Nuclear Astrophysics (I)

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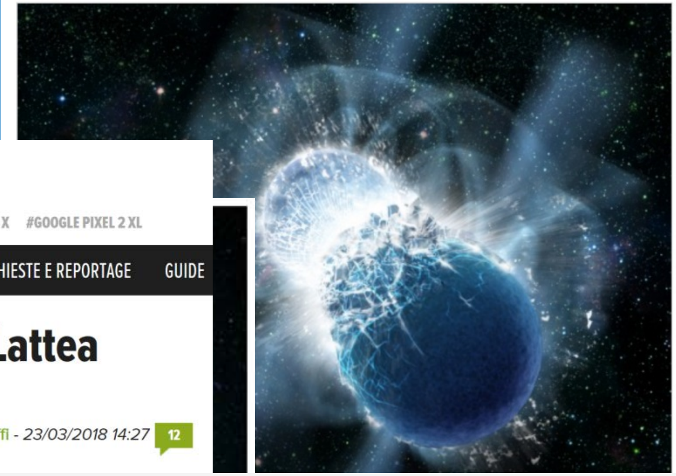
Nelle galassie nane il segreto dell'oro più antico dell'Universo

L'oro della Terra creato da collisioni stellari

Il prezioso metallo presente sul nostro pianeta sarebbe stato formato dalla collisione di due stelle di neutroni, secondo un nuovo studio che ha analizzato un lampo di raggi gamma

di Andrew Fazekas



Le stelle svelano il segreto dell' oro e del platino

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Collisione tra due stelle, la Via Lattea diventa una miniera d'oro

di Andrea Zuffi - *23/03/2018 14:27* 12

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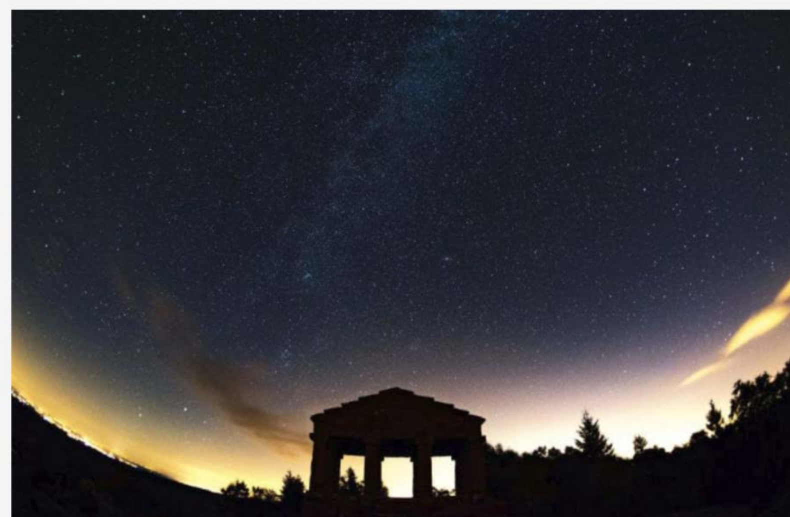
L'oro e gli altri elementi pesanti derivano dai collassi stellari?

L'oro e gli altri elementi pesanti si formano alla fine della vita delle stelle di maggiori d
All'inizio, in tutti i corpi stellari si trovano solo elementi leggeri: idrogeno e elio....

Una miniera d'oro nello spazio nata dalla collisione di due stelle



In their internal covering there are europium and terbium.

Europium provides the red and blue, terbium and yttrium give yellow and green.

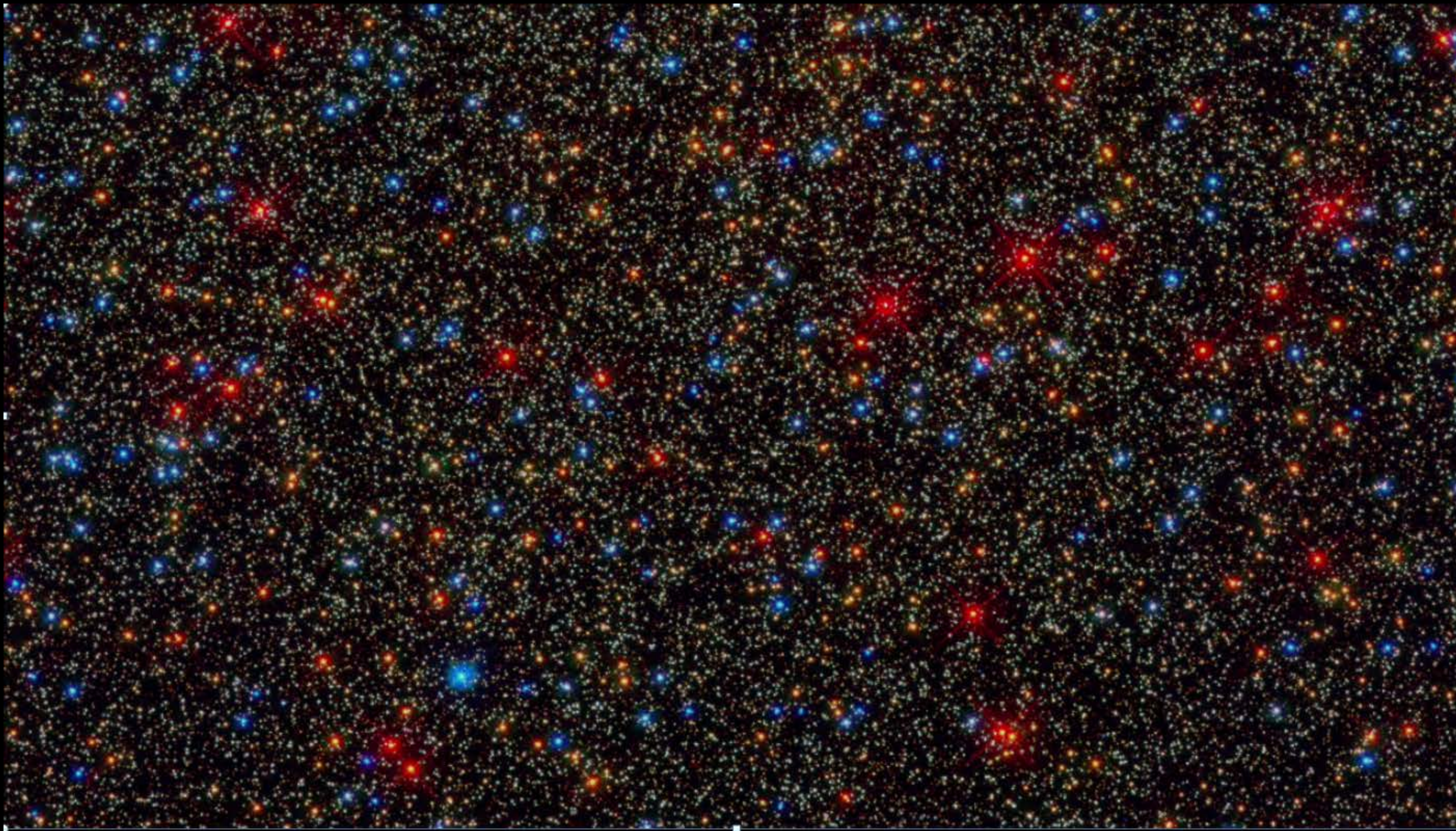
Hard disks need dysprosium. Erbium needed to speed signals via optic fibers.

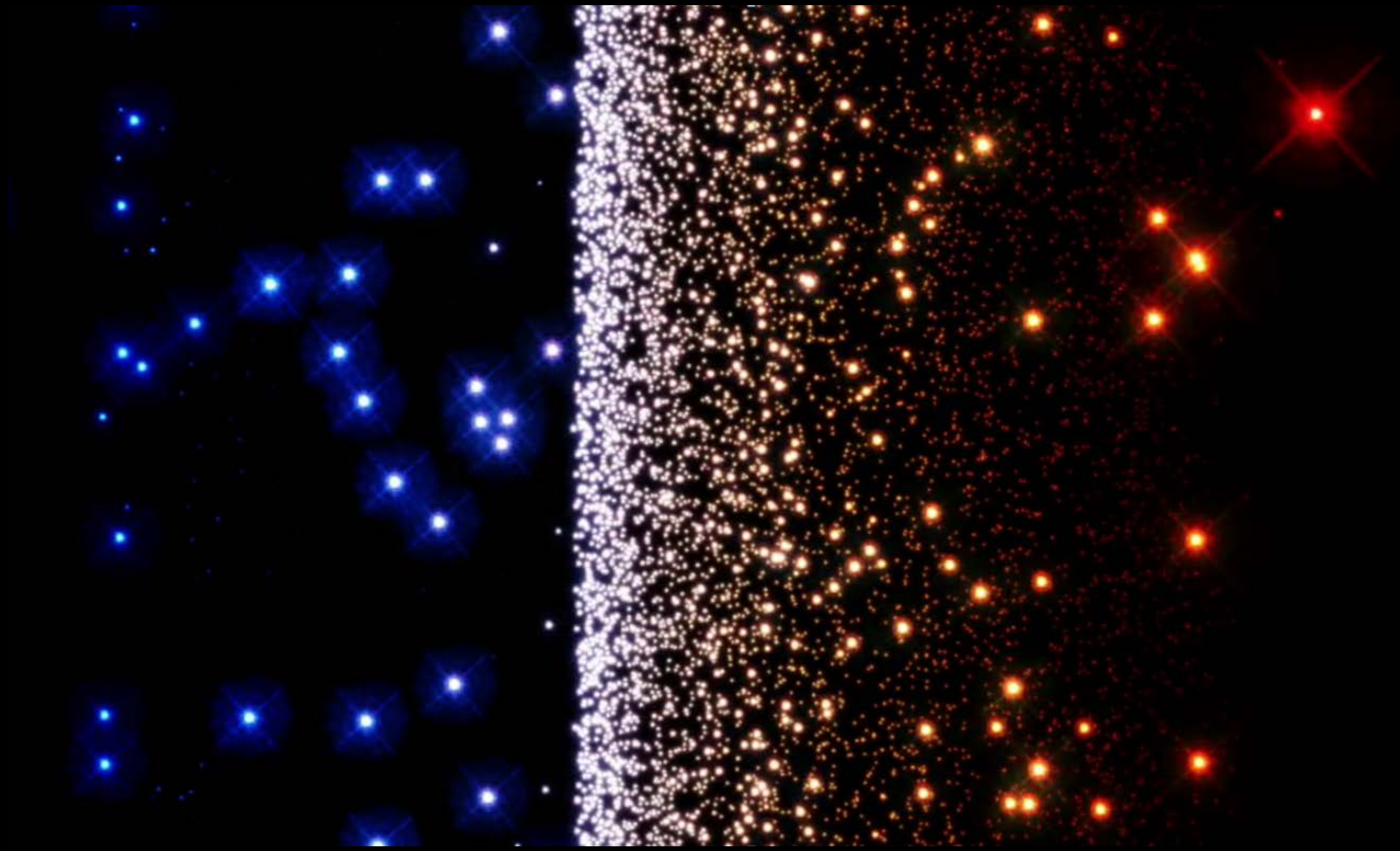
Touchscreen is made possible by indium.

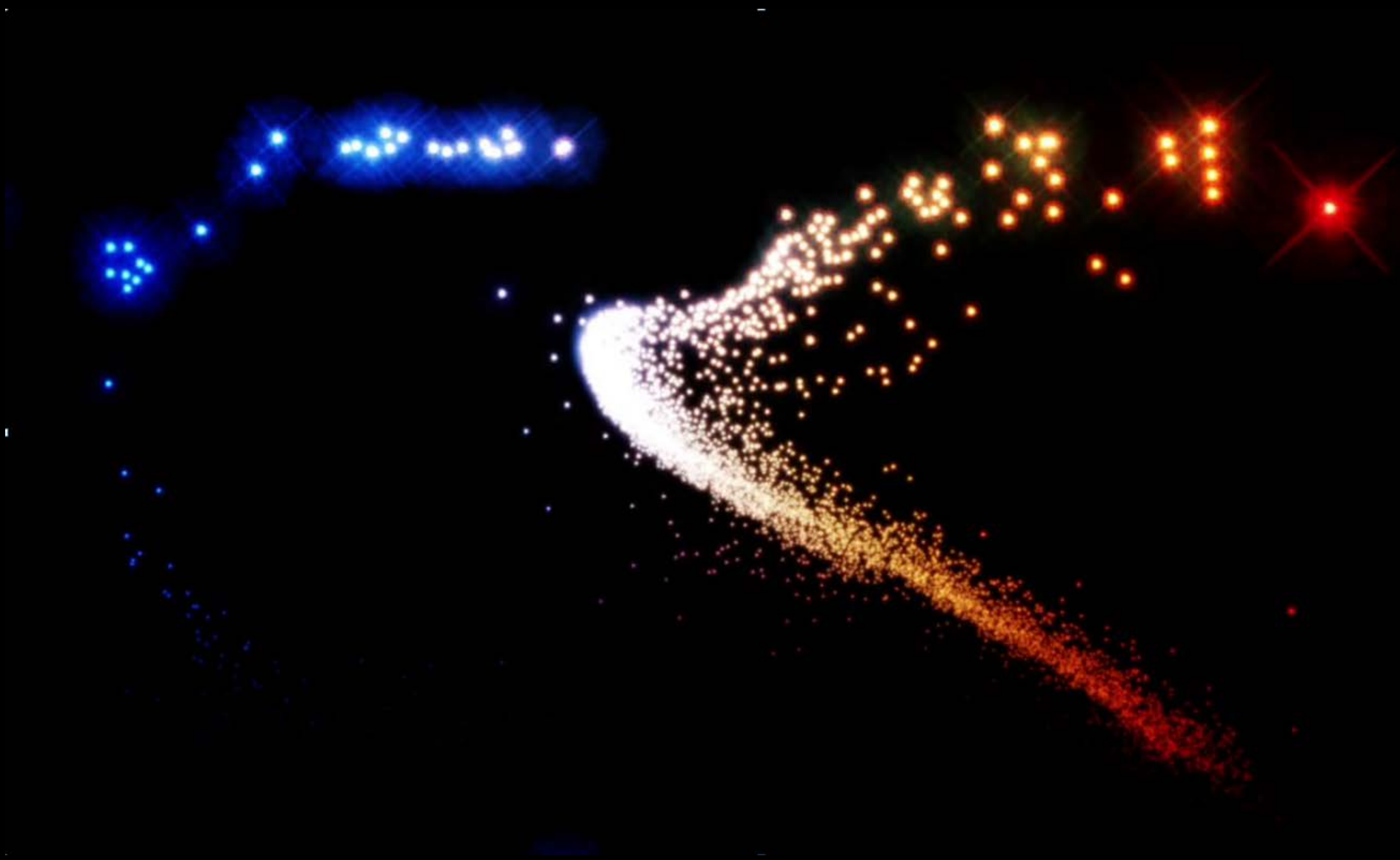
Tellurium and indium are crucial for new generation of solar panel.

Outlook

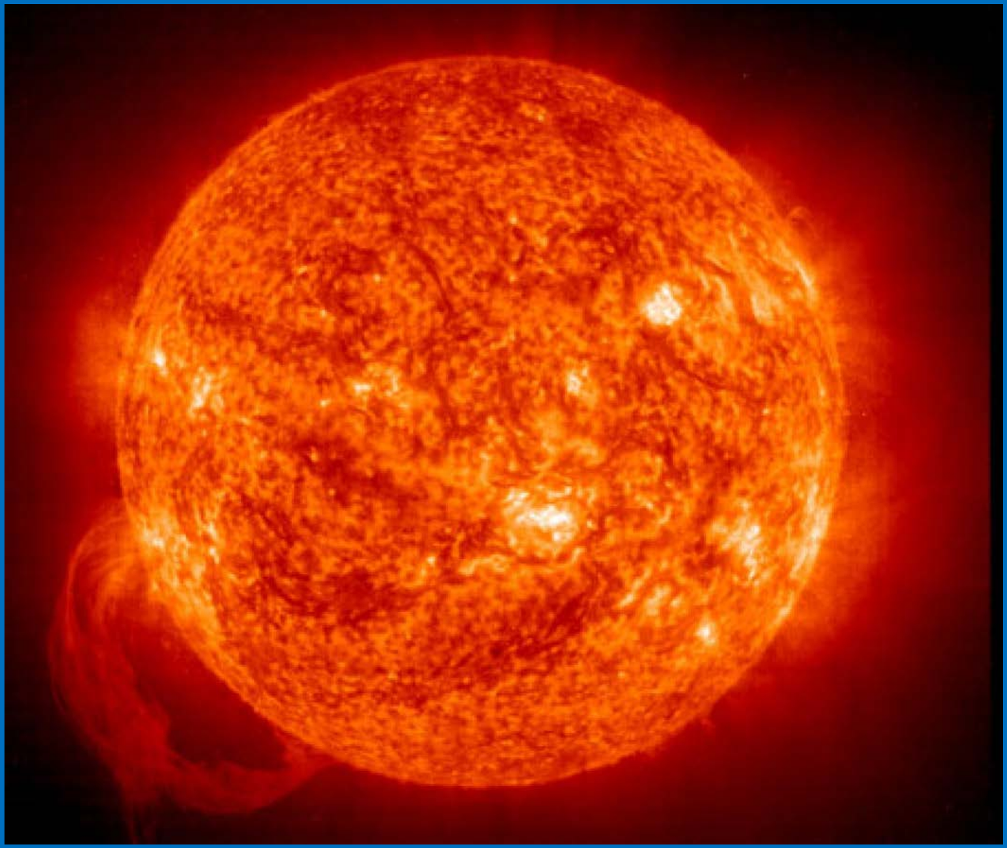
- Introduction: some basic concepts
- The rapid neutron capture process (r-process)
- Neutron Stars Mergers (NSMs) and the MAIN component of the r-process
- Magnetorotational driven Supernovae and the WEAK component of the r-process
- The slow neutron capture process (s-process)
- Asymptotic Giant Branch (AGB) stars and the MAIN component of the s-process
- Massive star and the WEAK component of the s-process
- Nuclear astrophysics in laboratory, a case study: the nTOF experiment







How do we know that nuclear reactions occur inside stars?



Four atoms of hydrogen form an atom of helium:

Bethe & Critchfield (1938)
[pp chains]

Bethe 1939; von Weizsäcker 1938
[CNO cycle]

Gain from nuclear binding energy

$4\ {}^{1}H \rightarrow {}^{4}He + 2e^{+} + 2\nu_e$

600 tons of ^{1}H in 596 tons of ^{4}He each second

GRAVITY

ELECTROMAGNETIC
FORCE

OPERATE AT DIFFERENT SCALES, IN TERMS OF DISTANCES AND COUPLING STRENGHTS, BUT…

WEAK
FORCE

STRONG
FORCE

NUCLEAR ASTROPHYSICS

GRAVITY

It governs stellar evolution and regulates the energy loss during mergers episodes via emission of gravitational waves.

ELECTROMAGNETIC FORCE

It limits the formation of heavy elements via fusion processes and overwhelmes the strong force in fissioning processes.

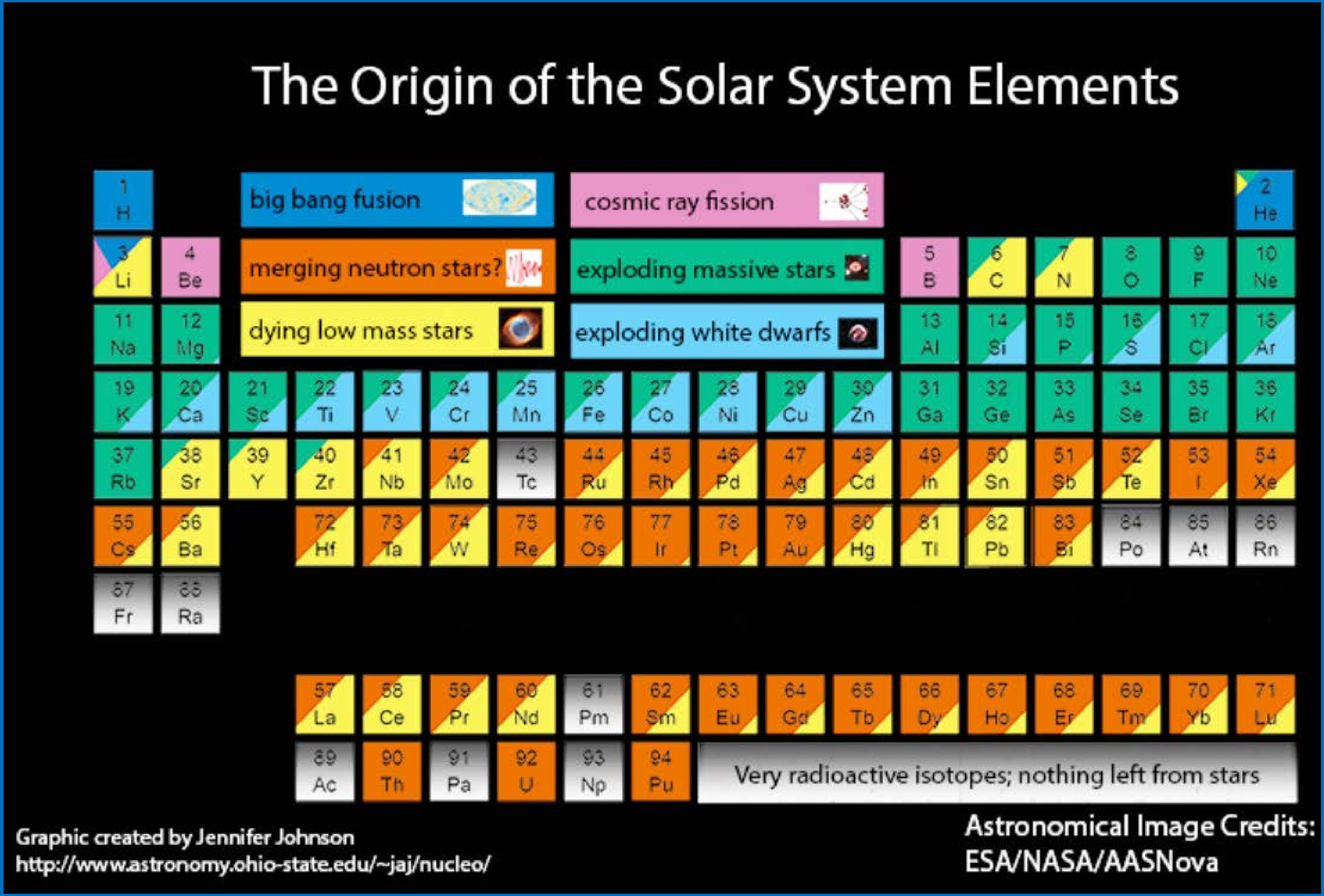
WEAK FORCE

It has a lasting effect on nuclear compositions via nuclear β-decays and interactions with leptons.

STRONG FORCE

It is highly attractive on extremely small distances, allowing the existence of nuclei of higher complexity.

Astronomy Picture of the Day



https://apod.nasa.gov/apod/ap171024.html

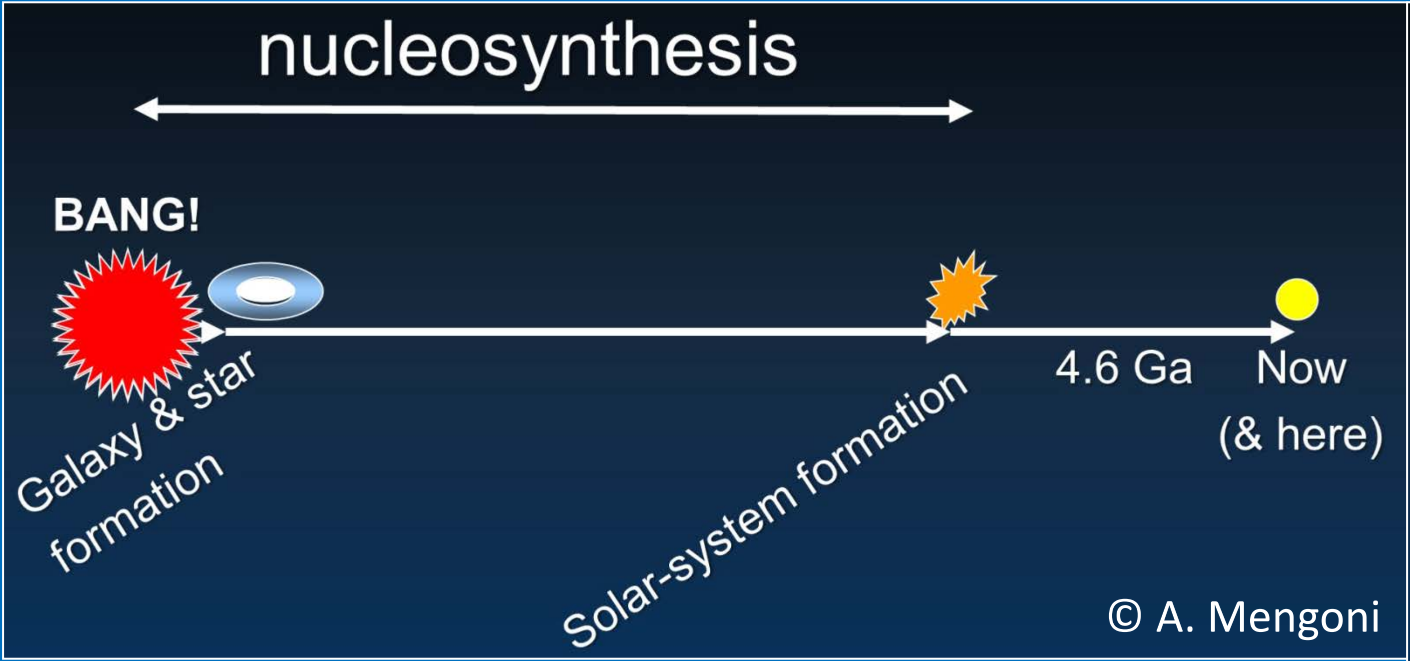
Some minutes after the BIG BANG ($\Delta t=0$) there were basically only hydrogen (≈75%) and helium (≈25%).

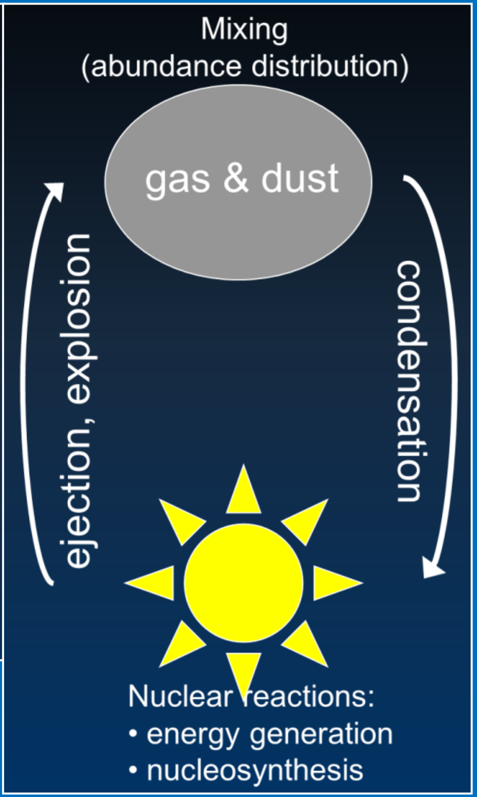
At the FORMATION OF THE SUN ($\Delta t \approx 9.1$ Gyr) there were 71% of hydrogen and 27% of helium. The remaining 2% are heavy elements (or metals).

