

# Making the Heaviest Elements in the Universe

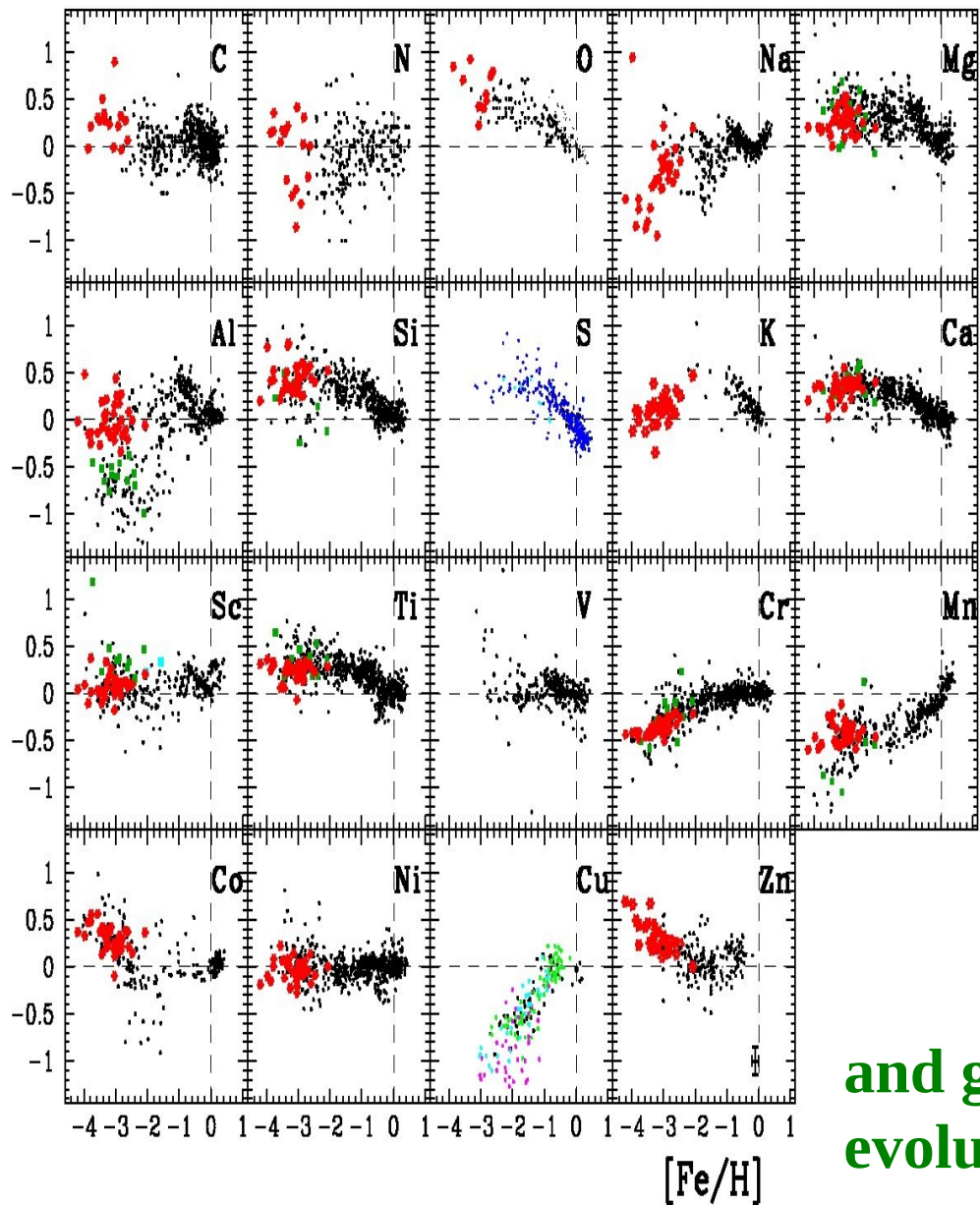
**Working of the astrophysical r-process:  
nuclear input, necessary environment  
conditions, astrophysical sites, observational  
constraints, and its role in galactic evolution**



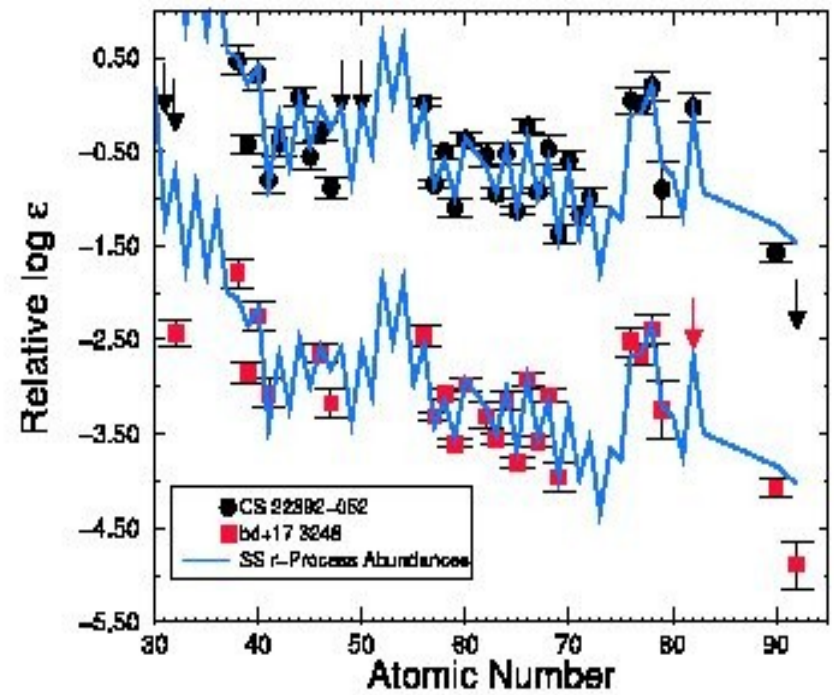
Friedrich-K. Thielemann  
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University of Basel



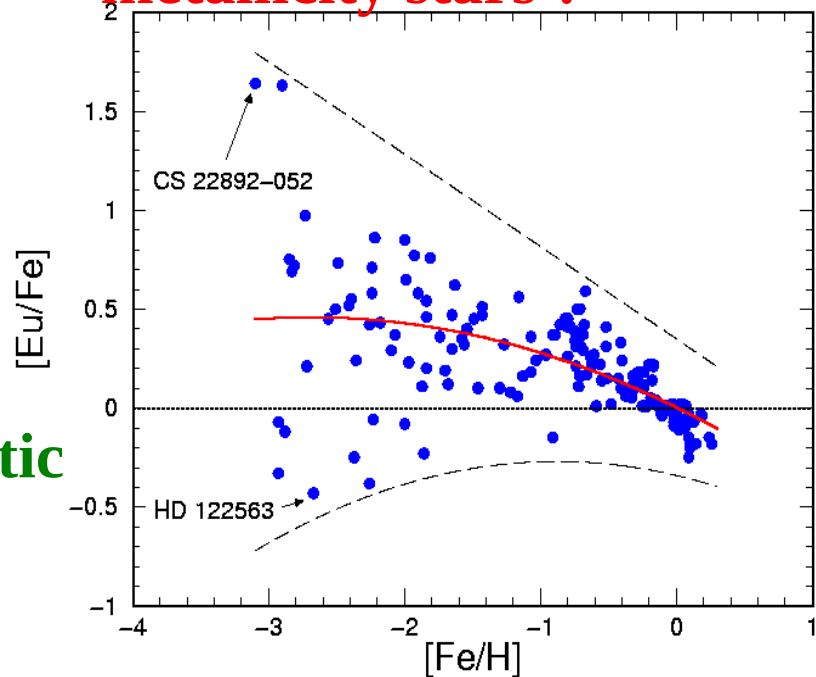
# How do we understand: solar system abundances..



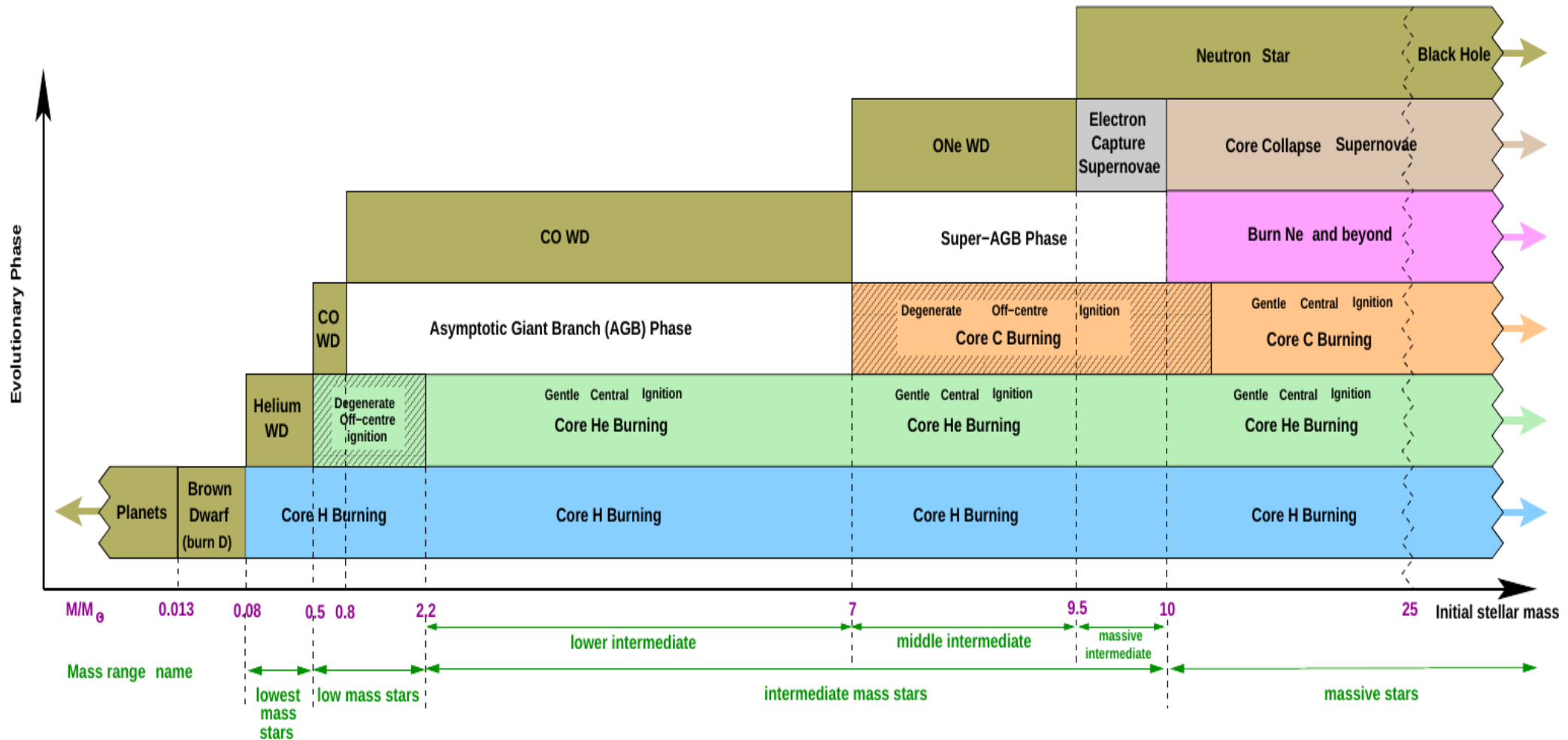
and galactic evolution



via observations of low metallicity stars ?



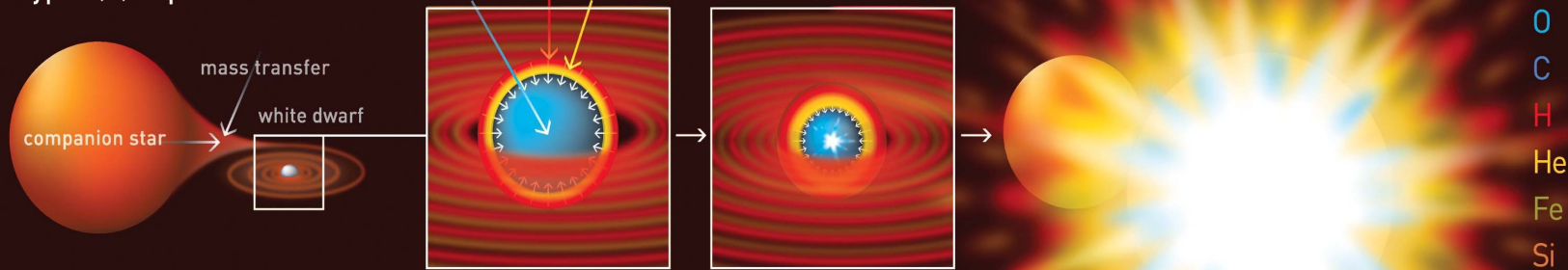
# Stellar Evolution as a Function of Mass



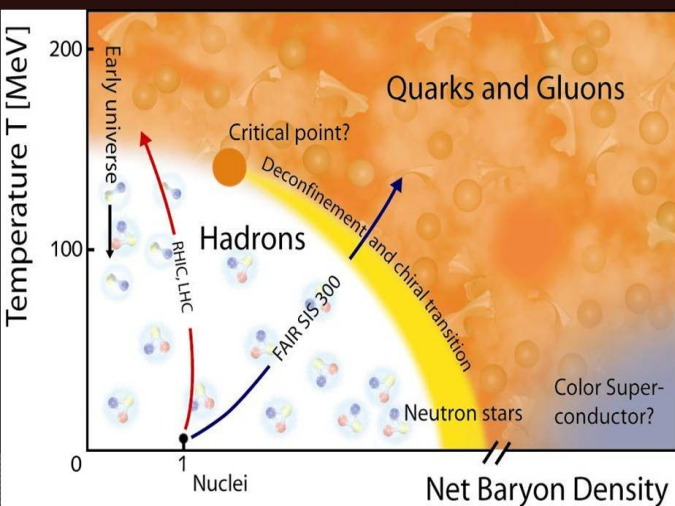
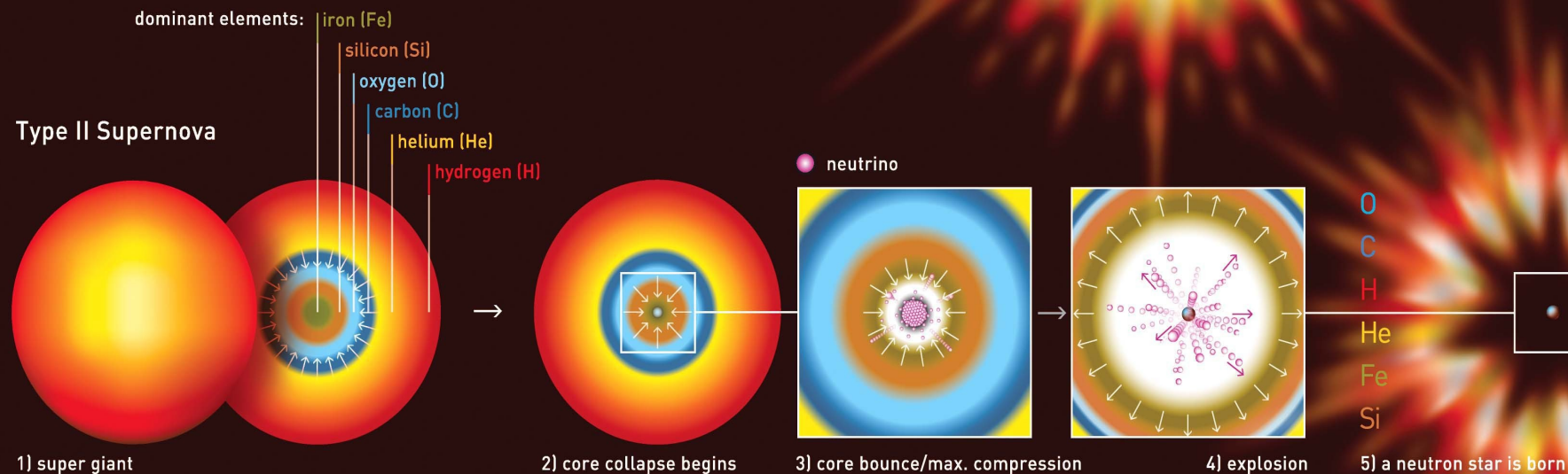
From Karakas & Lattanzio (2014)

s-process up to Pb and Bi via  $^{13}\text{C}(\alpha,n)$  and  $^{22}\text{Ne}(\alpha,n)$  in low and intermediate mass stars

