Astrofisica Nucleare e Subnucleare
MeV Astrophysics - 3

Nucleosynthesis

Basic Understanding of SNe Ia

What we know…:

• WD in binary system accretes hydrogen

• when Chandrasekhar mass is reached, WD collapses, explosively ignites Carbon, and is destroyed completely

• SNe Ia are very good *standard* candles: same maximum luminosity

• Powered by the decay of $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$

$\sim 0.6\ M_{sun} = 10^{43}$ erg/s at peak

this explains the light curves (temporal evolution of photometry)

• produces velocities ~ 0.1c

• Lack H/He, show strong intermediate mass and iron peak elements

• They occur in all types of galaxies

…and what we don't:

•Evolution with redshift

•Asphericities

Radioisotope Gamma-Ray Lines and their Messages

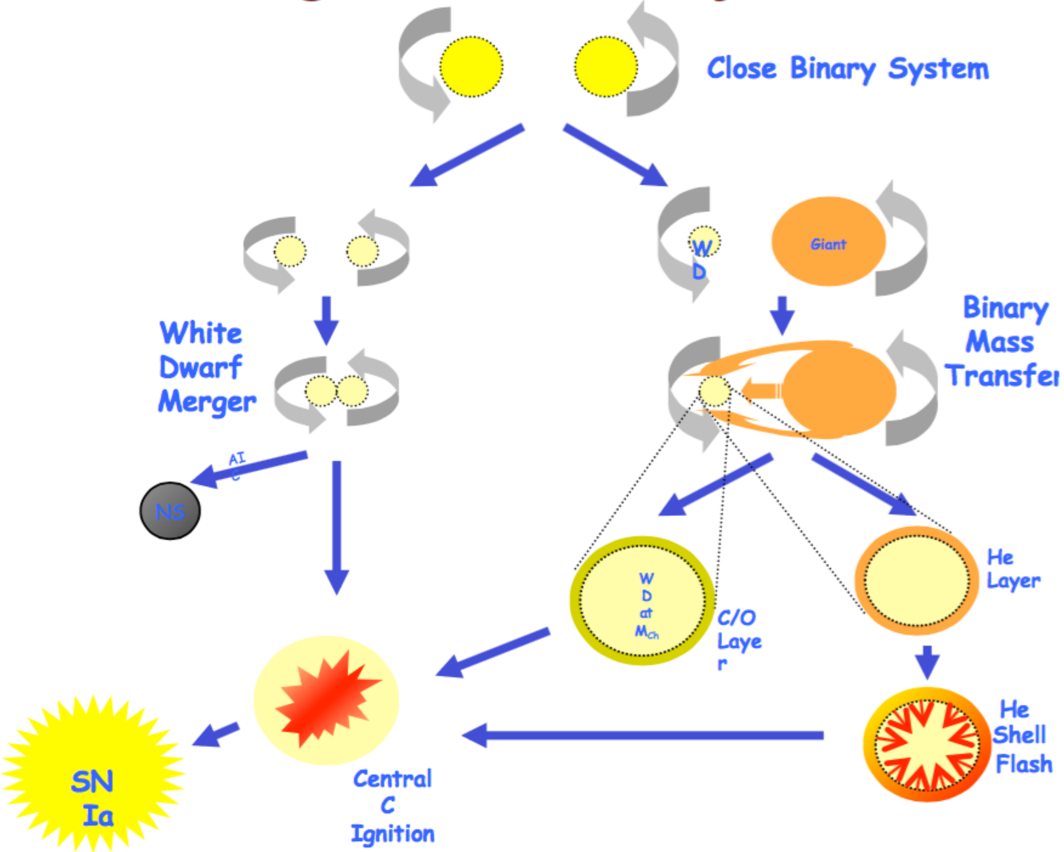
Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	^{7}Be $\rightarrow$ ^{7}Li*	478
^{56}Ni	111 d	^{56}Ni $\rightarrow$ ^{56}Co* $\rightarrow$ ^{56}Fe*+e^{+}	158, 812; 847, 1238
^{57}Ni	390 d	^{57}Co$\rightarrow$ ^{57}Fe*	122
^{22}Na	3.8 y	^{22}Na $\rightarrow$ ^{22}Ne* + e^{+}	1275
^{44}Ti	89 y	^{44}Ti$\rightarrow$^{44}Sc*$\rightarrow$^{44}Ca*+e^{+}	78, 68; 1157
^{26}Al	1.04 10^{6}y	^{26}Al $\rightarrow$ ^{26}Mg* + e^{+}	1809
^{60}Fe	3.8 10^{6}y	^{60}Fe $\rightarrow$ ^{60}Co* $\rightarrow$ ^{60}Ni*	59, 1173, 1332
e^{+}	.... 10^{5}y	e^{+}+e^{-} $\rightarrow$ Ps $\rightarrow$ $\gamma\gamma$..	511, <511

individual object/event (^{7}Be to ^{44}Ti)

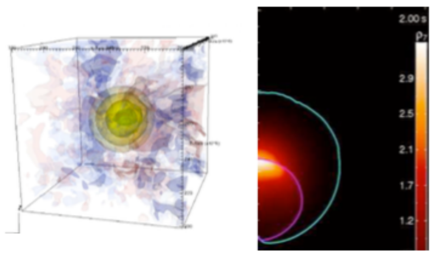
cumulative from many events (^{26}Al to e^{+})

- # SNIa Diversity

☞ Progenitor Diversity?



☆ Ignition Physics?



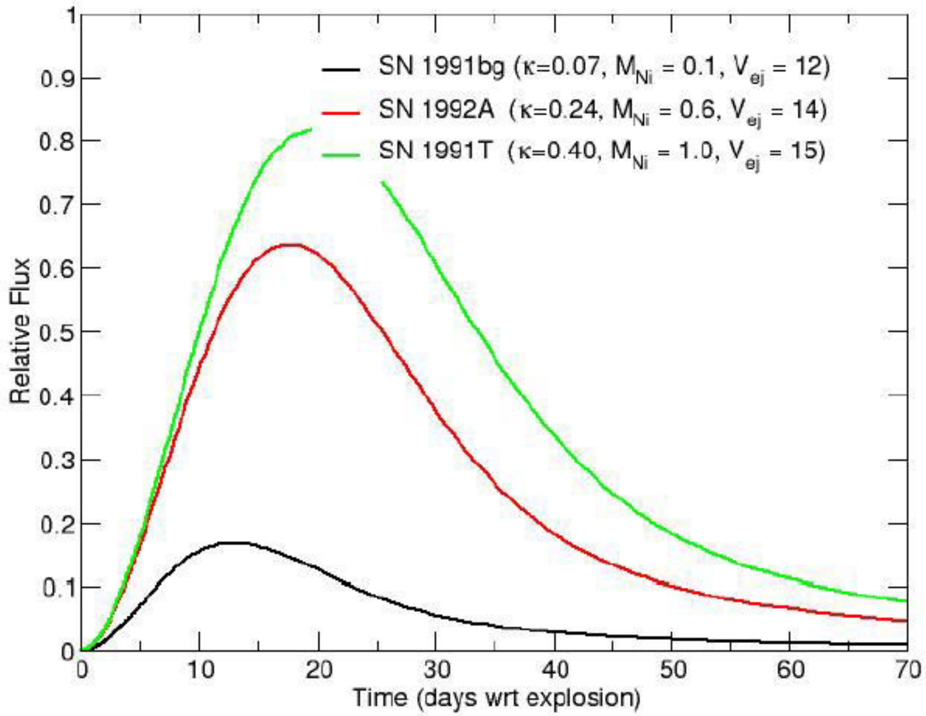
Nucleosynthesis

Modeling the SNe Ia

Simple relationship: More ^{56}Ni → Higher Temperatures → Higher Opacities

= Brighter/Broader SNe Ia

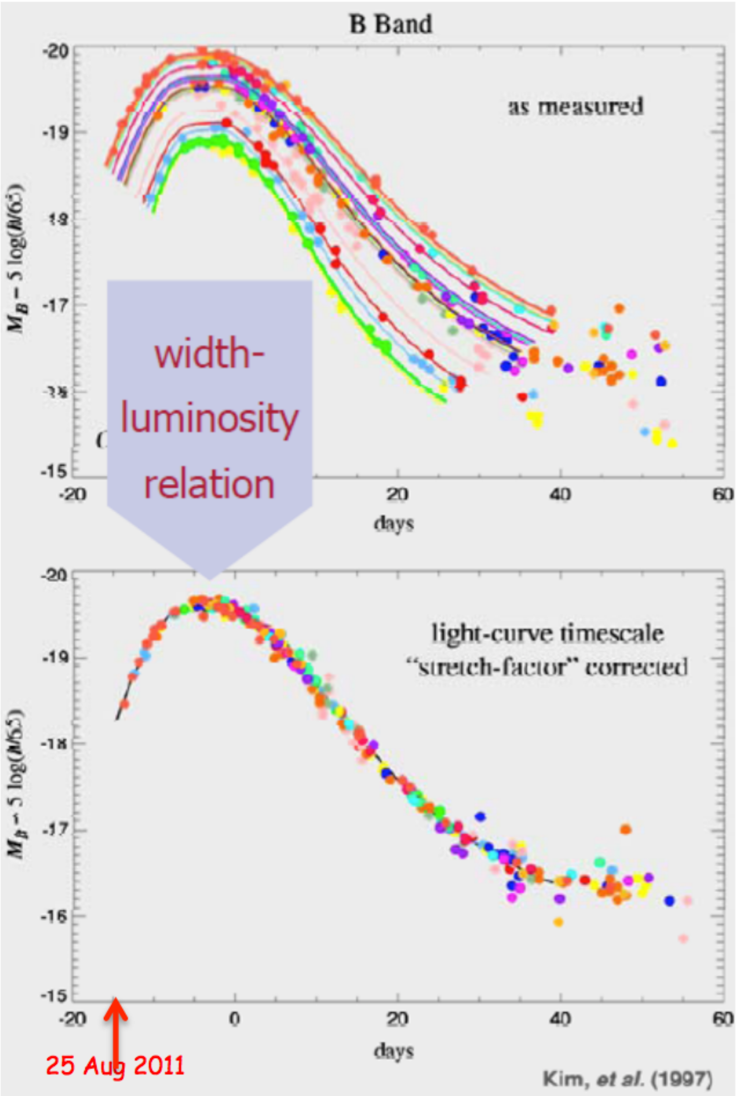
The higher opacities allow to trap the radiation more effectively and release it later making for broader light curves.

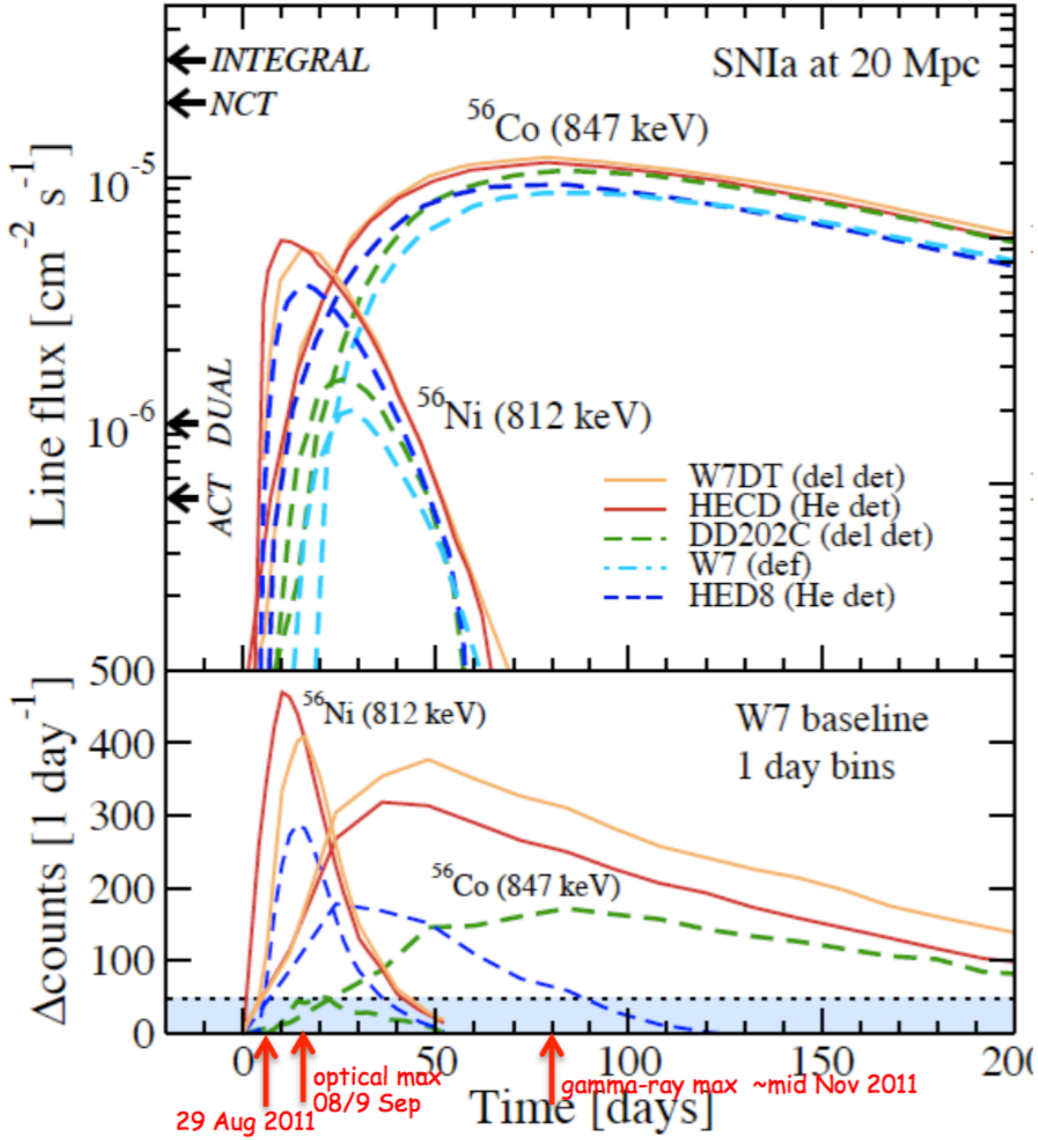


Parameters for modelling SN Ia light curve:

