NS kicks by gravitational tug boat mechanism

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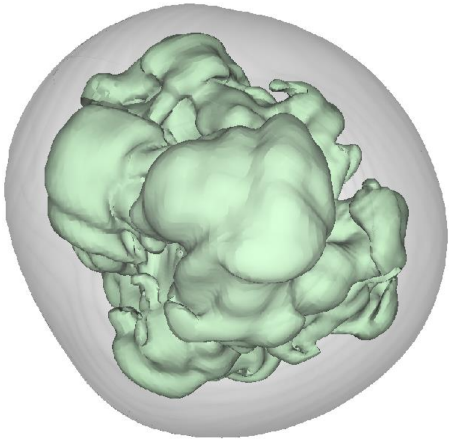
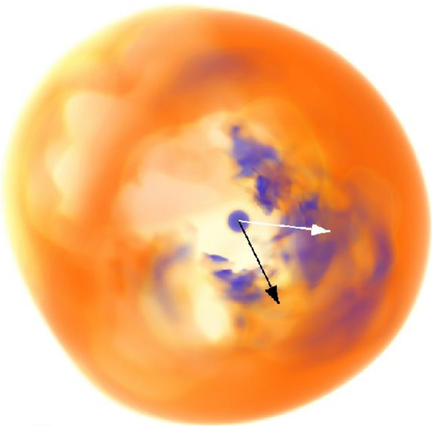
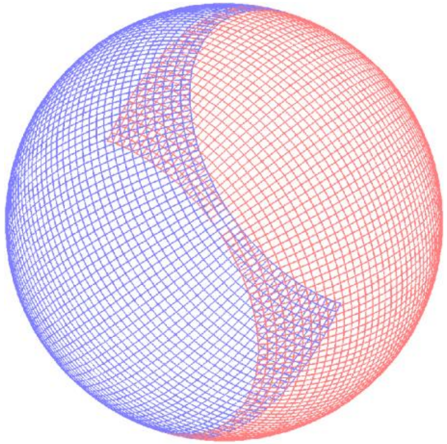






RESCEU-ABBL meeting

26 Jul 2016

Introduction

Figure from Janka et al. (2012)

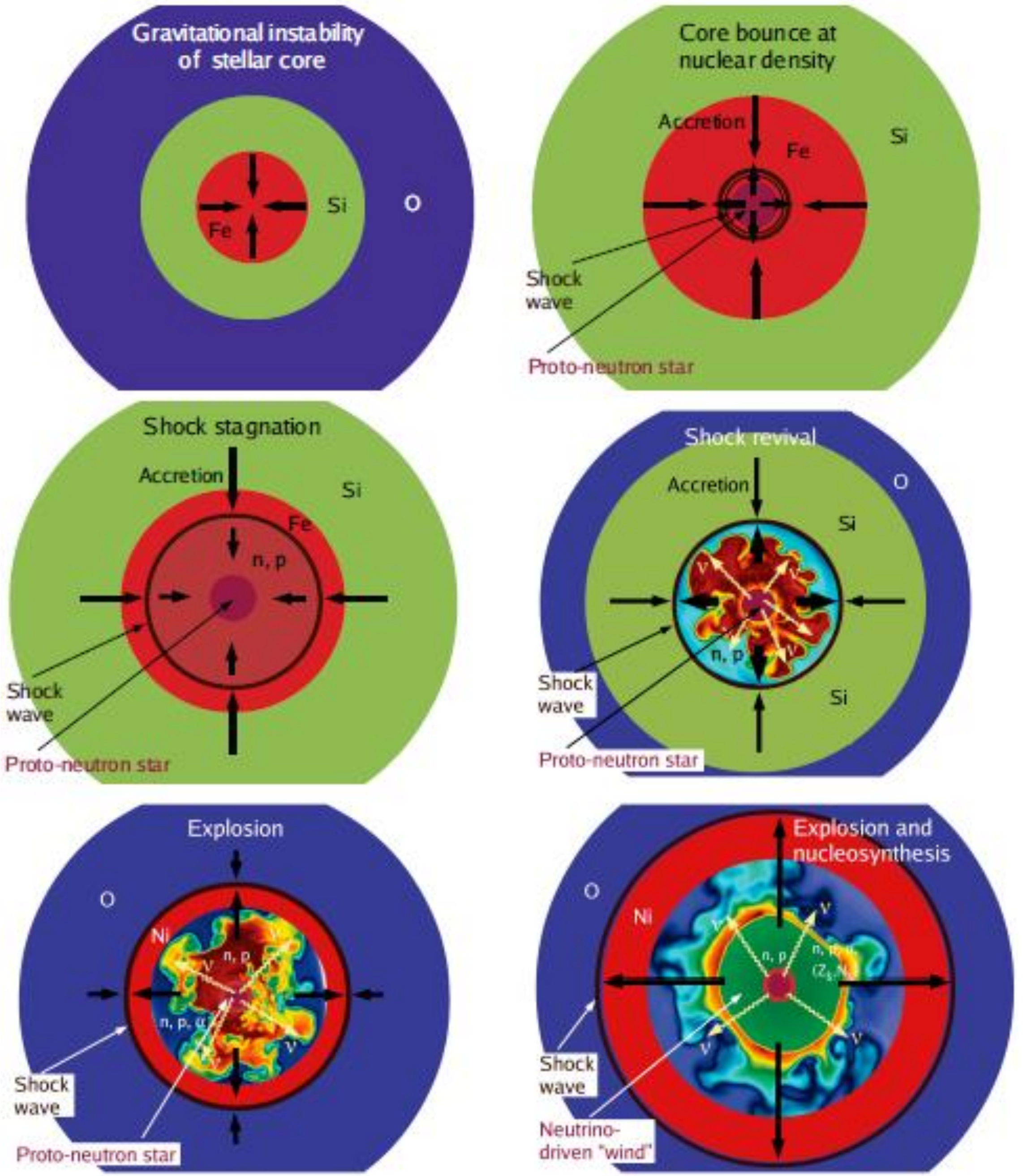
collapse >> bounce >> shock formation >> stalled accretion shock

how to revive the stalled shock???

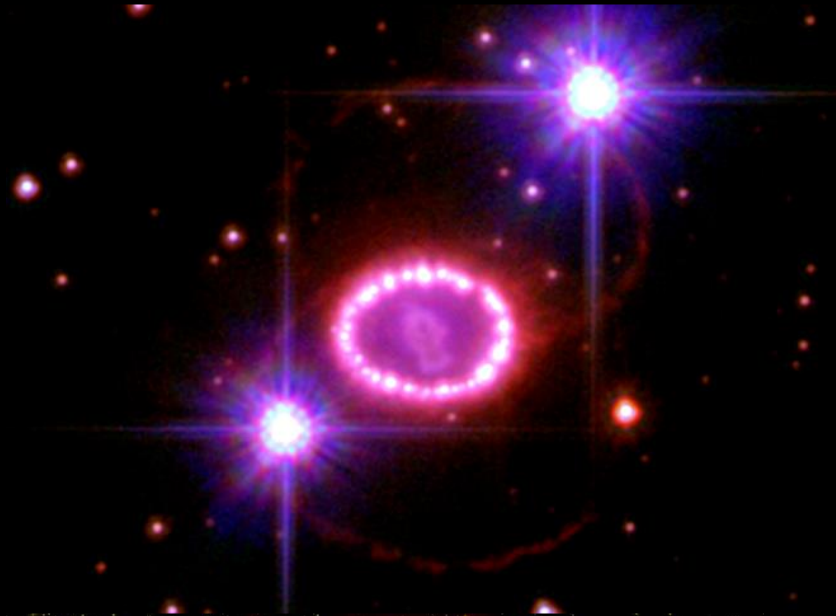
neutrino-driven mechanism

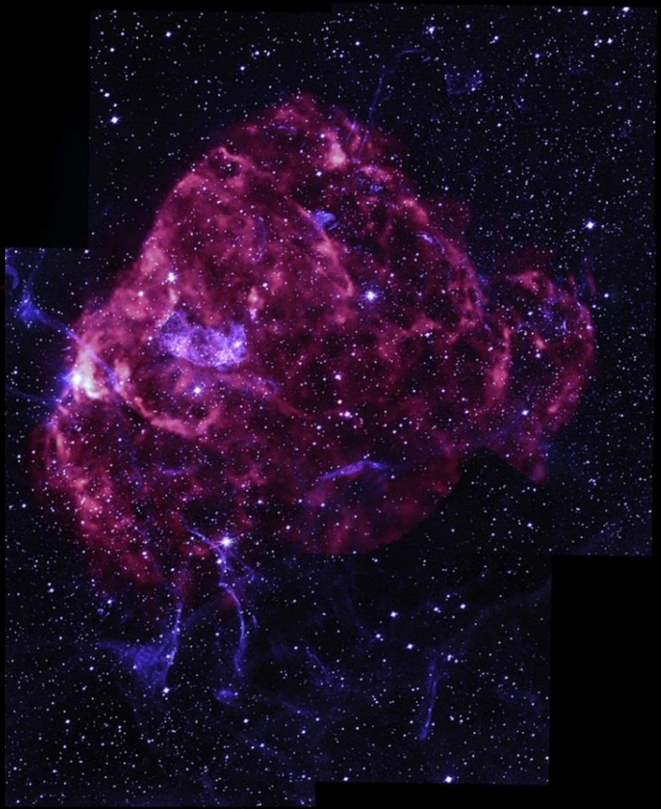
1D simulations don't explode …

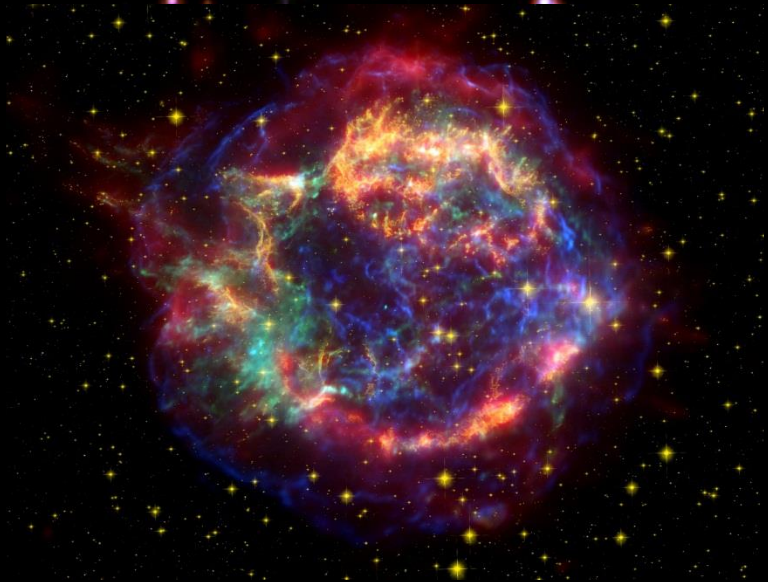
multi-D effects play important roles !!!



