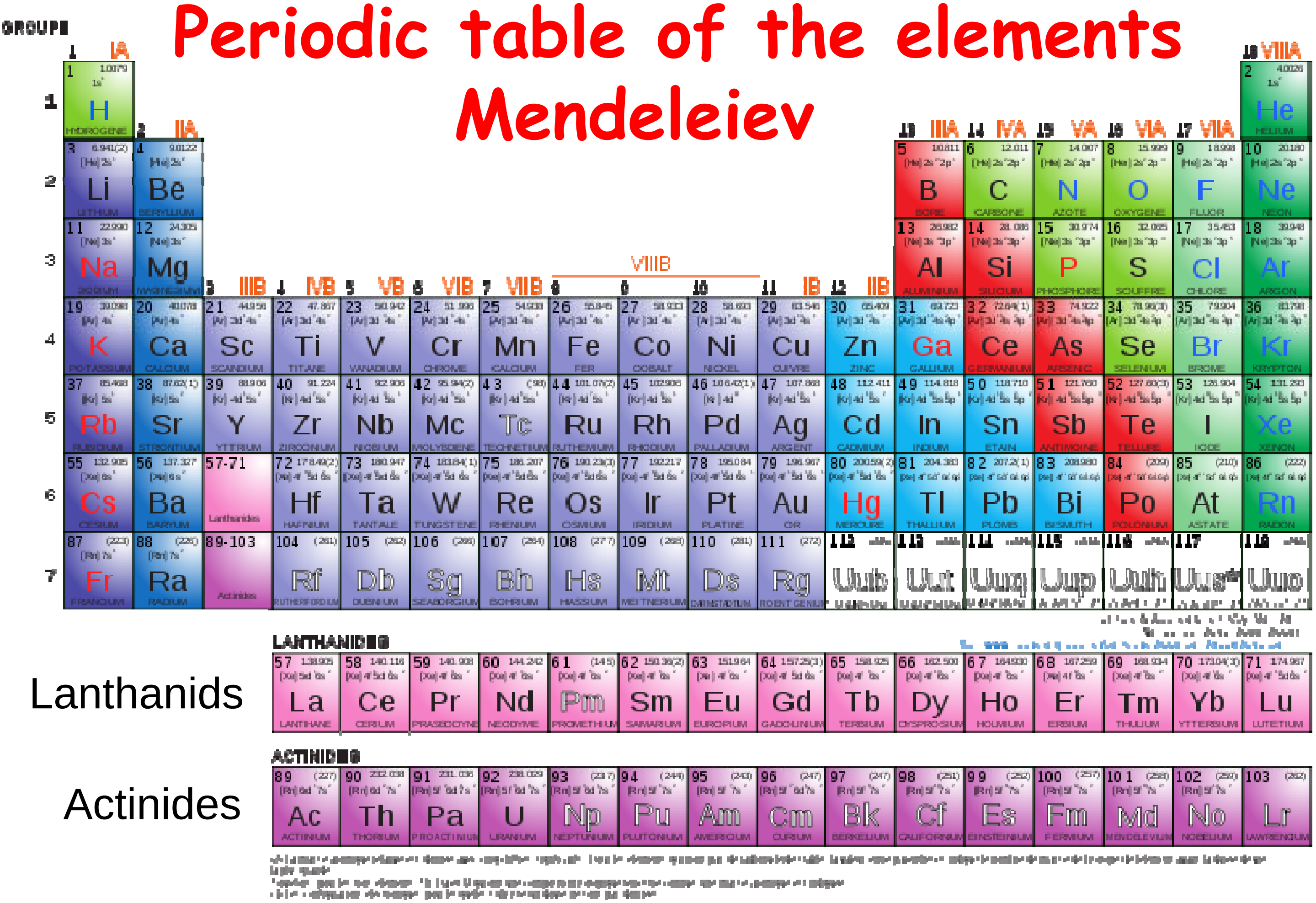
Stars and Nuclei,
from Cosmology to Stellar Evolution

Various phases of nucleosynthesis processes
Consequences on nuclei abundances,
on energy production
Nuclear physics characteristics

A. Lefebvre-Schuhl
CSNSM Orsay, France

July 2nd 2009
The Secrets of the Atomic Nucleus, Strasbourg

Periodic table of the elements Mendeleiev



GROUPE	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ce	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mc	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57-71 Lanthanides	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89-103 Actinides	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

Lanthanids

LANTHANIDES														
57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

Actinides

ACTINIDES														
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Chemistry → A few number of different elements

First spectroscopic observation of stars → The same elements

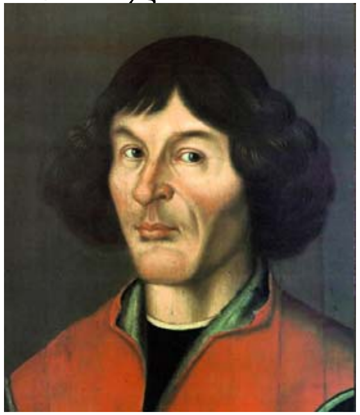
How to understand origin and abundance of elements in Universe ?

Where does the star energy production come from?

Sky fascination

Sun during the day; Stars and other celestial objects during the night

Observation ; Use



Technical advances → always more advanced observations

→ advances in physics knowledge

(Kepler laws ; velocity limitation…)

Now knowledge still advances from Sun and star study

Solar neutrino puzzle → Neutrino mass

Lens, mirror surface advances

New detectors

Numerous star observations

→ Researches in astrophysics ;

→ In nuclear physics ;

→ In particle physics ;

To the Hubble Space Telescope and …

→Some stars have similar characteristics

→ Star classification

→ Expansion of the Universe

From Galilei's lens,

Newton's telescope

But, a remaining haunting question !

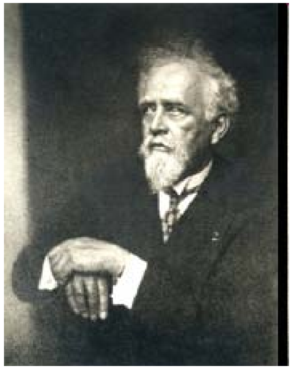
Will the Sun die ?

19th century : Thermodynamics laws

→ The Sun is shining! It's impossible

H. N. Russell in 1919

Too much energy during such a long time !



J. Perrin in 1920

Only in the 1920s : ~ 80 years later

Solar energy is produced inside the Sun by nuclear reactions

Consequences : → Solar energy may be understood

→ A lot of various results may be connected

→A new coherent theory appears

The Standard model ≡ Standard big-bang

SBB theory

One basic assumption : Laws of physics as presently known were valid at each time of cosmological evolution

In this framework:

Two fundamental SBB underlying assumptions :
1) General Relativity offers a valid description of gravity,
2) The Universe got hotter than ~ 10^{11} K, so that statistical equilibrium was established between all of its components
(i. e. Weinberg 1972, Kolb and Turner 1990)

Going back in the time → *origin of the Universe : 10^{10} years earlier*

within the SBB model → *back to ~10^{-12} s after the big-bang*

Then, « Beyond the standard model » until the Planck time : ~10^{-43} s after the big-bang

Supersymmetry ; String theories ;
Variation of the fundamental physical constants ; …
Totally outside this lecture

Preliminary remarks

Need to compare theory and observationnal data

Mainly electromagnetic radiation detections

in any wave-length range

from radiative sites as many and varied as possible

i.e. galaxy (ours and others) ; various kinds of stars ;
interstellar/intergalactic medium ; ***…***

Nuclear reaction importance

They change nuclear species in other nuclear species

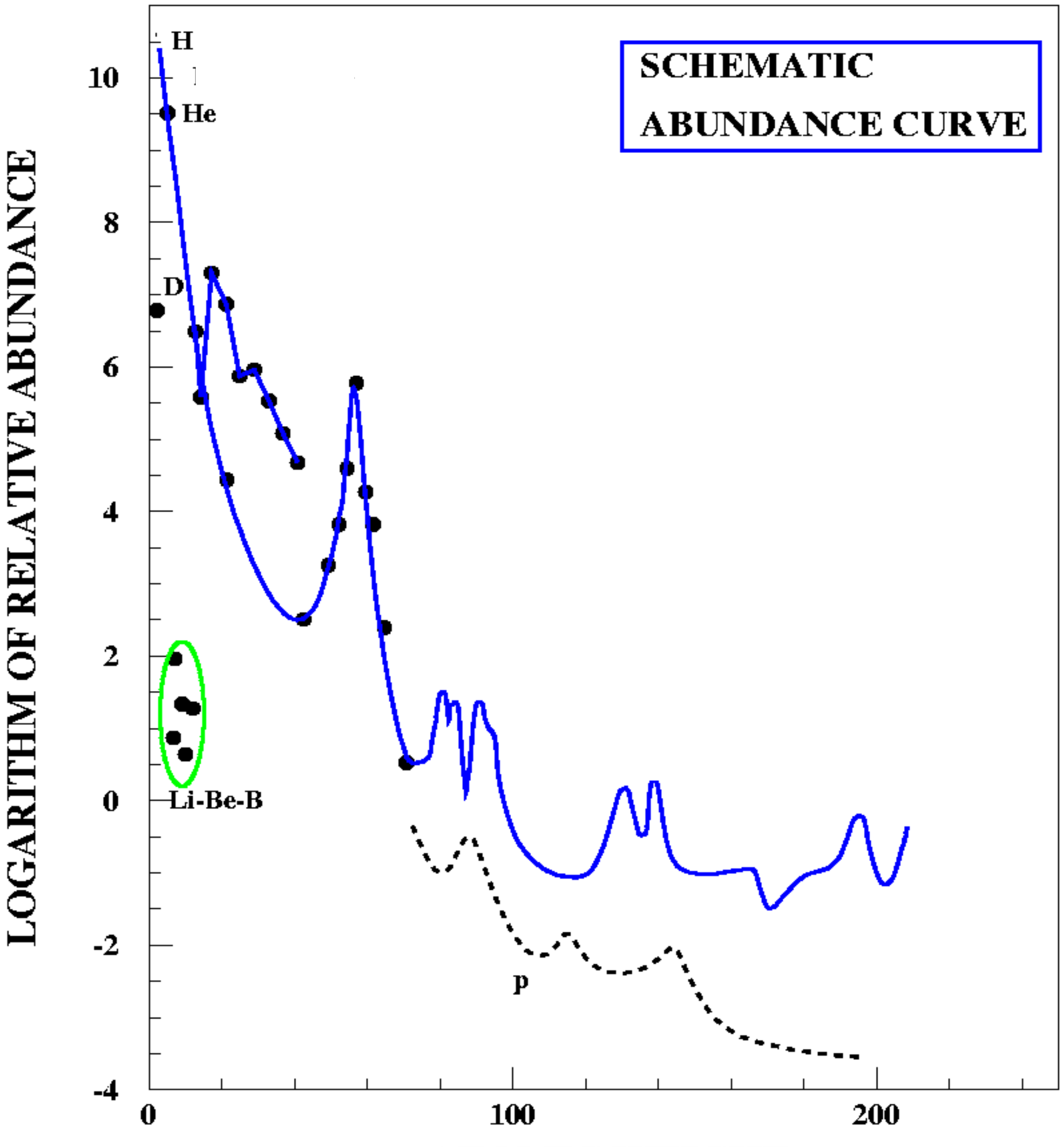
Source of the production of the various chemical elements

They produce or absorb energy

Source of star energy production

…

Some characteristics of the abundances



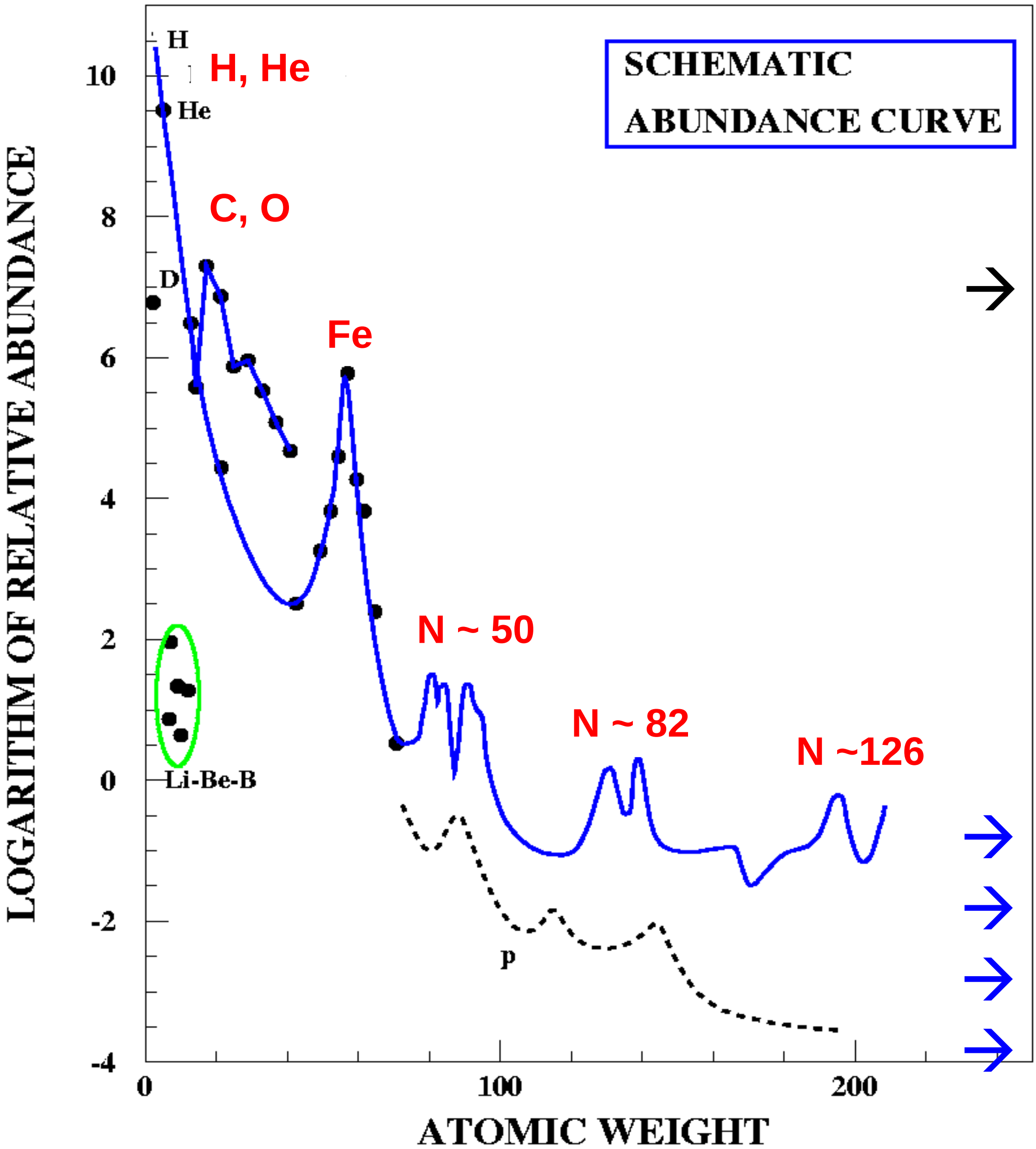
[H] and [He] far above the others

Li, Be and B extremely underabundant

Some peaks are superimposed to a curve decreasing with A

Double peaks appear around A = 80, 126, 200

Some characteristics of the abundances (II)



Abundant elements
for element species with
N,Z ~ 2, 8, 28, 50, 82, 126

→ magic numbers correlation

→ Nucleosynthesis is strongly correlated to the nuclear stability, nuclear properties

→ primordial nucleosynthesis
→ stellar nucleosynthesis
→ explosive nucleosynthesis
→ spallative nucleosynthesis

Thermonuclear reaction rate (I)

Reaction : $1 + 2 \rightarrow 3 + 4 + \ldots.$

$$Q = (M_3 + M_4 + \ldots) - (M_1 + M_2)$$

Number of reactions per time unit ↔ cross section

$$\frac{dN_{12}}{dt} = IxN_2\sigma$$

$\boldsymbol{I}$ = *beam intensity*

$\boldsymbol{x}$ = *target thickness*

$\boldsymbol{N_2}$ = *volumic density of the particle in the target*

$\boldsymbol{\sigma}$ = *cross section*

Stars ≠ targets :

Number of interactions per time and volume unit

$$\frac{d\mathcal{N}_{12}}{dt} = N_1 N_2 \sigma \mathrm{v}$$

v = *relative velocity of type 1 and 2 particles*

N_i = *volumic density of type i particles*

$\mathcal{N}_{12}$ = *number of interactions per volume unit*

Thermonuclear reaction rate (II)

Reaction : $1 + 2 \rightarrow 3 + 4 + \ldots.$

Star : gas mixing with ≠ velocities

→ *reaction rate per volume unit*

$$r_{12} = \frac{d\mathcal{N}_{12}}{dt} = N_1 N_2 \int_0^\infty \sigma(\mathrm{v})\varphi(\mathrm{v})\mathrm{v}\,d\mathrm{v}$$

$\varphi(\mathrm{v})$ = *velocity distribution*

N_i = *volumic densities of type i particles*

Thermonuclear reaction rate (per mole of interacting particles) :

$$\mathcal{N}_A \langle \sigma \mathrm{v} \rangle = \mathcal{N}_A \int_0^\infty \sigma(\mathrm{v})\mathrm{v}\varphi(\mathrm{v})\,d\mathrm{v}$$

where :

$\mathcal{N}_A$ = *Avogadro constant*

Should be multiplied by $(1+\delta_{12})^{-1}$*: true for ≠ or ≡ particles*

Reaction rate unit : $cm^3 s^{-1} mole^{-1}$

Thermonuclear reaction rate (II)

In a non degenerate gas mixing composed of non relativistic particles:

$\varphi(v)$ = *velocity distribution = Maxwell-Boltzmann distribution*

$$r_{12} = \mathcal{N}_A \langle \sigma \mathrm{v} \rangle = \mathcal{N}_A \int_0^\infty \sigma(\mathrm{v})\mathrm{v}\varphi(\mathrm{v})d\mathrm{v}$$

$$= \sqrt{8/\pi\mu}\left(\mathcal{N}_A/(kT)^{(3/2)}\right)\int_0^\infty E\sigma(\mathrm{E})e^{(-E/kT)}d\mathrm{E}$$

with $k_B = 8.62\ 10^{-8}$ *keV/K*

To integrate:

Need of σ(E) value for any energy E value

→ measurements, approximations, models …

Depends on the interacting particles (charged, neutrals, photons, …)

Astrophysical S factor: S(E)

To remove clearly, in σ(E) :

- *the barrier penetrability*
- *the de Broglie wave length*

$$S(E) = \sigma(E)\cdot E\cdot \exp(2\pi\eta) = \sigma(E)\cdot E\cdot \exp\left(\sqrt{\frac{E_G}{E}}\right)$$

Contributes as : $\sigma(E) \sim \lambdabar^2$
where $\lambdabar \propto E^{-1/2}$ is the de Broglie wave length

Penetrability correction (L=0)

Gamow energy: $E_G = \tfrac{1}{2}(2\pi\alpha Z_1 Z_2)^2 \mu c^2 = (0.989\cdot Z_1 Z_2 A^{1/2})^2$ [MeV]

⇒ *S(E)* varies more slowly with E compared to *σ(E)*

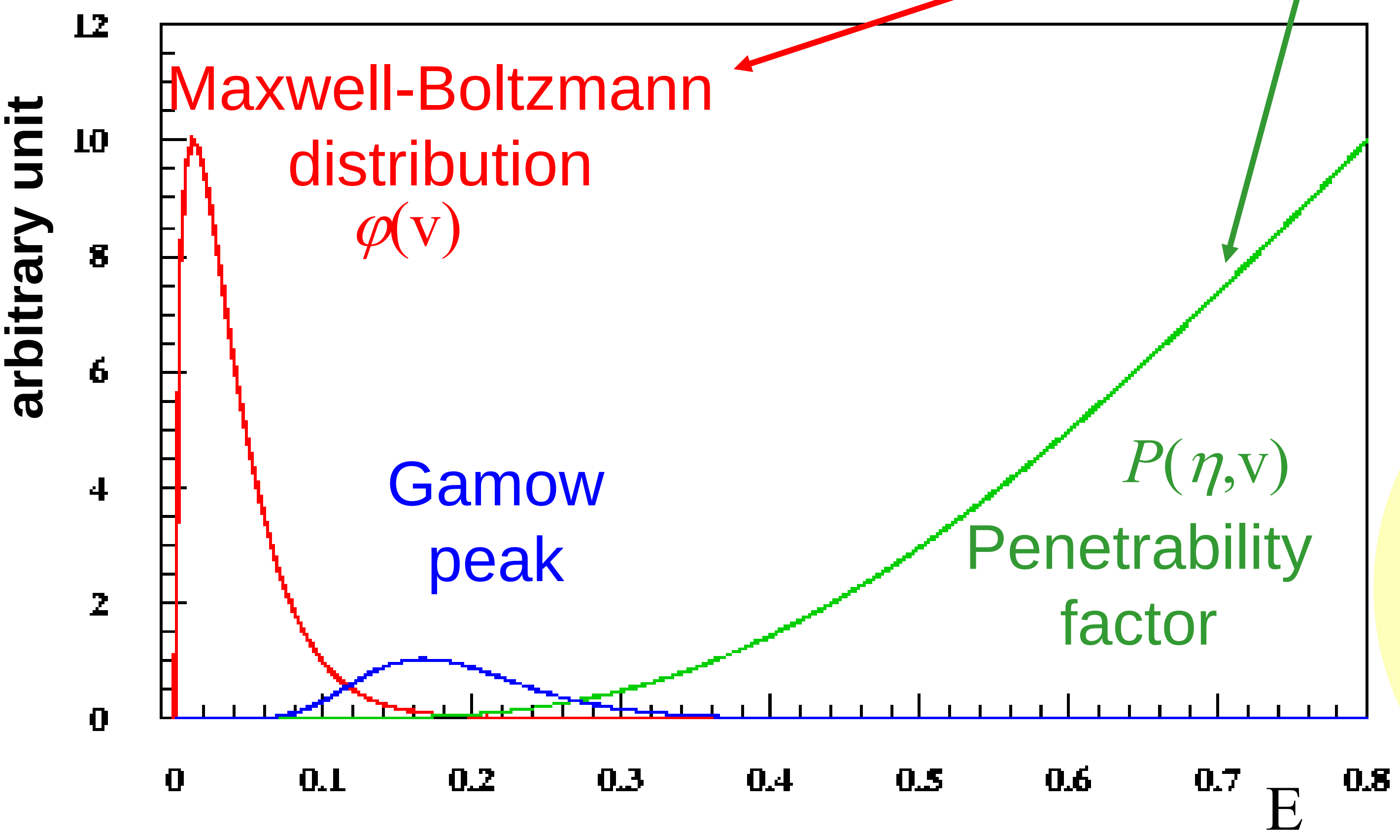
Easier for use when extrapolations are needed

Charged particle reactions: Gamow peak

$$r_{12} = \mathcal{N}_A\langle\sigma v\rangle = \sqrt{8/\pi\mu}\left(\mathcal{N}_A/(kT)^{(3/2)}\right)\int_0^\infty E\sigma(\mathrm{E})e^{(-E/kT)}d\mathrm{E}$$

Astrophysical S factor: $S(E) = E\ \sigma(E)\ e^{2\pi\eta} = E\ \sigma(E)\ e^{(Eg/E)^{1/2}}$

$$r_{12} = \mathcal{N}_A\langle\sigma v\rangle = \sqrt{8/\pi\mu}\left(\mathcal{N}_A/(kT)^{(3/2)}\right)\int_0^\infty S(\mathrm{E})e^{\left(-E/kT-\sqrt{E_G/E}\right)}d\mathrm{E}$$



If S(E) ≈cst :
Mainly the Gamow peak energy range will contribute

p + p

1st stellar reaction

$T \approx 15\ 10^6$K

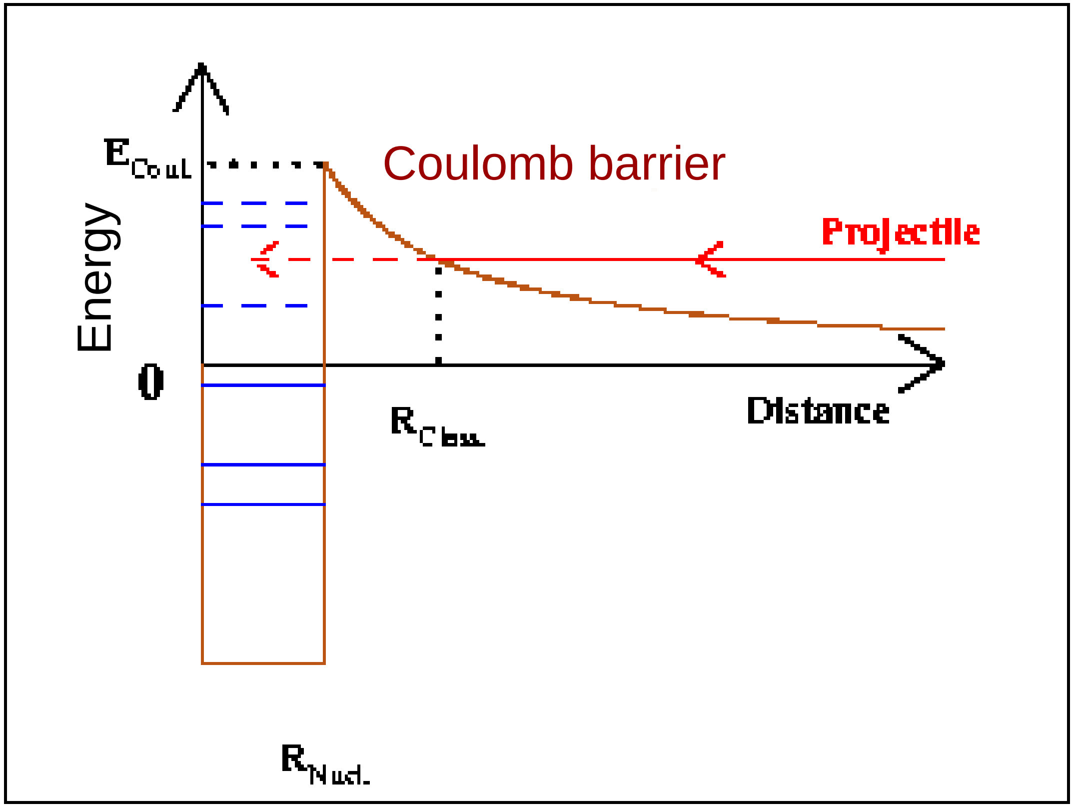
$E_0 \approx 6$ keV

$\Delta \approx 6.4$ keV

Charged particle reactions

In stars: energy is always smaller than the Coulomb barrier !

Very small cross sections



$$V_c = \frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 R}$$

p+p example :

$V_c \approx 550$ keV

(for $R = 1.3\left(A_1^{1/3} + A_1^{1/3}\right)$ in *fm*)

should be compared to E_{int}

In the core of the Sun : $T \sim 15\ 10^6$ K

$kT \sim 1.3$ keV $<< V_c \Leftrightarrow d_{min,Coul}(1.3\text{ keV}) = 1.1\ 10^3$ fm $>> R \approx 2.6$ fm

Very small interaction probability for p + p

Astrophysical S factor : S(E)

Cross section variation

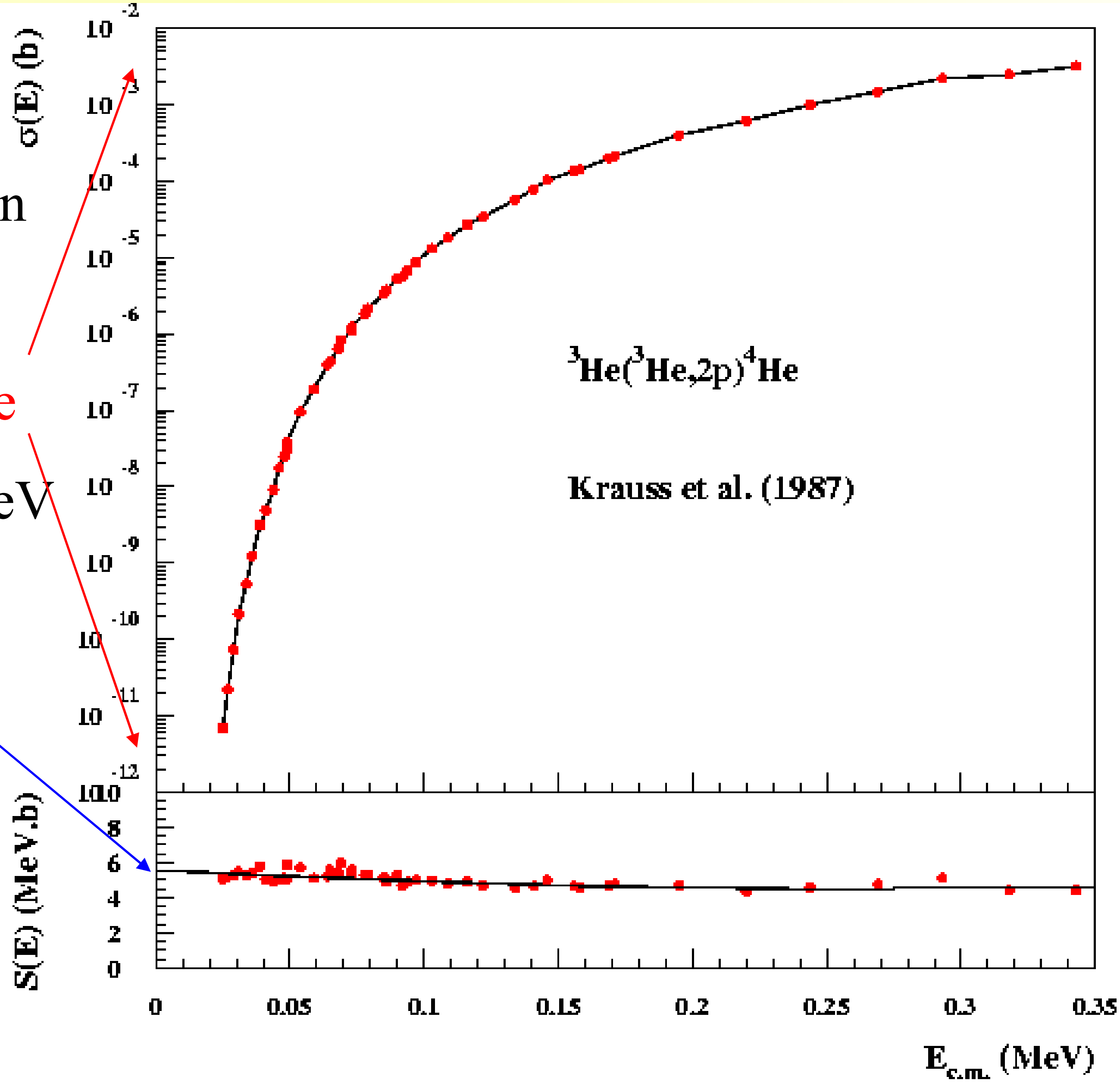
$\sigma(E)$:

