Max-Planck-Institut
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SFB-TR7

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Excellence Cluster Universe

Explosive Ideas about Massive Stars – from Observations to Modeling
Stockholm, AlbaNova University Center, August 10-13, 2011

Modeling Core-Collapse Supernova Explosions

Is dimension a key to the neutrino mechanism?

Hans-Thomas Janka
(Max Planck Institute for Astrophysics, Garching)

The Astrophysical Journal, 720:694–703, 2010 September 1 doi:10.1088/0004-637X/720/1/694

DIMENSION AS A KEY TO THE NEUTRINO MECHANISM OF CORE-COLLAPSE SUPERNOVA EXPLOSIONS

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Received 2010 June 18; accepted 2010 July 7; published 2010 August 12

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Outline

- Moving to the 3rd dimension: A really grand computational challenge
- Status of modeling neutrino-driven explosions in 2D
- The 3rd dimension as a key to the neutrino mechanism:
  Do we understand how the key fits into the keyhole?
- 3D models on their way to meet observations

Outline – Reversed

- 3D models on their way to meet observations
- Moving to the 3rd dimension: A really grand computational challenge
- Status of modeling neutrino-driven explosions in 2D
- The 3rd dimension as a key to the neutrino mechanism:
  Do we understand how the key fits into the keyhole?

Observational 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, Hammer er al. 2010)
- Characteristic neutrino-signal modulations
  (Marek et al. 2009; Müller et al. 2011)
- Gravitational-wave signals (Marek et al. 2009; Müller et al. 2011)

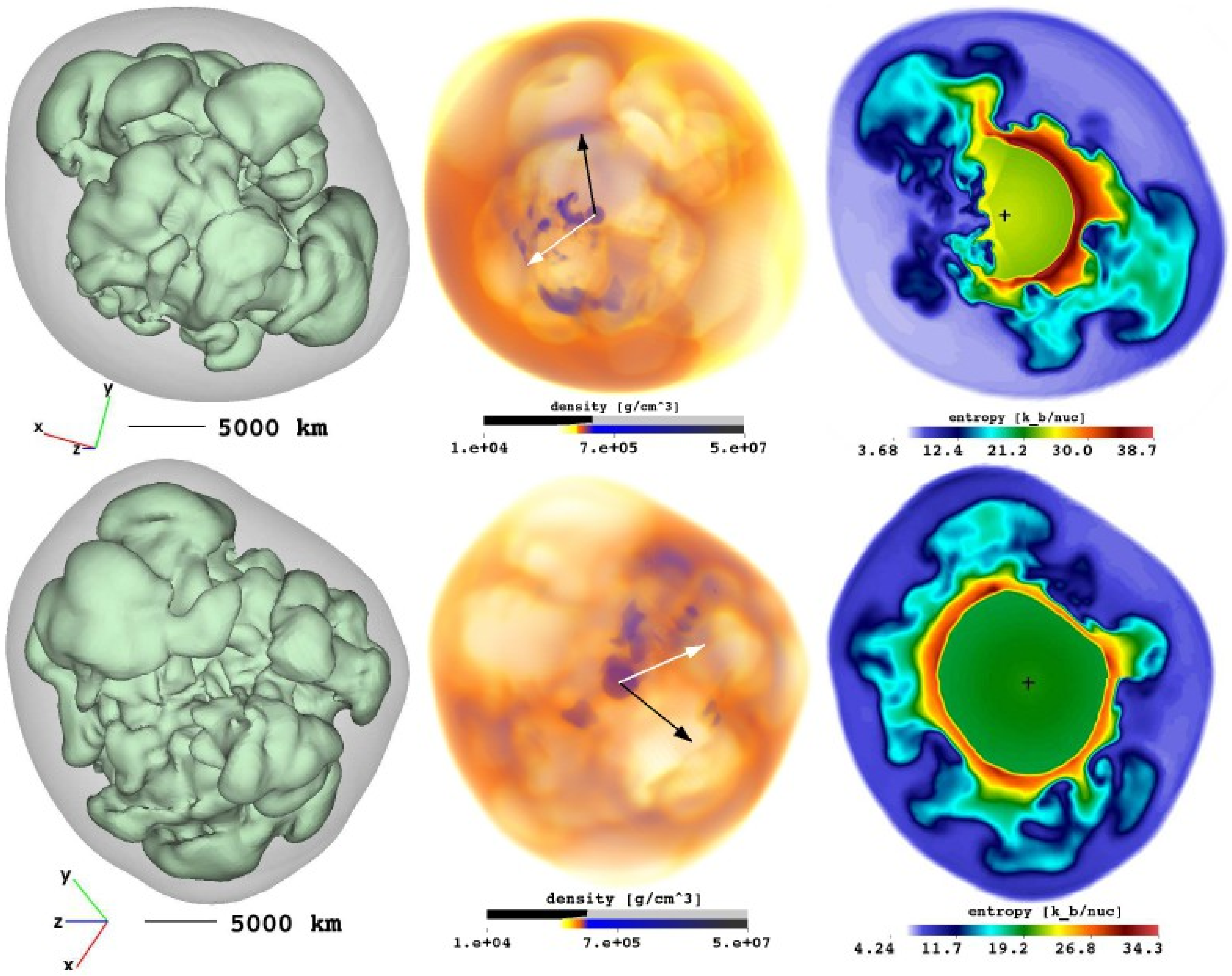
See Ewald Müller's talk on Saturday !

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)

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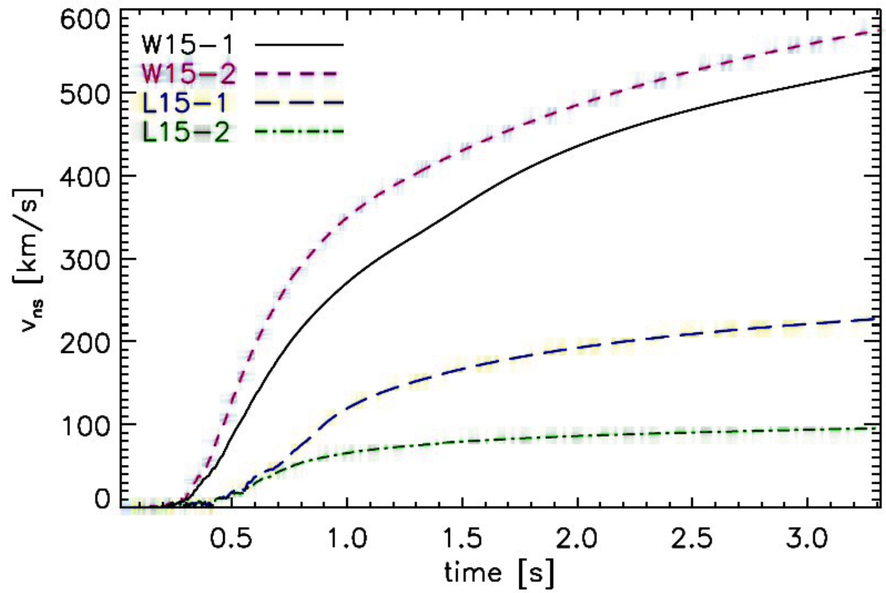
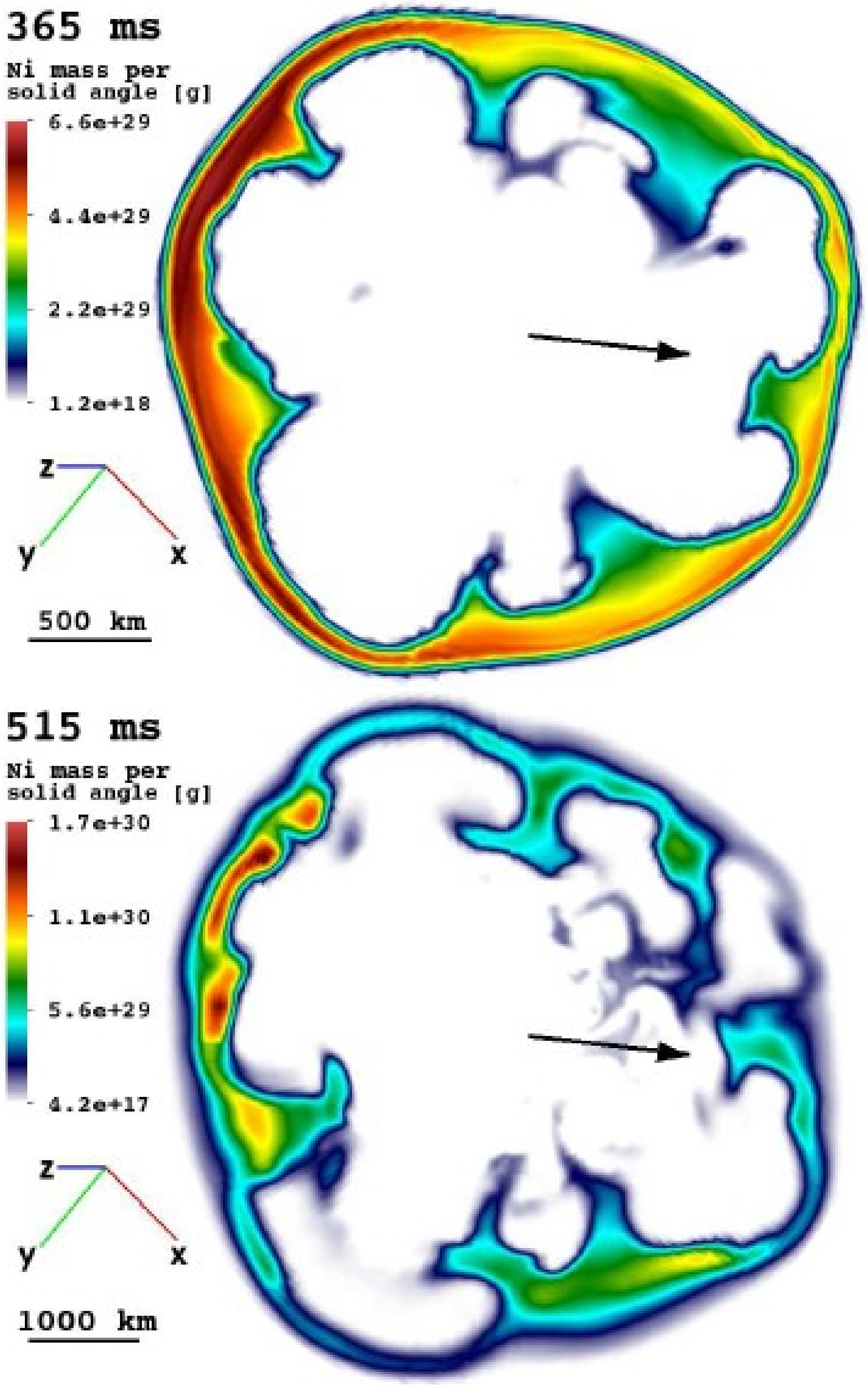


(Wongwathanarat, Janka, Müller, ApJL 725 (2010) 106; A&A, in preparation)

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	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

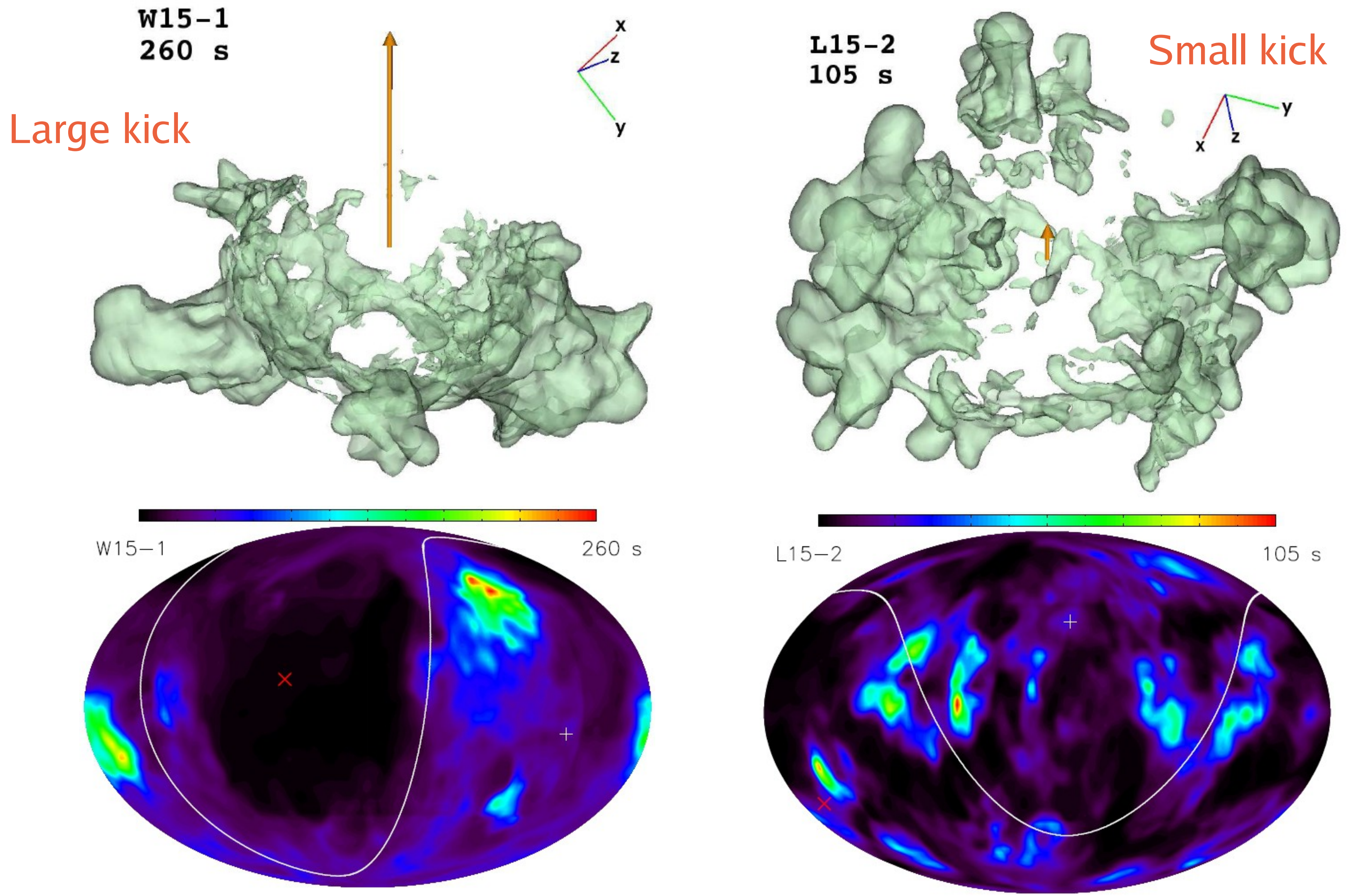
Neutron Star Recoil and Nickel Production