TODAY ($\Delta t=13.7$ Gyr) , in star forming regions hydrogen is about 65%, helium is about 31% and metal constitute the remaining 4%

H ↓ He ↑ Metals ↑

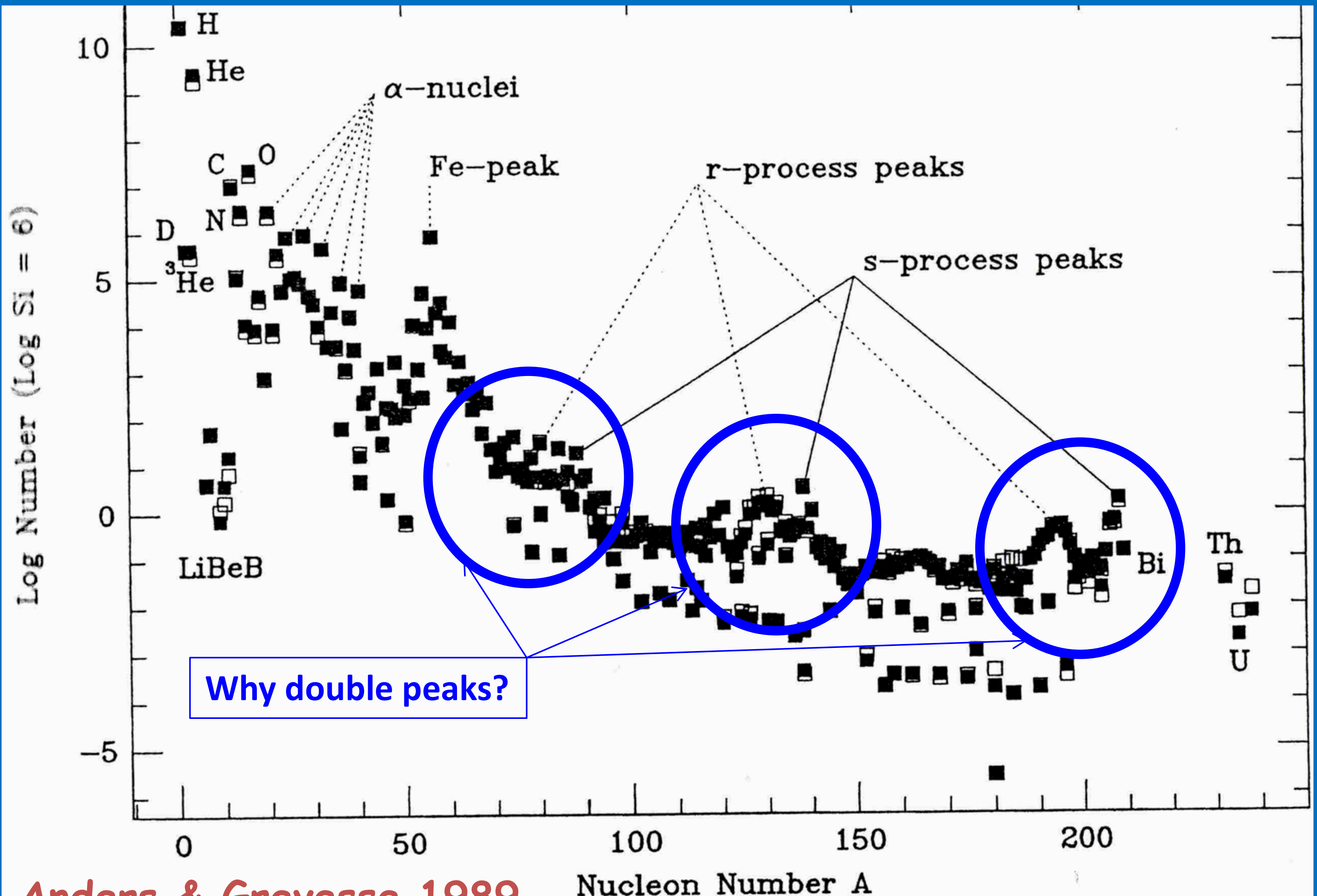
Our Galactic "heritage"





"We are stardust"
Joni Mitchell, Woodstock

Solar System Abundances



Anders & Grevesse 1989
Cameron 1982

FUNDAMENTAL CONCEPTS (1)

$$a+b \rightarrow c+d$$

$$\frac{dn_a}{dt} \propto n_a n_b < \sigma v >$$

FUNDAMENTAL CONCEPTS (2)

- **Cross section**

Unit: 1 barn=10^{-24} cm^2

$$\sigma = \frac{\text{(n of interaction per time)}}{\text{(n of incident particles per area per time) (n of target nuclei within the beam)}}$$

- **Stellar cross section**

In stars, reactions also occur on thermally excited target states, thus the stellar cross section is defined as the sum of the cross sections for those excited states with their excitation energies and spins, weighted by the Boltzmann excitation probability:

$$\sigma^* = \frac{\sum_x (2J_x + 1)\,\sigma^x e^{-\frac{E_x}{kT}}}{\sum_x (2J_x + 1)\,e^{-\frac{E_x}{kT}}} .$$

FUNDAMENTAL CONCEPTS (3)

$$\langle \sigma v \rangle_{12} = \int_0^\infty \sigma(v)\, v\, \Phi(v)\, \mathrm{d}v$$

Product of the reaction cross section σ and the relative velocity v of the interacting nuclei, averaged over the collisions in the stellar gas

The stellar cross section is determined by folding the stellar reaction cross section with a Maxwell-Boltzmann distribution of relative velocities between projectiles and targets (Fowler 1974):

$$m = \frac{m_a m_b}{m_a + m_b}$$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi m}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{k_B T}\right) dE$$

FUNDAMENTAL CONCEPTS (4)

$$\sigma(E) = \frac{1}{E} S(E) e^{-2\pi\eta}$$

S(E): S-factor and accounts for the short distance dependence of the cross section on the nuclear potential.

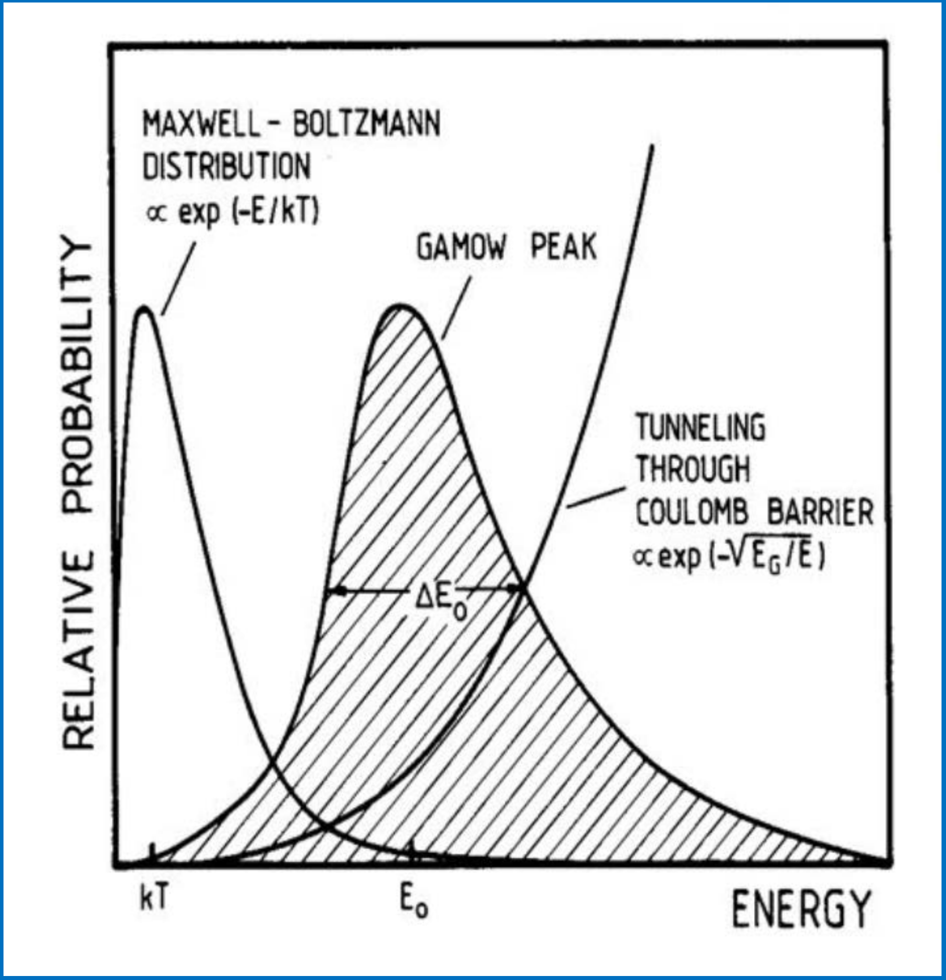
$$\eta = \frac{Z_a Z_A e^2}{\hbar} \sqrt{\frac{m}{2E}} = \frac{b}{E^{1/2}}$$

η: Sommerfeld parameter which accounts for tunneling through a Coulomb barrier.

$$N_{AV} \langle \sigma v \rangle = \left(\frac{8}{\pi m}\right)^{1/2} \frac{N_{AV}}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}}\right] dE$$

Stellar Reaction rate

The Gamow peak

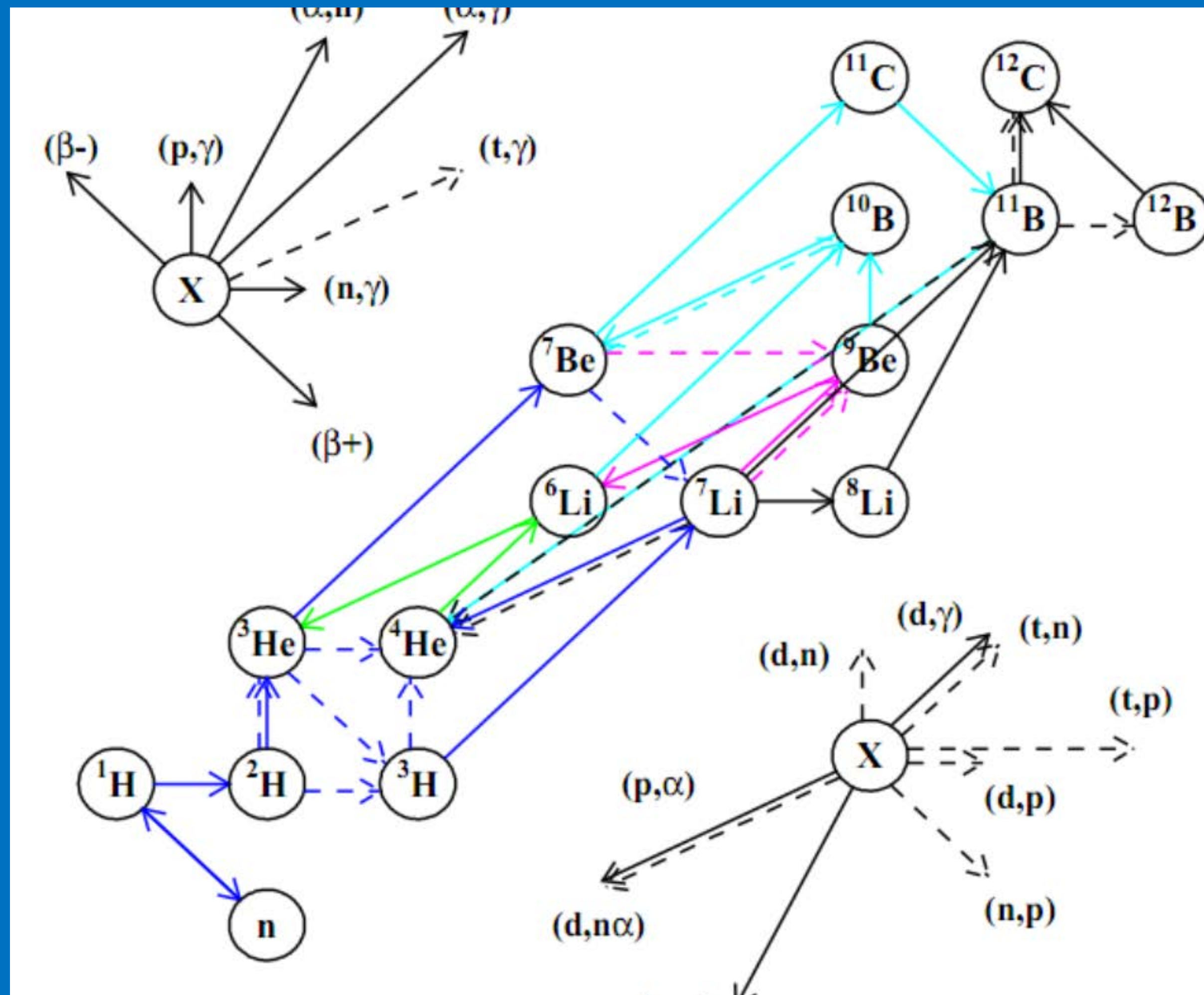


It identifies the energy range over which most nuclear reactions occur in a plasma

Nuclear network sizes (1)

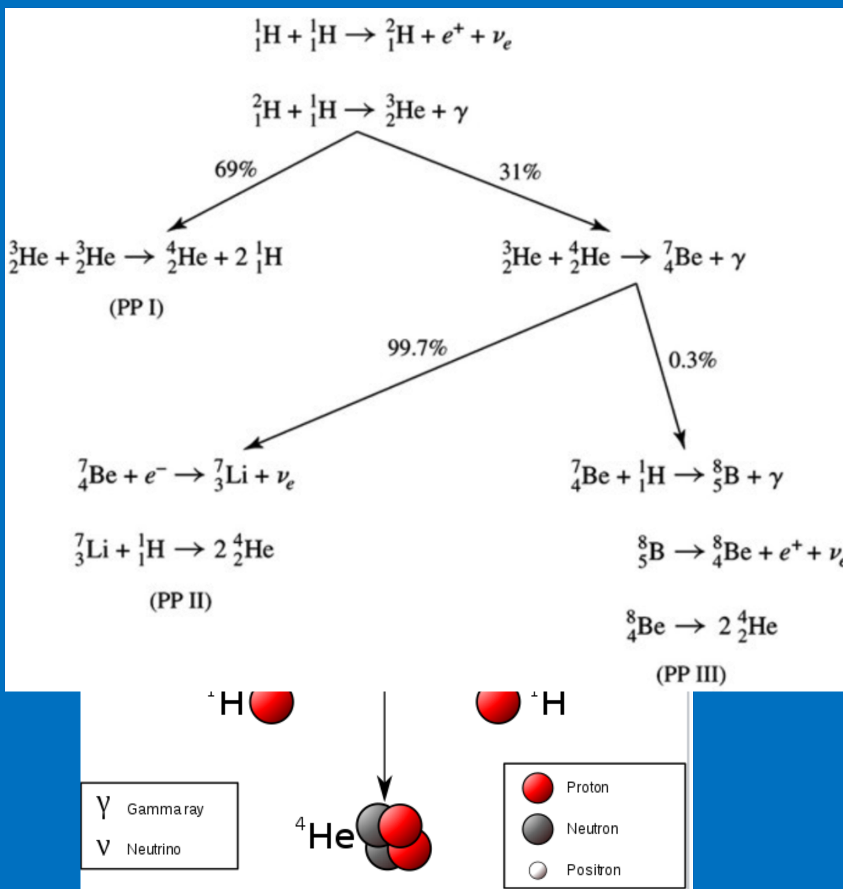
Big Bang Nucleosynthesis

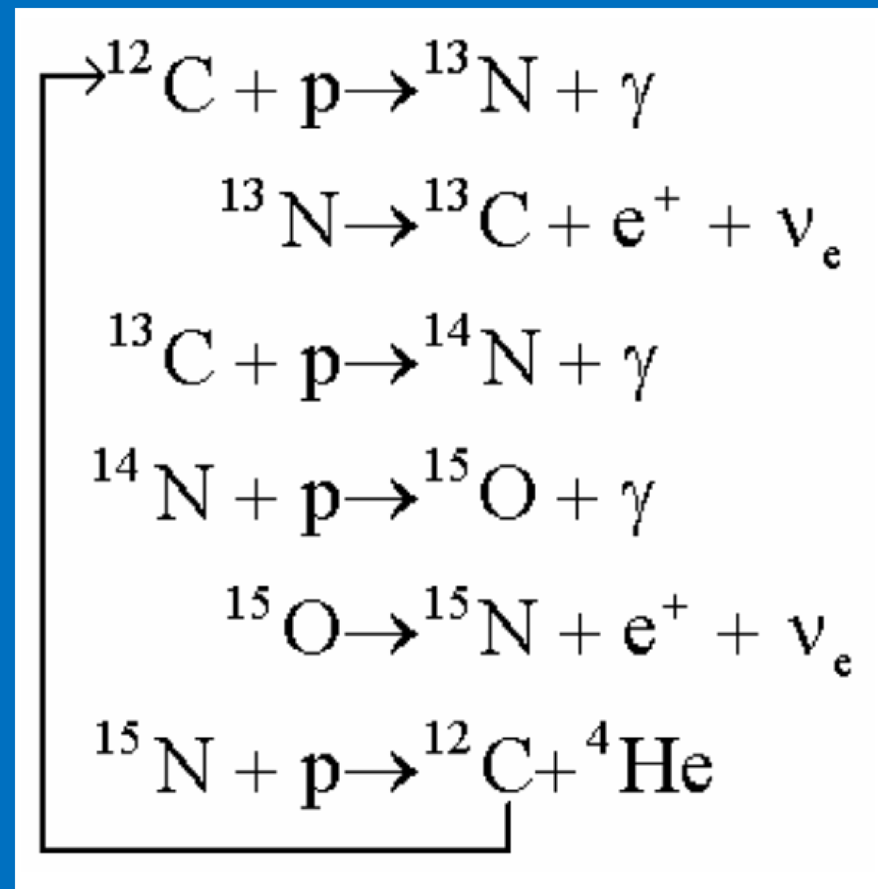
Reactions
n-decay
$p(n,\gamma)d$
$d(p,\gamma)^3\mathrm{He}$
$d(d,n)^3\mathrm{He}$
$d(d,p)t$
$^3\mathrm{He}(n,p)t$
$t(d,n)^4\mathrm{He}$
$^3\mathrm{He}(d,p)^4\mathrm{He}$
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
$t(\alpha,\gamma)^7\mathrm{Li}$
$^7\mathrm{Be}(n,p)^7\mathrm{Li}$
$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$



Nuclear network sizes (2)

Hydrogen burning





pp chain **CNO cycle**

Low and intermediate stars

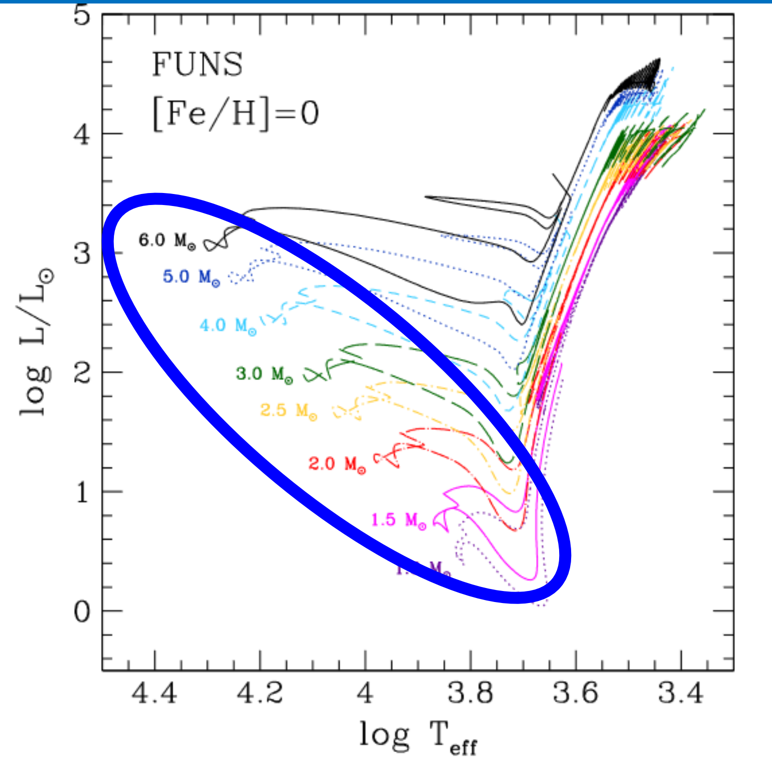


Figure 1. Hertzsprung–Russell diagram for models with initial solar metallicity.

Cristallo+ 2015

Limongi & Chieffi 2018

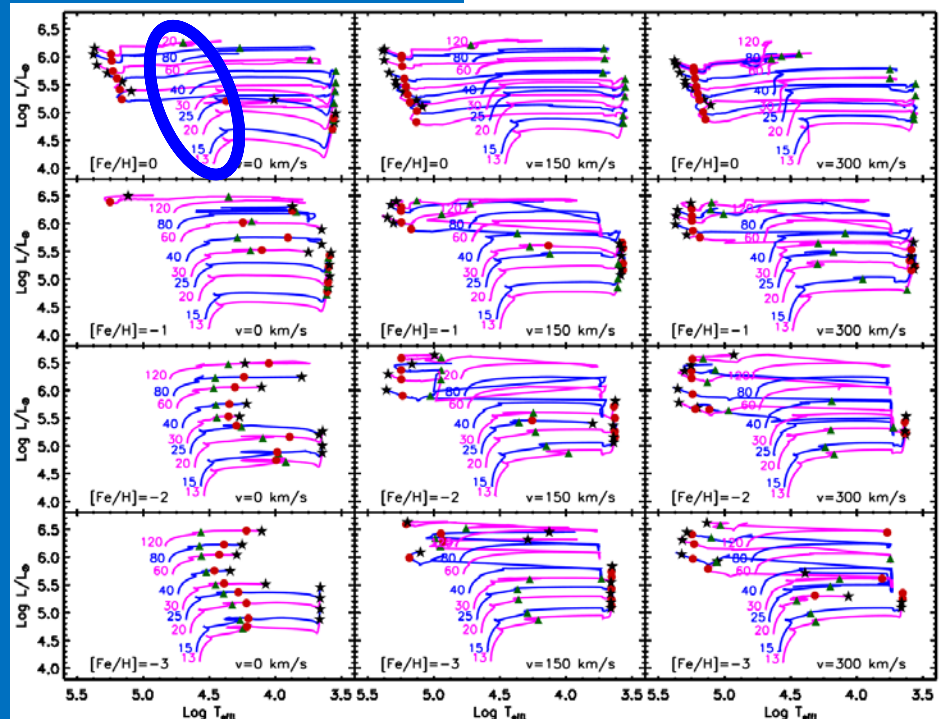
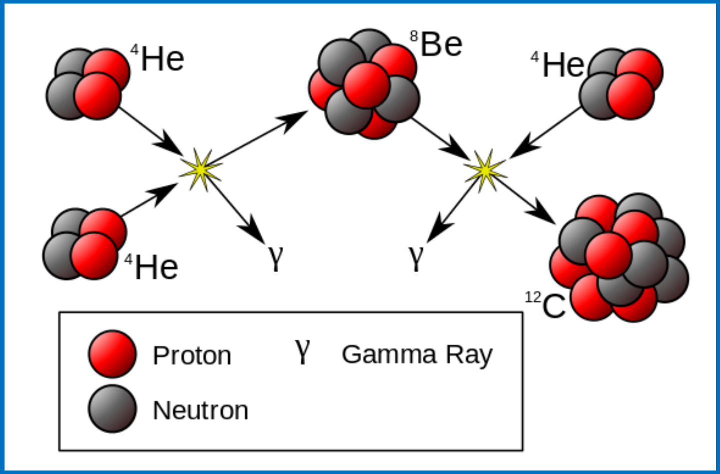


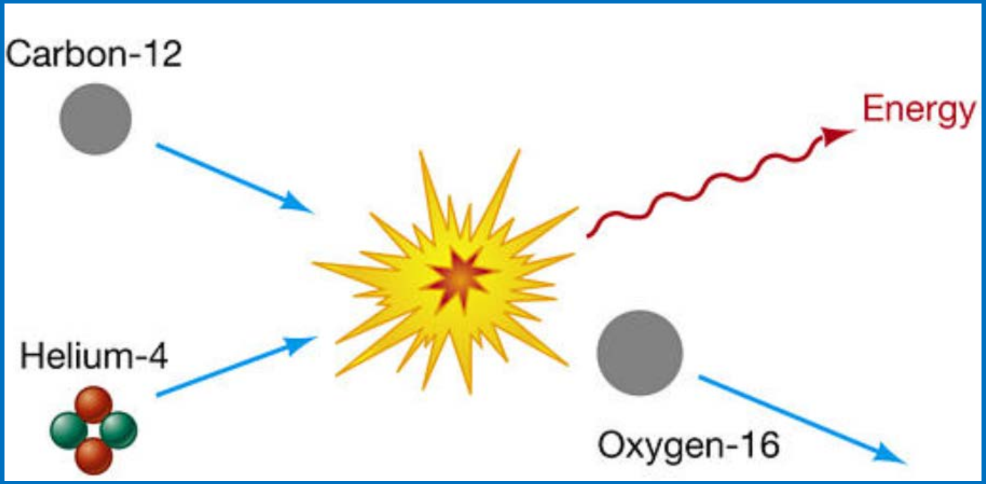
Figure 14. Evolutionary tracks of all our models in the HR diagram. The various symbols mark: the central He ignition (green triangles), the central He exhaustion (red dots) and the final position at the time of the core bounce (black star).

Massive stars

Nuclear network sizes (3)

Helium burning

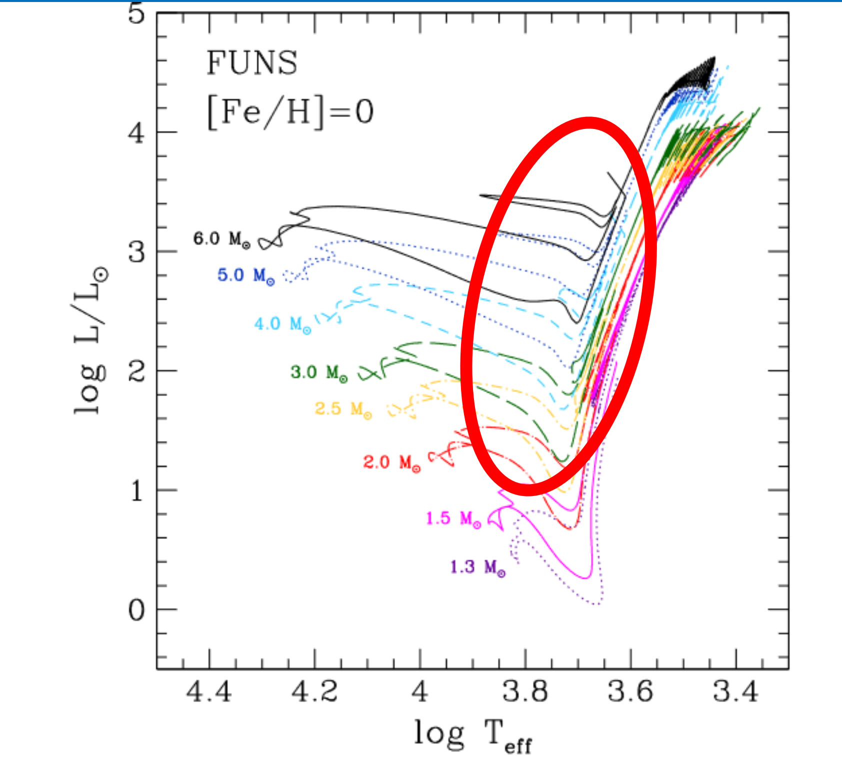




Hoyle postulated (and later measured) a resonance of ^{12}C at 7.65 MeV

"Such calculations show that a change of as little as 0.5% in the strength of the strong nuclear force, or 4 percent in the electric force, would destroy either nearly all carbon or all oxygen in every star, and hence the possibility of life as we know it."
[Cit: S. Hawking]

Low and intermediate stars



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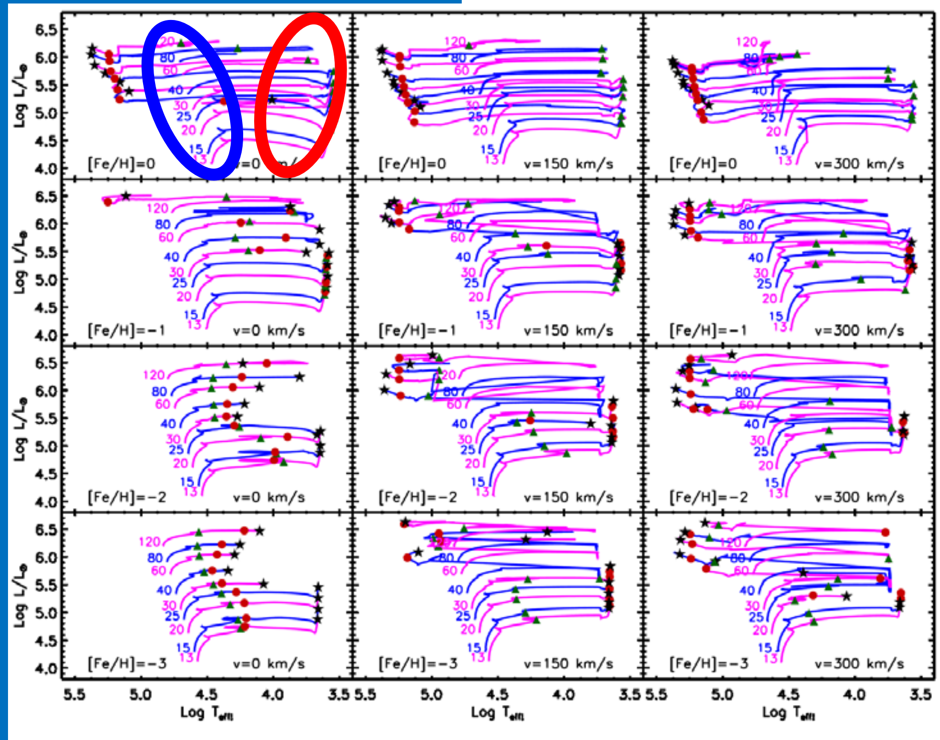