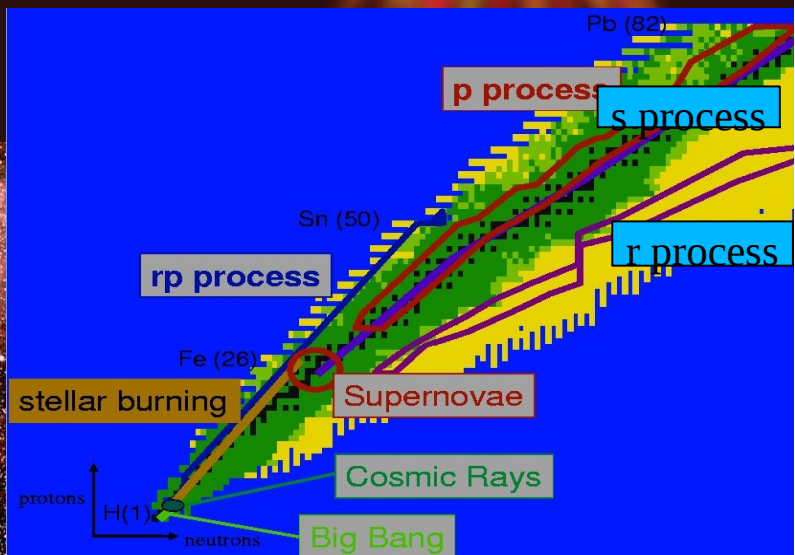
### Type I (a) Supernova



### Type II Supernova

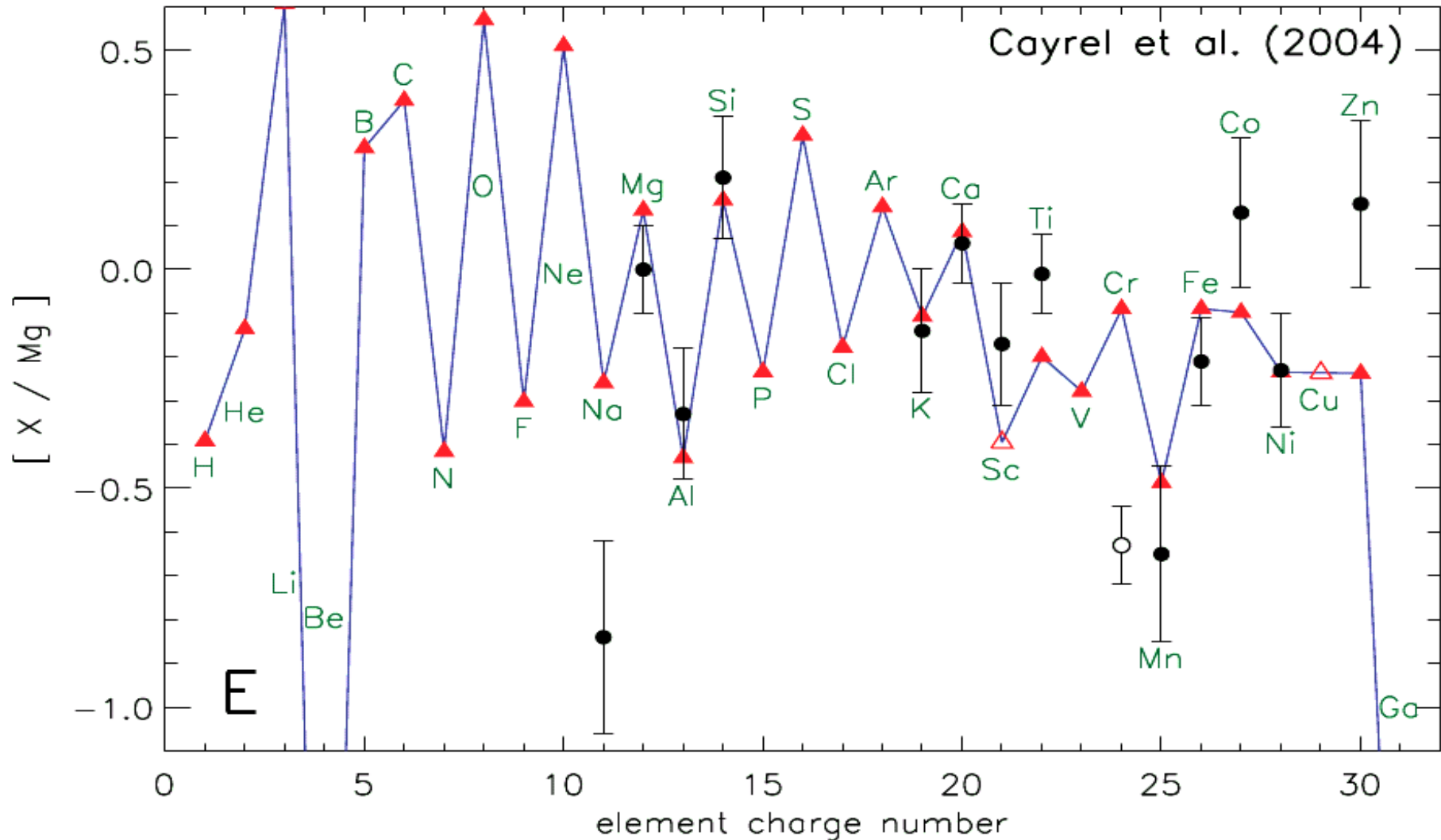


### SN 1987A

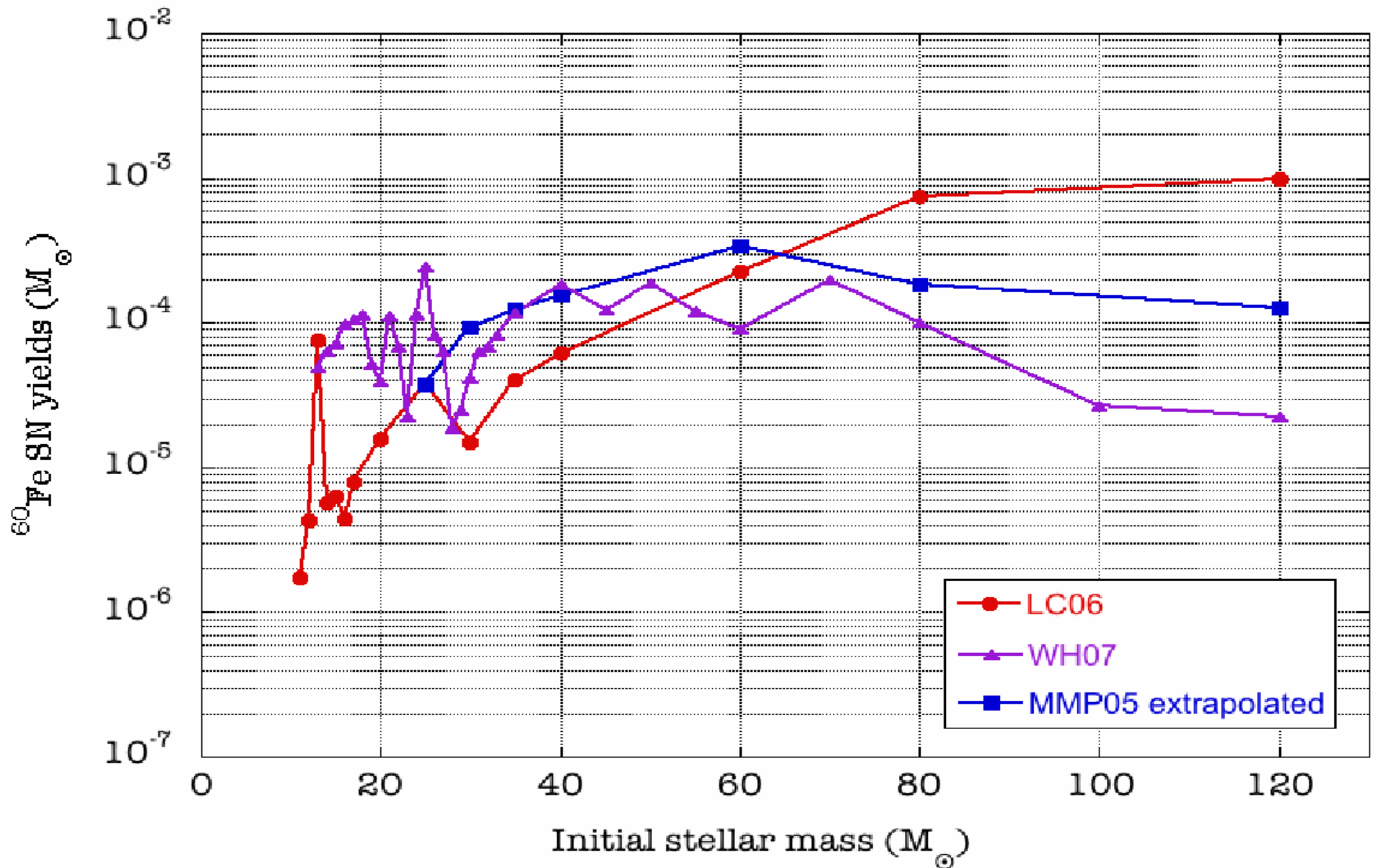


# Pop III yields (Heger & Woosley 2010)

## Evolution of metal-free stars



Cayrel et al. (2004). taken as representative sample for low metallicity stars (**representing core-collapse supernova yields**). E: “Standard” IMF integration of yields from  $M = 10 - 100 M_{\odot}$ , explosion energy  $E = 1.2 B$  (underproduction of Sc, Ti, Co and Zn).

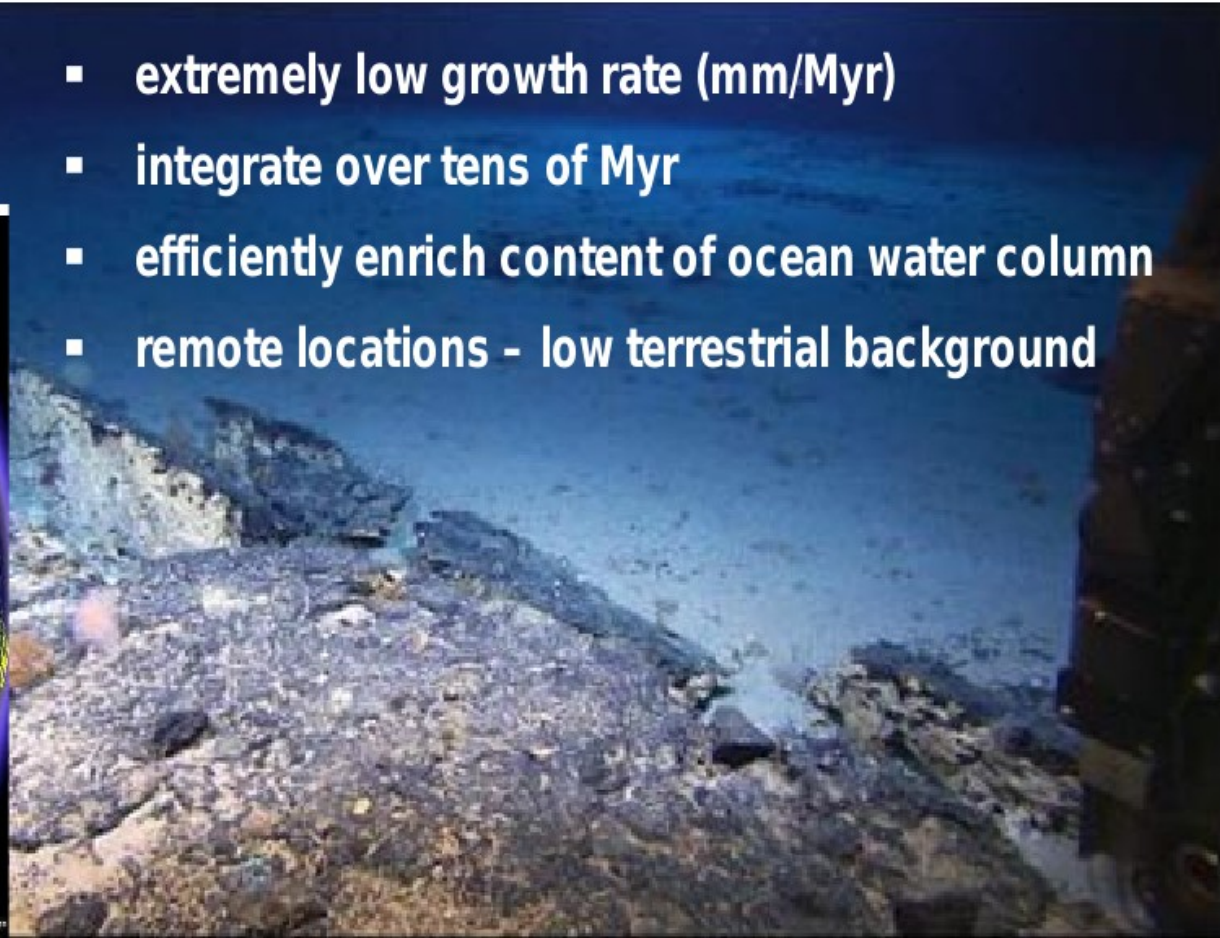
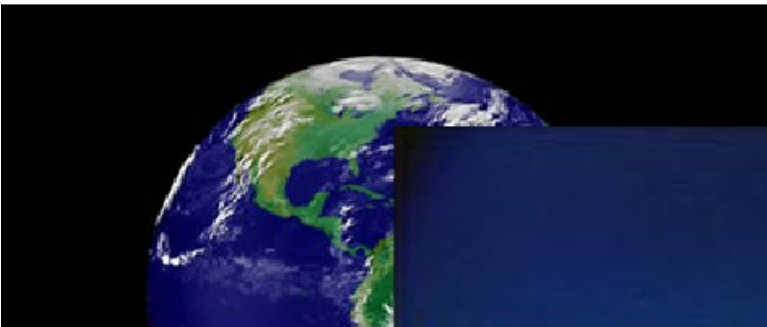


$^{60}\text{Fe}$  (half-life  $2.6 \cdot 10^6$  y) yields from Limongi & Chieffi; Woosley & Heger; Maeder, Meynet & Palacios, produced in He-shell burning of massive stars in late phases after core C-burning **and ejected afterwards in CCSNe**

# Extraterrestrial Radionuclides on Earth

“recent” uptake into terrestrial archives

- extremely low growth rate (mm/Myr)
- integrate over tens of Myr
- efficiently enrich content of ocean water column
- remote locations - low terrestrial background



**deep-sea manganese crusts & sediments**

[oceanexplorer.noaa.gov](http://oceanexplorer.noaa.gov)

Direct detection of live  $^{244}\text{Pu}$  and  $^{60}\text{Fe}$  on Earth -

NIC-2014 07/07/14

A. Wallner

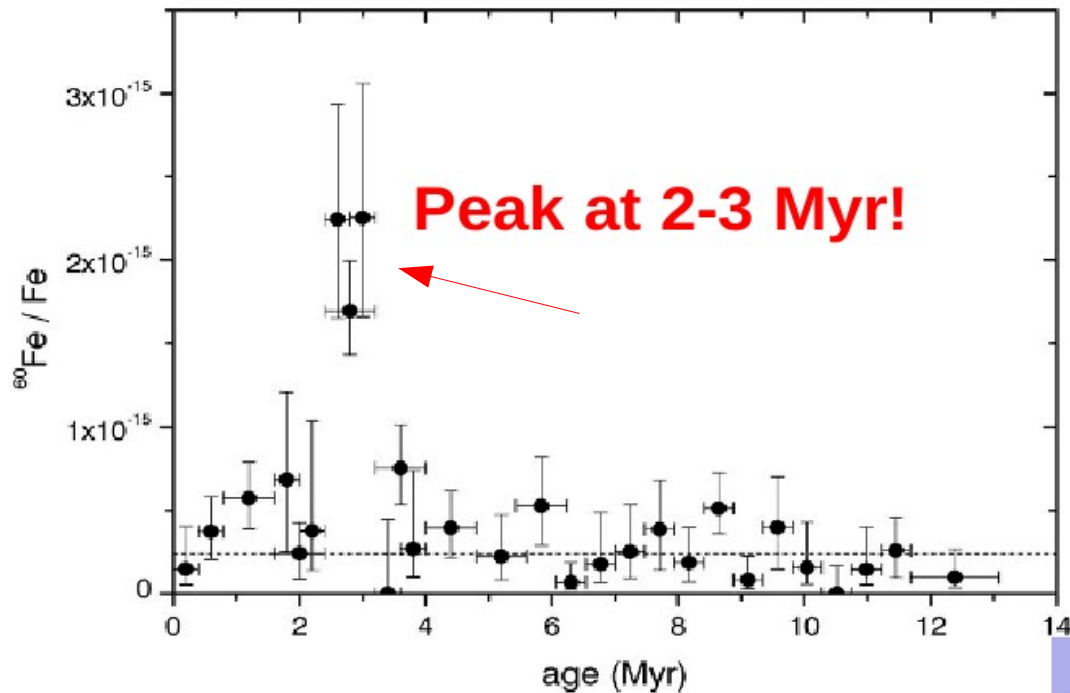


from A. Wallner



# ***$^{60}\text{Fe}$ -signal in a deep-sea crust***

## ***AMS at Munich***



AMS measurement of  $^{60}\text{Fe}$  content of crust at TU Munich

**• *the only lab yet !***

VOLUME 93, NUMBER 17

PHYSICAL REVIEW LETTERS

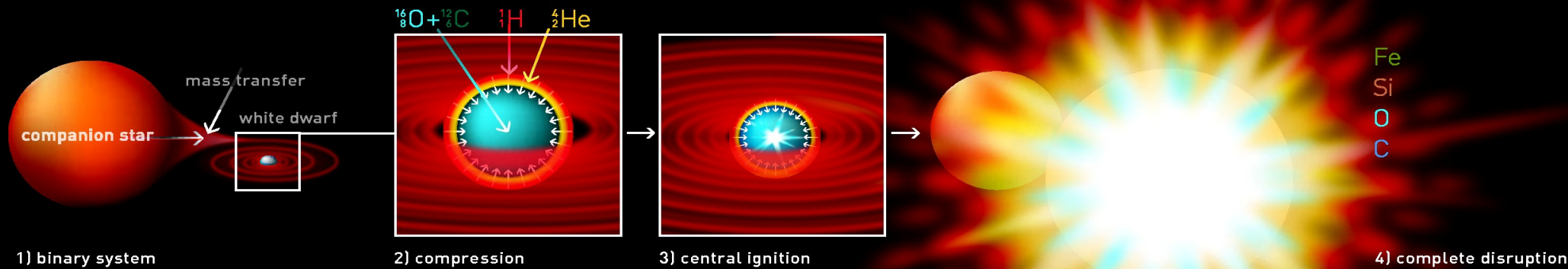
week ending  
22 OCTOBER 2004

$^{60}\text{Fe}$  Anomaly in a Deep-Sea Manganese Crust and Implications  
for a Nearby Supernova Source

K. Knie,<sup>1</sup> G. Korschinek,<sup>1,\*</sup> T. Faestermann,<sup>1</sup> E. A. Dorfi,<sup>2</sup> G. Rugel,<sup>1,3</sup> and A. Wallner<sup>1,3</sup>

# Explosions caused by accretion in binary stellar systems

## Type I (a) Supernova

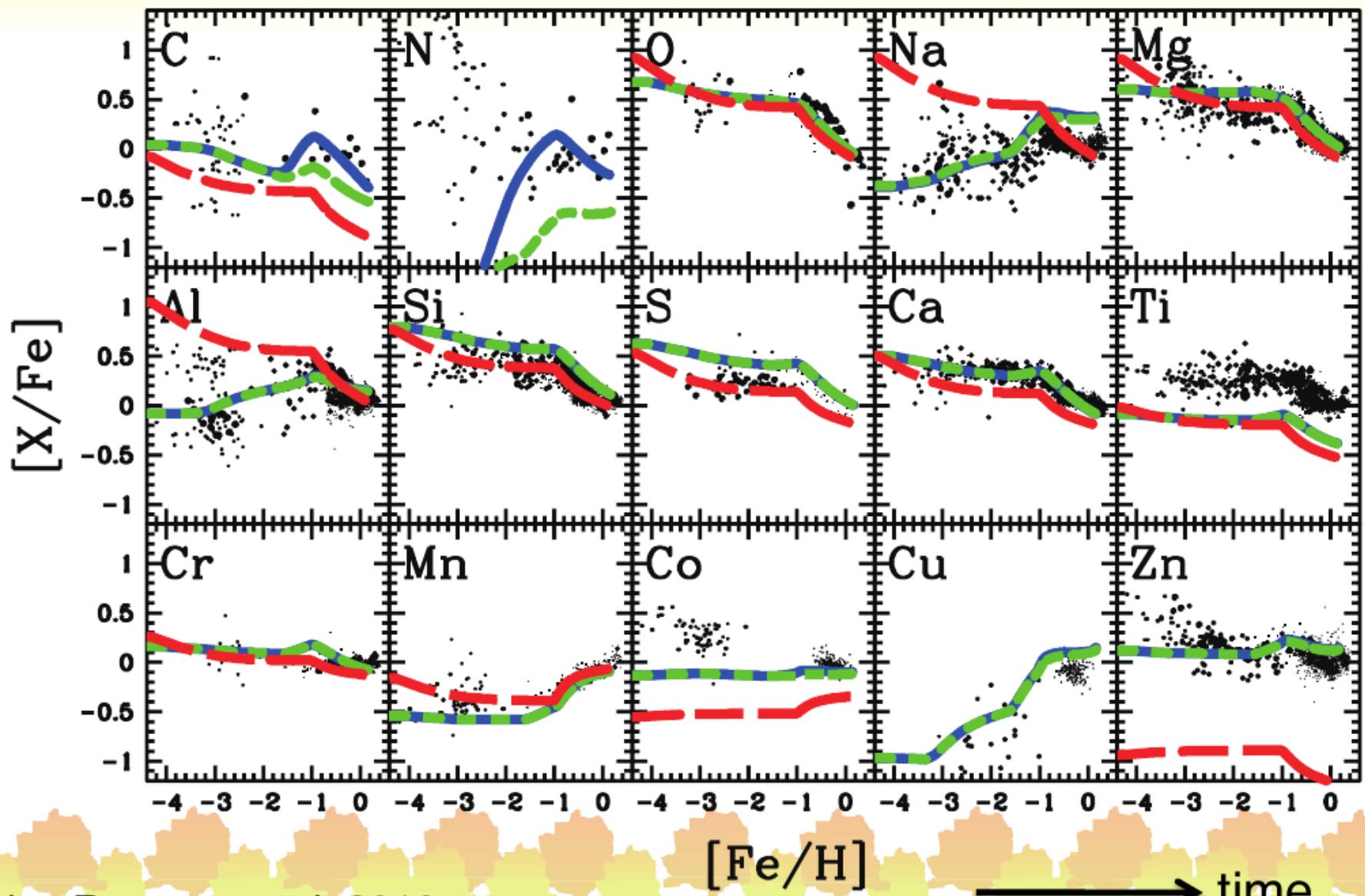


binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions)

- white dwarfs (novae, **type Ia supernovae => large amounts of Fe/Ni**)
- neutron stars (type I X-ray bursts, superbursts?)

