Nucleosynthesis of light trans-Fe isotopes in ccSNe: Implications from presolar SiC-X grains

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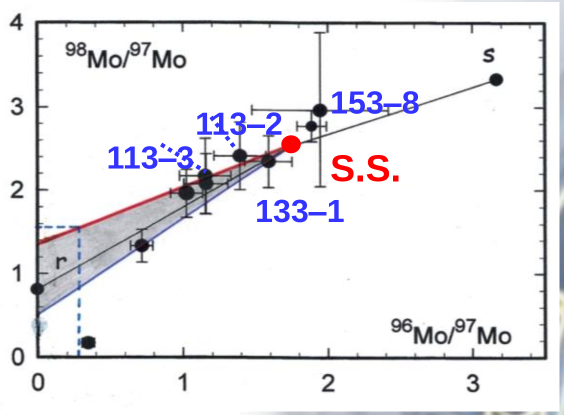
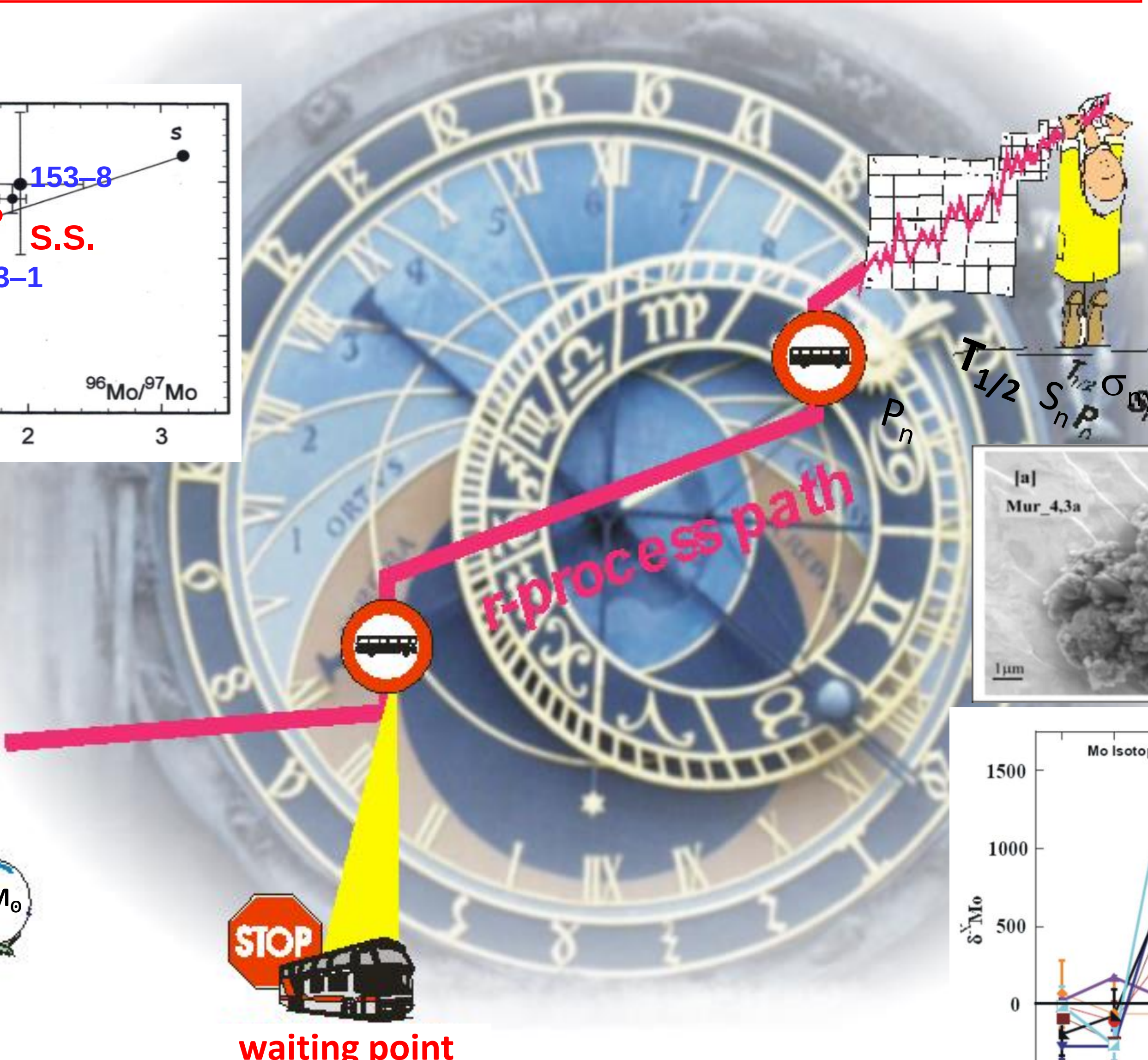
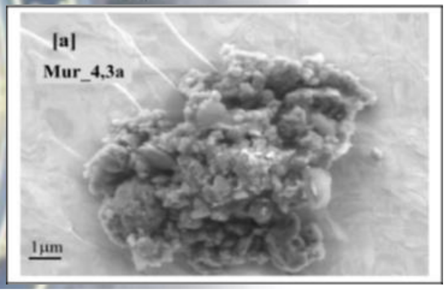
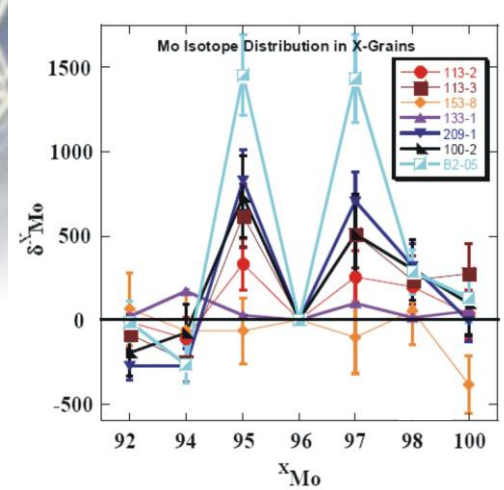








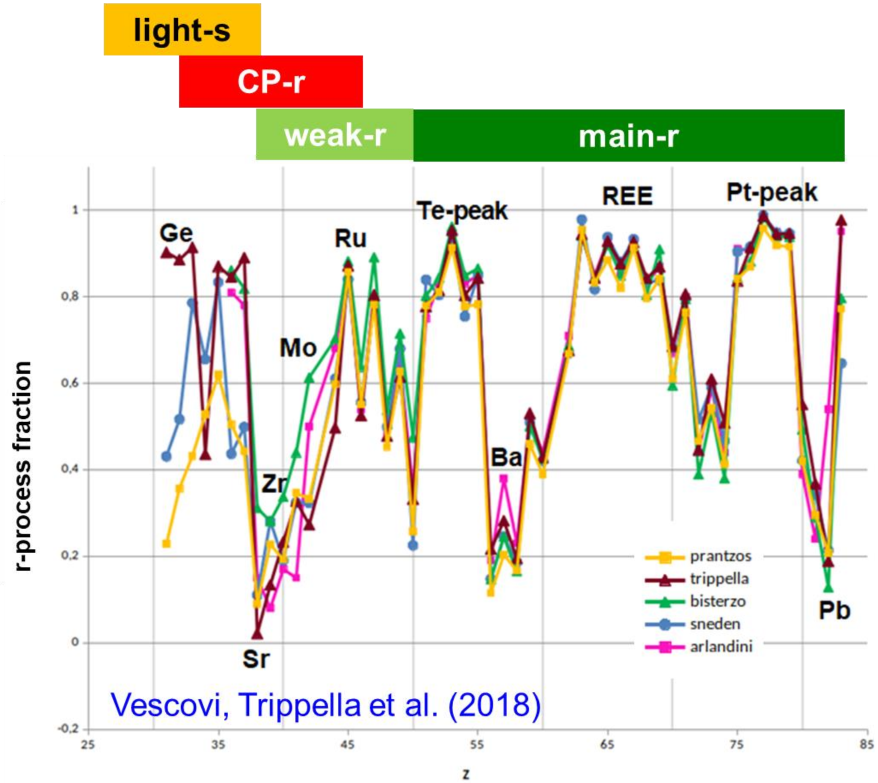
Karl-Ludwig Kratz

Perugia 2022

Motivation for our study of light trans-Fe isotopes (I)

