A Three-dimensional core-collapse supernova model resembling Cassiopeia A

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SNR II : an odyssey in space after stellar death, 5 Jun 2019

Ingredients in CCSN models and observables

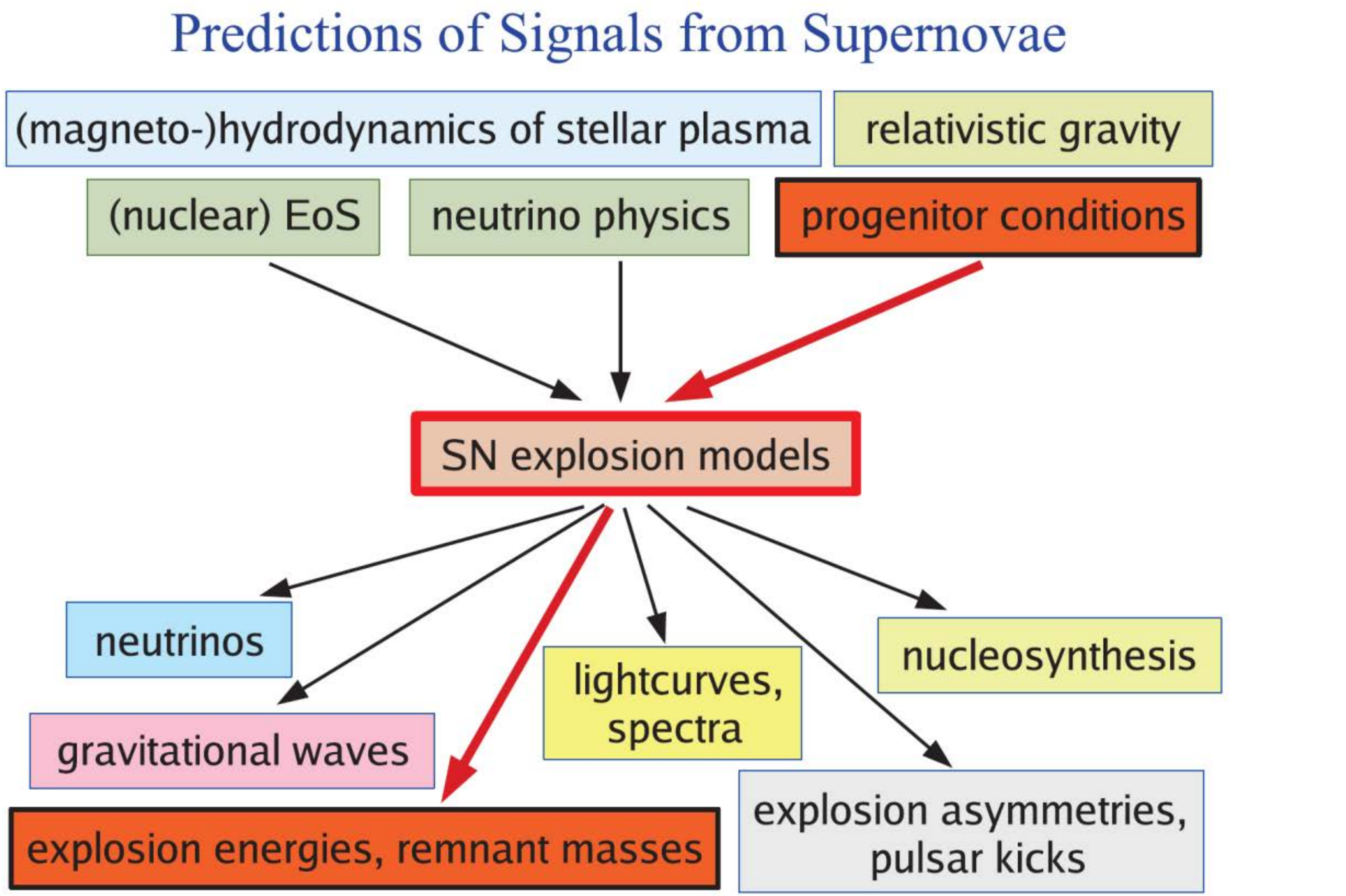
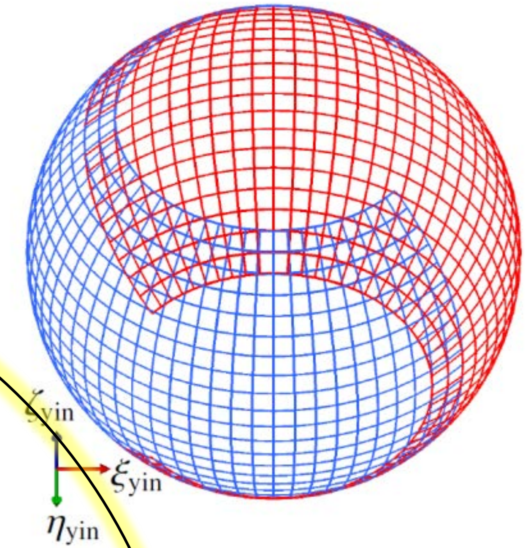


Figure from Janka et al. (2012)

Numerics in parametrized 3D setup



3D Newtonian self-gravity

monopole GR correction

tabulated EOS by Janka & Müller (1996)

4 nuclear species in NSE (n, p, ^{4}He, ^{54}Mn)

14 species (^{4}He- ^{56}Ni+X) alpha-reactions network

PROMETHEUS-HotB

ray-by-ray grey transport

L_ν

contracting inner grid

PNS

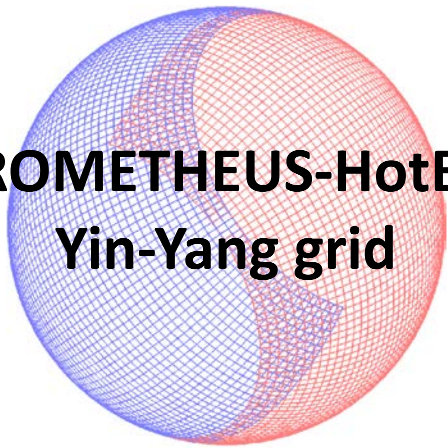
1.1 $M_\odot$

random perturbation of 0.1% amplitude

~60000 cpu hr /run

State-of-the-art long-time simulations

PROMETHEUS-HotB



Stellar evolution model

Thomas Ertl

1D

core-collapse and bounce

3D

Explosion >>> 1.3 s post bounce

1.25 day after explosions

>10 years after explosions

1D

Michael Gabler (paper in prep.)

Light curves calculations

Victor Utrobin
Sasha Kozyreva

X-ray, Gamma-ray, Etc. (e.g. Dennis Alp, Anders Jerkstrand)

