Stellar Explosions, Galactic Evolution, and my Encounters with Keith

Friedrich-Karl Thielemann

Department of Physics and Gesellschaft für Schwerionenforschung (GSI)

University of Basel, Switzerland

Darmstadt, Germany

FNSNF

European Research Council
Established by the European Commission

compstar

Cost Action ChETEC

Happy Birthday

Keith

Our first encounter was in early April 1980, when I arrived at Chicago's O'Hare Airport for my first postdoc with Dave Schramm and Dave Arnett. You picked me up with a sign for Karl Thielemann and on the way down to Hyde Park asked me whether I would like to change my initial accommodation from the International House to rather share an apartment with you and Stuart Sherman, a graduate student of Dave Arnett who worked on spectra and light curves of Supernonae.

This was a period of great exchanges, I was introduced by both of you to Chicago's North Side and all its Blues Bars on weekends and enjoyed your company tremendously. On other occasions I also explored the bars in the south with a German friend, was once on gunpoint, i.e. had enormous experiences.

I also watched the **Blues Brothers movie** and **the Empire Strikes Back** during that year of 1980, learned to ride the L,

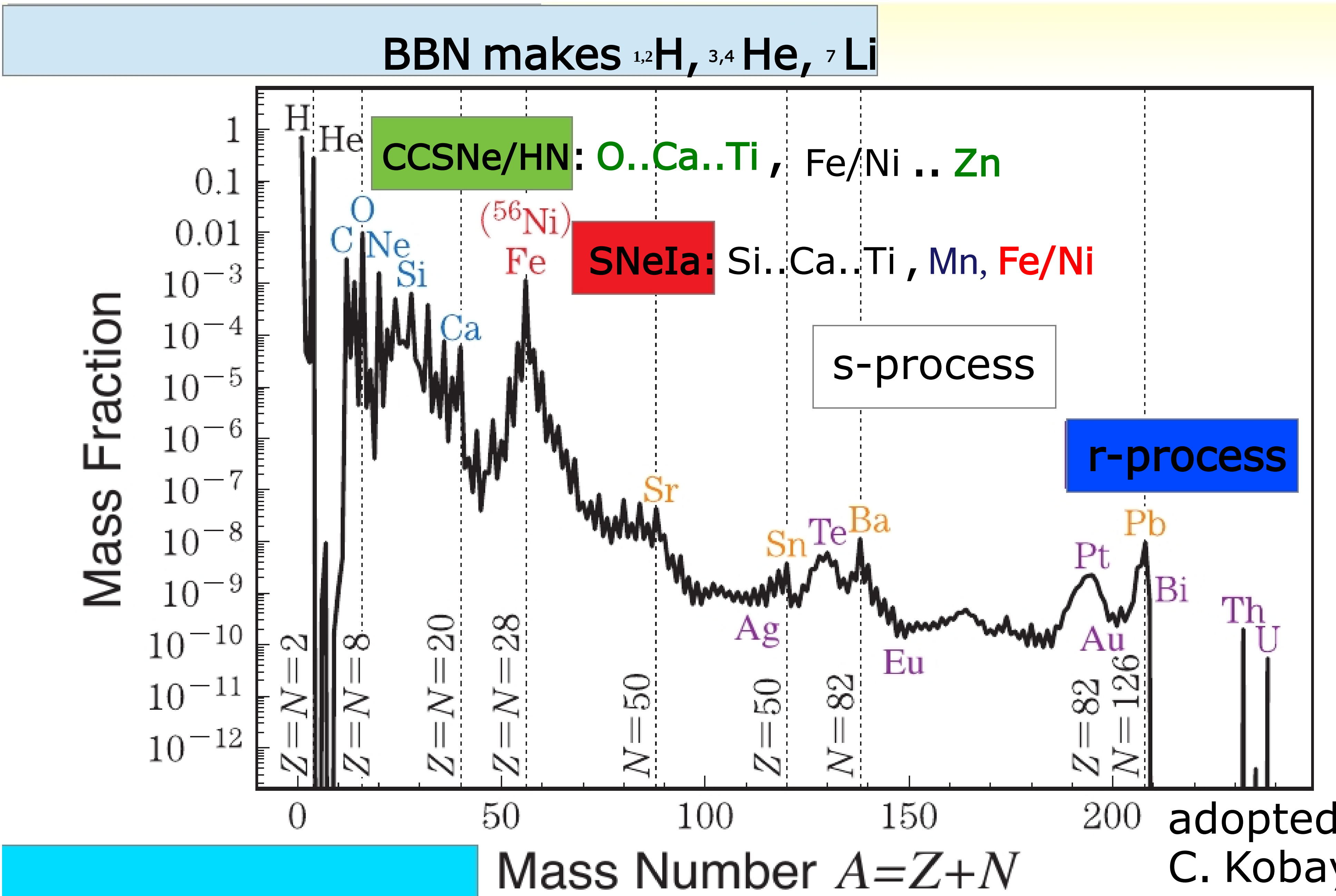
and besides all these great impressions about Chicago, learned a lot of astro/particle physics with the crowd of the Astrophysics & Astronomy Department and the Enrico Fermi Institute.

THE UNIVERSITY OF CHICAGO

After my return to Europe, I had a postdoc at the Max Planck Institute in Garching/Munich and Keith stayed at CERN. We had a number of exchanges, Keith still always with his husky Fog. Keith came to visit Munich for the October Fest, and I had a great visit to Geneva for Keith's wedding.

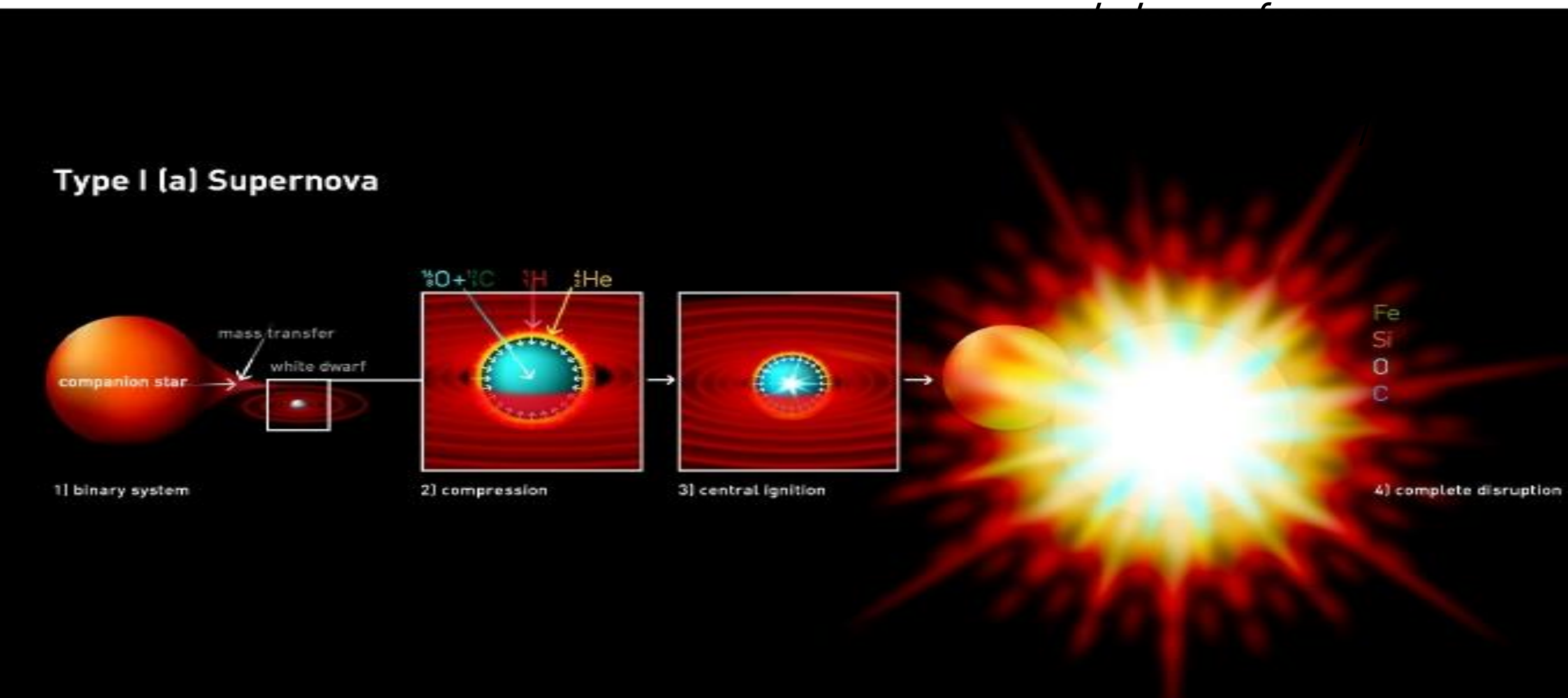
These are photographs of the wedding ceremony, unfortunately I have only the participants here, not groom and bride!