A decade ago:

- discussions with R. Gallino and C. Travaglio about the "LEPP" idea
- **discussions with U. Ott and A. Davis about isotopic anomalies in SiC grains**
- basic ν-driven wind paper by R. Hoffman et al. (1996, 2008)
- no convincing solution of **primary** production of light p-isotopes; with the hot topic of S.S. **^{92}Mo/^{94}Mo**



More recently:

- uncertainties of light trans-Fe S.S.-r "residuals"

Example ^{96}Zr r-"residual":	
Käppeler '89	**100 %**
Arlandini '99	**45.0 %**
Bisterzo '11	**48.7 %**
Bisterzo '14	**61.3 %**
Tripella '16	**98.6 %**
to be compared to r-"primary":	
Kratz '19	**98.4 %**

Motivation for our study of light trans-Fe isotopes (II)

Today:
Correlations of r-process elements in VMP halo stars

When Khalil Farouqi and I started in 2018, our main goal was to distinguish between

- r-elements **correlated** (co-produced?) with Fe, and
- r-elements **uncorrelated** (not produced?) with Fe

In contrast to the numerous model-speculation papers after the GW-NSM event,
our approach primarily based on experimental "**facts**":
databases for UMP halostars SAGA (and JINAbase); **[Fe/H] ≤ -2.5**

Choice of 3 "typical" r-elements:

- Z = 38 Sr ↷ classical "**weak-r**" element → SN-type ?
- Z = 63 Eu ↷ classical "**main-r**" element → Merger-type ?
- Z = 90 Th ↷ classical "**actinide-boost**" → Merger-type ?

Choice of "typical" r-parameters:

- [**Eu/Fe**] ↷ "r-enrichment" → historical stellar classes r-poor, r-I, r-II
- (**Sr/Eu**) ↷ "**weak-r**"/"**main-r**" → indication of fractions SN & Merger ?
  → indication of "pure" SN and/or Merger signatures ?
  → correlation with metallicity [Fe/H]?

Combination of exp. "facts" with statistical analyses (SCC, PCC, K-means clustering)

...in the following, focus on Zr, Mo, Ru

Light p-process isotopes in the S.S.

Historical papers “p-process”

B^2FH (1957)
Arnould (1976)
Woosley & Howard (1978)

Main goal:
explanation of nucleosynthetic origin of light p-nuclei, including **$^{92}Mo/^{94}Mo$**

Selected subsequent papers / scenarios

Howard *//* Meyer et al. (1992, **2000**)	n-burst in exploding massive stars
Hoffman et al. (1996, **2008**)	ν-driven winds in SN II
Schatz et al. (1998, 2003)	rp-process in X-ray bursters
Rauscher et al. (2002)	γ-process in pre-SN and SN
Fisker et al., (2006)	νp-process in SN II
Wanajo et al. (2009)	p-production in EC SN
Farouqi et al. (**2009**)	light p, s, r in SN-II at low S
Travaglio et al. (2011, **2018**)	p-process in SN Ia
Eichler et al. (2017)	nucleosynthesis in ccSN
Pignatari et al. (2018)	n-burst in He-shell of ccSN
Kratz et al. (**2018**)	light trans-Fe elements in SN-HEW
Sasaki et al. (2022)	hypernova νp-process

The classical "neutron-burst" model

The **"neutron-burst model"**
is the favoured nucleosynthesis scenario of the cosmochemistry community,
so far applied to isotopic abundances of Mo, Zr, Te, Xe & Ba

Basis:

Howard et al., Meteoritics 27 (1992)
"…neutron burst occurs in shocked He-rich matter in an exploding massive star…"

B.S. Meyer et al., ApJ 540 (2000); priv. comm. (2018)

A secondary/ternary model with **several steps**:

1) start with **S.S.** seed composition (already containing p-isotopes);
2) during partial **He-burning**, exposure to a weak n-fluence from **$^{13}C(\alpha, n)$**
   $\Rightarrow \tau = 2 \cdot 10^{24}$ cm^{-2} (0.02 mb^{-1}), mimics **weak s-processing**;
3) on these s-ashes (1500 g cm^{-3}) run **"n-burst"** with sudden heating to $T_9 \approx 1$;
   ↷ 2nd n-source **$^{22}Ne(\alpha, n)$** activated for 1 s $\Rightarrow n_n \approx 10^{17}$ n·cm^{-3} (0.08 mb^{-1});
4) expansion & cooling on 10 s hydrodynamical timescale.

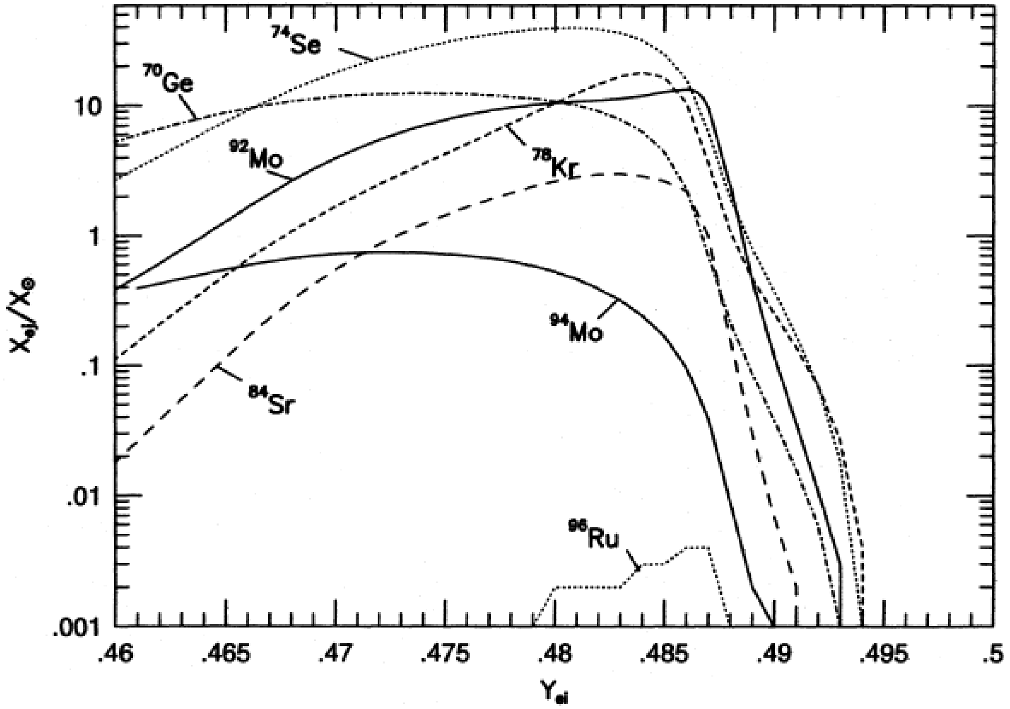
The n-burst shifts the s-like ashes of (Z, A) to (Z, A+x);
e.g. from initial S.S. ^{92}Mo / ^{97}Mo ≈ **1.5** to final ratio of ≈ $1.4 \cdot 10^{-3}$
↷ dilution of p-^{92}Mo and enhancement of (r+s) - ^{97}Mo .

Conclusion by authors:

n-burst can explain the **"anomalous and quite puzzling"** Mo-pattern in SiC X-grains.

Hoffman et al. (1996, 1997, 2008)

Production of the light p-process nuclei in neutrino-driven winds
Hoffman, Woosley, Fuller, Meyer, ApJ 460 (1996)



"normalized production factors"
$X_{ej}/X_{\odot} = f(Y_e)$
individual Y_e's; $S/(N_A k) \approx 50$

"No initial abundances of r- or s-process seed need be invoked
⇒ this component of the p-process is primary rather than secondary."

Result on ^{92}Mo:
Underproduction relative to solar

The authors give 3 possible explanations:

1) The νp-process is active, but ^{92}Mo is primarily produced at other sites
2) The νp-process is not active, so another explanation is needed
3) The νp-process is active, but the nuclear parameters (…) are incorrect

Mo isotopic abundances in the S.S.

