# ASTROFÍSICA NUCLEAR (EXPERIMENTAL)

***Visión general y algunos ejemplos***

César Domingo Pardo

# Outline

- Introducción
- X-ray bursts: rp-process
- Heavy elements nucleosynthesis: the slow (s-) and the rapid (r-) neutron capture processes
- R-process in core collapse supernovae: experiments with radioactive ion beams
- S-process in massive stars: neutron capture measurements

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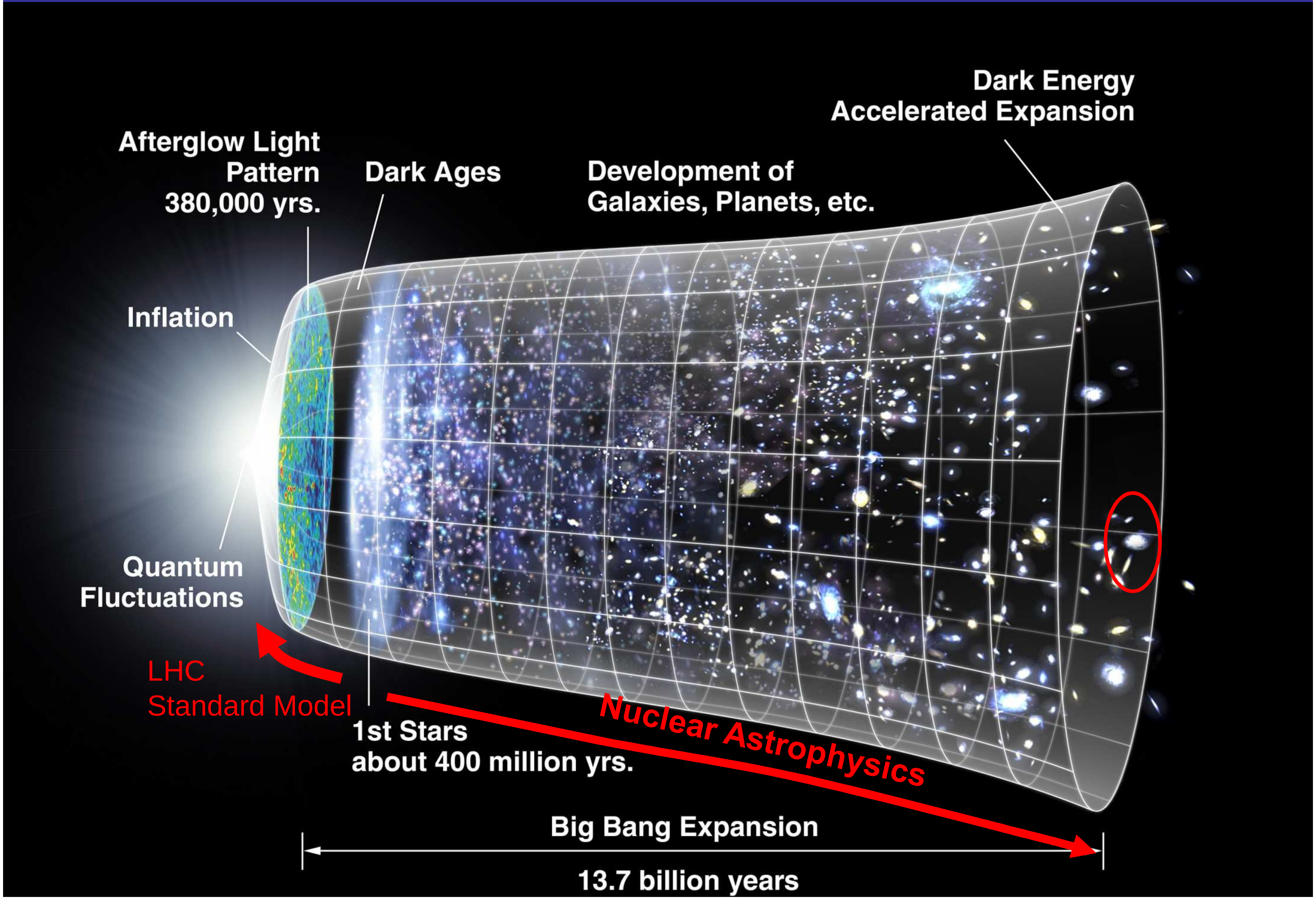
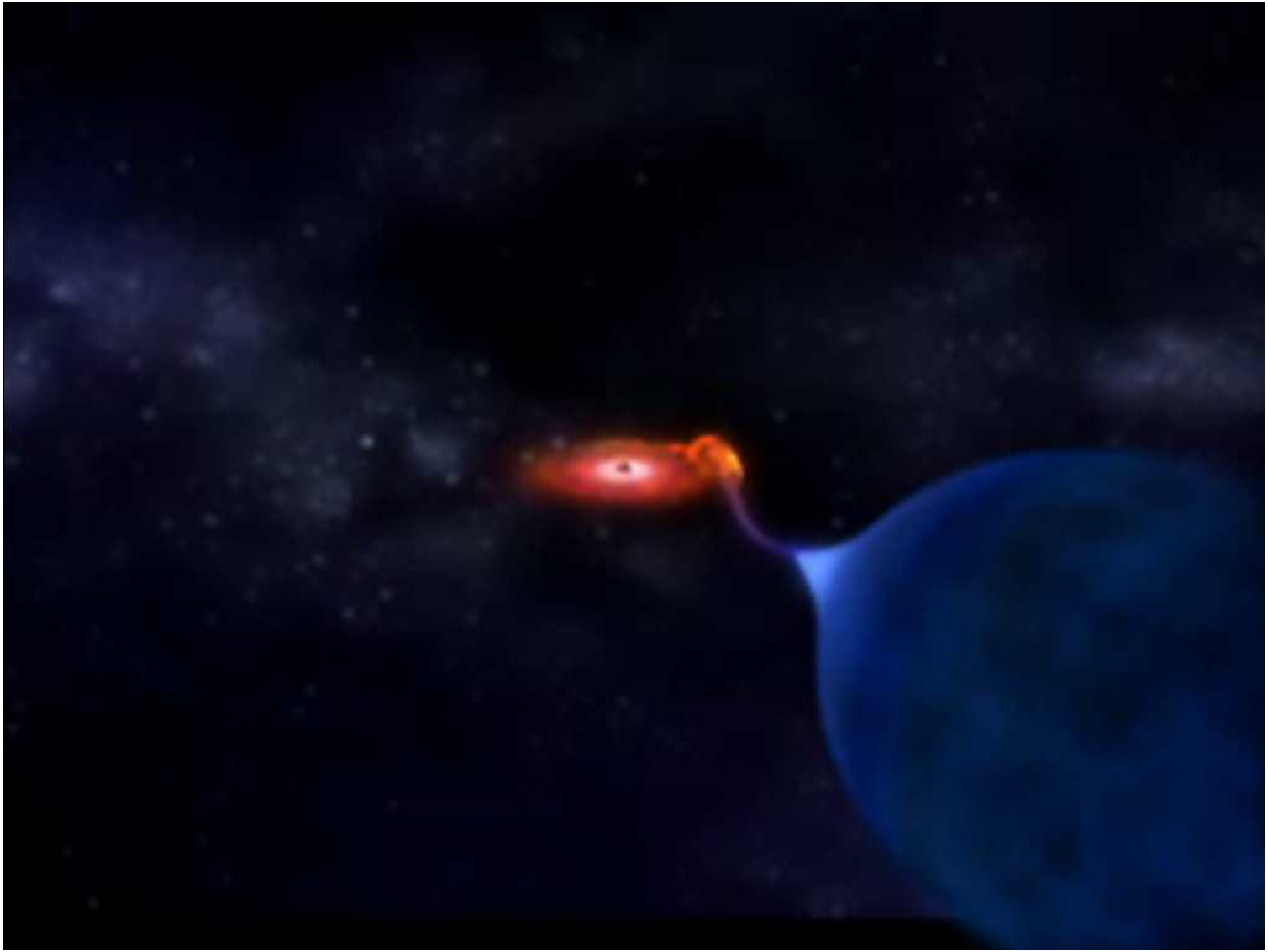
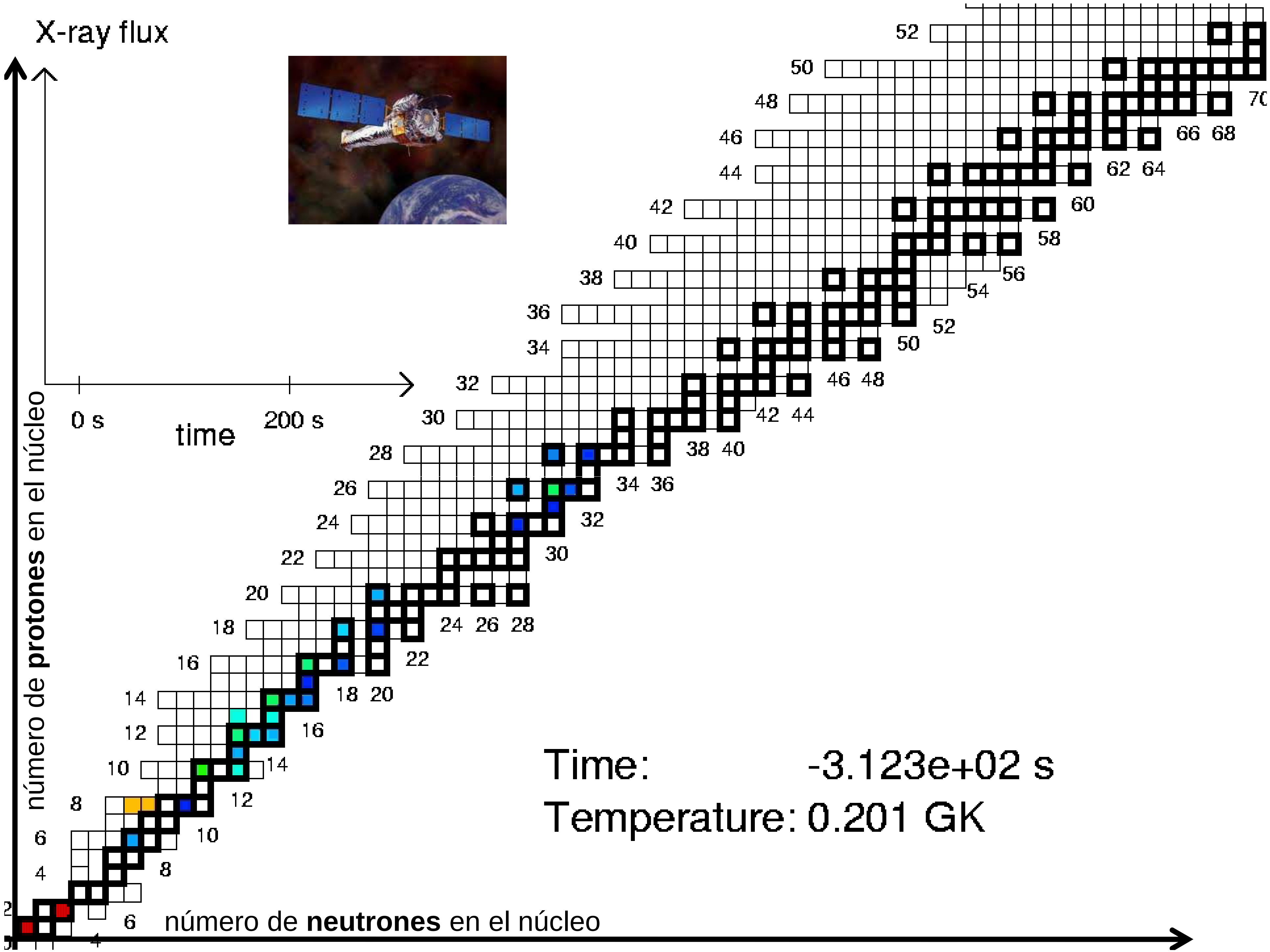
# The context of (experimental) nuclear astrophysics

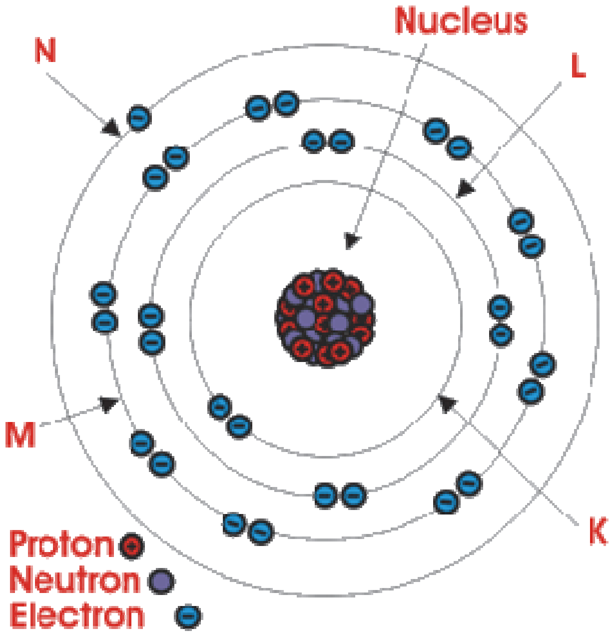


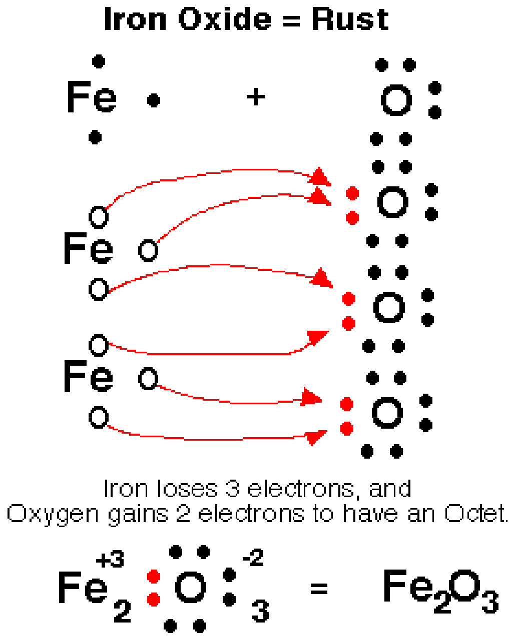



X-ray flux
0 s
time
200 s
número de protones en el núcleo
número de neutrones en el núcleo
Time: -3.123e+02 s
Temperature: 0.201 GK

## En química:

## Estructura atómica (e- valencia) → Reacciones químicas

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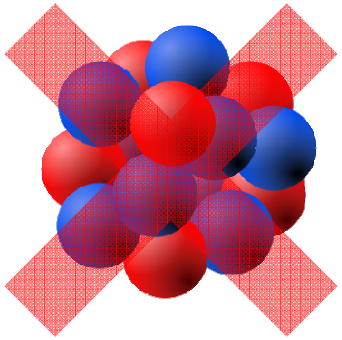
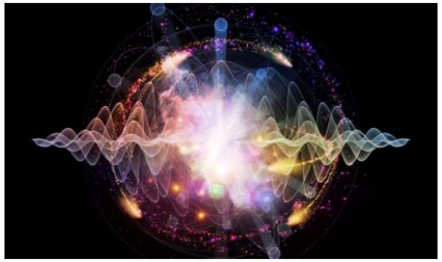
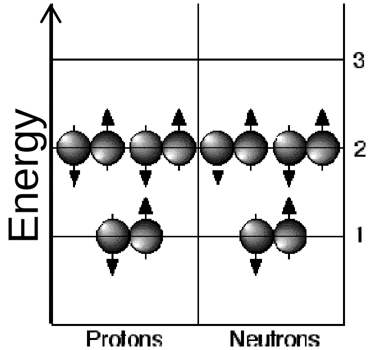
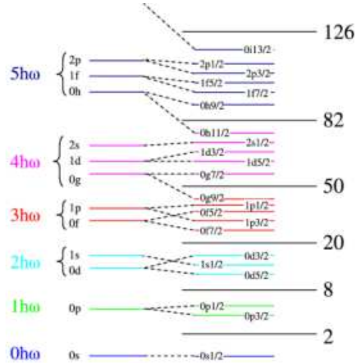
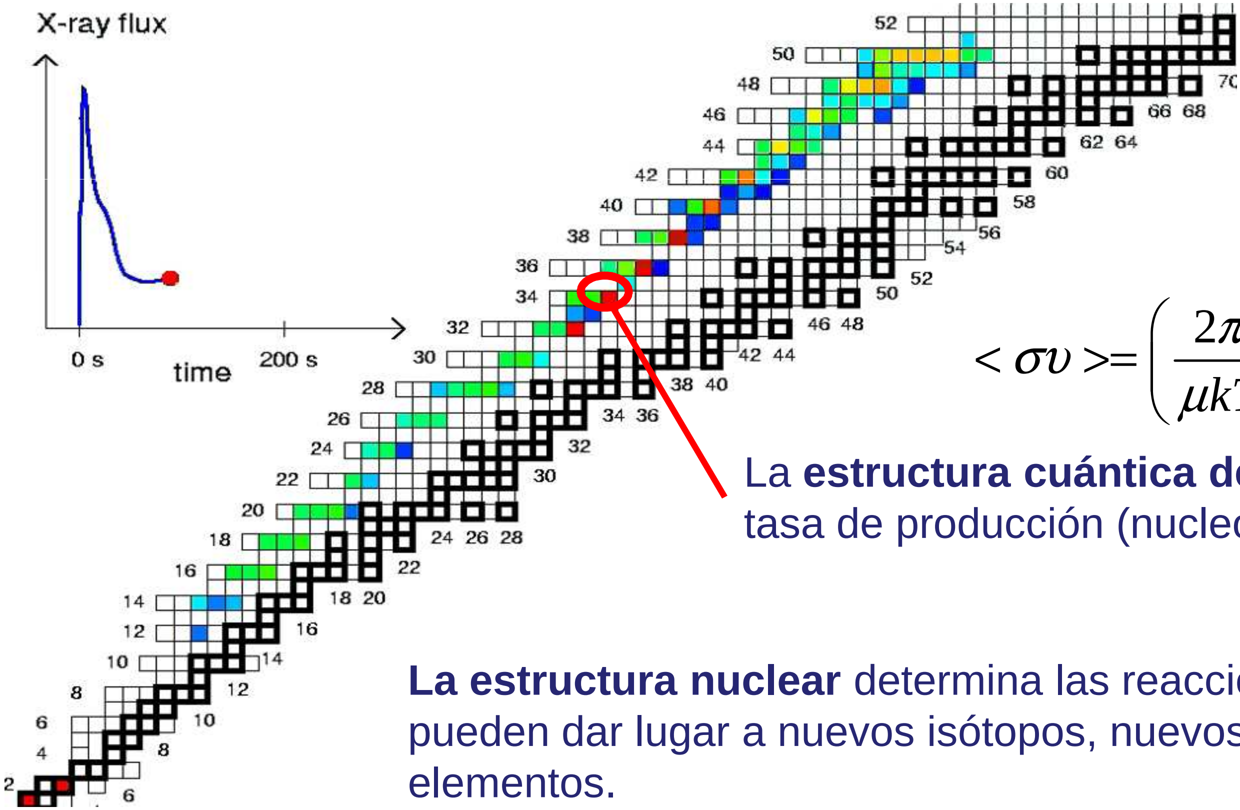
# En astrofísica: Estructura nuclear → Reacciones nucleares (NUCLEOSÍNTESIS)







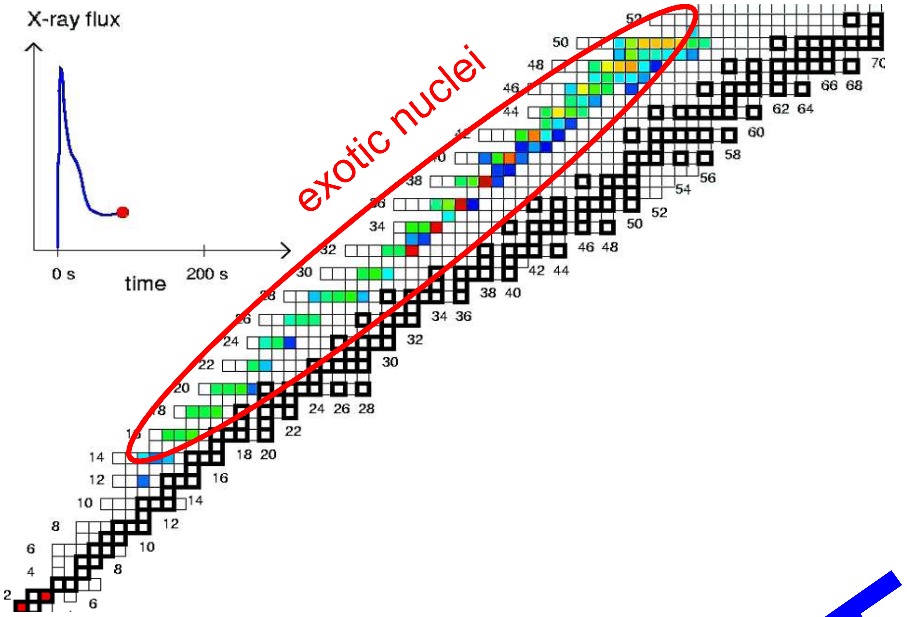




$$< \sigma\upsilon >= \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \sum_i (\omega\gamma)_i \exp\left(\frac{-(E_{R,i}^{CM})}{kT}\right)$$

La **estructura cuántica del núcleo** determina la tasa de producción (nucleosíntesis) estelar

**La estructura nuclear** determina las reacciones nucleares que pueden dar lugar a nuevos isótopos, nuevos núcleos, nuevos elementos.

