Comment sont formés les éléments lourds dans l'univers ?

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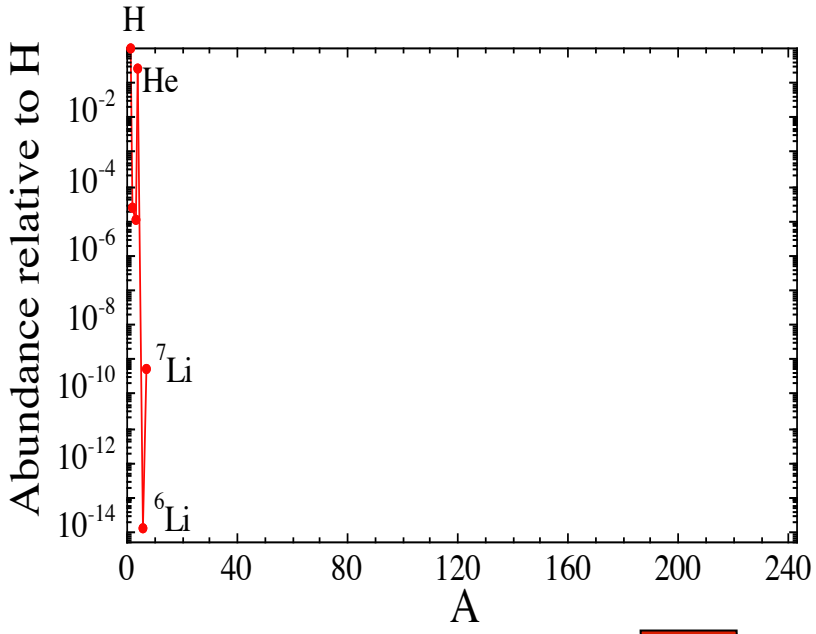
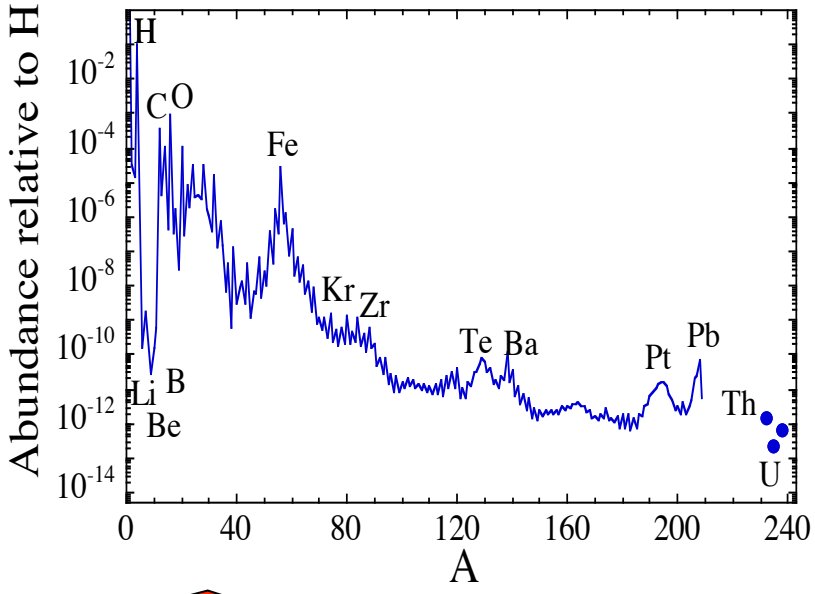
Big Bang nucleosynthesis



