Trans-Fe elements from Type Ia Supernovae

Umberto Battino (University of Naples "Federico II", INAF, NuGrid Collaboration)

Collaborators: J.D. Keegans, M. Allen, F. K. Röpke, F. Herwig, A. Best, L. Piersanti, O. Straniero, S. A. Sim, C. Travaglio, R. Hirschi, P. A. Denissenkov

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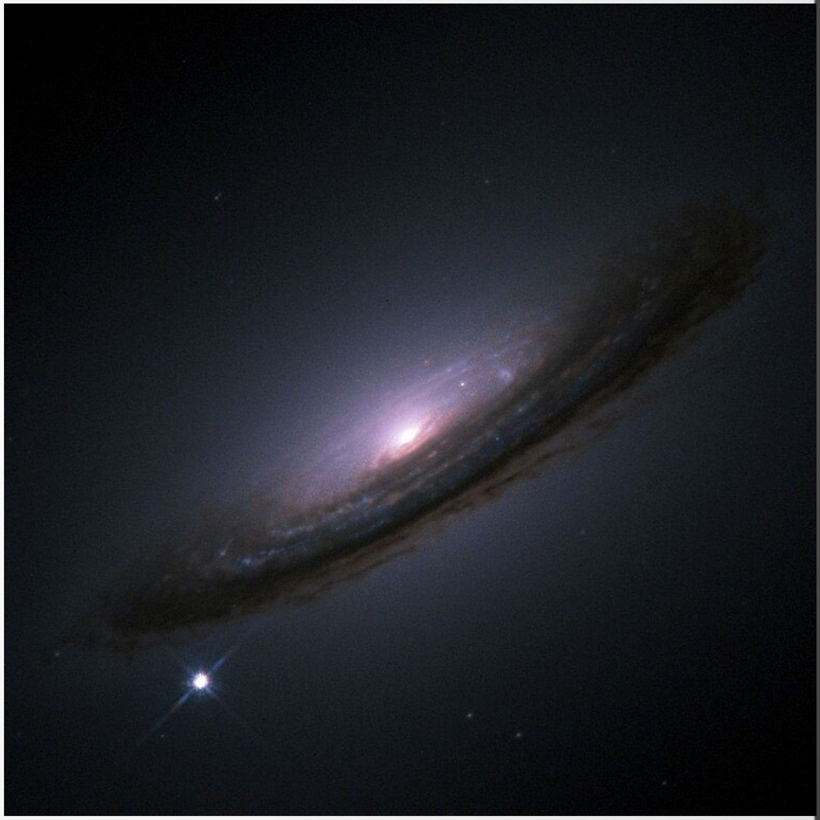
Type Ia Supernova and (Astro)physics

- 2/3 of the iron content in the Milky Way was produced by the explosion of white dwarfs in binary systems as **type Ia supernovae**.
- And maybe also a fraction of the **p-nuclei**! (see e.g. Howard & Meyer 1993, Travaglio et al. 2011, Battino et al. 2020)
- Iron is a crucial ingredient for planetary magnetic-field generation, the formation of proteins and enzyme systems (Wade et al. 2021) → central role played in the emergence of life as we know it on Earth.
- Additionally, due to their characteristic lightcurves, SNe Ia are standardizable candles for cosmic-distance measurements → evidence for the accelerated expansion of the Universe (Nobel Prize Physics, 2011)



NASA/ESA, The Hubble Key Project Team
The High-Z Supernova Search Team

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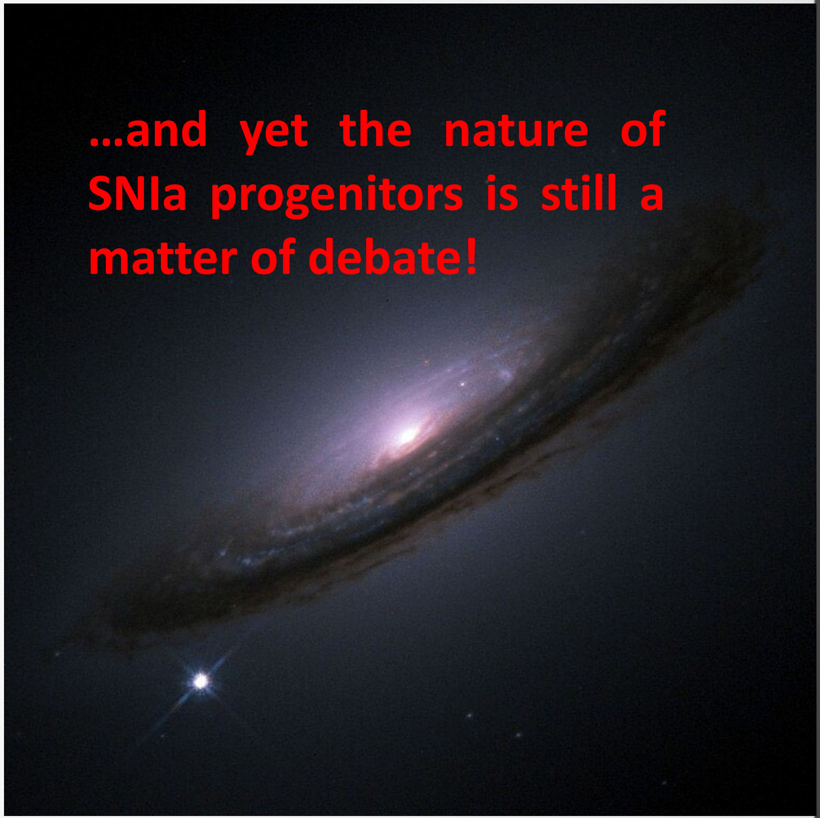