- ^{56}Ni mass
- Opacity
- Kinetic Energy

SNIa Models and Radioacivity Gamma-Rays

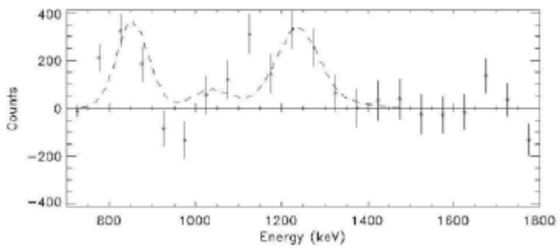




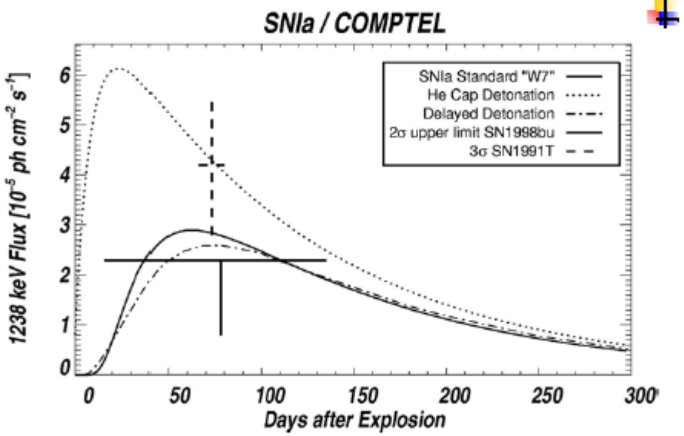
- **SN 2011fe in M101 is a Chance to Gamma-Calibrate SNIa Models** **(d~6.4 Mpc)**
  - ☆ **Phillips Relation, Light Transport Codes from Gamma to X/UV/OPT/IR**

Nucleosynthesis

Gamma-Rays from Supernovae Ia



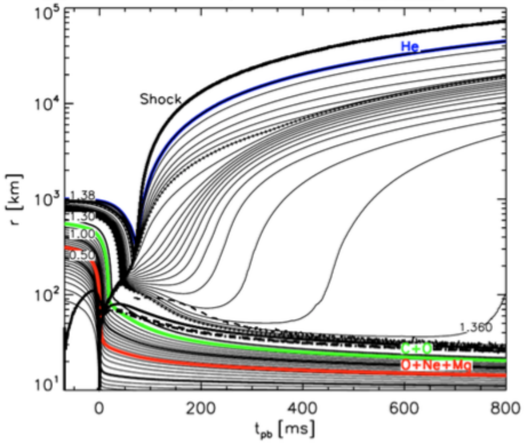
- Rarely SNIa ^{56}Ni Decay Gamma-Rays are Above Instrumental Limits ($\sim 10^{-5}$ ph cm^{-2} s^{-1})
  - ~2 Events / 9 Years CGRO
  - ~1 Event / Year INTEGRAL Mission?

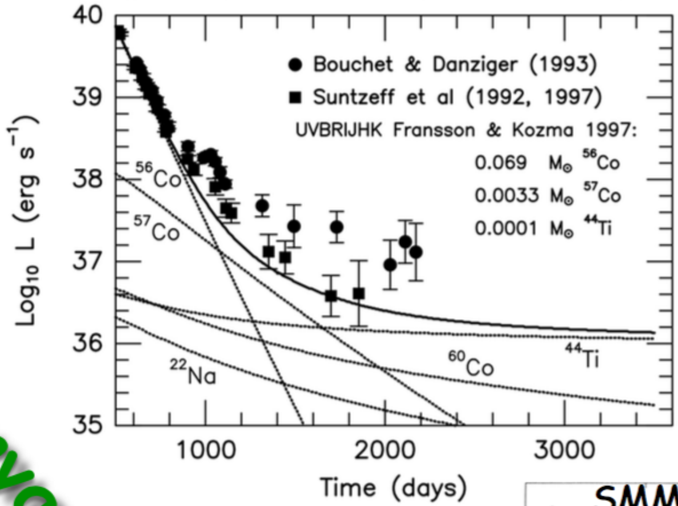


- COMPTEL
  - Signal from SN1991T (3σ) (13 Mpc)
  - Upper Limit for SN1998bu (11 Mpc)

- The ^{56}Ni Power Source: 0.5 M_o of ^{56}Ni ??
- Which Burning Profile and Mixing ?

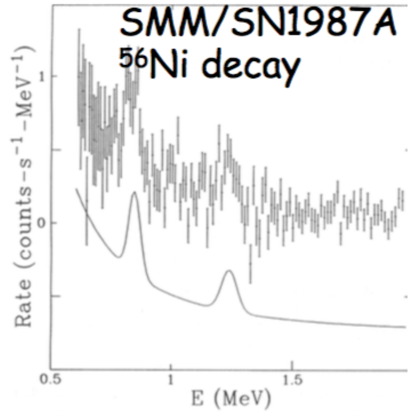
- **Nuclear Energy Conversions +...**
  - ☆ **Dynamics of Explosions**
  - ☆ **Structure of Stars**