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

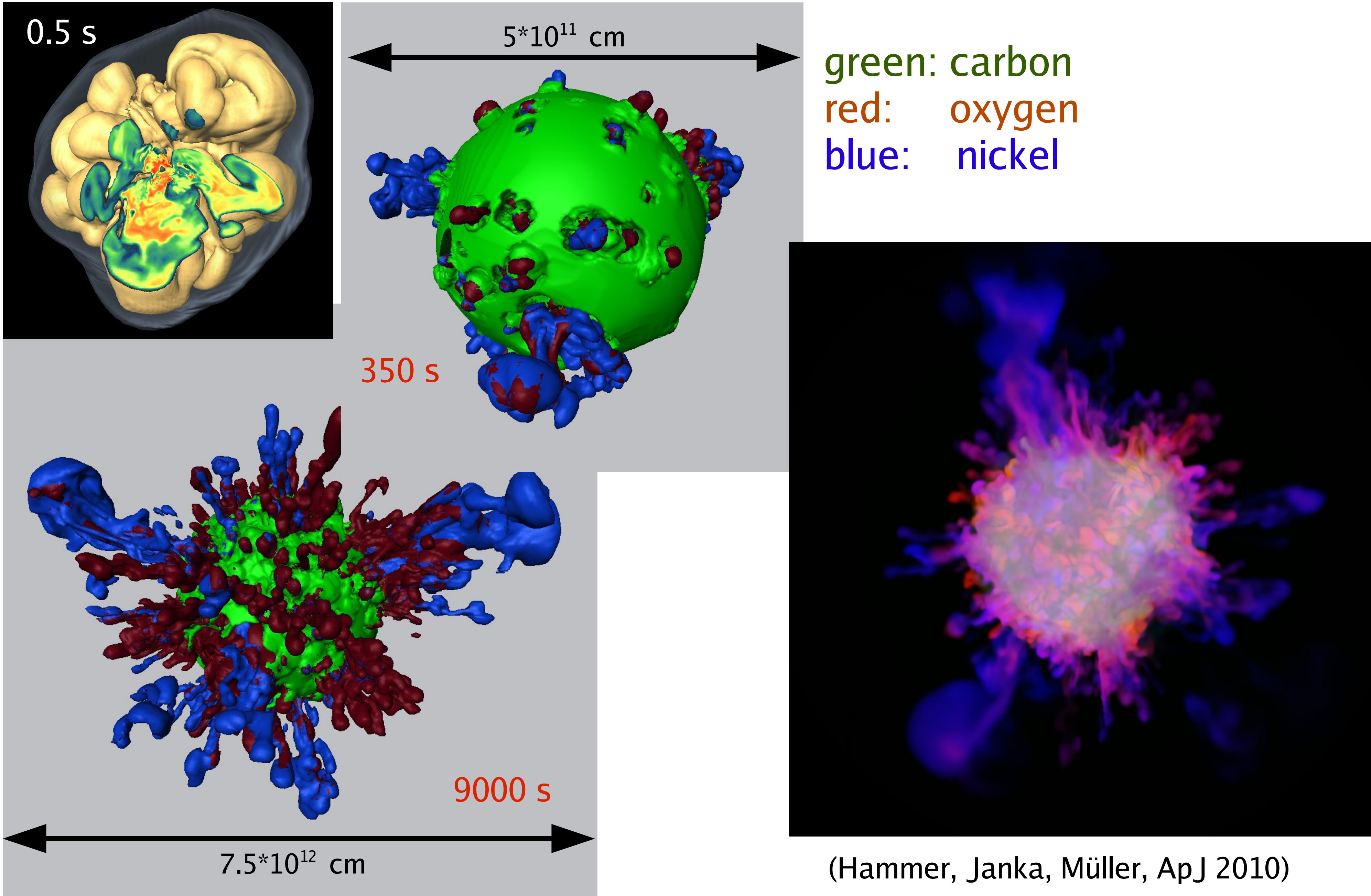


(Wongwathanarat, Janka, Müller, A&A, to be submitted)

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

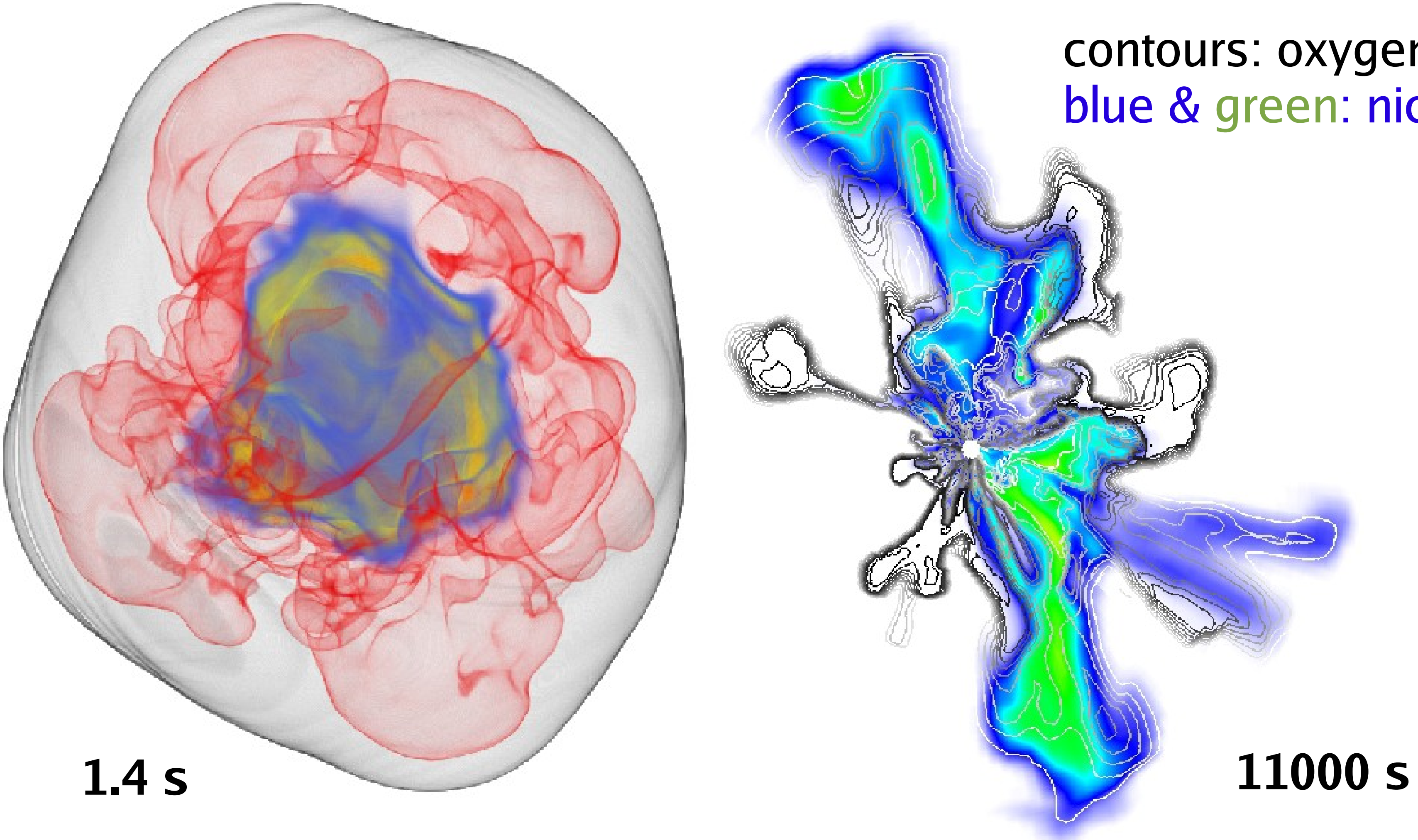
3D Explosions and Supernova Asymmetries

Mixing Instabilities in 3D SN Models



(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!

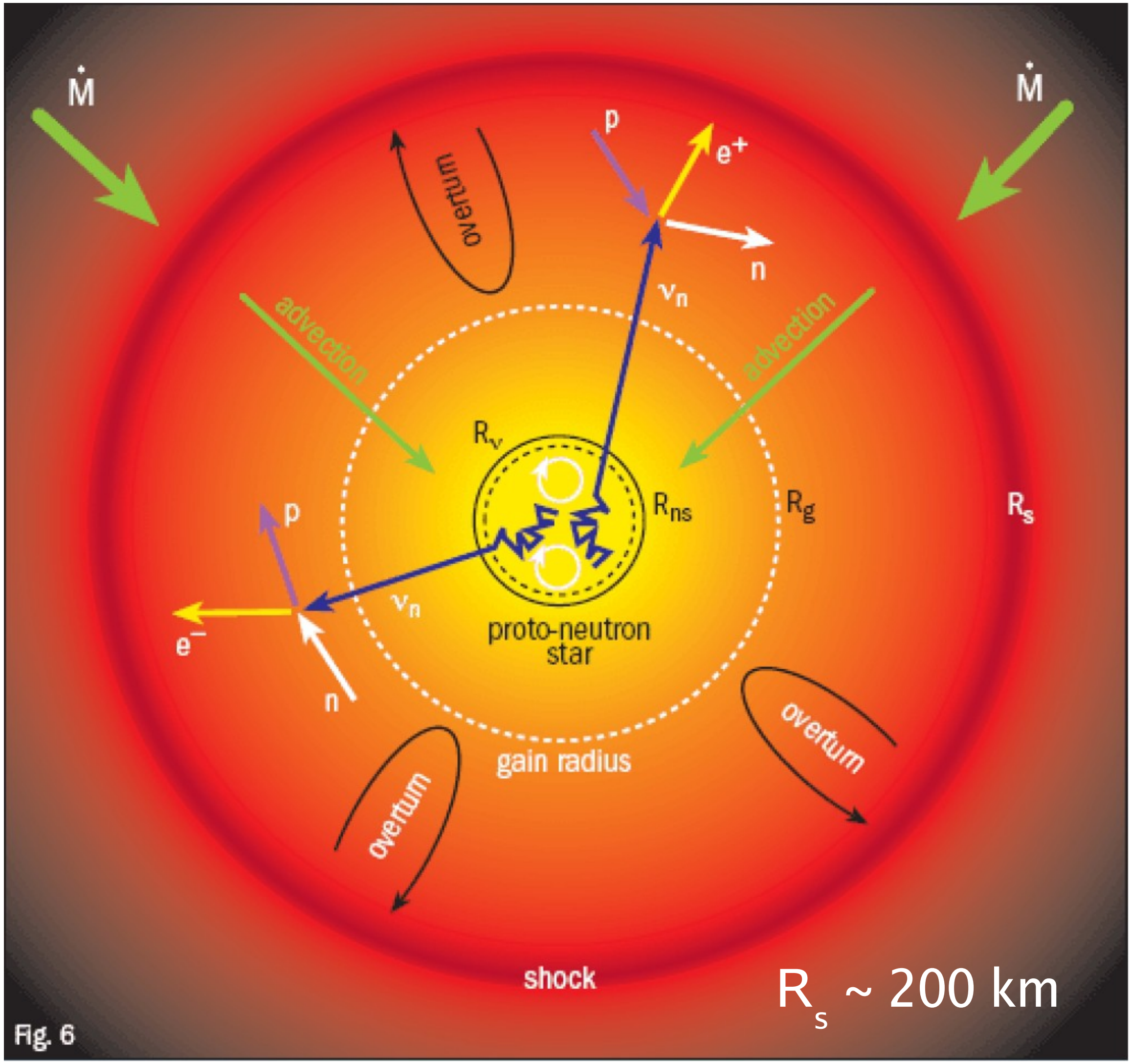
Supernova 1987A

BUT:

Do We Understand How It All Starts?

Neutrinos & Explosion Mechanism

Paradigm: Explosions by the convectively supported neutrino-heating mechanism



- "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:

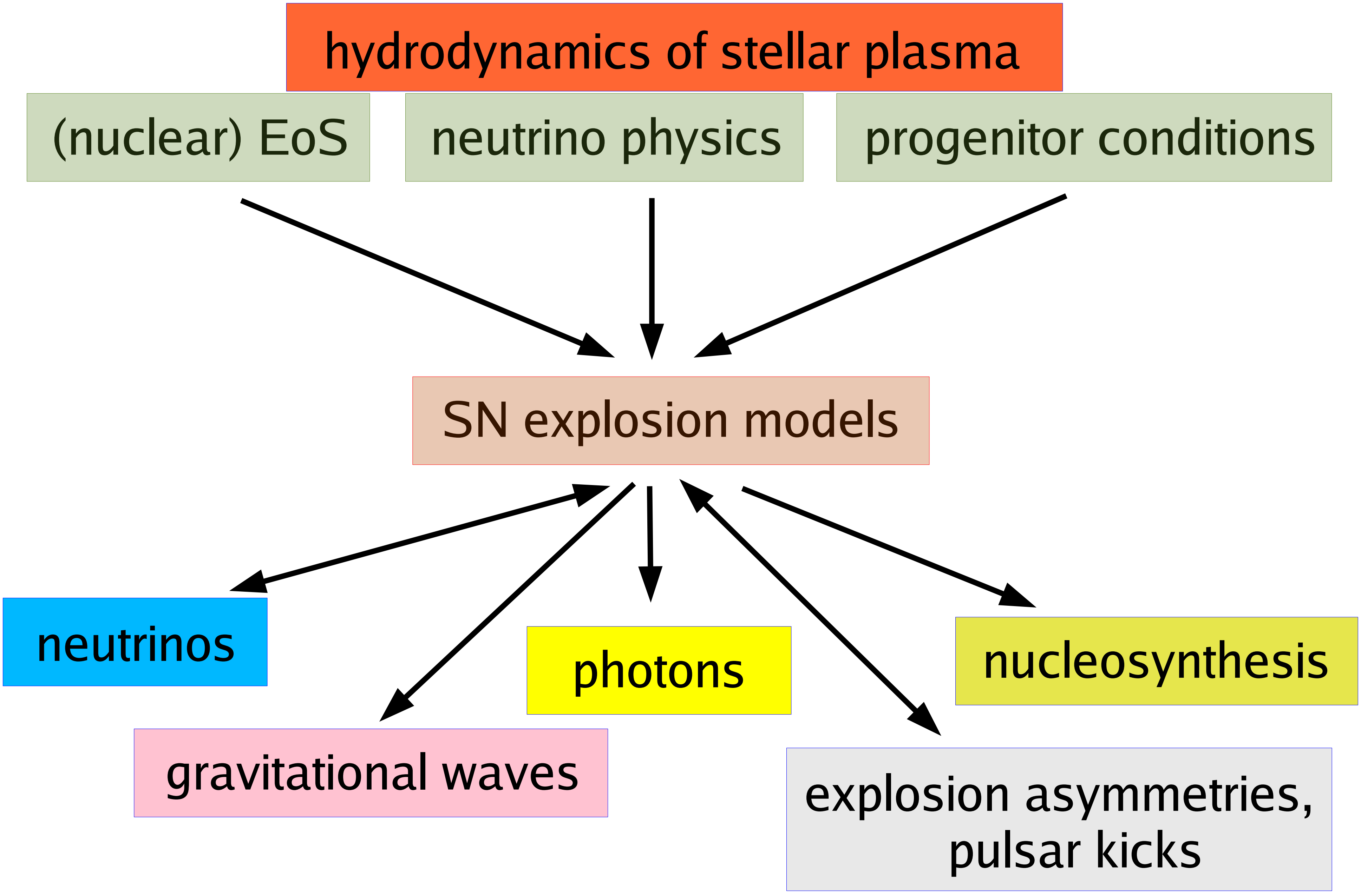
$$\mathcal{H} = 1.544 \times 10^{20} \left(\frac{L_{\nu_e}}{10^{52}\ \mathrm{erg\ s^{-1}}}\right) \left(\frac{T_{\nu_e}}{4\ \mathrm{MeV}}\right)^2 \times \left(\frac{100\,\mathrm{km}}{r}\right)^2 (Y_\mathrm{n} + Y_\mathrm{p}) \qquad \left[\frac{\mathrm{erg}}{\mathrm{g\ s}}\right]$$