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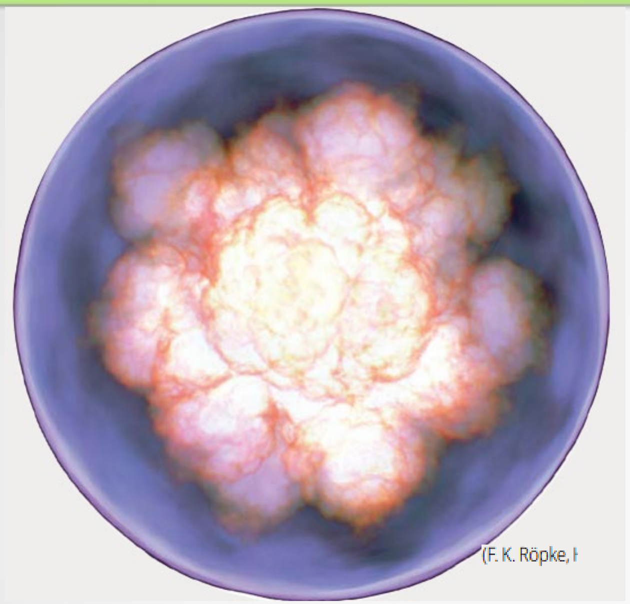
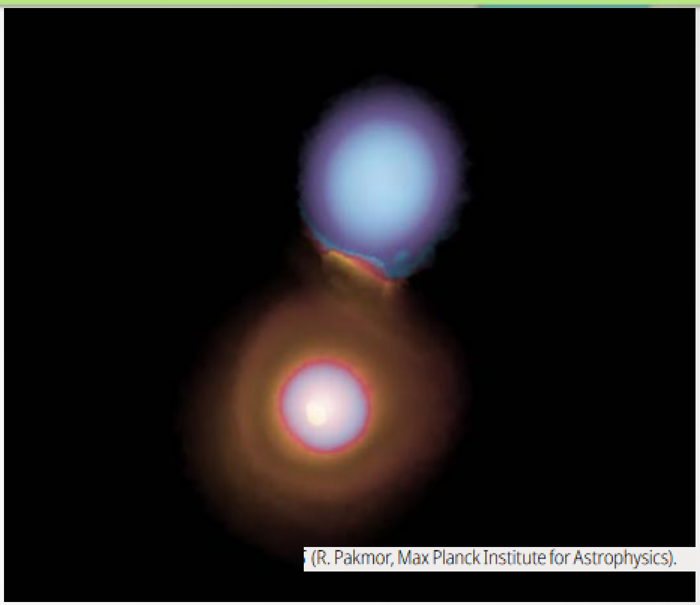
SNe Ia progenitors





Near-Chandrasekhar mass events

Deflagration of Deflagration+Detonation

H-accretor → But only ~6% of SN Ia from there (see e.g. Johansson et al. (2016))

Slow WD merger → Accretion disk formation → Final outcome depends on accretion rate and WD mass ratio (see e.g. Piersanti+2003)