But now to science, where explaining the elements and their isotopes in the cosmos is my research field



adopted from C. Kobayashi

Chandrasekhar mass models (single degenerates)



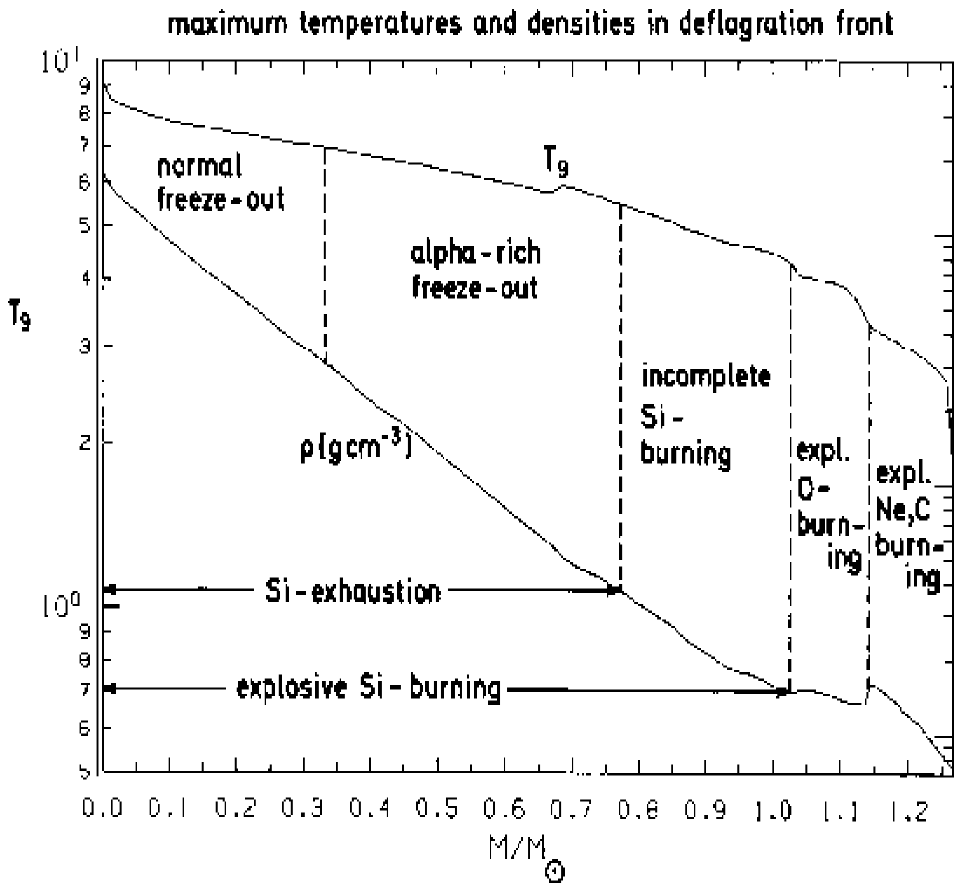
binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions)

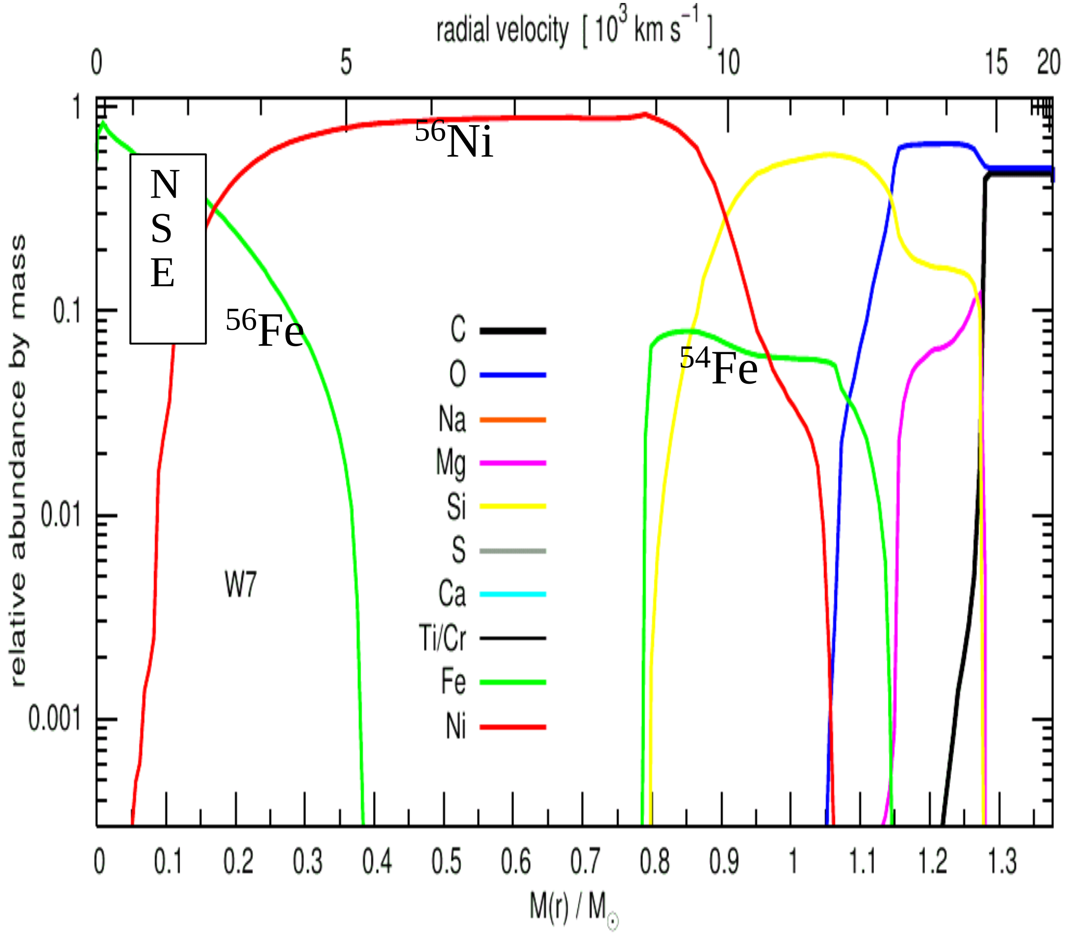
- white dwarfs (novae, type Ia supernovae= single degenerate)

Possible explanations: WD mergers (Röpke … double degenerates), He-accretion caused (double) detonations (Bildsten …), & collisions (Rosswog, Pakmor, Raskin, Cabezon)

"historical" understanding (W7, Nomoto, Thielemann, Yokoi et al.)

