3D Long-time Core-Collapse Supernova Simulations

Annop Wongwathanarat

Ewald Müller

Hans-Thomas Janka

Victor Utrobin

Astrophysical Big Bang Laboratory

Max-Planck-Institut für Astrophysik

Institute for Theoretical and Experimental Physics

SNR2016: an odyssey in space after stellar death

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Introduction

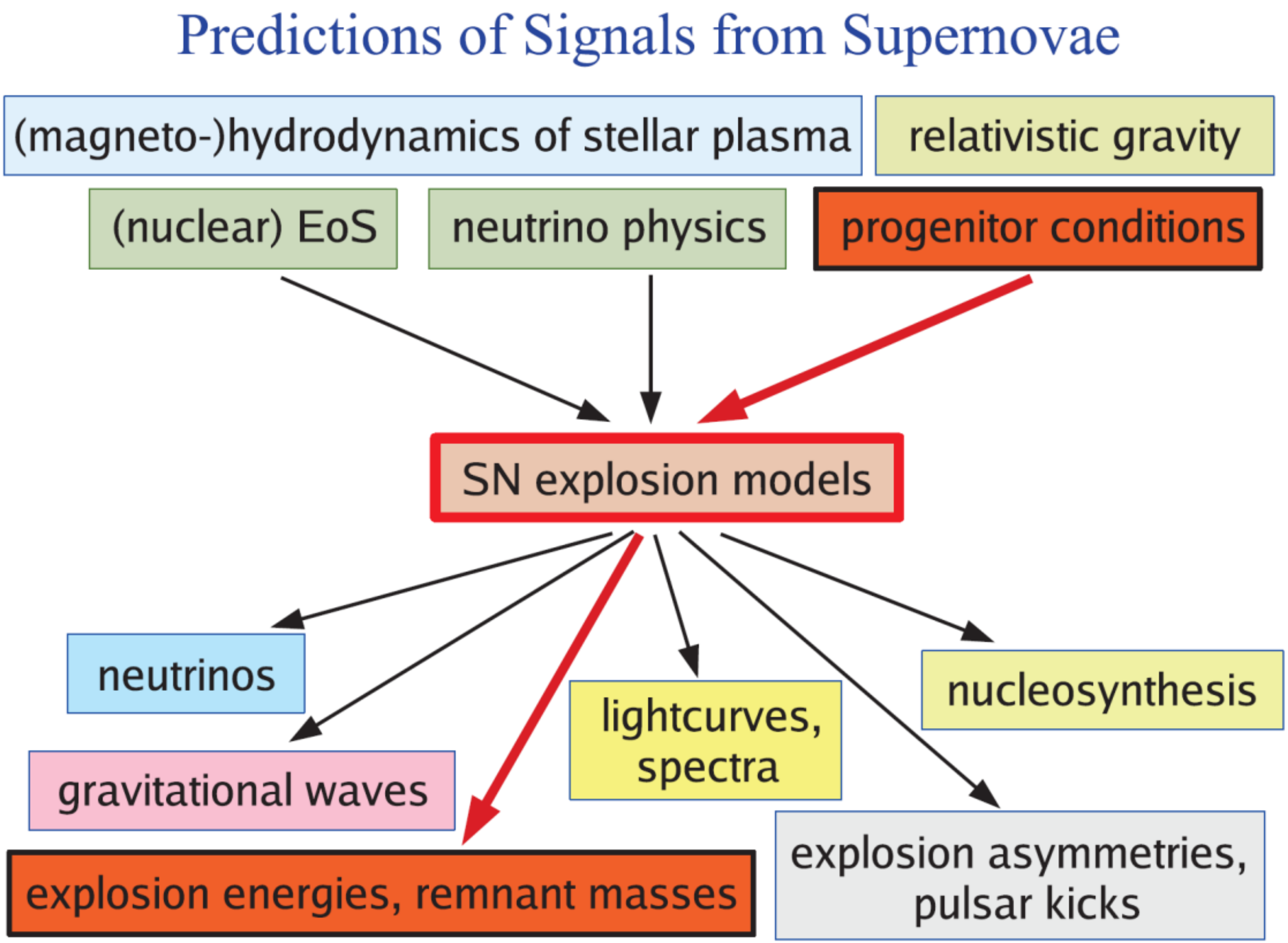
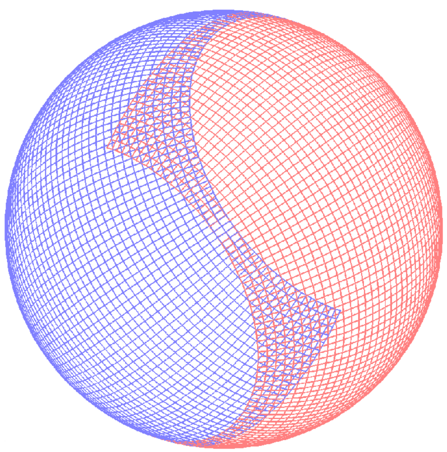


Figure from Janka et al. (2012)

