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International Conference Physics of Neutron Stars – 2011
St. Petersburg, Russia, July 11-15, 2011

Supernova Explosion Mechanisms

Advancing to the 3rd Dimension: Supernova Models Confronting Observations

Hans-Thomas Janka
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Questions

- Why and how do massive stars explode?
- What are the observable signals of the explosion: neutrinos, gravitational waves, heavy elements?
- What are the compact remnants of the explosion and their properties: neutron star or black hole masses, spins, kick velocities?
- How do the explosion and remnant properties vary with the properties of the progenitor stars?

Supernova Explosion Mechanisms

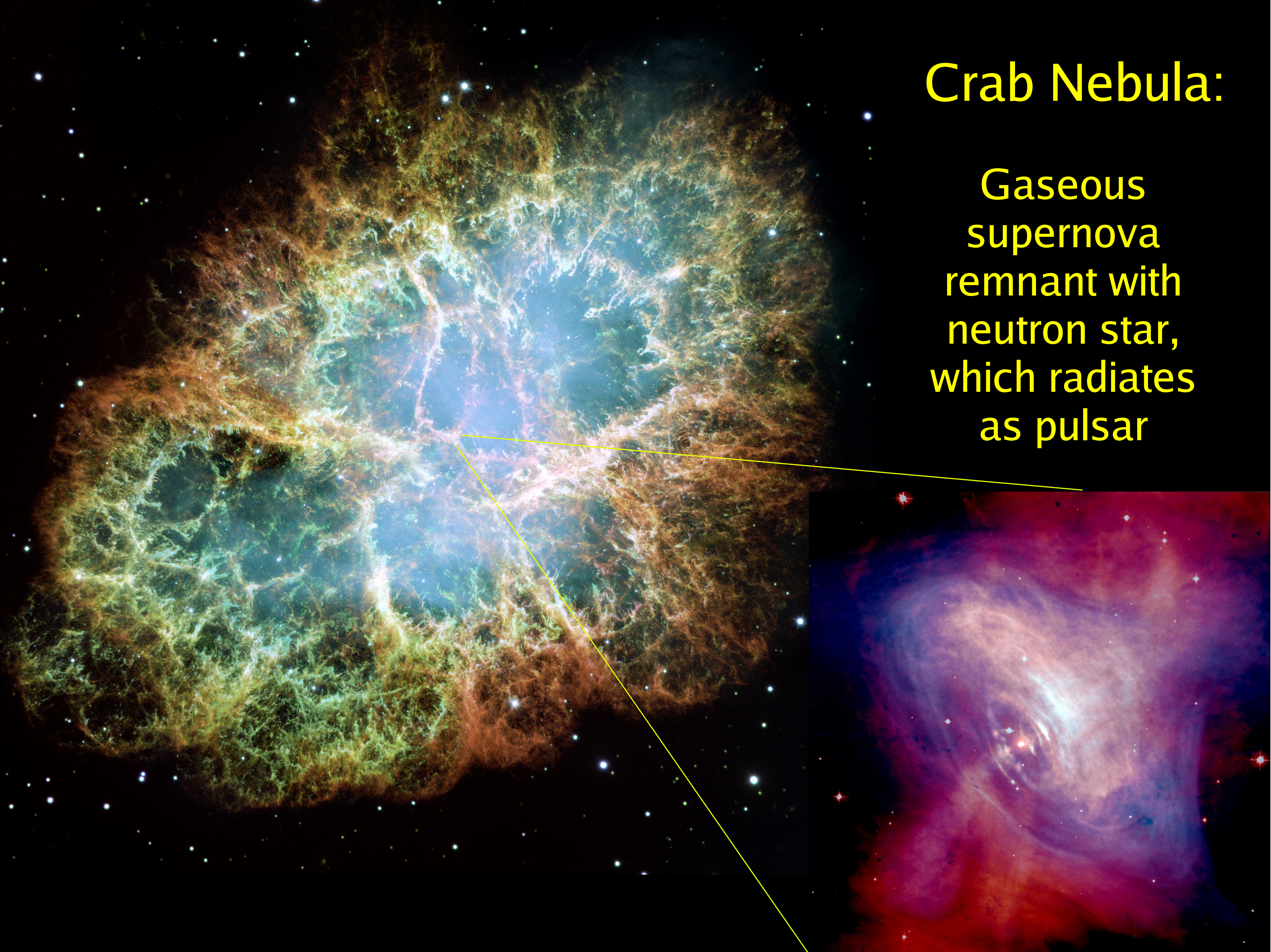
- Neutrino-driven mechanism?
- Magnetohydrodynamic mechanism?
- Acoustic mechanism?
- QCD phase transition mechanism?

Possibly/probably there is more than just one mechanism at work,
depending on the properties of progenitor stars
(i.e. their pre-collapse Fe-core mass, He-core size, and rotation as determined
by the initial stellar mass, metallicity, and binary effects)

Supernova Explosion Mechanisms

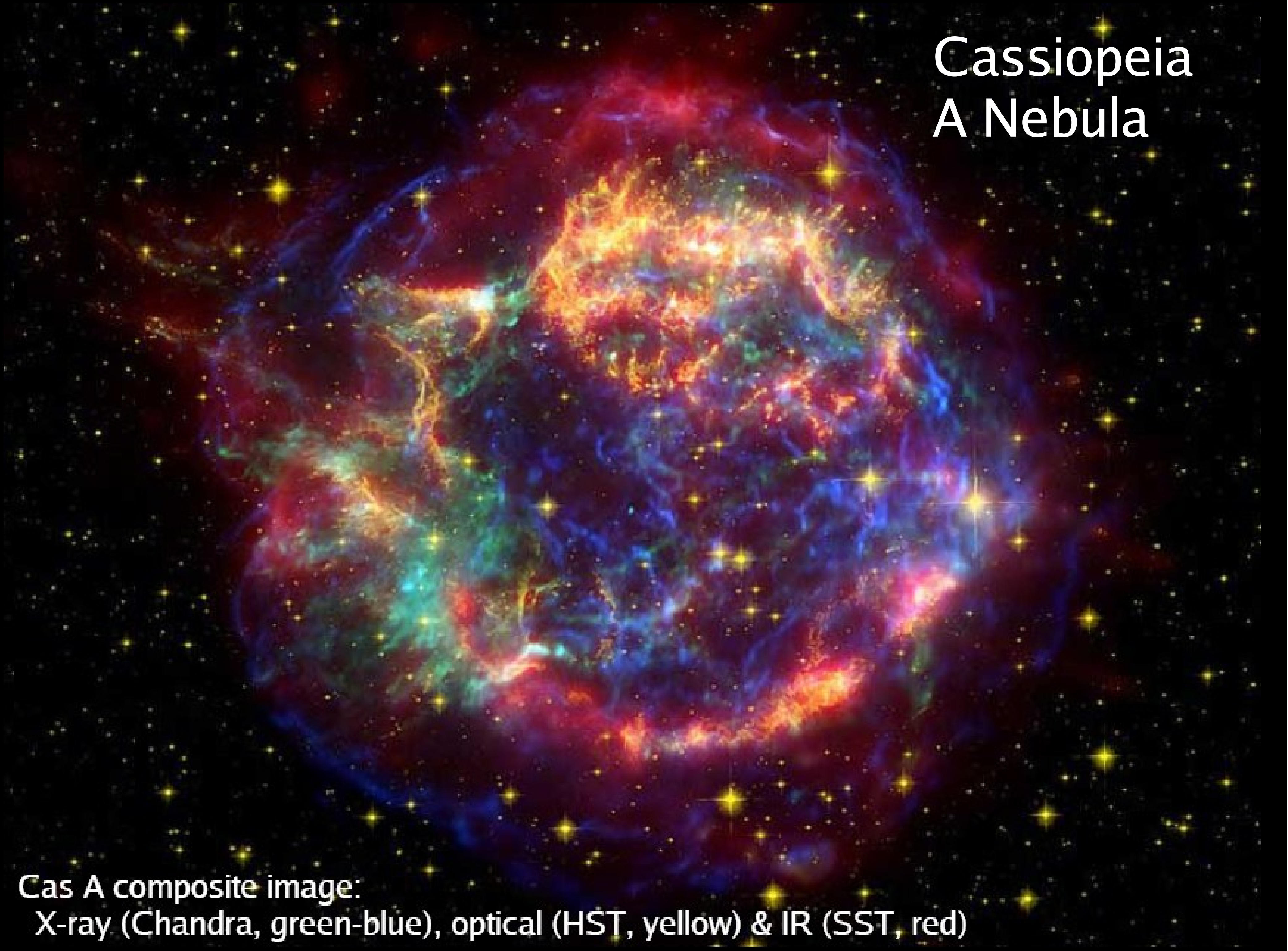
How can the different possibilities be observationally discriminated?

Crab Nebula:

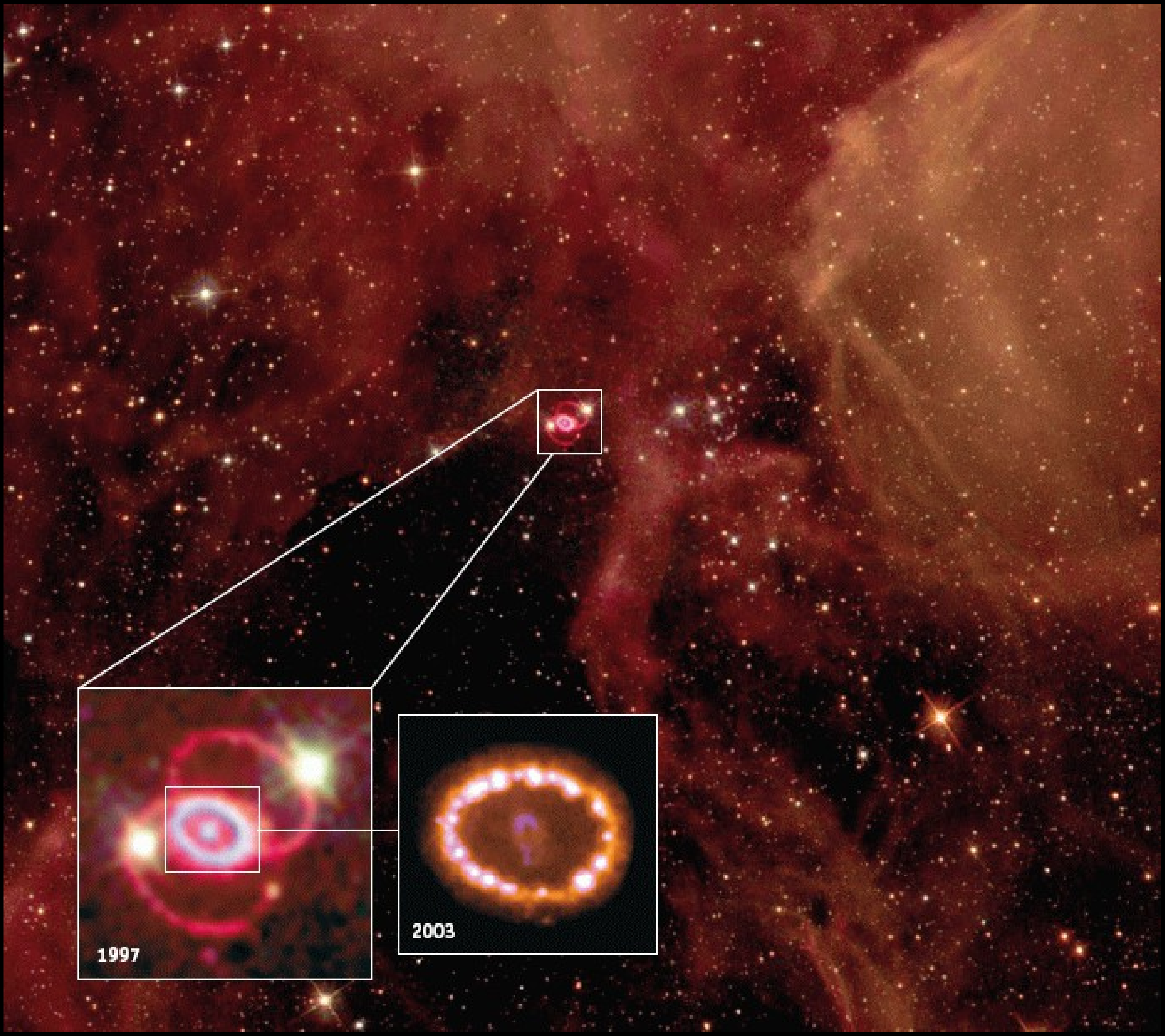


Gaseous
supernova
remnant with
neutron star,
which radiates
as pulsar

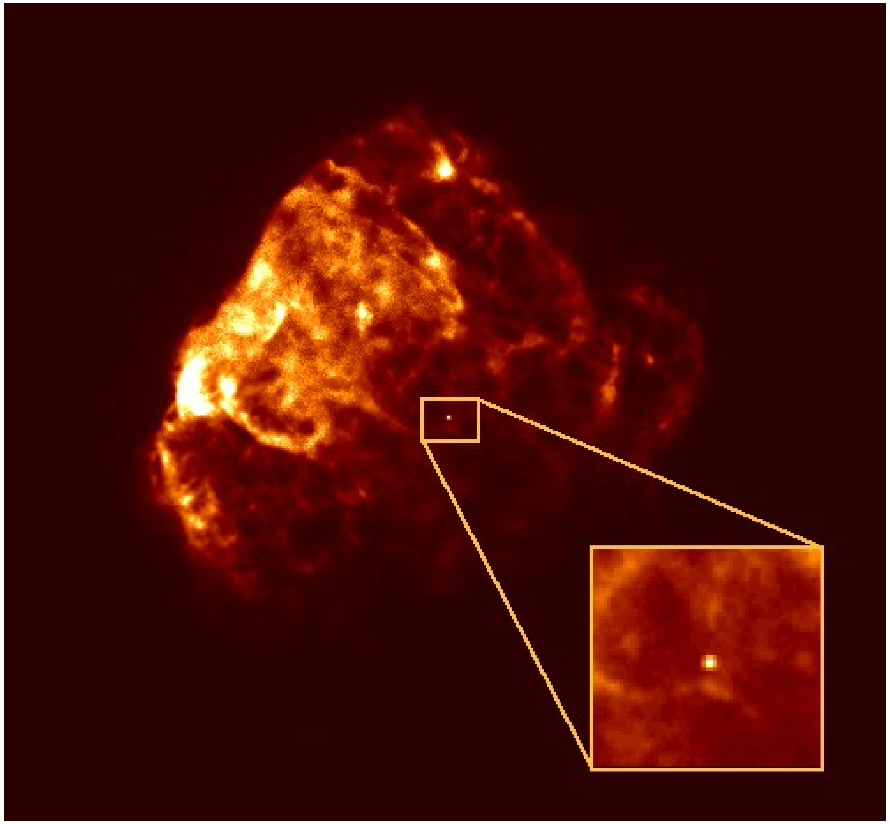
Cassiopeia A Nebula



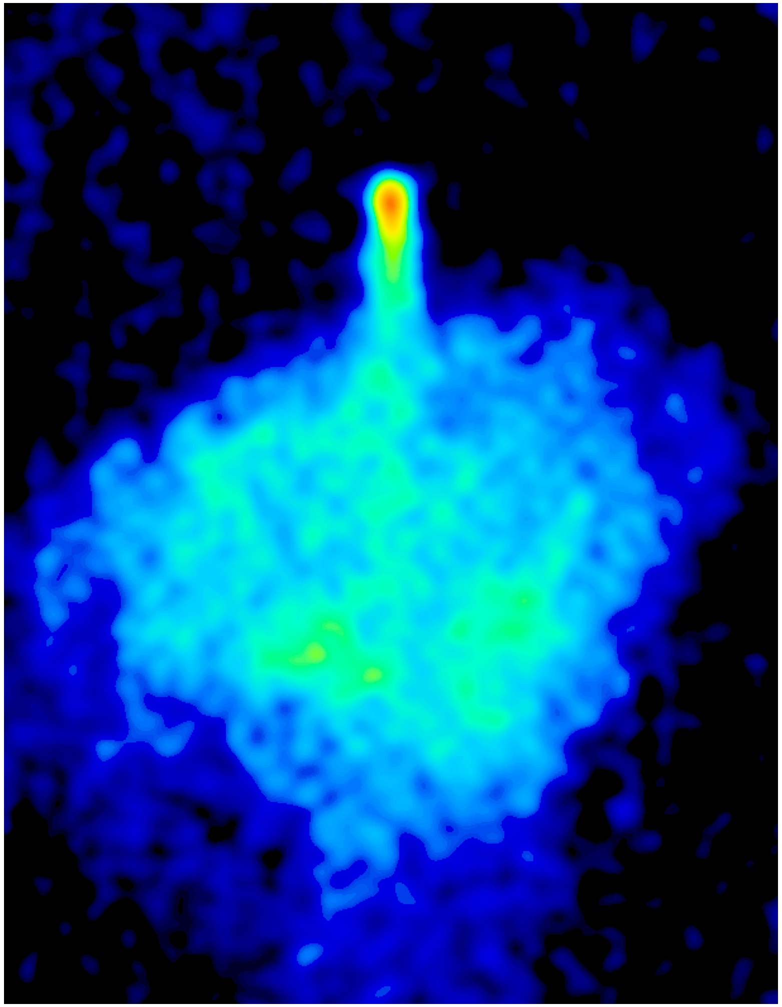
Cas A composite image:
X-ray (Chandra, green-blue), optical (HST, yellow) & IR (SST, red)