- Neutrino cooling:

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

Multi-Dimensional Modeling as Computational Challenge

Predictions of Signals from SN Core



General-Relativistic 2D Supernova Models

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

GR hydrodynamics

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

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

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

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

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

CFC metric equations

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

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

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

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

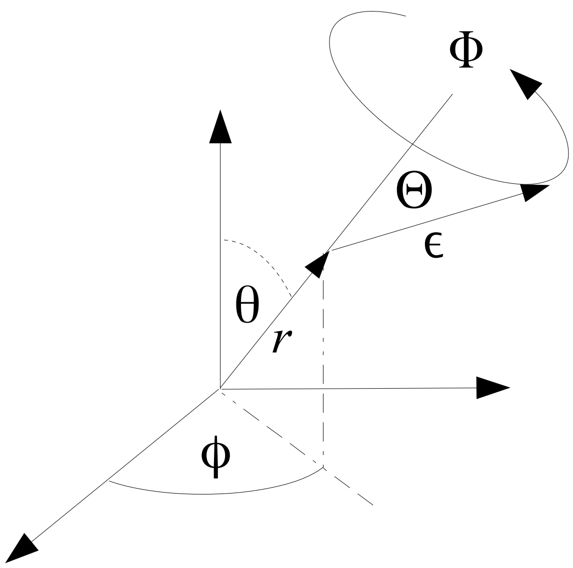
Neutrino transport

$$\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] - \quad (2.29)\\
&\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}$$

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 Transport Equation (no serious attempt yet)	• ≥ 1–10 Pflops/s (sustained!)
• **2D** hydro + **5D** direct discretization of Boltzmann transport Equation (only with reduced complexity)	• ≥ 10–100 Tflops/s, TBytes
• **2D** hydro + **"ray-by-ray-plus"** variable Eddington factor method (current method of MPA)	• ≥ 0.1–1 Tflops/s, < 1 Tbyte
• **3D** hydro + **"ray-by-ray-plus"** variable Eddington factor method (current method of MPA)	• ≥ 10–100 Tflops/s, 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, need ~3 years on 32 processor cores

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

~ $3*10^{20}$ Flops, need ~1.5 years on 8192 processor cores

Distributed European Infrastructure for Supercomputing Applications
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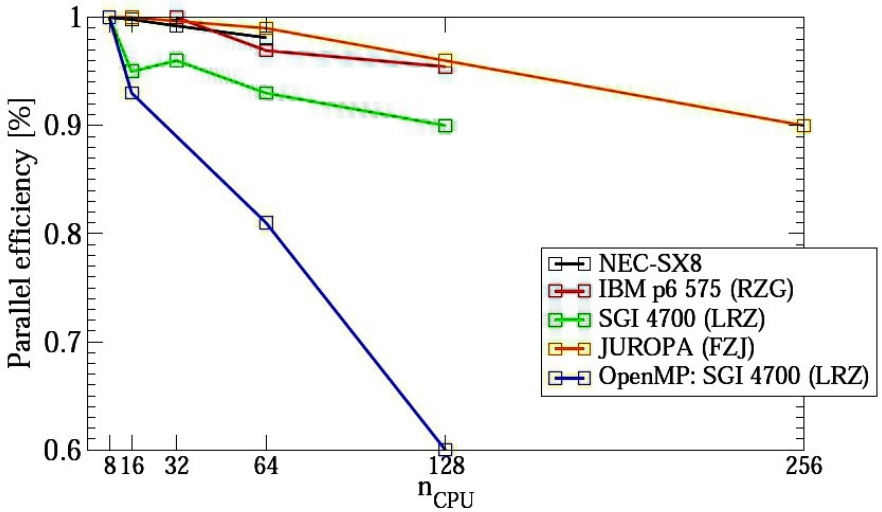
Leibniz-Rechenzentrum der Bayerischen Akademie der Wissenschaften

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

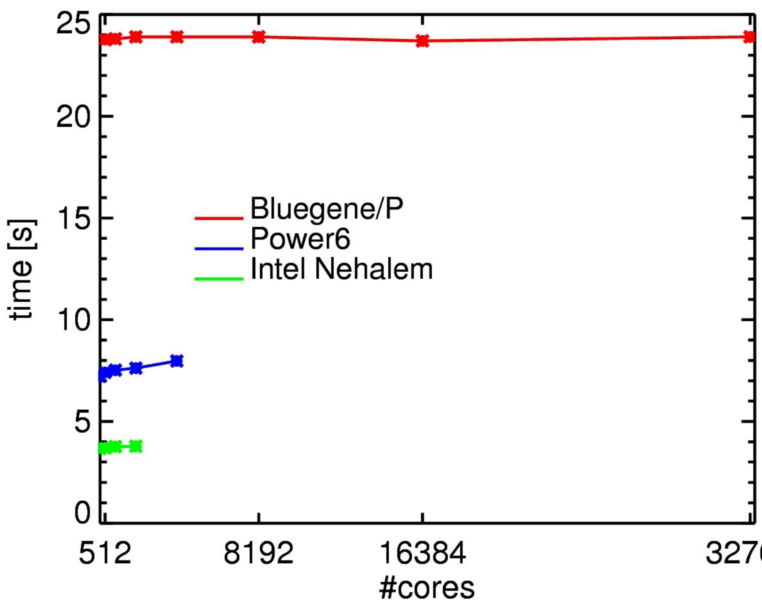
- Code employs hybrid MPI/OpenMP programming model.
- Code is portable to different computer platforms.
- Code shows excellent parallel efficiency, which will be fully exploited in 3D.

Strong Scaling

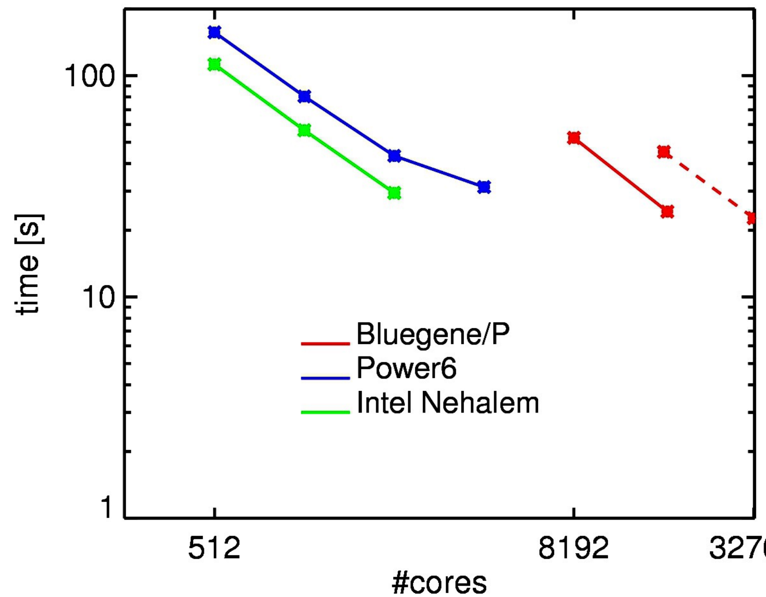


Bernhard Müller (2011)

Weak Scaling



Andreas Marek, RZG (2011)



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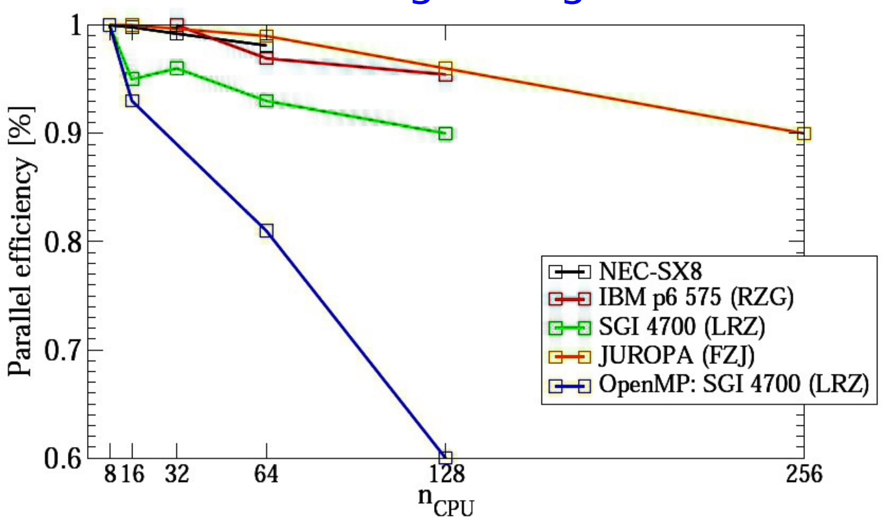

Bernhard Müller (2011)

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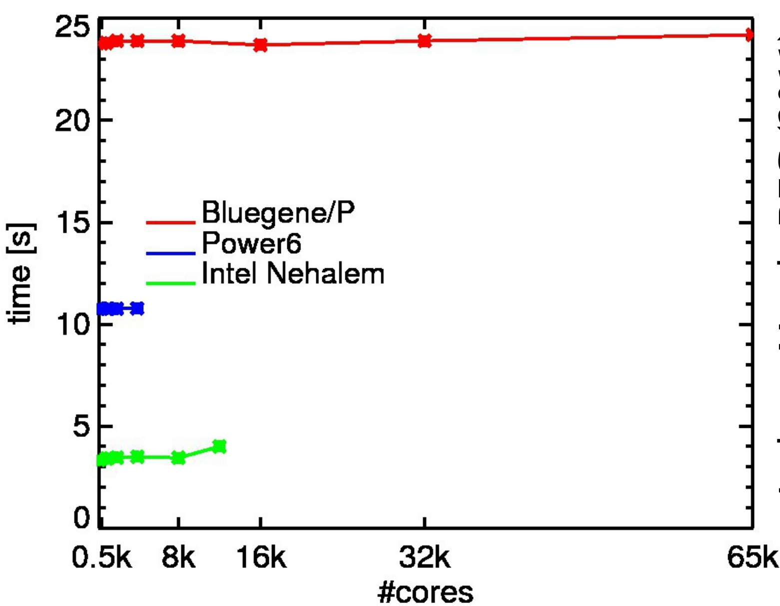

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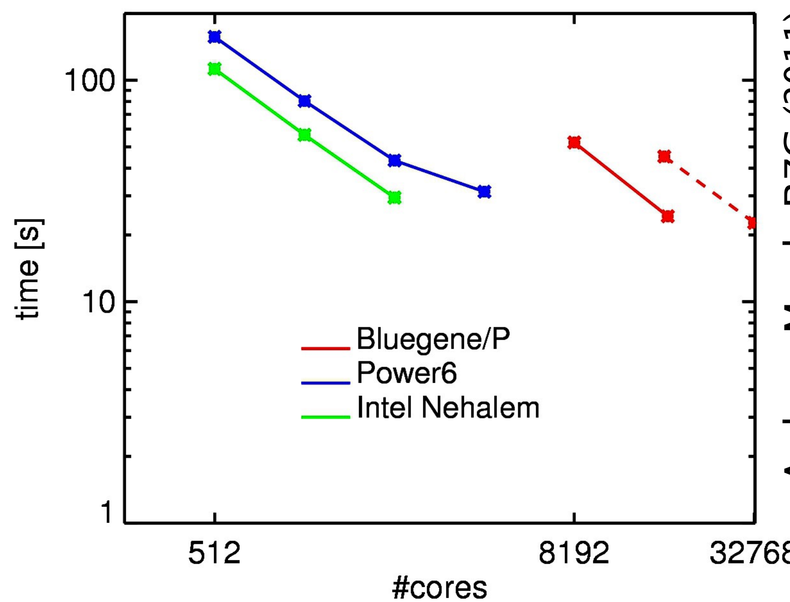


Andreas Marek, RZG (2011)

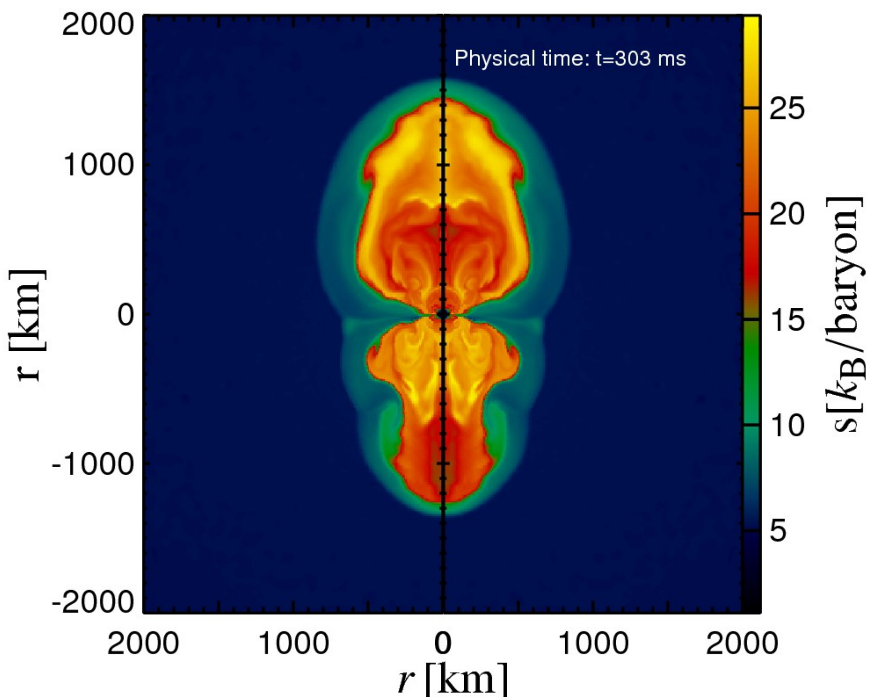
Results of 2D Simulations

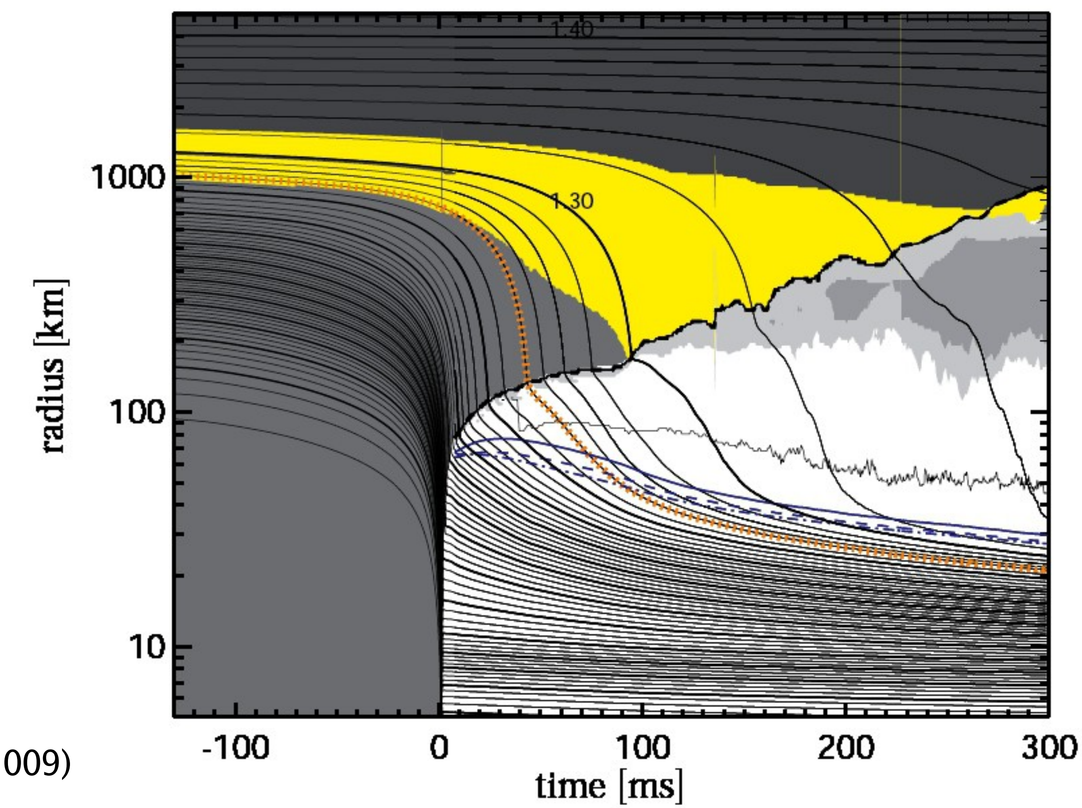
2D SN Simulations: $M_{star} \sim 11\ M_{sun}$

Nonradial hydrodynamic instabilities are crucial for the explosion !