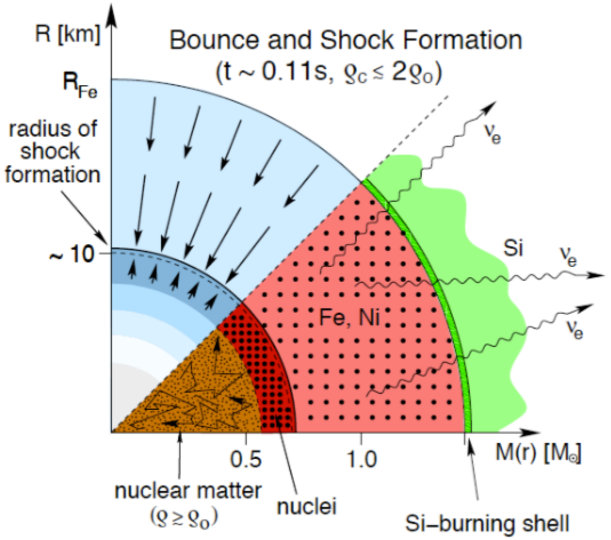


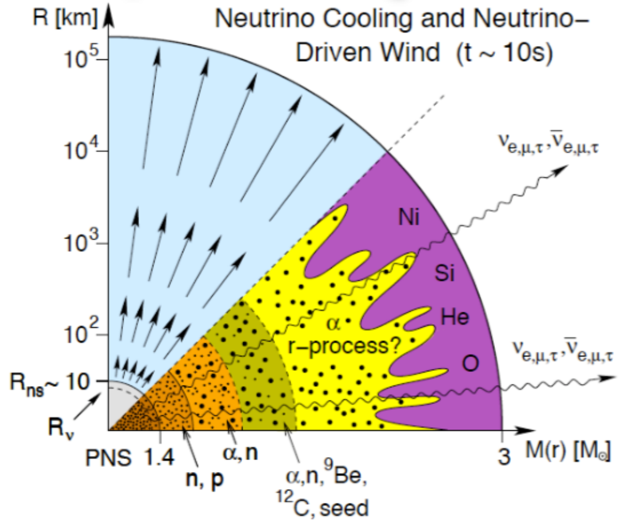


Models

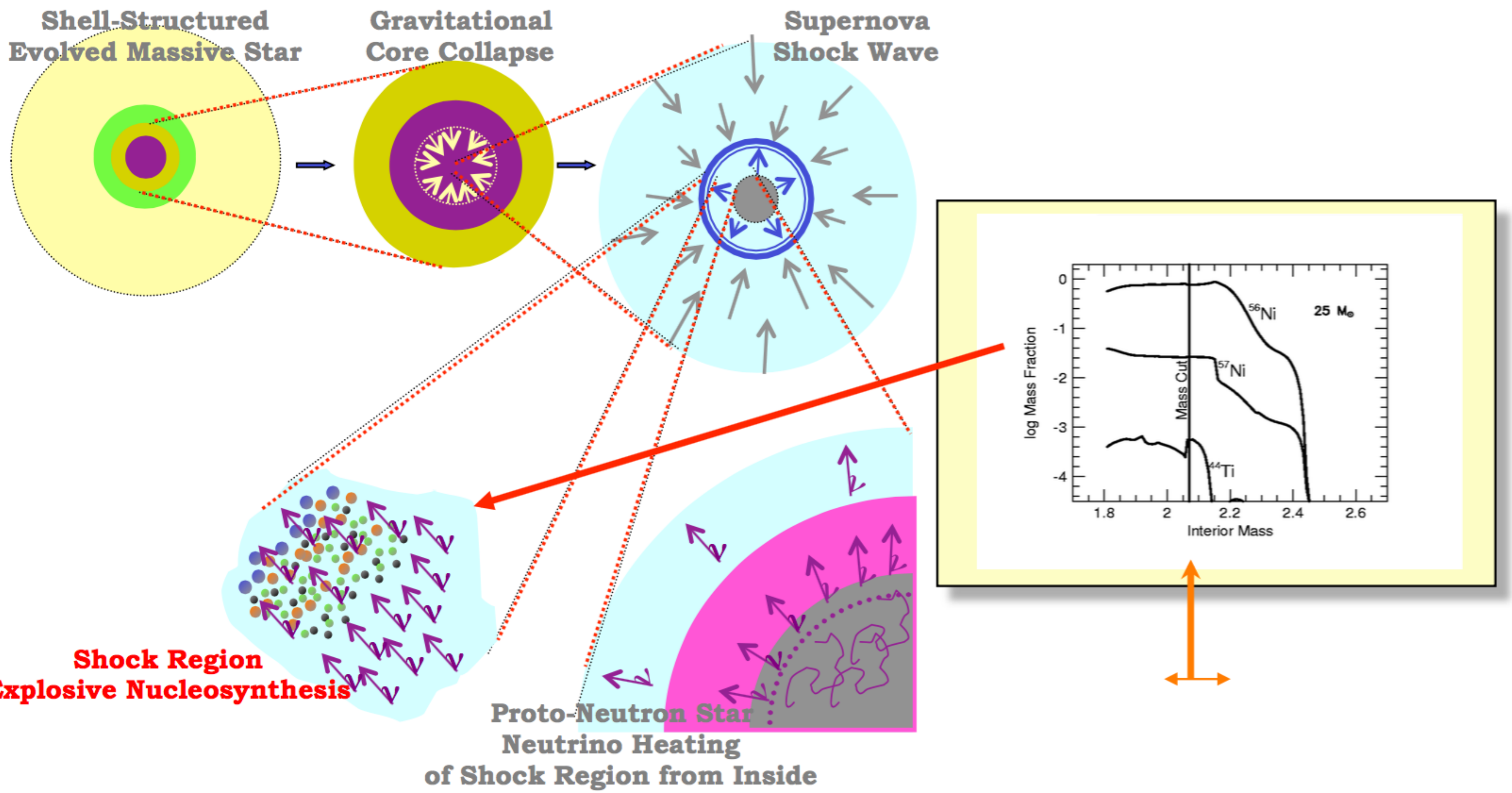
Observations







Nucleosynthesis in CC-Supernova Models and ^{44}Ti



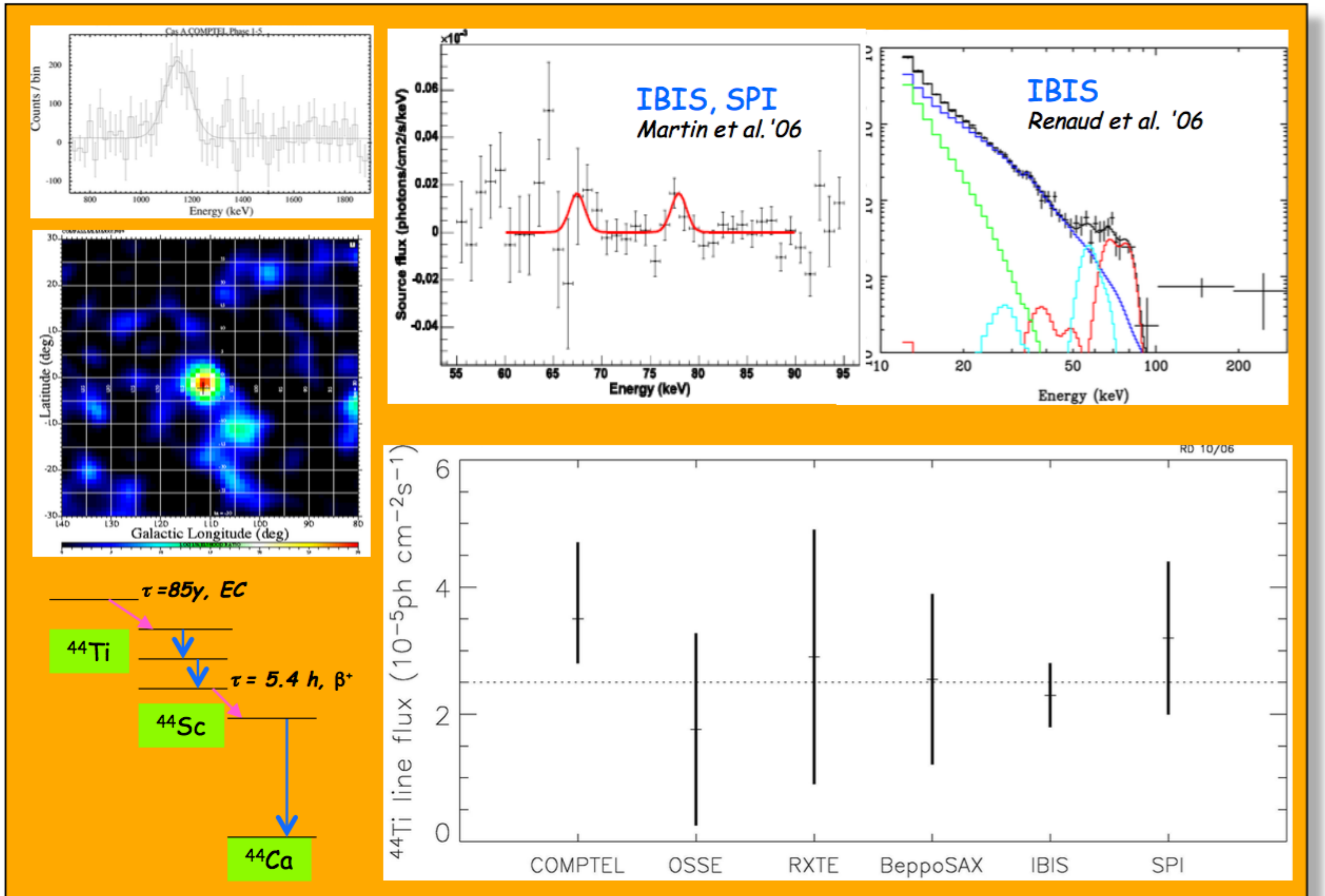
- ^{44}Ti Produced at r < 10^3 km from α-rich Freeze-Out,

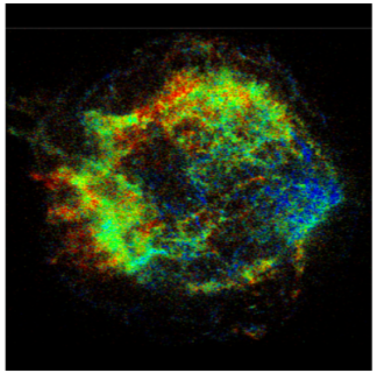
  => Unique Probe (+Ni Isotopes)

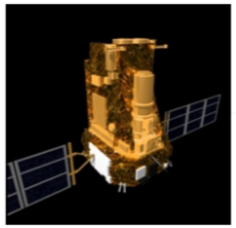
^{44}Ti γ-rays from Cas A

τ=85y (Ahmad et al. 2006)

89 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68; 1157

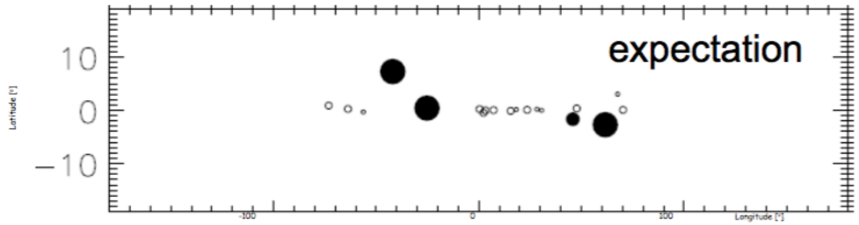


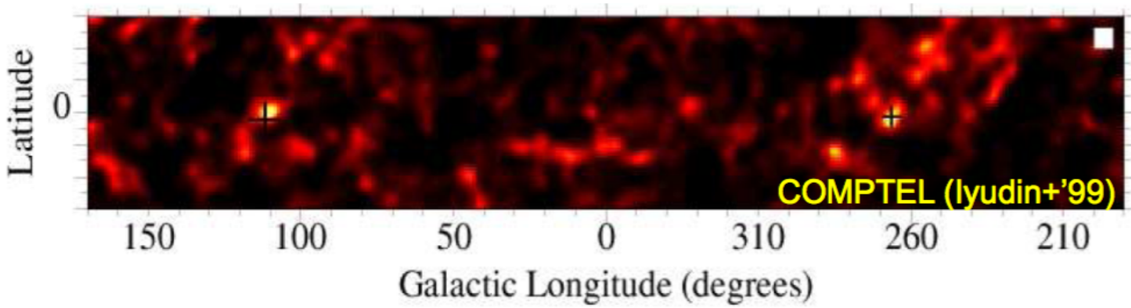




⇘ **^{44}Ti Ejected Mass** **~0.8-2.5 10^{-4} $M_{\odot}$**

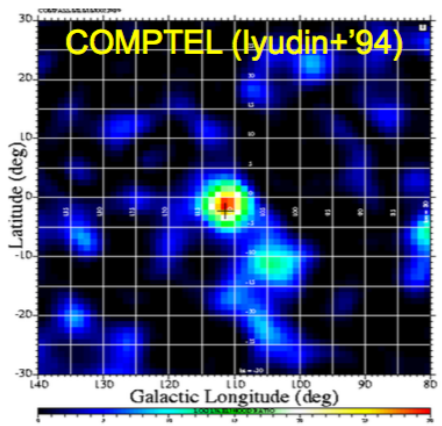
Are Core Collapse Supernovae ^{44}Ti Sources?

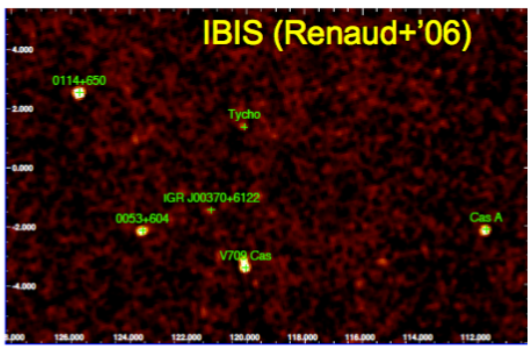




- ☆ Sky Regions with Most Massive Stars are ^{44}Ti Source-Free (COMPTEL, INTEGRAL)

- ☆ Cas A is the ONLY Source Seen in our Galaxy



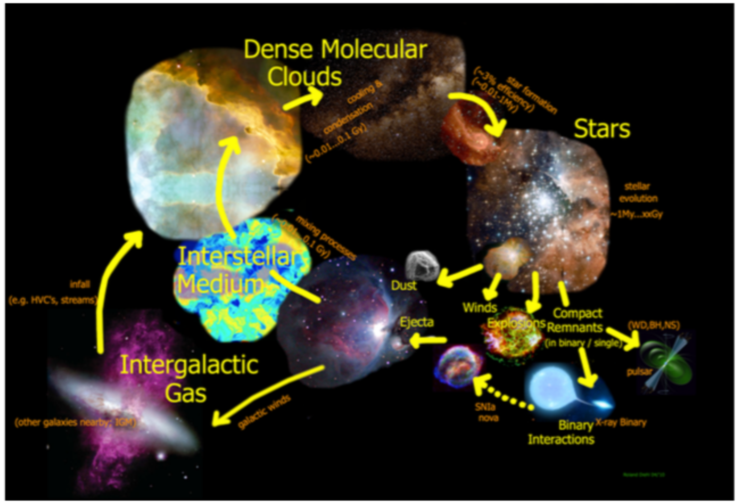


- ☆ ***^{44}Ti is from Rare Events??***

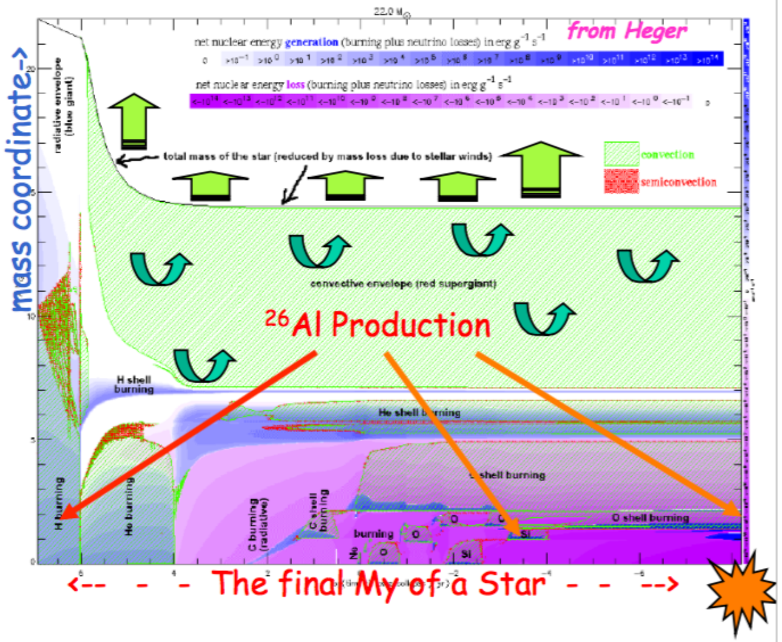
⇨ *The et al. 2006*

Massive-Star Interiors

- ☆ **Massive Stars are:**
  - ☞ **Key Producers of Cosmic 'Metals'**
  - ☞ **Key Agents for Cosmic Evolution in Galaxies**

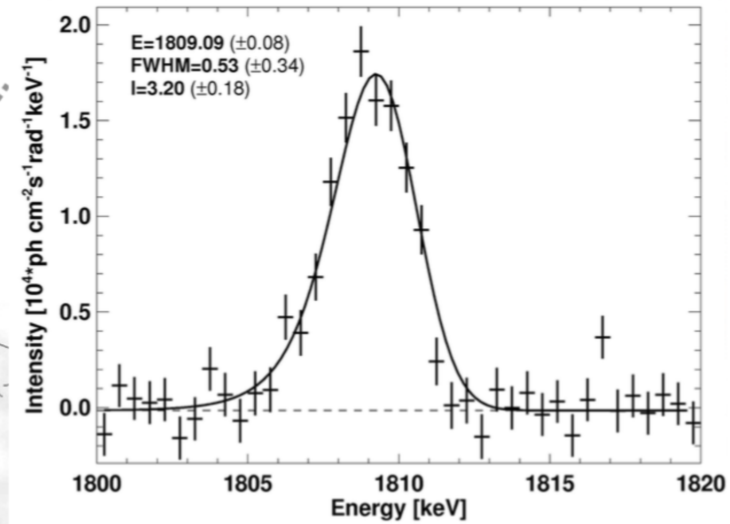


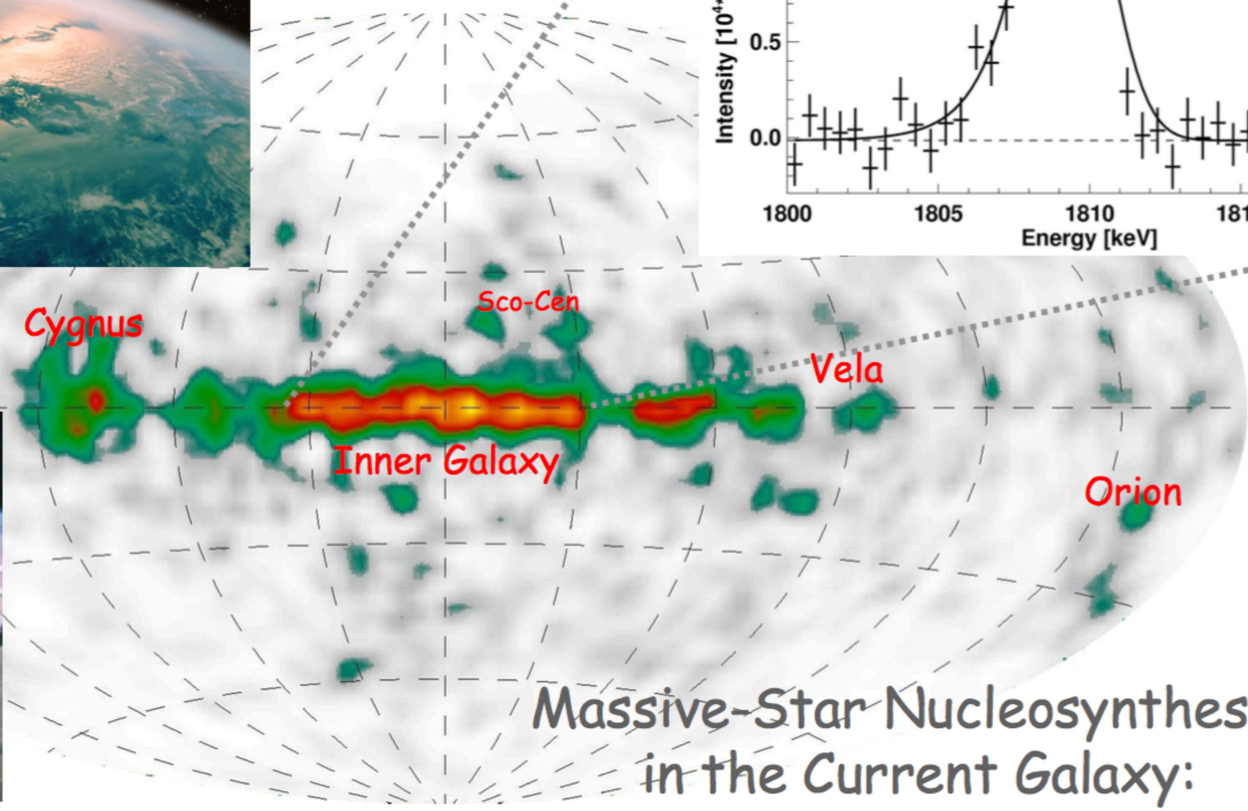
- ☆ **How does the Interior Structure Evolve in Late Stages?**
  - ☞ **Which "Shells" are Active?**
  - ☞ **Which Nuclei are Produced? (ejected?)**
  - ☞ **What are the Time Scales?**
  - ☞ **How does all this Depend on Rotation?**
  - ☞ **How does all this Depend on Metallicity?**



