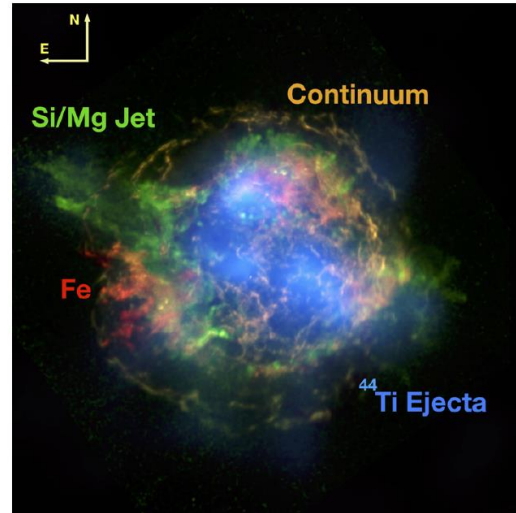
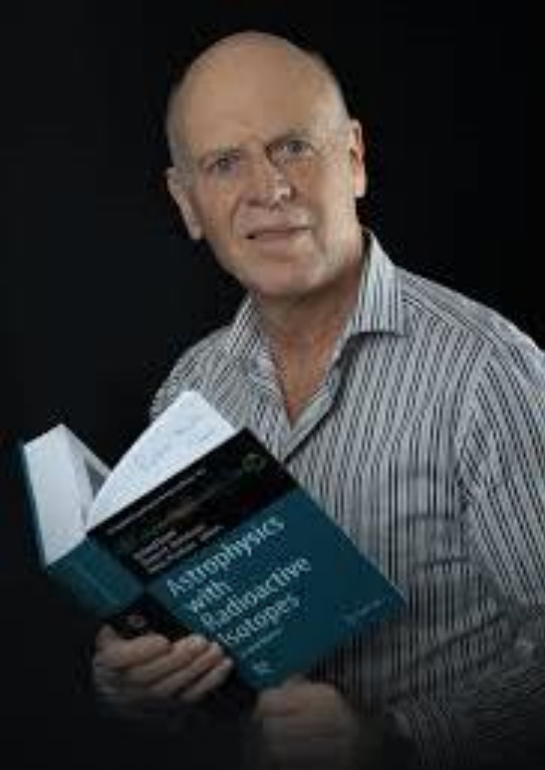
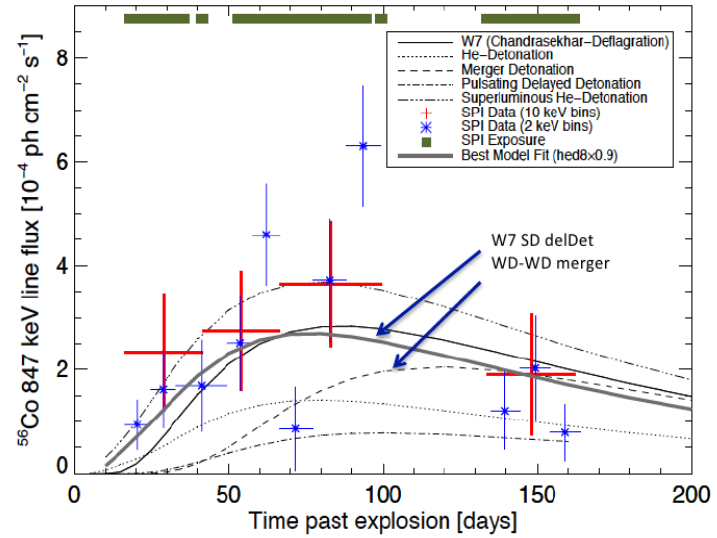


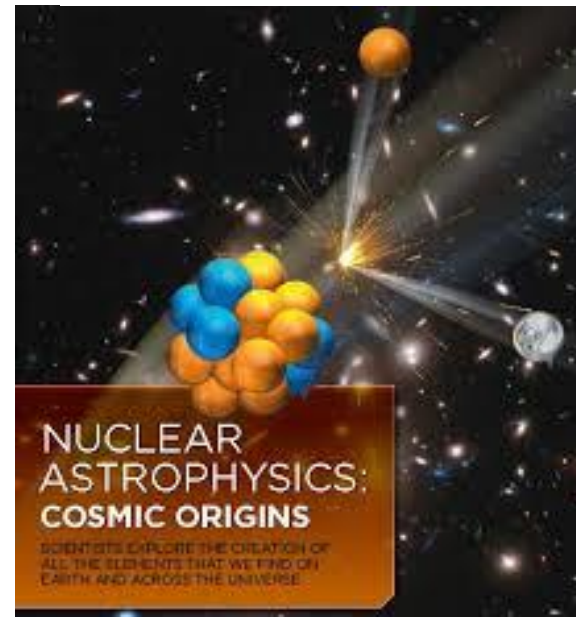
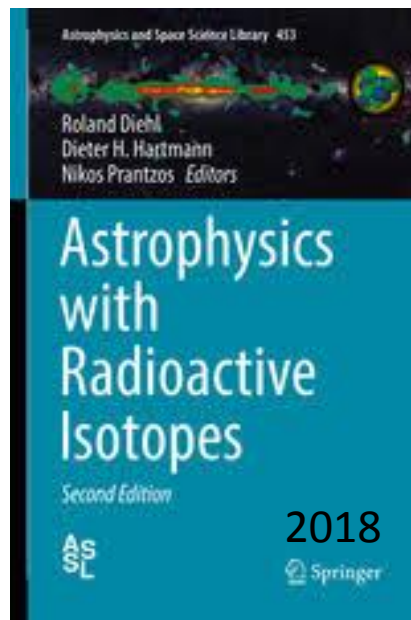
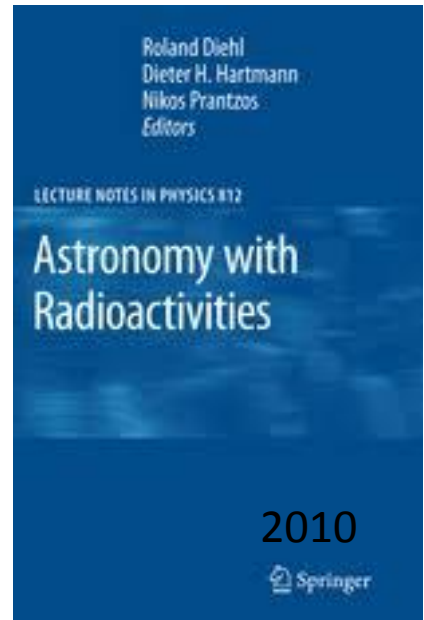
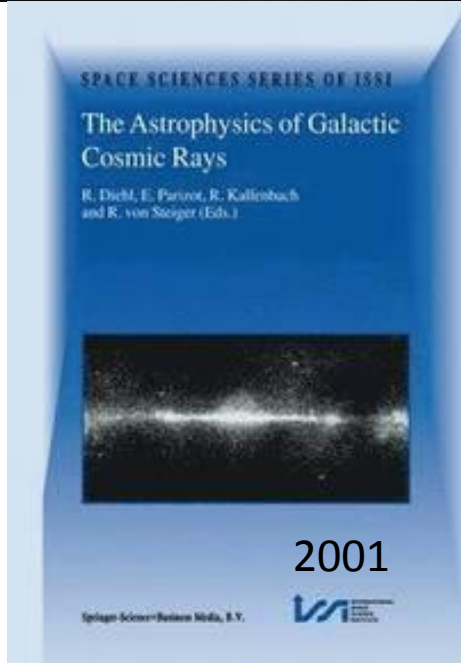
Stellar Explosions, Radioactive Books, and a joint European Cruise with EUROCORES and COST



Core-collapse
SN Cas A

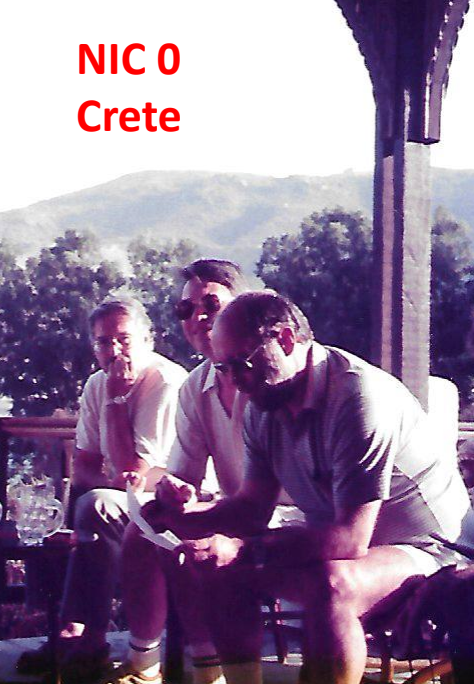


γ -rays
From
SN Ia
SN1914J



The outcome
of EUROCORE
Project
EuroGENESIS
2015

**NIC 0
Crete**



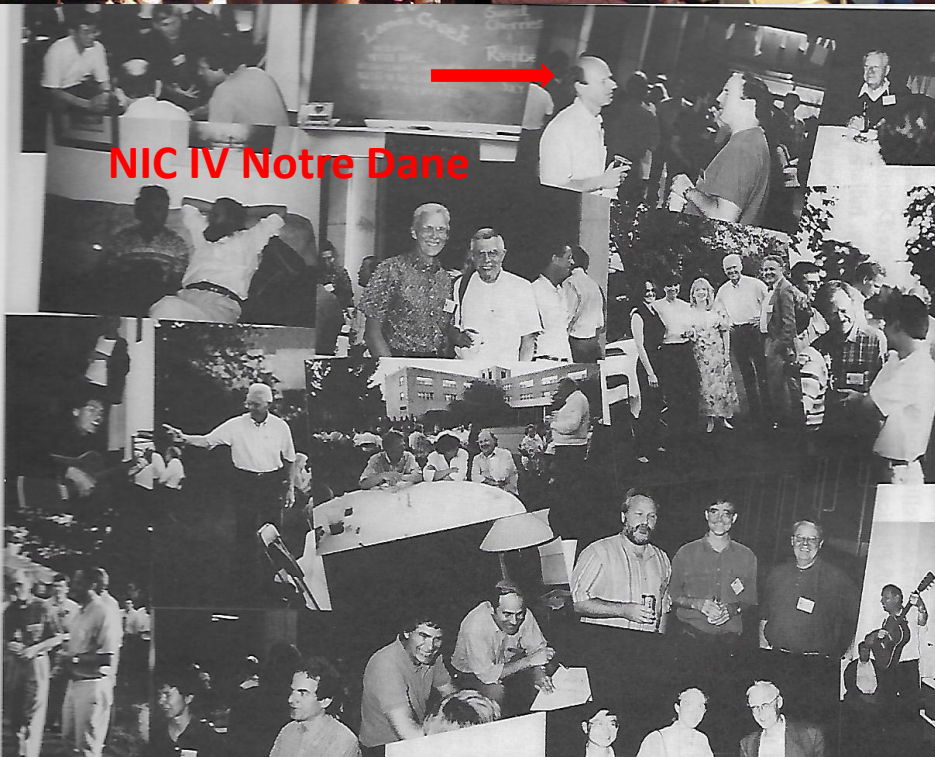
NIC I Baden/Vienna



NIC II Karlsruhe



NIC IV Notre Dame



Nuclei in the Cosmos, «the international Conference on nuclear astrophysics», was informally started in 1988 by Claus Rolfs in Crete, the official number I took place in Baden/Vienna, organized by Heinz Oberhummer

**NIC V Volos
1998**

Since then it has been hopping across continents (Europe, US, Japan, Australia, next on in PRC



Roland, initially from the high energy astrophysics gamma-ray community started to join in 1996

Nuclear Astrophysics
1957-2007
Beyond the First Fifty Years

California Institute of Technology • Pasadena, California, USA
July 23-27, 2007
 For more information, visit www.nic2007.caltech.edu

International Advisory Committee:
 R. Cayrol, W. Freedman, G. Fuller, W. Haxton, J. Lambert, J. Lattituro, K. Nomoto, M. Riege, E. Rolfs, F. Thielemann, J. Baron, G. Wasserburg, E. Stepan, M. Wiescher, S. Woosley (Chairman)

Local Organizing Committee:
 R. McKernan (Chairman), G. Wasserburg, E. Stepan, M. Wiescher, S. Woosley (Secretary)

Background photo: Star forming region in NGC 6052, ESO and the Hubble Heritage Team (STScI/NASA) ESA/ESA Public Collaboration

We met at many places since then, here the 50th Anniversary of the pioneering papers by Burbidge, Burbidge, Fowler & Hoyle, as well as in parallel, but of equal importance, by Al Cameron

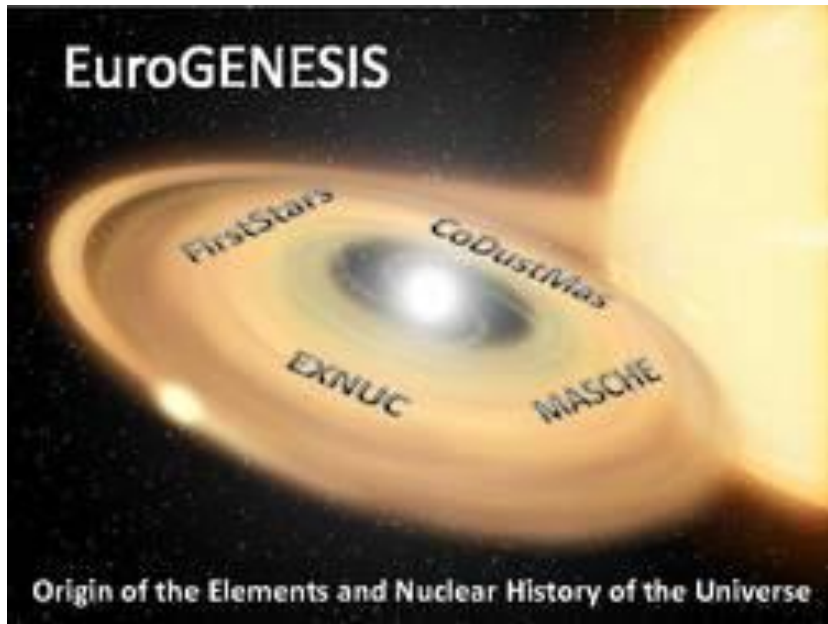


However, only at the NIC IX preschool (Argonne/Chicago), where we both lectured for a week, a closer interaction started



2006 at the NIC preschool
Argonne/Chicago





Roland initiated a proposal to the European Science Foundation for a EUROCORE project **EuroGENESIS**, consisting of four separate CRPs: **EXNUC** (nuclear input and explosive nucleosynthesis), **MASCHE** (Massive Stars as Agents of Chemical Evolution), **CoDustMas** (the condensation of dust and relation to meteoritic inclusions), and **FirstStars** (understanding galactic evolution via observation of low-metallicity stars). This project ran very successfully from 2010 to 2014, starting with a first meeting in Dubrovnik and fostered a lot of new collaborations on this subject in Europe with results summarized in a final pedagogical brochure.



CRP Number: 09-EuroGENESIS-FP-003

CRP Title and Acronym: Massive Stars as Agents of Chemical Evolution (MASCHE)

Project Leader (PI 1): Prof. Friedrich-Karl Thielemann, Switzerland

Co-Project Leader (PI 2): Prof. Roland Diehl, Germany

Principal Investigator 3: Prof. Klaus Blaum, Germany

Principal Investigator 4: Dr. Zsolt Fülöp, Hungary

Principal Investigator 5: Prof. Recep Taygun Güray, Turkey

Associated Partner 1: Dr. Daniel Bemmerer, Germany

Associated Partner 2: Dr. Alessandro Chieffi, Italy

Associated Partner 3: Prof. Claes Fransson, Sweden

Associated Partner 4: Dr. Raphael Hirschi, United Kingdom

Associated Partner 5: Dr. Gabriel Martinez-Pinedo, Germany

Associated Partner 6: Prof. Francesca Matteucci, Italy

Associated Partner 7: Dr. Nikolas Prantzos, France

Associated Partner 8: Dr. Anton Wallner, Austria

Associated Partner 9: Prof. Kai Zuber, Germany

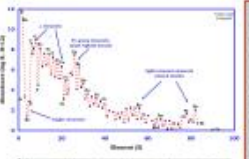
CRP start and end dates: **01 Sep 2010 / 30 Aug 2013**

CRP website: http://www.mpe.mpg.de/gamma/science/lines/eurogenesis/MASCHE_home.html

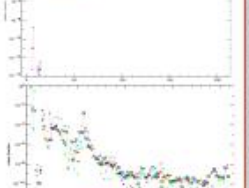
Goals

- Provide *extensive nuclear input* for stellar evolution and explosions plus tests on its impact in these events
- Test certainties and uncertainties in *massive star evolution* by *comparing two of the world-wide four evolution codes* which are able to follow all burning stages; *role of rotation, wind losses, primary ^{14}N , ^{22}Ne , s-process in massive stars*, provide models for collapse simulations
- Test and *understanding of the core collapse supernova explosion mechanism* in 1-3D simulations; *comparing two of the world-wide four SN explosion codes with sophisticated neutrino transport*
- *Provide the resulting explosive nucleosynthesis ejecta*, understanding the amount of radioactive species, s-, p-, vp, and (weak and strong/main?) r-process, *making the connection to supernova lightcurves, dust formation, and chemical enrichment of the galaxy (First Stars)*
- Utilize analysis of *observational results from SN lightcurves and SN remnants to test nucleosynthesis ejecta*
- *Test hydrostatic (winds) and explosive nucleosynthesis results in chemical evolution models (connection to First Stars)*
- ***UTILIZE IN ALL CASES FEEDBACK TO IMPROVE INPUT AND MODELING***

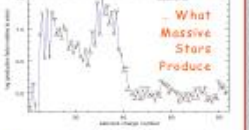
How was Today's Cosmic Variety of Chemical Elements and Isotopes Produced by Nuclear Reactions in Cosmic Objects?
What are Transport Processes of Cosmic Matter among the Materials in Cosmic Gas Clouds, Dust, Stars, and Tenuous Interstellar Space?



What the big bang made...

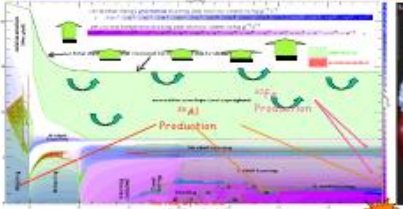


what we have today



What Massive Stars Produce

Understanding how nature made the variety of isotopes and nuclei from which our life has been made possible is one of the main challenges of astrophysical research still today, about a hundred years after atomic nuclei were discovered and almost a hundred years after nuclear energy was recognized to stabilize stars, and stellar-burning ashes were the origins of elements heavier than Helium.



EuroGenesis is a collaborative project, involving about 200 scientists from 35 different institutions in 11 countries, with a total budget of 2.5 MEUR. It includes four "Collaborative Research Programmes" (CRPs), called COOLSTARS (Leader: L. Cherchneff), EXMUC (Leader: J. Jose), FIRSTSTARS (Leader: M. Asplund), and MASCHÉ (Leader: F.K. Thielemann).

Professors Martin Asplund (D/AUS), Isabelle Cherchneff (CH), Roland Diehl (D), Jordi Jose (E), Friedrich-Karl Thielemann (CH) (The Science Steering Committee of EuroGenesis)

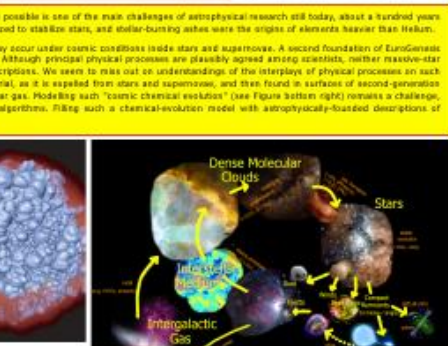
Stars are formed in groups, when interstellar gas is swept up and the conditions to cool and compactly under the force of gravity. How that happens in detail is not understood - but we can see stars of a variety of masses. The release of nuclear binding energy from transformation of light atomic nuclei into heavier ones makes sufficient energy available so that stars can exist as dynamically-stabilized objects, compressed by gravity and heated from the core by nuclear energy. Low-mass stars such as our Sun evolve slowly over ten billions of years, while much more massive stars may persist for only millions of years.

It is not easy to find out what happens inside a star. Radiation needs thousands to millions of years to travel from their cores to their surfaces, and thus less information about its origin. Even gamma-rays are not penetrating enough. Therefore, our observations of stars are indirect and tell us mostly about what happens at the surface, far from where the action of nuclear-physics takes place.

Messengers which do retain some imprint from nuclear reactions are long-lived radioactive isotopes which decay after ashes have been shed, and dust particles which have been embedded into meteorites and thus falls into the hands of physicists.

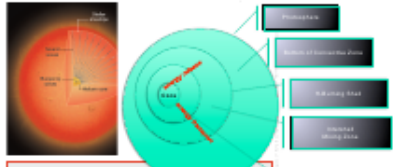
A supernova explosion marks the violent end of stability of a star. There are different circumstances which may de-stabilize stars. We distinguish the "core-collapse" supernovae which occur when a massive star has consumed its nuclear fuel and implodes, from "thermonuclear" supernovae where a compact stellar remnant object such as a white dwarf or a neutron star may become unstable as it receives mass from a binary companion or encounter of another star. In such violent circumstances, nuclear burning is intense, and produces ^{56}Ni as most-stable nuclear isotope; this is unstable, its radioactive decay makes supernovae shine as bright as entire galaxies for months.

Interstellar gas is held in a turbulent and dynamic state by the action of supernova explosions and heating and cooling processes, gravity always attempting to form clouds and clumps on the way. Supernovae and stellar winds eject freshly-produced isotopes into interstellar space. Larger clumps may form next generations of stars, and the stellar-evolution cycle with its nuclear-burning begins, but now with a gas composition enriched in some heavier elements and isotopes already. This cycle has been proceeding from first-generation stars a few hundred million years after the Big Bang until today, about fourteen billion years later.