State-of-the-art long-time simulations

PROMETHEUS-HOTB

PROMETHEUS-HOTB + Yin-Yang grid



CRAB Lagrangian radiation hydrodynamics

3D

Stellar evolution model

1D

core-collapse and bounce

Explosion >>> 1.3 s post bounce

1.25 day after explosions

1D

Light curves calculations

Models

As of 2013

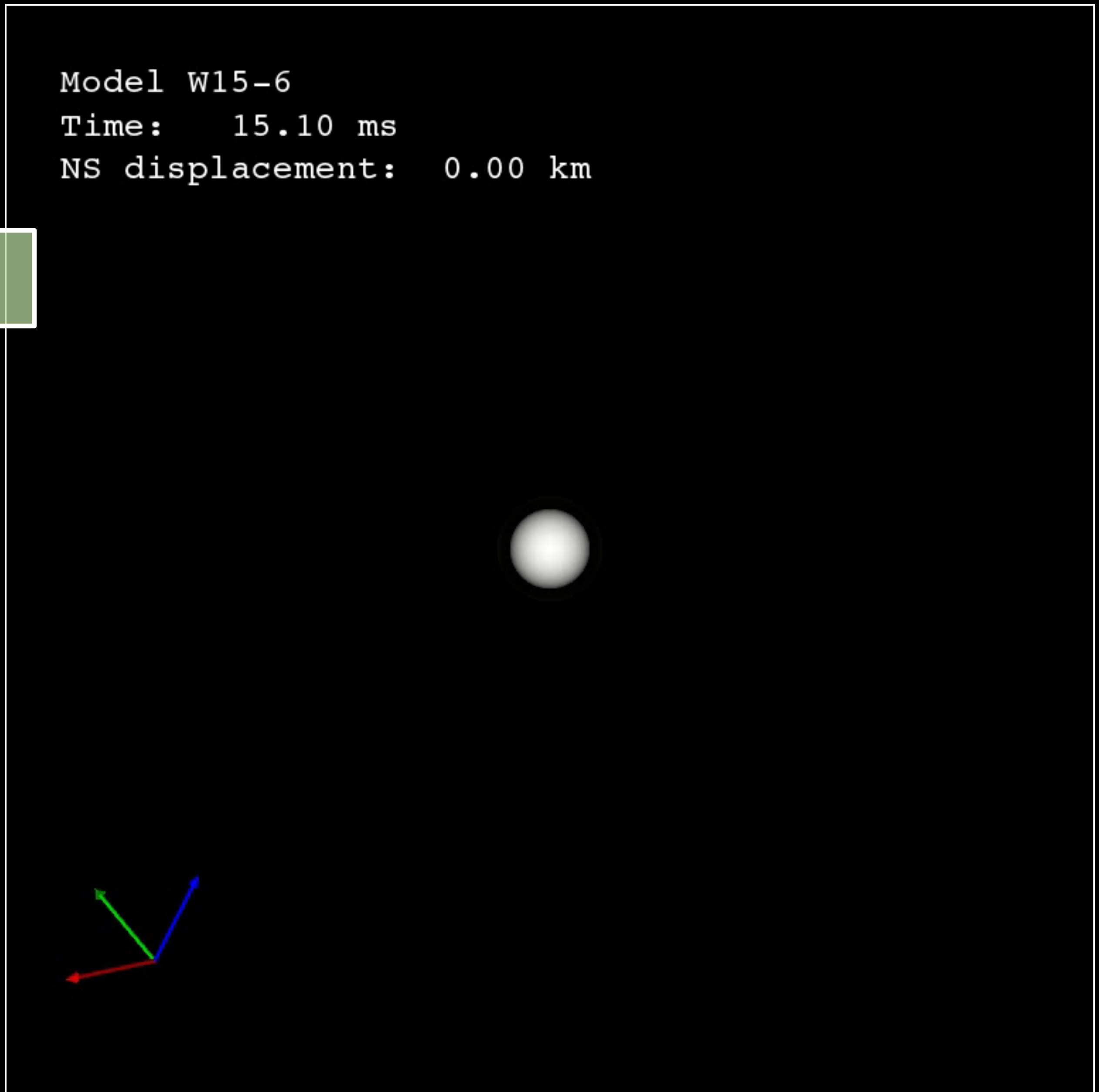
Model	M_{ns} $[M_\odot]$	t_{exp} [ms]	E_{exp} [B]	v_{ns} [km s^{-1}]	a_{ns} [km/s^2]	$v_{ns,\nu}$ [km s^{-1}]	$\alpha_{k\nu}$ [°]	v_{ns}^{long} [km s^{-1}]	a_{ns}^{long} [km/s^2]	$J_{ns,46}$ [10^{46} g cm^2/s]	α_{sk} [°]	T_{spin} [ms]
W15-1	1.37	246	1.12	331	167	2	151	524	44	1.51	117	652
W15-2	1.37	248	1.13	405	133	1	126	575	49	1.56	58	632
W15-3	1.36	250	1.11	267	102	1	160	–	–	1.13	105	864
W15-4	1.38	272	0.94	262	111	4	162	–	–	1.27	43	785
W15-5-lr	1.41	289	0.83	373	165	2	129	–	–	1.63	28	625
W15-6	1.39	272	0.90	437	222	2	136	704	71	0.97	127	1028
W15-7	1.37	258	1.07	215	85	1	81	–	–	0.45	48	2189
W15-8	1.41	289	0.72	336	168	3	160	–	–	4.33	104	235
L15-1	1.58	422	1.13	161	69	5	135	227	16	1.89	148	604
L15-2	1.51	382	1.74	78	14	1	150	95	4	1.04	62	1041
L15-3	1.62	478	0.84	31	27	1	51	–	–	1.55	123	750
L15-4-lr	1.64	502	0.75	199	123	4	120	–	–	1.39	93	846
L15-5	1.66	516	0.62	267	209	3	147	542	106	1.72	65	695
N20-1-lr	1.40	311	1.93	157	42	7	118	–	–	5.30	122	190
N20-2	1.28	276	3.12	101	12	4	159	–	–	7.26	43	127
N20-3	1.38	299	1.98	125	15	5	138	–	–	4.42	54	225
N20-4	1.45	334	1.35	98	18	1	98	125	9	2.04	45	512
B15-1	1.24	164	1.25	92	16	1	97	102	1	1.03	155	866
B15-2	1.24	162	1.25	143	37	1	140			0.12	162	7753
B15-3	1.26	175	1.04	85	19	1	24	99	3	0.44	148	2050

growing list !!!

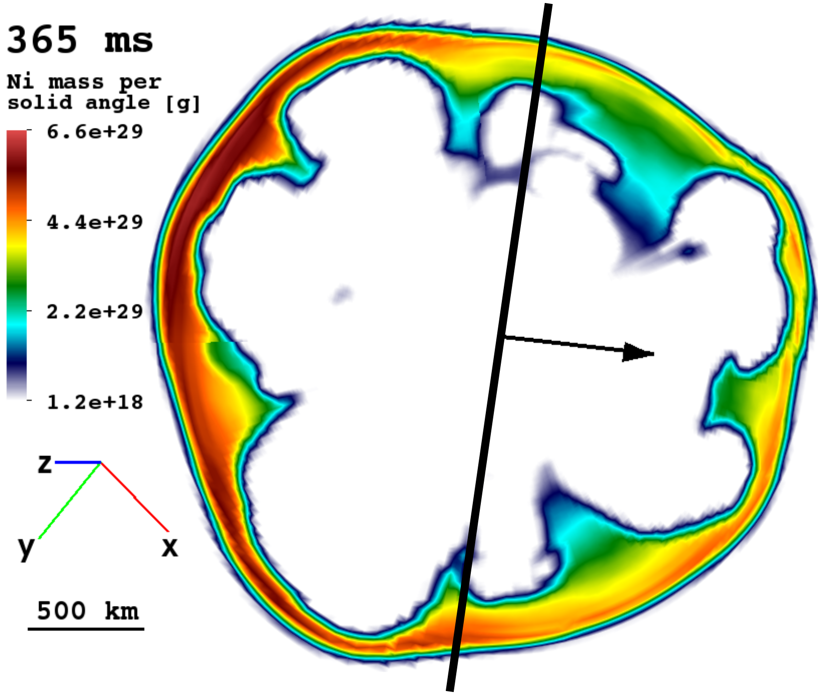
Neutron star kicks by Gravitational tug-boat mechanism

