Nucleosynthesis Beyond the Iron Peak

S. Cristallo

INAF - Osservatorio Astronomico d'Abruzzo

GraWITA
Gravitational waves @ INAF

INFN
Istituto Nazionale di Fisica Nucleare

nTOF

OUTLINE

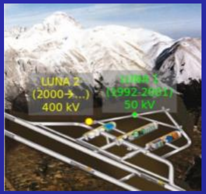
- **Brief introduction to neutron capture processes and their corresponding stellar sites**
- **Neutron «producers» (α,n reactions)**
- **Moderate neutron «consumers» (s-process)**
- **Compulsive neutron «consumers» (r-process)**
- **«Back-to-stability»: weak interactions (EC,β^-,β^+)**

ASFIN

SPES

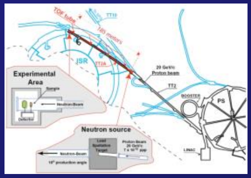
PANDORA

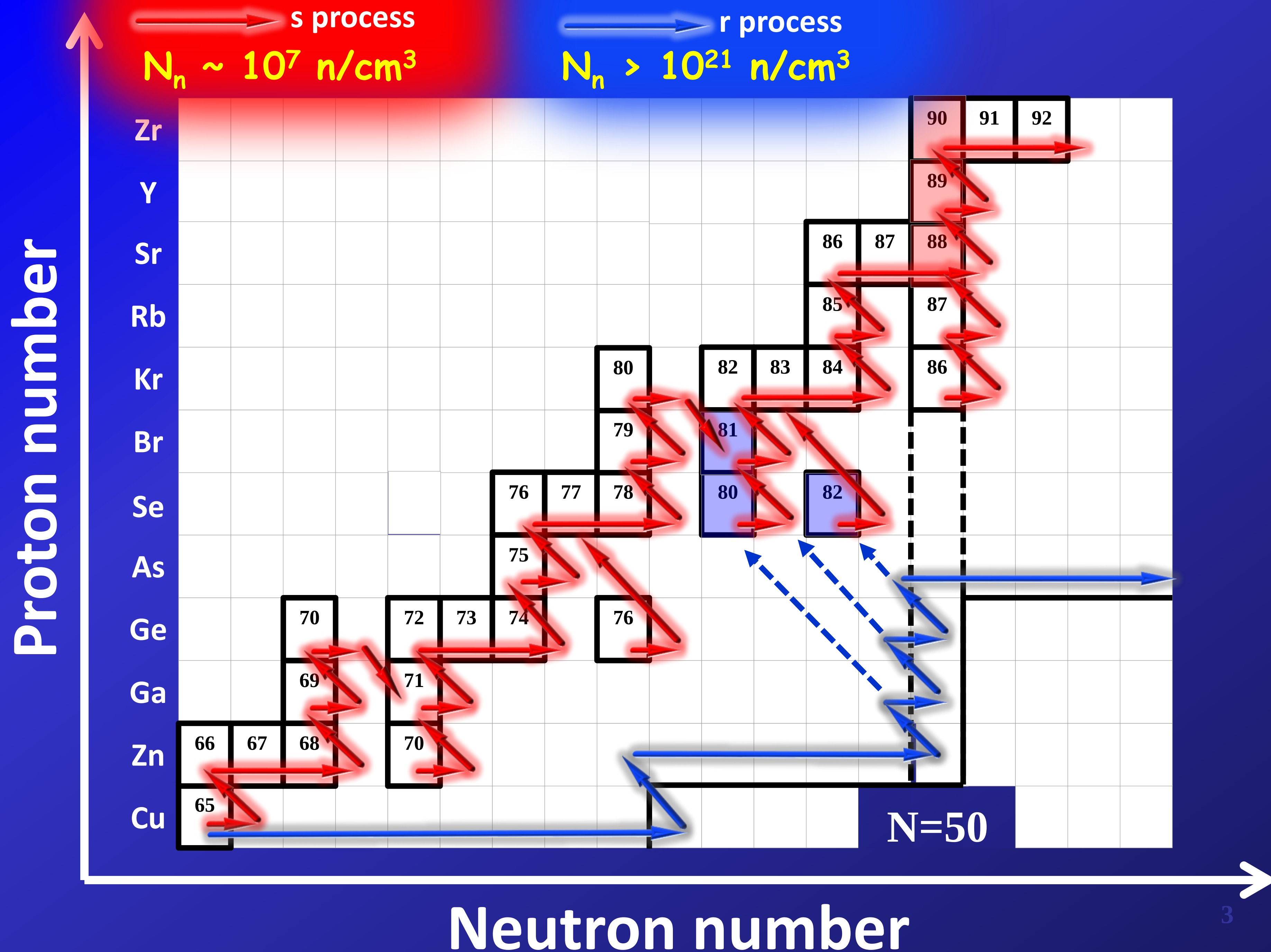
LUNA

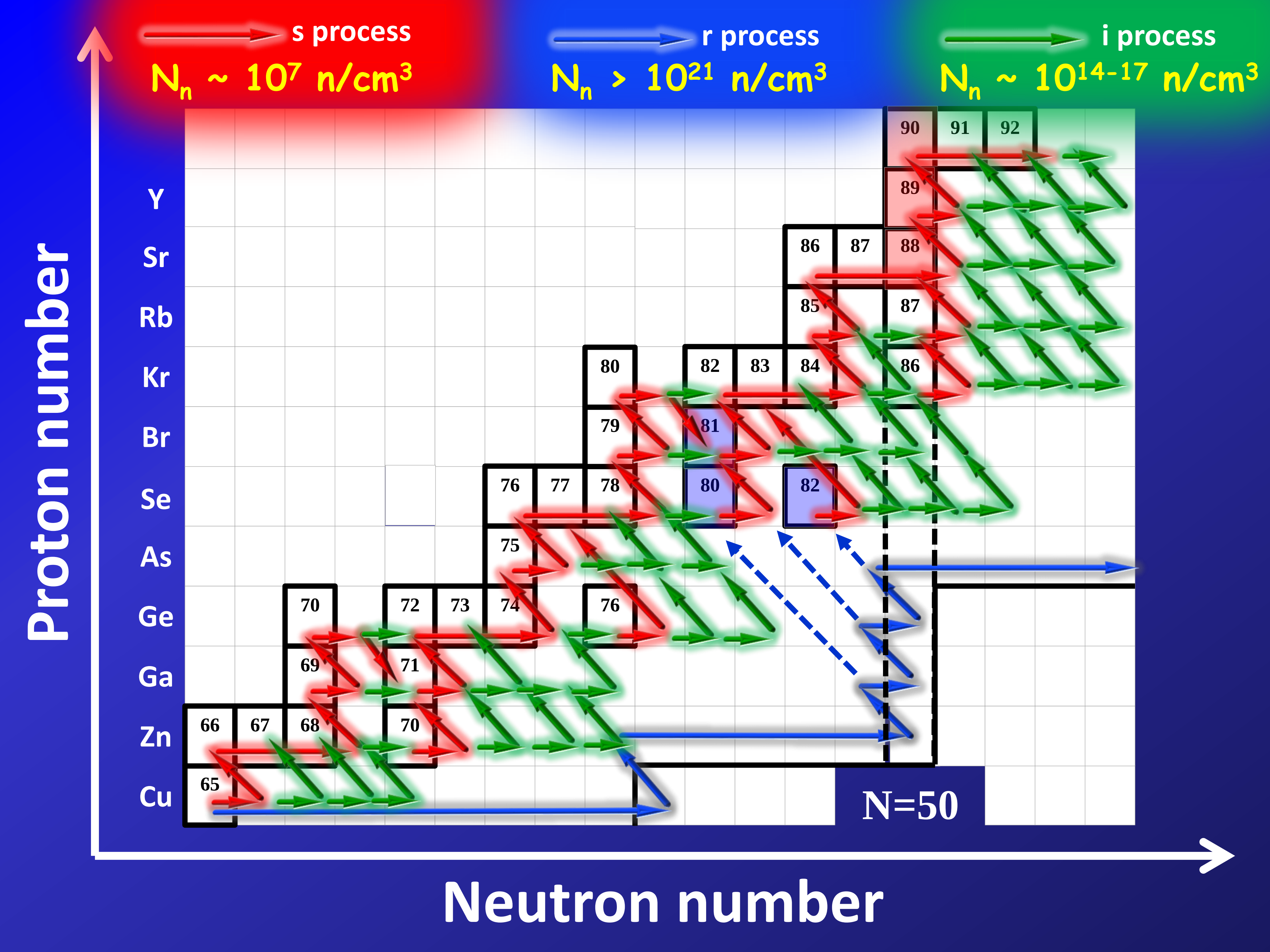


ERNA

n_TOF



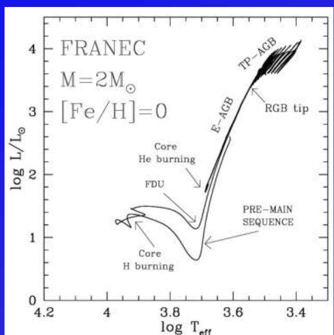

s process
$N_n \sim 10^7\ n/cm^3$
r process
$N_n > 10^{21}\ n/cm^3$
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90 91 92
89
86 87 88
85 87
80 82 83 84 86
79 81
76 77 78 80 82
75
70 72 73 74 76
69 71
66 67 68 70
65
N=50
Proton number
Neutron number

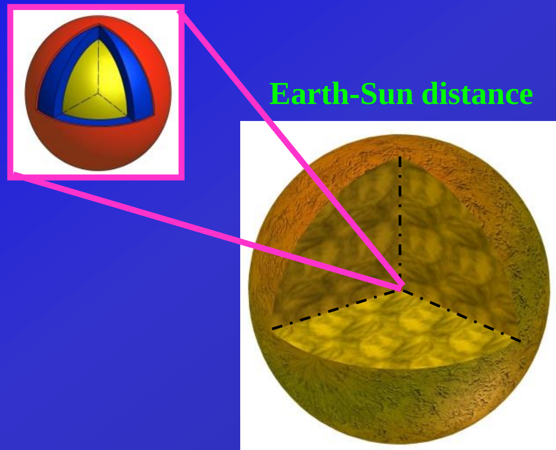


s process
$N_n \sim 10^7$ n/cm^3
r process
$N_n > 10^{21}$ n/cm^3
i process
$N_n \sim 10^{14-17}$ n/cm^3
Proton number
Neutron number
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90
91
92
89
86
87
88
85
87
80
82
83
84
86
79
81
76
77
78
80
82
75
70
72
73
74
76
69
71
66
67
68
70
65
N=50

Main s-process (A≳90)

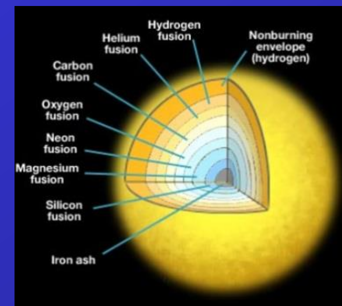
ASYMPTOTIC GIANT BRANCH STARS

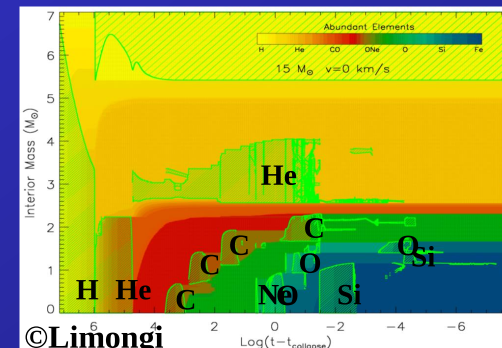




Weak s-process

QUIESCENT BURNINGS OF MASSIVE STARS



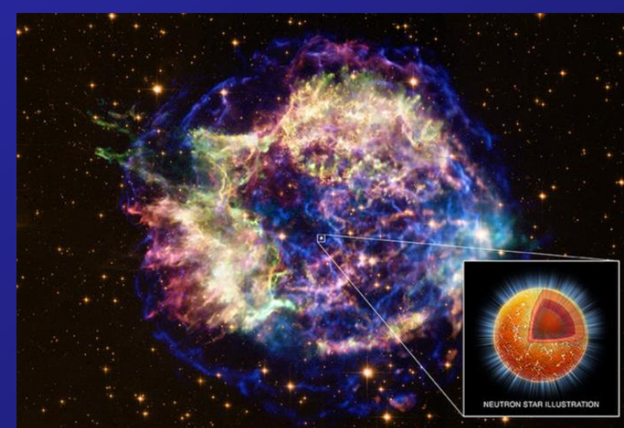


Main r-process (A≳130)

NEUTRON STARS MERGERS?

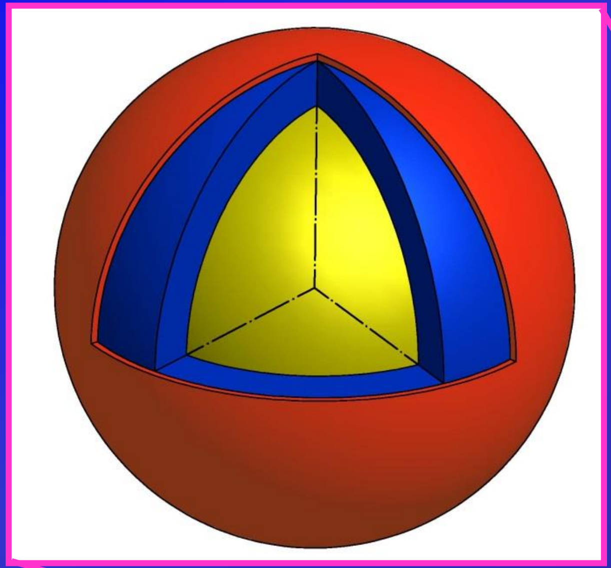
Weak r-process

EXPLOSIVE PHASE OF MASSIVE STARS?