# How to bring x-ray bursts to the lab?

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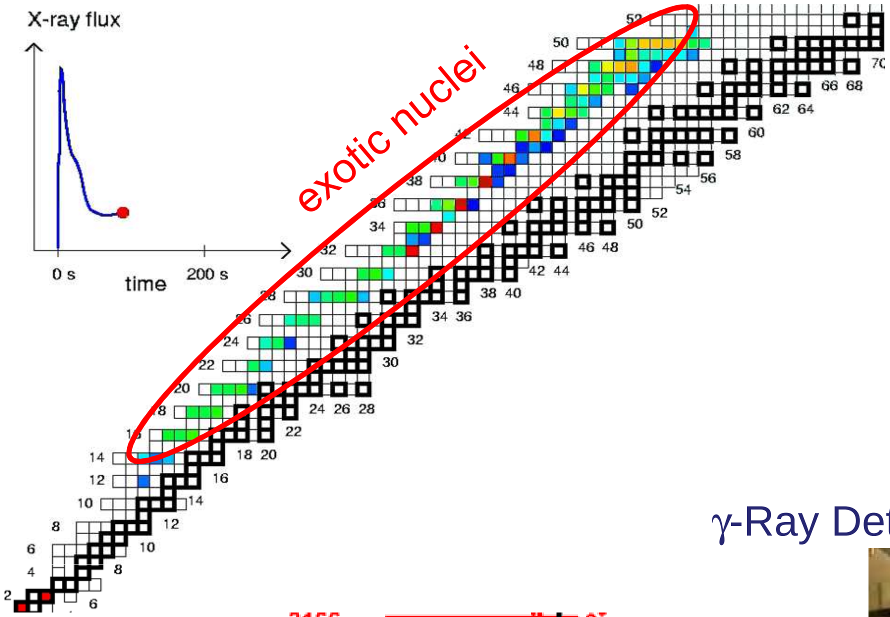
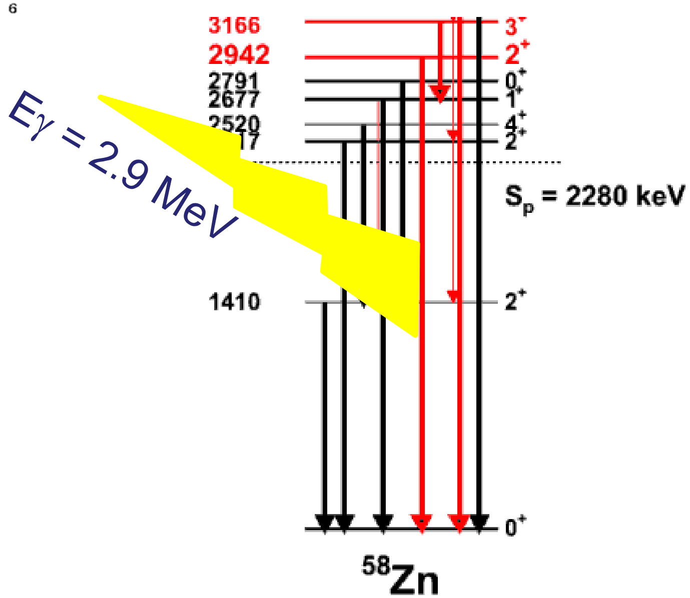


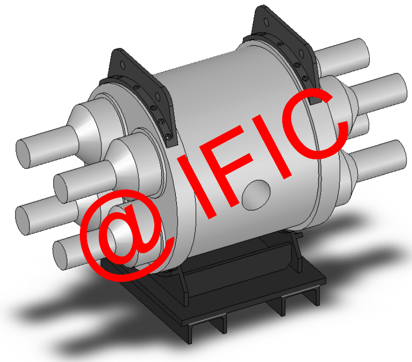

RIB Facility → Radioactive ion of interest (proton rich)

(see Alejandro's talk)

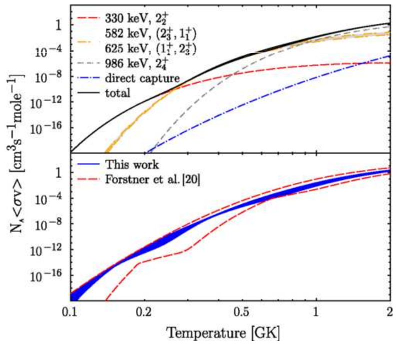


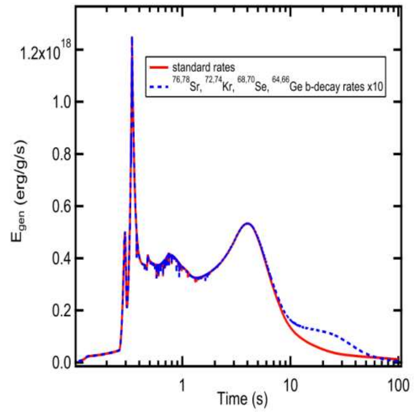

γ-Ray Detectors

AGATA




LUCRECIA



# To learn more…

- Bibliography:


- H. Schatz et al., Phys. Rev. Lett. 86, 3471 (2001) – Published 16 April 2001, **End Point of the *rp* Process on Accreting Neutron Stars**
- A.Parikh, et al., **The effects of variations in nuclear interactions on nucleosynthesis in thermonuclear supernovae**, Astronomy & Astrophysics, Volume 557, id.A3, 11 pp **DOI:** 10.1051/0004-6361/201321518
- A. Parikh, et al., **Nucleosynthesis in type I X-ray bursts**, Progress in Particle and Nuclear Physics, Volume 69, p. 225-253. (2013)
- *Nature* **302**, 317 - 319 (24 March 1983); doi:10.1038/302317a0 **Sub-second pulsations simultaneously observed at microwaves and hard X rays in a solar burst**

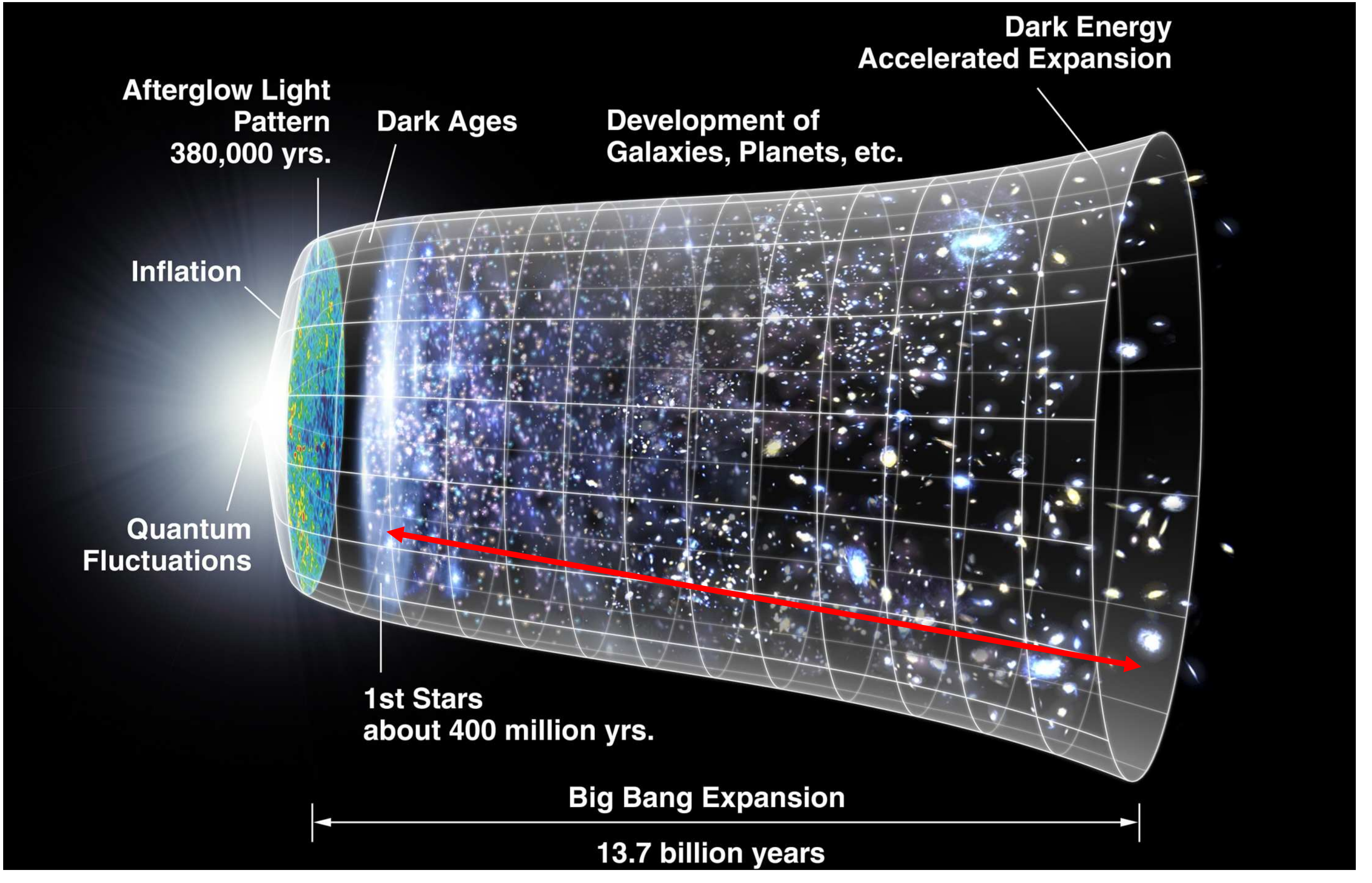

- The JINA center for the evolution of the elements:

http://www.jinaweb.org/

- Schools: 3rd Astrophysical Nuclear Reaction Network School

https://indico.gsi.de/conferenceDisplay.py?ovw=True&confId=4596

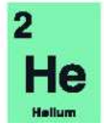
# The context of (experimental) nuclear astrophysics



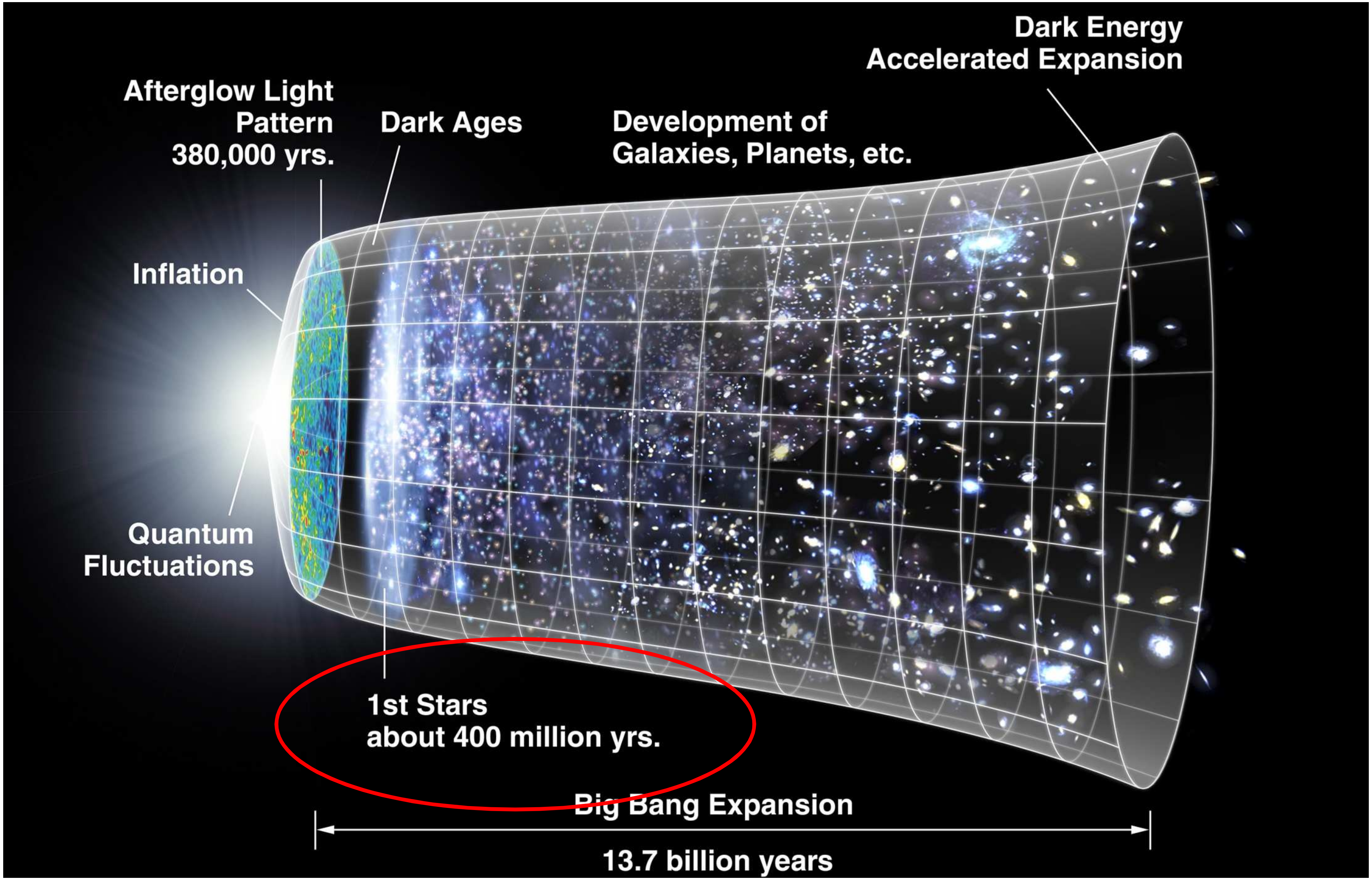
| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H Hydrogen | | | | | | | | | | | | | | | | | 2 He Helium |
| 3 Li Lithium | 4 Be Beryllium | | | | | | | | | | | 5 B Boron | 6 C Carbon | 7 N Nitrogen | 8 O Oxygen | 9 F Fluorine | 10 Ne Neon |
| 11 Na Sodium | 12 Mg Magnesium | | | | | | | | | | | 13 Al Aluminium | 14 Si Silicon | 15 P Phosphorus | 16 S Sulfur | 17 Cl Chlorine | 18 Ar Argon |
| 19 K Potassium | 20 Ca Calcium | 21 Sc Scandium | 22 Ti Titanium | 23 V Vanadium | 24 Cr Chromium | 25 Mn Manganese | 26 Fe Iron | 27 Co Cobalt | 28 Ni Nickel | 29 Cu Copper | 30 Zn Zinc | 31 Ga Gallium | 32 Ge Germanium | 33 As Arsenic | 34 Se Selenium | 35 Br Bromine | 36 Kr Krypton |
| 37 Rb Rubidium | 38 Sr Strontium | 39 Y Yttrium | 40 Zr Zirconium | 41 Nb Niobium | 42 Mo Molybdenum | 43 Tc Technetium | 44 Ru Ruthenium | 45 Rh Rhodium | 46 Pd Palladium | 47 Ag Silver | 48 Cd Cadmium | 49 In Indium | 50 Sn Tin | 51 Sb Antimony | 52 Te Tellurium | 53 I Iodine | 54 Xe Xenon |
| 55 Cs Cesium | 56 Ba Barium | 57 La* Lanthanum | 72 Hf Hafnium | 73 Ta Tantalum | 74 W Tungsten | 75 Re Rhenium | 76 Os Osmium | 77 Ir Iridium | 78 Pt Platinum | 79 Au Gold | 80 Hg Mercury | 81 Tl Thallium | 82 Pb Lead | 83 Bi Bismuth | 84 Po Polonium | 85 At Astatine | 86 Rn Radon |
| 87 Fr Francium | 88 Ra Radium | 89 Ac** Actinium | 104 Rf Rutherfordium | 105 Db Dubnium | 106 Sg Seaborgium | 107 Bh Bohrium | 108 Hs Hassium | 109 Mt Meitnerium | 110 Ds Darmstadtium | 111 Rg Roentgenium | 112 Cn Copernicium | 113 Uut Ununtrium | 114 Fl Flerovium | 115 Uup Ununpentium | 116 Lv Livermorium | 117 Uus Ununseptium | 118 Uuo Ununoctium |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * | 58 Ce Cerium | 59 Pr Praseodymium | 60 Nd Neodymium | 61 Pm Promethium | 62 Sm Samarium | 63 Eu Europium | 64 Gd Gadolinium | 65 Tb Terbium | 66 Dy Dysprosium | 67 Ho Holmium | 68 Er Erbium | 69 Tm Thulium | 70 Yb Ytterbium | 71 Lu Lutetium |
| ** | 90 Th Thorium | 91 Pa Protactinium | 92 U Uranium | 93 Np Neptunium | 94 Pu Plutonium | 95 Am Americium | 96 Cm Curium | 97 Bk Berkelium | 98 Cf Californium | 99 Es Einsteinium | 100 Fm Fermium | 101 Md Mendelevium | 102 No Nobelium | 103 Lr Lawrencium |


just after Big-Bang

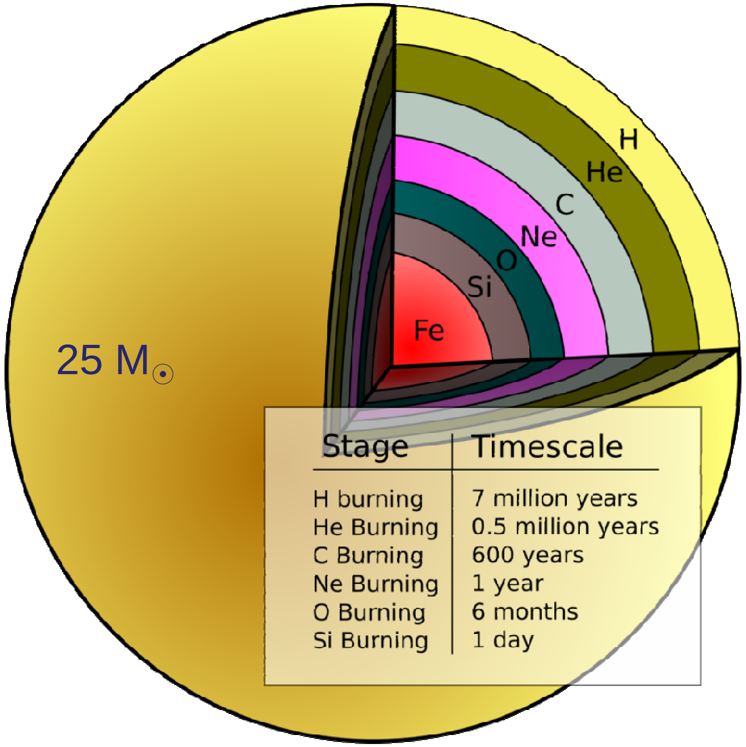


# The context of (experimental) nuclear astrophysics

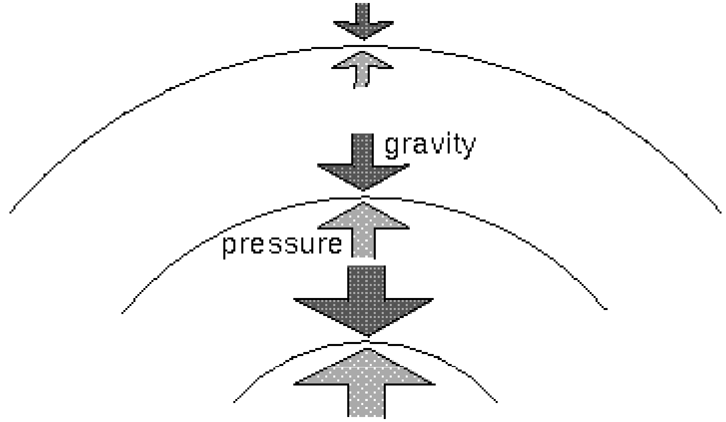


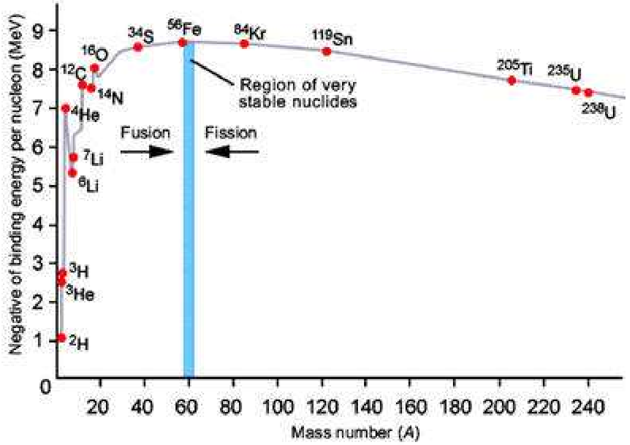
# Nucleosynthesis of the light-to-medium heavy nuclei (up to Fe)