Type Ia supernovae show large $^{56}Ni(\rightarrow {}^{56}Fe)$ productions



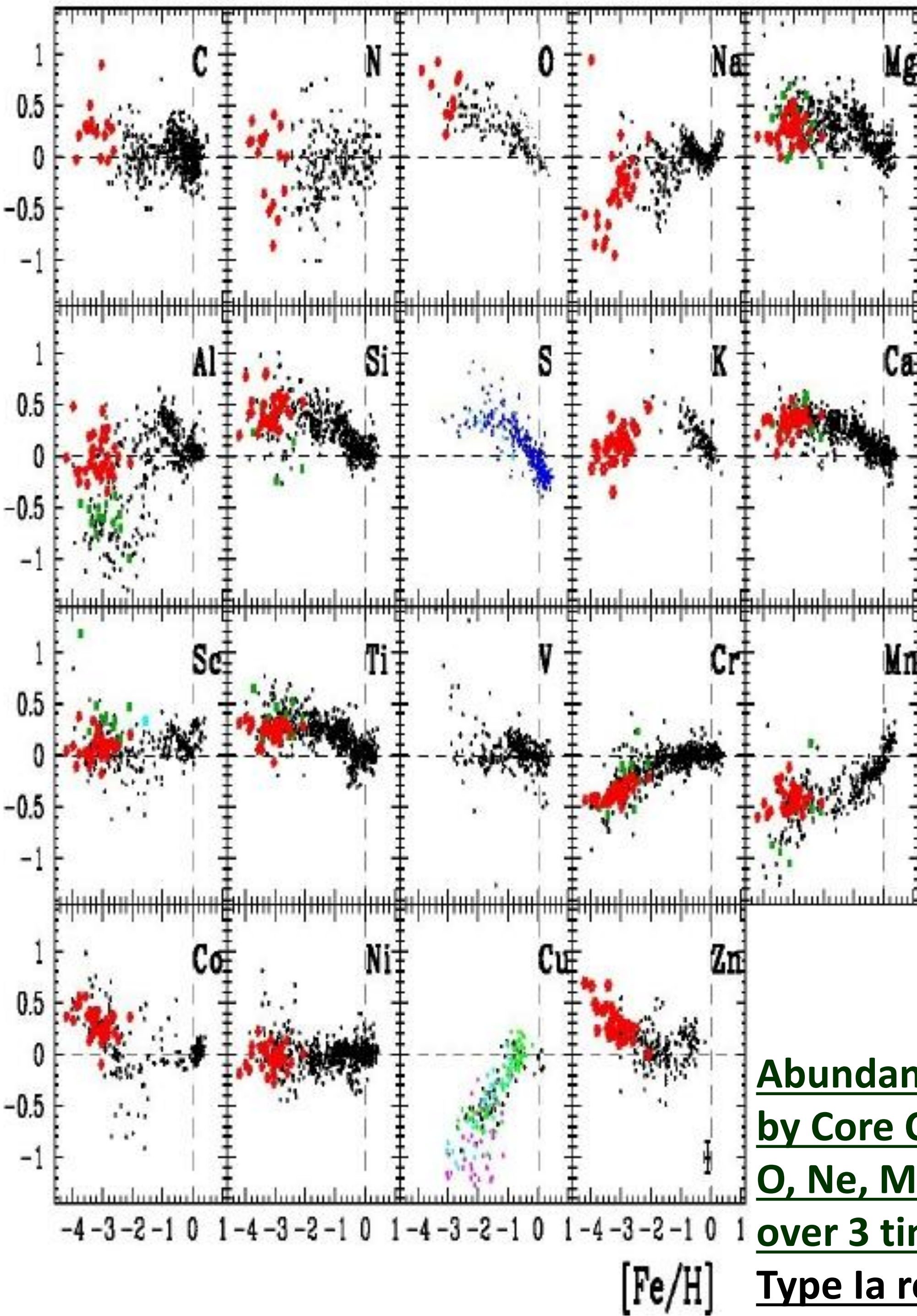


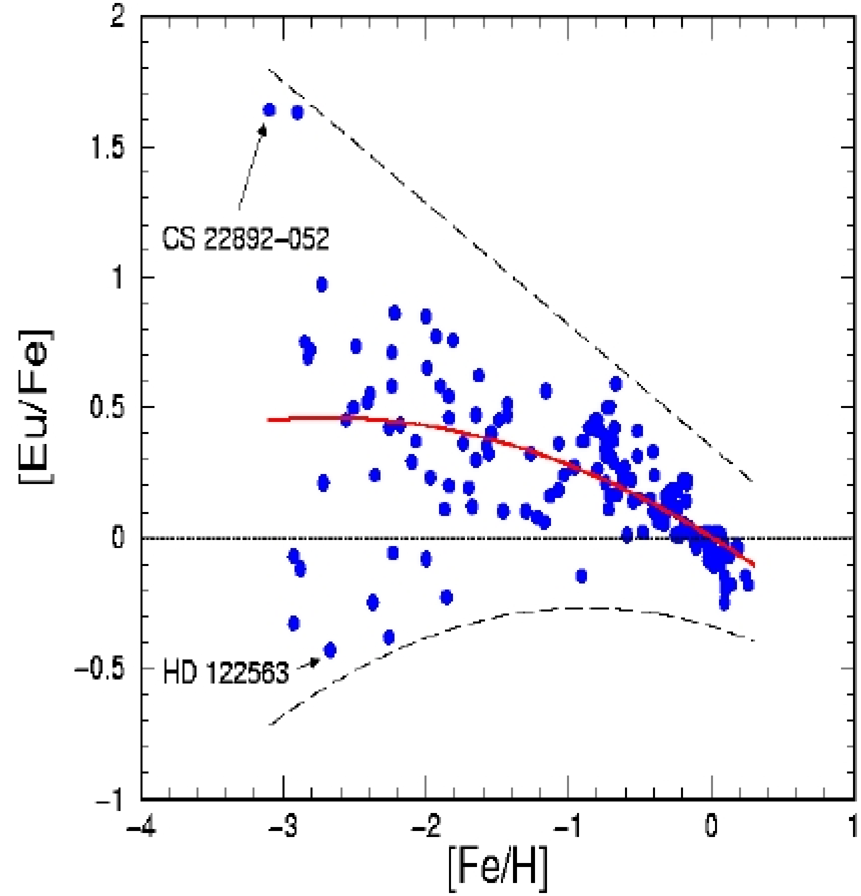
a **deflagration (subsonic burning front)** with a **propagation speed** related (initially) to **heat conduction** and (later) to **mixing via Rayleigh-Taylor instabilities** (treated in time-dependent mixing length theory of 0.7 times the pressure scale height).

Total outcome close to 0.6 Msol of ^{56}Ni, important for galactic evolution for [Fe/H]>-1

Y_e in inner zones determined by electron capture (electrons degenerate with high Fermi energy), in outer zones by metallicity (-> ^{54}Fe, ^{58}Ni).

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

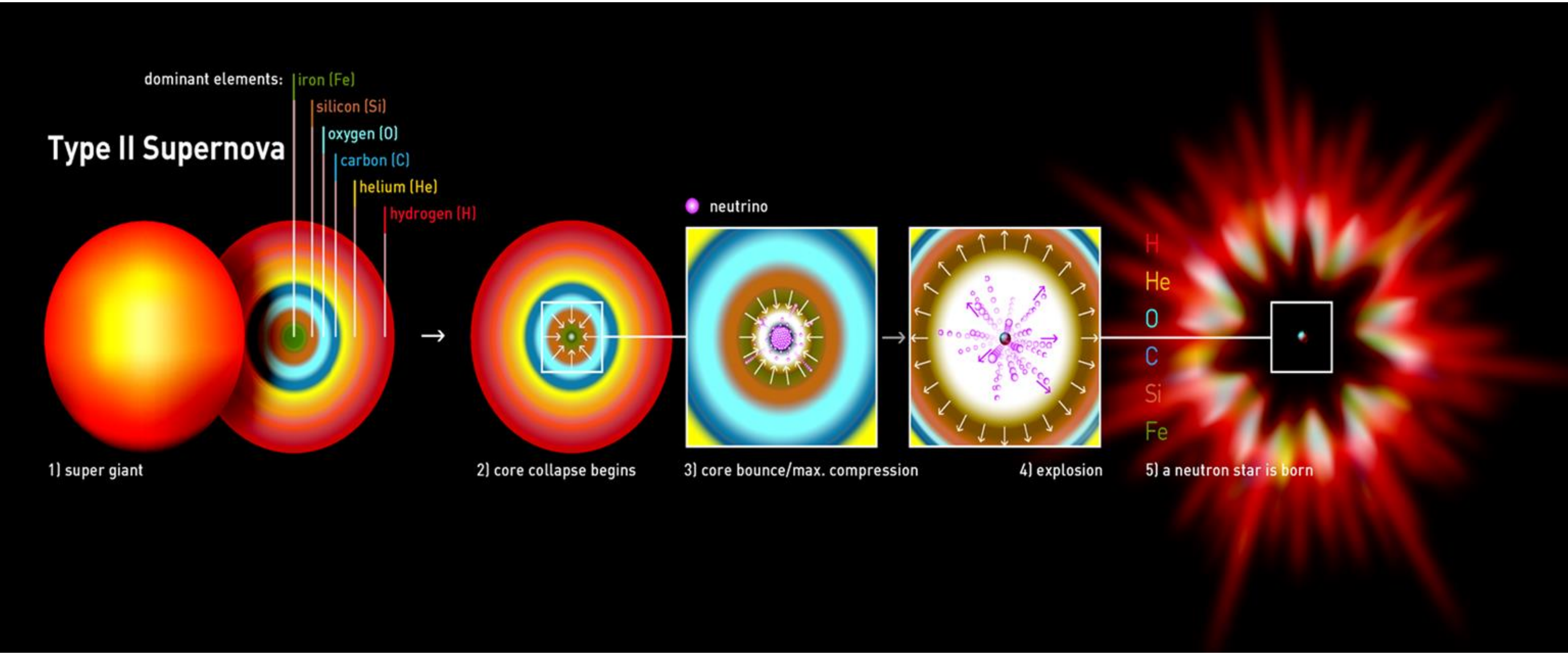




Average r-process (Eu) behavior resembles CCSN contribution, but large scatter at low metallicities!!

Abundances at metallicities below [Fe/H]=-1 are dominated by Core Collapse Supernovae, especially the alpha-elements O, Ne, Mg, Si, S, Ca, Ti to Fe ratios come with abundances over 3 times solar (log10=0.5] from CCSNe. Above [Fe/H]=-1 Type Ia reduce the [X/Fe] ratios.

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



Main products: O, Ne, Mg, Si, S, Ar, Ca, Ti and some Fe/Ni: How about heavier nuclei (Zn .. Sr, Y, Zr)

and the r-process ?????

Our only joint papers: 1 in ApJ, 1 Conf. Proc., just about the role of CCSNe and their upper mass limit (not yet resulting in black holes)

THE ASTROPHYSICAL JOURNAL, 313:813–819, 1987 February 15

CHEMICAL EVOLUTION, STELLAR NUCLEOSYNTHESIS, AND A VARIABLE STAR FORMATION RATE

KEITH A. OLIVE
School of Physics and Astronomy, University of Minnesota

AND

FRIEDRICH-KARL THIELEMANN AND JAMES W. TRURAN
Department of Astronomy, University of Illinois
Received 1986 May 30; accepted 1986 August 5

ABSTRACT

We consider the effects of a decreasing star formation rate (SFR) on the galactic abundances of elements produced in massive stars ($M \gtrsim 10\ M_\odot$). On the basis of a straightforward model of galactic evolution, a relation between the upper mass limit of Type II supernovae (M_{SN}) contributing to chemical evolution and the decline of the SFR (τ) is derived, when the oxygen abundance is determined only by massive stars. The additional requirement that all intermediate-mass elements (Ne–Ti), which are also predominantly due to nucleosynthesis in massive stars, be produced in solar proportions leads to unique values of M_{SN} and τ. The application of this method with abundance yields from Arnett and from Woosley and Weaver results, however, in contradicting solutions: $M_{SN} \approx 45\ M_\odot$, $\tau = \infty$; and $M_{SN} \approx 15\ M_\odot$, $\tau = 3 \times 10^9$ yr. Thus, in order that this approach provide an effective probe of the SFR over the history of our Galaxy, it is essential that converging and more accurate predictions of the consequences of stellar and supernova nucleosynthesis will be forthcoming.