# [X/Fe]-[Fe/H] relations

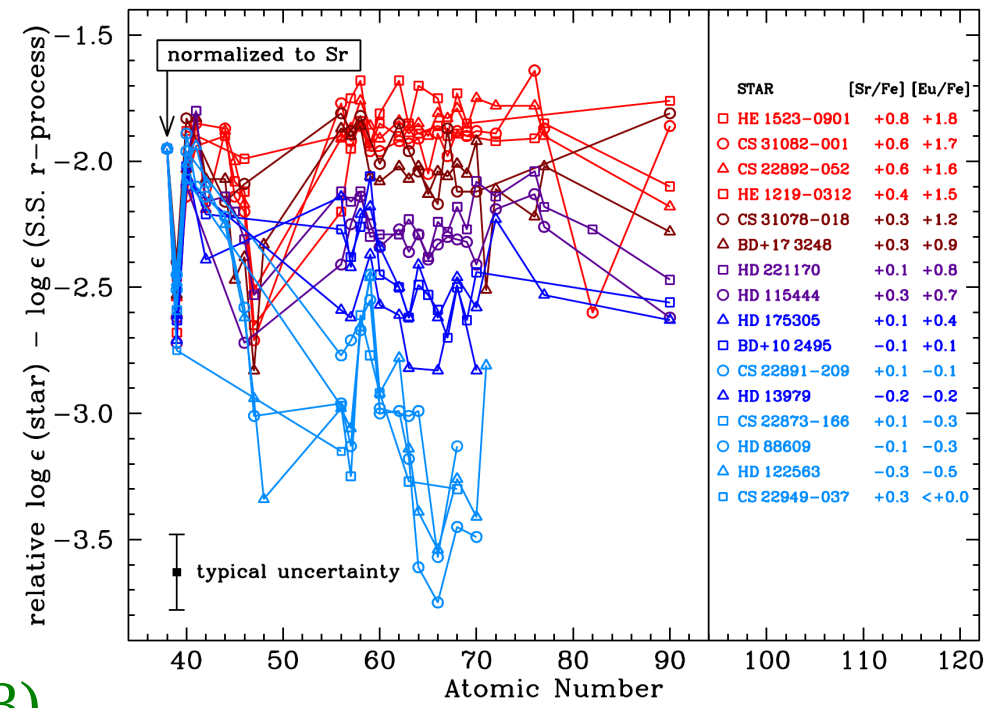
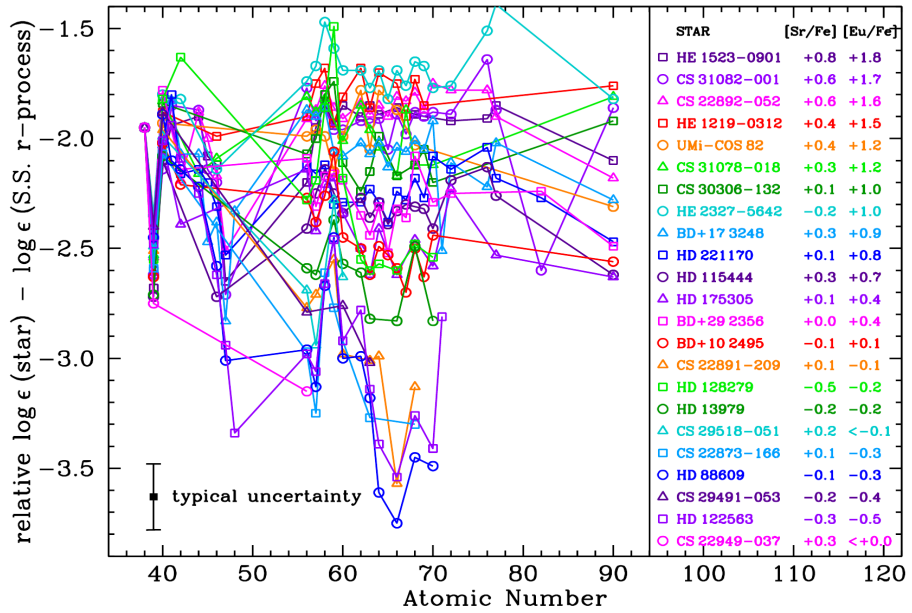
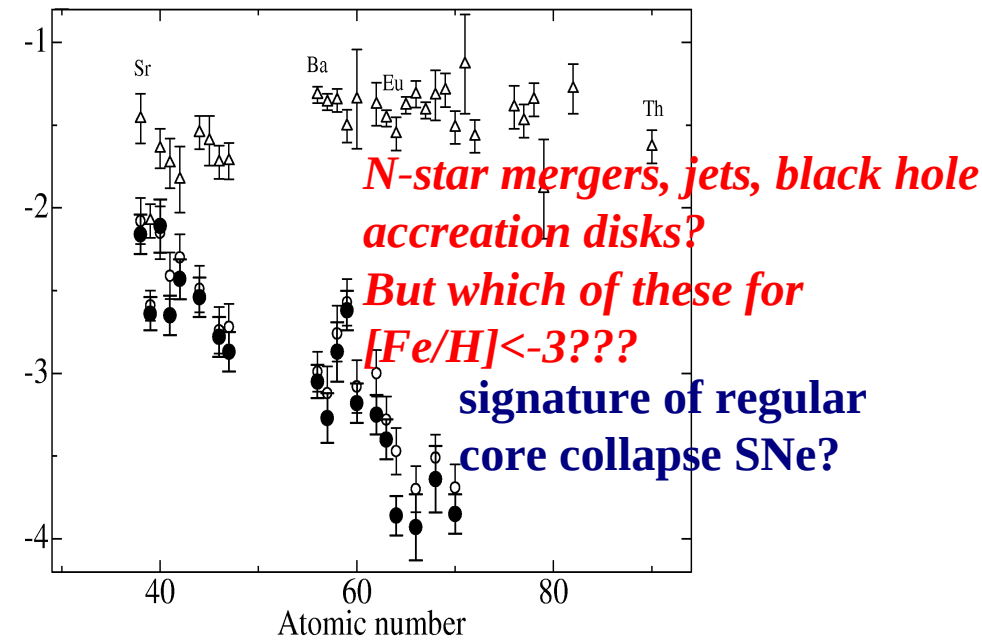
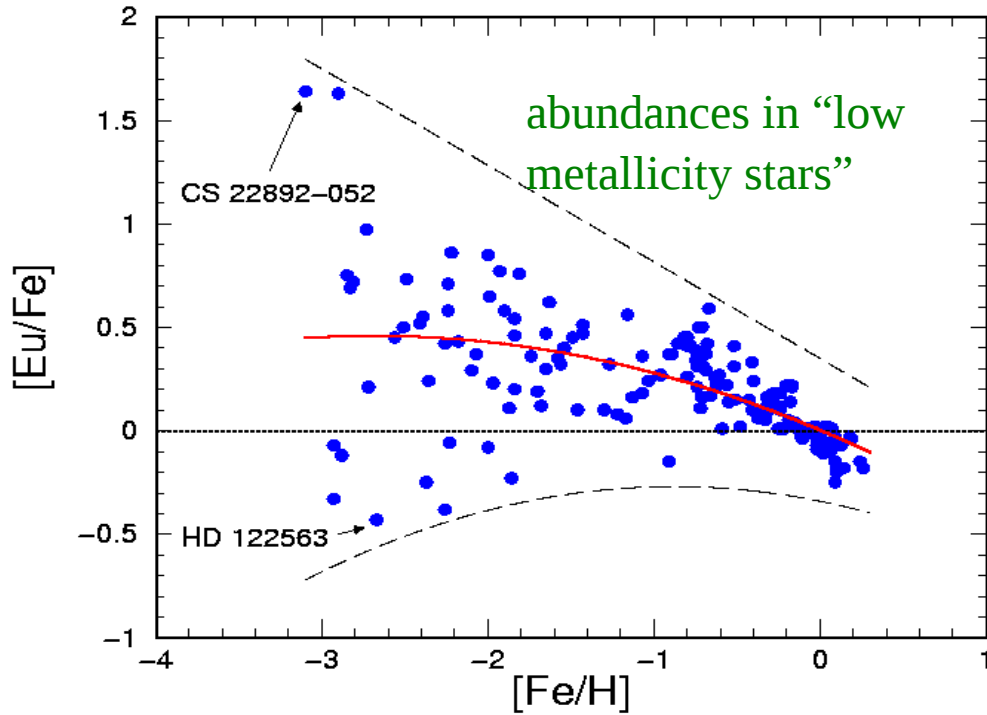
SN+HN+AGB (CK, Karakas, Umeda 2011), SN+HN; old SN yields only



from C. Kobayashi 2015

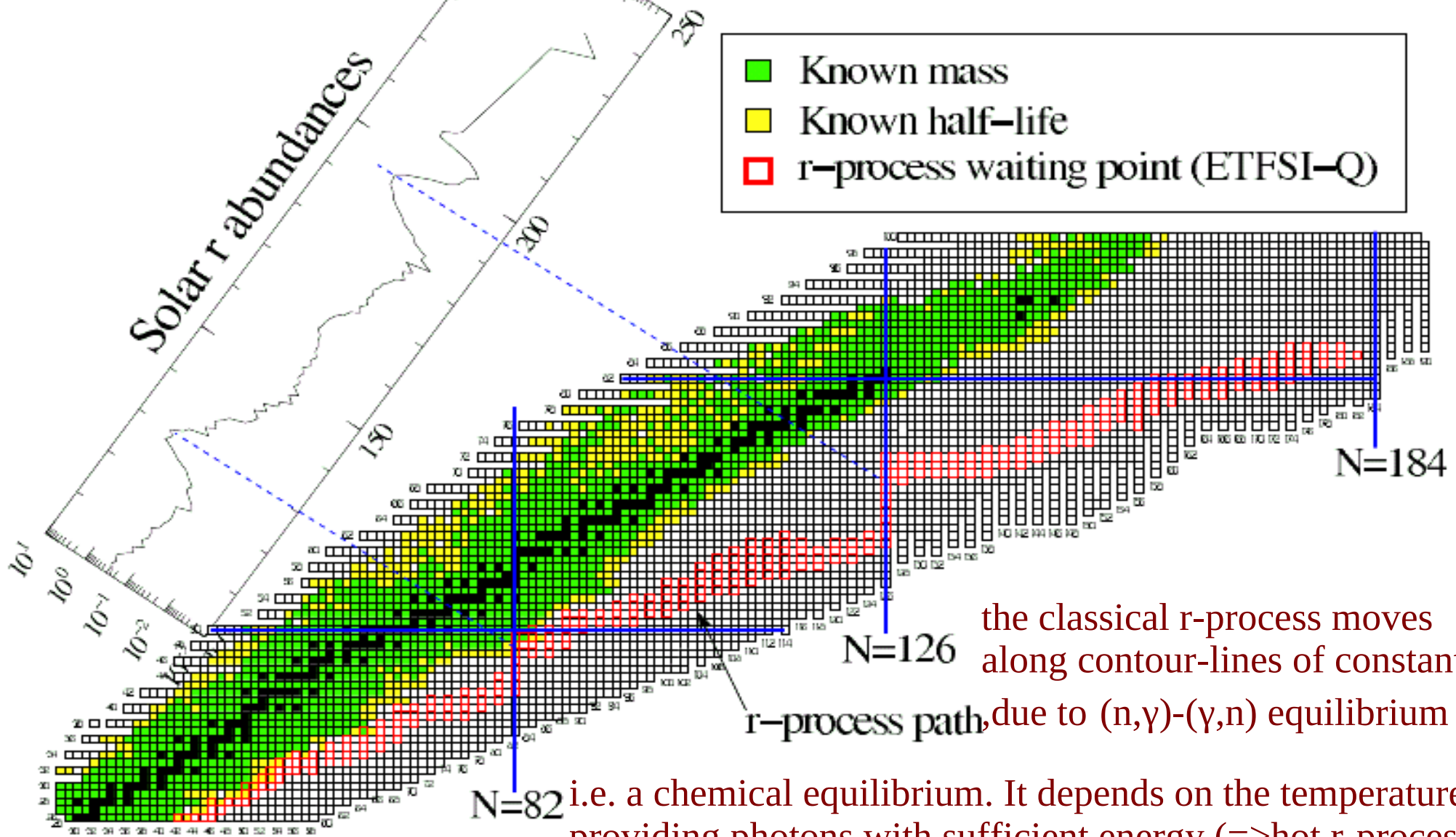
but where does the r-process take place??

# Observational Constraints on r-Process Sites



Roederer and Cowan (2013)

# r-Process Path

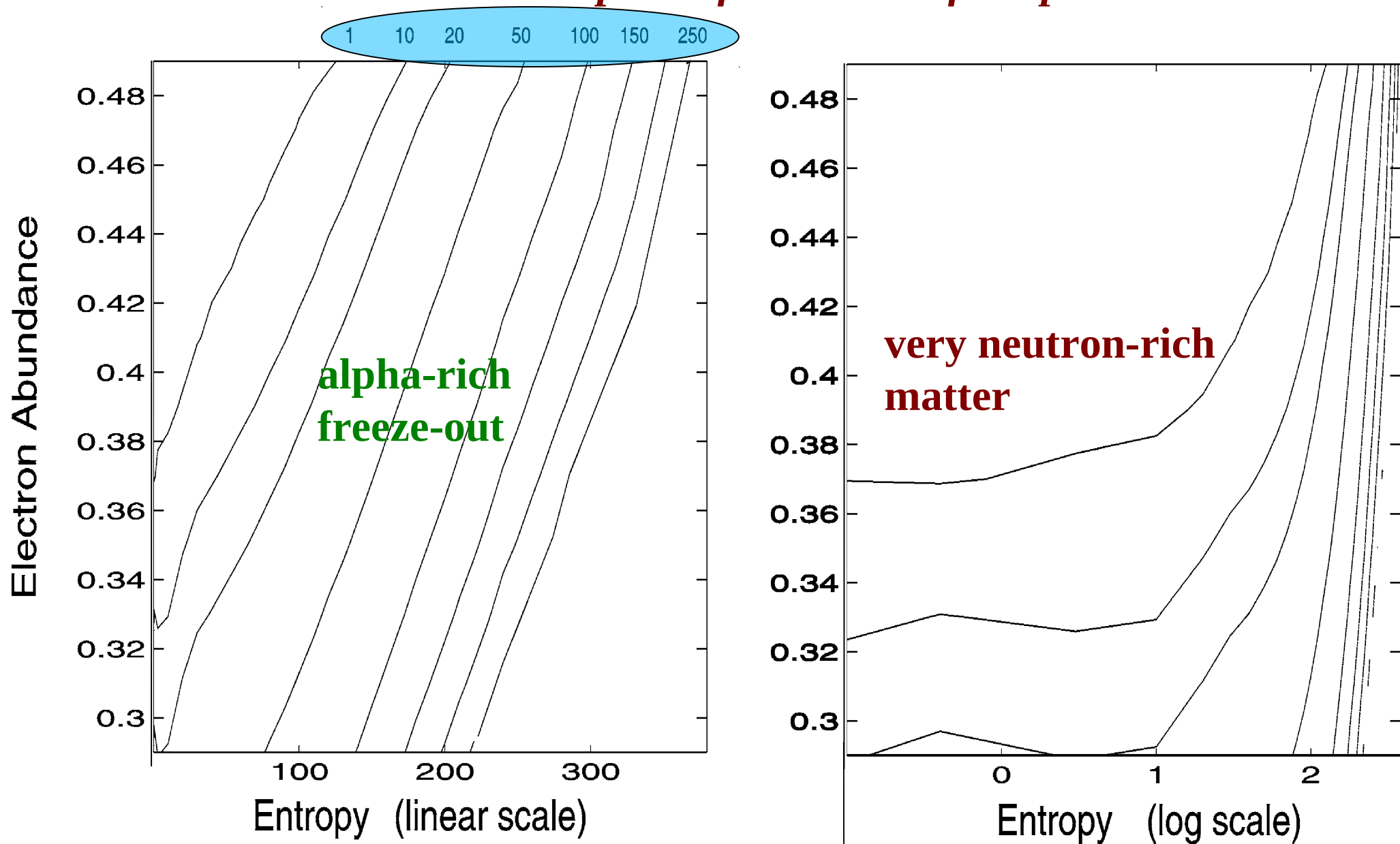


the classical r-process moves along contour-lines of constant  $S_n$ , due to  $(n,\gamma)$ - $(\gamma,n)$  equilibrium

i.e. a chemical equilibrium. It depends on the temperature, providing photons with sufficient energy ( $\Rightarrow$  hot r-process). In matter with fast expansion and still high neutron densities at low temperatures this might not be established ( $\Rightarrow$  smeared-out distribution, cold r-process)