Low-order (dipole, l=1, and quadrupole, l=2) modes of the "standing accretion shock instability" ("SASI"; Blondin et al. 2003) cause asymmetries and push shock to larger radii

===> This stretches residence time of matter in neutrino heating layer and thus increases energy absorbed by matter from neutrinos.
Leads to initiation of globally aspherical explosion even without rotation

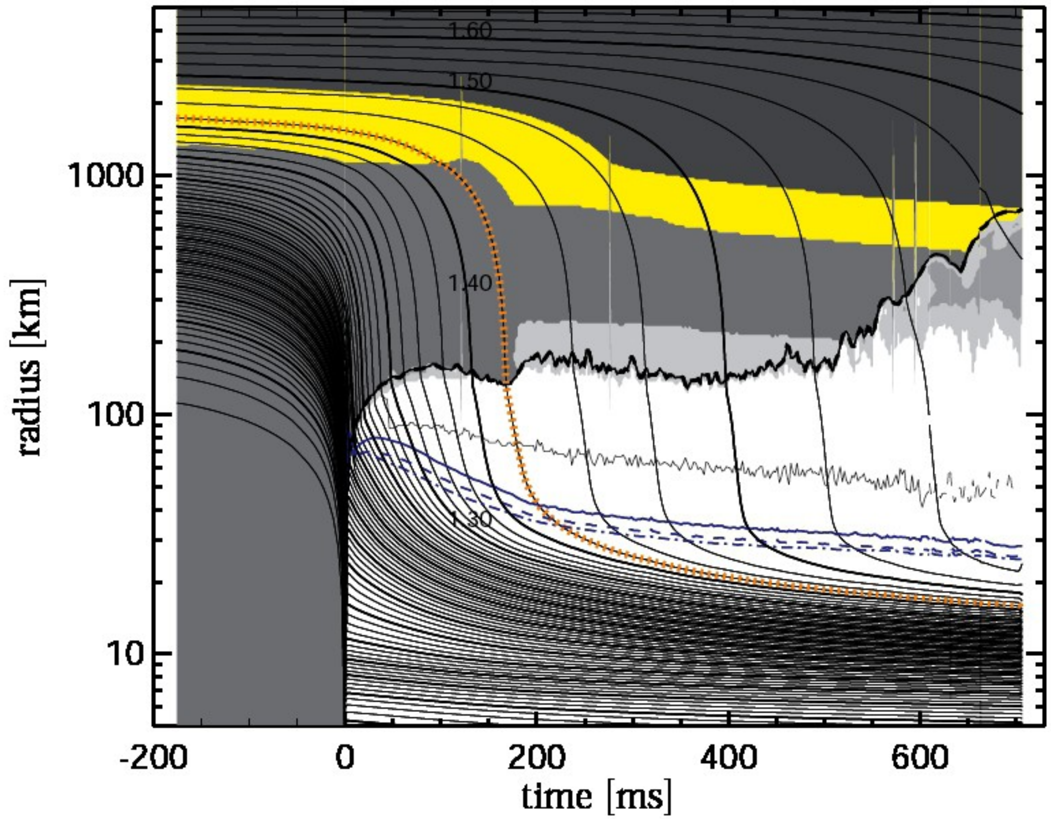


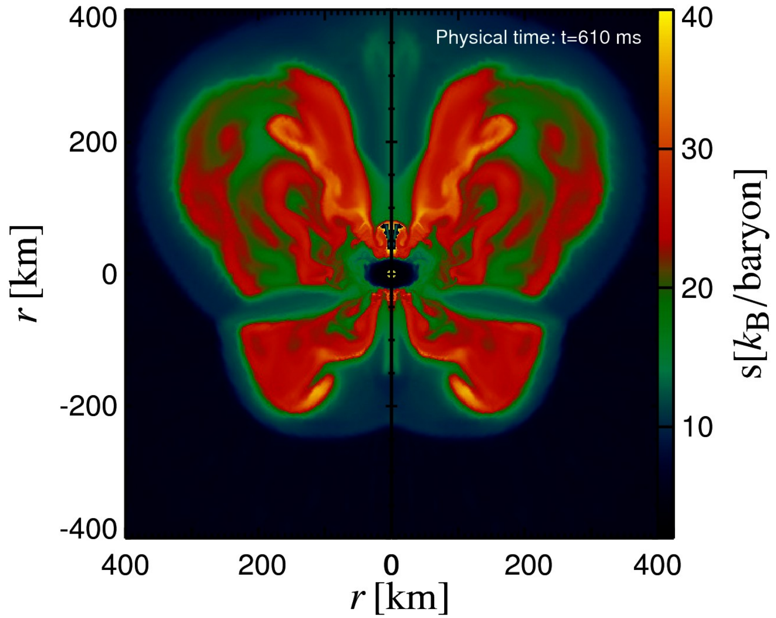


Buras et al., A&A 457 (2006) 281; Marek & Janka, ApJ (2009)

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

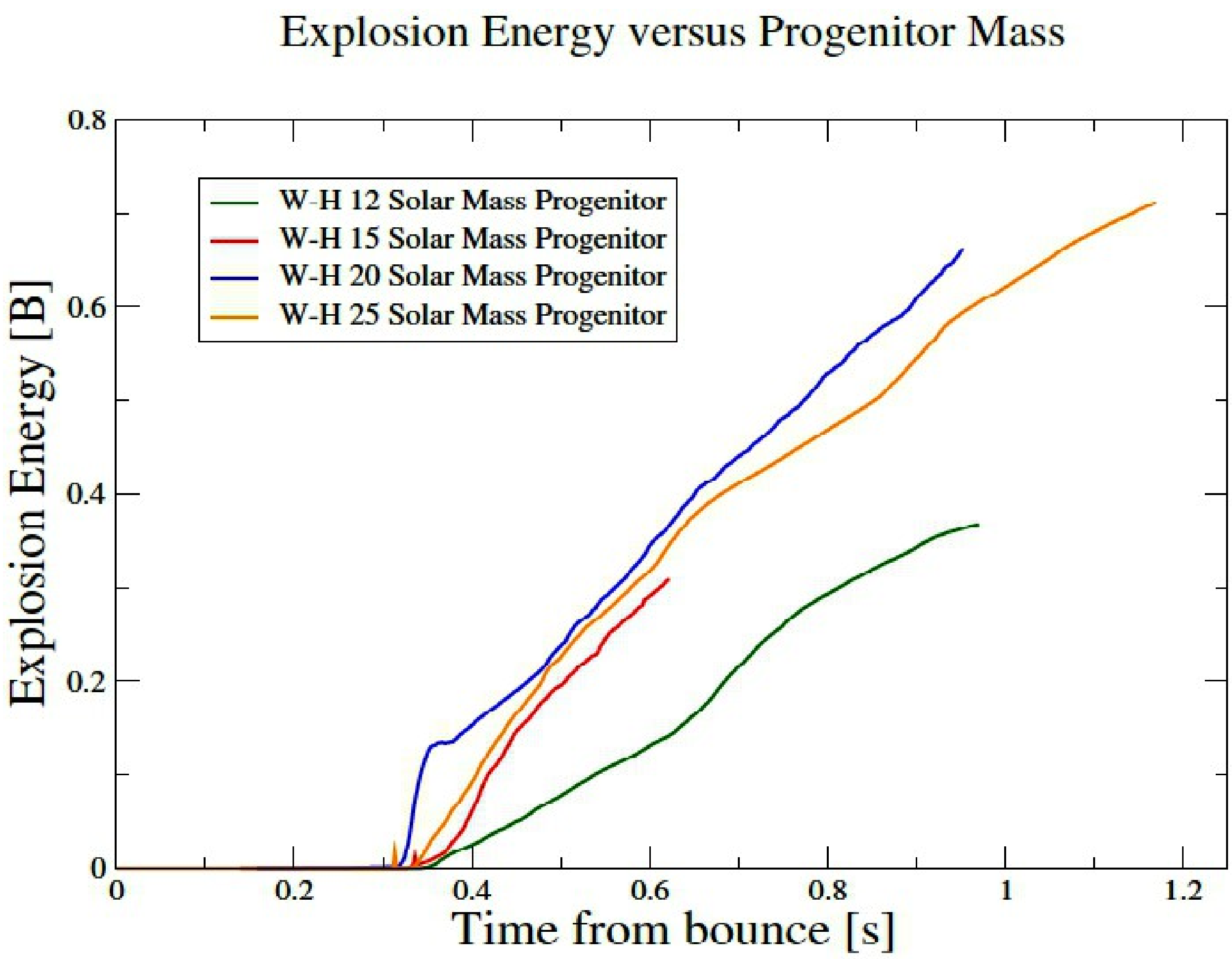
Violent SASI oscillations:
ν-driven explosion sets in
at t ~ 600 ms after bounce





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

Explosions by Oak Ridge Group

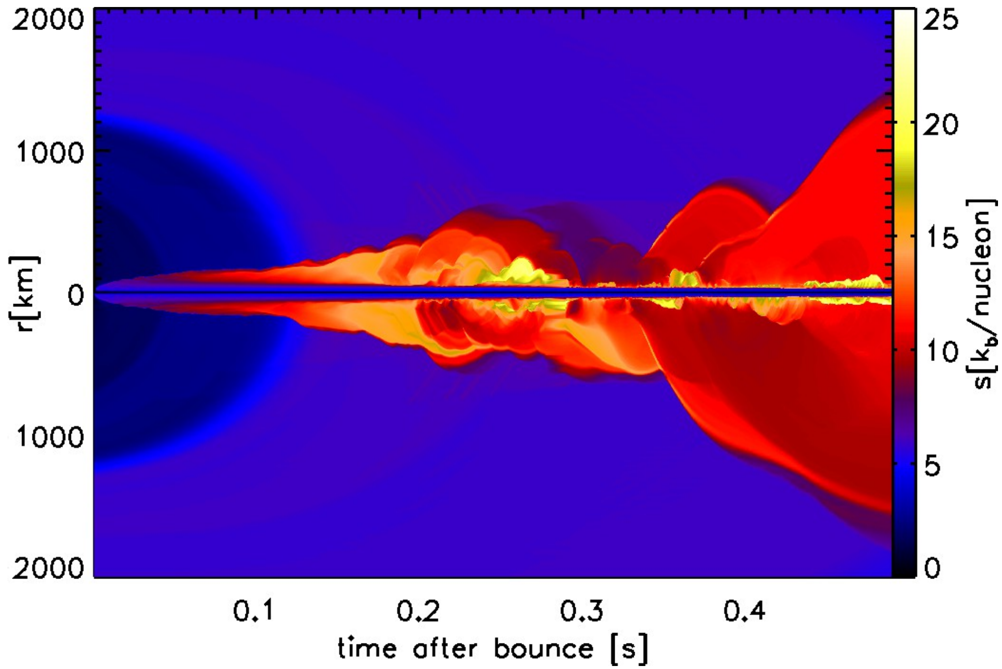


(Bruenn et al., SciDAC2009;
JoP Conf. Ser. 180 (2009) 012018)

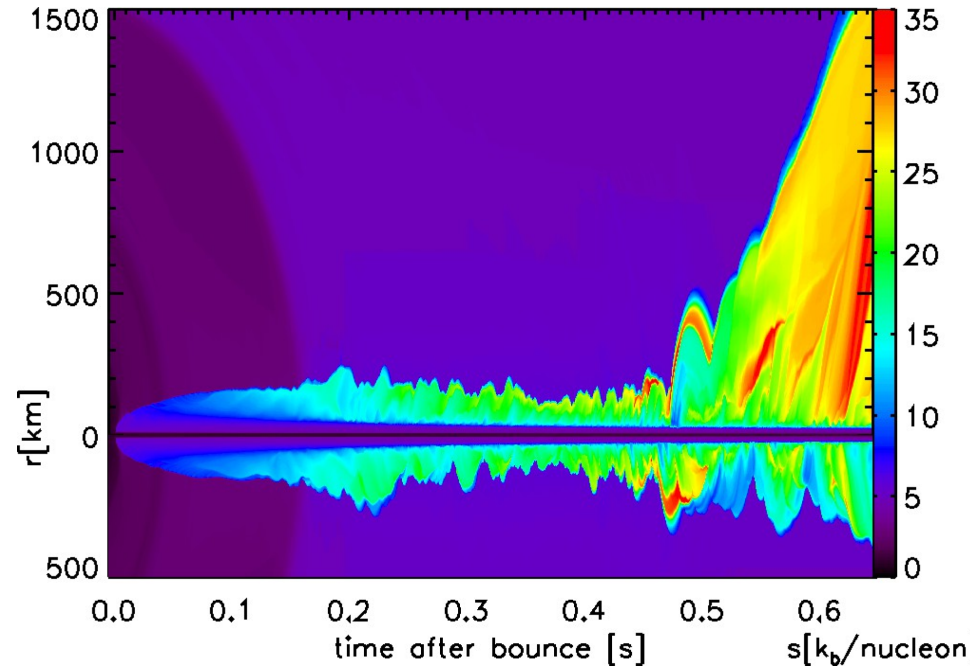
Simulations with CHIMERA code show faster and more energetic explosions.
Onset of explosion at essentially the same time for different progenitors (?)