Subject headings: nucleosynthesis — stars: abundances — stars: formation — stars: stellar statistics — stars: supernovae

In 1986 Keith visited Urbana/Champaign for a talk, I was in Illinois then before leaving for Harvard. This was the result!

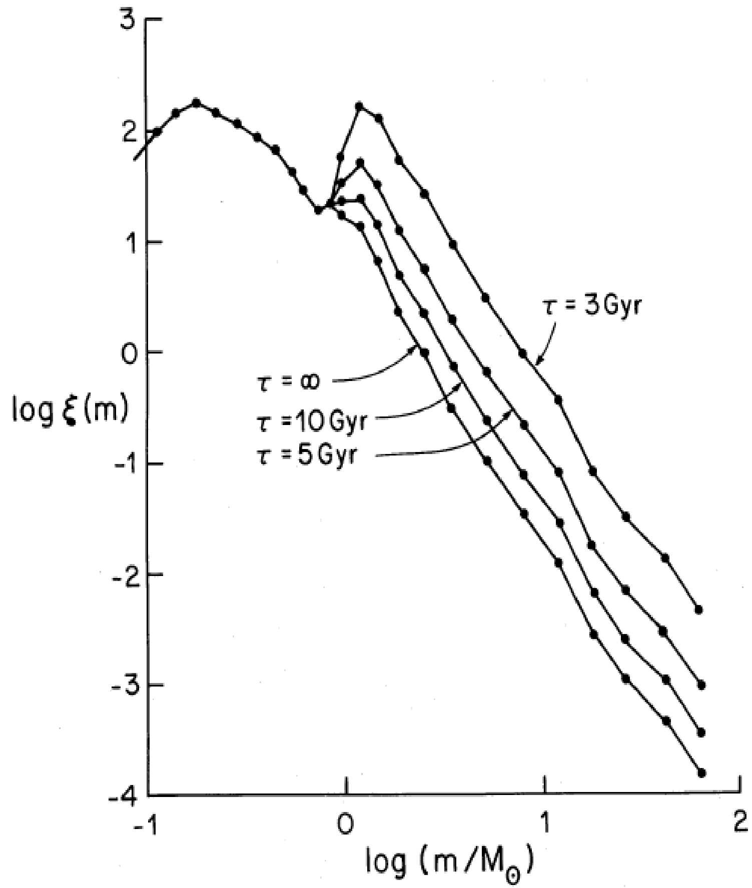


FIG. 1.—IMF (from Scalo 1986) for various values of τ (the decay constant of the SFR).

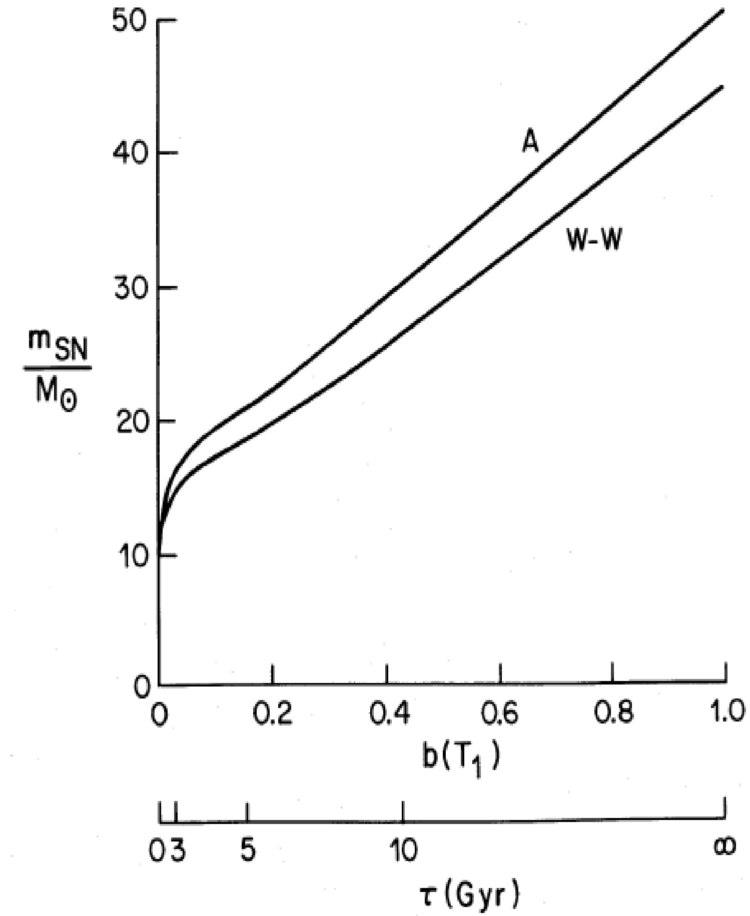


FIG. 2.—Upper mass limit for a supernova explosion as a function of τ or the present relative birthrate $b(T_1)$. The limit is derived assuming that the produced oxygen abundance agrees with the solar value.

Initial Mass Function for different decline time scales of the star formation rate

Upper Mass limit for CCSNe with neutron star formation, as a function of SFR decline time scale for different supernova yields from Arnett and Woosley & Weaver (*in 1985*)

Present Situation:

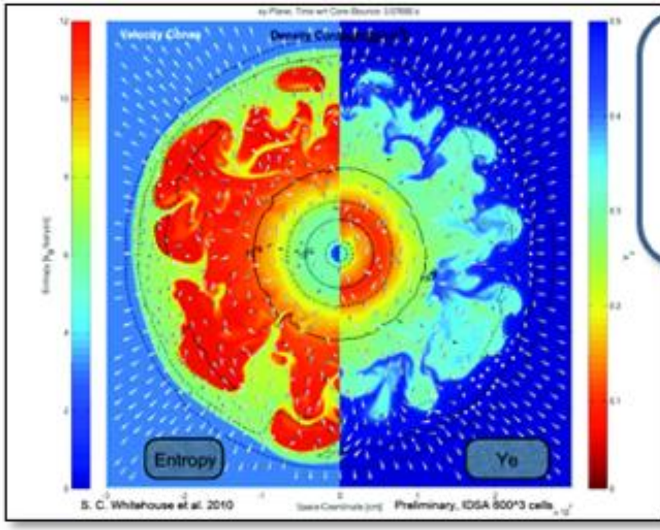
Solving the Core-Collapse Supernova Problem in a Self-Consistent Way

There exists a growing set of 2D and 3D CCSN explosions, see e.g. reviews (and talks) by:
Janka (2012, Ann. Rev. Nucl. Part. Sci.),
Burrows (2013, RMP),
Foglizzo+ (2015, PASA)

active groups:
Garching/Belfast/Monash (Janka+, Müller),
Princeton/Caltech/North Carolina (Burrows, Ott, Couch),
Oak Ridge (Mezzacappa, Hix, Lenz ..)
Tokyo/Kyushu (Takiwaki, Nakamura, Kotake),
Paris (Foglizzo+),
Basel (Liebendörfer, Cabezon, Kuroda, Pan)

but in order to provide complete nucleosynthesis predictions from self-consistent multi-D simulations it is still a bit too early!!!

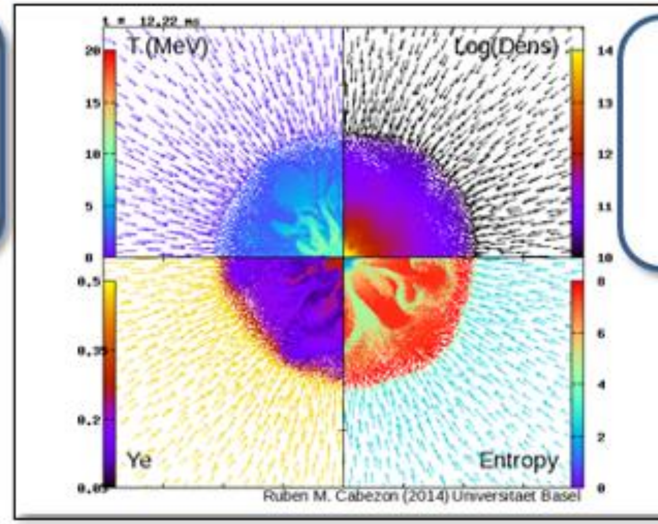
Basel activities with IDSA (Isotropic Diffuions Source Approximation)



Elephant

3D IDSA
Cartesian mesh
1D GR potential

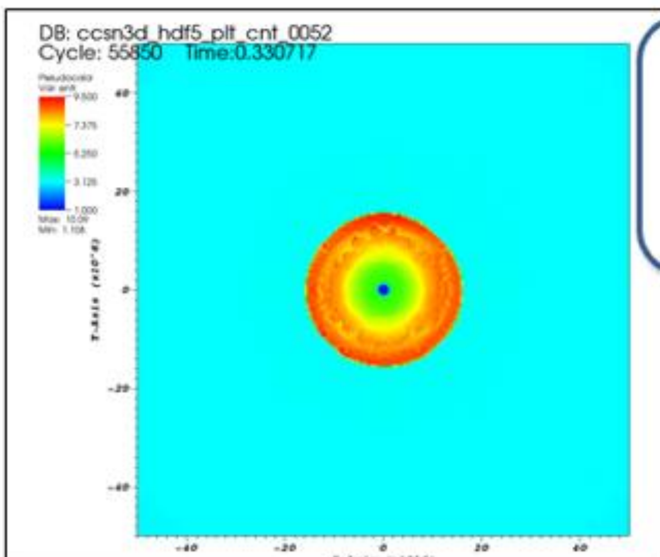
M. Liebendörfer
S. C. Whitehouse
R. Käppeli