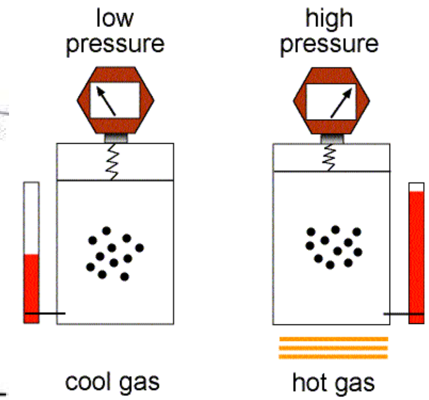
- Hydrostatic evolution stages of massive stars
- Iron group elements are built in the last burning phase before SN explosion




| Stage | Timescale |
|---|---|
| H burning | 7 million years |
| He Burning | 0.5 million years |
| C Burning | 600 years |
| Ne Burning | 1 year |
| O Burning | 6 months |
| Si Burning | 1 day |



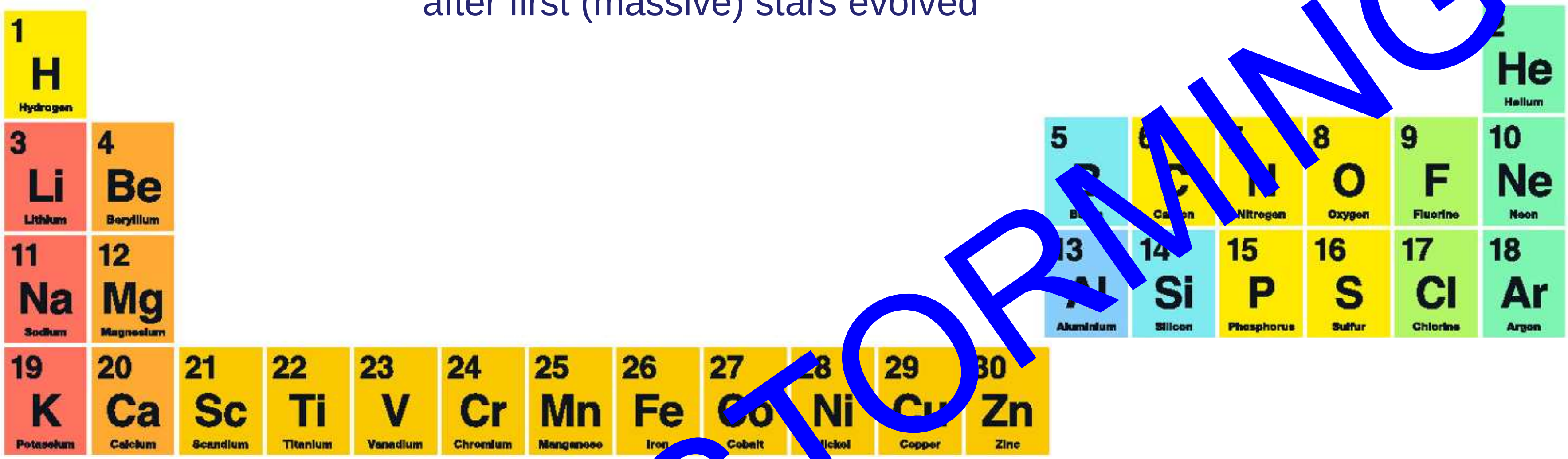




$$\text{pressure} = k \times \frac{\text{density} \times \text{temperature}}{\text{molecular weight}}$$

Massive stars 8 $M_\odot$ < M < 70 $M_\odot$

$M_\odot = 1.989\times10^{30}$ Kg

→Beyond the Fe-group, no further fusion reactions (charged particles) are possible after first (massive) stars evolved

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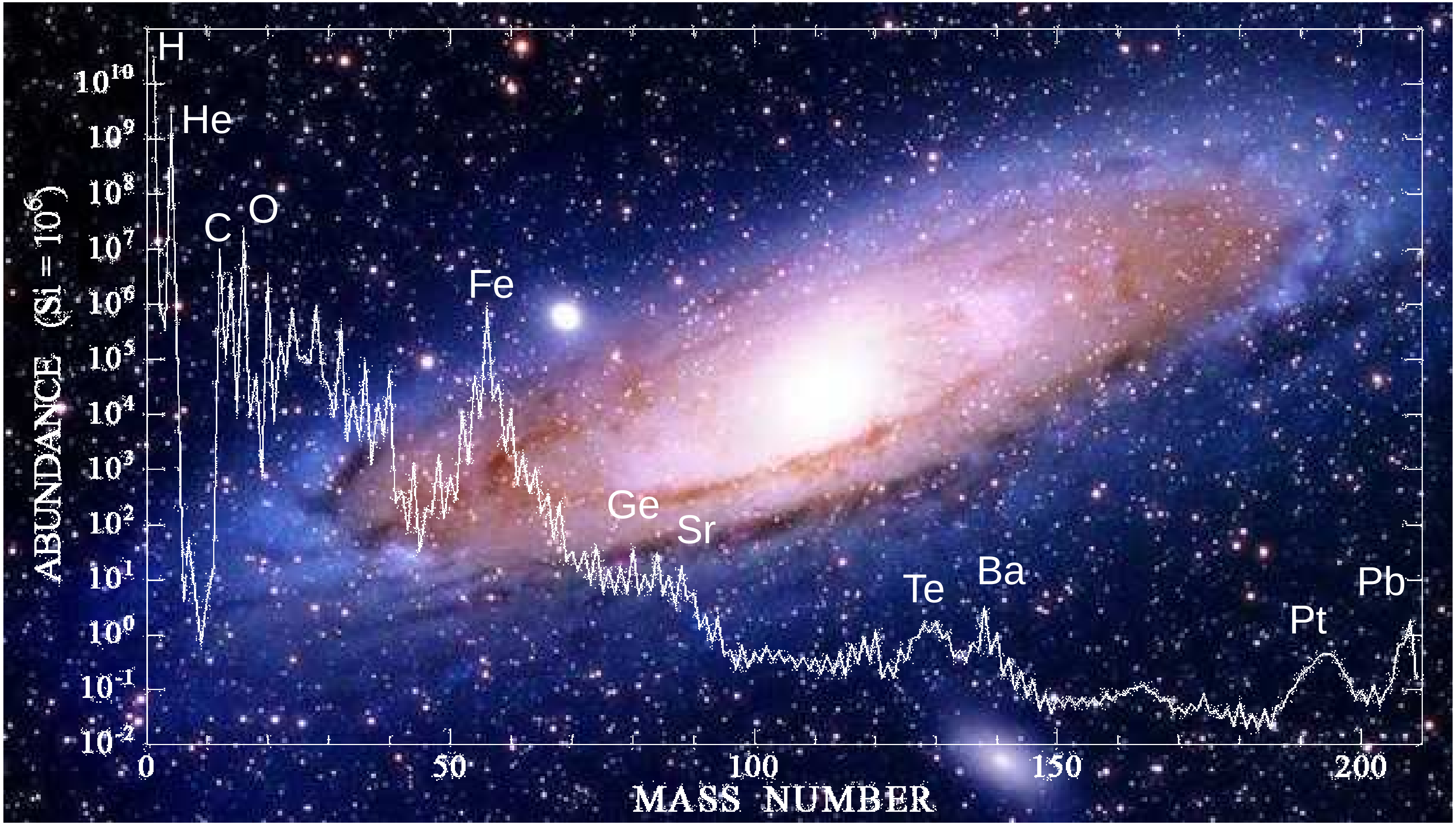
# What kind of reactions could originate the heaviest nuclei?

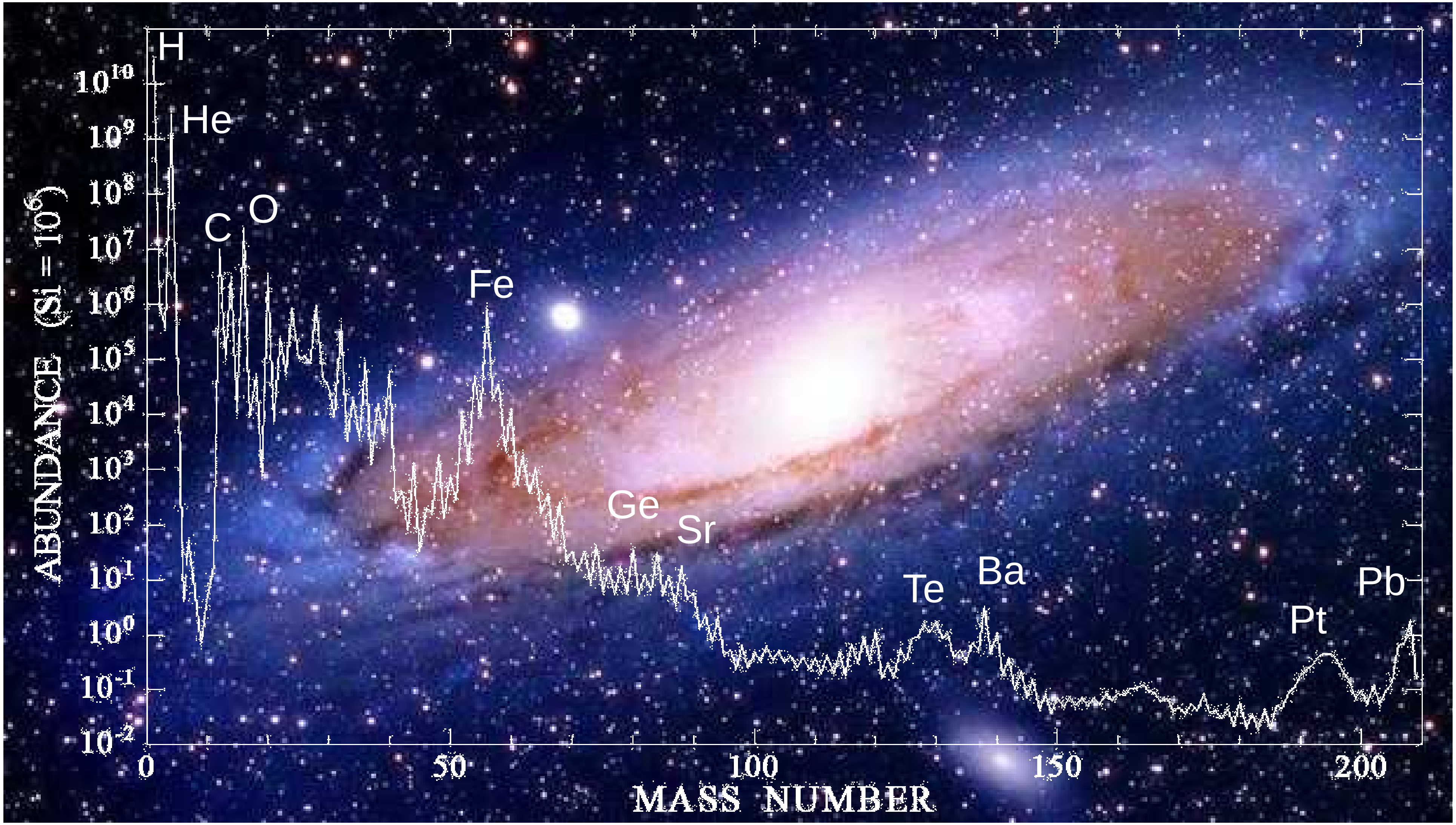
BB ⟵ Fusion ⟶



# What kind of reactions could originate the heaviest nuclei?

→Neutrons produce 75% of all the elements
→ 0.005% of the total abundances (!)
→ 10-12 orders-of-magnitude difference between H and the rarest (heaviest) nuclei (!)

BB ← Fusion → ← Neutrons →



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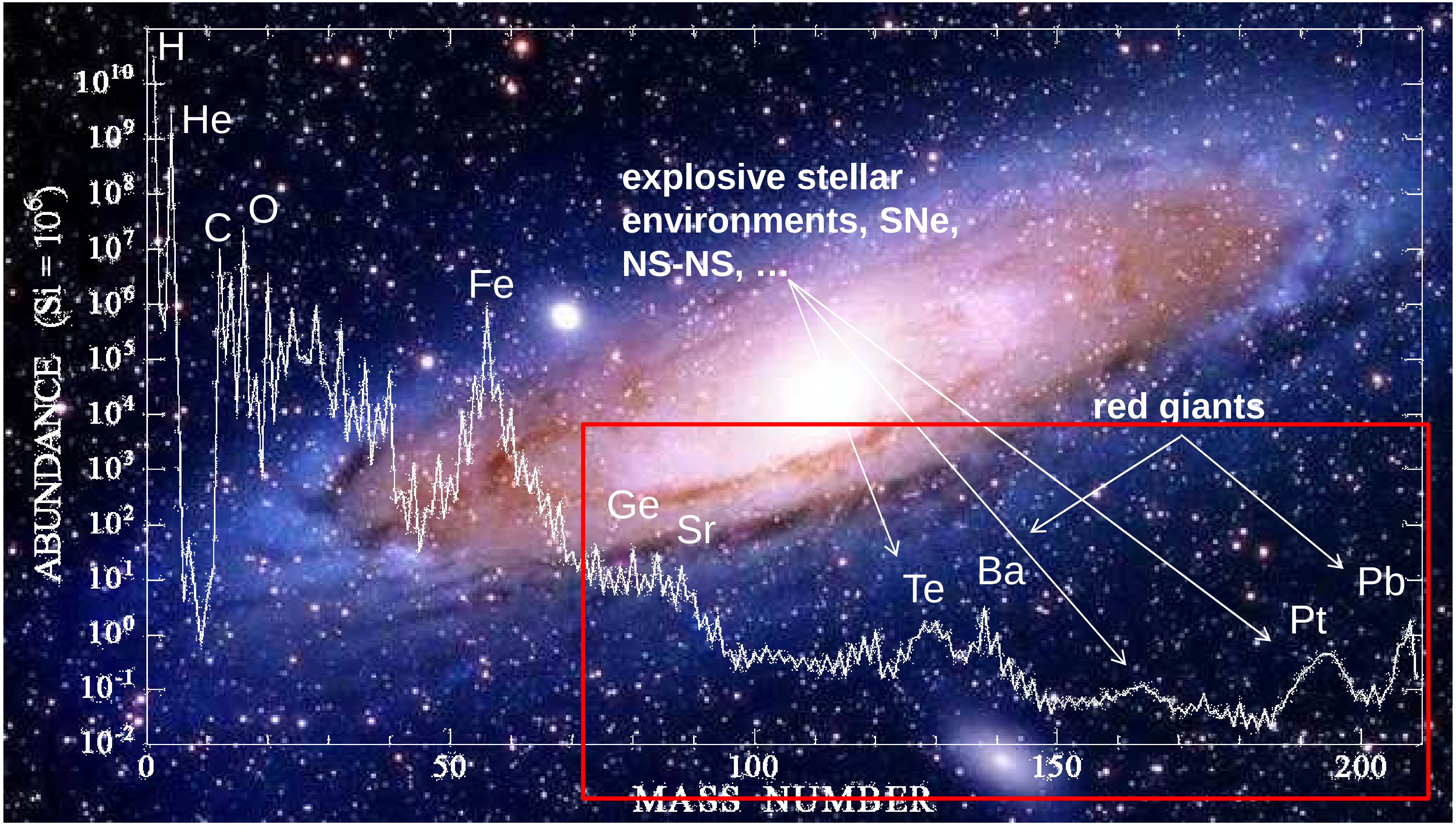
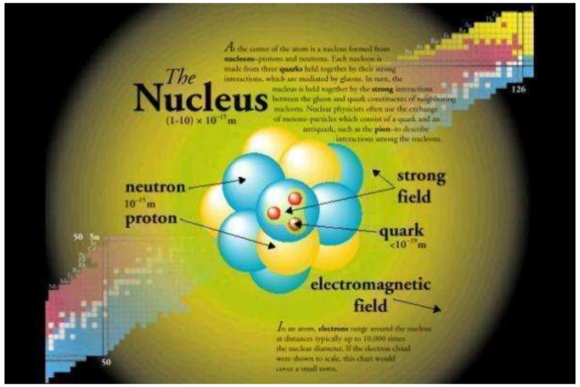
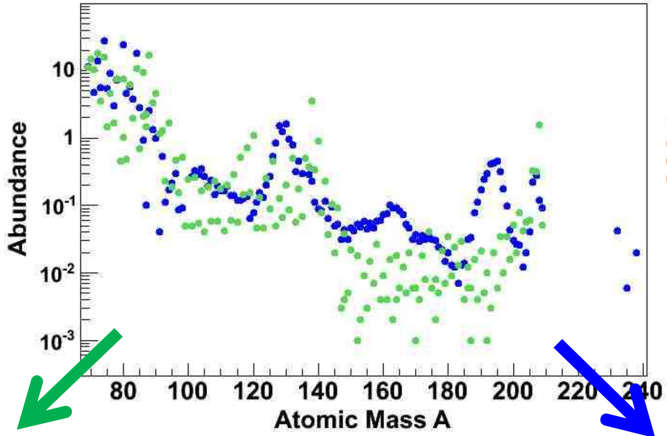
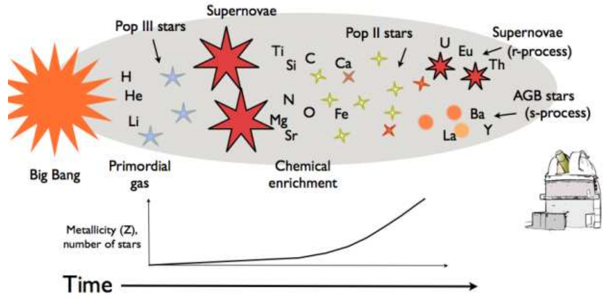


# El origen de los elementos pesados: procesos s y r



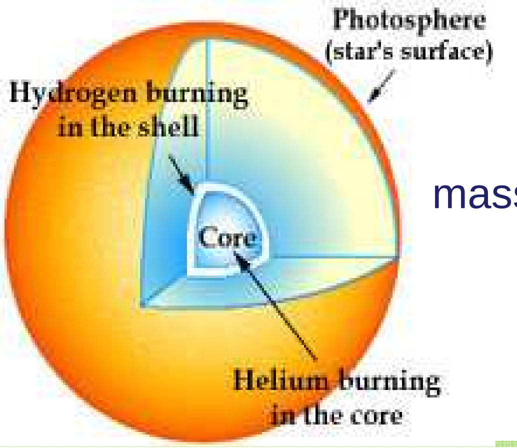




## s-process

core He-burning
$3\text{-}3.5\cdot10^{8}$ K
kT=26 keV
$10^{6}$ $cm^{-3}$

shell C-burning
$\sim1\cdot10^{9}$ K
kT=91 keV
$10^{11}\text{-}10^{12}$ $cm^{-3}$

