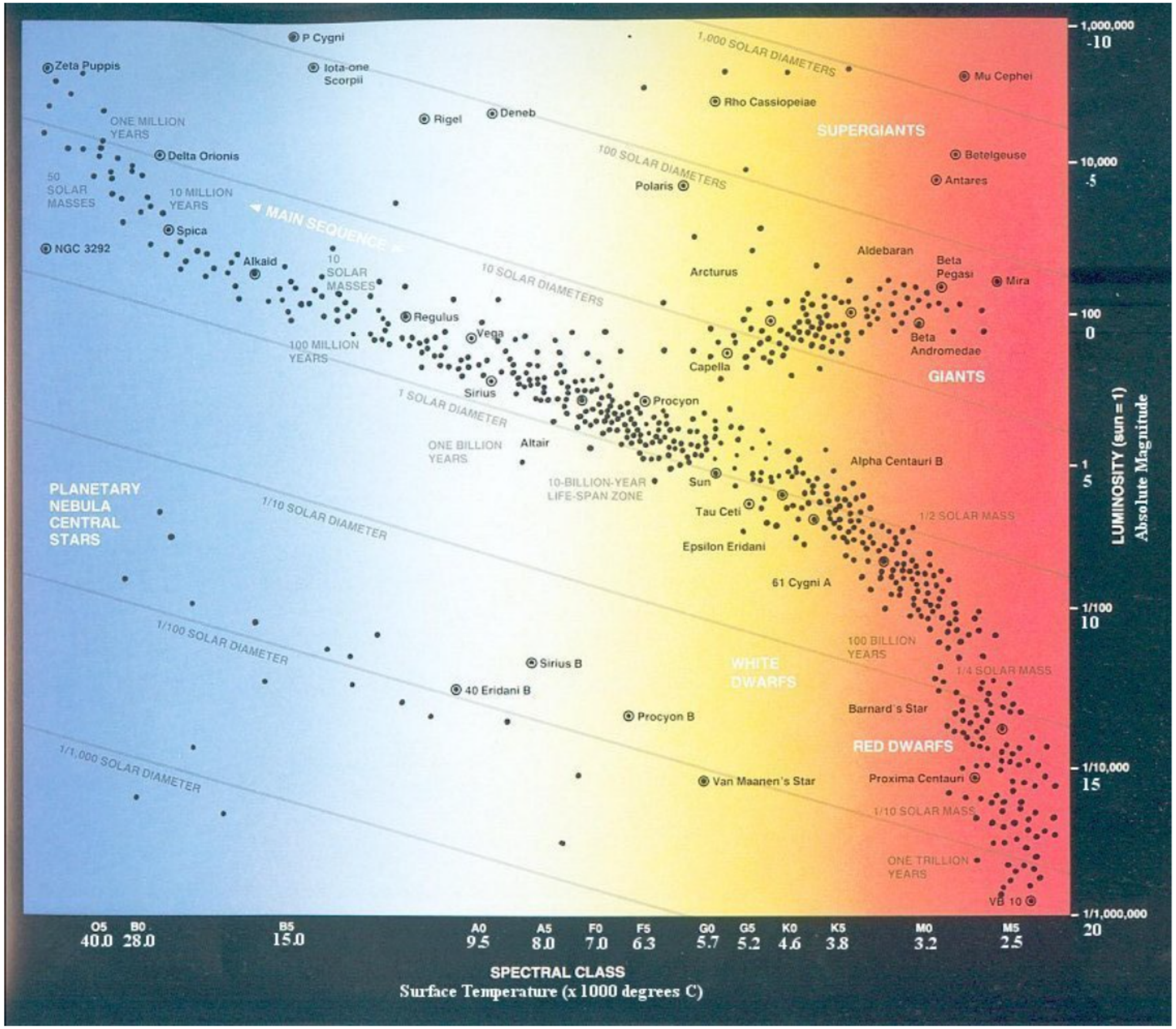
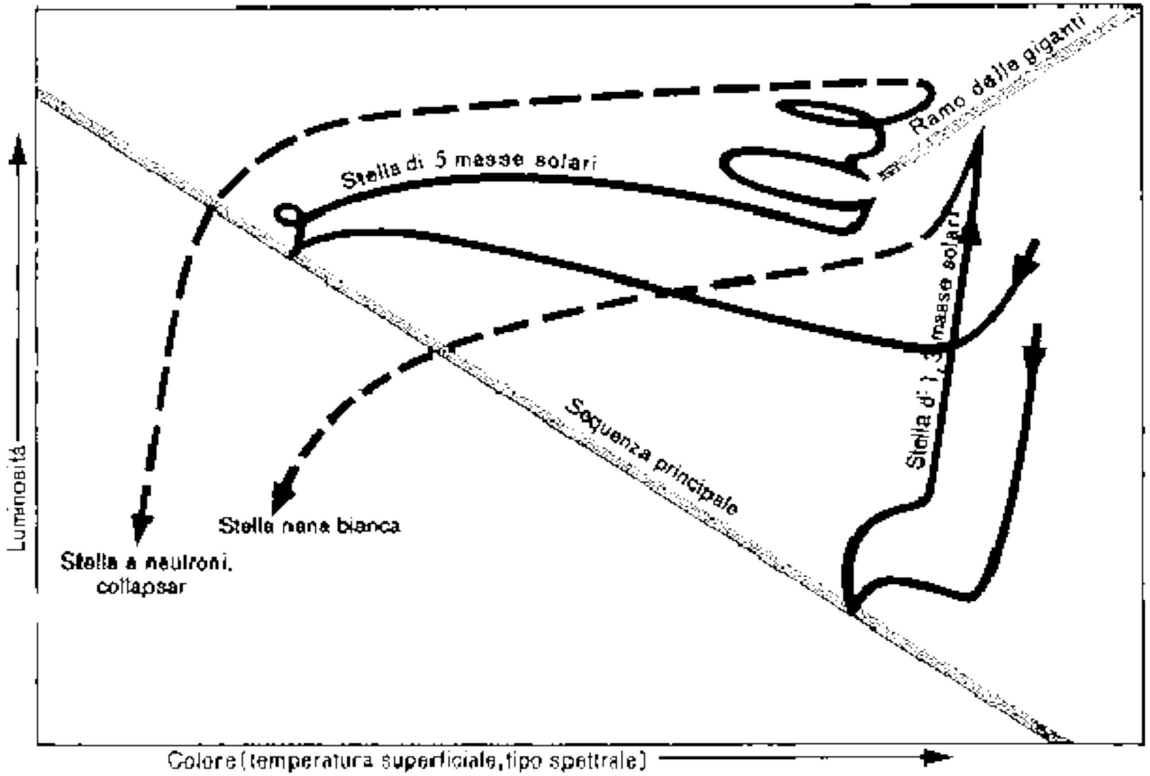


Figure 2.1: Left: a schematic representation of the H-R diagram (picture following [Lon94]). Notice how the mass itself distinguishes the different stars along the main sequence. Right: H-R diagram for 41704 single nearby stars determined from observations made by the *Hipparcos* astrometry satellite. Picture from [Gro99].

