Max-Planck-Institut
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Supernova Explosions and Observable Consequences

Hans-Thomas Janka
Max Planck Institute for Astrophysics, Garching

Outline

- Introduction: The neutrino-driven mechanism
- Status of self-consistent 2D and 3D models
- Asymmetric mass ejection & neutron star kicks
  (Scheck et al. 2004, 2006; Wongwathanat et al. 2010, 2012; Nordhaus et al. 2010, 2011)
- Asymmetric mass ejection & large-scale radial mixing
  (Kifonidis et al. 2005, Hammer er al. 2010, Wongwathanat et al., in preparation)
- Progenitor-explosion-remnant connection
  (Ugliano, THJ, Marek, Arcones 2012)
- Characteristic neutrino-signal modulations
  (Marek et al. 2009; Brandt et al. 2011; Müller et al. 2011)
- Gravitational-wave signals
  (Marek et al. 2009; Murphy & Burrows 2009; Müller et al. 2011)
- “Explosive” nucleosynthesis

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- “Explosive” nucleosynthesis

For a concise review of most of what I will say, see

arXiv:1206.2503

Explosion Mechanisms of Core-Collapse Supernovae

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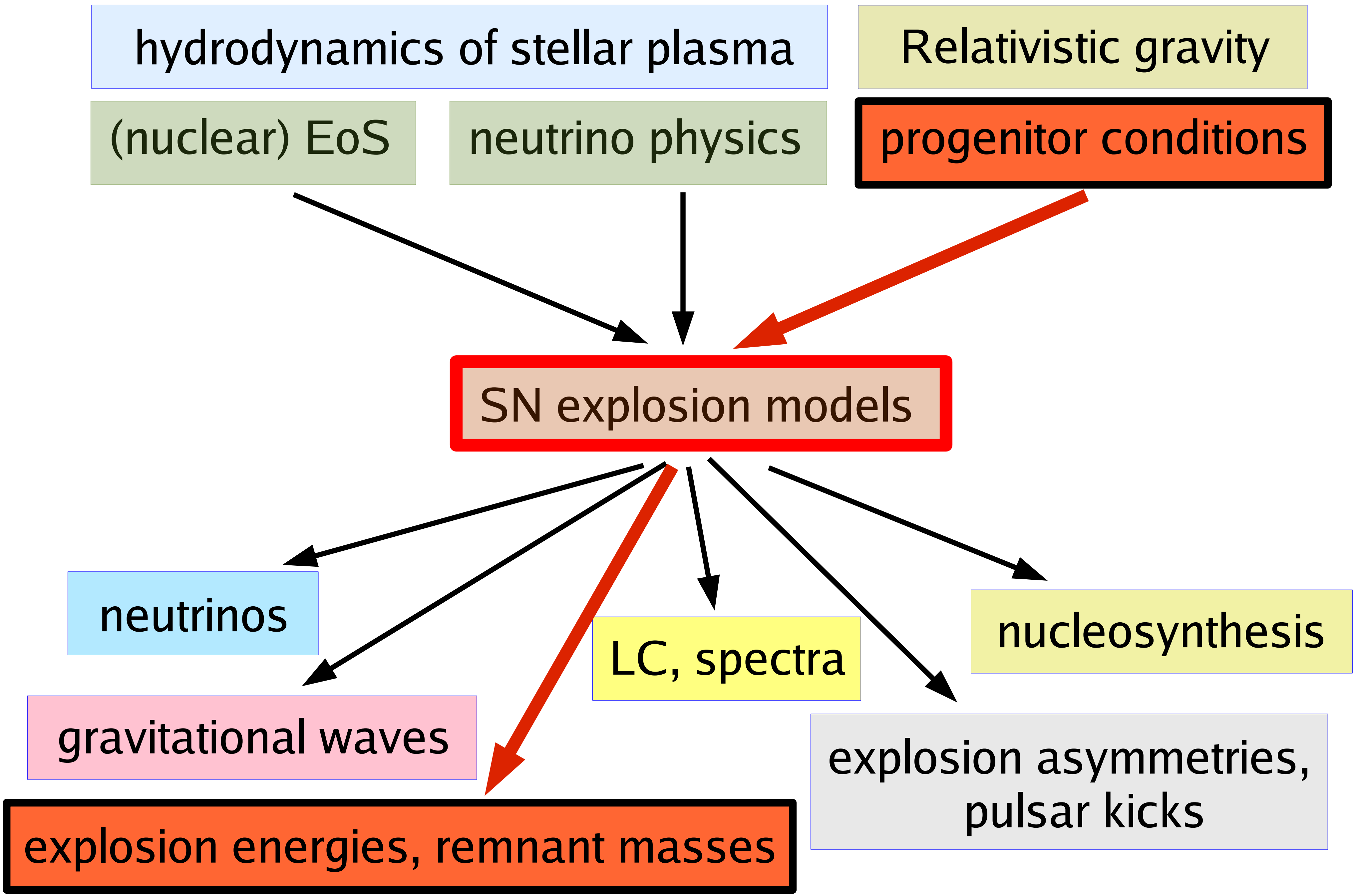
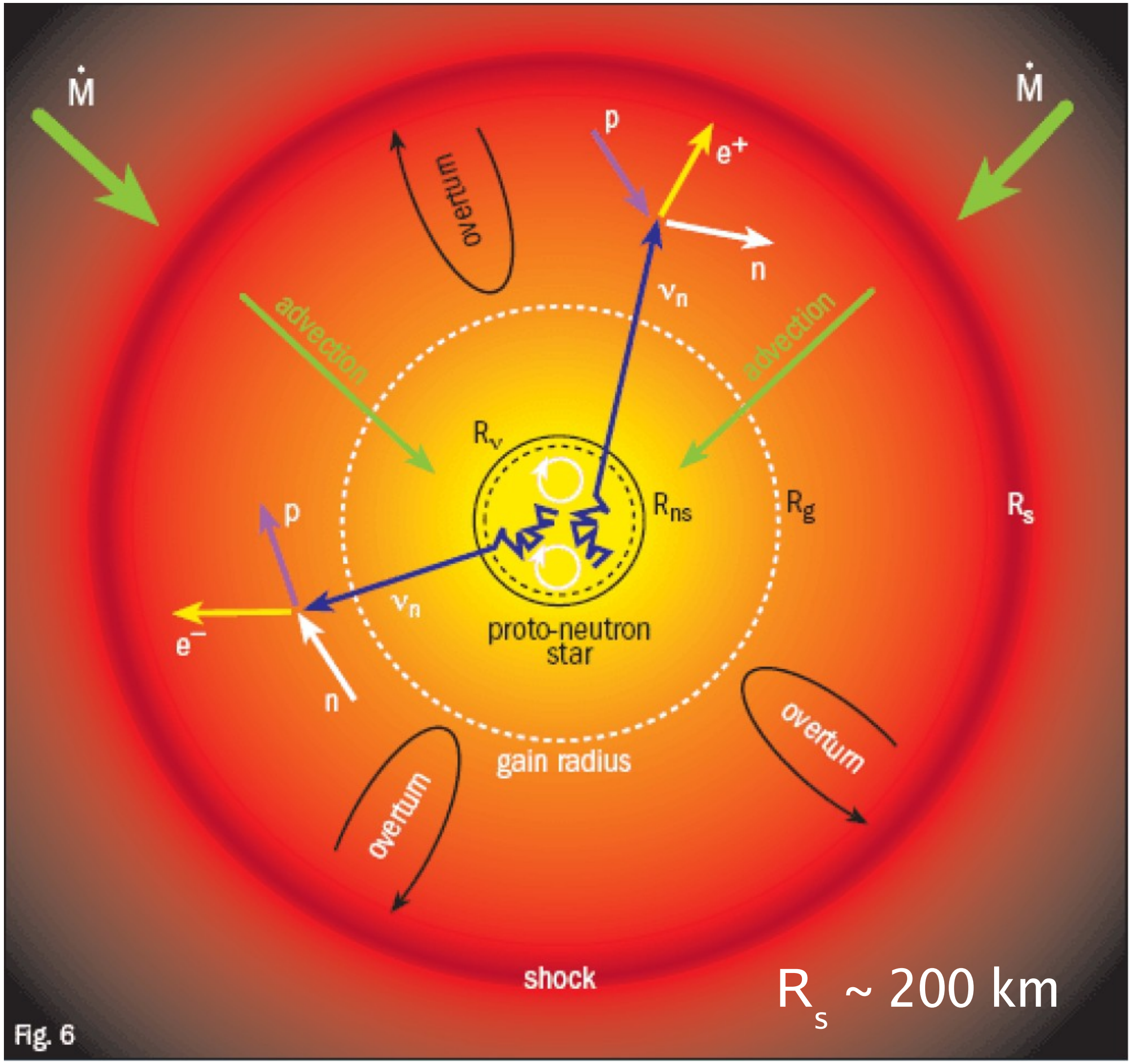
Predictions of Signals from SN Core



Explosion Mechanism
by
Neutrino Heating

Neutrinos & SN Explosion Mechanism

Paradigm: Explosions by the neutrino-heating mechanism, supported by hydrodynamic instabilities in the postshock layer

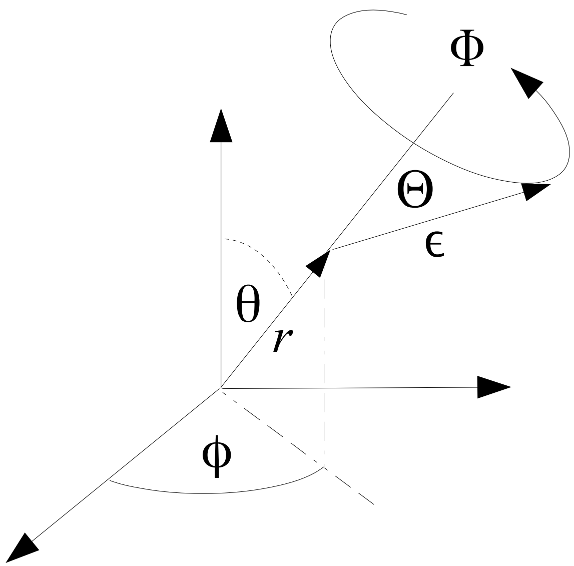


R_s ~ 200 km

- "Neutrino-heating mechanism": Neutrinos `revive' stalled shock by energy deposition
  (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
- Convective processes & hydrodynamic instabilities support the heating mechanism
  (Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; Fryer & Warren 2002, 2004; Blondin et al. 2003; Scheck et al. 2004,06,08).

Explosion Modeling in 2D and 3D

The Curse and Challenge of the Dimensions



Boltzmann equation determines neutrino distribution function in 6D phase space and time

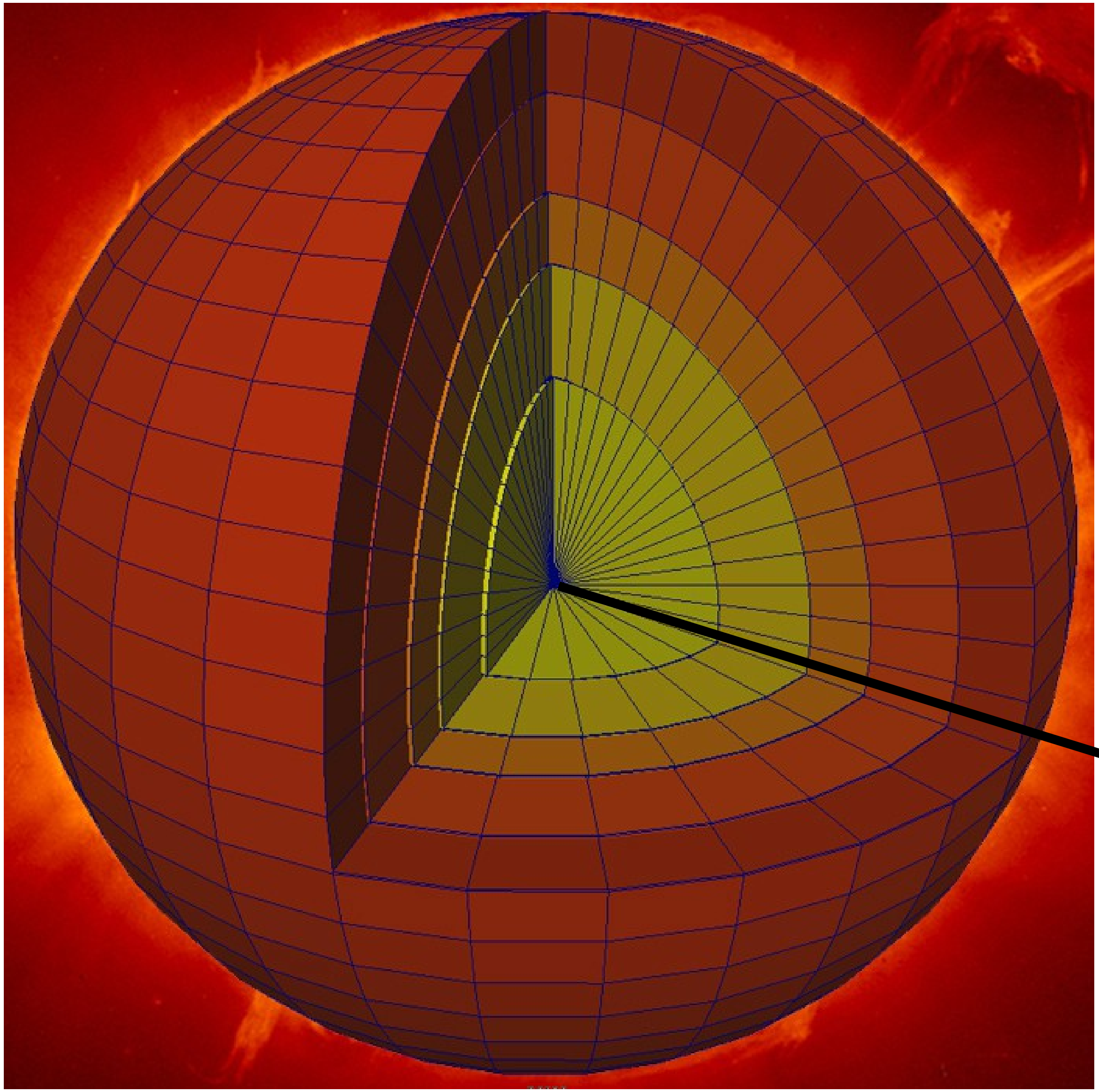
$$f(r,\theta,\phi,\Theta,\Phi,\epsilon,t)$$

Integration over 3D momentum space yields source terms for hydrodynamics

$$Q(r,\theta,\phi,t),\dot{Y}_e(r,\theta,\phi,t)$$

Solution approach	Required resources
• **3D** hydro + **6D** direct discretization of Boltzmann Eq. (code development by Sumiyoshi & Yamada '12)	• $\geq$ 10–100 PFlops/s (sustained!)
• **3D** hydro + two-moment closure of Boltzmann Eq. (may be next feasible step on way to full 3D)	• $\geq$ 1–10 Pflops/s, TBytes
• **3D** hydro + "**ray-by-ray-plus**" variable Eddington factor method (method used at MPA/Garching)	• $\geq$ 0.1–1 PFlops/s, Tbytes
• **2D** hydro + "**ray-by-ray-plus**" variable Eddington factor method (method used at MPA/Garching)	• $\geq$ 0.1–1 Tflops/s, < 1 TByte