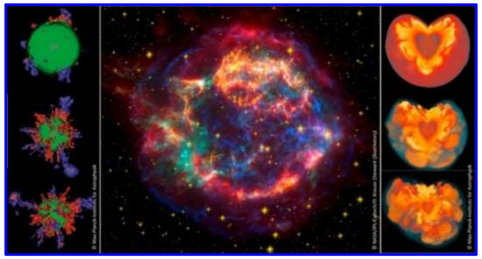
**$^{22}Ne(^{4}He,n)\,^{25}Mg$**

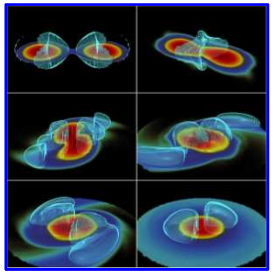



massive stars > 8 $M_{\odot}$

## r-process

**SN,N-Star Mergers, etc ?**





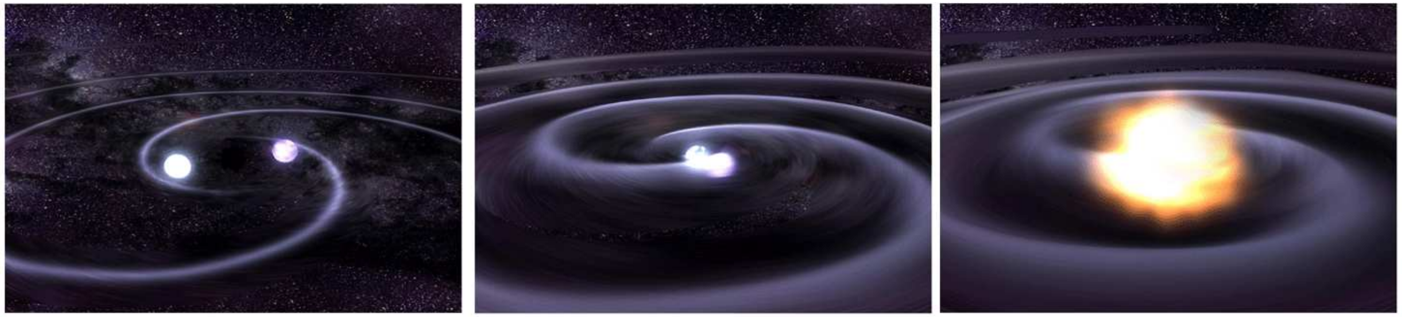
- **Where is the site?**
- **How is the environment?**
- **Entropy**
- **Rotation, 3D, etc**

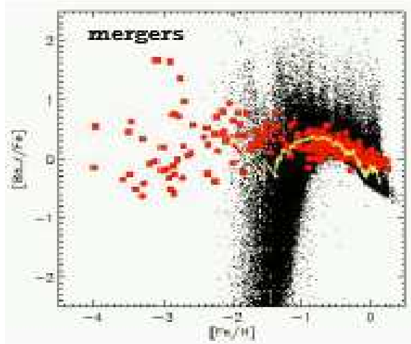
# The rapid (r-) neutron capture process

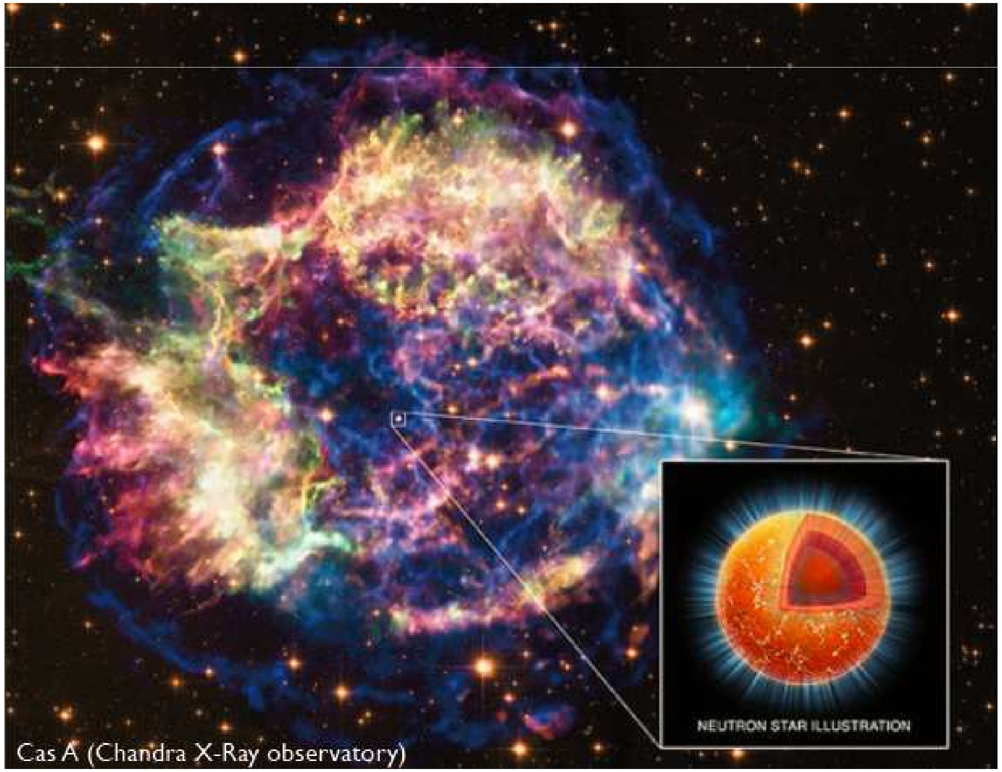
- Several candidates: SNe, NS-Mergers, NS-BH Mergers, etc
- High entropy and neutron density conditions required

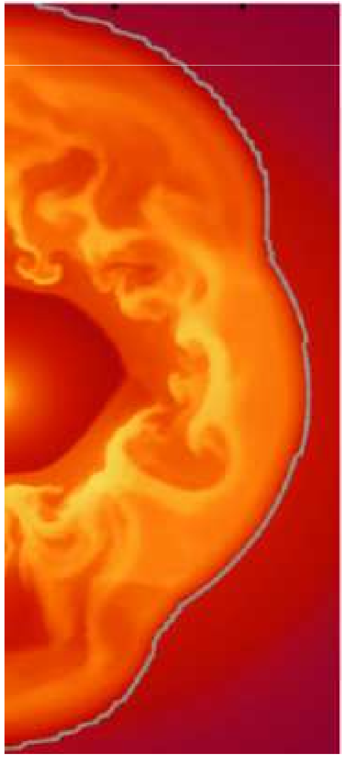
$T = 10^{8}\text{-}10^{10}$ K

$N_n = 10^{20}\text{-}10^{27}$ cm$^{-3}$



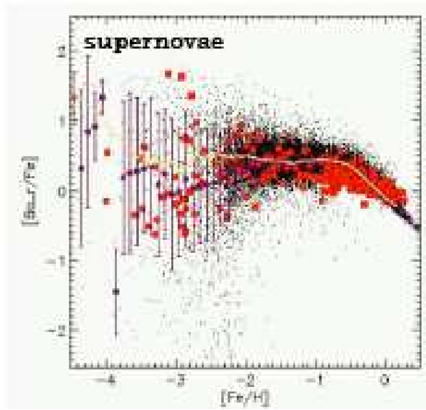


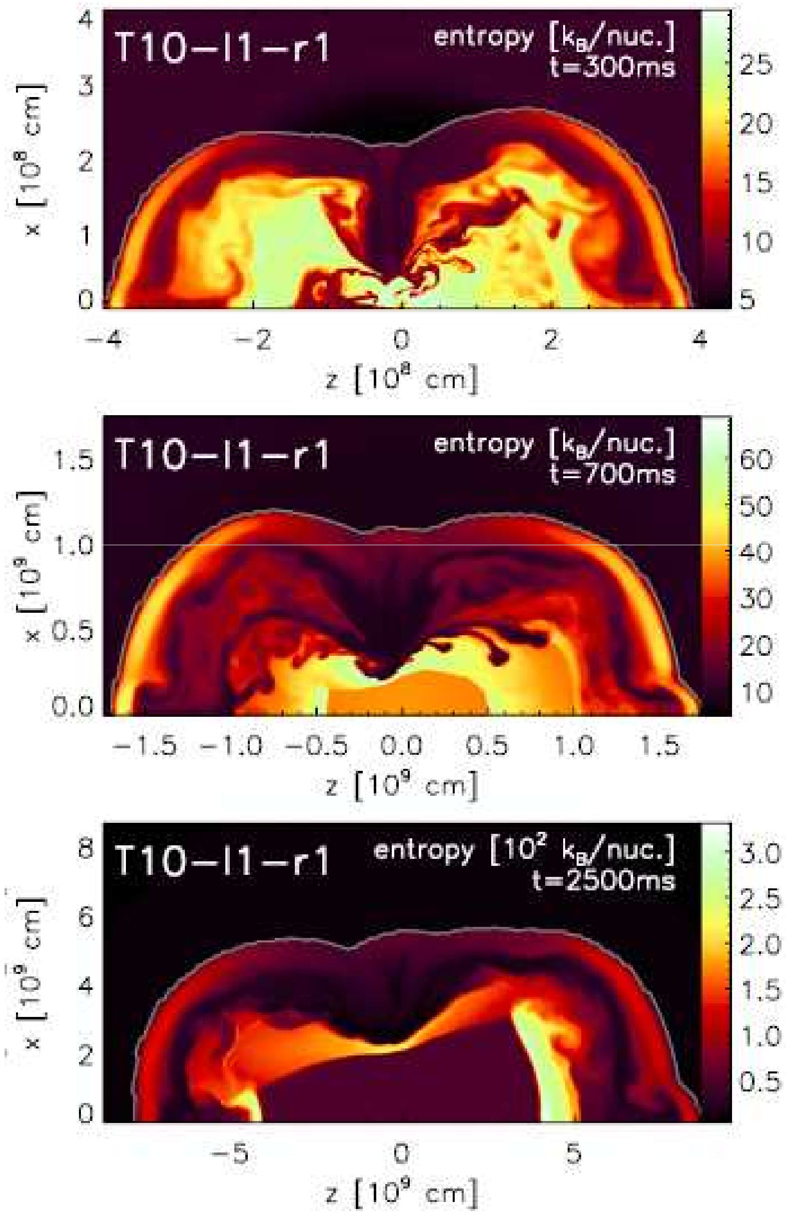
$\nu_e + n \rightarrow p + e^-$

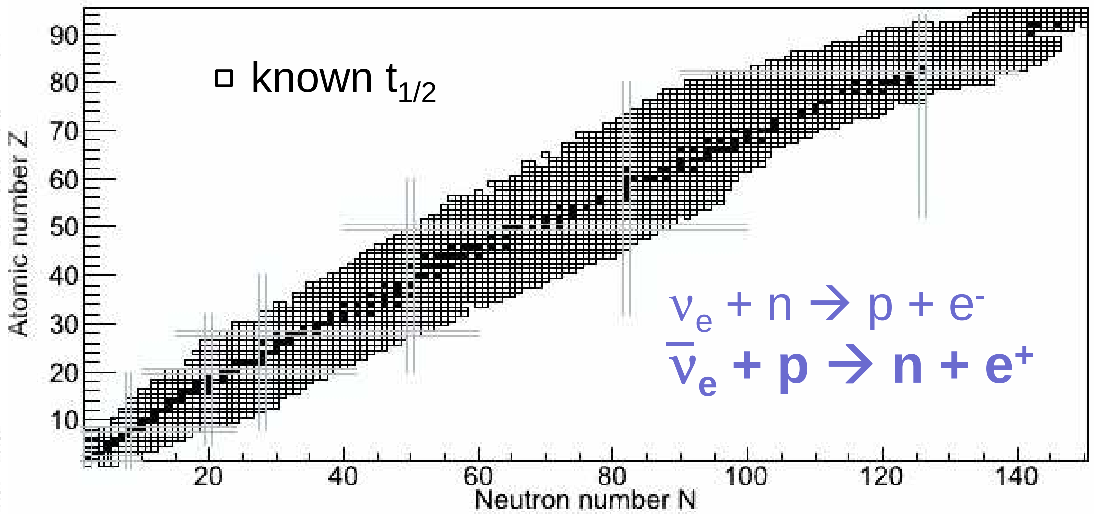
$\boldsymbol{\bar{\nu}_e + p \rightarrow n + e^+}$

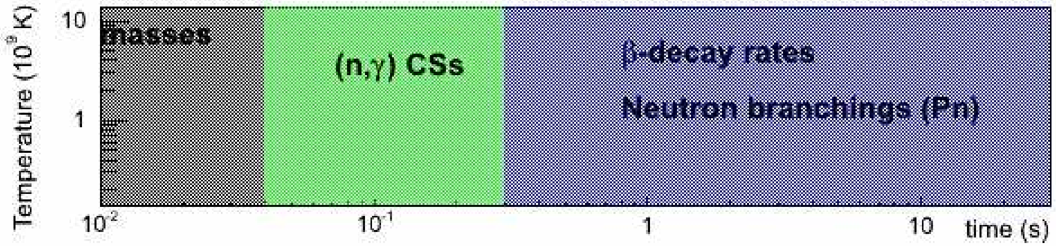


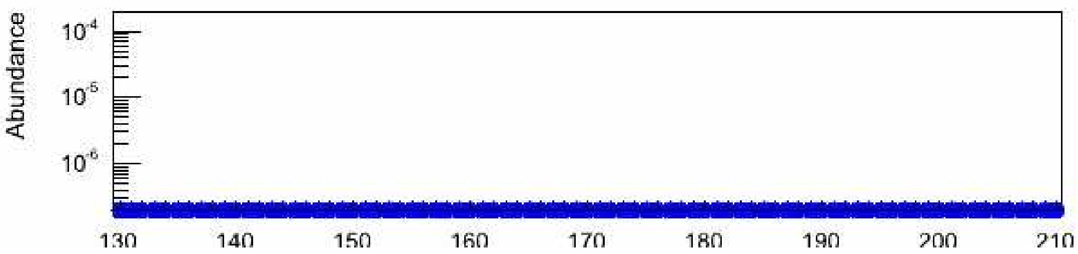

**Argast et al., 2004**

# R-process nucleosynthesis



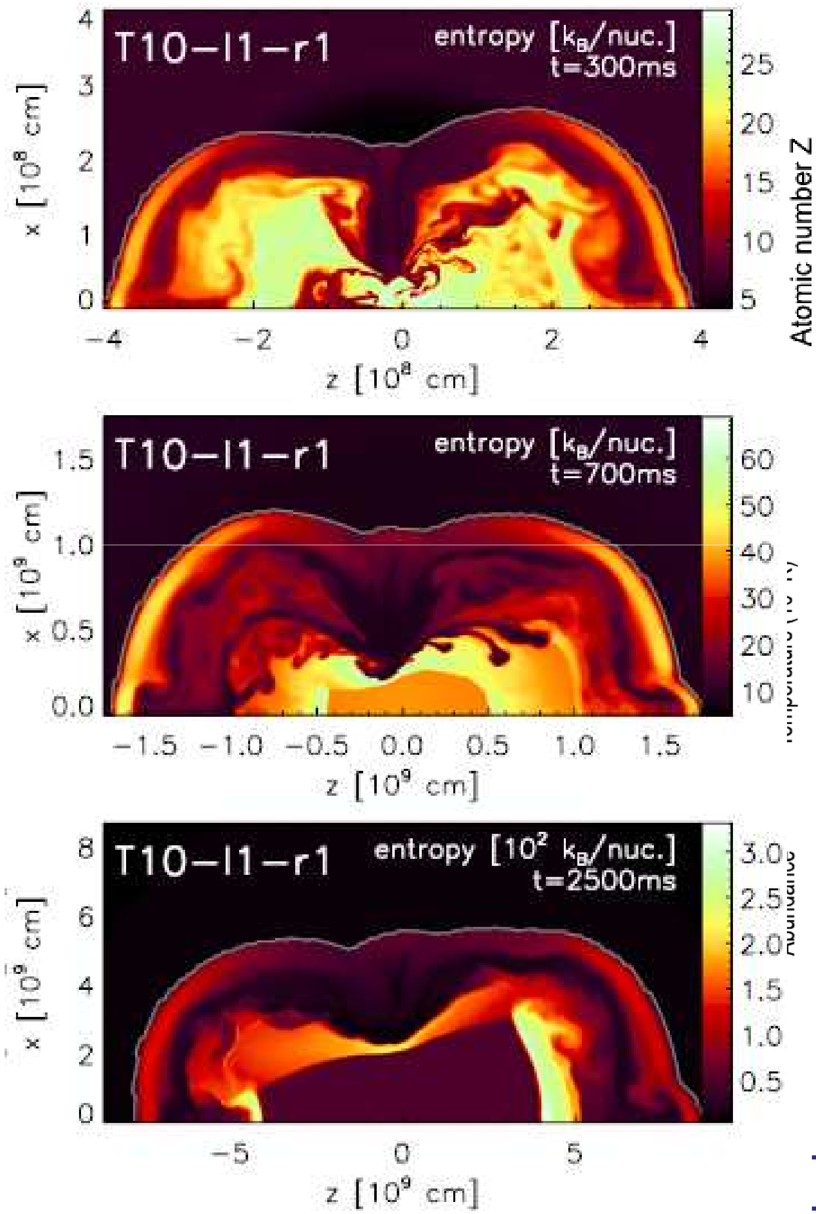



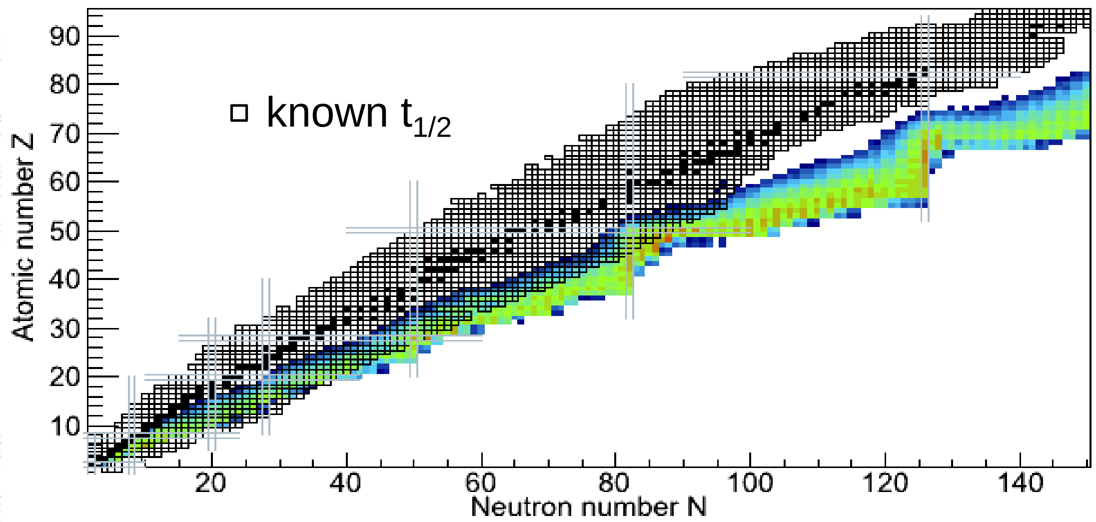



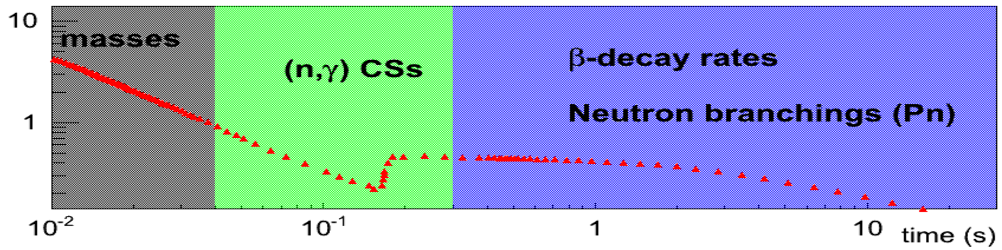



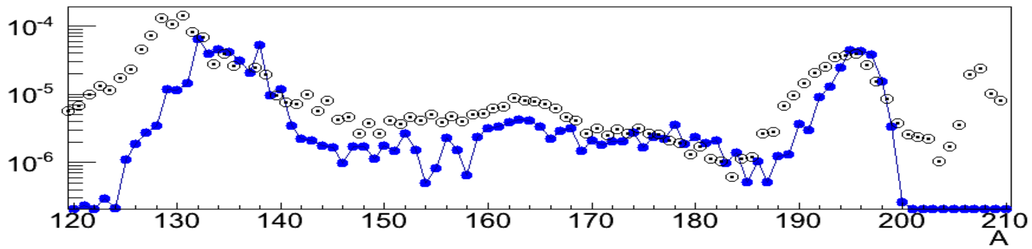

NucNet network code, B. Meyer et al., Clemson University
FRDM+QRPA (P. Möller) + JINA Reaclib Database (Cyburt)

# R-process nucleosynthesis: relevant nuclear input



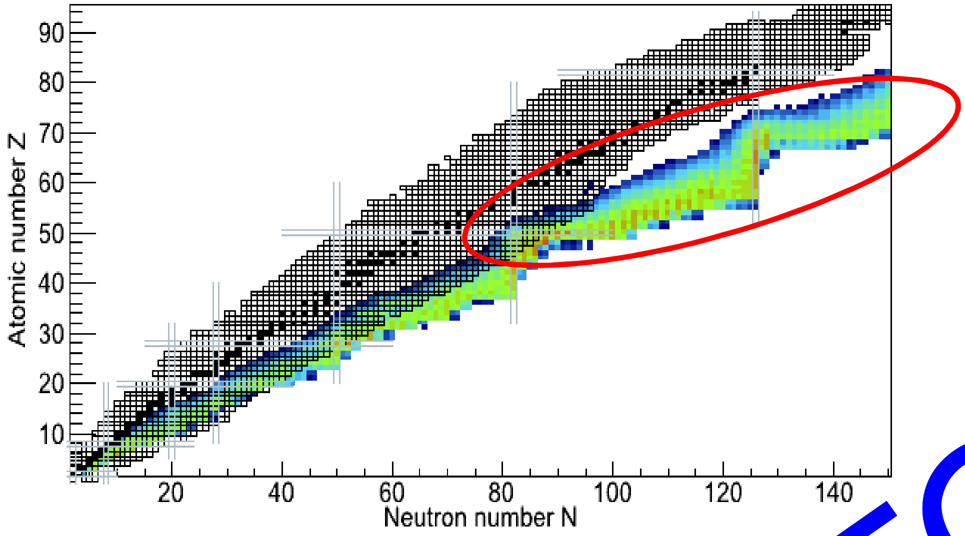




→Beta-decays tailor the final abundance pattern

→ How well do we know such β-decays?