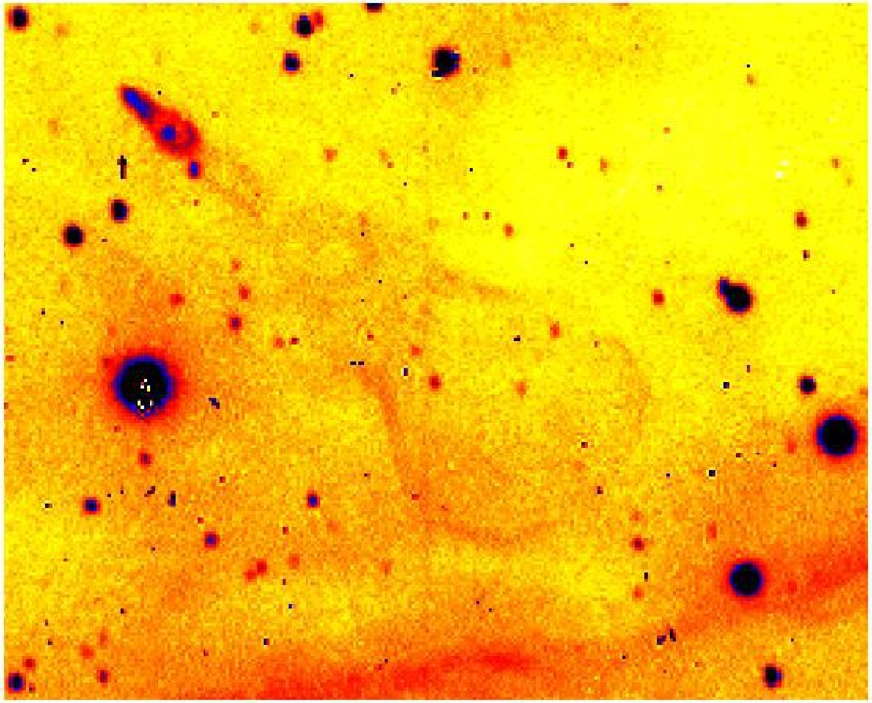


Supernova
1987A
as a
teenager



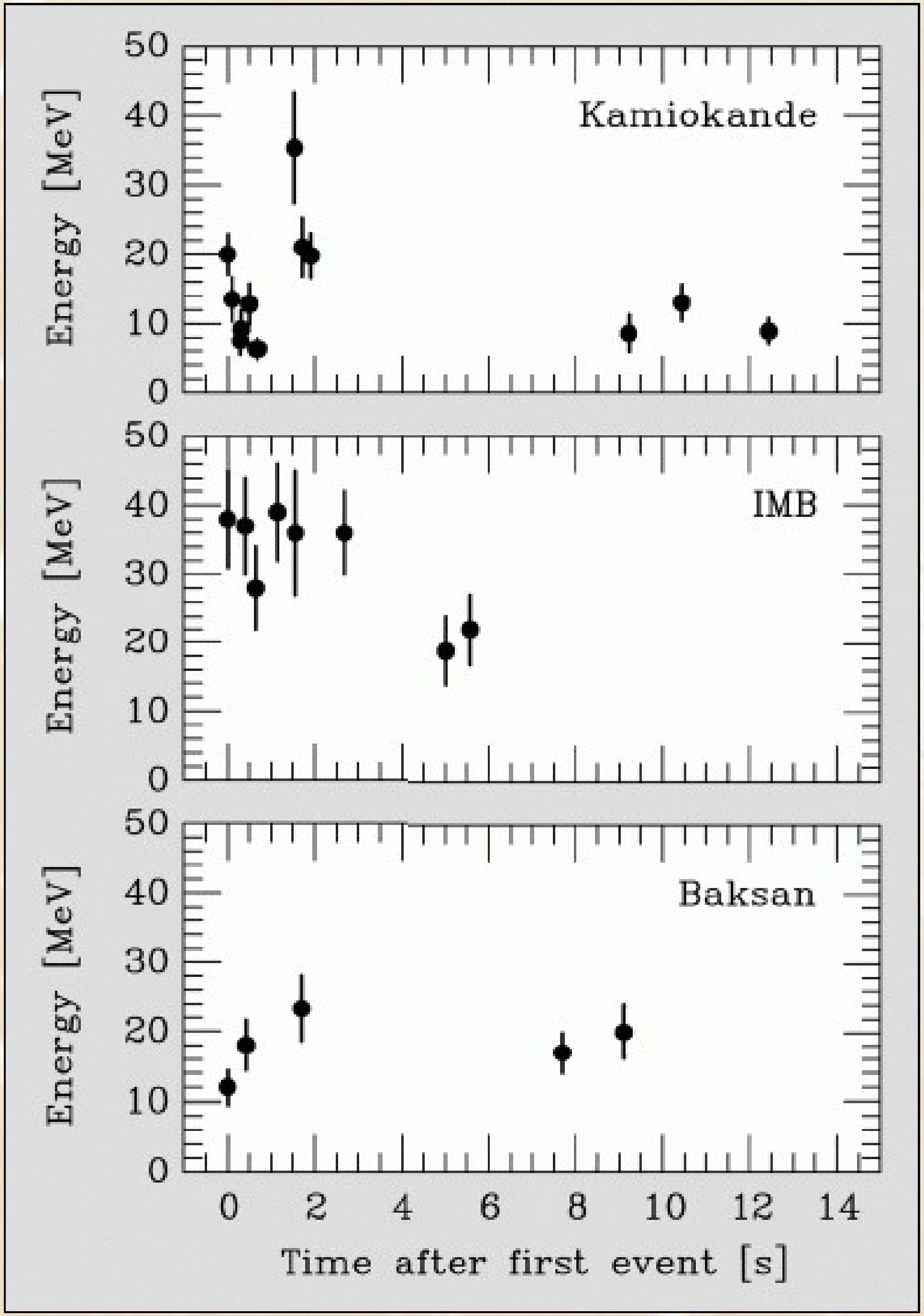
Puppis A





Guitar
Nebula

Neutrino Burst of Supernova 1987A



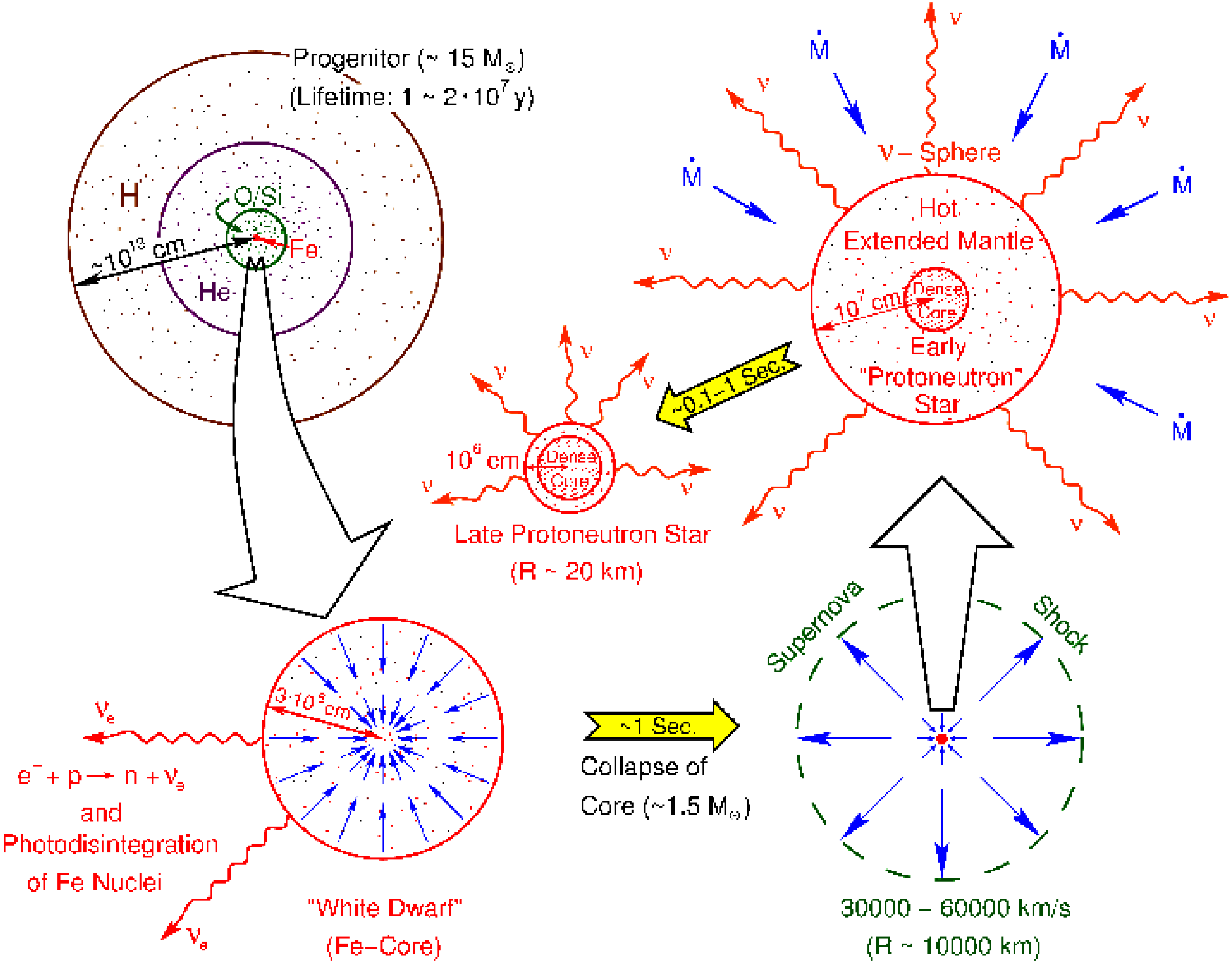
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

Stellar Collapse & Explosion



(adapted
from A.
Burrows)

Role of Neutrinos

- Neutrinos procuded in the hot, forming neutron star carry away the gravitational binding energy of the collapsing stellar core:

$$E \approx 3 \times 10^{53} \left(\frac{M}{\mathrm{M}_\odot}\right)^2 \left(\frac{R}{10\,\mathrm{km}}\right)^{-1} \quad \mathrm{ergs}$$

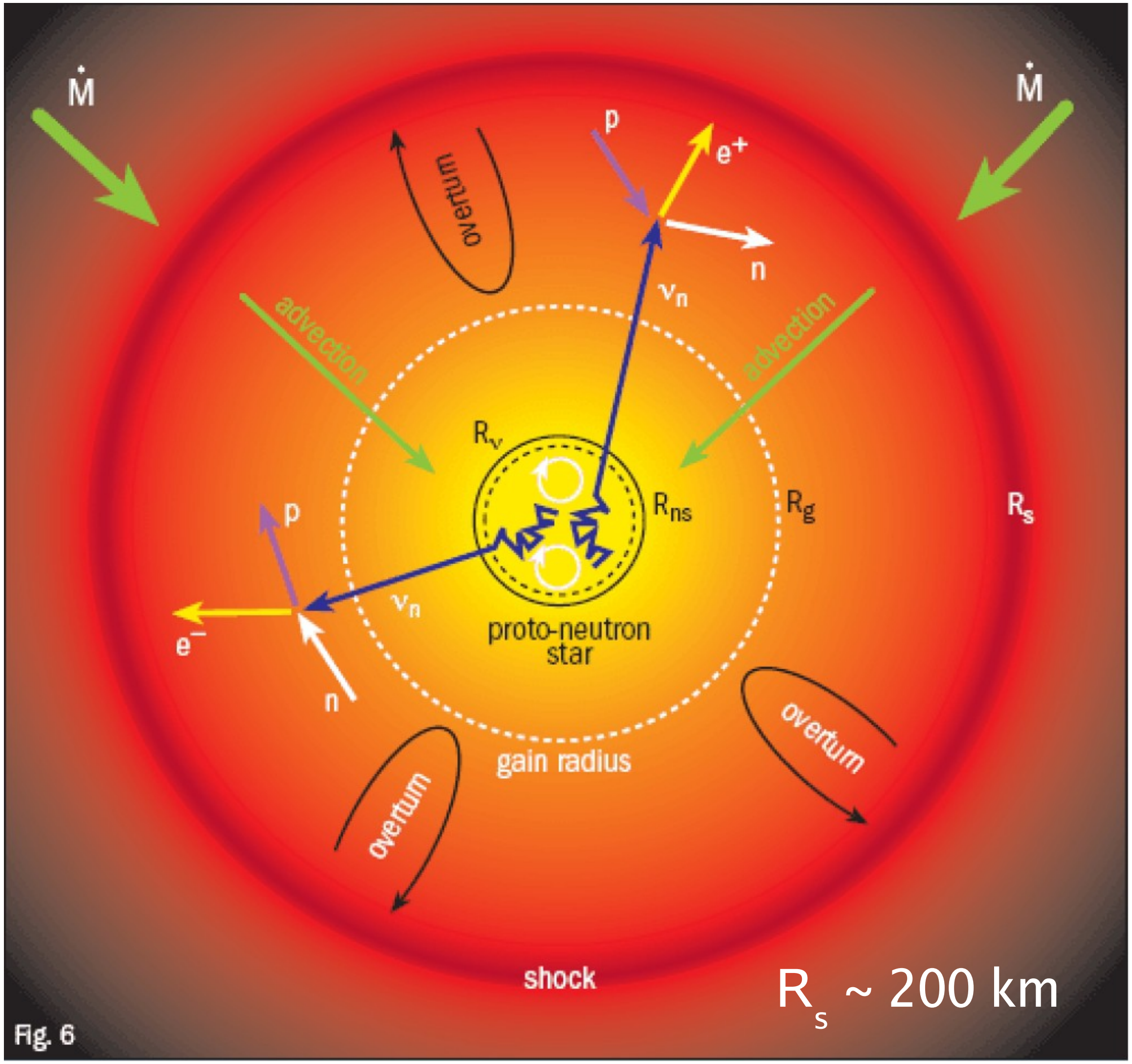
Neutrino energy $E_\nu \approx 100 \times E_{kin}$ of supernova explosion

- Neutrinos transfer energy to the collapsing stellar matter around the newly formed neutron star and could power supernova explosions.

Characteristic supernova energy unit: 10^{51} erg = 10^{44} J = 1 bethe = 1B

Neutrinos & Explosion Mechanism

Paradigm: Explosions by the convectively supported neutrino-heating mechanism



$R_s \sim 200$ km

- "Neutrino-heating mechanism": Neutrinos `revive' stalled shock by energy deposition (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
- Convective processes & hydrodynamic instabilities enhance 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).

Neutrino Heating and Cooling

- Neutrino heating:

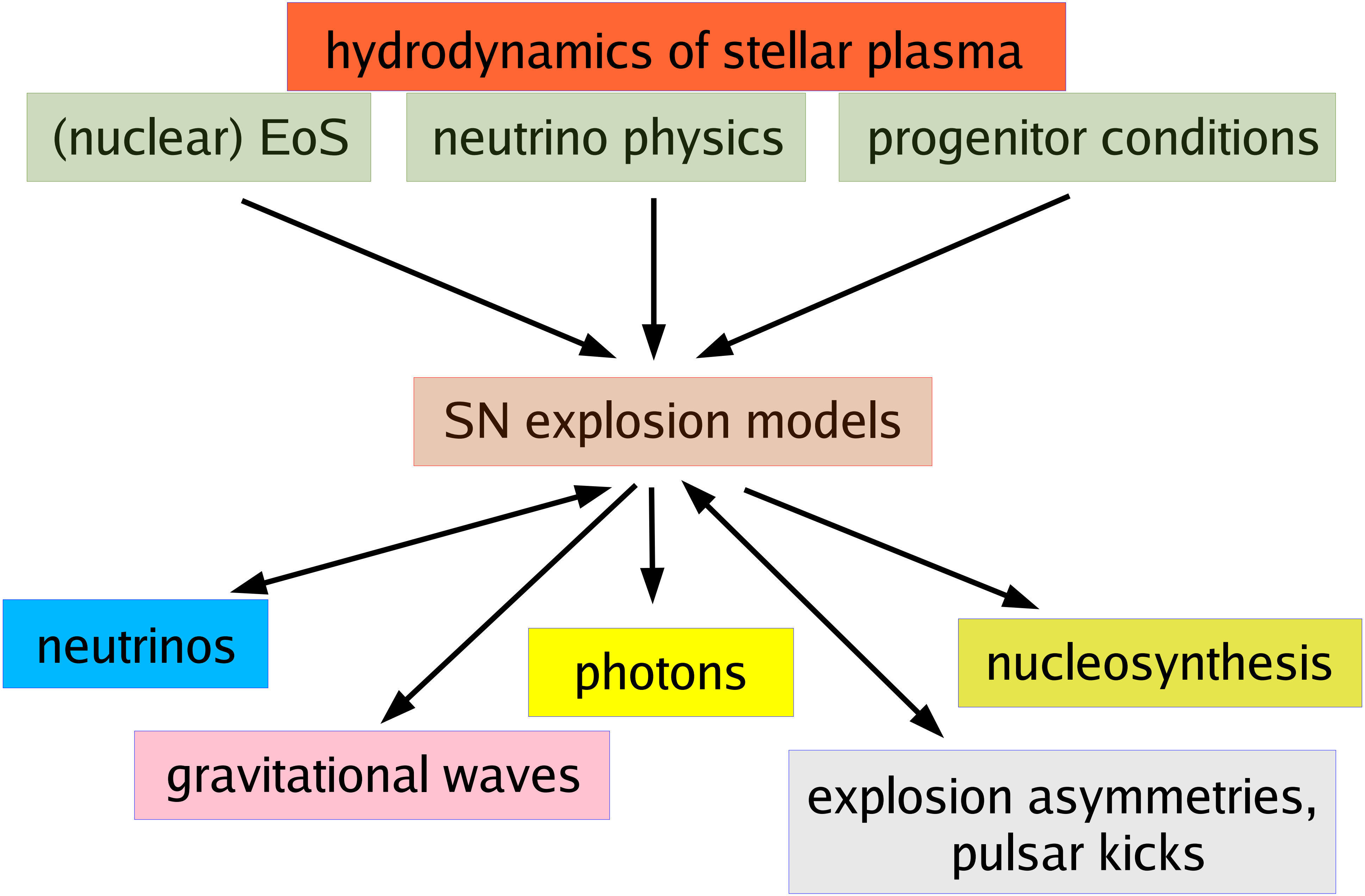
$$\mathcal{H} = 1.544 \times 10^{20} \left(\frac{L_{\nu_e}}{10^{52}\ \mathrm{erg\ s^{-1}}} \right) \left(\frac{T_{\nu_e}}{4\ \mathrm{MeV}} \right)^2 \times \left(\frac{100\,\mathrm{km}}{r} \right)^2 (Y_\mathrm{n} + Y_\mathrm{p}) \qquad \left[\frac{\mathrm{erg}}{\mathrm{g\ s}} \right]$$

- Neutrino cooling:

$$\mathcal{C} = 1.399 \times 10^{20} \left(\frac{T}{2\ \mathrm{MeV}} \right)^6 (Y_\mathrm{n} + Y_\mathrm{p}) \qquad \left[\frac{\mathrm{erg}}{\mathrm{g\ s}} \right]$$

Numerical Models of Stellar Collapse and Explosions

Predictions of Signals from SN Core



hydrodynamics of stellar plasma

(nuclear) EoS

neutrino physics

progenitor conditions

SN explosion models

neutrinos

photons

nucleosynthesis

gravitational waves

explosion asymmetries,
pulsar kicks

General-Relativistic 2D Supernova Models

(Müller B., PhD Thesis (2009);
Müller & THJ, ApJS, (2010))

$$\frac{\partial\sqrt{\gamma}\rho W}{\partial t} + \frac{\partial\sqrt{-g}\rho W\hat{v}^i}{\partial x^i} = 0, \tag{2.5}$$

$$\frac{\partial\sqrt{\gamma}\rho h W^2 v_j}{\partial t} + \frac{\partial\sqrt{-g}\left(\rho h W^2 v_j \hat{v}^i + \delta^i_j P\right)}{\partial x^i} = \frac{1}{2}\sqrt{-g}T^{\mu\nu}\frac{\partial g_{\mu\nu}}{\partial x^j} + \left(\frac{\partial\sqrt{\gamma}S_j}{\partial t}\right)_C, \tag{2.6}$$

$$\frac{\partial\sqrt{\gamma}\tau}{\partial t} + \frac{\partial\sqrt{-g}\left(\tau\hat{v}^i + P v^i\right)}{\partial x^i} = \alpha\sqrt{-g}\left(T^{\mu 0}\frac{\partial\ln\alpha}{\partial x^\mu} - T^{\mu\nu}\Gamma^0_{\mu\nu}\right) + \left(\frac{\partial\sqrt{\gamma}\tau}{\partial t}\right)_C. \tag{2.7}$$

$$\frac{\partial\sqrt{\gamma}\rho W Y_e}{\partial t} + \frac{\partial\sqrt{-g}\rho W Y_e \hat{v}^i}{\partial x^i} = \left(\frac{\partial\sqrt{\gamma}\rho W Y_e}{\partial t}\right)_C, \tag{2.8}$$

$$\frac{\partial\sqrt{\gamma}\rho W X_k}{\partial t} + \frac{\partial\sqrt{-g}\rho W X_k \hat{v}^i}{\partial x^i} = 0. \tag{2.9}$$

