Stellar Origins of the Heaviest Elements

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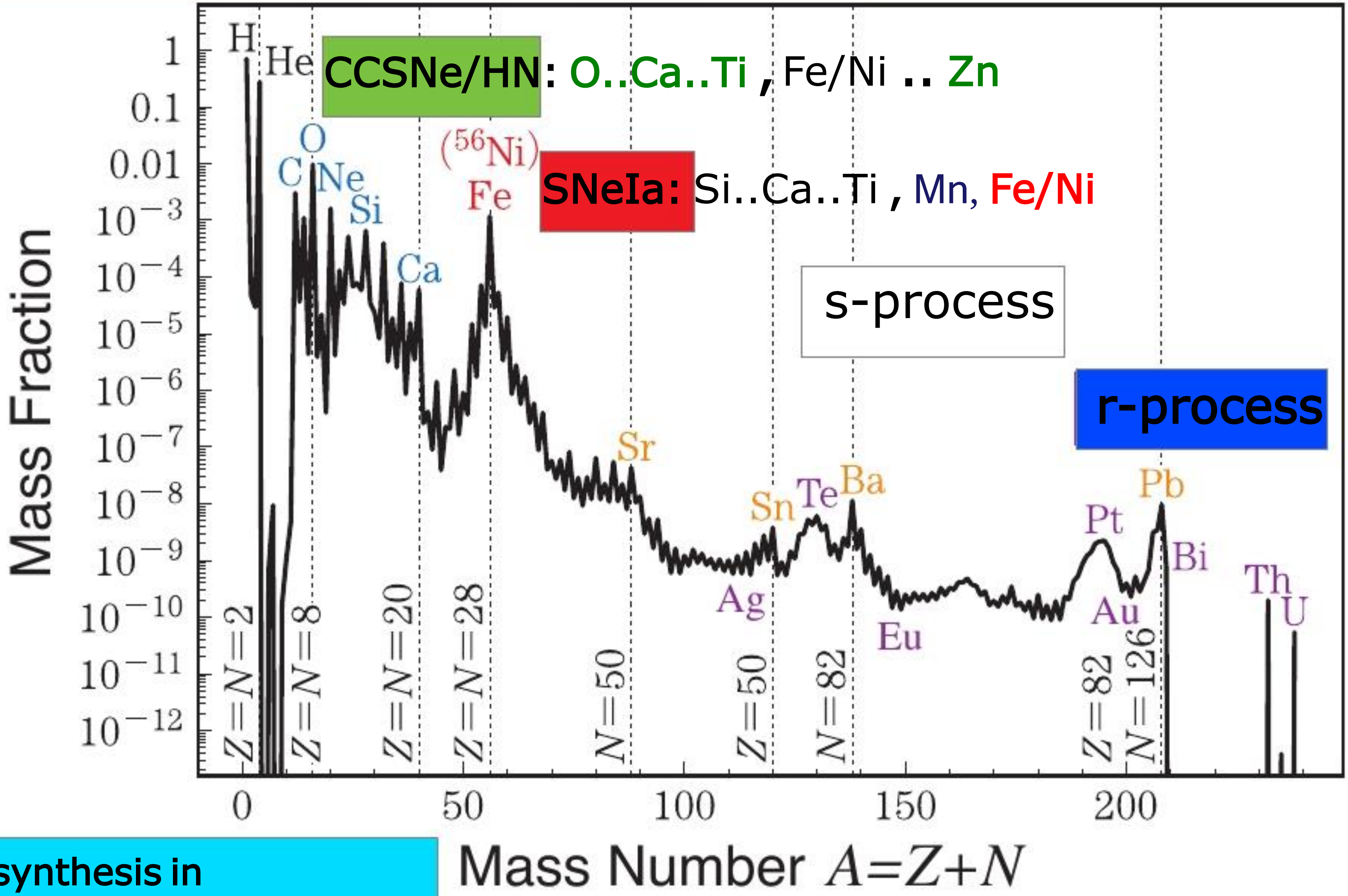
European Research Council
Established by the European Commission

Cost Action
ChETEC

BBN makes ^{1,2}H, ^{3,4}He, ^{7}Li



CCSNe/HN: O..Ca..Ti , Fe/Ni .. Zn

SNeIa: Si..Ca..Ti , Mn, Fe/Ni

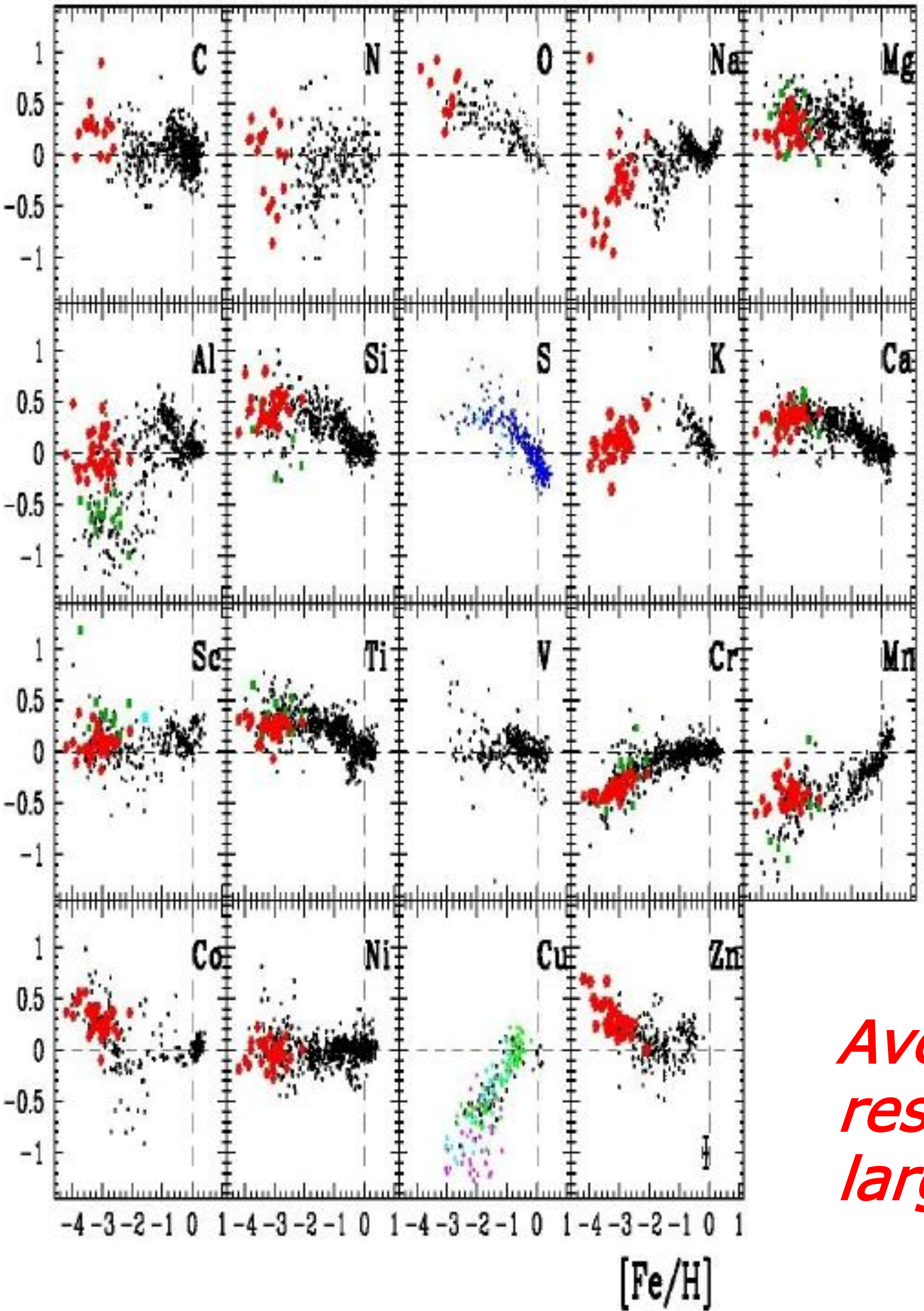
s-process

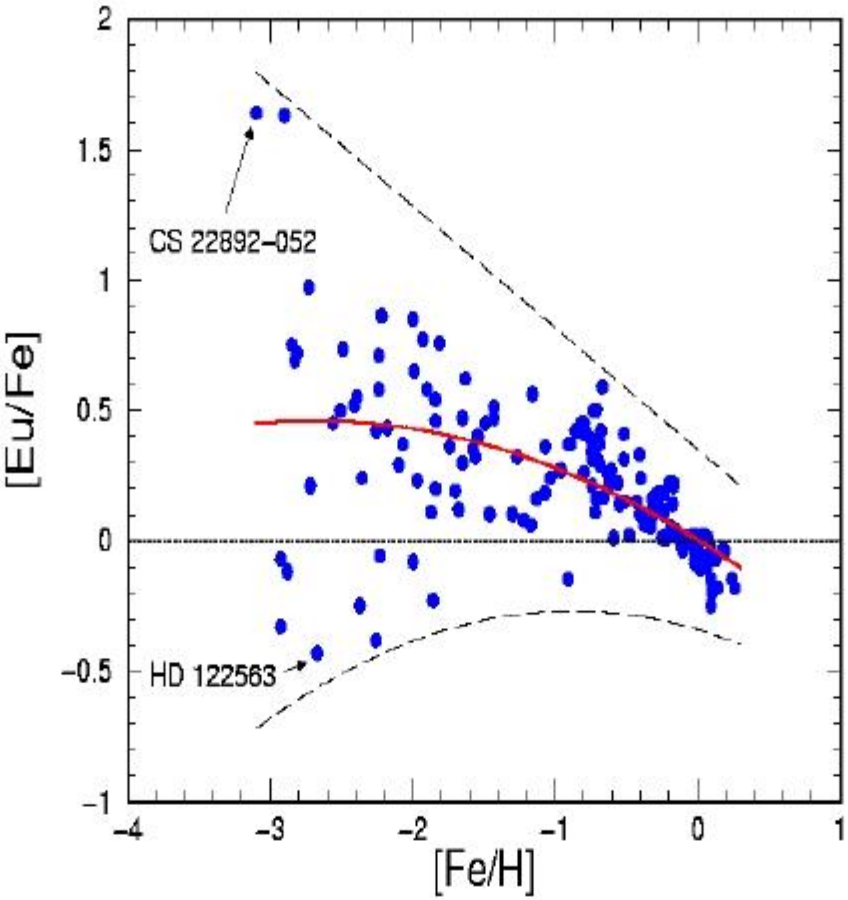
r-process

Nucleosynthesis in massive stars, their explosive endpoints, and explosions in binary stellar systems

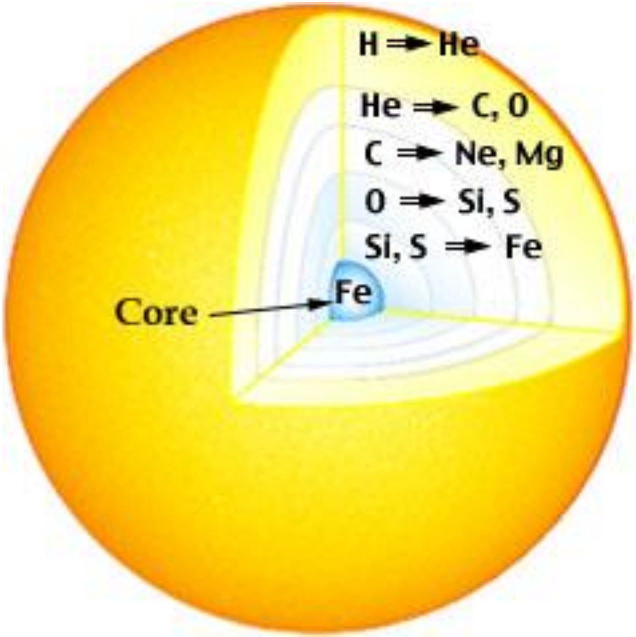
adopted from
C. Kobayashi

How do we understand: low metallicity stars … galactic evolution?





Average r-process (Eu) behavior resembles CCSN contribution, but large scatter at low metallicities!!

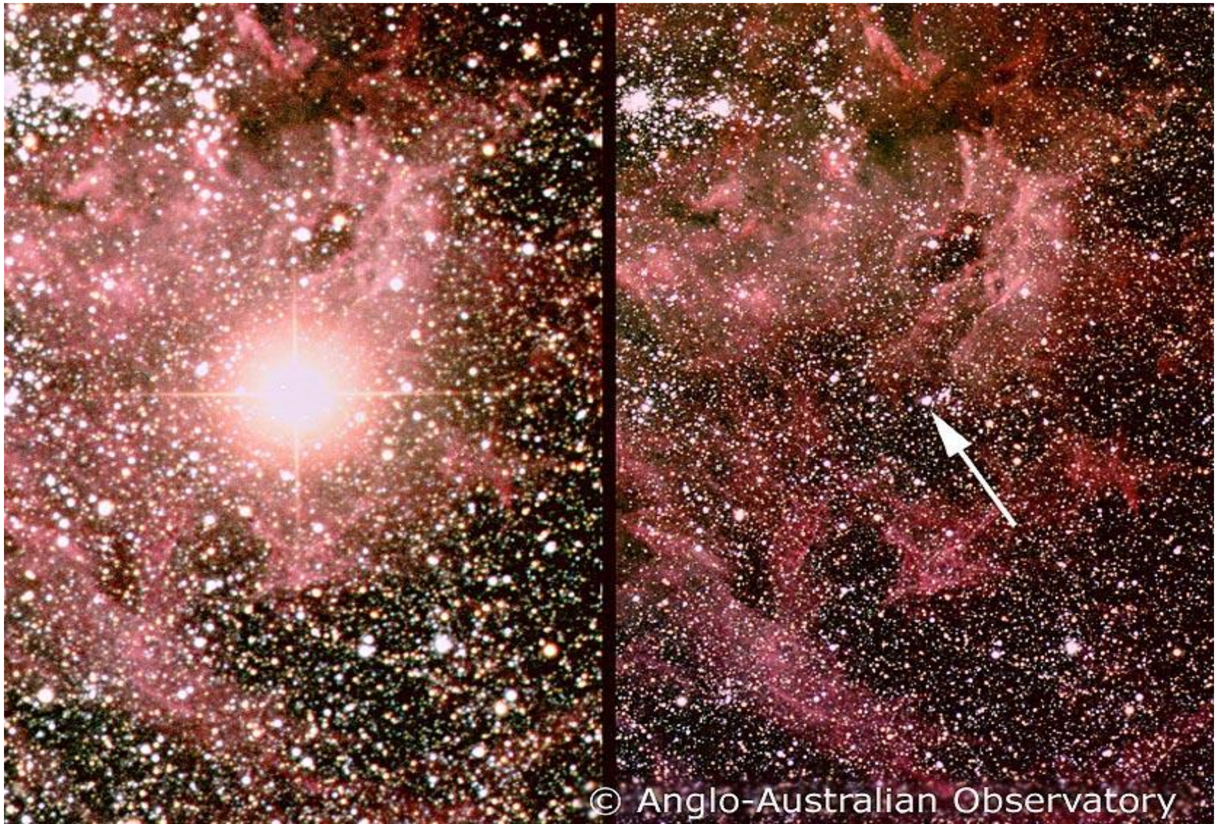


massive stars (> 8 Msol) pass through all burning stages up to a central Fe-core, which experiences subsequently a collapse to nuclear densities -> supernova, neutron star, black hole??

low/intermediate mass stars pass only through hydrogen and helium burning, loose their outer shells in a wind (planetary nebula) and leave a central white dwarf (supported by the pressure of a degenerate electron gas.

WD + PN

SN 1987A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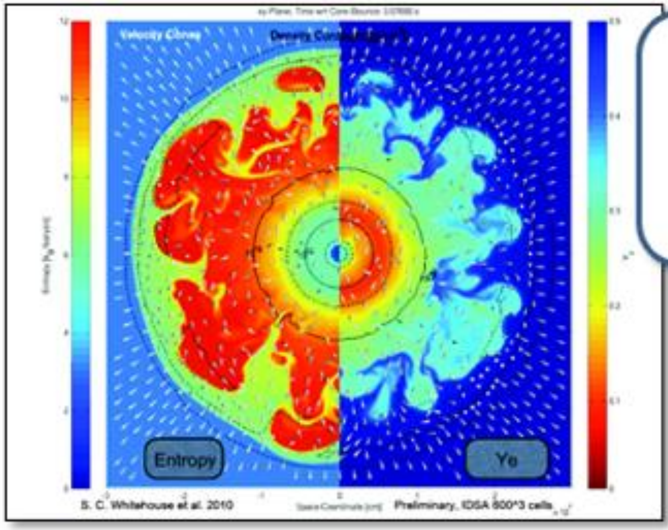
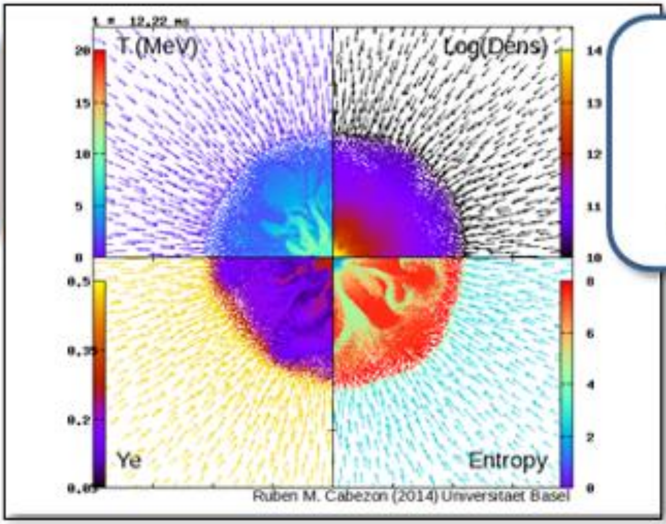
Basel activities with IDSA (Isotropic Diffuions Source Approximation for Neutrino Transport) in Multi-D



Elephant

3D IDSA
Cartesian mesh
1D GR potential

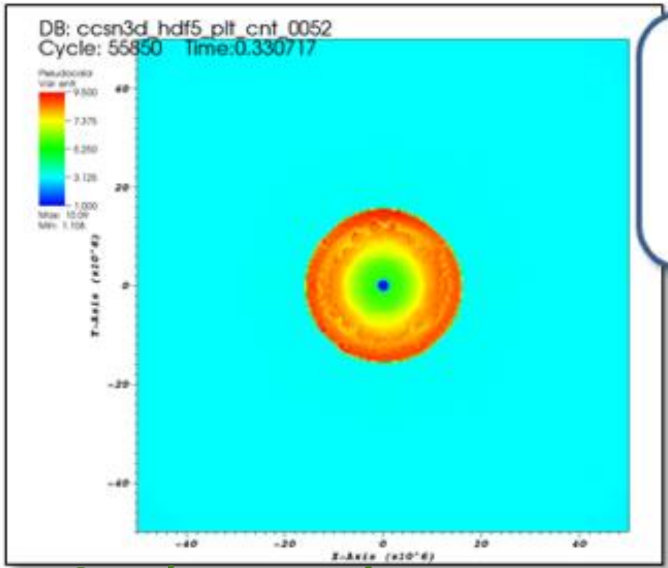
M. Liebendörfer
S. C. Whitehouse
R. Käppeli



SPHYNX

ASL
SPH
3D Newtonian

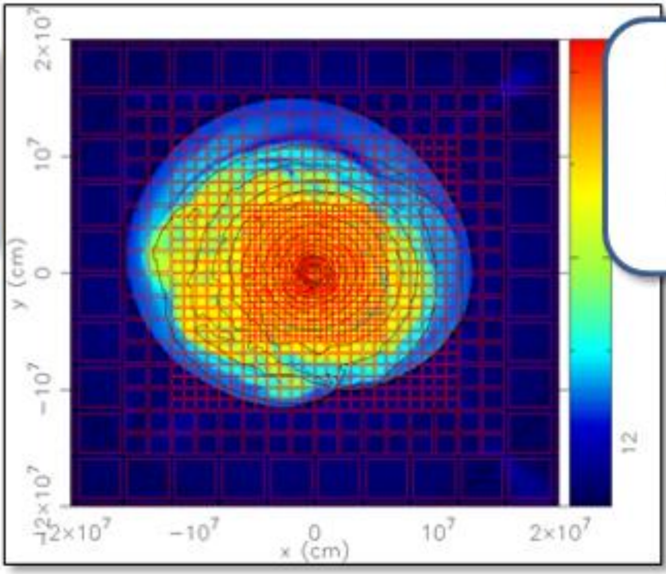
R. M. Cabezón



FLASH

3D IDSA
AMR
3D Newtonian

K.-C. Pan



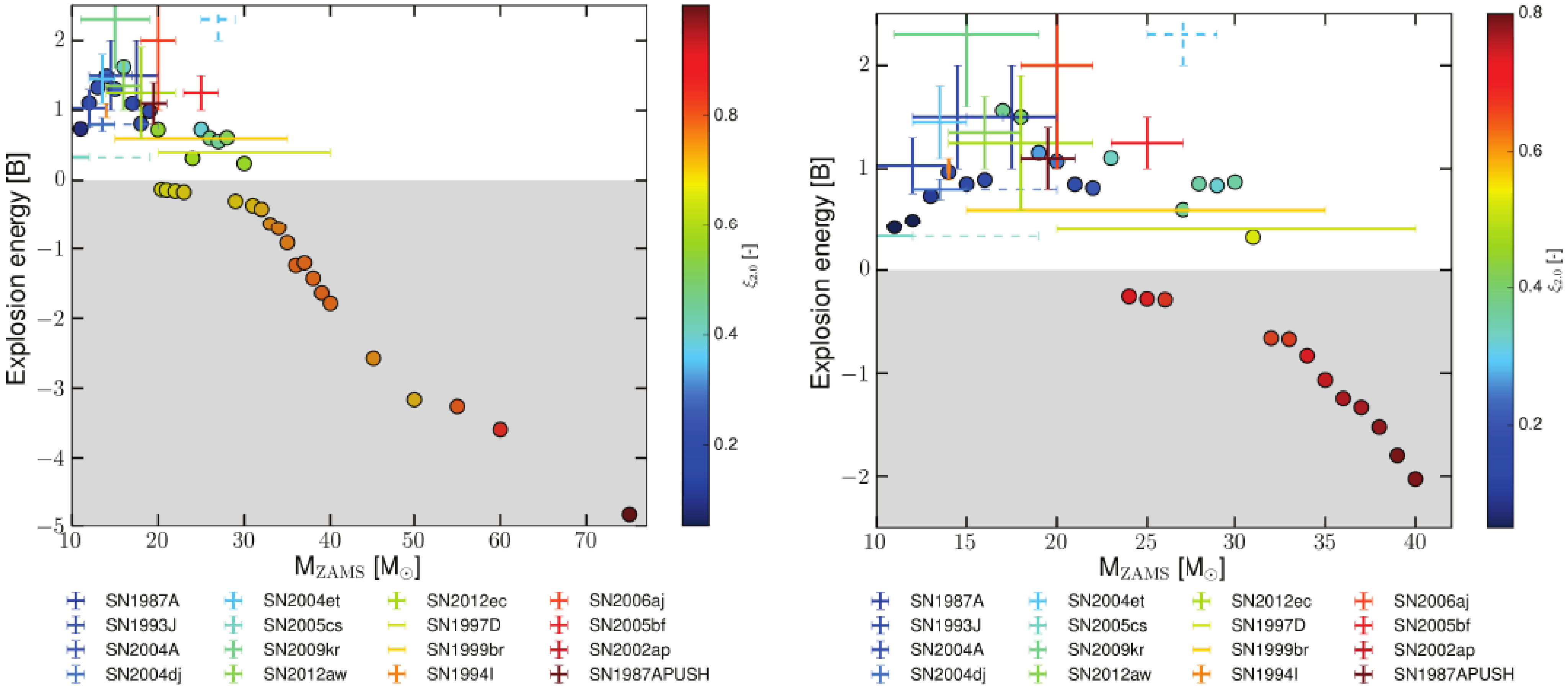
fGR_M1

M1
Nested meshes
3D GR

T. Kuroda

A code comparison paper coming out soon!!!

Results of the PUSH Approach:
Black hole formation beyond about 25-30 Msol



For 2 sets of stellar progenitor models (Woosley et al. 2002, Woosler & Heger 2007),
Results clearly depend on the compactness of the central stellar core!!!!!!

What determines the neutron/proton or proton/nucleon=Ye ratio?

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

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

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

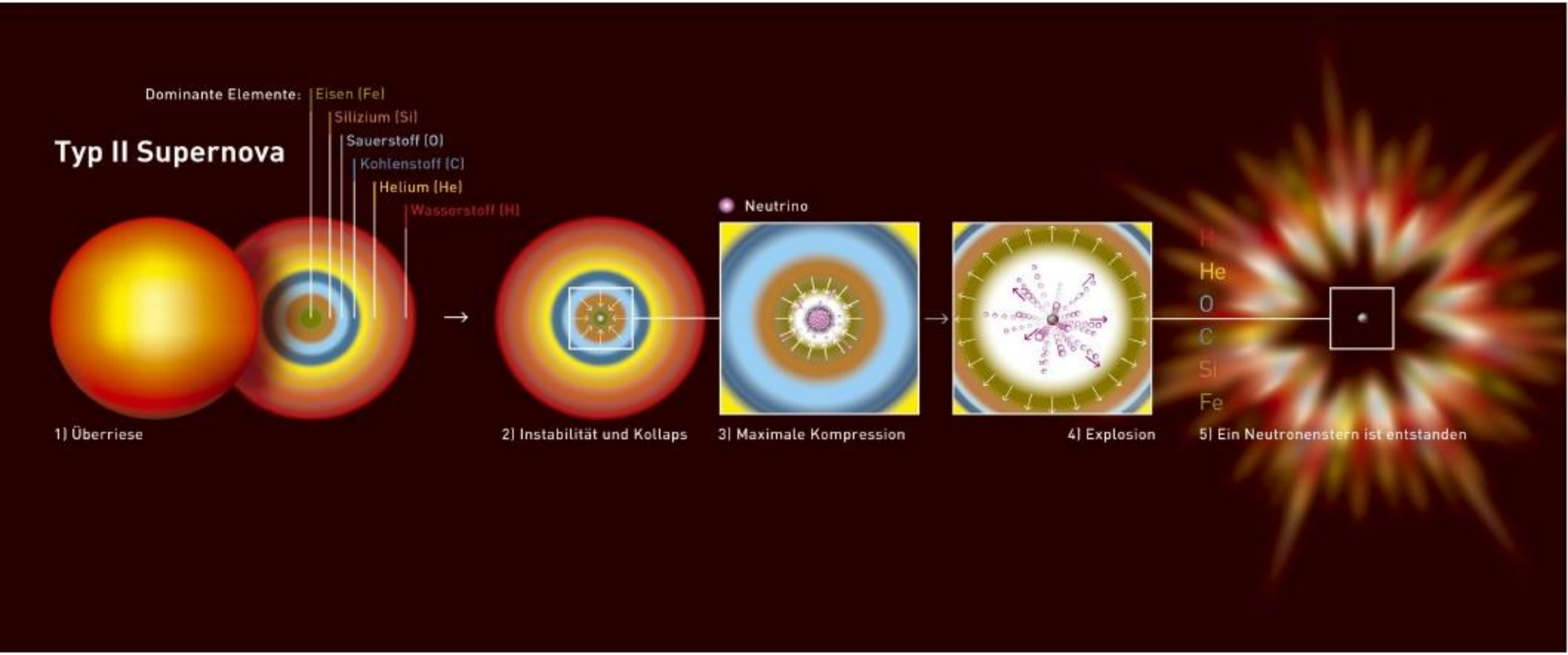
- high density / low temperature → high E_F for electrons → e-captures dominate → n-rich composition
- if el.-degeneracy lifted for high T → ν_e-capture dominates → due to n-p mass difference, p-rich composition

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 $E_{av,\bar{\nu}} - E_{av,\nu} > 4(m_n - m_p)$ lead to $Y_e < 0.5$!