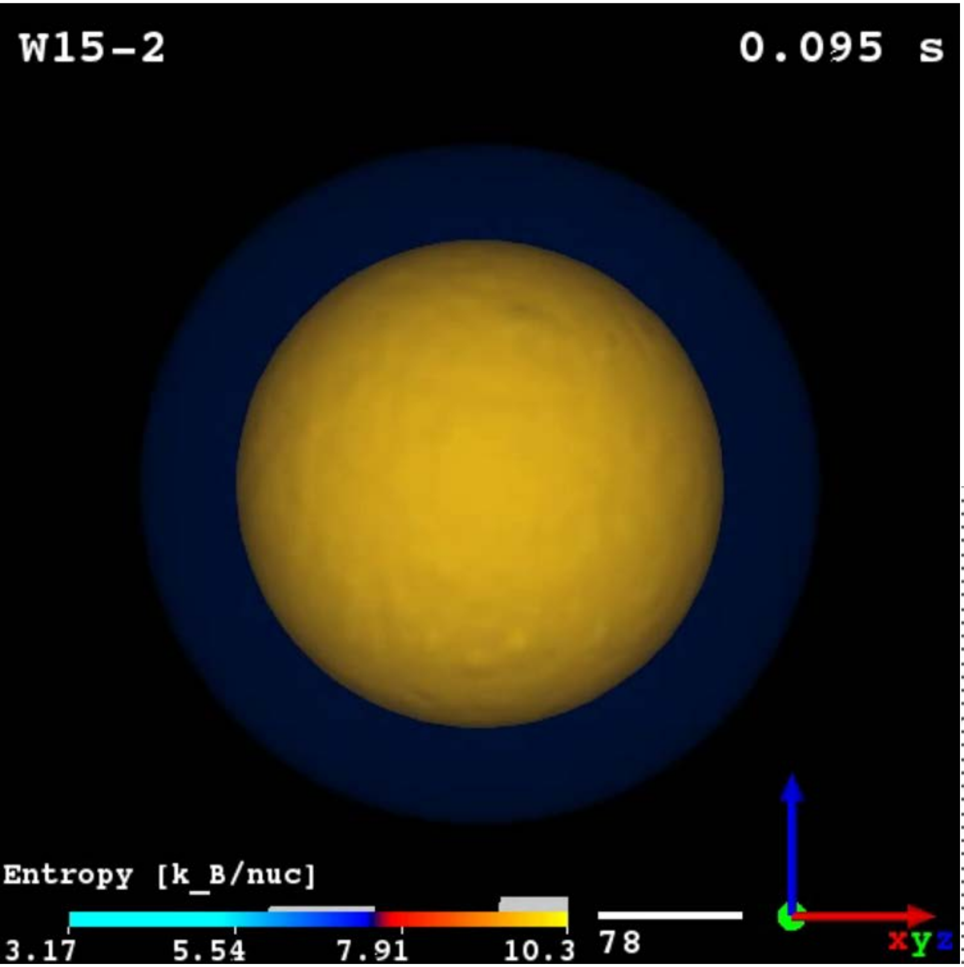
Progenitor models considered

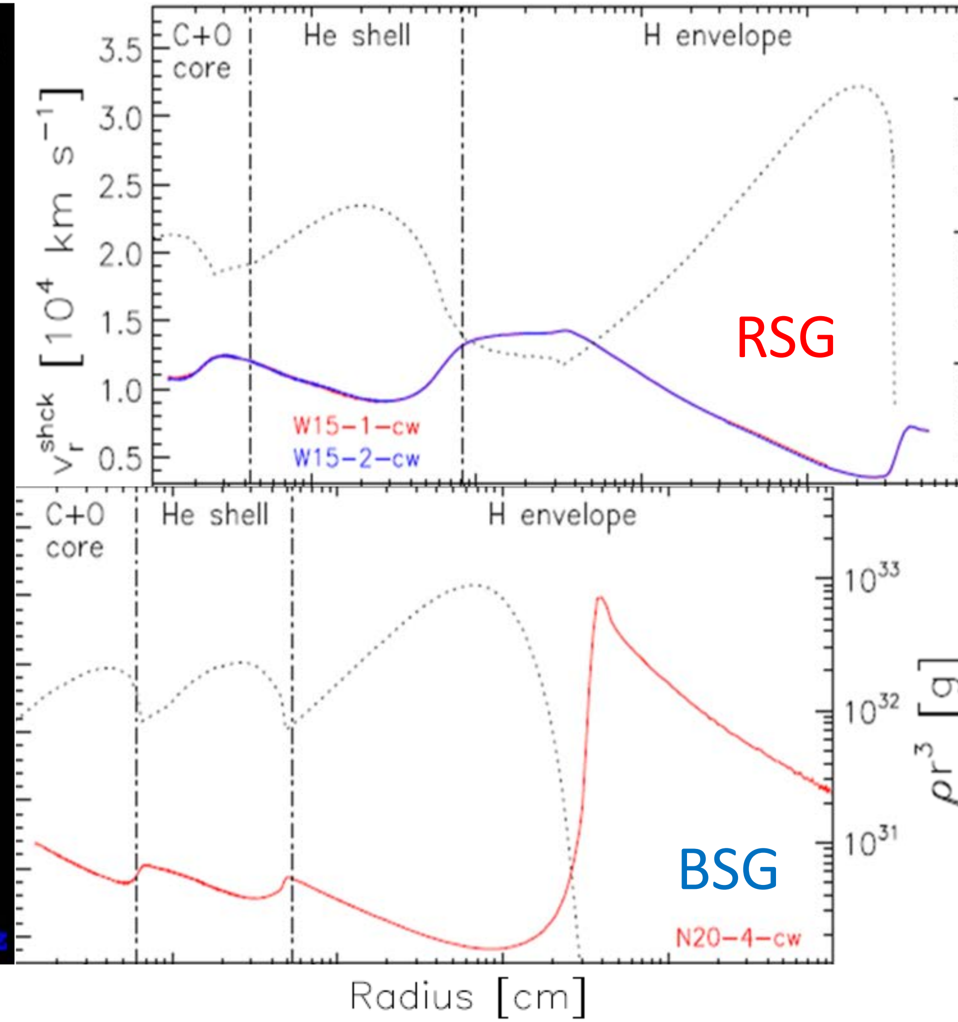
In 9 years , (>?)71 explosion models in 3D

Progenitor model	M_{pSN} [$M_\odot$]	M_{CO} [$M_\odot$]	M_{He} [$M_\odot$]	$\xi_{1.5}$	$\xi_{1.75}$	$\xi_{2.00}$
W15	15.08	2.47	4.34	0.53	0.28	0.19
L15	14.85	2.43	4.35	0.66	0.40	0.24
N20	16.27	3.77	6.00	0.91	0.36	0.19
B15[a]	15.01	1.68	4.04	0.21	0.04	0.03
W18	16.92	3.06	7.39	0.78	0.26	0.16
W20	19.38	2.33	5.78	1.08	0.35	0.18
W16	15.36	2.57	6.55	1.16	0.53	0.26
W18r	17.09	2.67	6.65	0.51	0.18	0.12
W18x	17.56	2.12	5.12	1.19	0.38	0.16
M15-7b[†b]	21.06	2.48	2.90	0.94	0.50	0.25
M15-8b[†b]	22.05	2.50	2.95	0.58	0.21	0.13
M16-4a[†b]	19.00	3.02	4.11	1.65	0.57	0.30
M17-7a[†b]	22.82	3.29	4.25	1.70	0.63	0.34
M15-7b	21.06	2.48	2.90	0.82	0.43	0.23
M15-8b	22.05	2.50	2.95	0.56	0.20	0.13
M16-4a	19.00	3.02	4.11	1.69	0.57	0.31
M16-7b	21.98	2.81	3.42	1.09	0.30	0.18
M17-7a	22.82	3.29	4.25	1.68	0.56	0.30
M17-8a	23.82	3.29	4.24	2.12	1.00	0.48

Explosion dynamics

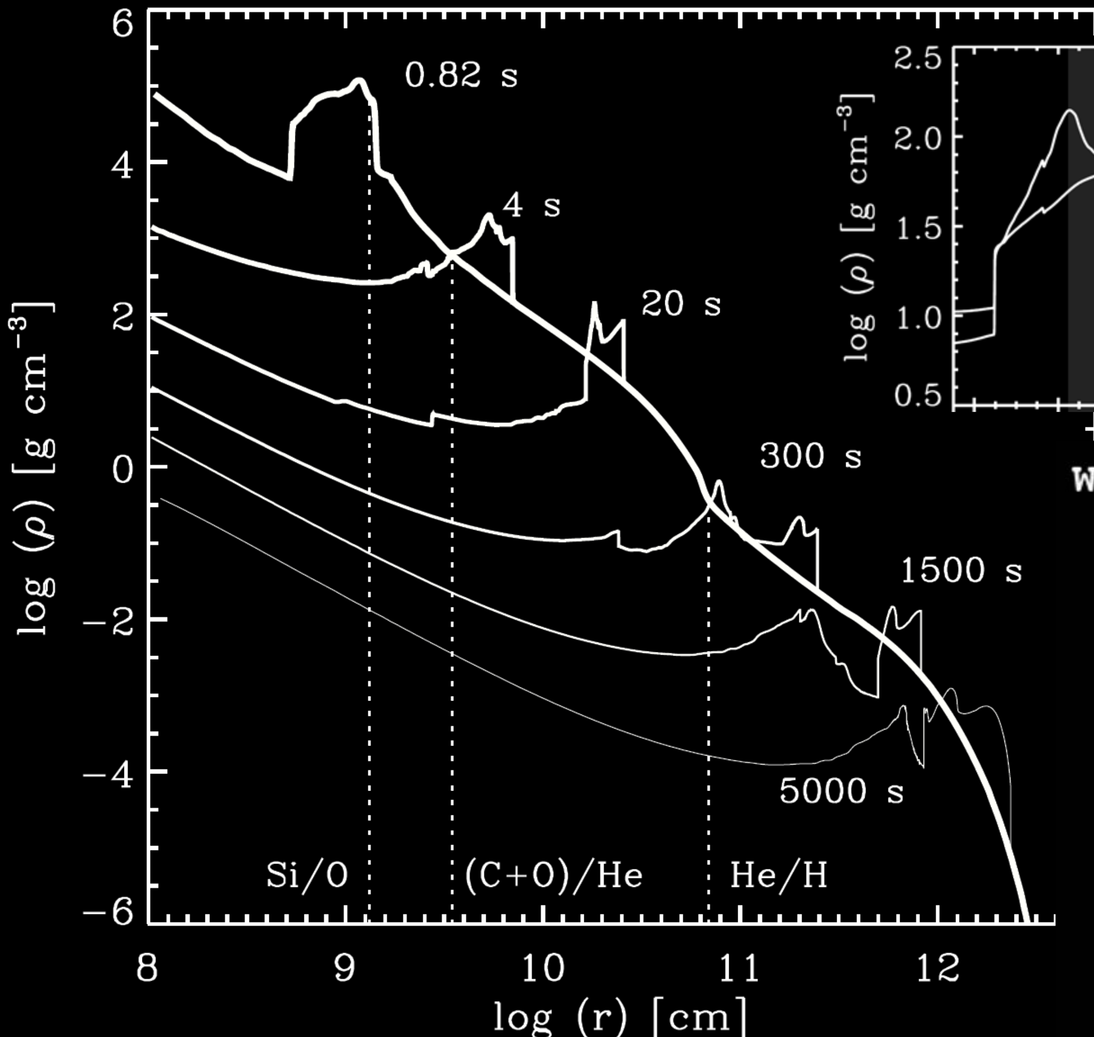
shock propagates according to blast wave solution (Sedov, 1959)