"Ray-by-Ray" Approximation for Neutrino Transport in 2D and 3D Geometry



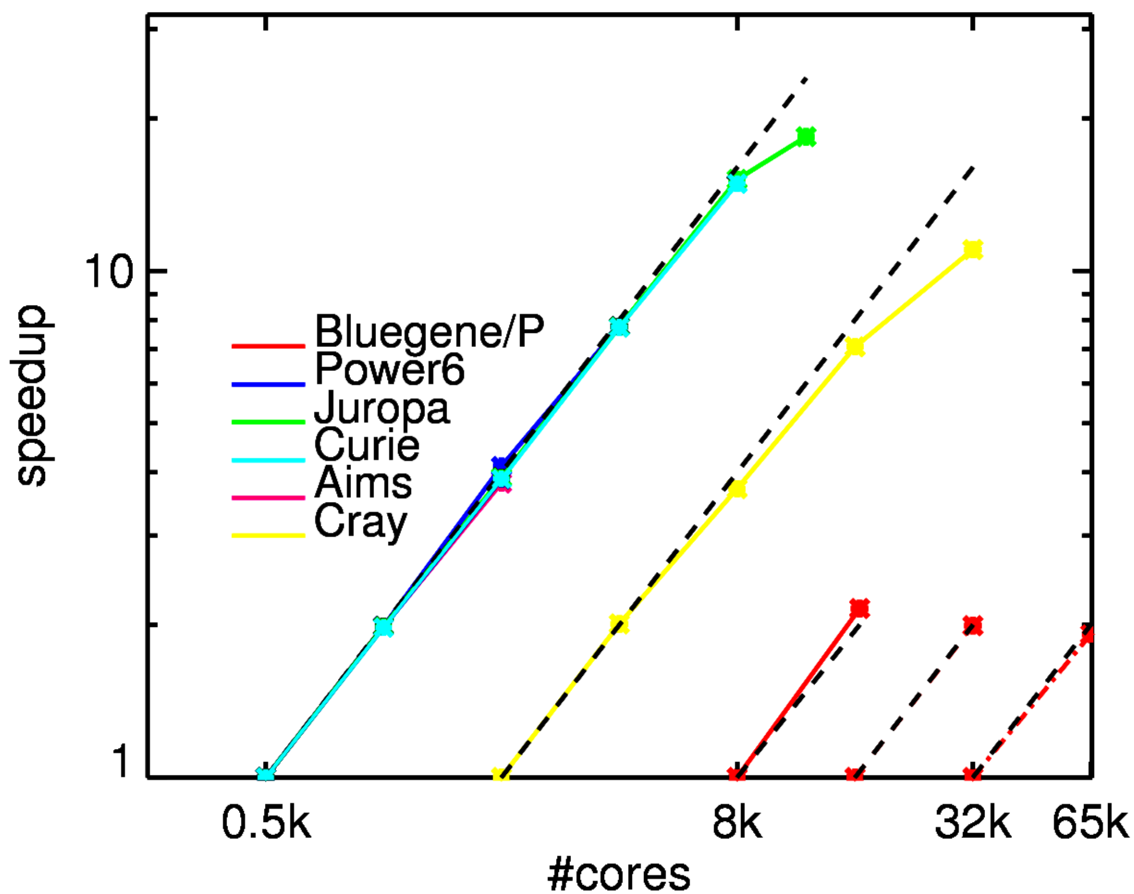
Solve large number of spherical transport problems on radial “rays” associated with angular zones of polar coordinate grid

Suggests efficient parallization over the “rays”

Performance and Portability of our Supernova Code *Prometheus-Vertex*

- Code employs hybrid MPI/OpenMP programming model (collaborative development with **Katharina Benkert, HLRS**).
- Code has been ported to different computer platforms by **Andreas Marek, High Level Application Support, Rechenzentrum Garching (RZG).**
- Code shows excellent parallel efficiency, which will be fully exploited in 3D.

Strong Scaling



Andreas Marek, RZG (2011)

Computing Requirements for 2D & 3D Supernova Modeling

Time-dependent simulations: t ~ 1 second, ~ 10^6 time steps!

CPU-time requirements for one model run:

- **In 2D with 600 radial zones, 1 degree lateral resolution:**

  ~ $3*10^{18}$ Flops, need ~10^6 processor-core hours.

- **In 3D with 600 radial zones, 1.5 degrees angular resolution:**

  ~ $3*10^{20}$ Flops, need ~10^8 processor-core hours.

PRACE Partnership for Advanced Computing in Europe

NIC John von Neumann Institut für Computing

HLRS

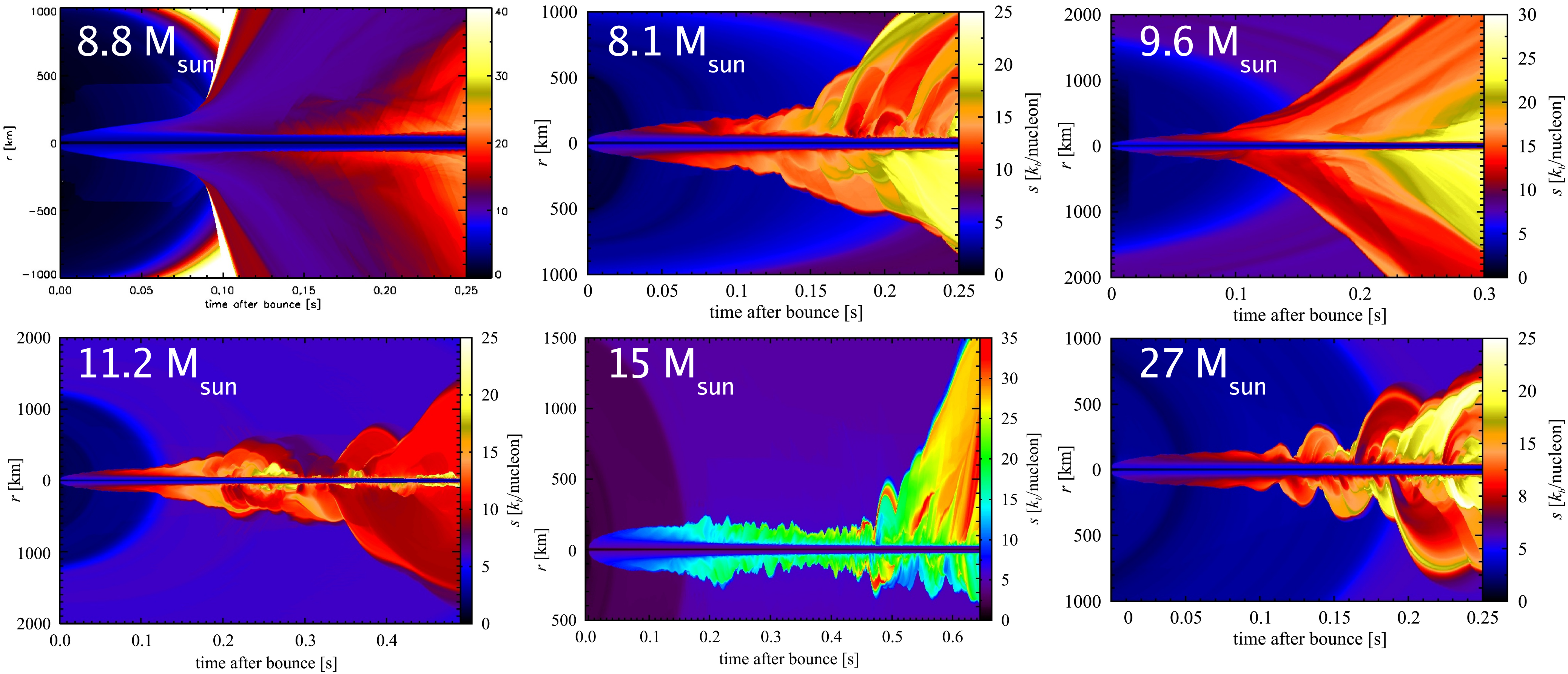
IPP rzg Rechen-Zentrum Garching

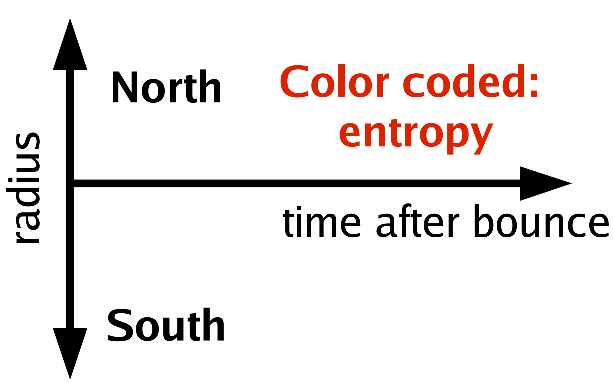
Leibniz-Rechenzentrum der Bayerischen Akademie der Wissenschaften

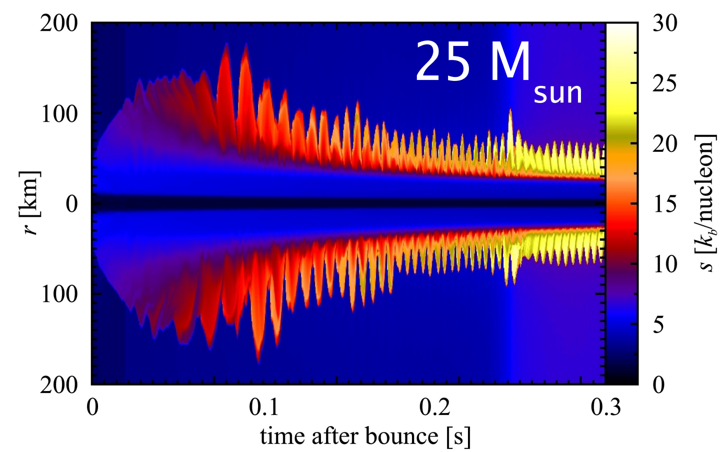
Explosion Mechanism: Most Sophisticated Current Models

See Bernhard Müller's talk for successful, self-consistent 2D simulations

Relativistic 2D CCSN Explosion Models





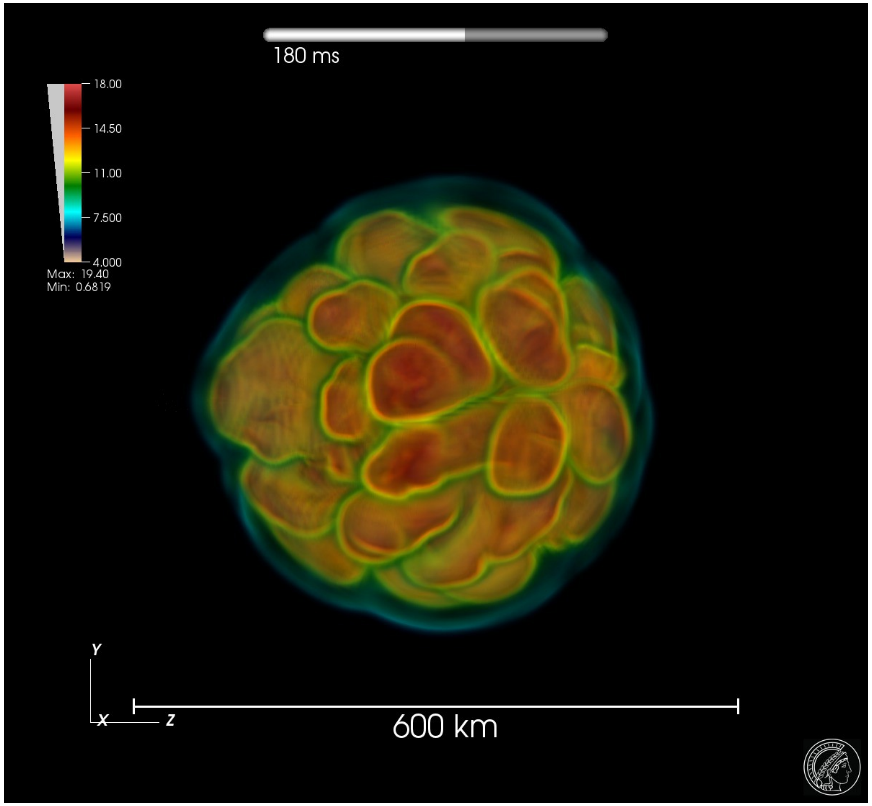


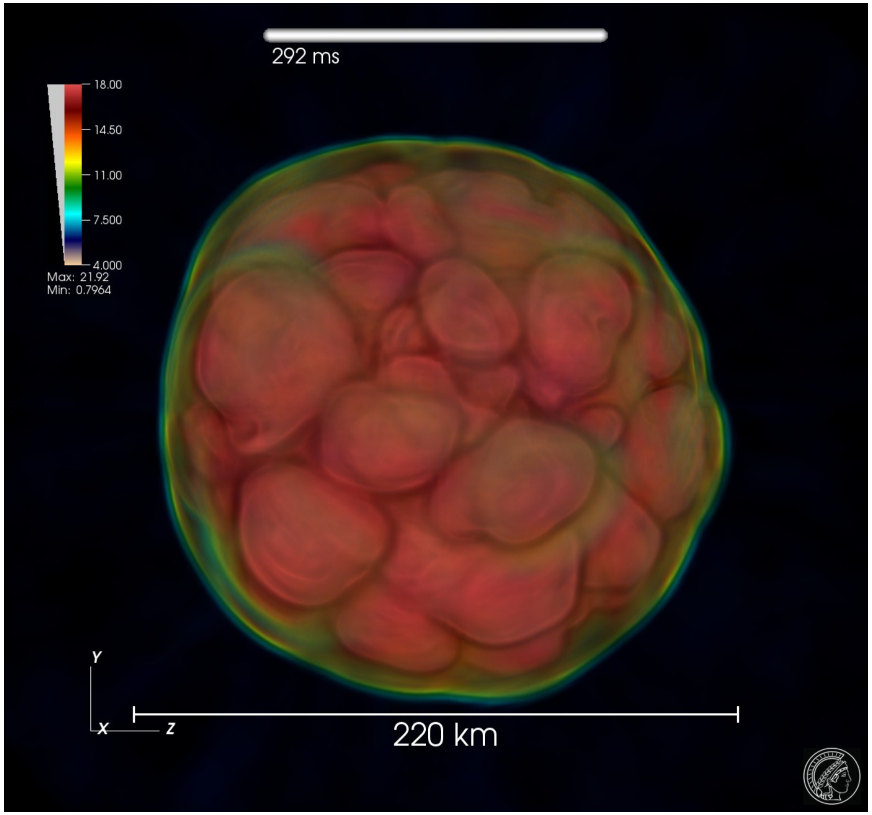
Bernhard Müller, THJ, et al. (2011, 2012)