Otherwise the interaction with neutrinos leads to proton-rich conditions. The latter favors improvements in the Fe-group composition Sc, Ti, Co, including the production of ^{64}Ge (→ ^{64}Zn!), and the νp-process, which can produce nuclei up to Sr, Y, Zr and Mo. (Fröhlich, Pruet, Wanajo ..Eichler, 2005,2006..).

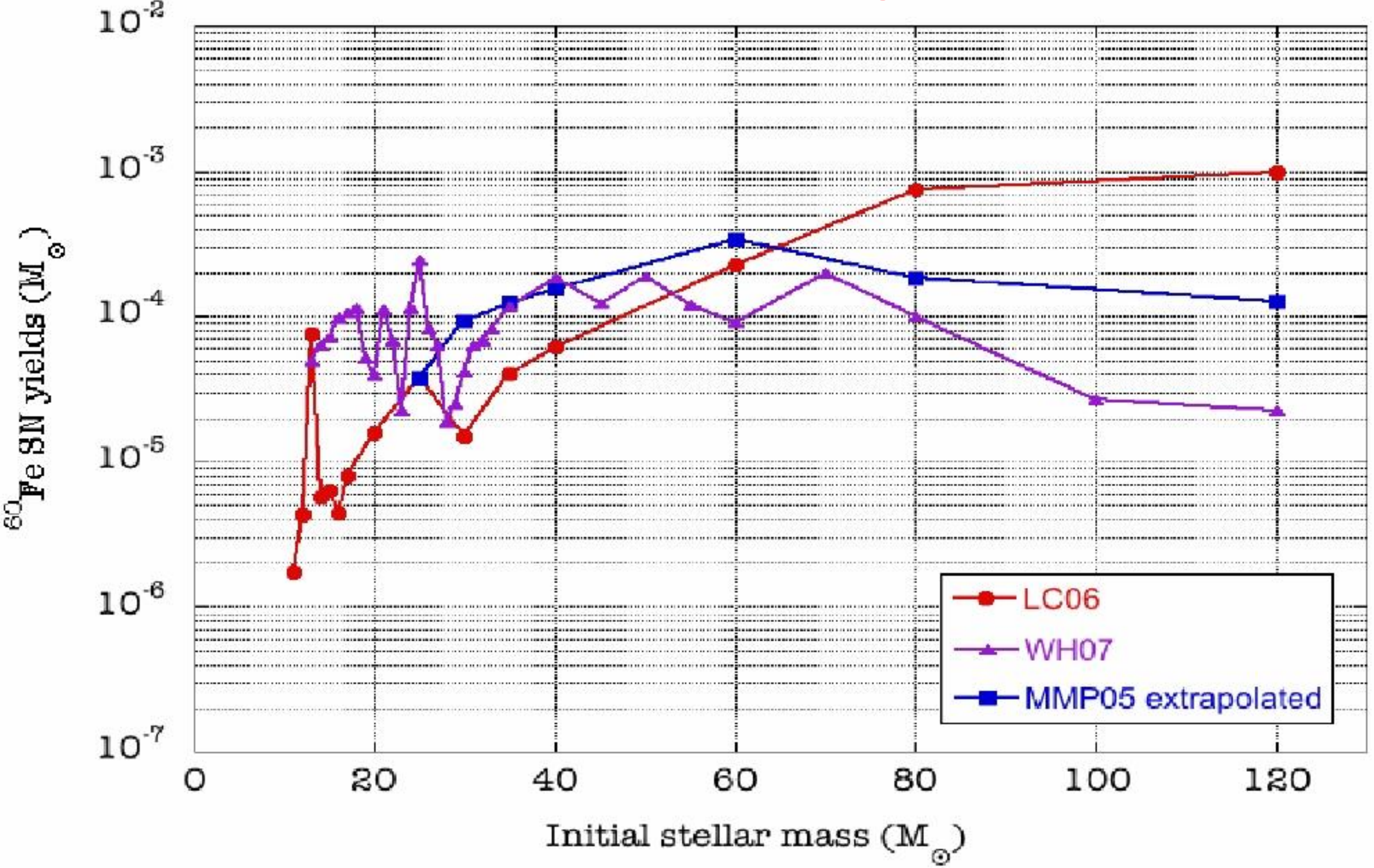
Thus, (at least) no strong r-process in regular CCSNe!!

Core-Collapse Supernovae and Neutron Stars as End Stages of Massive Stars



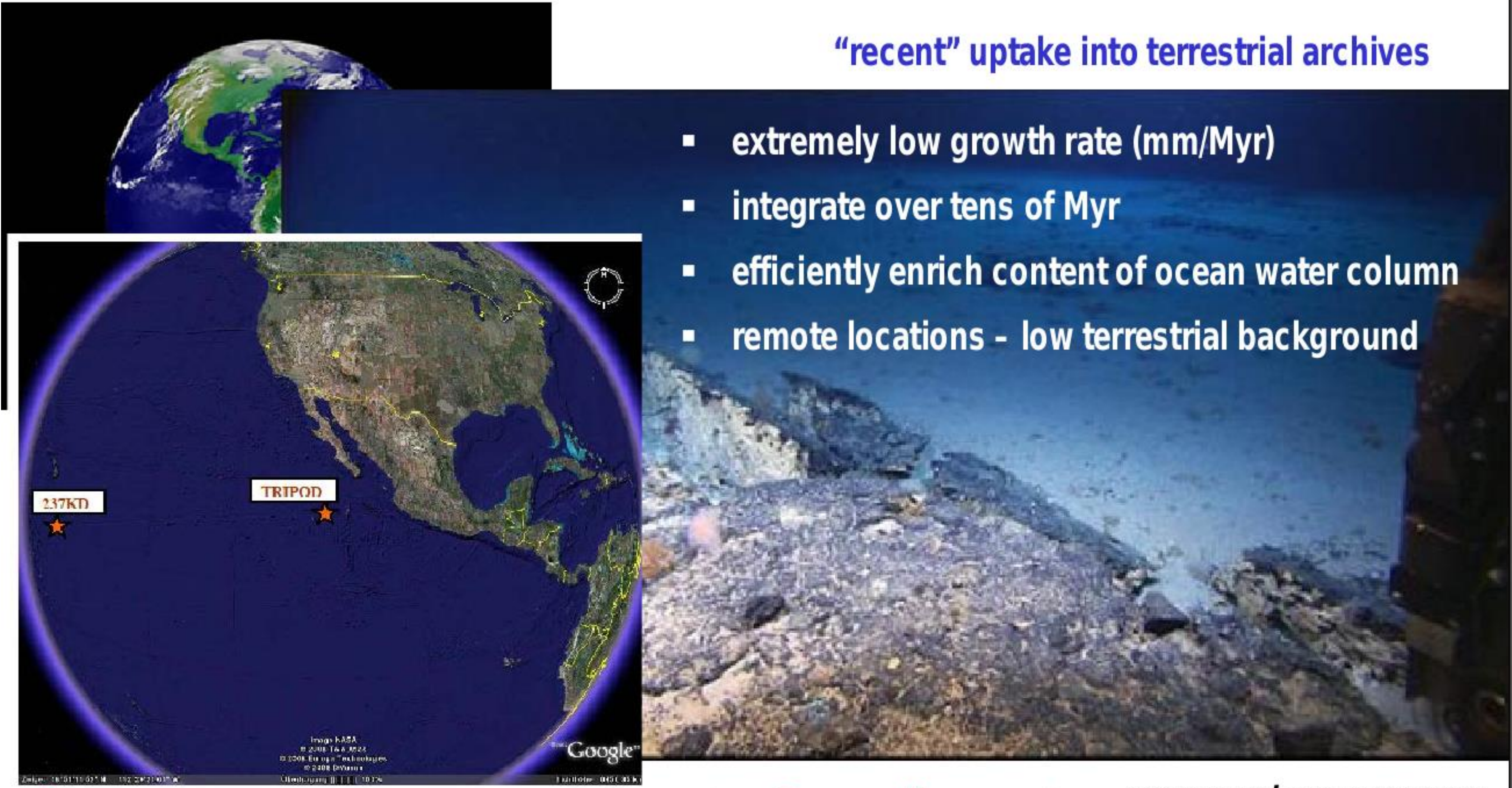
Main products: O,Ne,Mg,Si,S,Ar,CaTi and some Fe/Ni
How about Sc,V,Cr,Zn, heavier nuclei (.. Sr, Y, Zr),
and the r-process ????? not in regular CCSNe!!

^{60}Fe, a byproduct of massive stars, stemming from hydrostatic burning



^{60}Fe (half-life 2.6 10^6y) 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



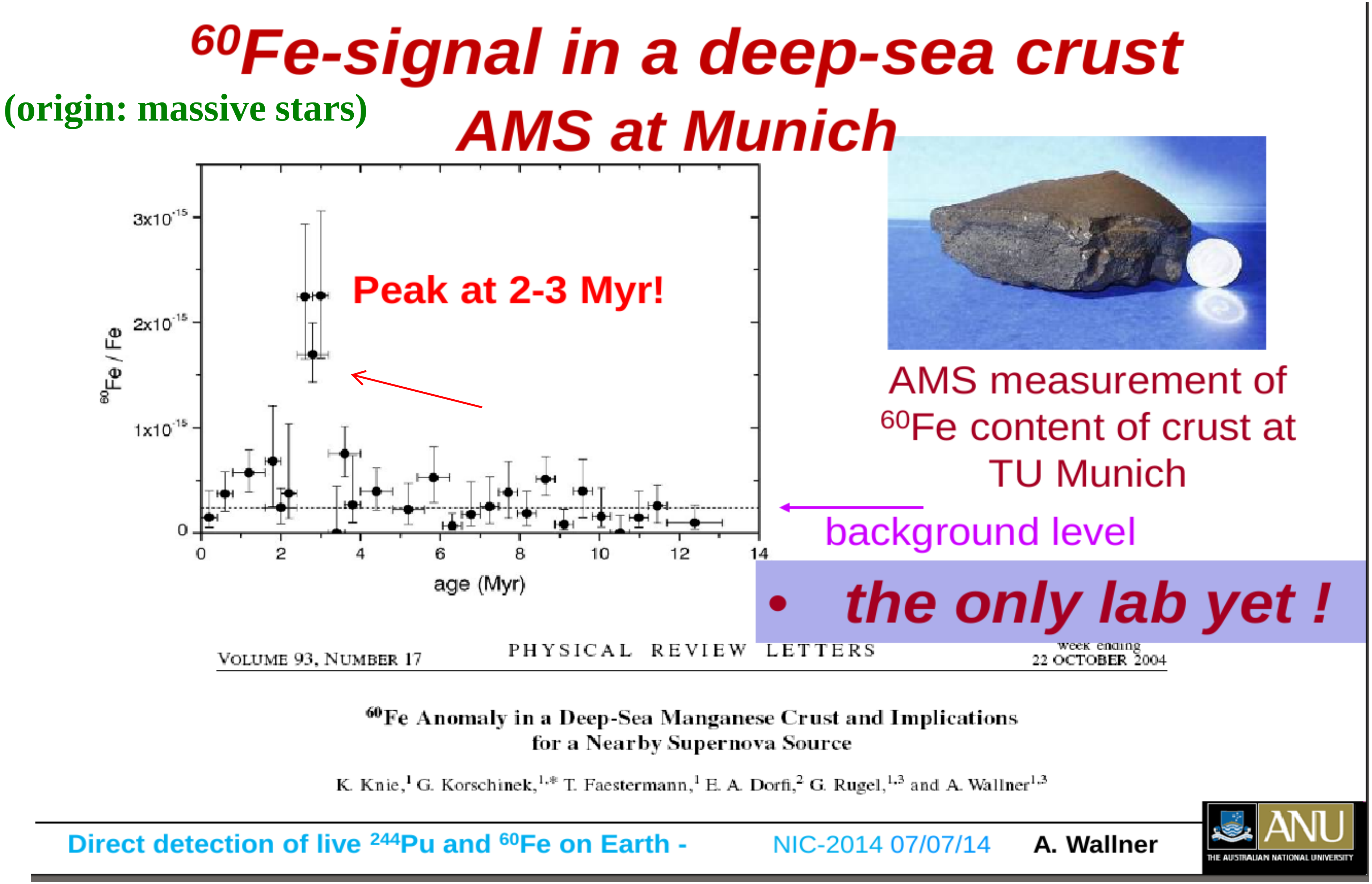
"recent" uptake into terrestrial archives

- 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 mangenese crusts & sediments

oceanexplorer.noaa.gov

from A. Wallner



^{60}Fe-signal in a deep-sea crust

(origin: massive stars)

AMS at Munich

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

- *the only lab yet !*

VOLUME 93, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 22 OCTOBER 2004

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

K. Knie,[1] G. Korschinek,[1,*] T. Faestermann,[1] E. A. Dorfi,[2] G. Rugel,[1,3] and A. Wallner[1,3]

Direct detection of live ^{244}Pu and ^{60}Fe on Earth - NIC-2014 07/07/14 **A. Wallner**

ANU THE AUSTRALIAN NATIONAL UNIVERSITY

Witnessing the last CCSNe near the solar system, see also recent theses by J. Feige (Vienna) and P. Ludwig (Munich)

Firestone (2014) finds a higher supernova rate from radiocarbon (^{14}C, cosmic ray induced) within local 300pc, but dust particles would be able to overcome solar wind only within 150pc and no dust particles from >100pc should arrive on earth due to delay travel time

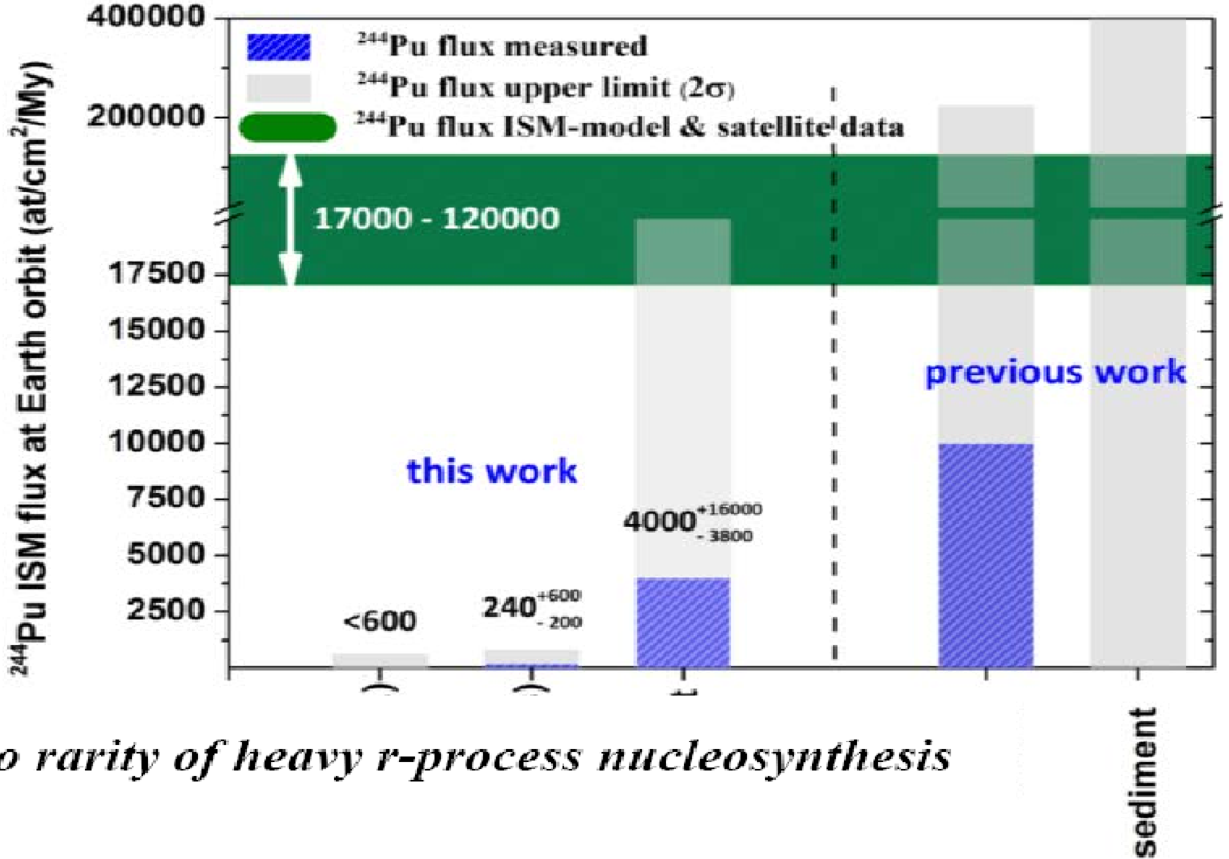
^{244}Pu, half-life 81 My

Status:

100:1 estimated vs measured

^{244}Pu in terrestrial crust:

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



New limit of ^{244}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

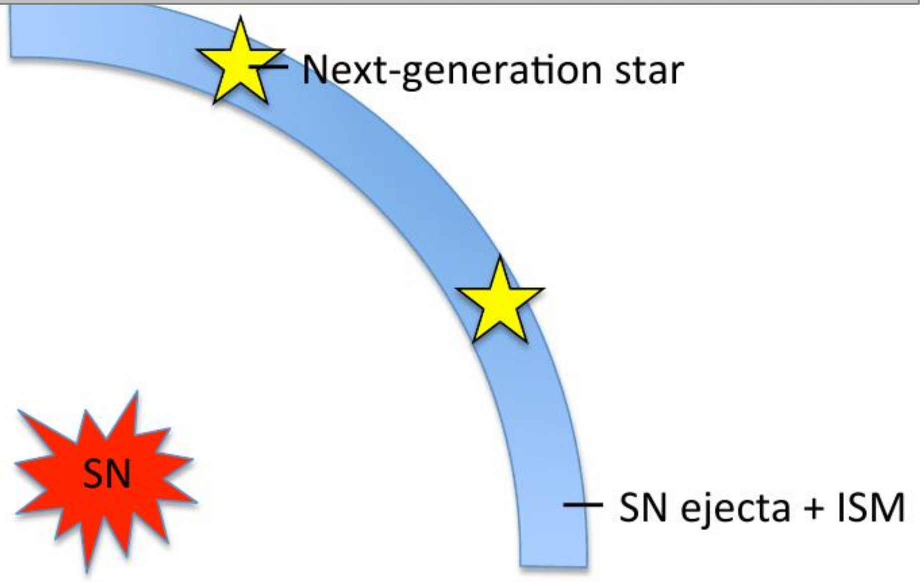
The continuous production of ^{244}Pu in regular CCSNe (10^{-4}-10^{-5} Msol each of r-process nuclei, in order to reproduce solar system abundances) would result in green band → no recent (regular) supernova contribution. Rare events with enhanced ejecta could also explain solar abundances, but the last event occurred in a more distant past and Pu has decayed (e.g. Hotokezaka+ 2015)

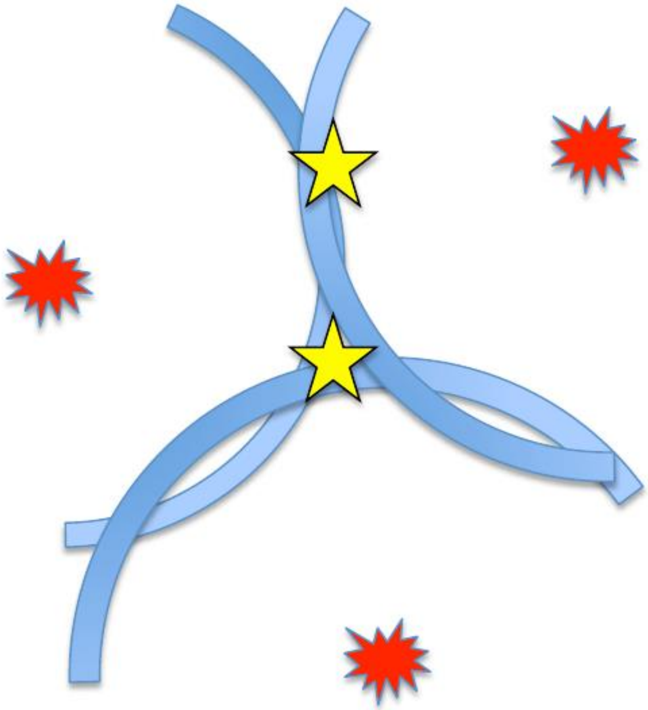
Stellar Abundances

Inhomogeneous „chemical evolution“ models do not assume immediate mixing of ejecta with surrounding interstellar medium, pollute only about 5 10^4 Msol (Sedov-Taylor blast wave).
After many events an averaging of ejecta composition is attained.

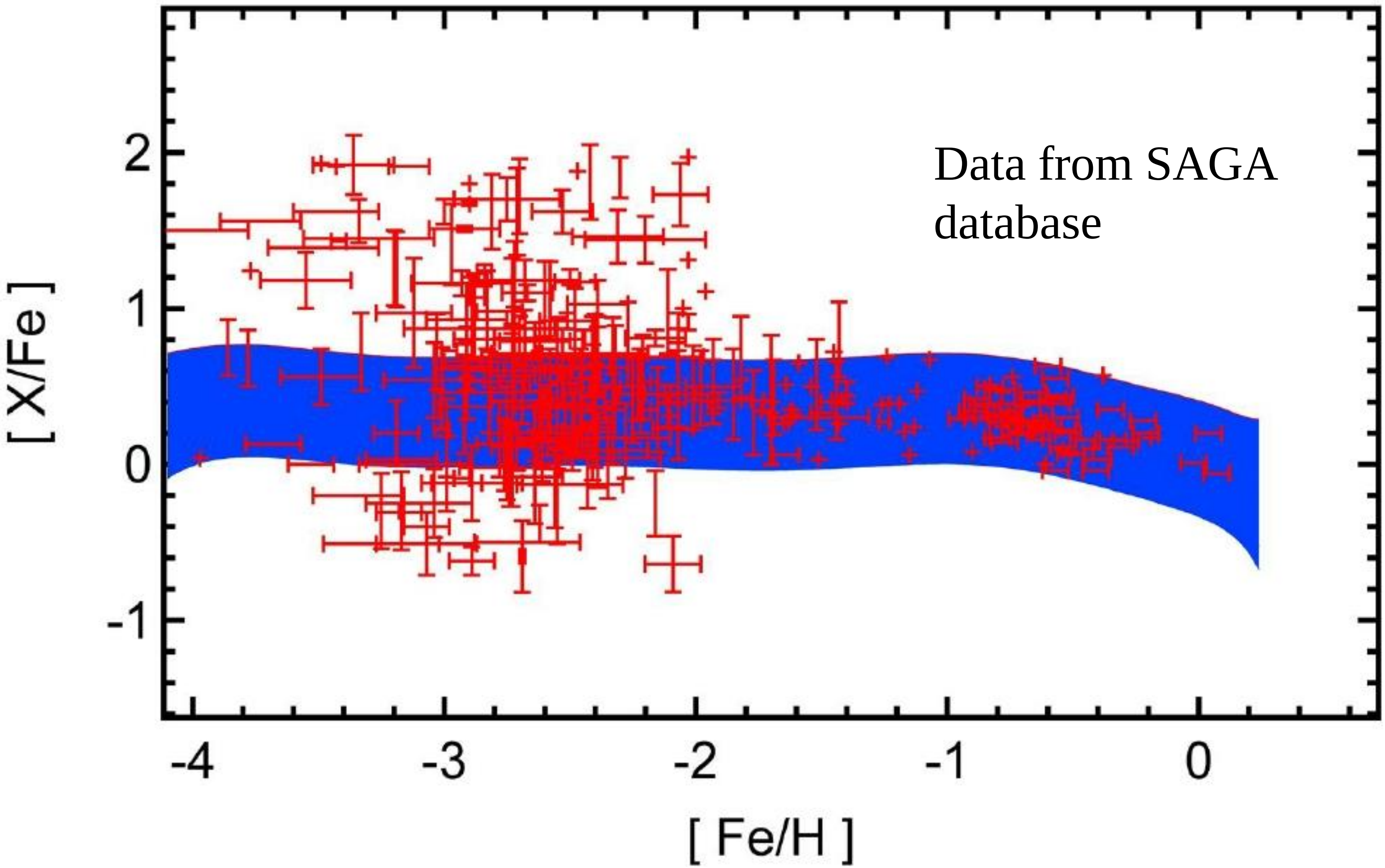
In the later phase

Contribution from multiple CCSNe
(unknown → average weighted by IMF)





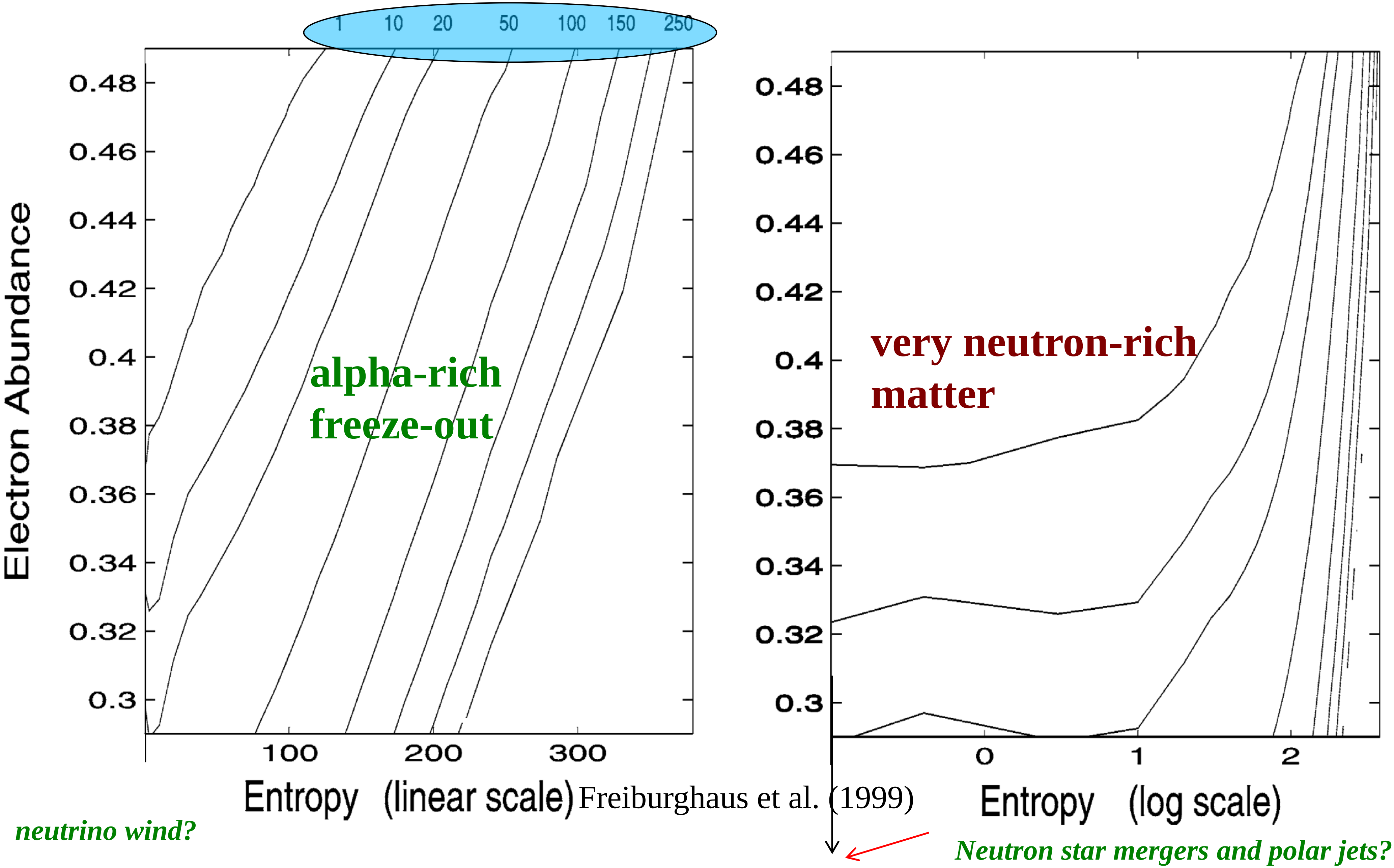
Rare events lead initially to large scatter before an average is attained!