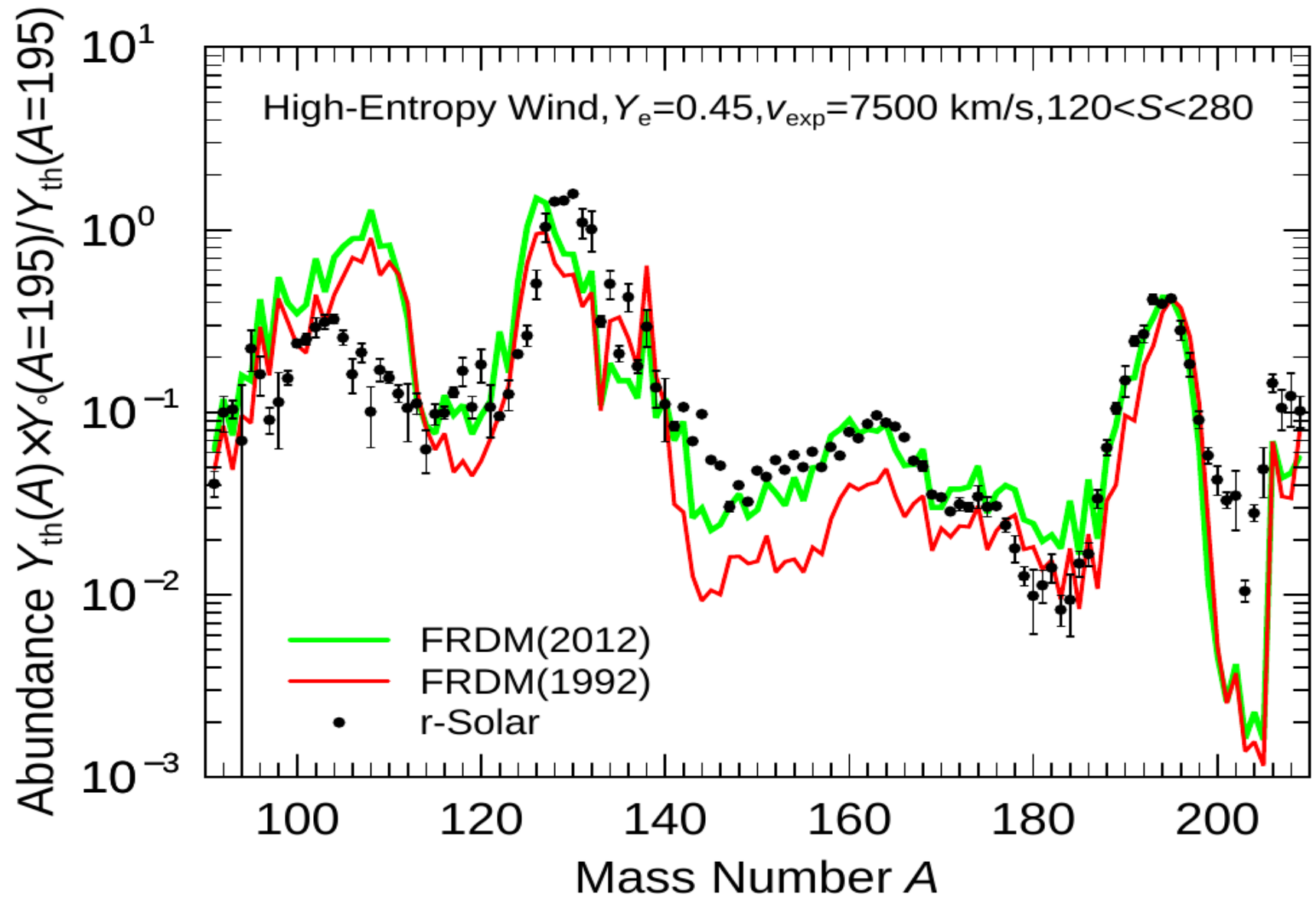
# $n$ /seed ratios as function of entropy $S$ and proton/nucleon ratio $Y_e$

## Two options for a successful $r$ -process



*neutrino wind?*

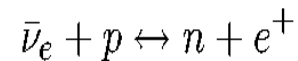
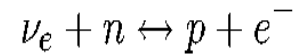
Freiburghaus et al. (1999) *Neutron star mergers and polar jets?*



Kratz et al. (2014): Update from nuclear mass model FRDM (1995=>2012).  
**Assuming superpositions of entropy  $S$ , initial  $Y_e$ , and expansion velocity (related to an expansion time scale) of the hot matter, existing in CCSNe?**

# What determines the neutron/proton or proton/nucleon= $Y_e$ ratio?

$Y_e$  dominantly determined by  $e^\pm$  and  $\nu_e, \bar{\nu}_e$  captures on neutrons and protons



- high density / low temperature  $\rightarrow$  high  $E_F$  for electrons  
 $\rightarrow$  e-captures dominate  $\rightarrow$  n-rich composition
- if el.-degeneracy lifted for high T  $\rightarrow$   $\nu_e$ -capture dominates  $\rightarrow$  due to n-p mass difference, p-rich composition ?

If neutrino flux sufficient to have an effect (scales with  $1/r^2$ ), and total luminosities are comparable for neutrinos and anti-neutrinos, only conditions with  $E_{\nu_e} - E_{\bar{\nu}_e} > 4(m_n - m_p)$  lead to  $Y_e < 0.5$ !

Otherwise the interaction with neutrinos leads to proton-rich conditions

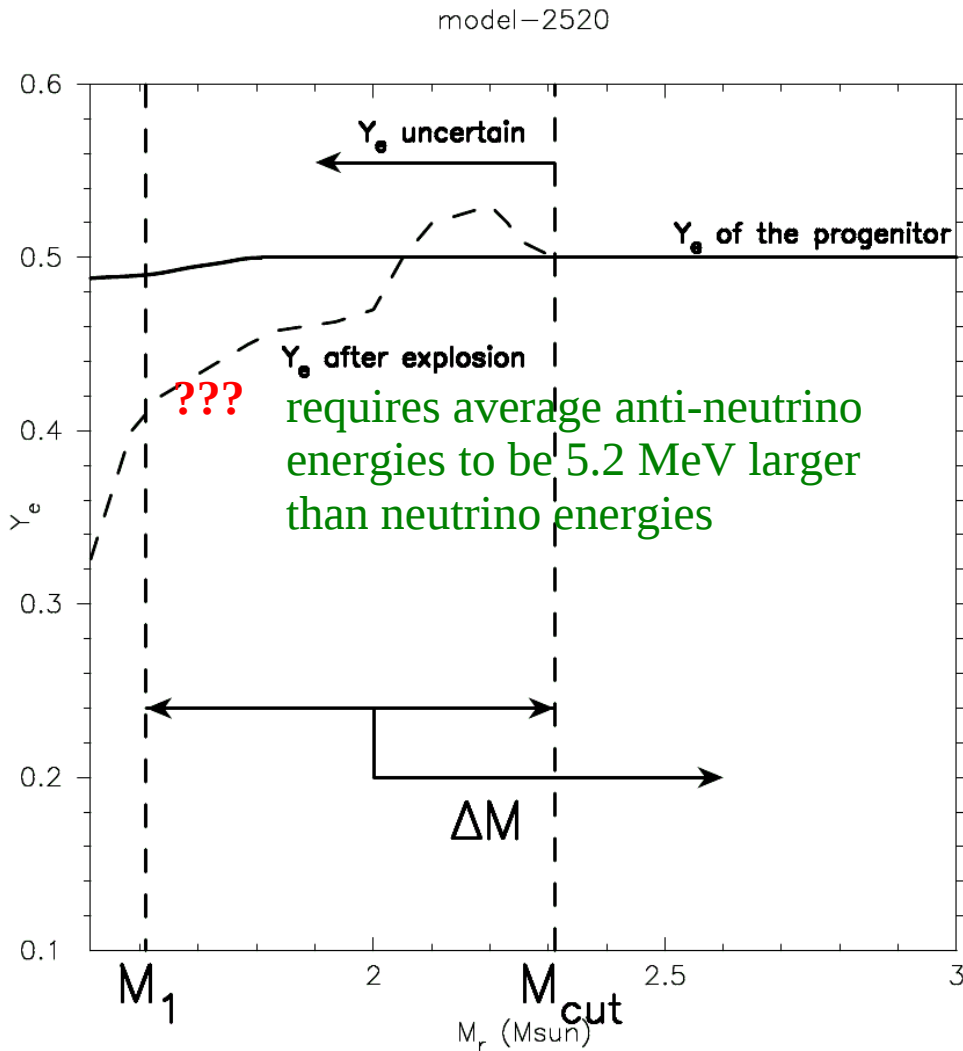
General strategy for a successful r-process:

1. either highly neutron-rich initial conditions + fast expansion (avoiding neutrino interactions!)
2. have neutrino properties to ensure (at least slightly) neutron-rich conditions (+ high entropies)
3. invoke (sterile?/collective) neutrino oscillations



# Possible Variations in Explosions and Ejecta

## (status before including medium effects)



Izutani et al. (2009)

- Initially proton-rich conditions are obtained (vp-process – possibly up to Sr, Y, Zr on proton-rich side)
- How to obtain moderately neutron-rich neutrino wind and weak r-process or more?
- under which (special?) conditions can very high entropies be obtained which produce the main r-process nuclei?

**Innermost ejecta as a function of initial radial mass and also time of ejection, innermost zones ejected latest in the wind!**

**Inclusion of medium Effects, potential U in dense medium**  
**Martinez-Pinedo et al. 2012, Roberts et al., Roberts &**  
**Reddy 2012, changes neutrino and anti-neutrino energies**

$$E_i(\mathbf{p}_i) = \frac{\mathbf{p}_i^2}{2m_i^*} + m_i + U_i, \quad i = n, p$$

$$E_{\nu_e} = E_{e^-} - (m_n - m_p) - (U_n - U_p)$$

$$E_{\bar{\nu}_e} = E_{e^+} + (m_n - m_p) + (U_n - U_p)$$

**Can reduce slightly proton-rich conditions ( $Y_e=0.55$ ) down to  $Y_e=0.4$ !** (further applications to supernova models result only in weak r-process?)

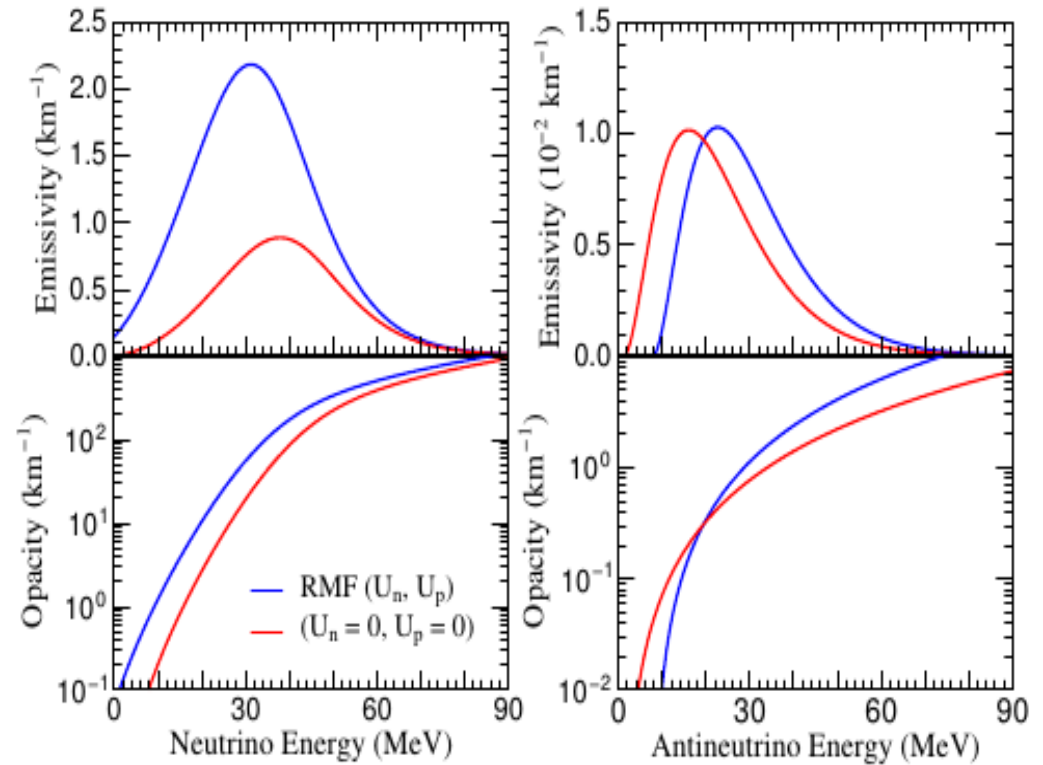
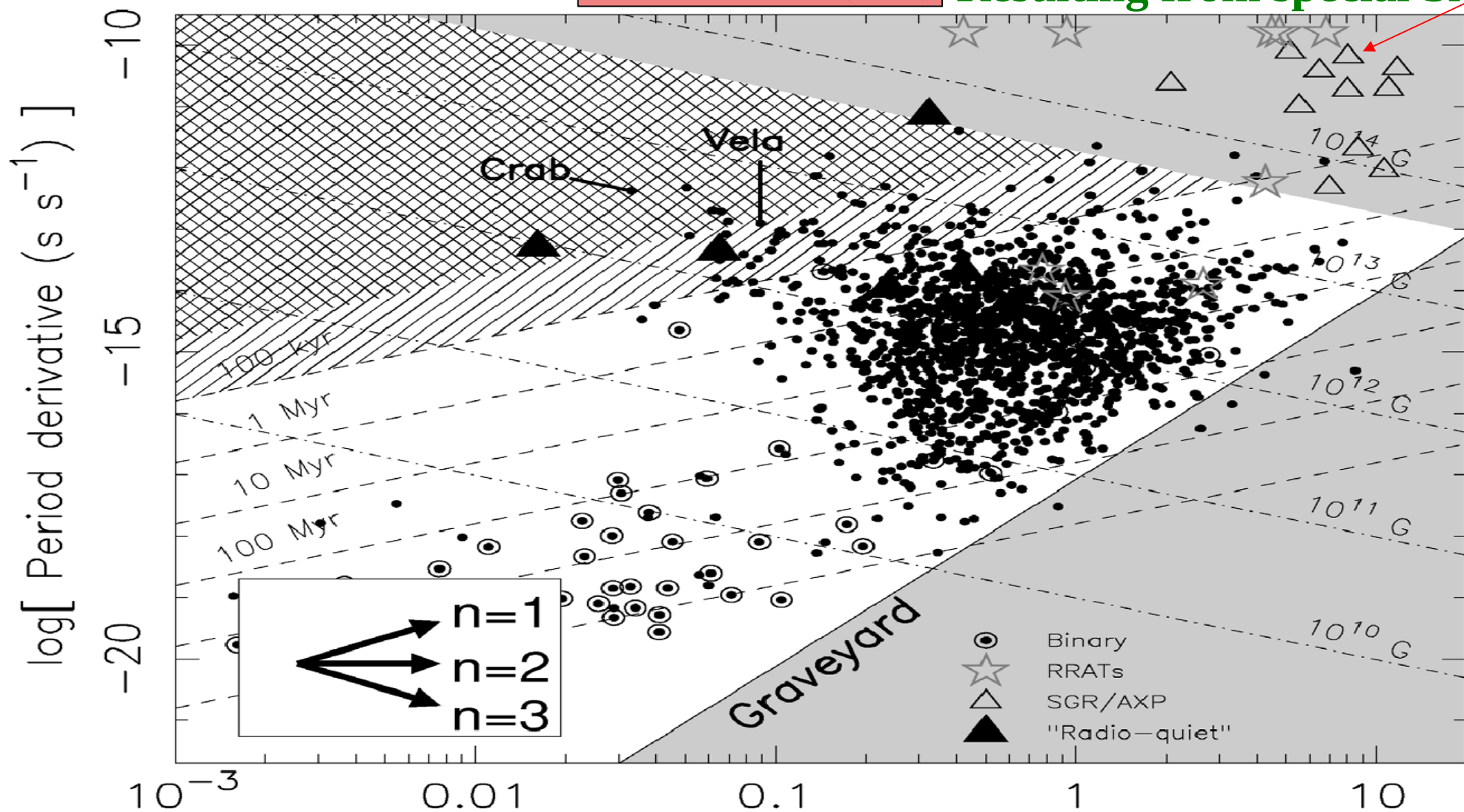


FIG. 1. (Color online) Opacity and emissivity for neutrino (left panels) and antineutrino (right panels), evaluated at conditions  $\rho = 2.1 \times 10^{13} \text{ g cm}^{-3}$ ,  $T = 7.4 \text{ MeV}$  and  $Y_e = 0.035$ .

**If including collective neutrinos oscillations, chance to also produce a weak component, but extending up to Eu? (Wu, Fischer, Huther, Martinez-Pinedo, Qian 2014, but no strong r-process in regular core-collapse supernovae!)**



## Neutron stars observed with $10^{15} \text{G}$

Period (s)

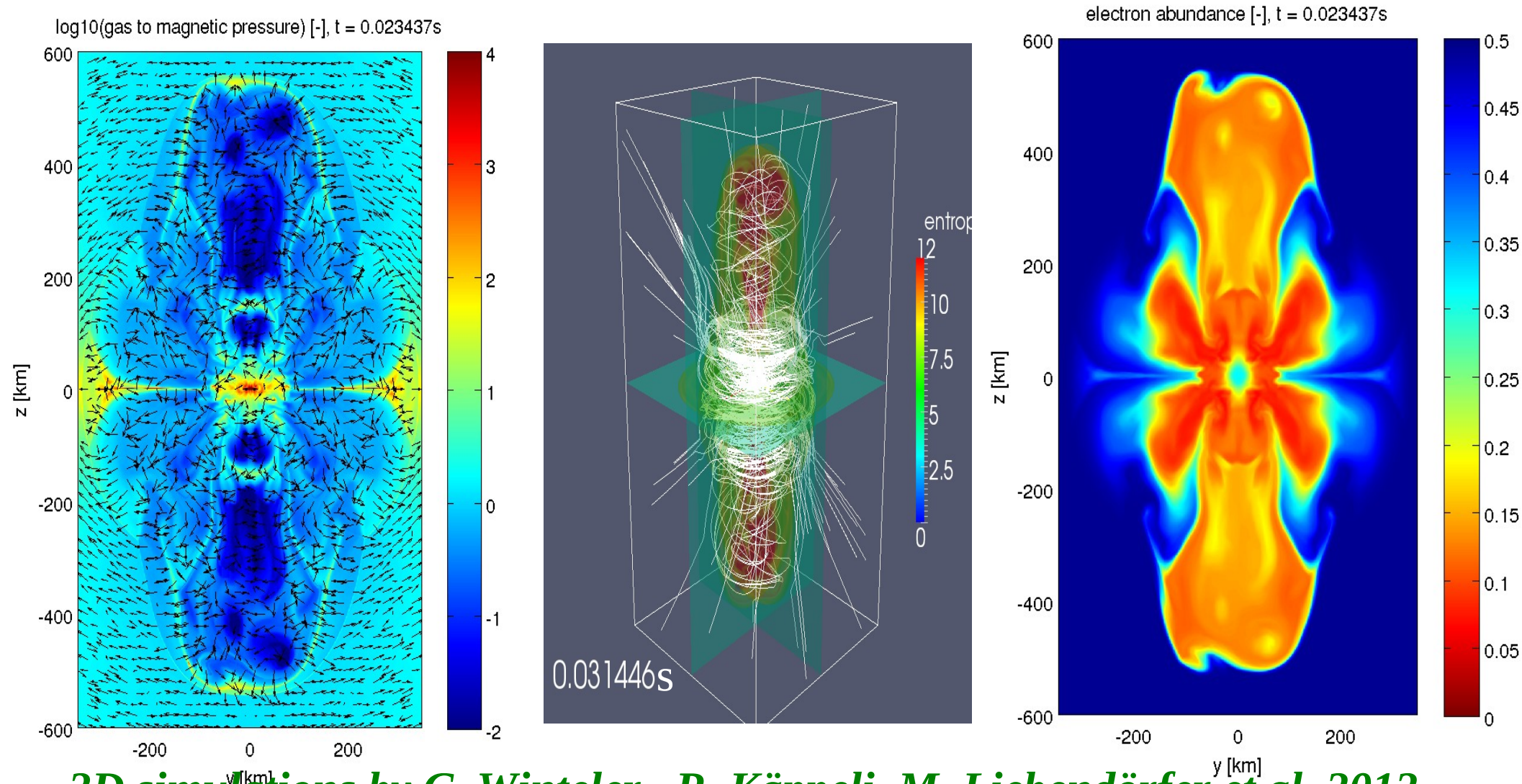
**Figure 2.** The  $P-\dot{P}$  diagram shown for a sample consisting of radio pulsars, ‘radio-quiet’ pulsars and magnetars, i.e. soft-gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Lines of constant characteristic age  $\tau_c$  and magnetic field  $B$  are also shown. The single hashed region shows ‘Vela-like’ pulsars with ages in the range 10–100 kyr, while the double-hashed region shows ‘Crab-like’ pulsars with ages below 10 kyr. The grey regions are areas where radio pulsars are not predicted to exist by theoretical models. The inset at the bottom-left indicates the expected direction of movement for pulsars with a braking index of  $n = 1, 2$  and  $3$ , respectively.