3D Explosion Models

3D Core-Collapse Models

11.2 M_{sun} progenitor

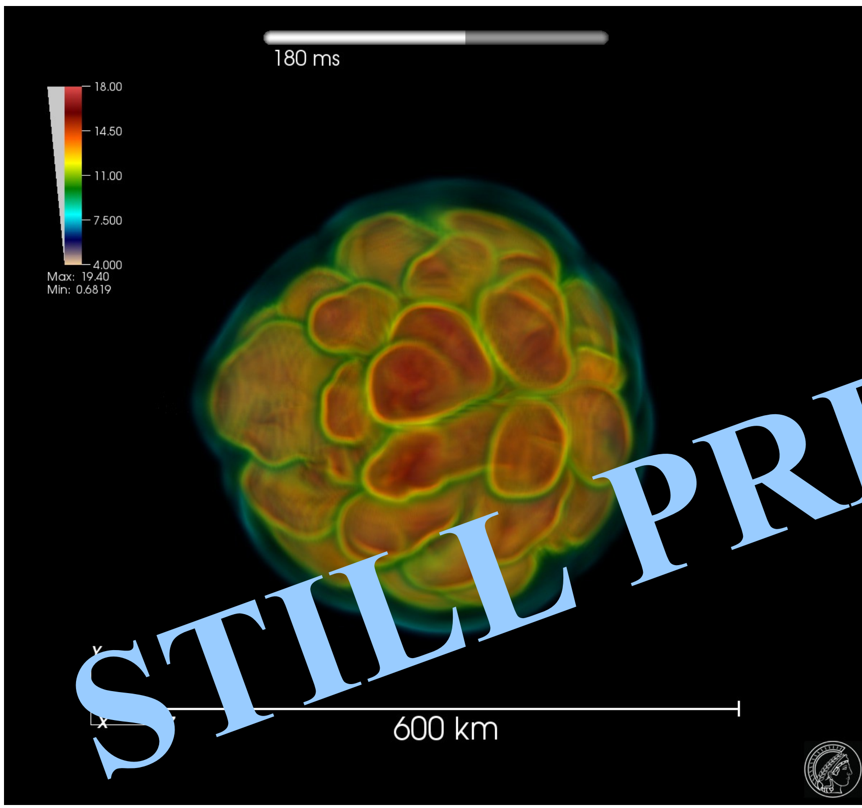


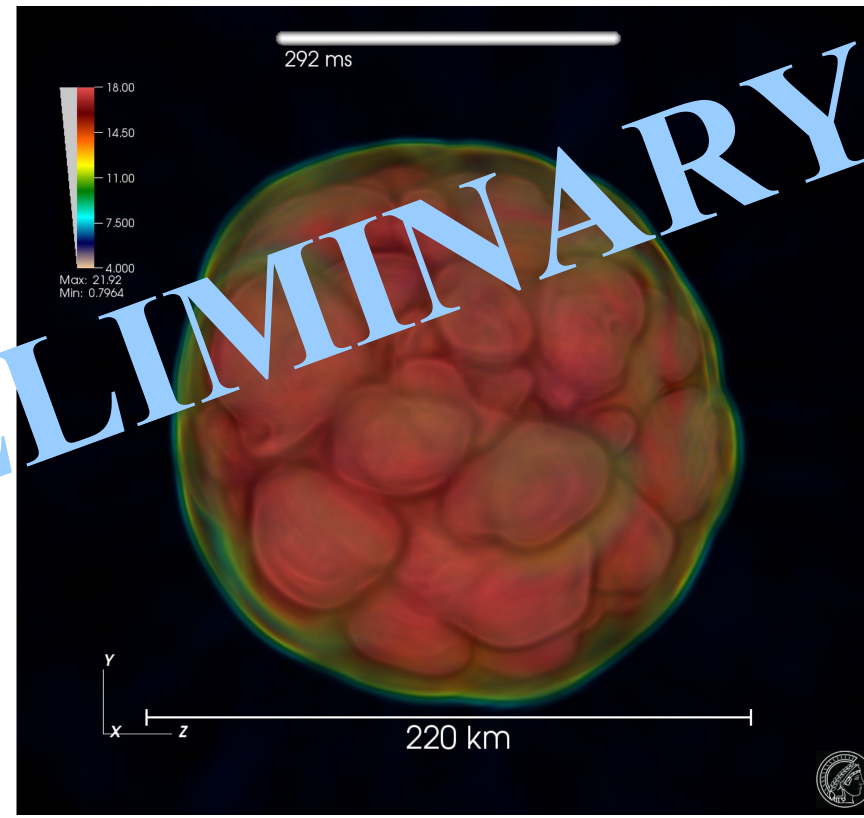


Florian Hanke, PhD project

3D CCSN Explosion Models

11.2 M_{sun} progenitor





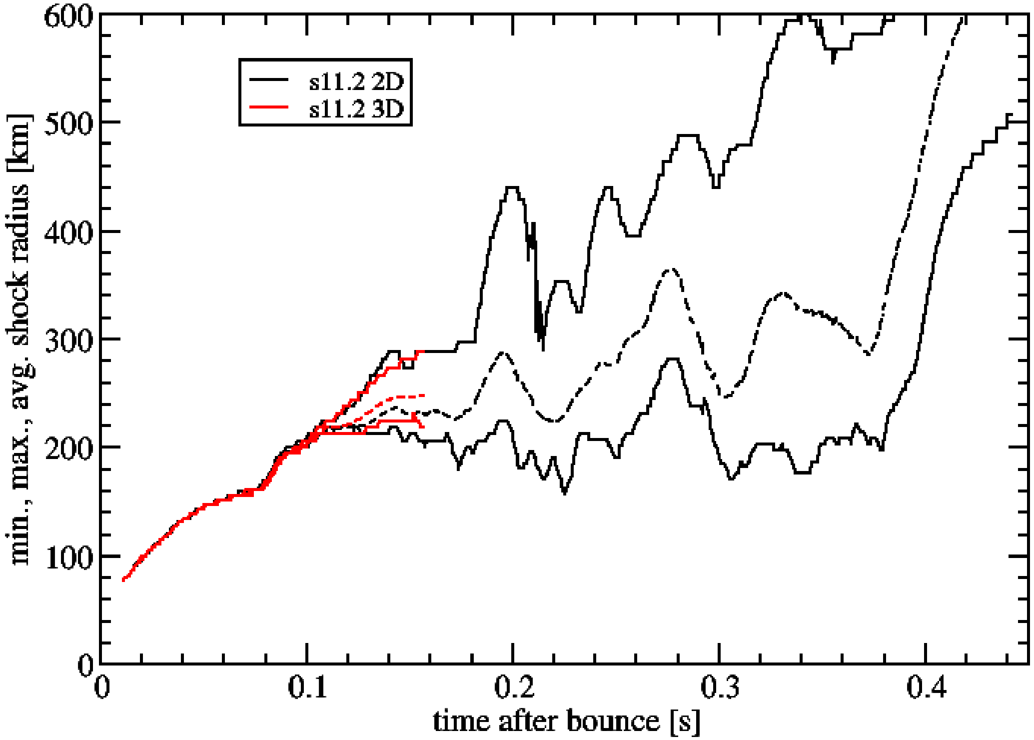
STILL PRELIMINARY

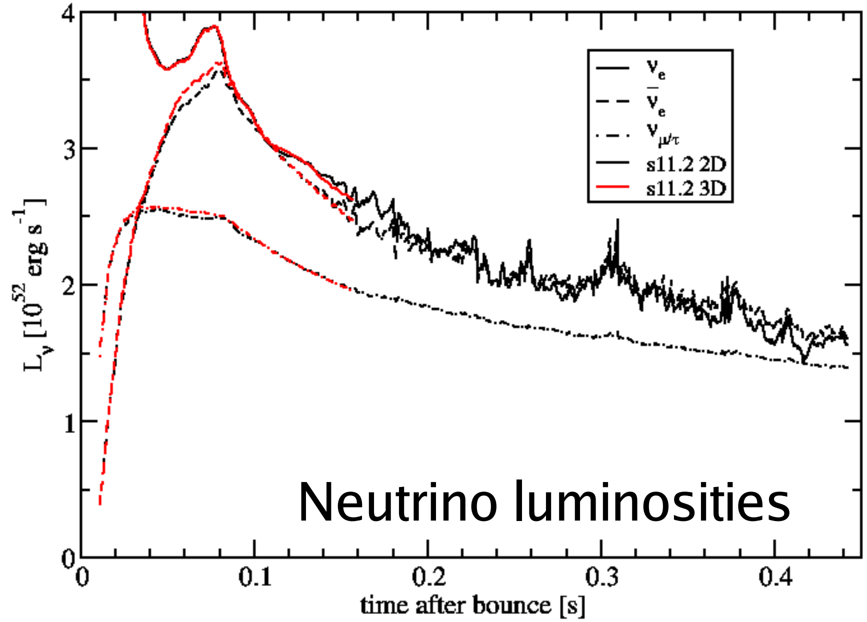
Florian Hanke, PhD project

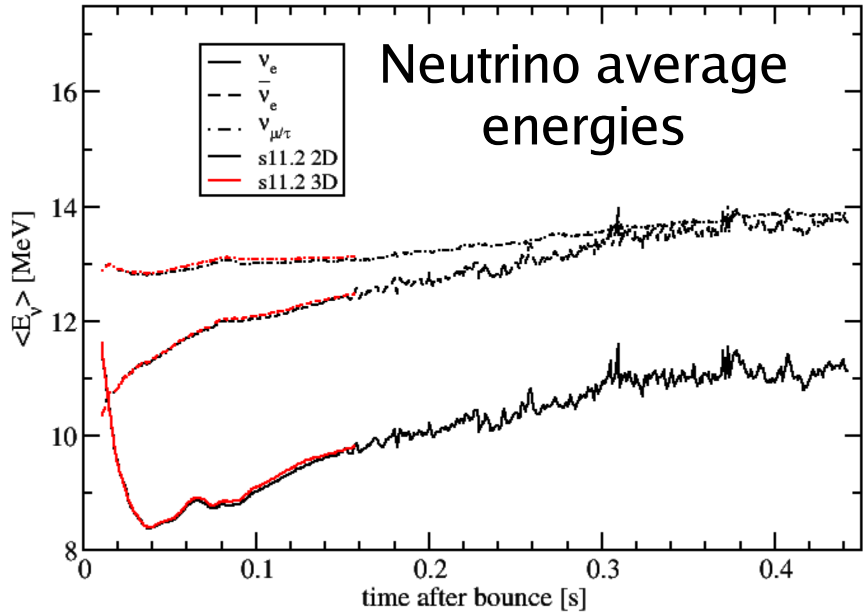
3D Core-Collapse Models

11.2 M_{sun} progenitor

Shock position (max., min., avg.)







Florian Hanke, PhD project

Neutron Star Kicks in 3D SN Explosions

Parametric explosion calculations:

Neutrino core luminosity of proto-NS chosen;
Accretion luminosity calculated with simple (grey) transport scheme

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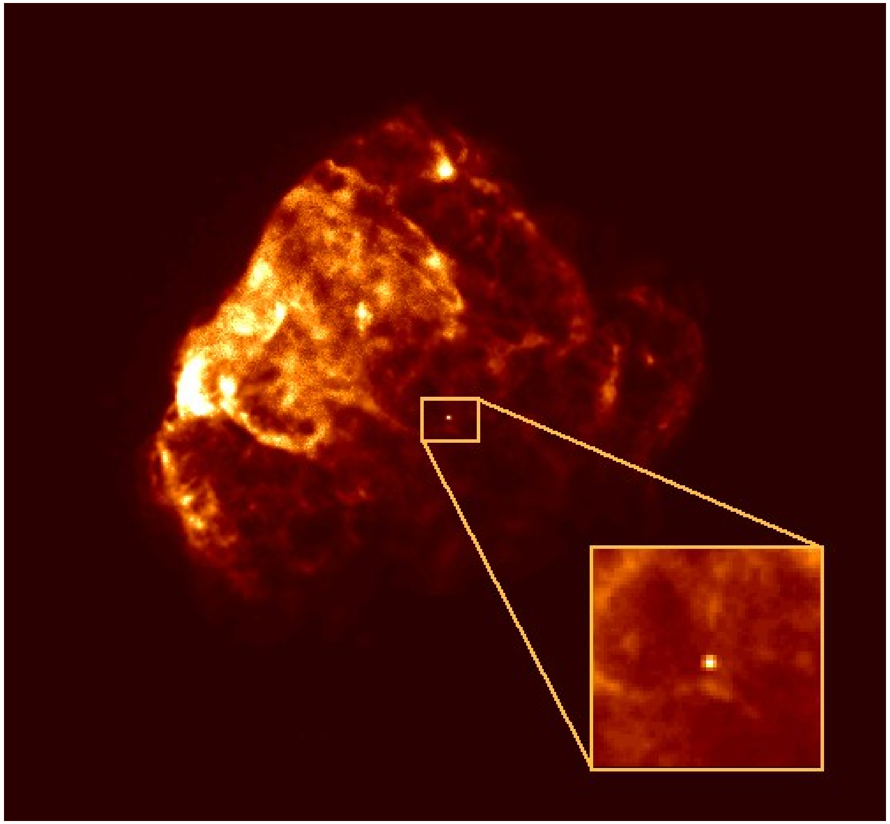
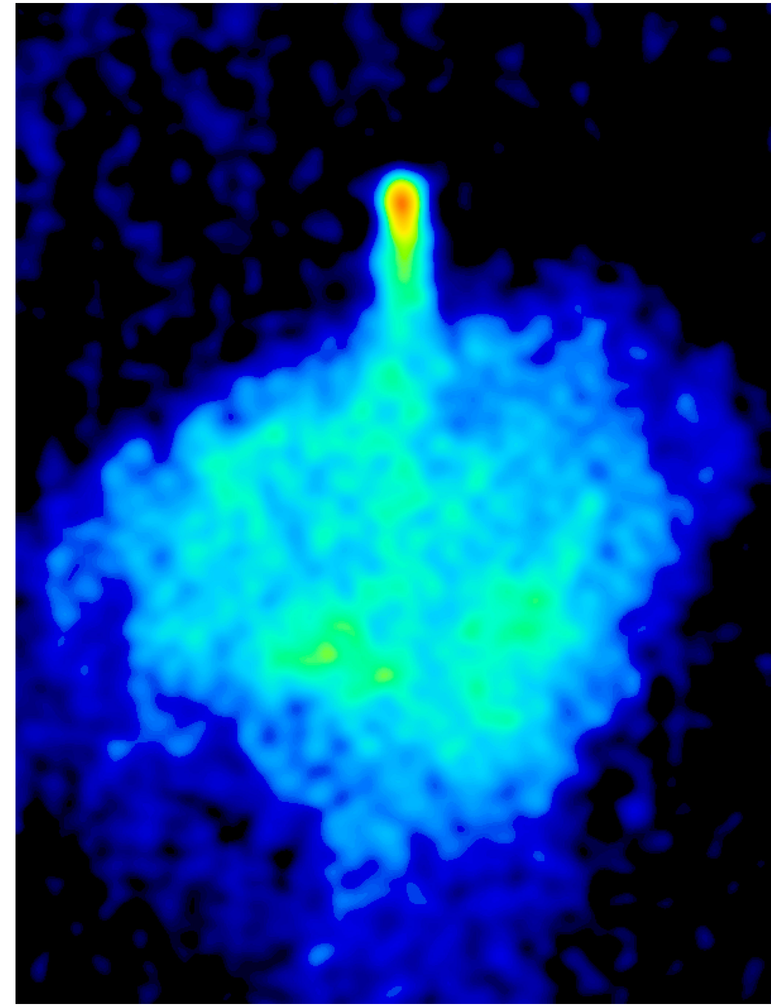
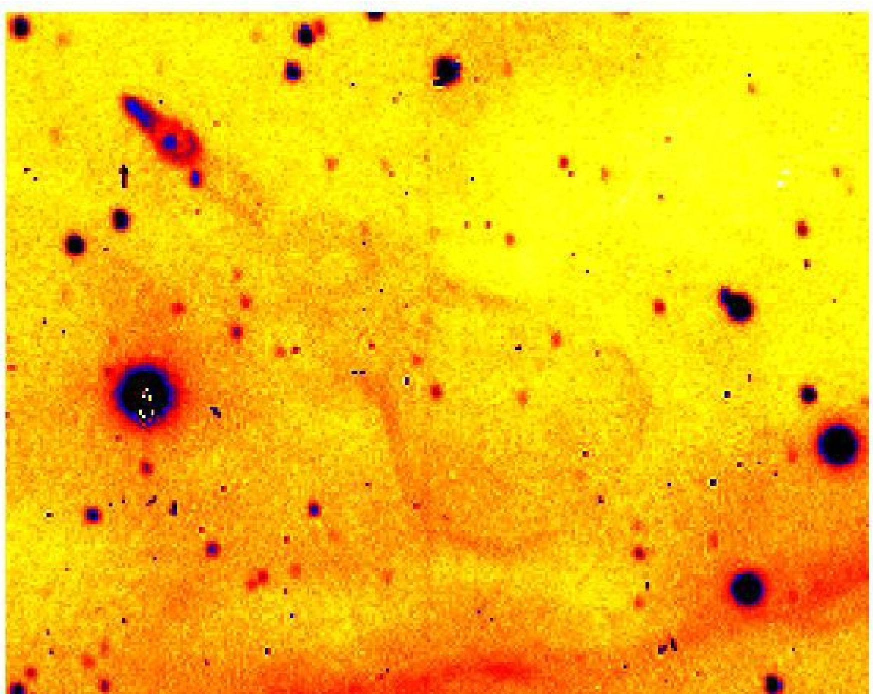