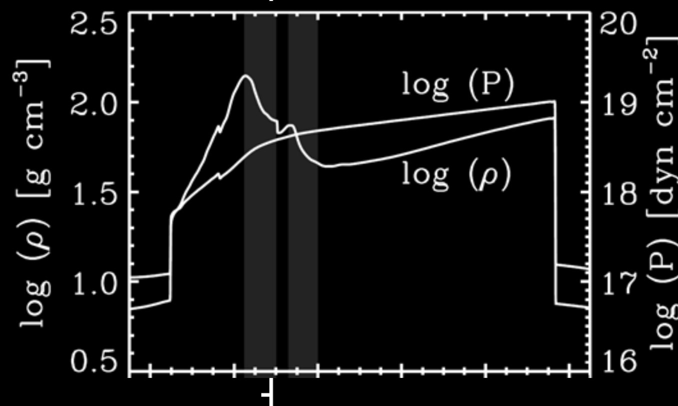


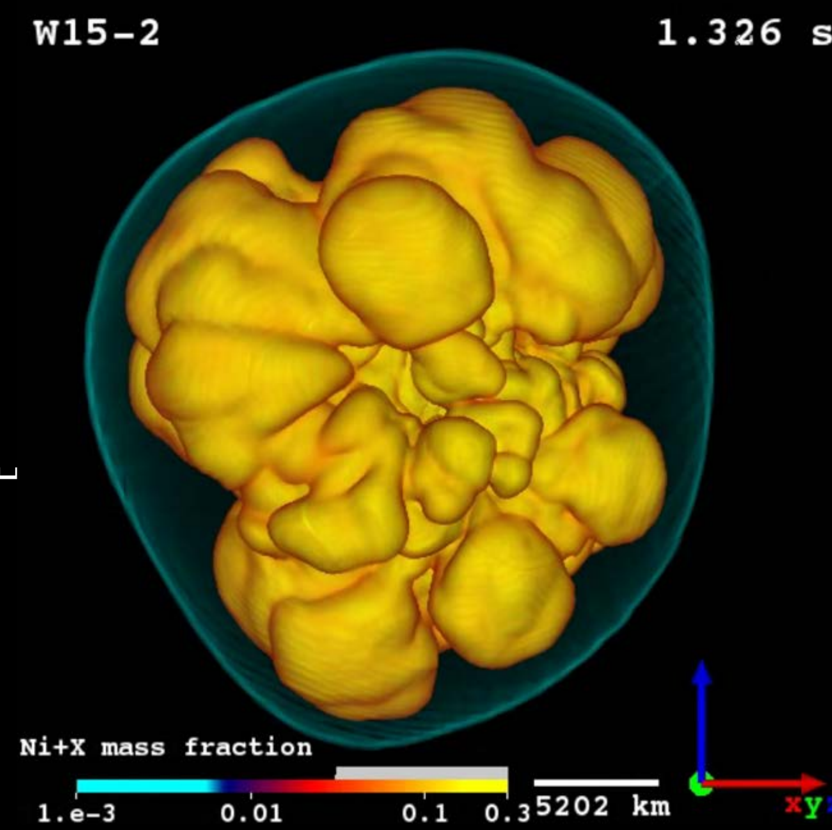


accelerates when ρr^3 decreases, and vice versa

Rayleigh-Taylor instabilities induce mixing

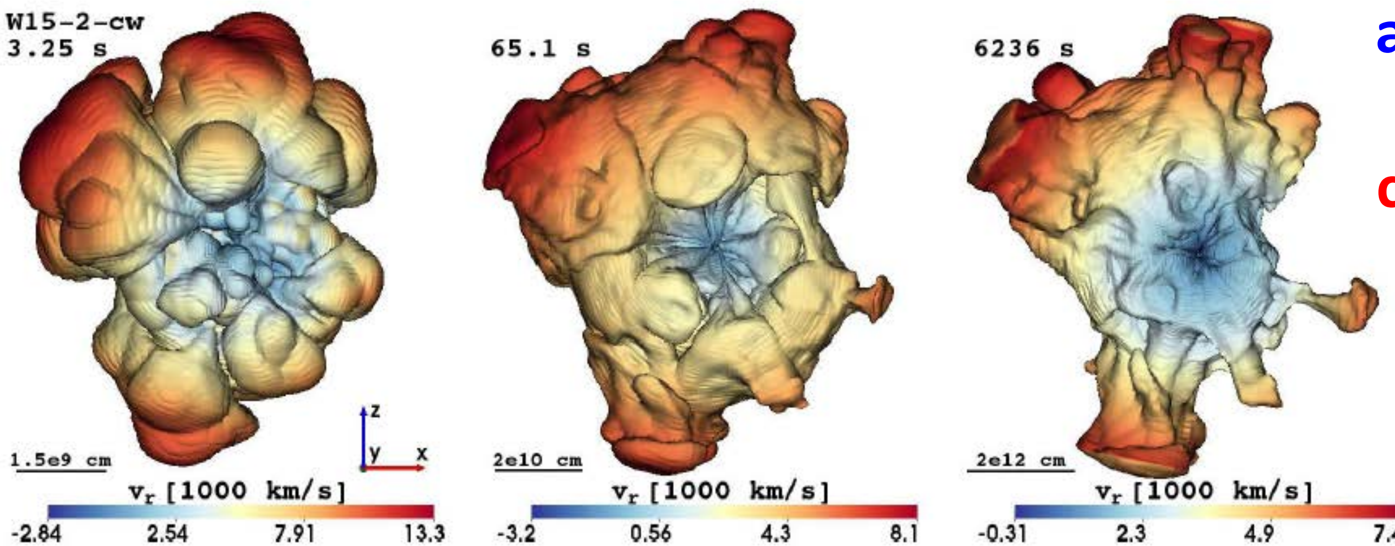






Kifonidis+ 2003

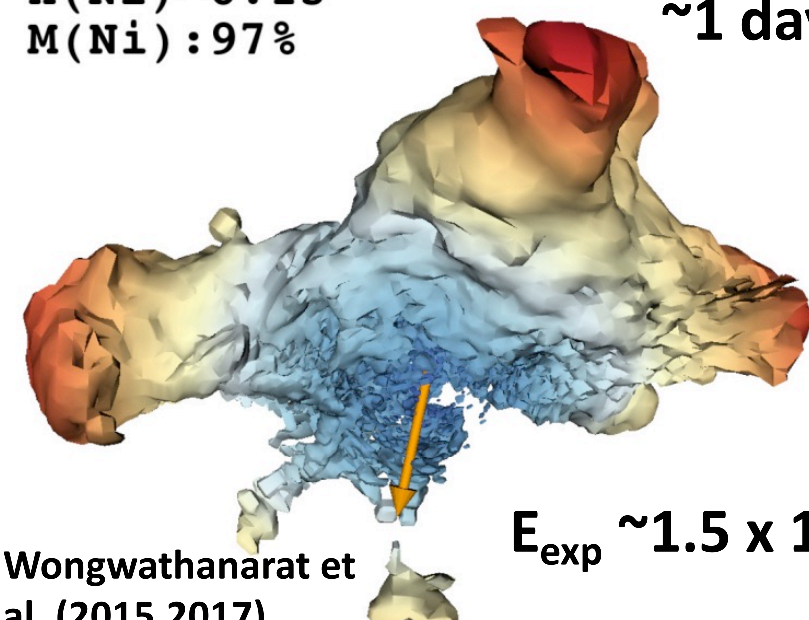
W15-IIb: explosion of H-stripped star



Our ejecta asymmetries came from chaotic (not controlled) growth of hydrodynamic instabilities