9 orders of magnitude

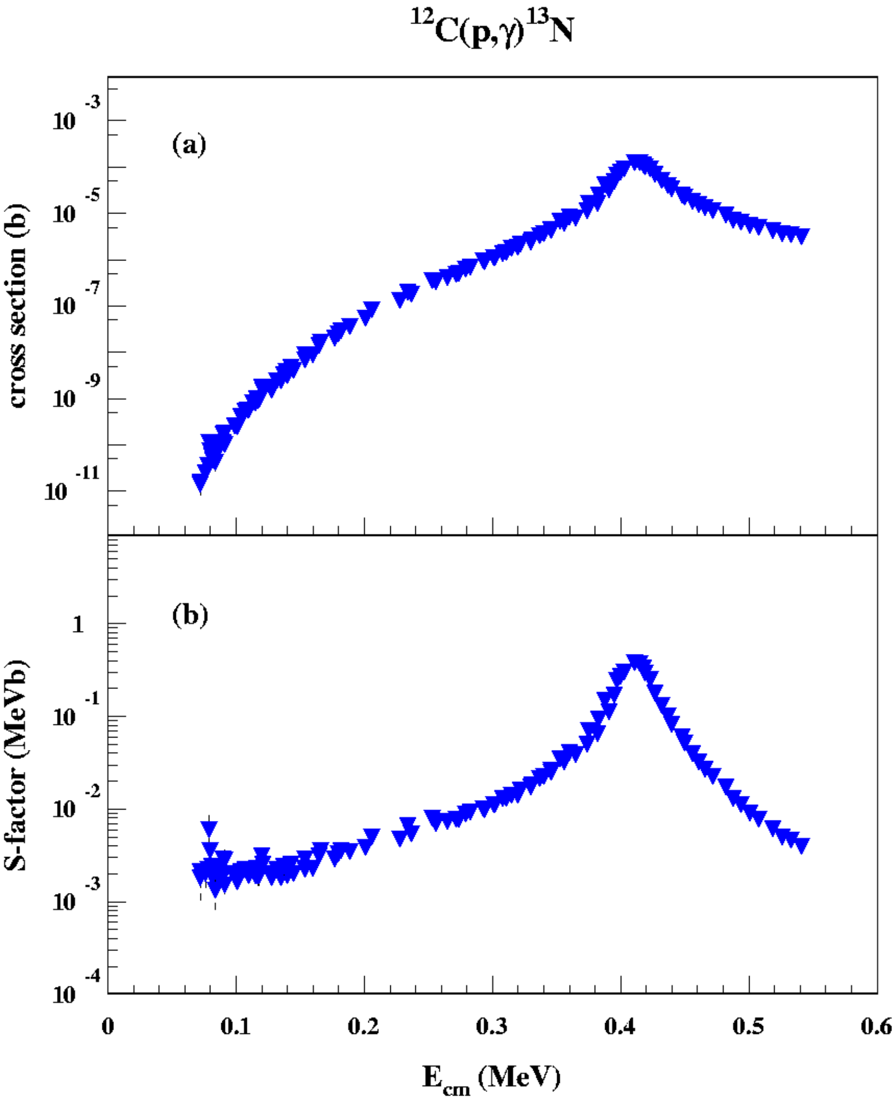
between 25 and 340 keV

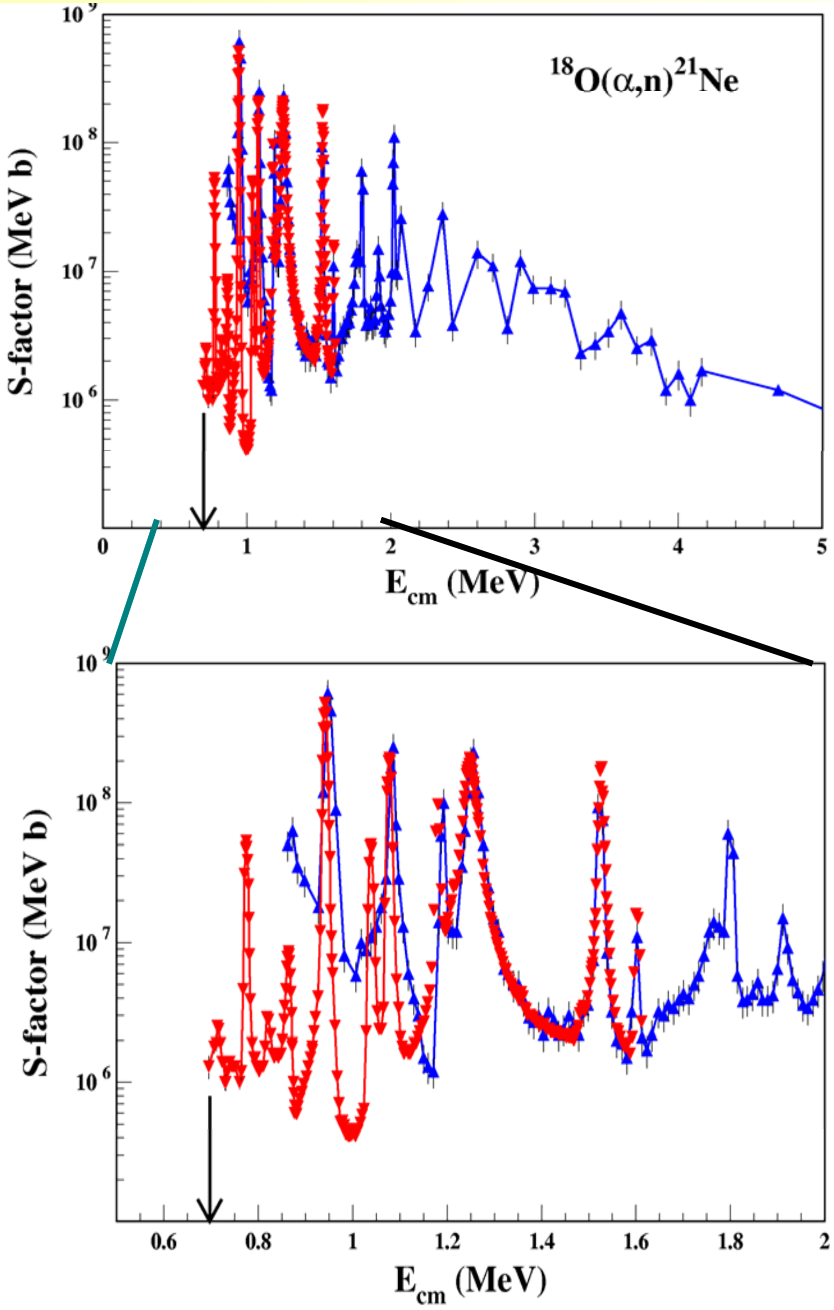
$S(E)$ variation : 50%

⇒ Extrapolation
at low energy

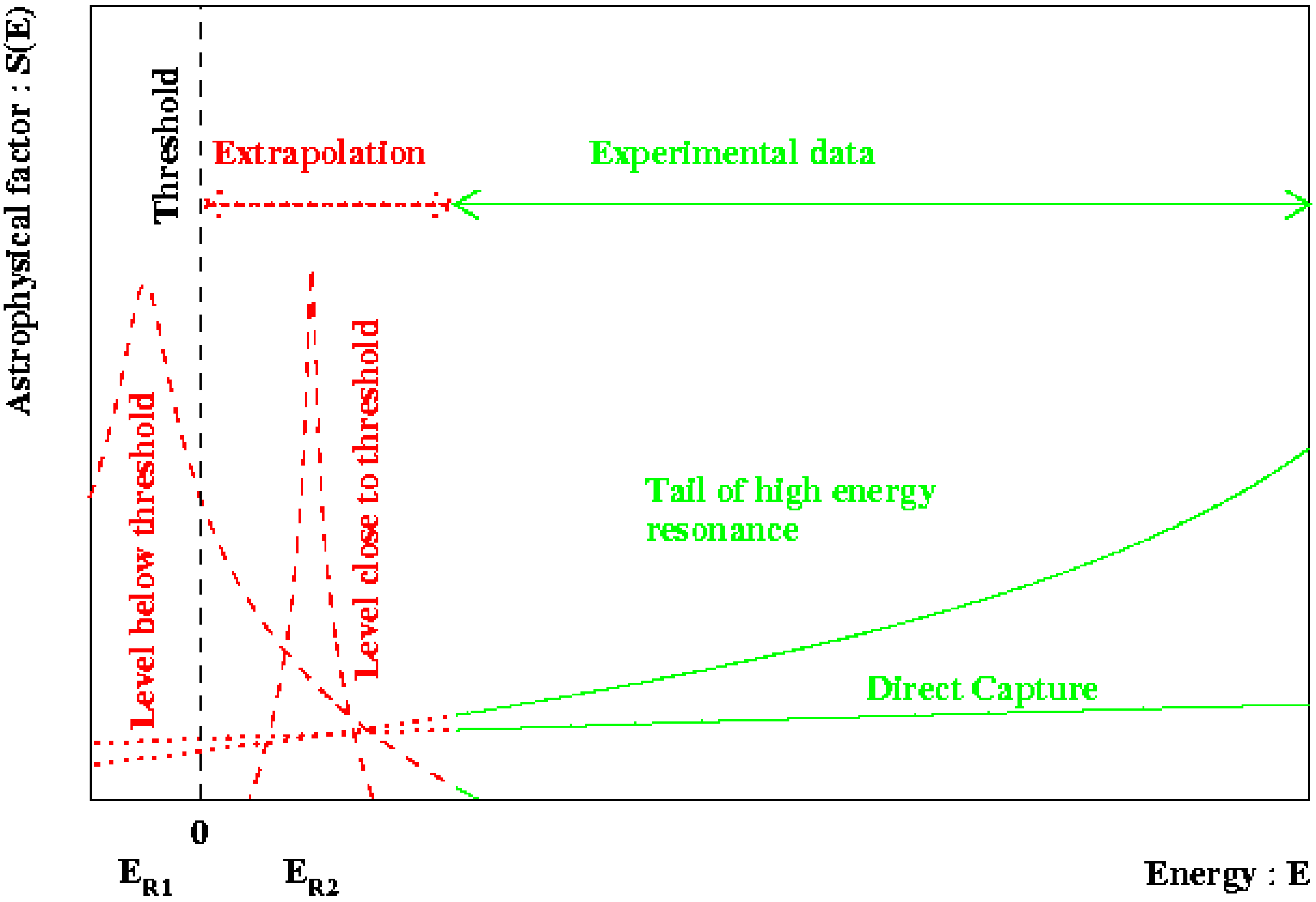


Simple or multiple resonances





Low energy extrapolation dangers



Nuclear models and experimental data are needed

SBBN framework

Quite well known : Universe is a hot and dense gas

Thermodynamics → Statistical equilibrium between all the particles

Expansion → quick temperature decrease

→ particle evolution

Age of the Universe in the range 1 s to 3 min ;

Temperature cooling down from 10x to 1×10^9 K

Energy decrease from 1 to 0.1 MeV

Thermodynamics →

Most probable state = state of minimum energy

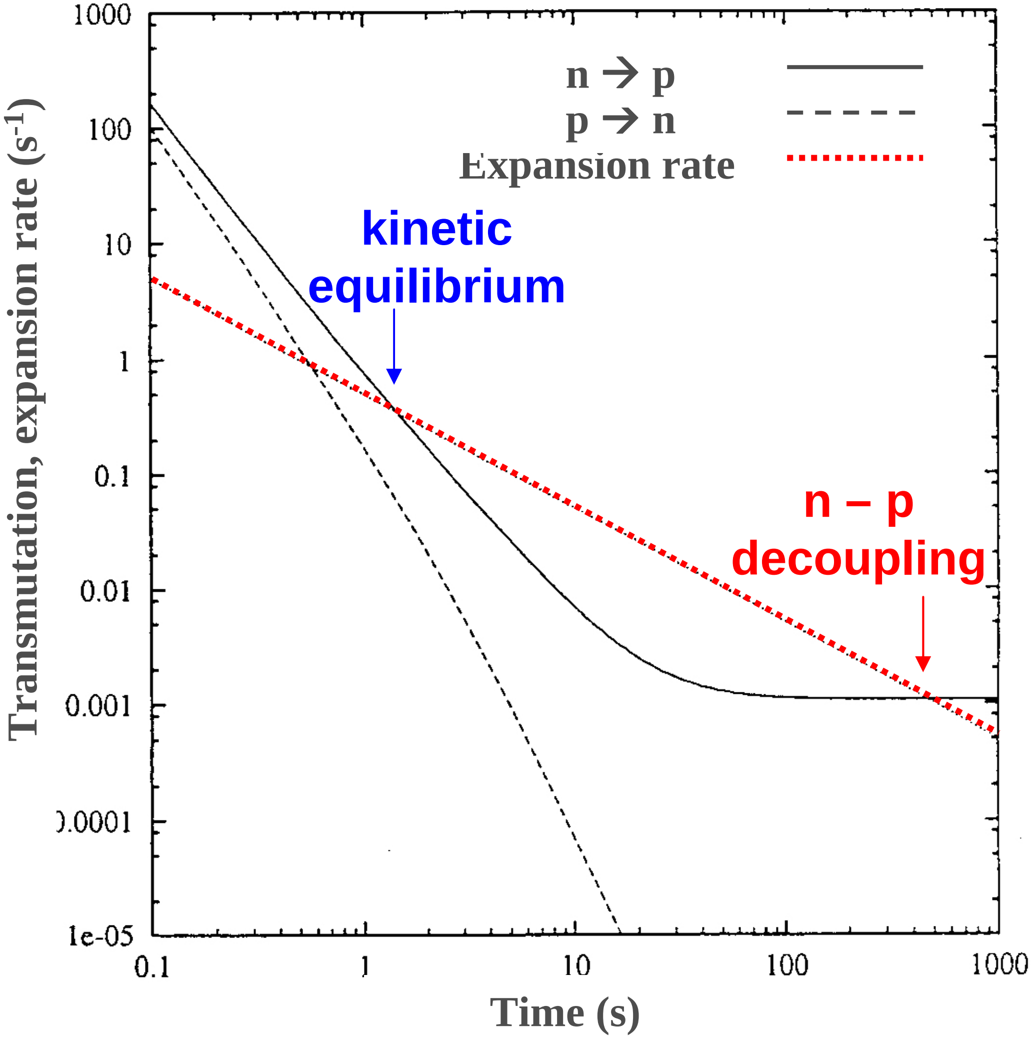
Governs the primordial plasma all along its evolution

Universe is mainly made of photons, ν, $\bar{\nu}$, e^+, e^-, p and n

Nucleosynthesis (-I)

T ~ 10^{10}K ⇔ 1 MeV : équilibrium $p \leftrightarrow n$

Nuclei heavier than A = 1 cannot exist : only p and n



$$p \leftrightarrow n + e^+ + \nu_e$$

$$n \leftrightarrow p + e^- + \overline{\nu}_e$$

$$n + \nu_e \leftrightarrow p + e^-$$

$$p + \overline{\nu}_e \leftrightarrow n + e^+$$

Equilibrium $p \leftrightarrow n$ as long as reaction rate > expansion rate

$N_n/N_p = \exp(-Q/kT)$

$Q = M_n - M_p = 1.29$ MeV

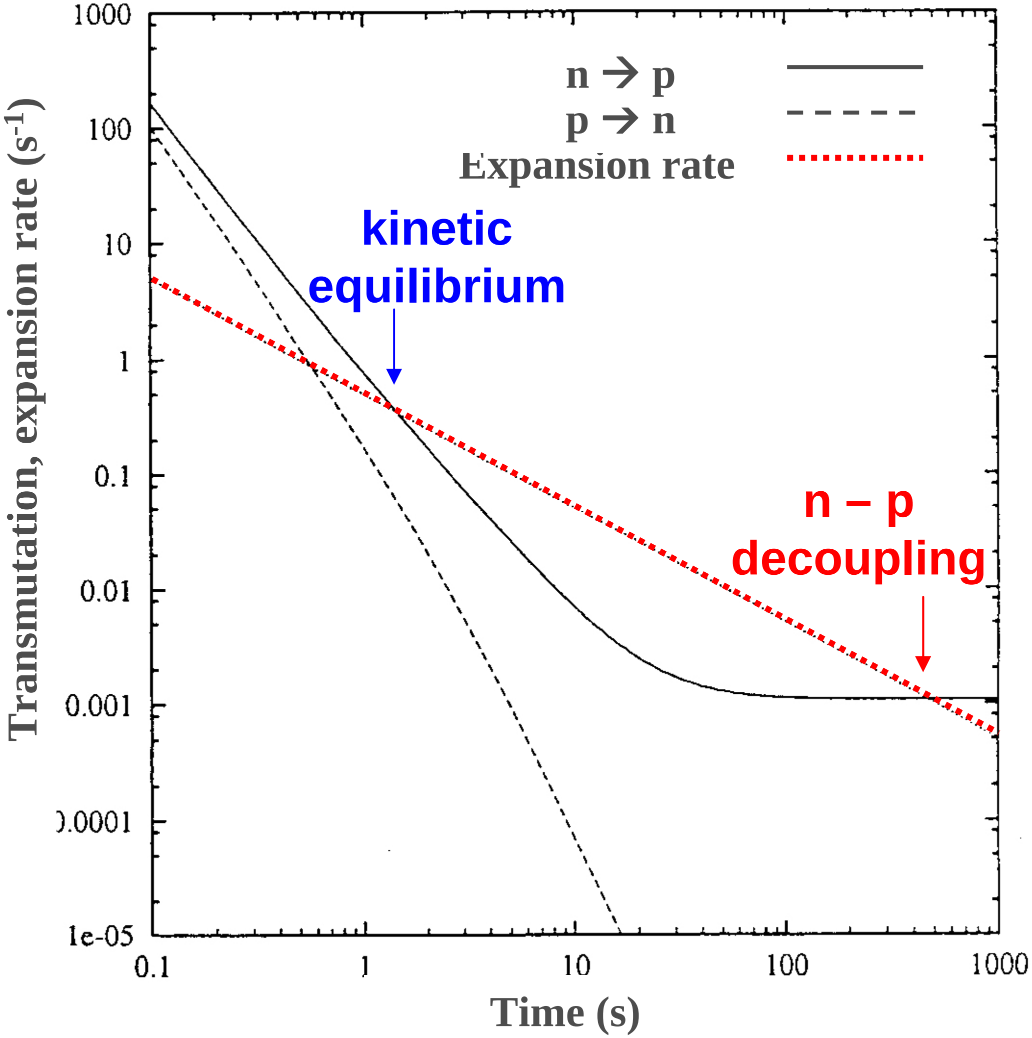
n, p = 2 quantum states of the same particle: the nucleus

Transmutation rate n → p

Expansion rate > reaction rate

→ decoupling → n, p = 2 different particles

→ different evolutions



Decrease of the neutron mass fraction

t ~ 1000 s

Reaction rate > expansion rate

but p is stable

and n → p

with $\tau_{1/2}$ = n lifetime in vacuum

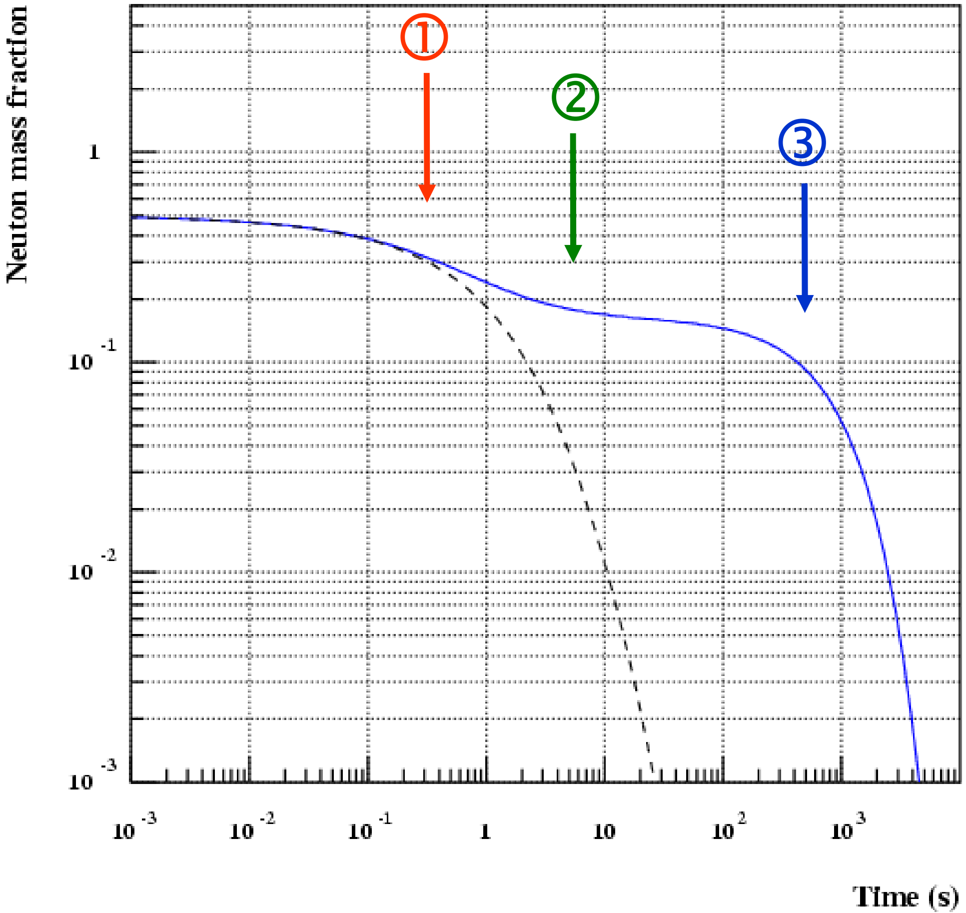
As soon as the more stable state becomes heavier nuclei

→ D formation

…

First steps of the BBN

Neutron mass fraction evolution



1. n ↔ p decoupling
2. free decrease of n
3. D formation

- - - - - - - n↔p equilibrium

——— Exact calculation

High T, minimal free energy states
→ n and p

Low T, minimal free energy states
→ heavier nuclei

Because of the low nucleon density
→ only 2 particle reactions

Primordial nucleosynthesis = succession of 2 particle reactions

The first one = D formation

n are preserved because trapped in the D nuclei

Primordial nucleosynthesis (I)

Neutrons decay until T is low enough: the n+p → D+γ reaction becomes faster than the deuterium photodisintegration : D+γ → n+p

(Q = -2.2 MeV)

D energy is smaller than n + p energy

Nuclei are forming : nucleosynthesis begins

Then, $t \approx 3$ mn, $T \approx 10^9$ K and N_n has decreased to $N_n/N_p \approx 0.1$

After enough D abundance increase, ^{4}He is quickly formed via T and ^{3}He

$D + p \rightarrow {}^3He + \gamma$
$D + D \rightarrow {}^3He + n$
$D + D \rightarrow T + p$

$T + D \rightarrow {}^4He + n$
$T + {}^4He \rightarrow {}^7Li + \gamma$
${}^3He + n \rightarrow p + T$
${}^3He + D \rightarrow p + {}^4He$
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^7Li + p \rightarrow {}^4He + {}^4H$
${}^7Be + n \rightarrow {}^7Li + p$

No stable nuclei with A=5 & A = 8 → primordial nucleosynthesis limits

only some traces of ^{7}Li, ^{7}Be are formed

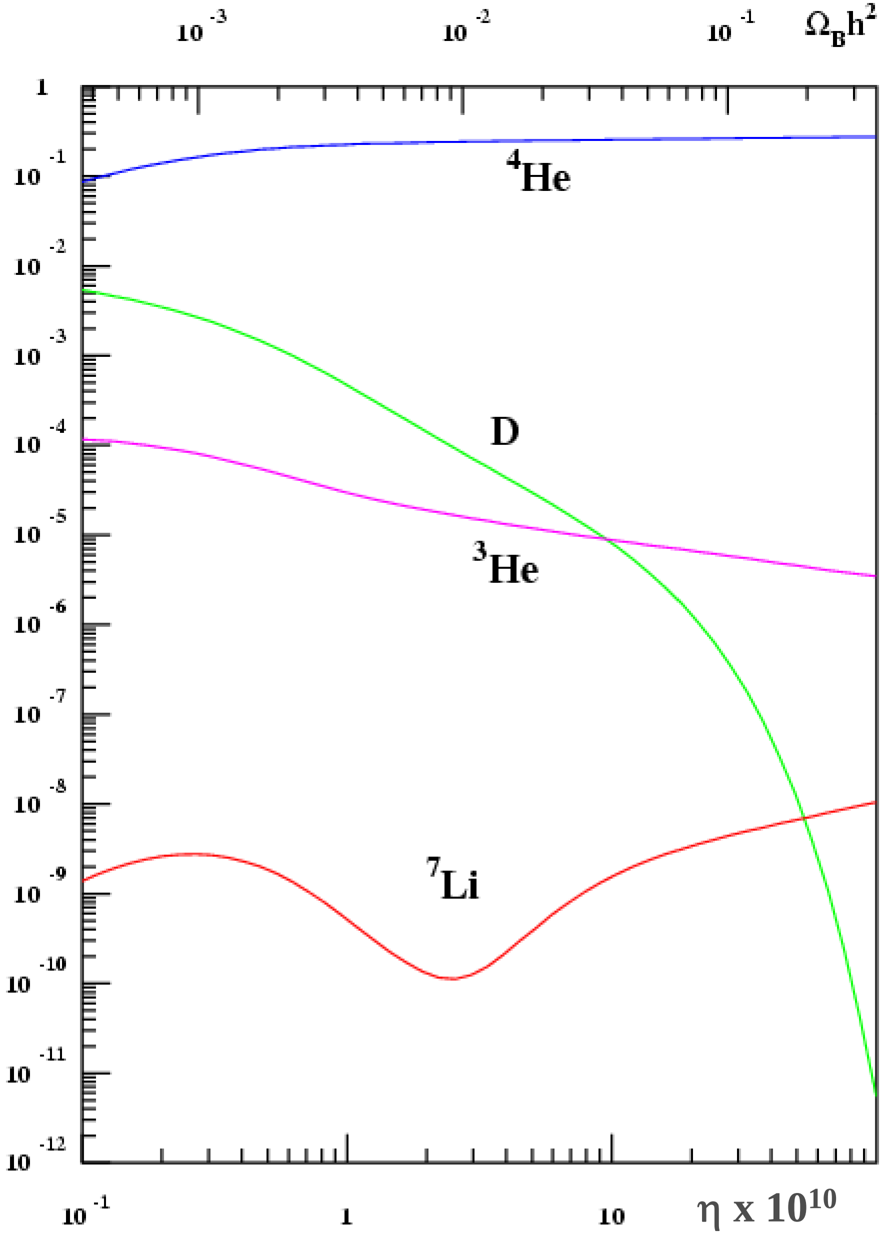
Primordial nucleosynthesis results

Succession of nuclear reactions out of kinetic equilibrium conditions

Light nuclei formation D, ^{3}He , ^{4}He and some traces of ^{7}Li, ^{7}Be

One important parameter of SBBN : the baryonic density η

Thanks to deuterium, η can be safely restricted to the 10^{-10} to 10^{-9} range



Baryonic density determination

❑ Standard primordial Nucleosynthesis (SBBN)

Comparison between calculated and observed primordial abundances of ^{4}He, D, ^{3}He, ^{7}Li $\Rightarrow \eta$ (ou $\Omega_B h^2$)

Needs:

✓ *precise observational data (primordials from extrapolated observations via chemical evolution models of the galaxies!)*

✓ *precise nuclear data*

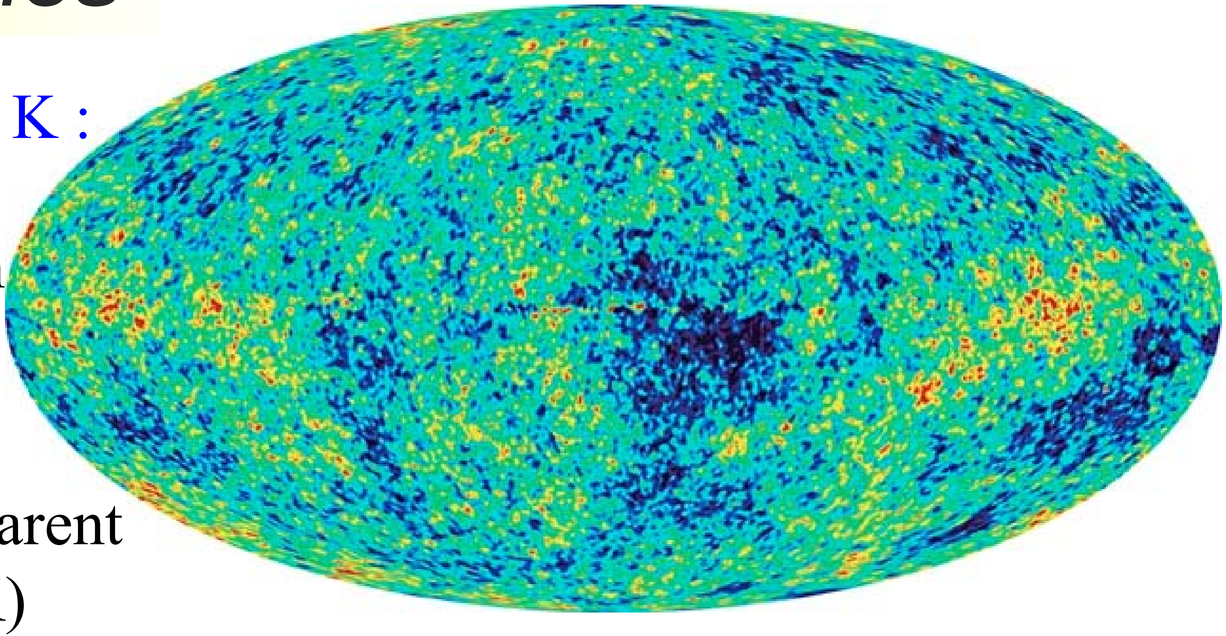
❑ Anisotropies of the cosmological microwave background (CMB)

BOOMERanG, CBI, DASI, MAXIMA, ARCHEOPS, WMAP, Planck…..

❑ Primordial abundance observations : Lyman-α HI and HeII absorption lines

(looking in the quasars direction)

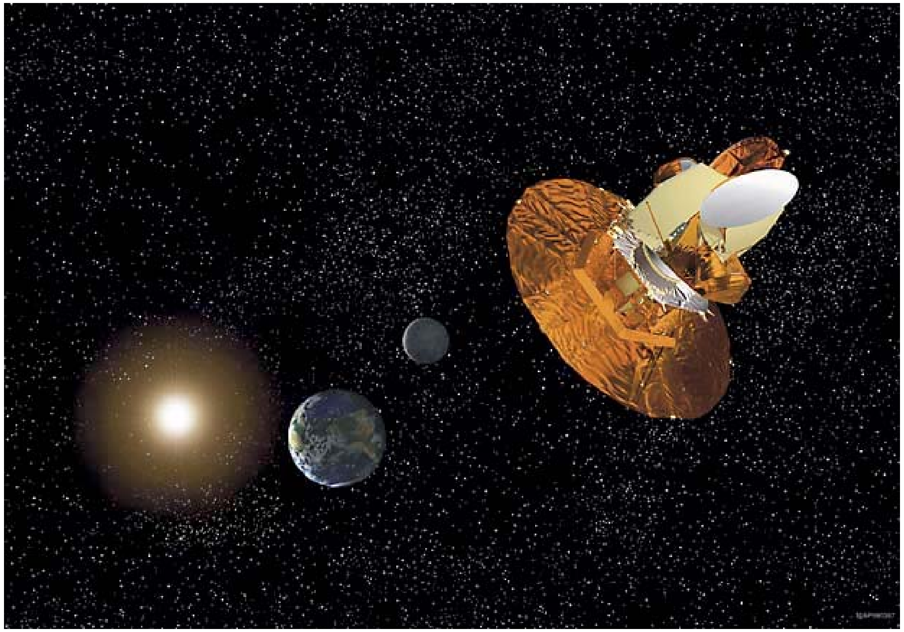
CMB anisotropies



At t≈0.3 My and T≈3000 K :
recombination:
e^- and nuclei combination
to nuclei to for neutral
atoms.

Universe becomes transparent
(now T = 2.725 K)
(microwave energy range)

After COBE, new generations of instruments (BOOMERanG, CBI, DASI, MAXIMA, ARCHEOPS)
Now WMAP and Planck/HFI dedicated to anisotropy studies of the CMB.



