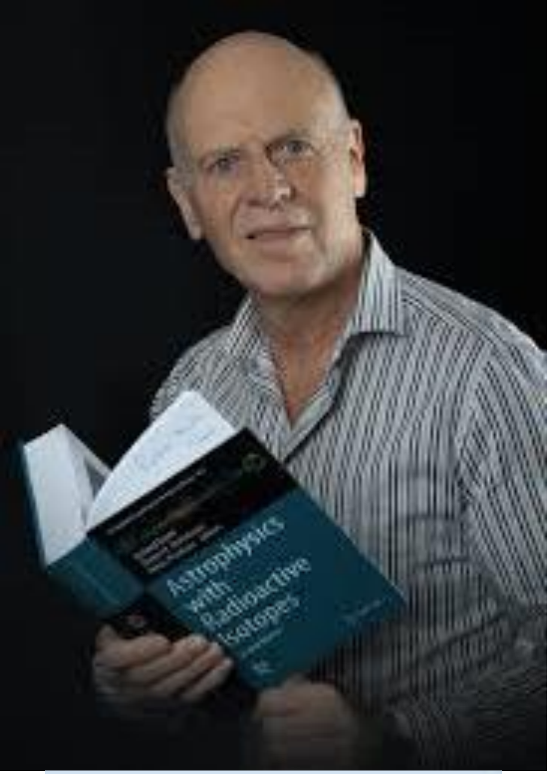
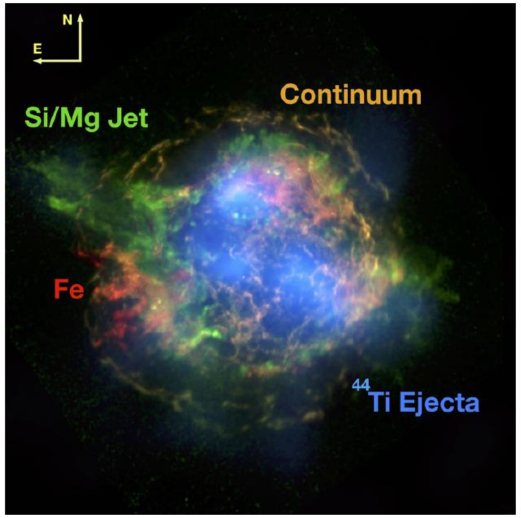
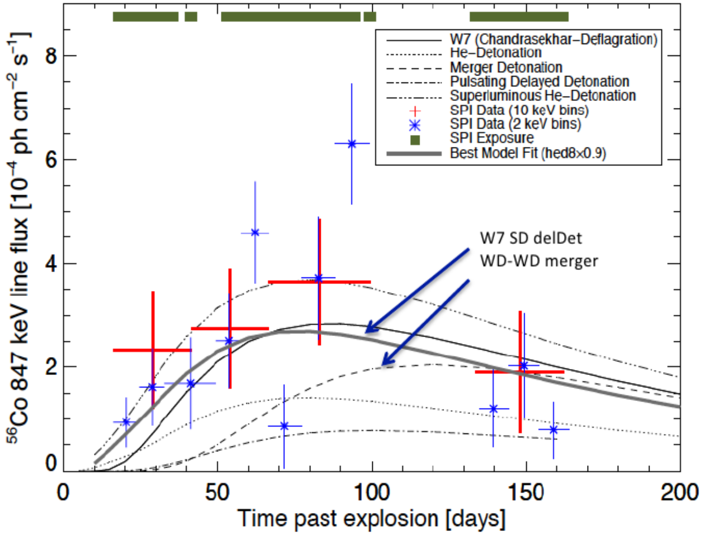
Stellar Explosions, Radioactive Books, and a joint European Cruise with EUROCORES and COST

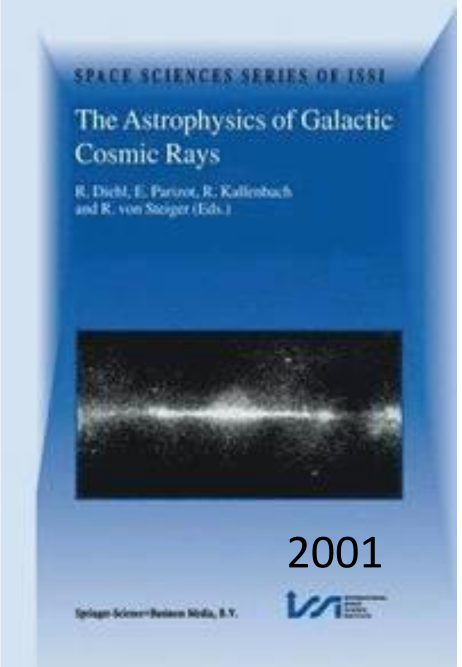




Core-collapse
SN Cas A



γ-rays
From
SN Ia
SN1914J



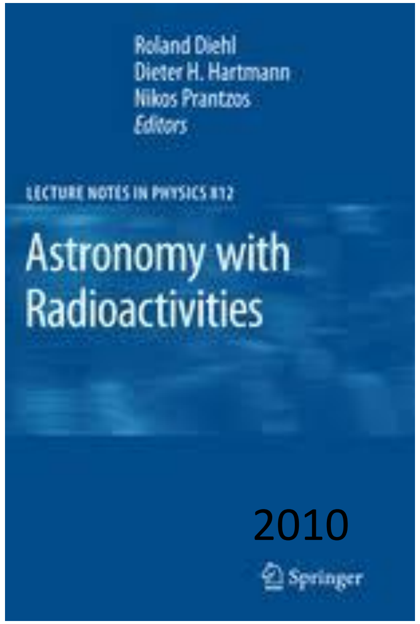
SPACE SCIENCES SERIES OF ISSI

The Astrophysics of Galactic Cosmic Rays

R. Diehl, E. Parizot, R. Kallenbach and R. von Steiger (Eds.)

Springer-Science+Business Media, B.V.

2001



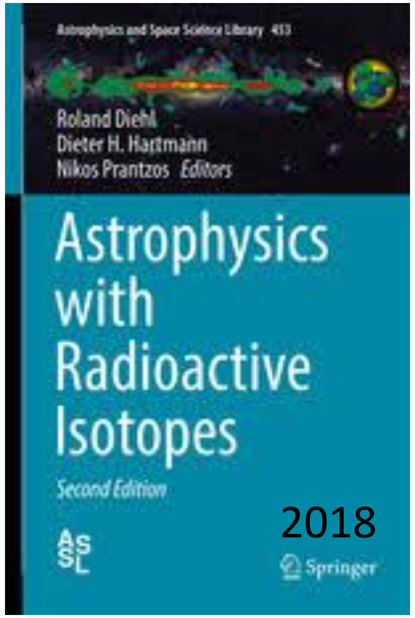
Roland Diehl
Dieter H. Hartmann
Nikos Prantzos
Editors

LECTURE NOTES IN PHYSICS 812

Astronomy with Radioactivities

Springer

2010



Astrophysics and Space Science Library 453

Roland Diehl
Dieter H. Hartmann
Nikos Prantzos Editors

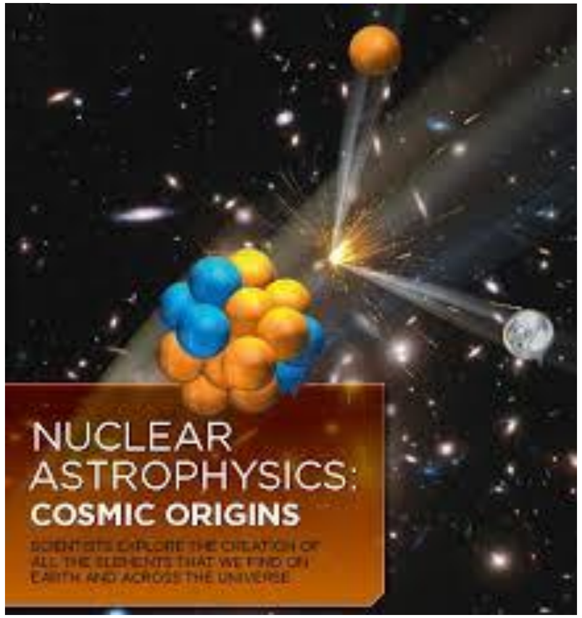
Astrophysics with Radioactive Isotopes

Second Edition

ASSL

Springer

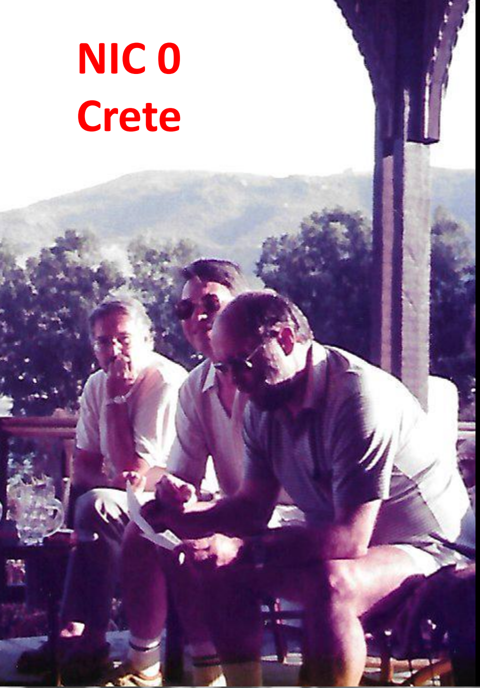
2018



NUCLEAR ASTROPHYSICS: COSMIC ORIGINS

SCIENTISTS EXPLORE THE CREATION OF ALL THE ELEMENTS THAT WE FIND ON EARTH AND ACROSS THE UNIVERSE

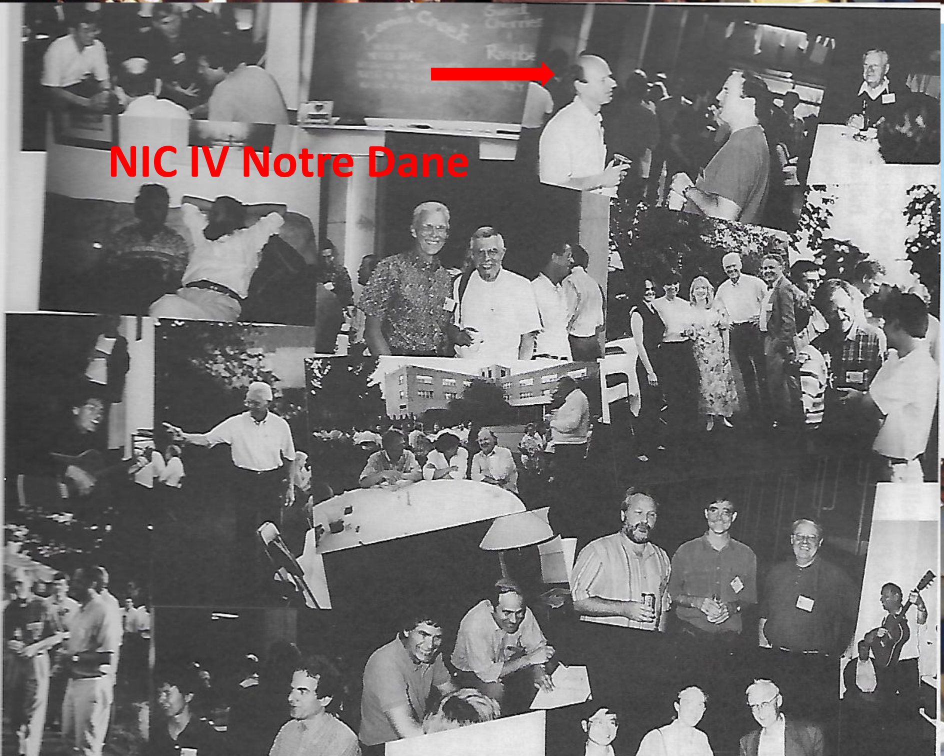
The outcome
of EUROCORE
Project
EuroGENESIS
2015



NIC 0
Crete

NIC I Baden/Vienna

NIC II Karlsruhe



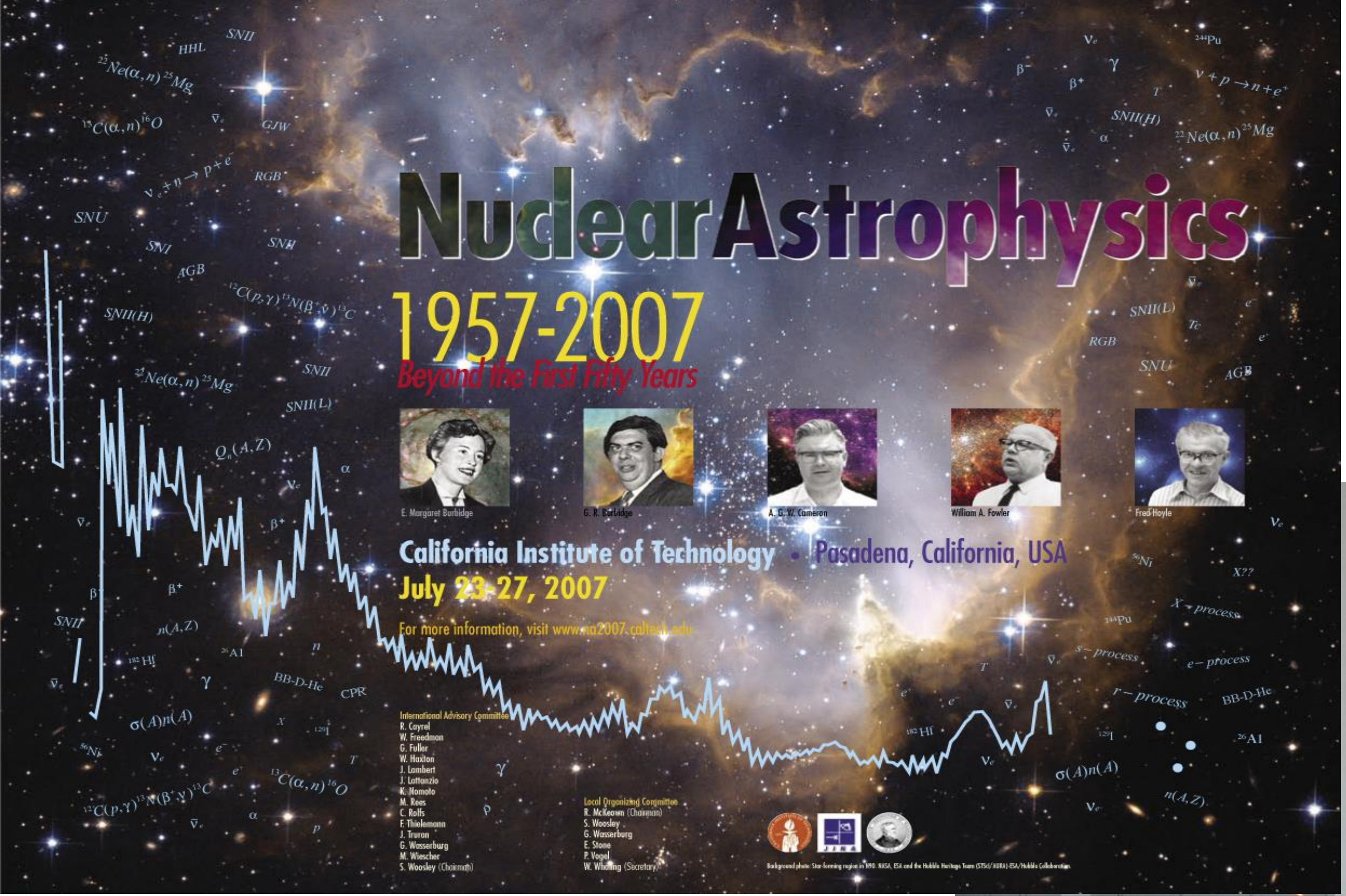
NIC IV Notre Dane

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.na2007.caltech.edu

International Advisory Committee
R. Cayrel
W. Freedman
G. Fuller
W. Haxton
J. Lambert
J. Lattanzio
K. Nomoto
M. Rees
C. Rolfs
F. Thielemann
J. Truran
G. Wasserburg
M. Wiescher
S. Woosley (Chairman)

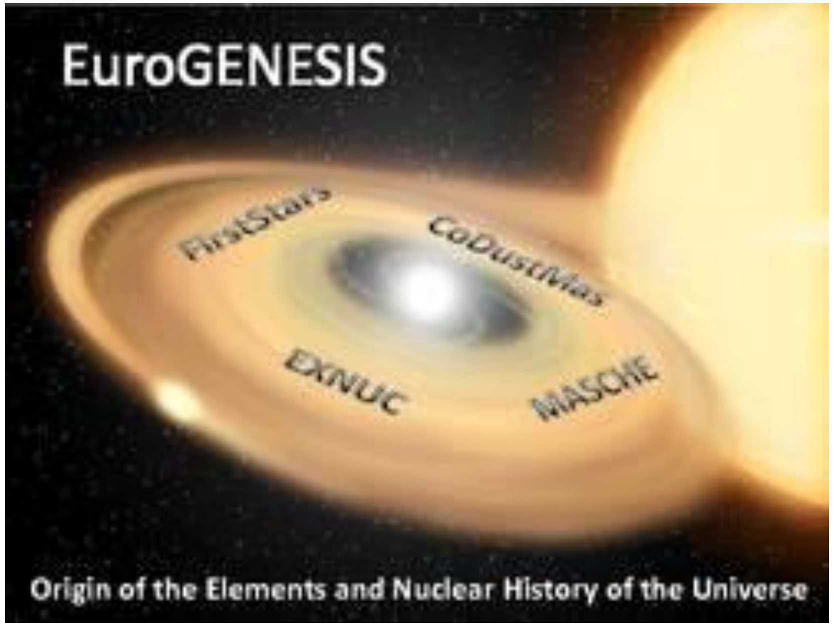
Local Organizing Committee
R. McKeown (Chairman)
S. Woosley
G. Wasserburg
E. Stone
P. Vogel
W. Whaling (Secretary)

Background photo: Star-forming region in N90. NASA, ESA and the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration.