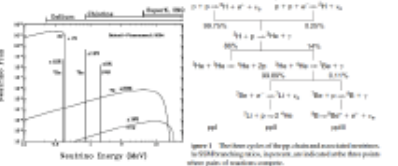


Presentation at the Brussels Exhibition of EuroCore Projects

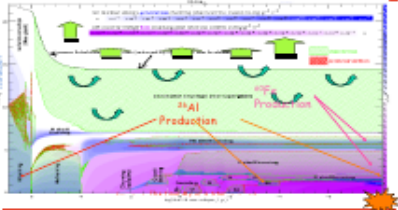
Inside Stars:
Stars are Stabilized Against Gravitational Collapse by the Pressure from Release of Nuclear Energy from Nuclear Reactions Deep in their Interiors. We Can "See" Only the "Photosphere" of a Star.
How Can We Learn?



Stellar Structure...
 ... is the result of energy release (mostly local) and transport over large distances. A stable equilibrium leads to the shape of most stars as we see them.



Neutrinos and their Role in Stellar Nuclear Burning:
 Due to their penetrating nature, neutrinos can leave the site of nuclear burning easily, and thus carry away a part of the released nuclear energy. Therefore, this part of released energy will not be available to heat and thus stabilize the star, and the burning rate will increase or the star may collapse. In hydrogen burning, neutrinos are e.g. created when a proton beta-decays into a neutron.



Complex Stellar Interiors:
 Stellar structure remains one of the harder to describe astrophysical phenomena: The release of nuclear energy inside stars is extremely sensitive to temperature. Heat transport may occur through a variety of processes, radiation and convective overturn being most prominent, but neutrinos playing a more important role as temperature increases (as it does for the later burning stages inside massive stars). As nuclear fuel is exhausted, gravity induces compression of the star which increases temperature, and eventually ignites the next-heavier fuel isotopes. Such core burning of H, He, C, etc. is then accompanied by nuclear burning of the lighter isotopes still in shells of the star, where such fuel still is available, and where temperatures may be adequate for such burning. The variety of heat transport ("cooling") mechanisms thus lead to a complex interplay for the late burning phases, where much of the heavier isotopes are generated. Measuring these isotopes thus is a precious diagnostic of what happened inside the star.

Insides of Stars, and EuroGenesis:
 "FirstStars" searches for elemental composition signatures from olded stars. MASCHÉ studies the structure and interiors of massive stars and supernovae. COOLSTARS studies how dust may form from massive stars and their ejecta. EXMUC studies how nucleosynthesis occurs and shapes stellar explosions.

EuroGenesis is a collaborative project, involving about 200 scientists from 35 different institutions in 11 countries, with a total budget of 2.5 MEUR. It includes four "Collaborative Research Programmes" (CRPs), called COOLSTARS (Leader: L. Cherchneff), EXMUC (Leader: J. Jose), FIRSTSTARS (Leader: M. Asplund), and MASCHÉ (Leader: F.K. Thielemann & R. Diehl).

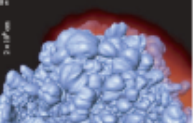
Professors Martin Asplund (D/AUS), Isabelle Cherchneff (CH), Roland Diehl (D), Jordi Jose (E), Friedrich-Karl Thielemann (CH) (The Science Steering Committee of EuroGenesis)

Looking at Appropriate Frequencies:
 The photosphere of a star depends upon the frequency of light. Optical light shows us the "surface" where atoms exist. Where temperatures are a few thousands degrees K. The core of the star is at millions of degrees K (~15 MK for our Sun, hotter for more massive stars). X-rays reveal deeper & hotter surface layers and the acceleration regions, and also hot plasma in the corona far above the optical photosphere. This helps to understand surface physics. But even penetrating gamma-rays do not reach deeper than a few "giga" depth, only a small percentage of a star's radius. We need other probes...



Looking at Neutrinos:
 The Neutrino is a highly-penetrating elementary particle, which is our only one direct probe of dense stellar interiors. Neutrinos are produced alongside nuclear reactions, in particular in beta decays when protons transform into neutrons and vice versa. The electron neutrinos, or its anti-particle, the electron antineutrino, are thus created. They have been measured in large underground detectors such as GALLEX on Earth. But for a long time, measurements reported neutrino fluxes much lower than what is expected from hydrogen burning inside the Sun, until in the late 20th century the property of flavor oscillations was discovered for neutrinos, and thus one learned that the missing fraction of electron antineutrinos had transformed into other neutrino flavors which detectors were not sensitive for.

Looking at Stellar Winds:
 Beyond electromagnetic light, stars shed a wind from their surface (see X-ray image above), which consists of gas and hot plasma. We know at Earth atmosphere and its magnetic field, and discuss arc-like light with aurora and ionospheric changes which are noticed as variations when receiving distant radio stations. Wind phases vary by orders of magnitude in intensity over the evolution of, in particular, massive stars. Mass ejection rates as high as the entire mass of our Sun in 100000 years are common for massive stars, while our Sun's wind is many thousands times weaker.



Variable wind phases create shells of variable density around stars. When these shells are enlightened by interstellar shocks or stellar explosions, we can see and analyze them, in their structure and composition, and thus learn about how the star peaked its outer parts.

Looking at Stellar Ejecta (directly):
 Stellar winds carry material from the star into interstellar space, where it can be observed and analyzed with respect to its composition. One way to extract characteristic elemental compositions is through measurements of absorption lines against background light sources with a known and continuous emission spectrum.

Looking at Stellar Ejecta (delayed):
 Stellar material as ejected into interstellar space through winds and supernovae will eventually condense, either into solids patterned by newly forming stars and found as meteorites in our Solar System, or more directly into stars which form out of such "enriched" interstellar gas.

Meteorites are aggregates of interstellar dust particles, formed in interstellar space by the action of the gravitational force. As they fall down onto Earth, we thus obtain samples of interstellar dust with its characteristic composition of isotopes and elements. Scientists have learned to disentangle the heterogeneous variety of materials of meteorites through chemical separation techniques, and thus have learned to analyze the composition of grains of stardust, which originate clearly from beyond the solar system. Their isotopic signatures deviate by orders of magnitude from solar-system material, and are exquisite probes of cosmic nucleosynthesis sources, such as supernovae, novae, and giant stars with their strong winds. EuroGenesis includes such studies of stardust in all programmes, and in particular the "COOLSTARS" program addressing how dust forms from massive stars and their ejecta in the first place.

When gas ejected from stars is built into newly forming stars, there is an alternative and more universal way to analyze the composition of this gas: As the newly-formed star begins to shine from nuclear burning in its interior its surface will remain essentially unprocessed and of original composition, in particular for lower-mass stars such as our Sun or even smaller stars. Thus we can measure from which gas composition those stars were formed originally. When only few or one first-generation star should be responsible for the gas enrichment prior to formation of that second-generation star, we would thus get a measurement of its ejecta composition in the form of characteristic photospheric absorption lines of our second-generation star. Such "galactic archaeology" is made within the "FirstStars" program of EuroGenesis.





EUROCORES Programme
European Collaborative Research

Origin of the Elements and Nuclear History of the Universe (EuroGENESIS)

EuroGENESIS Review Panel

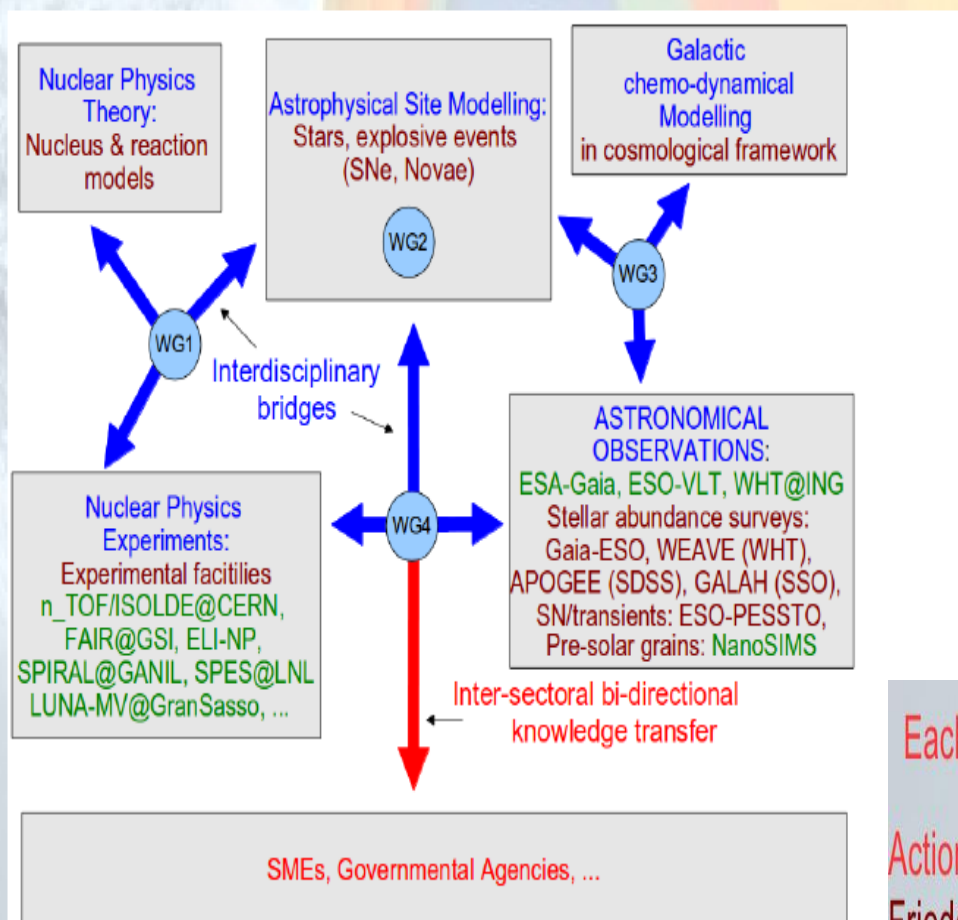
Final Evaluation Consensus Report

The goal of the EuroGENESIS programme, to improve the knowledge of the origin of the elements and the nuclear history of the universe, has been reached by the different Collaborative Research Projects (CRPs) with great success. Progress has been achieved through joint efforts of researchers working on astrophysics modelling and observations, measurement of nuclear reactions and isotopic assessment of meteorites. The interdisciplinary collaborations fostered by this programme have been one of its main strengths and the programme has acted as a platform enabling these communities to work together. EuroGENESIS has strengthened the field of nuclear astrophysics in Europe allowing it to flourish beyond the end of this programme.

It appears that a very good level of integration within the teams has been achieved. This is visible from a number of joint publications reported, scientific meetings, training schools and workshops organized within this programme. Annual progress meetings have also been held. The strongest collaboration was, naturally, within individual CRPs, i.e. their groups. Collaboration on a higher level, i.e. within the four CRPs was also present, giving a clear added value achieved by this Programme. However, this collaboration was not equally distributed across the four CRPs. There was a high level of interaction between CoDustMas, MASCHE, and EXNUC. The focus of EXNUC on binary systems and FirstStars on early evolution of the Galaxy complemented the focus on core collapse supernovae in the other two CRPs. The impression is that the CRP MASCHE played a lead role in building up collaboration among all CRPs and groups, initiated many activities, and took effort to collaborate with all the other CRPs. On the

In conclusion, EuroGENESIS was a successful programme that helped integrate research across fields and different countries to address some of the most important questions regarding astrophysical objects and their role in the chemical evolution of the Galaxy. The programme fostered collaborations that one can expect to continue in the future, provided that adequate funding mechanisms for supporting this highly interdisciplinary field of science are made available. Smaller countries have greatly benefitted from this programme as it allowed young researchers to be integrated in a research network across Europe. The programme served as a counterpart to the Physics Frontiers Centre in the US (the Joint Institute for Nuclear Astrophysics), and helped to increase the impact of European research in the broader research areas of astrophysics and nuclear physics.

Main challenge: The main aim and objective of the Action is to tackle key open questions concerning the evolution of the Universe and its constituents and obtain the best return on investments on the largest European facilities. For this purpose, research in Astronomy, Astrophysics and Nuclear Physics needs to be coordinated.

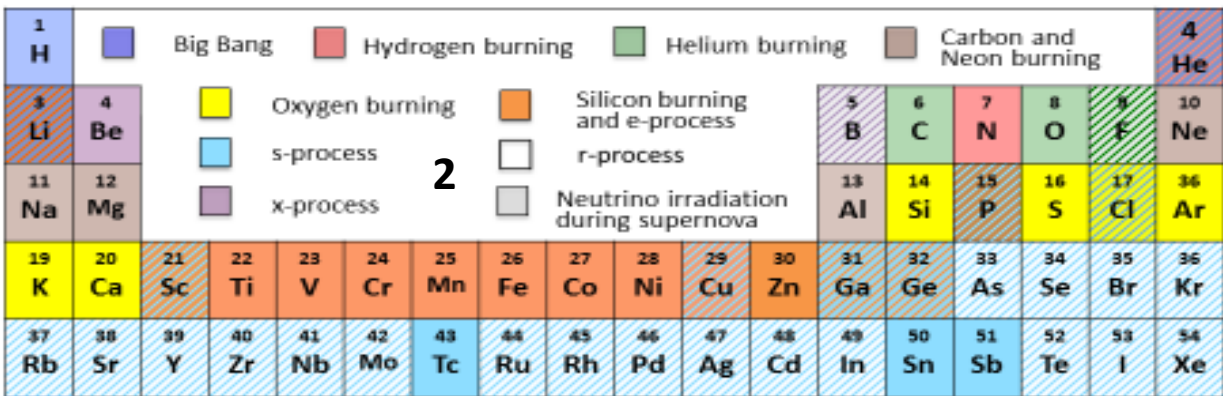
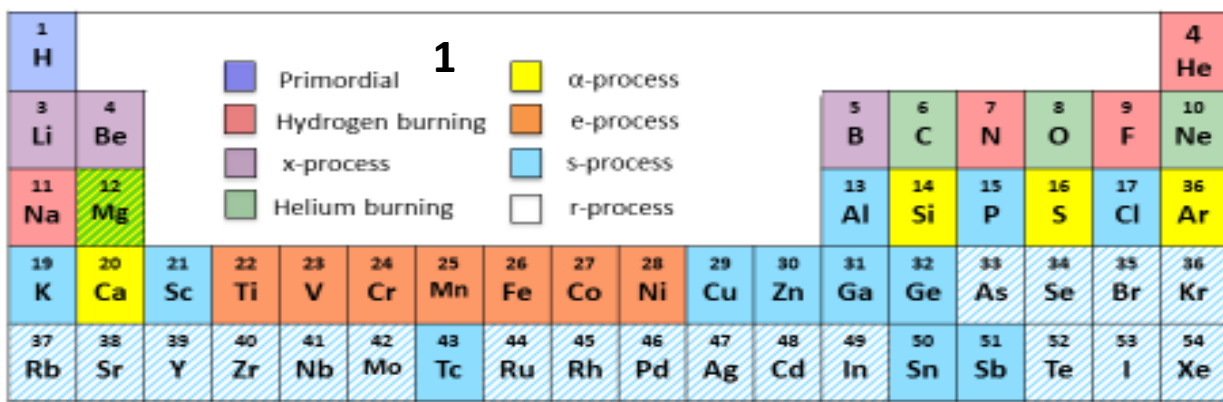


After the European Science Foundation was essentially dismantled by the European Funding agencies, we tried to follow and advance the success further within the European COST ACTION scheme. Under the lead of our MASCHE member Raphael Hirschi (Keele/UK), we were successful to create CHETEC (Chemical Elements as Tracers of the Evolution of the Cosmos), which runs from 2017-2021



Each CORE group member represents a management/leadership team! (candidates listed)

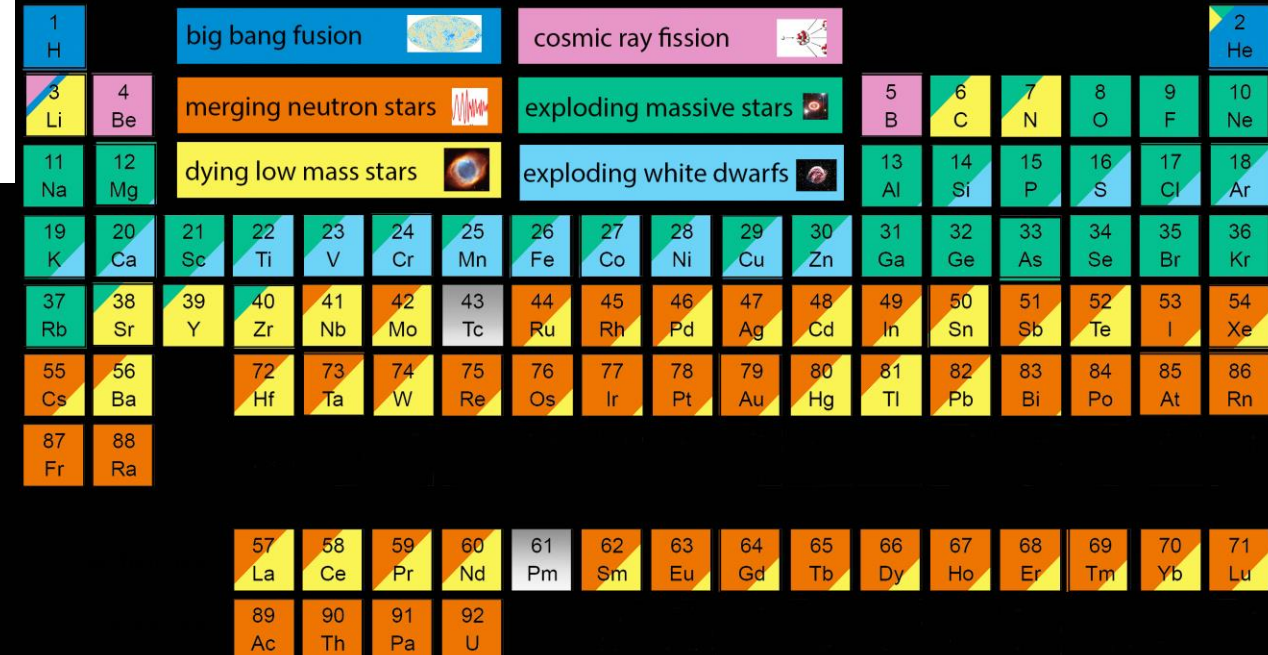
Action Chair/Vice Chair: Management team including synergy agents (Roland Diehl and Friedel Thielemann)
(the old farts with a bit of overview)



What is the origin of the elements in the solar system?

1. B²FH (1957) in terms of processes
2. Woosley, Trimble, Thielemann (2019) also via processes
3. J. Johnson (2019) in terms of stellar origins
(still a bit ambiguous, as there are weak and strong s-processes and r-processes, and possibly even multiple strong r-process sites, and additional processes like the vp-process)

3 The Origin of the Solar System Elements

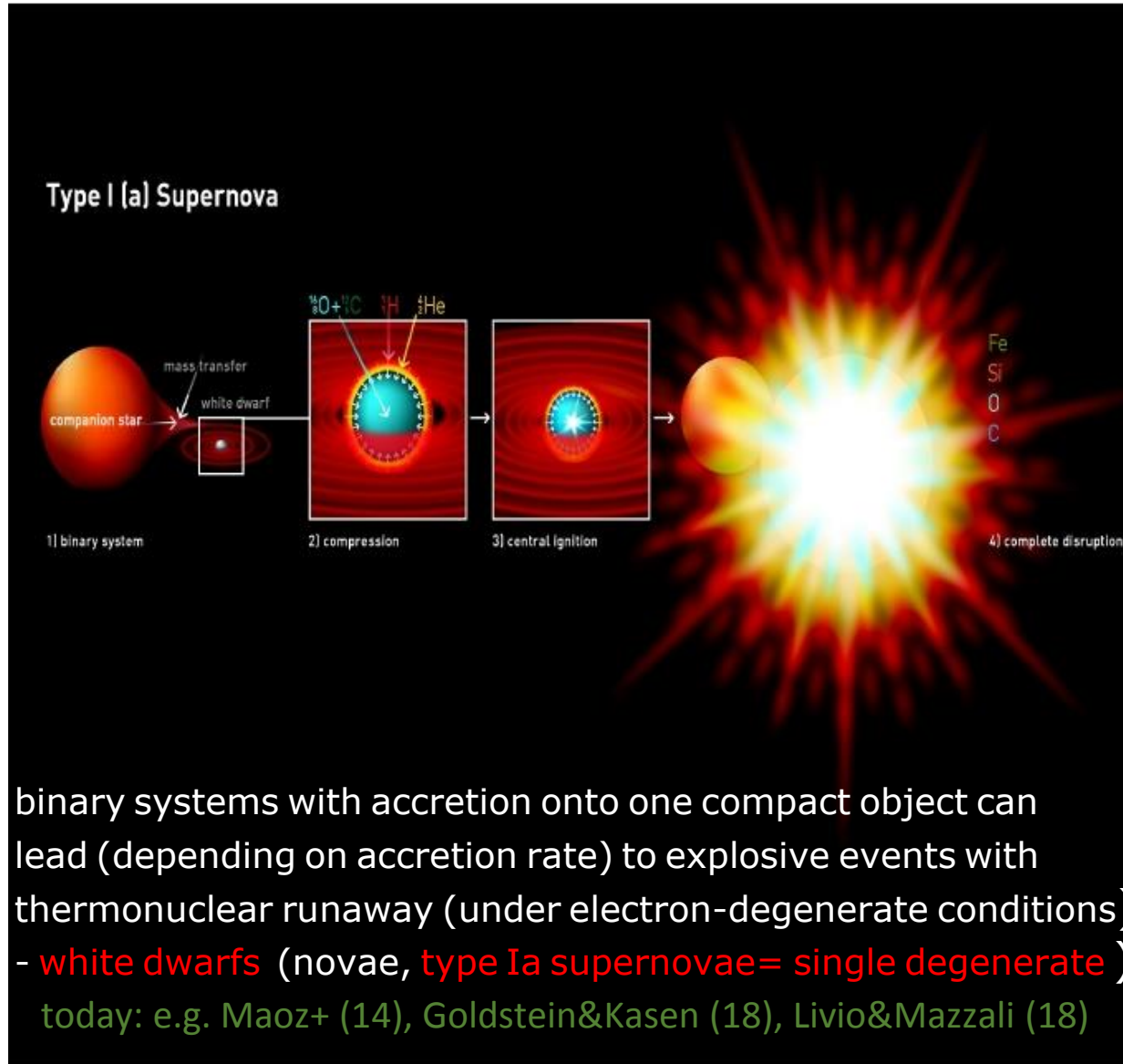


But it is even more important to link the individual sites and their occurrence frequency to the temporal evolution of the Galaxy. Such observations give an additional clue!