GR hydrodynamics

CFC metric equations

$$\hat{\Delta}\Phi = -2\pi\phi^5\left(E + \frac{K_{ij}K^{ij}}{16\pi}\right), \tag{2.10}$$

$$\hat{\Delta}(\alpha\Phi) = 2\pi\alpha\phi^5\left(E + 2S + \frac{7K_{ij}K^{ij}}{16\pi}\right), \tag{2.11}$$

$$\hat{\Delta}\beta^i = 16\pi\alpha\phi^4 S^i + 2\phi^{10}K^{ij}\hat{\nabla}_j\left(\frac{\alpha}{\Phi^6}\right) - \frac{1}{3}\hat{\nabla}^i\hat{\nabla}_j\beta^j, \tag{2.12}$$

$$\begin{aligned}
&\frac{\partial W\left(\hat{J} + v_r\hat{H}\right)}{\partial t} + \frac{\partial}{\partial r}\left[\left(W\frac{\alpha}{\phi^2} - \beta_r v_r\right)\hat{H} + \left(W v_r\frac{\alpha}{\phi^2} - \beta_r\right)\hat{J}\right] - \\
&\frac{\partial}{\partial\varepsilon}\left\{W\varepsilon\hat{J}\left[\frac{1}{r}\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right) + 2\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right] + \right. \\
&W\varepsilon\hat{H}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right) - \frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r} + \alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r} - \frac{\partial v_r}{\partial t}\right)\right] - \\
&\left.\varepsilon\hat{K}\left[\frac{\beta_r W}{r} - \frac{\partial\beta_r W}{\partial r} + W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right) + W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r} + v_r\frac{\partial v_r}{\partial t}\right)\right]\right\} - \\
&W\hat{J}\left[\frac{1}{r}\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right) + 2\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right] - \\
&W\hat{H}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right) - \frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r} + \alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r} - \frac{\partial v_r}{\partial t}\right)\right] + \\
&\hat{K}\left[\frac{\beta_r W}{r} - \frac{\partial\beta_r W}{\partial r} + W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right) + W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r} + v_r\frac{\partial v_r}{\partial t}\right)\right] = \alpha\hat{C}^{(0)},
\end{aligned} \tag{2.28}$$

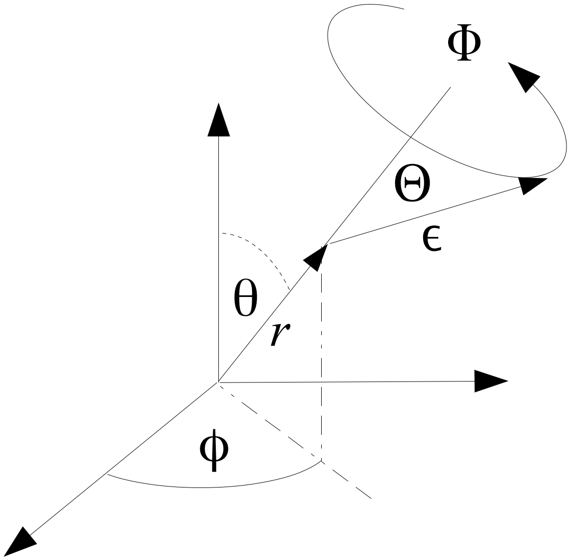
Neutrino transport

$$\begin{aligned}
&\frac{\partial W\left(\hat{H} + v_r\hat{K}\right)}{\partial t} + \frac{\partial}{\partial r}\left[\left(W\frac{\alpha}{\phi^2} - \beta_r v_r\right)\hat{K} + \left(W v_r\frac{\alpha}{\phi^2} - \beta_r\right)\hat{H}\right] - \\
&\frac{\partial}{\partial\varepsilon}\left\{W\varepsilon\hat{H}\left[\frac{1}{r}\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right) + 2\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right] + \right. \\
&W\varepsilon\hat{K}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right) - \frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r} + \alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r} - \frac{\partial v_r}{\partial t}\right)\right] - \\
&\left.\varepsilon\hat{L}\left[\frac{\beta_r W}{r} - \frac{\partial\beta_r W}{\partial r} + W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right) + W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r} + v_r\frac{\partial v_r}{\partial t}\right)\right]\right\} + \\
&\left(\hat{J} - \hat{K}\right)\left[v_r\left(\frac{\beta_r}{r} - \frac{\partial\beta_r}{\partial r}\right) + \frac{\partial}{\partial r}\left(\frac{W\alpha}{\phi^2}\right) - \frac{W\alpha}{r\phi^2} + W^3\left(\frac{\partial v_r}{\partial t} - \beta_r\frac{\partial v_r}{\partial r}\right)\right] + \\
&\left(\hat{H} - \hat{L}\right)\left[\frac{W^3\alpha}{\phi^2}\frac{\partial v_r}{\partial r} + \frac{\beta W}{r} - \frac{\partial\beta W}{\partial r} - W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right) + \frac{\partial W}{\partial t}\right] - \\
&W\hat{H}\left[\frac{1}{r}\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right) + 2\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right] - \\
&W\hat{K}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right) - \frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r} + \alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r} - \frac{\partial v_r}{\partial t}\right)\right] + \\
&\hat{L}\left[\frac{\beta_r W}{r} - \frac{\partial\beta_r W}{\partial r} + W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right) + W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r} + v_r\frac{\partial v_r}{\partial t}\right)\right] = \alpha\hat{C}^{(1)}.
\end{aligned} \tag{2.29}$$

Neutrino Reactions in Supernovae

Beta processes:	• $e^- + p \rightleftharpoons n + \nu_e$ • $e^+ + n \rightleftharpoons p + \bar{\nu}_e$ • $e^- + A \rightleftharpoons \nu_e + A^*$
Neutrino scattering:	• $\nu + n, p \rightleftharpoons \nu + n, p$ • $\nu + A \rightleftharpoons \nu + A$ • $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
Thermal pair processes:	• $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$ • $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
Neutrino-neutrino reactions:	• $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$ • $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

The Curse and Challenge of the Dimensions



Boltzmann equation determines neutrino distribution function in phase space

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

Integration over momentum space yields source terms for hydrodynamics

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

Solution approach	Required resources
3D hydro + **6D** direct discretization of Boltzmann Eq. (no serious attempt yet)	≥ 1–10 PFlops (sustained!)
2D hydro + **5D** direct discretization of Boltzmann Eq. (planned by DoE's TSI/SSC)	≥ 10–100 Tflops, TBytes
2D hydro + **"ray-by-ray-plus"** variable Eddington factor method (current method of MPA)	≥ 1 TFlops, < 1 Tbyte
3D hydro + **"ray-by-ray-plus"** variable Eddington factor method (current method of MPA)	≥ 10–100 Tflops, TBytes

Computing requirements for 2D & 3D SN 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, corresponds to ~3 years on 32 processor cores

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

~ $3*10^{20}$ Flops, corresponds to ~1 year on 8192 processor cores

Distributed European Infrastructure for Supercomputing Applications

DEISA

SEVENTH FRAMEWORK PROGRAMME

NIC

John von Neumann
Institut für Computing

HLRS

rzg

IPP

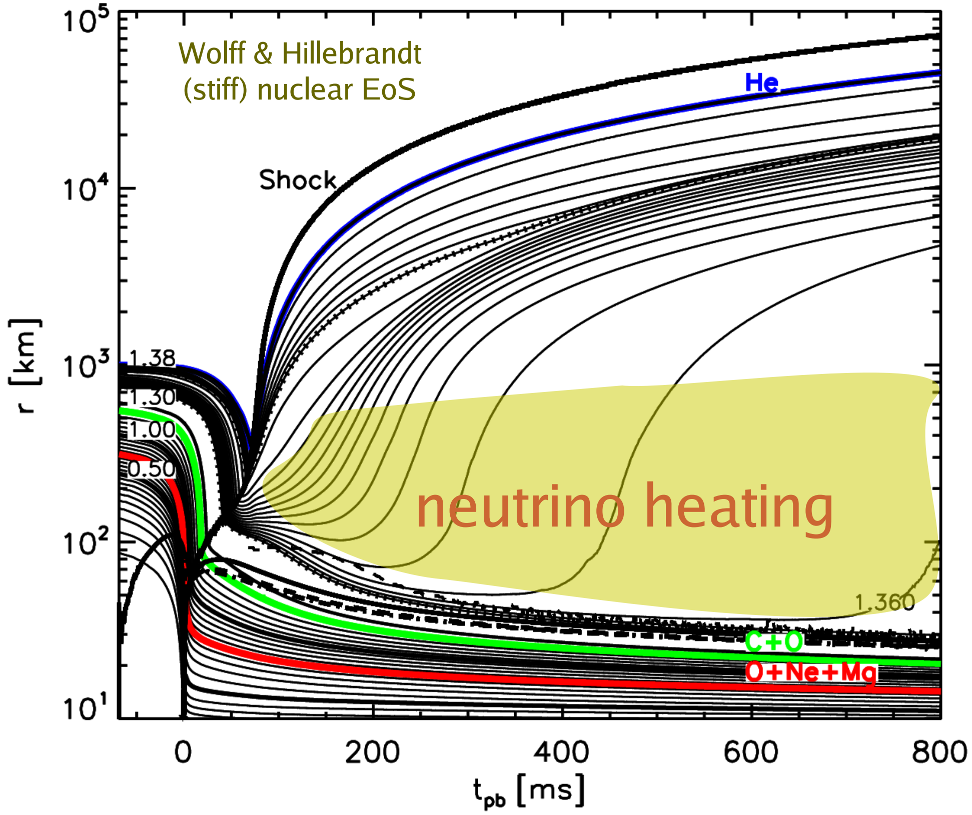
RECHEN-
ZENTRUM
GARCHING

Leibniz-Rechenzentrum
der Bayerischen Akademie der Wissenschaften

Explosions of $M_{star} \sim 8\text{–}10\ M_{sun}$ Stars

SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

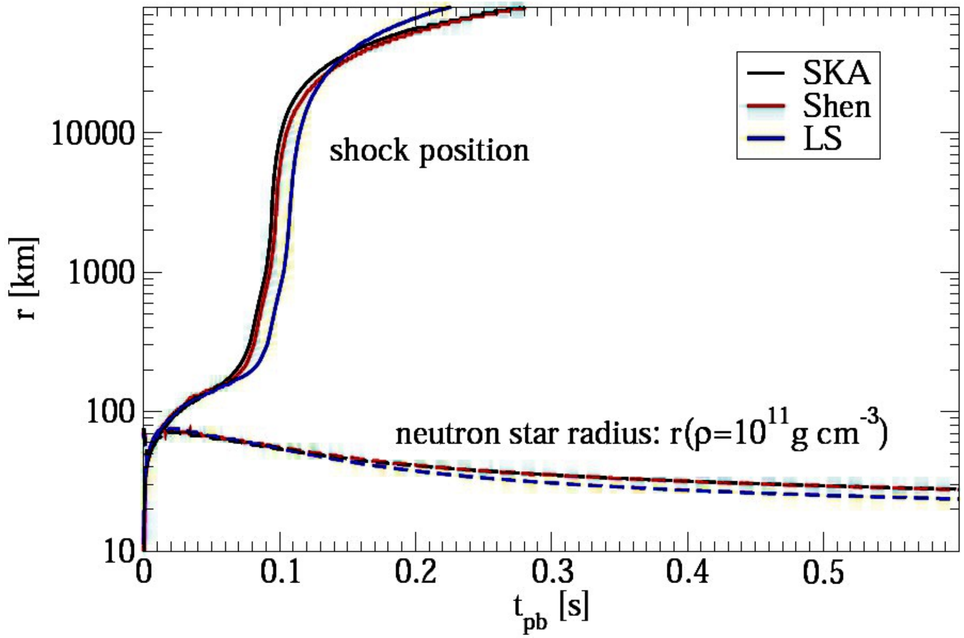
"Electron-capture supernovae"
or "ONeMg core supernovae"



Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199

Convection is not necessary for launching explosion but occurs in NS and in neutrino-heating layer

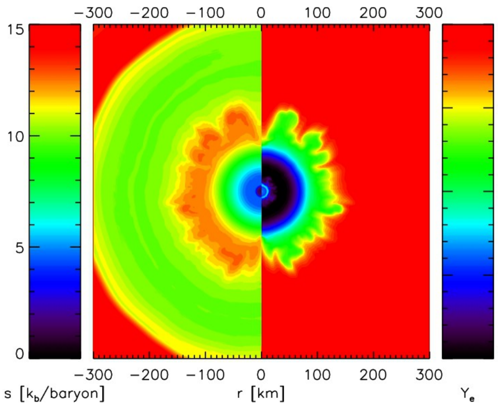
- No prompt explosion !
- Mass ejection by "neutrino-driven wind"
  (like Mayle & Wilson 1988
  and similar to AIC of WDs;
  see Woosley & Baron 1992, Fryer et al. 1999;
  Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)



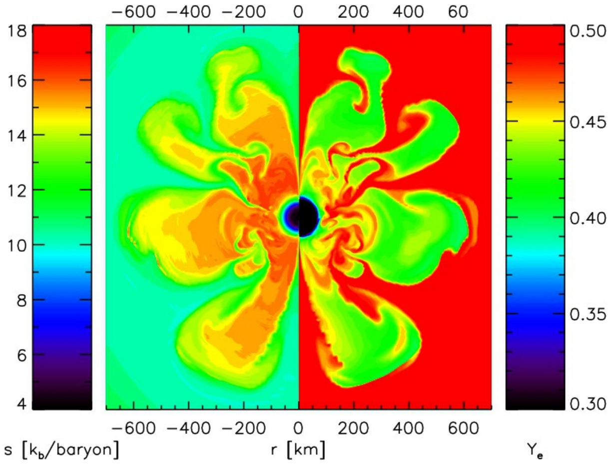
2D SN Simulations: $M_{star} \sim 8...10\,M_{sun}$

Convection leads to slight increase of explosion energy, causes explosion asymmetries, and ejects n-rich matter!

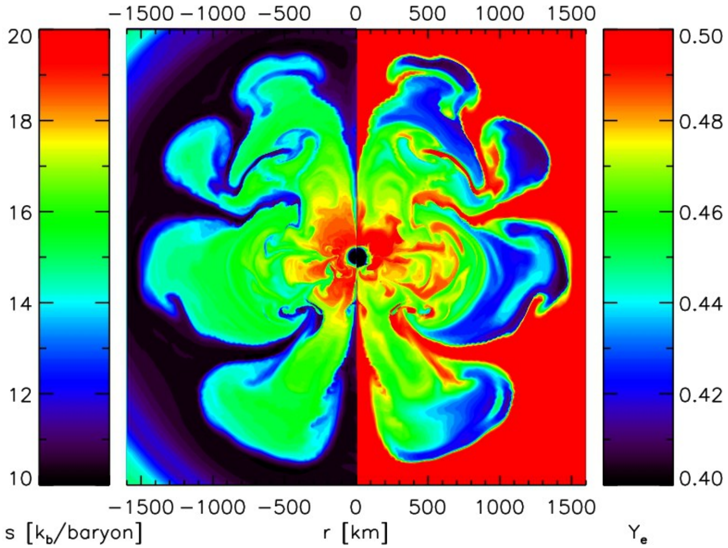
Entropy Y_e



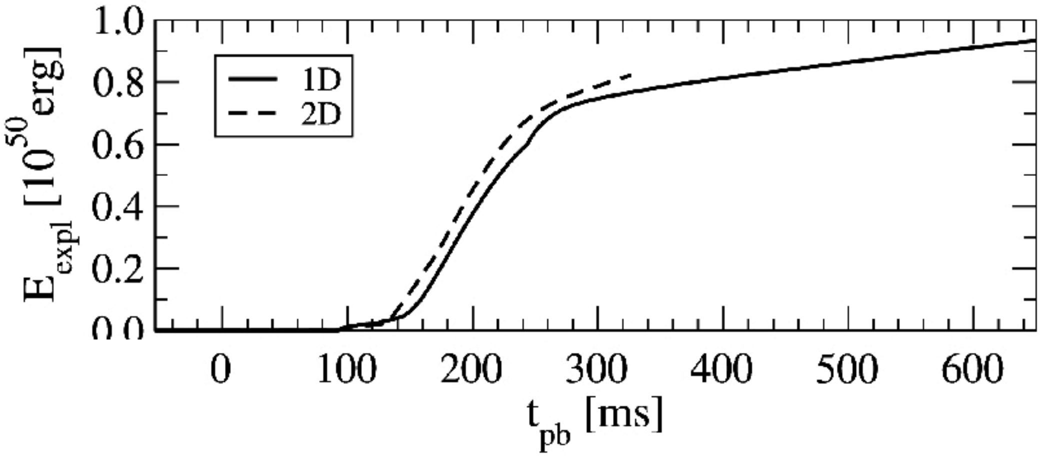
t = 0.097 s after core bounce



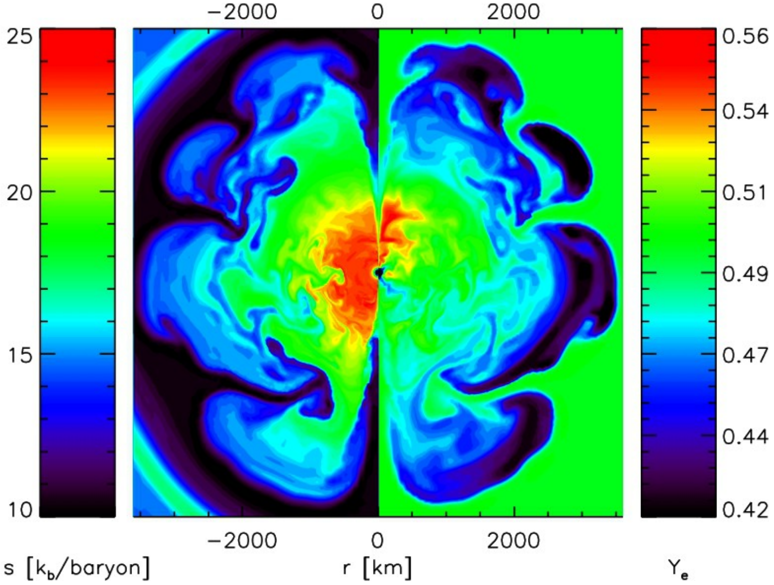
t = 0.144 s after core bounce



t = 0.185 s after core bounce



Janka et al. (2008), Müller et al. (in preparation)



t = 0.262 s after core bounce

CRAB Nebula with pulsar, remnant of Supernova 1054

Explosion properties:

E_{exp} ~ 10^{50} erg = 0.1 bethe
M_{Ni} ~ 0.003 M_{sun}

Low explosion energy and ejecta composition (little Ni, C, O) of ONeMg core explosion are compatible with CRAB (SN1054)

(Nomoto et al., Nature, 1982;
Hillebrandt, A&A, 1982)

Might also explain other low-luminosity supernovae (e.g. SN1997D, 2008S, 2008HA)

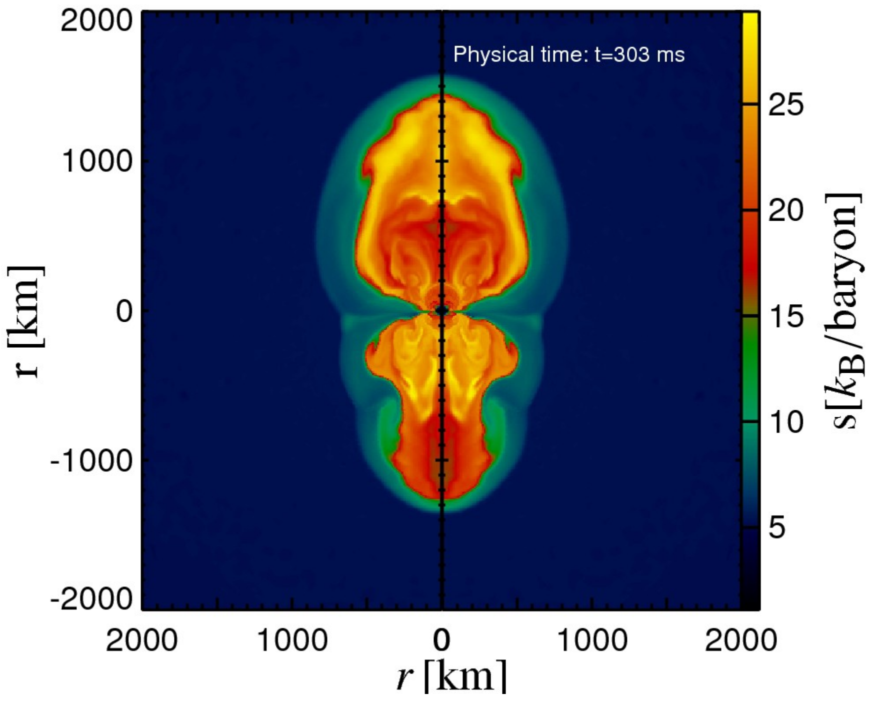
Explosions of $M_{star} > 10\ M_{sun}$ Stars

2D SN Simulations: $M_{star} \sim 11\ M_{sun}$

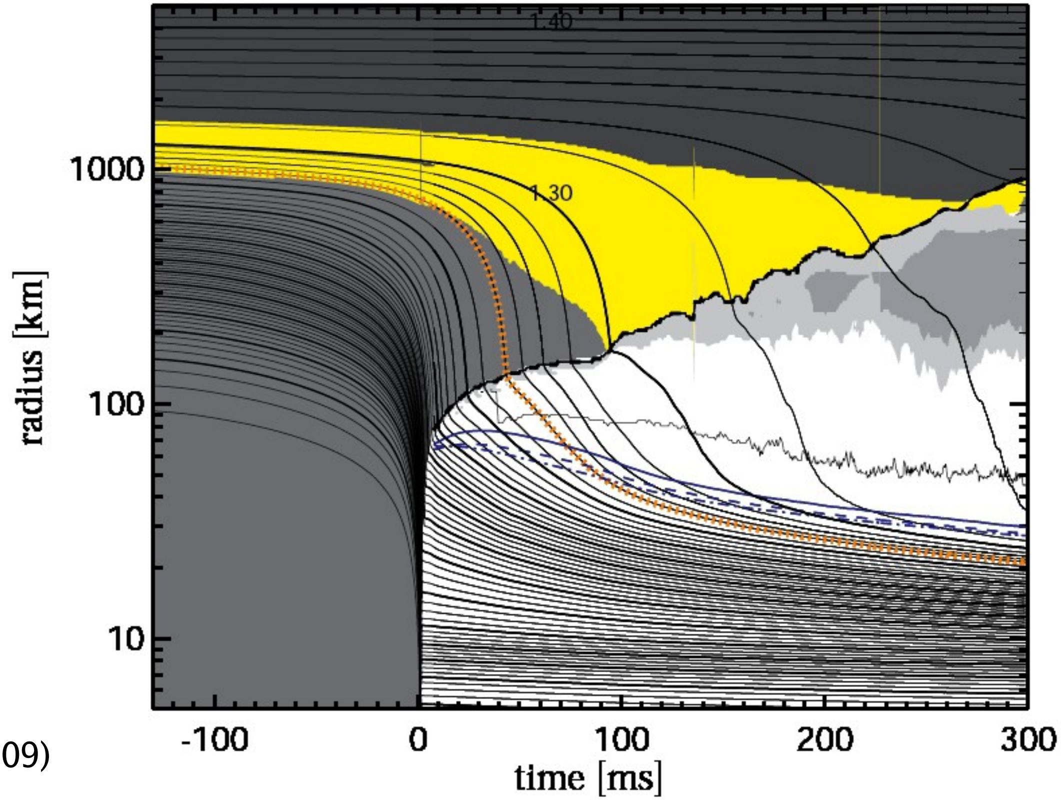
For explosions of stars with $M > 10\ M_{sun}$ multi-dimensional effects (nonradial hydrodynamic instabilities) are crucial !

Low-mode nonradial (dipole, l=1, and quadrupole, l=2) "standing accretion shock instability" ("SASI"; Blondin et al. 2003) develops and pushes shock to larger radii

===> This stretches dwelling time of matter in neutrino heating layer and thus increases energy deposition;
initiation of globally aspherical explosion by neutrino heating even without rotation

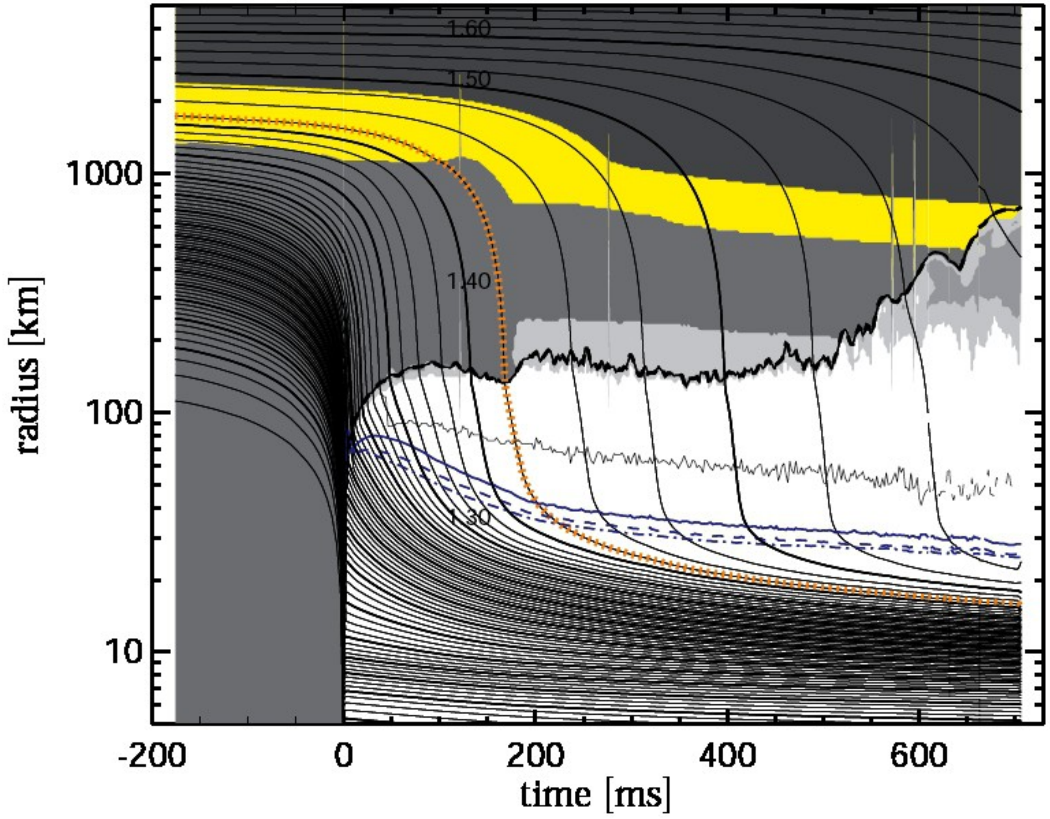


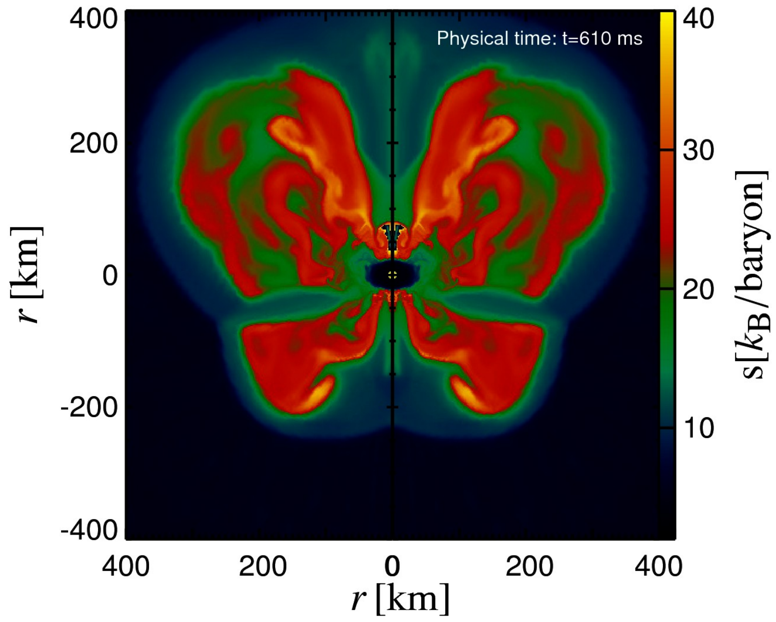
Buras et al., A&A 457 (2006) 281; Marek & Janka, ApJ (2009)



2D SN Simulations: $M_{star} = 15\ M_{sun}$

Violent SASI oscillations:
ν-driven explosion sets in
at t ~ 600 ms after bounce

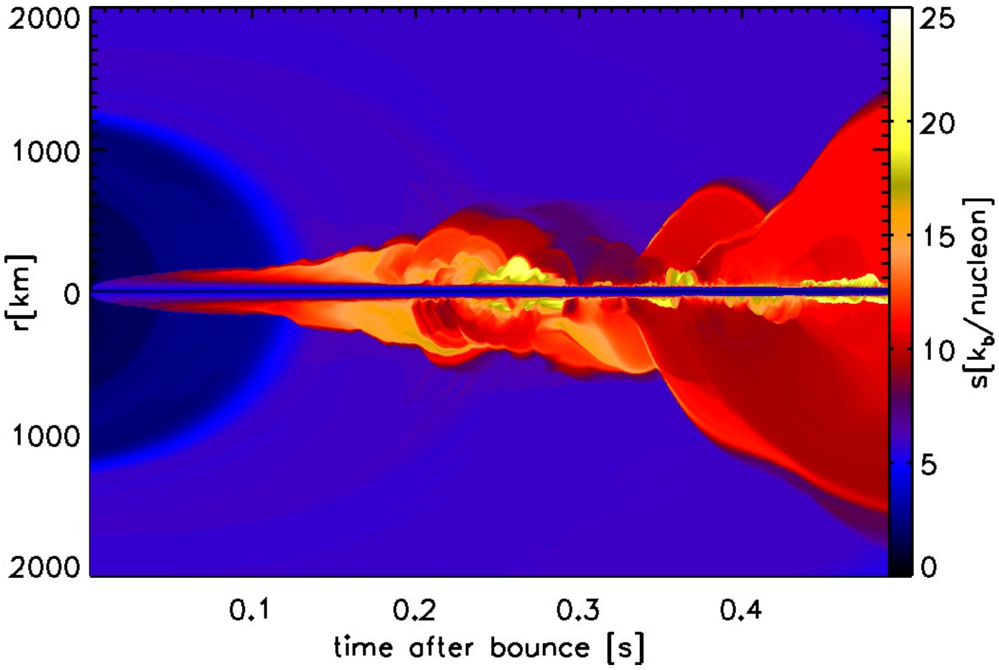




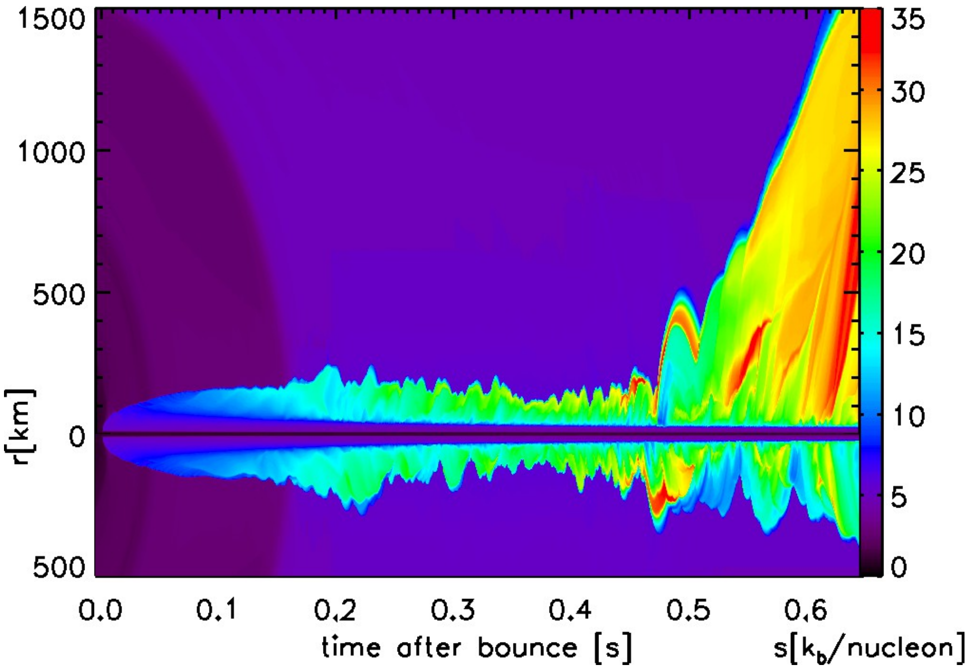
(Marek, PhD Thesis 2007;
Marek & THJ, ApJ, 2009)

Relativistic 2D SN Models:
11.2 and 15 M_{sun} Stars

11.2 M_{sun}



15 M_{sun}

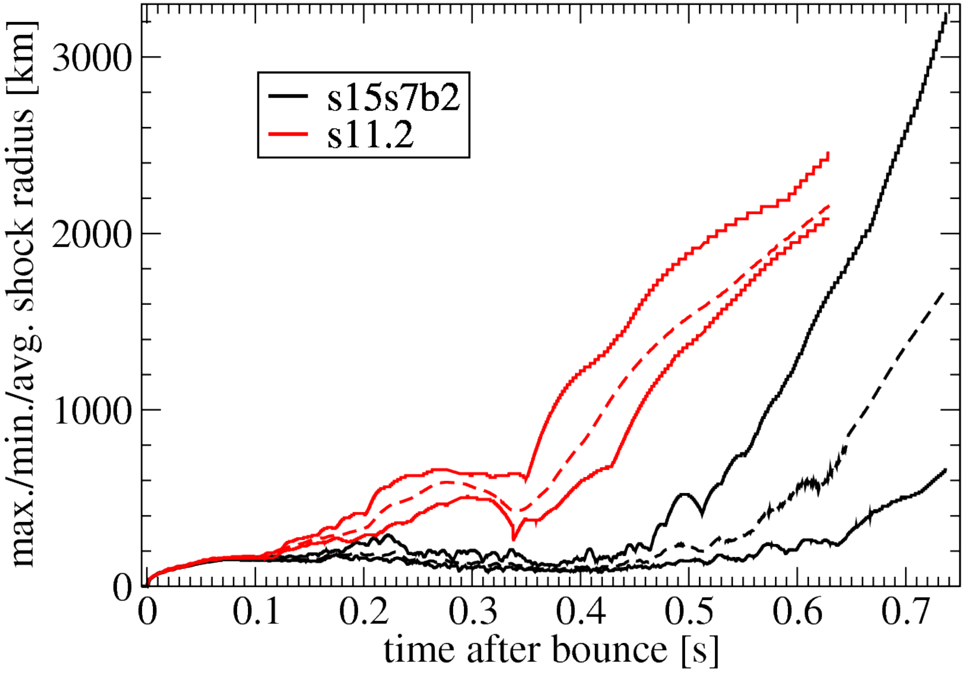


Violent, long lasting shock oscillations produce quasi-periodic variations of neutrino emission and gravitational-wave signal.

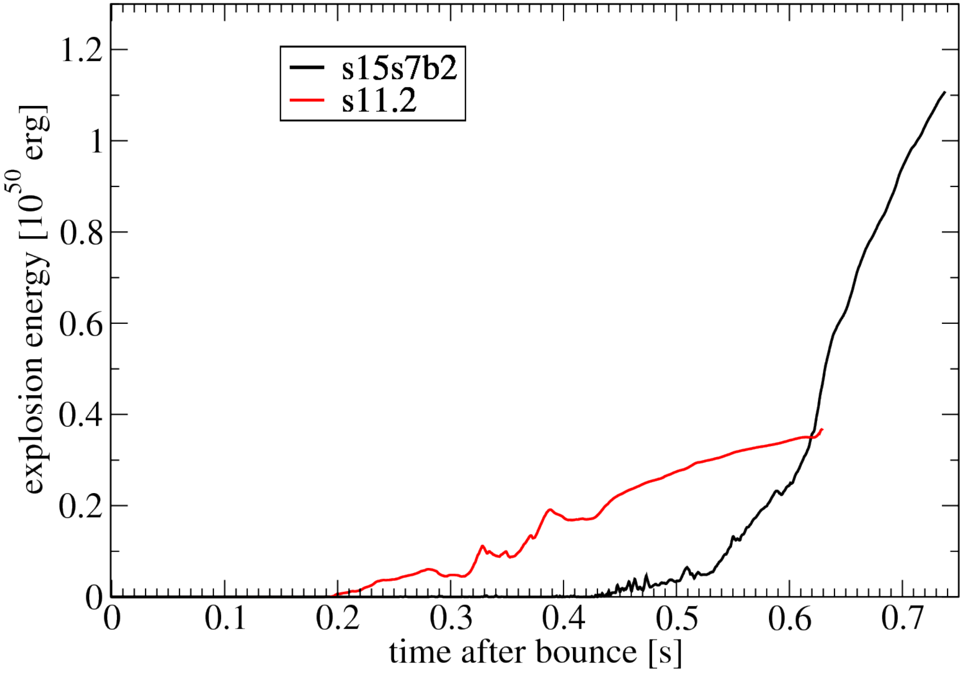
(Müller, THJ, Marek & Dimmelmeier, to be submitted)

Relativistic 2D SN Simulations

Shock radii



Explosion energies



(Müller, THJ, Marek & Dimmelmeier, to be submitted)

- Relativistic (GR) 2D calculations basically confirm our “post-Newtonian” results.
- Explosions with GR develop somewhat faster and earlier. GR effects help!
- 2D explosions are seemingly “marginal”, i.e., tend to set in late and to be relatively weak and highly deformed.