# 3D Collapse of Fast Rotator with Strong Magn. Fields:

15  $M_{\text{sol}}$  progenitor (Heger Woosley 2002), shellular rotation with period of 2s at

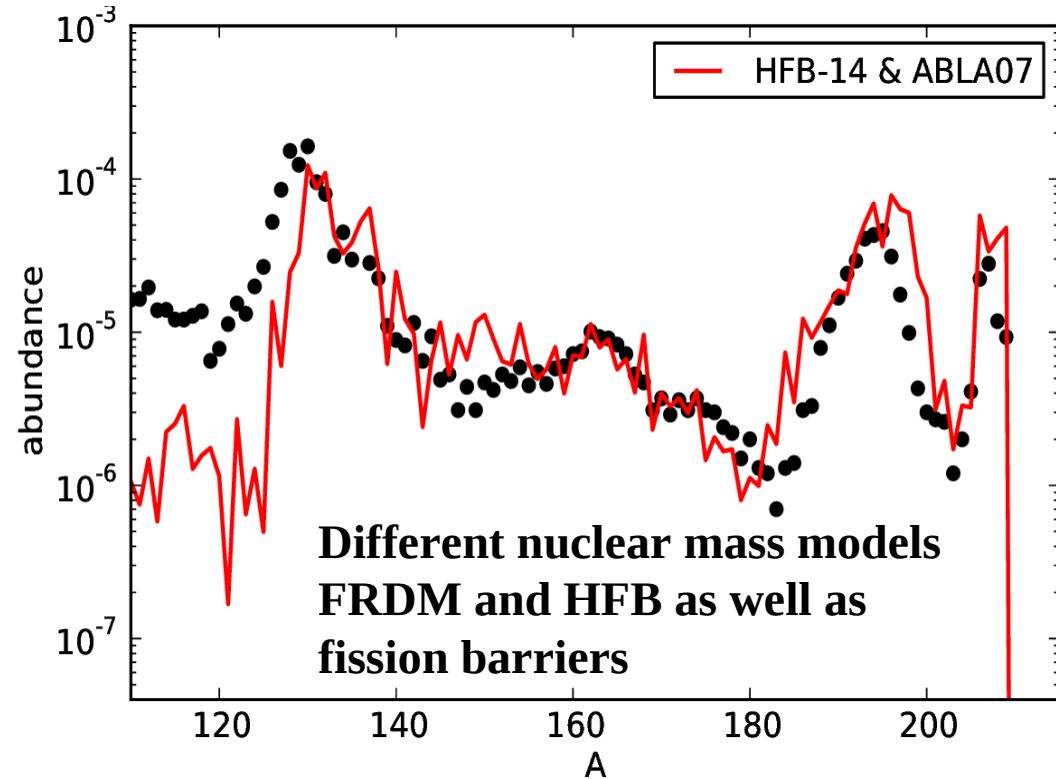
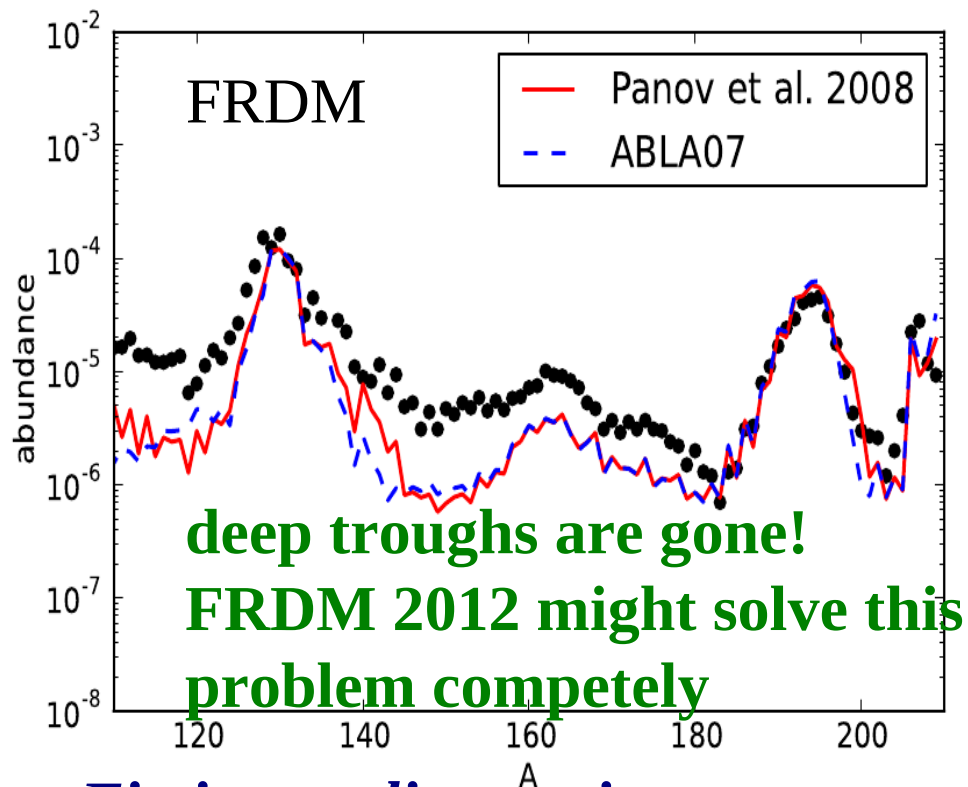
1000km, magnetic field in z-direction of  $5 \times 10^{12}$  Gauss,

*results in  $10^{15}$  Gauss neutron star*



3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012, Eichler et al. 2015, magnetars observed by Greiner et al. 2015

# Nucleosynthesis results, utilizing Winteler et al. (2012) model with variations in nuclear Mass Model and Fission Yield Distribution (Eichler et al. 2015)



*Fission-cycling environments permit n-capture due to fission neutrons in the late freeze-out phase and shifts peaks, but effect generally not strong and overall good fit in such “weak“ fission-cycling environments!*

Ejected matter with  $A > 62$        $M_{r, ej} \approx 6 \times 10^{-3} M_{\odot}$

# What is the site of the r-process(es)? All options?

- **Neutrino-driven Winds (in supernovae?)** ? *Arcones, Burrows, Janka, Farouqi, Hoffman, Kajino, Kratz, Martinez-Pinedo, Mathews, Meyer, Qian, Takahara, Takahashi, FKT, Thompson, Wanajo, Woosley ... (no!?)*

- **Electron Capture Supernovae** ? *Wanajo and Janka (weak!)*

- SNe due to quark-hadron phase transition *Fischer, Nishimura, FKT (if? weak!)*

- **Neutron Star Mergers?** *Freiburghaus, Goriely, Janka, Bauswein, Panov, Arcones, Martinez-Pinedo, Rosswog, FKT, Argast, Korobkin, Wanajo, Just, Martin, Perego*

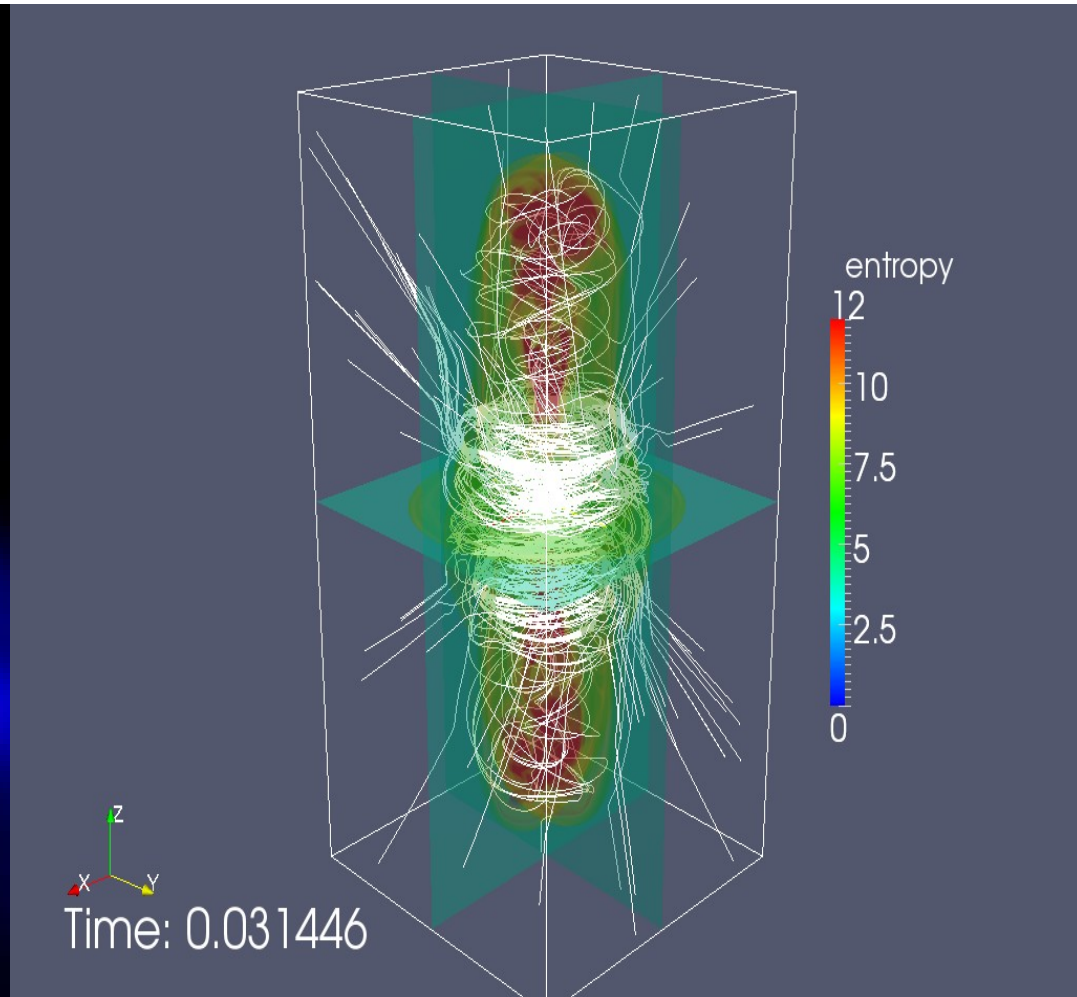
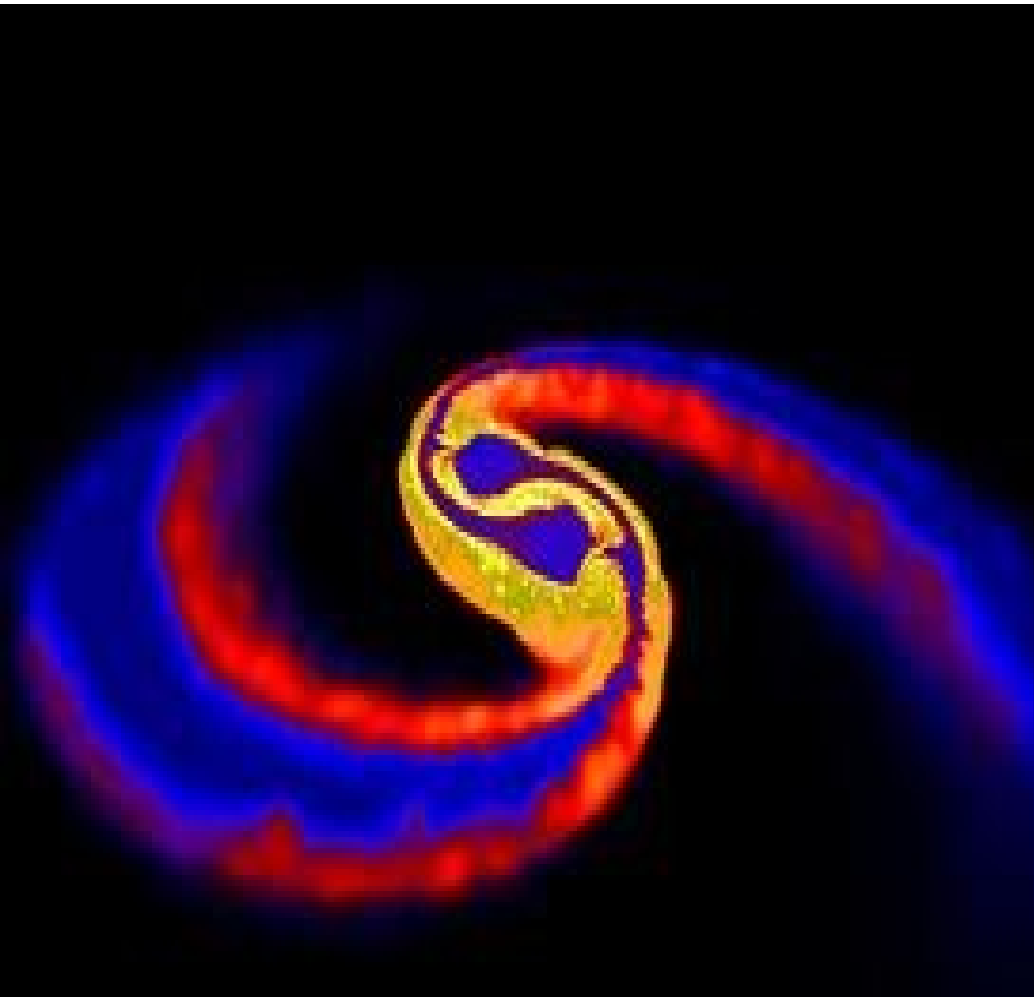
- **Black Hole Accretion Disks (massive stars as well as neutron star and neutron star BH mergers, neutrino properties)** *MacLaughlin, Surman, Wanajo, Janka, Ruffert, Perego, Just*

- Explosive He-burning in outer shells (???) *Cameron, Cowan, Truran, Hillebrandt, FKT, Wheeler, Nadyozhin, Panov*

- CC Neutrino Interactions in the Outer Zones of Supernovae *Haxton, Qian (abundance pattern ?)*

- **Polar Jets from Rotating Core Collapse?** *Cameron, Fujimoto, Käppeli, Liebendörfer, Nishimura, Nishimura, Takiwaki, FKT, Winteler, Mösta, Ott*

# Which events contribute to the strong r-Process??



**Neutron star mergers** in binary stellar systems vs. **supernovae** of massive stars with fast rotation and high magnetic fields