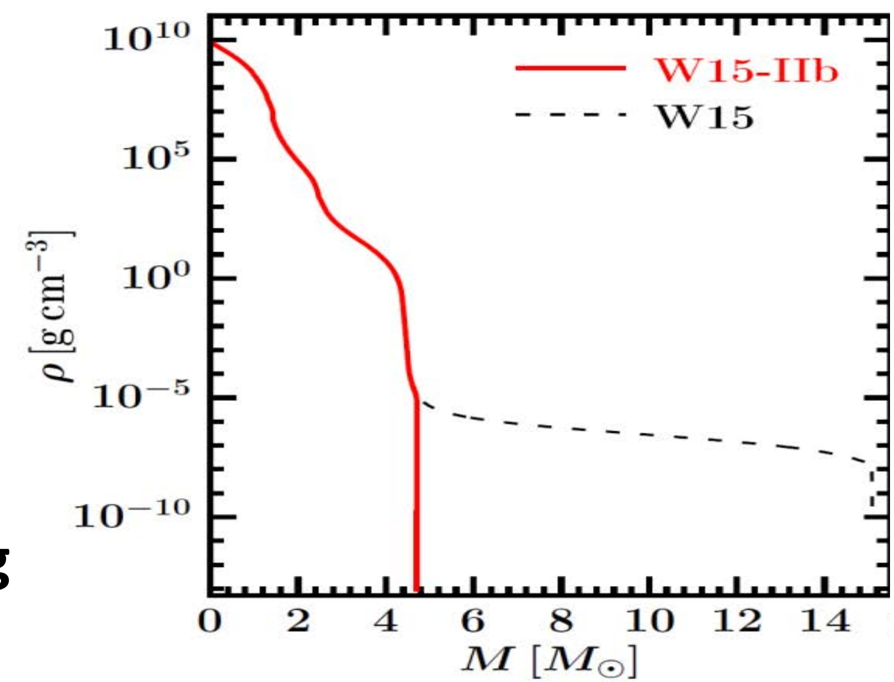
X(Ni)=0.13
M(Ni):97%

~1 day

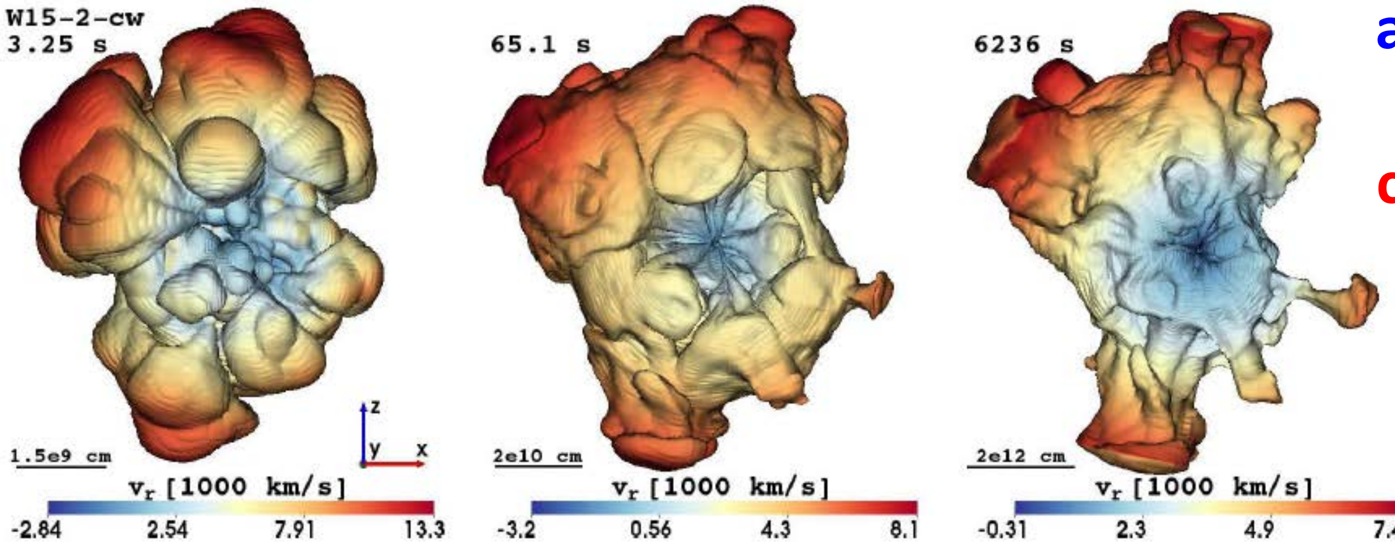


E_{exp} ~1.5 x 10^{51} erg

Wongwathanarat et al. (2015,2017)



W15-IIb: explosion of H-stripped star



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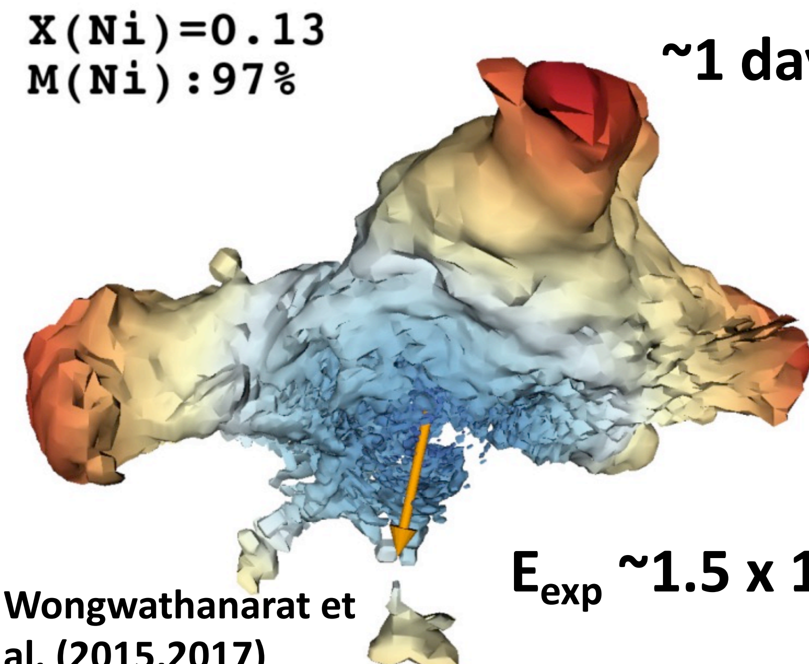
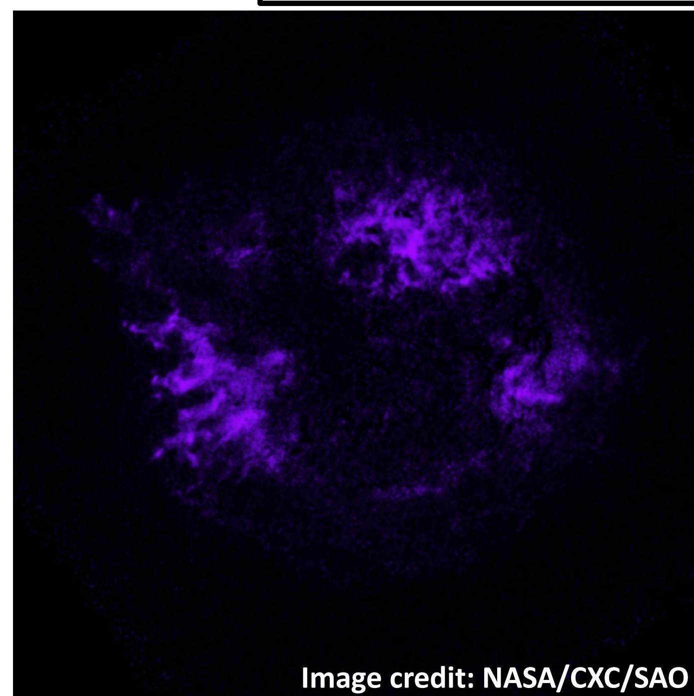