Blue band: Mg/Fe observations (95%), red crosses: individual Eu/Fe obs.
Further support: ^{60}Fe and ^{244}Pu measurements in deep sea sediments!
What are these possible r-events??

n/seed ratios as function of S and Y_e

Two options for a successful r-process



alpha-rich freeze-out

very neutron-rich matter

Freiburghaus et al. (1999)

neutrino wind?

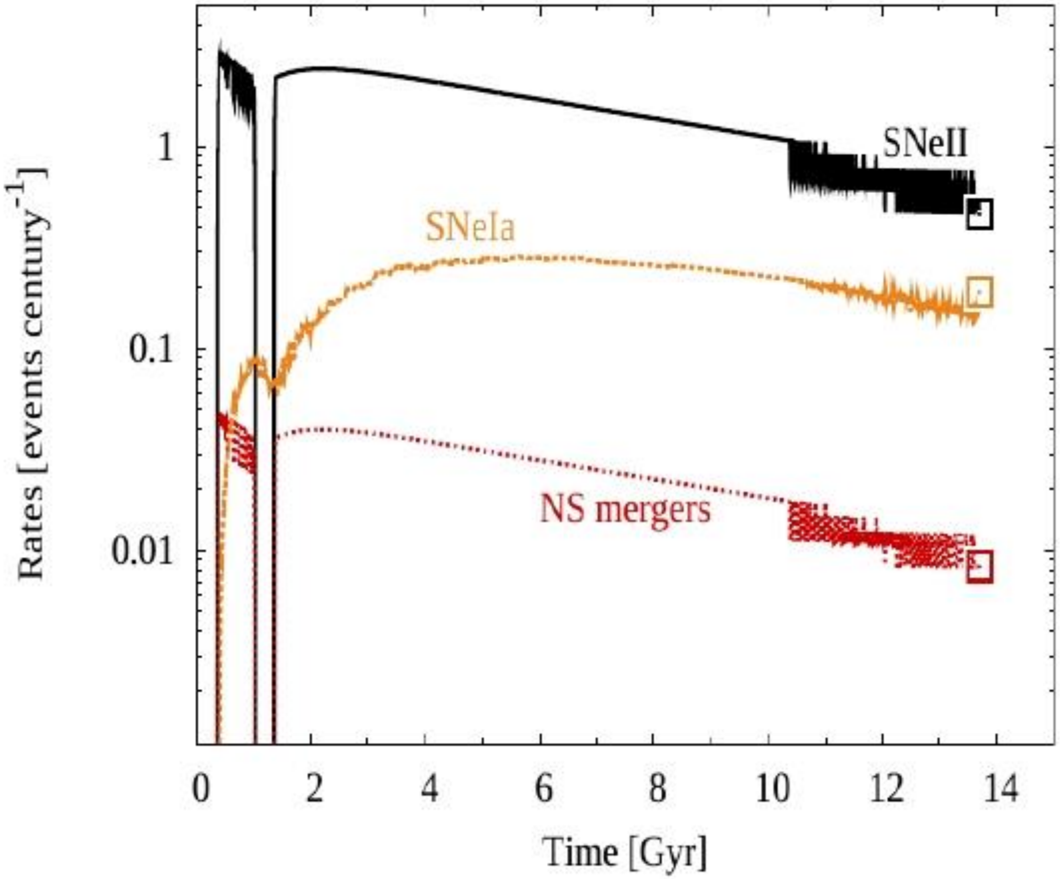
Neutron star mergers and polar jets?

The essential quantity for a successful r-process to occur is to have an n/seed ratio so that A_{seed}+n/seed=$A_{actinides}$!

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

-> this would be one option to explain such findings



This would relate to about 1 NS merger per 100 supernovae, other population synthesis studies result in 1 NS merger per 1000 supernovae (Chruslinska+2016)

Gravitational Wave Signal

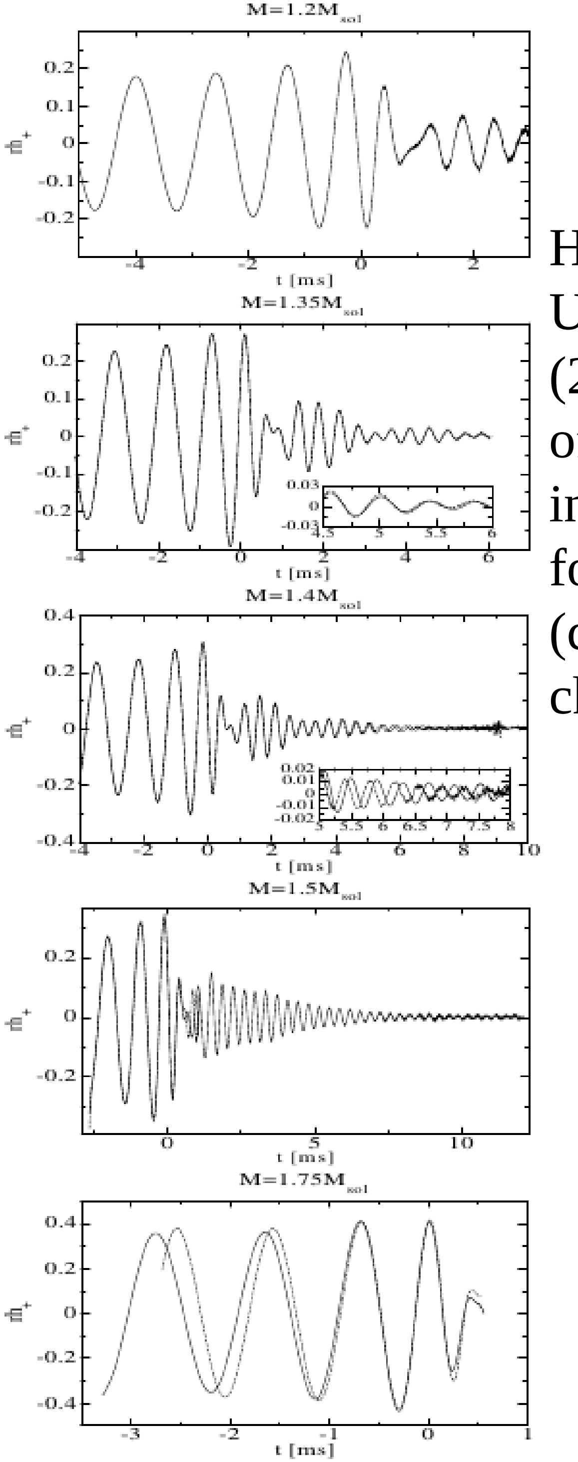


Figure 6. Gravitational waveforms of all models sorted according to their initial mass. The origin of the time axis has been shifted to the GW luminosity maximum. Solid lines correspond to hadronic models, dashed lines to hybrid models.

Here predictions by Oechslin, Uryu, Poghosian, Thielemann (2004), showing (a) the increase of the frequency during the inspiral, (b) lower frequencies for more massive binaries, and (c) small variations due to changes in the equation of state.

Notice: there is also a signal after the merger!

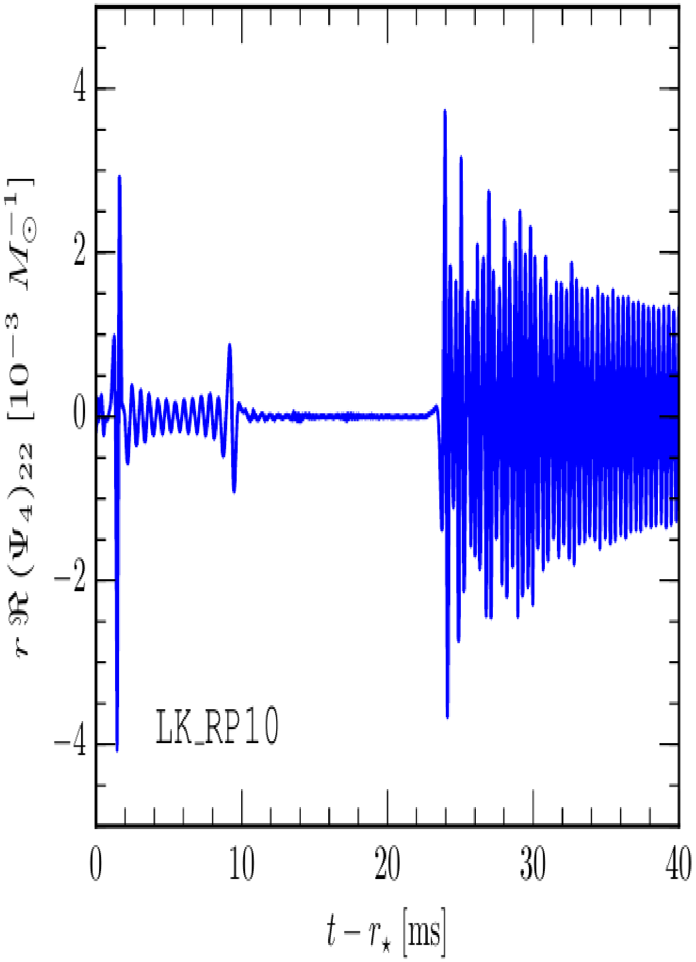
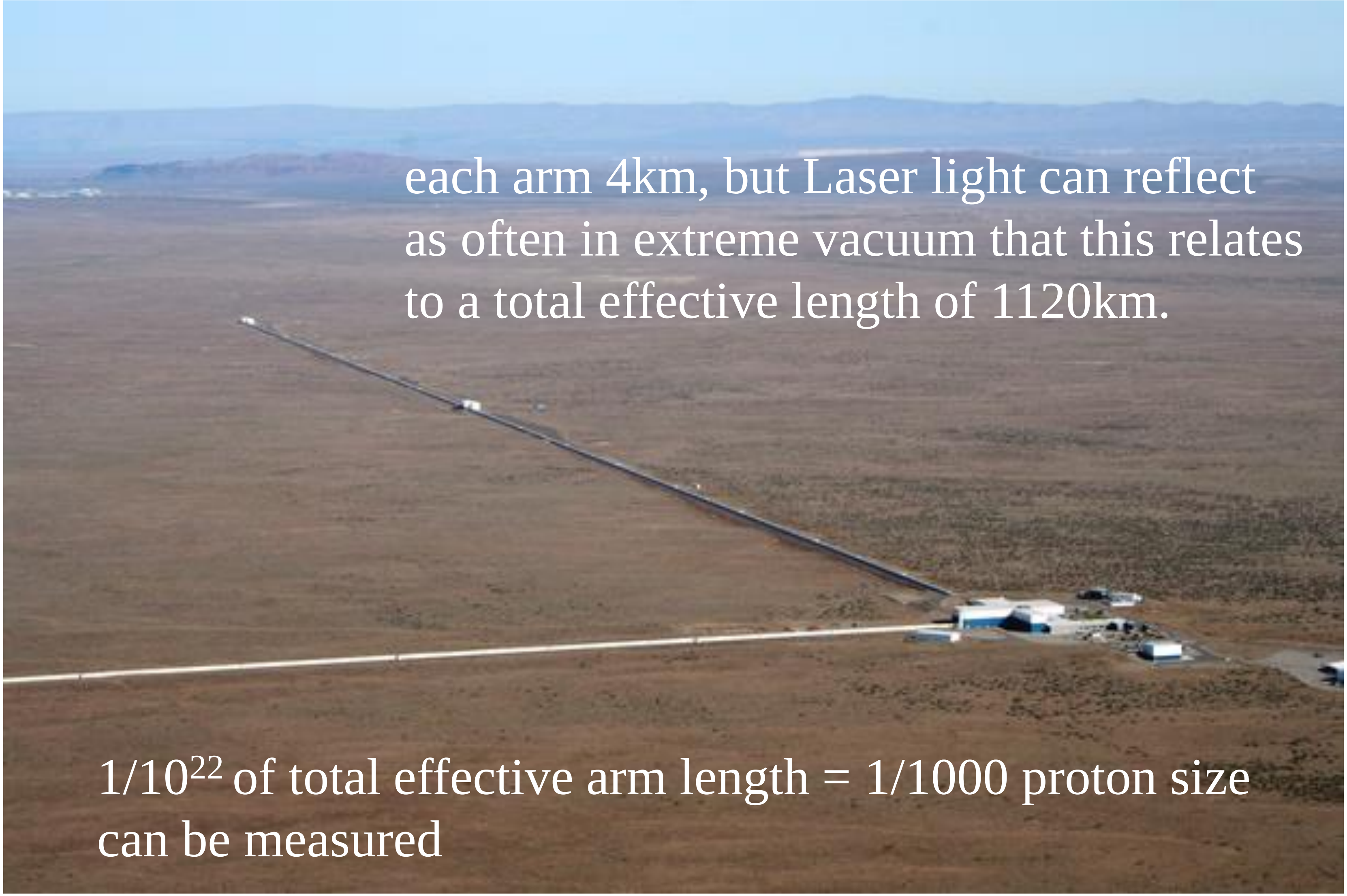


Figure 2. Real part of the $\ell = 2$, $m = 2$ spin-weighted spherical harmonics component of the Weyl scalar Ψ_4 for the LK_RP10, extracted at $r_\star = 400\ M_\odot \simeq 590$ km. The curvature GW signal shows a burst after the first encounter that excites violent oscillations in the two NSs. These oscillations are then suppressed by tidal interactions during the second encounter. The GW signal turns on again at merger.

More exotic things can happen in excentric orbits, leading to several collisions before the final merger (Radice 2016)

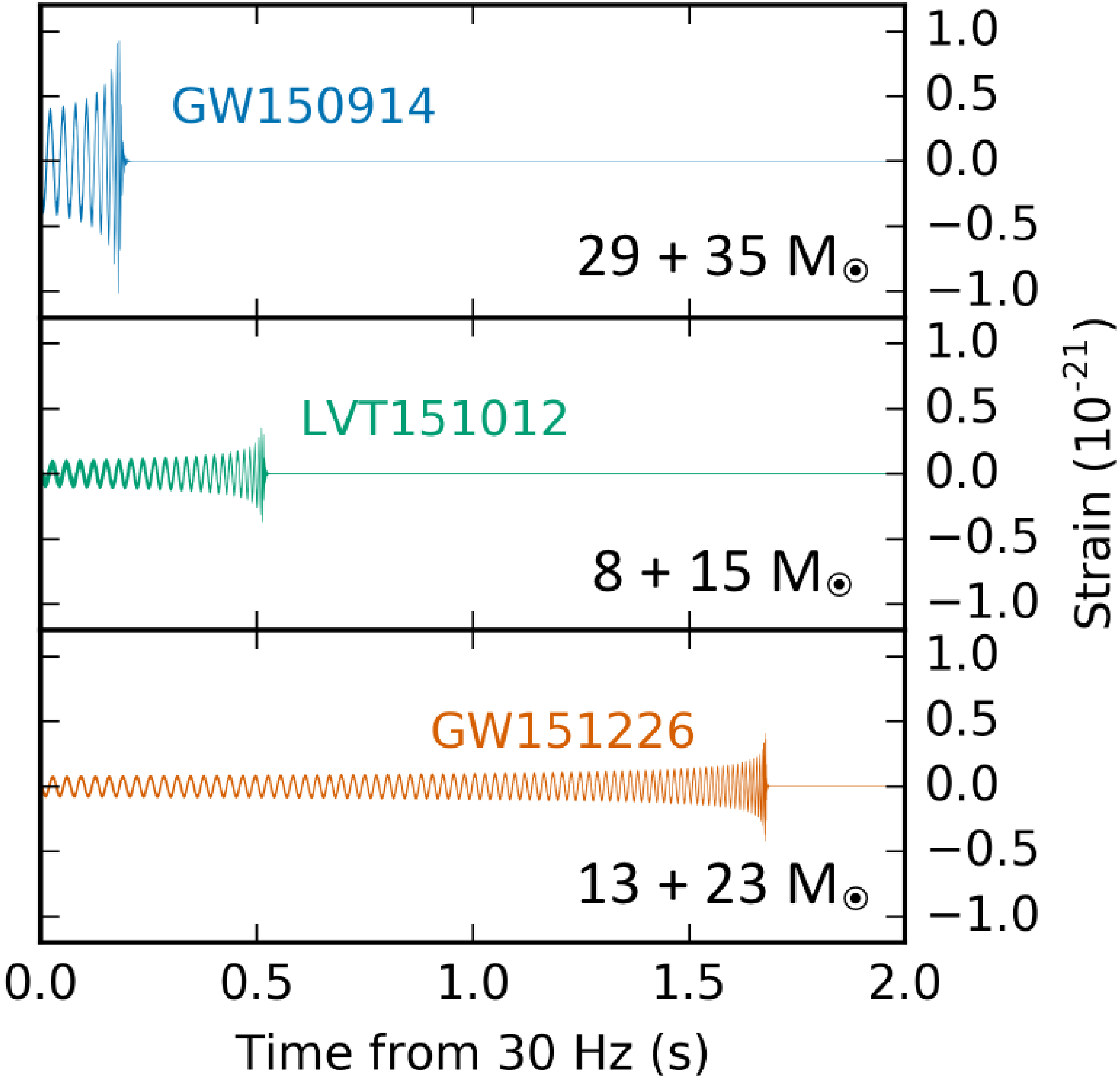
LIGO Hanford Detektor



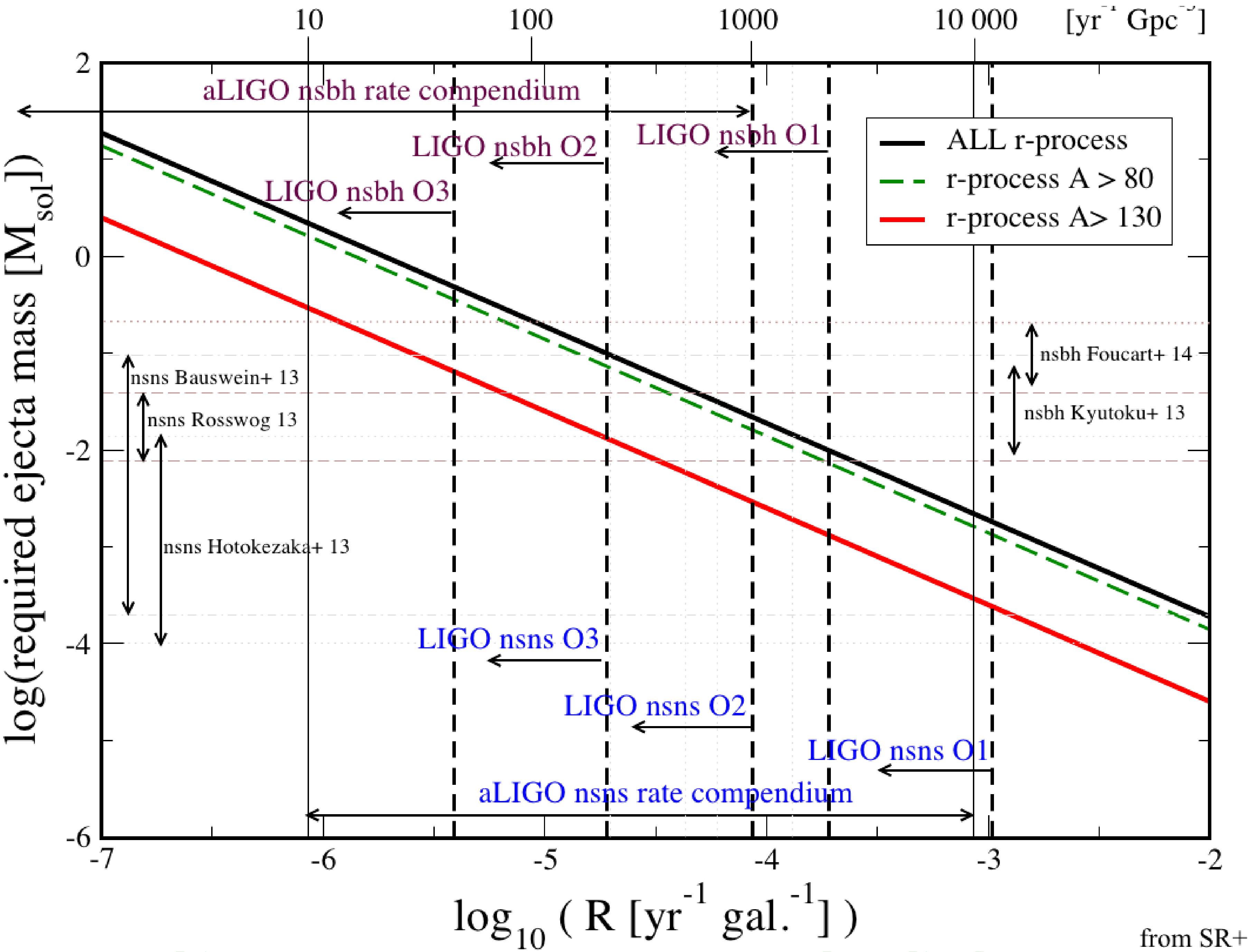
each arm 4km, but Laser light can reflect as often in extreme vacuum that this relates to a total effective length of 1120km.