SN asymmetries







Introduction

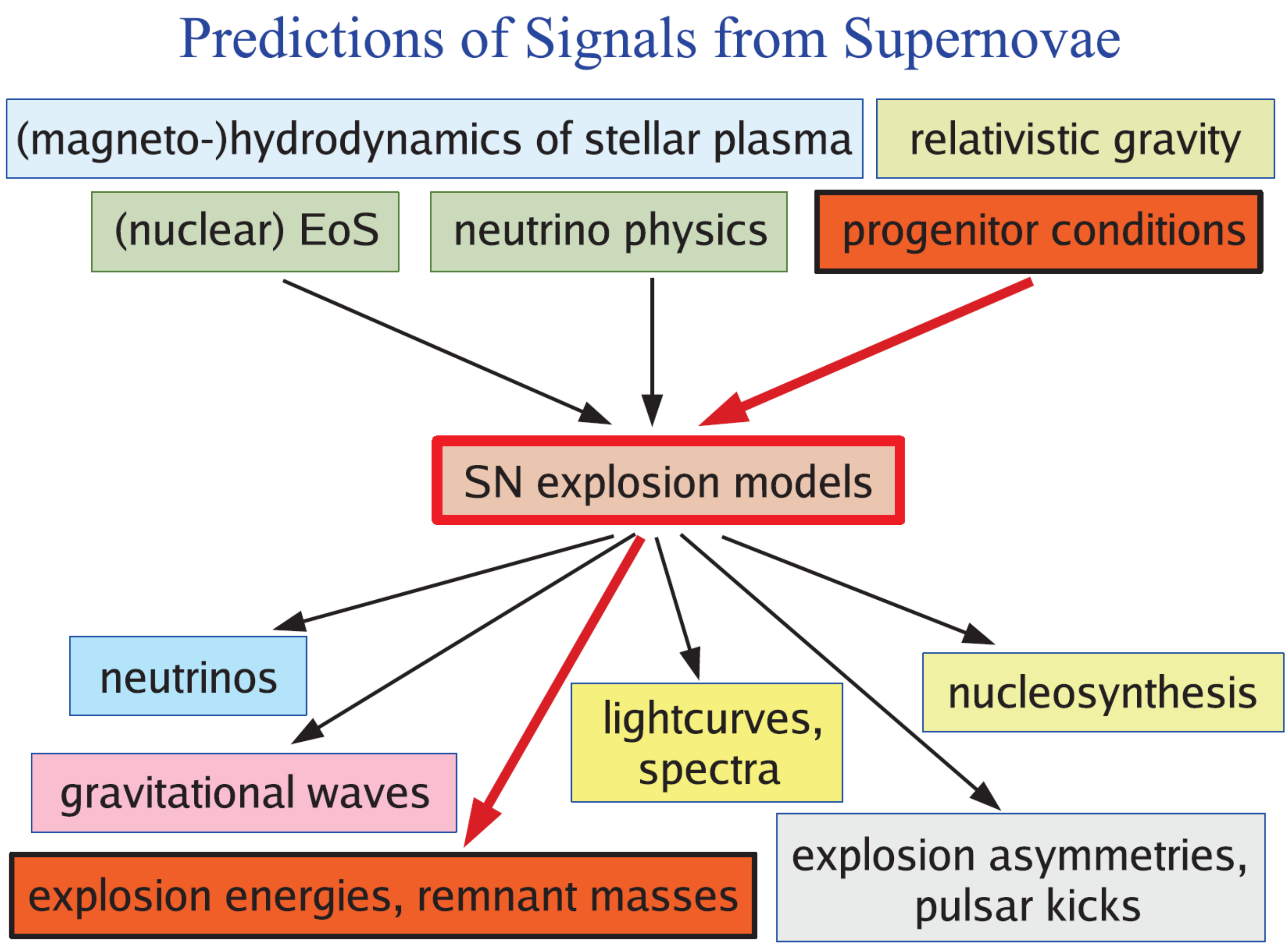


Figure from Janka et al. (2012)

Neutron star kicks

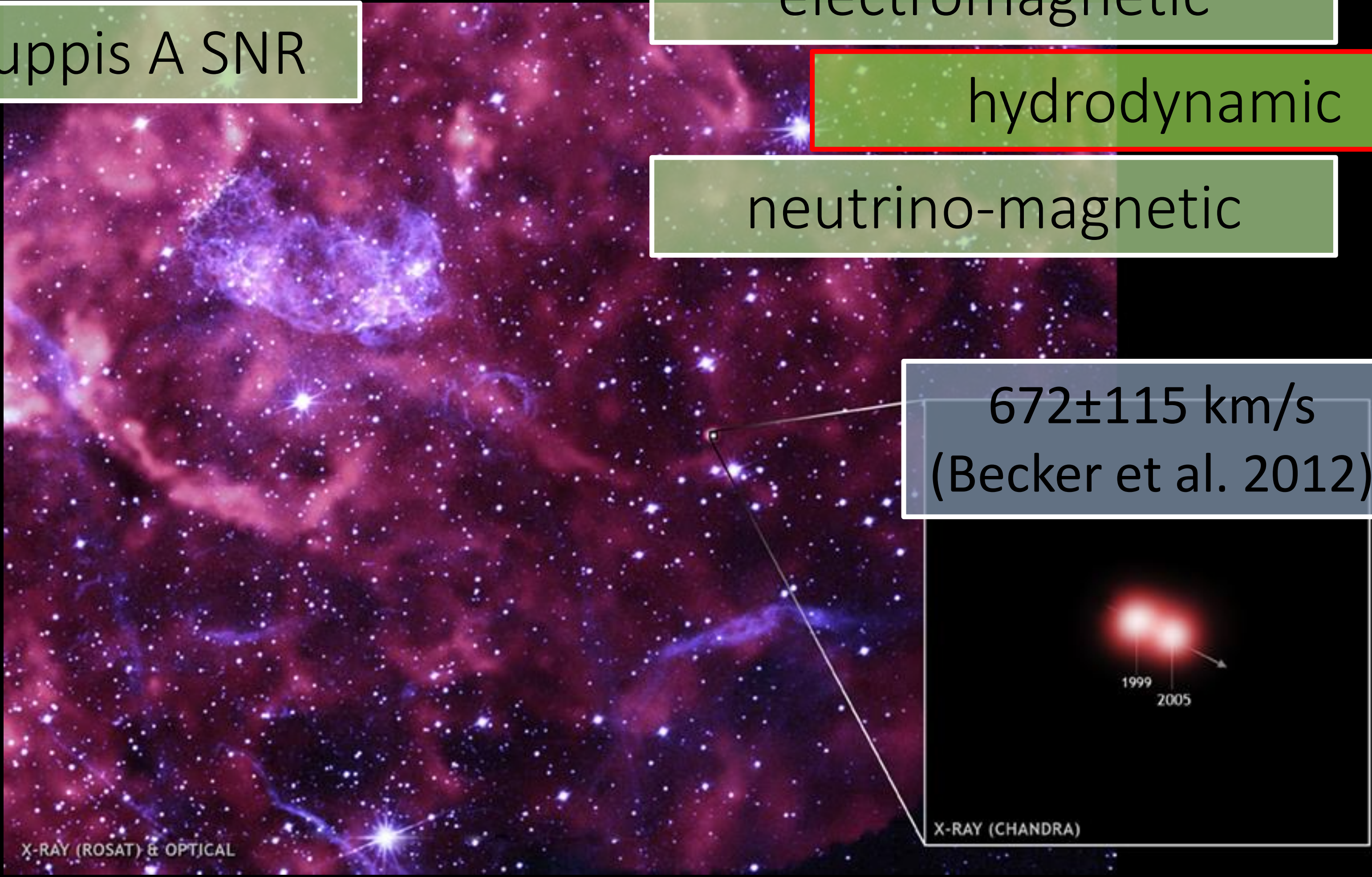
Kick mechanism??

electromagnetic

hydrodynamic

neutrino-magnetic

Puppis A SNR



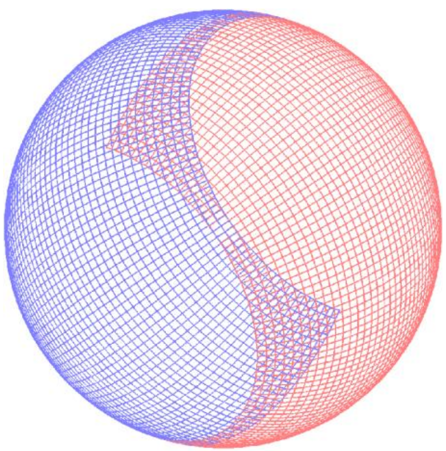
672±115 km/s
(Becker et al. 2012)

average pulsars velocity: 200-500 km/s

State-of-the-art long-time simulations

PROMETHEUS-HOTB

PROMETHEUS-HOTB + Yin-Yang grid



CRAB Lagrangian radiation hydrodynamics

Stellar evolution model

1D

core-collapse and bounce

3D

Explosion >>> 1.3 s post bounce

1.25 day after explosions

1D

Light curves calculations

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
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W15-8	1.41	289	0.72	336	168	3	160	–	–	4.33	104	235
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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
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v_{ns} from 31-437 km/s