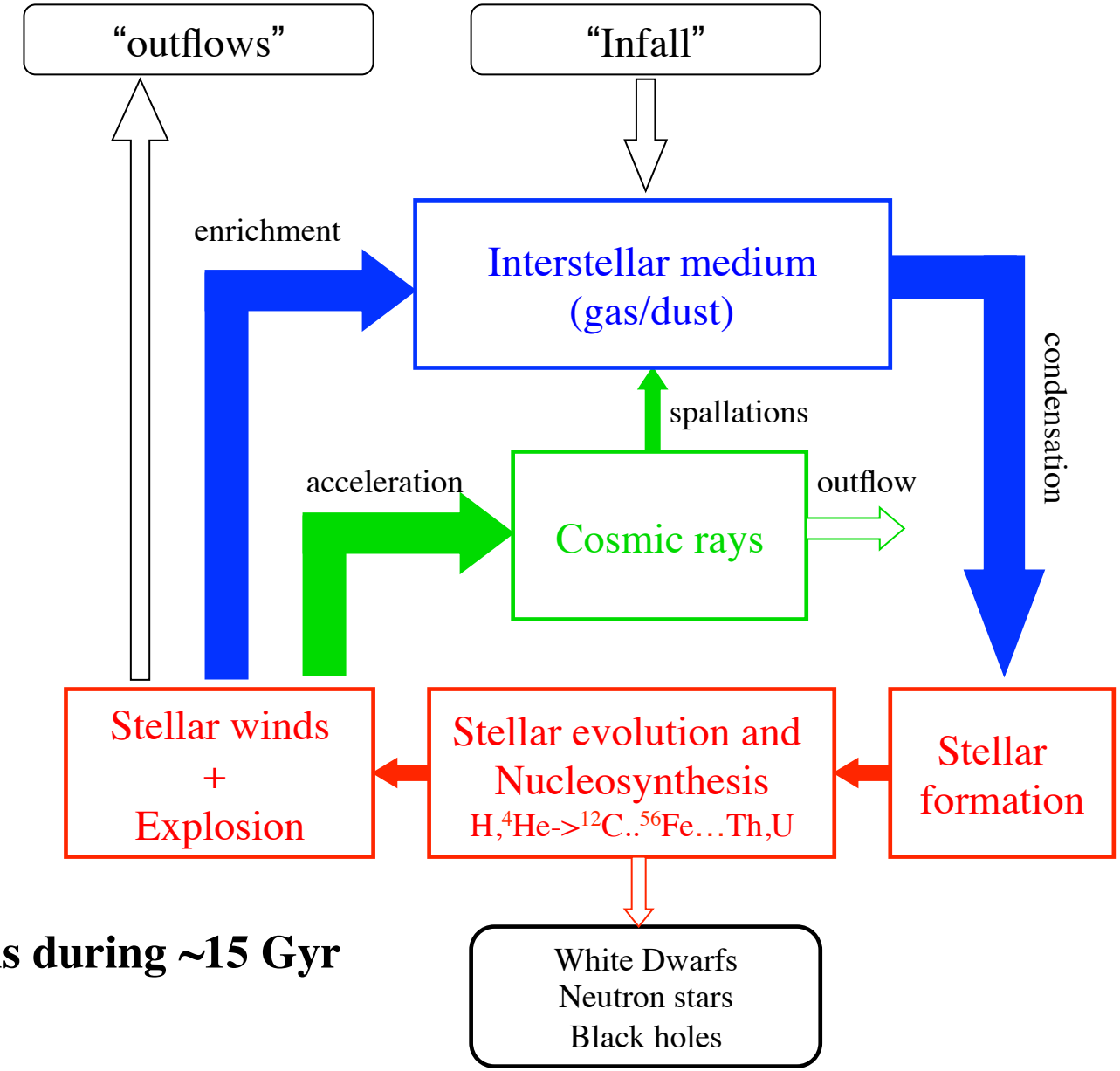
Stellar nucleosynthesis



some 15 Gy after BB

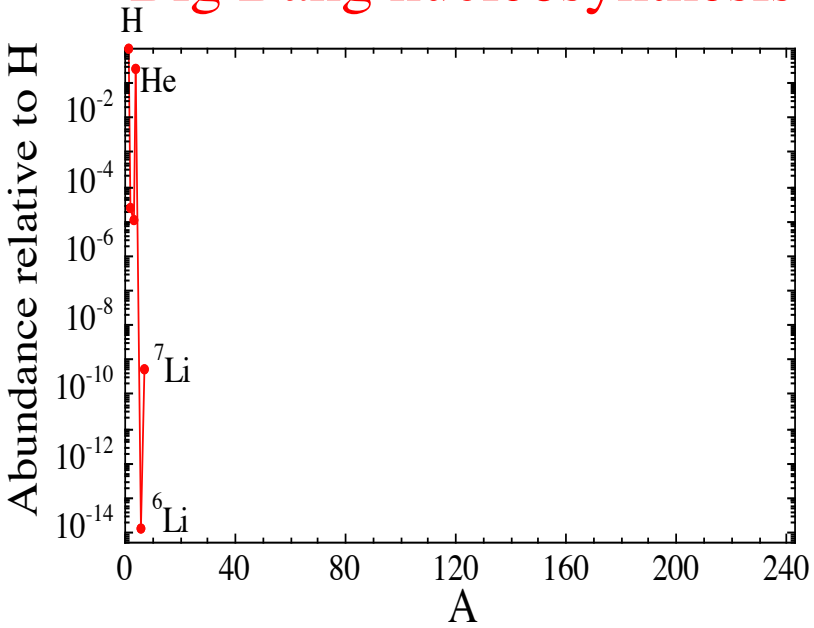
Stars are the cosmos cauldrons

Chemical evolution of the Galaxy

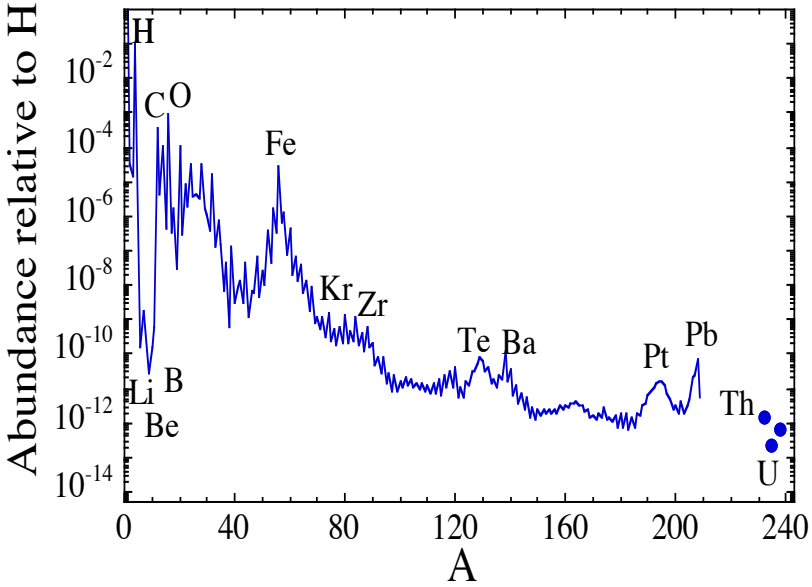


… and this during ~15 Gyr

Big Bang nucleosynthesis



Stellar nucleosynthesis

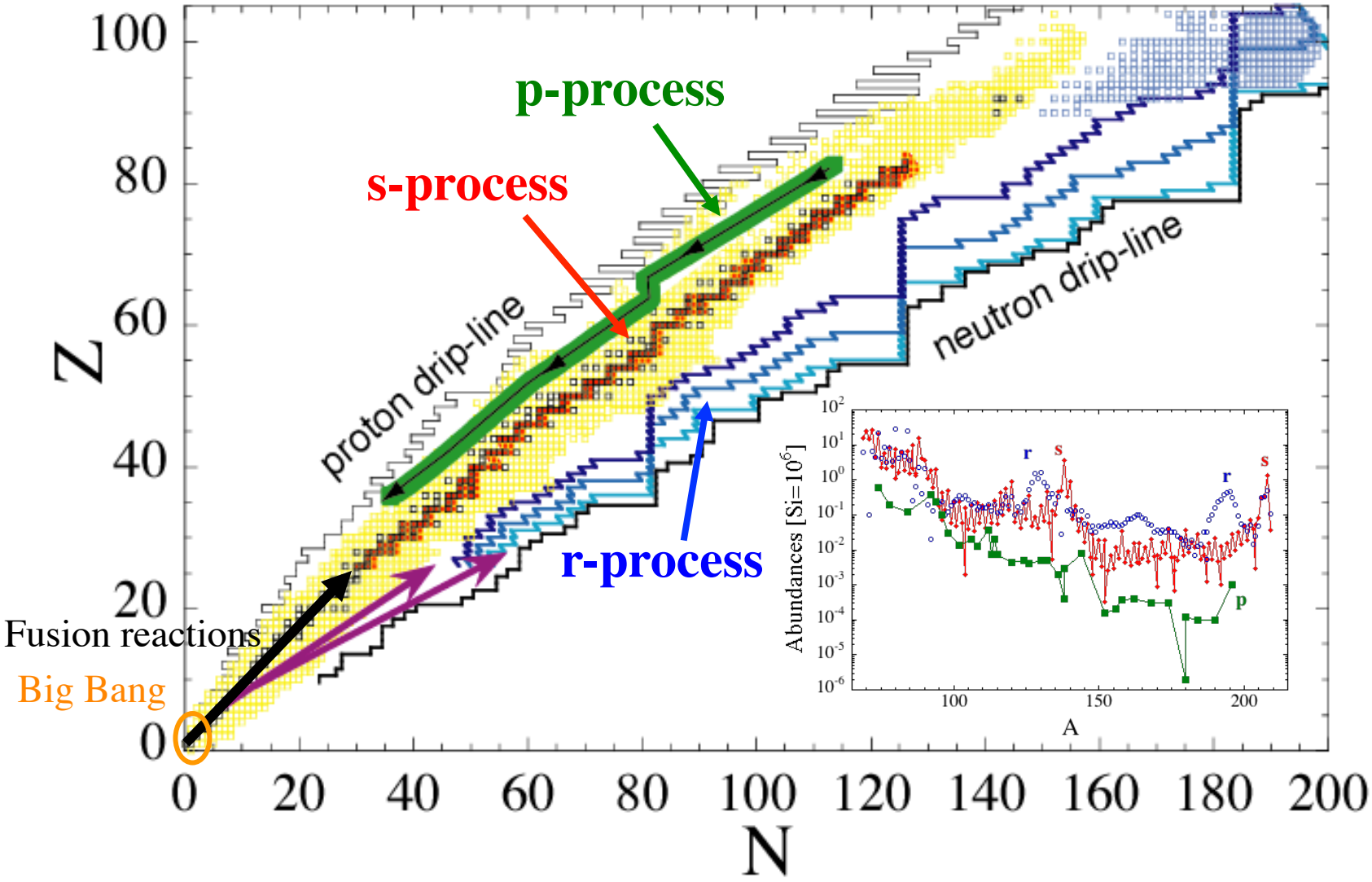