SPHYNX

ASL
SPH
3D Newtonian

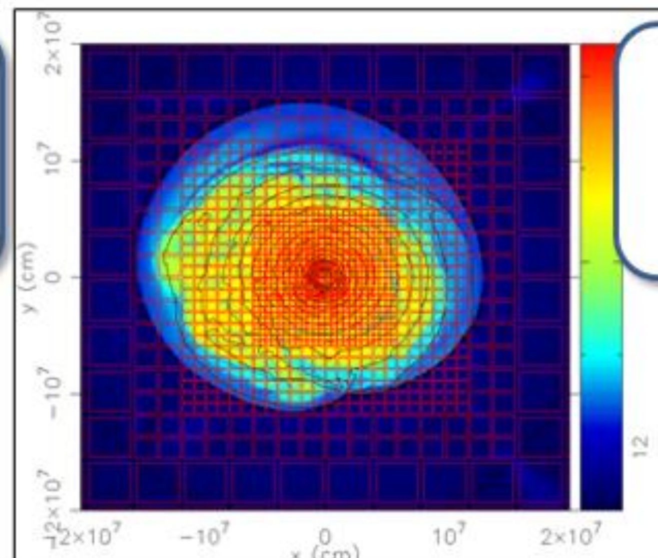
R. M. Cabezón



FLASH

3D IDSA
AMR
3D Newtonian

K.-C. Pan



fGR_M1

M1
Nested meshes
3D GR

T. Kuroda

Interim Approaches

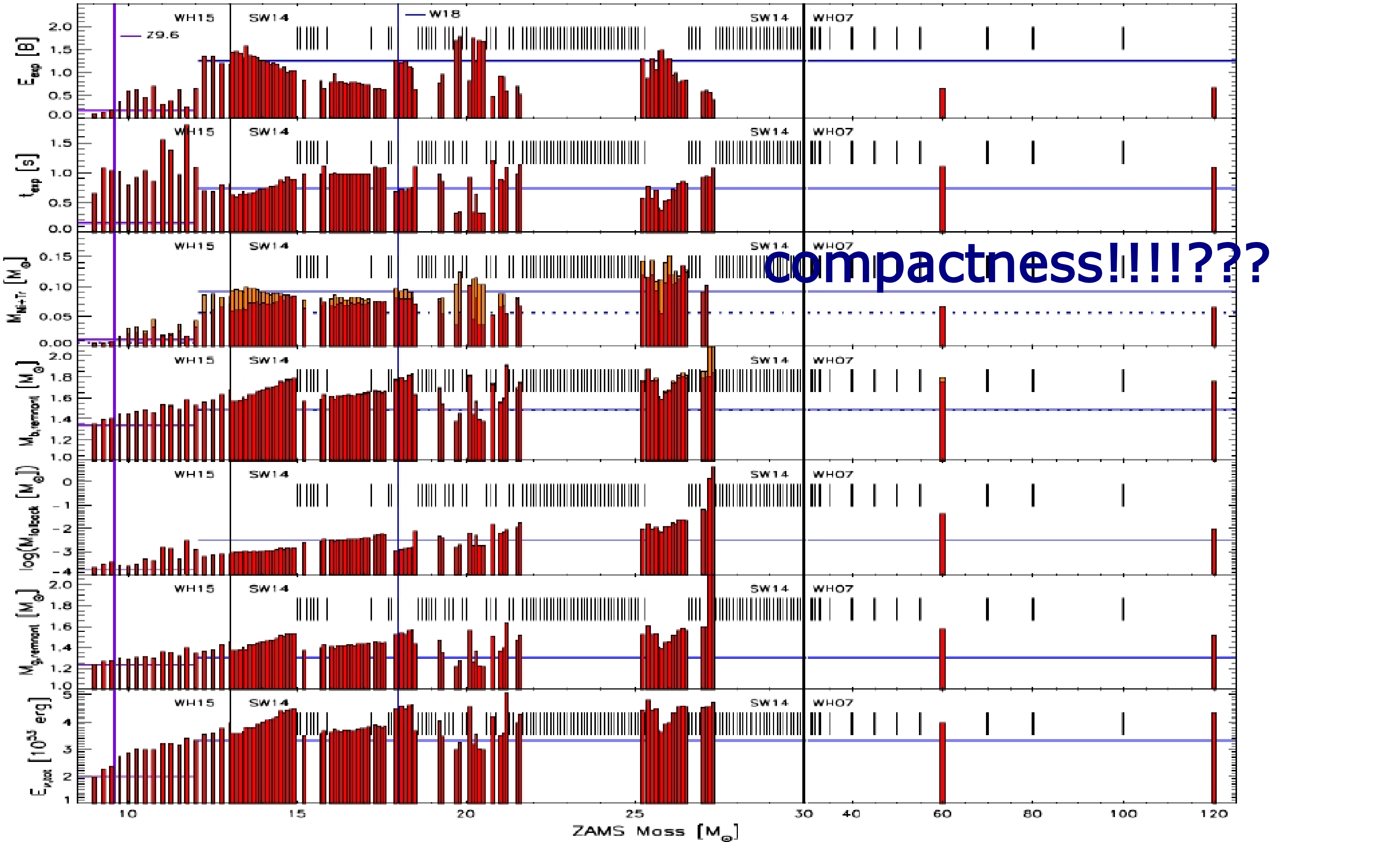
Trying to mimic multi-D neutrino heating in a spherical approach, for more appropriate predictions of the explosion energy, mass cut between neutron star and ejecta, as well as nucleosynthesis (including the effects of neutrinos on Ye, the proton/nucleon ratio):

- Fröhlich et al. (2006,2007) multiplying neutrino-capture rates by a factor to obtain observed explosion energies
- Ugliano et al. (2012), Ertl et al. (2015) – a tuned, time-dependent central neutrino source that approximately captures the essential effects of (3D) neutrino transport – **PHOTB**
- Perego et al. (2015), Ebinger et al. (2017, PhD and in preparation – utilizing energy in muon and tau neutrinos as an additional energy source that approximately captures the essential effects of (3D) neutrino transport - **PUSH**

The latter approaches make it possible, to predict a variation of explosion energies as a function of stellar mass (and other parameters) and thus improved nucleosynthesis yields for chemical evolution modeling → detailed results now from Sukhbold et al. (2016) (.. but only PUSH includes Ye-effects of neutrinos)

Outcome of Collapse: SN-Explosion or BH with PHOTB

(Sukhbold + 2016): Does this tell us something about explosion models or pre-collapse stellar models? (red bars - explosions, black bars – black hole formation)



Results with PUSH (Ebinger et al. 2017)