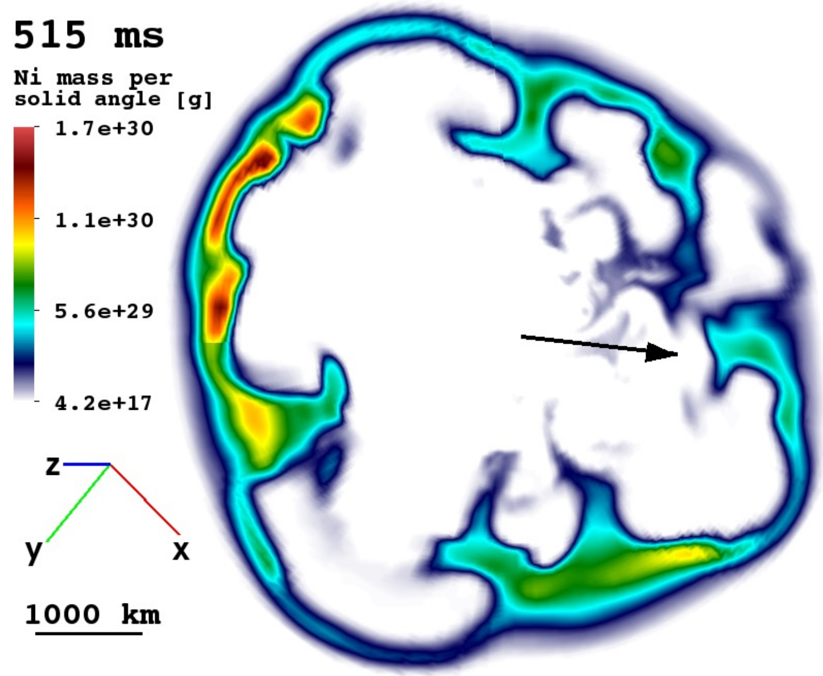
W15-6

704 km/s



Nickel distribution

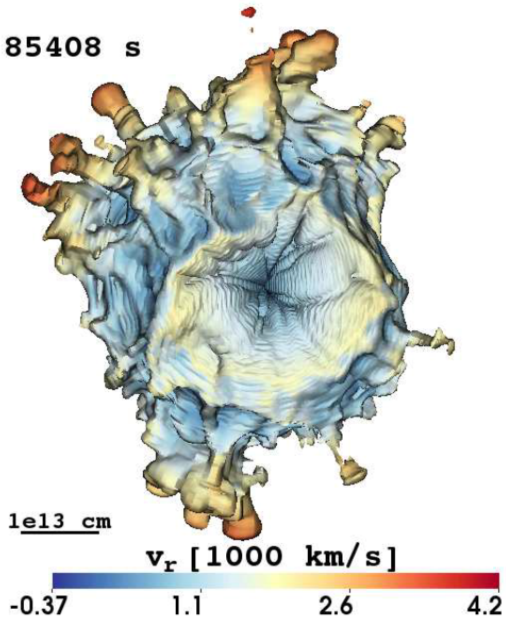




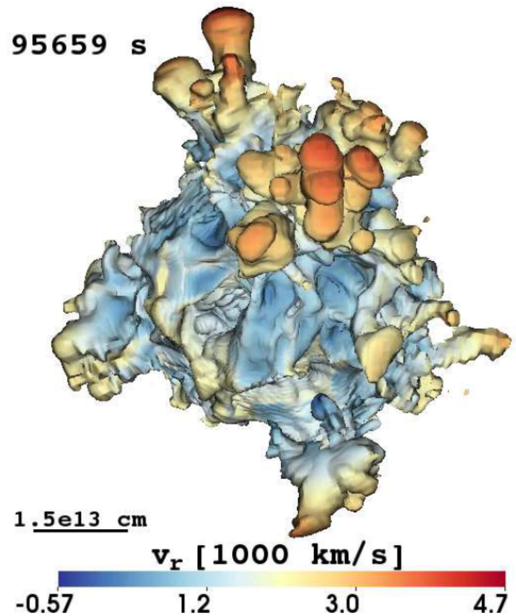
Ni shows hemispheric asymmetry

observed??? Constrain kick mechanism???