700 km/s later

T_{spin} from 127-7753 ms

no spin-kick alignment

Numerical techniques

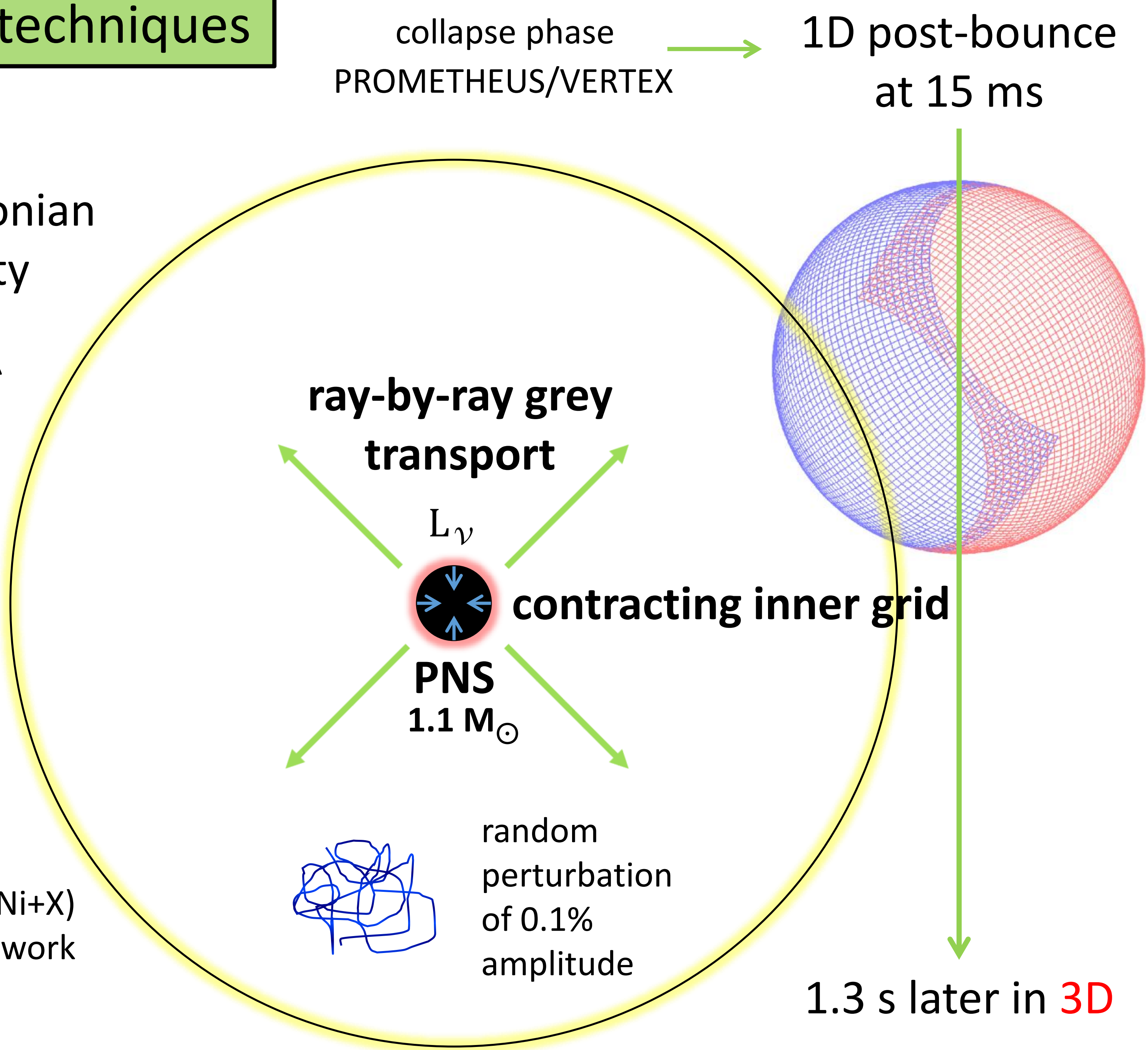
3D Newtonian self-gravity

monopole GR correction

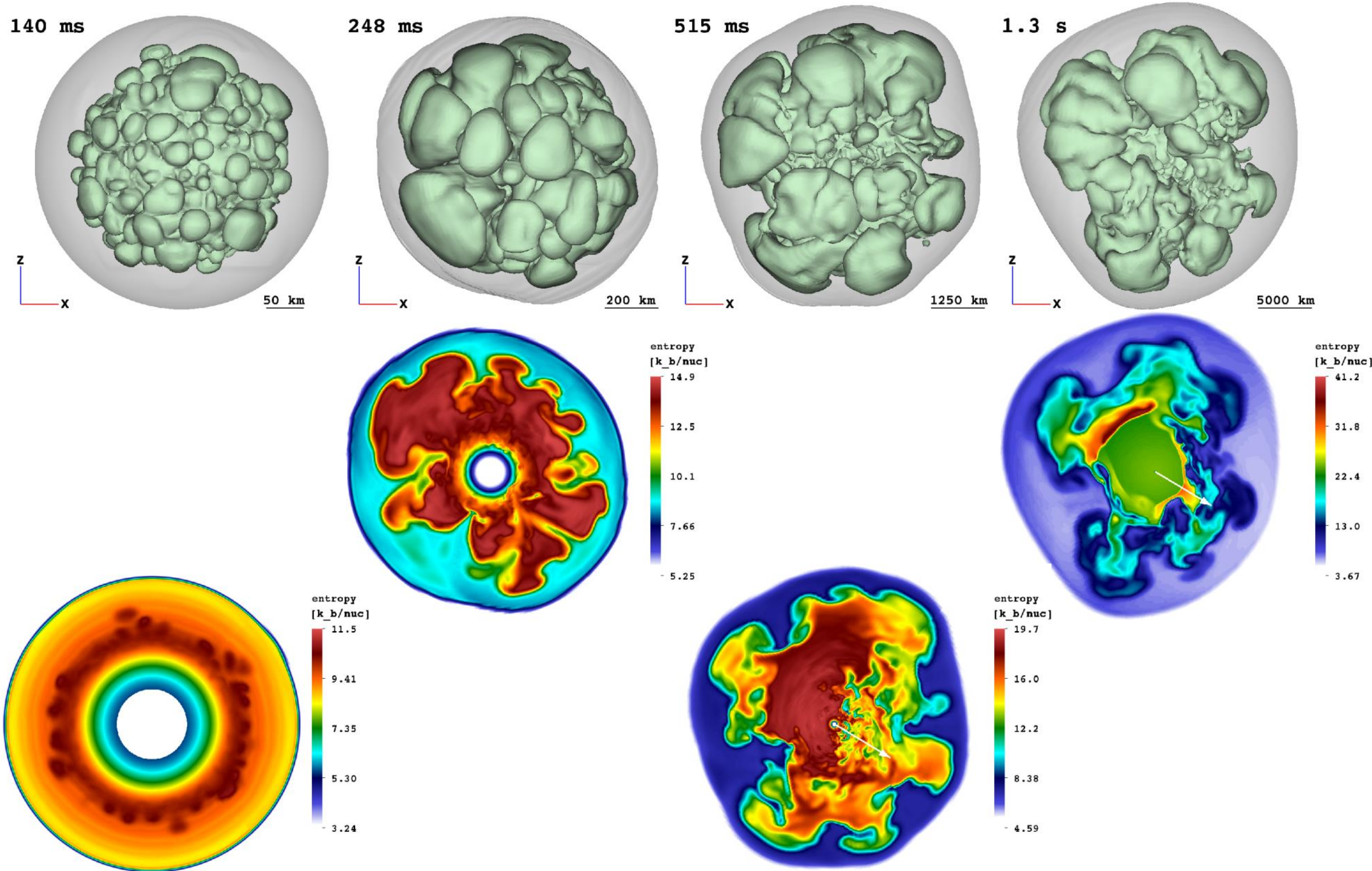
tabulated EOS by Janka & Müller (1996)

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

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



Results



140 ms
248 ms
515 ms
1.3 s
z
x
50 km
200 km
1250 km
5000 km
entropy
[k_b/nuc]
14.9
12.5
10.1
7.66
5.25
41.2
31.8
22.4
13.0
3.67
11.5
9.41
7.35
5.30
3.24
19.7
16.0
12.2
8.38
4.59

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]
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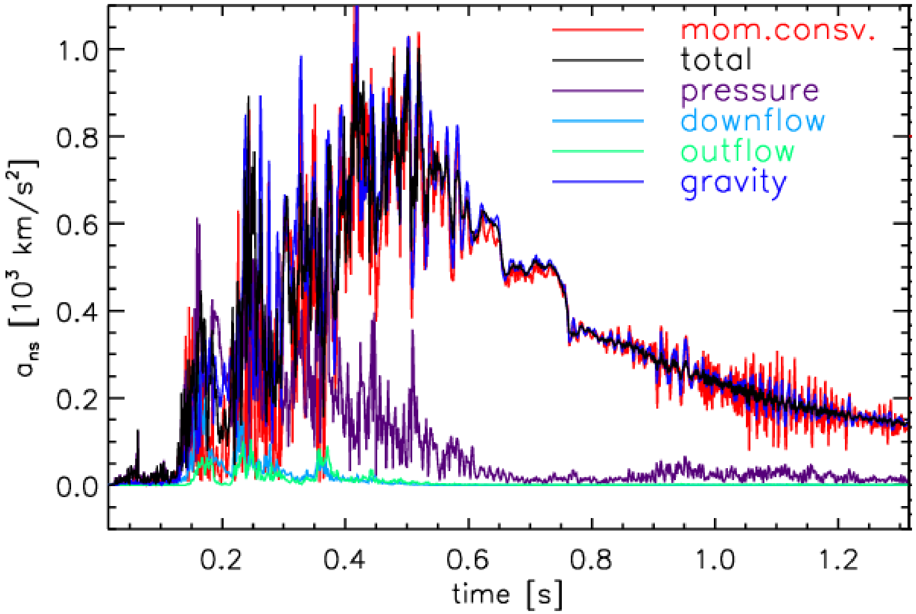
v_{ns} from 31-437 km/s

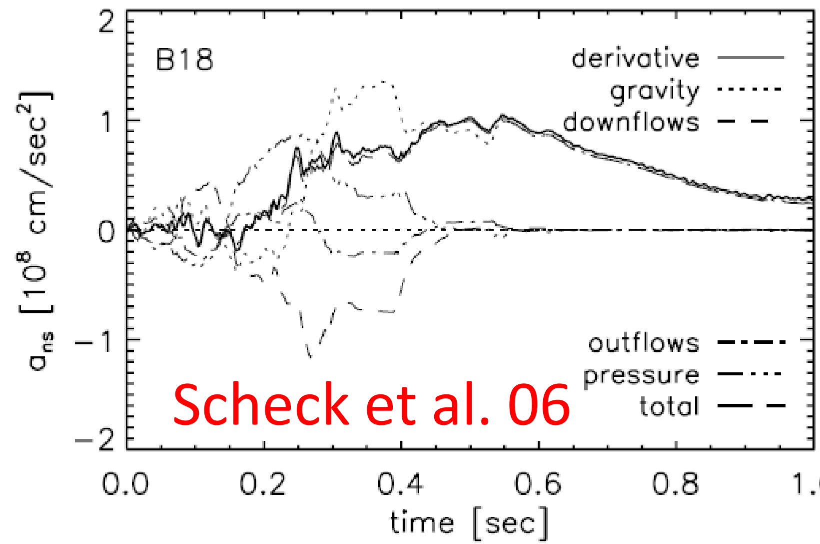
700 km/s later

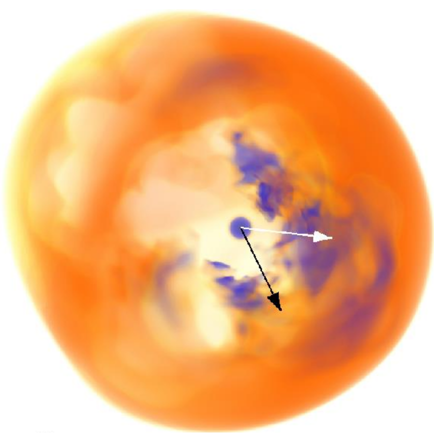
T_{spin} from 127-7753 ms

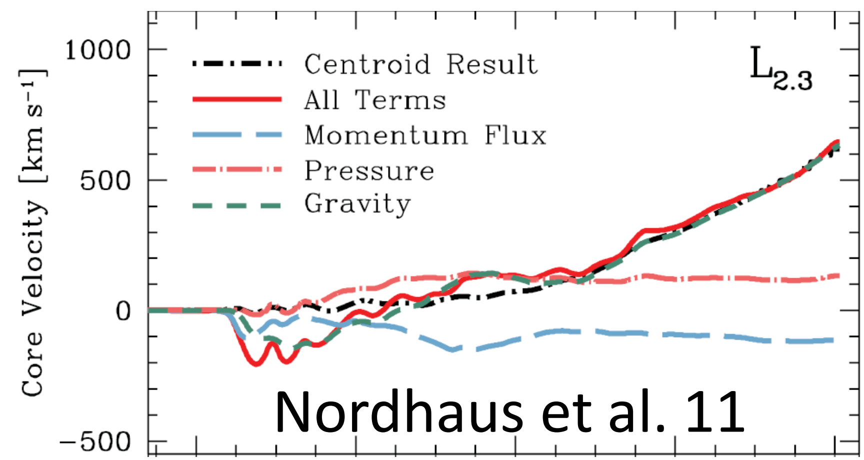
no spin-kick alignment

$$\dot{\vec{P}}_{ns} \approx -\oint_{r=r_0} P\, d\vec{S} - \oint_{r=r_0} \rho \vec{v} v_r dS + \int_{r>r_0} \frac{G M_{ns} \vec{r}}{r^3}\, dm$$