For this reason we have to have a more detailed look at the individual nucleosynthesis contributions!

After Hoyle & Fowler (1960), major impact by Iben/Tutukov/Webbink (1984)

Chandrasekhar mass models (single degenerates)



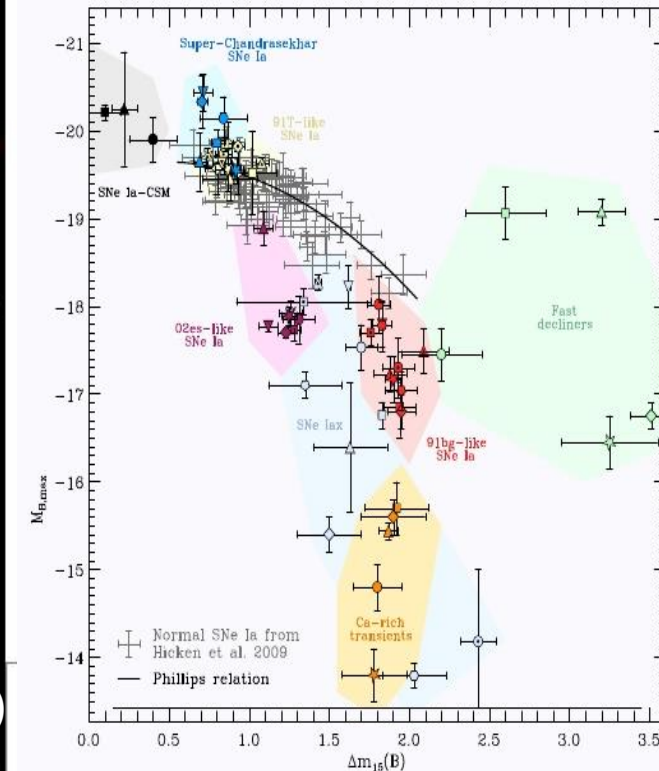
binary systems with accretion onto one compact object can lead (depending on accretion rate) to explosive events with thermonuclear runaway (under electron-degenerate conditions)

- **white dwarfs** (novae, **type Ia supernovae = single degenerate**)
- today: e.g. Maoz+ (14), Goldstein&Kasen (18), Livio&Mazzali (18)

First detonation model by Arnett & Truran (1969 ..71).

First 1D deflagration models by Nomoto et al. (1982, 1984), Woosley et al. (1986)

Müller, Arnett & Fryxell (later Khoklov & Höflich) 3D combustion ...

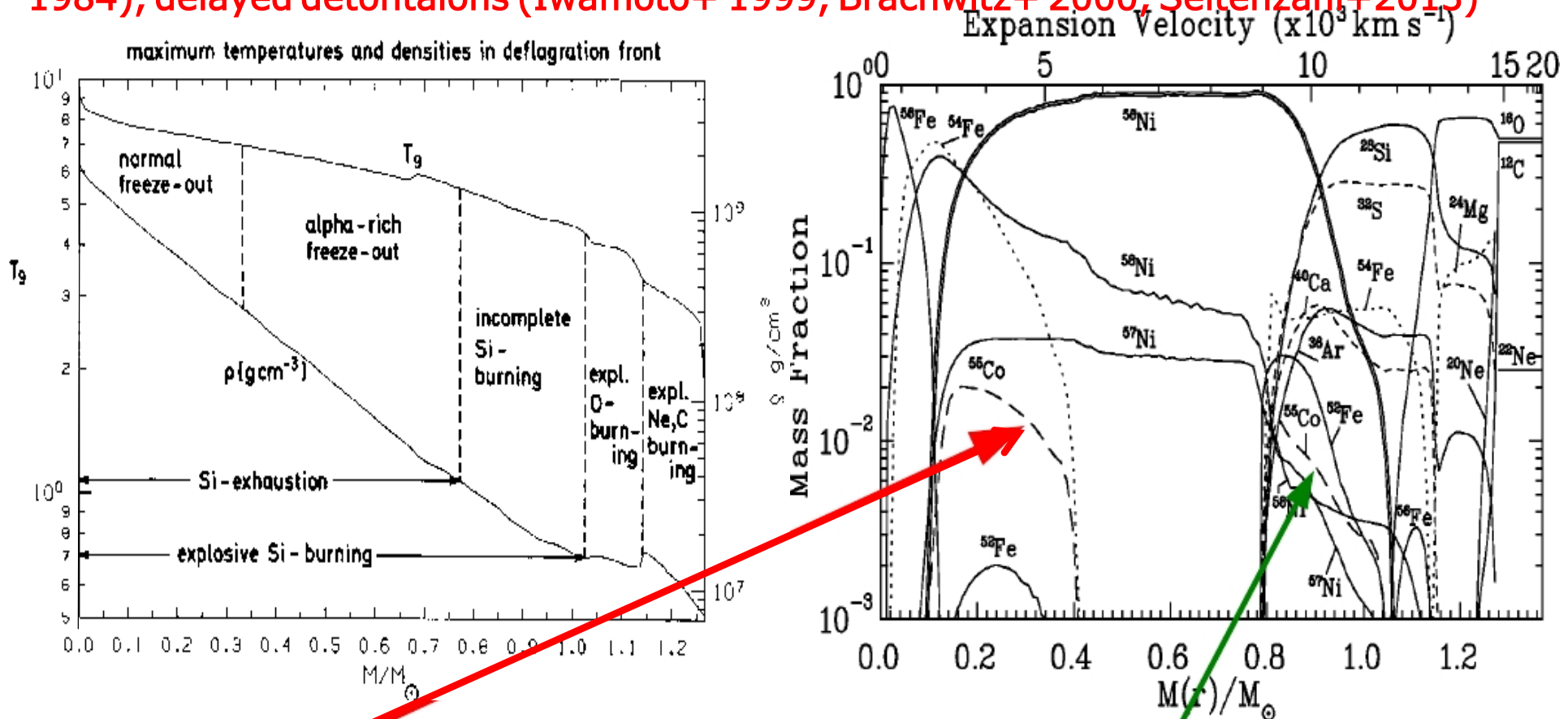


Recent surveys (Taubenberger 2017), more on this by Bruno Leibundgut and Wolfgang Hillebrandt

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

Type Ia supernovae: *in spherically symm. explosions of white dwarfs with simplified approximations for the burning front propagation*

Near Chandrasekhar Models (deflagrations W7, Nomoto, Thielemann, Yokoi et al. 1984), delayed detonations (Iwamoto+ 1999, Brachwitz+ 2000, Seitenzahl+2013)



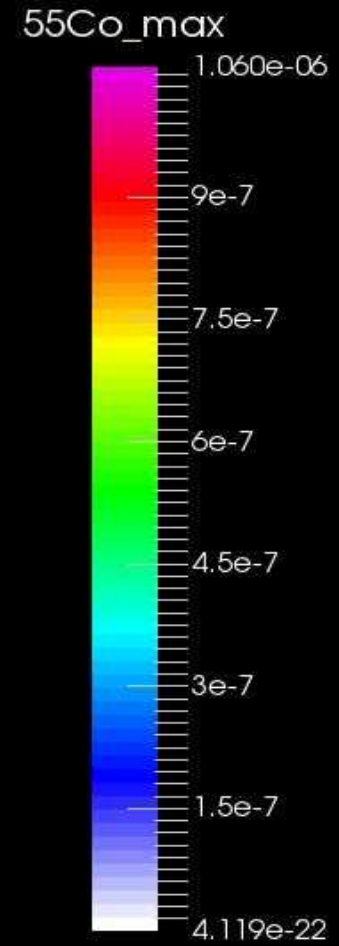
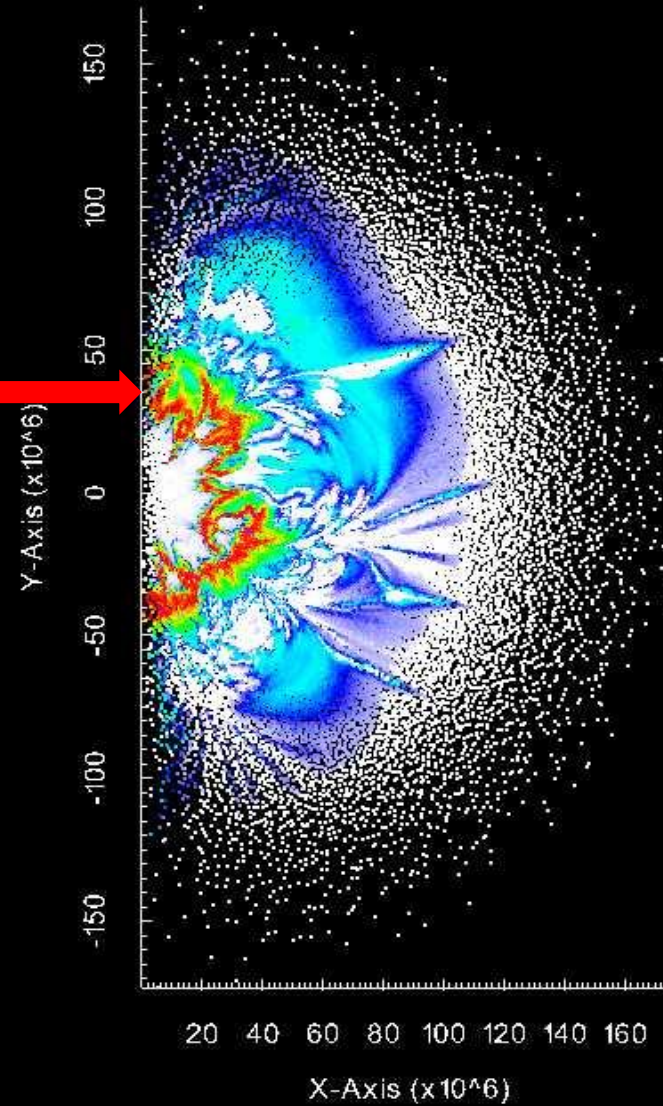
Mn comes in form of its only stable isotope ⁵⁵ Mn, and is the decay product of ⁵⁵ Co, produced in incomplete and complete Si-burning under *optimal conditions with $Ye=Z/A=0.491$* . In alpha-rich freeze-out, determined by entropy $S \propto T_9^3/\rho$, with values of T_9 and ρ_8 exceeding $T_9^3/\rho_8 > 180$, ⁵⁵ Co is moved to ⁵⁹ Cu (\rightarrow ⁵⁹ Co).

In the inner zones of M_{ch} -models this Ye is attained via electron capture (electrons are degenerate with high Fermi energy),

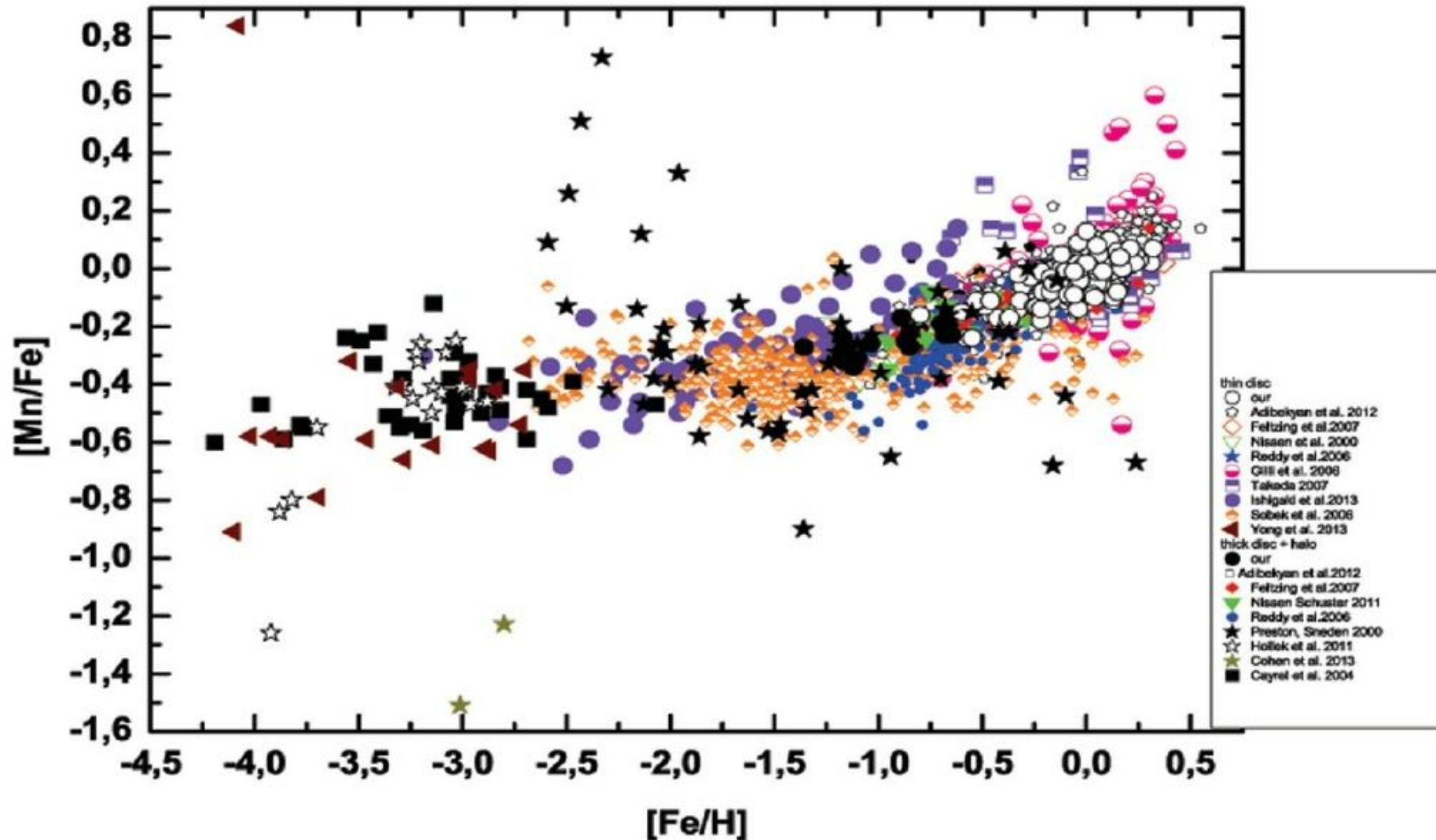
in the outer zones it can be approached by metallicity CNO \rightarrow ²² Ne, leading for $[Fe/H] = -\infty, 0, 0.25, 0.5$ to $Ye = 0.5, 0.499, 0.498, 0.496$ (also characterized by the appearance of ⁵⁴ Fe (moved to ⁵⁸ Ni in alpha-rich freeze-out). See for more details Seitenzahl and Townsley (2016), Höflich et al. (2017), Leung & Nomoto (2017)

Results from 3D delayed detonation model (C. Travaglio, private communication)

3D explosion model
by Travaglio & Röpke



Evolution of [Mn/Fe] as function of [Fe/H] (Mishenina et al. 2015)



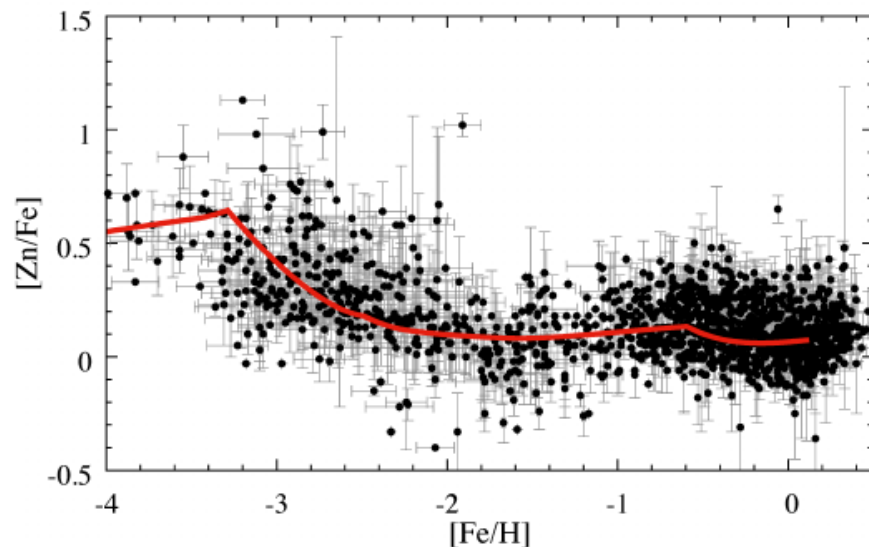
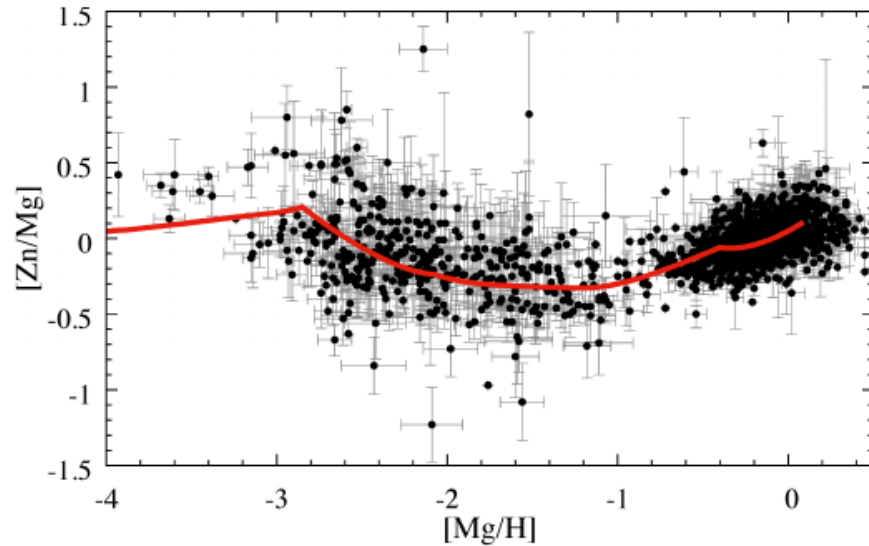
[Mn/Fe] from CCSNe results in about -0.4. The old W7-model predicts for SNe Ia ejecta $[Mn/Fe]=0.067, 0.227, 0.30, 0.38$ at $[Fe/H]=-\infty, 0, 0.25, 0.5$. Seitzzahl+13 find $[Mn/Fe]=0.4$ already for $[Fe/H]$ solar values and conclude that M_{ch} models have to contribute in order to explain the observed trend. (see also Kobayashi, Nomoto 2009, 2015 50%defl., 50%He-det)

The origin of Zn

from Tsujimoto & Nishimura (2018):

Explanation:

solar Zn/Fe can be made
in CCSNe via slightly proton-rich conditions
(Fröhlich et al. 2006, Curtis et al. 2018)
in moderately early galactic evolution
(see later in the talk, also possible supersolar
Zn/Fe contribution by hypernovae and MHD
supernovae with moderate magnetic fields at
lowest metallicities)



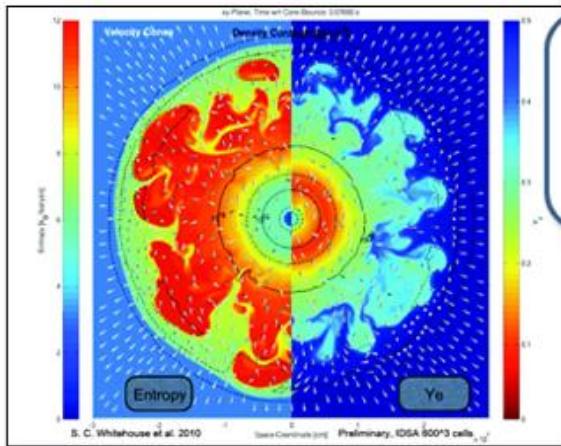
In carbon deflagration/detonation type Ia models Zn/Fe is clearly subsolar, but stays in observations at a solar level, although for [Fe/H]>-1 type Ia supernovae are the main producers of the Fe-group

→ there must be a type Ia component with solar Zn/Fe. This points to a contribution by He-detonations with alpha-rich freeze-out and ^{64}Ge production, decaying to ^{64}Zn .

(see e.g. Maoz et al. 2014, Goldstein & Kasen 2018, Livio & Mazzali 2018)

This would also ask for a higher ^{44}Ti production, two types of Ia's visible in future gamma-ray observations?