Main Sources of ^{44}Ti, ^{26}Al, ^{60}Fe

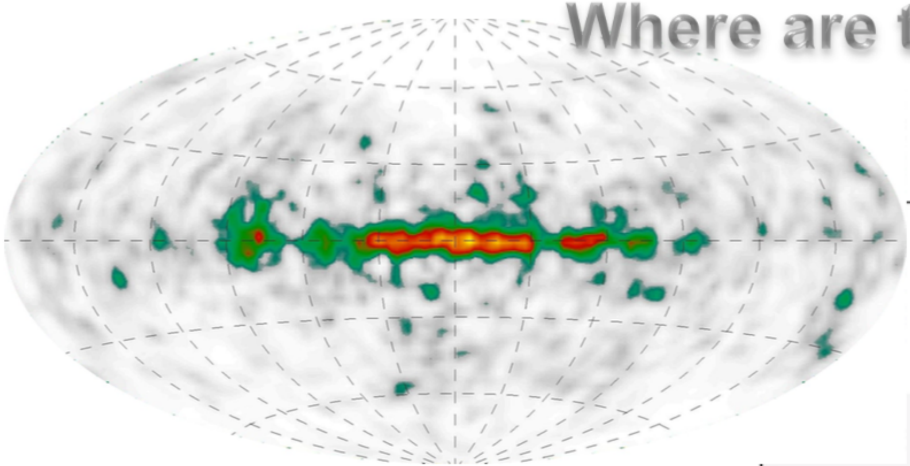
^{26}Al in our Galaxy: γ-ray Image and Spectrum

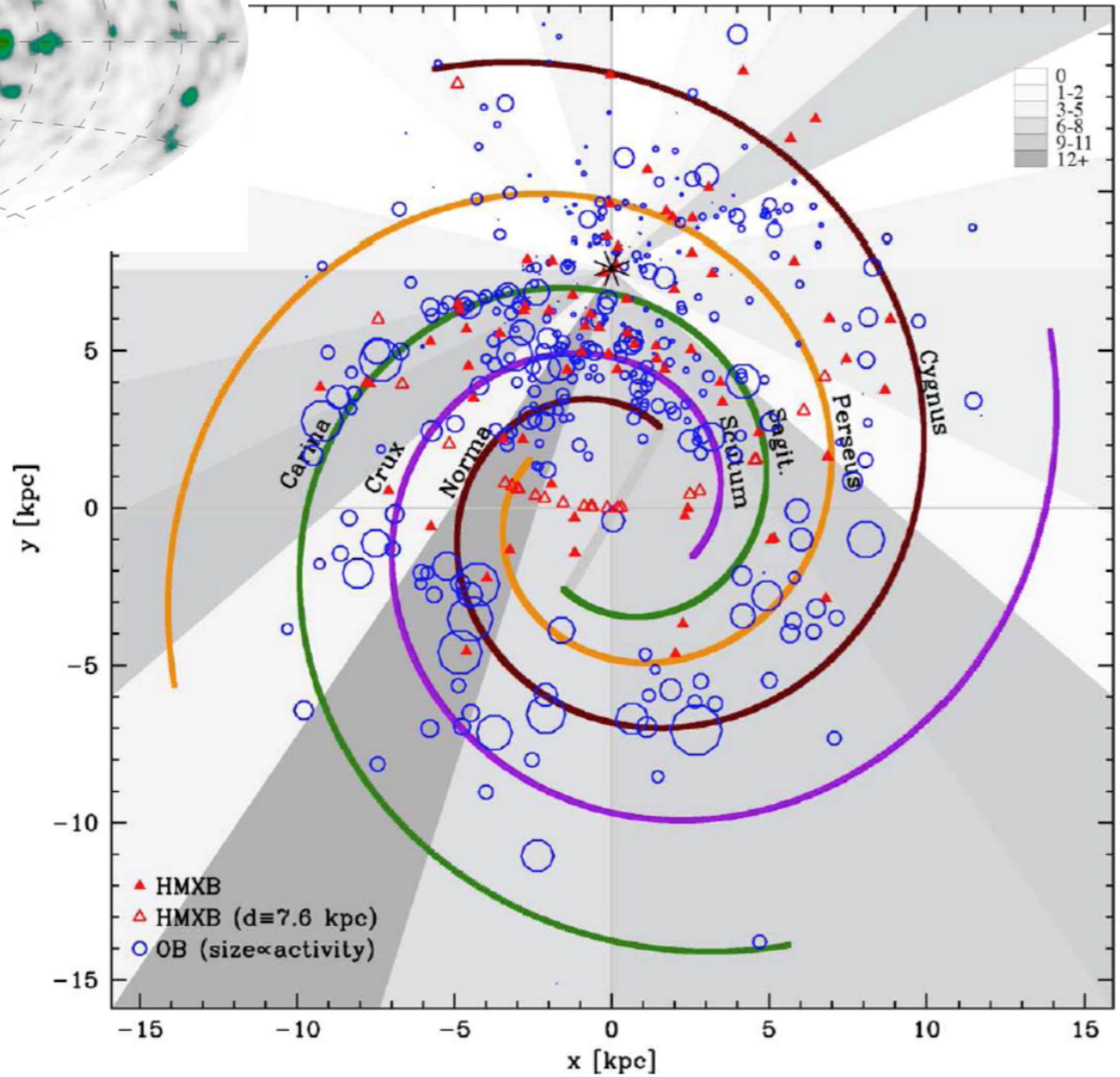




Massive-Star Nucleosynthesis in the Current Galaxy:
Exploiting the Message from ^{26}Al γ-rays

Where are the Candidate Sources?

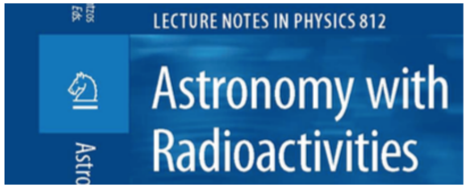




☆ **OB Associations, Massive Binaries, ...**

☞ **We Need to Account for Incomplete Knowledge:**

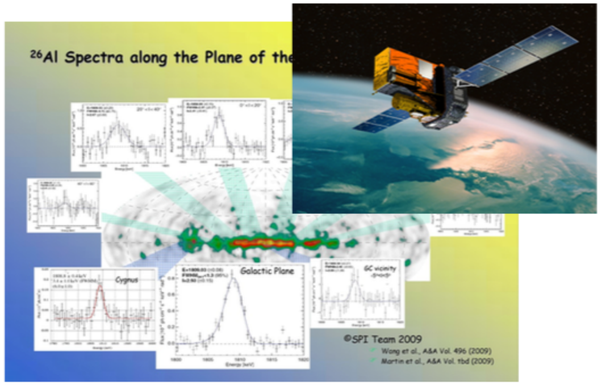
- **Biases in Time**
- **Biases in Radiation**
- **Biases in Space**



Lessons from Cosmic Radioactivities
Summary

☆ **Radioactivity provides a unique / different astronomical tool**

- **Intensity change only due to radioactive decay**
- **Thermodynamic gas state unimportant**

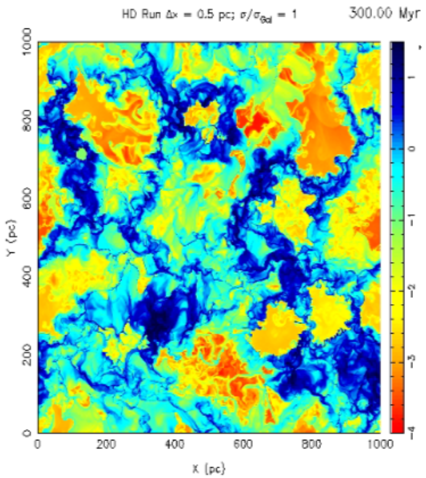


☆ **Supernova interiors can be explored**

- **SNIa brightness evolution and ^{56}Ni yield calibration**
- **Core collapse evolution into an explosion with ^{56}Ni and ^{44}Ti production**

☆ **Massive-star shell structure and evolution can be explored**

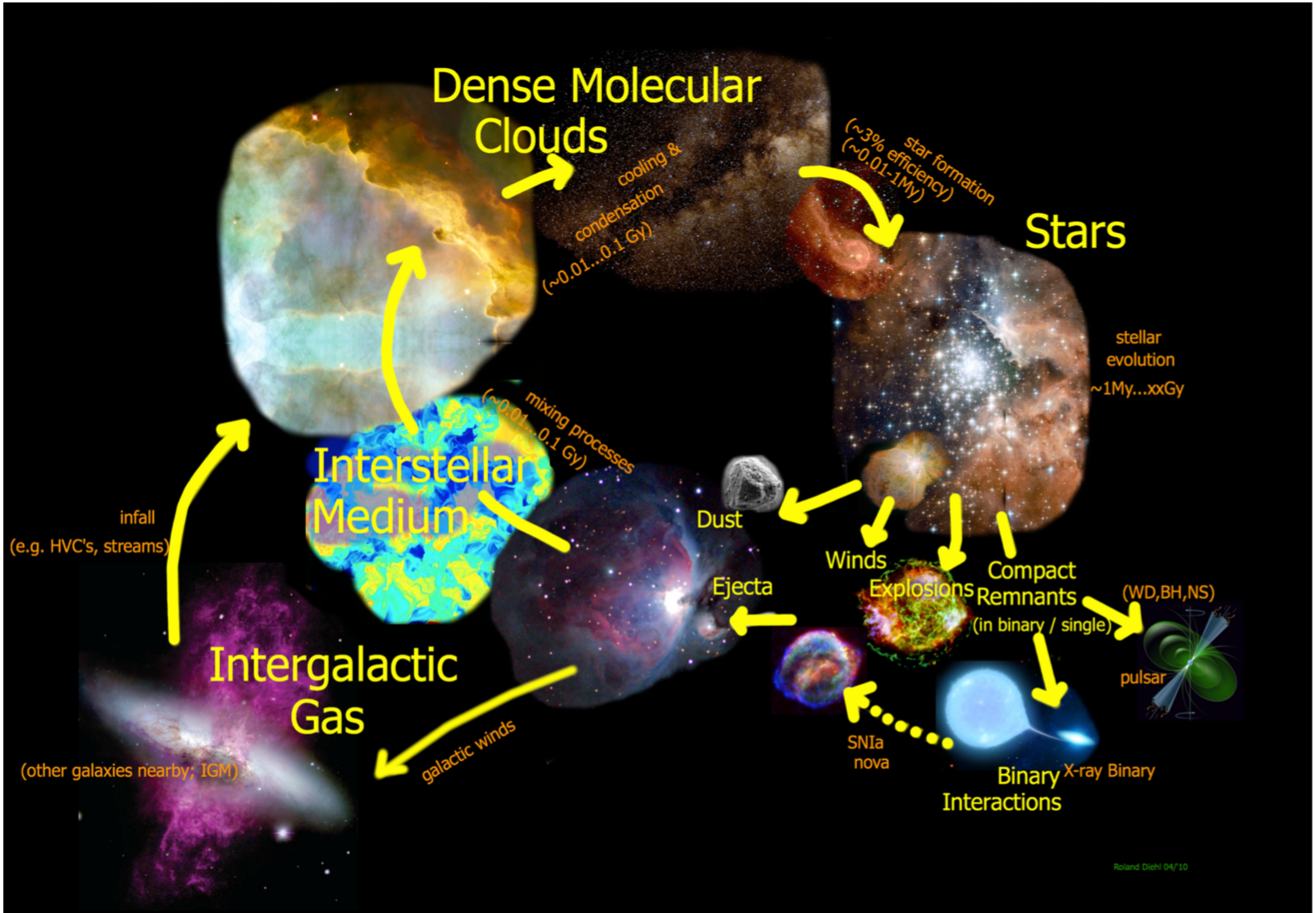
- **^{26}Al production in core H burning and late shell burning**
- **^{60}Fe production in C and He shells**



☆ **Chemical evolution uncertainties can be explored**

- **ISM state and dynamics around massive-star regions**
- **Nucleosynthesis ejecta recycling times**