Explosion Energies and NS masses

$$E_{\rm exp} \approx \dot{E}_\nu \tau_{\rm acc} + E_{\rm wind} + E_{\rm burn} - E_{\rm bind}$$

$$\dot{E}_\nu \sim \zeta \dot{M}_{\rm acc} \dot{q}_\nu \tau_{\rm adv}$$

$$\sim 2 \times 10^{51} \frac{\rm erg}{\rm s} \left(\frac{\zeta}{0.5}\right) \left(\frac{\dot{M}_{\rm acc}}{0.2\, M_\odot/{\rm s}}\right) \times$$

$$\times \left(\frac{\dot{q}_\nu m_{\rm B}}{300\,{\rm MeV/s}}\right) \left(\frac{\tau_{\rm adv}}{30\,{\rm ms}}\right)$$

($E_{\rm exp}$ depends on the duration of simultaneous accretion & outflow after onset of explosion: $t_{\rm acc}$~0.5 sec)

$$\tau_{\rm acc} \approx \frac{R_{\rm esc}}{v_{\rm s}} \sim 0.5\,{\rm s}\; M_{1.5}\, v_{\rm s,9}^{-3}$$

Stellar mass [$M_{\rm sun}$]	$t_{\rm exp}$ [ms]	$\Delta M_{\rm gain}$ [$M_{\rm sun}$]	$E_{\rm exp}$ [B]	$M_{\rm ns}$(baryonic) [$M_{\rm sun}$]
8 – 10	150	< 0.01	~ 0.1	1.35
~11	250	0.01	0.1 – 0.2	1.35
15	600	0.08	~ 1.0	1.55

NOTE: The stellar properties do not vary monotonically with the progenitor mass (cf. Woosley, Heger, & Weaver 2005)

Questions & Challenges

- 2D simulations seem to yield “marginal” successes for some progenitor models.
- Is neutrino heating indeed the power behind explosions of Fe-core progenitors with > 10 solar masses?
- 3D simulations needed !!
- Is 3D hydrodynamics more favorable for explosions than 2D?
  The answer is not finally clear!

Consequences and Implications of Neutrino Heating and SASI in Stellar Explosions

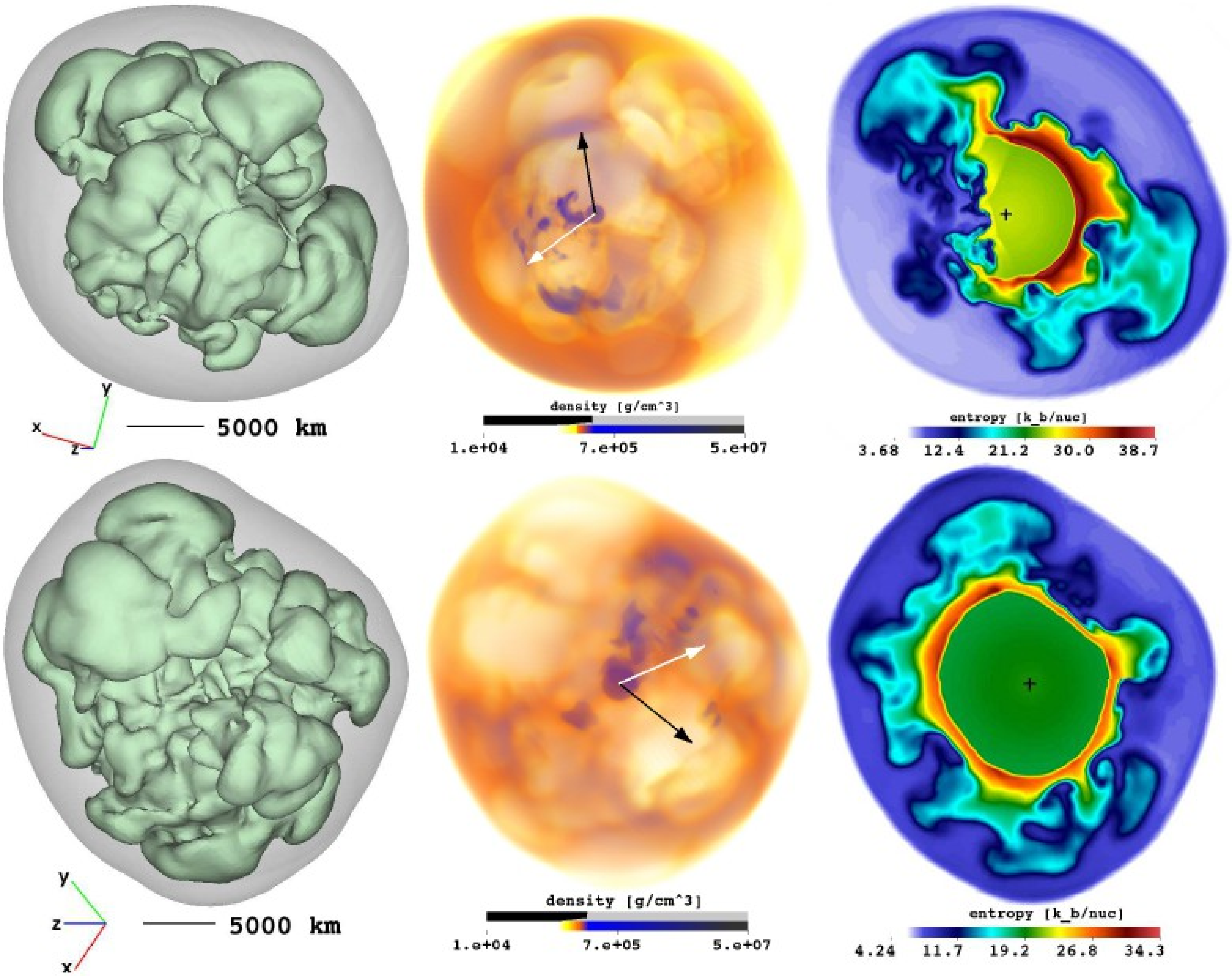
- Neutron star kicks (Scheck et al. 2004, 2006; Wongwathanat et al. 2010)
- Asymmetric mass ejection & large-scale radial mixing (Kifonidis et al. 2005)
- Charactersitic neutrino signal modulations (Marek et al. 2009; Müller et al. 2011)
- Gravitational wave signals (Marek et al. 2009; Müller et al. 2011)

Neutron Star Kicks in 3D Explosions

Parametric explosion calculations:

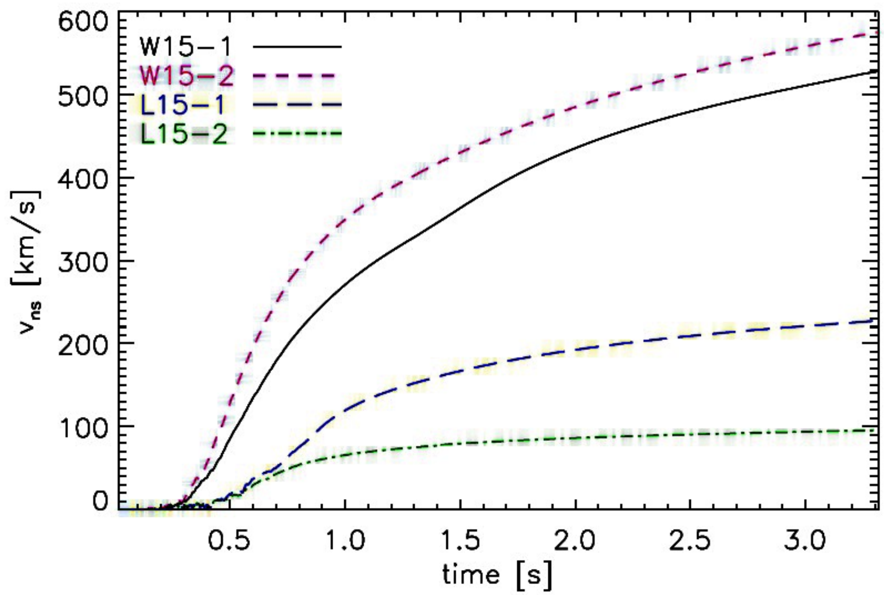
Neutrino core luminosity of proto-NS chosen;
Accretion luminosity calculated with simple (grey) transport scheme.

Neutron Star Recoil in 3D

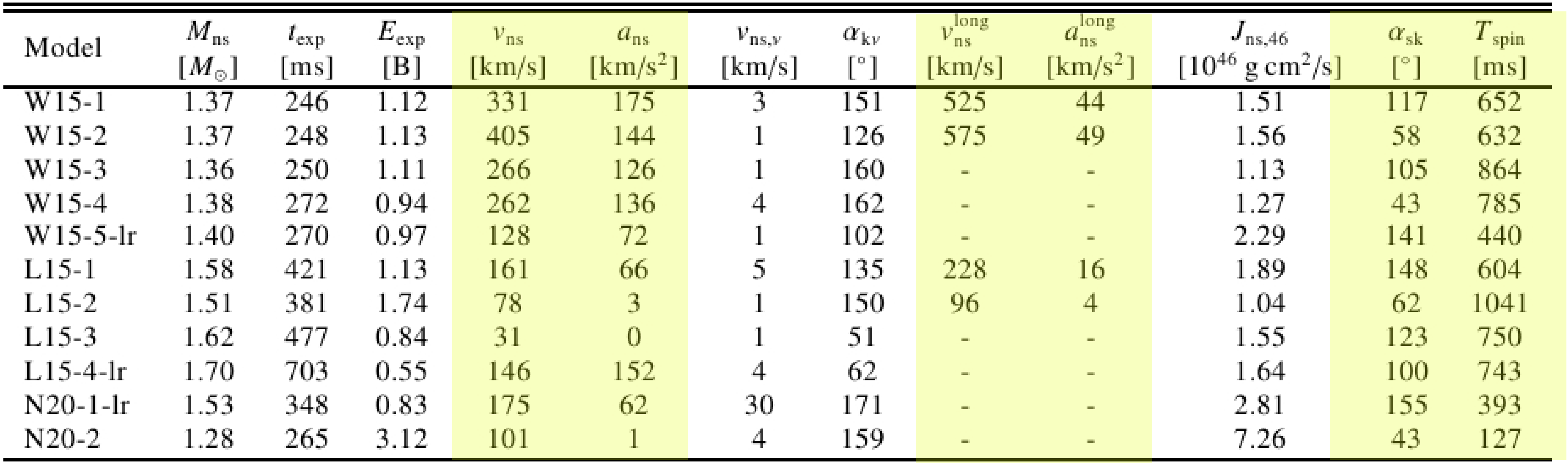


(Wongwathanarat, Janka, Müller, ApJL 725 (2010) 106; A&A, in preparation)

Neutron Star Recoil in 3D



(Wongwathanarat, Janka, Müller, ApJL 725 (2010) 106; A&A, in preparation)

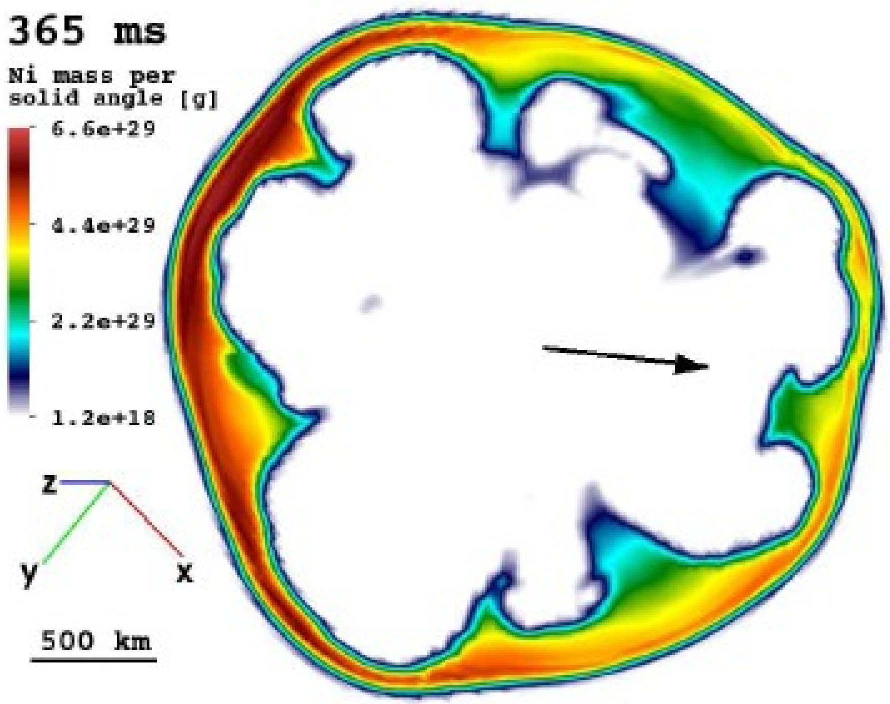


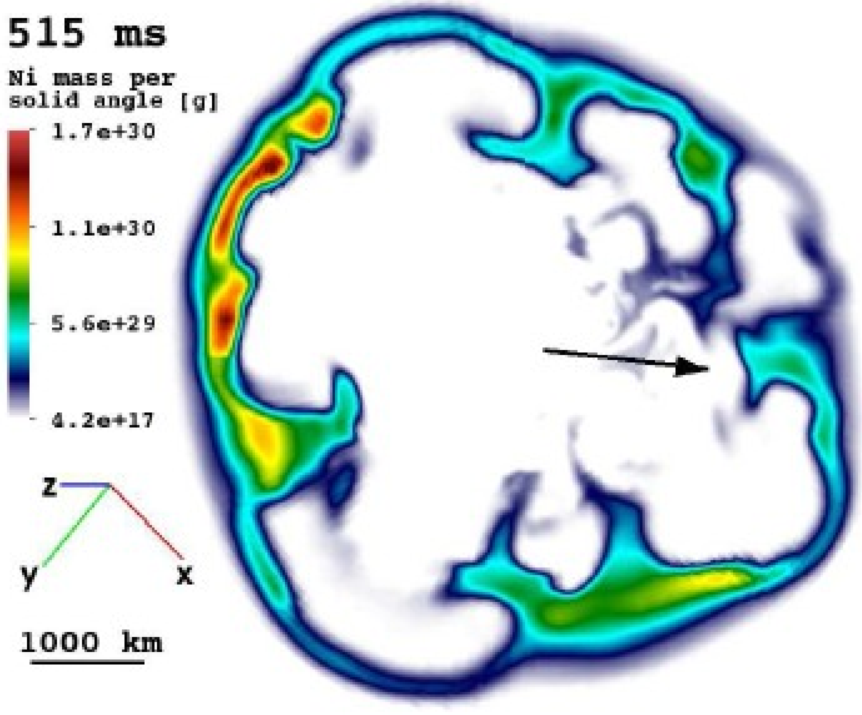
Model	$M_{\rm ns}$ $[M_\odot]$	$t_{\rm exp}$ [ms]	$E_{\rm exp}$ [B]	$v_{\rm ns}$ [km/s]	$a_{\rm ns}$ [km/s^2]	$v_{{\rm ns},\nu}$ [km/s]	$\alpha_{{\rm k}\nu}$ [°]	$v_{\rm ns}^{\rm long}$ [km/s]	$a_{\rm ns}^{\rm long}$ [km/s^2]	$J_{\rm ns,46}$ [10^{46} g cm^2/s]	$\alpha_{\rm sk}$ [°]	$T_{\rm spin}$ [ms]
W15-1	1.37	246	1.12	331	175	3	151	525	44	1.51	117	652
W15-2	1.37	248	1.13	405	144	1	126	575	49	1.56	58	632
W15-3	1.36	250	1.11	266	126	1	160	-	-	1.13	105	864
W15-4	1.38	272	0.94	262	136	4	162	-	-	1.27	43	785
W15-5-lr	1.40	270	0.97	128	72	1	102	-	-	2.29	141	440
L15-1	1.58	421	1.13	161	66	5	135	228	16	1.89	148	604
L15-2	1.51	381	1.74	78	3	1	150	96	4	1.04	62	1041
L15-3	1.62	477	0.84	31	0	1	51	-	-	1.55	123	750
L15-4-lr	1.70	703	0.55	146	152	4	62	-	-	1.64	100	743
N20-1-lr	1.53	348	0.83	175	62	30	171	-	-	2.81	155	393
N20-2	1.28	265	3.12	101	1	4	159	-	-	7.26	43	127

Neutron Star Recoil and Nickel Production

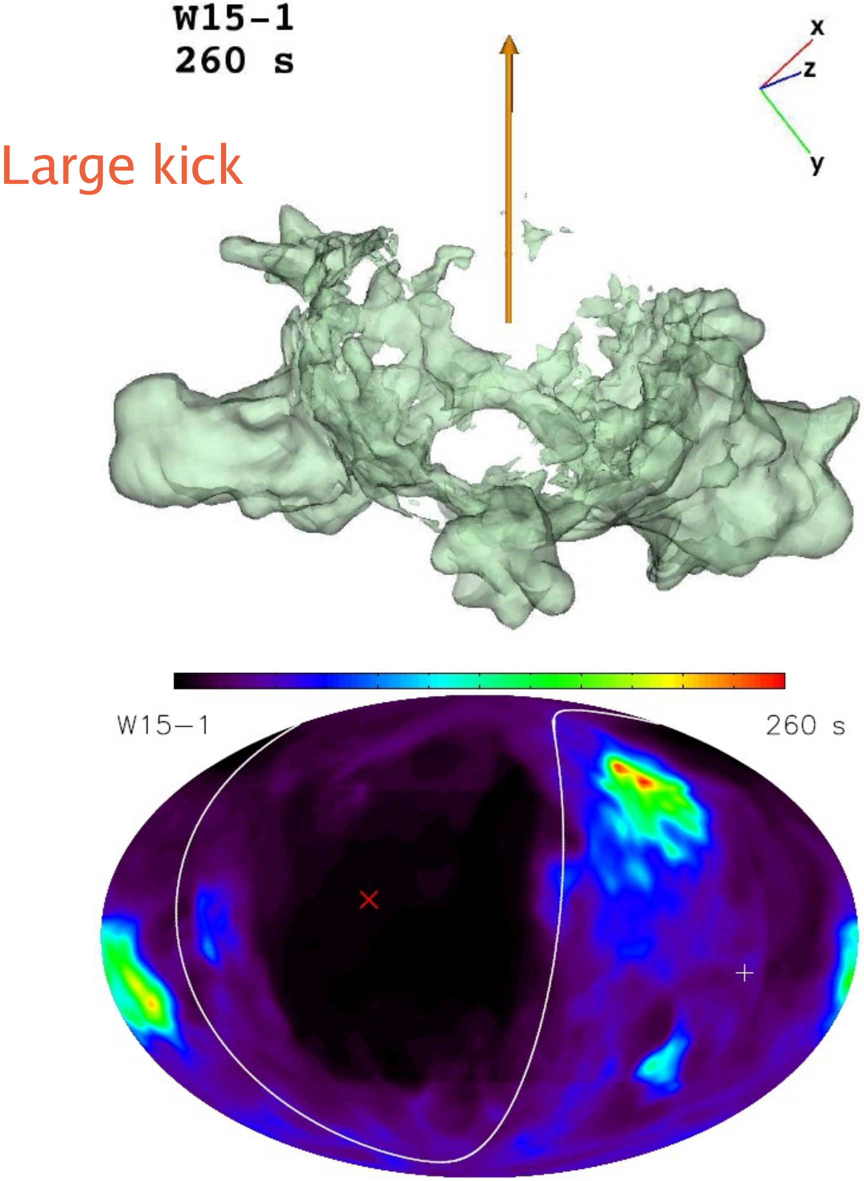
Nickel production is enhanced in direction of stronger explosion, i.e. opposite to NS kick