Particularly **"hot topic"**

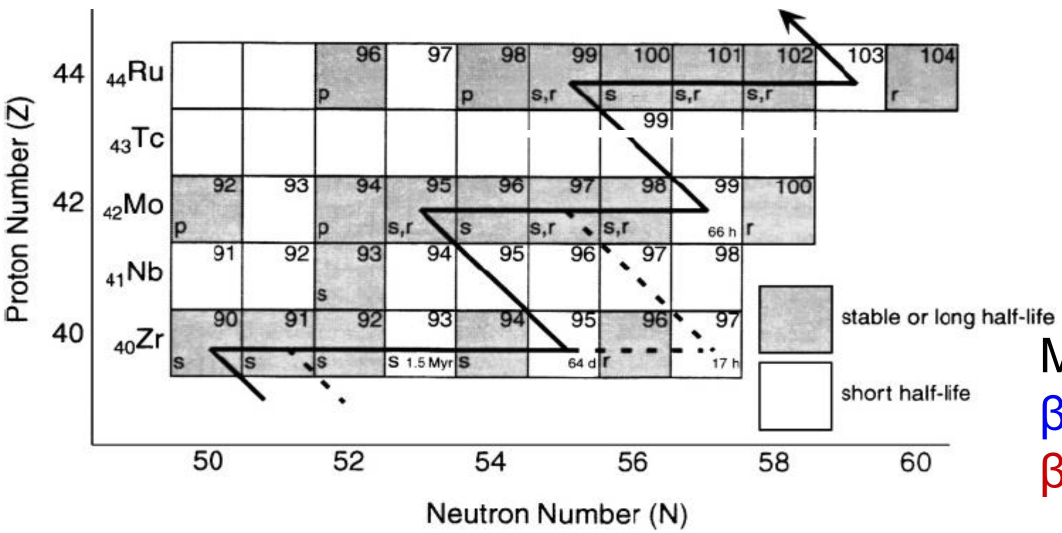
$^{92}Mo/^{94}Mo$

The two most abundant p-nuclei in the S.S.

	Lodders (2009)
^{92}Mo	14.525
^{94}Mo	9.151
$^{92}Mo/^{94}Mo$	**1.587**

…despite all attempts / scenarios studied up to now,

primary production of $^{92}Mo/^{94}Mo$ has remained an "unsolved problem"



7 stable isotopes:

$^{92,94}Mo$ p-only; ^{96}Mo s-only
$^{95,97,98}Mo$ s+r, ^{100}Mo r-only

Mo isotopes "shielded" from both sides:

β^- **$^{92,94,96}Zr$** (Z=40)

β^+ **$^{96,98\text{-}100}Ru$** (Z=44)

narrow Z-path for production!

However, note:

S.S. represents a **blend** of various nucleosynthesis processes**!**

Therefore, it is **not the "ideal observable"…**

Are there better ones? **YES, Mo in SiC-X grains!**

Abundances of light trans-Fe ISOTOPES in the ccSN-HEW scenario

Continuing the work of Hoffman, Woosley et al. (1996)…

Farouqi, Kratz & Pfeiffer;
Publications of the Astron. Soc. of Australia (PASA) 26 (**2009**)
"Co-production of light p-, s- and r-process isotopes in the high-entropy wind of type II supernovae"

Typical yields ($M_⊙$) for Y_e = 0.46			
^{64}Zn	$5.6*10^{-5}$	^{78}Kr	$4.0*10^{-8}$
^{70}Ge	$8.9*10^{-6}$	^{84}Sr	$1.2*10^{-8}$
^{74}Se	$5.4*10^{-8}$	^{92}Mo	$2.6*10^{-8}$

sizeable abundance yields, comparable to SN Ia of Travaglio et al. (2011, 2015)

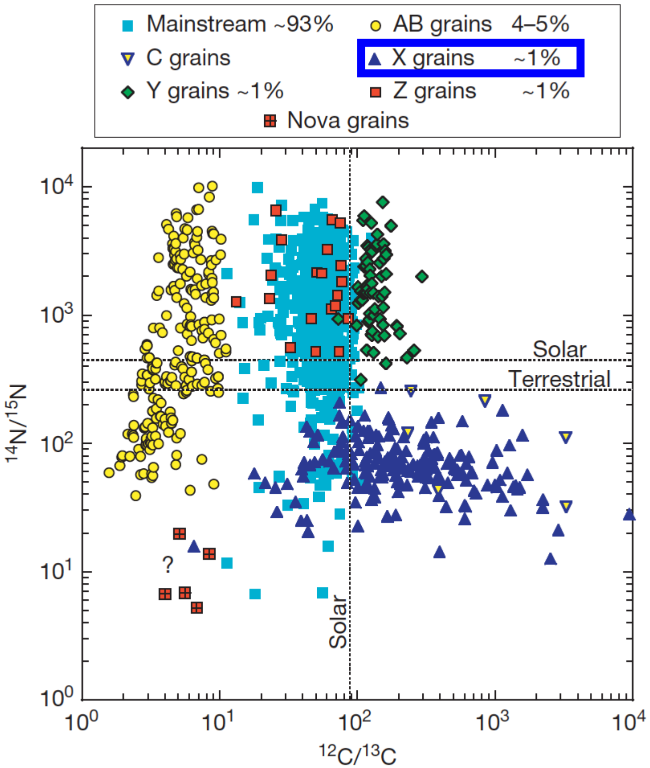
Isotopic pairs (nucleosynth. origin)	**Isotopic abundance ratios**	
	S.S.	**HEW**
^{64}Zn(**p**) / ^{70}Zn(**r**)	78.4	79.4
^{70}Ge(**s**,**p**) / ^{76}Ge(**r**)	2.84	4.61
^{74}Se(**p**) / ^{76}Se(**s**)	$9.4*10^{-2}$	$9*10^{-2}$
^{74}Se(**p**) / ^{82}Se(**r**)	0.101	0.113
^{78}Kr(**p**) / ^{86}Kr(**r**,**s**)	$2.1*10^{-2}$	$8*10^{-4}$
^{84}Sr(**p**) / ^{86}Sr(**s**)	$5.7*10^{-2}$	$4*10^{-2}$
^{90}Sr(**s**,**r**) / ^{96}Zr(**r**,**s**)	18.4	5.56
^{92}Mo(**p**) / ^{94}Mo(**p**)	1.60	1.73
^{96}Ru(**p**) / ^{98}Ru(**p**)	2.97	2.57

all historical p-, s- and r-"**only**" isotopes are co-produced, from ^{64}Zn to ^{104}Ru

Types of presolar SiC grains

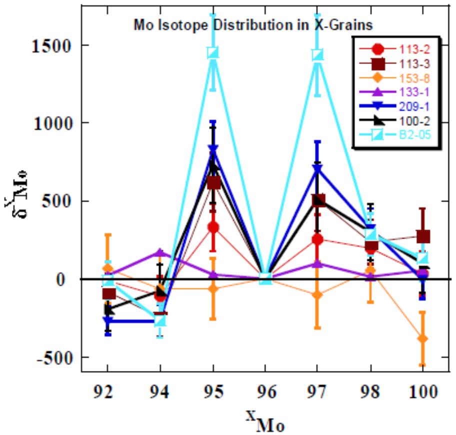
SiC grains:

- Fourth most abundant and one of the best-studied type of presolar grains
- Further divided into subgroups based on C, N, O & Si isotope ratios
- Most (93%) have C, N, O & Si isotope signatures consistent with TP-AGB stars → **mainstream grains**
- Just 1% have isotopic signatures consistent with explosive scenarios → **Type X grains**
- However, the light trans-Fe element composition (e.g. Zr, Mo, Ru) of Type X grains have so far defied a straightforward interpretation.