$1/10^{22}$ of total effective arm length = 1/1000 proton size can be measured

Different from LIGO Black Hole Mergers



Necessary event rate / production for final solar r-process abundances: This applies to any type of rare r-event, whether MR-superova or NS-merger



from SR++ (2017)

Matteucchi+ 2014: 1 NSM / 100 CCSNe – Chruslinska+ 2016 1 / 1000

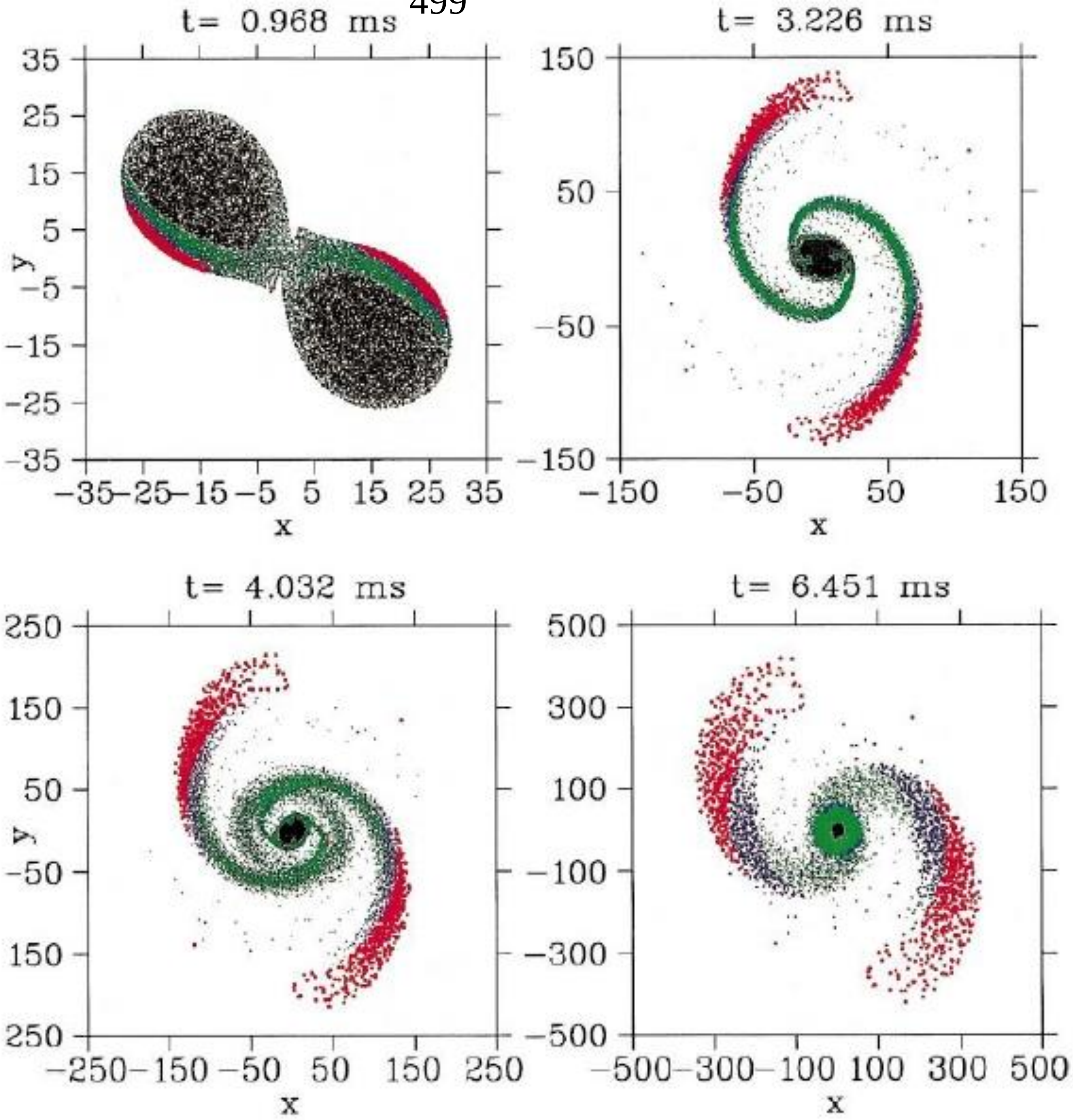
A bit of (selected?) history on NS-mergers

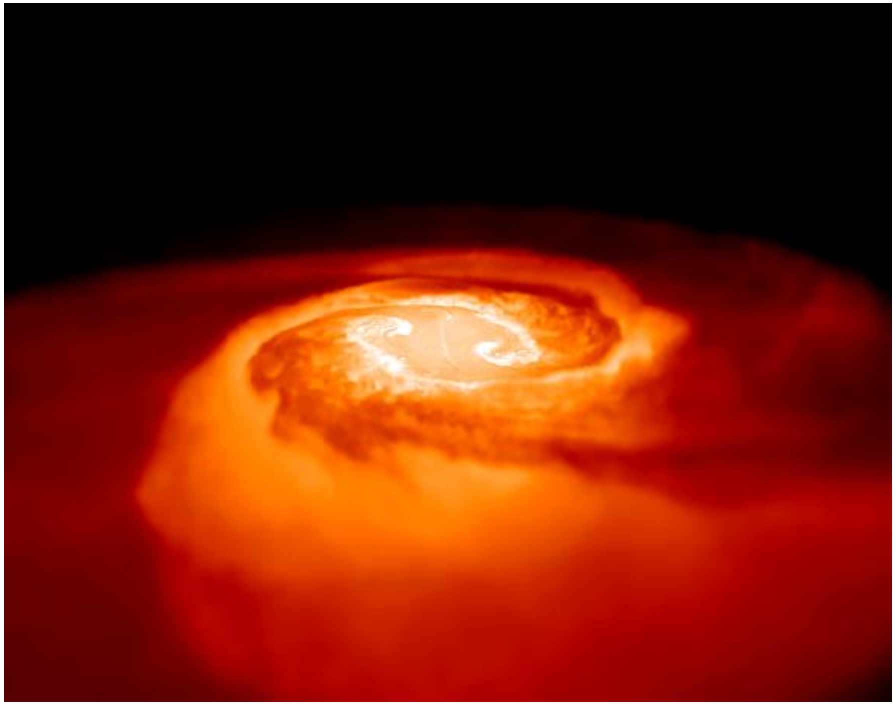
- Lattimer & Schramm (1974/76) suggested neutron star – BH or implicitely als neutron star mergers as r-process sites
- Symbalisty & Schramm (1982) explicitely mentioned neutron star mergers as r-process sites
- Nucleosynthesis from the decompression of initially cold neutron star matter (Meyer & Schramm 1988, general decompression consideration)
- Nucleosynthesis, neutrino bursts & gamma-rays from coalescing neutron stars (Eichler, Livio, Piran, Schramm 1989, setting up the scheme)
- Merging neutron stars. 1. Initial results for coalescence of noncorotating systems (Davis, Benz, Piran, Thielemann 1994, estimate: obout $10^{-2}M_{\odot}$ of ejecta)
- Mass ejection in neutron star mergers (Rosswog, Liebendörfer, Thielemann, Davies, Benz, Piran 1999, $4\times10^{-3} – 4\times10^{-2}$ $M_{\odot}$ get unbound in realistic simulations)
- r-Process in Neutron Star Mergers (Freiburghaus, Rosswog, Thielemann 1999, **first detailed abundance distribution prediction**)

Early SPH simulations

„Classical“ r -process site: NSMs and their «dynamic ejecta»

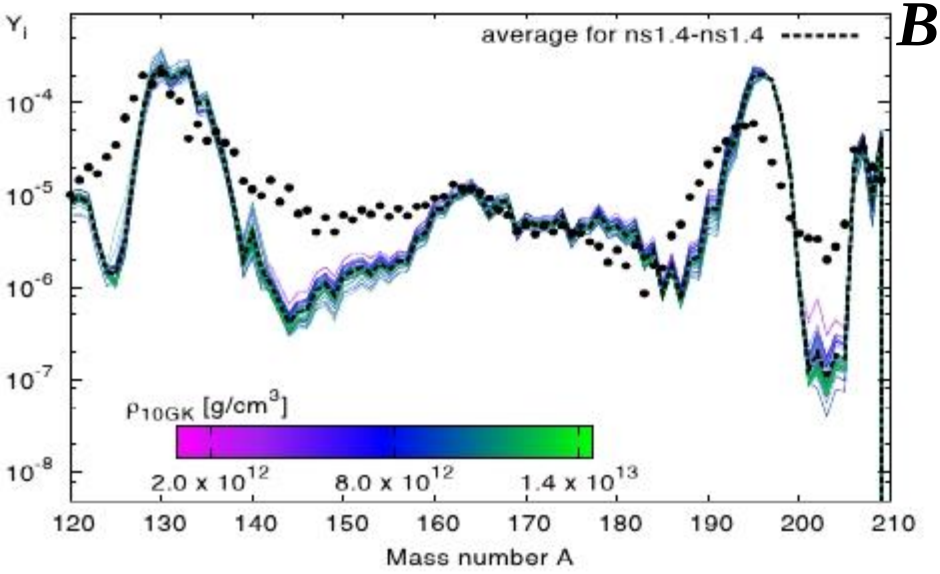
Rosswog et al.
A&A 341 (1999)
499





Rosswog et al. 2014

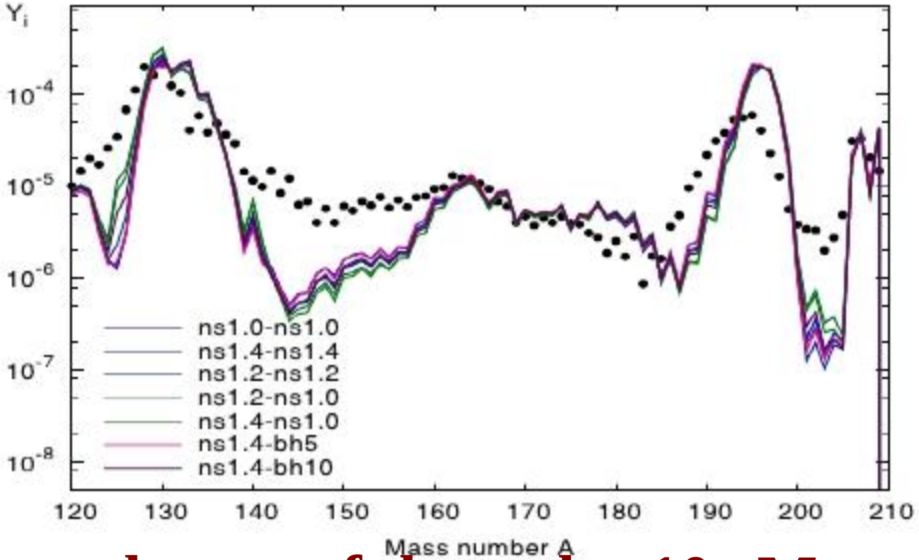
Based on early ideas by Lattimer and Schramm, first detailed calculations by Freiburghaus et al. 1999, Fujimoto/Nishimura 2006-08, Panov et al. 2007, 2009, Bauswein et al. 2012, Goriely et al. 2012...

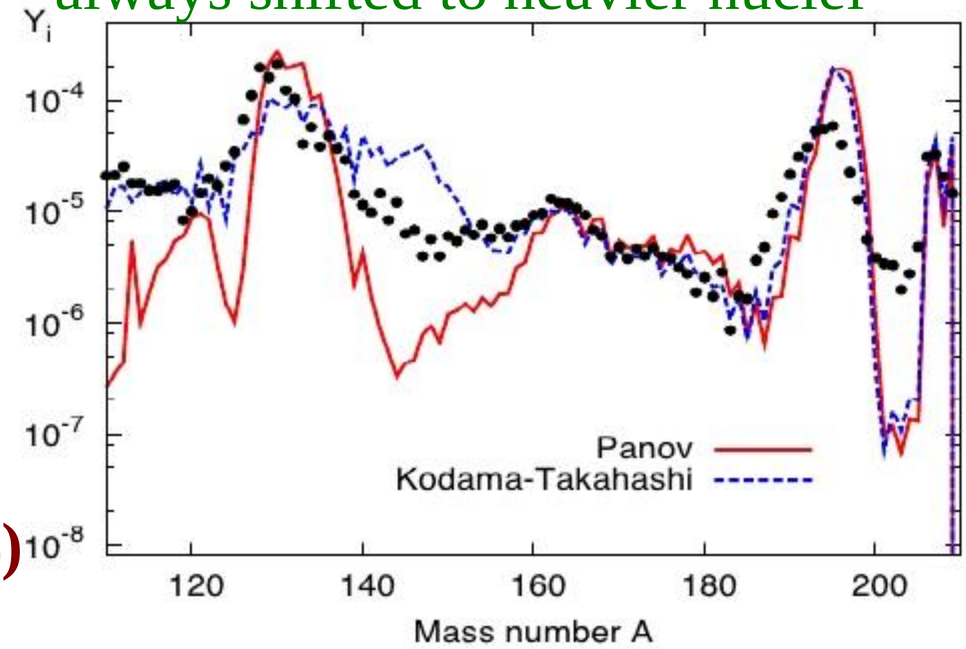


Neutron star merger updates of *dynamic ejecta* in non-relativistic calculations (Korobkin et al. 2012, see also Rosswog + 2014)

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 (Ye=0.04)

[all related to dynamic ejecta]

After charged-particle freeze-out quasi-equilibrium clusters emerge along isotopic chains, leading to (n,γ)-(γ,n) equilibrium which is in place up to about 1s

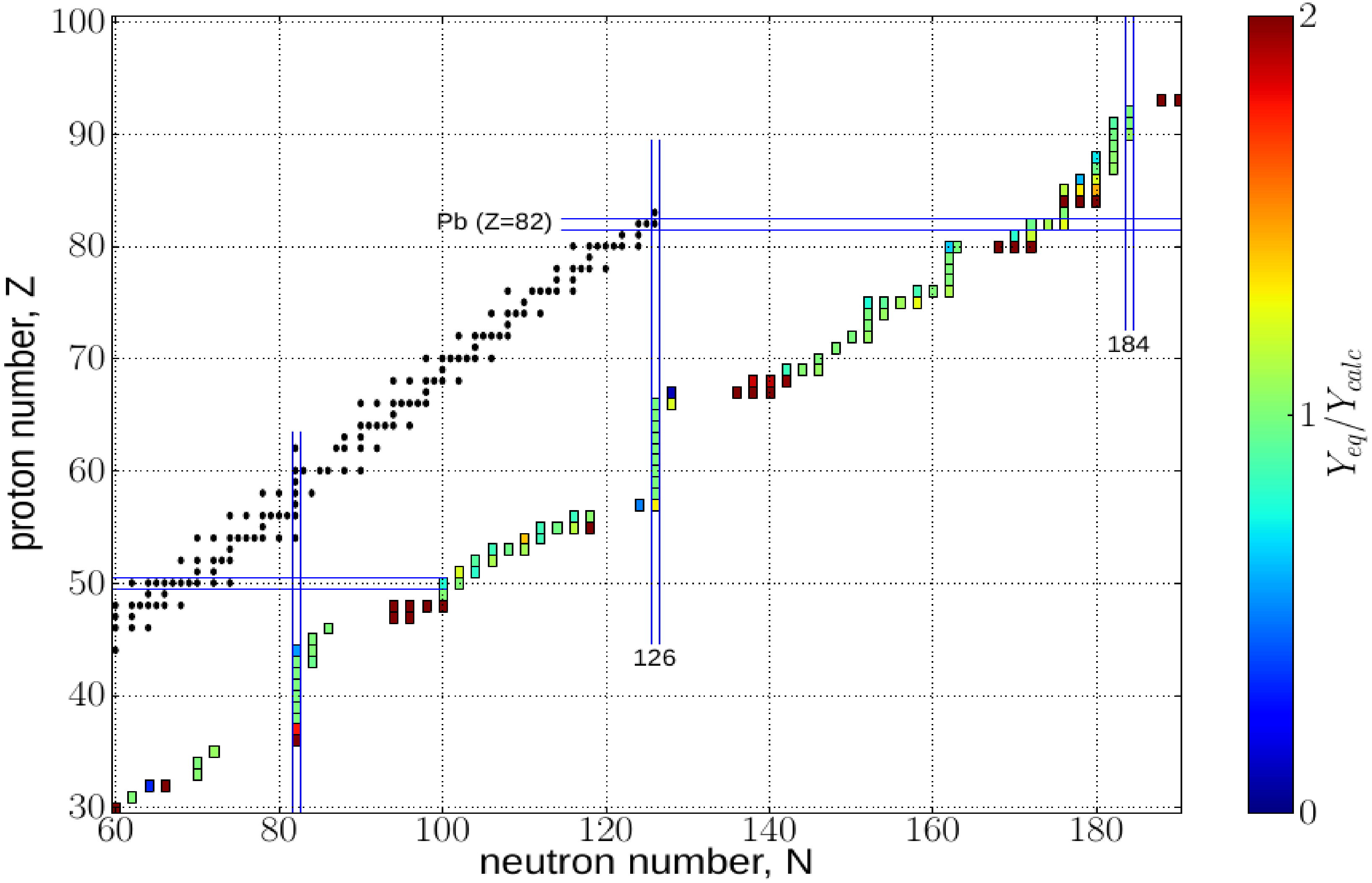
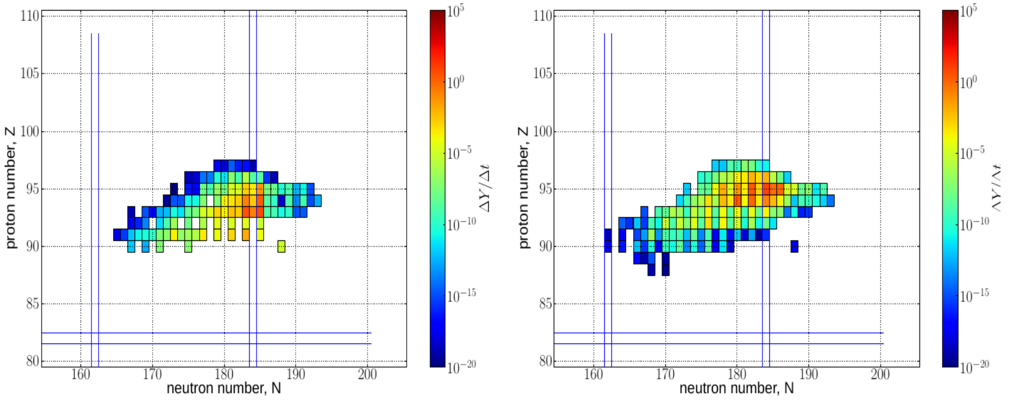
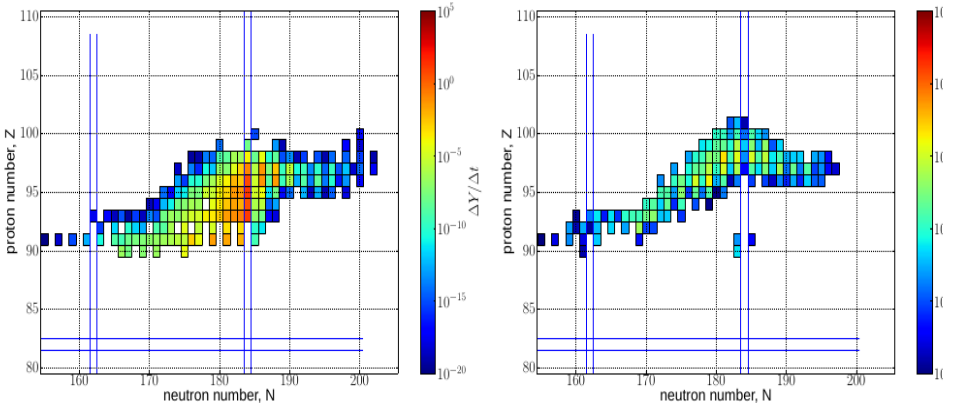


Fig. 7.—: Comparison of abundances from our calculations with (n,γ)-(γ,n) equilibrium abundances on the r-process path for the FRDM mass model. The colours show the factor Y_{eq}/Y_{calc}. Only the most abundant nuclei are shown for each isotopic chain. See text for details.

(n,f), (β,f) and fission yield distribution FRDM/TF and HFB-14/ETFSI (Eichler et al. 2015)

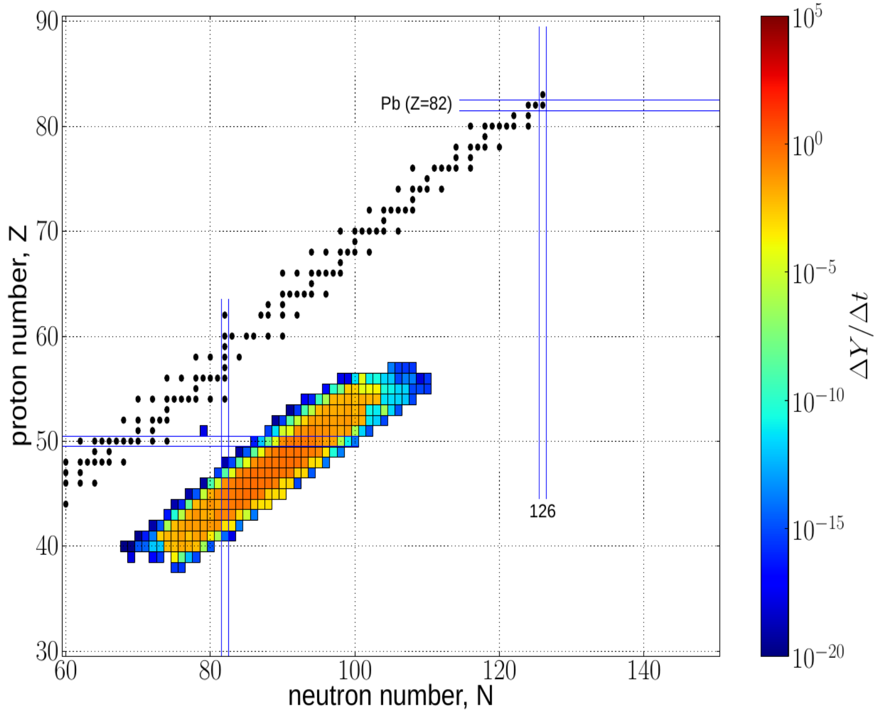


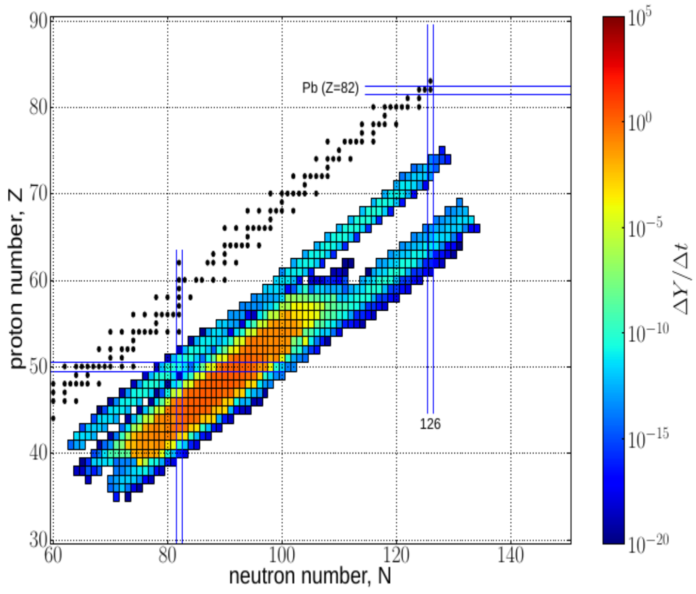


(a) β-delayed fission

(b) neutron-induced fission

N=184 shell closure important!!



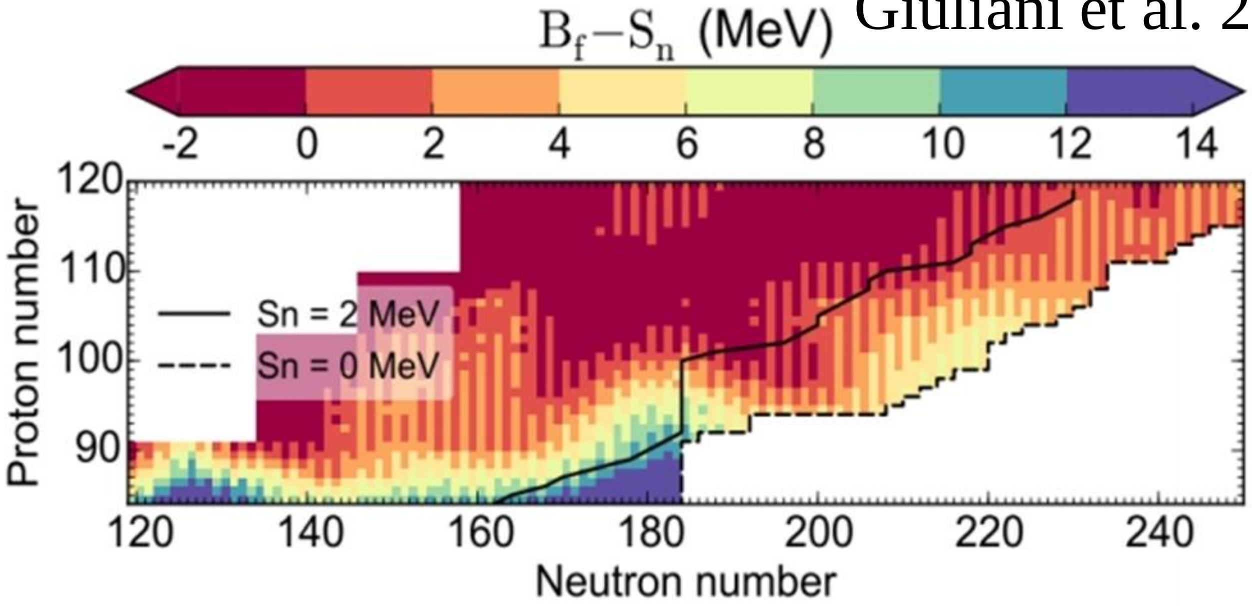


(c) fission fragments

fission rates and fragment distributions

Giuliani et al. 2017

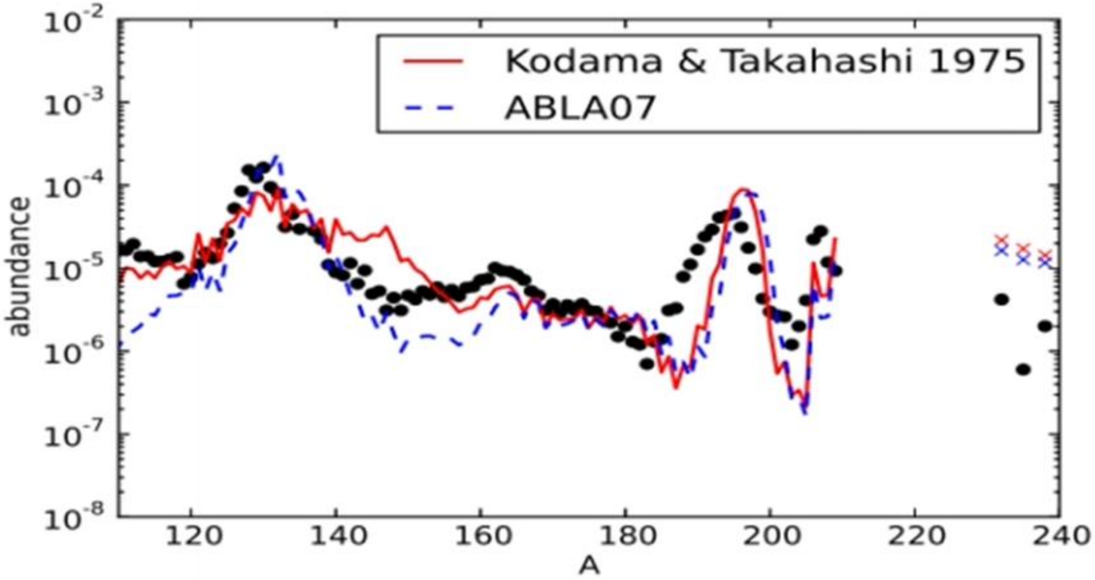
fission barrier height prediction determines where the r-process ends



fragment distributions can shape the patterns around and above the 2nd peak

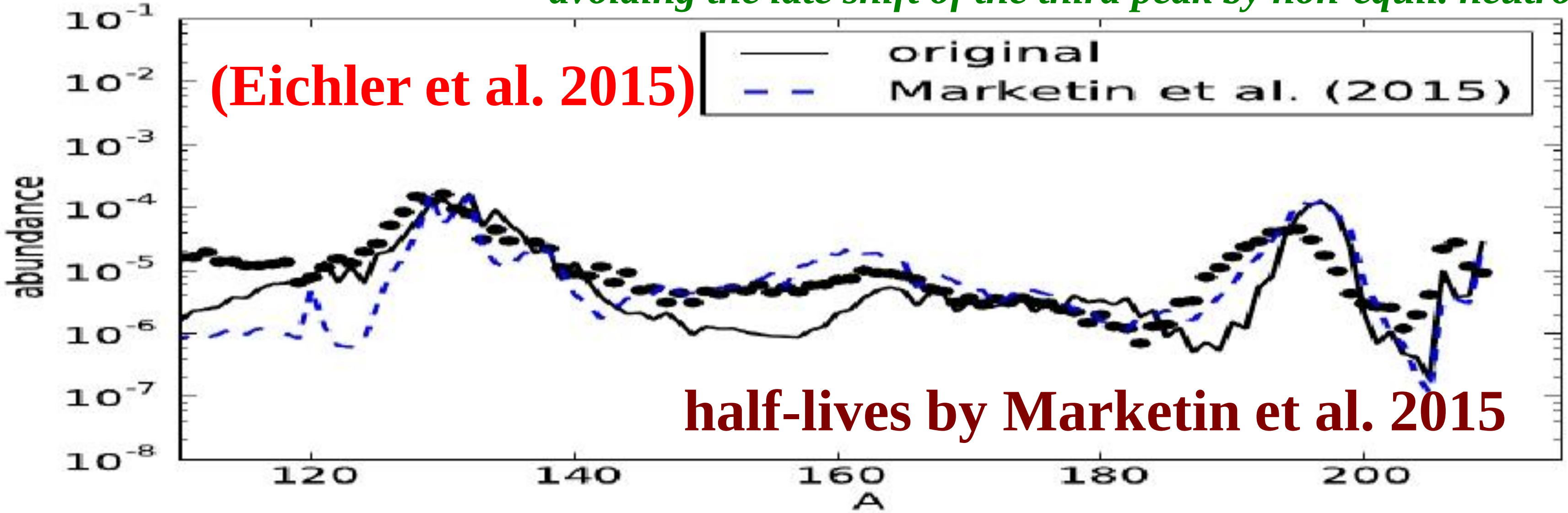
plus shifting the 3rd peak via fission neutrons!!!!

adopted from Wu+ 2017



Exploring variations in beta-decay rates and fission fragment distributions

Shorter half-lives of heavies release neutrons (from fission/fragments) earlier ***(still in n,γ - γ,n equilibrium) ,***
avoiding the late shift of the third peak by non-equil. neutron captures???