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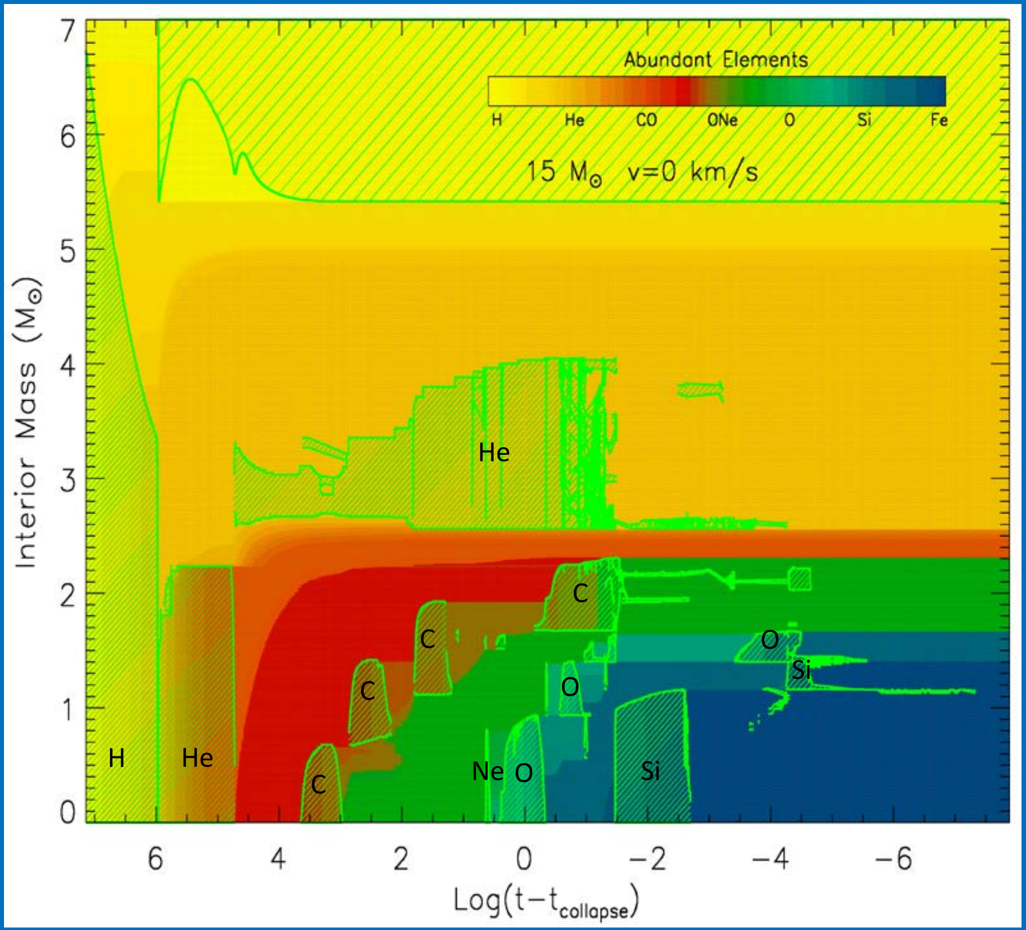
Massive stars

Nuclear network sizes (4)

Carbon burning

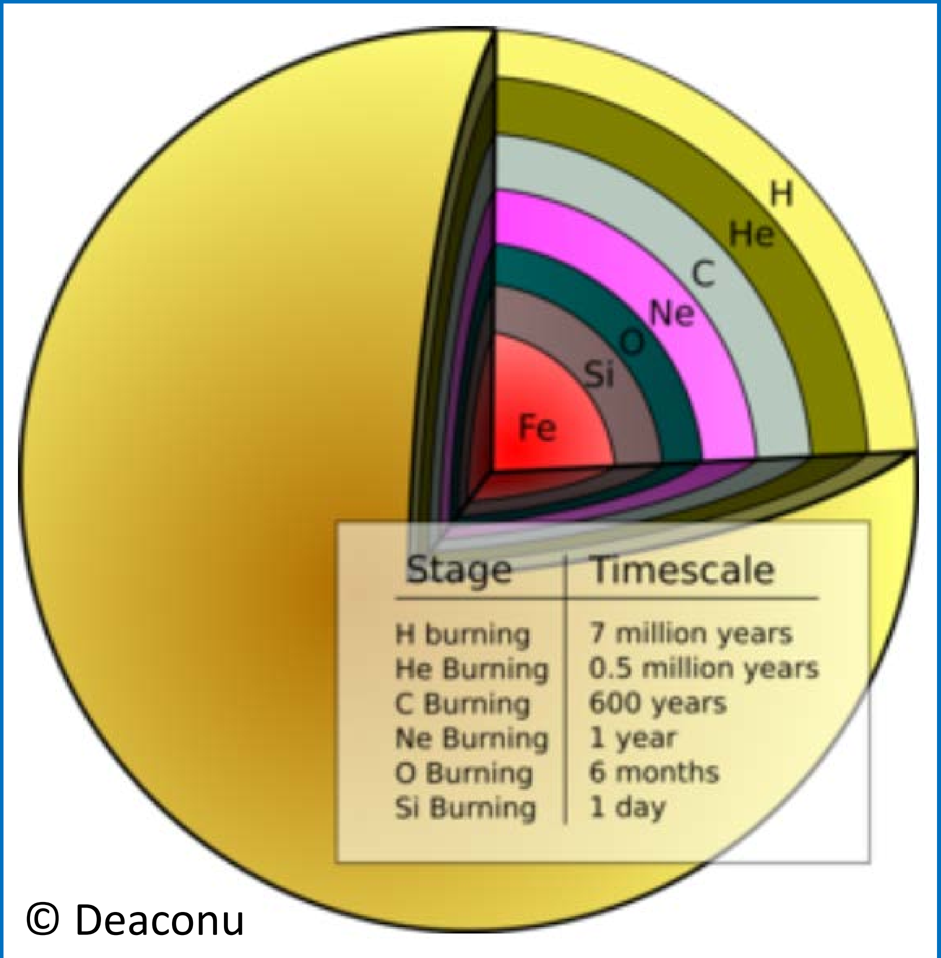


$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C(^{12}C,p)^{23}Na$

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

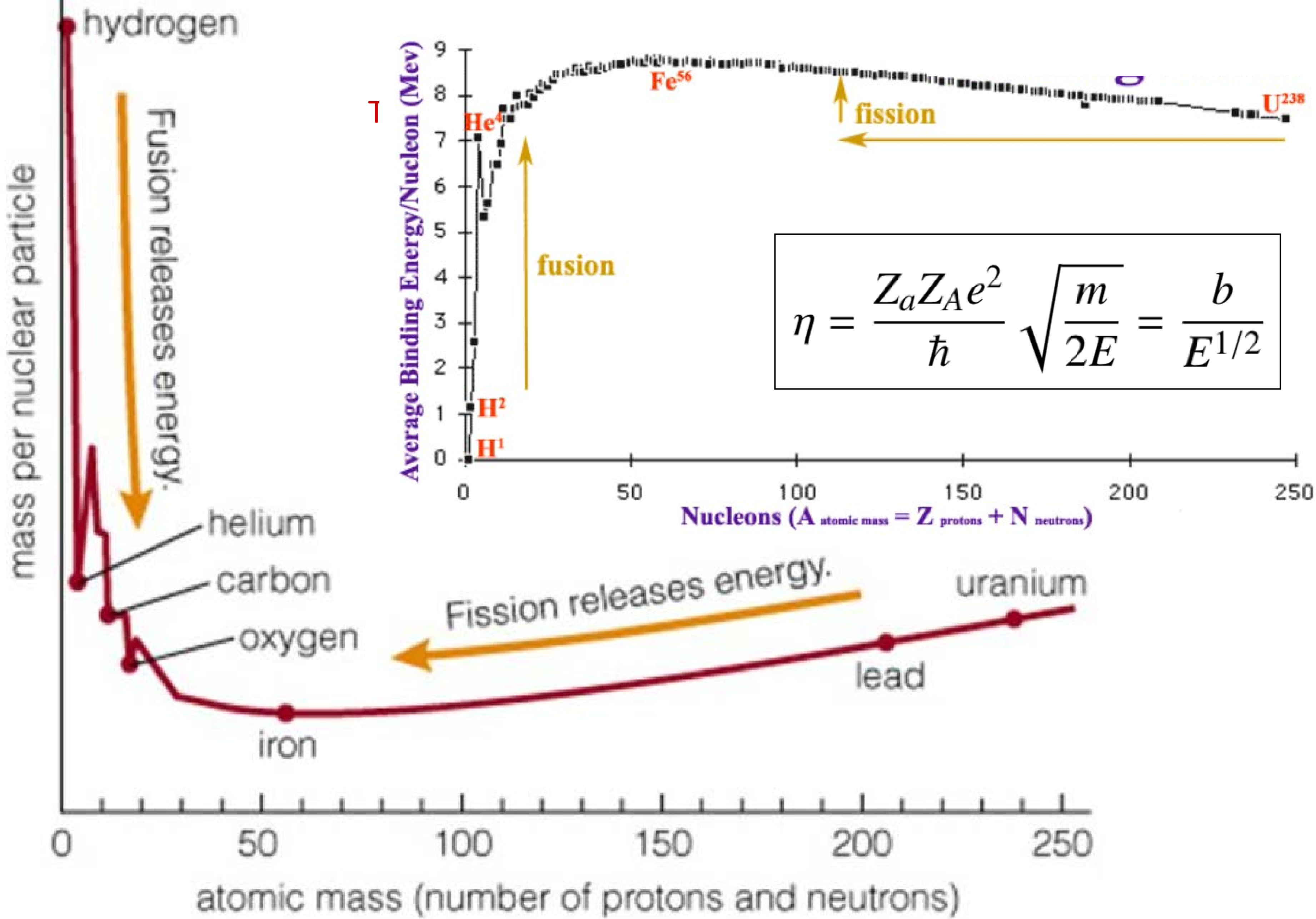
Nuclear network sizes (5)



α burning

$${}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{16}_{8}\mathrm{O} + \gamma \qquad E = 7.16\ \mathrm{MeV}$$
$${}^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{20}_{10}\mathrm{Ne} + \gamma \qquad E = 4.73\ \mathrm{MeV}$$
$${}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{24}_{12}\mathrm{Mg} + \gamma \qquad E = 9.32\ \mathrm{MeV}$$
$${}^{24}_{12}\mathrm{Mg} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{28}_{14}\mathrm{Si} + \gamma \qquad E = 9.98\ \mathrm{MeV}$$
$${}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{32}_{16}\mathrm{S} + \gamma \qquad E = 6.95\ \mathrm{MeV}$$
$${}^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{36}_{18}\mathrm{Ar} + \gamma \qquad E = 6.64\ \mathrm{MeV}$$
$${}^{36}_{18}\mathrm{Ar} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{40}_{20}\mathrm{Ca} + \gamma \qquad E = 7.04\ \mathrm{MeV}$$
$${}^{40}_{20}\mathrm{Ca} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{44}_{22}\mathrm{Ti} + \gamma \qquad E = 5.13\ \mathrm{MeV}$$
$${}^{44}_{22}\mathrm{Ti} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{48}_{24}\mathrm{Cr} + \gamma \qquad E = 7.70\ \mathrm{MeV}$$
$${}^{48}_{24}\mathrm{Cr} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{52}_{26}\mathrm{Fe} + \gamma \qquad E = 7.94\ \mathrm{MeV}$$
$${}^{52}_{26}\mathrm{Fe} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{56}_{28}\mathrm{Ni} + \gamma \qquad E = 8.00\ \mathrm{MeV}$$

Neither fusion nor fission release energy from iron because it has the lowest mass per nuclear particle



$$\eta = \frac{Z_a Z_A e^2}{\hbar} \sqrt{\frac{m}{2E}} = \frac{b}{E^{1/2}}$$


nickelodeon
The Adventures of
JIMMY
NEUTRON
BOY GENIUS™
SEASON
ONE
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Neutron capture reactions

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

With NO Coulomb barrier to overcome, heavy elements capture neutrons easily, even at extremely low energies.

Neutron cross section, in fact, generally INCREASES with decreasing energy.

QUESTION:

why those elements are not synthesized during the MS phase? Or He-burning phase?

$(Z,A) + n \rightarrow (Z,A+1) + \gamma$

If the nucleus (Z,A+1) is stable, it waits until it captures another neutron, and so on.
If the nucleus (Z,A+1) is radioactive, the question whether it β-decays to (Z+1,A+1) or captures a second neutron depends upon the relative lifetimes of (Z,A+1) against β-decay and against capture of neutrons.

DEFINITION:

$$\tau_n(X) = \frac{1}{N_n < \sigma v >}$$

Mean lifetime of nucleus X against destruction by a neutron capture

(<σv> represents the destruction rate of the nucleus)

τ_β = beta-decay lifetime (seconds → years)

if $\tau_n > \tau_\beta \Rightarrow$ unstable nucleus decays
if $\tau_n < \tau_\beta \Rightarrow$ unstable reacts

The r-process

$\tau_\beta \gg \tau_n \quad \Leftrightarrow \quad N_n > 10^{20}\ n/cm^3$

Unstable nucleus captures another neutron before decaying

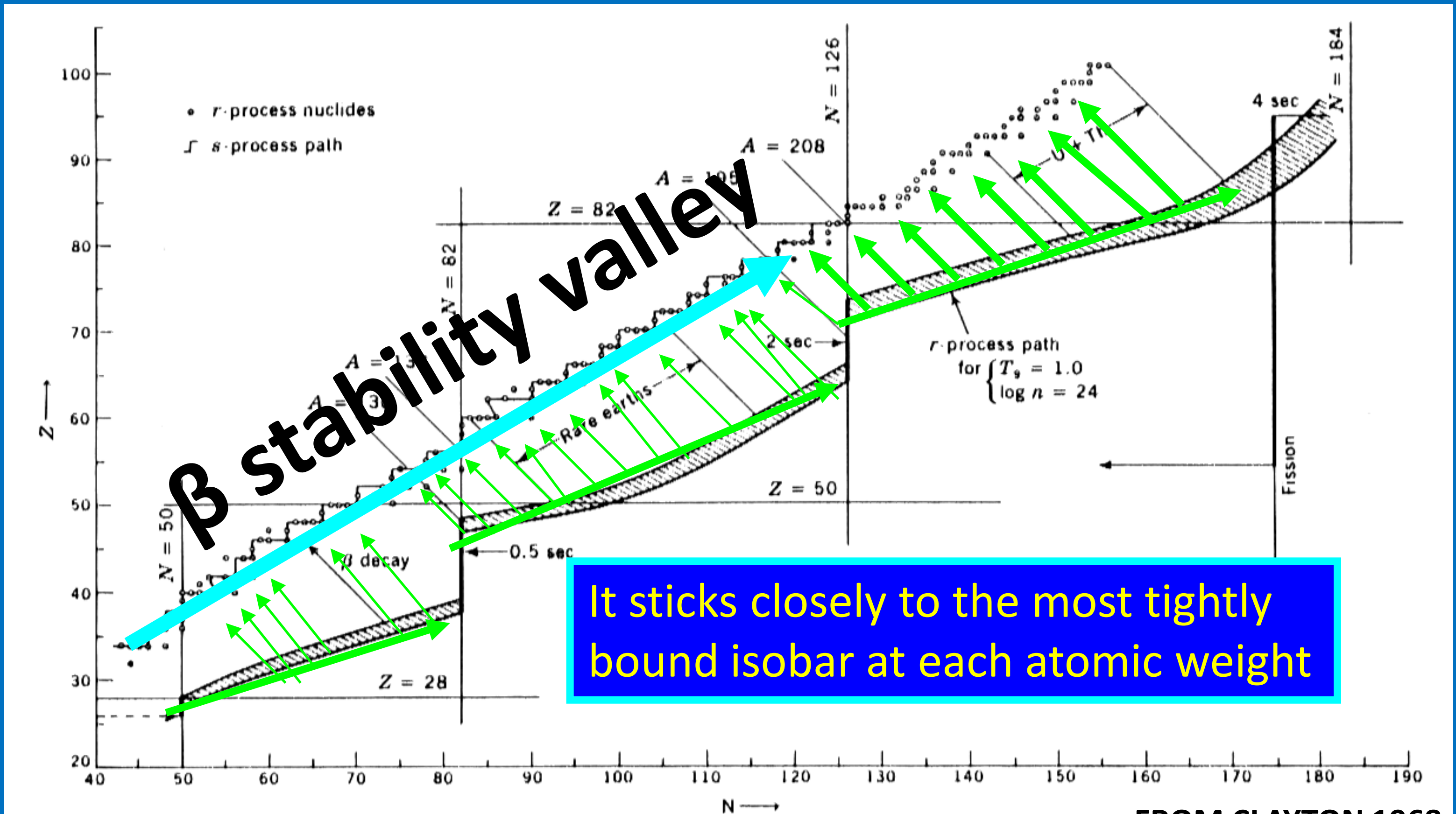
The s-process

$\tau_\beta \ll \tau_n \quad \Leftrightarrow \quad N_n \sim 10^{7}\ n/cm^3$

Unstable nucleus decays before capturing another neutron

In principle one might expect to encounter astrophysical neutron fluxes in the large region between these two densities and have thereby intermediate processes between s and r. Such events are apparently not common, and it is one of the fortunate simplifications in the application theory of synthesis by neutron capture that the most common fluxes are either quite small or quite large...

B2FH (Burbidge, Burbidge, Fowler & Hoyle, Rev. Mod. Phys. 1957)



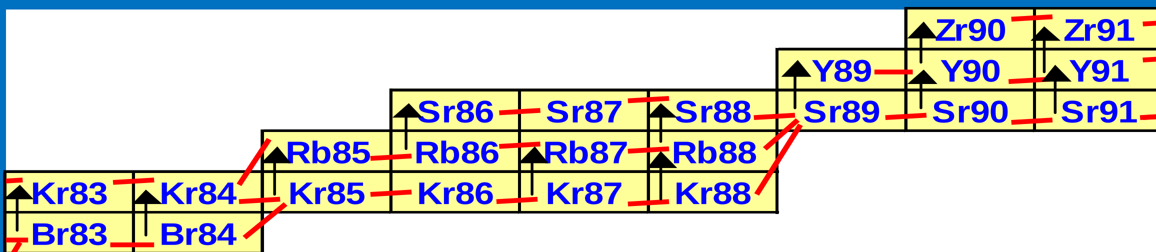
FROM CLAYTON 1968

s-process

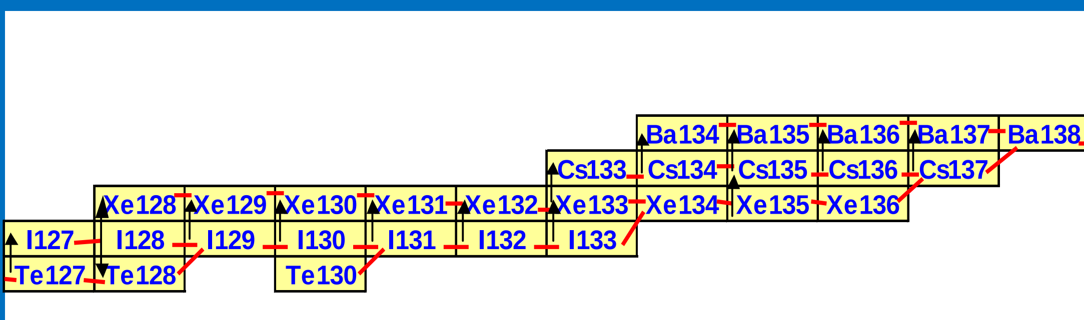
r-process

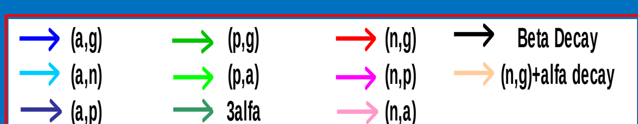
Nuclear network sizes (6)

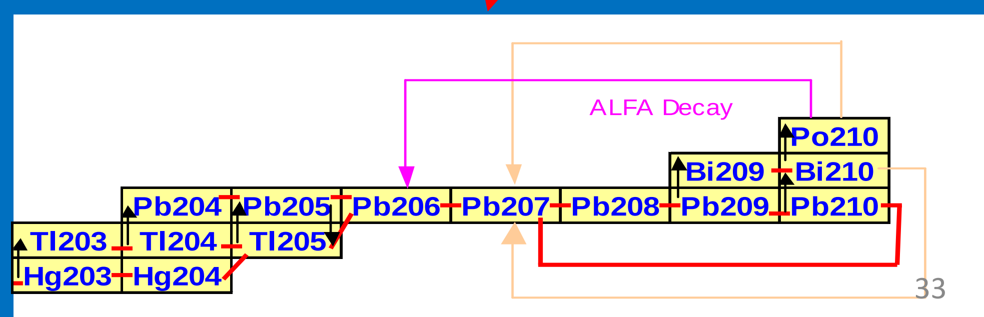
slow neutron capture process



s-process peaks





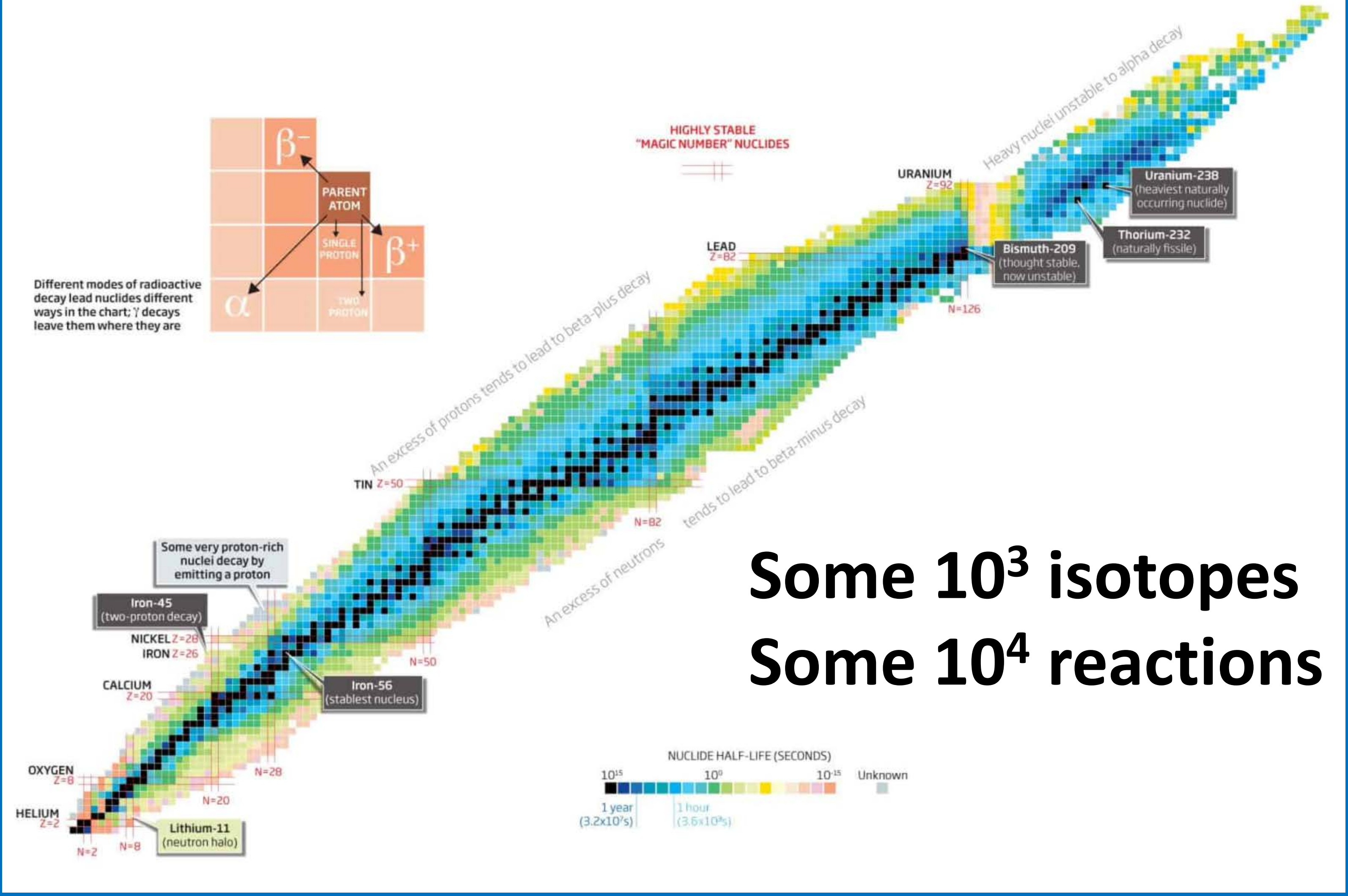


≈ 500 isotopes

≈ 1000 reactions

Nuclear network sizes (7)

rapid neutron capture process

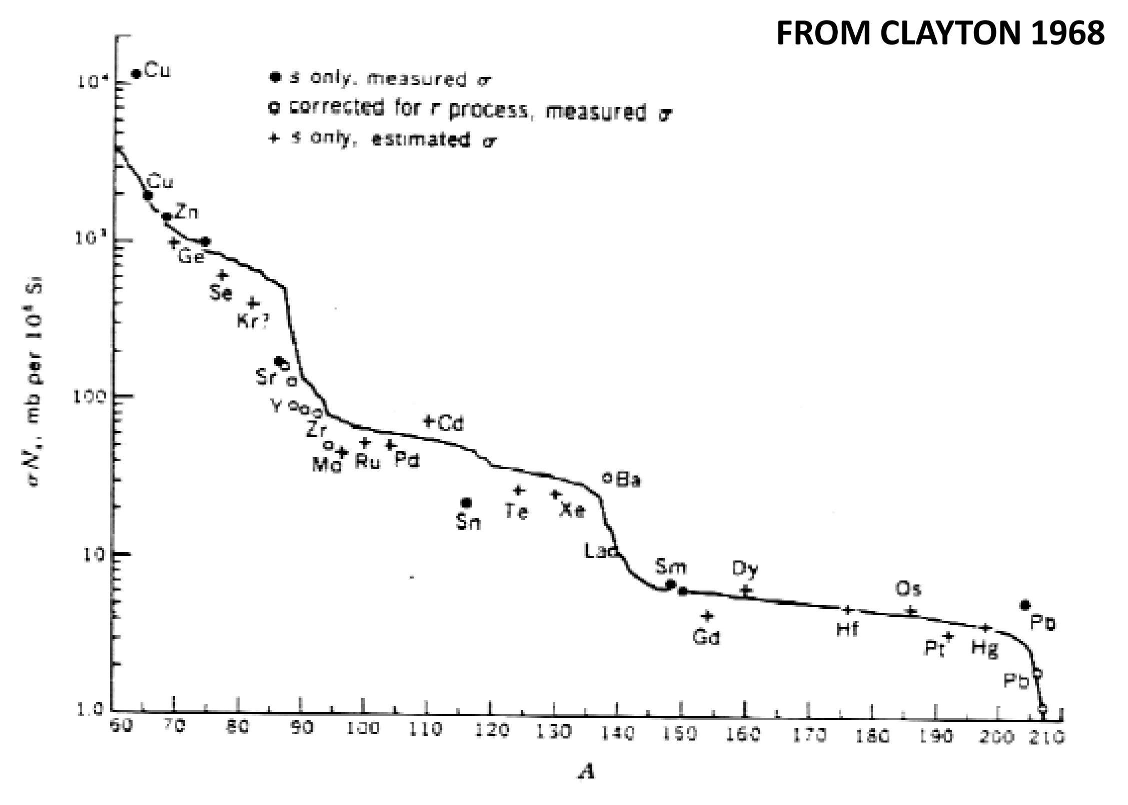


Some 10^3 isotopes

Some 10^4 reactions

s-process

Easy to be reproduced with an exponential distribution of neutron exposures.

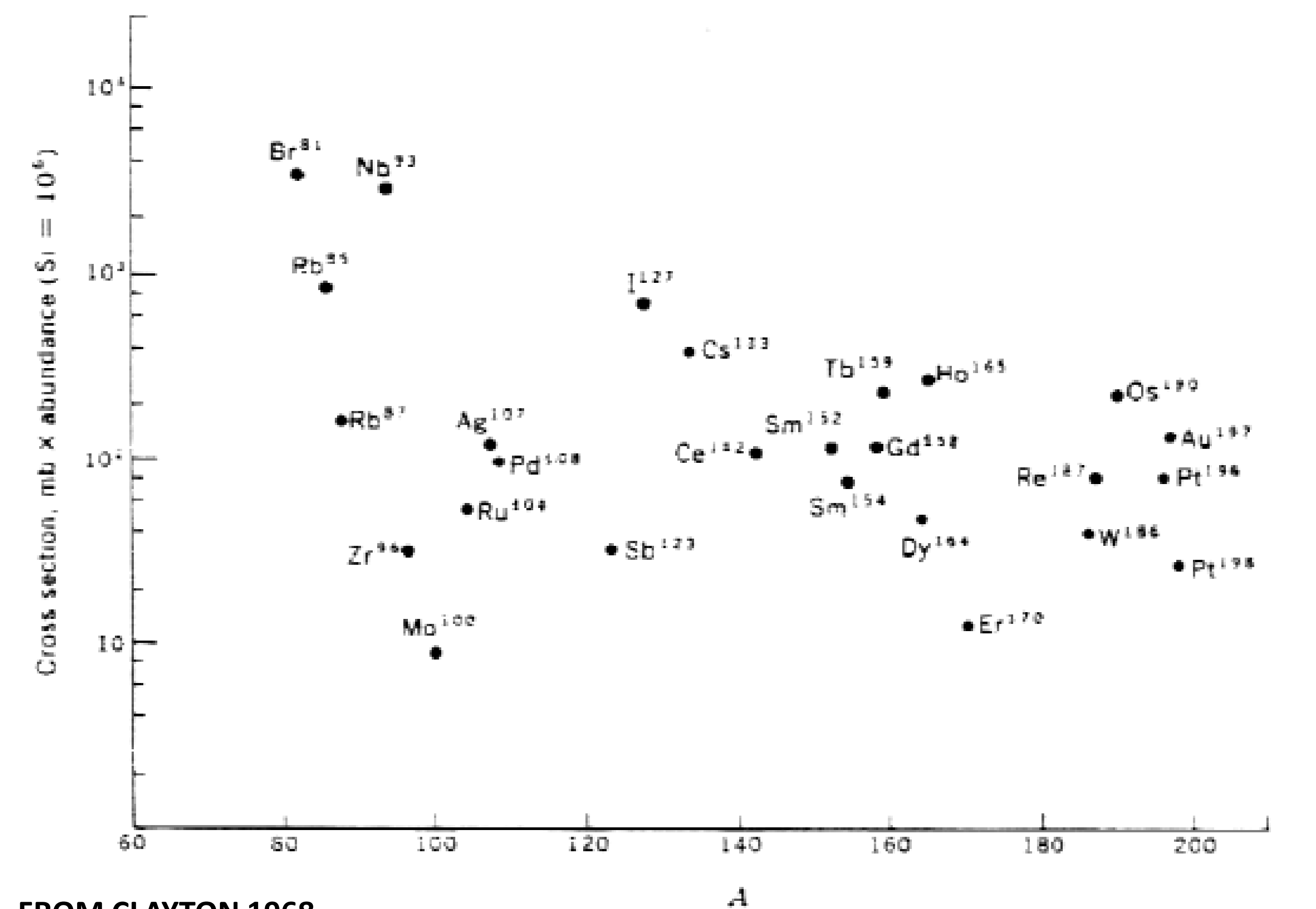


Moreover, given that the *s*-process occurs in a relatively low neutron-density environment, the neutron flow reaches equilibrium between nuclei with magic neutron numbers, where the product of the Maxwellian averaged stellar (n,γ) cross section of a nuclide, $\langle\sigma\rangle$, and its corresponding abundance, N_s, remains almost constant (the difference in the two product is much smaller than the magnitude of either one of them):

$$\langle\sigma\rangle_A N_A \approx \langle\sigma\rangle_{A+1} N_{A+1}$$

LOCAL APPROXIMATION

What about the r-process?