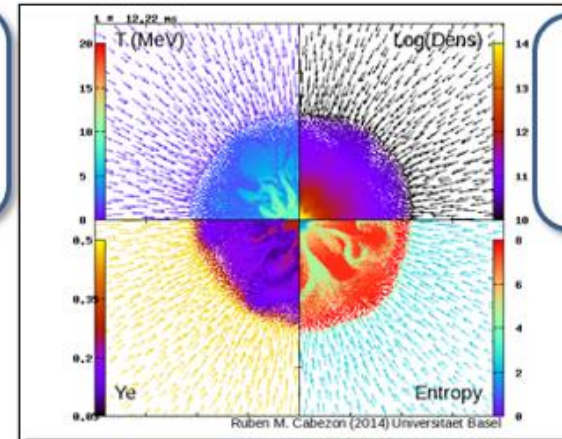
Basel activities in Multi-D Core Collapse Supernova Simulations



Elephant

3D IDSA
Cartesian mesh
1D GR potential

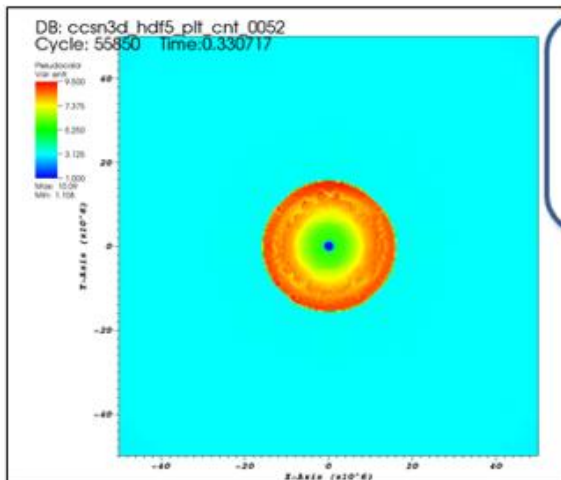
M. Liebendörfer
S. C. Whitehouse
R. Käppeli



SPHYNX

ASL
SPH
3D Newtonian

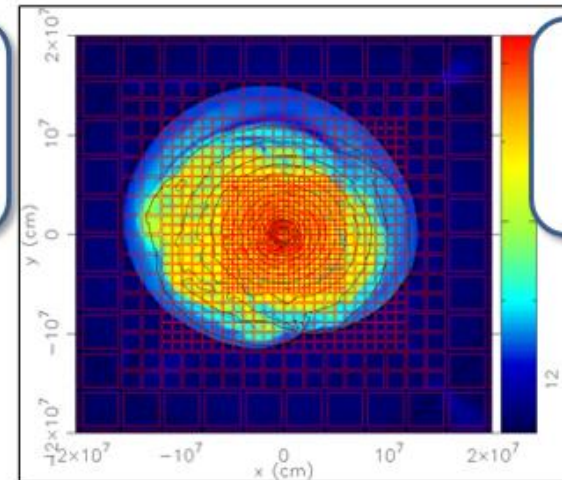
R. M. Cabezón



FLASH

3D IDSA
AMR
3D Newtonian

K.-C. Pan



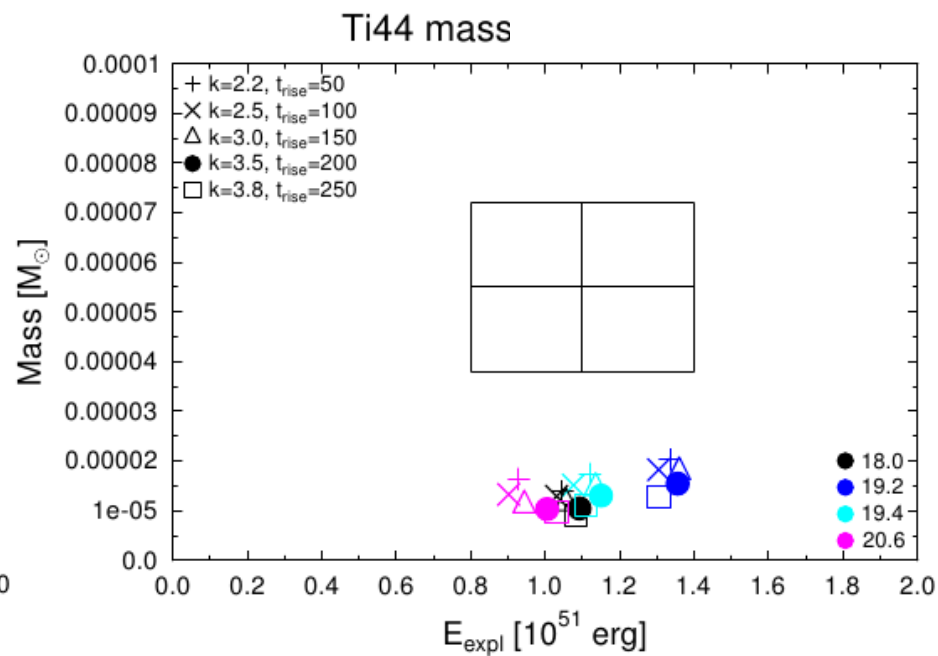
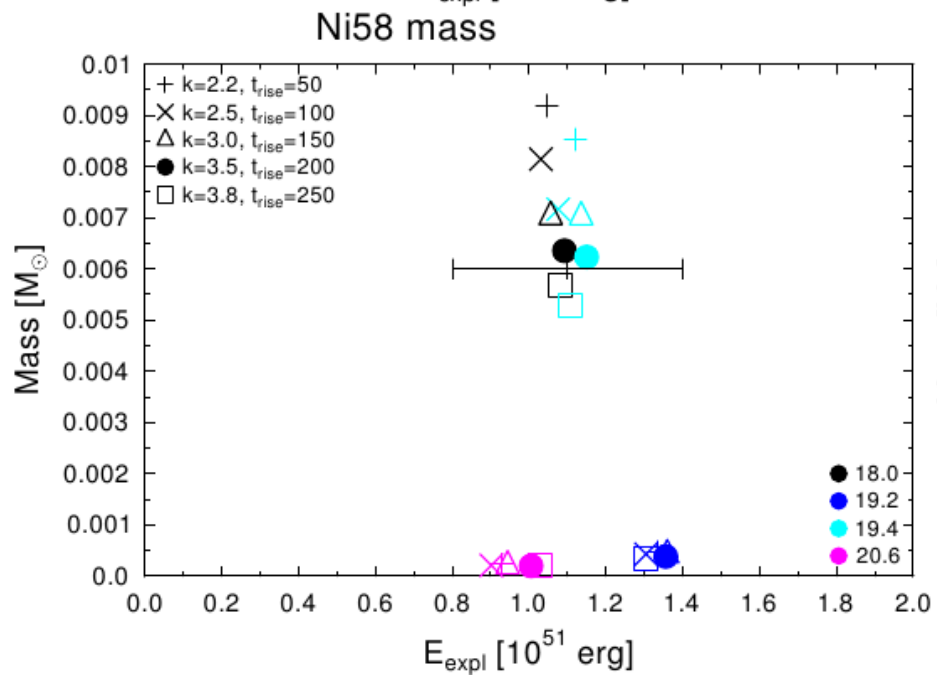
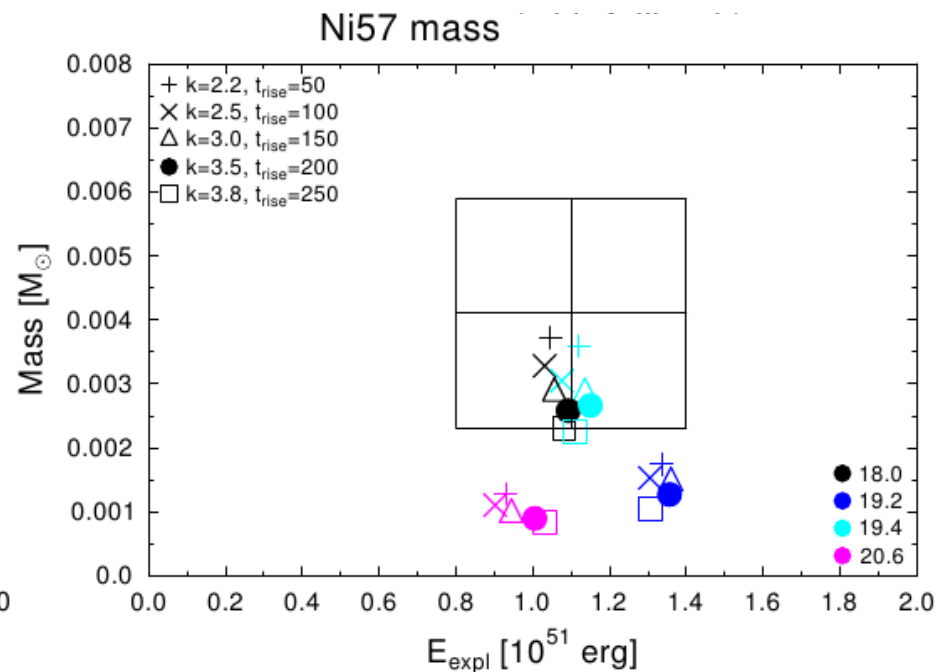
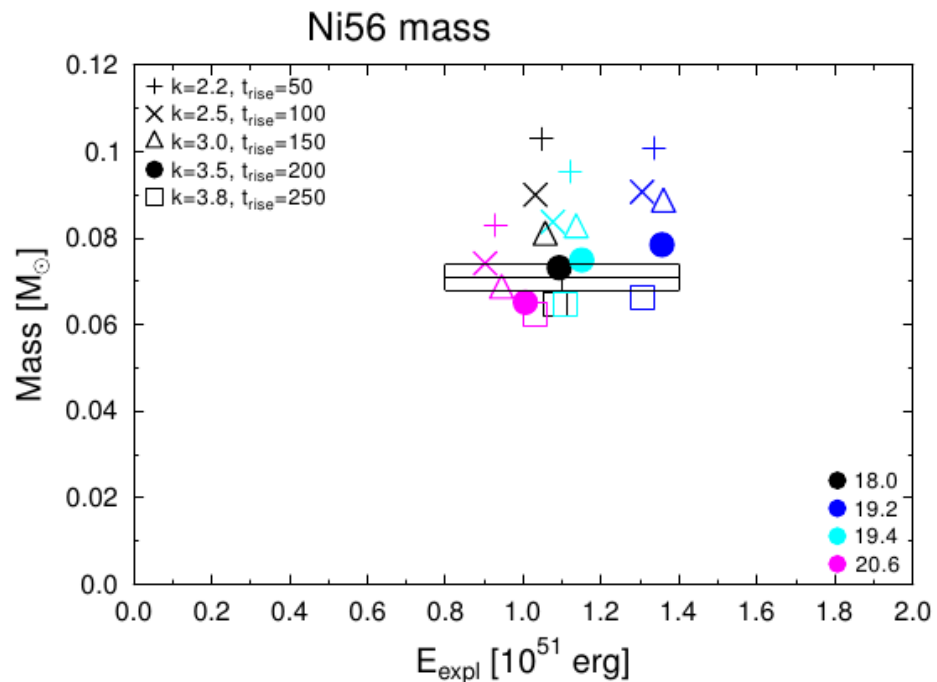
fGR_M1

M1
Nested meshes
3D GR

T. Kuroda

[Cabezón et al. \(2018\)](#): a three-dimensional code-comparison project

For further comparison projects see also [Just et al. \(2018\)](#), 1D and 2D, [O'Connor et al. \(2018\)](#), 1D, but for more extended times after bounce!



**Calibrating the
 PUSH 1D explosion
 simulations in order
 to mimic 3D results
 with the aim to
 reproduce the
 SN1987A
 observations
 (Perego et al. 2015)**

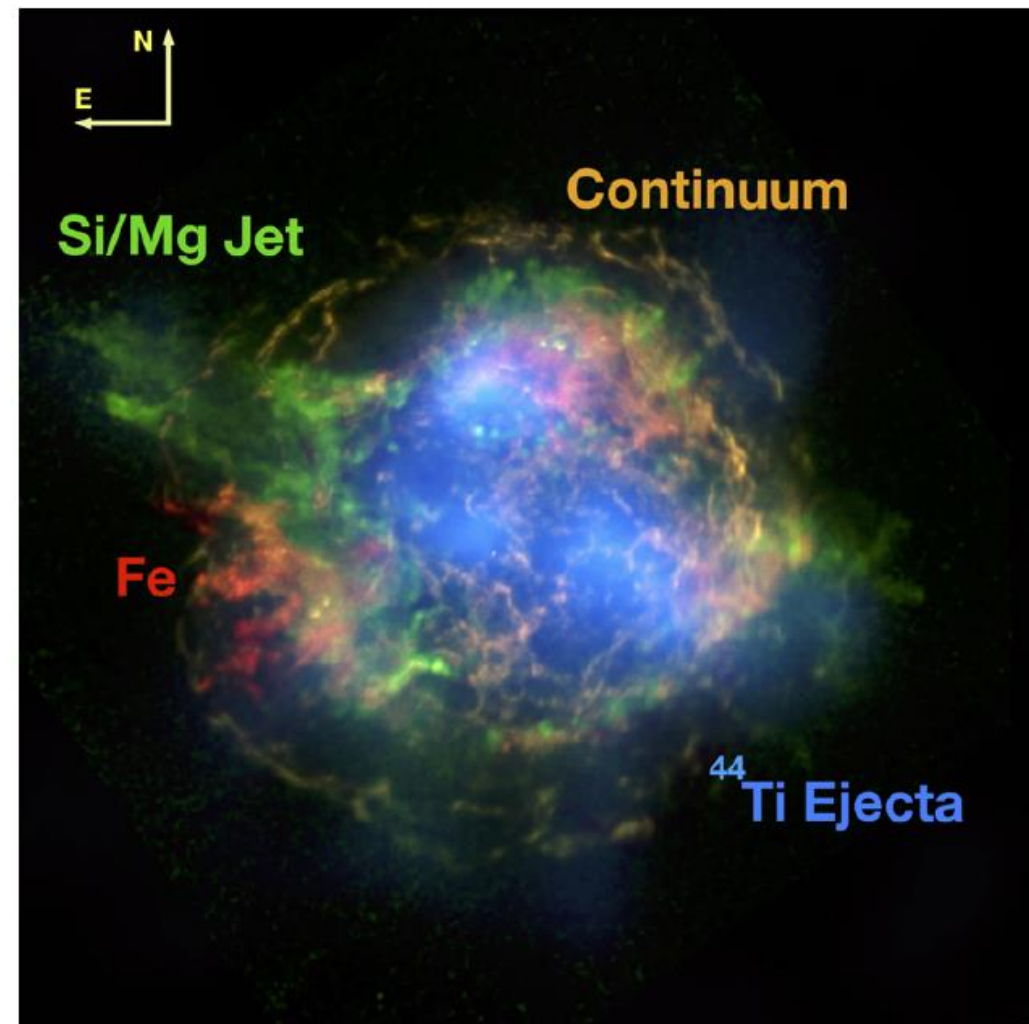
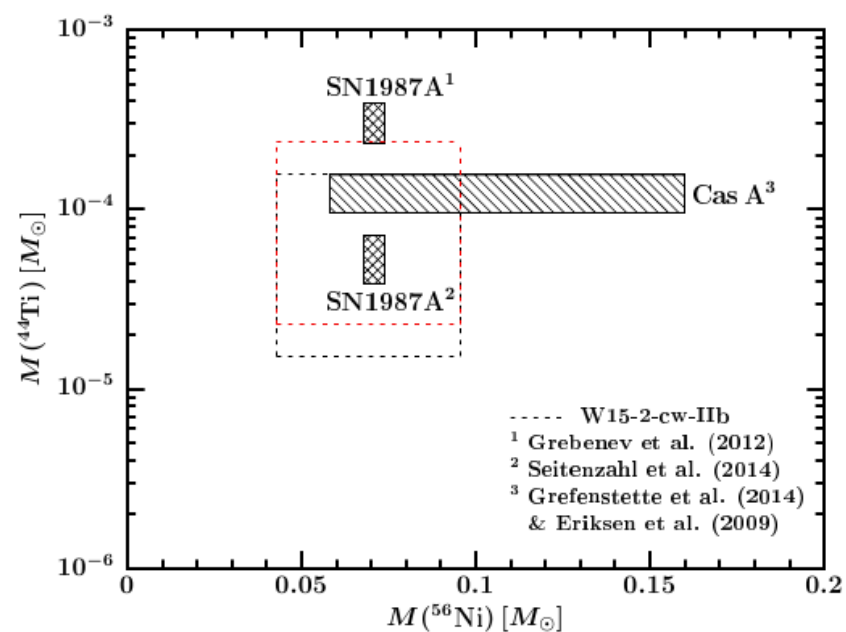


Figure 2: 3D distribution of Cas A ejecta. *NuSTAR* ⁴⁴Ti in blue, Chandra continuum in gold, Si/Mg band in green, X-ray emitting iron in red^[43].



Wongwathanarat+ (2017); similar results by Harris, Hix+ in **multi-D modeling of ejected high entropy blobs**

⁴⁴Ti AND ⁵⁶Ni IN A CASSIOPEIA A LIKE 3D SUPERNOVA MODEL

7

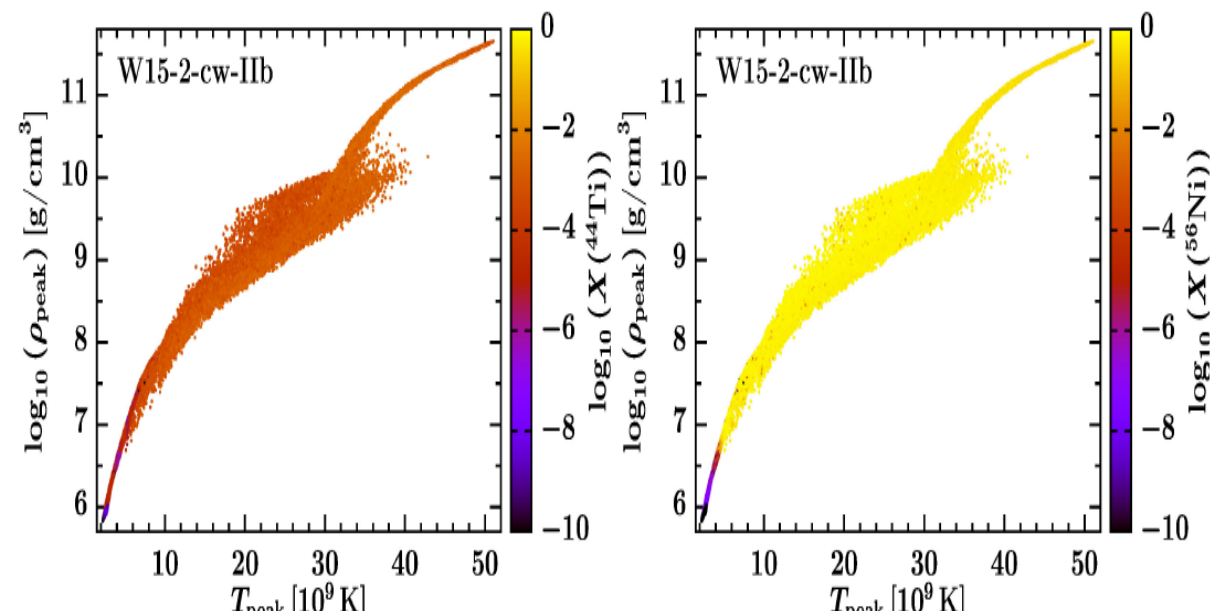


Table 4. Observed and calculated properties of SN 1987A

Quantity	SN 1987A (observed)	PUSH (s18.8)
E_{expl} (10^{51} erg)	1.1 ± 0.3	1.2
M_{prog} (M_{\odot})	18-21	18.8
^{56}Ni (M_{\odot})	(0.071 ± 0.003)	0.069
^{57}Ni (M_{\odot})	(0.0041 ± 0.0018)	0.0027
^{58}Ni (M_{\odot})	0.006	0.0066
^{44}Ti (M_{\odot})	$(1.5 \pm 0.3) \times 10^{-4}$	3.05×10^{-5}

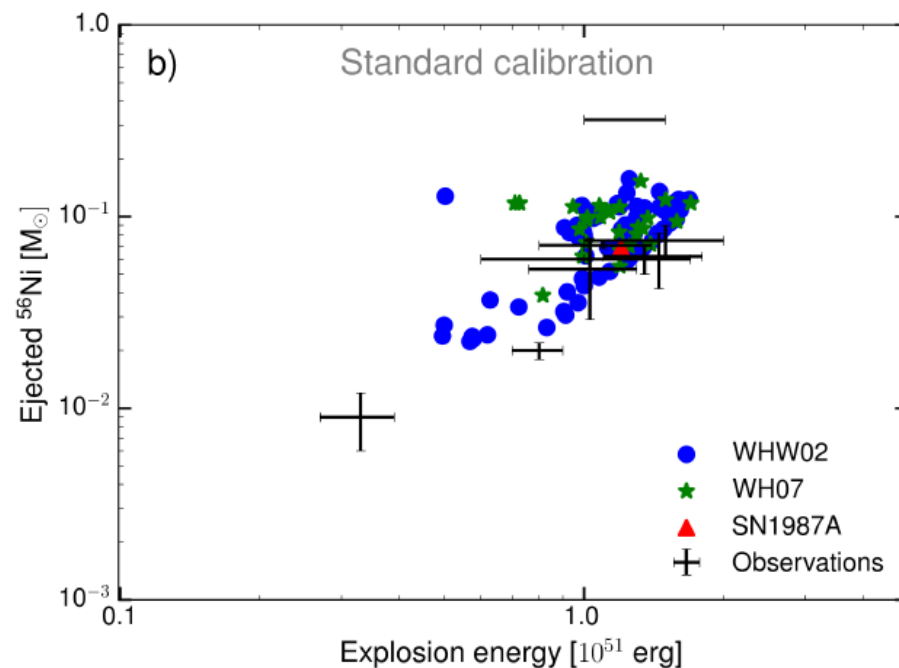
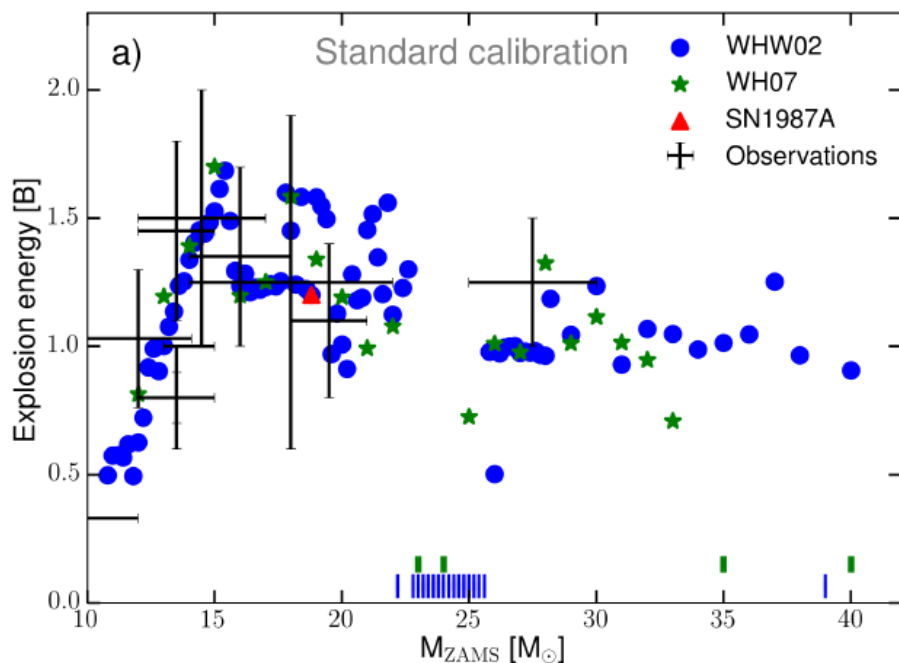
NUSTAR