~1 day

E_{exp} ~1.5 x 10^{51} erg

Wongwathanarat et al. (2015,2017)

Iron in Cas A



W15-IIb

Interactive 3D figure for ^{44}Ti and ^{56}Ni distribution

Our model

https://wwwmpa.mpa-garching.mpg.de/mpa/institute/news_archives/news1706_thj/ti.html
https://wwwmpa.mpa-garching.mpg.de/mpa/institute/news_archives/news1706_thj/ni.html

Smithsonian 3D

https://3d.si.edu/model/fullscreen/p1b-1474716020541-1478115220819-0

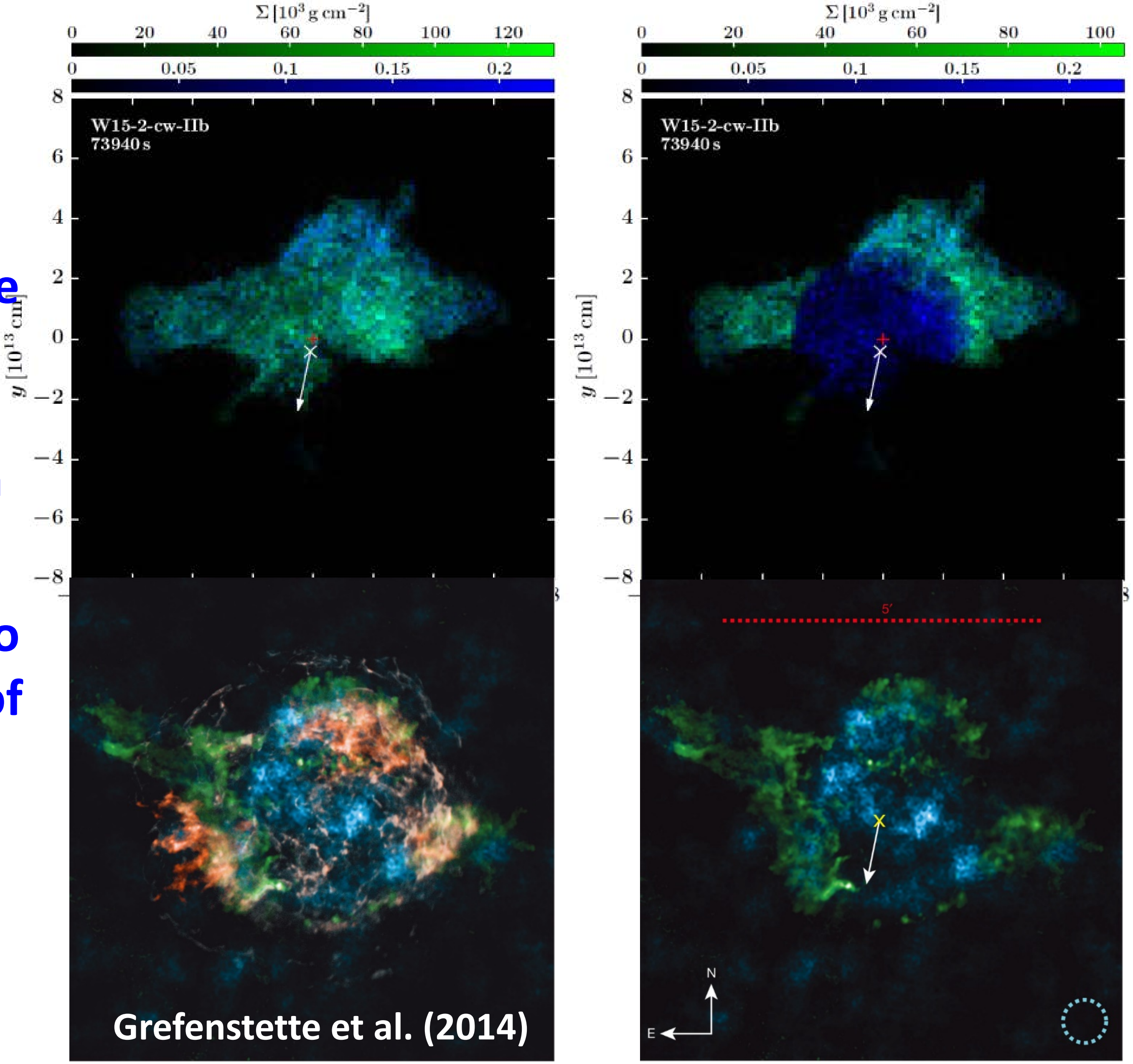
Type IIb model

Simulation

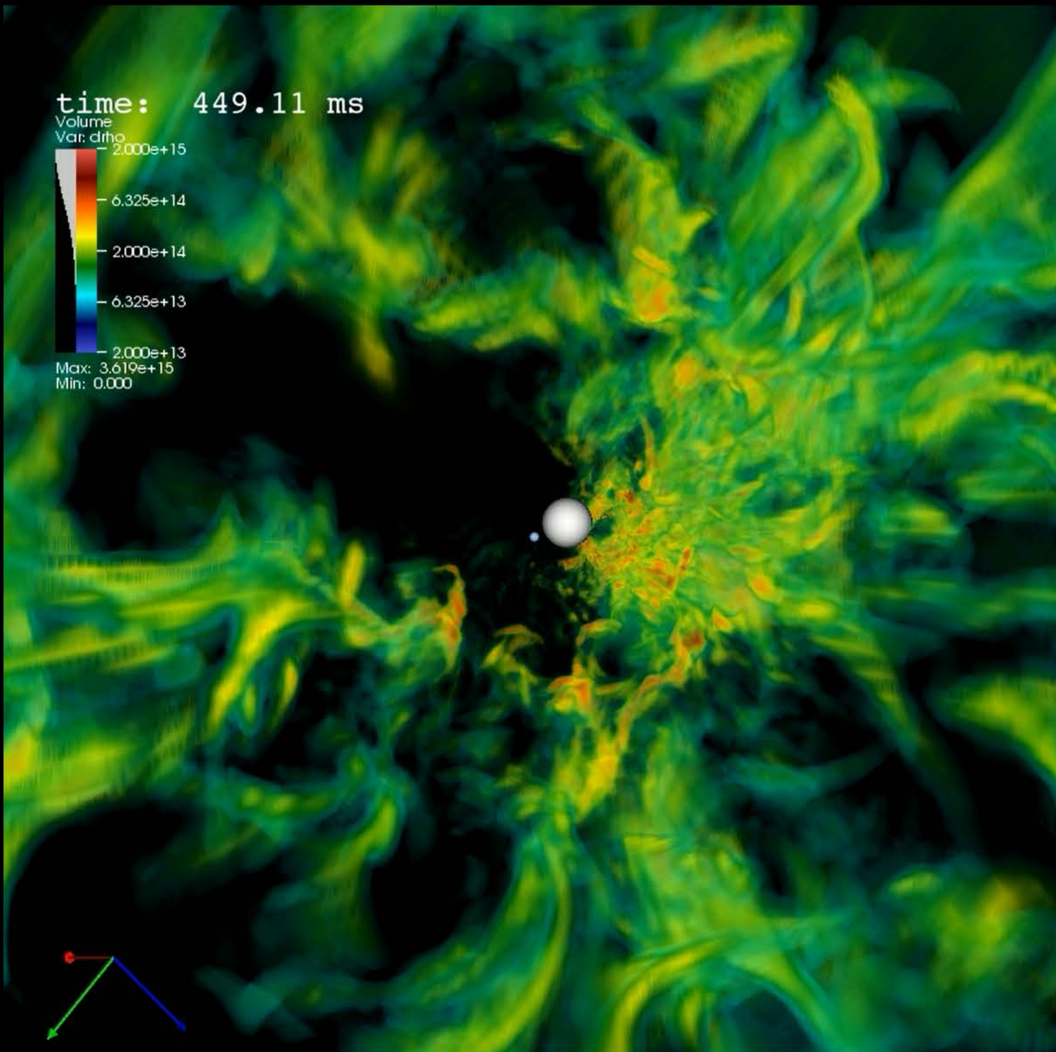
Similarities in orientation of three large Fe plumes in our model and observations from Cas A