Zinner: Treatise on Geochemistry (2004)

Pellin et al.: LPS (2006)



Taking Mo as an example, rel. to ^{96}Mo:

$^{92,94}Mo$ depleted

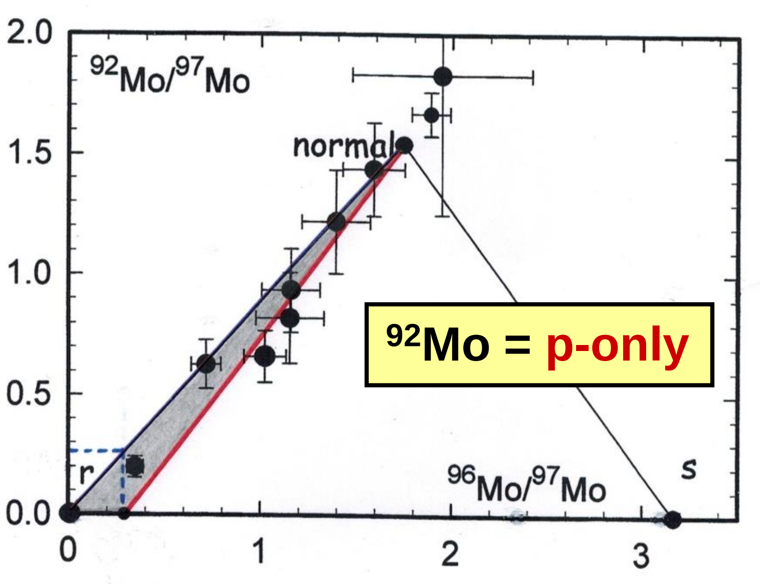
$^{95,97,98}Mo$ enriched

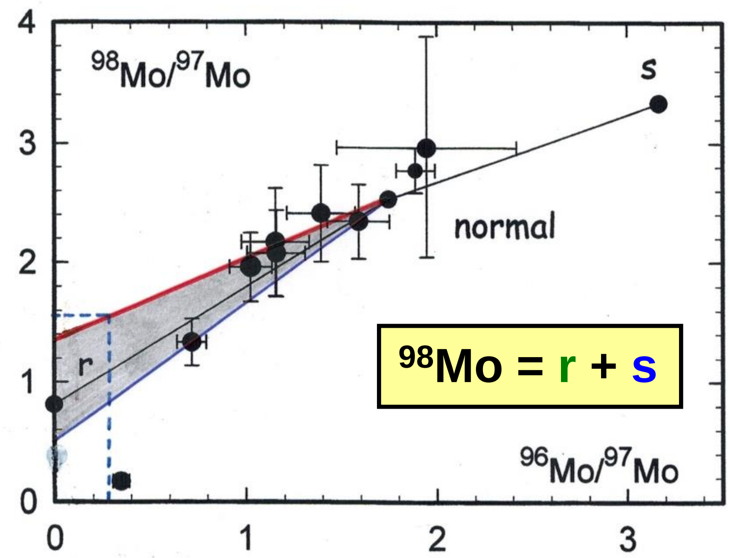
^{100}Mo approx. S.S.

"Clean" signature of ccSN–low-S component?

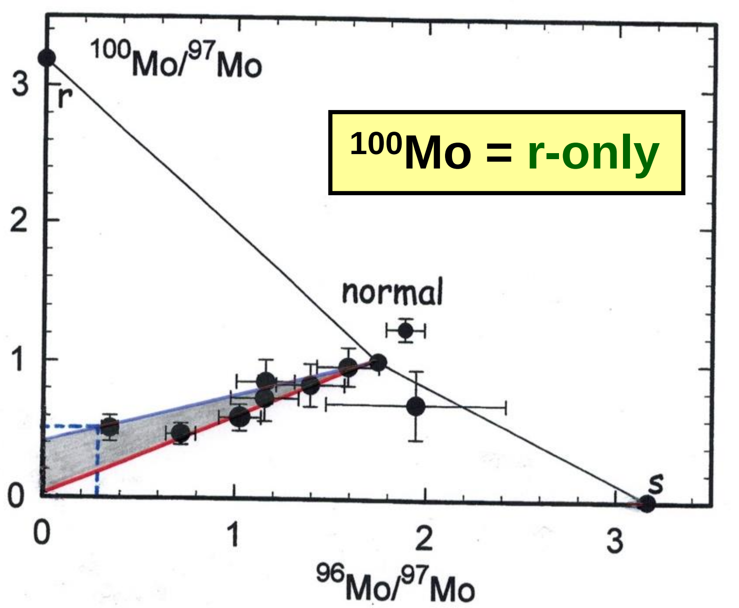
δ notation: permill deviation from S.S.

Cosmochemical Mo "three-isotope plots"





Ott, Kratz (2007)



Convention of cosmochemists:
"three-isotope plots"
extrapolation of mixing lines with S.S.
yields "clean" nucleosynthesis signature

Here, S.S. data point **included** in mixing-line fits

X-axis: ^{96}Mo / ^{97}Mo

Y-axis: ^{X}Mo / ^{97}Mo

To be compared to model predictions:
definitely neither classical s nor r !

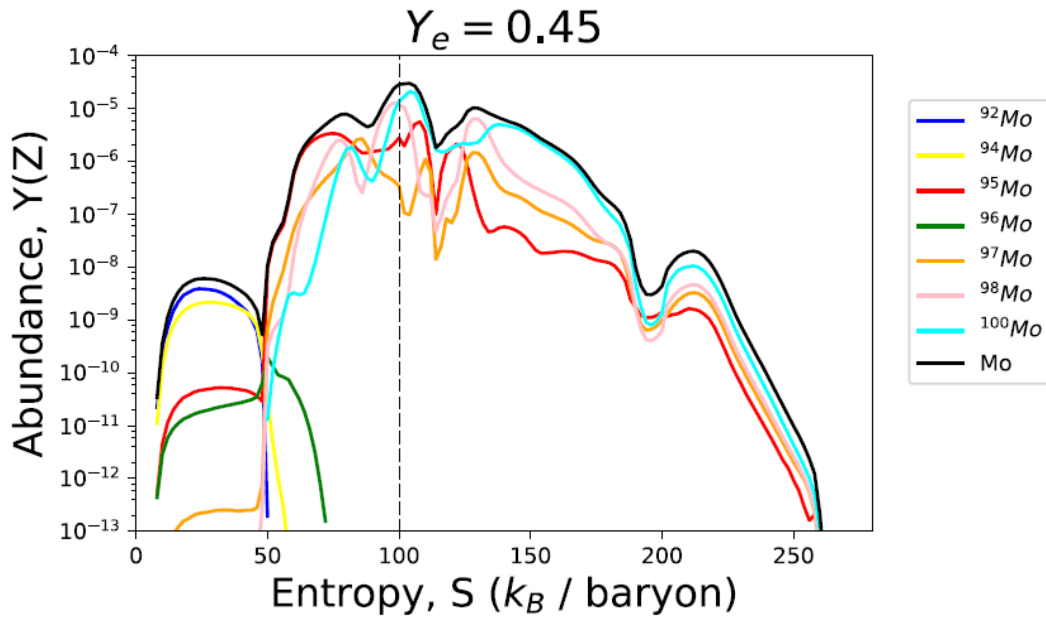
"New" Mo isotopic abundances in ccSN-HEW

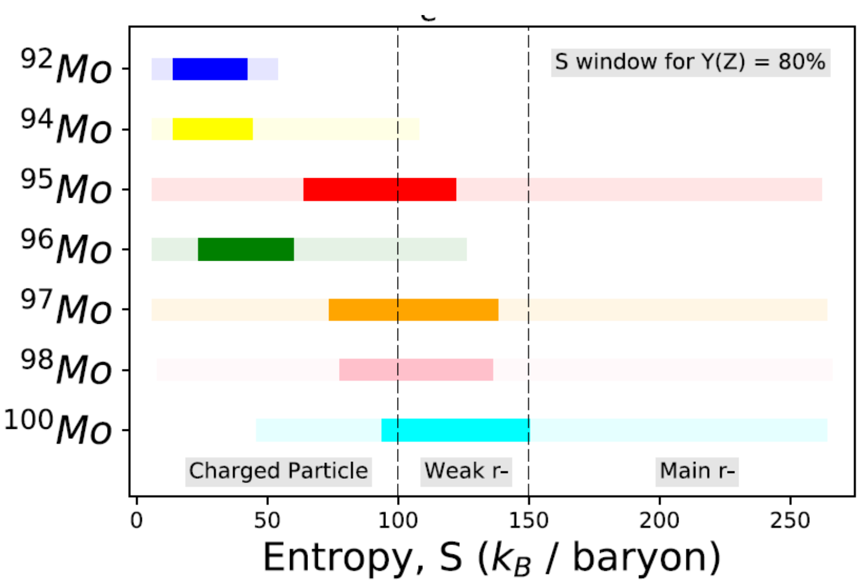
Kratz et al., AIPC 2076 (2019):