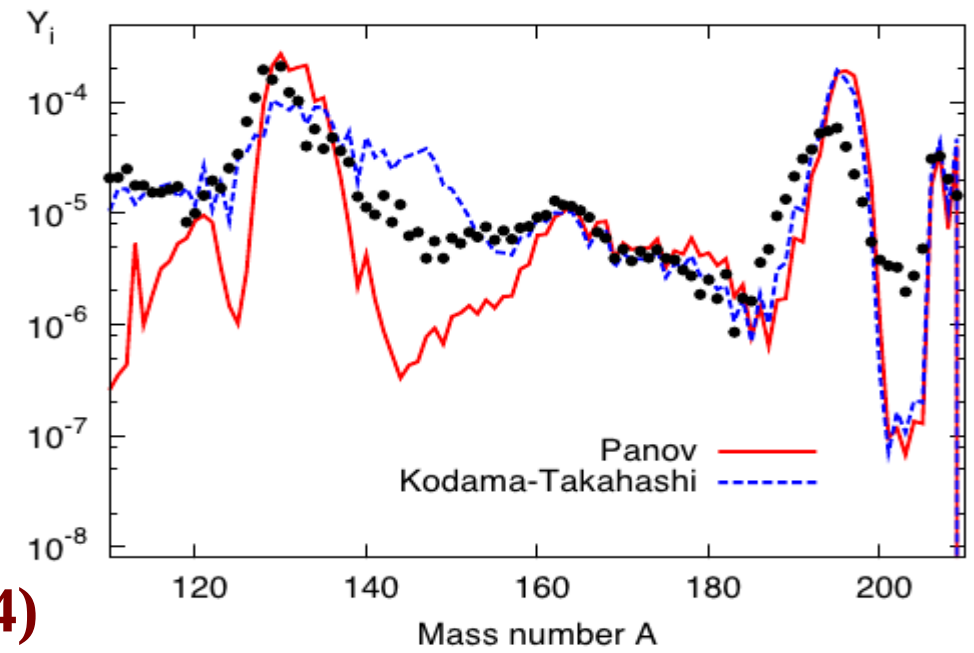
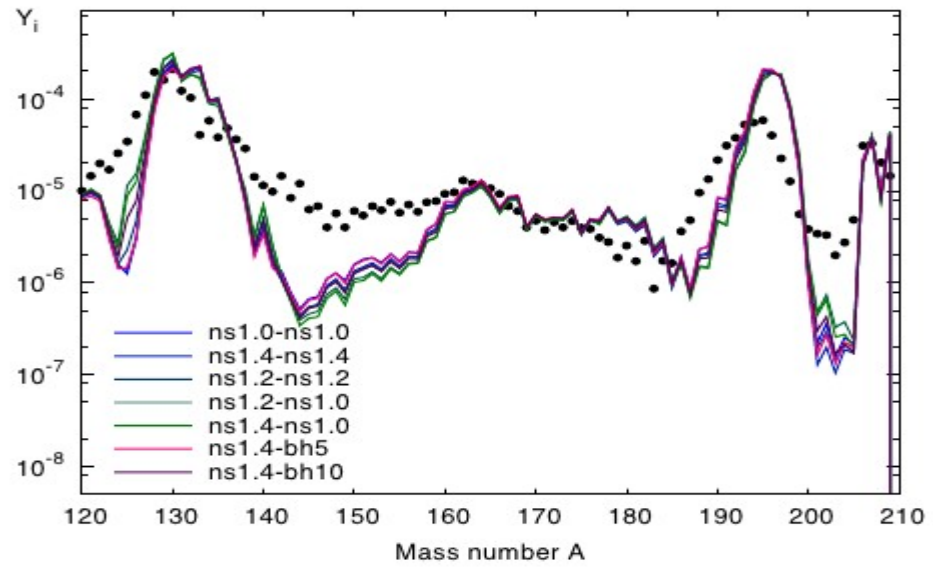
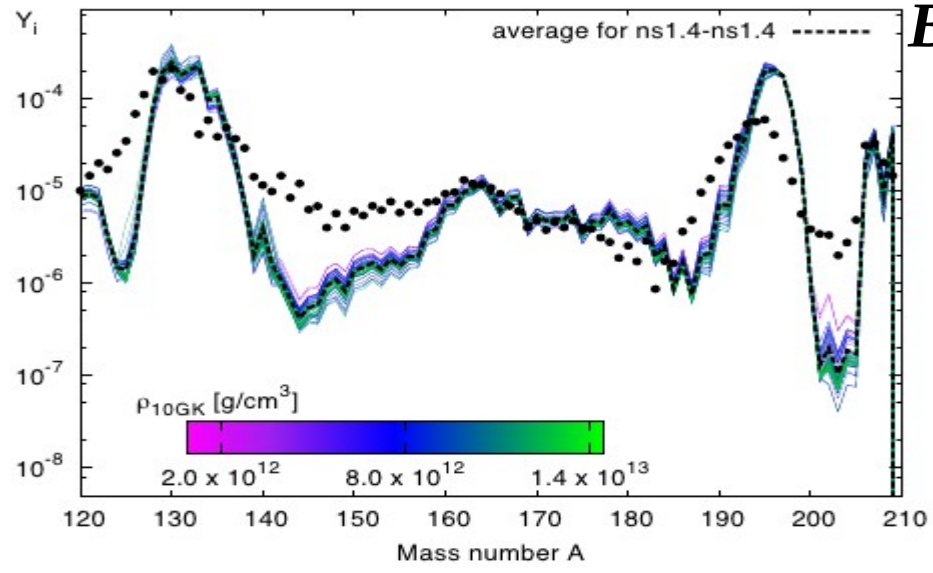
Based on early ideas by Lattimer and Schramm, first detailed calculations by  
 Freiburghaus et al. 1999, Fujimoto/Nishimura 2006-08, Panov et al. 2007, 2009,

Bauswein et al. 2012, Goriely et al. 2012...

Neutron star merger updates of  
 dynamic ejecta in non-relativistic  
 calculations (Korobkin et al. 2012)

Variation in neutron star masses  
 fission yield prescription

Fission yields affect abundances  
 below  $A=165$ , the third peak seems  
 always shifted to heavier nuclei

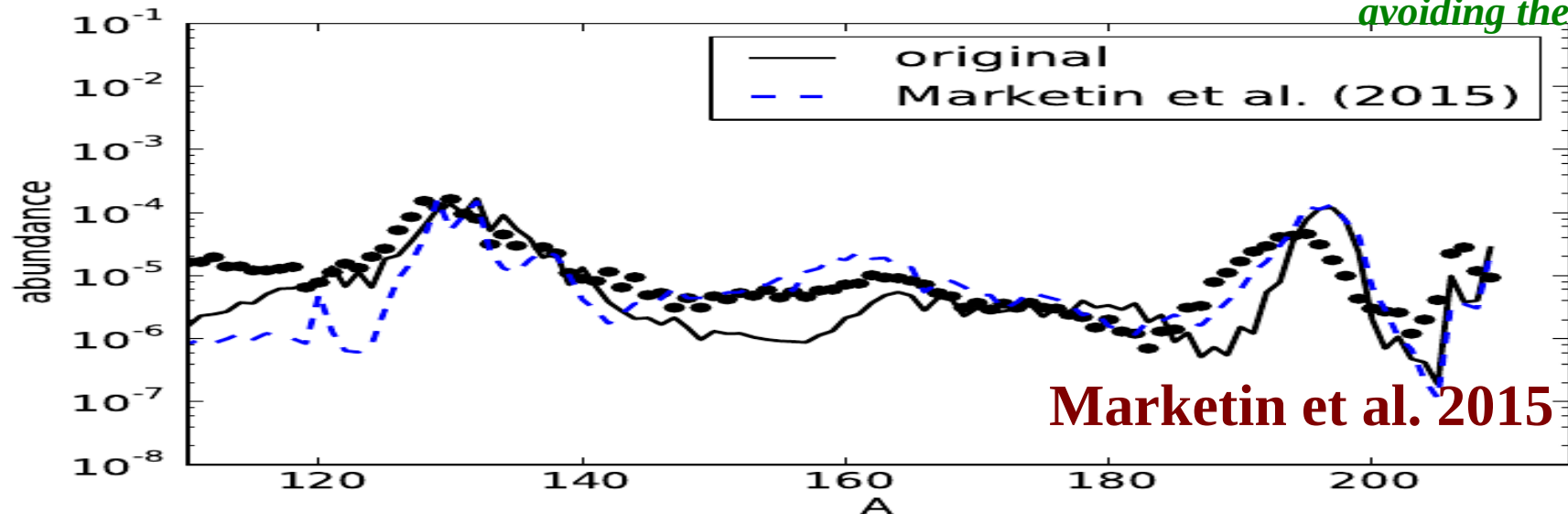


Ejected mass of the order  $10^{-2} M_{sol}$   
 conditions very neutron-rich ( $Y_e=0.04$ )



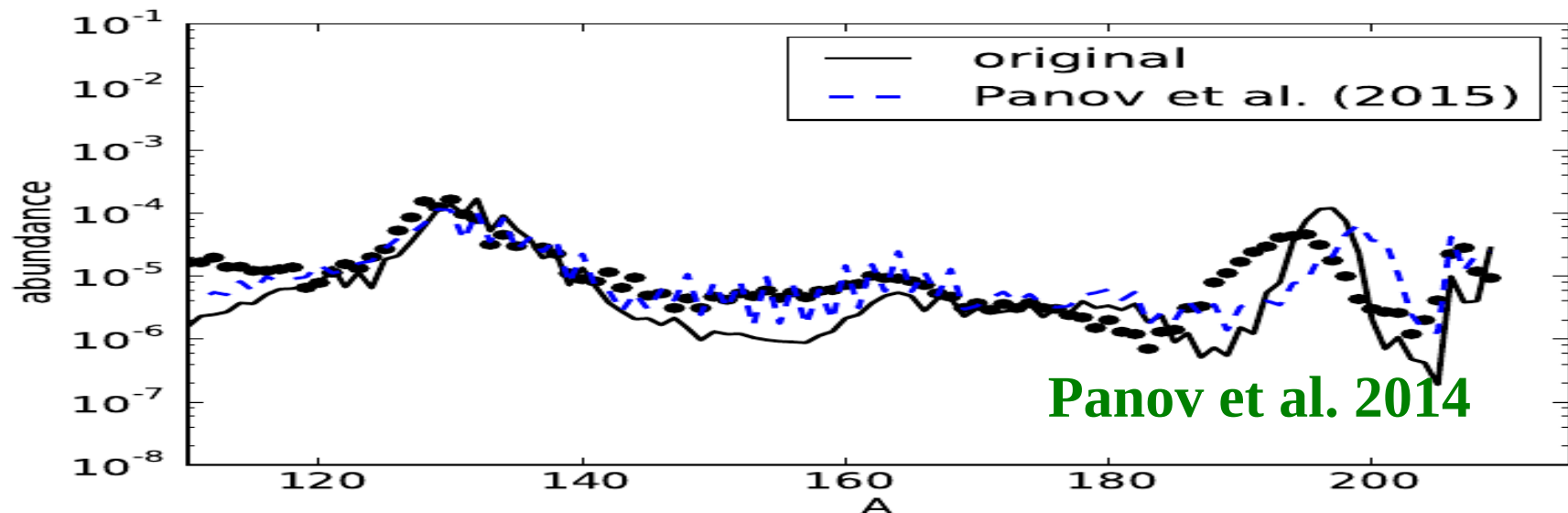
# Exploring variations in beta-decay rates

Shorter half-lives of heavies release neutrons (from fission/fragments) earlier (still in  $n, \gamma, n$  equilibrium), avoiding the late shift???



Similar results seen in Caballero et al. (2014), due to DF3 half-lives (Borzov 2011)

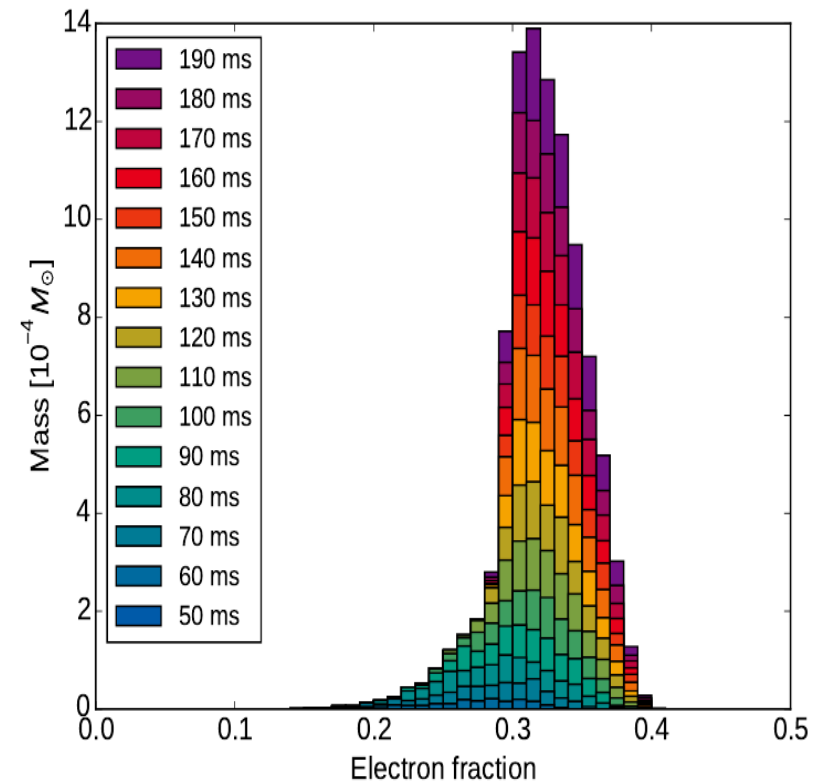
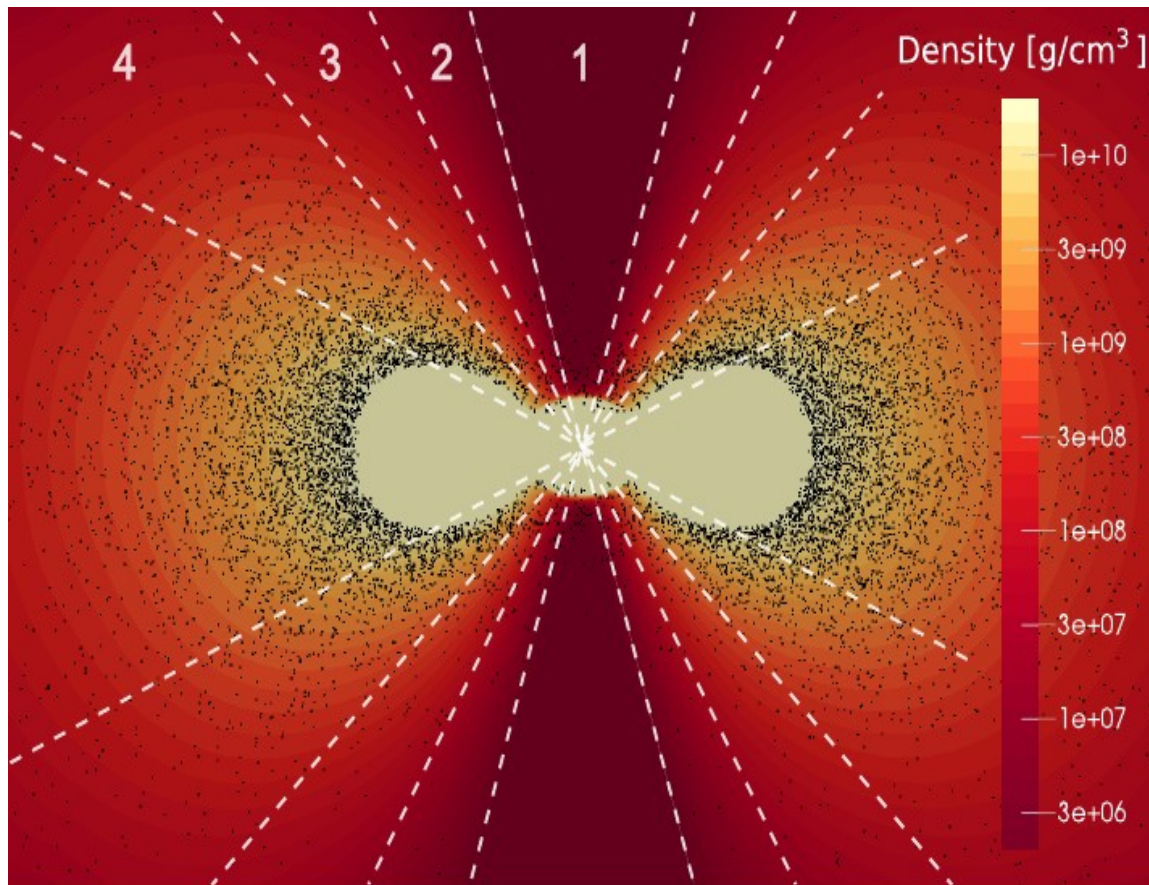
(a) FRDM, Marketin (2015)



Longer half-lives give the opposite effect

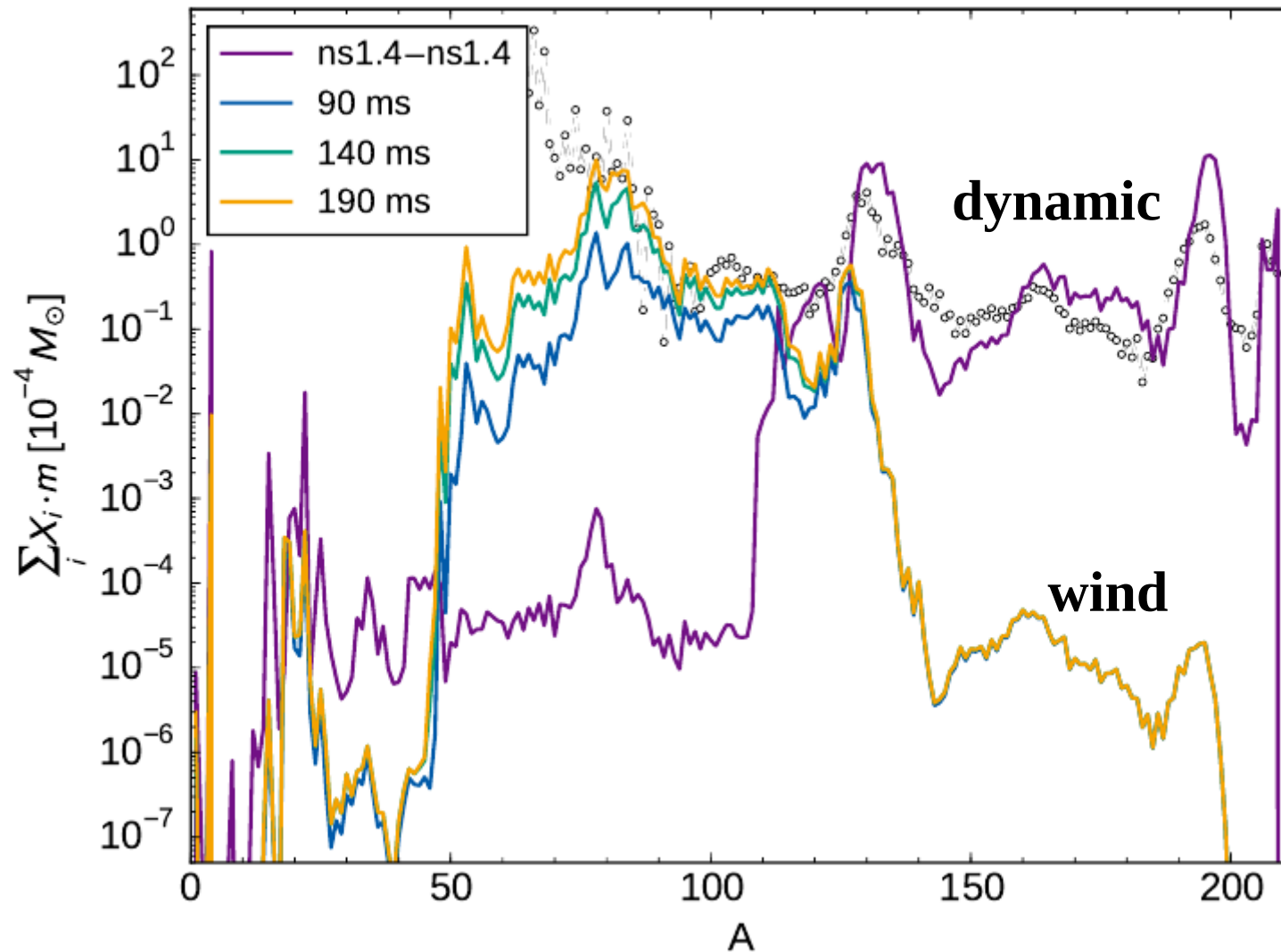
(c) FRDM, Panov (2015)