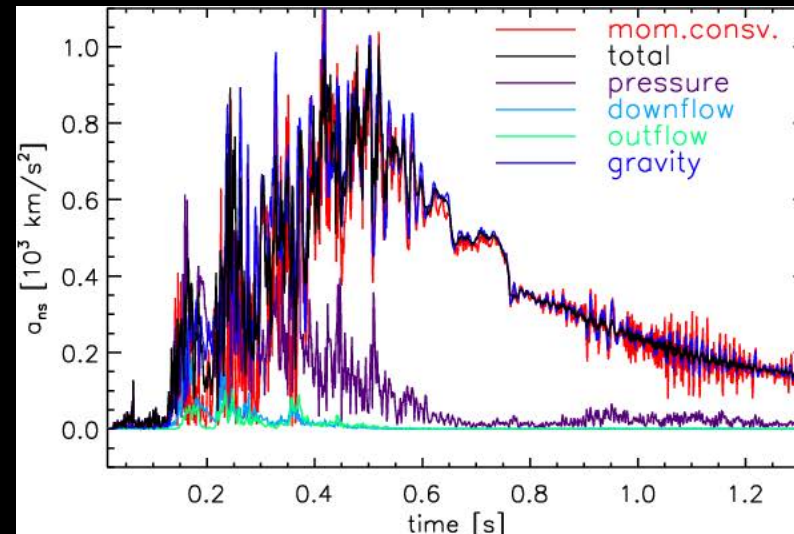
More Fe opposite to NS kick as a result of gravitational tug boat mechanism

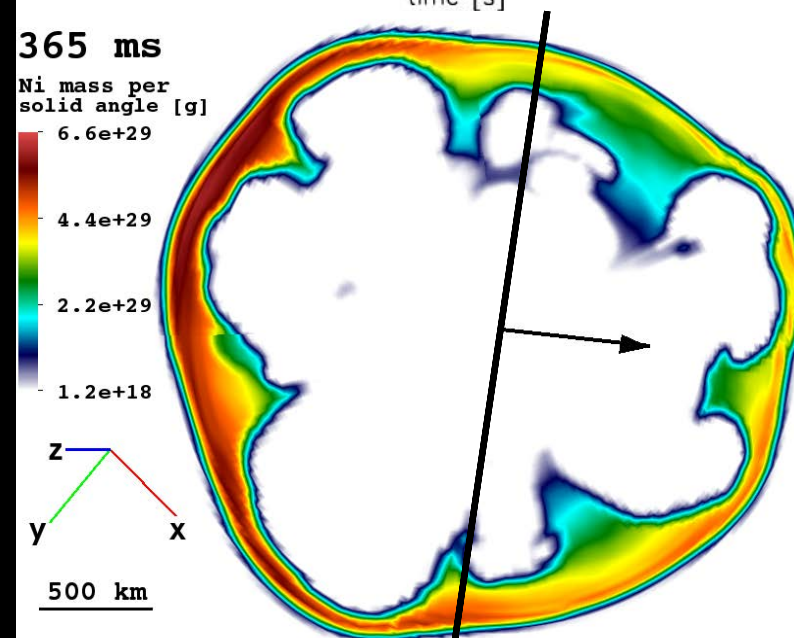
NuSTAR observation



Neutron star kicks by gravitational tug boat mechanism







Hemispheric asymmetries of heavy and intermediate mass elements

Wongwathanarat et al. (2013)

Spins and kicks

Wongwathanarat+ (2013)

Model	M_{ns} [$M_\odot$]	t_{exp} [ms]	E_{exp} [B]	v_{ns} [km s^{-1}]	α_{sk} [°]	T_{spin} [ms]
W15-1	1.37	246	1.12	331	117	652
W15-2	1.37	248	1.13	405	58	632
W15-3	1.36	250	1.11	267	105	864
W15-4	1.38	272	0.94	262	43	785
W15-5-lr	1.41	289	0.83	373	28	625
W15-6	1.39	272	0.90	437	127	1028
W15-7	1.37	258	1.07	215	48	2189
W15-8	1.41	289	0.72	336	104	235
L15-1	1.58	422	1.13	161	148	604
L15-2	1.51	382	1.74	78	62	1041
L15-3	1.62	478	0.84	31	123	750
L15-4-lr	1.64	502	0.75	199	93	846
L15-5	1.66	516	0.62	267	65	695
N20-1-lr	1.40	311	1.93	157	122	190
N20-2	1.28	276	3.12	101	43	127
N20-3	1.38	299	1.98	125	54	225
N20-4	1.45	334	1.35	98	45	512
B15-1	1.24	164	1.25	92	155	866
B15-2	1.24	162	1.25	143	162	7753
B15-3	1.26	175	1.04	85	148	2050

Wongwathanarat+ (in prep.)

Model
W15-1-cw
W15-2-cw
W15-6-cw
L15-1-cw
L15-2-cw
L15-3-pw
L15-5-cw
L15-5-pw
N20-4-cw
B15-1-cw
B15-1-pw
B15-3-pw
W18-pw
W20-pw
W16-1-pw
W16-2-pw
W16-3-pw
W16-4-pw
W18r-1-pw
W18r-2-pw
W18r-3-pw
W18r-4-pw
W18x-1-pw
W18x-2-pw
M15-7b†-3-pw
M15-7b†-4-pw
M15-8b†-2-pw
M15-8b†-3-pw
M16-4a†-1-pw
M16-4a†-2-pw
M16-4a†-3-pw
M17-7a†-2-pw
M17-7a†-3-pw
M15-7b-1-pw
M15-7b-2-pw
M15-7b-3-pw
M15-8b-1-pw
M15-8b-2-pw
M16-4a-1-pw
M16-4a-2-pw
M16-7b-1-pw
M16-7b-2-pw
M17-7a-1-pw
M17-7a-1-pw
M17-8a-3-pw
M17-8a-4-pw