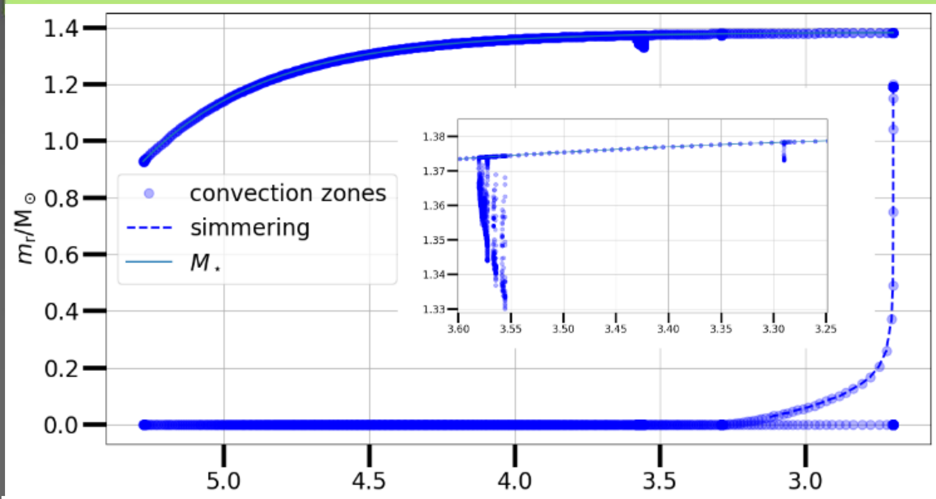
Sub-Chandrasekhar mass events

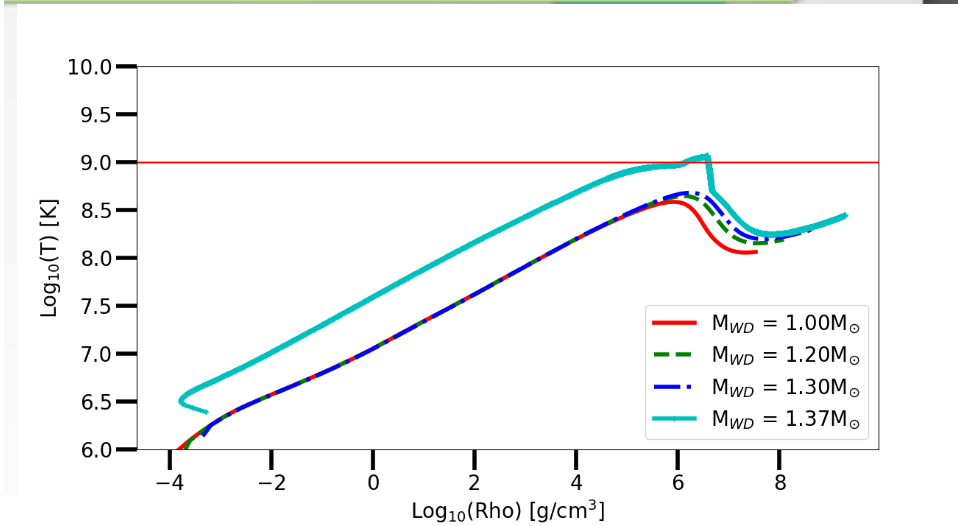
He-accretor → Double-detonation (see Fink+2010; Magee+2021)

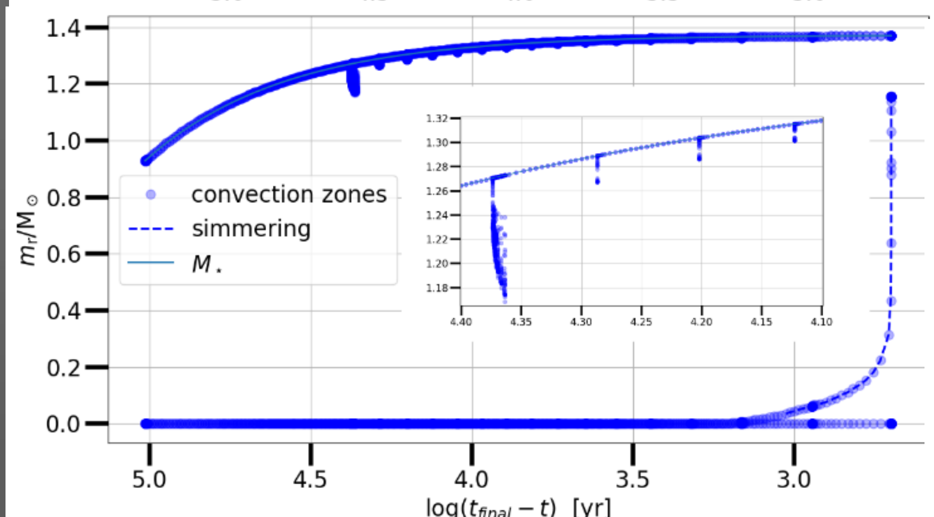
Major channel (~70%), but we still need ~30% near-Ch (Lach+2020, Collins+2022)

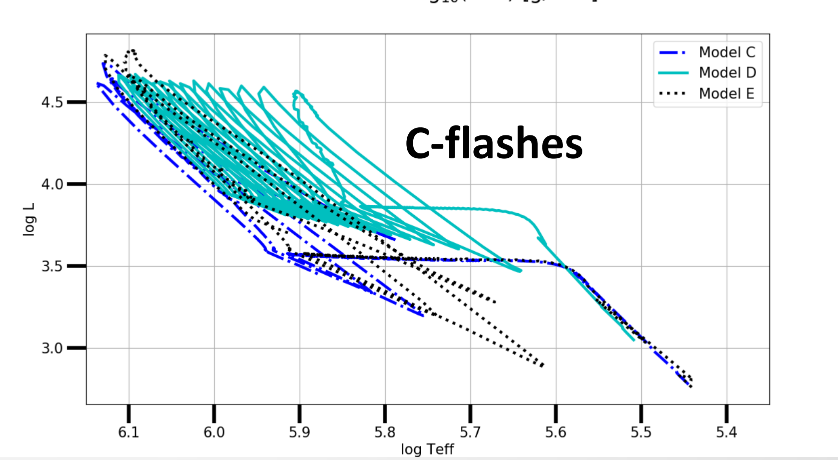
Violent merger → Prompt detonation during the merger process (if mass ratio q > ~0.8 or at least ~0.01 M_{sun} He present; see Pakmor et al. 2010, 2011, 2012, 2013)