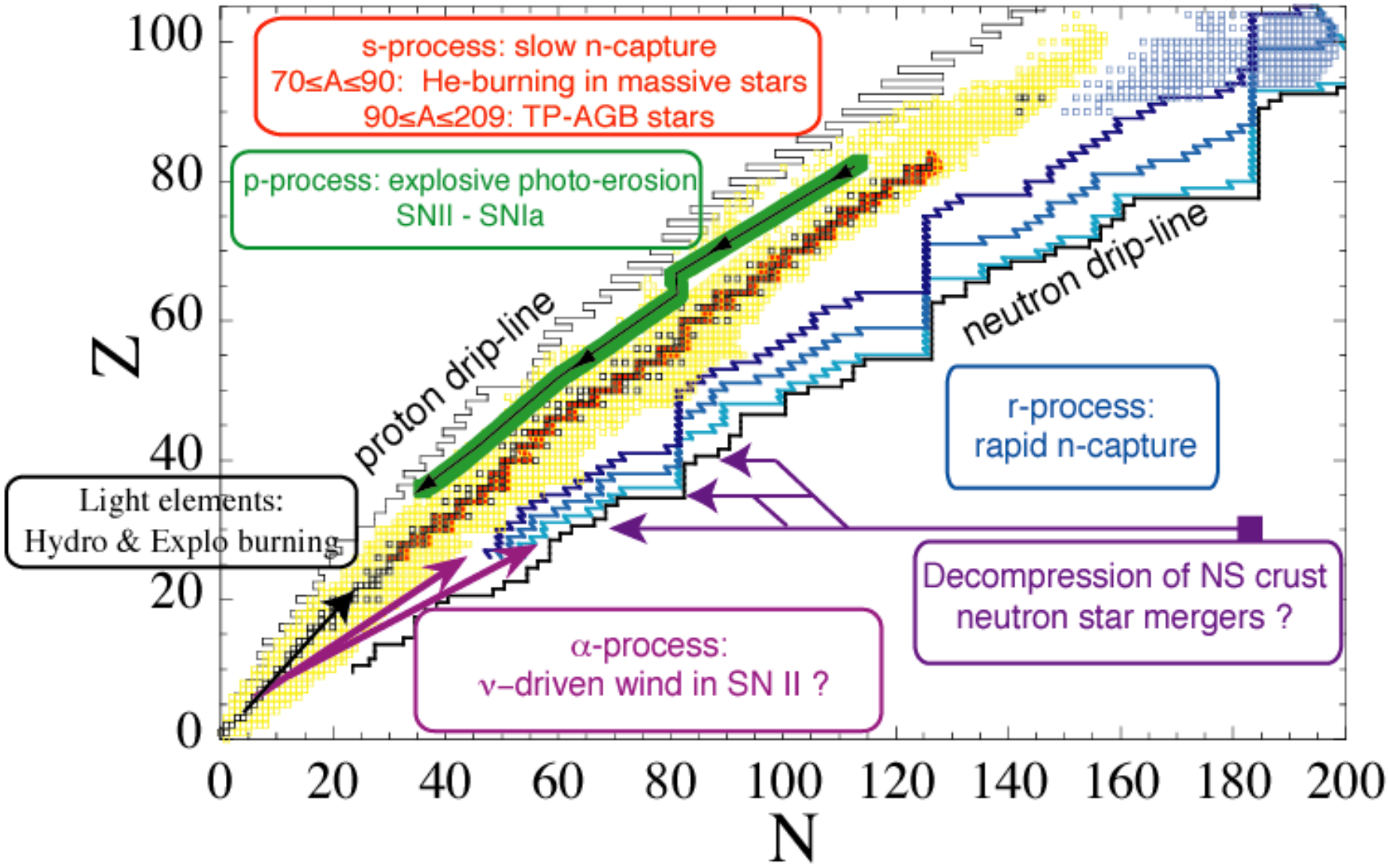
some 10 Gy after BB

Stars are the cosmos cauldrons: need to understand

- **stellar structure and stellar evolution (birth, life and death)**
- **various classes of stars (M, Z, binarity, accretion, …)**
- **interaction with cosmic rays**
- **nuclear physics properties of interacting nuclei**