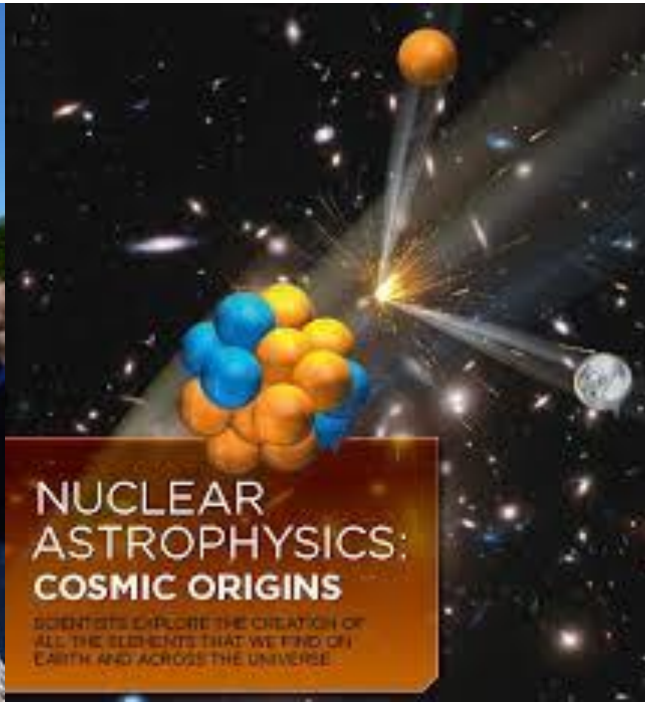
We met at many places since then, here the 50th Anniversary of the pioneering papers by Burbudge, Burbidge, Fowler & Hoyle, as well as in parallel, but of equal importance, by Al Cameron

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)

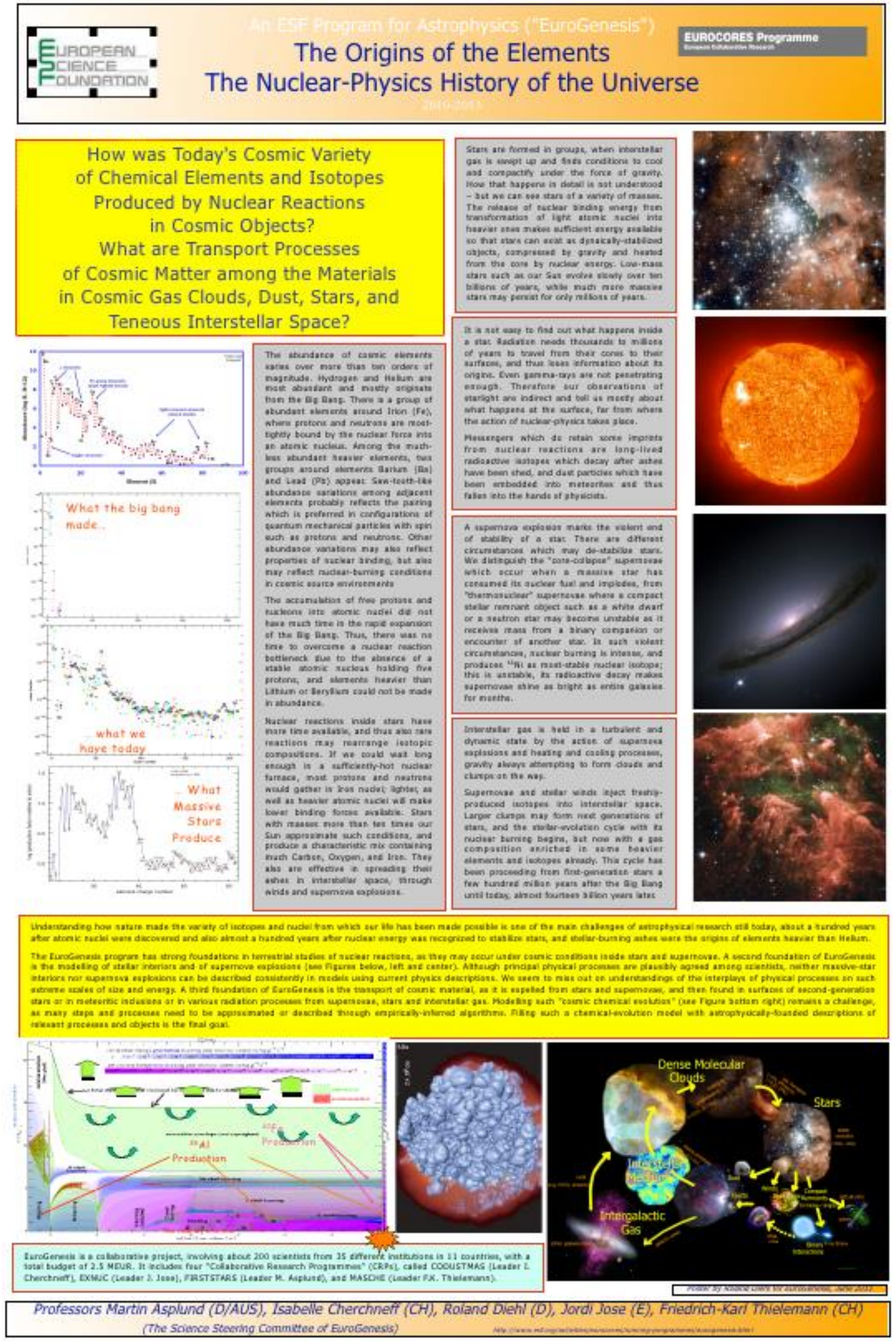
Project Leader (PI 1): Prof. Friedrich-Karl Thielemann, Switzerland
Co-Project Leader (PI 2): Prof. Roland Diehl, Germany
Principal Investigator 3: Prof. Klaus Blaum, Germany
Principal Investigator 4: Dr. Zsolt Fülöp, Hungary
Principal Investigator 5: Prof. Recep Taygun Güray, Turkey
Associated Partner 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-, νp, 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 ejacta*
- *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*

Presentation at the Brussels Exhibition of EuroCore Projects



An ESF Program for Astrophysics ("EuroGenesis")

The Origins of the Elements

The Nuclear-Physics History of the Universe

2010-2013

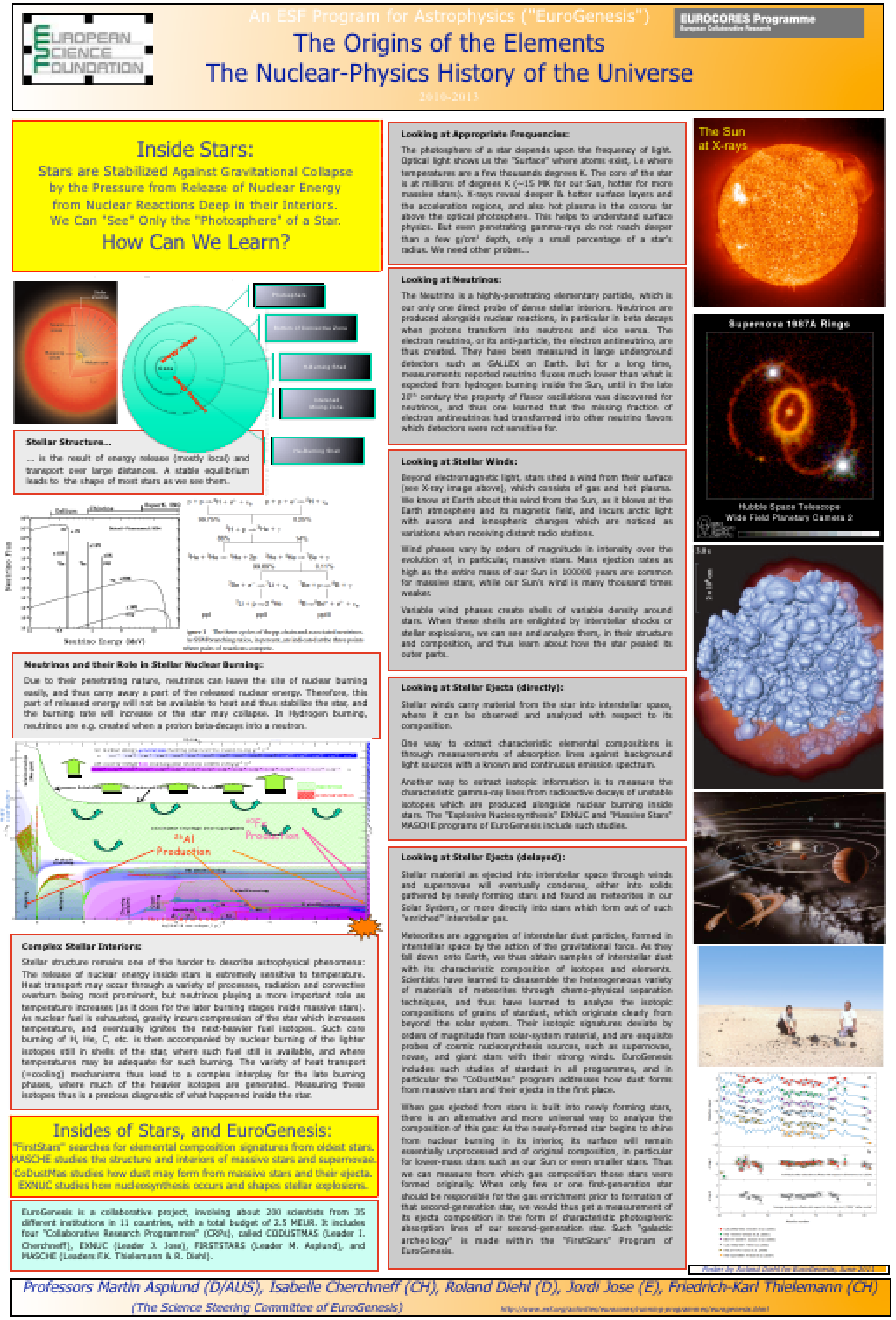
EUROCORES Programme

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 Teneous Interstellar Space?

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 CODUSTMAS (Leader I. Cherchneff), EXNUC (Leader J. Jose), FIRSTSTARS (Leader M. Asplund), and MASCHE (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)



An ESF Program for Astrophysics ("EuroGenesis")

The Origins of the Elements

The Nuclear-Physics History of the Universe

2010-2013

EUROCORES Programme

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?

Looking at Appropriate Frequencies:

Looking at Neutrinos:

Stellar Structure...

Looking at Stellar Winds:

Neutrinos and their Role in Stellar Nuclear Burning:

Looking at Stellar Ejecta (directly):

Looking at Stellar Ejecta (delayed):

Complex Stellar Interiors:

Insides of Stars, and EuroGenesis:

"FirstStars" searches for elemental composition signatures from oldest stars. MASCHE studies the structure and interiors of massive stars and supernovae. CoDustMas studies how dust may form from massive stars and their ejecta. EXNUC 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 CODUSTMAS (Leader I. Cherchneff), EXNUC (Leader J. Jose), FIRSTSTARS (Leader M. Asplund), and MASCHE (Leaders 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)

EUROPEAN
SCIENCE
FOUNDATION

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.

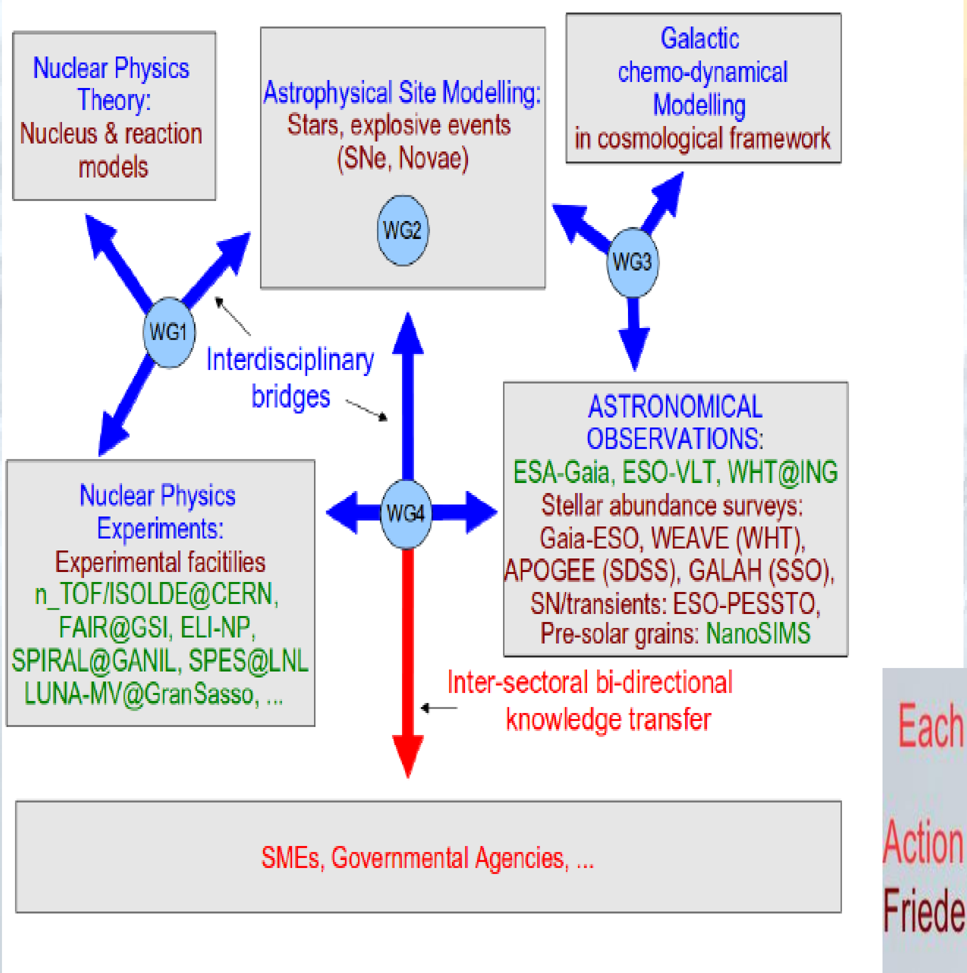
It appears that a very good level of integration within the teams has been achieved. This is visible from a number of joint publications reported, scientific meetings, training schools and workshops organized within this programme. Annual progress meetings have also been held. The strongest collaboration 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 and advance the success further within the Euopean 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

ChETEC Action



Nuclear Physics Theory:
Nucleus & reaction models

Astrophysical Site Modelling:
Stars, explosive events (SNe, Novae)

Galactic chemo-dynamical Modelling
in cosmological framework

WG1

WG2

WG3

WG4

Interdisciplinary bridges

ASTRONOMICAL OBSERVATIONS:
ESA-Gaia, ESO-VLT, WHT@ING
Stellar abundance surveys:
Gaia-ESO, WEAVE (WHT), APOGEE (SDSS), GALAH (SSO),
SN/transients: ESO-PESSTO,
Pre-solar grains: NanoSIMS

Nuclear Physics Experiments:
Experimental facitlities
n_TOF/ISOLDE@CERN, FAIR@GSI, ELI-NP, SPIRAL@GANIL, SPES@LNL
LUNA-MV@GranSasso, ...

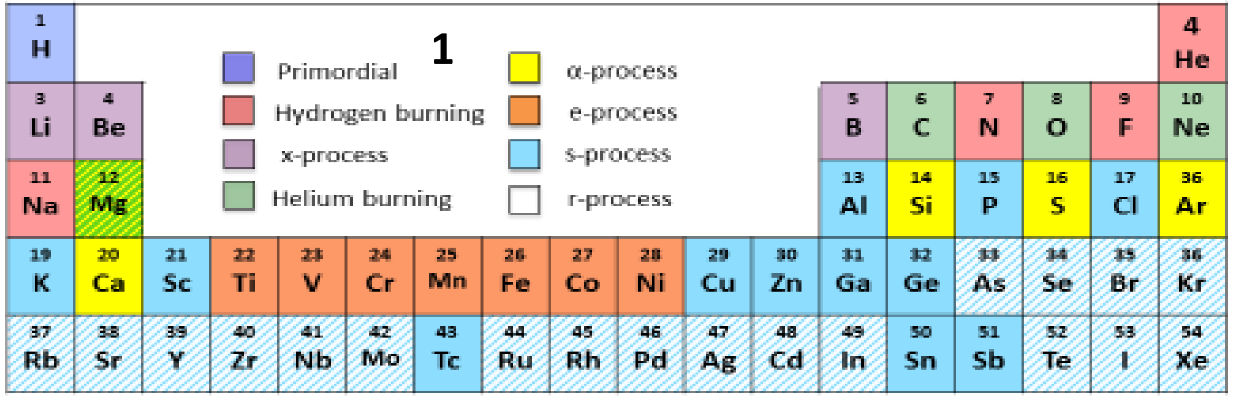
Inter-sectoral bi-directional knowledge transfer

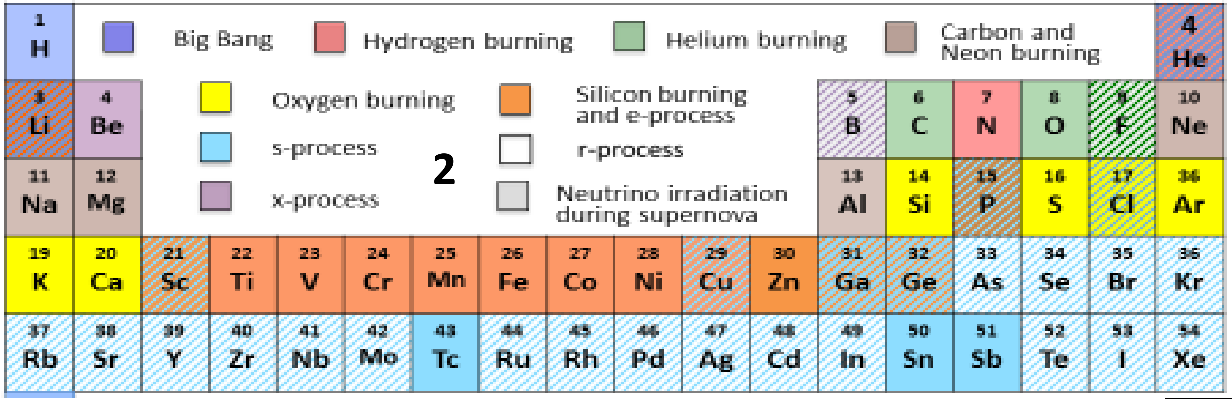
SMEs, Governmental Agencies, ...

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)

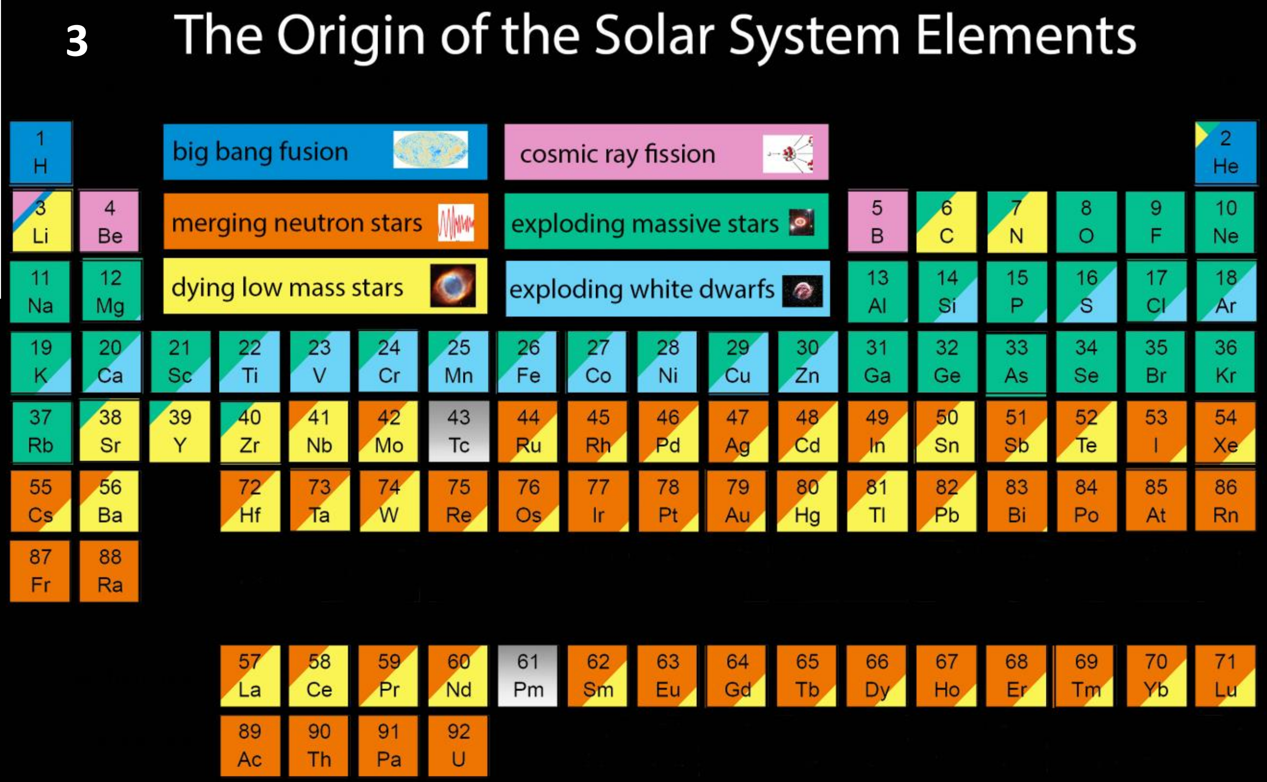




What is the origin of the elements in the solar system?

