Nuclear Physics Mid Term Plan in Italy

LNL – Session

Legnaro, April 11th-12th 2022

# Nuclear astrophysics theory


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# OUTLINE

- Nuclear Astrophysics: a brief introduction
- Nucleosynthesis of elements up to iron
- Nucleosynthesis of elements beyond iron

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- Nuclear Astrophysics: a brief introduction
- Nucleosynthesis of elements up to iron
- Nucleosynthesis of elements beyond iron

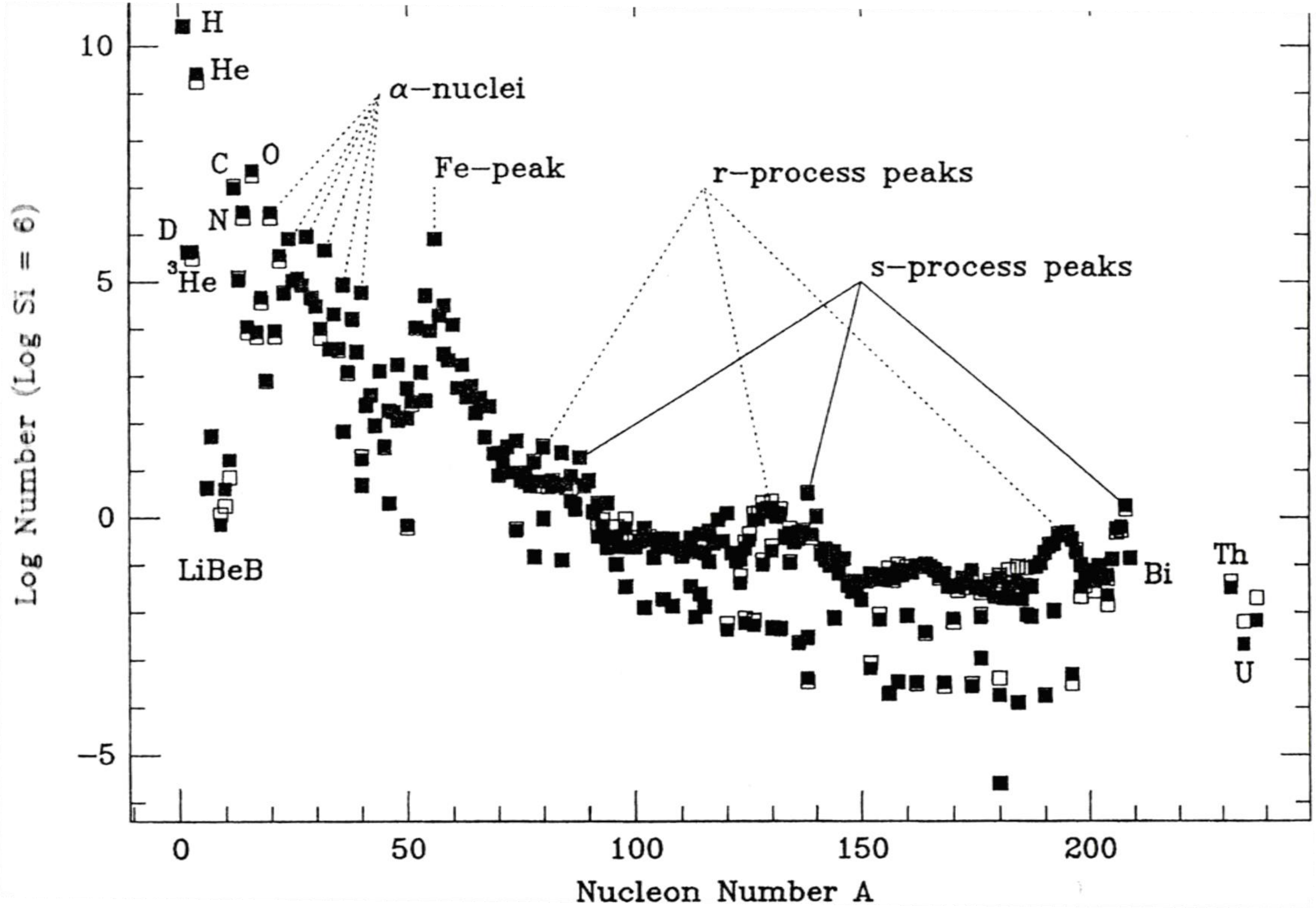

I will concentrate on **WHY** and **WHAT**.

For **HOW** and **WHEN**, please....

SEE TALK BY T. KURTUKIAN-NIETO

SEE TALK BY A. CACIOLLI

# Solar System Abundances



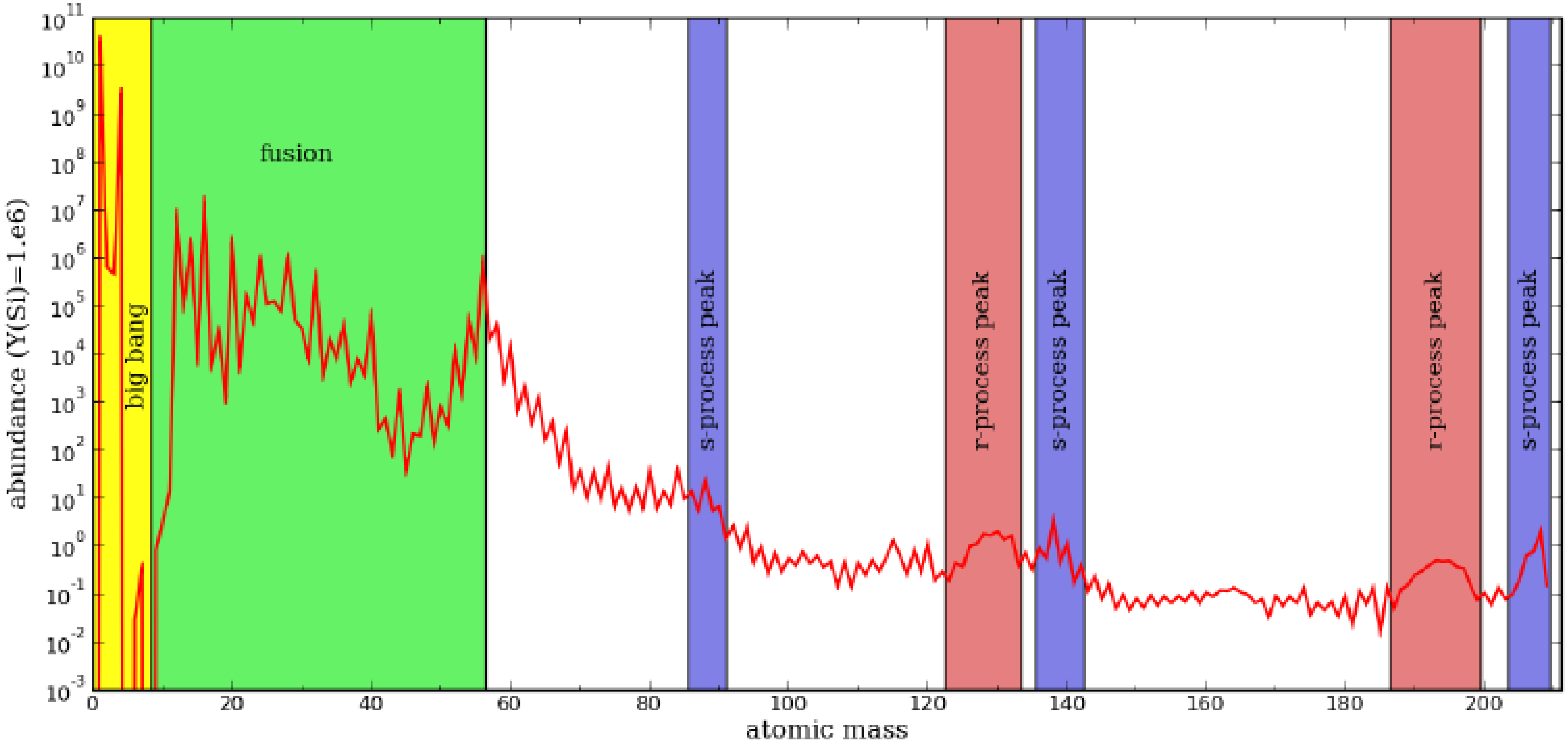

**Anders & Grevesse 1989**
**Cameron 1982**

Features:

- 12 orders-of-magnitude span
- C → U ~ 2% ("metals")
- D, Li, Be, B under-abundant
- exponential decrease up to Fe peak
- almost flat distribution beyond Fe

# Solar System Abundances

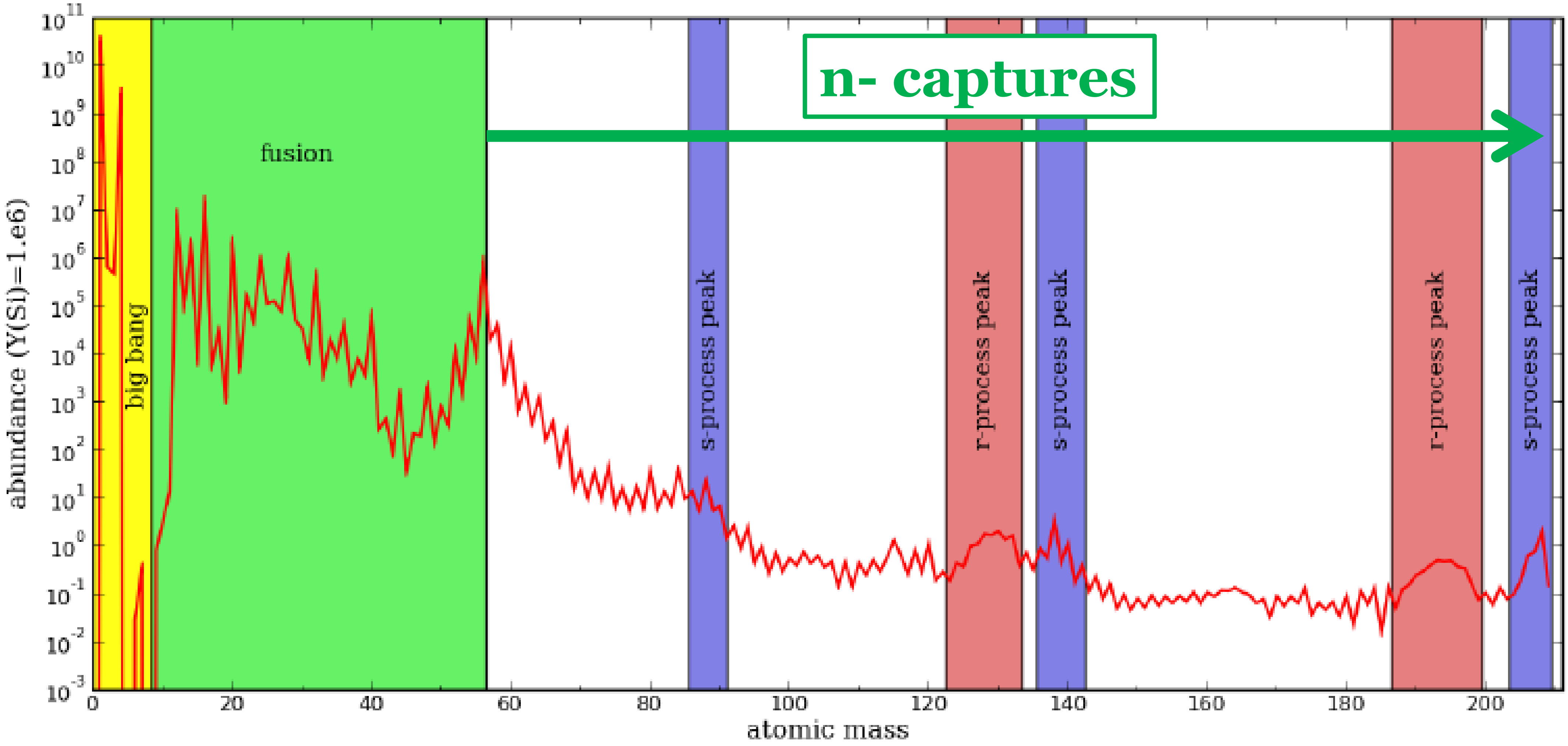
Cowan+2021




Data sources: Earth, Moon, meteorites, Sun spectra, cosmic rays…

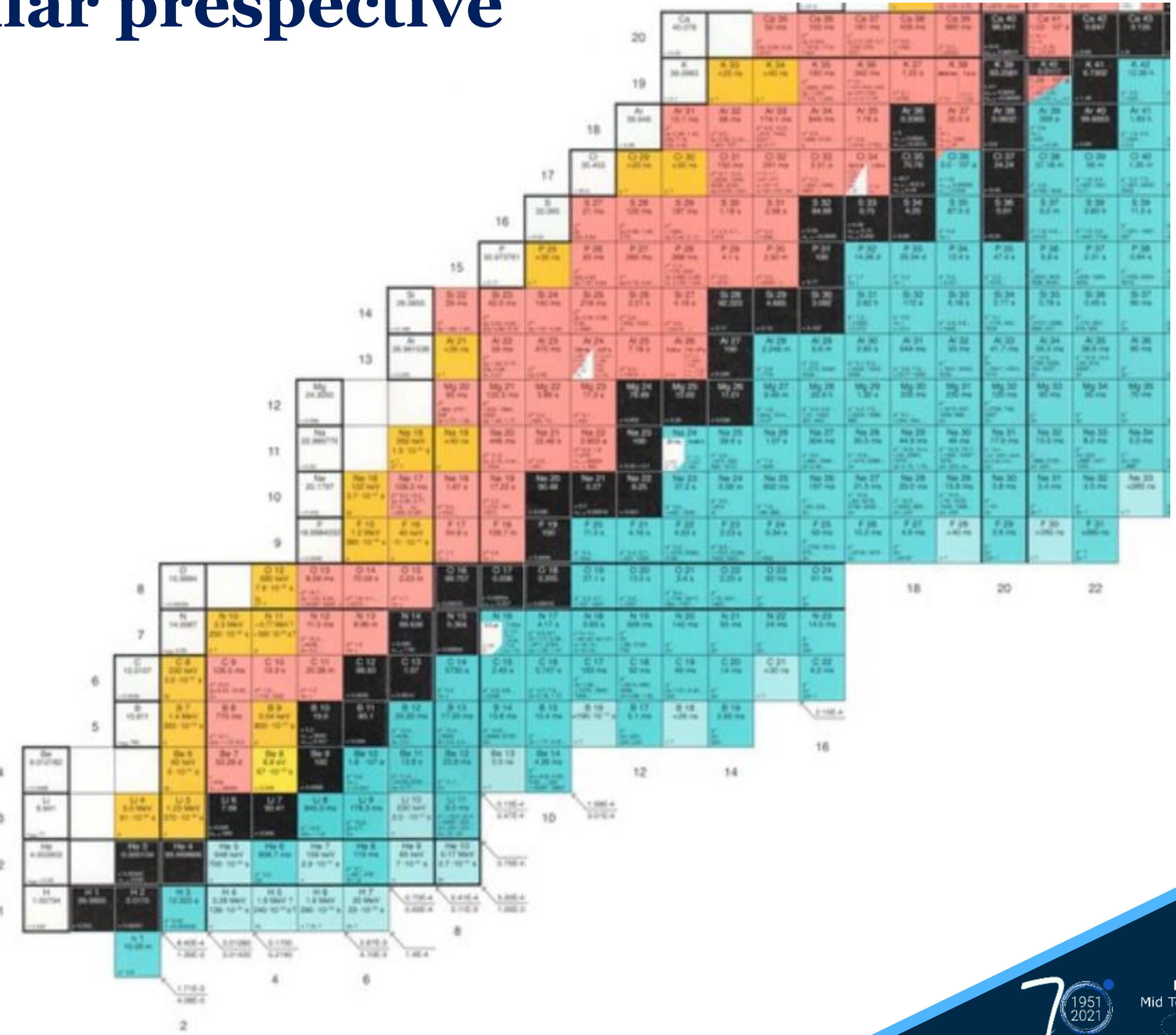
# Solar System Abundances

Cowan+2021




Data sources: Earth, Moon, meteorites, Sun spectra, cosmic rays...

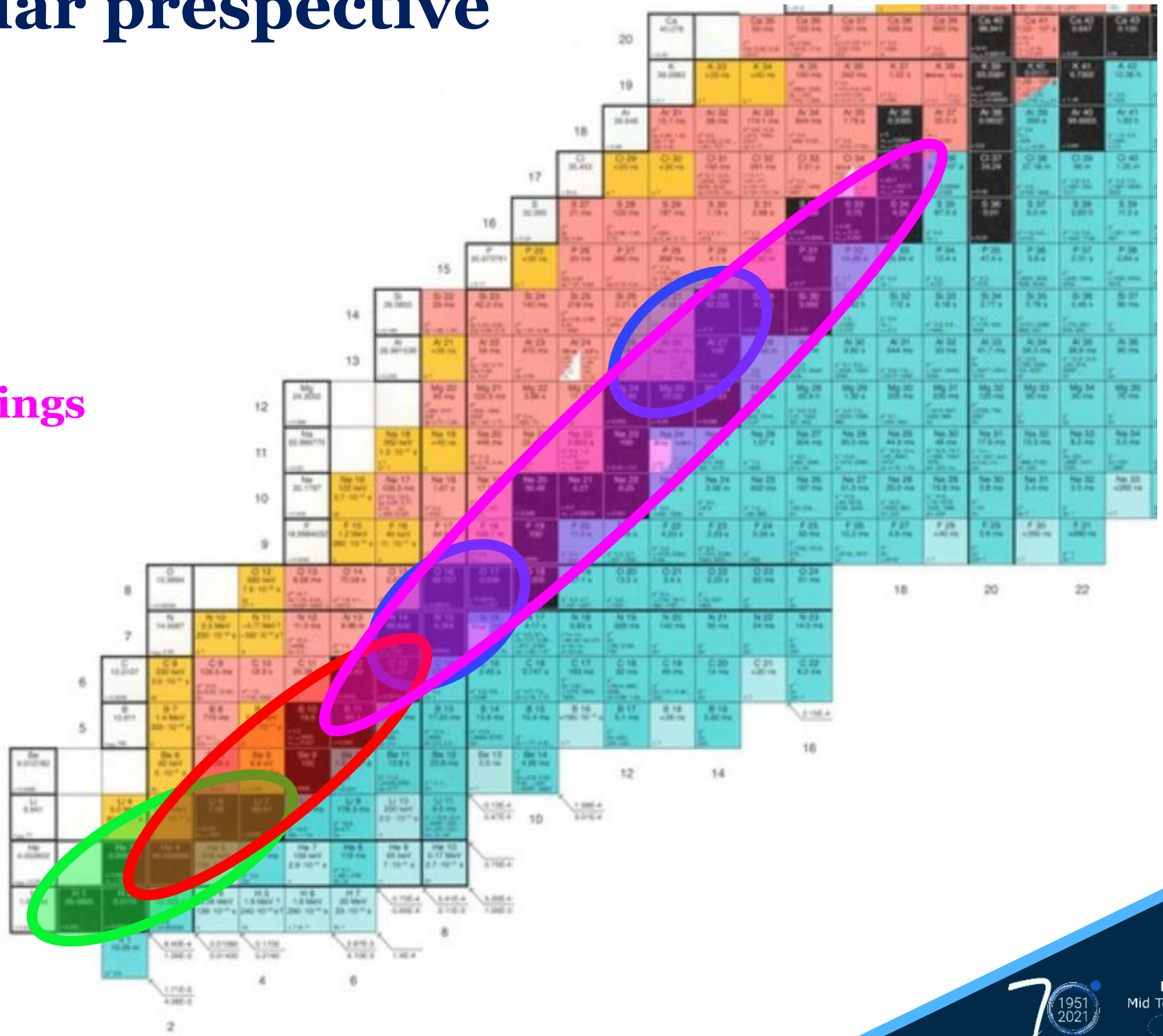
# The Nuclide chart: a stellar prespective



**Where does LNL can contribute?**

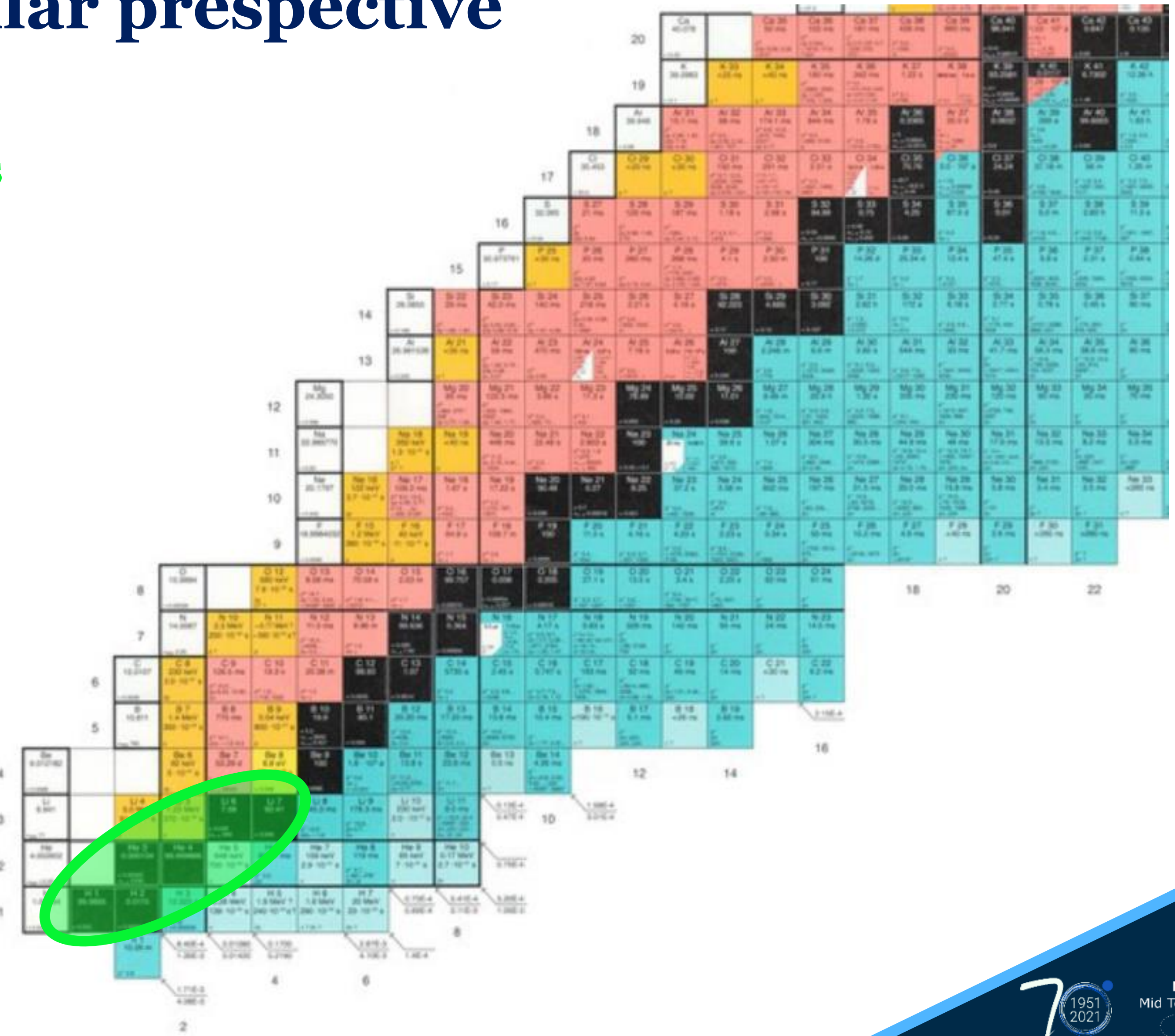
# The Nuclide chart: a stellar prespective

- BIG BANG Nucleosynthesis
- HYDROGEN burning
- HELIUM burning
- ADVANCED quiescent burnings

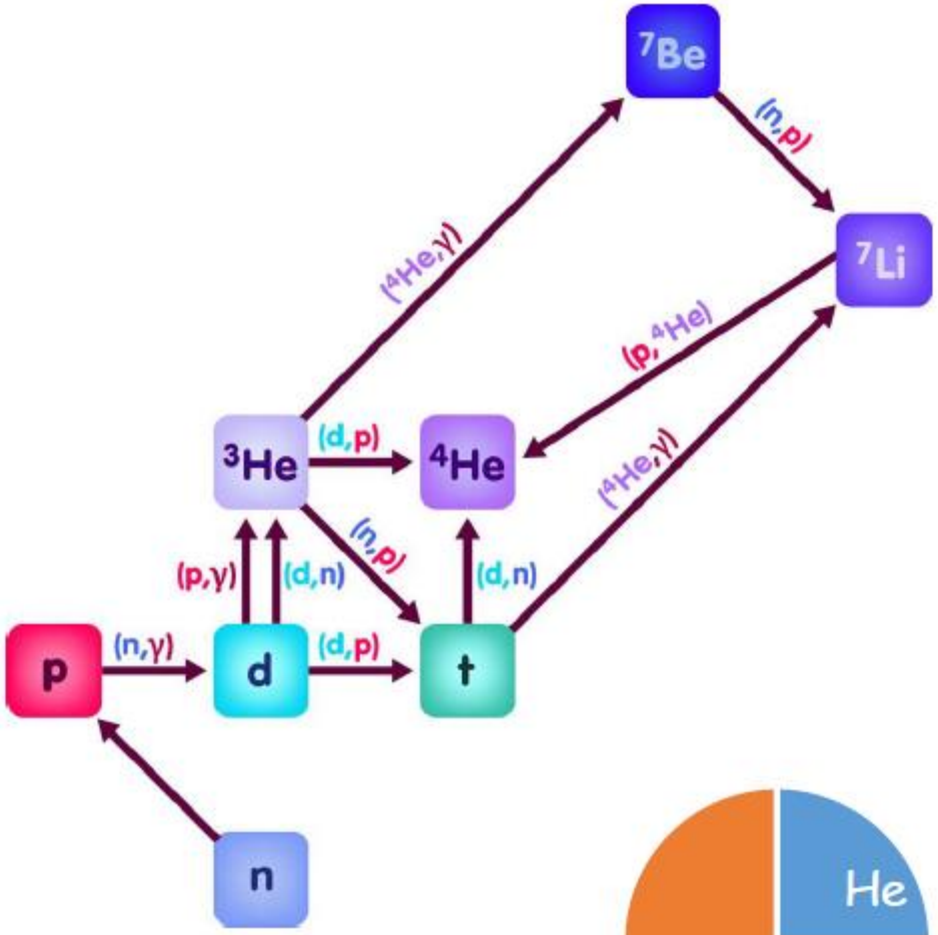


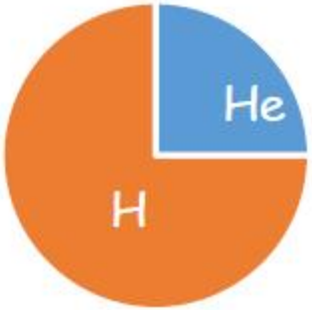
# The Nuclide chart: a stellar prespective

BIG BANG Nucleosynthesis



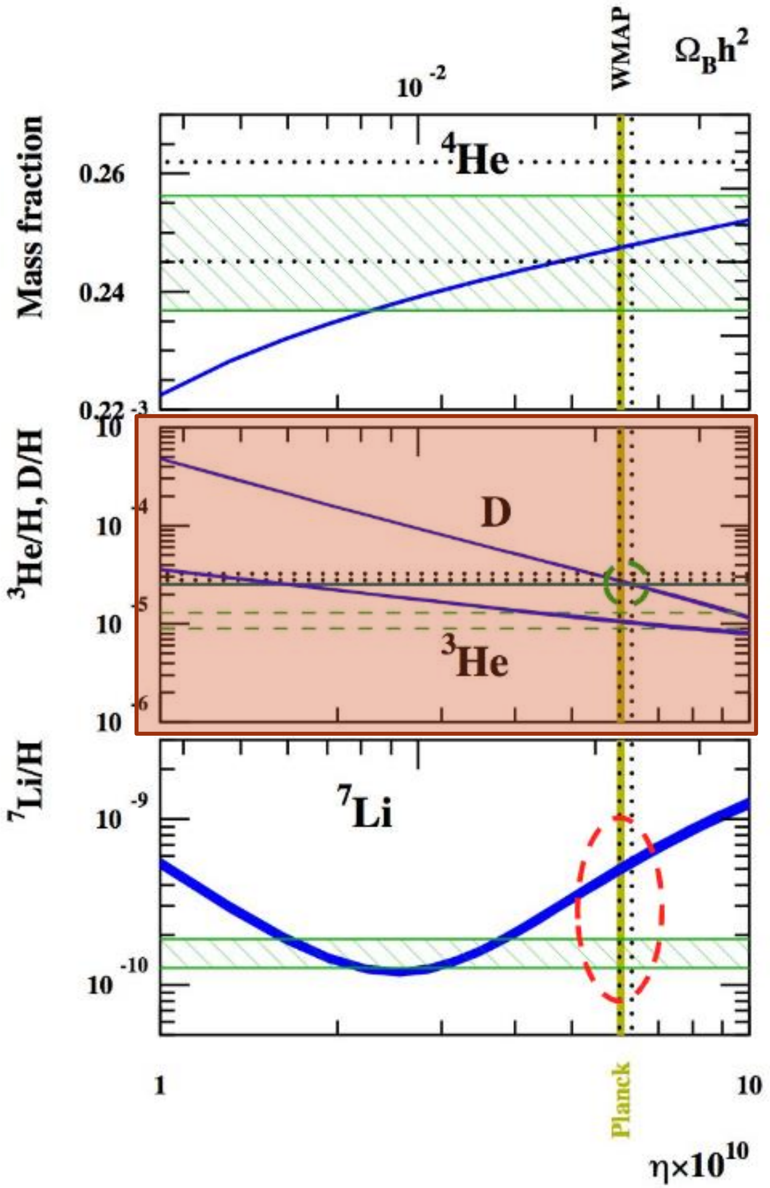
# BIG BANG Nucleosynthesis



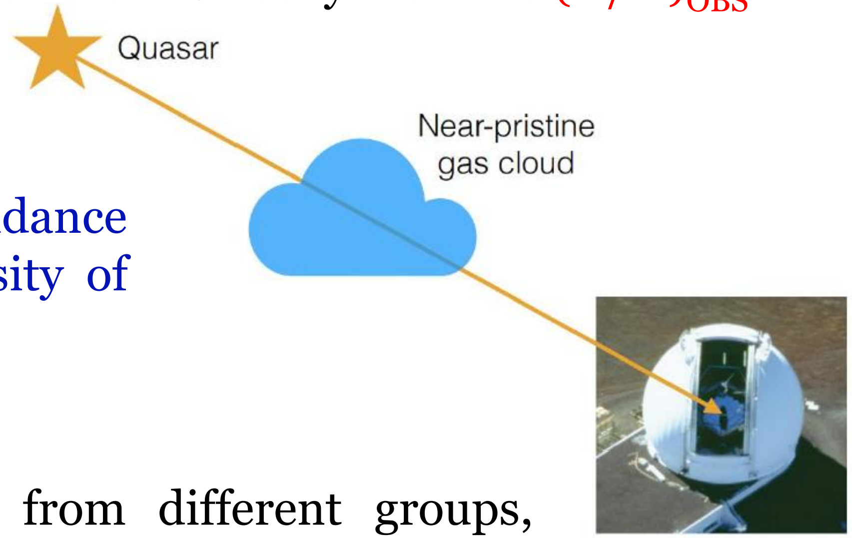




- BBN started about 1 minute after Big Bang and lasted for about 20 minutes;
- Main products of BBN are H (≈75%) and $^4$He (≈25%), plus tiny amounts of D, $^3$He, $^6$Li and $^7$Li;
- Due to the two mass gaps at A=5 and A=8, coupled to the rapid decrease of the Universe density, no heavy elements have been synthesized;
- The nuclear network needed to follow BBN is quite small!