# How to bring Supernovae to the lab?




RIB Facility

Radioactive ion of interest (neutron rich)

(see Alejandro's talk)

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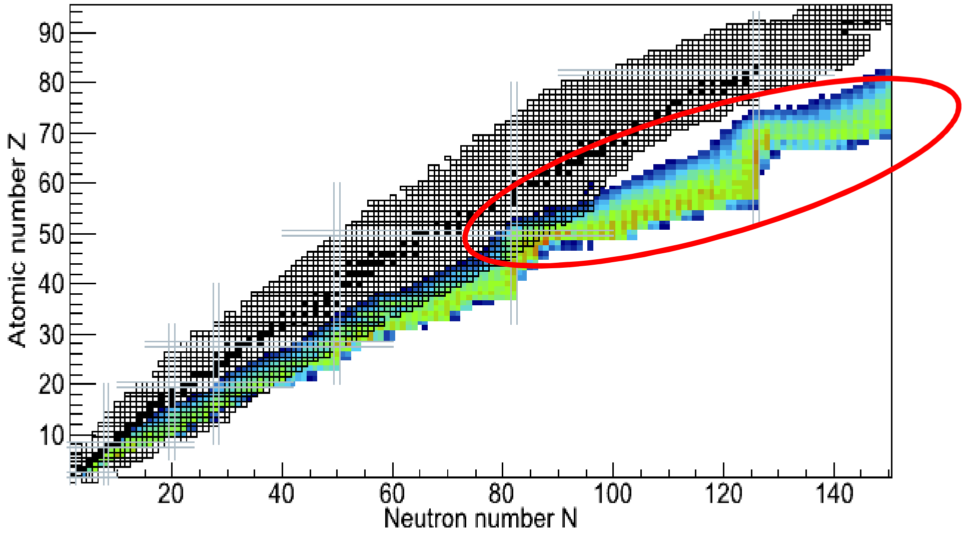


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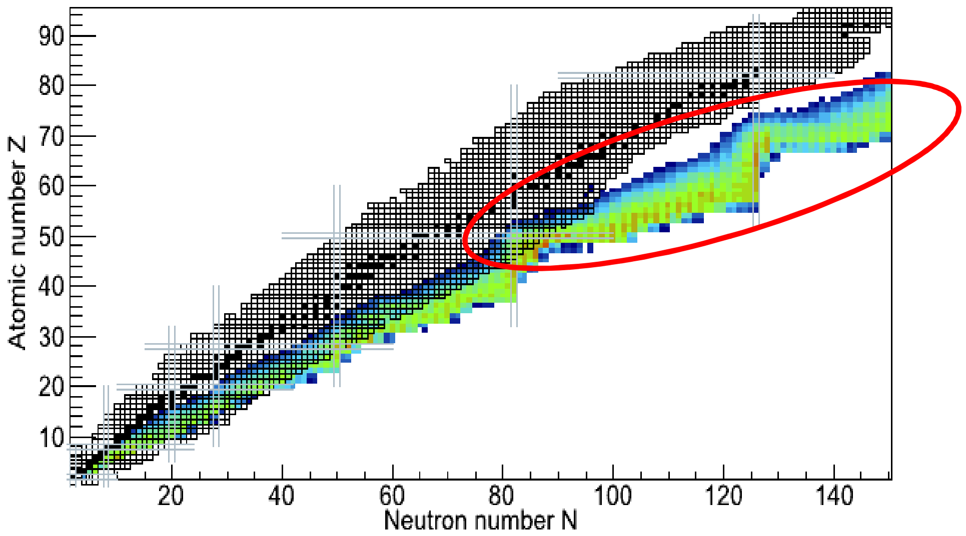


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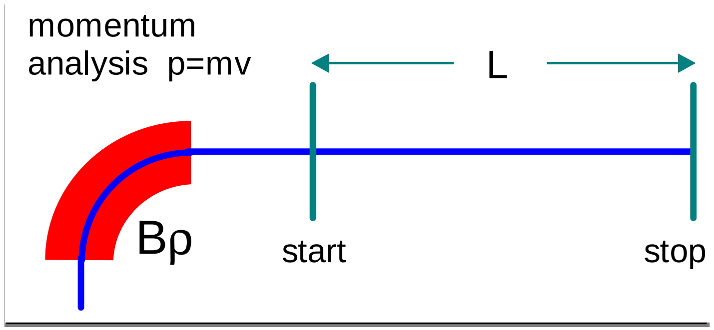
$$Q_\beta = \mathrm{M}_{Z,N} - \mathrm{M}_{Z+1,N-1}$$

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \cdot M_{Z,N}}} (kT)^{3/2} \int_0^\infty E \cdot \sigma(E) \cdot \exp(-E/kT) dE$$

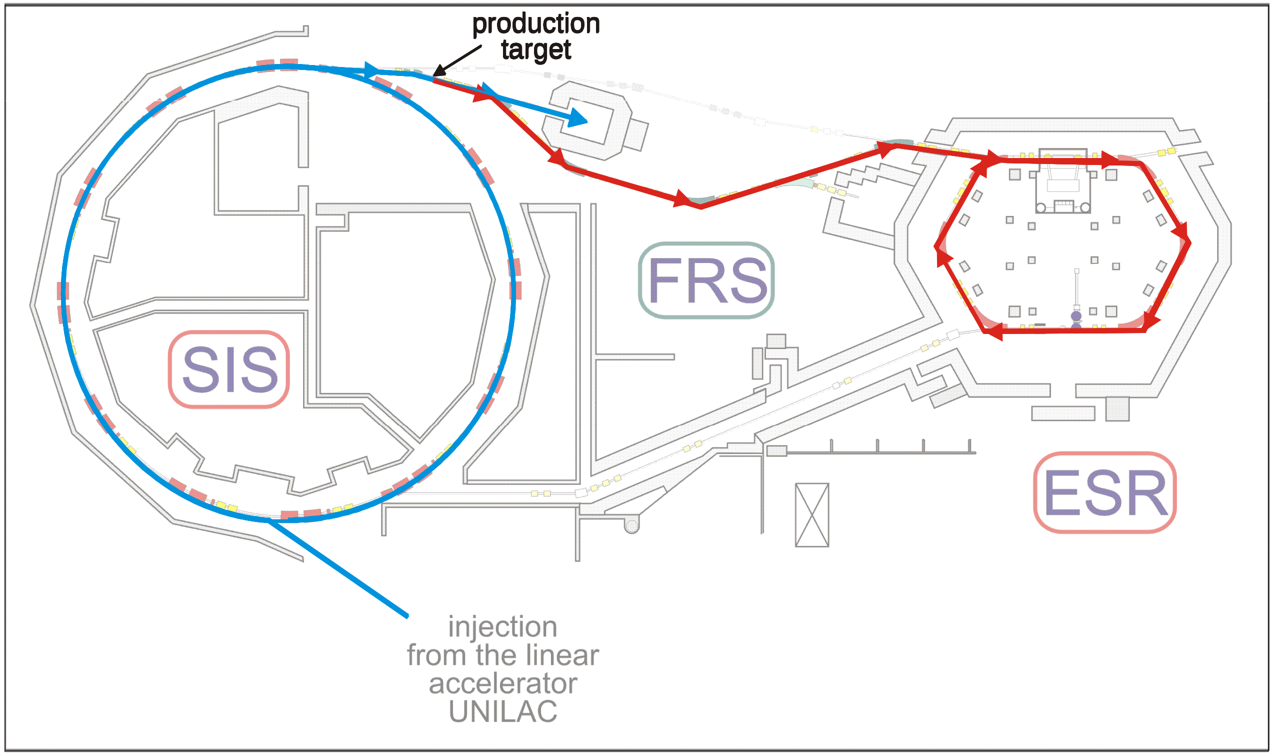
$$T_{1/2} = \frac{1}{\sum_{0 \le E_i \le Q_\beta} S_\beta(E_i) \times f(Z, R, M_{Z,N} - M_{z+1,N-1} - Ei)}$$

$$P_n = \frac{\sum_{S_n \le E_i \le Q_\beta} S_\beta(E_i) \times f(Z, R, M_{Z,N} - M_{z+1,N-1} - Ei)}{\sum_{0 \le E_i \le Q_\beta} S_\beta(E_i) \times f(Z, R, M_{Z,N} - M_{z+1,N-1} - Ei)}$$

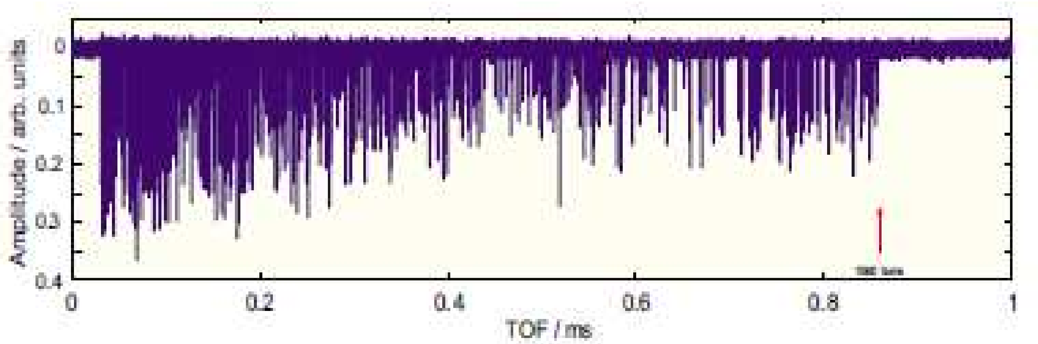
# Principle of TOF Mass Measurements



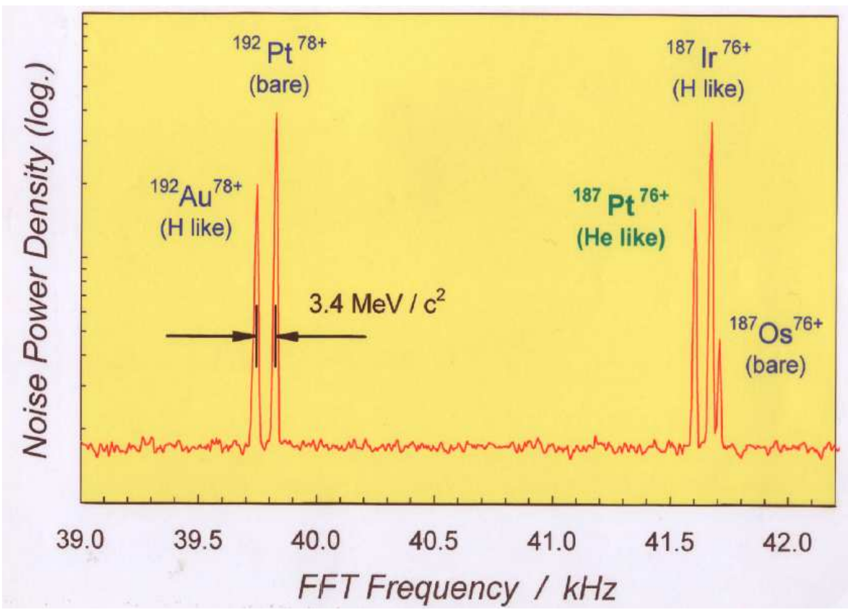

$$B\rho = \frac{m}{q} v \quad \xrightarrow[\substack{L = const \\ B\rho = const}]{v = \frac{L}{t}} \quad \frac{m}{q} = const \times t$$

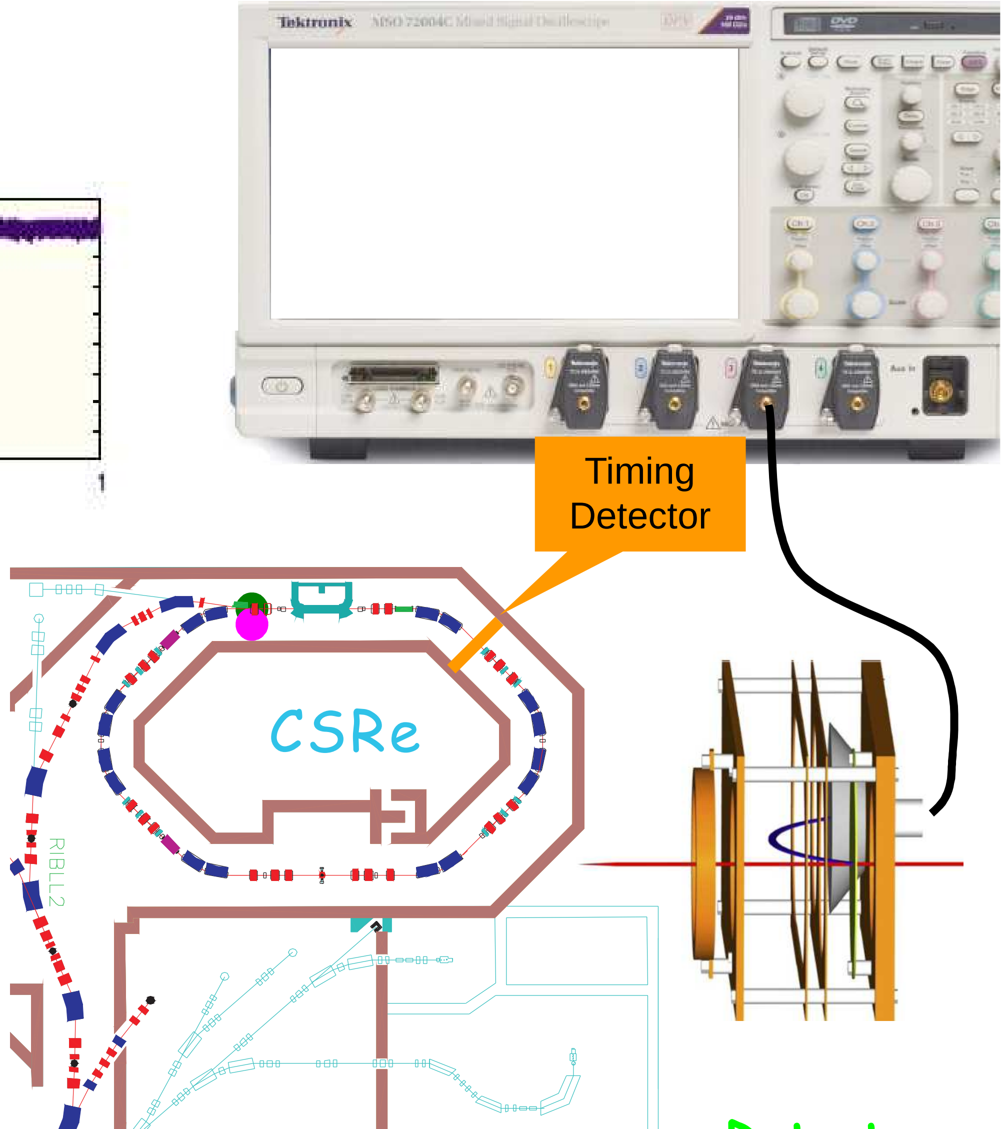


time-domain (oscilloscope):




Fourier analysis (frequency domain):

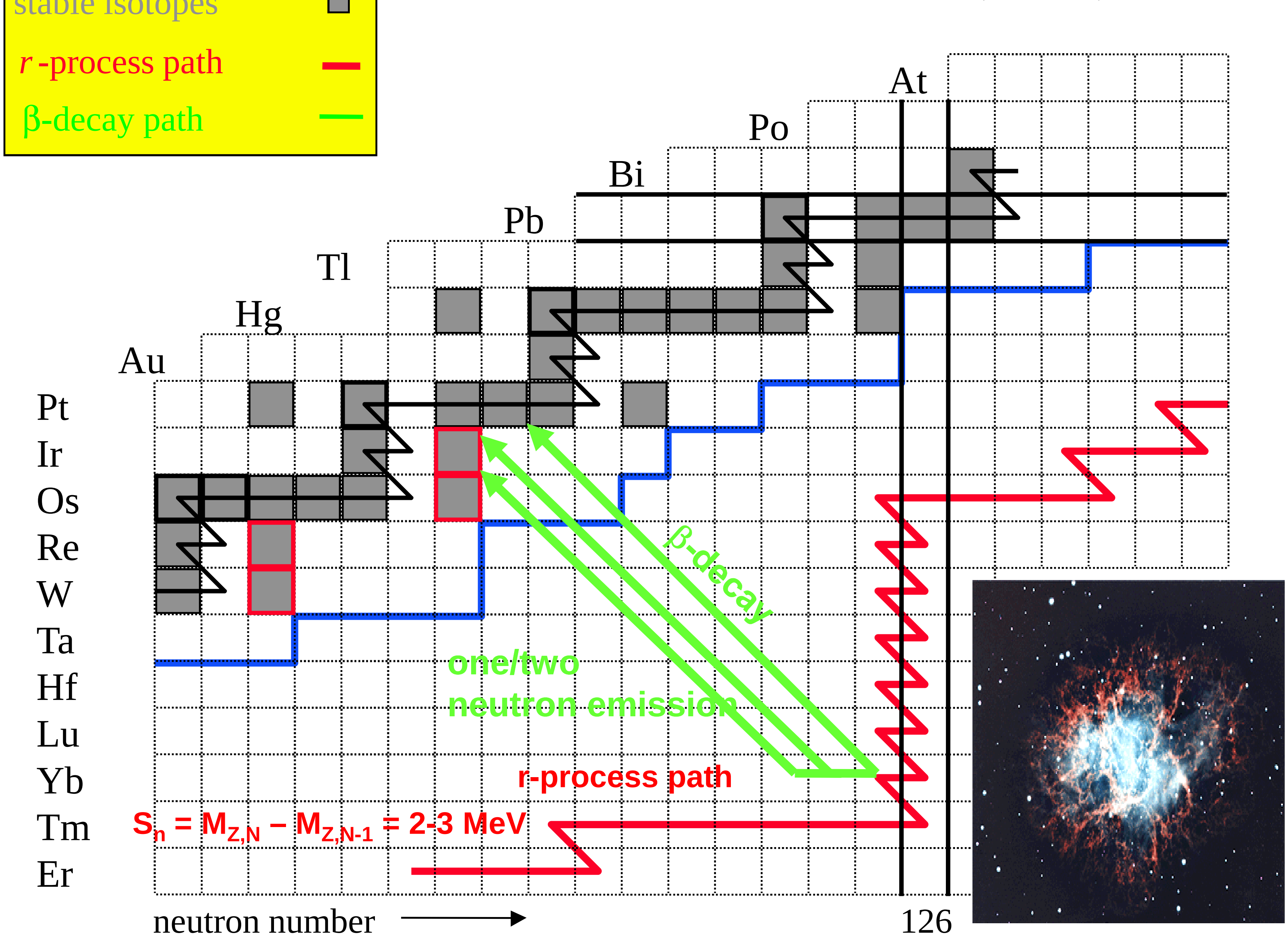


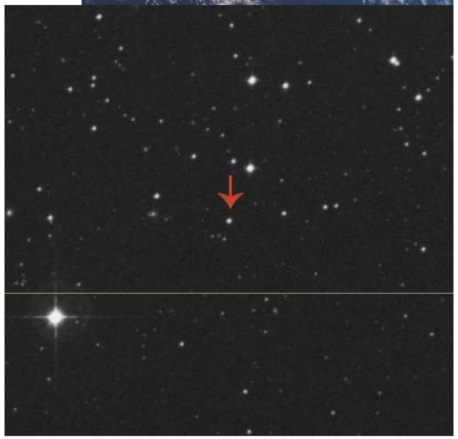

Detector

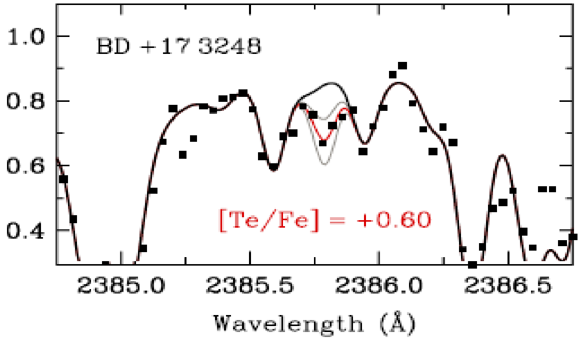
$$\frac{f_1 - f_2}{f} = -\frac{1}{\gamma_t^2}\frac{(m/q)_1 - (m/q)_2}{m/q}$$