1. B^2FH (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)



Graphic created by Jennifer Johnson

Astronomical Image Credits: ESA/NASA/AASNova

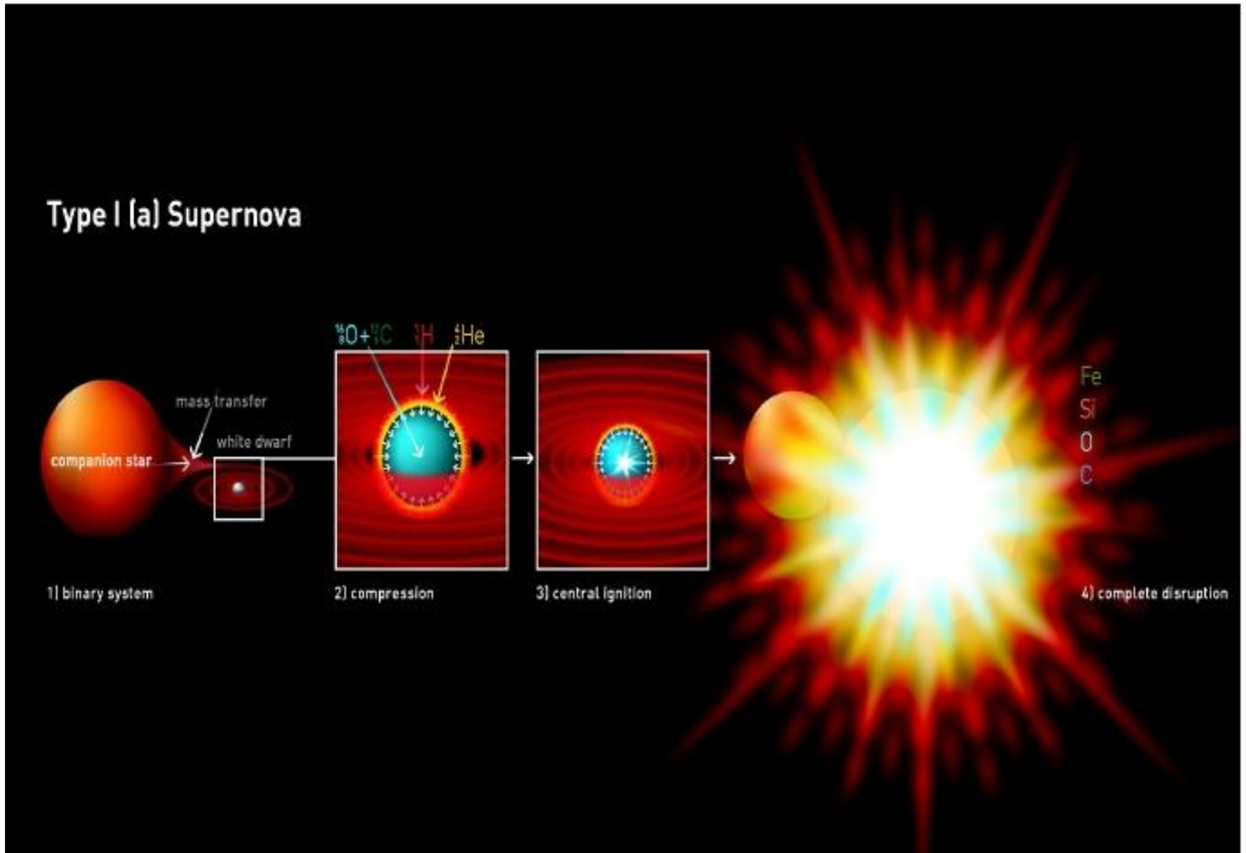
But it is even more important to link the individual sites and their occurrence frequency to the temporal evolution of the Galaxy. Such observations give an additional clue!

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)

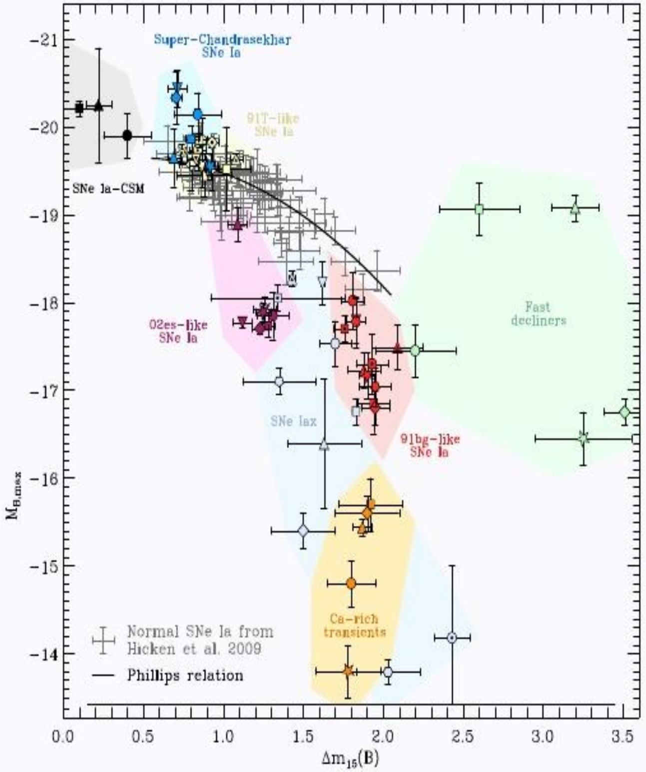
First detonation model by Arnett & Truran (1969 ..71).
First 1D deflagration models by Nomoto et al. (1982, 1984), Woosley et al. (1986)
Müller, Arnett & Fryxell (later Khoklov & Höflich) 3D combustion …



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)

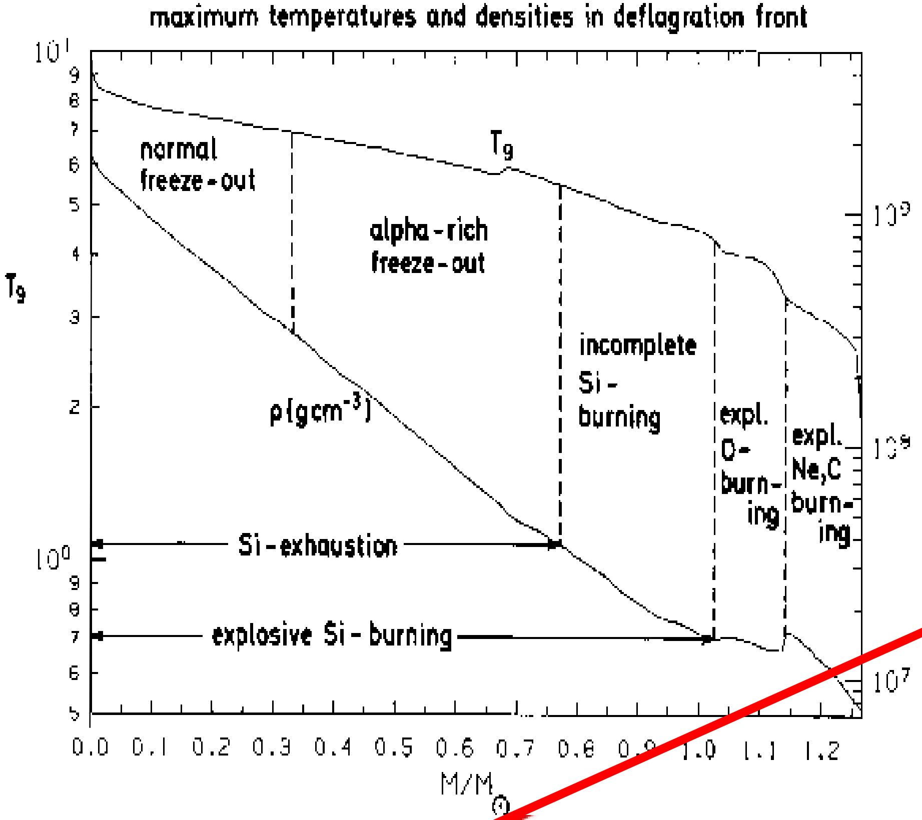


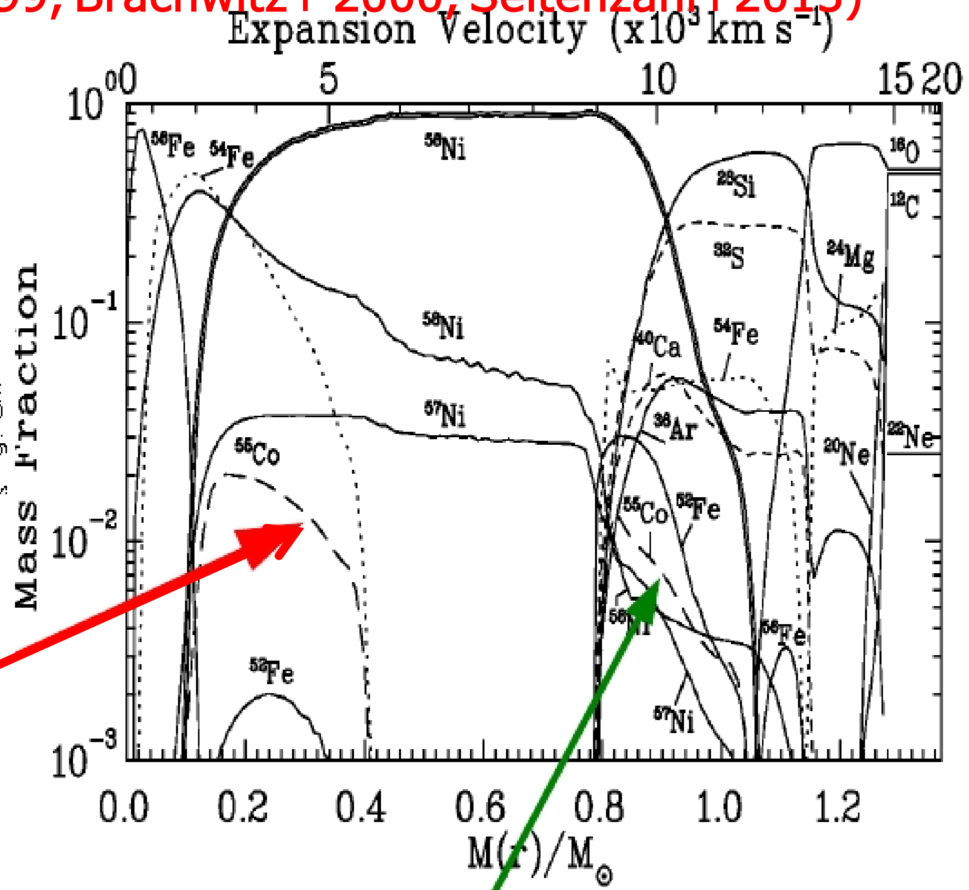
Recent surveys (Taubenberger 2017), more on this by Bruno Leibundgut and Wolfgang Hillebrandt

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 detontaions (Iwamoto+ 1999, Brachwitz+ 2000, Seitenzahl+2013)



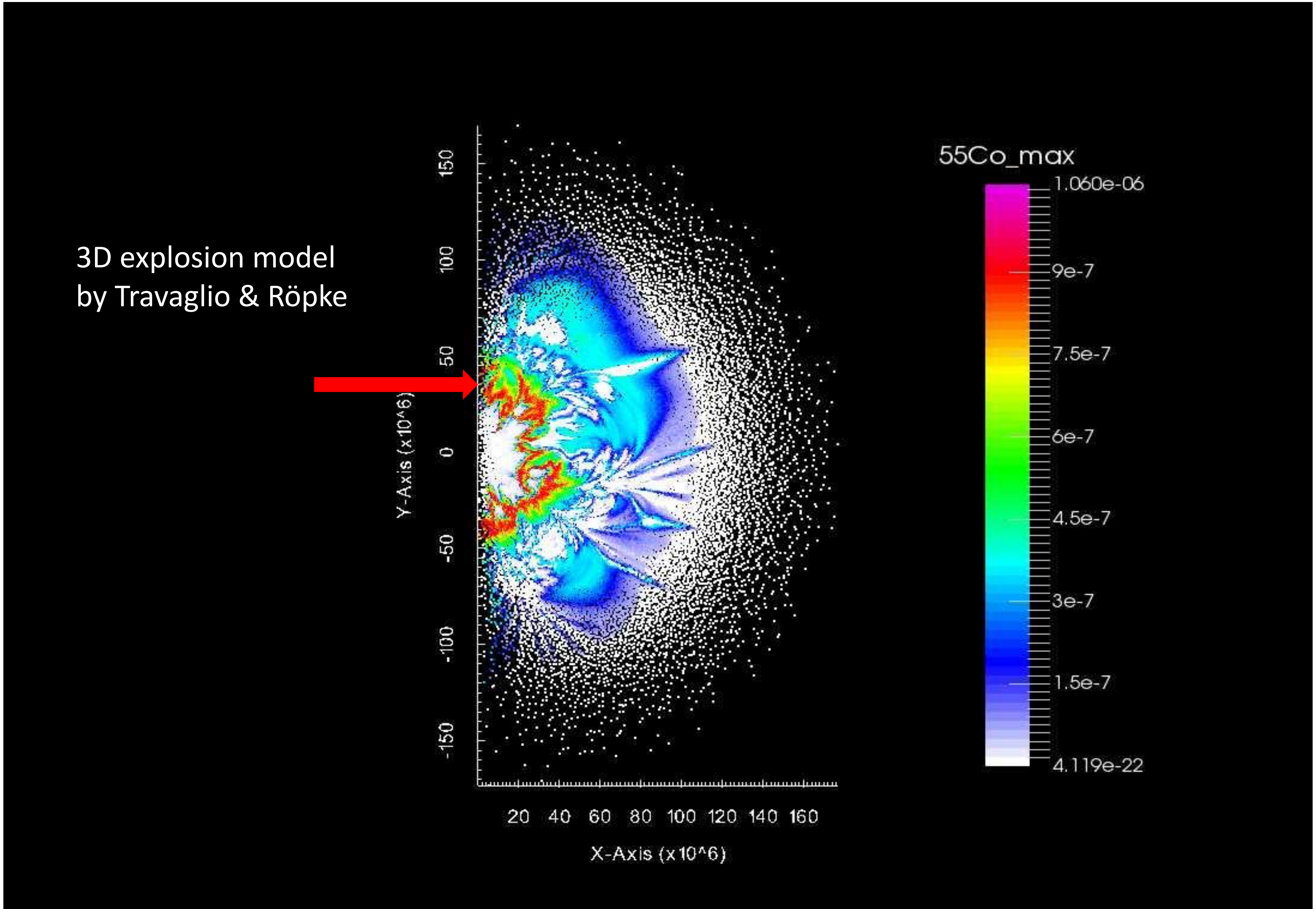


Mn comes in form of its only stable isotope ^{55}Mn, and is the decay product of ^{55}Co, produced in incomplete and complete Si-burning under *optimal conditions with Ye=Z/A=0.491*. In alpha-rich freeze-out, determined by entropy $S \propto T_9^3/\rho$, with values of T_9 and ρ_8 exceeding $T_9^3/\rho_8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

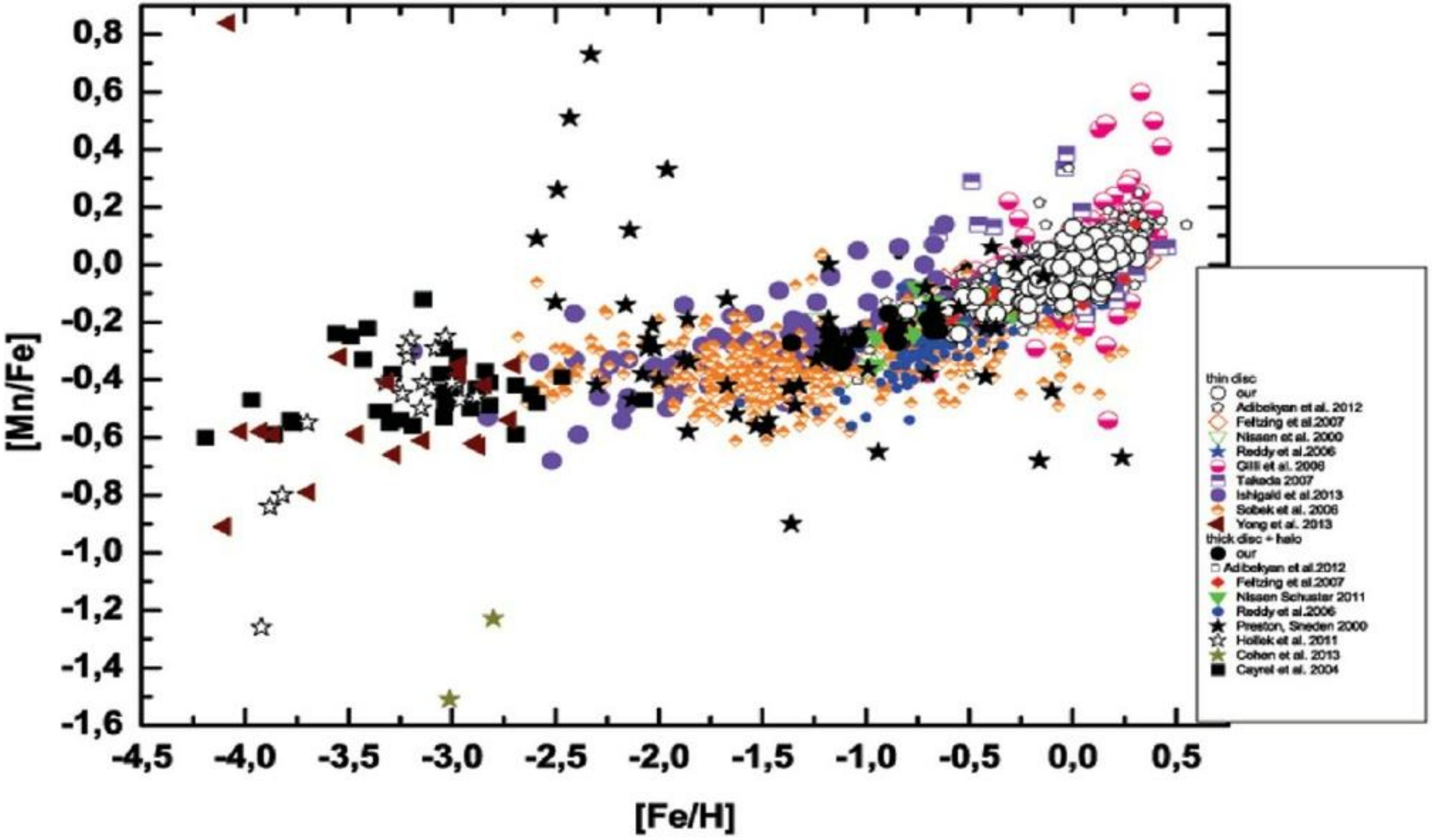
In the inner zones of M_{ch}-models this Ye is attained via electron capture (electrons are degenerate with high Fermi energy),

in the outer zones it can be approached by metallicity CNO → ^{22}Ne, leading for [Fe/H]=-∞,0,025,0.5 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)

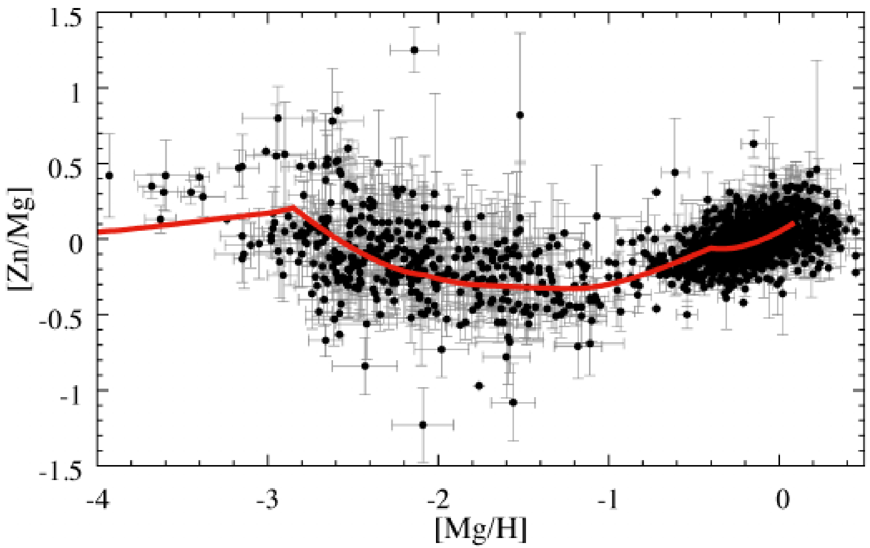

3D explosion model
by Travaglio & Röpke

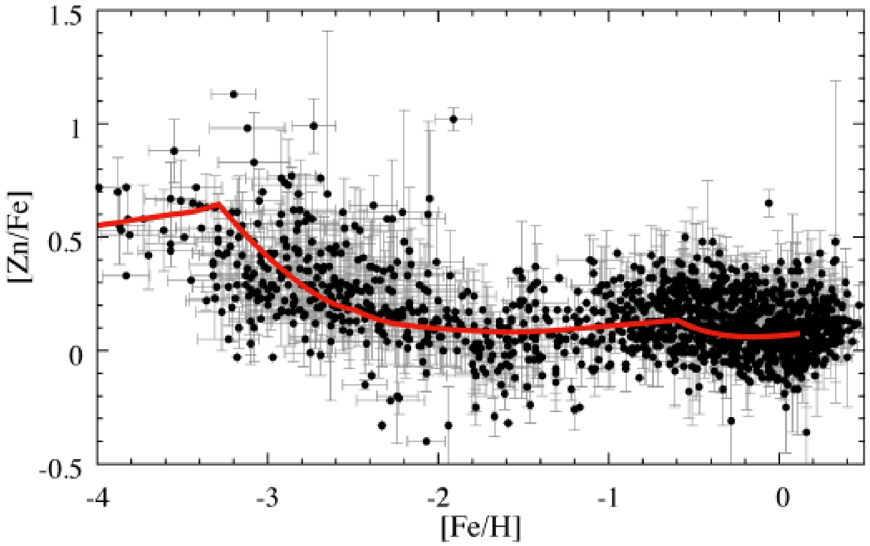
Evolution of [Mn/Fe] as function of [Fe/H] (Mishenina et al. 2015)



