Nucleosynthesis across the Galaxy: AGB Stars and Neutron Stars Mergers

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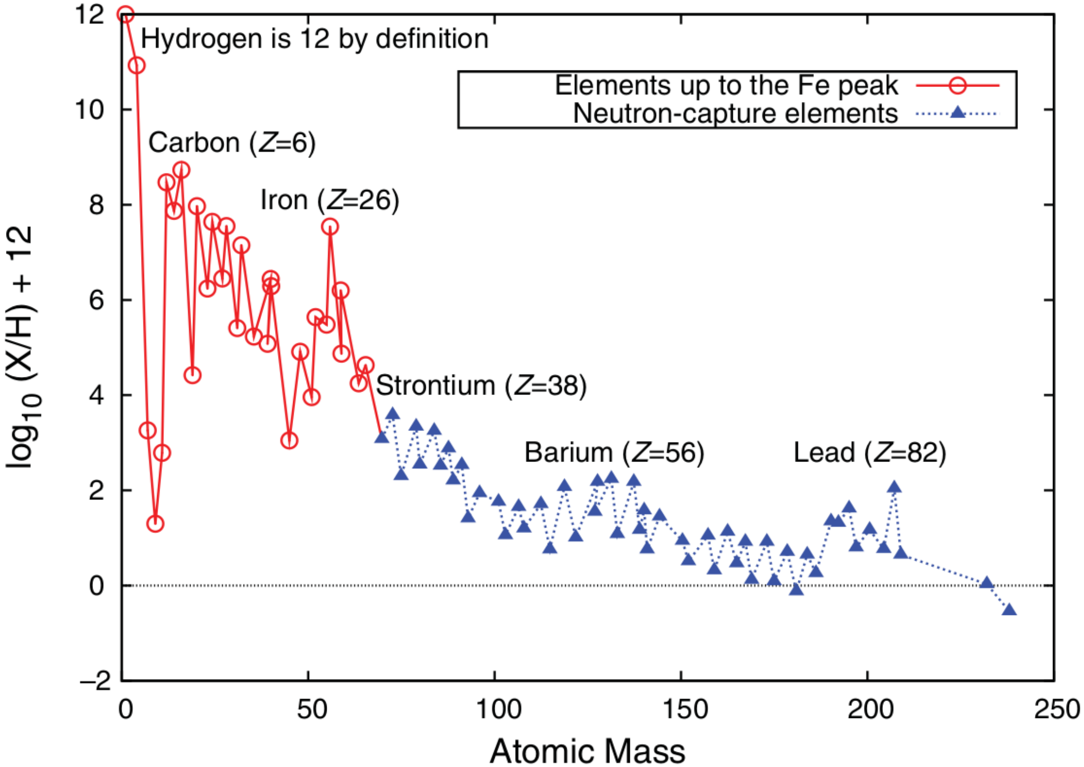
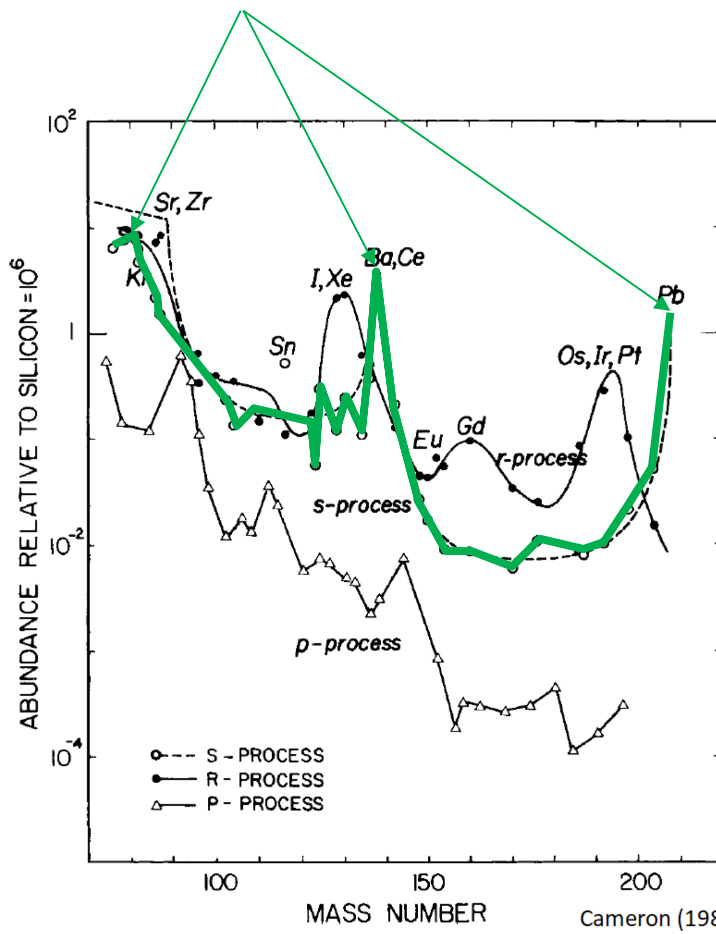
The origin of heavy elements in the Solar System



Location of peaks indicates *n*-captures along valley of stability ➡ *s*-process

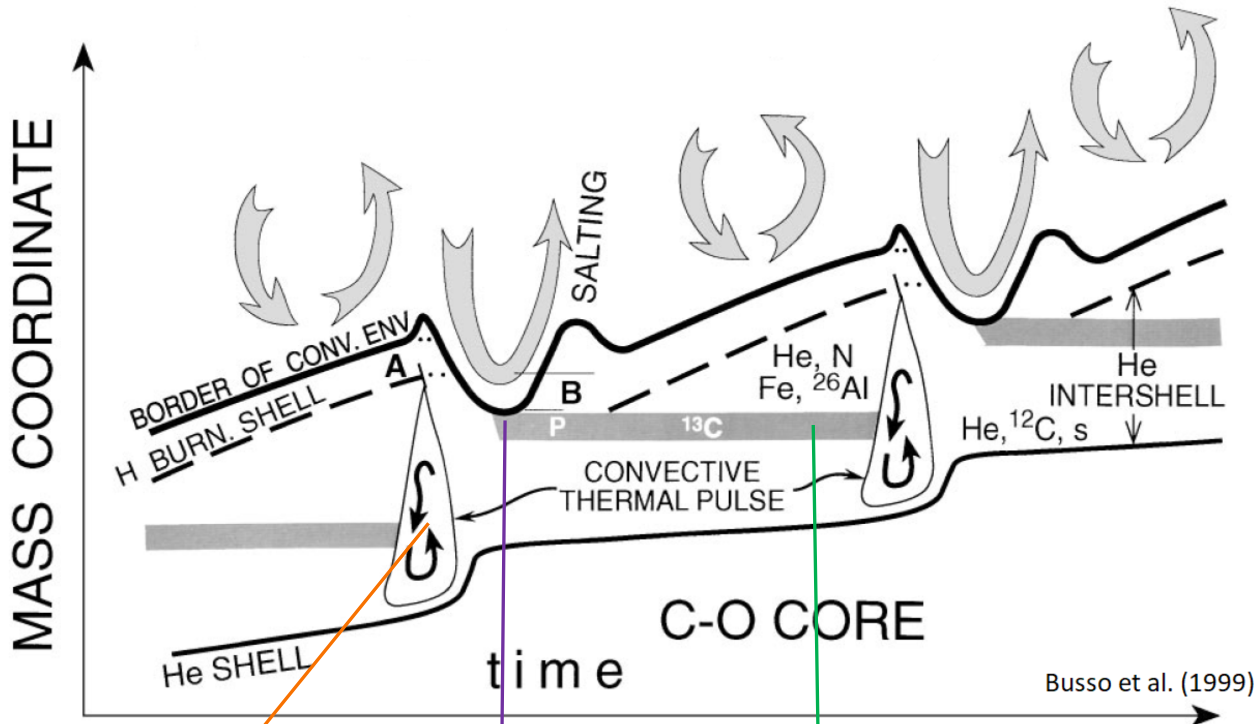


Cameron (1982)