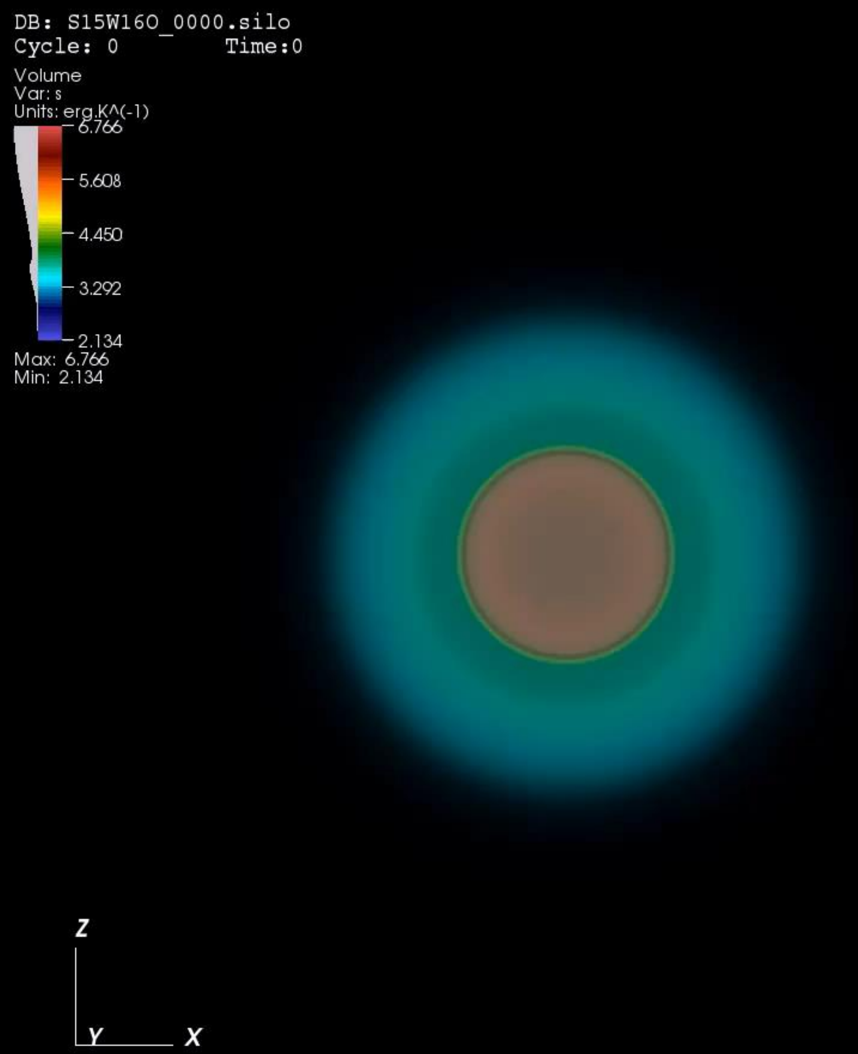




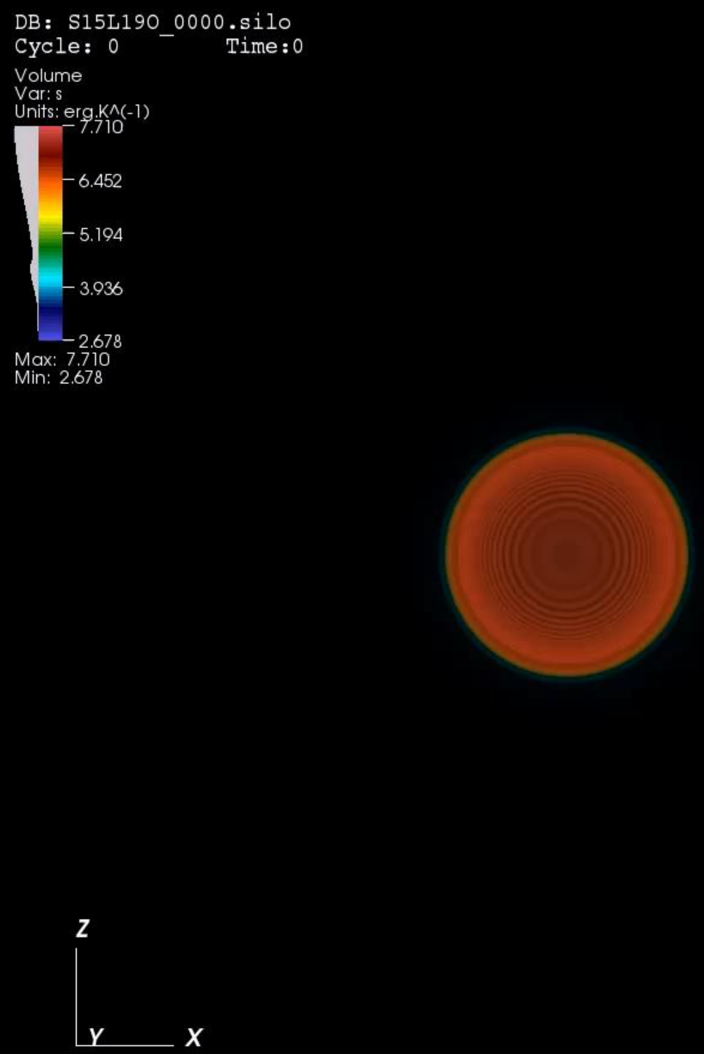


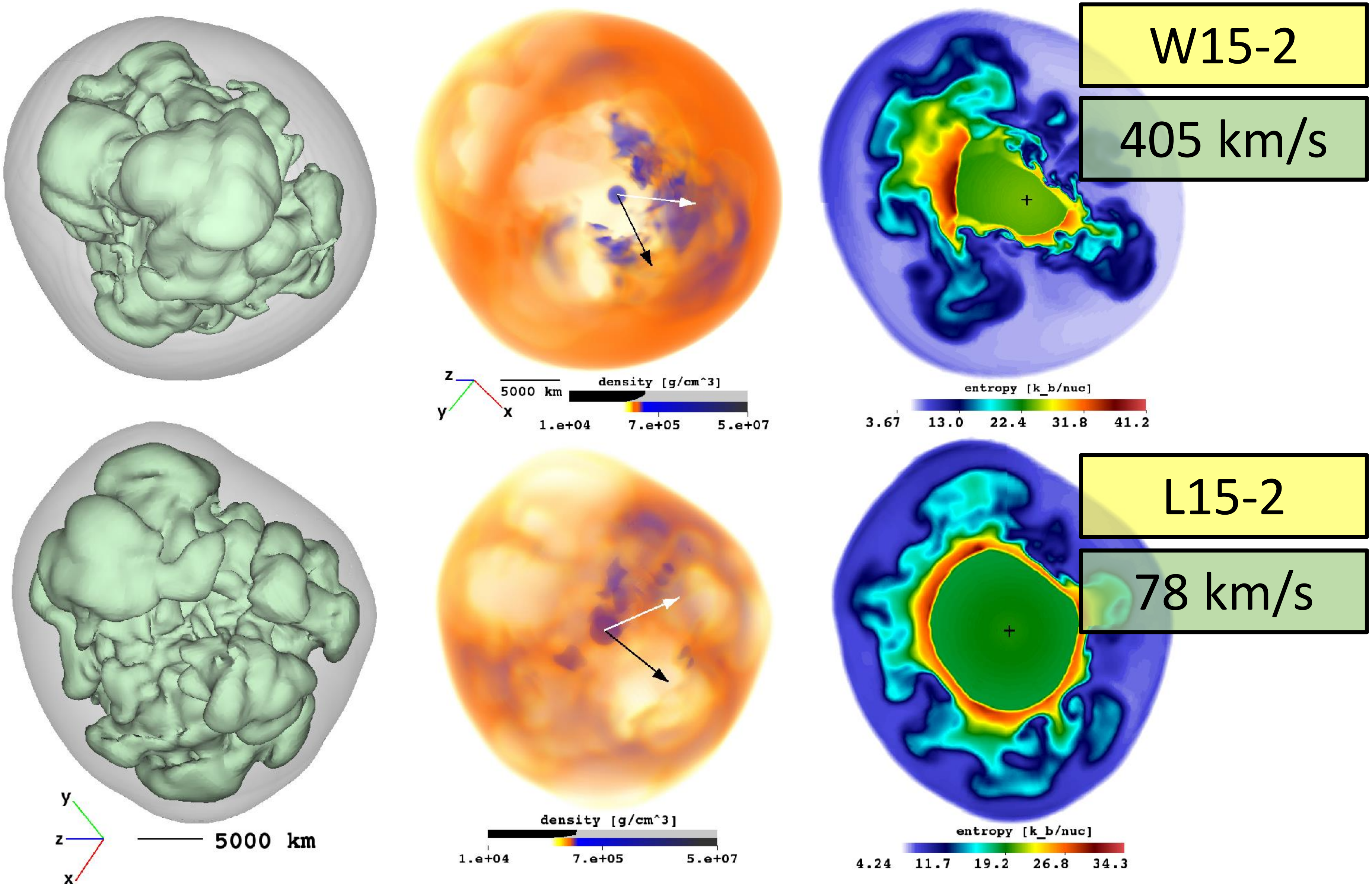
gravitational drag term is dominant

high kick

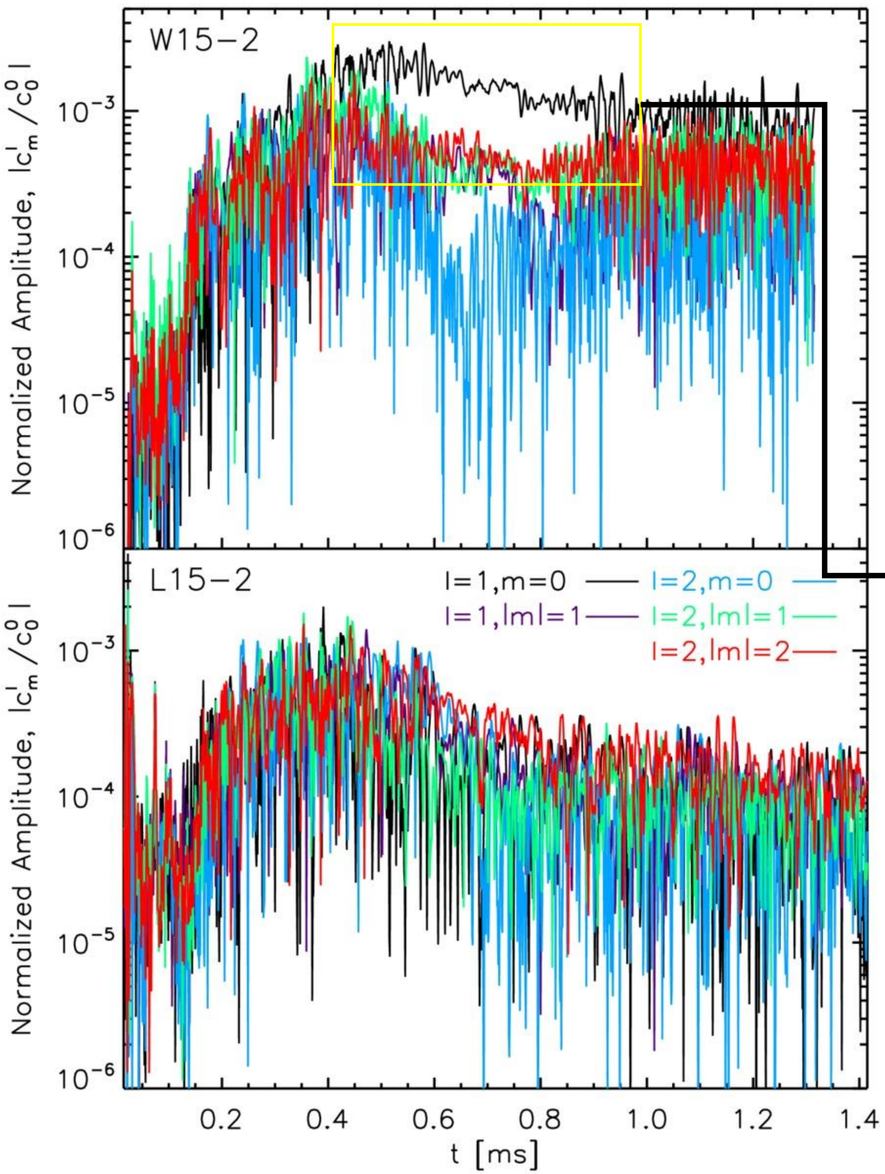

DB: S15W16O_0000.silo
Cycle: 0
Time:0
Volume
Var: s
Units: erg.K^(-1)
6.766
5.608
4.450
3.292
2.134
Max: 6.766
Min: 2.134
Z
Y
X

low kick


DB: S15L190_0000.silo
Cycle: 0
Time:0
Volume
Var: s
Units: erg.K^(-1)
7.710
6.452
5.194
3.936
2.678
Max: 7.710
Min: 2.678
Z
Y
X


W15-2
405 km/s
L15-2
78 km/s
5000 km
density [g/cm^3]
1.e+04
7.e+05
5.e+07
entropy [k_b/nuc]
3.67
13.0
22.4
31.8
41.2
4.24
11.7
19.2
26.8
34.3
x
y
z

Neutron star kicks



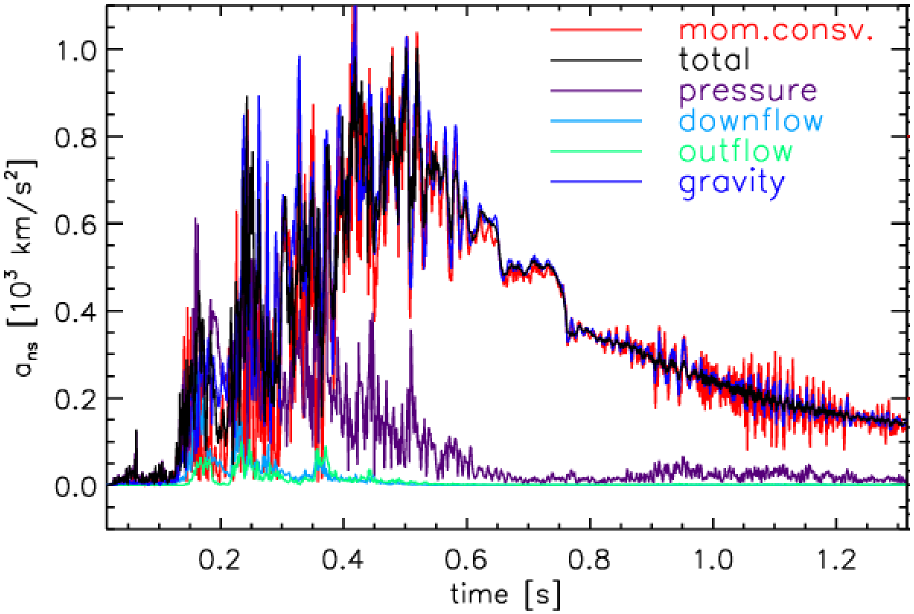
surface mass density

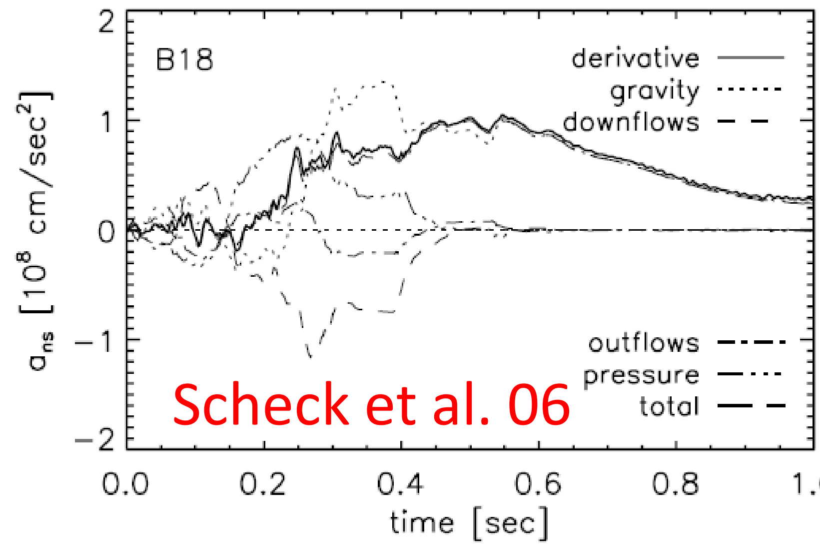
$$\Sigma(\mathrm{r},\theta,\phi) = \int \rho(r,\theta,\phi)\, dr$$