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

11.2 M_{sun}



15 M_{sun}



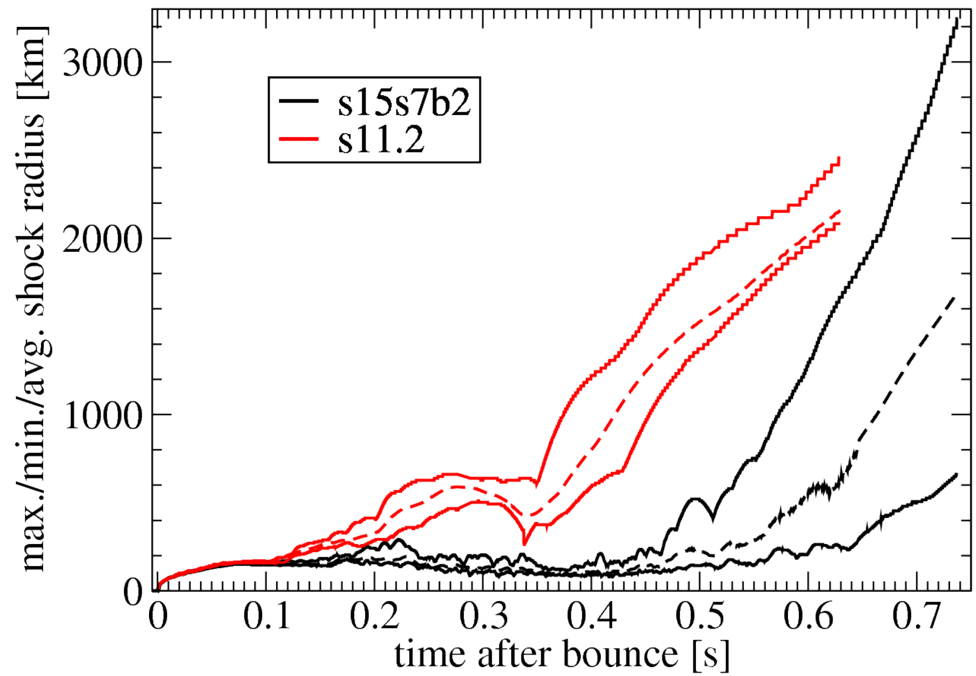
(Müller, THJ, Marek & Dimmelmeier, to be submitted)

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

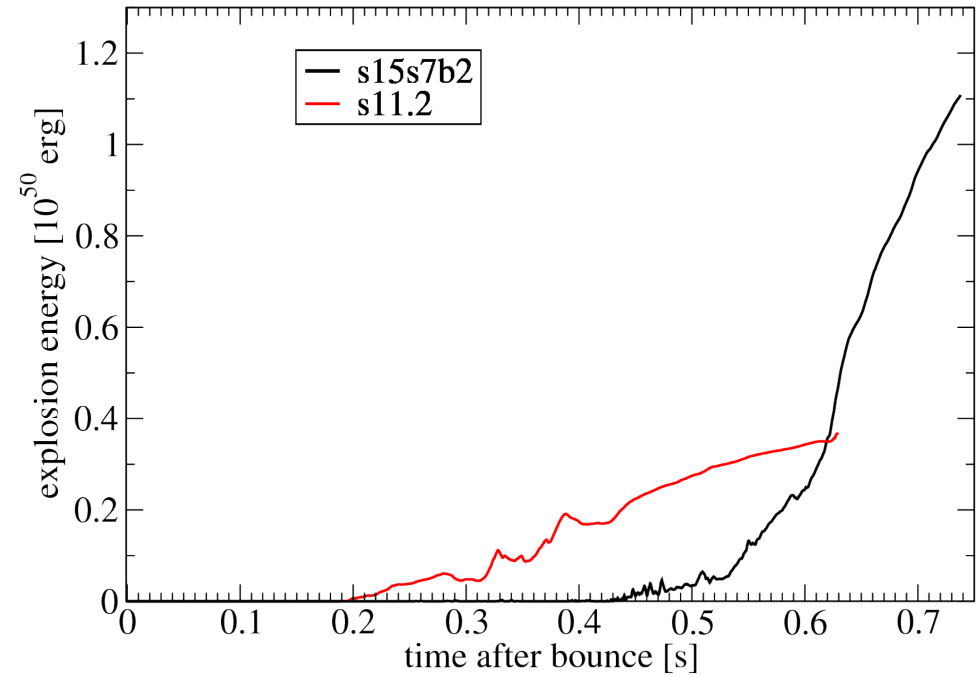
See poster !

Relativistic 2D SN Simulations

Shock radii



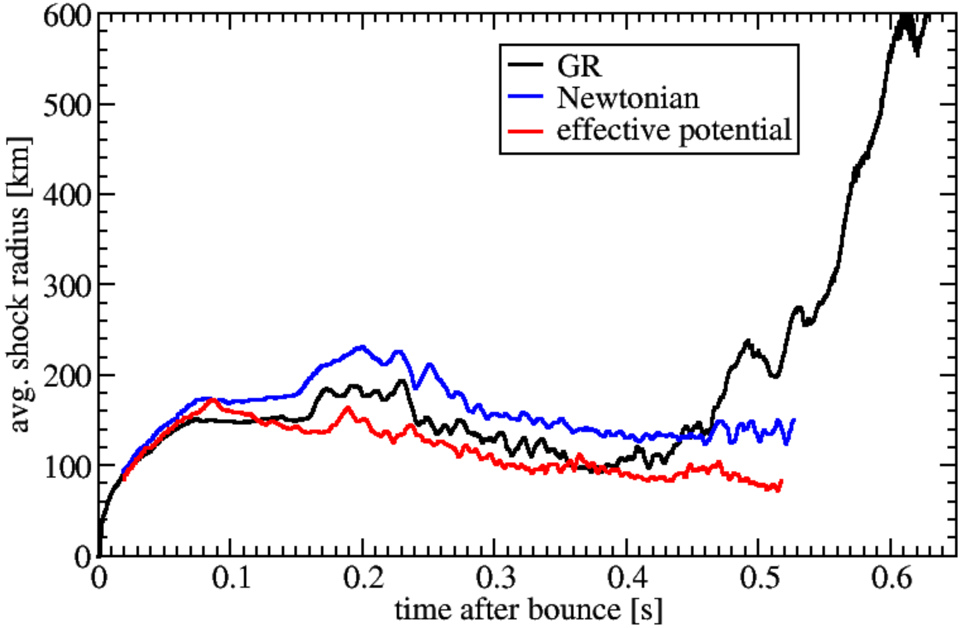
Explosion energies

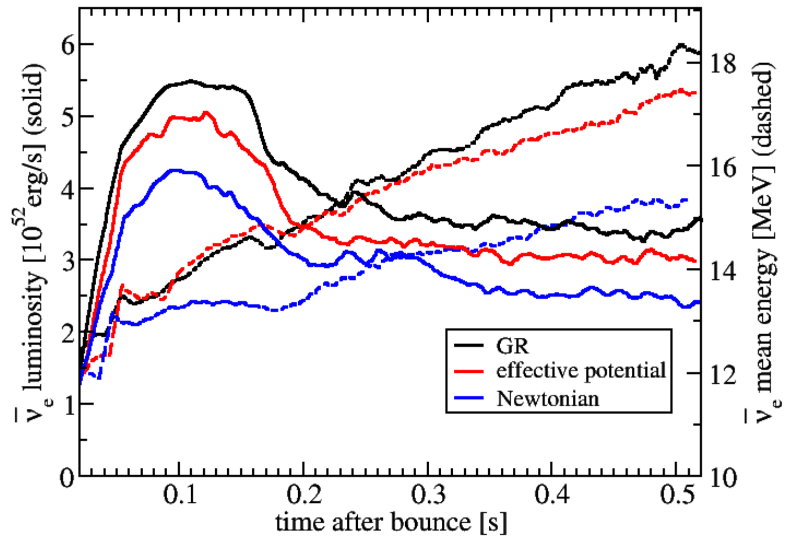


(Müller, THJ, Marek & Dimmelmeier, to be submitted)

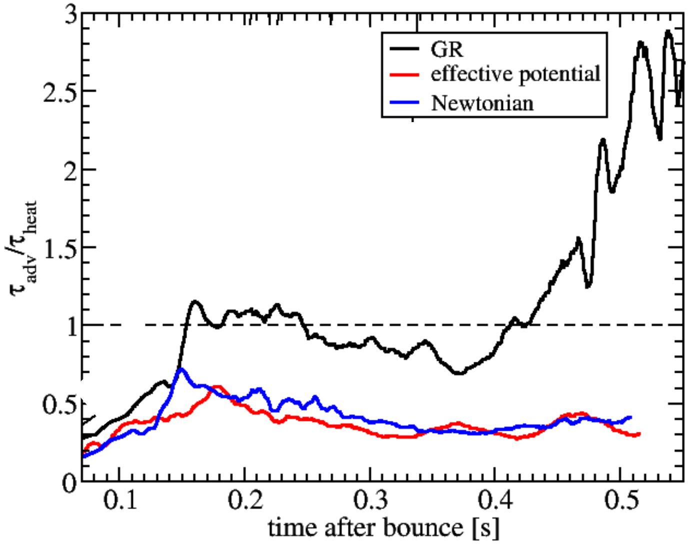
- Relativistic (GR) 2D calculations basically confirm our "post-Newtonian" results.
- Explosions with GR develop somewhat faster and earlier. GR effects help!
- 2D explosions are seemingly "marginal", i.e., tend to set in late and to be relatively weak and highly deformed.

General Relativity Fosters Explosions





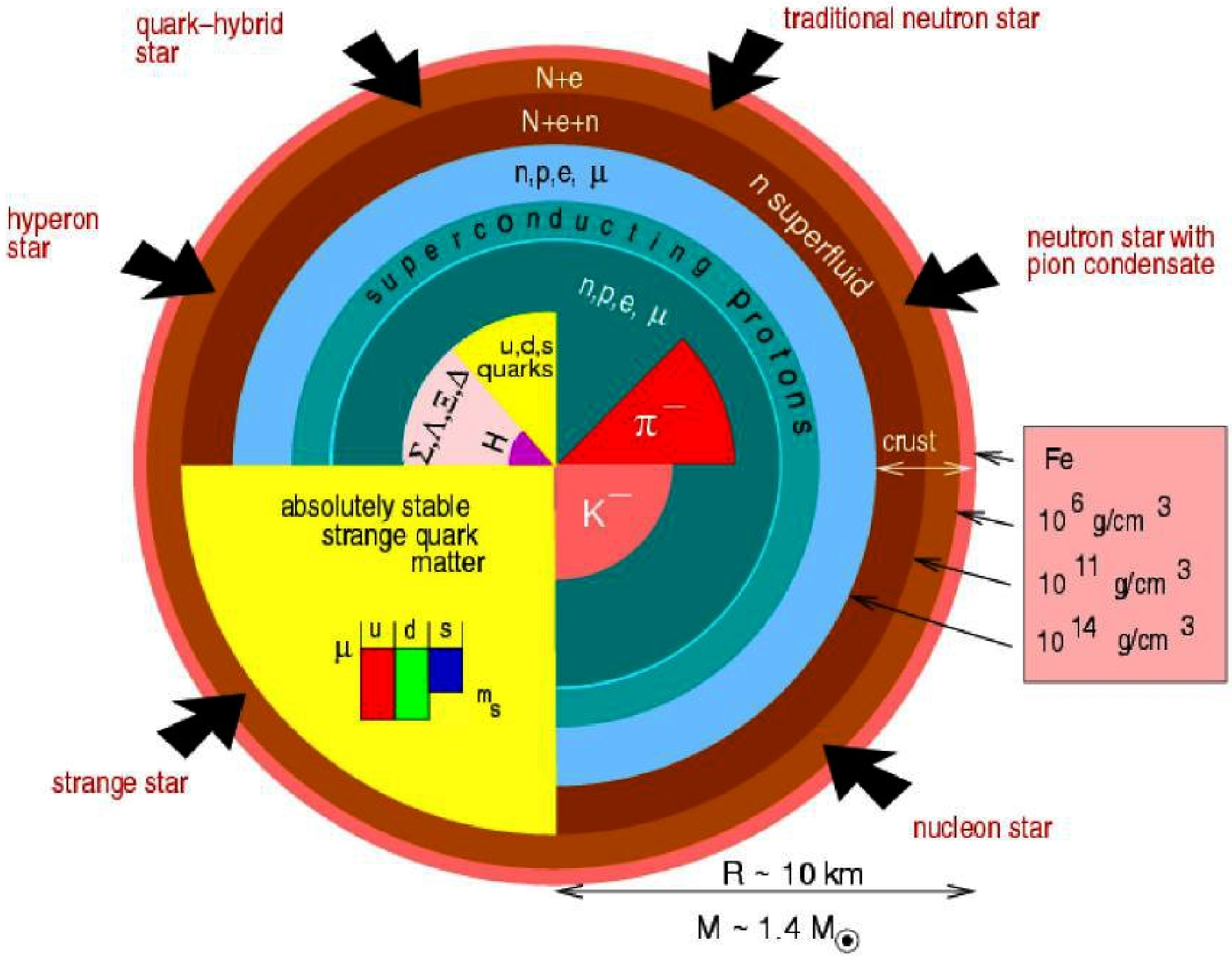
See poster !



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

Neutron Star Equations of State

Neutron star EoS is crucial ingredient but highly uncertain!



(Source: F. Weber)

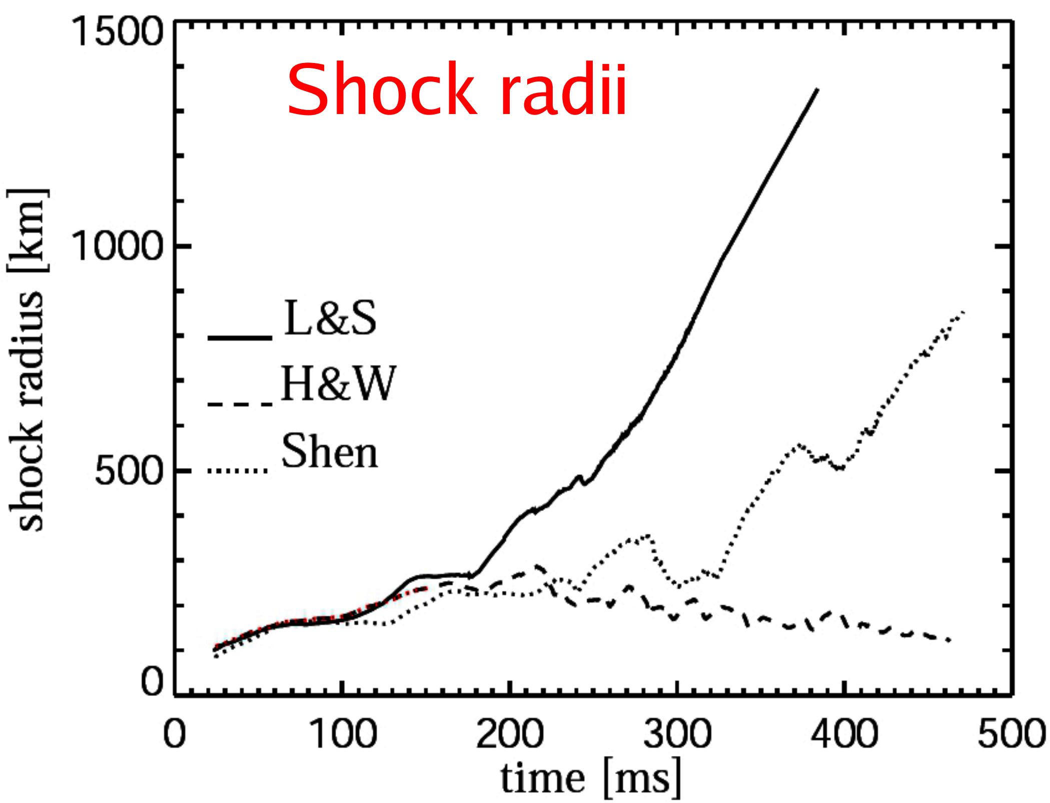
2D Explosions of 11.2 M_{sun} star : Test of EoS Influence