# Open problems with BBN: primordial D abundance




- From BBN theory, knowing the cosmological parameters and the cross sections of the processes responsible for D creation and destruction, we can derive $(D/H)_{BBN}$;
- From astronomical observations we can directly measure $(D/H)_{OBS}$.

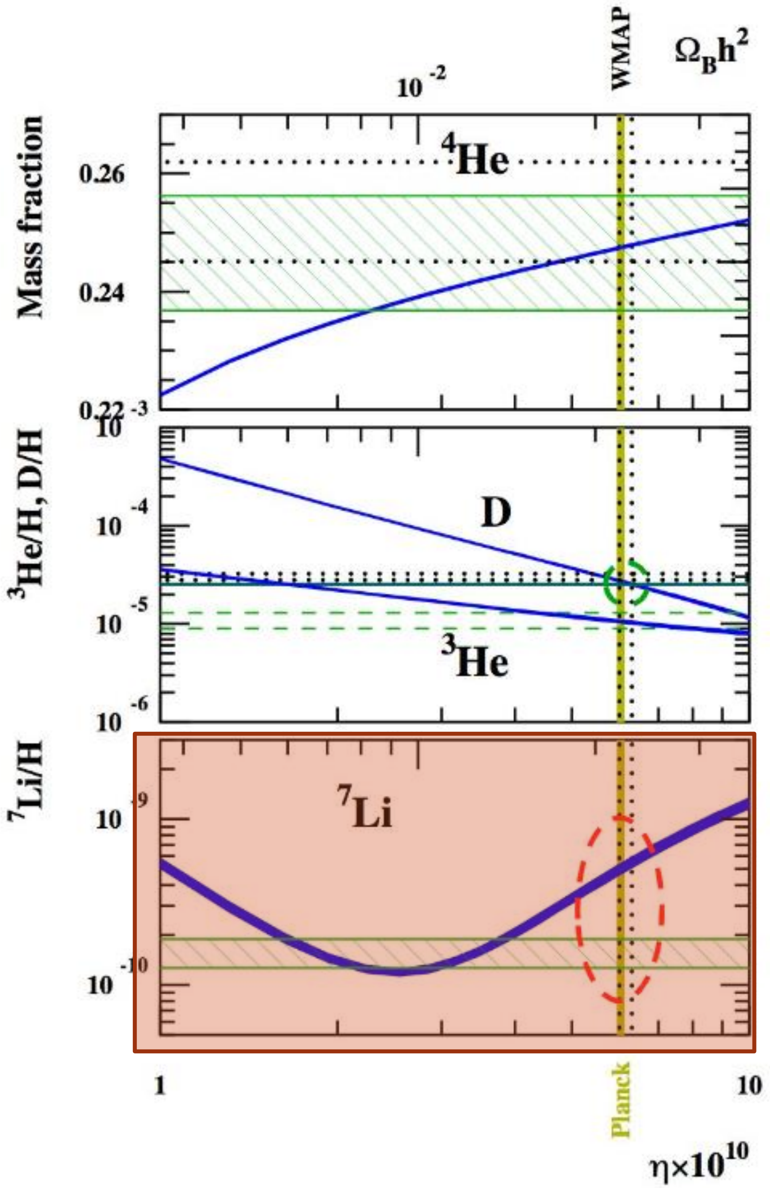



The primordial deuterium abundance is sensitive to the baryon density of the Universe.

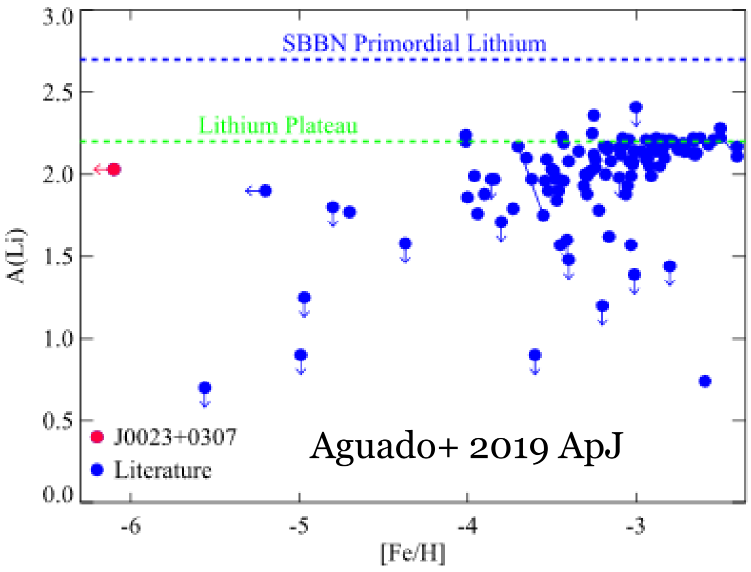
There is tension between results from different groups, whose baryon density is in very good agreement (or disagree within 1.8σ) with Cosmic Microwave Background data.

**R.o.I.: $D(D,n)^3He$ & $D(D,p)^3H$**

# Open problems with BBN: the cosmological Li




There is a **factor 3 discrepancy** between the $^7$Li predicted by observations of Halo stars (which identify the so-called **Lithium Spite Plateau**) and BBN Nucleosynthesis predictions.

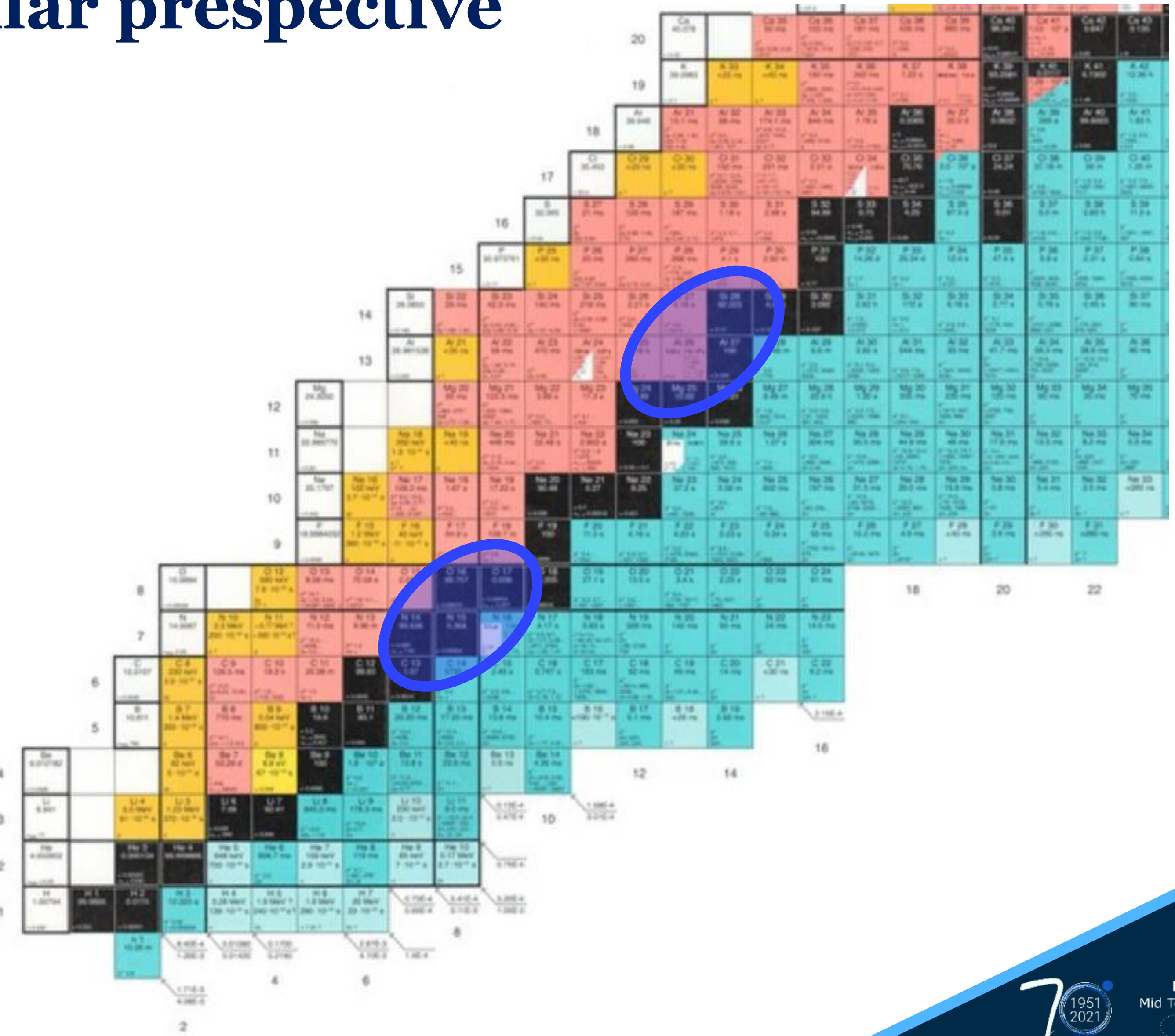



In the past, a possible solution has been searched in the nuclear inputs adopted in BBN calculations.
Large effort from italian experimental groups (**n_TOF@CERN**; **ASFIN**) in the last years!!

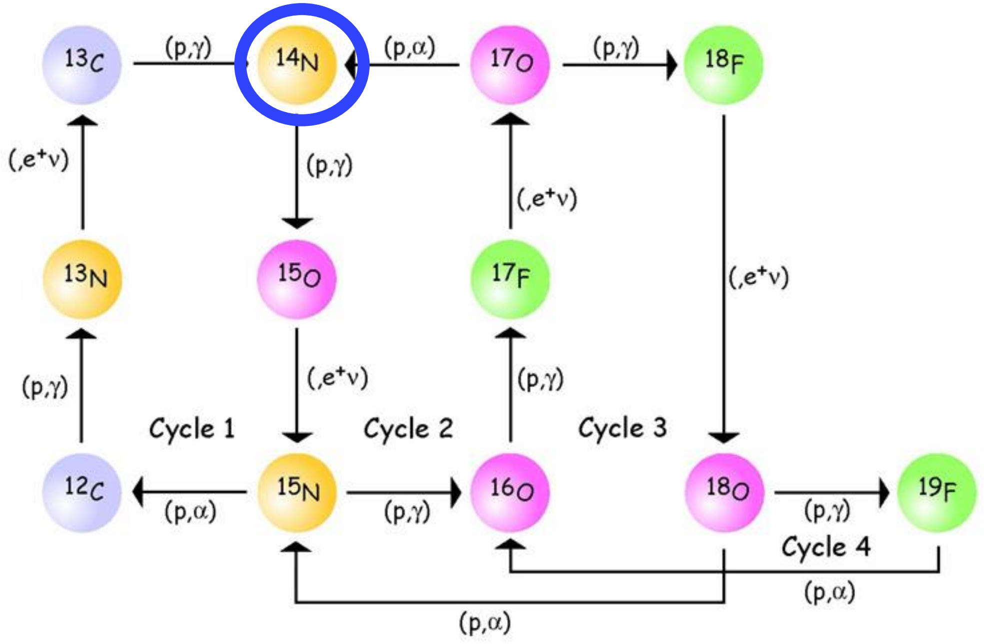
R.o.I.: $^7$Be(n,p)$^7$Li & $^7$Be(n,α)$^4$He

# The Nuclide chart: a stellar prespective

HYDROGEN burning



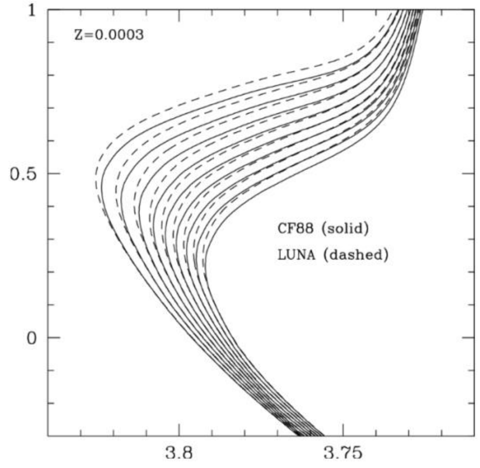
# Open problems with the (cold) CNO cycle




The CNO cycle is the dominant H-burning mechanism in upper Main Sequence stars ($M>1.5\ M_\odot$).

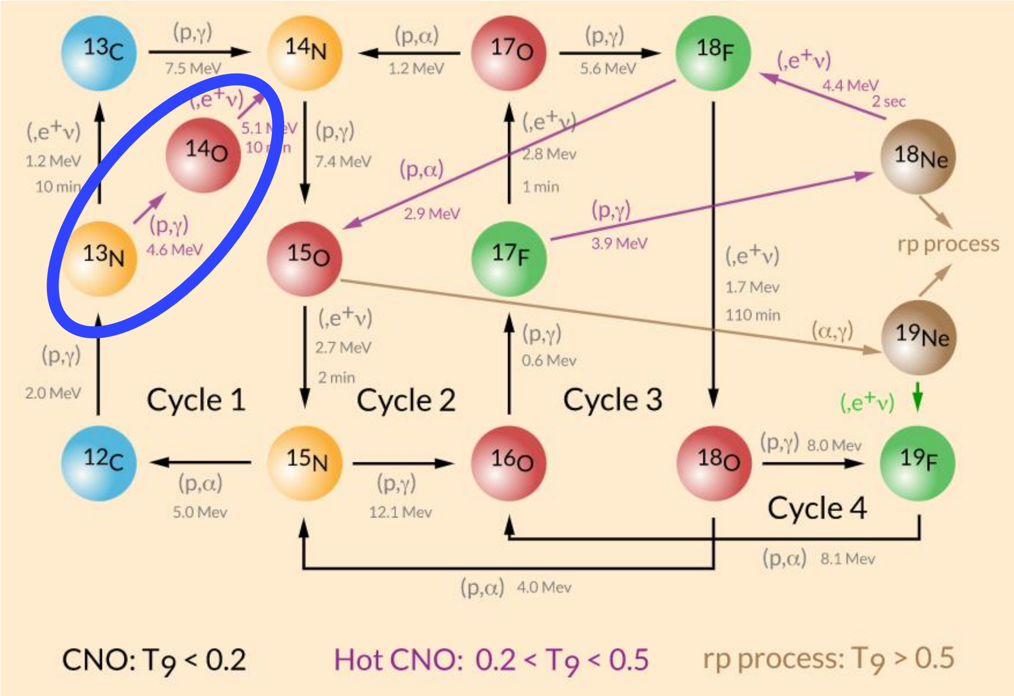
- The $^{14}N(p,\gamma)^{15}O$ is the **bootleneck of the CNO cycle**. The last significative change of its rate lead to a revision of Globular Clusters Age by almost 1 Gyr.
- High precision needed in **Standard Solar Models**;
- The Gamow peak is located down to **30 keV**, the lowest measured energy is 117 keV.
- The extrapolation at astrophysical energies is **dominated by the subthreshold 6.79 MeV resonance**.

The only way to constrain the extrapolations is **to measure the lifetime** of the 6.79 MeV subthreshold resonance.




**R.o.I.: $^{14}N(p,\gamma)^{15}O$**

# Open problems with the hot CNO cycle




By incresing the temperature, the rate of proton-capture reactions within the CNO cycle exponentially increases. These are the typycal conditions attained in **NOVAE explosions**.

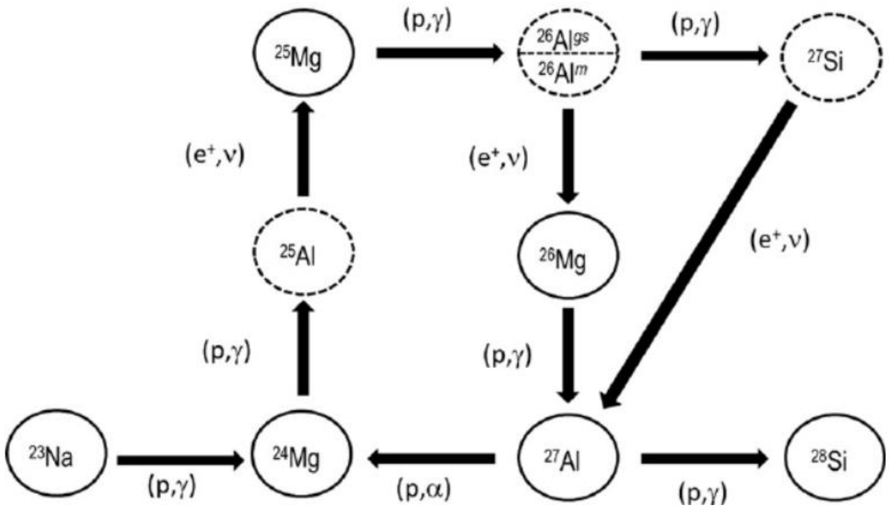
The reaction rate for the **$^{13}N(p,\gamma)^{14}O$ exceeds** the rate of **$^{13}N$ β decay.**

There is **TENSION** between current measurements (discrepancy of about **30%**).

Synergic effort with **LNS** experimentS through the application of Indirect Methods.

R.o.I.: $^{13}N(p,\gamma)^{14}O$

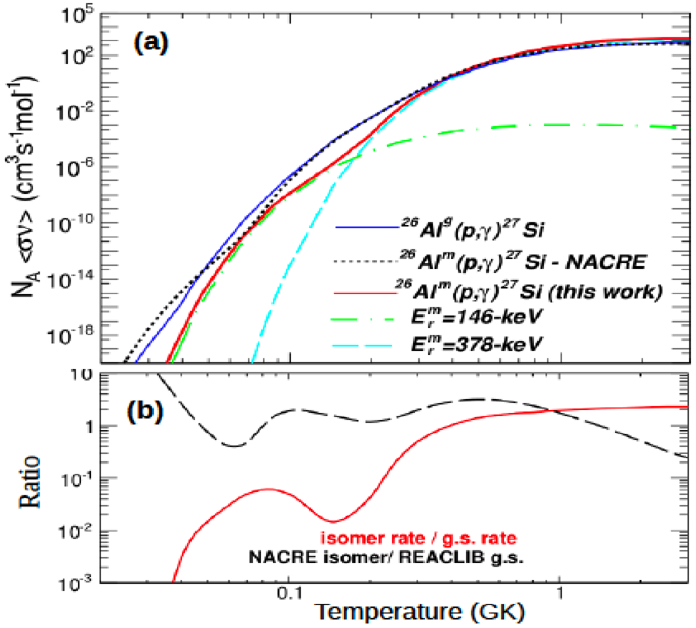
# Aluminum-26 reaction uncertainties at high temperature

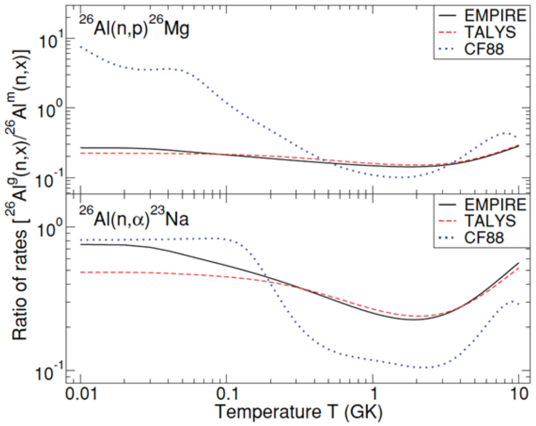



Mg-Al cycle

At large temperature, other nuclear chain activate, among which the Mg-Al cycle.
Aluminum-26 has a ground and an isomeric state, which may not thermalize in stellar interiors.
Sensitivity studies have highlighted that uncertainties in the **$^{26}Al^m(p,\gamma)^{27}Si$, $^{26}Al^m(n,p)^{26}Mg$ and $^{26}Al^m(n,\alpha)^{23}Na$** reactions have an high impact to understand the $^{26}$Al production in massive stars and the isotopic abundances of $^{26}$Mg synthesized in novae.

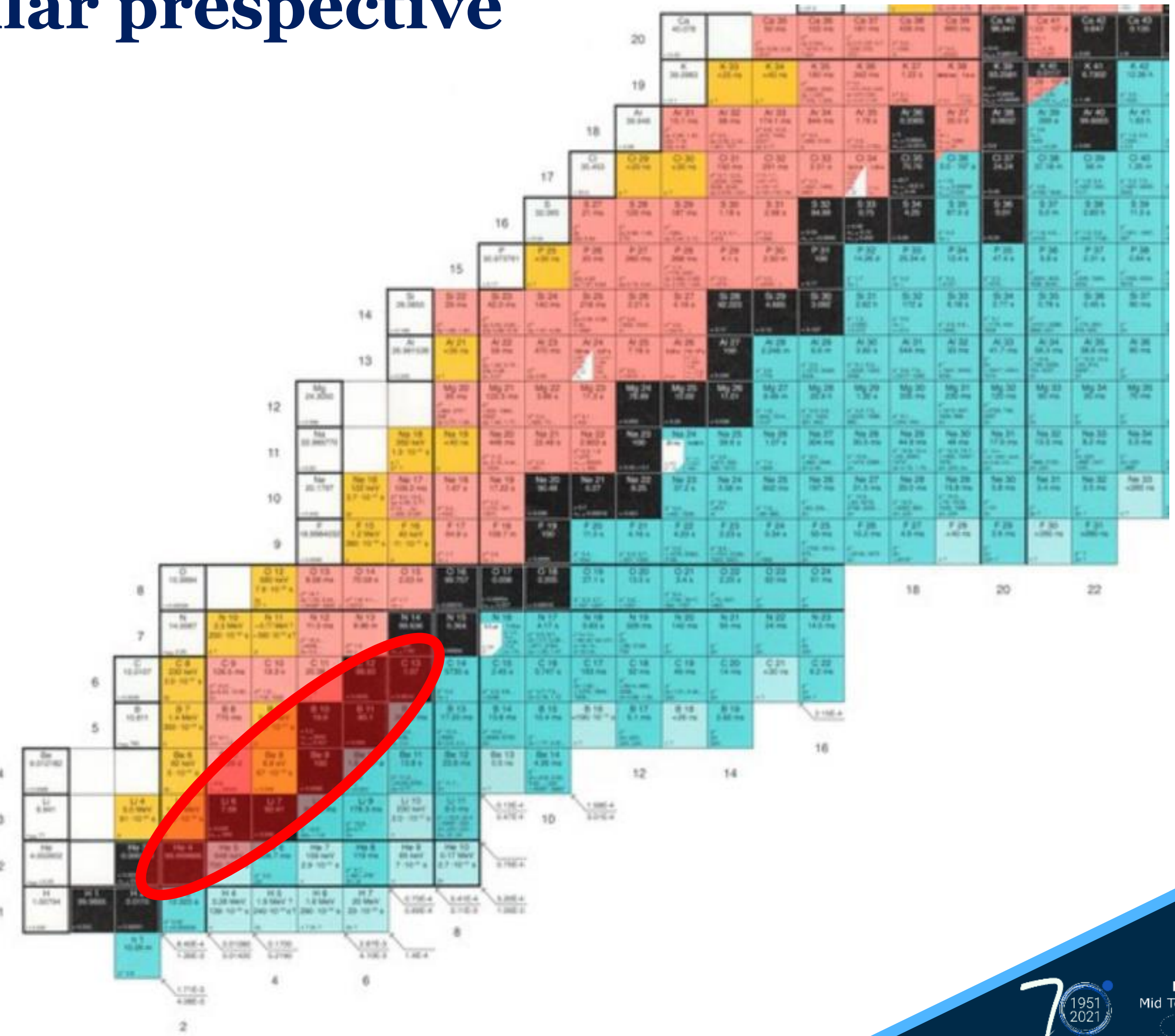
**R.o.I.**
**$^{26}Al^m(p,\gamma)^{27}Si$**
**$^{26}Al^m(n,p)^{26}Mg$**
**$^{26}Al^m(n,\alpha)^{23}Na$**