Ebinger et al. (2018, for solar metallicities)

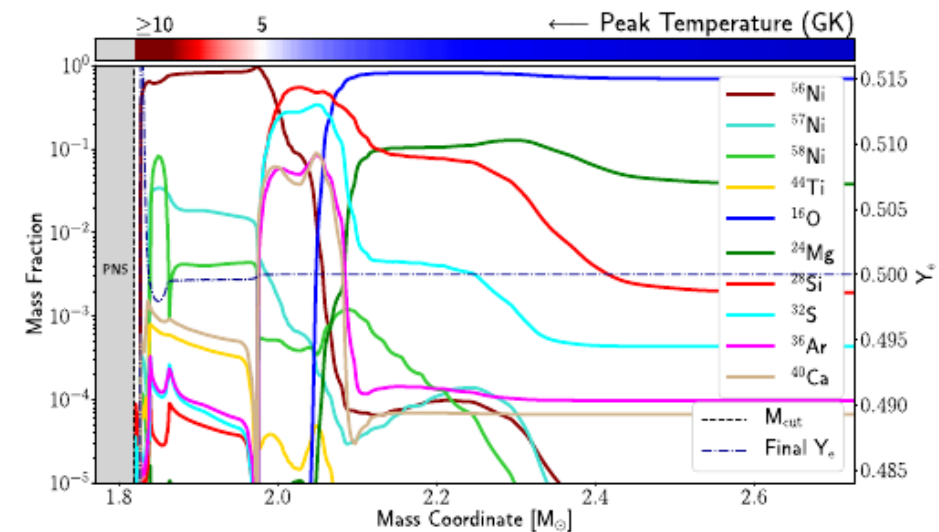
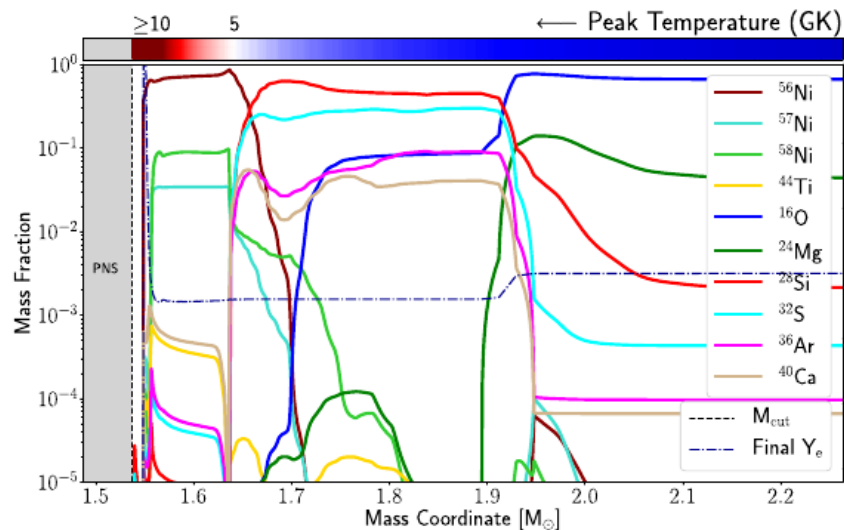
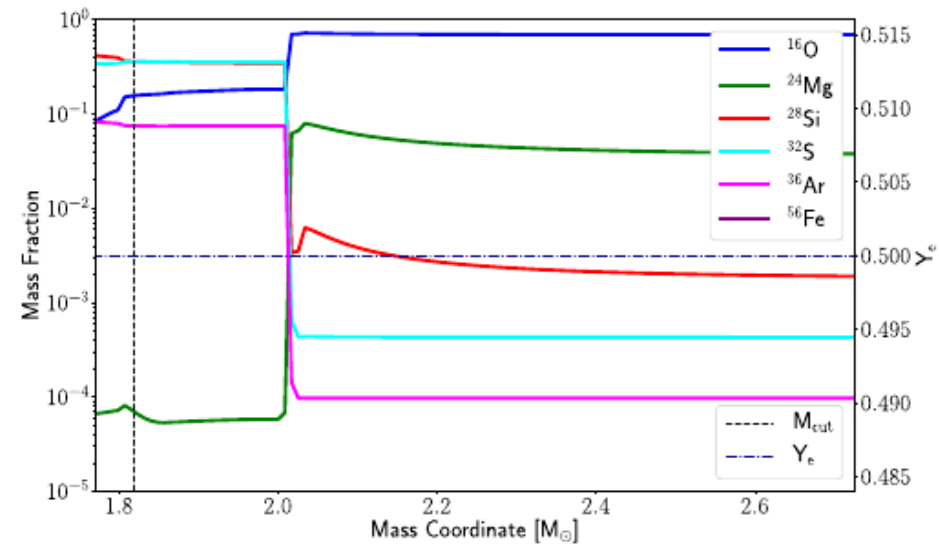
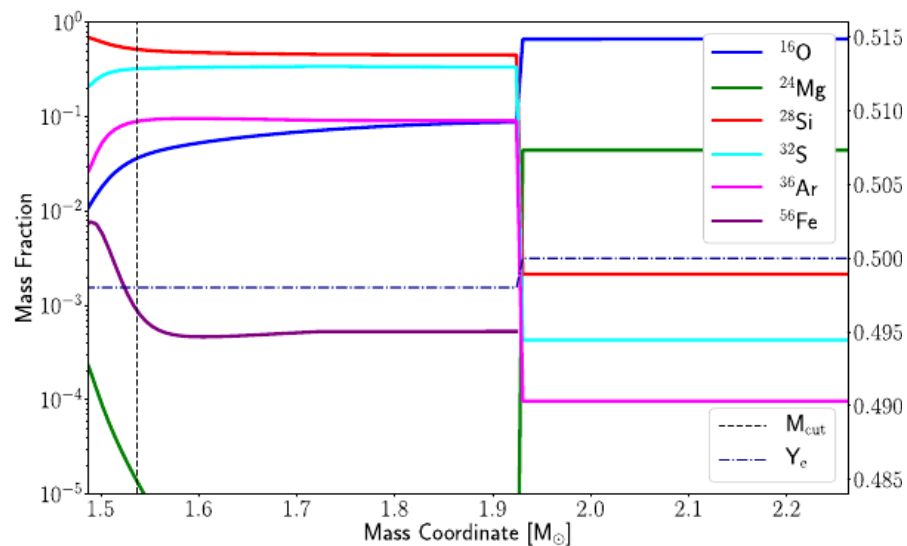
Parameters adjusted to SN1987A, other supernova observations and 3D simulations of the earlier mentioned comparison project

Reasonable fit to explosion energy and ejected Ni-Fe masses. ^{44}Ti , resulting from ejected high entropy blobs, which apparently can only be predicted well in 3D models.

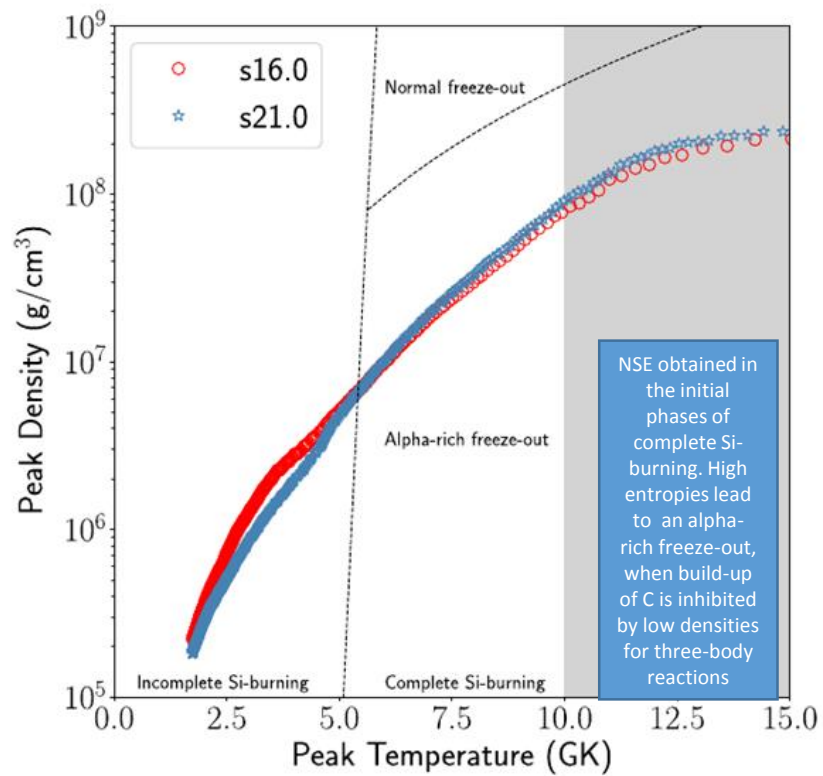


Composition in Pre-Explosion Model and Explosive Ejecta (Curtis et al. 2019)

for 16 and 21 Msol progenitors (based on PUSH approach)



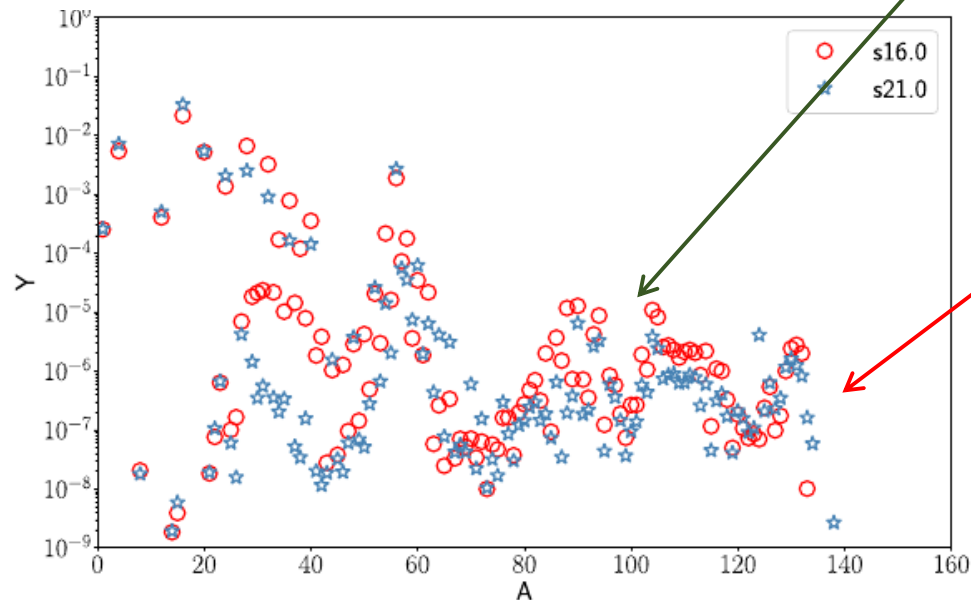
Y_e on right abscissa (dashed), being in the outer layers unchanged from the initial (hydrostatic) Y_e close to 0.5, decreased due to (beta⁺-decays and e-captures) in explosive Si-burning, and enhanced via neutrino interactions with matter in inner layers at small radii. Innermost layers not well visible here, see next transparency



Types of explosive Si-burning: all explosive Si-burning zones in CCSNe lead to an alpha-rich freeze-out.

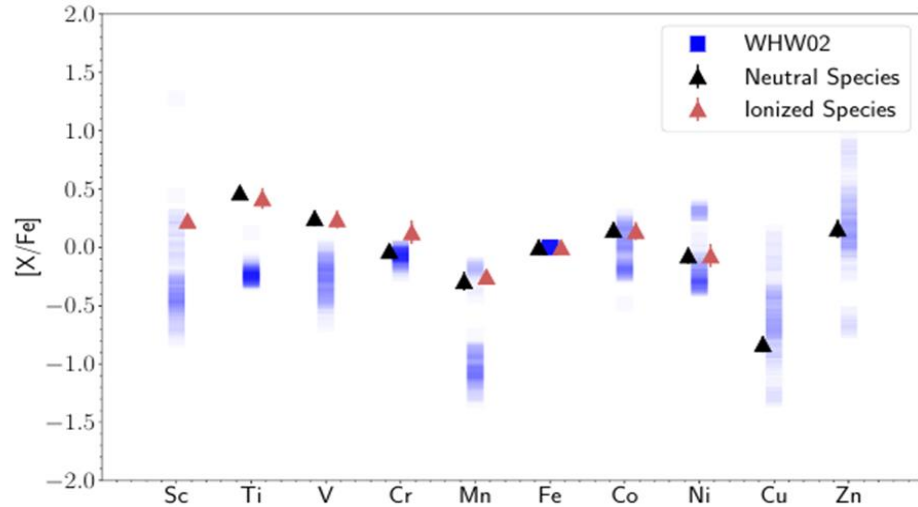
Another feature is the Y_e or neutron-richness encountered (see previous transparency)

- (1) *In outer layers, Y_e is essentially given by pre-explosive (hydrostatic) values.*
- (2) *Then follows a region where explosive Si-burning led to unstable nuclei which experience β^+ -decay. In a similar way electron captures can lower Y_e slightly below 0.5.*
- (3) *Neutrino interactions with nucleons and nuclei can enhance Y_e , for similar luminosities of neutrinos and antineutrinos the latter win, making Y_e proton-rich >0.5 . This, together with the less proton-rich layers of explosive Si-burning (see 2) provides a good fit to the Fe-group composition (next transparency) and also permits a νp -process with abundance produced up to $A=100$.*
- (4) *The very innermost ejected layers come late, originate from regions deeper in the collapsed core which had become very neutron-rich via e -captures during core collapse, and neutrino interactions were not sufficient to turn them proton-rich. Y_e 's encountered here range from 0.32 to 0.42. These zone are responsible for a weak r -process and abundances up to $A=140$.*

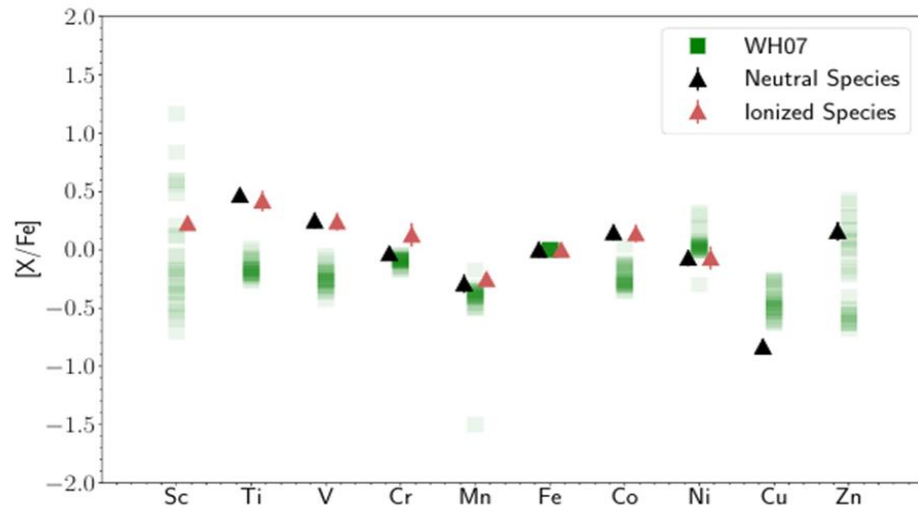


Abundances of explosive ejecta for two progenitor masses

Comparison of low metallicity star HD 84937 (Sneden et al. 2016) with predicted CCSN yields



Good fit to Fe-group composition of low metallicity stars which is dominated by core-collapse supernovae and essentially due to introducing the Ye-variations caused by neutrino interactions during core-collapse and explosion (first suggested by Fröhlich et al. 2006a).



The shaded boxes pass through the whole mass sequence of the two progenitor sets.

Curtis et al. (2019), as previous transparencies

A rare class of CCSNe from fast rotating massive stars with high magnetic fields

Full MHD calculations resolving the magneto-rotational instability MRI

(Nishimura, Sawai, Takiwaki, Yamada, Thielemann, 2017)

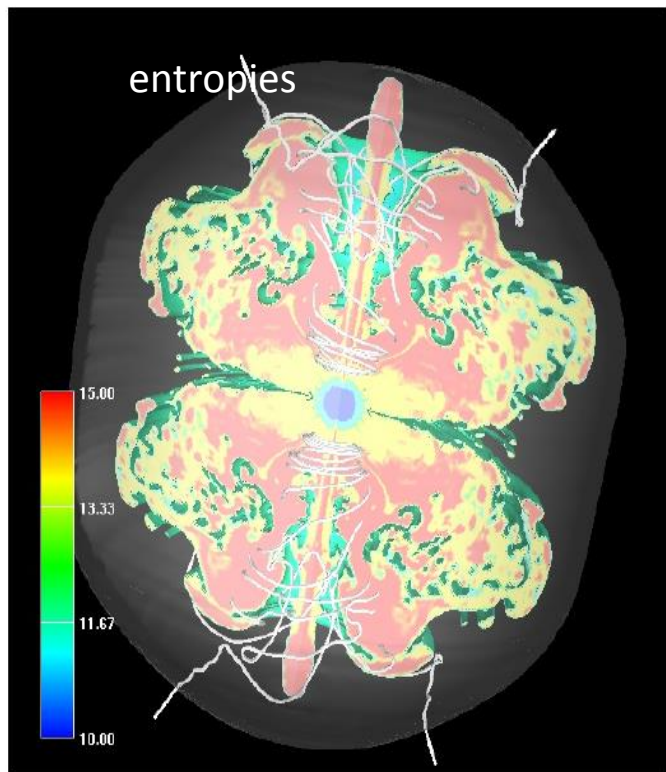
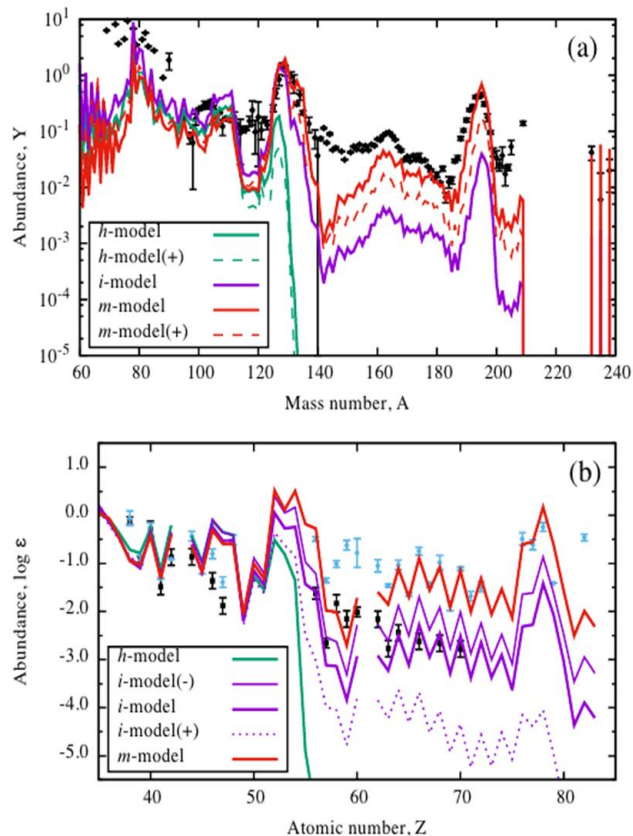


Figure 1. Entropy distribution with magnetic field lines of an MR-SN model (a cube with 2000 km). The surrounded



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

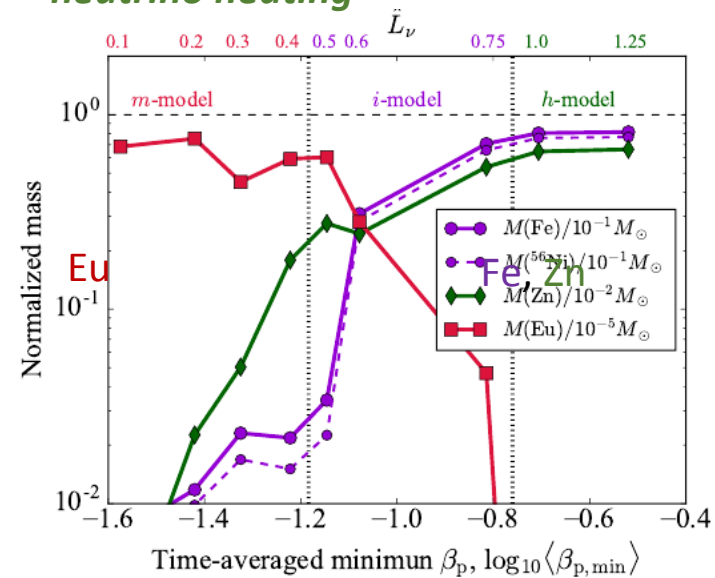


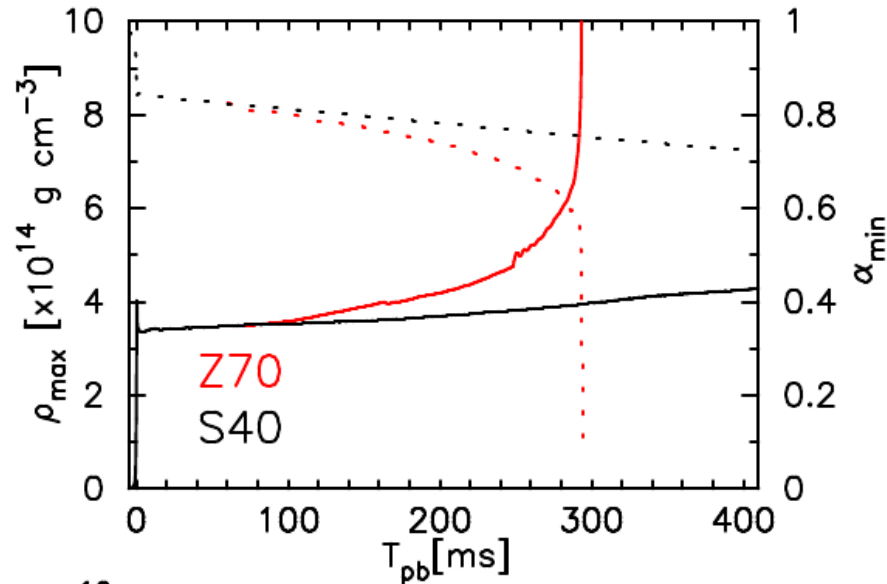
Figure 5. Ejected masses of Fe, ^{56}Ni (before decay), Zn and Eu, normalized by 0.1 , 0.1 , 10^{-2} and $10^{-5} M_{\odot}$, respectively, as a function of $\langle \beta_{p,\min} \rangle$ with corresponding \tilde{L}_{ν} (top).