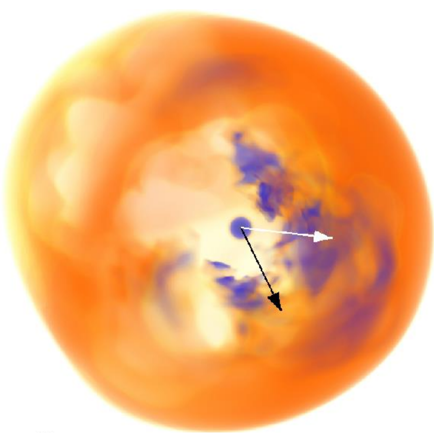
Spherical harmonics decomposition

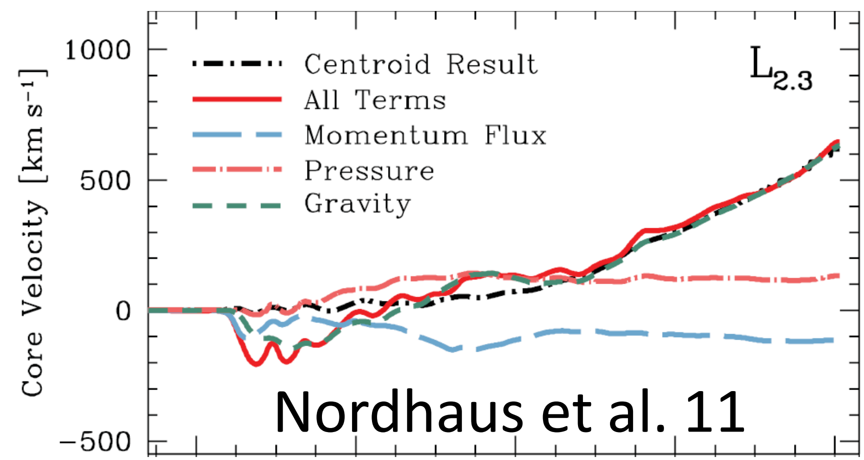
Large *ℓ=1,m=0* mode

$$\dot{\vec{P}}_{ns} \approx -\oint_{r=r_0} P\, d\vec{S} - \oint_{r=r_0} \rho \vec{v} v_r dS + \int_{r>r_0} \frac{G M_{ns} \vec{r}}{r^3}\, dm$$