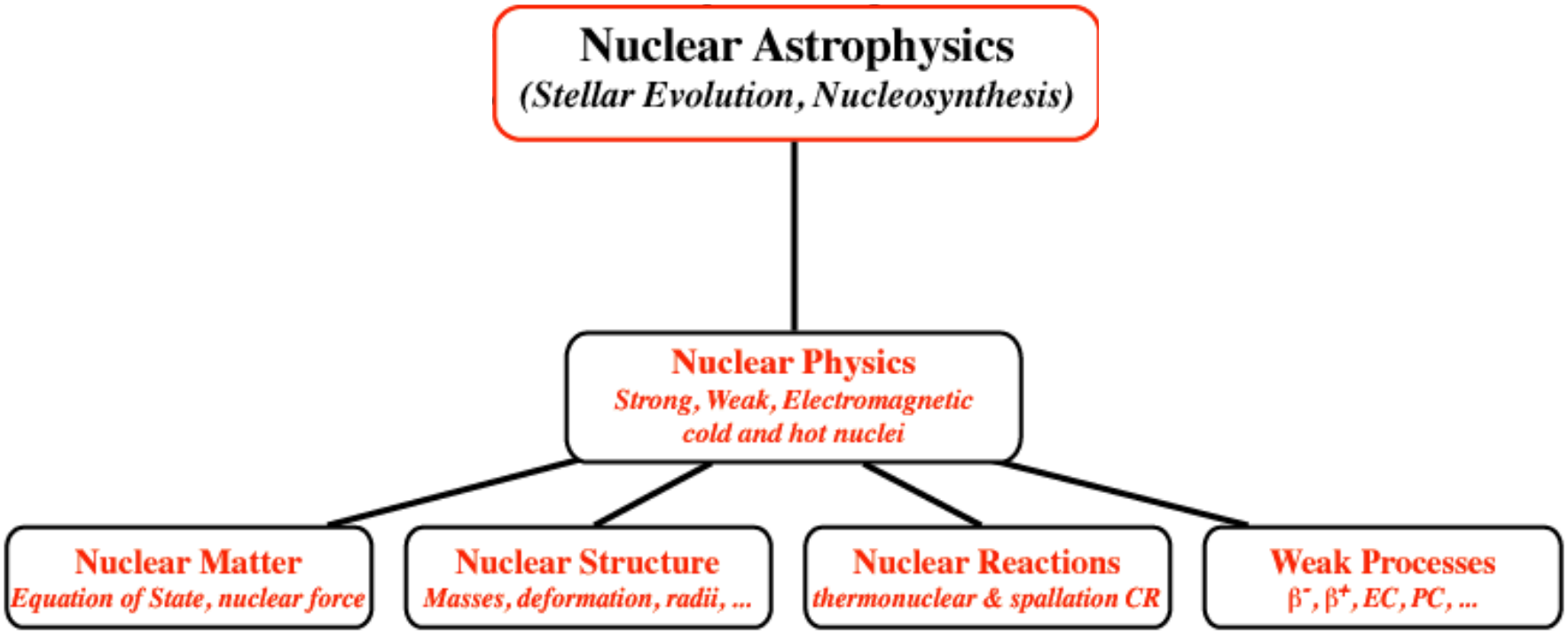
The various nucleosynthesis processes



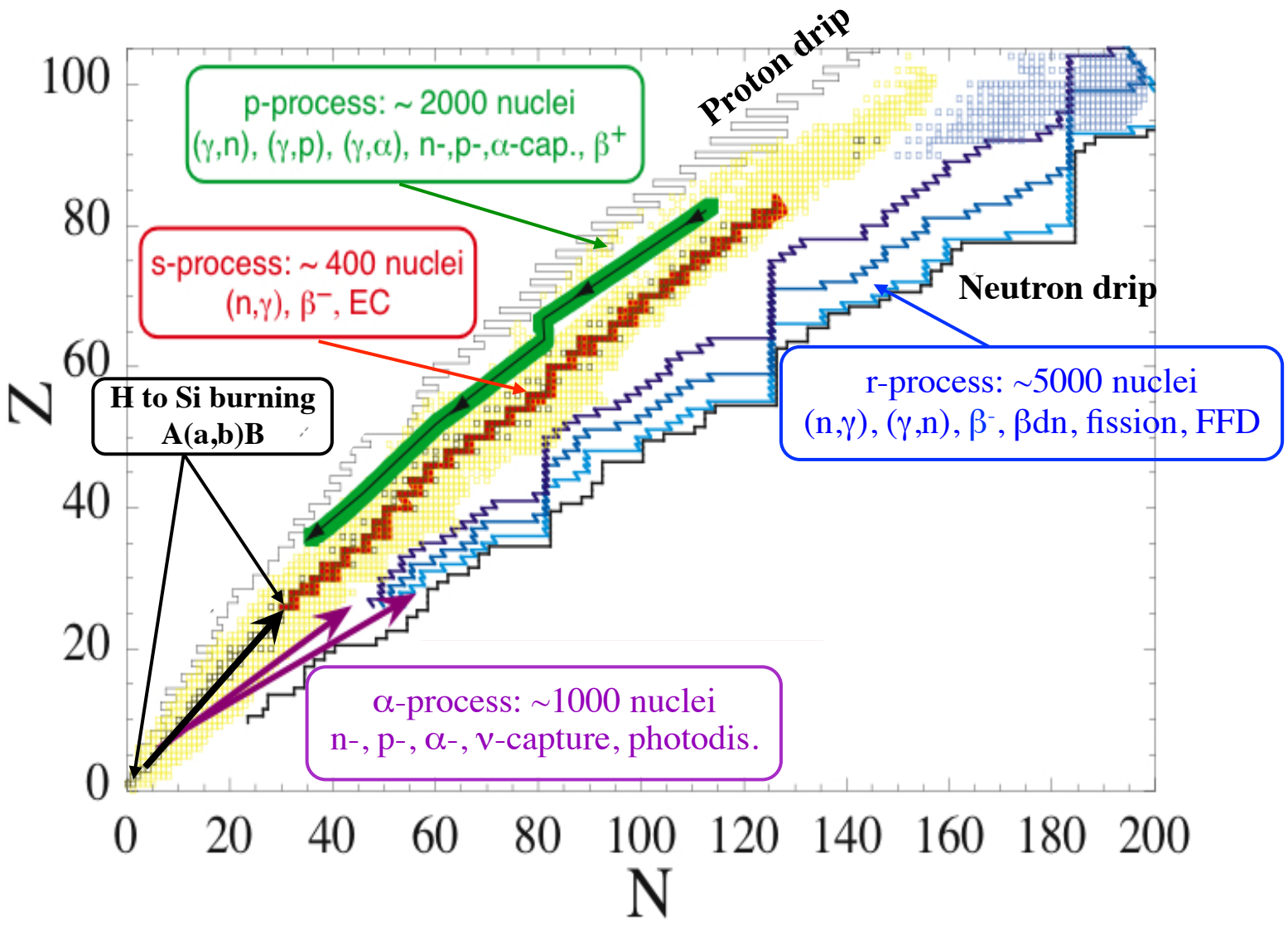

s-process: slow n-capture
70≤A≤90: He-burning in massive stars
90≤A≤209: TP-AGB stars
p-process: explosive photo-erosion
SNII - SNIa
proton drip-line
neutron drip-line
r-process:
rapid n-capture
Light elements:
Hydro & Explo burning
α-process:
ν–driven wind in SN II ?
Decompression of NS crust
neutron star mergers ?
Z
N
0
20
40
60
80
100
120
140
160
180
200

Nuclear Physics is a necessary condition for Nuclear Astrophysics

Strong correlations between stellar abundances and nuclear properties



Many different nuclear needs for the different nucleosynthesis applications



Experimental and theoretical efforts are continuously needed

Direct measurements of cross sections are limited

- Major burning phases (pp, CNO, He)
- Specific nucleosynthesis (e.g novae, supernovae, …)
- S-process nucleosynthesis
- Cosmochronometry (e.g Re/Os)

More generally, only indirect/partial information can be obtained

- $\langle \sigma v \rangle^*$ in a stellar plasma
- full energy range not accessible / regime of no event
- many nuclei (radioactive, exotic)
- many properties (n-, p-, α-, γ-capture, fission)

In MOST cases, a direct experimental determination of the reaction rate is impossible, difficult or not sufficient (easy cases are DONE) !

⟶ Theoretical models are required in a way or another…

Challenge in theoretical nuclear physics (essential for r-process applications)

PHENOMENOLOGICAL DESCRIPTION

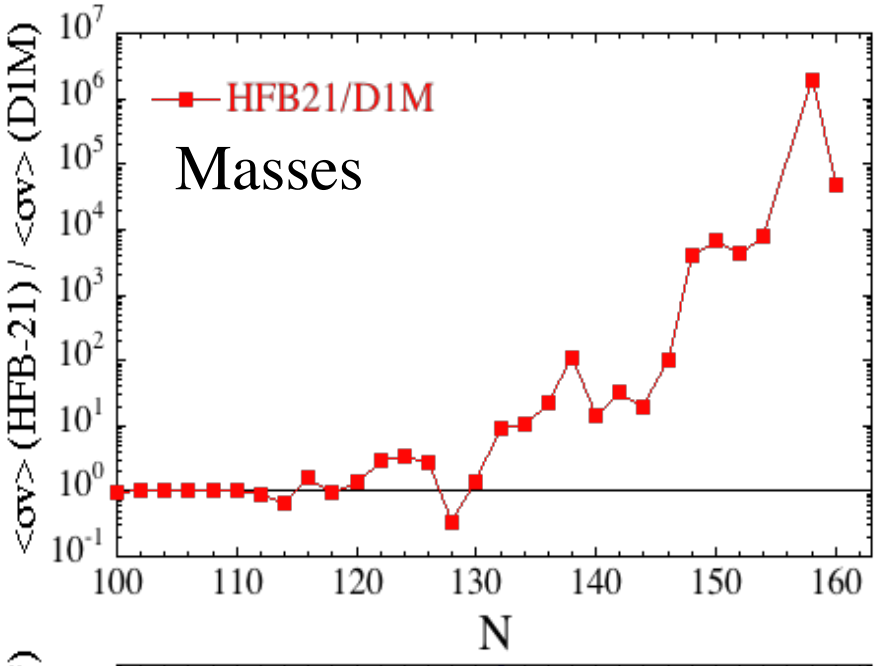
UNIVERSAL GLOBAL MICROSCOPIC DESCRIPTION

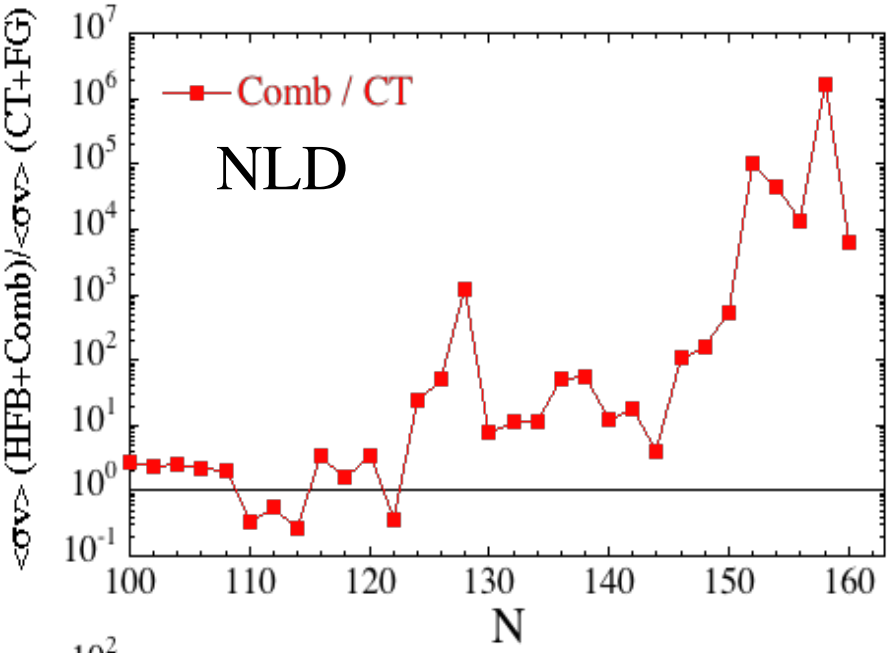
UNIVERSAL:	capable of predicting *all properties* of relevance
GLOBAL:	capable of predicting the properties of *all nuclei*
MICROSCOPIC:	for more *reliable extrapolations* from valley of stability to drip lines