CMB anisotropies

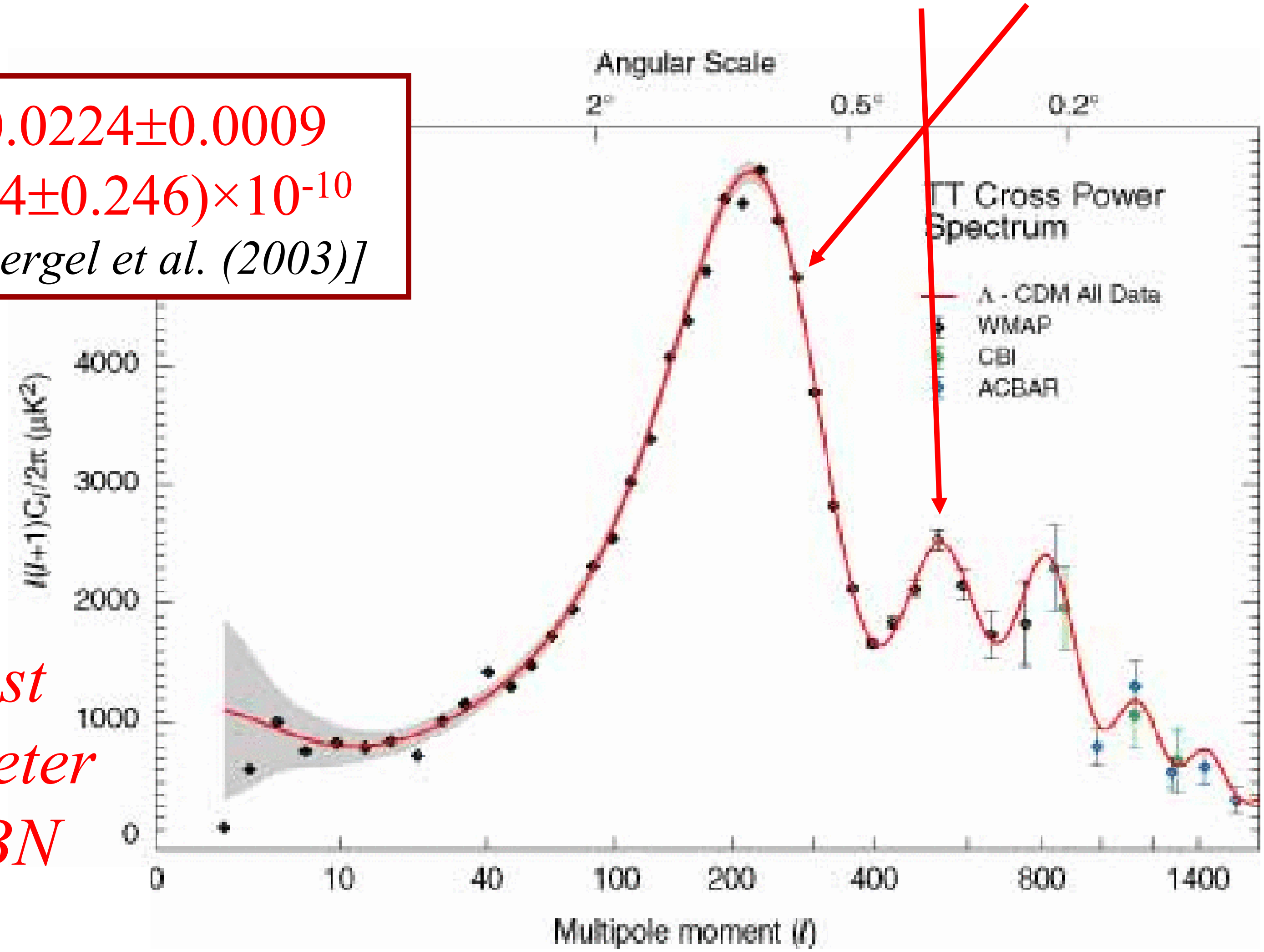
Spatial fluctuations spectrum of CMB

- **Geometry ($\Omega_T \approx 1$), 1st peak**
- **Ω_b (2nd/1st peaks)**

$\Omega_b h^2 = 0.0224 \pm 0.0009$

$\eta = (6.134 \pm 0.246) \times 10^{-10}$

[WMAP: Spergel et al. (2003)]



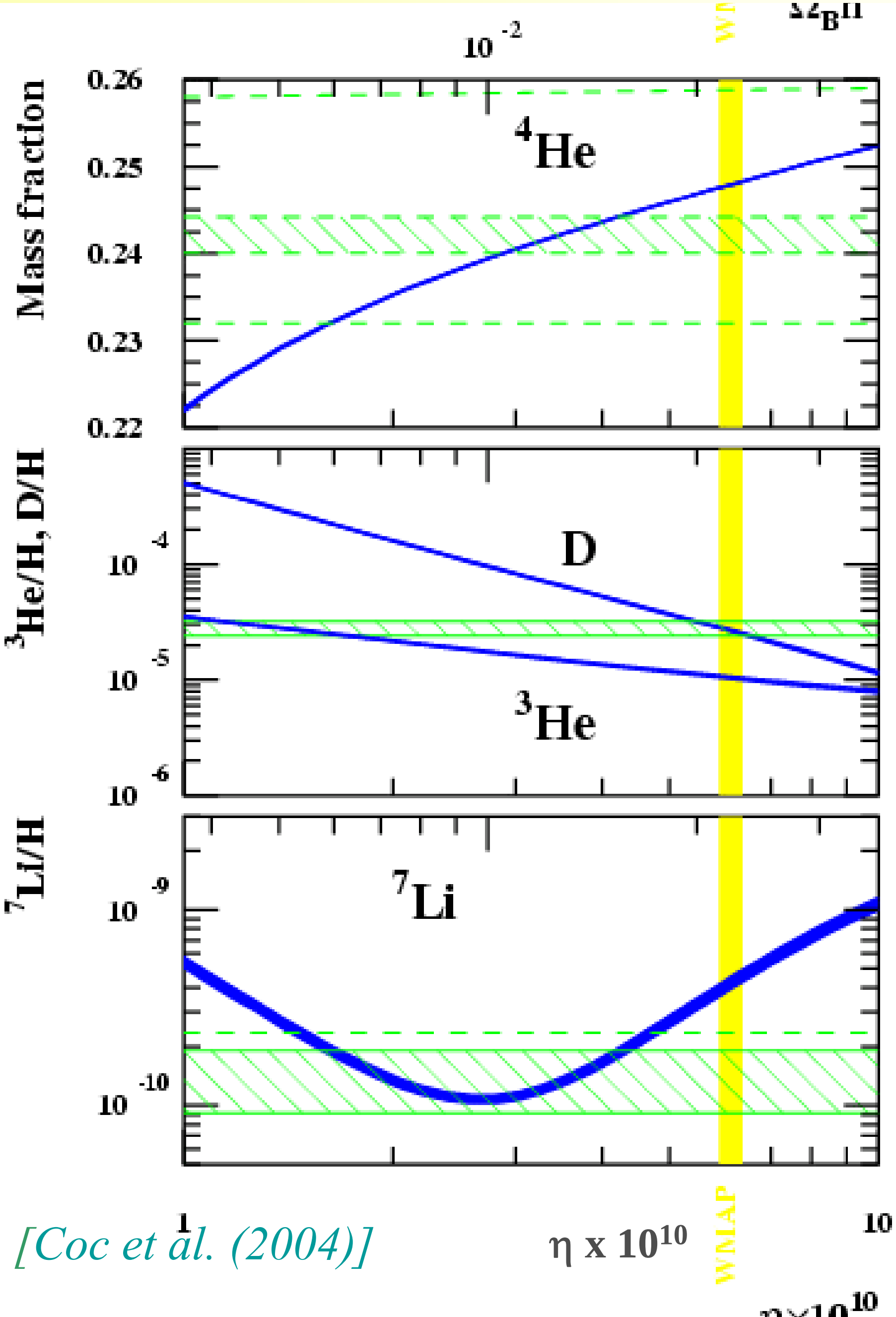
Fix the last free parameter of the SBBN

Observed vs calculated abundances

Primordial abundances

- H : more than 75% in mass
- ^{4}He : blue compact galaxy observations → 24% in mass
- D : local interstellar medium; protosolar clouds; cosmological clouds
- ^{7}Li : low metallicity stars
- $\Omega_B h^2 = 0.0224 \pm 0.0009$

[WMAP: Spergel et al. (2003)]



[Coc et al. (2004)]

Primordial nucleosynthesis

To find a model in agreement with observation data :

a new theory is needed, « beyond the standard model »

Then?

Universe is around 3 minutes old ;

It is mainly a plasma made of photons, ν, $\overline{\nu}$, e^+, e^-, p, ^{4}He and traces

Temperature and density are too low to allow other reactions but too high : neutral atoms, molecules, cannot be formed

(Coulomb forces are too small compared to thermal energy)

Universe will expand during ~ 10^9 years before the gas may condensate because of tiny density variations, and form proto stars;
before nuclear reactions may be initiated (beginning of a star life);

and before the stellar nucleosynthesis will begin

Metallicity and stars

Equilibrium condition: during the whole life of the star

In astrophysics:

"metals" = everything heavier than helium

Metallicity = "metal" mass fraction (Z)

Solar metallicity : $Z_{\odot} \approx 0.013$

A first generation star was formed with primordial gas
metallicity ~ 0 : ~3/4 of H and 1/4 of ^{4}He in mass

Stars formed with metal enriched gas : second generation star
metallicity as high as the gas was metal enriched
Always a small amount : < 3%

Important observational data

Determination of elemental and isotopic abundances

from reachable material (only a tiny amount of the universe) ;

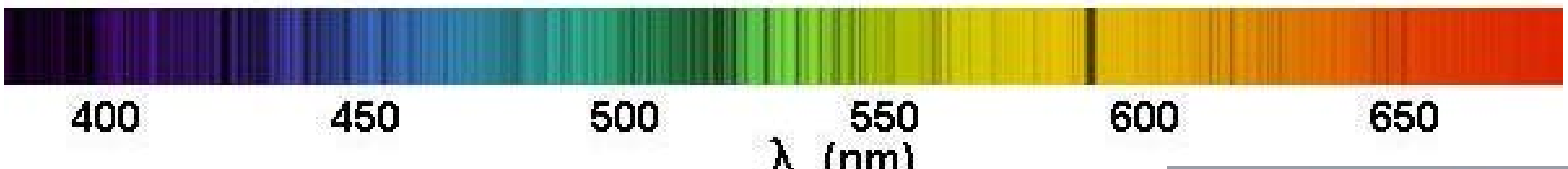
solar photosphere observations ; chondrites collection ;

cosmic radiation observations

Variety of sources with quite uniform composition

Electromagnetic observables

Traditionally : radio, visible wave lengths



in addition now : IR, UV, X, γ

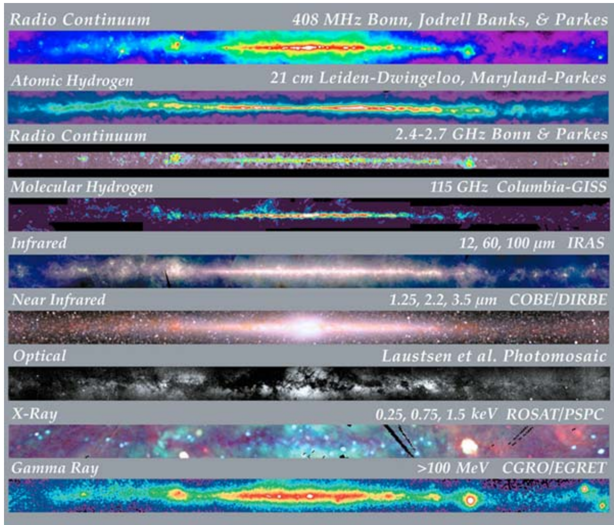
(until PeV and beyond)

→Elemental abundances relative to H

→Isotopic ratio of abundances

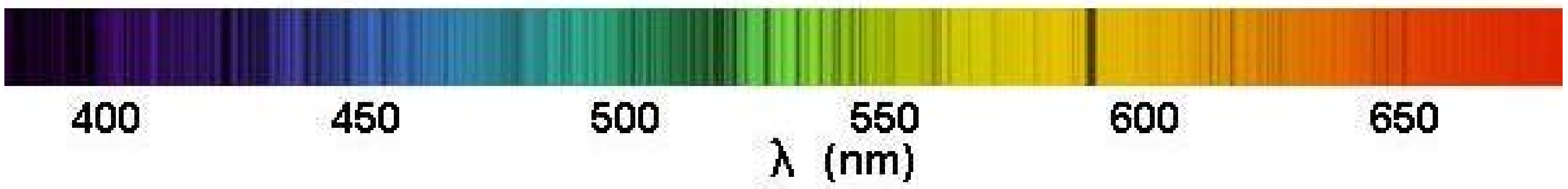
→Temperature and Luminosity

A new observable : *neutrinos*



Important observational data

Stellar electromagnetic spectra



Continuous spectrum + (dark or intensive) lines

Continuous spectrum : *black body distribution* → Temperature (T)

dark lines : *absorption (→ some material lies between the emitting star and the detector)*

intensive lines : *emission (→ some processes excite atoms and/or molecules on the stellar surface, they deexcite by radiation emission)*

→ Elemental abundances relative to H

→Isotopic abundance ratios

Luminosity (L) → *amount of energy radiated per time unit : deduced from the magnitude (amount of energy received per time and surface unit on top of the atmosphere) and the distance of the star*

→ Star classification : luminosity vs temperature

Hertzsprung-Russell Diagram

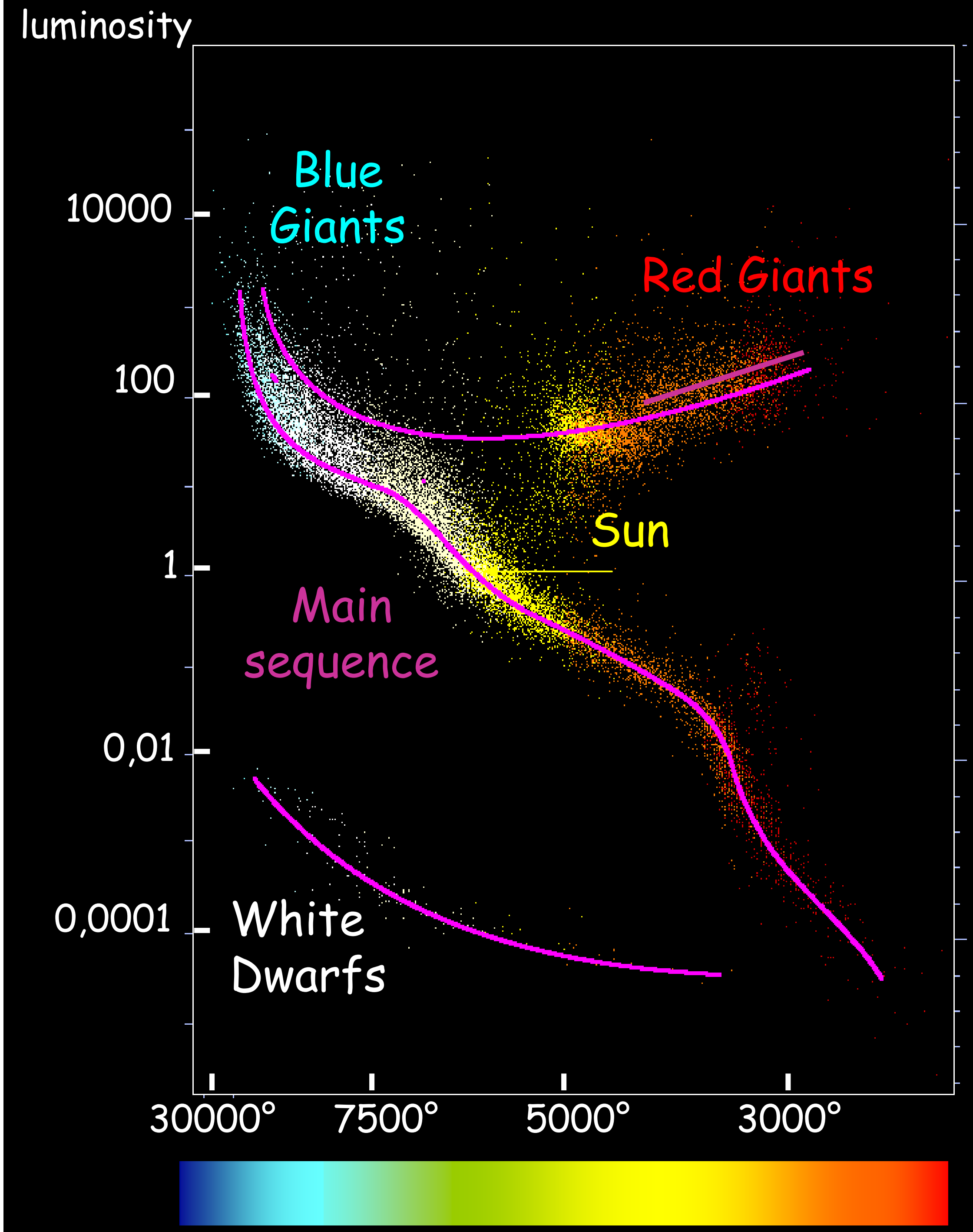
temperature - luminosity

Correlation lines :

→ star classification

$T \Leftrightarrow E = k_B T$

with $k_B = 8.62 \, 10^{-8}$ keV/K



Surface temperature

Color

HR Diagram

temperature - luminosity

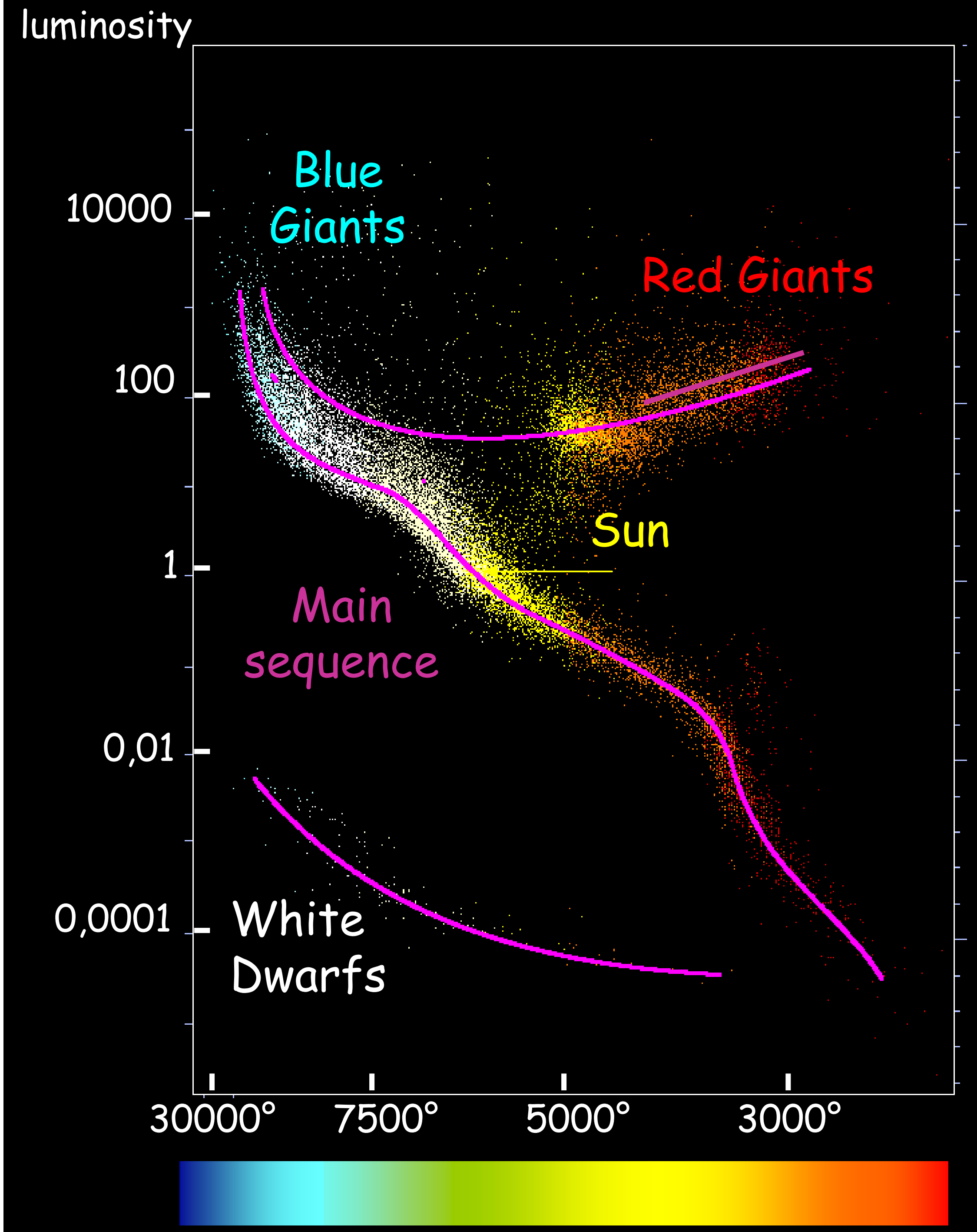
At a given time

Interpretation in terms of stellar population :

Relative proportion of the various kinds of star

Surface temperature

Color



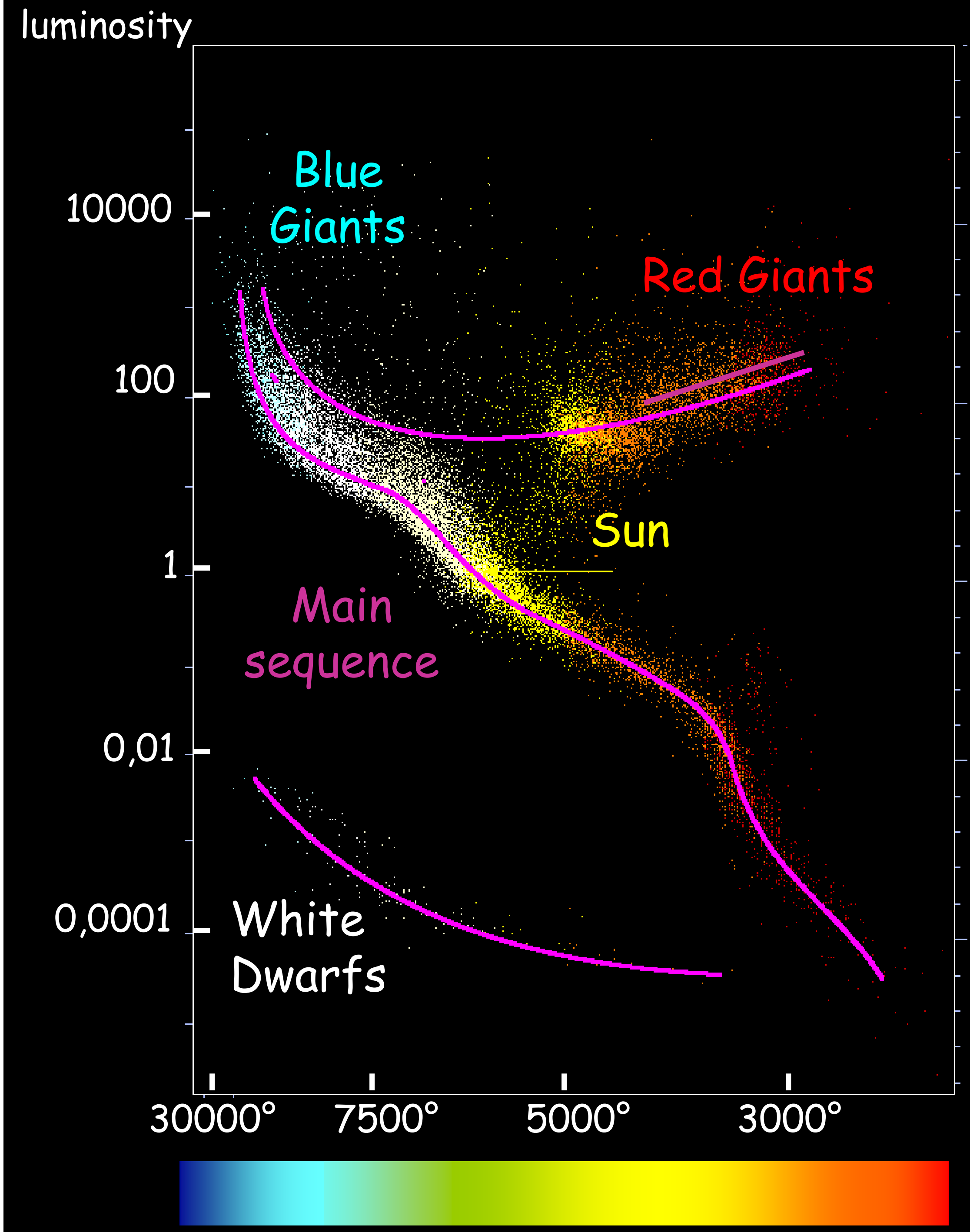
HR Diagram

temperature - luminosity

In terms of star evolution

Star classification :

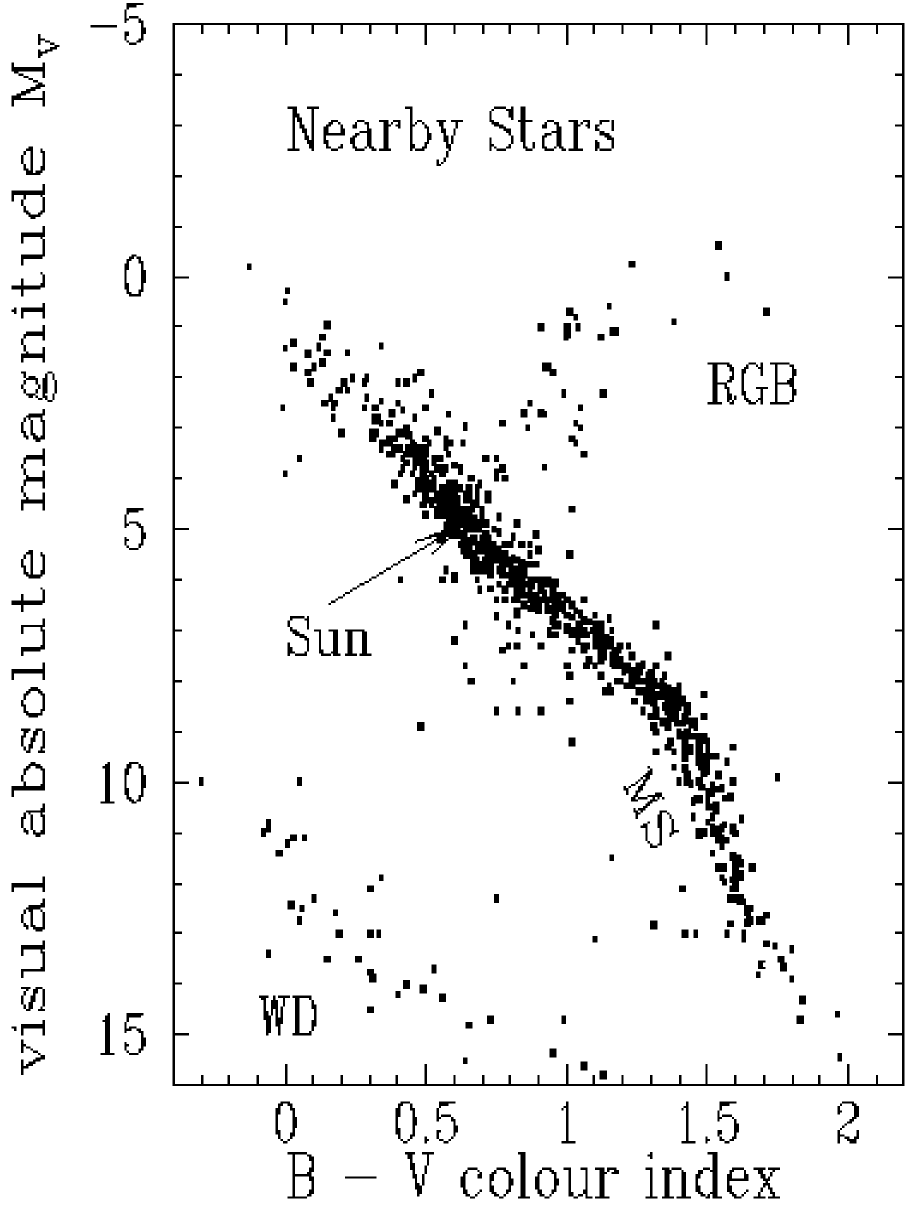
correlation lines



Surface temperature

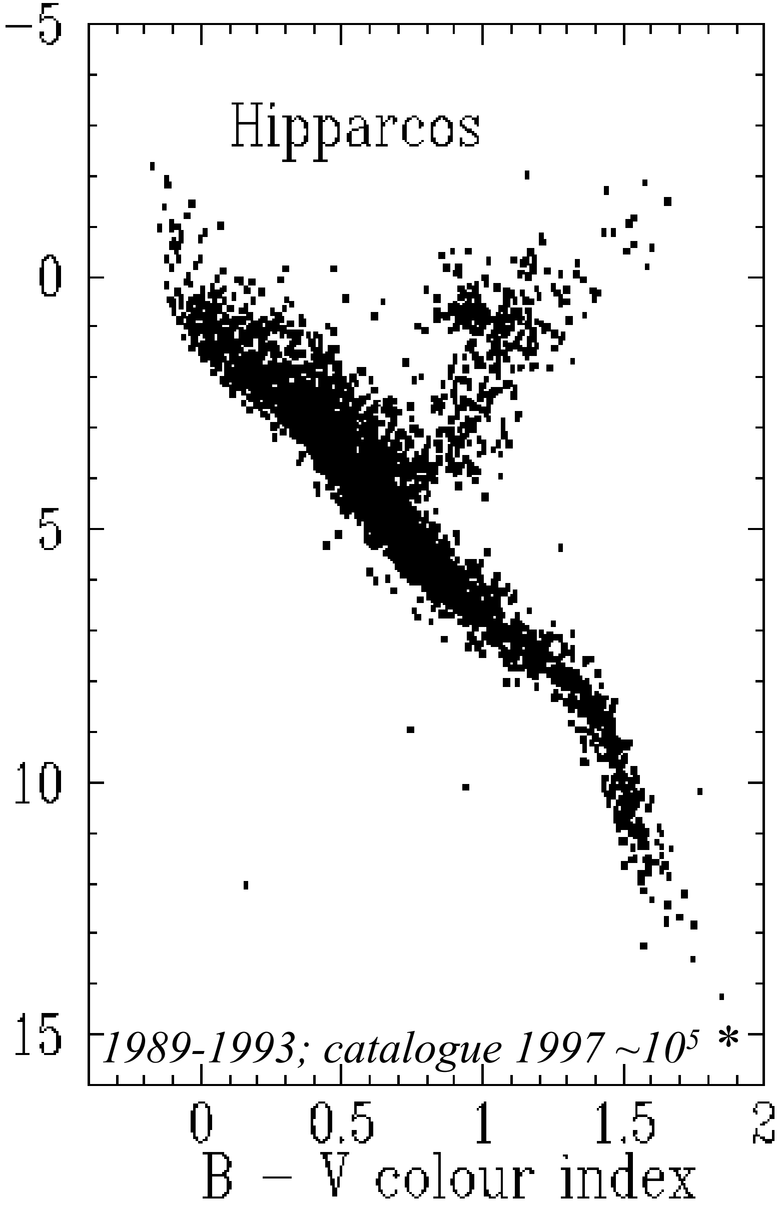
Color

~ 1000 *



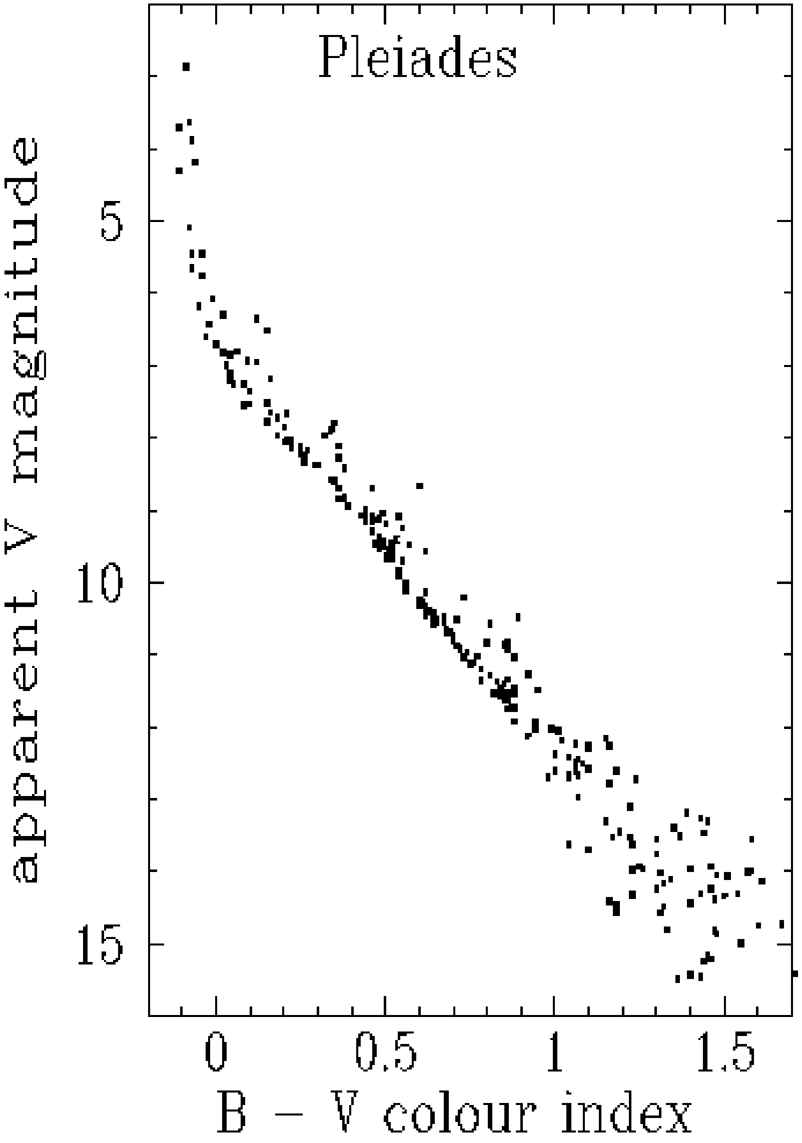
$D < 20pc$

~ 5000 *

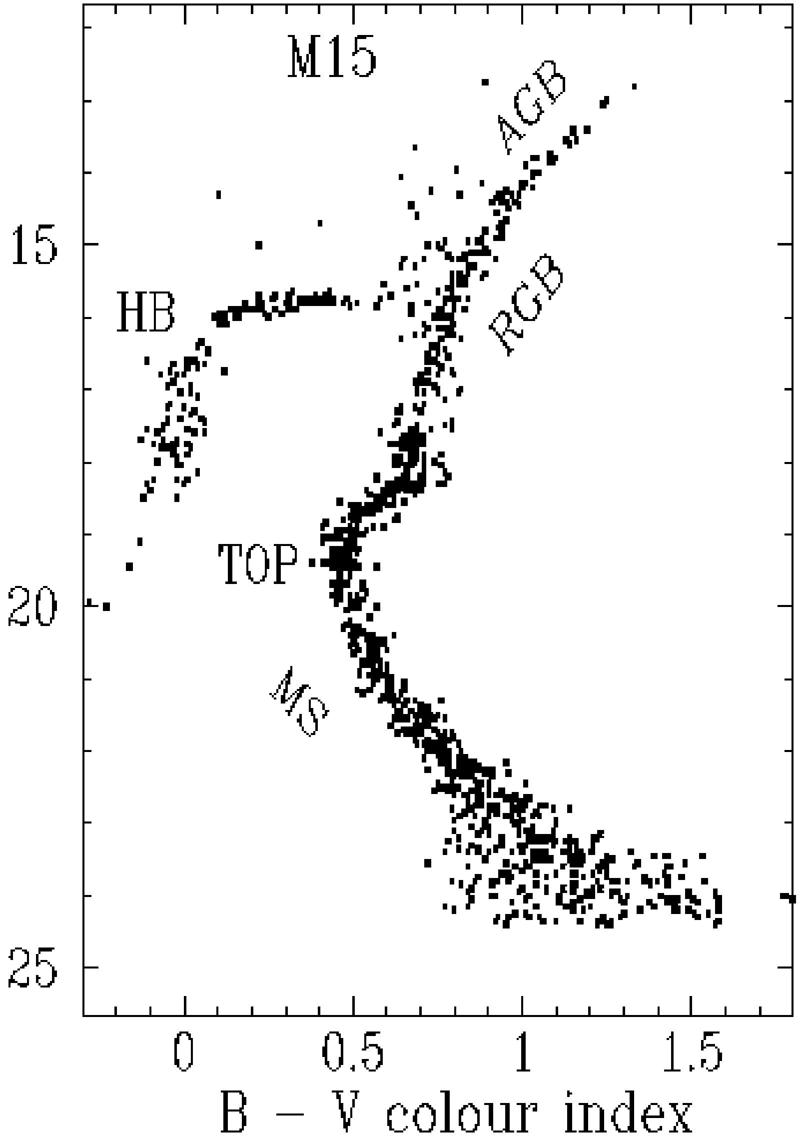


*1989-1993; catalogue 1997 ~10^5 **

$60\ pc < D < 70pc$



Young galactic cluster



Old globular cluster

Star formation (-1)