Neutron captures processes :

- *r*-process
- *s*-process
  1) Weak component (A<90)
     Massive Stars
  2) Main component (from Sr to Bi)
     AGB stars

H- and He-burning in TP-AGB stars



- What?
  Low-Mass Stars
- When?
  Asymptotic Giant Branch (AGB)
- How?
  Thermally Pulsing (TP)

He-flash

proton penetration

^{13}C-pocket

$^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C$

$^{22}Ne(\alpha,n)$ → $^{13}C(\alpha,n)$ → heavy elements!!

The ^{13}C-pocket: formation

- **Protons can penetrate** into the He-rich region at each **TDU (Third Dredge-Up) phenomenon**

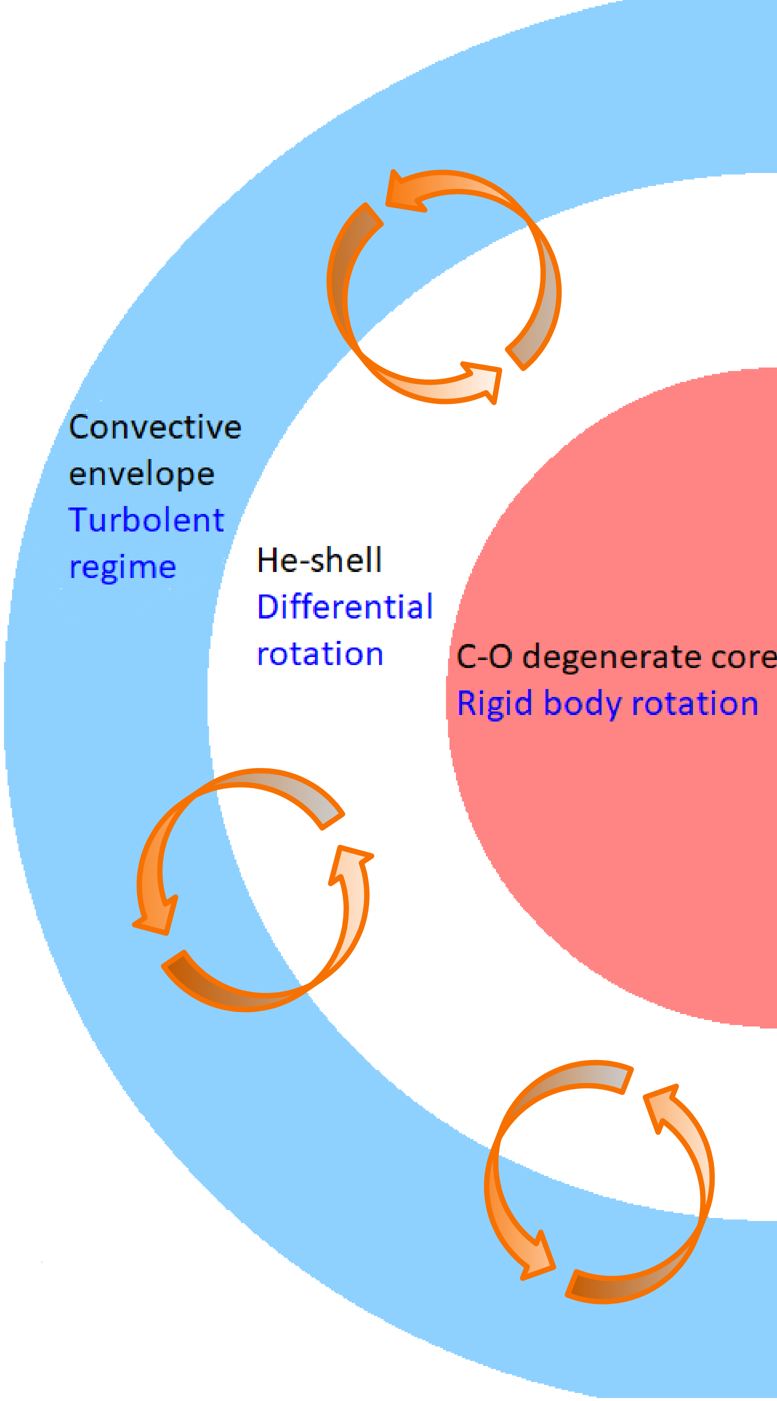
Which is the physical mechanism?

Classic models **assume** the ^{13}C-pocket formation

Many recent physical approaches:

- Opacity induced overshoot (Cristallo+ 2009, 2011, 2015)
- Convective Boundary Mixing (Battino+ 2016)
- Magnetic fields (Trippella+ 2016; Palmerini+ 2018)
  ➡ bottom-up mechanism through **magnetic buoyancy**

1a) Rotational shears promote magnetic fields?
1b) Fossil magnetic fields?
2) Magnetic structures reach the envelope
3) Protons are injected into the He-rich region



Magnetic buoyancy

- MagnetoHydroDynamics (**MHD**) solutions (Nucci & Busso 2014):
  - No numerical approximations (exact analytic solution)
  - Simple geometry: toroidal magnetic field

Equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) - \nu_m \Delta \mathbf{B} = 0$$

$$\rho \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} - c_d \mathbf{v} + \nabla \Psi \right] - \mu \Delta \mathbf{v} + \nabla P + \frac{1}{4\pi} \mathbf{B} \times (\nabla \times \mathbf{B}) = 0$$

$$\rho \left[\frac{\partial \epsilon}{\partial t} + (\mathbf{v} \cdot \nabla)\epsilon \right] + P \nabla \cdot \mathbf{v} - \nabla \cdot (\kappa \nabla T) + \frac{\nu_m}{4\pi} (\nabla \times \mathbf{B})^2 = 0$$

Solutions:

$$v_r = v_p \left(\frac{r_p}{r} \right)^{k+1}$$

$$B_\varphi = B_{\varphi,p} \left(\frac{r}{r_p} \right)^{k+1}$$

where k is the exponent of the density distribution: $\rho(r) = \frac{\rho_p}{r_p^k} r^k$

Implementation

- **Exponential decay** of the convective velocity (Straniero+ 2006, Cristallo+ 2009): ➡ $$v = v_{\rm IN} \exp\left(-\frac{\Delta r}{\beta H_p}\right)$$

  Parameters:
  - Radius extention of the overshooting region
  - β

- **Magnetic** contribution (**<u>this work</u>**), acting when the density distribution is $\rho \propto r^k$:

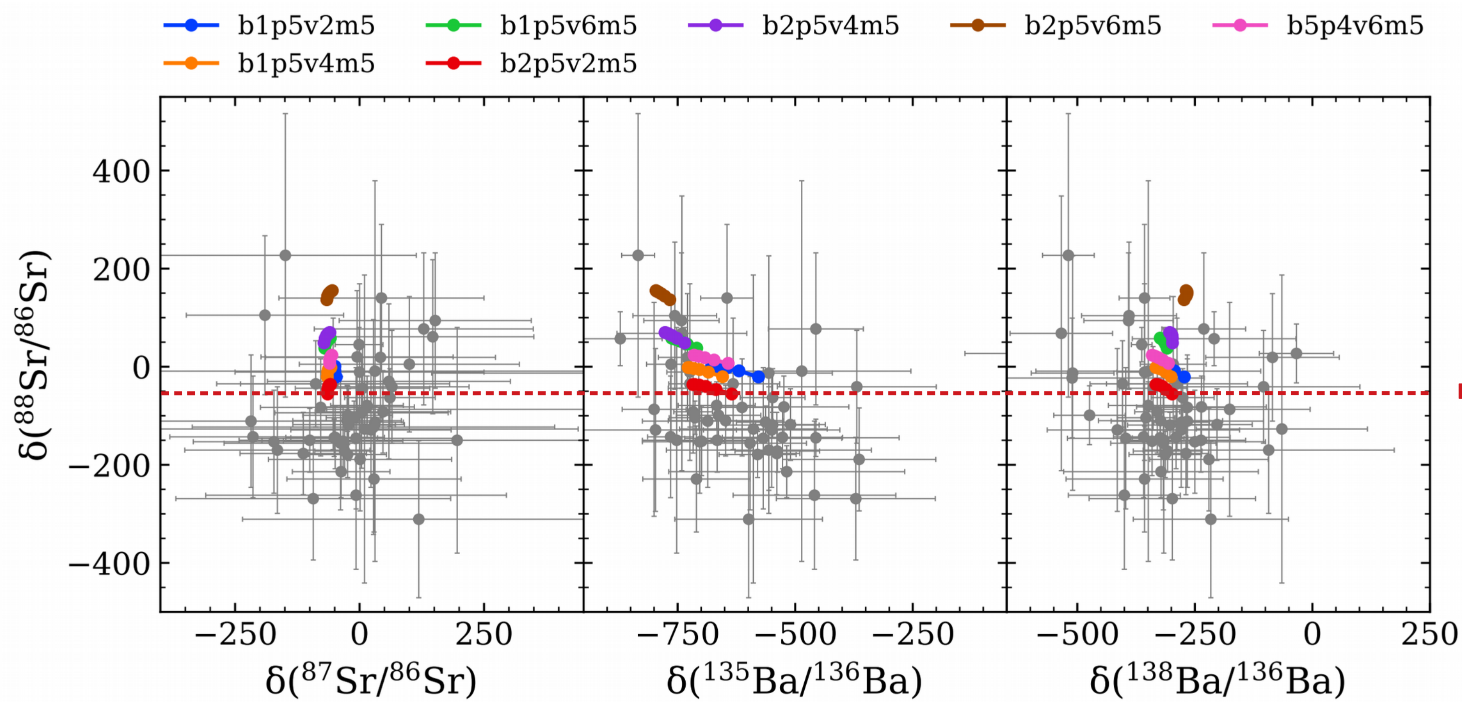
$$v_{down}(r) = v(r_p)\frac{\rho(r_p)}{\rho(r_{h+1})}\left(\frac{r_h}{r_p}\right)^{k+2}\left(\frac{r_h}{r}\right)^{k+1}$$

  Parameters:
  - Layer "*p*" at the deepest coordinate from which buoyancy starts (can be identified from the corresponding **critical toroidal B_φ** value) ➡ $$B_\varphi \gtrsim \left(4\pi\rho r N^2 H_{\rm p}\frac{\eta}{K}\right)^{1/2}$$
  - Starting velocity v_p of the buoyant material

<u>Calibration</u> is needed!

SiC Grains I

- We considered **isotopic data** including Sr and Ba isotope ratios in **presolar SiC grains**.
- We considered **magnetic contribution** to the partial mixing of hydrogen.
- **One stellar model**: $2M_\odot$ $Z=Z_\odot$
- **Fixed** value of β (0.1) and maximum envelope penetration (1.7 H_p)
- **Variable** v_p (2, 4, 6 x10^{-5} cm s^{-1}) and B_φ (0.5, 1, 2 x10^5 G)



Minimum δ^{88}Sr

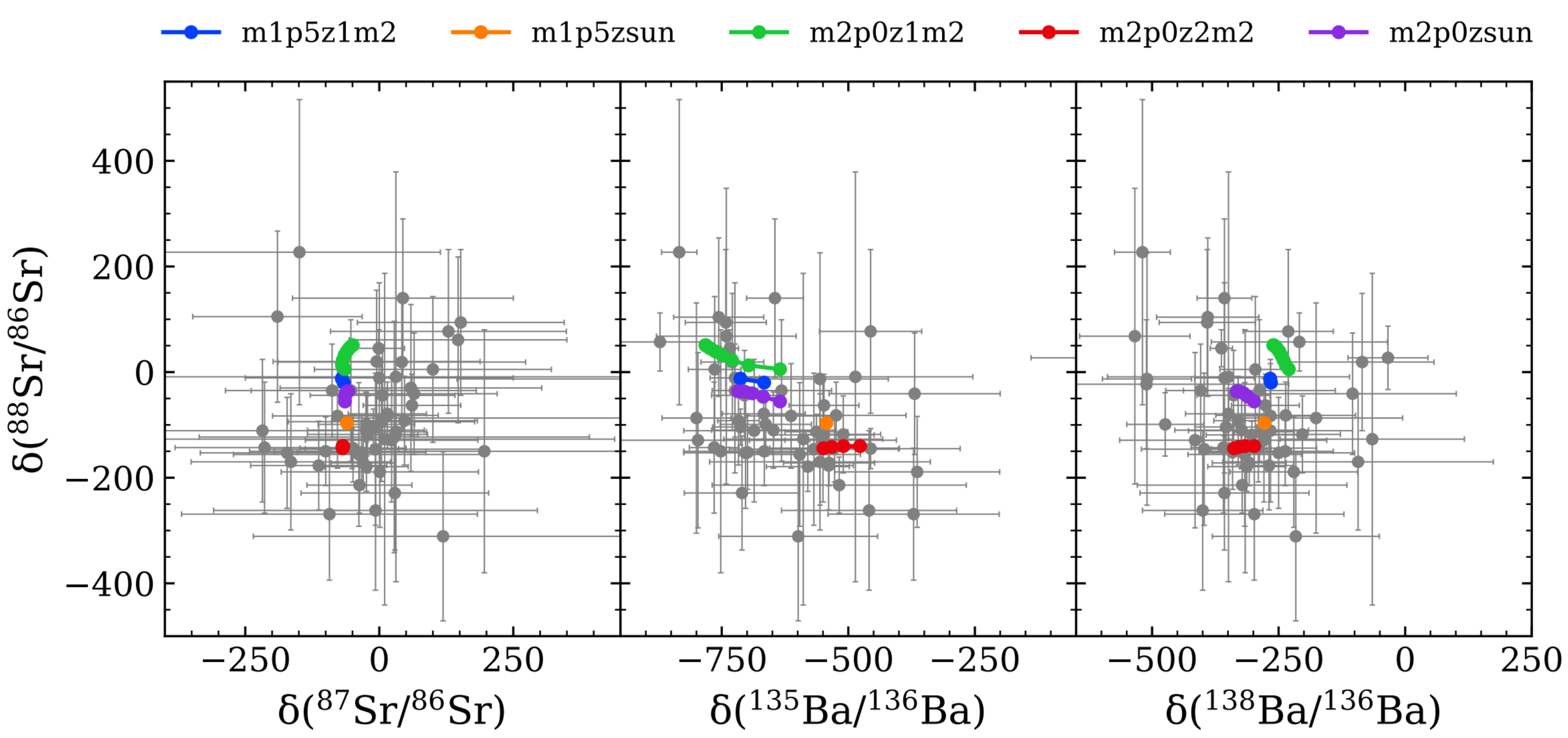
The ^{13}C-pocket: parametric space

- Our **current** best (not yet definitive) choice can be summarized as:

Parameter	Adopted value	References or motivation
v_p	2×10^{-5} cm/s	Best fit to the grains data
β	0.1	Cristallo+ 2009
Radius extention of the overshooting region	1.7 Hp	Same amount of H-depleted dredged-up material of FRUITY
Layer from which buoyancy starts (critical toroidal B_φ value)	2×10^5 G	Best fit to the grains data

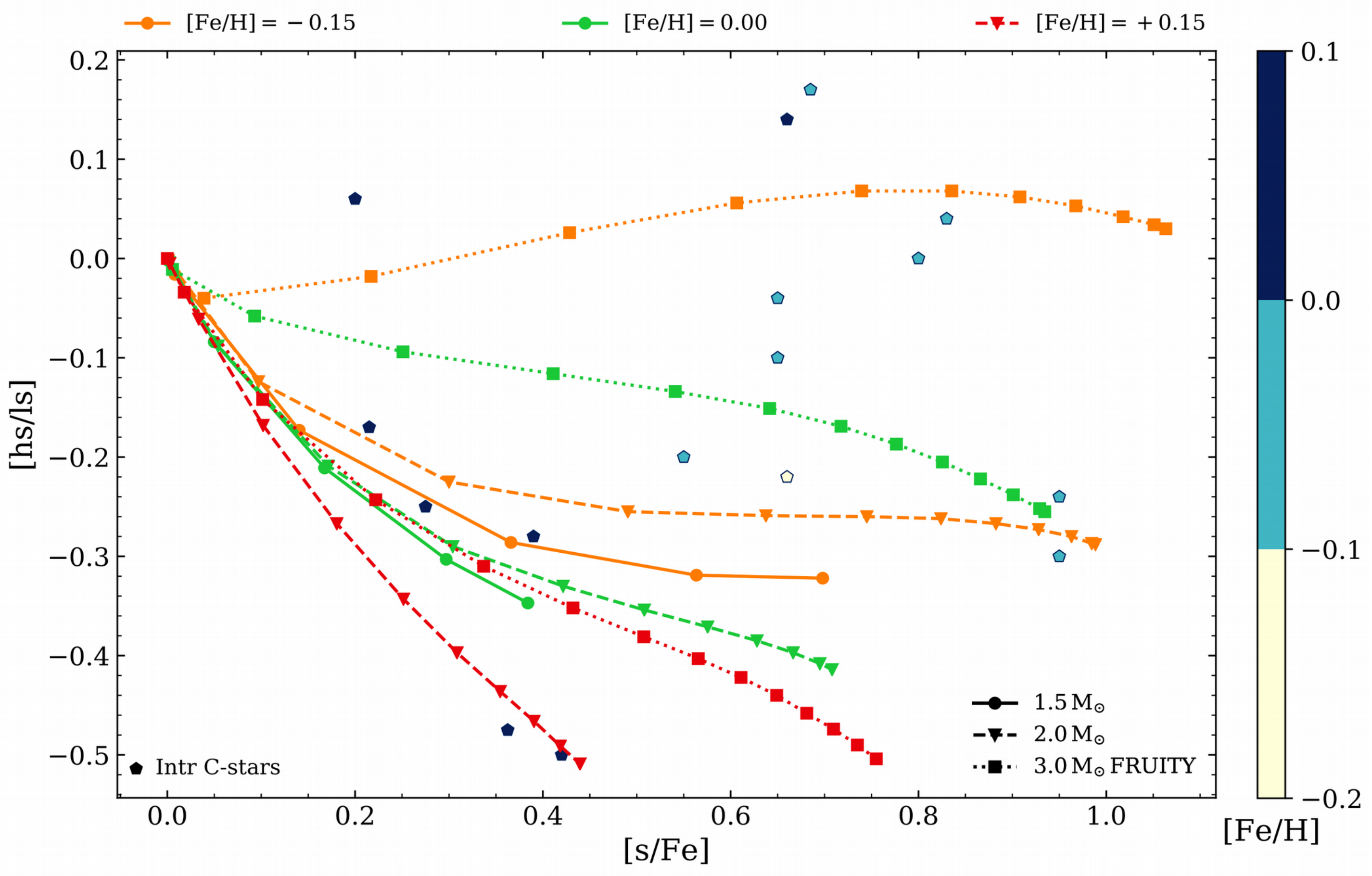
SiC Grains II

- Stellar models with **different initial mass** and **metallicity**
  - ➔ different numbers of thermal pulses experienced
  - ➔ different extention of ^{13}C-pockets
- ➔ Isotopic ratios of mainstream grains are <u>quite well reproduced</u>