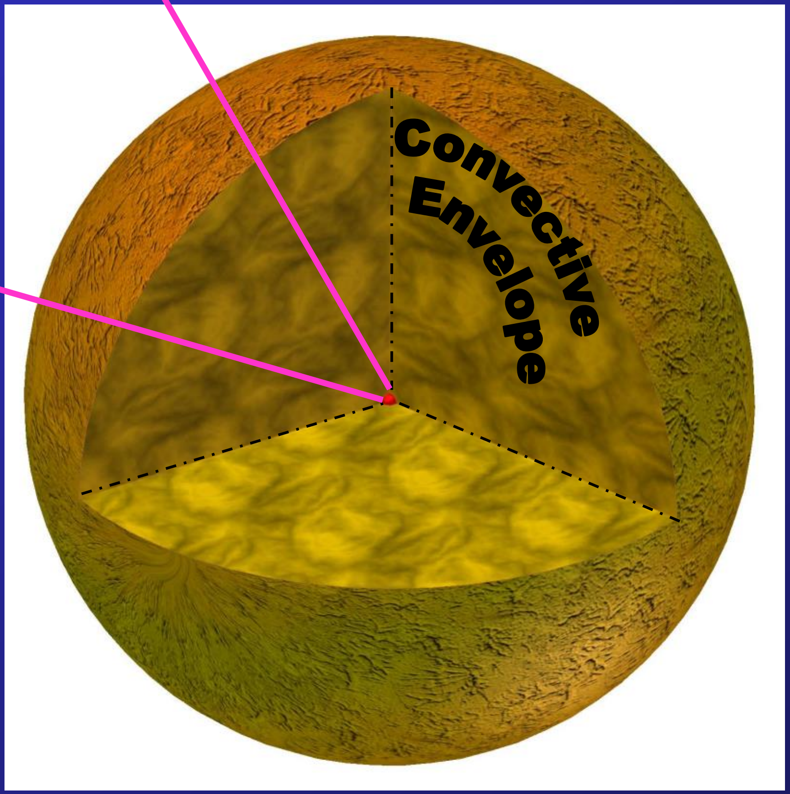
s-process: AGB stars

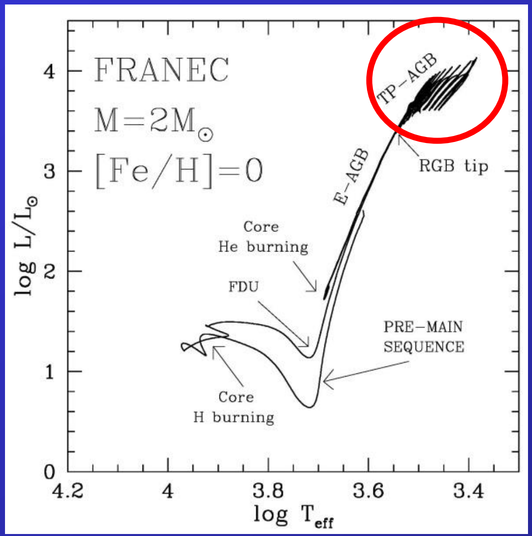
Earth radius (~10^{-2} R_{SUN})



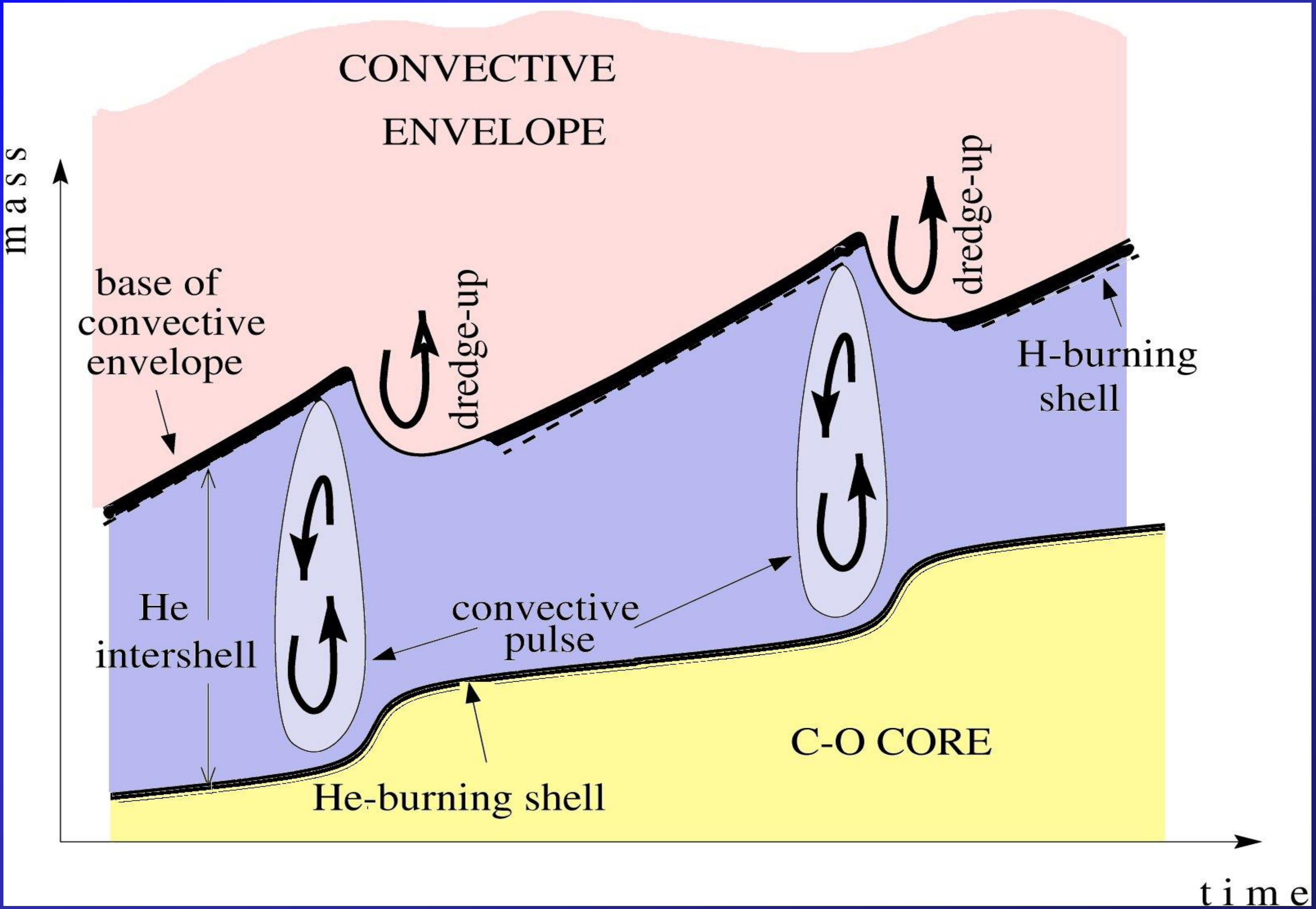
CO Core
He-shell
H-shell

Earth-Sun (~200 R_{SUN})