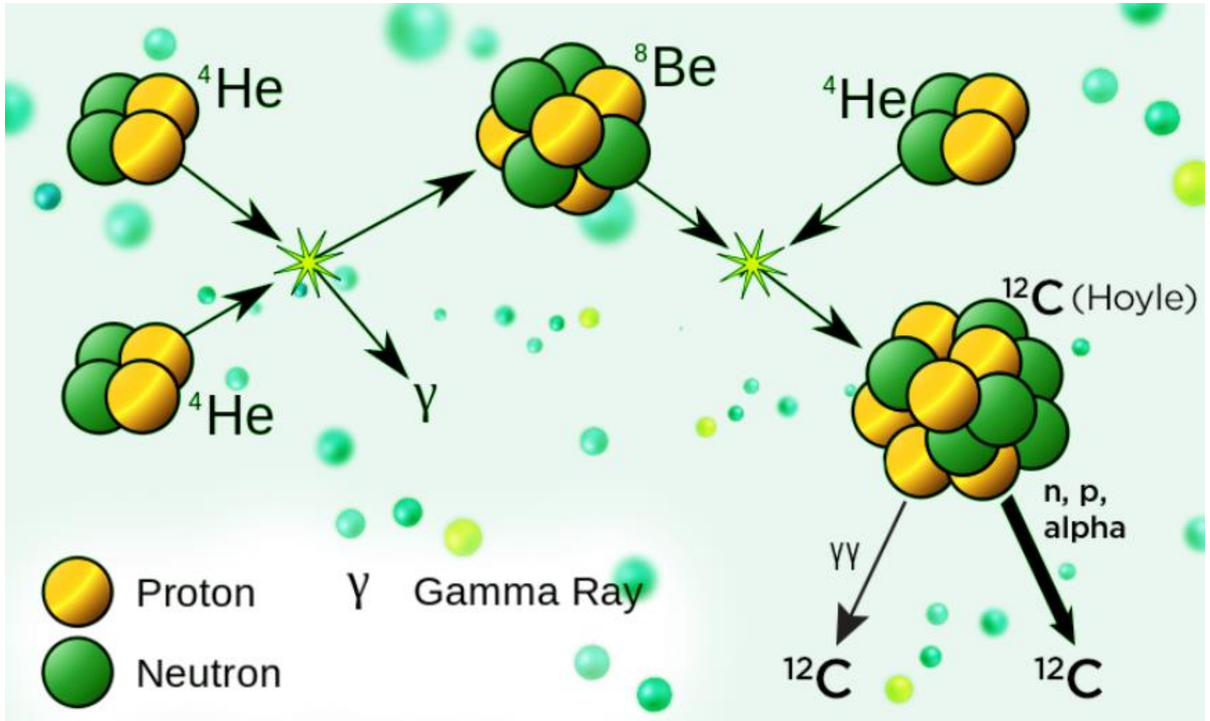



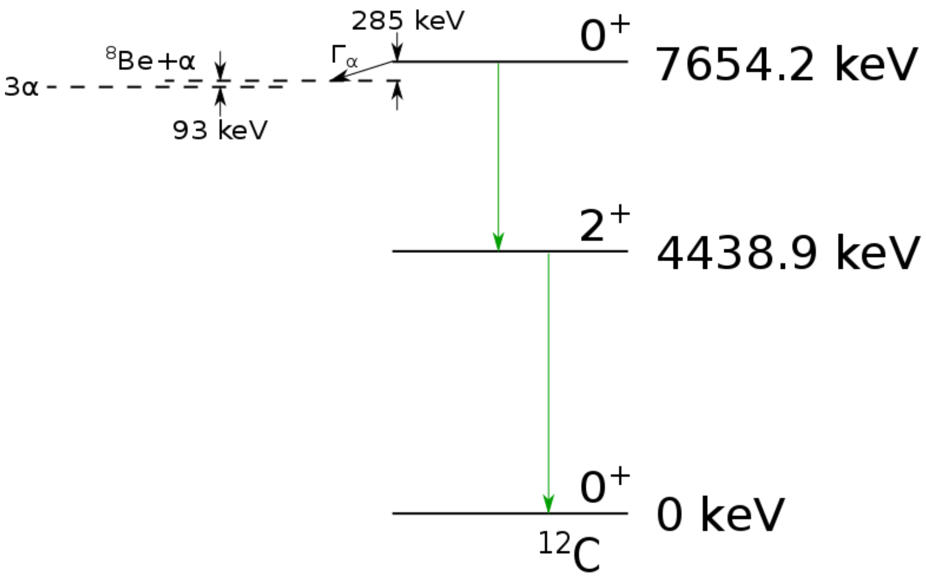
# The Nuclide chart: a stellar prespective

HELIUM burning



# The importance of the 3α reaction rate



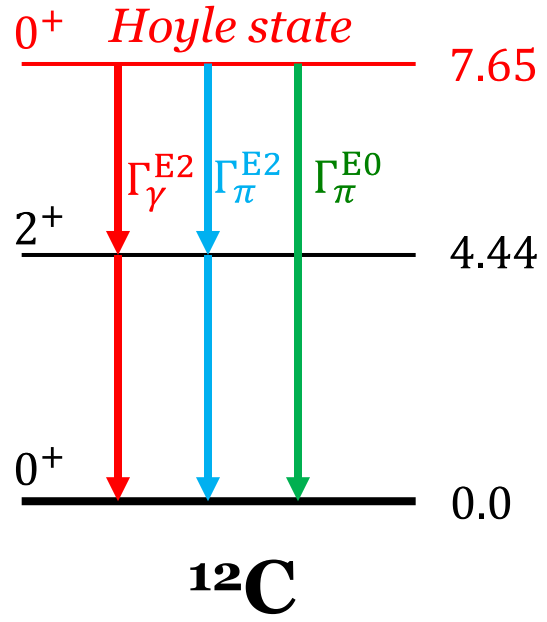




The triple alpha process is responsible for the **conversion in stars of $^4$He nuclei made in the Big Bang to the carbon we find around us and in us**.
This process occurs thanks to the famous Hoyle state, with an excitation energy of about 7.6 MeV in $^{12}$C.
After its prediction, it was found experimentally, being one of the triumphs of nuclear astrophysics.

The $^{12}$C production is proportional to the probability of decay of the Hoyle state to the ground state of $^{12}$C.

# Tension with the 3α reaction rate

For the conditions found in helium burning stars, the Hoyle state decays to the ground state by emitting two gamma rays, with a probability that can be measured in the laboratory.
However, the reaction takes place in a plasma, where other particles are present (protons, neutrons or α particles), **which may induce such a decays**.
This **increases the probability of decay** to the ground state and so the rate of the triple alpha process. Obivouly, large densities are needed. Thus, it turns out that very large densities, these enhancements can be large, **a factor of 50** or more if the particles are neutrons.




Recently, a new radiative width of the Hoyle state has been proposed (**34% larger**).

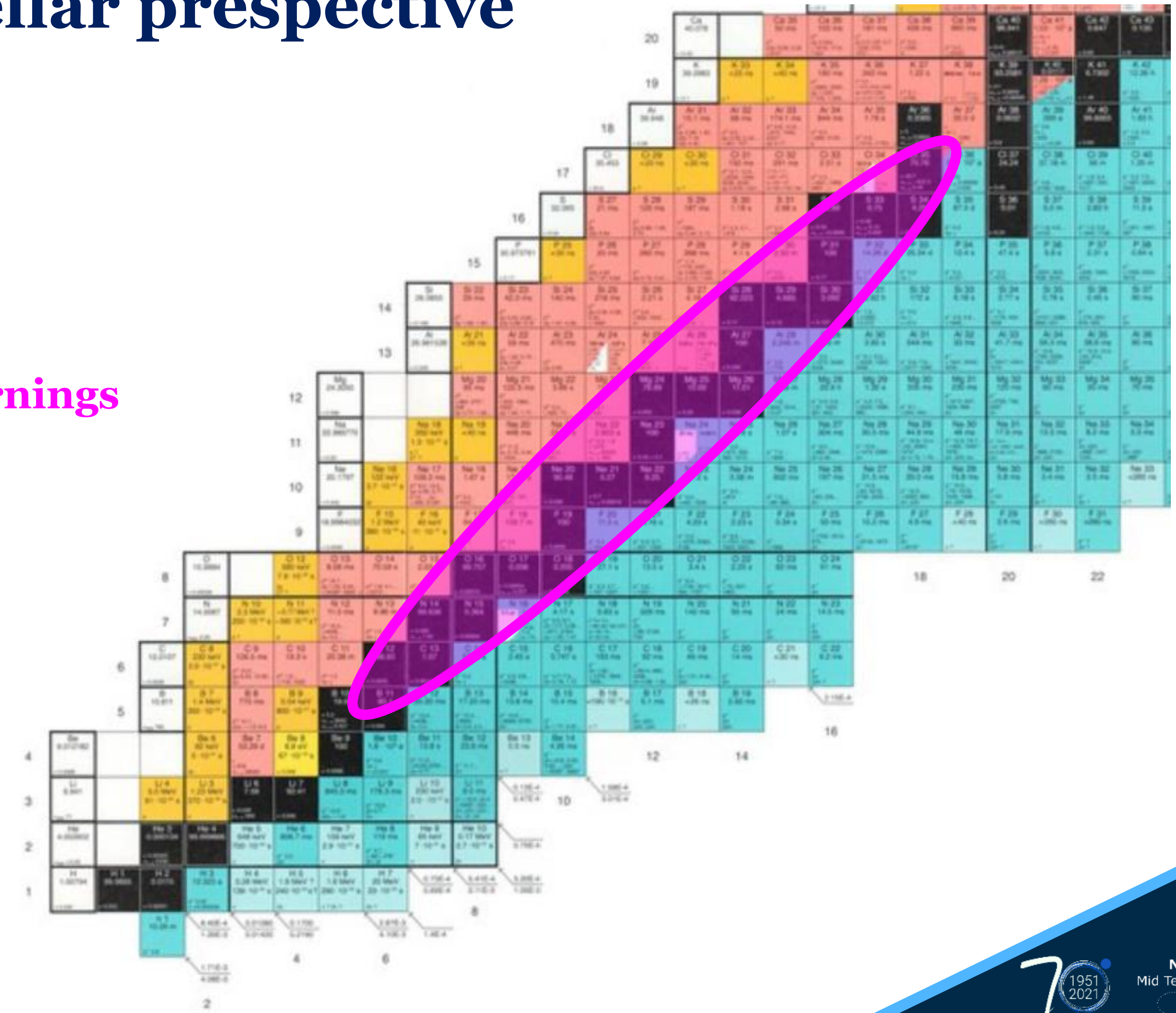
**Astrophysics sumulations** show that a variation of this rate has sizeable consequences on the final fate of massive stars, affecting the extension of convective layers and the compactness parameter.
Note that an increase in the 3α reaction rate would **also** imply a sizeable increase of the **$^{12}C(\alpha,\gamma)^{16}O$**.

Synergic effort with **LNS** experimentS through the application of Indirect Methods.

R.o.I.: **$\alpha(\alpha\ \alpha,\gamma)^{12}C$**

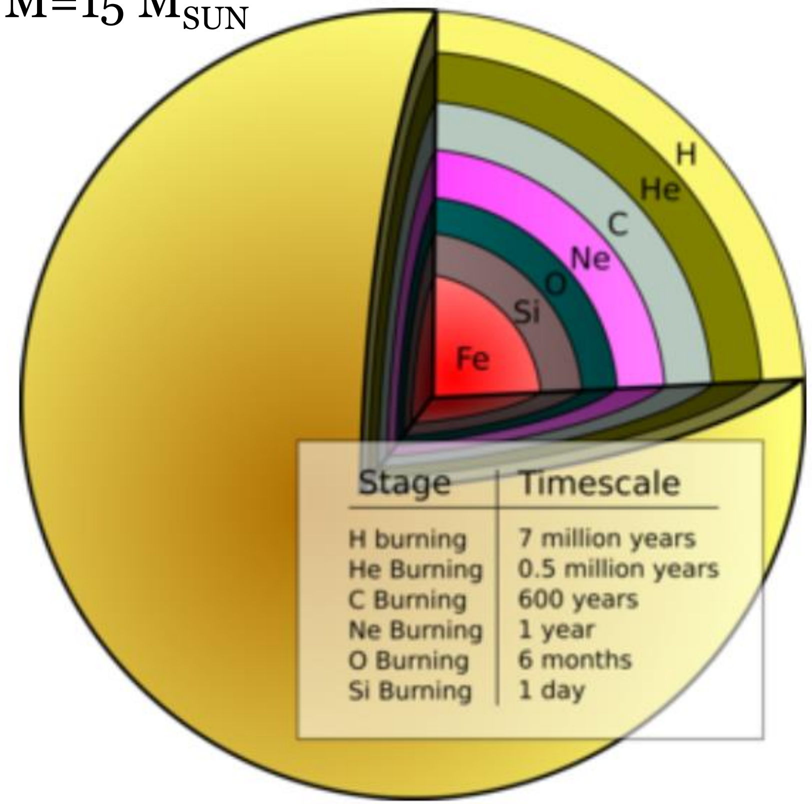
# The Nuclide chart: a stellar prespective

ADVANCED quiescent burnings



# Uncertainty in the $^{12}C+^{12}C$ rate

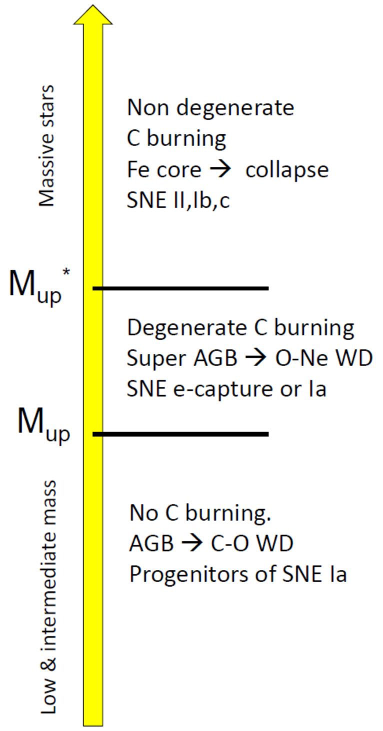
M=15 $M_{SUN}$




In massive stars the gravitational collapse increases the core temperature and density enough to ignite advanced burnings:

- **C-burning**
- Ne-burning
- O-burning
- Si-burning

COMPACTNESS & FINAL ρ DISTRIBUTION: **EXPLOSION YES/NO**




Recent new proposed **larger** rate by **ASFIN group**, questioned by other groups.
**More data needed at large energies!**

<u>**Aim:**</u> study the properties of $^{24}$Mg excited levels in the energy range from 14 and 17 MeV corresponding to the astrophysical region of interest.

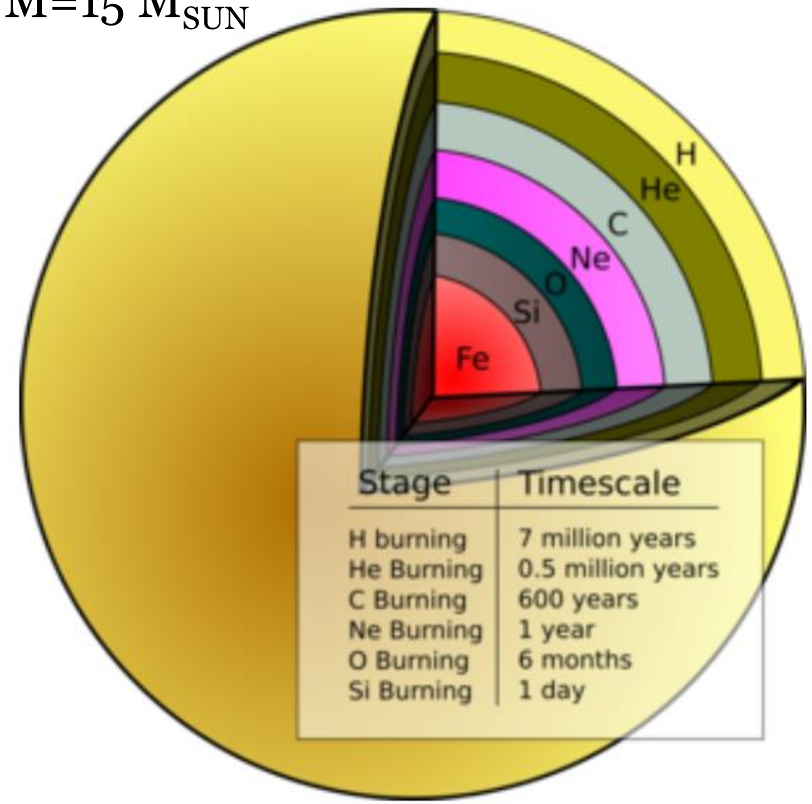
**$^{12}$C + $^{12}$C** → ($^{24}$Mg)* → **$^{23}$Na + p** + 2.24 MeV ≈50%
**$^{20}$Ne + α** + 4.62 MeV ≈50%
$^{23}$Mg + n – 2.60 MeV

R.o.I.

Synergic effort with **LNS** experiments through the application of <u>Indirect Methods</u>.

# Uncertainty in the $^{16}O+^{16}O$ rate

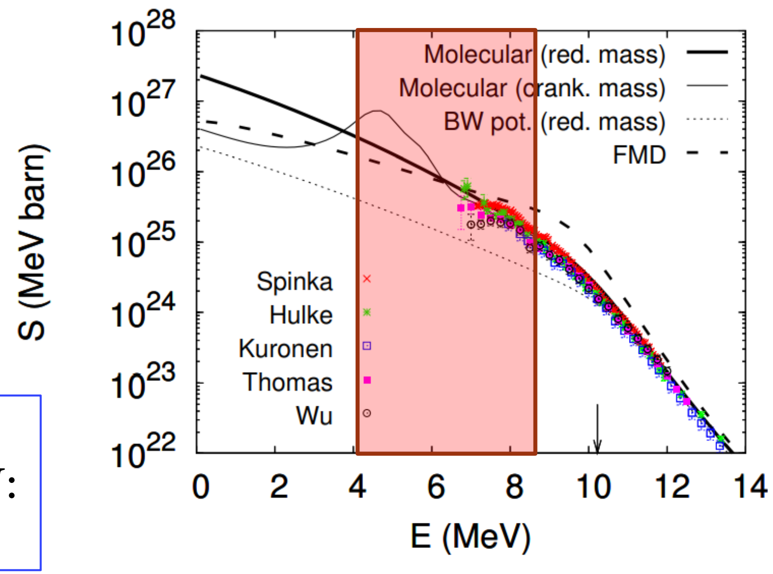
$M=15\ M_{SUN}$




In massive stars the gravitational collapse increases the core temperature and density enough to ignite advanced burnings:

- C-burning
- Ne-burning
- **O-burning**
- Si-burning

COMPACTNESS &
FINAL ρ DISTRIBUTION:
**EXPLOSION** YES/NO

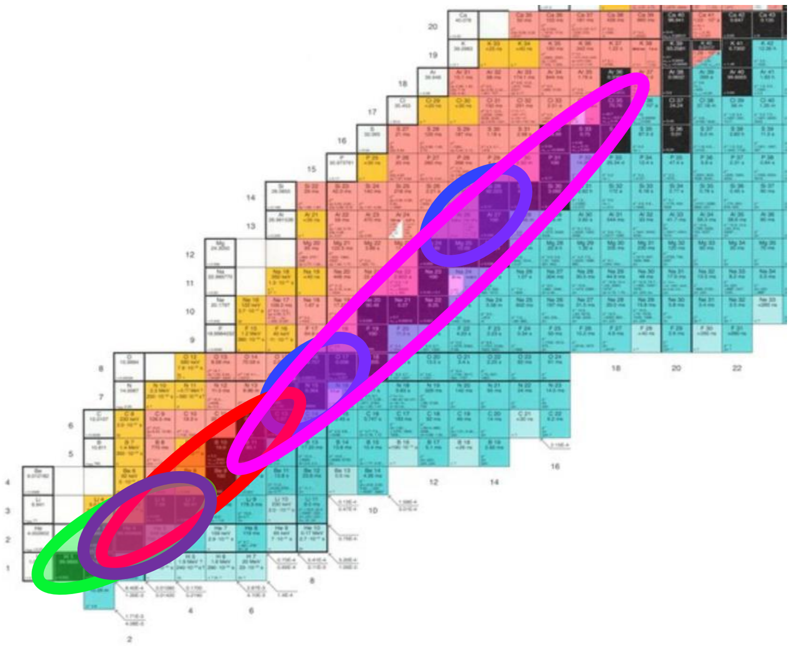



Besides the rate, also the exit channels branching between proton, neutron, or alpha decay channels of the fused compound nucleus.

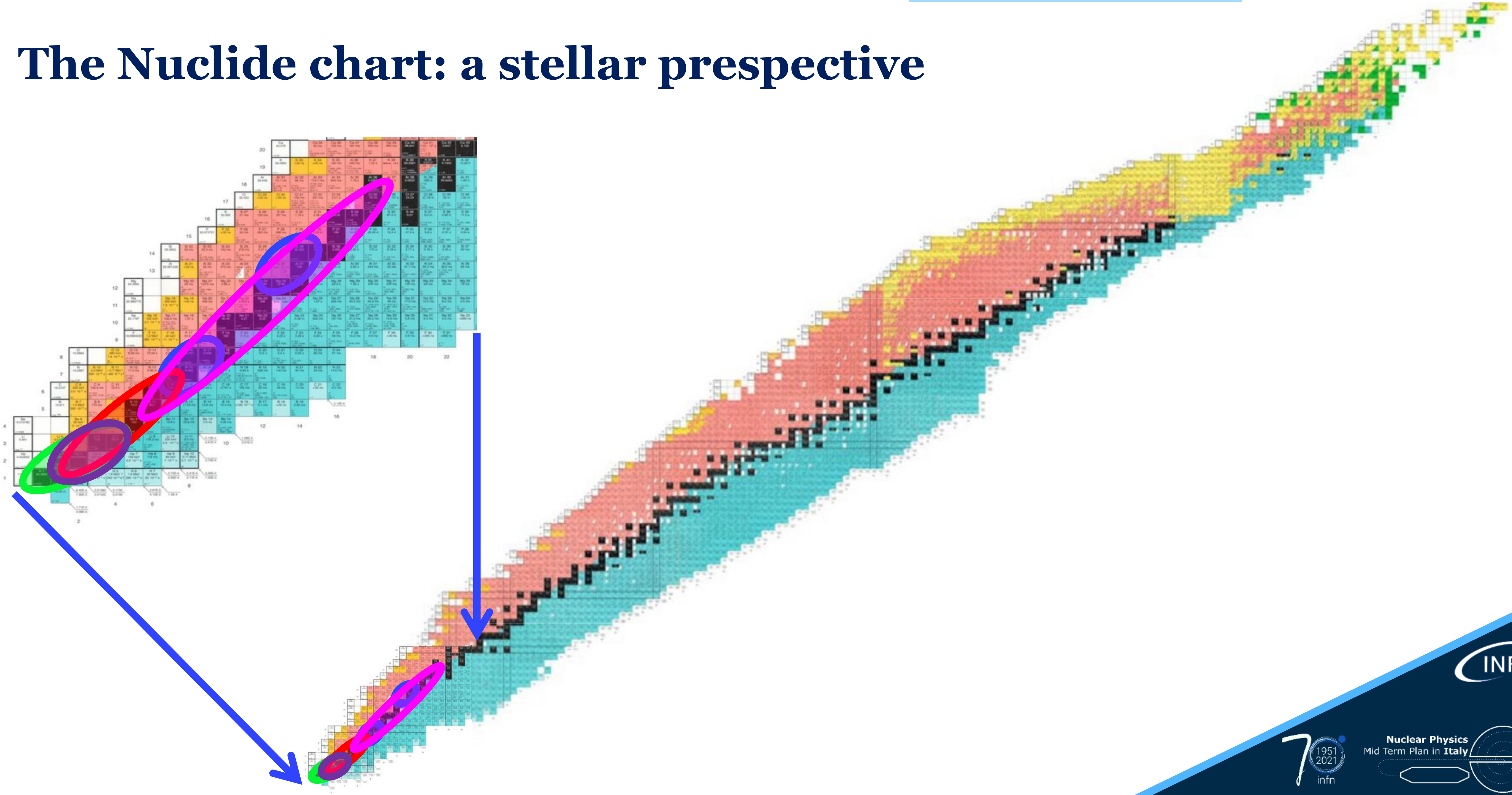
**Theoretical predictions at relevant energies of the astrophysical factor show different behaviours!**

| | | | |
|---|---|---|---|
| $^{16}$**O** + $^{16}$**O** → $(^{32}S)^*$ → | $^{31}$**P** + **p** + 7.68 MeV | 56% |
| | $^{28}$**Si** + **α** + 9.59 MeV | 34% |
| R.o.I. | $^{31}$S + n + 1.45 MeV | 5% |
| | $^{30}$P + d – 2.41 MeV | 5% |

# The Nuclide chart: a stellar prespective

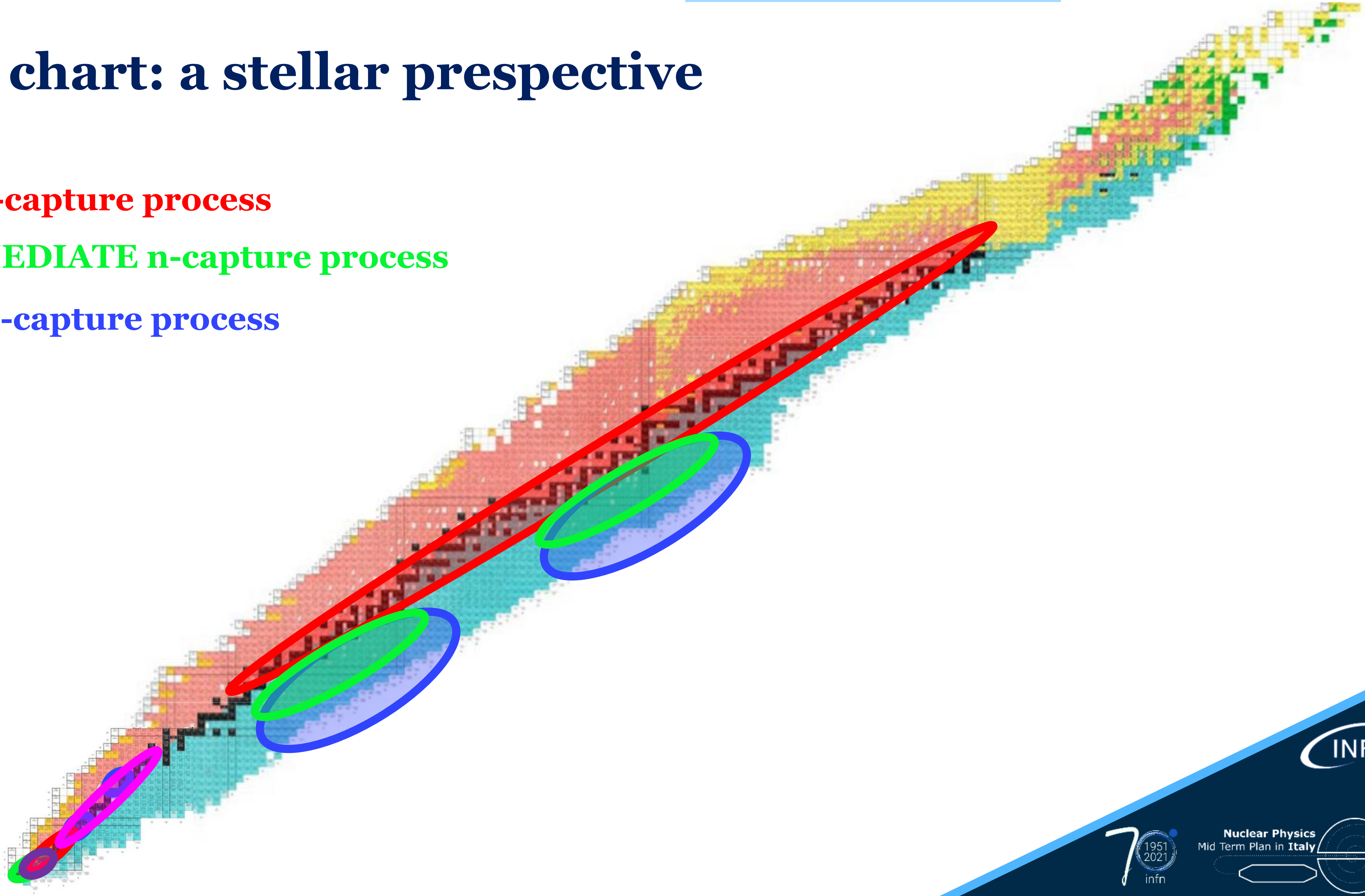


# The Nuclide chart: a stellar prespective



# The Nuclide chart: a stellar prespective

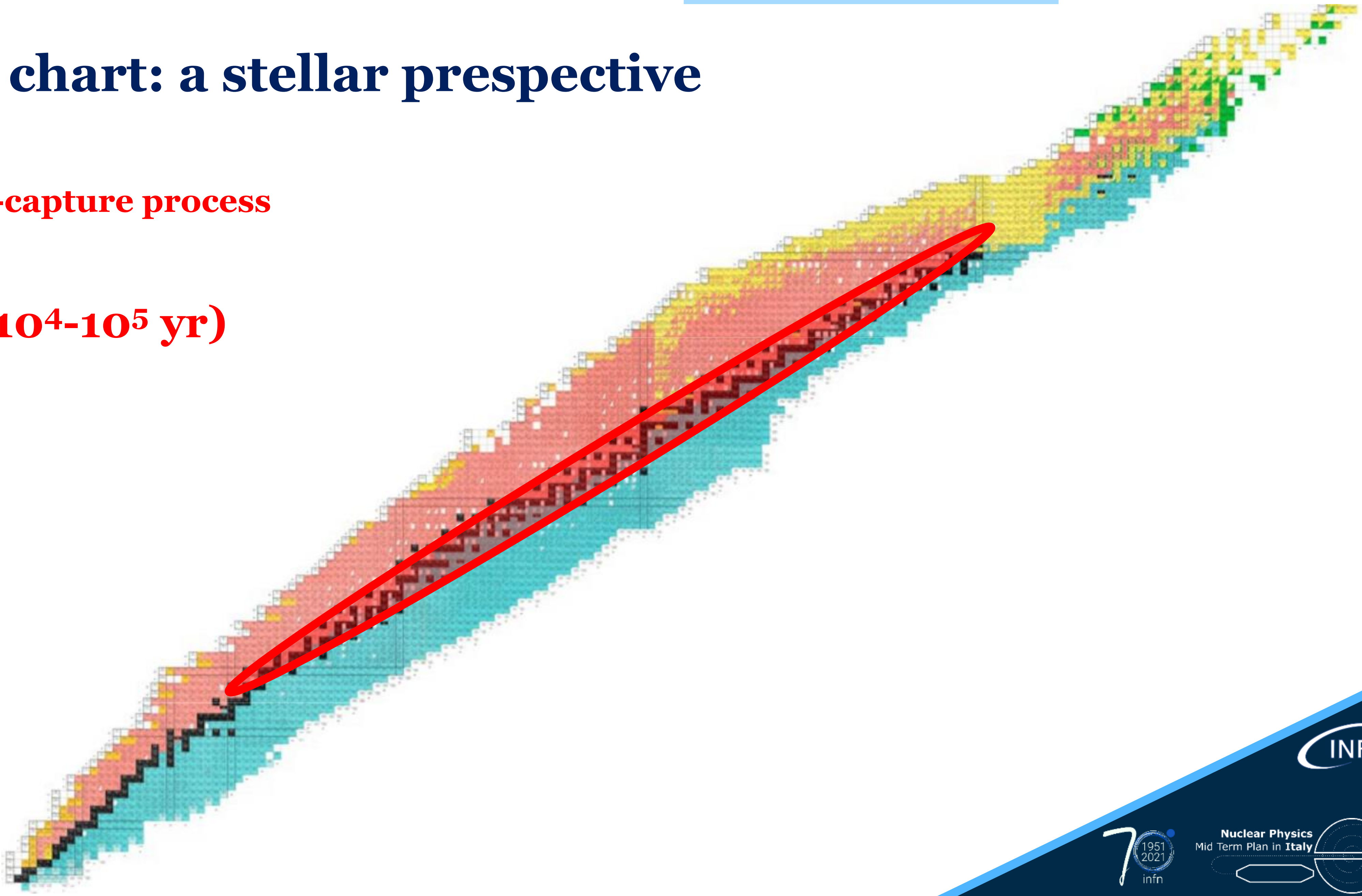
- SLOW n-capture process
- INTERMEDIATE n-capture process
- RAPID n-capture process