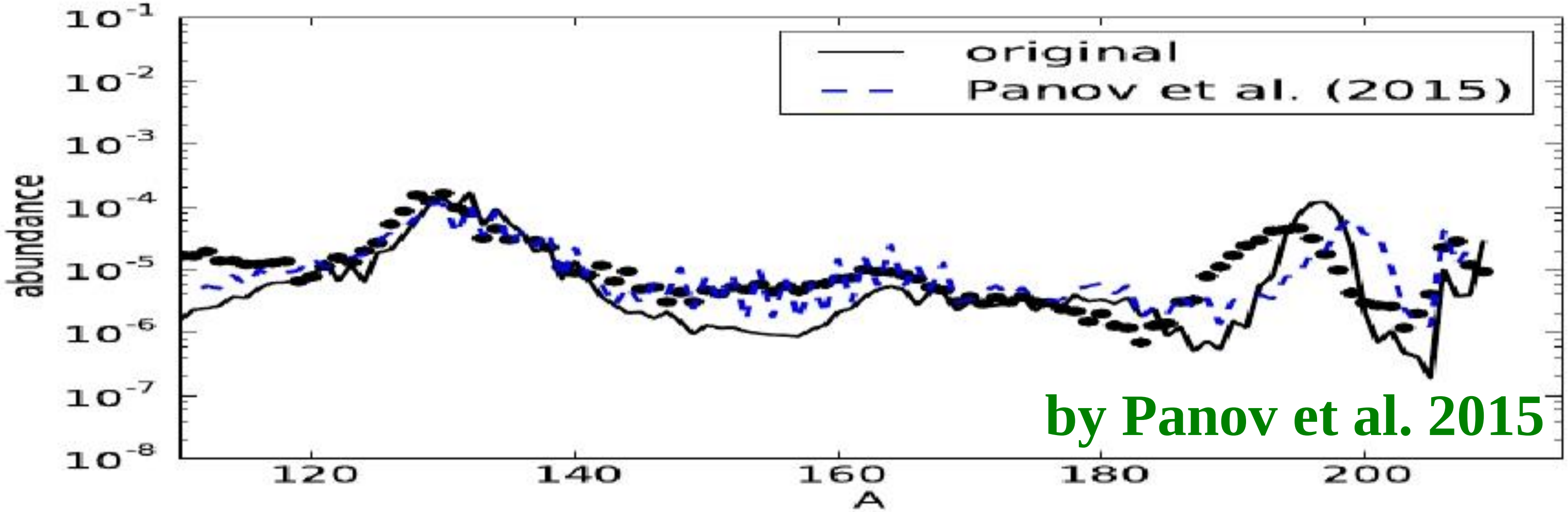


(Eichler et al. 2015)

half-lives by Marketin et al. 2015

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

(a) FRDM, Marketin (2015)



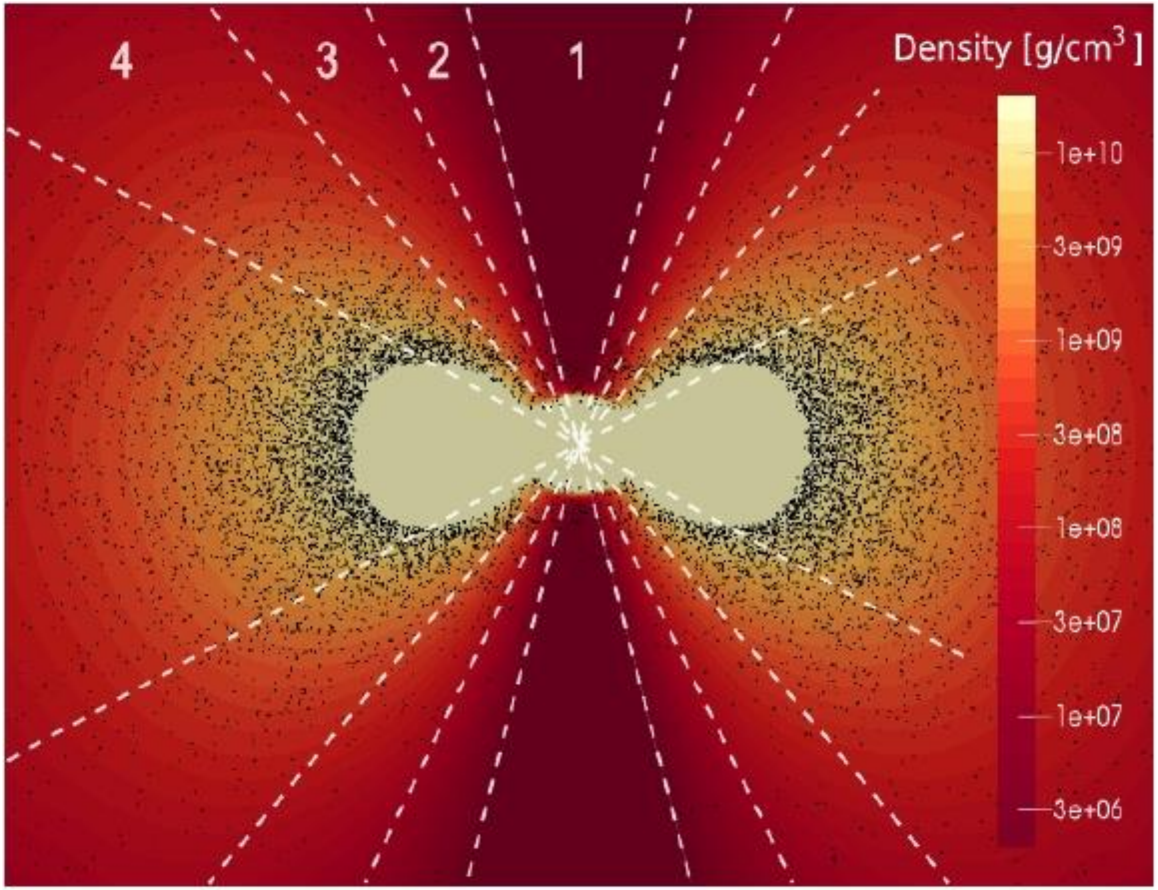
by Panov et al. 2015

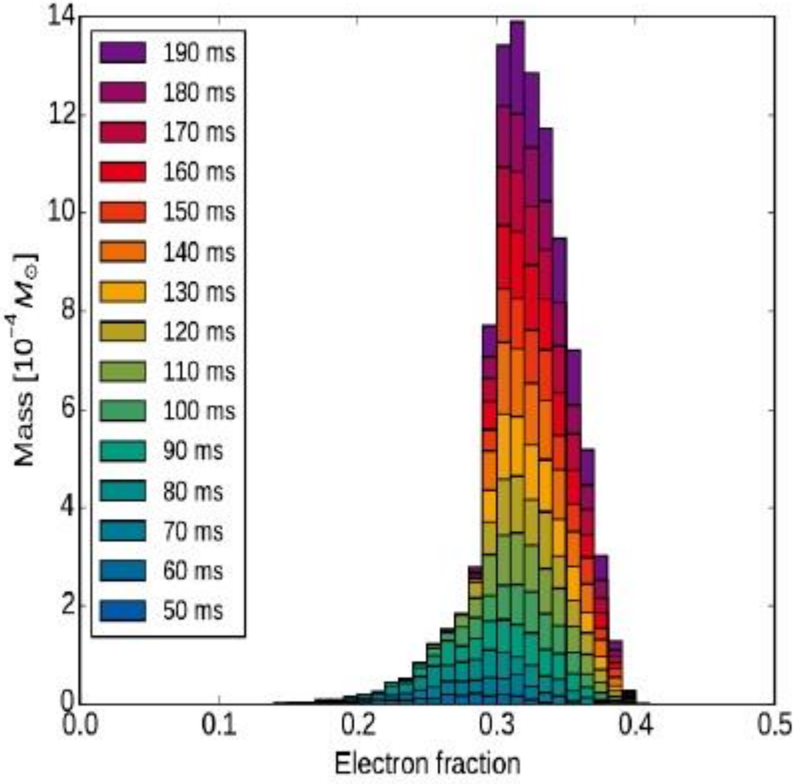
Longer half-lives give the opposite effect

(c) FRDM, Panov (2015)

Dynamic Ejecta and *Wind Contribution* before BH formation (Perego et al. 2014, Martin et al. 2015)

(still non-relativistic)



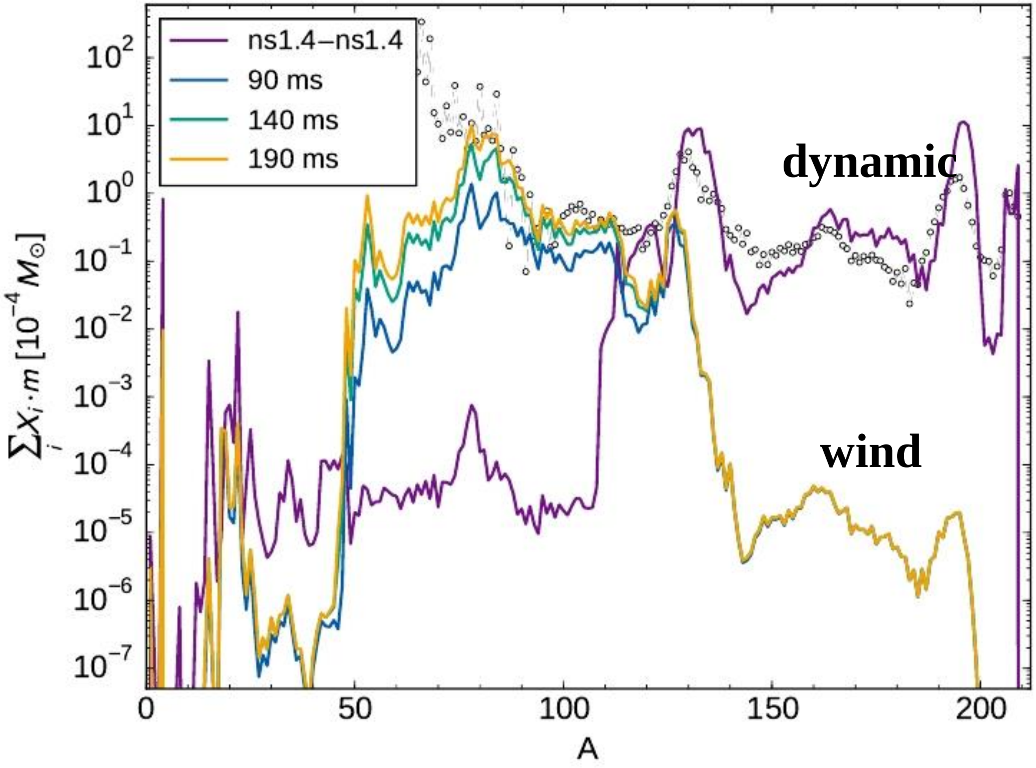


Ye in neutrino wind

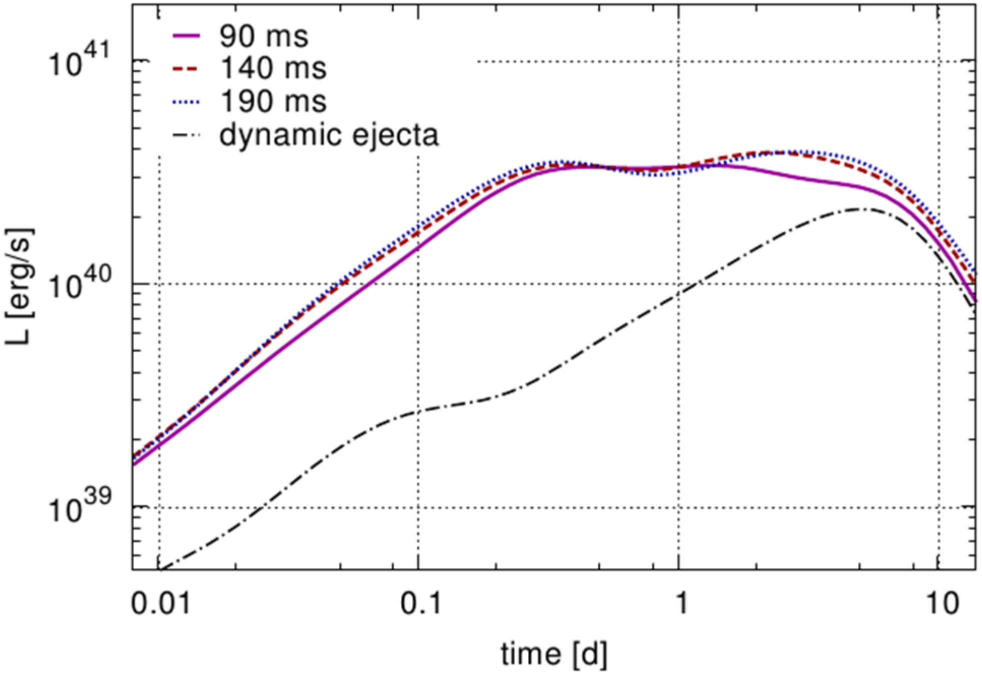
The «wind» runs into very low density matter, relativistic (fireball-like) expansion with high Lorentz boost can boost 1 MeV to 100 MeV photons (short duration gamma-ray burst)

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

abundances



Energy production due to nuclear decay

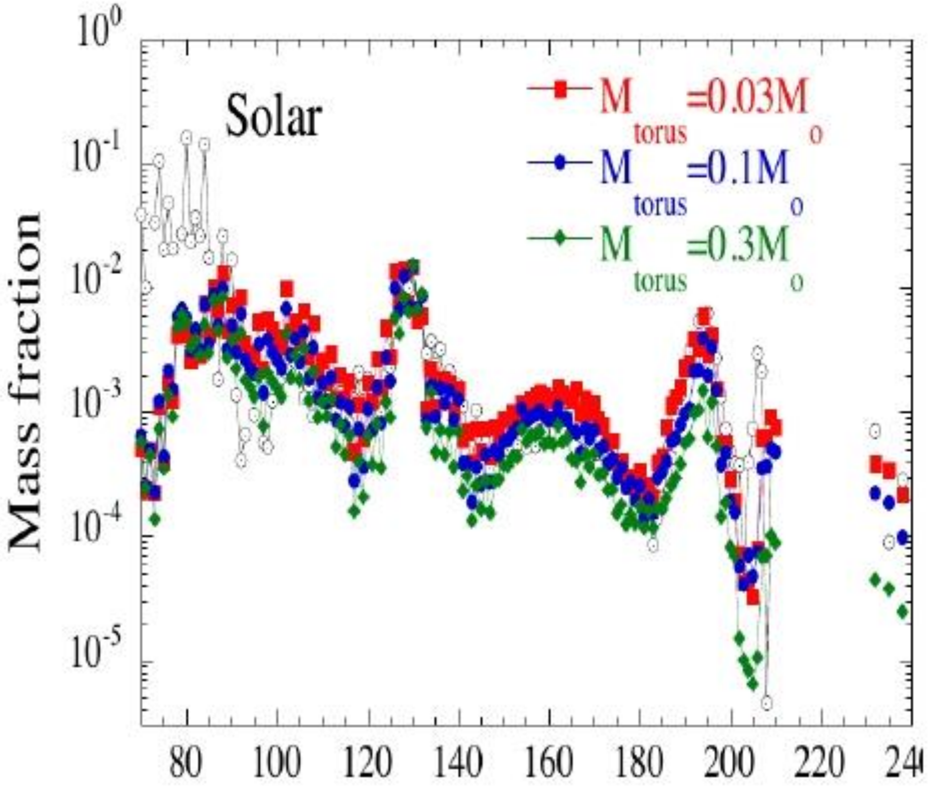


Martin et al. (2016) with neutrino wind contributions from matter in polar directions

The need to go beyond Newtonian methods and model BH accretion disk ejecta as 3rd stage

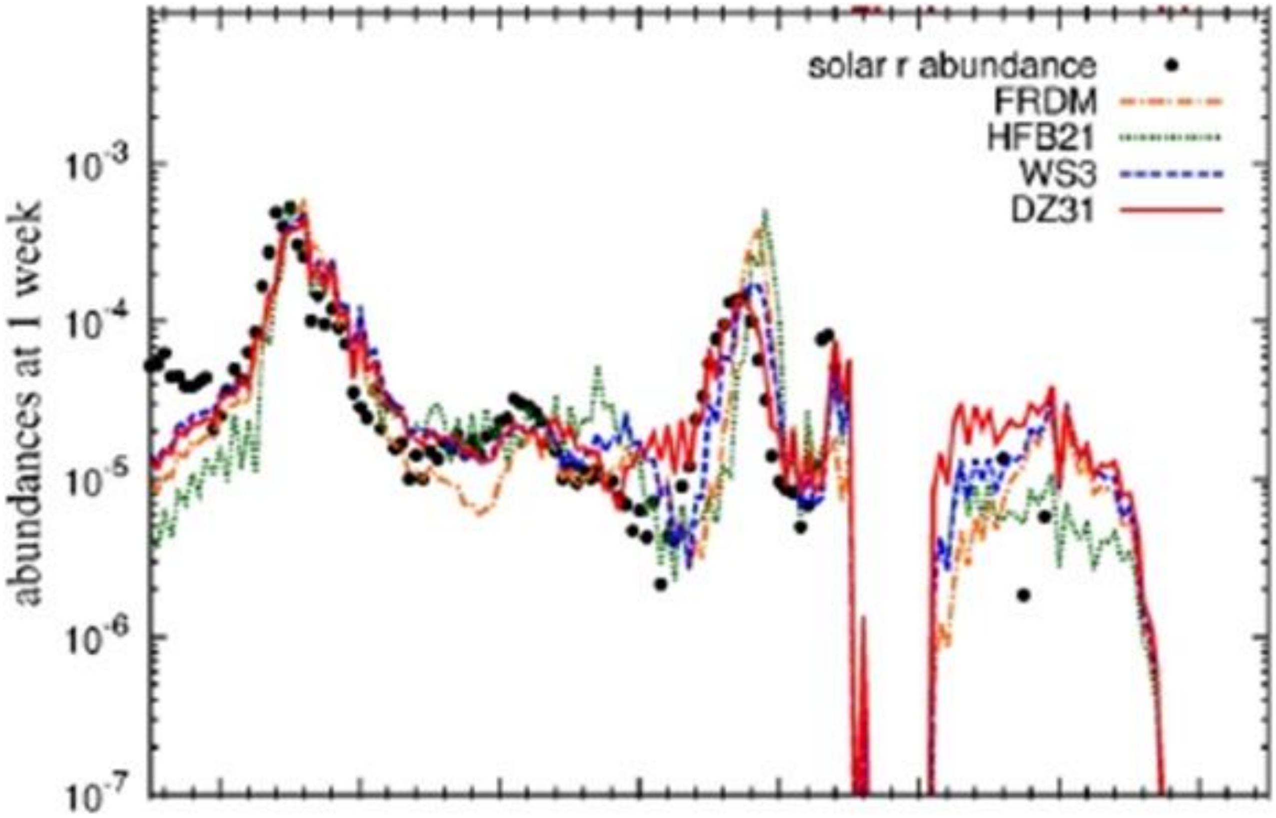
- Conformally flat smoothed particle hydrodynamics application to neutron star mergers (Oechslin, Rosswog, Thielemann, 2002), plus the first tests for EoS effects (influence of quark matter at high densities Oechslin, Uryu, Poghosian, Thielemann, 2004)

- the Garching conformal flat approach and many applications (Bauswein, Oechslin, Janka, Goriely, Just, Mendoza-Themis…)



Full predictions with **dynamic ejecta + viscous disk ejection (but no fission neutrons)**, and late neutrino wind *(Just et al. 2015),*
based on smooth particle hydrodynamics and conformal flat treatment of GR
(*see also Just et al. 2016, Guilet et al. 2017*)

Latest results within this approach (but only utilizing dynamic ejecta)

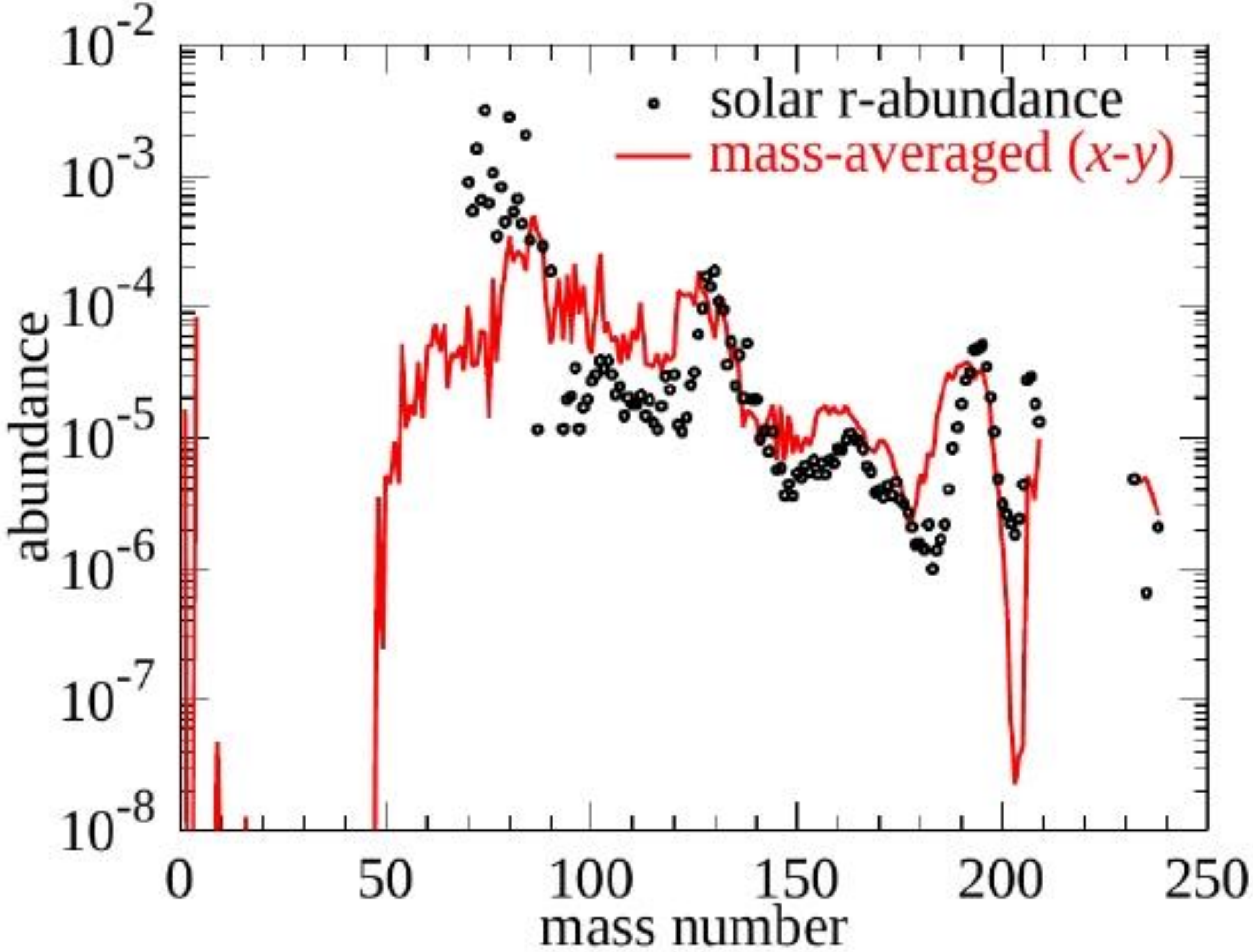


Variations based on different nuclear mass models.
Mendoza-Temis, Wu, Langanke, Martinez-Pinedo, Bauswein, Janka (2015)