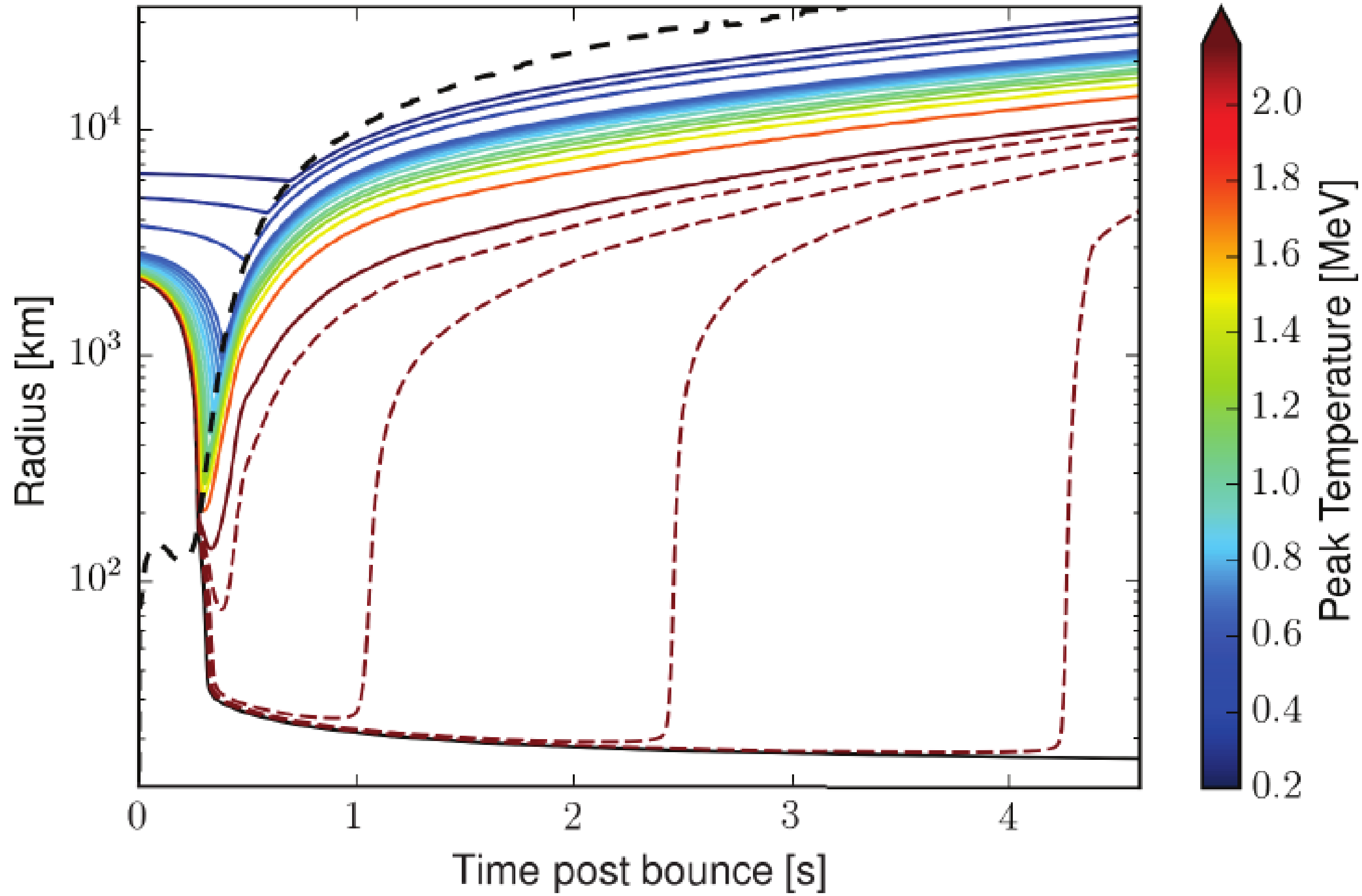
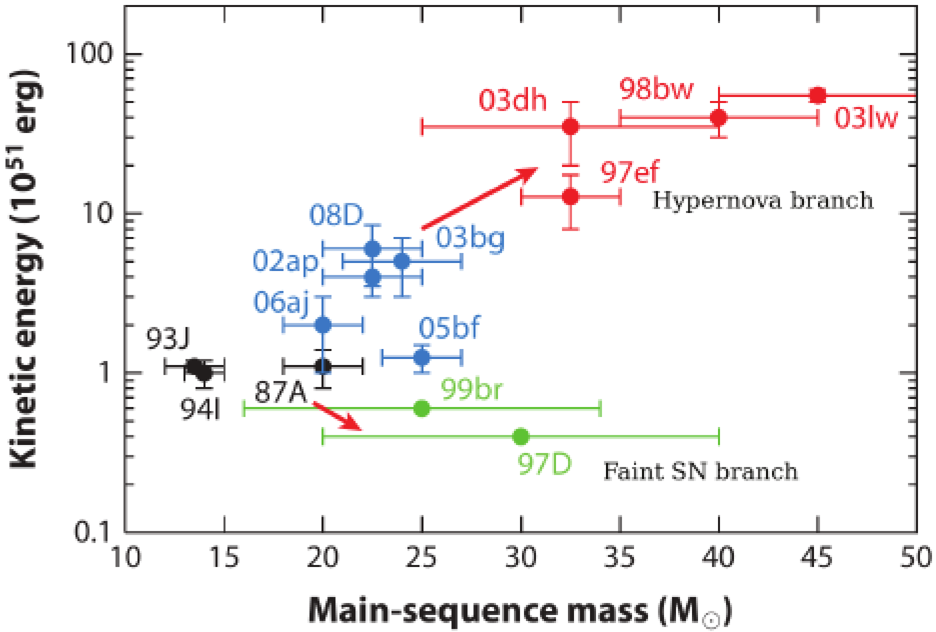
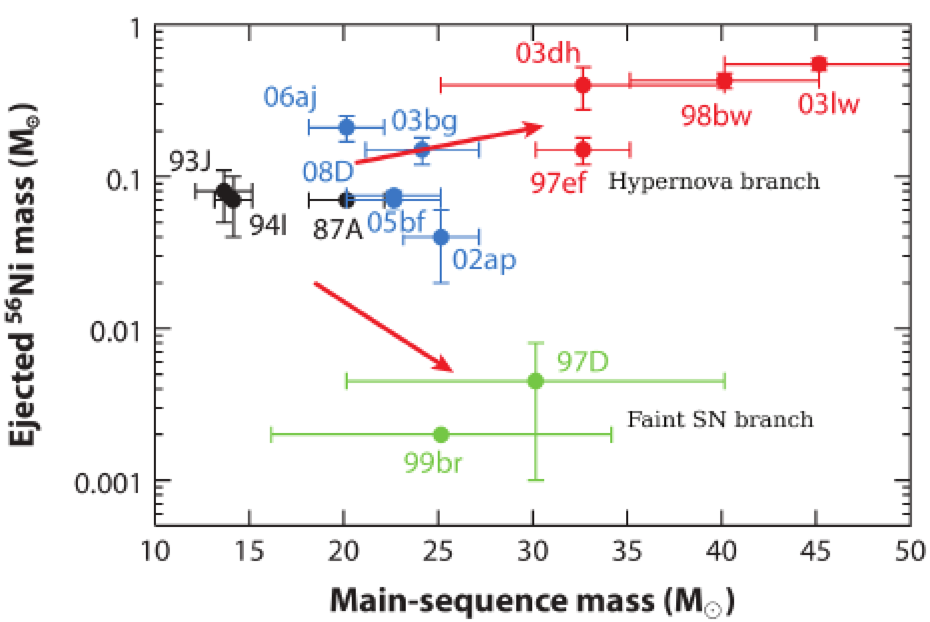


Fig. 3.8.: We show the mass tracers for a PUSH model (progenitor: 15 $M_\odot$ [47], $k_{\rm PUSH}$ =3.5, $t_{\rm rise}$ =200). The black line denotes the PNS surface, the dashed tracer lines (increasing in mass with steps of 10^{-3} $M_\odot$) are delayed ejecta (wind) that reach temperatures around 4 MeV before they are ejected. The colors of the remaining tracers denote their peak temperatures (the first six colored lines are separated by 5×10^{-3} $M_\odot$, then the next six by 10^{-2} $M_\odot$, and the last three tracers are separated by 0.1 $M_\odot$. The black dashed line denotes the shock front.

What do we expect from observations? according to Nomoto et al. (2015):



(a) Explosion energy as a function of the ZAMS mass of the progenitors for several SN and HNe reported by different authors.



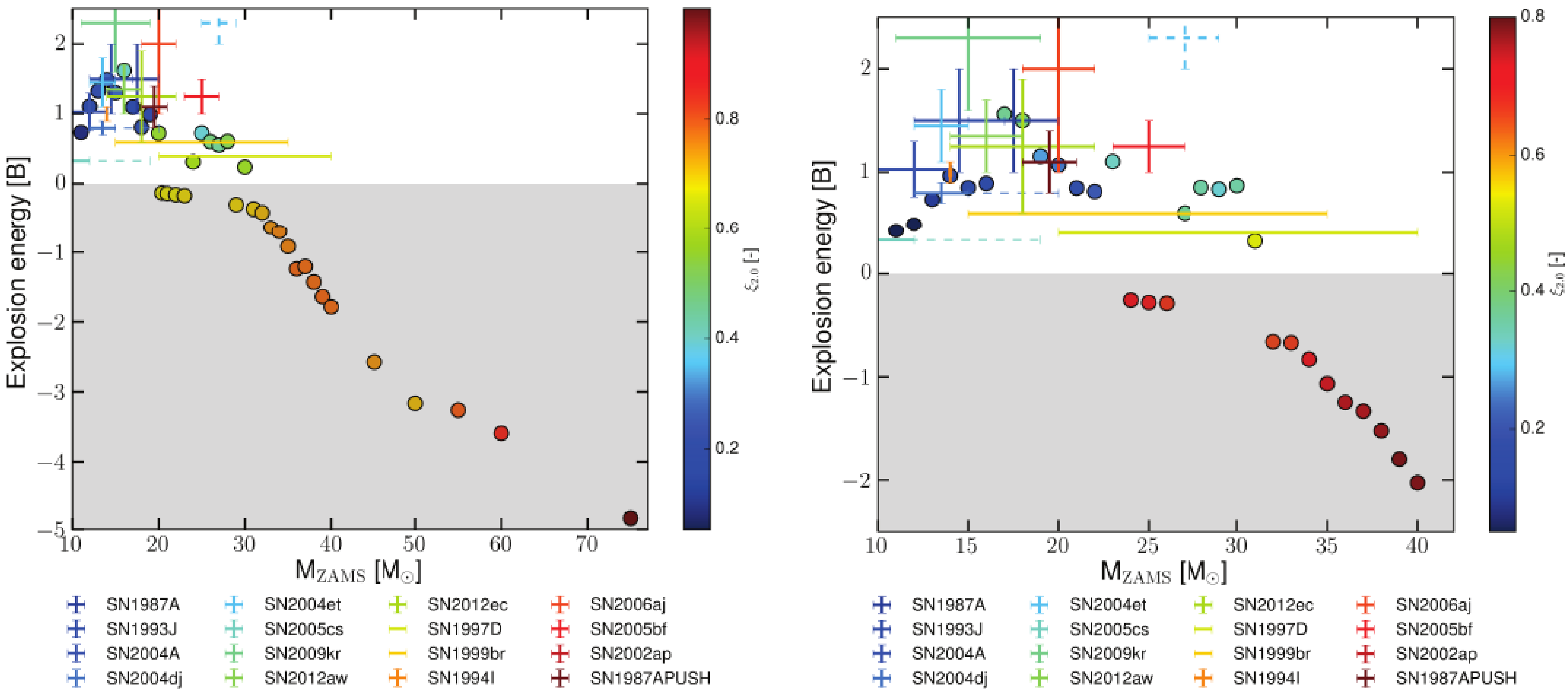
(b) Ejected ^{56}Ni masses as a function of the ZAMS mass of the progenitors for several SN and HNe reported by different authors.