Hertzspung-Russell diagram

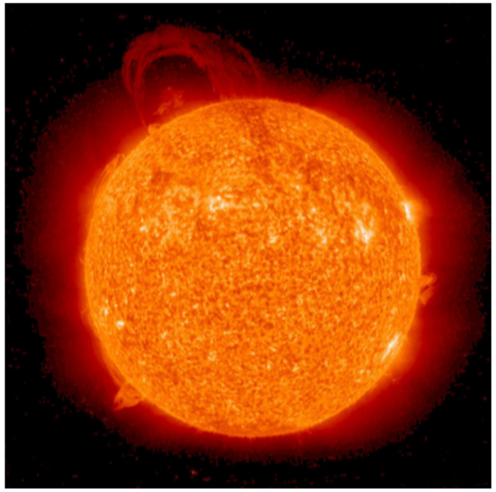


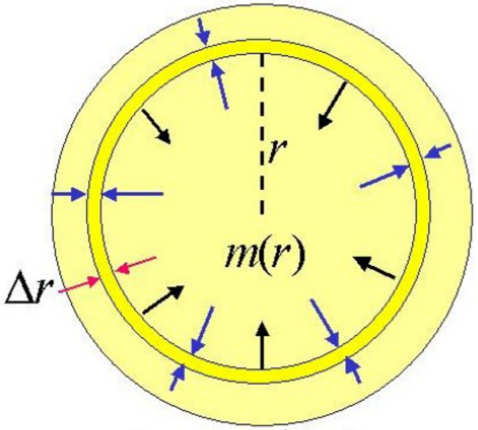
Stellar Evolution



HR diagram

What is a star?





$\Delta m = (A\Delta r)\rho$

- A star is a self-luminous gaseous sphere.
- Stars produce energy by nuclear fusion reactions. A star is a self-regulated nuclear reactor.
- Gravitational collapse is balanced by pressure gradient: hydrostatic equilibrium.

$$dF_{\text{grav}} = -G\frac{m\,dm}{r^2} = [P(r+dr) - P(r)]dA = dF_{\text{pres}}$$
$$dm = 4\pi r^2 \rho dr$$
$$-G\frac{m\rho}{r^2} = \frac{dP}{dr}$$

- Further equations needed to describe the transport of energy from the core to the surface, and the change of composition (nuclear reactions). Supplemented by an EoS: $P(\rho, T)$.

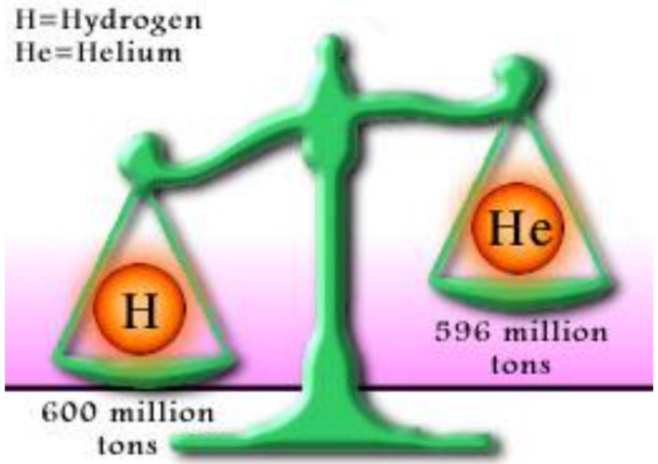
- Star evolution, lifetime and death depends on mass. Two groups
  - Stars with masses less than 9 solar masses (white dwarfs)
  - Stars with masses greater than 9 solar masses (supernova explosions)

Where does the energy come from?

Energy comes from nuclear reactions in the core.

$$4\,^1\mathrm{H} \rightarrow \,^4\mathrm{He} + 2e^+ + 2\nu_e + 26.7\ \mathrm{MeV}$$

$$E = mc^2$$



The Sun converts 600 million tons of hydrogen into 596 million tons of helium every second. The difference in mass is converted into energy. The Sun will continue burning hydrogen during 5 billions years.

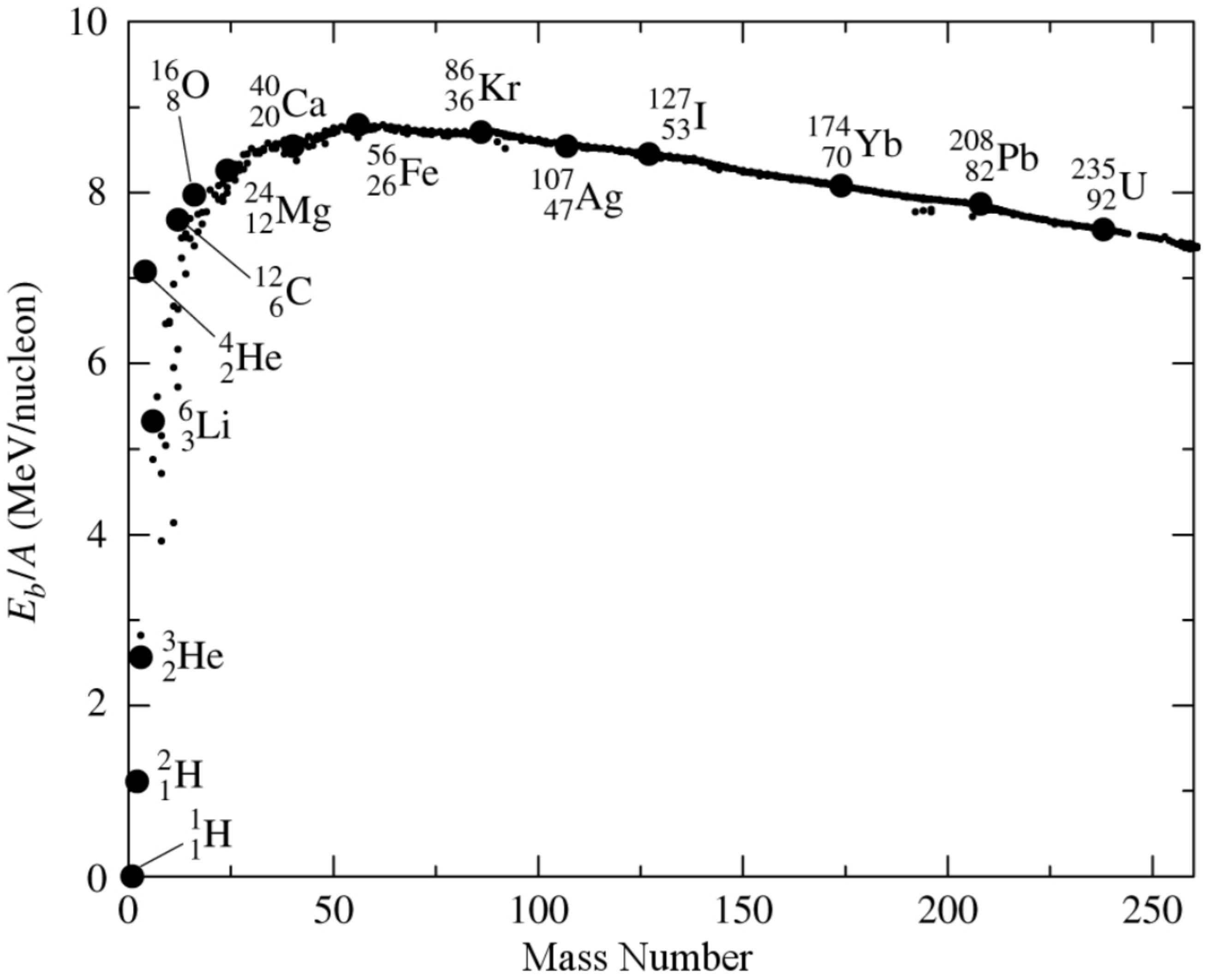
Energy released by H-burning:

6.45×10^{18} erg g^{-1} $= 6.7$ MeV/nuc

Solar Luminosity: 3.85×10^{33} erg s^{-1}

Nuclear Binding Energy

Liberated energy is due to the gain in nuclear binding energy.



Type of processes

Transfer (strong interaction)

$$^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}, \qquad \sigma \simeq 0.5\ \mathrm{b\ at}\ E_p = 2.0\ \mathrm{MeV}$$

Capture (electromagnetic interaction)

$$^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}, \qquad \sigma \simeq 10^{-6}\ \mathrm{b\ at}\ E_p = 2.0\ \mathrm{MeV}$$

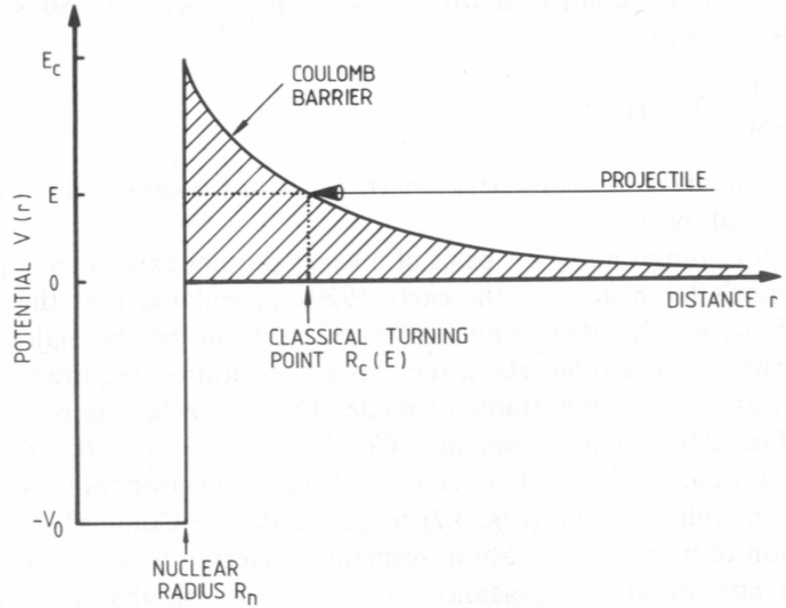
Weak (weak interaction)

$$p(p,e^{+}\nu)d, \qquad \sigma \simeq 10^{-20}\ \mathrm{b\ at}\ E_p = 2.0\ \mathrm{MeV}$$

$$\mathrm{b} = 100\ \mathrm{fm}^2 = 10^{-24}\ \mathrm{cm}^2$$

Charged-particle reactions

Stars' interior is a neutral plasma made of charged particles (nuclei and electrons). Nuclear reactions proceed by tunnel effect. For the $p + p$ reaction the Coulomb barrier is 550 keV, but the typical proton energy in the Sun is only 1.35 keV.



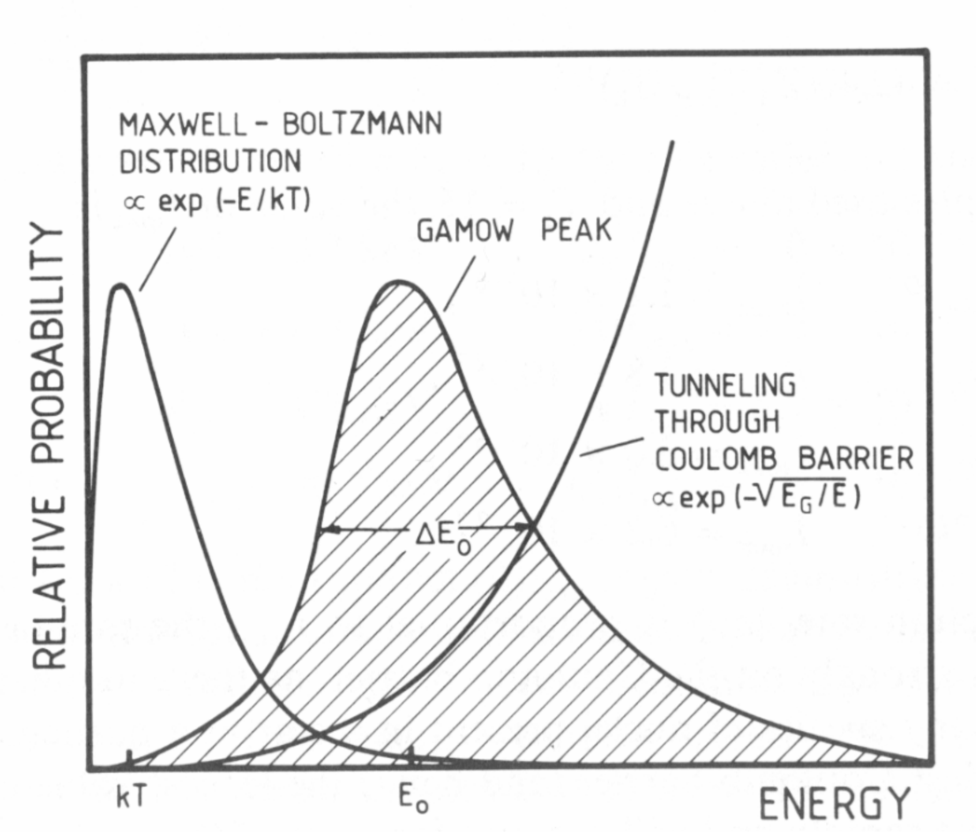
Cross section given by:

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E), \quad \eta = \frac{Z_1 Z_2 e^2}{\hbar} \sqrt{\frac{m}{2E}} = \frac{b}{E^{1/2}}$$

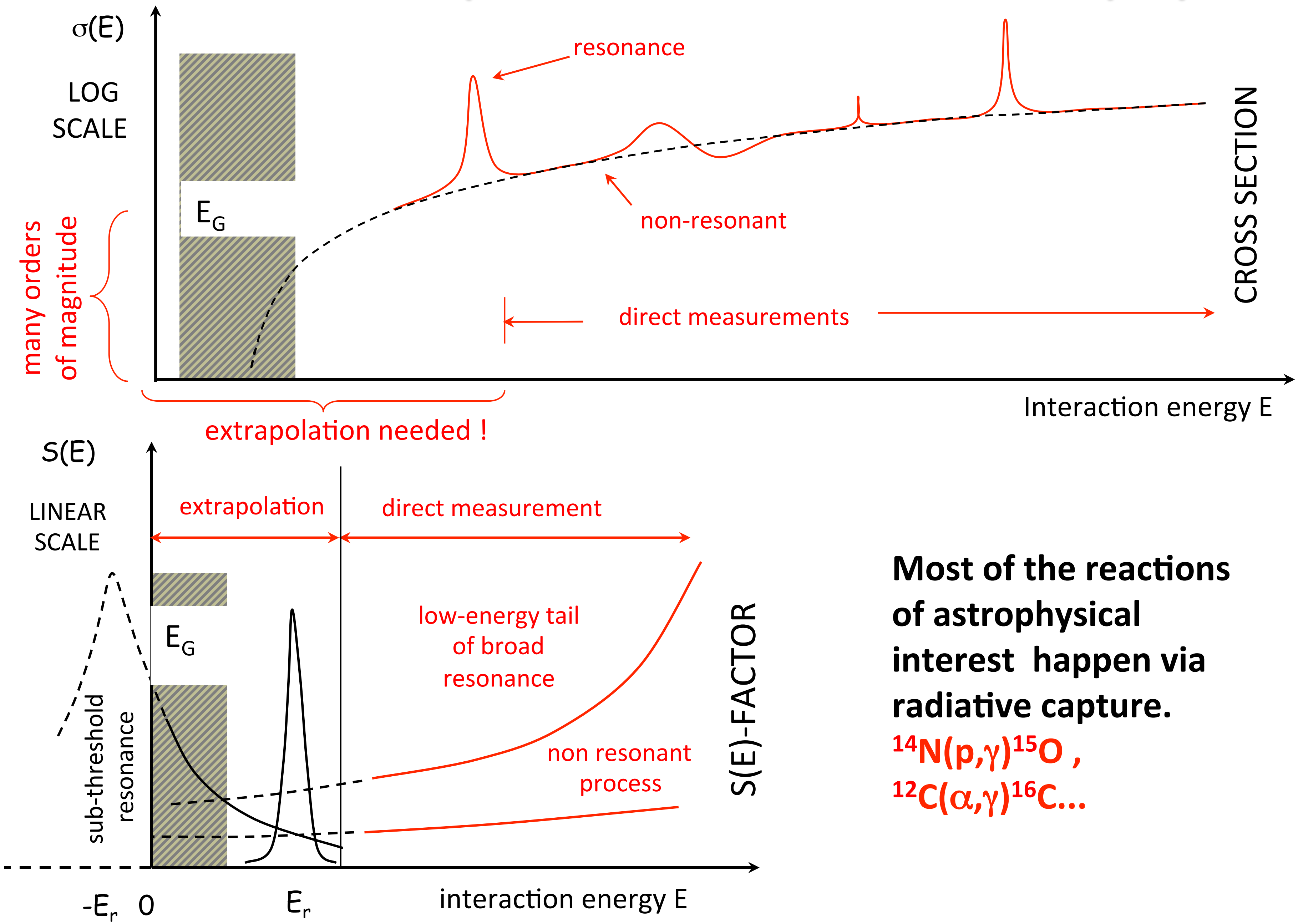
Gamow window

Using definition S factor:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi m} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}} \right] dE$$



Problem of extrapolation in nuclear astrophysics



Most of the reactions of astrophysical interest happen via radiative capture.

$^{14}N(p,\gamma)^{15}O$, $^{12}C(\alpha,\gamma)^{16}C$...