Slow WD mergers



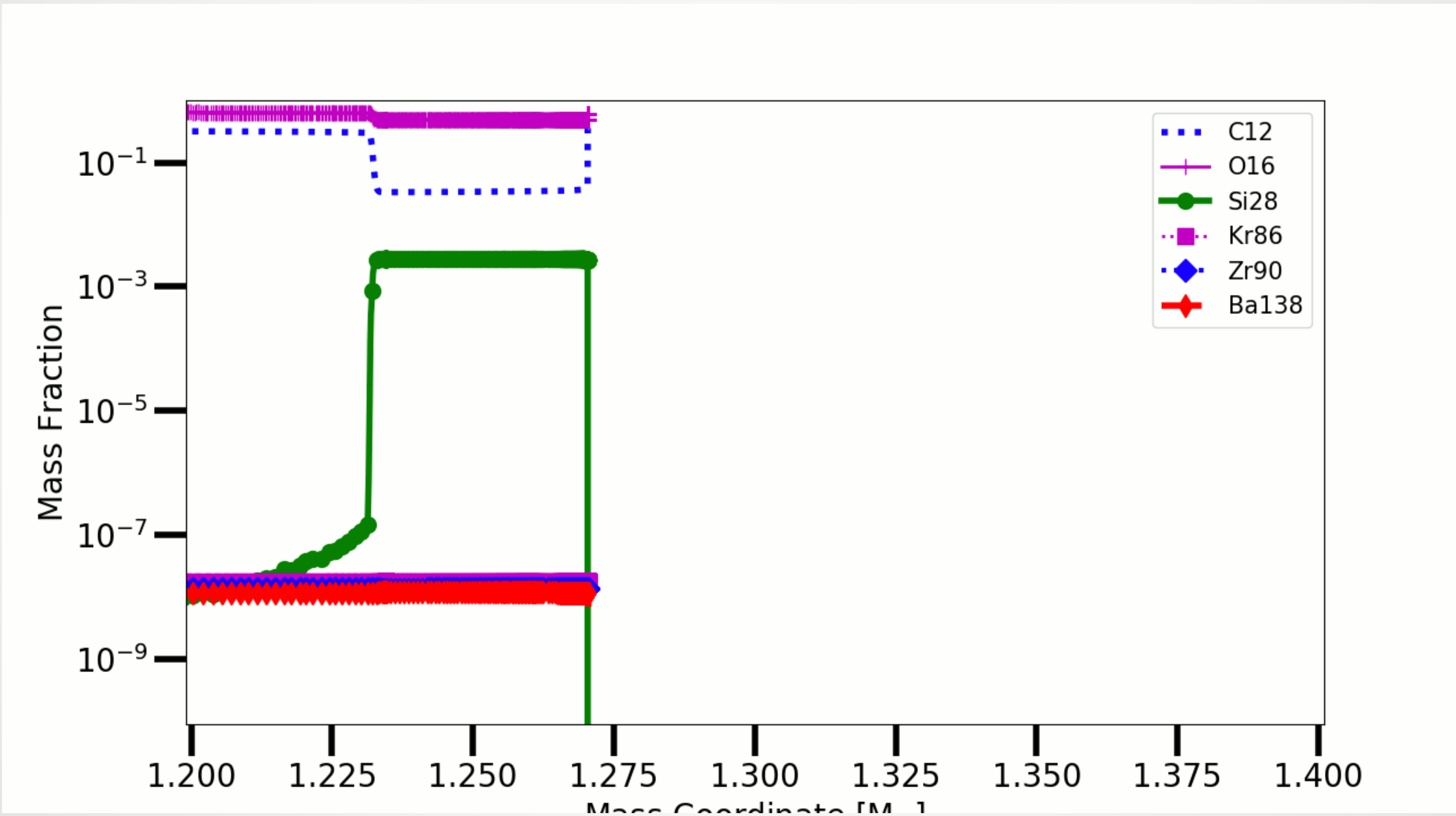






IF mass acc rate > 2 10^{-6} M_{sun}/yr… → $^{12}C(^{12}C,a)^{20}Ne$ → $^{22}Ne(a,n)^{25}Mg$