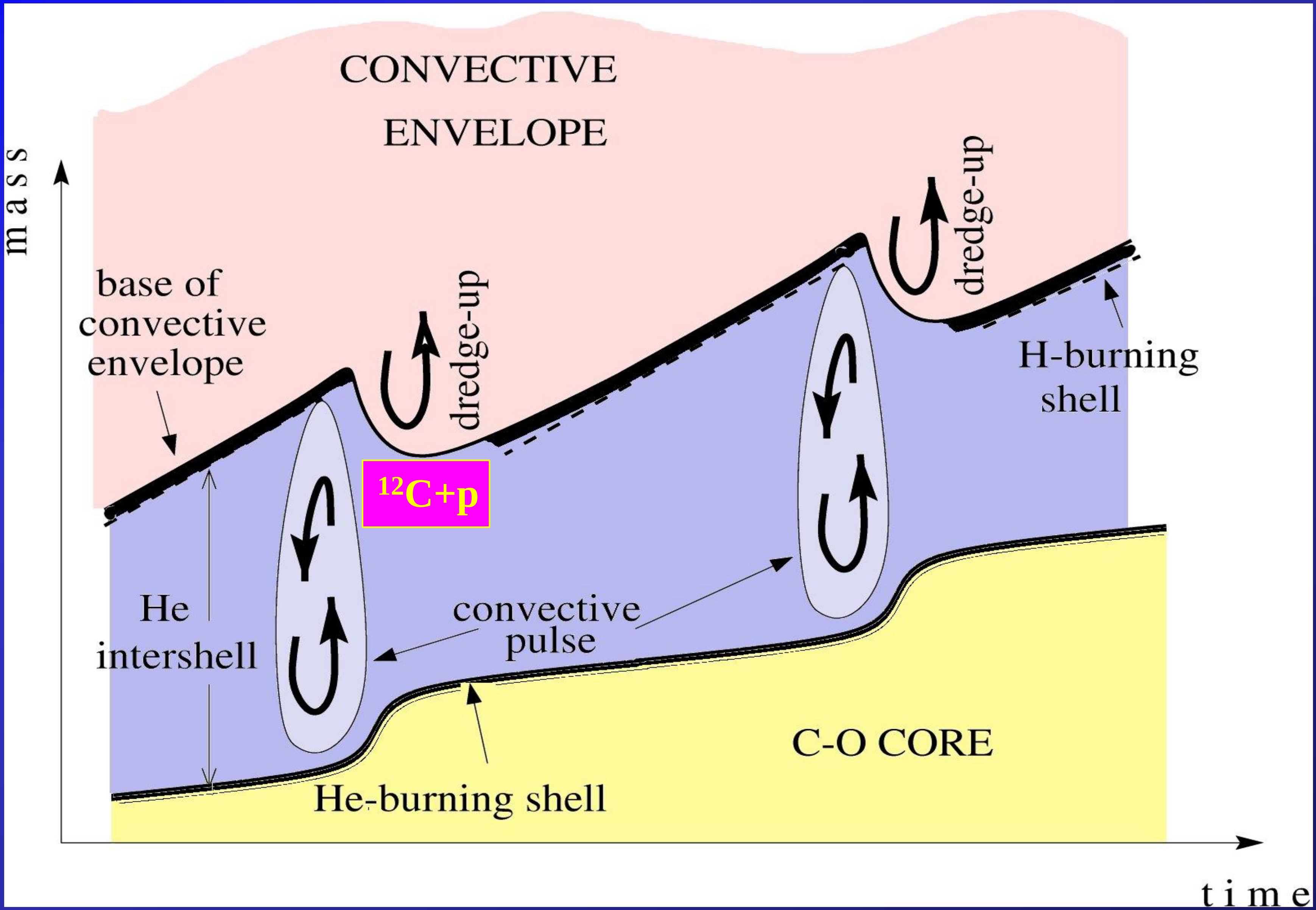




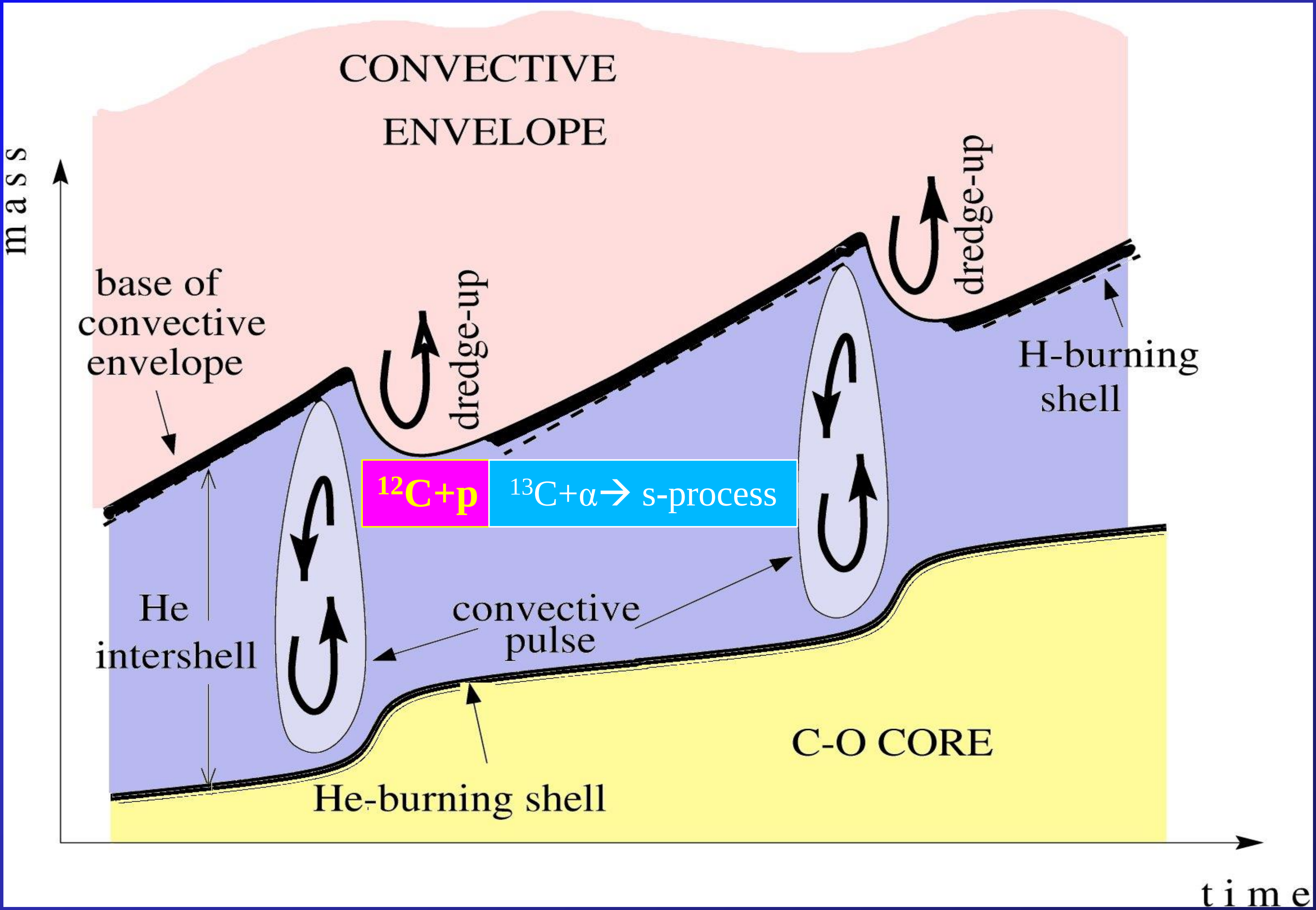
AGB structure



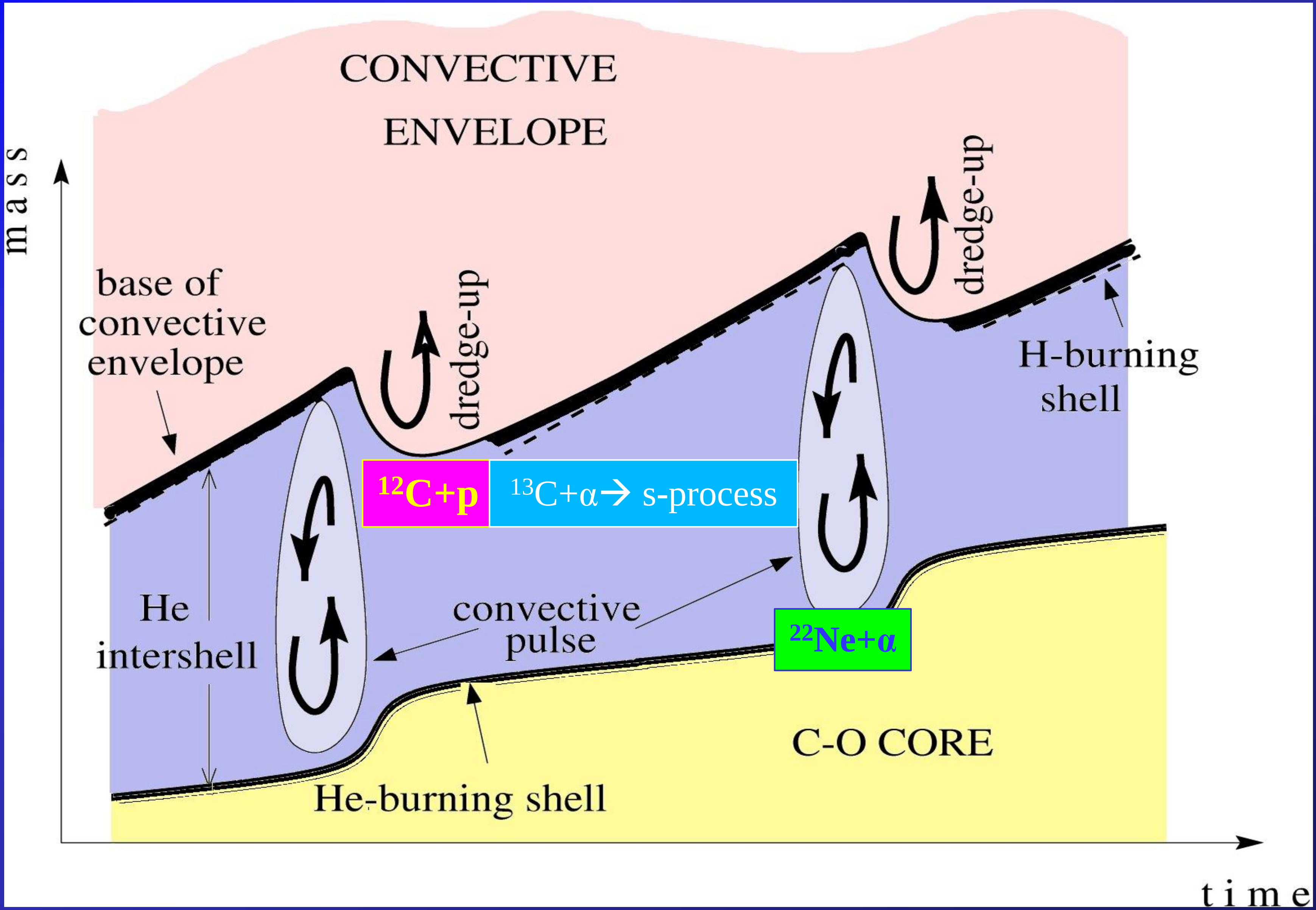
AGB structure



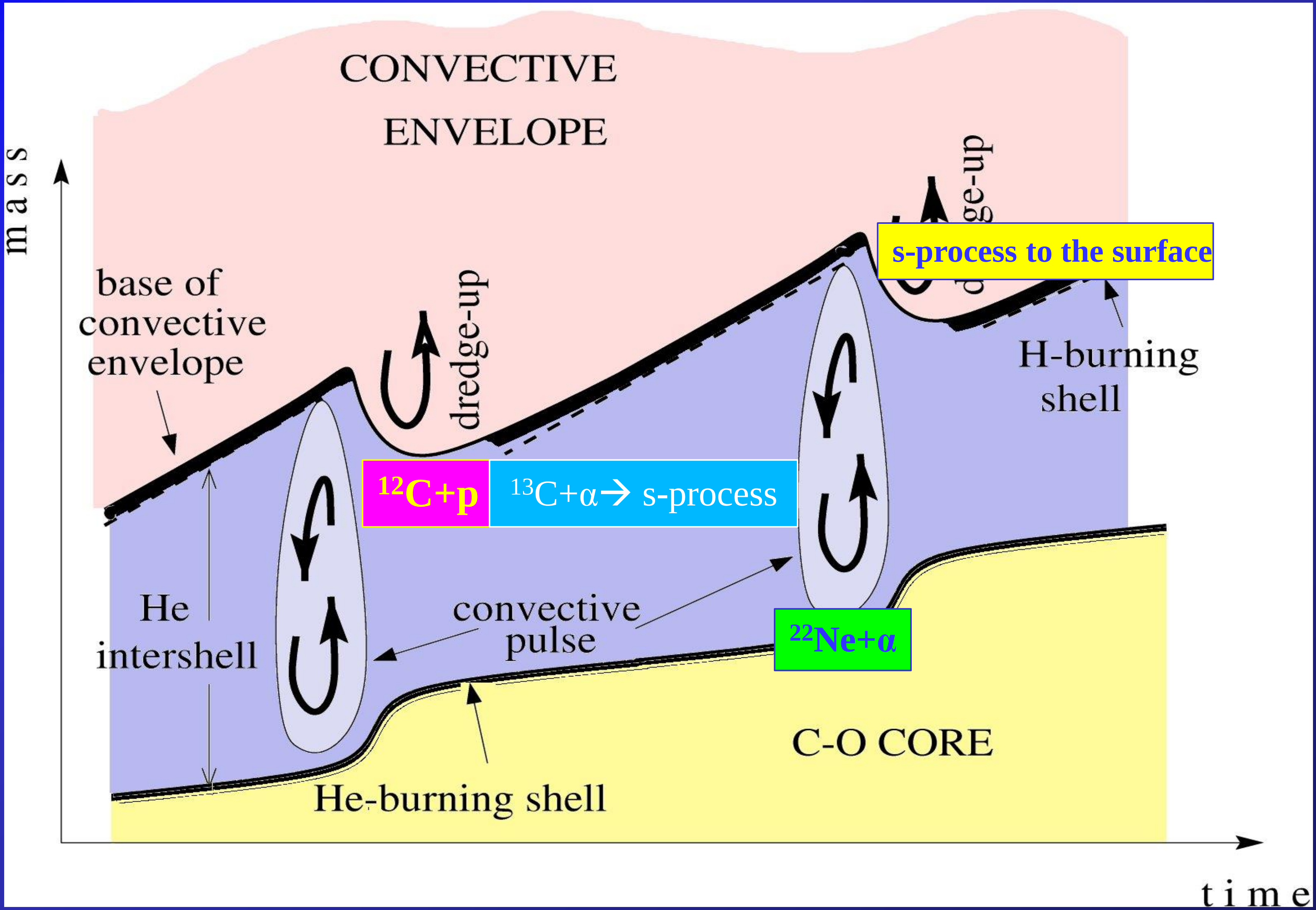
AGB structure



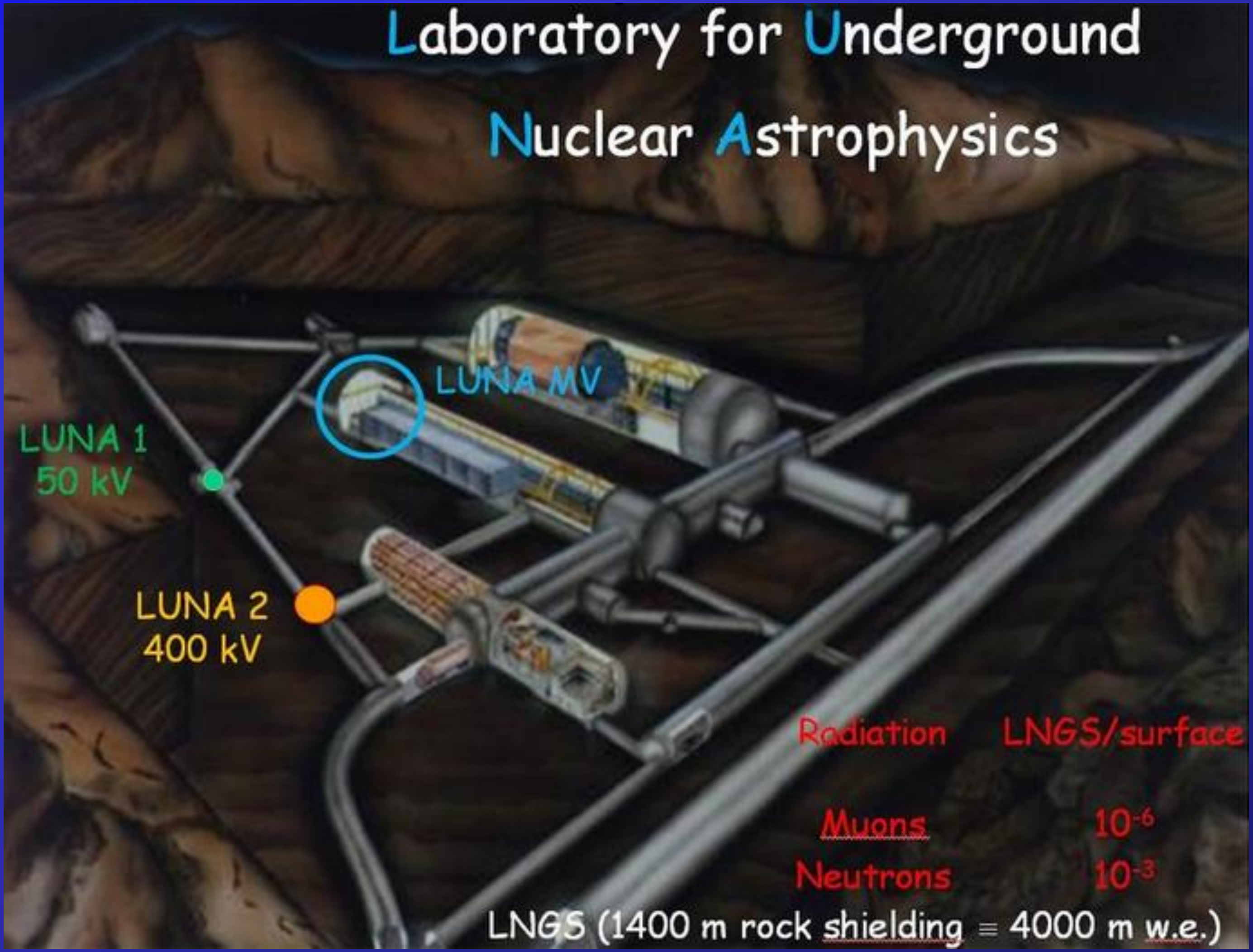
AGB structure



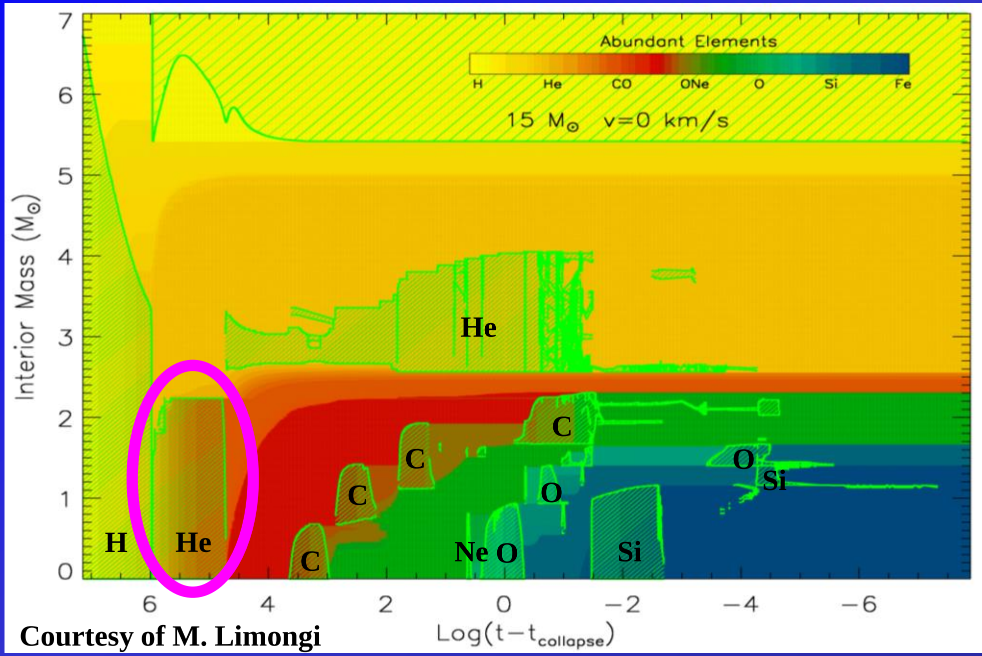
AGB structure



Neutron production: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ LUNA experiment



He-burning in massive stars



$3\alpha \rightarrow {}^{12}C$

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

${}^{14}N(\alpha,\gamma){}^{18}F(\beta^+){}^{18}O(\alpha,\gamma){}^{22}Ne$

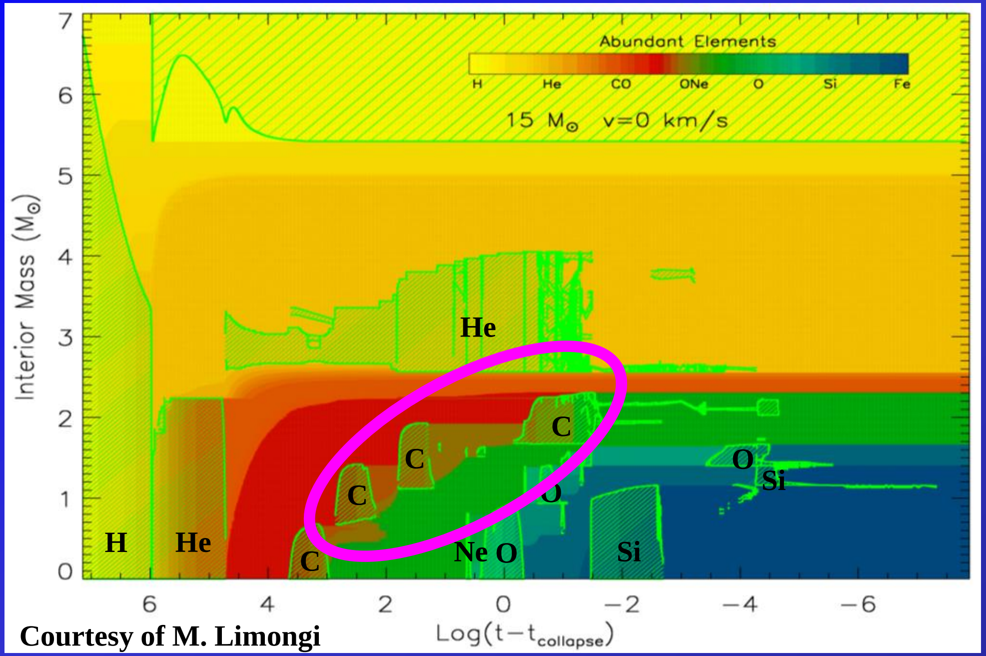
$\tau \approx 1$ Myr

When T~3x10^{8} K the ${}^{22}Ne(\alpha,n){}^{25}Mg$ is efficiently activated

The resulting neutron density is low (~10^{6} n/cm^{3})…
…similar to the s-process in AGB stars!!!