[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]=-∞,0,0.25,0.5. Seitenzahl+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):

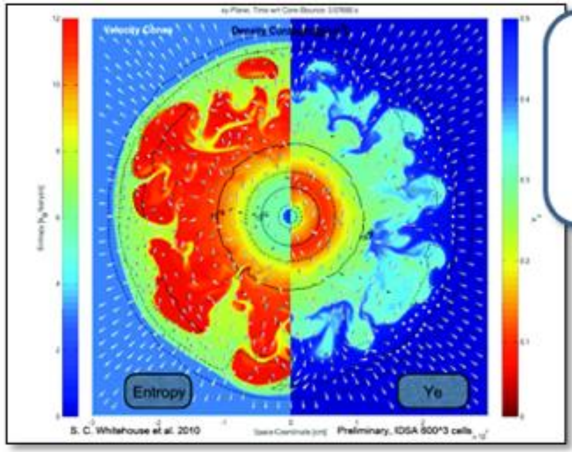
Explanation:
solar Zn/Fe can be made
in CCSNe via slightly proton-rich conditions
(Fröhlich et al. 2006, Curtis et al. 2018)
in moderately early galactic evolution
(see later in the talk, also possible supersolar Zn/Fe contribution by hypernovae and MHD supernovae with moderate magnetic fields at lowest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



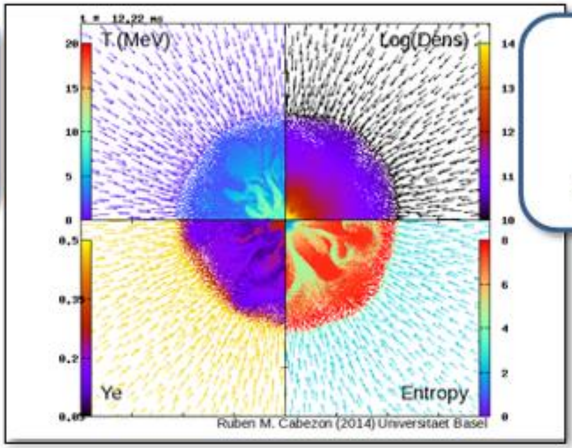
S. C. Whitehouse et al. 2010

Preliminary, IDSA 600^3 cells

Elephant

3D IDSA
Cartesian mesh
1D GR potential

M. Liebendörfer
S. C. Whitehouse
R. Käppeli

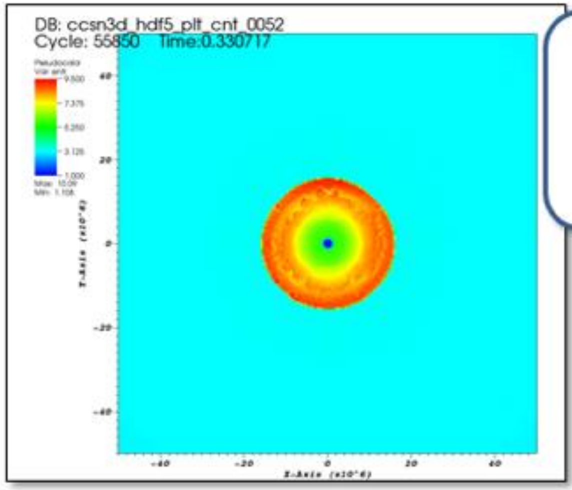


Ruben M. Cabezon (2014) Universitaet Basel

SPHYNX

ASL
SPH
3D Newtonian

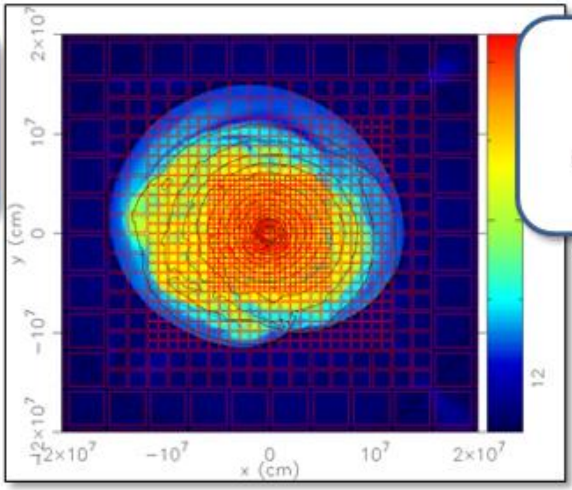
R. M. Cabezón



FLASH

3D IDSA
AMR
3D Newtonian

K.-C. Pan



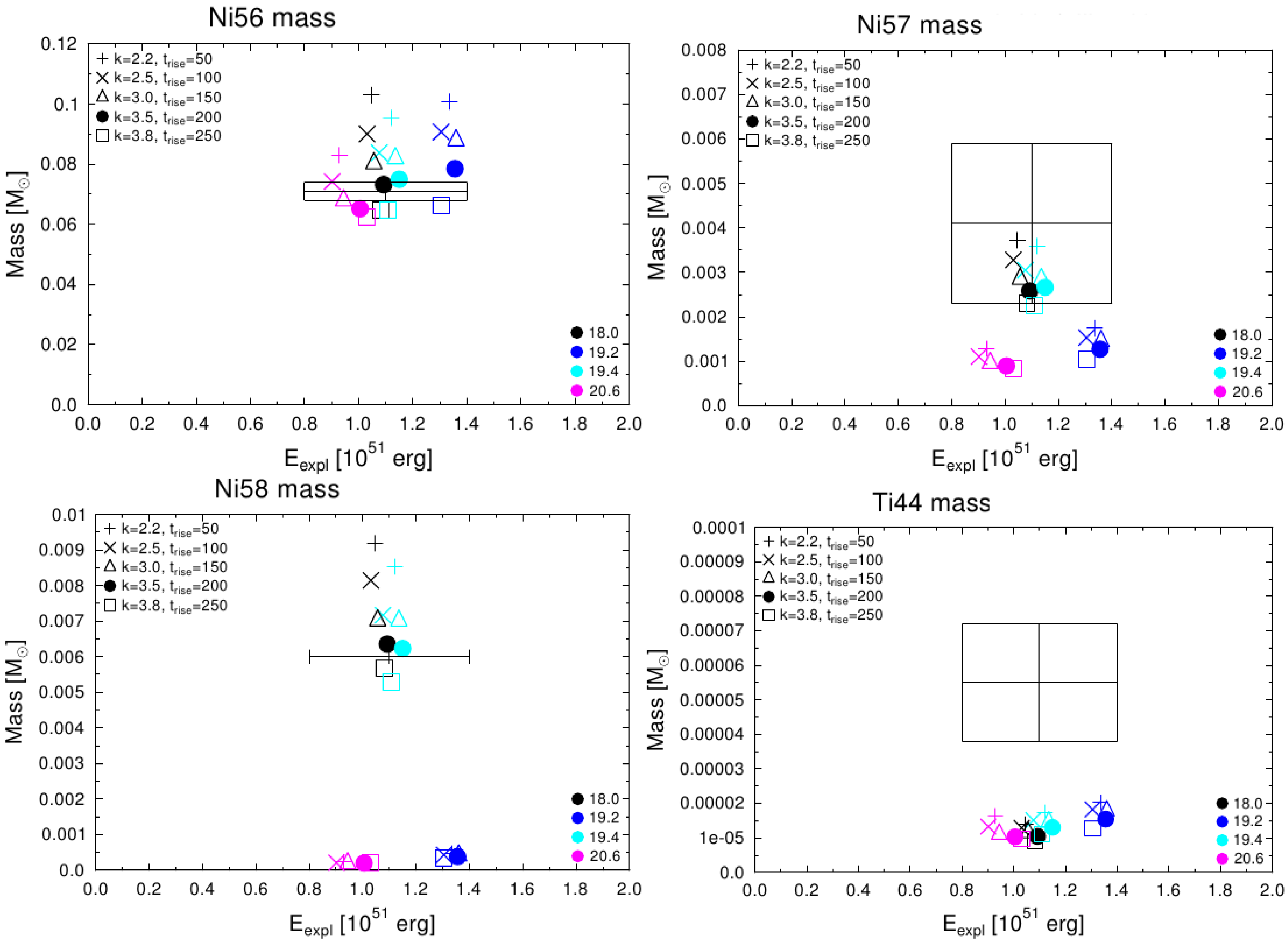
fGR_M1

M1
Nested meshes
3D GR

T. Kuroda

Cabezon et al. (2018): a three-dimensional code-comparison project

For futher 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)

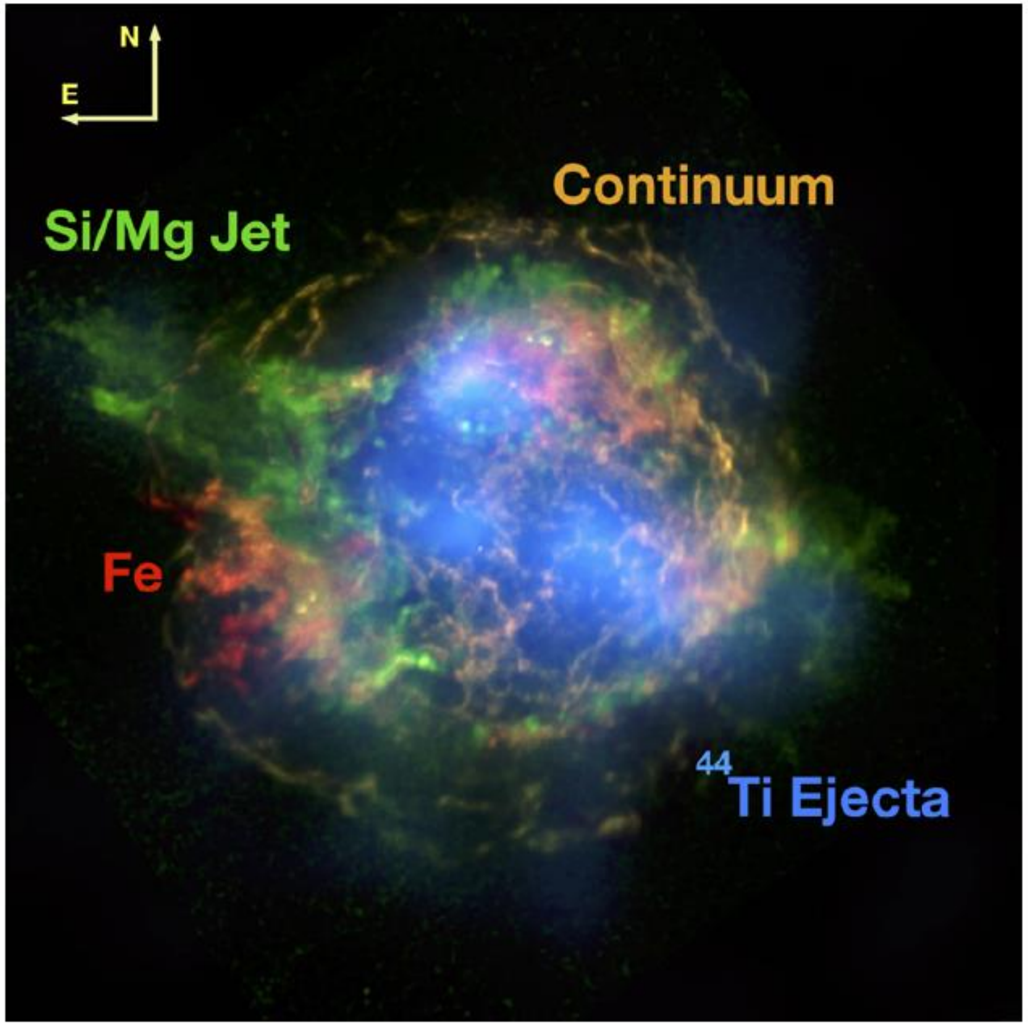
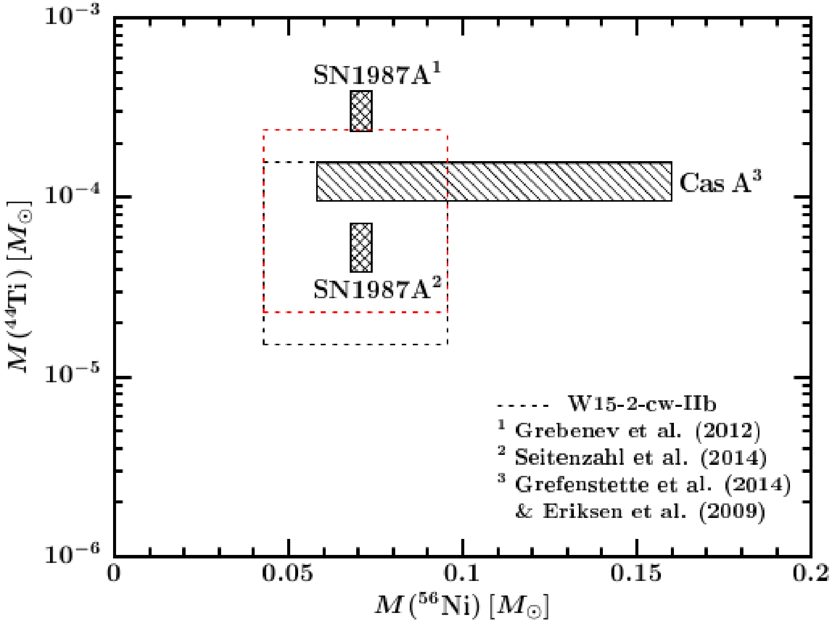
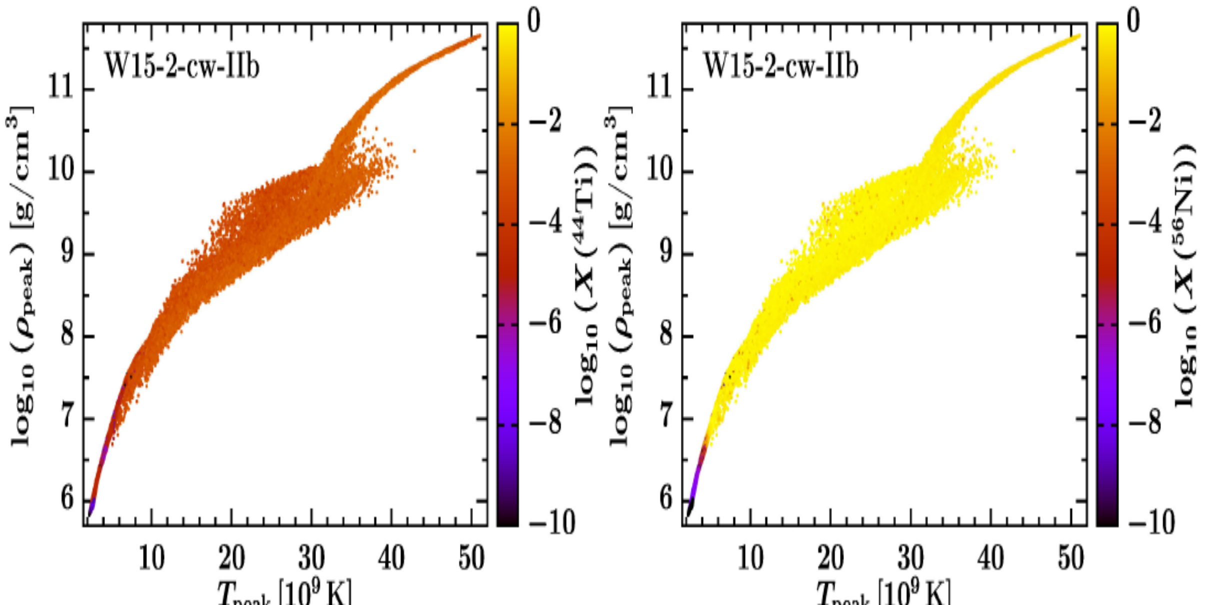


Figure 2: *3D distribution of Cas A ejecta. NuSTAR ^{44}Ti in blue, Chandra continuum in gold, Si/Mg band in green, X-ray emitting iron in red*[43].



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

^{44}Ti and ^{56}Ni in a Cassiopeia A like 3D Supernova Model 7



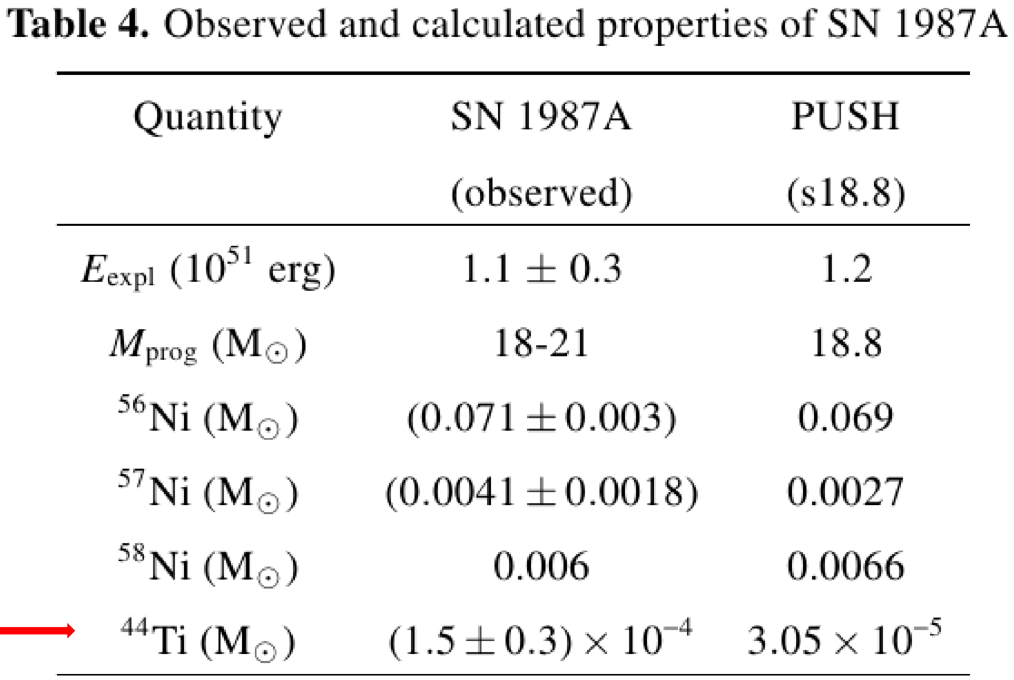


Table 4. Observed and calculated properties of SN 1987A

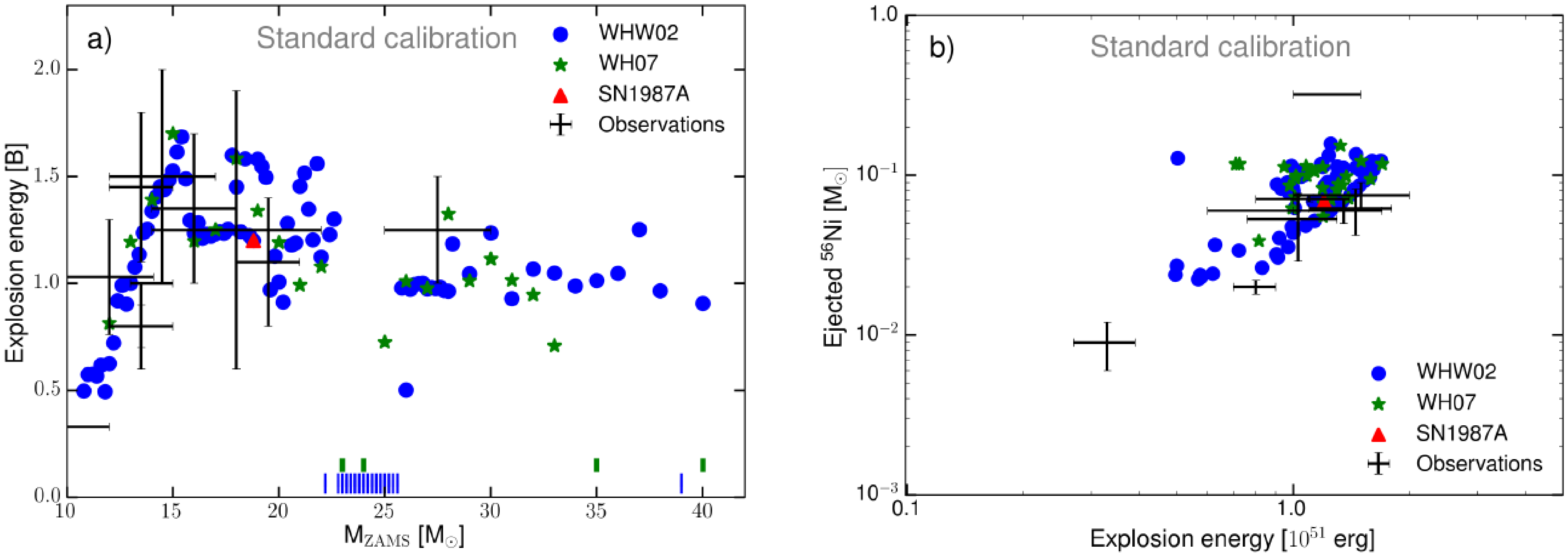
Quantity	SN 1987A (observed)	PUSH (s18.8)
$E_{\rm expl}$ (10^{51} erg)	1.1 ± 0.3	1.2
$M_{\rm prog}$ ($M_\odot$)	18-21	18.8
^{56}Ni ($M_\odot$)	(0.071 ± 0.003)	0.069
^{57}Ni ($M_\odot$)	(0.0041 ± 0.0018)	0.0027
^{58}Ni ($M_\odot$)	0.006	0.0066
^{44}Ti ($M_\odot$)	$(1.5 \pm 0.3) \times 10^{-4}$	3.05×10^{-5}