FROM CLAYTON 1968

Do you see any distribution?

QUESTION:
Do you know how the r-process contribution to the solar distribution is determined?

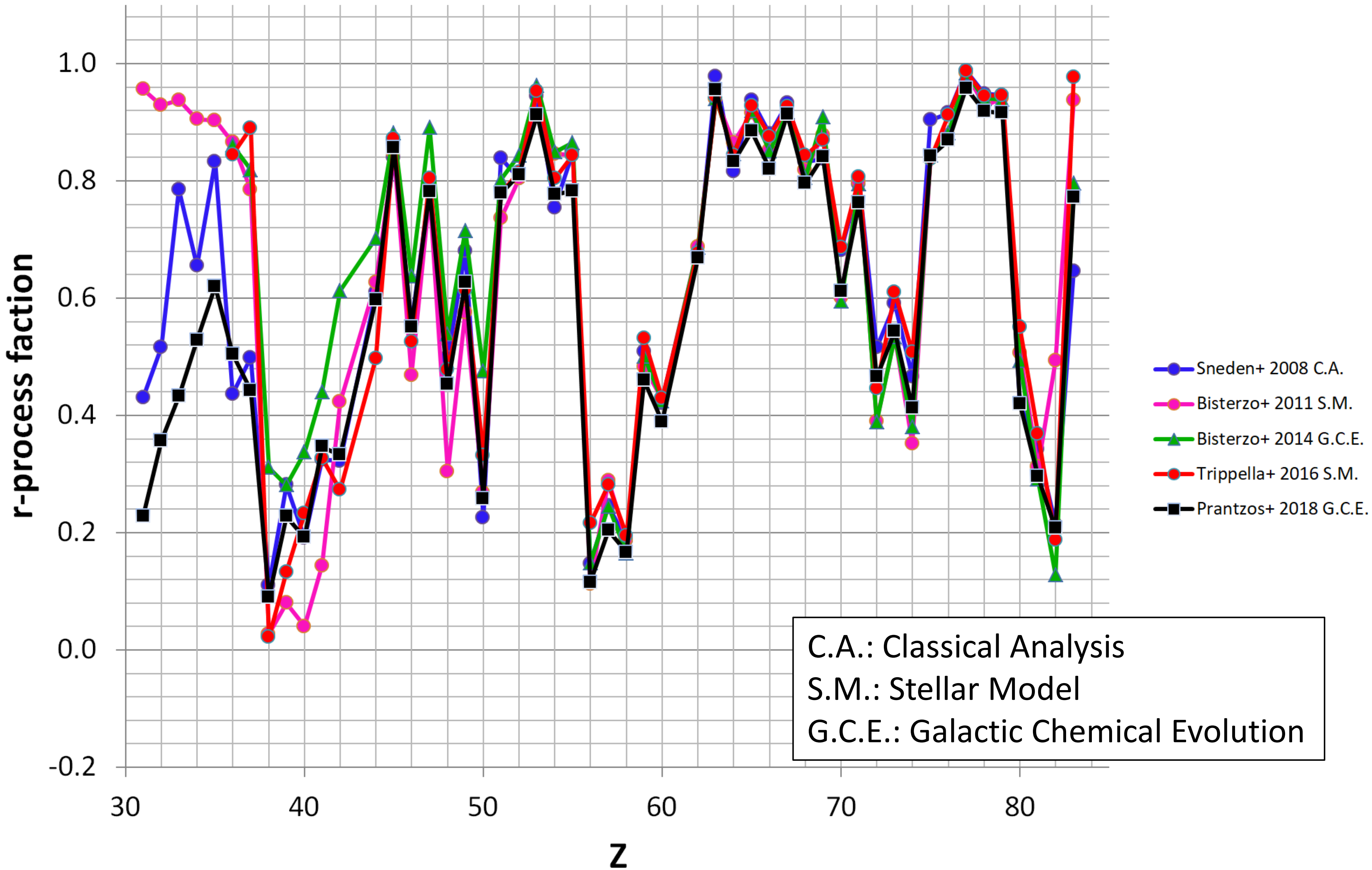
r = ?

QUESTION:

Do you know how the r-process contribution to the solar distribution is determined?

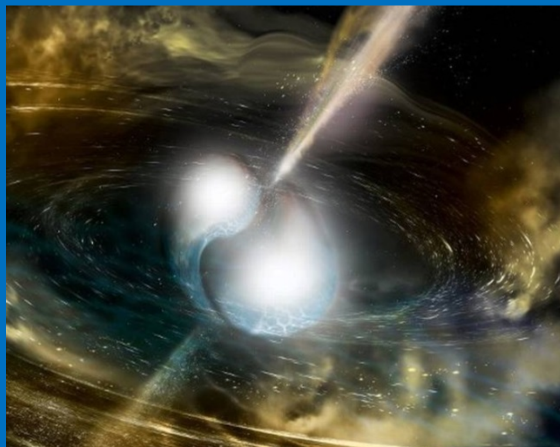
$$r = 1 - s$$

r-process residuals from s-process studies



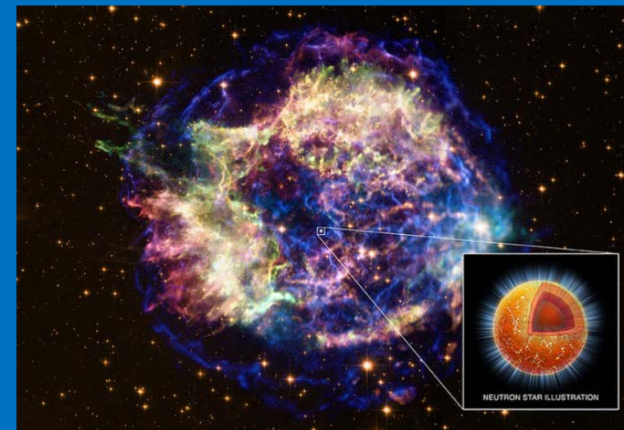
Main r-process (A≥130)

NEUTRON STARS MERGERS?



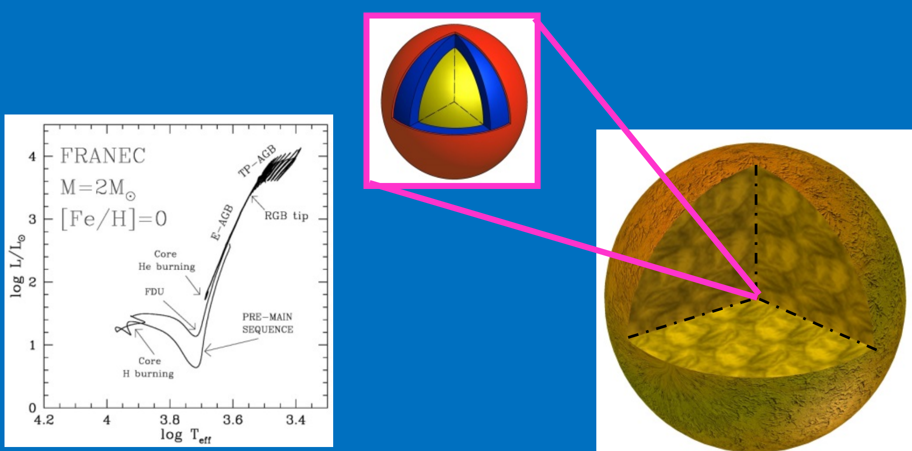
Weak r-process (A≤130)

MAGNETOROTATIONALLY DRIVEN SUPENOVAE?



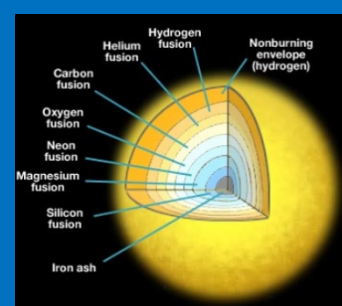
Main s-process (A≥90)

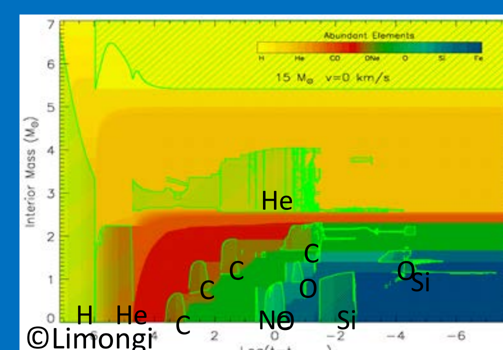
ASYMPTOTIC GIANT BRANCH STARS



Weak s-process (A≤90)

QUIESCENT BURNINGS OF MASSIVE STARS





The rapid neutron capture process

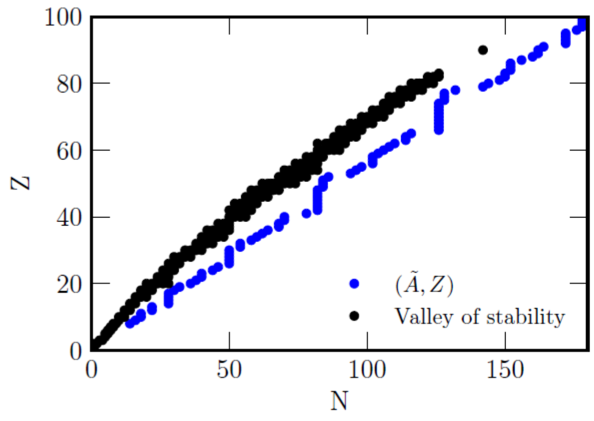
How does the r-process work?

- r-process requires initial high n_n and T
- high n_n: $\tau_{(n,\gamma)} << \tau_{\beta\text{-decay}}$
- high n_n and T: $(n,\gamma) \leftrightarrow (\gamma,n)$ along isotopic chains

$$\frac{n_{(A+1)}}{n_A} = n_n \frac{G_{A+1}}{2\,G_A} \left(\frac{h^2}{2\pi\, m_b\, k_B T} \right)^{3/2} \left(\frac{A+1}{A} \right)^{3/2} \exp \frac{S_n(A+1,Z)}{k_B T}$$

Partition functions

Neutron separation energies



r-process path for

- $n_n = 5 \times 10^{21}$ cm^{-3}
- $T = 1.3$ GK
- FRDM mass model

If we want to find the most probable synthesized isotope, it must hold

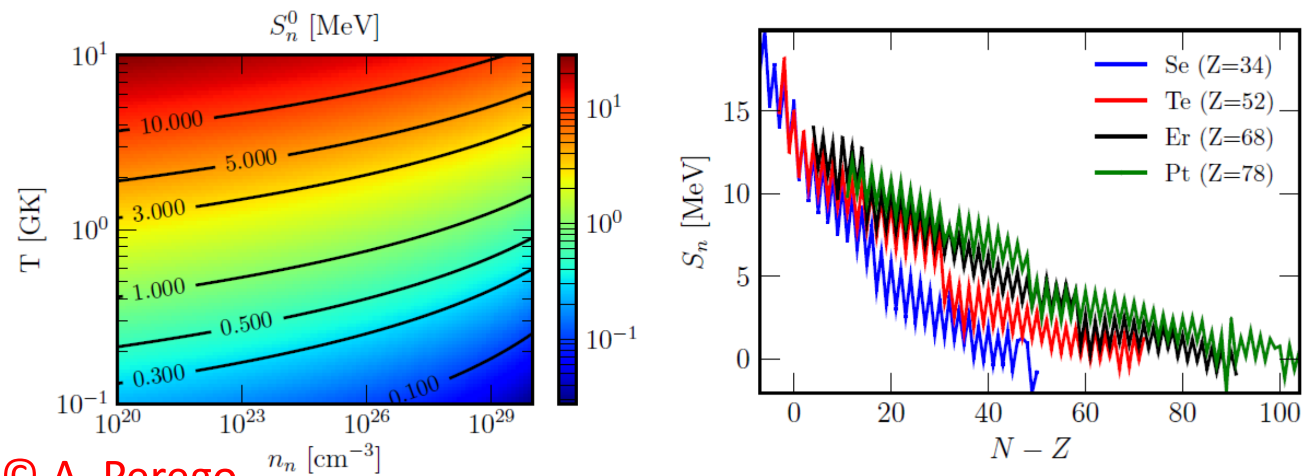
$$dn/dA \approx 0$$

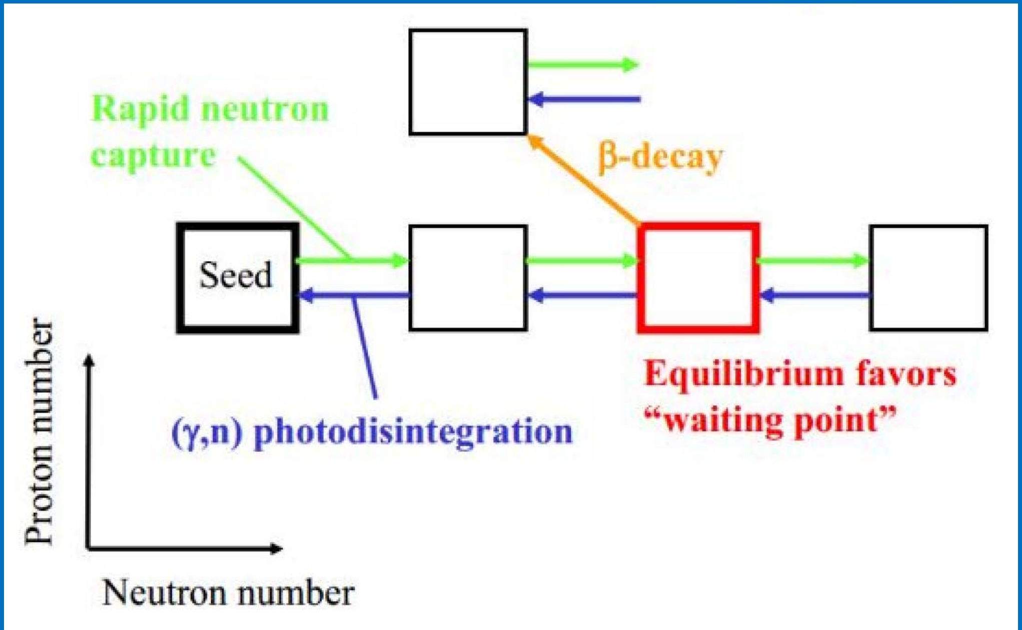
which translates to

$$n(A+1,Z)=n(A,Z) \approx 1$$

In this condition:

$$S_n^0(n_n, T) = k_B T \ln \left(\frac{2}{n_n} \left(\frac{h^2}{m_b k_B T} \right)^{-3/2} \right)$$

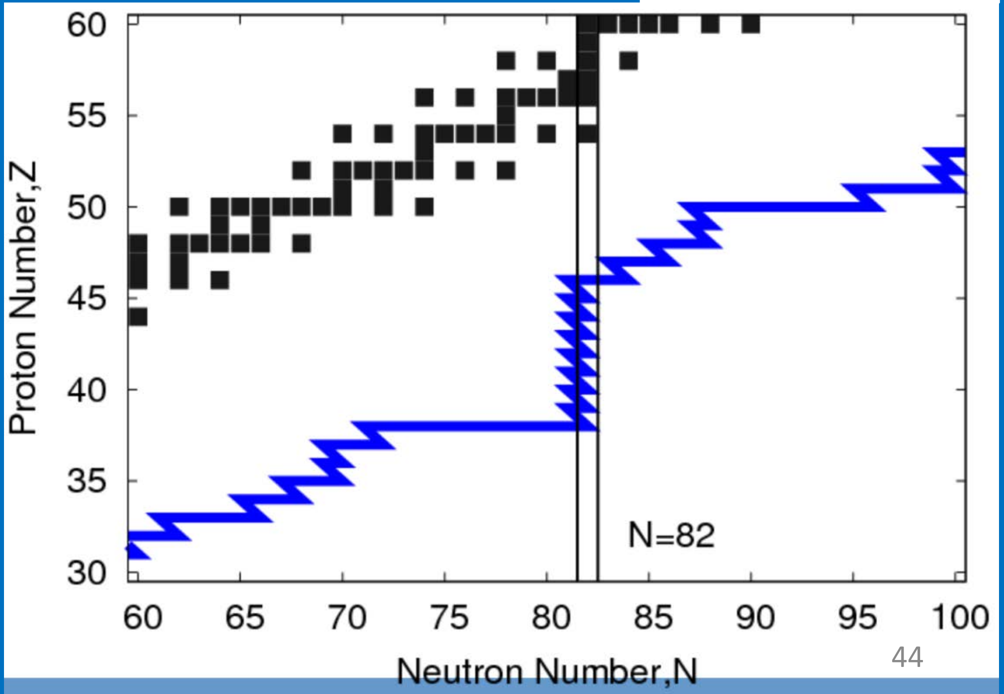




Moderate neutron densities

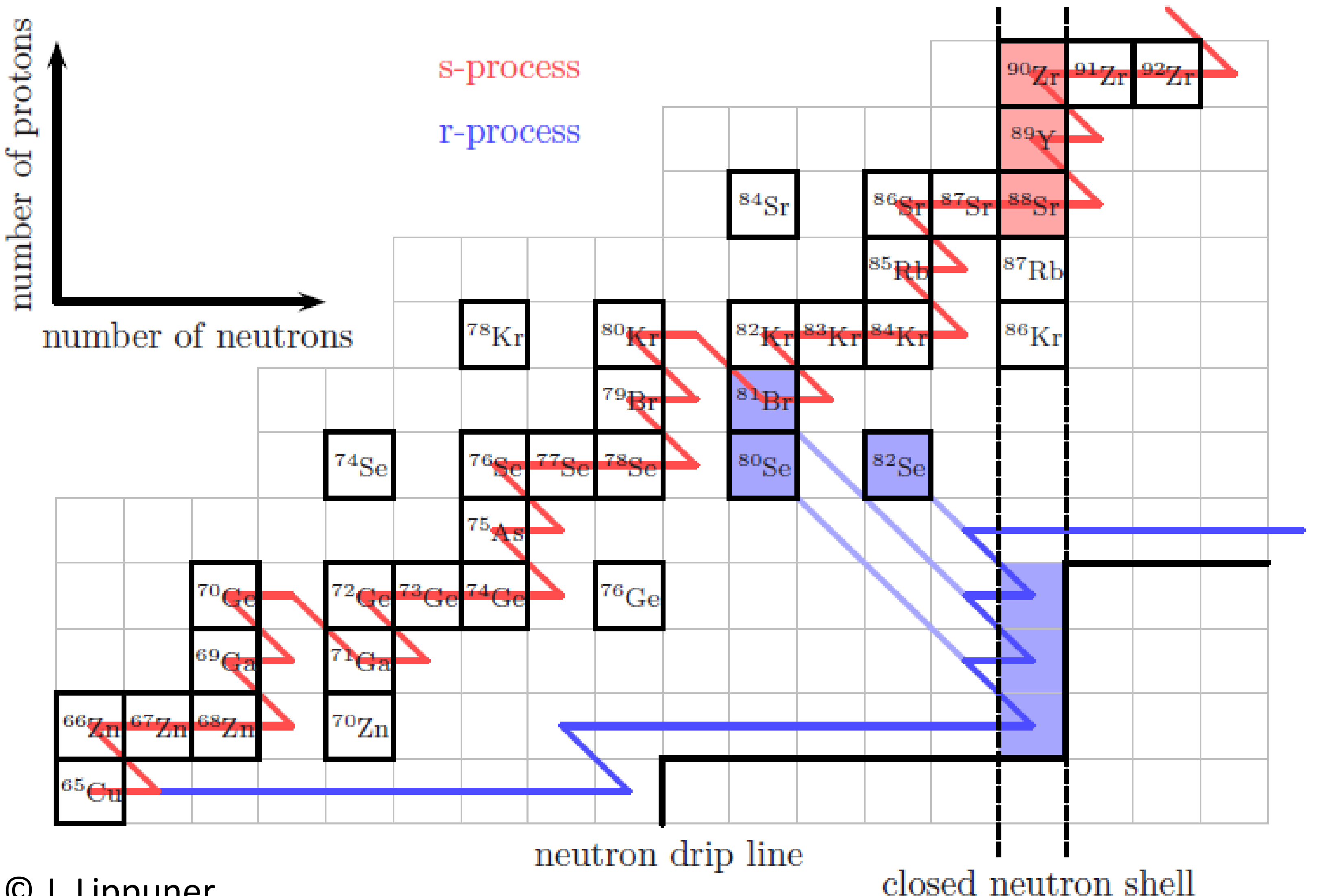
Very high neutron densities

Shibagaki+ 2016



The waiting points is on the drip line

Why double peaks for the heavy elements?



Seeds for r-process: Nuclear Statistical Equilibrium

QUASI EQUILIBRIUM: groups of adjacent isotopes (not all) have come into equilibrium with respect to the exchange of n, p, α and γ. This occurs during advanced burnings in massive stars.

NUCLEAR STATISTICAL EQUILIBRIUM (NSE): all isotopes have come into equilibrium.

$B(Z,N)=(ZM_p+Nm_n-m_{Z,N})c^2$

If other two terms are equally strong: tighly bound nuclei are preferred

$$Y(Z,N) = G_{Z,N}(\rho N_A)^{A-1}\frac{A^{3/2}}{2^A}\left(\frac{2\pi\hbar^2}{m_u kT}\right)^{\frac{3}{2}(A-1)}\exp\left(\frac{B_{Z,N}}{kT}\right)Y_n^N Y_p^Z$$

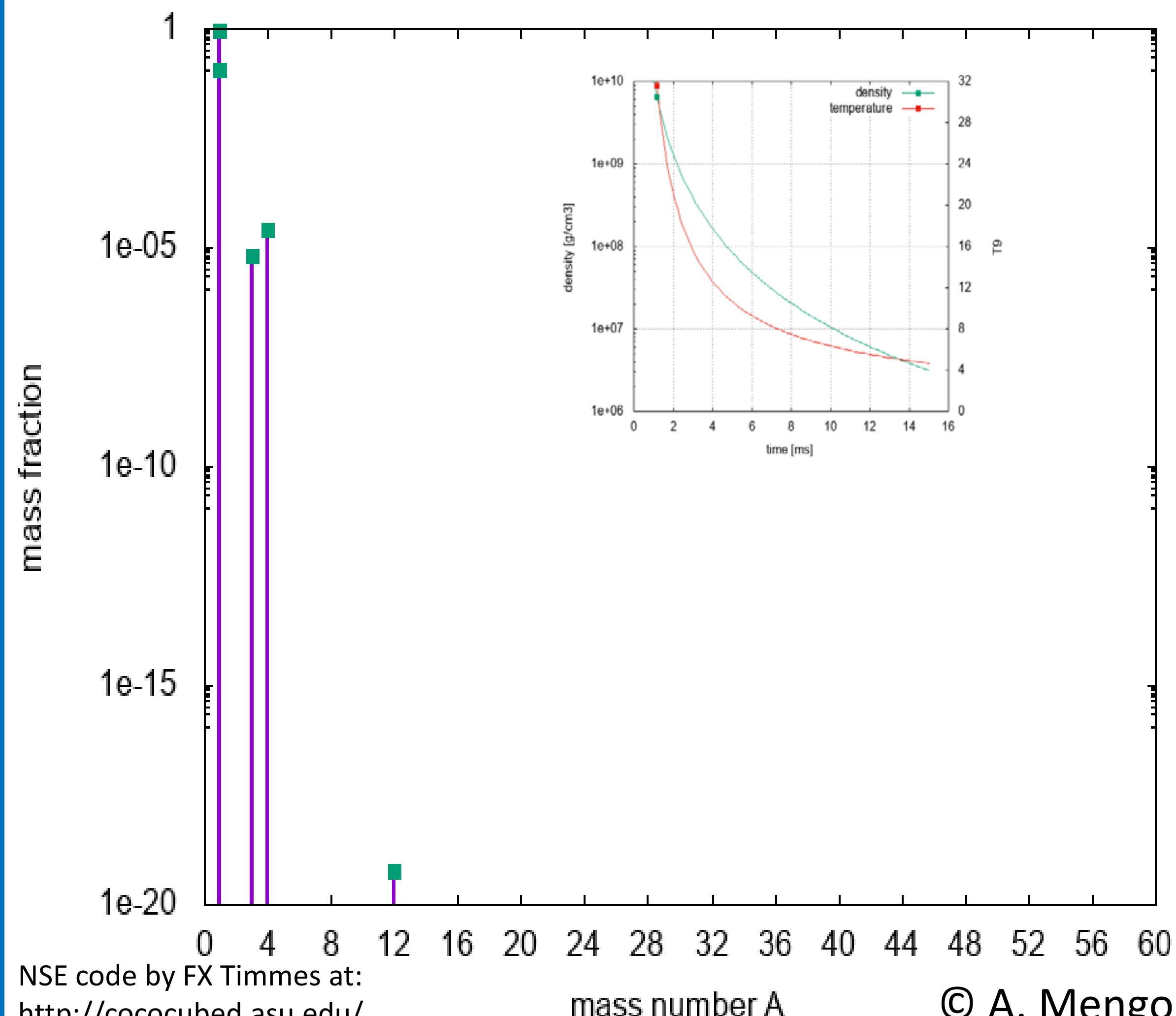
High ρ: large A favored

High T: small A favored

Seeds for r-process: Nuclear Statistical Equilibrium

Above $\simeq 5\times10^9$ K, conditions are energetic enough for forward and reverse reactions to be balanced. In this case abundances are in a state of nuclear statistical equilibrium, NSE.

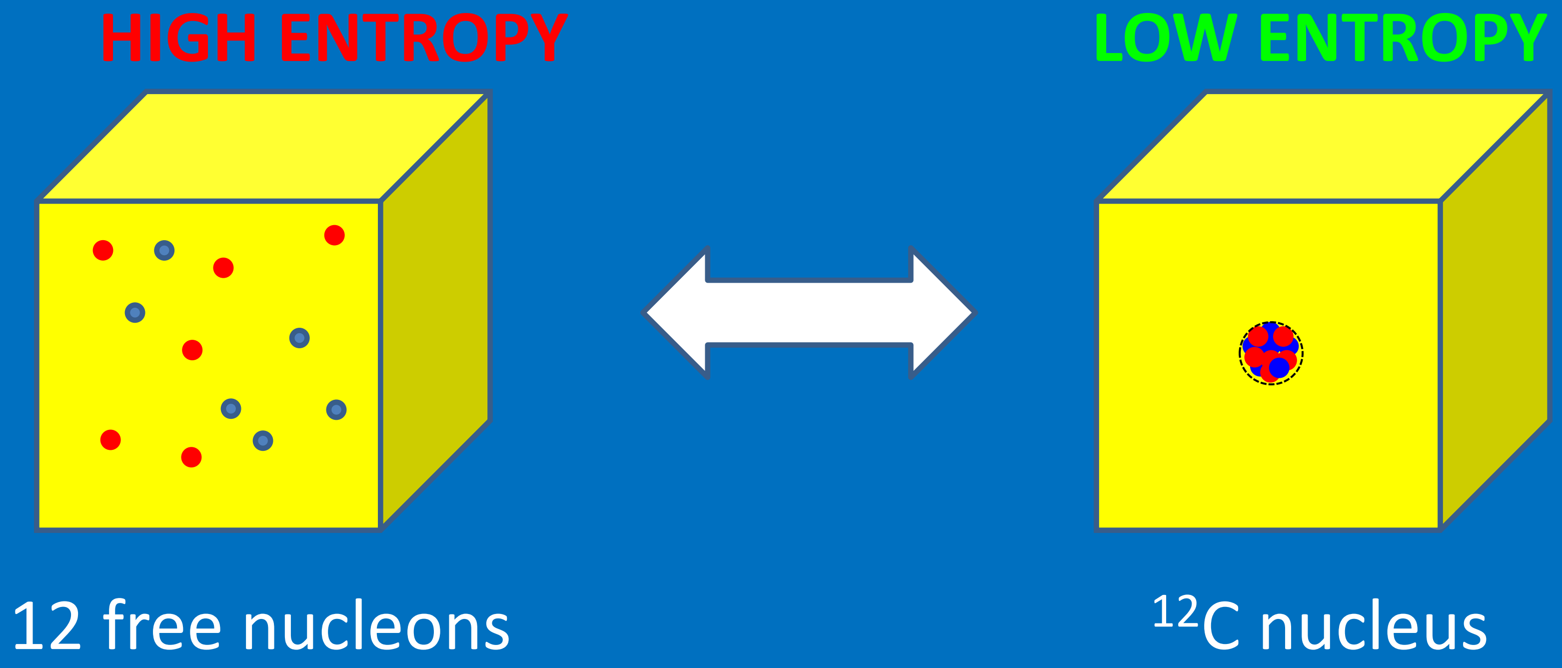
Below $\simeq 5\times10^9$ K a full nuclear reaction network is needed to follow the abundances.