# The Nuclide chart: a stellar prespective

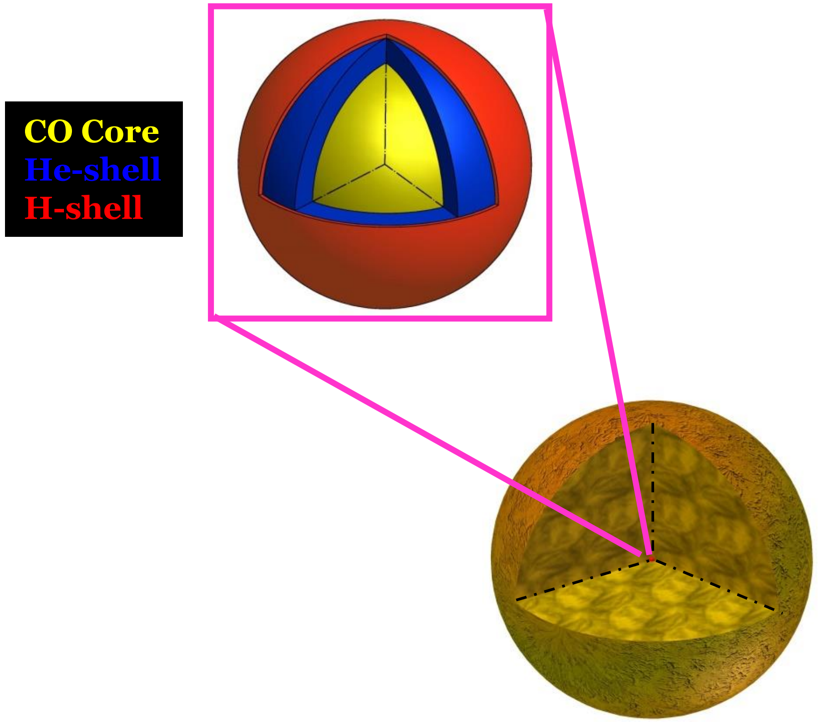
SLOW n-capture process

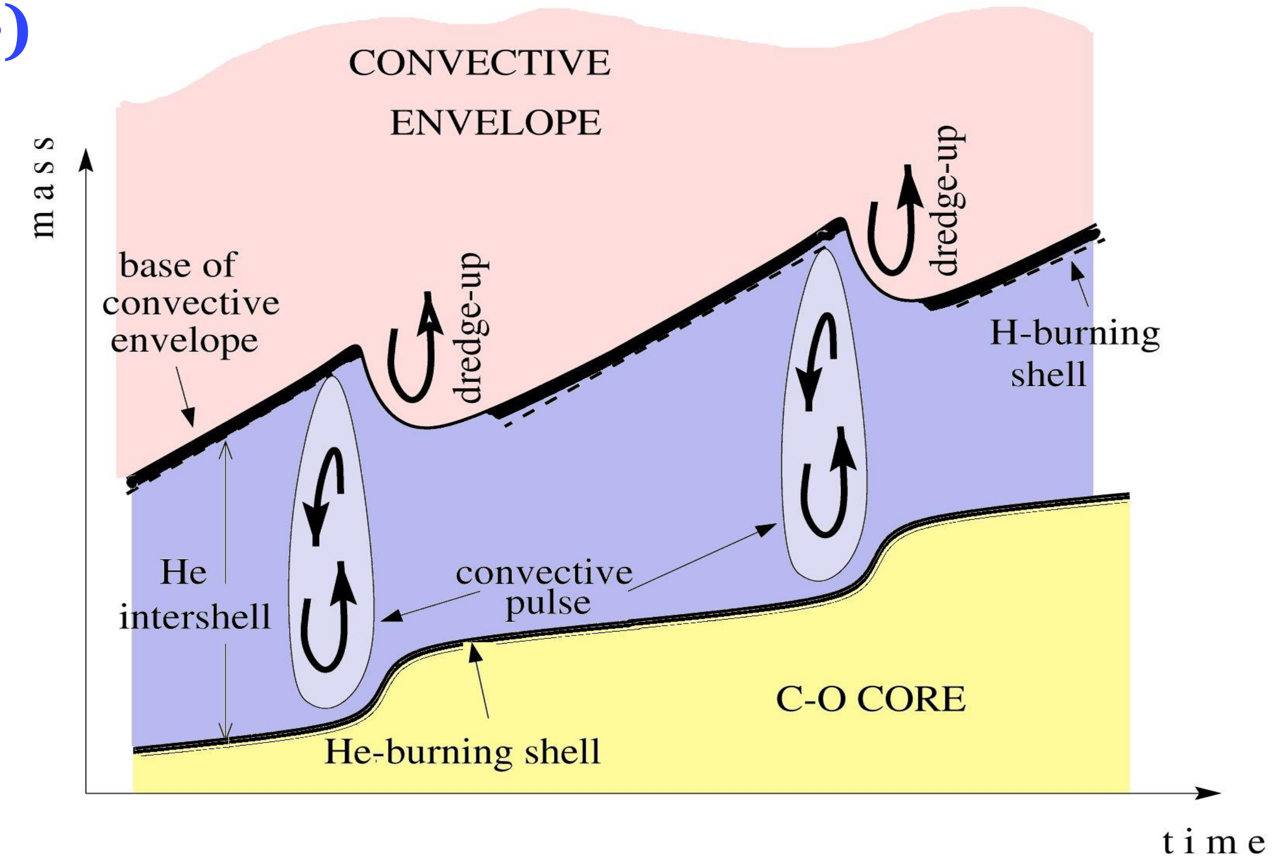
($\tau \approx 10^4$-$10^5$ yr)



# Stellar sites of the s-process: Asymptotic Giant Branch stars

## MAIN COMPONENT ($n_n \approx 10^7$ cm$^{-3}$)



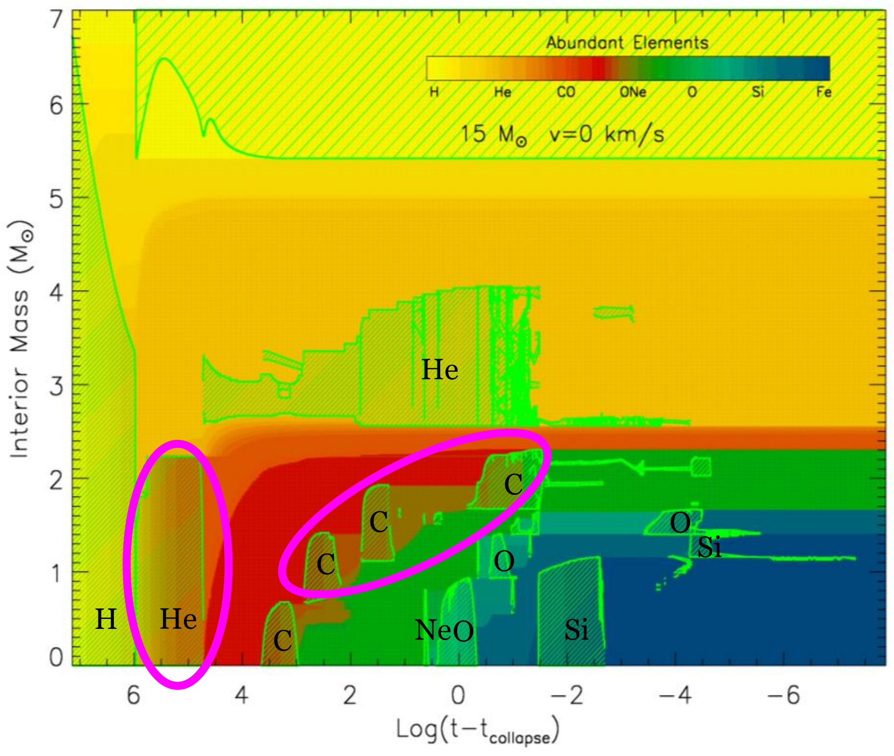



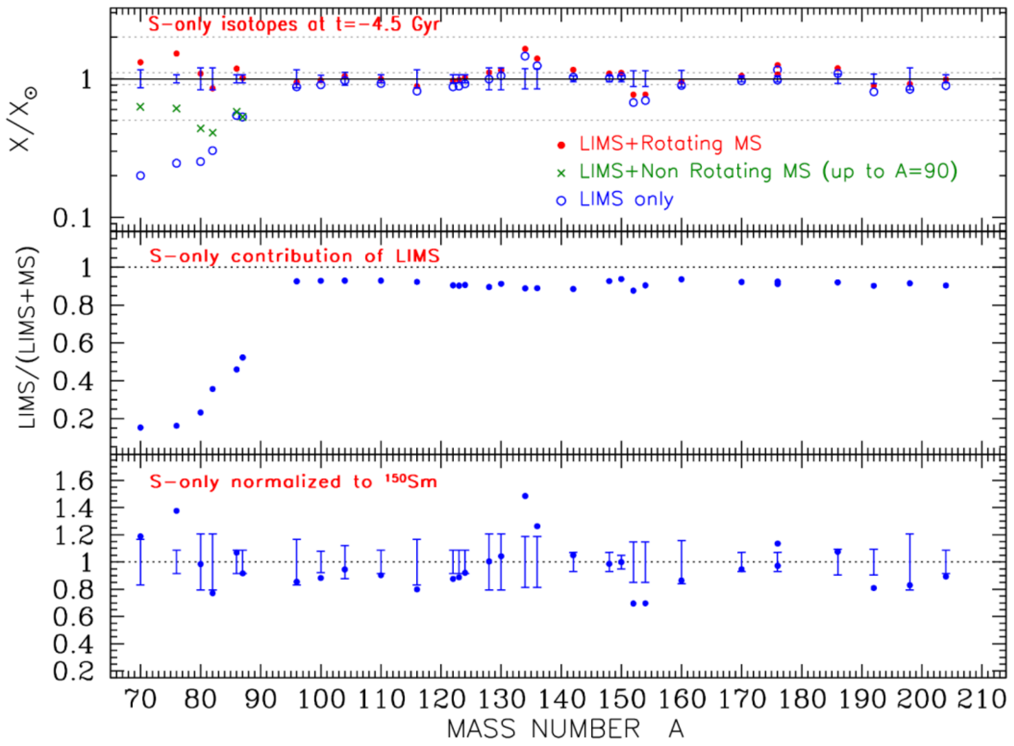

Energy of interest: 5-30 KeV

- Main polluters for lead and other heavy elements in the Universe
- Most of the Cosmic dust is produced by these ojects
- Large part of Cosmic carbon synthesized in their interiors

# Stellar sites of the s-process: massive stars

## WEAK COMPONENT ($n_n \approx 10^6$ cm$^{-3}$ & $n_n \approx 10^{12}$ cm$^{-3}$)

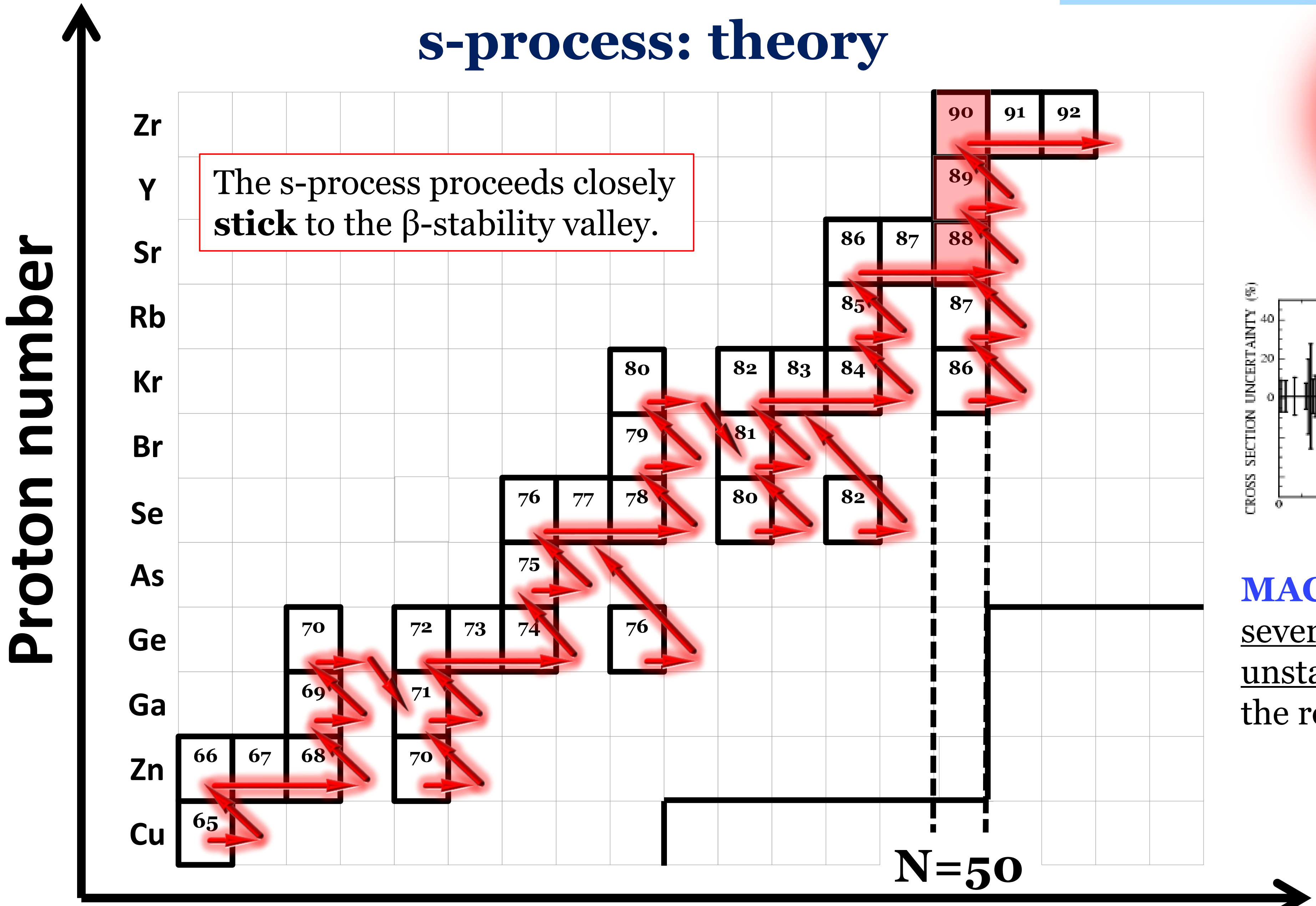



- Main polluters for elements between Cu and Sr in the Universe
- Most of the Cosmic oxygen synthesized in their interiors

Energy of interest: 5-90 KeV

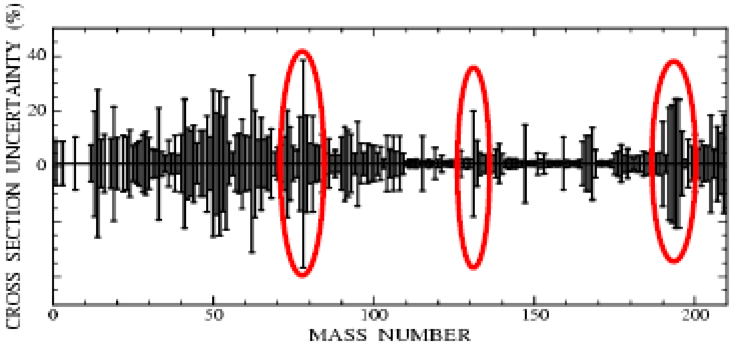
# s-process: theory




The s-process proceeds closely **stick** to the β-stability valley.

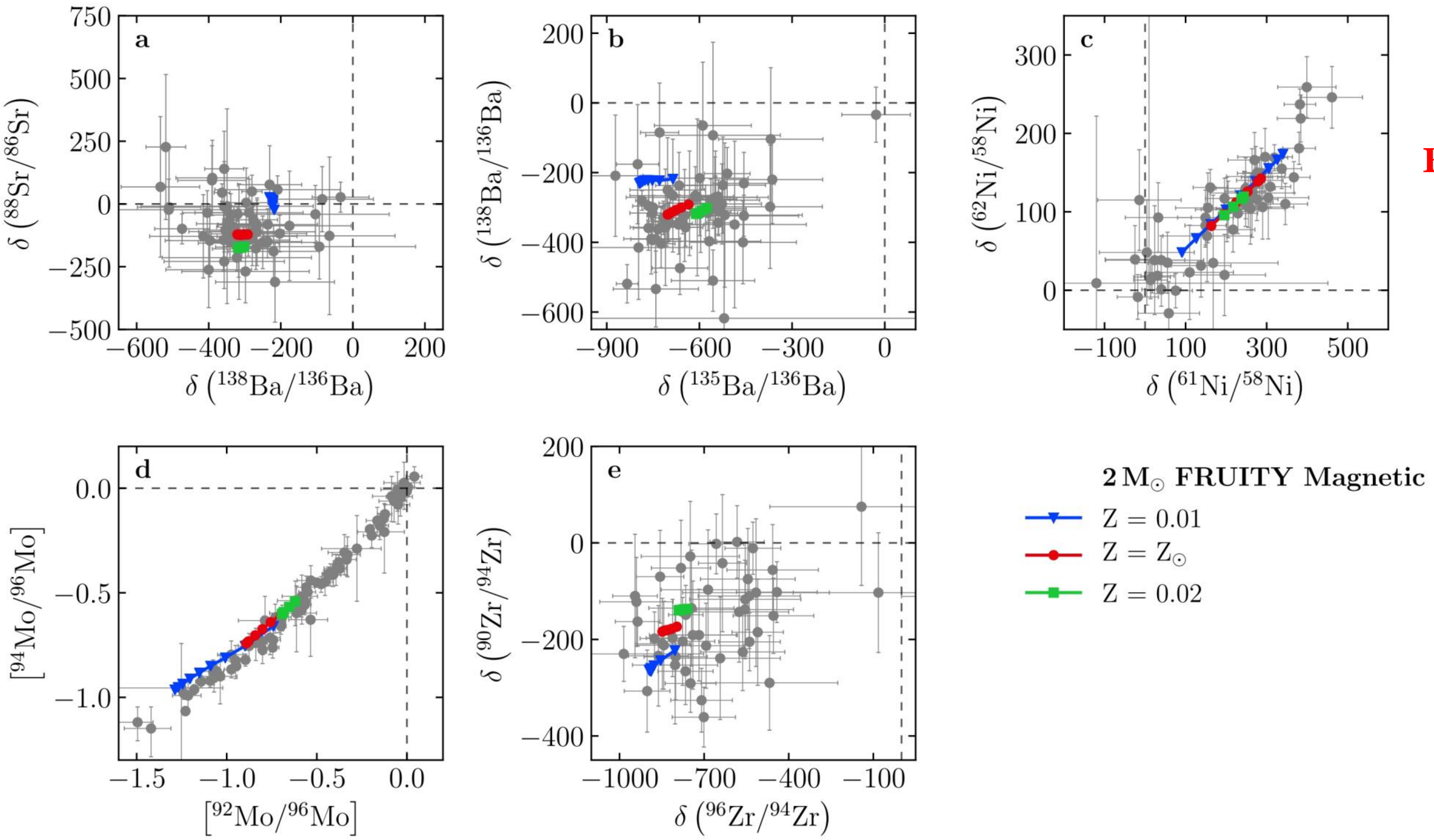
s process

$N_n \sim 10^7$ n/cm$^3$




**MACS** calculated uncertainties of several stable and most of the unstable isotopes are higher than the requested accuracy (**3-5**%).

# s-process in laboratory presolar grain measurements



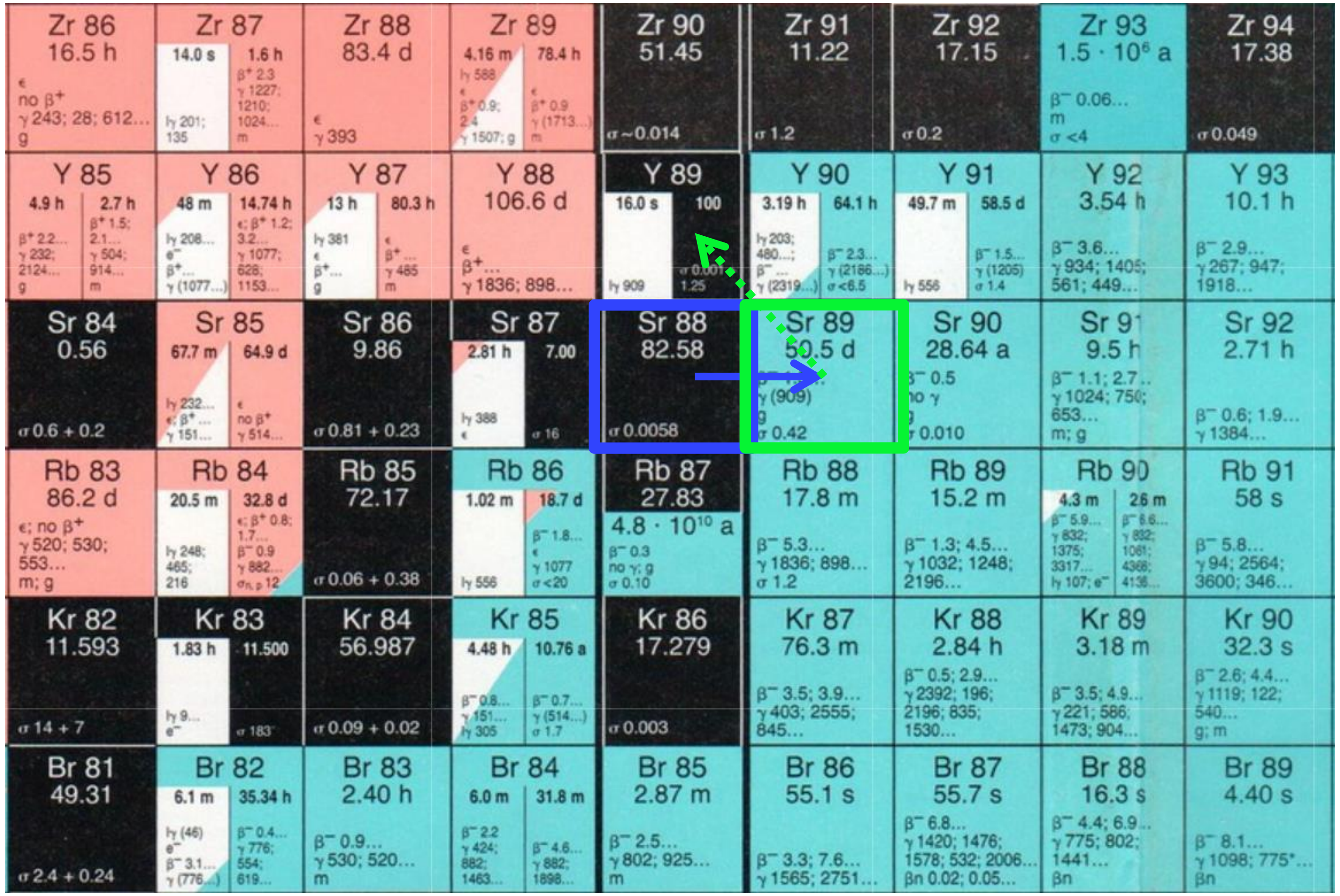

**Better than spectroscopic observations!!**

**Extremely precise data (5%)**

↓

**Extremely precise nuclear data are needed (at least with the same uncertainty)**

# s-process: experiments




## Neutron captures on stable isotopes

**Activation techniques**: study of the decay product:

- Ideally the MACS is needed at various energies (to trace different stellar environments, as in TOF experiments!);
- **Smart IDEA**: perform activation measurements on ax experiment with a **flexible easy-to-change** setup;
- Before any MACS measurement, a characterized neutron beam with a stellar spectrum is mandatory.

$^{197}$Au, $^{89}$Y, $^{94}$Zr measures already on going!

**Dozens** of candidate isotopes (provided that the daughter nucleus is unstable):

1. s-process **branchings**;
2. s-process **magic nuclei**.

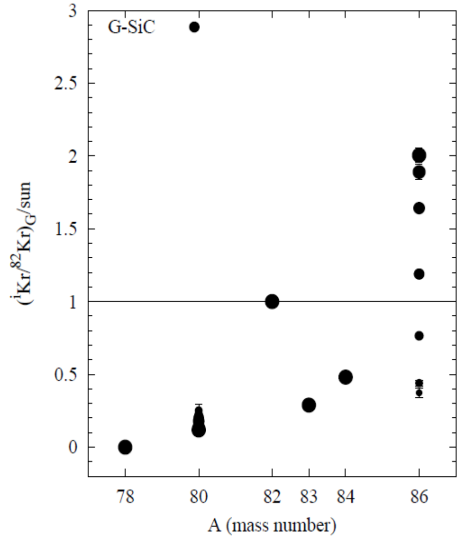
Synergic effort with the **n_TOF** experiment at **CERN**.

# s-process: experiments

## Neutron captures on unstable isotopes


**Surrogate method**: indirect method for determining cross section of Compound-Nucleus reactions difficult to measure directly.