Orion nebula

http://www.nasa.gov/mission_pages/hubble/multimedia/orion_nebula.html

After BBN, the primordial gas contains mainly, ν, $\bar{\nu}$, e^+, e^-, p and light nuclei

Tiny density variations allow gas concentrations : massive, dense and cold molecular clouds

Stars are formed by gas condensation because of the gravitation

Initially : cold gas

gravitation induces the free-fall collapse of gas fragment

(τ_{ff}~ hour for the ⊙)

→ proto stellar gas fragment

Star formation(0)

Free-fall collapse → progressive increase of the internal pressure
→ particle ionization
→temperature increase due to opacity increase
→ gas collapse slows down

Until the proto-star reaches a hydrostatic quasi-equilibrium state :
a large amount of gas is totally ionized in the core

Then new contraction with new temperature increase
until density and temperature high enough to initiate nuclear reactions

Only if the mass of the gas fragment is high enough
otherwise, it will never radiate enough energy :
the gas fragment remains in a quasi equilibrium state
never a star

Star formation

When the gas fragment is massive enough

T increases up to $\sim 15 \times 10^6$ ($T_6 = 15$)

Nuclear reactions may occur → beginning of the star life

Mechanical equilibrium : stationnary state

gravitation + internal pressure = 0

stationnary evolution → scaling time >> free-fall time

Energetical equilibrium : stationnary state

Nuclear energy compensates energy losses in each point of the star

radiation + convection + ν *+ thermal conduction*

+ mass losses (stellar winds)

stationnary → long scaling time >> Helmholtz - Kelvin time

(time needed to release all the emitted power without nuclear energy source :

$\tau_{HK} \sim 10\ 10^6$ *years for the* $\odot >> \tau_{ff}$)

D burning stage …

Mainly H and He ; but some D traces

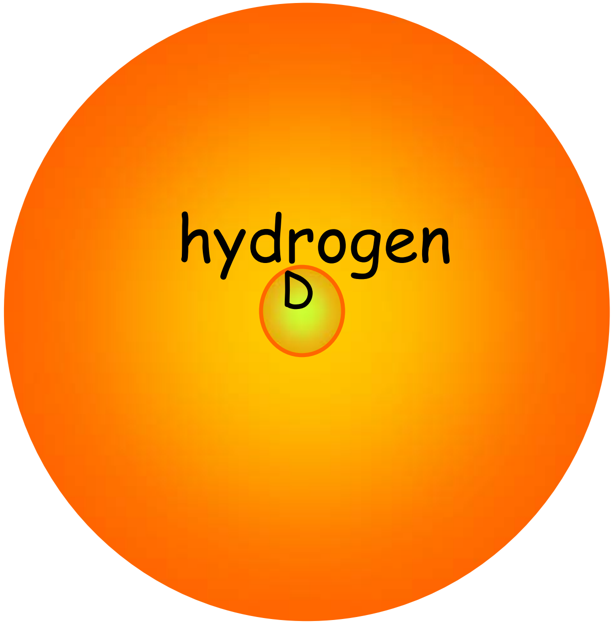
(a few 10^{-4} in mass compared to H)

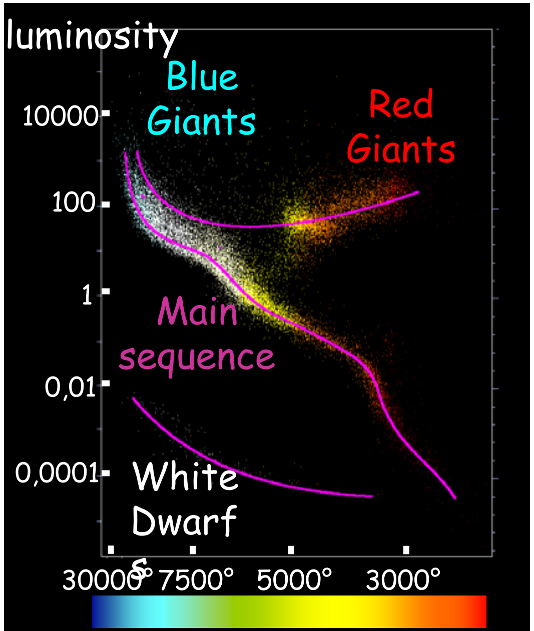
D is not very stable

→ D photodissociation

1st possible nuclear reaction

1st signals of the star





Then gravitationnal contraction

The star is getting closer to the main sequence

At the beginning of its life,
the star is on the main sequence
in the HR diagram

Stellar evolution (0)

Reference model framework (approximation)

Chemical homogeneity (when formed)

Stationnary state

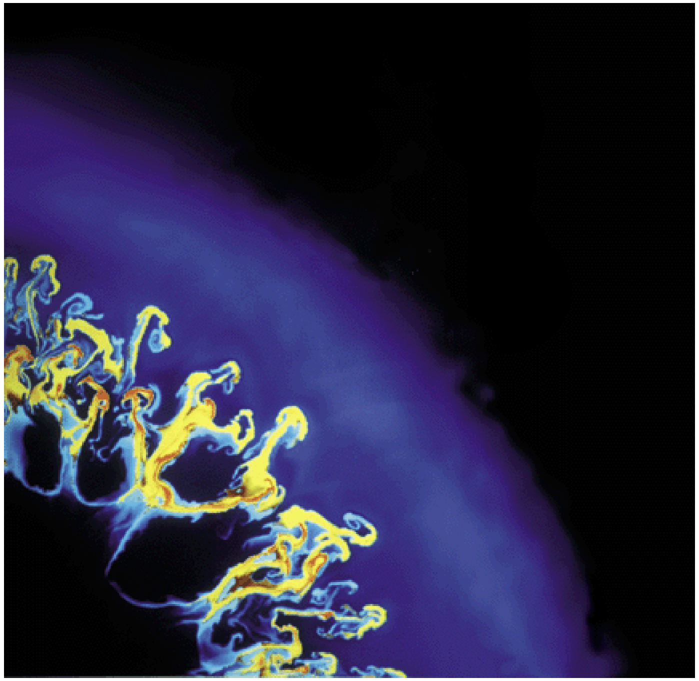
No magnetic field

No rotation

↓

Allows , in first approximation, a description of stellar evolution

~3/4 of H and 1/4 of ^{4}He



Supernova 1987A provided strong evidence of turbulence emanating from the core of the exploded star because core materials were observed well before they were predicted. The turbulence caused mixing among the layers and greatly complicated the tidy "onion" model of dying stars. [Image reproduced from Muller, Fryxell, and Arnett, Astronomy & Astrophysics 251, 505 (1991).]

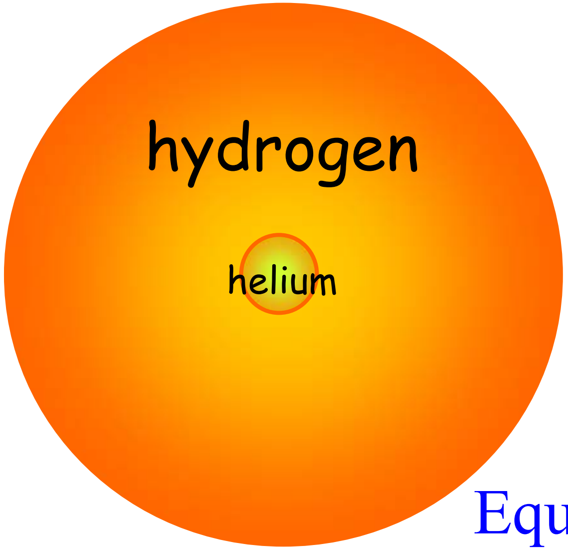
Ionized particles→ Electromagentic field → Coulomb barrier

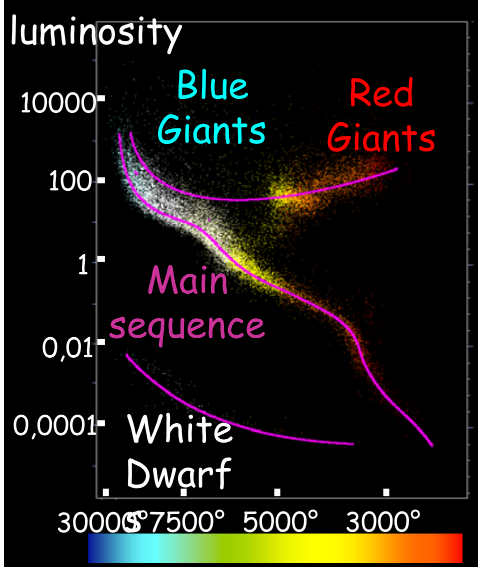
First allowed reactions between H particles

Hydrogen burning phase

Stars on the main sequence are in the hydrogen burning stage

H burning (Main sequence)





Mainly H and He

First enabled reactions :

Hydrogen fusion

→ He formation

Star is on the Main Sequence

Equilibrium : gravitation vs radiation

Increase of the central He concentration

≠ kind of burning processes depending on the chemical composition of the star gas (generation) and on its mass

First generation (tiny traces of metal –Li,Be-) and light stars → pp chains

(equilibrium at $T_6 \sim 15$; no CNO nuclei)

Second generation and massive stars → CNO cycles

(equilibrium at $T_6 \gtrsim 20$; $\exists$ CNO nuclei)

1st generation star observations: mainly H lines

pp chains (H burning)

Weak interaction
$^1H(p,e^+\nu)^2H$
→ This combustion
takes time

$\sigma \approx 8\ 10^{-27}$ b
at 5.9 keV
$\sigma \approx 2\ 10^{-23}$ b
at 1 MeV

$p+p \rightarrow {}^2H+e^++\nu_e$ 99.75%

$p+e^-+p \rightarrow {}^2H+\nu_e$ 0.25%

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

86%

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

14%

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

99.89%

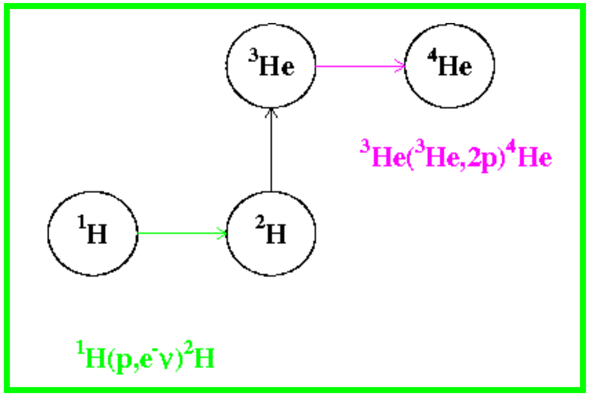
$^7Be+e^- \rightarrow {}^7Li+\nu_e$

$^7Li+p \rightarrow 2\ {}^4He$

0.11%

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

$^8B \rightarrow {}^8Be+e^++\nu_e$



$4\,{}^1H \rightarrow {}^4He$
$+ 26$ MeV

ppI **ppII** **ppIII**

pp chains (H burning)

Stops because of the lack of stable nuclei with A = 8

Central T and ρ too small to enabled any 3 body reaction

→ The end of the H burning when H is missing in the core

Time correlation with the mass of the star and its initial composition

(calculated H burning duration for the Sun : ~ 10^{10} years)

(only 10^{7} years for a 15 $M_{\odot}$ star: 1000 times less)

→ *a 1st-generation 2-$M_{\odot}$ star went out of the H burning stage a long time ago*

As H burning stage is longer than all the others together

→ *such a star also died a long time ago*

→ *only lightest 1st generation stars are still alive*

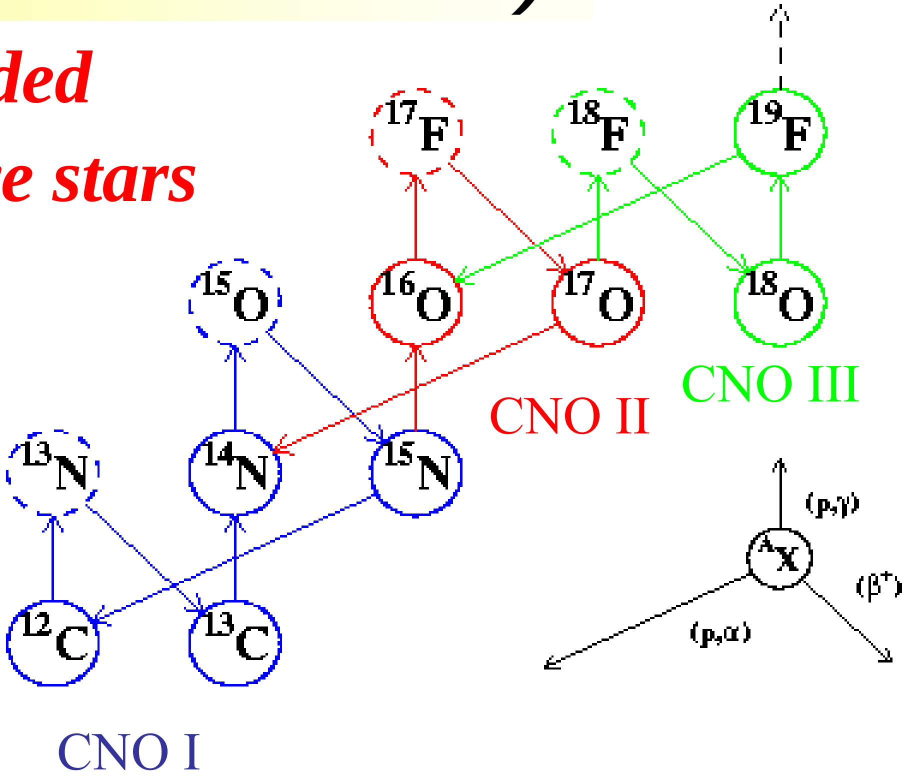
New gravitationnal contraction

The star is leaving the main sequence

(cold) CNO cycle (H combustion)

CNO nuclei are needed

2nd generation or massive stars



- $T \gtrsim 20\ 10^6$ K
- Via 3 (p,γ), 1 (p,α) reactions and 2 β^+ disintegration
- on CNO (+F) isotopes as catalysts
- $^{14}N(p,\gamma)^{15}O$, slowest reaction, it limits the energy production

it induces initial CNO change in ^{14}N

$4\,^1H \rightarrow {}^4He$

$CNO \rightarrow {}^{14}N$

Only strong interaction: quicker process

∃ other possible « cycles » for H combustion but negligible for energy production: Ne-Na and Mg-Al cycles

Will dominate in stars heavier than 1.8 $M_\odot$

End of H burning …

Only a few hydrogen in the core:

* *End of H central burning*

* *He core contraction (gravitation)*

* *Star contraction (gravitation)…*

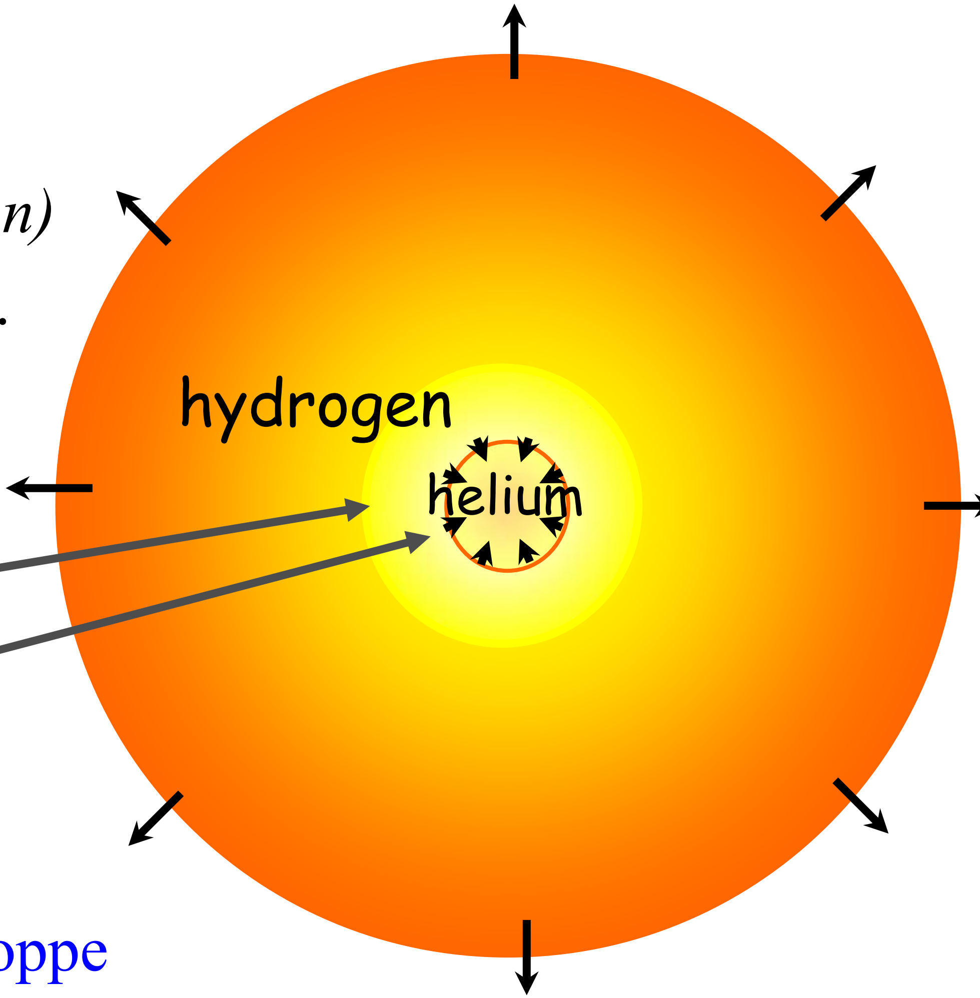
Core temperature increase
and around the core ;

→*Shell H burning*

→ *He core increase*

→*Star expansion*

Depends on the star's mass



Convective enveloppe

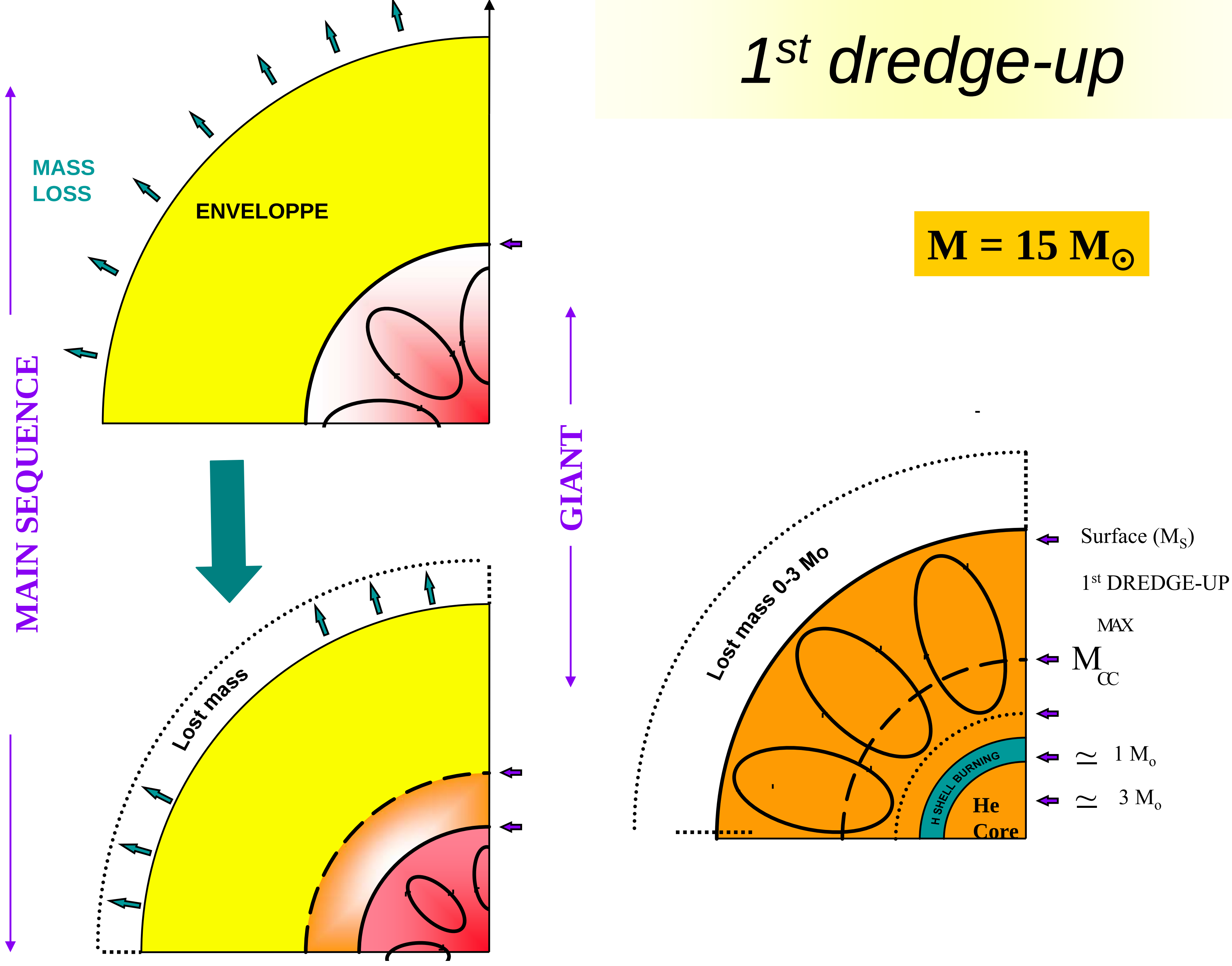
Radius increases by a few order of magnitude

Some H burning ashes are driven to the surface (1st « dredge-up »)

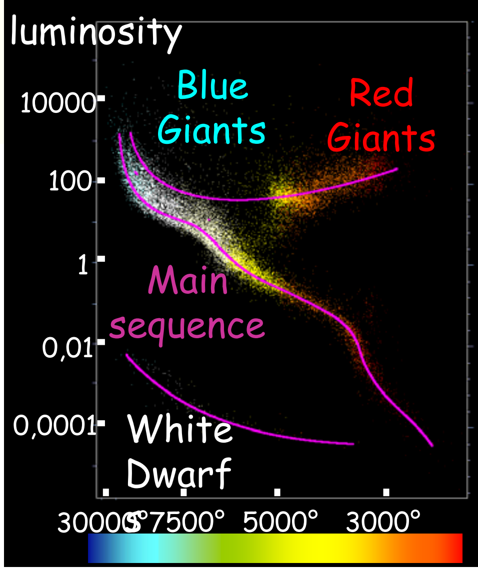
1st generation stars: more He lines may be observed

1^{st} dredge-up

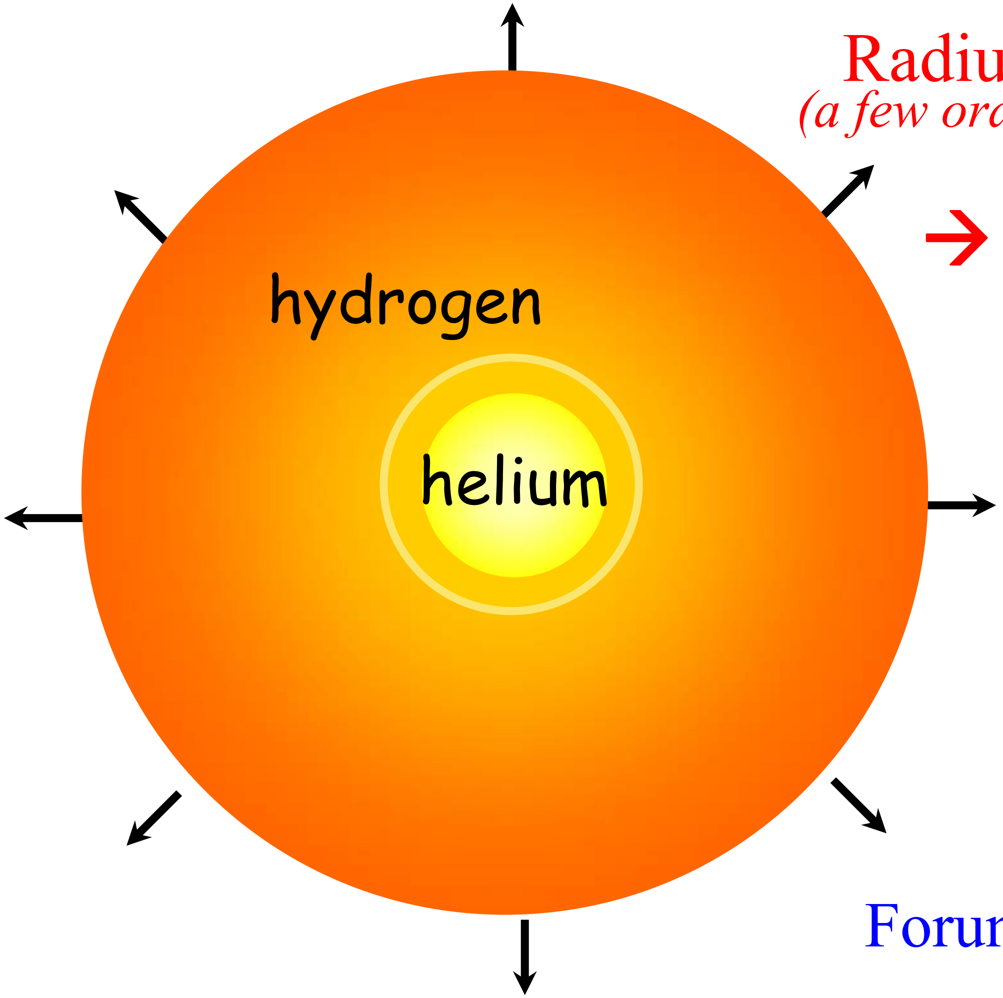
$M = 15\ M_\odot$



End of H burning → He burning



Surface farther from the core: colder temperature



Radius increase
(a few order of magnitude)

→ **Red Giant**

Central T ↗ ;

Until nuclear reactions with He are allowed

→He core contraction stops

But no stable A = 8 nucleus

Forunately: ∃ a resonant level in ^{12}C

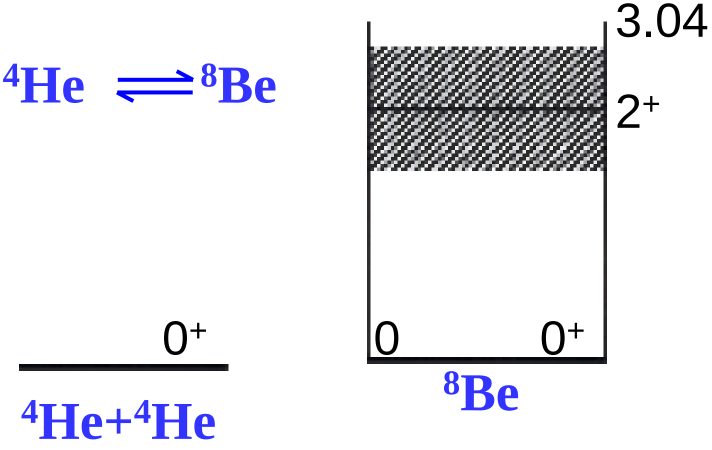
it allows α capture by ^{8}Be during the short life of ^{8}Be ($\tau \approx 2.6\ 10^{-16}$ s):

→ Triple-α process ($T_6 \approx 100$, $\rho \approx 10^5$ g/cm^3)

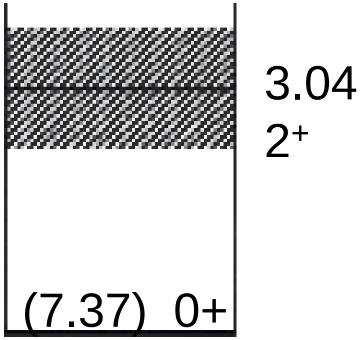
He burning

2-steps reaction via unstable ^{8}Be ($\tau \approx 10^{-16}$ s)

^{4}He+^{4}He $\rightleftharpoons$ ^{8}Be



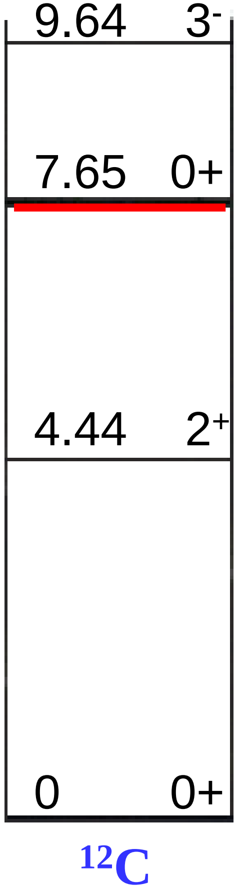
$$2\alpha \leftrightarrow {}^8Be$$



^{4}He+^{4}He+^{4}He $\rightleftharpoons$ ^{8}Be+^{4}He

$$^8Be+\alpha \rightarrow {}^{12}C$$

Resonnant reaction through 7.65 MeV (0^+) level in ^{12}C, predicted by Hoyle



3α process :