NSE code by FX Timmes at: http://cococubed.asu.edu/

Fundamental quantities (I)

s: Entropy (in k_b/baryon)



s measures the system's degree of order/disorder

Fundamental quantities (II)

Electron fraction Y_e:

$$Y_e \equiv \frac{n_{e^-} - n_{e^+}}{n_b} = (1+n_n/n_p)^{-1}$$

Y_e is a measure of the neutron richness

$$Y_i \equiv \frac{n_i}{n_b} = \frac{X_i}{A_i} \Longrightarrow Y_e = \sum_i Z_i Y_i$$

Mass fraction (X_i)

Mass number (A_i)

Fundamental quantities (III)

Neutron-to-seed ratio for the r-process

Entropy (in k_b/baryon)

High entropy is equivalent to high photon-to-baryon ratio: photons dissociate seed nuclei into nucleons

Dynamical time of the event

$$n_n/n_{\rm seed} \quad \propto \quad s^3/\left(\tau_{\rm dyn} Y_e^3\right)$$

Electron fraction

$Y_e = \sum_i Z_i Y_i$

CCSNe

Large Ye (≈0.4)

High entropy r-process

(S ≈ 200)

NSMs

Low Ye (≈0.1)

Low entropy r-process

(S ≈ 30)

Fundamental quantities (IV)

NEUTRINOS acting as masters

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

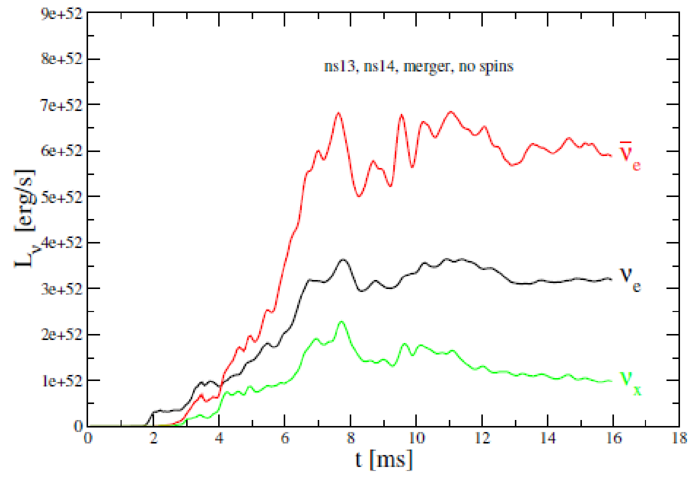
Y_e, which is a key input for the nucleosynthesis, strongly depends on details of the challenging neutrino transport.

$$Y_e \approx \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e})}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e})}\right]^{-1}$$

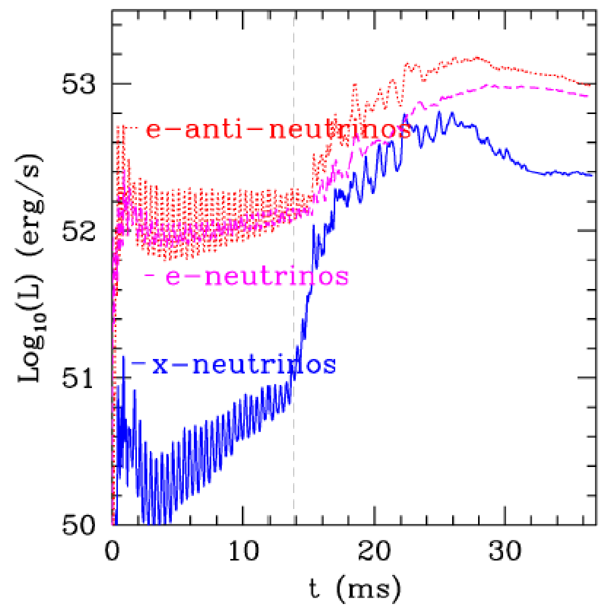
Qian&Woosley 1996

$\Delta = m_n - m_p$

At very high densities ($\rho \simeq 10^{12}$ g cm^{-3}), neutrinos cannot escape freely anymore and scatter off nuclei and electrons, loosing energy, facilitating their escape from the trapping region (mean free path $\lambda \propto E_\nu^{-2}$). Between the trapping radius and the neutrinosphere radius, they have to cover a large distance where they can still scatter off matter, increase its entropy.



Rosswog+13 (up), Neilsen+15 (down)



The modelling of neutrinos interaction Is one of the key ingredients for the following nucleosynthesis.
(Shibata+ 2011; Foucart+ 2015,2018; Perego+ 2015; Radice+ 2016; …)

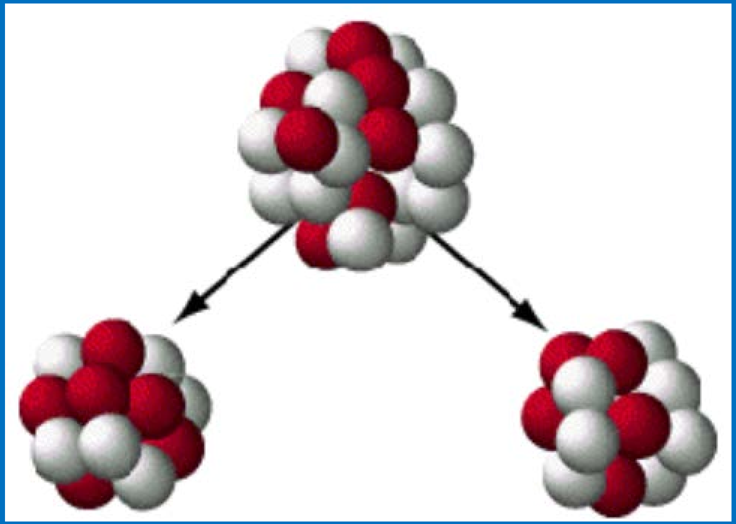
Fundamental quantities (V)

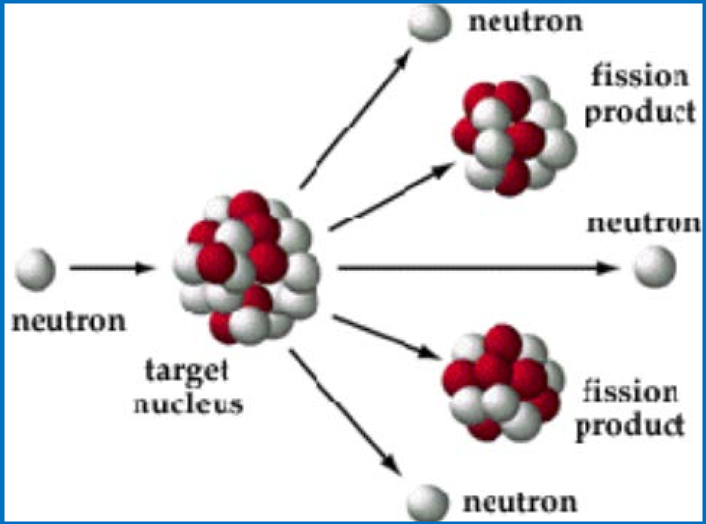
Fission recycling

Fission has often been **neglected** in astrophysical calculations.

In early nucleosynthesis calculations only beta-delayed fission mode was considered (Thielemann et al. 1983) or a phenomenological model of spontaneous fission (Goriely & Clerbaux 1999; Freiburghaus et al. 1999; Cowan et al. 1999).

It has been demonstrated (Panov & Thielemann 2003, 2004; Martínez-Pinedo et al. 2007) that **neutron-induced fission** is more important than beta-delayed fission in r-process nucleosynthesis.

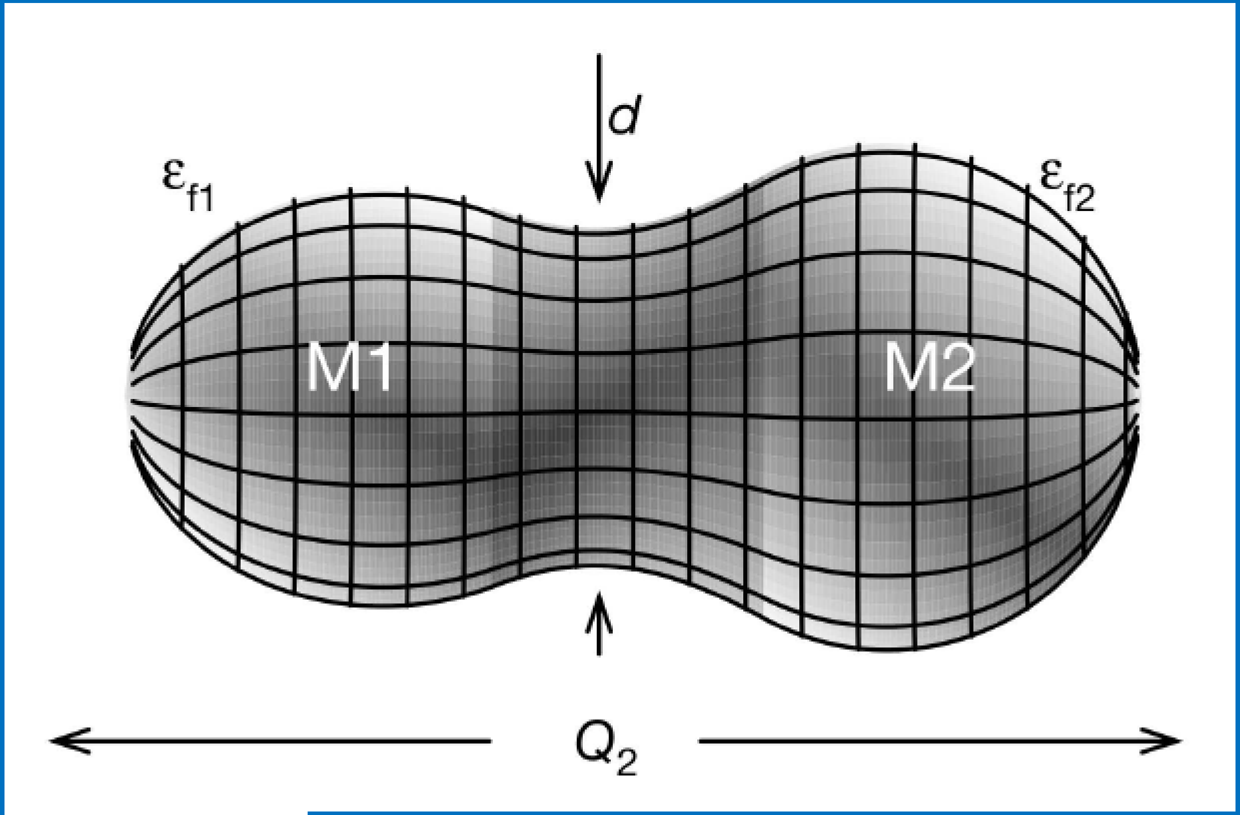




A precursor nucleus (Z,A) with Z protons and A nucleons, β±-decays into a daughter nucleus (Z∓1,A) that has a probability to fission.

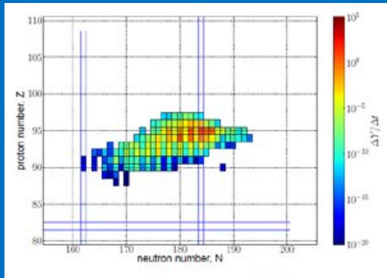
Fission recycling

Nuclei with a large number of protons and/or neutrons are not only massive, but may increase in volume. In fact, while the strong force (holding nucleons together) only acts between neighboring nucleons (a range of one to a few femto-meters), the Coulomb repulsion of the protons, has a long range and gains in influence with increasing proton number. Therefore, heavier nuclei are generally less bound and can easily deform.



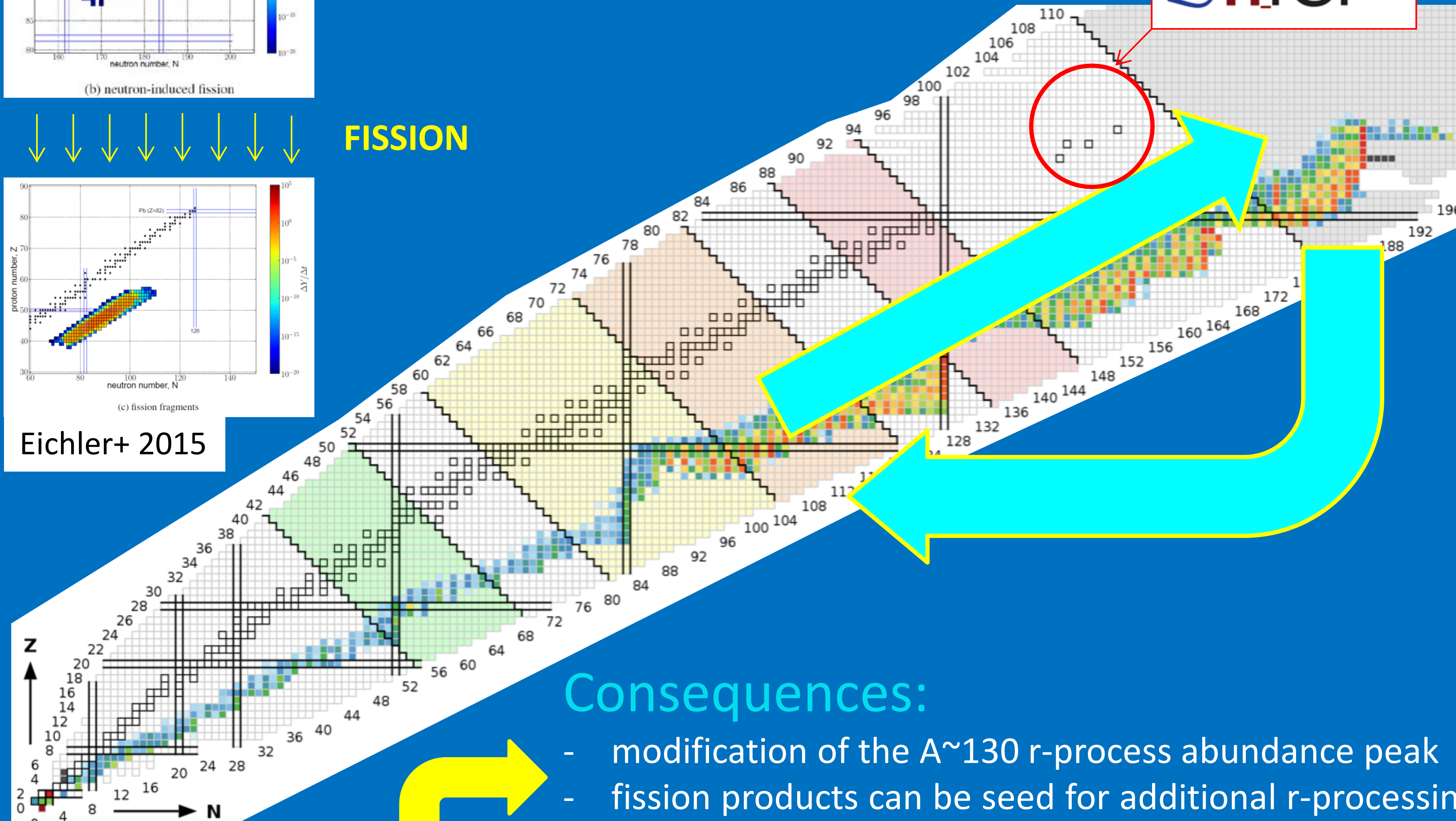
Moeller 2001

Fission recycling



(b) neutron-induced fission

FISSION



(c) fission fragments

Eichler+ 2015

Consequences:

- modification of the A~130 r-process abundance peak
- fission products can be seed for additional r-processing up to A~250 fission again

fission recycling

Fission recycling

This insensitivity of the strong r-process abundance pattern to the parameters of the merging system is explained by an extremely low-Y_e environment, which guarantees the occurrence of several fission cycles before the r-process freezes out.

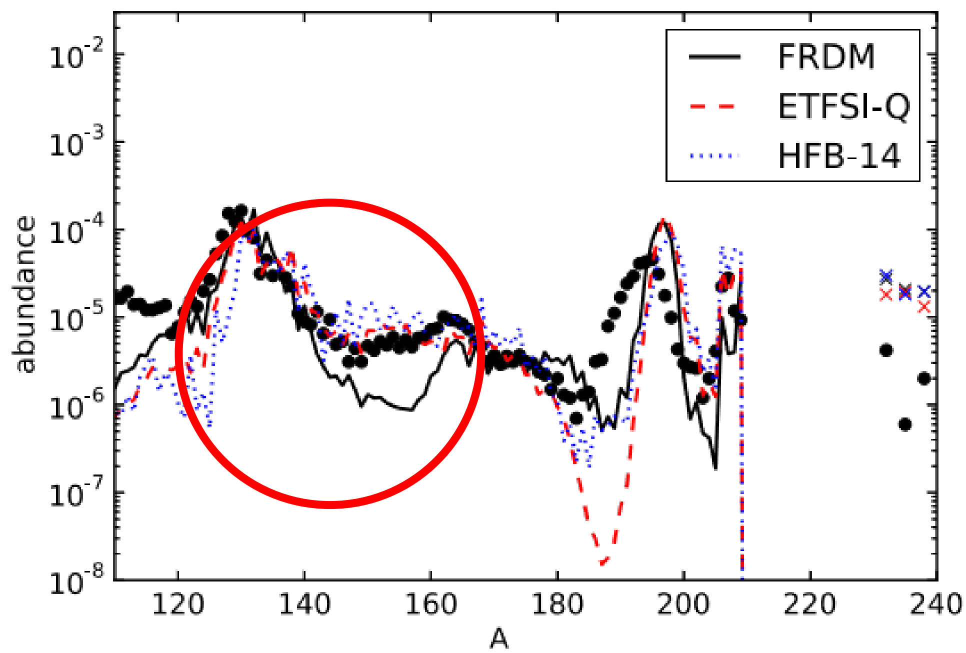
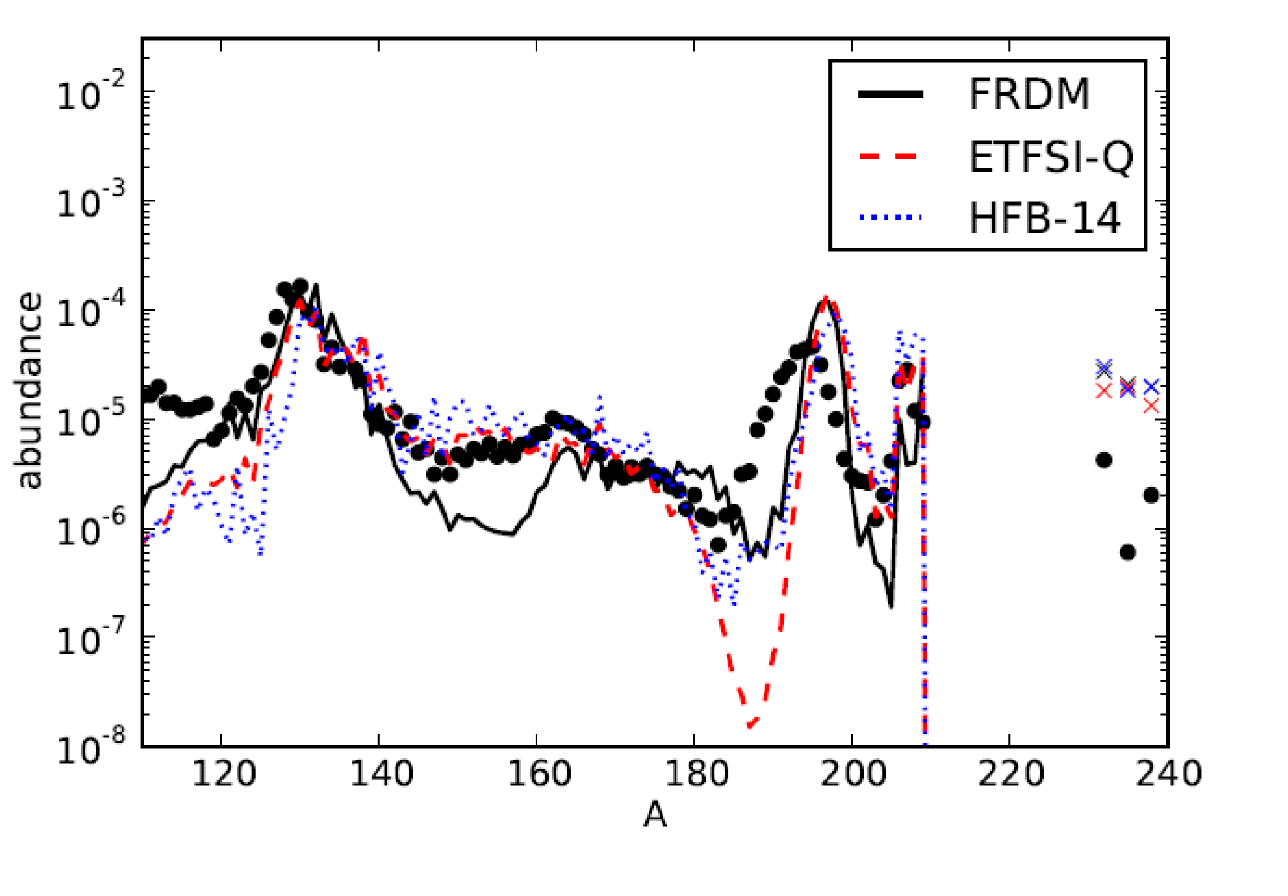


Figure 5. Comparison of nuclear mass models FRDM, ETFSI-Q, and HFB-14. The underproduction of $140 < A < 160$ nuclei apparent in the FRDM model does not occur in the ETFSI-Q or HFB-14 model cases. The fission fragment distribution model used here is ABLA07.

Eichler+ 2015

Fission recycling



M. Eichler, PhD Thesis

The position of the third peak in the final abundances is strongly dependent on the characteristics of the conditions encountered during/after the r-process freezeout, which are characterized by a steep decline in neutron density and a fast increase in the timescales for neutron captures and photodissociations…the third peak is shifted to higher masses during/after freeze-out, caused by the final neutron captures from neutrons which are released during fission of the heaviest nuclei in the final phases of nucleosynthesis.

Where does the rapid neutron capture process occur?

SuperNovae

Woosley et al. 1994

Neutron stars mergers

Lattimer & Schramm 1974
Freiburghaus et al. 1999

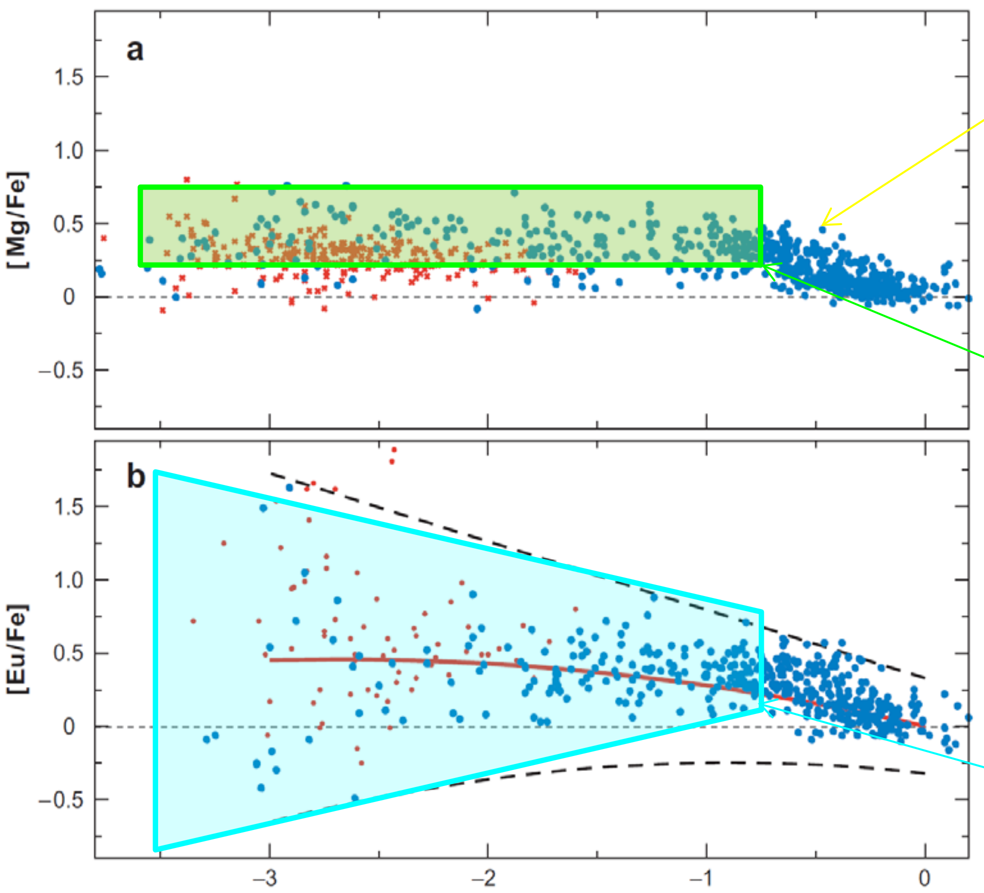
What do very metal-poor stars tell us (I)

Magnesium traces the enrichment of α-elements.

Iron is a suitable representative of metallicity.

Europium is used to identify the level of r-process enrichment (95%).

$[X/Y]=\log(X/Y)_{STAR}-\log(X/Y)_{SUN}$



Sneden+ 2008

Appearance of SN Ia (strong Fe producers)

SMALL SCATTER

Simultaneous production of Mg and Fe.

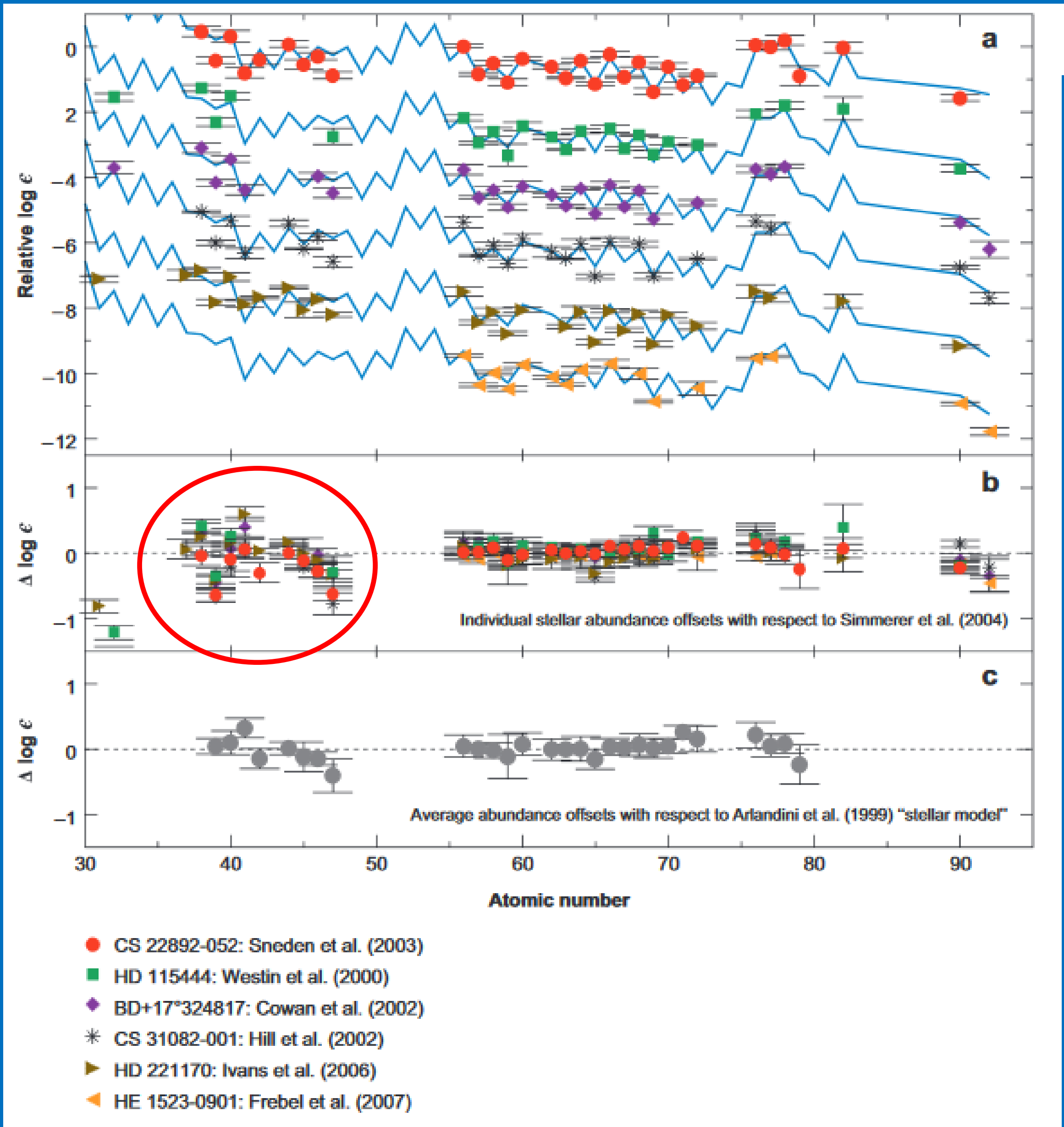
Homogeneous mixing: HIGH frequency event.