How Stars Shape Galaxies



Astrofisica Nucleare e Subnucleare

Nuclear Astrophysics - 2

Nuclear Astrophysics: Supernova Evolution and Explosive Nucleosynthesis

Gabriel Martínez Pinedo

Advances in Nuclear Physics 2011
International Center Goa, November 9 – 11, 2011

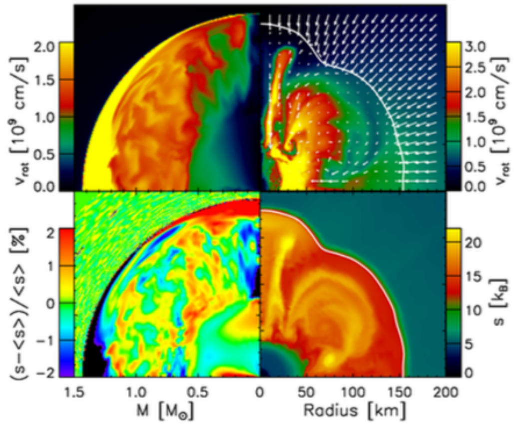
TECHNISCHE UNIVERSITÄT DARMSTADT

HIC for FAIR
Helmholtz International Center

A new Era for Nuclear Astrophysics

Improved observational capabilities

Improved supernovae models

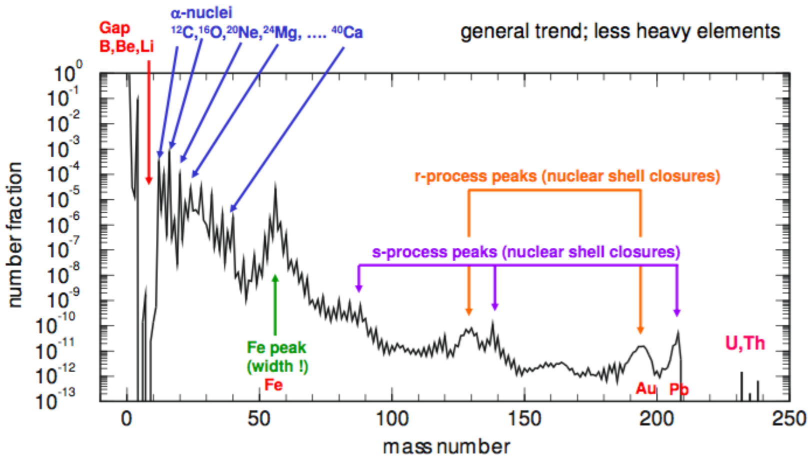


- New radioactive ion beam facilities (RIBF, SPIRAL 2, FAIR, FRIB) are being built or developed that will study many of the nuclei produced in explosive events. Hydrostatic burning phases studied in underground labs (LUNA)
- We need improved theoretical models to fully exploit the potential offered by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

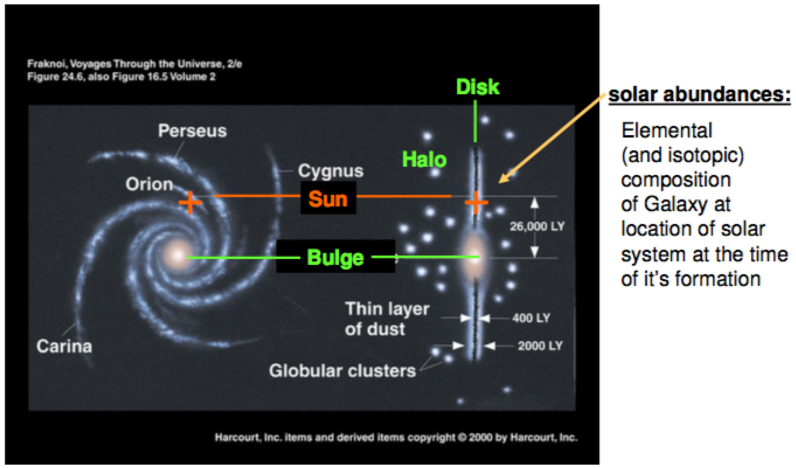
What is Nuclear Astrophysics?

- 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

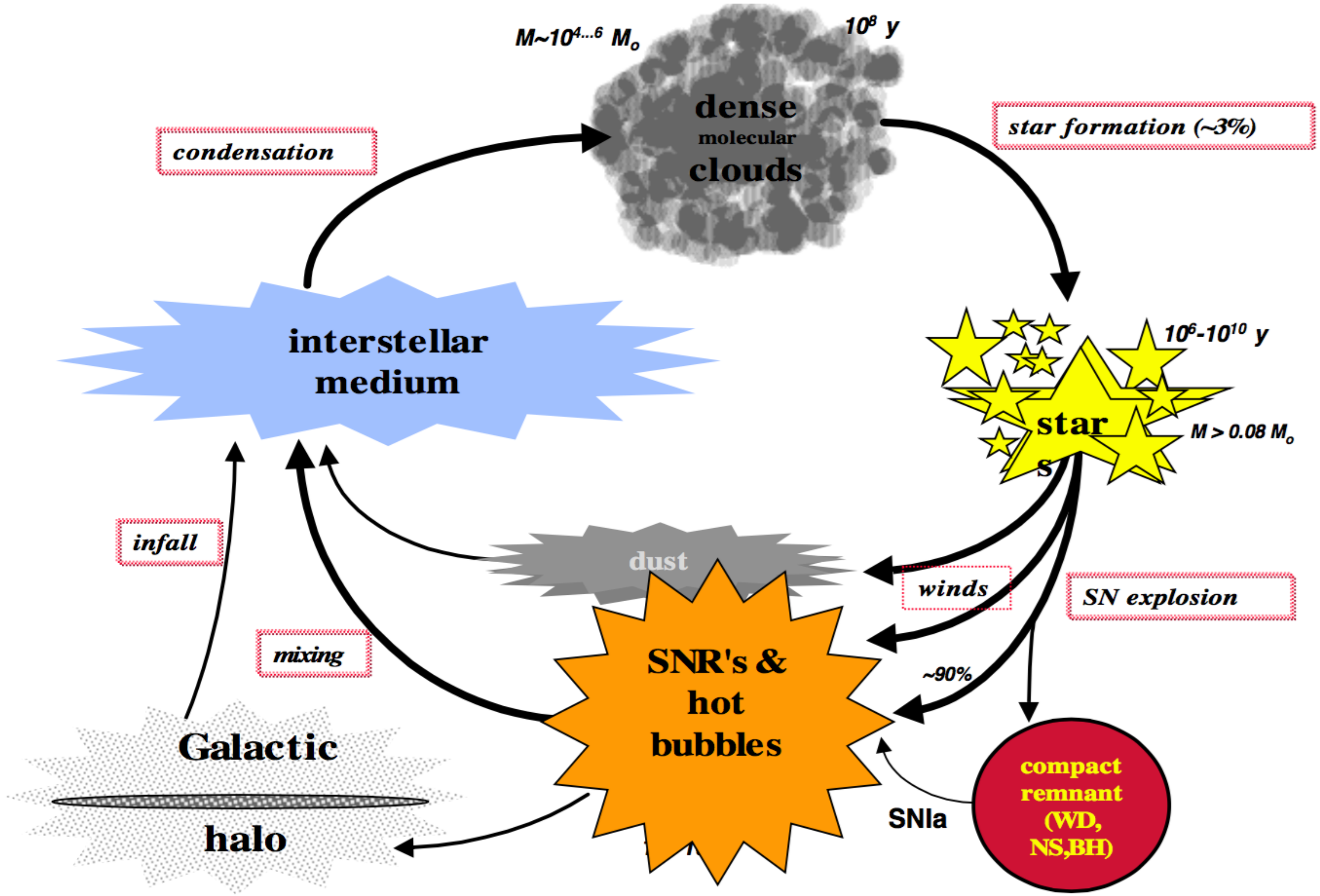


3. The solar abundance distribution



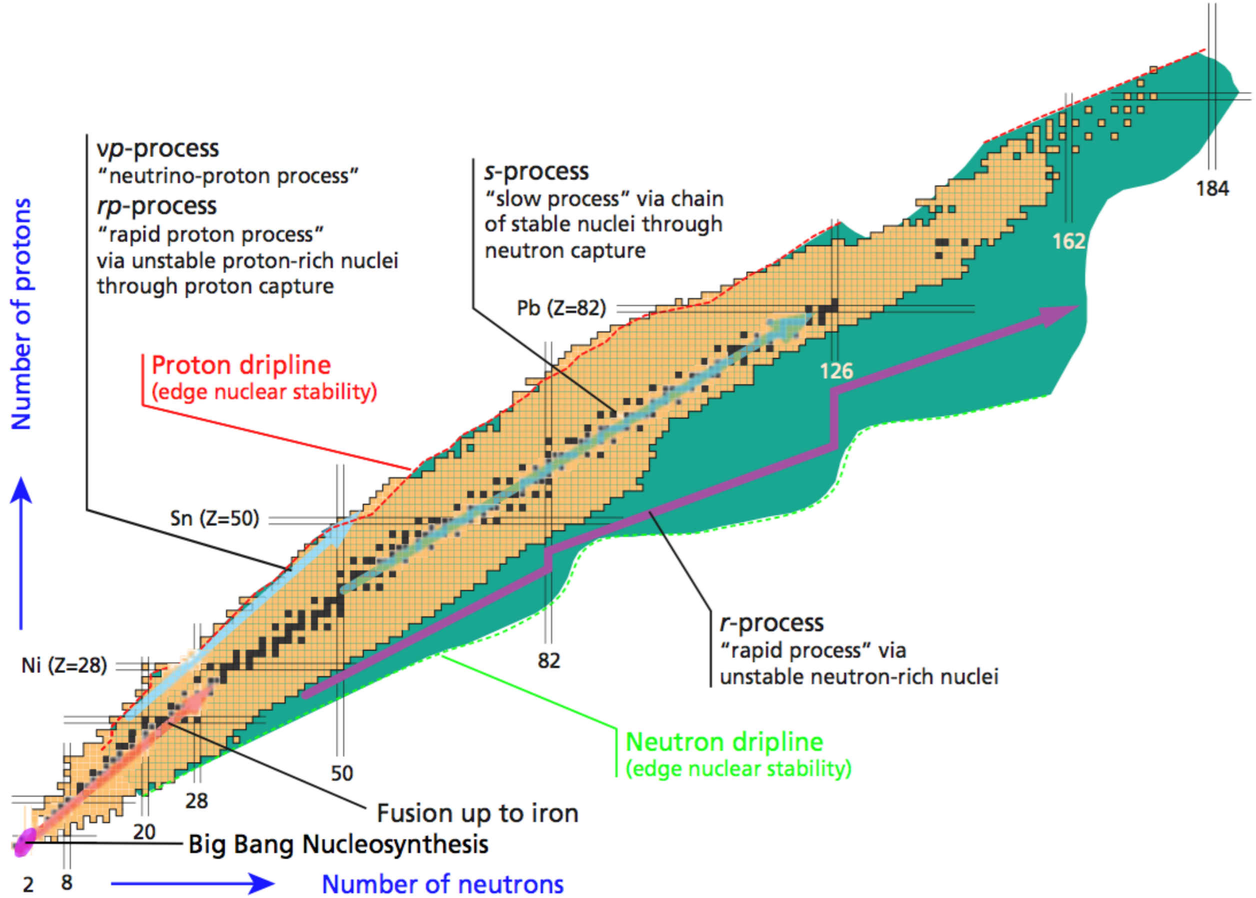
K. Lodders, Astrophys. J. **591**, 1220-1247 (2003)