all 7 stable Mo isotopes

^{92,94}Mo p-only
^{95,97,98}Mo r+s
^{96}Mo s-only
^{100}Mo r-only

are co-produced within the CP component 10 < S < 100; $Y_n/Y_{seed} < 1$





Main production of different Mo isotopes in different S-regions

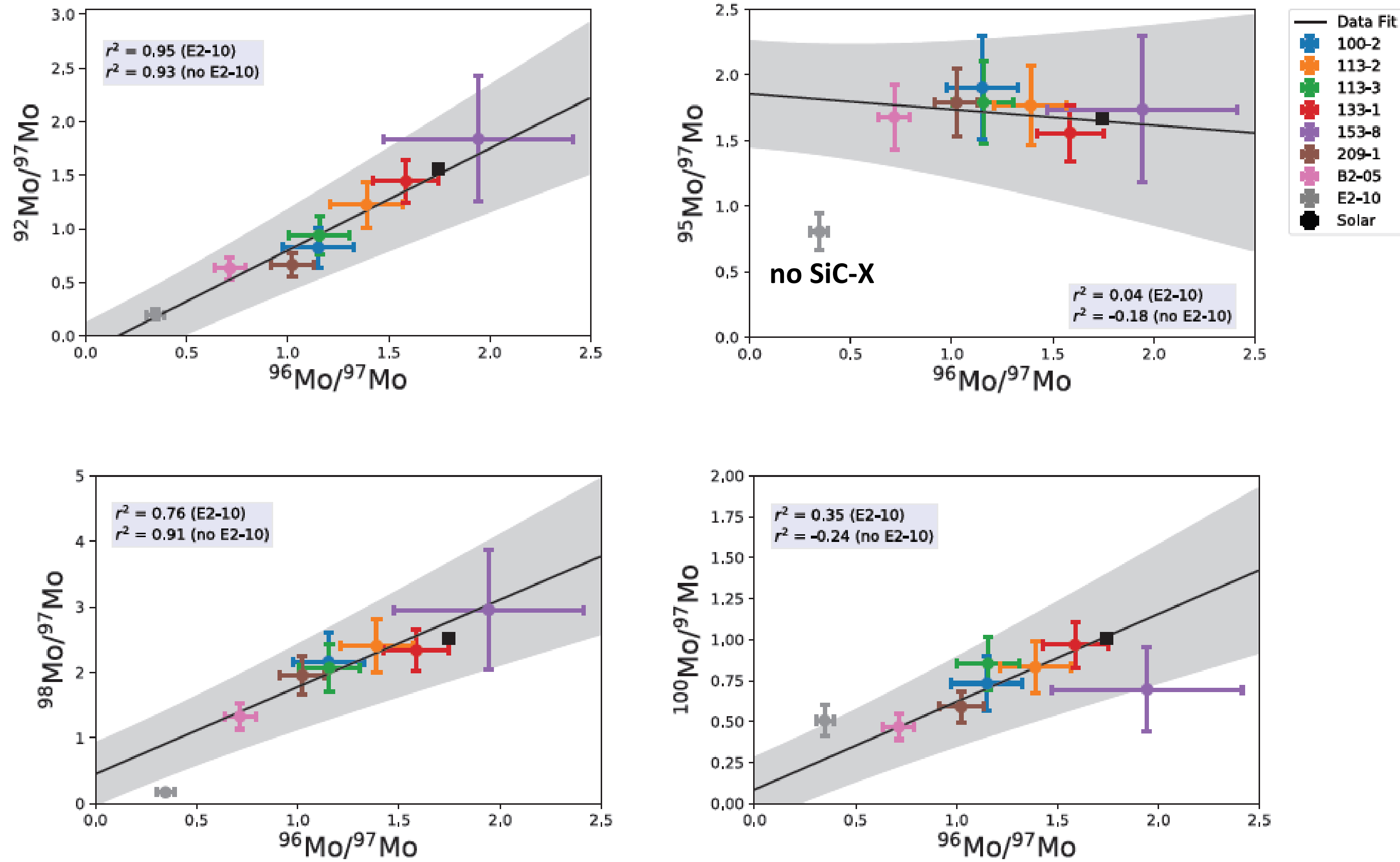
Note:

- Only the p- ^{92,94}Mo and s- ^{96}Mo are **completely** produced in the CP component
- ^{100}Mo mainly produced under weak-r conditions; corresponding to more n-rich wind ejecta; main progenitor **^{100}Sr**

"New" cosmochemical Mo three-isotope plots

Here:

mixing-line fits **without** S.S. datapoint



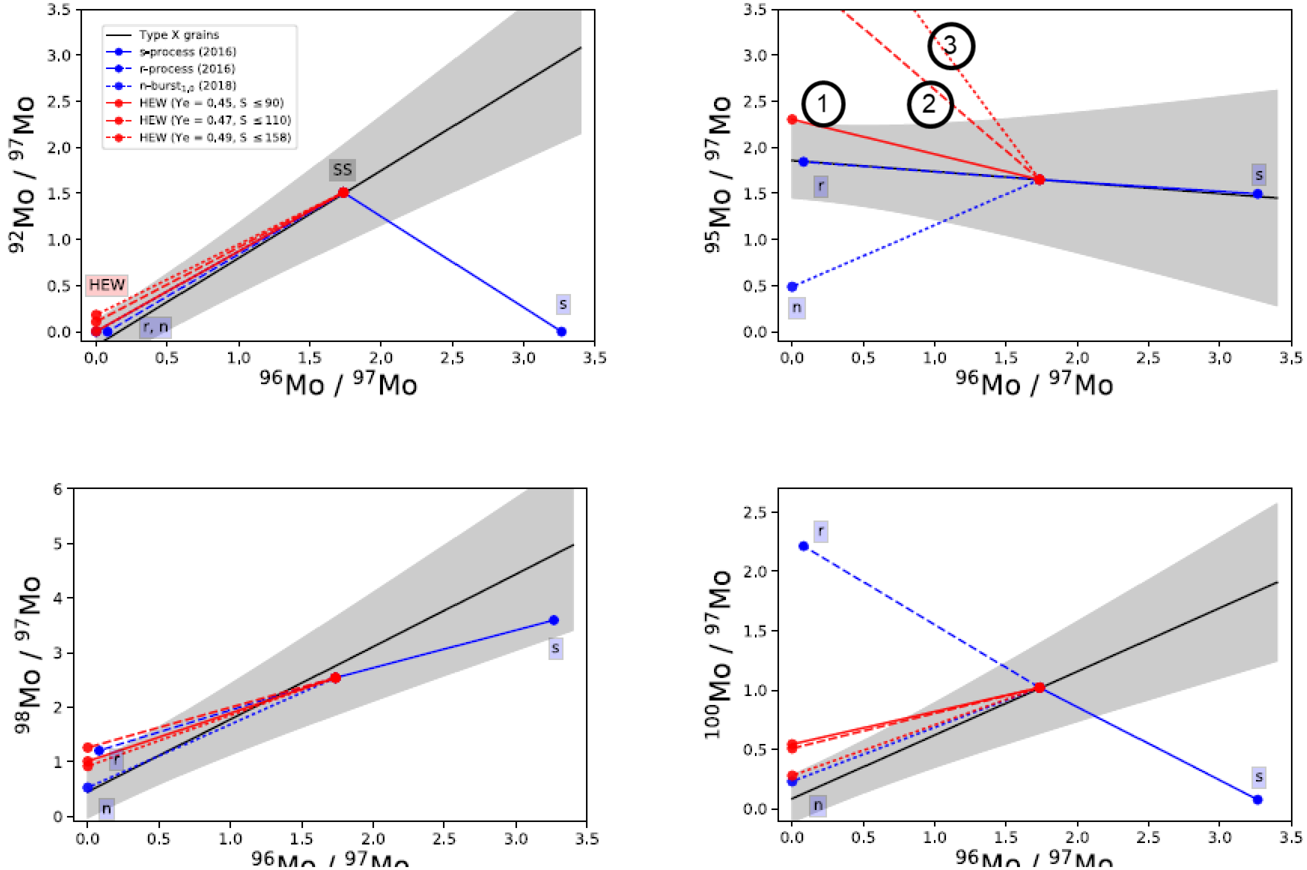
Mixing-line fits go through S.S. data points ↷ **confirmation that SiC-X grains are a mixture of an exotic nucleosynthesis component with homogenized S.S. stardust**

Exp. data to be compared to astro-model predictions; e.g. n-burst, ccSN-II, SN-Ia

Comparison of Mo mixing-line results with model predictions

Astro-models:

- **ccSN-HEW, charged-particle component (CP),** $Y_n/Y_{seed} < 1$
- new **"n-burst"**; $T_9 = 1.0$



1. $Y_e = 0.45$ with $S_{max} = 90$
2. $Y_e = 0.47$ with $S_{max} = 110$
3. $Y_e = 0.49$ with $S_{max} = 158$

Shaded areas represent uncertainties of experimental mixing-line fits

Plot ^{95}Mo/^{97}Mo demonstrates most clearly ↷ **"high" Y_e-S combinations can be excluded**

Comparison of Mo mixing-line results with model predictions

Astro-models (new analyses):

- **"primary"** **ccSN, HEW-CP**; Y_e = 0.45 – 0.46; S_{max} = 50 - 80; Y_n/Y_{seed} < 1
- **"secondary"** **new n-burst**; Meyer (2018)

$^{x}Mo/^{97}Mo$	Isotopic abundance ratios		
	SiC X-grains	This work	New "n-burst"
$^{92}Mo/^{97}Mo$	0.15	0.06	1.43 E-3
$^{94}Mo/^{97}Mo$	0.09	0.02	3.28 E-3
$^{95}Mo/^{97}Mo$	1.86	2.96	1.54
$^{96}Mo/^{97}Mo$	0.10	0.02	0.01
$^{98}Mo/^{97}Mo$	0.50	0.66	0.38
$^{100}Mo/^{97}Mo$	0.10	0.17	0.10
$^{92}Mo/^{94}Mo$	1.67	1.73	0.44 !

For $^{95, 96, 98, 100}Mo/^{97}Mo$, HEW-CP and new n-burst yield similar results.

Not so for $^{92, 94}Mo/^{97}Mo$ and $^{92}Mo/^{94}Mo$!

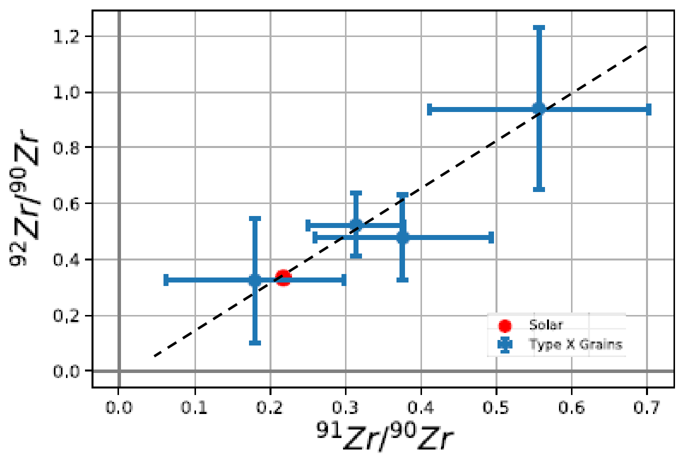
"New" cosmochemical three-isotope plots for Zr & Ru

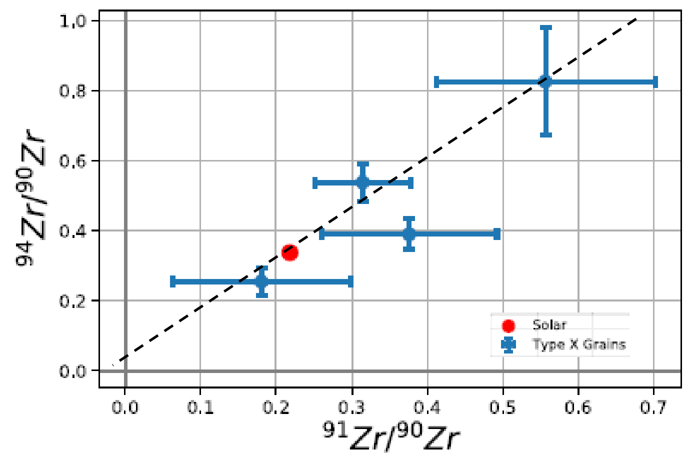
5 stable Zr isotopes:

^{90}Zr s+r (+p?)

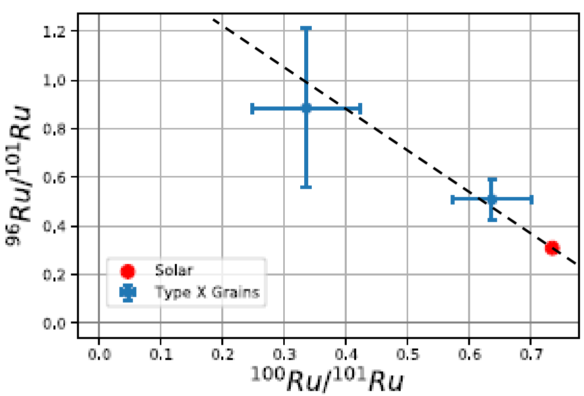
$^{91,92,94}Zr$ s+r

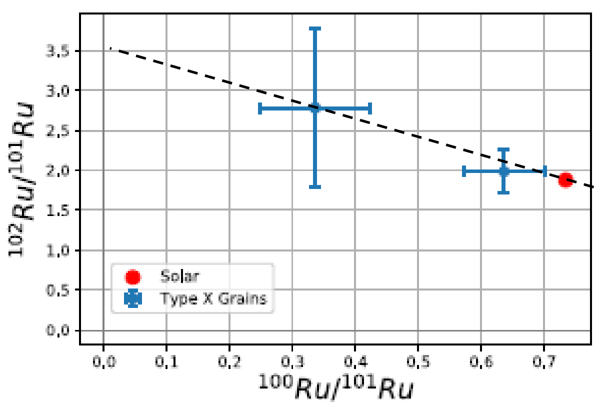
^{96}Zr r+s





SiC-X grains from Pellin et al. (2006)





7 stable Ru isotopes:

$^{96,98}Ru$ p-only

$^{99,101,102}Ru$ r+s

^{100}Ru s-only

^{104}Ru r-only

all 5 Zr isotopes, and all 7 Ru isotopes are co-produced in our ccSN-CP model with $0.45 < Y_e < 0.47$; $Y_n/Y_{seed} < 1$

Comparison of Ru mixing-line results with model predictions

Astro-models (new analyses):

- **"primary"** **ccSN, HEW-CP**; $Y_e = 0.45 - 0.47$; $S_{max} = 50 - 80$; $Y_n/Y_{seed} < 1$
- **"secondary"** **new n-burst**, Meyer (2018)

$^{x}Ru/^{101}Ru$	Isotopic abundance ratios		
	SiC X-grains	**This work**	**New "n-burst"**
$^{96}Ru/^{101}Ru$	**1.28**	**1.09**	**3.70 E-9**
$^{98}Ru/^{101}Ru$	**0.20**	**0.22**	**5.72 E-7**
$^{99}Ru/^{101}Ru$	**1.33**	**1.46**	**0.47**
$^{100}Ru/^{101}Ru$	**0.15**	**0.16**	**1.42 E-3**
$^{102}Ru/^{101}Ru$	**3.16**	**3.03**	**10.2**
$^{104}Ru/^{101}Ru$	**3.68**	**2.96**	**7.41**
$^{96}Ru/^{98}Ru$	**6.12**	**4.83**	**6.47 E-3** !

As for Mo, our HEW-CP results for Ru agree with measured grain data, whereas the **new n-burst clearly fails**.