Analysis of Supernova Observations:

1. **Beyond 25-30 Msol there is a transition from regular CCSNe with neutron stars to black hole formation**
2. **The explosions get less energetic and black holes form -> fainter and fainter supernovae**
3. **In rare cases for fast rotation (and possibly large magnetic fields) a black hole forms , combined with a long-duration gamma-ray burst (hypernova)**

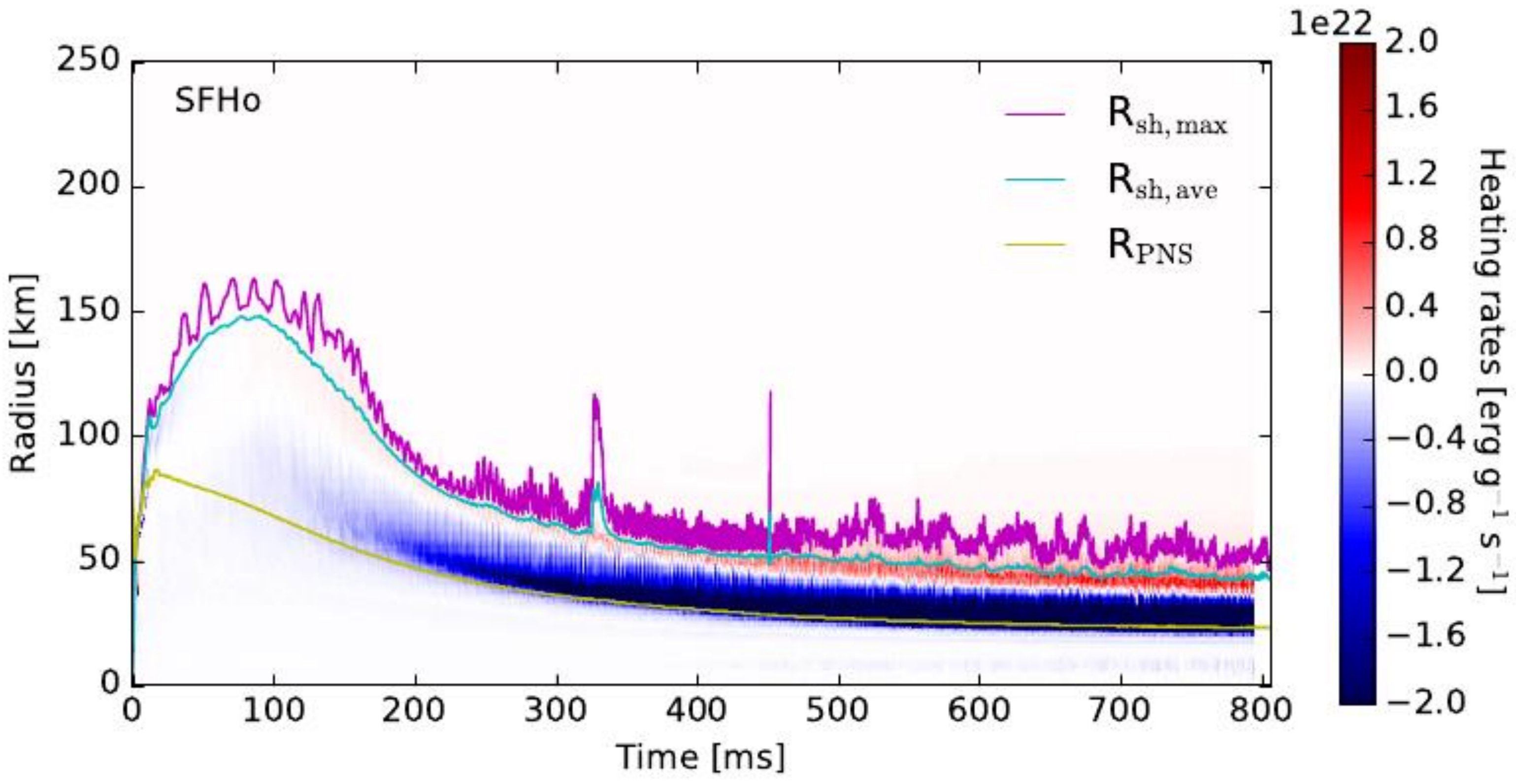
(for models without rotation 2. should be obtained)

Results of the PUSH Approach:
Black hole formation beyond about 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!!!!!!

Multi-D Simulations of a 40 Msol Progenitor Star
K.-C. Pan et al. (2017, in preparation)



This is a 2D simulation, which are typically more favorable than full 3D models, and it shows the collapse to a black hole. Due to convective blobs of material the maximum of the shock radius ($R_{sh,max}$) seems to oscillate with time, and it recedes with time. SFHo is a specific Equation of State (EoS) for hot and dense matter utilzed here,

Predicted Gravitational Wave strength, when utilizing different EoS for the simulations
K.-C. Pan et al. (2017, in preparation)

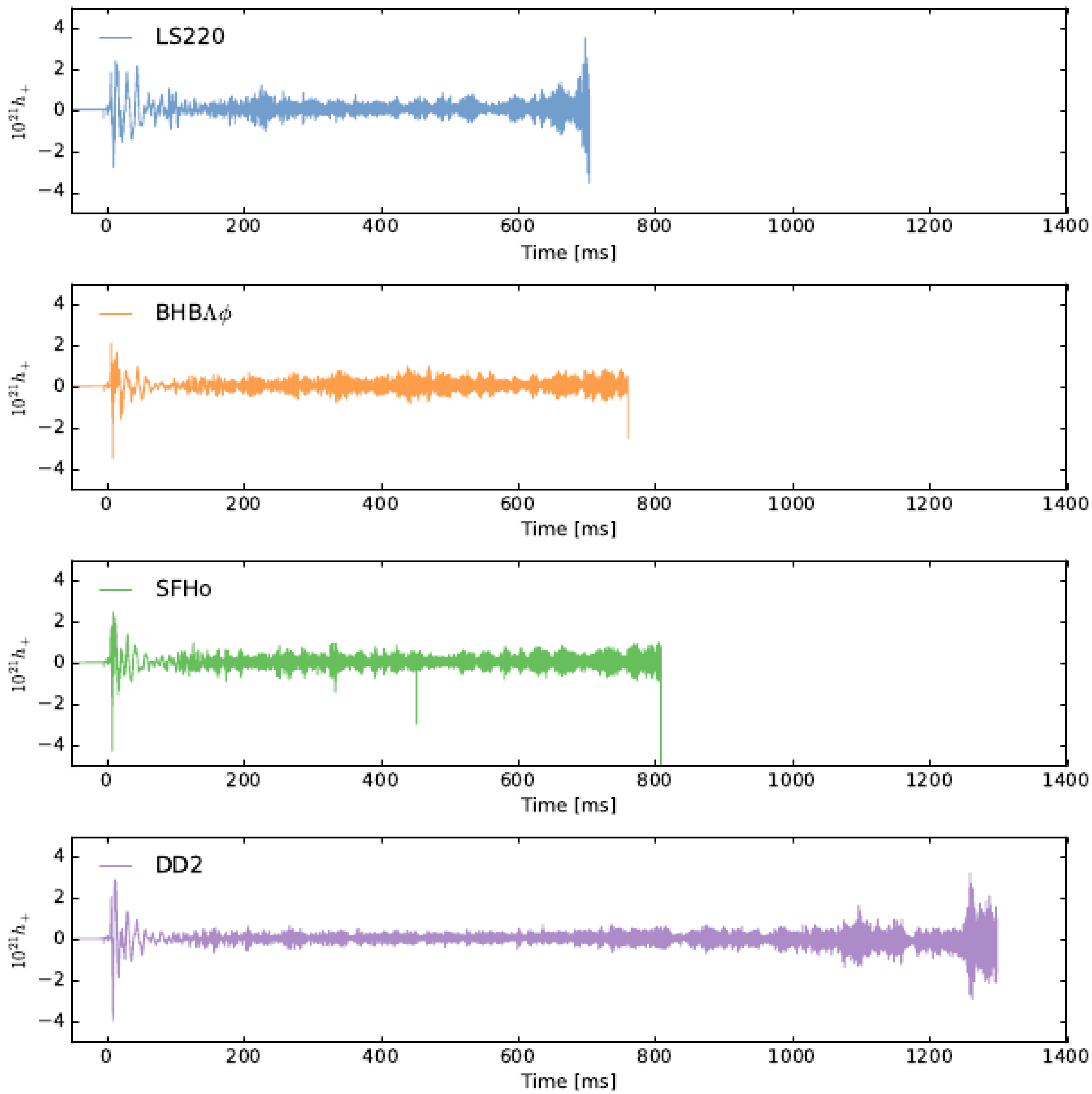
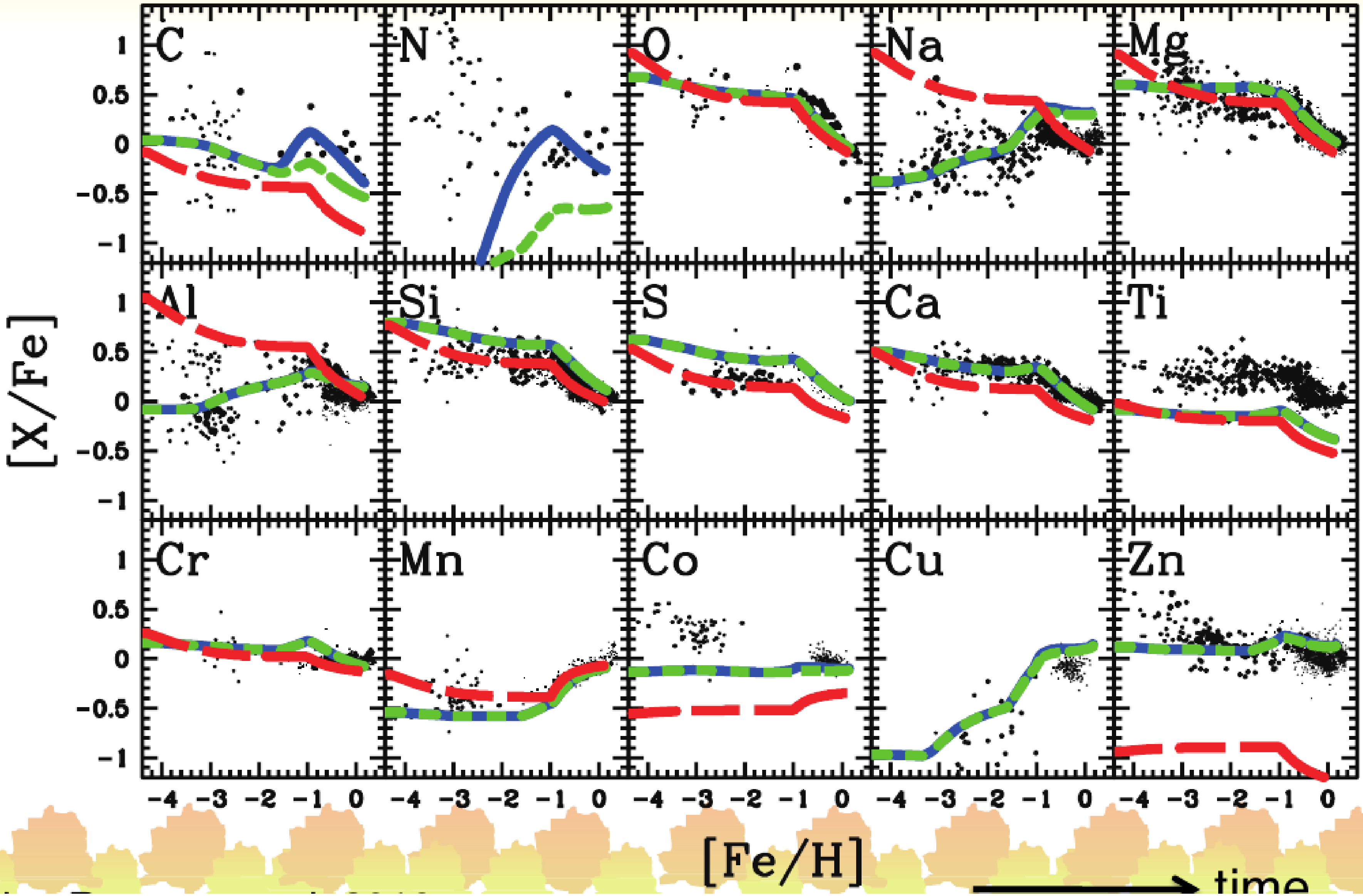