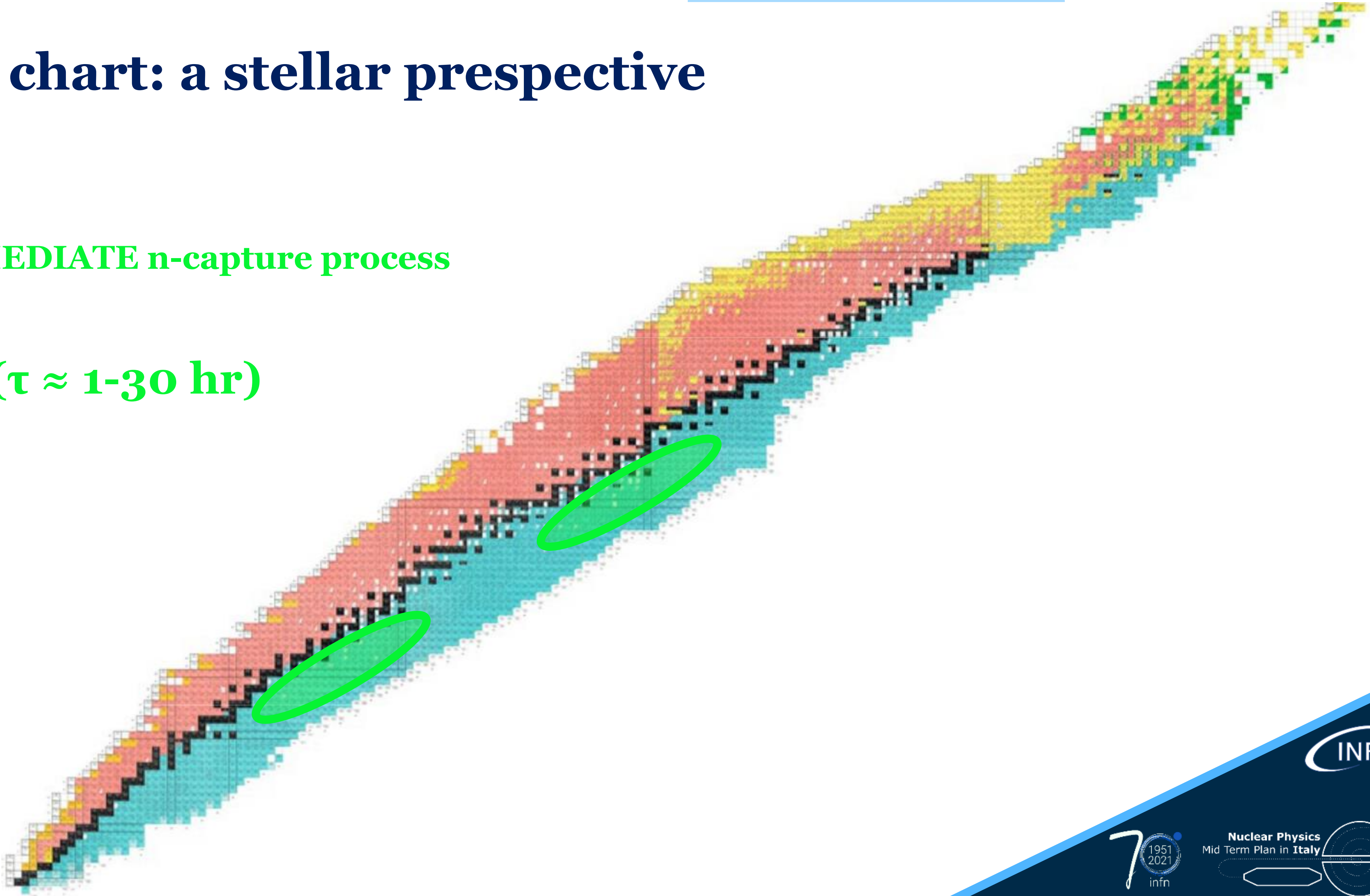
Selected list of **unstable isotopes** close to s-process **branchings**.
E.g.: $^{79}$Se, $^{81,85}$Kr, $^{95}$Zr, $^{86}$Rb,etc…




**Kr** isotopic ratios in presolar SiC grains

Synergic effort with the **AGATA** campaign at **GANIL**.

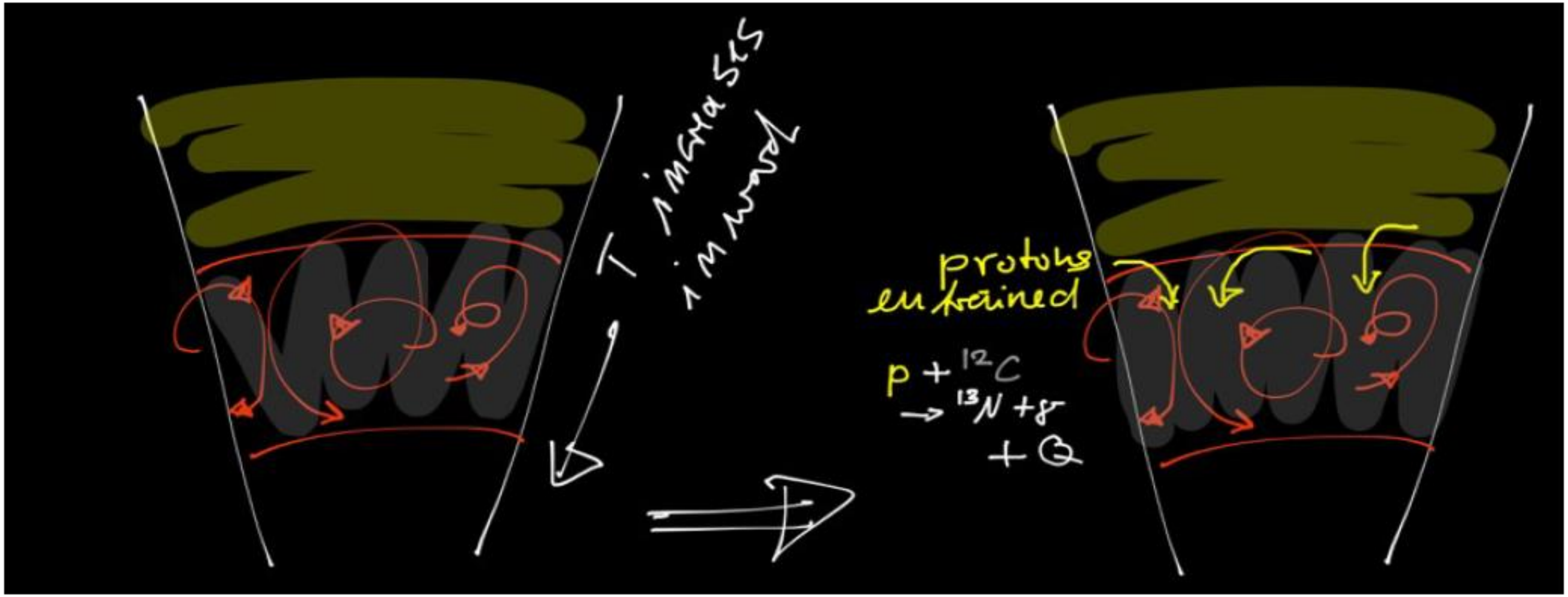
# The Nuclide chart: a stellar prespective



INTERMEDIATE n-capture process

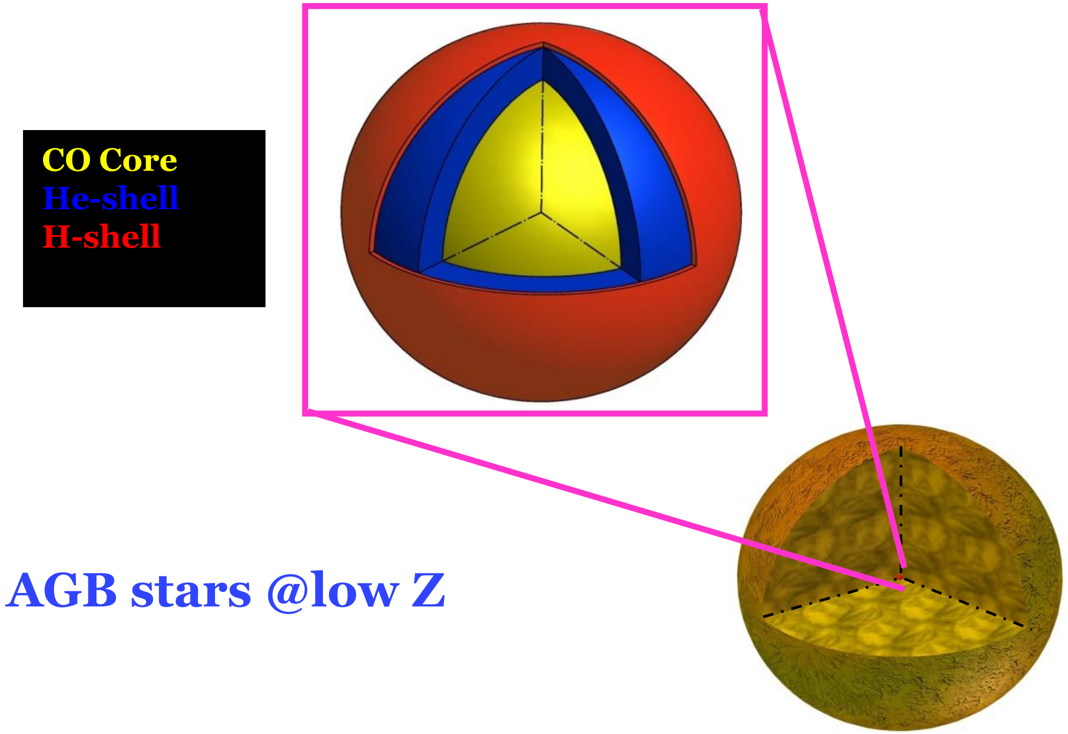
(τ ≈ 1-30 hr)

# The physics of the i-process

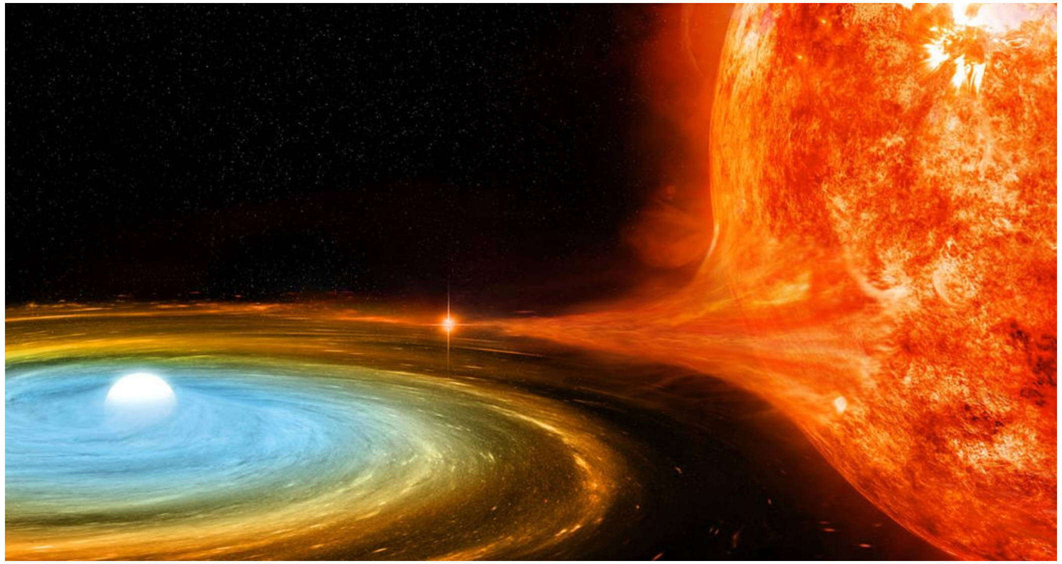



An “Intermediate” neutron capture process occurs whenever **protons** are mixed in regions with typical He-burning temperatures (**T ~ 200-300 MK**).
Hydrogen burns **on-fly** producing $^{13}$N and/or $^{13}$C.
The typical timescale is of the order of **hours**.

# Stellar sites of the i-process



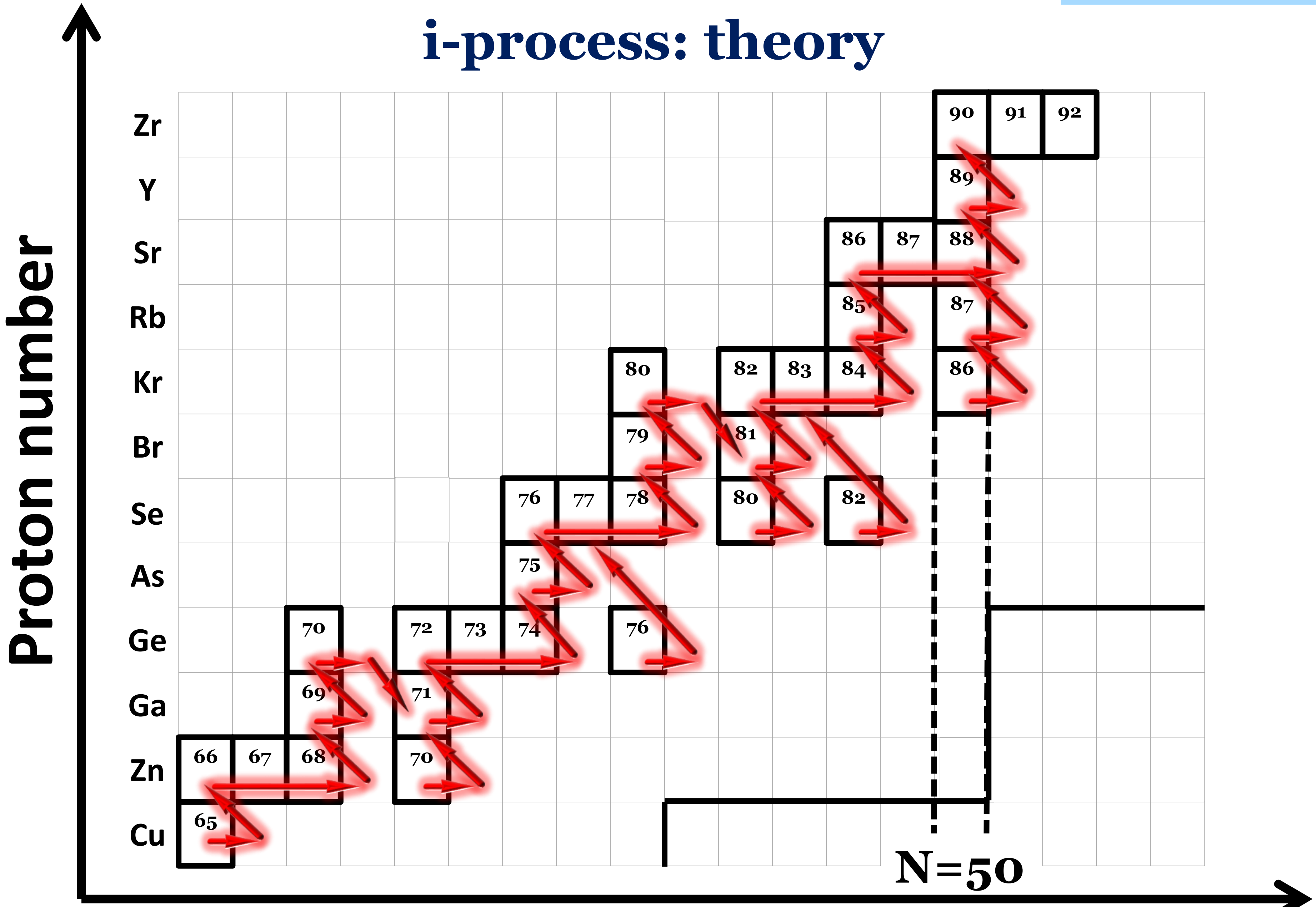

**AGB stars @low Z**



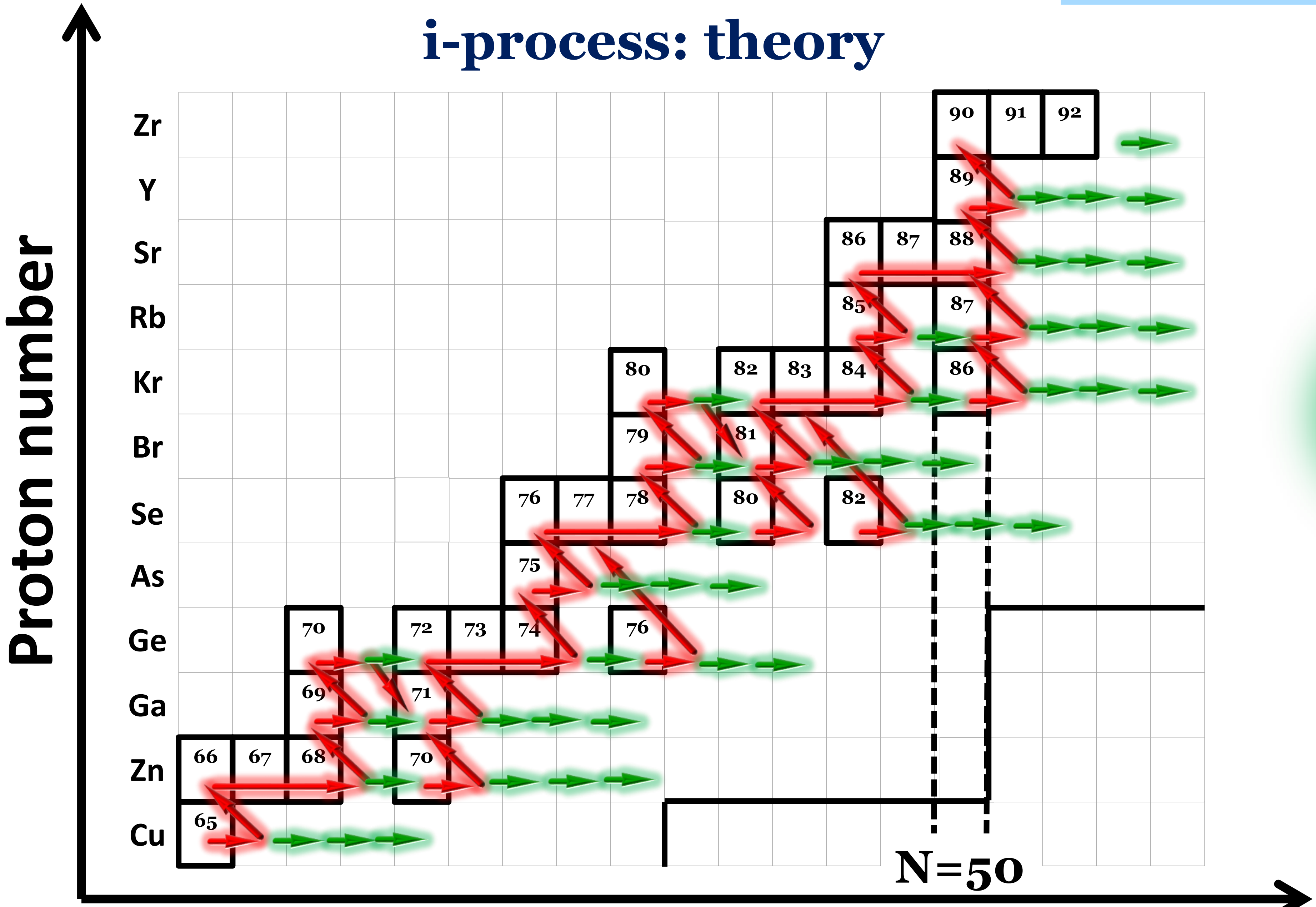
**Rapidly Accreting White Dwarfs (RAWD)**

An "Intermediate" neutron capture process occurs whenever **protons** are mixed in regions with typical He-burning temperatures (**T ~ 200-300 MK**).
Hydrogen burns **on-fly** producing $^{13}N$ and/or $^{13}C$.
The typical timescale is of the order of **hours**.

# i-process: theory



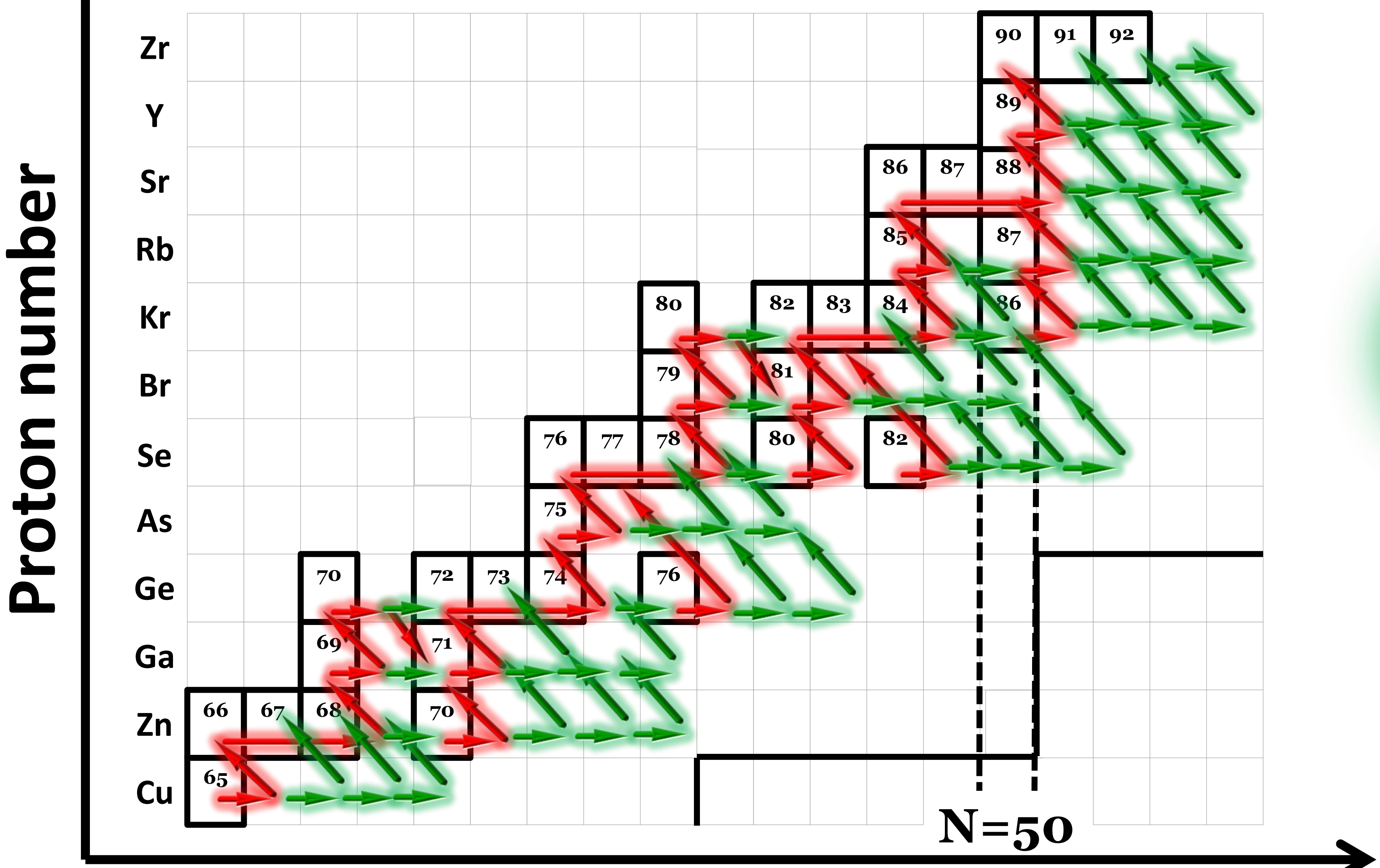
# i-process: theory




i process

$N_n \sim 10^{14-17}$ n/cm$^3$

# i-process: theory




i process

$N_n \sim 10^{14-17}$ n/cm$^3$

# i-process: experiments


## Neutron captures on unstable isotopes

**Surrogate method**: indirect method for determining cross section of Compound-Nucleus reactions difficult to measure directly.

**Dozens** of candidate isotopes, with particular focus on those with closed-shell configurations (e.g. $^{89}$Kr & $^{135}$I).

# i-process: experiments

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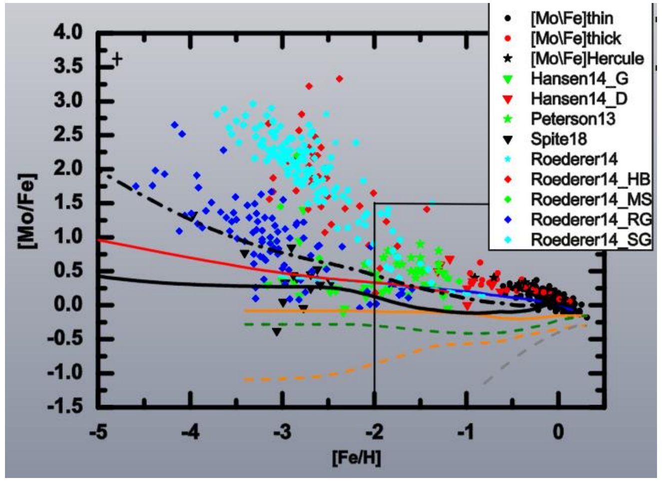
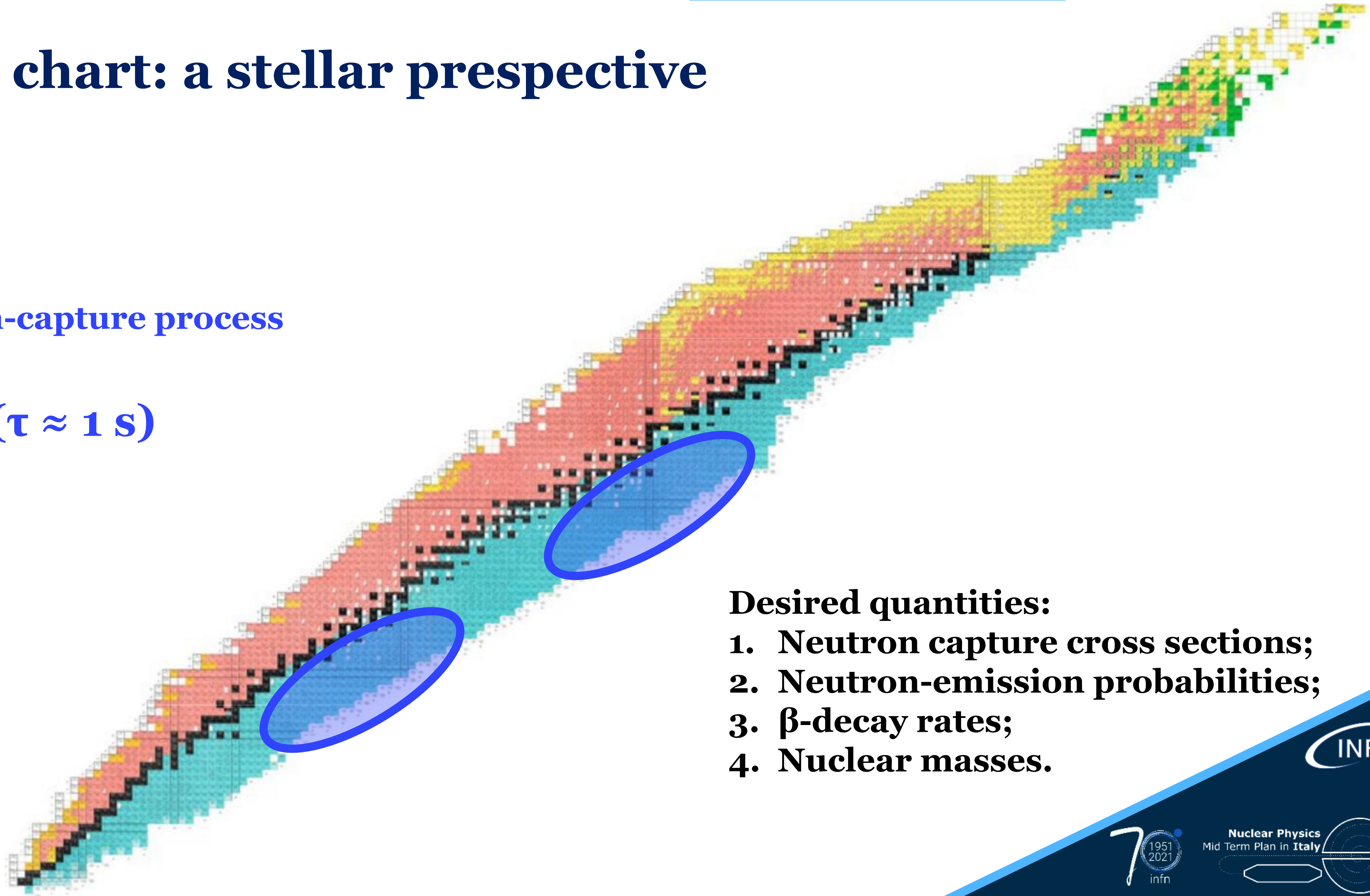
**Dozens** of candidate isotopes, with particular focus on those with closed-shell configurations (e.g. $^{89}$**Kr** & $^{135}$**I**).