LUNA @ LNGS

LUNA - Laboratory for Underground Nuclear Astrophysics

Laboratori Nazionali del Gran Sasso

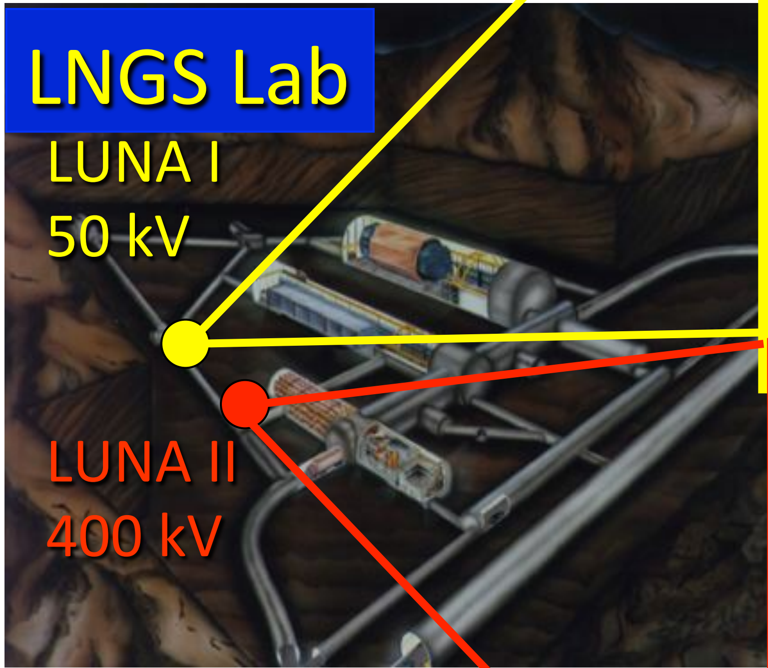
Welcome on the LUNA pages at LNGS

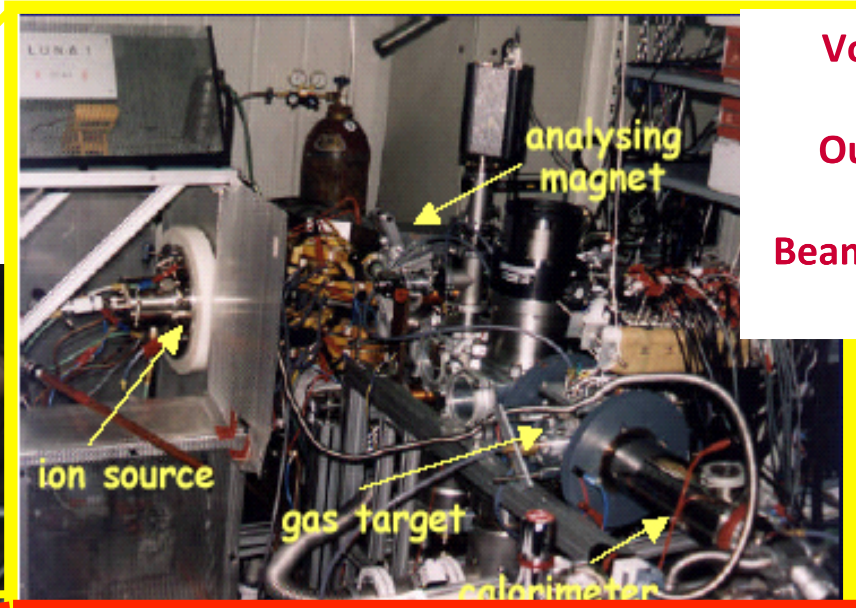
What is LUNA about

It is in the nature of astrophysics that many of the processes and objects one tries to understand are physically inaccessible. Thus, it is important that those aspects that can be studied in the laboratory be rather well understood. One such aspect are the nuclear fusion reactions, which are at the heart of nuclear astrophysics: they influence sensitively the nucleosynthesis of the elements in the earliest stages of the universe and in all the objects formed thereafter, and control the associated energy generation, neutrino luminosity, and evolution of stars. LUNA (*L*aboratory for *U*nderground *N*uclear *A*strophysics) is a new experimental approach for the study of nuclear fusion reactions based on an underground accelerator laboratory.
Since 20 years the LUNA Collaboration has been directly measuring cross sections of the Hydrogen burning in the underground laboratories of Laboratori Nazionali del Gran Sasso (LNGS) publishing more than 40 papers.

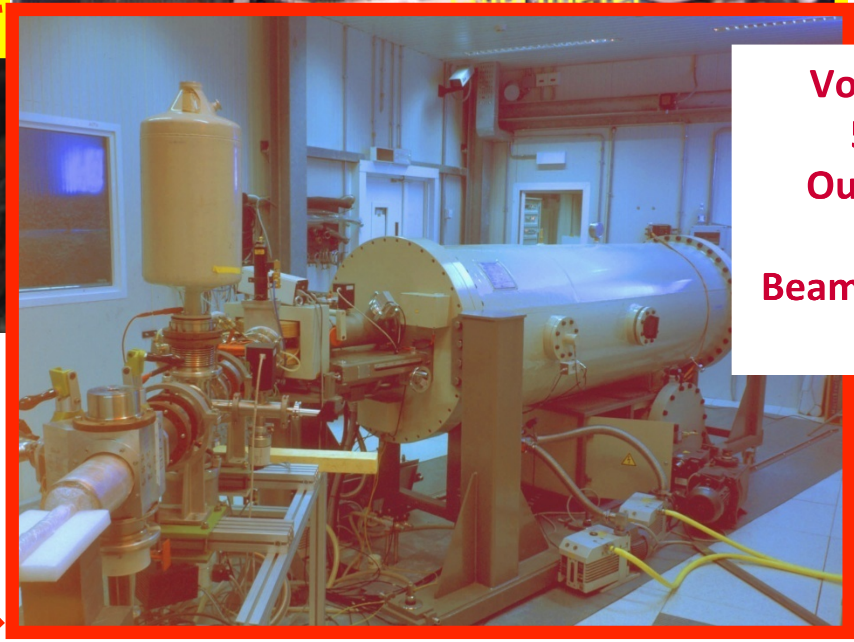
The present program of LUNA is descibed in the Proposal presented to the Scientific Commitee of LNGS in March 2007.

LUNA 1992-2012 - experimental set-ups





Voltage Range :
1 - 50 kV
Output Current:
1 mA
Beam energy spread:
20 eV



Voltage Range :
50 - 400 kV
Output Current:
500 μA
Beam energy spread:
70 eV

Hydrogen burning: ppI-chain

Step 1: $p + p \rightarrow {}^{2}\mathrm{He}$ (not possible)

$p + p \rightarrow d + e^{+} + \nu_e$

Step 2: $d + p \rightarrow {}^{3}\mathrm{He}$

$d + d \rightarrow {}^{4}\mathrm{He}$ (d abundance too low)

Step 3: ${}^{3}\mathrm{He} + p \rightarrow {}^{4}\mathrm{Li}$ (^{4}Li is unbound)

${}^{3}\mathrm{He} + d \rightarrow {}^{4}\mathrm{He} + n$ (d abundance too low)

${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2p$

$d + d$ not going because Y_d is small and $d + p$ leads to rapid destruction.
${}^{3}\mathrm{He} + {}^{3}\mathrm{He}$ goes because $Y_{3\mathrm{He}}$ gets large as nothing destroys it.

The relevant S-factors

$p(p, e^+\nu_e)d$: $S_{11}(0) = (4.00 \pm 0.05) \times 10^{25}$ MeV b
calculated

$p(d,\gamma)^3$He: $S_{12}(0) = 2.5 \times 10^{-7}$ MeV b
measured at LUNA

^{3}He(^{3}He, $2p$)^{4}He: $S_{33}(0) = 5.4$ MeV b
measured at LUNA

Laboratory Underground for Nuclear Astrophysics (Gran Sasso).