Long-time models

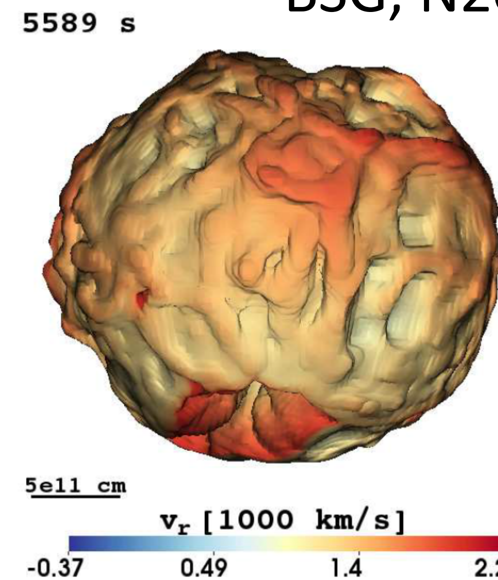


Woosley&Weaver (1995)
RSG, W15

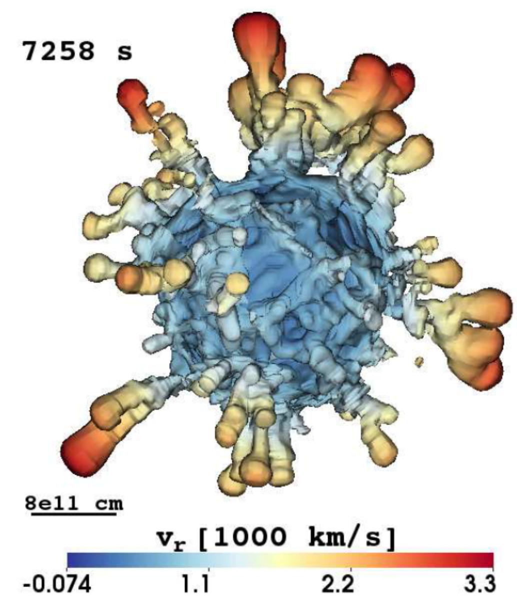


Limongi+ (2000)
RSG, L15

Shigeyama&Nomoto (1990)
BSG, N20



Nickel-rich ejecta at shock breakout

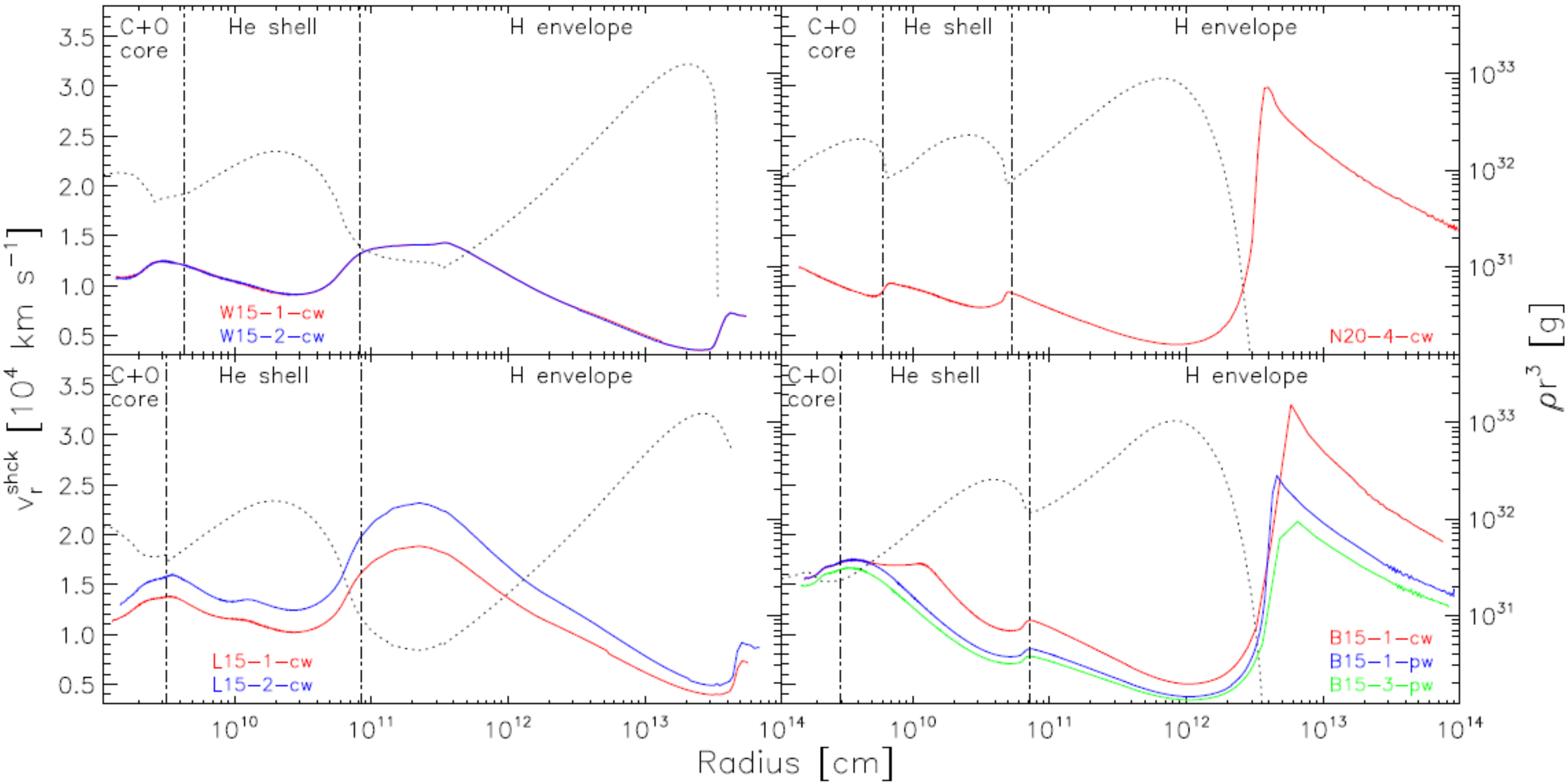


Woosley+ (1988) BSG, B15

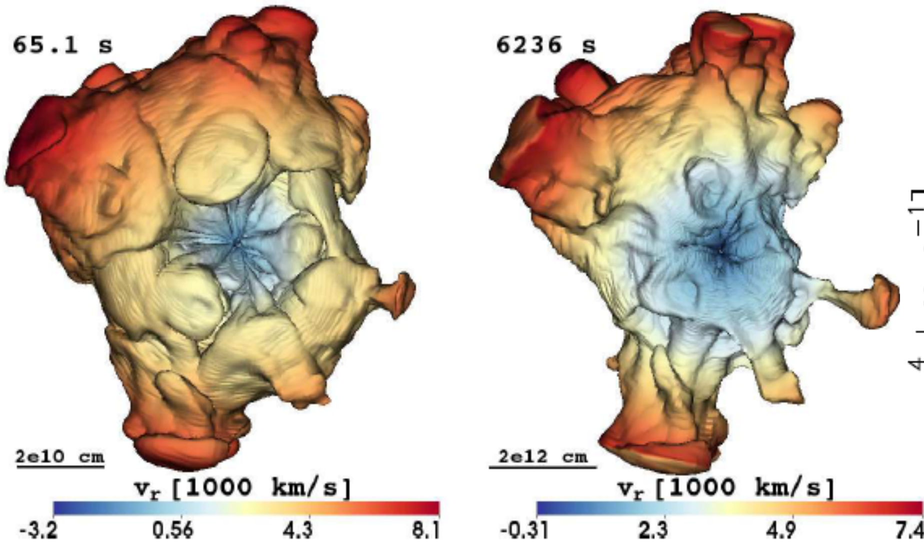
Shock dynamics

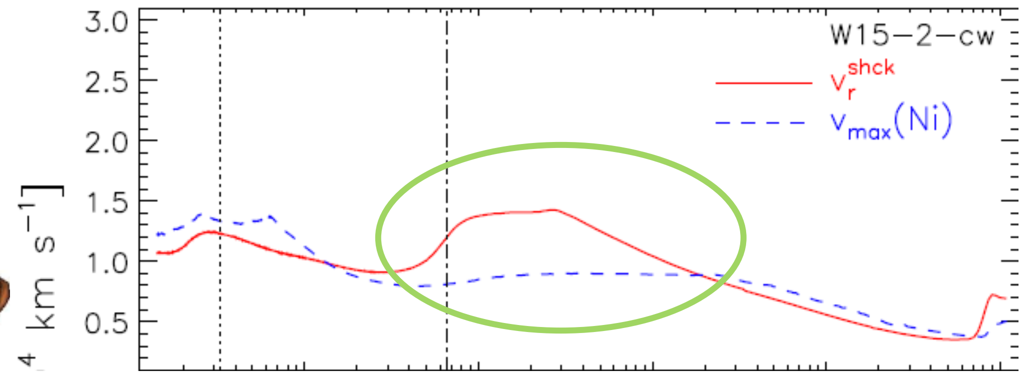
shock propagates according to blast wave solution (Sedov, 1959)

accelerates when ρr^3 decreases, and vice versa



RSG model



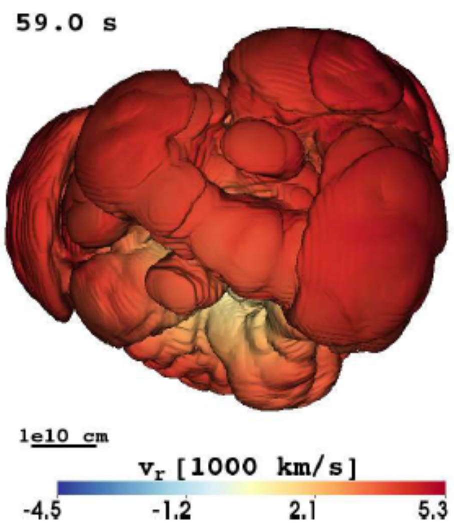


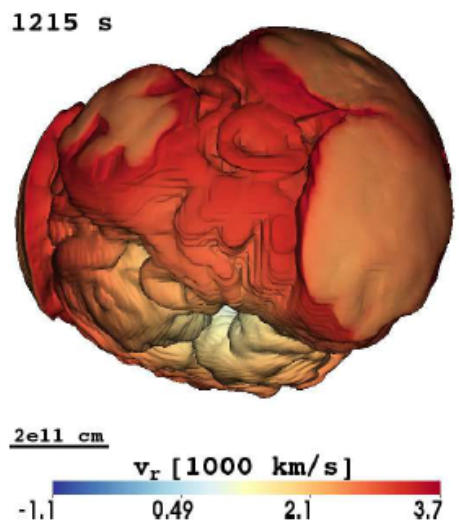
at He/H interface

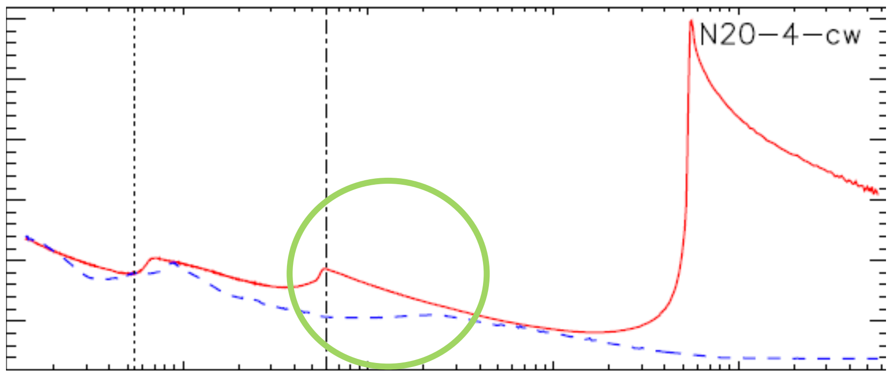
→ meet reverse shock

Shock strongly accelerates --> RTI fingers stretch --> Reverse shock forms --> RTI fingers collide with Reverse shock