Core He-burning in massive stars provide the so-called WEAK COMPONENT of the s-process

Shell C-burning in massive stars



$^{12}C(^{12}C,\alpha)^{20}Ne$ ≈50%

$^{12}C(^{12}C,p)^{23}Na$ ≈50%

$^{12}C(^{12}C,n)^{23}Mg$

Recently measured by the ASFIN group

$\tau \approx 1$ Kyr

All (α,n) channels are activated:

$^{13}C(\alpha,n)^{16}O$ - $^{17}O(\alpha,n)^{20}Ne$

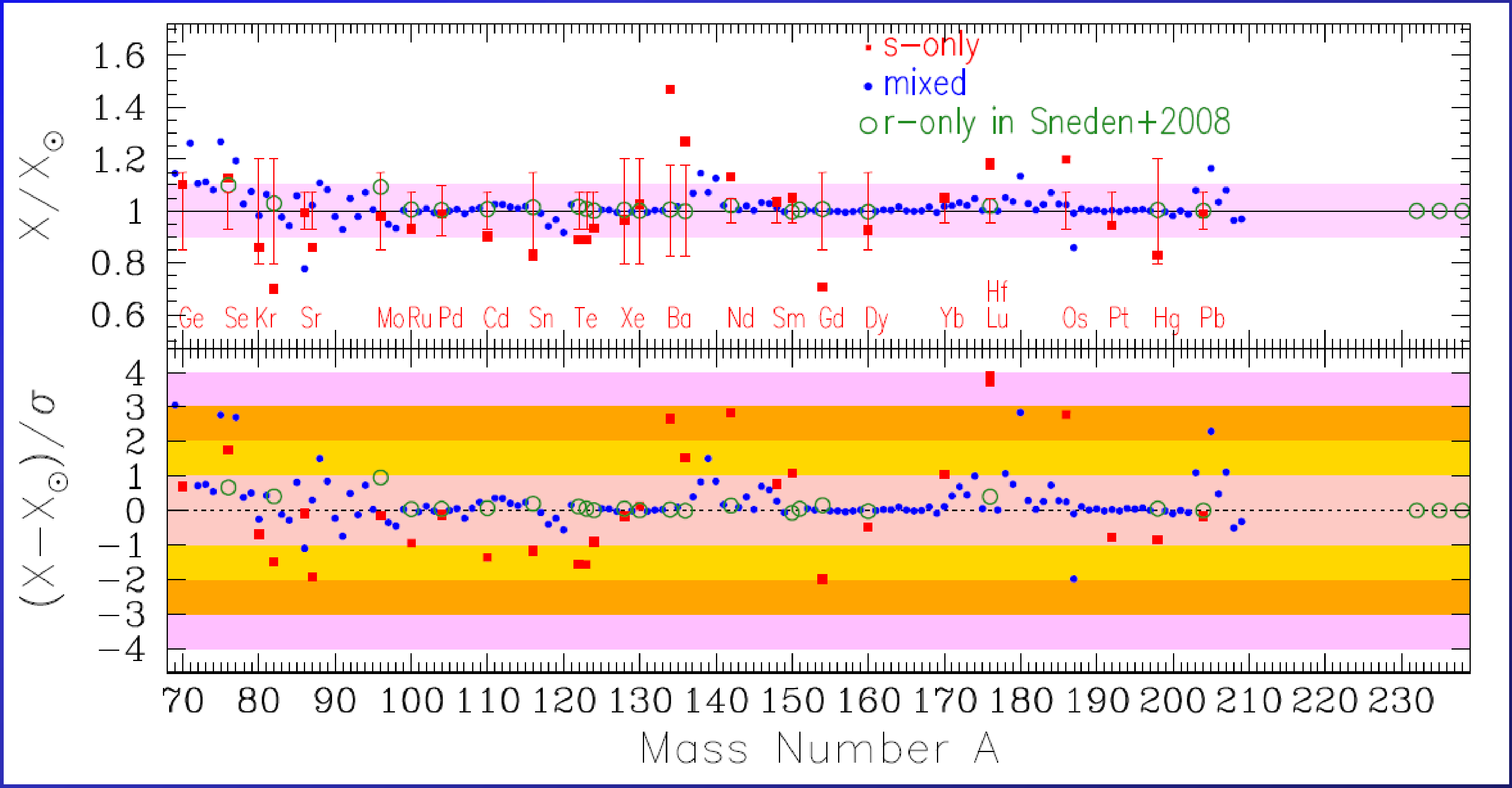
$^{18}O(\alpha,n)^{21}Ne$ - $^{21}Ne(\alpha,n)^{24}Mg$

$^{22}Ne(\alpha,n)^{25}Mg$ - $^{25}Mg(\alpha,n)^{28}Si$

$^{26}Mg(\alpha,n)^{29}Si$

The resulting neutron density is higher: 10^{11}-10^{12} n/cm^3

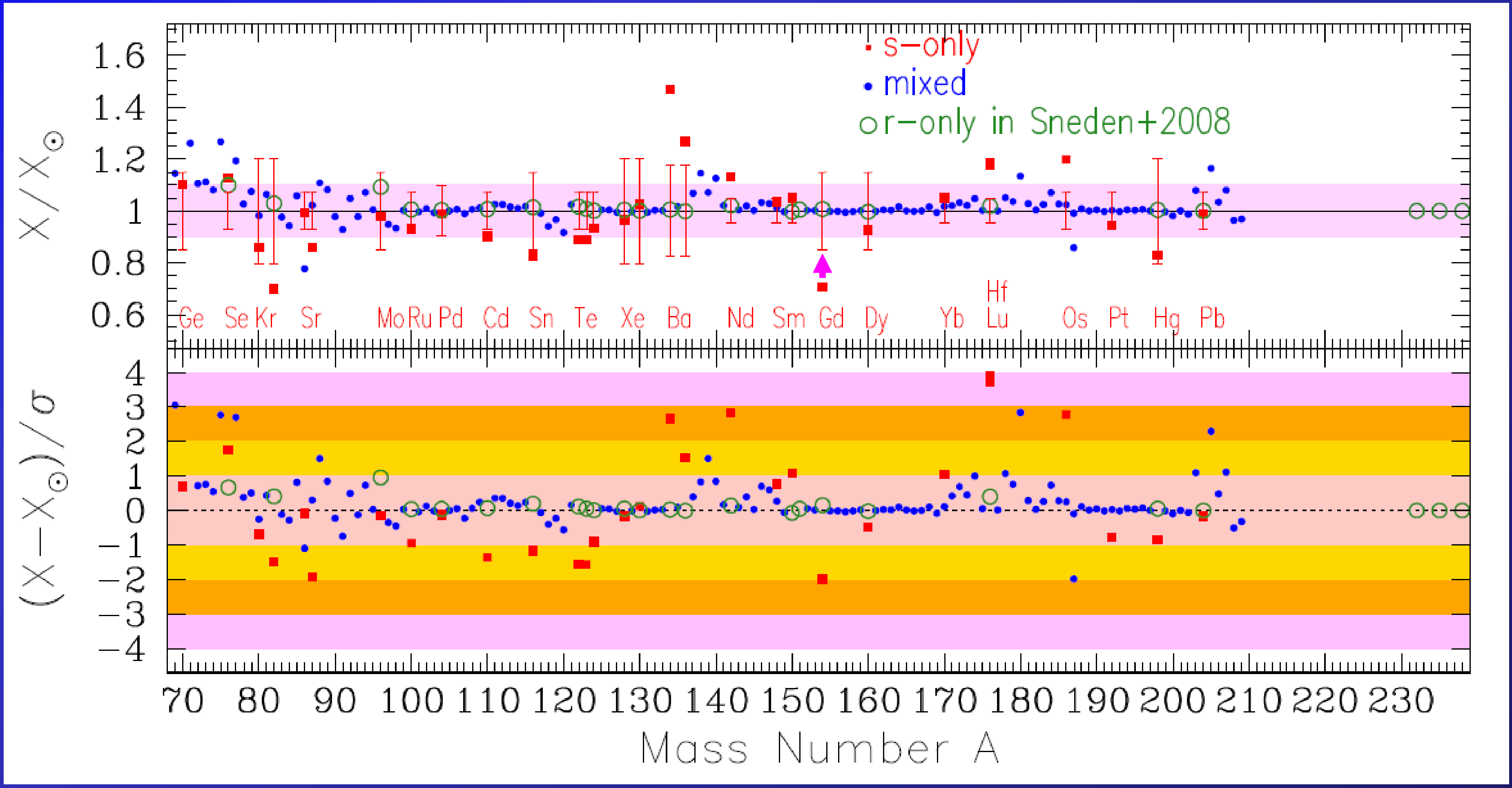
Comparison to solar distribution



Prantzos+ 2020

Comparison to solar distribution

Mazzone+ 2020
(n,γ)

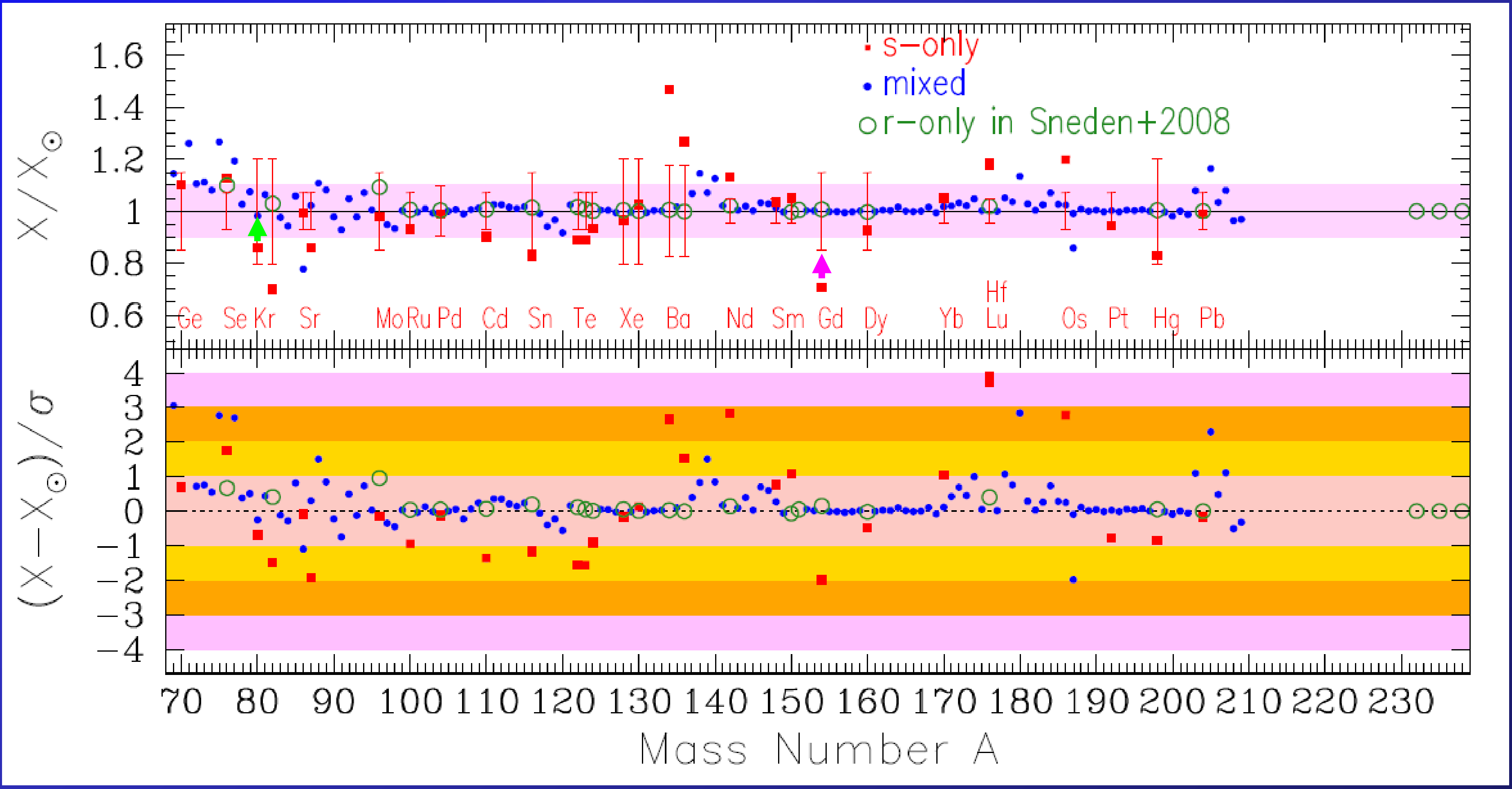


Prantzos+ 2020

Comparison to solar distribution

Mazzone+ 2020
(n,γ)

Tessler+2021
(n,γ)