Figure 7. GW amplitudes as functions of time after core bounce with an assumption of 10 pc distance. From top to bottom, LS220, BHBΛφ, SFHo, and DD2 EoS, respectively. In the top three panels, a BH formed at the end of simulation.

Improvements in understanding chemical evolution of galaxies

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

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



from C. Kobayashi 2015

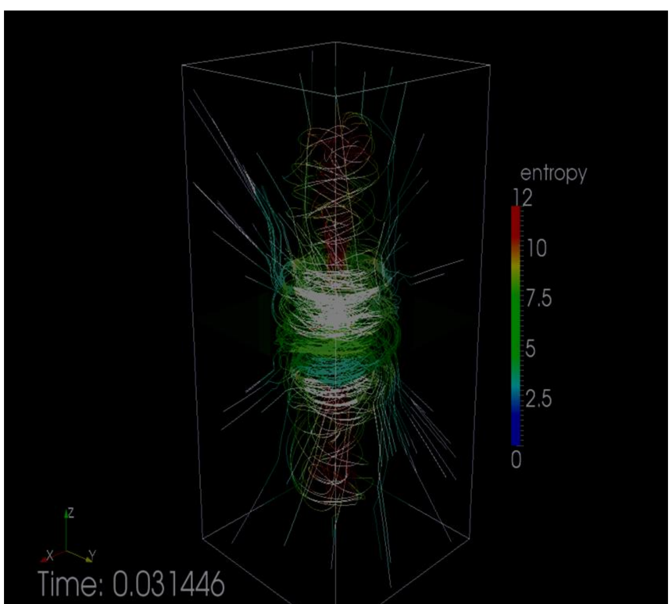
but where does the r-process take place??

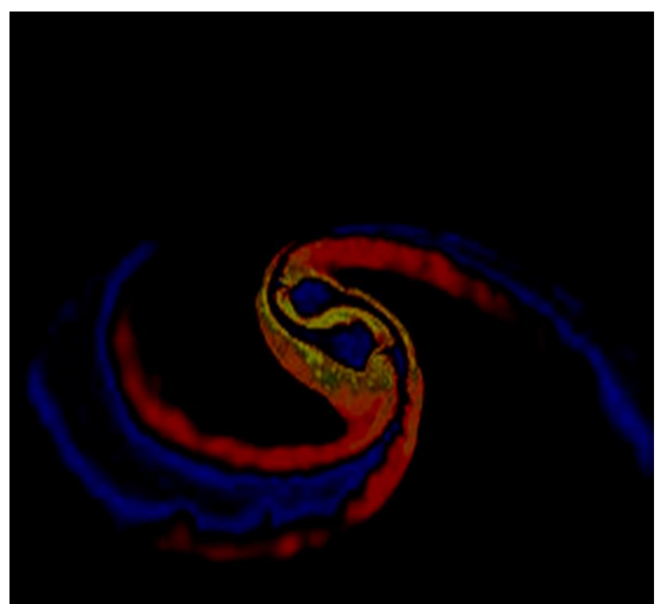
r-Process Sites? not in regular core collapse supernovae!

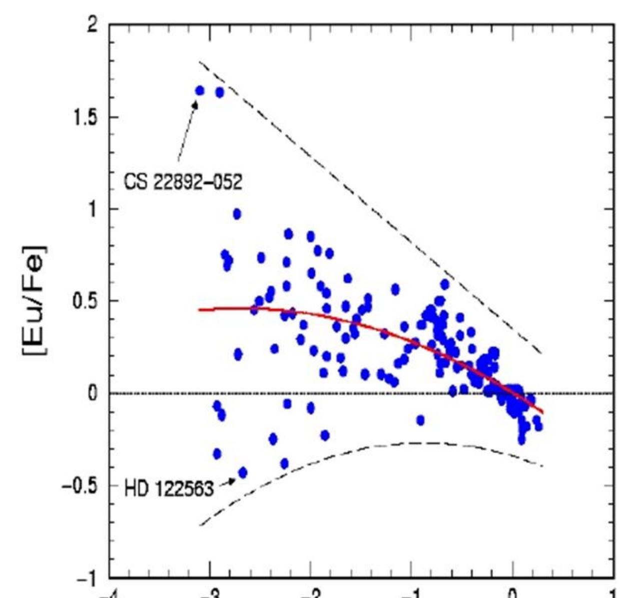
0. They eject rather slightly proton-rich matter from the innermost ejecta

1. **But possibly a rare class (0.1-1%) of all supernovae with large rotation rates and strong magnetic fields, causing jet ejection of strongly neutron-rich matter along the poles and forming a 10^{15} Gauss neutron star (magnetar); e.g. Winteler et al. (2012), Mösta et al. (2014), Nishimura et al. (2015, 2017)**

2. **Neutron star mergers with their dynamic, wind, and viscous disk ejecta (see e.g. Thielemann et al. 2017, Ann. Rev. Nucl. Part. Sci.), with a similar rare frequency -> large scatter of [Eu/Fe] ratio in the early Galaxy until average ratio obtained**







Dear Keith,

As you see, 30 years ago you had the right idea that the upper mass limit for core collapse supernovae should be between 15 and 45 Msol, based on the stellar/eplosion models of 1986.

Now, with improved understanding, it seems to be between 20-30 Msol, With some possible staggering, due to varying compactness of stellar modes.

We learned a lot of physics and nucleosynthesis in the meamtime. But your Instinct pointed already in the right direction.

Thanks, and good luck for further endavors after reaching the age of maturity 60!!!

Cheers Friedel