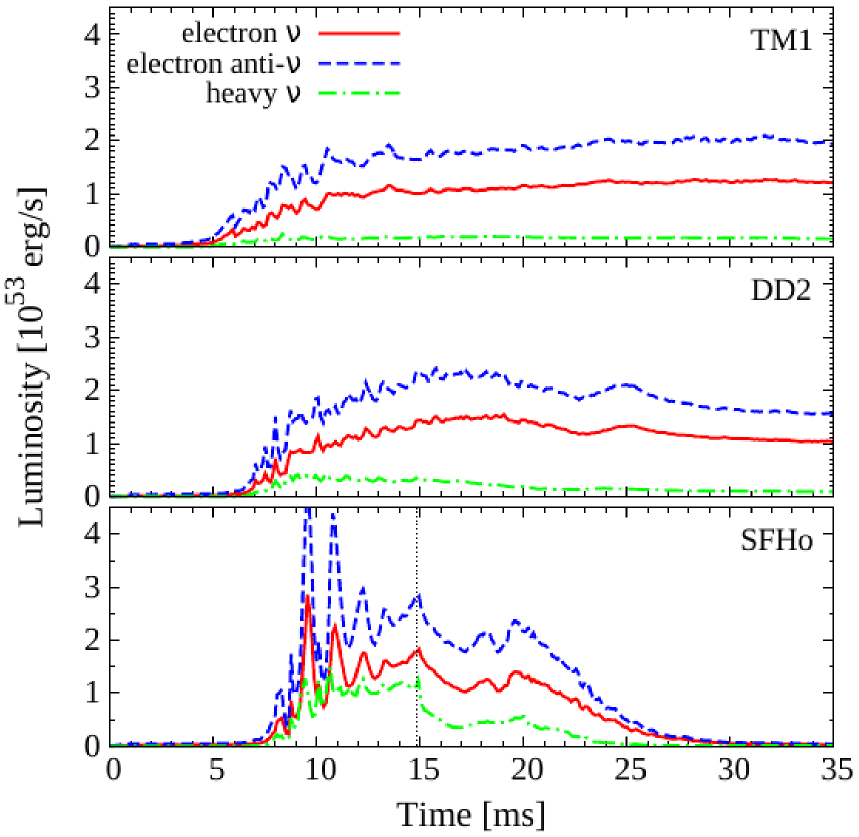
Fully General Relativistic calculations (utilizing grid methods)

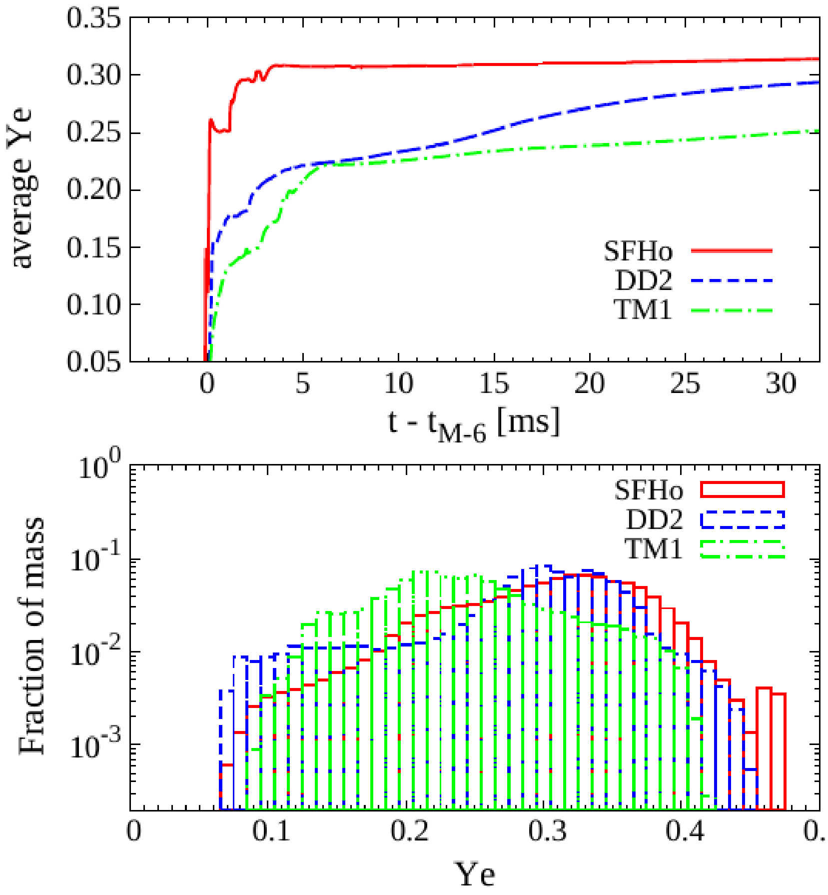
- first full-GR work by the Kyoto group (Hotokezaka et al. 2013)
- full-GR + approximate neutrino transport (gray) by Sekiguchi et al. (2015), Foucart et al. (2015, 2016)
- full-GR + approximate neutrino transport (spectral) by Radice et al. (2016)
- inclusion of magnetic-field amplification due to high-resolution Kelvin-Helmholtz instability by Kiuchi et al. (2015)

General relativistic calculations (based on the Sekiguchi et al. calculations), find higher Ye’s, but also changed positions of the r-process peaks **(Wanajo et al. 2014)**



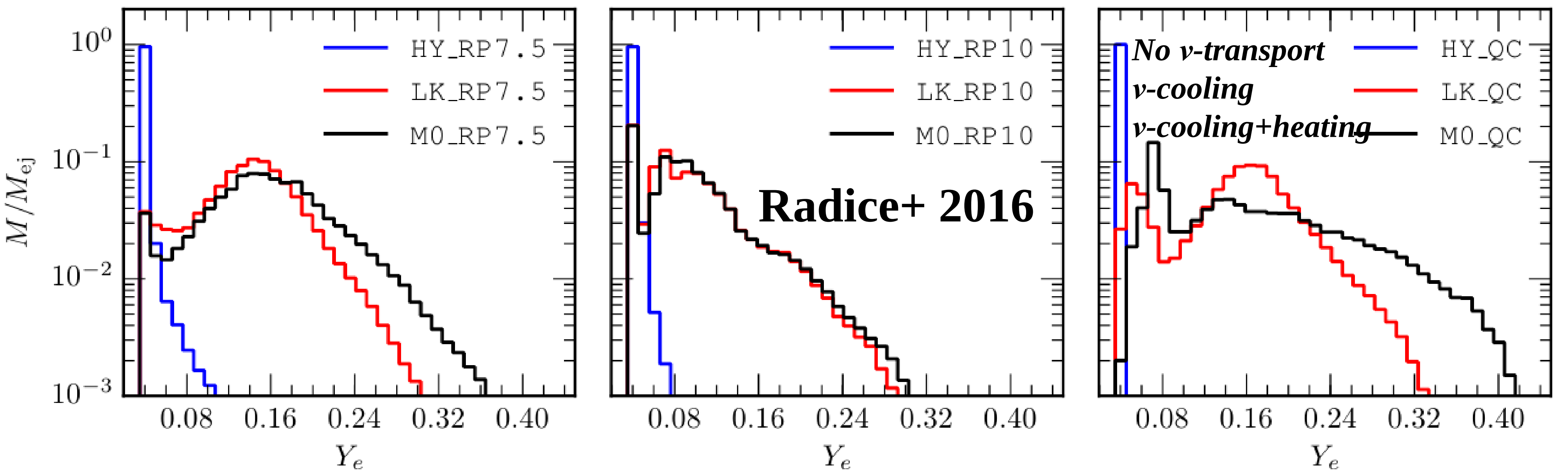
Sekiguchi et al. (2015), relativistic calculations lead to deeper grav. potentials, apparently also stronger shocks, both enhancing the temperature, higher neutrino luminosities, and e+e- pairs. All of this enhances Ye, permitting to have abundance distribution with A<130!.





3 different EoS, TM1, DD2, and SFH

Is the enhanced Ye only due to the relativistic approach or also due to numerical methods and/or neutrino transport utilized?



No ν-transport

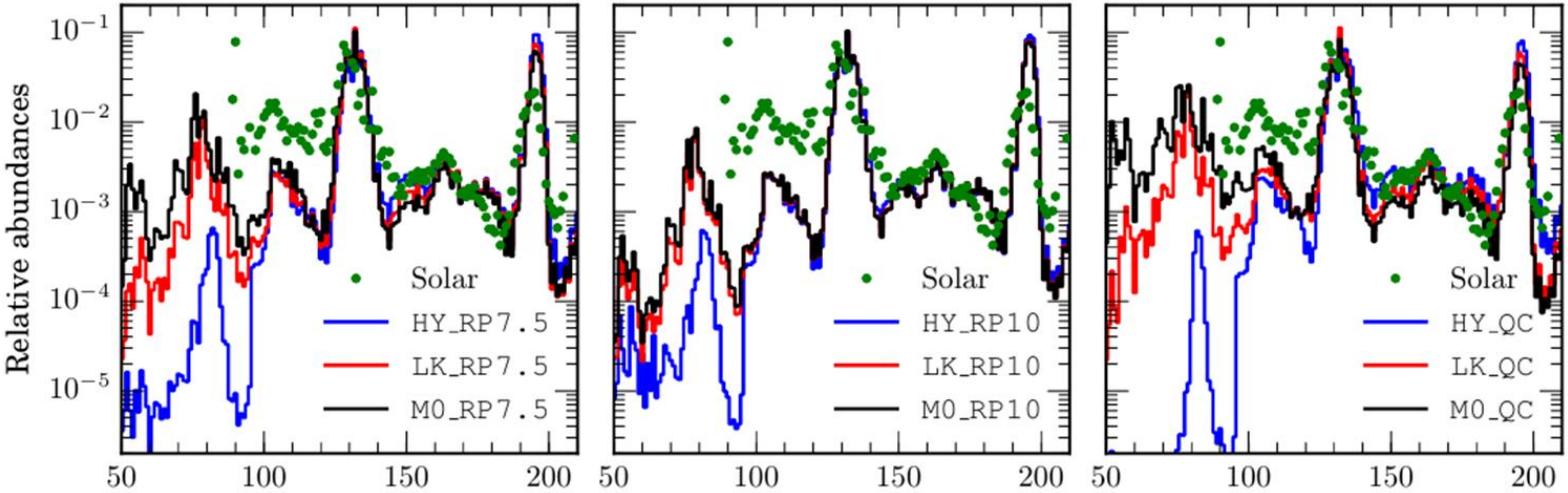
ν-cooling

ν-cooling+heating

Radice+ 2016

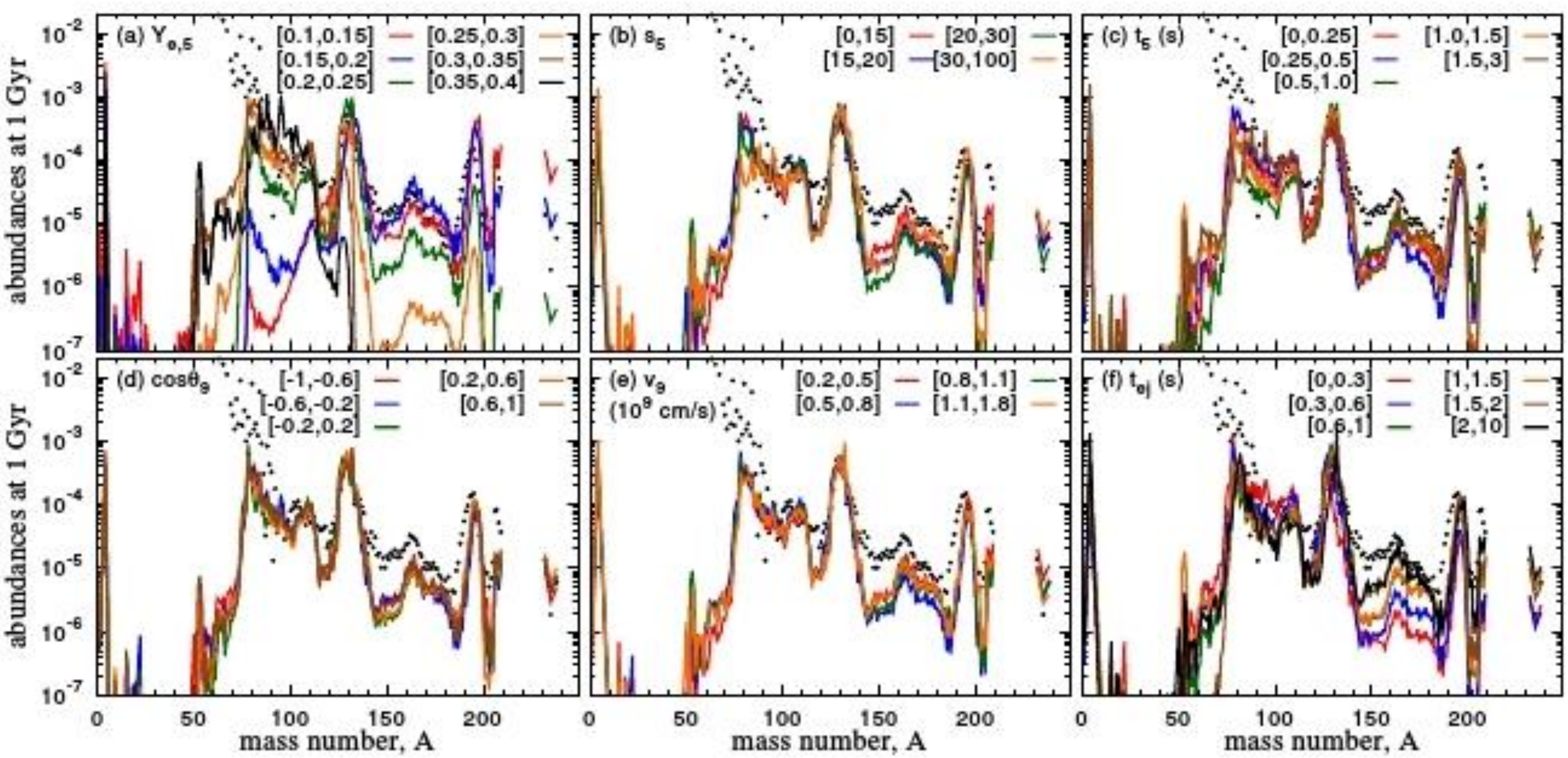
Figure 7. Electron fraction (*top row*), specific entropy per baryon (*second row*), asymptotic velocity (*third row*), and angular distribution (*bottom row*) of the ejecta. θ is the angle from the orbital plane. The first, second, and third columns show results from models `RP7.5`, `RP10`, and `QC` respectively. For each configuration we consider three different levels of microphysical description: pure hydrodynamics (`HY`), neutrino cooling (`LK`), or neutrino cooling and heating (`M0`). The histograms are computed from the mass fraction of the matter crossing a spherical surface at radius $r = 200\ M_\odot \simeq 295$ km with positive specific energy (*i.e.*, with $u_t \leqslant -1$). The bump in the angular distribution at $\theta = 45°$ is a numerical artefact generated by our Cartesian simulation grid.

Excentricity of orbital collision

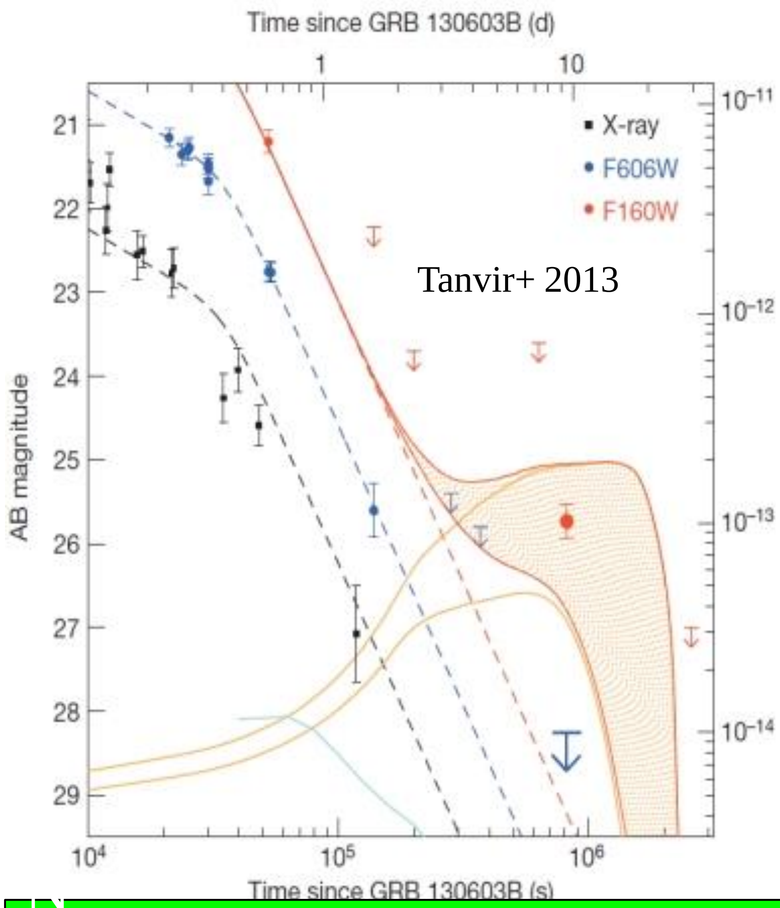


Nucleosynthesis from BH accretion disks (after merger and BH formation, but without dynamical ejecta)

Variations in BH mass, spin, disk mass, viscosity, entropy in alpha-disk models: r-process nuclides up to lanthinides and actinides *can* be produced.



Wu, Fernandez, Martinez-Pinedo, Metzger (2016) adopted from Wu

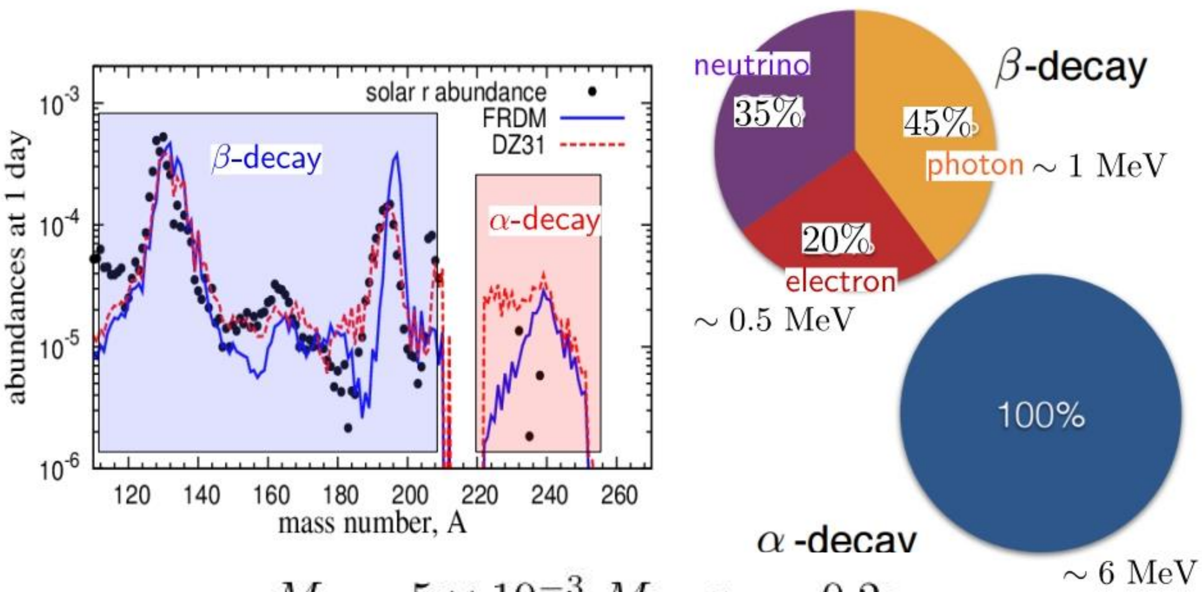


Tanvir+ 2013

F606W optical, F160W nIR

Nuclear physics impact on kilonova heating

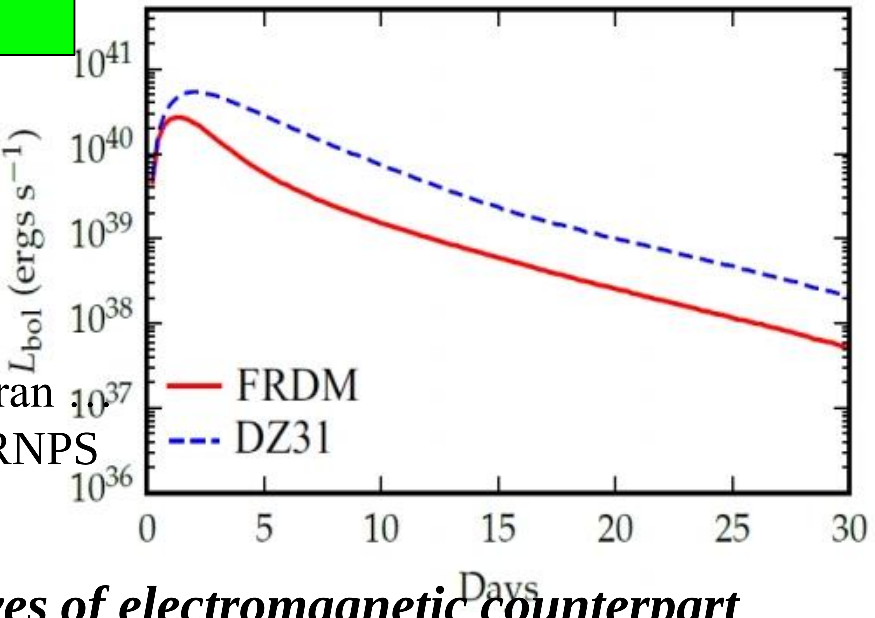
At kilonova time, large difference for $220 \lesssim A \lesssim 240$



$$M_{\rm ej} = 5 \times 10^{-3}\ M_\odot,\ v_{\rm ej} = 0.2c$$

Barnes+ 2016

Wu+ 2017

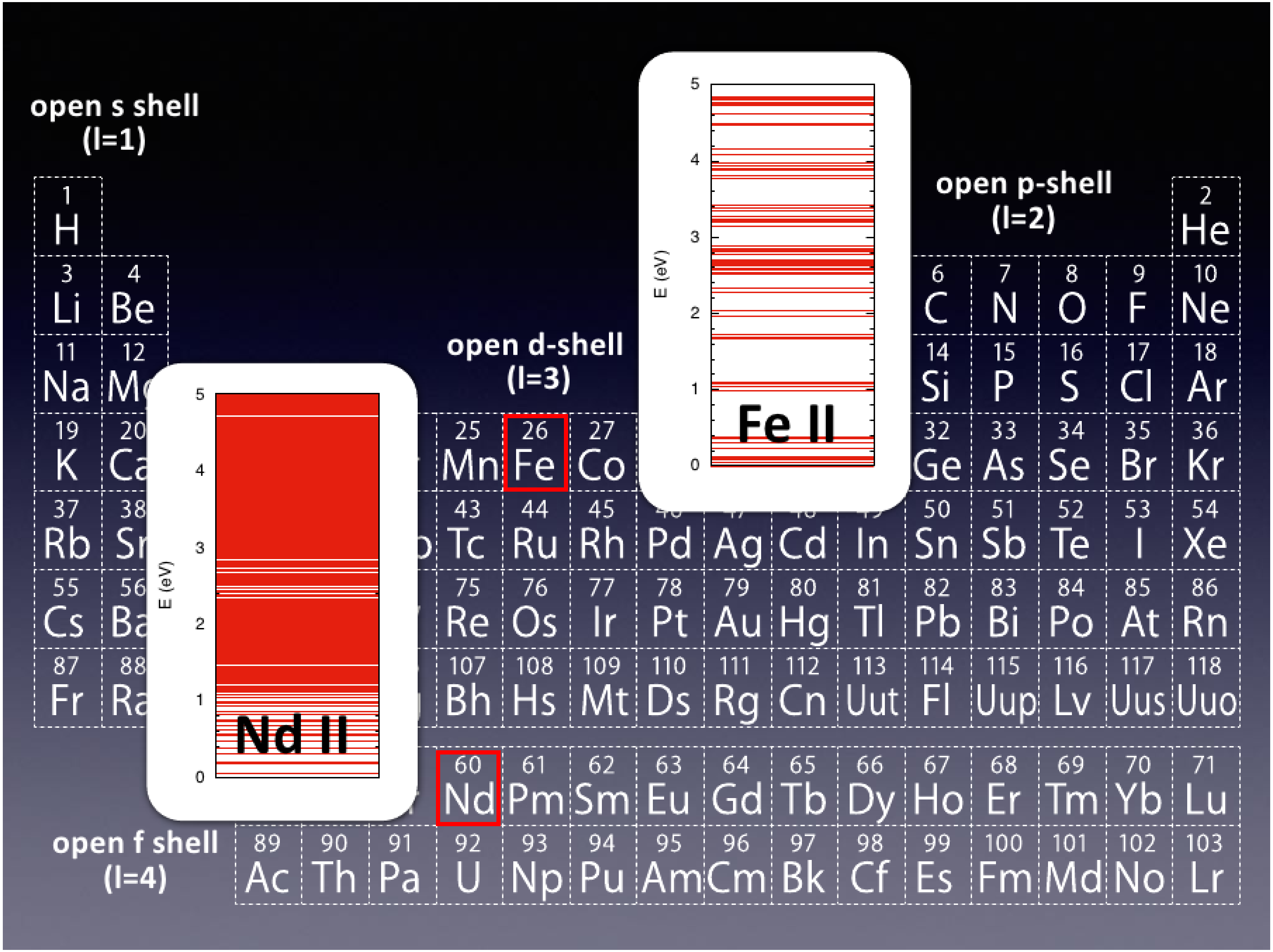


for detailed preductions of spectral evolution of electrogamnetic counterpart, involving opacities of ejected compositions see e.g. Metzger+ 2010, plus further developments by Barnes, Fernandez, Kasen, Tanaka, Fryer, Hotokezata,Grossman, Korobkin, Rosswog, Piran ... (see reviews by Fernandez & Metzger 2015 ARNPS and Metzger 2017 LRR)

nuclear uncertainties can affect lightcurves of electromagnetic counterpart

Different opacities of matter due to density of atomic states

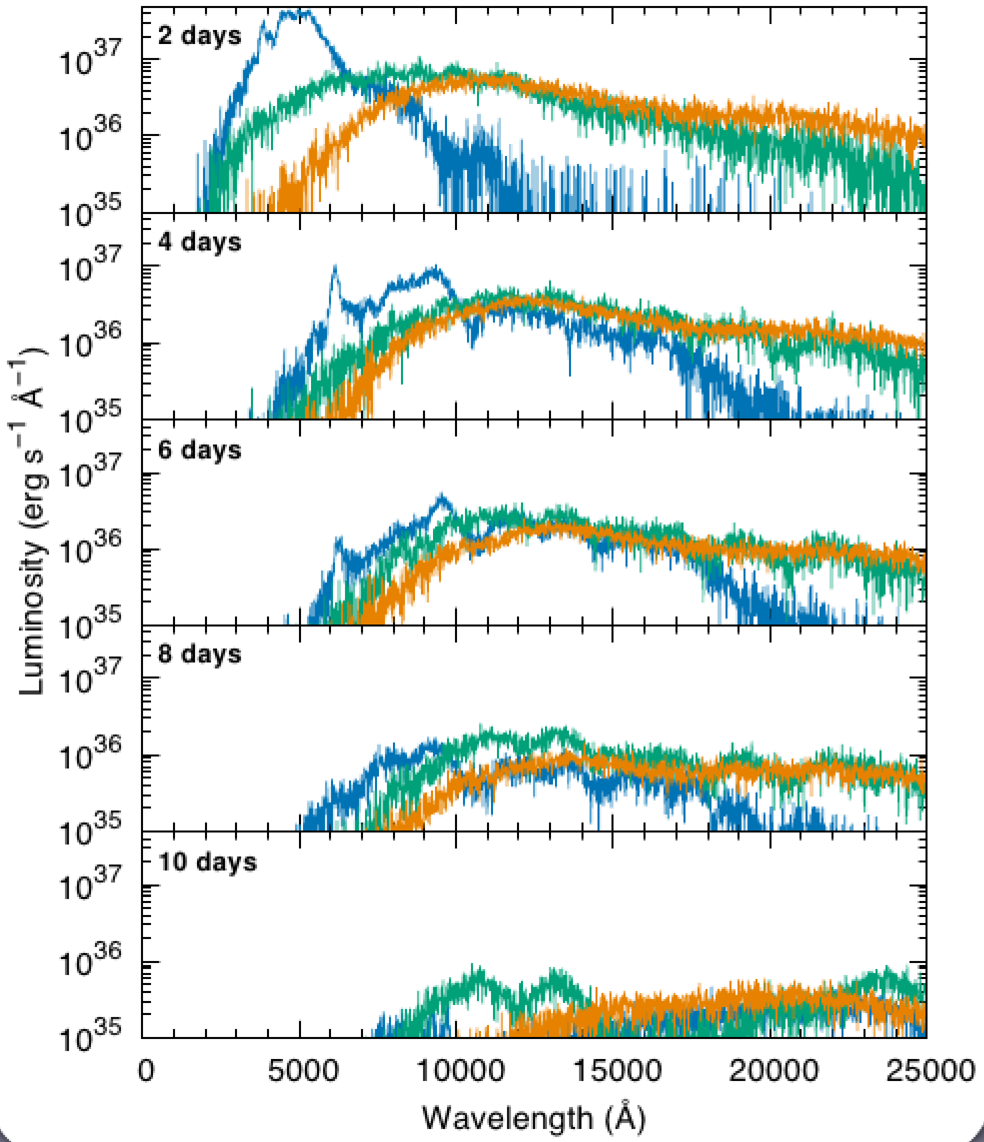
(from M. Tanaka 2017)



Spectra

Differences in Ye are imprinted in the spectra!!