LUNA program: pp chain

$p + p \rightarrow {}^2H + e^+ + \nu$ [0.27 MeV] — 99.75%

$p + e^- + p \rightarrow {}^2H + \nu$ [1.44 MeV] — 0.25%

$^2H + p \rightarrow {}^3He + \gamma$

50 kV 2001

86% | 14% | $2 \cdot 10^{-5}$%

$^3He + {}^3He \rightarrow {}^4He + 2p$

50 kV 1999

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

400 kV 2006

$^3He + p \rightarrow {}^4He + e^+ + \nu$

99.89% | 0.11%

$^7Be + e^- \rightarrow {}^7Li + \nu$ [0.81 MeV]

$^7Be + p \rightarrow {}^8B + \gamma$

$^7Li + p \rightarrow {}^8Be$

$^8B \rightarrow {}^8Be + e^+ + \nu$ [6.80 MeV]

$^8Be \rightarrow 2\,{}^4He$

$^8Be \rightarrow 2\,{}^4He$

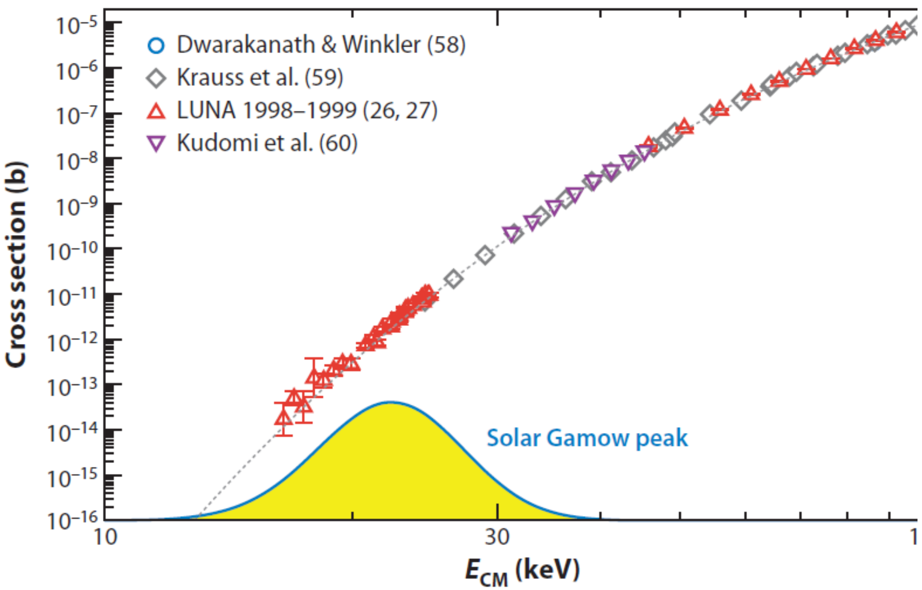
CHAIN I Q_{eff} = 26.20 MeV	CHAIN II Q_{eff} = 25.66 MeV	CHAIN III Q_{eff} = 19.67 MeV	CHAIN IV Q_{eff} = 16.84 MeV

LUNA (**L**aboratory **U**nderground for **N**uclear **A**strophysics)

50 kV accelerator @ Gran Sasso – Italy (1400 m rock -> 10^6 shielding factor)

$^3He(^3He,2p)^4He$

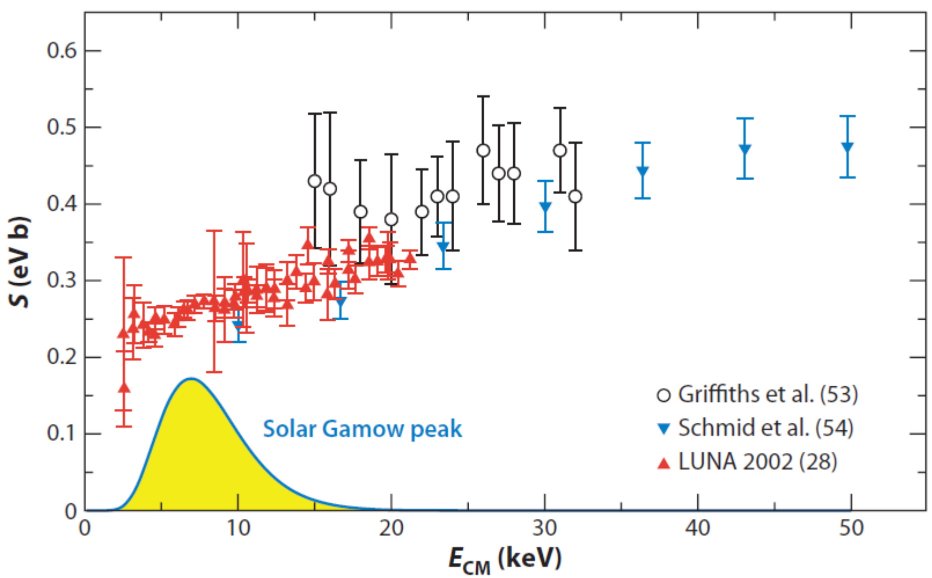
R. Bonetti et al.: Phys. Rev. Lett. 82 (1999) 5205