Comparison of observations with Galactic evolution models shows that canonical stellar sources of **Mo**, such as the s-process in massive stars and AGB stars or the r-process, **do not produce a sufficient amount of this element**: may the **i-process** help??

# The Nuclide chart: a stellar prespective



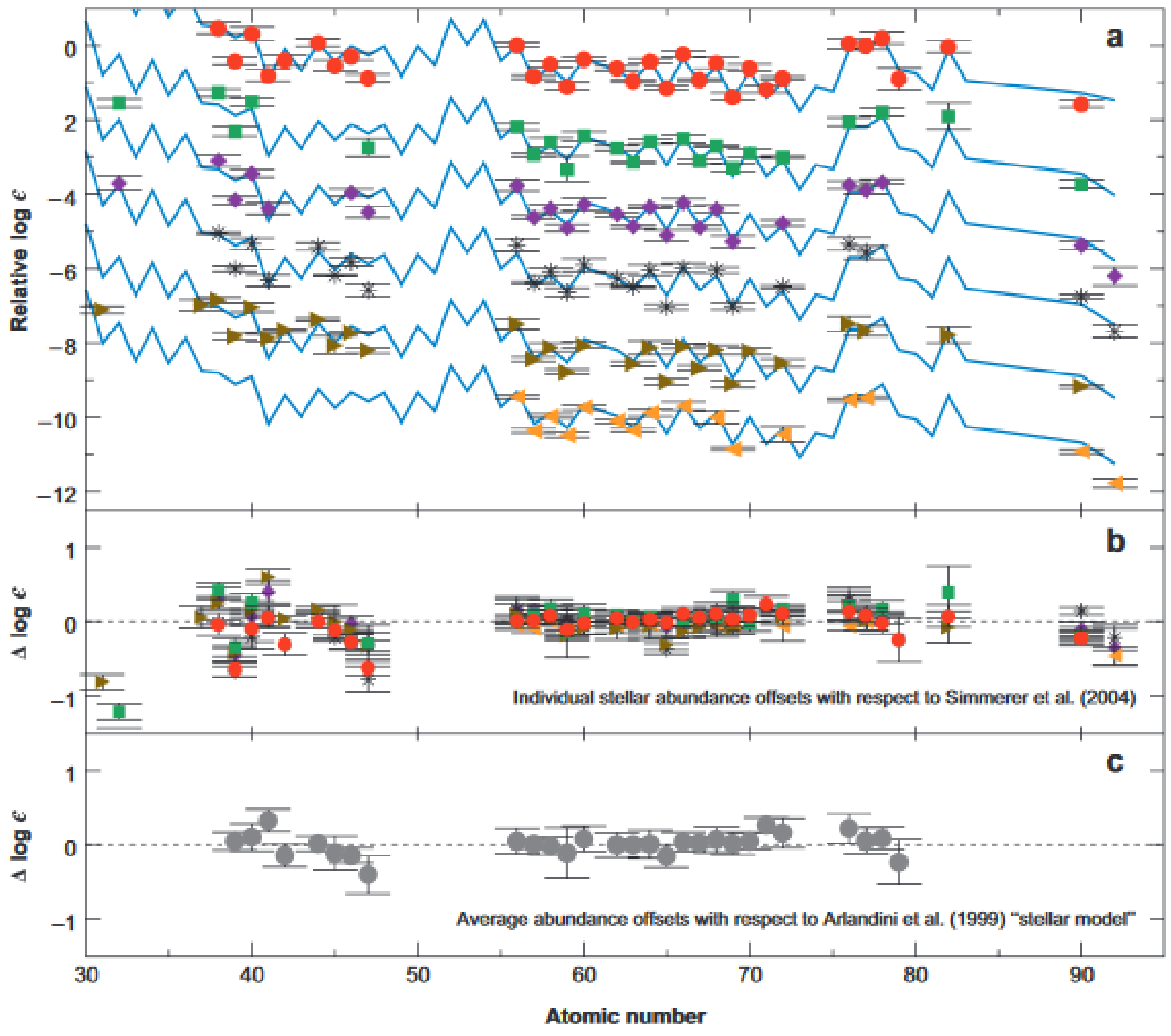
RAPID n-capture process

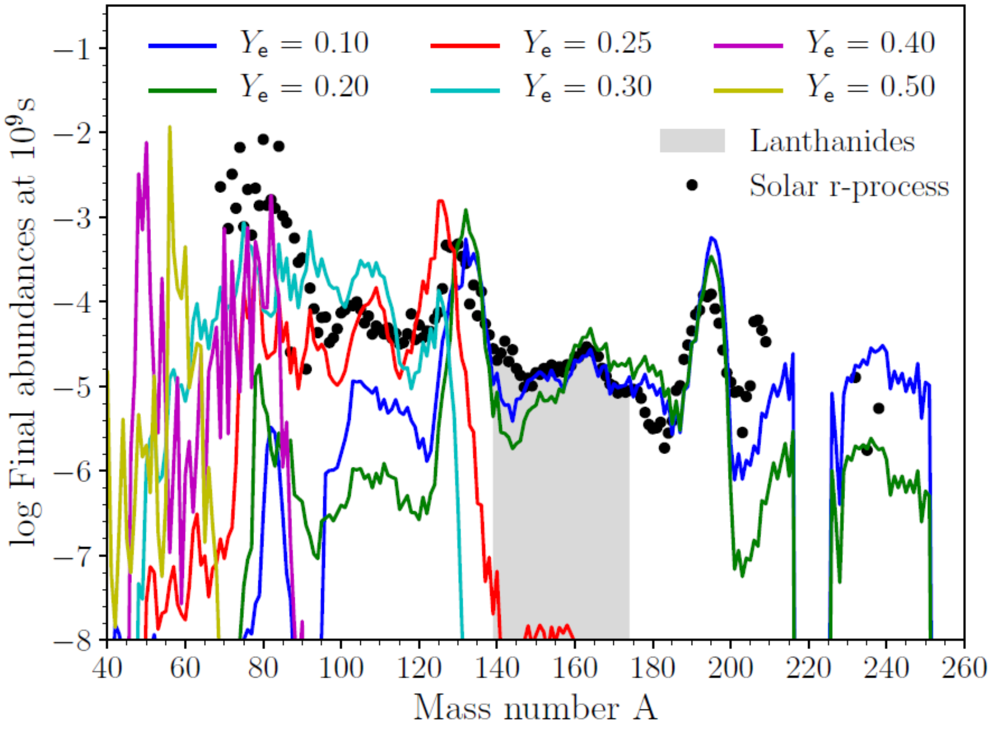
(τ ≈ 1 s)

**Desired quantities:**

1. **Neutron capture cross sections;**
2. **Neutron-emission probabilities;**
3. **β-decay rates;**
4. **Nuclear masses.**

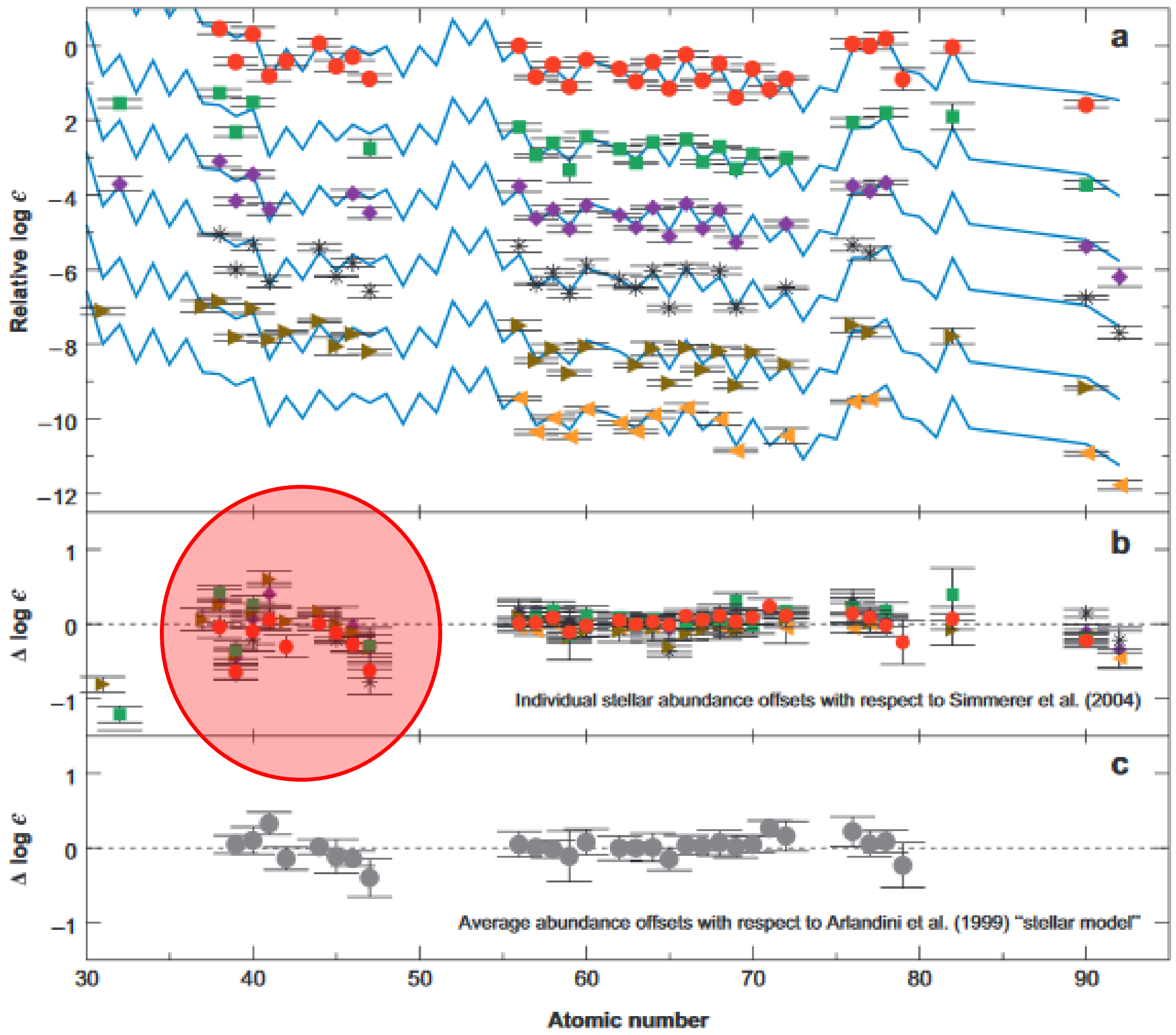
# The Ubiquity of the (main) r-process

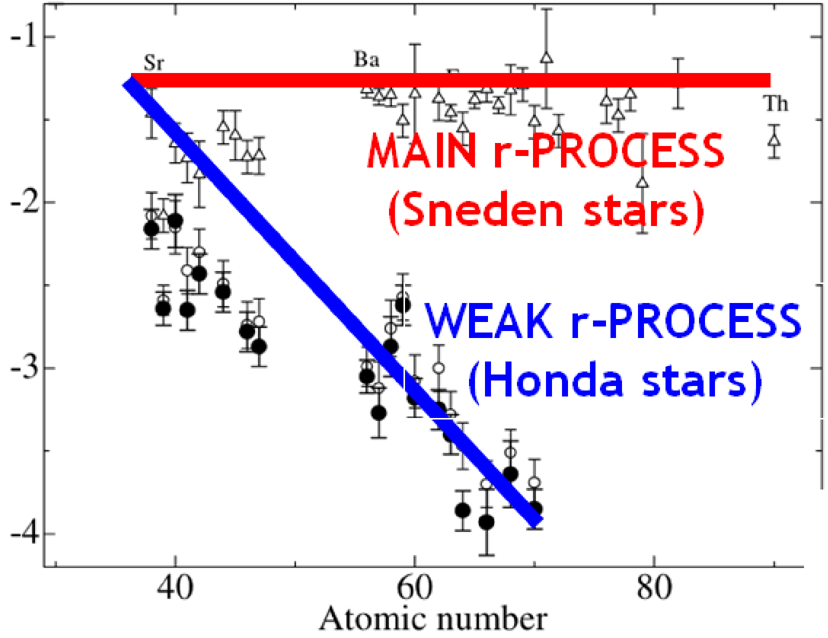


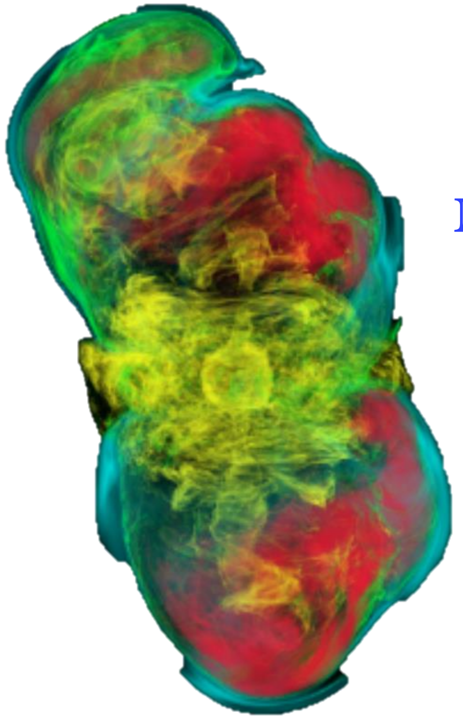

The distribution of the heaviest elements point to a **unique** (and very robust) nucleosynthesis site.
This is quite easy to be understood in term of the environmental **neutronization**.
We refer to this component as **MAIN**.

# The non-Ubiquity of the (weak) r-process



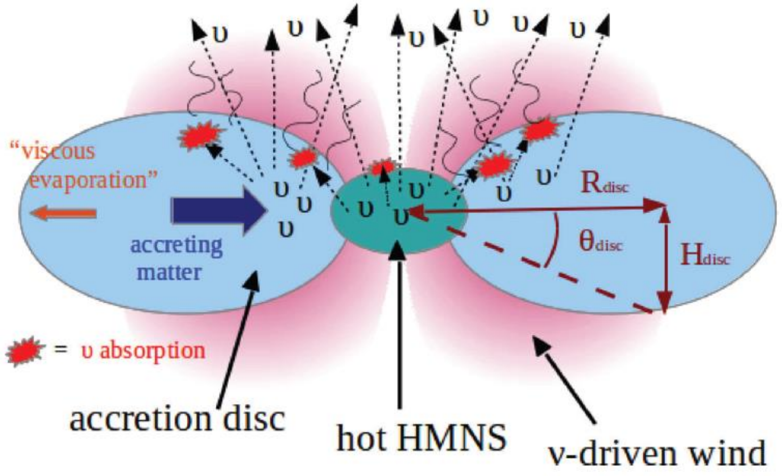

There are stars with a completely different heavy element distributions. This lead scientists to identify a **WEAK** component of the r-process.
The problem is that **both component can be matched within the same theoretical scenario**.

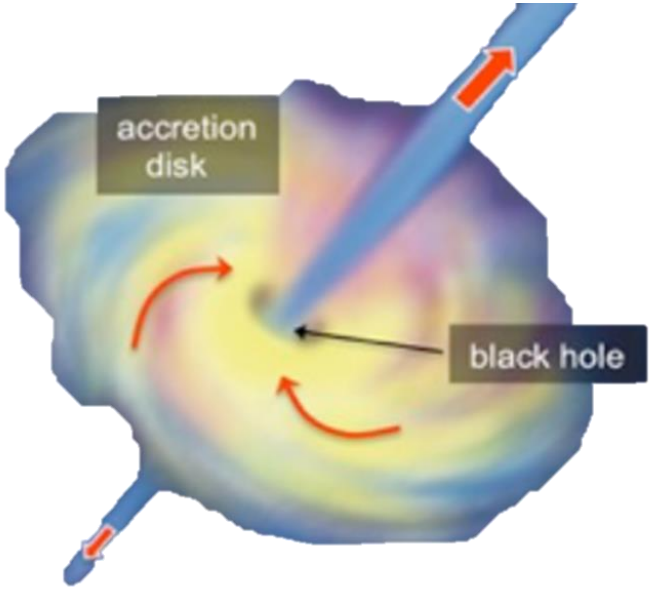


# Stellar site(s) of the r-process

**Magneto-Rotation-Driven Supernovae (MRD-SNe)**

**Neutron Star Mergers (NSMs)**



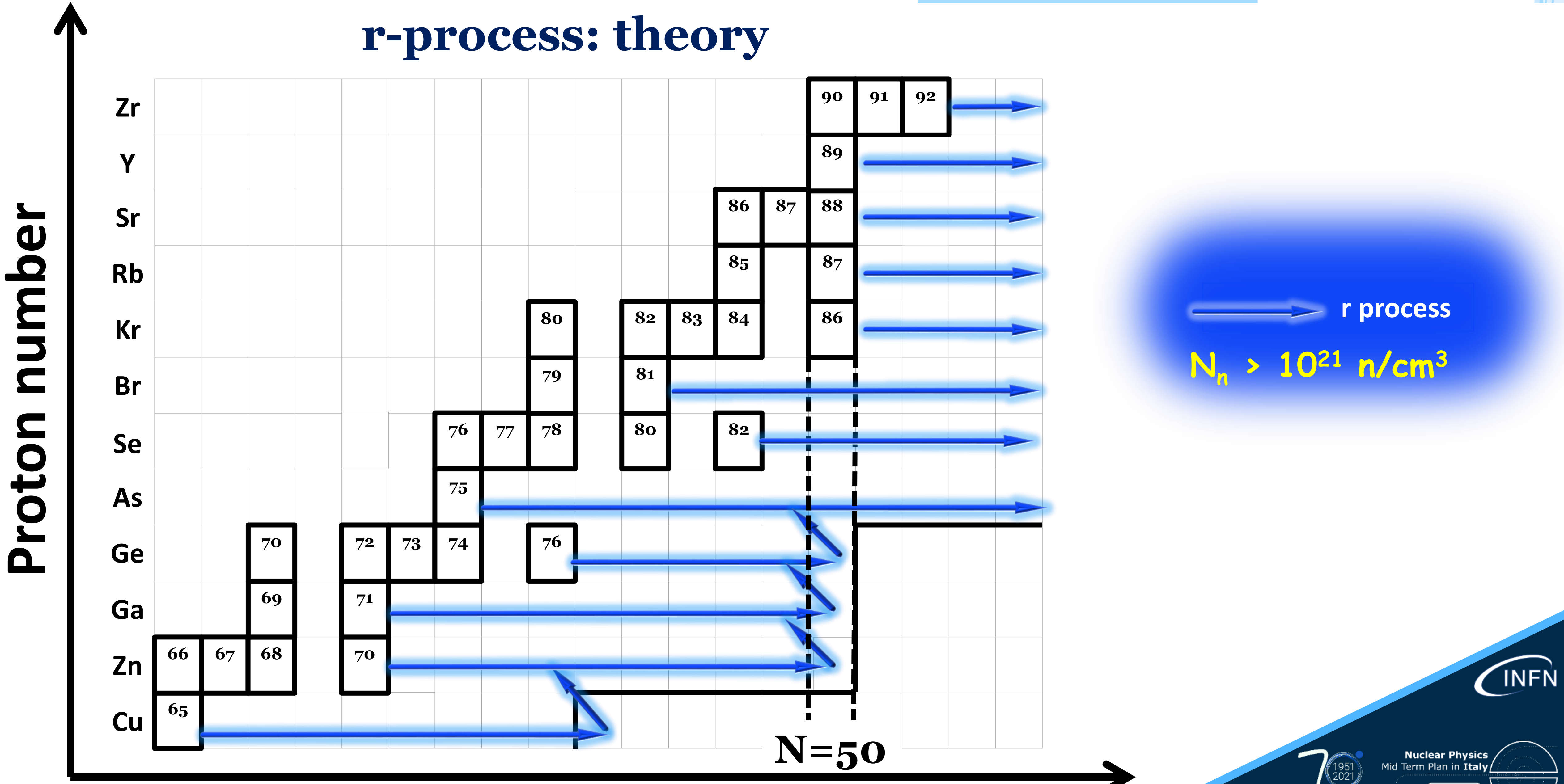




**Collapsars**

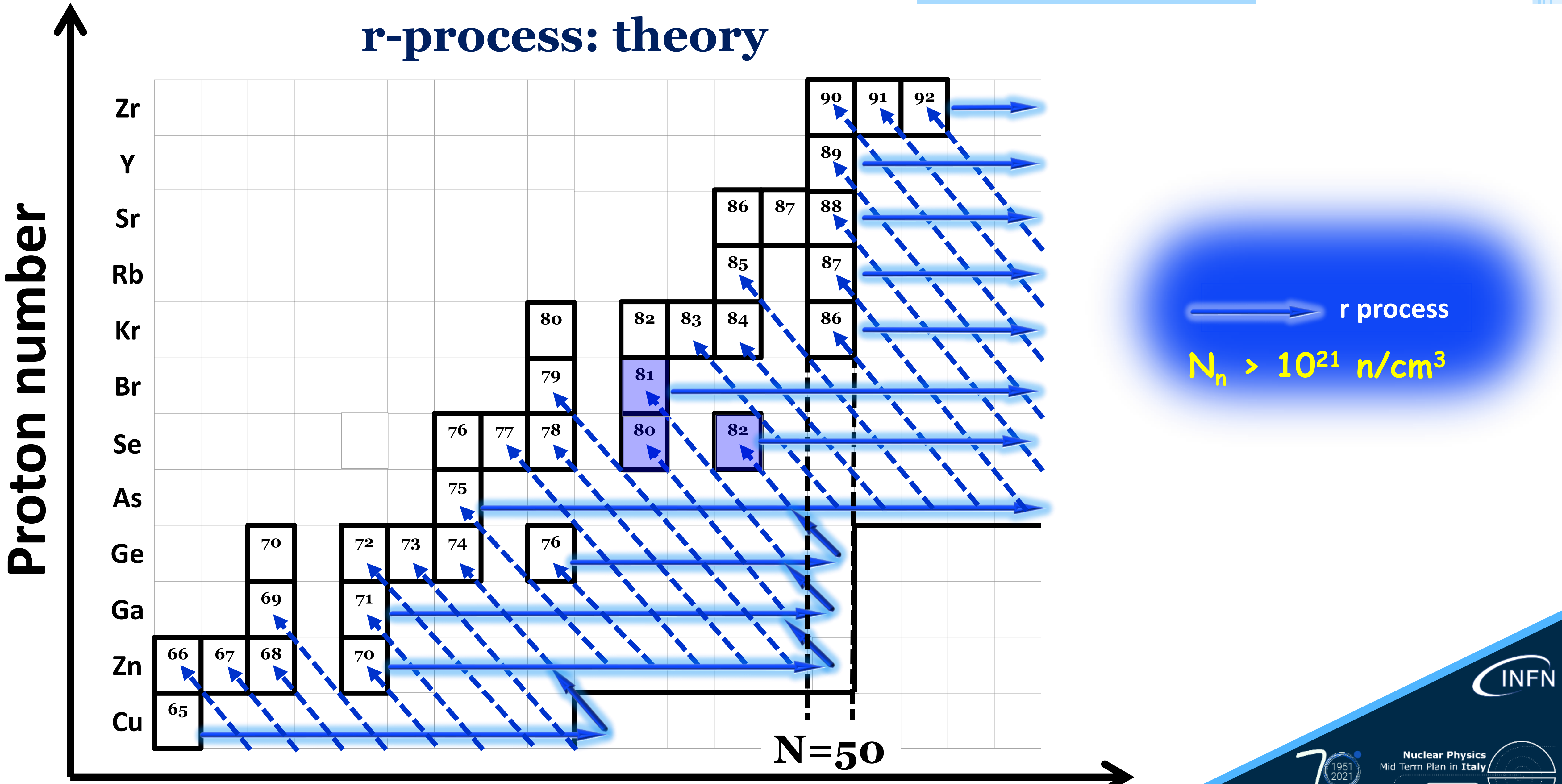
To date, the only astrophysical site in which the r-process has been demonstrated to occur is a **NSM**. In particular, the electromagnetic counterpart (**AT2017gfo**) of the gravitational wave detection **GW170817** is in agreement with the heating rate and opacity expected from **a distribution of freshly synthesized r-process elements.**

**Isotopic yields** and **opacities** shape the corresponding **Kilonova lightcurve**.

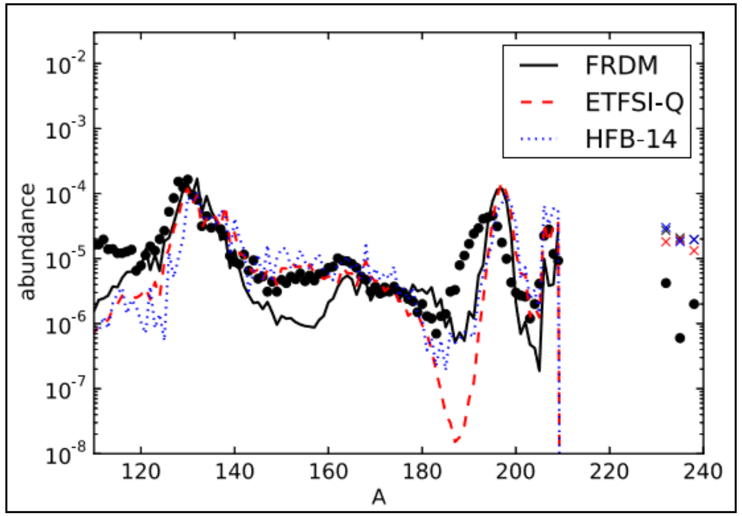
# r-process: theory



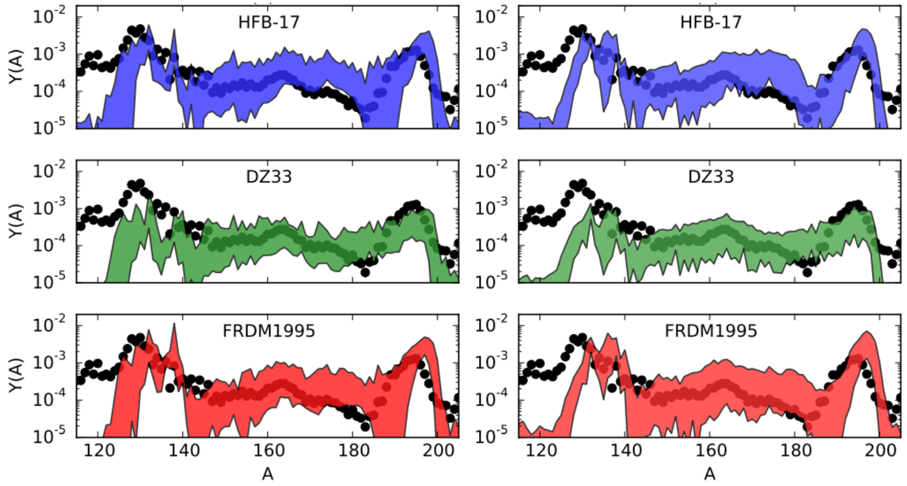
# r-process: theory



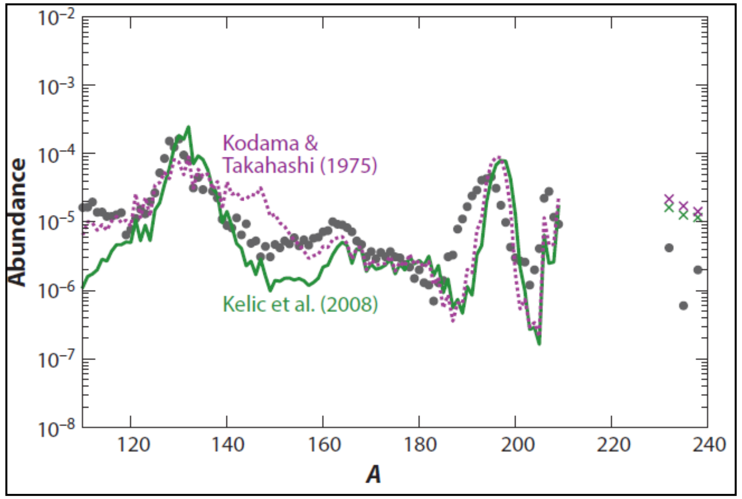
# The (many) nuclear inputs of the r-process



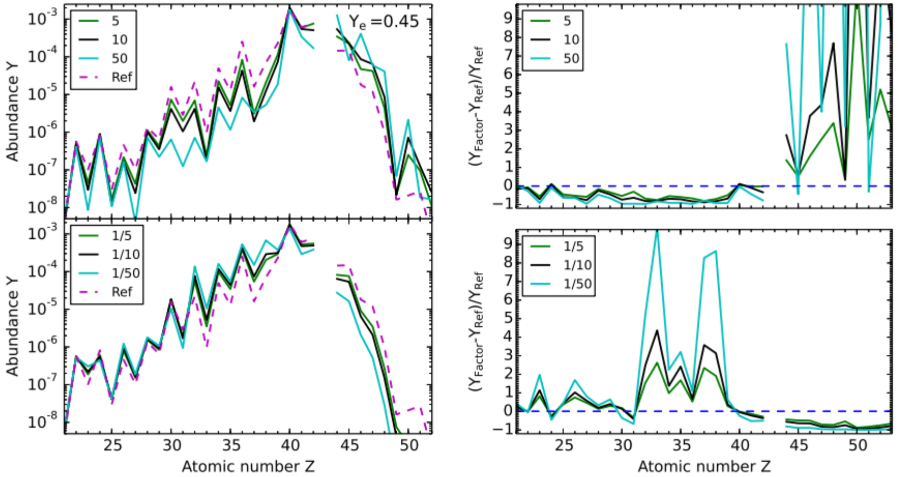

**Nuclear masses**




**β-decay rates** **n-captures**




**Fission fragment distibutions**

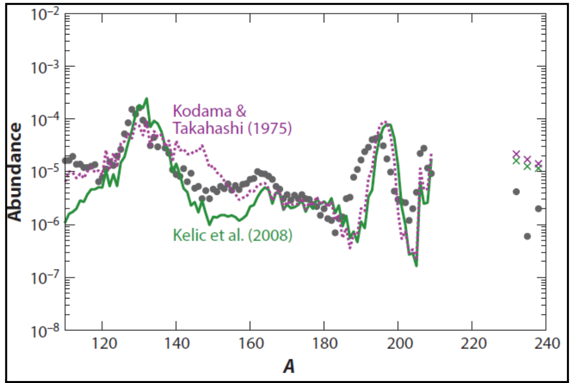



**(α,n) reactions**

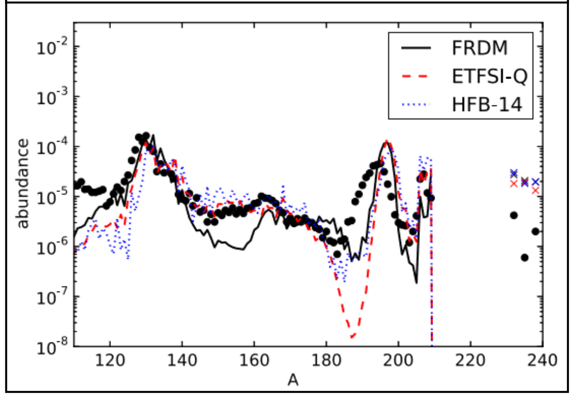
# The (many) nuclear inputs of the r-process

This (apparent) insensitivity of the strong r-process abundance pattern to the parameters of the merging system is explained by the extremely **large neutronization** of the environment, which guarantees the occurrence of several fission cycles before the r-process freezes out.
However, the devil is into details…

## Nuclear masses




The most basic nuclear property for any r-process calculation is the **mass of the nuclei involved**, because it determines the threshold energy for decays, neutron captures and photodissociations.