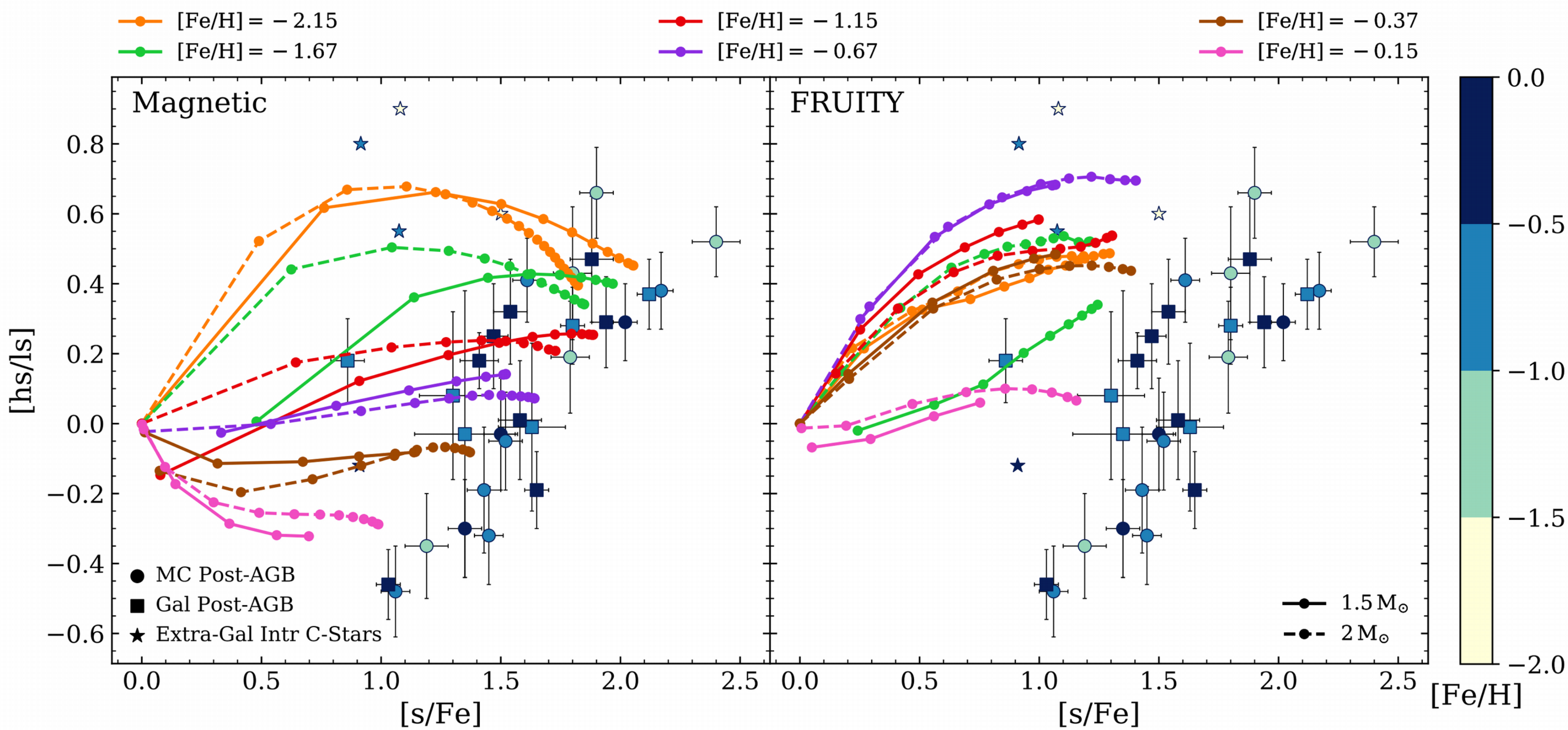
Intrinsic C-rich AGB Stars

- Stellar models with **close-to-solar** metallicity
  - **Low** [hs/ls]
  - **High** [s/Fe]
- Does magnetism <u>fade out</u> for low-to-intermediate mass (3 to 6 $M_\odot$)?



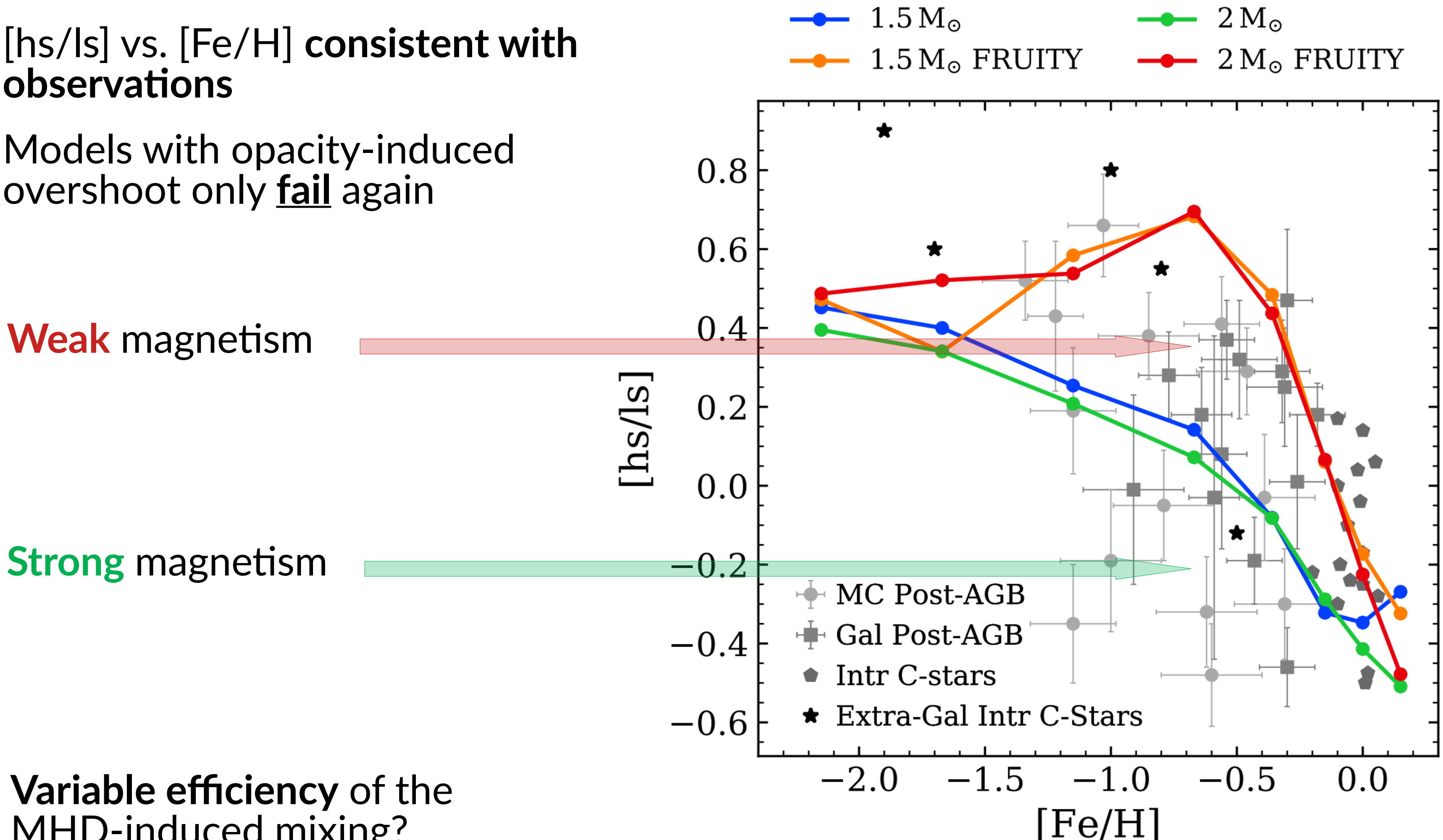
Post- and Intrinsic C-rich AGB Stars I

- Stellar models with **low metallicity**
  - [hs/ls] vs. [s/Fe] **consistent with observations**
  - Models with opacity-induced overshoot only **<u>fail</u>**



Post- and Intrinsic C-rich AGB Stars II

- Stellar models at different metallicities
  - [hs/ls] vs. [Fe/H] **consistent with observations**
  - Models with opacity-induced overshoot only **fail** again