Cosmic Cycle

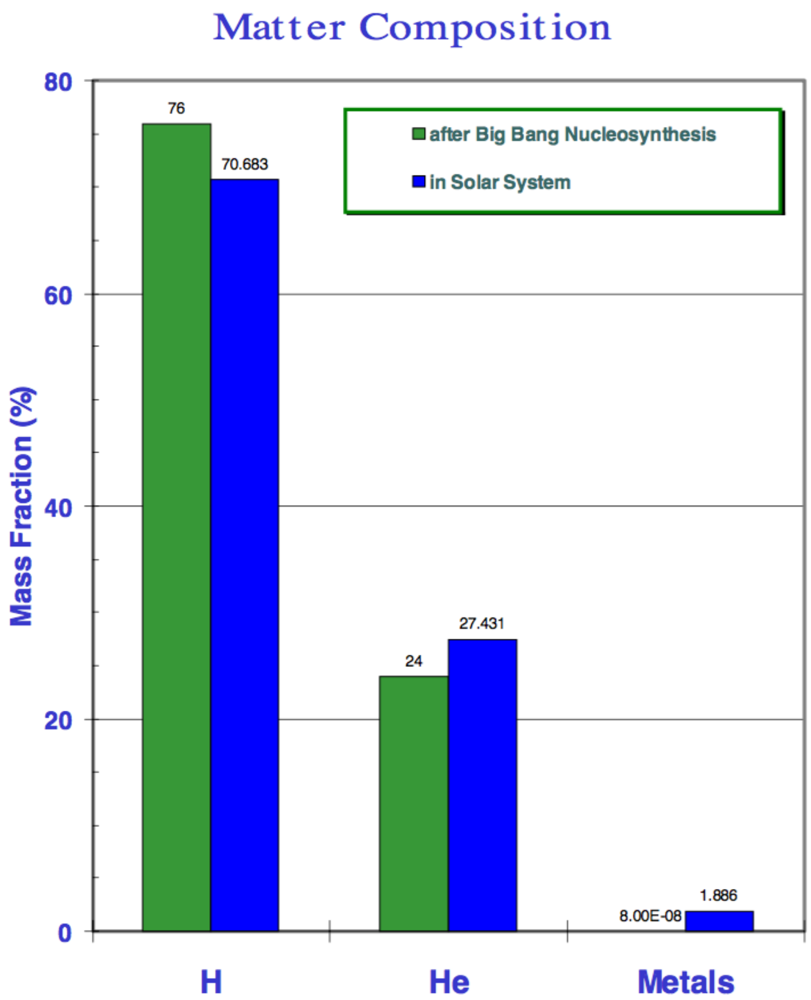


Nucleosynthesis processes

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

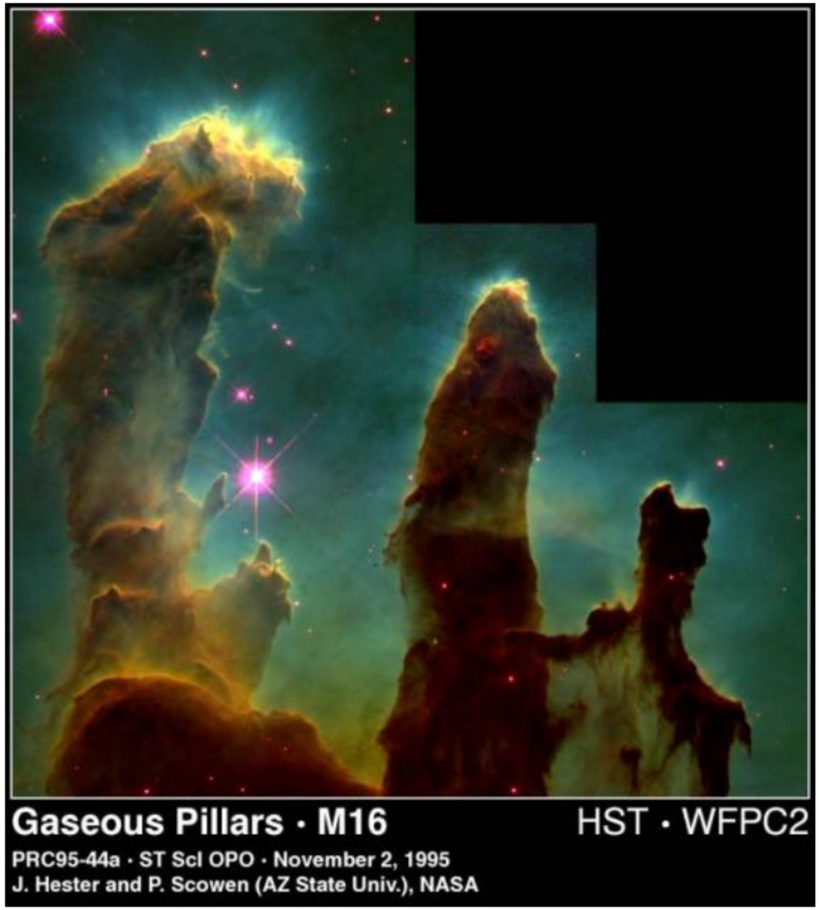


Composition of the Universe after Big Bang



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

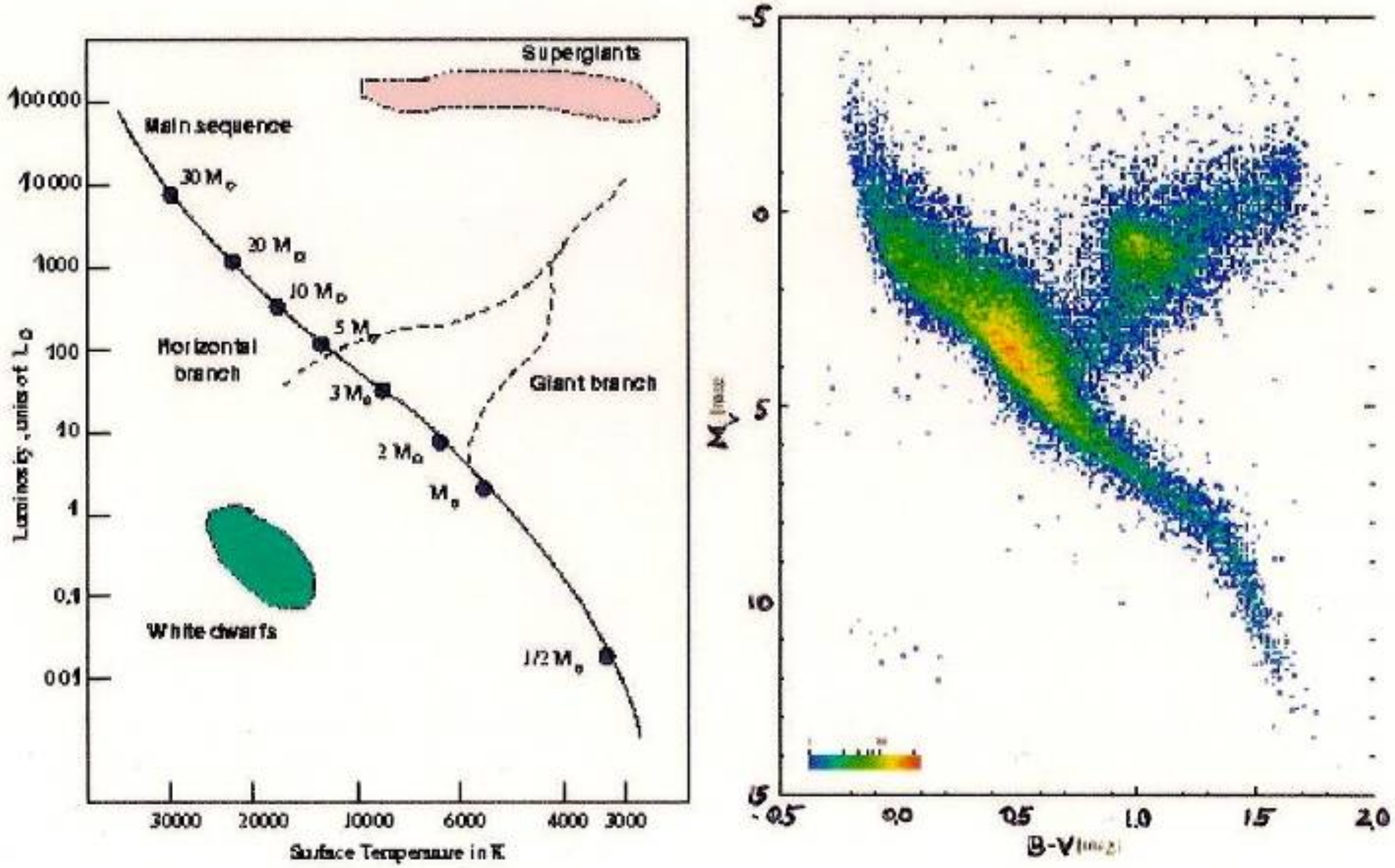
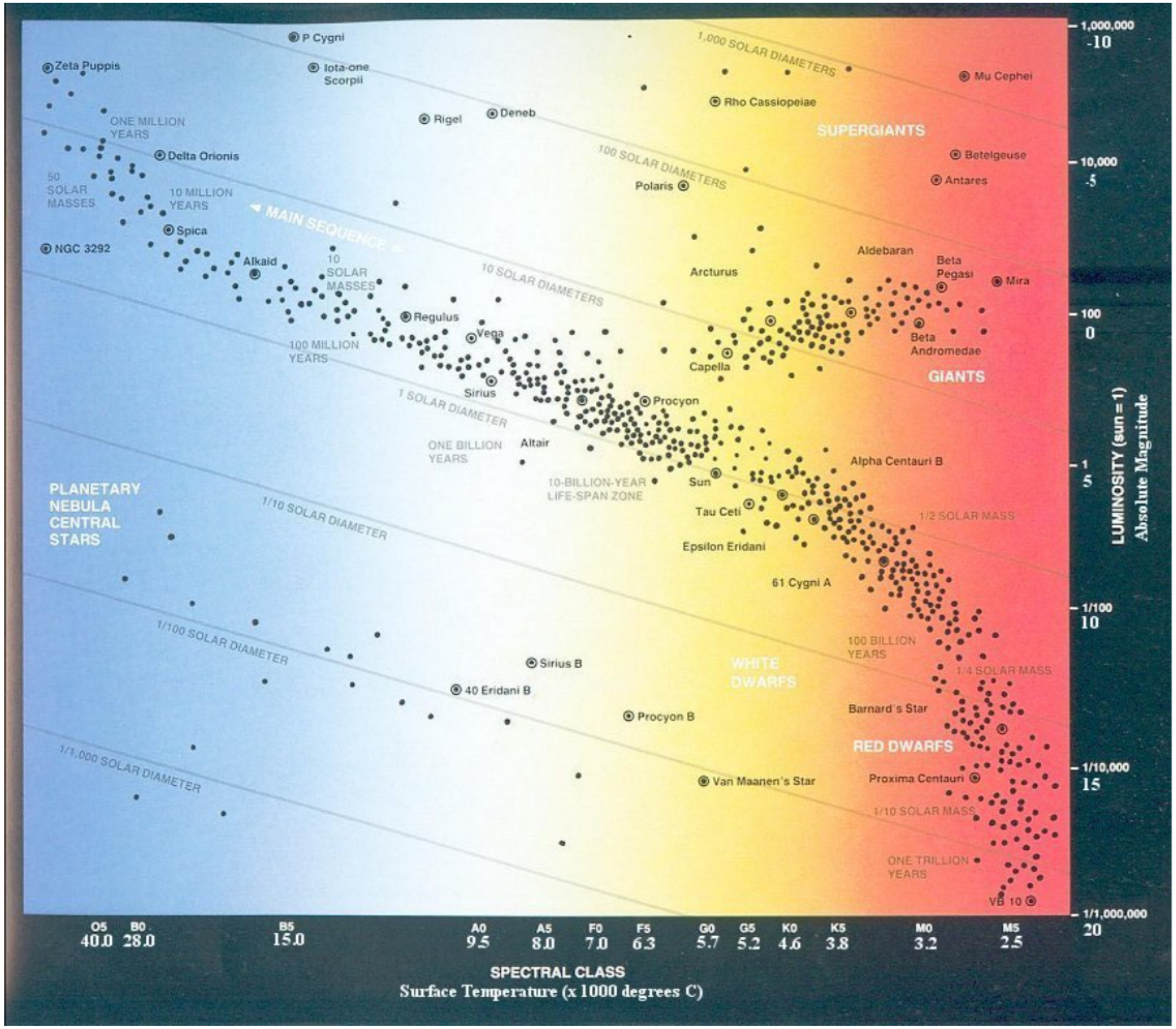
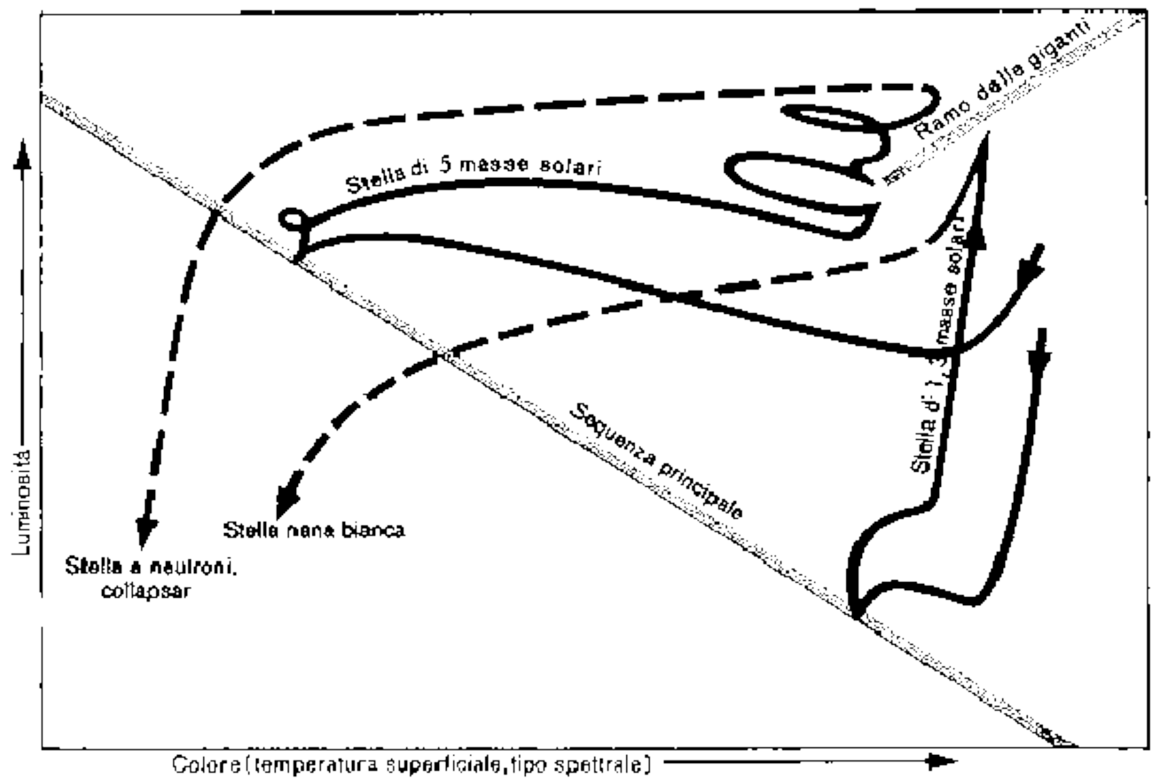


Figure 2.1: Left: a schematic representation of the H-R diagram (picture following [Lon94]). Notice how the mass itself distinguishes the different stars along the main sequence. Right: H-R diagram for 4170 single nearby stars determined from observations made by the *Hipparcos* astrometry satellite. Picture from [Gro99].