N20 model





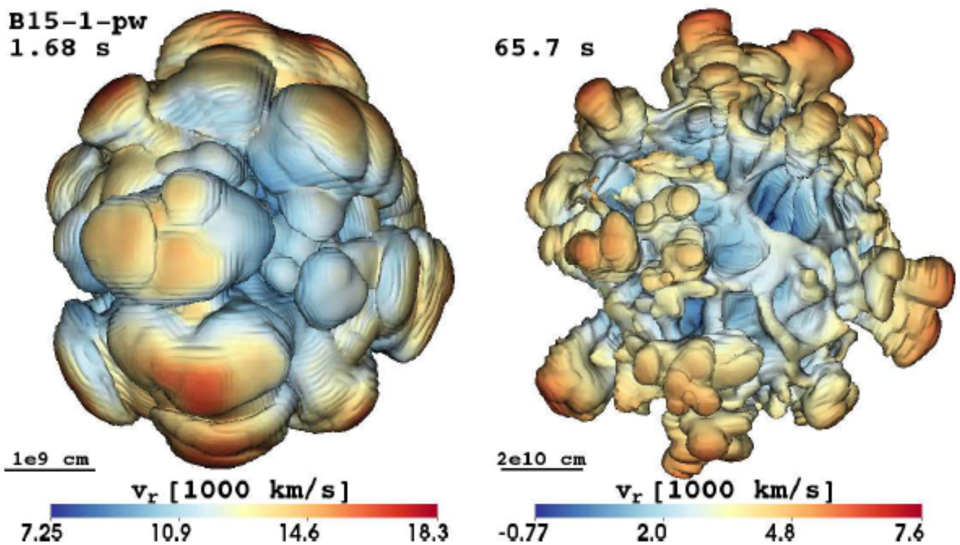


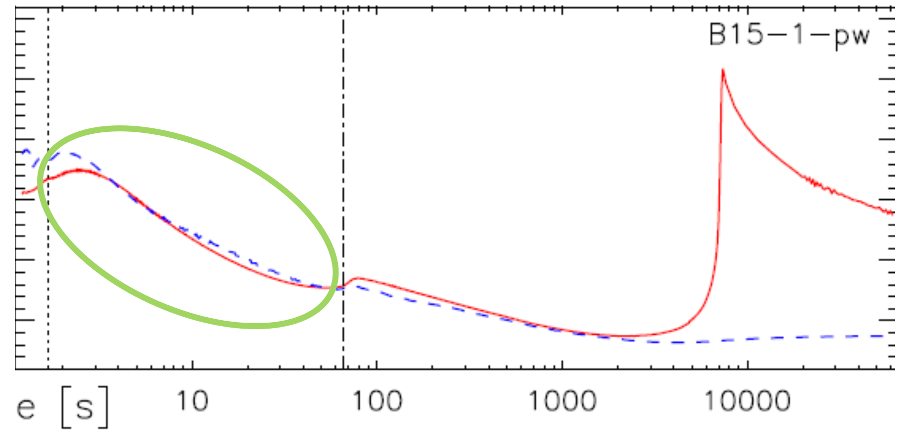
at He/H interface

→ meet reverse shock

Shock accelerates briefly --> Reverse shock forms --> Slow nickel bubbles collide with reverse shock and flattened