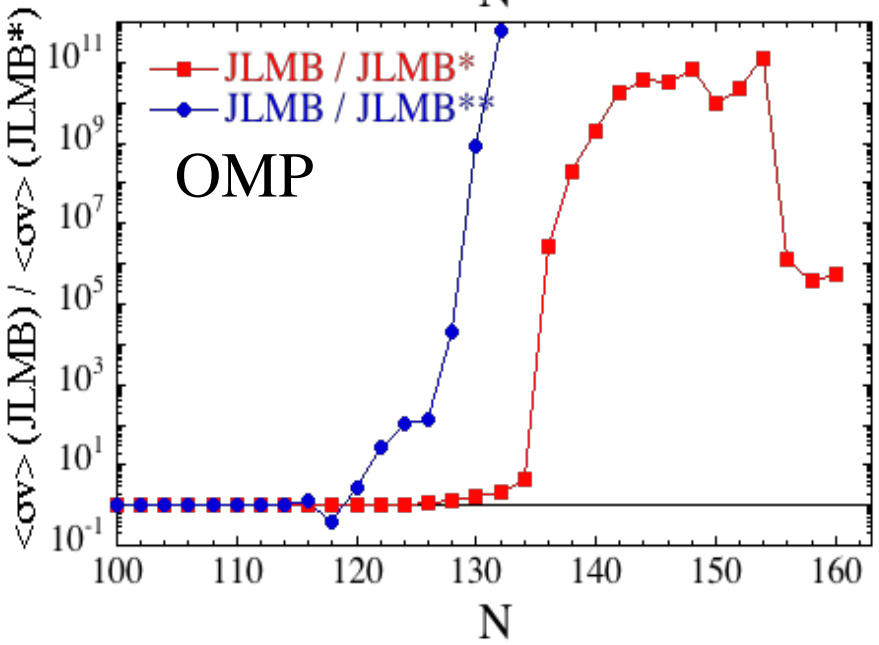
A necessary condition for a true predictive power

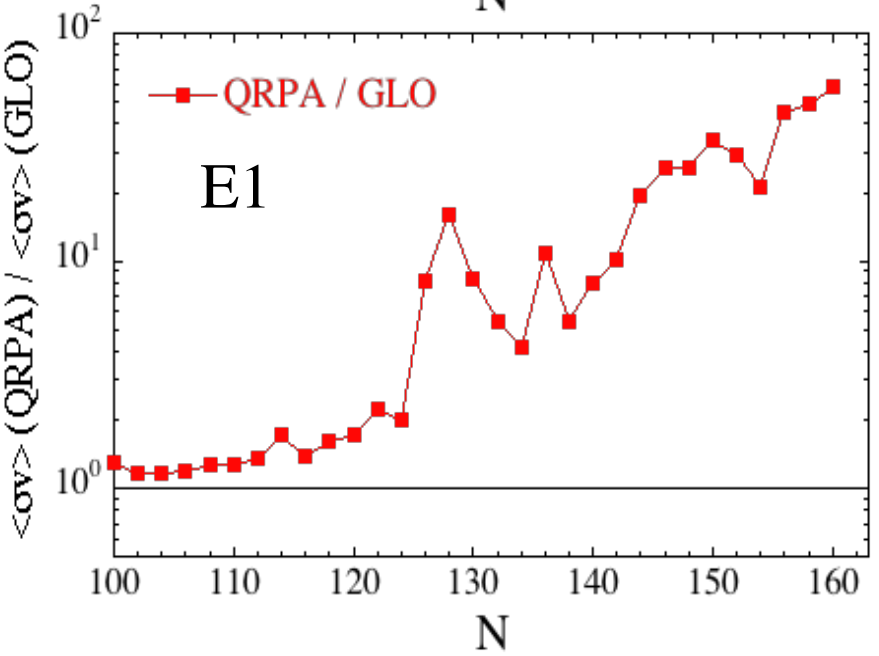
a challenge that will require a continued experimental & theoretical effort