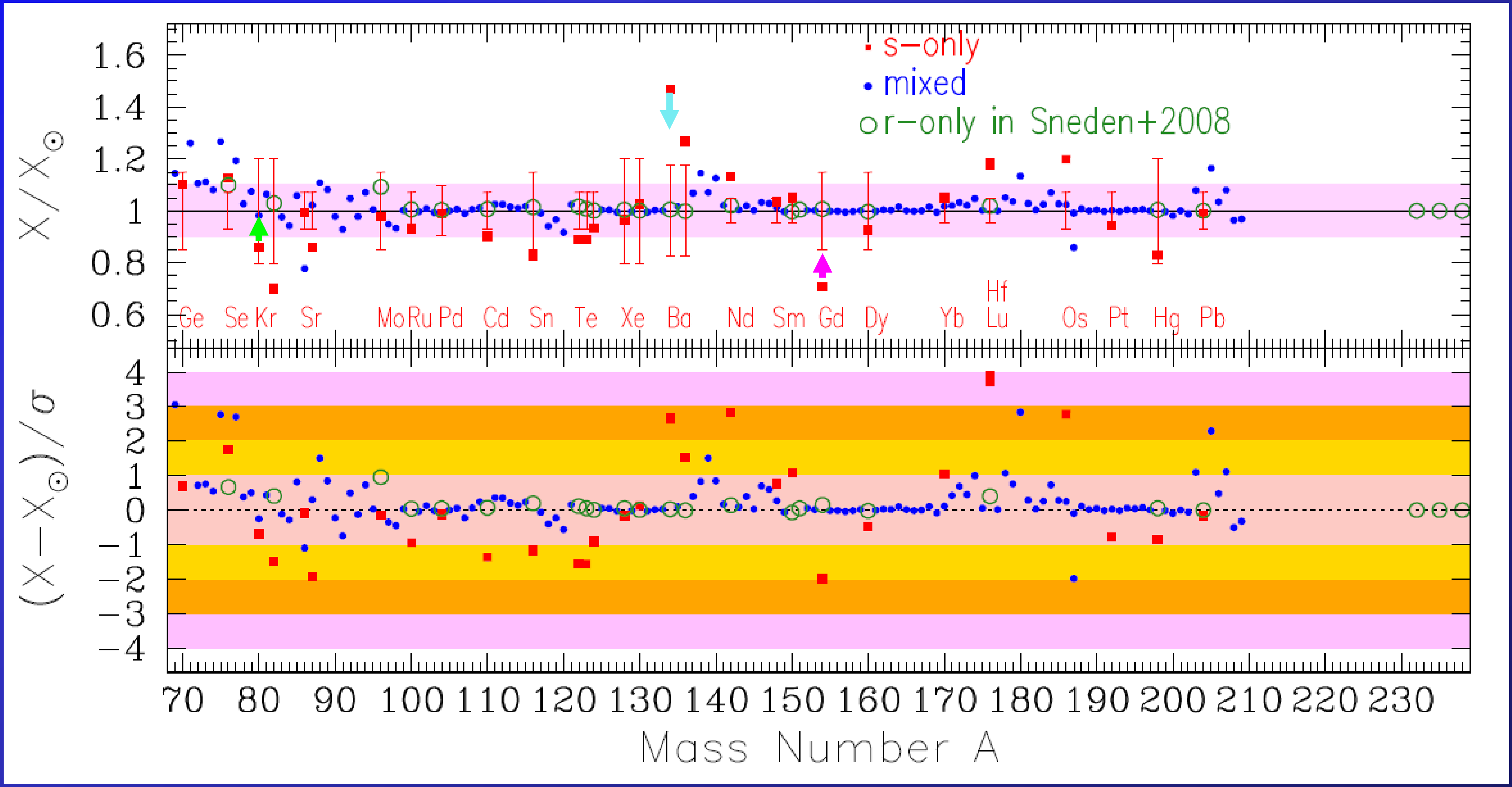
Prantzos+ 2020

Comparison to solar distribution

Mazzone+ 2020
(n,γ)

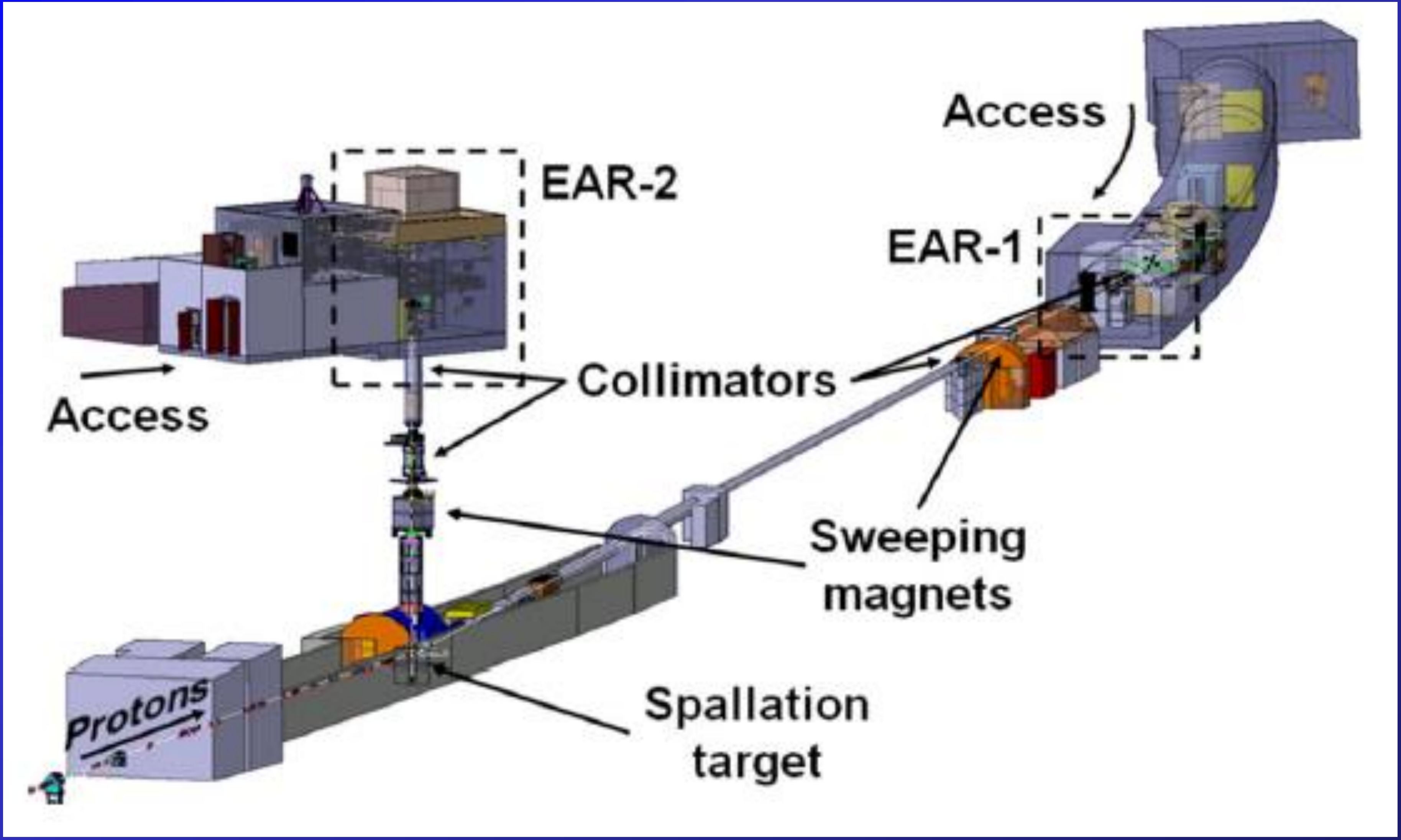
Tessler+2021
(n,γ)

Taioli+2022
(β⁻)

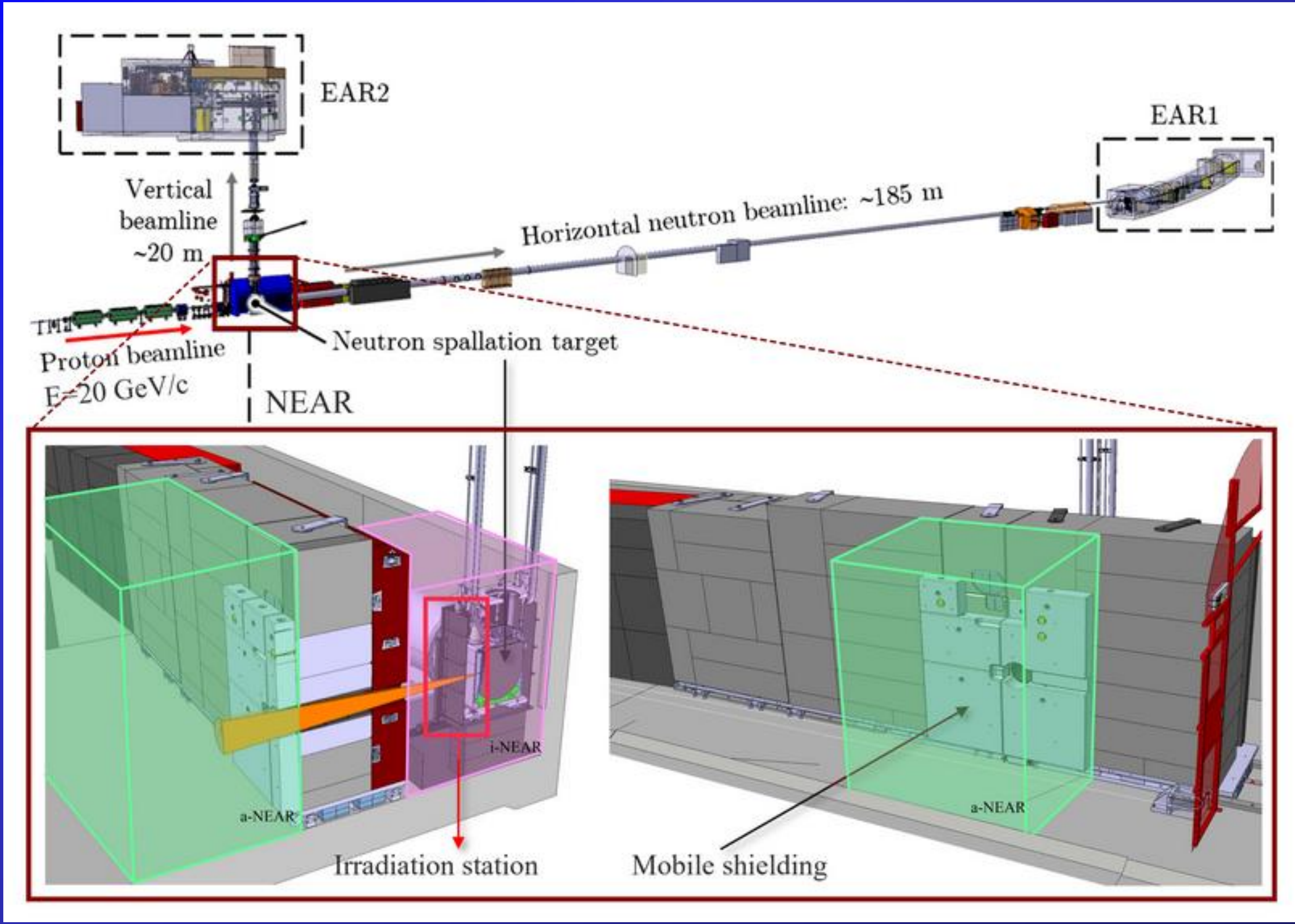


Prantzos+ 2020

Facilities for the s-process → (n,γ)@n_TOF up to … yesterday

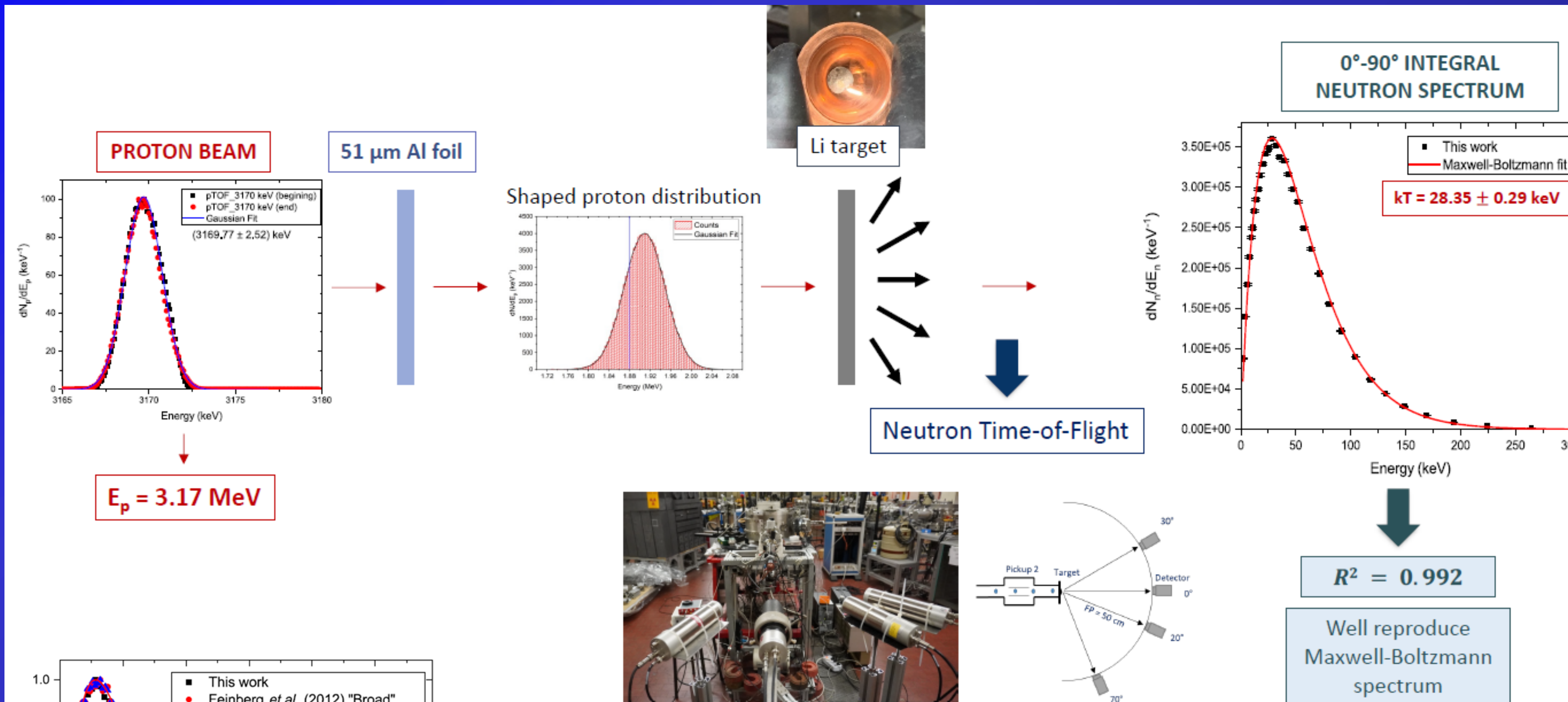


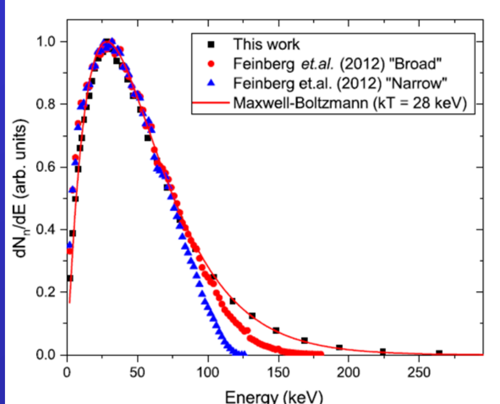
Facilities for the s-(i-)process →(n,γ)@n_TOF (2022 campaign)