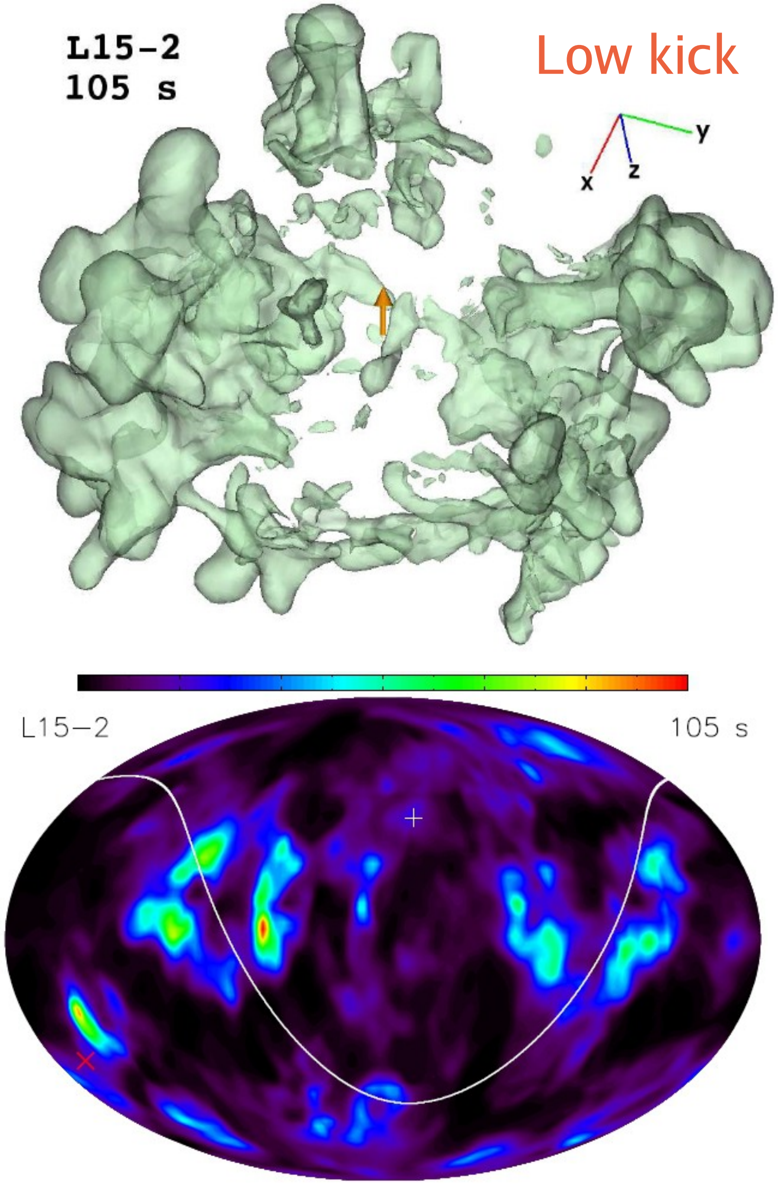
(Wongwathanarat, Janka, Müller, A&A, to be submitted)





Neutron Star Recoil and Nickel Production



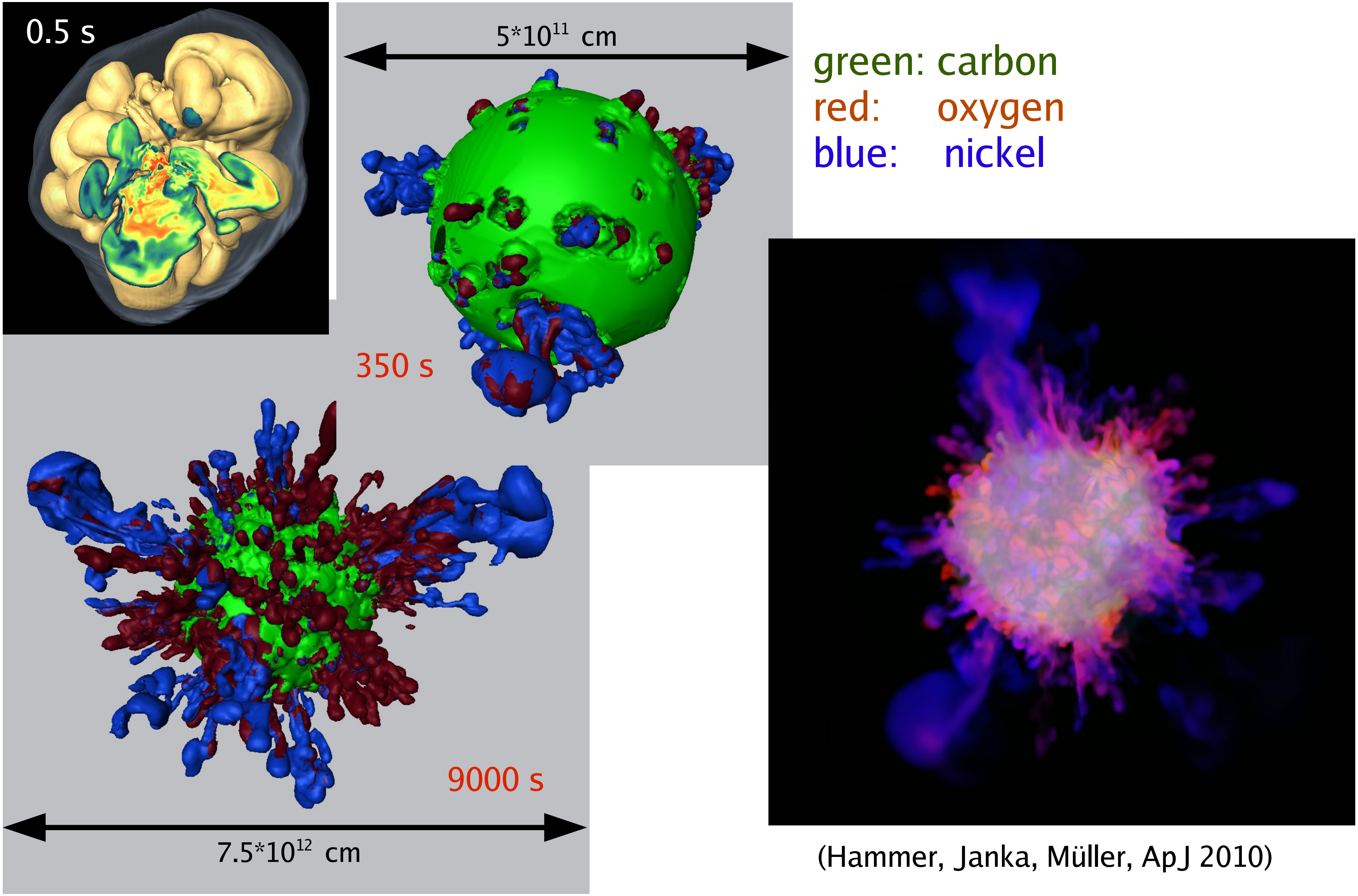


(Wongwathanarat, Janka, Müller, A&A, to be submitted)

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

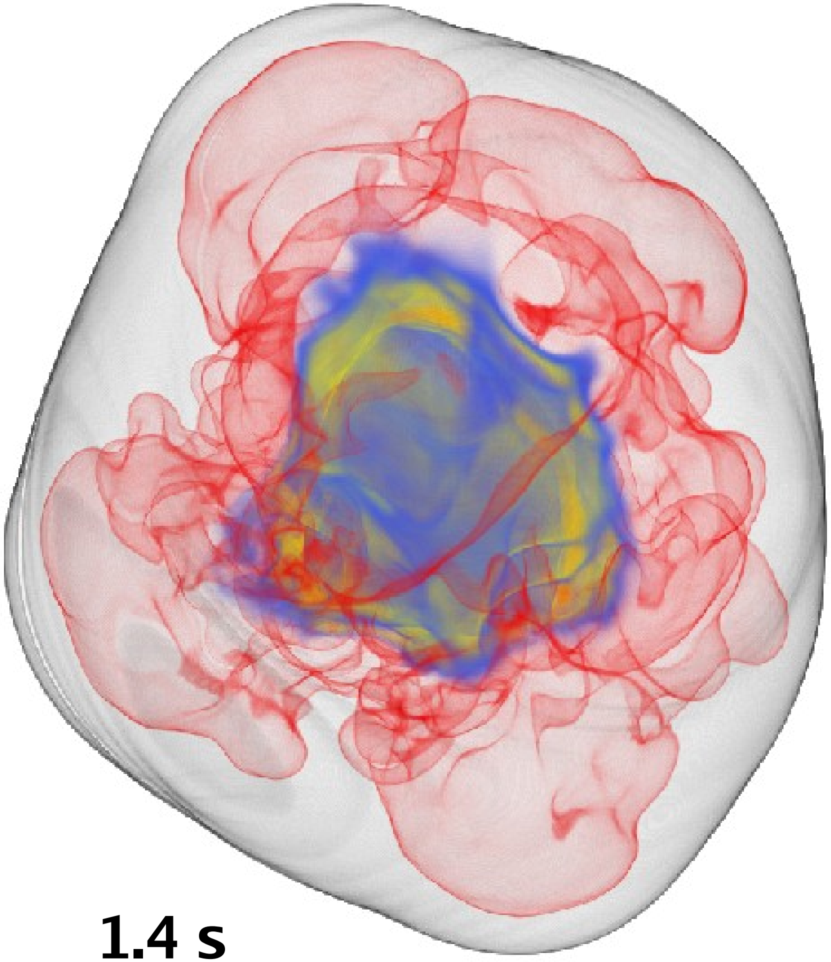
Mixing Instabilities in 3D SN Models



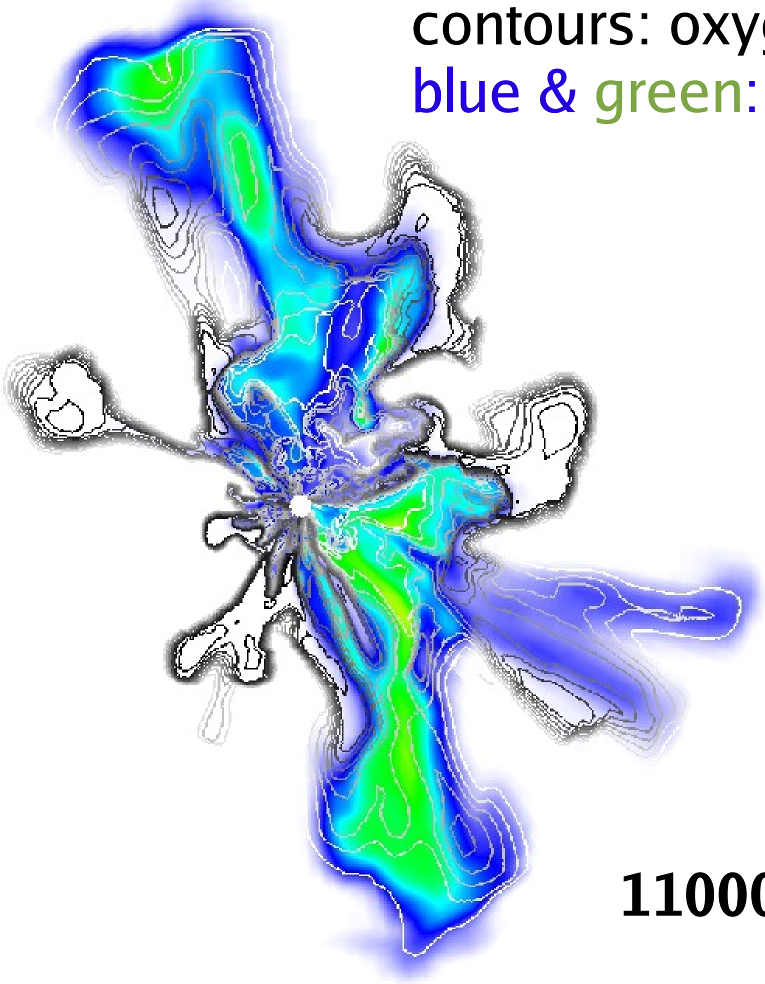
green: carbon
red: oxygen
blue: nickel

(Hammer, Janka, Müller, ApJ 2010)

Asymmetry of Supernova 1987A



1.4 s



contours: oxygen
blue & green: nickel

11000 s

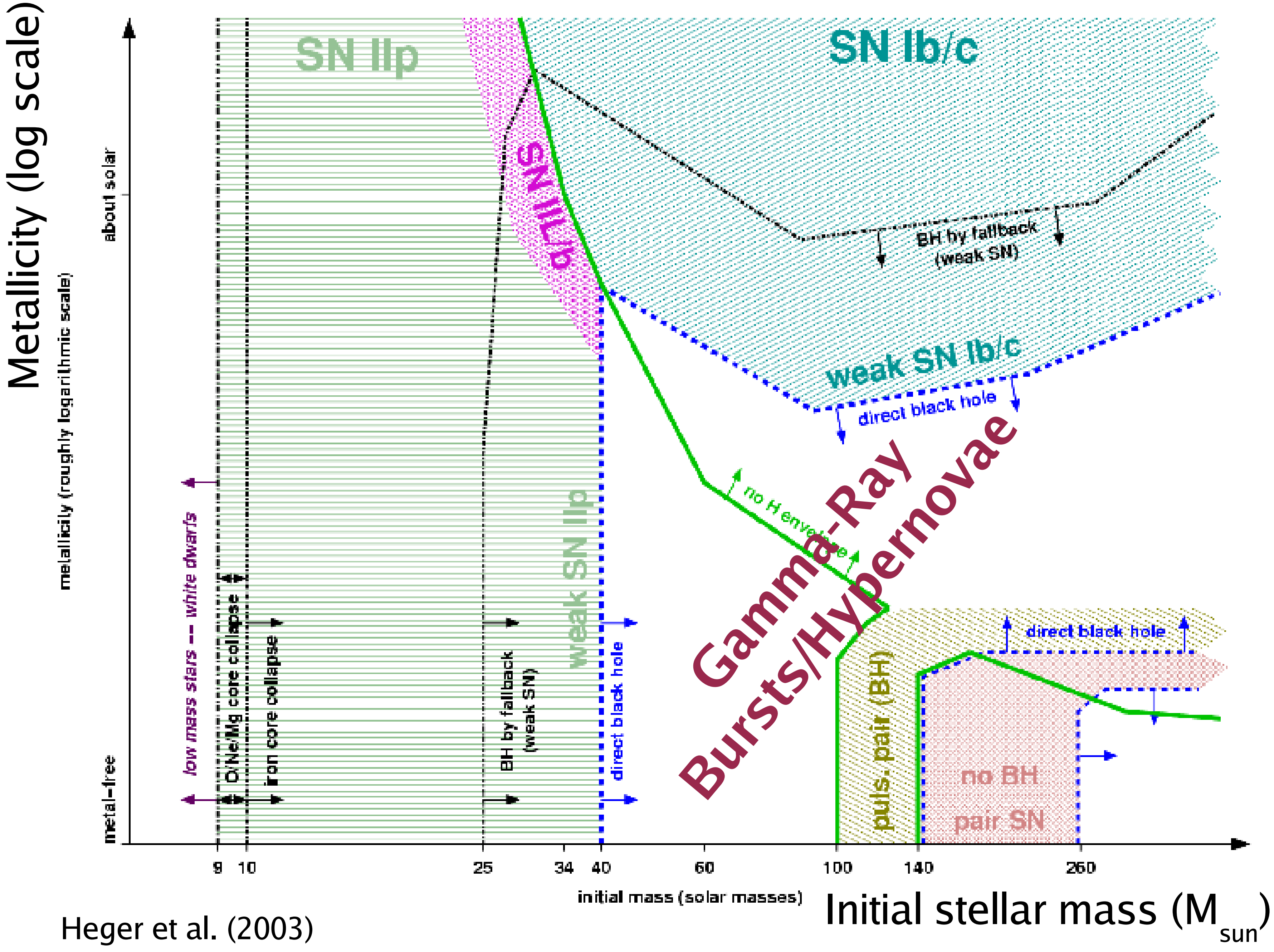
(Wongwathanarat, Janka, Müller, in preparation)