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?? (Zn discussed earlier, Eu to be discussed later)**

see also Winteler+ (2012), Eichler+ (2015), Nishimura+ (2015), Mösta+ (2014, 2015, 2017) and Halevi+ (2018), main question: what magnetic field strength and rotation rates do result from consistent stellar evolution models?

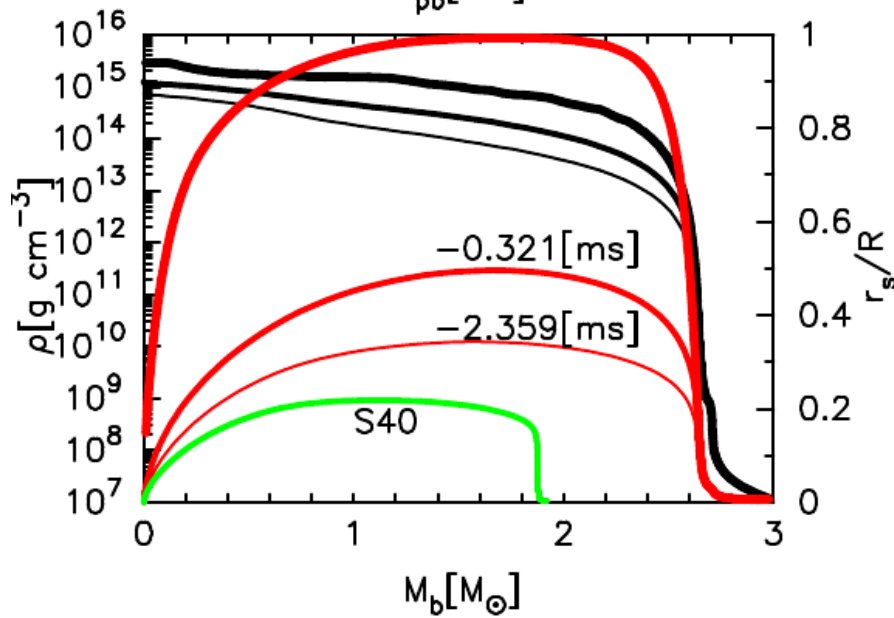
When do massive stars end in black holes?

Fully relativistic 3D simulations by Kuroda, Kotake, Takiwaki, FKT (2018)



70 Msol star leads to BH formation within 300ms, 40 Msol star seems to take longer

see other investigations for a 40 Msol collapse by Pan, Liebendörfer, Couch, FKT (2018)



Black: Rest mass density at three points in time for 70 Msol star

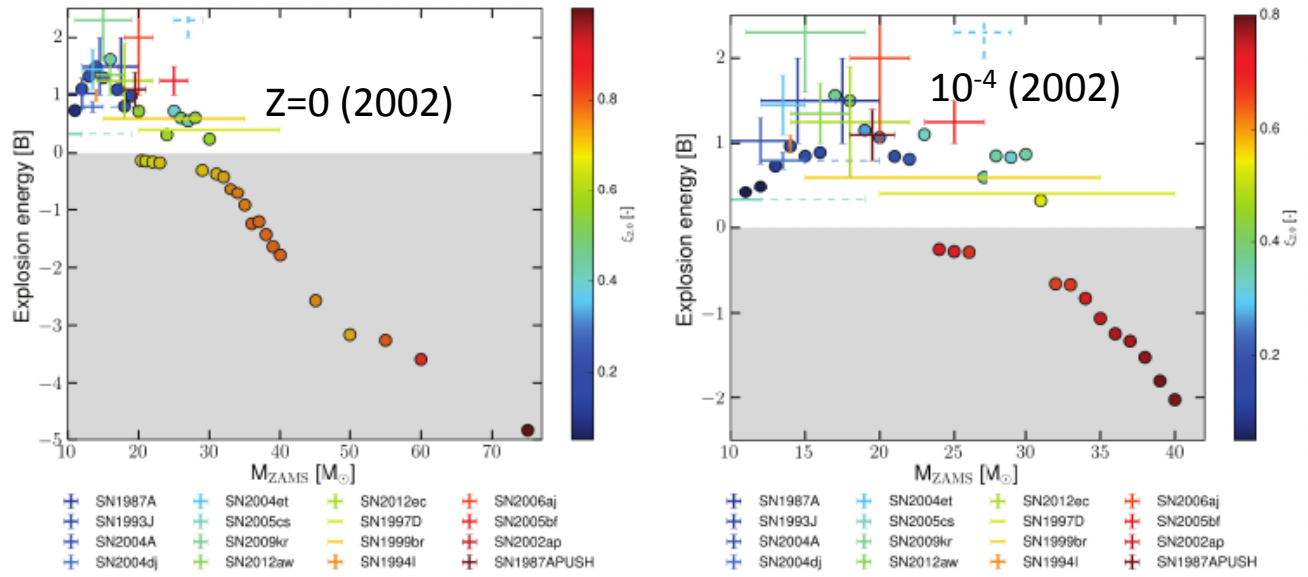
Red: r_s/R (Schwarzschild radius divided by radial coordinate) at corresponding times. BH formation is indicated when Schwarzschild radius and radius become identical ($r_s/R=1$)

Green: r_s/R for 40Msol star at $t=400\text{ms}$

Progenitor set	Metallicity	Black Hole fraction
z (2002)	$Z = 0$	$\lesssim 17.6\%$
u (2002)	$Z = Z_{\odot} \times 10^{-4}$	$\lesssim 21\%$
s (2002)	$Z = Z_{\odot}$	$\lesssim 4.5\%$
w (2007)	$Z = Z_{\odot}$	$\lesssim 8.3\%$

Explosion energies as function of stellar progenitor mass for different sets of stellar models **also for low metallicities**

(Ebinger+ 2019 PRELIMINARY!!!)



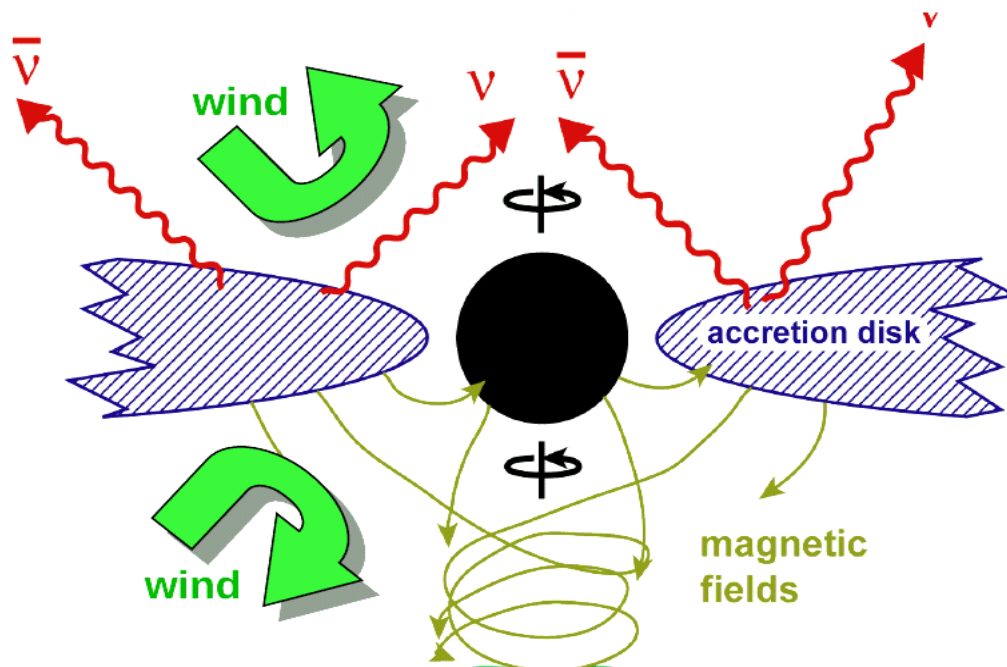
How else can massive stars explode?

Long Duration Gamma-Ray Bursts

$$25M_{\odot} < M < 100M_{\odot},$$

$$M > 250M_{\odot}$$

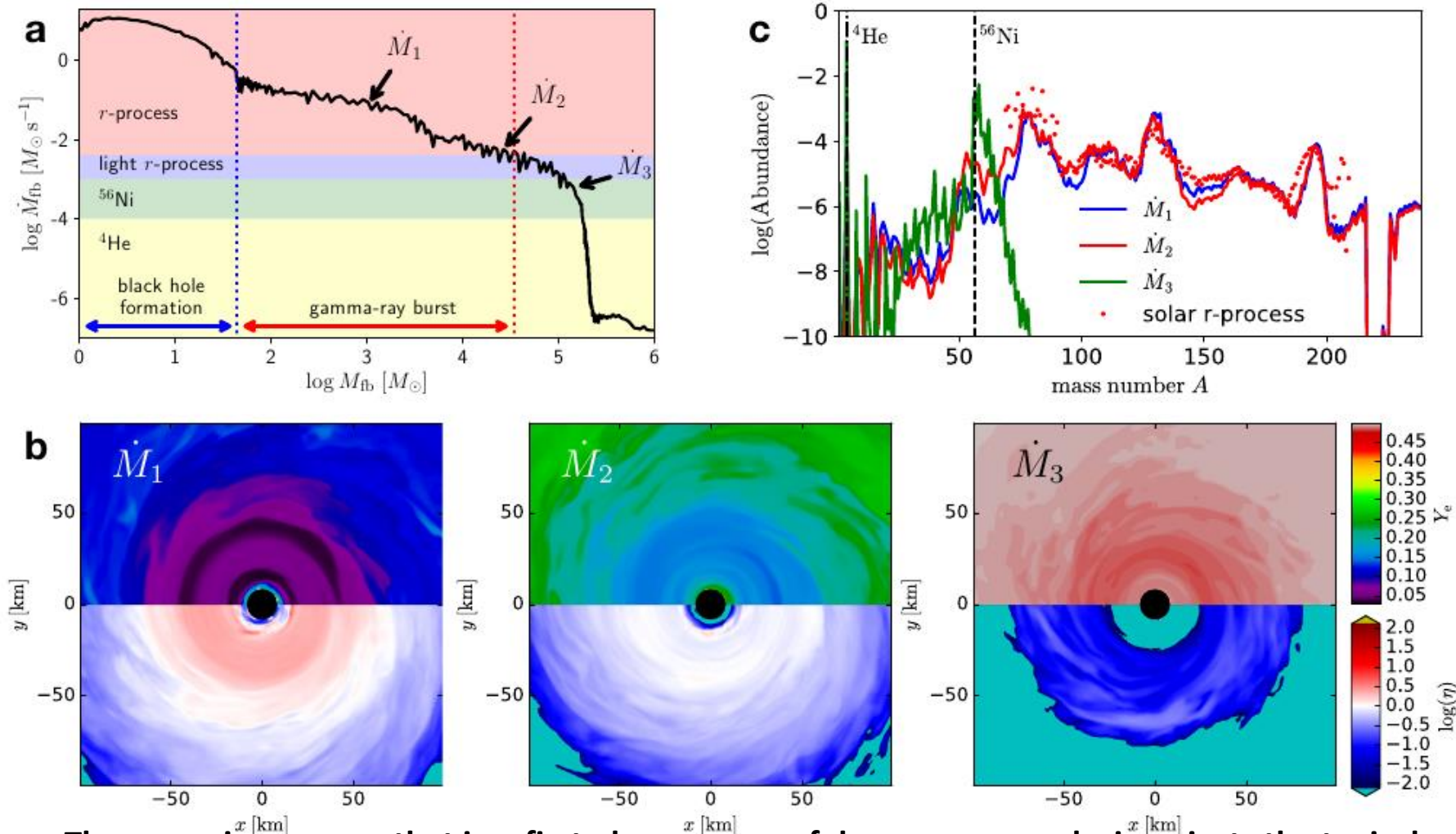
The “Collapsar Engine”



1. black hole forms inside the collapsing star after failure or neutrino-powered explosion
2. The infalling matter forms an accretion disk
 $\approx 0.1 M_{\odot}/\text{sec}$
3. The accretion disk releases gravitational energy (up to 42.3% of rest mass for Kerr BH)
4. Part of the released energy or winds off the hot disk explode the star

Adopted from MacFadyen (requiring black hole formation and rotation)

Siegel+ (2018) find in in general relativistic MHD simulations, making use of weak interactions (including also electron degeneracy and electron capture on protons) and approximate neutrino transport (leakage scheme) in total the ejection of up to $1M_{\odot}$ of r -process ejecta (Janiuk, private communication, seems to obtain similar results).

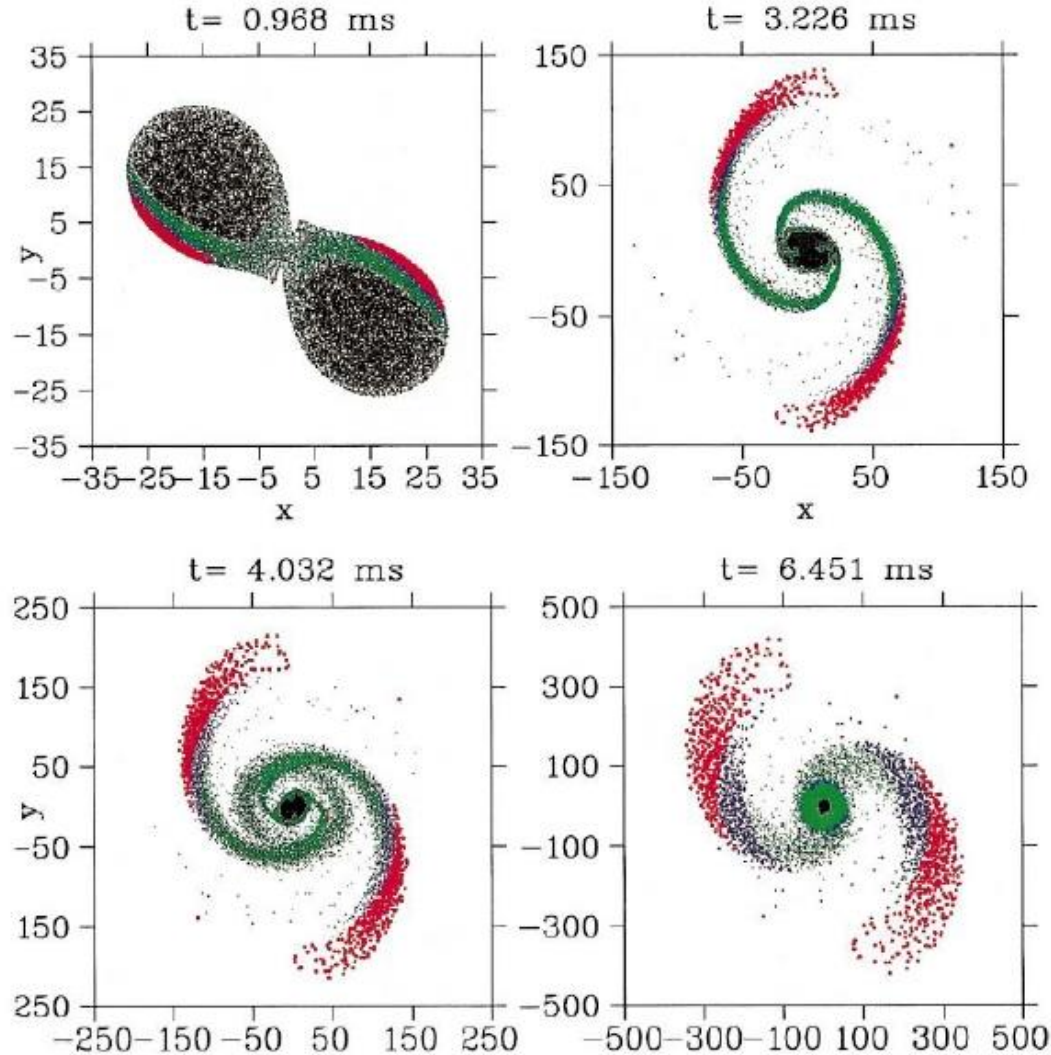


The scenario assumes that in a first phase a powerful supernova explosion ejects the typical up to $0.5M_{\odot}$ of ^{56}Ni and further accretion leads to a black hole and plus the BH accretion disk. Is this a somewhat fine-tuned scenario??

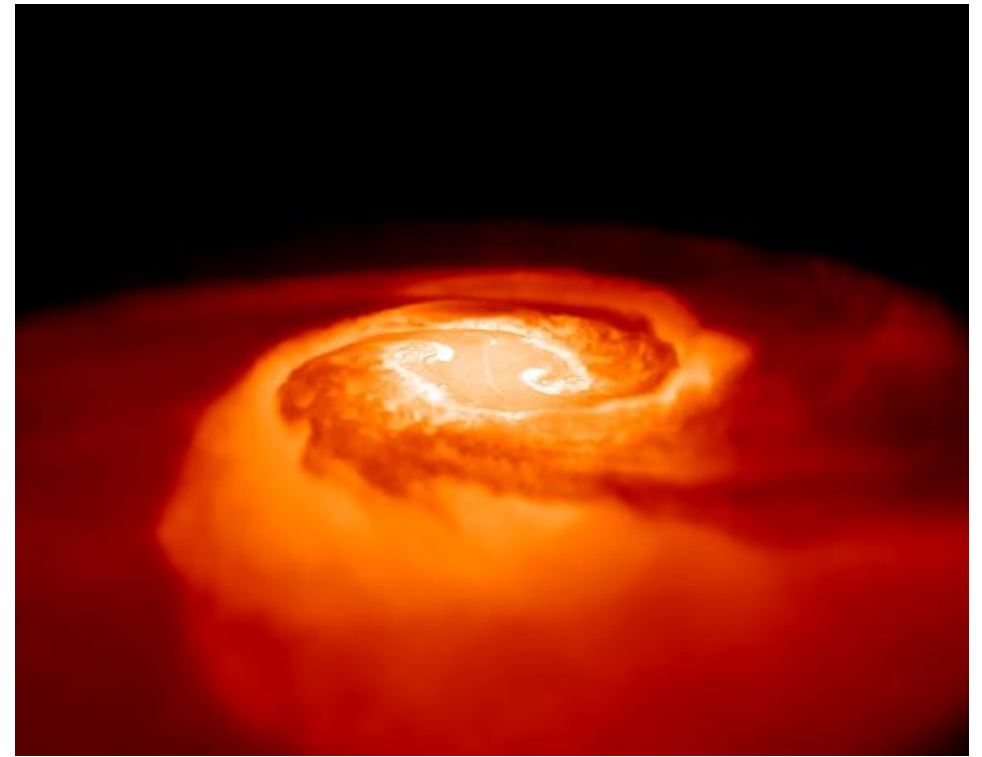
Neutron Star Mergers: The dominant site for the r-process?