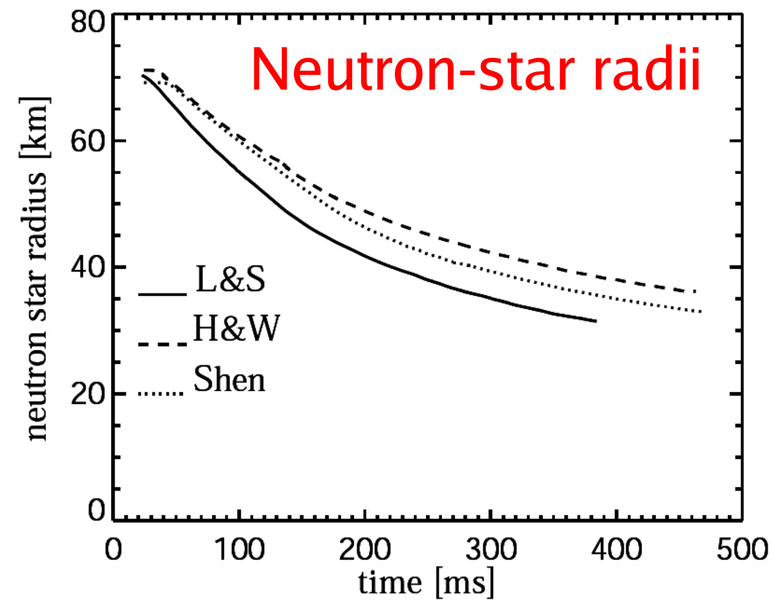
- Simulations for 3 different nuclear EoSs:

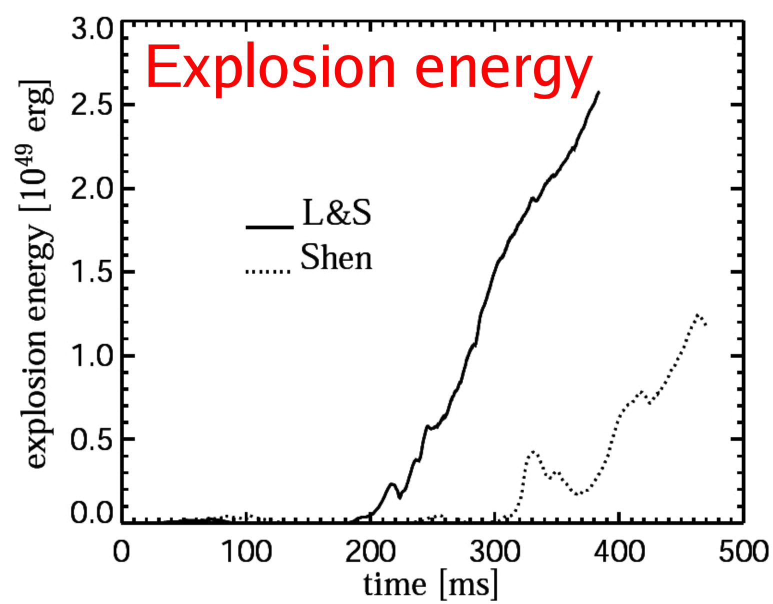
  Lattimer & Swesty (L&S), Hillebrandt & Wolff (H&W), Shen et al.

- “Softer” (L&S) EoS and thus more compact PNS leads to earlier explosion.

- Reasons: more neutrino heating, more violent convective activity.

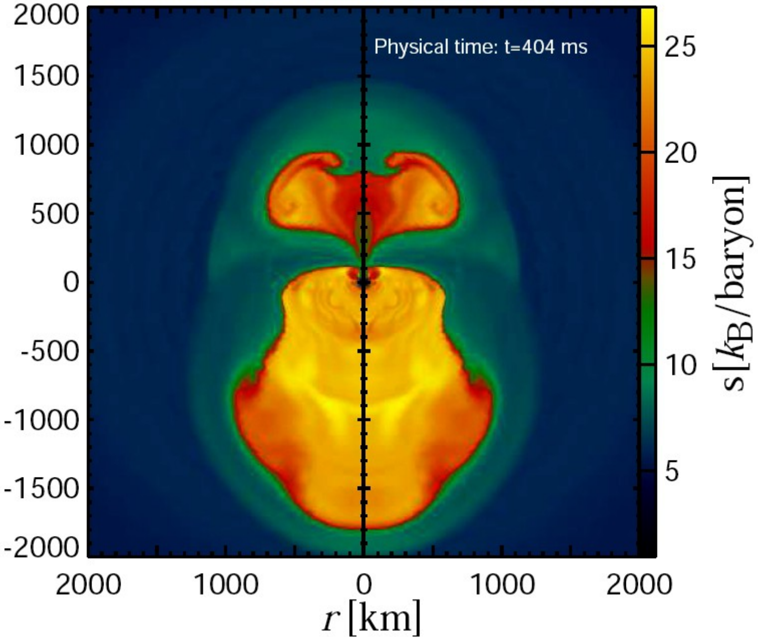




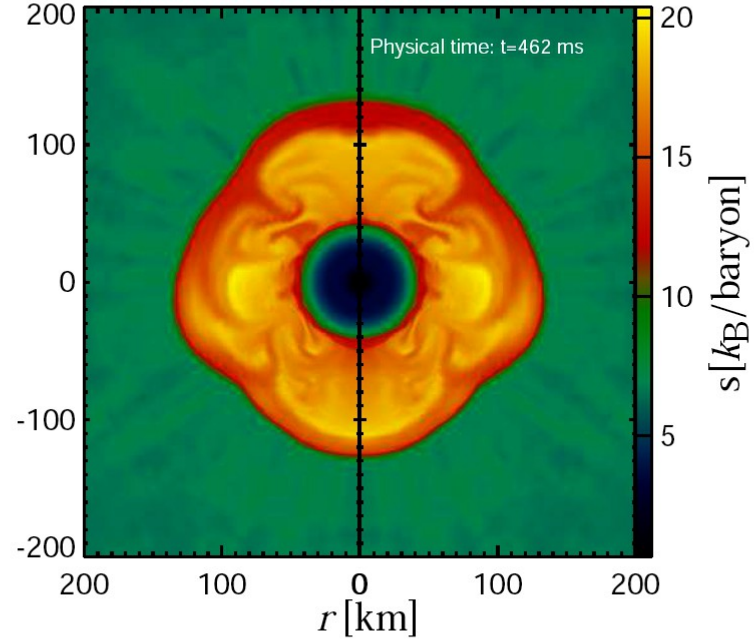


(Andreas Marek 2010, unpublished)

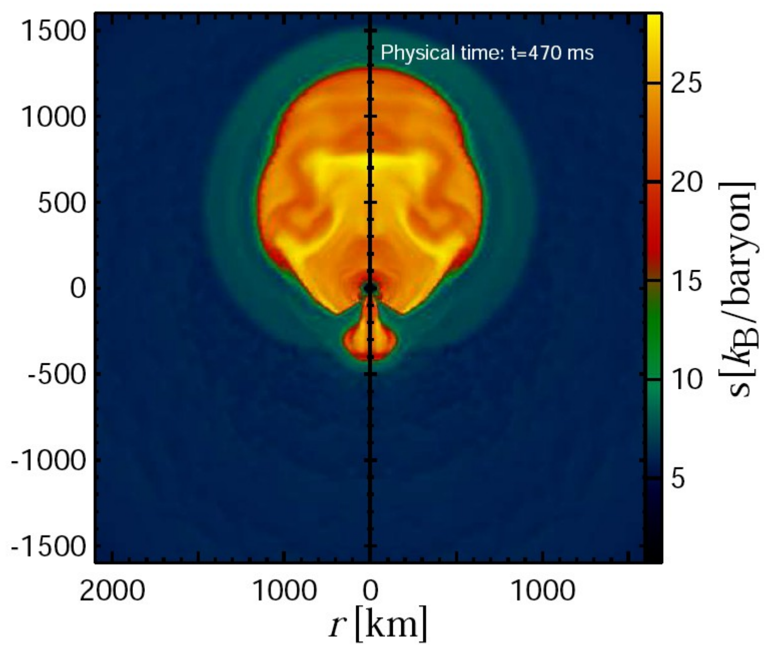
2D Explosions of 11.2 M_{sun} star : Test of EoS Influence



L&S EoS, t ~ 400 ms p.b.



H&W EoS, t ~ 460 ms p.b.



Shen EoS,
t ~ 470 ms p.b.

(Andreas Marek 2010,
unpublished)

3D vs. 2D Differences ?

The Astrophysical Journal, 720:694–703, 2010 September 1 doi:10.1088/0004-637X/720/1/694

DIMENSION AS A KEY TO THE NEUTRINO MECHANISM OF CORE-COLLAPSE SUPERNOVA EXPLOSIONS

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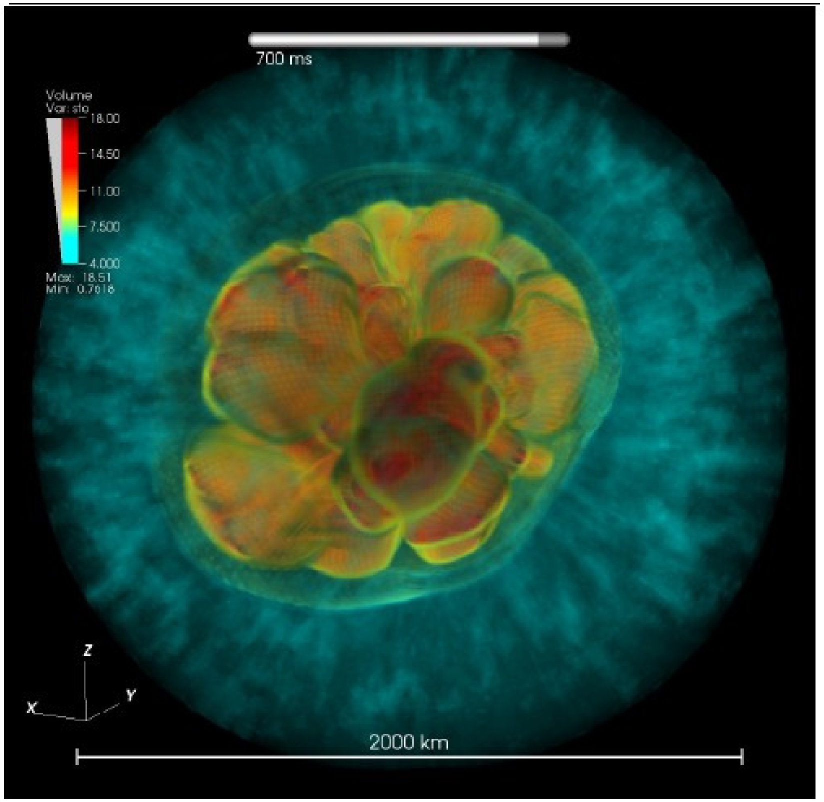
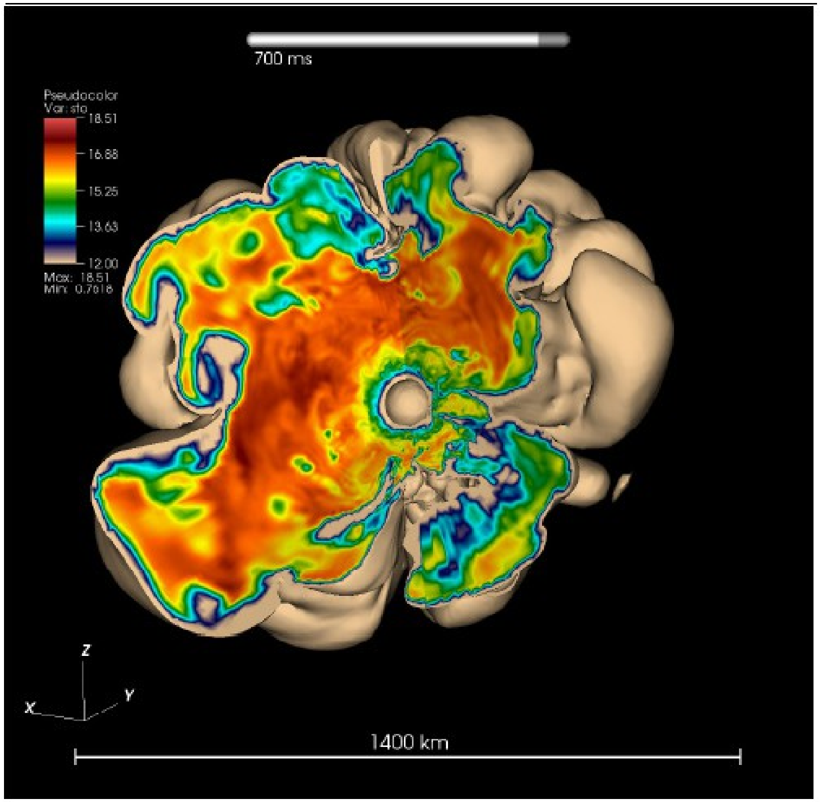
Received 2010 June 18; accepted 2010 July 7; published 2010 August 12

However, the difference in the character of 3D turbulence, with its extra degree of freedom and inverse cascade to smaller turbule scales than are found in 2D, may further increase the time matter spends in the gain region, so that the critical condition for explosion (Burrows & Goshy 1993; Murphy & Burrows 2008) is more easily achieved. Our thesis in embarking upon this project was that if going from 2D to 3D improves prospects for the neutrino-driven explosion by the same degree as already demonstrated by going from 1D to 2D (see Section 2), then the neutrino-driven mechanism would perhaps be shown to be not only viable, but also robust. In that case, the details of neutrino interactions, general relativity, and nuclear physics would be of secondary importance for demonstrating the mechanism of explosion,

3D Supernova Simulations are Needed!

- 3D code version is presently constructed and in test phase (F. Hanke, L. Hüdepohl, B. Müller; Andreas Marek (RZG)).
- We are beginning to explore 3D phenomena and effects (F. Hanke).