Trans-Fe element nucleosynthesis



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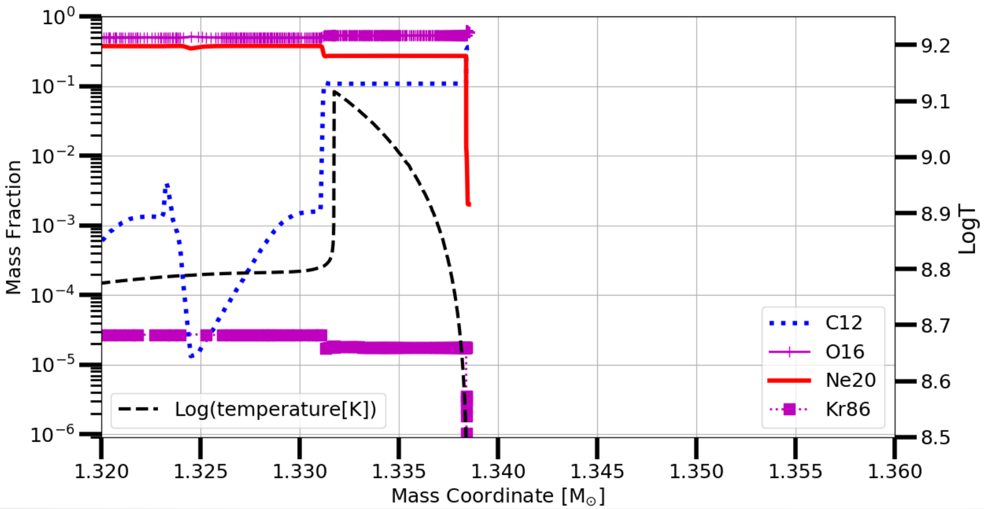
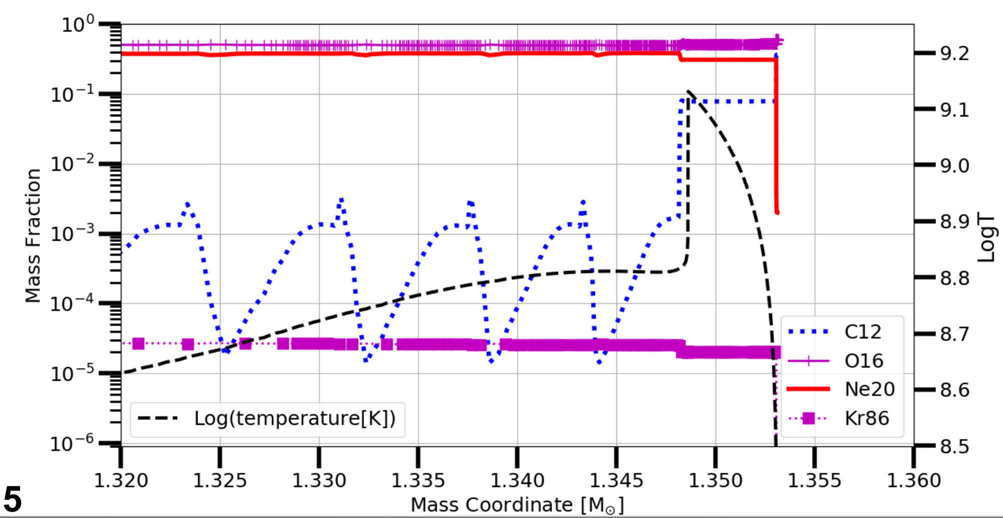
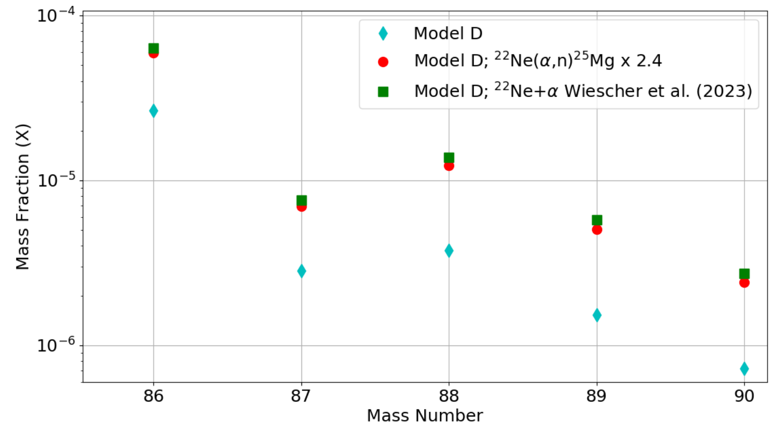
$^{12}C(^{12}C,a)\,^{20}Ne$ → $^{22}Ne(a,n)\,^{25}Mg$

Impact of the $^{22}Ne(a,n)^{25}Mg$







New direct measurement currently underway at the INFN Gran Sasso National laboratory (ERC starting grant **SHADES;** PI: **A. Best**). (See also posters <u>#143</u> by **D. Mercogliano** and <u>#84</u> by **T. Chillery**)