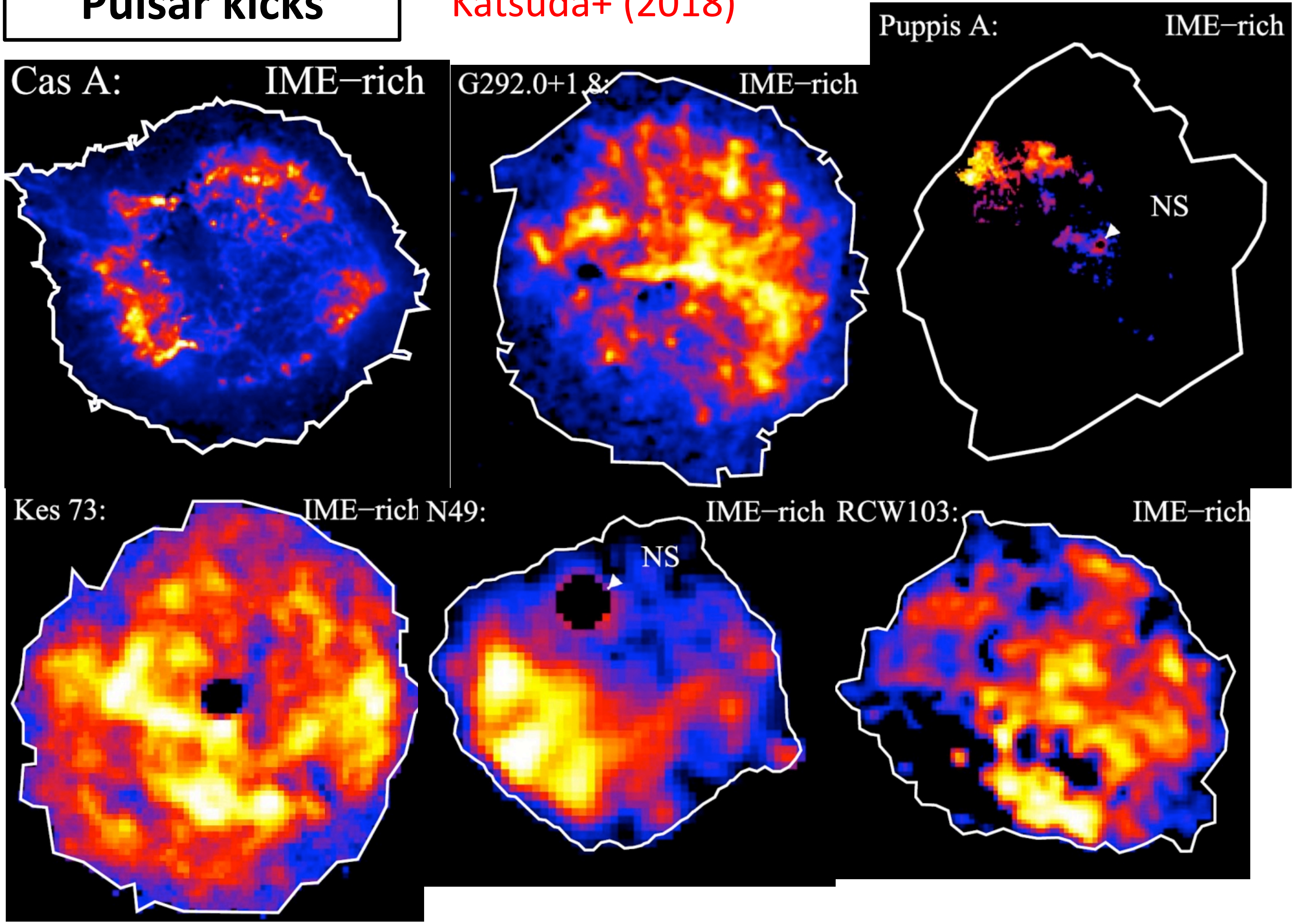
Kicks ~ several hundreds km/s

Spins ~100 ms – 7 s

No spin-kick alignment

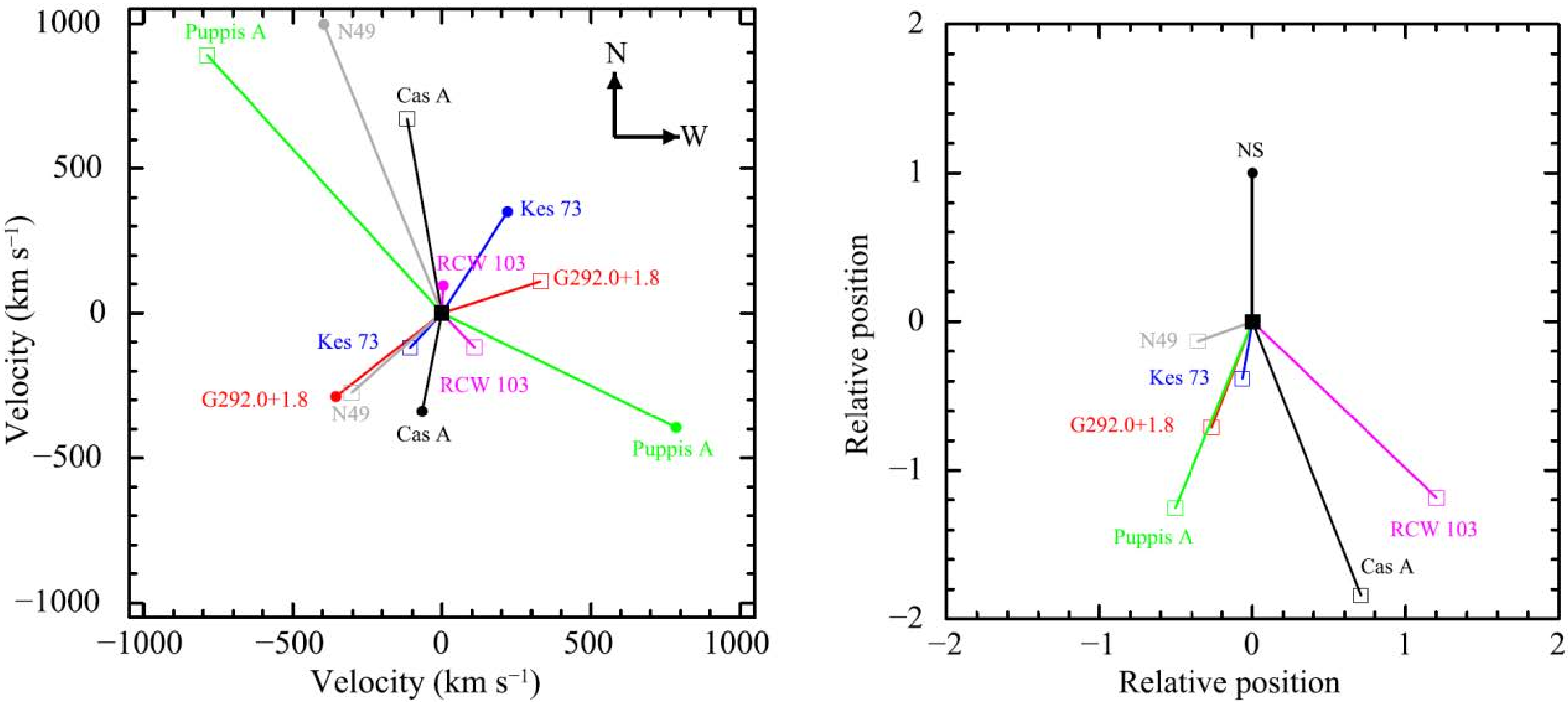
Pulsar kicks

Katsuda+ (2018)



Pulsar kicks

Katsuda+ (2018)



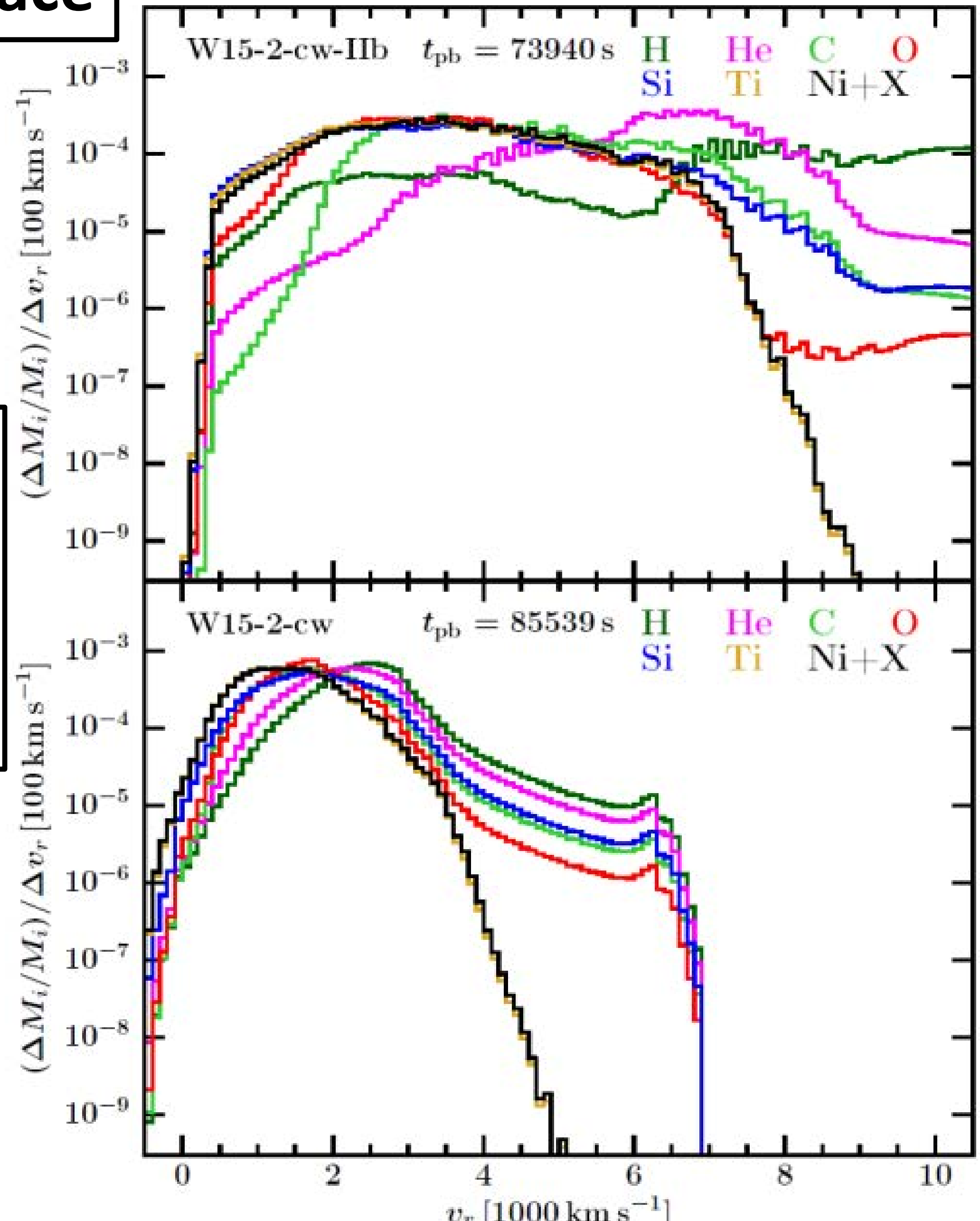
- **IME ejecta ejected preferentially opposite to the NS kick direction**
- **Strong support for hydrodynamic kick mechanism**
- **See also talk by Holland-Ashford on Friday**