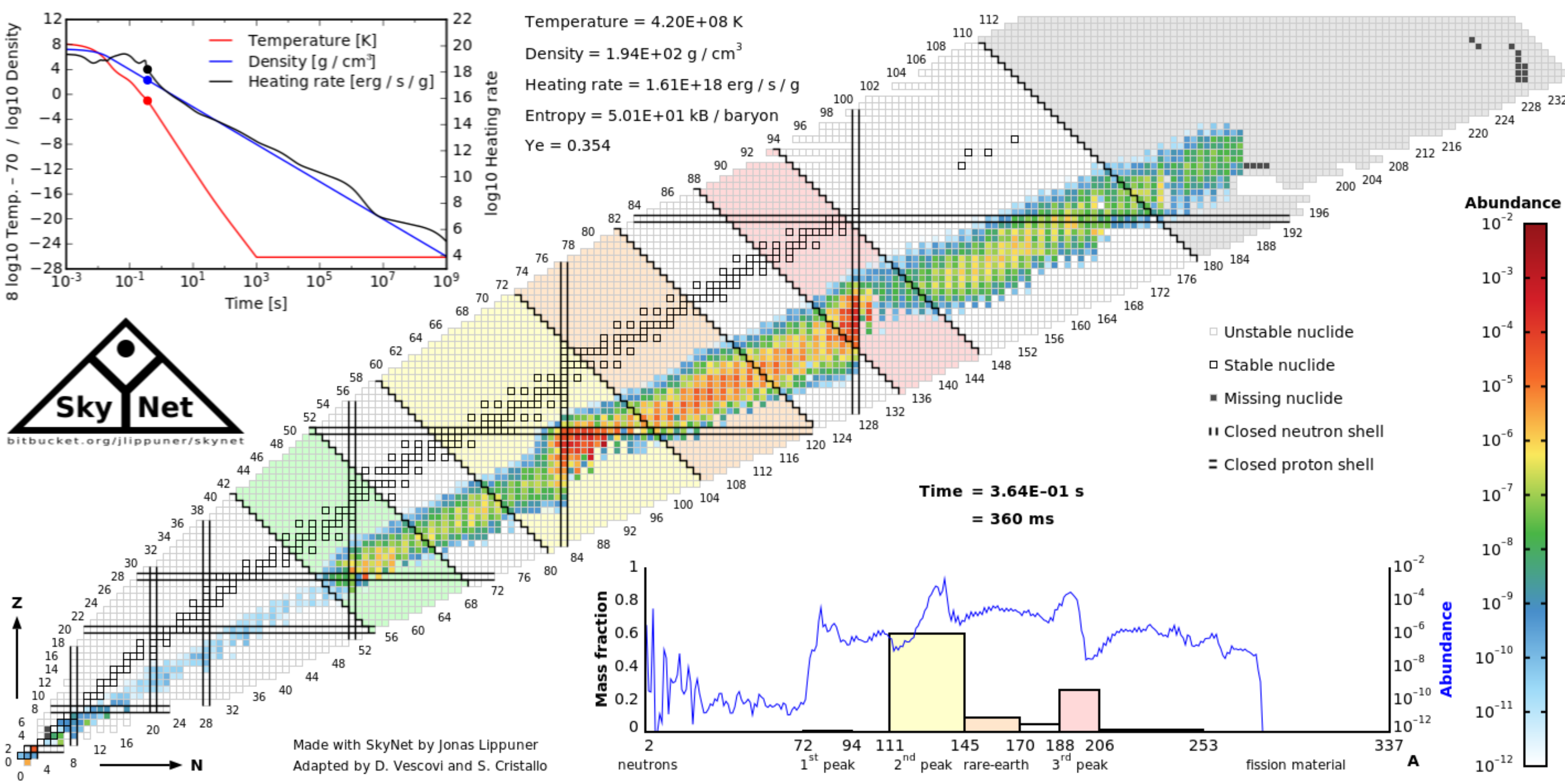
- **Variable efficiency** of the MHD-induced mixing?
- **Mass-dependent efficiency**?

Summary I

- Most of what we know has been learned through a lengthy work with parameterized models, trying to constrain the parameters gradually, from the increasing accuracy of observations
- This allowed recently the development of physical models for the mixing mechanisms required to produce the ^{13}C neutron source.
- Taking into account magnetic fields in radiative regions might be crucial in modeling the mixing episodes (e.g. through **magnetic buoyancy**).
- First outcomes confirms recent results from Trippella+ (2016), Palmerini+ (2018), and Liu+ (2018, 2019)
- **More extended and flatter** ^{13}C-pocket
- The majority of isotopic ratios of mainstream grains are quite well reproduced
- [hs/ls] vs. [s/Fe] and [hs/ls] vs. [Fe/H] **consistent with observations** of post-AGB and intrinsic AGB stars
- Magnetism has (most problably) **variable intensity**

r-process: basic ideas

- key reactions: $(A, Z) + n \leftrightarrow (A + 1, Z) + \gamma$
- 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 chain
  - steady abundances intra-chain with one dominant nucleus
- β-decay rates of dominant nuclei regulate inter-chain flow
- equilibrium freeze-out: n_n drops and β-decays take over



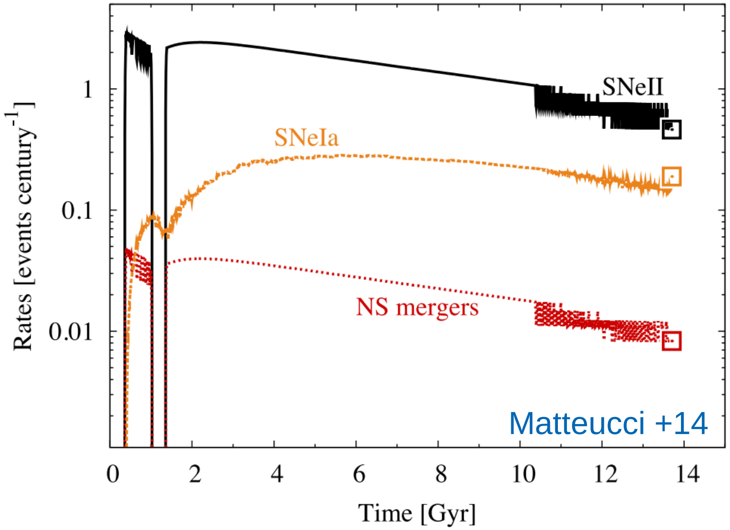
Neutron star mergers as *r*-process site

- *r*-process requires free *n* and seed nuclei (<*A*>, <Z>)
- seed properties/abundances depend on nuclear-statistical equilibrium (NSE) freeze-out
- in adiabatic expansion, neutron-to-seed ratio depends on three parameters:

1) entropy $s \sim T^3/\rho$
2) $Y_e \sim n_p/(n_n+n_p)$
3) τ_{dyn} $(T(t) \approx T_0 \exp(-t/\tau_{dyn}))$

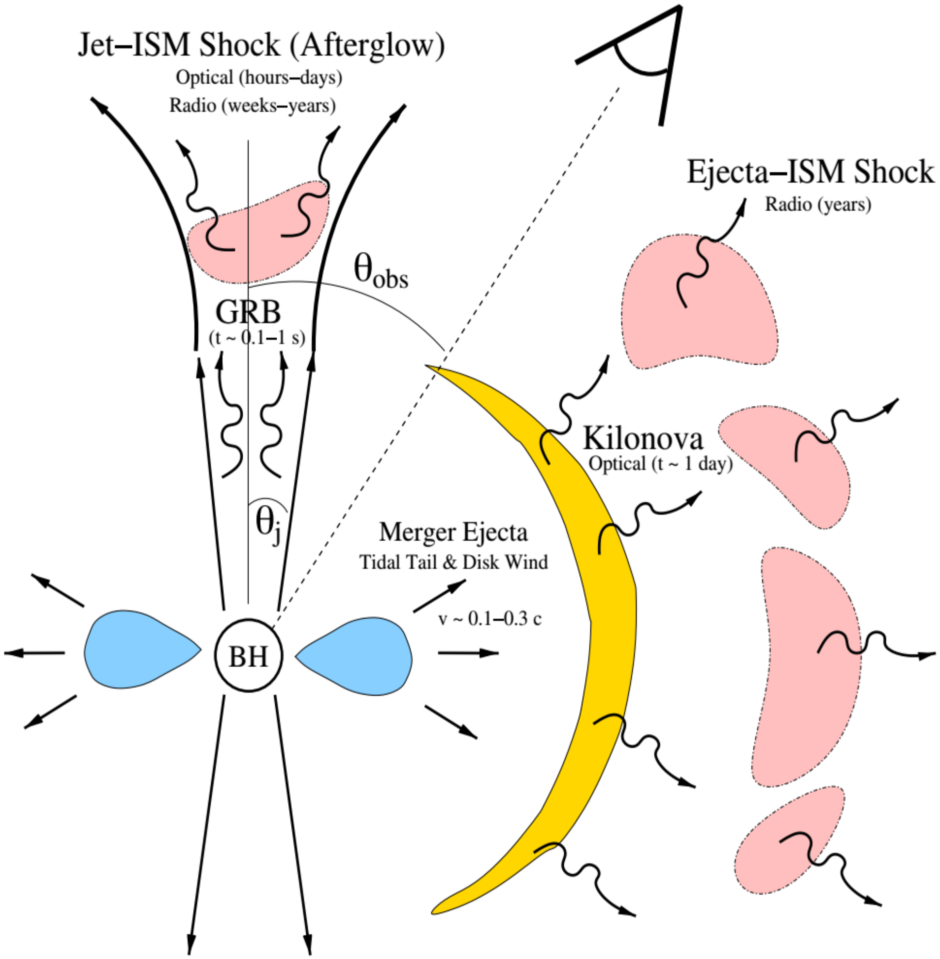
→ $n_n/n_{seed} \propto s^3/(\tau_{dyn} Y_e^3)$