Hertzspung-Russell diagram

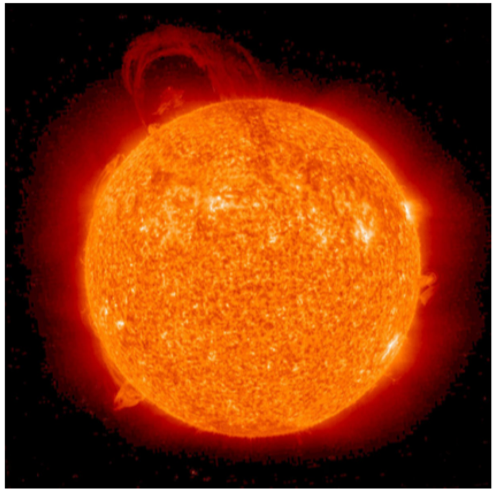


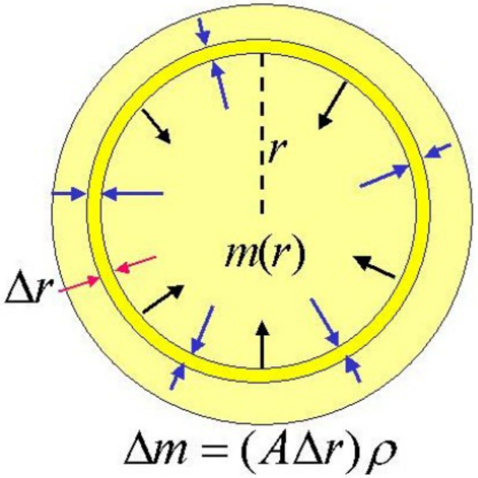
Stellar Evolution



HR diagram

What is a star?





- 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.

$$dF_{\text{grav}} = -G\frac{mdm}{r^2} = [P(r+dr) - P(r)]dA = dF_{\text{pres}}$$

$$dm = 4\pi r^2 \rho dr$$

$$-G\frac{m\rho}{r^2} = \frac{dP}{dr}$$

- 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: $P(\rho, T)$.

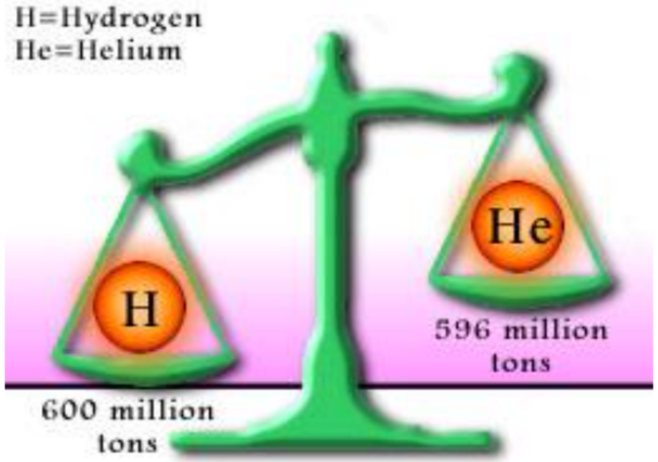
- Star evolution, lifetime and death depends on mass. Two groups
  - Stars with masses less than 9 solar masses (white dwarfs)
  - Stars with masses greater than 9 solar masses (supernova explosions)

Where does the energy come from?

Energy comes from nuclear reactions in the core.

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

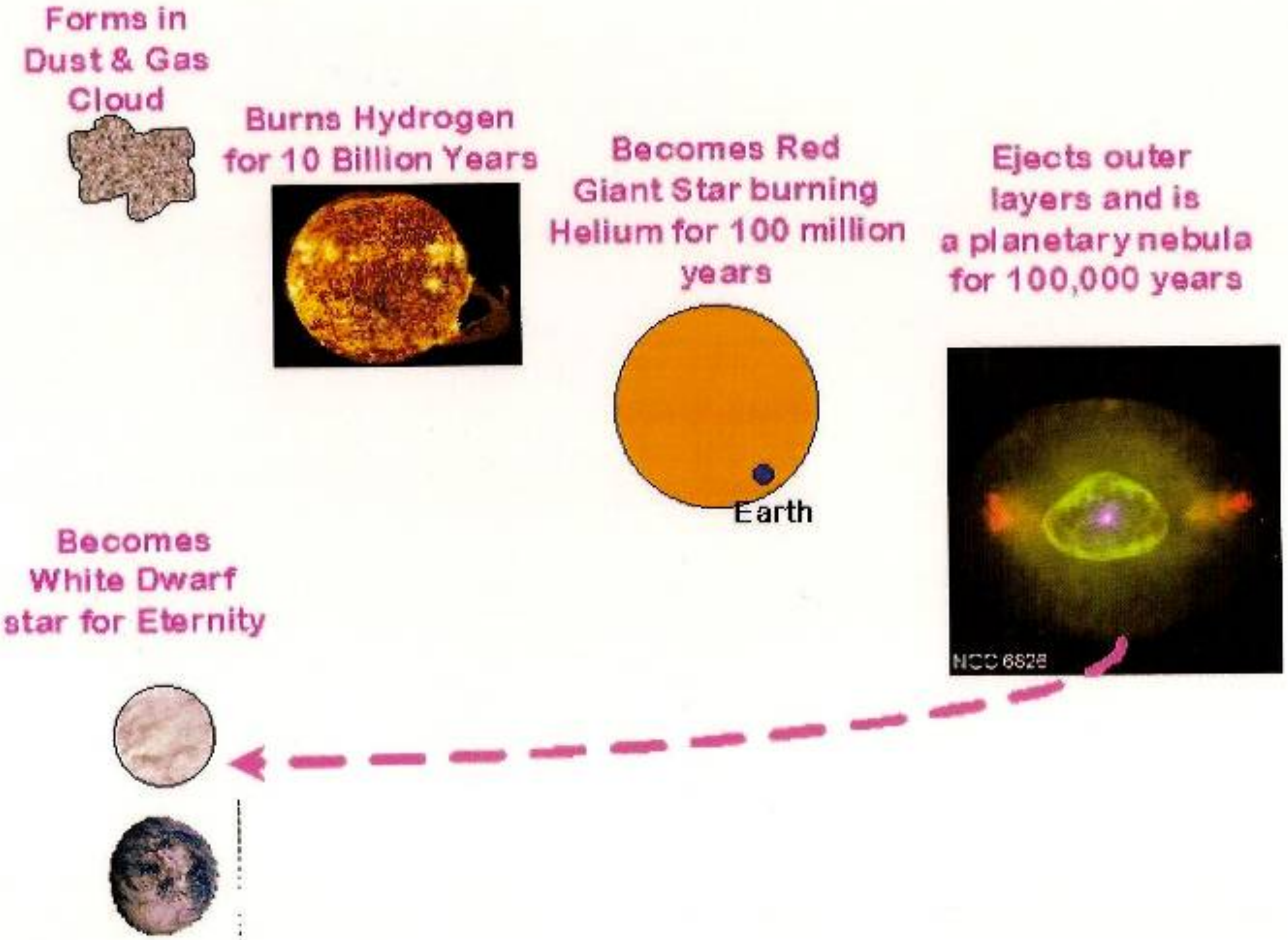
$$E = mc^2$$



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.

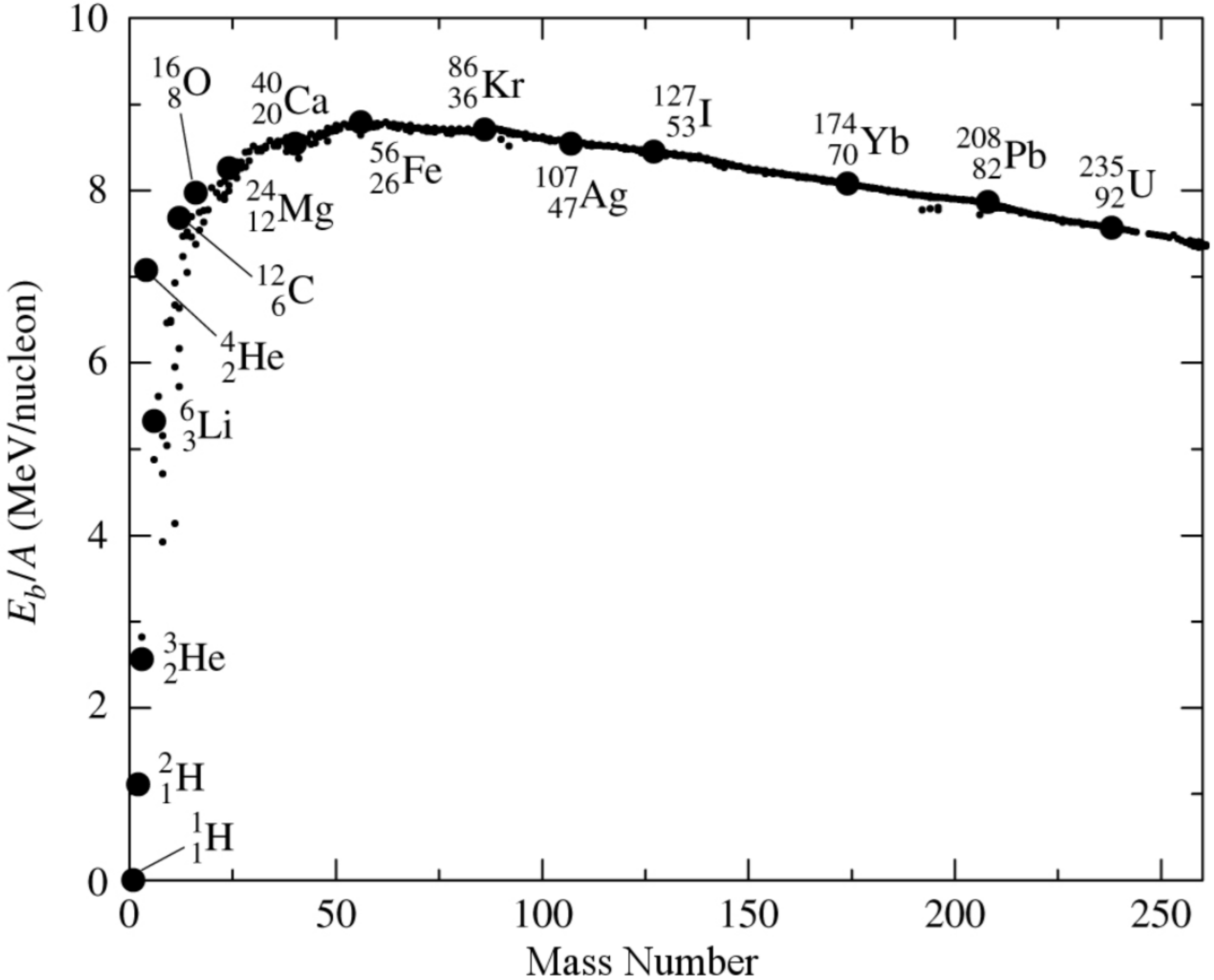
Energy released by H-burning:
6.45×10^{18} erg g^{-1} $= 6.7$ MeV/nuc
Solar Luminosity: 3.85×10^{33} erg s^{-1}

Life of small star (< 1,4 $M_{\odot}$)



Nuclear Binding Energy

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



Type of processes

Transfer (strong interaction)

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

Capture (electromagnetic interaction)

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

Weak (weak interaction)

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

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

Types of reactions

Nuclei in the astrophysical environment can suffer different reactions:

- Decay

$$^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} + e^{+} + \nu_e$$
$$^{15}\mathrm{O} + \gamma \rightarrow {}^{14}\mathrm{N} + p$$

$$\frac{dn_a}{dt} = -\lambda_a n_a$$

In order to dissentangle changes in the density (hydrodynamics) from changes in the composition (nuclear dynamics), the abundance is introduced:

$$Y_a = \frac{n_a}{n}, \quad n \approx \frac{\rho}{m_u} = \text{Number density of nucleons (constant)}$$

$$\frac{dY_a}{dt} = -\lambda_a Y_a$$

Rate can depend on temperature and density

Types of reactions

Nuclei in the astrophysical environment can suffer different reactions:

- Capture processes

$$a + b \rightarrow c + d$$

$$\frac{dn_a}{dt} = -n_a n_b \langle \sigma v \rangle$$

$$\frac{dY_a}{dt} = -\frac{\rho}{m_u} Y_a Y_b \langle \sigma v \rangle$$

decay rate: $\lambda_a = \rho Y_b \langle \sigma v \rangle / m_u$

- 3-body reactions:

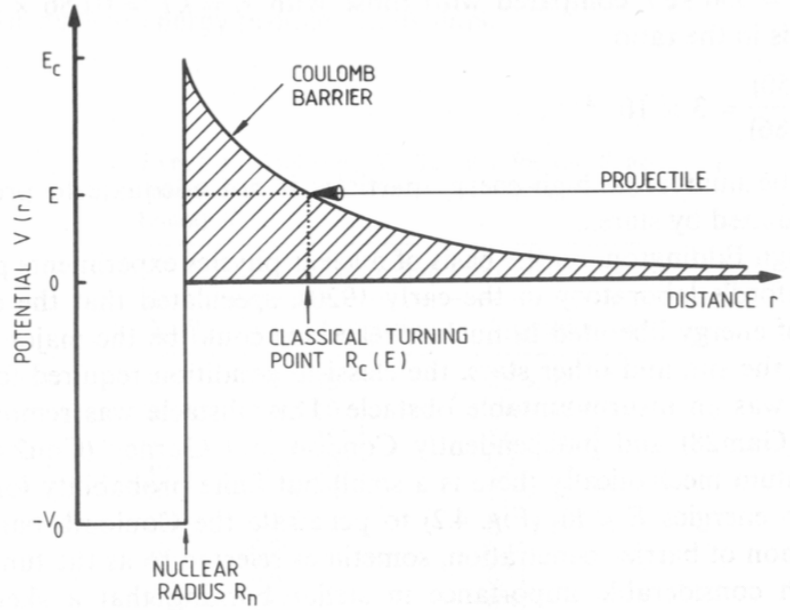
$$3\,{}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

$$\frac{dY_\alpha}{dt} = -\frac{\rho^2}{2m_u^2} Y_\alpha^3 \langle \alpha\alpha\alpha \rangle$$

decay rate: $\lambda_\alpha = Y_\alpha^2 \rho^2 \langle \alpha\alpha\alpha \rangle / (2m_u^2)$

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.