B15 model



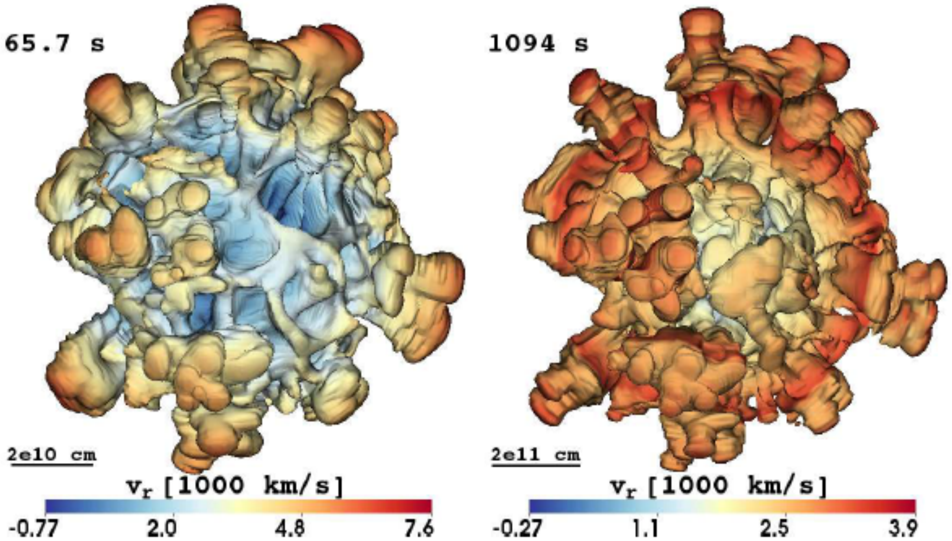


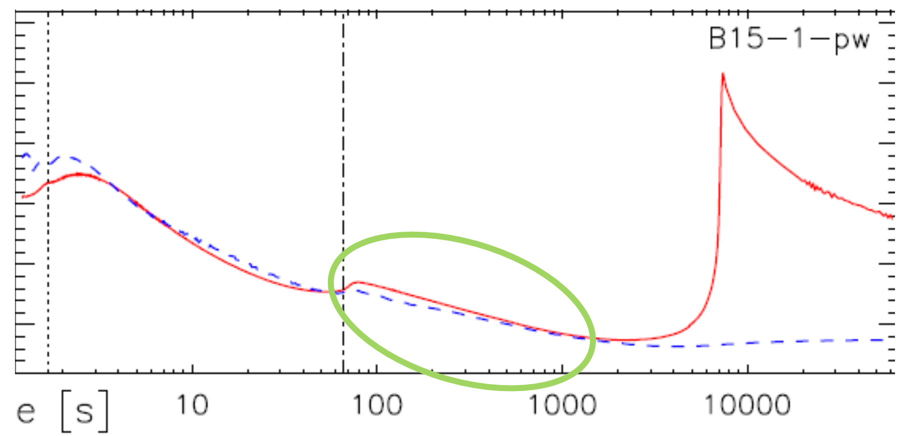
at C+O/He interface

→ at He/H interface

Significant growth of RTIs --> fragmentation of nickel bubbles

B15 model





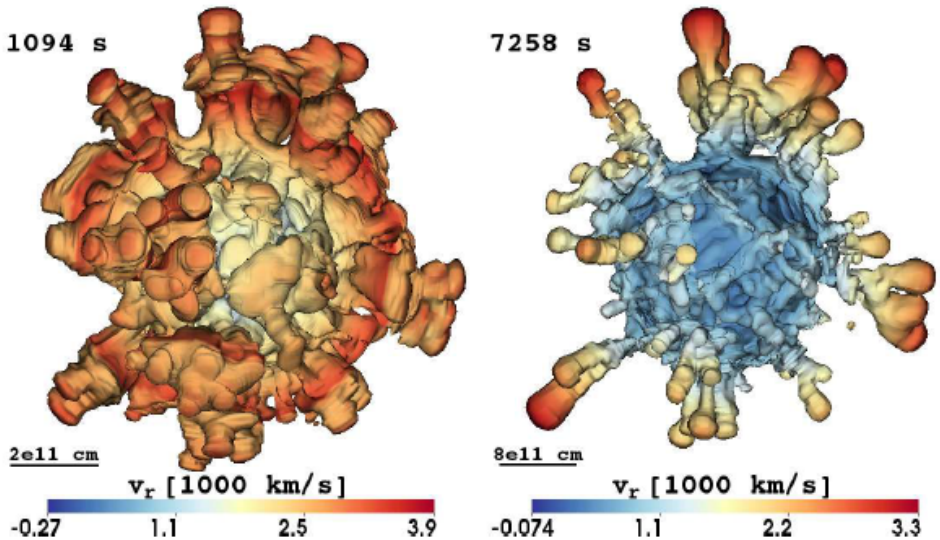
at He/H interface

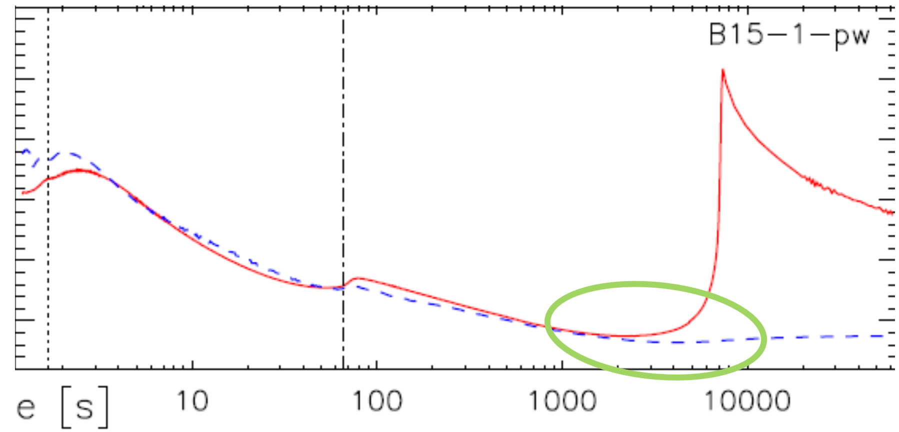
meet reverse shock

Shock accelerates briefly --> Reverse shock forms -->

Fast nickel fingers ahead of reverse shock !!!

B15 model



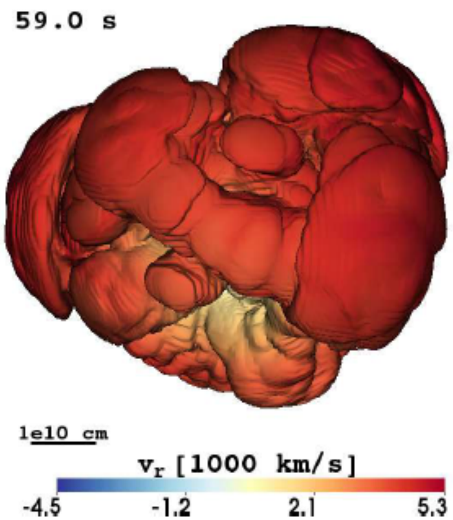


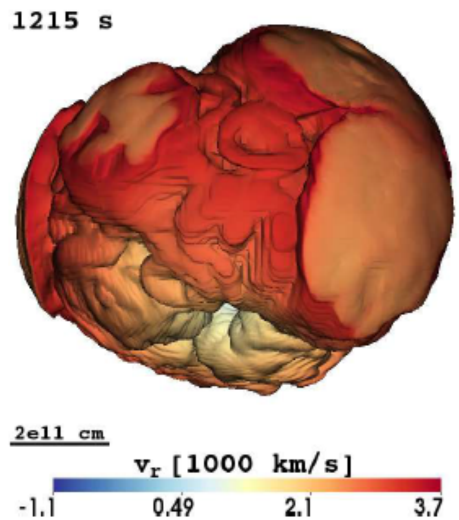
meet reverse shock

→ shock breakout

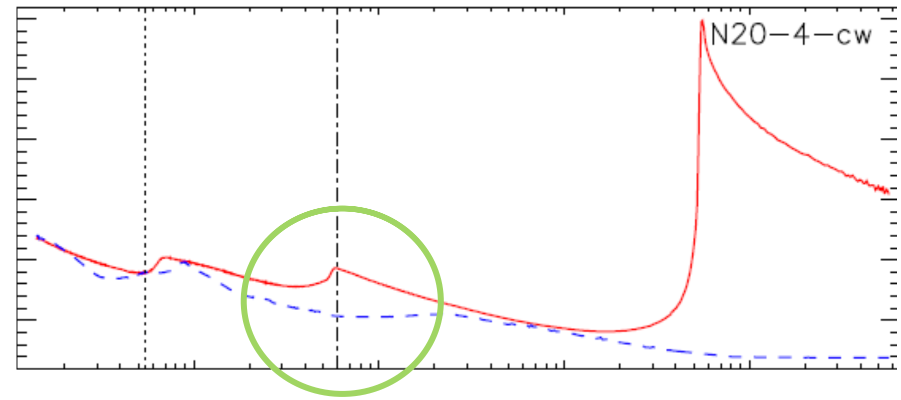
Fast nickel fingers stretch --> inner part of ejecta trapped by reverse shock