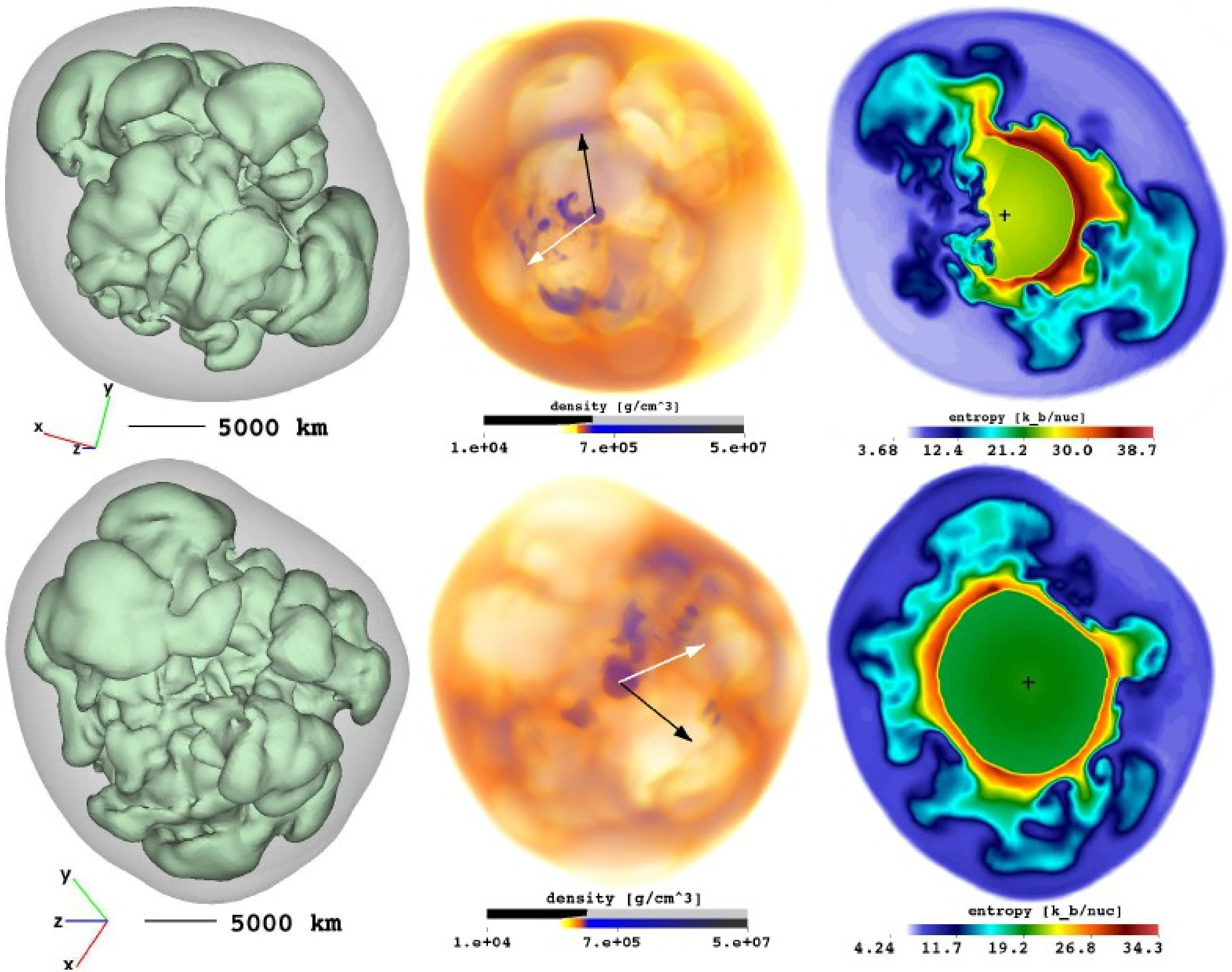
Puppis A





Guitar
Nebula

Neutron Star Recoil in 3D Explosion Models



(Wongwathanarat, Janka, Müller, ApJL 725 (2010) 106; A&A, to be submitted)

Neutron Star Recoil in 3DExplosion Models

@ t = 1.4 s   @ t = 3.3 s

Model	M_{ns} [$M_\odot$]	t_{exp} [ms]	E_{exp} [B]	v_{ns} [km/s]	a_{ns} [km/s^2]	$v_{ns,\nu}$ [km/s]	$\alpha_{k\nu}$ [°]	v_{ns}^{long} [km/s]	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

(Wongwathanarat, Janka, Müller,   ApJL 725 (2010) 106;   A&A, to be submitted)

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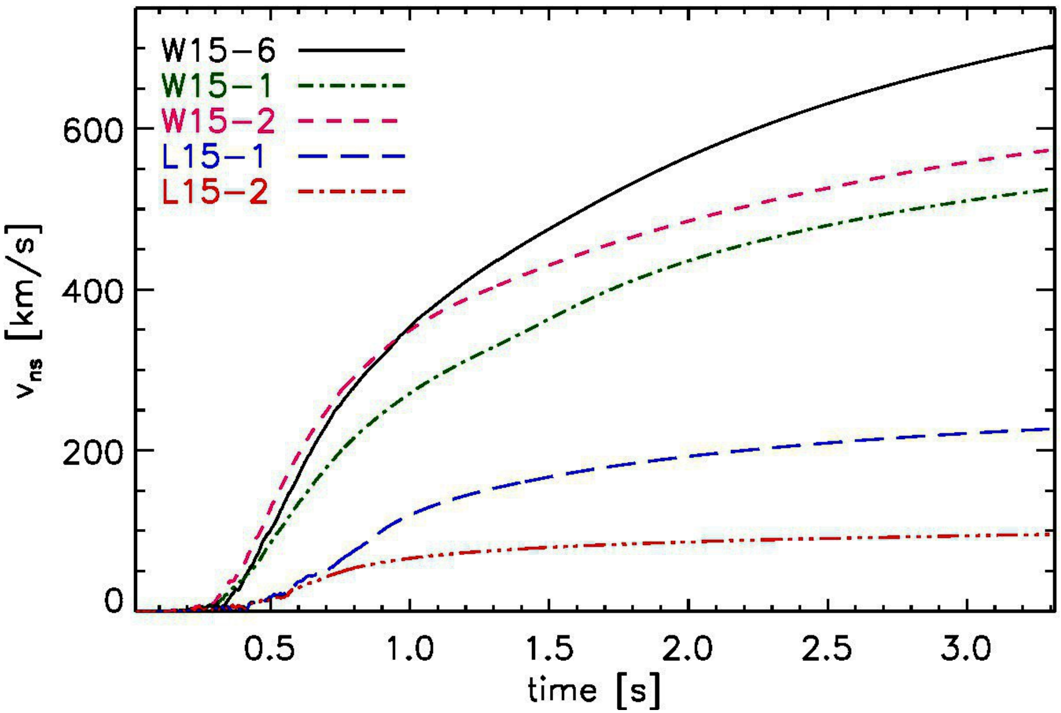
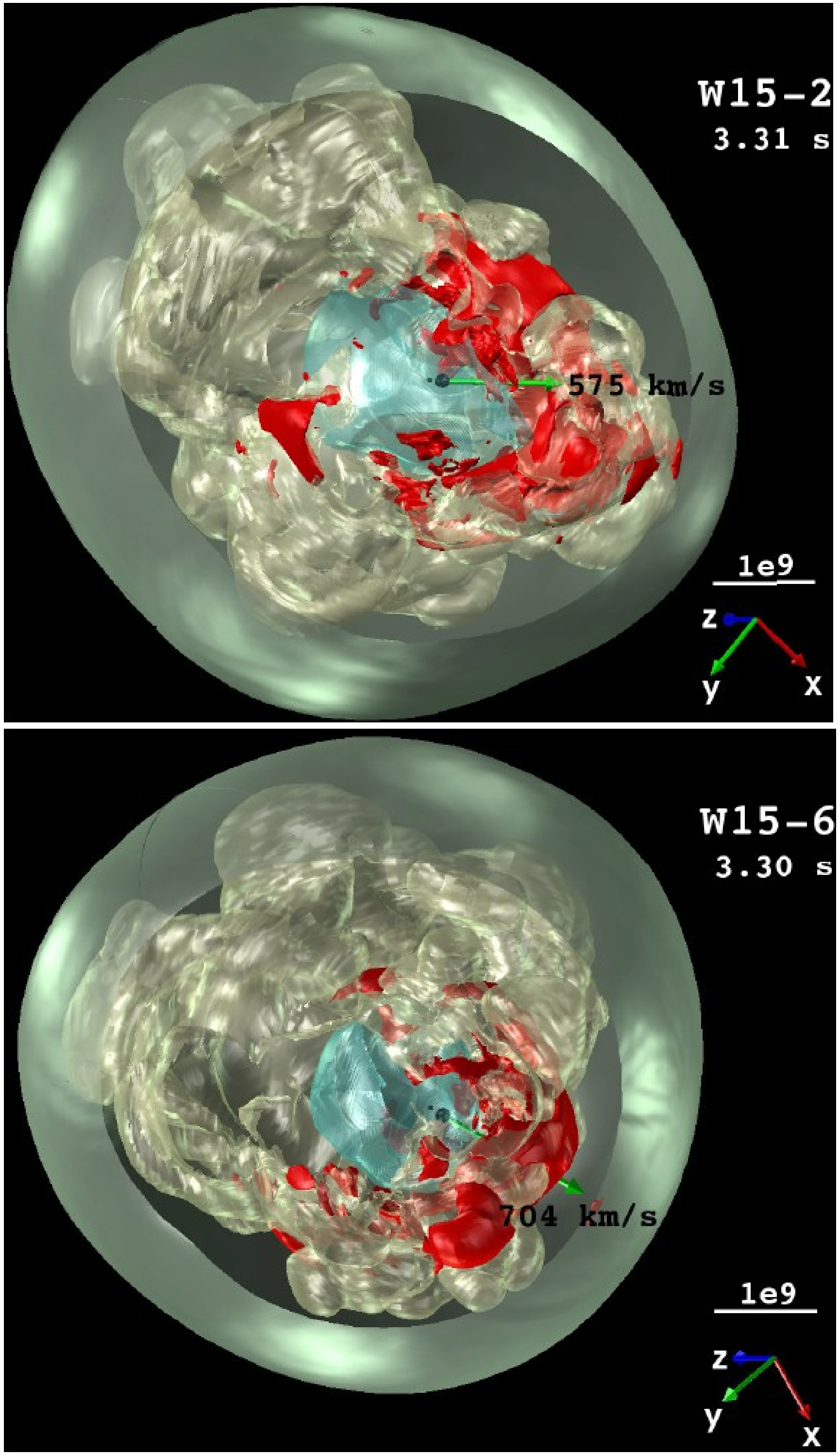
Neutron Star Recoil in 3D Explosion Models

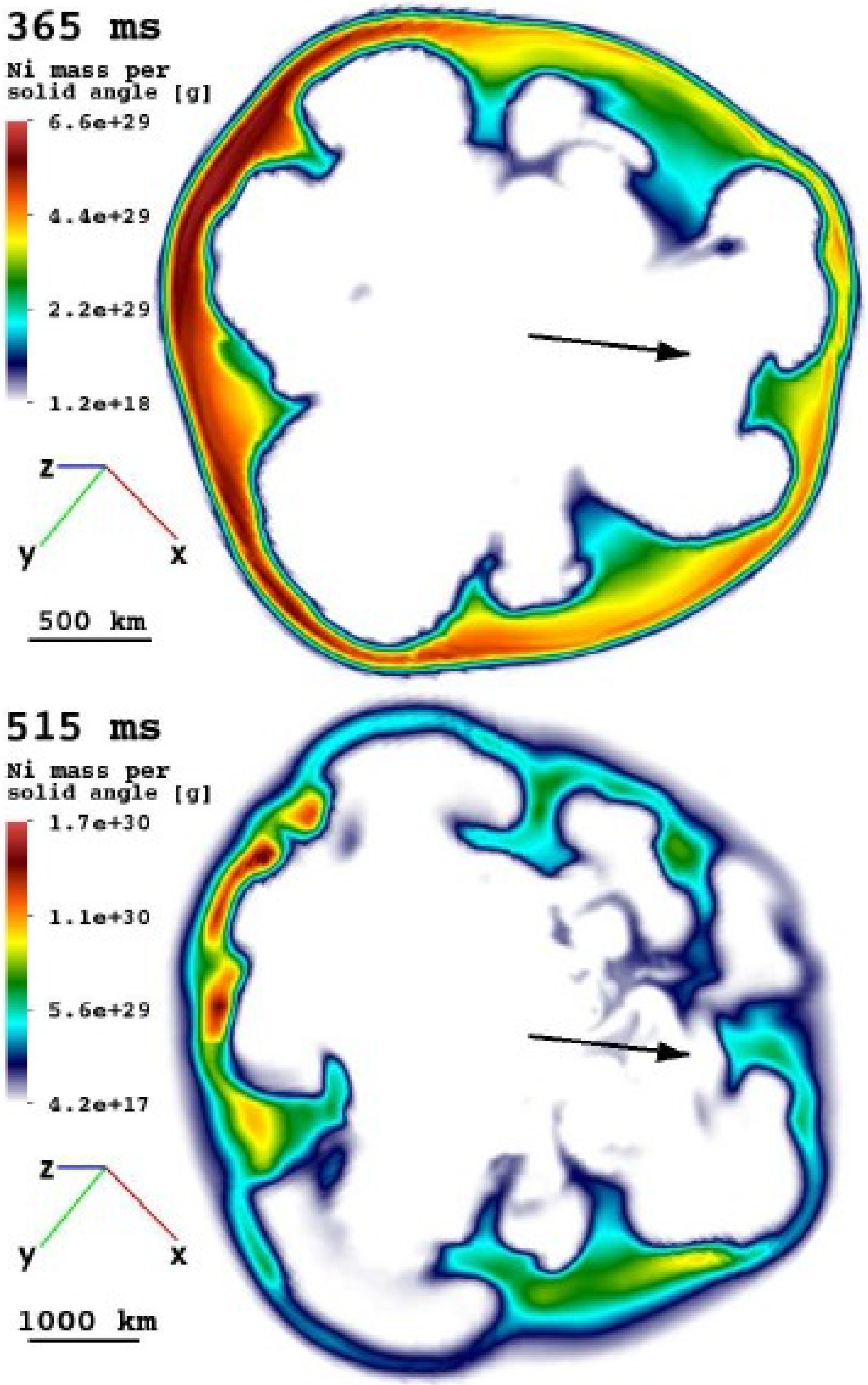




(Wongwathanarat, Janka, Müller, ApJL 725 (2010) 106;
A&A, to be submitted)