NUSTAR →

Ebinger et al. (2018, for solar metallicities**)**

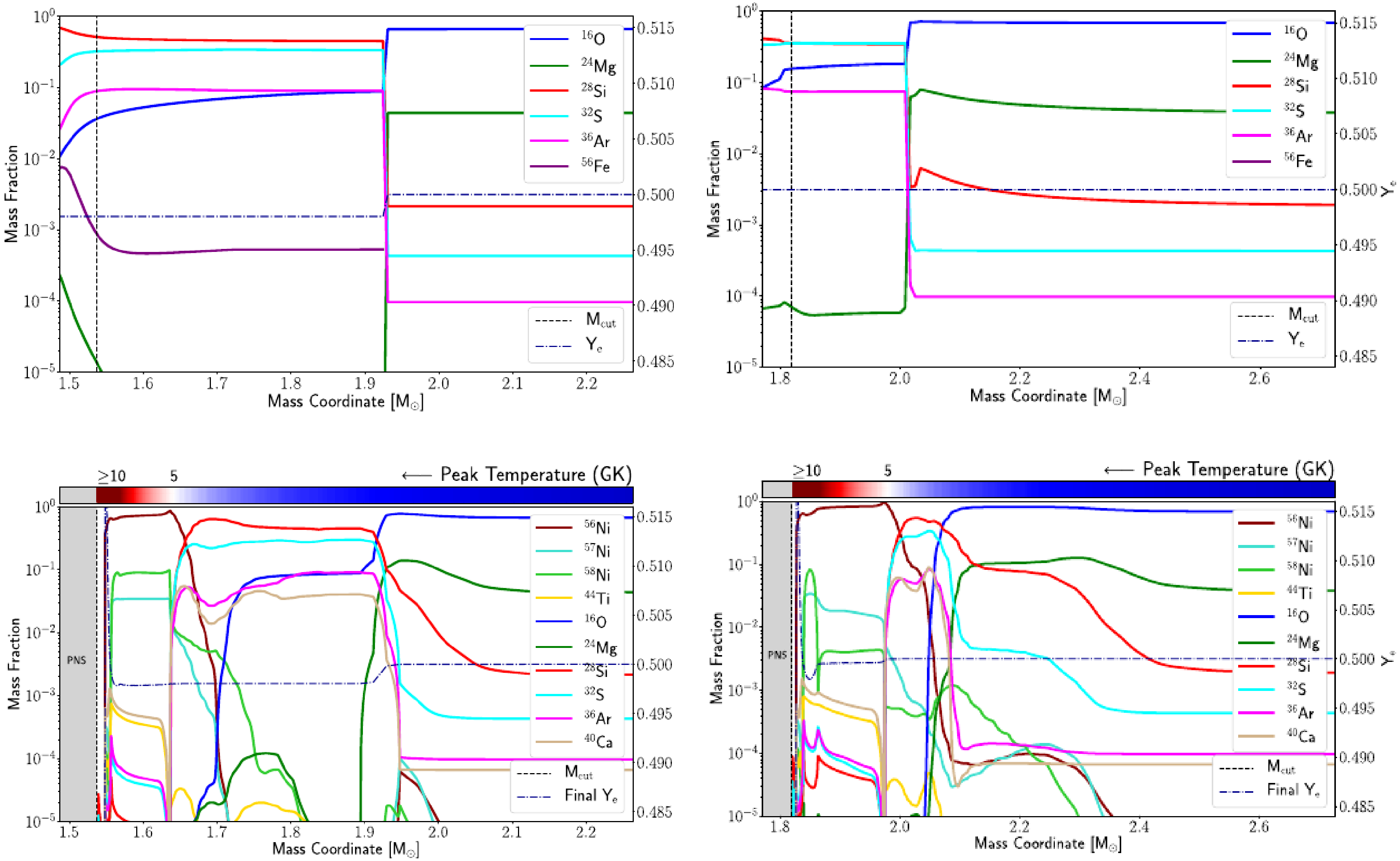
Parameters adjusted to SN1987A, other supernova observations and 3D simulations of the earlier mentioned comparison project

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)

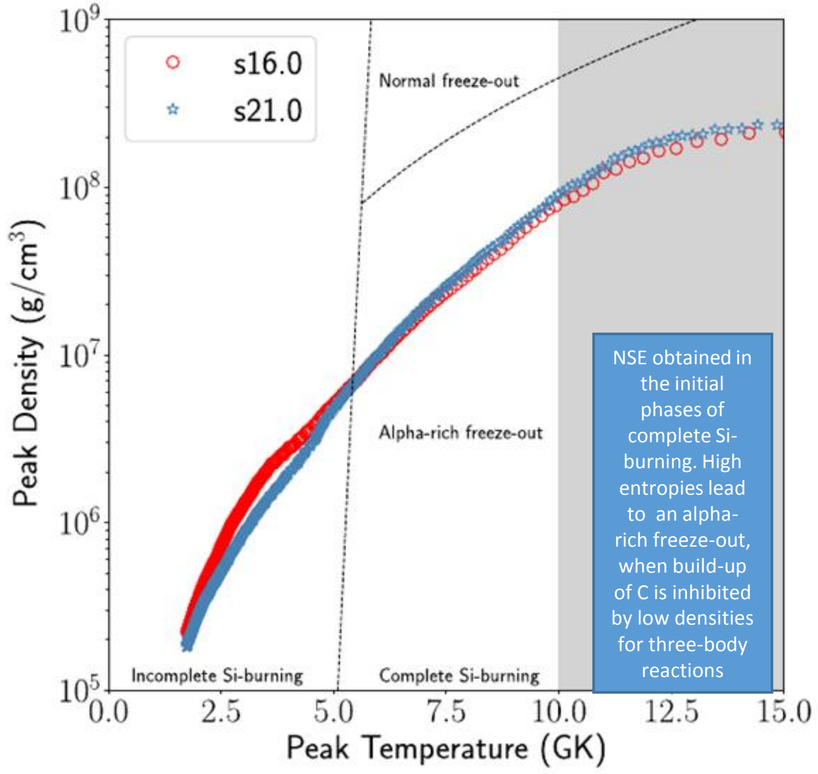
for 16 and 21 Msol progenitors (based on PUSH approach)



Ye on right abzissa (dashed), being in the outer layers unchanged from the initial (hydrostatic) Ye 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 Ye or neutron-richness encountered (see previous transparency)



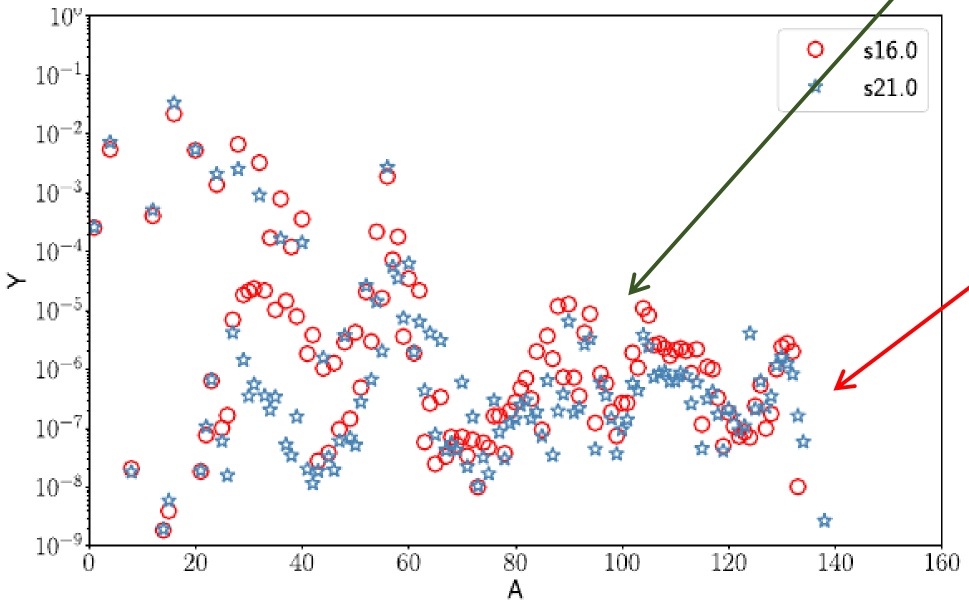
NSE obtained in the initial phases of complete Si-burning. High entropies lead to an alpha-rich freeze-out, when build-up of C is inhibited by low densities for three-body reactions

(1) In outer layers, Ye is essentially given by pre-explosive (hydrostatic) values.

(2) Then follows a region where explosive Si-burning led to unstable nuclei which experience beta$^+$-decay. In a similar way electron captures can lower Ye slightly below 0.5.

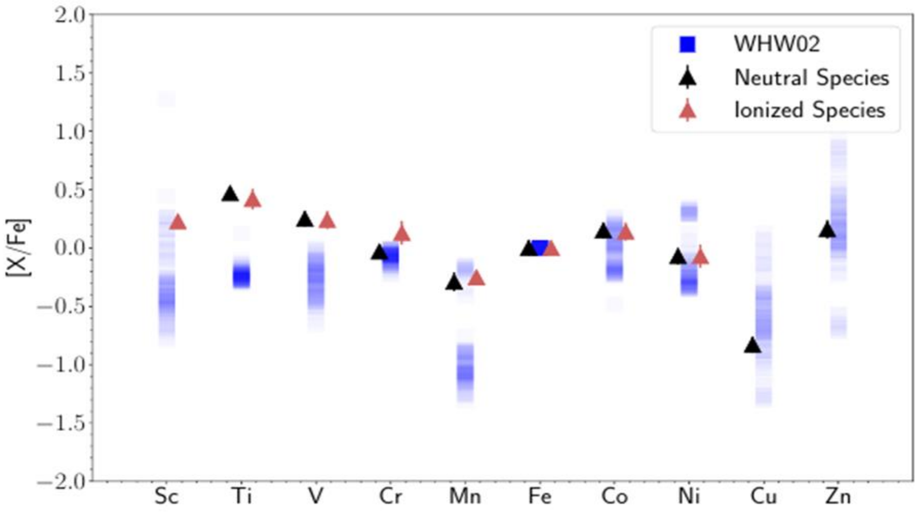
(3) Neutrino interactions with nucleons and nuclei can enhance Ye, for similar luminosities of neutrinos and antineutrinos the latter win, making Ye proton-rich >0.5 This, together with the less proton-rich layers of explosive Si-burning (see 2) provides a good fit to the Fe-group composition (next transparency) and also permits a vp-process with abundance produced up to A=100.

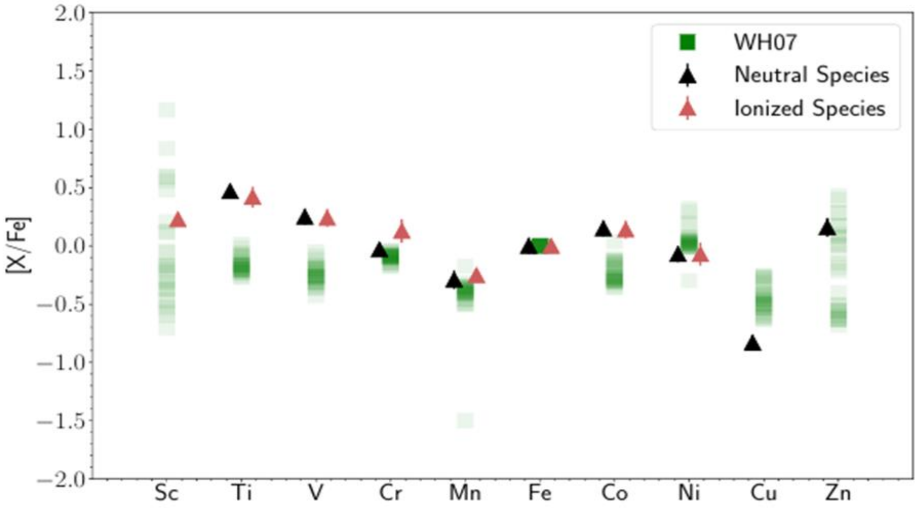
(4) The very innermost ejected layers come late, originate from regions deeper in the collapsed core which had become very neutron-rich via e-captures during core collapse, and neutrino interactions were not sufficient to turn them proton-rich. Ye's encountered here range from 0.32 to 0.42. These zone 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)

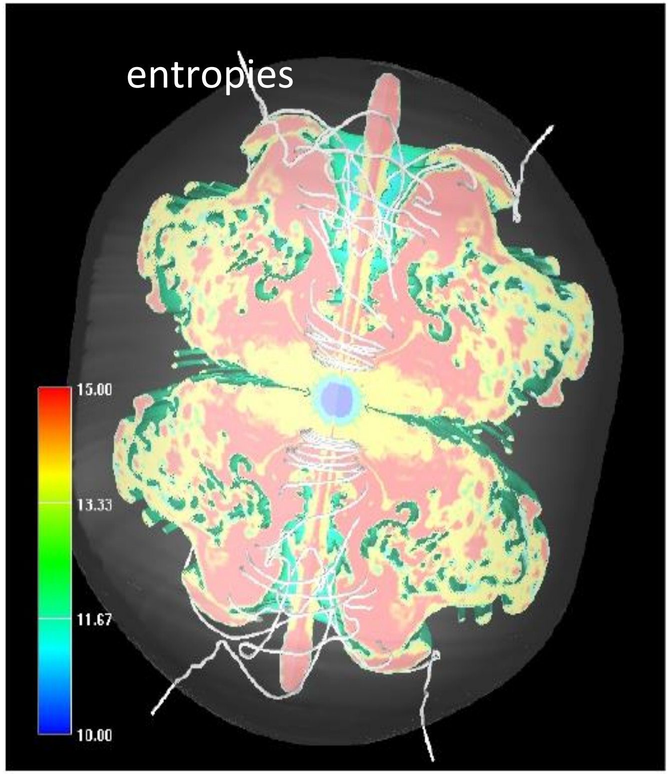
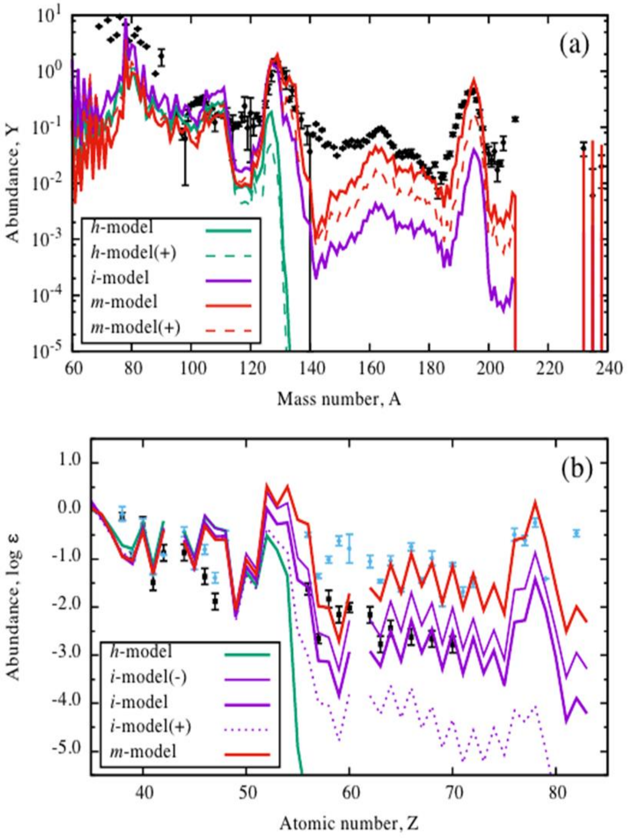


Figure 1. Entropy distribution with magnetic field lines of an MR-SN model (a cube with 2000 km). The surrounded



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

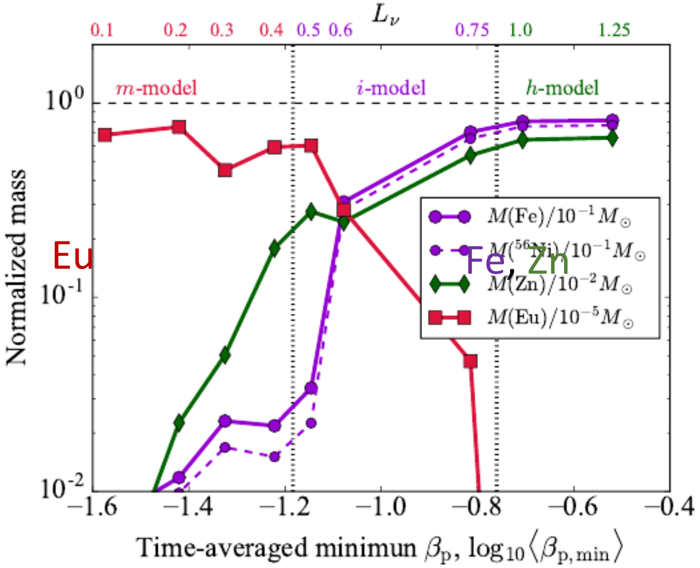


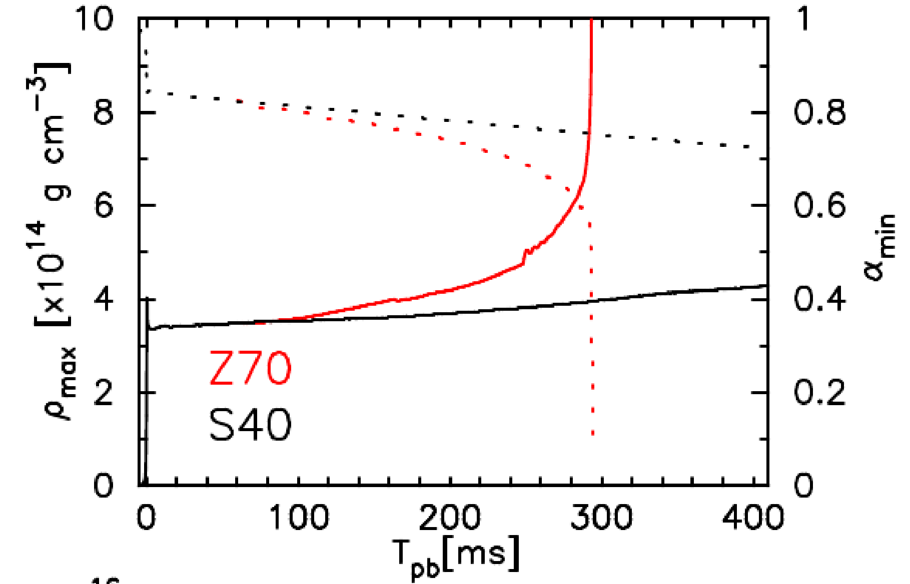
Figure 5. Ejected masses of Fe, ^{56}Ni (before decay), Zn and Eu, normalized by 0.1, 0.1, 10^{-2} and $10^{-5}M_\odot$, respectively, as a function of $\langle\beta_{\mathrm{p,min}}\rangle$ with corresponding $\hat{L}_\nu$ (top).

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 consistant stellar evolution models?