Summary

We confirm

- earlier studies of Hoffman et al. $\Rightarrow$ ν-driven wind
- Mainz cosmochemistry group $\Rightarrow$ SiC-X mixing-lines

We find

- all historical p-, s- & r-isotopes in the light trans-Fe region (from ^{64}Zn to ^{104}Ru) co-produced in the CP component of a ccSN-HEW

"Best" ccSN-HEW conditions

- CP component $0.45 < Y_e < 0.47$ with $10 < S < 100 \Rightarrow Y_n/Y_{seed} < 1$

As select examples

- the ccSN-CP scenario can provide a consistent picture for all stable Zr, Mo and Ru isotopes in presolar SiC-X grains
- it can also reproduce the S.S. ratio of ^{92}Mo/^{94}Mo $\approx$ 1.6

"Clean" signature of low-S ccSN scenario

- from **"intercepts"** of SiC-X grain mixing lines

Main collaborators

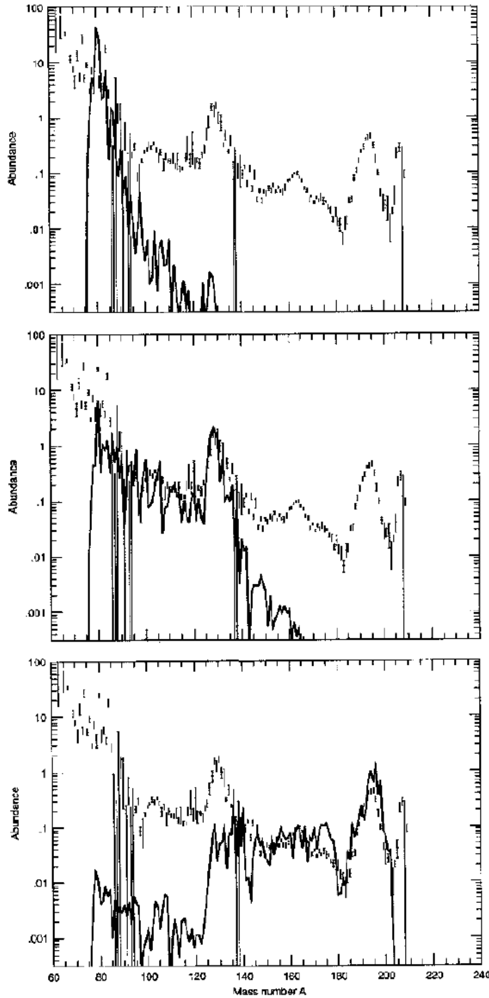
W. Akram, K. Farouqi, O. Hallmann, U. Ott, B. Pfeiffer

My Catania summary: From Supernovae to Kilonovae

1993

…site-independent secondary process

r-process components

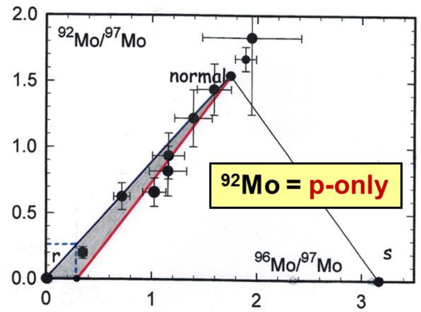


importance of N = 50, 82, 126, main r-process „bottle-necks“

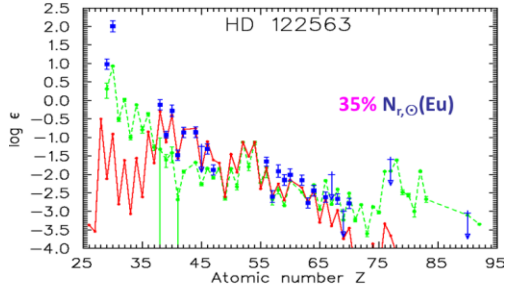
2006

primary process

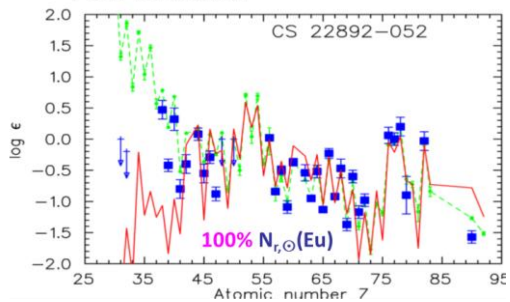
SN-II



r-poor "Honda star"



r-rich "Sneden star"



today

1. „weak“ r-process without Eu (e.g. presolar SiC-X grains) — **regular ccSNe**
2. „incomplete“ r-process without 3rd peak (e.g. Honda star) — **MHD-Jet SNe**
3. „main/strong“ r-process (e.g. Sneden / Cayrel stars) — **NS Mergers** (and **Collapsars**)

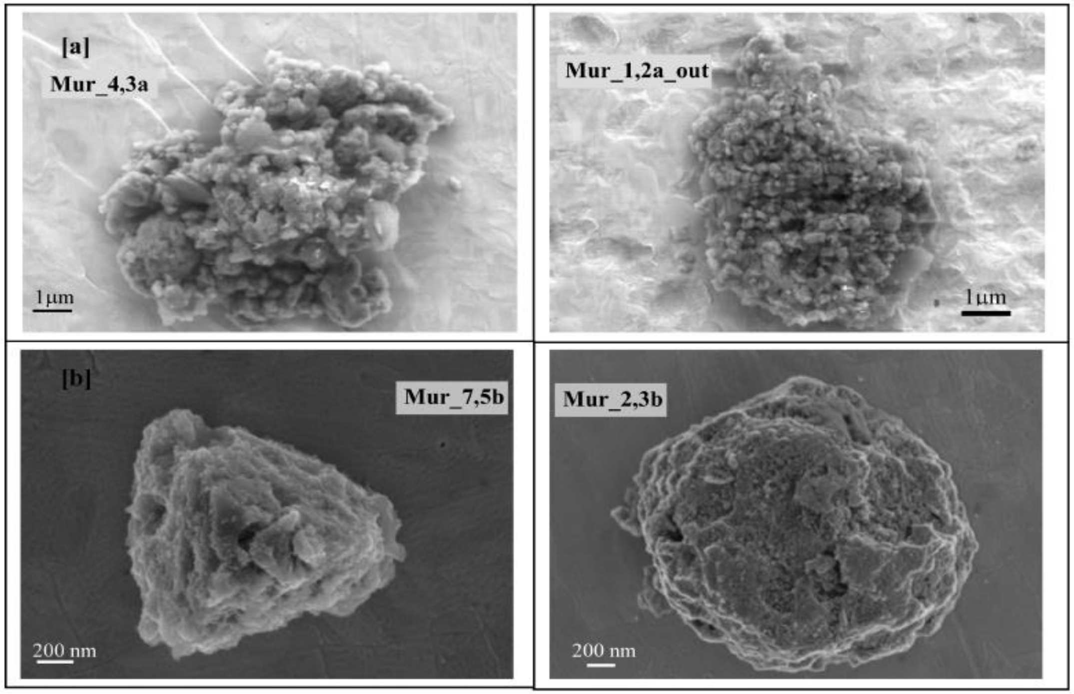
up to 90% Sr & 50% Eu in S.S.-r from SN-types !

RESERVE

Star-dust observables of Zr, Mo and Ru in SiC-X grains

Zr, Mo, Ru in **presolar SiC X-grains** (sub-micron size)
measured with **NanoSIMS** or **RIMS**

… ejecta of stars that contributed to the proto-solar nebula;
due to SiC's refractory nature, these grains survived S.S. formation;
type X-grains are believed to contain isotopic patterns from **presolar** explosive nucleosynthesis events.



Marhas, Ott & Hoppe, MPS 42 (2007)

Remember:

Mo of particular interest:
7 stable isotopes with **^{92,94}Mo "p-only"**
^{96}Mo "s-only"
^{95,97,98}Mo s+r
^{100}Mo "r-only"

Among suggested nucleosynthesis scenarios:

- "n-burst" in shocked He shell in SNe
- rp-process in X-ray bursters
- p-process in SN-Ia or EC-SN
- **ν-driven wind in cc-SN-II**

Question:

can the low-S CP-r component of the HEW r-process produce all 7 Mo isotopes at the same time?