$3\,\alpha \rightleftharpoons {}^{12}C$

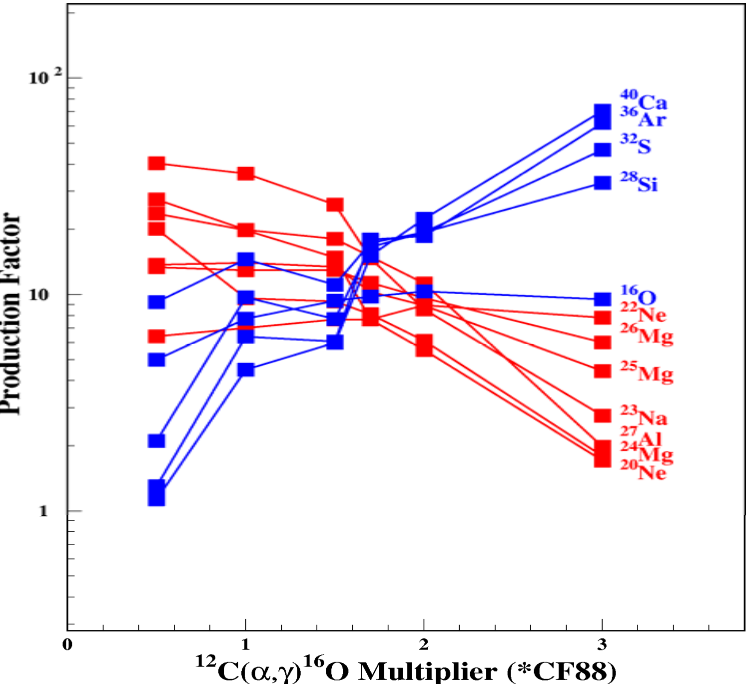
He burning

$^{12}C + ^{4}He \rightleftharpoons ^{16}O$

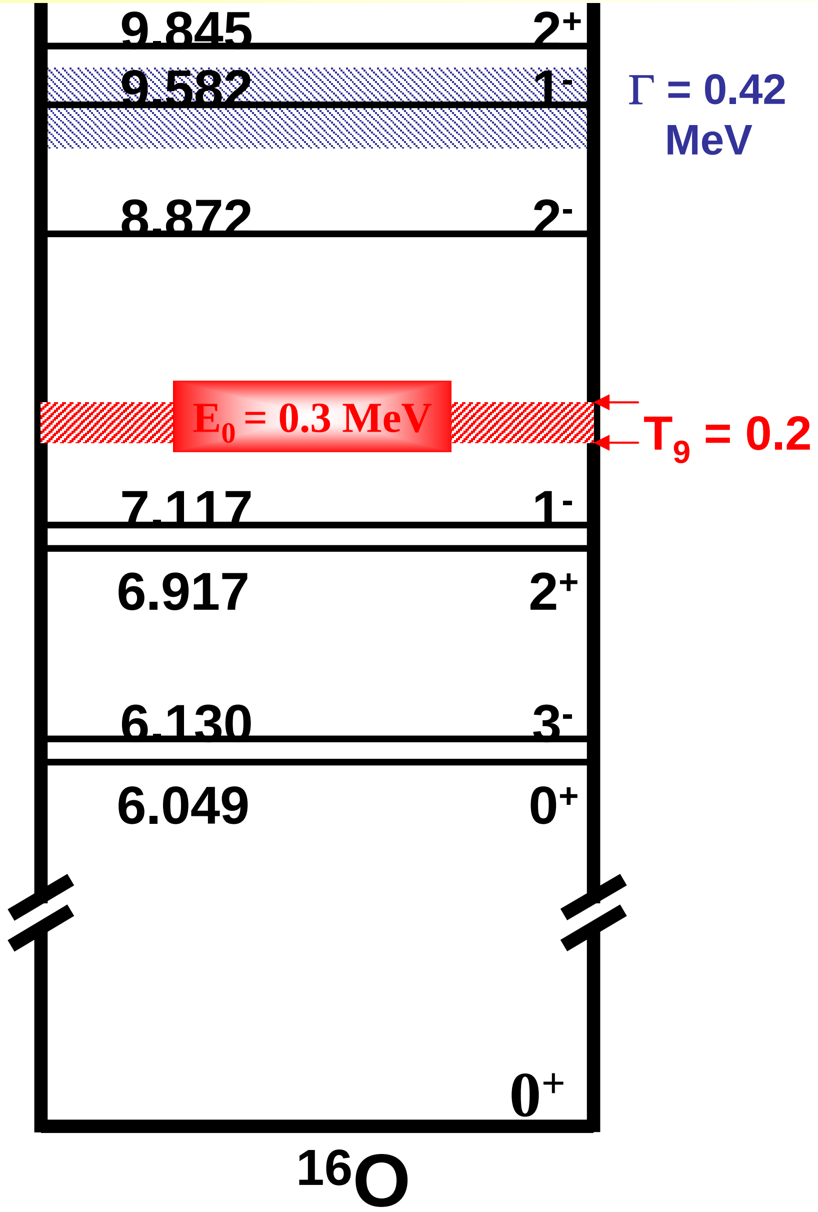
Massive-stars model calculations

7.162 $0^+,0^+,L$

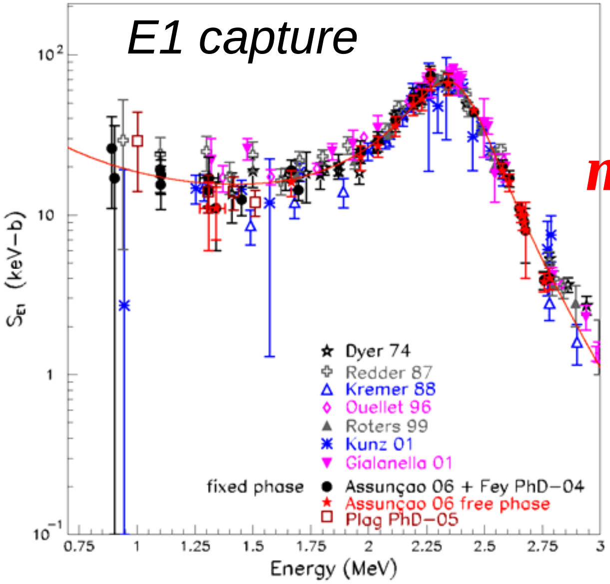
$^{12}C + \alpha$



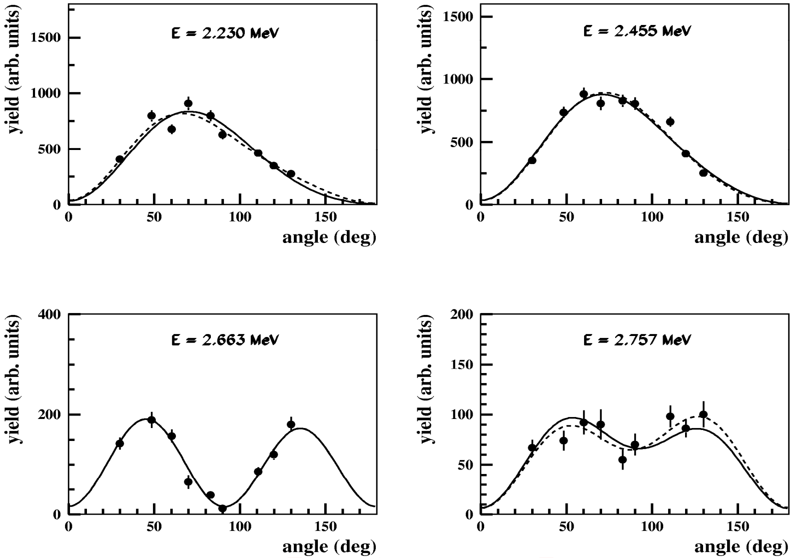
For 12-13 15-20 25-30 35-40 $M_\odot$

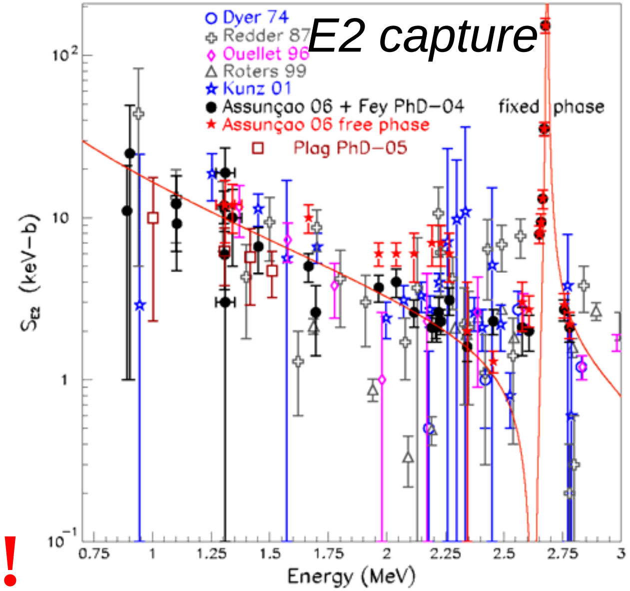


Experimental data for $^{12}C(\alpha,\gamma)^{16}O$



Low energy measurements down to $\sigma \sim 0.1$ nb



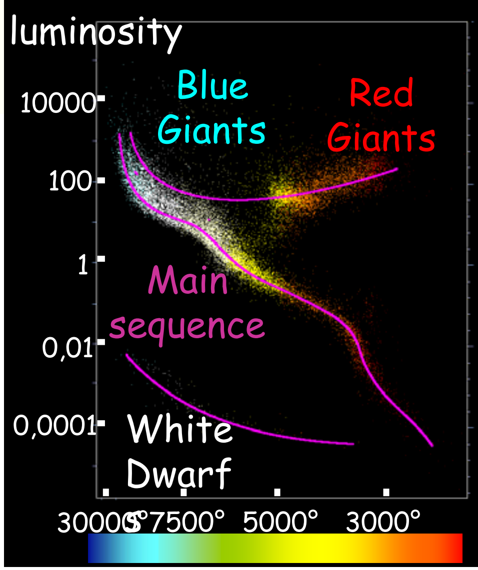


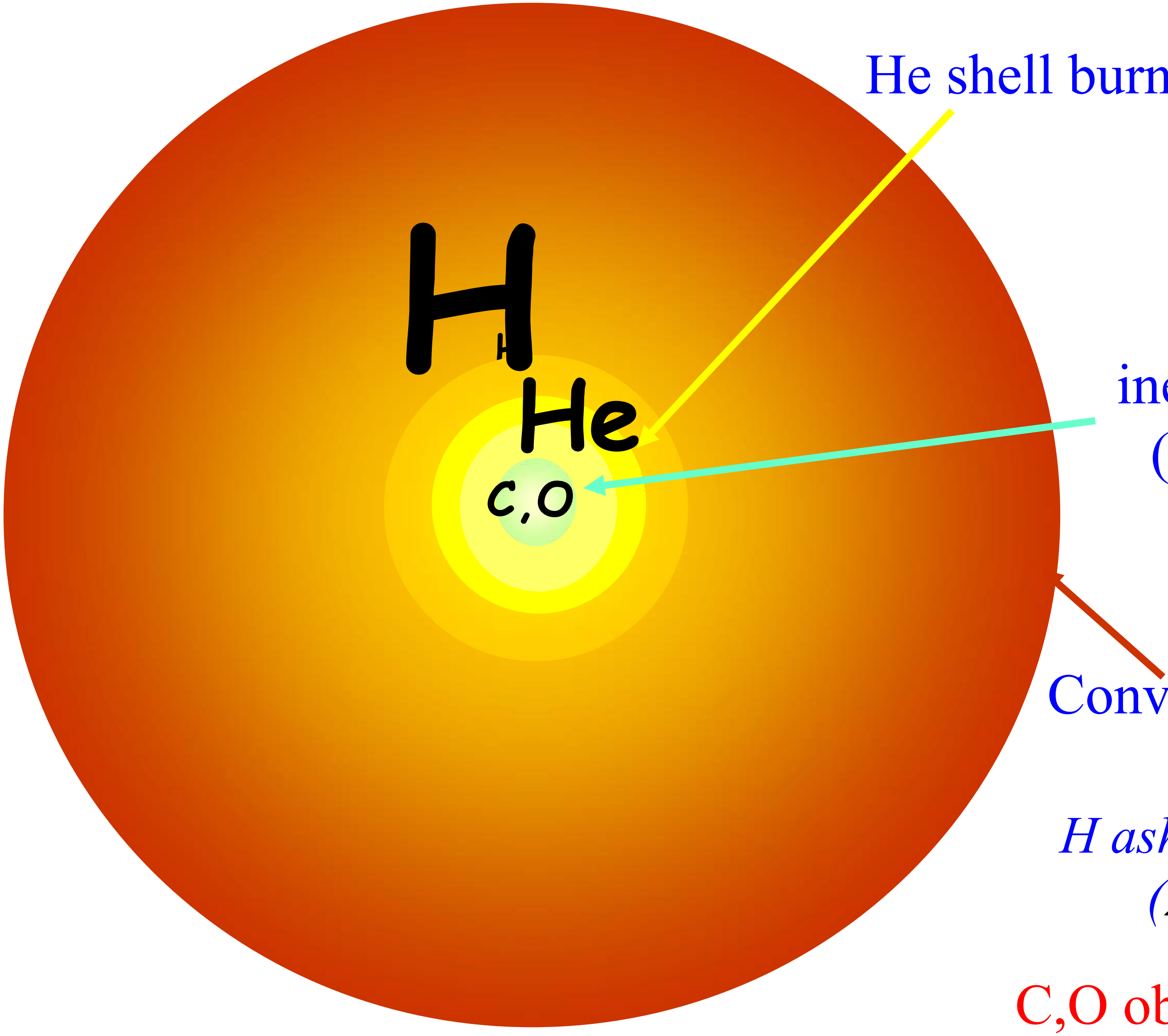
Extrapolations down to 300keV !

Projects: i.e. Triumf; Strasbourg-Orsay-Naples (down to 700keV ?)

He shell burning

(Asymptotic red giants : AGB)





He shell burning

inert ^{12}C and ^{16}O core (He is exhausted) :

gravitational contraction

Convective enveloppe (H)

radius ↗

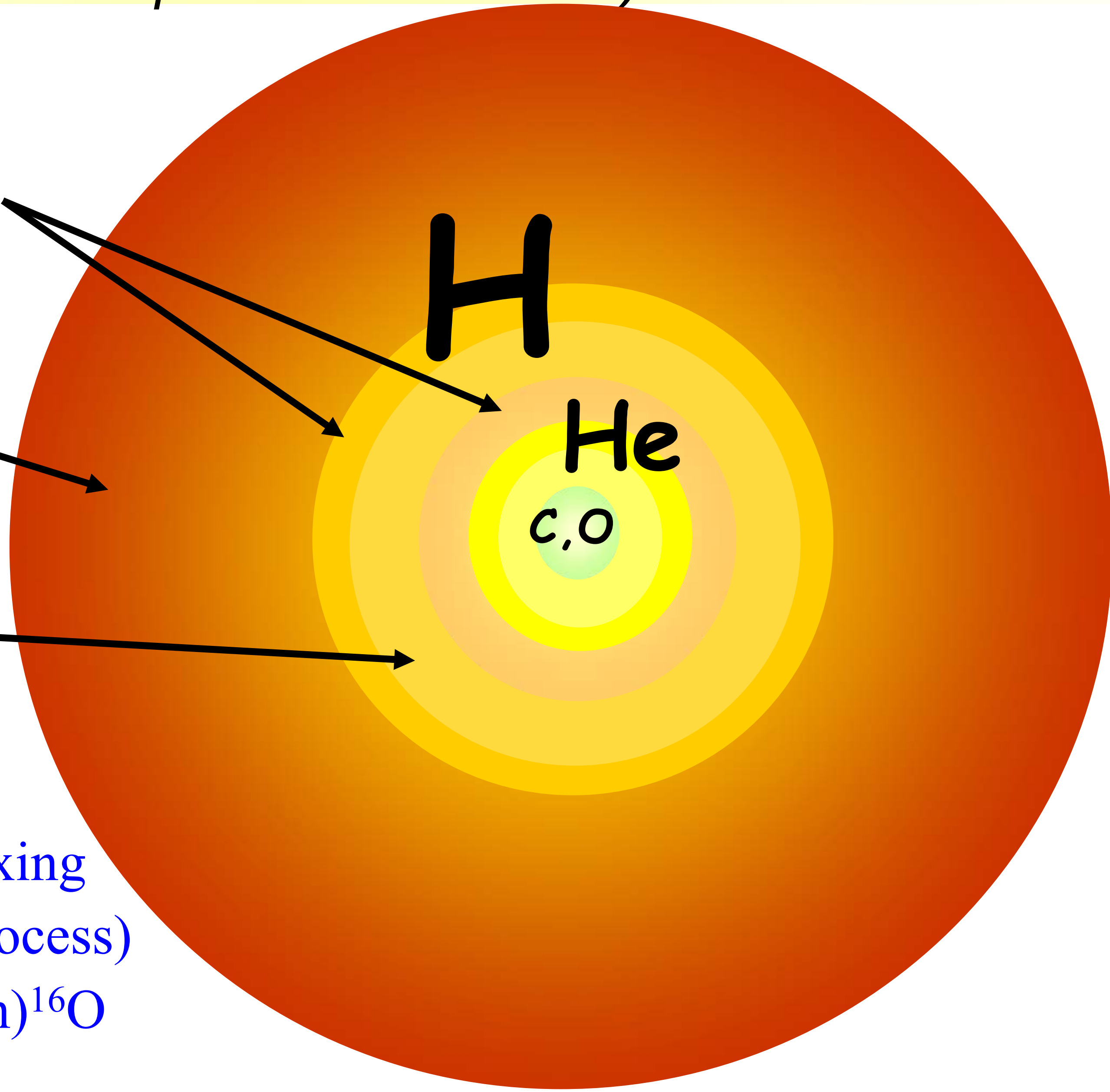
H ashes burning → surface

(2nd « dredge-up »)

C,O observations

H and He shell burnings

(Thermal pulses « TP-AGB »)



Unstable burning
in H and He shells

Convection in the
enveloppe :
(3rd « dredge-up »)

Convective zones
between
« thermal pulses »

H and He and ^{12}C mixing
→n production (→ s process)
$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)^{16}O$

Advanced burnings : C, Ne, O

1. Carbon : T ~ 10^9 K

$^{12}C+^{12}C \rightarrow {}^{23}Na+p$

$\rightarrow {}^{20}Ne+\alpha$

$^{23}Na(p,\alpha)^{20}Ne$;

$^{20}Ne, ^{23}Na+ p,\alpha \rightarrow {}^{24\text{-}26}Mg$; ^{27}Al;….

2. Neon: T ~ 2×10^9 K

$^{20}Ne+\gamma \rightarrow {}^{16}O+\alpha$

$^{20}Ne+\alpha \rightarrow {}^{24}Mg$

$^{24}Mg(\alpha,\gamma)^{28}Si$; $^{25}Mg(\alpha,n)^{28}Si$; $^{26}Mg(\alpha,n)^{29}Si$;

$^{26}Mg(\alpha,\gamma)^{30}Si$; $^{27}Al(\alpha,p)^{30}Si$; $^{30}Si(p,\gamma)^{31}P$

3. Oxygen: T ~ 3×10^9 K

$^{16}O+^{16}O \rightarrow {}^{28}Si+\alpha$

$\rightarrow {}^{31}P+p$

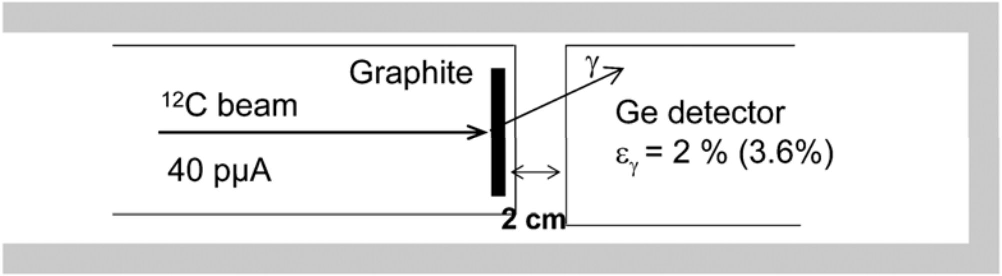
$\rightarrow {}^{31}S+n$

$\rightarrow$ **^{28}Si; ^{32}S**

Super Red Giant star

∃ mass loss: function of the star's mass: red → blue

Advanced burnings : C, Ne, O



$^{12}C + ^{12}C$

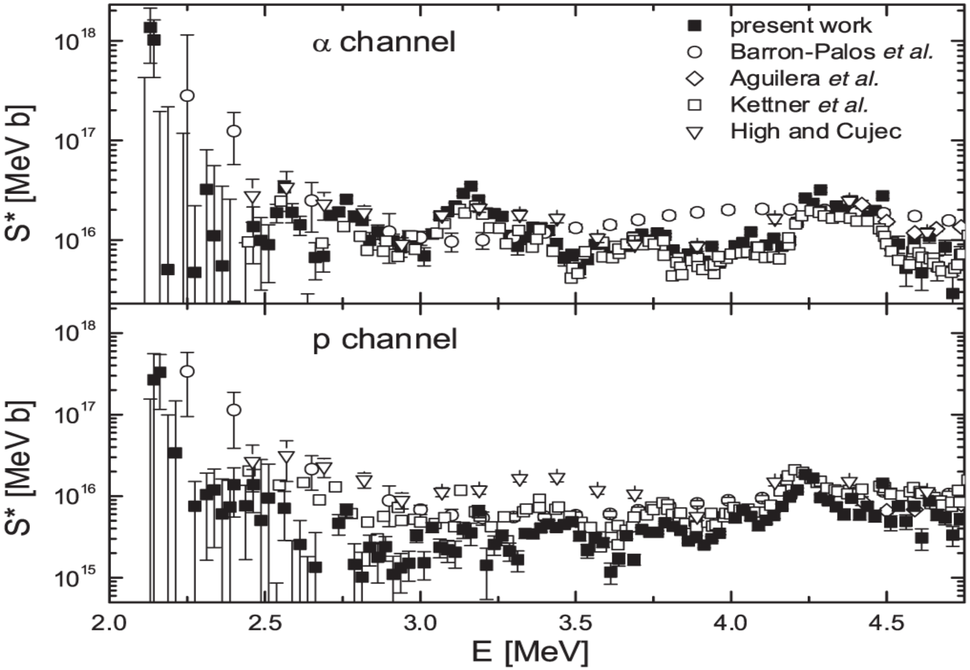
Spillane PRL 122501 (2007)

$^{12}C+^{12}C \rightarrow$ $^{20}Ne+\alpha$

$\rightarrow$ $^{23}Na+p$

Resonances

at E < 3.0 MeV



How to extrapolate down to 1.5 MeV ?

Projects: i.e. Strasbourg-Triumf (nuclear structure);

with Naples (down to 1.5 MeV ?)

Silicon burning

~ 4 10^4 K : ^{28}Si photodissociation : $^{28}\mathrm{Si}(\gamma,p)^{27}\mathrm{Al}$, $^{28}\mathrm{Si}(\gamma,\alpha)^{24}\mathrm{Mg}$,

→ fast photodissociation of less bound products : Al, Mg, Ne, O

free p, α, n : react with remaining nuclei.

Reaction rates ==> *« Statistical nuclear equilibrium »* :

$(\gamma,p) \leftrightarrows (p,\gamma)$; $(\gamma,\alpha) \leftrightarrows (\alpha,\gamma)$; $(\gamma,n) \leftrightarrows (n,\gamma)$; $(p,n) \leftrightarrows (n,p)$,..

==> most bound nuclei formation: ^{56}Ni (→^{56}Fe)

^{56}Fe is the most bound nucleus:

→any reaction between charged particles will dissipate energy (instead of create in earlier stages)

→ Fe core will increase up to Chandrasekhar mass: unstability

→ Shock wave between core unstability and free falling layers

→ Supernova explosion

Core → n star or black hole

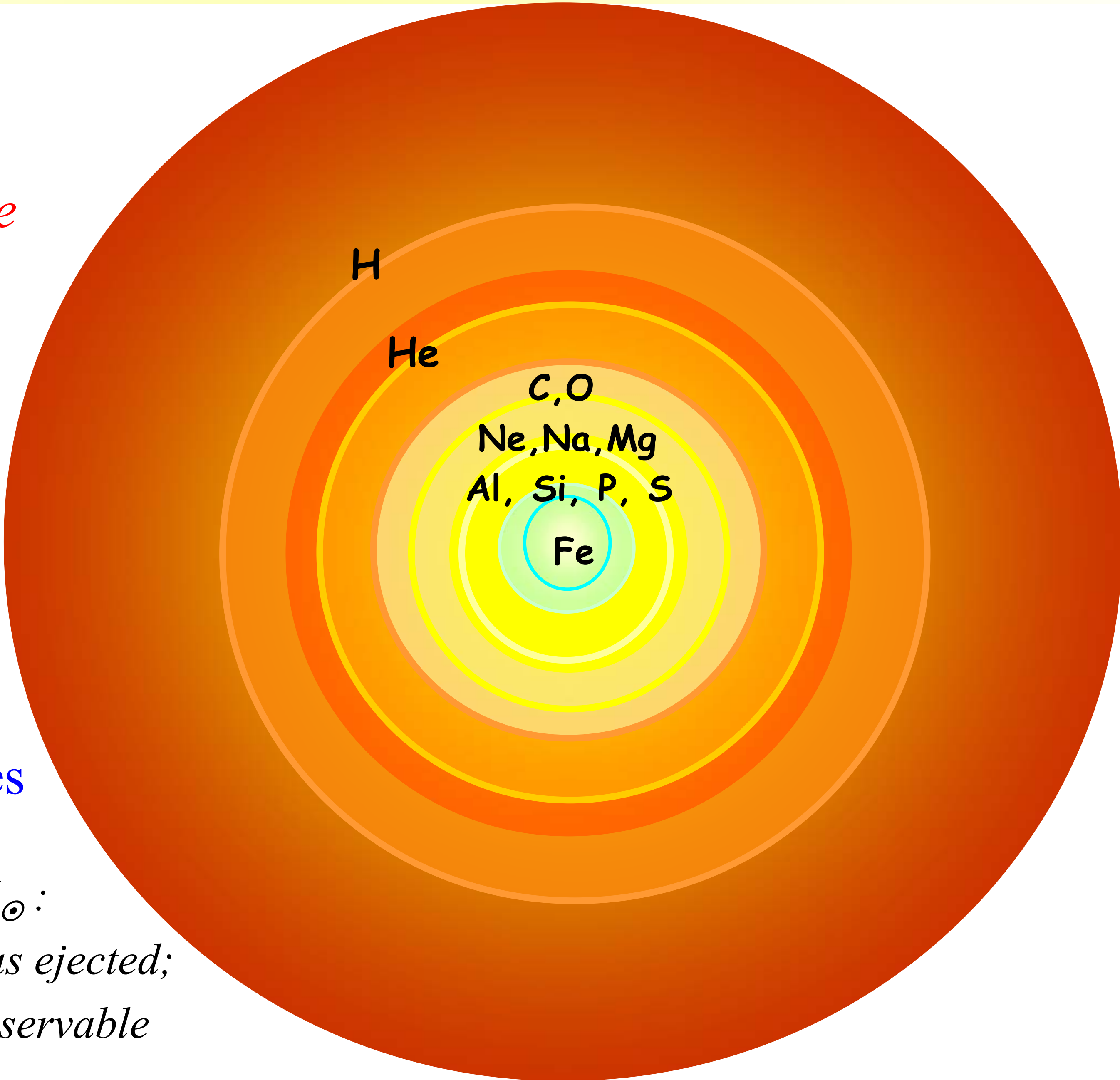
Tidy « onion » star : pre supernova

Burning stages:

core + shells

« Onion » structure

Only the most massive stars ($M_{\star} \geq 10\ M_{\odot}$) will live all these stages



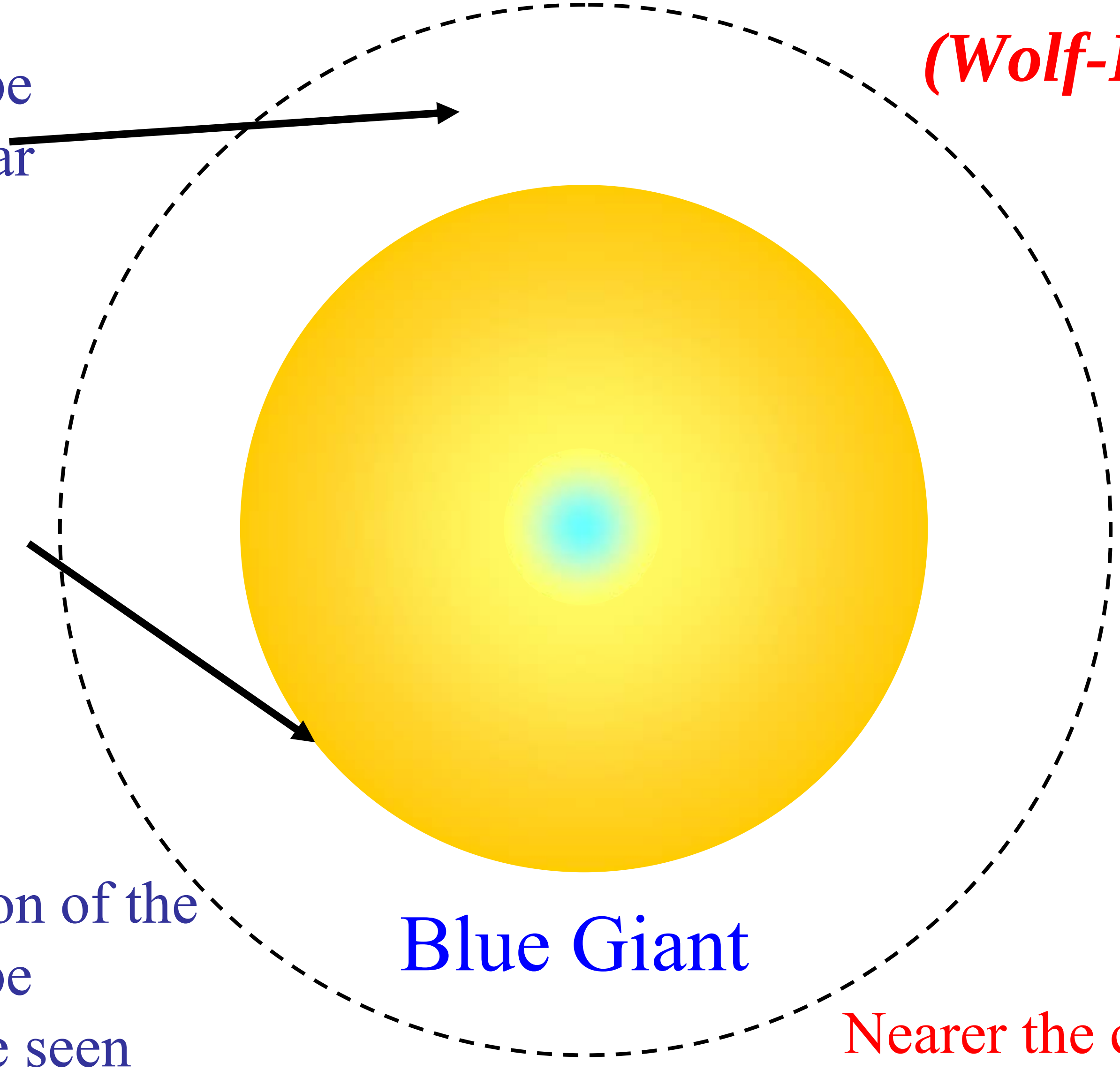
Heaviest stars: important mass losses

(For $M_{\star} > 40\ M_{\odot}$:

the whole H envelope was ejected;

He envelope may be observable

Wolf-Rayet star (« WR »)



Heaviest stars (Wolf-Rayet)

Part of the envelope was ejected by solar winds (radiation pressure)

H burning ashes may be observed on the surface (He, N)