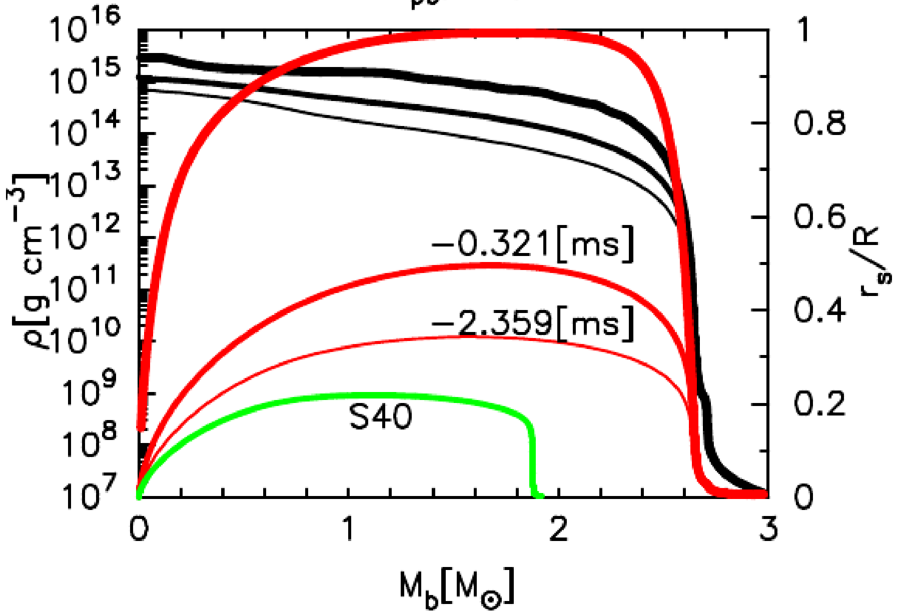
When do massive stars end in black holes?

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)

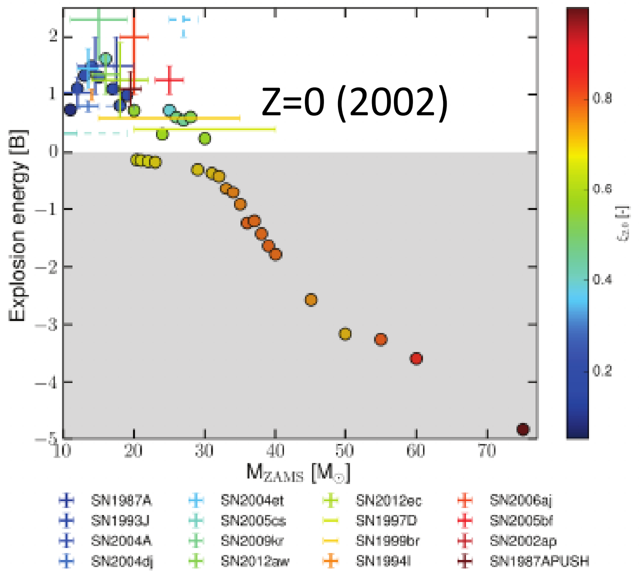


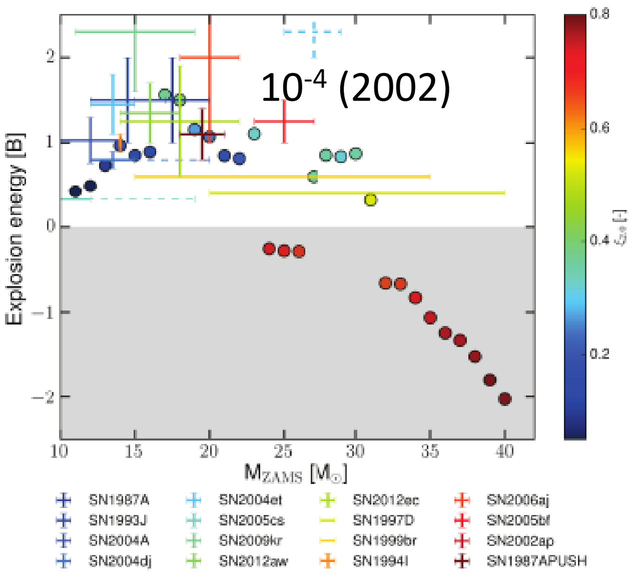
Black: Rest mass density at three points in time for 70 Msol star

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

Green: rs/R for 40Msol star at t=400ms

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!!!)

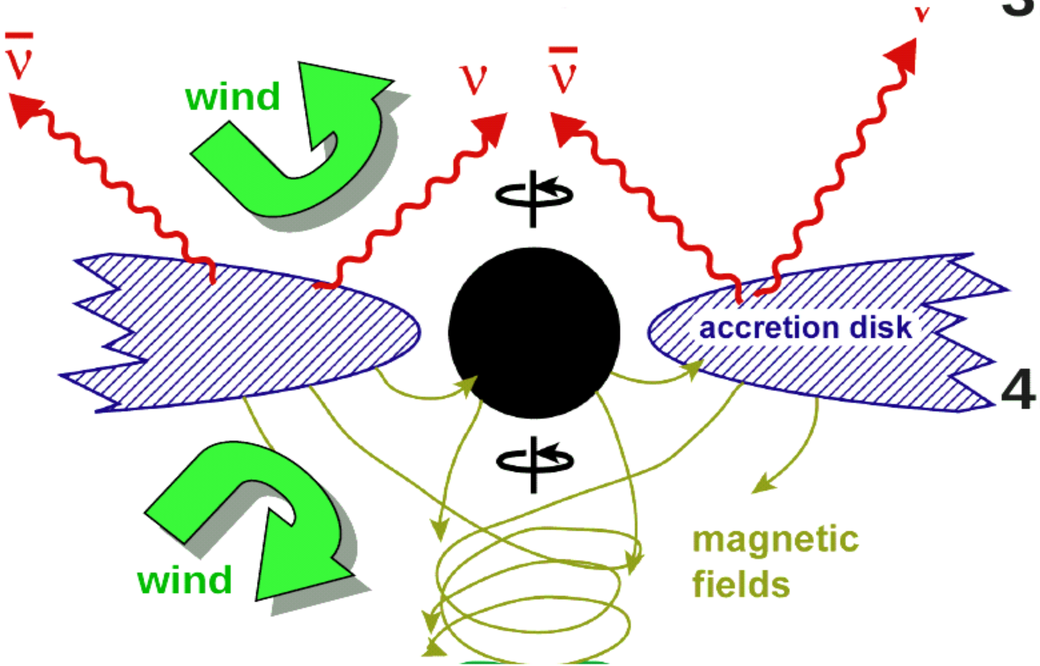
How else can massive stars explode?

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

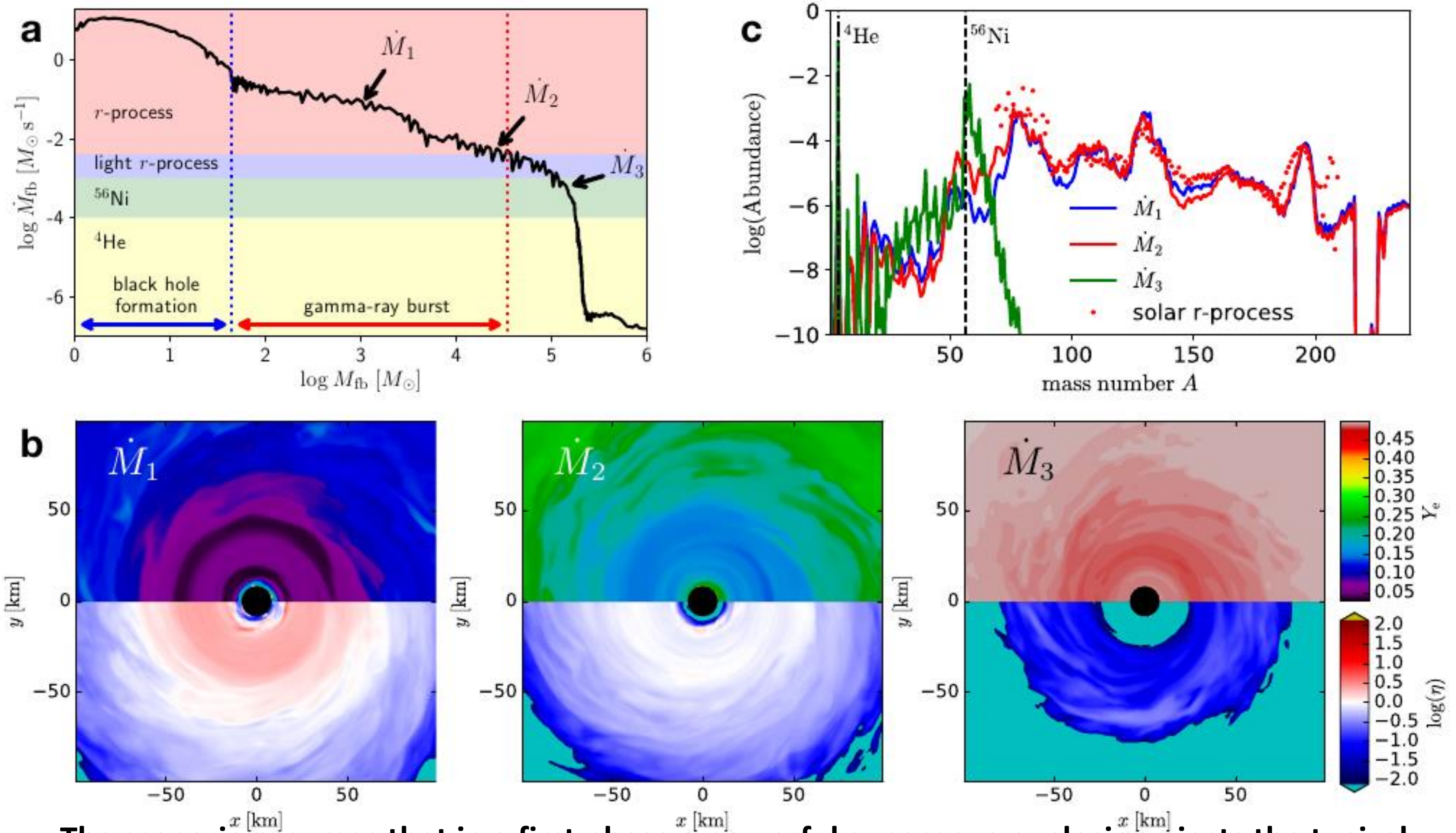
$\simeq 0.1\ M_\odot/\mathrm{sec}$

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).

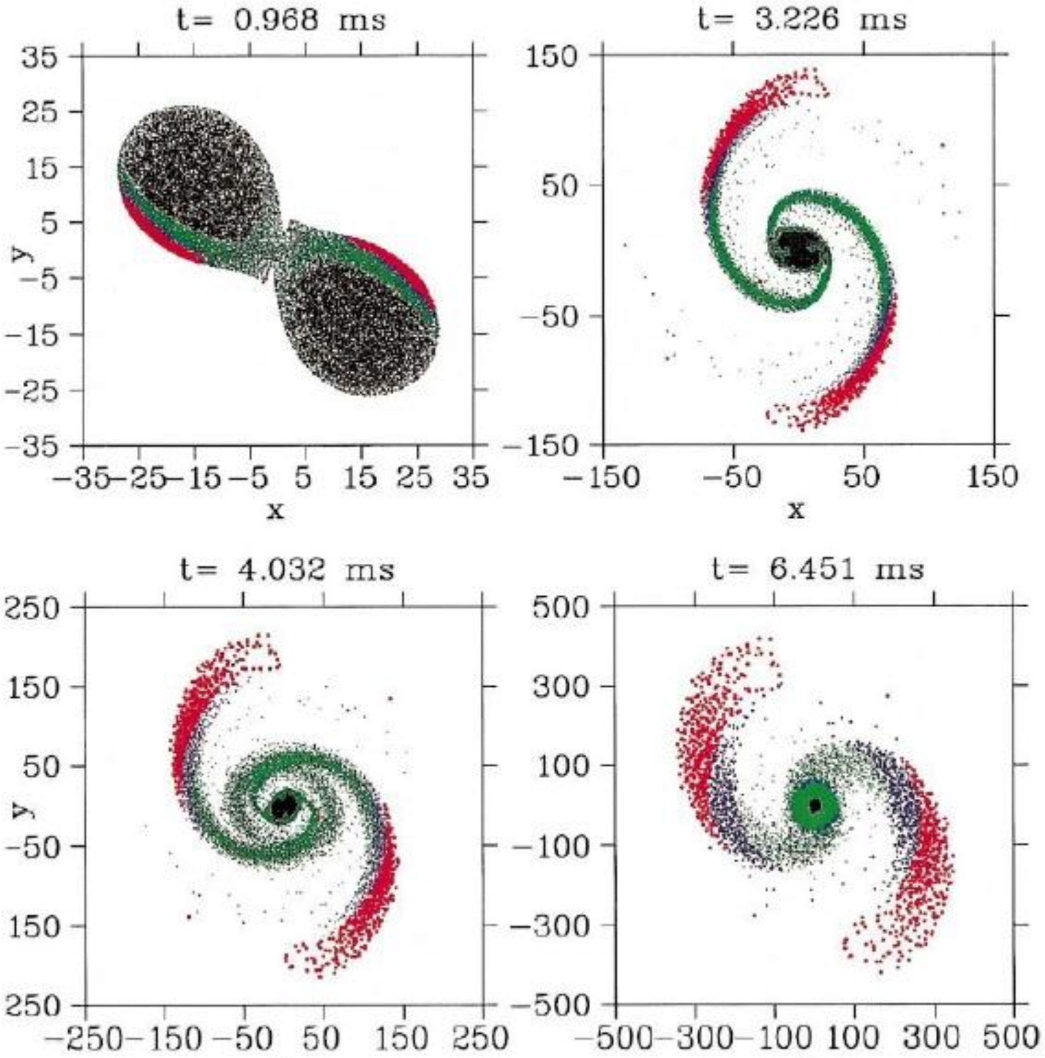


The scenario assumes that in a first phase a powerful supernova explosion ejects the typical up to $0.5M_{\odot}$ of ^{56}Ni and further accretion leads to a black hole and plus the BH accretion disk. Is this a somewhat fine-tuned scenario??

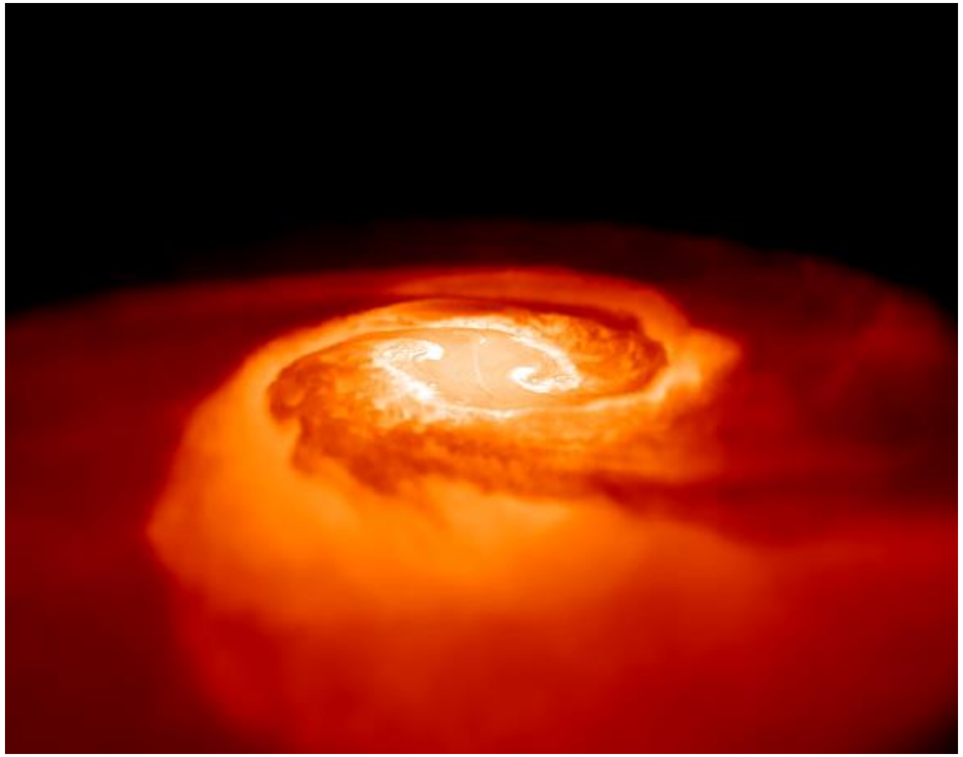
Neutron Star Mergers: The dominant site for the r-process?

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

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



only tidal arms in early approaches

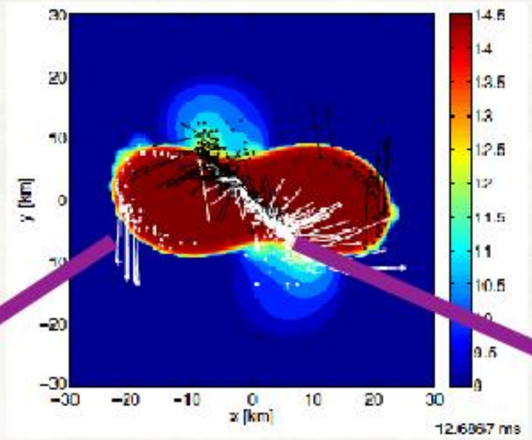


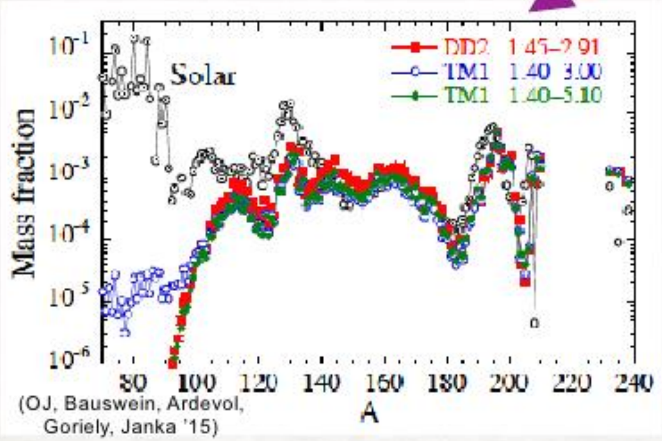
Rosswog et al. 2014

Prompt / dynamical Ejecta

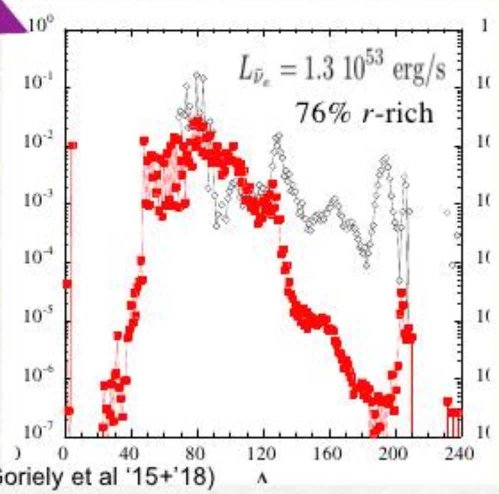
(qualitatively consistent
with works by, e.g.,
Hotokezaka '13,
Wanajo+Sekiguchi '14,'16,
Radice '16, Foucart '16)

from Just (2018)
Shanghai talk





(OJ, Bauswein, Ardevol, Goriely, Janka '15)