LARGE SCATTER

Eu and Fe are not produced in the same event.

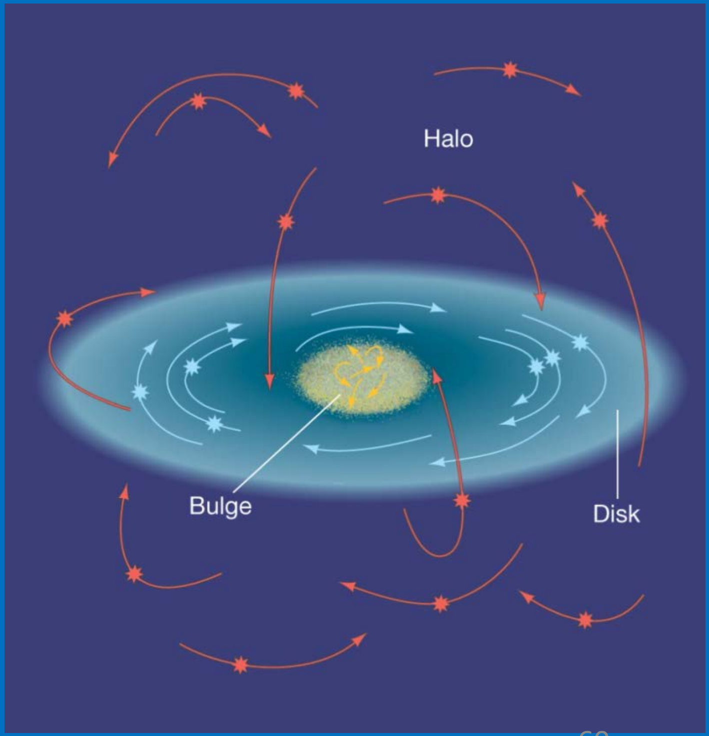
Inhomogeneous mixing: LOW frequency event.

What do very metal-poor stars tell us (I)



Sneden, Cowan & Gallino 2008

ROBUST pattern starting from Z=55



The LARGE SCATTER – LOW FREQUENCY hypothesis naturally favor NSMs!!!

HOWEVER, NSMs are expected to appear relatively late in the galactic history:

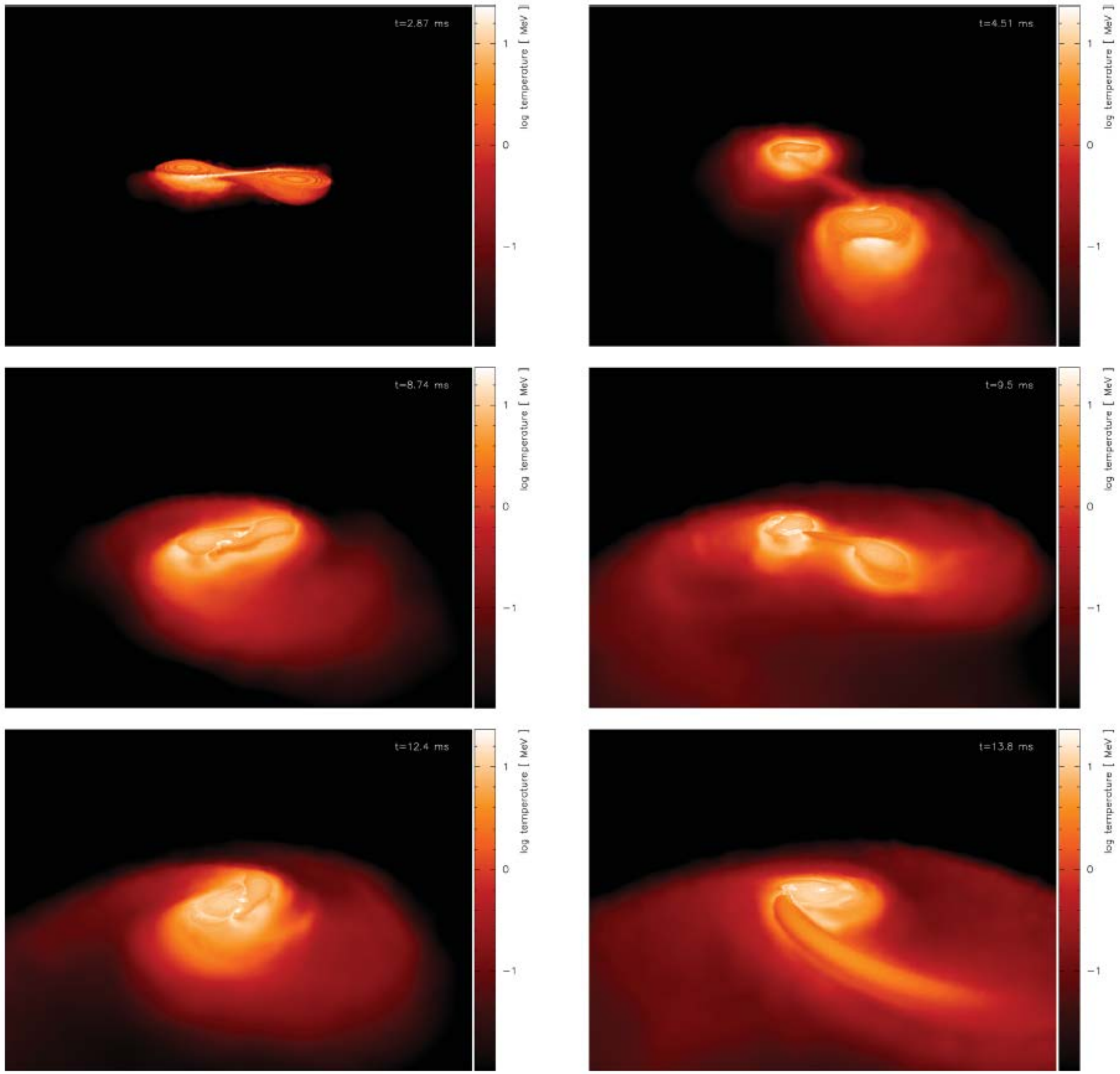
- both stars need time to evolve to the supernova explosion;
- their ejecta need time to pollute the surrounding ISM;
- the two neutron stars need time to spiral inwards until the final collision.

POSSIBLE SOLUTIONS

Magnetorotationally driven SuperNovae

Hierarchical formation of the halo (pollution by NSMs)

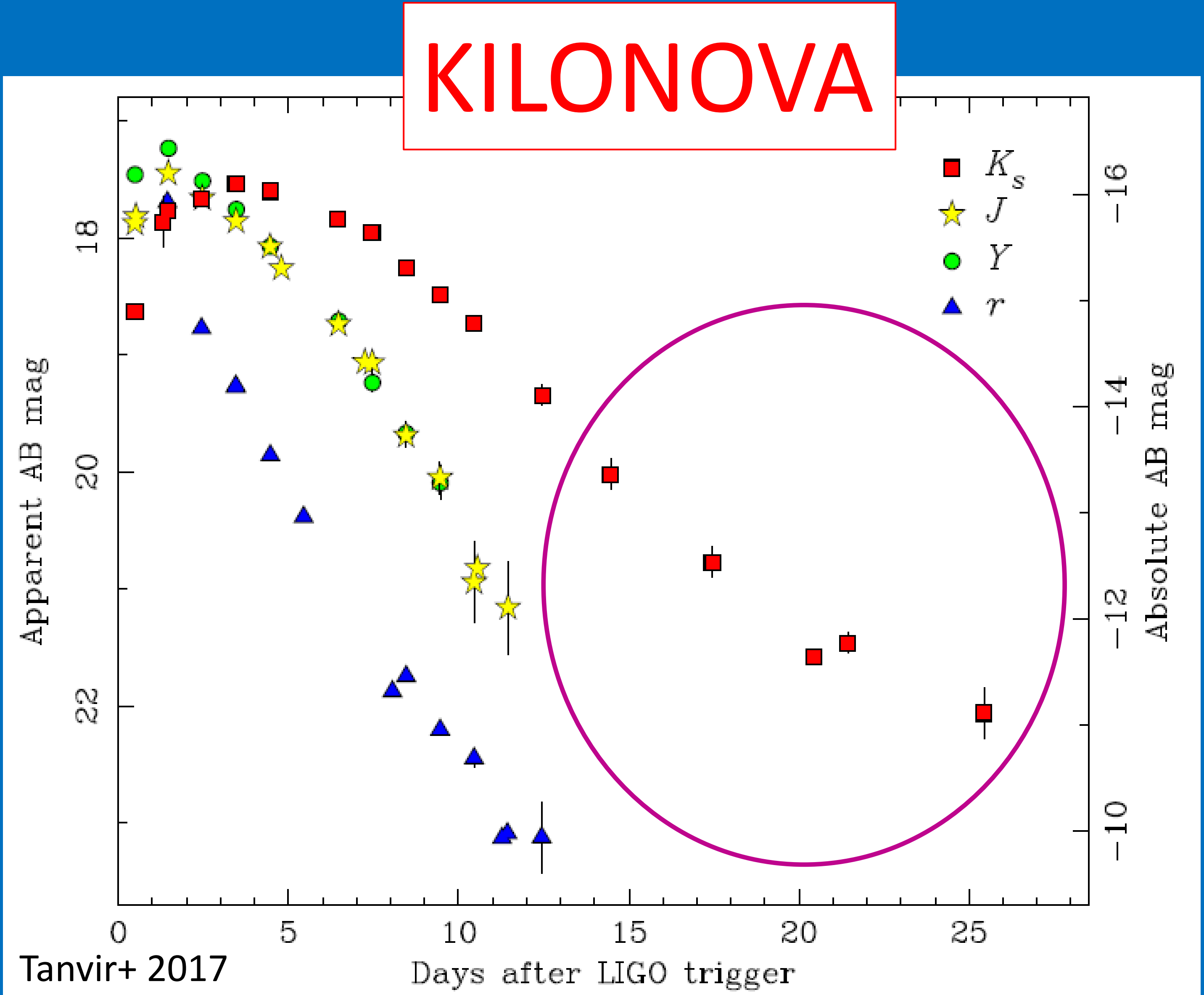
Neutron Stars Mergers



Rosswog+ 2013

Pros for NSMs

GW170817 infrared rebrightening



Tanvir+ 2017

Radiative transfer equations

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = S_\nu - I_\nu$$

Radiation Intensity

Optical depth

Source function
(ratio between emissivity and absorbption)

$$\tau_\nu(D) = \int_0^D \alpha_\nu(s)\,\mathrm{d}s$$

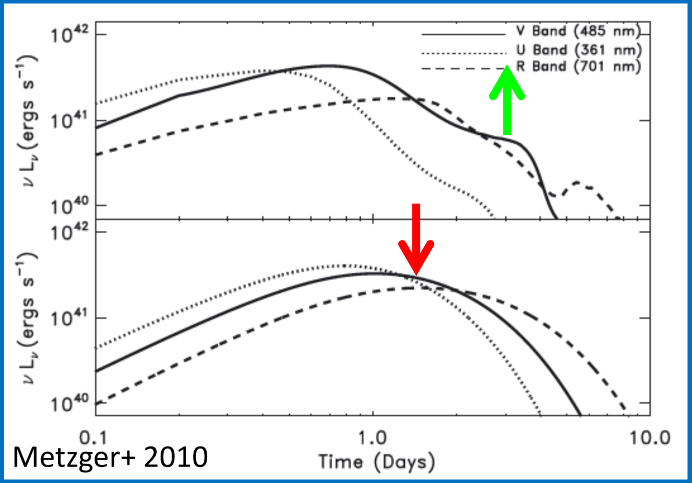
$$\alpha_\nu = \kappa_\nu \rho$$

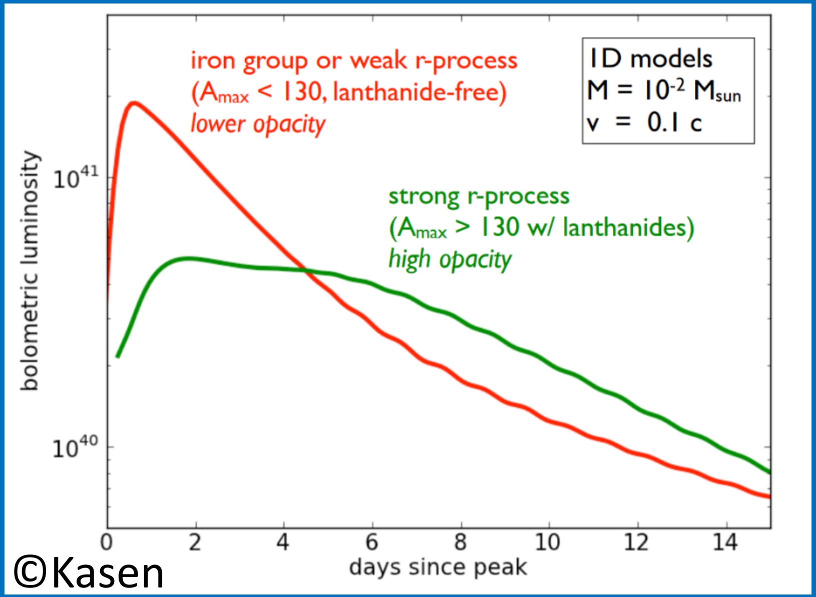
K_ν is the opacity

LINE BLANKETING

Lantanides opacity

Grey opacity

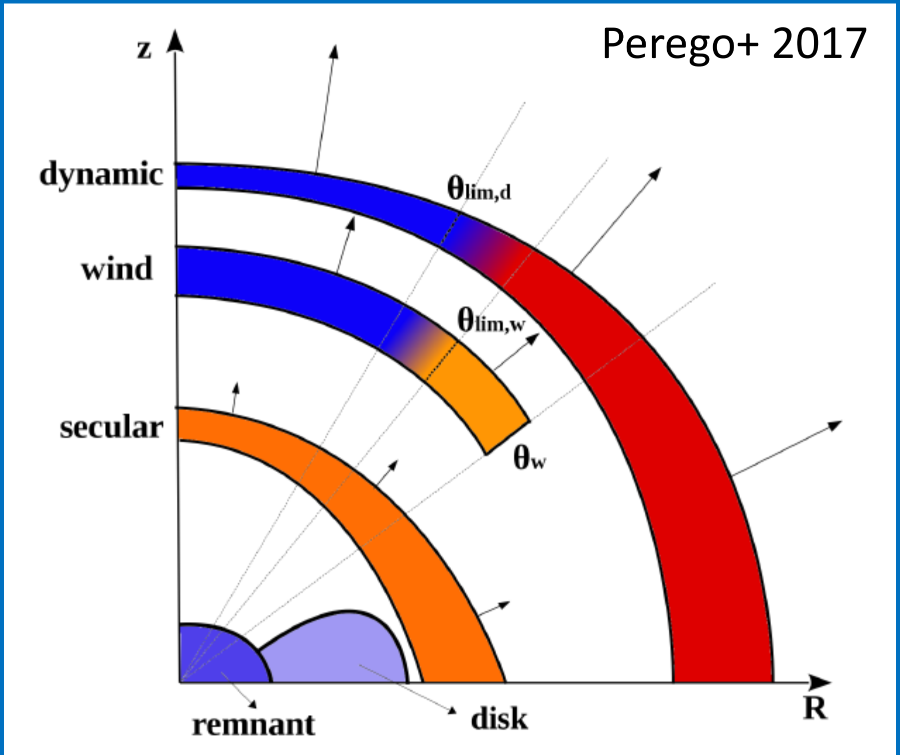


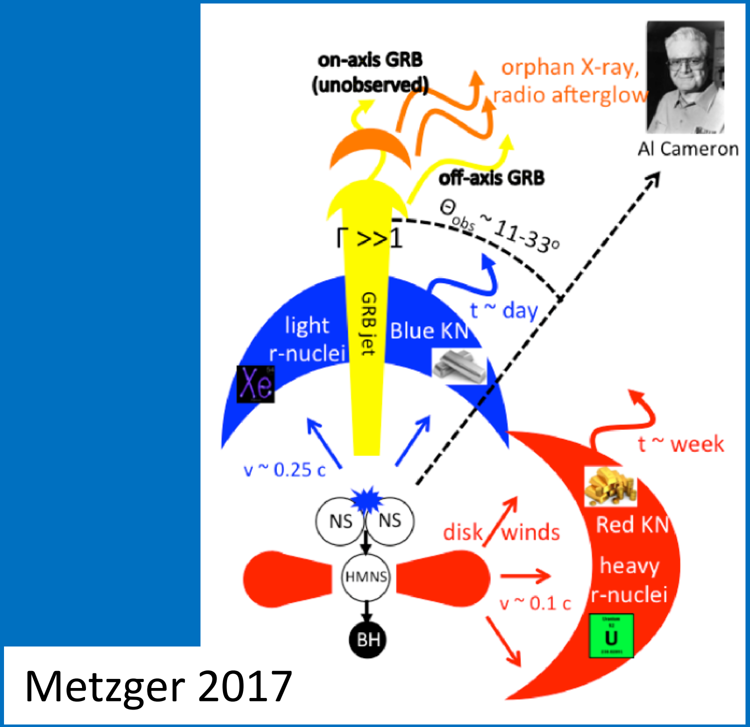


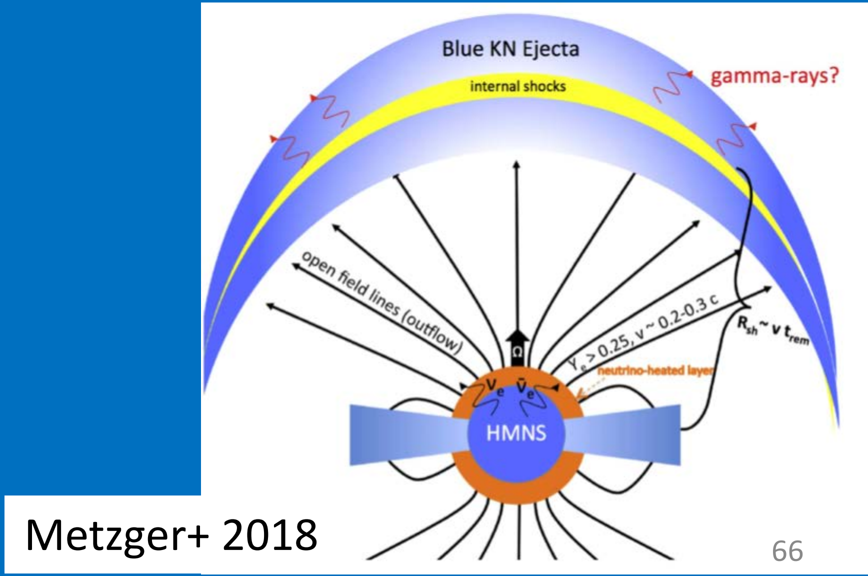
Line blanketing: absorbed photons (those forming spectral lines) are thermalized and re-emitted at other frequencies (or wavelenghts), in particular in the continuum (absorption lines behave as a «blank», heating internal layers). The energy from decays is absorbed and re-emitted so many times in lantanieds-rich layers to be completely redistributed as a black body spectrum, peaked in the infrared.