Moreover, during the final phase the **fission of the heaviest nuclei** produces large numbers of neutrons, producing a shift of the third peak.

## Fission fragment distibutions

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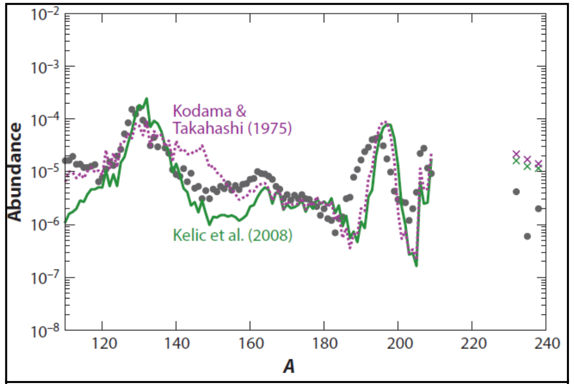
## Nuclear masses

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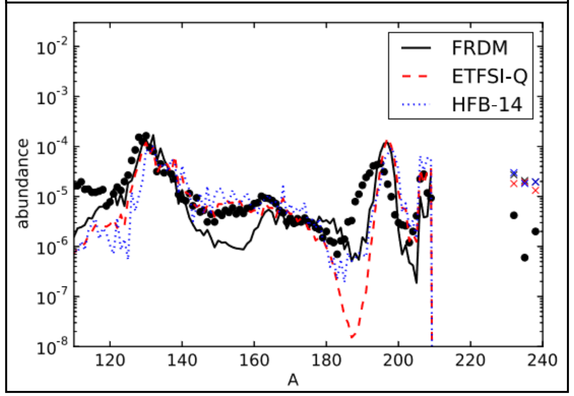


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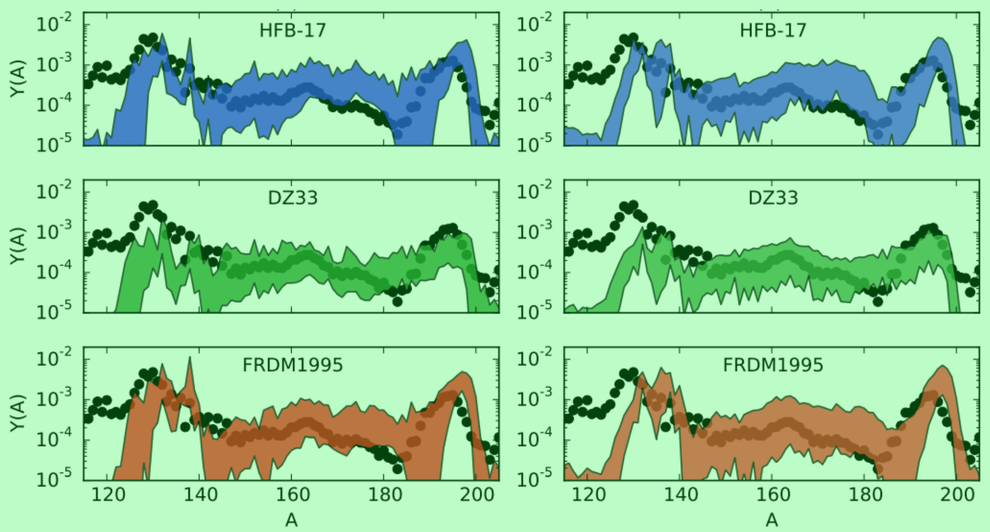



**β-decay rates** **n-capture σ**

At LNL the more approachable measurements are on **β-decays** and **n-captures**.

# Sensitivity studies for the r-process: strongness…

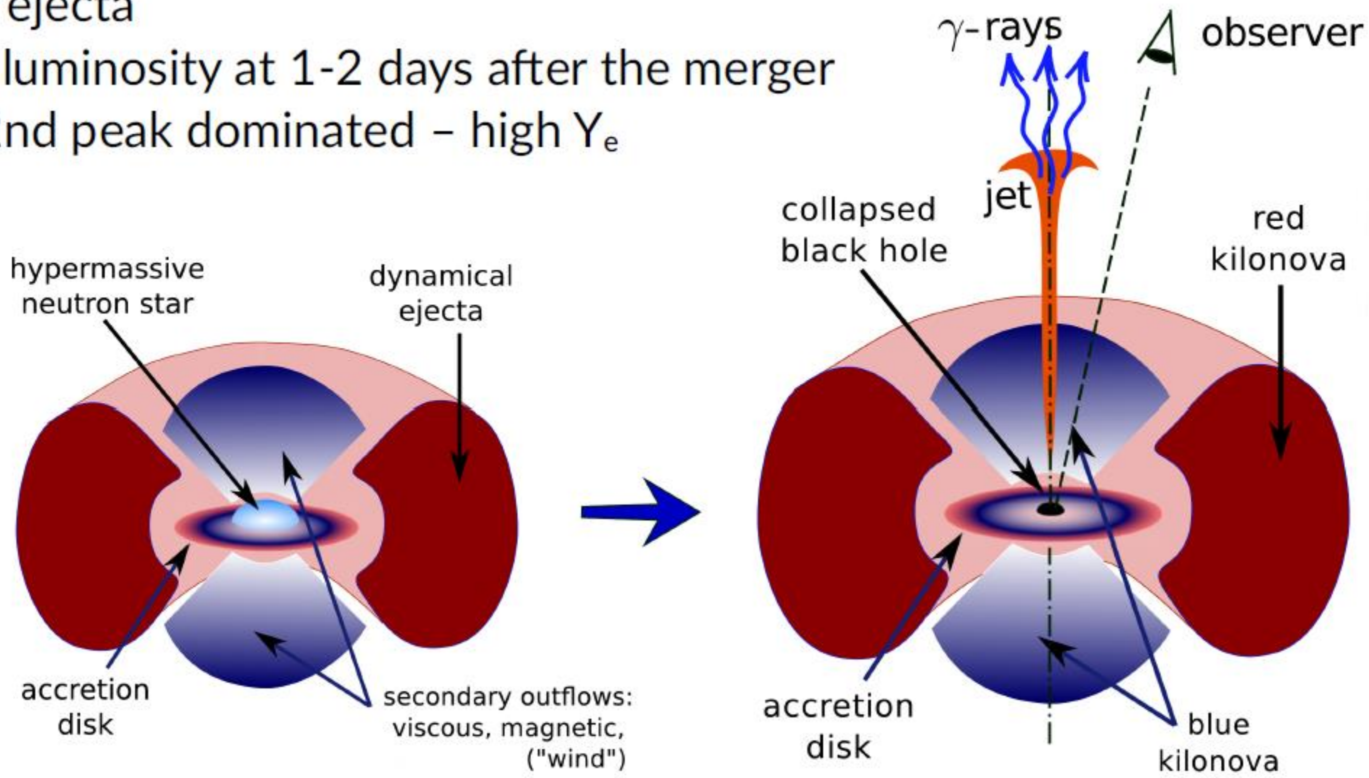
Improvements will require progress in modeling nuclei far from stability as well as new experiments that measure key quantities directly. **Sensitivity studies** are a powerful instrument to identify these key quantities.

In the past weeks we focused on the sensitivity of the properties of specific nuclei **to the largest magnitude changes** in the overall abundance pattern.

The power of these studies is to point out the nuclear properties which play the most important role in shaping the final abundances in an astrophysical event. Sensitivity studies thus play a key role in facilitating state-of-the-art measurements as they provide **crucial astrophysical motivation** to focus experimental campaigns on the most impactful nuclei.

# Sensitivity studies for the r-process: ...and weakness

- Red emission:
  - Tidal ejecta
  - Peak luminosity at days - 1 week after the merger
  - Lanthanide dominated – low $Y_e$
- Blue emission:
  - Polar ejecta
  - Peak luminosity at 1-2 days after the merger
  - 1st/2nd peak dominated – high $Y_e$



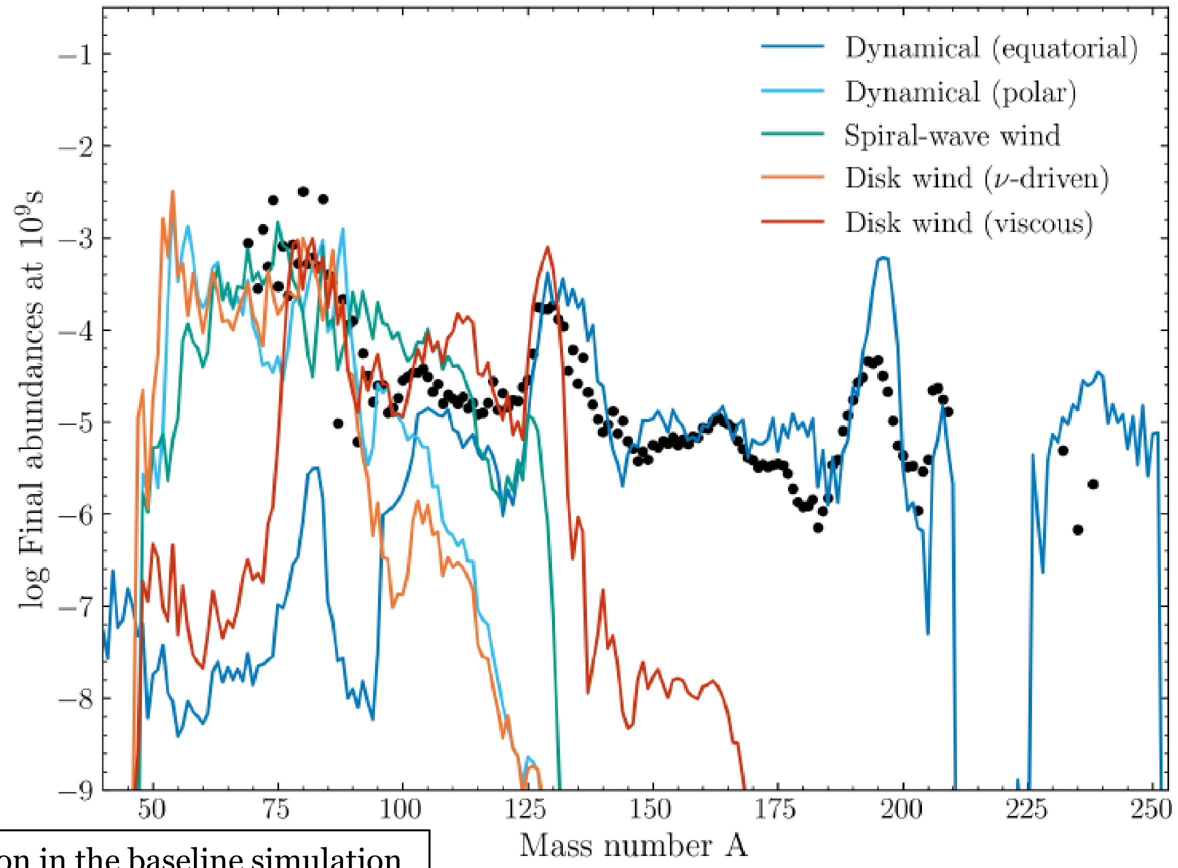

Courtesy of O. Korobkin

**WARNING!!**

The results of any sensitivity study have to be **taken lenghtly**, because even considering just one stellar site (as NMSs), the physical charachteristics of various tracers at different angles can lead to completely different chemical patterns.
The latter are mainly regulated by the neutronization level **(Ye, or electron fraction)**.
Moreover, details about interactions with **neutrinos** are fundamental.

# Sensitivity studies for the r-process: n-capture rates

- Neutron-capture rates (n, γ)
- Uncertainty of a **factor 100**
- Isotopes with **half-life > 1s**
- 5 trajectories corresponding to different ejecta from a NSM
- Each time a rate is changed, a corresponding final abundance pattern is produced
- Comparison between the simulation with varied *n*-capture rate and the baseline simulation




Final isobaric number fraction in the baseline simulation

Final isobaric number fraction in the simulation with varie nuclear input

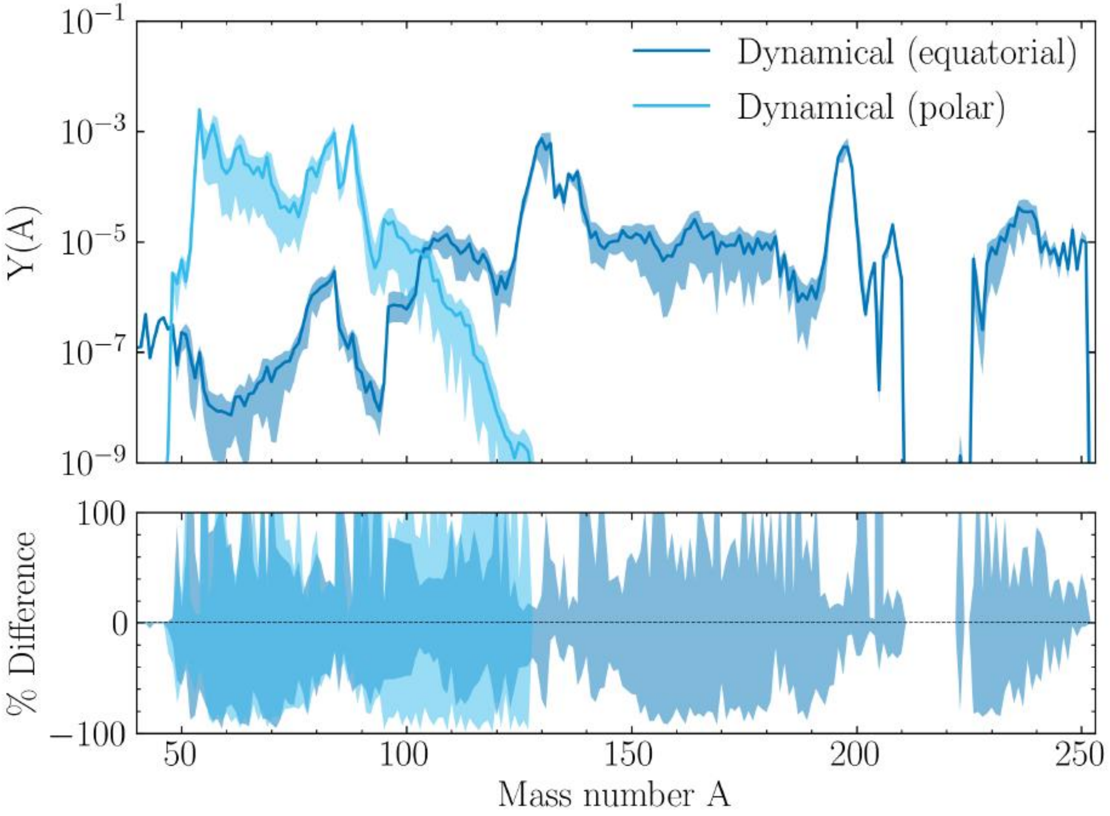
Summation over the entire baseline pattern

Impact parameter *F* →

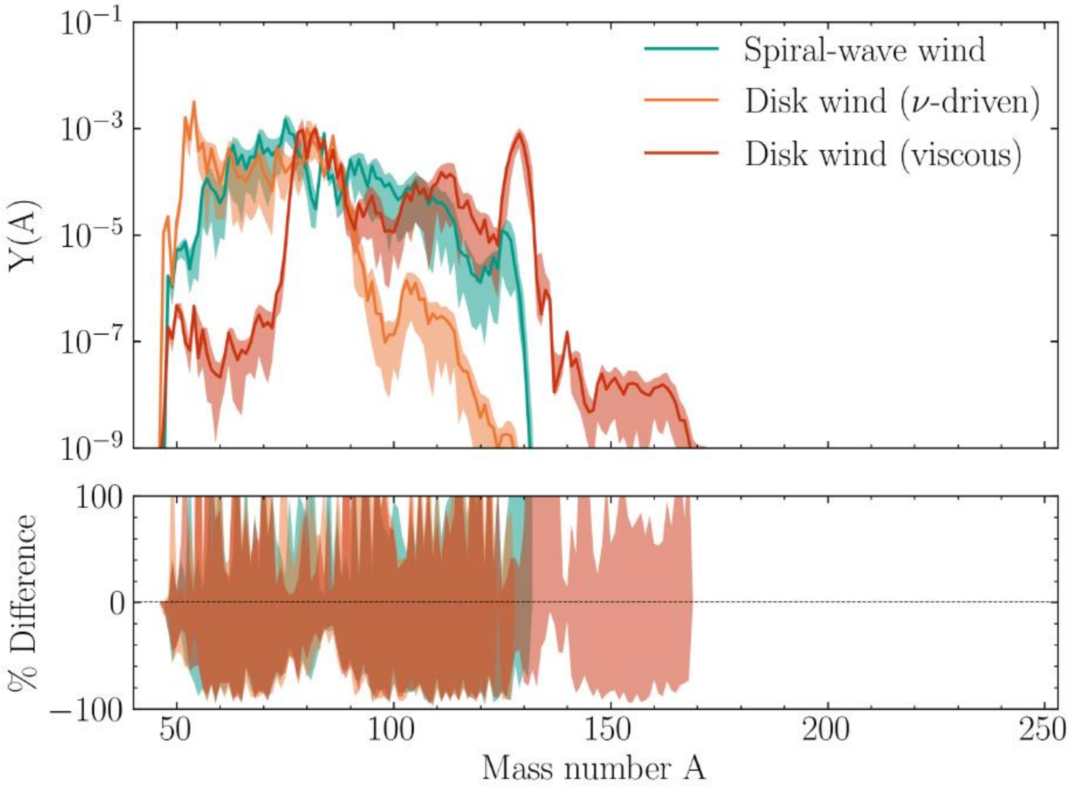
$$F = \frac{\sum_{A} \left| Y(A) - Y_b(A) \right|}{Y_b(A)}$$

# Sensitivity studies for the r-process: n-capture rates

## Dynamical Ejecta



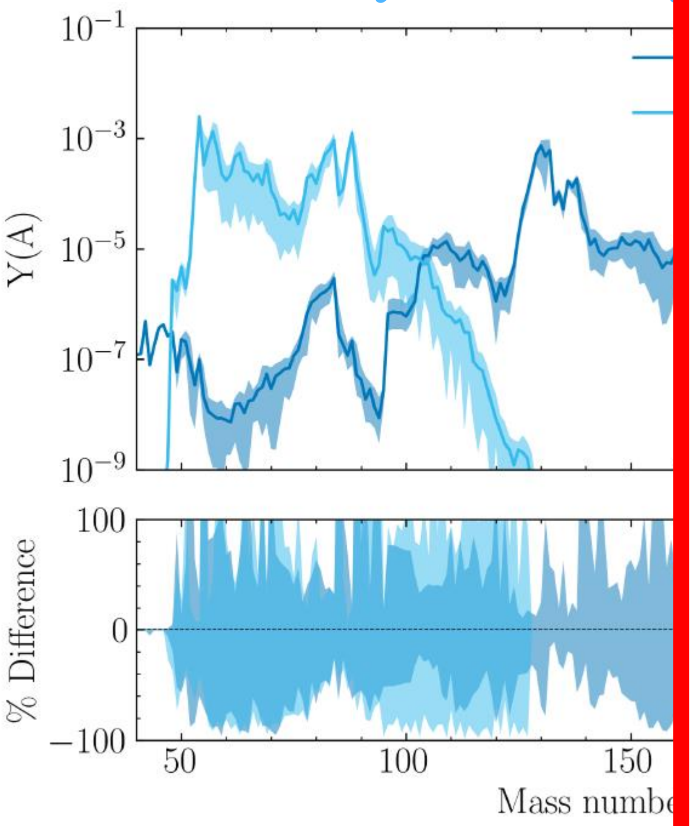

## Wind Ejecta




Depending on the studied component, **different isotopes** cause the largest variations.

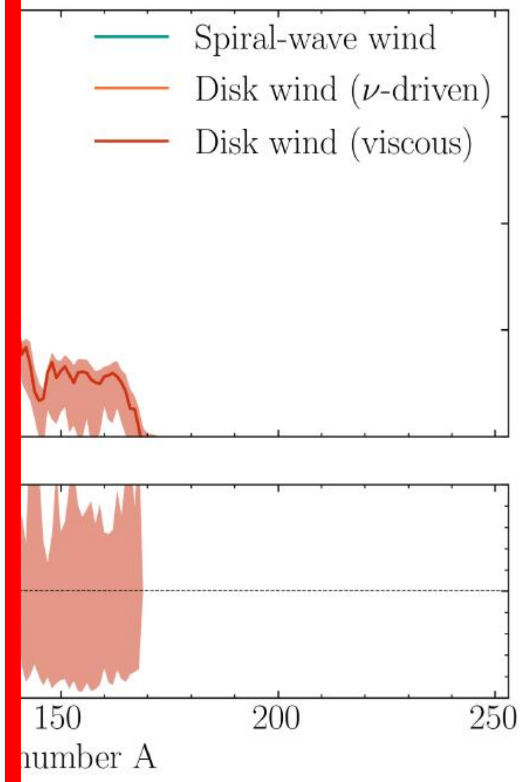
# Sensitivity studies for the r-process: n-capture rates

Dynamical E




| #Isotope | F_max | Ejecta |
|---|---|---|
| 204au | 22.890 | dyn_eq |
| 205ir | 17.838 | dyn_eq |
| 197w | 16.202 | dyn_eq |
| 57cr | 15.841 | dyn_po |
| 133sn | 15.645 | disk_wi_vis |
| 130sn | 15.177 | spiral_wa_wi |
| 54ti | 14.205 | dyn_po |
| 54v | 13.314 | disk_wi_nu |
| 80ga | 13.096 | disk_wi_nu |
| 54ti | 12.626 | disk_wi_nu |
| 54v | 12.608 | dyn_po |
| 130sn | 12.202 | dyn_eq |
| 88br | 10.889 | dyn_po |
| 88se | 10.409 | dyn_po |
| 129sn | 10.041 | spiral_wa_wi |
| 138te | 9.811 | dyn_eq |
| 56cr | 9.798 | disk_wi_nu |
| 56cr | 9.650 | dyn_po |
| 129in | 9.321 | spiral_wa_wi |
| 52ca | 9.194 | dyn_eq |

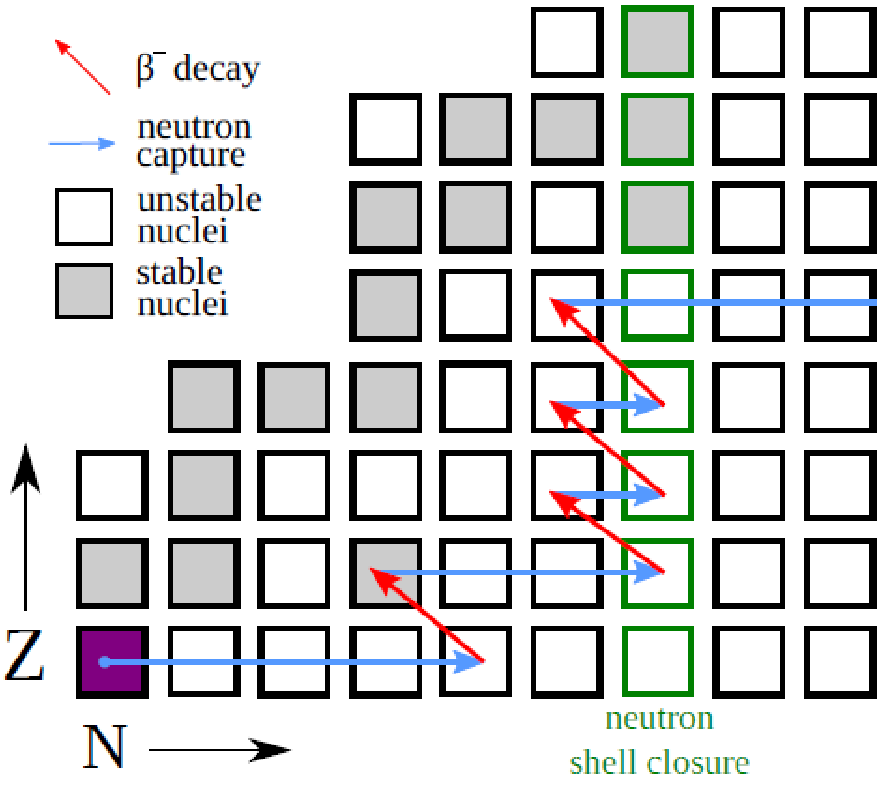
jecta



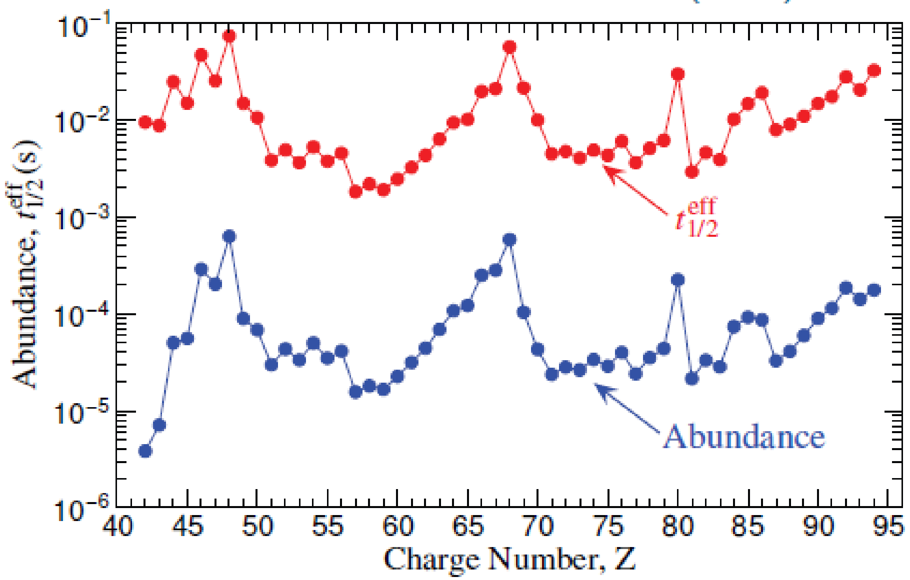

Depending on the studied com… ons.