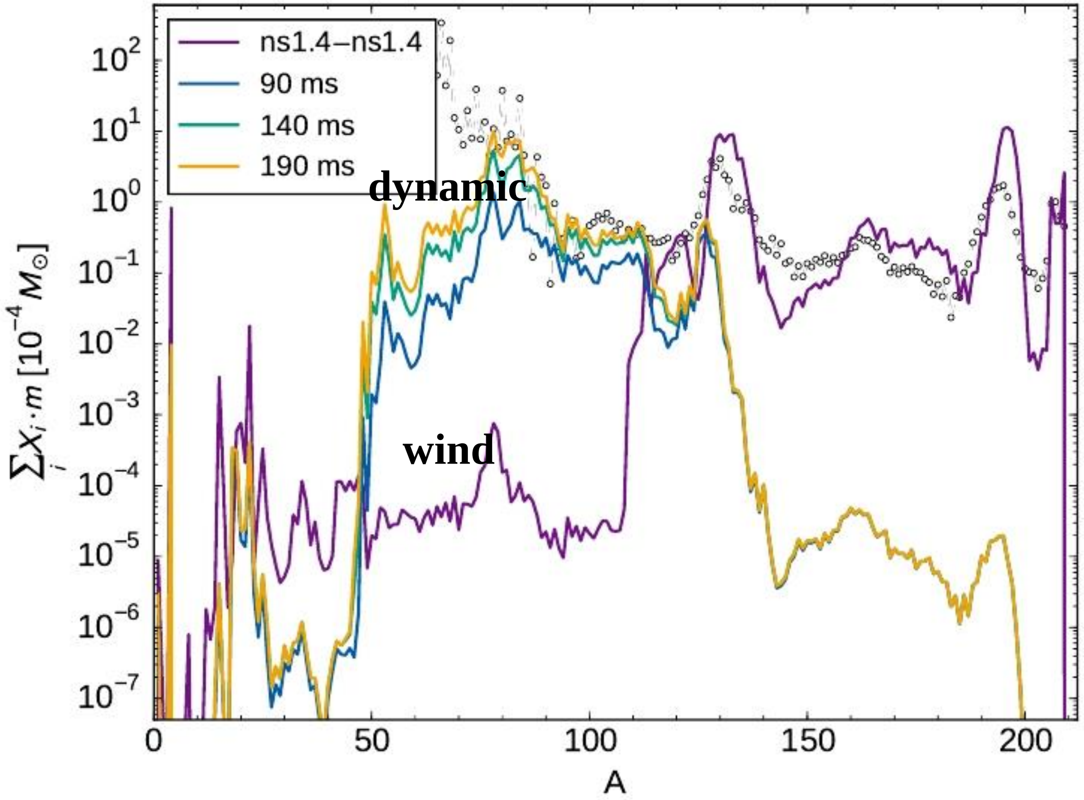
(Goriely et al '15+'18)

from tidal tails
-> low Ye
-> more lanthanides
-> higher opacity
-> red Kilonova
(if observed independently)

from collision shock
-> high Ye
-> 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)**

abundances

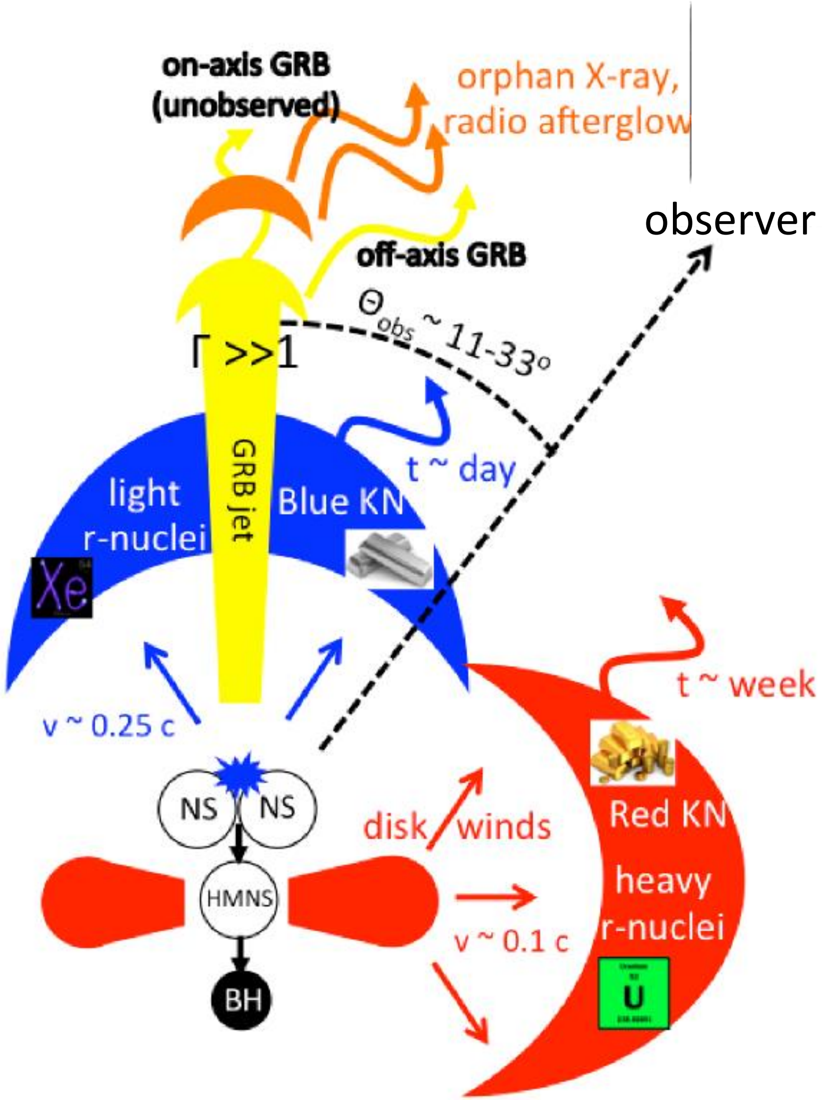


dynamic

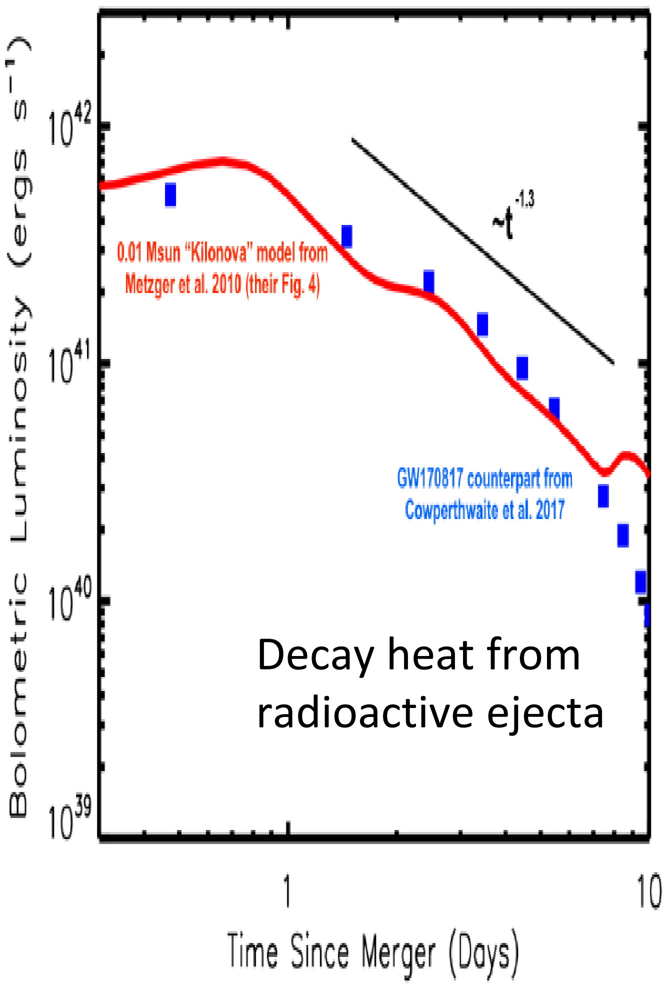
wind

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

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

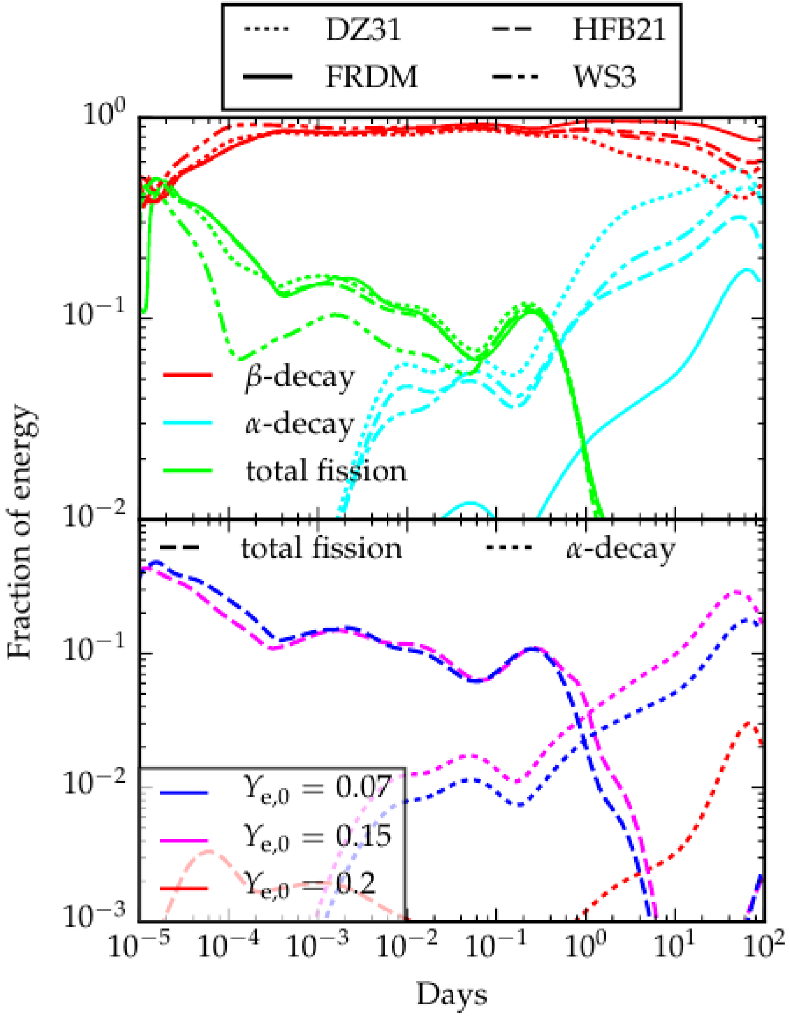


Metzger, Martinez-Pinedo
et al. (2010)



Decay heat from
radioactive ejecta

Barnes et al. (2016)

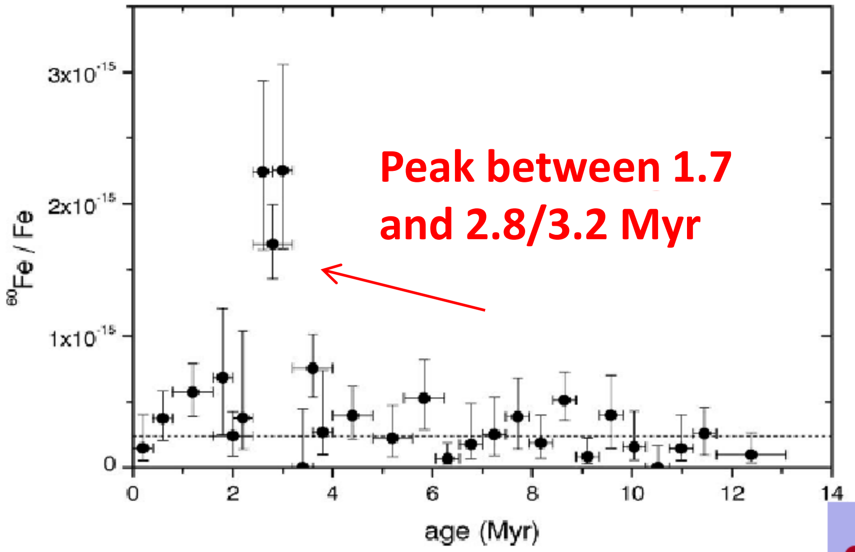


Interpretation of GW170817 (Metzger 2017); NS-merger collision, dynamic ejecta, hypermassive NS and neutrino wind, accretion disk outflow, BH formation, see also recent r-process review Cowan+ (2019)

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

(origin: massive stars, supernovae)

AMS at Munich



Peak between 1.7 and 2.8/3.2 Myr

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**

ANU THE AUSTRALIAN NATIONAL UNIVERSITY

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

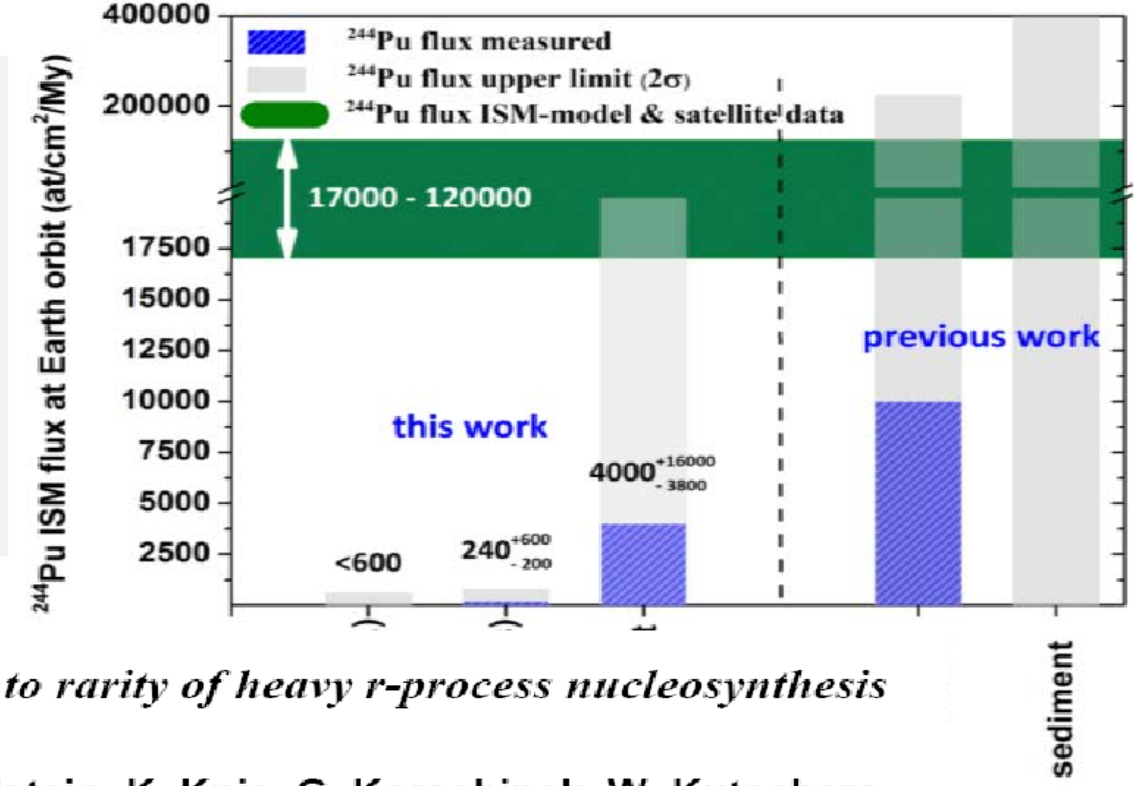
^{244}Pu, half-life 81 My

Status:

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?***



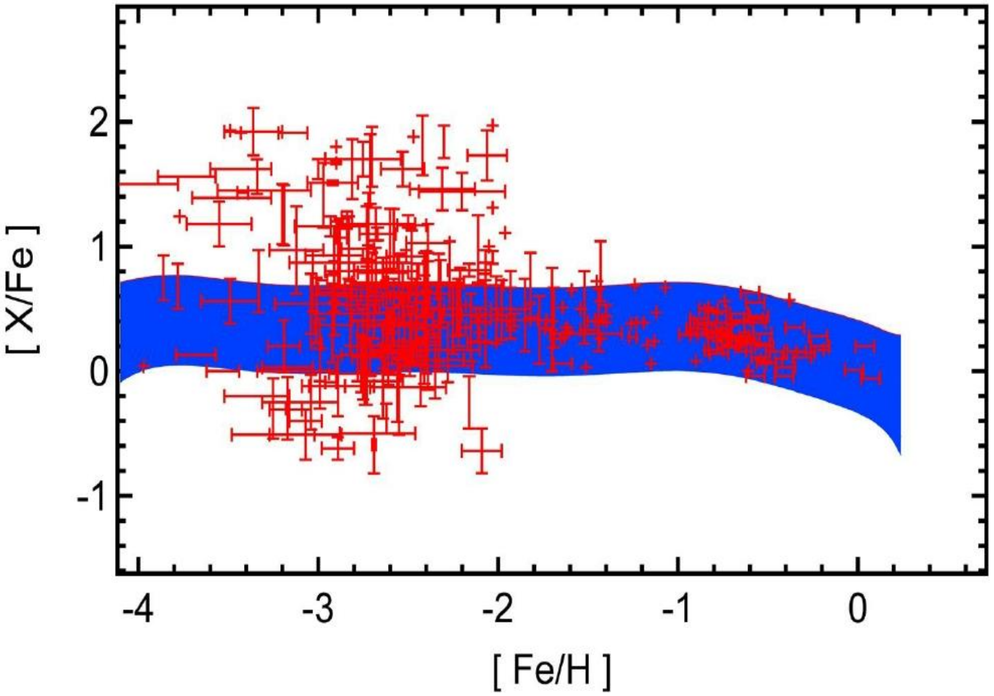
New limit of ^{244}Pu on Earth points to rarity of heavy r-process nucleosynthesis

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

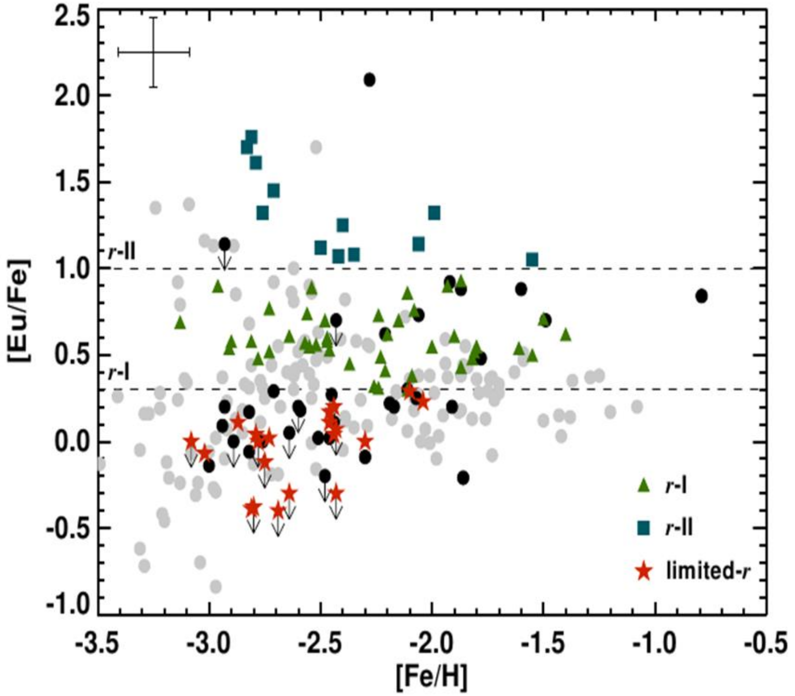
The continuous production of ^{244}Pu in regular CCSNe (10^{-4}-10^{-5} Msol each of r-process nuclei, in order to reproduce solar system abundances) would result in green band → no recent (regular) supernova contribution. Rare events with enhanced ejecta could also explain solar abundances, but the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