Facilities for the s-process: CN@LNL

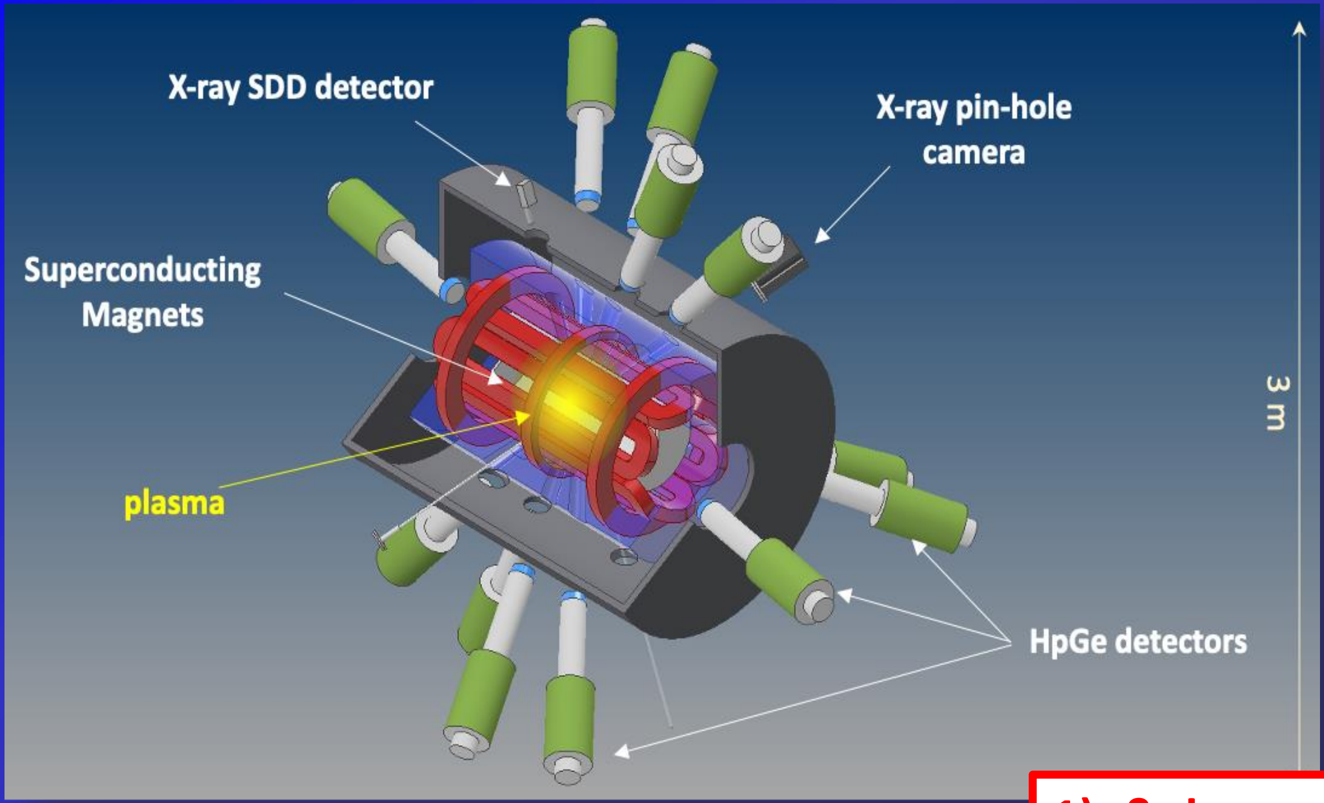
Activation measurements of isotopes of interest for the s-process





Mastinu, P.F.,Martín-Hernández, G.,Praena, J., 2009.Nucl.Instrum.Methods.A 601, 333.

Facilities for the s-process: PANDORA

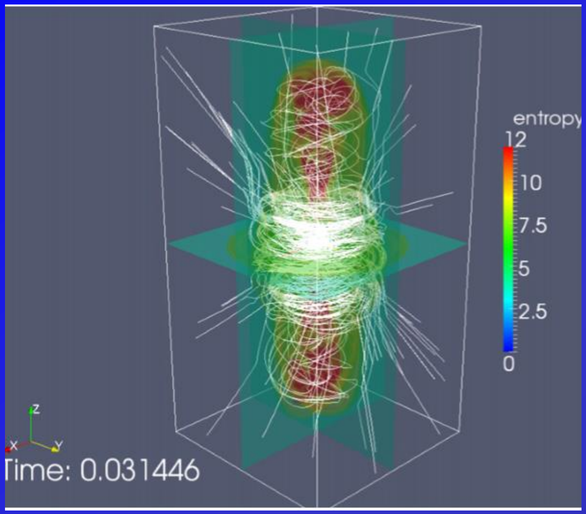


1) β-decay measurements in plasmas;
2) …

PANDORA consists of:

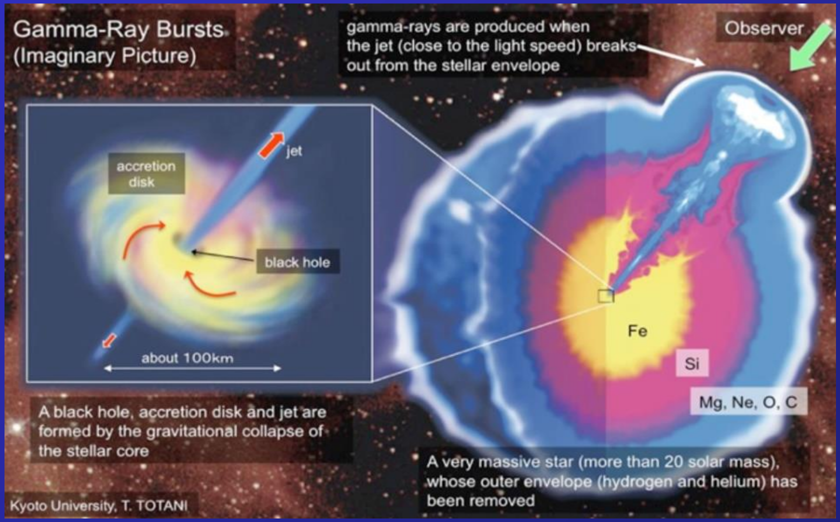
1) Superconducting Magnetic Plasma Trap;
2) HpGe Array;
3) Plasma Diagnostics System.

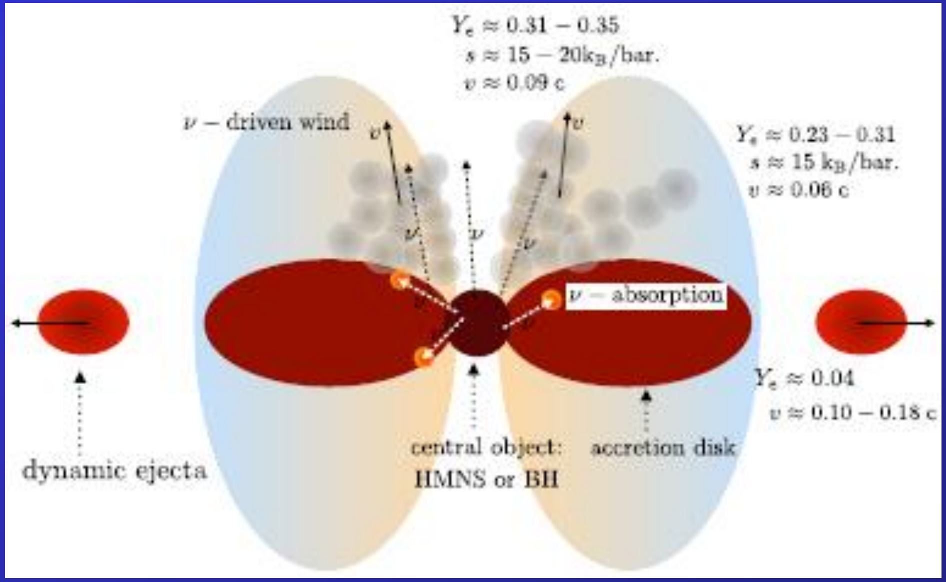
Main r-process



Magneto-rotationally driven SuperNovae

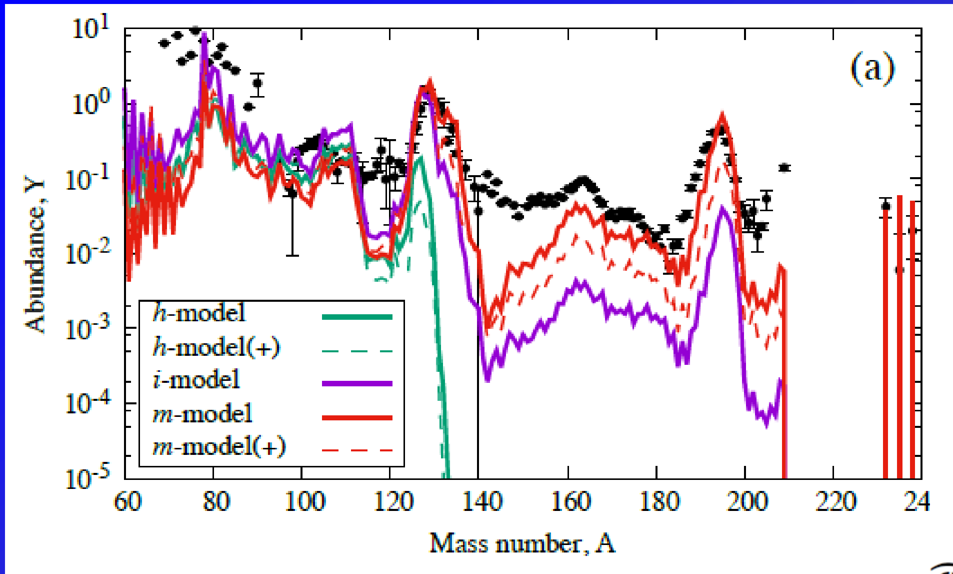
Magnetars





Neutron Star Mergers

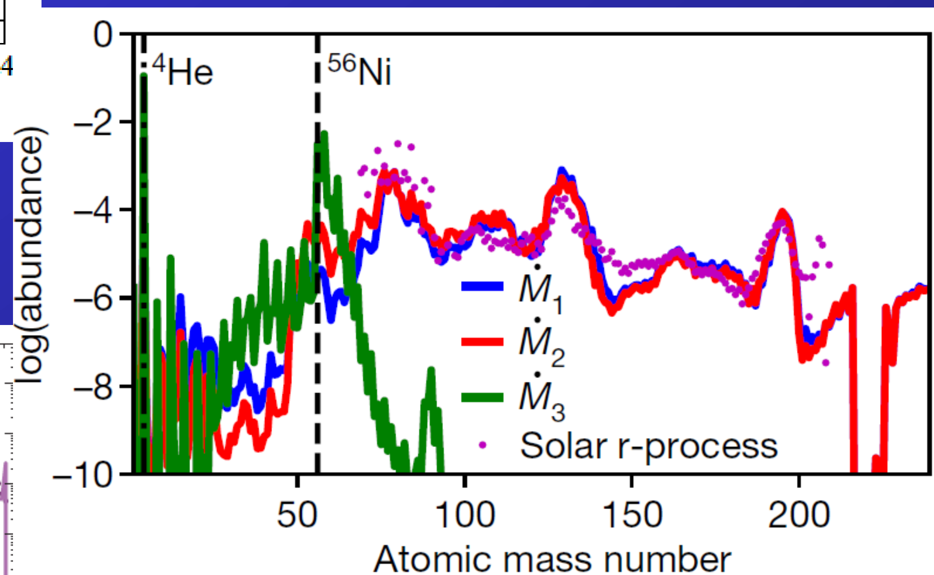
(GW170817 →Kilonova emission)

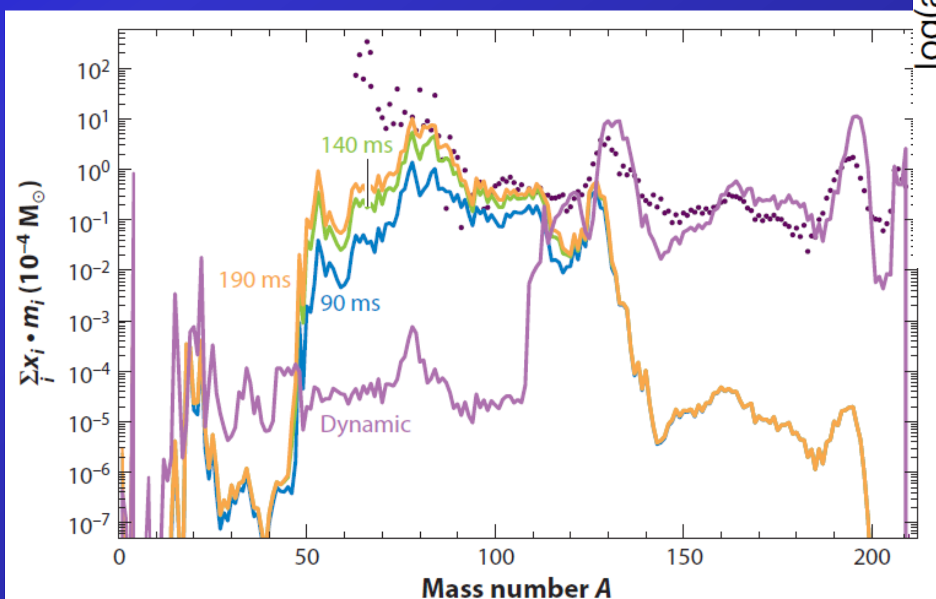


MRD SNe

CAVEAT!