Distribution in velocity space

W15-IIb

Without strong reverse shock from He/H interface heavy elements retain high velocities

W15-2

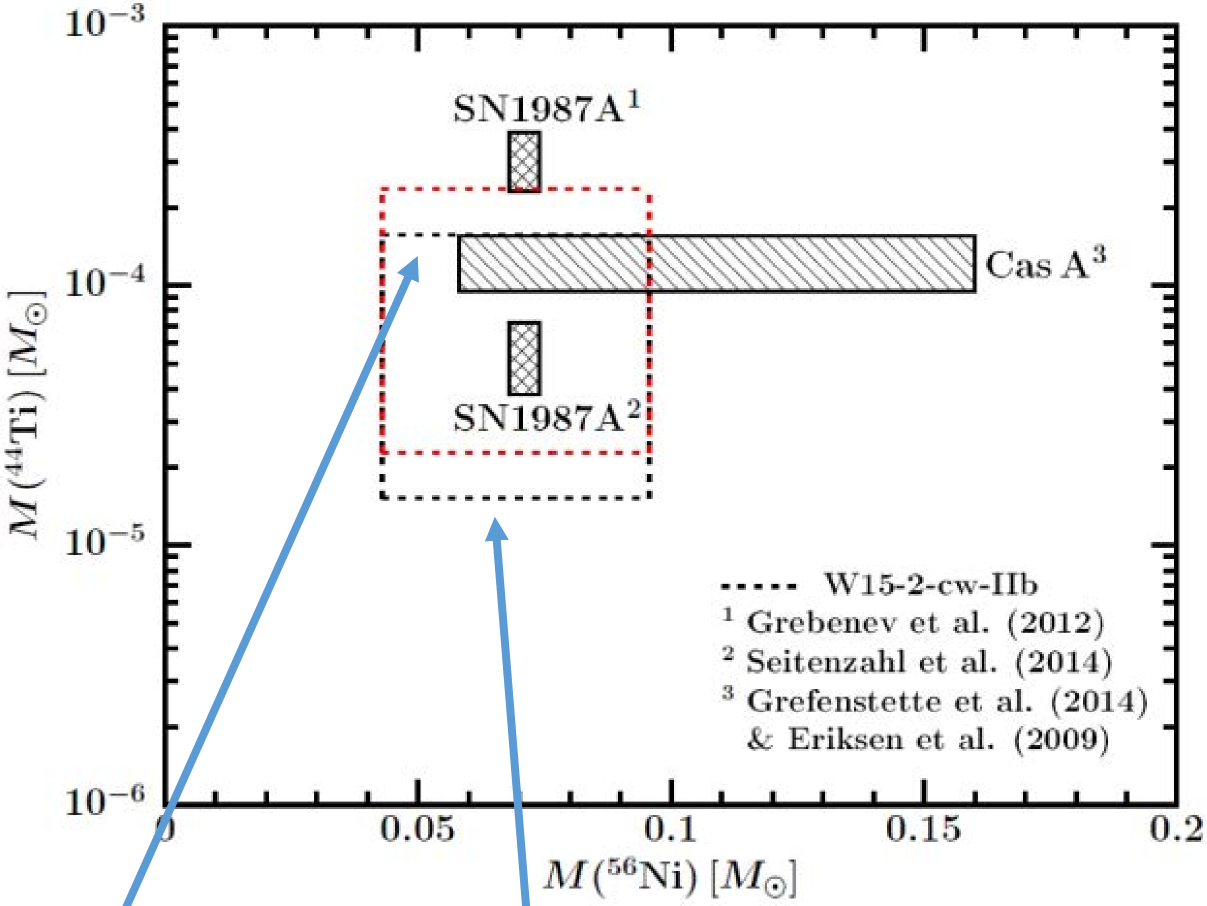


Type IIb model

Our model can synthesize 56Ni and 44Ti roughly in the ballpark of observational values, without having to assume rapid rotation or jet-driven explosion

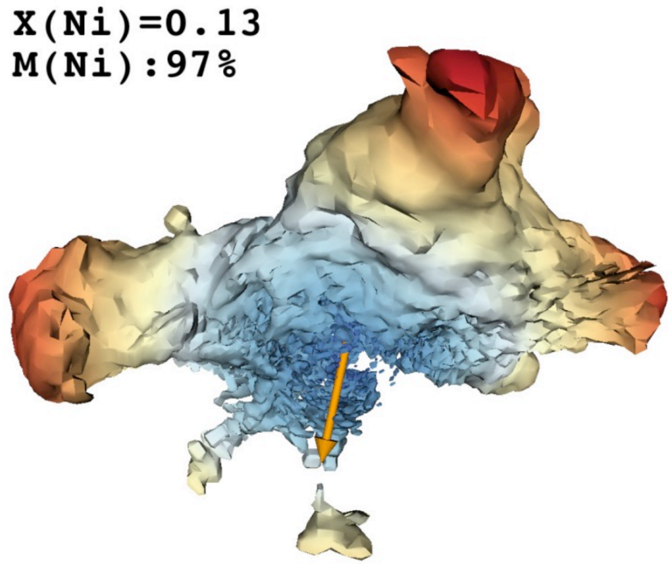
BUT !!, subject to Ye uncertainties in SN ejecta which still cannot be determined accurately

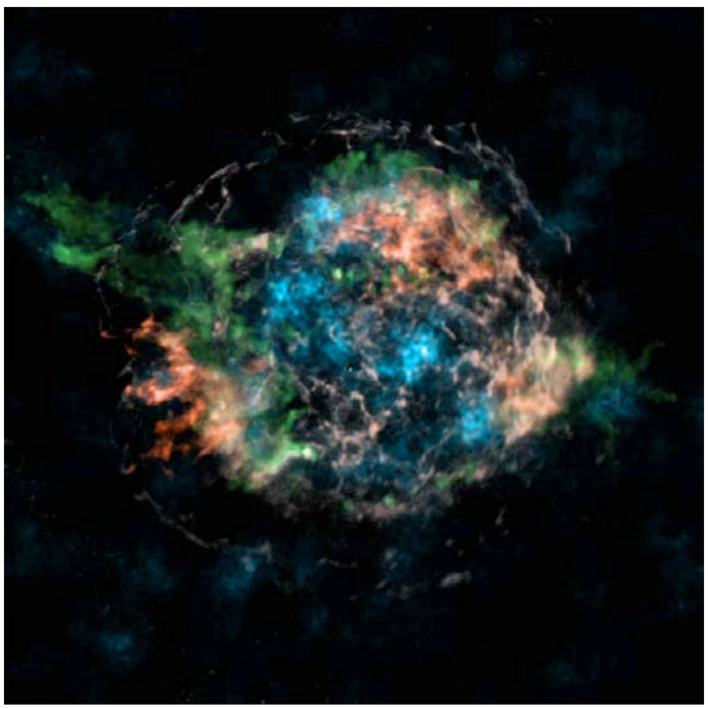
Major contribution from alpha-rich freeze-out in neutrino-processed high-entropy ejecta



Model	$M(^{44}Ti)\ [M_\odot]$	$M(^{56}Ni)\ [M_\odot]$
W15-2-cw-IIb	1.57×10^{-4}	9.57×10^{-2}
W15-2-cw-IIb-shock	8.66×10^{-6}	4.20×10^{-2}
W15-2-cw-IIb-νproc	1.49×10^{-4}	5.38×10^{-2}
W15-2-cw-IIb-Ye_{sim}	1.58×10^{-5}	4.29×10^{-2}
W15-2-cw-IIb-shock	8.66×10^{-6}	4.20×10^{-2}
W15-2-cw-IIb-νproc-Ye_{sim}	7.16×10^{-6}	0.10×10^{-2}

Conclusions





- perform 3D simulations of CCSN from shortly after core bounce until shock breakout
- High 44Ti mass observed in Cas A can be accounted for by neutrino-driven mechanism, given the favorable condition of Ye close to 0.5
- velocities of heavy elements compatible with high values observed in stripped envelope case
- Morphology of ^{44}Ti and ^{56}Ni roughly in agreement with observations
- NS kick & heavy element distributions agree with theoretical expectation
- Large set of parametrized 3D models becoming feasible