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

Supernova 1987A

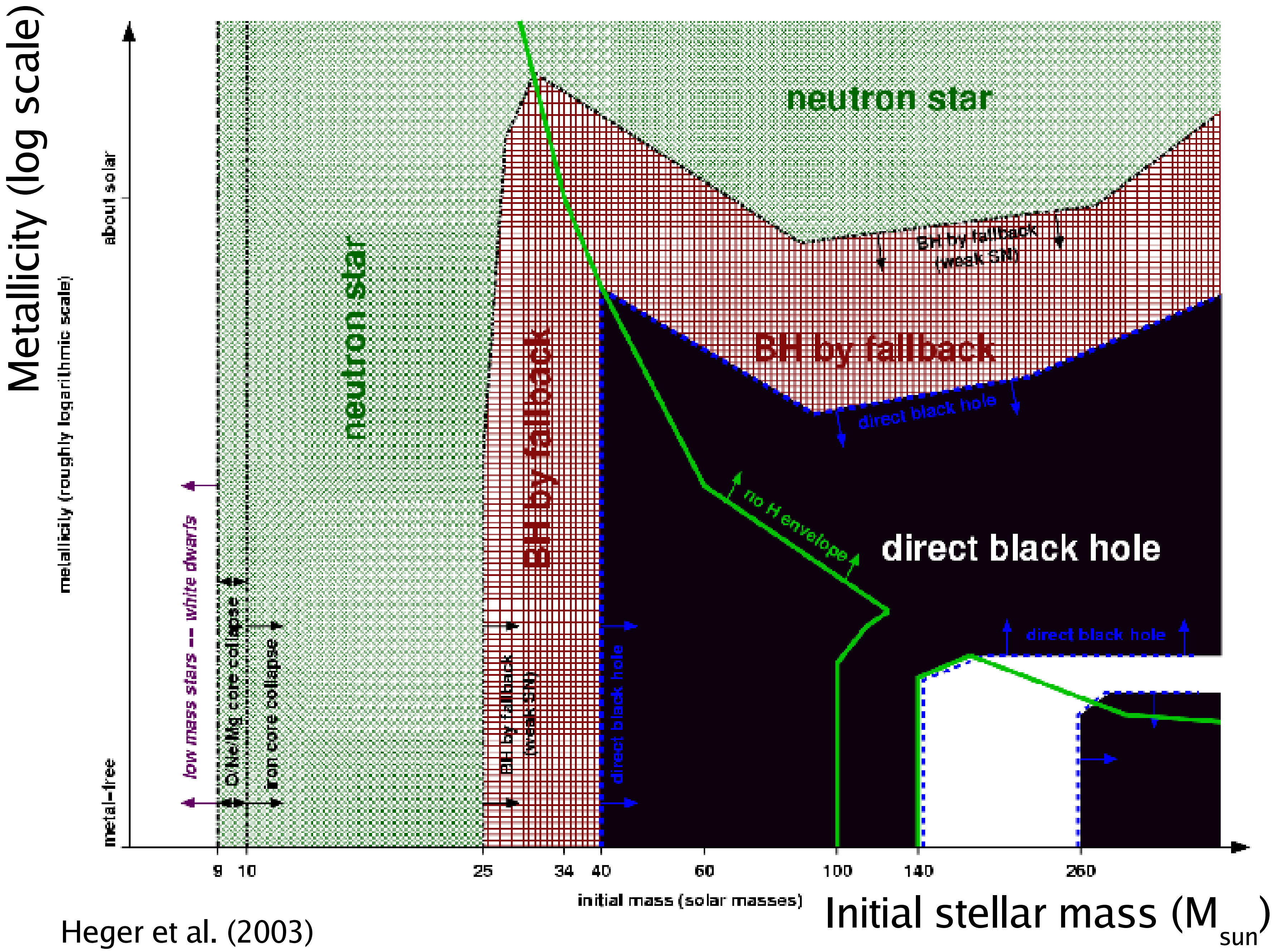
Alternative Explosion Mechanisms

Core Collapse Events and Remnants



Heger et al. (2003)

Core Collapse Events and Remnants



Heger et al. (2003)

Supernova Explosion Mechanisms

- Neutrino-driven mechanism?
- Magnetohydrodynamic mechanism?
- Acoustic mechanism?
- QCD phase transition?

Possibly/probably there is more than just one mechanism at work, depending on the properties of progenitor stars (i.e. their pre-collapse Fe-core mass, He-core size, and rotation rate and profile, as determined by the initial stellar mass, metallicity, angular momentum transport in star, and binary effects)

Supernova Explosion Mechanisms

- Magnetohydrodynamic (MHD) explosion mechanism

Free energy of rotation is converted to magnetic energy; magnetic pressure or dissipative heating via magnetorotational instability (MRI) can drive explosion!
(e.g., Meier et al. 1976, Akiyama & Wheeler 2003, Kotake et al. 2004, 2005, Moiseenko et al. 2005, Thompson et al. 2005, Obergaulinger et al. 2006, Burrows et al. 2007)

Requires a lot of rotational energy ====> very fast initial rotation;
probably at work in GRBs and possibly in magnetar-producing supernovae,
because Fe cores of ordinary SN progenitors rotate slowly (P_{ini} > 100 sec)

(Heger et al. 2005)

$$E_{\mathrm{rot}}^{\mathrm{free}} < E_{\mathrm{rot}} \approx 2\times10^{52}\,\mathrm{erg}\left(\frac{M_{\mathrm{ns}}}{1.5\,M_\odot}\right)\left(\frac{R_{\mathrm{ns}}}{10\,\mathrm{km}}\right)^2\left(\frac{1\,\mathrm{ms}}{P_{\mathrm{ns}}}\right)^2 ,$$

$$P_{\mathrm{ini}} \sim P_{\mathrm{ns}}\left(\frac{R_{\mathrm{ini}}}{R_{\mathrm{ns}}}\right)^2 \sim 10\,\mathrm{s}\left(\frac{P_{\mathrm{ns}}}{1\,\mathrm{ms}}\right) .$$

But: Heger, Woosley, & Spruit (2005; ApJ 626, 350) predict:

$$P_{\mathrm{ini}} \gtrsim 100\,\mathrm{s},\ \Omega_{\mathrm{ini}} \lesssim 0.05\,\mathrm{rad\,s^{-1}} \longrightarrow P_{\mathrm{ns}} \gtrsim 10\,\mathrm{ms}$$

Simulations show: MHD explosions need P_{ini} < 2 sec

(Burrows et al. 2007; Thompson et al. 2005)

Magnetohydrodynamic Explosions

Magnetohydrodynamic (MHD) explosion:

- * globally aspherical, jets
- * potentially very energetic
- * hypernovae, collapsars, BH-forming & GRB SNe

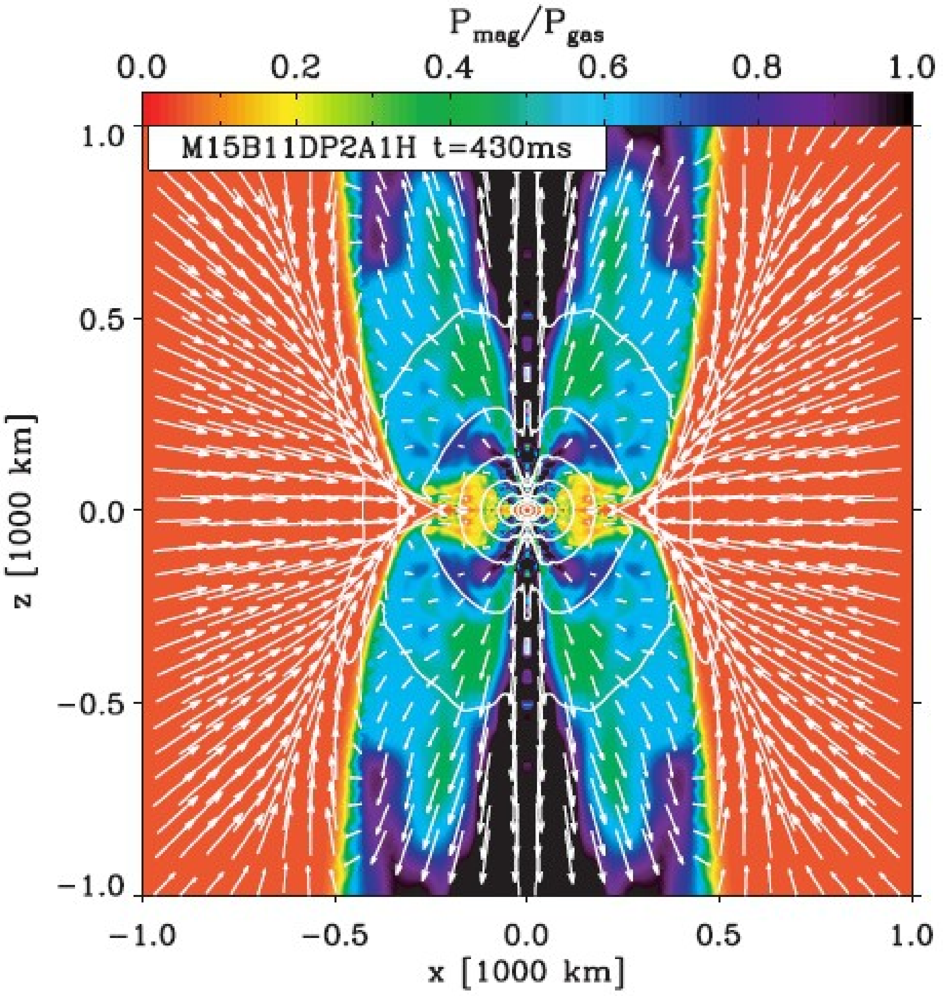


FIG. 9.—Color map for model M15B11DP2A1H at 430 ms after bounce of the ratio of magnetic to gas pressure, overplotted with white isodensity contours (every decade downward from 10^{14} g cm^{-3}) and velocity vectors (length saturated to 15% of the width of the figure and corresponding to a velocity of 10,000 km s^{-1}).

Burrows et al., ApJ (2007)

Black-Hole Forming Stellar Collapses

The collapsing stellar core and forming & accreting neutron star (NS) or black hole (BH) radiates huge neutrino energy:

$E_\nu \sim 3\text{x}10^{53}$ erg $(M_{ns}/M_{sun})^2/(R_{ns}/10\text{ km})$ for NS

$E_\nu \sim 10^{54}$ erg $\xi\,(\Delta M_{acc}/M_{sun})\,c^2$ for accreting BH

in the case of rotation: $\xi \sim 0.05\text{–}0.42$

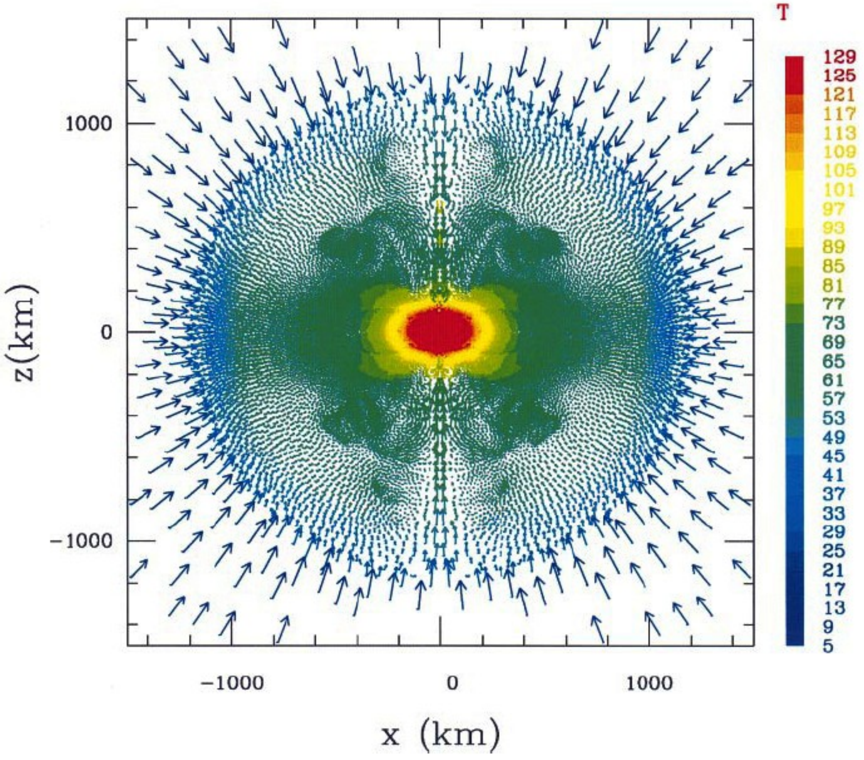
otherwise: $\xi \sim 0$

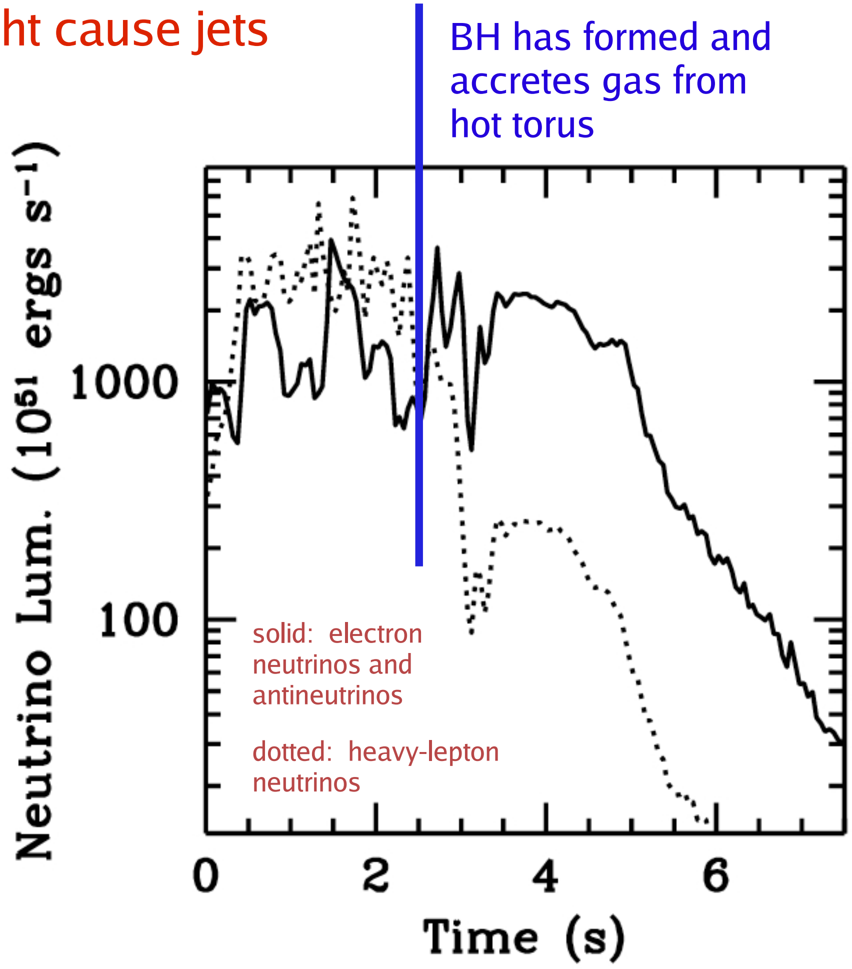
Neutrinos are main channel of energy loss of collapsing stars!

Collapse of Rotating 300 M_{sun} Star

- Formation of a BH with thick accretion torus
- Neutrino luminosities > 10^{54} erg/s
- After BH formation: reduction of muon and neutrino luminosities
- Magnetohydrodynamics and neutrinos might cause jets and stellar explosion

Proto-BH 0.5 seconds before BH formation





BH has formed and accretes gas from hot torus

solid: electron neutrinos and antineutrinos

dotted: heavy-lepton neutrinos

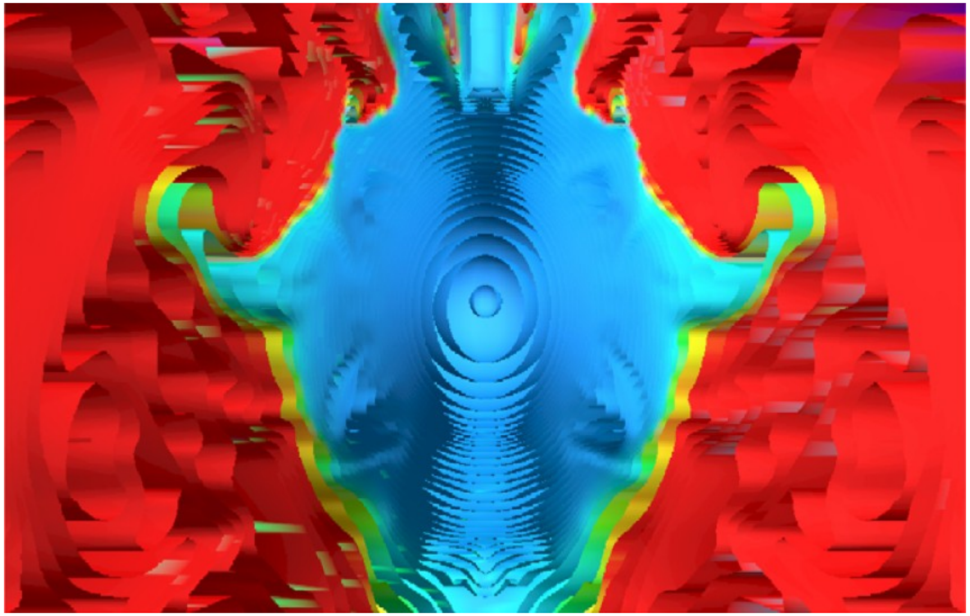
(Fryer et al., ApJ 550 (2001) 372; see also Sekiguchi & Shibata 2011)

Supernova Explosion Mechanisms

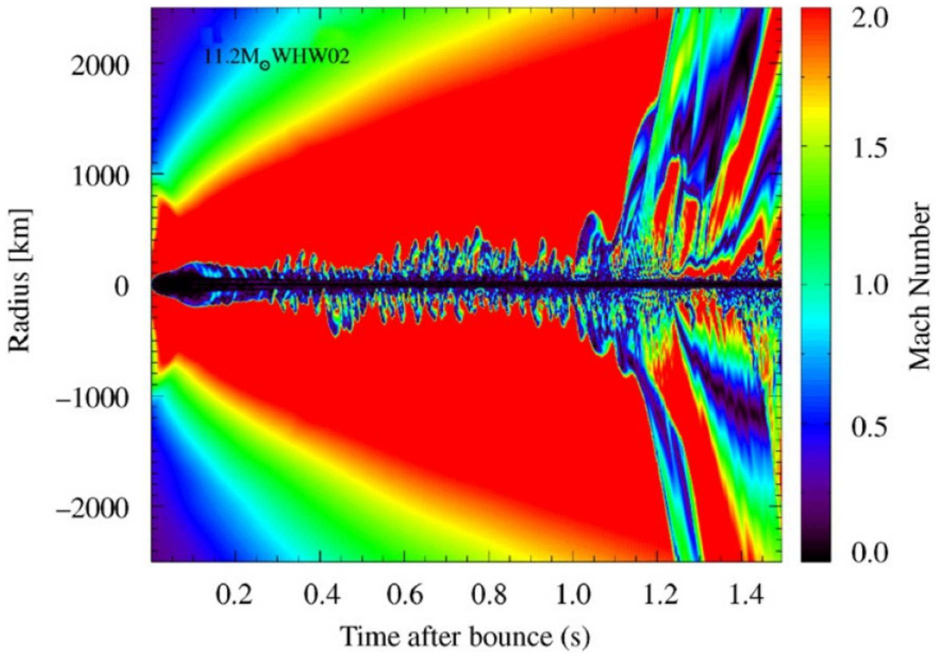
- Acoustically-driven?
  - Neutron star is excited to l=1 g-mode oscillations by (non)steady accretion
  - Transfers accretion power through acoustic waves to explosion
  - Neutron star acts as transducer

$$\dot{E} \sim \frac{\pi\rho}{2}(gR_0)^{3/2}H_0^2 \sim 0.5\times 10^{51}\,\mathrm{erg\,s^{-1}}\,\rho_{11}(g_{13})^{3/2}\left(\frac{R_0}{10\,\mathrm{km}}\right)^{3/2}\left(\frac{H_0}{3\,\mathrm{km}}\right)^{2},$$