Magnetars

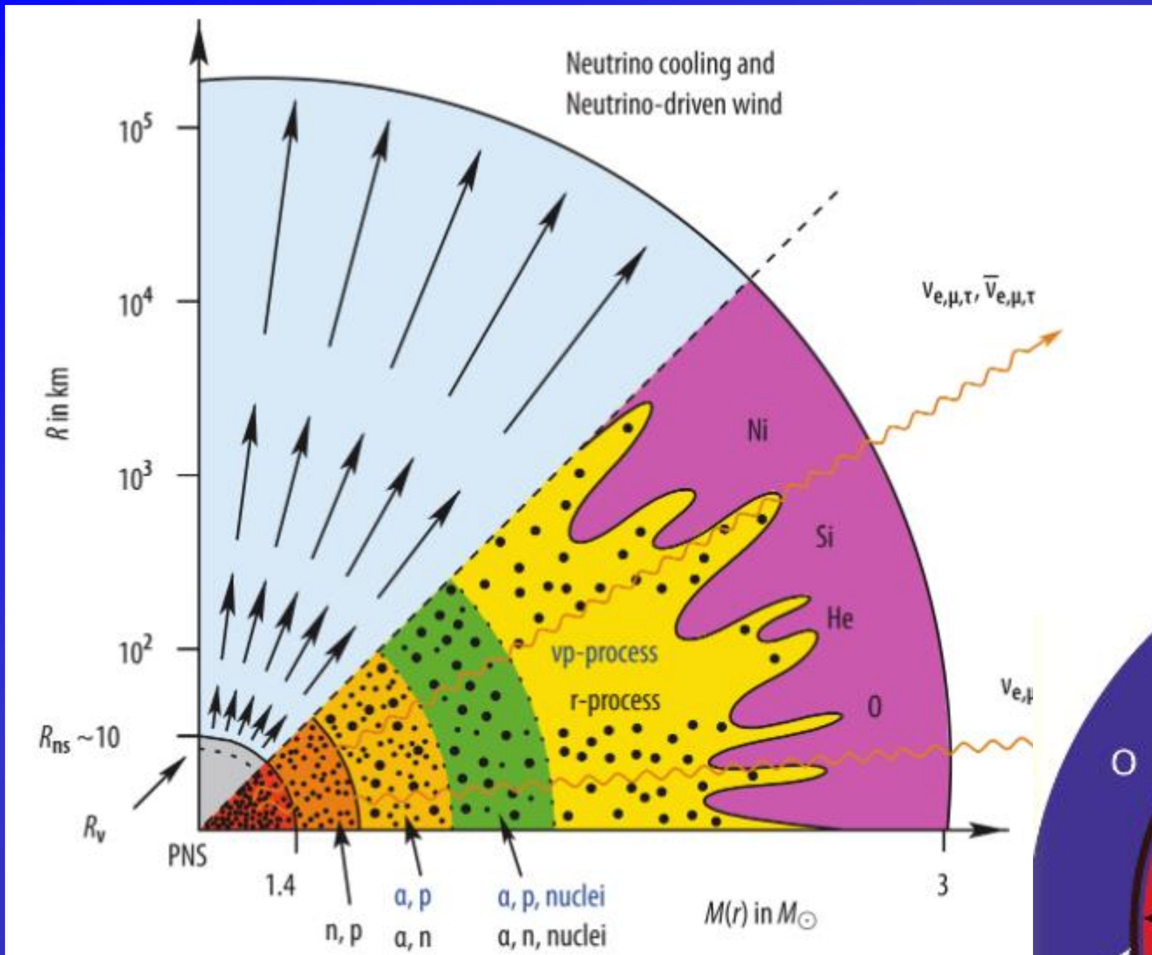




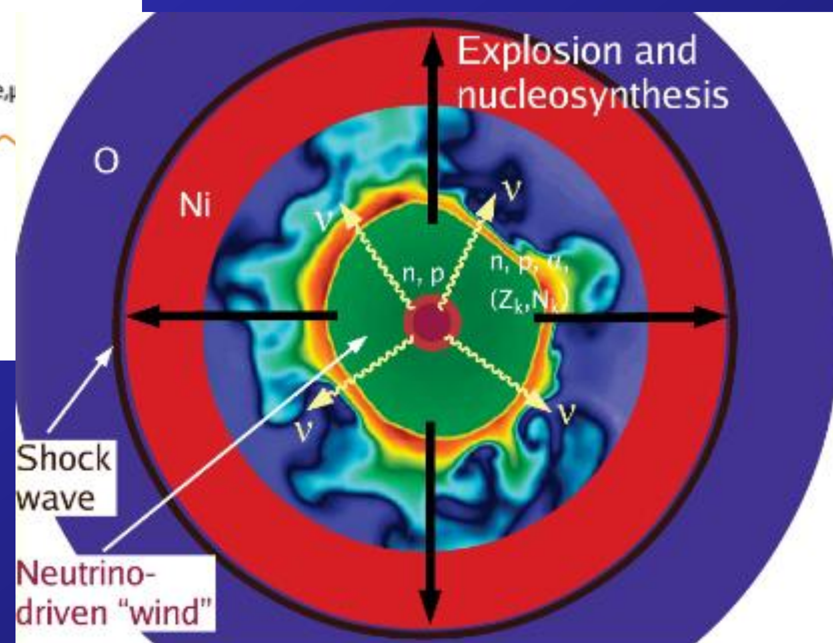
WARNING!

NSMs

Weak r-process

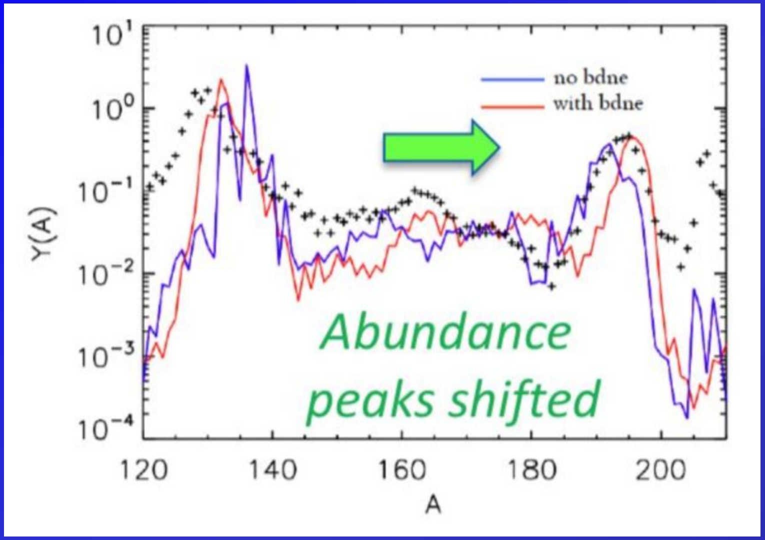


- Standard Supernovae?
- Low B MHD-Sne?
- NSMs wind ejecta?



Facilities for the r-process: POLIFEMO

(POLYcube detector system For Experimental Multimessenger astrOnomy)

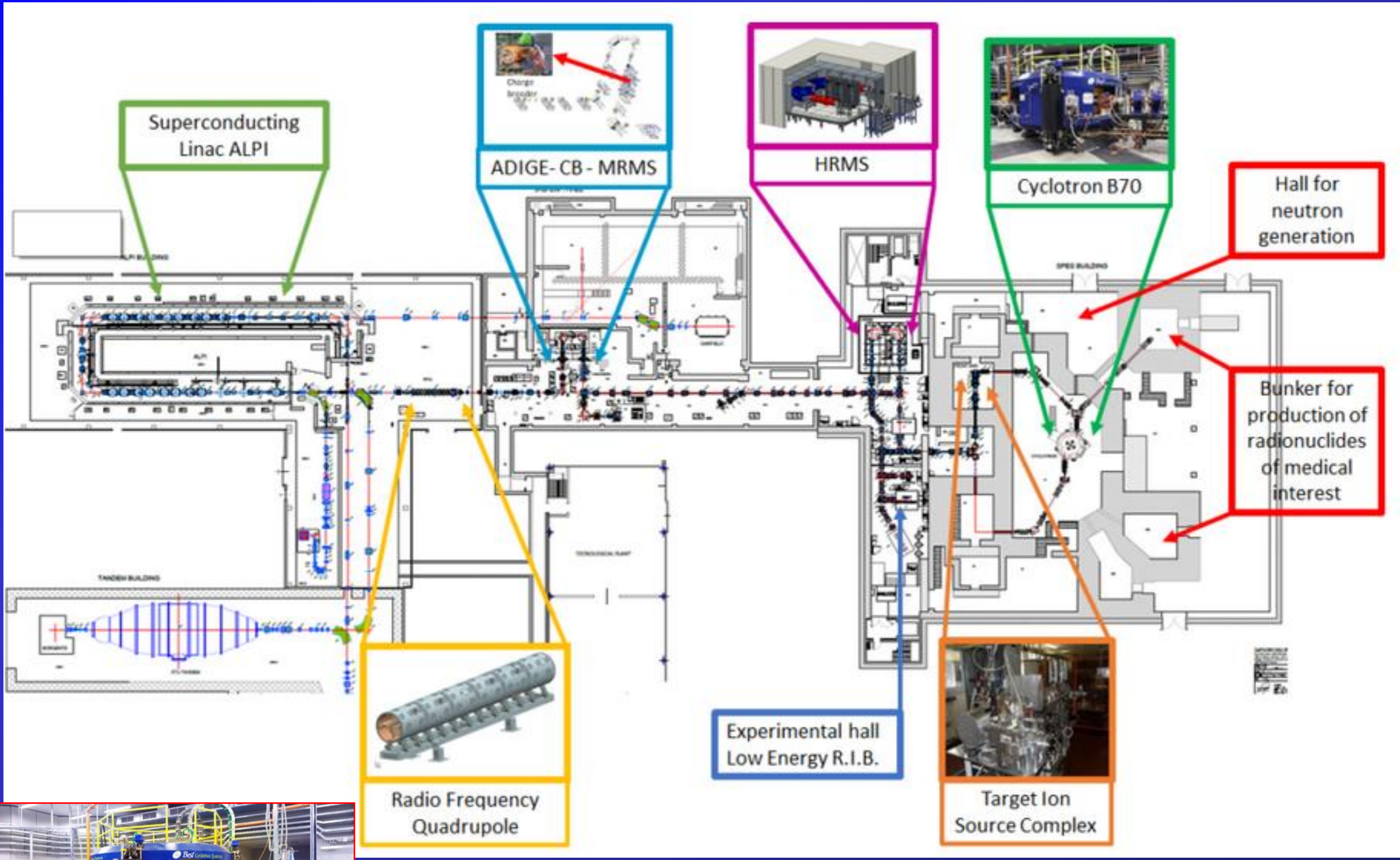


Example of the effect on the r-process yield of the **β-delayed neutron emission**.

The effect of P_n is sizeable.

Thank to the availability of a high efficiency neutron counter (polycube), successfully used in the past in the $^8Li(\alpha,n)^{11}B$ measurement, and of the FRAISE facility for the production of short lived radioactive nuclei, LNS can play an important role in the accurate determination of P_n.

Facilities for the r-process: SPES



RIBs + surrogate methods

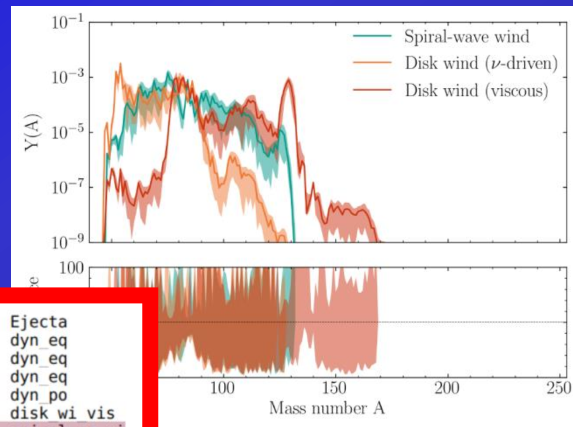
Theoretical support: sensitivity studies for the r-process