# Sensitivity studies for the r-process: β-decay rates and $P_n$ emissions

$r$(apid neutron capture) process: $\tau_{(n,\gamma)} \ll \tau_{\beta^-}$




J. J. Cowan et al., RMP 93 (2021)

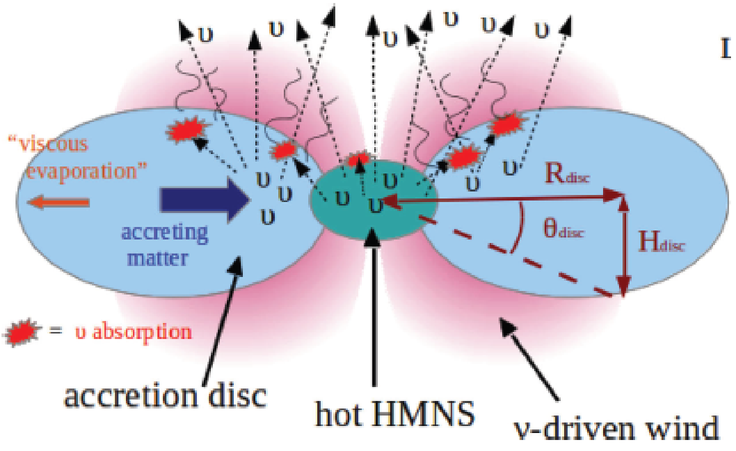


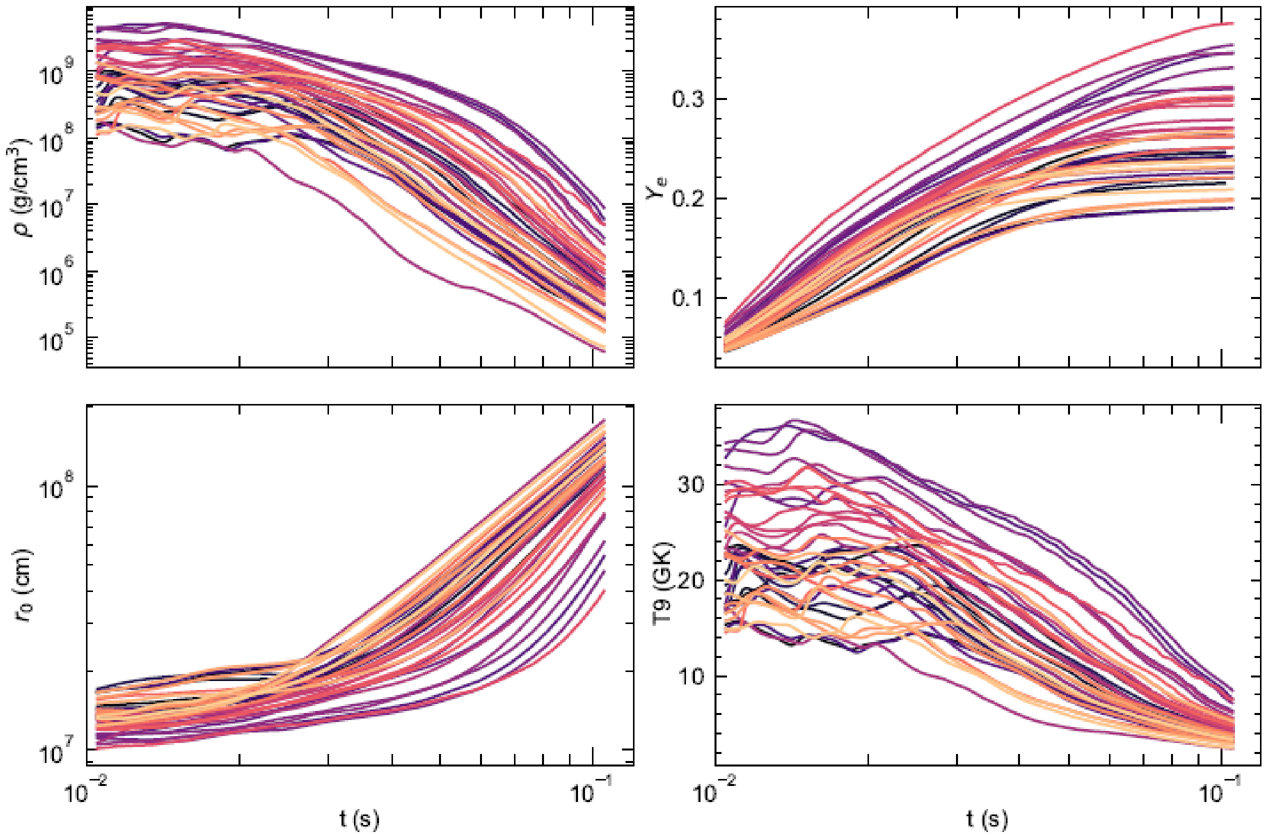

*β* decays regulate the **speed** at which the *r* process proceeds, shaping abundances and **kilonova** light curves.

# Sensitivity studies for the r-process: β-decay rates and $P_n$ emissions

A. Perego *et al.*,

Mon. Not. R. Astron. Soc. 443, 3134 (2014).



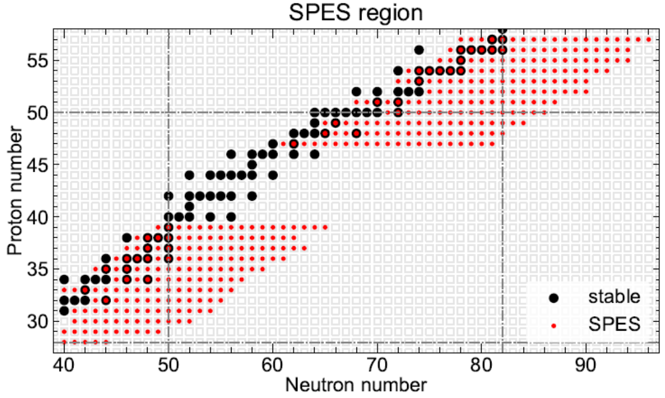




- **Baryonic wind produced by ν absorption** in accretion disc and central hypermassive neutron star
- $Ye \approx 0.2 - 0.4 \longrightarrow A \approx 80 - 195$ (but mostly $A \lesssim 130$).
- 40 trajectories spanning a wide range of $\rho$, $Y_e$ and temperature.

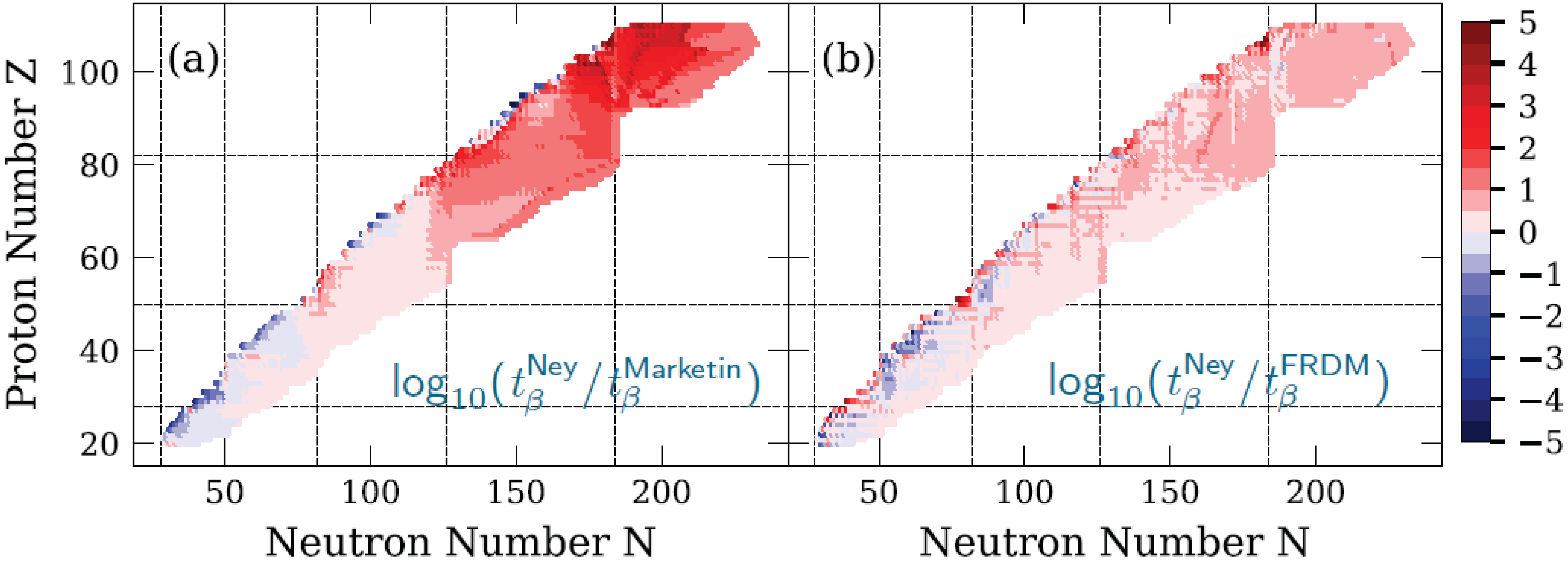
# Sensitivity studies for the r-process: β-decay rates and $P_n$ emissions

– 3 global calculations of beta-decay rates:

- **FRDM**: P. Möller *et al.*, Phys. Rev. C**67**, 055802 (2003).
- **Marketin16**: T. Marketin, *et al.*, Phys. Rev. C**93**, 025805 (2016).
- **Ney20**: E. M. Ney, *et al.*, Phys. Rev. C**102**, 034326 (2020).




E. M. Ney, *et al.*, Physical Review C102, 034326 (2020).




Impact on *r*-process when $t^{\beta}_{1/2}$ in the SPES region are varied according to global models.

# Sensitivity studies for the r-process: β-decay rates and $P_n$ emissions

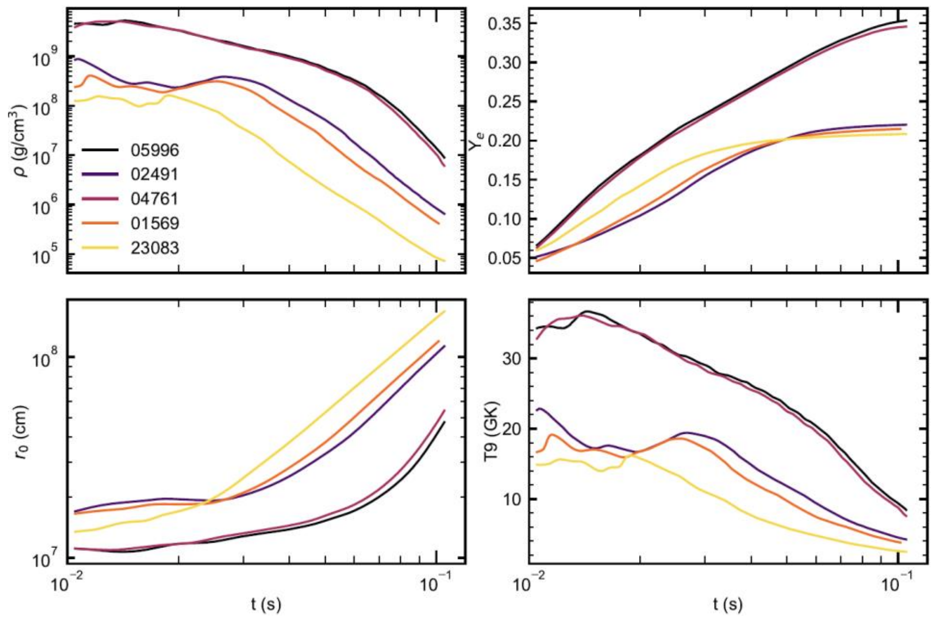
On average, we found **minor variations**.

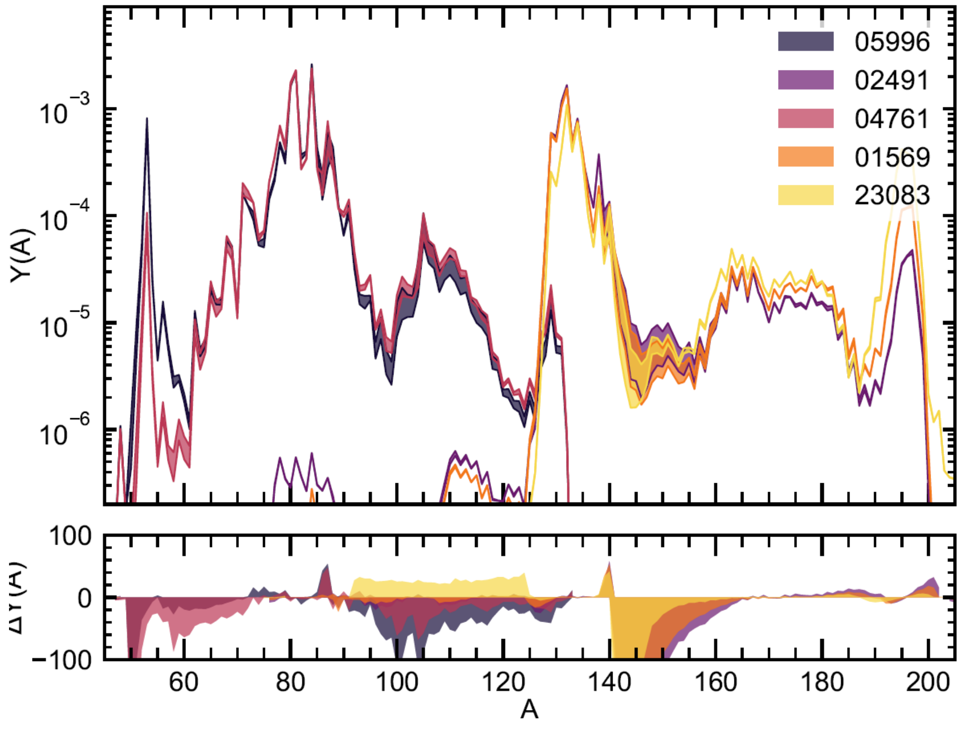
Thus, we isolated the 5 trajectories with the largest final variations in isotopic distributions.

≈45° wind

We isolated two «macro-groups»:
- one more cold & n-rich (T9~4GK, Ye~0.21, A_final = 120-200)
- one more hot & less n-rich (T9~8GK, Ye~0.35, Y-final = 50-130)

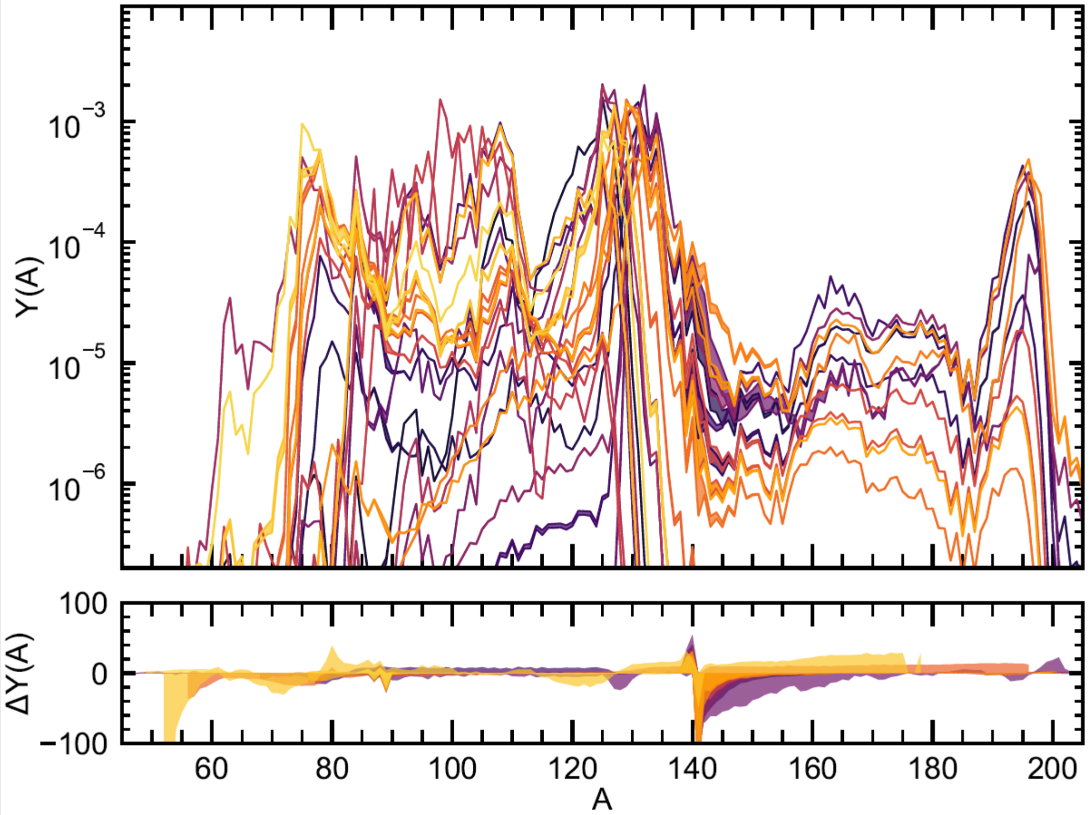
Polar wind

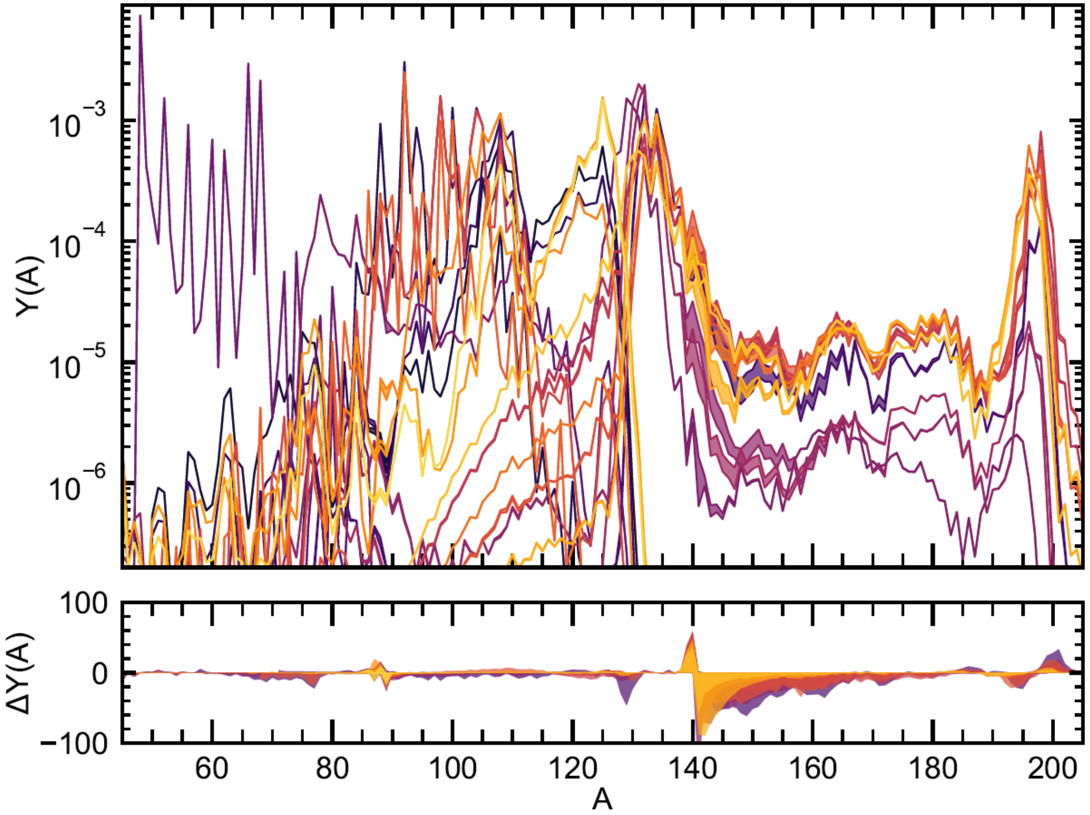


# Sensitivity studies for the r-process: β-decay rates and $P_n$ emissions

We also performed a sensitivity study on a different NSM component: the **dynamical ejecta**.
Thus, we isolated 20 trajectories for **two different simulations**.



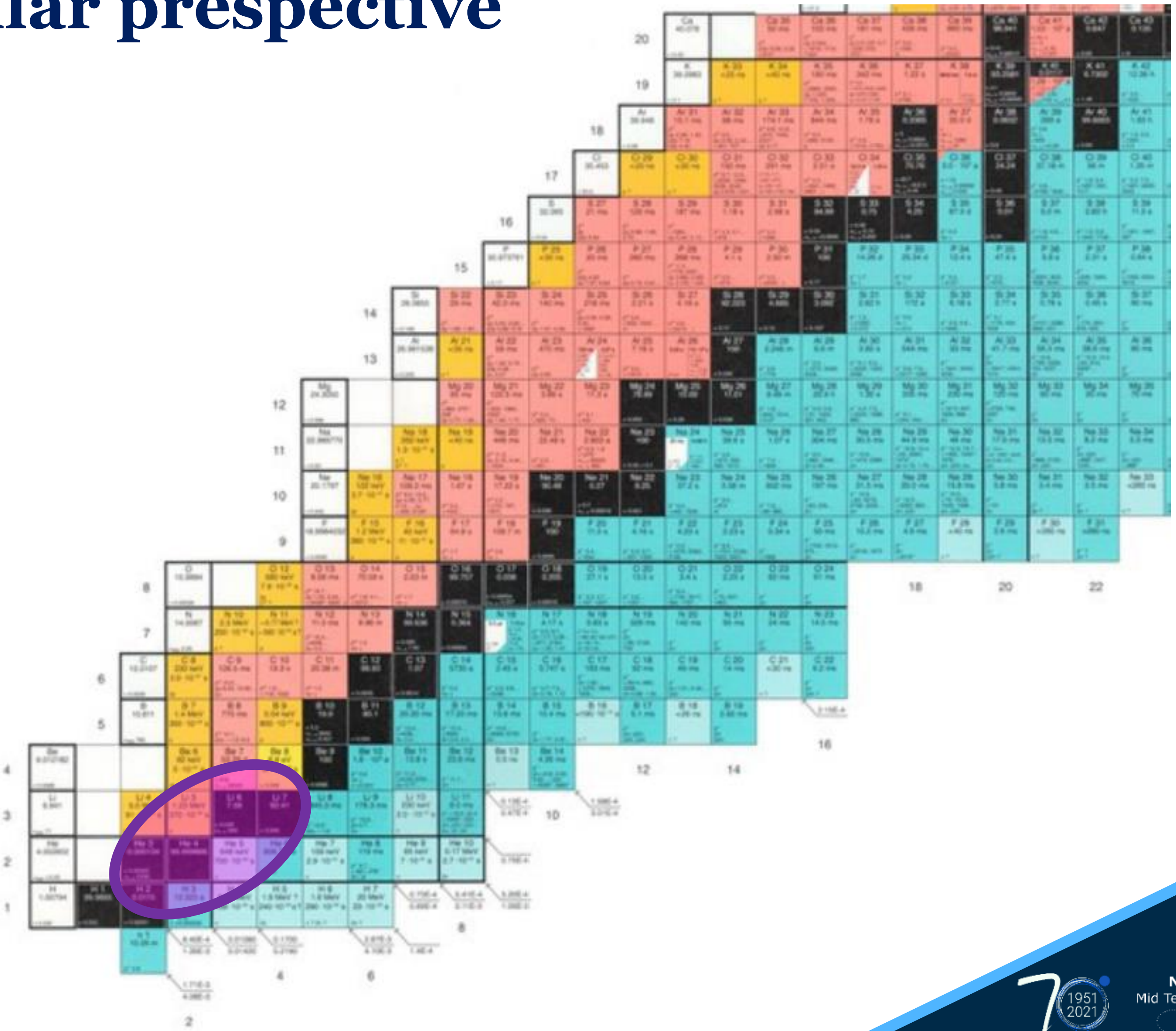

An overall sensitivity for nuclei with **A>140** is found, highlighting the presence of some **key isotopes with N=82 ($^{131}$In,$^{132}$Sn,$^{133}$Sb,$^{134}$Te,$^{135}$I)**.

# (PARTIAL) CONCLUSIONS

- Nucleosynthesis in (almost) all known stellar objects (plus BBN) can be studied at LNL;
- We highlighted many sinergies (active and potential) with other groups at different laboratories;
- An effort of the laboratory is required to support existing groups (able to guarantee a short- and mid-term scientific return) and to favor the growth of new ones on new topics not yet developed at LNL.

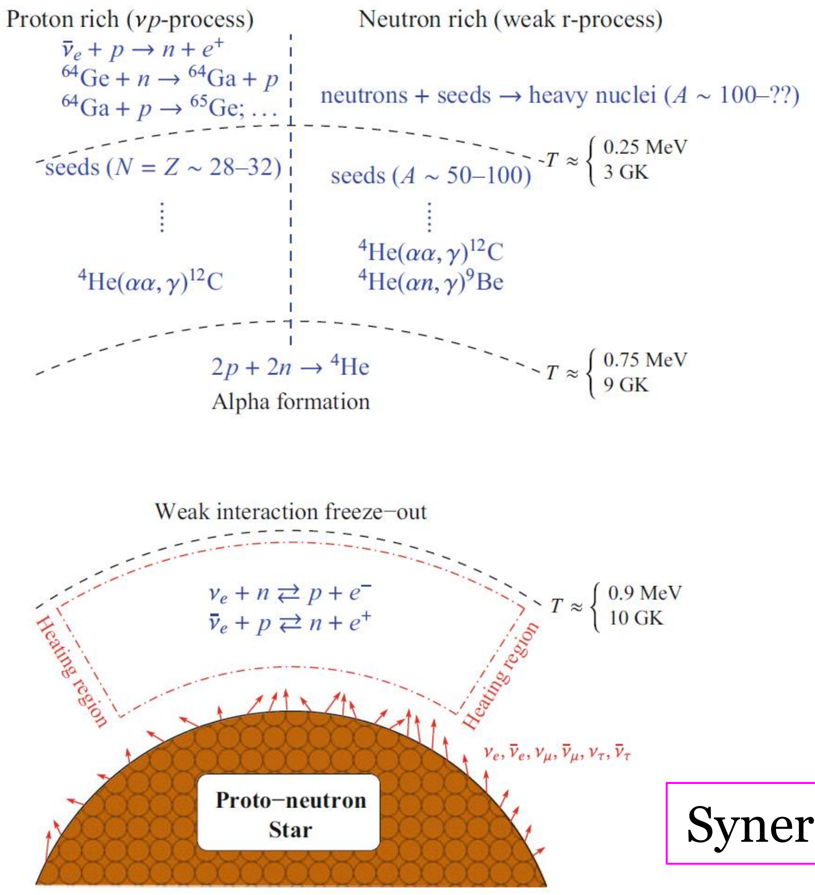
# EXTRA SLIDES

# The Nuclide chart: a stellar prespective



## EXPLOSIVE burnings

# Effects of light reactions on heavy element production




In neutron rich environments, the reaction **$^9Be(\alpha,n)^{12}C$** may dominate over the 3α reaction, depending on the astrophysical conditions.

The relevance of this process has been linked to the nucleosynthesis by rapid neutron capture (or r process) in type II supernovae.

$^4He(\alpha n,\gamma)^9Be$

$^4He(nn,\gamma)^6He(\alpha,n)^9Be$

→ $^9Be(\alpha,n)^{12}C$

Synergic effort with **Notre Dame University** experiment at **Trisol** facility.

R.o.I.: **$^4He(nn,\gamma)^6He$ & $^9Be(\alpha,n)^{12}C$**