Explosive Yields

PRE-SUPERNOVA TRANS-FE ABUNDANCES

Isotope	Model A	Model B	Model C	Model D	Model D $^{22}Ne+\alpha$ Wiescher et al. (2023)	Model E
^{16}O	7.62e-03	7.96e-02	2.54e-01	4.95e-01	4.89e-01	3.63e-02
^{20}Ne	1.02e-07	1.87e-06	6.21e-02	3.84e-01	3.87e-01	5.88e-07
^{22}Ne	5.04e-09	8.75e-08	1.59e-04	5.60e-06	2.81e-05	2.29e-09
^{23}Na	8.65e-08	1.26e-07	3.12e-03	8.12e-03	8.01e-03	1.52e-07
^{24}Mg	1.76e-05	2.62e-04	2.22e-02	6.10e-02	6.23e-02	6.86e-05
^{25}Mg	1.11e-06	6.89e-06	5.46e-03	1.39e-02	1.34e-02	7.52e-07
^{26}Mg	4.78e-02	4.55e-02	3.04e-02	2.94e-02	2.97e-02	5.69e-02
^{27}Al	3.12e-03	1.28e-02	2.74e-02	5.00e-03	5.11e-03	5.76e-03
^{28}Si	4.43e-01	4.24e-01	2.89e-01	3.80e-03	3.86e-03	4.83e-01
^{32}S	3.96e-01	3.52e-01	2.46e-01	1.34e-06	1.38e-06	3.52e-01
^{52}Cr	3.51e-08	8.02e-08	1.23e-06	5.37e-07	3.94e-07	7.08e-08
^{53}Cr	2.20e-08	2.32e-08	3.55e-07	2.12e-07	1.54e-07	1.77e-08
^{54}Cr	5.04e-06	1.65e-06	1.61e-06	2.20e-06	1.72e-06	3.26e-06
^{55}Mn	2.37e-07	2.98e-07	2.80e-06	1.02e-06	7.89e-07	2.46e-07
^{56}Fe	2.10e-06	1.36e-05	9.74e-05	3.07e-05	2.17e-05	7.10e-06
^{57}Fe	6.92e-07	2.09e-06	2.78e-05	1.49e-05	1.02e-05	6.77e-07
^{58}Fe	3.35e-04	2.93e-04	1.10e-04	7.54e-05	5.37e-05	3.34e-04
^{60}Fe	1.47e-06	1.92e-07	3.27e-05	5.63e-05	3.96e-05	2.20e-07
^{59}Co	4.98e-07	1.51e-06	9.88e-05	1.02e-04	7.37e-05	1.05e-06
^{60}Ni	5.82e-08	7.03e-07	1.99e-05	5.73e-05	4.07e-05	5.66e-07
^{61}Ni	4.52e-08	2.45e-07	1.58e-05	1.91e-05	1.45e-05	1.25e-07
^{62}Ni	2.96e-04	4.14e-04	1.49e-04	1.00e-04	8.87e-05	4.14e-04
^{63}Ni	1.86e-06	1.10e-06	4.16e-05	7.85e-05	7.16e-05	4.42e-08
^{64}Ni	1.86e-04	3.76e-05	7.45e-05	1.22e-04	1.28e-04	7.23e-05
^{65}Cu	2.49e-07	1.96e-07	1.25e-05	2.63e-05	2.85e-05	3.65e-07
^{66}Zn	3.12e-08	2.42e-06	1.62e-05	2.69e-05	3.02e-05	2.60e-07
^{68}Zn	5.99e-07	7.48e-06	2.82e-05	4.14e-05	5.23e-05	4.87e-07
^{70}Zn	1.12e-08	2.02e-08	1.21e-06	1.27e-05	1.68e-05	2.28e-09
^{71}Ga	4.11e-10	2.71e-09	2.25e-06	6.30e-06	8.38e-06	4.69e-10
^{70}Ge	4.59e-10	9.12e-08	5.86e-06	7.01e-06	9.32e-06	5.26e-09
^{72}Ge	8.60e-07	1.98e-05	8.68e-06	6.62e-06	9.01e-06	1.99e-06
^{73}Ge	1.24e-08	1.20e-07	4.75e-06	8.36e-06	1.12e-05	3.16e-10
^{74}Ge	5.63e-06	1.91e-05	1.15e-05	1.27e-05	1.79e-05	3.67e-06
^{76}Ge	2.97e-07	1.46e-07	9.65e-06	8.25e-06	1.26e-05	5.53e-08
^{75}As	1.44e-09	1.67e-08	1.81e-06	3.03e-06	4.22e-06	7.70e-08
^{76}Se	6.96e-09	2.53e-07	8.74e-07	2.01e-06	2.96e-06	4.85e-08
^{77}Se	1.32e-09	2.07e-08	1.72e-06	8.94e-06	1.34e-05	6.28e-10
^{78}Se	3.12e-06	1.37e-05	8.77e-06	6.10e-06	1.00e-05	5.62e-06
^{79}Se	6.86e-08	1.29e-07	3.16e-06	2.95e-06	4.65e-06	2.63e-09
^{80}Se	1.05e-05	6.72e-06	1.01e-05	1.04e-05	1.74e-05	4.59e-06
^{82}Se	6.25e-07	5.96e-08	7.97e-06	6.54e-06	1.43e-05	1.82e-07
^{81}Br	1.82e-08	5.90e-08	1.53e-06	1.78e-06	2.98e-06	5.64e-07
^{82}Kr	6.83e-09	4.42e-07	6.68e-07	7.91e-07	1.38e-06	2.35e-07
^{83}Kr	2.30e-09	6.35e-08	2.05e-06	3.37e-06	5.99e-06	1.06e-08
^{84}Kr	5.37e-06	3.57e-05	1.31e-05	1.03e-05	2.00e-05	1.31e-05
^{86}Kr	2.59e-05	2.61e-05	1.90e-05	2.52e-05	6.22e-05	1.86e-05
^{85}Rb	3.71e-10	3.05e-09	6.30e-07	6.08e-06	1.21e-05	2.61e-08
^{87}Rb	3.44e-06	2.44e-06	3.32e-06	2.74e-06	7.67e-06	3.02e-06
^{88}Sr	2.27e-06	3.52e-06	3.62e-06	3.82e-06	1.40e-05	1.68e-06
^{89}Y	4.20e-10	5.03e-09	2.15e-07	1.46e-06	5.48e-06	4.79e-10
^{90}Zr	7.06e-09	3.35e-07	7.59e-08	6.65e-07	2.51e-06	2.01e-08
^{110}Cd	4.44e-09	7.05e-09	7.34e-10	1.29e-09	1.12e-08	5.59e-09
^{116}Sn	4.91e-08	4.18e-08	9.94e-10	4.80e-10	4.93e-09	5.50e-08
^{118}Sn	1.13e-08	1.44e-09	5.04e-09	9.15e-09	7.84e-08	3.43e-09
^{123}Sb	1.84e-15	1.63e-14	6.81e-10	4.51e-09	4.38e-08	6.83e-16

<u>Explosive model</u>: 1.4 M_{sun} def-to-det model (Townsley et al. 2016 T1.4),