N20 BSG model





Nickel too slow

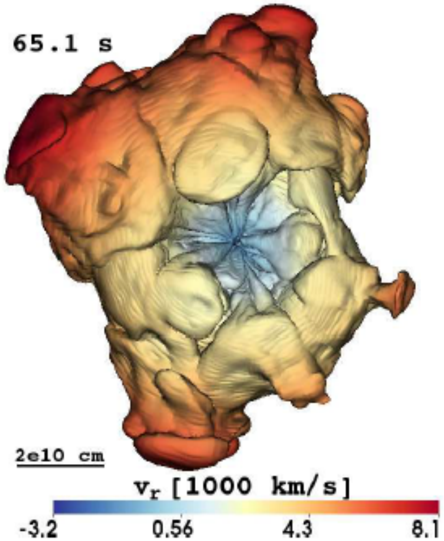


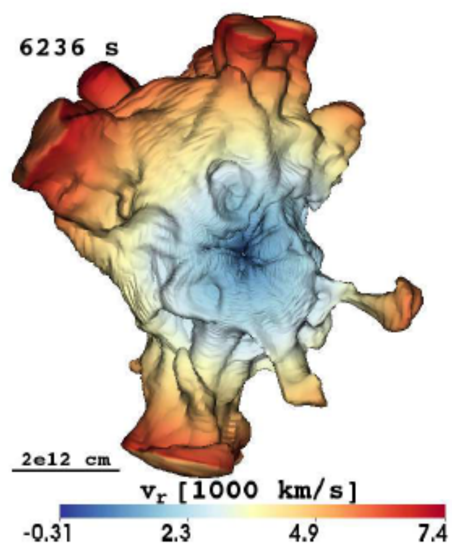
at He/H interface

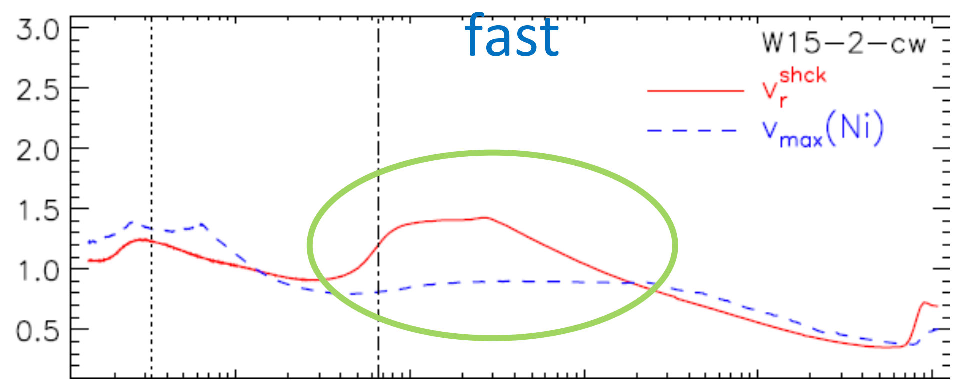
meet reverse shock

RSG model

Shock too fast



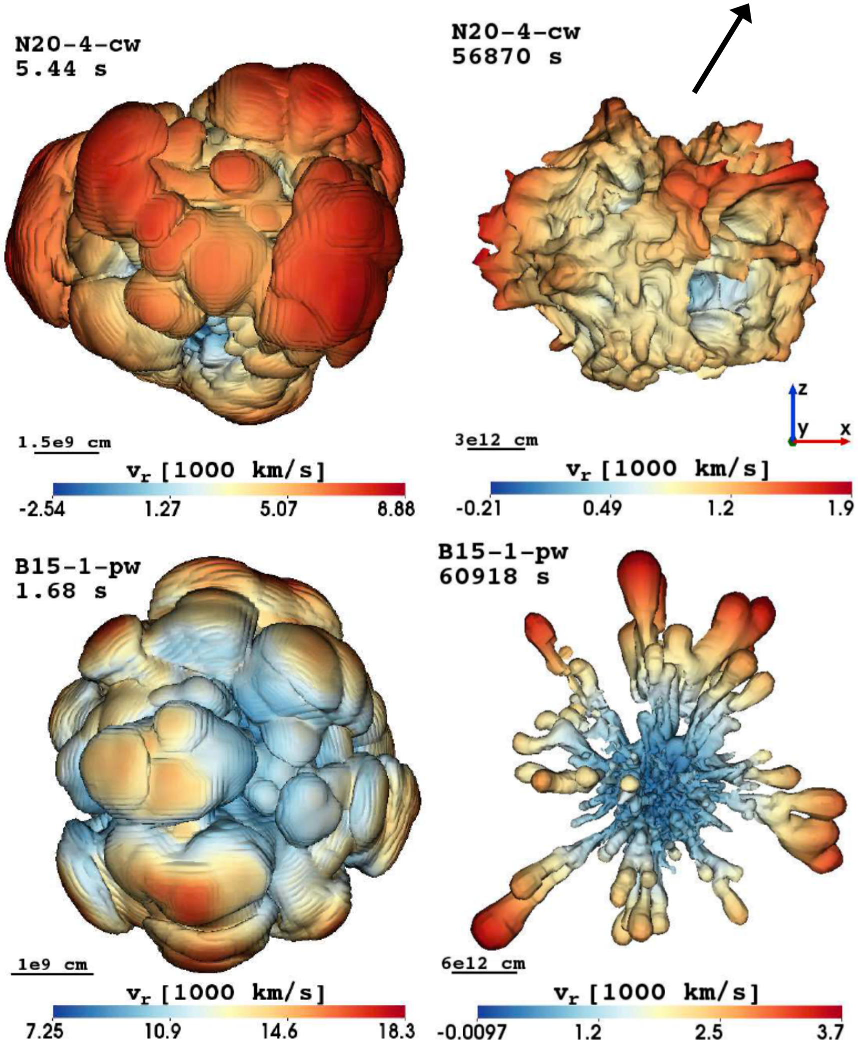


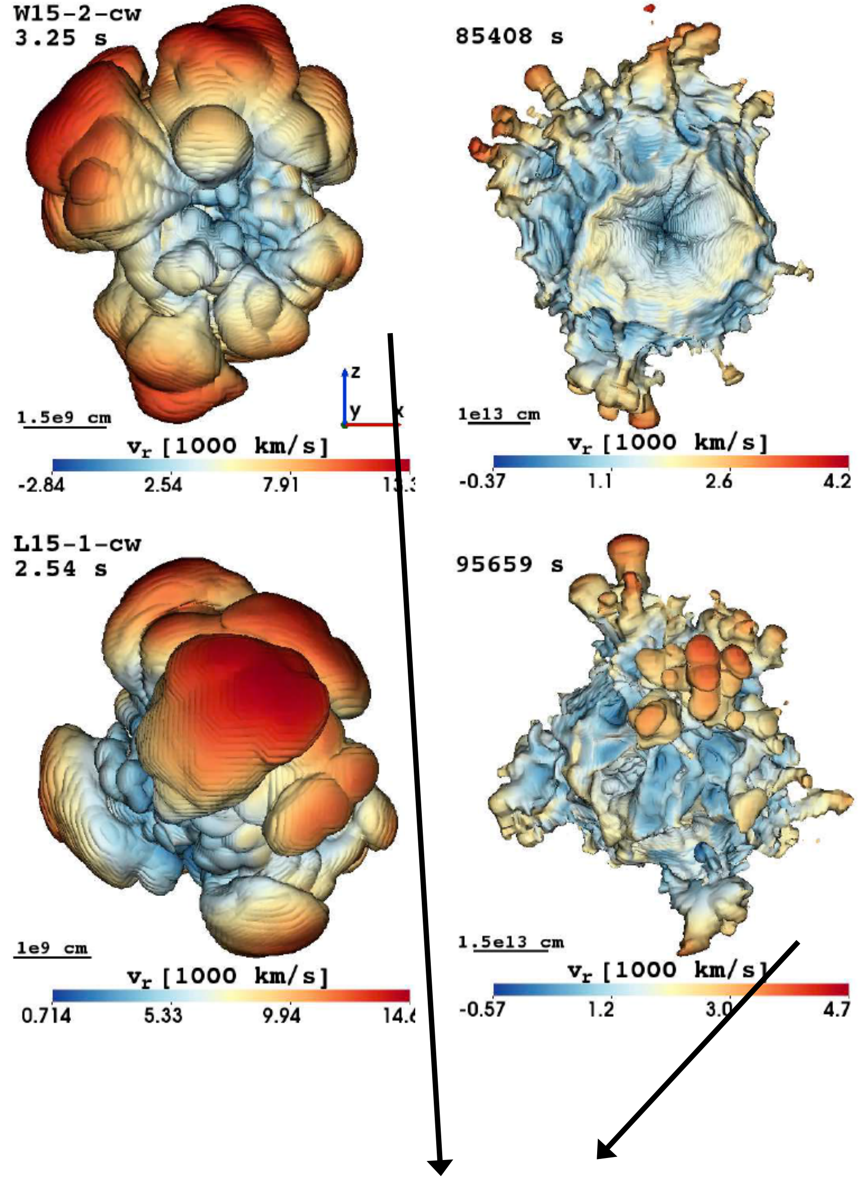


Early vs. late morphology

Explosion vs. late-time asymmetries

not so clear??