Early and later SPH simulations: NSMs and their «dynamic ejecta»

Rosswog et al. (1999), Freiburghaus et al. (1999)



only tidal arms in early approaches

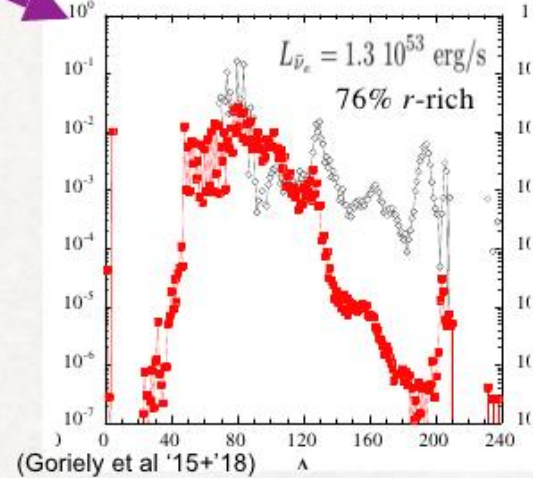
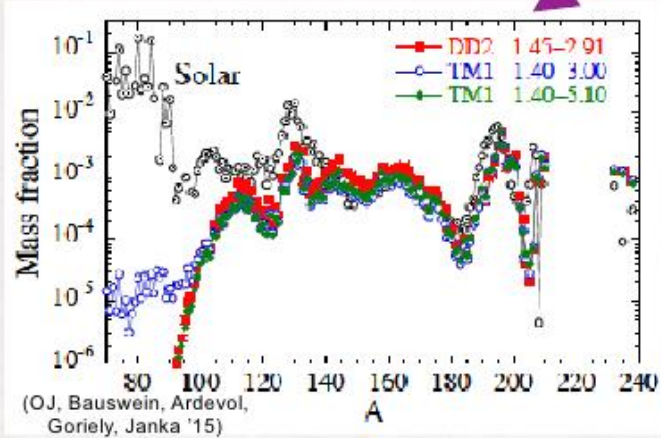
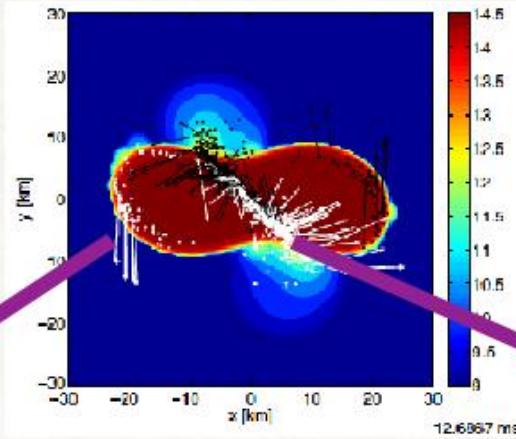


Rosswog et al. 2014

Prompt / dynamical Ejecta

(qualitatively consistent with works by, e.g., Hotokezaka '13, Wanajo+Sekiguchi '14,'16, Radice '16, Foucart '16)

from Just (2018)
Shanghai talk



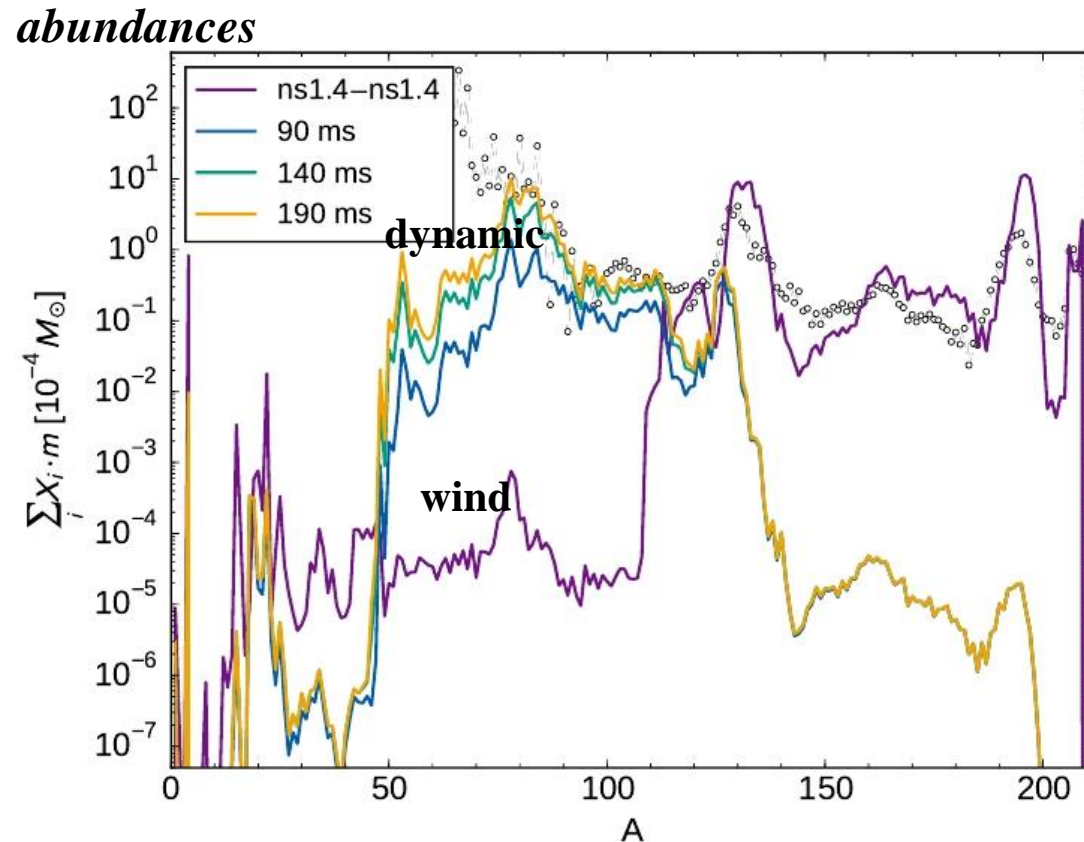
from tidal tails

- > low Y_e
 - > more lanthanides
 - > higher opacity
 - > **red Kilonova**
- (if observed independently)

from collision shock

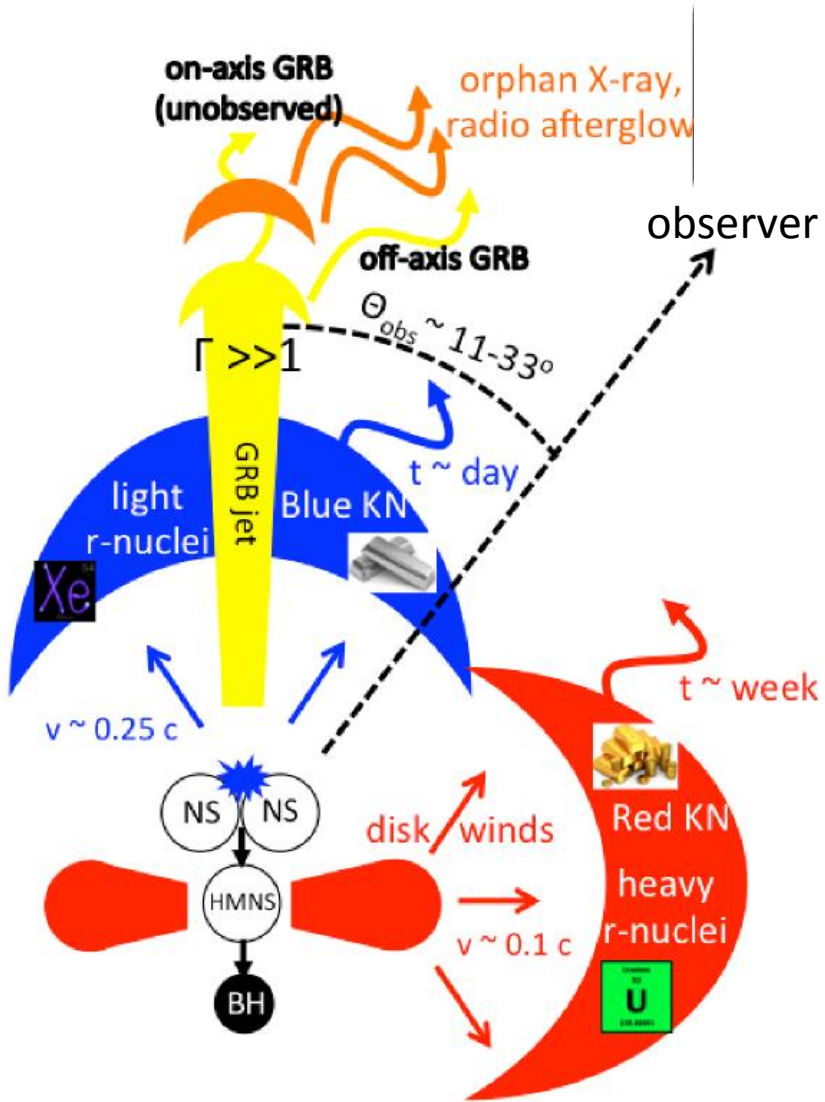
- > high Y_e
 - > less lanthanides
 - > lower opacity
 - > **blue Kilonova**
- (if observed independently)

After dynamic ejection of matter, the hot, hypermassive neutron star (before – possibly and with which delay - collapsing to a black hole) evaporates a neutrino wind (Rosswog et al. 2014, Perego et al. 2014), Martin et al. (2015)

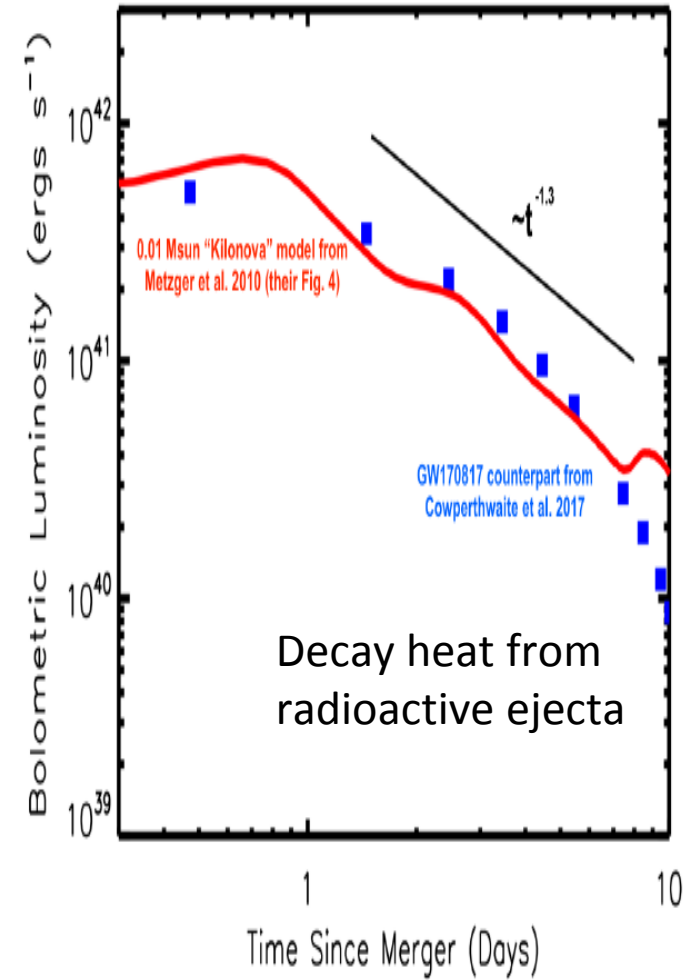


Martin et al. (2015) with neutrino wind contributions, here still combined with composition of dynamic ejecta of Korobkin+ (2012) with their known deficiencies.

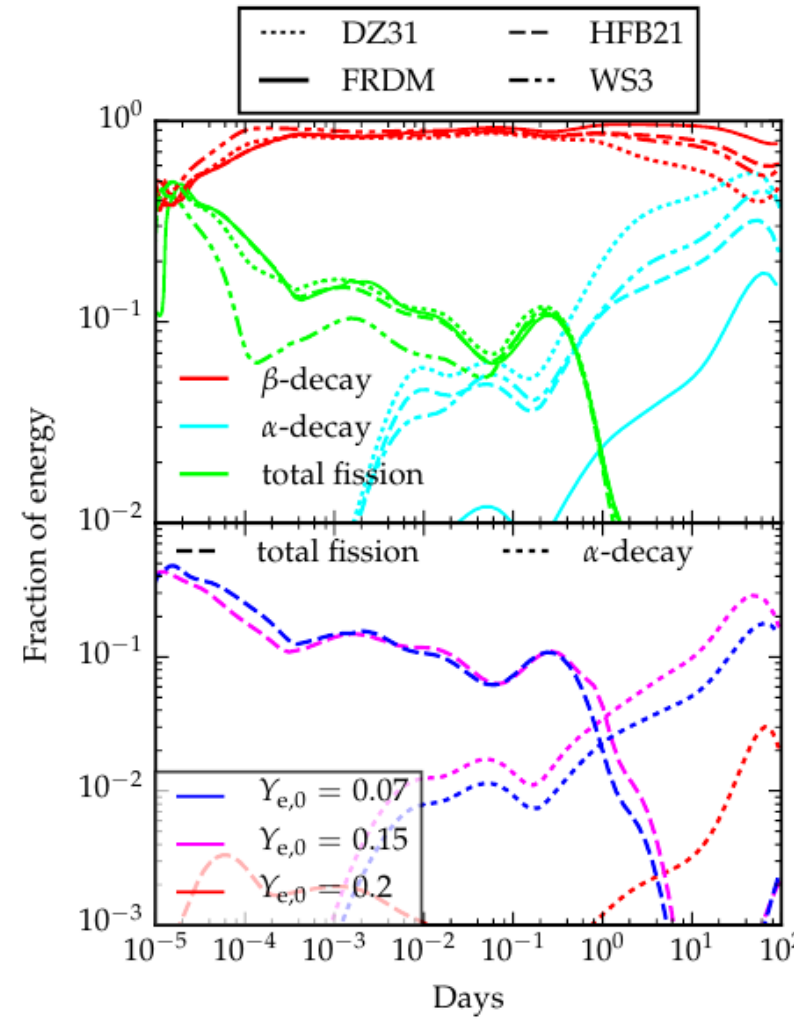
Roland was involved
in the INTEGRAL observations
of the short-duration GRB



Metzger, Martinez-Pinedo
et al. (2010)

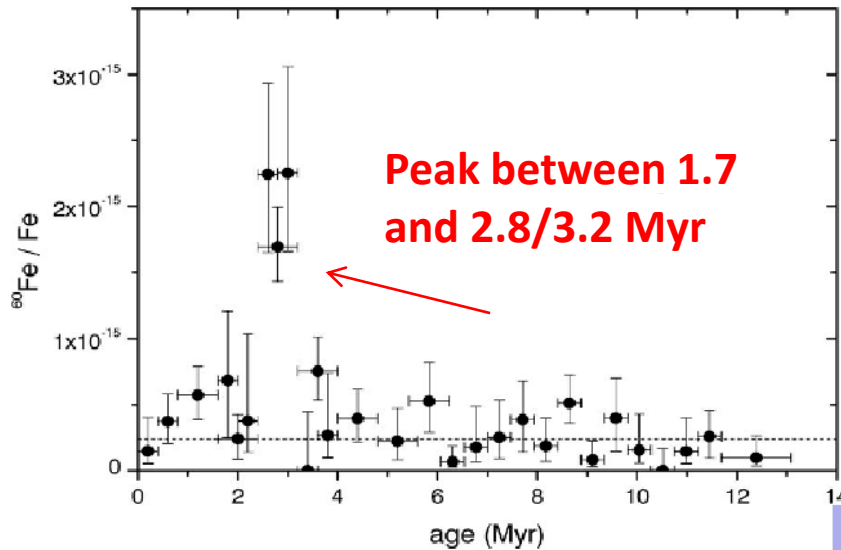


Barnes et al. (2016)



Interpretation of GW170817 (Metzger 2017); NS-merger collision, dynamic ejecta, hypermassive NS and neutrino wind, accretion disk outflow, BH formation, see also recent r-process review Cowan+ (2019)

^{60}Fe -signal in a deep-sea crust (origin: massive stars, supernovae) **AMS at Munich**



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

background level

• ***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



Witnessing the last CCSNe near the solar system, see recent papers by P. Ludwig et al. (2016) and J. Feige et al. (2018, in tune with ^{26}Al predictions!)

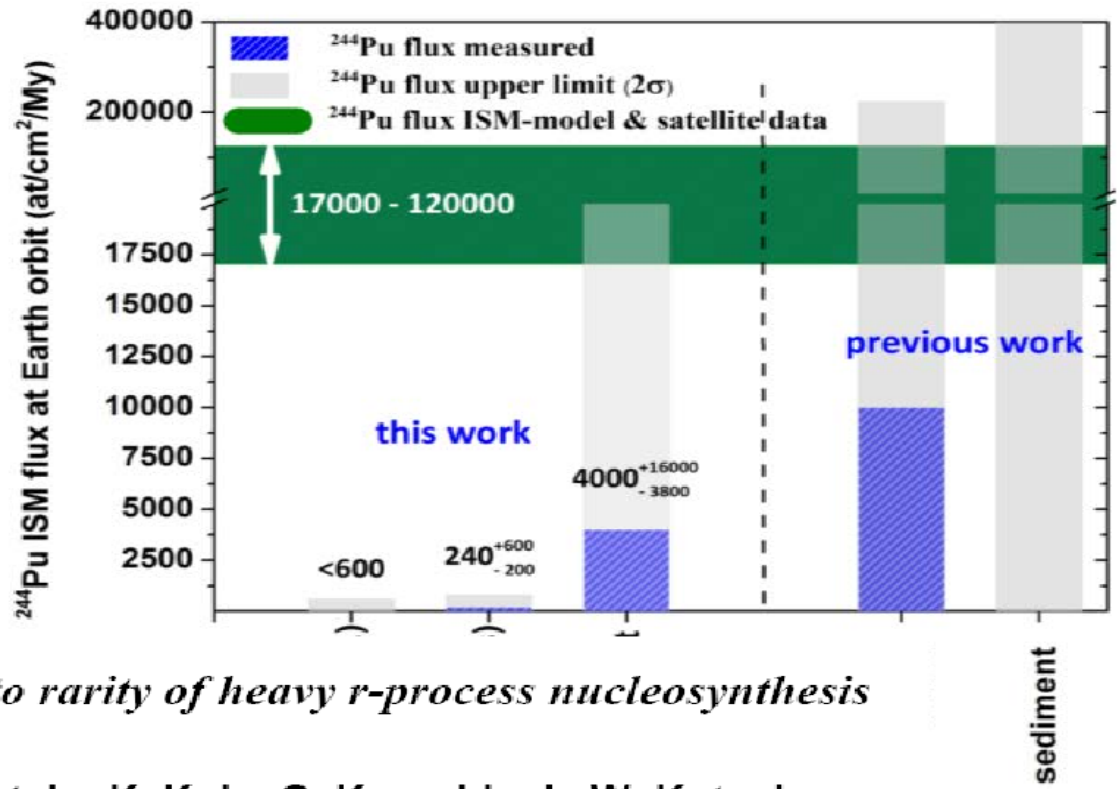
Firestone (2014) finds a higher supernova rate from radiocarbon (^{14}C , cosmic ray induced) within local 300pc, but dust particles would be able to overcome solar wind only within 150pc and no dust particles from >100pc should arrive on earth due to delay travel time

^{244}Pu , half-life 81 My Status:

^{244}Pu in terrestrial crust:

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

100:1 estimated vs measured



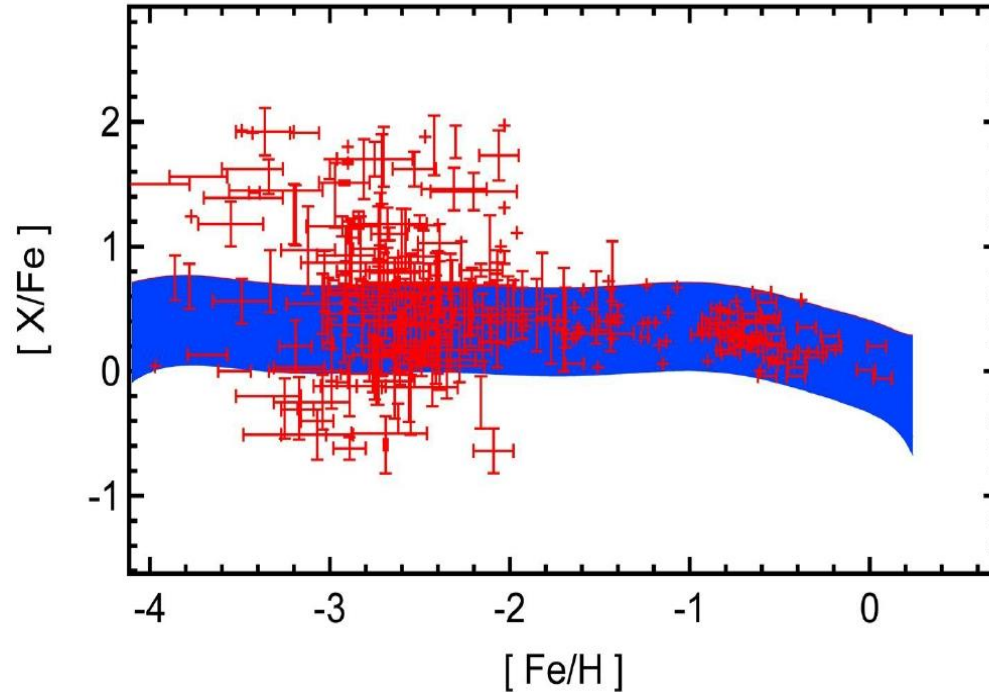
New limit of ^{244}Pu on Earth points to rarity of heavy r-process nucleosynthesis

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

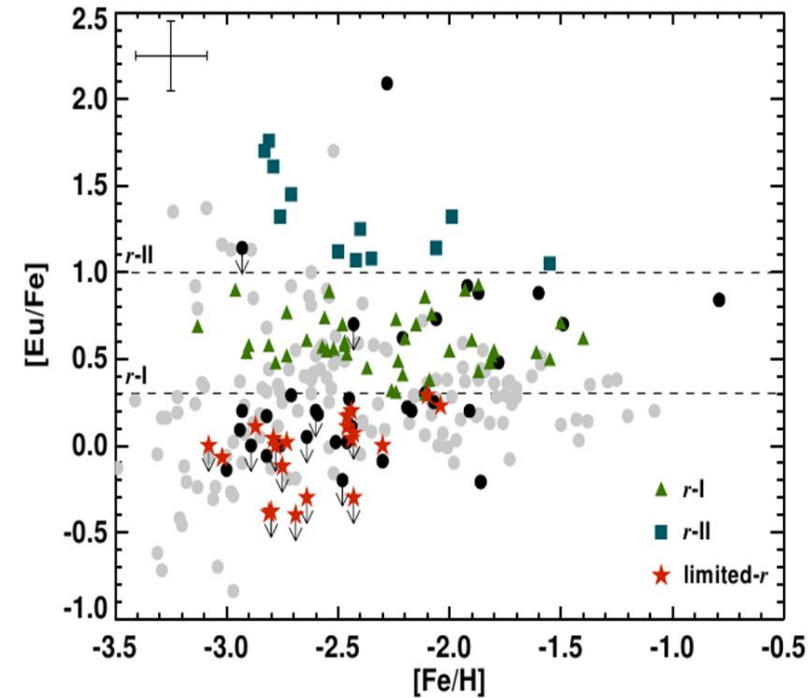
The continuous production of ^{244}Pu in regular CCSNe (10^{-4} - 10^{-5} Msol each of r-process nuclei, in order to reproduce solar system abundances) would result in green band → no recent (regular) supernova contribution. Rare events with enhanced ejecta could also explain solar abundances, but the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