Blue Giant

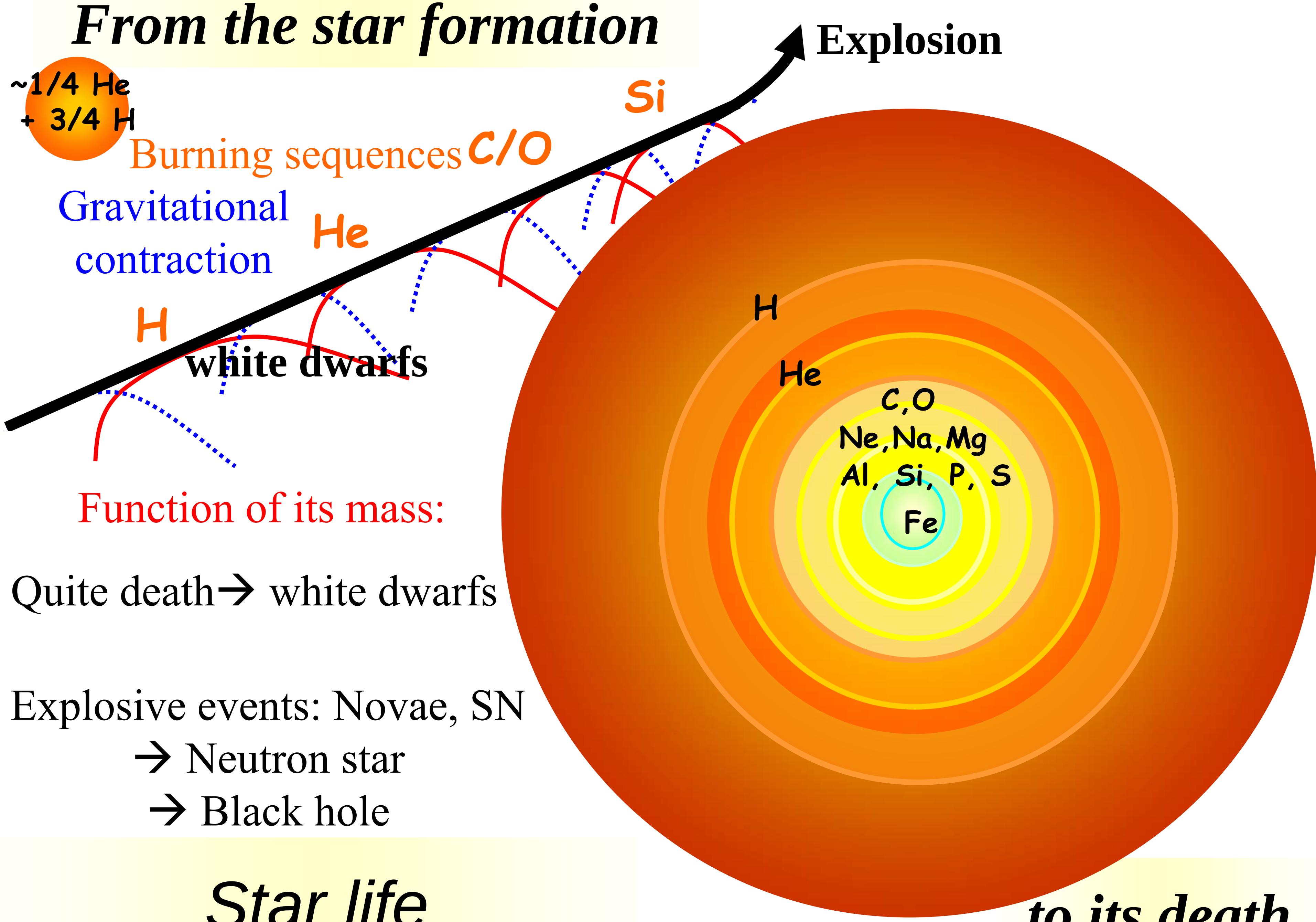
Eventually, ejection of the He envelope
→ C, O may be seen

Nearer the core
→ higher temperature

White dwarfs

- Final evolution stage of a star with a mass lighter than 6-9 $M_{\odot}$
- After He or C burnings for the heaviest
- Stabilized by the degenerate electron pressure
- $M_{WD} < 1.35\ M_{\odot}$ (Chandrasekhar mass)
- Radii of a few thousands of km

From the star formation



Function of its mass:

Quite death→ white dwarfs

Explosive events: Novae, SN

→ Neutron star

→ Black hole

Star life

to its death

Nuclear/chemical species synthesis

Hydrogen burning

$^{1}H \rightarrow {}^{4}He$

Helium burning

$^{4}He \rightarrow {}^{12}C, {}^{16}O$

Carbon burning

$^{12}C \rightarrow {}^{16}O, {}^{20}Ne, {}^{24}Mg, \ldots$

Neon burning

$^{20}Ne \rightarrow {}^{16}O, {}^{24}Mg, \ldots$

Oxygen burning

$^{16}O \rightarrow {}^{28}Si, {}^{32}S, \ldots$

Silicon burning

Photodisintegration

$^{28}Si(\gamma,p), {}^{28}Si(\gamma,\alpha), {}^{28}Si(\gamma,n), \ldots$

Statistical nuclear equilibrium

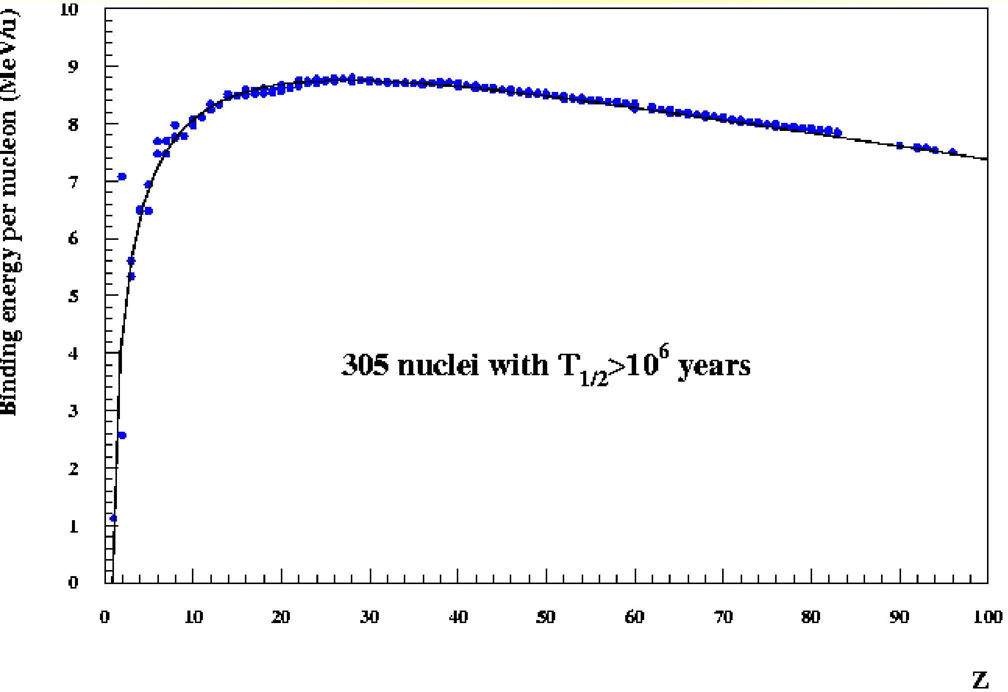
$(\gamma,p) \approx (p,\gamma), (\gamma,\alpha) \approx (\alpha,\gamma), (\gamma,n) \approx (n,\gamma), (p,n) \approx (n,p), ..$

$\rightarrow$Most bound nulei

$^{56}Ni \rightarrow {}^{56}Fe$

$^{28}Si \rightarrow {}^{56}Ni, \ldots$

MASS, TIME



Interstellar gas enrichment:

stellar winds

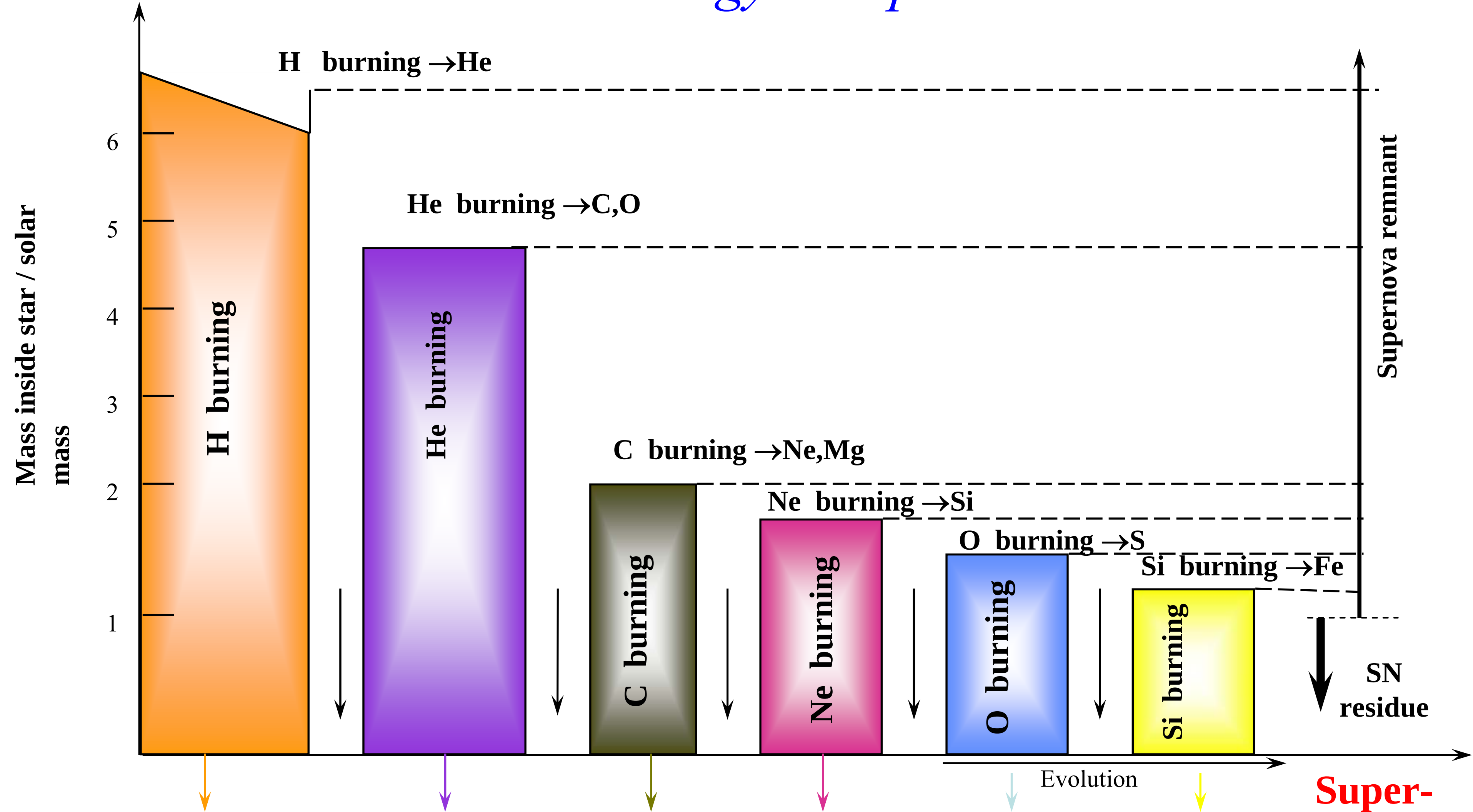
explosions

→ 2nd generations stars

are metal enriched

Internal structure evolution for a $M = 25M_\odot$ star

Δt ↘ when H → heavier: Energy rate poduction ↘ n number ↗



T_c (K)	6×10^7	2×10^8	9×10^8	1.7×10^9	2.3×10^9	4×10^9
ρ(g cm^{-3})	5	700	2×10^5	4×10^6	1×10^7	3×10^7
Time scale	7×10^7 year	5×10^3 year	600 year	6 month	6 day	1 day

Super-nova

Crab Nebula: in optic wave lengths

SN 1054 remnant

FORS team, 8.2-meter VLT, ESO

Some star-death examples

☆ *low-mass stars* ($0.08\ M_\odot \lesssim M \lesssim 0.45\ M_\odot$):
H core burning then white dwarfs

☆ *low-mass stars* ($0.45\ M_\odot \lesssim M \lesssim 8\ M_\odot$):
H and He core burnings then white dwarfs

…

☆ *massives stars* ($M \geq 10\ M_\odot$) :
Any stages then *SN II (H envelope), SN Ib (H envelope loss)*
or SN Ic (H and He envelope loss)

∃ *Numerous binary systems: « binary stars »*
Evolution of one star may influence the other star evolution
Ex. : white dwarf + companion (as a red giant star) → *Nova, SNIa*
neutron star + companion (as a red giant star) → *γ-ray burst*

…

Physical conditions in stars

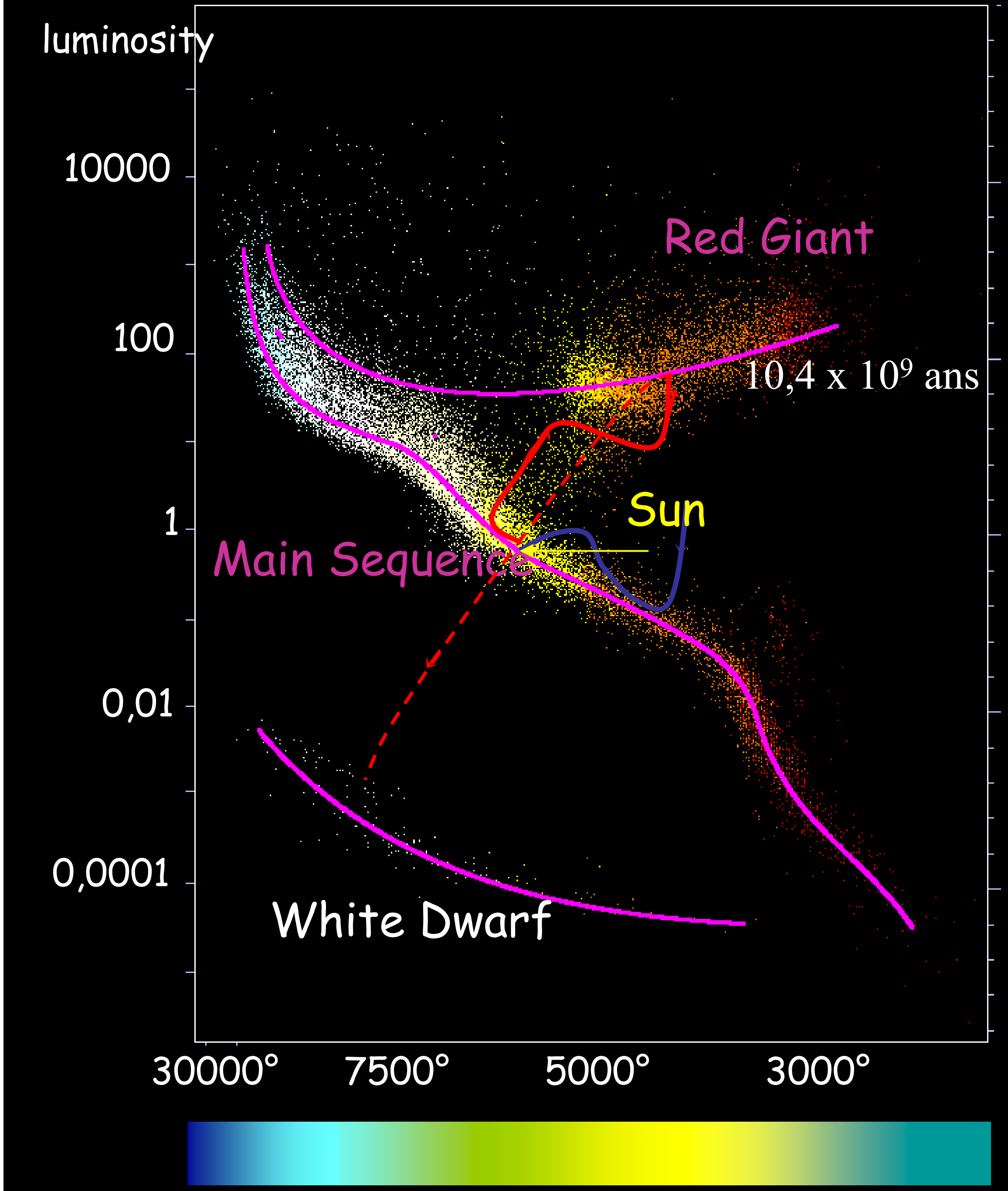
	Core temperatures		
Sun :	15 T_6	$E(k_BT) = 1.3$ keV	(H burning)
Red Giant :	~ 0.2 T_9	$E(k_BT) = 17$ keV	(He burning)
Pre Supernova :	~ 4 T_9	$E(k_BT) = 344$ keV	(Si burning)
Nova :	~ 0.3 T_9	$E(k_BT) = 26$ keV	(Si burning)
Primordial : Universe (~min)	1 to 0.1 T_9	$E(k_BT) \sim 100\text{-}10$ keV	(‘’Big Bang’’) (nucleosynthesis)

Core density: 150 g/cm^3 for the Sun

10^{10} g/cm^3 for a white dwarf

Temperatures: $a\ T_6 = a{\times}10^6\ K$; $a\ T_9 = a{\times}10^9\ K$

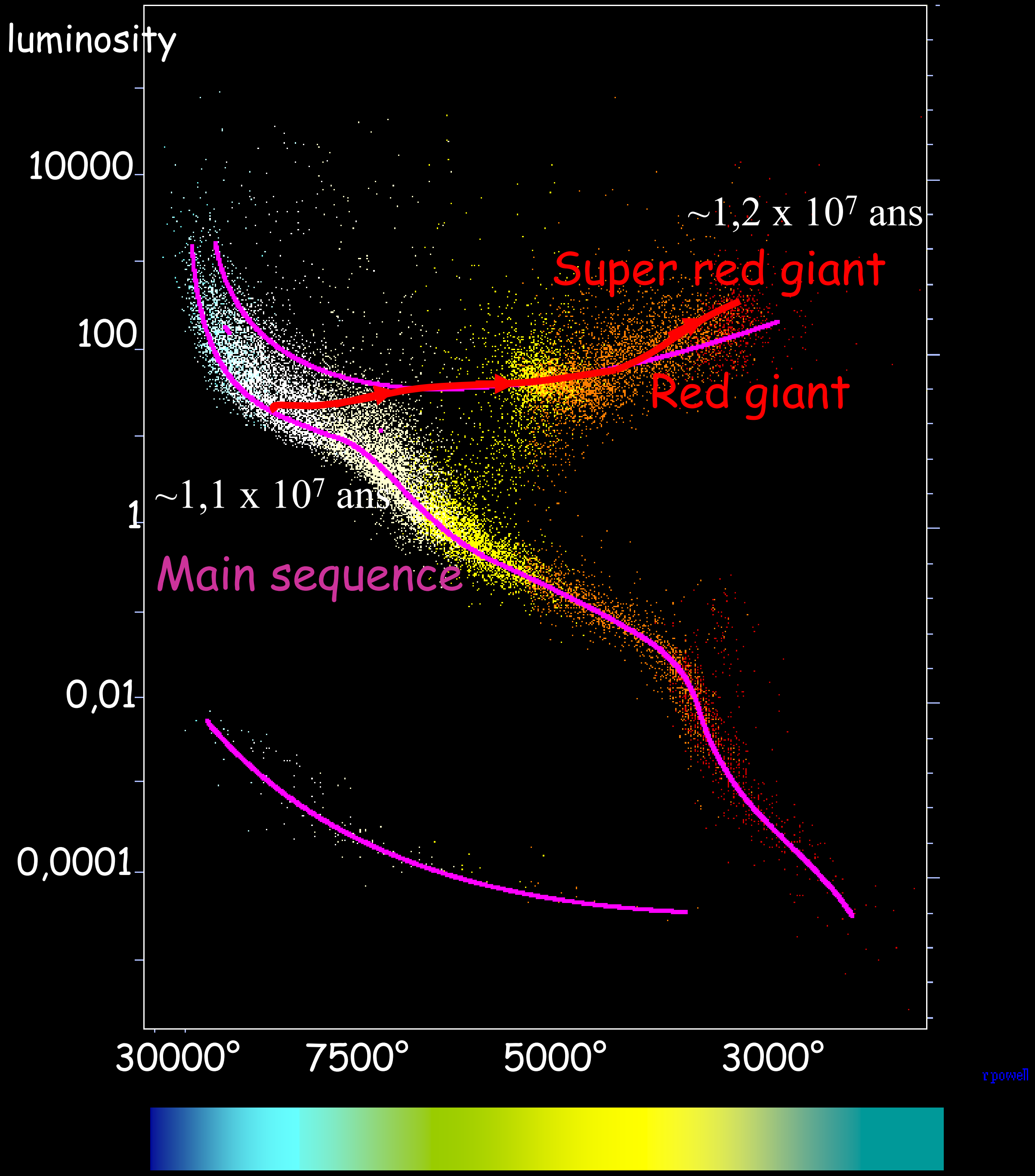
Life of the Sun



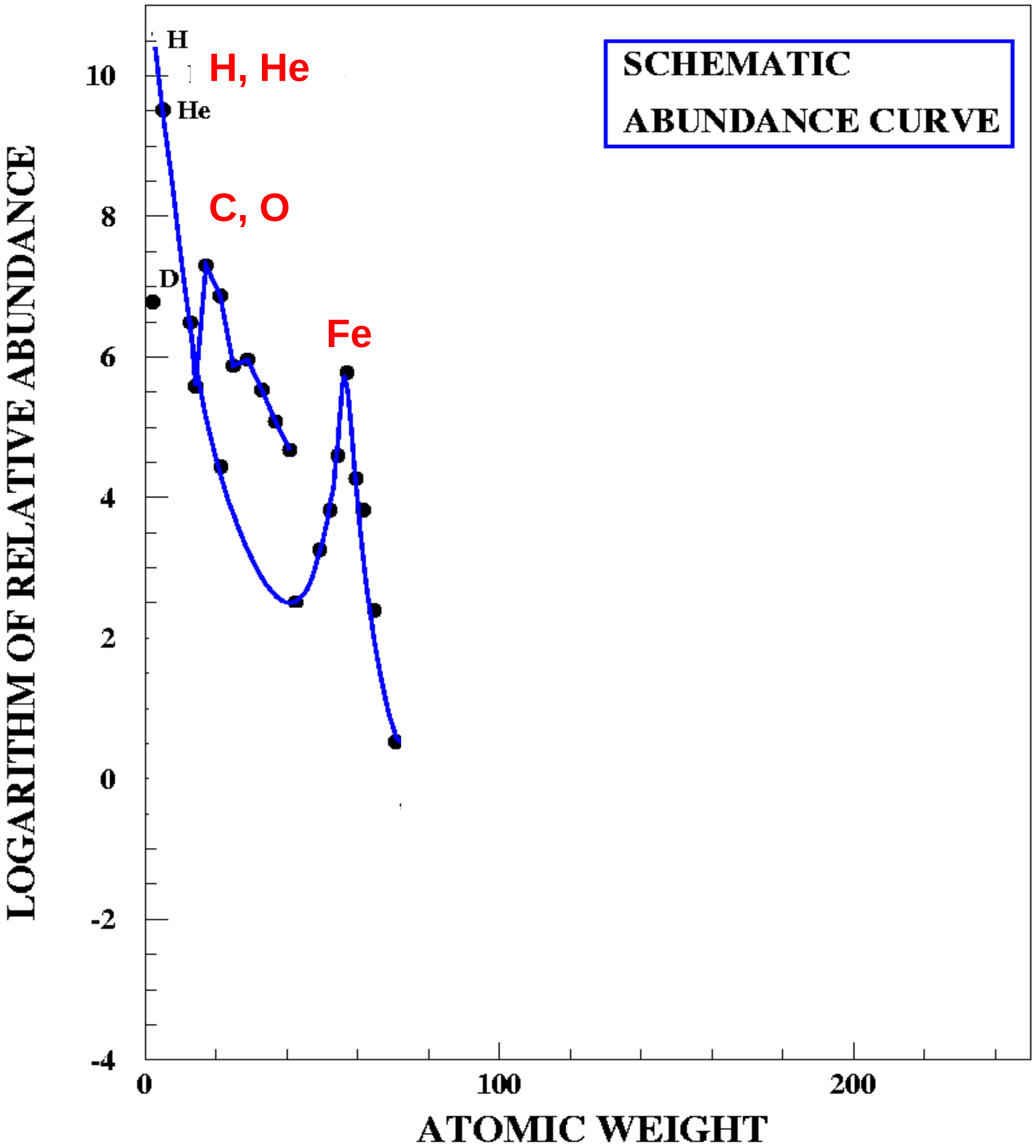
r powel

Life of a 15 M⊙ star

Will die in Supernova



Abundance understandings



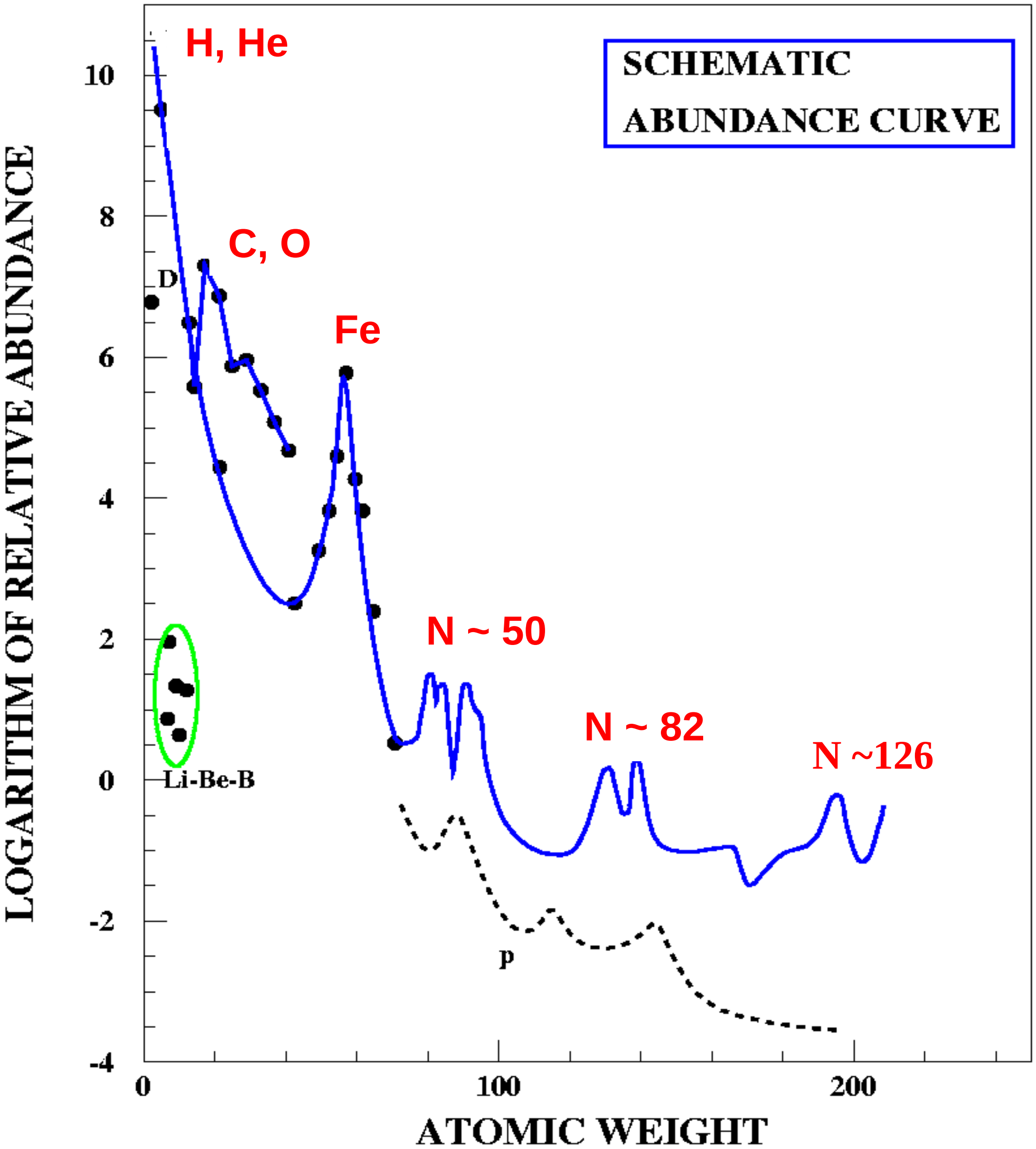
Abundant light elements ;
High abundances
for element species
with N,Z ~ 2, 8, 28

→burning stages
→magic-numbers
correlation

Primordial
nucleosynthesis:
→H and He
highest abundances

Stellar nucleosynthesis:
→ C, O, Si, Fe peaks

And the others?



Other processes are needed

^{56}Fe: most bound nucleus:

Only reactions with neutrons
may explain
heavier nuclei abundances

no Coulomb barrier

Where?
When?

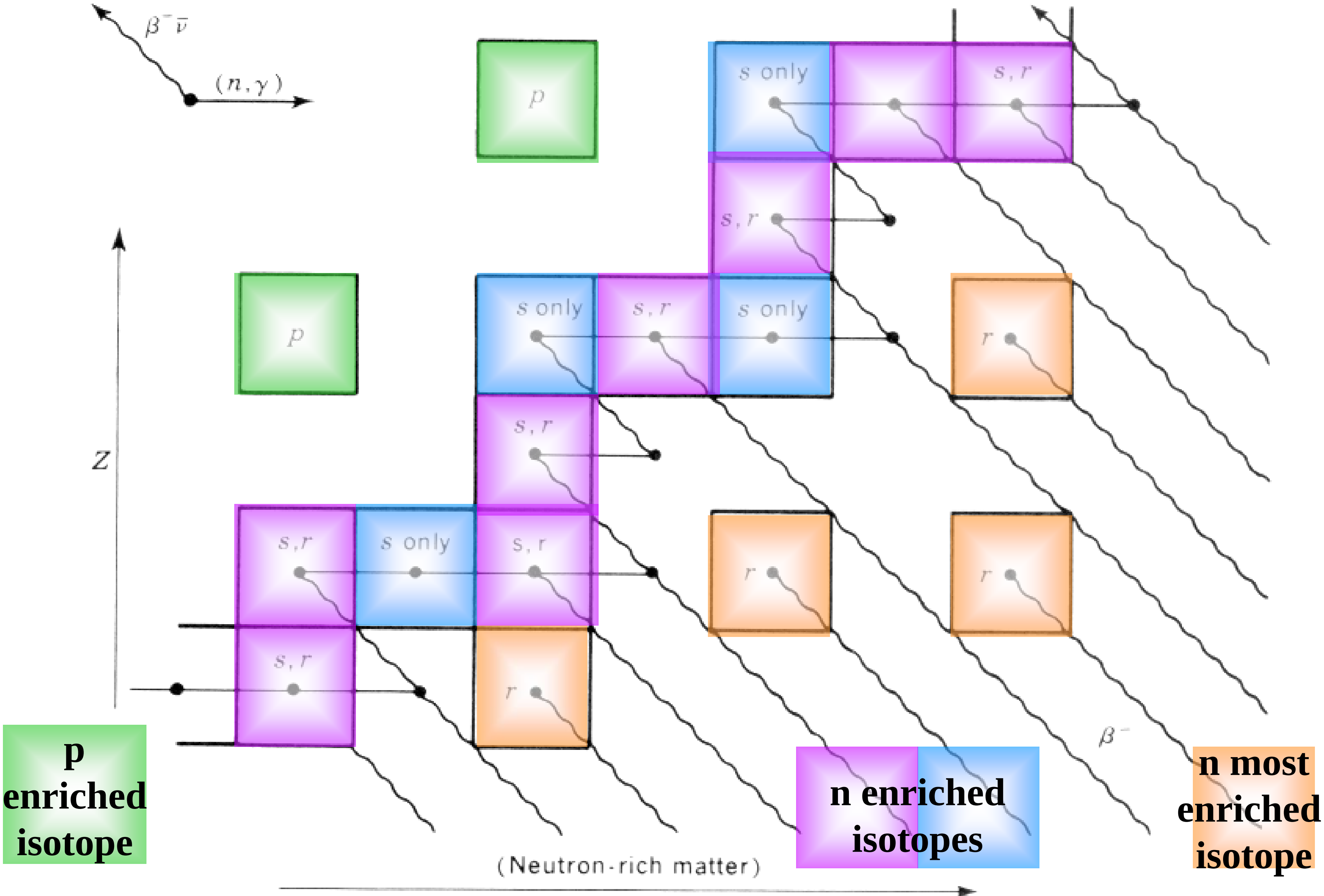
And LiBeB?
How?
Where?
When?