Element	Atomic number	Ejected mass [$M_\odot$]
Ga	31	1.36e-06
Ge	32	6.03e-06
As	33	8.10e-07
Se	34	5.00e-06
Br	35	4.37e-07
Kr	36	6.66e-06
Rb	37	1.41e-06
Sr	38	1.74e-06
Y	39	3.70e-07
Zr	40	7.64e-07
Nb	41	1.63e-09
Mo	42	5.10e-08
Tc	43	5.22e-10
Ru	44	7.29e-09
Rh	45	5.20e-10
Pd	46	1.94e-08
Ag	47	1.48e-10
Cd	48	1.95e-08
In	49	1.03e-10
Sn	50	5.56e-08
Sb	51	1.41e-09
Te	52	2.94e-09
I	53	6.48e-10
Xe	54	1.20e-08
Cs	55	1.16e-09
Ba	56	1.62e-08

New observable 'smoking gun' of a Chandrasekhar explosion? (~10^{-5} M_{sun} of Sr successfully detected in the AT2017gfo kilonova, see Watson et al. 2019)

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^{55}Mn	2.37e-07	2.98e-07	2.80e-06	1.02e-06	7.89e-07	2.46e-07
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^{76}Se	6.96e-09	2.53e-07	8.74e-07	2.01e-06	2.96e-06	4.85e-08
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^{78}Se	3.12e-06	1.37e-05	8.77e-06	6.10e-06	1.00e-05	5.62e-06
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^{81}Br	1.82e-08	5.90e-08	1.53e-06	1.78e-06	2.98e-06	5.64e-07
^{82}Kr	6.83e-09	4.42e-07	6.68e-07	7.91e-07	1.38e-06	2.35e-07
^{83}Kr	2.30e-09	6.35e-08	2.05e-06	3.37e-06	5.99e-06	1.06e-08
^{84}Kr	5.37e-06	3.57e-05	1.31e-05	1.03e-05	2.00e-05	1.31e-05
^{86}Kr	2.59e-05	2.61e-05	1.90e-05	2.52e-05	6.22e-05	1.86e-05
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^{123}Sb	1.84e-15	1.63e-14	6.81e-10	4.51e-09	4.38e-08	6.83e-16

^{60}Fe increased by ~20 times compared to cases without pre-SN trans-Fe element enrichment.

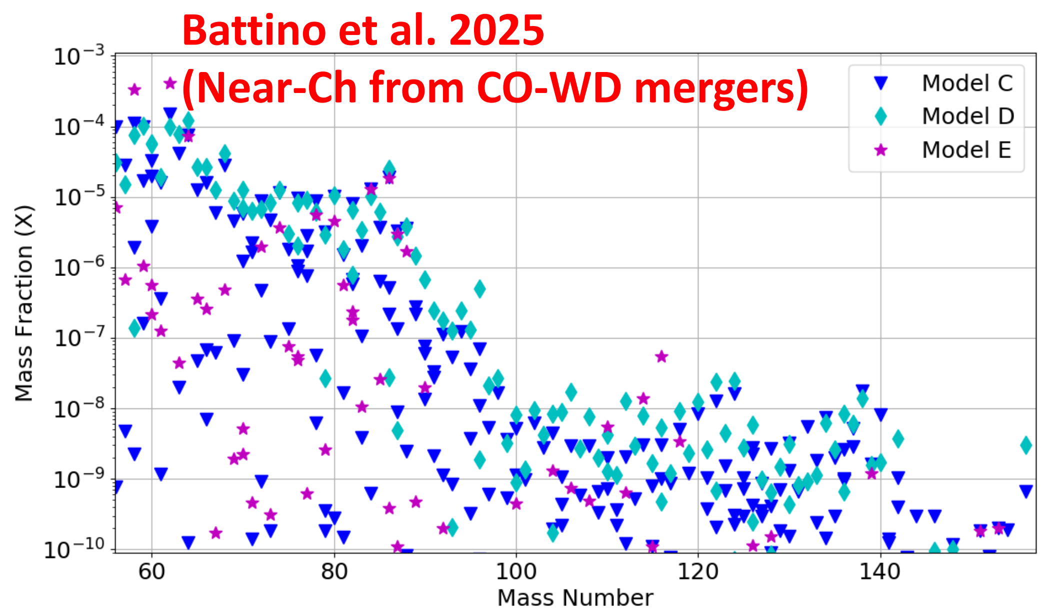
Next-generation gamma-ray telescopes will have the potential to detect a single SNR directly!