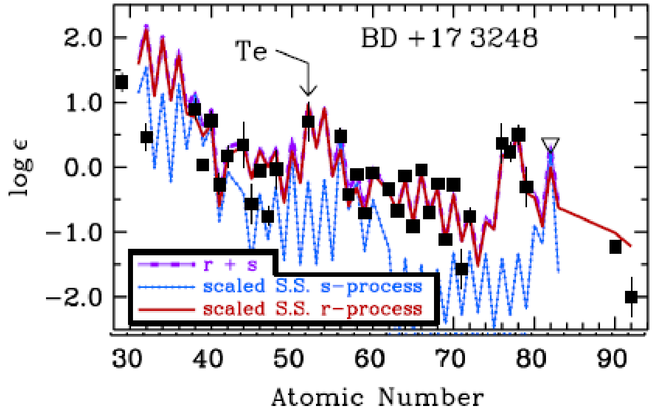
# Stellar Nucleosynthesis
## ($A$ ~ 200)

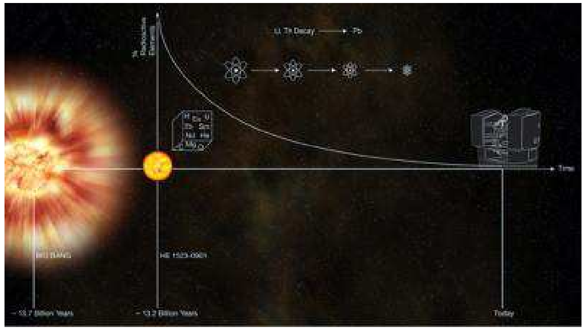


# First observation of Te in metal poor stars (!!)



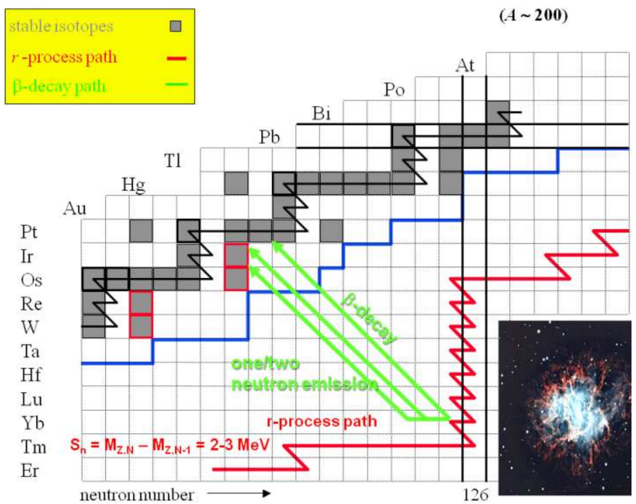


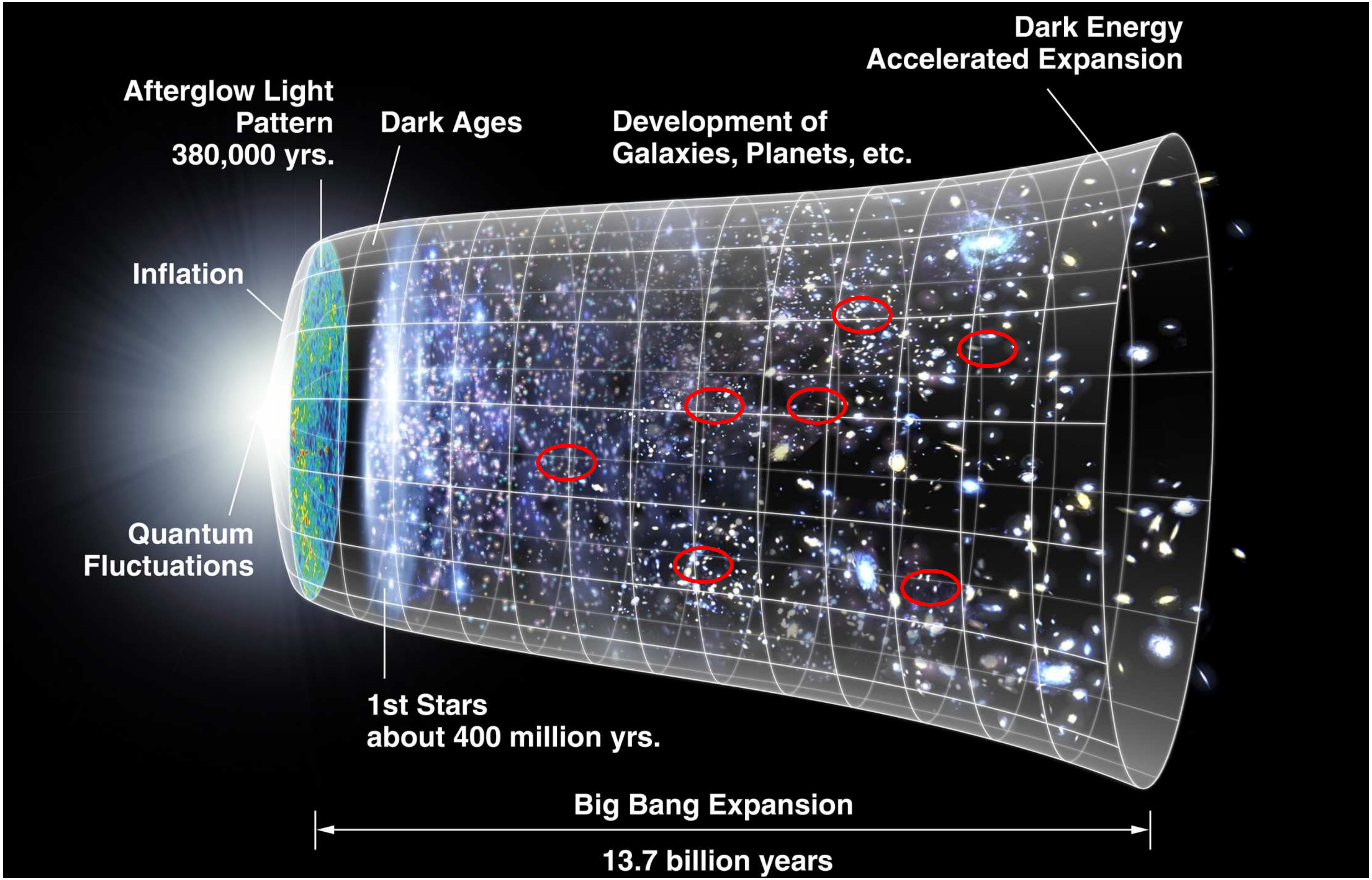



Connection with RIKEN

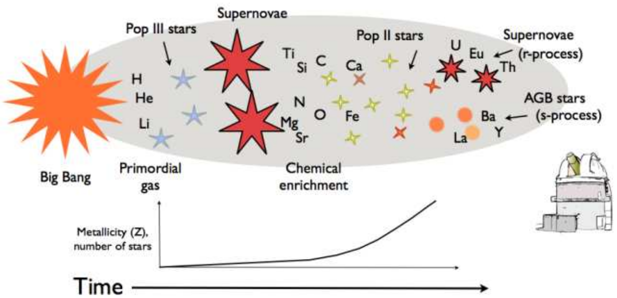
*I. Roederer et al., The Astroph. Journ. Lett. 2012*




# Other (weaker) neutron sources in the universe: red giants



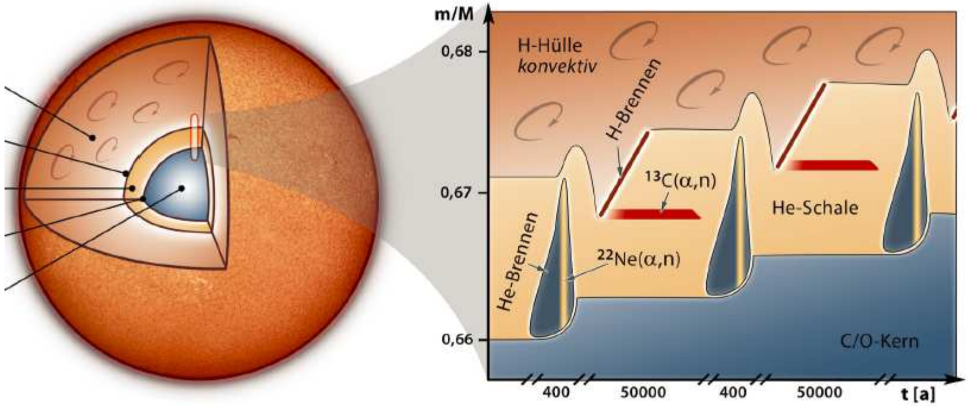
# Two different s-process sites

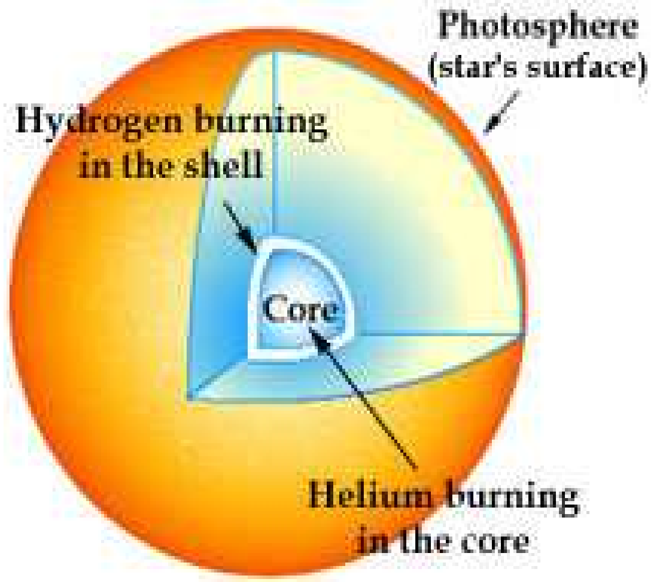



**Main s-process 90<A<210**

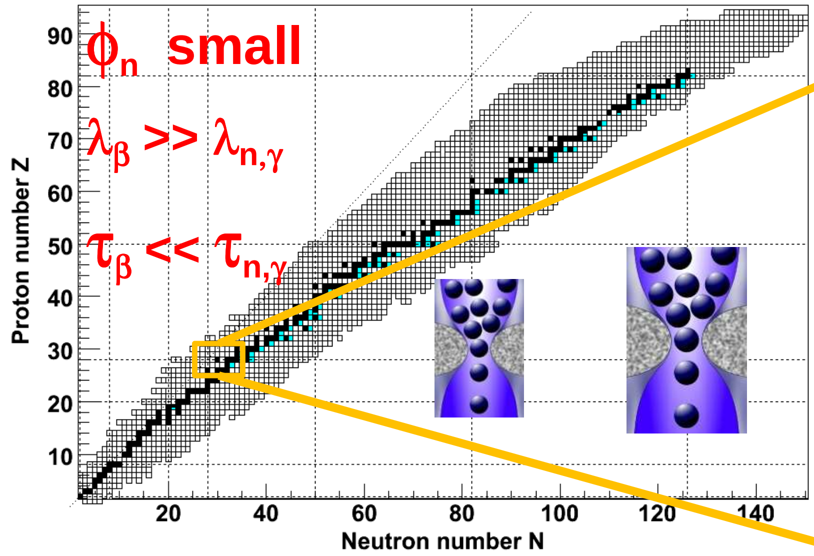
**Weak s-process A<90**

| TP-AGB stars 1-3 $M_\odot$ | | massive stars > 8 $M_\odot$ | |
|---|---|---|---|
| shell H-burning | He-flash | core He-burning | shell C-burning |
| $0.9 \cdot 10^8$ K | $3\text{-}3.5 \cdot 10^8$ K | $3\text{-}3.5 \cdot 10^8$ K | $\sim 1 \cdot 10^9$ K |
| kT=8 keV | kT=23 keV | kT=26 keV | kT=91 keV |
| $10^7\text{-}10^8$ cm$^{-3}$ | $10^{10}\text{-}10^{11}$ cm$^{-3}$ | $10^6$ cm$^{-3}$ | $10^{11}\text{-}10^{12}$ cm$^{-3}$ |
| **$^{13}C(^4He,n)^{16}O$** | **$^{22}Ne(^4He,n)^{25}Mg$** | **$^{22}Ne(^4He,n)^{25}Mg$** | |

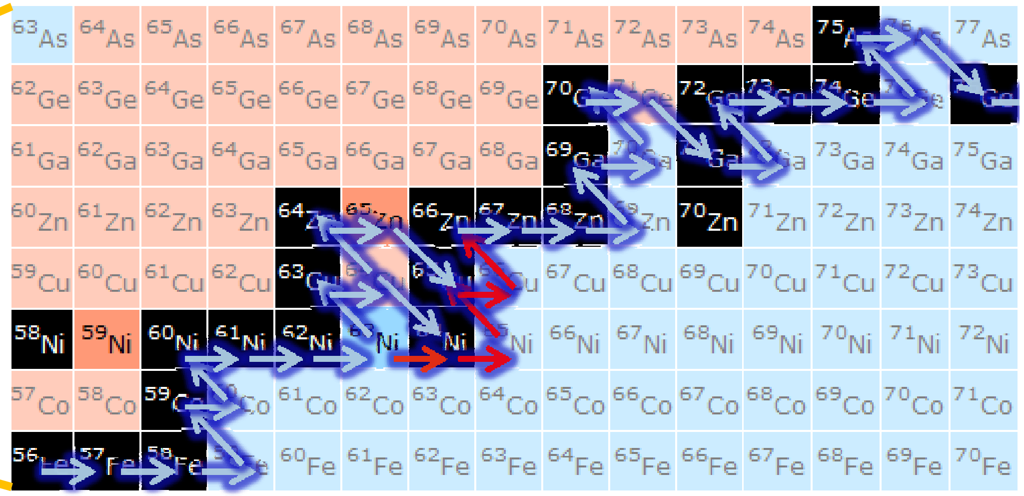


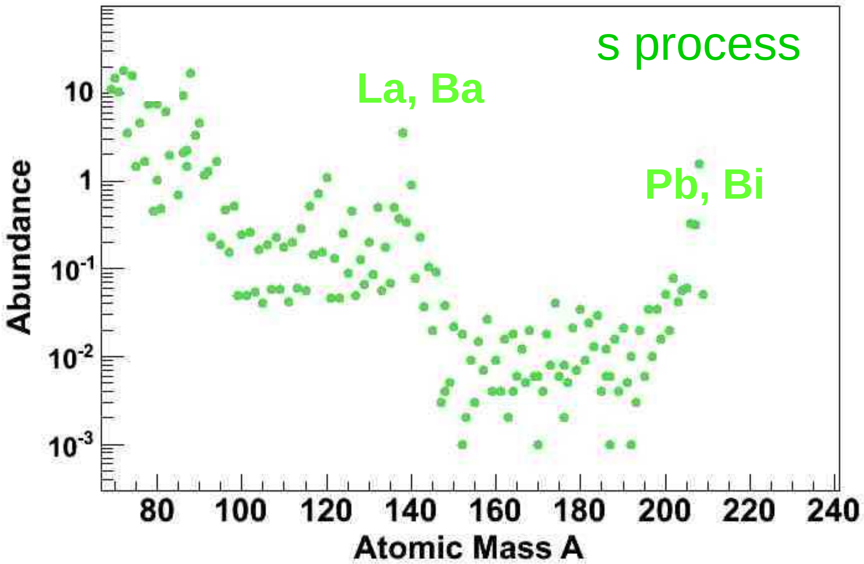



# The s-process mechanism




## s process in Massive Stars (Red Giants)



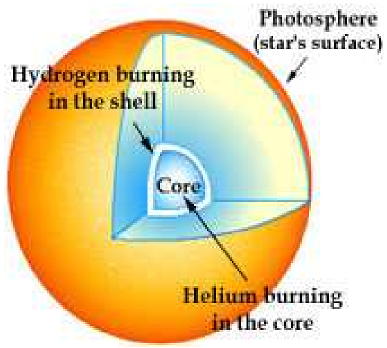




| core He-burning | shell C-burning |
|---|---|
| $3\text{-}3.5\cdot10^8$ K | $\sim1\cdot10^9$ K |
| kT=25 keV | kT=90 keV |
| **$10^6$ cm$^{-3}$** | **$10^{11}$-$10^{12}$ cm$^{-3}$** |

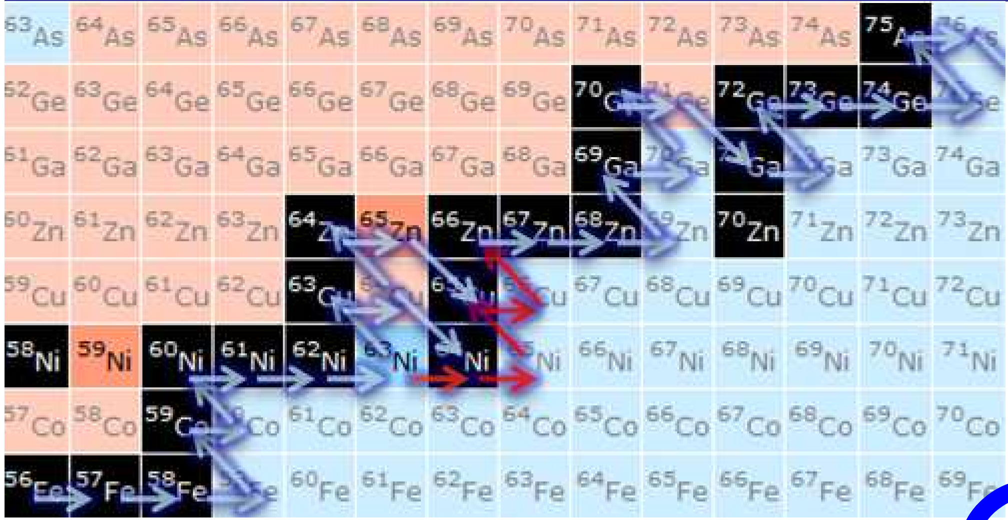
**$^{22}Ne(^4He,n)^{25}Mg$**

$= {}^{A}Z(n,\gamma)\,{}^{A+1}Z$

**(n,γ) Cross Sections**



# How to bring AGB and Massive Stars to the lab?

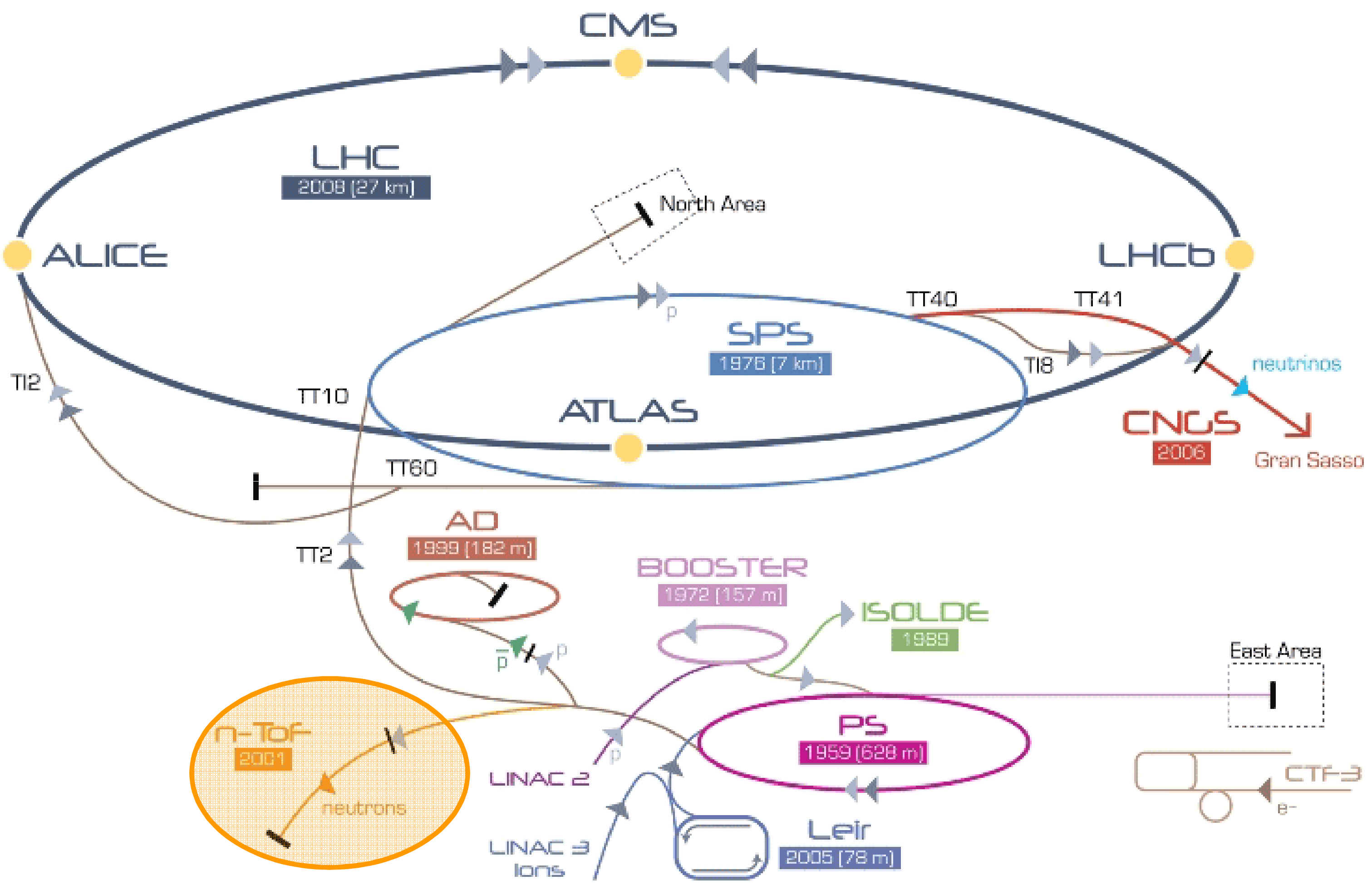


→ Neutron beam facility with neutron energies similar to the stellar envionment

→ Sample of the isotope of interest (stable or radioactive)