Production of elements beyond Fe

Charged particle burnings : impossible (Coulomb barrier and binding energy) ⇒ neutron capture reactions and photodissociation

- s process
  - Slow neutron capture (compared to τ_β)
  - During He burning in AGB and massive star cores
  - Neutron sources: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$
- r process
  - Rapid neutron capture (compared to τ_β)
  - In deep layers during SNII (?)
- p process
  - Photodissociation of « s » and « r » nuclei
  - Massive stars and (pre-)supernovae

s, r and p processes

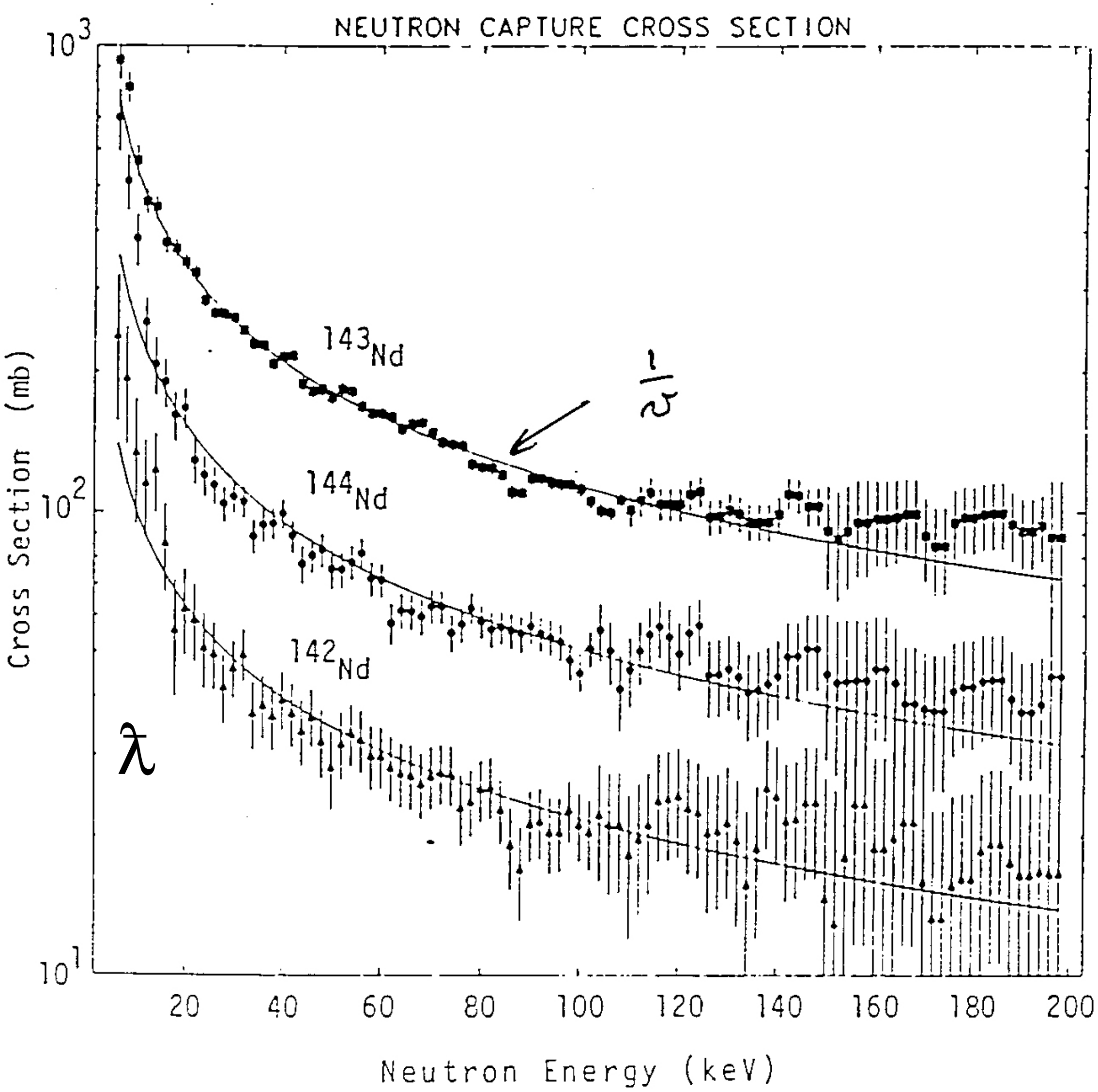


🟩 **p enriched isotope**

🟪🟦 **n enriched isotopes**

🟧 **n most enriched isotope**

Neutron captures



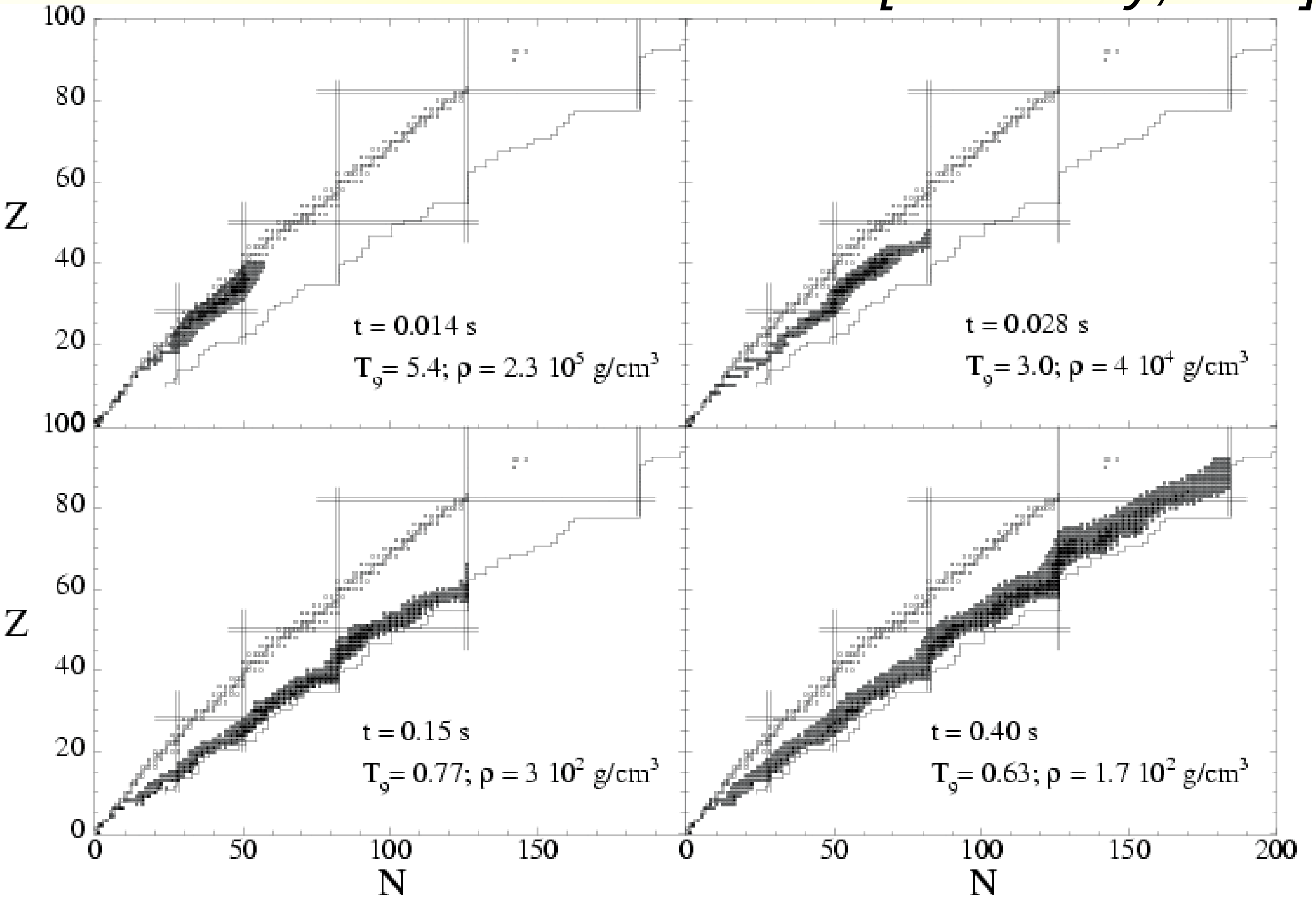
$$\sigma \propto \lambdabar T \propto 1/\mathrm{v}$$

In this case :
variation in $E^{1/2}$

$$\langle \sigma \mathrm{v} \rangle \approx \mathrm{cste}$$

A dynamical r process calculation

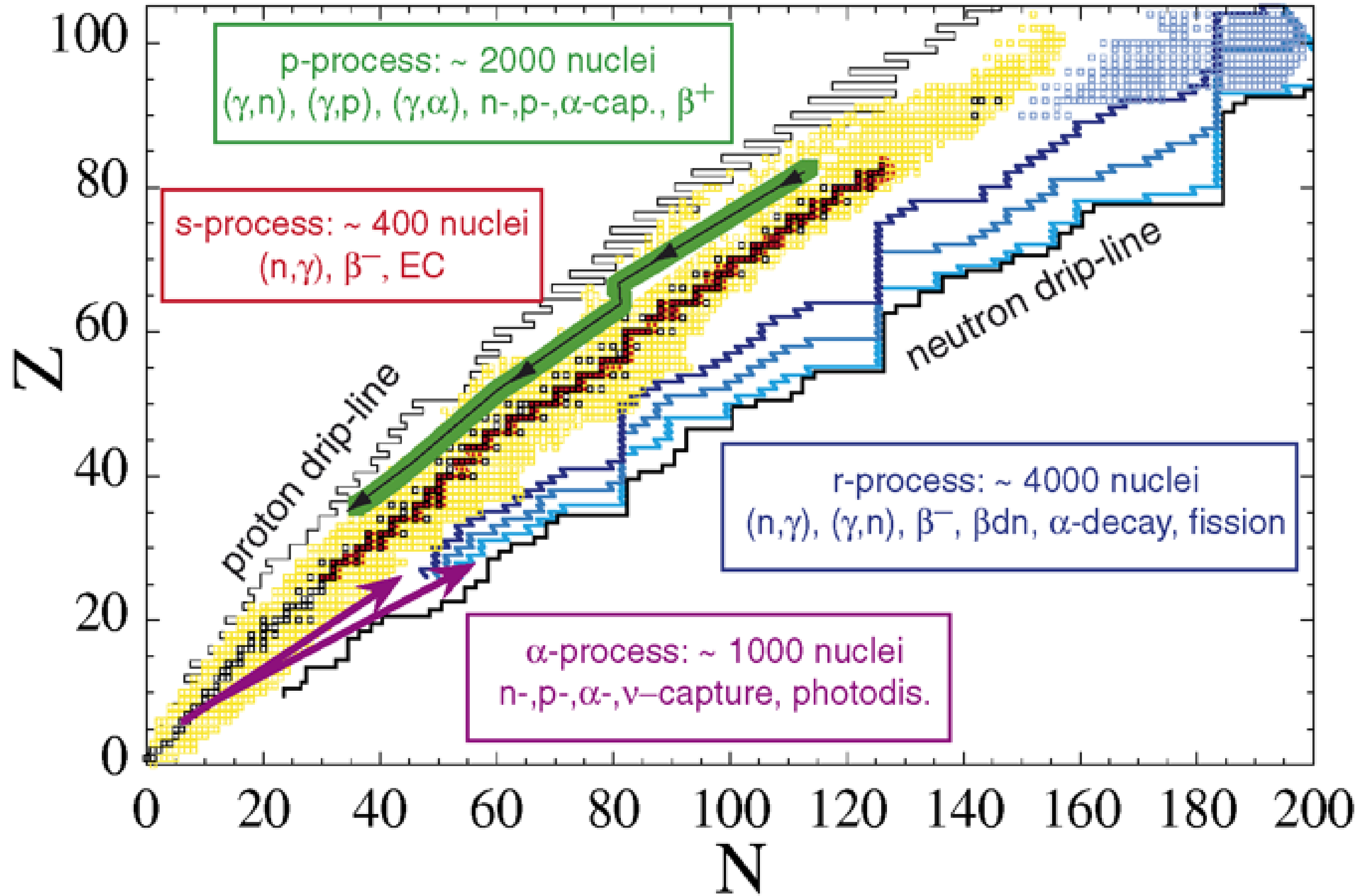
model of the « neutrinic wind » [S. Goriely, ULB]



∃ various ways of the r process. Thousands of nuclei, capture reactions, periods, fission and neutrino induced reactions,…

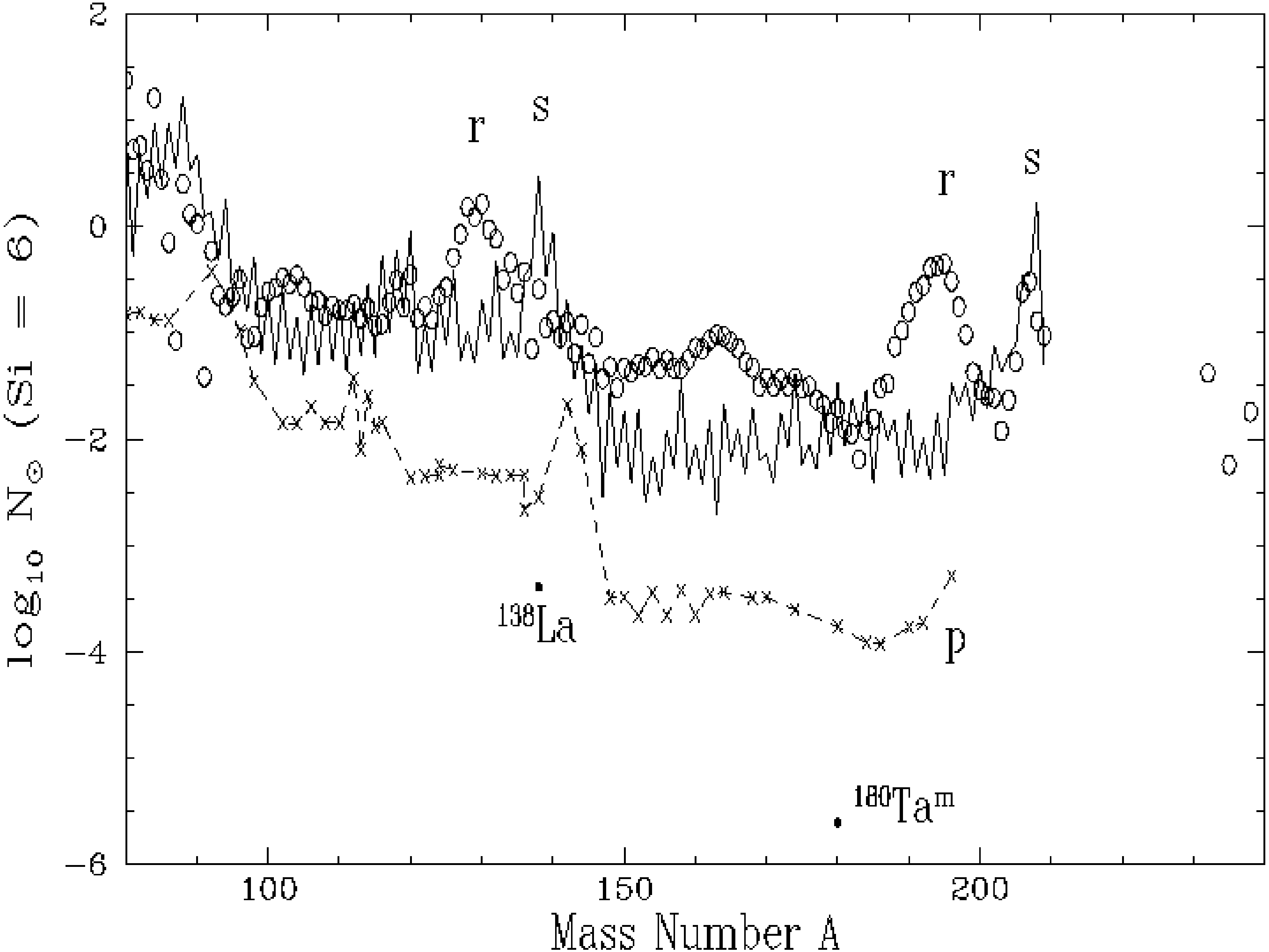
- ✓ **Theory : phenomenological models vs microscopic calculations**
- ✓ **Choosen measurements (Rikken, GSI, SPIRAL2, EURISOL)**

s, r, p processes

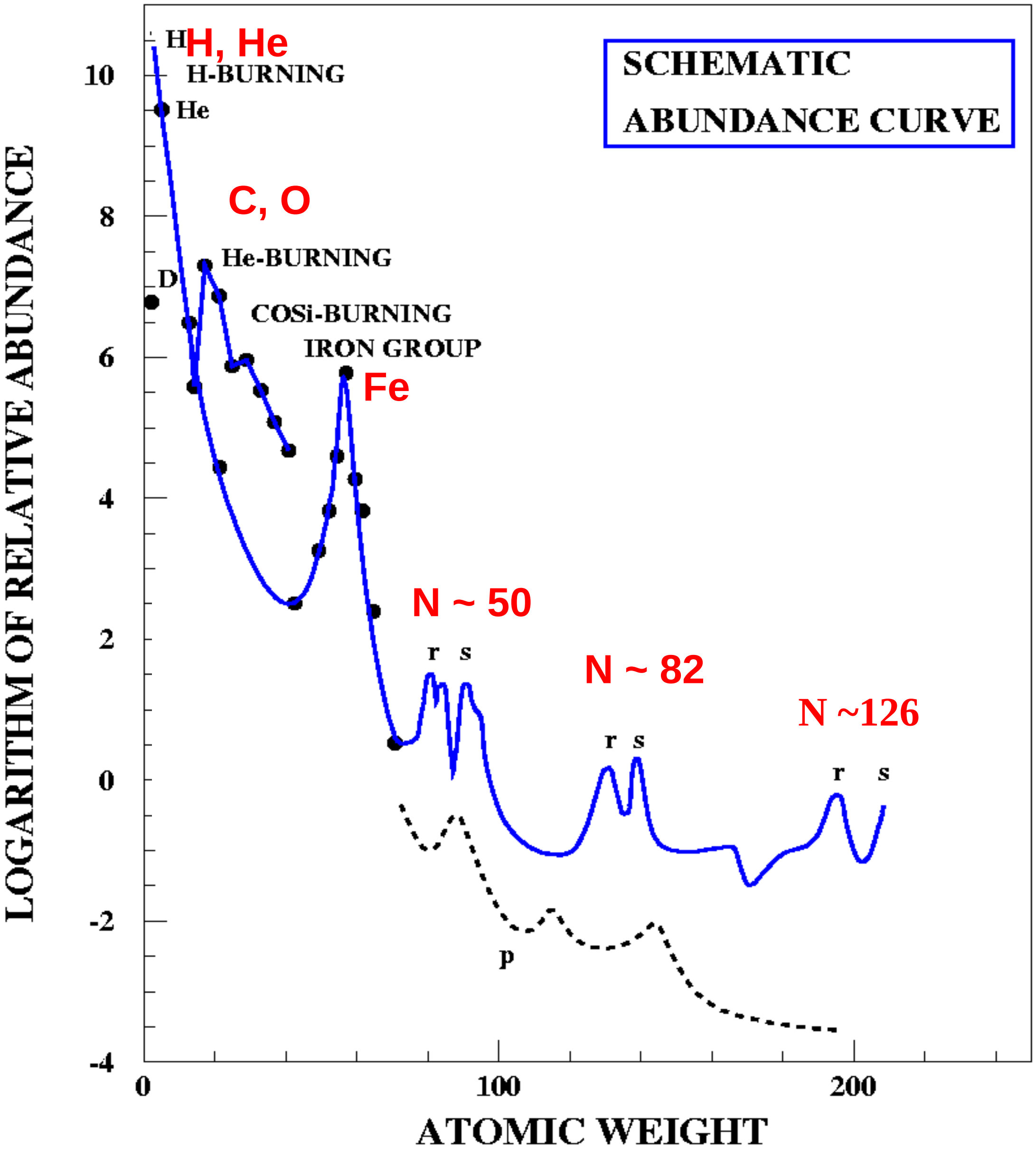


S. Goriely ULB

s and r nuclei



Abundance interpretations?



Other processes are needed

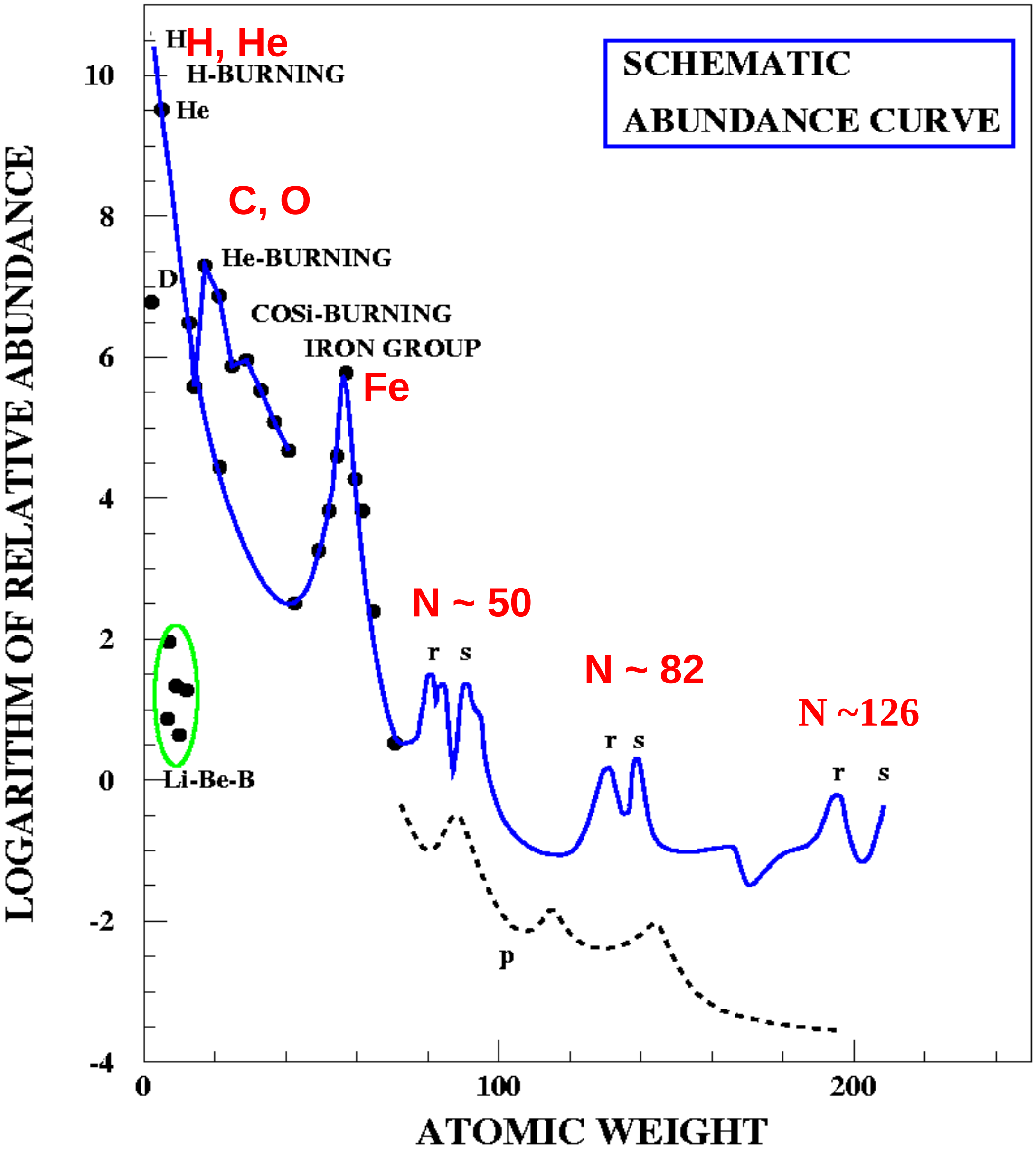
^{56}Fe: most bound nucleus:

Only reactions with neutrons may explain heavier nuclei abundances

no Coulomb barrier

→double peaks:
r and s processes

And LiBeB ?



Other processes are needed

And LiBeB?

How?
Where?
When?

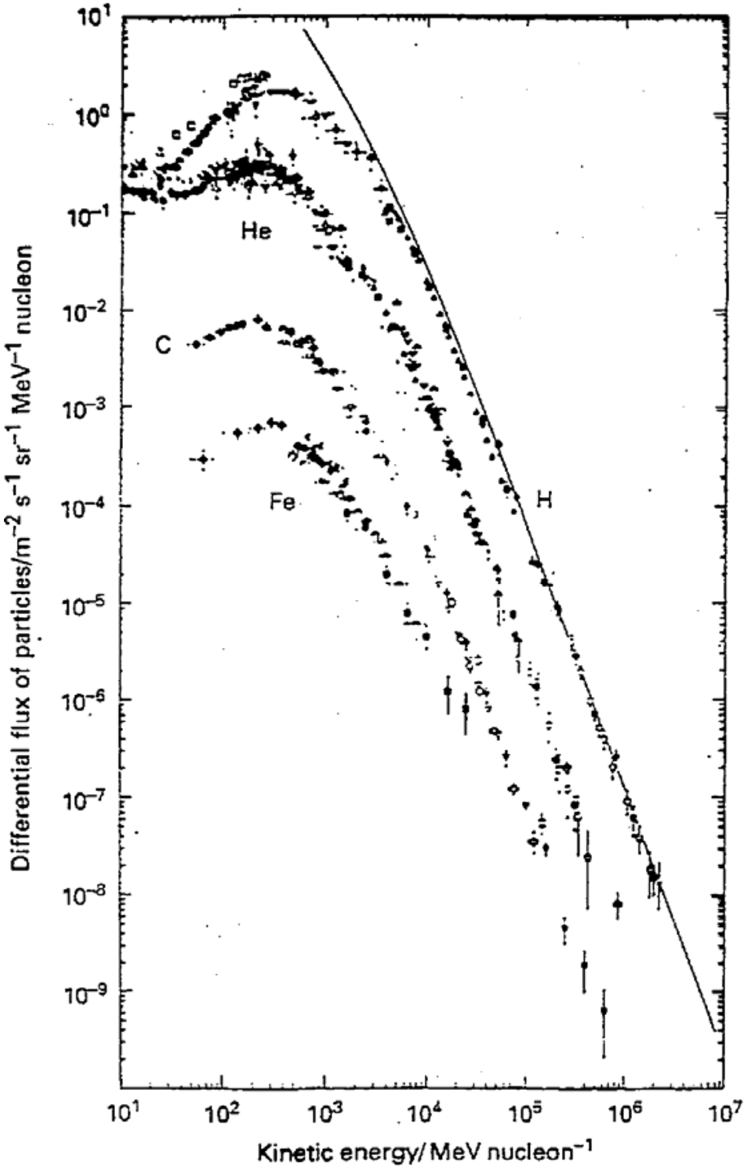
Spallation reactions:
With cosmic rays

LiBeB synthesis

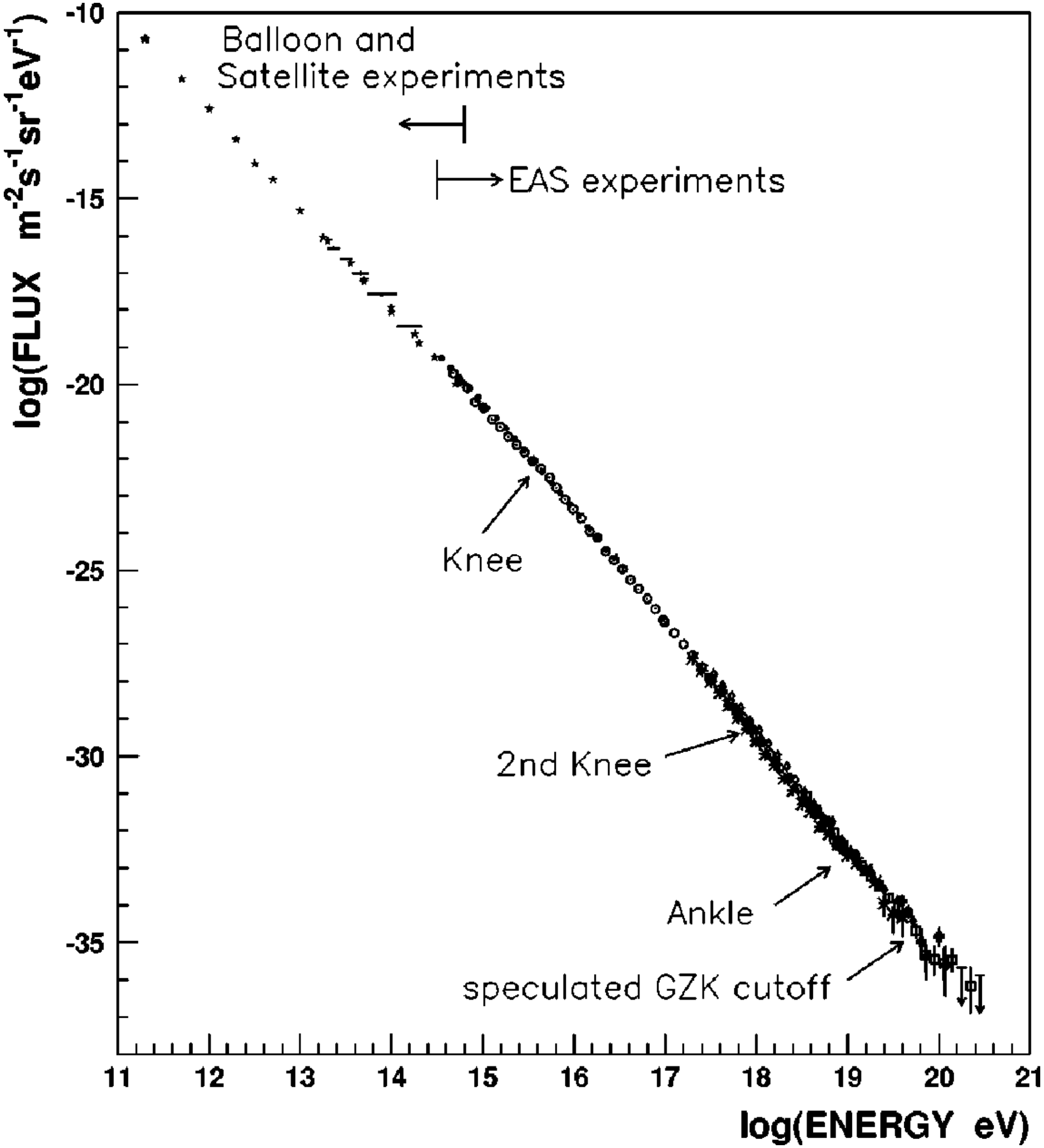
- LiBeB synthesis: spallation reactions in
  - galactic disk : RC (p, α ; GeV/nucl) & MIS (C, N, O) (Meneguzzi et al, 1971)
  - halo : SN (α, C, N, O ; MeV/nucl) & MIS (p, α)

- Observations :
  - visible-UV in galactic halo (CFH, HST, Keck, VLT)
  - gamma (COMPTEL, INTEGRAL)
  - RC (ACE, AMS)