- 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

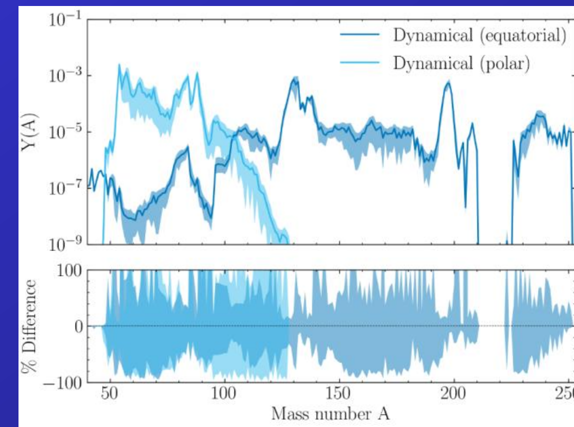
Vescovi+ 2022

#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		

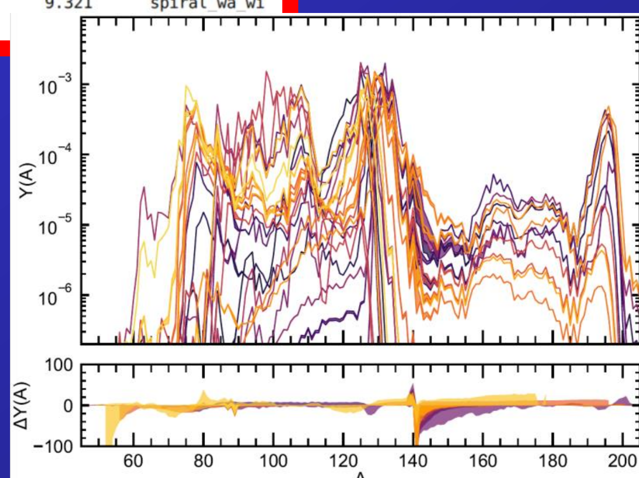
n-capture in Wind…

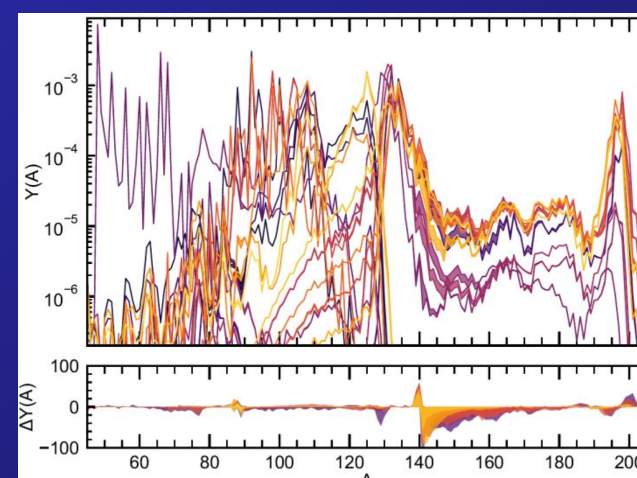


…and Dynamical Ejecta



Sensitivity study on dynamical ejecta: β-decay rates and P_n emissions

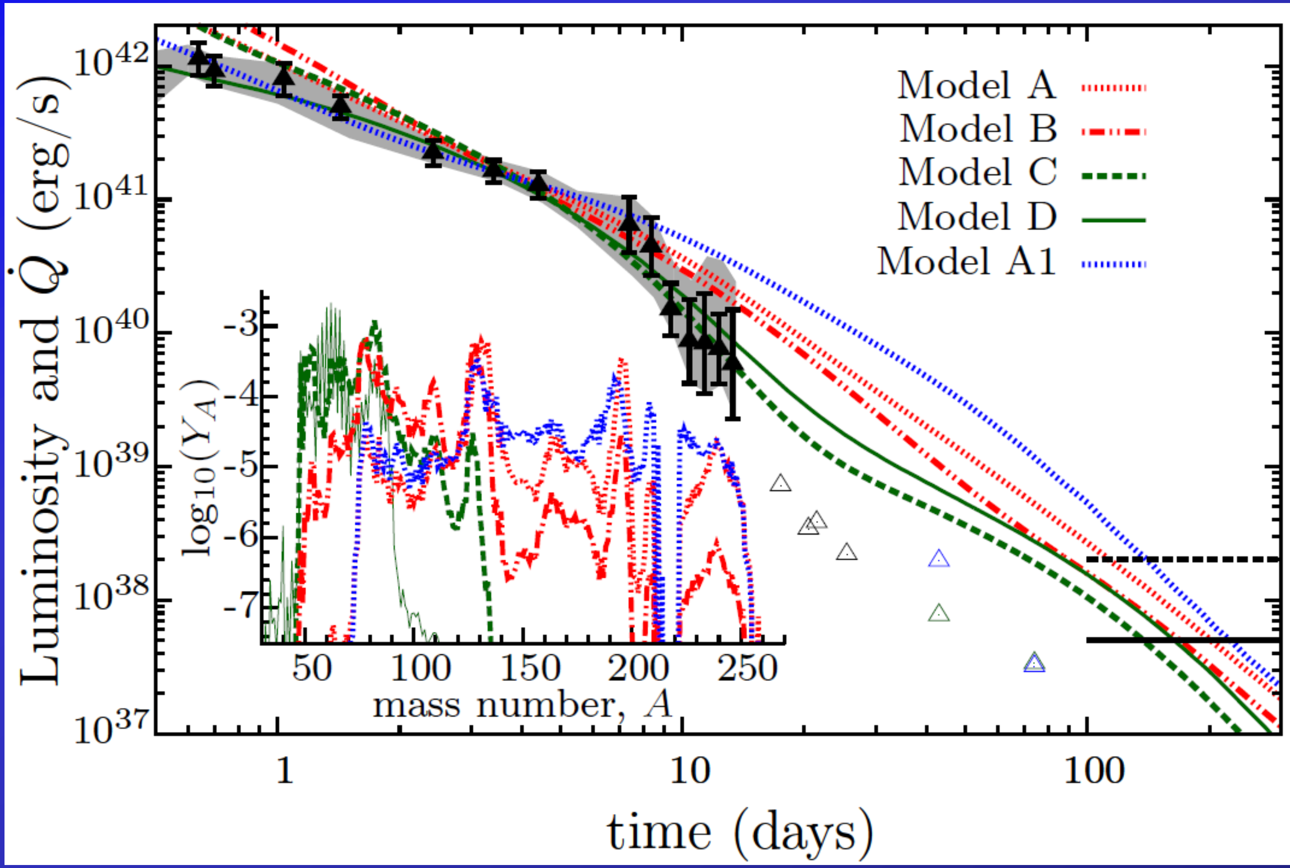




Key isotopes with N=82 (^{131}In, ^{132}Sn, ^{133}Sb, ^{134}Te, ^{135}I)

LNL Mid-term plan

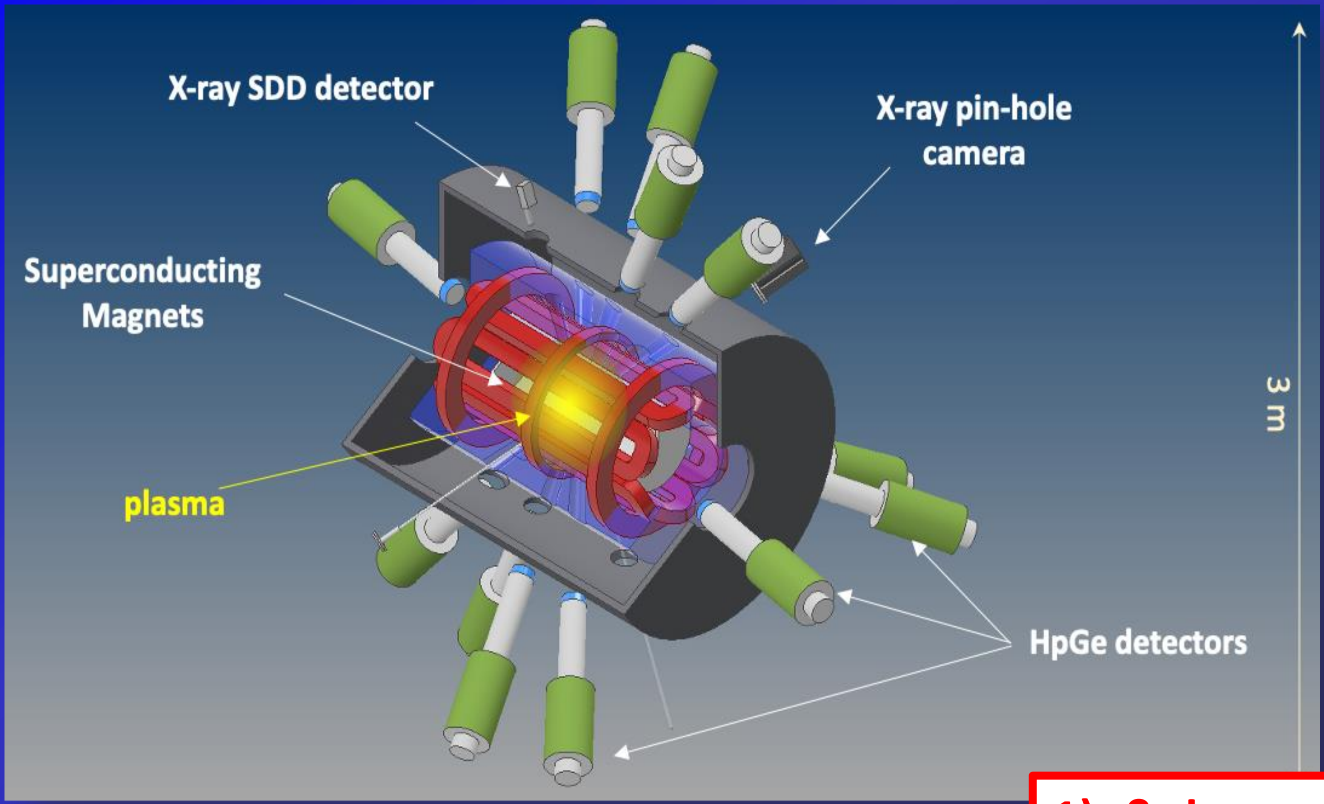
A very hot-topic: Kilonovae lightcurves



They depend on:

1. **numerical relativity (NR) simulations;**
2. **heating rate ε (and thus from nucleosynthesis);**
3. **opacities κ_ν**

Facilities for the r-process: PANDORA



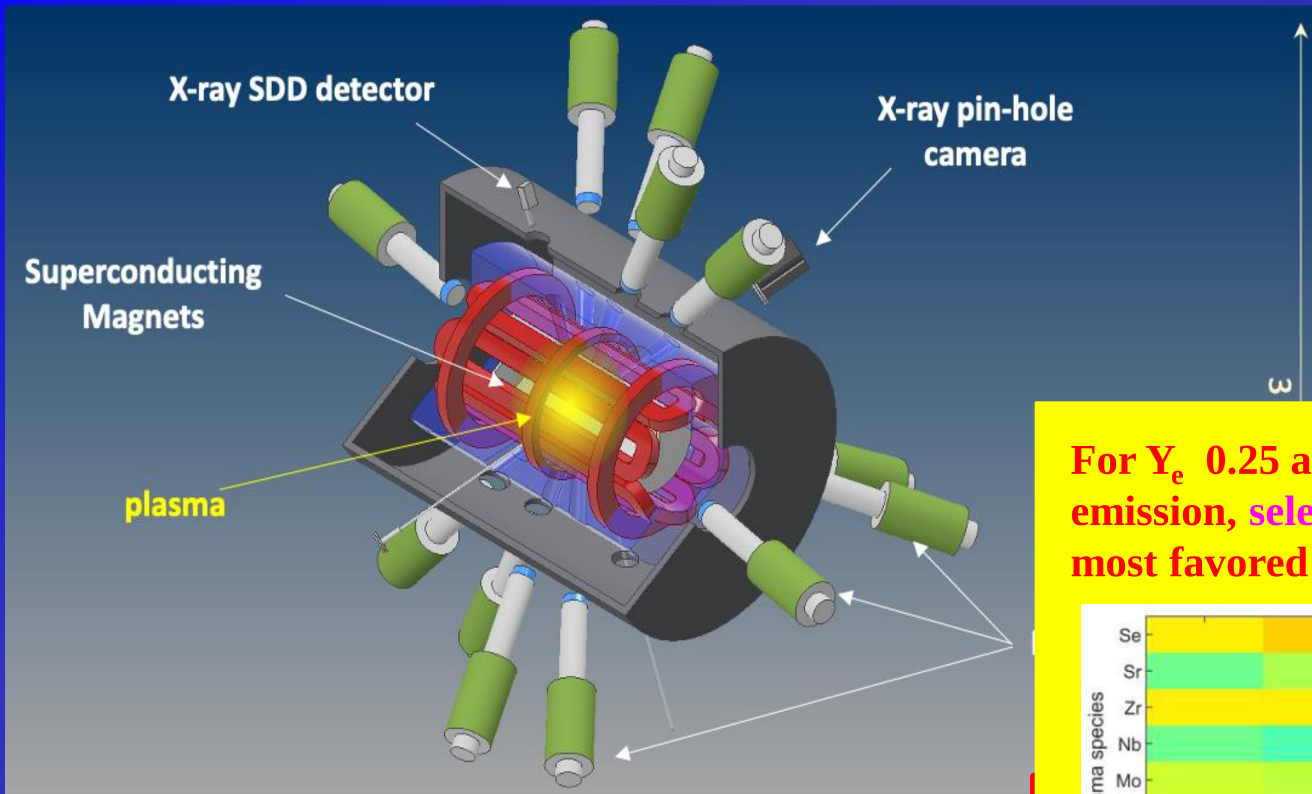
PANDORA consists of:

1) Superconducting Magnetic Plasma Trap;
2) HpGe Array;
3) Plasma Diagnostics System.

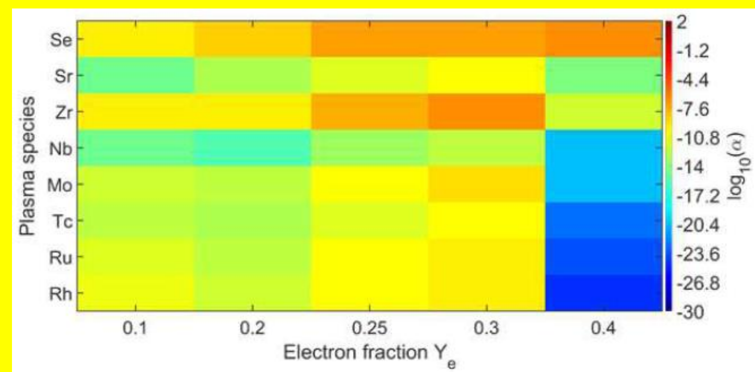
1) β-decay measurements in plasmas;

2) plasma opacity measurements in conditions similar to kilonovae ejecta

Facilities for the r-process: PANDORA



For Y_e 0.25 and T typical of blue-kilonova emission, selenium plasma as one of the most favored for the experiment.



MNRAS 000, 1–5 (2022) Preprint 5 April 2022 Compiled using MNRAS LaTeX style file v3.0

Tungsten vs Selenium as a potential source of kilonova nebular emission observed by Spitzer

Kenta Hotokezaka,[1,2⋆] Masaomi Tanaka,[3,4] Daiji Kato,[5,6] Gediminas Gaigalas[7]

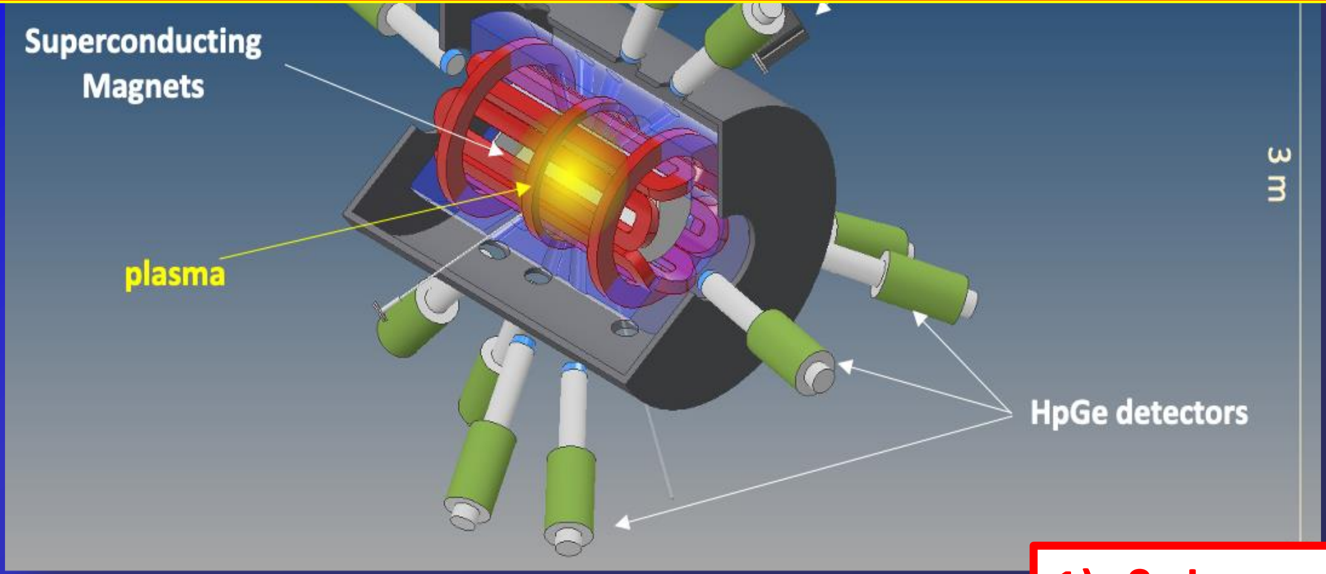
PANDORA consists of:

1) Superconducting Magnetic Plasma Trap;
2) HpGe Array;
3) Plasma Diagnostics System.

Facilities for the r-process: PANDORA

Further theoretical support: kilonovae lightcurves code to test opacities and yields

Ph.D. Thesis of Matteo Bezmalinovich



PANDORA consists of:

1) Superconducting Magnetic Plasma Trap;
2) HpGe Array;
3) Plasma Diagnostics System.

1) β-decay measurements in plasmas;

2) plasma opacity measurements in conditions similar to kilonovae ejecta