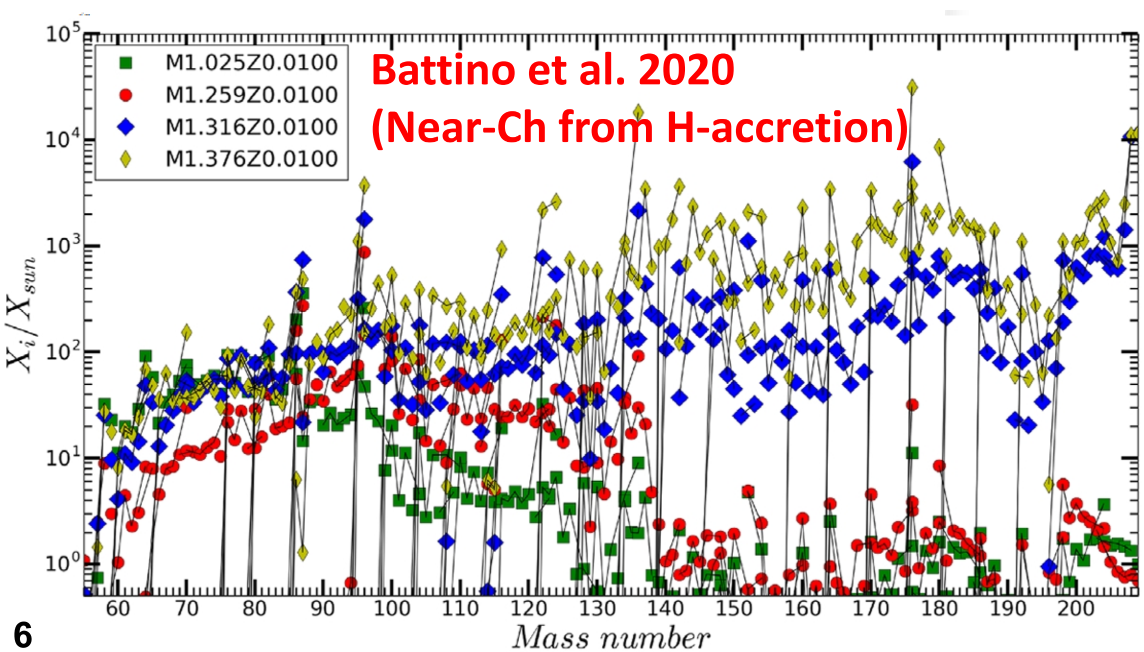
Explosive model: 1.4 M_{sun} def-to-det model (Townsley et al. 2016 T1.4),

Element	Atomic number	Ejected mass [$M_{\odot}$]
Ga	31	1.36e-06
Ge	32	6.03e-06
As	33	8.10e-07
Se	34	5.00e-06
Br	35	4.37e-07
Kr	36	6.66e-06
Rb	37	1.41e-06
Sr	38	1.74e-06
Y	39	3.70e-07
Zr	40	7.64e-07
Nb	41	1.63e-09
Mo	42	5.10e-08
Tc	43	5.22e-10
Ru	44	7.29e-09
Rh	45	5.20e-10
Pd	46	1.94e-08
Ag	47	1.48e-10
Cd	48	1.95e-08
In	49	1.03e-10
Sn	50	5.56e-08
Sb	51	1.41e-09
Te	52	2.94e-09
I	53	6.48e-10
Xe	54	1.20e-08
Cs	55	1.16e-09
Ba	56	1.62e-08

New observable 'smoking gun' of a Chandrasekhar explosion? (~10^{-5} M_{sun} of Sr successfully detected in the AT2017gfo kilonova, see Watson et al. 2019)

Explosive Yields





<u>model</u>: 1.4 M_{sun} def-to-det model et al. 2016 T1.4),

Element	Atomic number	Ejected mass [$M_\odot$]
Ga	31	1.36e-06
Ge	32	6.03e-06
As	33	8.10e-07
Se	34	5.00e-06
Br	35	4.37e-07
Kr	36	6.66e-06
Rb	37	1.41e-06
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Summary and future perspectives

- As our slowly merging CO WDs models approach the Chandrasekhar mass, C-burning ignites on the surface before it does in the center → $^{12}C(^{12}C,\alpha)^{20}Ne$ → $^{22}Ne(\alpha,n)^{25}Mg$.

- Large production of trans-Fe elements in the outermost $\sim 0.04 M_\odot$ to $\sim 0.11 M_\odot$. Something similar happens also in the case of in near-Ch WD from H-accreting systems **(see Battino+2020)**.

- Kr, Rb and Sr overproduced by up to ~1000 times compared to solar, Ga, Ge, Se, Kr, Rb, and Sr are all ejected in high amounts ($>10^{-6} M_\odot$) during the explosion.

- **A new observable 'smoking gun' of a Chandrasekhar explosion?** It's highly possible trans-Fe elements from SNIa can **only** be produced by near-Chandrasekhar events → **New way to constrain the progenitors?** (Synthetic spectra from radiative transfer needed)

- **Can we see this?** Great deep and all-sky surveys are about to start! (LSST, 4MOST-TiDES)

- ^{60}Fe increased by a factor of ~ 20 compared to what is obtained from models without the inclusion of pre-SN trans-Fe element enrichment → Potential good case for next-generation gamma-ray telescopes

Summary and future perspectives

- As our slowly merging CO WDs models approach the Chandrasekhar mass, C-burning ignites on the surface before it does in the center → $^{12}C(^{12}C,\alpha)^{20}Ne$ → $^{22}Ne(\alpha,n)^{25}Mg$.

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Trans-Fe elements from Type Ia Supernovae

I. Heavy element nucleosynthesis during the formation of near-Chandrasekhar white dwarfs

U. Battino,[1,2,3] J. D. Keegans,[4,3] M. Allen,[4,5] F. K. Röpke,[6,7,8] F. Herwig,[9,10,3] A. Best,[1,11] R. Hirschi,[12,3] L. Piersanti,[2,13] O. Straniero,[2,13] S. A. Sim,[14] C. Travaglio,[15] and P. A. Denissenkov[9,10,3]

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Full results in Battino et al. 2025 (Submitted to A&A)


Grazie!
Thank you!!

C-burning flame propagation