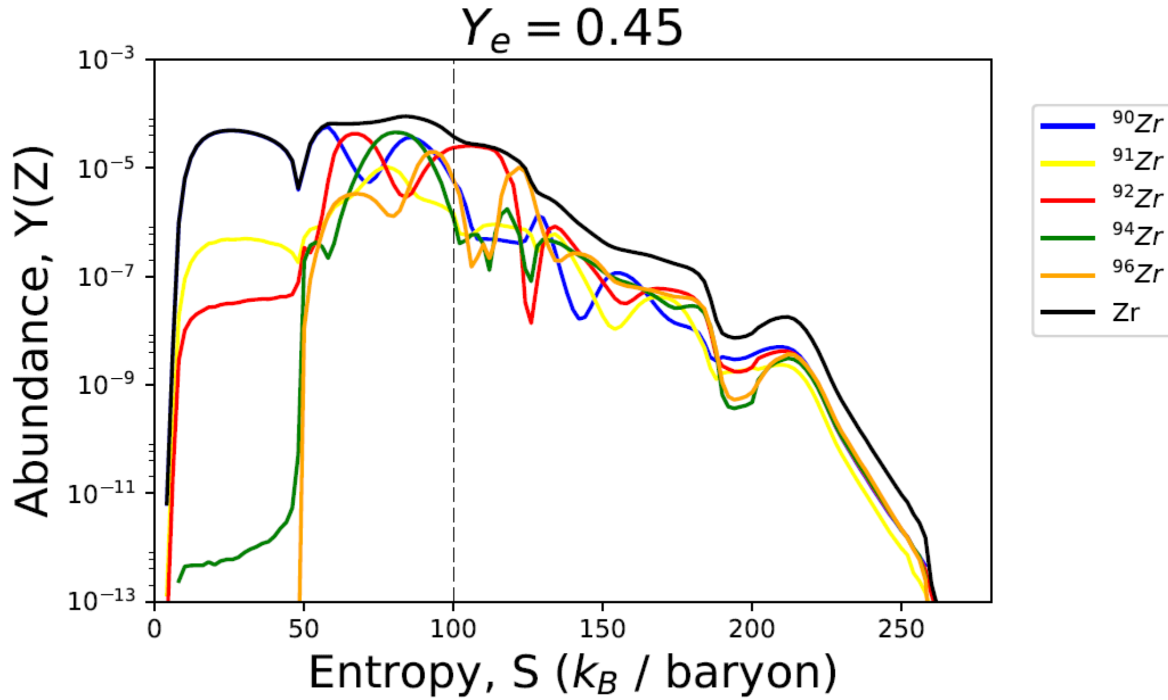
"New" Zr isotopic abundances in ccSN-HEW

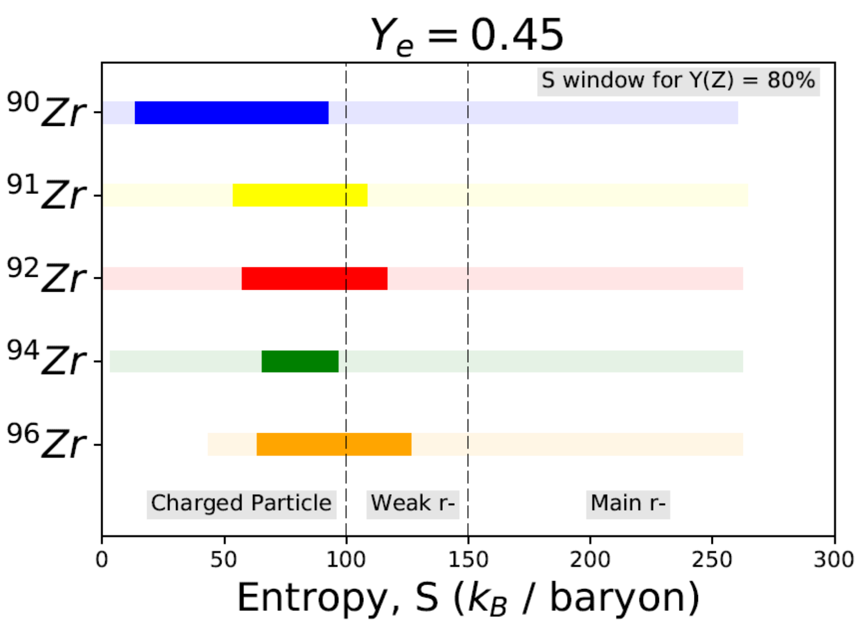
New analysis (2018):

all 5 stable Zr isotopes

^{90}Zr s+r (+p?)
^{91,92,94}Zr s+r
^{96}Zr r+s

are co-produced within the CP component 10 < S < 100; $Y_n/Y_{seed} < 1$





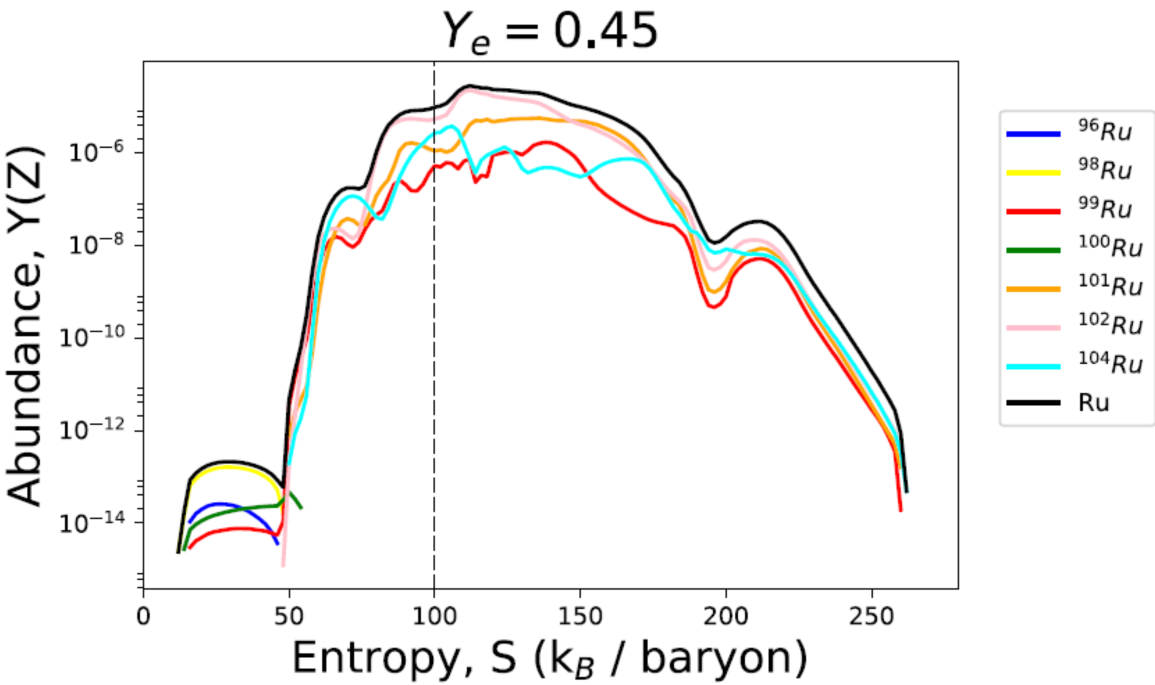
Main production of all 5 **Zr** (Z=40) isotopes within the CP component, in contrast to **Mo** (Z=42) and **Ru** (Z=44)

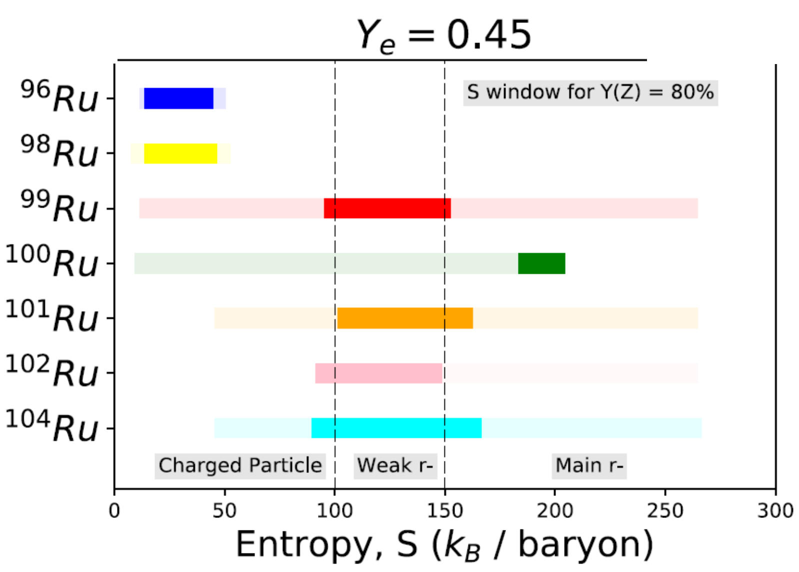
"New" Ru isotopic abundances in ccSN-HEW

Again, **all 7** stable Ru isotopes

$^{96,98}Ru$ p-only
$^{99,101,102}Ru$ r+s
^{100}Ru s-only
^{104}Ru r-only

are co-produced within the CP component 10 < S < 100; $Y_n/Y_{seed} < 1$





Main production of different Ru isotopes in different S-regions

Note:

- only the 2 p-isotopes are **completely** produced in the CP component
- all heavier isotopes are mainly formed under weak-r (or ^{100}Ru, even under main-r) conditions