	high entropy *r*-process	low entropy *r*-process
Possible scenarios	hot CCSN winds	BNS and BHNS mergers MHD supernovae



First evidences of *r*-process nucleosynthesis in kilonova from GW170817

BNS merger + kilonova



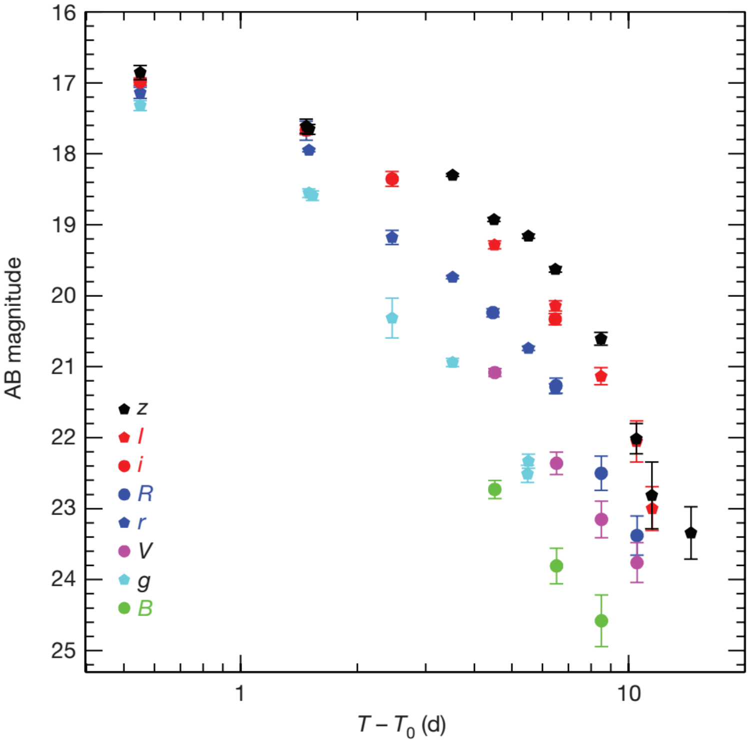
Metzger & Berger 12

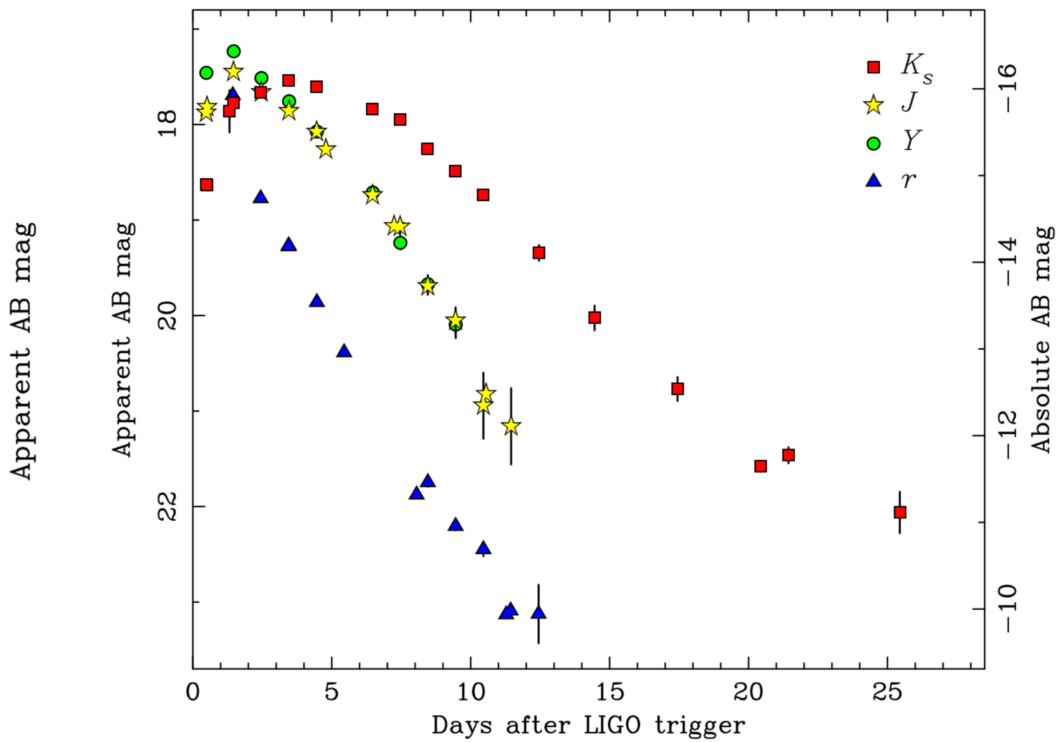
Basic ideas:

- radioactive decay of freshly sinthetized *r*-process elements in ejecta: release of **nuclear energy**
- thermalization of high energy decay products with ejecta
- **diffusion** of thermal photons during ejecta expansion
- thermal emission of photons at photosphere

Properties of GW170817/AT2017gfo

- 17/08/17, GW+EM detection of an event compatible with BNS merger (LVC PRL 2017)
- rather bright, nIR component, with a peak at ∼ 5 days (red component)
- bright, UV/O component, with a peak at ∼ 1 day (blue component)