Illustration of the impact on the $_{70}$Yb(n,γ) rates at T=10^{9}K





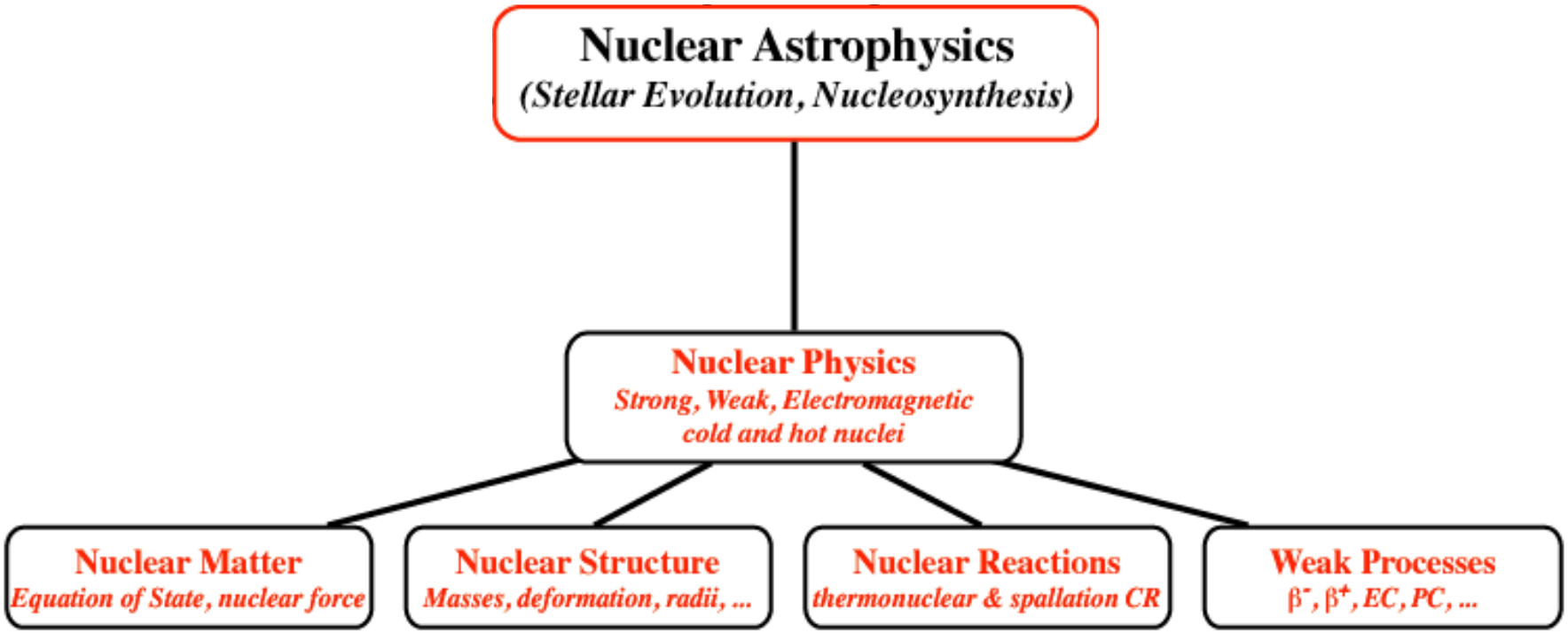




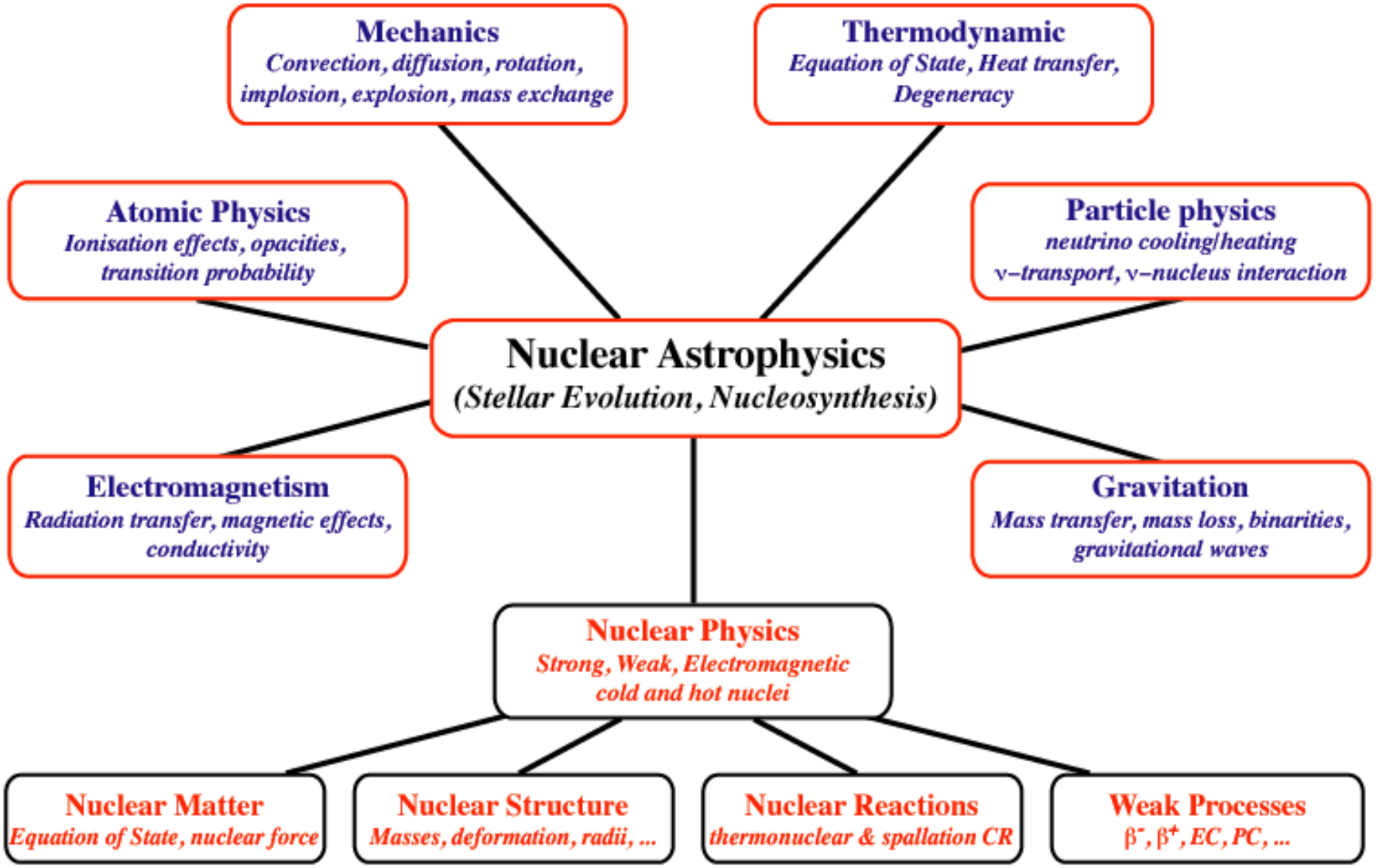
BUT

Astrophysics needs for nuclear data are defined by the sensitivity of the astrophysics predictions to the nuclear inputs

Nuclear Physics is a necessary condition for Nuclear Astrophysics



Nuclear physics is a necessary but not sufficient condition for Nuclear Astrophysics



Different types of astrophysics models

+ + – State of the art: 3D (~ self-consistent) models

p-process in SNIa explosions, r-process in NSM

+ – Realistic 1D (~ self-consistent) models

s-process in Massive Stars

– Parametrized (semi-realistic) 1D models

s-process in AGB Stars

– – Parametrized (unrealistic) 1D models

r-process in ν-driven wind

– – – Phenomenological parametrized site independent models

Canonical s- and r-processes

Remain critical about the astrophysics models

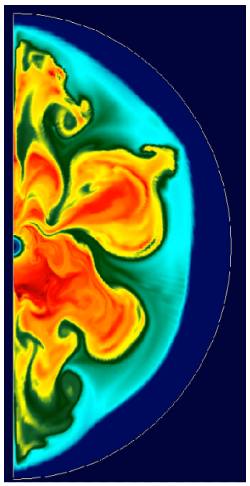
(even the 3D simulations are far from being free from astrophysical uncertainties!)

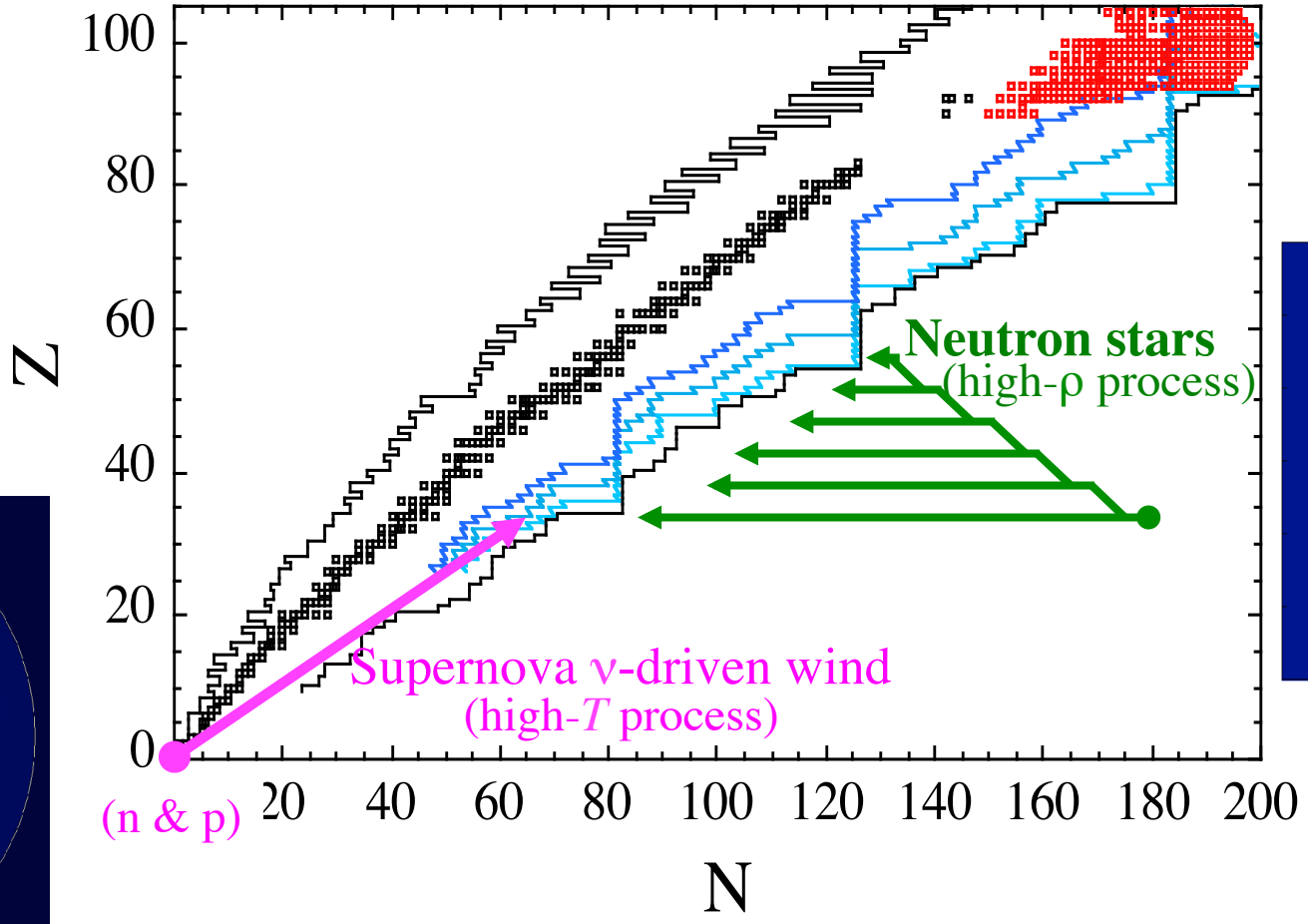
Obvious need for accurate and reliable nuclear data, … but
the uncertainties in the astrophysics models most of the time prevail