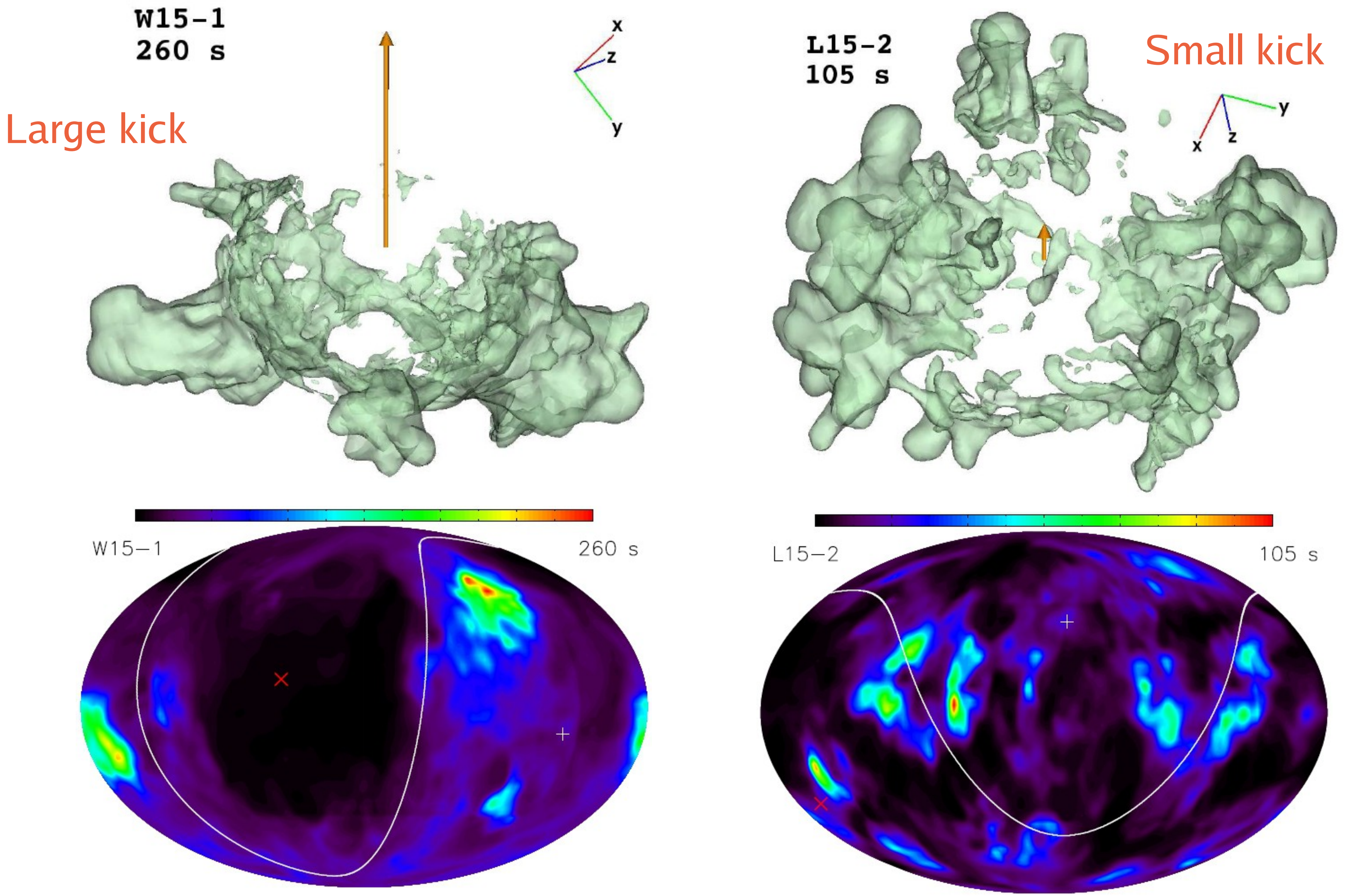
Neutron Star Recoil and Nickel Production

Nickel production is enhanced in direction of stronger explosion, i.e. opposite to NS kick



(Wongwathanarat, Janka, Müller, A&A, to be submitted)

Neutron Star Recoil and Nickel Production

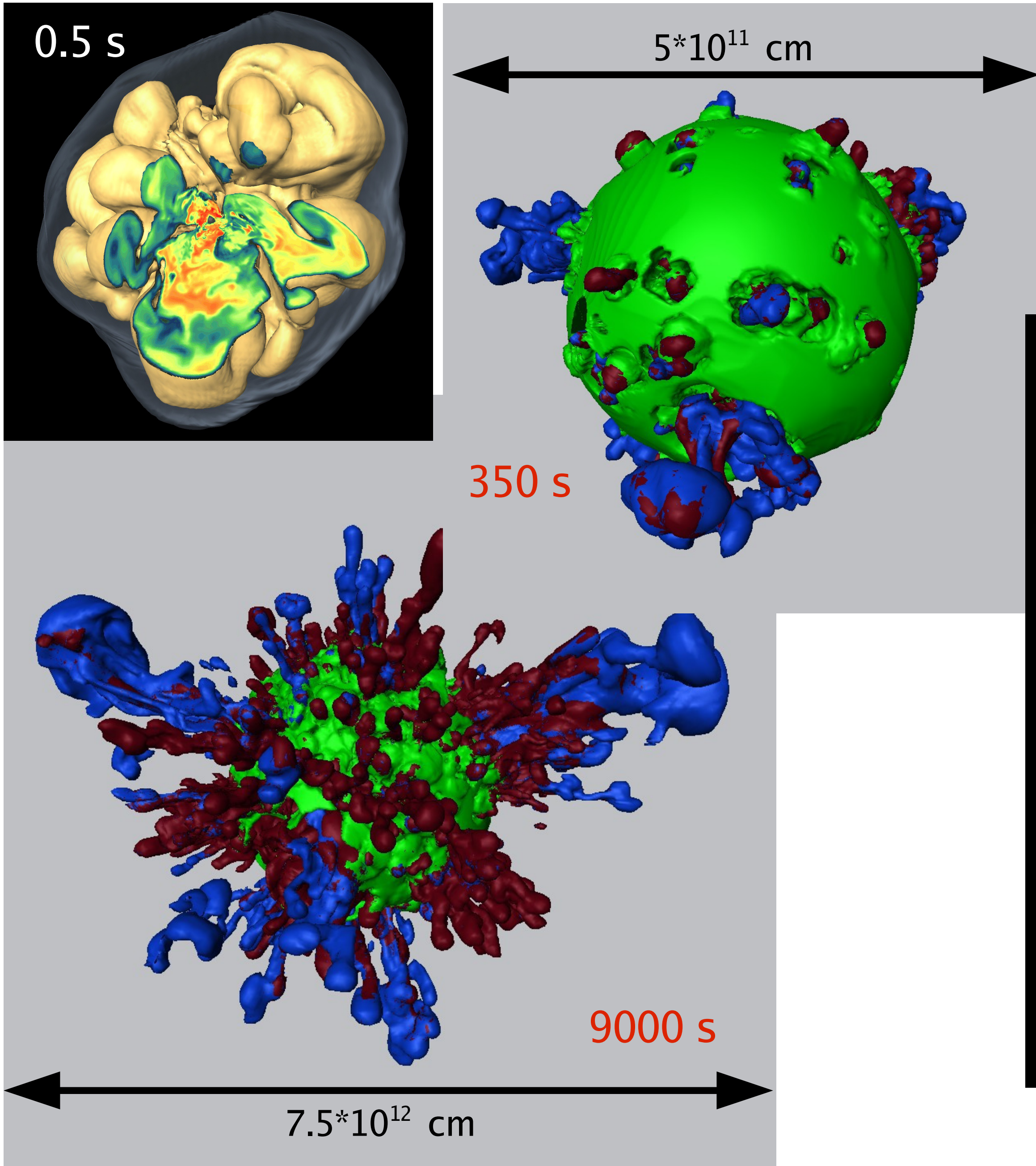


(Wongwathanarat, Janka, Müller, A&A, to be submitted)

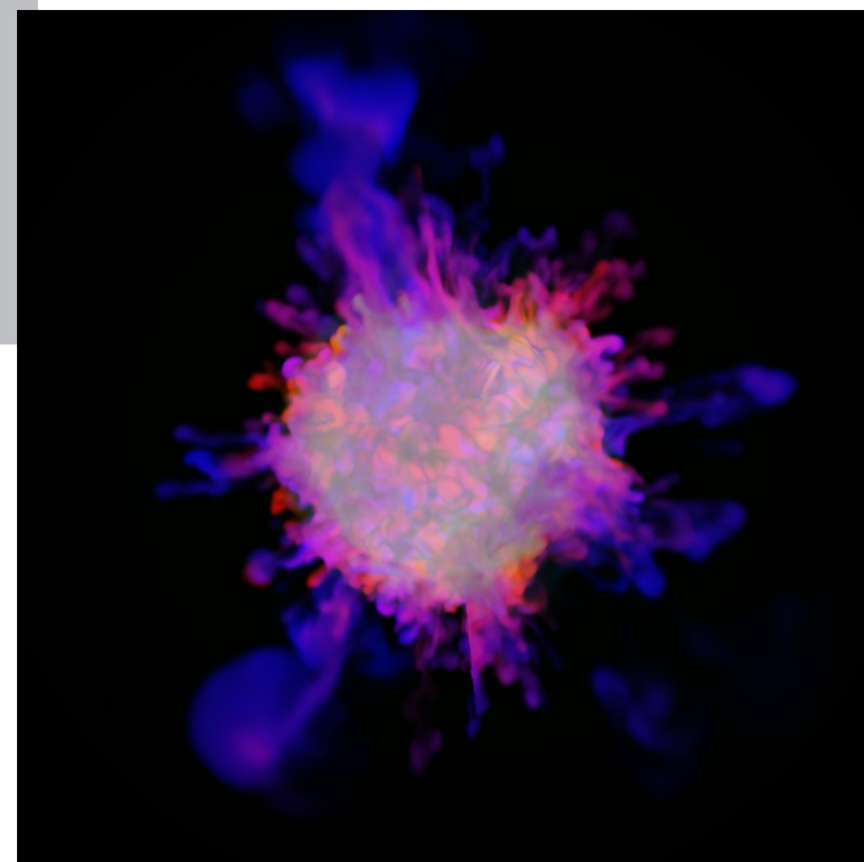
Enhanced concentration of iron in supernova remnants opposite to direction of large pulsar kick can be observable consequence of hydrodynamical kick mechanism.

3D Explosions and Supernova Asymmetries

Mixing Instabilities in 3D SN Models

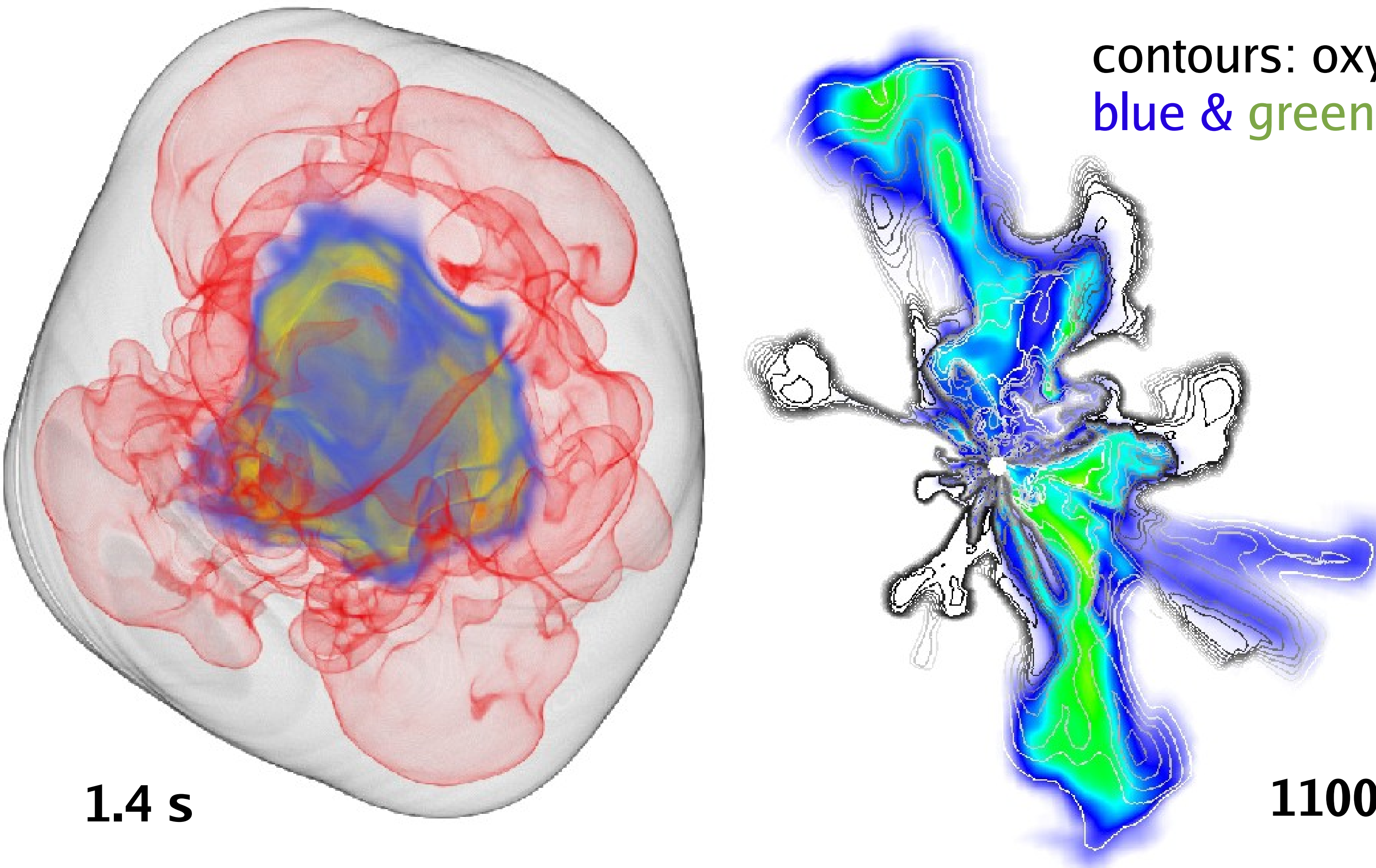


green: carbon
red: oxygen
blue: nickel



(Hammer, Janka, Müller, ApJ 2010)