But individual element is difficult to identify



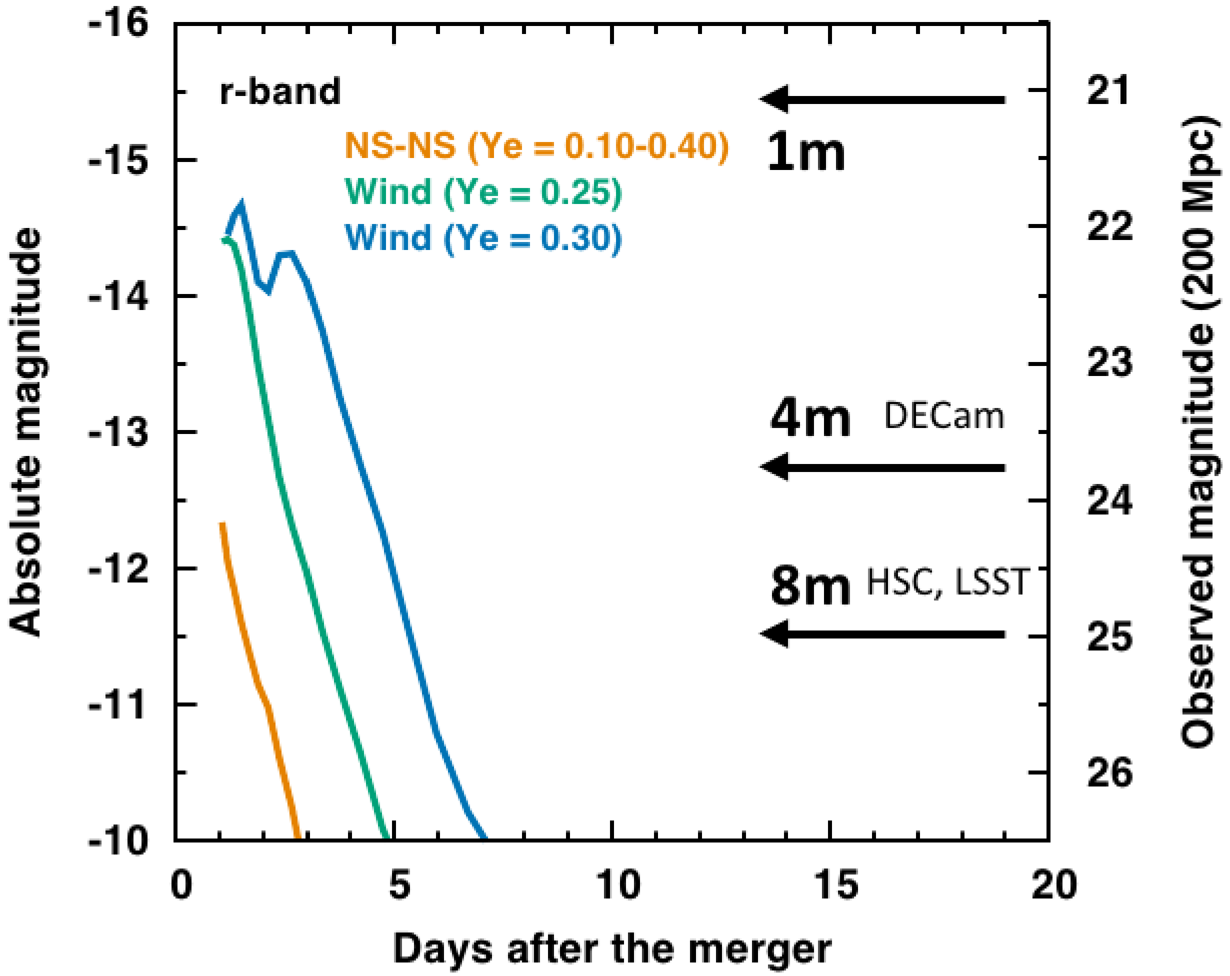
High Ye (0.30) (Lanthanide-free)

Medium Ye (0.25)

Low Ye (Lanthanide-rich)

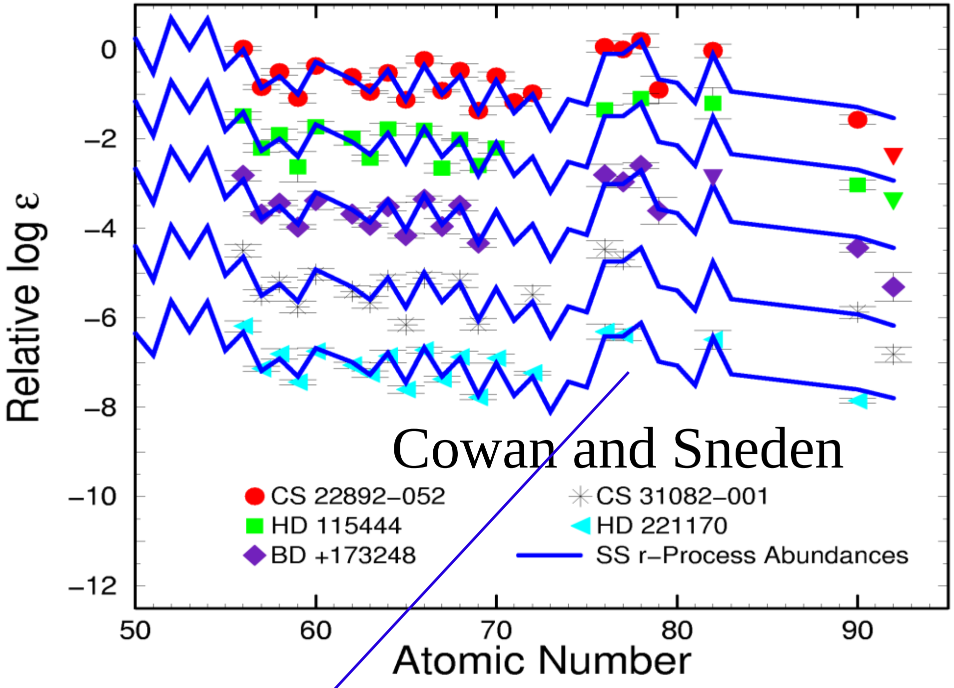
M.Tanaka et al. (2017)

MT+17



from M. Tanaka et al. 2017

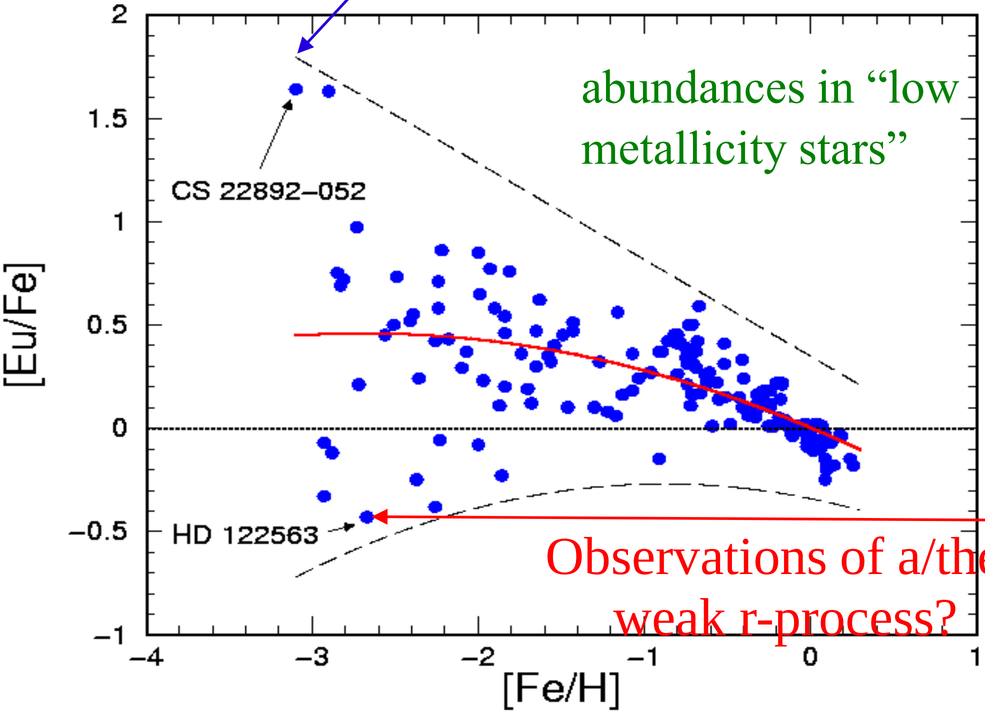
Can NSMs reproduce low-metallicity observations?



Cowan and Sneden

apparently uniform abundances above Z=56 (and up to Z=82?) -> “unique” astrophysical event for these “Sneden-type” stars

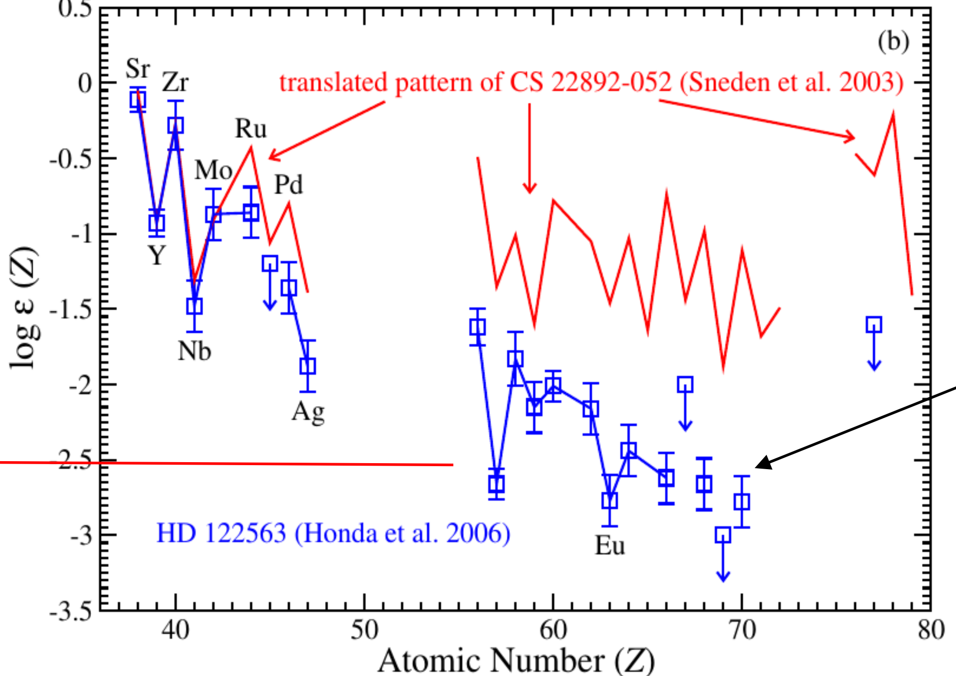
Weak (non-solar) r-process in Honda-type stars



abundances in “low metallicity stars”

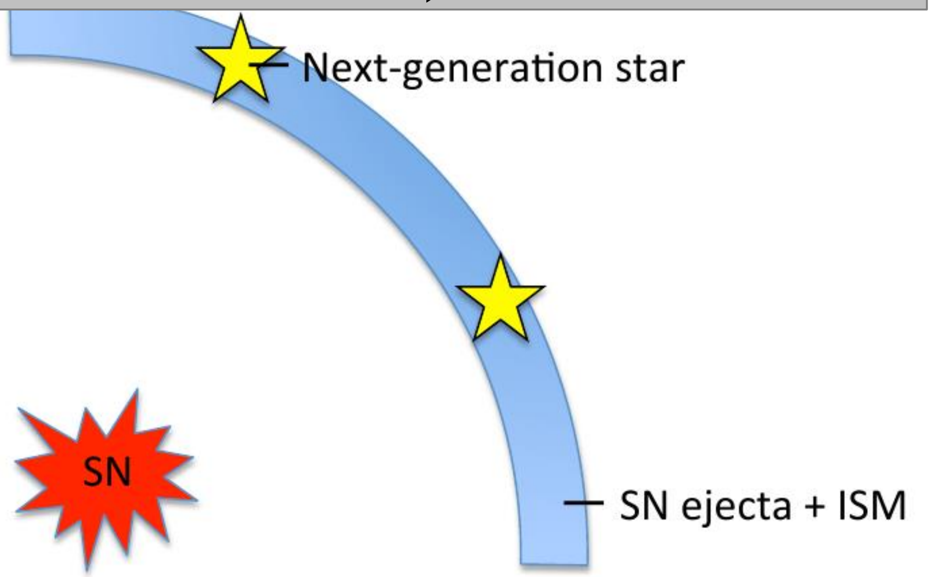
Observations of a/the? weak r-process?

Qian & Wasserburg (2007)



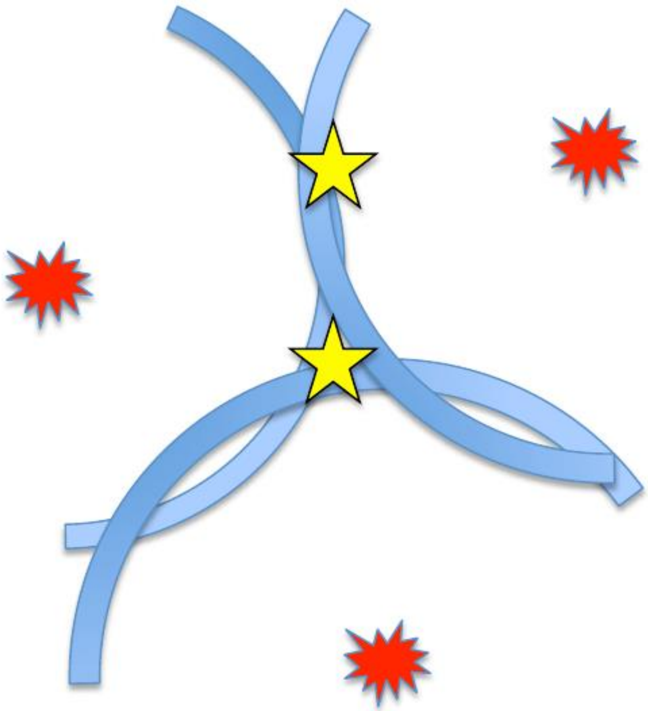
Stellar Abundances

Inhomogeneous „chemical evolution“ : Models do not assume immediate mixing of ejecta with surrounding interstellar medium, pollute only about 5 10^4 Msol, according to Sedov-Taylor blast wave. After many events an averaging of ejecta composition is attained (Argast, Samland, Thielemann, Qian 2004)

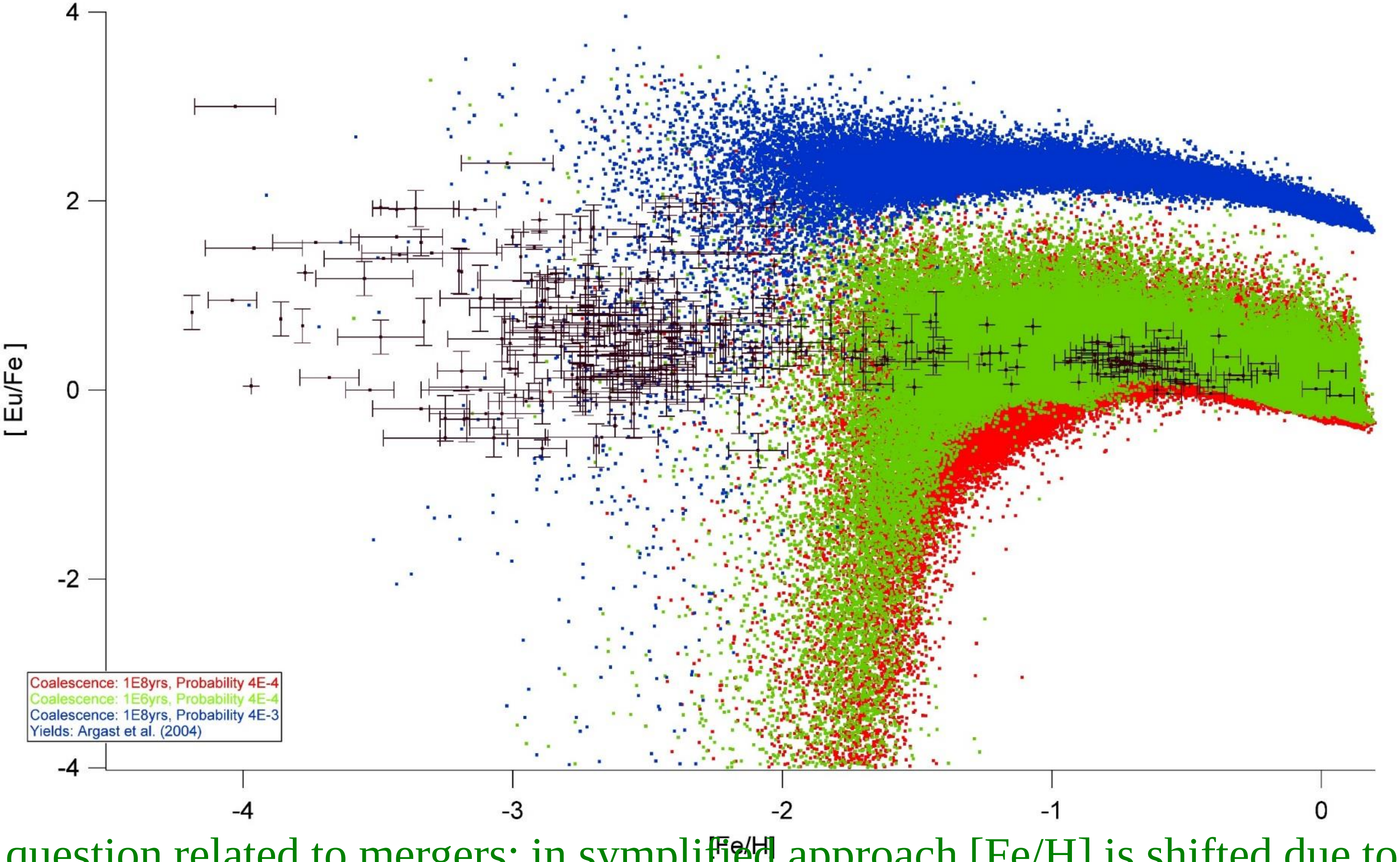


In the later phase

Contribution from multiple CCSNe
(unknown → average weighted by IMF)



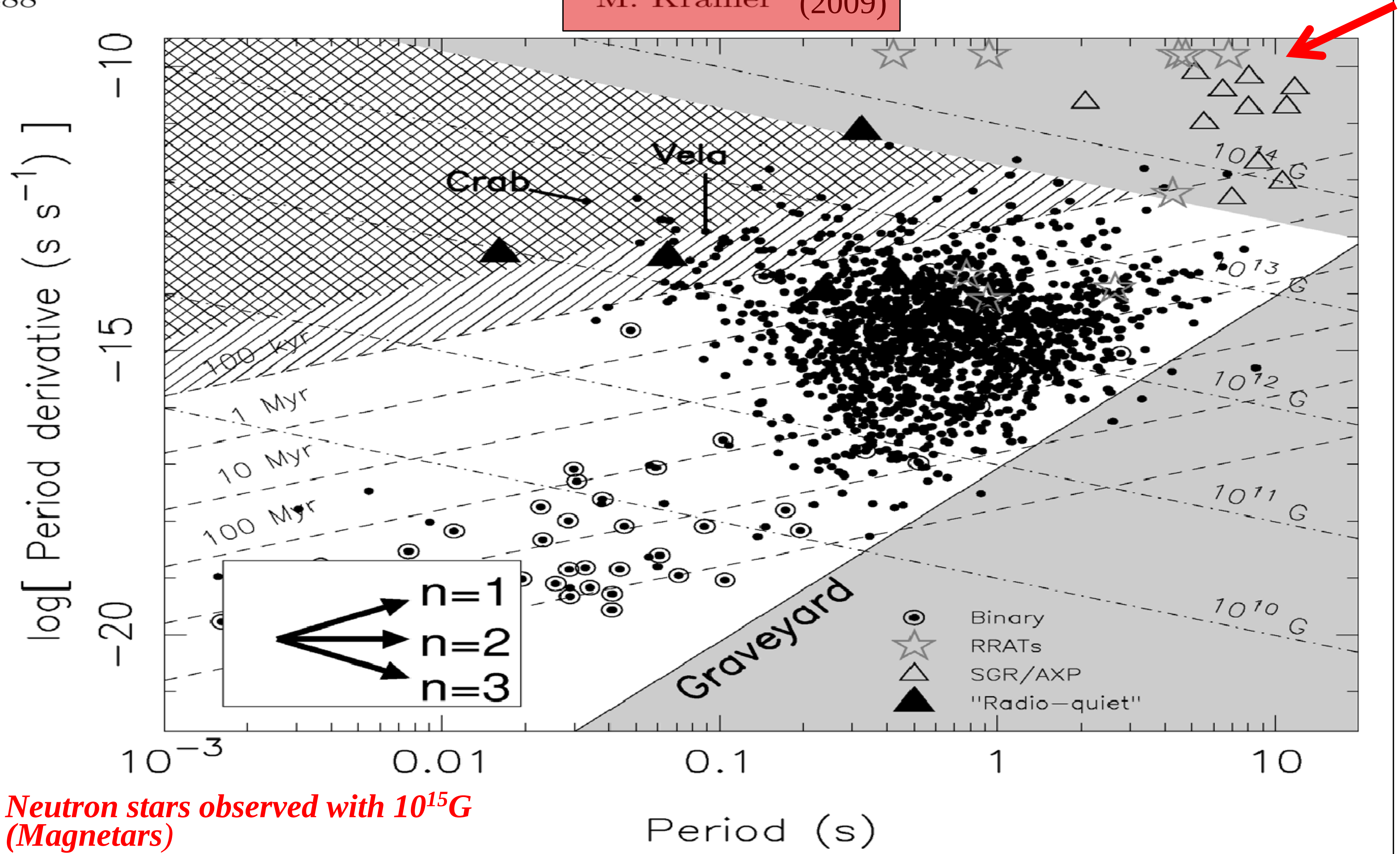
Inhomogenous models undertaken by Van de Voort+ (2015), Shen+ (2015), Cescutti+ (2014), Wehmeyer+ (2015), Hirai+ (2016), effect of turbulent mixing?