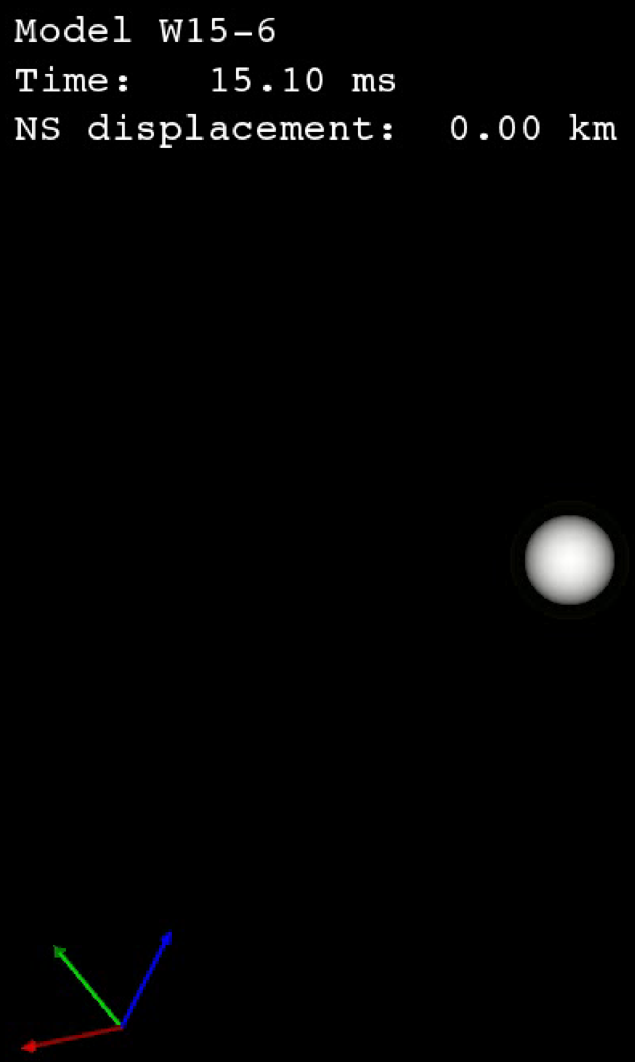


gravitational drag term is dominant

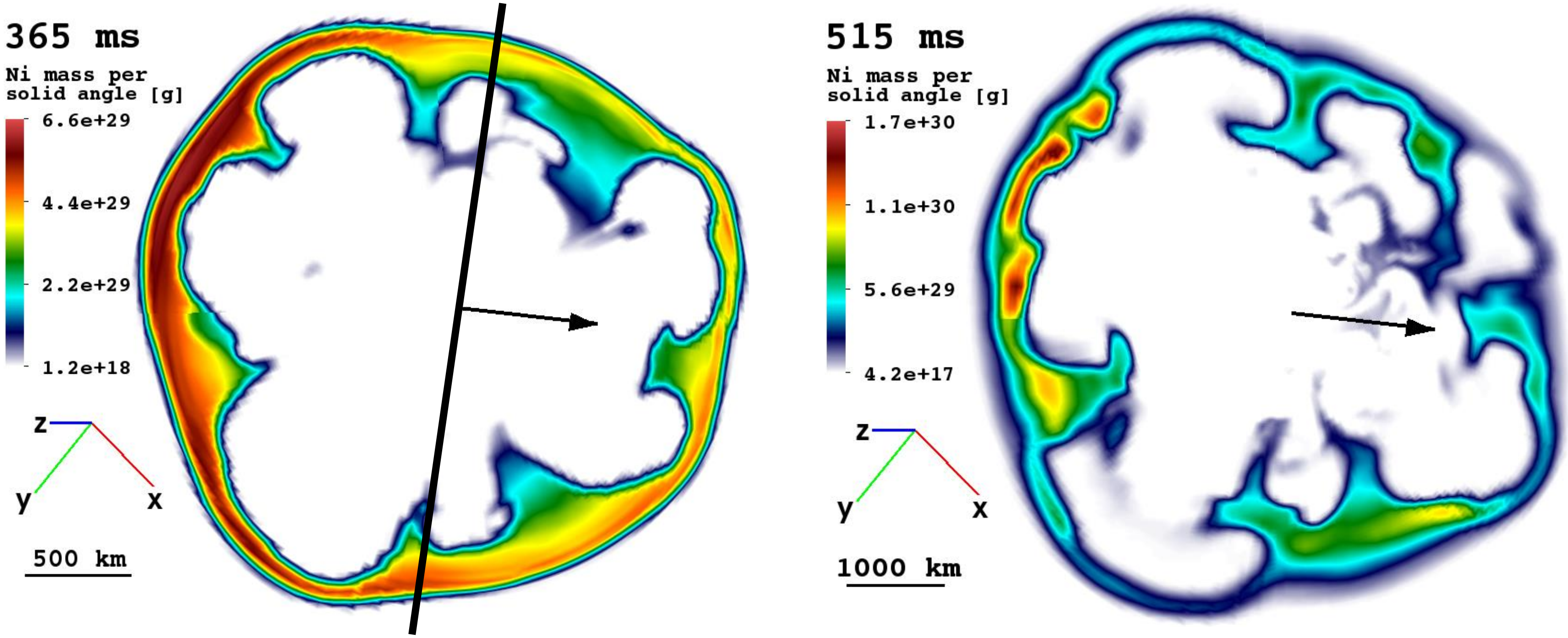
Neutron star kicks

W15-6

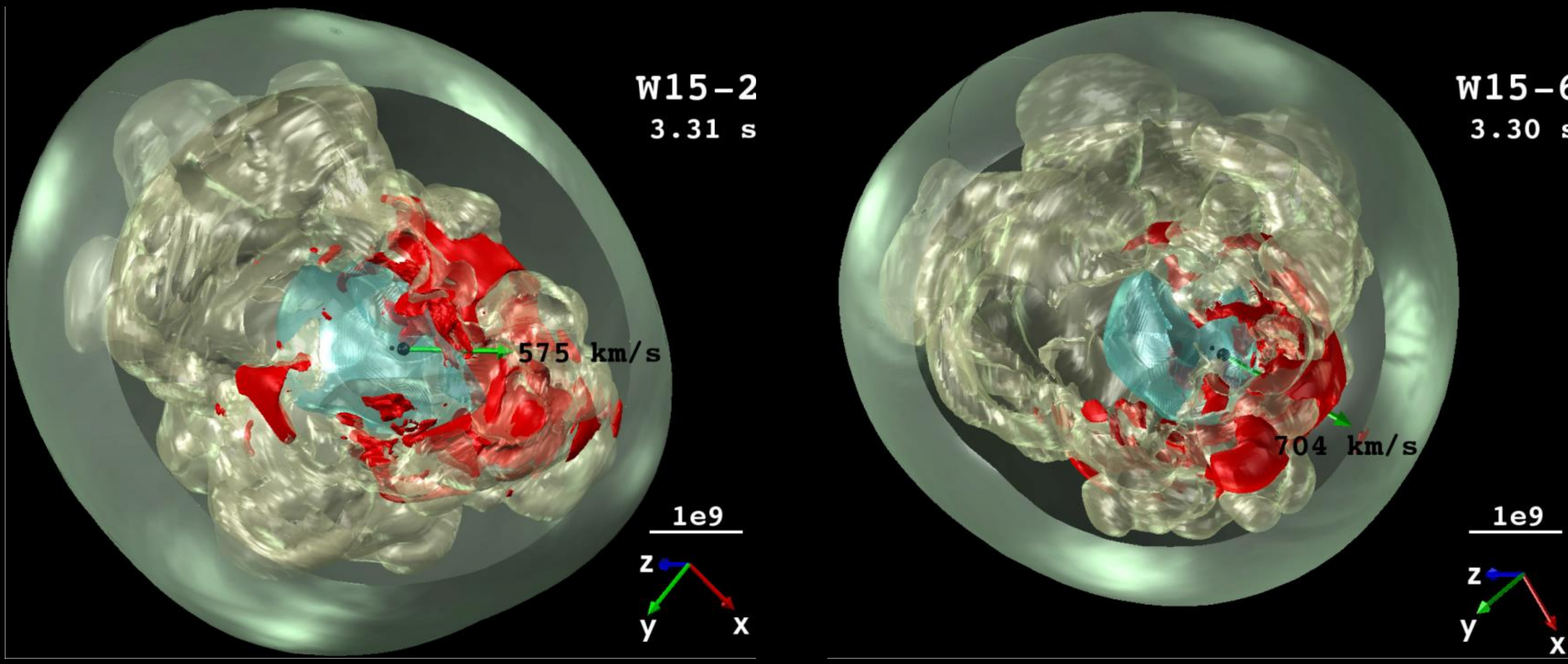
704 km/s



Nickel distribution



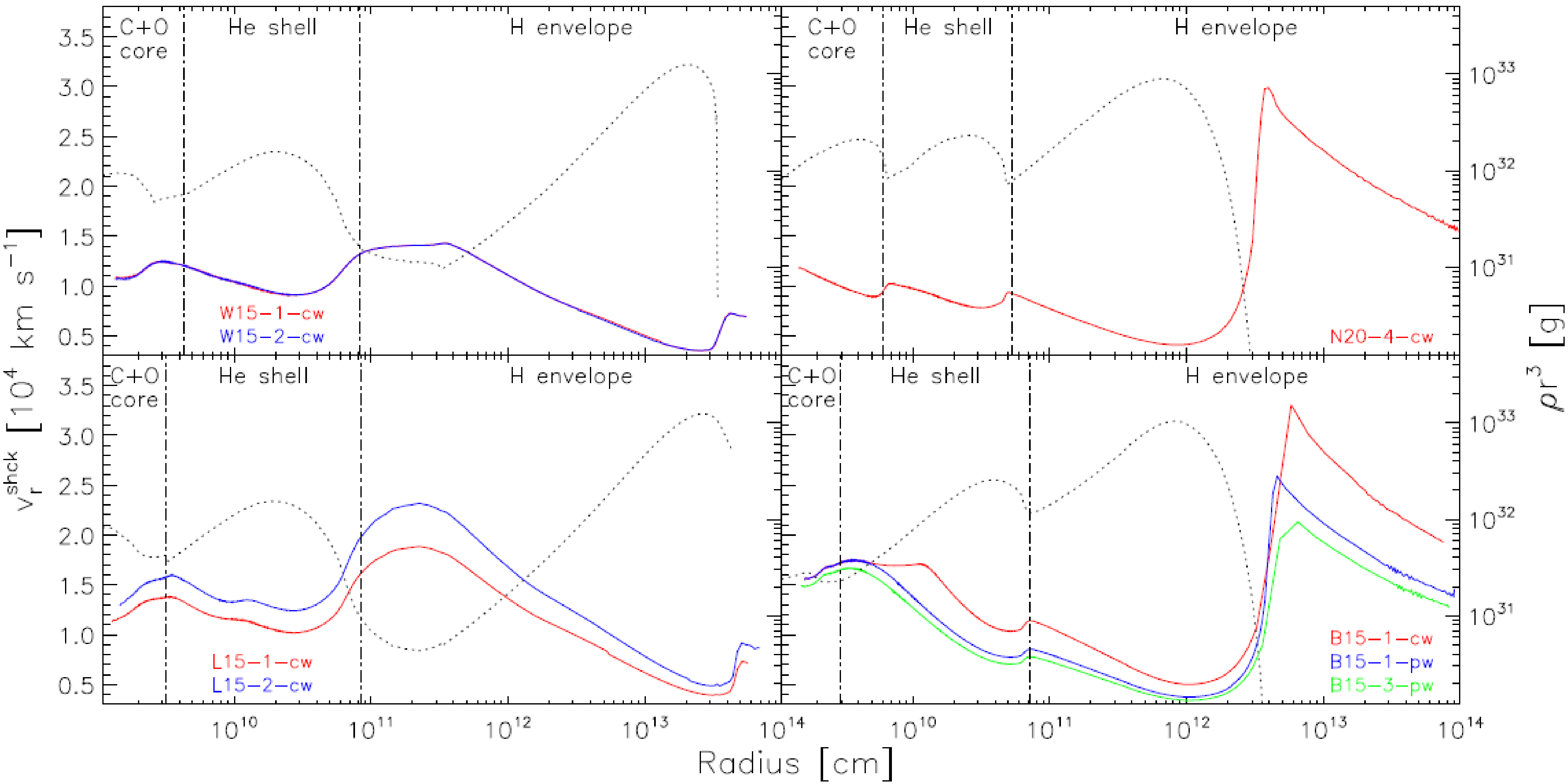
Ni shows hemispheric asymmetry


W15-2
3.31 s
575 km/s
1e9
z
y
x
W15-6
3.30 s
704 km/s
1e9
z
y
x

Shock dynamics

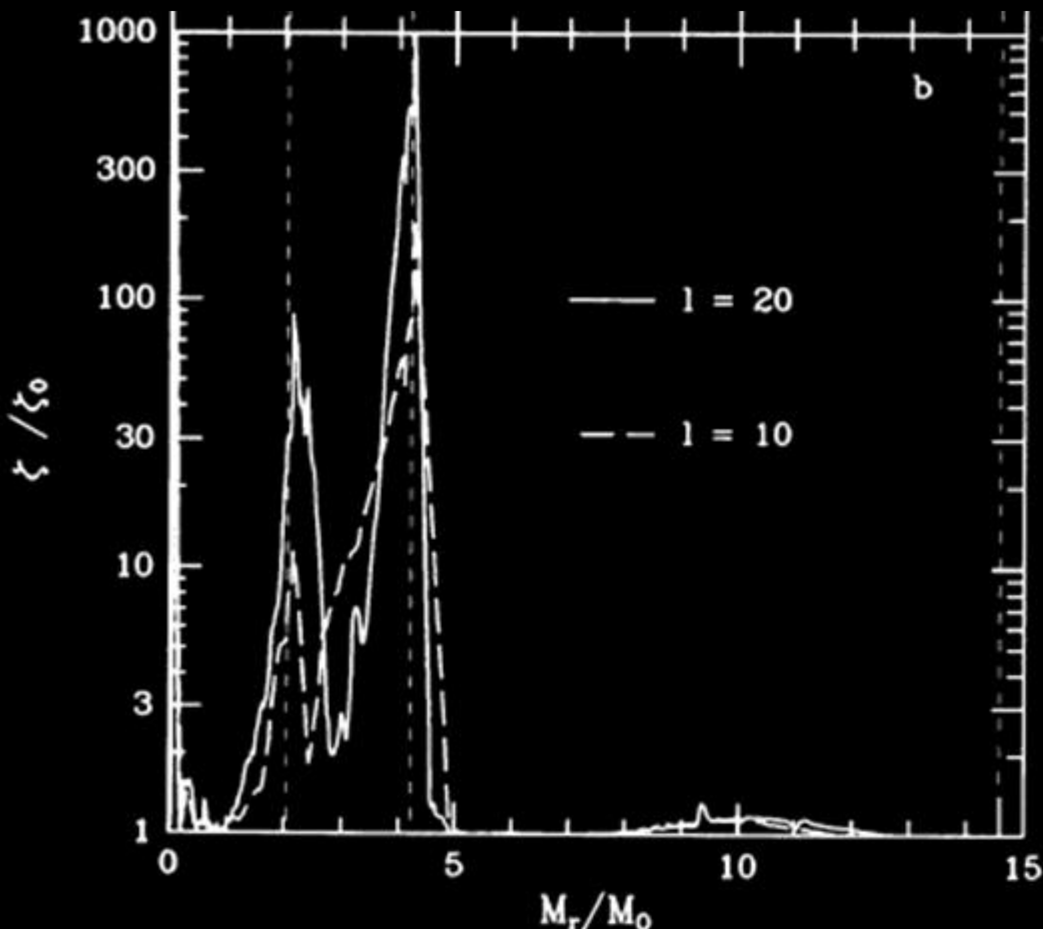
shock propagates according to blast wave solution (Sedov, 1959)

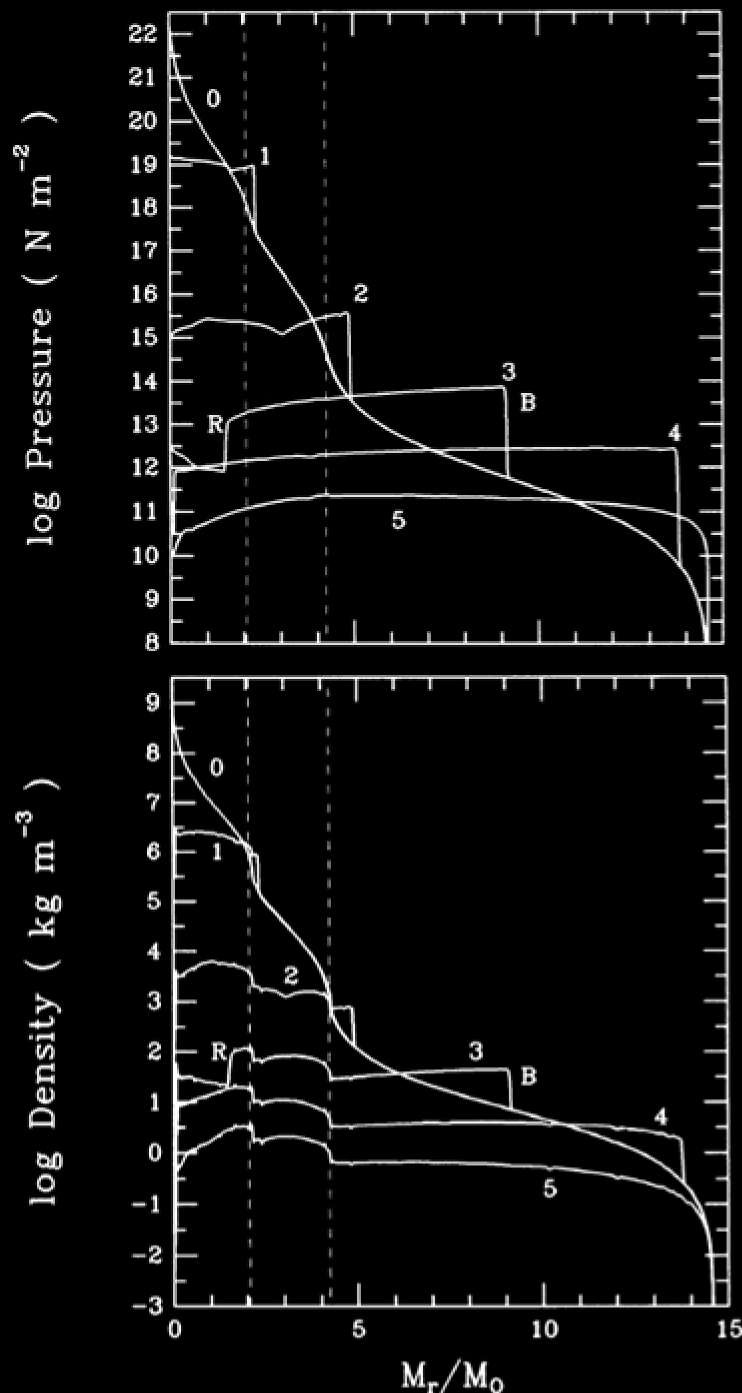
accelerates when ρr^3 decreases, and vice versa



Rayleigh-Taylor instabilities induce mixing

Ebisuzaki et al. (1989)