Components of NSMs event

1. Dynamical ejecta;
2. Neutrino wind;
3. Disk ejecta

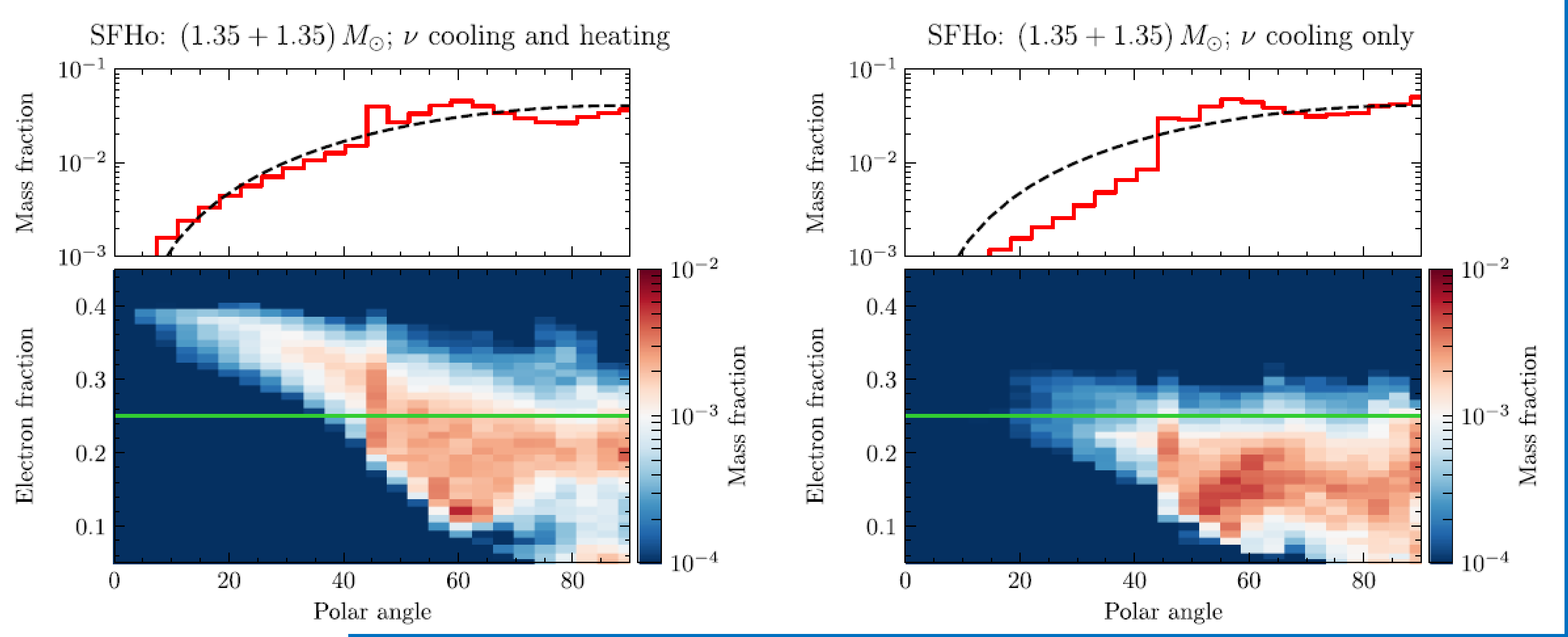






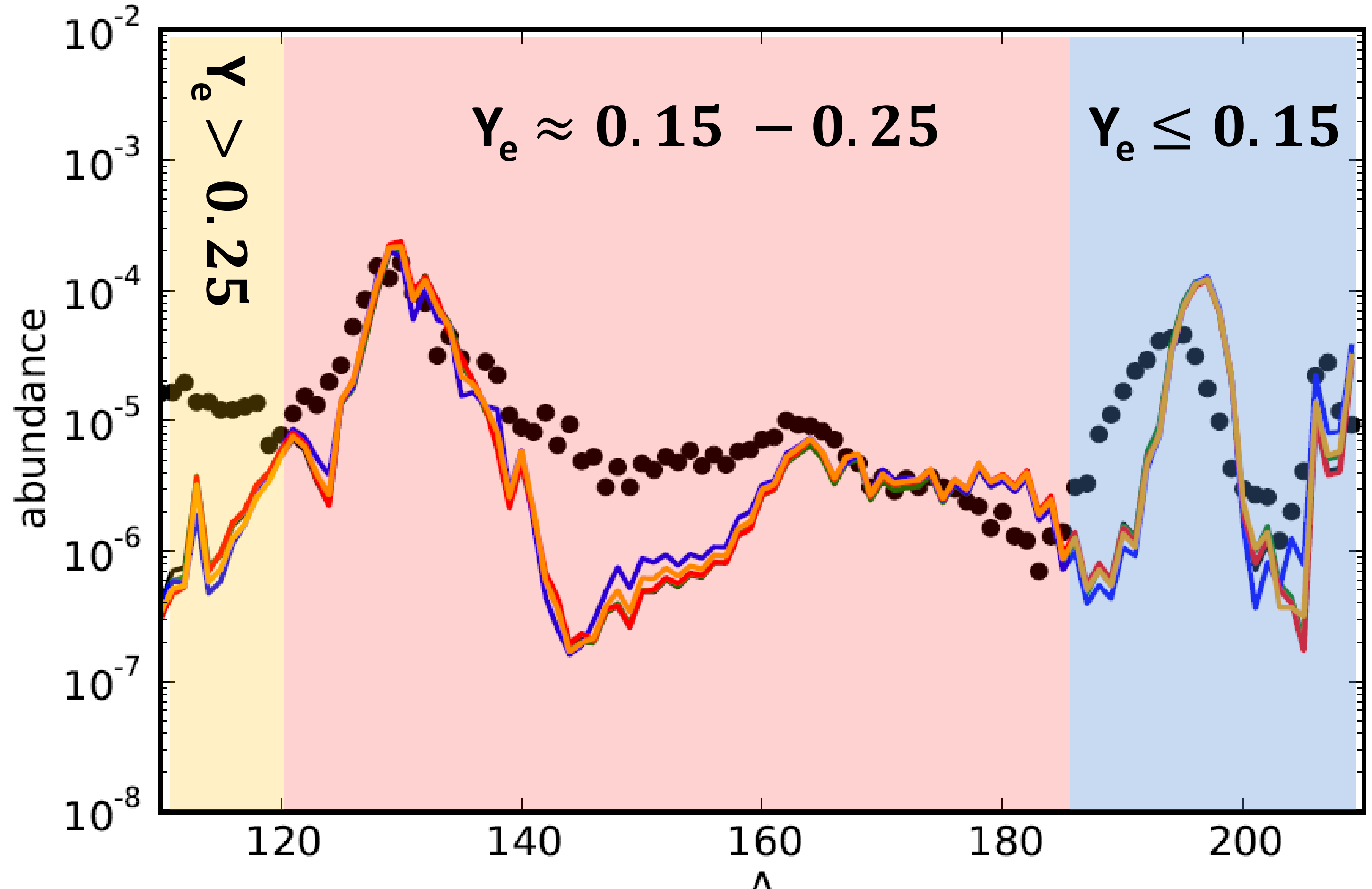
The role of neutrinos

The presence of neutrinos increases Y_e in the polar direction



Perego+ 2017

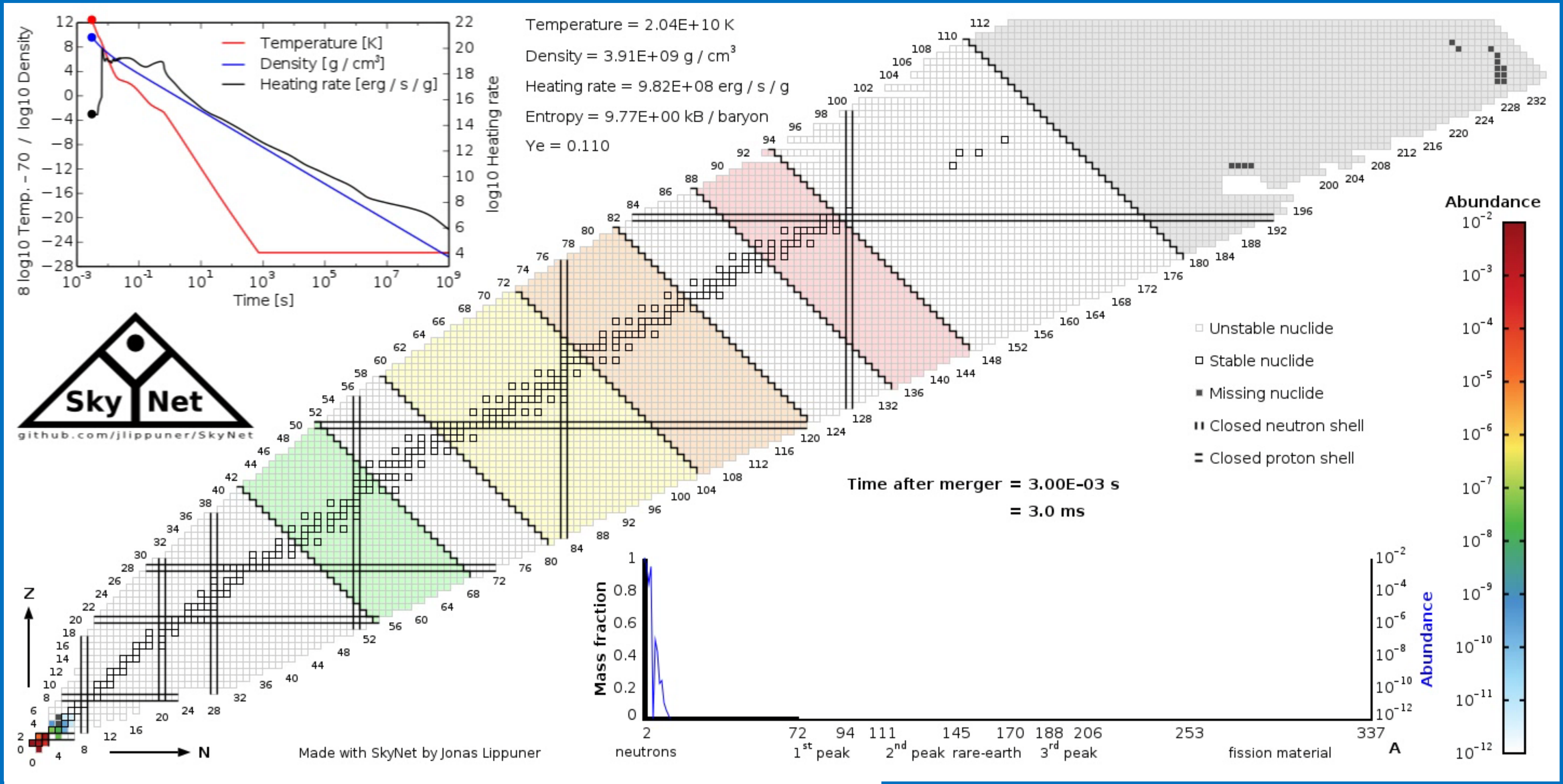
Neutron Stars Mergers



M. Eichler, PhD Thesis

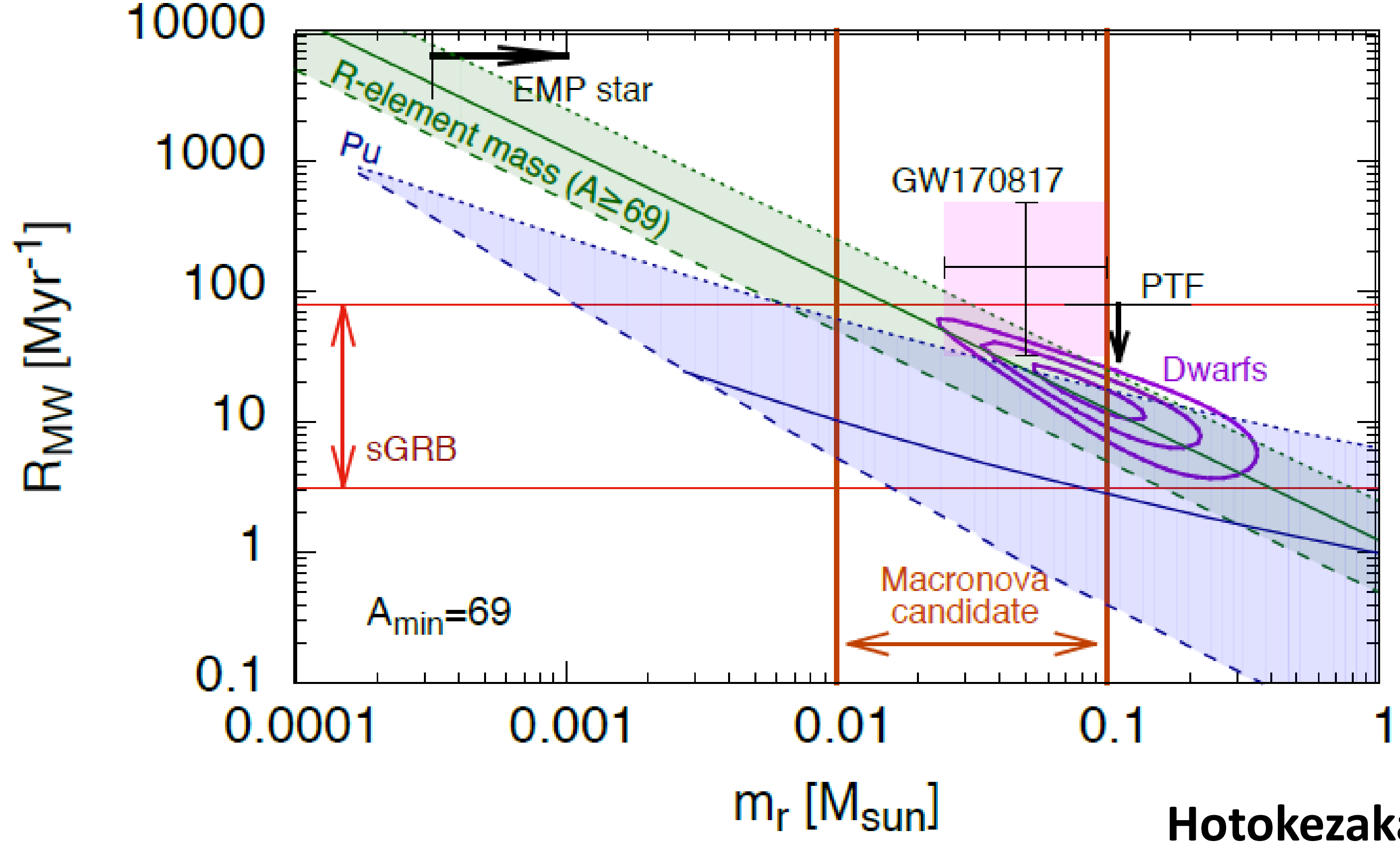
The extremely high neutron-to-seed ratios make nucleosynthesis results very robust, because the reaction path runs close to the neutron dripline. Moreover, several fission cycles occur before the r-process freeze-out.

r-process simulation in a NSM



SkyNet (J. Lippuner' PhD Thesis, 2018)

Pros for NSMs



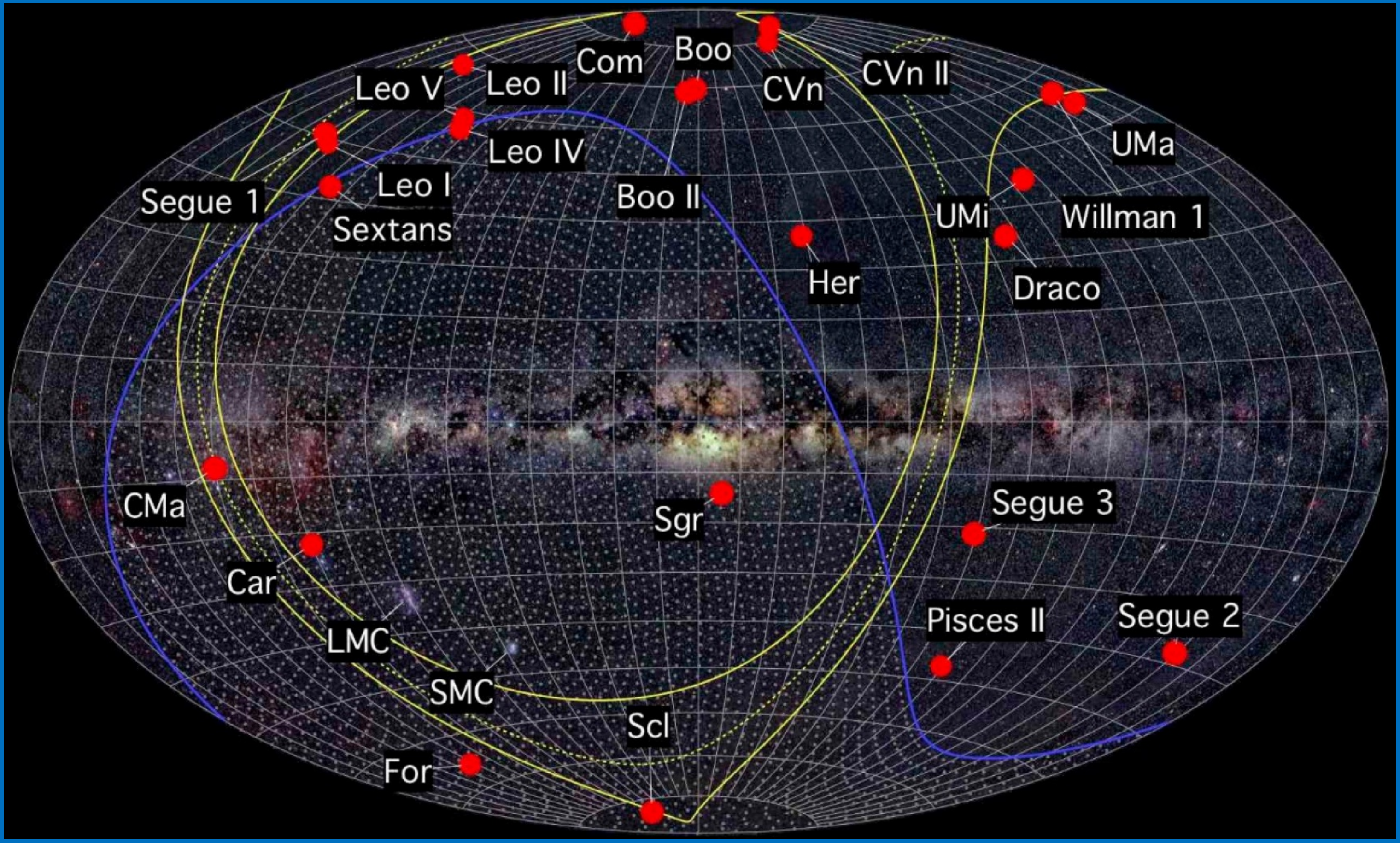
Hotokezaka+ 2018

The current abundance of ^{244}Pu (half-life 81 Myr) in the Interstellar medium (infos derived from deep-sea crust), is much lower than in the early solar system. This implies a low-rate/high-yield process (Wallner+ 2015).

Pros for NSMs

Ultra Faint Dwarf galaxies (UFDs): no gas, old stellar populations (first 1-2 Gyr of the Universe).

Each UFDs experienced a short burst of star formation: ideal to investigate the chemical enrichment in the early Universe (as occurred in the halo of our Galaxy).



Pros for NSMs

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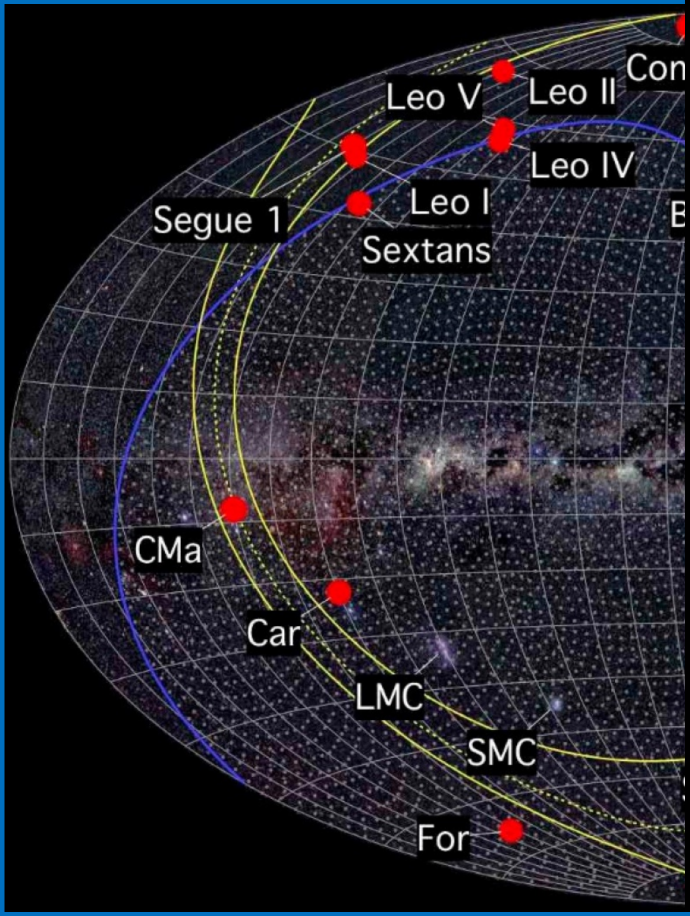
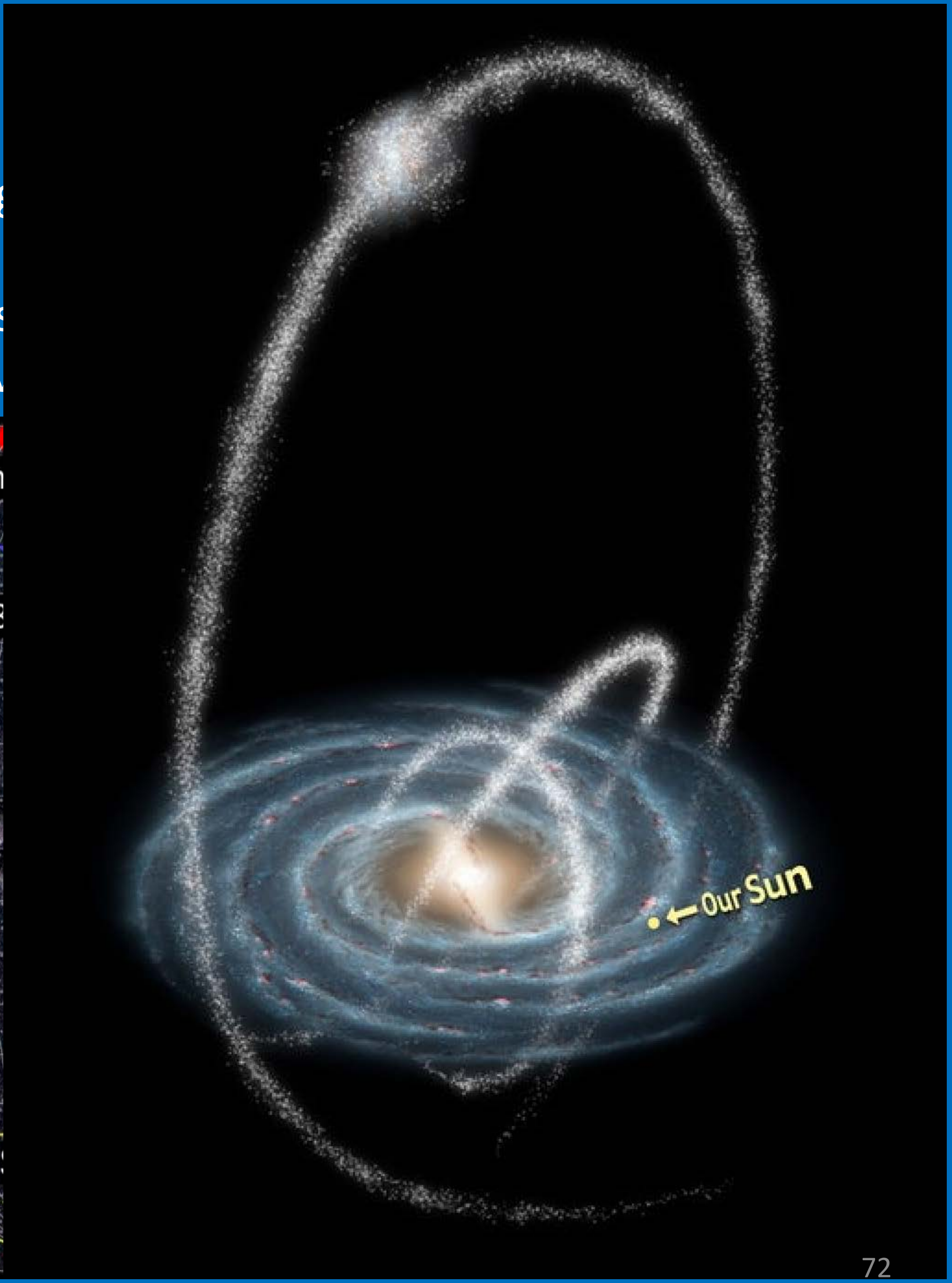
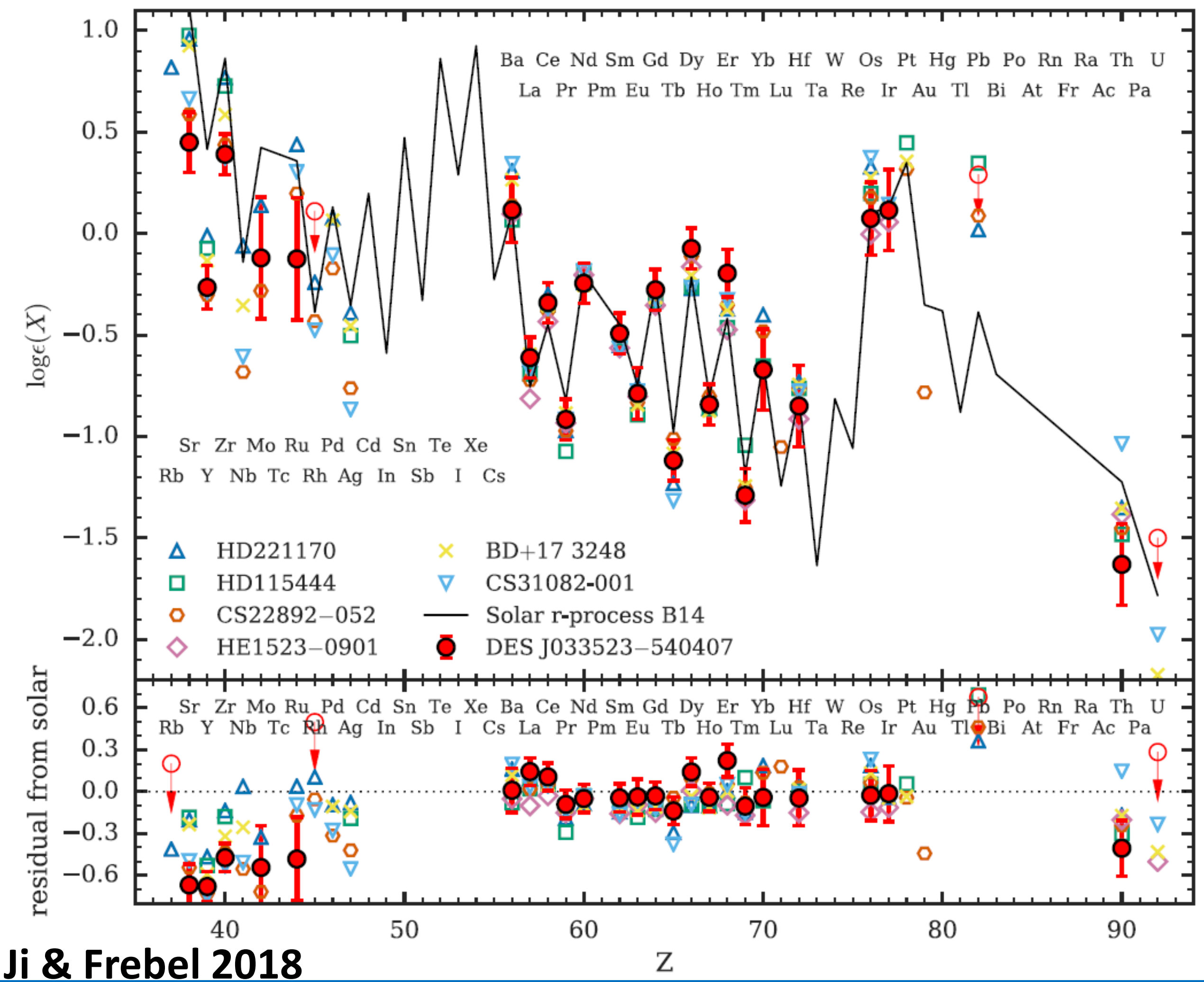




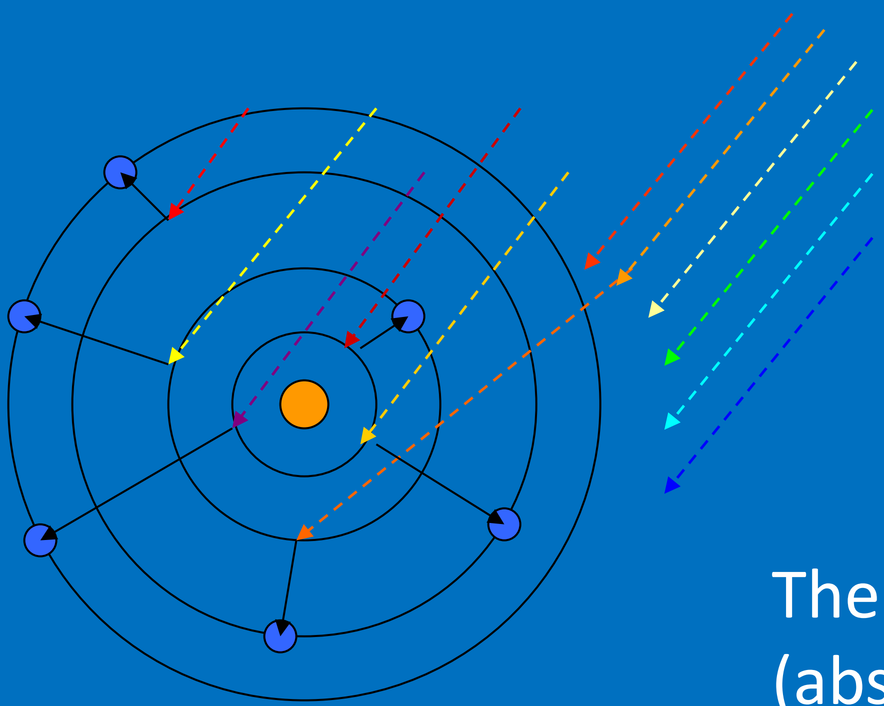
Pros for NSMs

DES J033523-540407 is a star belonging to Reticulum II: its surface enrichment is consistent with a pure r-process from a single event.



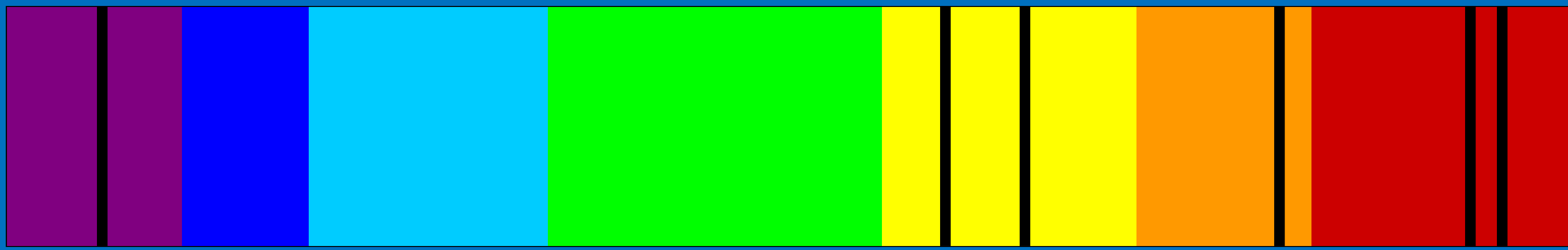
Ji & Frebel 2018

Reverse problem: do SNe show r-process enrichment?

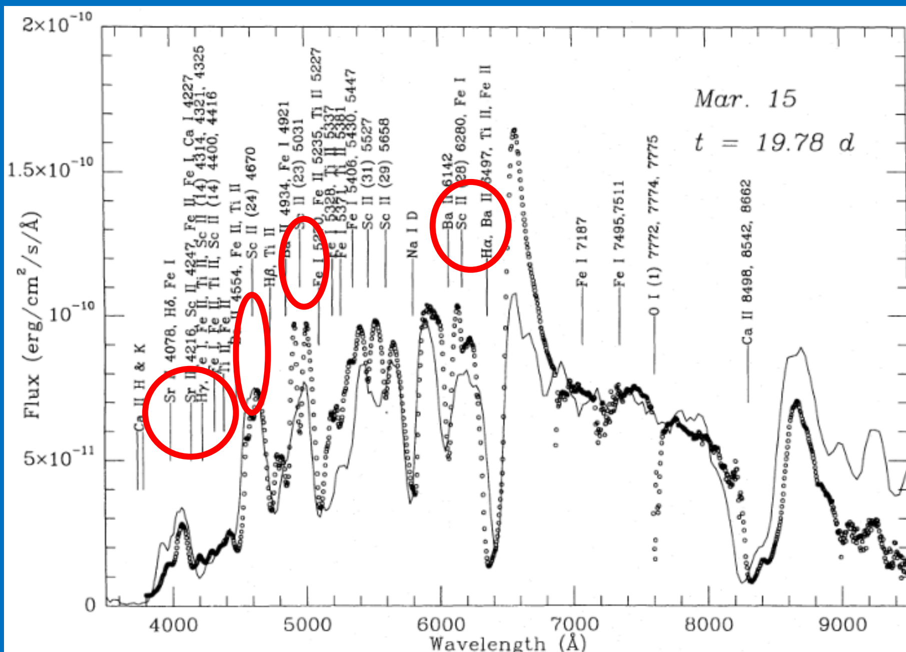


In a stellar atmosphere, only photons of the correct colors will be used to “jump” the electrons to higher orbits.

The result is a spectrum with dark (absorbpion) lines located where the bright lines would be in the atom’s emission spectrum…



Reverse problem: do SNe show r-process enrichment?

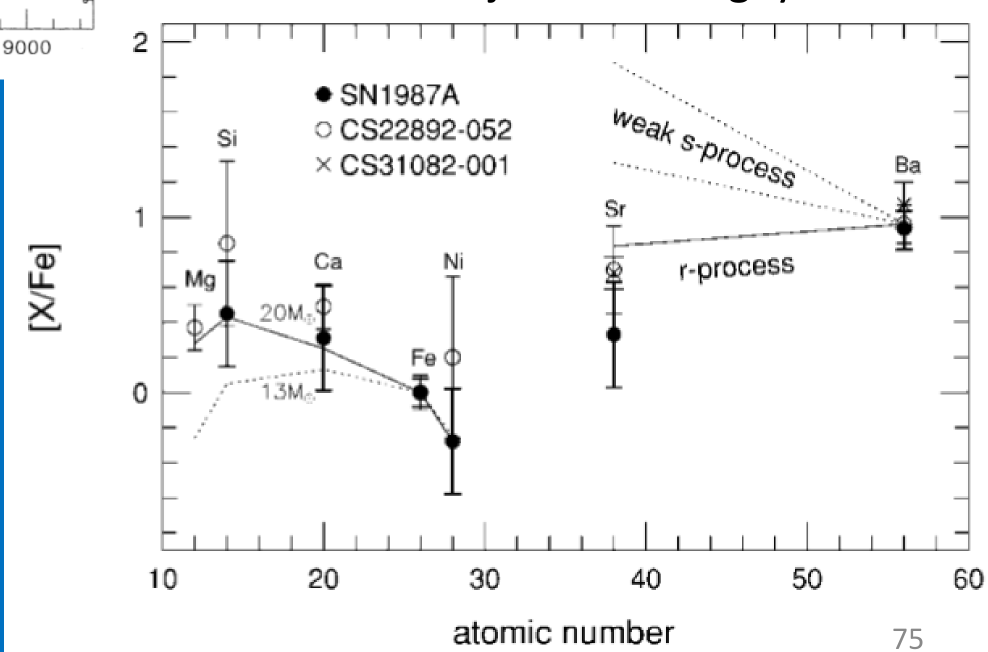


Mazzali+ 1995

SN 1987A (d=0,05 Mpc)

800 times closer than GW170817

Tsujimoto & Shigeyama 2001



The strength of Ba II lines might be affected by variable ionization and temperature issues (Utrobin & Chugai 2005; Pastorello et al. 2012).
However, these effects should be valid in general and might not explain completely why in other CCSNe the Ba and Sr lines are signicantly weaker (Branch & Wheeler 2017).

Toward the explosion of a SuperNova

1) The core is made of iron-peak nuclei (NSE) and electrons. There are Y_e electrons per nucleon;
2) The pressure against the collapse is mainly provided by degenerate electrons;
3) As long as $M_c < M_{CH} = 1.44(2Y_e)^2 M_{SUN}$ there is no explosion.

BUT:

- Shell Si-burning accretes mass on the core
- Electrons can be captured by protons (free or bound in nuclei):

$$e^- + A(Z,n) \rightarrow A(Z-1, N+1) + \nu_e$$

Y_e decreases ← → heat carried out

But the pressure is given by degenerate electrons, i.e.

$$P \approx n_e \mu_e \approx 1.11\ (\rho_7 Y_e)^{1/3}\ \text{MeV}$$

Chemical potential (Fermi energy; increases with ρ)

At $\rho_7=1$ electron captures become energetically favored, this fact triggering the collapse.