Main question related to mergers: in symplified approach [Fe/H] is shifted due to the earlier supernova ejecta which produce Fe, before the neutron star merger takes place and its r-process products are ejected into the ISM, being available for later star formation. Thus: Is inhomogenous galactic evolution implemented correctly?? This problem could be avoided if neutron star kicks are strong enough that the merger will take place in unpolluted region)

Wehmeyer et al. (2015), green/red different merging time scales, blue higher merger rate (not a solution, but (i) turbulent mixing would shift the onset to lower metallicities, (ii) different SFR in initial substructures can do so, too Ishimaru+ 2015)

M. Kramer (2009)



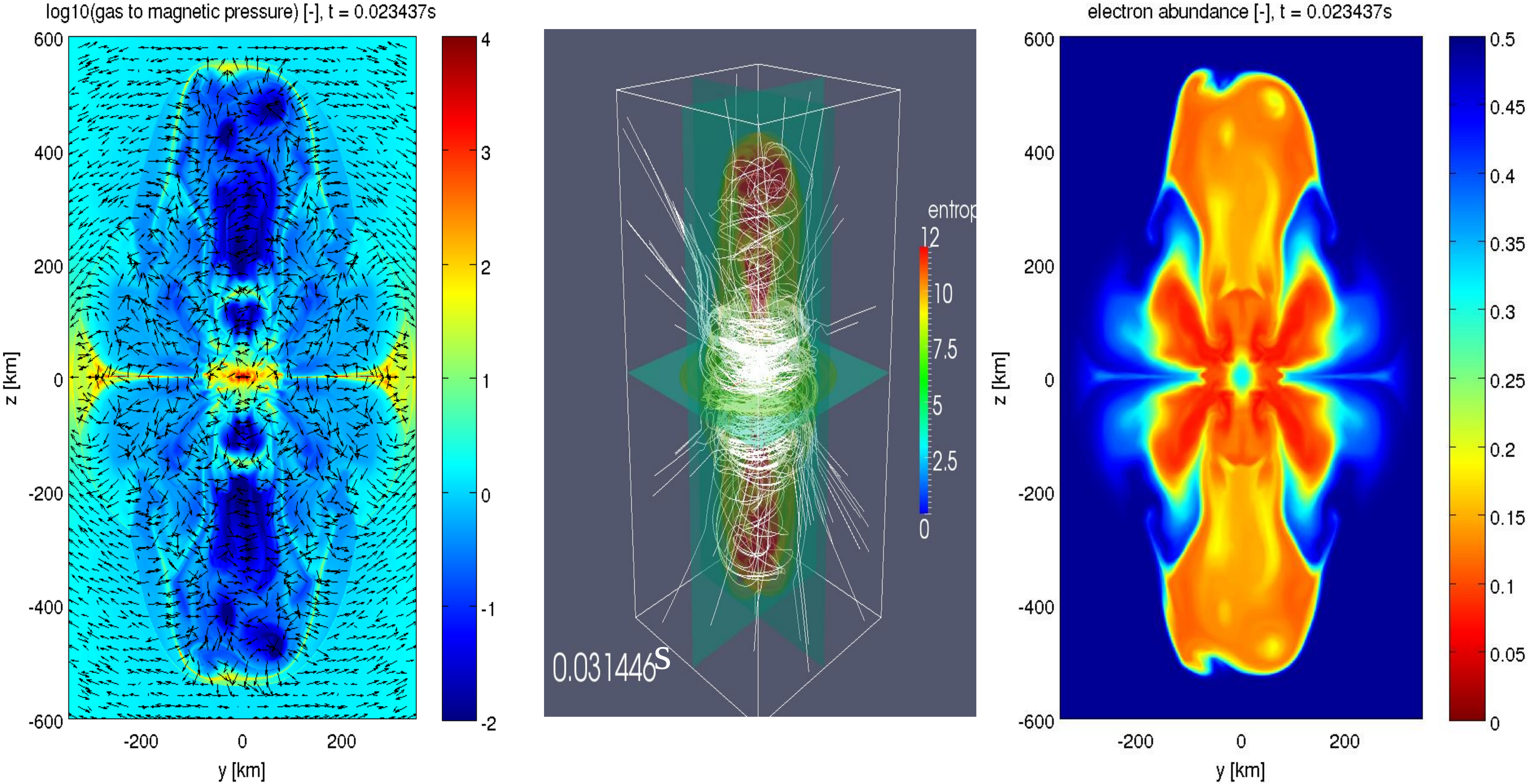
Neutron stars observed with 10^{15}G (Magnetars)

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 τ_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 Magnetic Fields:

15 M_{sol} progenitor (Heger Woosley 2002), shellular rotation with period of 2s at 1000km, magnetic field in z-direction of 5 x10^{12} Gauss,

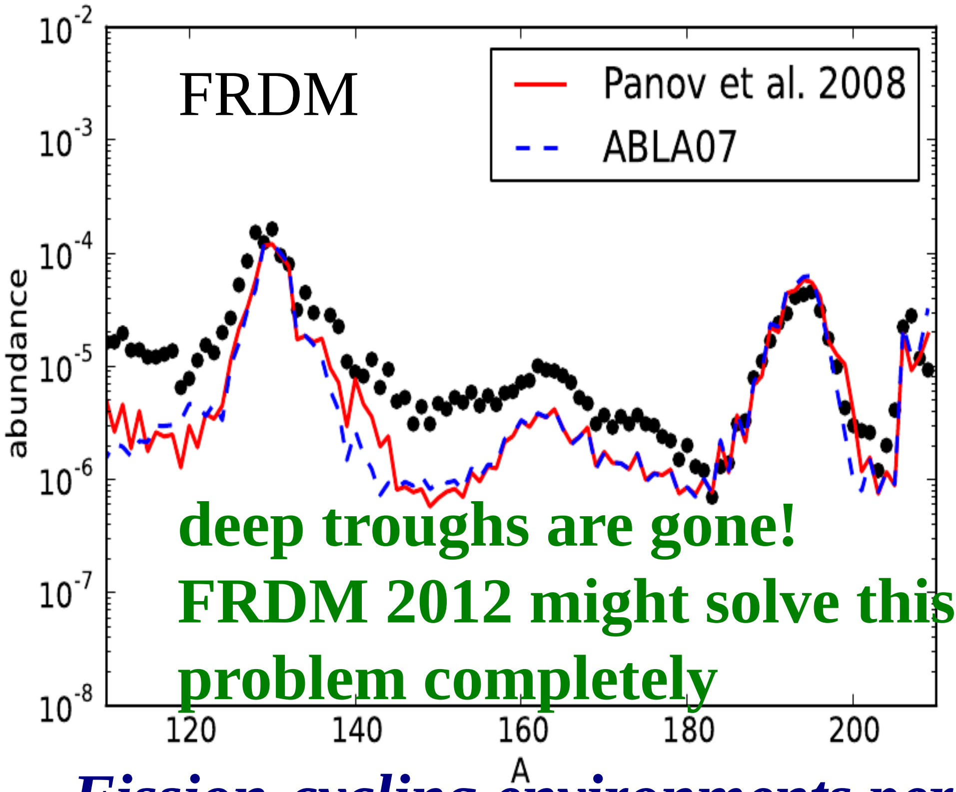
results in 10^{15} Gauss neutron star (magnetar)



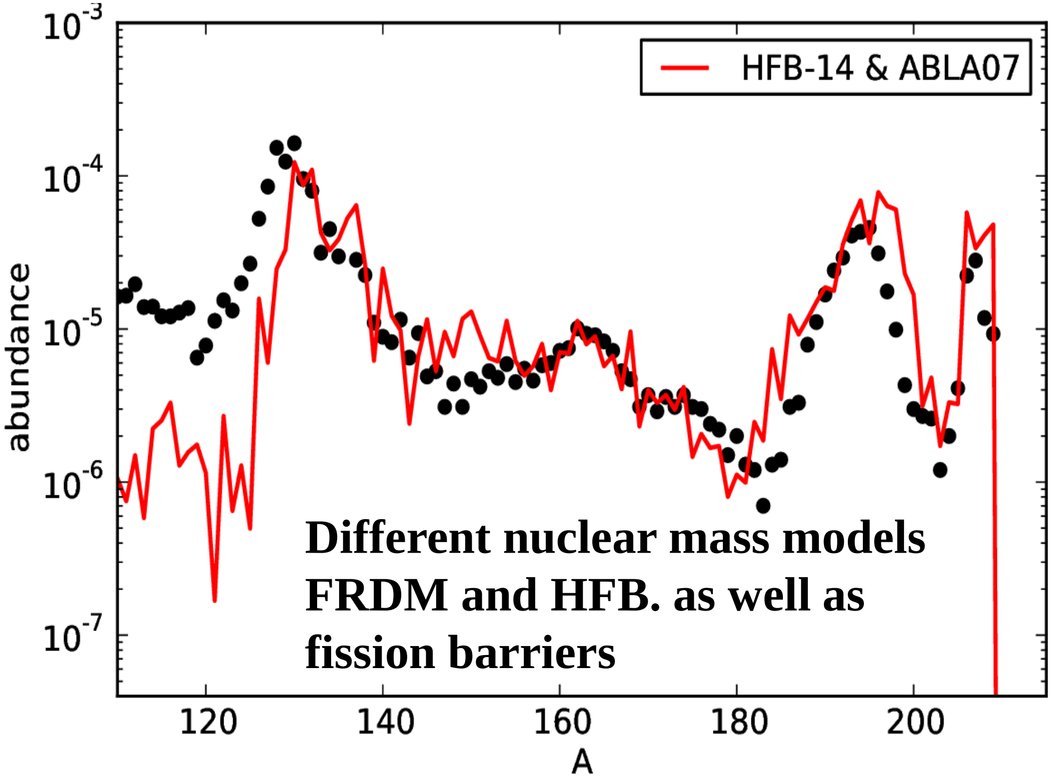
3D simulations by C. Winteler, R. Käppeli, M. Liebendörfer et al. 2012, Eichler et al. 2015 (resulting in neutron-rich jets) – see also Mösta et al. 2014, 2015

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

(Eichler et al. 2015)



deep troughs are gone!
FRDM 2012 might solve this problem completely

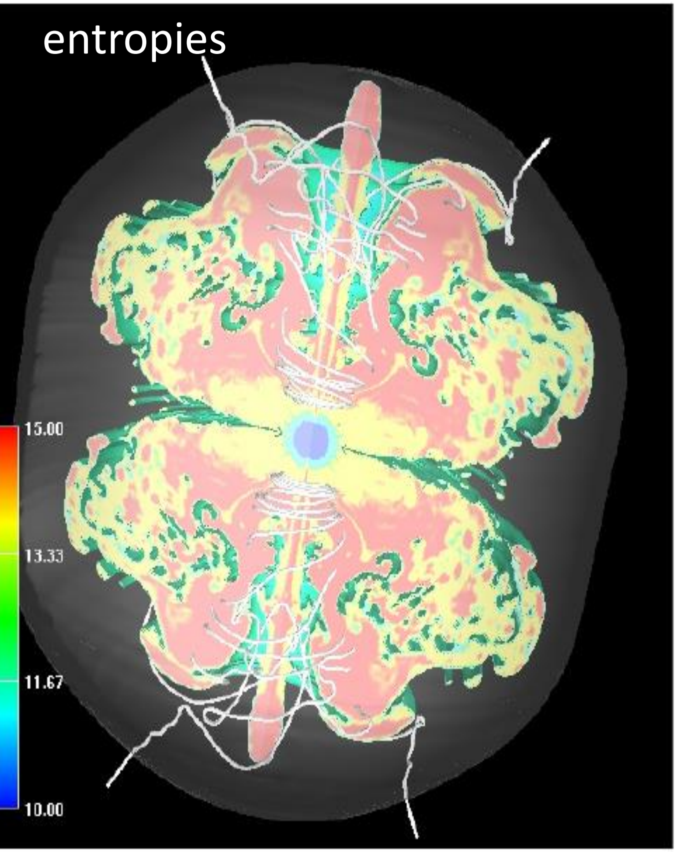


Different nuclear mass models FRDM and HFB. as well as fission barriers

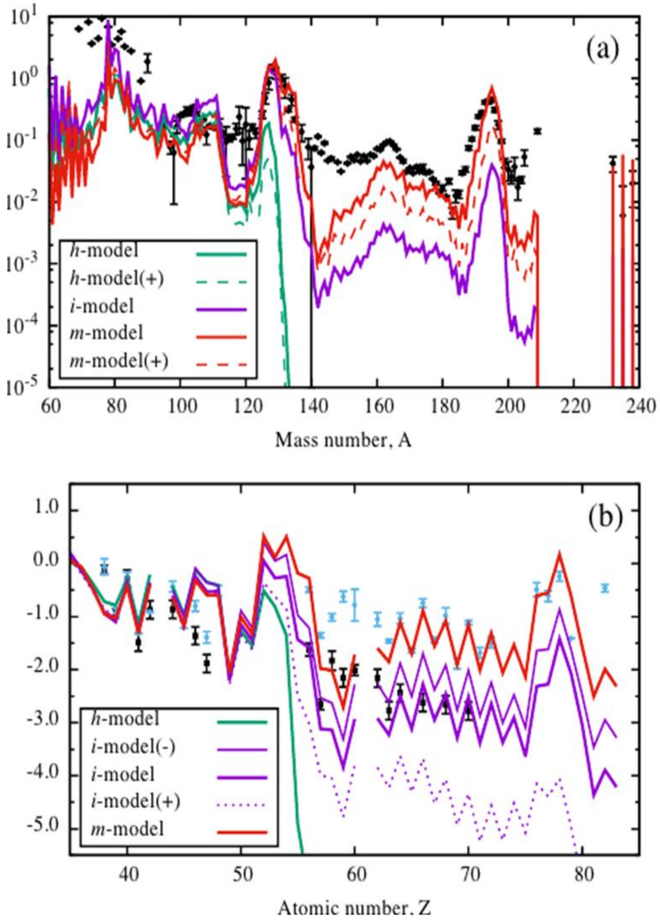
Fission-cycling environments permit n-capture due to fission neutrons in the late freeze-out phase and shifts peaks, but effect generally not strong and overall good fit in such “weak“ fission-cycling environments!

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

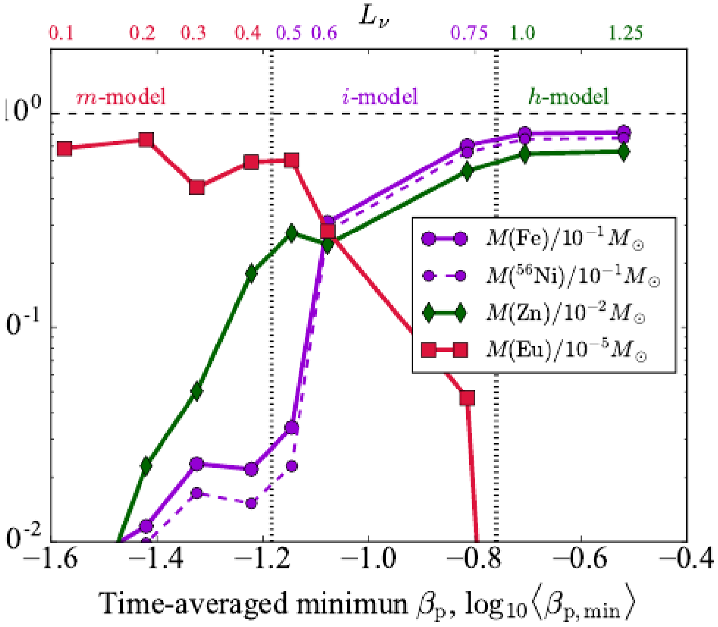
Full MHD calculations resolving the magneto-rotational instability MRI (Nishimura, Takiwaki, Thielemann 2015, Nishimura, Sawai, Takiwaki, Yamada, Thielemann, 2017)



ure 1. Entropy distribution with magnetic field lines of

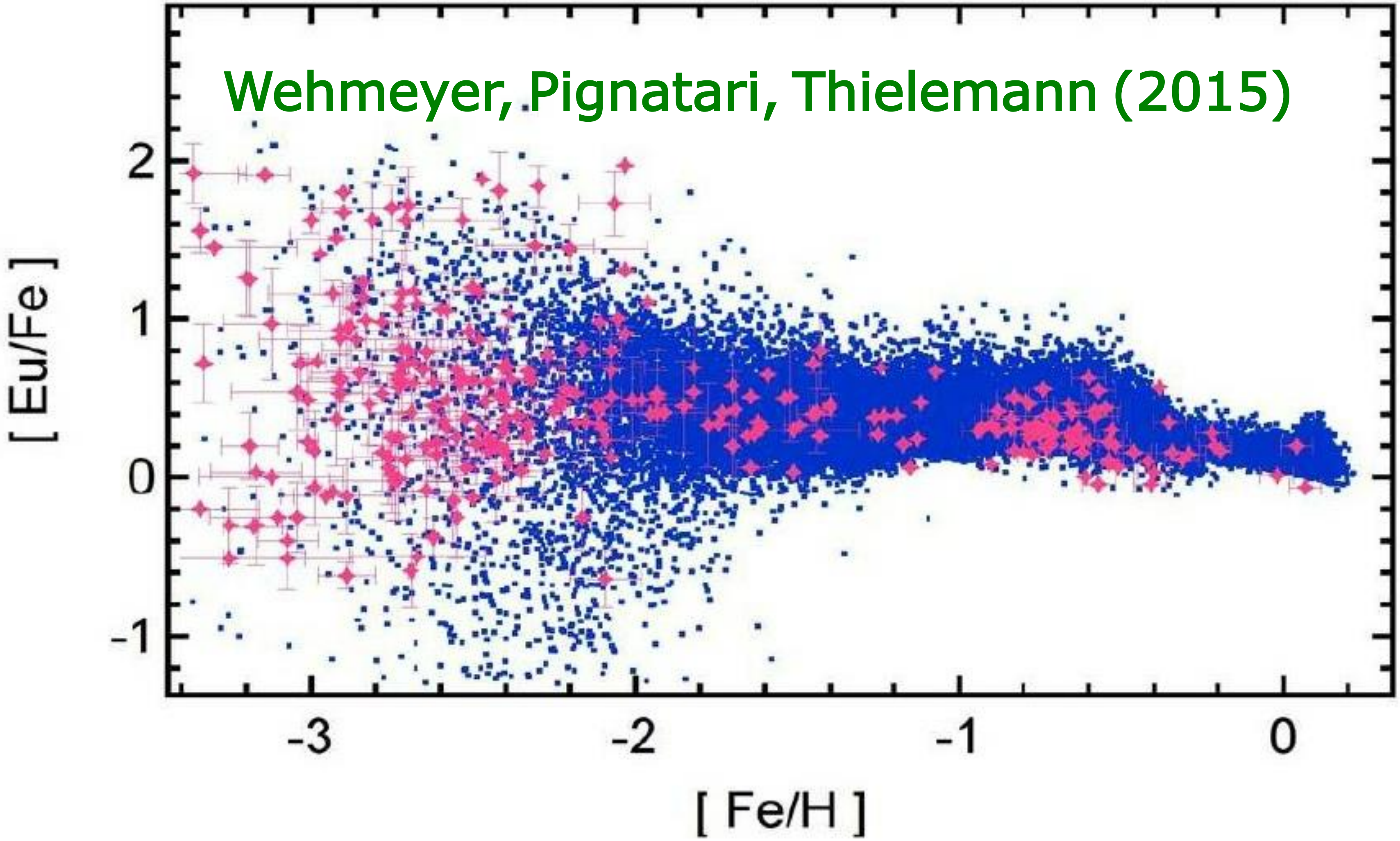


Measuring the ratio of magnetic field strength in comparison to neutrino heating



Dependent on the relation between neutrino luminosity and magnetic fields the nucleosynthesis behavior changes from regular CCSNe to neutron-rich jets with strong r-process. ***Could this be the explanation of the lowest- metallicity behavior in the Milky Way??? What would be the frequency of such objects in comparison to regular CCSNe??? 0.1 to 1 percent?? This would require initial models with rotation and magnetic fields as input.***

Combination of NS mergers and magneto-rotational jets in (stochastic) inhomogeneous GCE

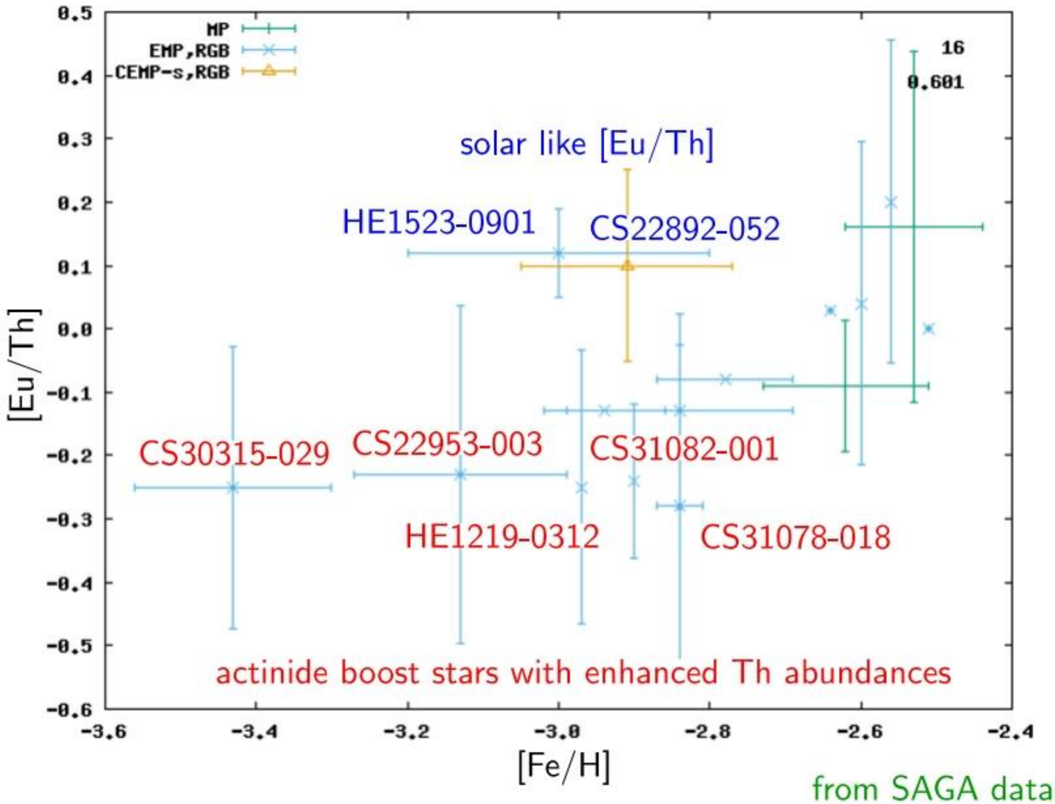


=> in either case, the strong r-process which also produces the actinides is a rare event!!!!!!!!!!!!!

(see also Van de Voort+, Shen+, Hirai, Ishimaru+, Cescutti+)

Actinide abundances in Metal-poor stars

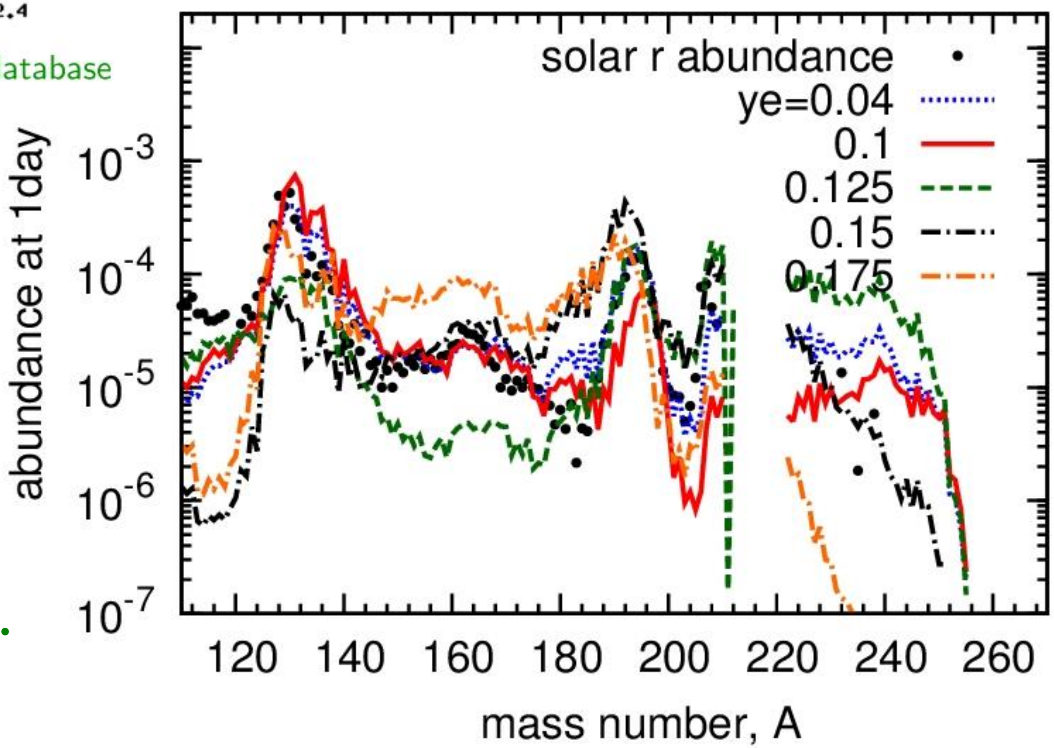
adopted from Wu



from SAGA database

At low metallicities there exist stars with enhanced actinide (here Th) abundances, i.e. [Eu/Th] reduced, not showing the typical «Sneden» pattern. This requires a variation in r-process production pattern. (If NSM pattern robust, what is the stellar origin?)

From Wu+ 2017:
The DZ mass model permits large variations of actinide production, even at «higher» low Ye's, typical in MR-supernovae, which also should contain inherant variation of Ye's, due to variation in rotation/magnetic fields.



Conclusions

- **One can (very probably) reproduce solar system r-process abundances with NSM mergers, the abundances below A=130 might vary, due to individual Ye's obtained in NS winds or viscous disk ejecta**
- ***MHD- (or MR magneto-rotational)-SNe can in the case of fast rotation and high magnetic fields also produce a strong r-process in polar jets; there are probably also intermediate cases leading to a weak r-process or no r-process, the latter essentially resembling regular CC-SNe***
- **Both types of events are rare processes with large ejection masses**
- **NSMs might have problems explaining the r-process history of low-metallicity stars with [Fe/H]<-2.5**
- Possible solutions: large-scale turbulent mixing (to be explained and pushing results towards IMA) or different SFRs in early galactic substructures, or NS kicks have NSM explode in regions not previously polluted by CCSNe
- This can be tested in such substructures, i.e. dwarf galaxies
- ***In all cases (for dwarfs and the entire Galaxy) a better fit might be obtained when also including MR-SNe, which might also explain the observed variation (spread) in [Eu/Fe] at lowest metallicites and also varying U/Th/Eu.***