# Dynamic Ejecta and Wind Contribution (Martin et al. 2015)

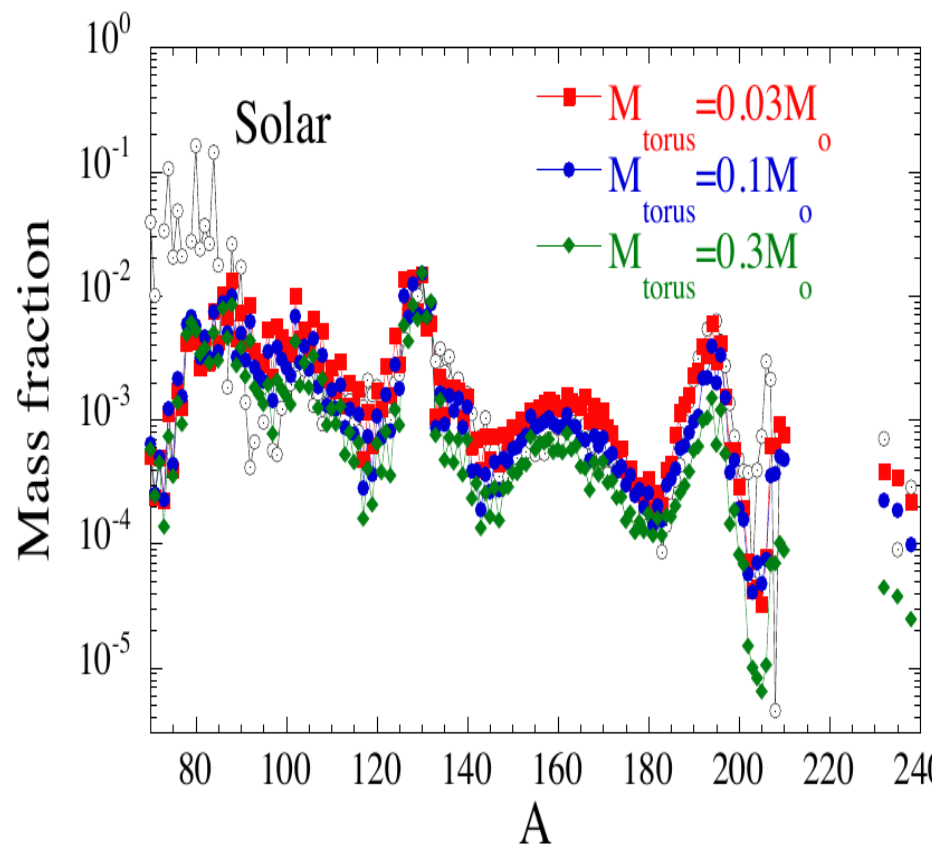


**Ye in neutrino wind**

**After ballistic/hydrodynamic ejection of matter, the hot, massive combined neutron star (before collapsing to a black hole) evaporates a neutrino wind (Rosswog et al. 2014, Perego et al. 2014)**

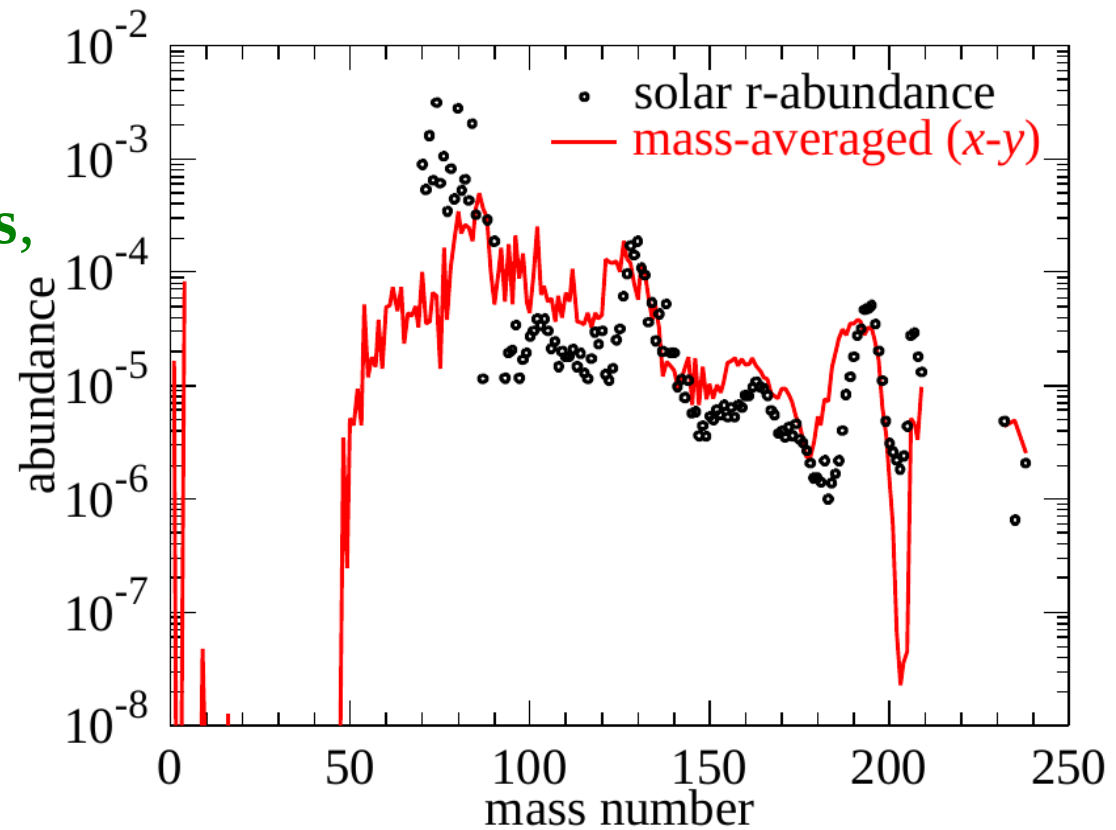


**Martin et al. (2015) with neutrino wind contributions from matter in More polar directions (of course, the problem with the dynamical ejecta composition persists).**



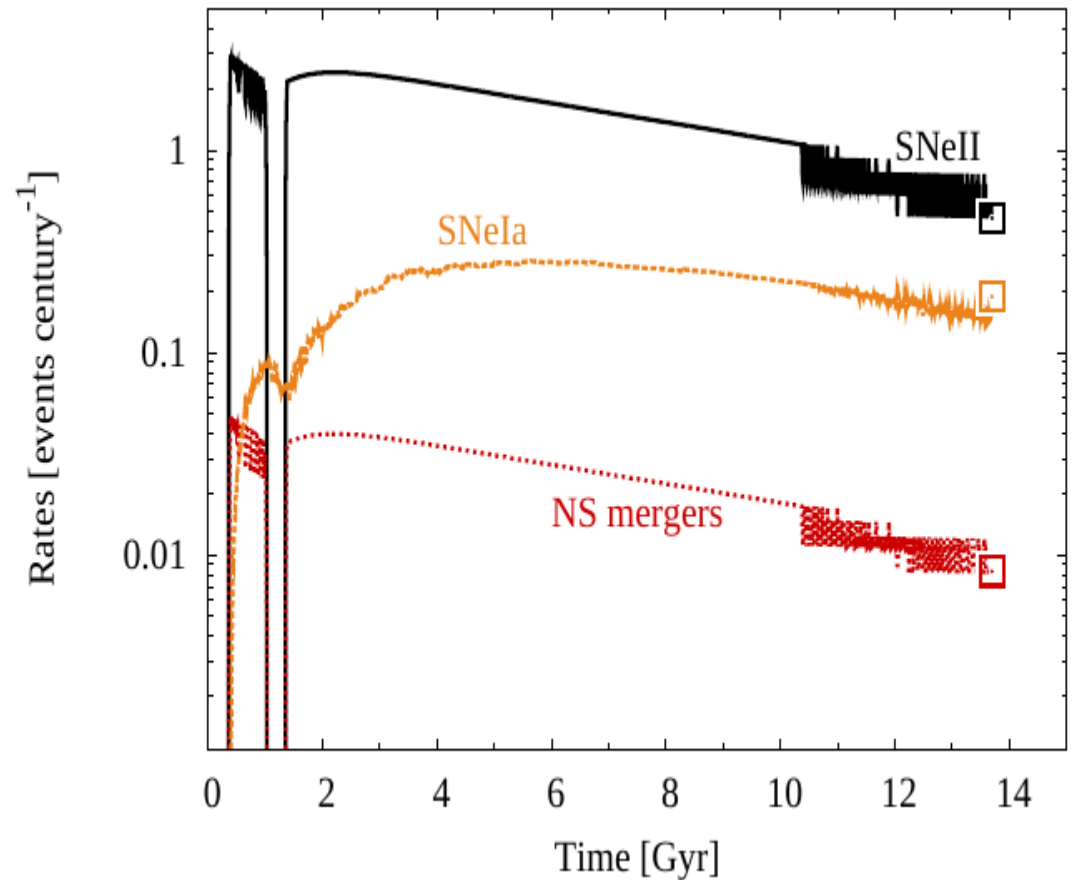
**General relativistic grid calculations,** possibly leading to hot shocks, and  $e^+e^-$  pairs, which affect  $Y_e$  and the position of the r-process peaks (**Wanajo et al. 2014**). Higher  $Y_e$  leads to similar results as in jets.

Full predictions with dynamic ejecta, viscous disk ejection, and late neutrino wind, **but neutron-less fission fragment distribution?** (*Just et al. 2015*), based on smooth particle hydrodynamics and conformal flat treatment of GR



# SN II and Ia rates compared to NS merging rate (from Matteucci 2014)

***The rate of mergers is by a factor of about 100 smaller than CCSNe, but they also produce more  $r$ -process by a factor of 100 than required if CCSNe would be the origin***



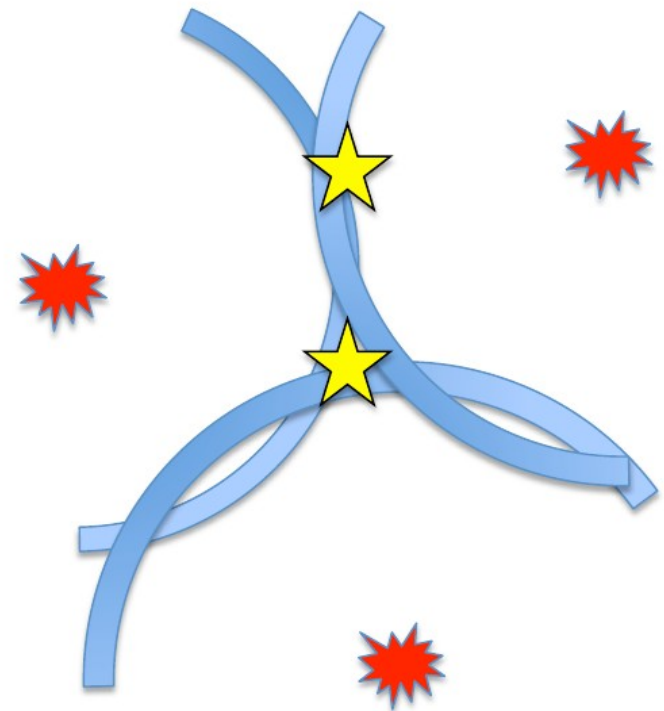
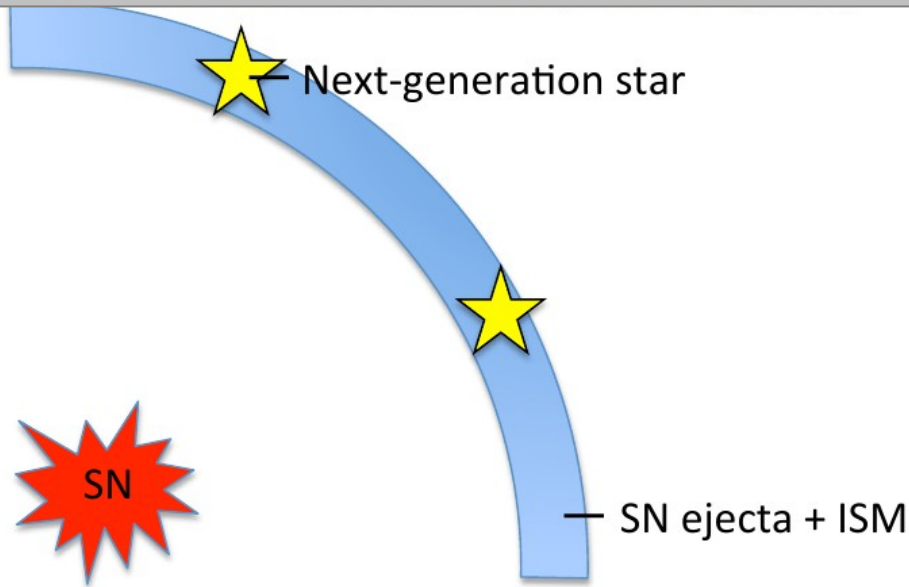
# Stellar Abundances

Inhomogeneous „chemical evolution“ models do not assume immediate mixing of ejecta with surrounding interstellar medium, pollute only about about  $5 \times 10^4 M_{\text{sol}}$ . After many events an averaging of ejecta composition is attained (Argast et al. 2004)