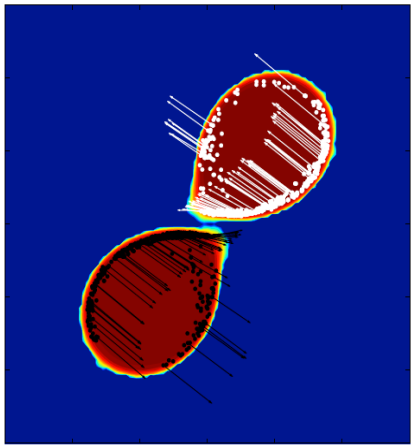
The r-process nucleosynthesis responsible for half the elements heavier than iron in the Universe

one of the still unsolved puzzles in nuclear astrophysics

… the r-process site remains unknown ...







Our understanding of the r-process nucleosynthesis, i.e. the origin of about half of the nuclei heavier than Fe in the Universe is considered as one of the top 11 questions in Physics and Astronomy

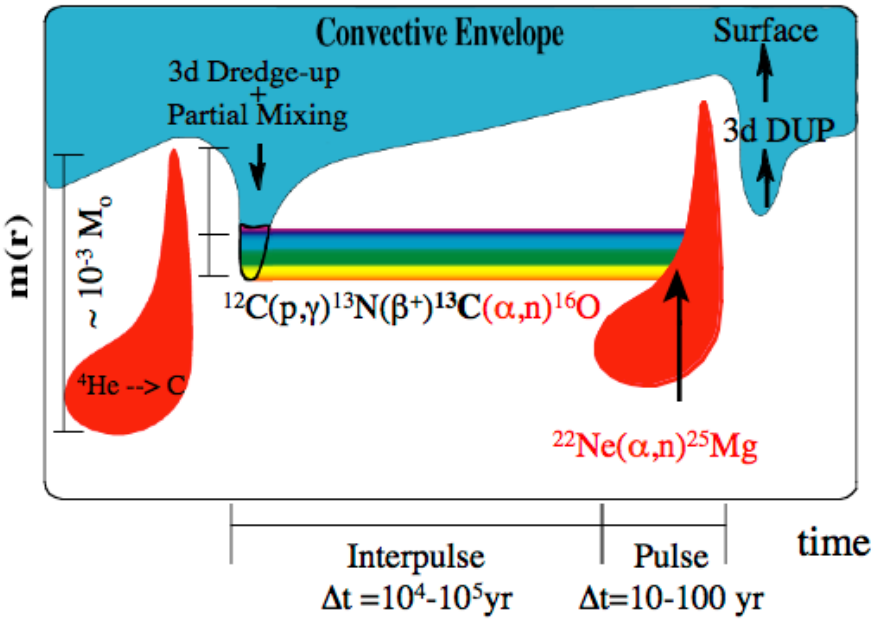
("Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century": 2003, National research council of the national academies, USA)

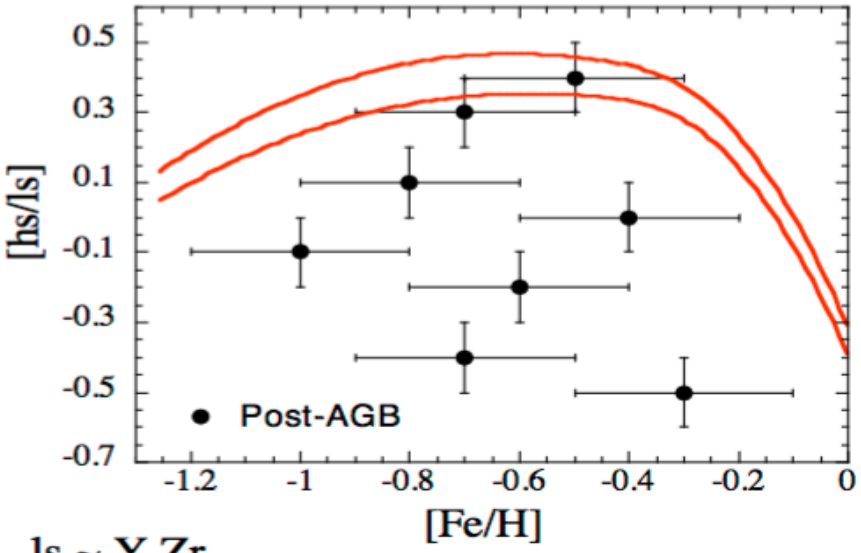
Still many open questions

- Site of the r-process ?
- Nuclear needs (site-dependent) ?
- Nuclear inputs (many properties on thousands of exotic n-rich nuclei) ?
- Galactic chemical evolution ?
- Agreement with observation (spectroscopic, GCR, …) ?

The s-process nucleosynthesis is responsible for the other half the elements heavier than iron in the Universe

- How are the neutrons produced in AGB stars ?
- What is the contributions stemming from intermediate mass AGB stars ?
- How to explain specific observations ?
- (n,γ) and T-dependent β-decay rates of branching points ?