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

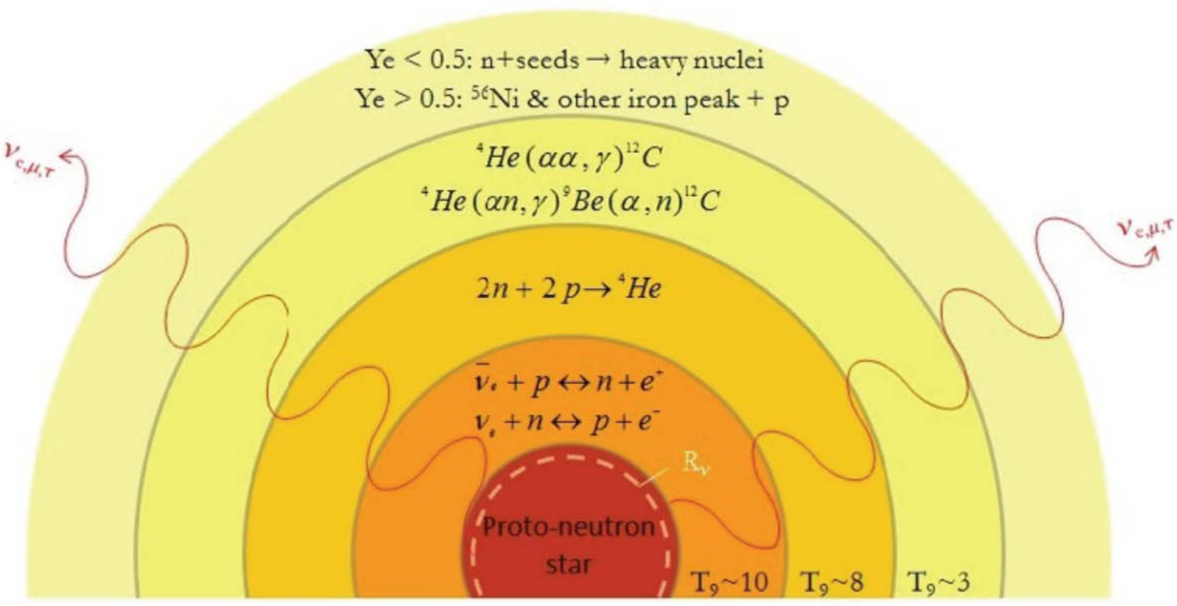
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

The High Entropy wind in SuperNovae

Before proceeding, a little step back, in 1994:

«We find that an excellent fit to the solar r-process abundance distribution is obtained with no adjustable parameters in the nucleosynthesis calculations. Moreover, the abundances are produced in the quantities required to account for the present Galactic abundances.» [from Woosley+ 1994]

νp-process or rp-process (Frolich+ 2006)



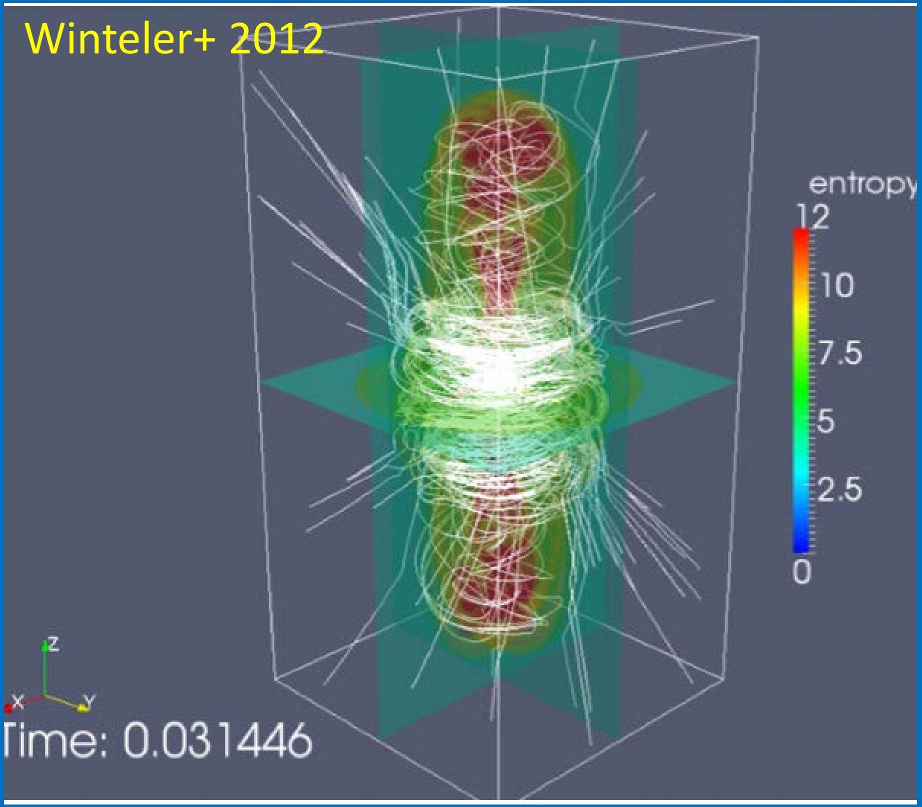
Arcones&Thielemann 2013

$$n_n/n_{\rm seed} \propto s^3/\left(\tau_{\rm dyn} Y_e^3\right)$$

The large Y_e (≈0.5) implies too large entropies (≈200)

STANDARD SNe NOT A VIABLE MECHANISM!!!

Magnetorotationally driven SuperNovae

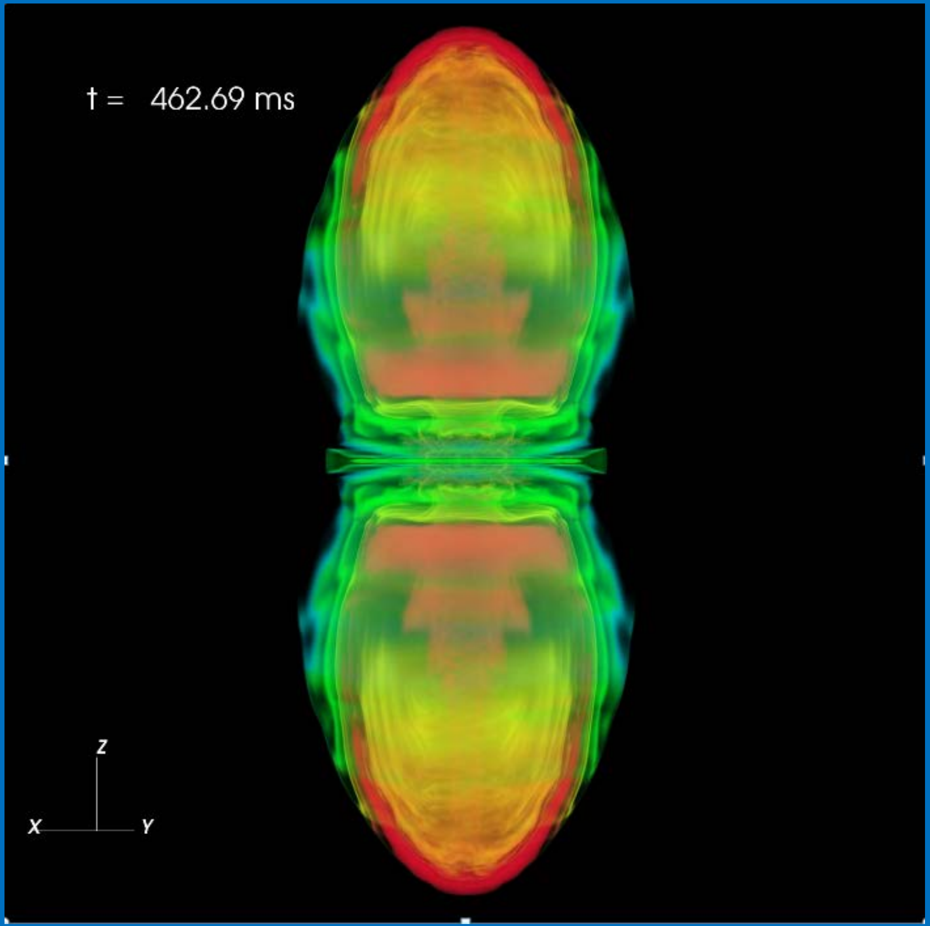


Those supernovae may provide a strong r-process already at low metallicities (Nishimura+ 2006; Winteler+ 2012).

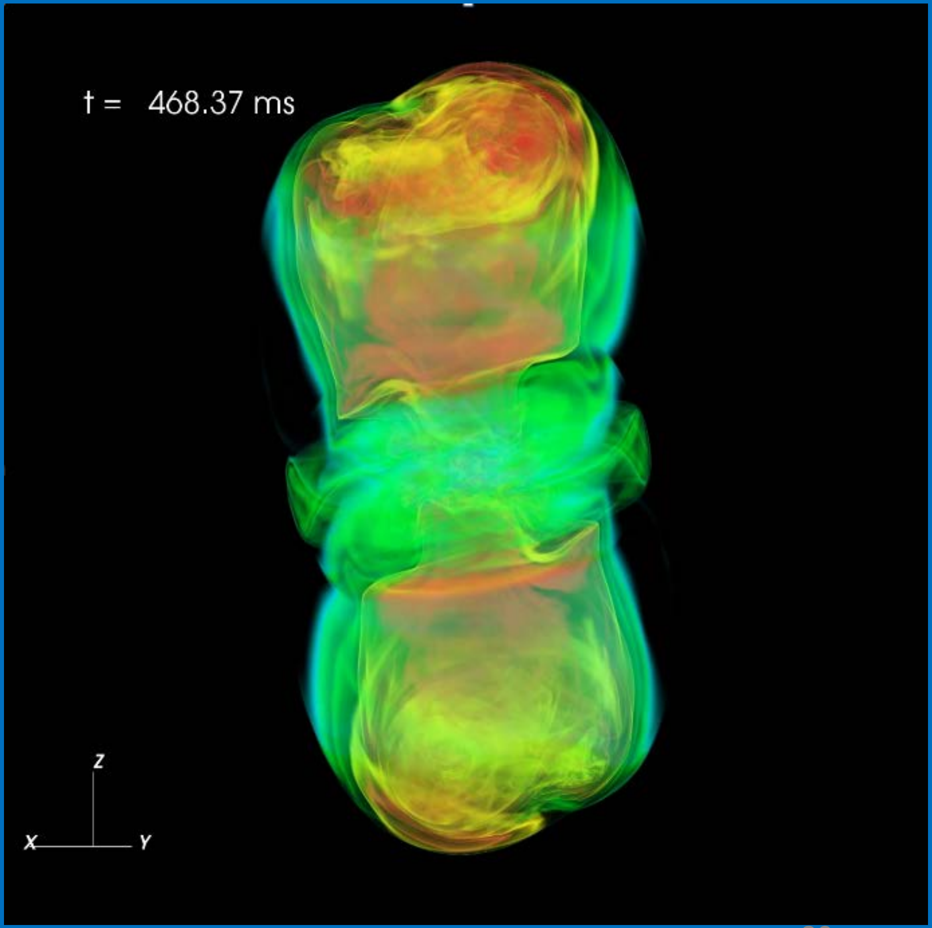
At the collapse and the following core-bounce (due to the stiffening of the EOS above nuclear saturation density), the core spins up for the conservation of angular momentum and the magnetic flux is amplified. The polidal field turns into a toroidal field. Rotational energy is conserved in magnetic energy, with an increase of the magnetic pressure, local exceeding the gas pressure. At the end, matter is ilfted from the PNS and drives a bipolar outflow.

Magnetorotationally driven SuperNovae

Main critical point: the simultaneous presence of fast rotation and strong magnetic fields (10^{15} Gauss) in the progenitor before collapse. At low metallicities, perhaps for 1% of all massive stars, favorable conditions can appear under special circumstances (Woosley & Heger 2006). **HOWEVER**, if the poloidal magnetic field component is at least moderately (within 30^{O}) aligned with the rotation axis, robust r-process nucleosynthesis emerges (e.g. Halevi&Mosta 2018)!



0 degree

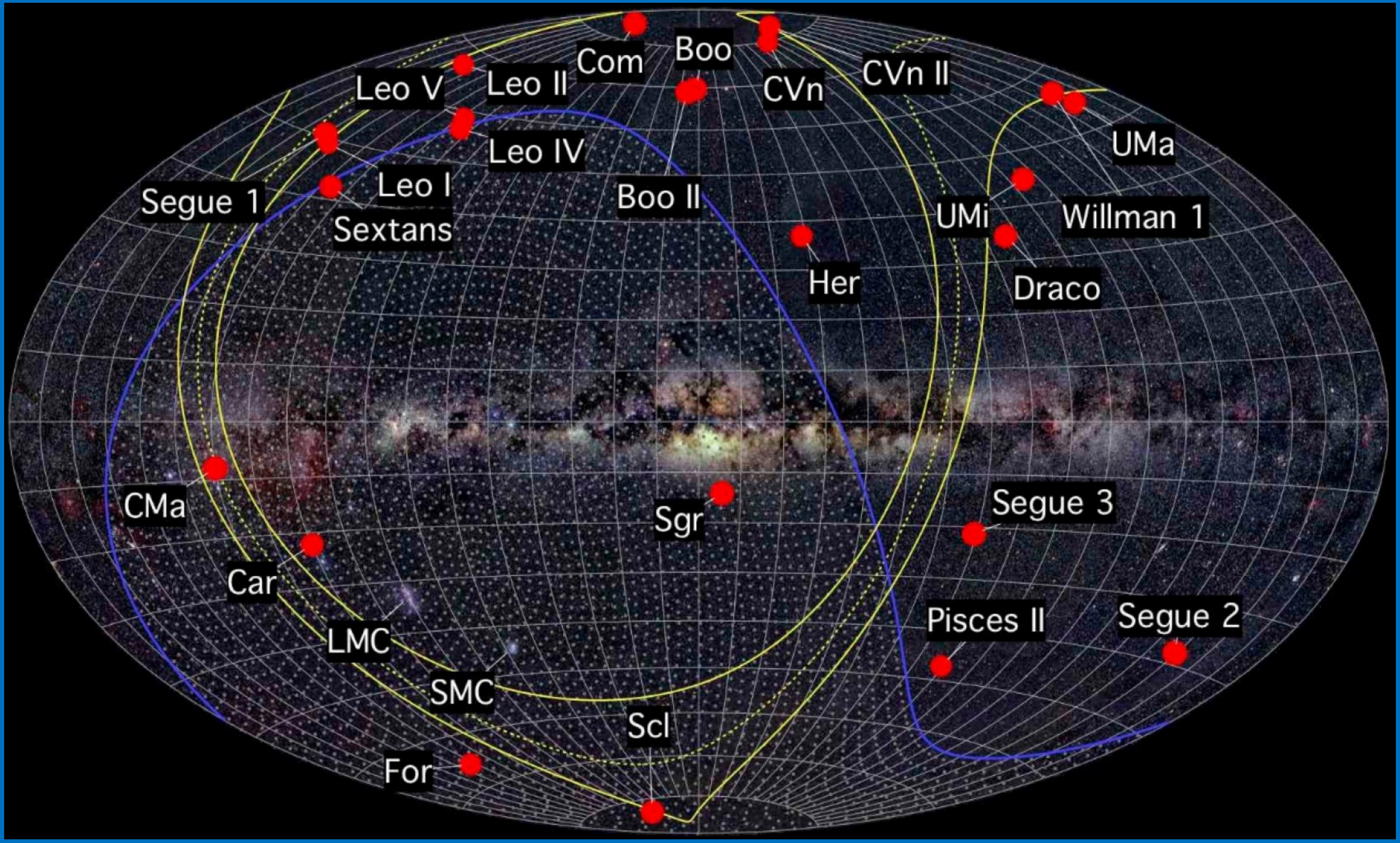


30 degrees

Pros for NSMs

Ultra Faint Dwarf galaxies (UFDs): no gas, old stellar populations (first 1-2 Gyr of the Universe).

Each UFDs experienced a short burst of star formation: ideal to investigate the chemical enrichment in the early Universe (as occurred in the halo of our Galaxy).



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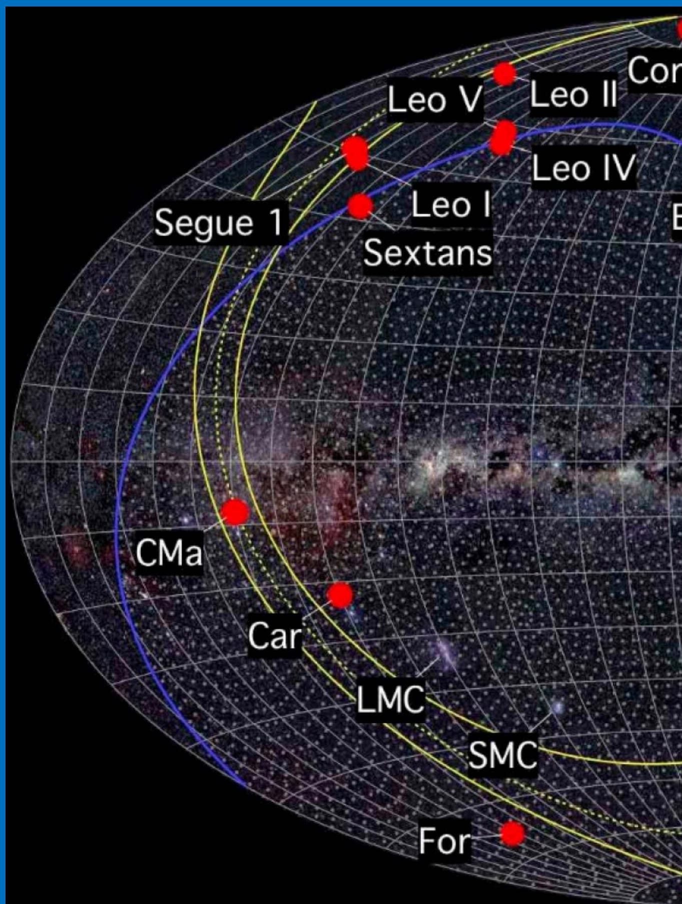
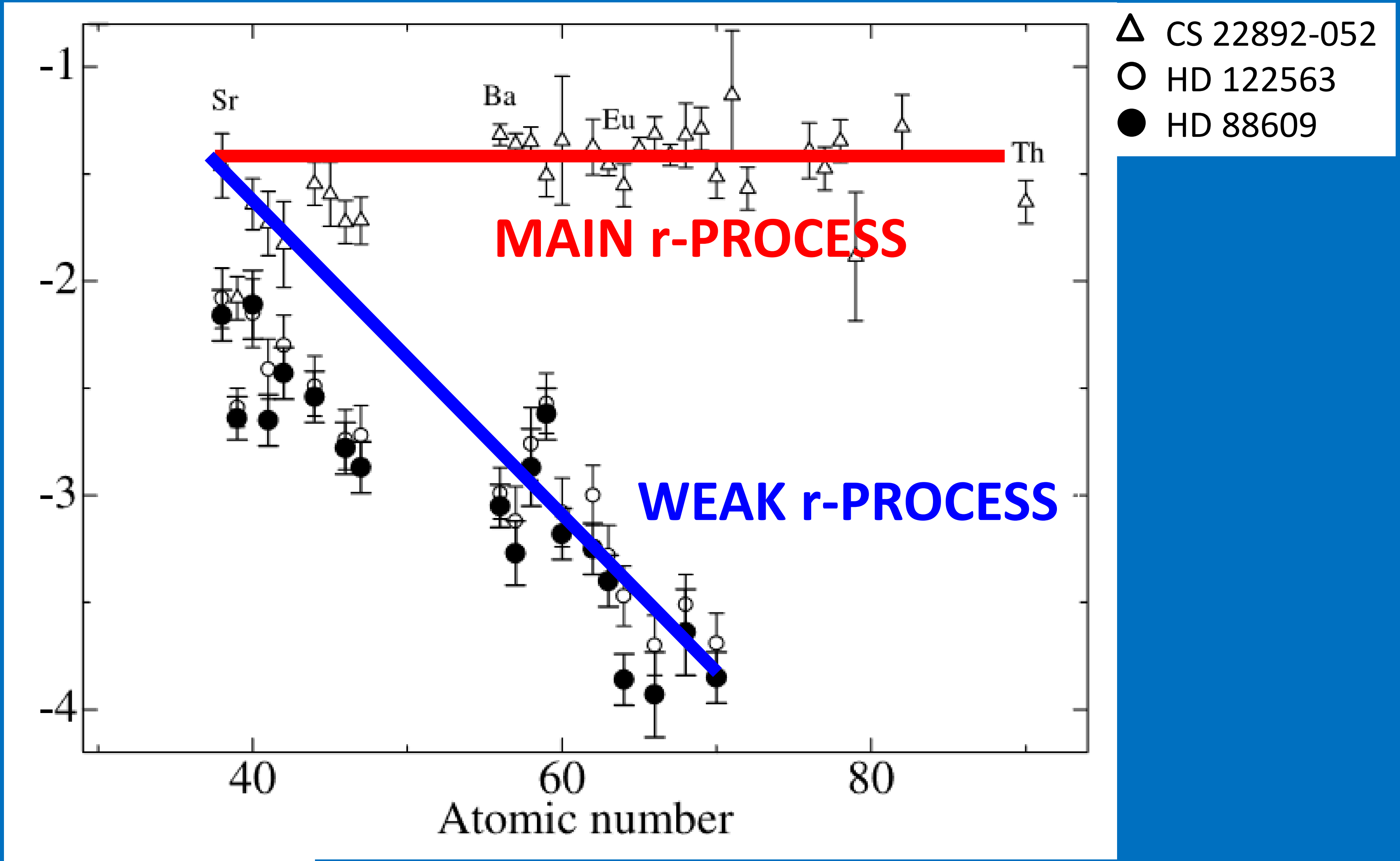
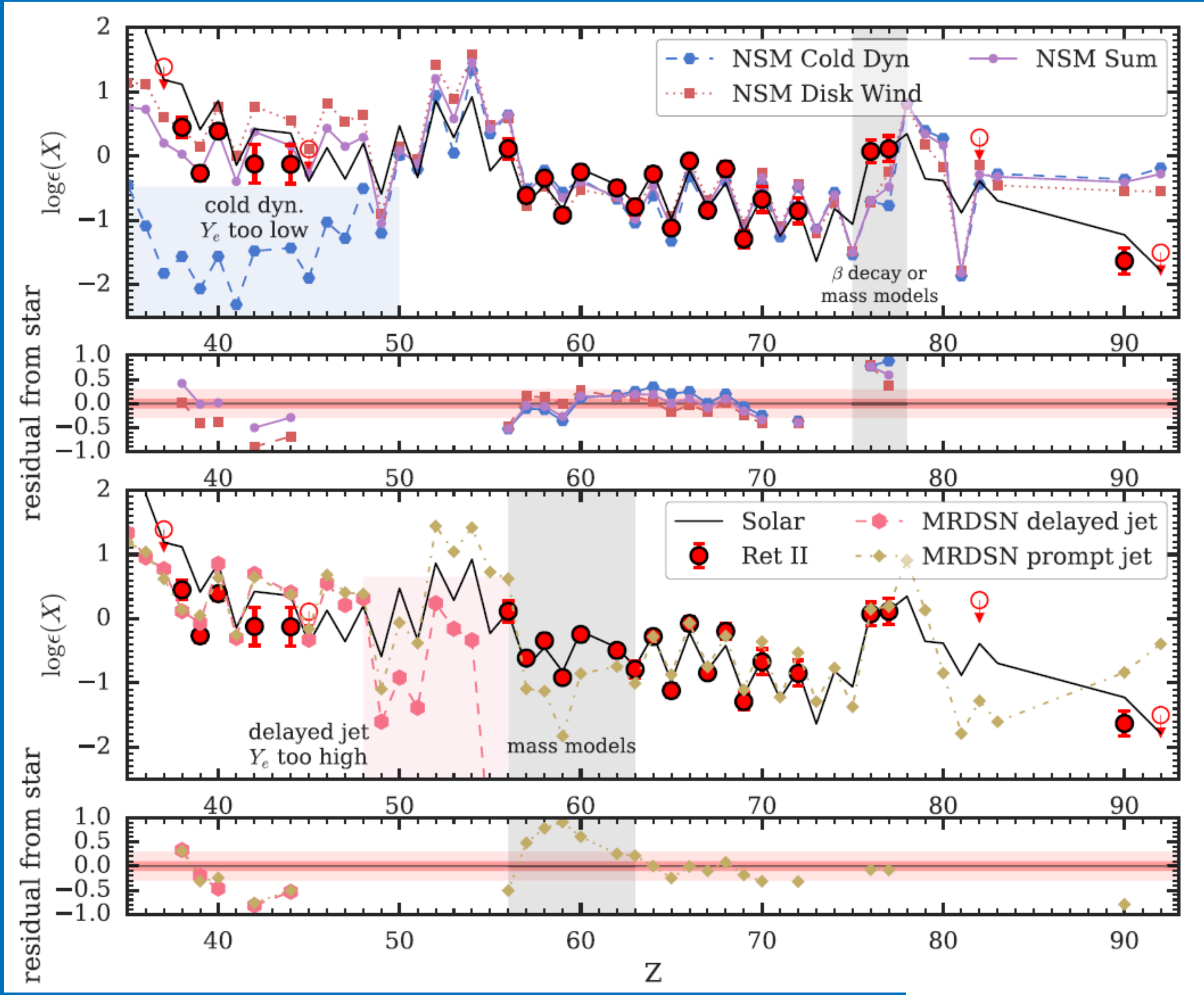


Honda-like stars



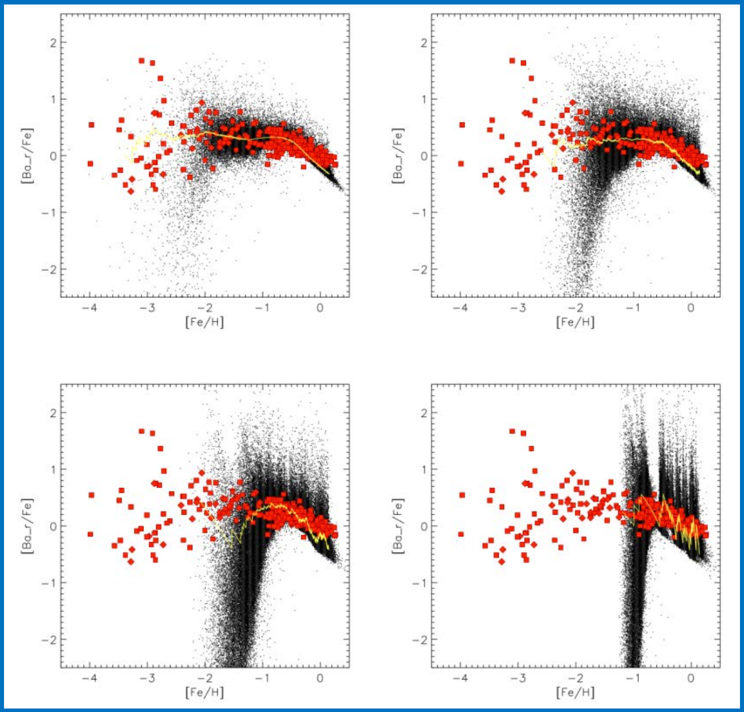
Honda+ 2007

And the winner is…

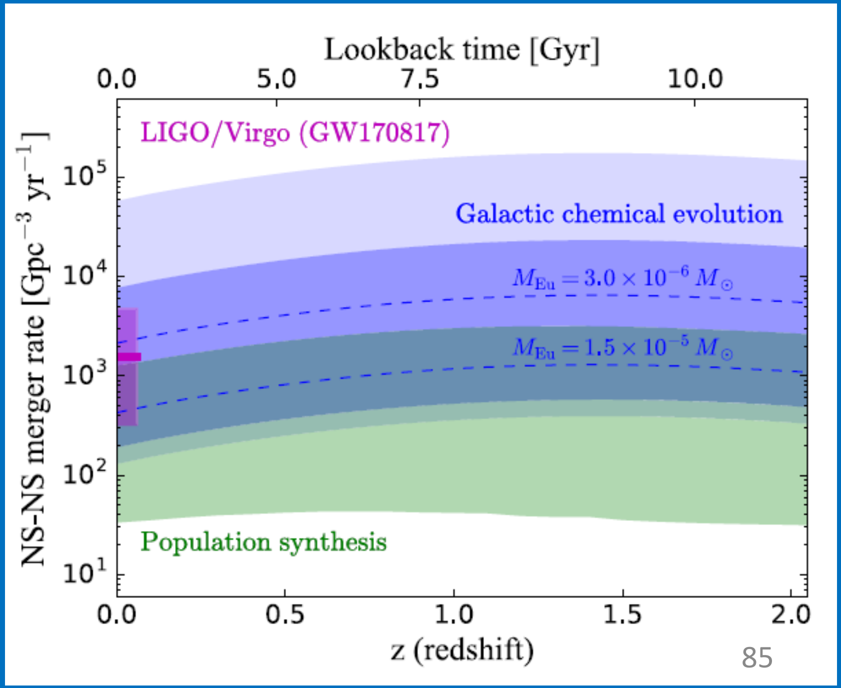


Ji & Frebel 2018

Galactic Chemical Evolution Models



NSMs cannot account for the first phase of the halo evolution, even adopting a coalesce time of 1 Myr (Argast+ 2004).



NSMs are the dominant source of r-process elements (Cotè+ 2018).