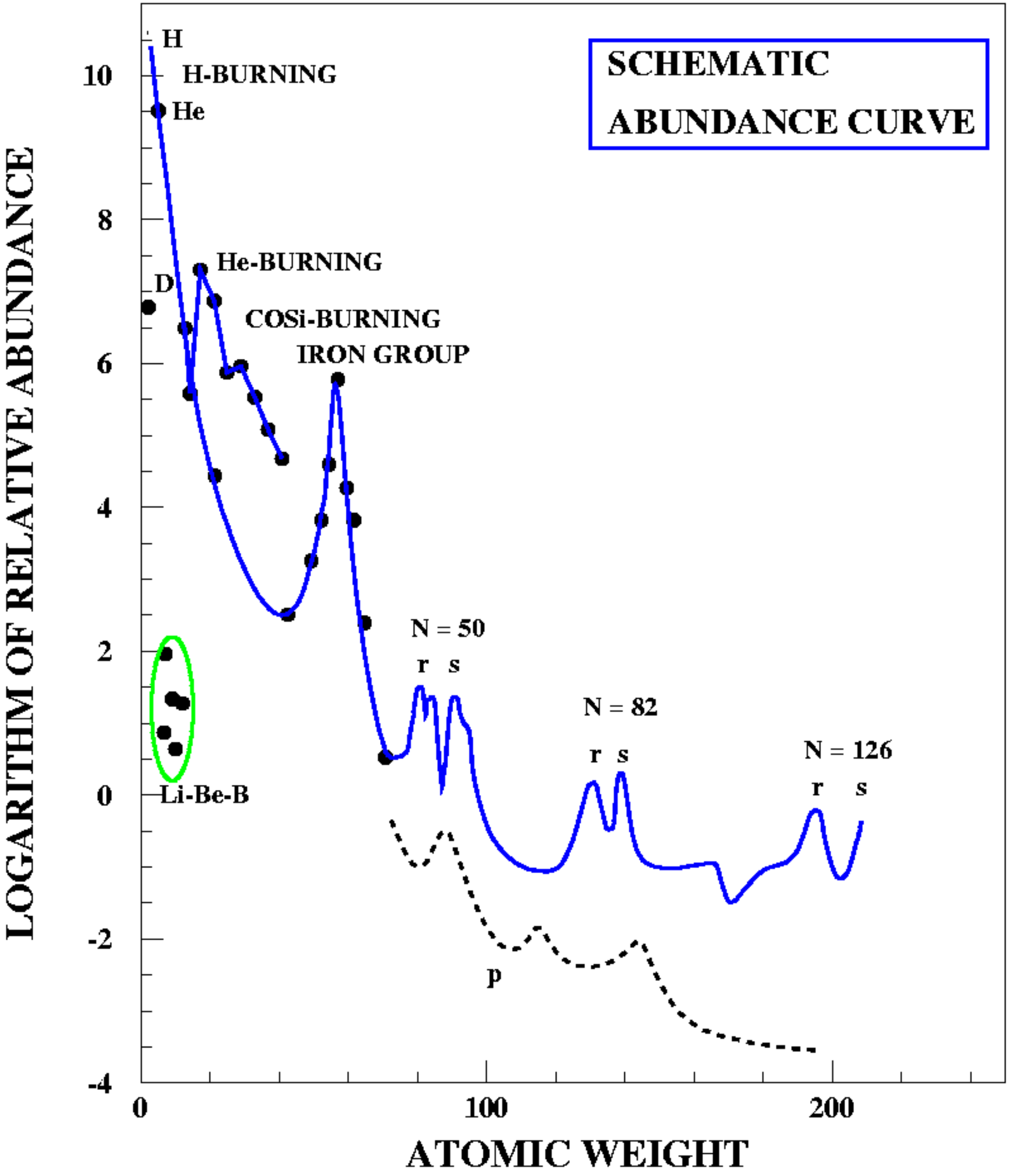
- Neutrino spallation during SN explosions
  - ^{7}Li et ^{10}B production
  - cross sections are needed



Cosmic rays


Balloon and
Satellite experiments
EAS experiments
Knee
2nd Knee
Ankle
speculated GZK cutoff
log(FLUX m^{-2}s^{-1}sr^{-1}eV^{-1})
-10
-15
-20
-25
-30
-35
11
12
13
14
15
16
17
18
19
20
21
log(ENERGY eV)

Abundance interpretation



May be explained via nucleosynthesis processes:

→ primordial

→ stellar

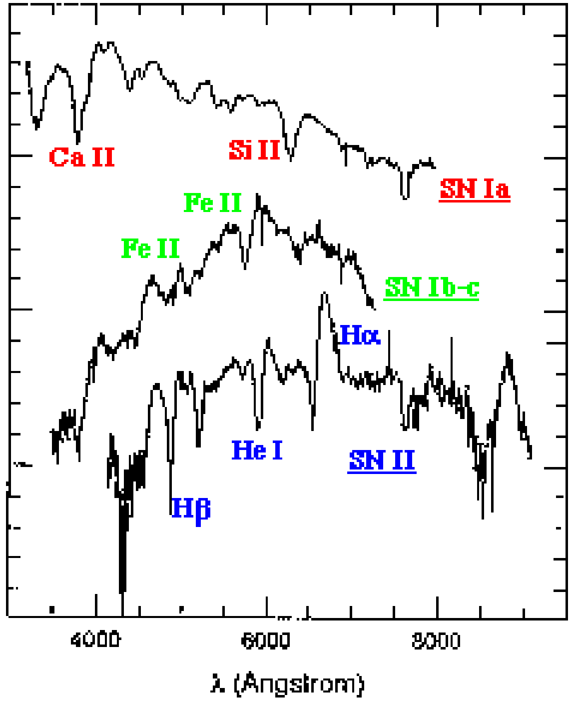
→ explosive

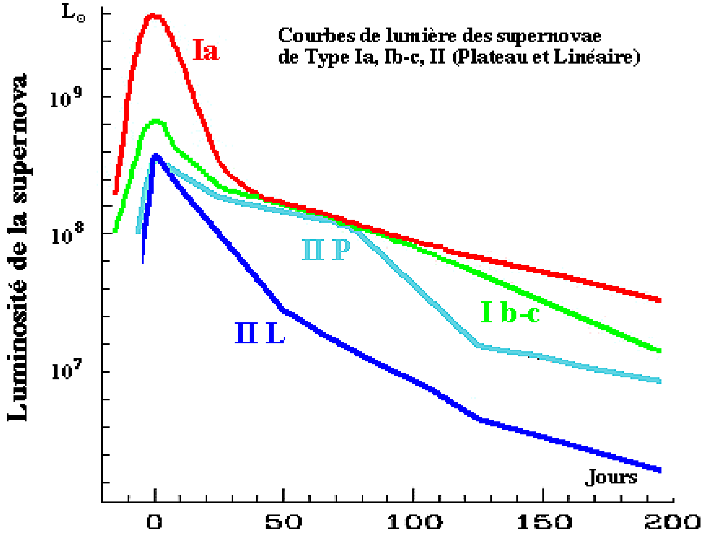
→ spallative

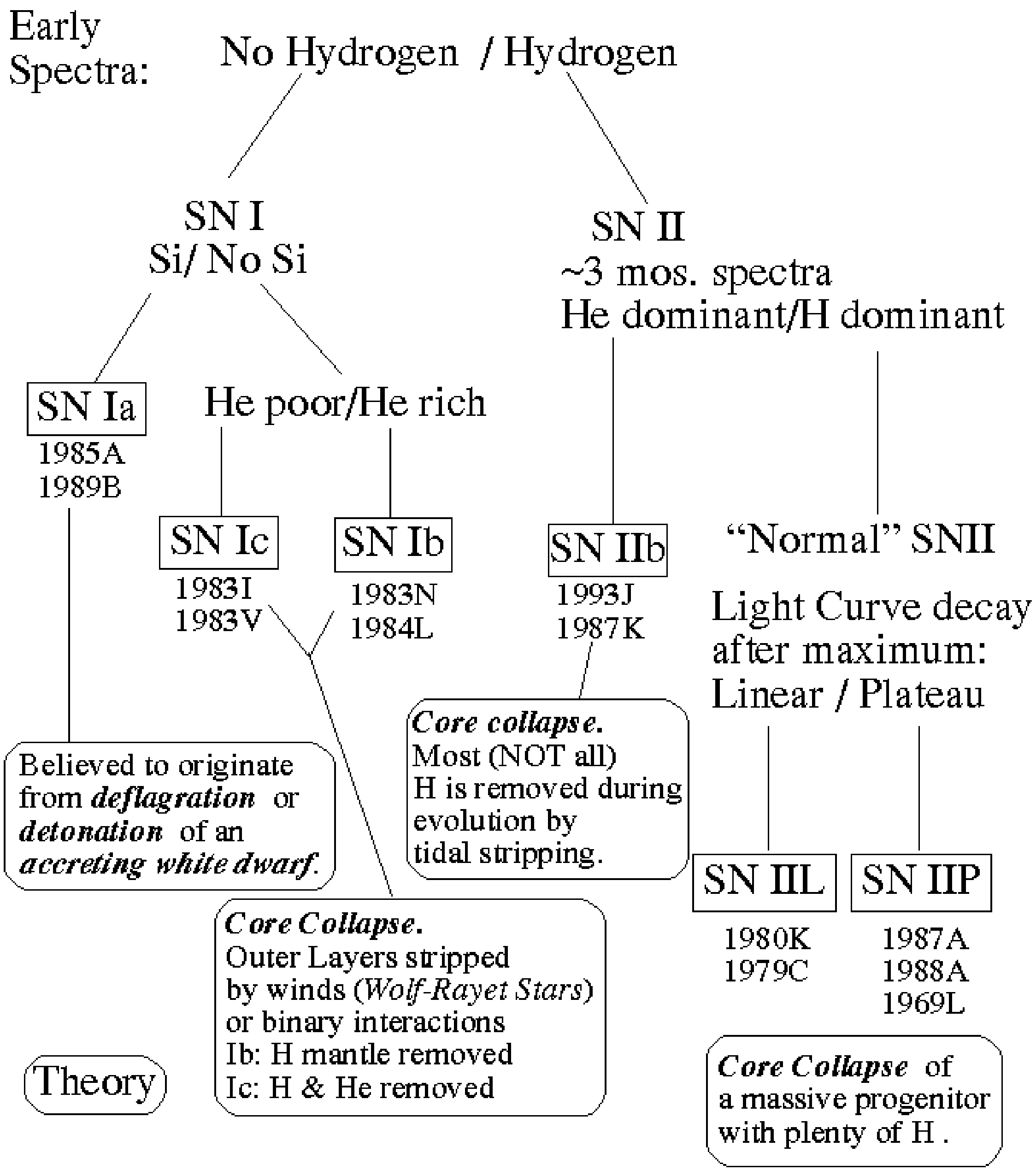
Summary of Origins

Element	Site	Element	Site
H	Big Bang	Ar	Oxygen burning
He	Big Bang + stars	K	Oxygen burning + s-process
Li	Big Bang, L* + nu process	Ca	Oxygen burning
Be	Cosmic rays	Sc	s-process
B	Nu-process	Ti	Expl Si burning
C	Helium burning, L*+M*	V	Expl Si burning
N	CNO cycle, L*+ VMS	Cr	Expl Si burning
O	Helium burning	Mn	Expl Si burning, Ia
F	Nu-process	Fe	Expl Si burning, Ia
Ne	Carbon burning	Co	alpha-rich freeze out
Na	Carbon burning	Ni	alpha-rich freeze out
Mg	Carbon burning	Cu	alpha-rich freeze out + s-process
Al	Neon burning	Zn	Nu-powered wind
Si	Oxygen burning	p-proc	Explosive neon burning, O-burning
P	Neon Burning	s-proc	Helium burning, L* and M*
S	Oxygen burning	r-proc	Nu wind, jets?
Cl	Oxygen burning + s-proc		

Supernovae typology







Early
Spectra:

No Hydrogen / Hydrogen

SN I
Si/ No Si

SN II
~3 mos. spectra
He dominant/H dominant

SN Ia
1985A
1989B

He poor/He rich

SN Ic
1983I
1983V

SN Ib
1983N
1984L

SN IIb
1993J
1987K

"Normal" SNII

Light Curve decay
after maximum:
Linear / Plateau

SN IIL
1980K
1979C

SN IIP
1987A
1988A
1969L

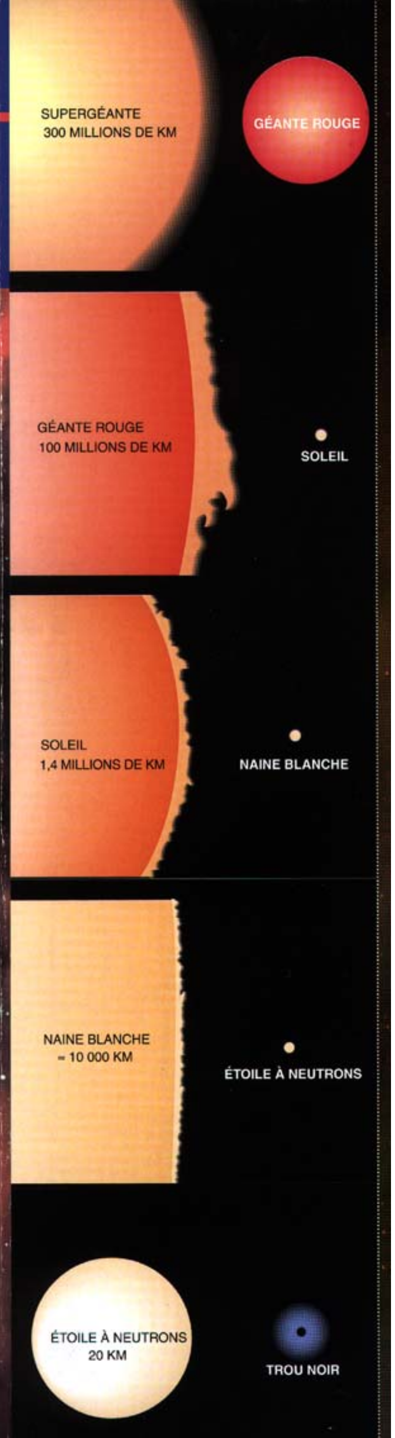
Believed to originate from ***deflagration*** or ***detonation*** of an ***accreting white dwarf.***

Core collapse. Most (NOT all) H is removed during evolution by tidal stripping.

Core Collapse. Outer Layers stripped by winds (*Wolf-Rayet Stars*) or binary interactions
Ib: H mantle removed
Ic: H & He removed

Core Collapse of a massive progenitor with plenty of H .

Theory



Relative sizes of stars

Nuclear gamma-ray astronomy (<10 MeV)

Interest

- ➢New spectral energy range
- ➢Gamma-ray penetrability
- ➢Constraints on nucleosynthesis (isotopes)
- ➢Cosmic-ray study (acceleration processes, gamma-ray sources)

Production mechanisms

- Annihilation $[e^+e^-]$

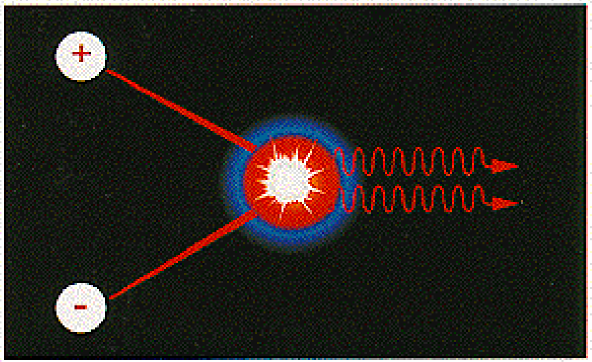
(Galaxy, novae)

- Nuclear excitations [(p,p'), (α,α'), ...)]

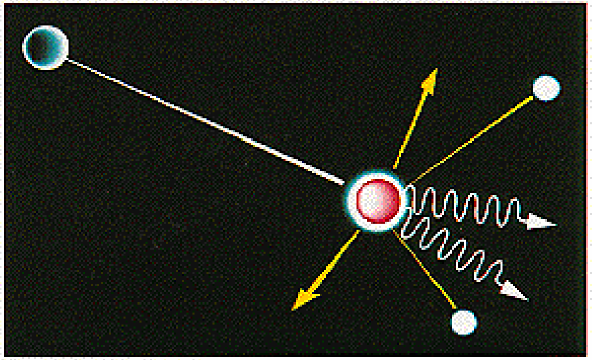
(Solar flares)

- Radioactivities [^{26}Al, ^{44}Ti, ^{56}Co, ...]

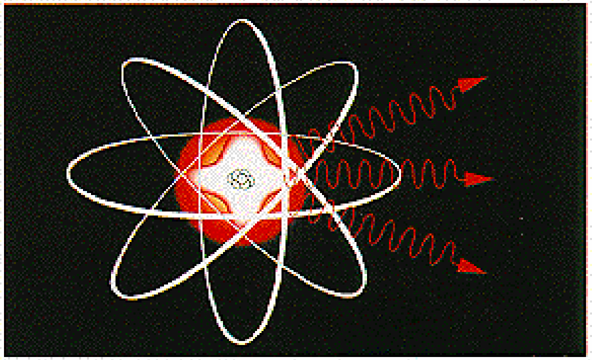
(Supernovae, novae, ...)



MATTER-ANTIMATTER ANNIHILATION

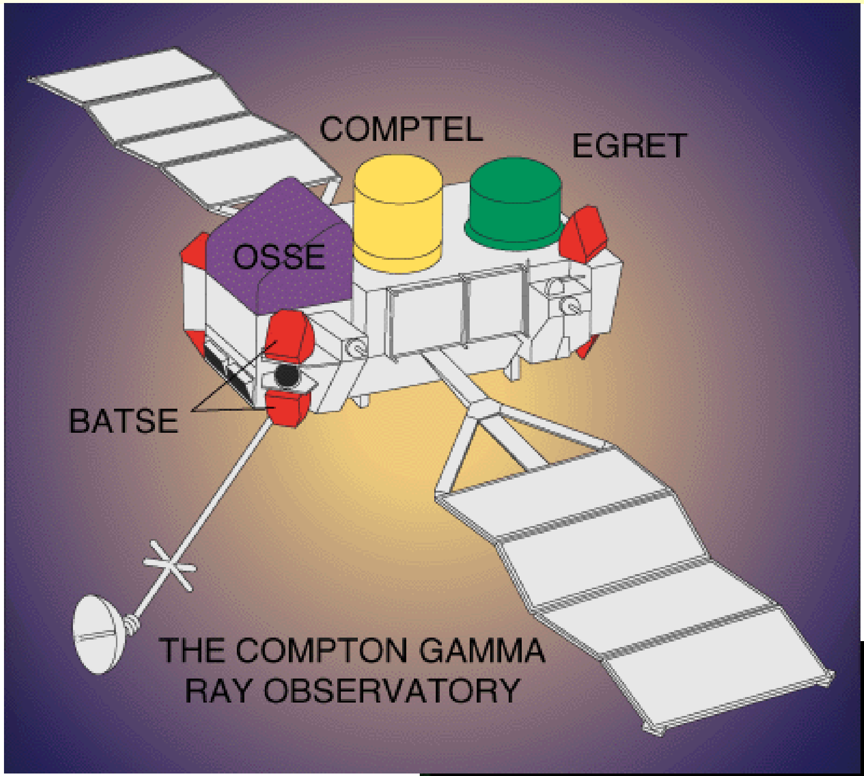


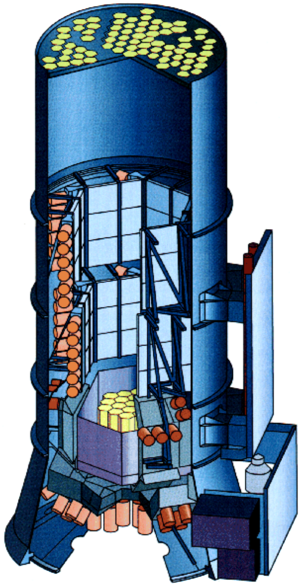
PARTICLE-PARTICLE COLLISIONS

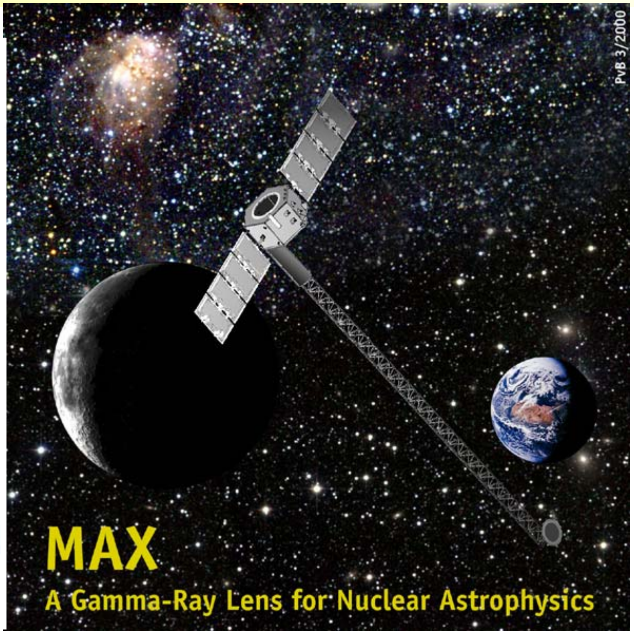


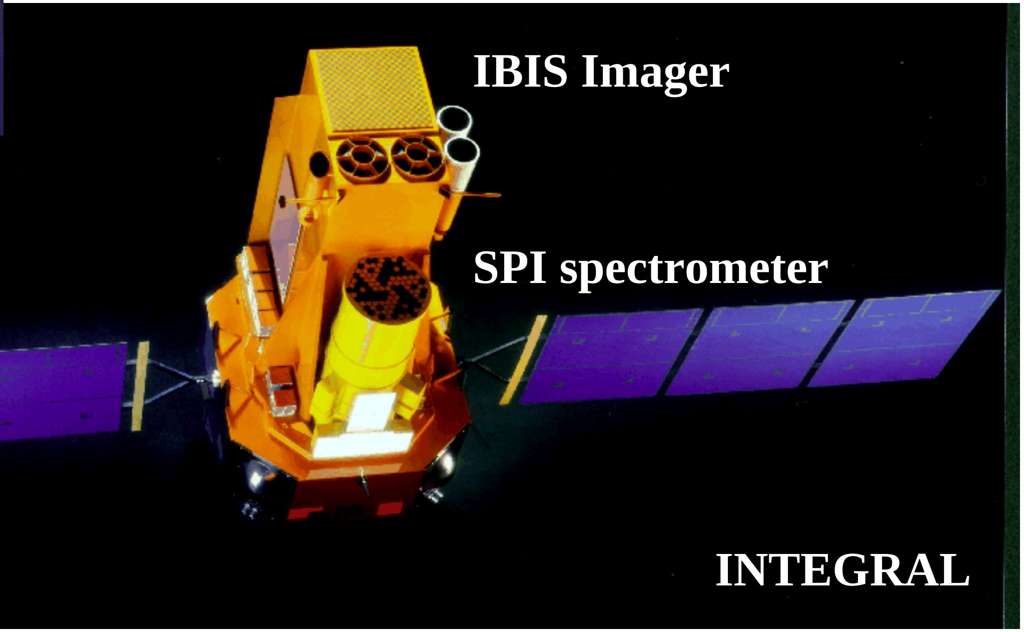
RADIOACTIVE NUCLEI

Some gamma telescopes

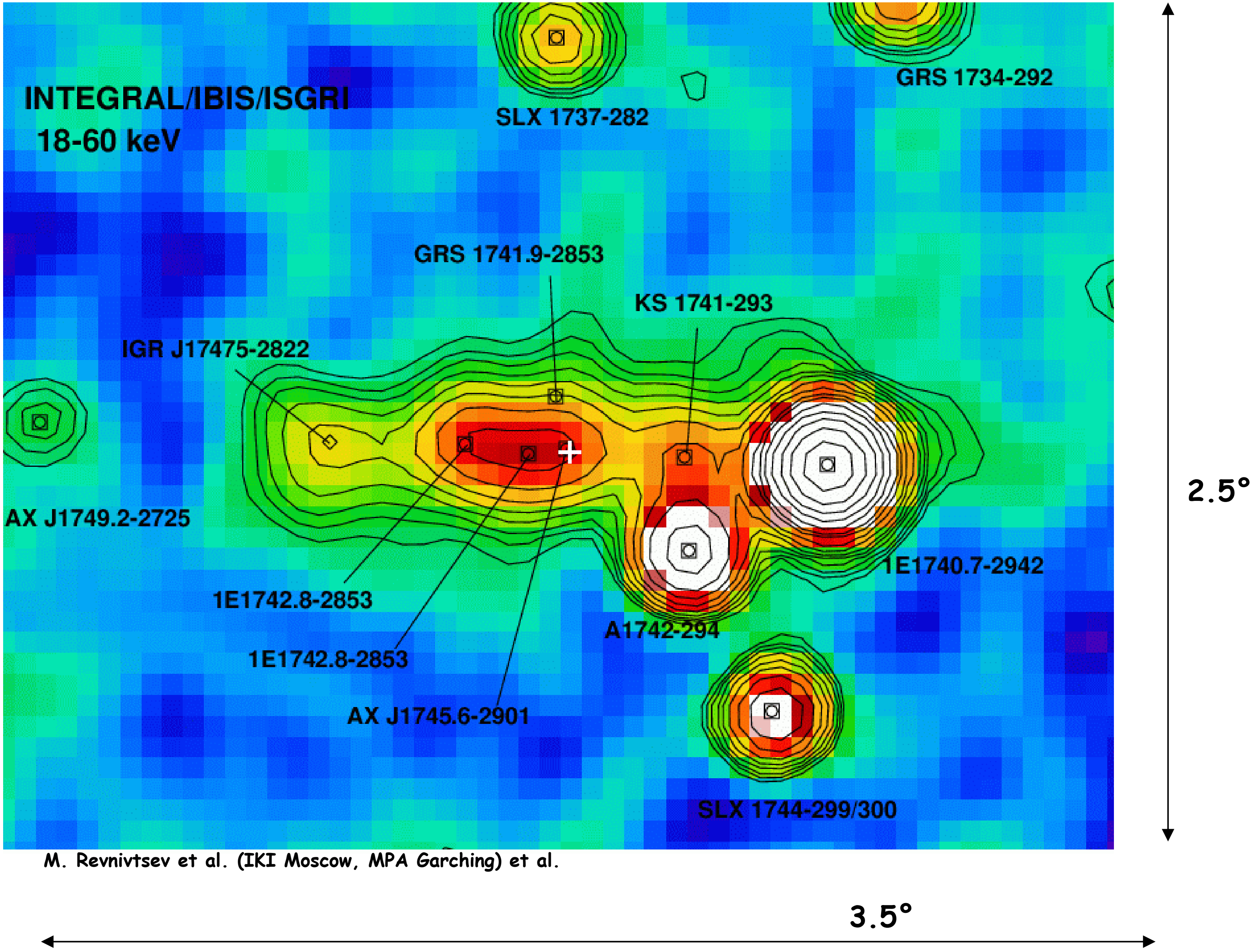








INTEGRAL/IBIS imager: galactic center



M. Revnivtsev et al. (IKI Moscow, MPA Garching) et al.

Mostly observable gamma-rays

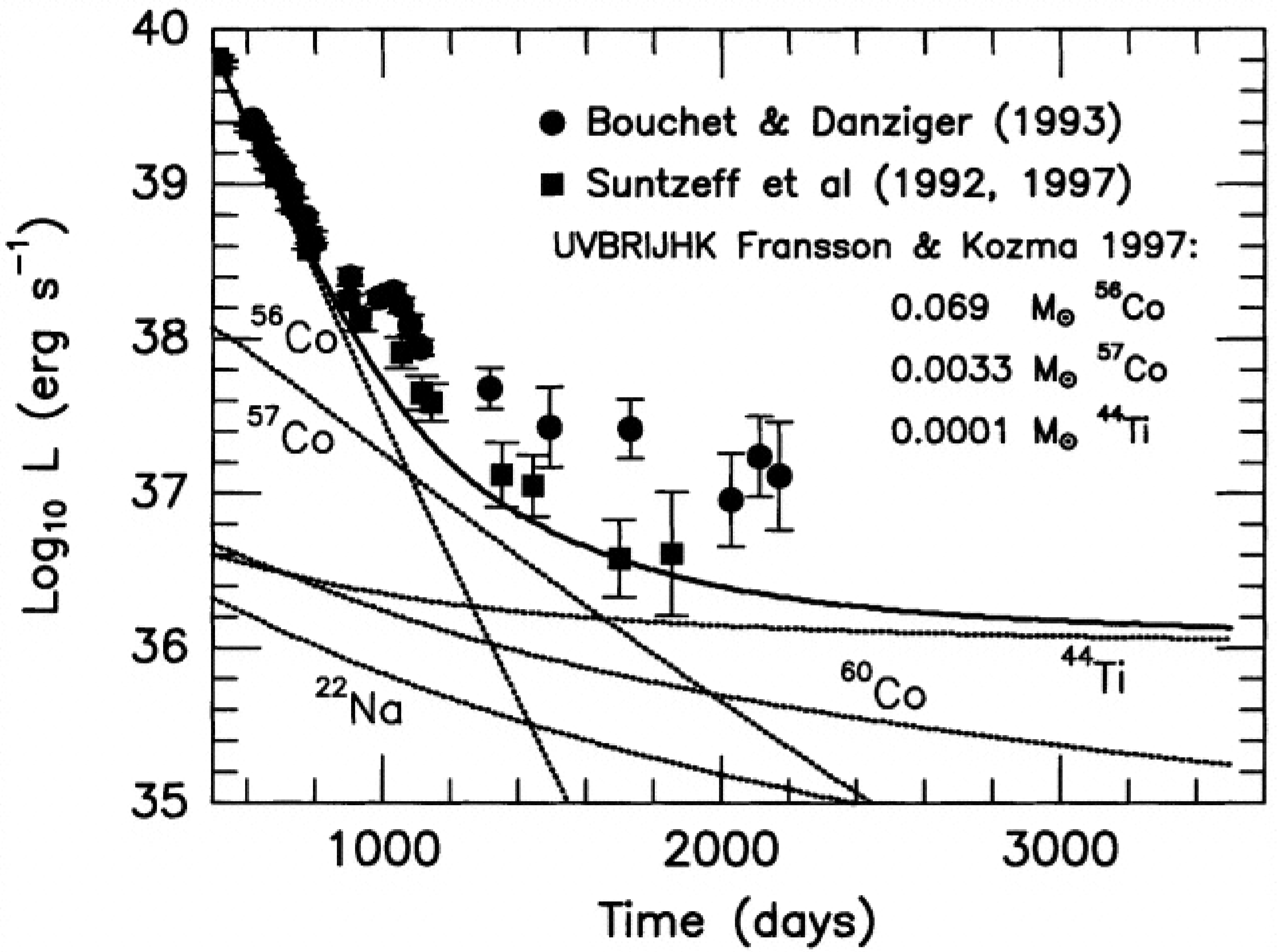
Isotope	Eγ (MeV)	$T_{1/2}$	Origine	Observé
^{7}Be	0,478	53,3 j	N, AGB	--
e+e-	0,511	--	β+	Galaxie
^{18}F(β+)+ e-	$\leq$0,511	110 mn	N	--
^{22}Na	1,275	2,6 an	N	?
^{26}Al	1,809	7,4 10^{5} an	SN,WR,AGB, N	Galaxie
^{44}Ti	1,157	60 an	SN	Cas A, Vela?
^{56}Ni/Co	0,847; 1,238	77,3 j	SN	SN1987A, SN1991T
^{57}Ni/Co	0,122;….	271,8 j	SN	SN1987A
^{60}Fe	1,173; 1,333;..	1,5 10^{6} an	SN	--

AGB : Asymptotic Giant Branch stars
WR : Wolf-Rayet stars
N : Novae
SN : Supernovae

SN1987A light curves

(Diehl & Timmes 1998)

Indirect observation of Co radioactivity:



Some references

General :

Clayton	"Principles of Stellar Evolution and Nucléosynthesis University of Chicago Press
Rolfs & Rodney	"Cauldrons in the Cosmos" University of Chicago Press
Lang	"Astrophysical Formulae" (2 Volumes) Springer
Ecole Joliot Curie	1990 et 2000 (IN2P3)
Burbridge et al. (B^{2}FH)	"Synthesis of Elements in Stars" (historique) Reviews of Modern Physics 29 (1957) 547
Wallerstein et al.	"Synthesis of Elements in stars: forty years..." Reviews of Modern Physics 69 (1997) 995
Slezak & Thévenin	"Nucléosynthèse et Abondance dans l'Univers" CEPADUES-Editions

s process:

Kaeppeler	"S-process nucleosynthesis - nulcear physics ..." Rep. Prog. Phys. 52 (1989) 945

Some references

Primordial nucleosynthesis:

Sarkar	(Rep. Prog. Phys. 59 (1996) 1493)
Schramm & Turner	"Big-Bang enters the precision era" Reviews of Modern Physics 70 (1998) 303
J. Rich	"Fundamentals of Cosmology" Springer

rp process

Schatz et al.	"rp-process nucleosynthesis at extreme ..." Physics Reports 294 (1998) 167

Novae:

Bode & Evans (Ed.)	"Classical Novae" John Wiley & Sons

Gamma ray astronomy:

Schoenfelder (Editeur)	"The Universe in Gamma Rays" Springer

Supernovae:

Arnett	"Supernovae and Nucleosynthesis" Princeton University Press

Cosmic rays:

Schlickeiser	"Cosmic Ray Astrophysics" Springer