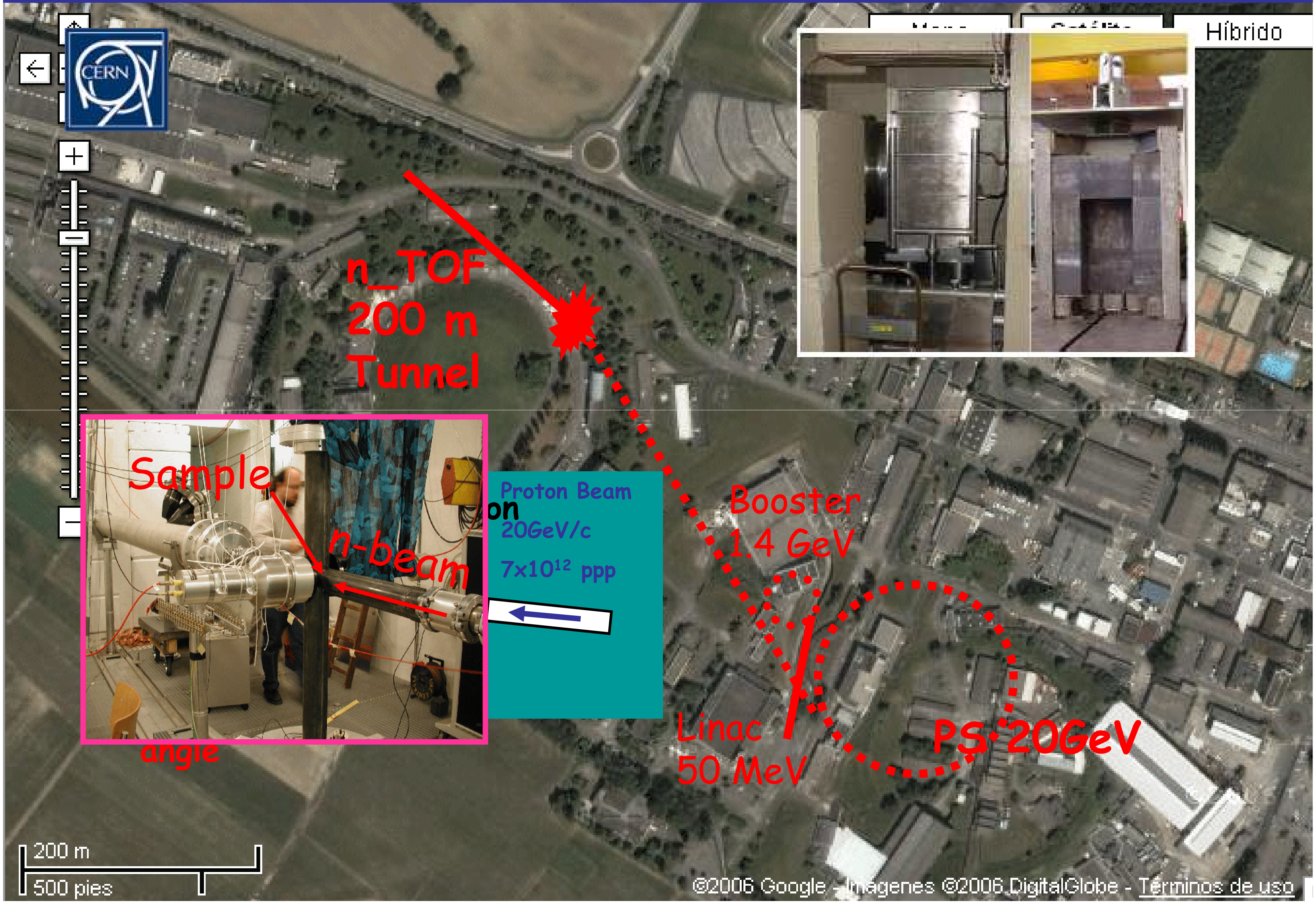
BRAINSTORMING

# CERN n_TOF facility



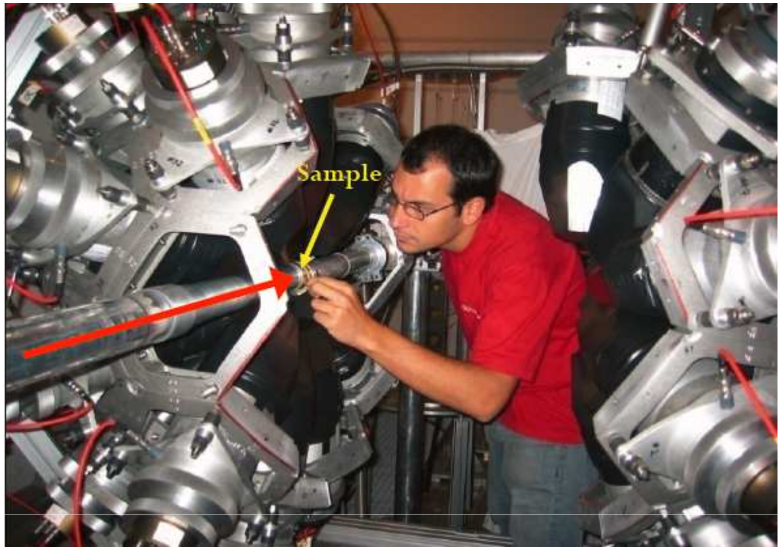

C. Rubbia et al., ***A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV***, CERN/LHC/98-02(EET) 1998.

# CERN n_TOF facility

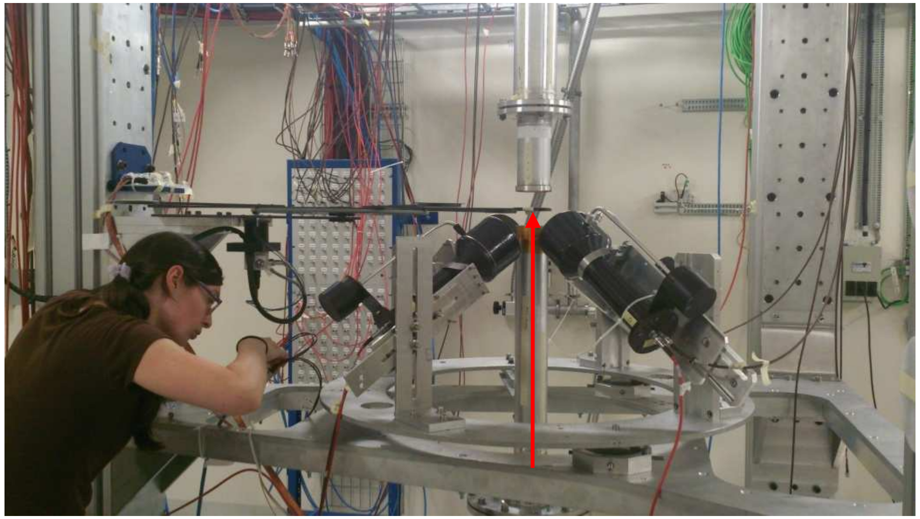


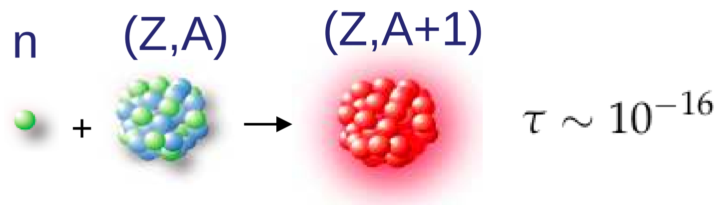
# (n,γ) Cross sections via prompt γ-ray(s) detection

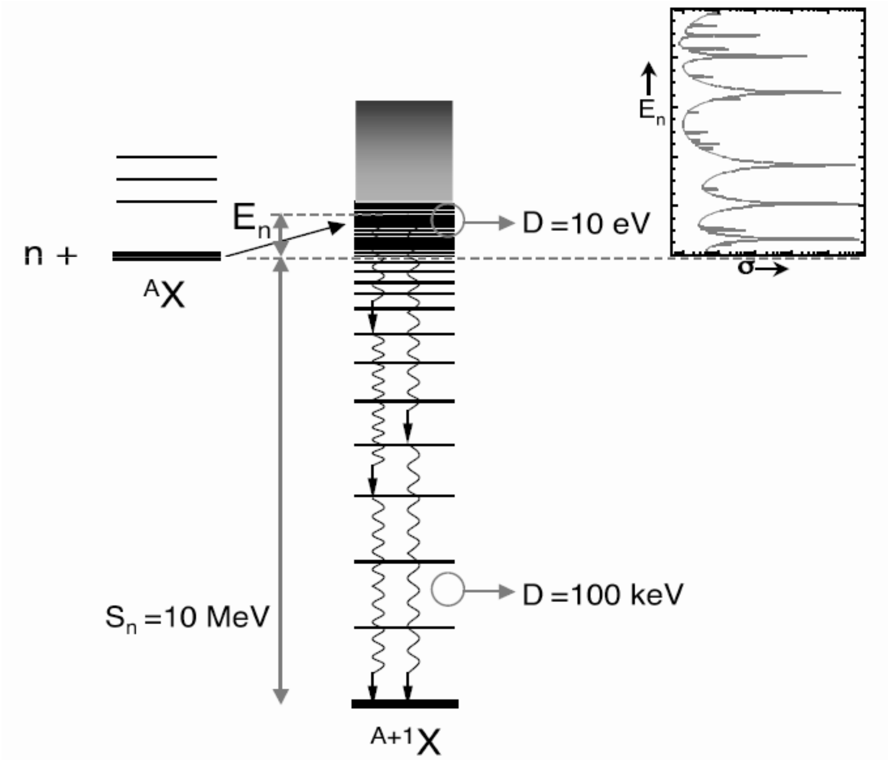
$BaF_2$ Total Absorption Calorimeter (TAC)




$C_6D_6$ based Total Energy Detector (TED)

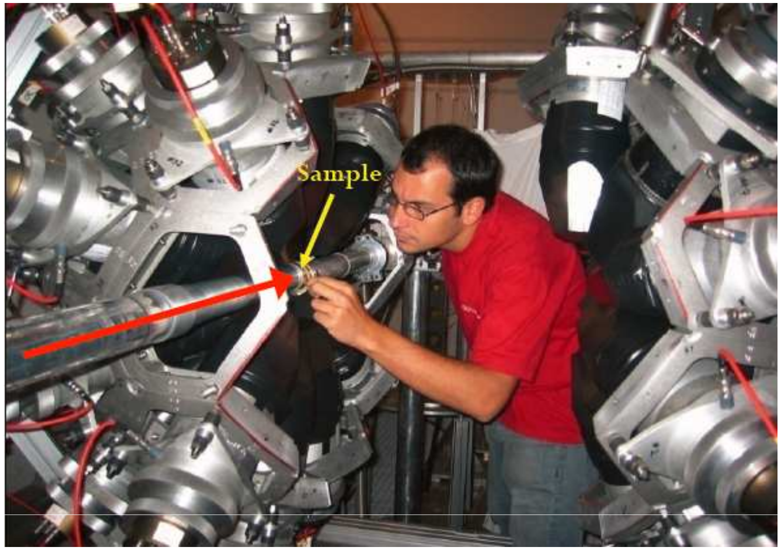


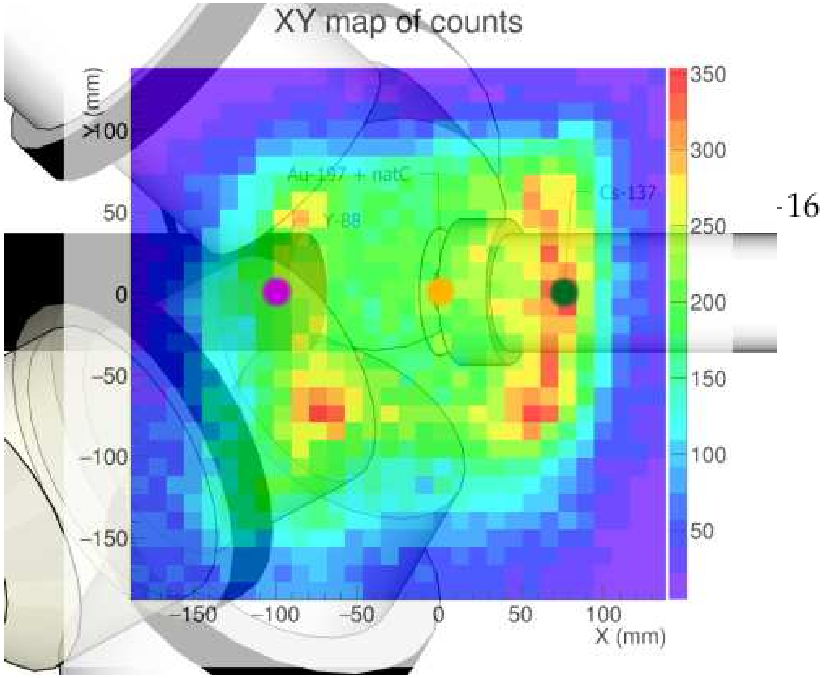


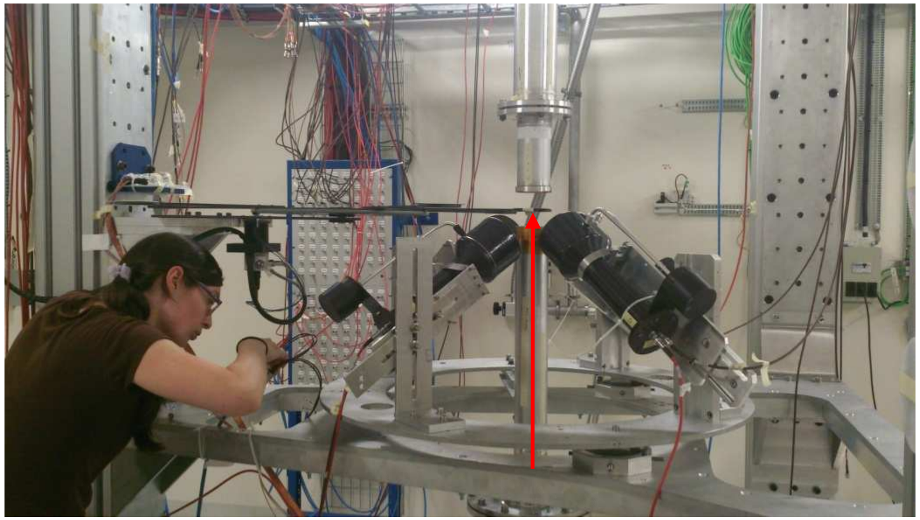
# (n,γ) Cross sections via prompt γ-ray(s) detection

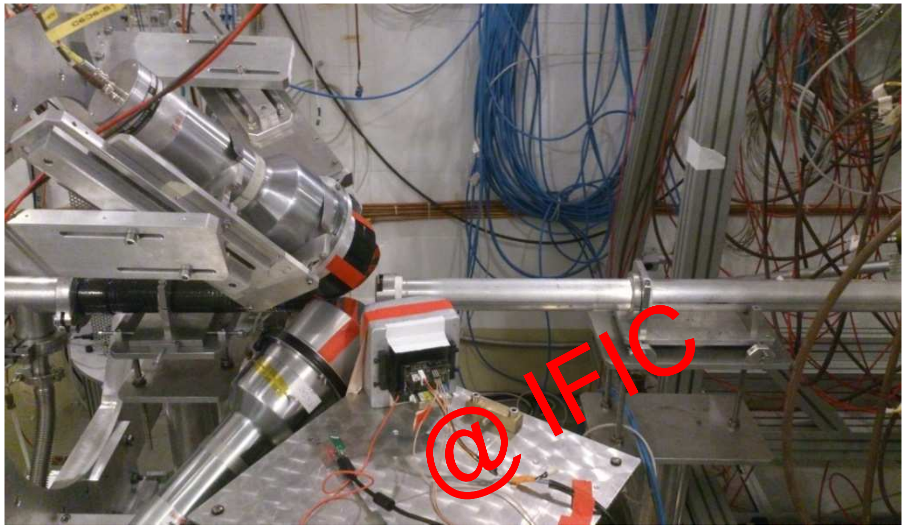
## $BaF_2$ Total Absorption Calorimeter (TAC)