At lowest energy: σ ~ 20 fb → 1 event/month

$d(p,\gamma)^3He$

C. Casella et al.: Nucl. Phys. A706 (2002) 203-216

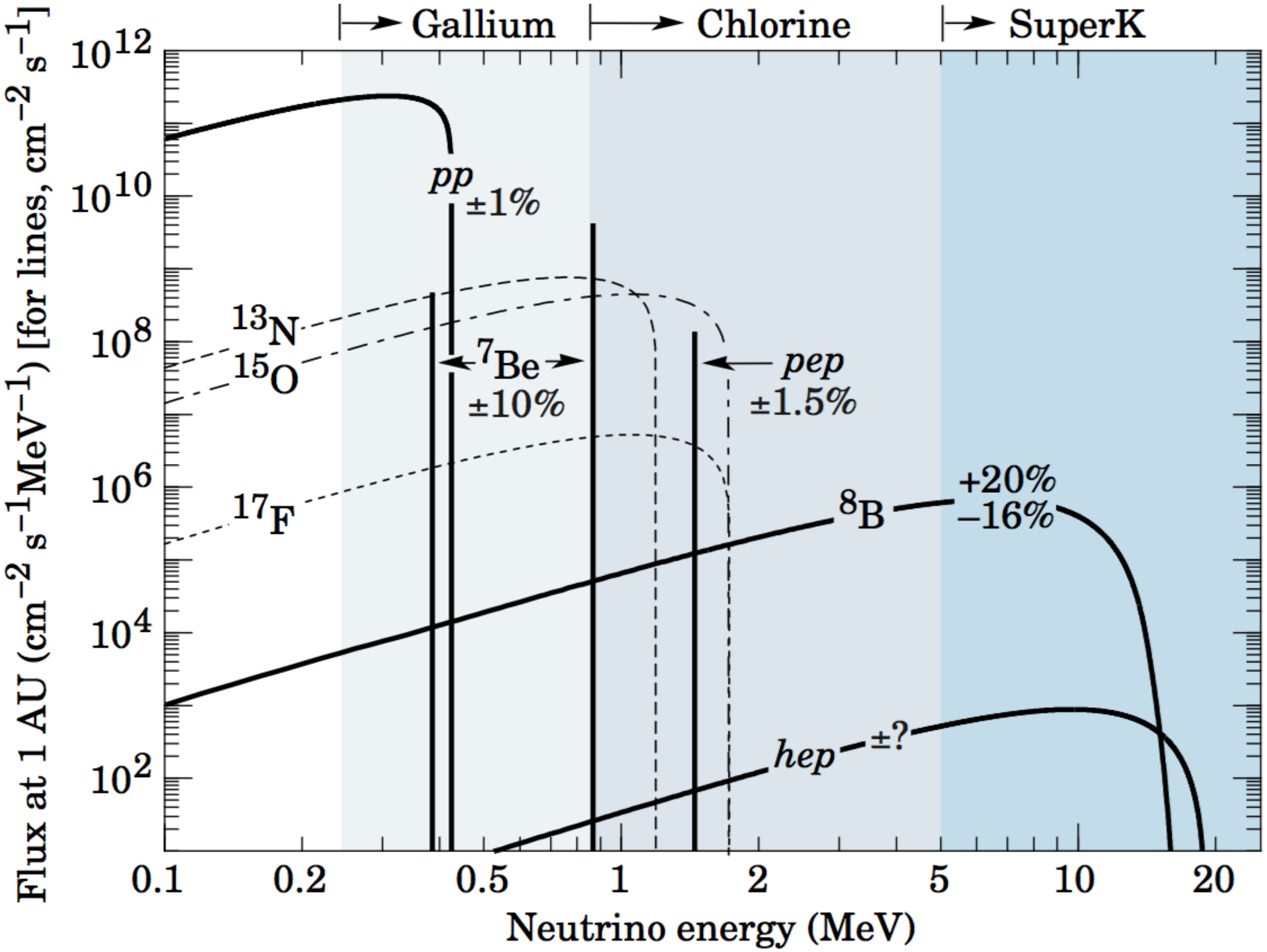


At lowest energy: σ ~ 9 pb → 50 counts/day

No *extrapolation* needed!

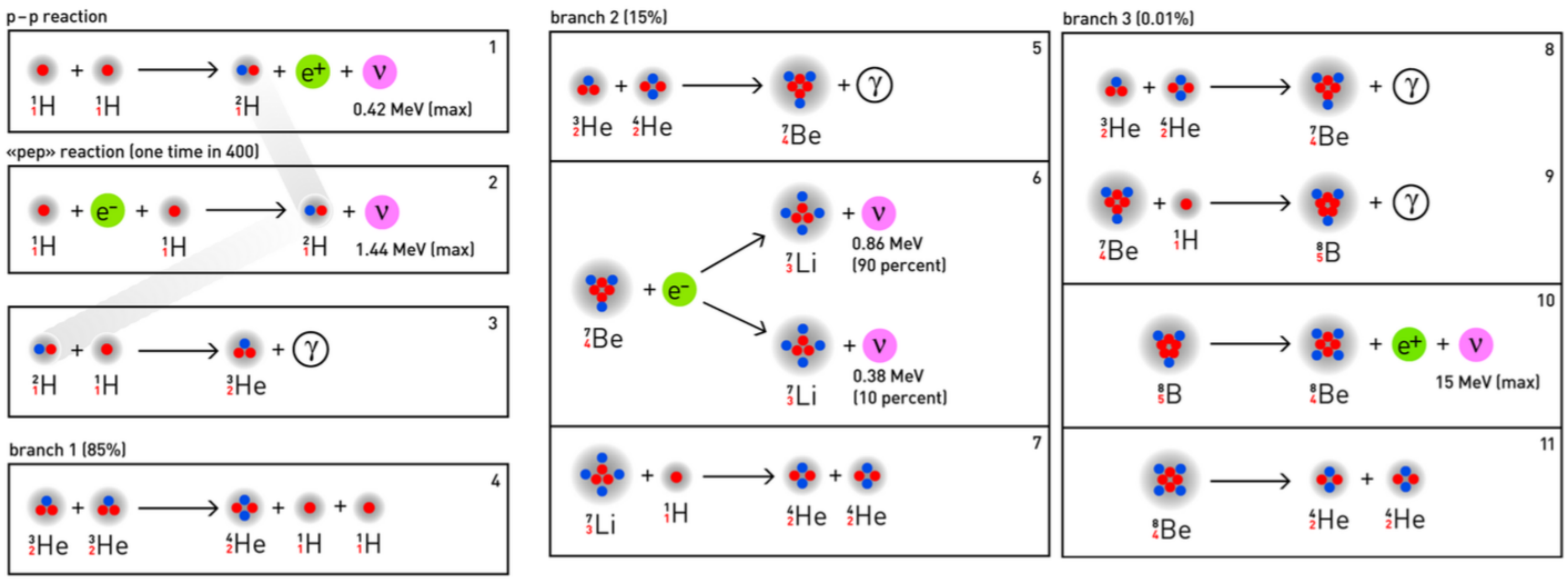
Neutrino spectrum (Sun)