Asymmetry of Supernova 1987A

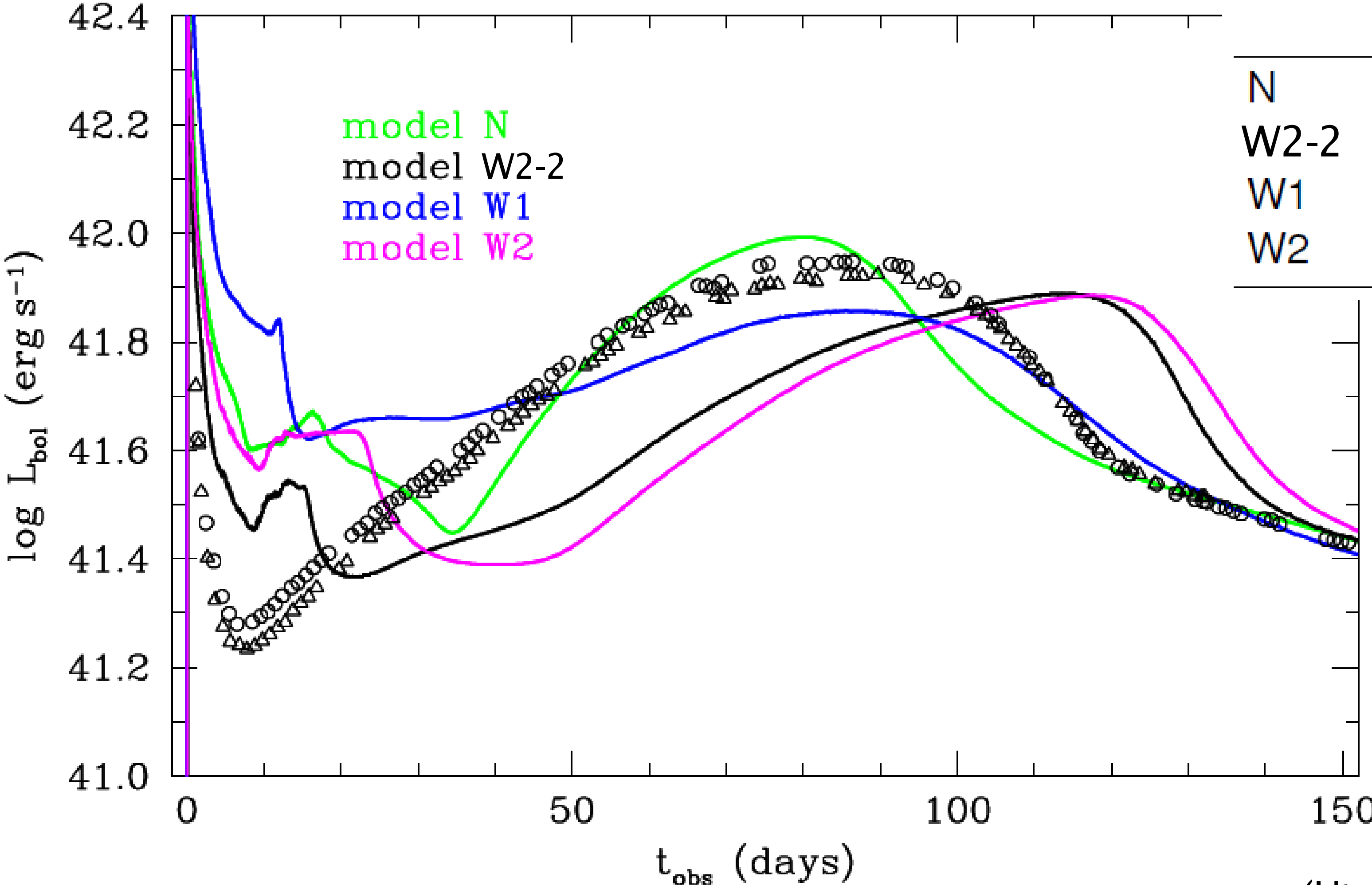


(Wongwathanarat, Janka, Müller, in preparation)

Relatively small convective asymmetries of early explosion can grow into large-scale asymmetry of the nickel and heavy-elements distributions!

Supernova 1987A

Supernova 1987A: Bolometric Lightcurves



Model	pre-SN	E (10^{51} erg)
N	Nomoto	1.68
W2-2	Woosley	1.01
W1	Woosley	2.62
W2	Woosley	1.16

$M_{\rm Ni} = 0.0765 M_\odot$. Circles and triangles are the SN 1987A observations.

(Utrobin, Wongwathanarat, Janka, Müller, in preparation)

Progenitor-Explosion and SN-Remnant Connections

Large Set of 1D SN Explosion Models

(Ugliano, THJ, Marek, Arcones, ApJ 757, 69 (2012))

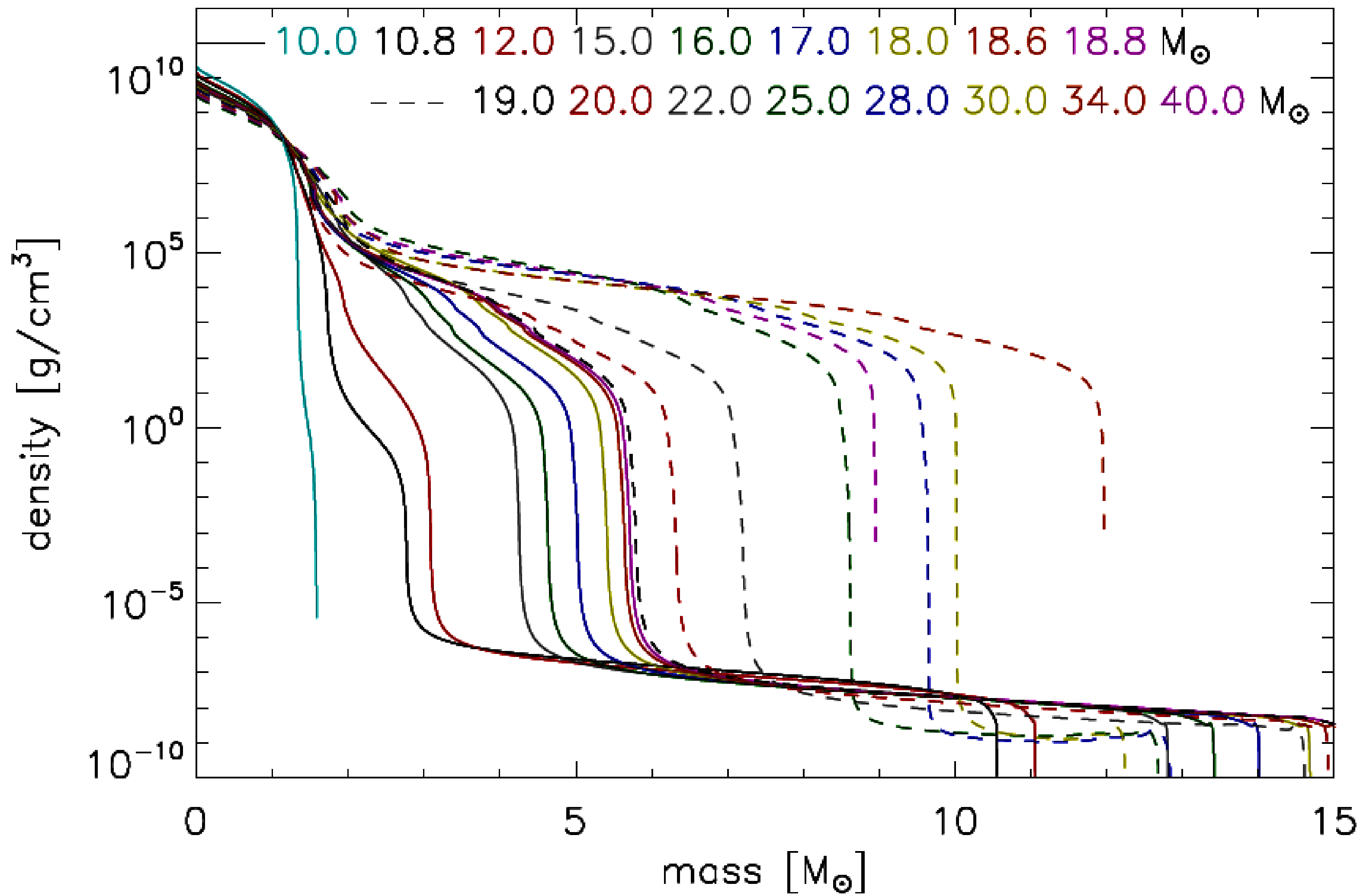
- Hydrodynamic simulations of neutrino-driven explosions in 1D:
  After onset of explosion follow neutron-star cooling for 15−20 s,
  continue to track SN explosion with fallback for days to weeks
- Core-collapse simulations for 101 solar-metallicity progenitors
  (from Woosley, Heger, & Weaver 2002)

Approximations:

- 1D
- Analytic, parametrized neutron-star core-cooling model,
  but self-consistent simulation of accretion luminosity
- Parameters of NS core-cooling calibrated for reproducing
  explosion energy, nickel mass, and (roughly) remnant
  mass/neutrino-energy loss observed for SN 1987A

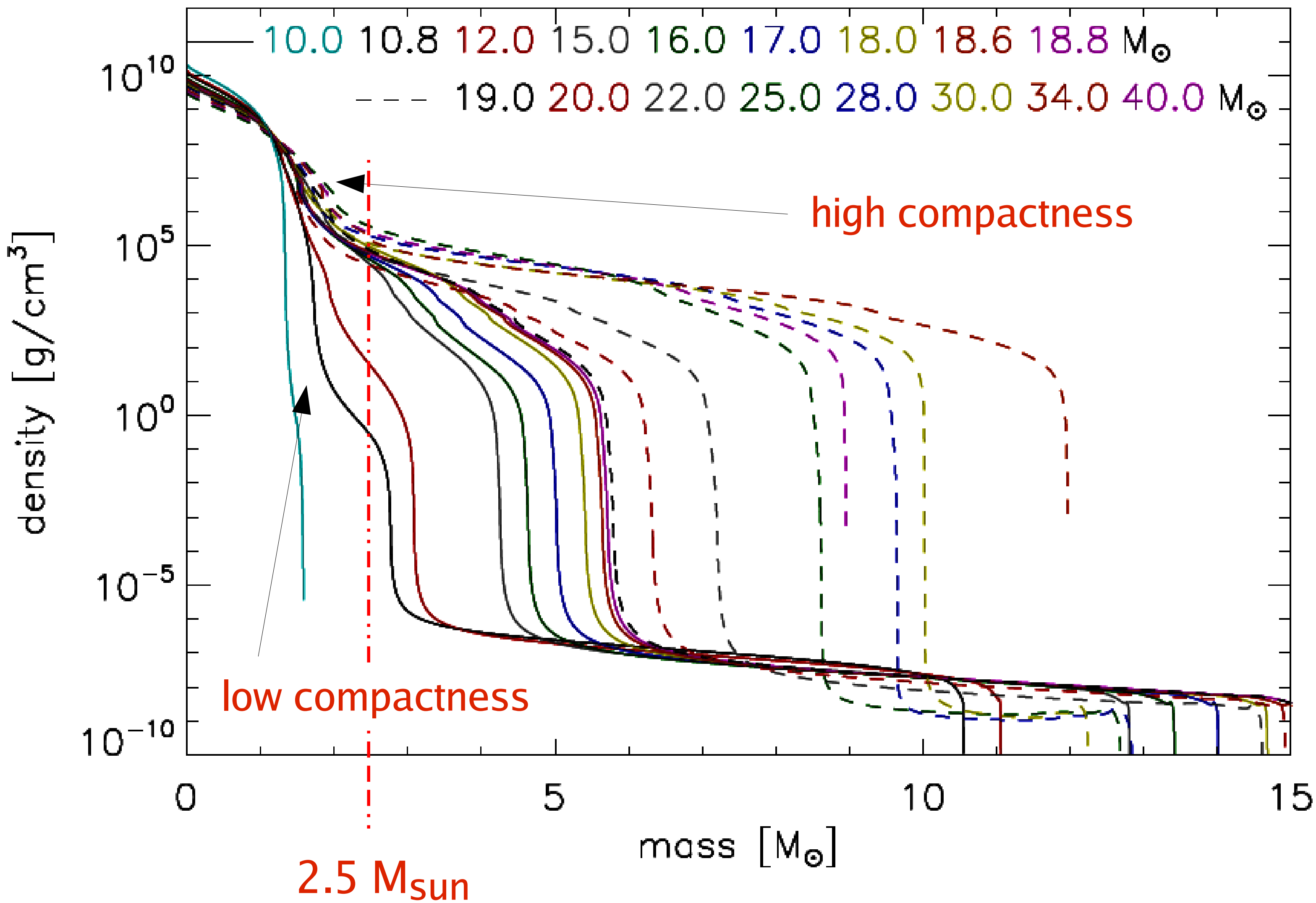
Progenitor Variations

Progenitor models from Woosley, Heger, & Weaver (2002)

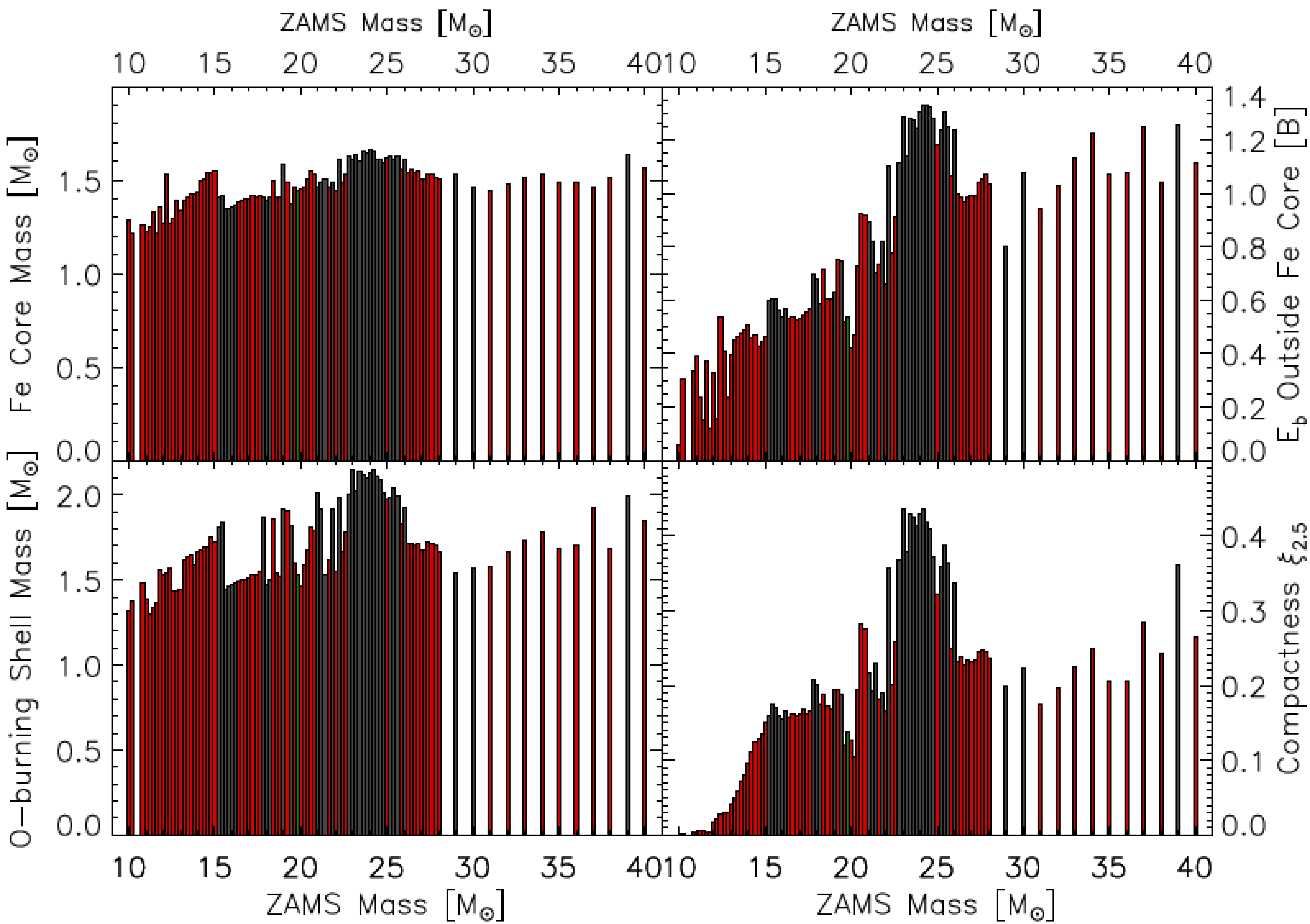


Progenitor Variations

Progenitor models from Woosley, Heger, & Weaver (2002)