(Burrows et al., ApJ, 2006, 2007)



(Burrows et al., Phys. Rep. 442, 2007)



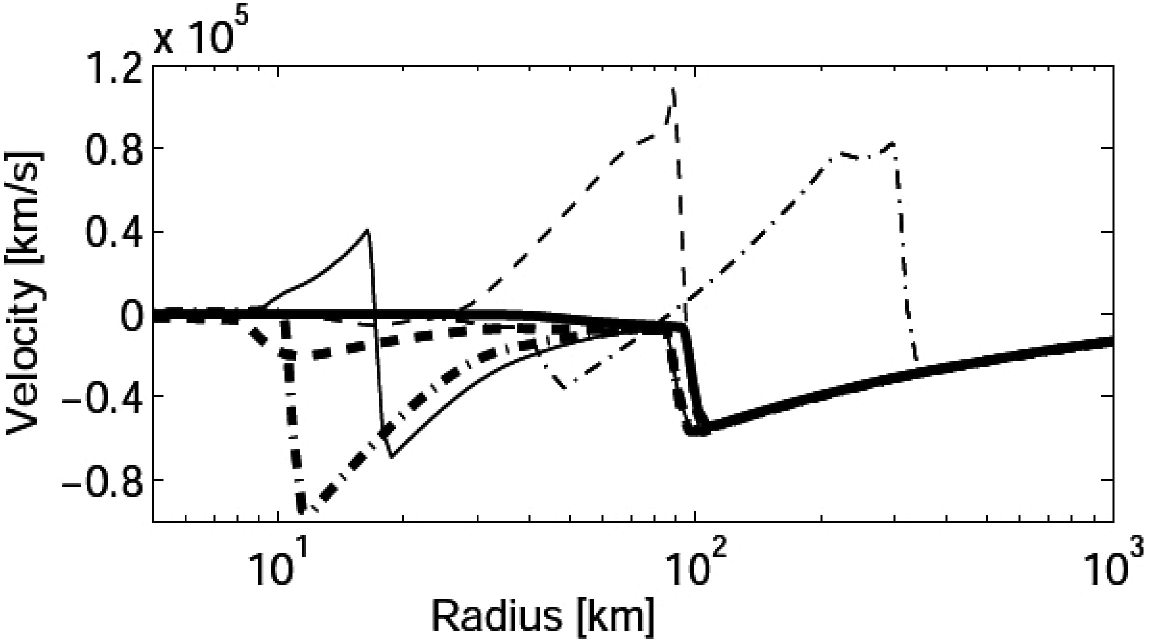
Supernova Explosion Mechanisms

- Acoustically-driven?
  Accretion induces neutron star l=1 g-mode oscillations, which transfer energy outward by acoustic waves, power explosion (Burrows et al. 2006a,b)

  BUT:
  Can large-amplitude g-mode oscillations of the NS really be excited, also in 3D? Are they damped by mode coupling and dissipation? (Weinberg & Quataert 2008)

Supernova Explosion Mechanisms

- Driven by QCD phase transition?
  QCD phase transition in forming compact remnant releases energy and triggers second shock wave that causes explosion:



(Sagert et al., PRL (2009))

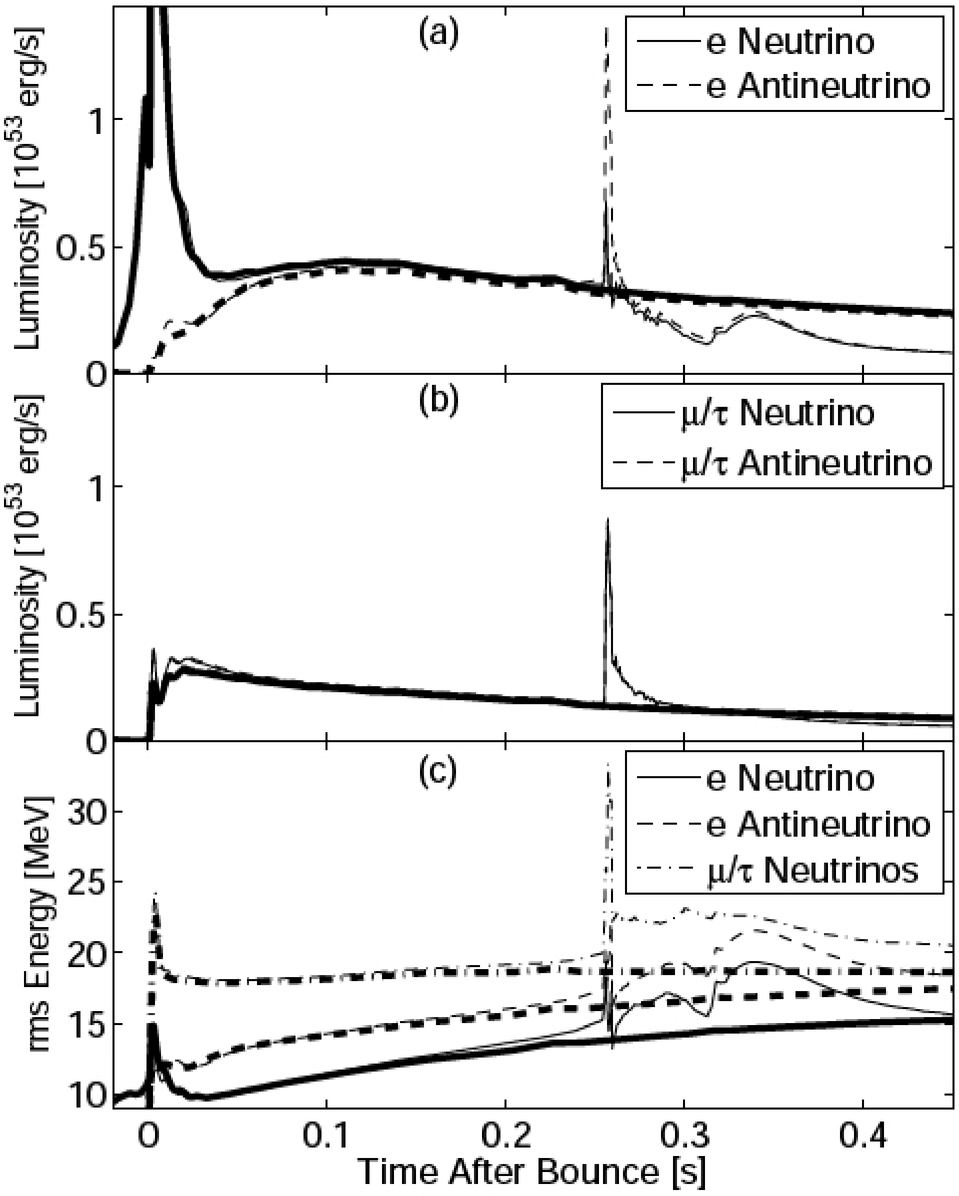
- **BUT:**

Requires transition to denser quark matter phase at rather low density;
Soft quark matter EoS leads to BH formation already for 15 M_{sun} stars;
Seems not compatible with long-duration neutrino signal from SN 1987A

Likely to be incompatible with observation of ~2 solar mass NS (Demorest et al. 2010)

Collapse of Neutron Star to Quark Star

- QCD phase transition with small MIT bag model constants
- Phase transition to quark matter leads to second shock wave
- Second peak in the neutrino signal
- Significant changes in mean energies of emitted neutrinos



bold: hadronic EoS
thin: quark EoS

(Sagert et al., PRL, PRL 2009)

Conclusions

- Neutrino heating can power explosions of 8–10 M_{sun} stars with ONeMg cores
  ------> seems to explain observations of Crab-like supernovae
  (agreement between results of different groups)

- For stars with M > 10 M_{sun}: non-radial asymmetries seem to be generic to explosion mechanism (SASI, convection, MHD, NS core g-modes)

- Most sophisticated present models show SASI & convectively supported neutrino-driven explosions at least for 11–15 M_{sun} stars.
  Need to verify robustness and need independent confirmation!

- Step to 3D simulations is necessary!

- Other than neutrino-driven explosion mechanisms may be at work in rapidly rotating and/or very massive stellar cores

- Urgently need observations (neutrinos, GWs, better determination of SN explosion parameters) to constrain models!

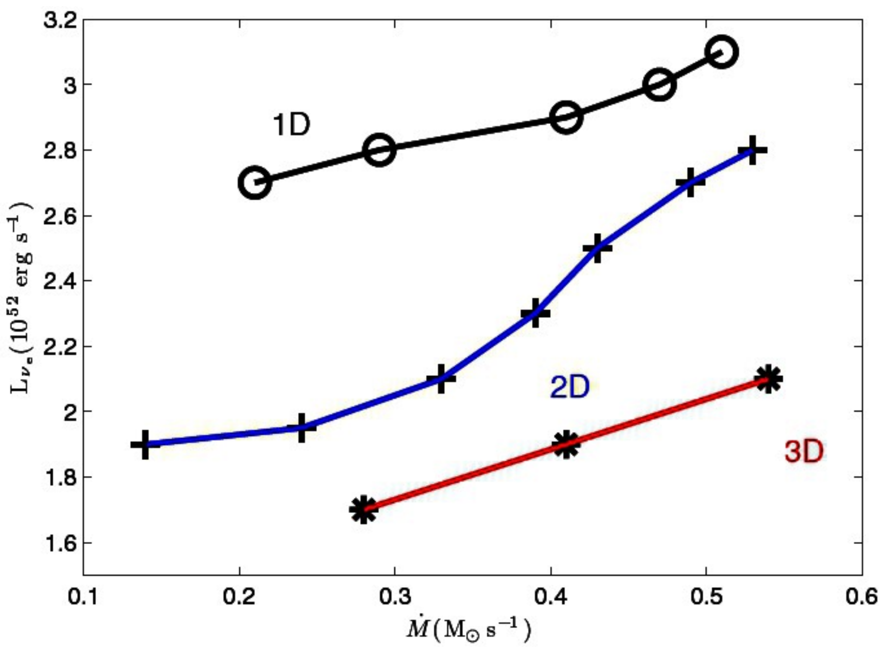
3D vs. 2D Differences

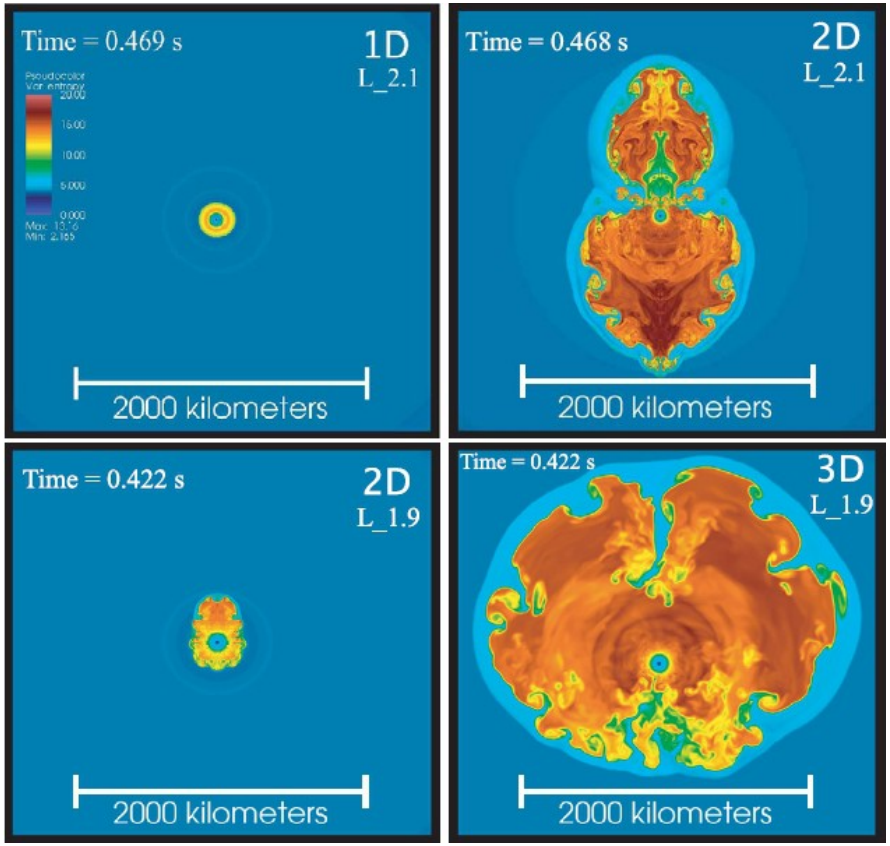
2D-3D Differences in Parametric Explosion Models

- Nordhaus, Burrows et al. performed 2D & 3D simulations with simple neutrino-heating and cooling terms and found 15-20% improvement in 3D for 15 M_{sun} progenitor star (ApJ 720 (2010) 694)

$$\mathcal{H} = 1.544 \times 10^{20} \left(\frac{L_{\nu_e}}{10^{52}\ \mathrm{erg\ s^{-1}}} \right) \left(\frac{T_{\nu_e}}{4\ \mathrm{MeV}} \right)^2 \times \left(\frac{100\ \mathrm{km}}{r} \right)^2 (Y_\mathrm{n} + Y_\mathrm{p}) e^{-\tau_{\nu_e}} \left[\frac{\mathrm{erg}}{\mathrm{g\ s}} \right]$$

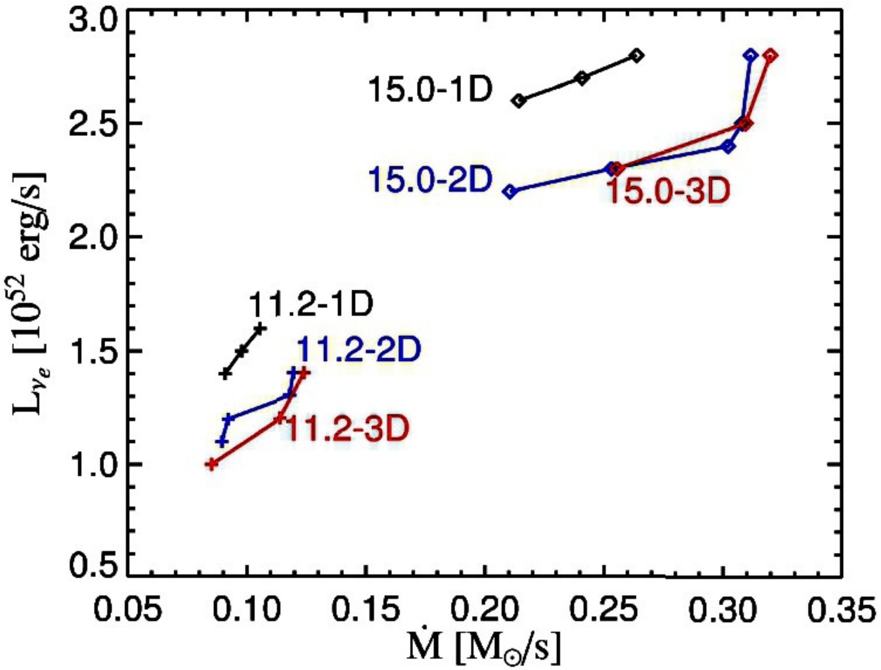
$$\mathcal{C} = 1.399 \times 10^{20} \left(\frac{T}{2\ \mathrm{MeV}} \right)^6 (Y_\mathrm{n} + Y_\mathrm{p}) e^{-\tau_{\nu_e}} \left[\frac{\mathrm{erg}}{\mathrm{g\ s}} \right]$$

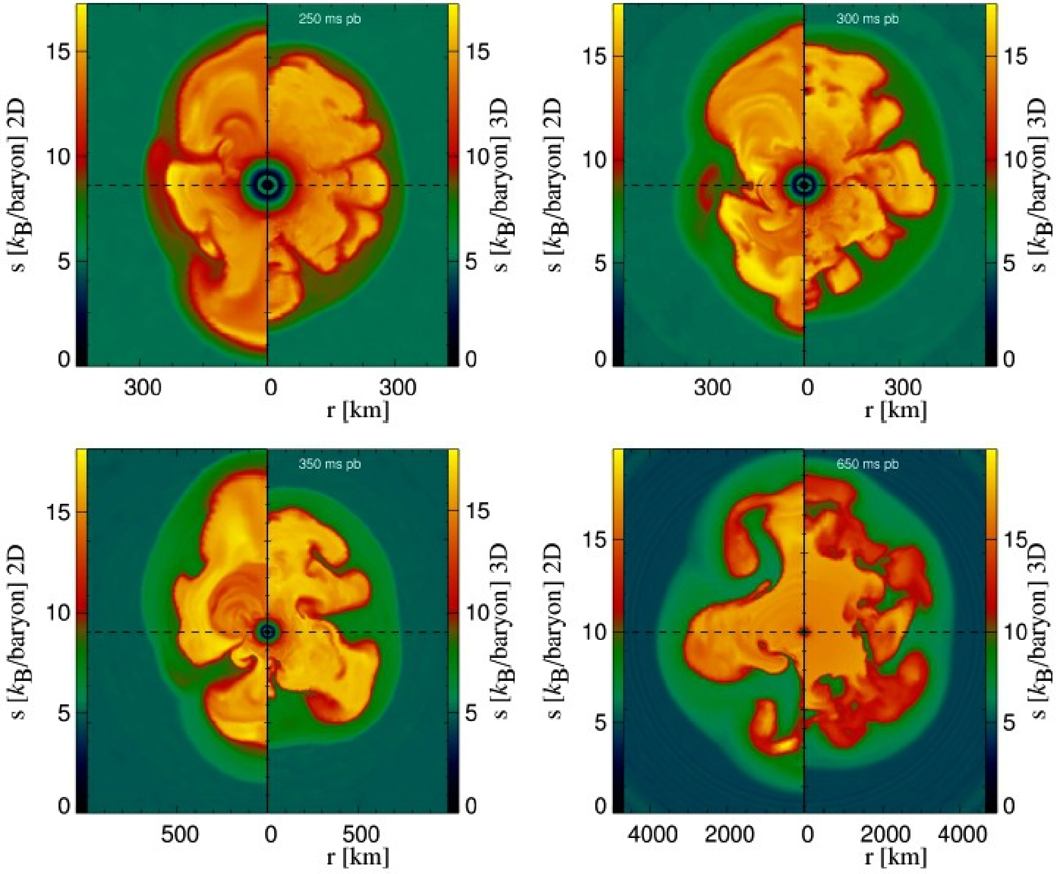




2D-3D Differences in Parametric Explosion Models

- F. Hanke (Diploma Thesis, MPA, Garching, 2010) in agreement with L. Scheck (PhD Thesis, MPA, 2007) cannot confirm the findings by Nordhaus et al. (2010) ! 2D and 3D simulations for 11.2 M_{sun} and 15 M_{sun} progenitors are very similar!





2D & 3D slices for 15 M_{sun} model, L = 2.5*10^{52} erg/s