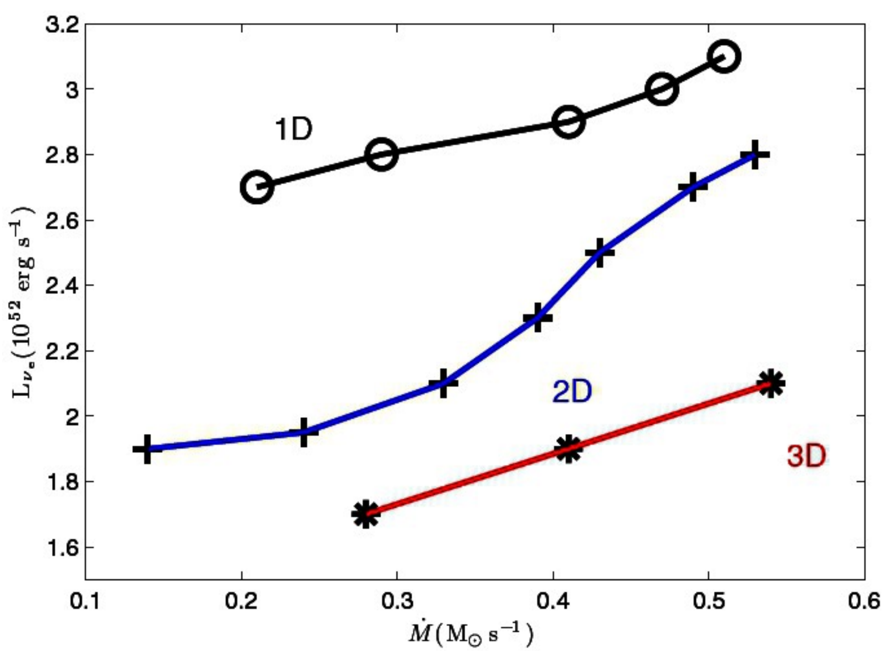
Simulations: Florian Hanke;
Visualization: Elena Erastova, Markus Rampp (RZG)

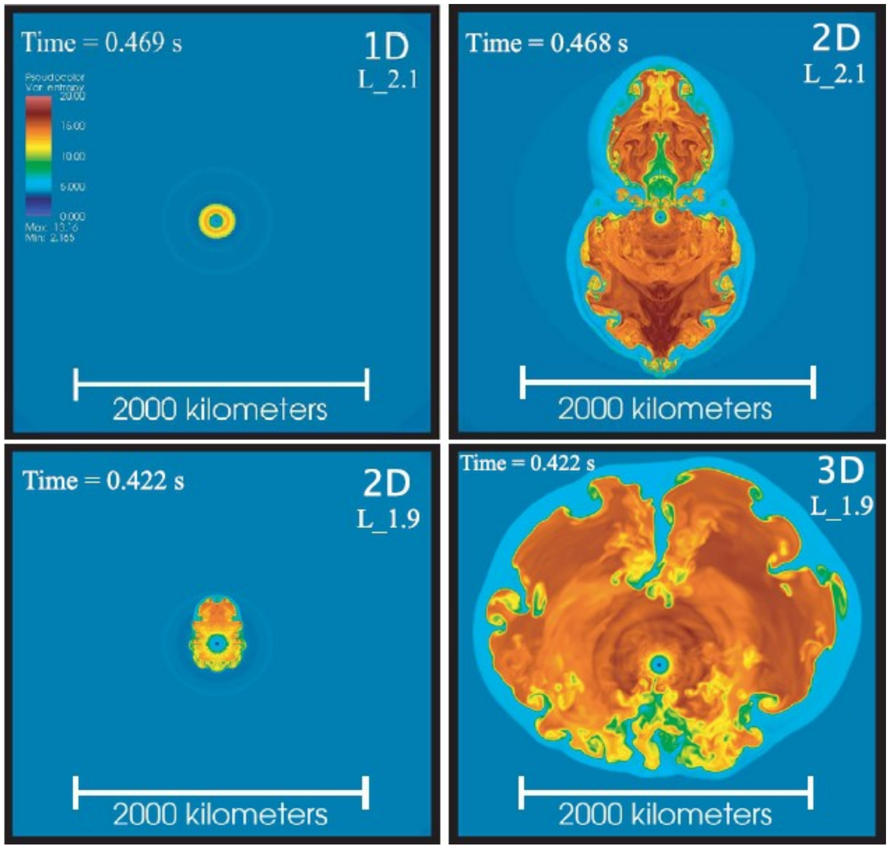
2D-3D Differences in Parametric Explosion Models

- Nordhaus, Burrows et al. performed 2D & 3D simulations with simple neutrino-heating and cooling terms and found 15–25% improvement in 3D for 15 M_{sun} progenitor star (ApJ 720 (2010) 694)

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

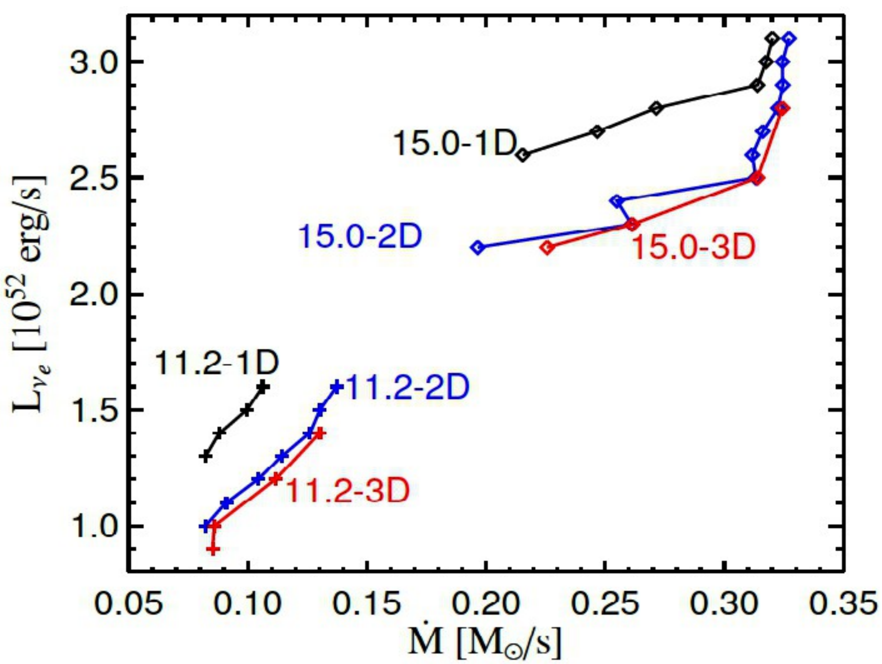
$$\mathcal{C} = 1.399 \times 10^{20} \left(\frac{T}{2\ \mathrm{MeV}}\right)^6 (Y_\mathrm{n} + Y_\mathrm{p}) e^{-\tau_{\nu_e}} \left[\frac{\mathrm{erg}}{\mathrm{g\ s}}\right]$$

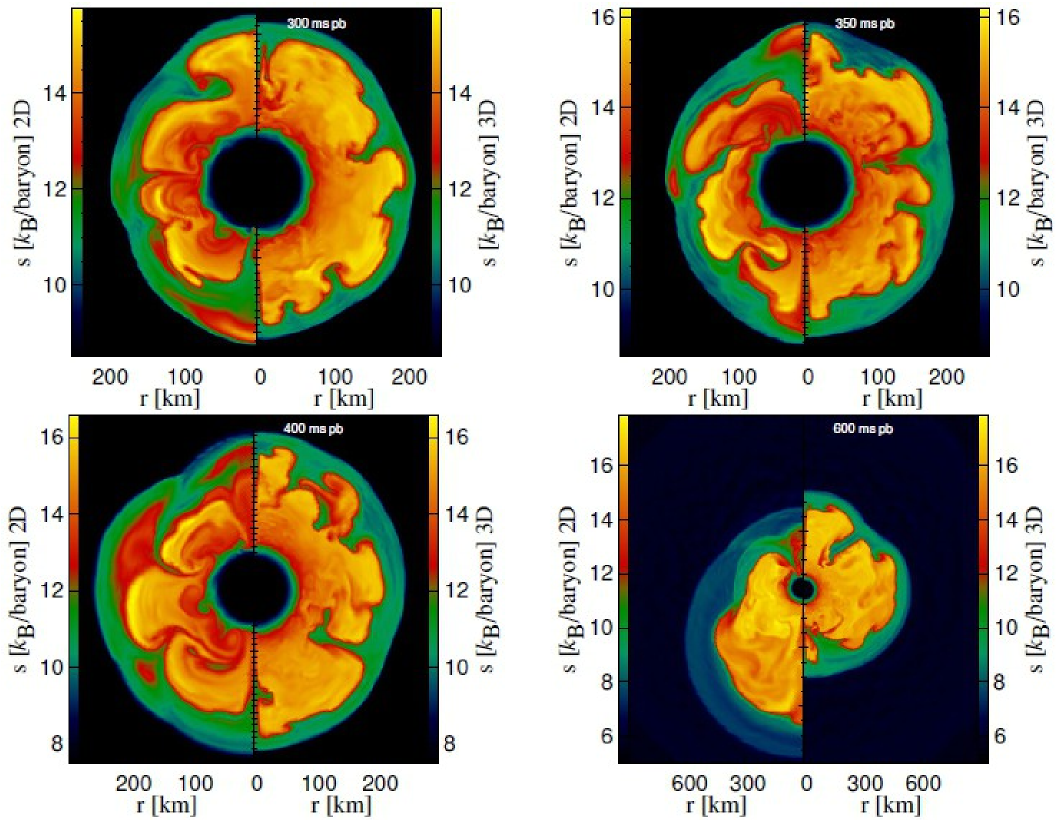




2D-3D Differences in Parametric Explosion Models

- 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 11.2 M_{sun} model, L = 1.0*10^{52} erg/s

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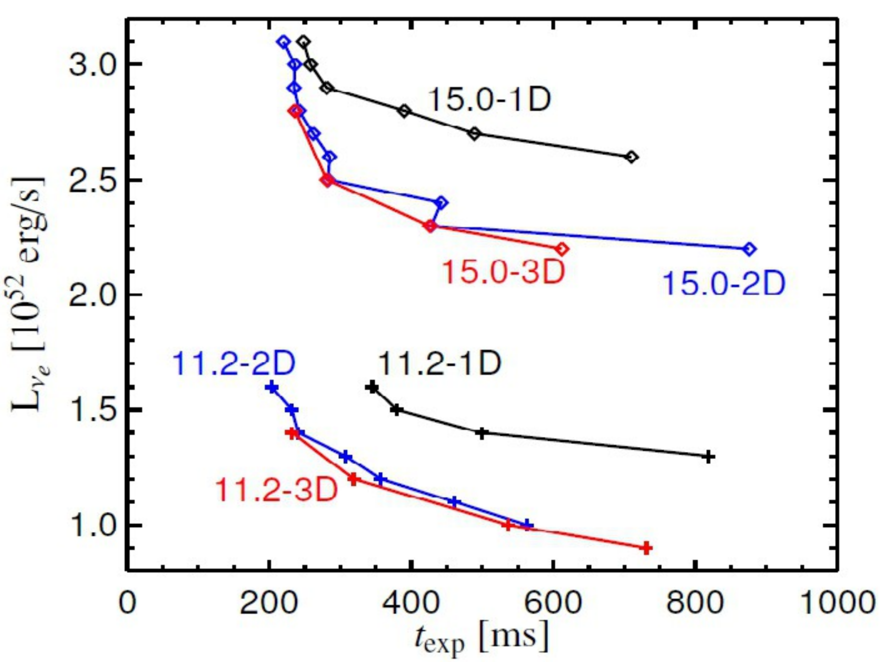
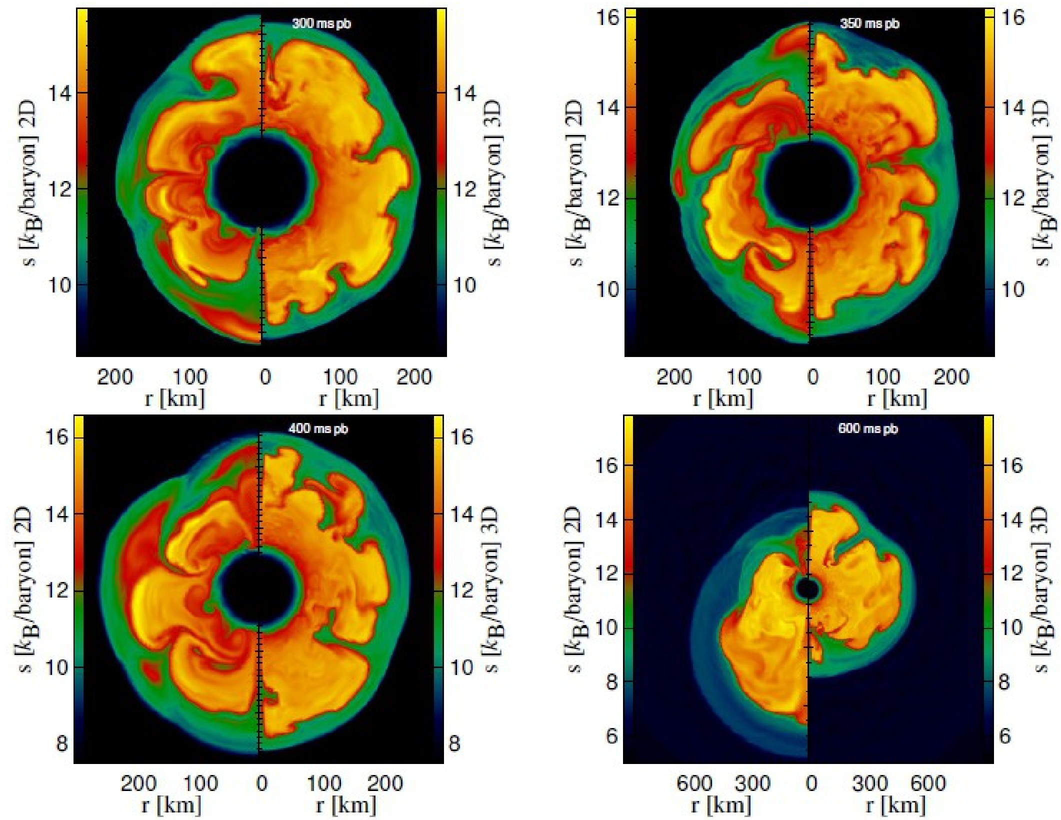
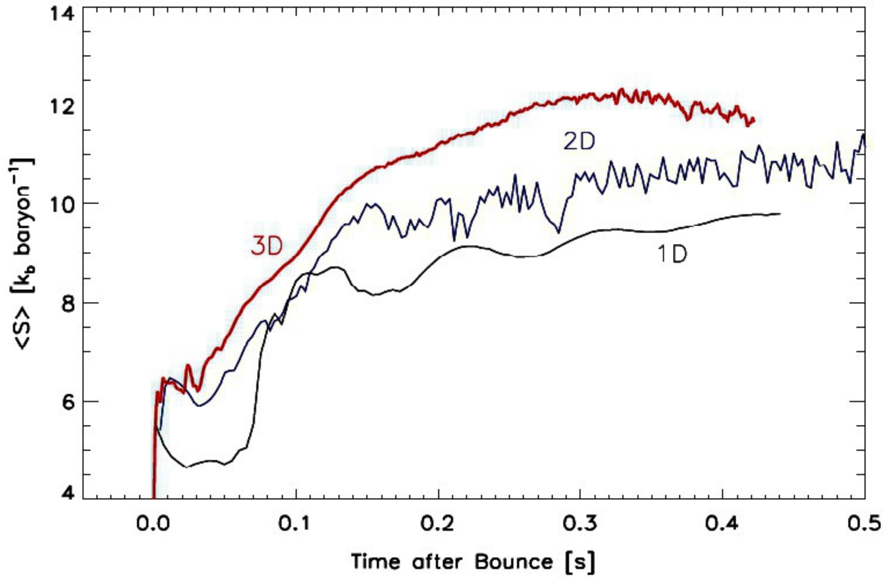