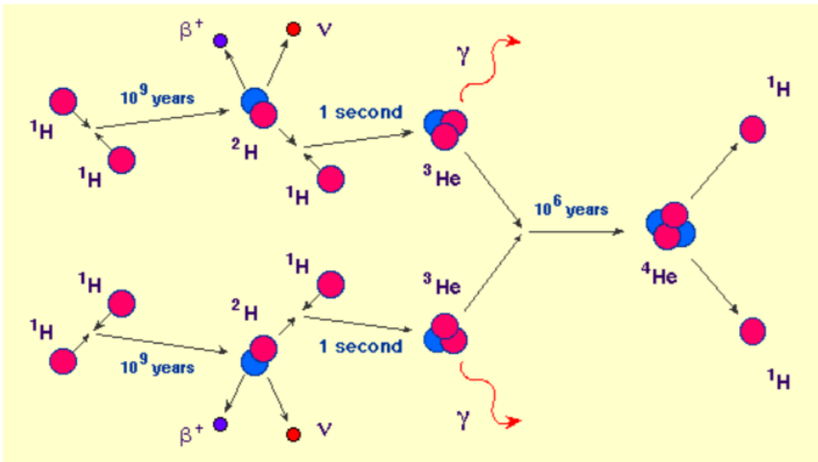
This is the predicted neutrino spectrum



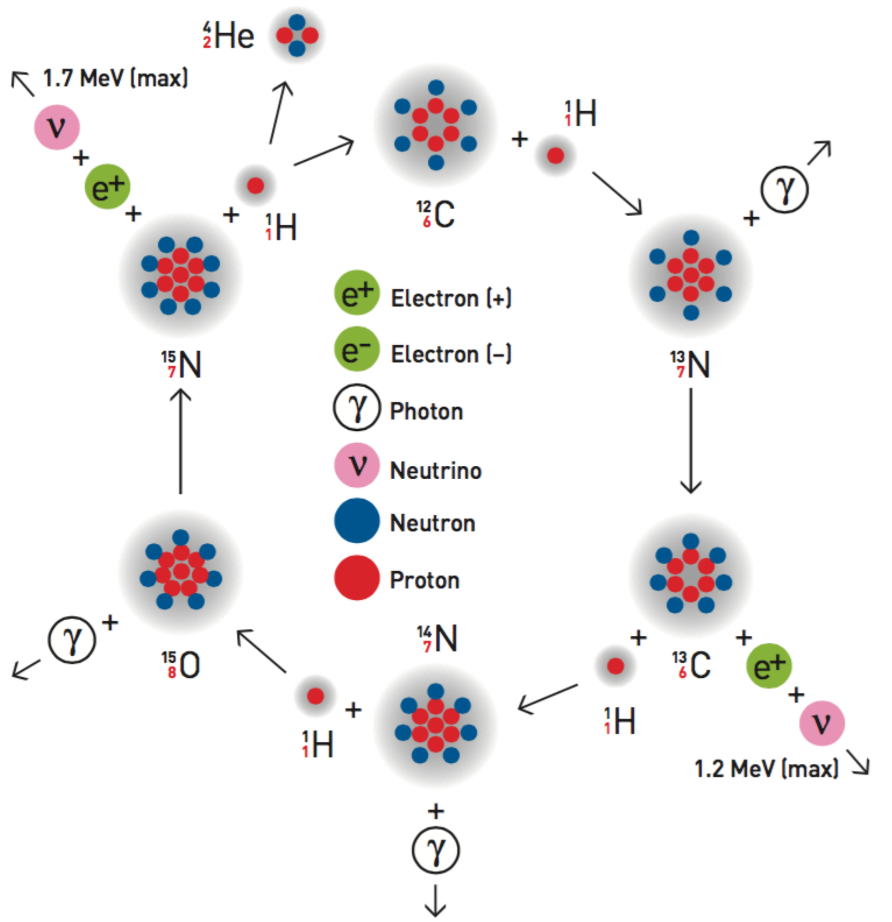
pp chains

Once ^{4}He is produced can act as catalyst initializing the ppII and ppIII chains.



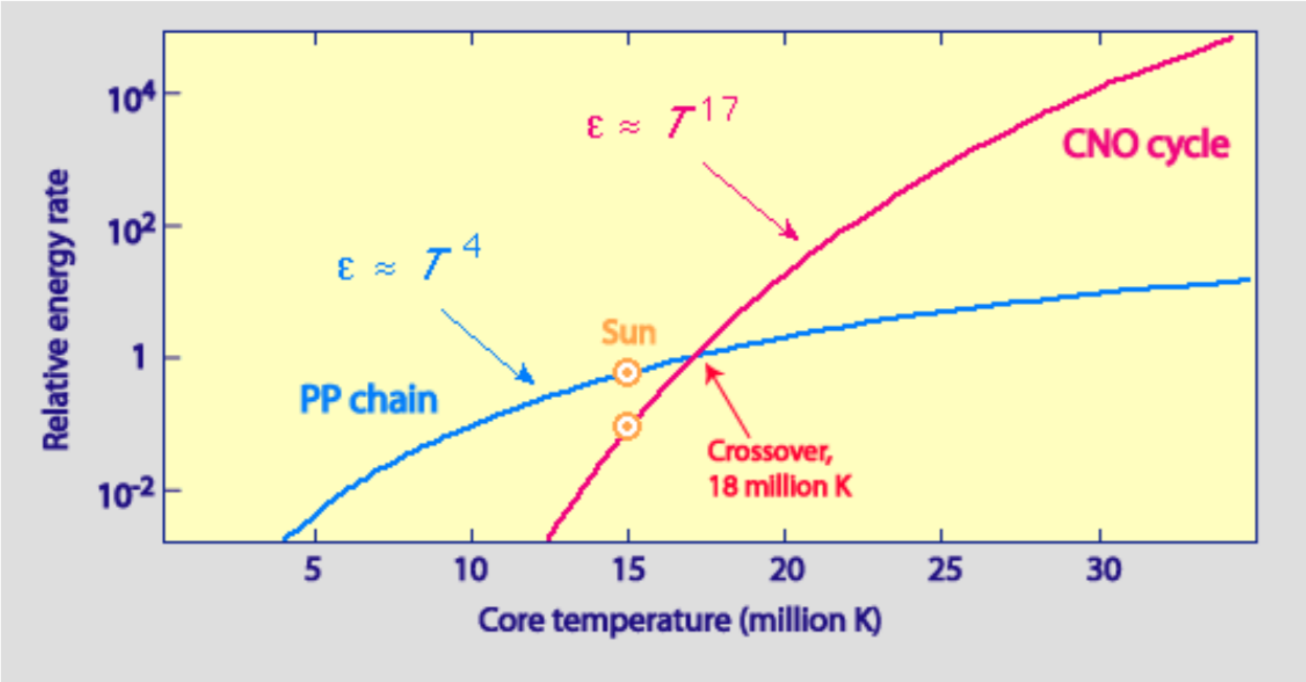


The other hydrogen burning: CNO cycle



requires presence of ^{12}C as catalyst.

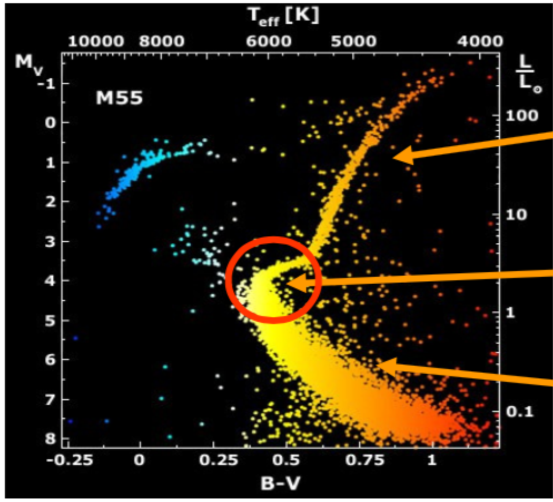
Energy generation: CNO cycle vs pp-chains



Consequences

- Stars slightly heavier than the Sun burn hydrogen via CNO cycle.
- CNO cycle goes significantly faster. Such stars have much shorter lifetimes

Mass ($M_\odot$)	lifetime (yr)
0.8	1.4×10^{10}
1.0	1×10^{10}
1.7	2.7×10^{9}
3.0	2.2×10^{8}
5.0	6×10^{7}
9.0	2×10^{7}
16.0	1×10^{7}
25.0	7×10^{6}
40.0	1×10^{6}



High-mass stars evolved onto the giant branch

Turn-off point

Low-mass stars still on the main sequence