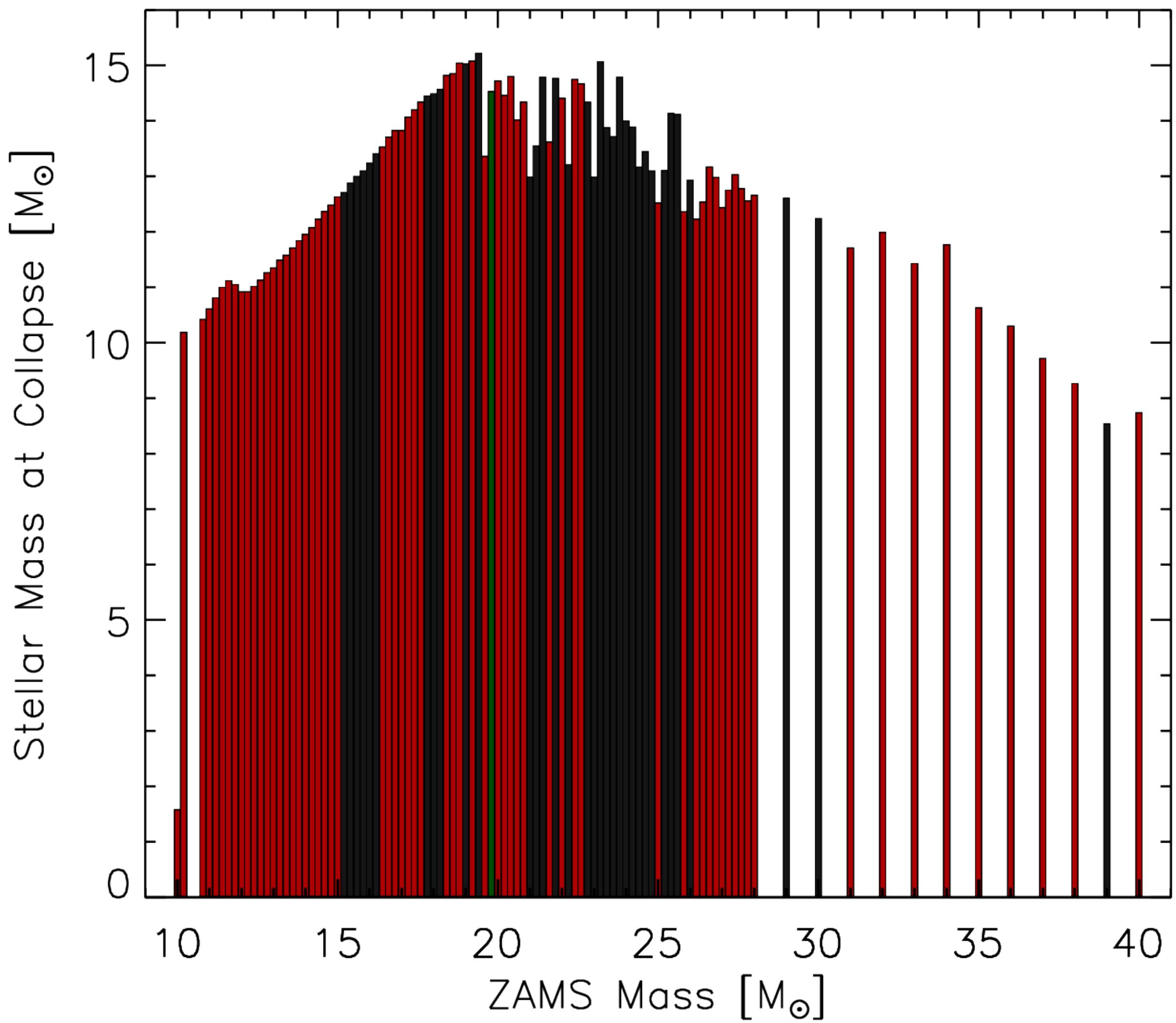
Progenitor Properties



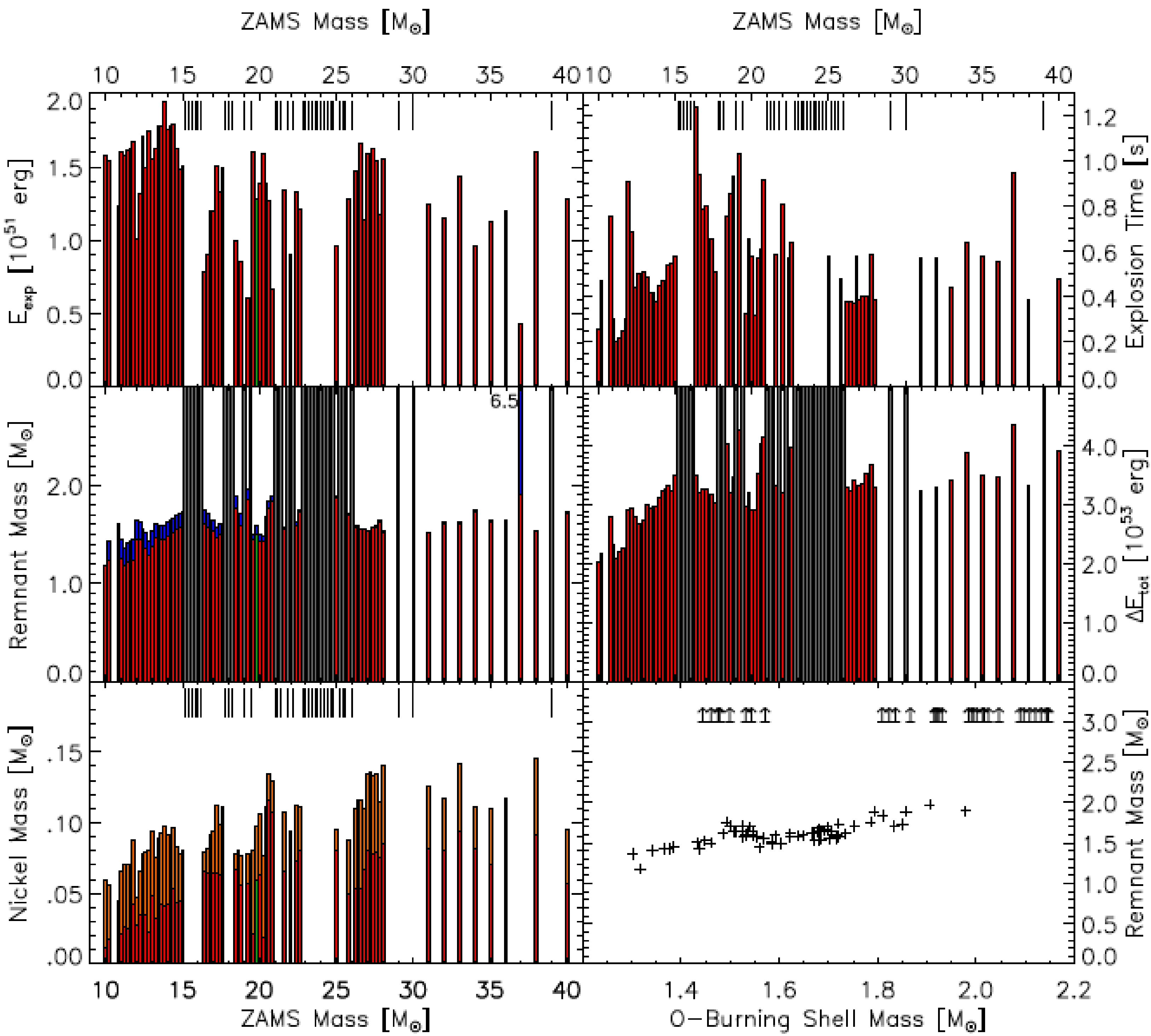
Grey = BH formation cases

(Ugliano, THJ, Marek, Arcones, ApJ 757, 69 (2012))

Stellar Mass at Collapse

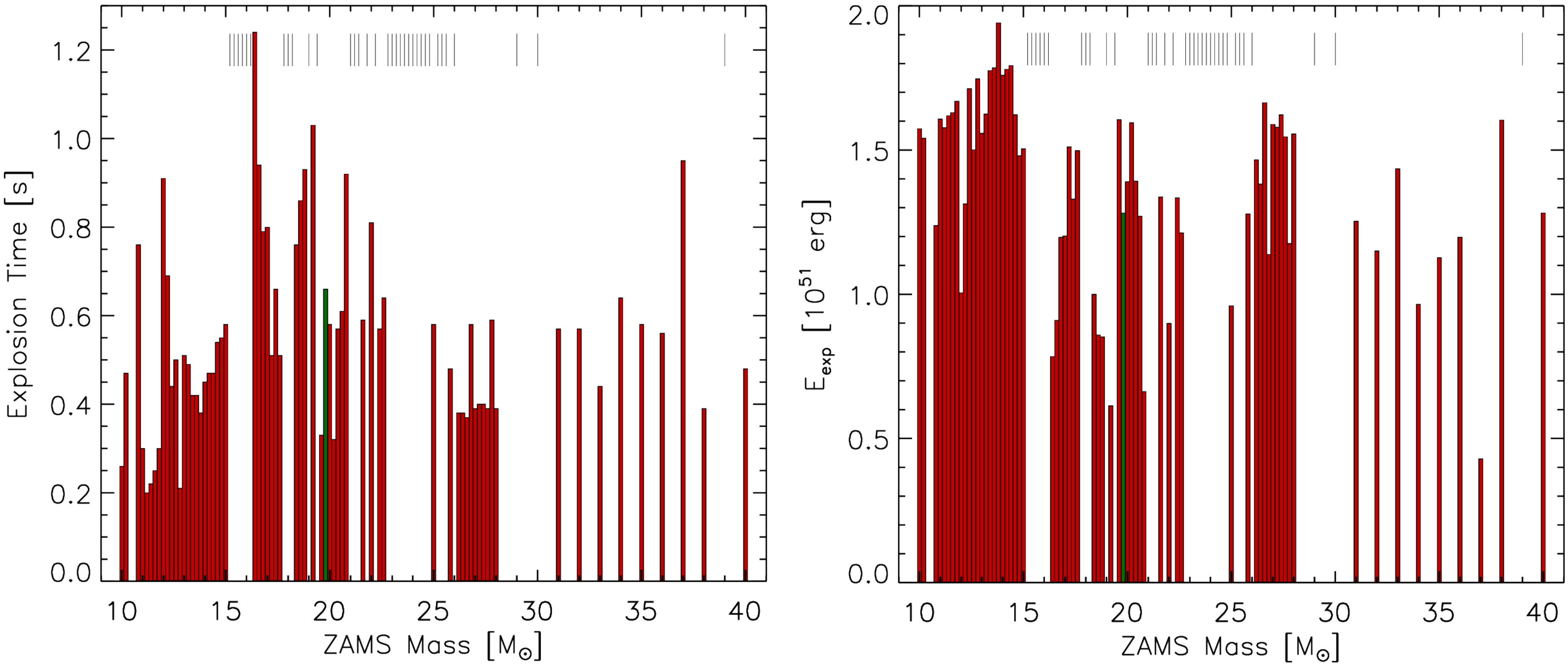


Explosion Properties

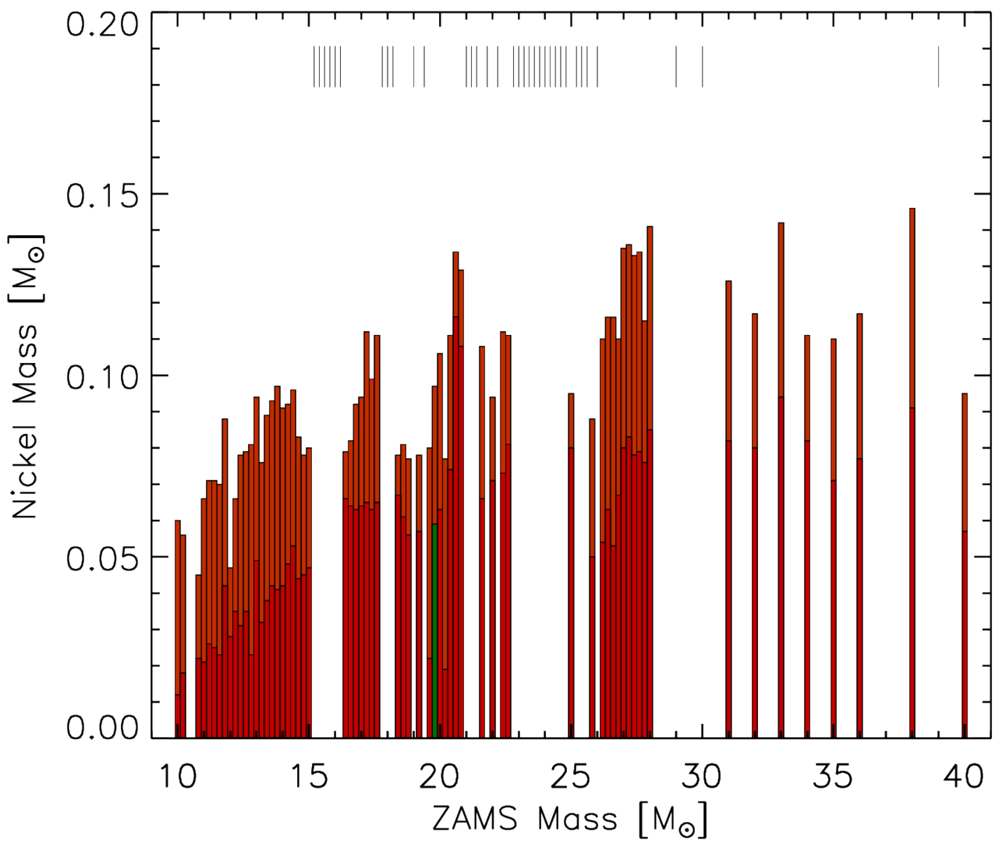


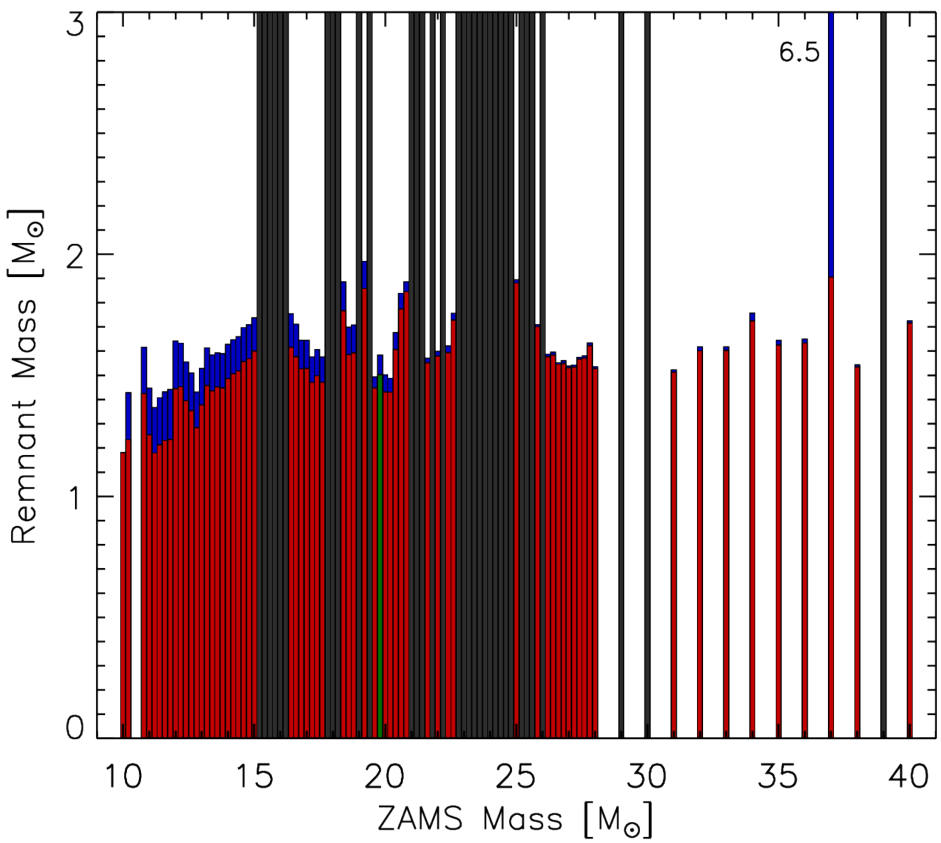
(Ugliano, THJ, Marek, Arcones, ApJ 757, 69 (2012))