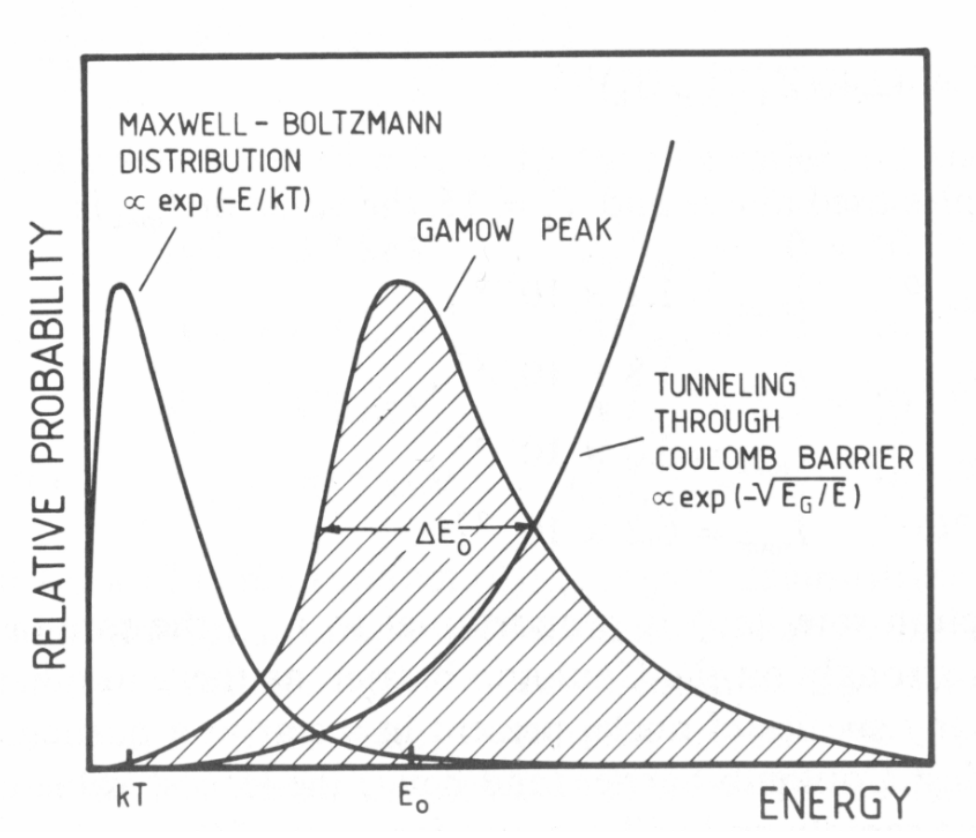
Cross section given by:

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

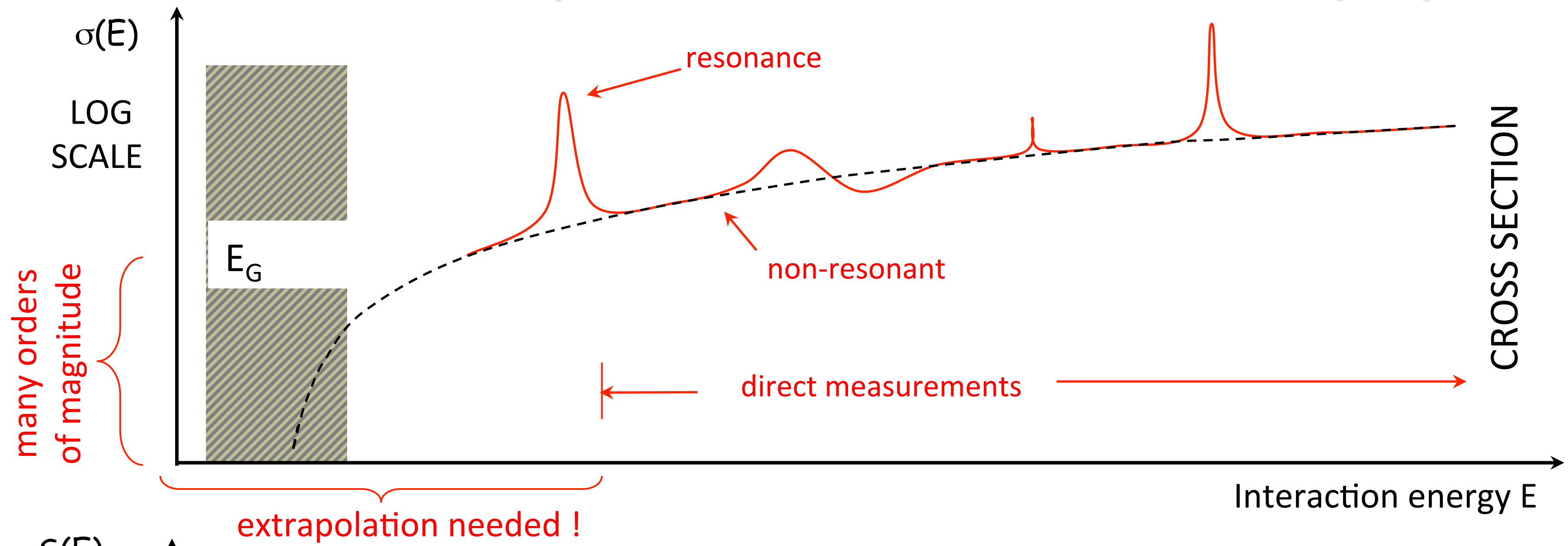
Gamow window

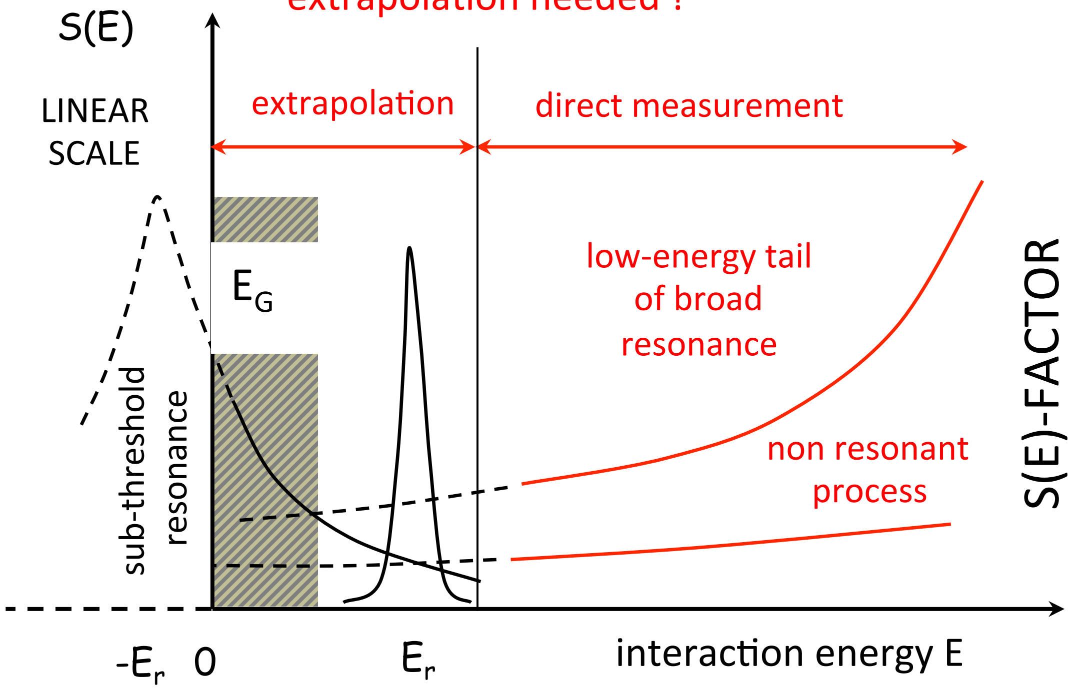
Using definition S factor:

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



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

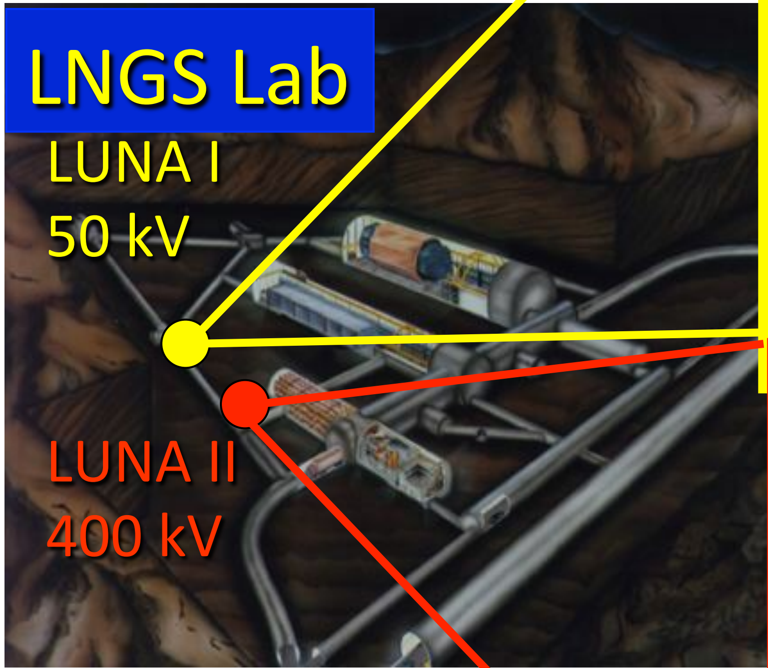
Welcome on the LUNA pages at LNGS

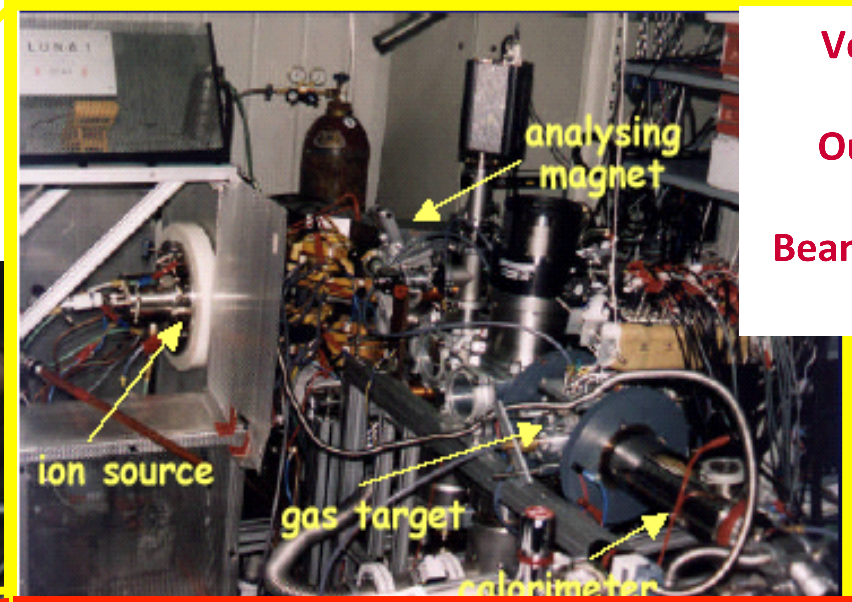
What is LUNA about

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.

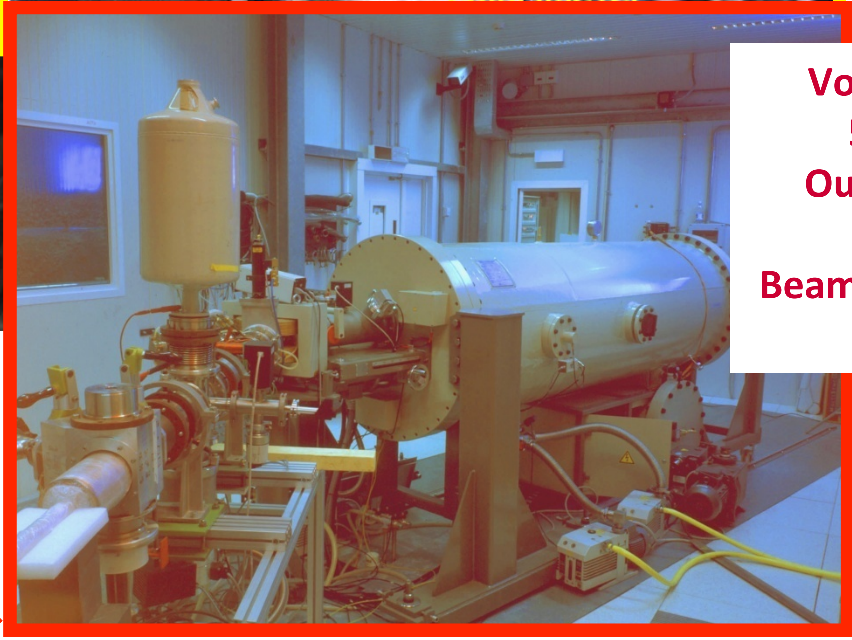
The present program of LUNA is descibed in the Proposal presented to the Scientific Commitee of LNGS in March 2007.

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: $p + p \longrightarrow {}^2\text{He}$ (not possible)

$p + p \longrightarrow d + e^+ + \nu_e$

Step 2: $d + p \longrightarrow {}^3\text{He}$

$d + d \longrightarrow {}^4\text{He}$ (d abundance too low)

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

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

${}^3\text{He} + {}^3\text{He} \longrightarrow {}^4\text{He} + 2p$

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

pp chains

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