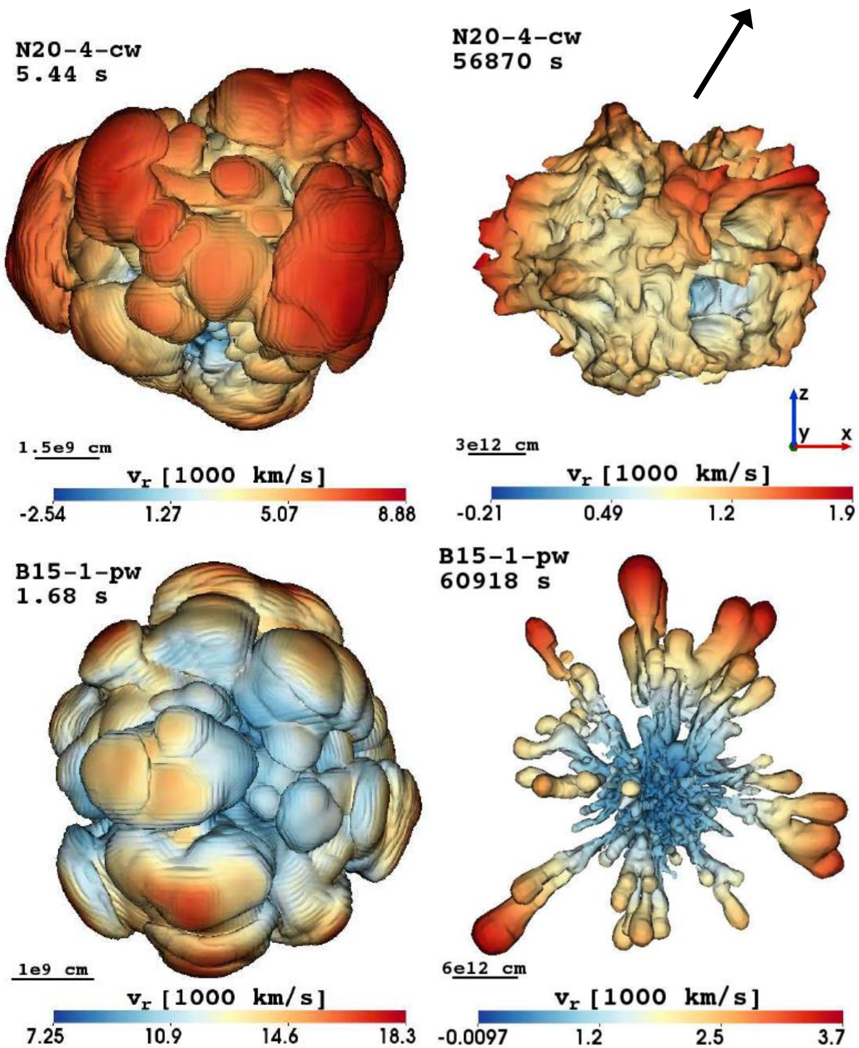


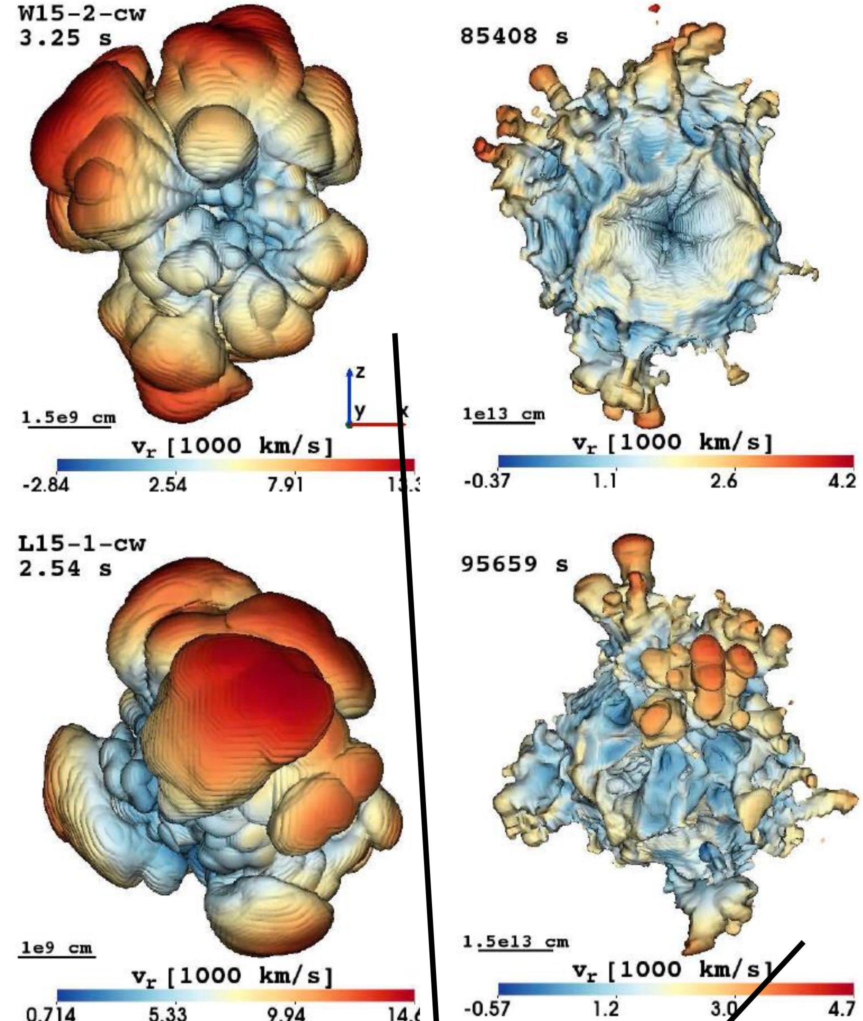


Early vs. late morphology

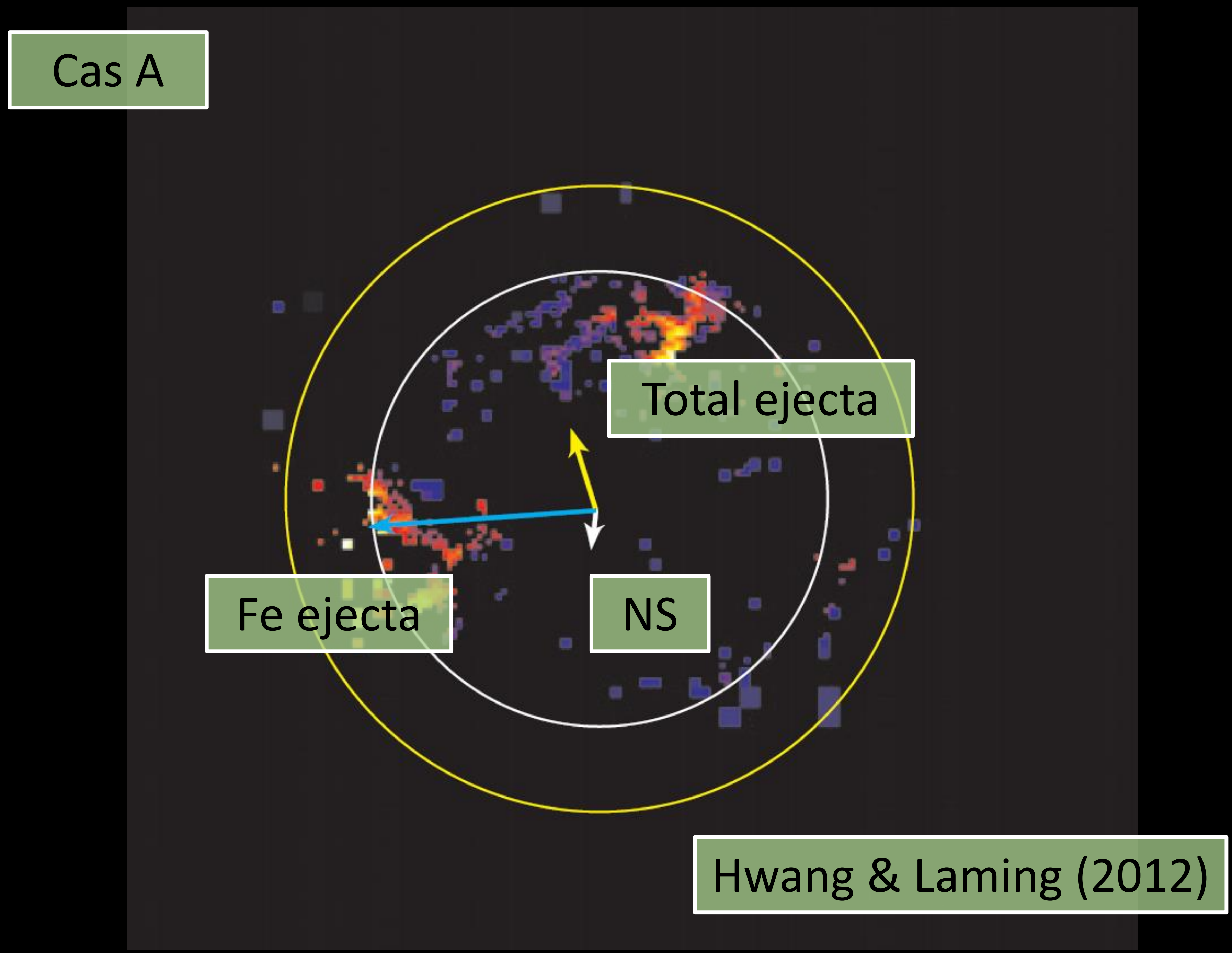
Explosion vs. late-time asymmetries

not so clear??

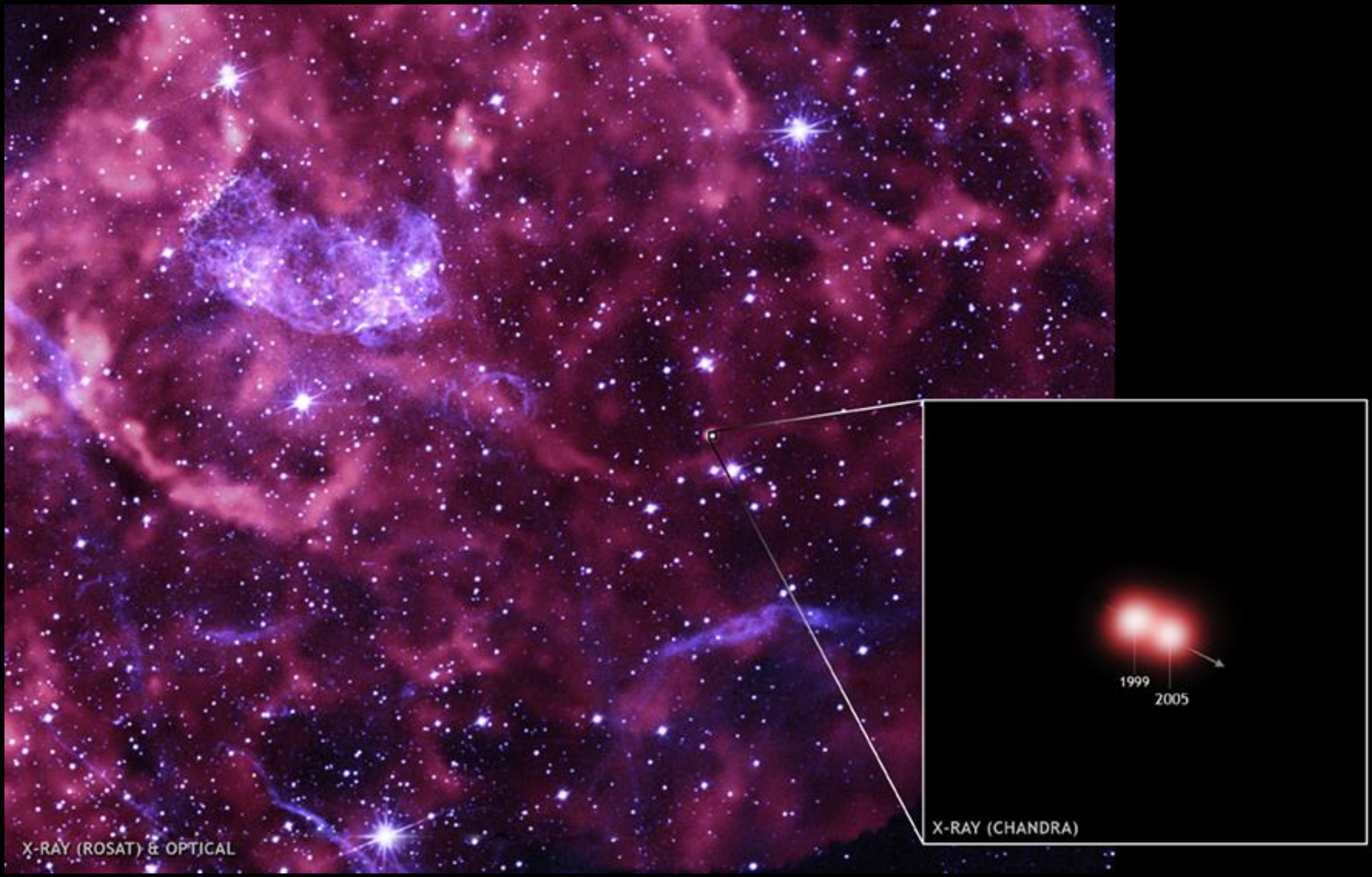




clear correlation


Cas A
Total ejecta
Fe ejecta
NS
Hwang & Laming (2012)

Puppis A



Need to find NS in remnants

Need obs. with large coverage

Need obs. with good angular resolution

Conclusions

- 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
- observe no spin-kick alignment
- progenitor dependence??
- progenitor asymmetries??
- rotation??

Outlook

Progenitor dependence

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]
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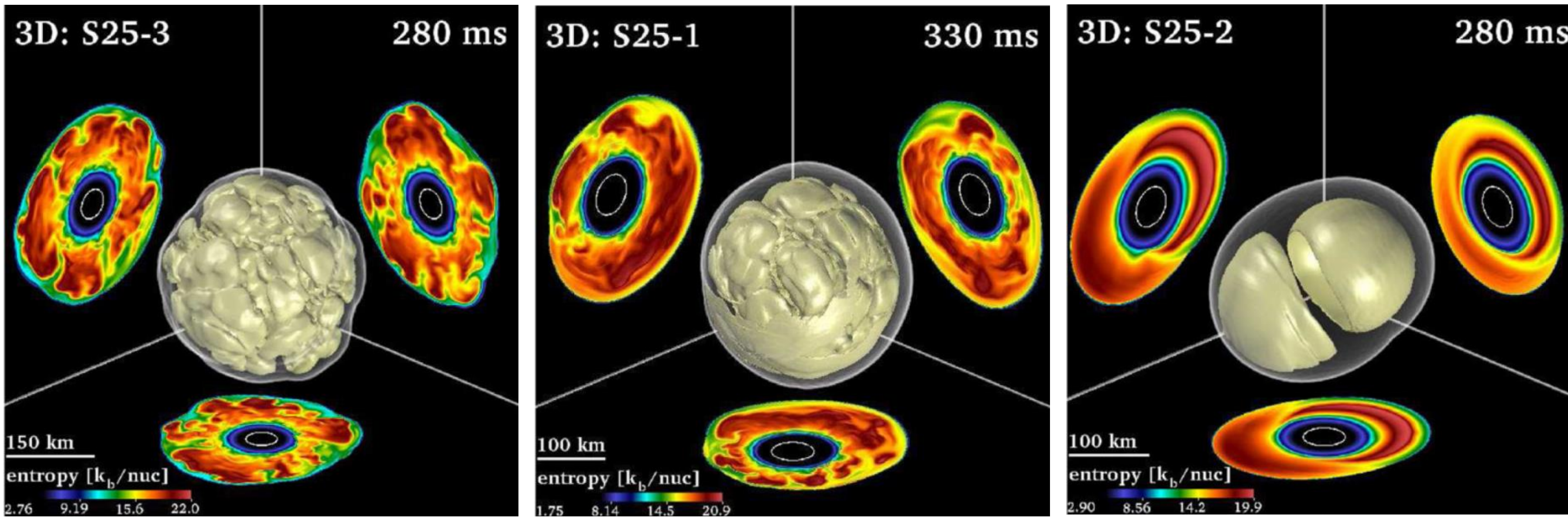
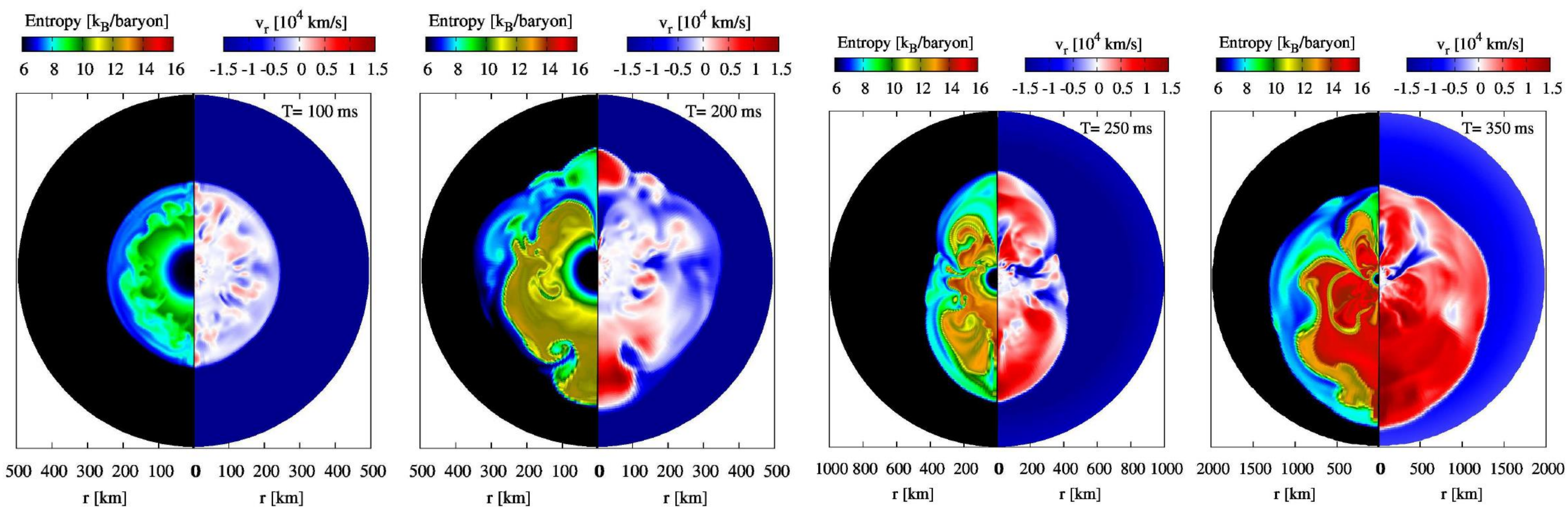
Parametric study (Hanke et al. 2013)