Explosion Time and Energy

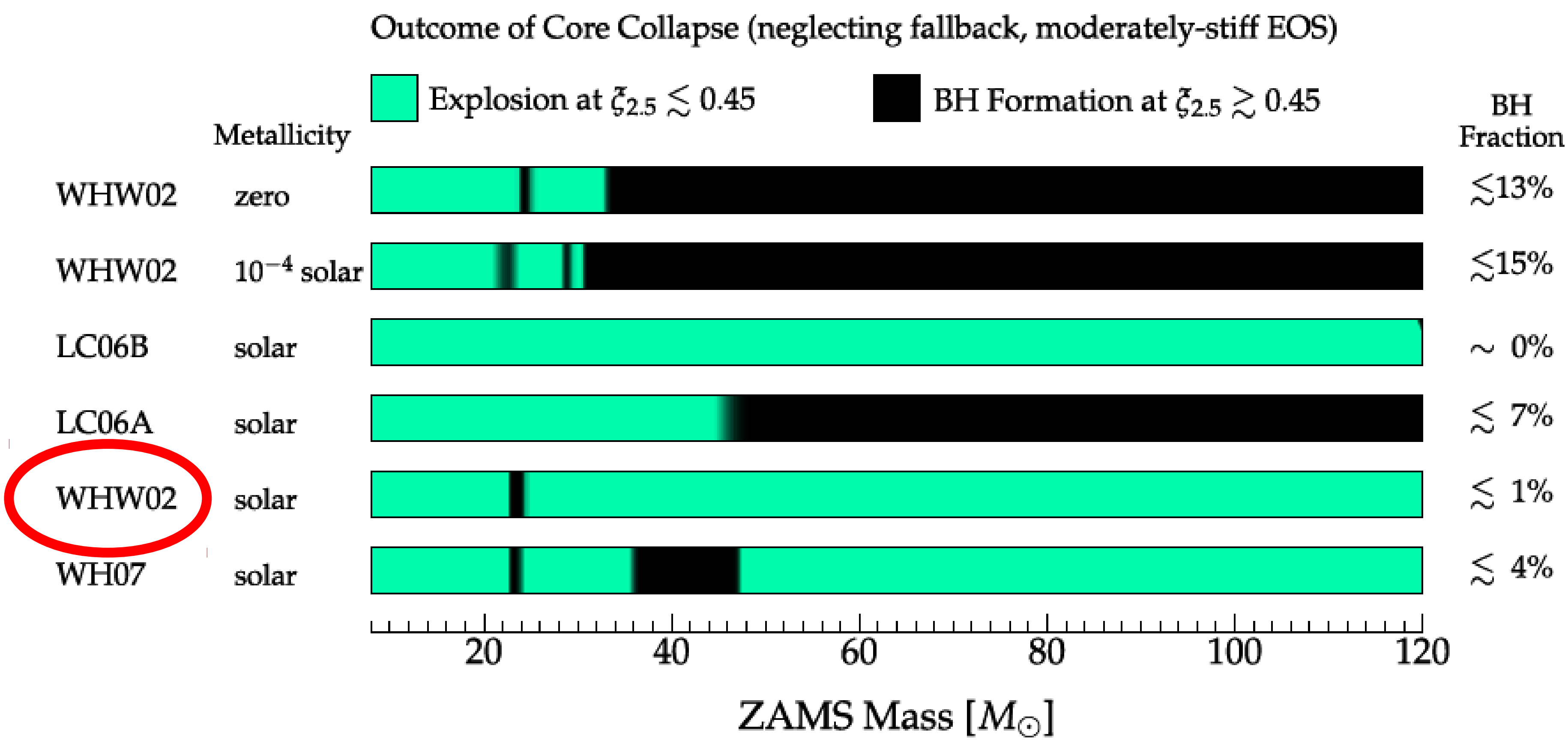


Ejected Ni Mass and Compact Remnant Mass





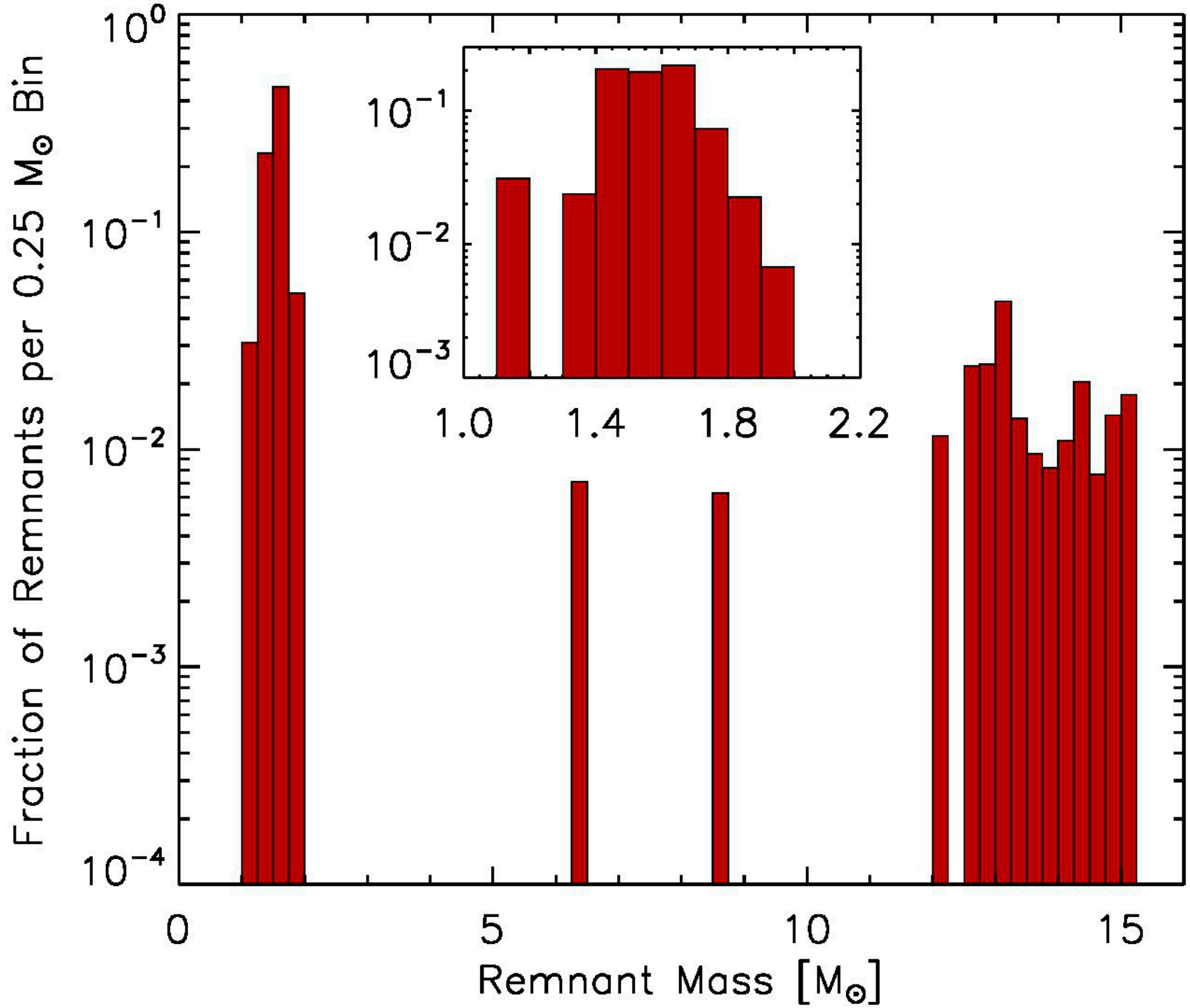
NS and BH Regimes



O'Connor & Ott, ApJ 730:70 (2011)

Remnant Mass Distribution

Model results folded with Salpeter IMF:
23% of all stellar core collapses produce BHs

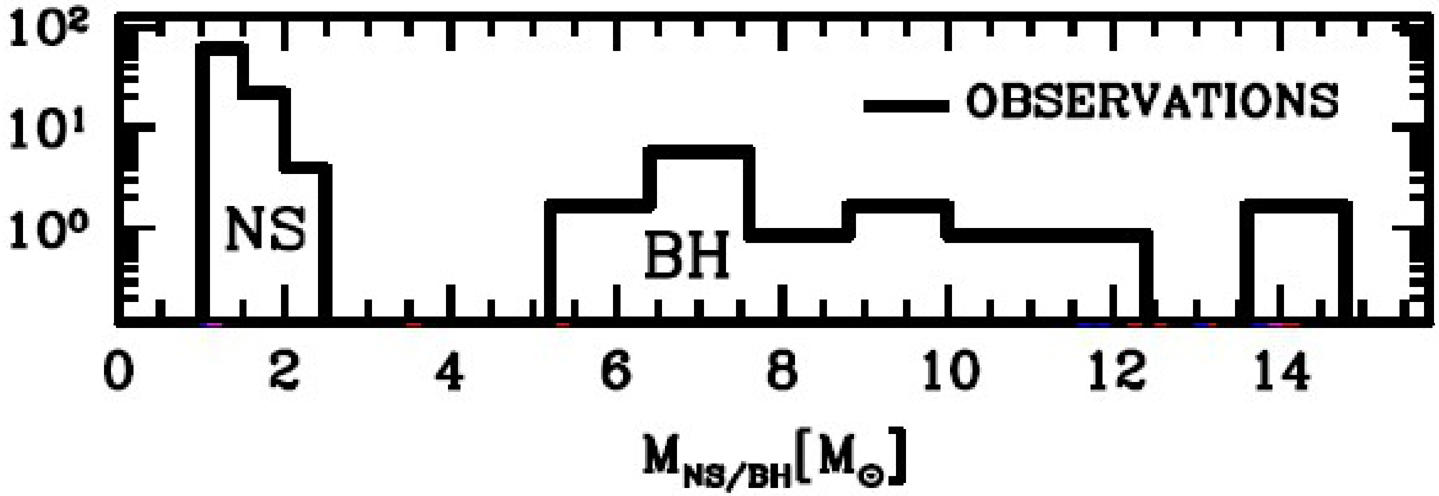


Baryonic Remnant Mass

Ugliano, THJ, Marek, & Arcones (arXiv:1205.3657)

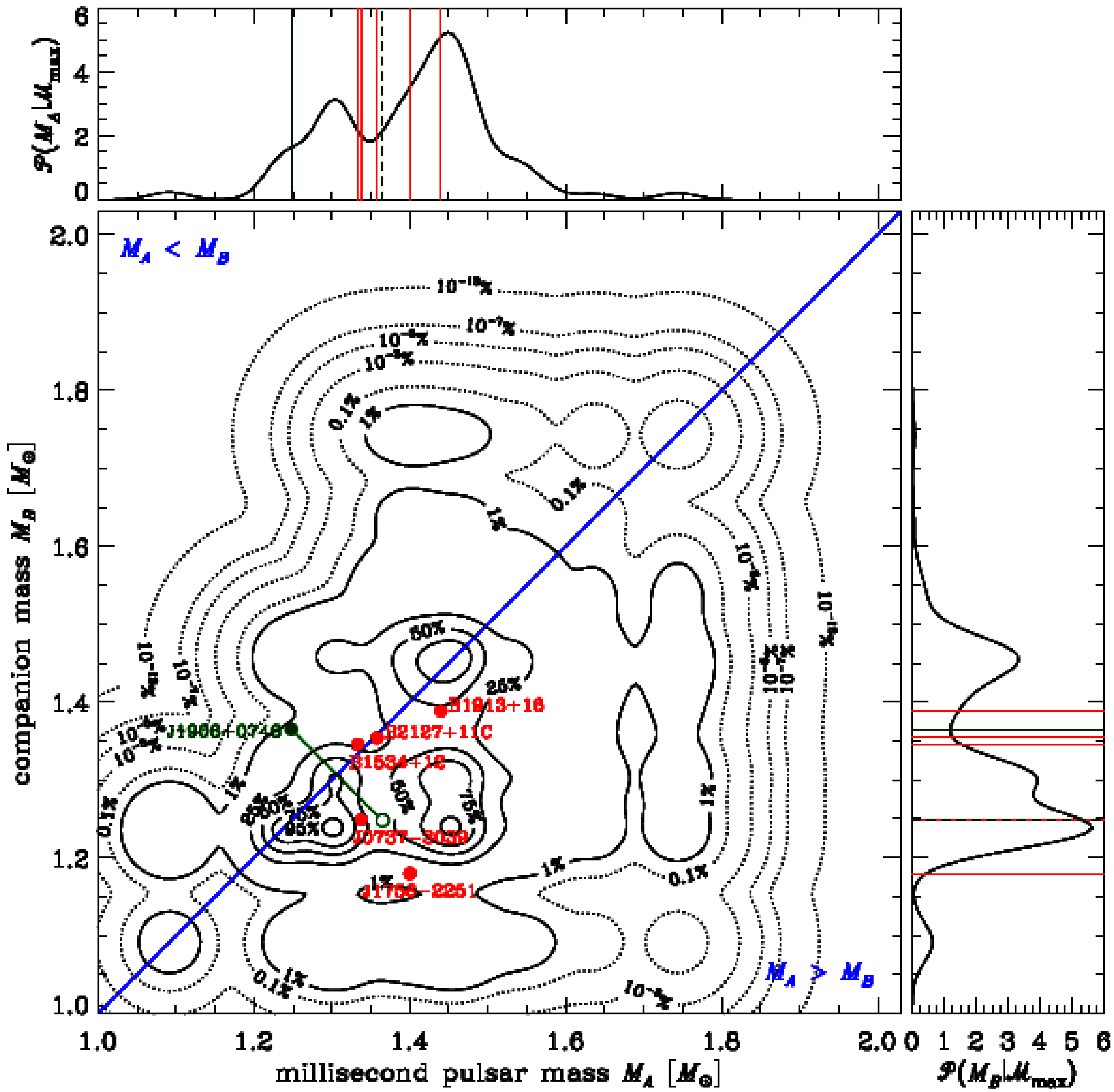
Remnant Mass Distribution

Model results reproduce possible gap in the observed distribution of NS and BH masses



Belczynski et al. (2011)

Bayesian analysis: Observed double NS systems vs. theoretical mass distribution



Pejcha, Thompson & Kochanek, MNRAS (2012)

Results

- BH formation seems possible for progenitors with $M < 15\ M_{sun}$ (ZAMS mass).
- Neutrino-driven explosions can explain SN energies $< 2*10^{51}$ erg and nickel masses $< 0.2\ M_{sun}$.
- Hypernovae with higher energies and more Ni ejection seem to require a different mechanism.
- Gap of remnant distribution between NS and BH masses naturally occurs.
- Results of supernova and remnant systematics depend on set (e.g., metallicity) of progenitor models, of course.
- Influence of calibration (SN1987A) model and multi-D effects needs to be explored.

Summary

- Understanding of SN explosion mechanism has made BIG progress.

- 2-dimensional relativistic models yield explosions for “soft” EoS. Explosion energy tends to be on low side.

- 3D models are on their way.

- 3D models are likely to explain observed pulsar kicks as well as mixing processes and global explosion asymmetries seen in SN 1987A and other SNII.

- Neutrino-driven mechanism is likely to shed new light on some of the paradigms for progenitor-supernova-remnant connection.