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

Data from SAGA database



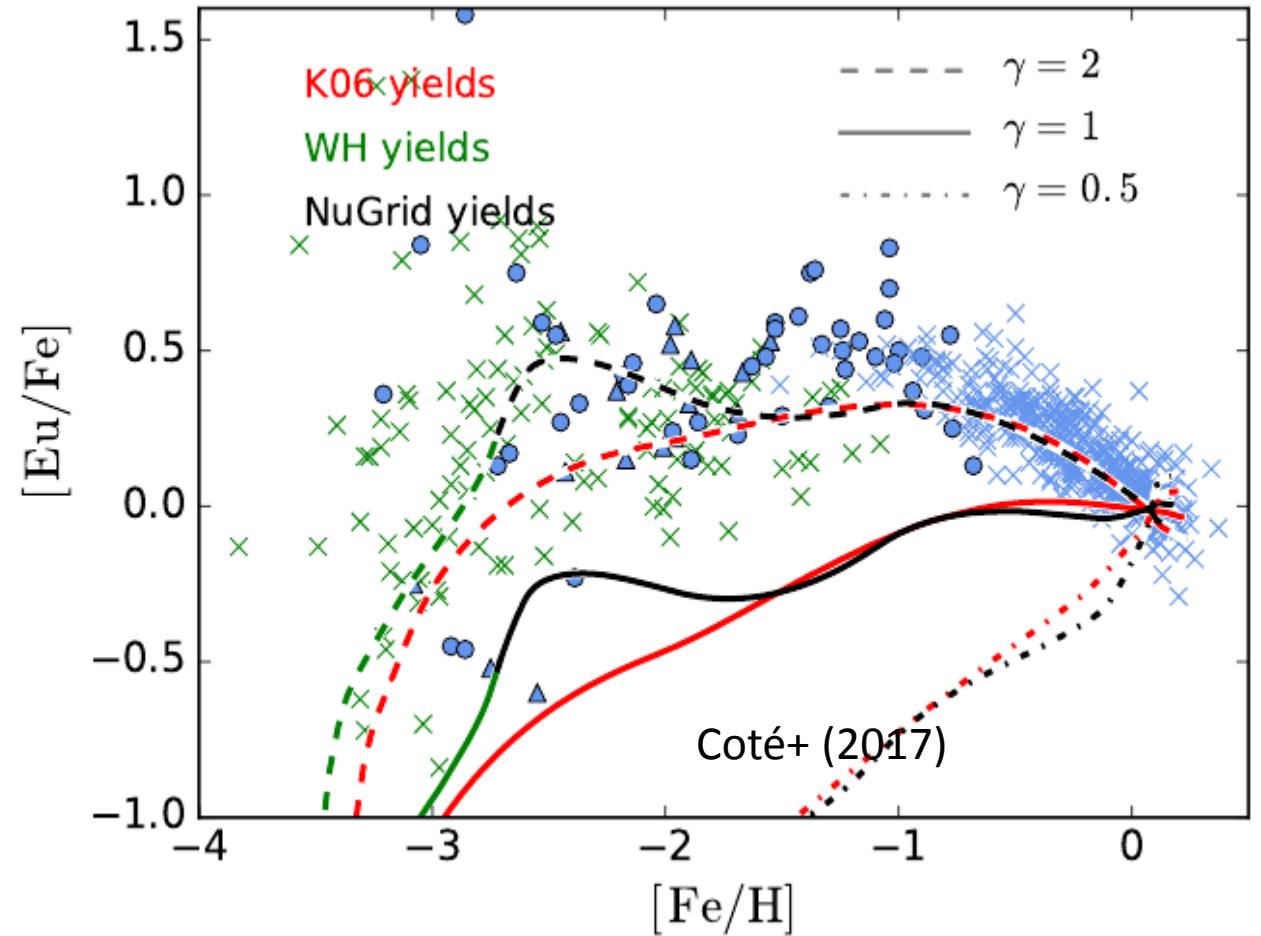
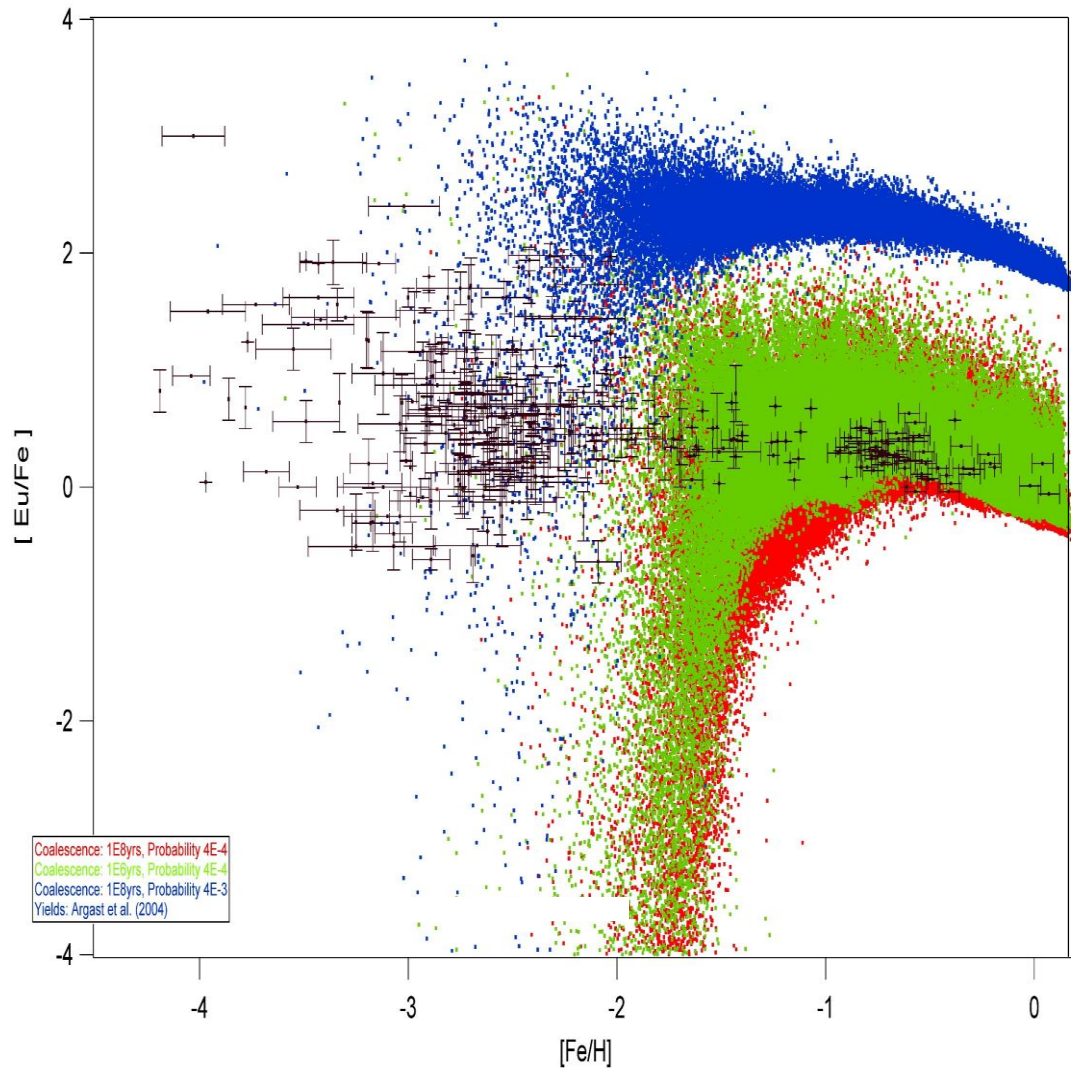
«The r-process alliance» Hansen et al. (2018)
In comparison to Roederer et al. (2014, grey dots)



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

^{60}Fe and ^{244}Pu measurements in deep sea sediments also indicate that the strong r-process is rare in comparison to CCSNe!

What are these possible r-events??

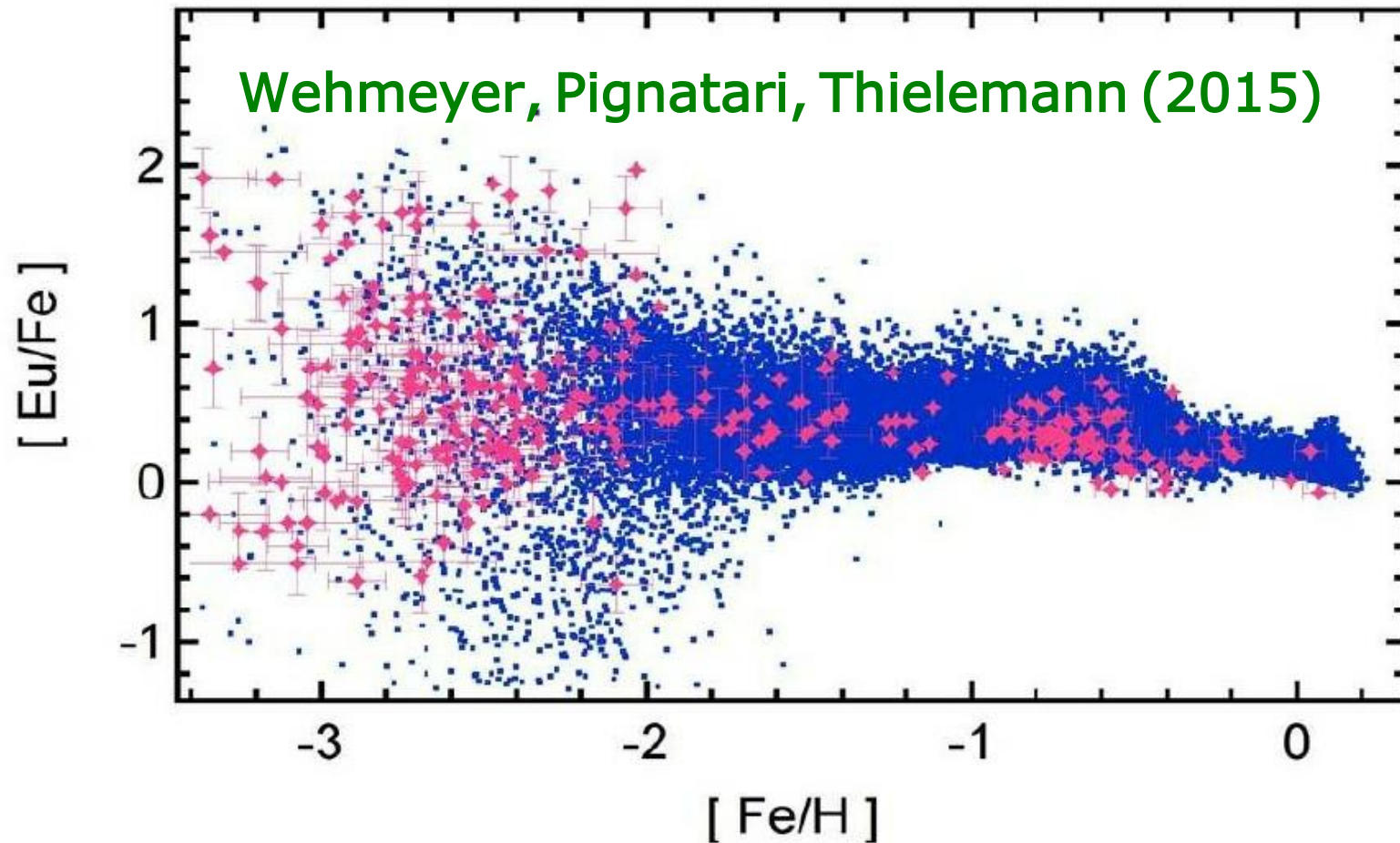


Wehmeyer et al. (2015, following Argast+ 2004 description), utilizing only NS merger: green/red different (constant) merging delay times, blue higher merger rate (not a solution, but turbulent mixing would shift the onset to lower metallicities), see for discussion of all options Shen+ 2015, Hirai+ 2015, Cescutti+ 2015, van de Voort+ 2015,2019, Coté+2017,2018, Hotokezaka+ 2018, Ojima+ 2018, Haynes & Kobayashi 2018, Wehmeyer+ 2018

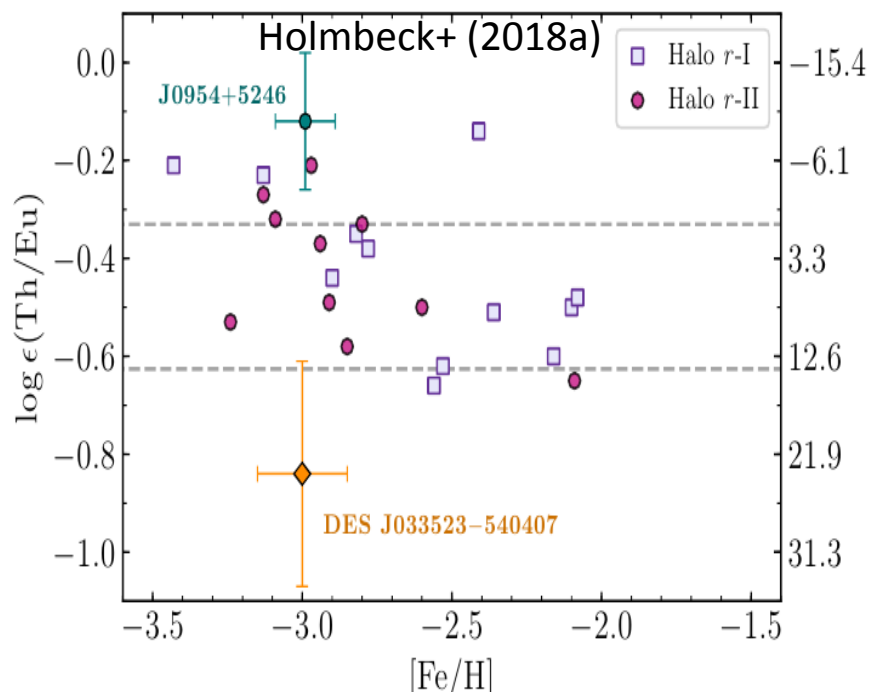
Combination of NS mergers and magneto-rotational jets

(as an event related to massive stars occurring very early in galactic evolution)

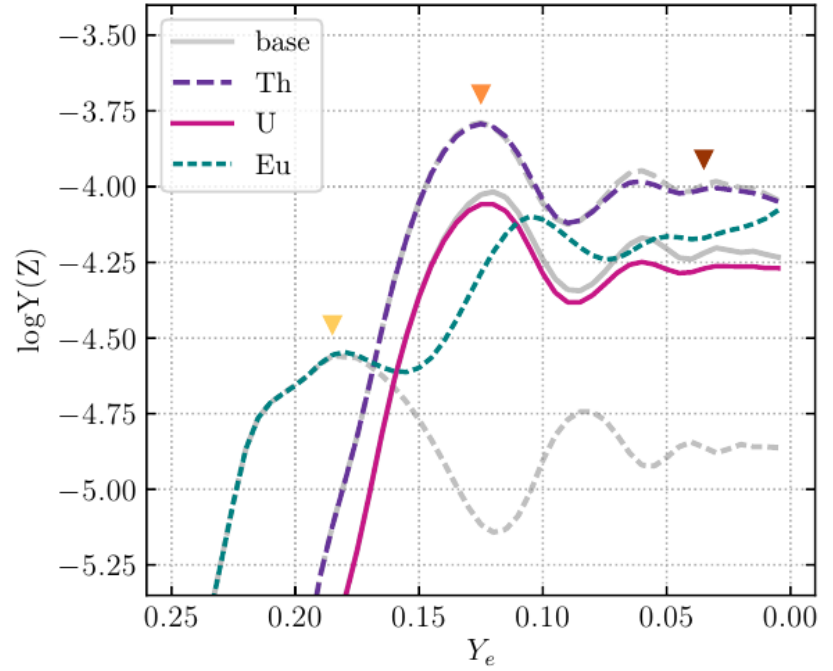
in (stochastic) inhomogeneous GCE



⇒ One option to solve the low metallicity problem,
see also Coté+ (2017, 2018), Hotokezaka+ (2018), Siegel+ (2018), Haynes & Kobayashi (2018)



Th/U, Th/Eu, U/Eu chronometers

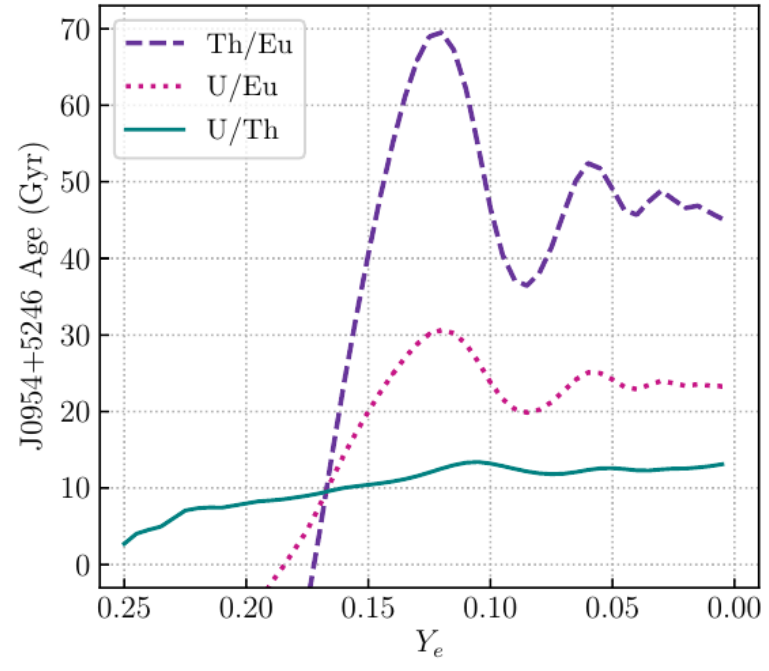


Independent of the question whether galactic evolution modeling requires a further r-process source in addition to NS-mergers or not, are there any other features which point to different events at the lowest metallicities (actinide boost stars at about $[Fe/H] \approx -3$)?

One finds different production of Eu, U, Th for different Y_e conditions in r-process environments.

When utilizing element production ratios which would fit well the solar r-abundances, unreasonable ages for these stars would result when making use of the Th/Eu and U/Eu chronometers.

When employing Y_e -values in the range 0.15-0.17, also these chronometers lead to ages agreeing with the early Galaxy (Holmbeck+ 2018b, Eichler 2019)





Roland, have fun as story teller, synergy agent, and active scientist in future gamma-ray missions

Here from

Catching Element Formation In The Act

The Case for a New MeV Gamma-Ray Mission:
Radionuclide Astronomy in the 2020s

Fryer et al. (2019), A White Paper for the 2020 Decadal Survey

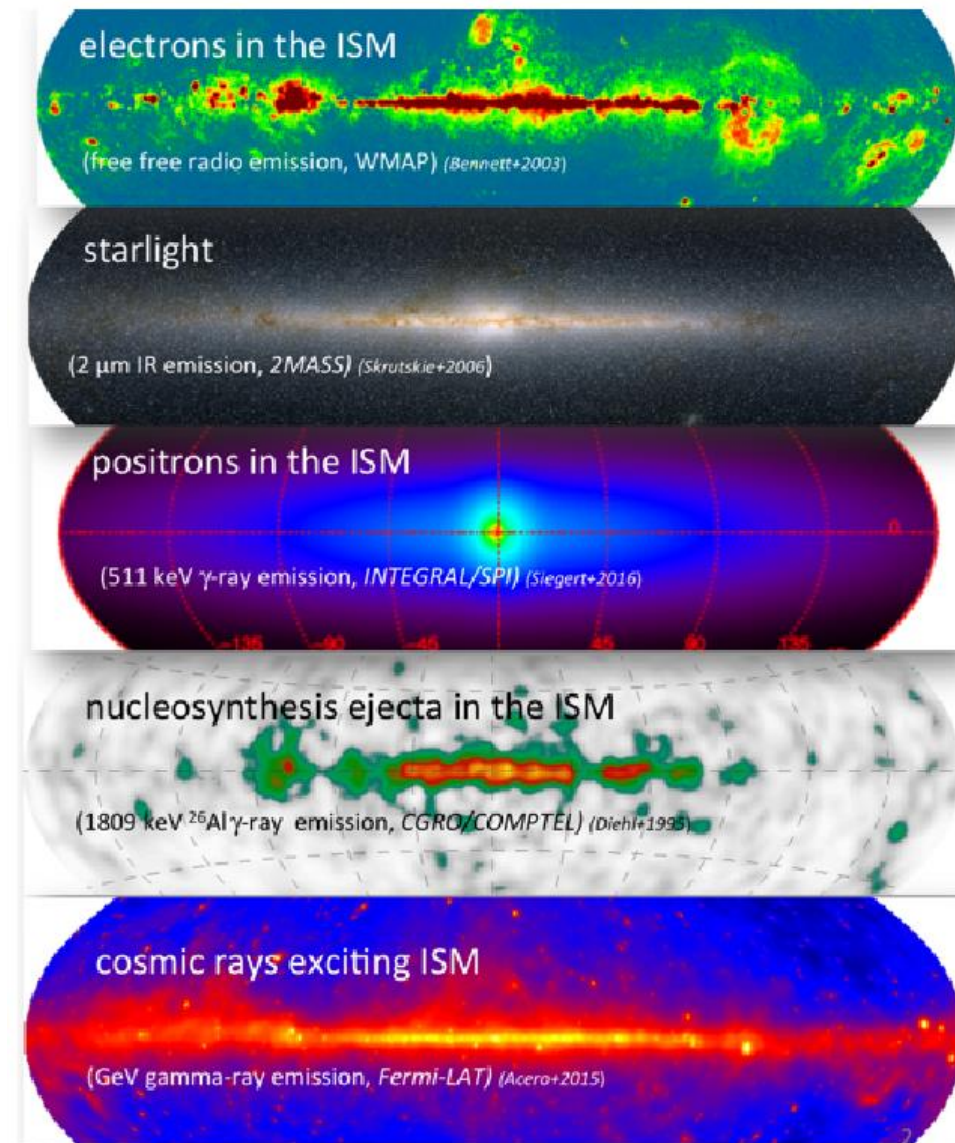


Figure 3: *Deciphering the Milky Way.* A modern MeV γ -ray instrument will help solve how newly created elements are produced, transported, mixed, and distributed.