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

Data from SAGA database



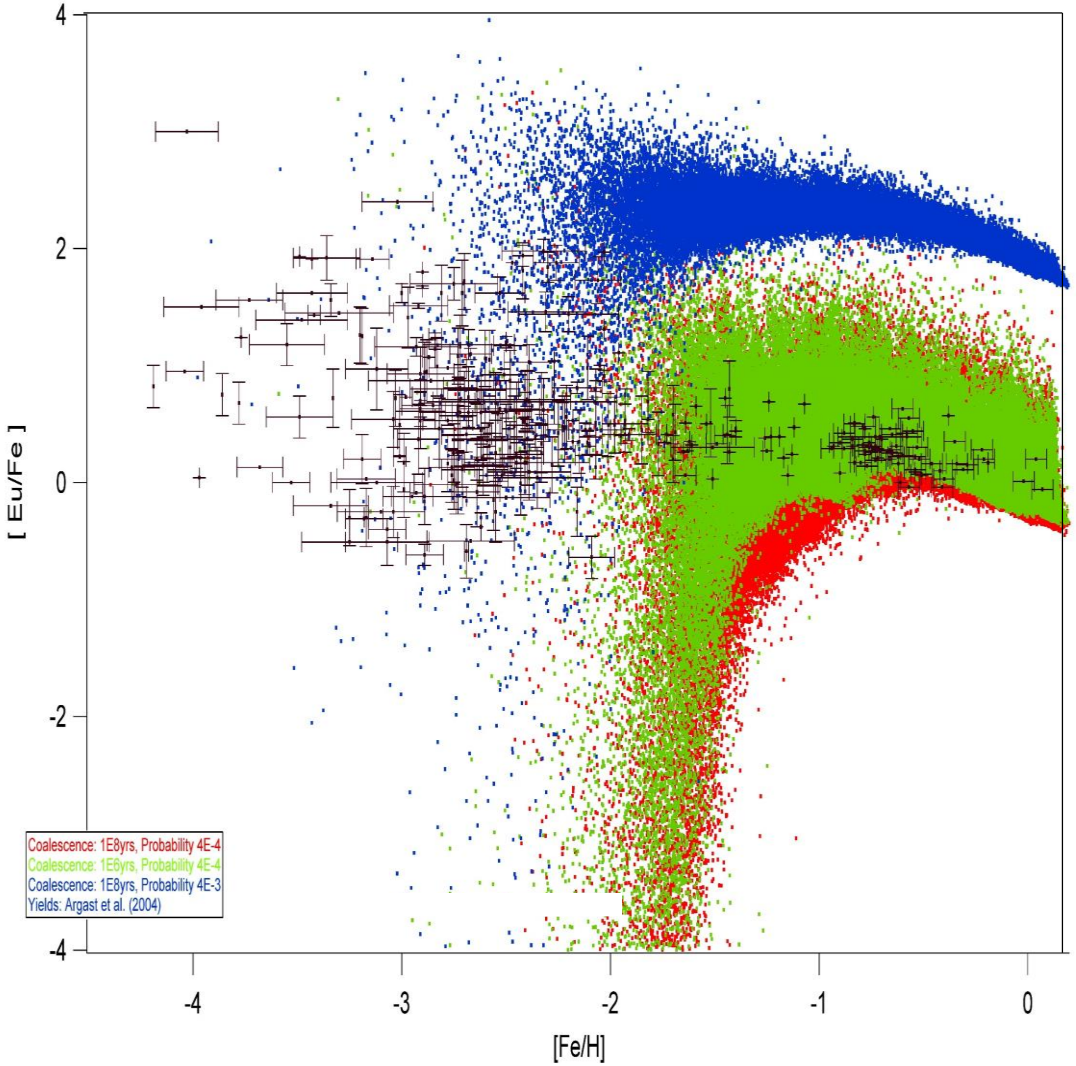
«The r-process alliance» Hansen et al. (2018)
In comparison to Roederer et al. (2014, grey dots)

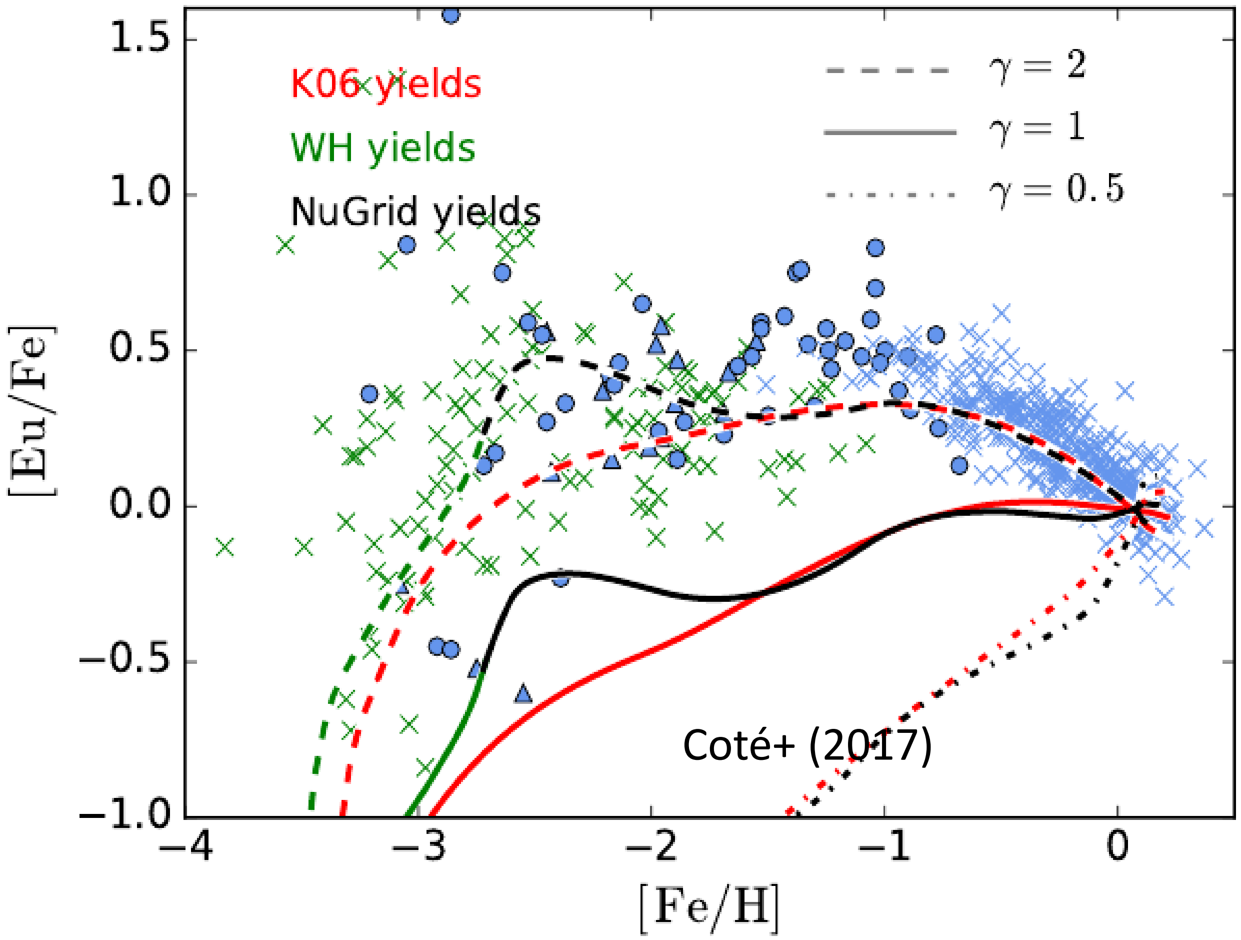


Blue band: Mg/Fe observations (95%), explained from *frequent* CCSNe,
red crosses: individual Eu/Fe obs.

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

What are these possible r-events??





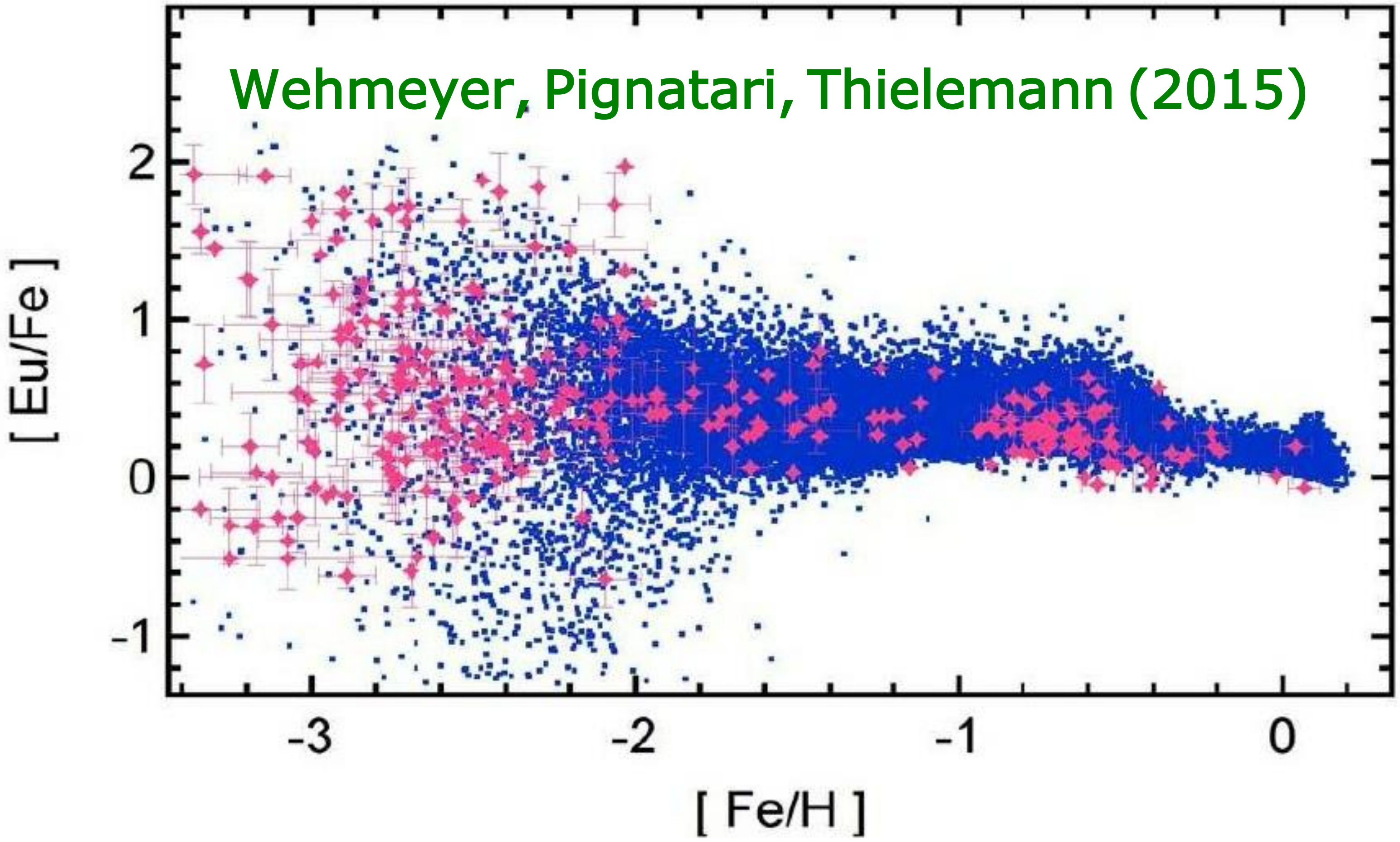
Coté+ (2017)

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

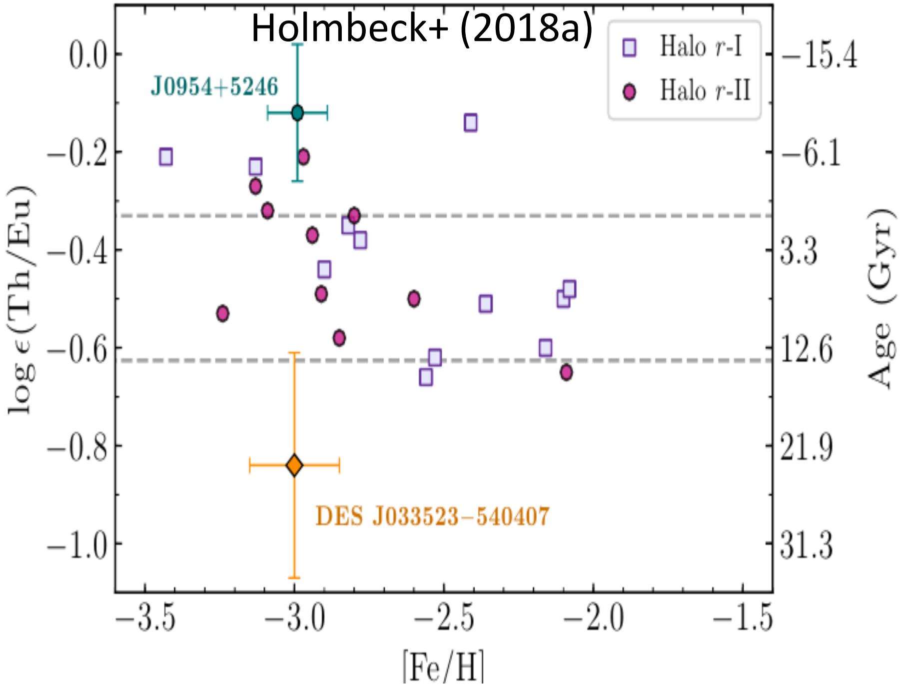
Combination of NS mergers *and magneto-rotational jets*

(as an event related to massive stars occuring 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)


Holmbeck+ (2018a)

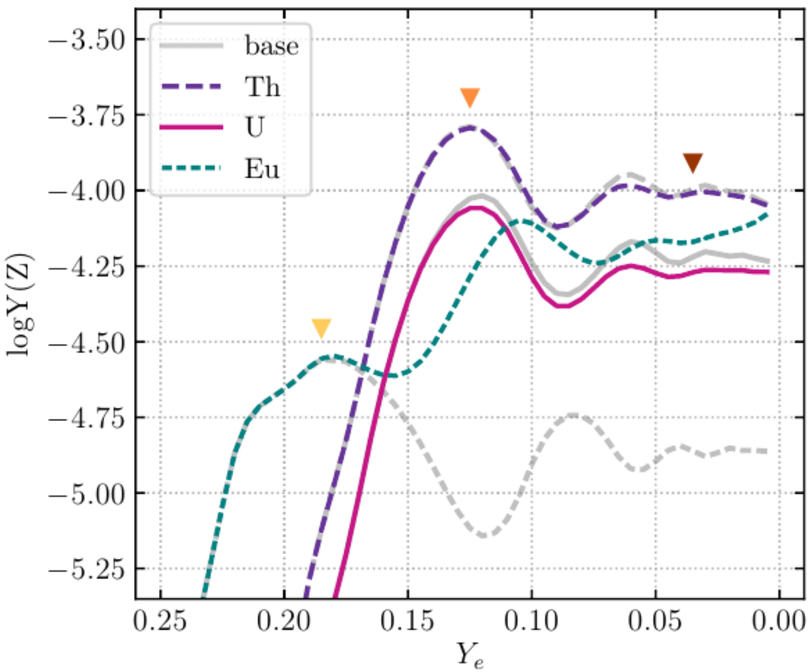
Independent of the question whether galactic evolution modeling requires a further r-process source in addition to NS-mergers or not, are there any other features which point to different events at the lowest metallicities (actinide boost stars at about [Fe/H]≈-3)?

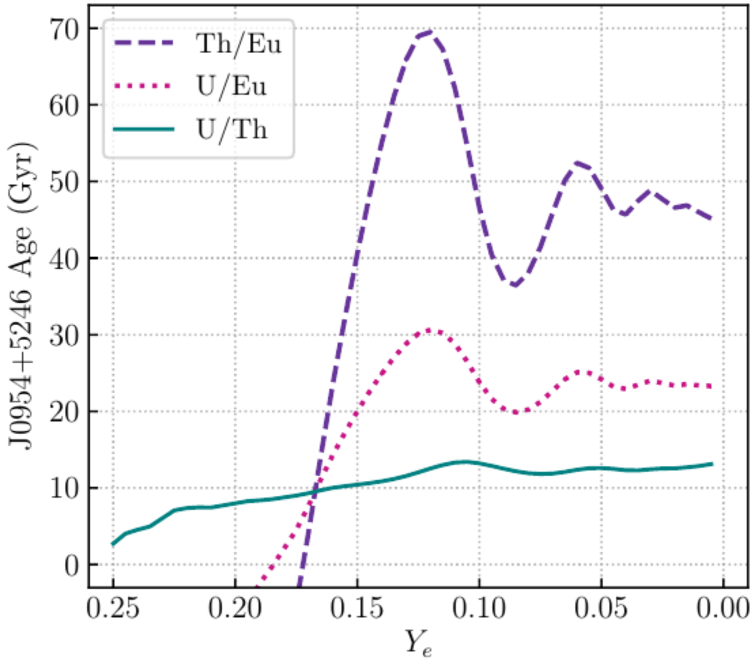
One finds different production of Eu, U, Th for different Ye conditions in r-process enviroments.

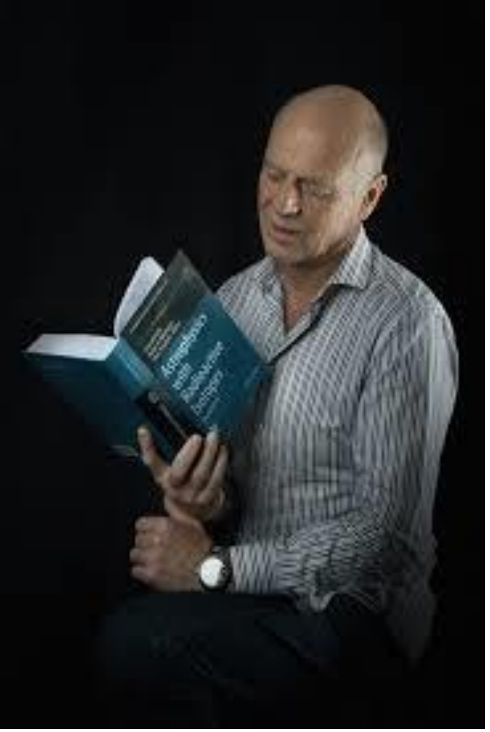
When utilizing element production ratios which would fit well the solar r-abundances, unreasonable ages for these stars would result when making use of the Th/Eu and U/Eu chronometers.

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

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







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

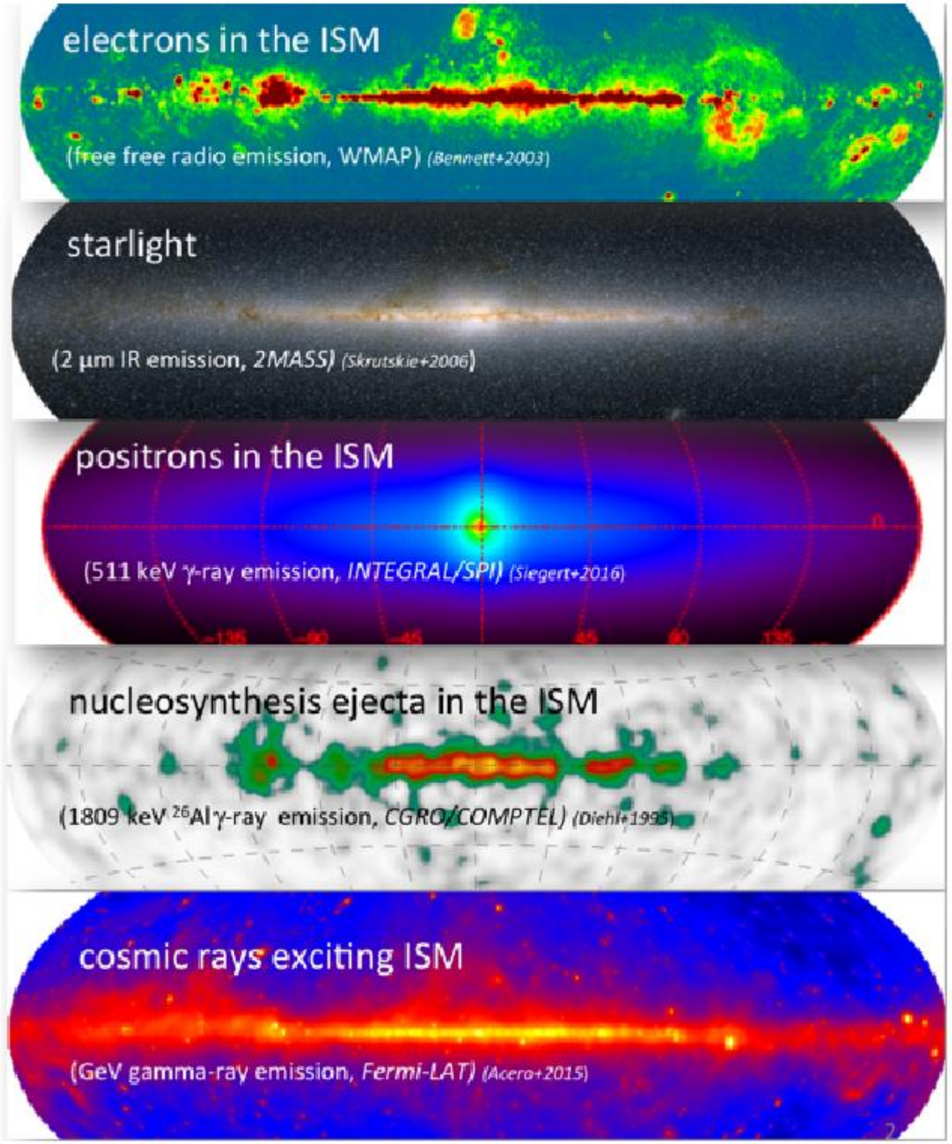


Figure 3: *Deciphering the Milky Way. A modern MeV γ-ray instrument will help solve how newly created elements are produced, transported, mixed, and distributed.*