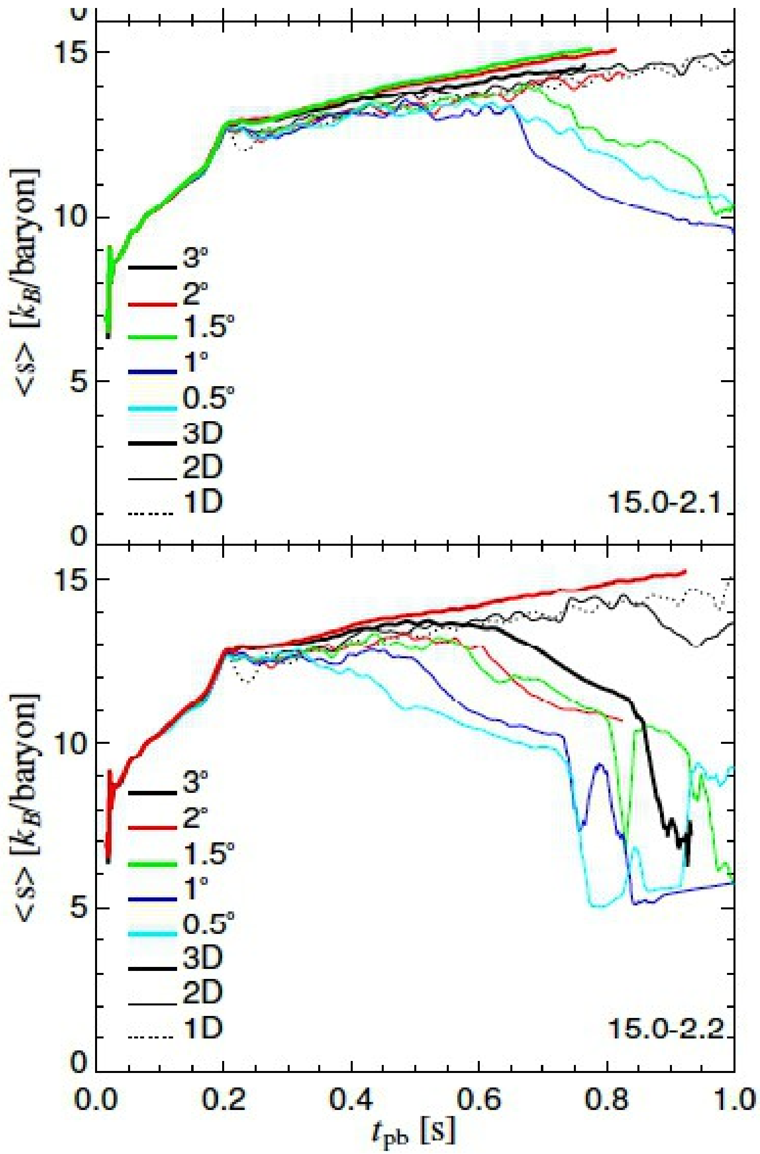
2D & 3D slices for 11.2 M_{sun} model, L = 1.0*10^{52} erg/s

2D-3D Differences

Average entropy of gas in gain layer is not good diagnostic quantity for proximity to explosion



Nordhaus et al., ApJ (2010)

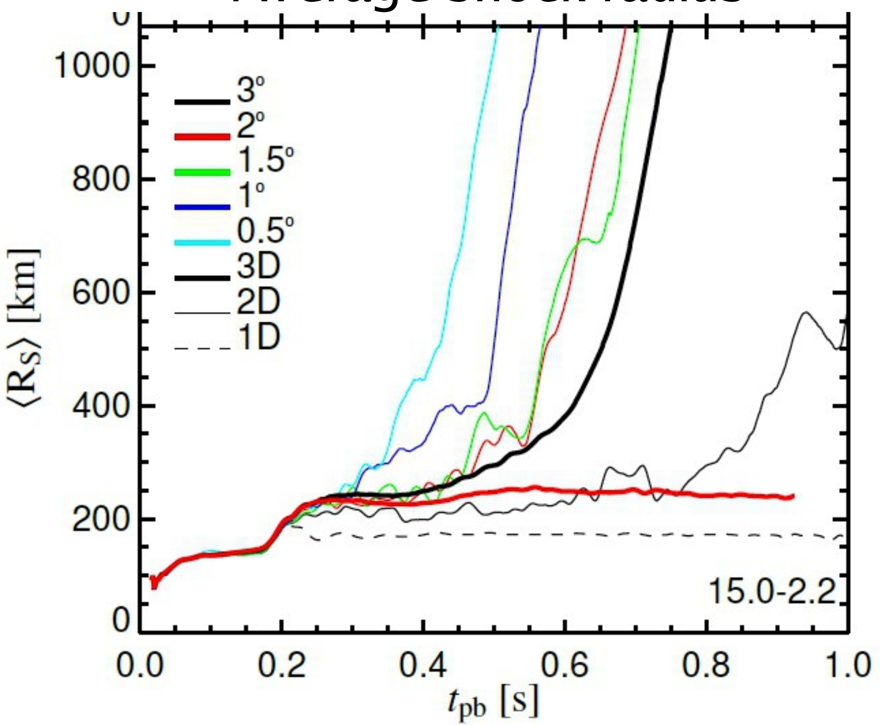


Hanke et al., to be submitted (2011)

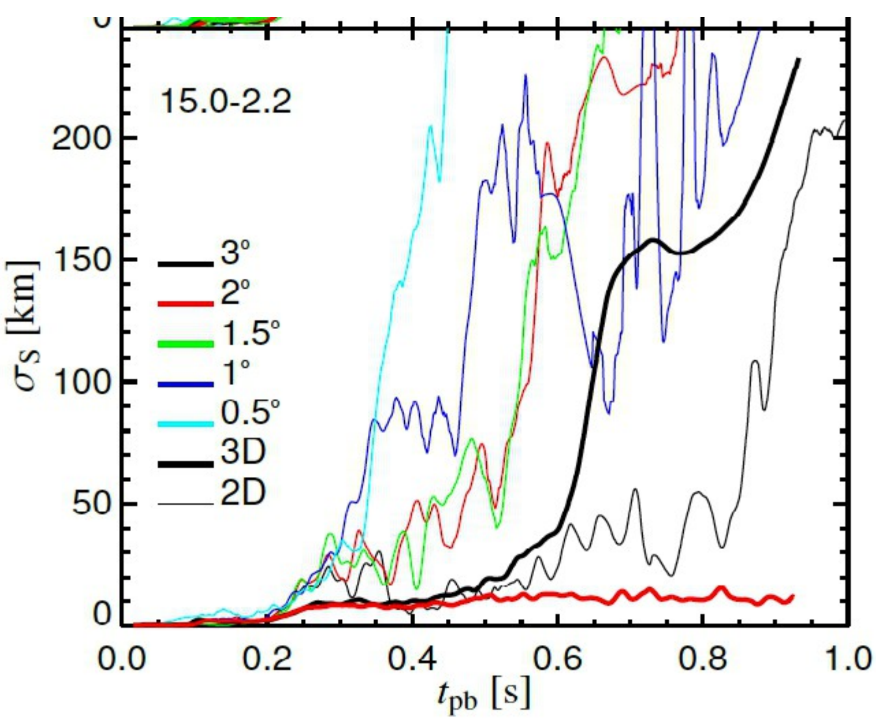
2D-3D Differences

Higher angular resolution fosters explosions in 2D but delays or prevents explosions in 3D !!!

Average shock radius



Standard deviation of shock radius

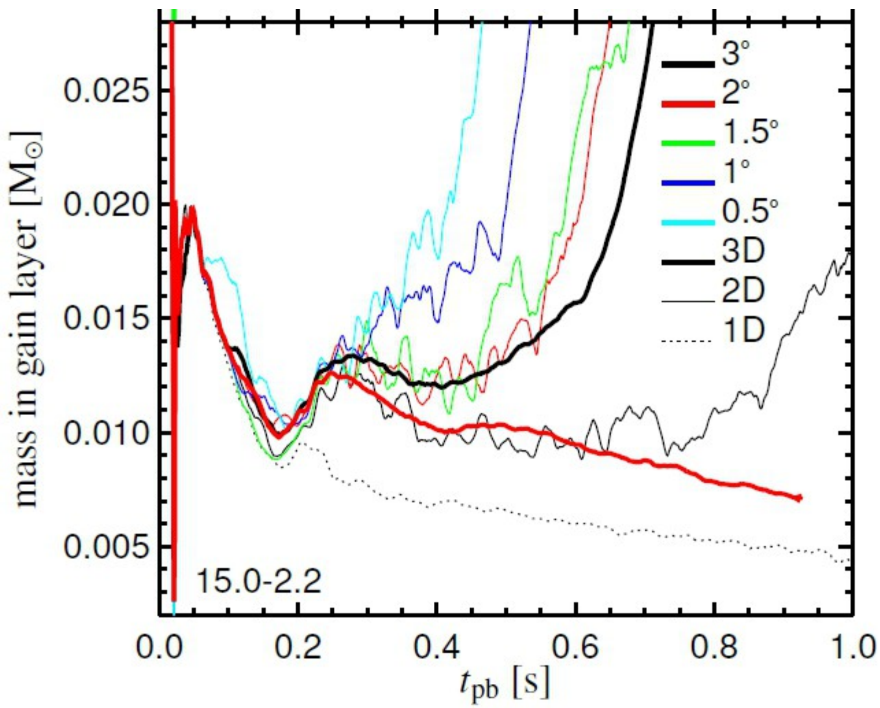


Hanke et al., to be submitted (2011)

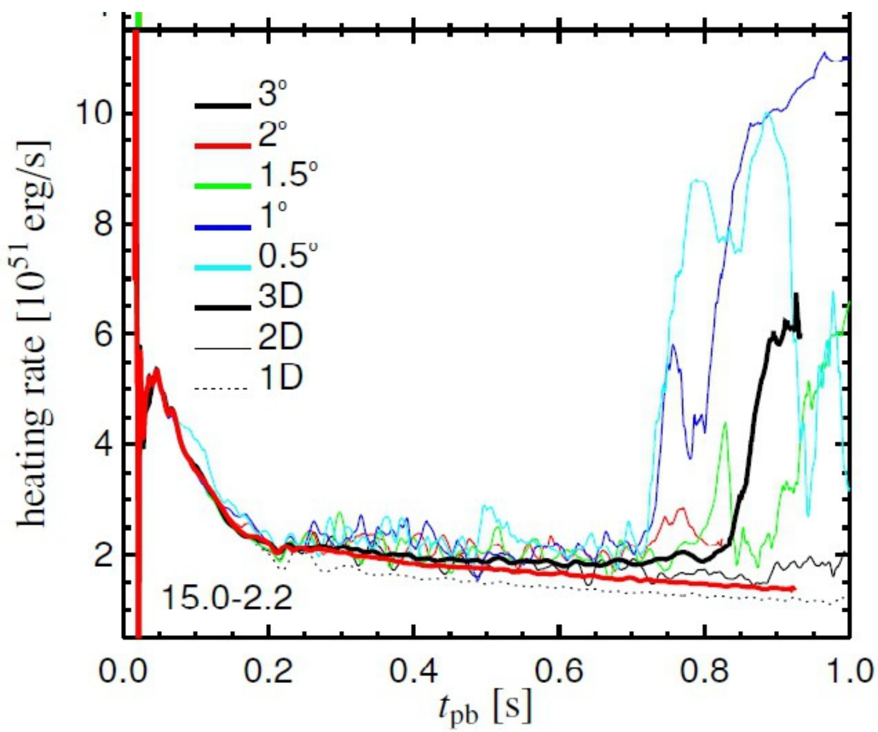
2D-3D Differences

3D models with higher angular resolution become more similar to 1D models !!!

Mass in gain layer



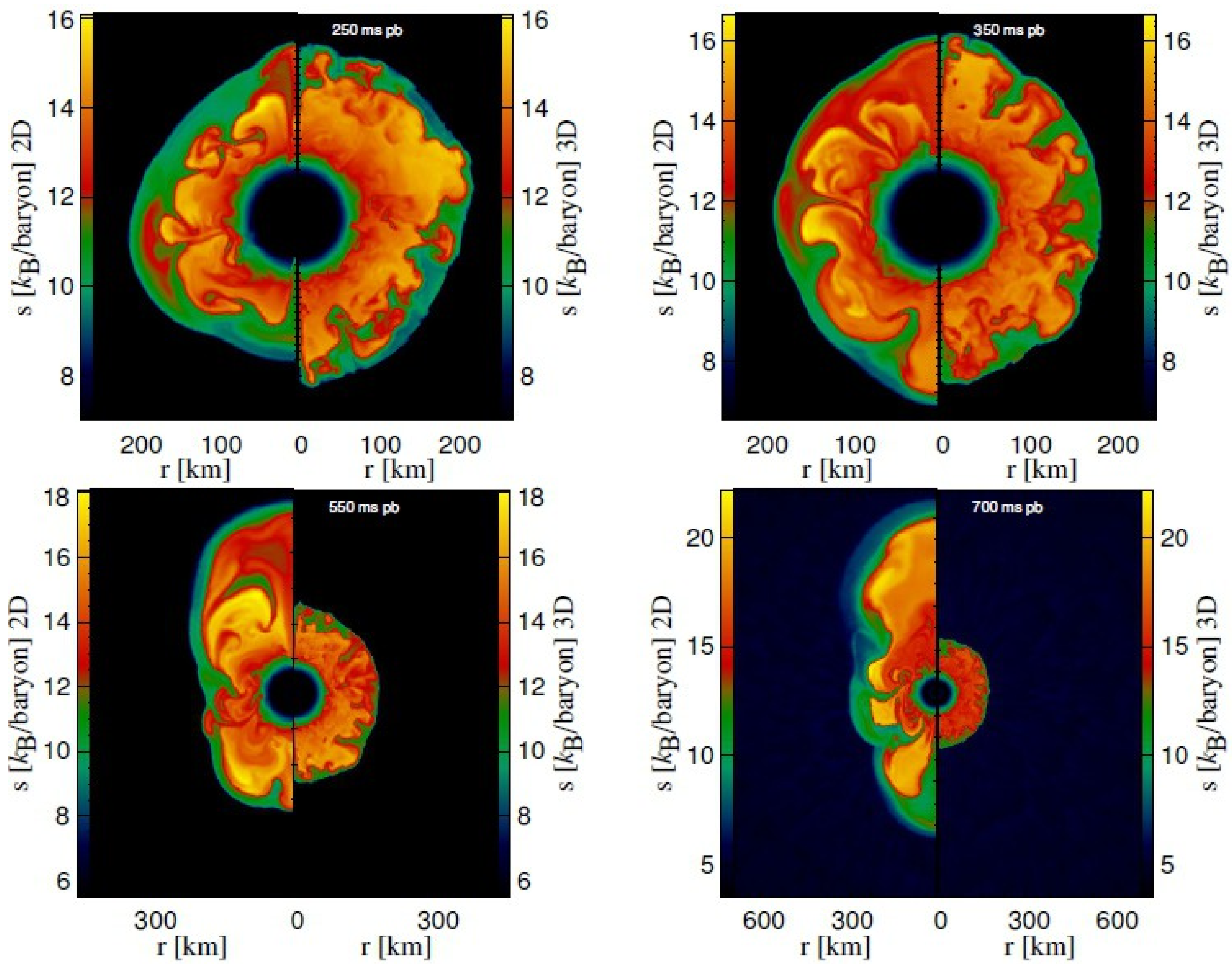
Neutrino heating rate in gain layer



Hanke et al., to be submitted (2011)

2D-3D Differences

Turbulent energy cascade in 2D "powers" SASI, but in 3D drives small-scale vortex flows and fragmentation



Hanke et al., to be submitted (2011)

Questions & Challenges

- OF COURSE, 3D IS IMPORTANT!
- 2D–3D difference depends on neutrino treatment.
  Detailed transport will be necessary to clarify 3D effects!
- Findings by Nordhaus et al. are NOT "robust".
- We find evidence that turbulent energy cascade fosters SASI in 2D with higher resolution, but to damp it in 3D
- Large-scale mass motions improve explosion conditions, enhanced turbulence on small scales does not in our simulations!
- Is 3D hydrodynamics more favorable for explosions than 2D?
  The answer is not clear yet!!
- What could stir SASI in 3D? Better neutrino physics? Stellar rotation to seed spiral modes? Progenitor anisotropies/perturbations?
- We need detailed comparisons of physics and numerics between different groups!