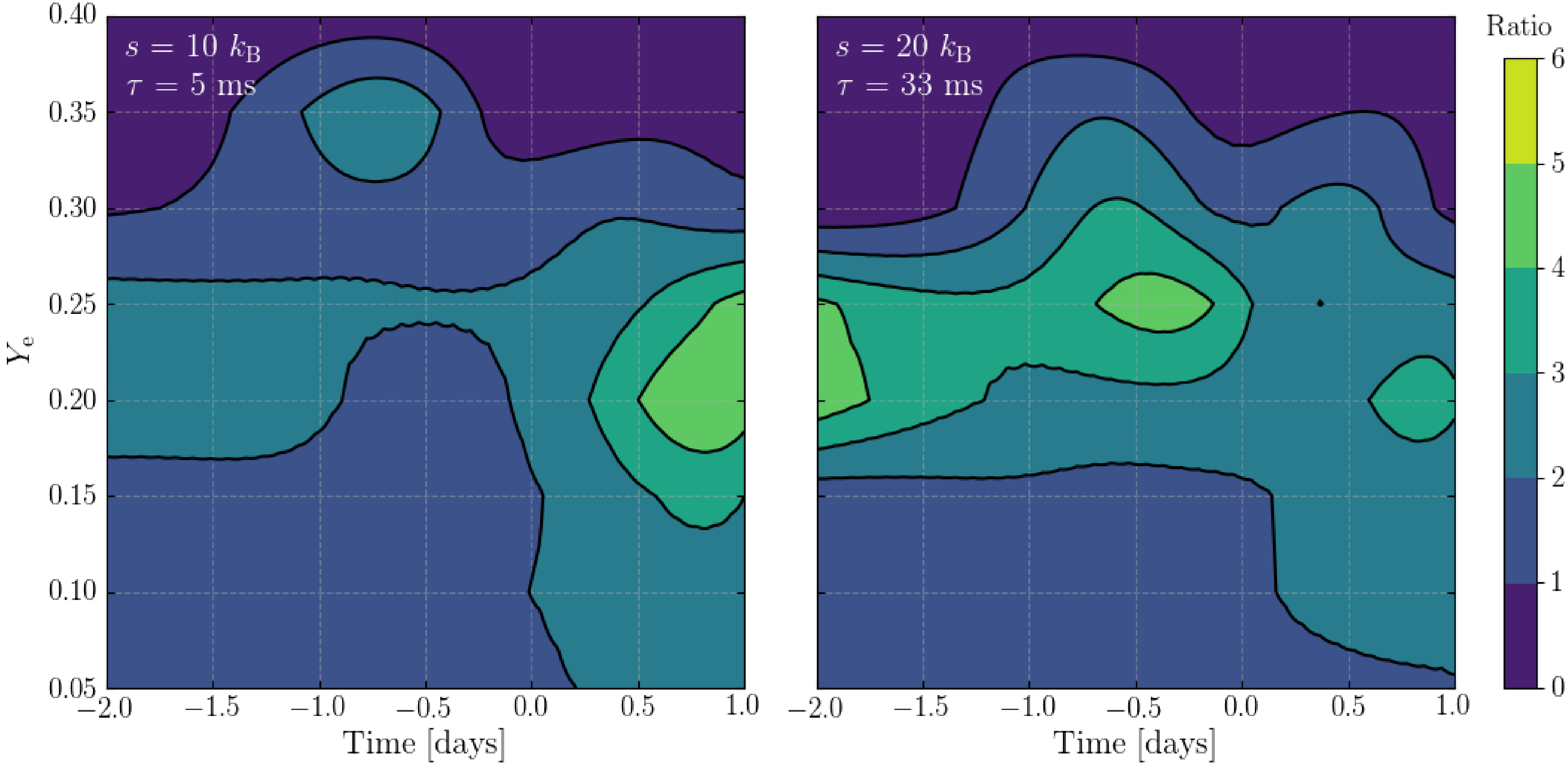


Light curves; Pian, D'Avanzo+ 2017 (left); Tanvir+ 2017 (right)

- → Kilonova models fail in explaining the early behavior of the UV and visible light curves
- → The presence of a larger nuclear heating rate at t ≲ 1 day **can increase the light curves by half a magnitude during the first day**

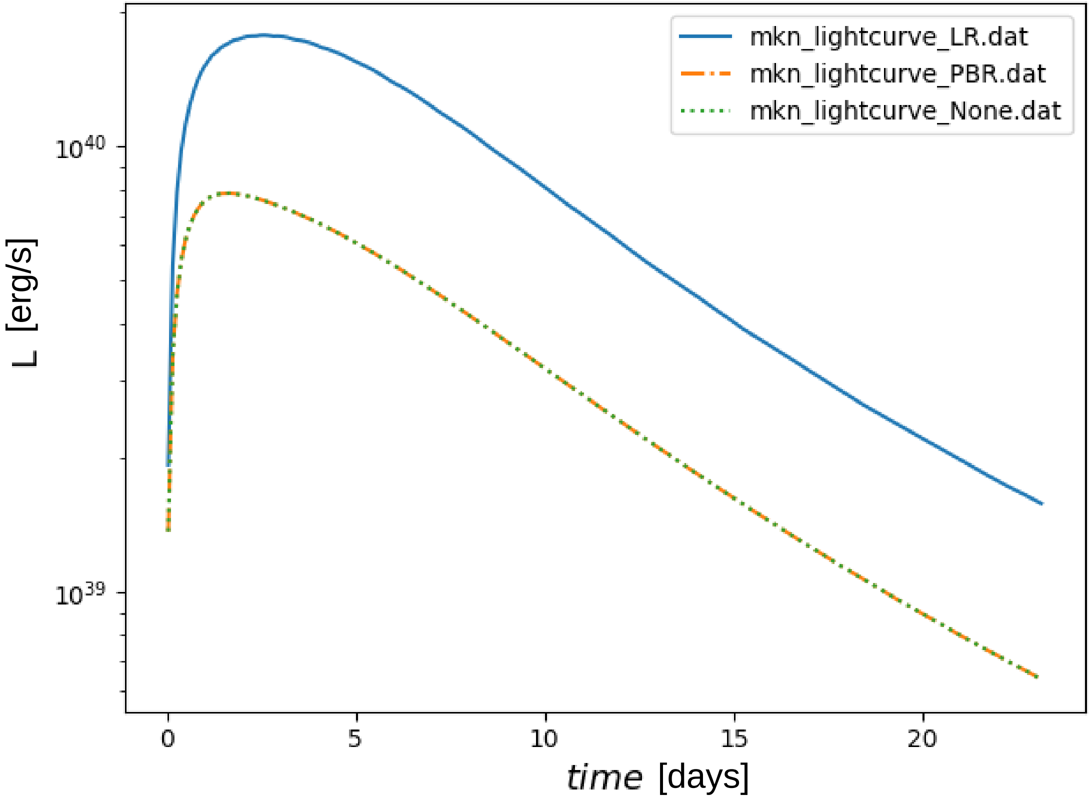
Heating rate vs. electron fraction Y_e

- $\dot{Q}$ is usually **approximated** by an analytic fitting formula as $\dot{Q}_{fit}(t) = 10^{10} t_d^{-1.3} erg\, g^{-1} s^{-1}$
- Detailed nucleosynthesis calculations show a complex dependence
- Heating rates normalized to $\dot{Q}_{fit}$ point out that all the **normalized heating rates show considerable excess at different times**



Implementation and first tests

- Inclusion of new detailed nuclear heating rates obtained by nuclear network calculations in an anisotropic, multicomponent kilonova model (Perego+ 2017)
- Coupled with a parallelized Monte Carlo Markov Chain (MCMC) algorithm.
- **Goal:** re-analize AT2017gfo data by computing the posterior distributions associated to several different models



- First outcome (simple isotropic dynamical ejecta) :
  - **brighter lightcurve**

Next steps:

1) different matter ejection mechanisms (multi-component)
2) angular dependence (anisotropy)

Summary II

- Kilonova from GW170817 originates from the **radioactive decay** of heavy elements
- Signature of *r*-process nucleosynthesis in ejecta from neutron star mergers
- Astrophysical site of the *r*-process is identified, but further observations are necessary
- Having identified the astrophysical site it becomes fundamental to **reduce the nuclear physics uncertainties**
- Lanthanide-rich for $Y_e \lesssim 0.25$
- Insensitivity of the abundance pattern to the parameters of the merging system because of an extremely Y_e environment, which guarantees the occurrence of several fission cycles before the *r*-process freezes out
- **Nuclear heating rates are**, at the times relevant for the kilonova emission, **uncertain for a factor a few**
- Kilonova emission seems to be **strongly affected** by non-approximated heating rates