## $C_6D_6$ based Total Energy Detector (TED)

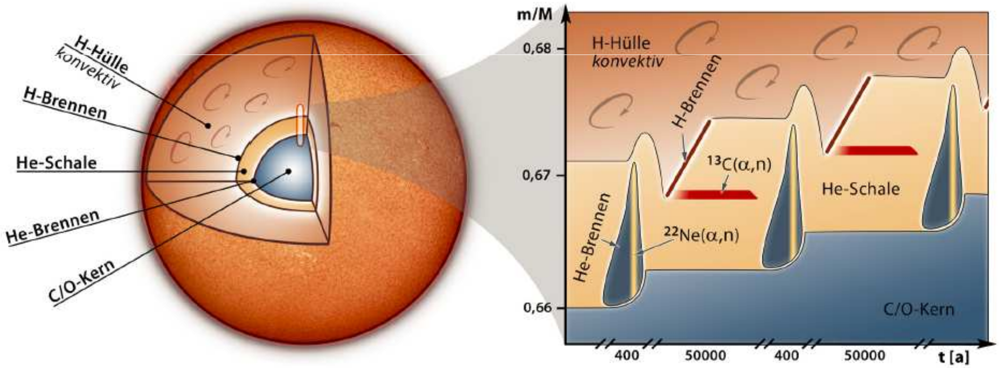


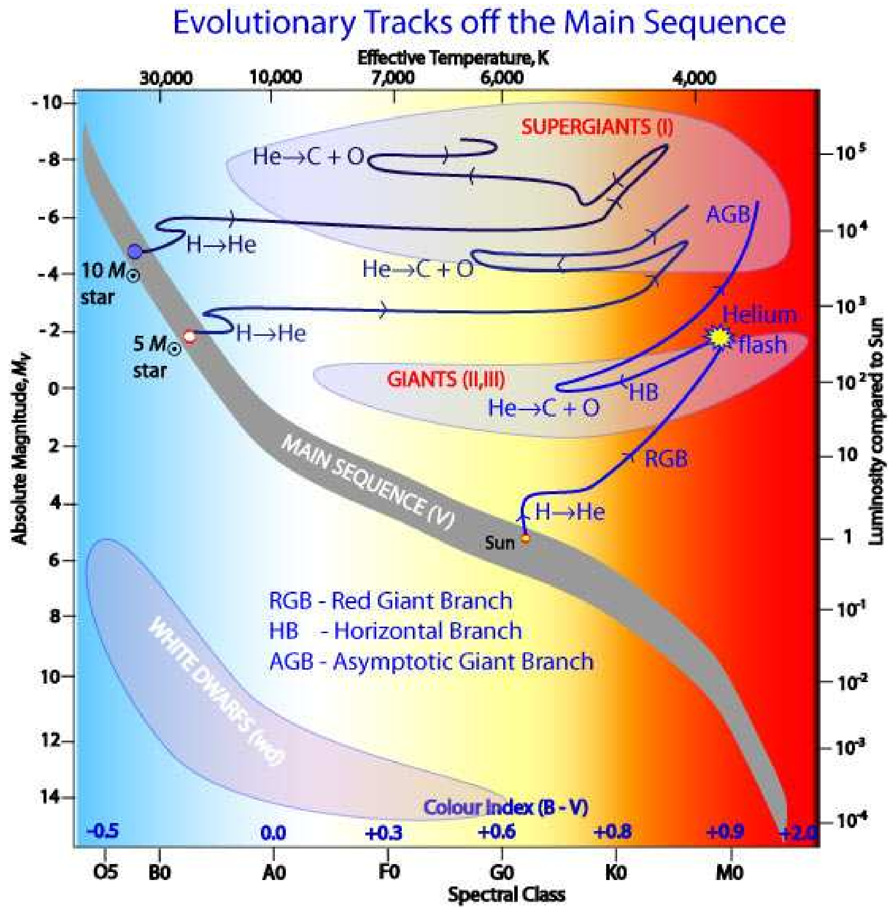


# Example: Temperature in TP AGB Stars

## TP-AGB stars 1-3 $M_\odot$

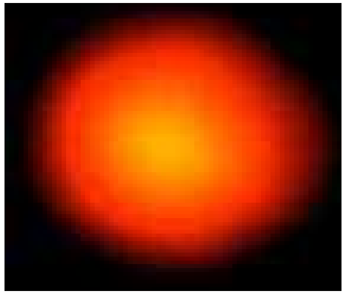
| shell H-burning | He-flash |
|---|---|
| $0.9 \cdot 10^8$ K | $3\text{-}3.5 \cdot 10^8$ K |
| kT=8 keV | kT=23 keV |
| $10^7\text{-}10^8$ cm$^{-3}$ | $10^{10}\text{-}10^{11}$ cm$^{-3}$ |
| $^{13}C(^4He,n)^{16}O$ | $^{22}Ne(^4He,n)^{25}Mg$ |

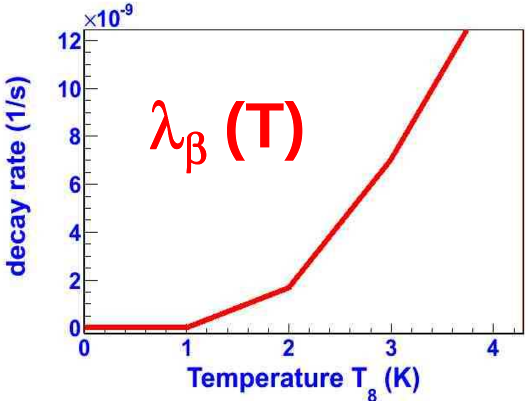


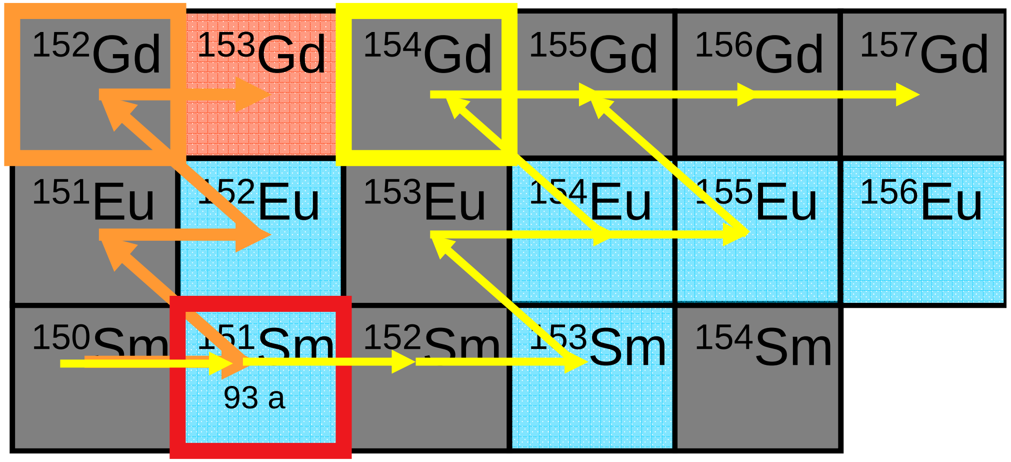



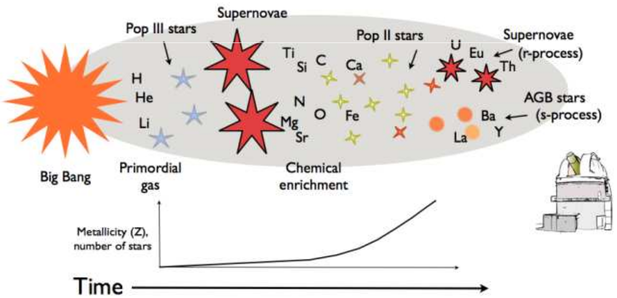
# Temperature in TP AGB Stars

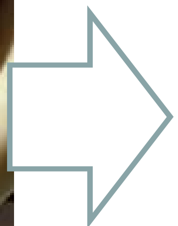
- How hot is the stellar environment where s-process nucleosynthesis takes place?





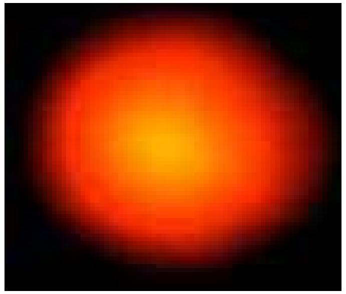



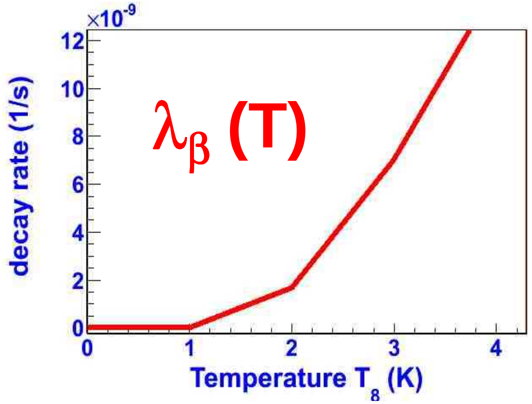



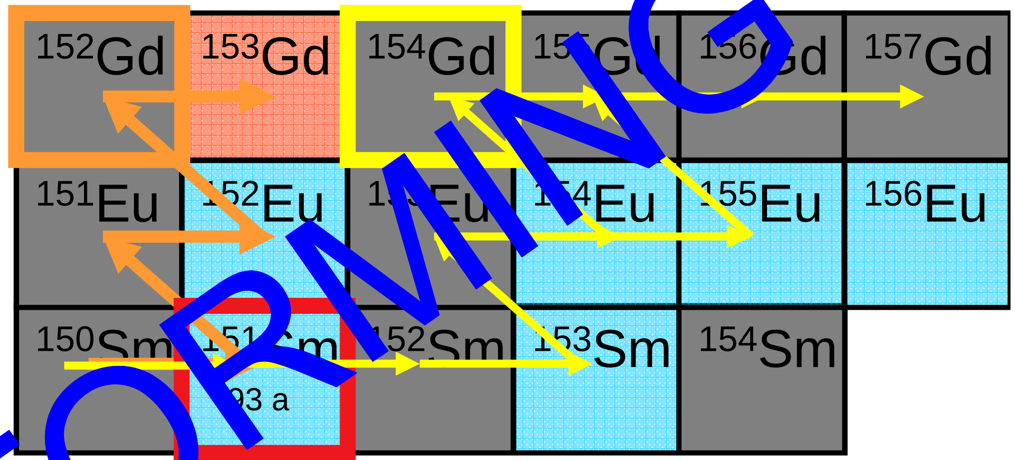
$N_{s,152Gd}$ & $N_{s,154Gd}$

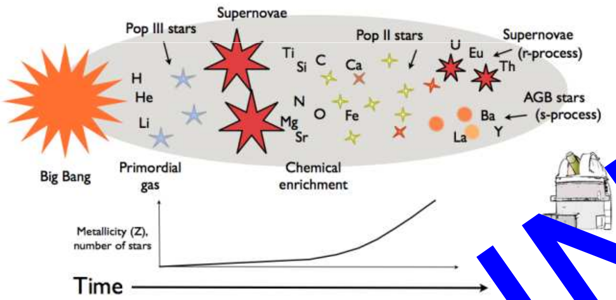
# Temperature in TP AGB Stars

- How hot is the stellar environment where s-process nucleosynthesis takes place?






$$f_\beta = \frac{(<\sigma_\gamma> N_s)_{152Gd}}{(<\sigma_\gamma> N_s)_{154Gd}} = \frac{\lambda_\beta^{151Sm}(T)}{\lambda_\beta^{151Sm} - v_T n_n <\sigma_\gamma>_{151Sm}}$$

→Just measure $<\sigma_\gamma>_{151Sm}$

$N_{s,152Gd}$

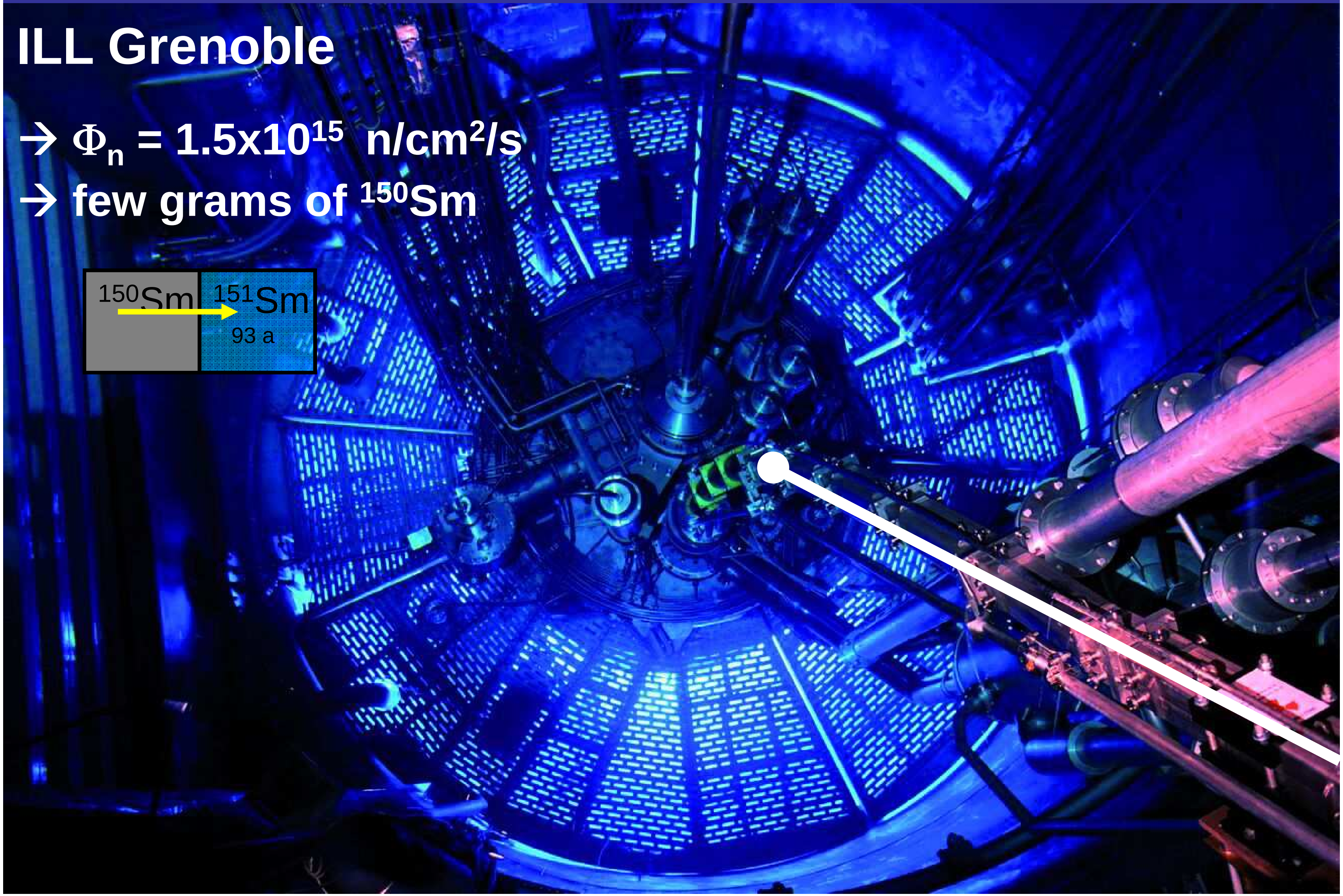
First challenge:
$^{151}$Sm does not exist in Earth!!!

# Temperature in TP AGB Stars

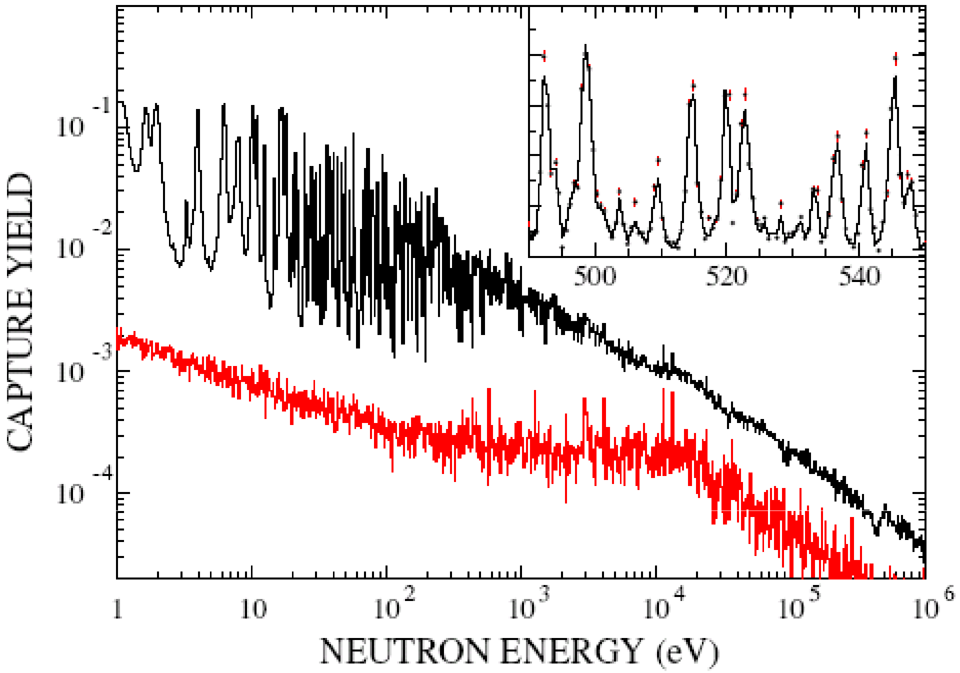
## ILL Grenoble

→ $\Phi_n = 1.5\text{x}10^{15}$ n/cm$^2$/s

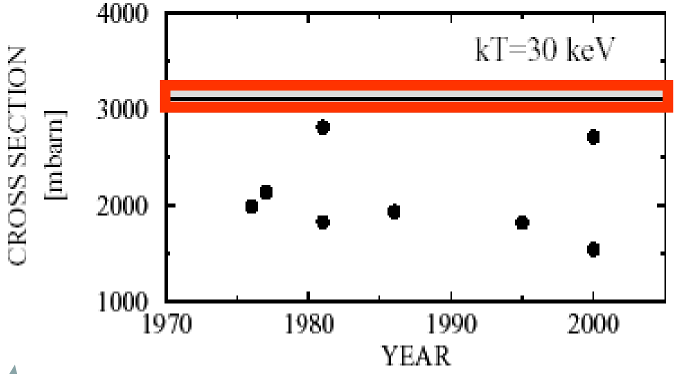
→ few grams of $^{150}$Sm

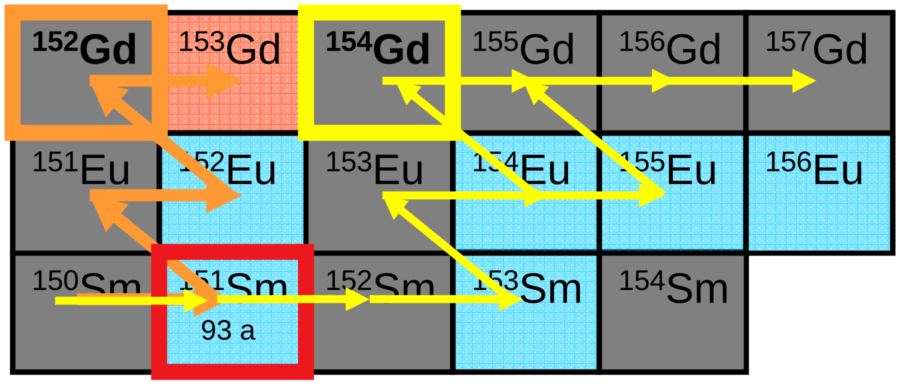


# Temperature in TP AGB Stars

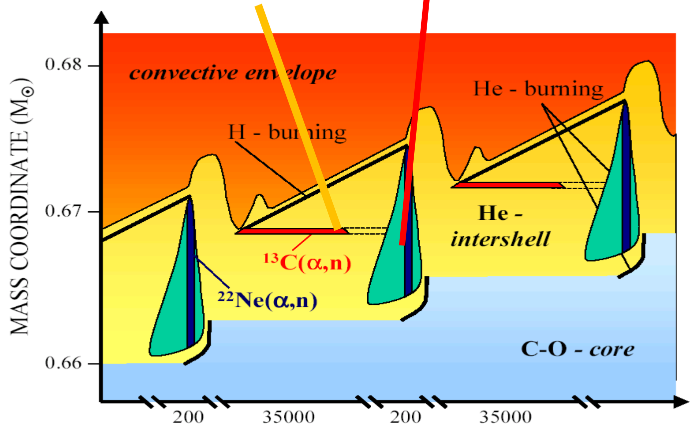



MACS-30 = 3100 ± 160 mb




$T_{He}$ = 2.5-2.8x$10^8$ K
$T_H$ = 1x$10^8$ K

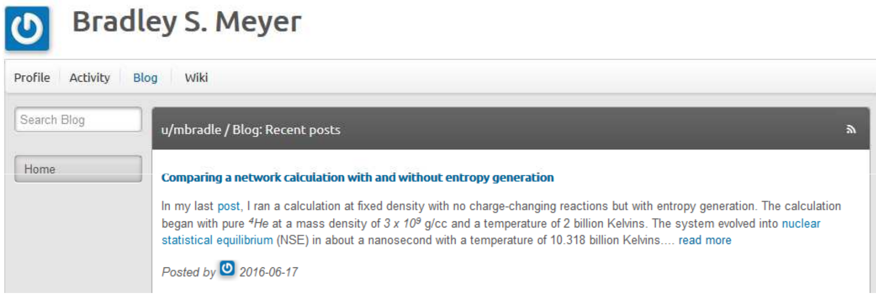



U Abbondanno et al. Phys. Rev. Lett. 93 (2004), 161103
S. Marrone et al. Phys. Rev. C 73 (2006) 03604

# Last slide: links to learn more

- JINA-CEE youtube seminar series: nucleosynthesis topics, theory, observations and experiments
https://www.youtube.com/channel/UCTa4Bt0wQ6mYduyOCvsYR5A


- WEBNUCLEO (B. Meyer's blog and code): nuclosynthesis network code + examples to learn
https://sourceforge.net/u/mbradle/blog/




- MESA (Modules for Experiments in Stellar Astrophysics) https://sourceforge.net/projects/mesa/
- NuGRID: http://www.nugridstars.org/


- NuPECC:Nuclear Physics European Collaboration Committee
http://www.nupecc.org/?display=lrp2010/main