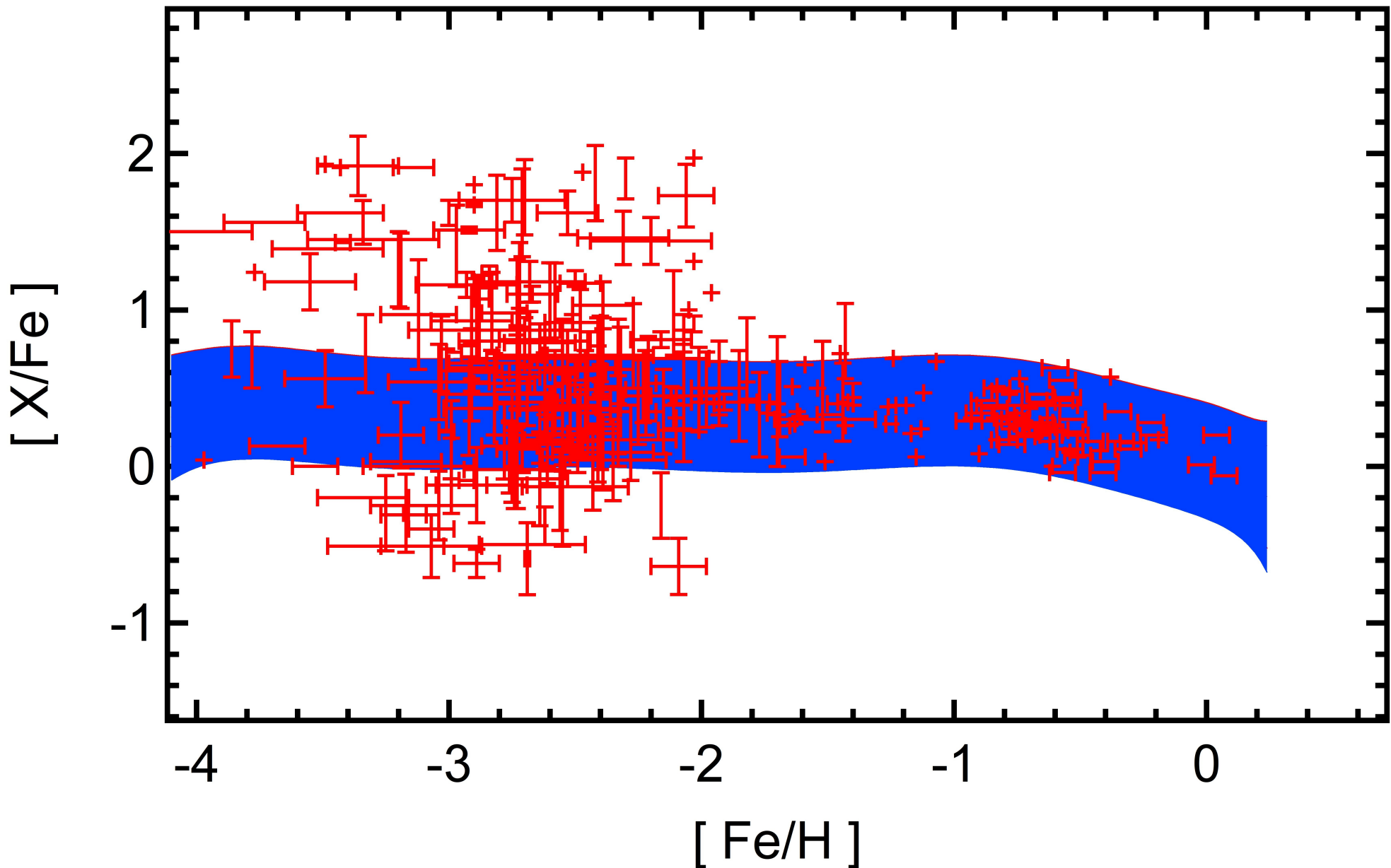
In the later phase

Contribution from multiple CCSNe

*from Ko Nakamura*

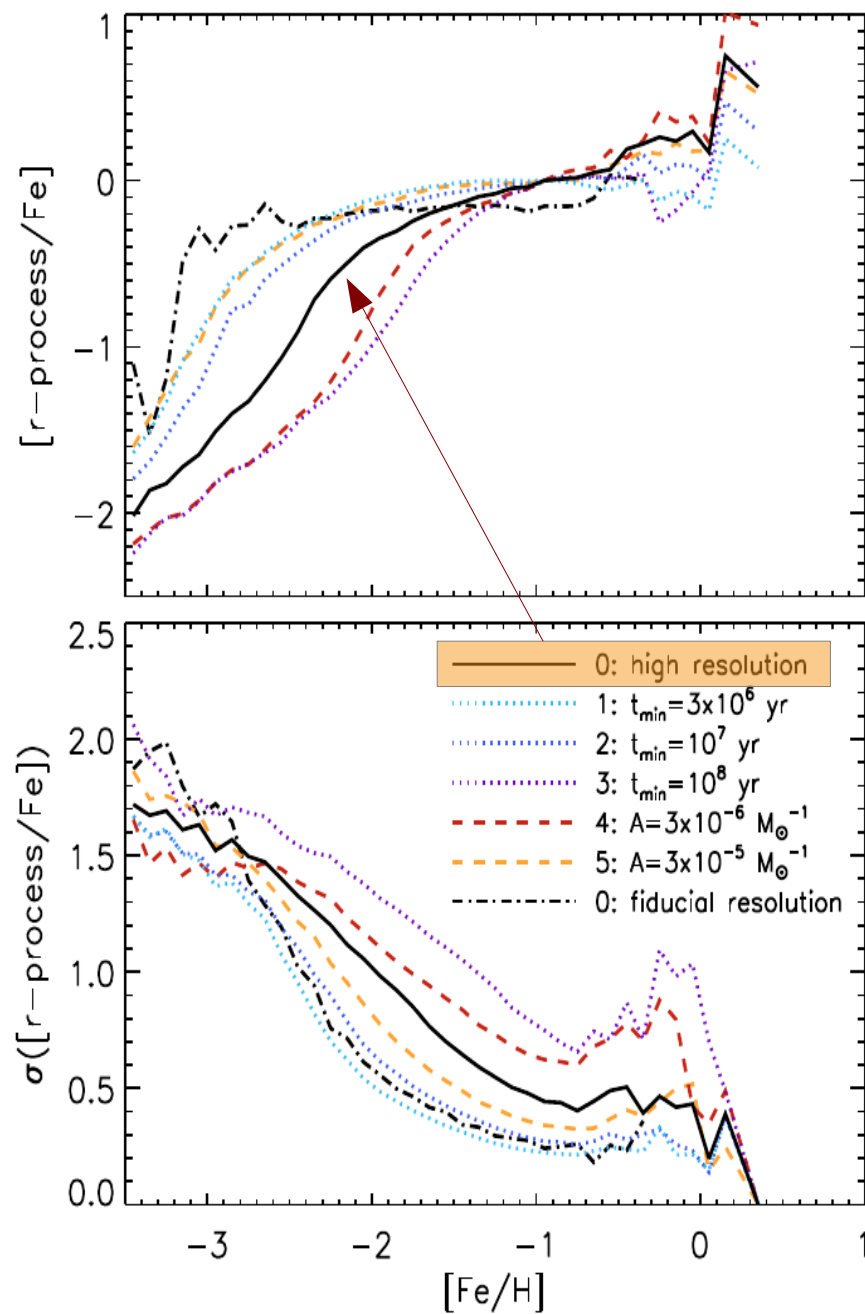
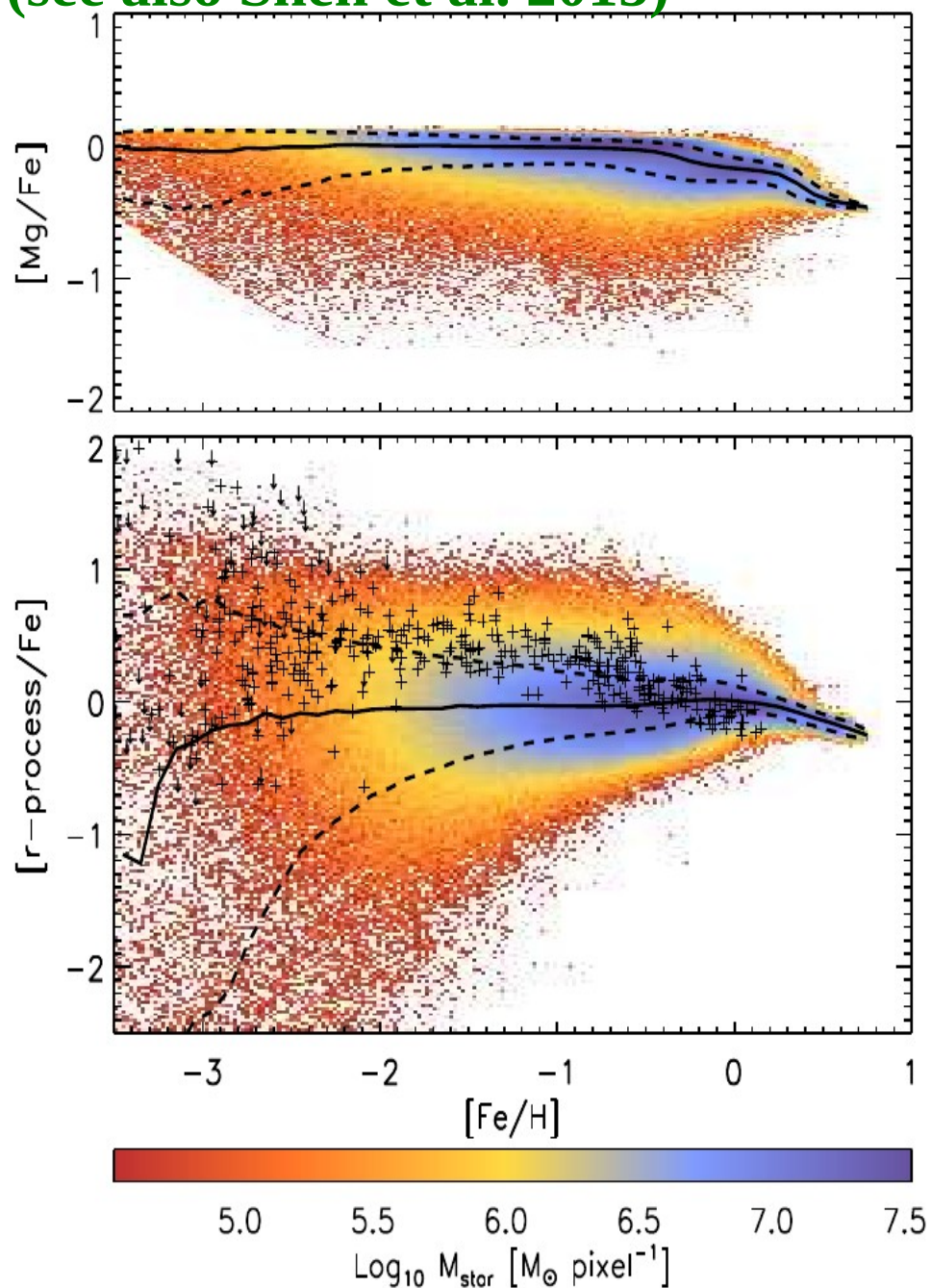


**Rare events lead initially to large scatter before an average is attained!**

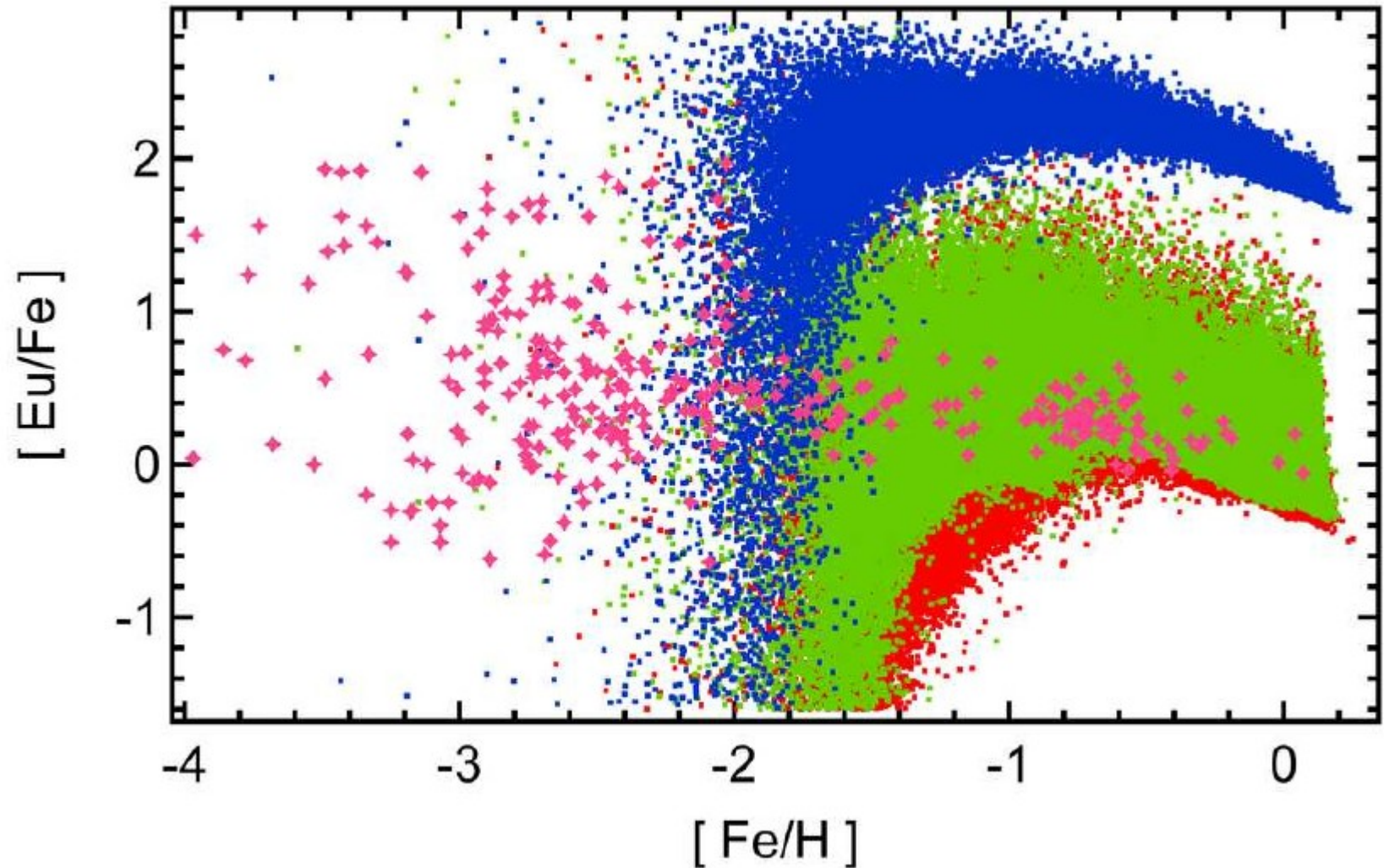


**Blue band: Mg/Fe observations (95%), red crosses: individual Eu/Fe obs.**

# Inhomogeneous Chemical Evolution with SPH (van de Voort et al. 2015), Left ejecta mixed in $5 \times 10^6 M_{\odot}$ , right high resolution mixed in $5 \times 10^4 M_{\odot}$ (see also Shen et al. 2015)

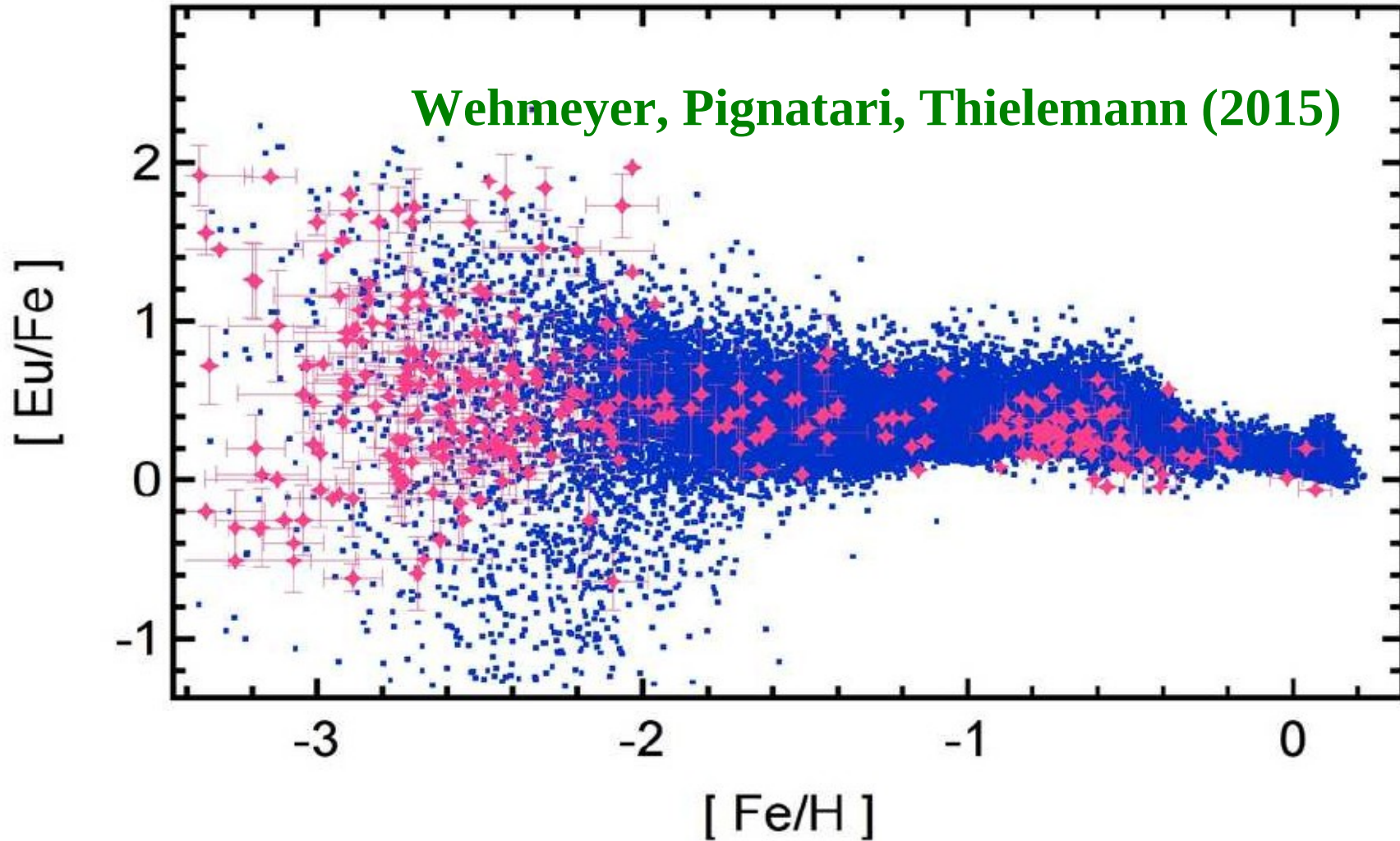






*Update by Wehmeyer et al. (2015), green/red different merging time scales, blue higher merger rate (not a solution)*

# Combination of NS mergers and magneto-rotational jets



**=> in either case, the strong r-process which also produces the actinides is a rare event!!!!!!!!!!!!!!**

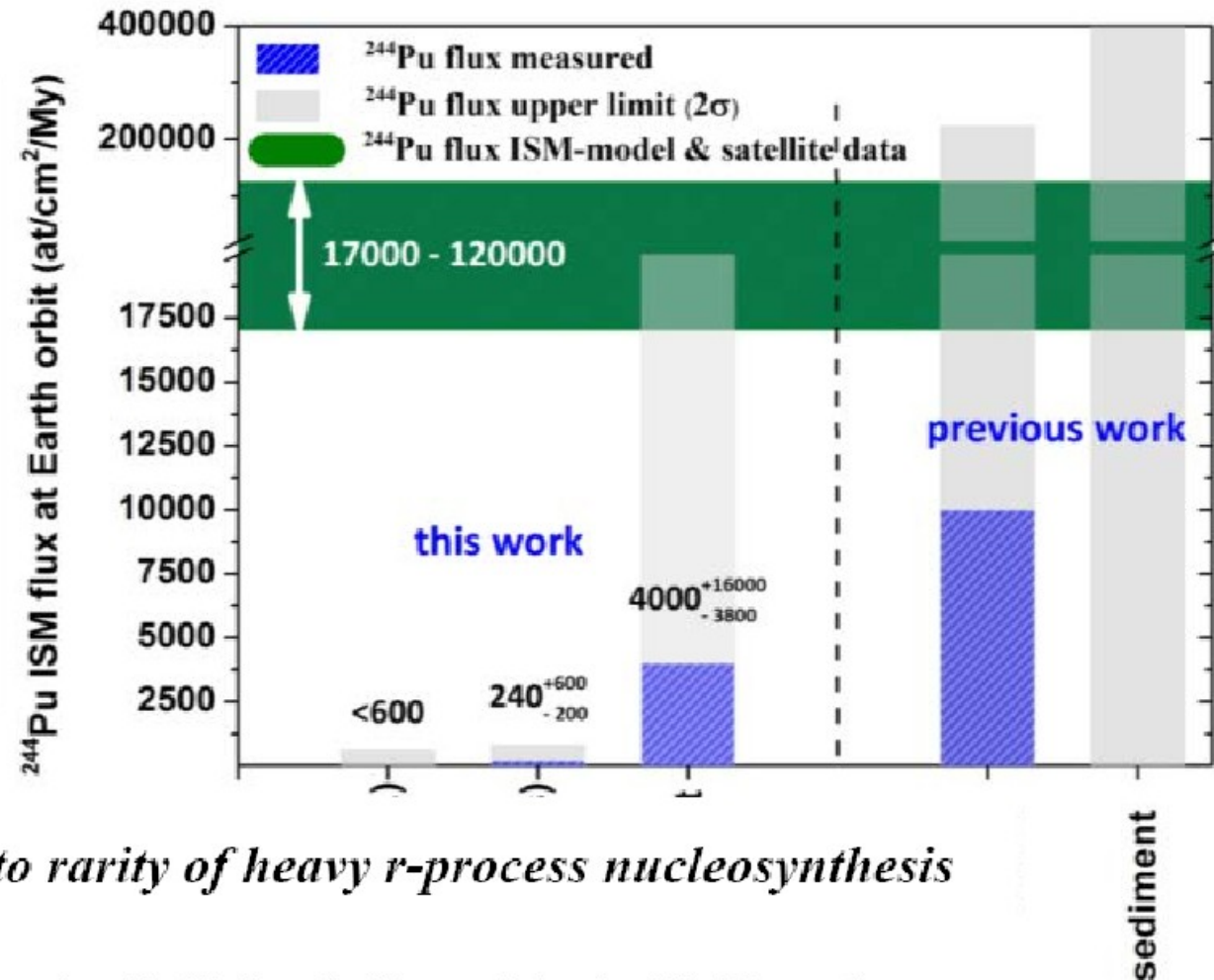
$^{244}\text{Pu}$ , half-life 81 My

## Status:

### $^{244}\text{Pu}$ in terrestrial crust:

- crust: dust collection over 25 Myr
- $^{244}\text{Pu}$ : time window - alive a few 100 Myr
- neutron star mergers?

100:1 estimated vs measured



*New limit of  $^{244}\text{Pu}$  on Earth points to rarity of heavy r-process nucleosynthesis*

A. Wallner, T. Faestermann, C. Feldstein, K. Knie, G. Korschinek, W. Kutschera, A. Ofan, M. Paul, F. Quinto, G. Rugel & P. Steier 2015, Nature Communications

**The continuous production of  $^{244}\text{Pu}$  in regular CCSNe ( $10^{-4}$ - $10^{-5}$  Msol each, in order to reproduce solar system abundances) would result in green band**

# Summary

*The r-process in astrophysical environments comes in at least two versions (weak-main/strong)??*

*Does the neutrino wind in core collapse SNe lead initially to proton-rich conditions (and vp-process) or also to a weak r-process (extending up to Eu)?*

*The main/strong r-process comes apparently in each event in solar proportions, but the events are rare. The site is not clearly identified, yet. Options include rotating core collapse events with jet ejection, neutron star mergers and accretion disks around black holes (either from mergers or massive star collapse).*

*Findings by Knie et al. (2004), Feige (2015), Ludwig (2015) with  $^{60}\text{Fe}$  detection from latest nearby supernova without corresponding  $^{244}\text{Pu}$  from a strong r-process (Wallner et al. 2015) give an additional indication that heavy r-process is not coming from regular supernovae but only from rare events!*

*Perform simulatutions with the best available microphysics and in order to identify the signatures in chemical evolution for these different contributions!*

*(only low metallicity r-observations of U and Th seem to show variations in their contributions – sign of different r-process strength in MHD-jets, opposite to robust abundances in mergers?)*

**Hotokezaka, Piran, Paul 2015, Thielemann, F.-K.,  
December Issue 2015, Nature Physics**

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