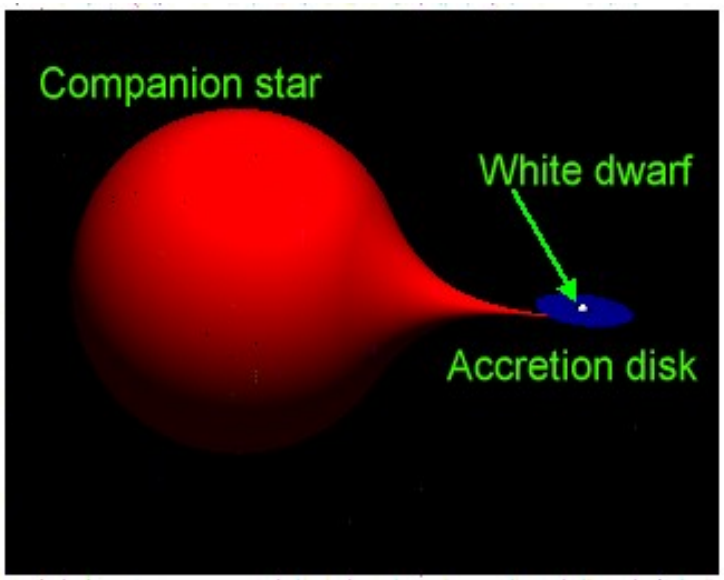


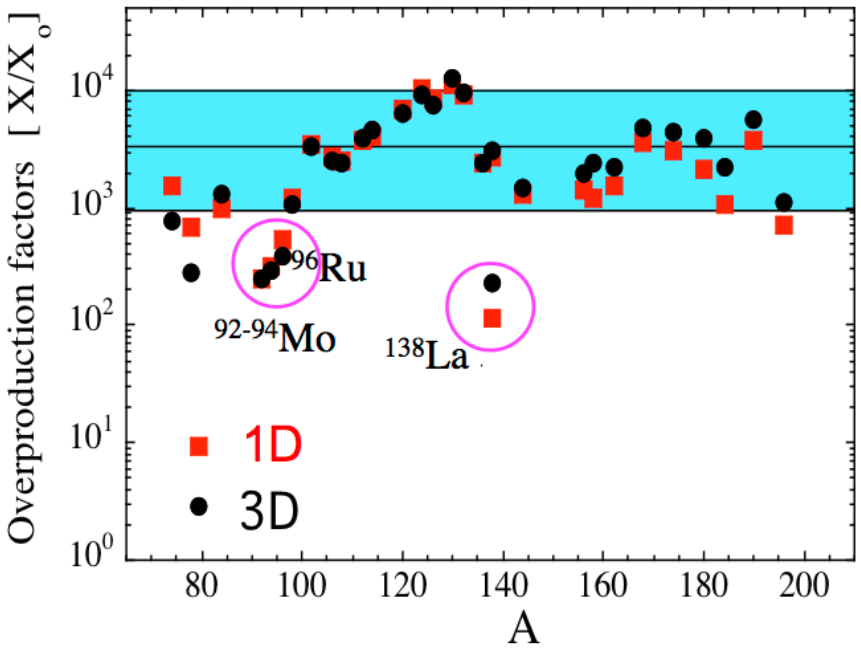
ls ~ Y,Zr

hs ~ Ba,La,Nd

The p-process nucleosynthesis is responsible for n-deficient elements heavier than iron in the Universe

- How to explain the origin of ^{92,94}Mo, ^{96}Ru, ^{138}La ?
- What is the contributions of SN Ia or p-rich ν-wind, if any ?
- What are the seed nuclei feeding the p-process ?
- What is the photodissociation rates of nuclei involved ?
- What is the role of neutrinos for rare species ?





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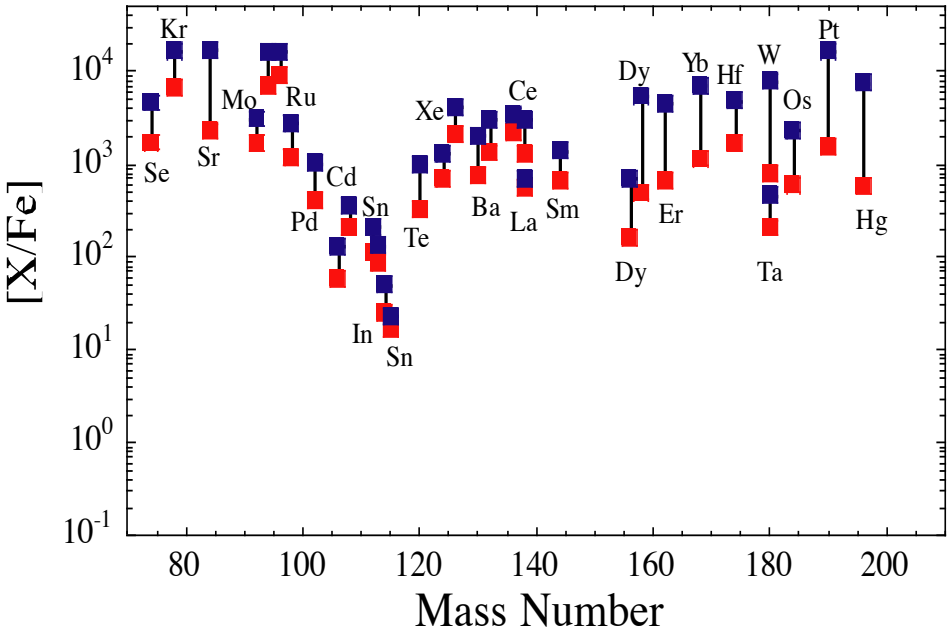
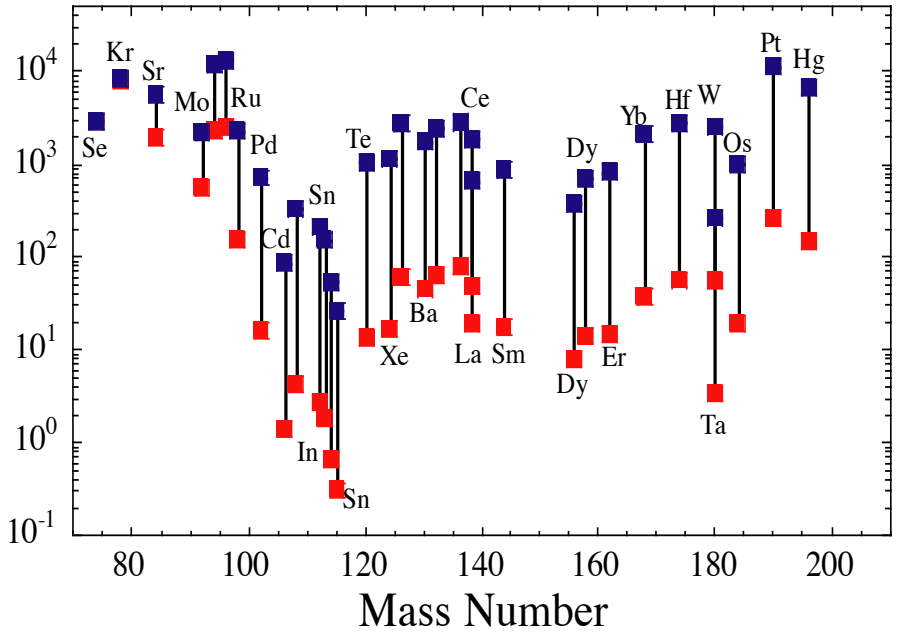
Impact of the nuclear uncertainties on the p-nuclide overproduction factor



Impact of the initial seed abundances on the p-nuclide overproduction factor



Conclusions

	ASTRO	NUCLEAR	OBS
BIG-BANG	+	+	+
A<56 SYNTHESIS	+	+	+
S-PROCESS	–	+ –	+ –
P-PROCESS	–	–	–
R-PROCESS	– –	– –	–

Conclusions

Role of Nuclear Physics is to provide the best nuclear (exp & th) physics inputs

Nuclear physics is a necessary but a not sufficient condition for Nuclear Astrophysics

The exact role of nuclear physics in Astrophysics will remain unclear as long as the astrophysics sites and the exact nuclear mechanisms of relevance are not fully under control

P-process (-/+) S-process (+/-) R-process (–)

Need to develop a 'real' nuclear astrophysics community !