SASI or Convection ???
Depending on the conditions in the post-shock flows

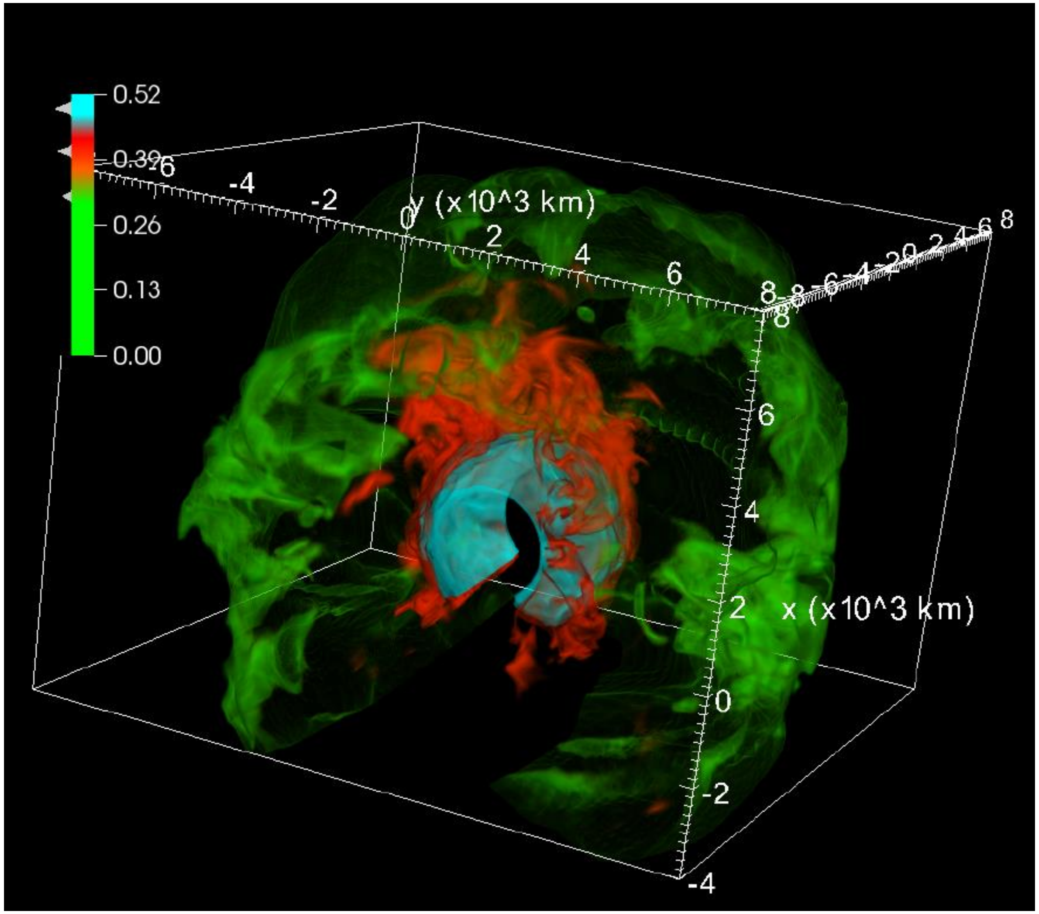
Neutrino-driven explosions of ultra-stripped type Ic supernovae generating binary neutron stars

Model	$t_{\rm final}$[a] [ms]	$R_{\rm sh}$[b] [km]	$E_{\rm exp}$[c] [B]	$M_{\rm NS,baryon}$[d] $[M_\odot]$	$M_{\rm NS,grav}$[e] $[M_\odot]$	$M_{\rm ej}$[f] $[10^{-1} M_\odot]$	$M_{\rm Ni}$[g] $[10^{-2} M_\odot]$	$v_{\rm kick}$[h] [km s^{-1}]
CO145	491	4220	0.177	1.35	1.24	0.973	3.54	3.20
CO15	584	4640	0.153	1.36	1.24	1.36	3.39	75.1
CO16	578	3430	0.124	1.42	1.29	1.76	2.90	47.6
CO18	784	2230	0.120	1.49	1.35	3.07	2.56	36.7
CO20[i]	959	1050	0.0524	1.60	1.44	3.95	0.782	10.5

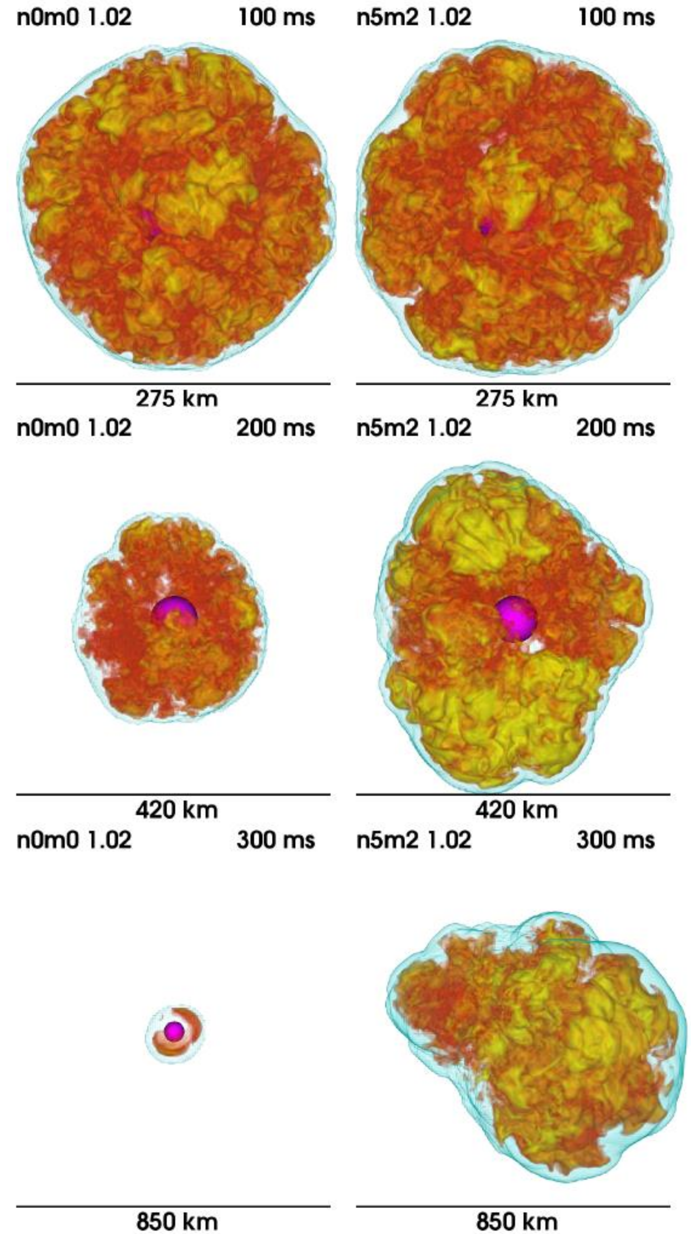


Suwa+ (2015)

Progenitor asymmetries

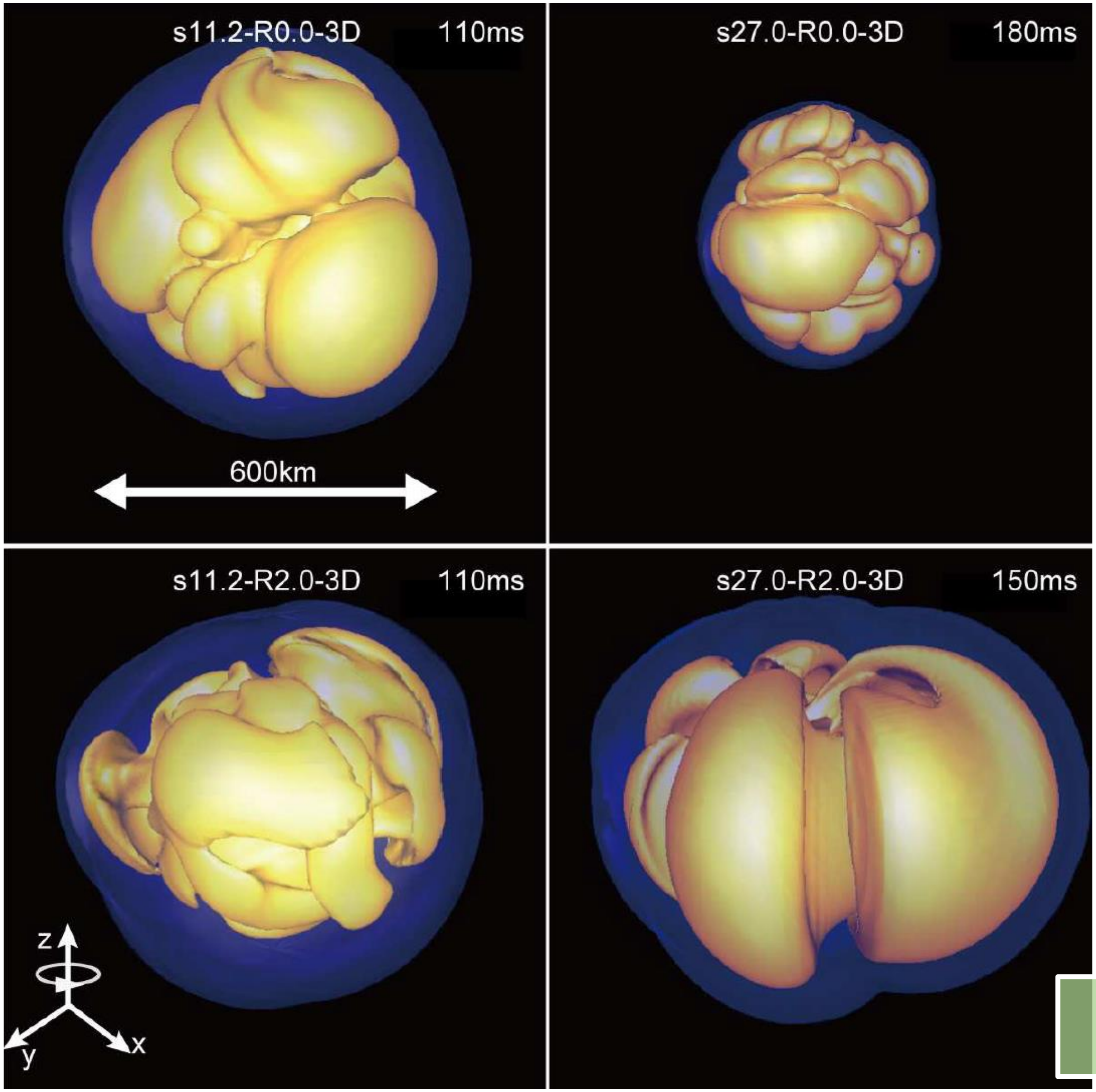


Mueller+ (2016)



Couch & Ott (2013)

Rotation



Takiwaki+ (2016)