clear correlation

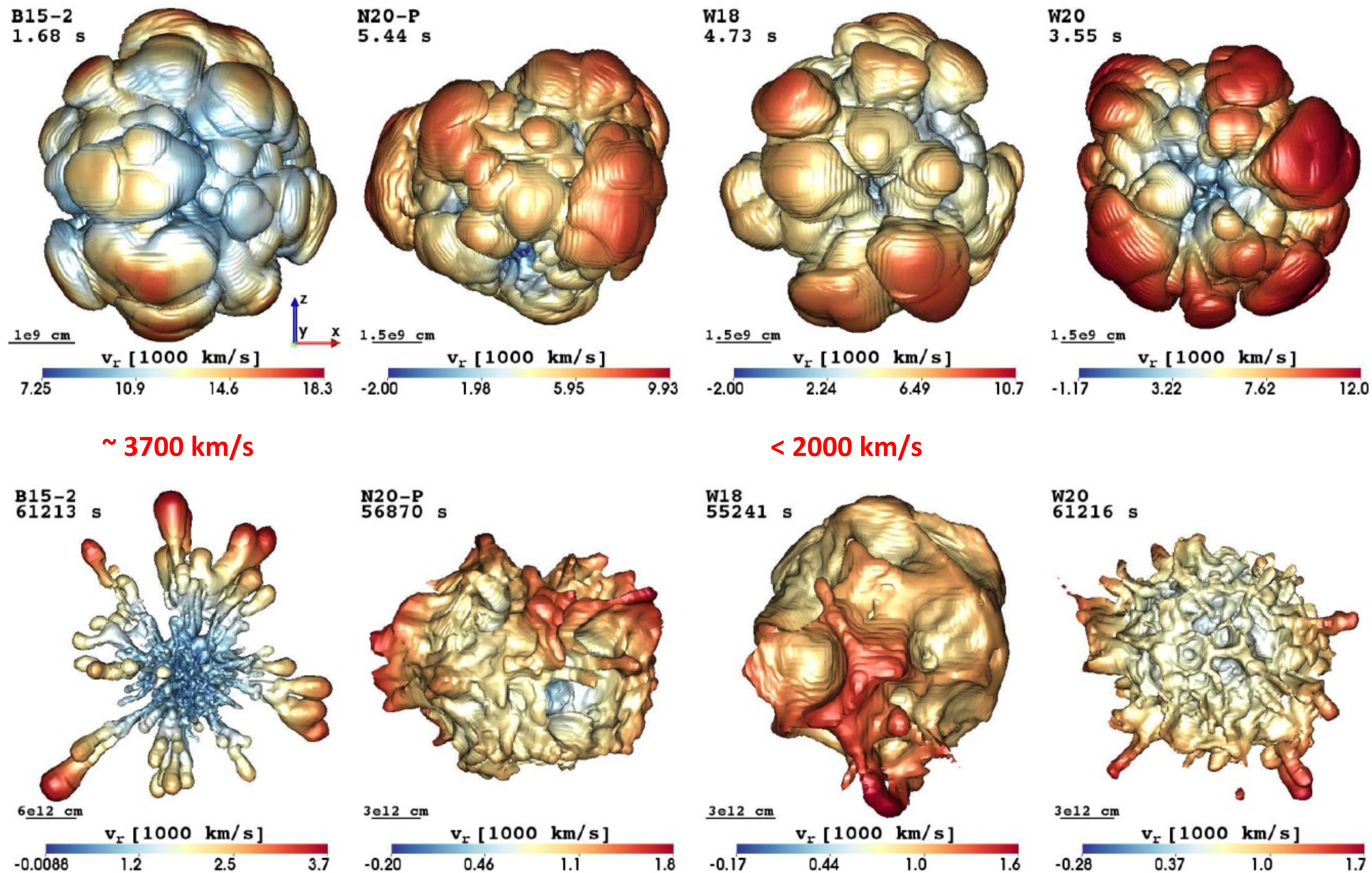
SN1987A

Woosley et al. (1988)

Woosley (2007)

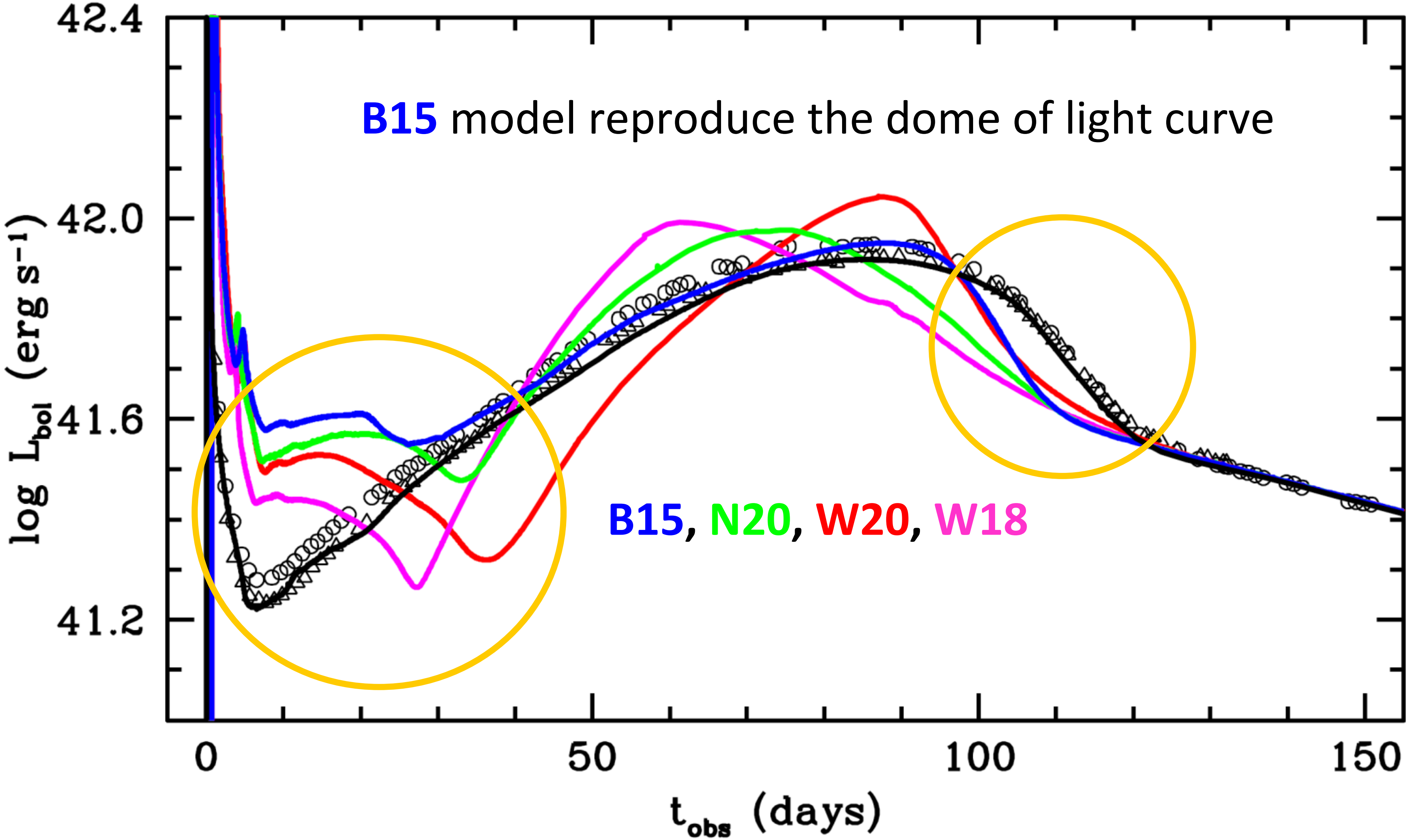
Shigeyama & Nomoto (1990)

Woosley et al. (1997)



Light Curves of SN1987A

Utrobin et al. (2015)



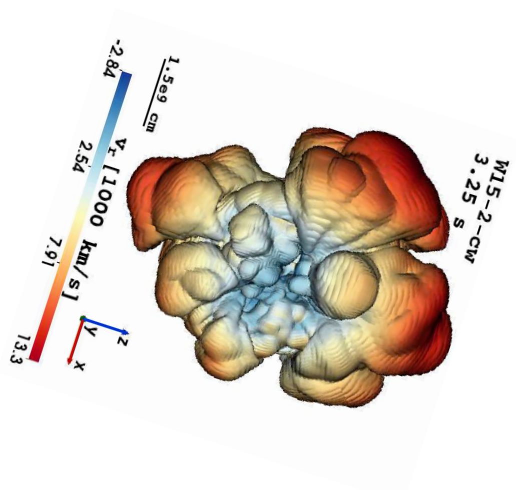
Conclusion

- NS kick by gravitational tug boat mechanism can explain observed average pulsar space velocity
- In high kick cases, hemispheric asymmetries of heavy elements are produced
- evolution of asymmetries associated with explosion mechanism connects to the density structure of the progenitor star
- Density structure of He shell and He/H interface are very important in determining the fate of heavy clumps

Conclusion II

- extending simulations to later phases, connecting SN ---> SNR (see poster by Michael Gabler)

- State-of-the-art approach for CCSN light curves using 3D explosion models --- > 1D radiation hydro taking into account 3D mixing



Beginning to connect SNe to SNRs !!!